Status and open problems in Ultra High Energy Cosmic Rays and High Energy Astrophysics

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Multi-Messenger Astrophysics

and the study of:

“High Energy Universe”

The ensemble of astrophysical objects, environments
and mechanisms that generate and store high energy particles
in the Milky Way and in the entire universe.

This field is one of the most significant and fascinating
“Frontiers” in Science today.

1. Understanding the *“COSMOS*" where we live

2. The sources of the High Energy radiation
   are “laboratories” where we can test
   (in conditions that are not achievable in “Earth based laboratories”)
   the Fundamental Laws of Physics.

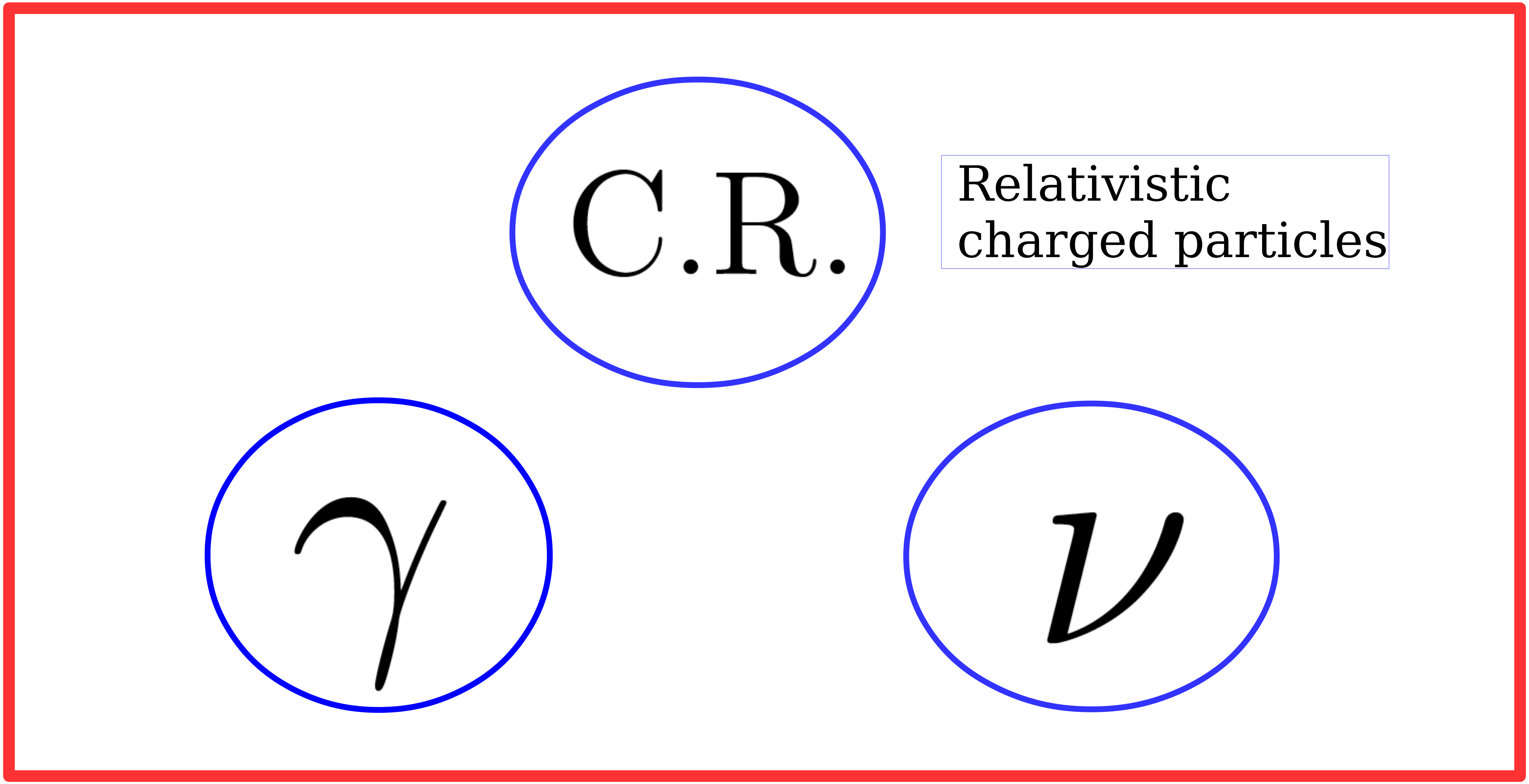
Four Messengers
for the study of the
“High Energy Universe”

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

Three messengers are *"inextricably" tied together*
[Cosmic Rays, Gamma Rays, High Energy Neutrinos]

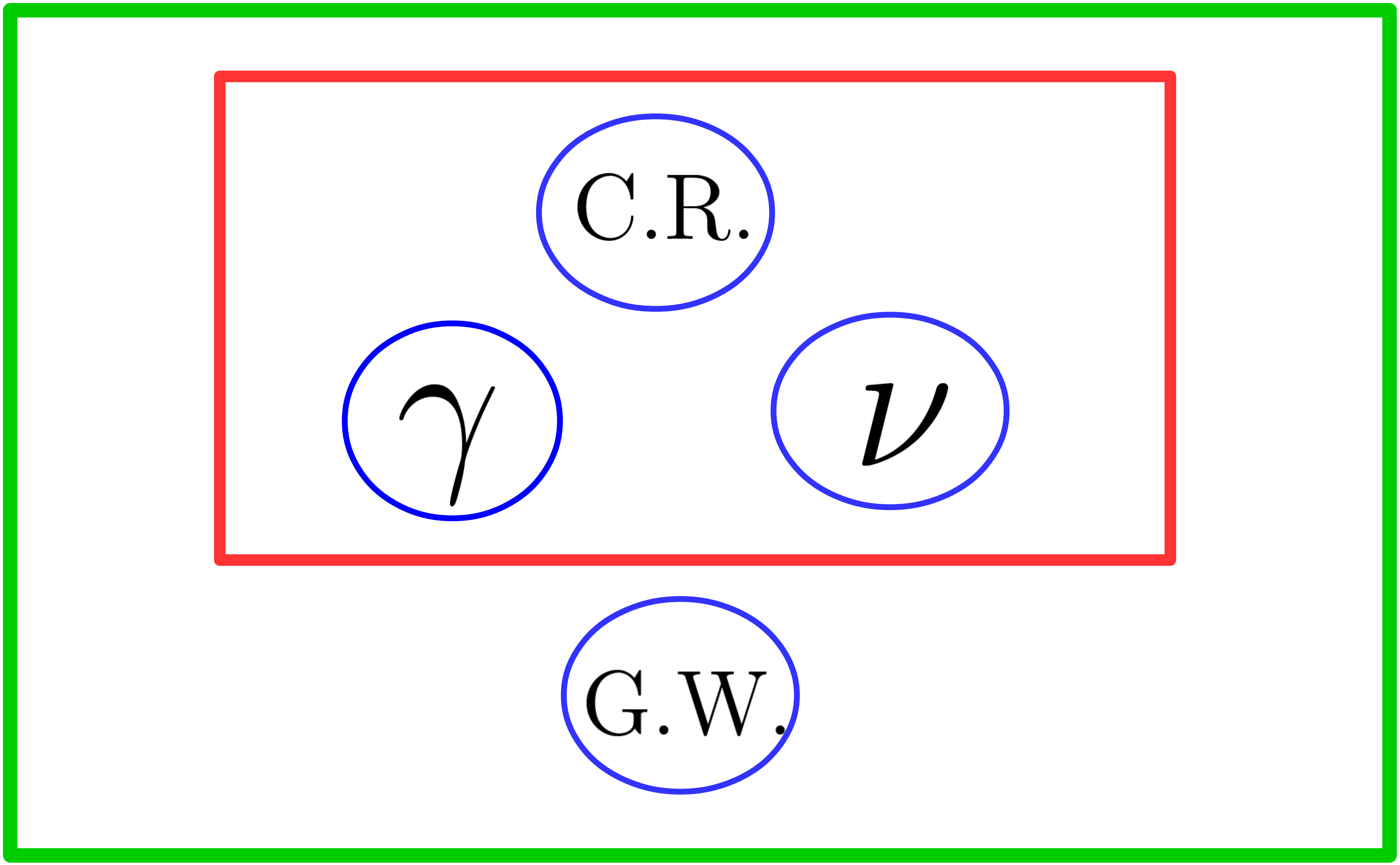
three probes that study the same underlying physical phenomena *(giving complementary information)*



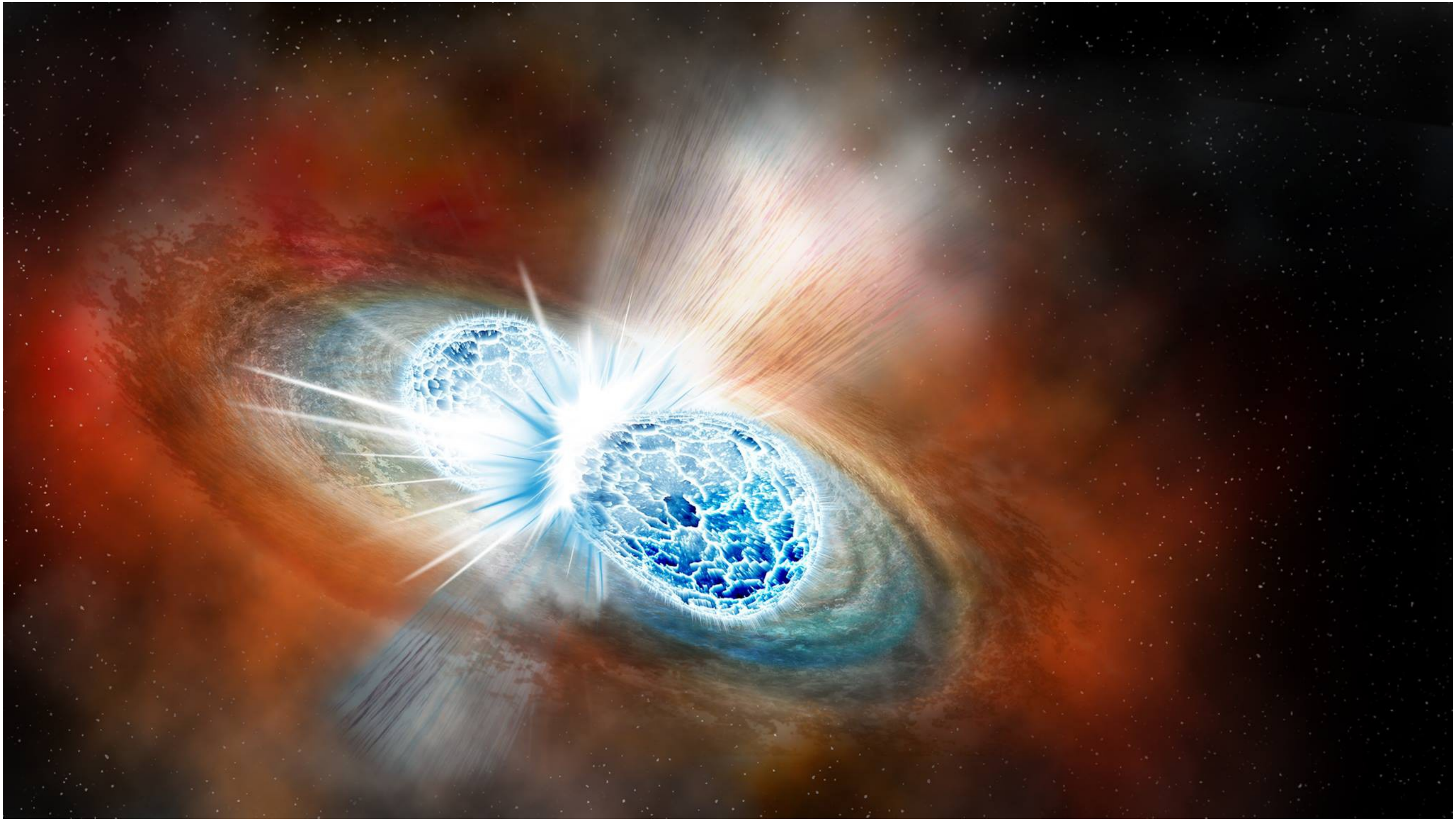
(Some) High Energy Sources can emit observable signals of Gravitational Waves (!!)

Transient sources associated with the formation of compact objects

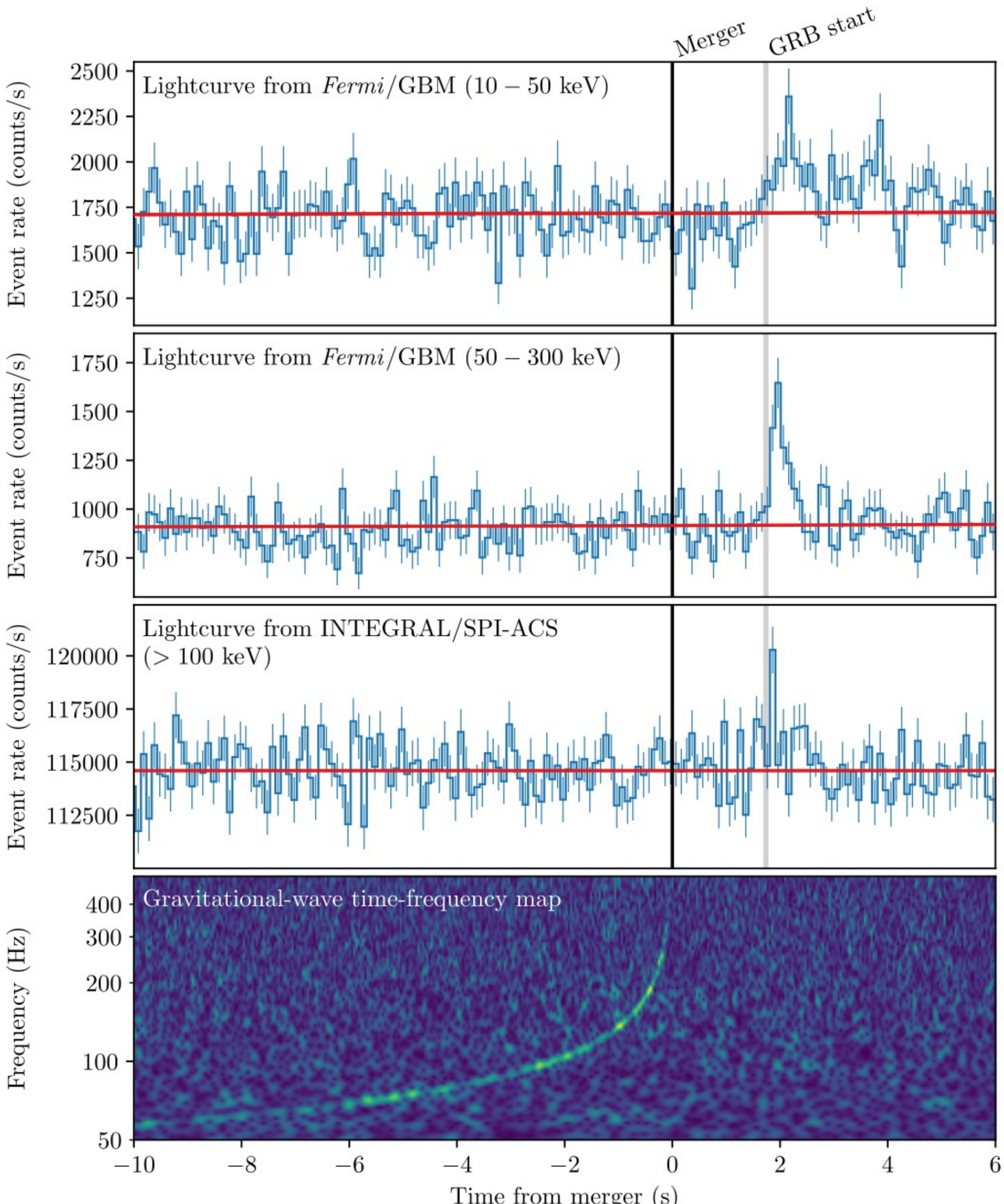
Entering a new exciting era with LIGO/VIRGO



GW 170817 GRB 170817A



(neutron-star)-(neutron-star) coalescence
detected by LIGO/VIRGO [short Gamma Ray Burst]



GRB 170817A

17/08/2017

Neutron stars merger

Extraordinary event !

GW 170817

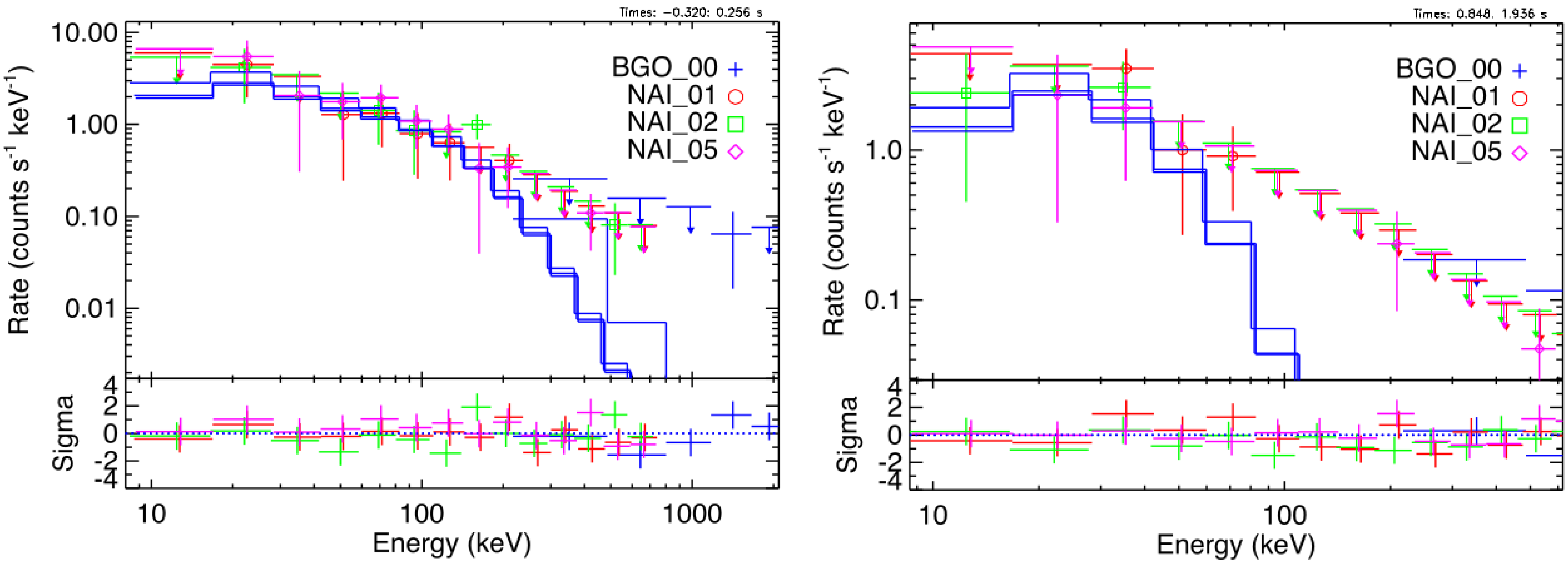
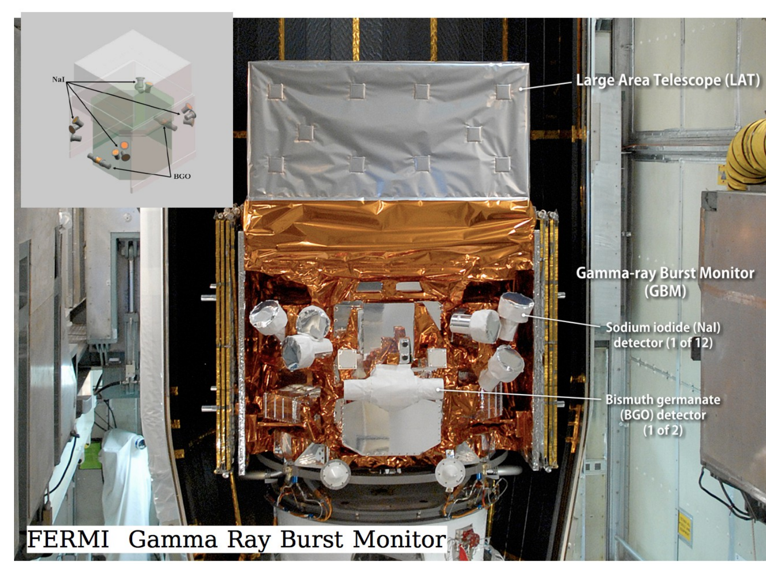


Figure 8. Spectral fits of the count rate spectrum for the (left) main pulse (Comptonized) and (right) softer emission (blackbody). The blue bins are the forward-folded model fit to the count rate spectrum, the data points are colored based on the detector, and 2σ upper limits estimated from the model variance are shown as downward-pointing arrows. The residuals are shown in the lower subpanels.

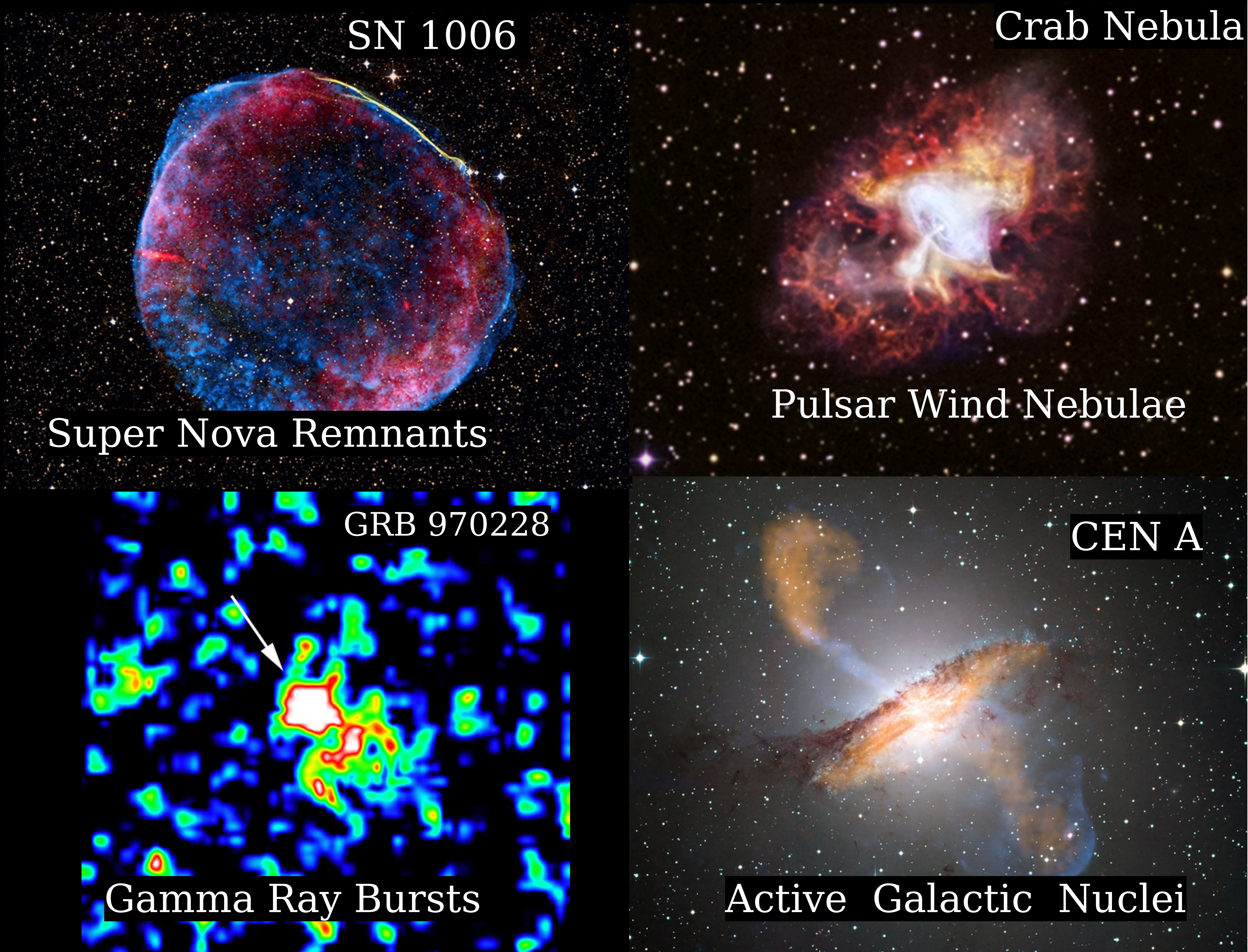
INTEGRAL
SPI-ADC



“High Energy Sources”

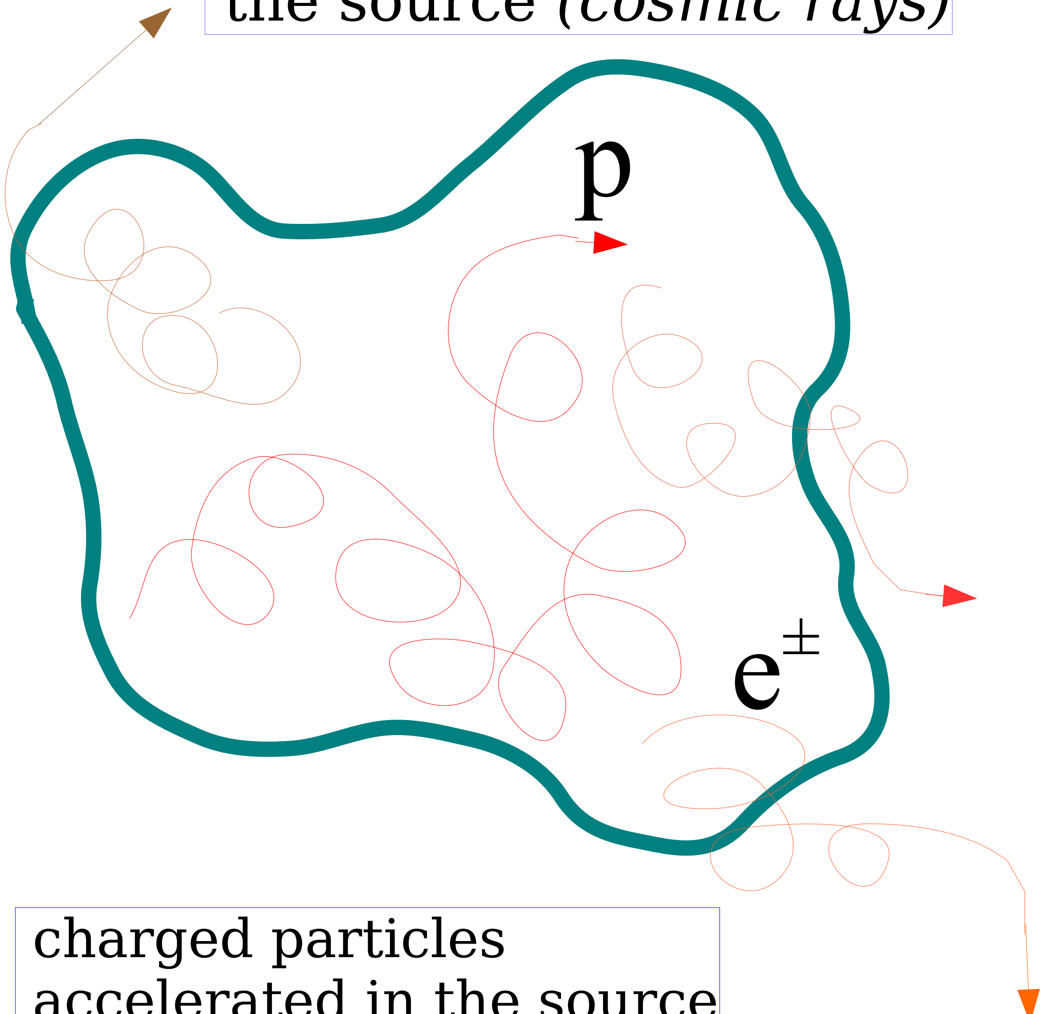
Discovery of *several different classes*
of astrophysical objects/events that are capable
of accelerating particles to relativistic energies

Strange and wonderful beasts in the Sky]


SN 1006
Super Nova Remnants
Crab Nebula
Pulsar Wind Nebulae
GRB 970228
Gamma Ray Bursts
CEN A
Active Galactic Nuclei

Cosmic Ray Source

particles escaping
the source *(cosmic rays)*



charged particles
accelerated in the source

Interactions with gas and
radiation fields *(photons, neutrinos)*

Hadronic emission

$$p + \mathrm{X} \to \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \to \gamma \; \gamma$$

$$\pi^+ \to \mu^+ \; \nu_\mu$$

$$\hookrightarrow \; e^+ \; \nu_e \; \overline{\nu}_\mu$$

Leptonic emission

$$e^\pm \; \gamma_{\mathrm{soft}} \to e^\pm \; \gamma$$

$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\mathrm{syn}}$$

Emission of photons and Neutrinos

$$[p + \text{gas}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \text{gas}] \to \pi^\pm \ (K) \to \nu$$

$$[p + \gamma_{\text{soft}}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \gamma_{\text{soft}}] \to \pi^\pm \ (K) \to \nu$$

(p, He, ...A, ...)

"hadronic emissions"

versus

"leptonic emissions"

Simple clear connection between emissions

Neutrino

and

Gamma Ray

But:
Gamma absorption in source
Gamma absorption in space
Leptonic mechanisms

Emission of photons and Neutrinos

$$[p + \text{gas}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \text{gas}] \to \pi^\pm \ (K) \to \nu$$

$$[p + \gamma_{\text{soft}}] \to \pi^0 \ (\eta) \to \gamma$$

$$[p + \gamma_{\text{soft}}] \to \pi^\pm \ (K) \to \nu$$

$$[e + \gamma_{\text{soft}}] \to e + \gamma$$

$$[e + \text{gas}] \to e + \gamma$$

$$[e + \vec{B}] \to e + \gamma_{\text{syn}}$$

Understanding the "co-acceleration of protons and electrons a fundamental problem

Relation between Comic Rays, Gamma-Rays ans Neutrinos:

Electrically charged particles can acquire very large energies propagating in the electromagnetic fields of astrophysical objects/transients.

Neutrinos and Gamma-rays are *generated with approximately equal rate* in the decay of pions (and other particles) created in the interactions of protons and nuclei *[hadronic mechanism].*

Gamma-rays are also created by radiation processes of relativistic electrons/positrons *[leptonic mechanism]*

Gamma Rays and neutrinos trace the populations of relativistic charged particles (protons/nuclei/electrons/positrons) in the sources

The relation of the fluxes of neutrino and Gamma-rays: reflects:

[1.] The relative importance of the acceleration of
electrons/positrons versus *protons/nuclei*
[a problem of central importance]

[2.] The effects of absorption (of photons)
inside the sources and during propagation
[and neutrino flavor oscillations
+ possibly other (new physics) phenomena]

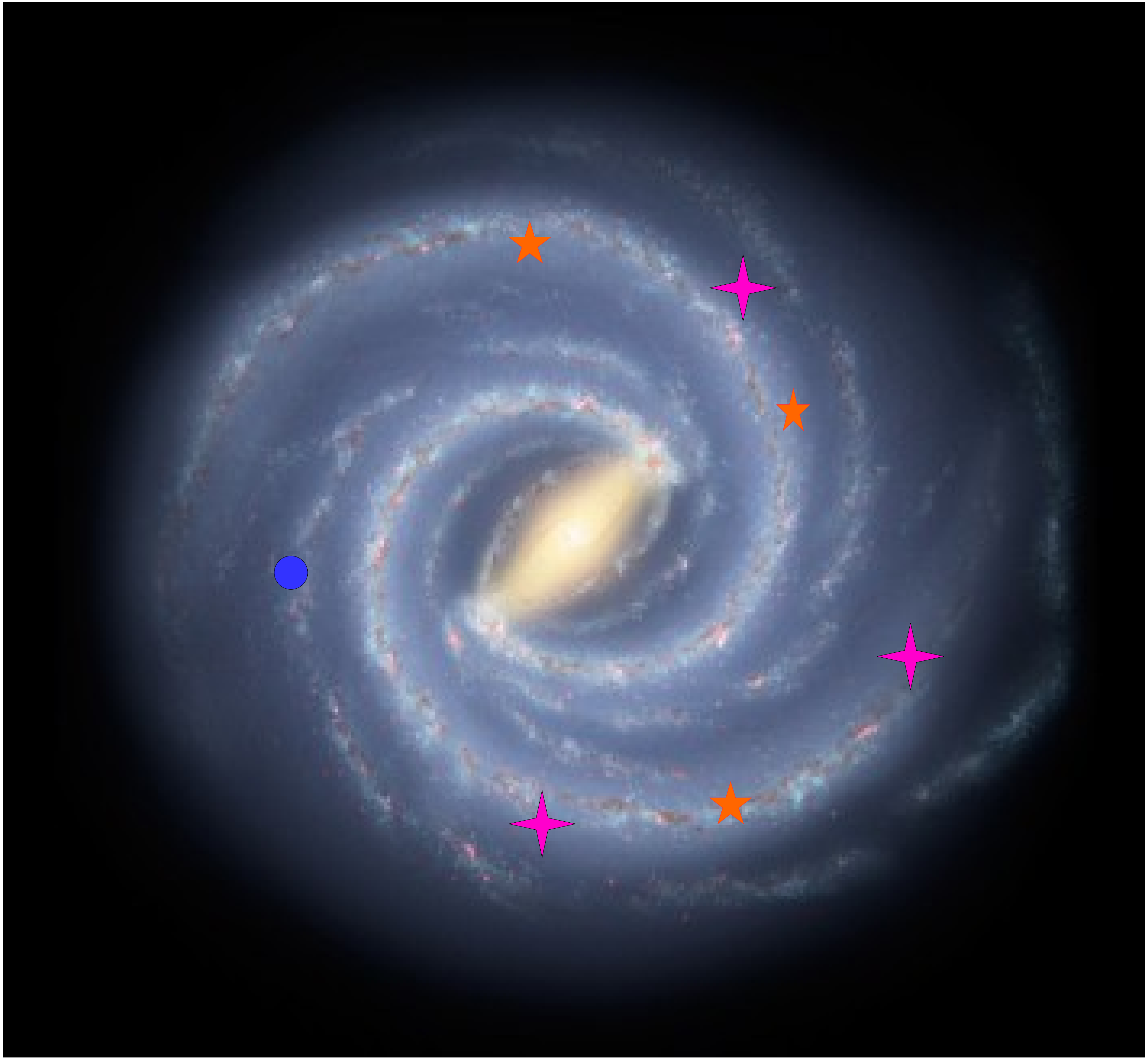
The relation between the
Fluxes of Cosmic Rays observed at the Earth
and the gamma rays and neutrino fluxes is a
much more difficult and less understood problem
because it depends on
(a) Escape of CR from the sources
(b) Propagation (in the Milky Way or/and extra-galactic space)
[Very large uncertainties for both problems]

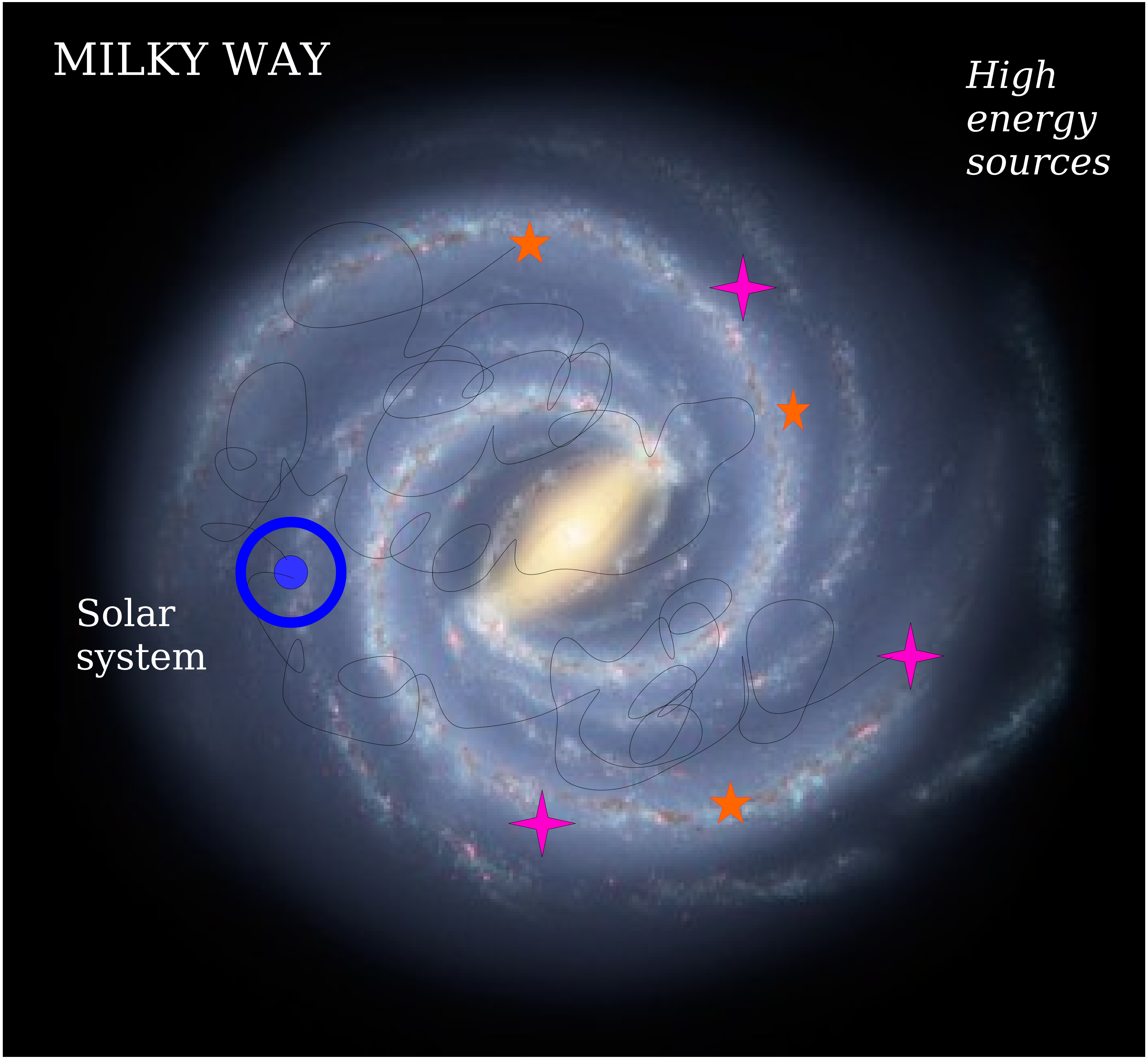
COSMIC RAYS

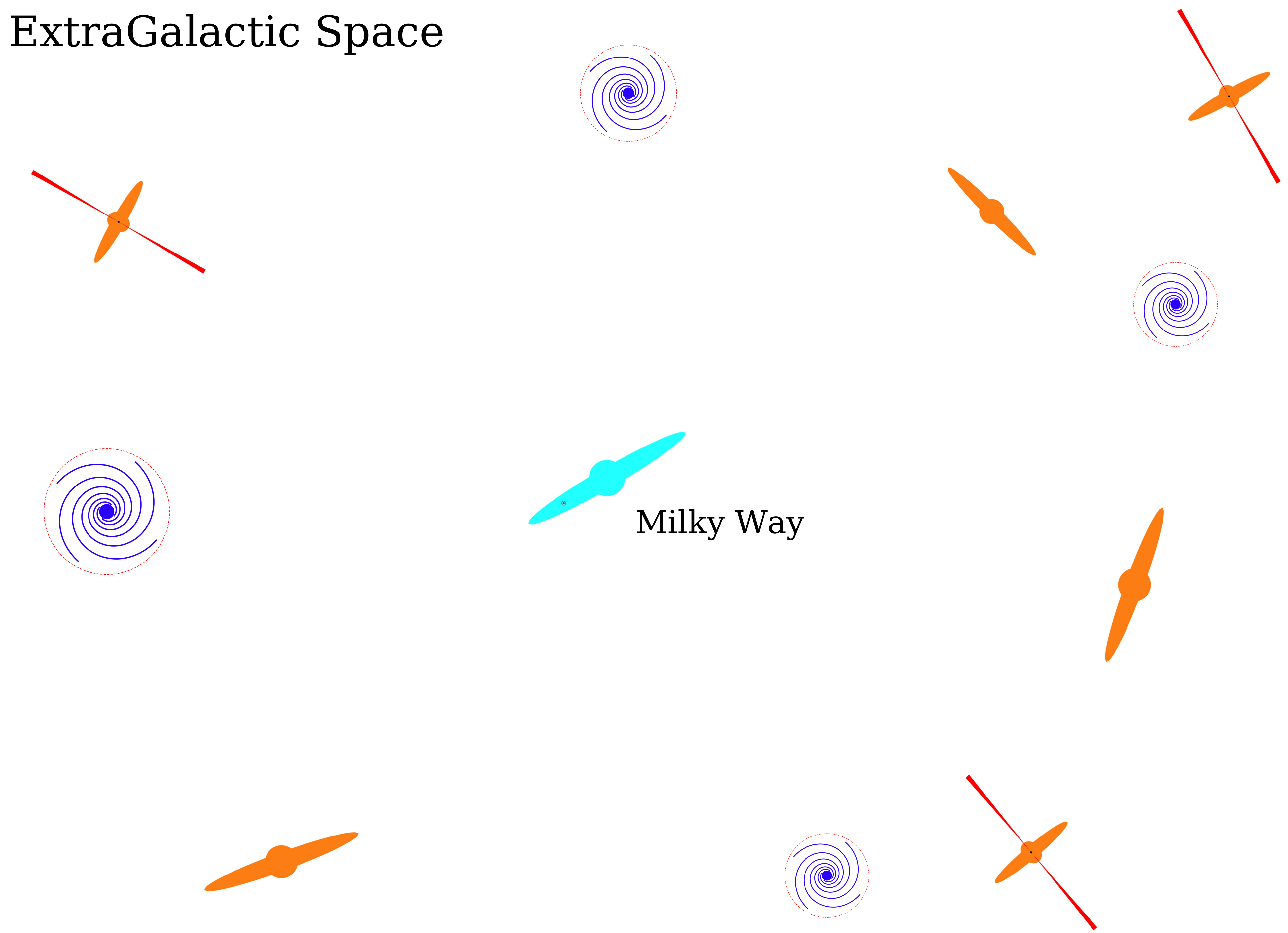
Measurements at the Earth

Space and time integrated average of particles
generated by many sources in the Galaxy
and in the universe, *also shaped by propagation effects*.

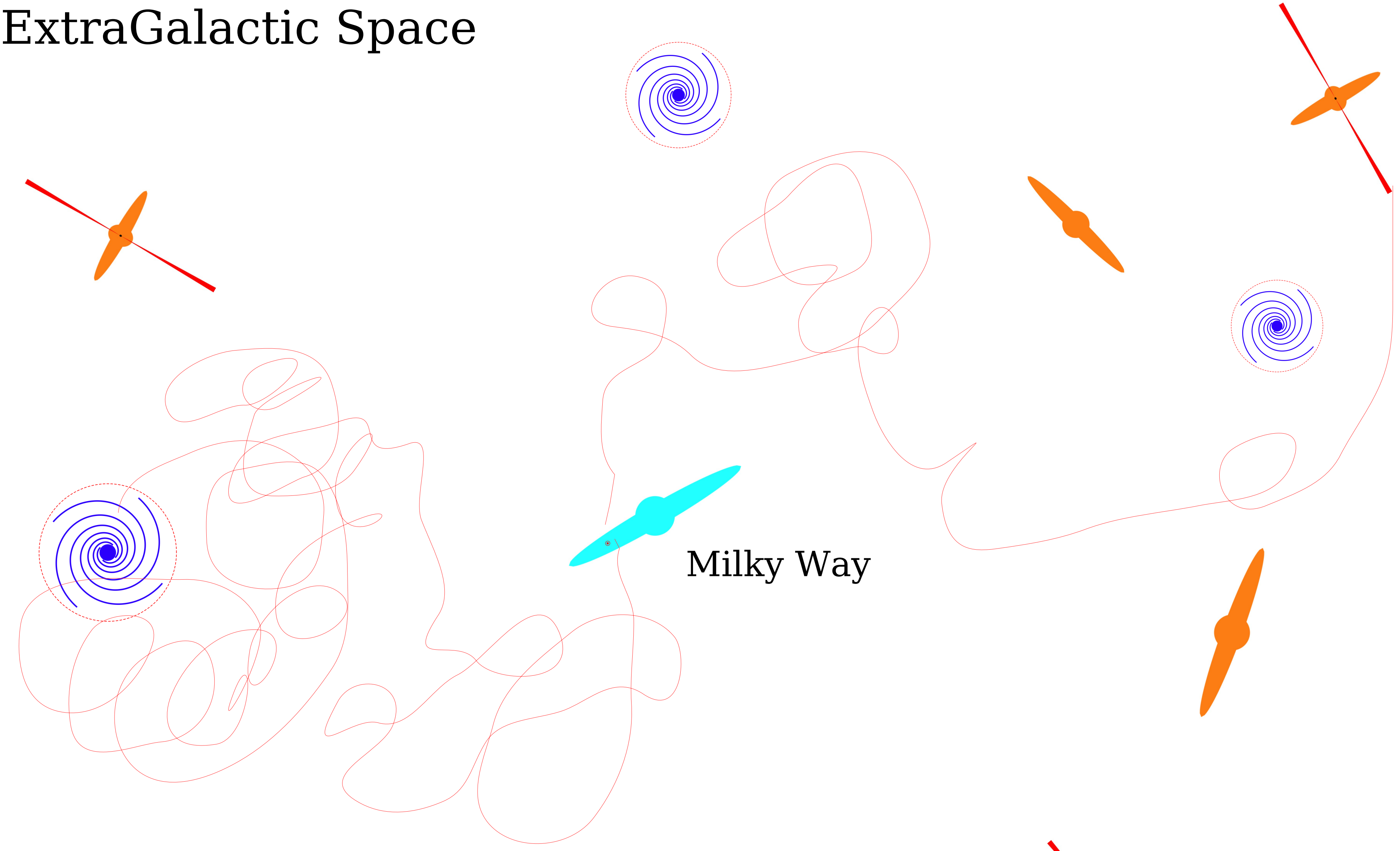
Measurement at
single point, and (effectively) single time.
[slow time variations,
geological record carries some information]

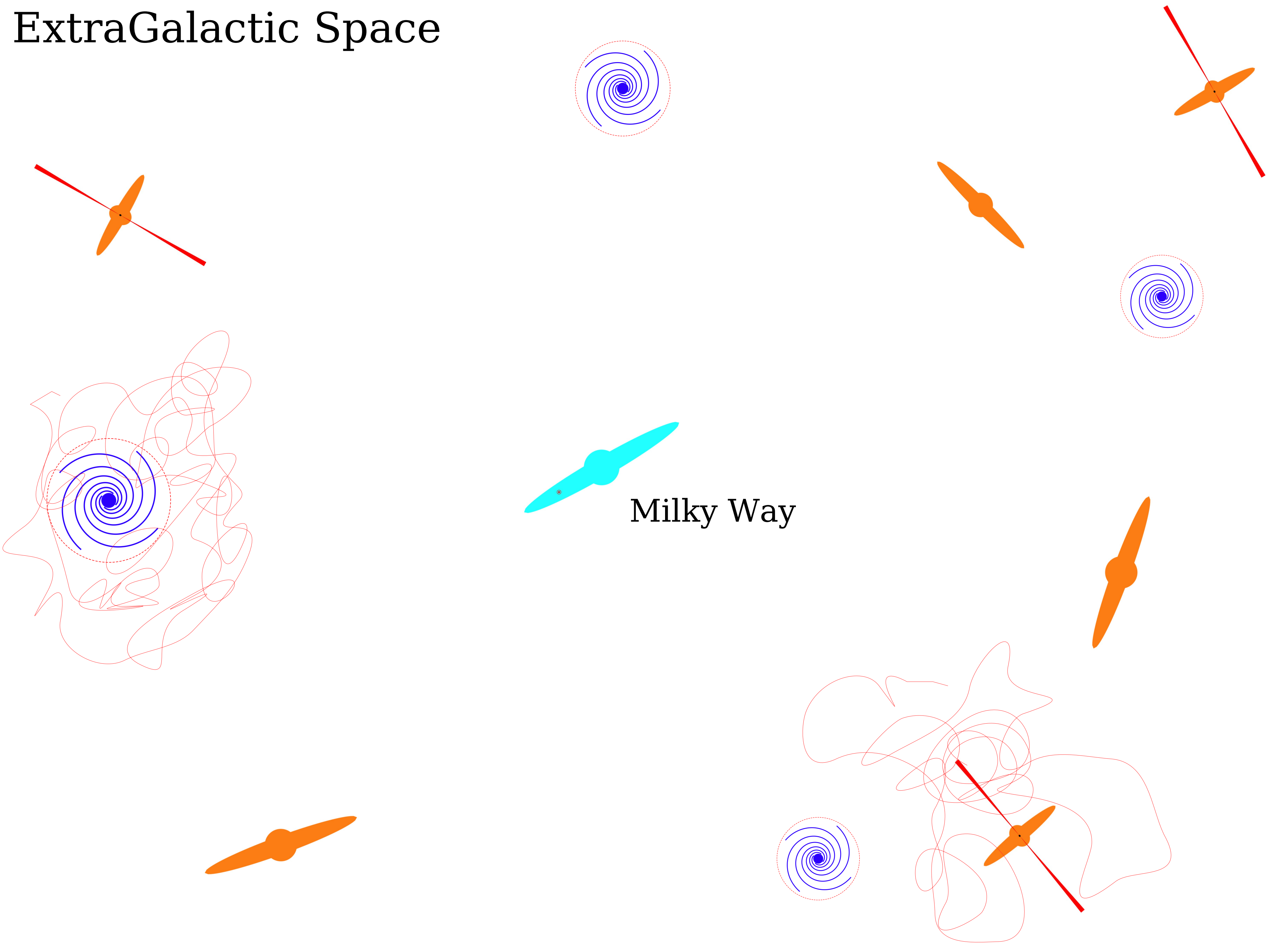



MILKY WAY
High energy sources
Solar system


ExtraGalactic Space
Milky Way

ExtraGalactic Space

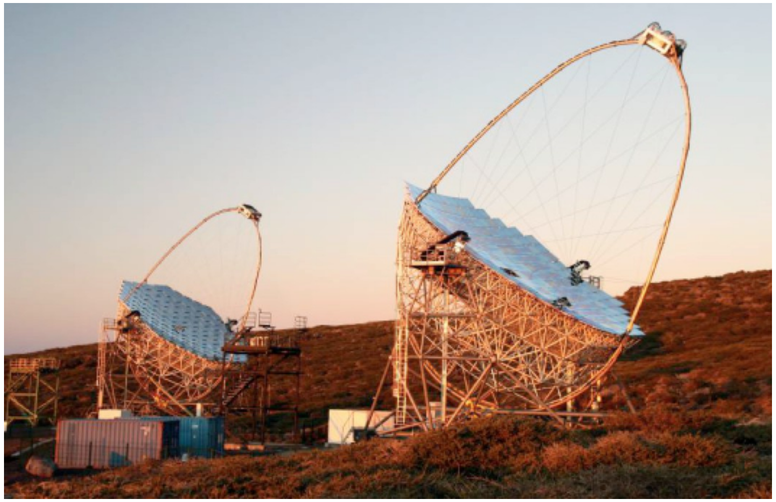



ExtraGalactic Space
Milky Way

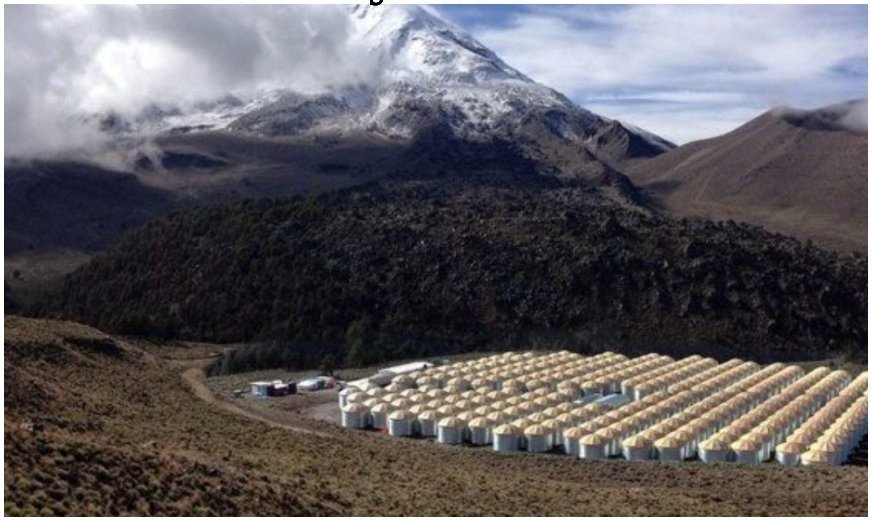
Gamma Rays

Space $E_\gamma \simeq 0.1 \div 1000$ GeV

Cherenkov $E_\gamma \simeq 0.1 \div 100$ TeV

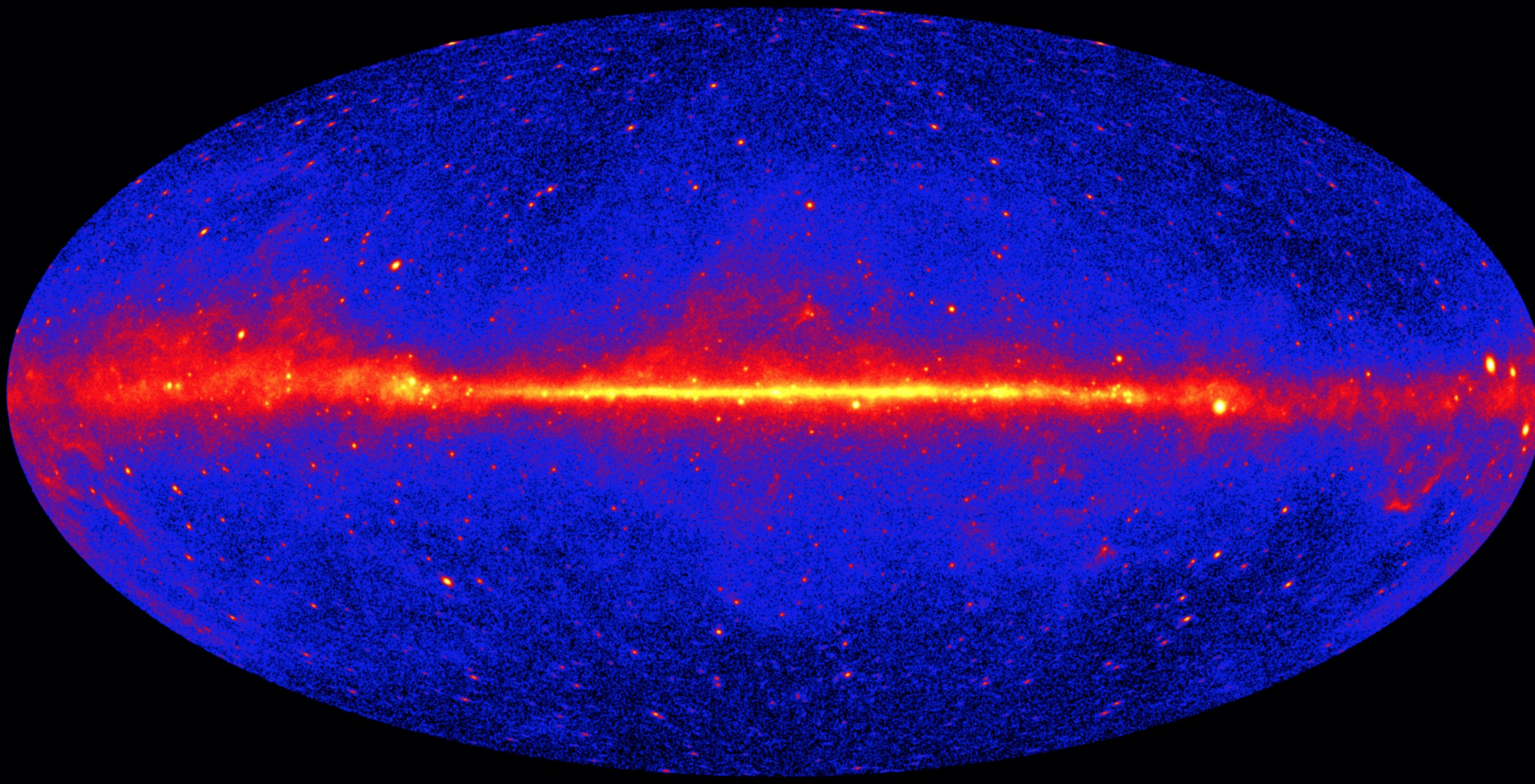


Ground Arrays



$E_\gamma \lesssim 30$ PeV LHAASO

The “Richness” of the Gamma Ray Sky



FERMI-LAT sky map

Components of the Gamma Ray flux (0.1 – 1000 GeV)
Galactic/Extragalactic sources + “diffuse"

$$\phi_\gamma(E,\Omega) = \sum_{j\in\{\text{Galactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Galactic}}_{\text{diffuse}}(E,\Omega)$$

$$+ \sum_{j\in\{\text{extragal.}\}} \phi_j(E,\Omega_j) + \phi^{\text{extragal.}}_{\text{isotropic}}(E,\Omega)$$

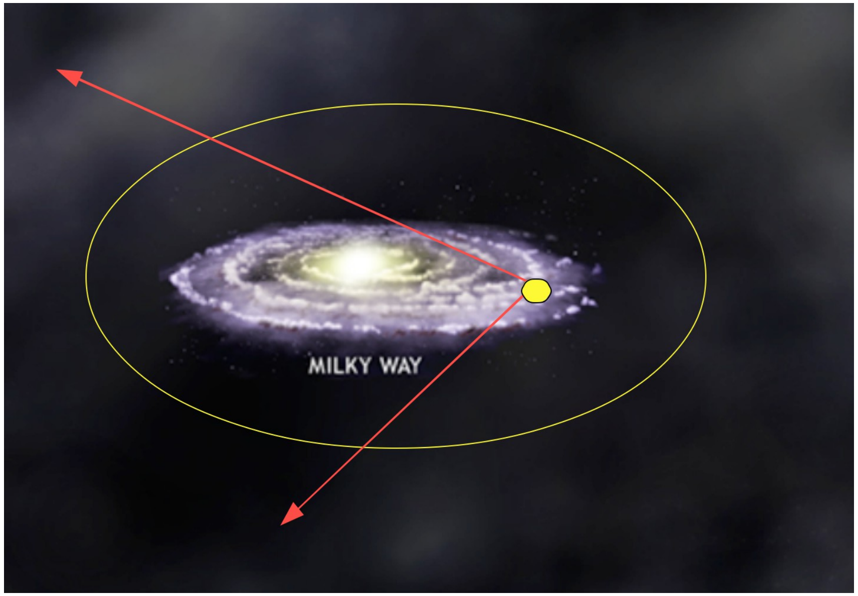
$$\phi^{\text{extragal.}}_{\text{isotropic}}(E,\Omega) = \phi^{\text{extragal.}}_{\text{unresolved sources}}(E) + \phi^{\text{extragal.}}_{\text{diffuse}}(E,\Omega)$$

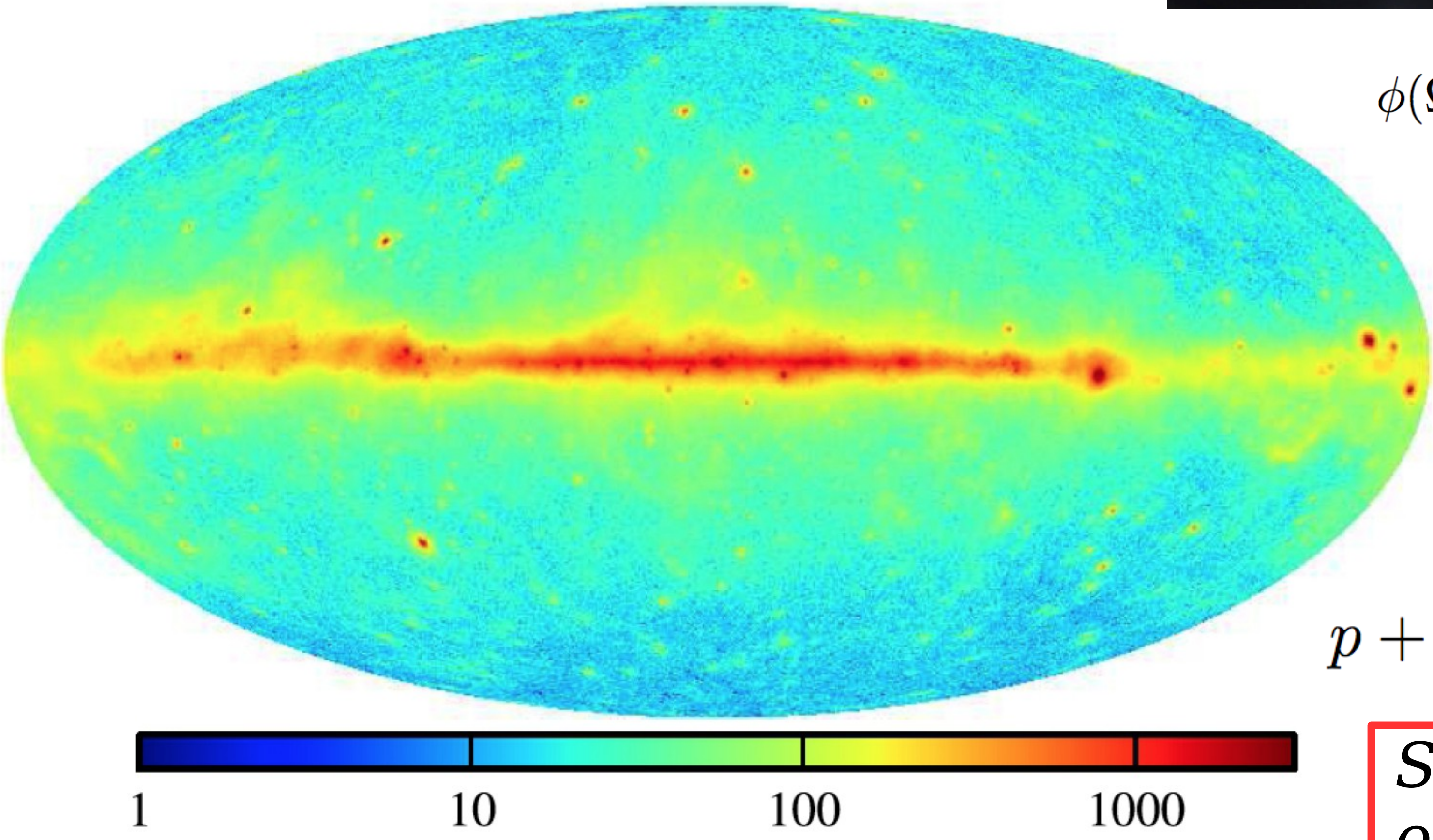
Note : The Neutrino sky will have the same 5 components
(perhaps in different proportions)

Diffuse Emission

Fermi–LAT counts

Galactic coordinates





energy range 200 MeV to 100 GeV

$$\phi(\Omega) \propto \int d\ell \; n_{\rm cr}(\vec{\ell}) \; n_{\rm ism}(\vec{\ell})$$

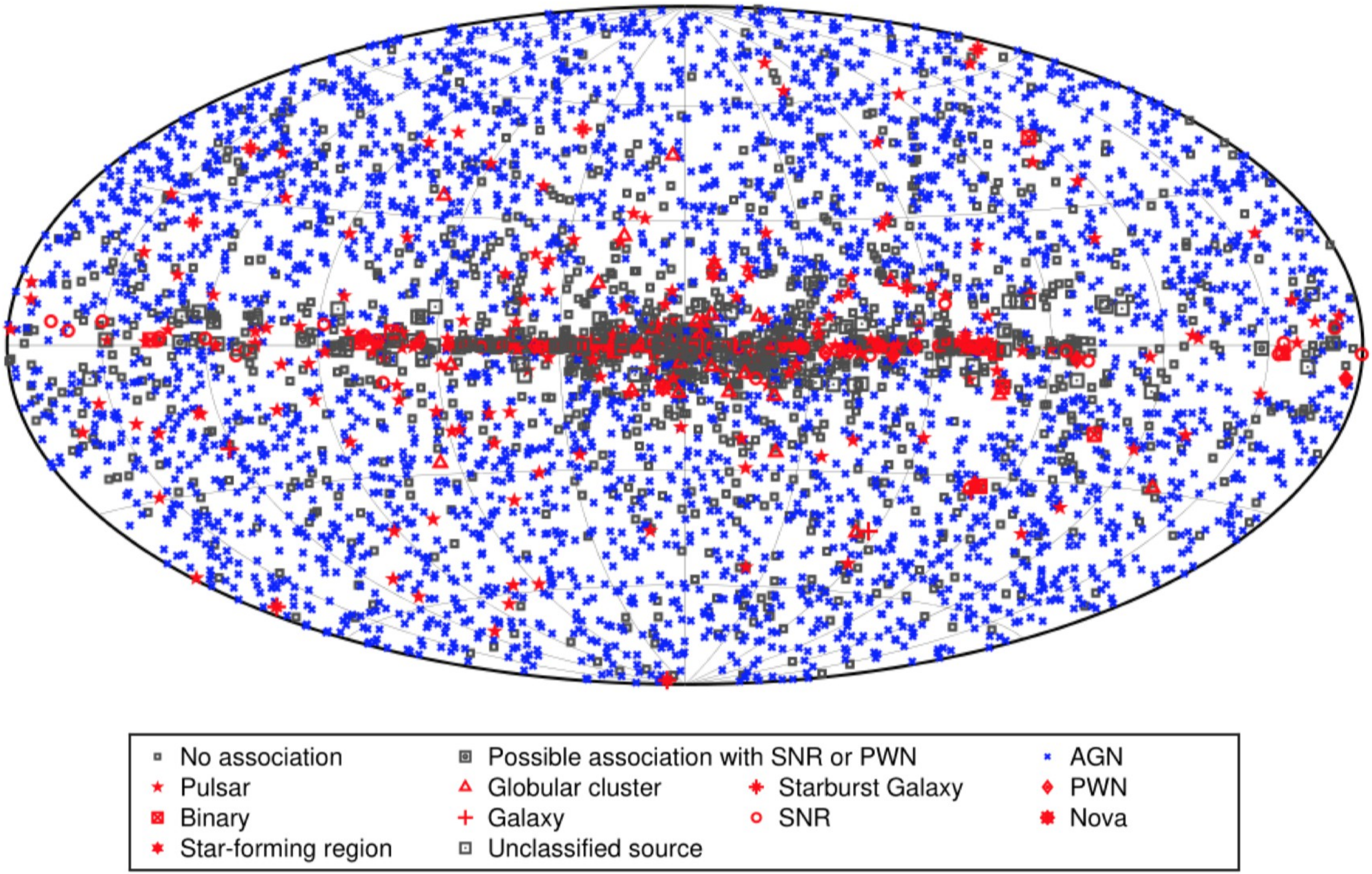
Integral
over line of sight

[(CR density) *
(gas density)]

$$p + p_{\rm ISM} \rightarrow \pi^\circ \rightarrow \gamma \;\; \gamma$$

Study distribution of Cosmic Rays in the Galaxy

FERMI 4th General Catalog 4FGL (5064 sources)



Sources are obviously in two main classes

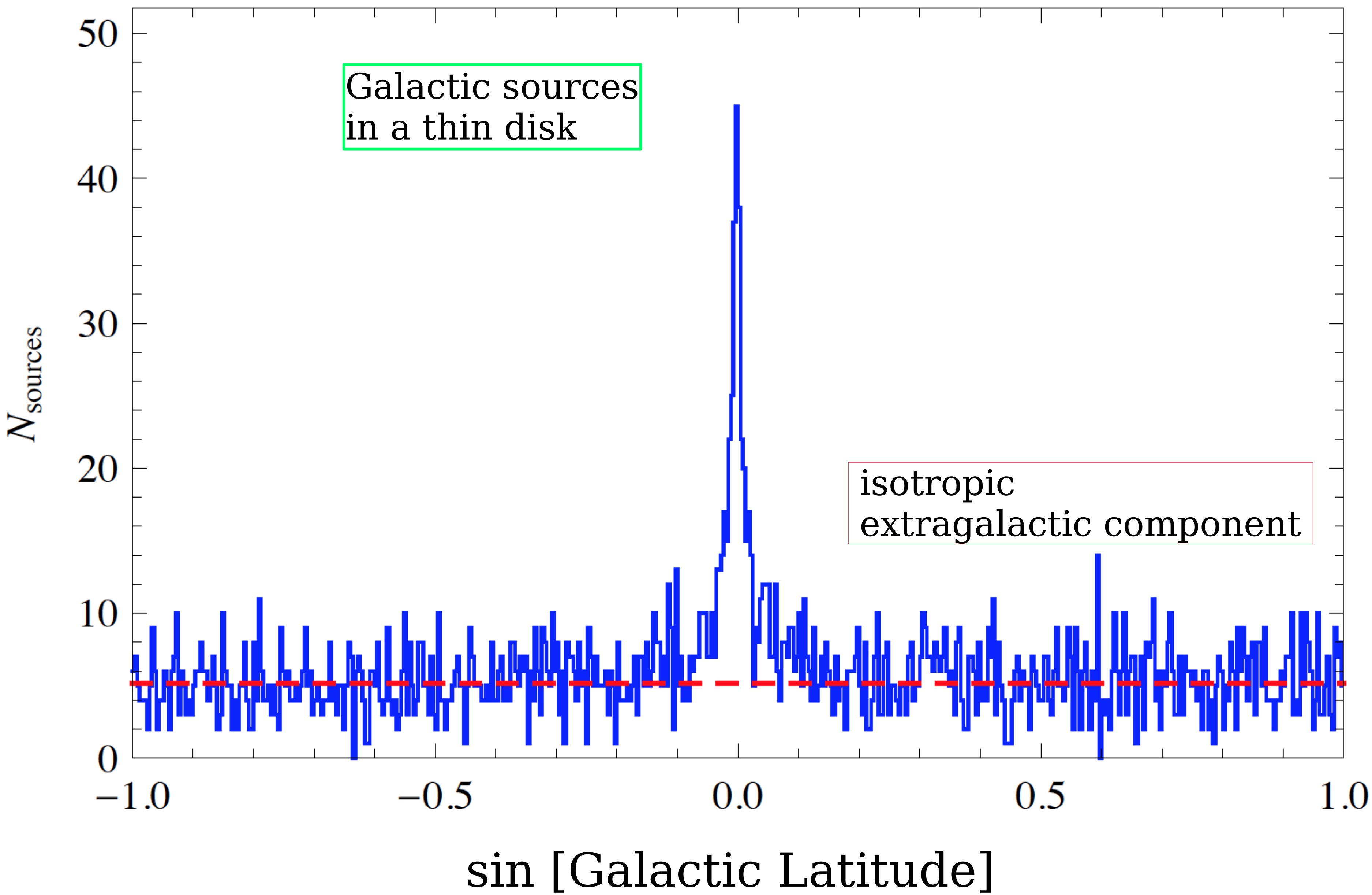


Table 7. LAT 4FGL Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	232	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	7
Pulsar wind nebula	PWN	11	pwn	6
Supernova remnant	SNR	24	snr	16
Supernova remnant / Pulsar wind nebula	SPP	0	spp	78
Globular cluster	GLC	0	glc	30
Star-forming region	SFR	3	sfr	0
High-mass binary	HMB	5	hmb	3
Low-mass binary	LMB	1	lmb	1
Binary	BIN	1	bin	0
Nova	NOV	1	nov	0
BL Lac type of blazar	BLL	22	bll	1109
FSRQ type of blazar	FSRQ	43	fsrq	651
Radio galaxy	RDG	6	rdg	36
Non-blazar active galaxy	AGN	1	agn	10
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact Steep Spectrum radio source	CSS	0	css	5
Blazar candidate of uncertain type	BCU	2	bcu	1310
Narrow-line Seyfert 1	NLSY1	4	nlsy1	5
Seyfert galaxy	SEY	0	sey	1
Starburst galaxy	SBG	0	sbg	7
Normal galaxy (or part)	GAL	2	gal	1
Unknown	UNK	0	unk	92
Total	...	358	...	3370
Unassociated	...	...	...	1336

Classes of Sources

[Fermi sources associated with known objects]

72% of sources

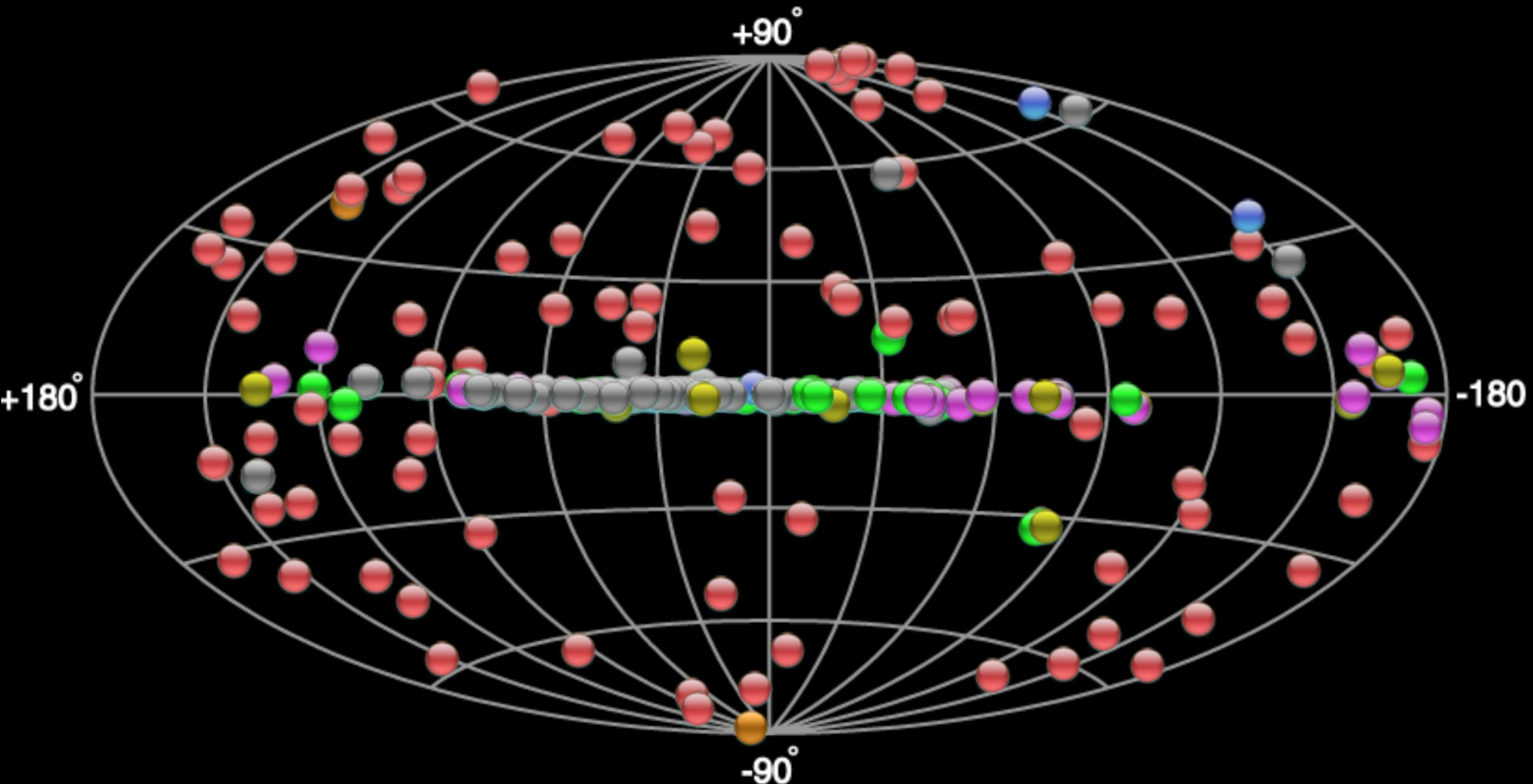
extra-galactic

Active Galactic Nuclei (AGN)	3208	88%
[AGN of "Blazar" class	3137	86%]
Galaxies (Normal)	4	
Galaxies (Star Forming)	7	

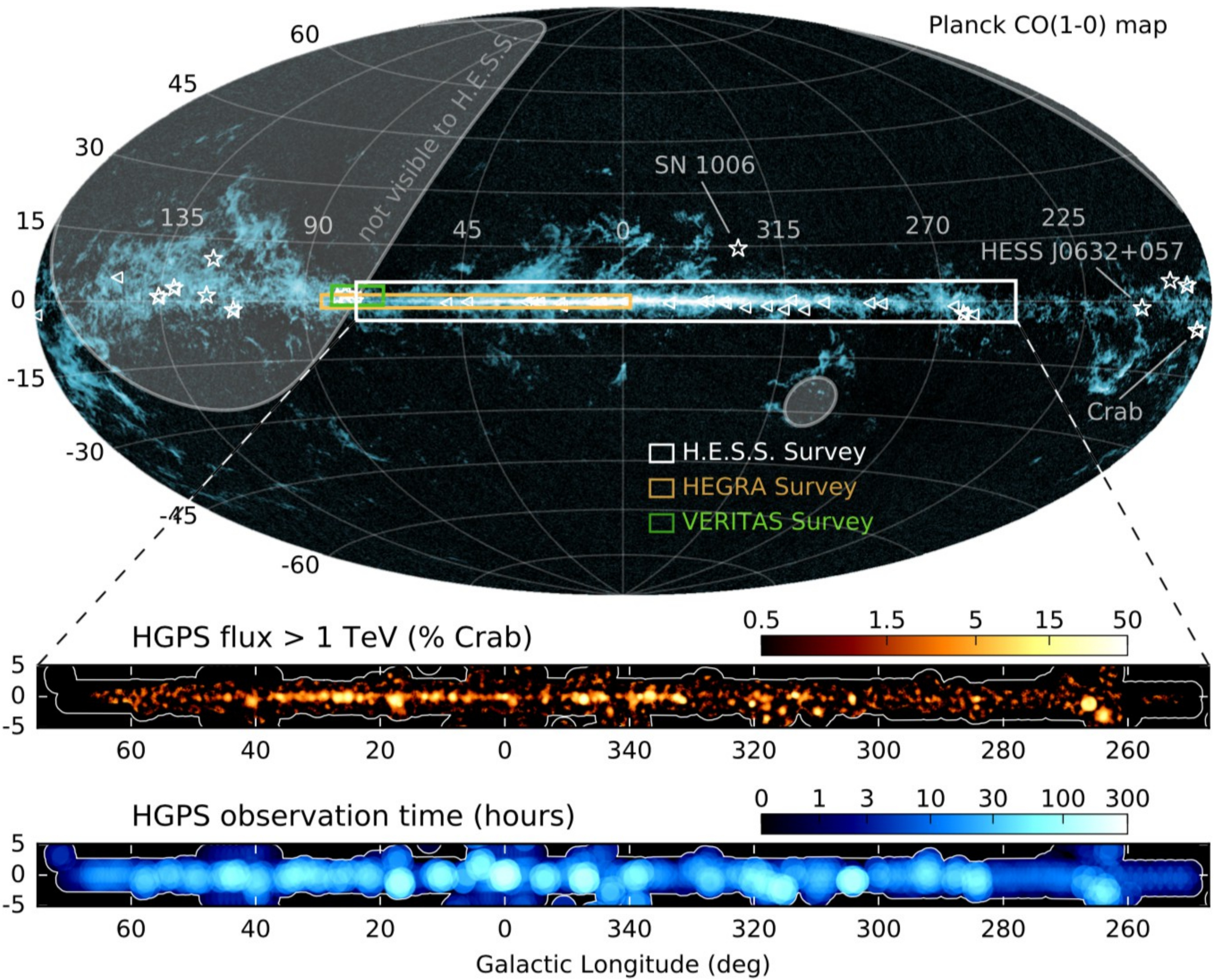
Galactic

Pulsars	239	6.5%
SuperNova Remnants (SNR)	40	1.1%
SNR + Pulsar Wind Nebulae	108	3.0%
Globular Clusters (many ms Pulsars [?])	30	
Accreting Binary Stars	11	
Novae	1	

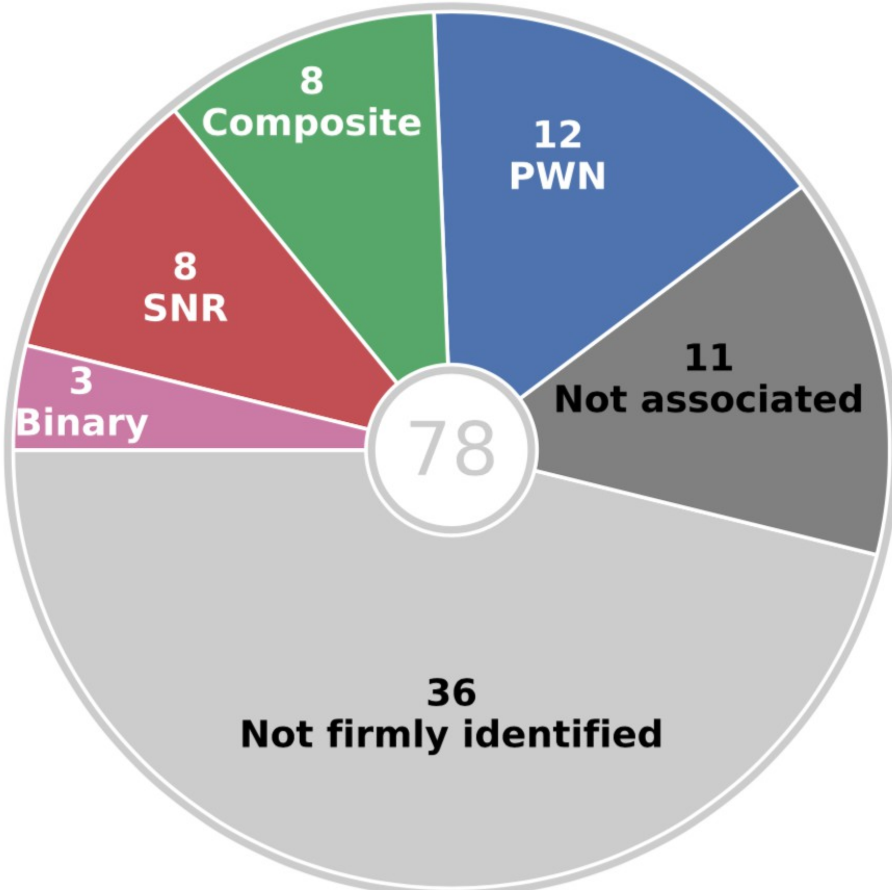
TeVCAT catalogue of TeV sources

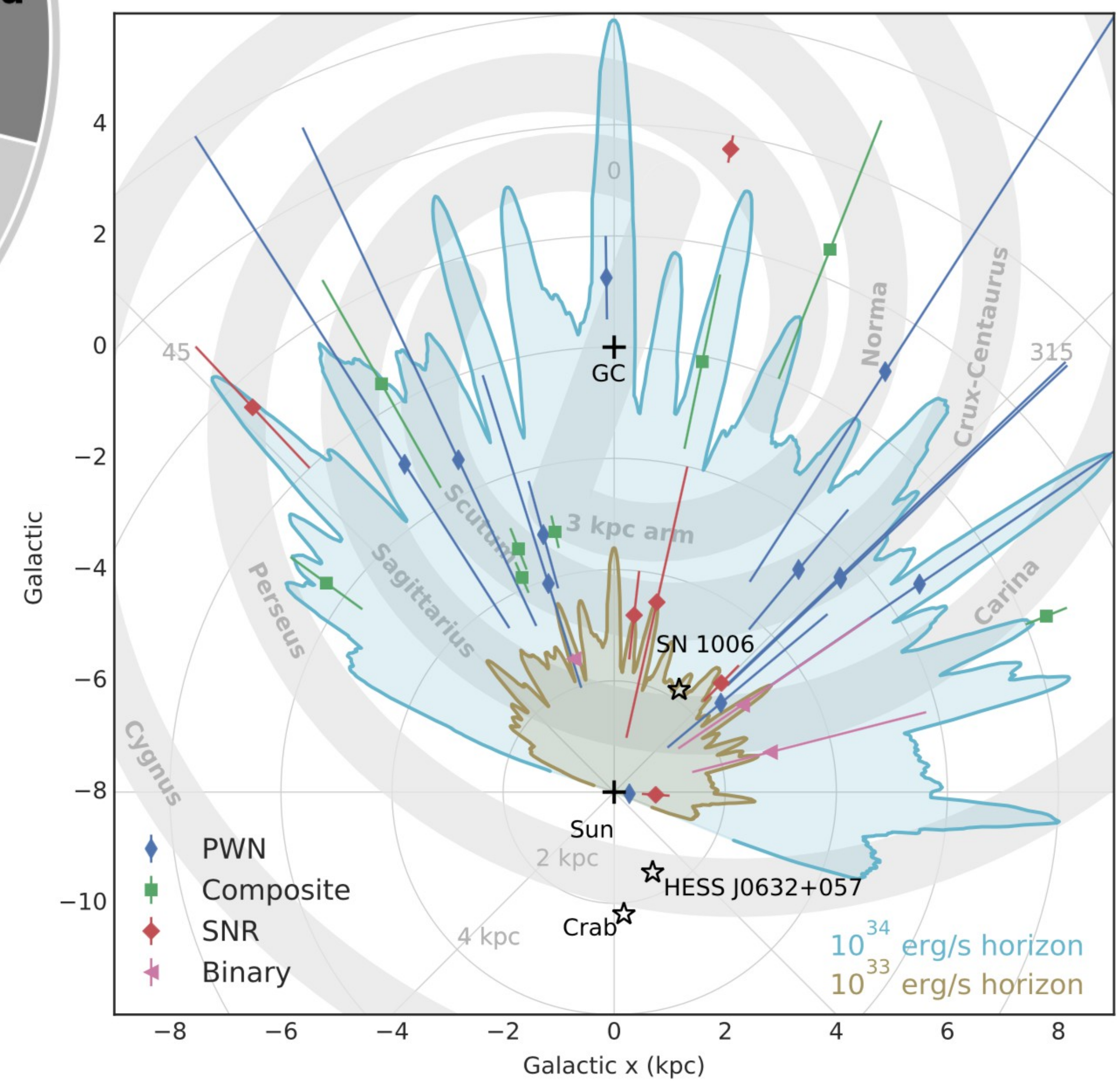


247 sources



Planck CO(1-0) map
not visible to H.E.S.S.
SN 1006
HESS J0632+057
Crab
H.E.S.S. Survey
HEGRA Survey
VERITAS Survey
60
45
30
15
0
-15
-30
-45
-60
135
90
45
0
315
270
225
HGPS flux > 1 TeV (% Crab)
0.5
1.5
5
15
50
HGPS observation time (hours)
0
1
3
10
30
100
300
5
0
-5
60
40
20
0
340
320
300
280
260
Galactic Longitude (deg)





HESS Survey
78 Galactic sources

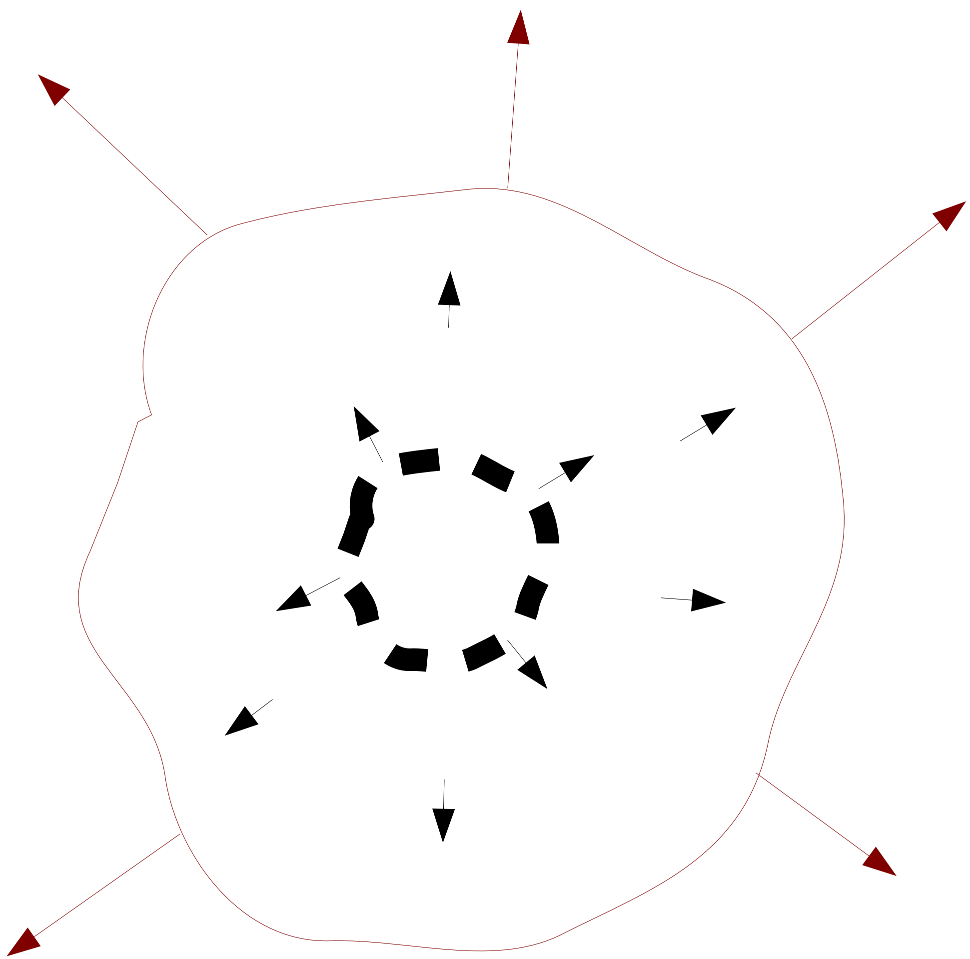
- PWN
- SNR
- Composite
- Binary systems

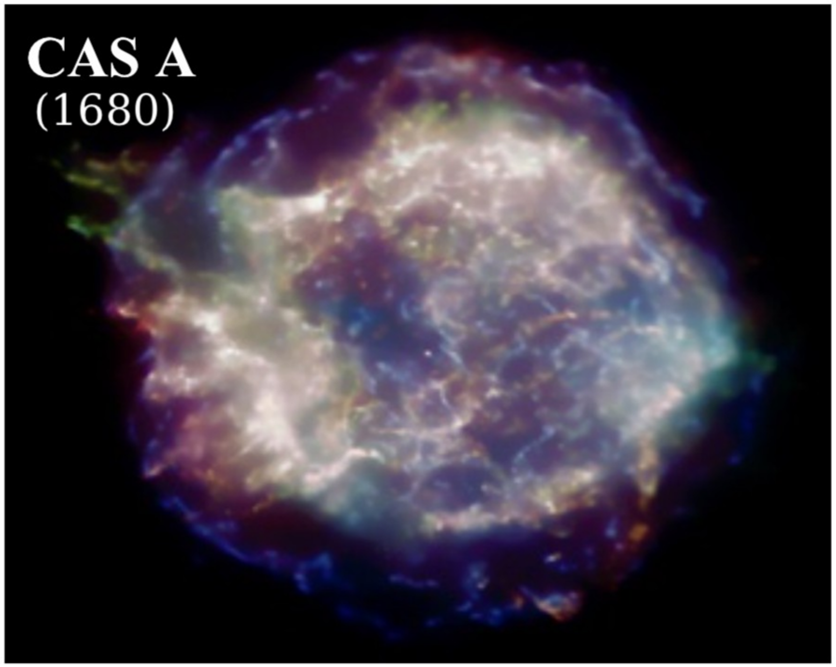
The SuperNova "Paradigm"

Most of the Galactic Cosmic Rays are accelerated in the Shock Waves of SN explosions

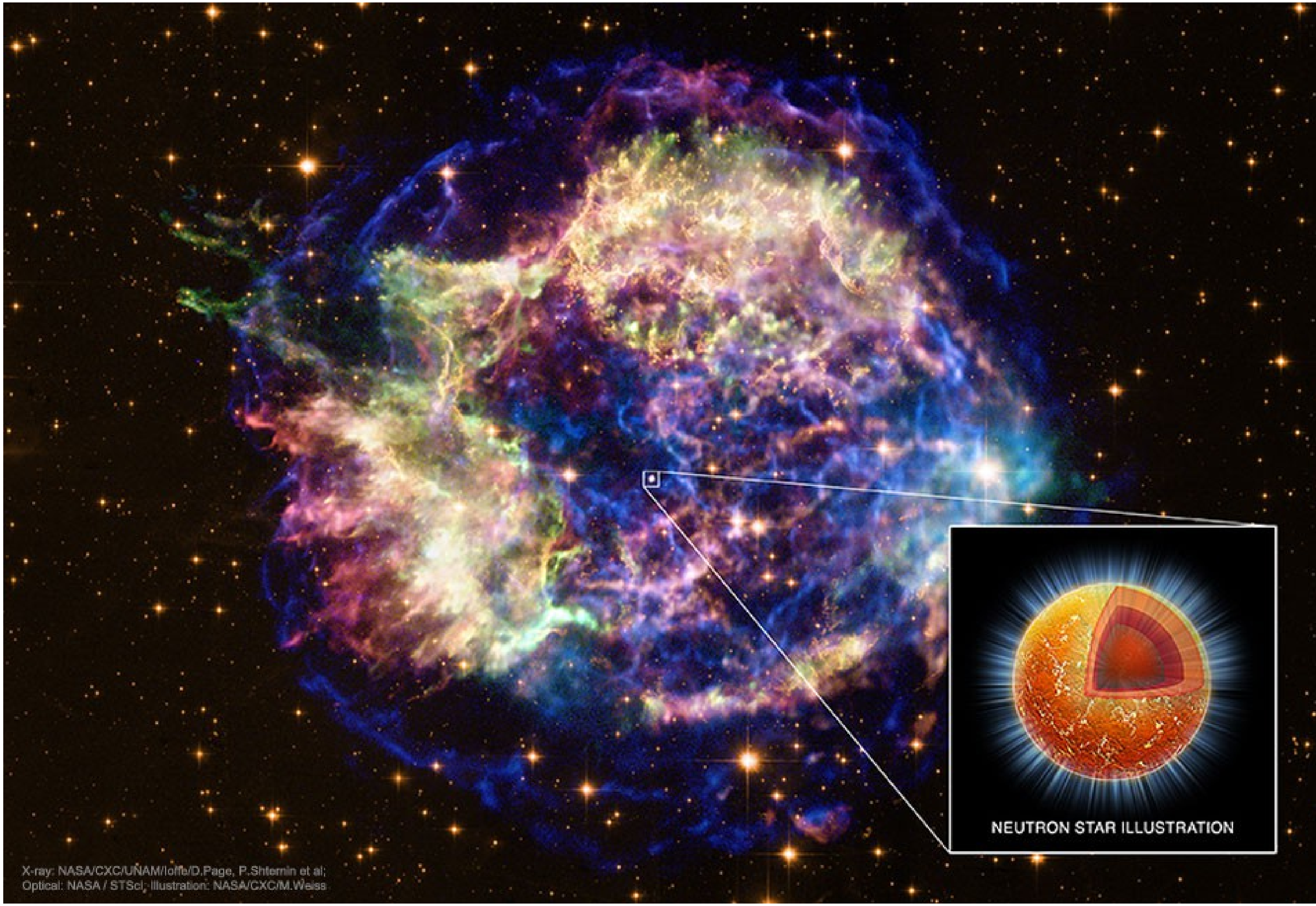
- Energy Balance
- Spectral shape

Maximum Energy [?]



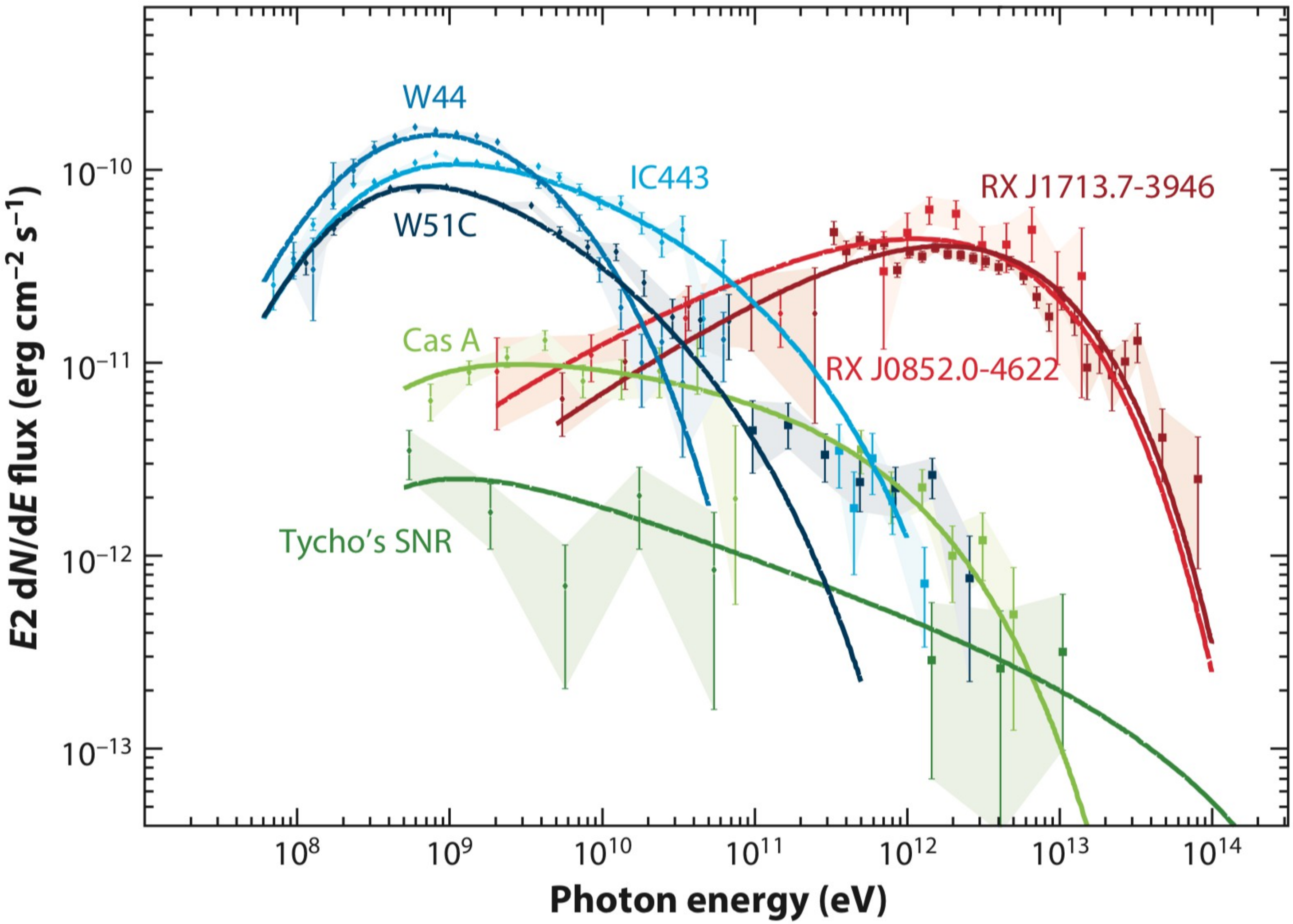


Creation of a Neutron Star in a SuperNova explosion



Pulsar Formation [Pulsar Wind Nebulae]

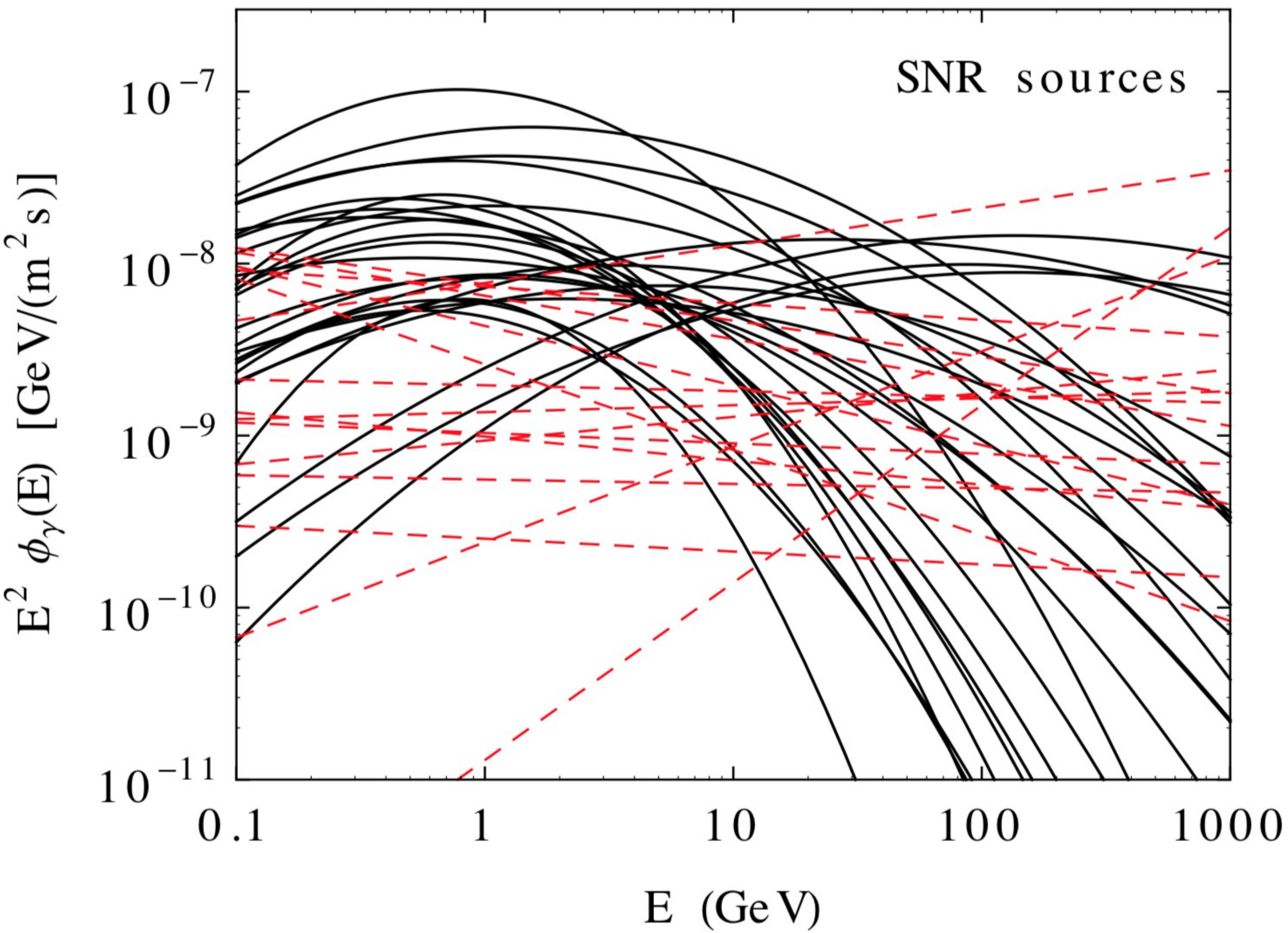
S.Funk,
Ann.Rev.Nuc.Part. (2015)



Typical γ-ray energy spectra for several of the most prominent supernova remnants (SNRs). Young SNRs (<1,000 years) are shown in green. These typically show smaller γ-ray fluxes but rather hard spectra in the GeV and TeV bands. The older (but still referred to as young) shell-type SNRs RX J1713.7-3946 and RX J0852.0-4622 (Vela Junior) of ages ~2,000 years are shown in shades of red. These show very hard spectra in the GeV band ($\Gamma = 1.5$) and a peak in the TeV band with an exponential cutoff beyond 10 TeV. The middle-aged SNRs (~20,000 years) interacting with molecular clouds (W44, W51C, and IC443) are shown in blue. Also shown are hadronic fits to the data (*solid lines*).

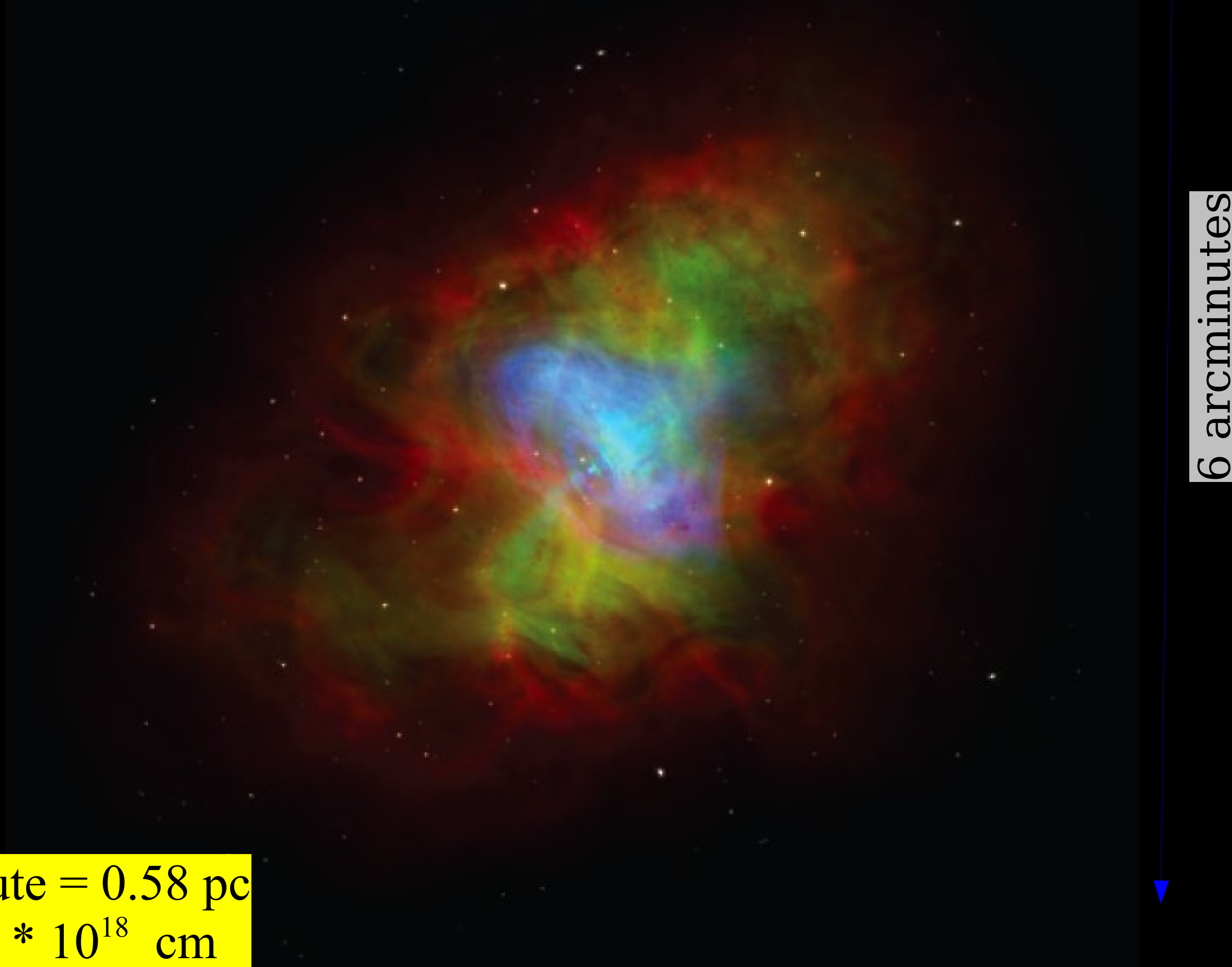
All 40 FERMI-LAT SNR (snr) sources

[PL: arXiv:2020.102507]
Astropart.. Phys. 125, 102507 (2021)



[note all bright sources fitted with curved (logparabola) spectra]

The CRAB Nebula



1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

A very interesting chapter:

PULSARS

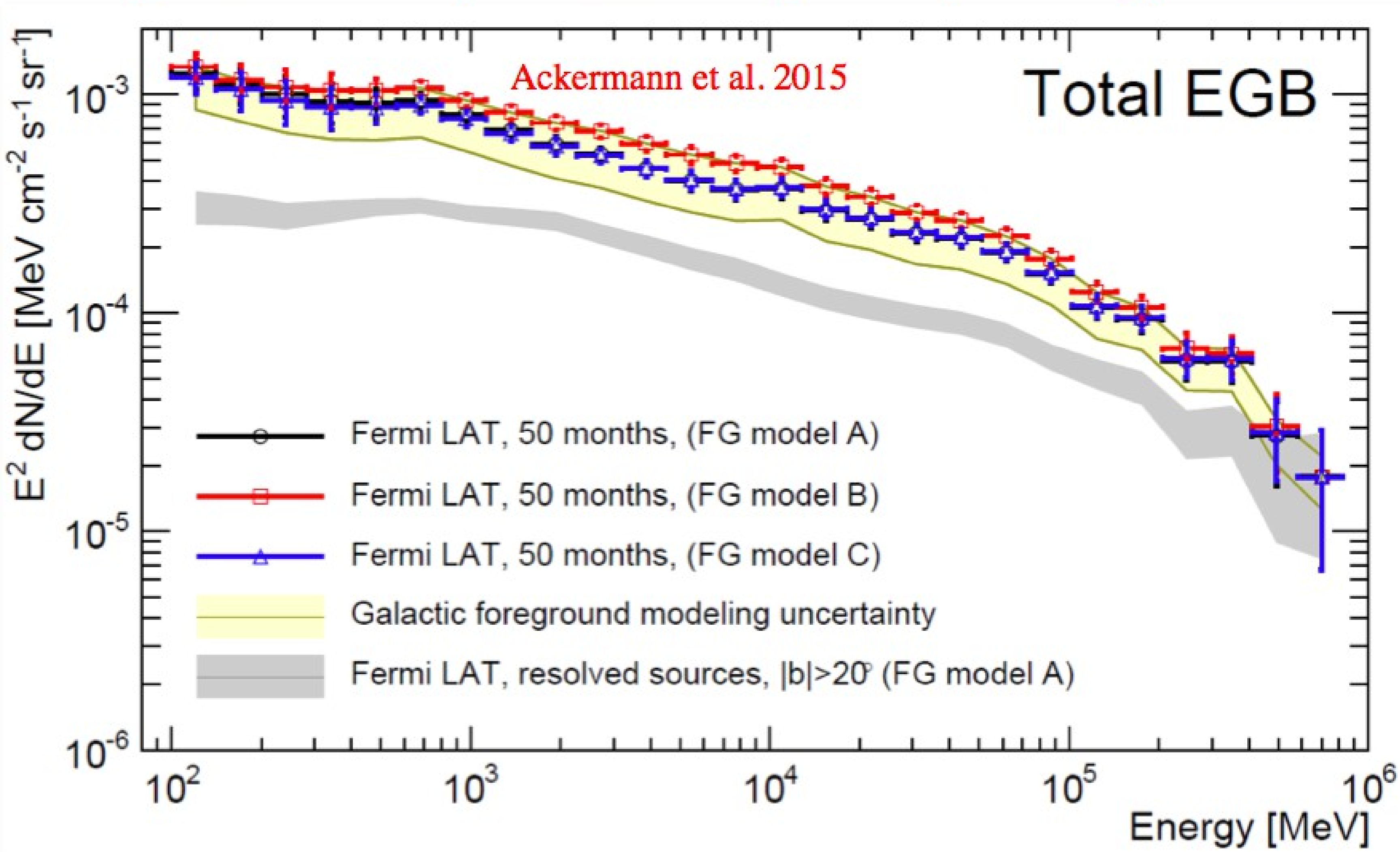
Different Mechanisms for particle acceleration

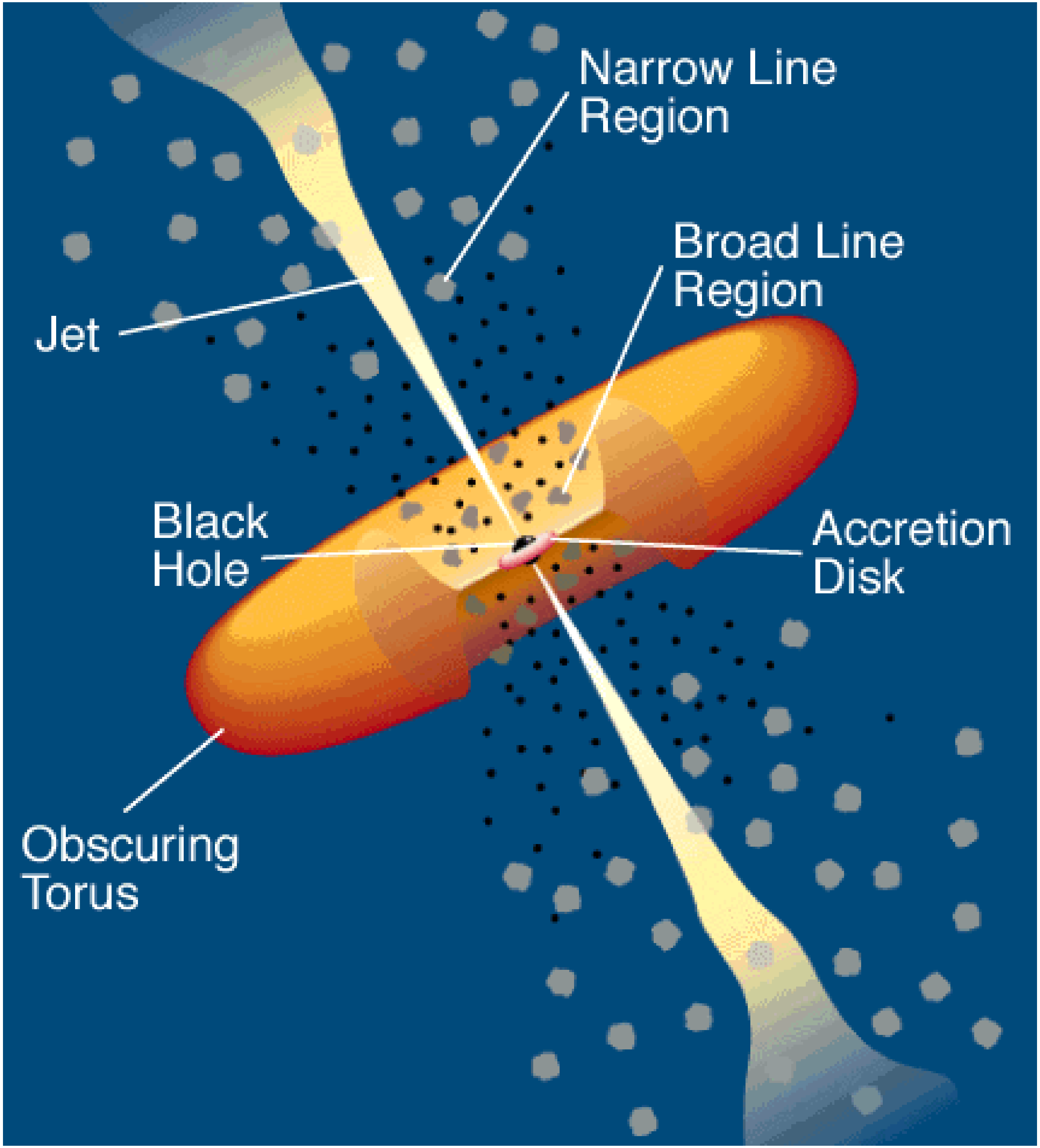
Pulsar Wind Nebulae

Acceleration of positrons (and electrons) ?

Total Extragalactic Gamma-ray Background

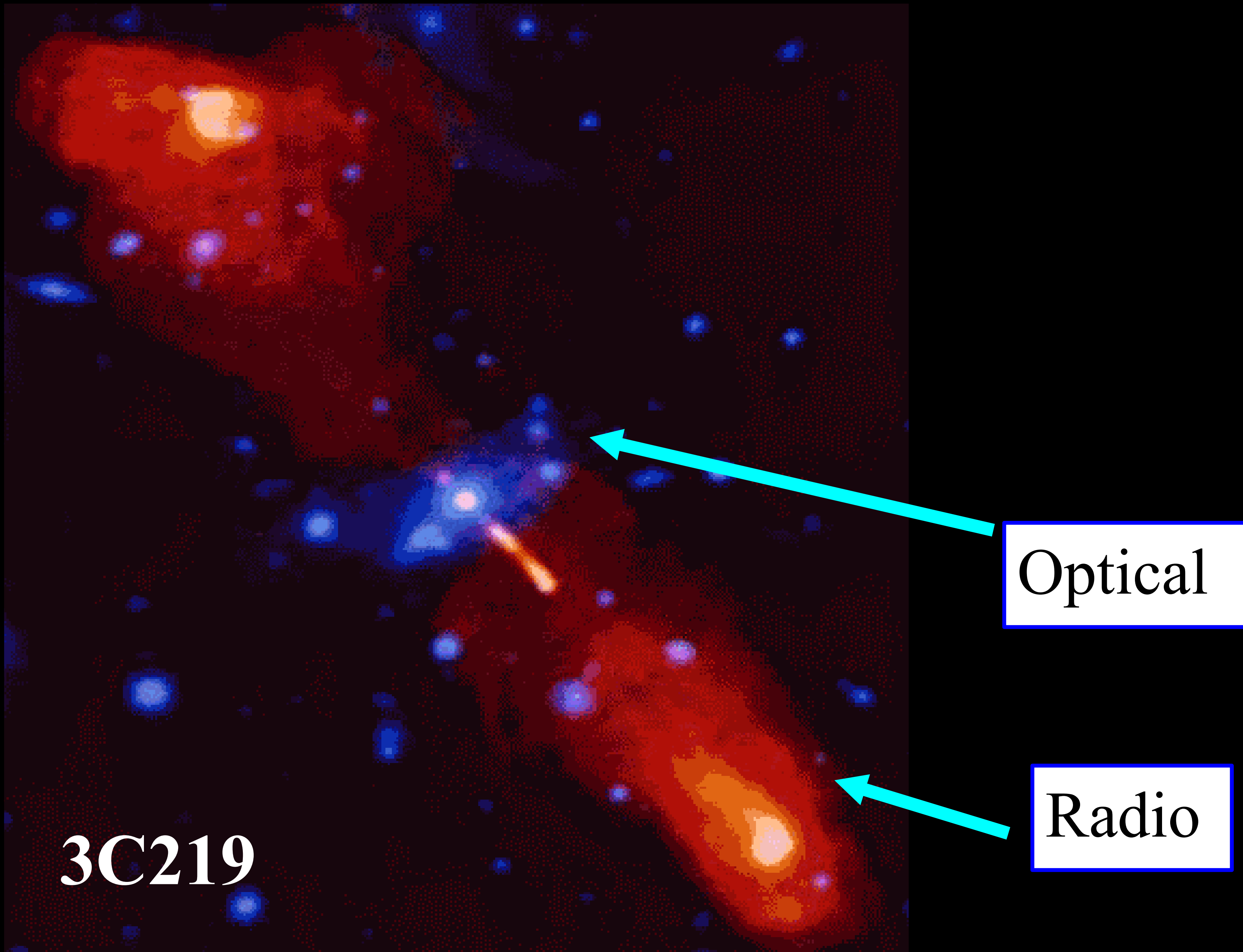
Systematic uncertainty from Galactic foreground represented by yellow band

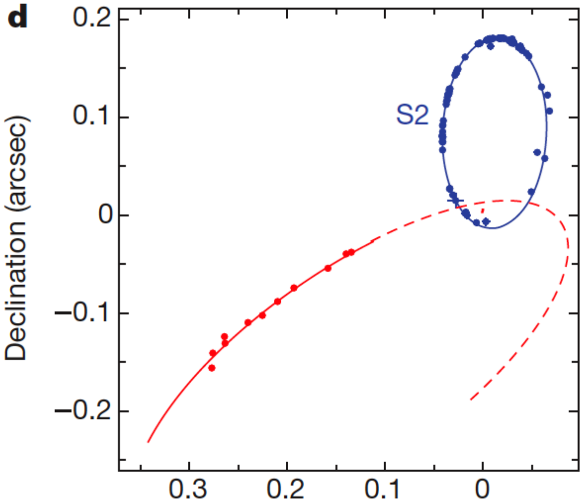




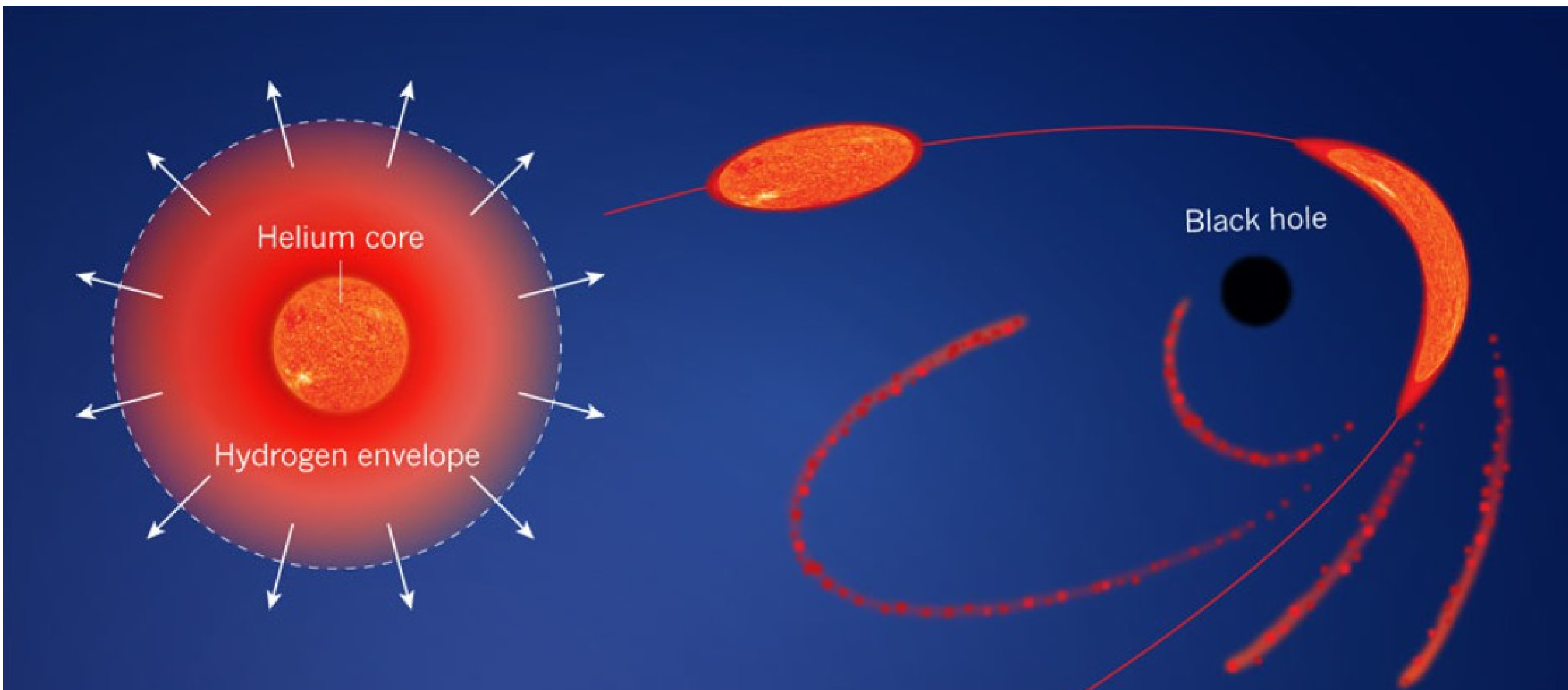
Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

ACTIVE GALACTIC NUCLEI



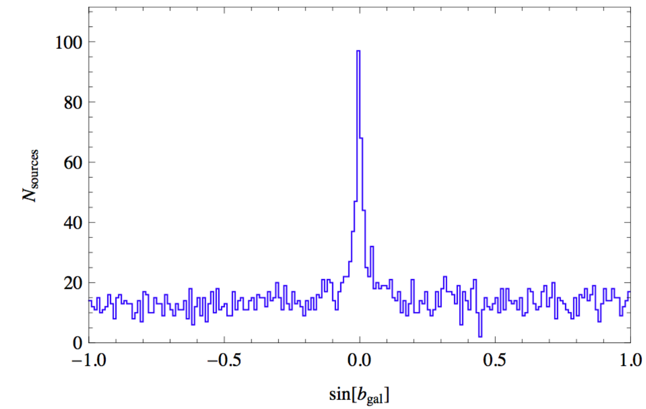


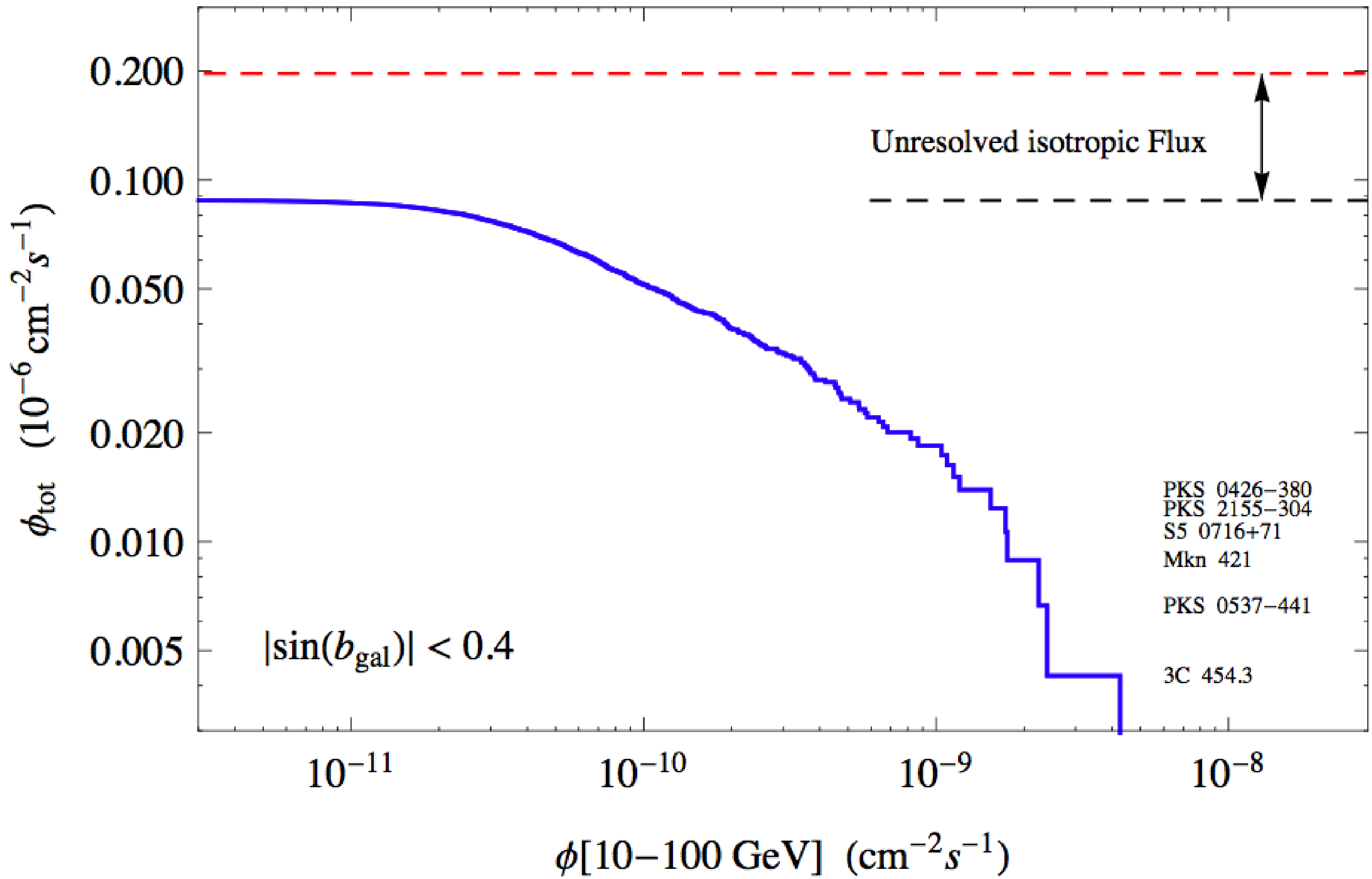
Infalling gas from the disruption of a star.

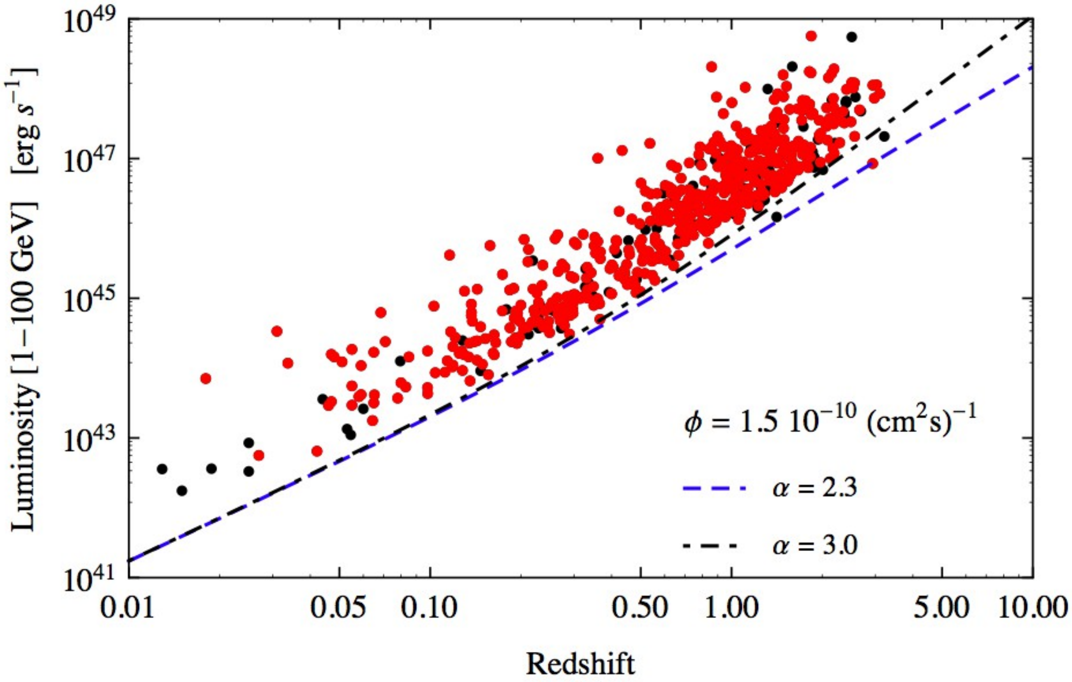


The helium-rich core of a red-giant star that had previously lost its hydrogen envelope moves on an almost parabolic orbit (red) towards a supermassive black hole. The sequence of blobs illustrates the progressive distortion of the star's core due to the tidal pull of the black hole. After the point of closest approach to the black hole, the core is completely disrupted, with part of the resulting debris being expelled from the system and part being launched into highly eccentric orbits, eventually falling onto the black hole. Accretion of this debris gives rise to the intense ultraviolet–optical flare that has been observed by Gezari and colleagues[1].

Fermi finds that the extragalactic sky is dominated by "Blazar"emission

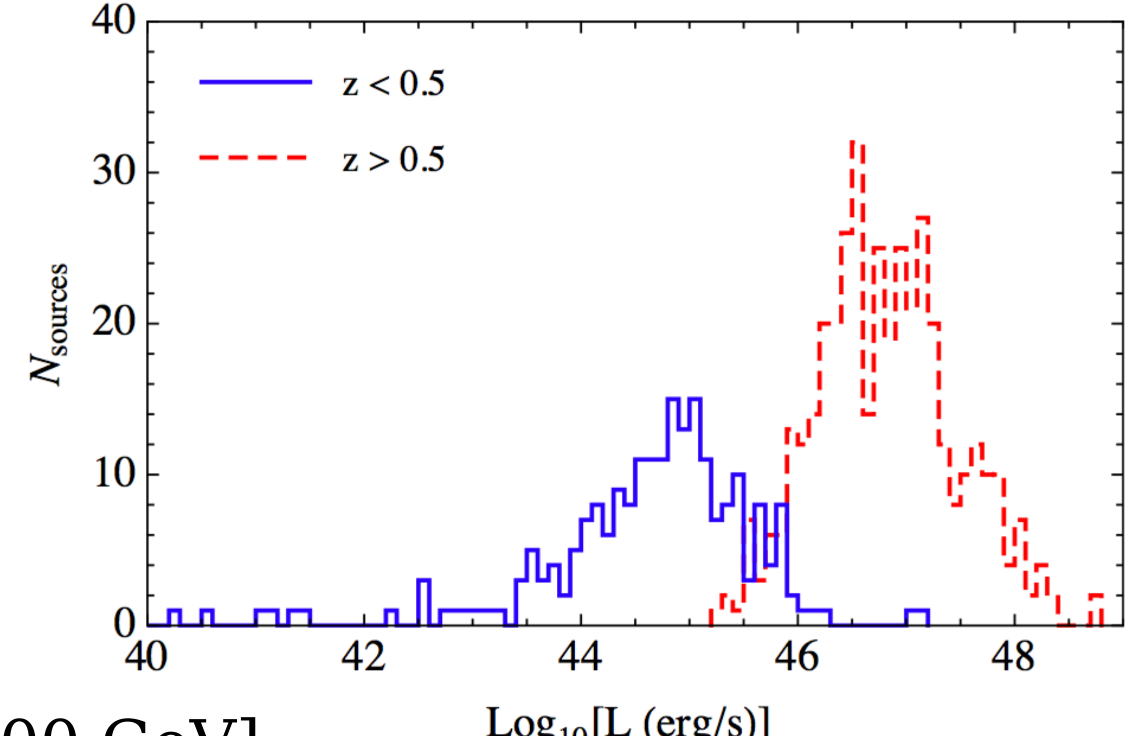






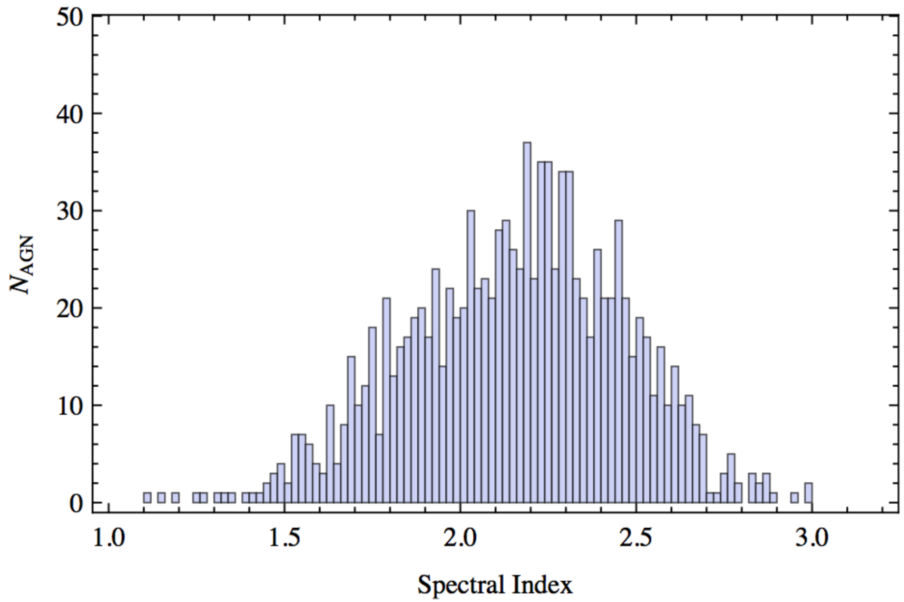
Blazars in the 2LAC FERMI catalog
(1121 objects)
618 with redshift known

Very broad distribution
luminosity distribution

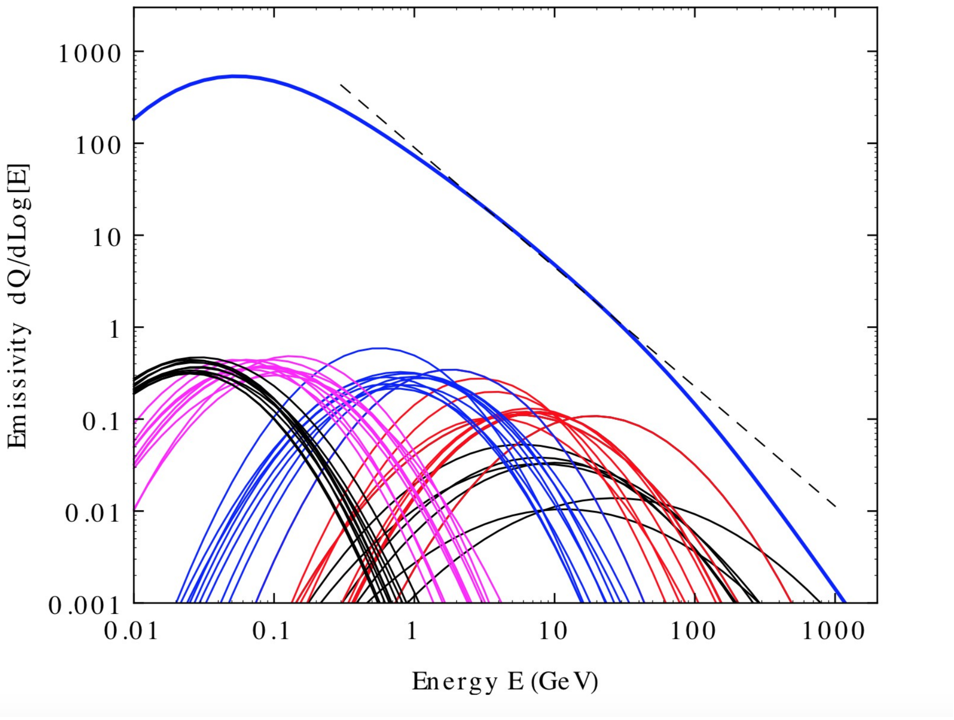


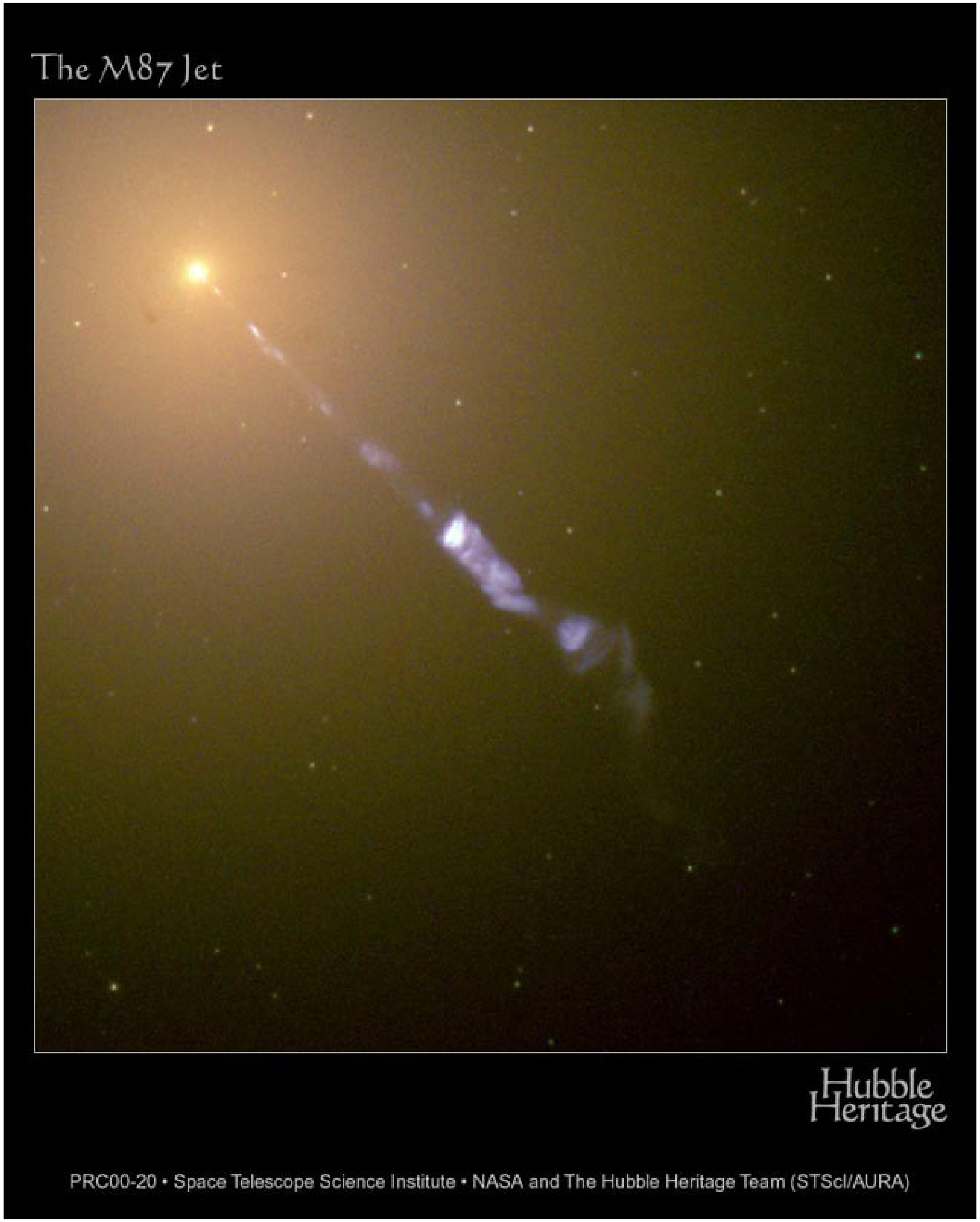
Luminosity [1-100 GeV]

Spectral Index of the Blazars in the FERMI 2LAC catalog.



P.L., "The origin of the power–law form of the extragalactic gamma–ray flux"
Astropart. Phys. **125**, 102507 (2021)
[arXiv:2001.00982 [astro-ph.HE]].





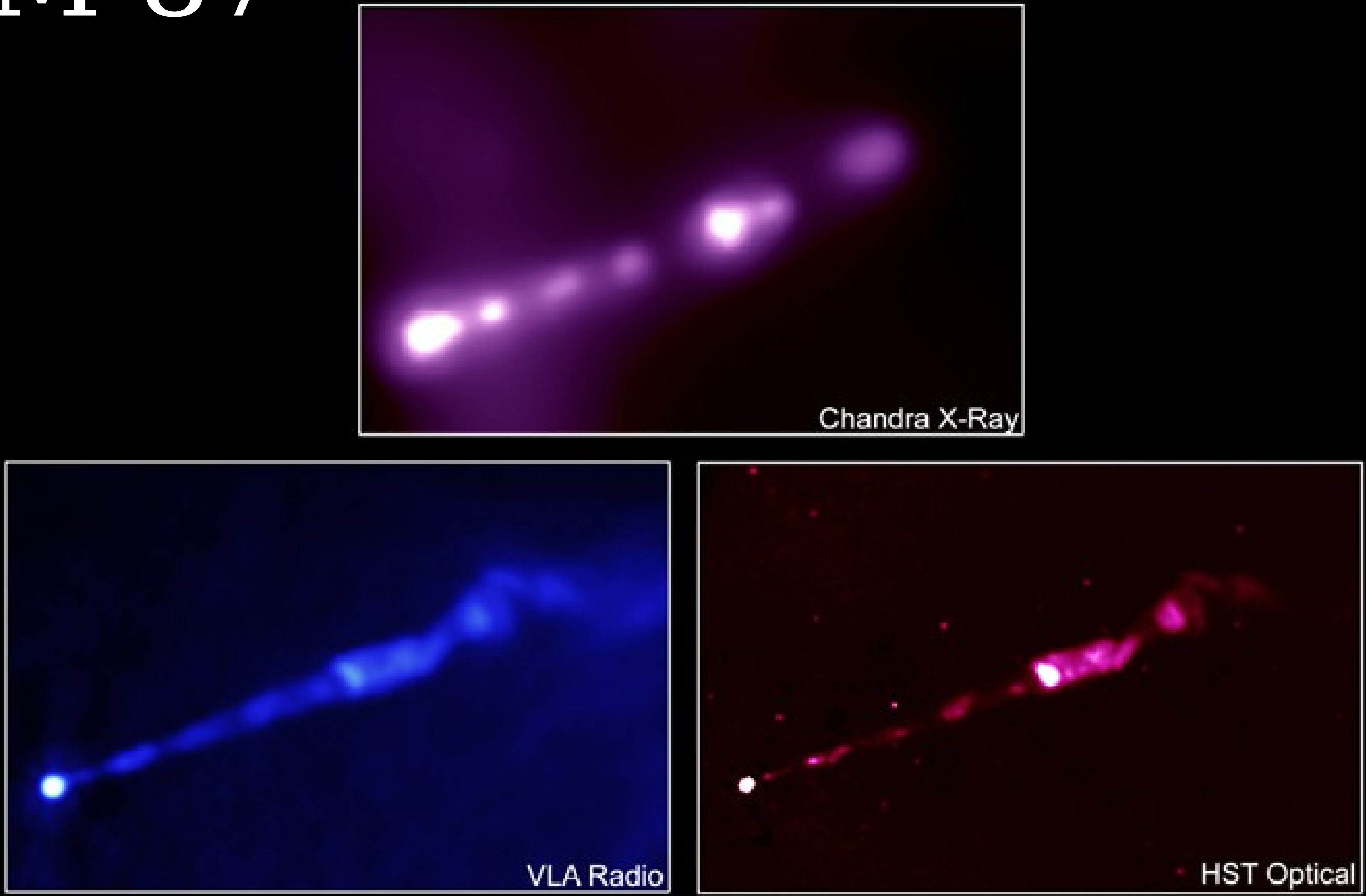
M87 JET

Heber Curtis (1918)
[Lick Observatory]

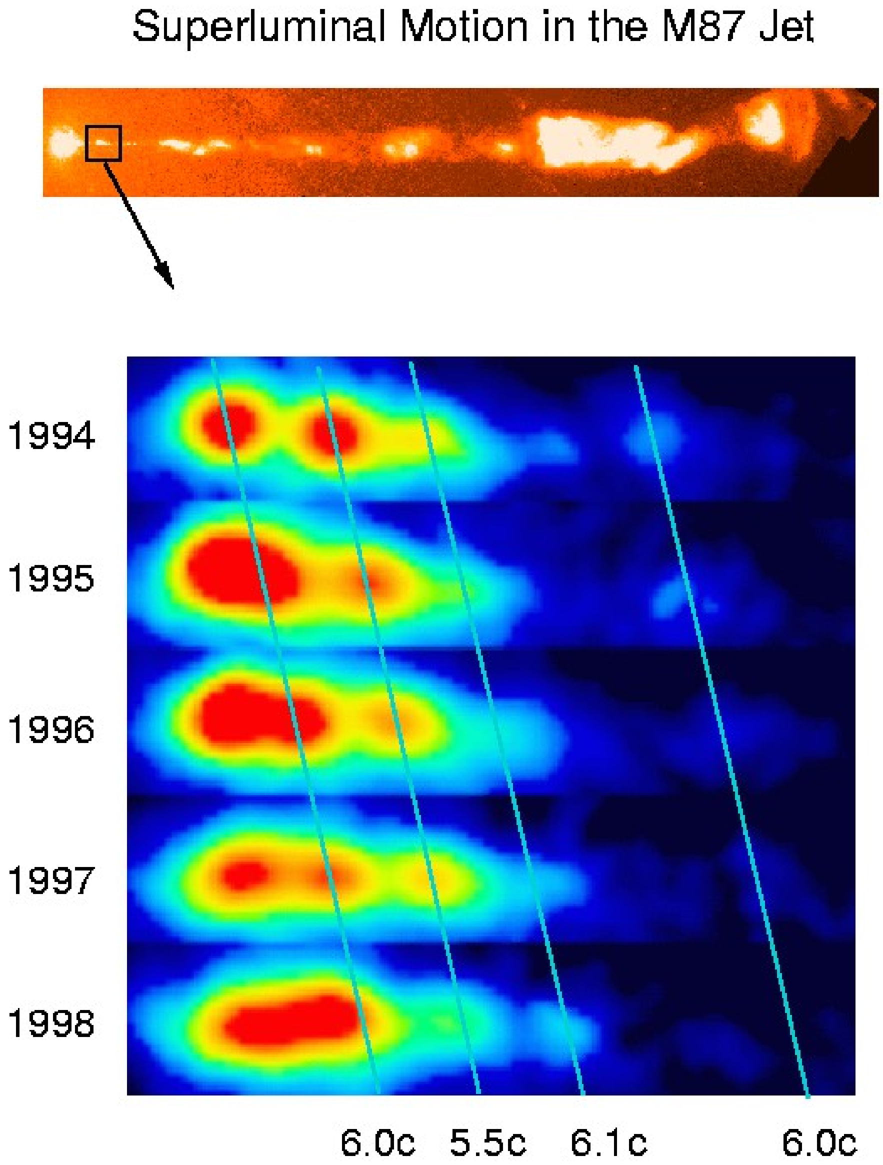
"Descriptions of 762
Nebulae and Clusters …."

"…curious straight ray …
apparently connected
with the nucleus by a
thin line of matter."

M 87



Superluminal Motions



Source moving
on the celestial sphere

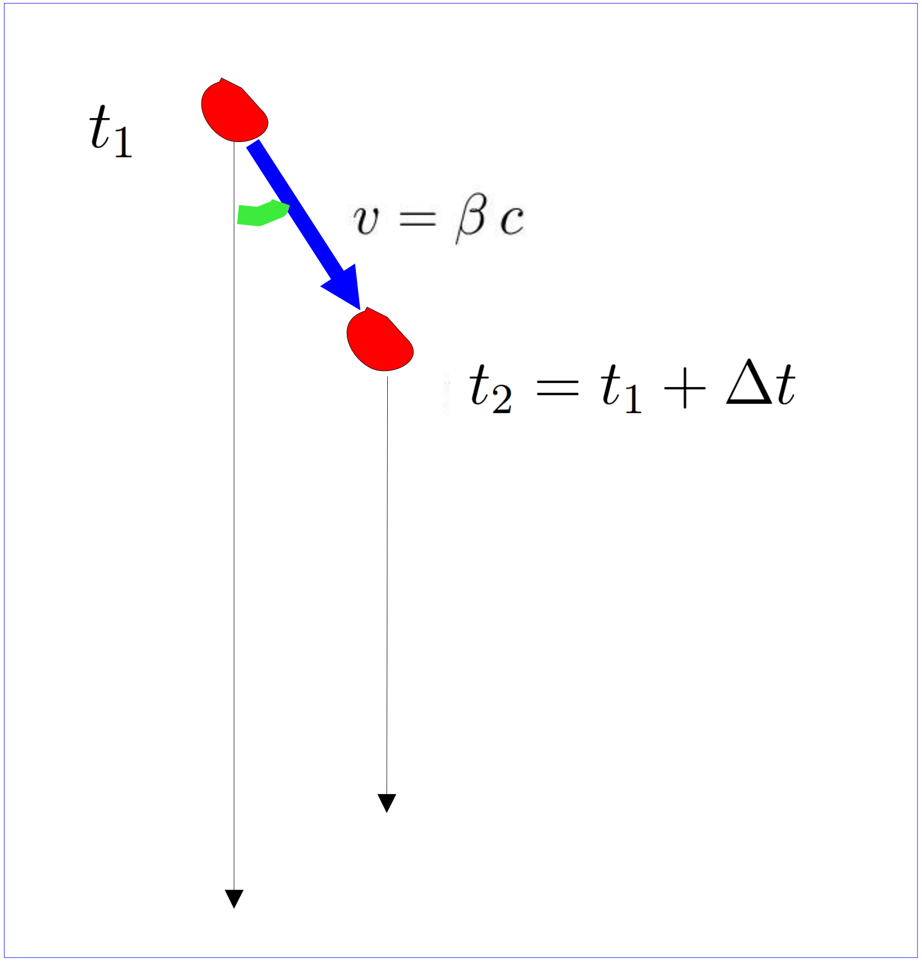
$$c\,\beta_{\mathrm{app}} = L\,\dot{\omega}$$

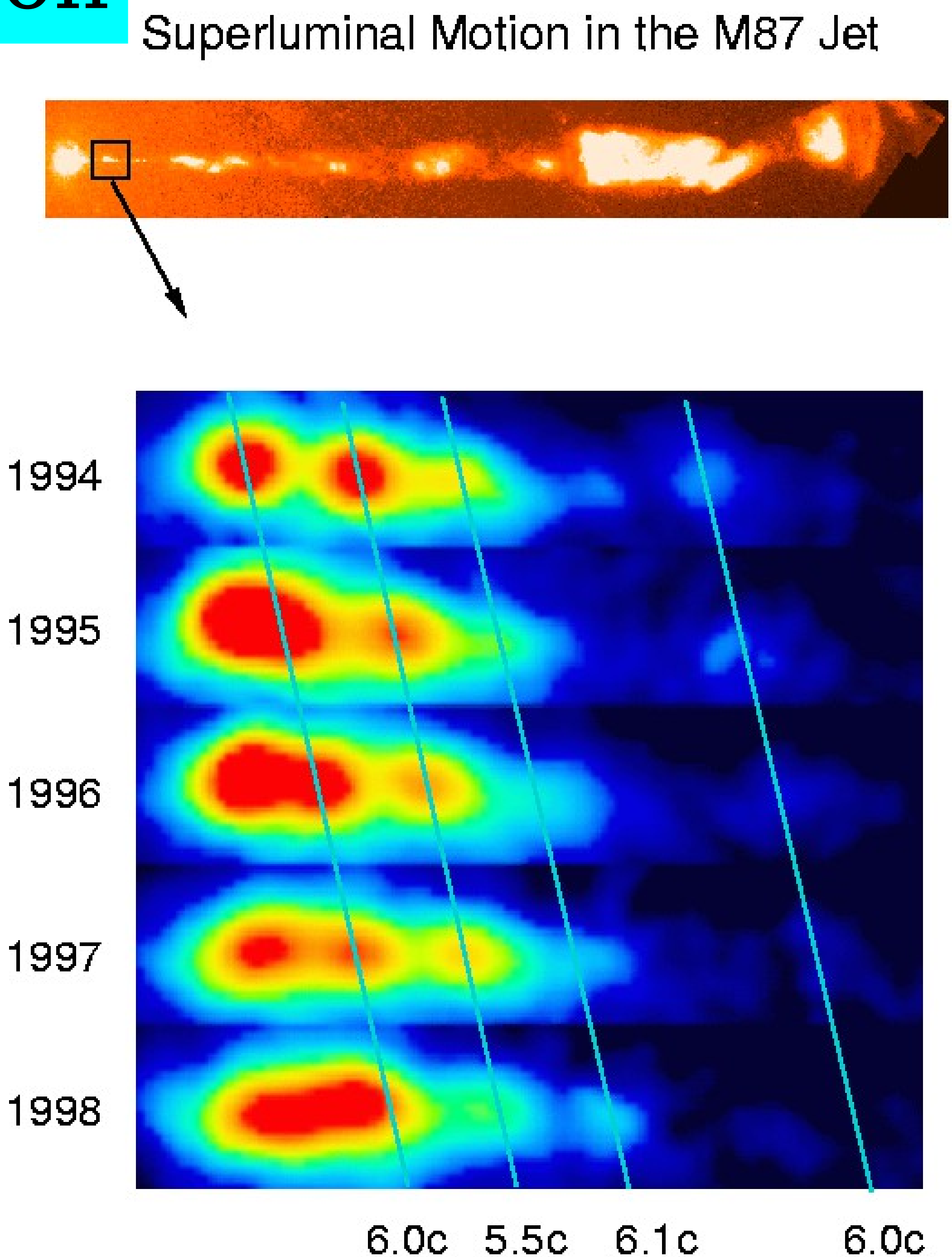
M87 :

$$\beta_{\mathrm{app}} \simeq 6$$

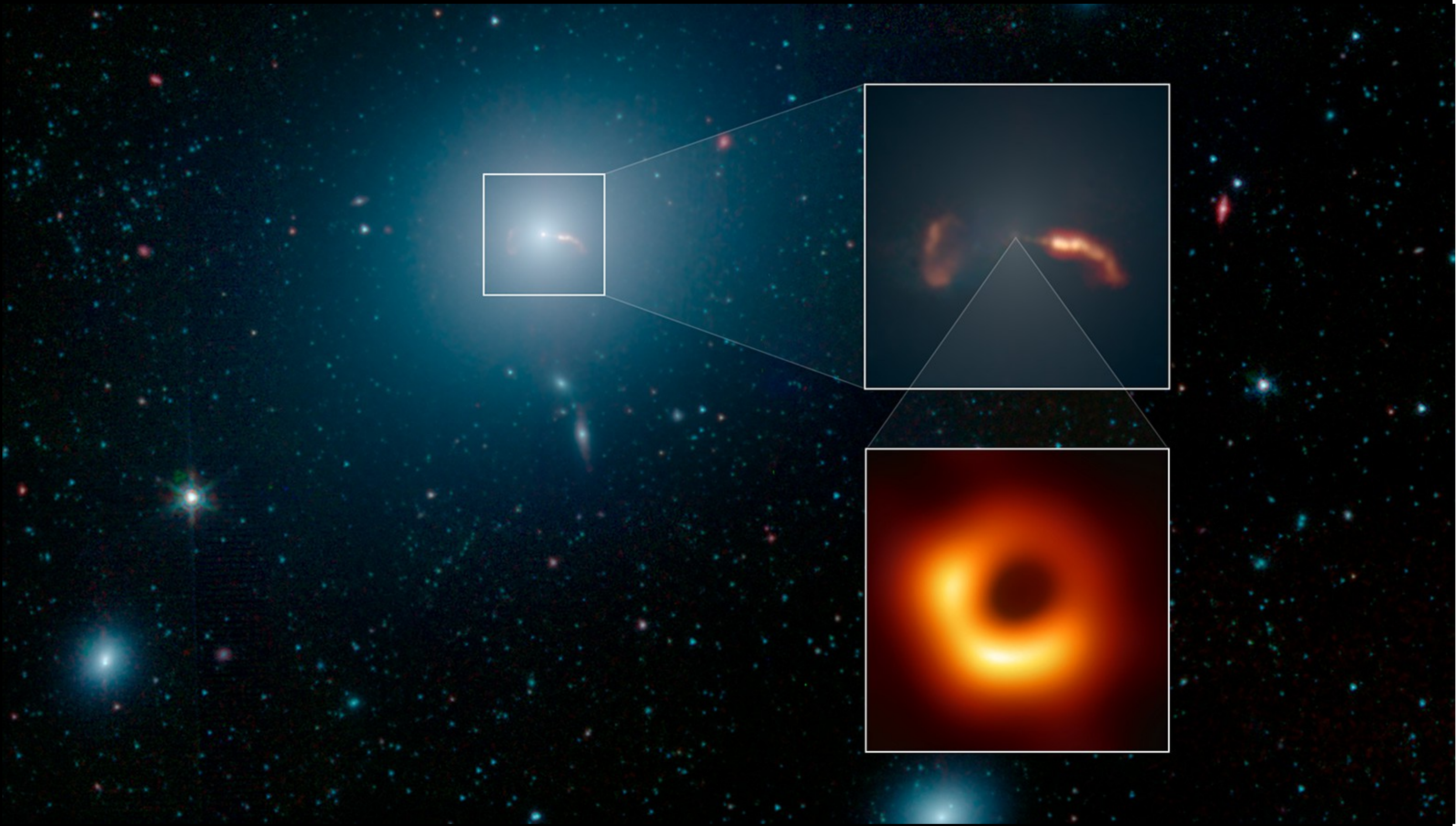
Superluminal Motion

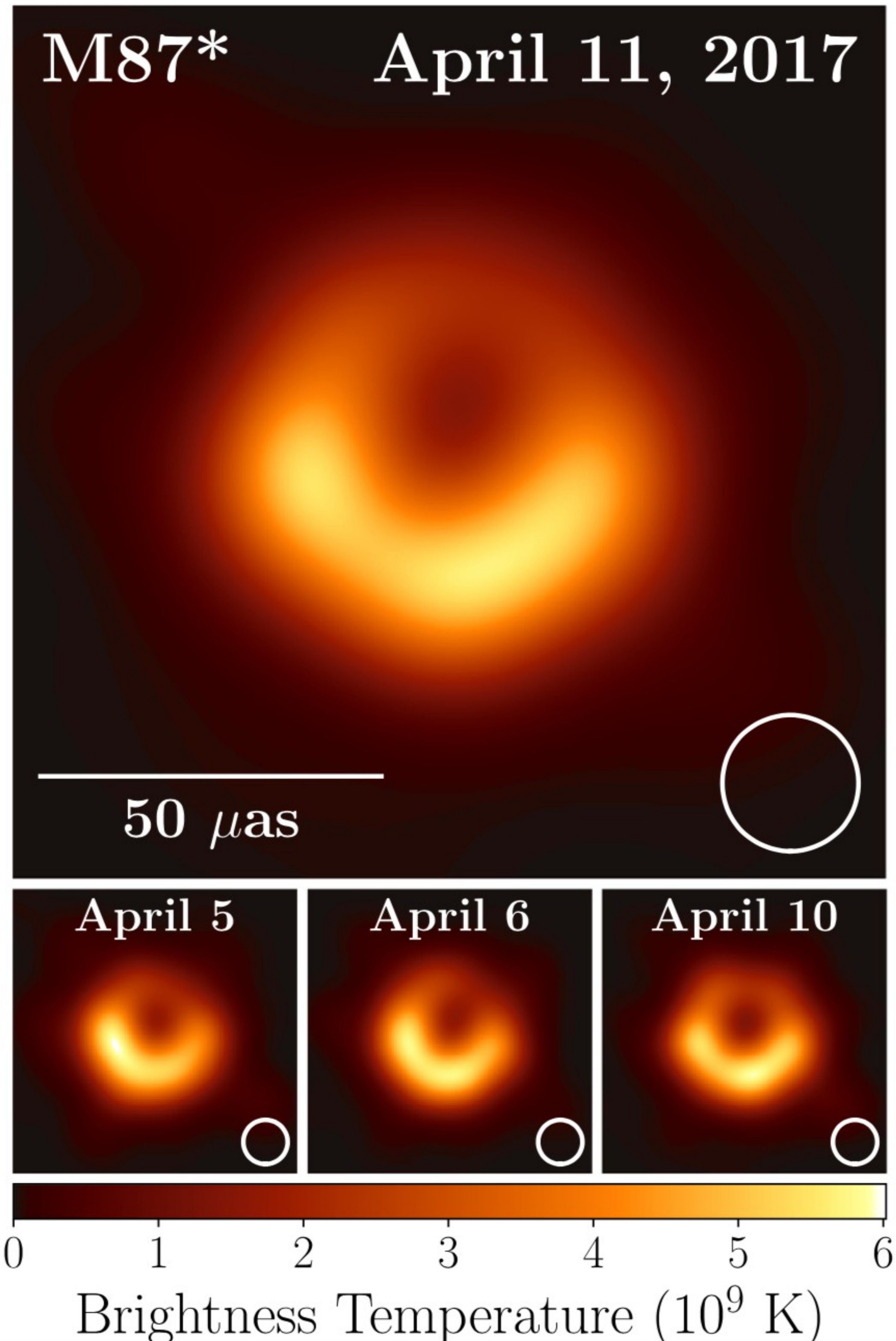
$$v_{\perp,\mathrm{app}} = \frac{L\,(\varphi_2 - \varphi_1)}{\Delta t_{\mathrm{obs}}}$$





M87 (d=17 Mpc)





$$\text{diameter} = 42 \pm 3\ \mu\text{as}$$

Schwarzschild radius

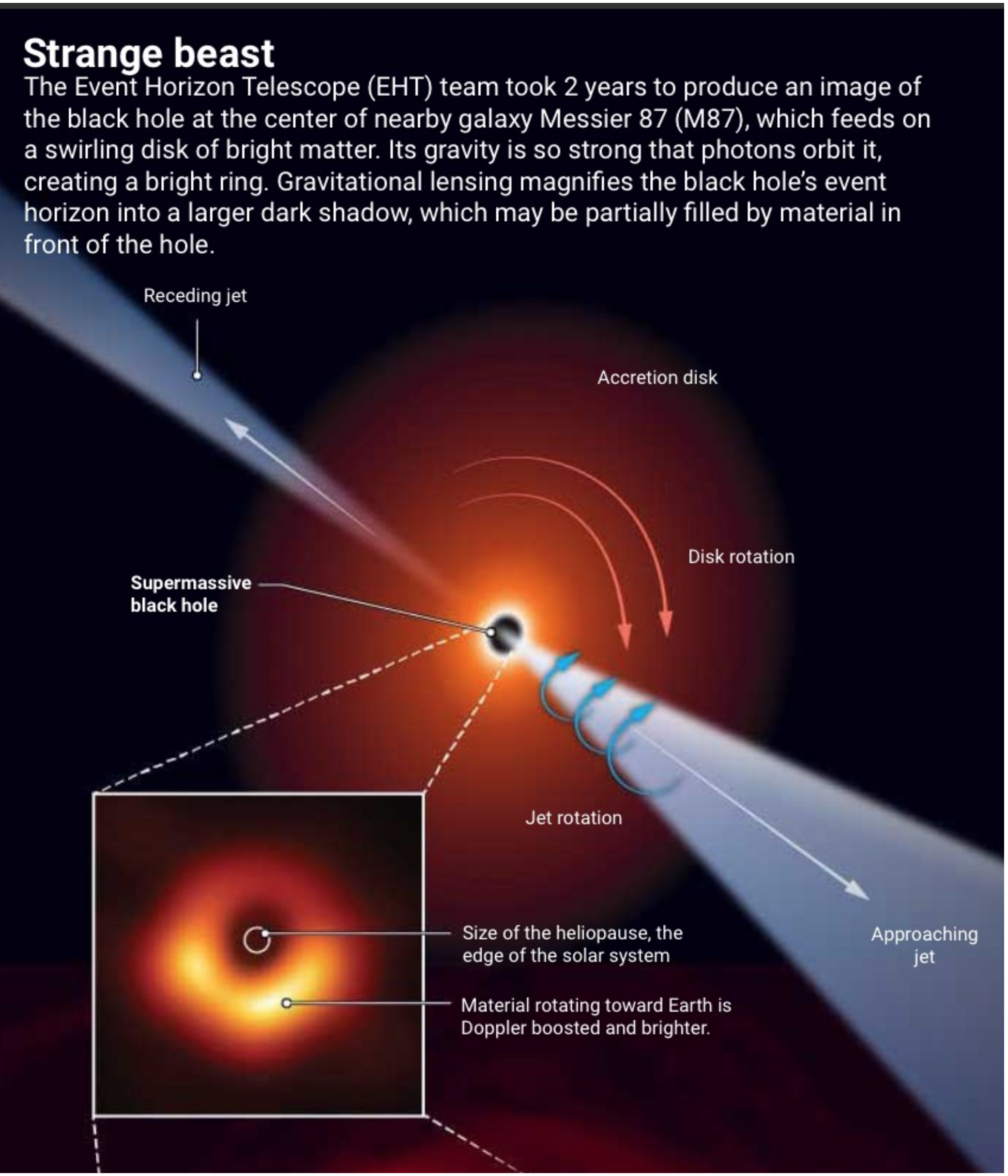
$$R_S = \frac{2\,G}{c^2}\ M$$

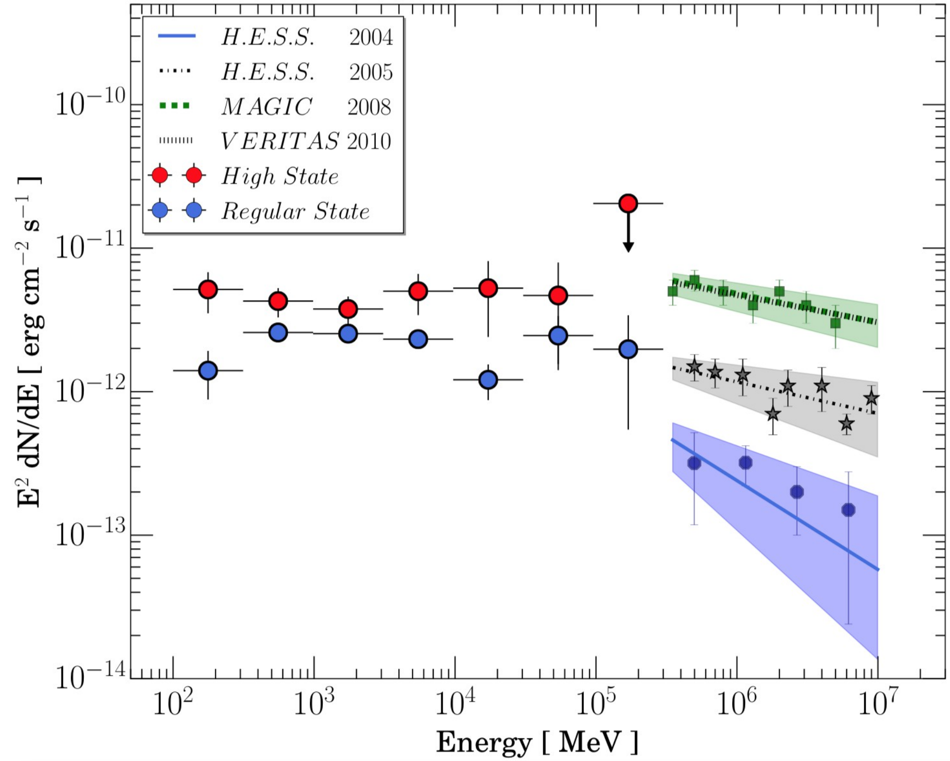
Photon capture radius

$$R_c = \sqrt{27}\ \frac{G}{c^2}\ M$$

$$d = 16.8 \pm 0.8\ \text{Mpc}$$

$$M = (6.5 \pm 0.7) \times 10^9\ M_\odot$$





High energy gamma rays from M87

Continued campaign of observations of the *"Event Horizon Telescope"*

[Event Horizon Telescope, Fermi-LAT, H.E.S.S., MAGIC, VERITAS and EAVN], "Broadband Multi-wavelength Properties of M87 during the 2017 Event Horizon Telescope Campaign" Astrophys. J. Lett. **911**, no.1, L11 (2021) [arXiv:2104.06855 [astro-ph.HE]].

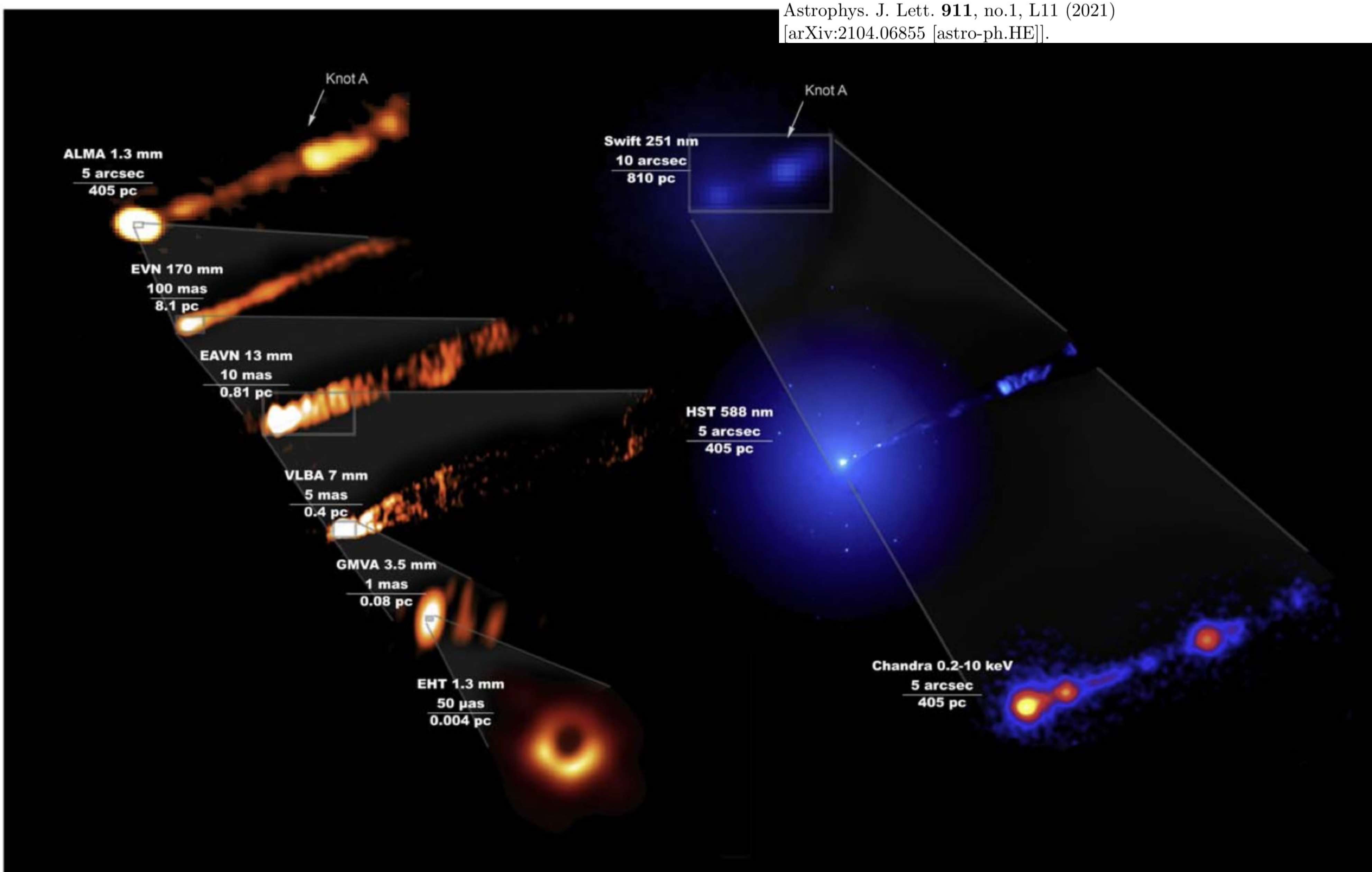


Figure 13. Compilation of the quasi-simultaneous M87 jet images at various scales during the 2017 campaign. The instrument, observing wavelength, and scale are shown on the top-left side of each image. Note that the color scale has been chosen to highlight the observed features for each scale, and should not be used for rms or flux density calculation purposes. Location of the Knot A (far beyond the core and HST-1) is shown in the top figures for visual aid.

Observations of M87

2005
2008
2010

HESS
MAGIC
VERITAS

$E \geq 350$ GeV

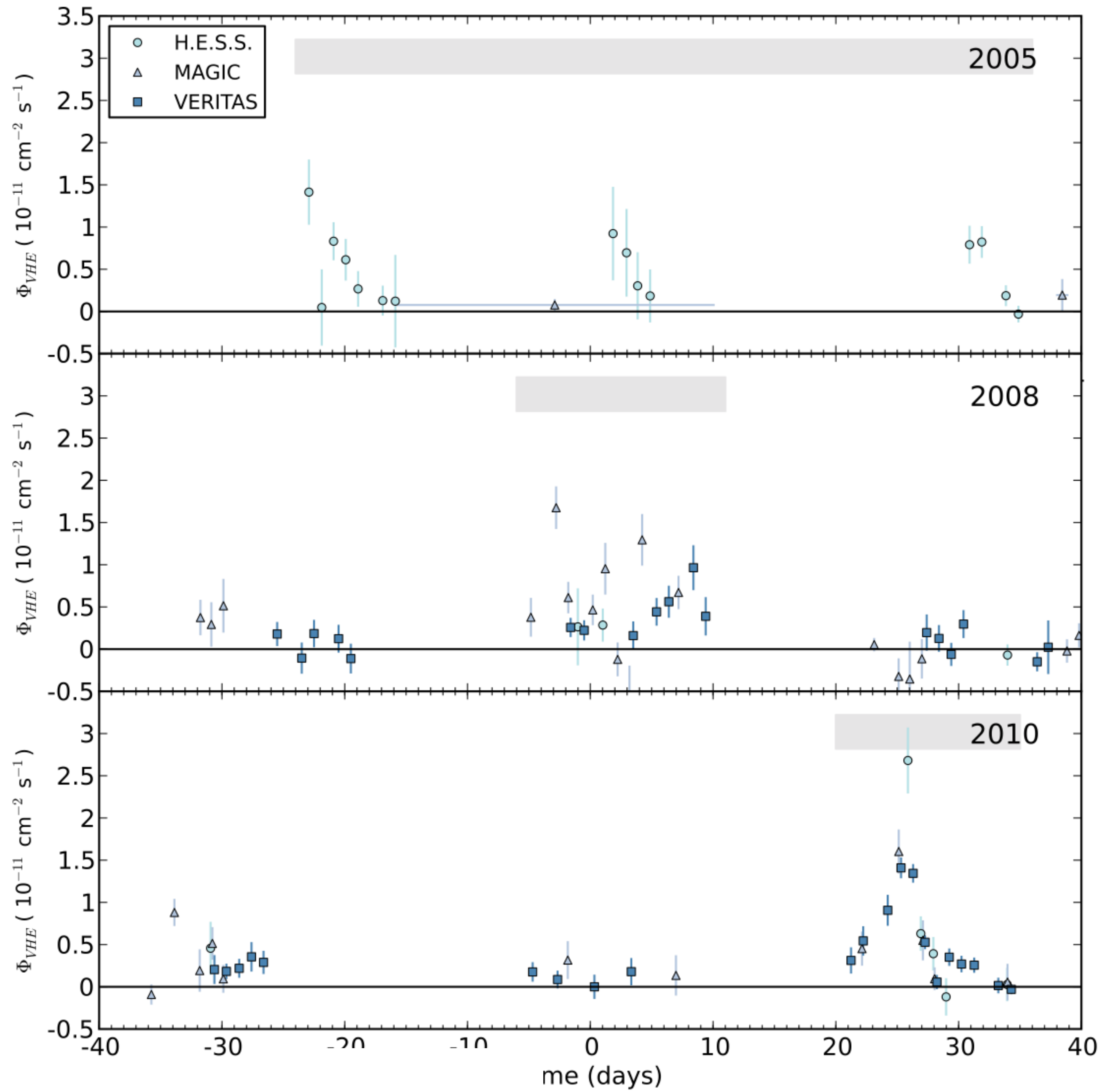
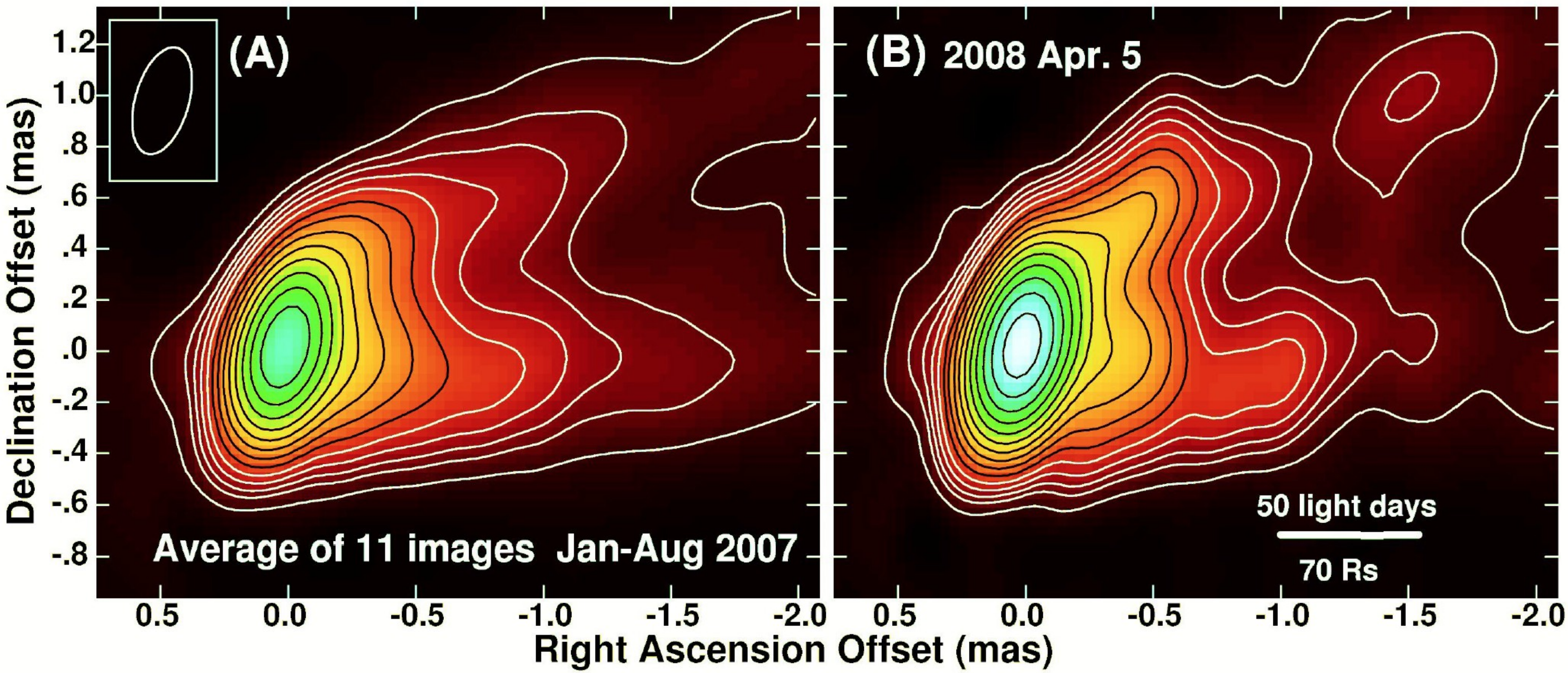


Figure 2. VHE light curve of M 87 of the flaring episodes in 2005 (top), 2008 (middle), and 2010 (bottom). Integral fluxes are given above an energy of 350 GeV. The lengths of the gray bars correspond to the length of the gray shaded areas in Figure 1. A time of 0 days corresponds to MJD 53460, MJD 54500, and MJD 55270 for 2005, 2008, and 2010, respectively. Flux error bars denote the 1 s.d. statistical error. Horizontal error bars denote the time span the flux has been averaged over. Note that in the case of time spans longer than one night the coverage is not continuous.

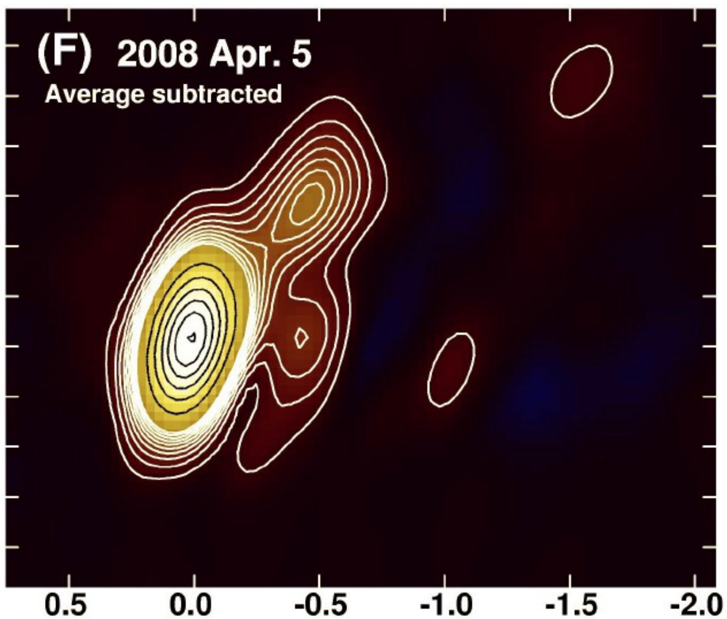


VLBA radio images
of M87 at 43 GHz

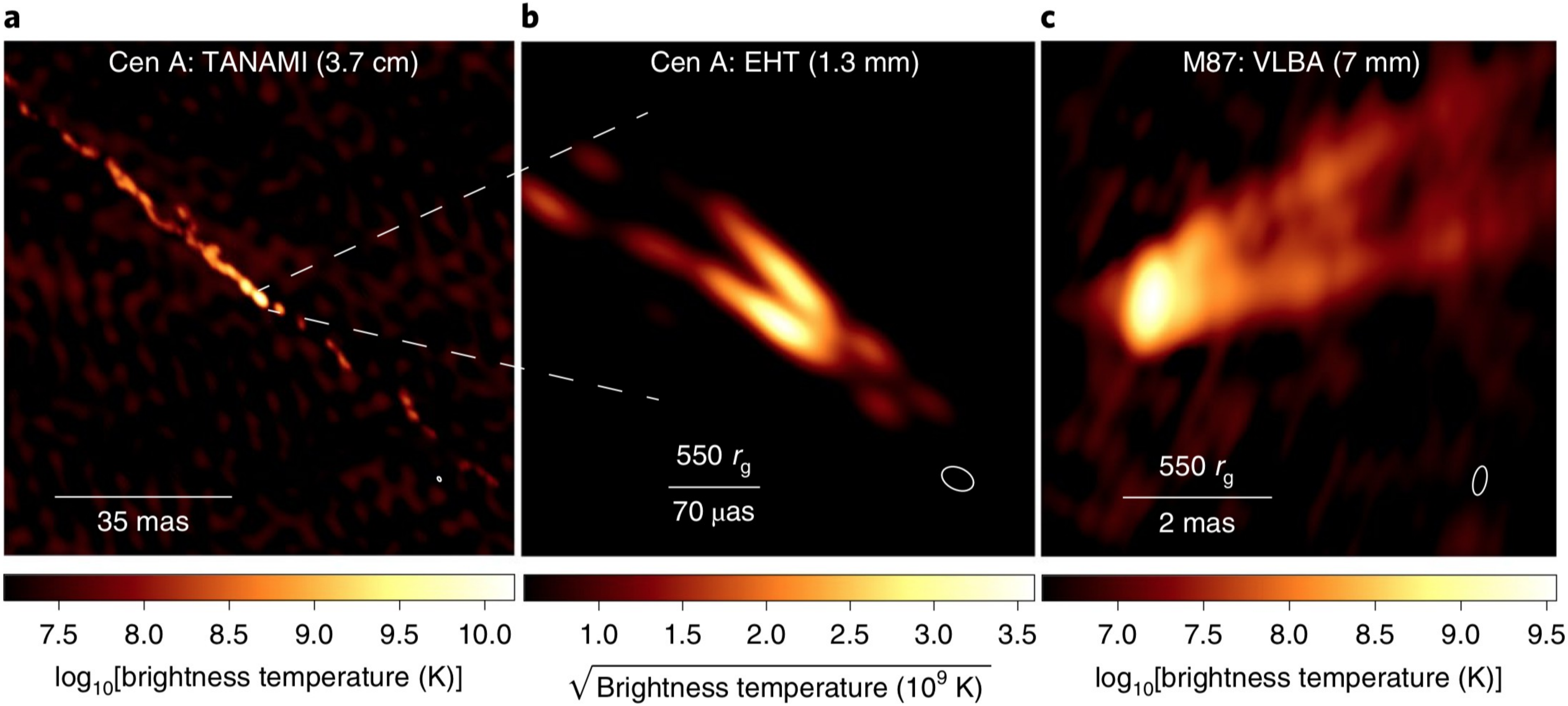
Science 24 Jul 2009:
Vol. 325, Issue 5939, pp. 444-448
DOI: 10.1126/science.1175406

Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration

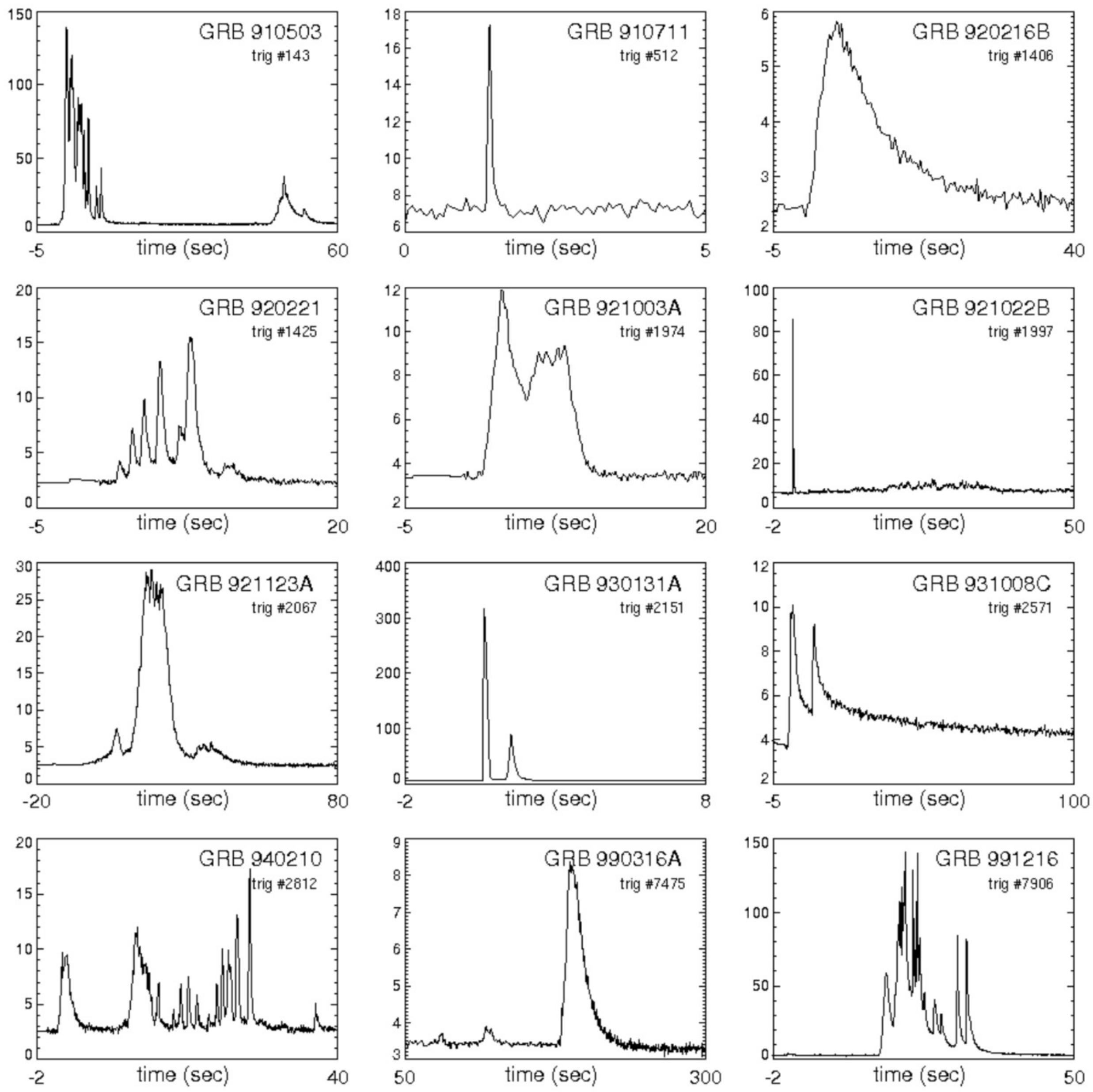


The jet of Centaurus A $\quad M_\bullet = (5.5 \pm 3) \times 10^7\ M_\odot$



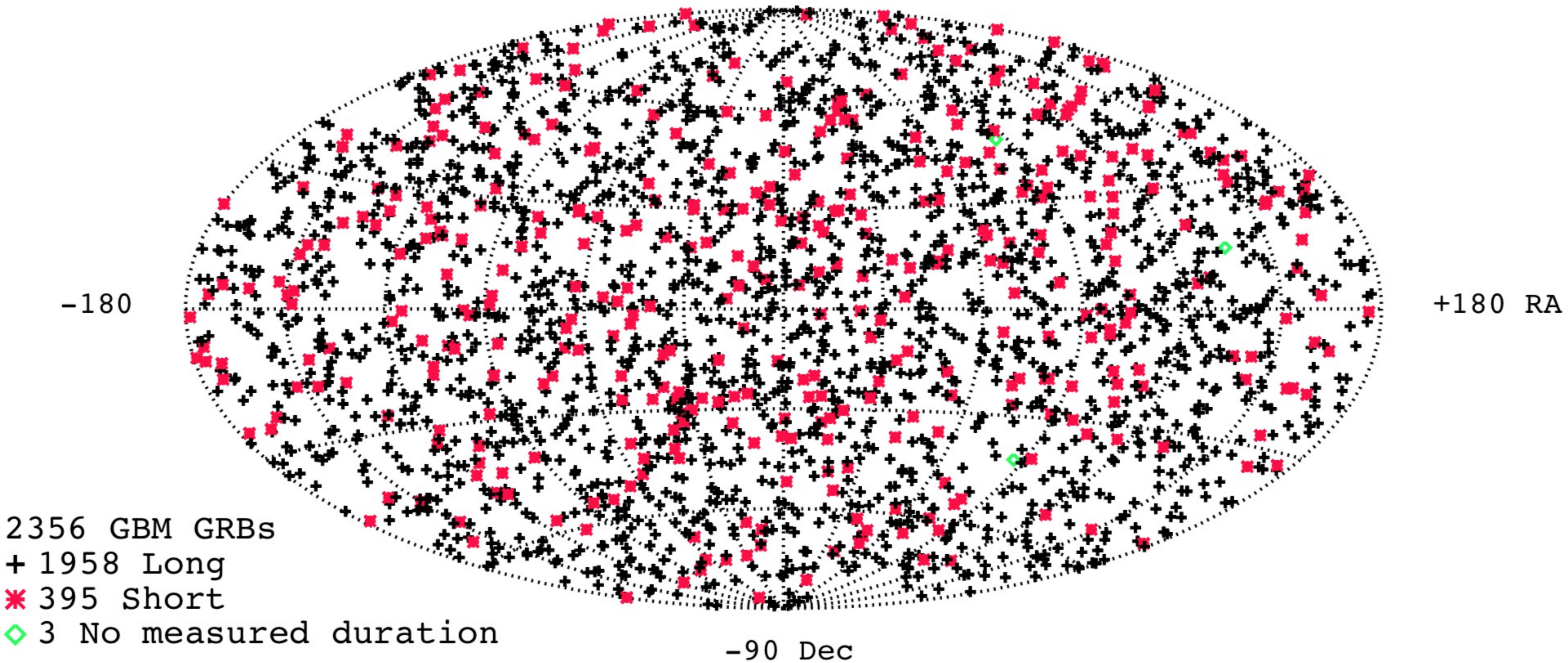
"Event Horizon Telescope observations of the jet launching and collimation in Centaurus A" Nature Astron. **5**, no.10, 1017-1028 (2021)

Examples of GRB time profiles (from BATSE 1991-2000)



FERMI satellite Gamma Ray Burst Monitor (GBM)

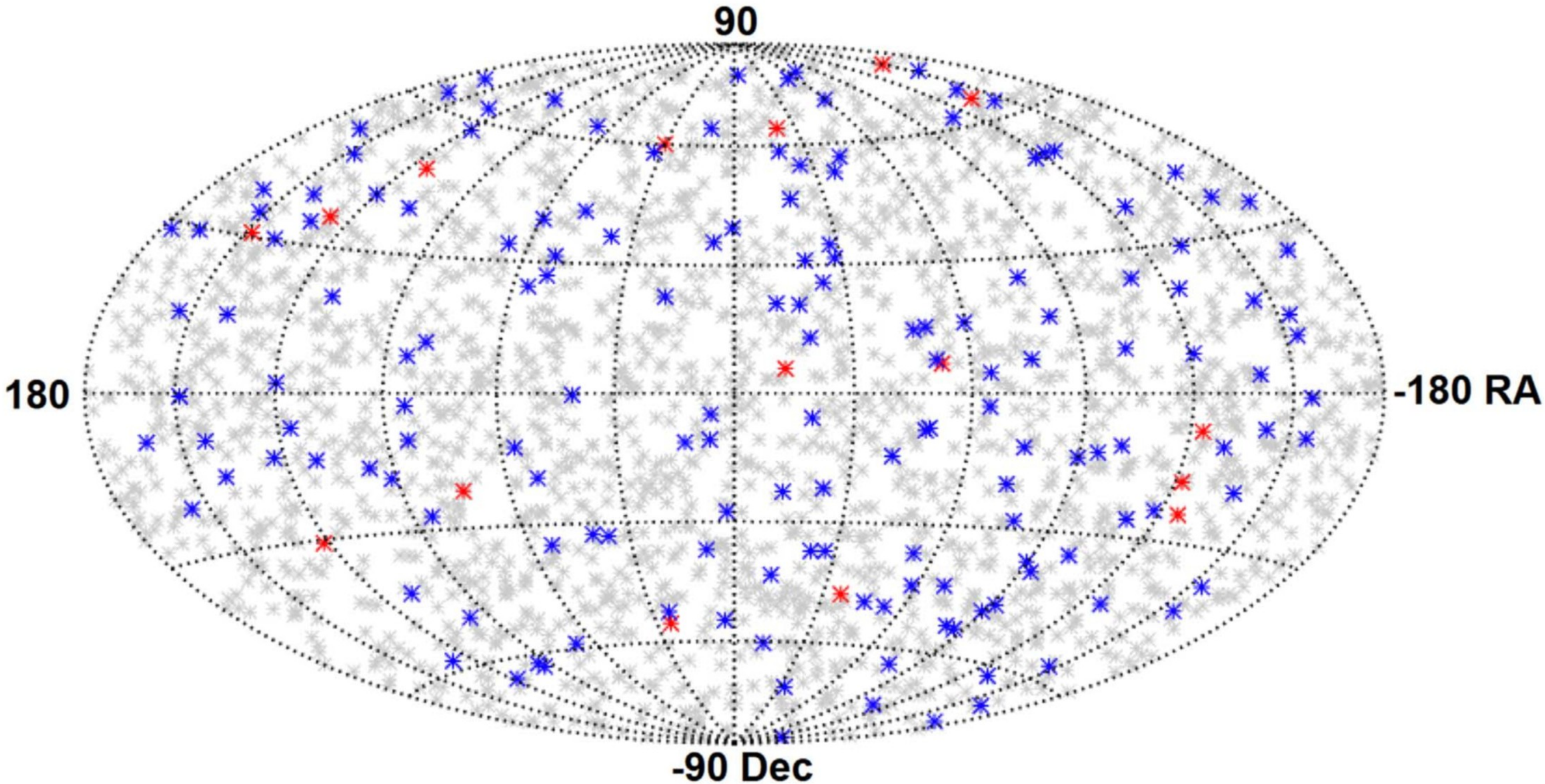
10 years catalog 1998-2008 [50-300 KeV]



Isotropic distribution

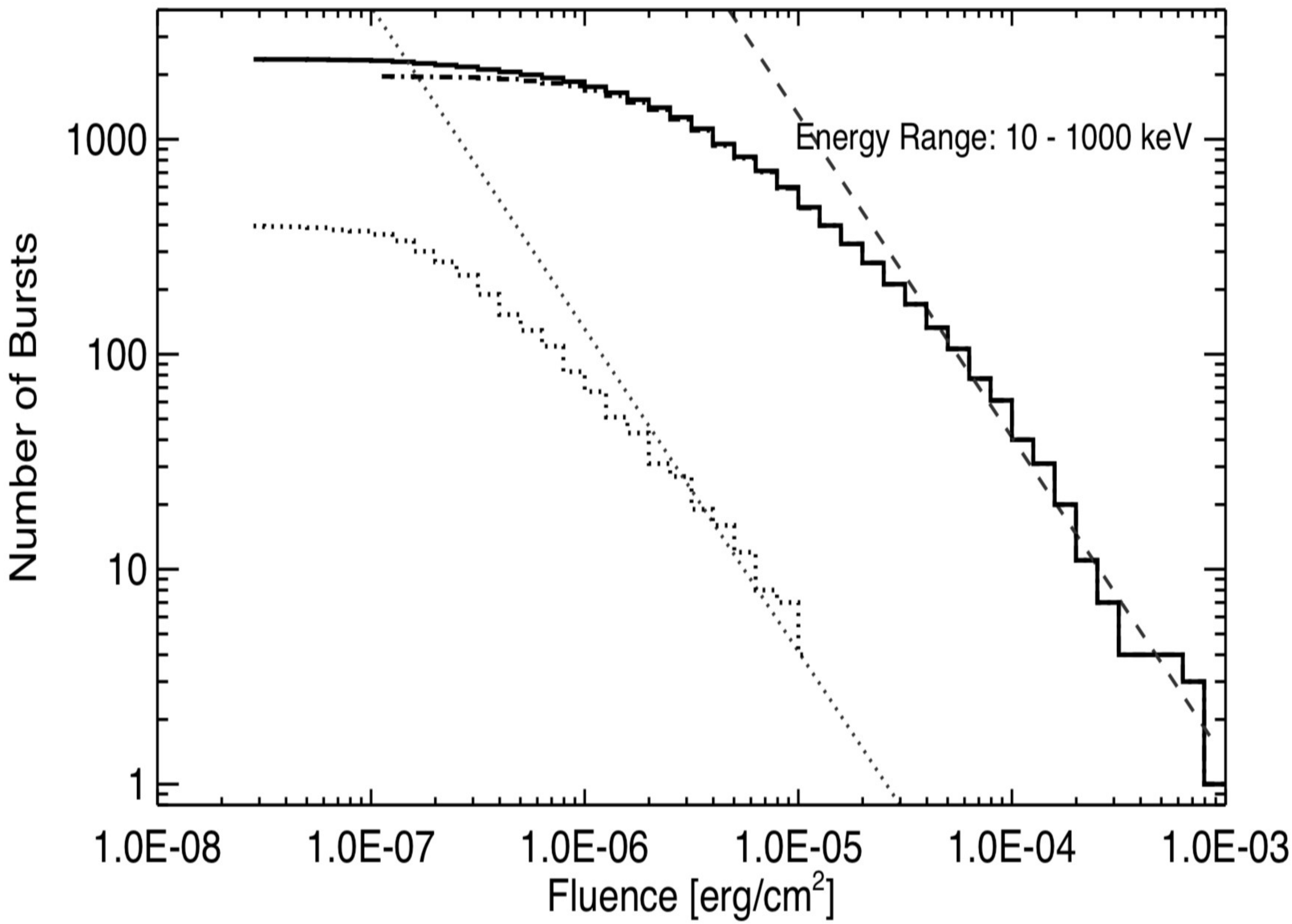
2nd FERMI-LAT GRB catalog (2008/ July/14 – 2018/July/31)

[0.1 – 100 GeV]

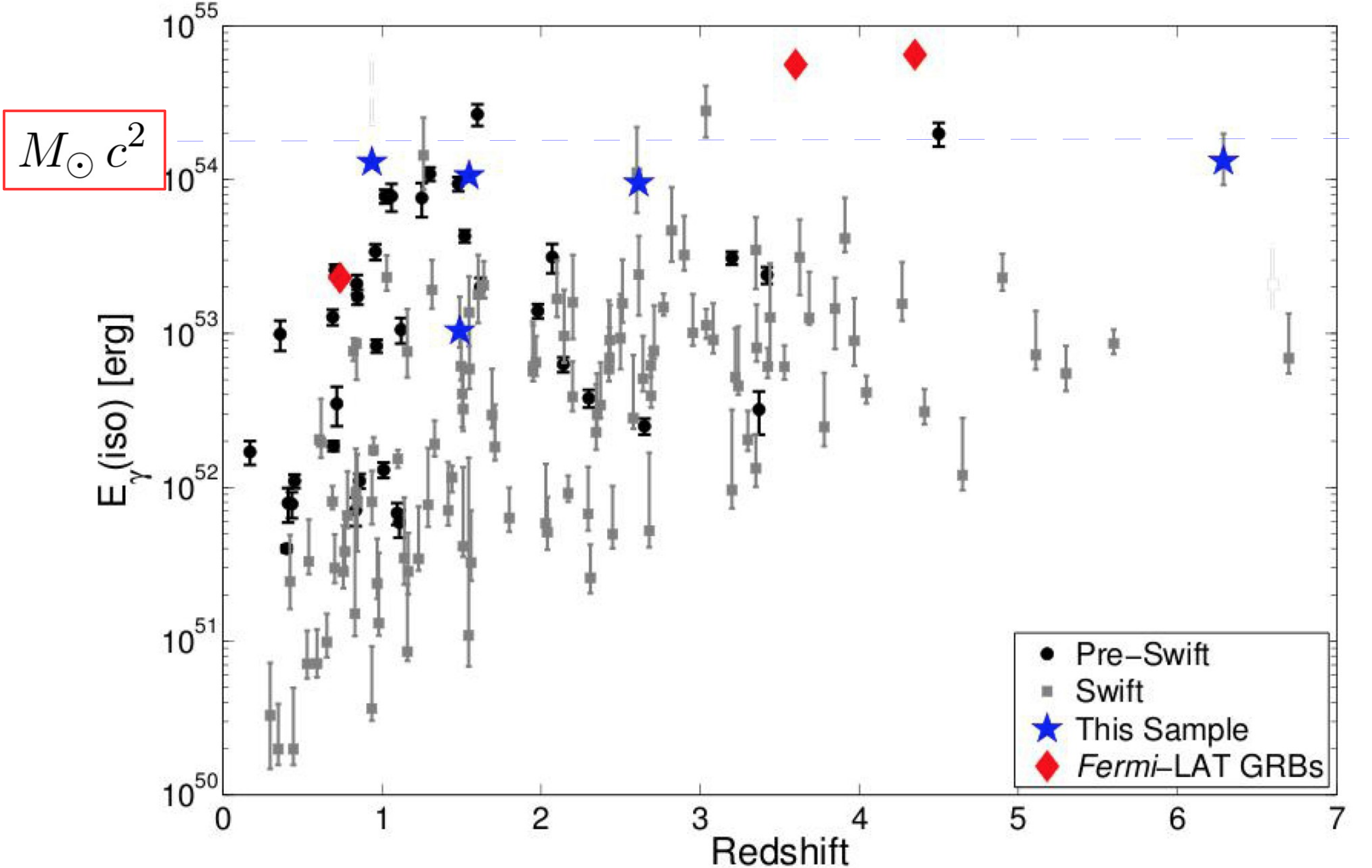


2357 GBM GRBs (gray asterisks)

(160 + 16) long (short) LAT-detected GRB


Energy Range: 10 - 1000 keV
Number of Bursts
1000
100
10
1
1.0E-08
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
Fluence [erg/cm2]

Extraordinary Large (beamed) Energy Output



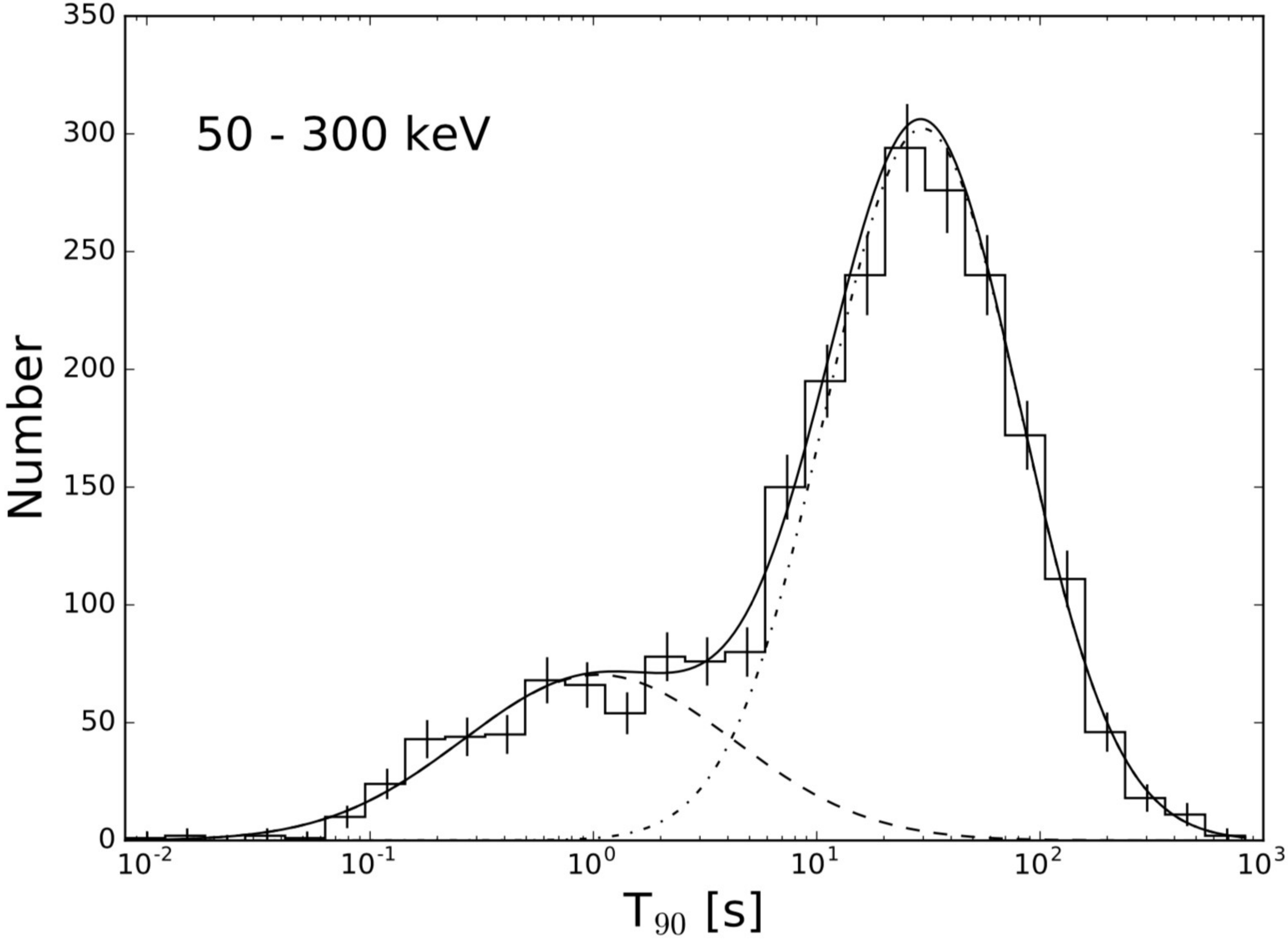
GBM time-duration distribution

T[90% of fluence]

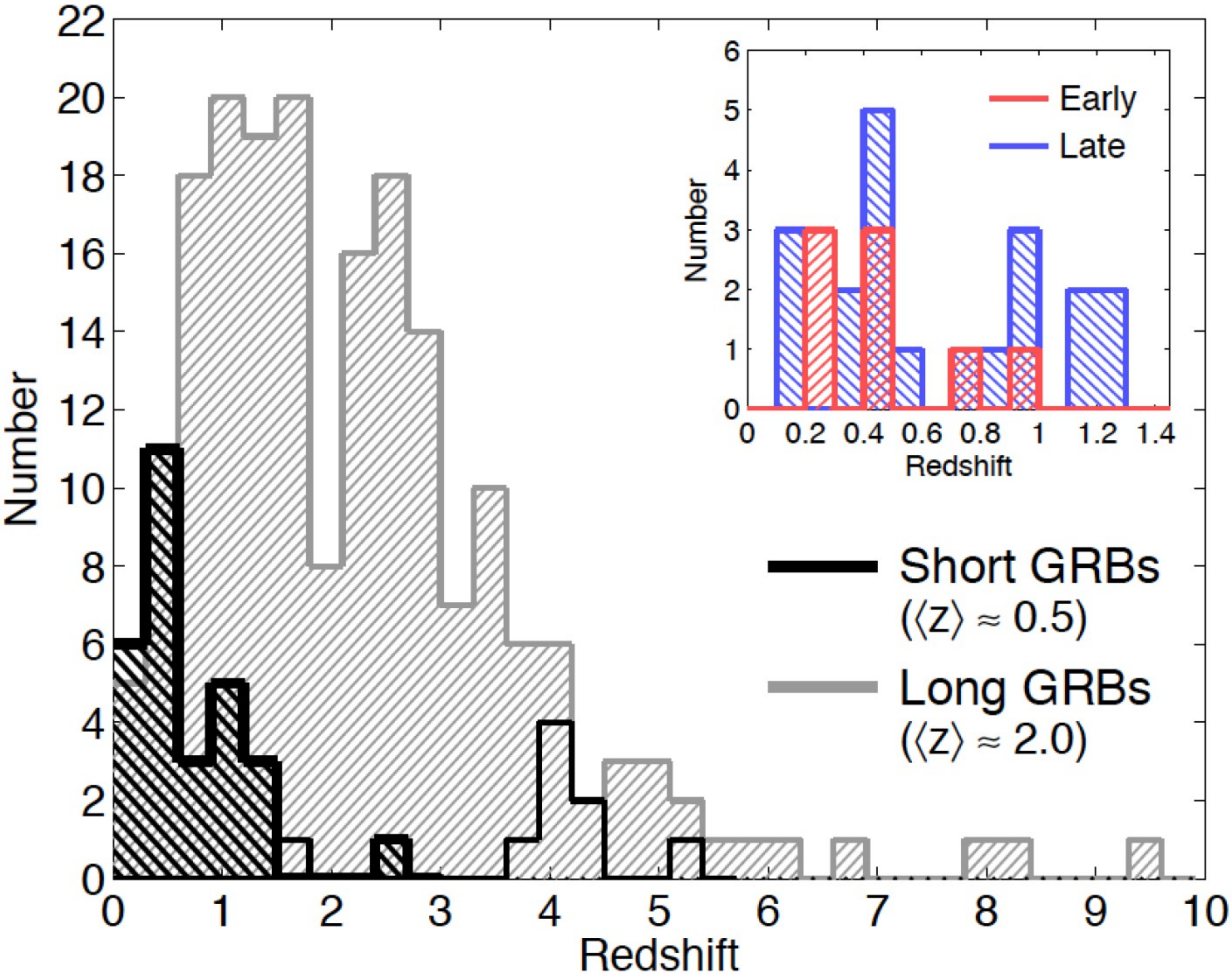
LogNormal distribution fits

$$10^{\langle \log T \rangle} = 1.05 \text{ sec}$$

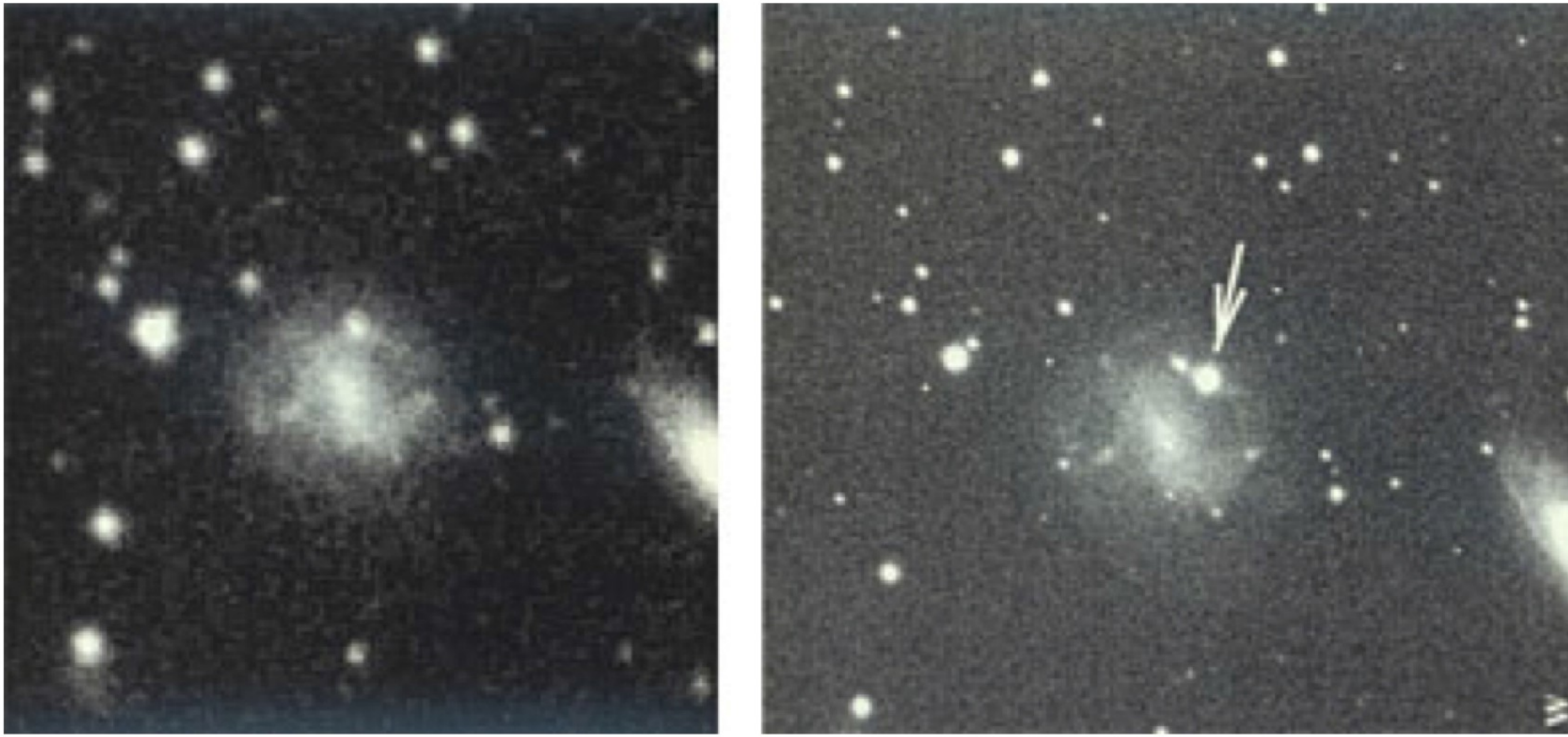
$$10^{\langle \log T \rangle} = 29.9 \text{ sec}$$



Short versus Long GRB's

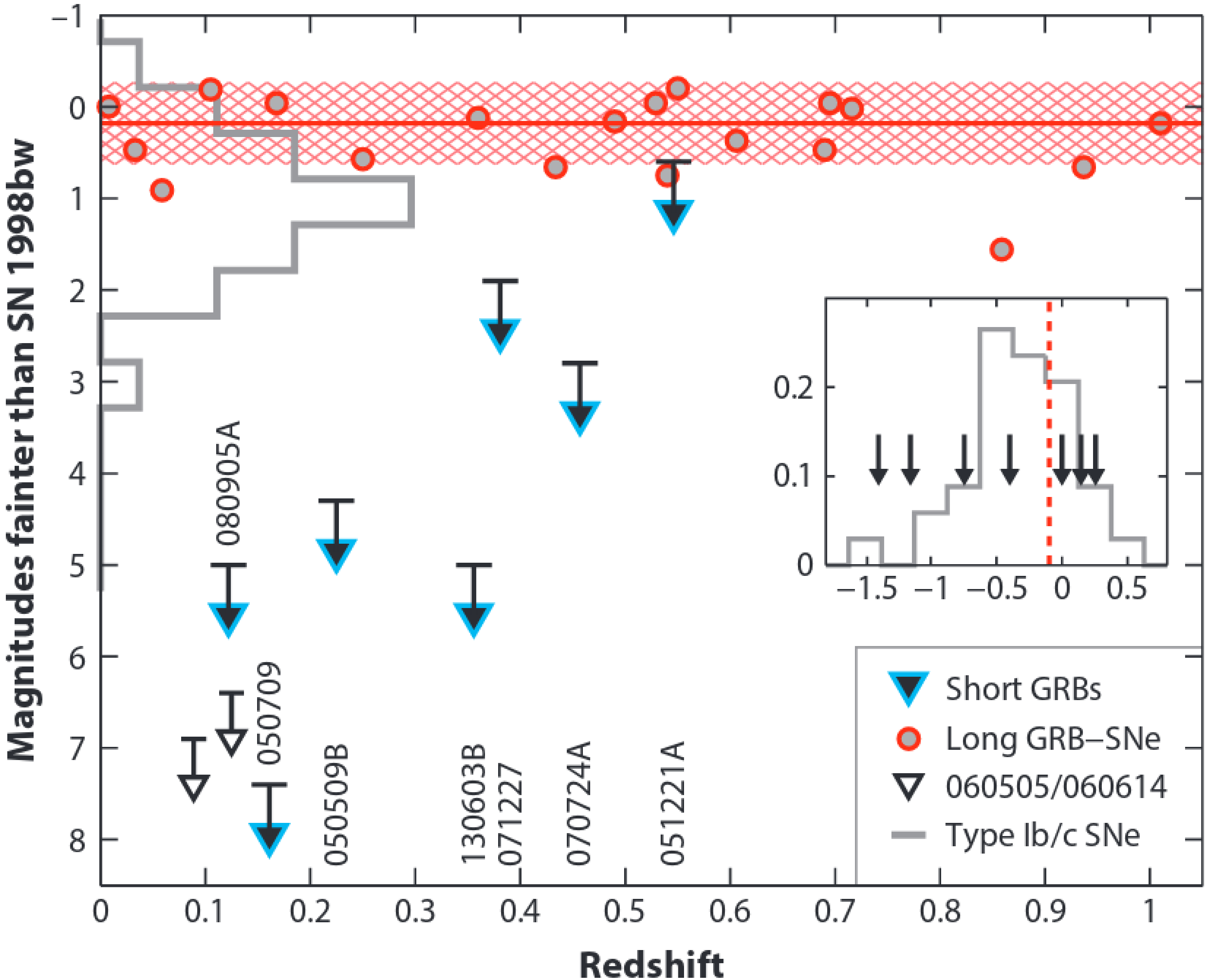


Association Long GRB's with SN explosions



Images: A 1998 supernova (*SN 1998bw*, left) and the corresponding gamma-ray burst on April 25, 1998 (*GRB 980425*, right). Courtesy of Dr. Kulkarni.

SN 1998bw GRB 980425



Magnitudes fainter than SN 1998bw
Redshift
080905A
050709
050509B
130603B
071227
070724A
051221A
Short GRBs
Long GRB–SNe
060505/060614
Type Ib/c SNe

GRB 130427A

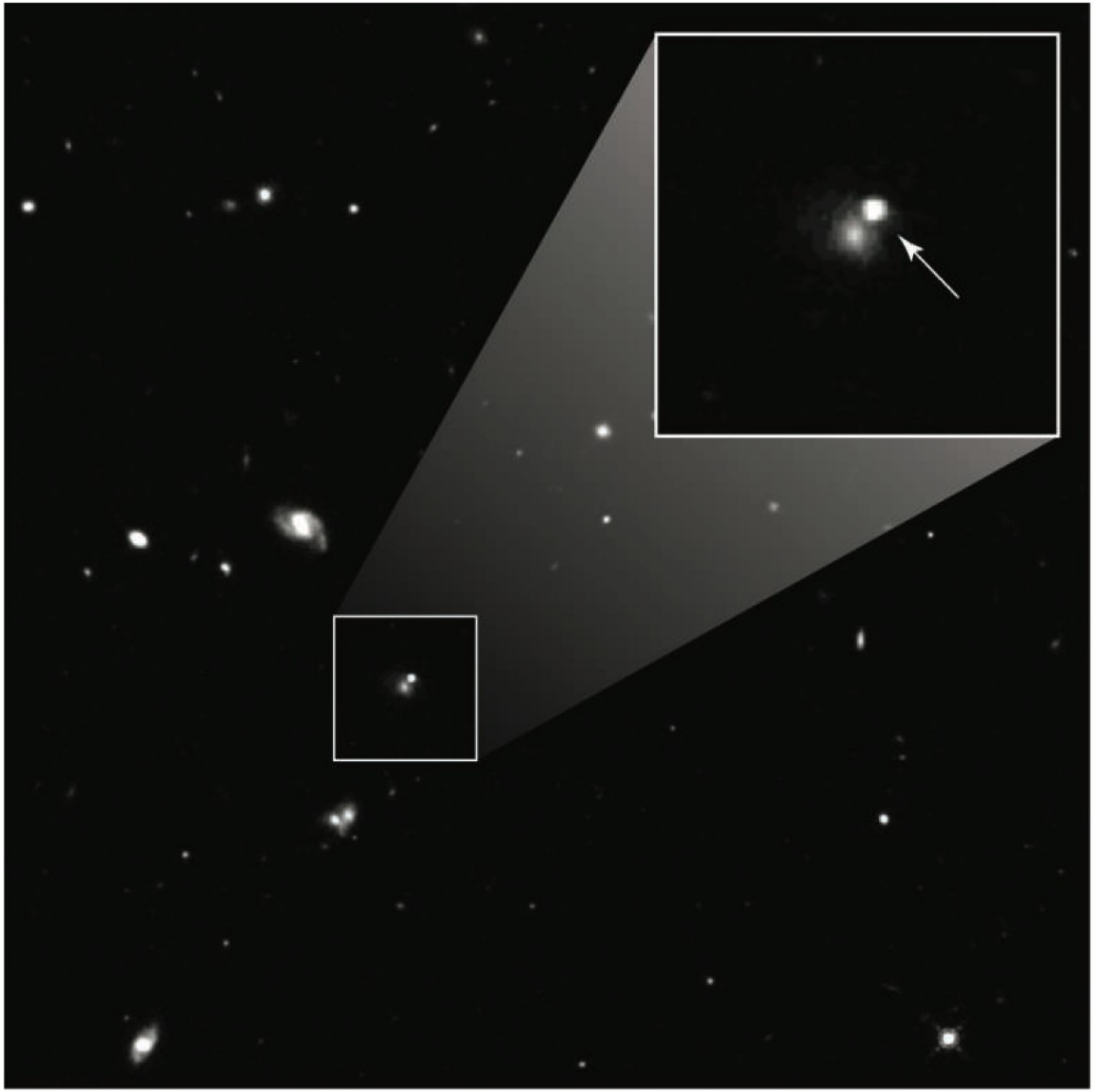
Science

3rd January 2014

GRB 130427A: A Nearby Ordinary Monster

Fermi paper lower limit on Lorentz Factor of outflow

$$\Gamma_{\rm min} = 455^{+16}_{-13}$$

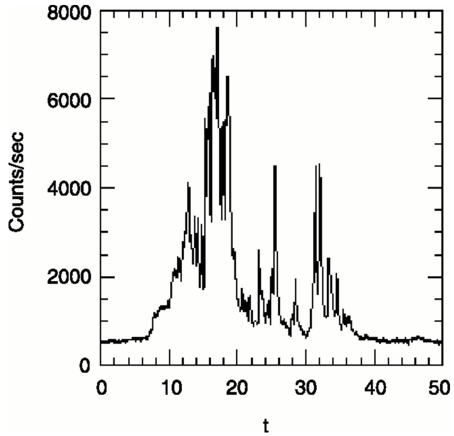


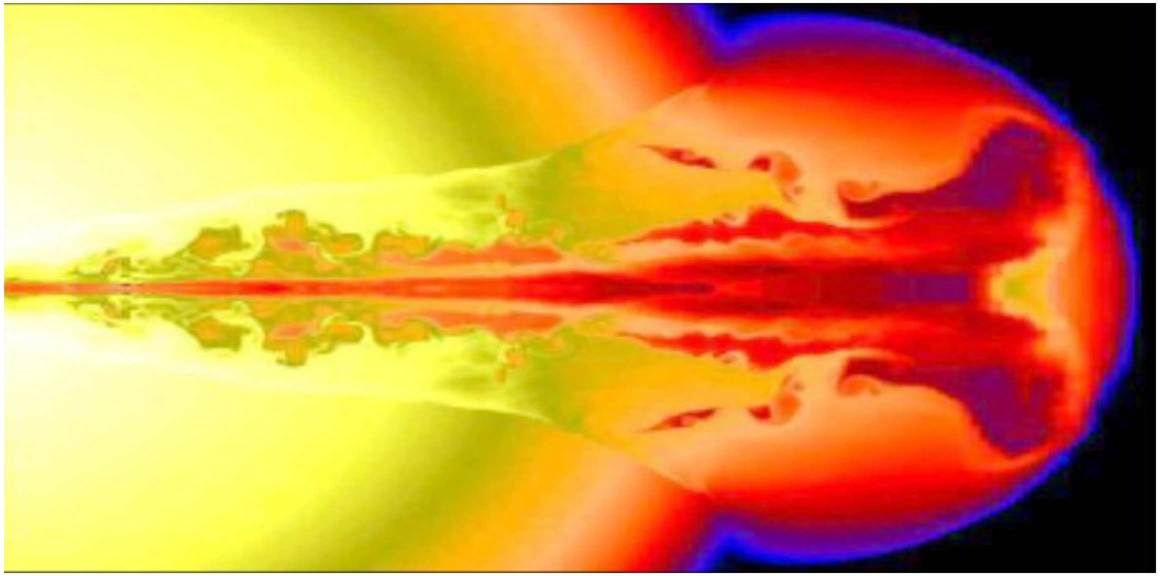
Hubble
Space Telescope

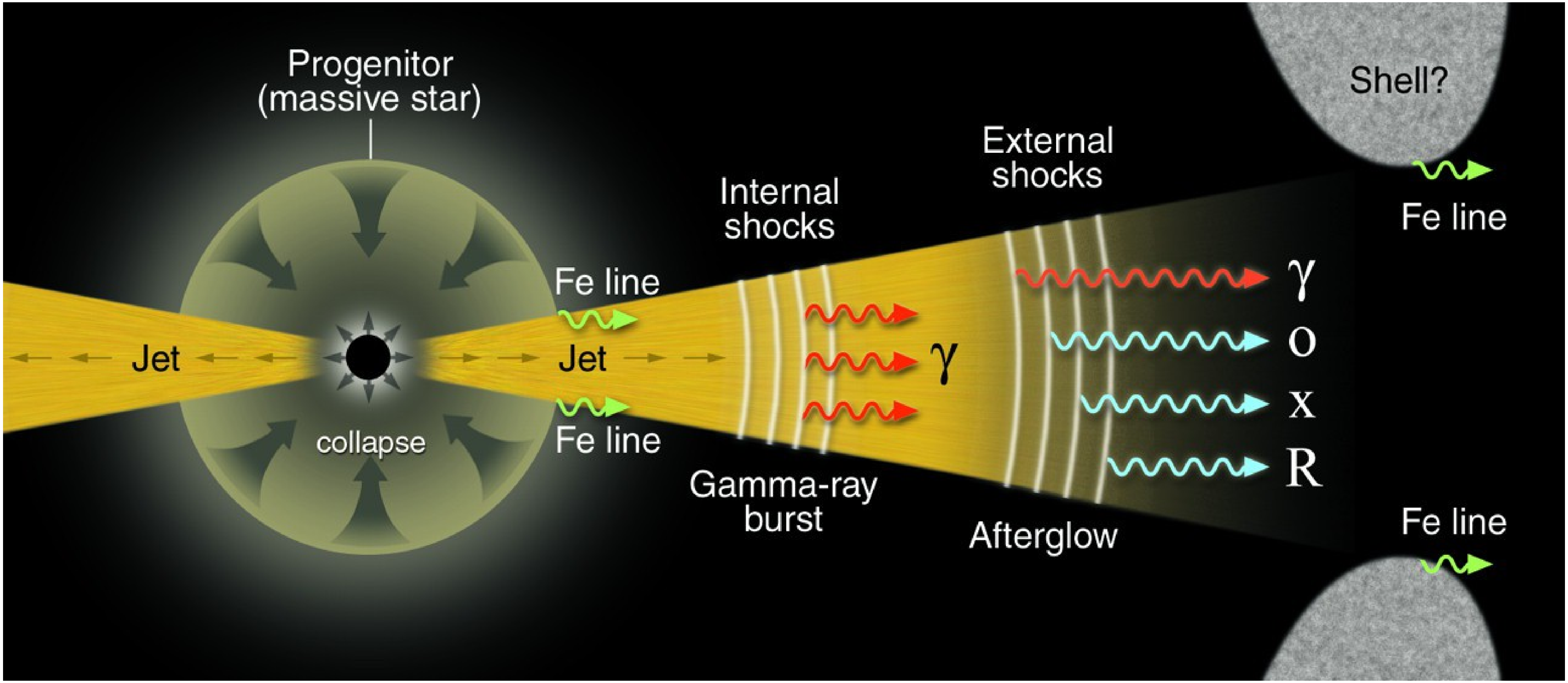
Detection
of SN 2013 cq
and its host galaxy

[at z = 0.3399]

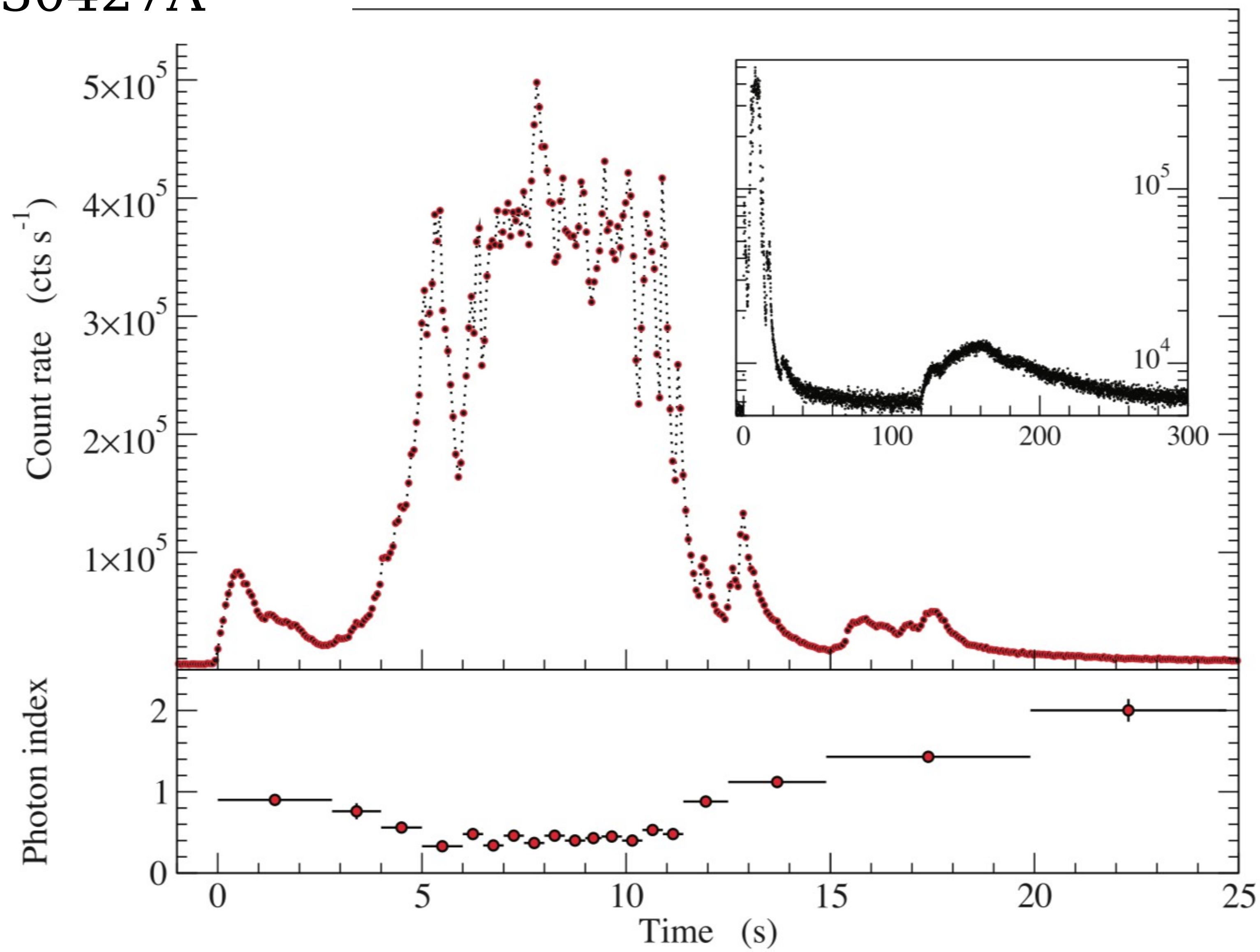
GRB 0.83''
from center if Galaxy
(4 kpc)


8000
6000
4000
2000
0
Counts/sec
0
10
20
30
40
50
t



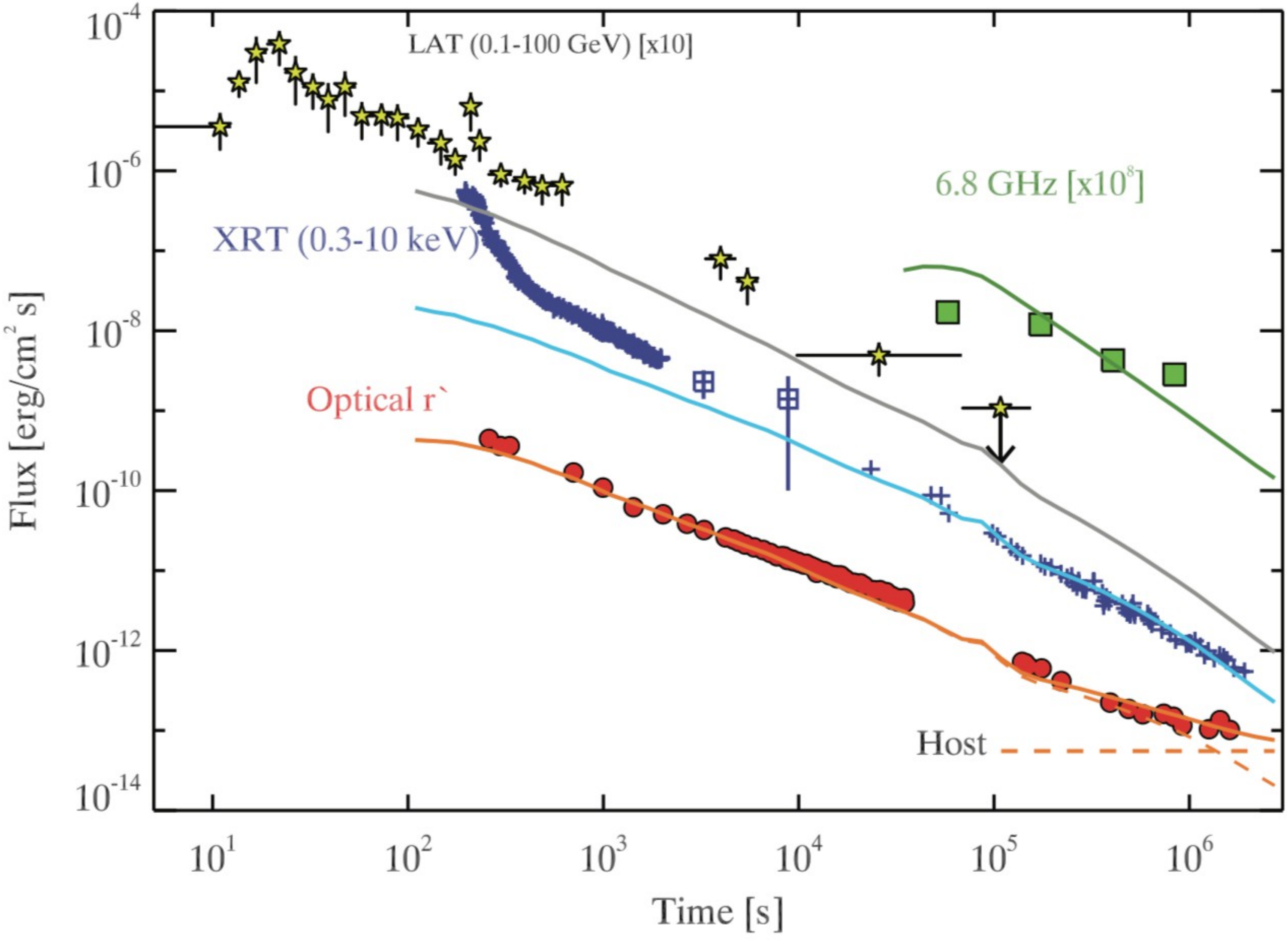

Progenitor
(massive star)
Jet
Jet
collapse
Fe line
Fe line
Internal
shocks
Gamma-ray
burst
γ
External
shocks
Afterglow
γ
o
x
R
Shell?
Fe line
Fe line

GRB 130427A



Time profile [SWIFT (Bat)] [15-350 keV]

Afterglow of GRB 130427A



Why do we think that GRB are "jet like" with a very large relativistic velocity ?

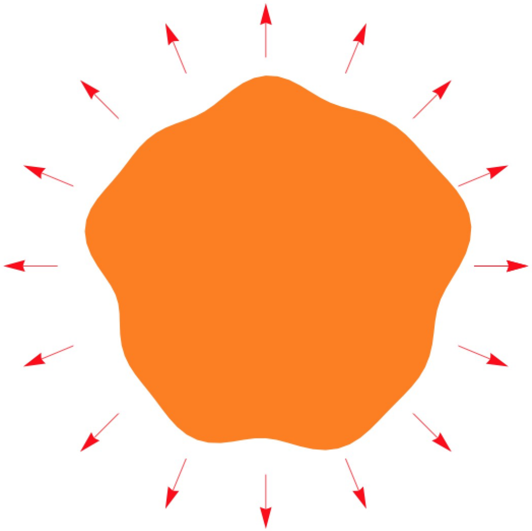
$\Delta t_{\rm obs}$ Duration

$\mathcal{F}$ energy fluence $\mathrm{erg/(cm^2\,s)}$

GRB event
(assume no beaming)

size of source

$$R \simeq \Delta t_{\rm obs}\, c$$



At the "explosion" time
enormous photons density in source

$$n_\gamma \approx \frac{4\,\pi\, d^2\ \mathcal{F}}{\langle \varepsilon \rangle}\ \frac{1}{R^3}$$

The source is not transparent

Opacity $\tau \approx R\, n_\gamma\, \sigma_{\gamma\gamma} \approx \dfrac{4\,\pi\, d^2\ \mathcal{F}}{\langle \varepsilon \rangle\ (\Delta t_{\rm obs}\, c)^2}\, \sigma_{\gamma\gamma}$

Parameters of GRB139427A $\tau \approx 10^{12}$

enormous opacity
system "thermalized"
with Black body emission

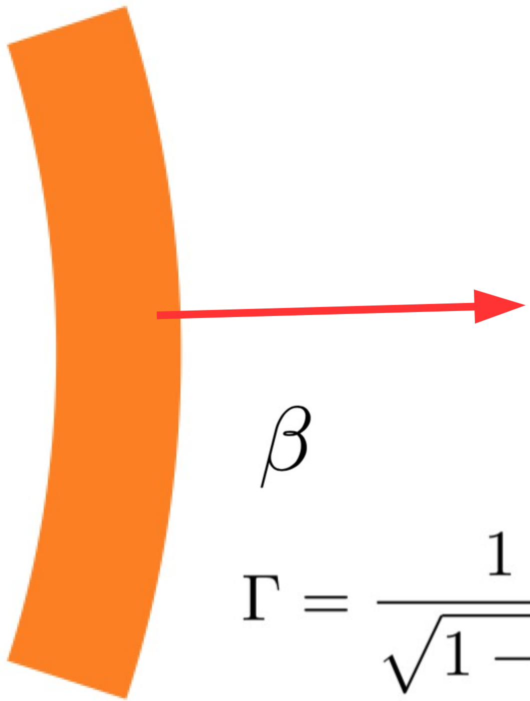
How can one reduce the opacity ? $\tau \lesssim 1$

$$\tau \approx \frac{4\,\pi\, d^2\; \mathcal{F}}{\langle \varepsilon \rangle\; (\Delta t\, c)^2}\; \sigma_{\gamma\gamma}$$

Relativistic beaming $\Gamma \gtrsim 1200$

$$(\Delta t)_{\rm obs} \simeq \; \Delta t\; (1 - \beta) \approx \Delta t\; \frac{1}{2\Gamma^2}$$

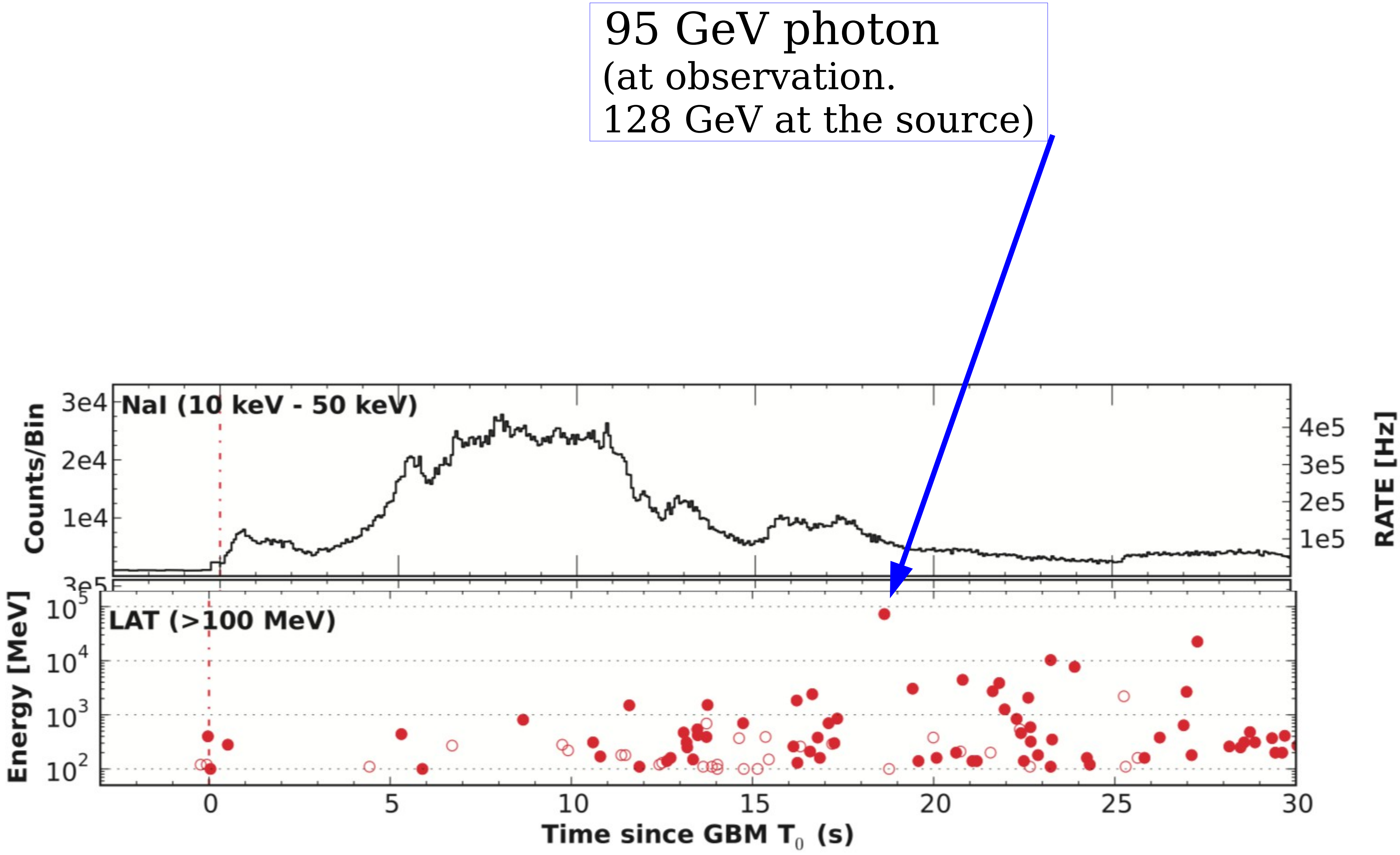
$$\Delta t_{\rm obs} \simeq 10 \text{ sec} \qquad \Delta t \gtrsim 1 \text{ yr}$$



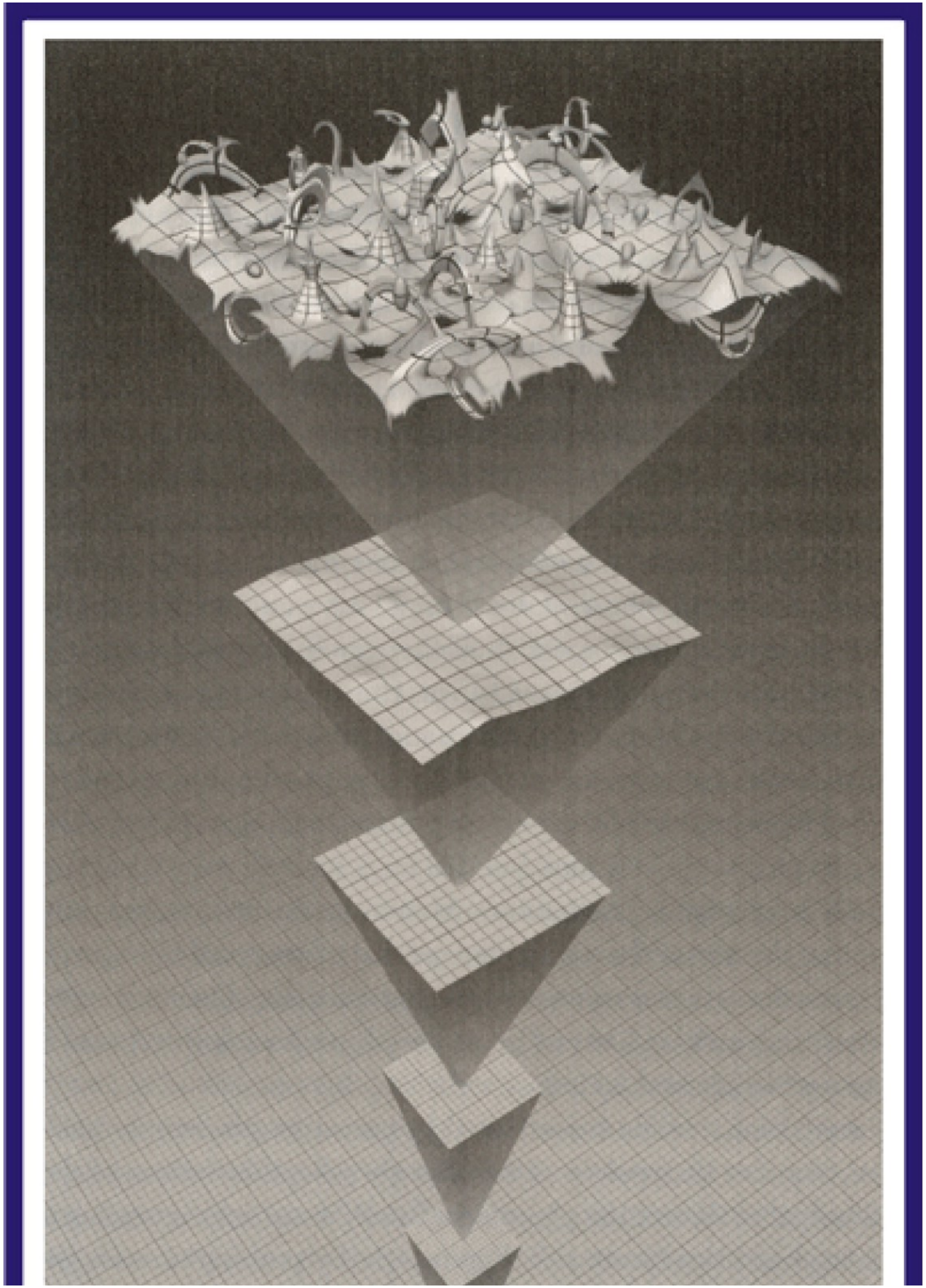
β

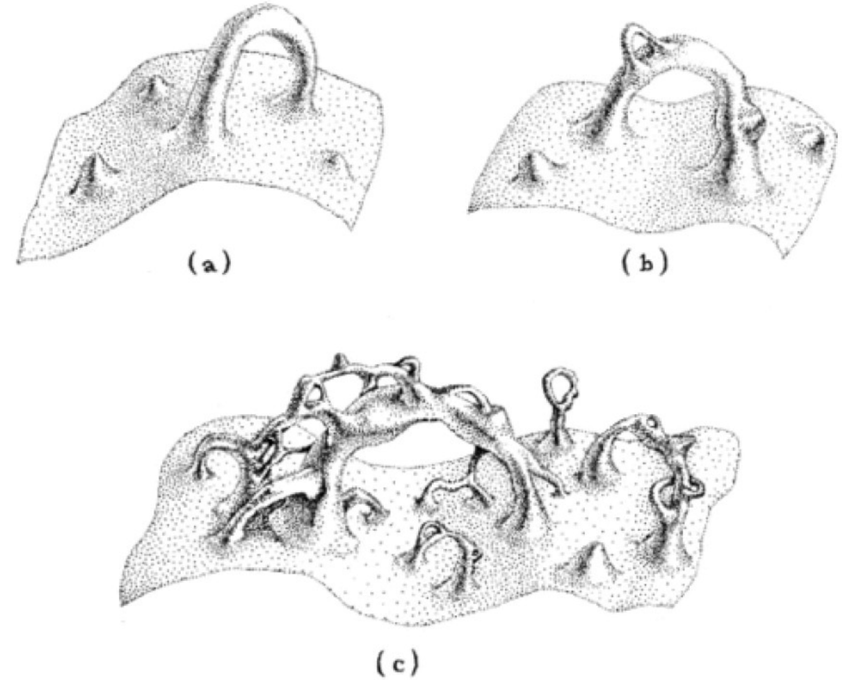
$$\Gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

[all energies in source frame
lower (fewer photons above threshold)

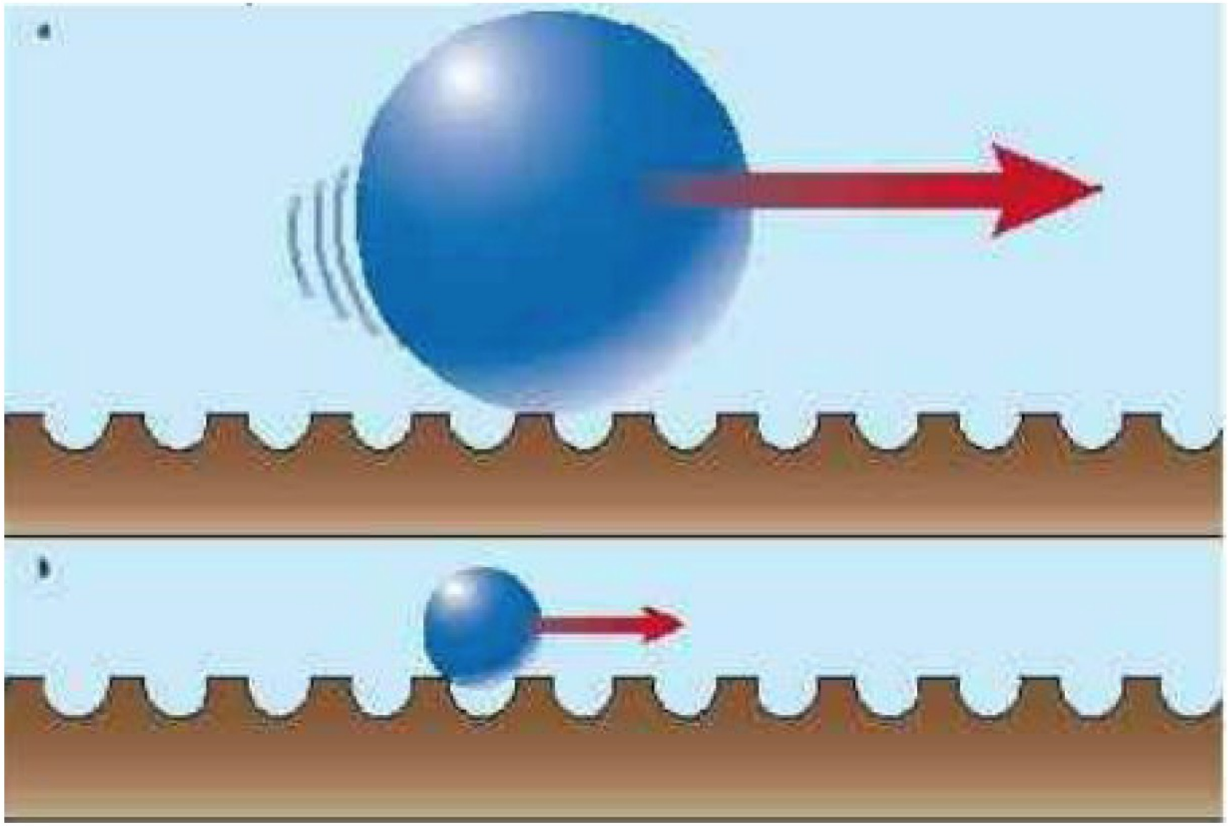


95 GeV photon
(at observation.
128 GeV at the source)
NaI (10 keV - 50 keV)
Counts/Bin
RATE [Hz]
LAT (>100 MeV)
Energy [MeV]
Time since GBM T_0 (s)





Quantum Gravity effects
[space-time granularity]



$$E_{\text{Planck}} = \sqrt{\frac{\hbar\, c^5}{G_{\text{Newton}}}}$$

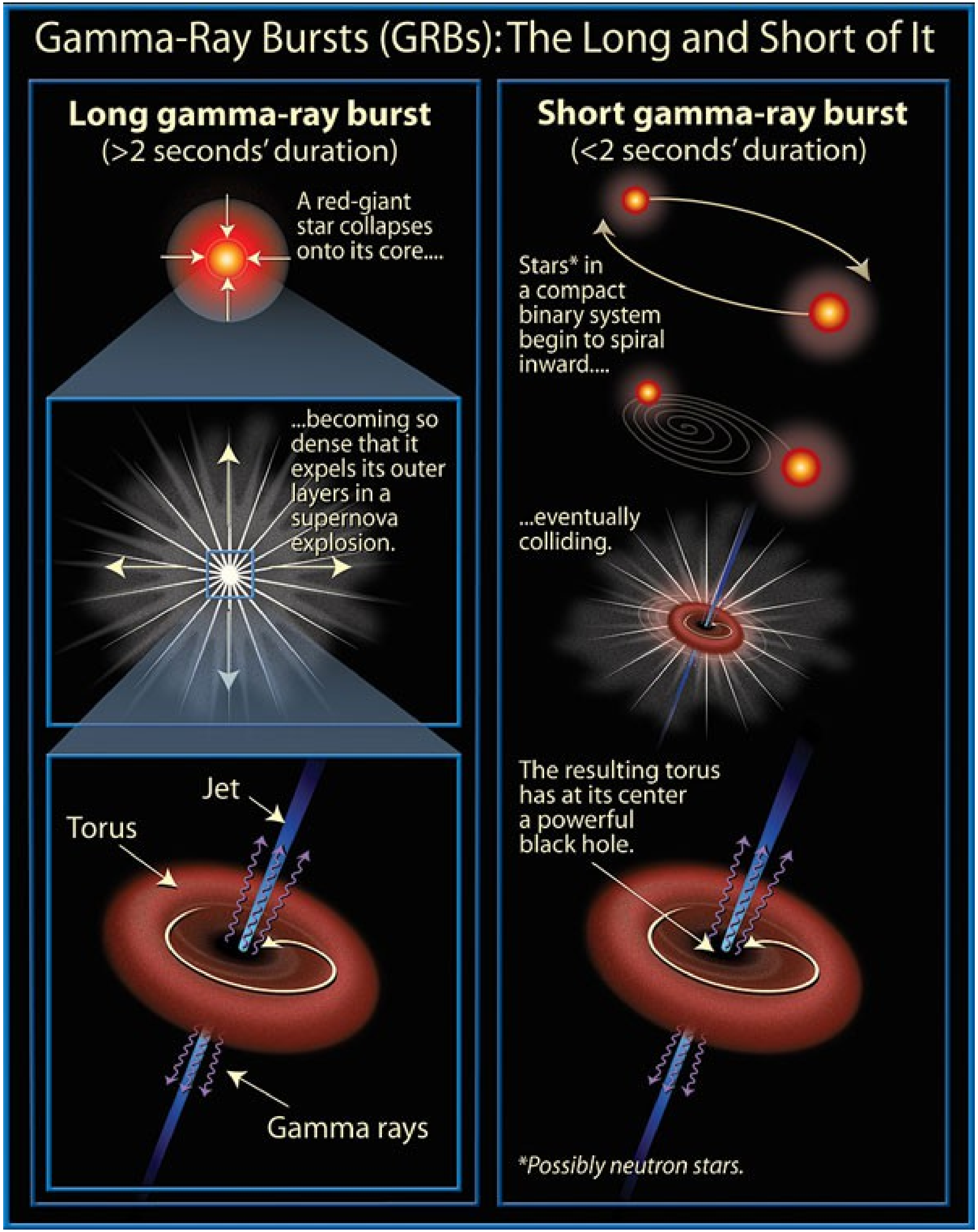
$$\simeq 1.22 \times 10^{19}\ \text{GeV}$$

$$L_{\text{Planck}} = \frac{\hbar\, c}{E_{\text{Planck}}}$$

$$\simeq 1.62 \times 10^{-33}\ \text{cm}$$

$$v_\gamma \simeq c\ \left(1 - \xi\, \frac{E}{E_{\text{Planck}}} + \ldots\right)$$

$$v_\gamma \simeq c\ \left(1 - \frac{E}{E_{\text{QG}}} + \ldots\right)$$


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

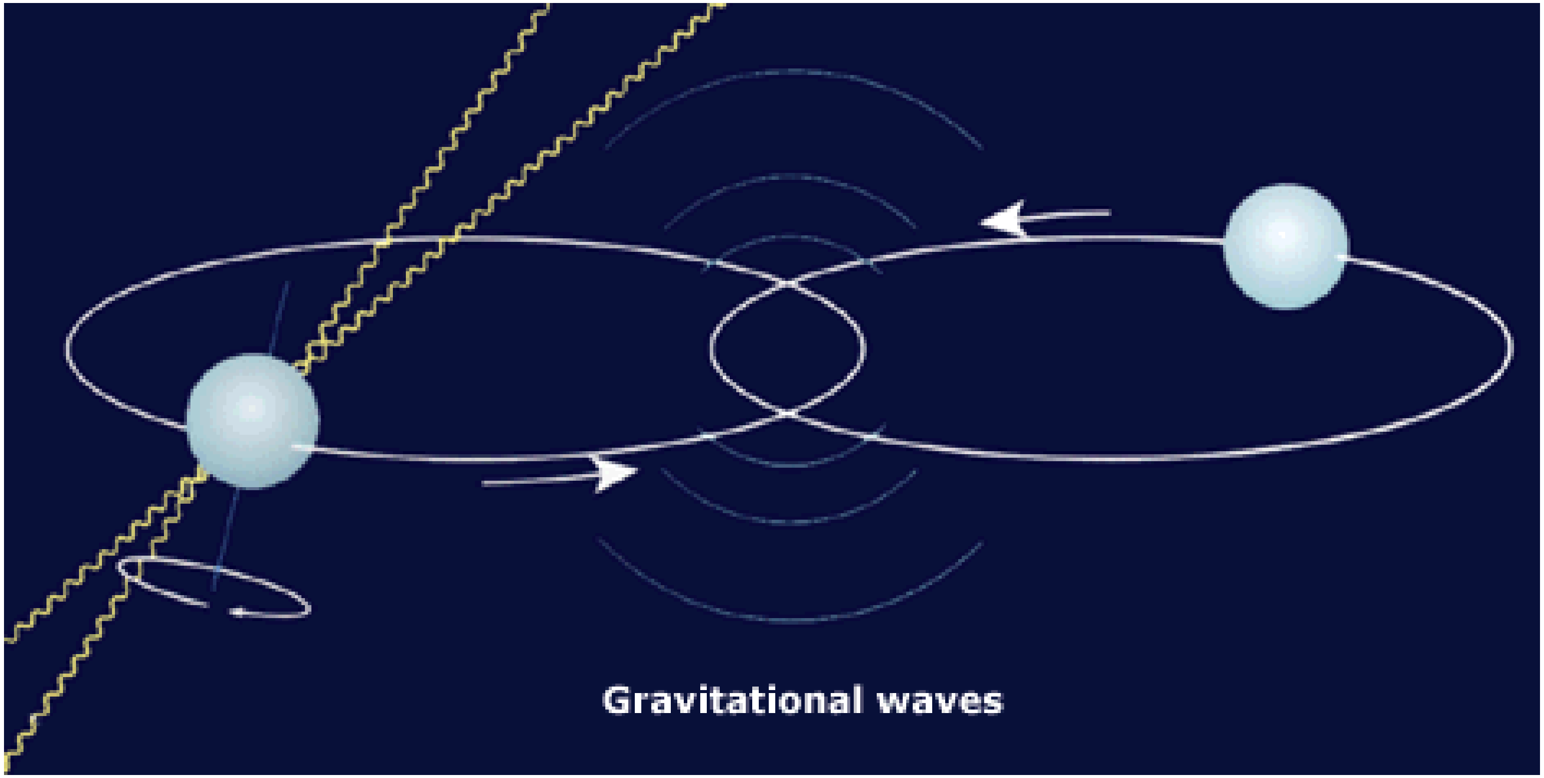
Binary Pulsars
(PSR 1913+16)
(discovery Hulse & Taylor (1978)
(Nobel prize 1993)
[Pulsar 17 rotation/second]

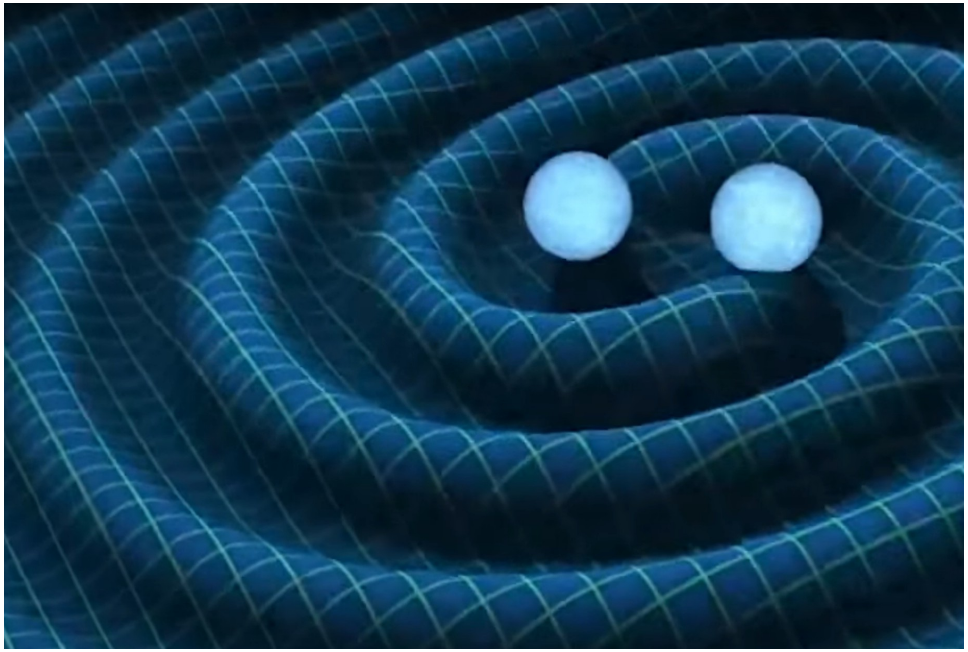
300 Myr
two neutron star coalesce

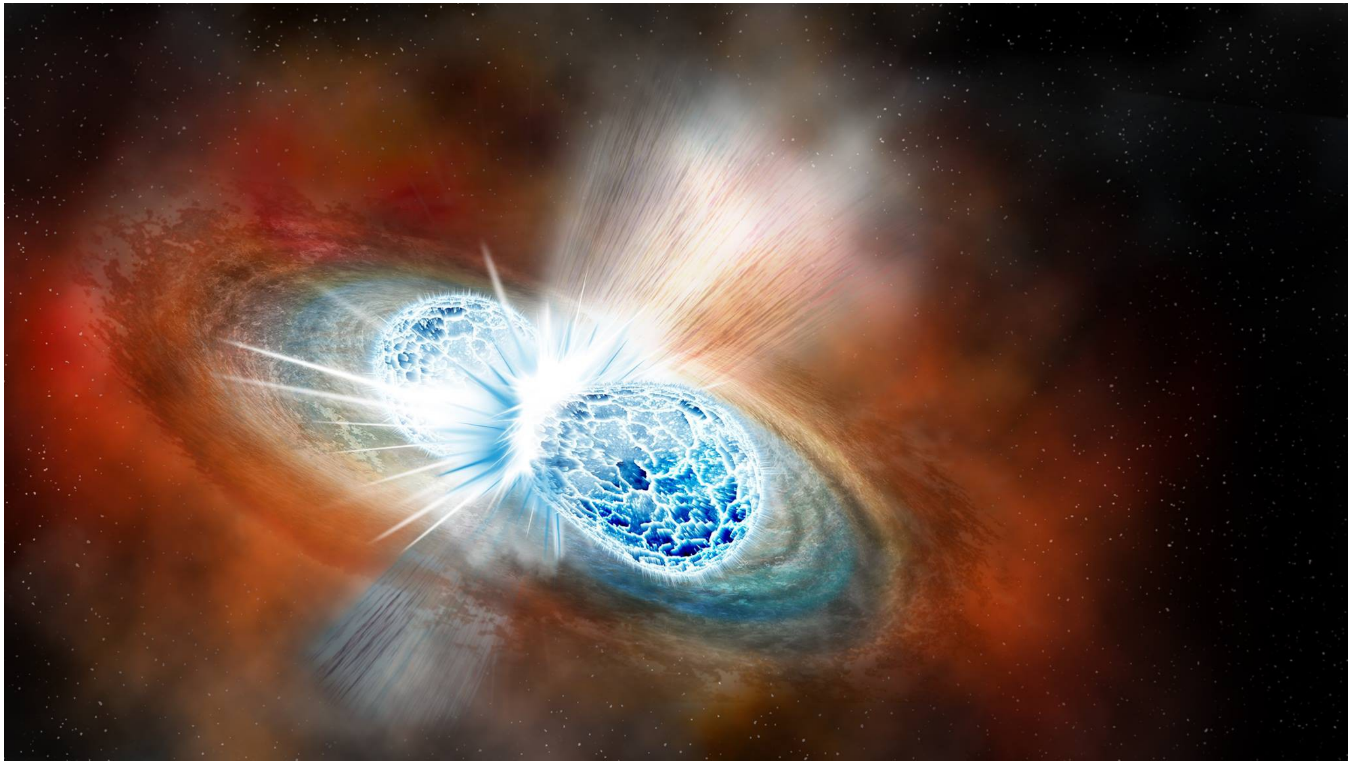
Orbit : 1.1 – 4.8 solar radii

Rotation period 7.75 hours
Period shorter
76.5 microsecond/year

Orbit smaller
3.5 m/year

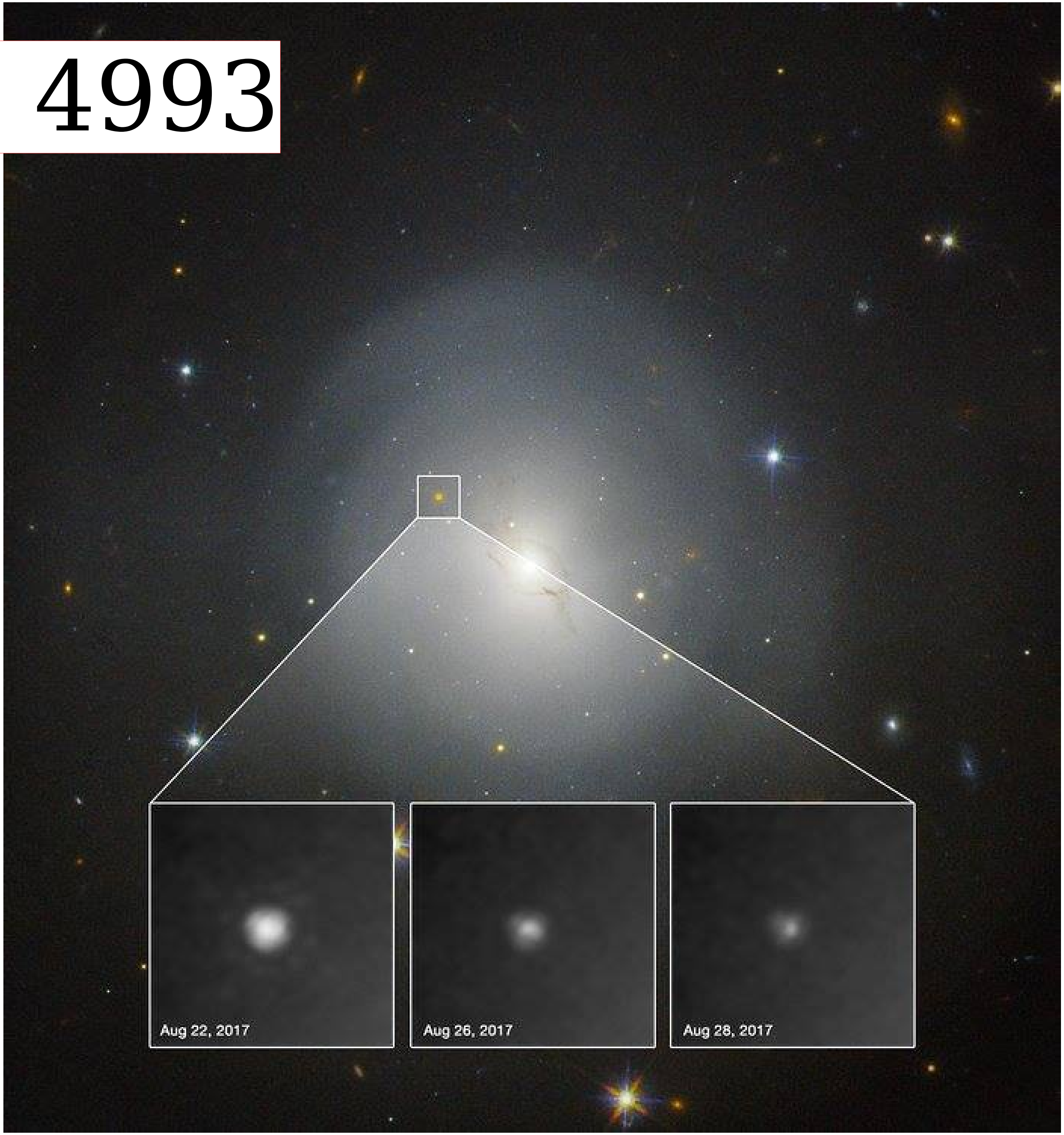




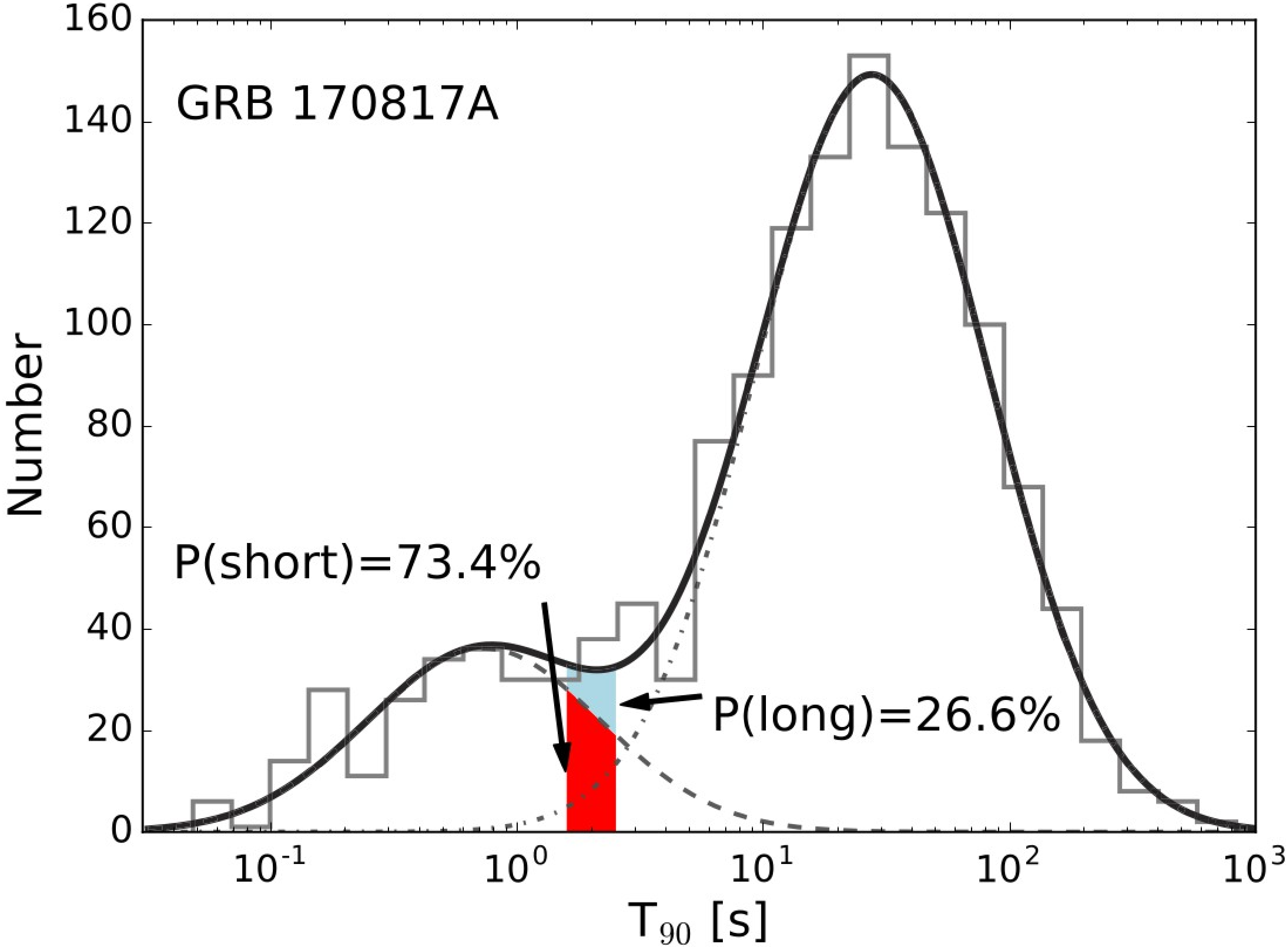


GW 170817

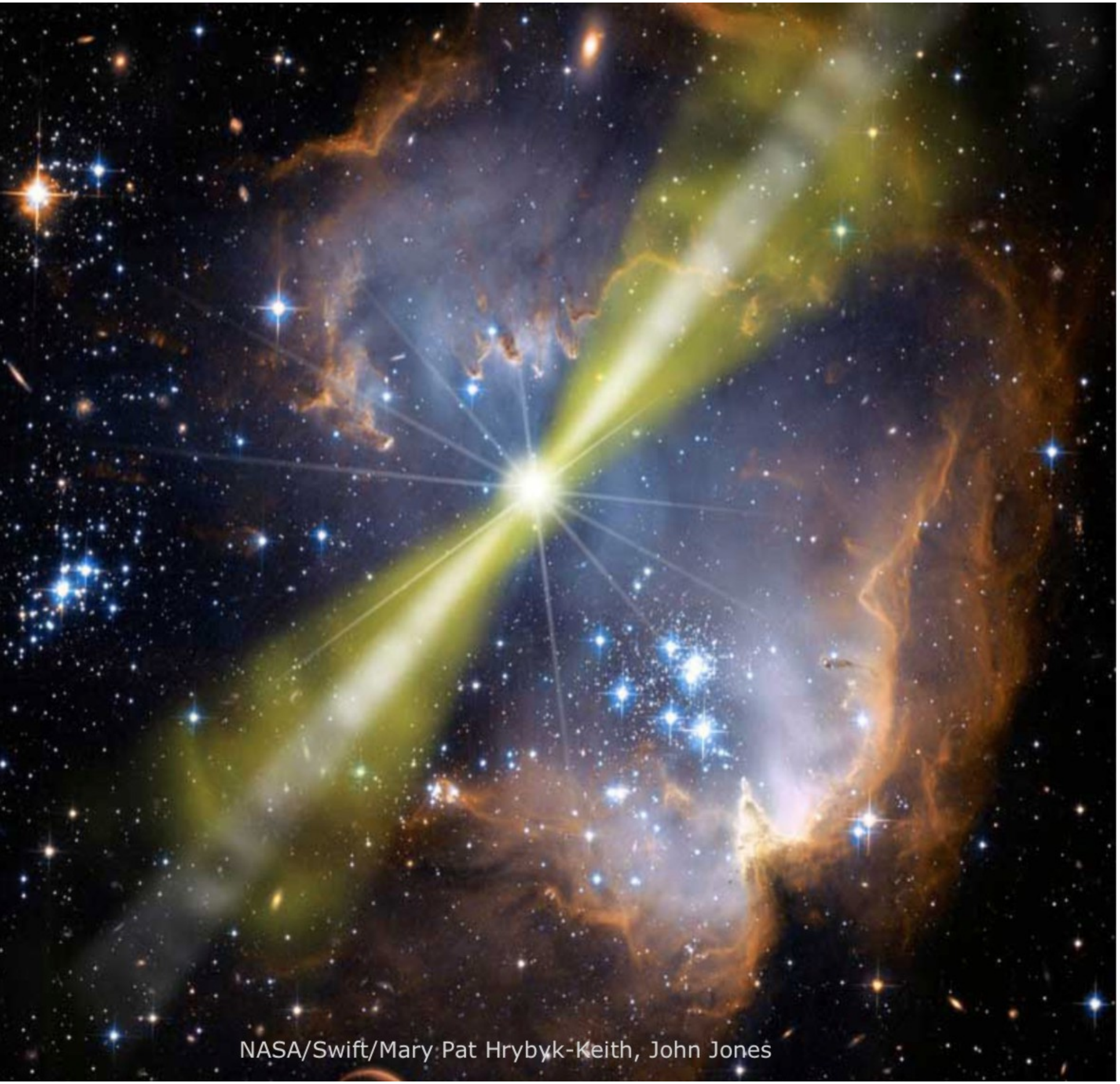
NGC 4993



Two Classes of Gamma Ray Bursts: “Short” and “Long”

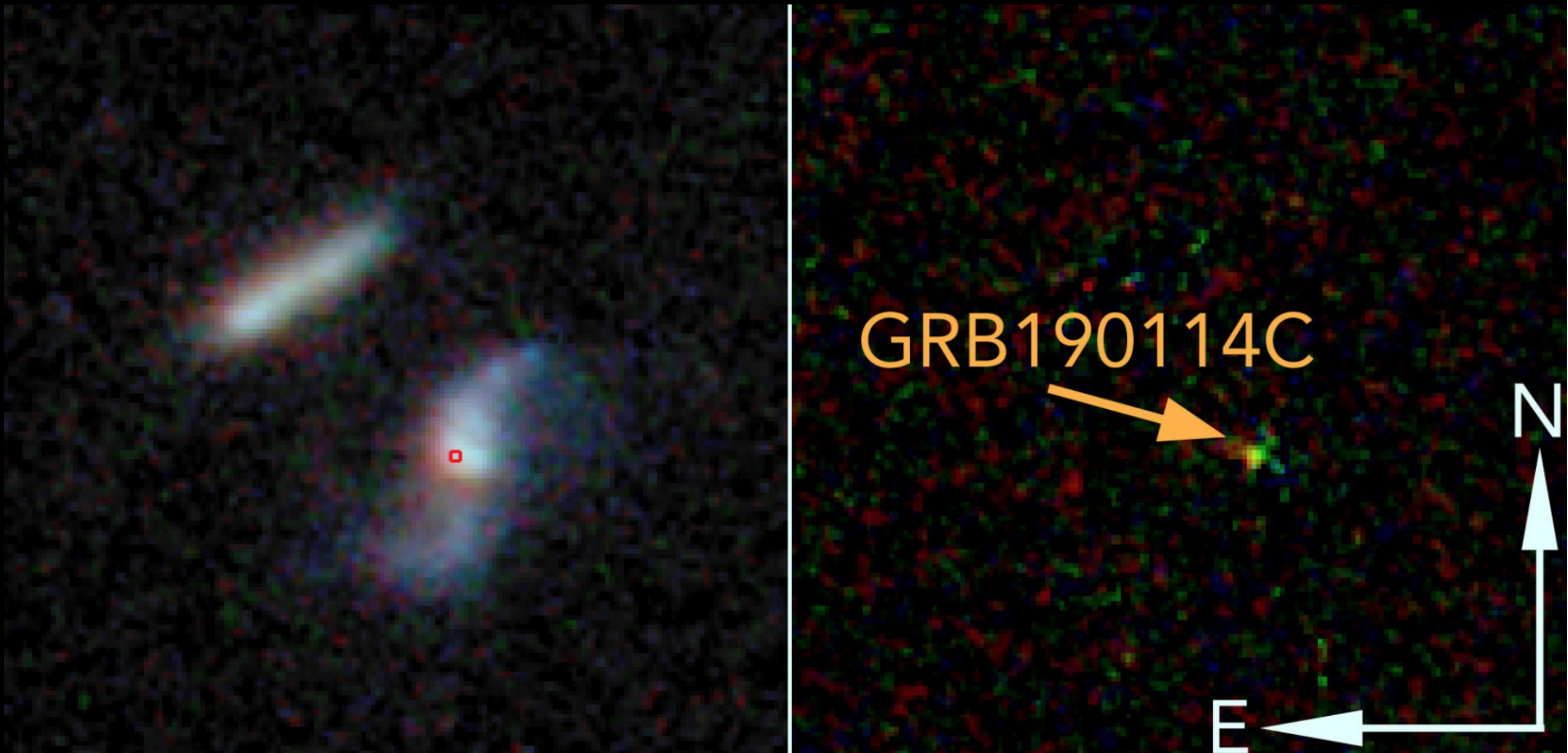


Cherenkov Detection of GRB's



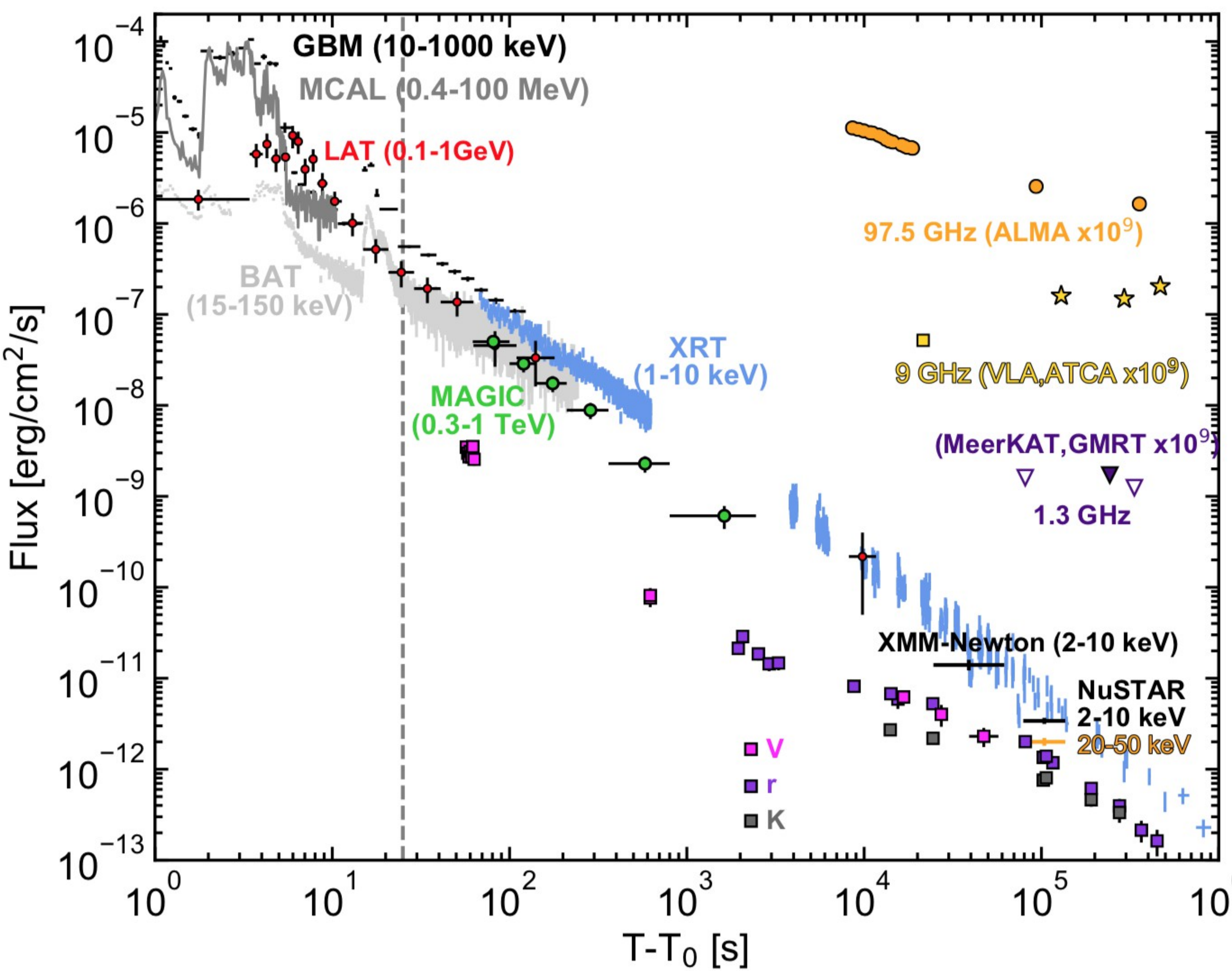
- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB
  - z = 0.42
  - for 40' after T0 +60 s
  - 0.2 -1 TeV
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB
  - z = 0.65
  - after T_0 + 10h
- **GRB 190829A** *(H.E.S.S. Coll., Science)*
  - long GRB
  - z = 0.078
  - for 3 nights after T_0 + 4,3h
  - 0.18-3.3 TeV
- **GRB 160821B** *(MAGIC Coll. ApjL 2021)*
  - short GRB
  - z =0.162
  - 3σ @ E>500 GeV
  - for 4h after T_0+24s
- **GRB 201015A** *(PoS ID 305, Y.Suda)*
  - long GRB
  - z=0.42
  - for 3,4 h after T_0+40s
  - 3.5σ above 50 GeV
- **GRB 201216C** *(PoS ID 395, S.Fukami)*
  - long GRB
  - z=1.1
  - for 20' after T_0+56s
  - 6σ E<100 GeV

Hubble Telescope image of the Afterglow of GRB 19114C

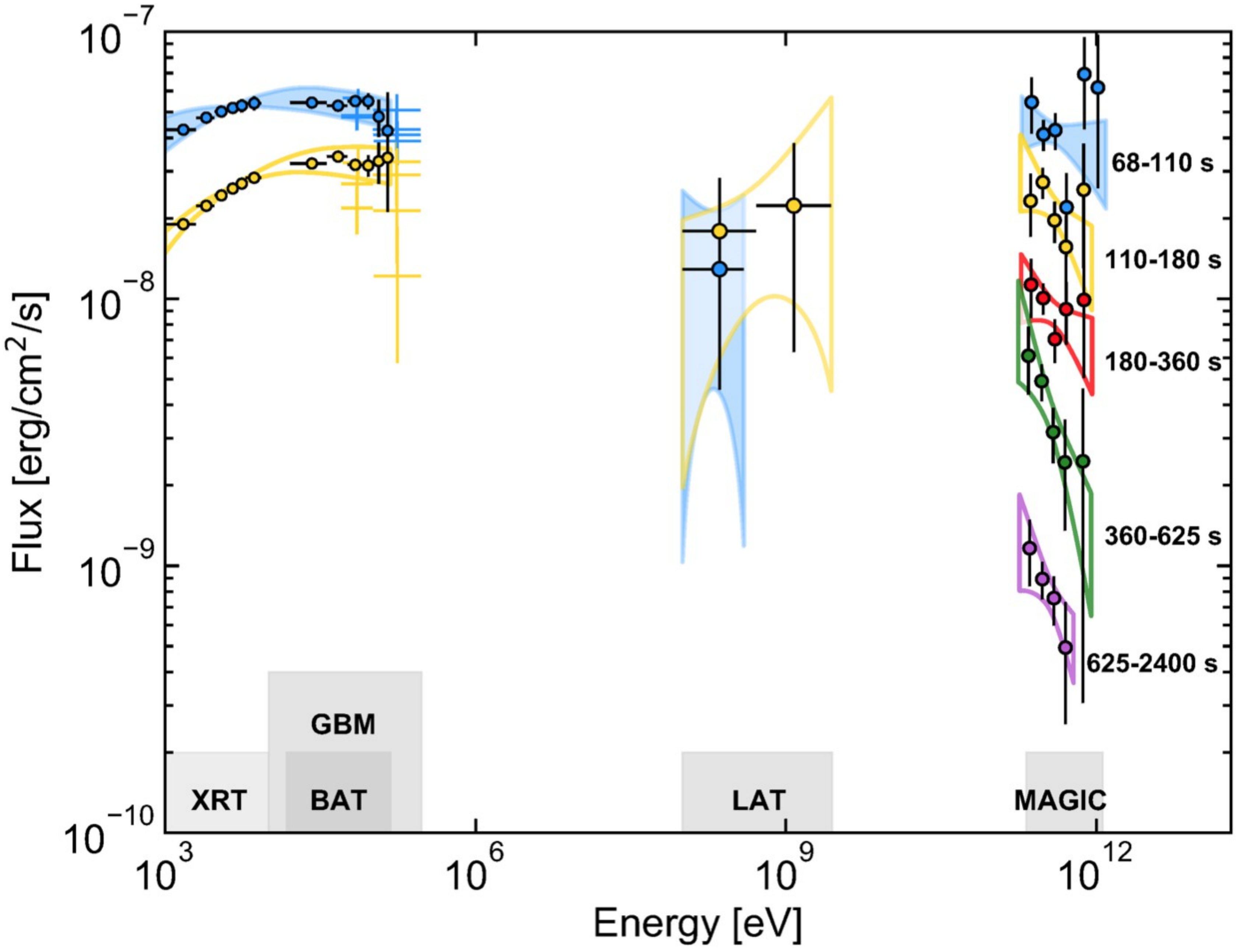


Galaxy at z=0.42

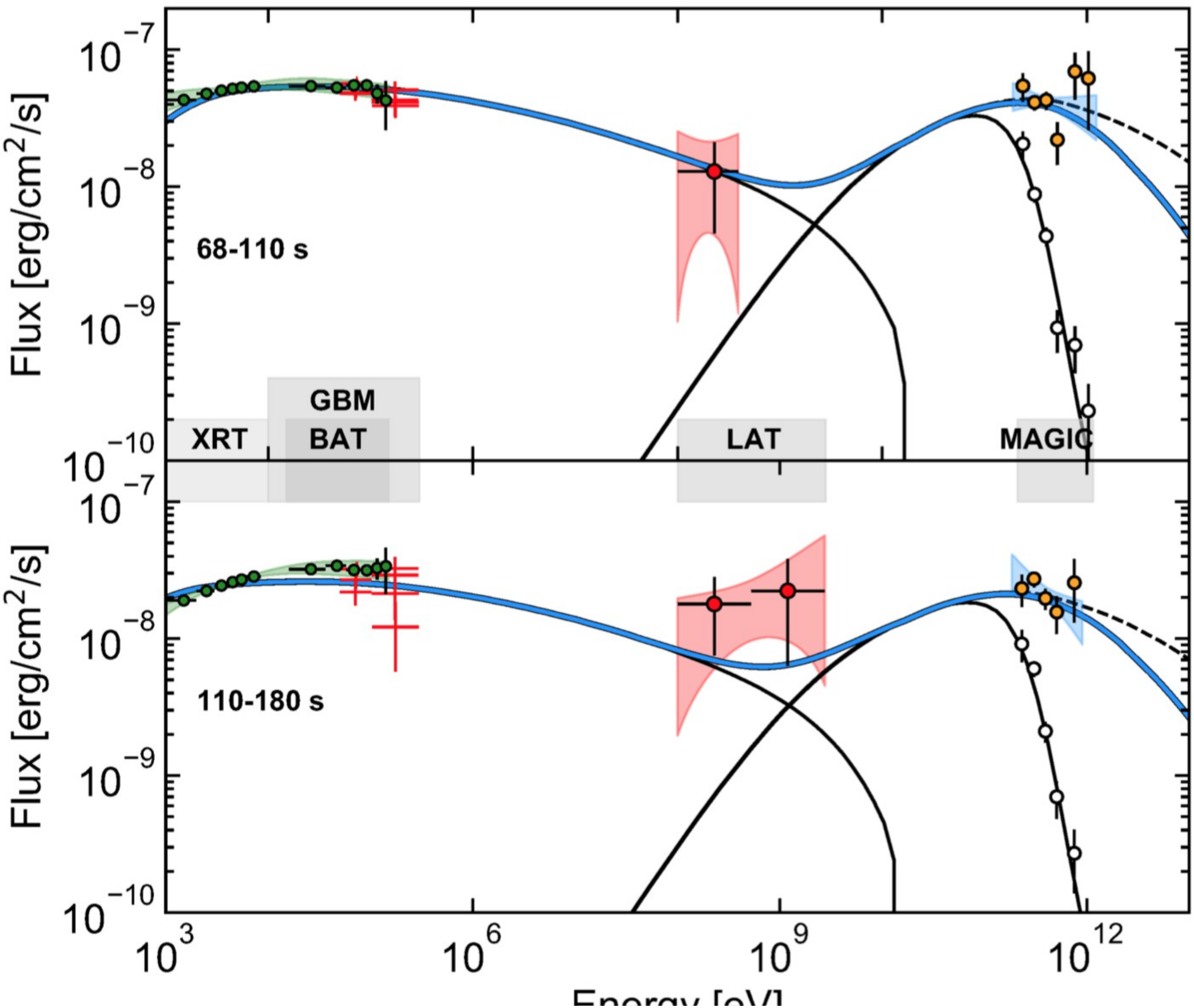
Detected by MAGIC (0.3-10 TeV)



GBM (10-1000 keV)
MCAL (0.4-100 MeV)
LAT (0.1-1GeV)
BAT
(15-150 keV)
XRT
(1-10 keV)
MAGIC
(0.3-1 TeV)
97.5 GHz (ALMA x10^9)
9 GHz (VLA,ATCA x10^9)
(MeerKAT,GMRT x10^9)
1.3 GHz
XMM-Newton (2-10 keV)
NuSTAR
2-10 keV
20-50 keV
V
r
K
Flux [erg/cm^2/s]
T-T_0 [s]

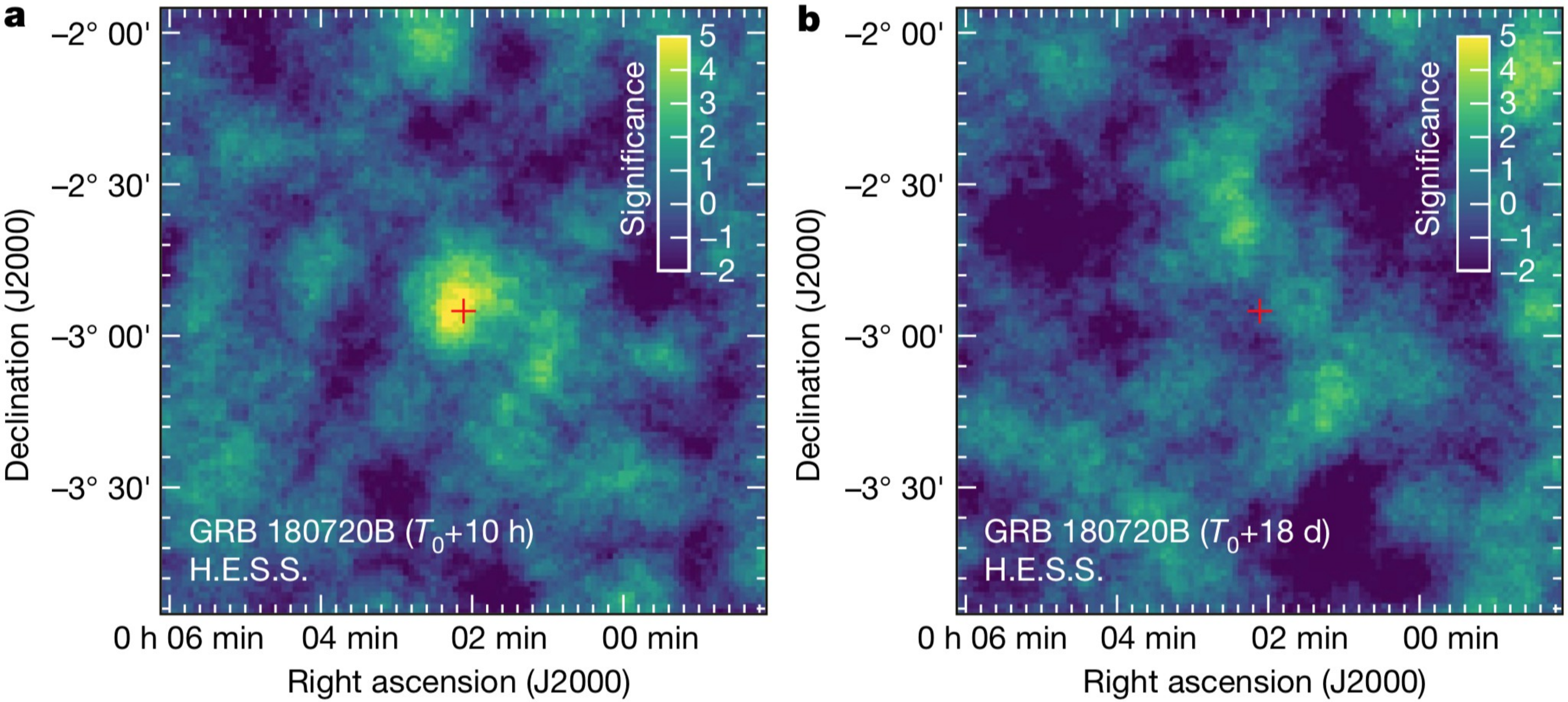


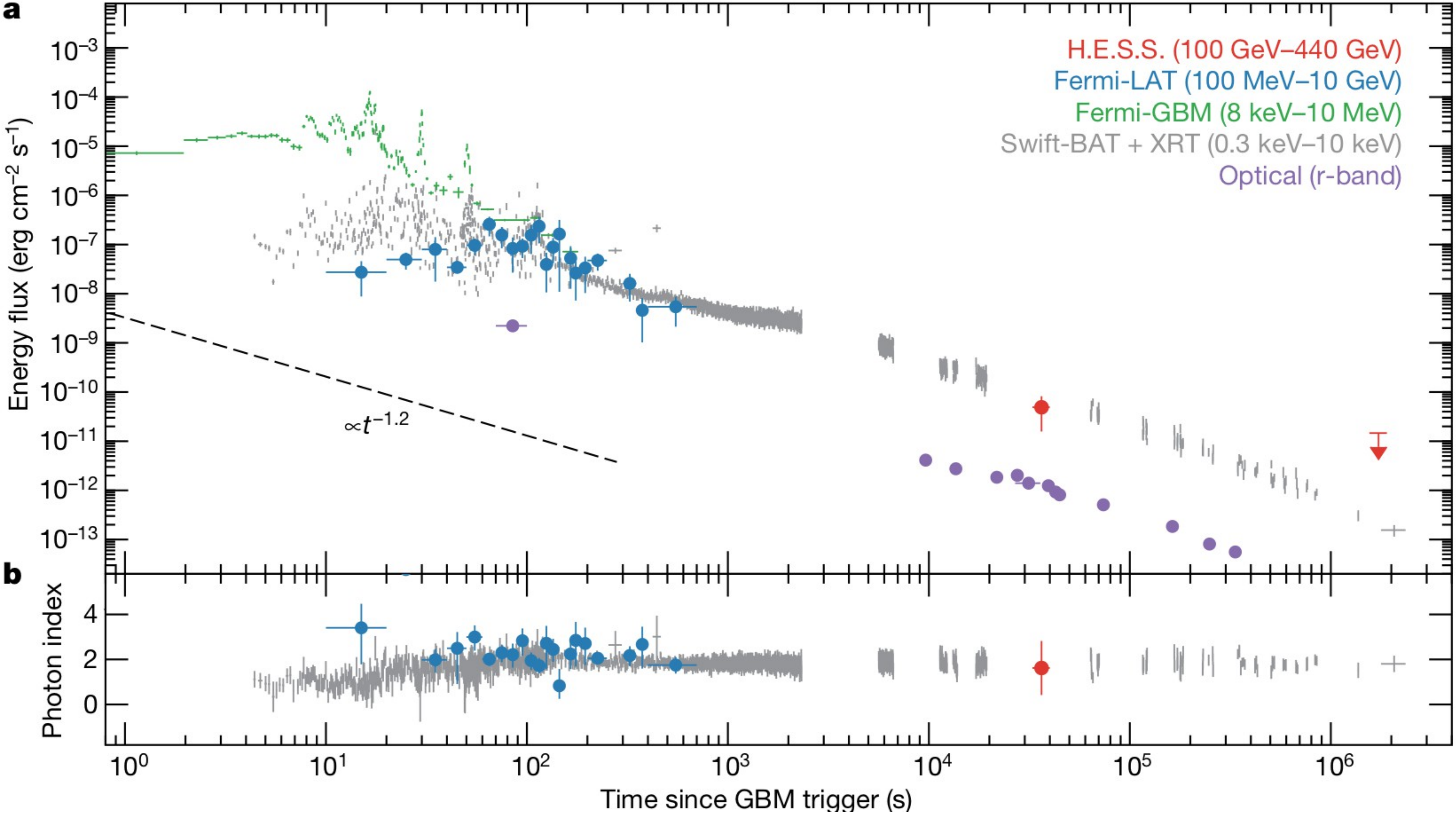
Multi-band spectra in different time intervals



Modeling of the broadband spectra in the time intervals 68-110 s and 110-180 s.

HESS detection of GRB 180720B





HESS observation:

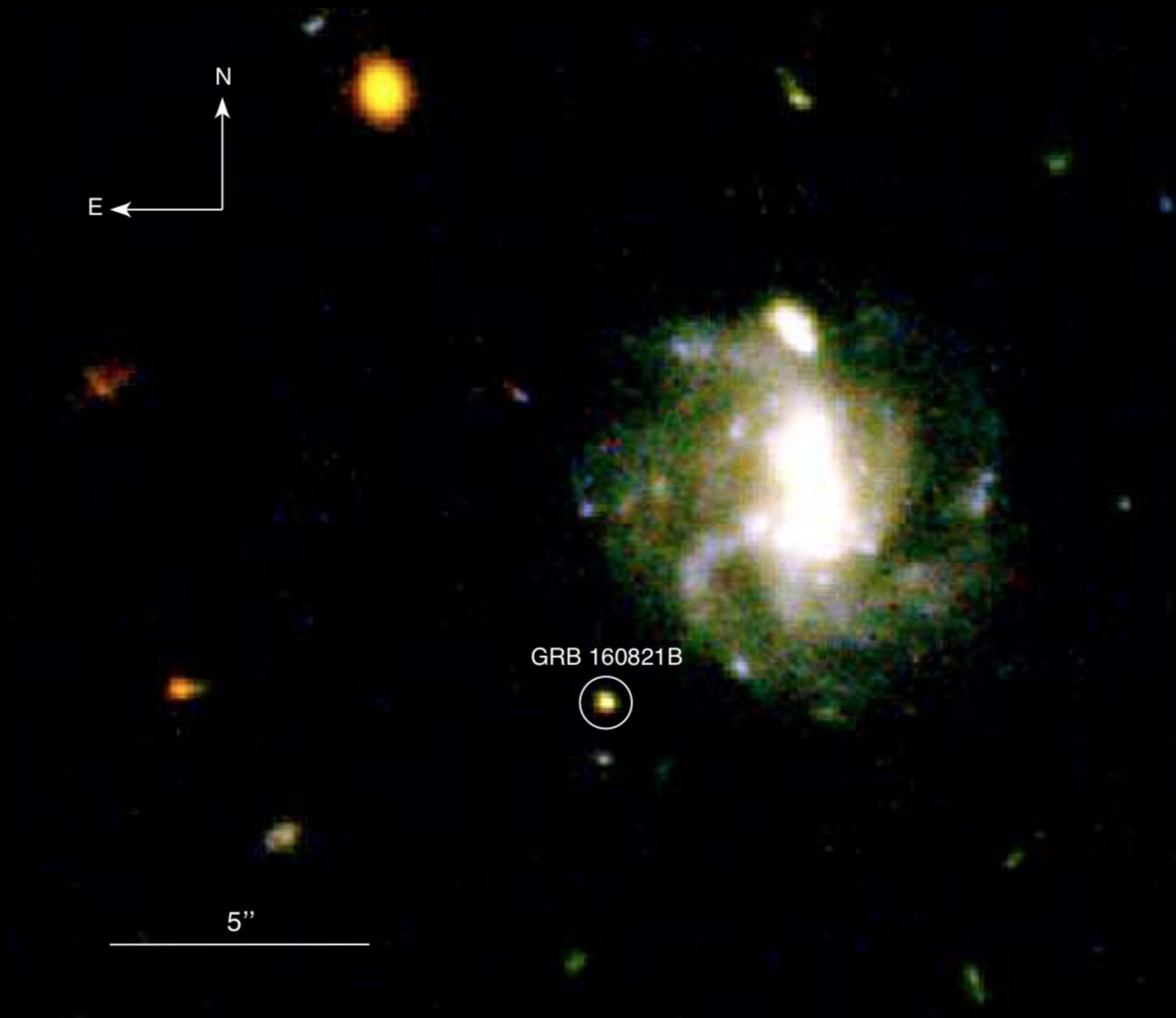
$T_0 + 10.1$ hours

$+(2$ hours$)$

Observed and intrinsic spectral shape (z=0.653)

$$\gamma_{\rm obs} = 3.7 \pm 1.0(\rm stat)\ ^{+0.2}_{-0.1}(\rm sys)$$

$$\gamma_{\rm int} = 1.6 \pm 1.2(\rm stat)\ ^{+0.4}_{-0.4}(\rm sys)$$



Hubble Space telescope image of
afterglow/Kilonova
of short GRB 160821B

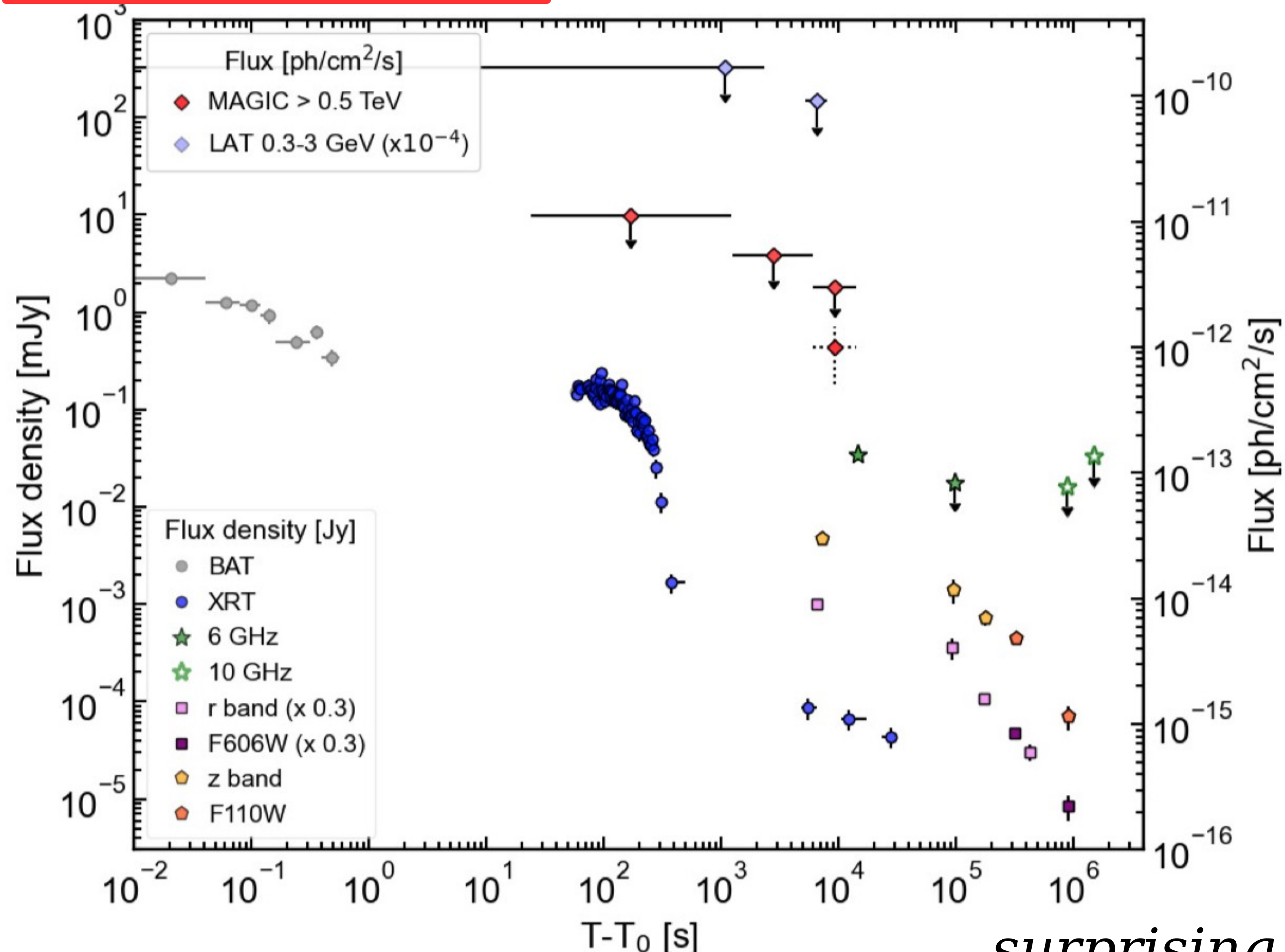
z = 0.1613
distance fromg
galaxy center = 16 Kpc

Short GRB 160821B

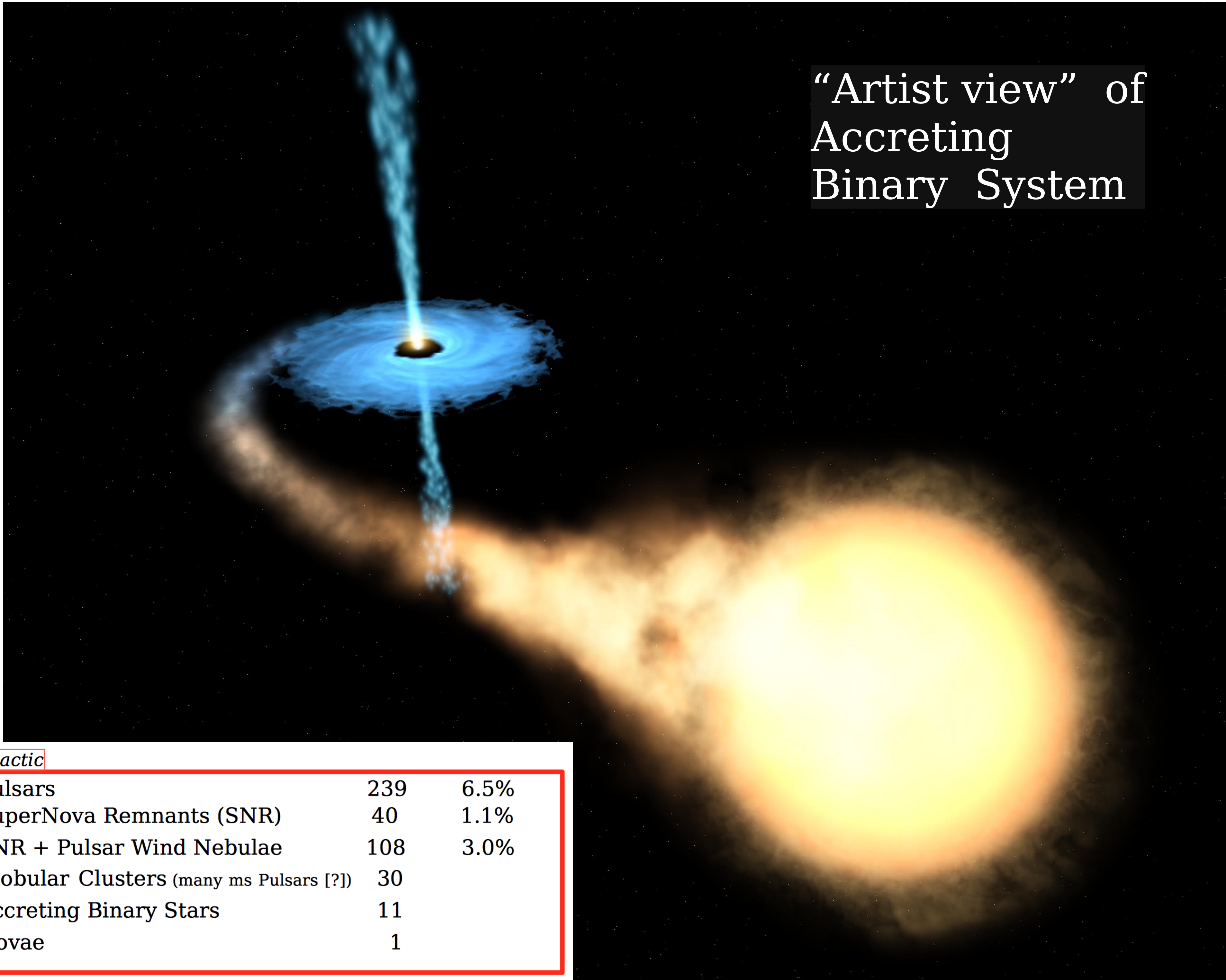
clear evidence of "Kilonova"

(possible 3 sigma) MAGIC detection

[Published ApJ 908, 20 (2021)]



surprising large flux



Galactic

Pulsars	239	6.5%
SuperNova Remnants (SNR)	40	1.1%
SNR + Pulsar Wind Nebulae	108	3.0%
Globular Clusters (many ms Pulsars [?])	30	
Accreting Binary Stars	11	
Novae	1	

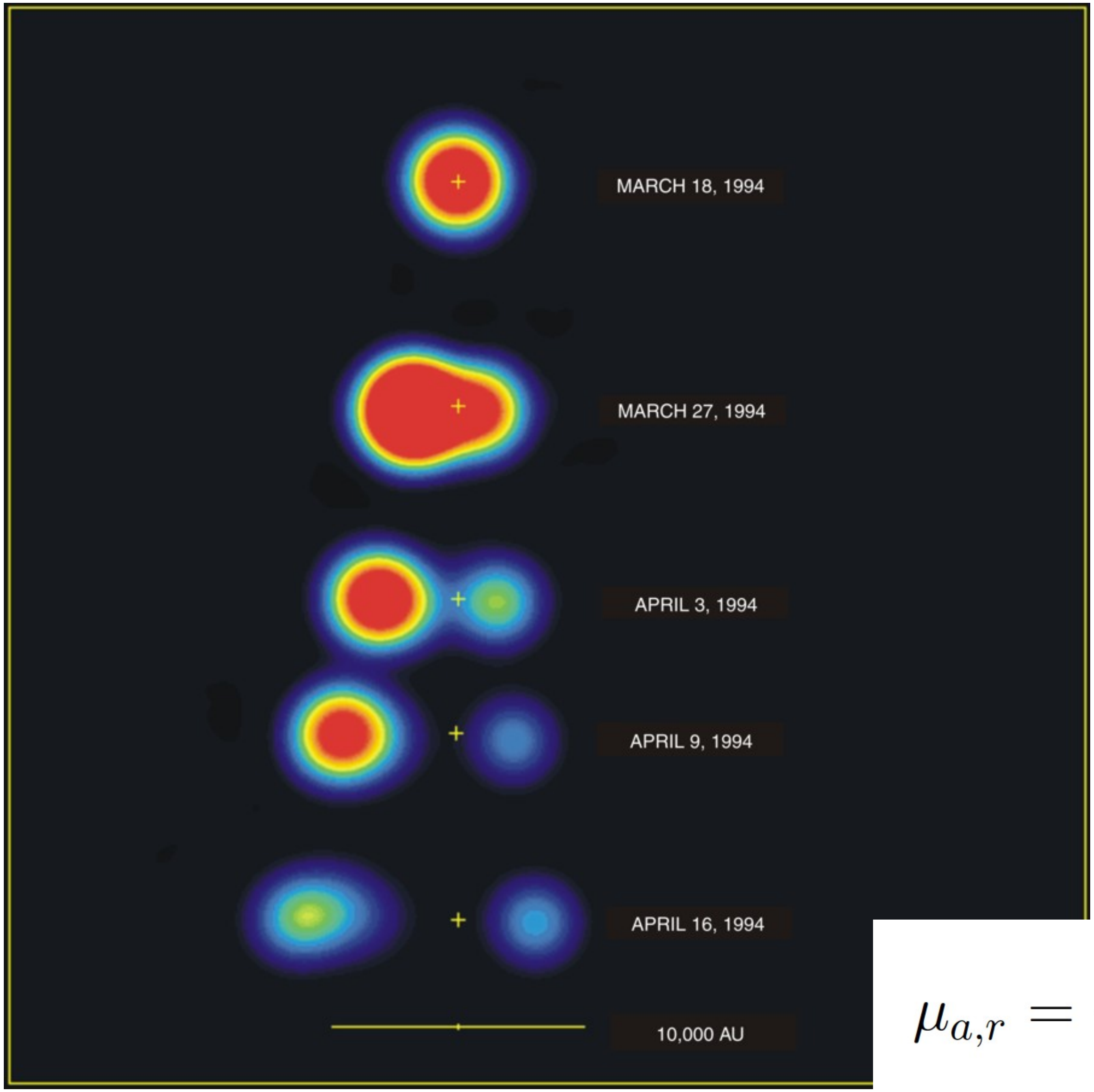
Superluminal Motions in microQuasars in our Galaxy

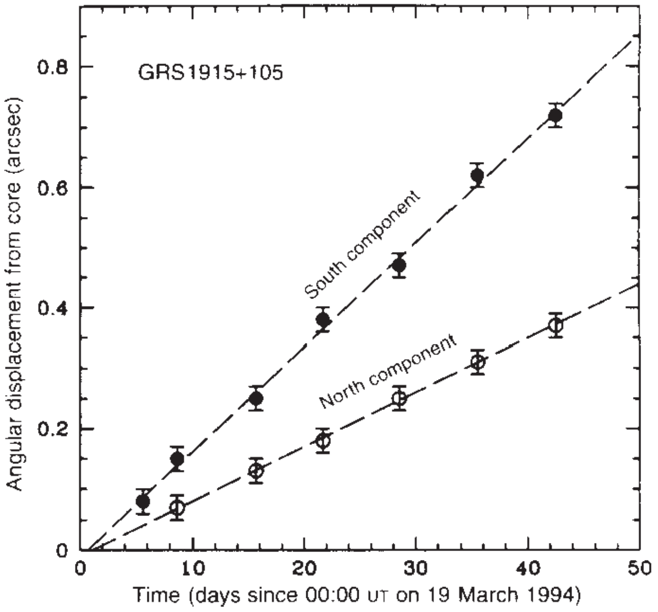
GRS1915+105

Observations in radio

$$\lambda = 3.5 \text{ cm}$$

"Two pairs of bright radio condensations"





$$\mu_{a,r} = \frac{\beta \ \sin\theta}{1 \pm \beta \ \cos\theta} \ \frac{c}{D}$$

$$\beta = 0.92 \pm 0.08$$

$$\theta = (70 \pm 2)^\circ$$

Understanding the *formation of the "relativistic jet"* in

- Active Galactic Nuclei
- MicroQuasars
- Gamma Ray Bursts (short and long)

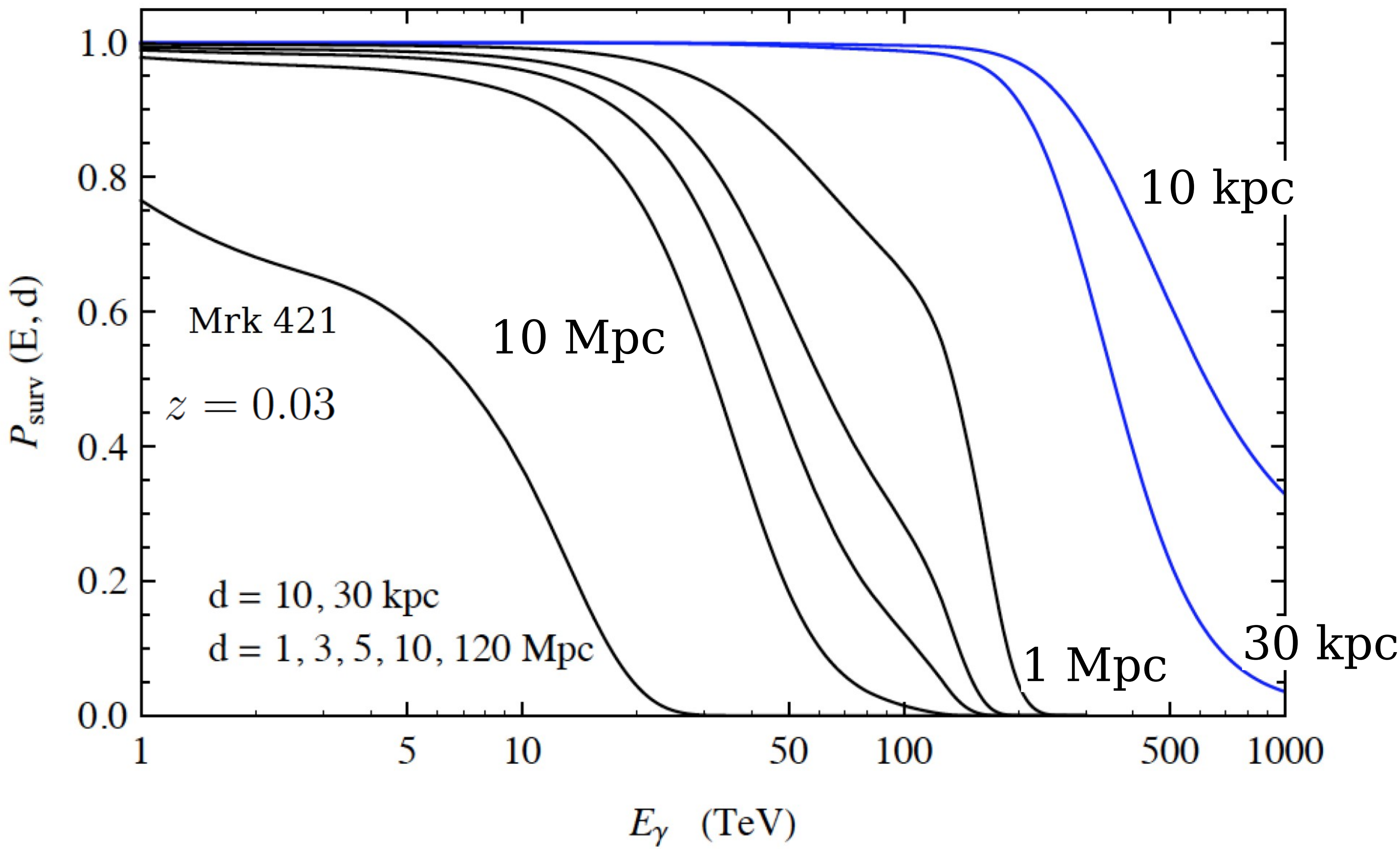
and the acceleration of particles associated to the phenomenon

are problems that are intimately related to each other, and a full understanding will require putting together information obtained with all messengers.

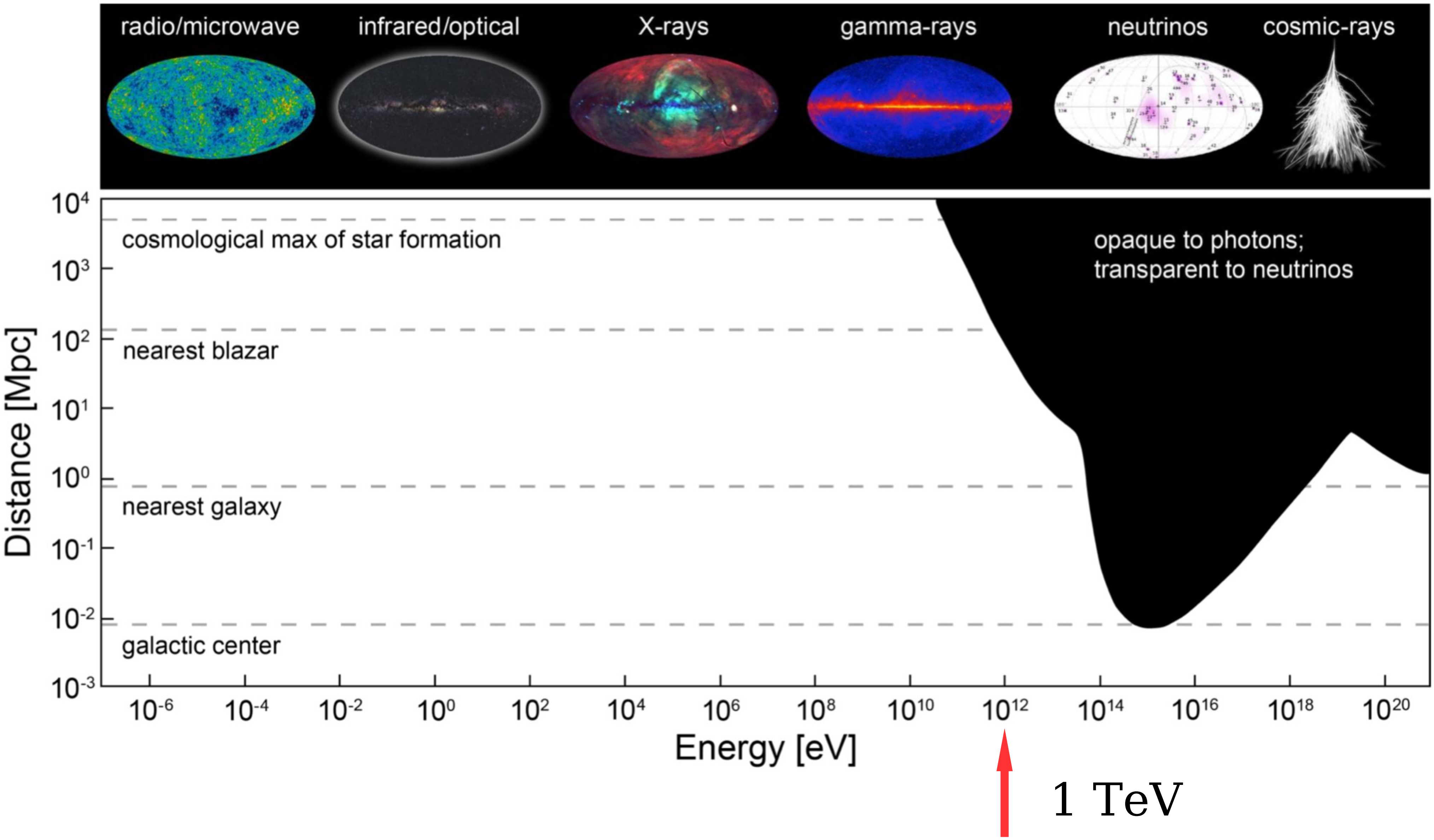
Neutrinos

Extragalactic Gamma rays
absorbed for E > 1TeV

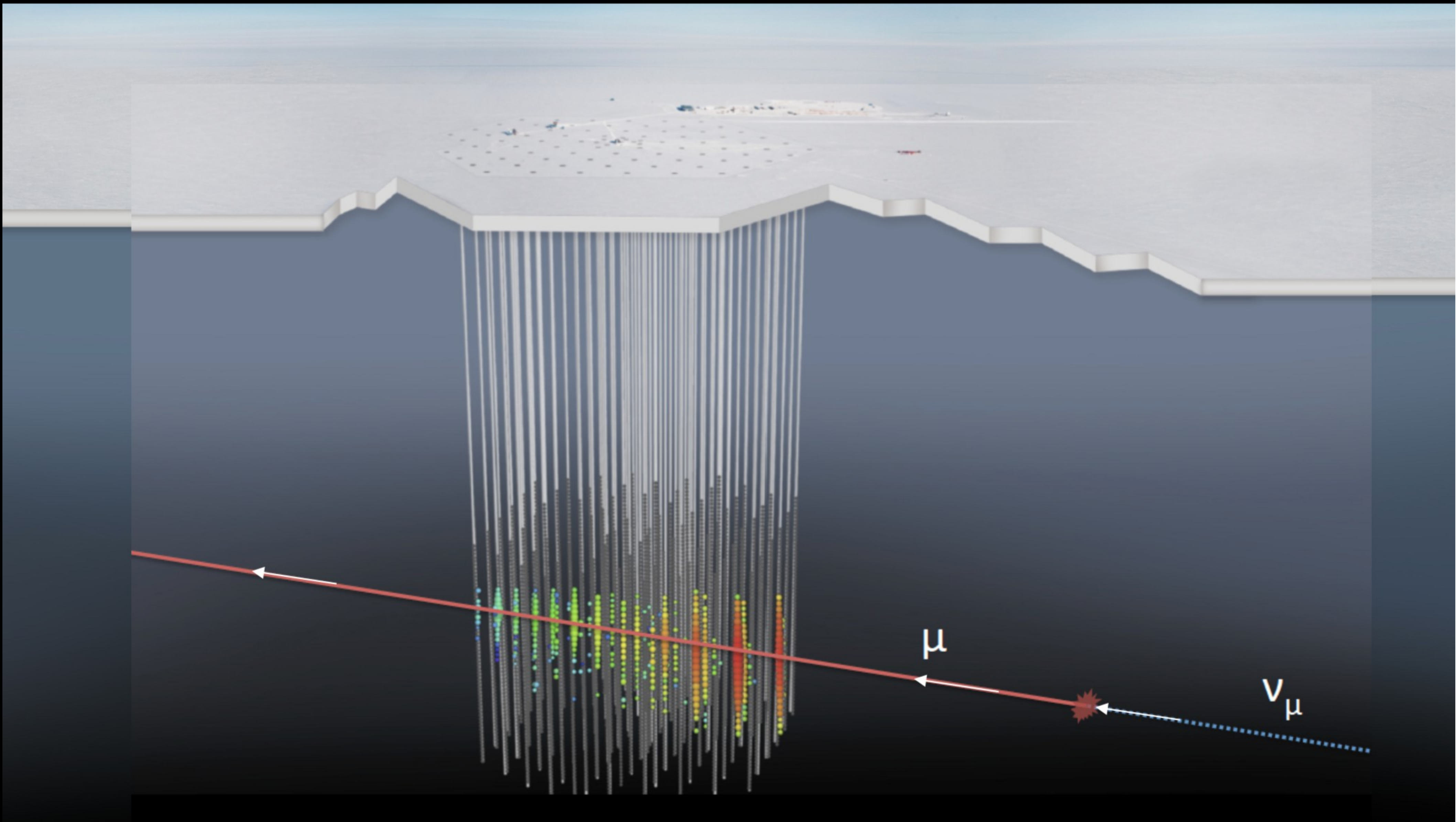
Gamma Ray Astronomy above 10-100 TeV
possible only for near (Galactic) sources *[Absorption]*



“*Horizon*” for gamma rays shrinks for $E \gtrsim 10$ TeV

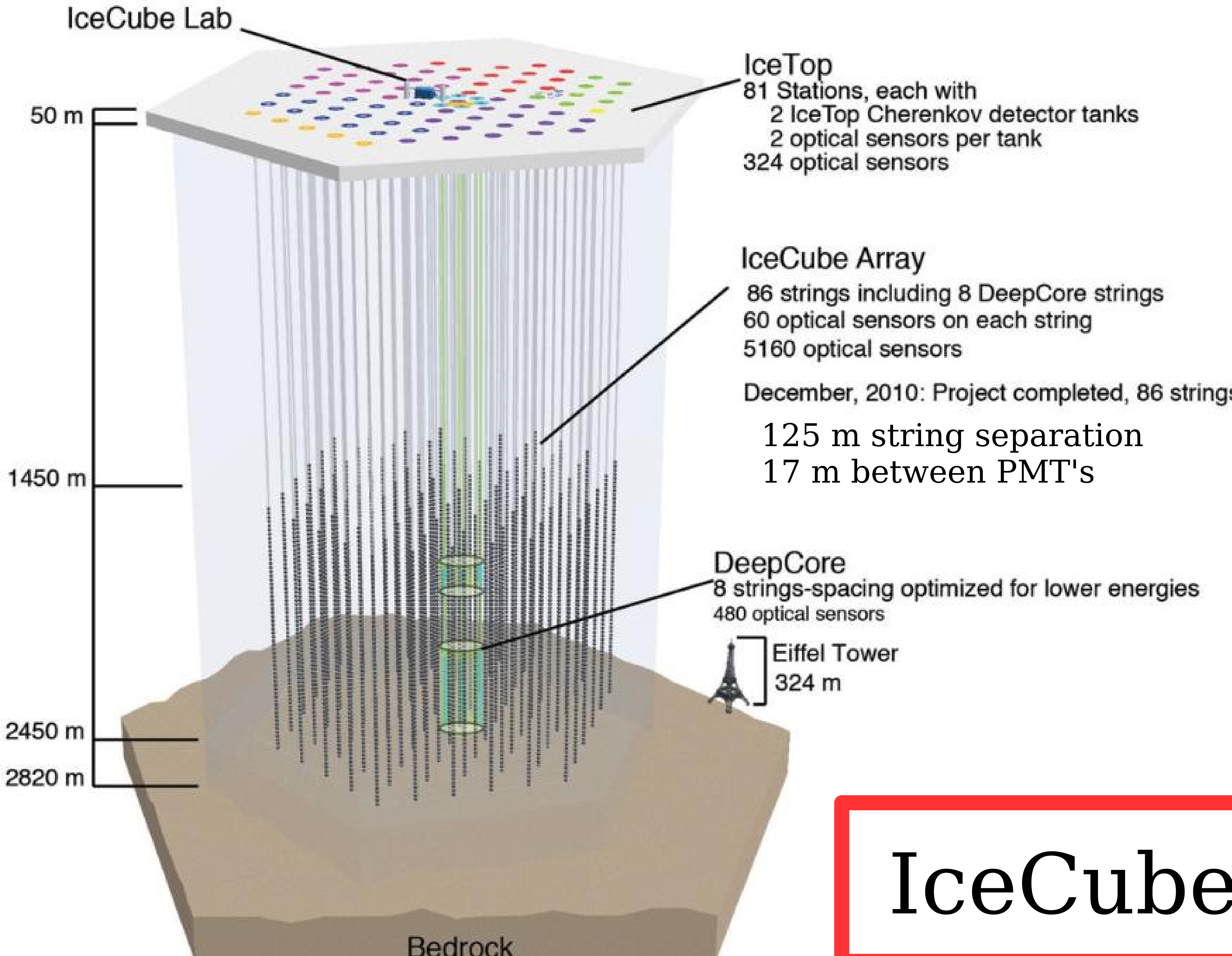


Neutrinos can be the messengers from extragalactic high energy sources



IceCube Detector at the South Pole (1 Km3 of ice instrumented)

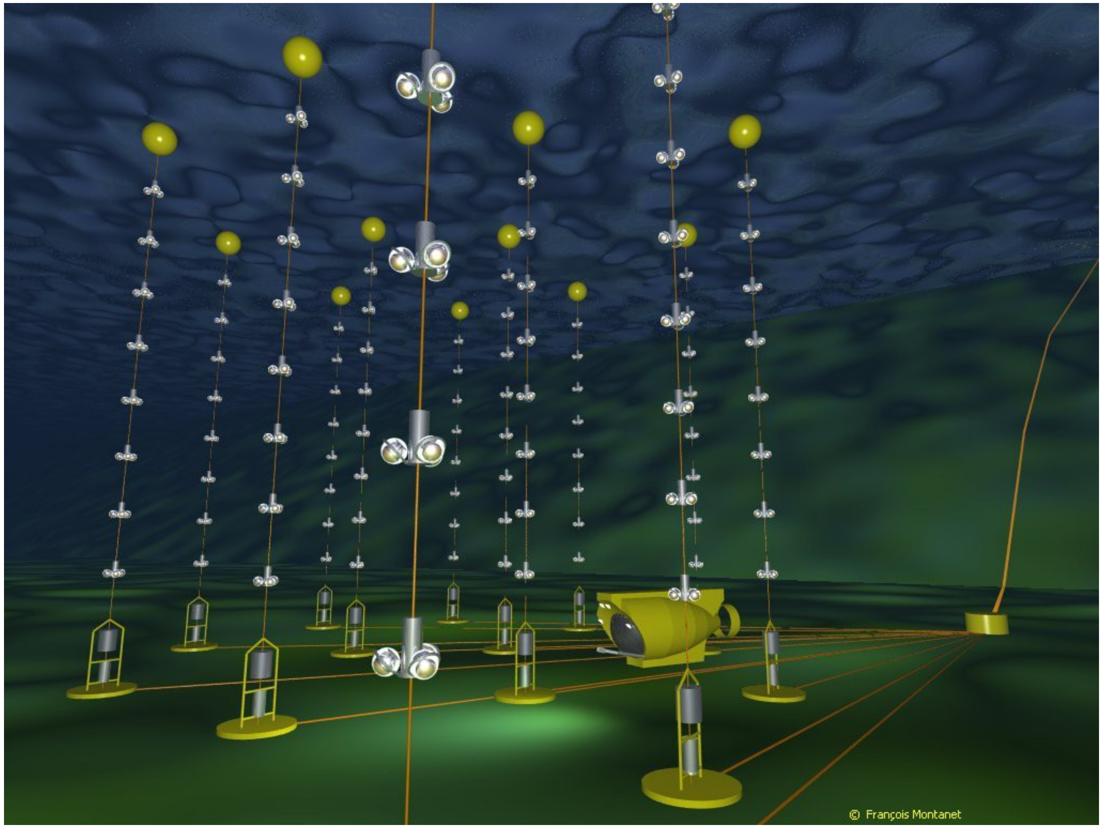
IceCube



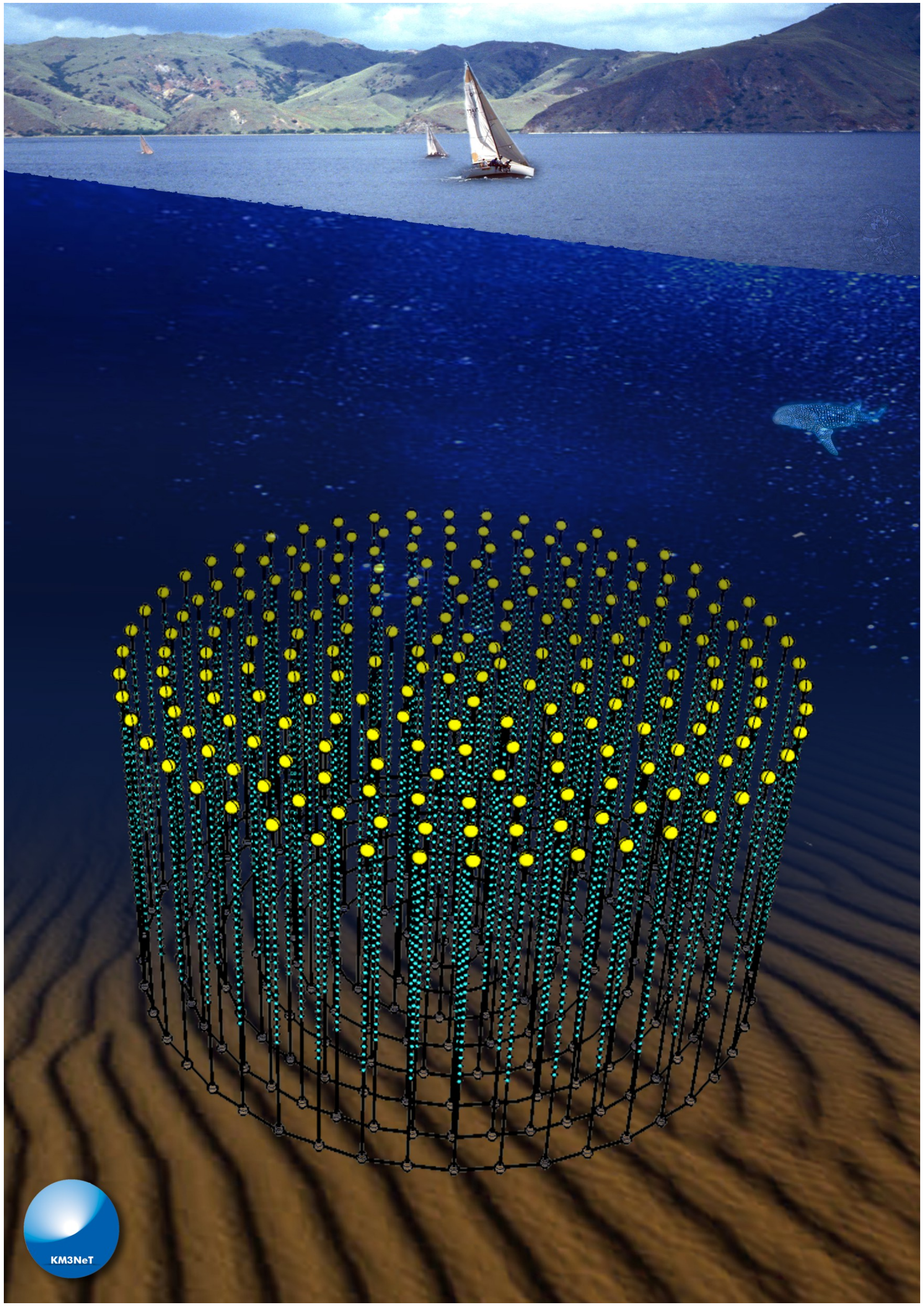
125 m string separation
17 m between PMT's

Detectors in the
Mediterranean Sea

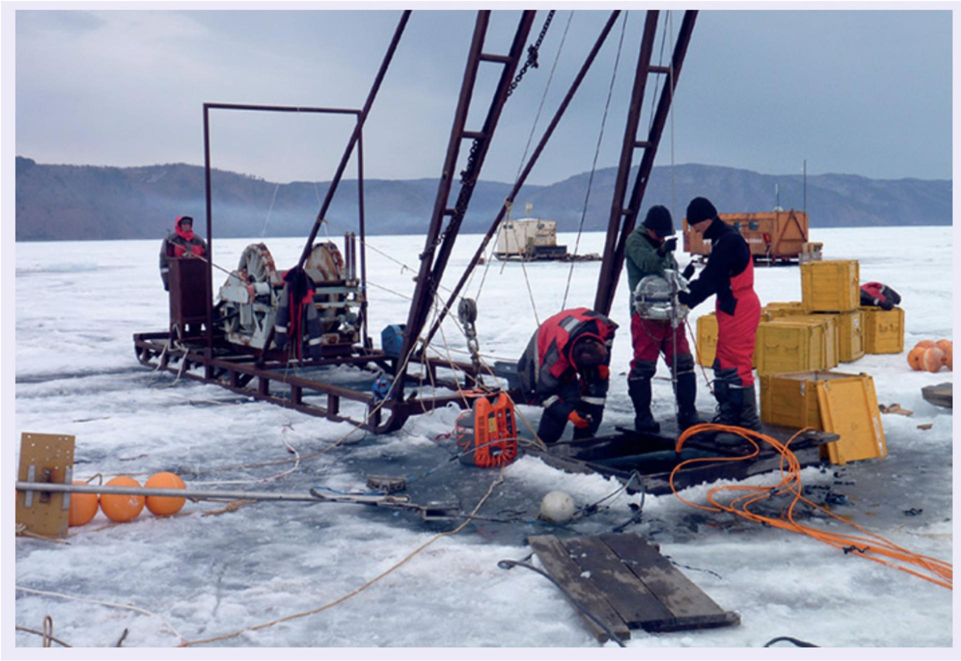
Km3Net (project)

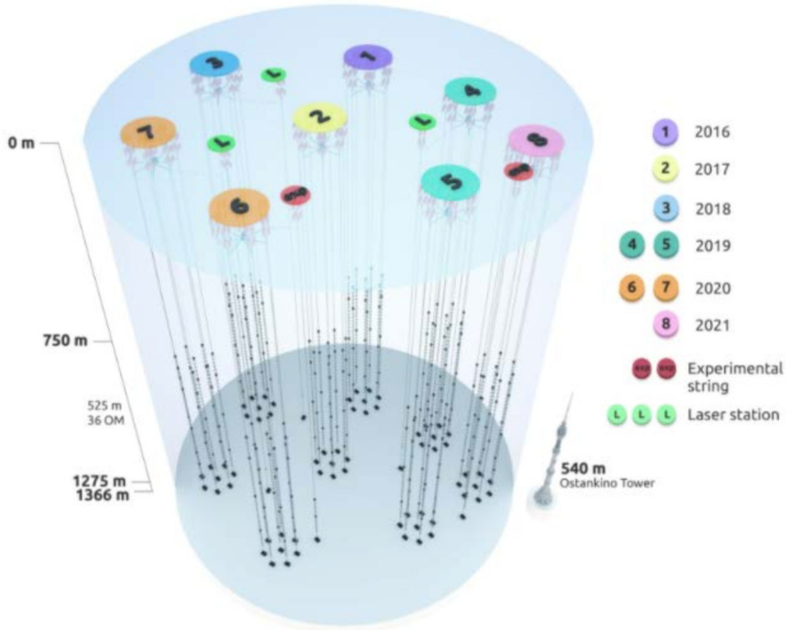


ANTARES (0.1 Km3)

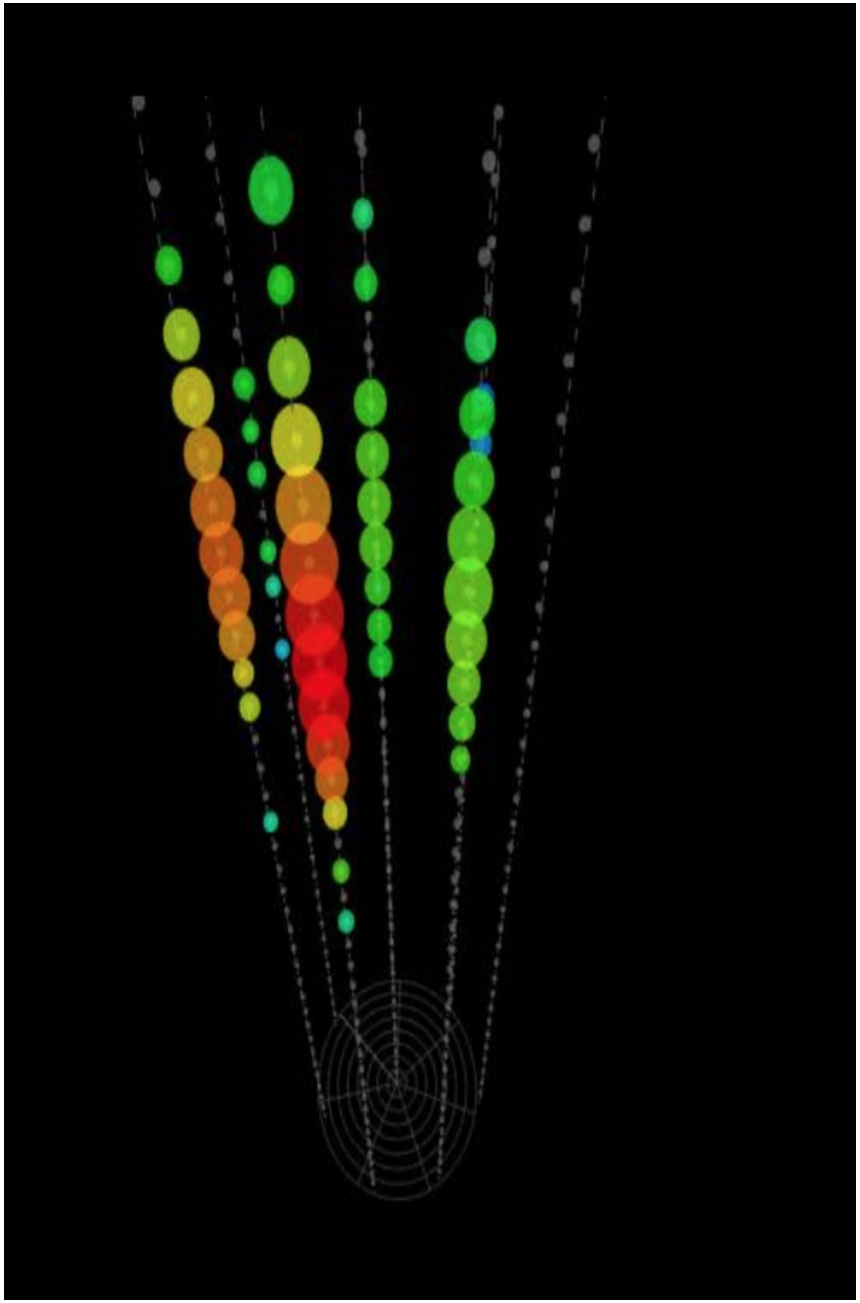


Baikal lake detector (1360 m depth)

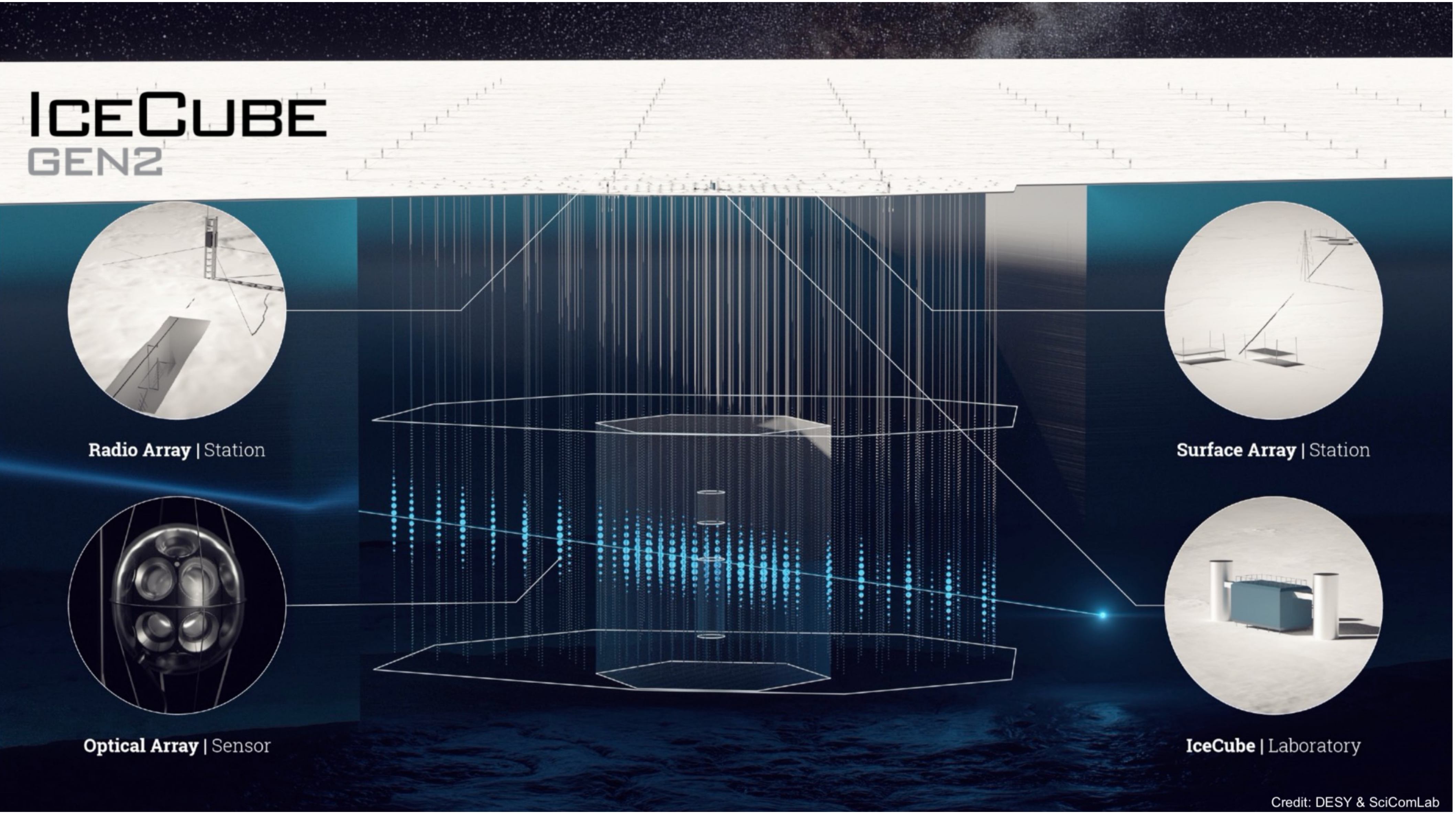




Effective volume 2021: 0.40 km^3 (cascade mode)



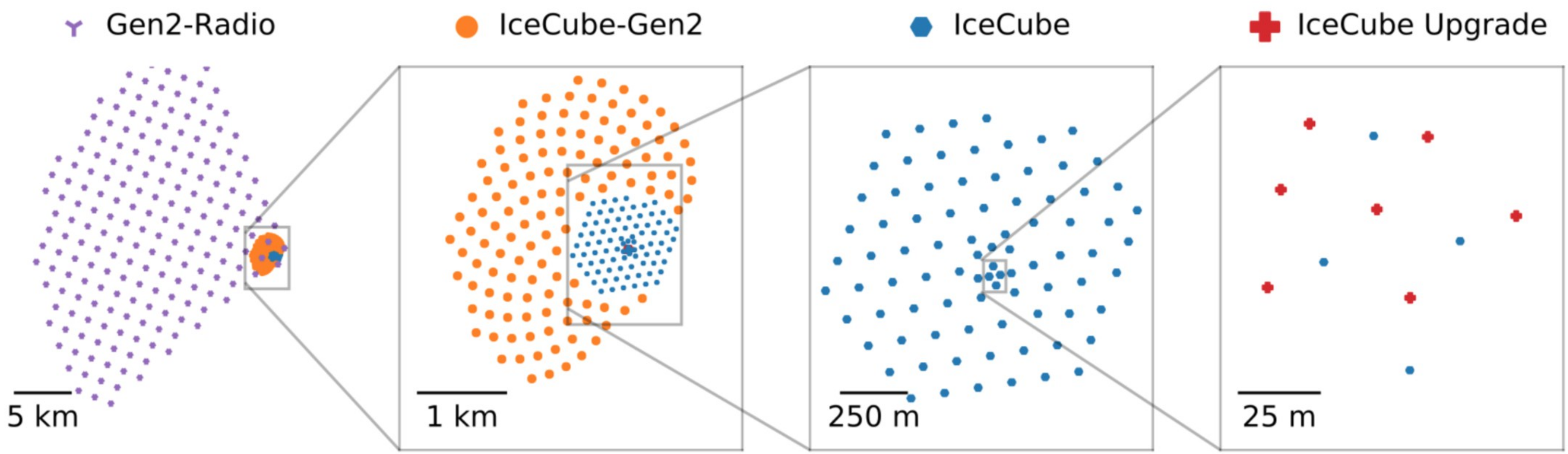
E = 1.2 PeV neutrino event
(30 % uncertainty)



Planned extension: IceCube Gen2 Optical + Radio sensors

The IceCube Gen2 facility at the South Pole

Wide-band observatory: Optimizing scales for leading sensitivity from 10^9 to 10^{20} eV



IceCube-Gen2 planed construction: 2024-2032

completed in 2010

under construction

Gen2 white paper: 2008.04323

$$\phi_{\nu_\alpha}(E,\Omega) = \phi_{\nu_\alpha}^{\text{atm. standard}}(E,\Omega)$$

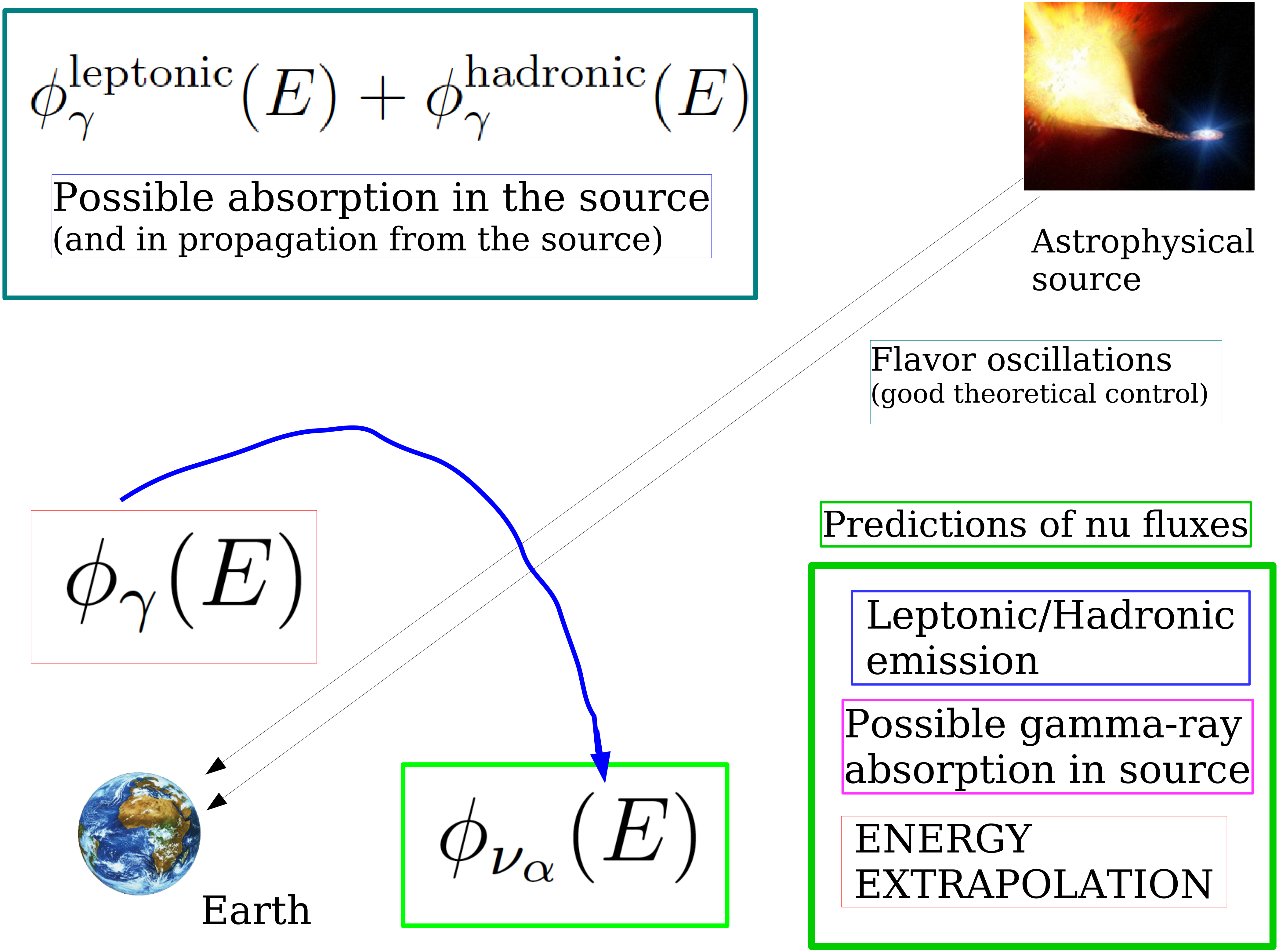
Foreground of atmospheric neutrinos

$$+\ \phi_{\nu_\alpha}^{\text{atm. charm}}(E,\Omega)$$

$$+\ \phi_{\nu_\alpha}^{\text{astro. extragalactic}}(E,\Omega)$$

Astrophysical neutrinos signal

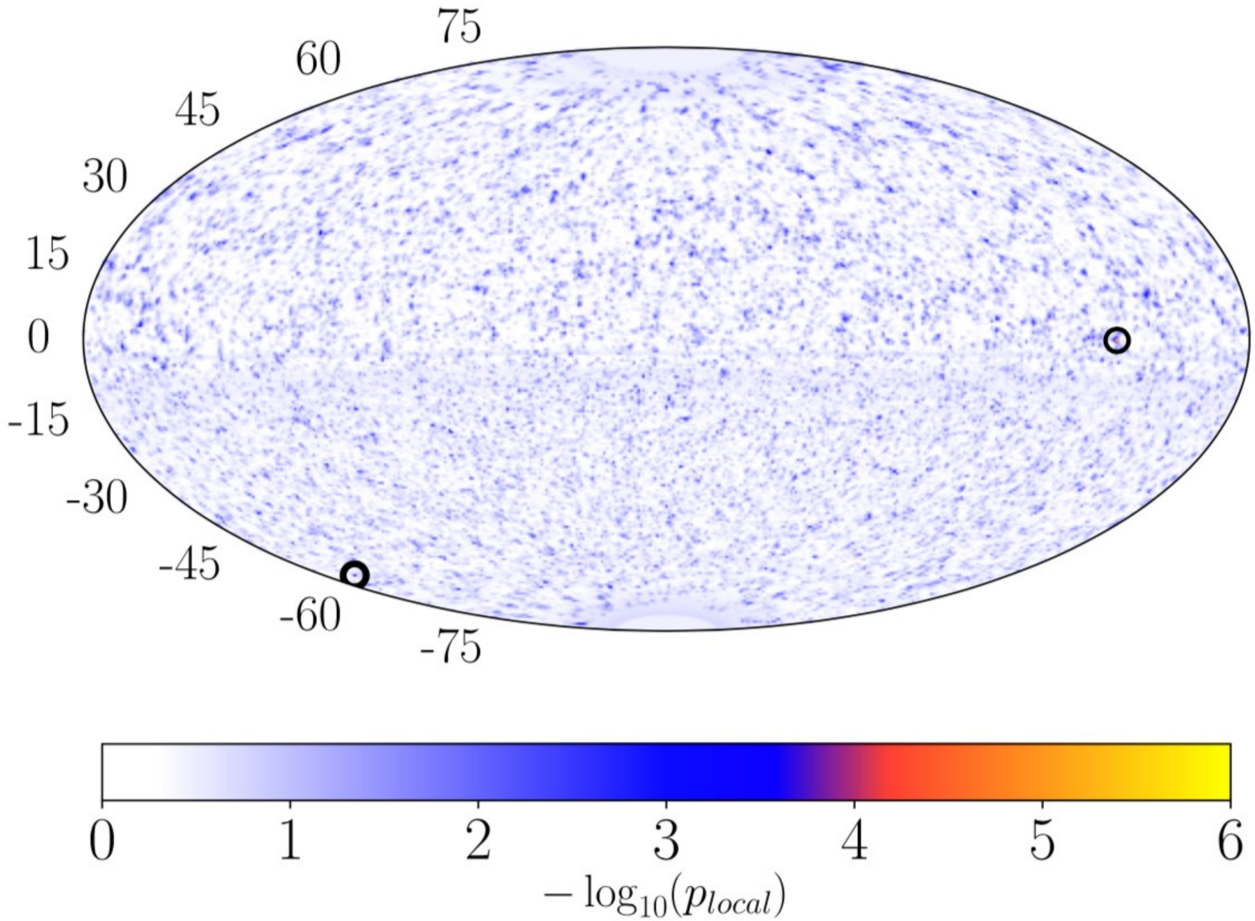
$$+\ \phi_{\nu_\alpha}^{\text{astro. Galactic}}(E,\Omega)$$


$\phi_\gamma^{\text{leptonic}}(E) + \phi_\gamma^{\text{hadronic}}(E)$
Possible absorption in the source
(and in propagation from the source)
Astrophysical source
Flavor oscillations
(good theoretical control)
$\phi_\gamma(E)$
Predictions of nu fluxes
Leptonic/Hadronic emission
Possible gamma-ray absorption in source
ENERGY EXTRAPOLATION
$\phi_{\nu_\alpha}(E)$
Earth

Search for Neutrino Point Sources

At present only limits
but this is not unexpected
given the sensitivity
of the existing instruments

IceCube 10 years search

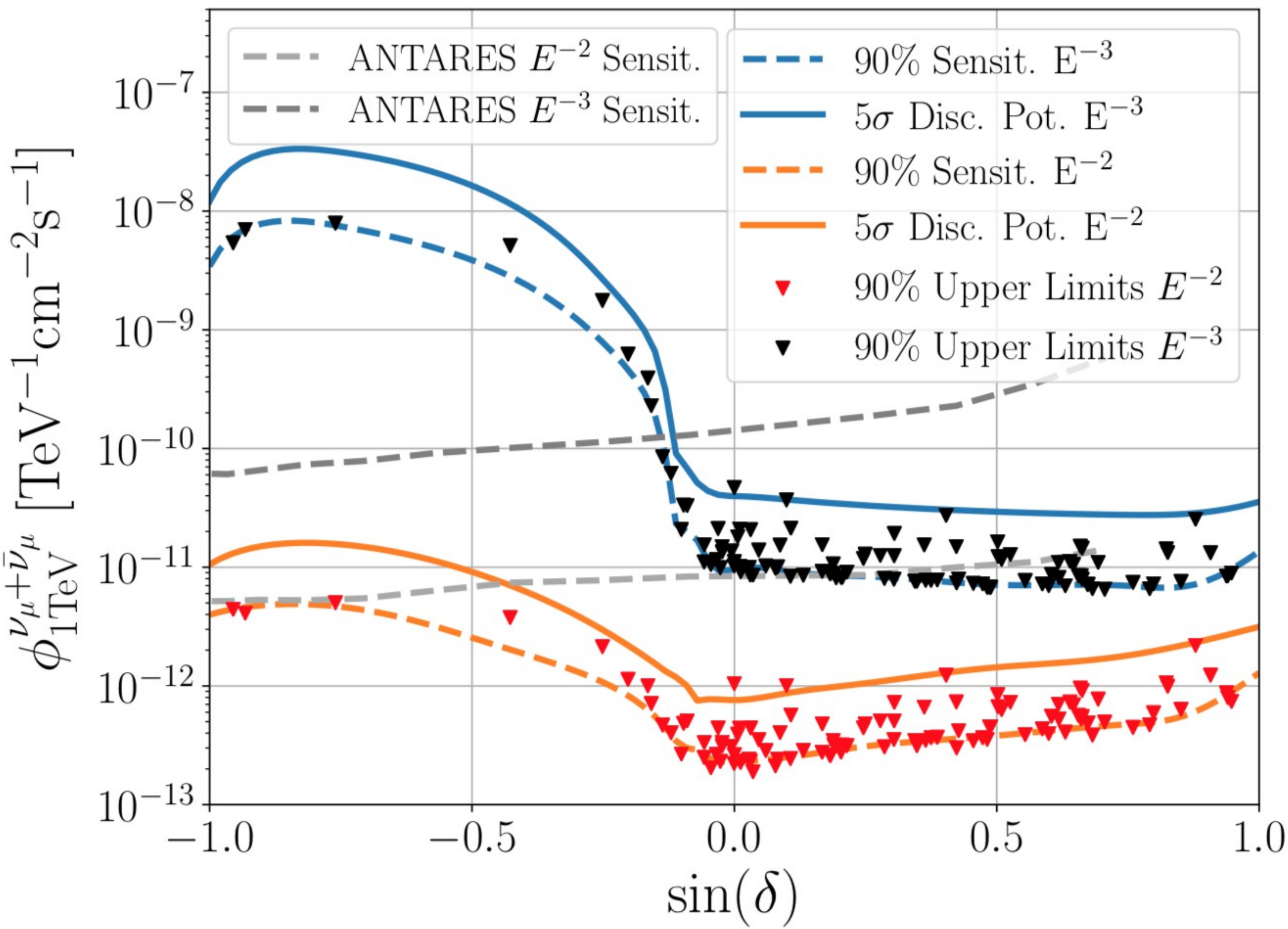


Two most
significant excesses

2 AGN

NGC 1068
(2.9 sigma)

TXS 0506+056
(3.3 sigma)



IceCube 10 years data
[from Catalog of potential sources]

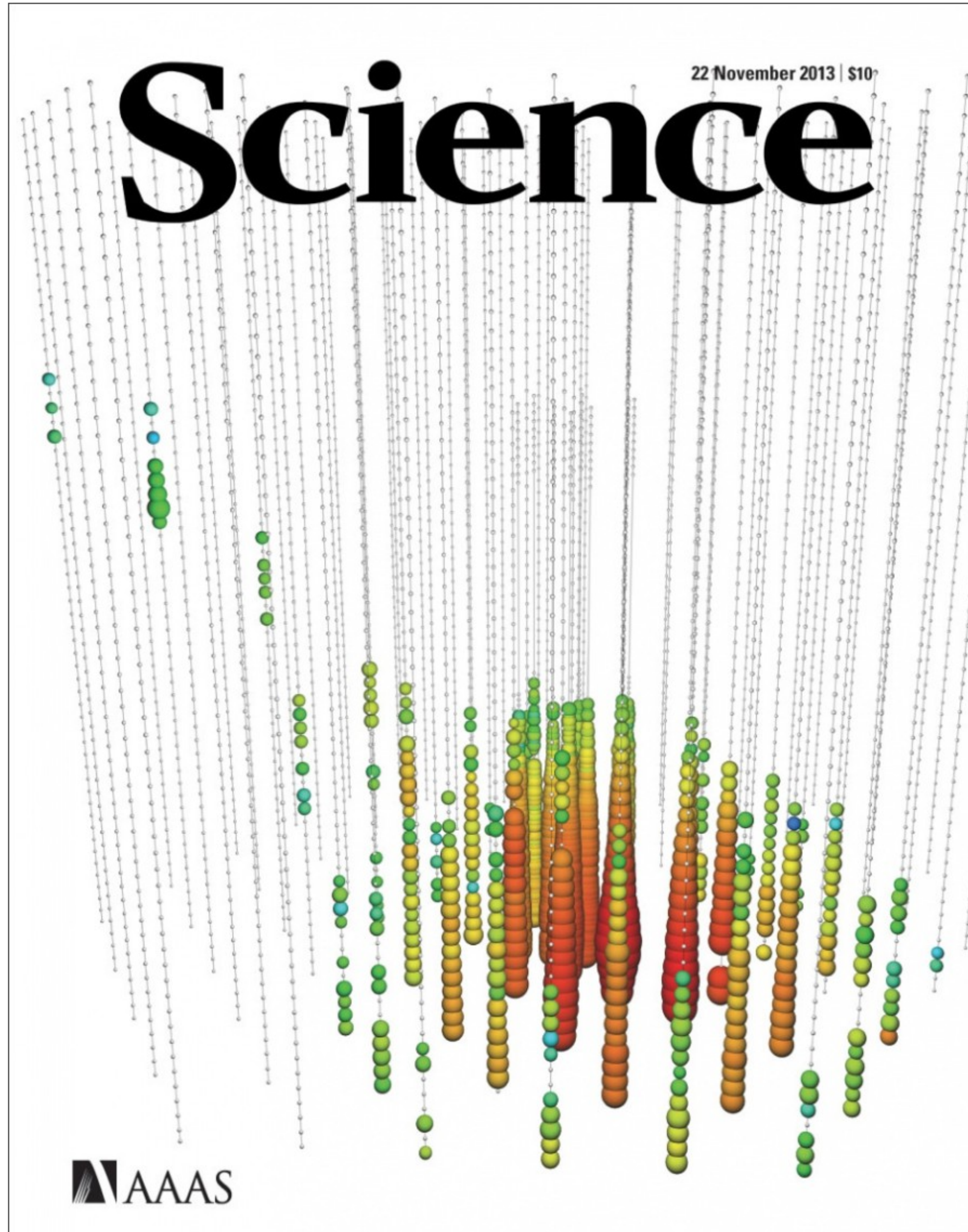
$E_\nu \gtrsim 1$ TeV

IceCube 2013

[Science Journal
“breakthrough
of the year” 2013]

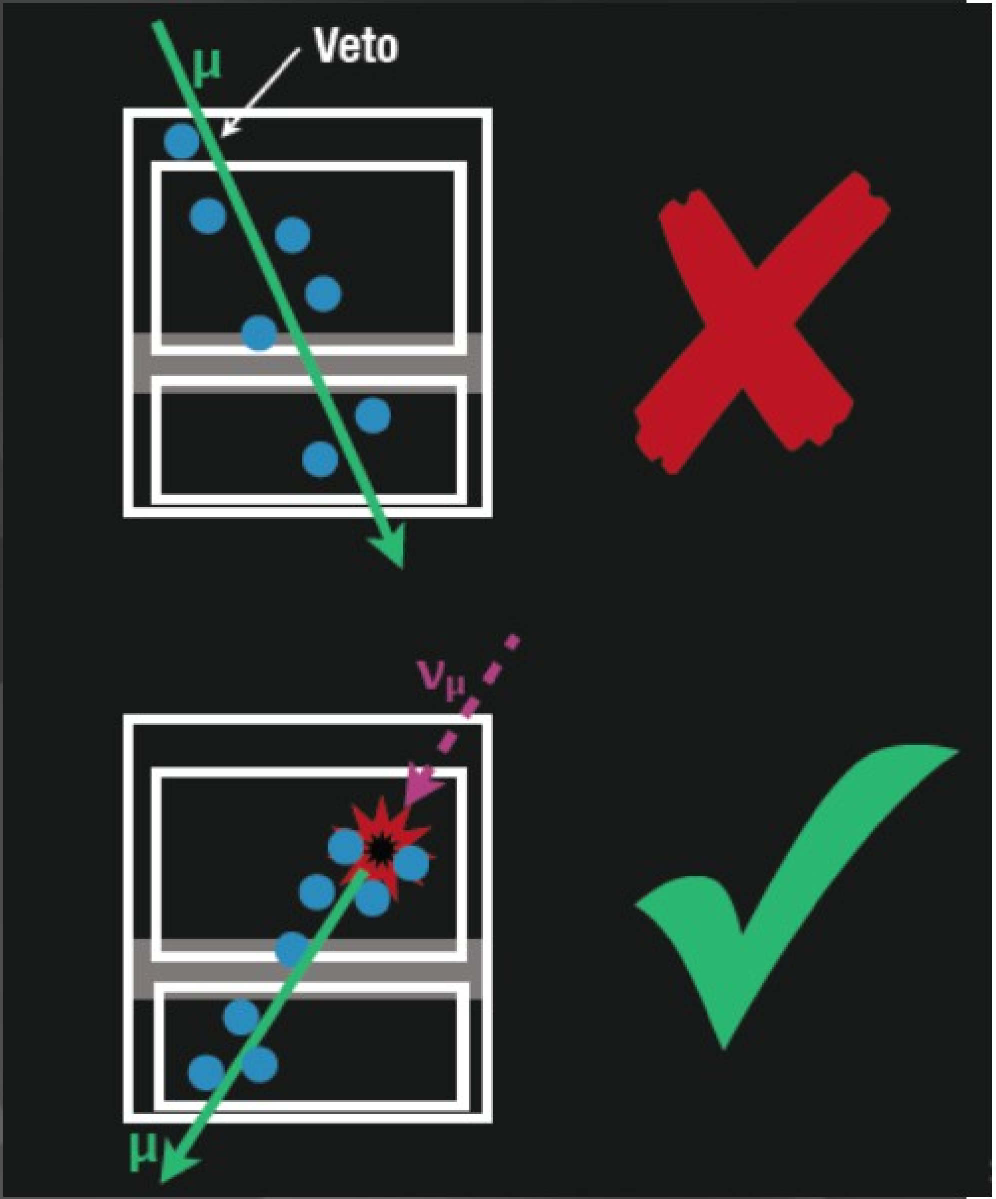
*Evidence for
an astrophysical
neutrino signal*

E > 30 TeV



High Energy Starting Events (HESE)

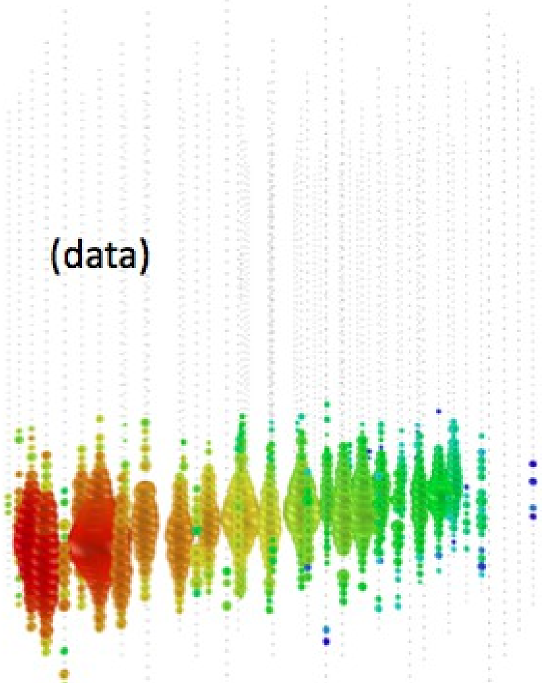
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



loss in statistics is compensated by event definition

Types of events and interactions

Charged-current ν_μ

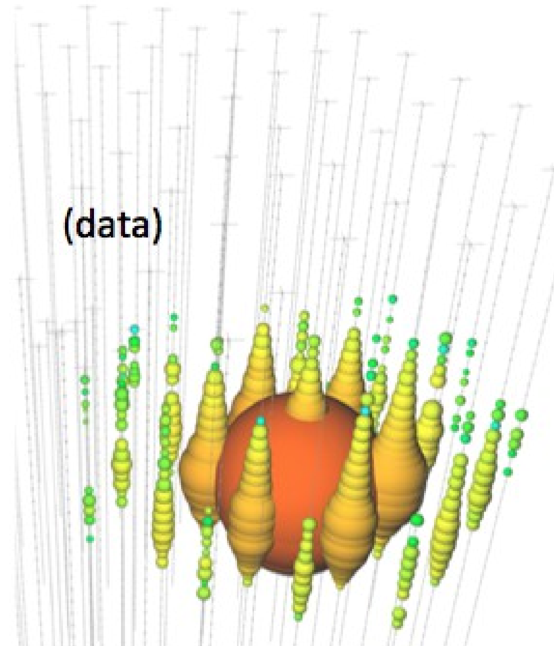


Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

0.3° above 100 TeV

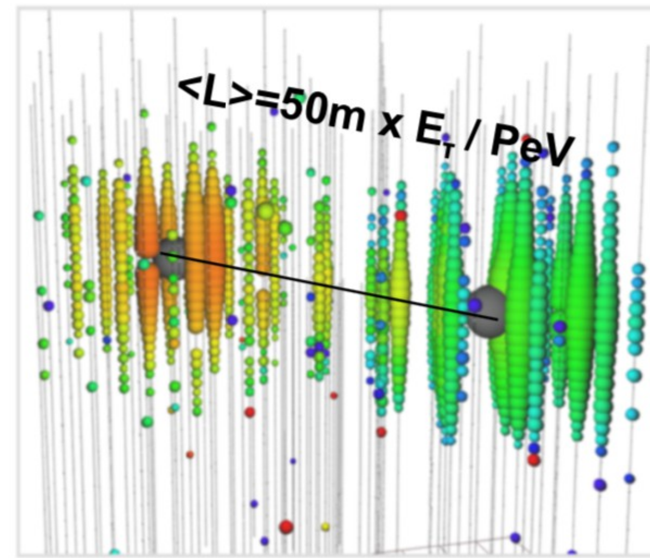
Neutral-current / ν_e



Isolated energy deposition
(cascade) with no track

15% deposited energy resolution
10-15° angular resolution (above 100 TeV)
Working on improving that.

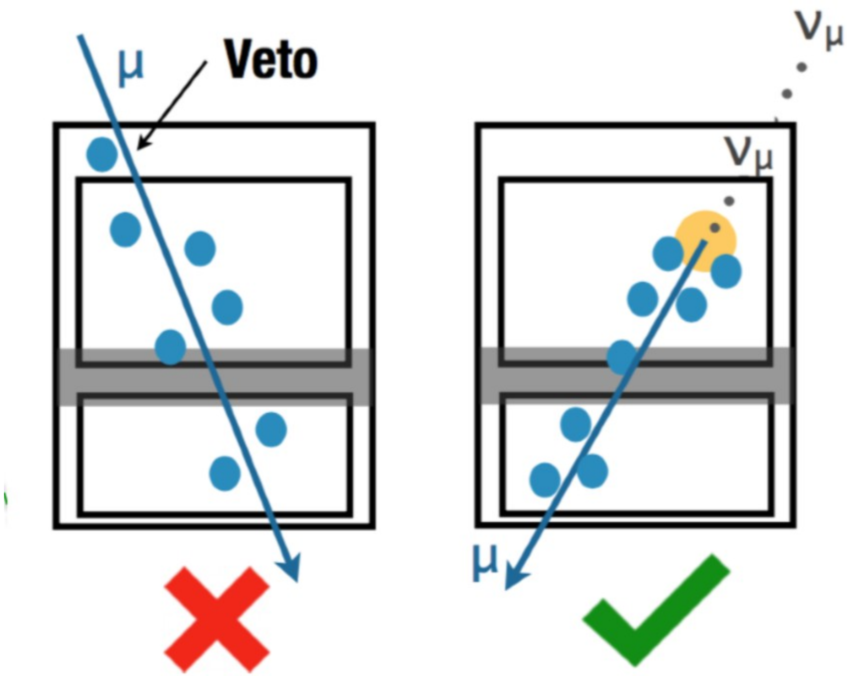
Charged-current ν_τ

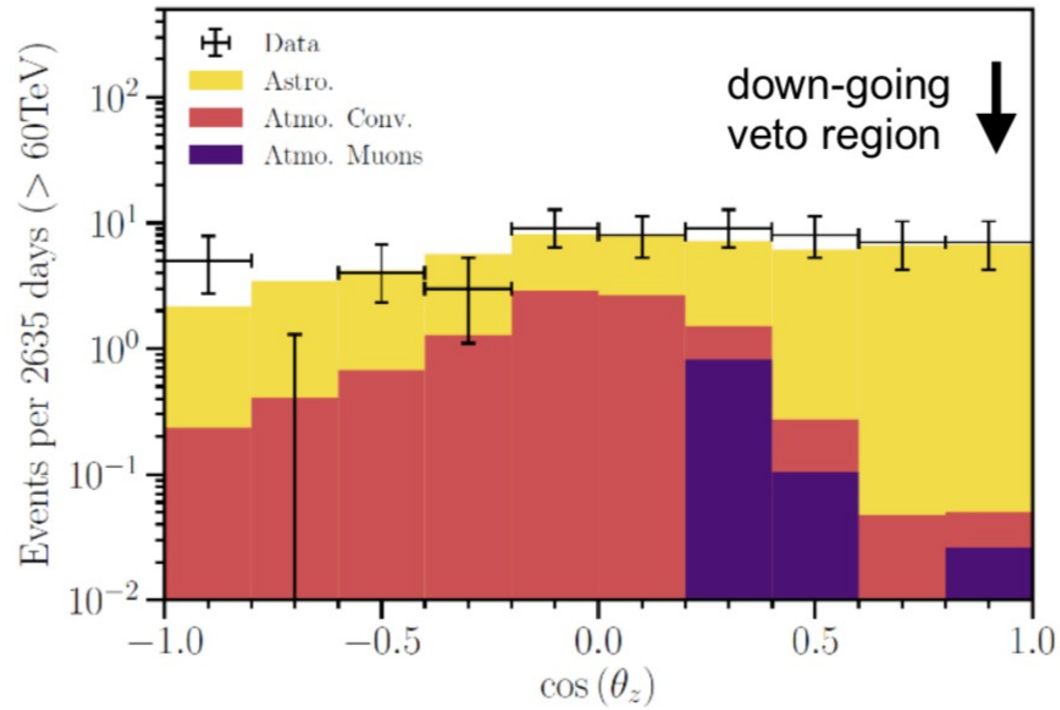


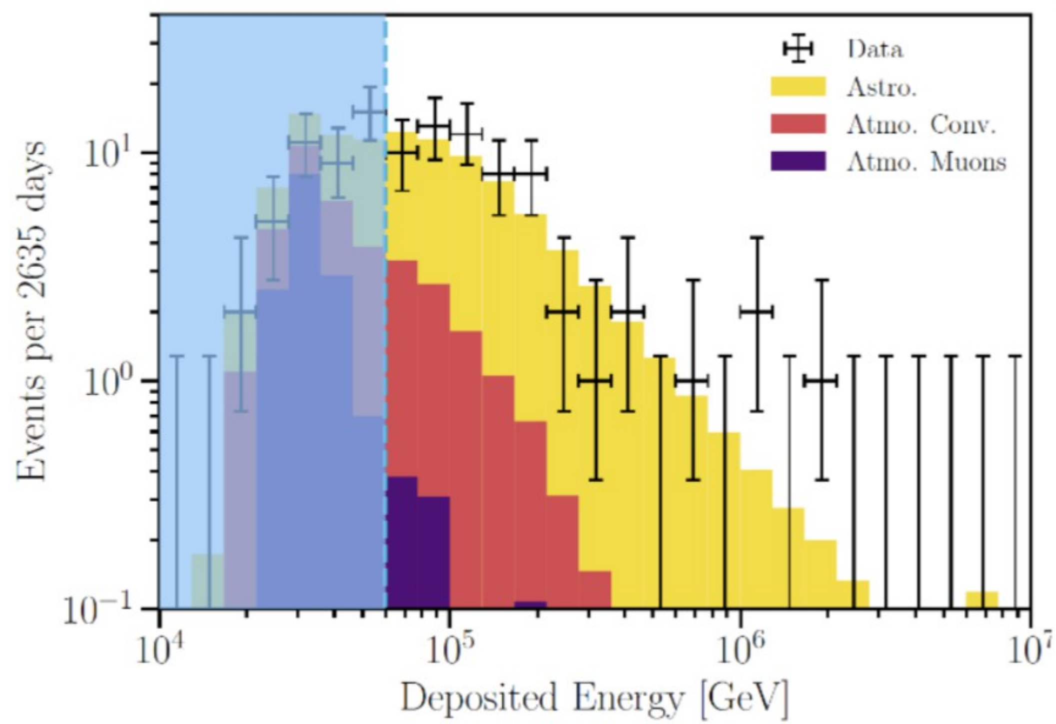
"Double-bang"

Early  Late

7.5 years
of HESE events





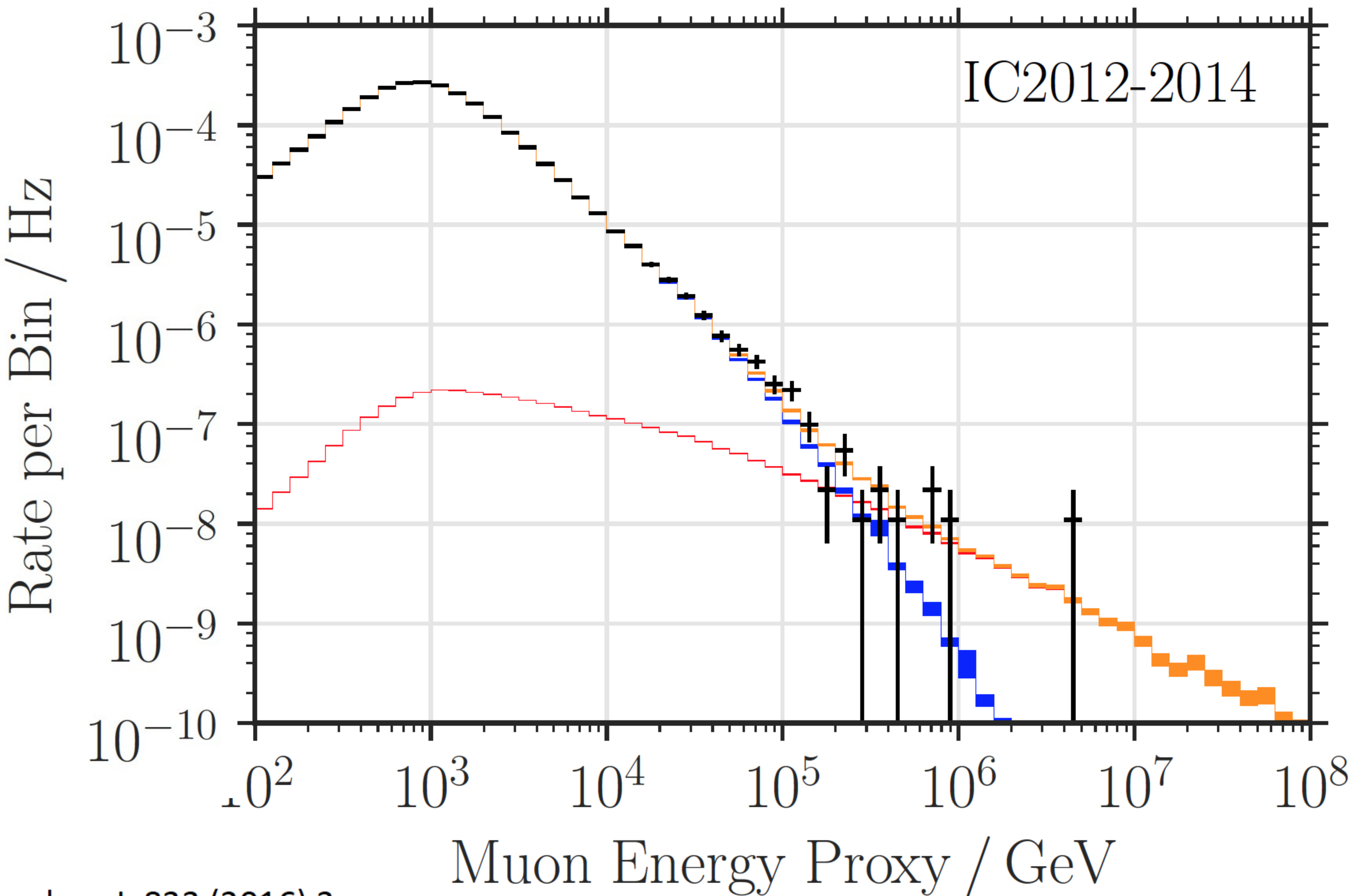


Angular distribution consistent with ISOTROPY
(+ absorption in the Earth)

[extragalactic origin]

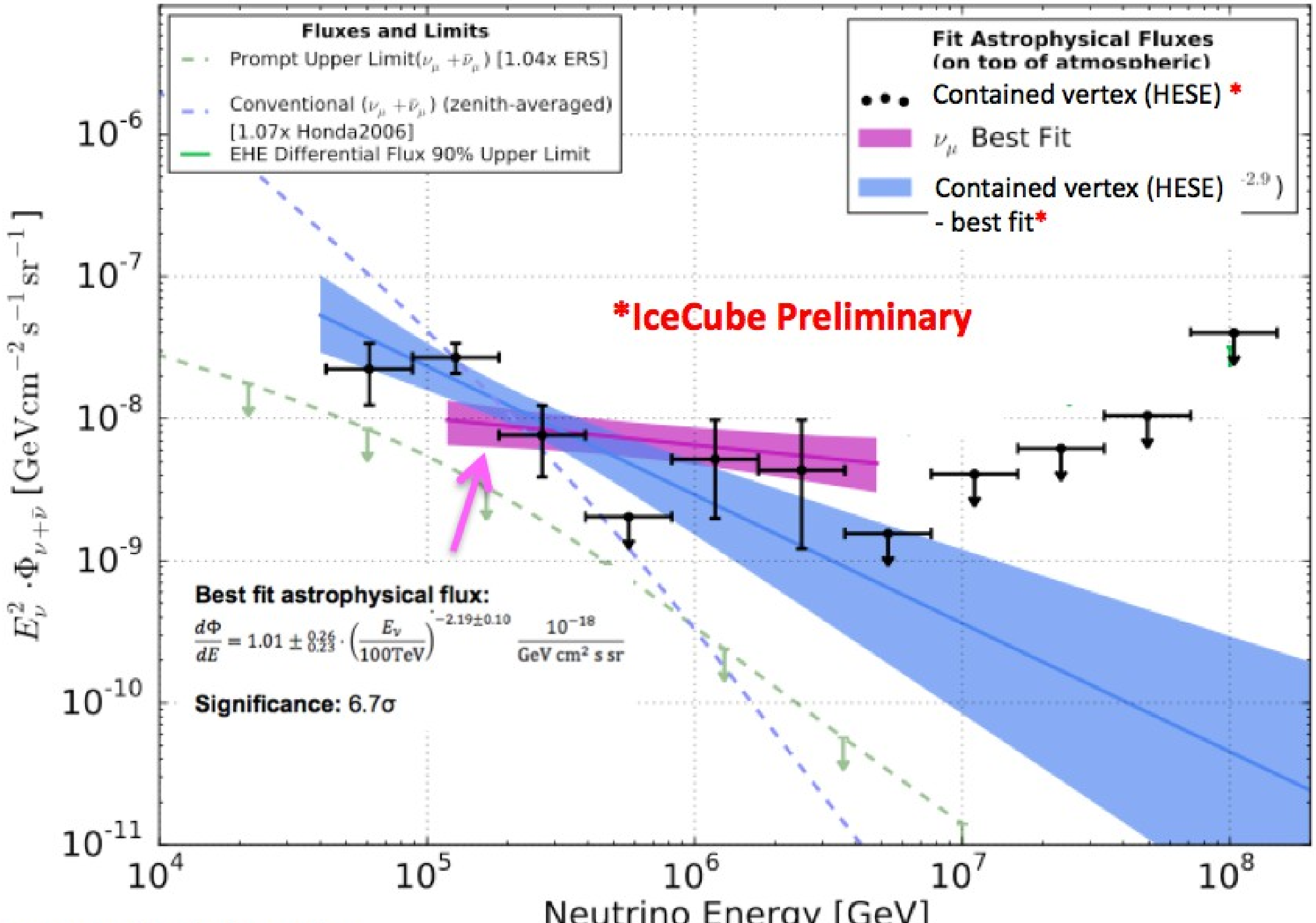
PRD (2021), https://arxiv.org/abs/2011.03545

Upgoing (neutrino induced) Muons



Astrophys. J. 833 (2016) 3

Energy spectrum with these event samples:
1.) upgoing muon neutrinos 2.) contained vertex events



ICRC 2017: Kopper, Wandkowsky for IceCube C.
ICRC 2017: Haack for IceCube C.

ICRC 2019

Questions on the IceCube signal:

1. Is the signal of astrophysical neutrinos real ?
   (or is the background/foreground poorly estimated) ?

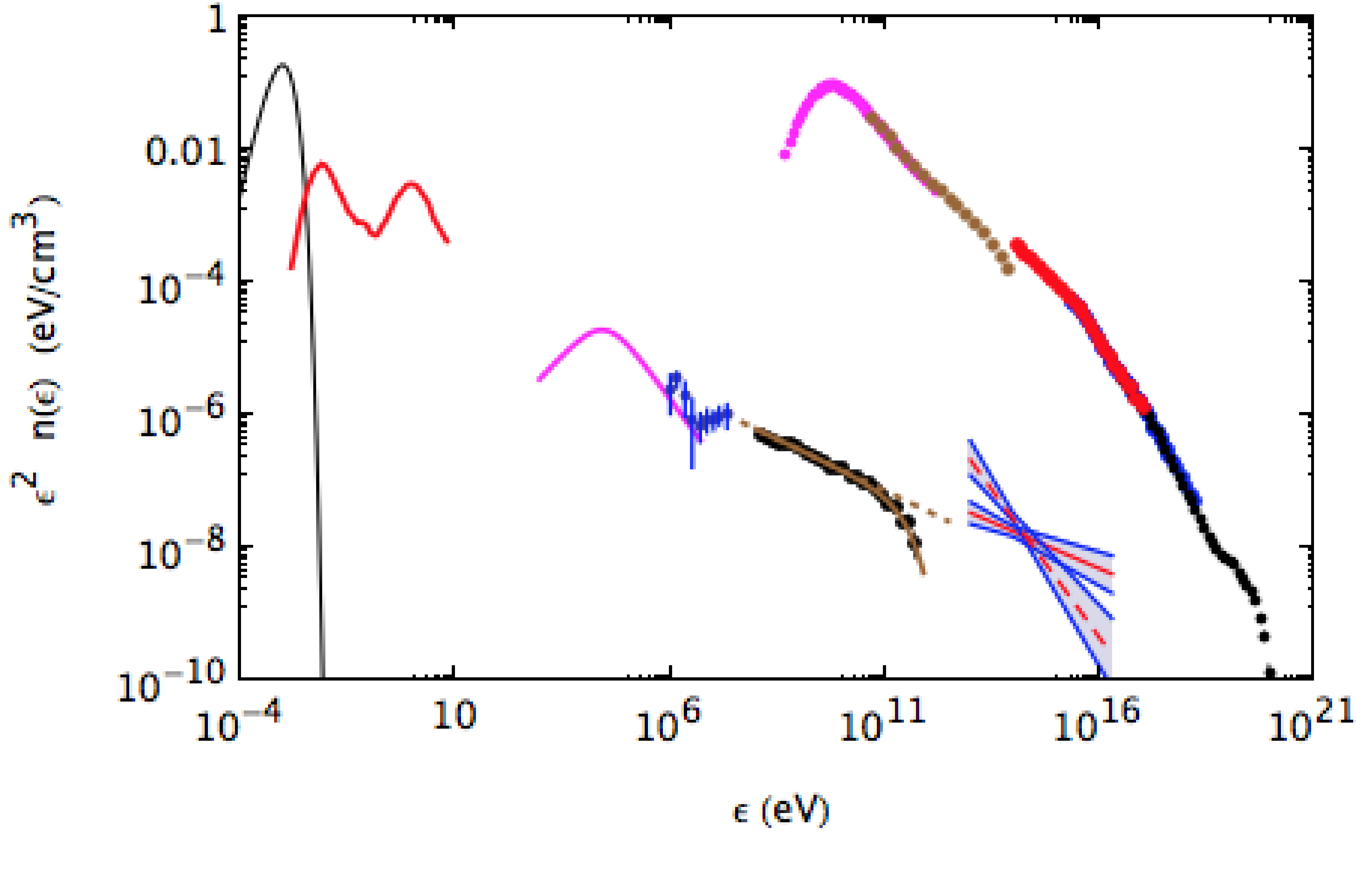
1a. Could the signal be contaminated by a non negligible contribution of atmospheric neutrinos ?

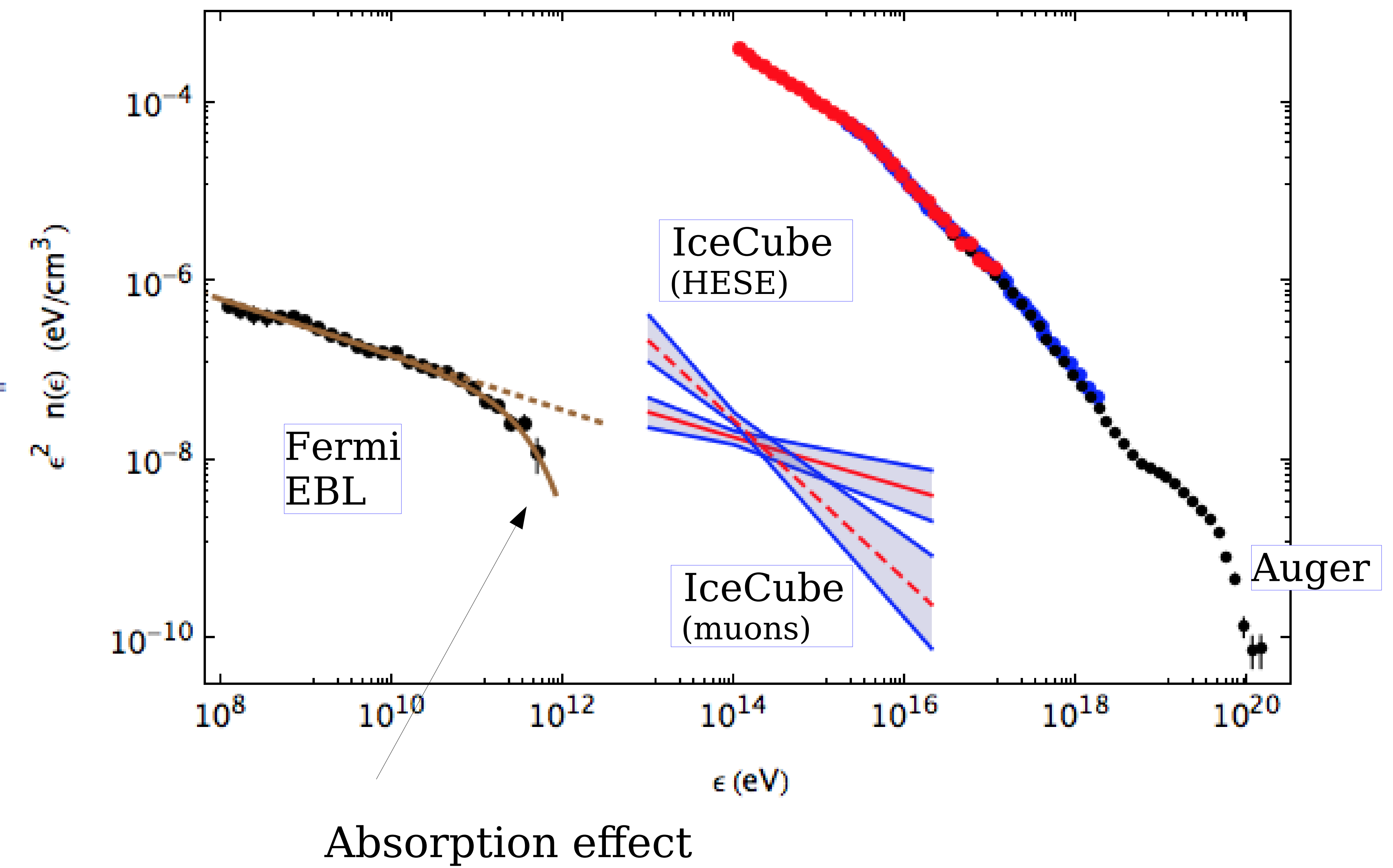
2. Is the signal entirely extragalactic ?
   or does it contains a non negligible Galactic component ?

3. If most of the signal is extragalactic,
   what can we say about the sources ?

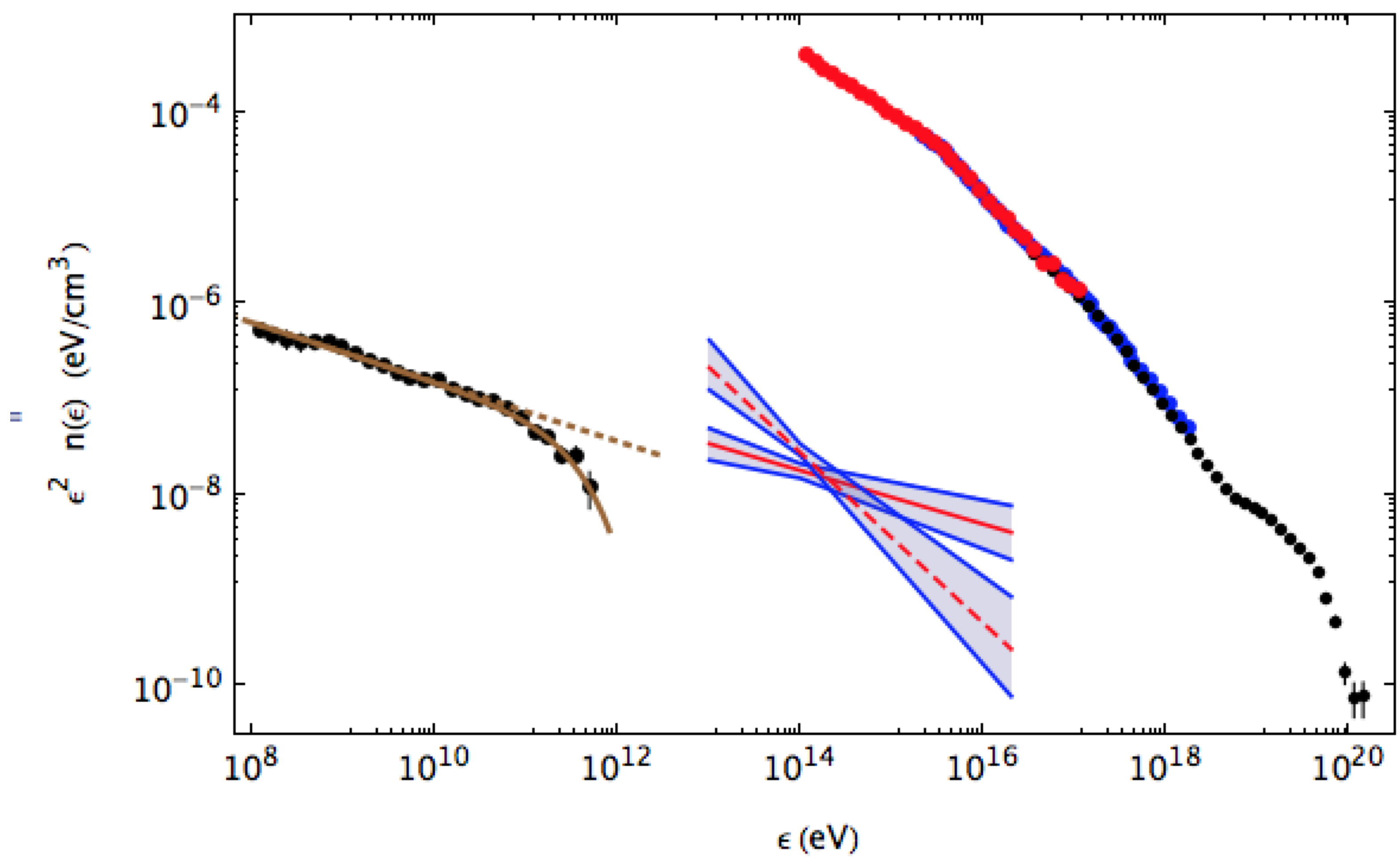
3a. If there is a Galactic (perhaps subdominant) component what is its nature ?

Local Energy density





$\epsilon^2\ n(\epsilon)\ (eV/cm^3)$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
ϵ (eV)
IceCube
(HESE)
Fermi
EBL
IceCube
(muons)
Auger
Absorption effect



Comparison of the gamma-ray and neutrino spectra:

Two questions emerge naturally :

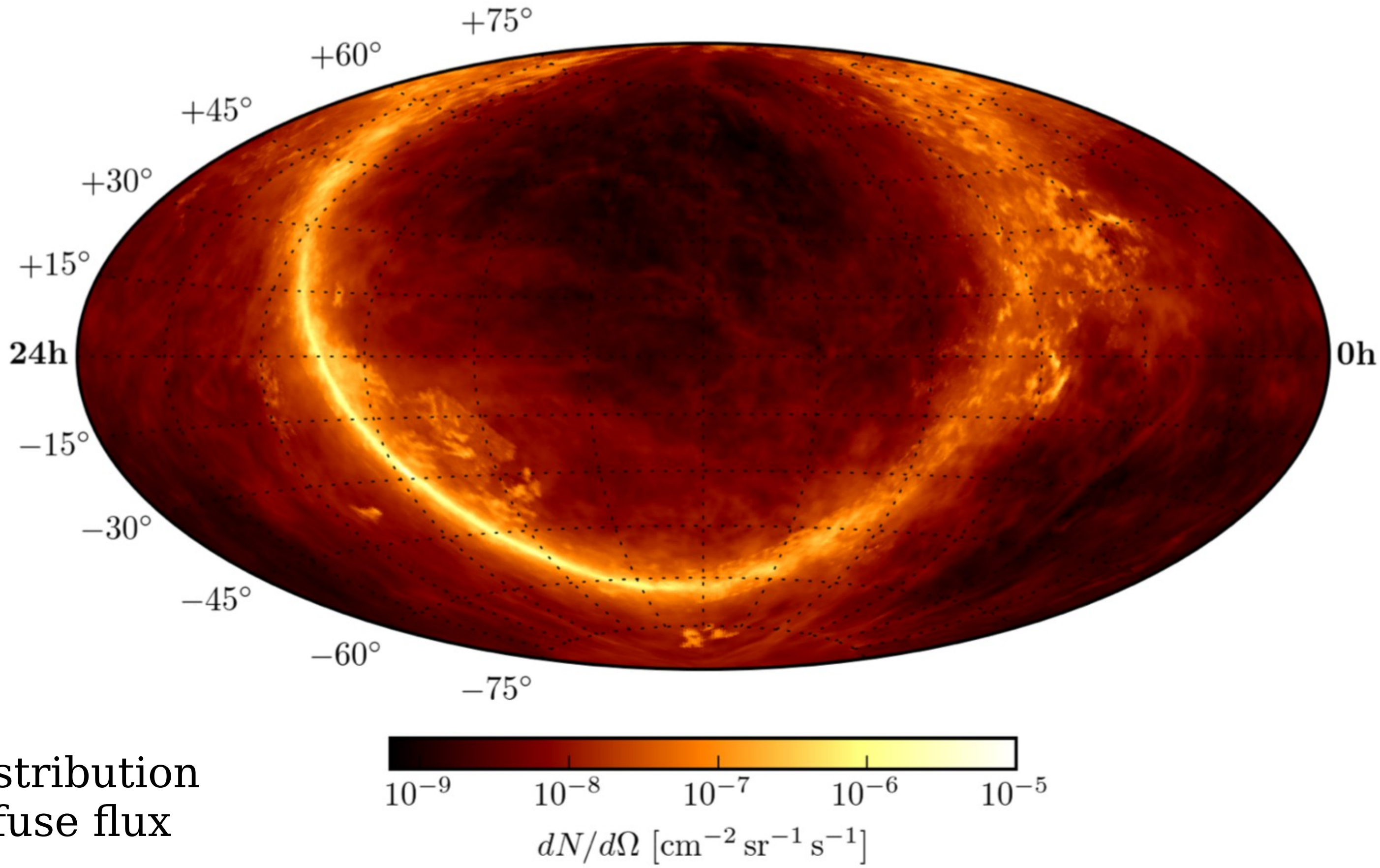
1. Is there an "excess of neutrinos" [Do neutrino only sources exist?]
2. Are there distinct classes of sources for photons and neutrinos ?
   [or rephrasing: can Blazars be the dominant neutrino source]

What fraction of the IceCube neutrino signal comes from the Milky Way ?

Joint paper of the ANTARES and IceCube Collaborations

ANTARES and IceCube Collaborations,
"Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes,"
Astrophys. J. Lett. **868**, no.2, L20 (2018)
[arXiv:1808.03531 [astro-ph.HE]].

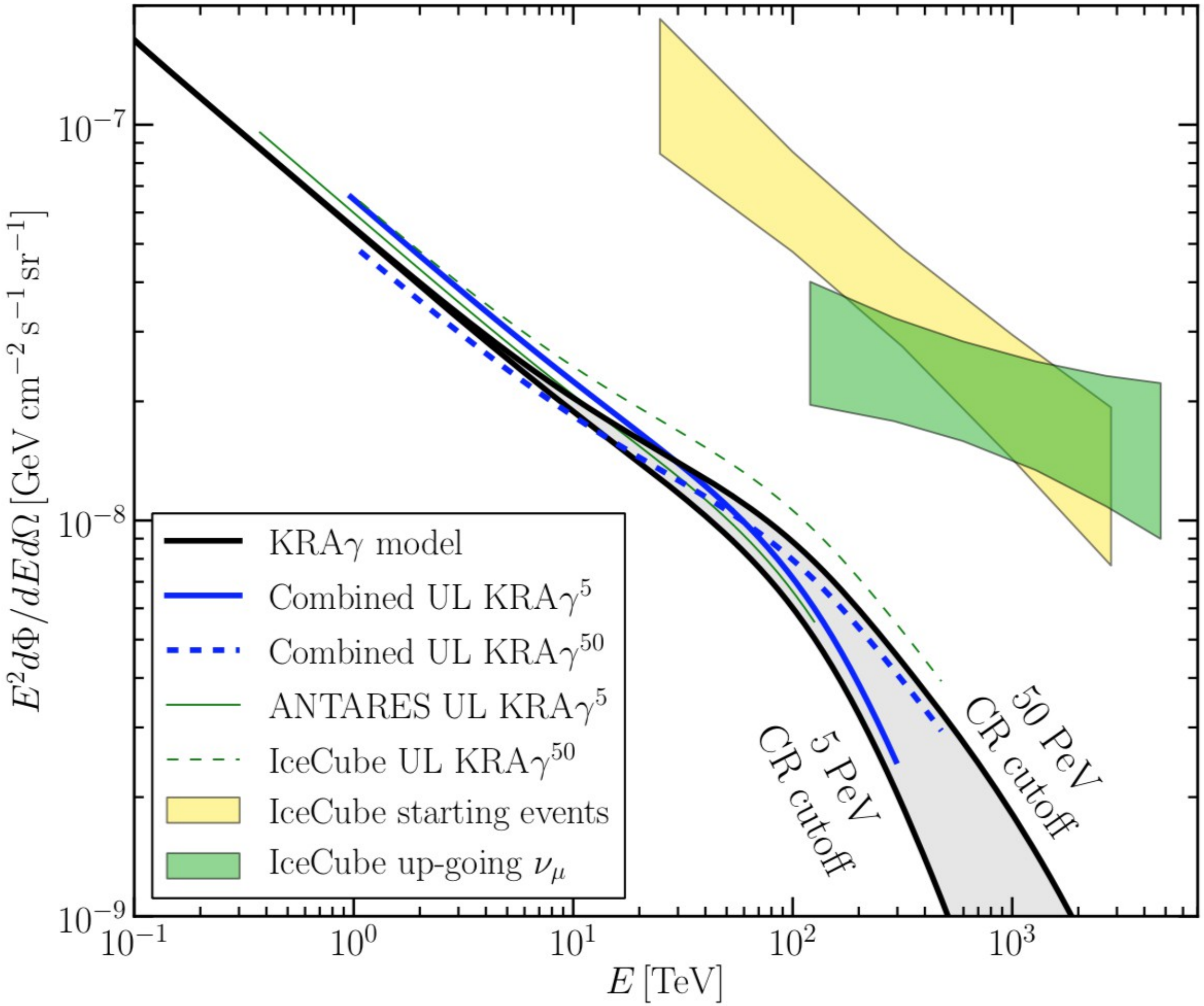
No excess
(based on template)



Template

for the Angular distribution
of the Galactic diffuse flux

The upper limit on the Galactic diffuse component is close to the predictions (that are however model dependent)

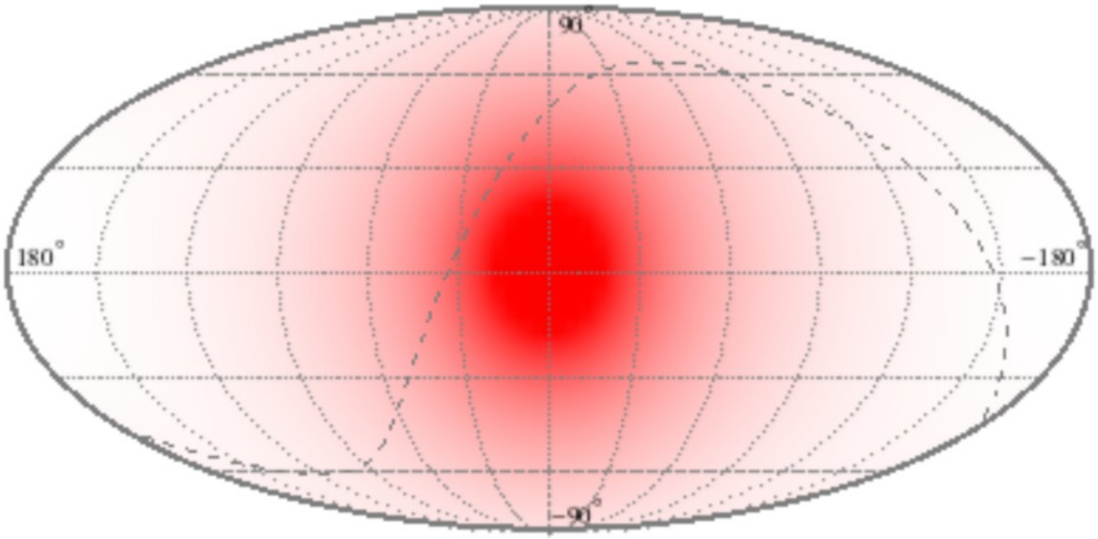


Does the IceCube signal have a Galactic component ?

There are models where the signal is *entirely* of Galactic origin.

A. Esmaili and P. D. Serpico,
"Are IceCube neutrinos unveiling PeV-scale decaying dark matter?,"
JCAP **1311**, 054 (2013)
[arXiv:1308.1105 [hep-ph]].

Expected angular distribution distribution

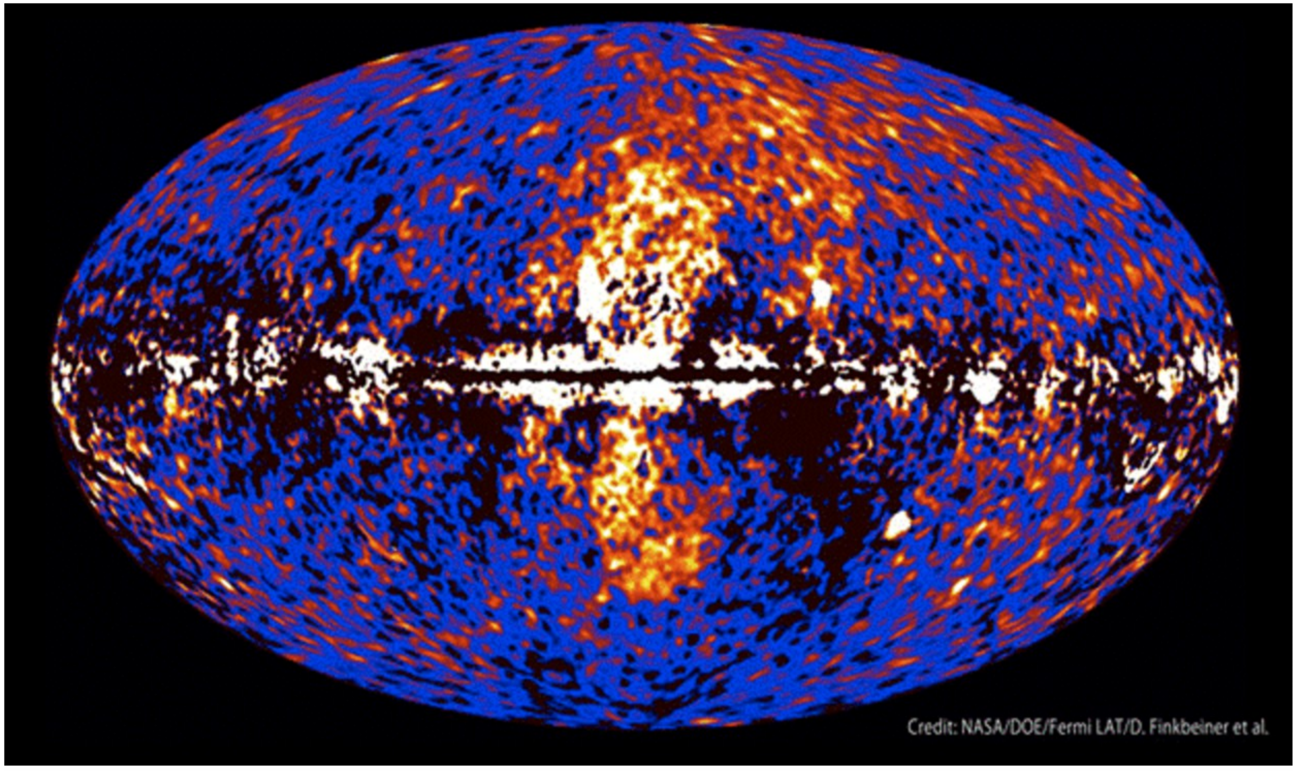


(a) PDF of DM decay

A. M. Taylor, S. Gabici and F. Aharonian,
"Galactic halo origin of the neutrinos detected by IceCube,"
Phys. Rev. D **89**, no. 10, 103003 (2014)
doi:10.1103/PhysRevD.89.103003 [arXiv:1403.3206 [astro-ph.HE]].

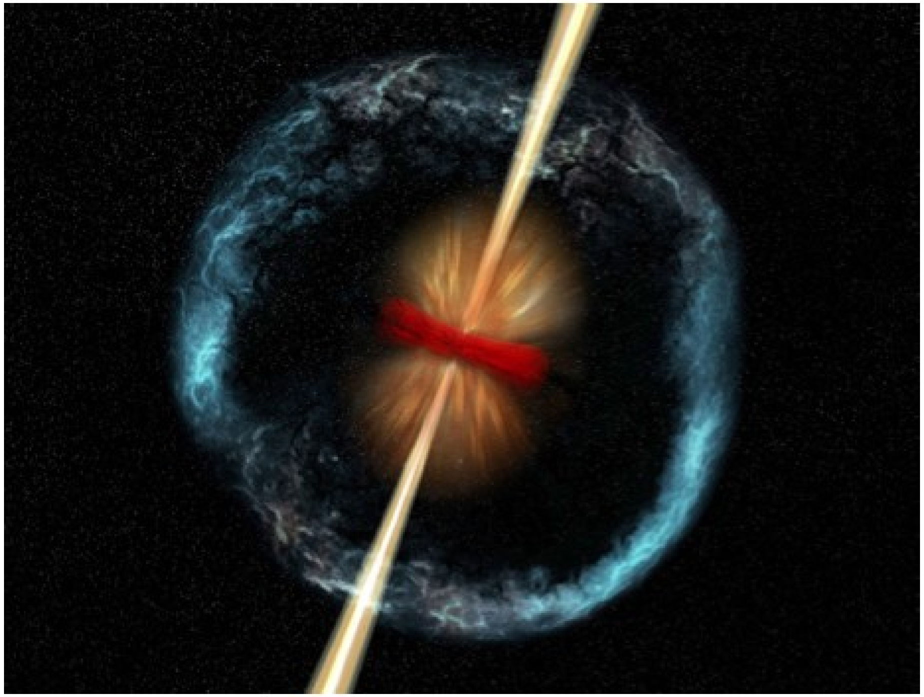
Very large (100 kpc) halo of cosmic rays

[Inspired (to a large extent) by the observations of the "Fermi Bubbles"]



What fraction of the cosmic neutrino flux comes from prompt GRB?

Gamma Ray Bursts



807 GRB's monitored for prompt neutrino emission at TeV to PeV energy range.

]

Illustration credit: NASA/CXC/M.Weiss

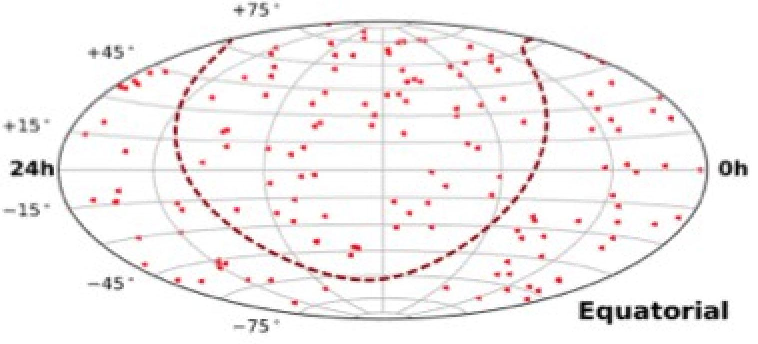
Answer: < 1%

Ref: arxiv: 1702.06868

What fraction of the cosmic neutrino flux comes from Fermi blazars?

Active Galaxies - Blazars

AGN with supermassive black hole, with Jet pointing at us.



Fermi reports that ~85% of the gamma rays from the "diffuse" gamma ray flux originate fro blazars.

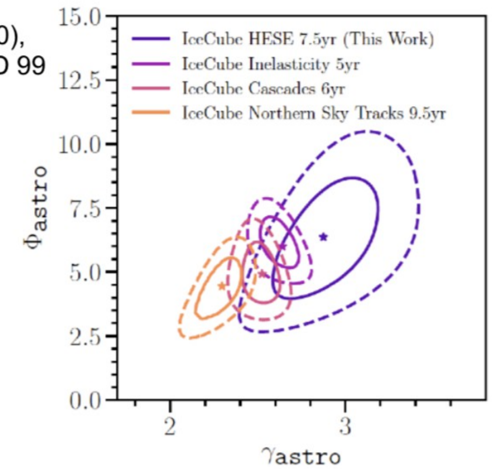
Answer: only a small fraction (< 6% to 27%) of events from Fermi blazar catalogues.

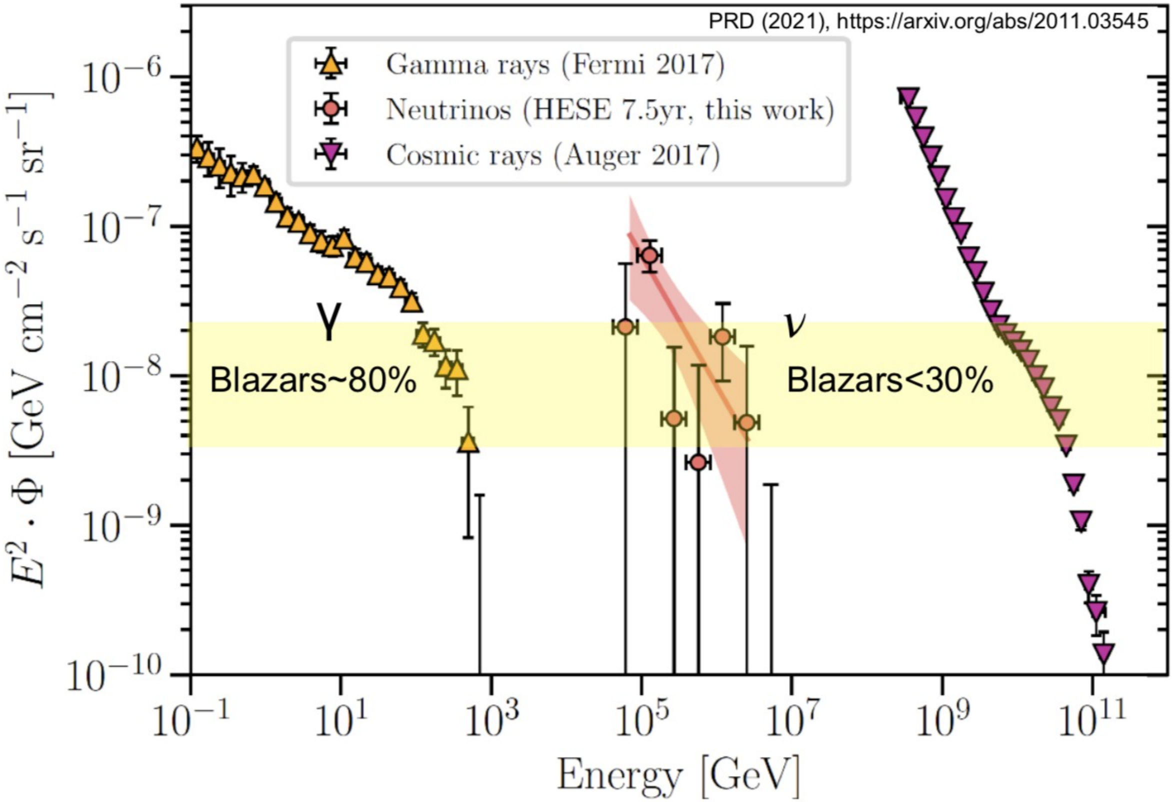
(Some assumptions, eg assume energy spectrum, apply.
Ref: - Astrophys. J **835**, 45 (2017)
- ICRC 2017, Huber for IceCube C.

Multimessenger spectroscopy

with 7.5 years of High-Energy Starting Events

Other channels: Phys.Rev.Lett. 125 (2020), PoS ICRC2019, 1017 (2020), Phys.Rev.D 99 (2019) 3, 032004



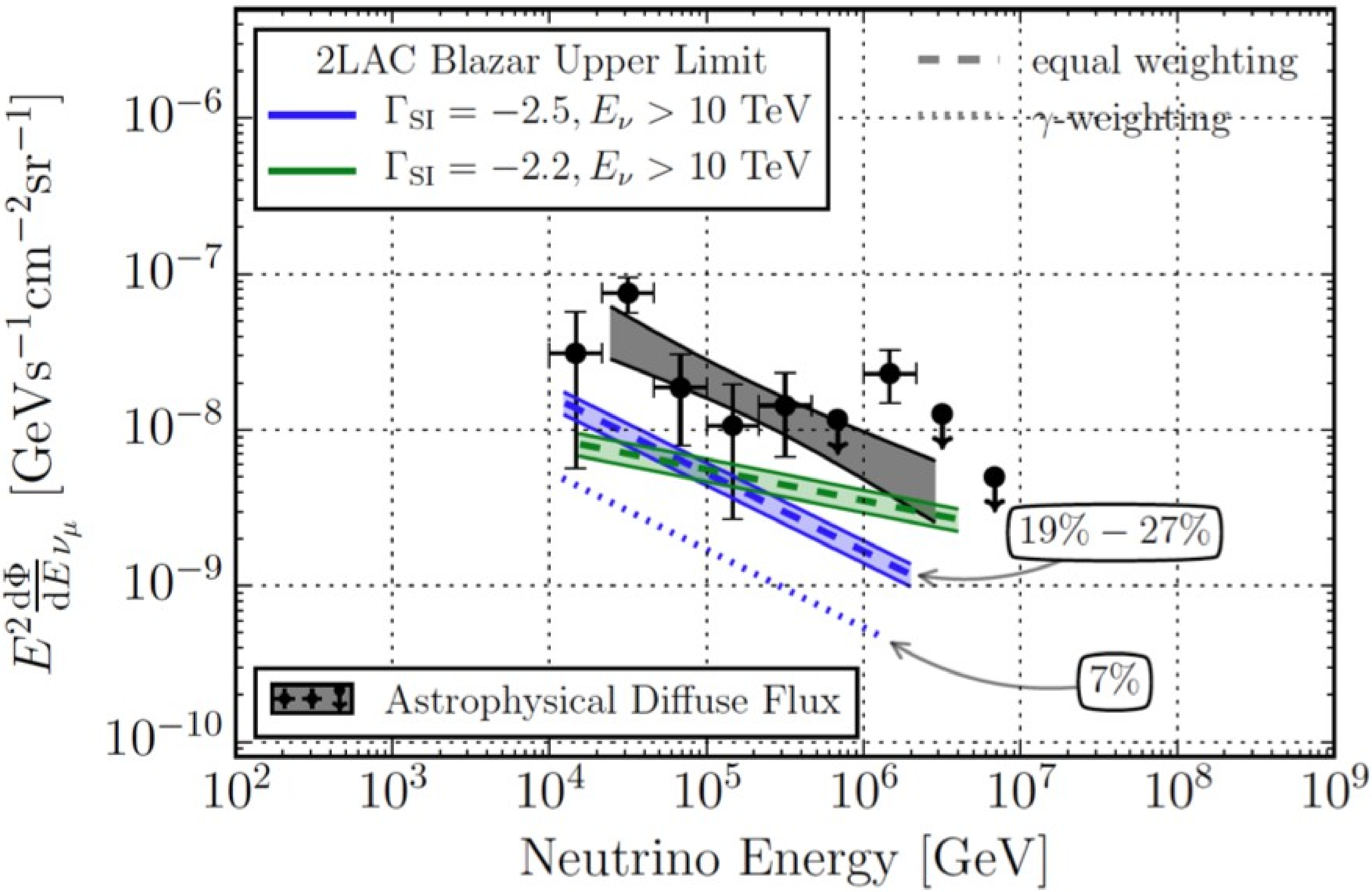


- Spectral index of astro. flux: γ=2.3-2.9 depends on analysis / energy range
- Similar energies among messengers …
- … but also evidence for different origin!
- Gamma-obscured sources?

The first decade of discoveries

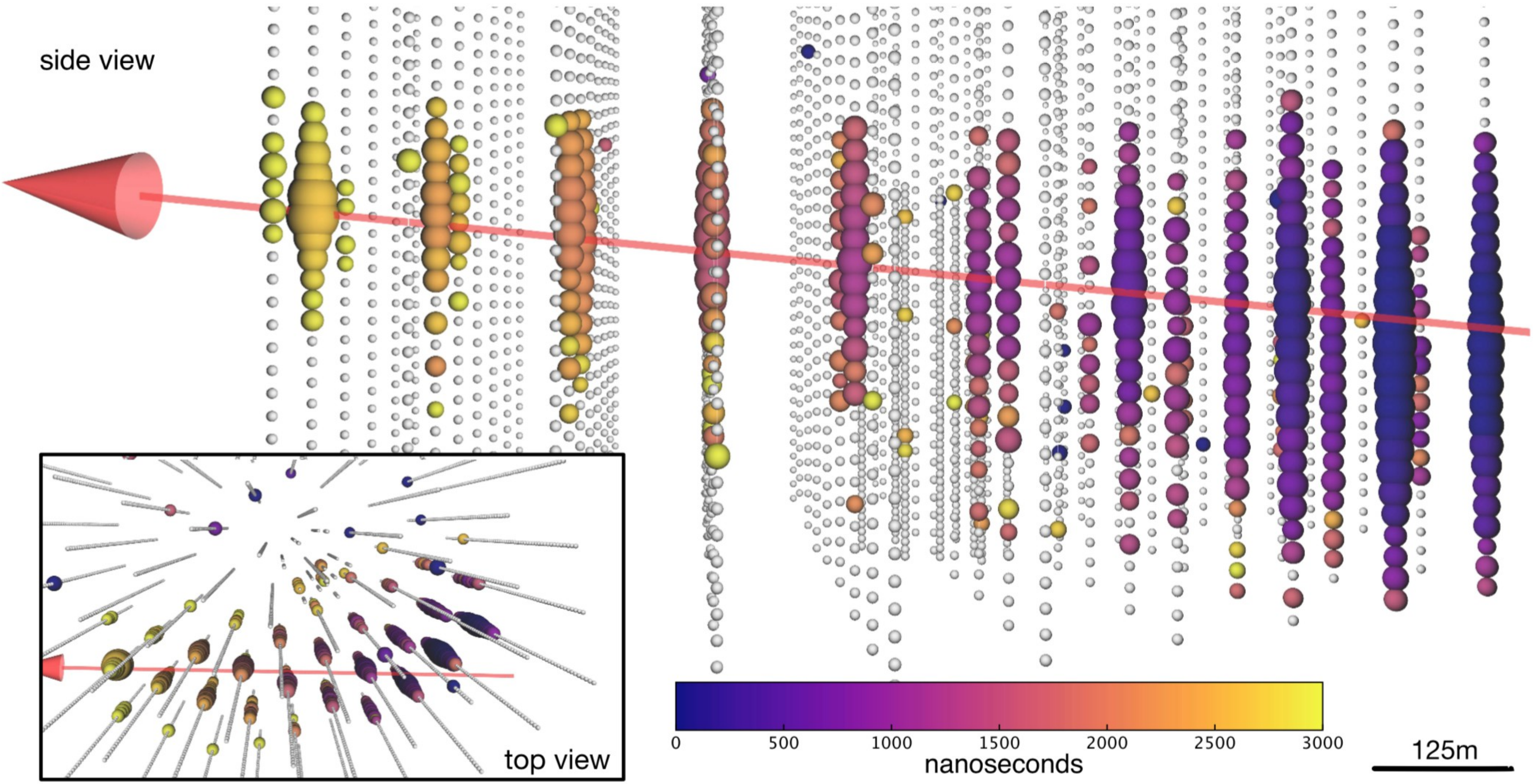
Marek Kowalski ICRC 2021 (IceCube highlight talk)

IceCube study of correlations with the FERMI 2LAC



Neutrinos from Blazars

22 /sept/ 2017



Icecube event

(Muon entering the detector)

E_{vis} = 23.7 +- 2.8 TeV

IceCube GCN 21916 23rd September 2017

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of  Maryland) report on behalf of the IceCube
Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical
origin. The event was identified by the  Extremely High Energy (EHE) track event selection. The IceCube detector was in a
normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon
that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the
candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica.
The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu
```

IceCube Automated alert 23rd September 2017

28th September Fermi-LAT GCN

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430

.... Great source of excitement ......

Texas Survey of Radio Sources [365 Mhz, (1974-1983)]
66841 sources [TXS .....]

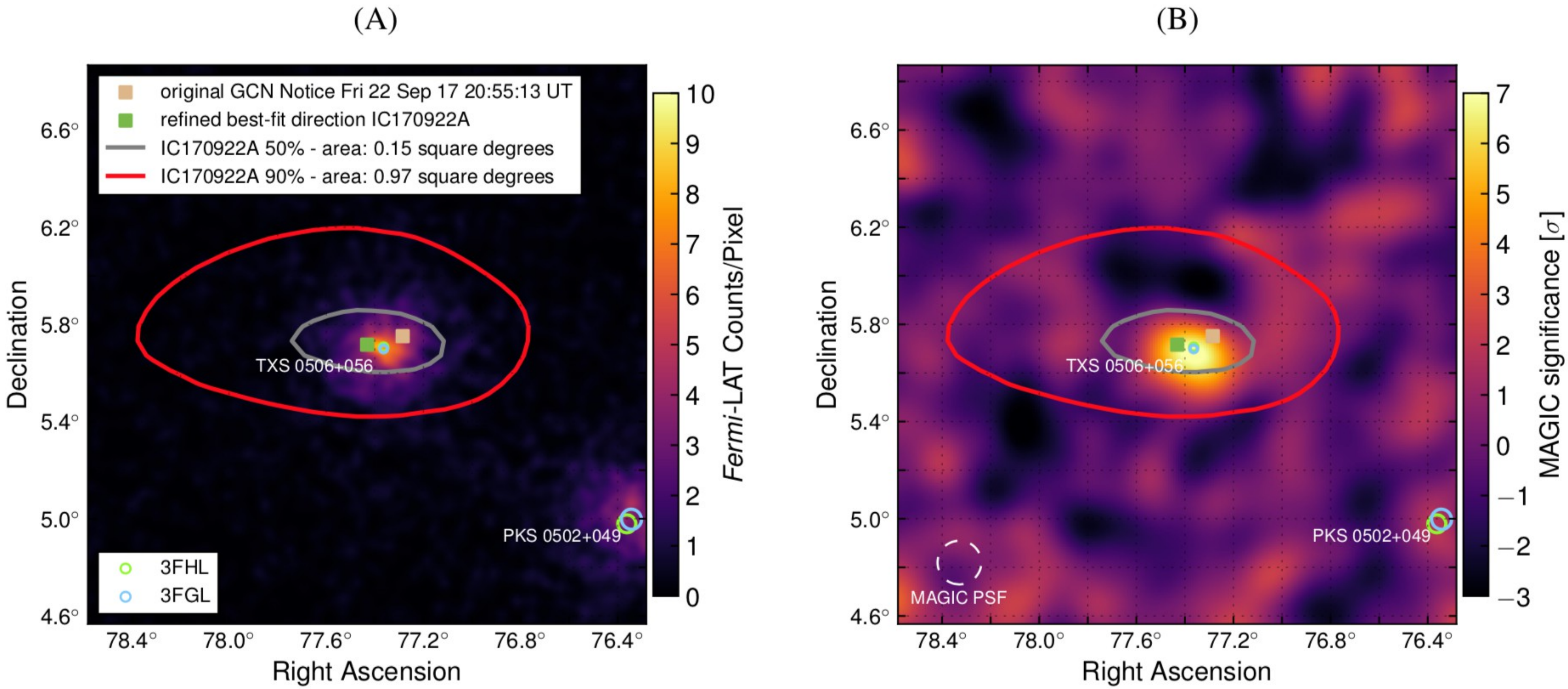
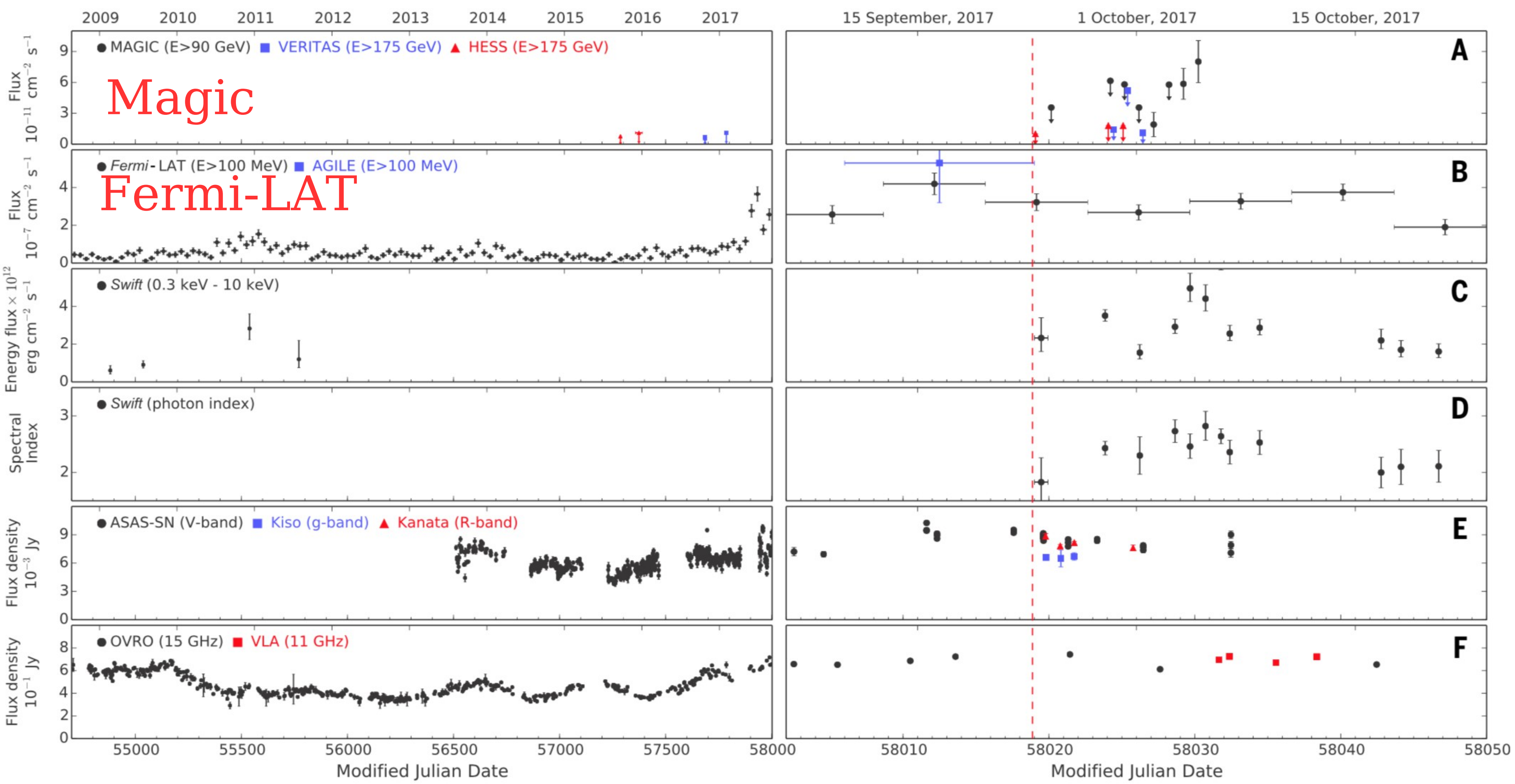
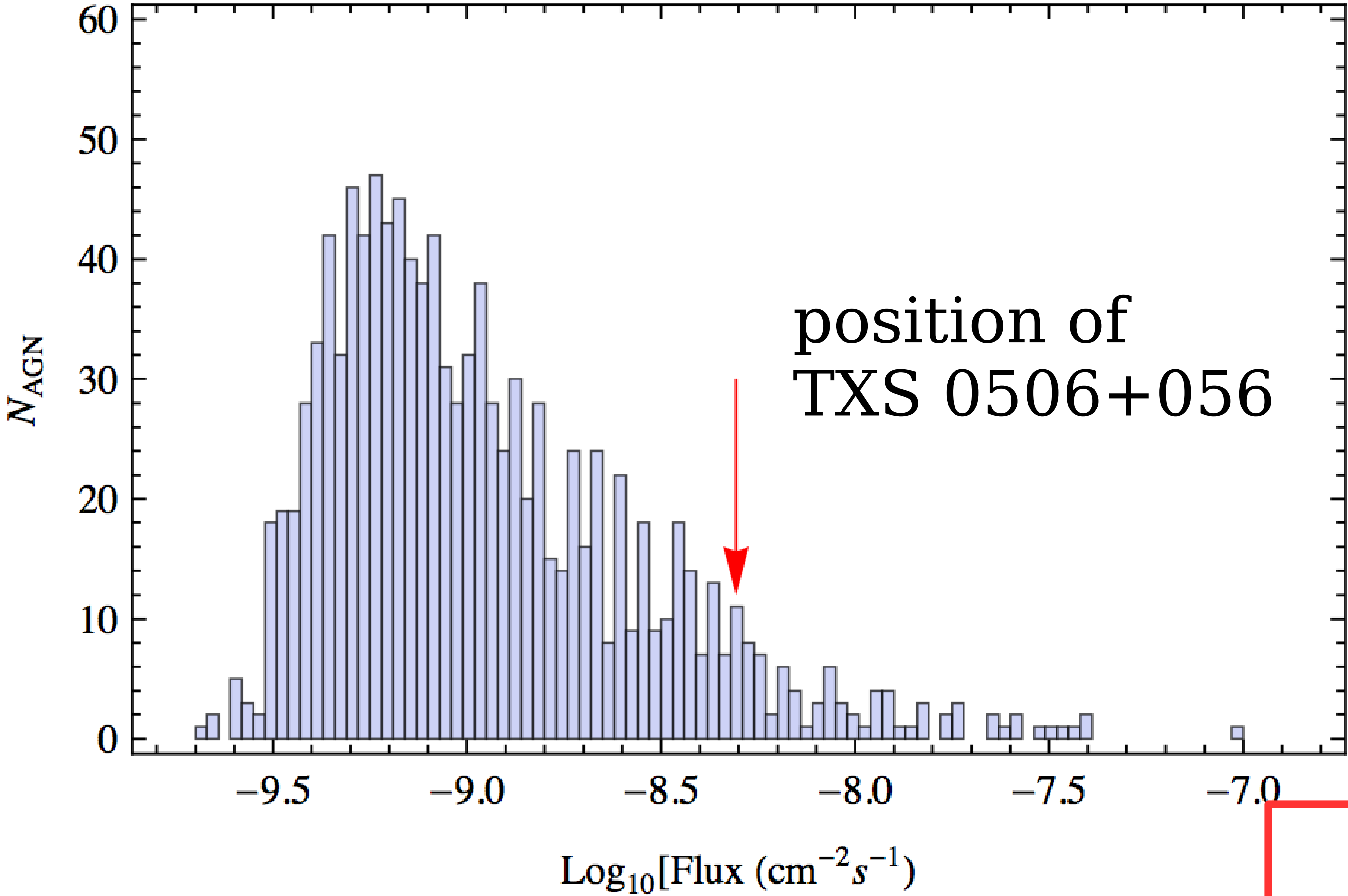


Figure 2: ***Fermi*-LAT and MAGIC observations of IceCube-170922A's location.** Sky position of IceCube-170922A in J2000 equatorial coordinates overlaying the γ-ray counts from *Fermi*-LAT above 1 GeV (A) and the signal significance as observed by MAGIC (B) in this region. The tan square indicates the position reported in the initial alert and the green square indicates the final best-fitting position from follow-up reconstructions (*18*). Gray and red curves show the 50% and 90% neutrino containment regions, respectively, including statistical and systematic errors. *Fermi*-LAT data are shown as a photon counts map in 9.5 years of data in units of counts per pixel, using detected photons with energy of 1 to 300 GeV in a 2° by 2° region around TXS0506+056. The map has a pixel size of 0.02° and was smoothed with a 0.02 degree-wide Gaussian kernel. MAGIC data are shown as signal significance for γ-rays above 90 GeV. Also shown are the locations of a γ-ray source observed by *Fermi*-LAT as given in the *Fermi*-LAT Third Source Catalog (3FGL) (*23*) and the Third Catalog of Hard *Fermi*-LAT Sources (3FHL) (*24*) source catalogs, including the identified positionally coincident 3FGL object TXS 0506+056. For *Fermi*-LAT catalog objects, marker sizes indicate the 95% C.L. positional uncertainty of the source.

Multi-wavelength Observations



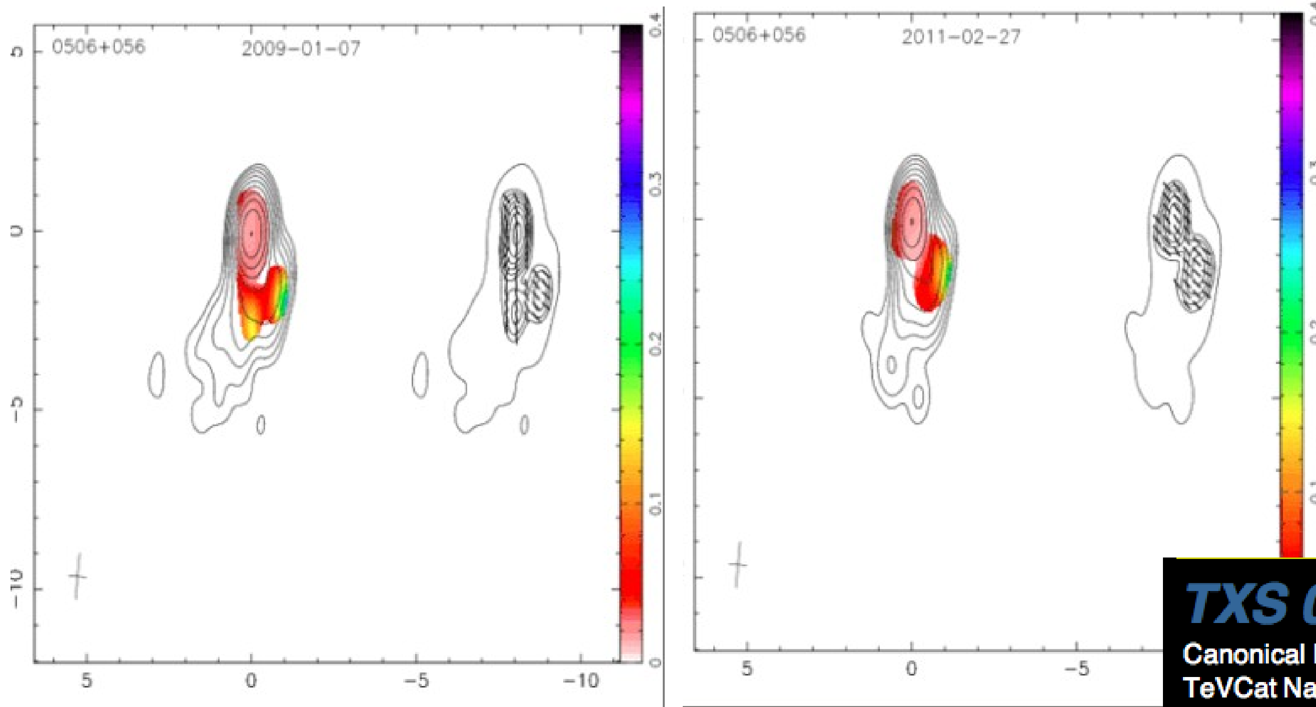


Bright Blazar
in the Fermi
Catalog

$$\alpha = 2.059 \pm 0.042$$

$$\Phi_\gamma[1 \div 100 \text{ GeV}] = 4.94 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$$

$$L(E) = \phi_\gamma(E) \times E^2 \simeq 4.5 \times 10^{45} \ \frac{\text{erg}}{\text{s}}$$



TXS 0506+056

VLBI
radio observations

$$z = 0.3365 \pm 0.0010$$

$$d = 706 \text{ Mpc}$$

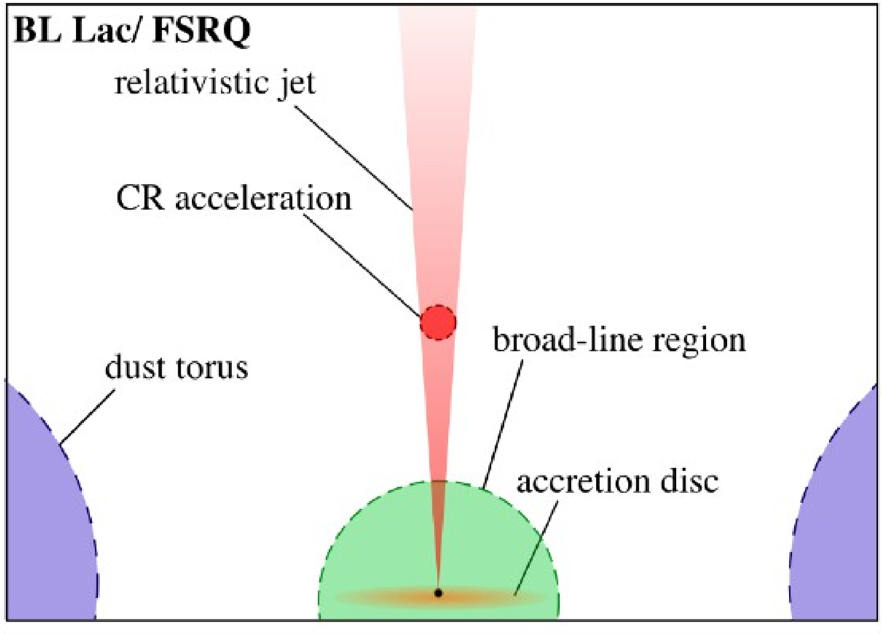
$$\dot{\Omega} = 332 \pm 82 \ \mu\text{as/year}$$

$$\beta_{\text{app}} = \frac{\dot{\Omega}\, d}{c} = 3.7 \pm 0.9$$

TXS 0506+056 SIMBAD

Canonical Name:	TXS 0506+056
TeVCat Name:	TeV J0509+056
Other Names:	EHE 170922A 3FGL J0509.4+0541 3FHL J0509.4+0542
Source Type:	Blazar
R.A.:	05 09 25.96370 (hh mm ss)
Dec.:	+05 41 35.3279 (dd mm ss)
Gal Long:	195.41 (deg)
Gal Lat:	-19.64 (deg)
Distance:	z=0.3365
Flux:	(Crab Units)
Energy Threshold:	100 GeV
Spectral Index:	
Extended:	No
Discovery Date:	2017-10
Discovered By:	MAGIC
TeVCat SubCat:	Newly Announced
Source Notes:	

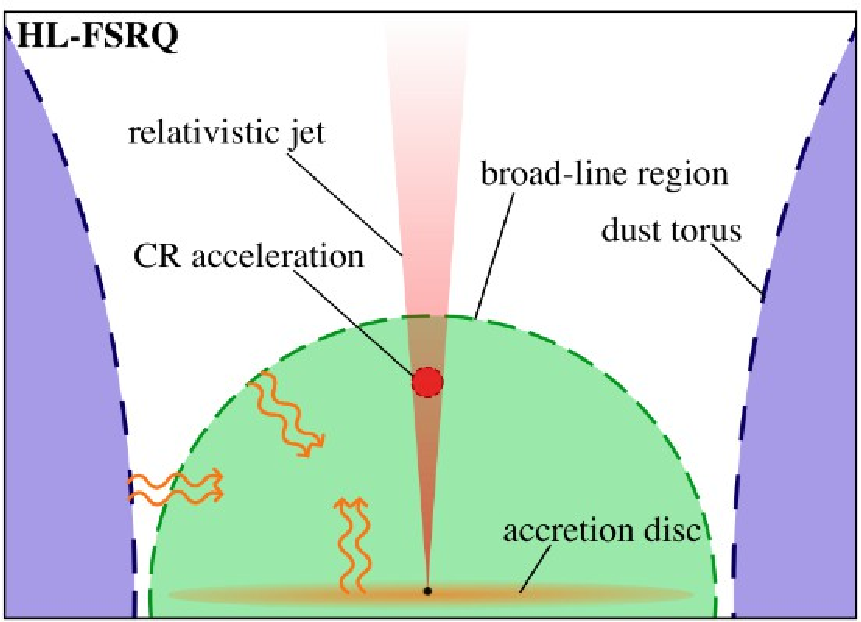
The blazar TXS 0506+056 lies within the error circle of IceCube-170922A, the IceCube high-energy neutrion candidate event whose detection was reported in GCN circular #21916. Follow-up observations were performed by a number of GeV-TeV instruments with both Fermi-LAT and MAGIC reporting evidence for gamma-ray emission from positions consistent with the IceCube neutrino error circle which they thus associate with the blazar TXS 0506+056. Upper limits on the gamma-ray emission from the region were reported by H.E.S.S, HAWC and VERITAS.

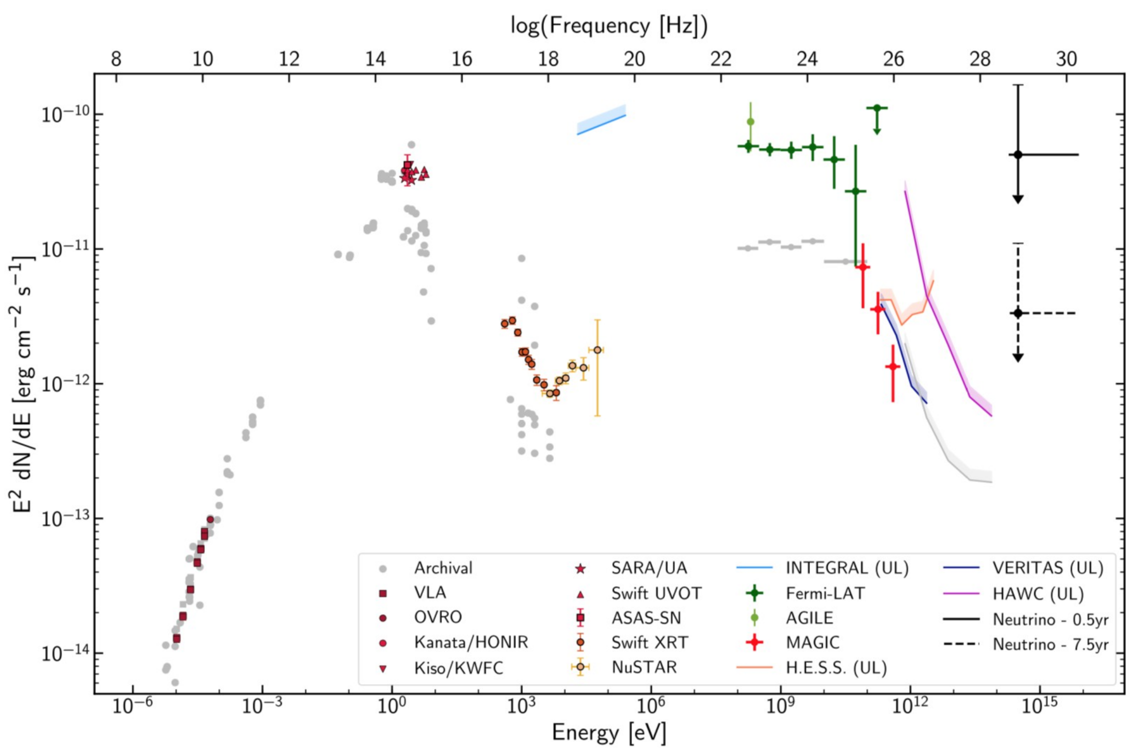


Modeling of
the flare

Electron +
proton acceleration

[Several papers]





Oscillations of Astrophysical Neutrinos

Expected flavor composition

[Standard mechanism of production]

$$\nu_e \simeq \nu_\mu \simeq \nu_\tau$$

Oscillation lengths:

$$L_{\rm osc}^{(12)} \simeq 108 \left(\frac{E}{10^{20}\ \rm eV}\right)\ \rm pc$$

short for astrophysical distances

$$L_{\rm osc}^{(23)} \simeq L_{\rm osc}^{(13)} \simeq 3.2 \left(\frac{E}{10^{20}\ \rm eV}\right)\ \rm pc$$

$$P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) = \left| \sum_j U_{\beta j} U^*_{\alpha j} \, e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2$$

$$= \sum_{j=1,3} |U_{\beta j}|^2 \, |U_{\alpha j}|^2$$

$$+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \cos\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

$$+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \sin\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

Space averaged
flavor transition probability

Neutrinos created in volume
of sufficiently large linear size

$$X_{\text{source}} \gg E / |\Delta m^2_{jk}|$$

Oscillating terms average to zero

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2$$

$$\simeq \begin{pmatrix} 1-2v & v & v \\ v & (1-v)/2 & (1-v)/2 \\ v & (1-v)/2 & (1-v)/2 \end{pmatrix} \simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

$$\theta_{13} \simeq 0$$

$$\theta_{23} \simeq 45^\circ$$

$$v = \cos^2\theta_{12}\sin^2\theta_{12} \simeq 0.2$$

$$\begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$\pi^+ \to \mu^+ \quad \nu_\mu$$

$$\hookrightarrow \quad e^+ \quad \nu_e \quad \overline{\nu}_\mu$$

"Standard mechanism"

$$\begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

much more "astrophysically plausible"

"Muon absorption"

Very high magnetic field

$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} v \\ (1-v)/2 \\ (1-v)/2 \end{pmatrix} \approx \begin{pmatrix} 0.2 \\ 0.4 \\ 0.4 \end{pmatrix}$$

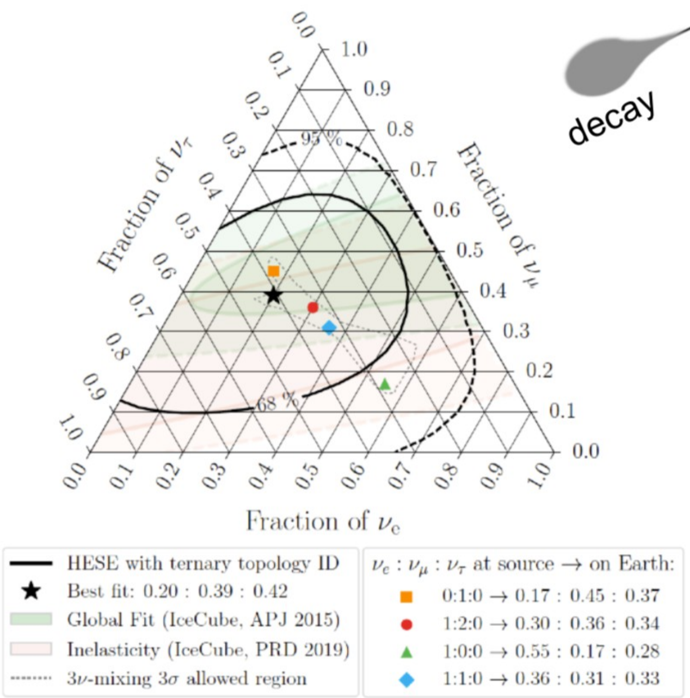
"Neutron decay"

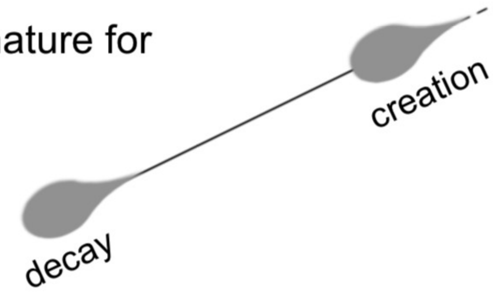
Nuclear fragmentation

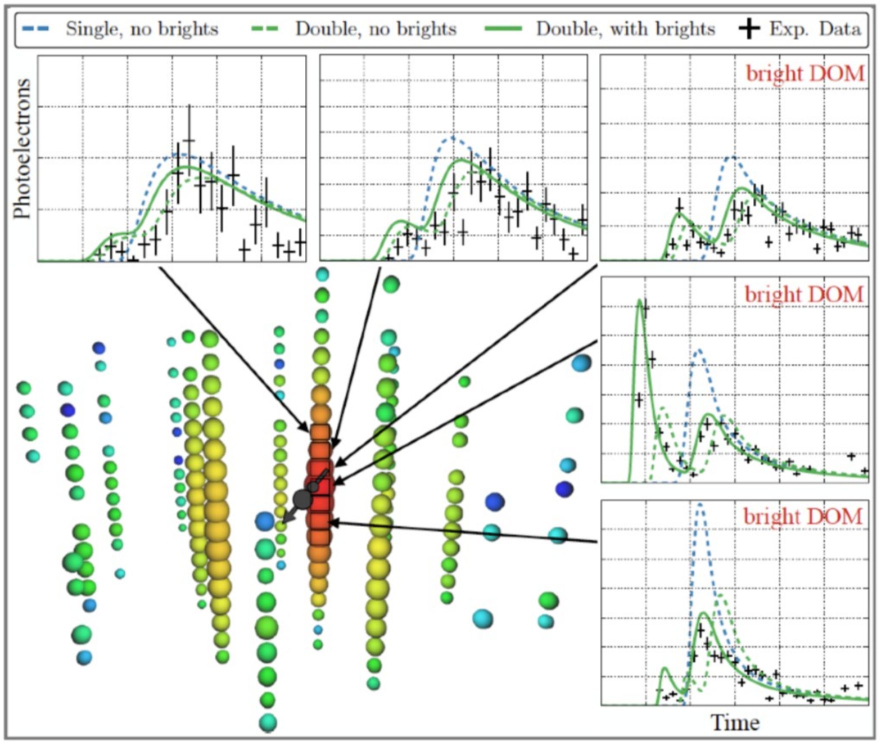
$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1-2\,v \\ v \\ v \end{pmatrix} \approx \begin{pmatrix} 0.6 \\ 0.2 \\ 0.2 \end{pmatrix}$$

First cosmic tau-neutrino event(s) candidate in IceCube

- First convincing "Double-Bang" event signature detected by IceCube
- Tau-neutrinos smoking gun signature for astrophysical origin







https://arxiv.org/abs/2011.03561
Also @ ICRC 2021: PoS ID 1146

Best Fit :
{e,mu,tau} = {0.20, 0.39, 0.42}

ICRC 2021

Studies of *PARTICLE PHYSICS* with very high energy Neutrinos

Very High Energy $\sim$ PeV

10^6 GeV

Very Long Path-length (extragalactic) $\sim$ Gpc

10^{27} cm

Very large (astrophysical) uncertainties about source spectra

Possibility of
"Modifications" of the neutrino flux
during propagation.

Investigate :
Flavor Oscillations
(with very long path-lengths)

[Pseudo-Dirac neutrinos
mass doublets with tiny
mass splitting]

$$z \simeq 1 \qquad \Delta m^2 \approx 10^{-18} \left(\frac{E}{100 \text{ TeV}} \right) \text{eV}^2$$

Neutrino Decay [with very long lifetimes]

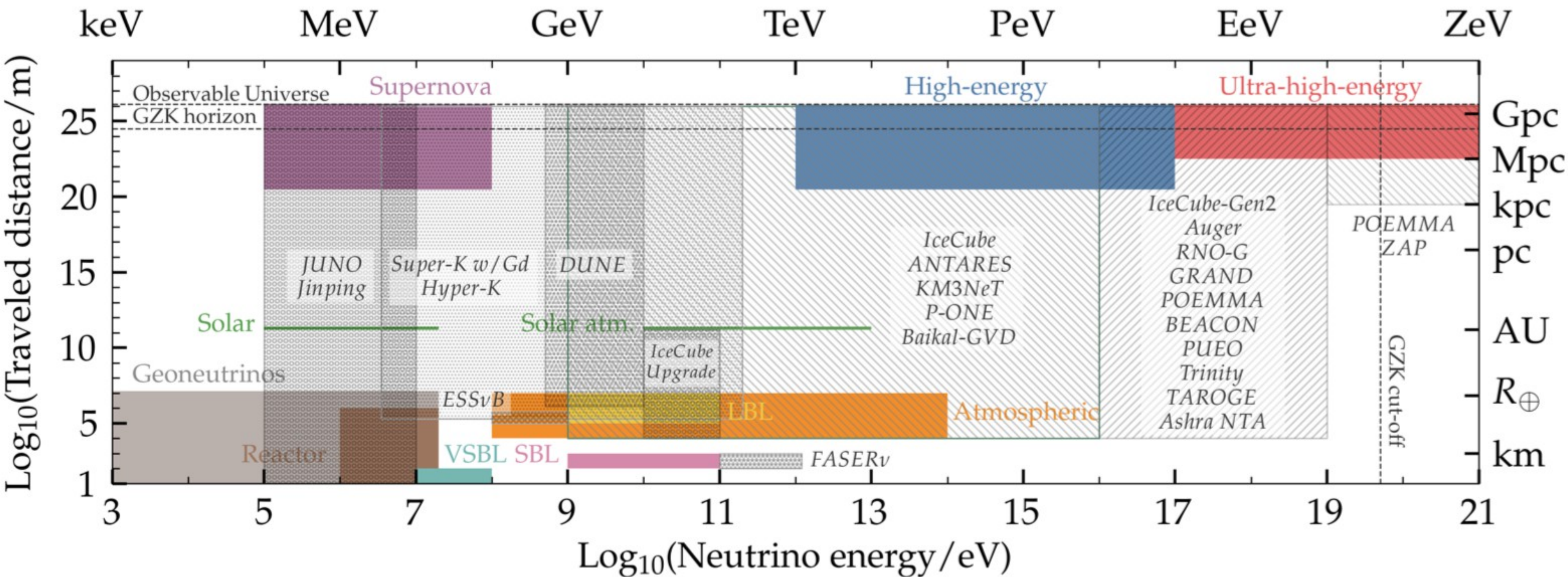
.... (9 orders of magnitude improvement)

Important difficulty:
Properties of the neutrinos at the source
must be sufficiently well understood.

New Physics effects

$$\propto k\ E^n\ L$$

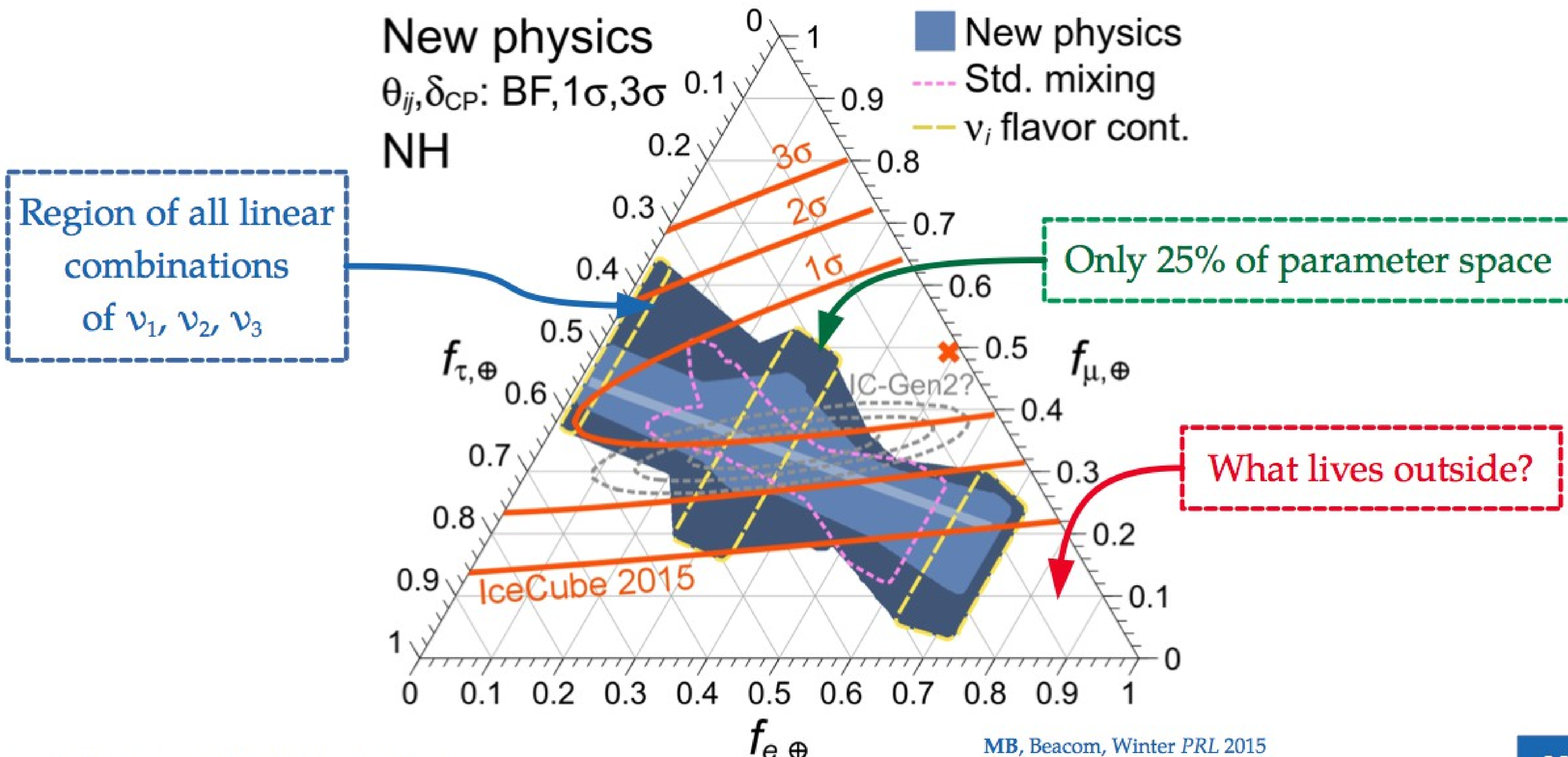
Study very favorable with Astrophysical Neutrinos



Cosmic Neutrino Probes of Fundamental Physics

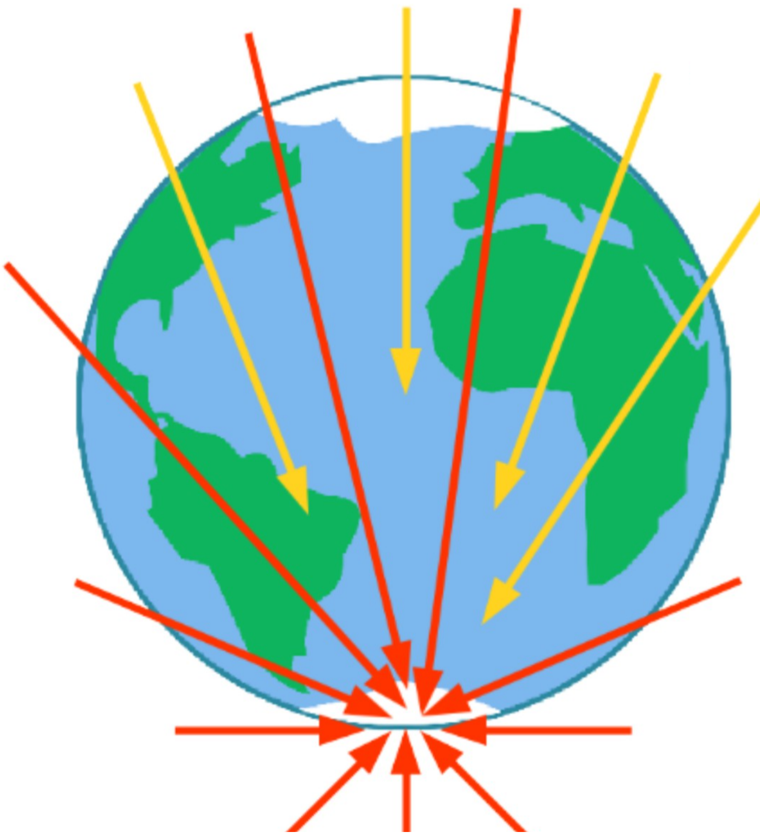
LoI Snowmass 2021

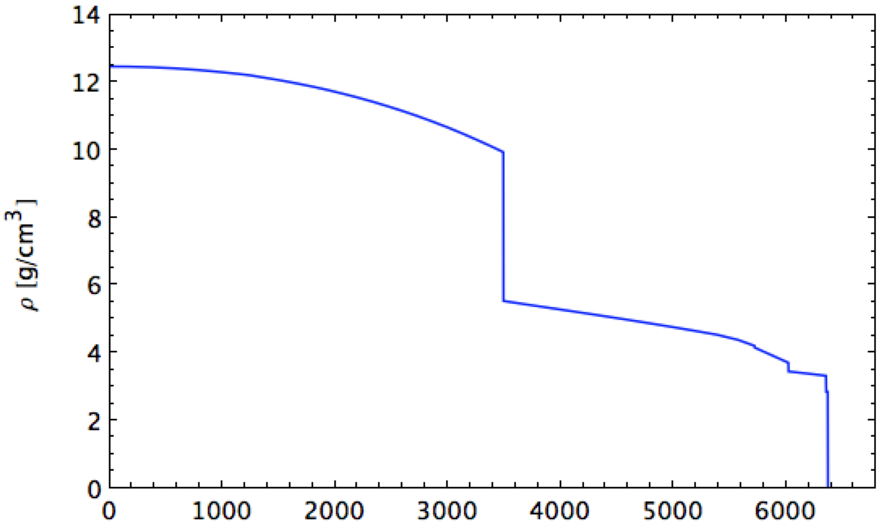
Flavor ratios accessible with decay-like physics



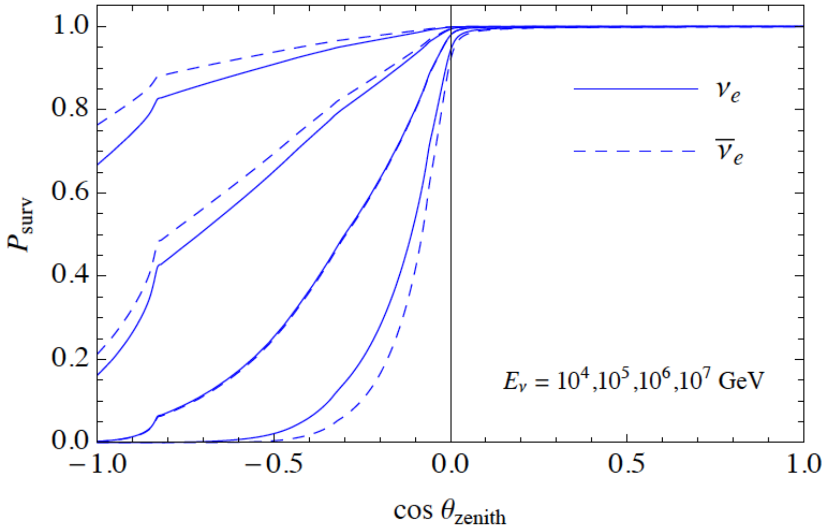
MB, Beacom, Winter *PRL* 2015

Measure Neutrino Cross section





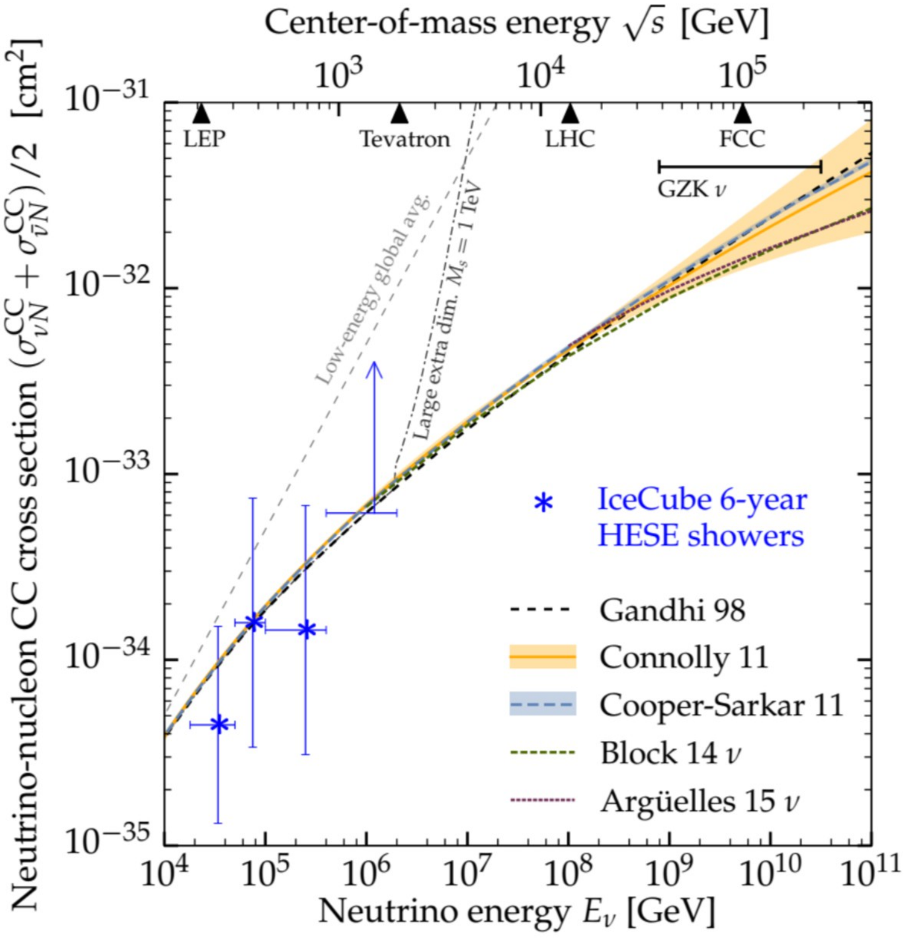
$$P_{\rm surv} = e^{-\tau(E,\Omega)}$$

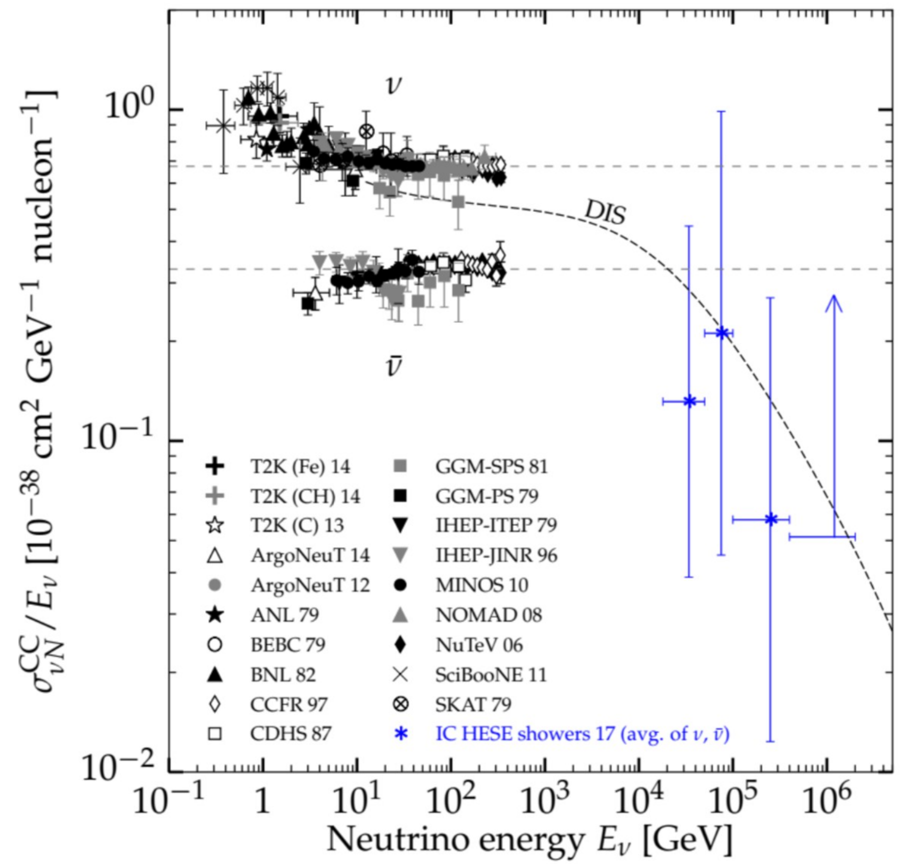


$$\tau = \frac{X}{m_p}\,\sigma_\nu$$

$$\frac{X_\oplus}{m_p} \simeq 6.5\ {\rm nb}^{-1}$$

$$\tau = 1 \Longleftrightarrow E \simeq 40\ {\rm TeV}$$





Neutrino Cross section as a function of energy

$$\frac{\sigma(E_\nu)}{E_\nu}$$

COSMOGENIC NEUTRINOS

Intimately related to UHECR

Study the Redshift dependence
(and the composition)
of the source of UHECR

COSMIC RAYS

Space and time integrated average of particles generated by many sources in the Galaxy and in the universe, *also shaped by propagation effects*.

Measurement at single point, and (effectively) single time.

[slow time variations, geological record carries some information]

Spectra nearly (but not exactly !) perfectly isotropic

$$\phi(E, \Omega) \simeq \phi(E)$$

Measurements of **Cosmic Rays**

as Messengers at the Earth:

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\ \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

$$\phi_{e^-}(E,\Omega)$$

electrons

$$\phi_{e^+}(E,\Omega)$$

$$\phi_{\overline{p}}(E,\Omega)$$

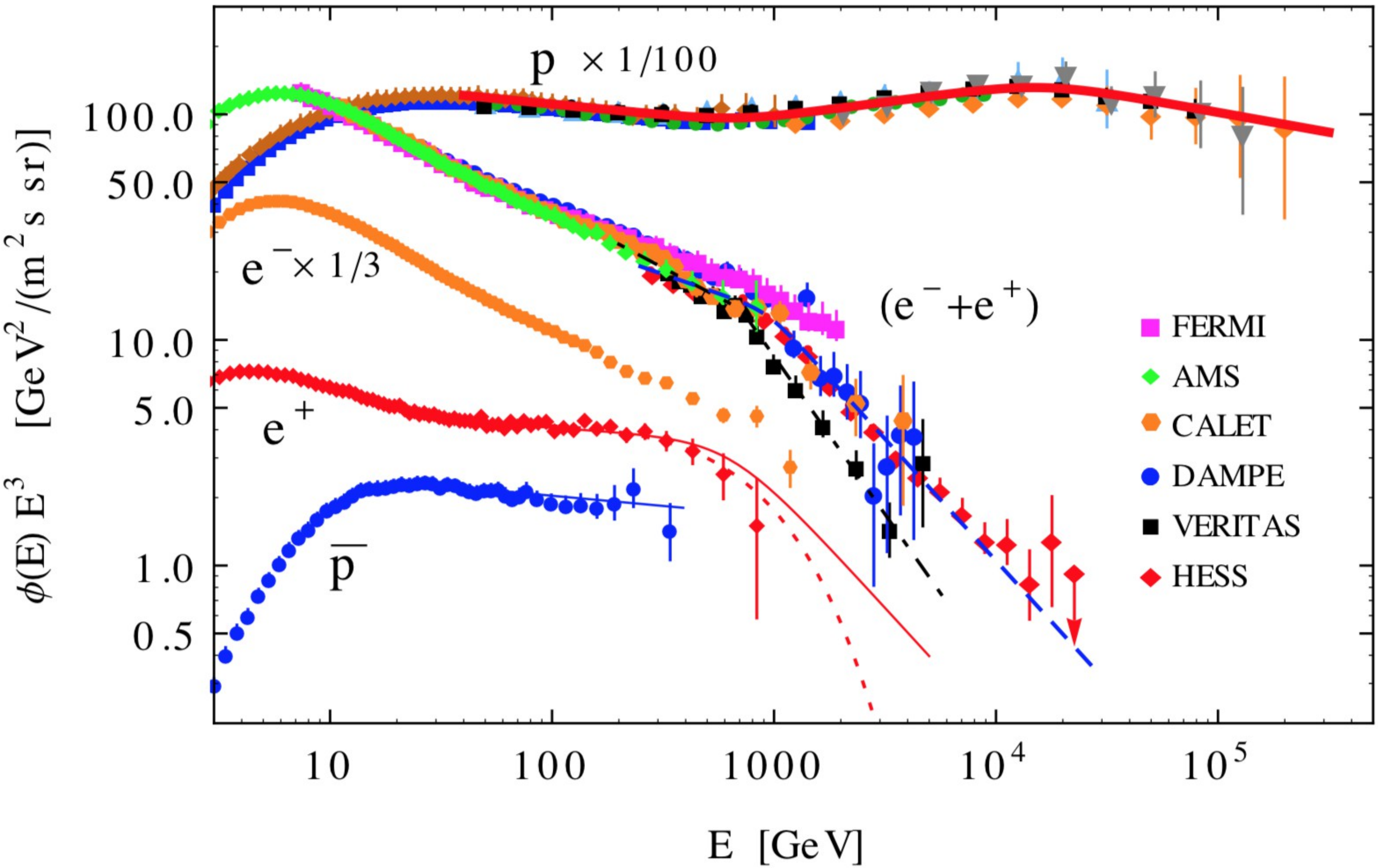
anti-particles

Precision measurements of the
Cosmic Ray Spectra [*at the Earth!*]

$p \quad e^-$

$\bar{p} \quad e^+$

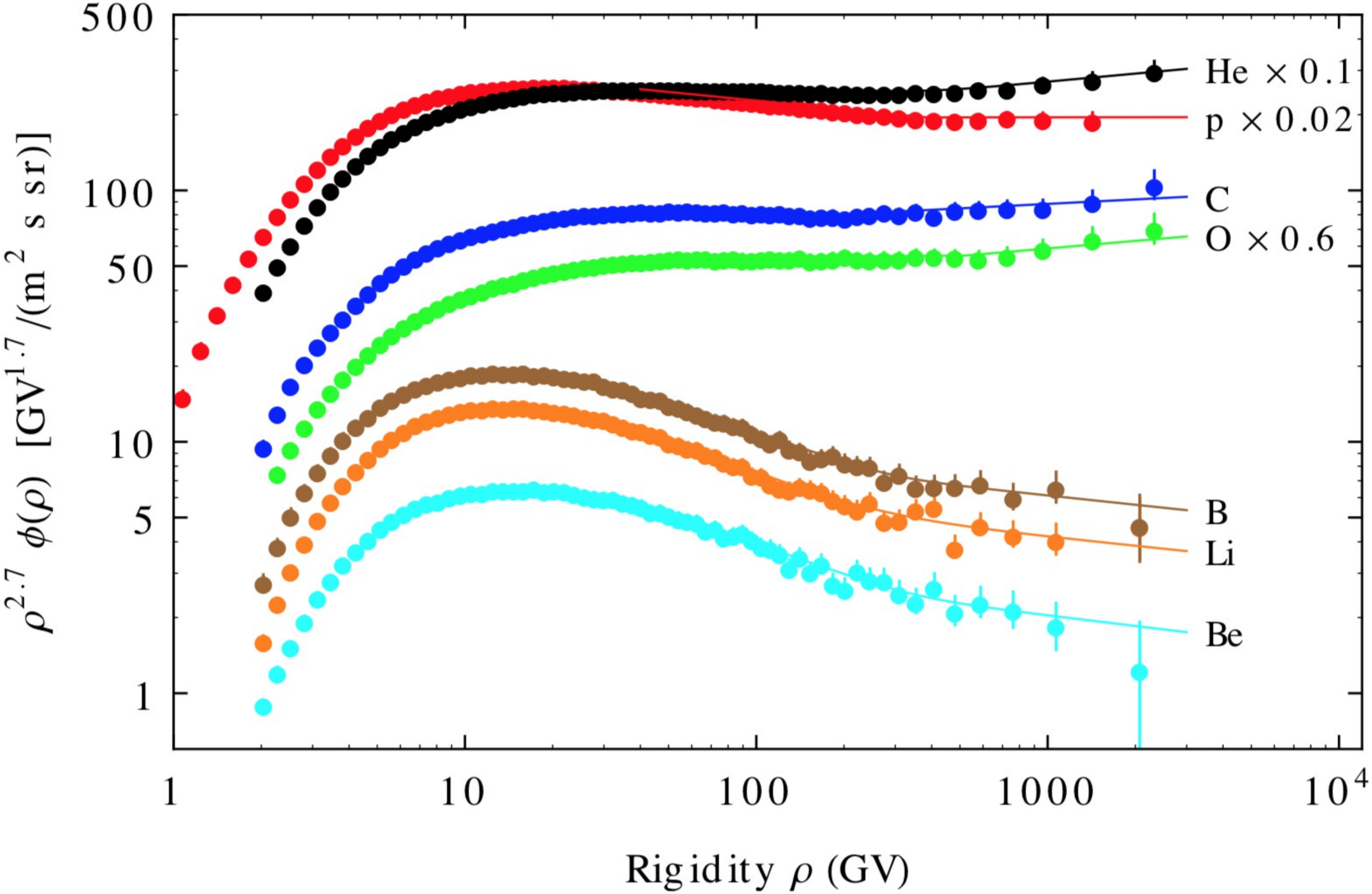
Why these spectral shapes ?



Precision measurements of the Cosmic Ray Spectra [*at the Earth!*]

p
He
C, O
Li, Be, B

Nuclei (AMS02)



Observable fluxes: Source Spectra + Propagation

$$\phi_j(E, \vec{x}, t)$$

$$q_j(E, \vec{x}, t)$$

Flux of particles of type j

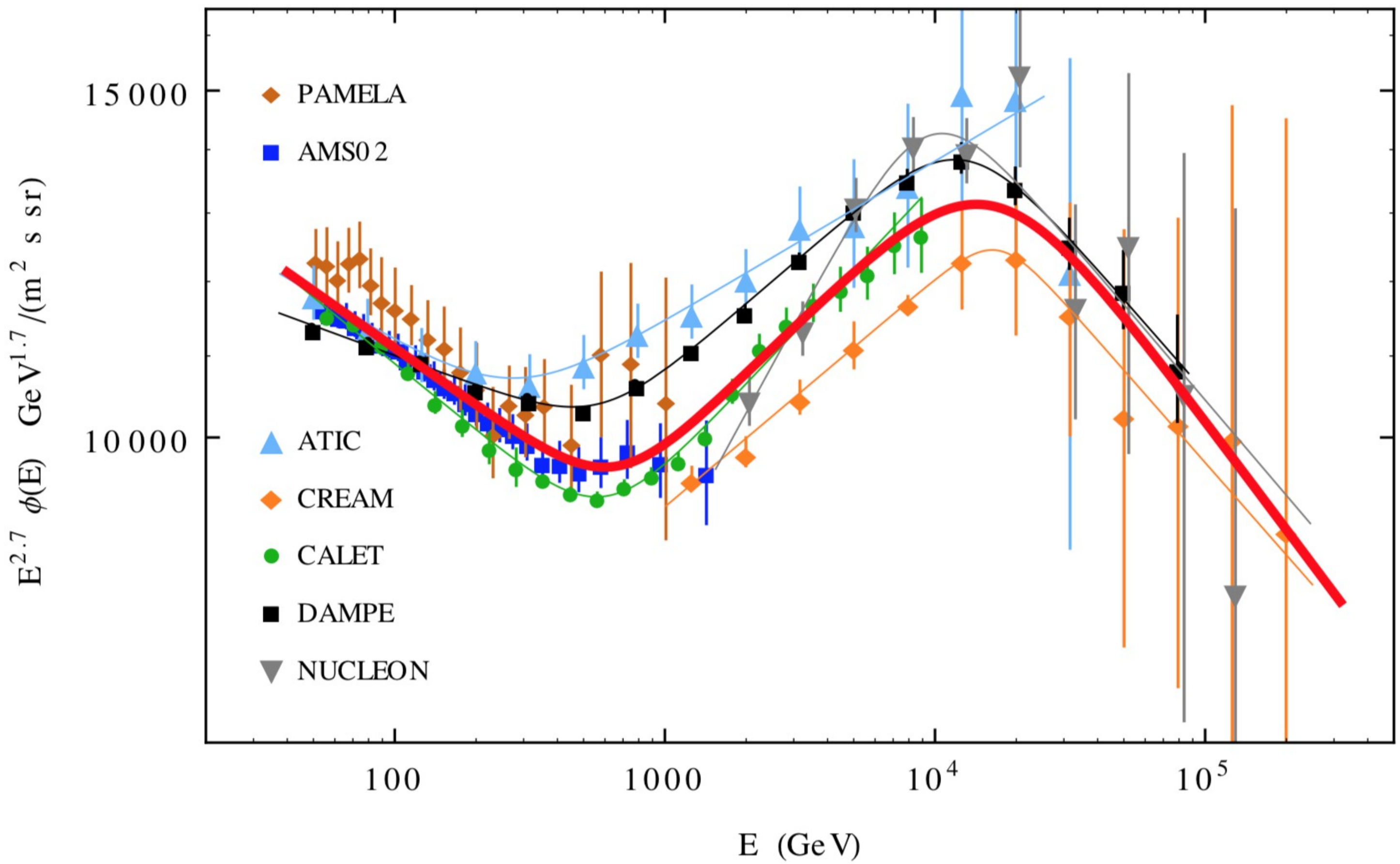
Source spectrum of particles of type j

$j \in \{p\ ,\ e^-\ ,\ e^+\ ,\ \overline{p}\ ,\ {}^3\mathrm{He}\ ,\ {}^4\mathrm{He}\ ,\ {}^6\mathrm{Li}\ ,\ \ldots\}$

$$\phi_j = q_j \otimes \mathcal{P}_j$$

$$[\mathrm{Flux}]_j = [\mathrm{Source\ spectrum}]_j \otimes [\mathrm{Propagation}]_j$$

The origin of the
Power-Law Spectra of Cosmic Rays
(and its deviations)



Global fit to to the CR proton flux [PL + Silvia Vernetto astro-ph/1911.01311]

In my opinion:

Understanding the shapes of the CR spectra
in the 1-GeV 10-TeV range is a fundamental problem
and there are several important questions open.

Is there a "non-standard" positron source

How are electrons accelerated ?

How CR propagate in the Galaxy ?

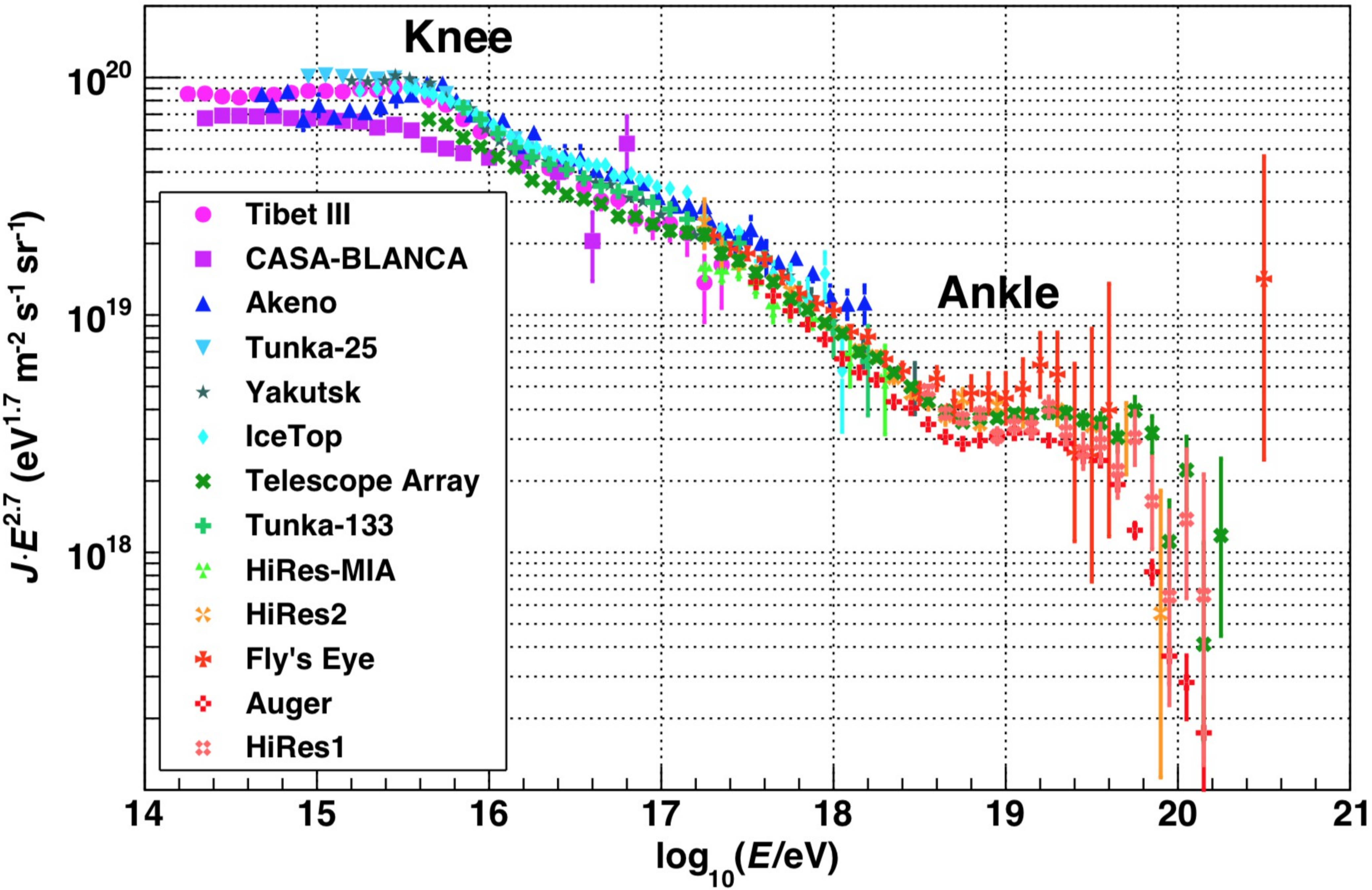
Connection between energy ranges

"Low energy" [GeV-TeV]

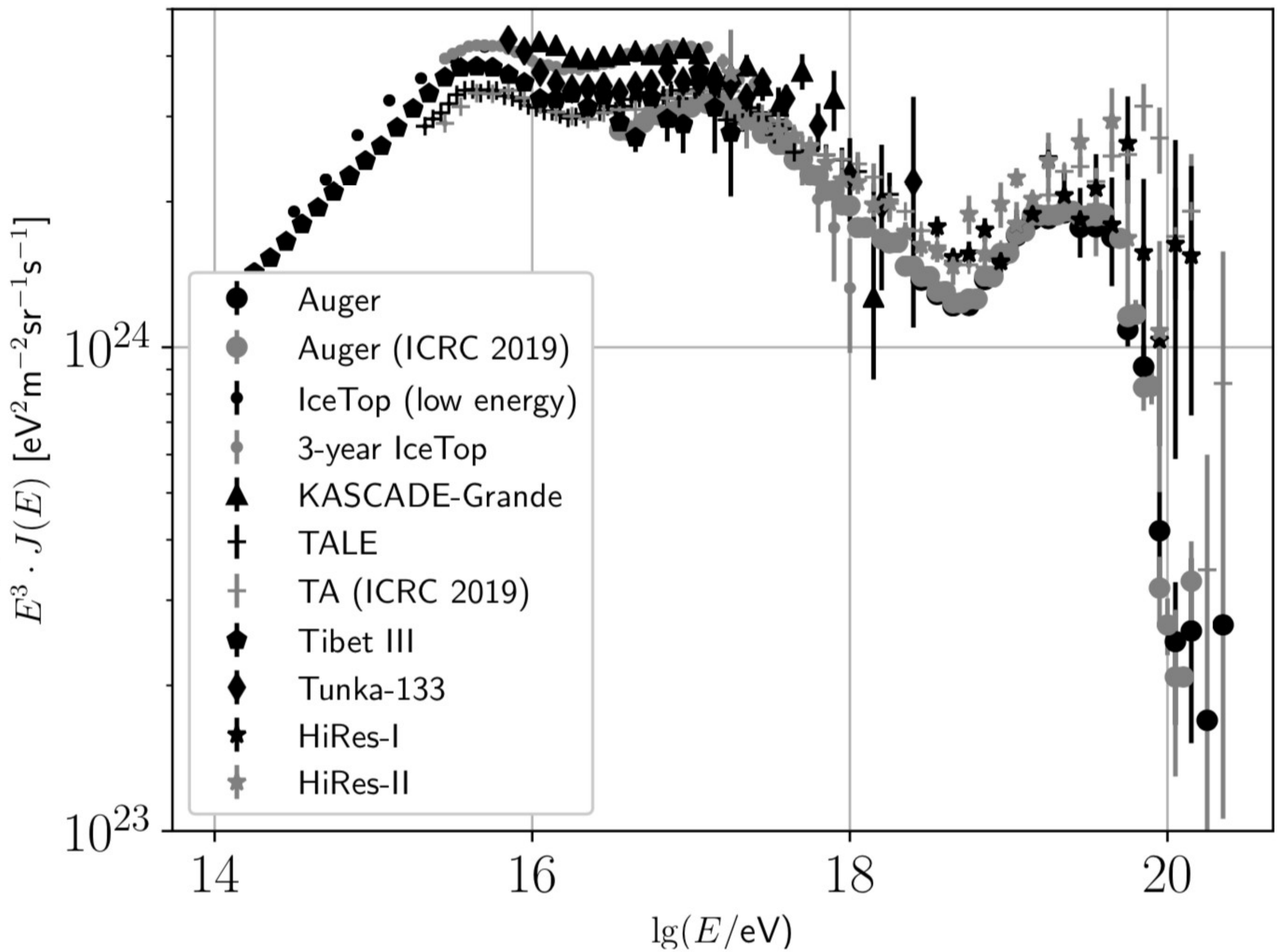
"High Energy" [PeV]

"Ultra High Energy" [EeV]

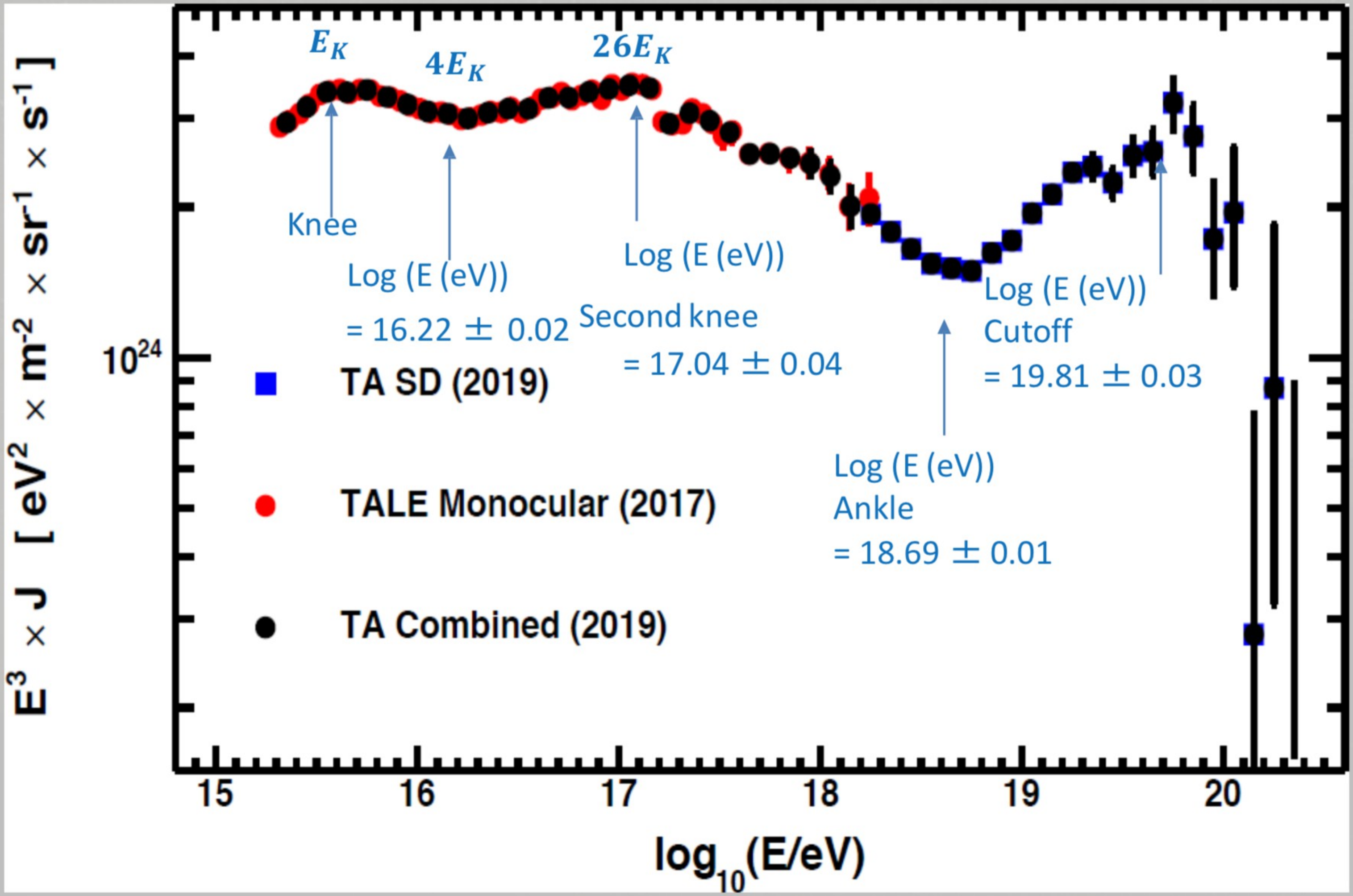
High energy all-particle CR spectrum *EAS measurements*



Cosmic Ray Spectra at High Energy (E >100 TeV) measured by Air Shower Experiments



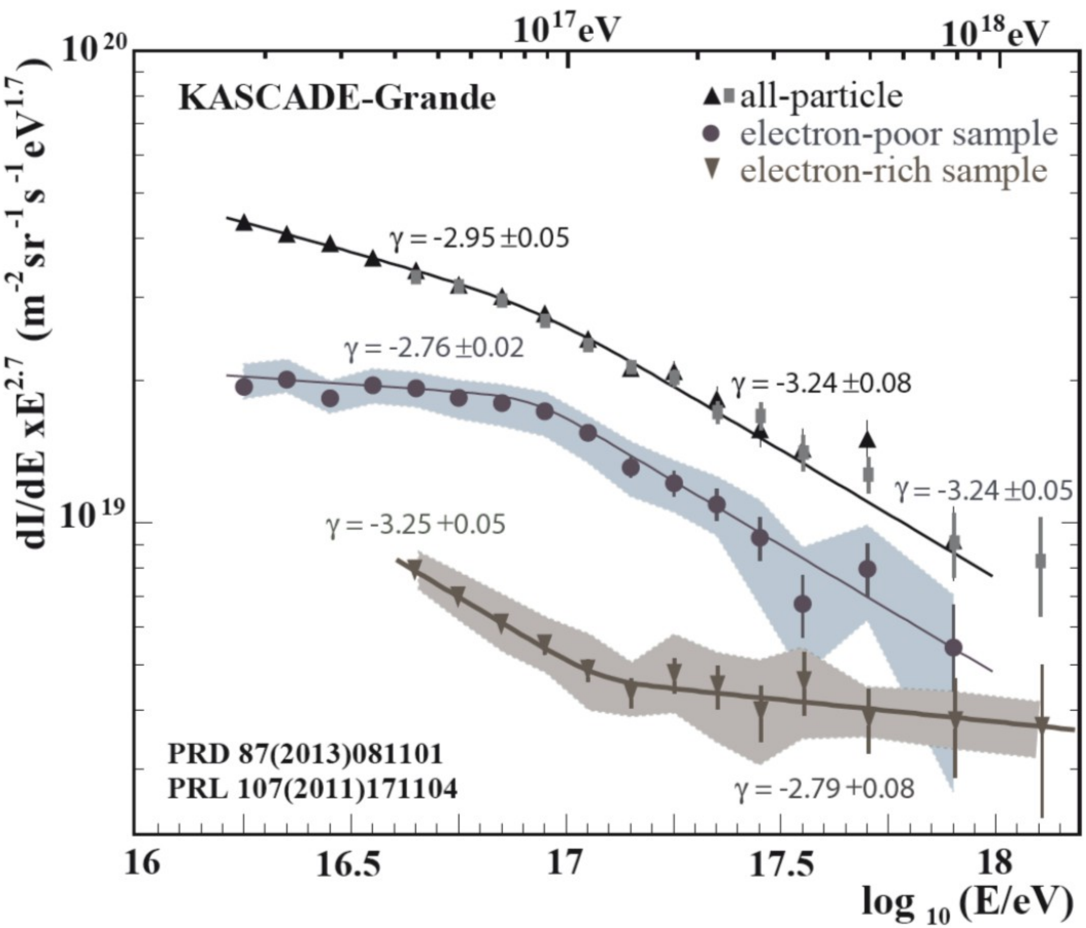
Combined Energy Spectrum



Combined TA spectrum using 22 months TALE FD monocular data + 11 years TA SD data

Telescope Array + TALE (ICRC2021)

KASCADE-Grande
energy spectra of mass groups

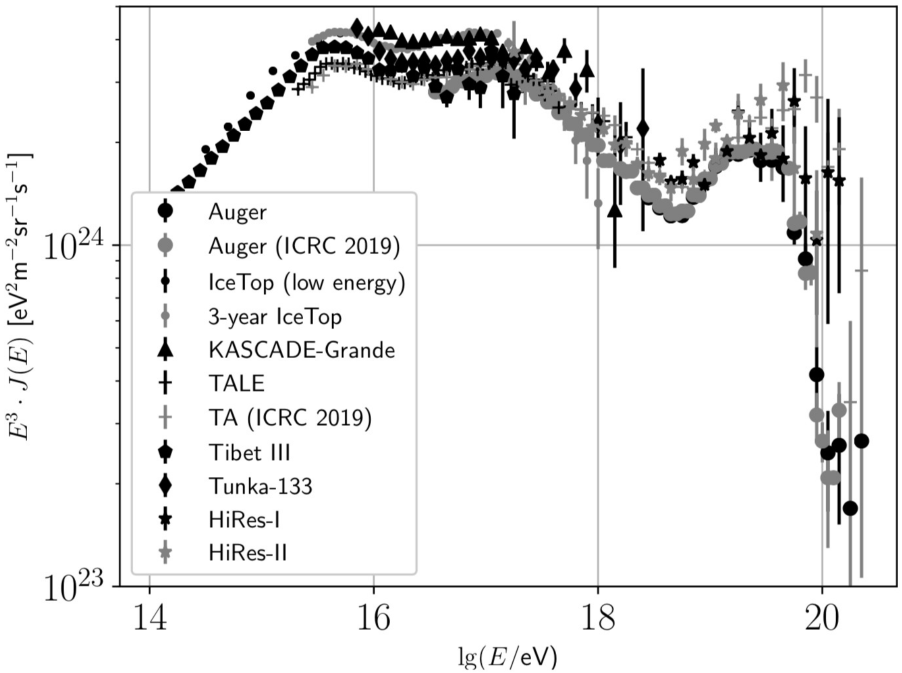


- **steepening due to heavy primaries (3.5σ)**
- **hardening at $10^{17.08}$ eV (5.8σ) in light spectrum**
- **slope change from $\gamma = -3.25$ to $\gamma = -2.79$!**

Phys.Rev.Lett. 107 (2011) 171104
Phys.Rev.D (R) 87 (2013) 081101

Structures in the High Energy CR Spectrum

1.	The "KNEE"	$\log_{10}[E(\mathrm{eV})] \simeq 15.5$
2.	"Low energy Ankle"	≈ 16.3
2a.	The "Iron Knee" of Kascade Grande	16.92 ± 0.08
2b.	The "proton (+Helium) Ankle"	17.08 ± 0.05
3.	The "Second Knee"	17.6 ± 0.2
4.	The "ANKLE"	18.6
5.	The UHECR suppression	19.4–19.8



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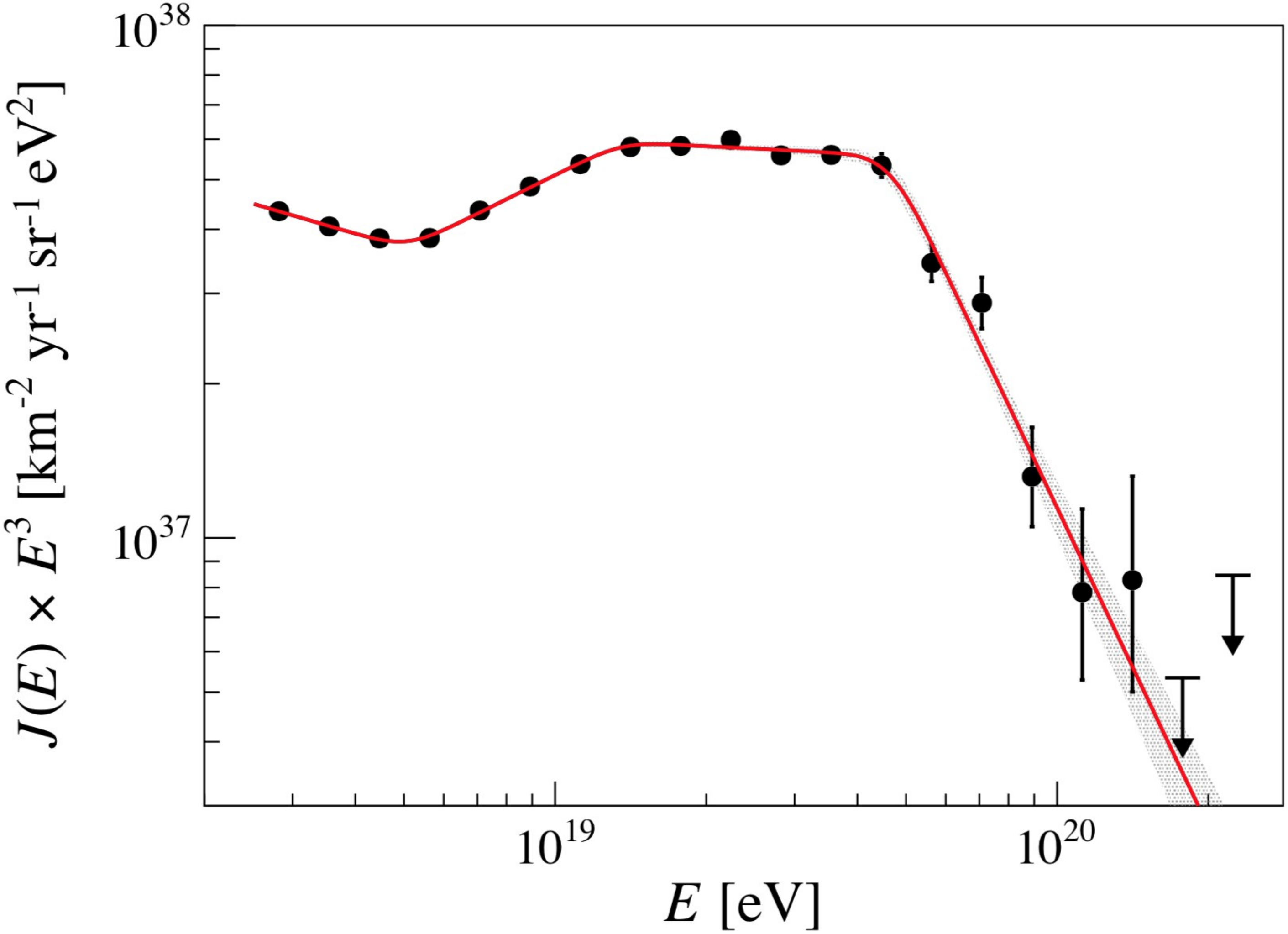
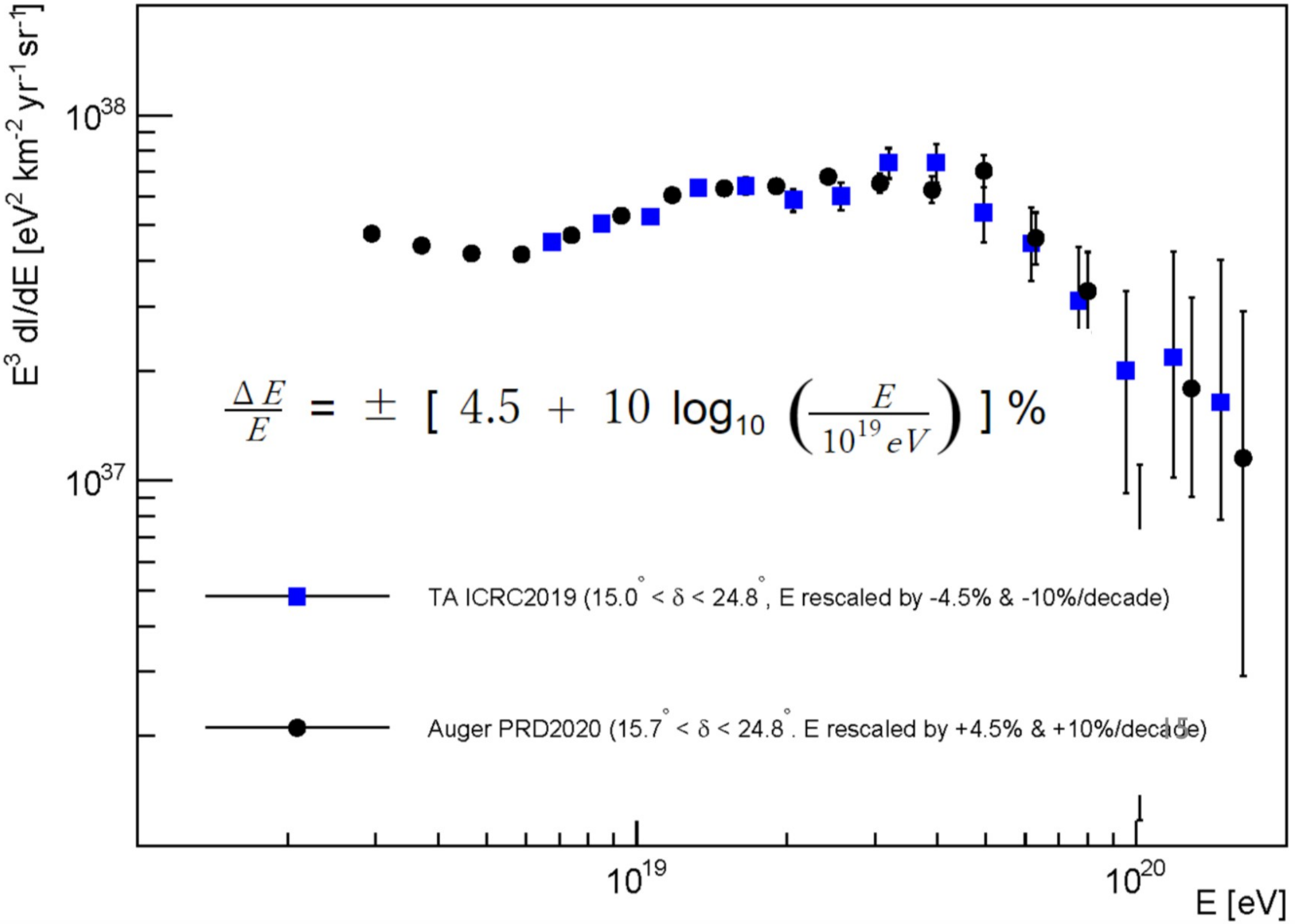


Auger PRD 2020

$$J(E) = J_0 \left(\frac{E}{10^{16}\ \text{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}, j = i + 1$$

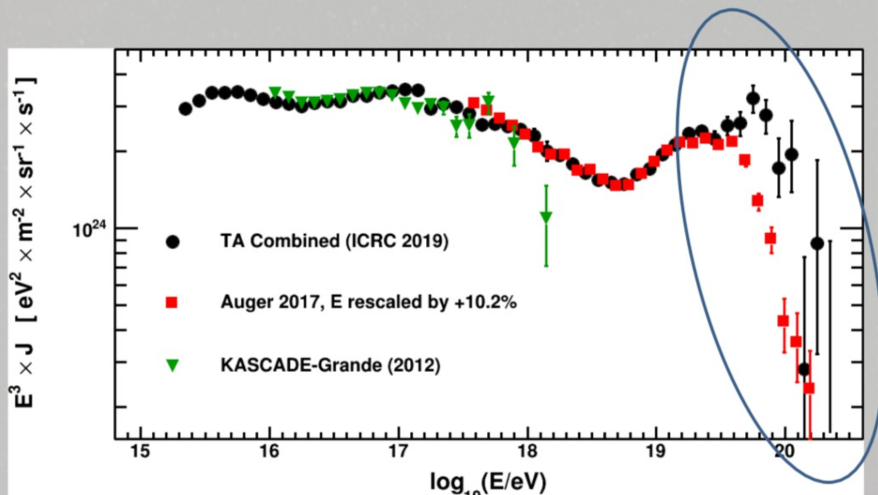
parameter	value $\pm\sigma_{\text{stat.}} \pm \sigma_{\text{sys.}}$
J_0 [km^{-2}sr^{-1}yr^{-1}eV^{-1}]	$(1.315 \pm 0.004 \pm 0.400)\times10^{-18}$
γ_1	$3.29 \pm 0.02 \pm 0.10$
γ_2	$2.51 \pm 0.03 \pm 0.05$
γ_3	$3.05 \pm 0.05 \pm 0.10$
γ_4	$5.1 \pm 0.3 \pm 0.1$
E_{12} [eV] (ankle)	$(5.0 \pm 0.1 \pm 0.8)\times10^{18}$
E_{23} [eV]	$(13 \pm 1 \pm 2)\times10^{18}$
E_{34} [eV] (suppression)	$(46 \pm 3 \pm 6)\times10^{18}$
D/n_{dof}	17.0/12

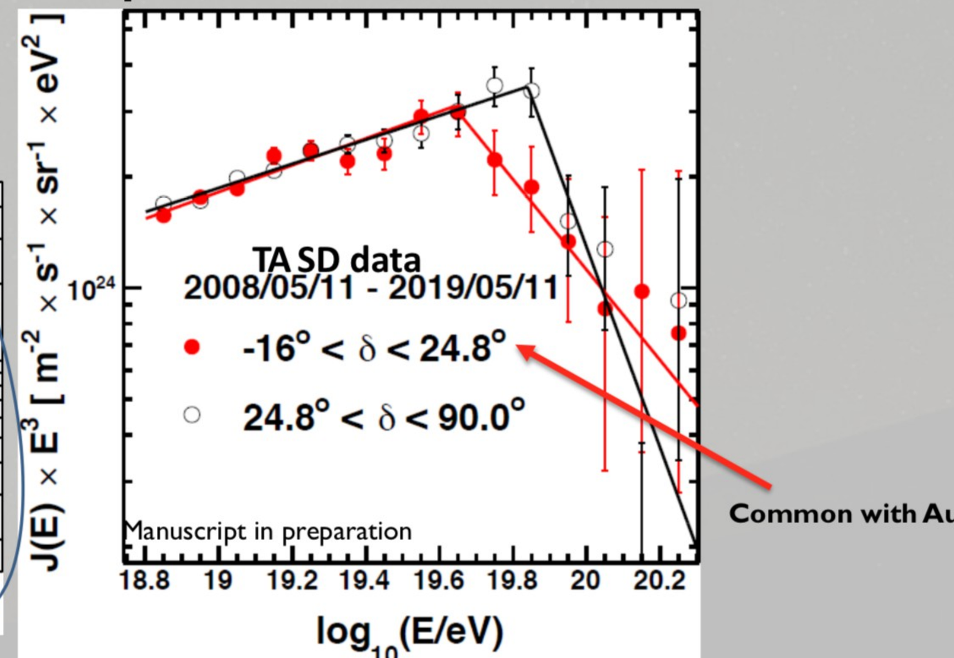


Energy Spectra of Auger and Telescope Array after rescaling *(in the common sky region)*

Very good agreement

Declination Dependence of Spectrum





- Difference of the cutoff energies of energy spectra
  - log(E/eV) = 19.64 ± 0.04 for lower dec. band (-16° - 24.8°)
  - log(E/eV) = 19.84 ± 0.02 for higher dec. band (24.8° - 90°)
- The global significance of the difference is estimated to be **4.3σ**

Dmitry Ivanov, this conference

ICRC 2021

27

Telescope Array Possile Anisotropy effect [...?...]

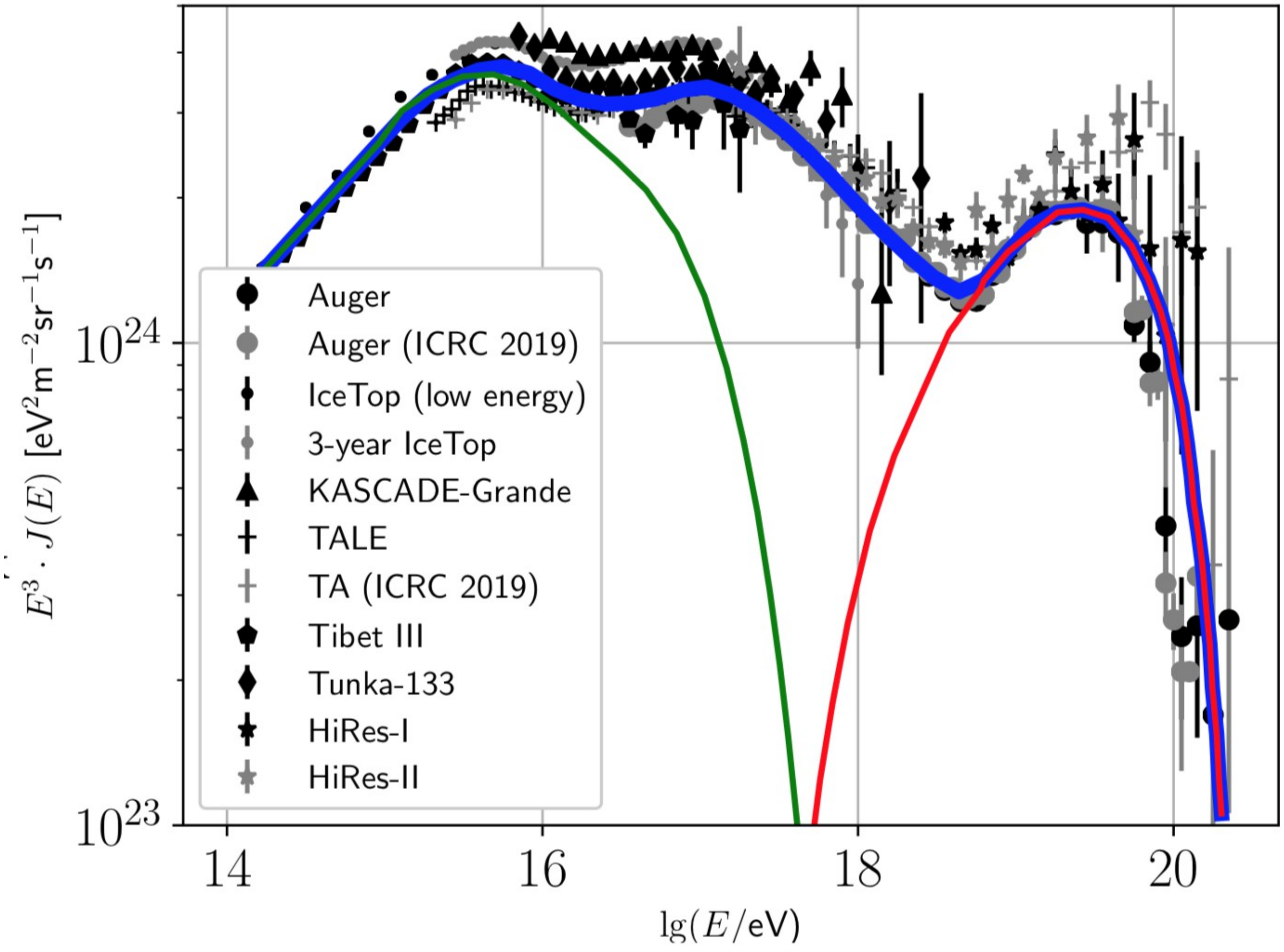
The Nature of the "KNEE" in the Cosmic Ray Spectrum

Accelerator feature
[Maximum energy of acceleration.
implies that all accelerators are similar]

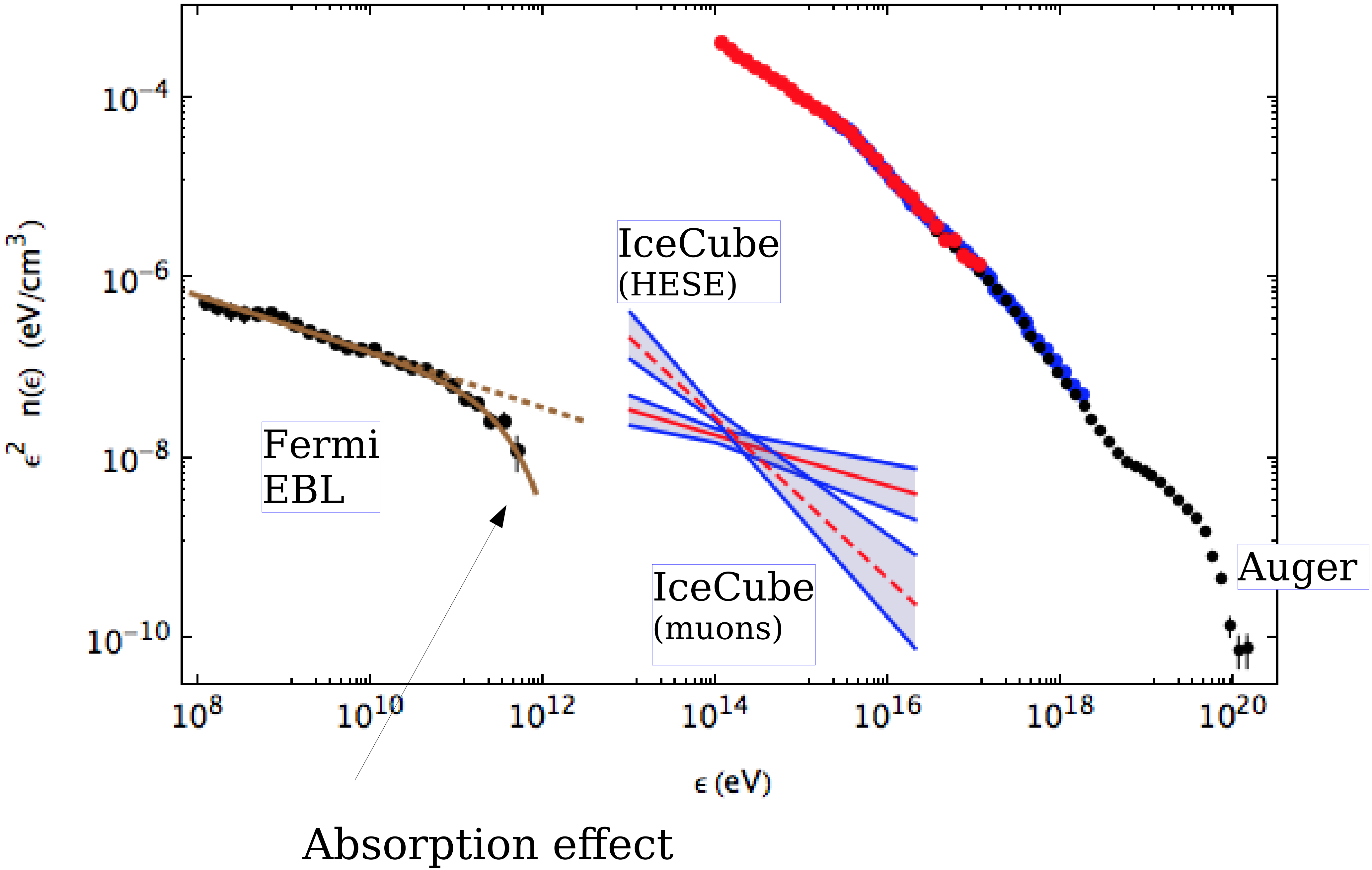
Structure generated by propagation
[implies that the (main) Galactic CR accelerators must be capable to accelerate to much higher energy]

Alex Kääpä

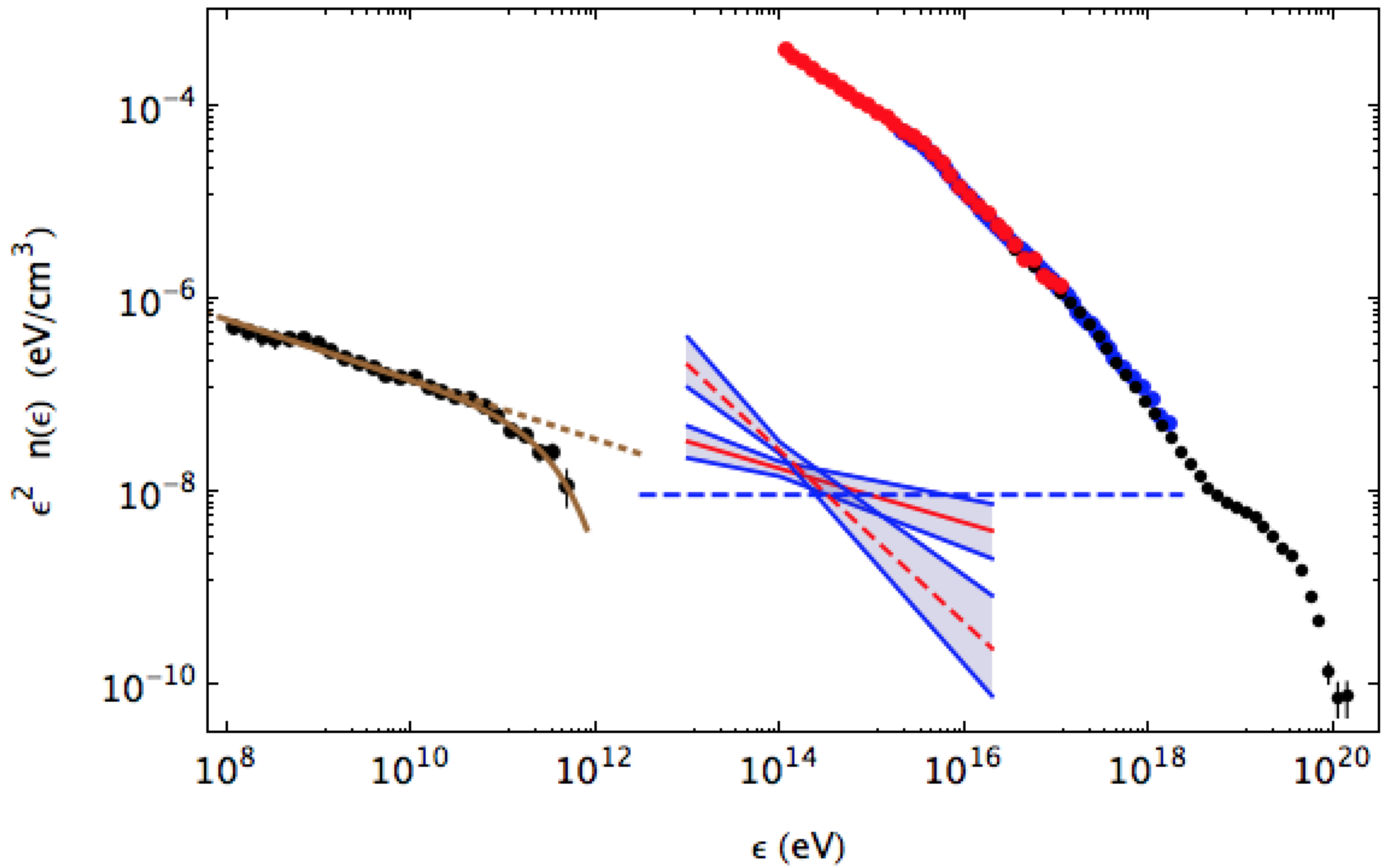
Highlight talk at ICRC2021
"On the transition between Galactic and extragalactic cosmic rays"



Galactic *unexplained* extragalactic



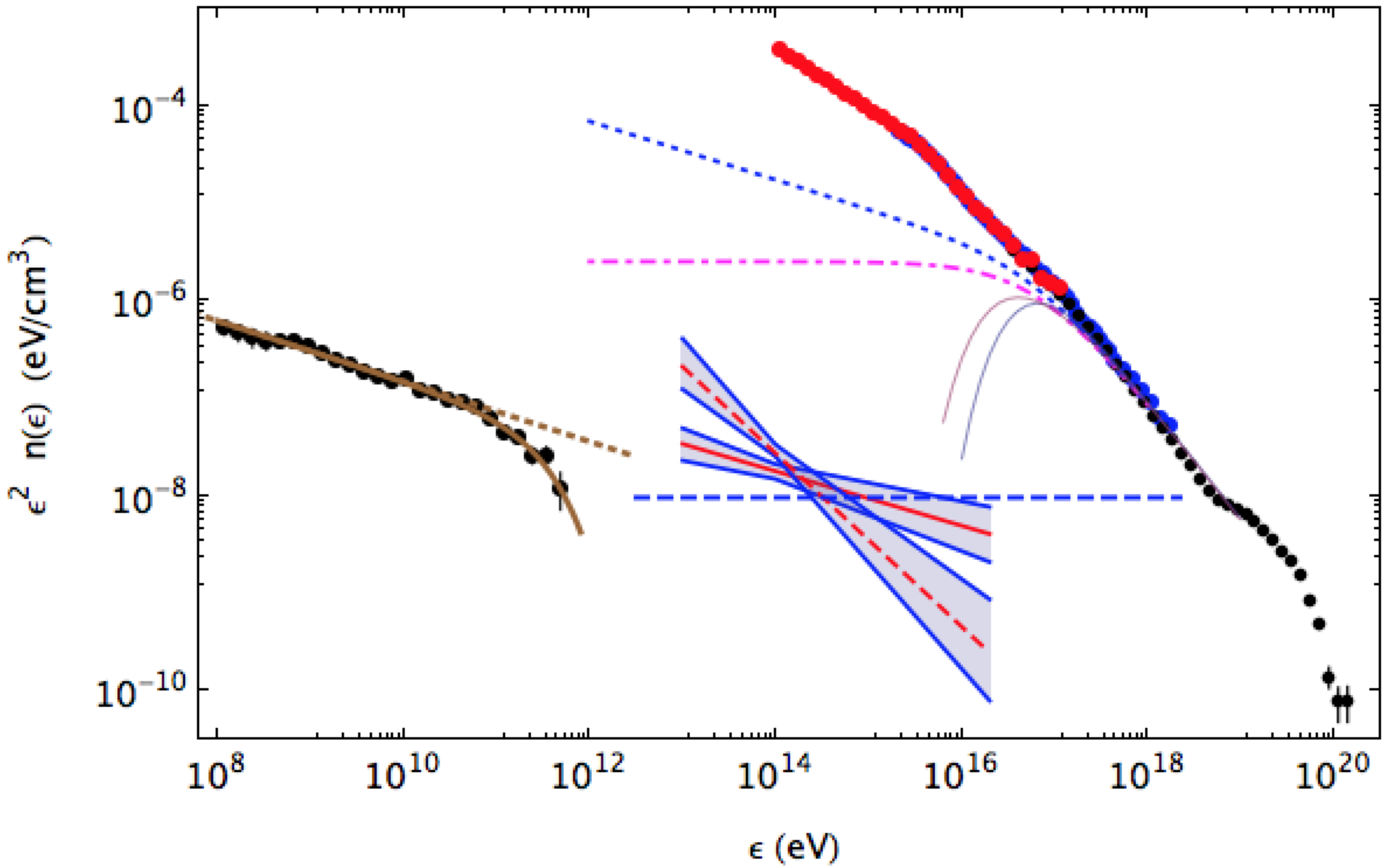
IceCube
(HESE)
Fermi
EBL
IceCube
(muons)
Auger
$\epsilon^2\ n(\epsilon)\ (\mathrm{eV/cm^3})$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
ϵ (eV)
Absorption effect



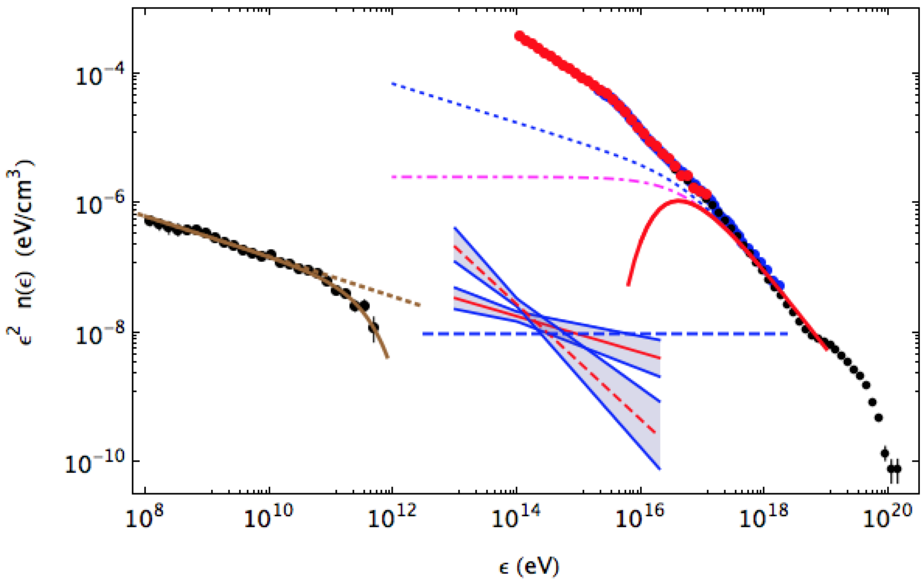
Line: Waxman-Bahcall (1998) extragalactic proton flux
[+ "bound" on extragalactic neutrinos]

Assumptions: 1. Transition Galactic/extra-galactic at the Ankle

2. Spectrum $\propto E^{-2}$

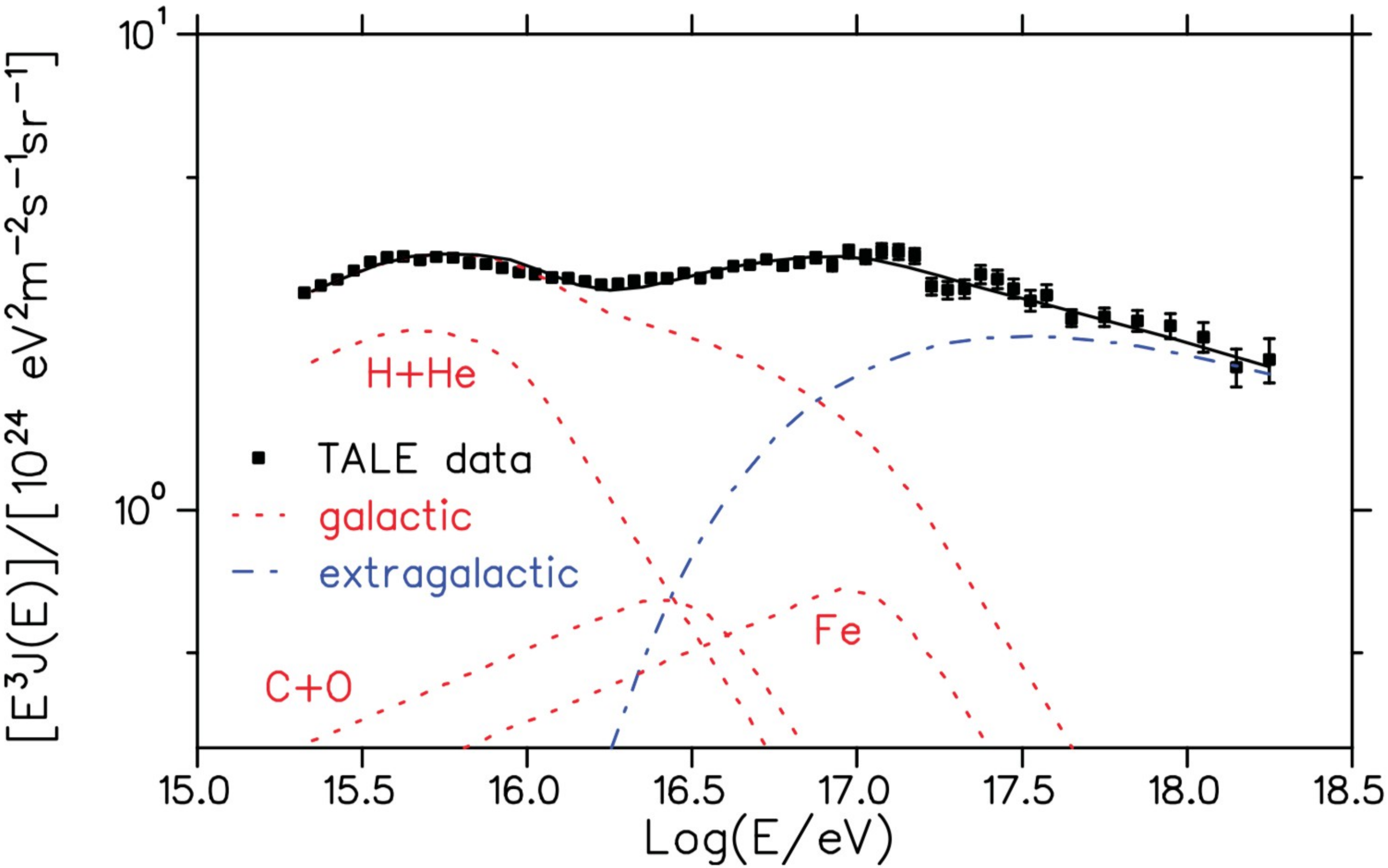


Models of the extra-galactic cosmic ray spectrum
where the transitions is below the ankle
(associated to the “second Knee”)



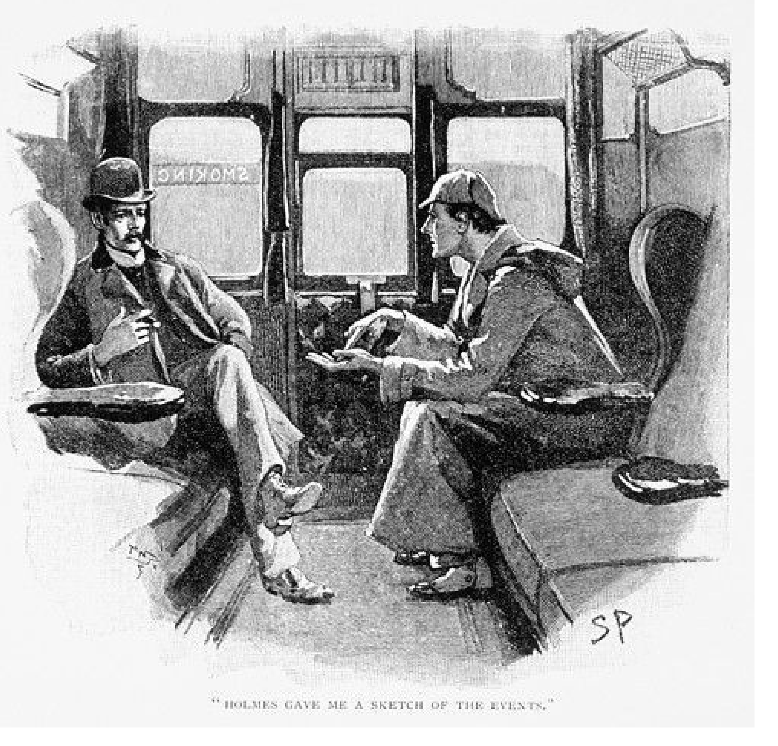
Abu-Zayad et al.
arXiv:1803.07052

Mollerach, Roulet
arXiv:1812.04026
(very similar model)



The dogs that did not bark: at the *Galactic/extragalactic Transition:*

[1] The “hardening”
[2] The anisotropy



"HOLMES GAVE ME A SKETCH OF THE EVENTS."

Energy Spectra

Mass Composition

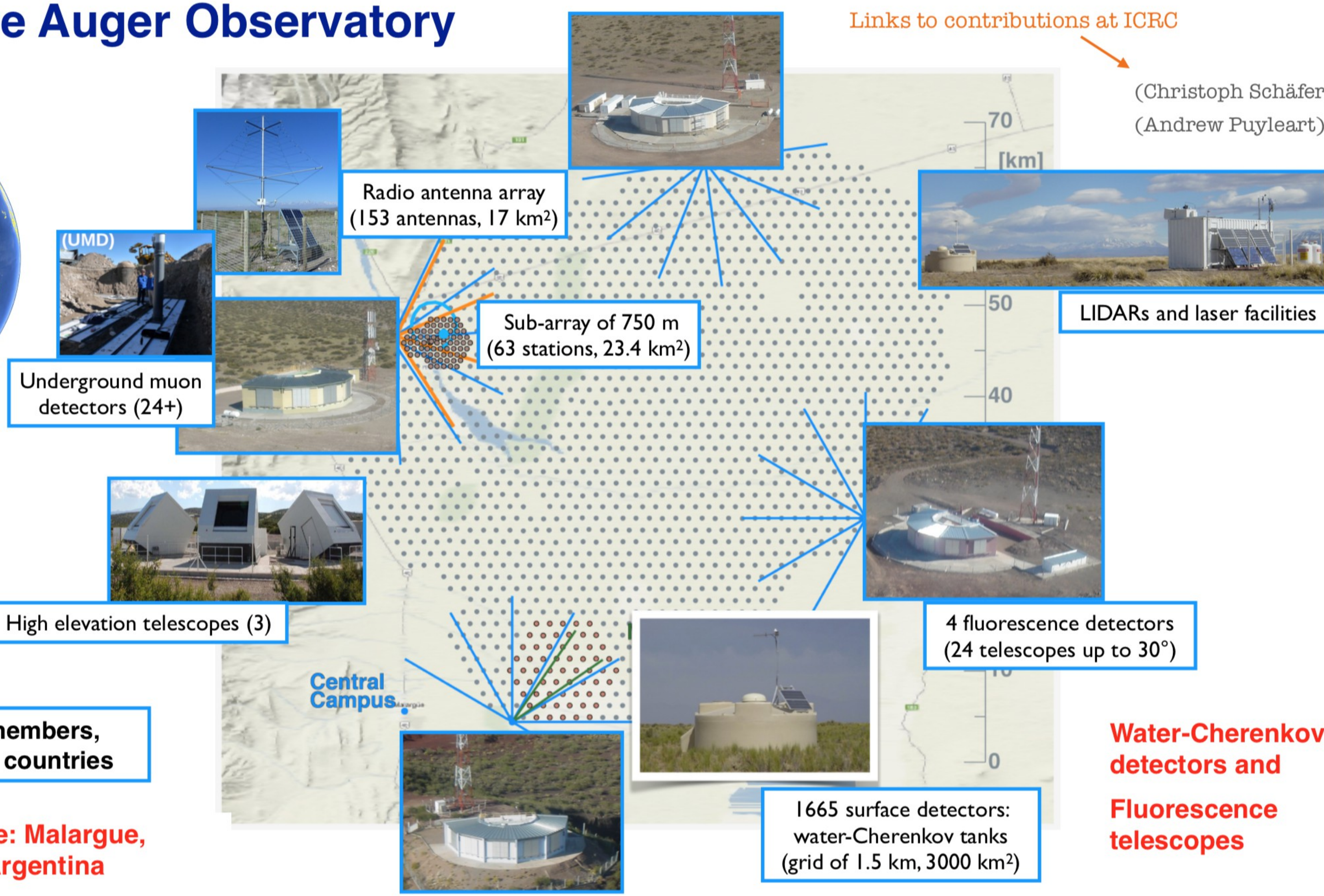
Anisotropies

The Pierre Auger Observatory

Links to contributions at ICRC

(Christoph Schäfer)
(Andrew Puyleart)

Pierre Auger Observatory
Province Mendoza, Argentina

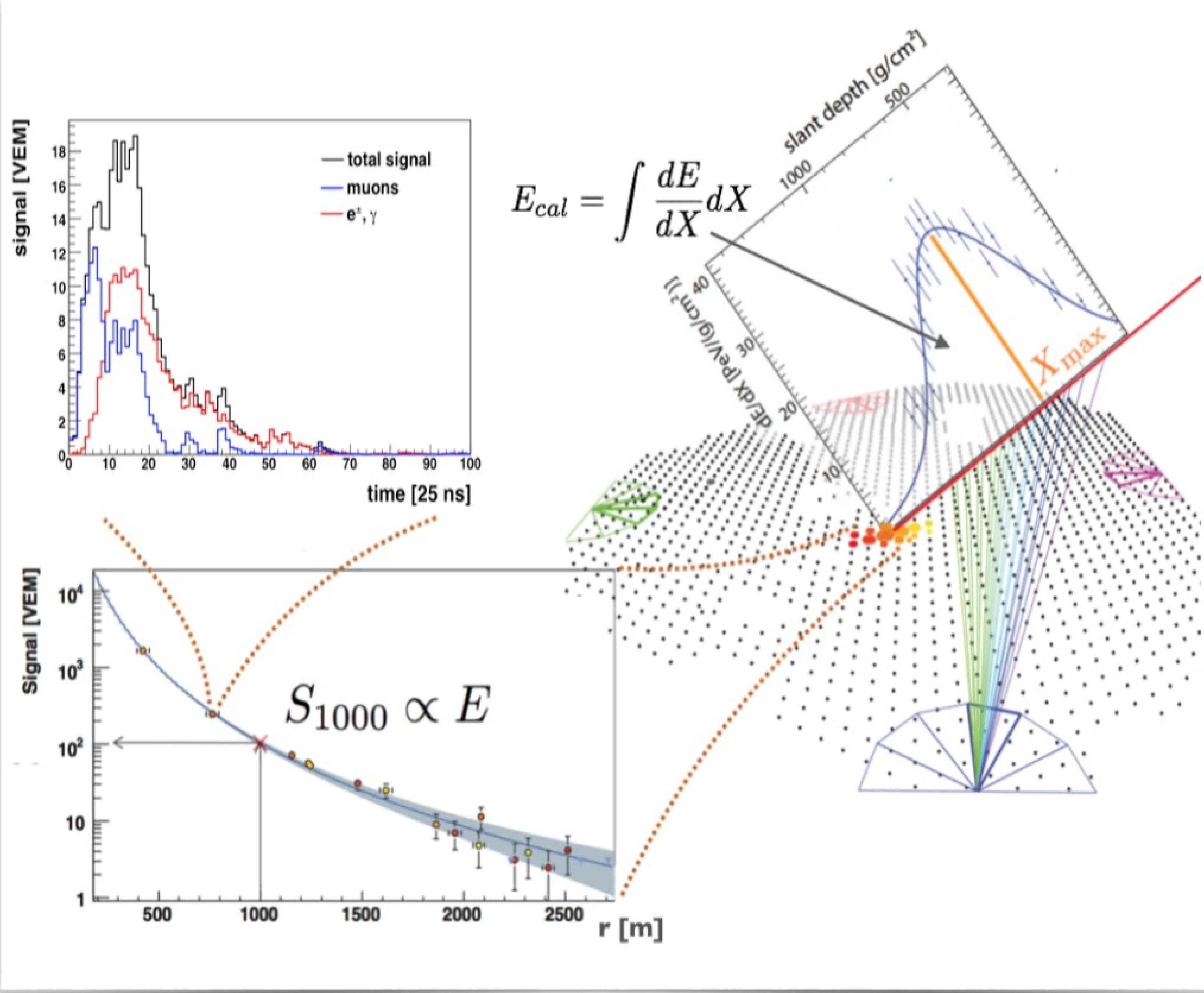


More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

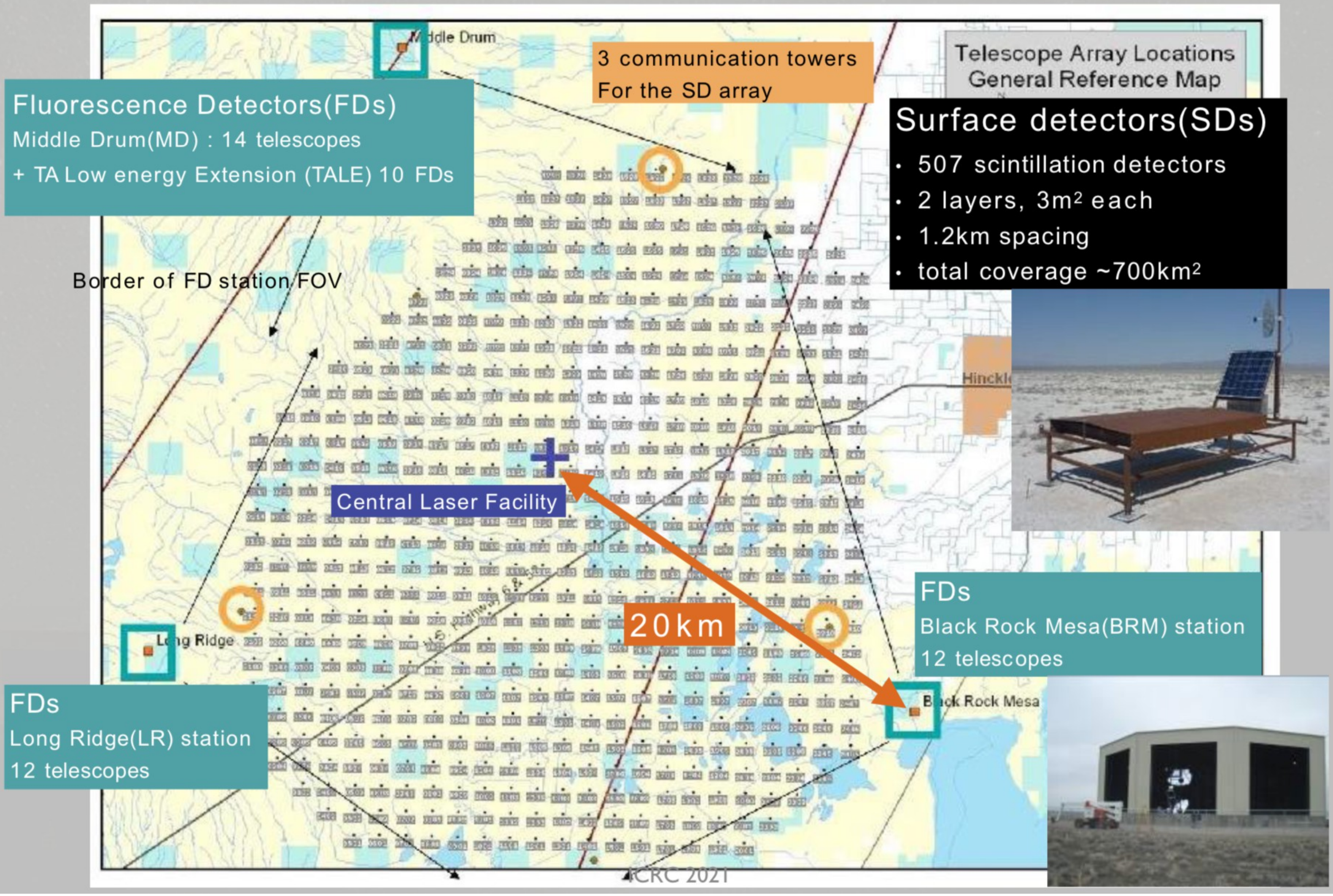
Water-Cherenkov detectors and

Fluorescence telescopes

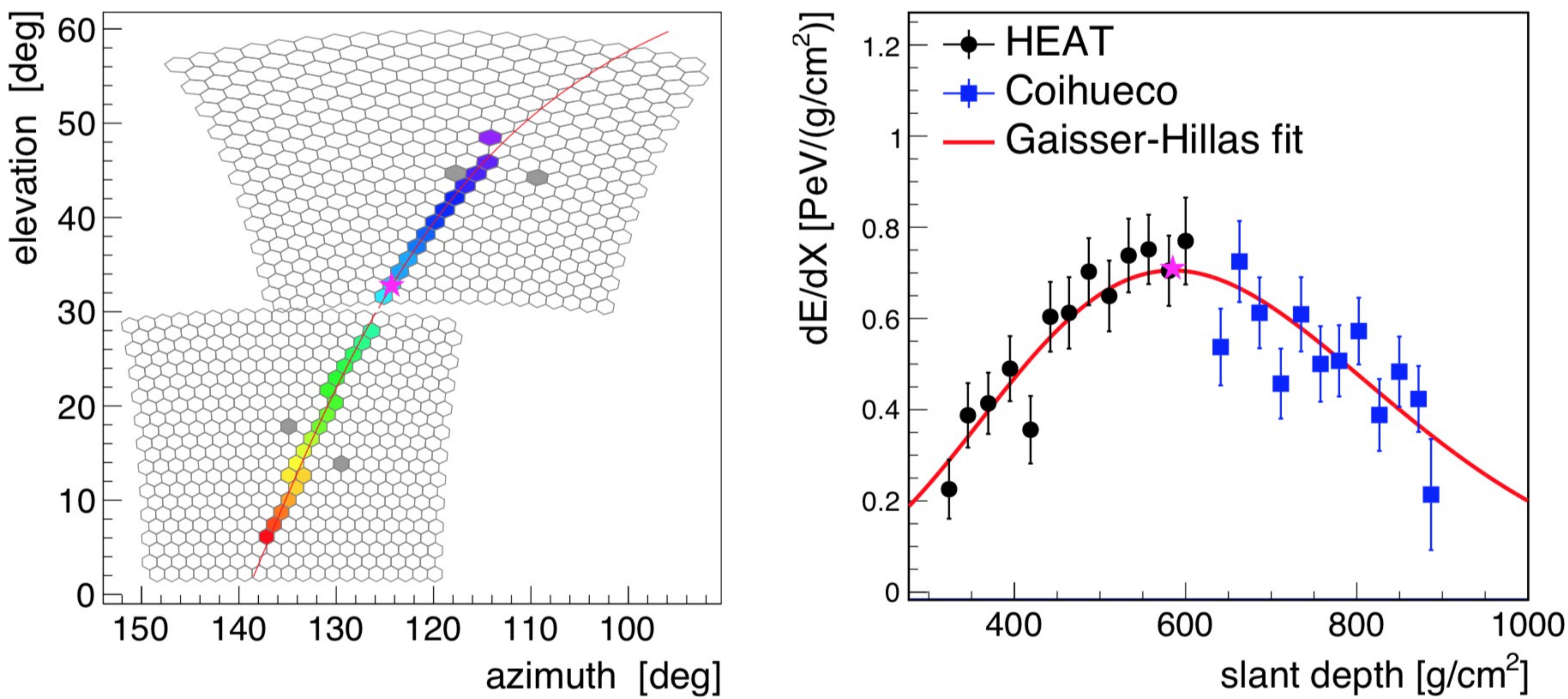


signal [VEM]
total signal
muons
e±, γ
time [25 ns]
$E_{cal} = \int \frac{dE}{dX} dX$
slant depth [g/cm²]
dE/dX [PeV/(g/cm²)]
X_{max}
X [g/cm²]
Signal [VEM]
$S_{1000} \propto E$
r [m]

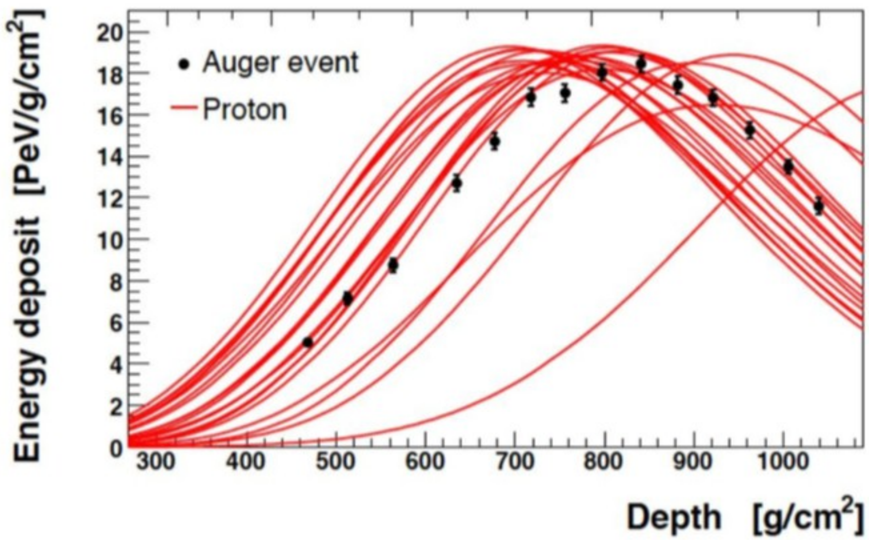
Map of theTA site



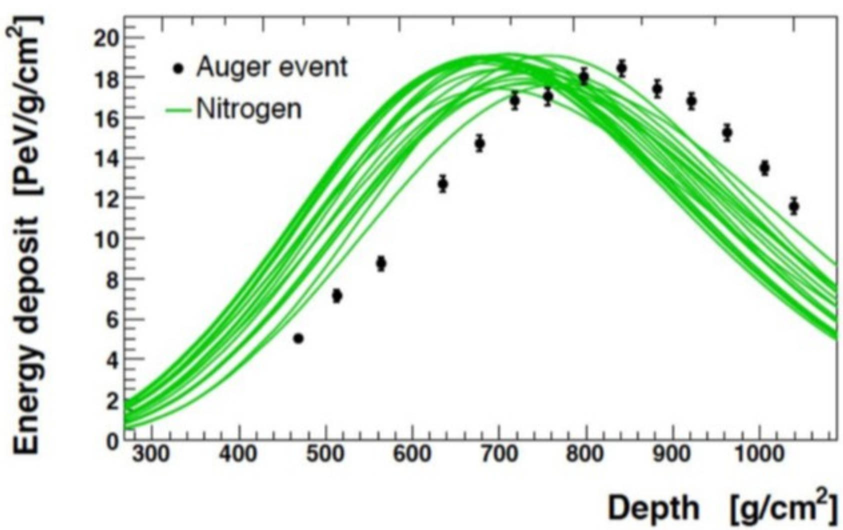
Telescope Array Detector (hybrid with 3 Cherenkov Telescopes)

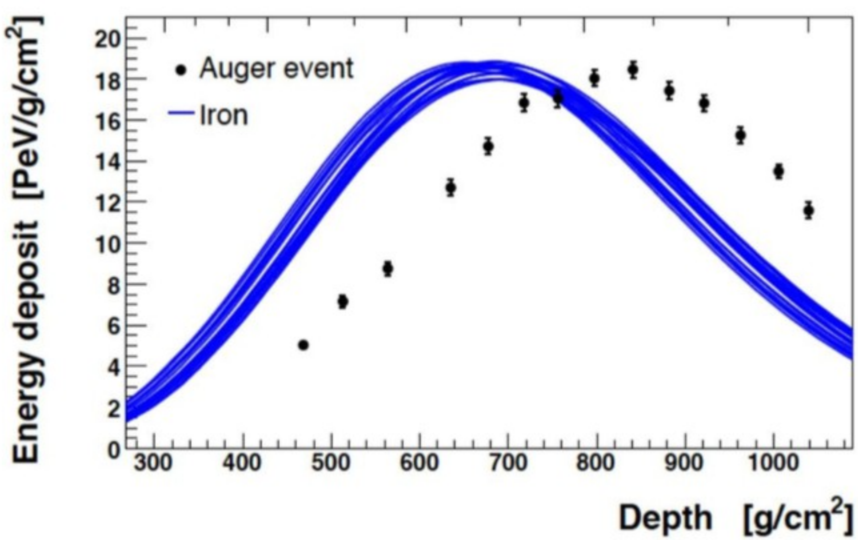


elevation [deg]
azimuth [deg]
HEAT
Coihueco
Gaisser-Hillas fit
dE/dX [PeV/(g/cm^2)]
slant depth [g/cm^2]

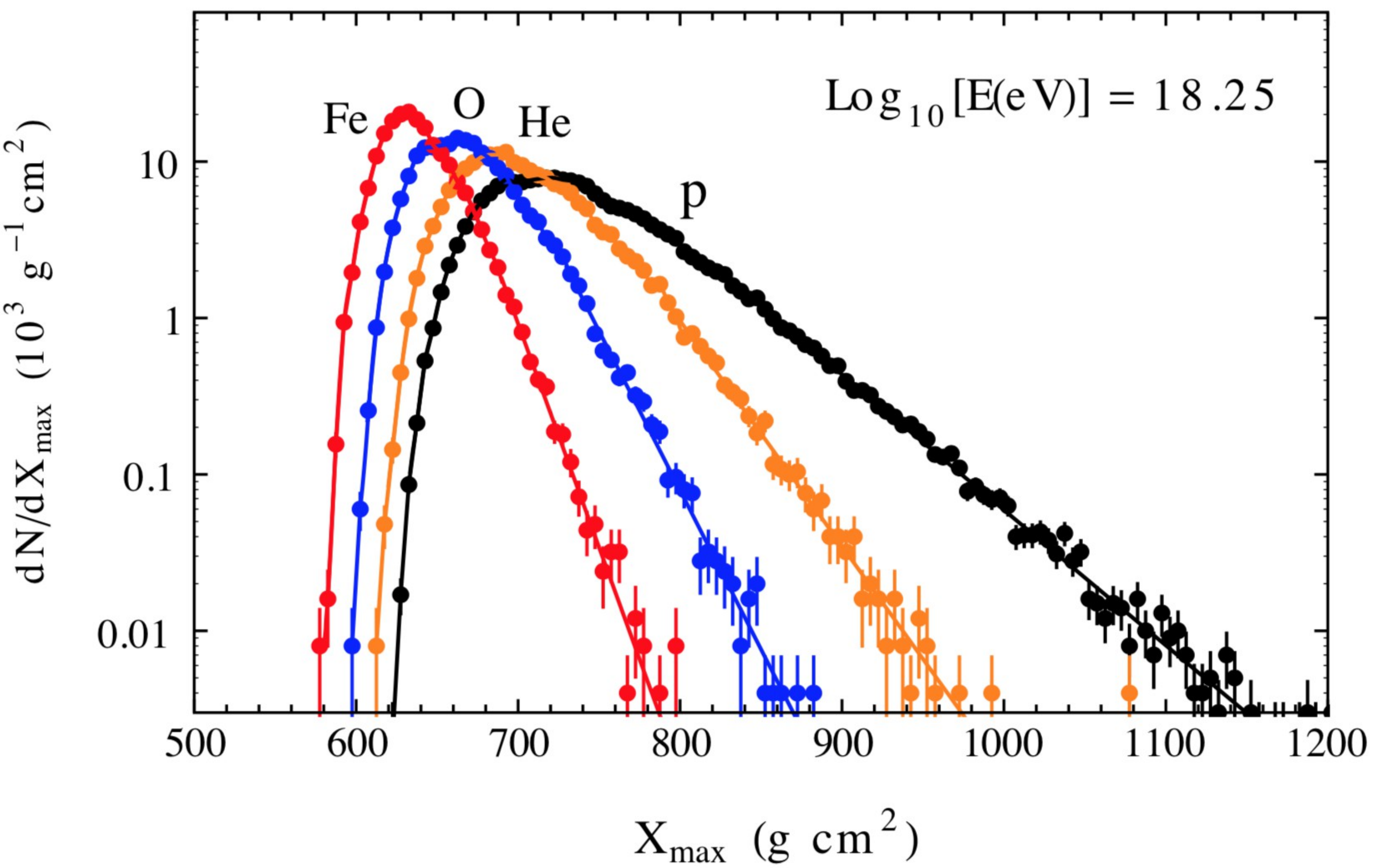


$$E \simeq 10^{20}\ \mathrm{eV}$$



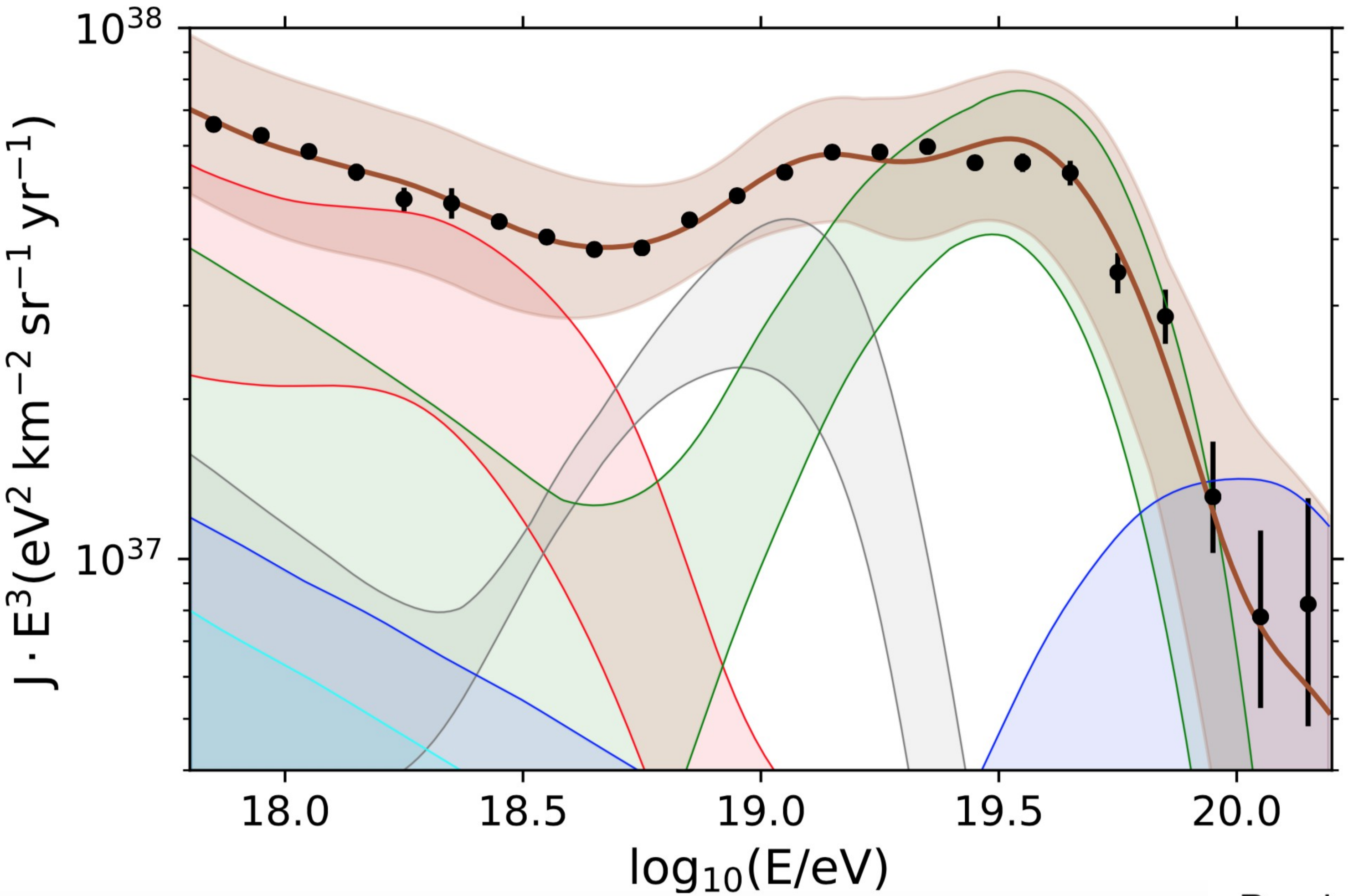


Monte Carlo calculation of the Xmax distributions (different elements)



The "extraordinary" Mass Composition of Auger

[A result of potentially profound significance]



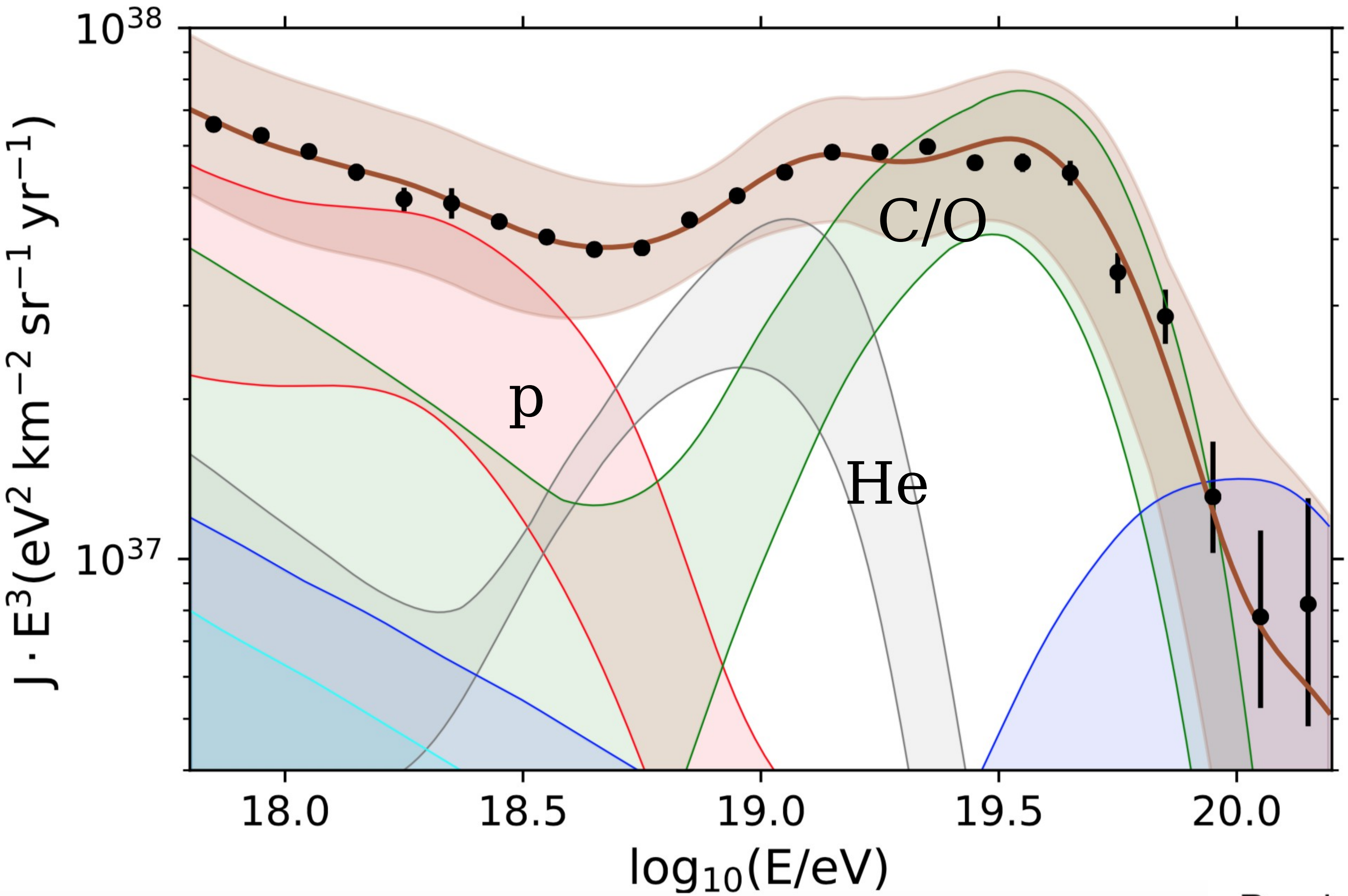
Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{\rm sys}(E)/E = 14\,\%$

$\mathbf{X_{max}}$ **scale:** $\sigma_{\rm sys}(X_{\rm max}) = 6 \div 9\ \mathrm{g\ cm^{-2}}$

The “extraordinary” Mass Composition of Auger

[A result of potentially profound significance]



A = 1
1 < A < 5
4 < A < 23
22 < A < 39
38 < A < 57

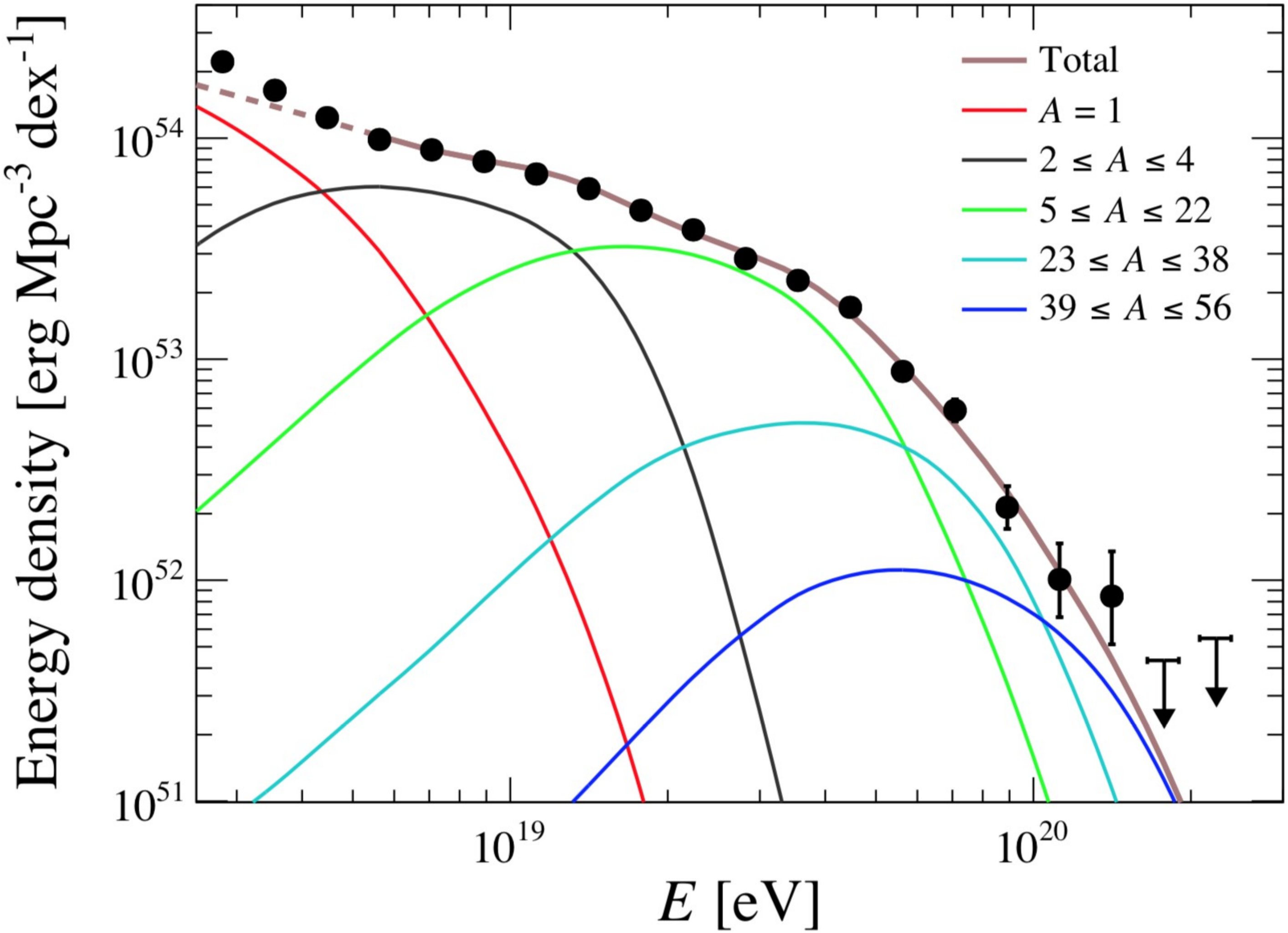
“Spectacular" structure

Hard spectra with sharp cutoffs

Bands:
Experimental uncertainties
(model uncertainties smaller)

Energy scale: $\sigma_{\rm sys}(E)/E = 14\,\%$

X_{max} scale: $\sigma_{\rm sys}(X_{\rm max}) = 6 \div 9$ g cm^{-2}

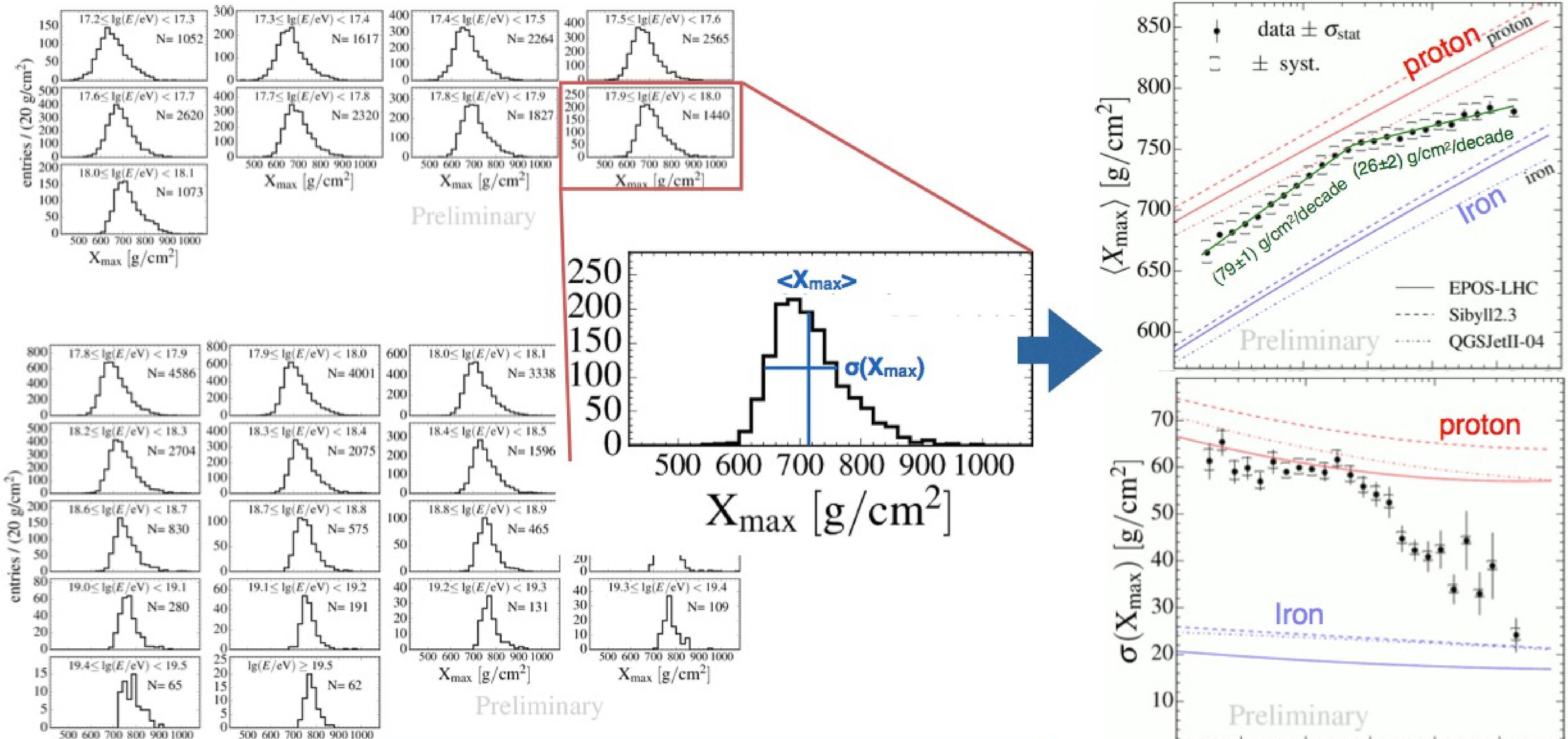


Auger PRL 2020

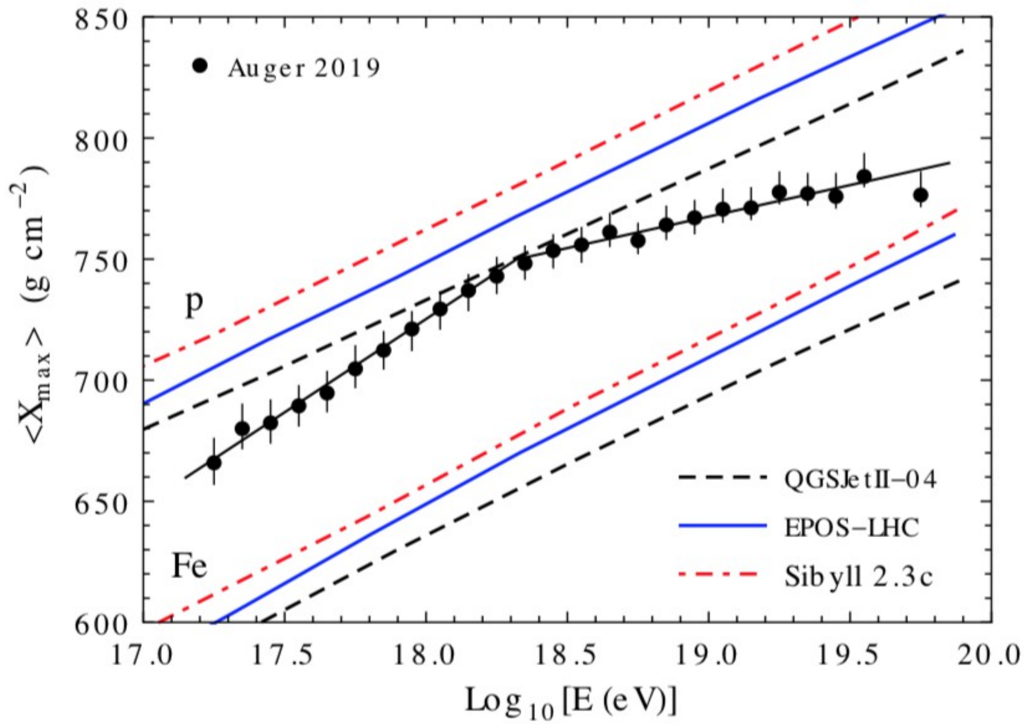
1. Very hard spectra
2. Cutoff is the maximum energy of acceleration in the sources

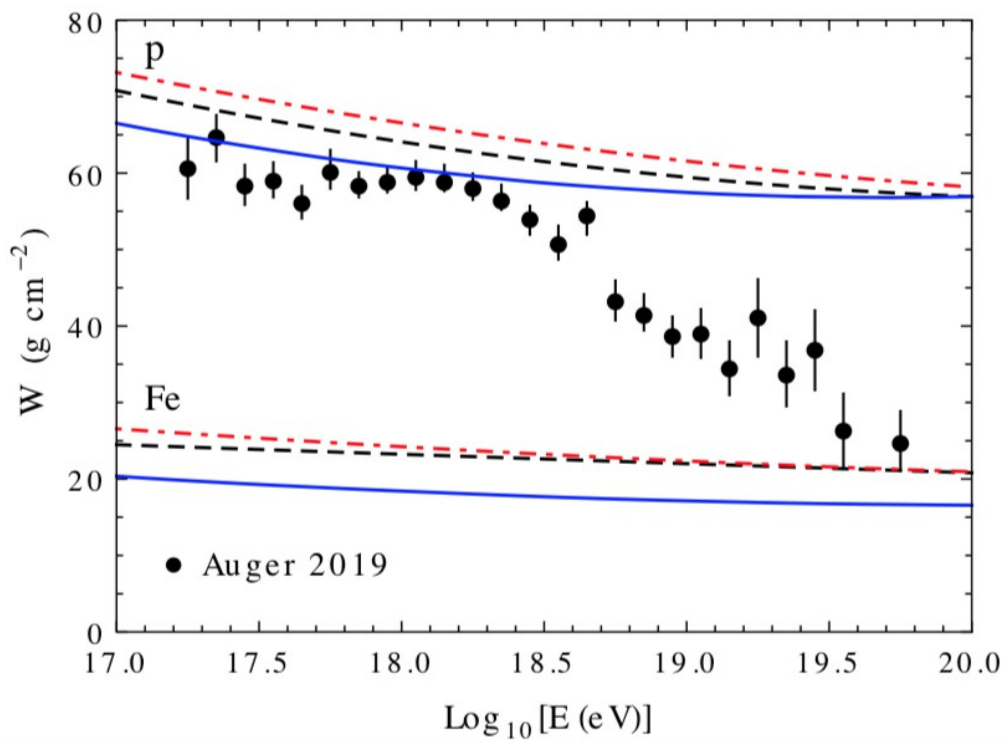
$$E_{\max}(Z) = Z\ E_p$$

X_{max} Distributions



Bellido (Auger) @ ICRC2017 ; arXiv:1708.06592





Elongation Rate

$$D(E) = \frac{d\langle X_{\max}\rangle}{d\log_{10} E}$$

Predictions for a constant composition

$D_p = 54.0\ \mathrm{g\,cm^{-2}}$ QGSJet II–04

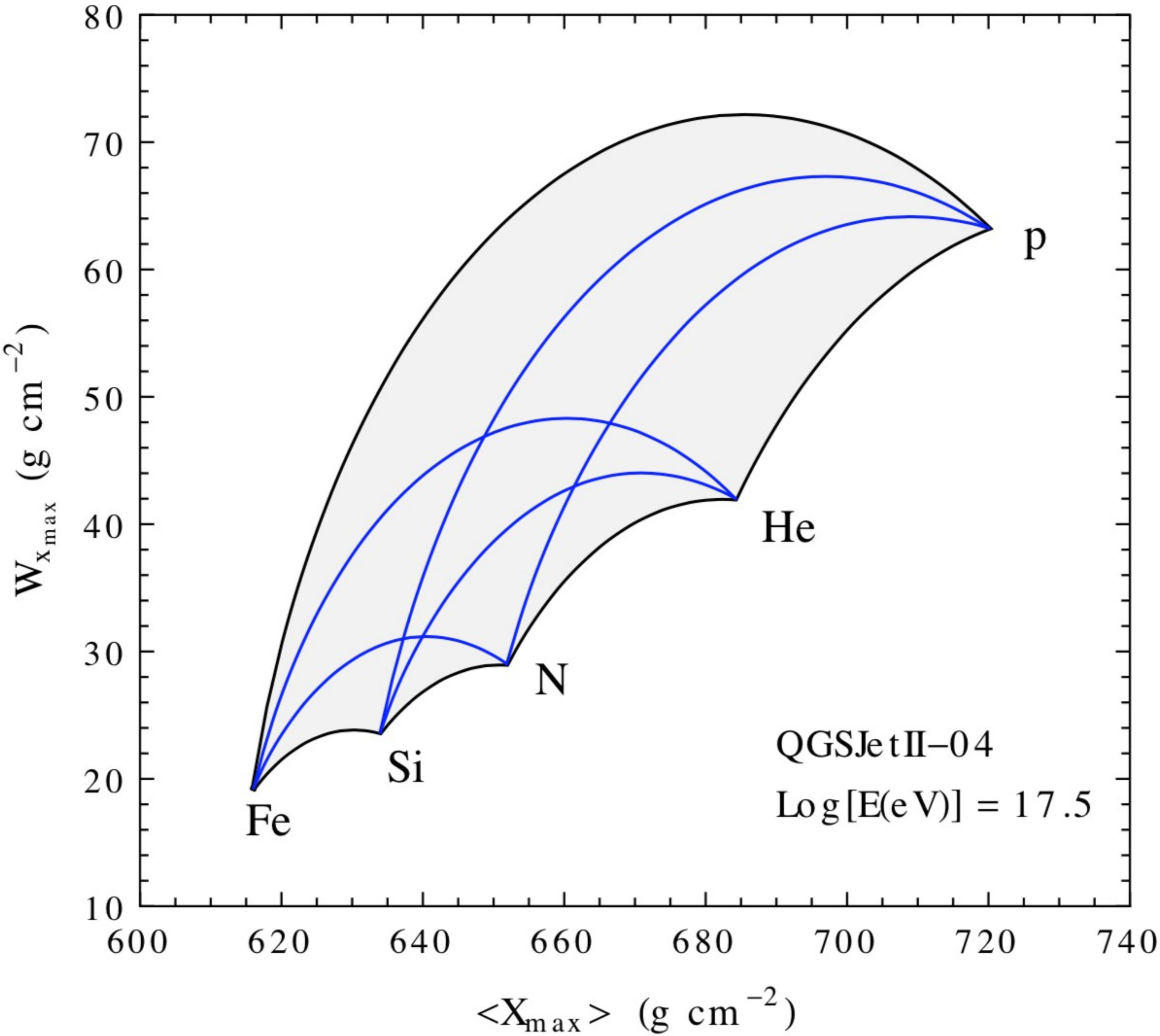
$D_p = 56.7\ \mathrm{g\,cm^{-2}}$ EPOS–LHC

$D_p = 57.2\ \mathrm{g\,cm^{-2}}$ Sibyll 2.3c

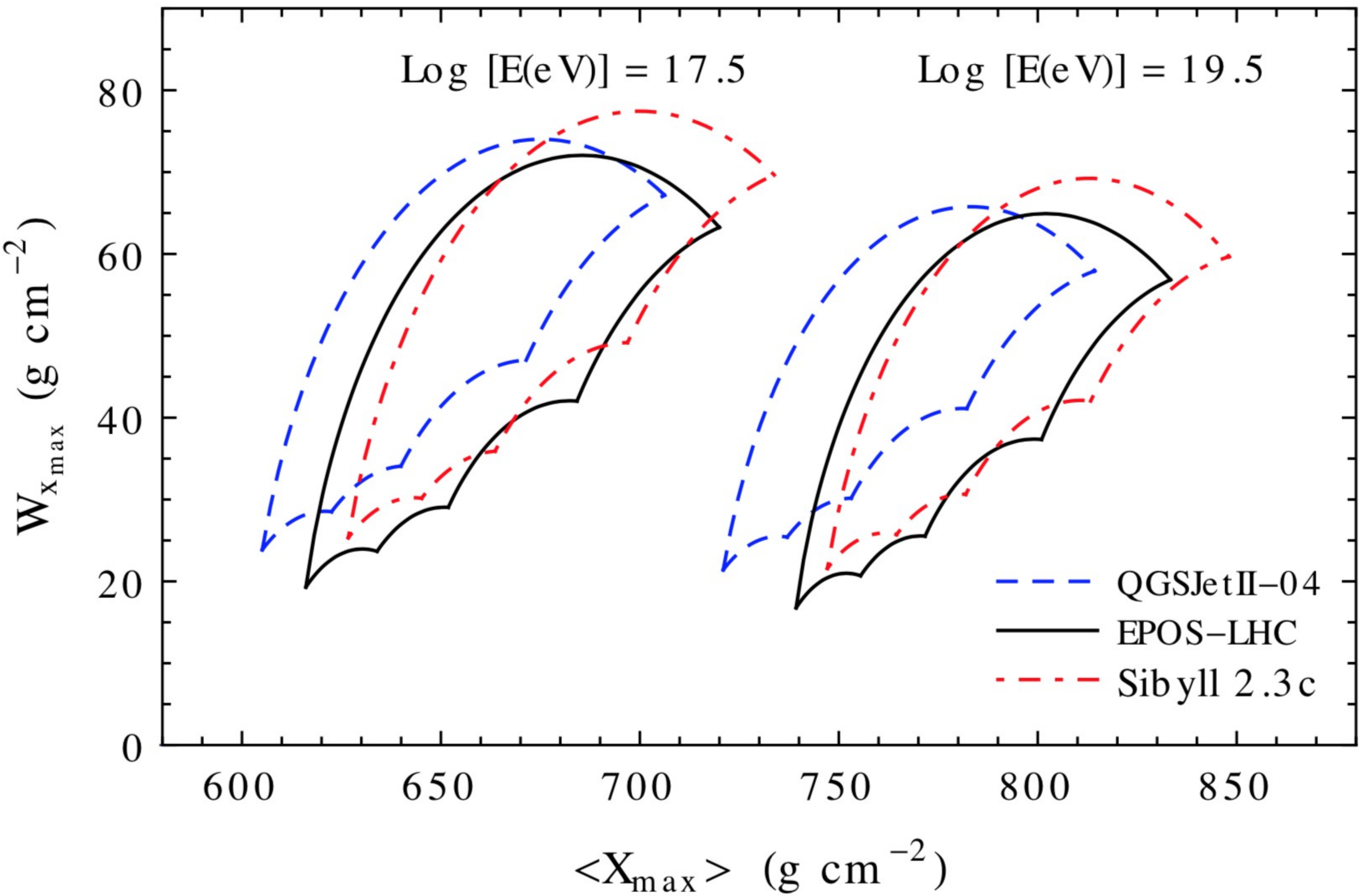
$D_{\mathrm{data}} = 77 \pm 2 \quad E < E^*$

$D_{\mathrm{data}} = 26 \pm 2 \quad E > E^*$

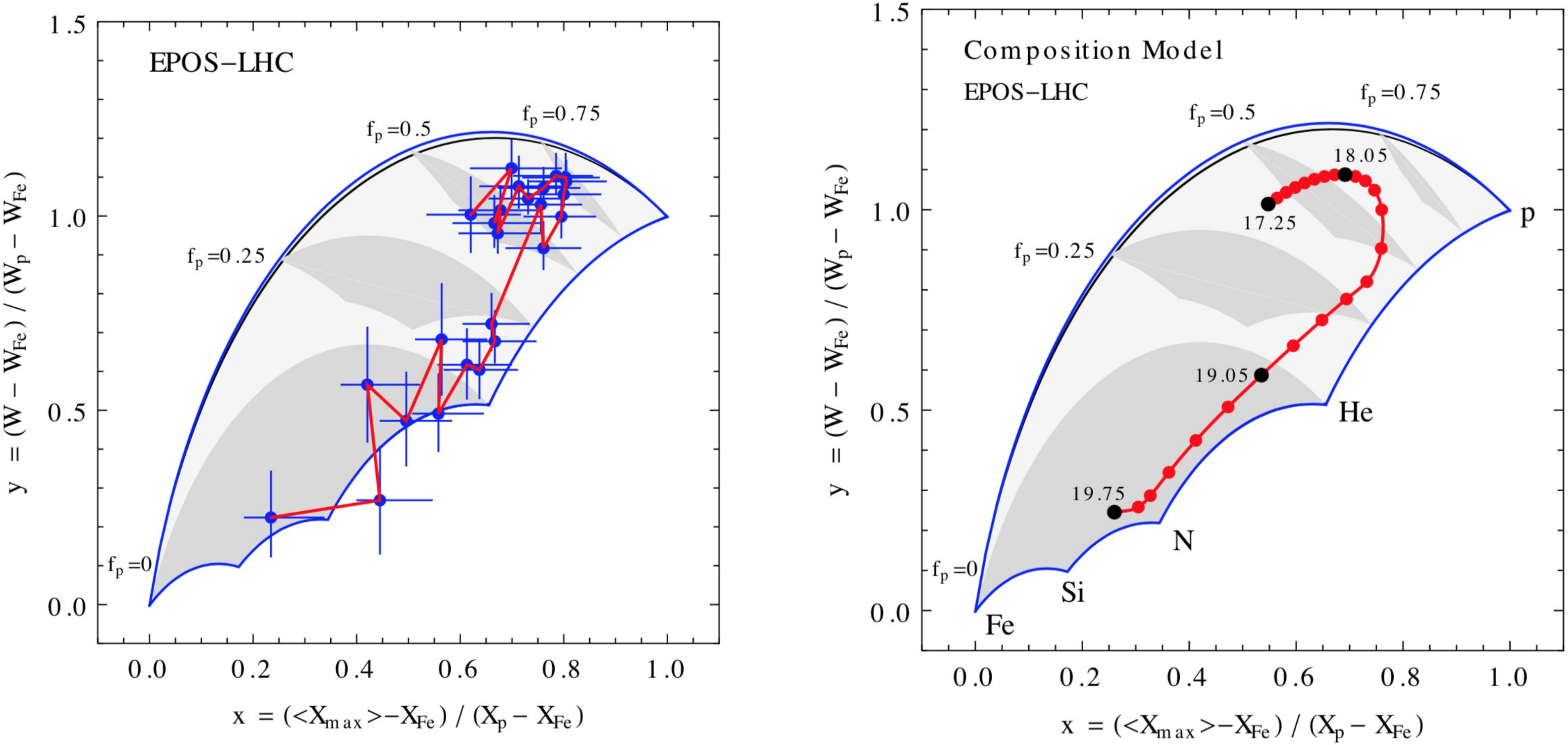
$E^* = 10^{18.3}$ eV

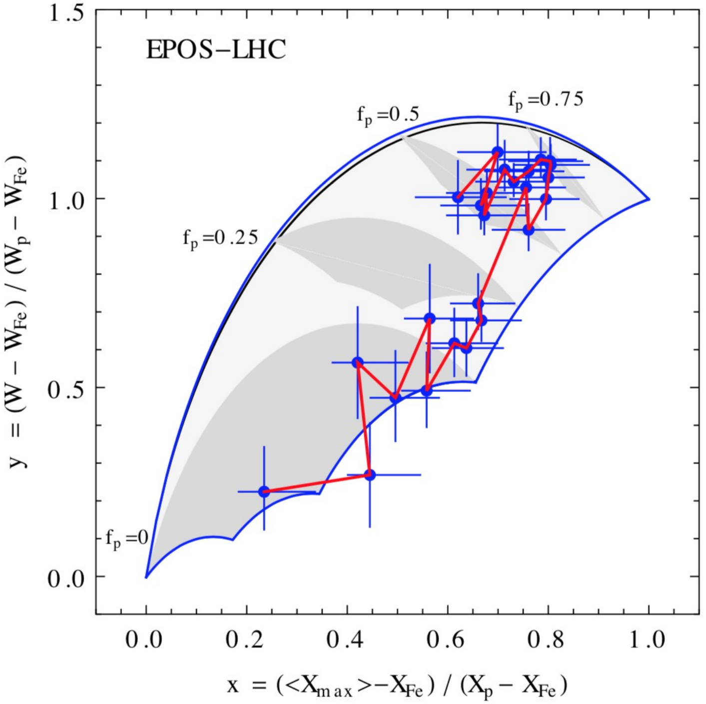


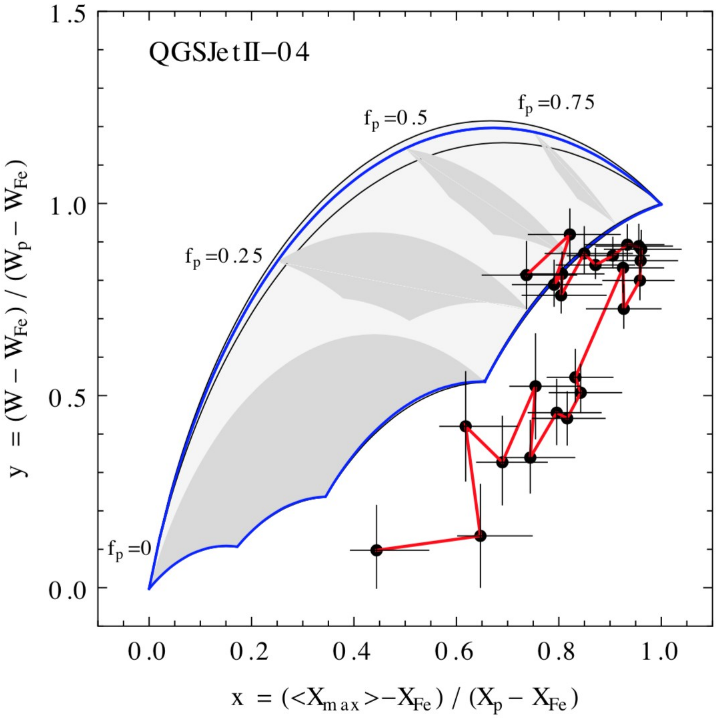
80
70
60
50
40
30
20
10
$W_{X_{max}}$ (g cm^{-2})
600
620
640
660
680
700
720
740
<X_{max}> (g cm^{-2})
p
He
N
Si
Fe
QGSJetII−04
Log[E(eV)] = 17.5

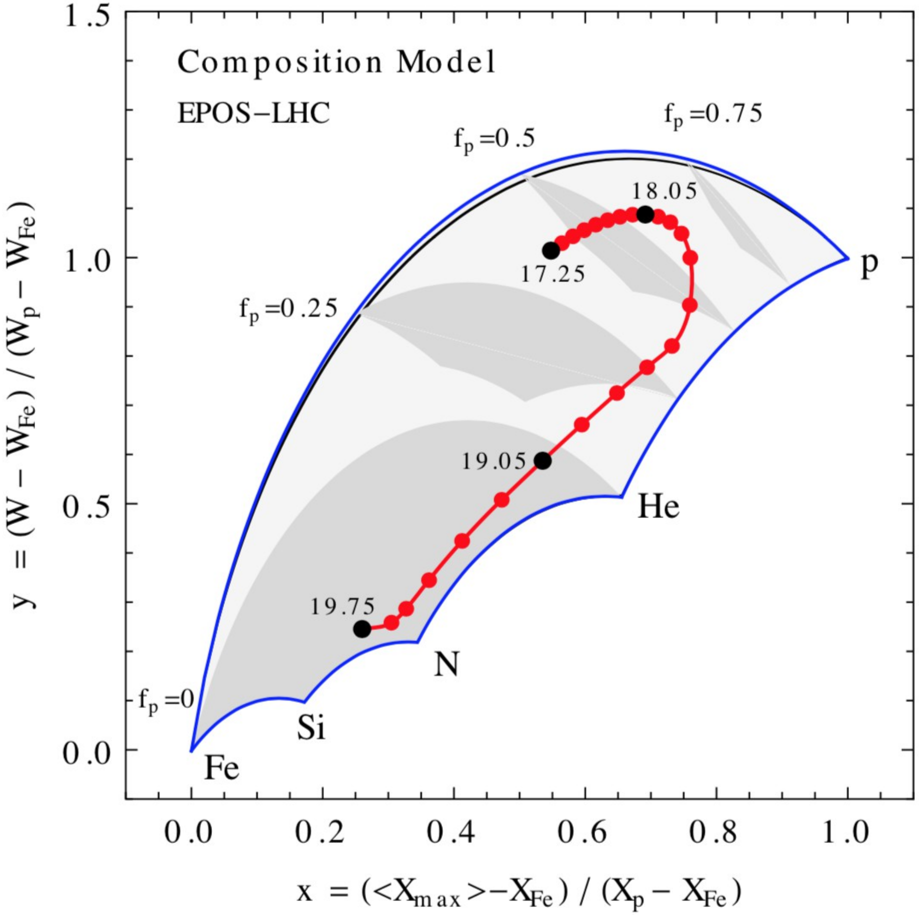


Log [E(eV)] = 17.5
Log [E(eV)] = 19.5
QGSJetII−04
EPOS−LHC
Sibyll 2.3c
$W_{X_{max}}$ (g cm^{-2})
0
20
40
60
80
600
650
700
750
800
850
<X_{max}> (g cm^{-2})

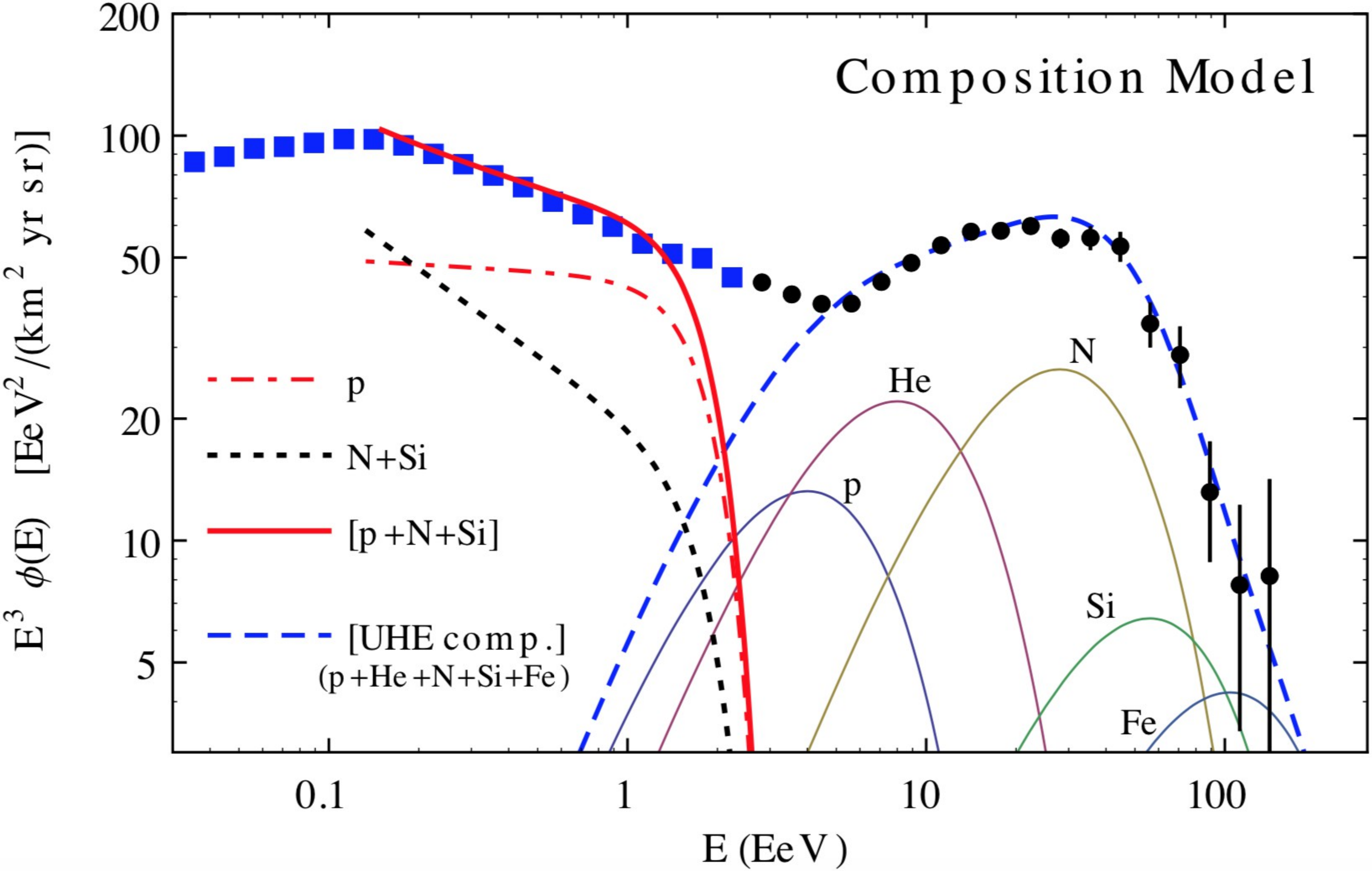

EPOS−LHC
f_p =0.5
f_p =0.75
f_p =0.25
f_p =0
y = (W − W$_{Fe}$) / (W$_p$ − W$_{Fe}$)
x = (<X$_{max}$>−X$_{Fe}$) / (X$_p$ − X$_{Fe}$)
Composition Model
EPOS−LHC
18.05
17.25
19.05
19.75
Fe
Si
N
He
p





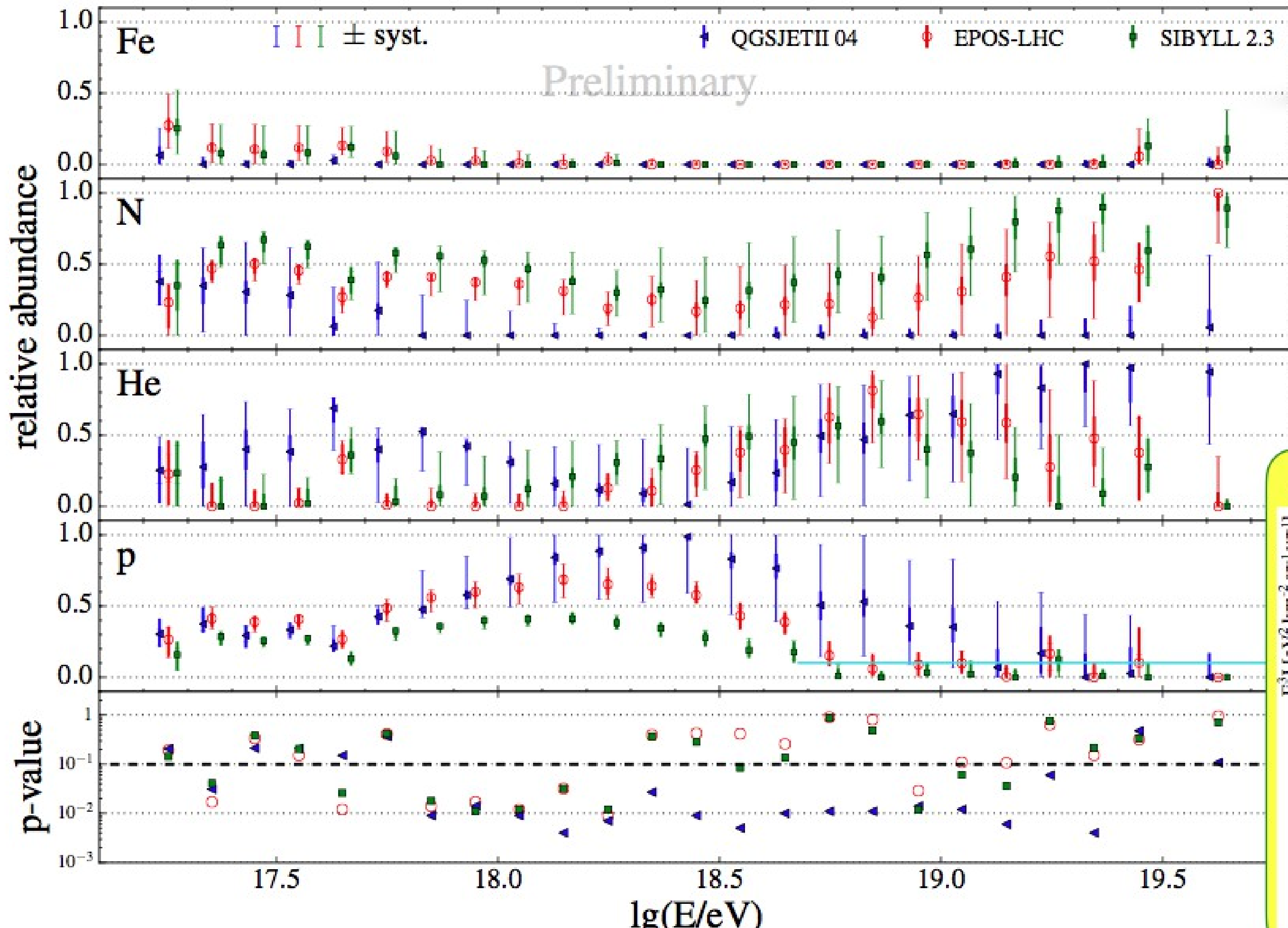


Possibility to exclude models



Composition Model
200
100
50
20
10
5
0.1
1
10
100
E (EeV)
E^3 ϕ(E) [EeV^2/(km^2 yr sr)]
p
N+Si
[p+N+Si]
[UHE comp.]
(p+He+N+Si+Fe)
He
N
p
Si
Fe

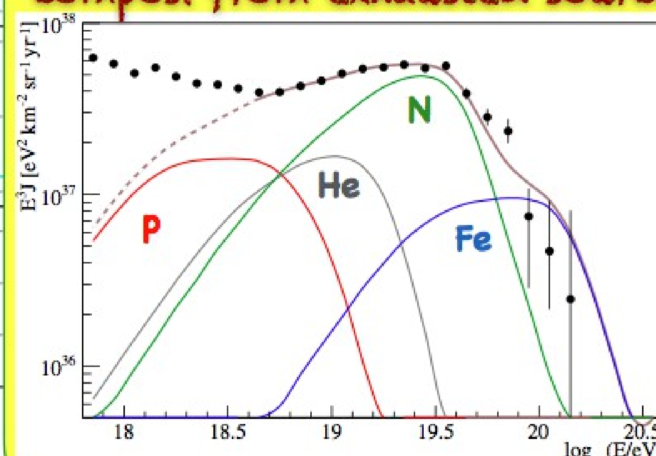
Mass Fractions from Auger



Bellido (Auger) @ ICRC2017 ;
arXiv:1708.06592

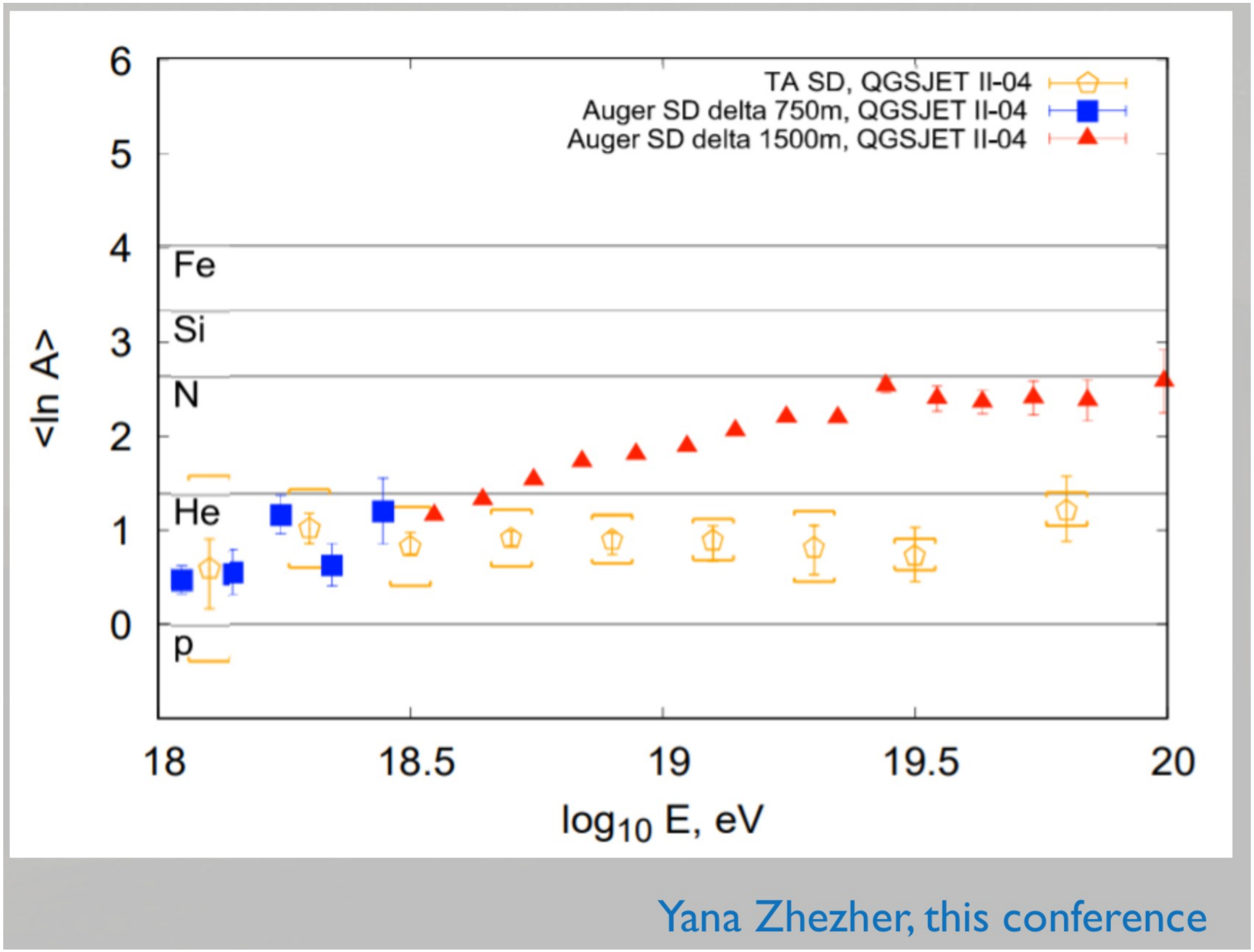
remember....

compos. from exhausted sources ?



Are the Auger results on composition confirmed by other detectors ?

Is there a discrepancy with Telescope Array



ICRC 2021

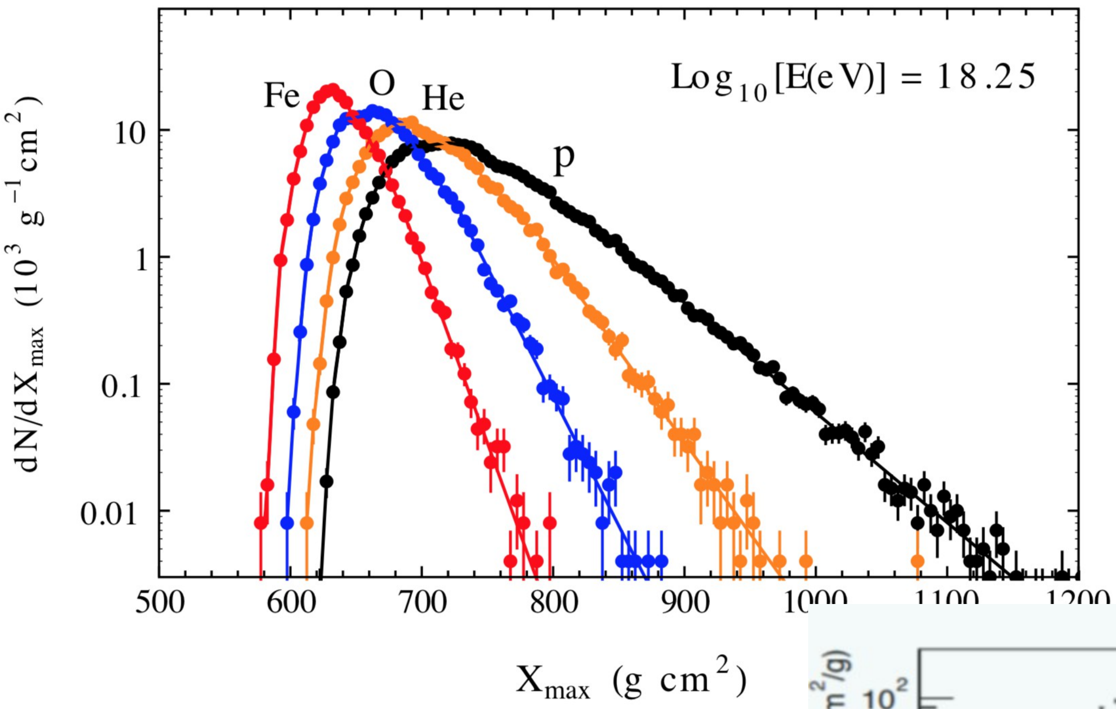
Results presented at the 35th ICRC

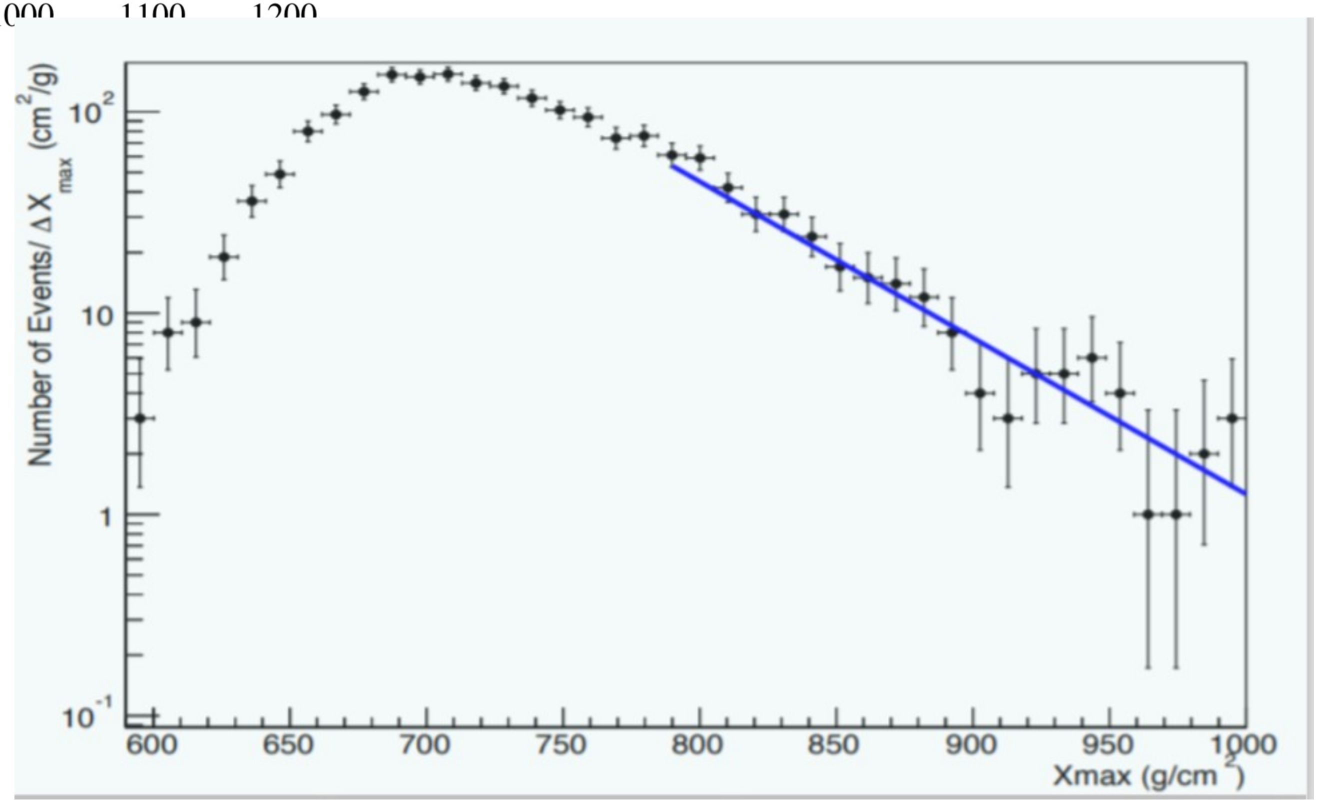
[V. de Souza, PoS (ICRC2017) 522]

Comparison of $X_{\max}$ distributions measured by Auger and TA

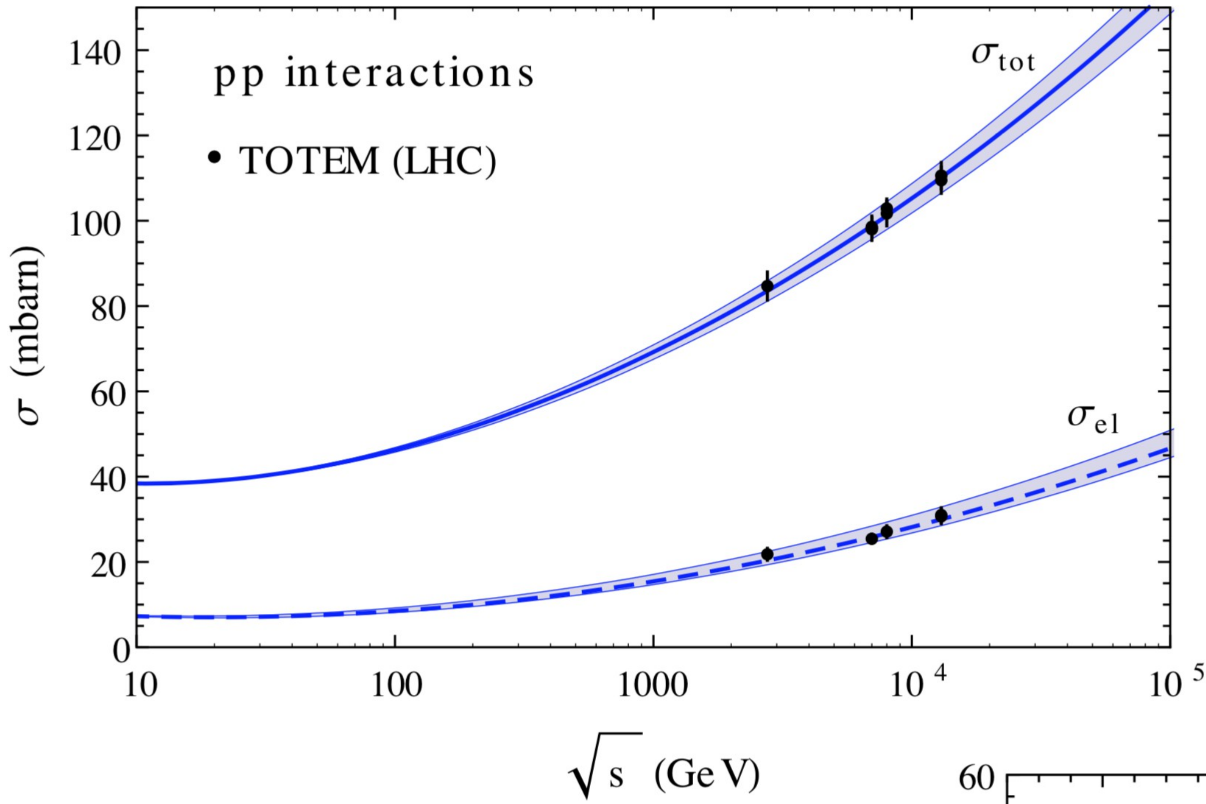
"At the current level of statistics and understanding of systematics, the TA data is consistent with the proton models used in this paper for energies less than 10^{19} eV and it is also consistent with the AugerMix composition"

Monte Carlo calculation of the Xmax distributions (different elements)





Telescope Array measurement of the p-air cross section

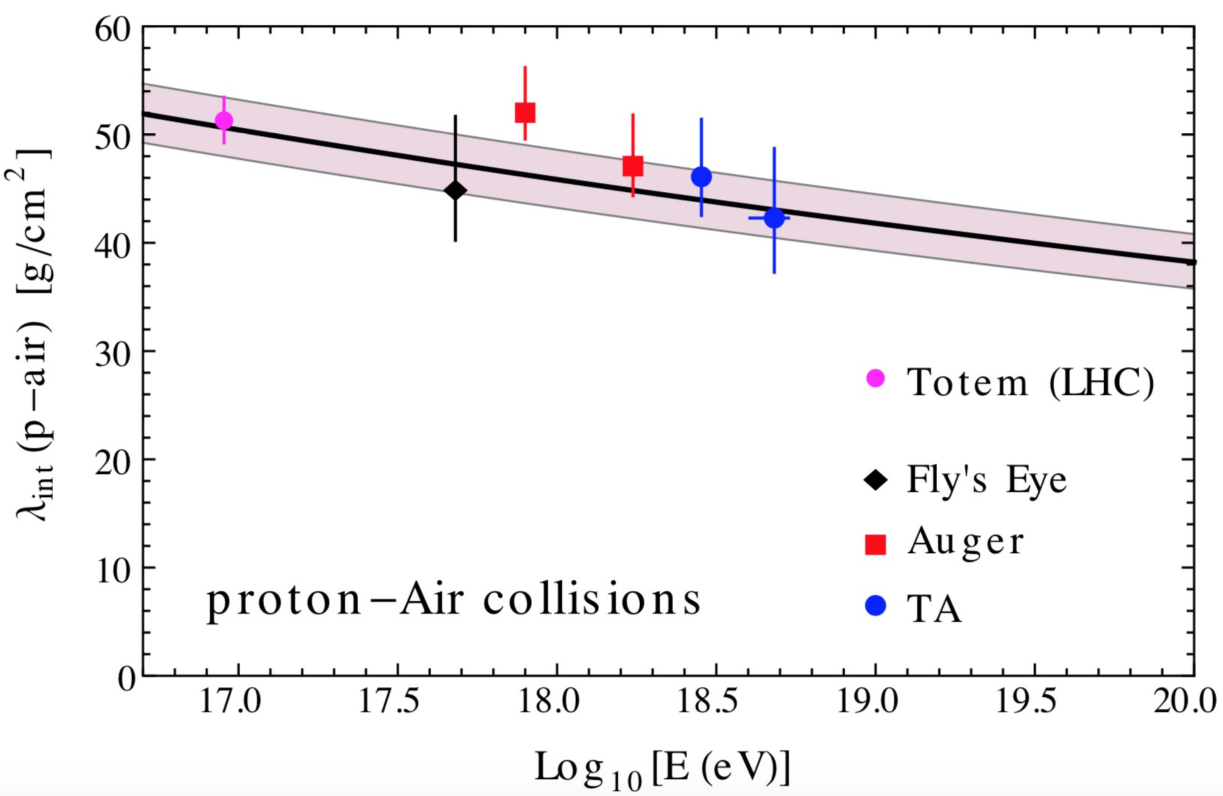


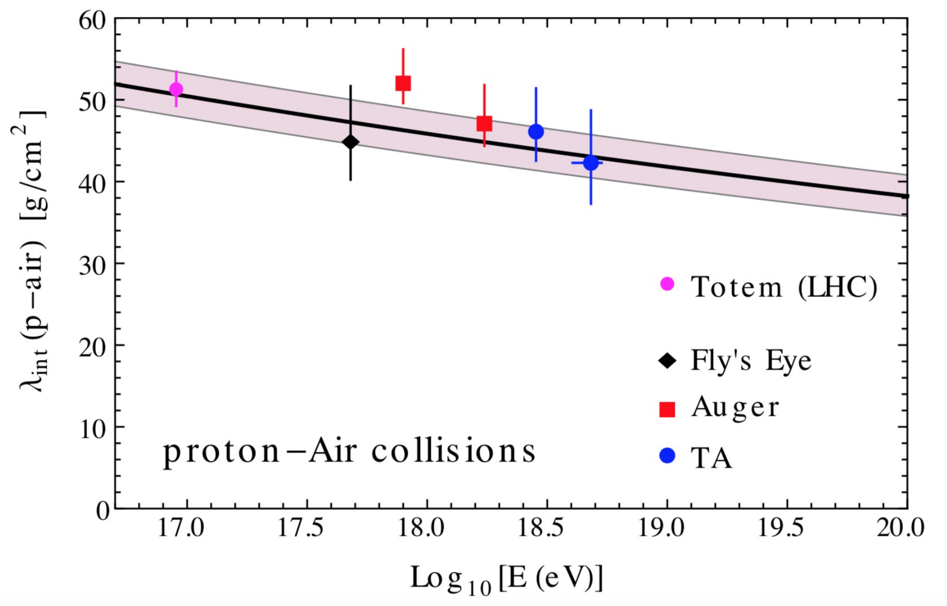
pp total/elastic cross sections at LHC

Glauber calculation of the p-Air cross section

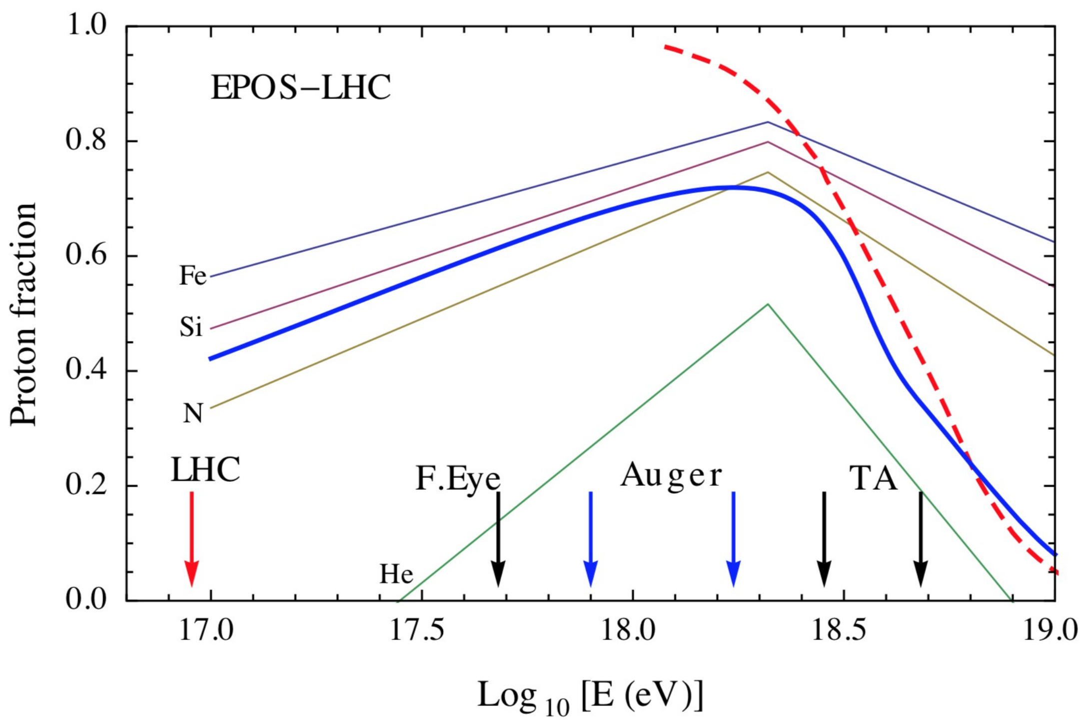
Measurements of Air Shower experiments

(Auger, Telescope Array)





Measurements of the *proton-air interaction length* from air-shower observations.



Significant tension between the Auger results that estimate a small proton fraction at high energy and the two Telescope Array measurements of the proton-air cross section.

P.L. PRD 103.103009
arXiv:2012.06861

Anisotropies

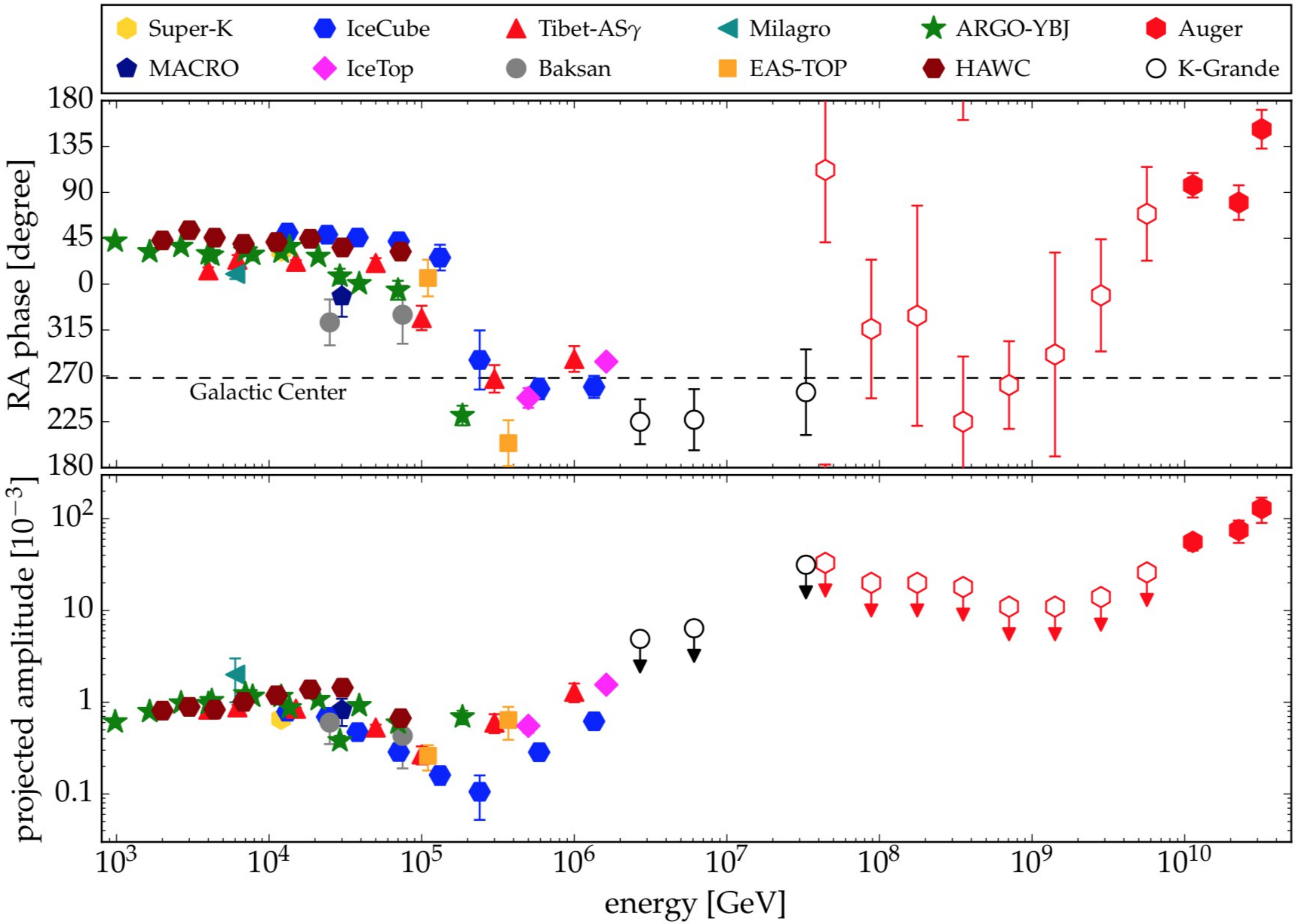
Large scale

Intermediate scale

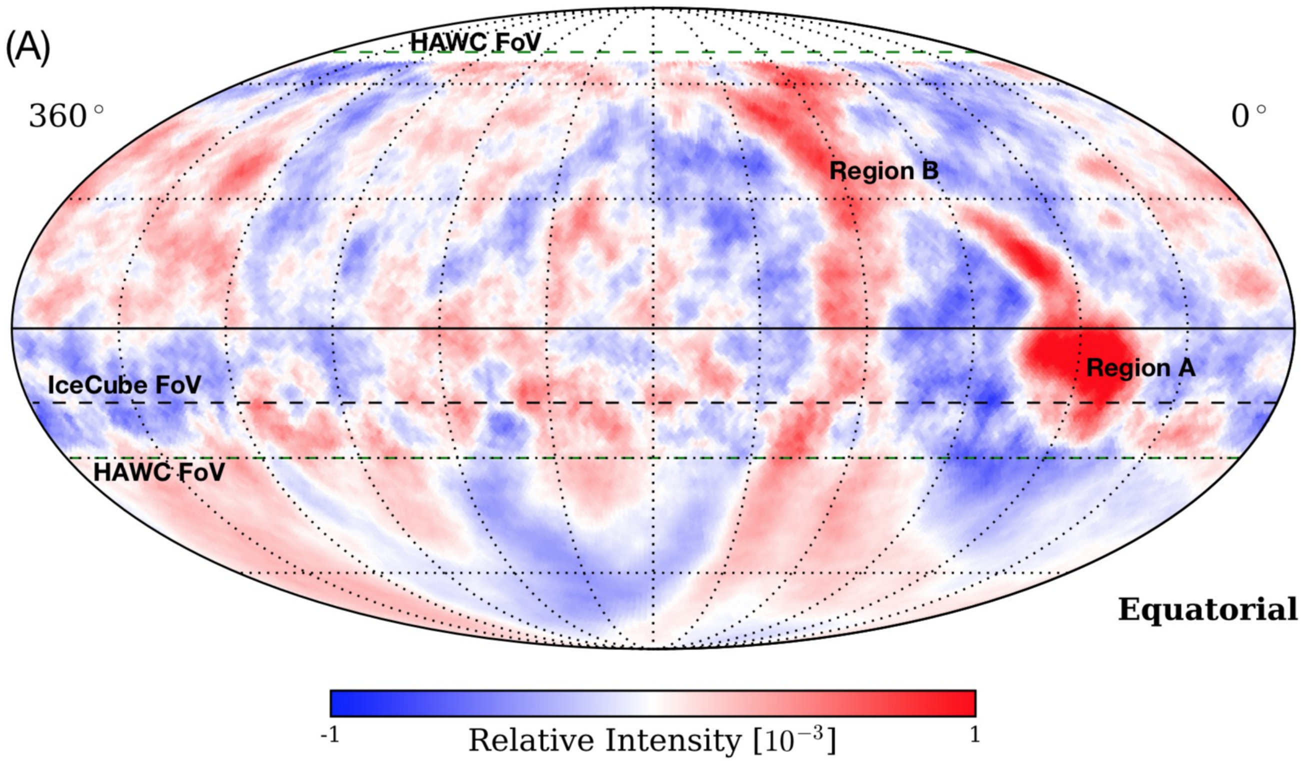
Point sources

Large Scale Anisotropy

Amplitude, Phase of dipole



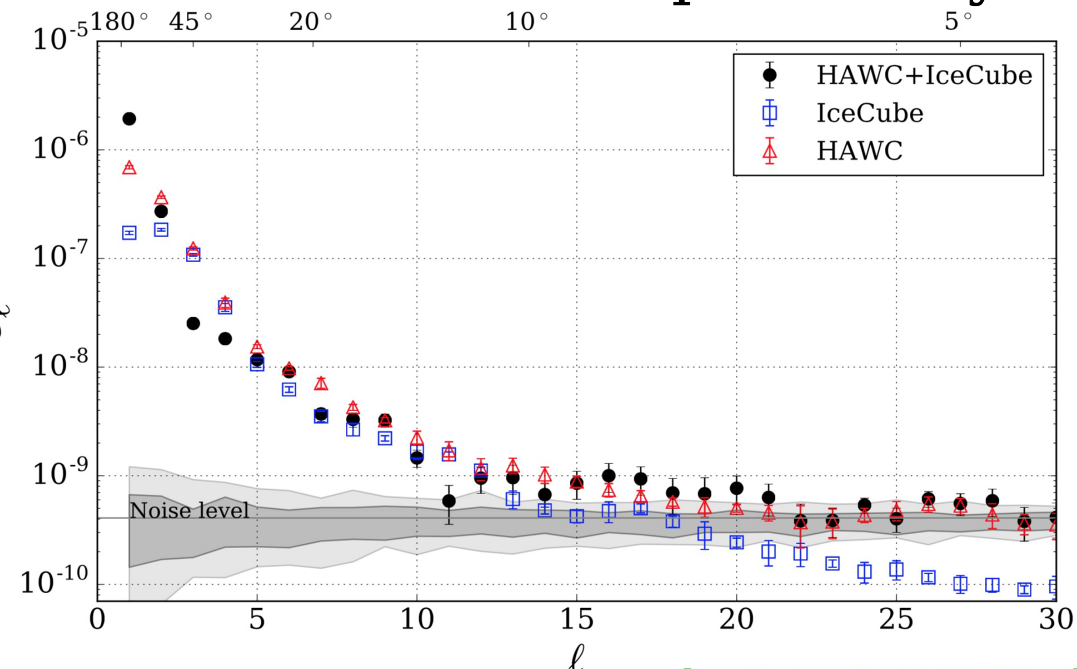
Markus Ahlers (Paris-Saclay 2021)



multipole analysis

10 TeV energy scale

Anisotropy at angular scale of 10 degrees



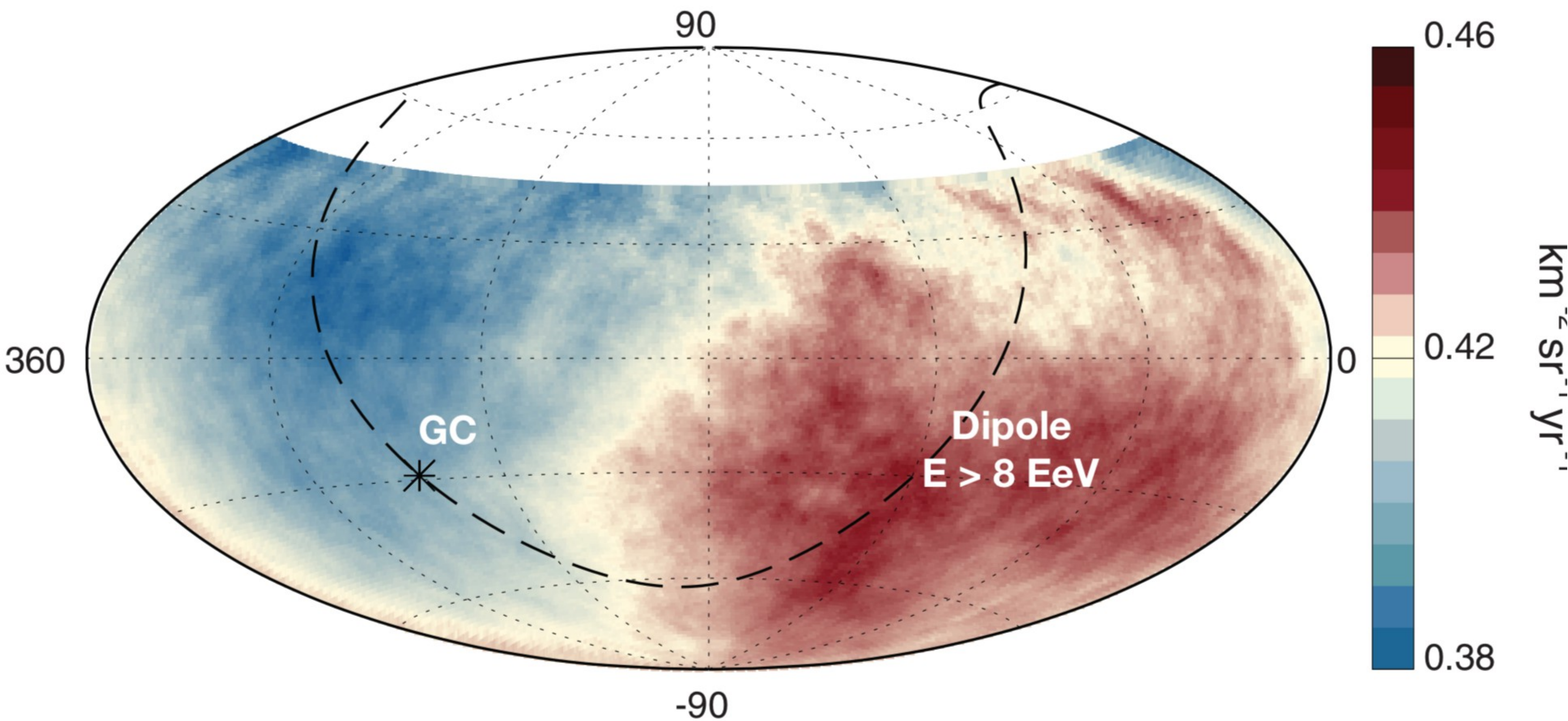
[IceCube & HAWC'18]

Markus Ahlers (Paris-Saclay 2021)

Large-scale analysis: reconstruction of the dipole

Amplitude: $6.5^{+1.3}_{-0.9}$%

Right ascension: 100˚±10˚, Declination: -24˚±13˚



The direction of the dipole lies ≈ 125˚ from the Galactic Center

Origin hard to explain with a Galactic origin

Large-scale analysis: other studies

Study of a possible evolution of the first harmonic in RA vs energy

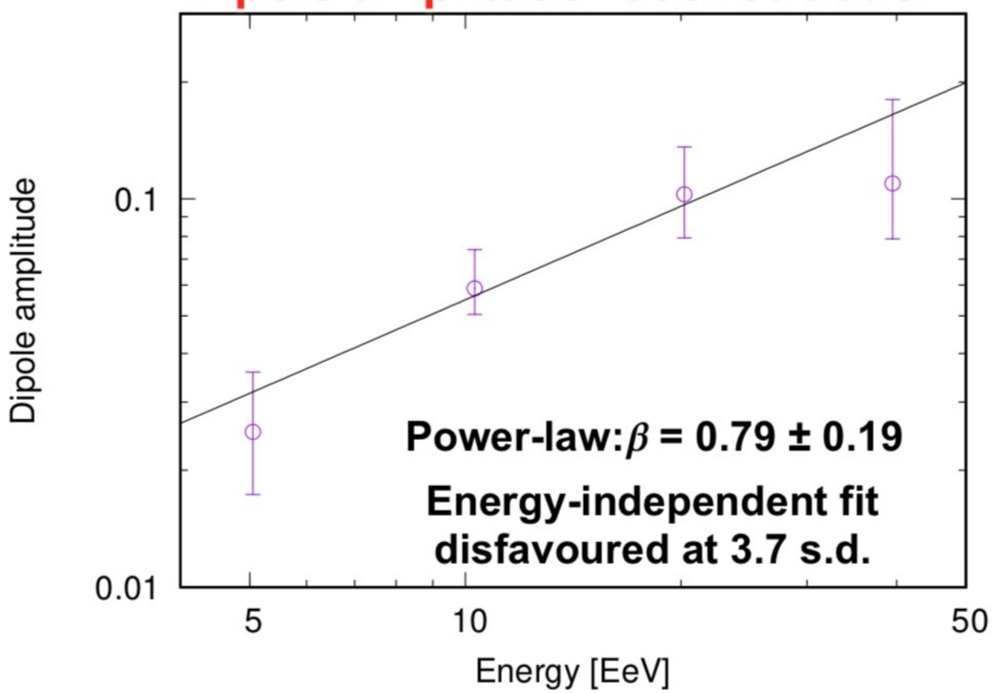
[Auger Coll. arXiv 1808.03579, just accepted by ApJ]

Dividing the E > 8 EeV bin into three

Energy [EeV]	events	a_1^α	b_1^α	r_1^α	φ_1^α [°]	$P(\geq r_1^\alpha)$
8 - 16	24,070	-0.011 ± 0.009	0.044 ± 0.009	0.046	104 ± 11	3.7×10^{-6}
16 - 32	6,604	0.007 ± 0.017	0.050 ± 0.017	0.051	82 ± 20	0.014
≥ 32	1,513	-0.03 ± 0.04	0.05 ± 0.04	0.06	115 ± 35	0.26

Constant phase in spite of a (naturally) more limited significance of the amplitude

Dipole amplitude reconstruction



Indication of an increase of the dipole amplitude vs energy

Constant direction

Large-scale analysis: other studies

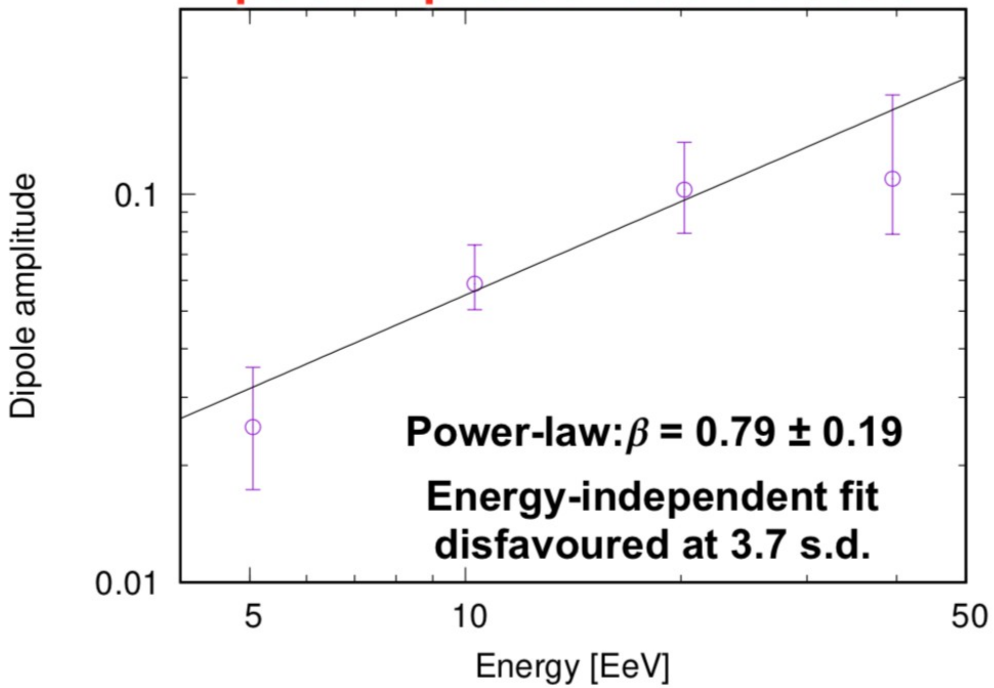
Obviously
Very Important !

But: *What does it mean ?*

Is this evidence for extragalactic origin ?

$\geq r_1^{\alpha}$)
10^{-6}
014
26
amplitude

Dipole amplitude reconstruction



Indication of an increase of the dipole amplitude vs energy

Constant direction

IDICATION OF ANISOTROPY IN ARRIVAL DIRECTIONS OF ULTRA-HIGH-ENERGY COSMIC RAYS THROUGH COMPARISON TO THE FLUX PATTERN OF EXTRAGALACTIC GAMMA-RAY SOURCES

THE PIERRE AUGER COLLABORATION
see the end matter for the full list of authors.

(Published in ApJL as DOI:10.3847/2041-8213/aaa66d)

ABSTRACT

A new analysis of the dataset from the Pierre Auger Observatory provides evidence for anisotropy in the arrival directions of ultra-high-energy cosmic rays on an intermediate angular scale, which is indicative of excess arrivals from strong, nearby sources. The data consist of 5514 events above 20 EeV with zenith angles up to 80° recorded before 2017 April 30. Sky models have been created for two distinct populations of extragalactic gamma-ray emitters: active galactic nuclei from the second catalog of hard *Fermi*-LAT sources (2FHL) and starburst galaxies from a sample that was examined with *Fermi*-LAT. Flux-limited samples, which include all types of galaxies from the *Swift*-BAT and 2MASS surveys, have been investigated for comparison. The sky model of cosmic-ray density constructed using each catalog has two free parameters, the fraction of events correlating with astrophysical objects and an angular scale characterizing the clustering of cosmic rays around extragalactic sources. A maximum-likelihood ratio test is used to evaluate the best values of these parameters and to quantify the strength of each model by contrast with isotropy. It is found that the starburst model fits the data better than the hypothesis of isotropy with a statistical significance of 4.0σ, the highest value of the test statistic being for energies above 39 EeV. The three alternative models are favored against isotropy with $2.7-3.2\sigma$ significance. The origin of the indicated deviation from isotropy is examined and prospects for more sensitive future studies are discussed.

≈ 5500 UHECRs exploited (≈ 90000 km² sr y)

[Auger Coll. ApJL 853 (2018) L29]

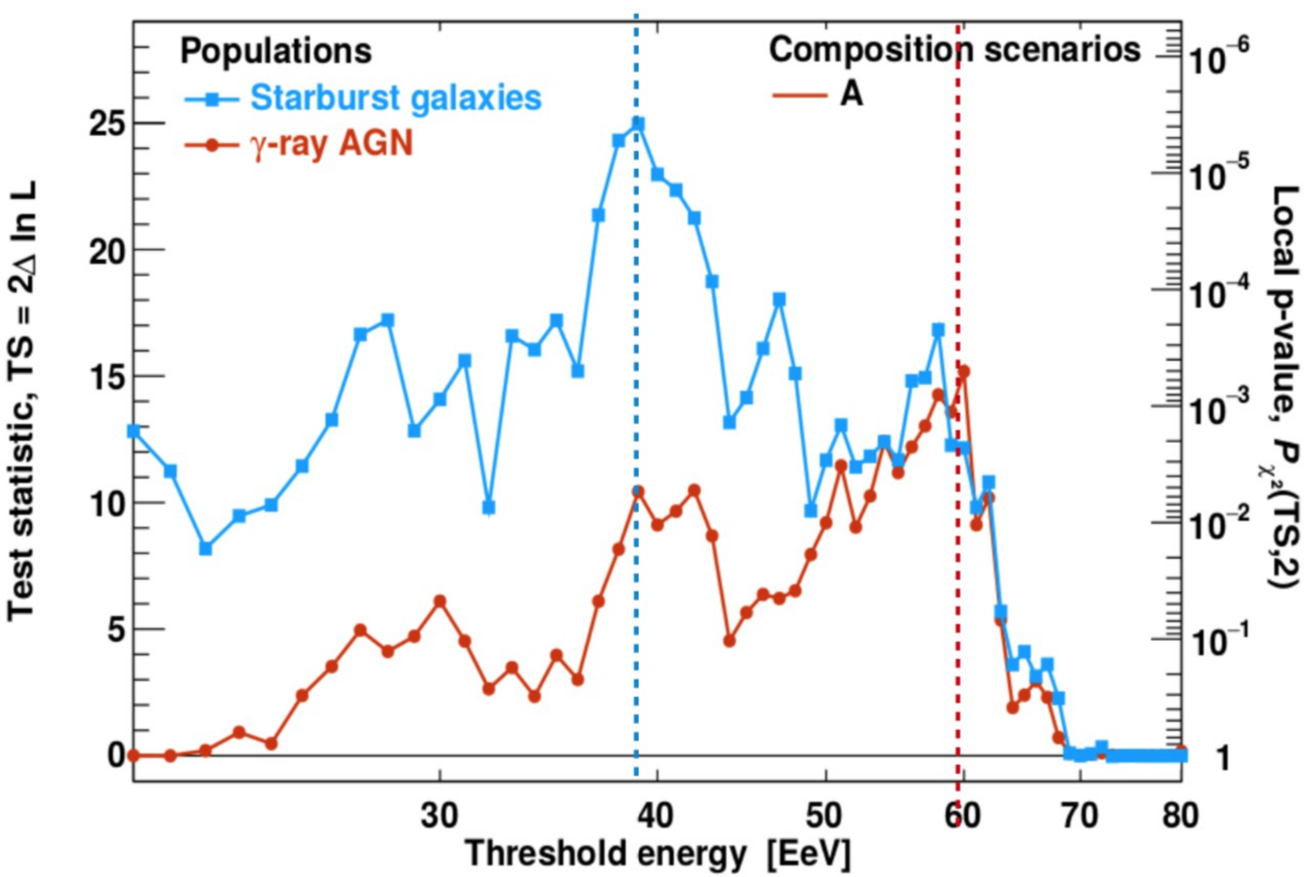
AGNs

TS is maximum for E > 60 EeV (177 events)

SBGs

TS is maximum for E > 39 EeV (894 events)

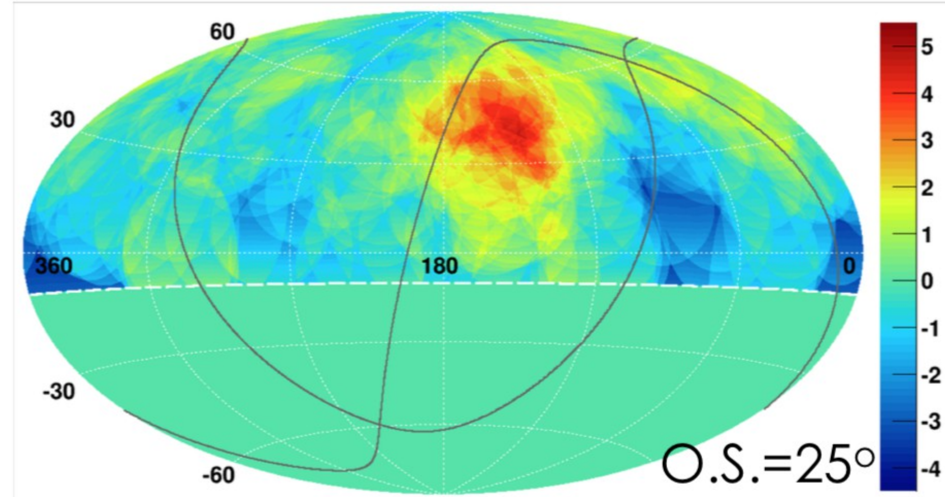
TS as a function of energy threshold

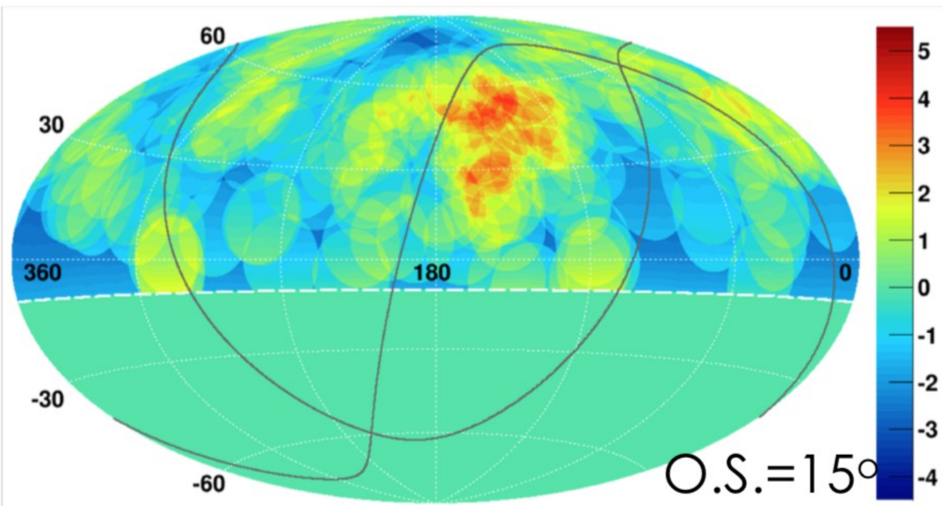


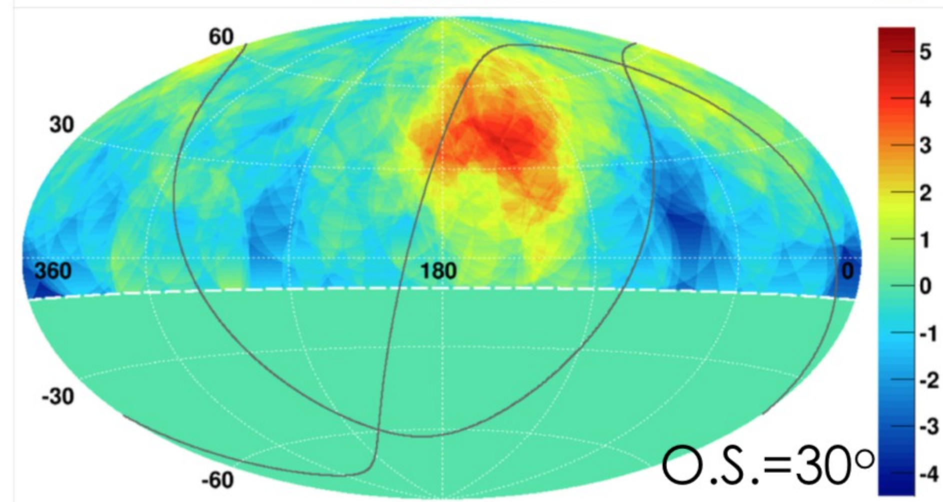
Angular Scan (>57EeV,10 years)

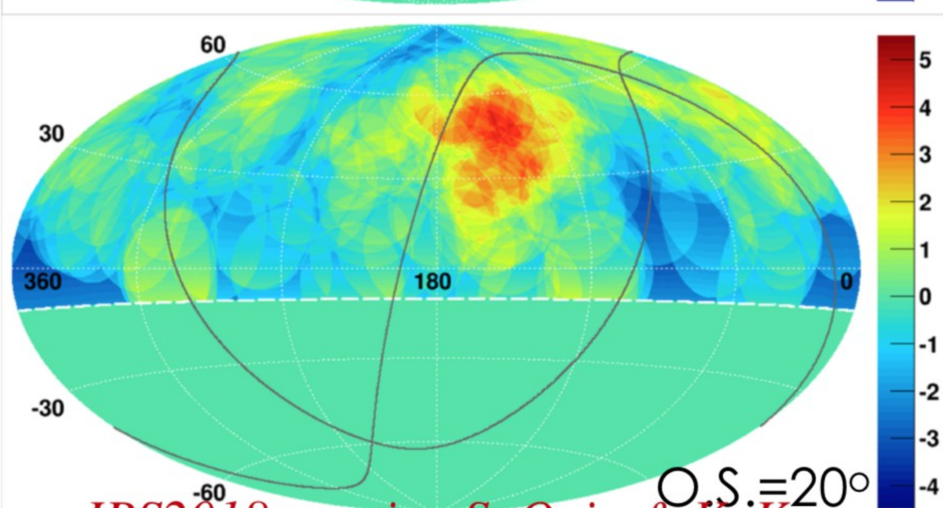
Preliminary

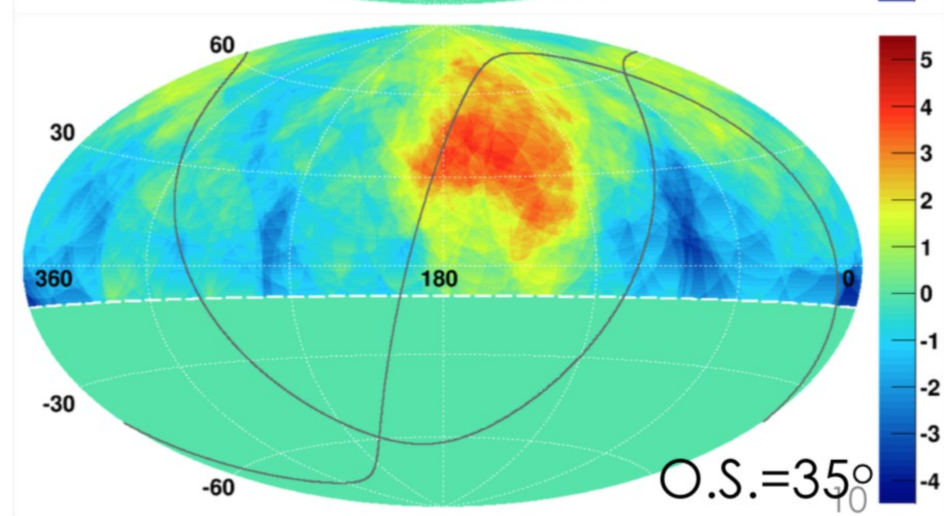
O.S. : oversampling radius











From JPS2018 meeting S. Ogio & K. Kawata

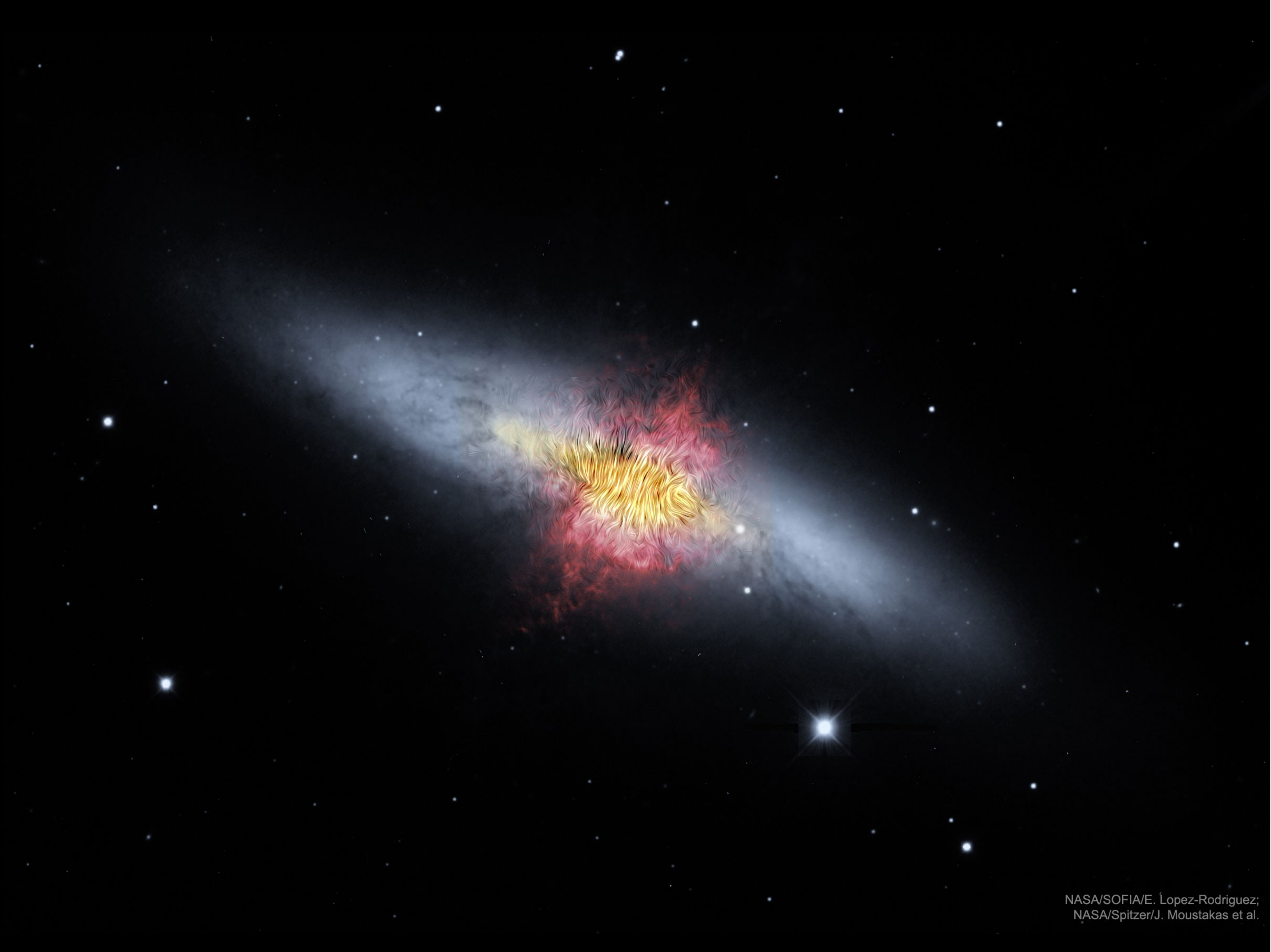
Star Burst Galaxies   (?!)

Final Stages of stellar evolution ?

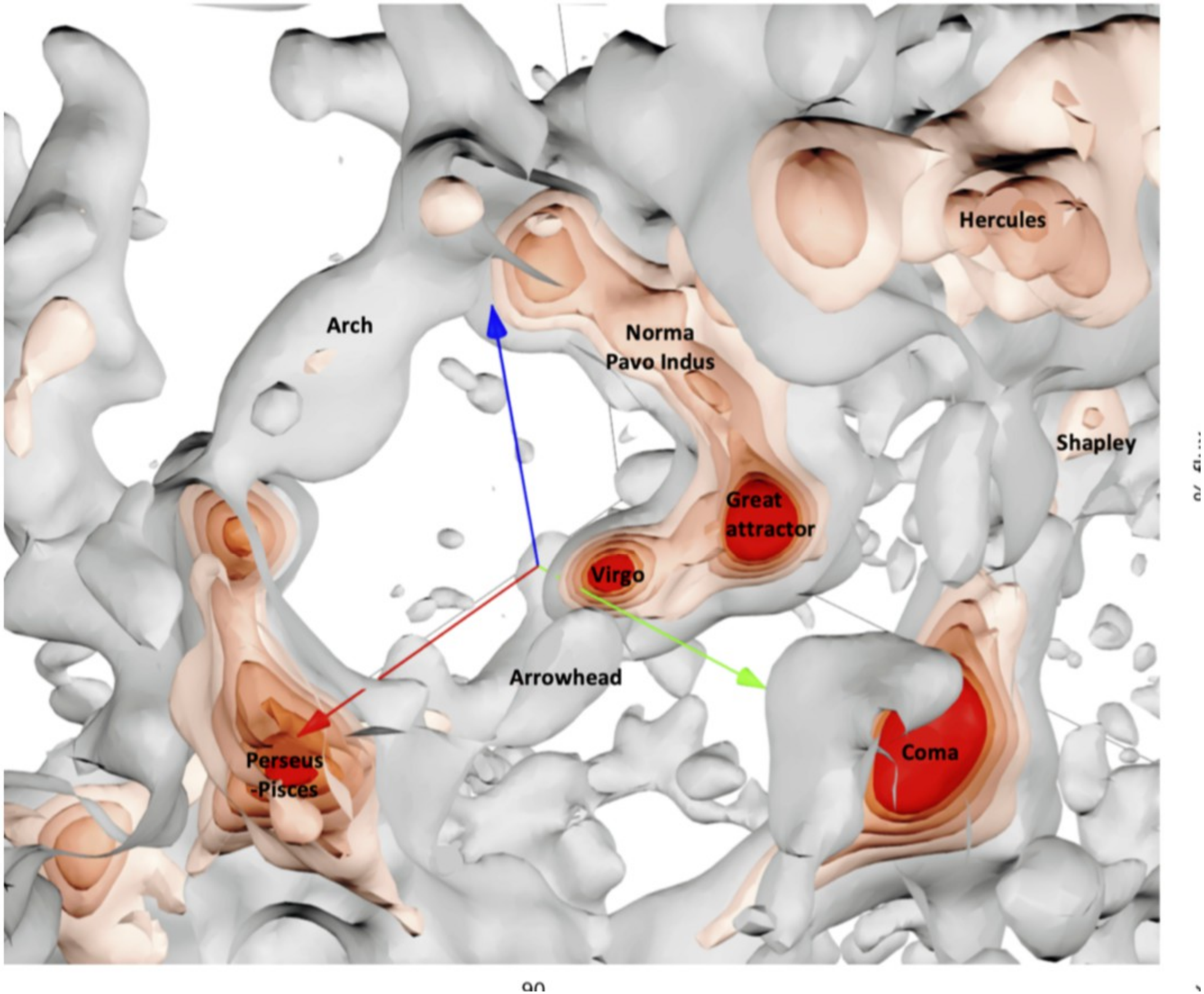
Collective effect due to
Galactic Wind generated by the ensemble
of SN explosions ?


COSGROVE'S
COSMOS
Astrophotography by Patrick A. Cosgrove ©2021
Bode's Galaxy (Messier 81) and the CigarGalaxy(Messier 82)


2019 - Hubble



NASA/SOFIA/E. Lopez-Rodriguez;
NASA/Spitzer/J. Moustakas et al.

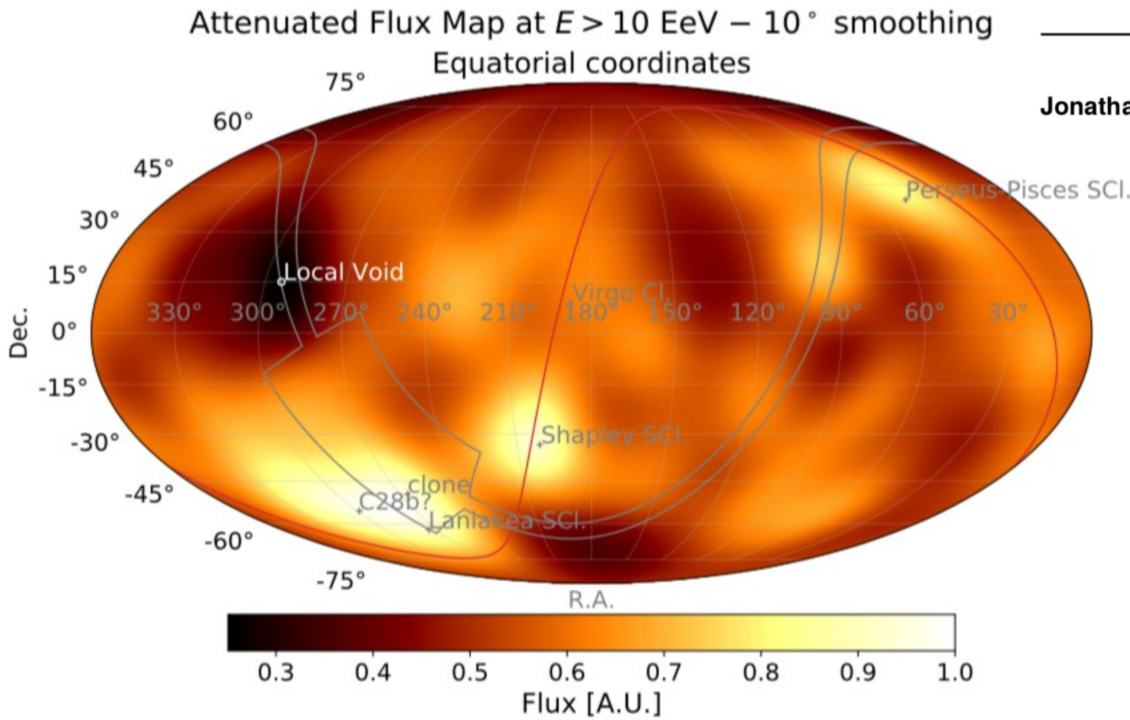


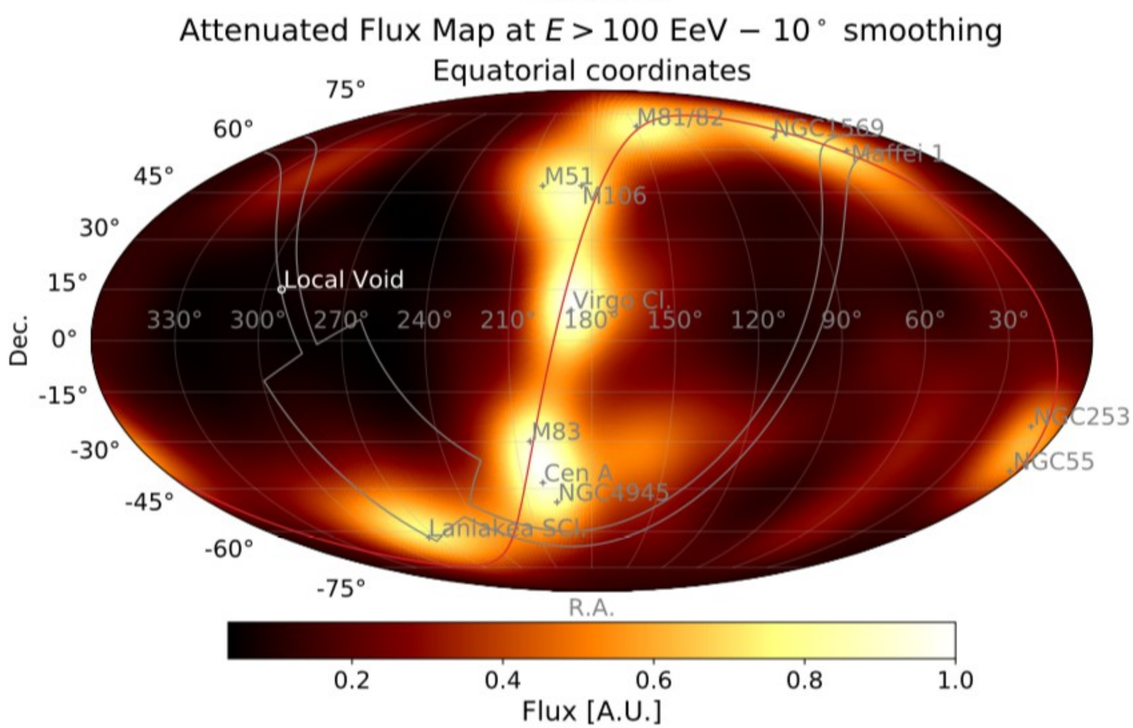
https://sketchfab.com/3d-models/
quasi-linear-construction-of-the-density-field
-91448f58ed5b4a30b5dc270a34fb4352

Cosmographic model of the astroparticle skies

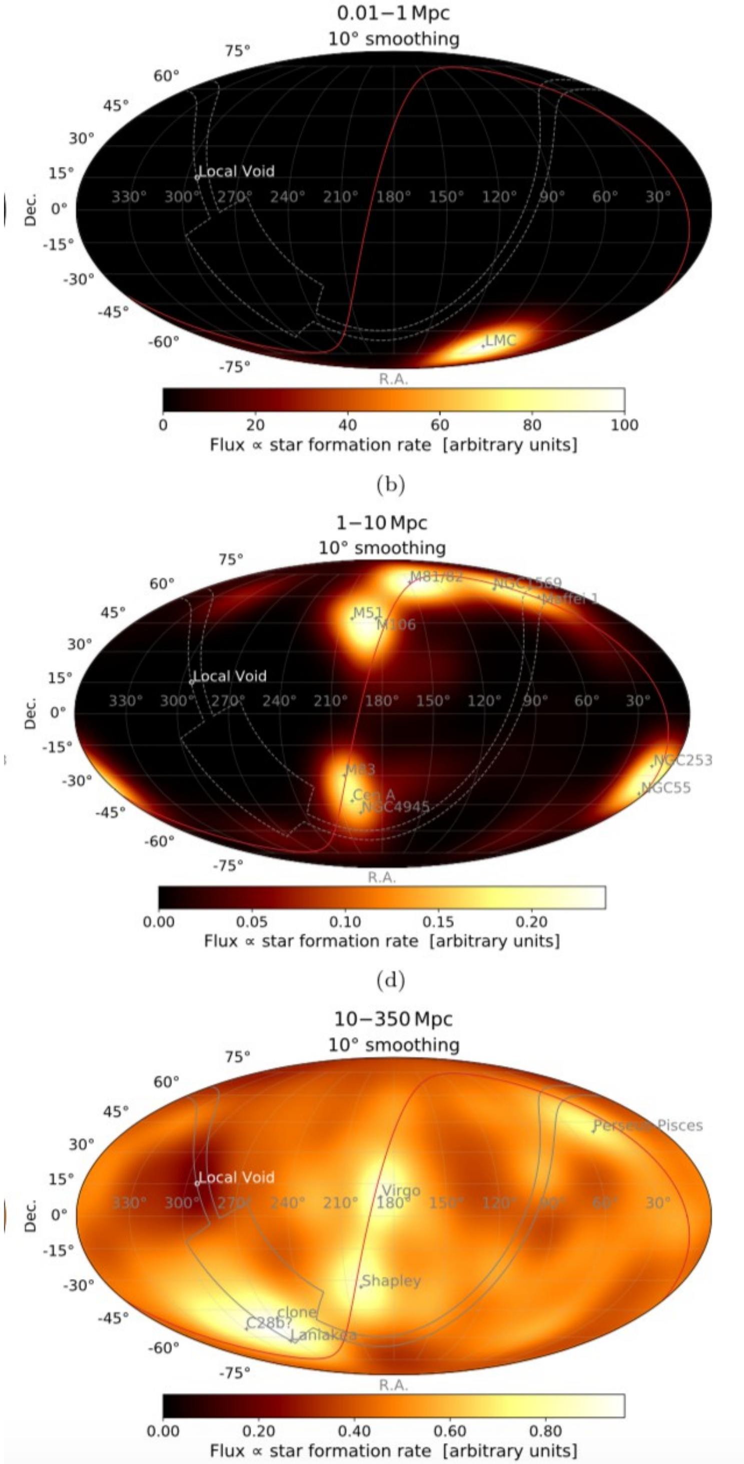
Jonathan Biteau,[a,*] Sullivan Marafico,[a] Younes Kerfis[a] and Olivier Deligny[a]

ICRC 2021



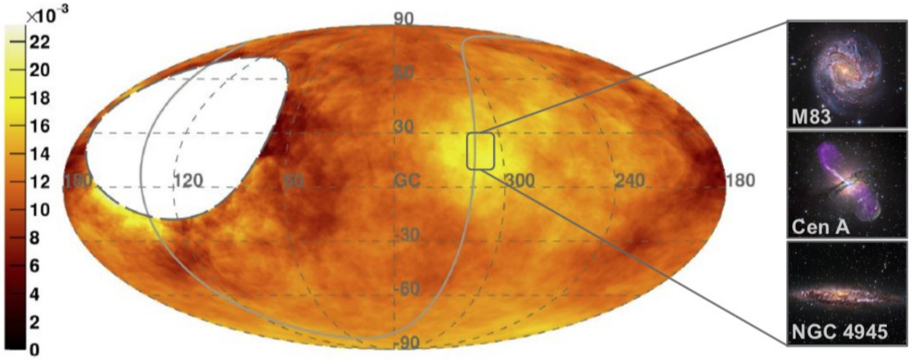


J. Biteau:
Stellar formation rate map



Anisotropy searches at highest energies – catalogs

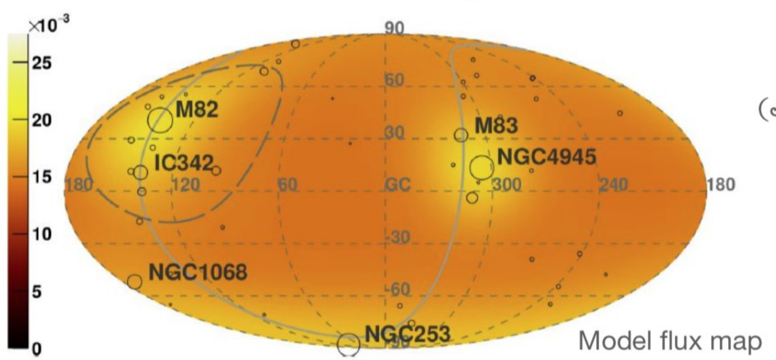
$\Phi(E_{Auger} > 41$ EeV) [km^{-2} sr^{-1} yr^{-1}] - Galactic coordinates - $\Psi = 24°$



Direction fixed to that of Cen A, free E_{th} and Ψ

$E_{th} > 41$ EeV, $\Psi = 27°$: **3.9σ post-trial** deviation from isotropy (5% excess)

Starburst galaxies (radio) - expected $\Phi(E_{Auger} > 38$ EeV) [km^{-2} sr^{-1} yr^{-1}]

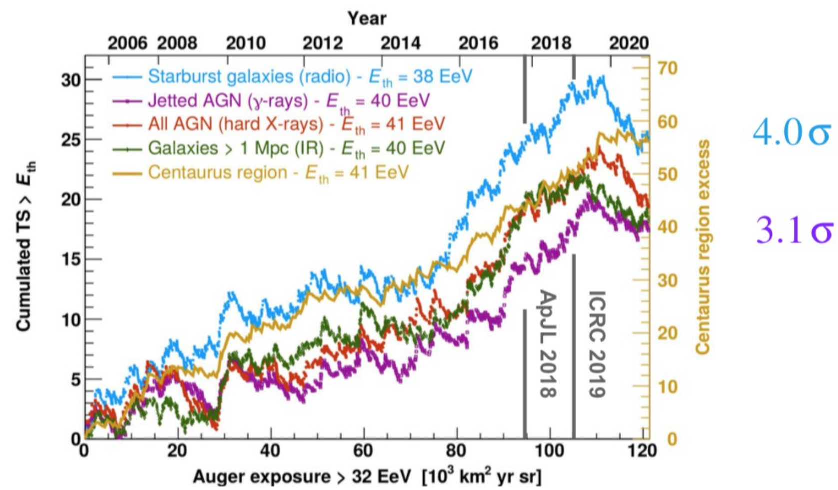


Model flux map

(Jonathan Biteau)

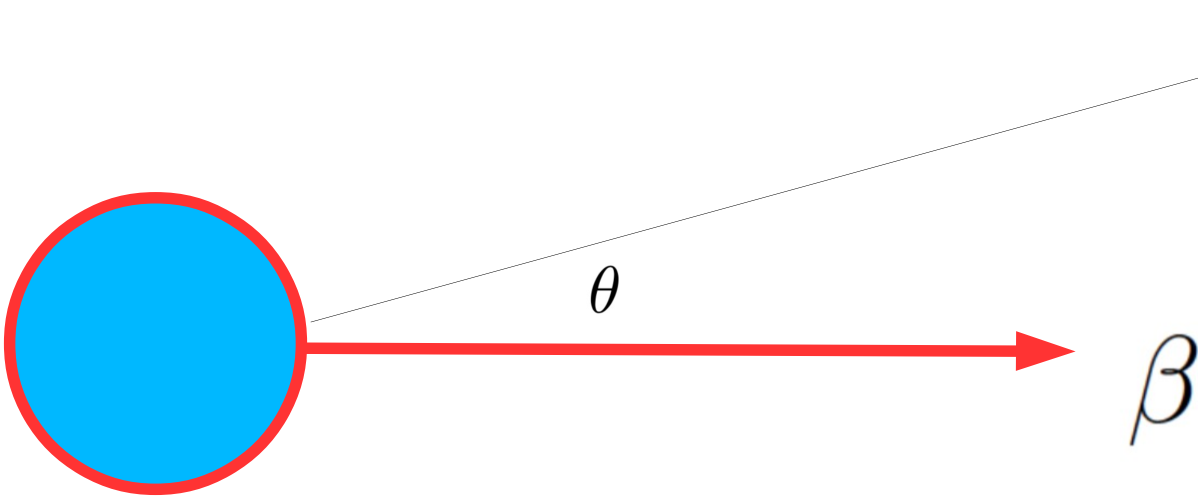
All data until end of 2020, optimized quality cuts: 120,000 km² sr yr

Catalog	E_{th} [EeV]	Ψ [deg]	α [%]	TS	Post-trial p-value
All galaxies (IR)	40	24^{+16}_{-8}	15^{+10}_{-6}	18.2	6.7×10^{-4}
Starbursts (radio)	38	25^{+11}_{-7}	9^{+6}_{-4}	24.8	3.1×10^{-5}
All AGNs (X-rays)	41	27^{+14}_{-9}	8^{+5}_{-4}	19.3	4.0×10^{-4}
Jetted AGNs (γ-rays)	40	23^{+9}_{-8}	6^{+4}_{-3}	17.3	1.0×10^{-3}



Growth of test statistic (TS) compatible with linear increase
Discovery threshold of 5σ expected in 2025 – 2030 (Phase II)
Other means to increase sensitivity (Auger 85% sky coverage)

Effects of Relativistic Beaming



$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Lorentz factor

Simplest modeling of a source
as a plasma "blob" moving relativistically
and emitting particles i*sotropically in the "blob frame"*

Emission strongly peaked forward in "lab frame"

[Doppler Factor]

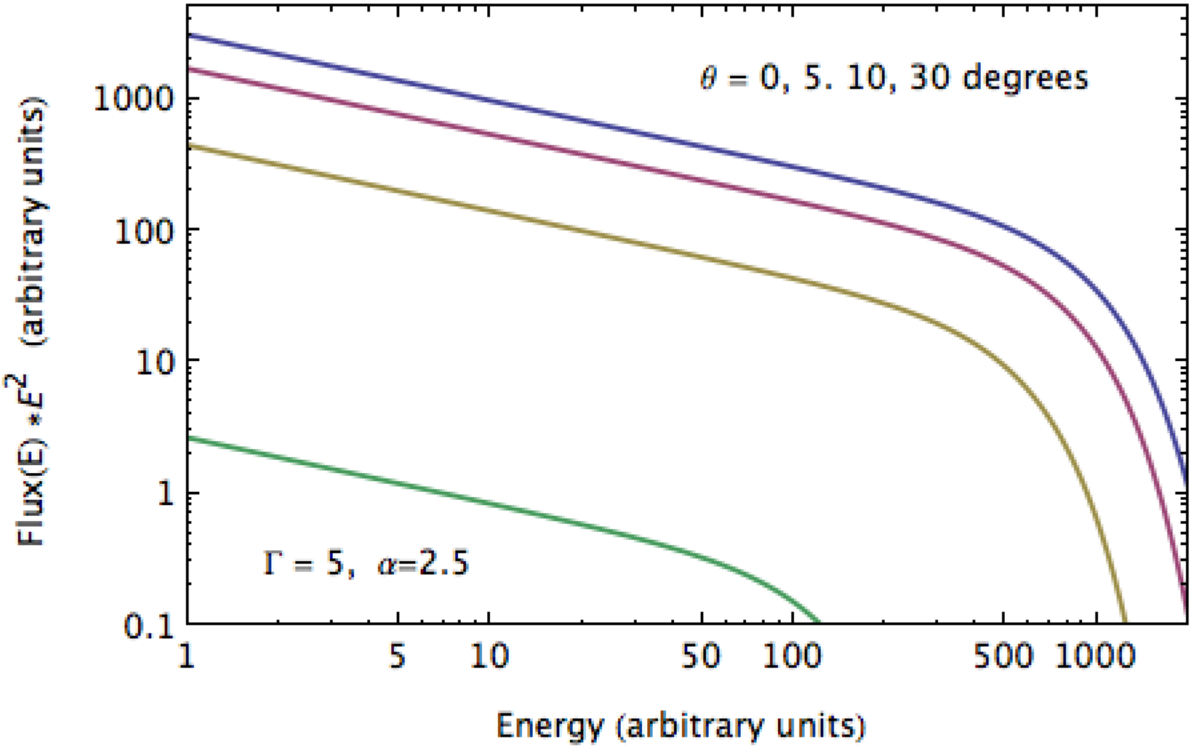
$$\delta = \frac{1}{\Gamma\,(1-\beta\cos\theta)} \simeq \frac{2\,\Gamma}{1+(\Gamma\,\theta)^2}$$

$$\frac{dN}{dE^*\, d\cos\theta^*} = q(E^*)$$

Isotropic emission
in “blob frame”

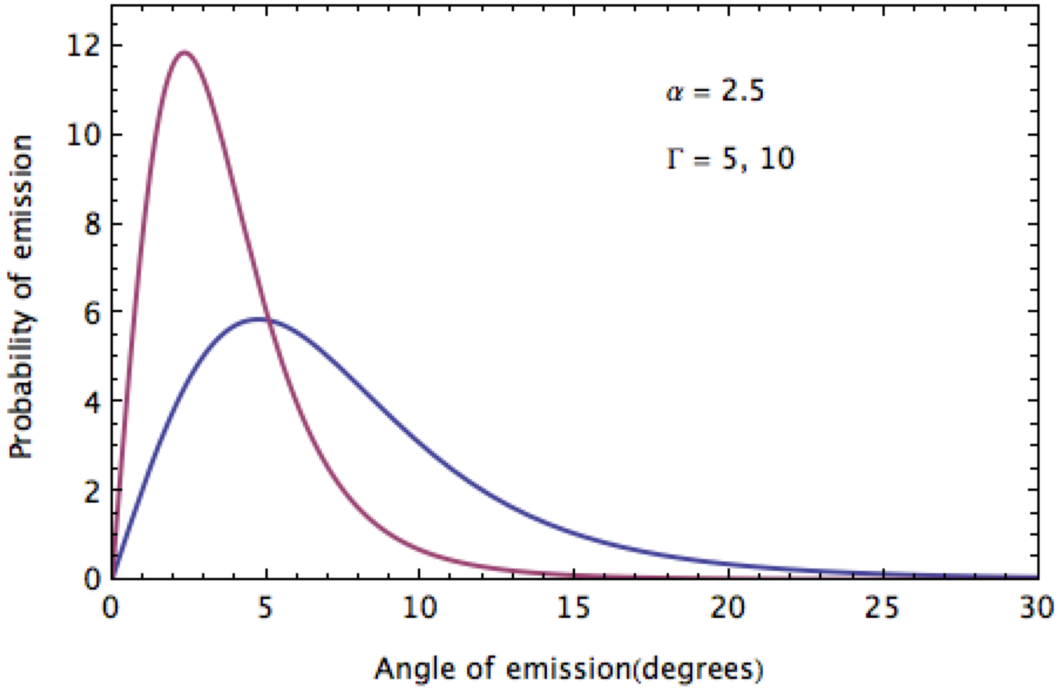
$$\frac{dN}{dE\, d\cos\theta} = q\left(\frac{E}{\delta}\right)\ \delta$$

Relativistic
Beaming:
(in lab frame)



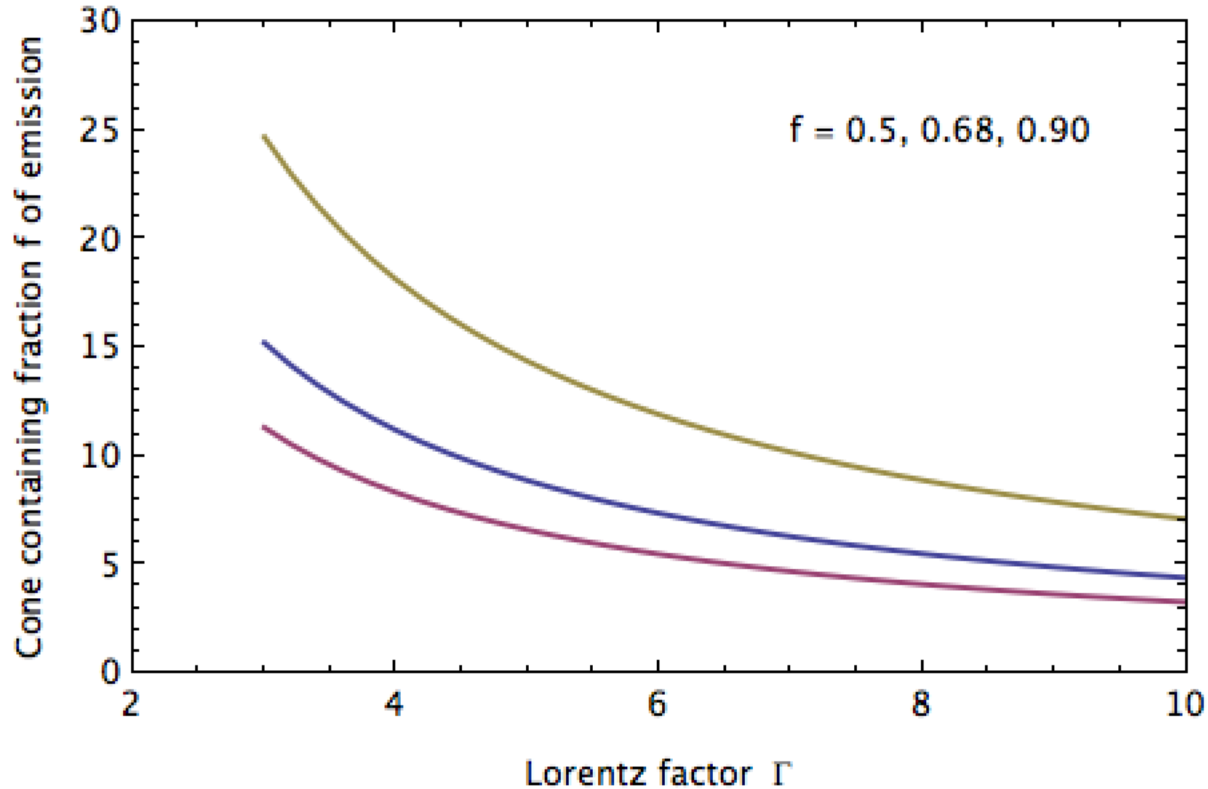
$$N(\theta) \propto \delta^{1+\alpha}$$

$$\propto [1 + (\Gamma\,\theta)^2]^{-(1+\alpha)}$$

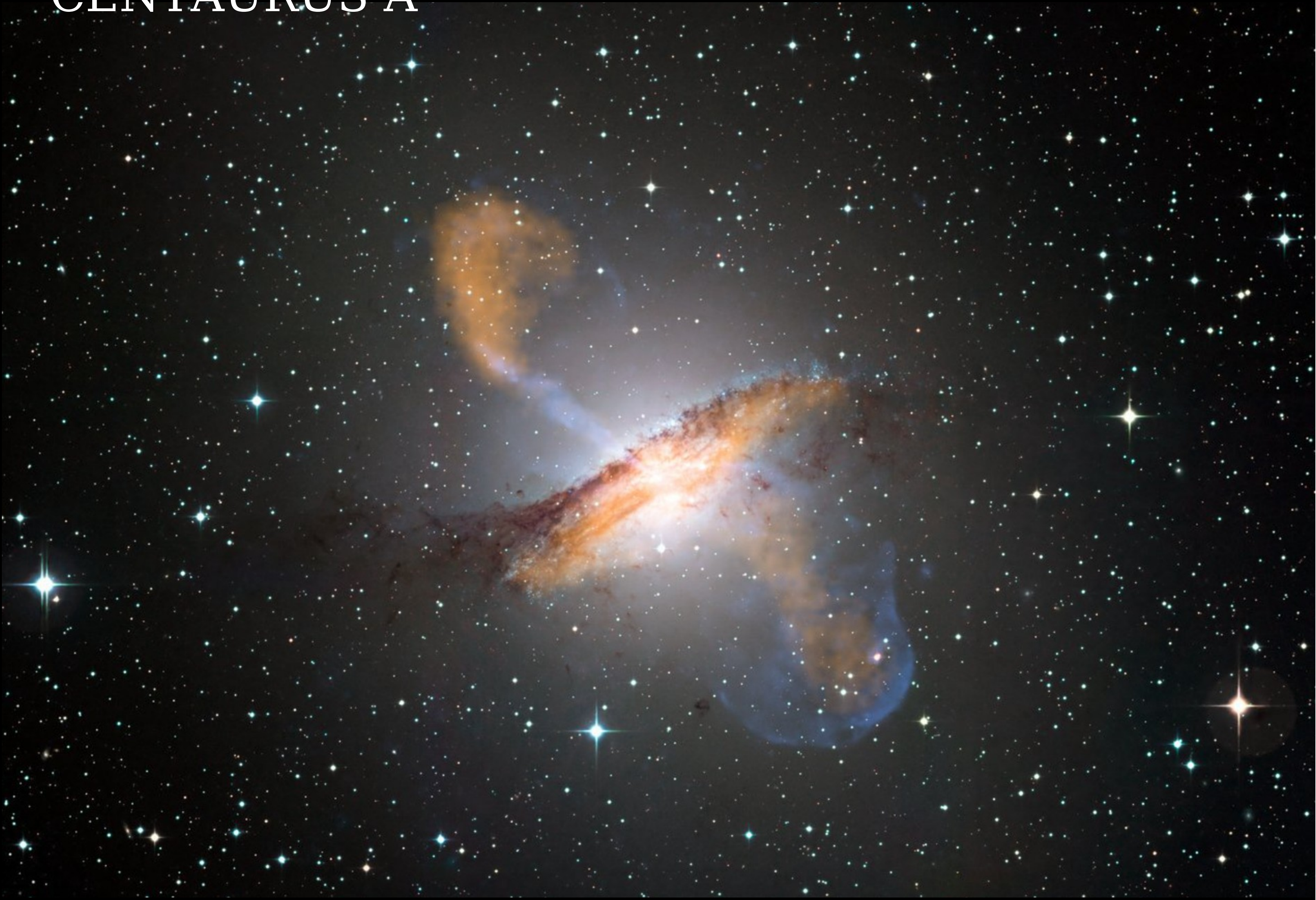


Ensemble of sources with the same Lorentz factor

Distribution of emission angle, forward peaked



CENTAURUS A



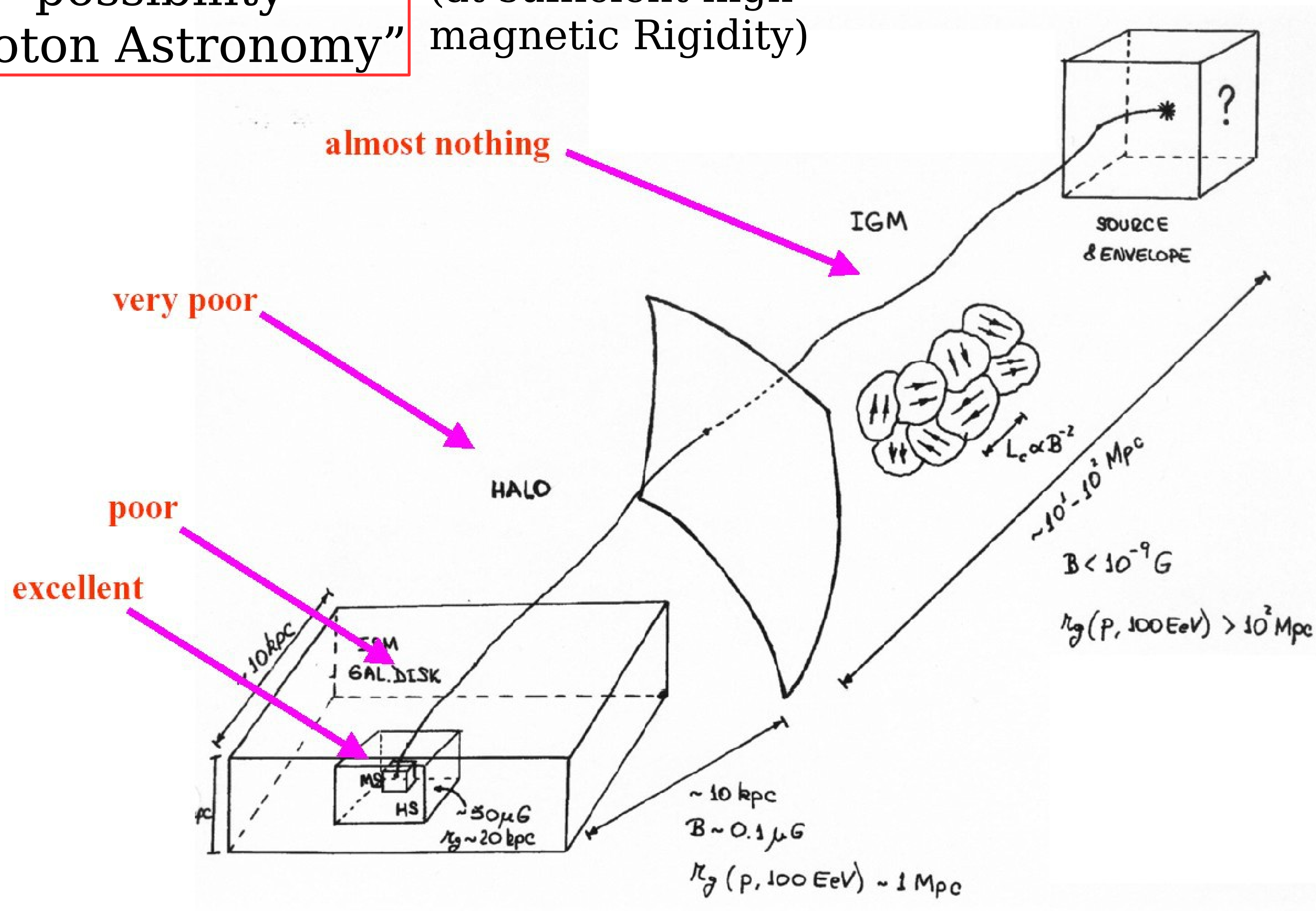
MAGNETIC

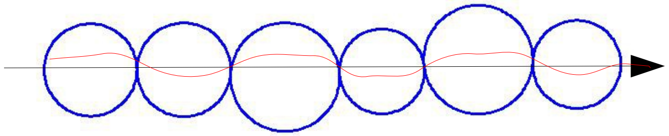
FIELDS

Galactic and extragalactic

The possibility "proton Astronomy"

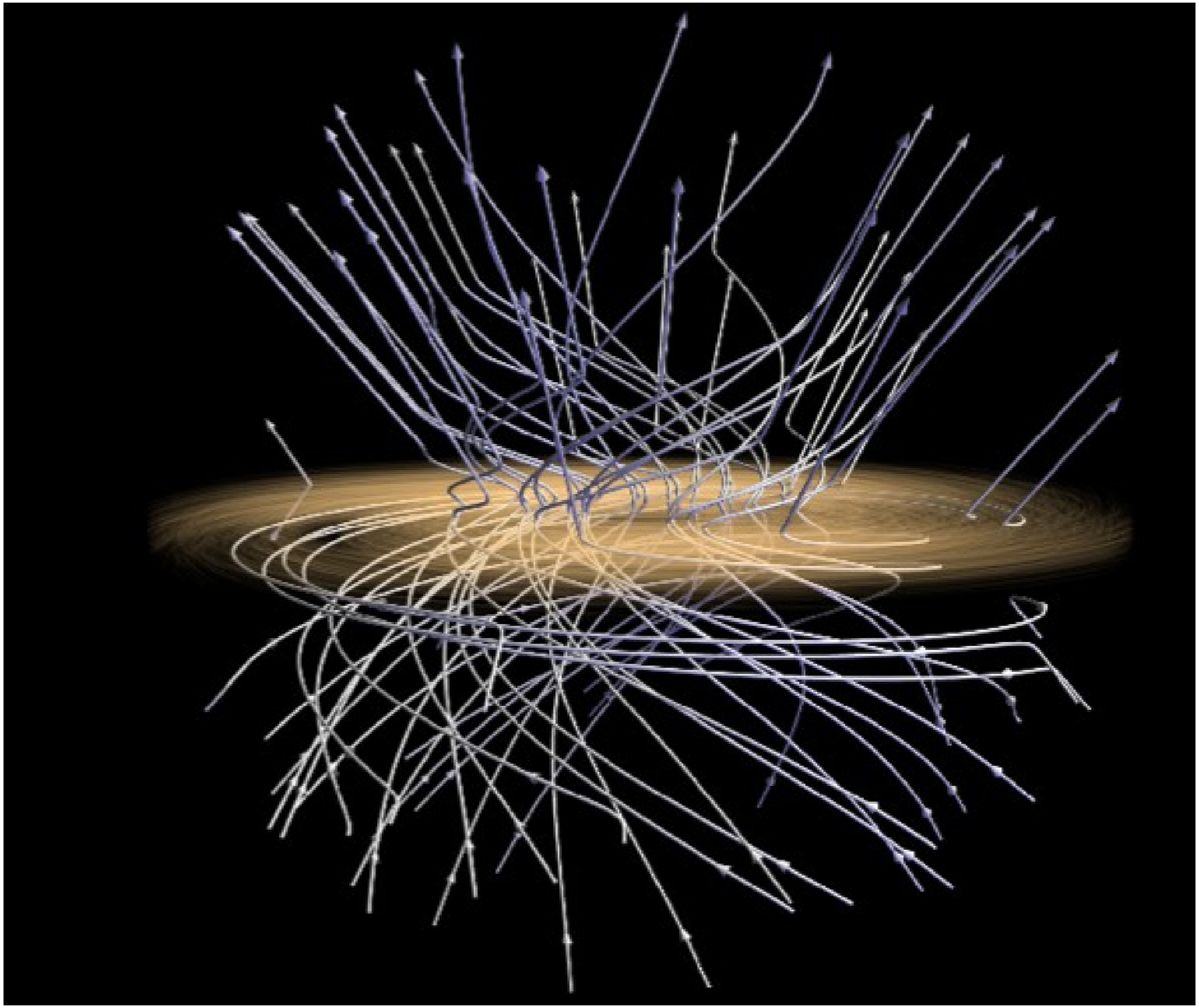
(at sufficient high magnetic Rigidity)





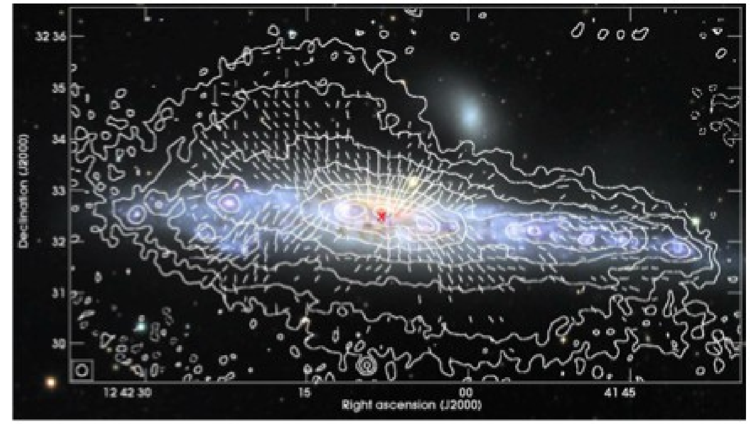
$$\Delta\theta \simeq 0.53^\circ \; Z \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \left(\frac{\sqrt{D\, d}}{\mathrm{Mpc}}\right) \left(\frac{\langle B\rangle}{nG}\right)$$

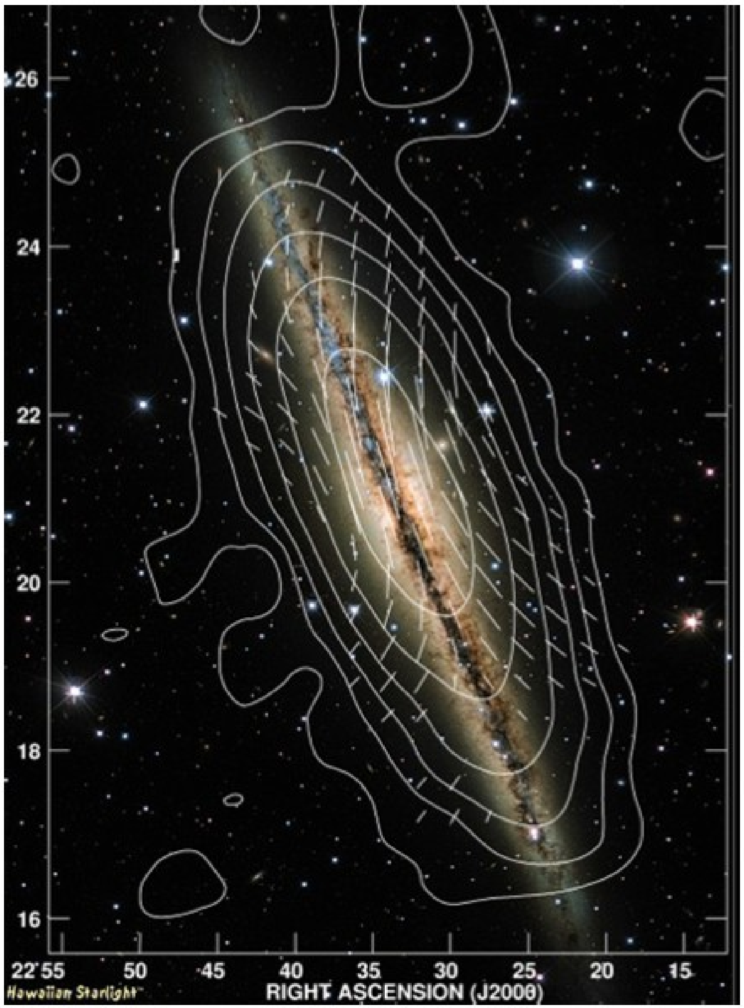
Structure of the Milky Way Magnetic Field



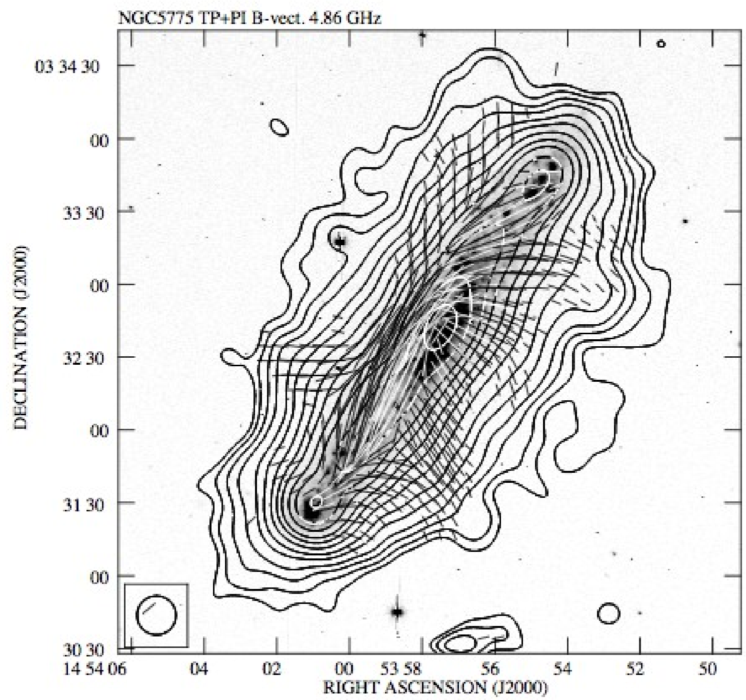
X-field

NGC 4631, M. Krause, arXiv:1401.1317





NGC891, M. Krause MPIfR

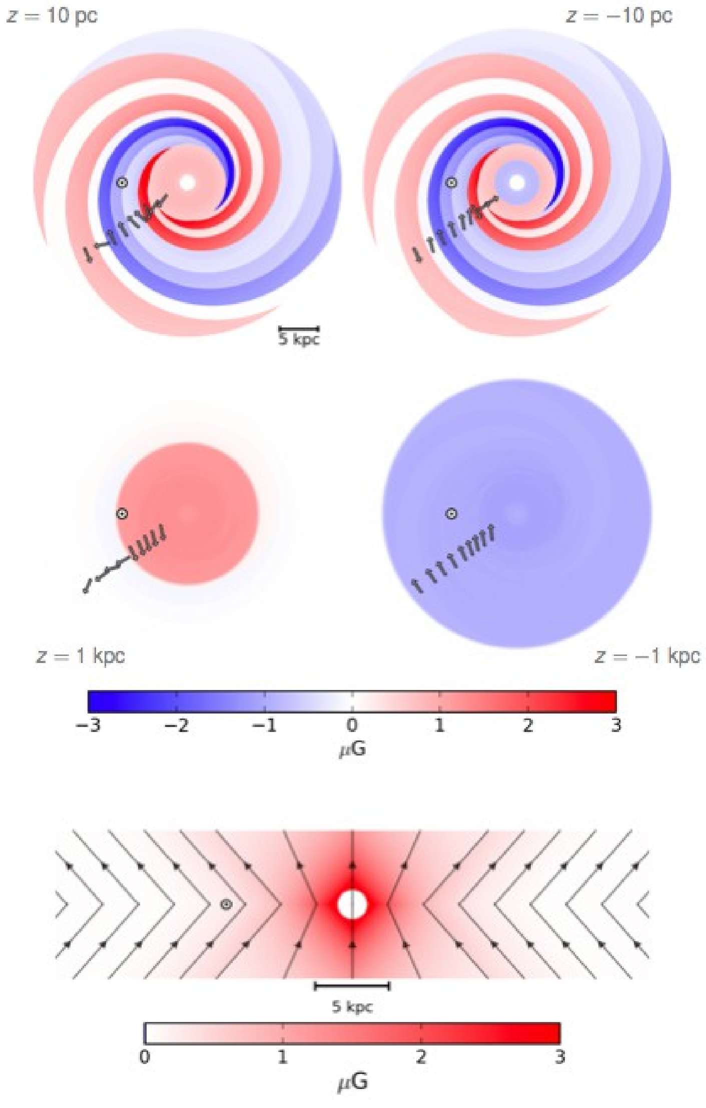


NGC 5775, M. Krause, arXiv:1401.1317

Jansson&Farrar Global Magnetic Field Model (JF12)

three (divergence-free!) components:

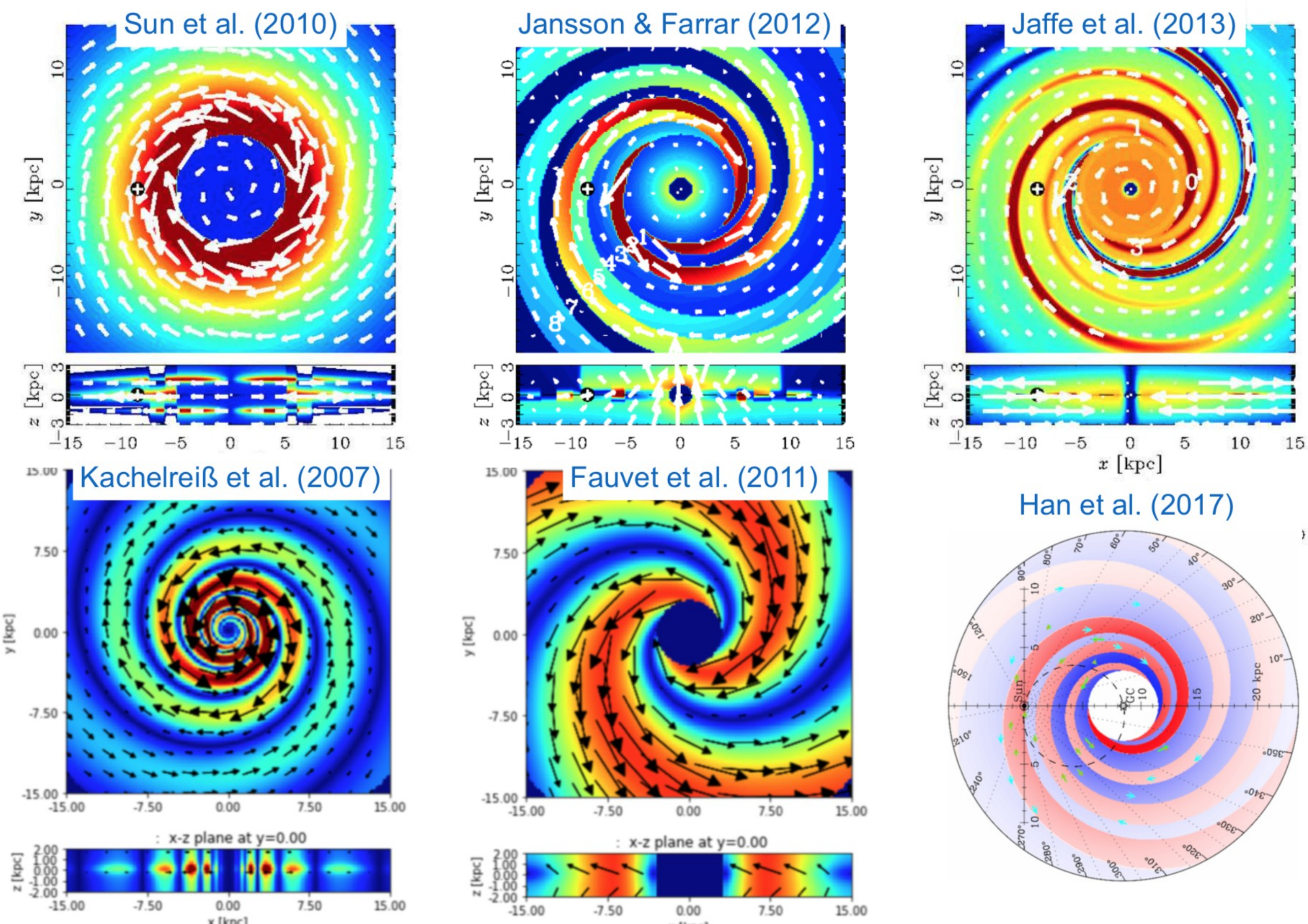
- disk field, ($h \lesssim 0.4$ kpc)
- toroidal halo field ($h_{\text{scale}} \sim 5.3$ kpc)
- "X-field" (halo) NEW
- regular field[a]: 21 parameters
- random field[b]: 13 parameters
- striation: 1 parameter
- CR electron norm.: 1 parameter

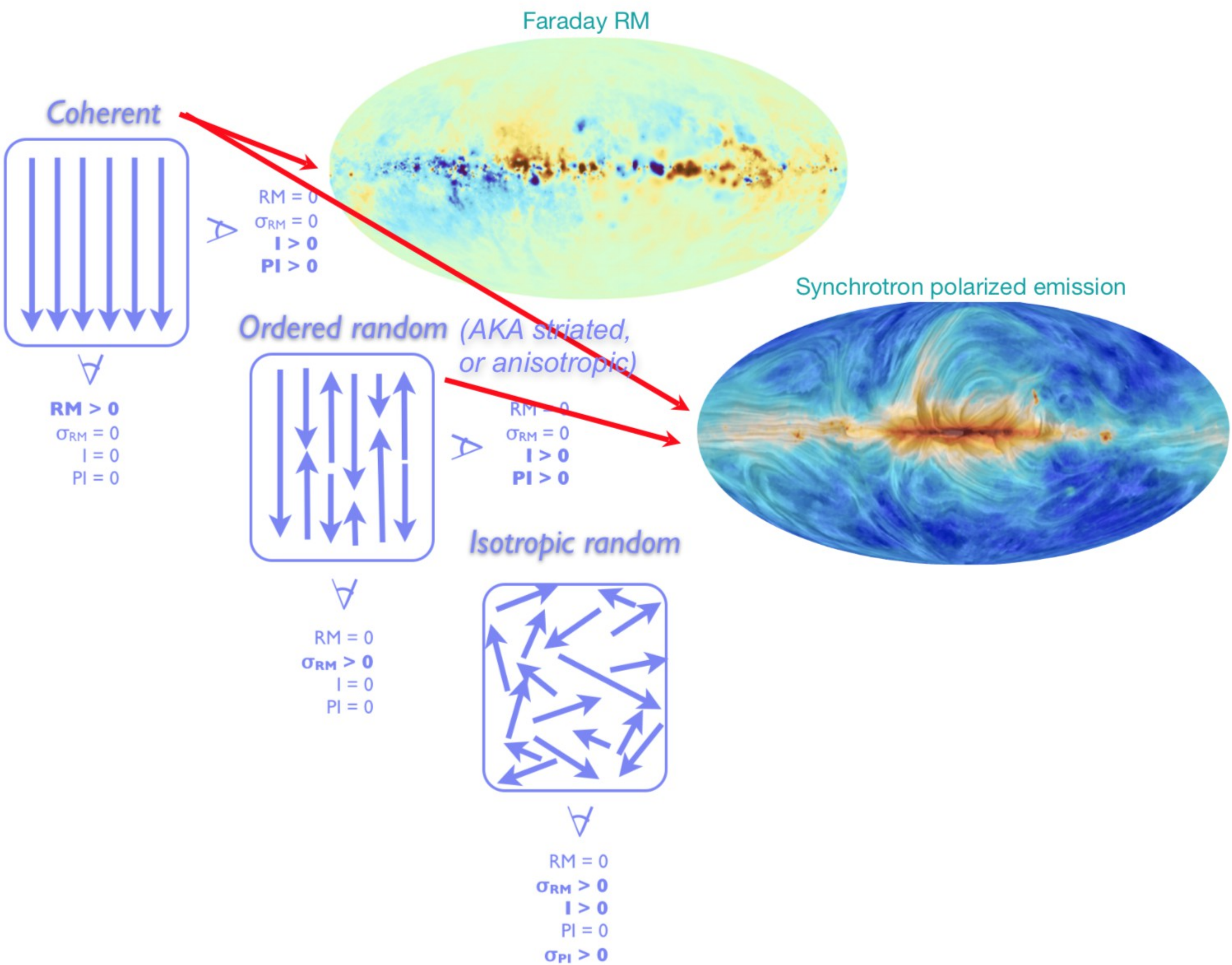


[a] R. Jansson & G.F. Farrar, ApJ **757** (2012) 14
[b] R. Jansson & G.F. Farrar, ApJ **761** (2012) L11

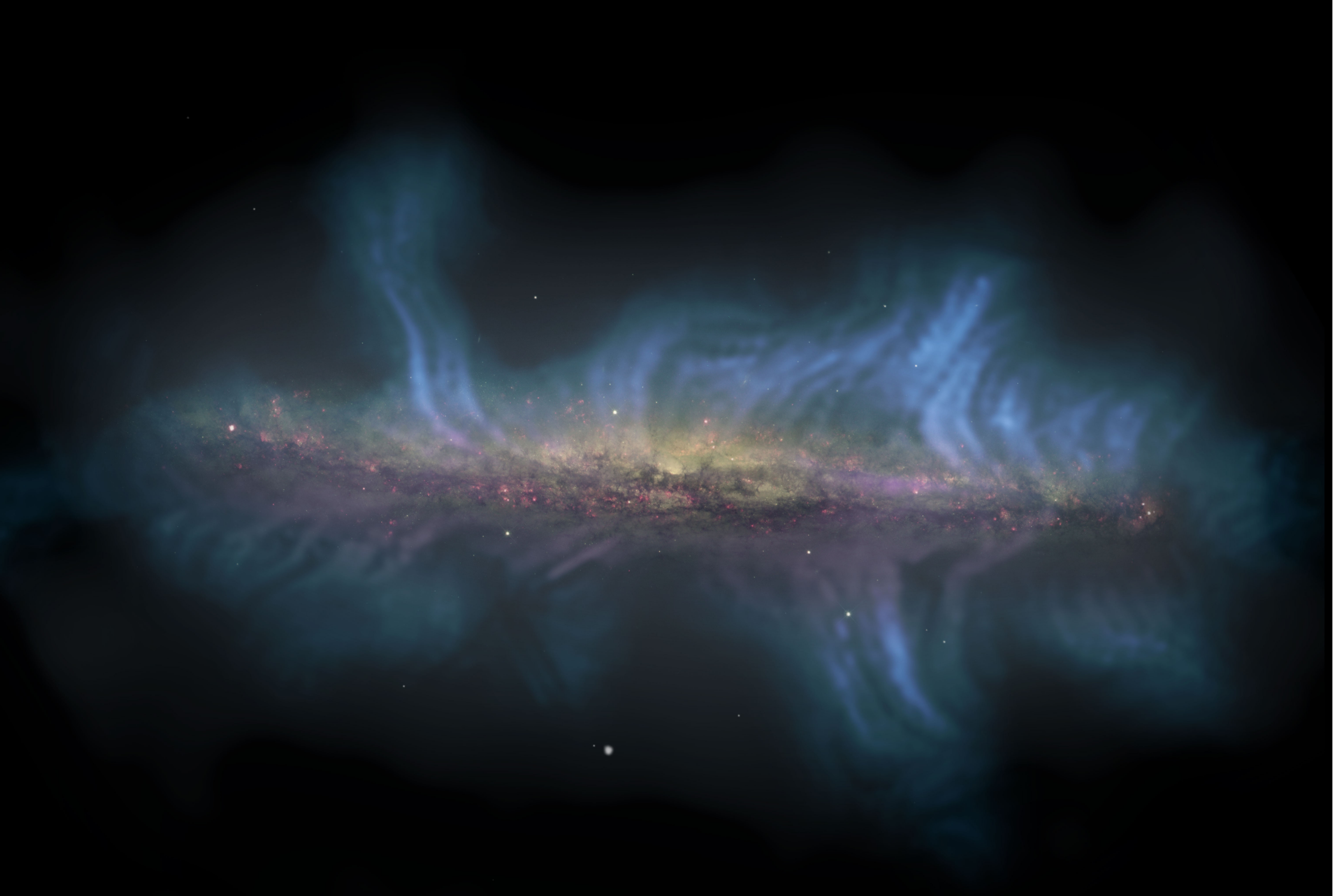
The state of the art

- Very different morphologies can roughly match the same(ish) observables.



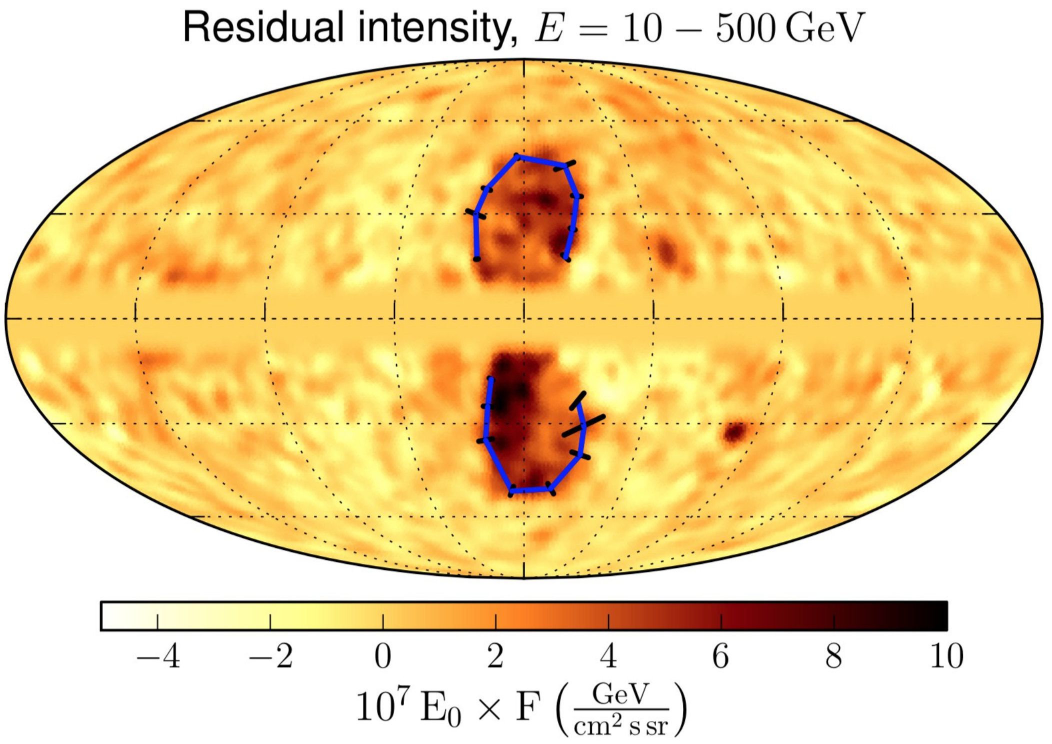


Faraday RM
Synchrotron polarized emission
Coherent
RM = 0
σRM = 0
I > 0
PI > 0
RM > 0
σRM = 0
I = 0
PI = 0
Ordered random (AKA striated, or anisotropic)
RM = 0
σRM = 0
I > 0
PI > 0
RM = 0
σRM > 0
I = 0
PI = 0
Isotropic random
RM = 0
σRM > 0
I > 0
PI = 0
σPI > 0



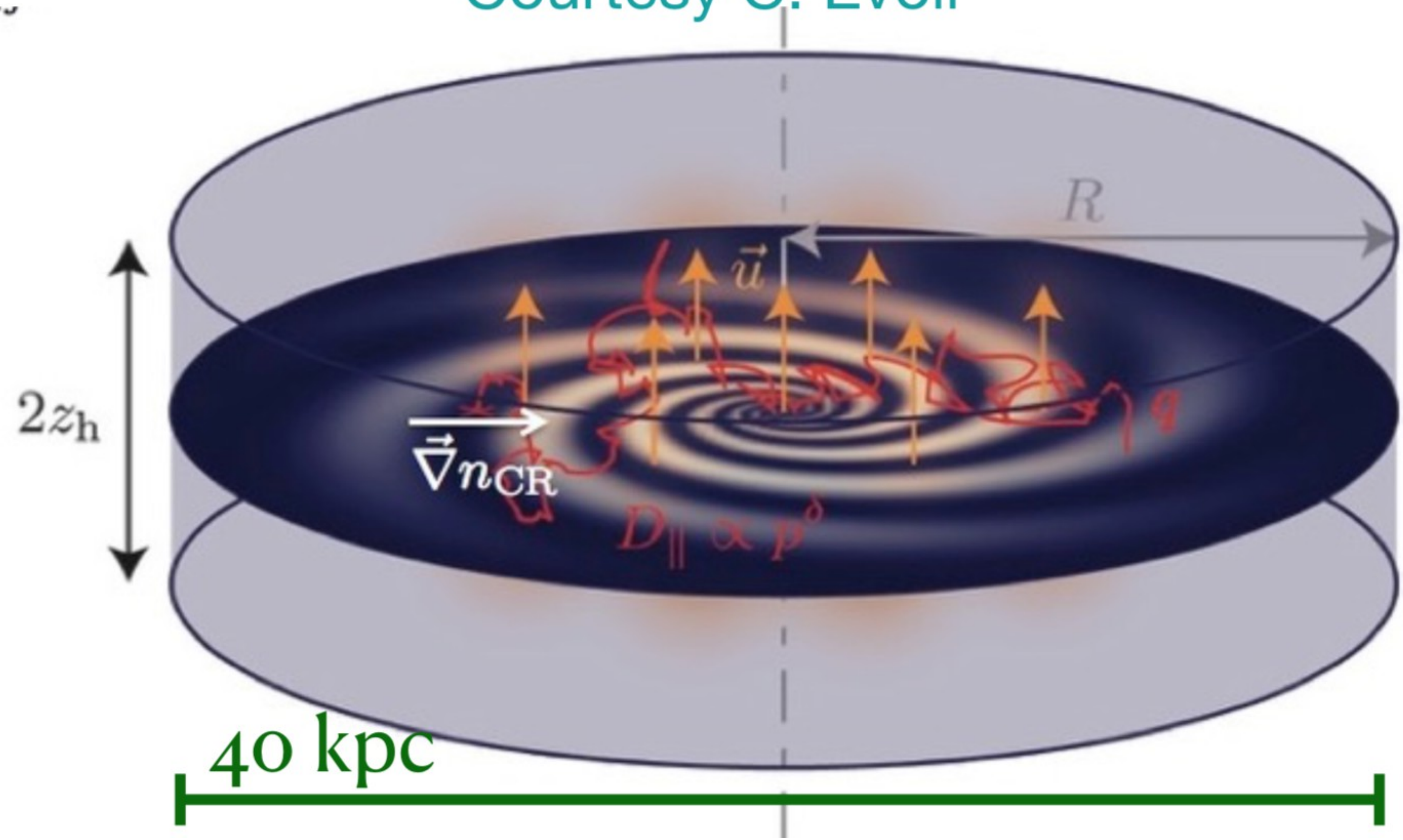
Importance of the “vertical field”

Data: NRAO, NASA, ESA
Composiion: Jayanne English (U. Manitoba)

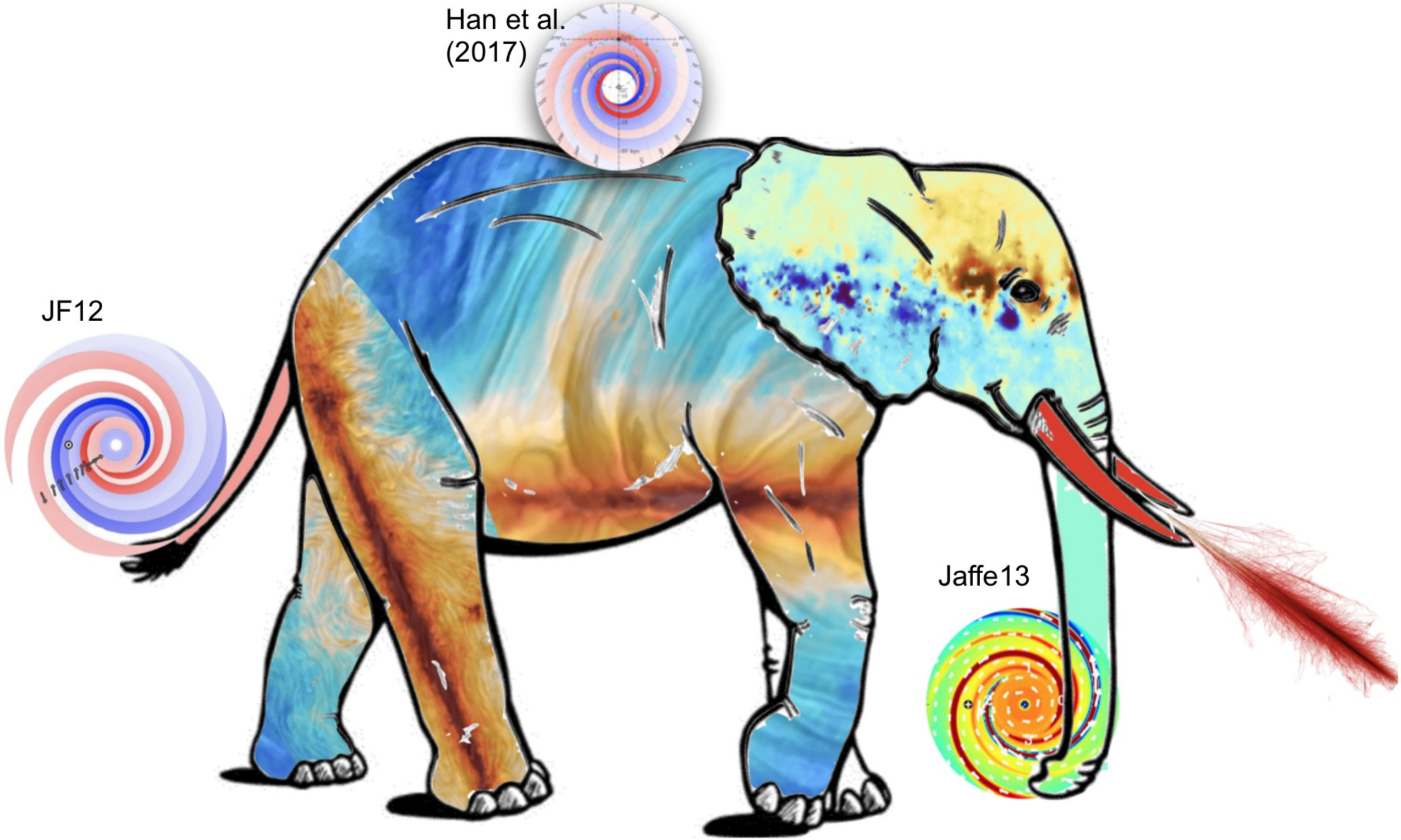


The “FERMI bubbles”

Courtesy C. Evoli

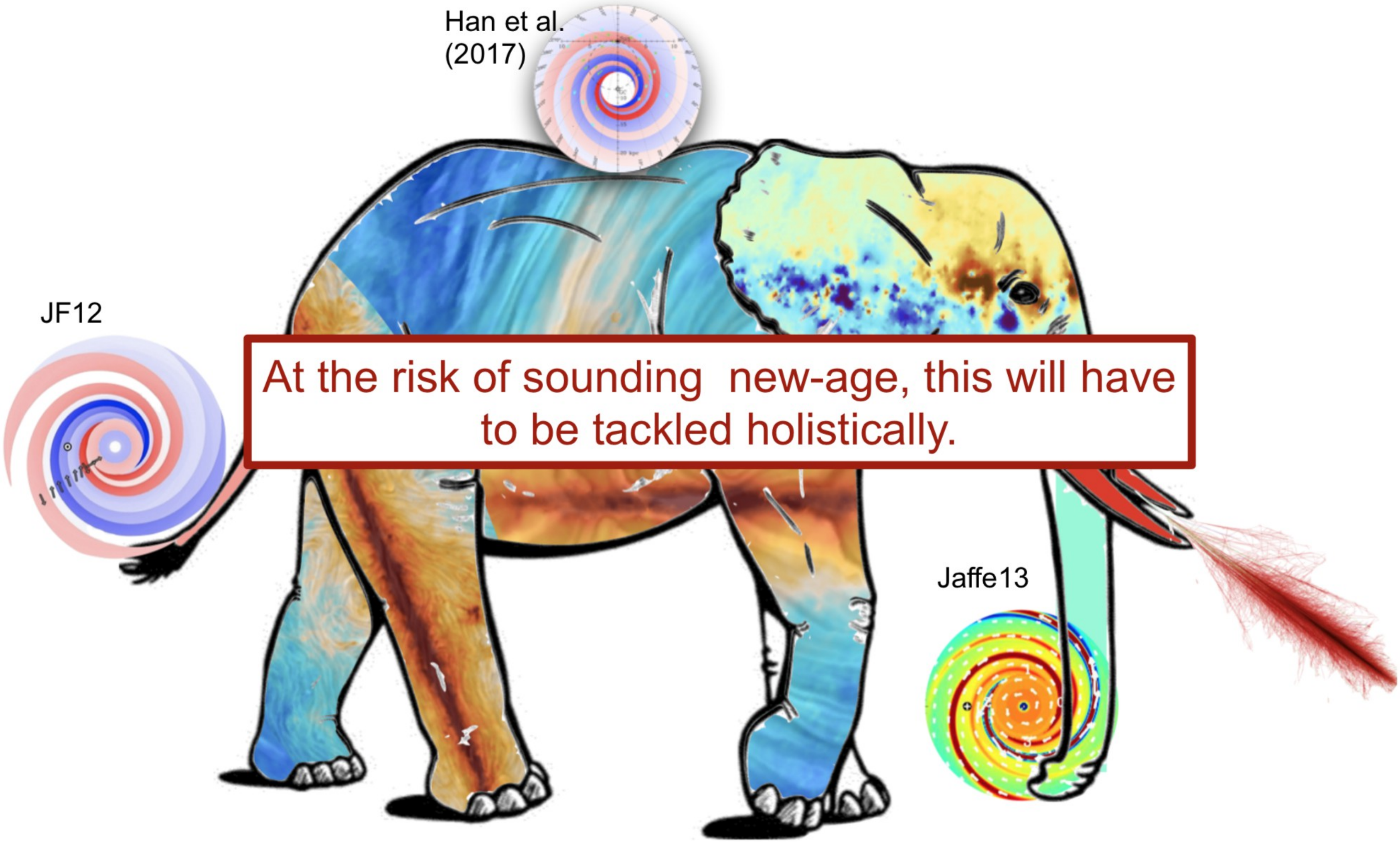


The proverbial elephant



Or maybe an elephant swallowing its tail: “If we knew the GMF, we could then use X to constrain Y. Likewise, if we knew Y, we could use X to constrain the GMF.”

The proverbial elephant



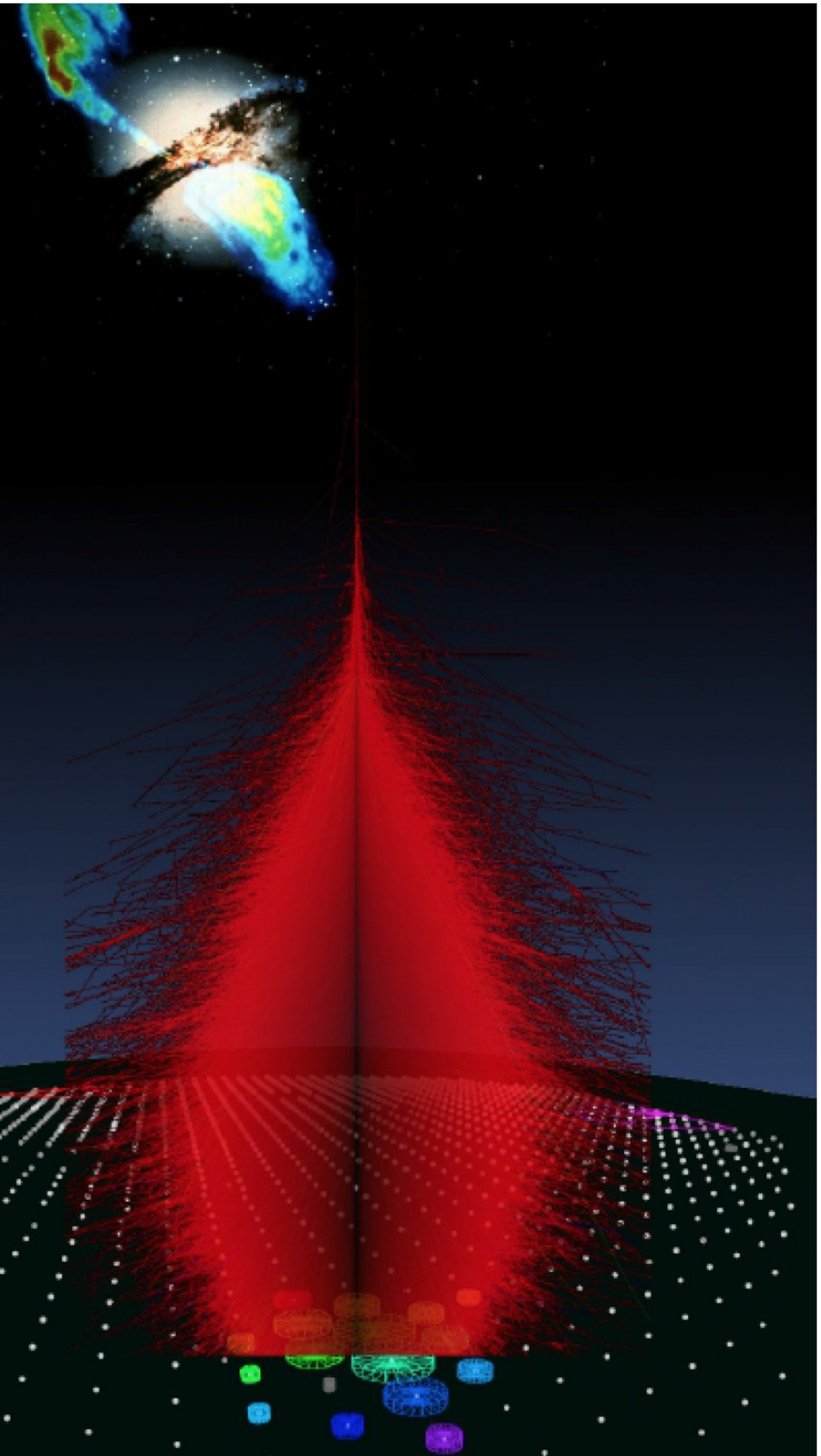
At the risk of sounding new-age, this will have to be tackled holistically.

Or maybe an elephant swallowing its tail: "If we knew the GMF, we could then use X to constrain Y. Likewise, if we knew Y, we could use X to constrain the GMF."

Cosmic Ray Physics
[Astroparticle Physics]

and

HADRONIC INTERACTIONS



the Source

$$E_{\text{lab}} \simeq 10^{20}\ \text{eV}$$

$$\sqrt{s} \simeq 430\ \text{TeV}$$

the Shower

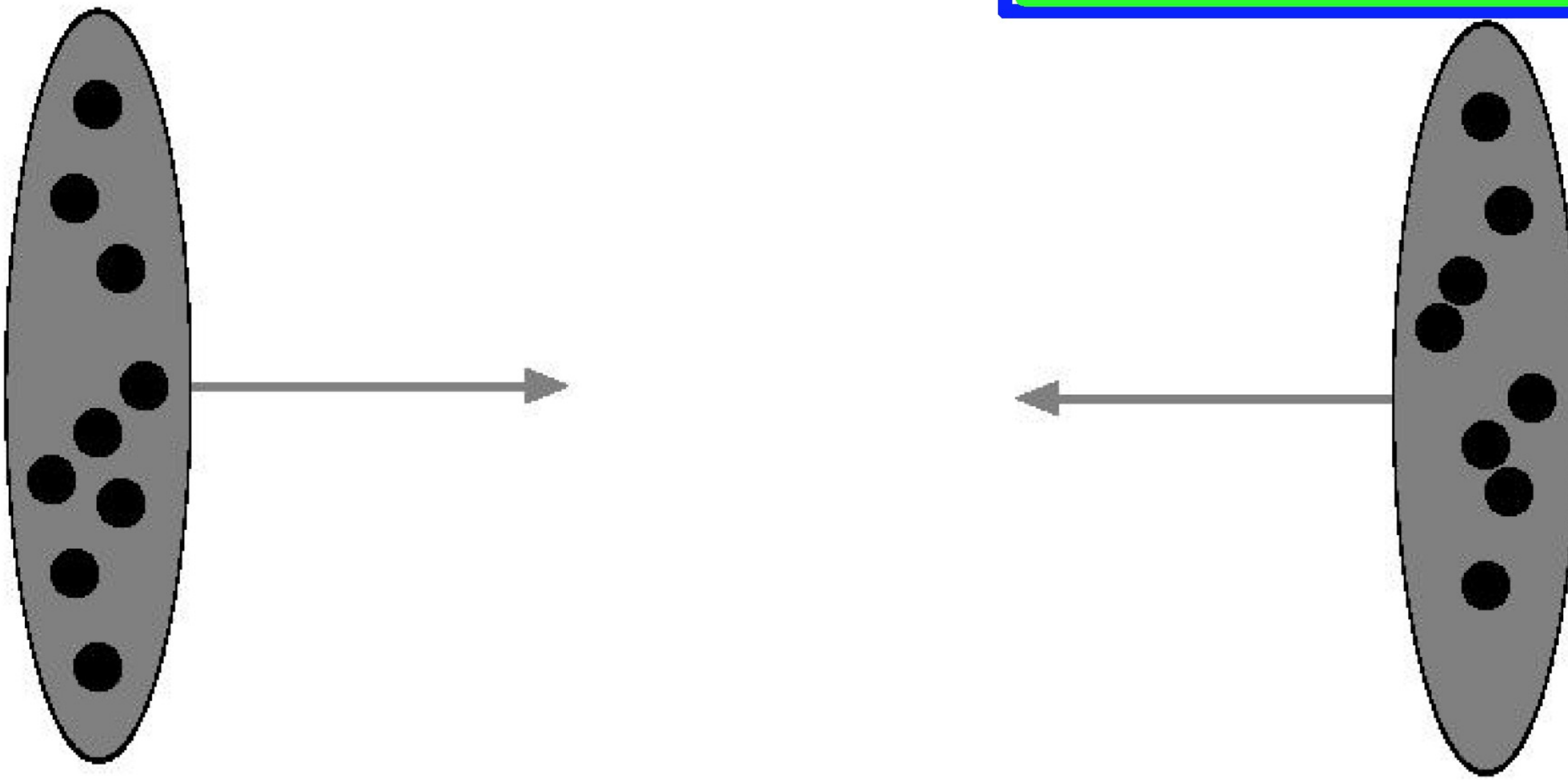
[The estimate of the Energy and Mass of the shower requires the detailed modeling of shower development]

the Data

Hadronic Interactions

Composite (complex) Objects
Multiple interaction structure

QCD



p

Multiple parton interactions
in the same collision

p

Great importance of the LHC data

Total, elastic, inelastic cross sections
"Minimum bias" events
Diffractive events
....
[Need all phase space, including the very forward]

Also potentially important measurements at much lower energy (Fixed Target)

Where are we with the modeling of Hadronic Interactions ?

How large are the uncertainties ?

What are the perspectives to make them smaller ?

What is the impact for present and future studies ?

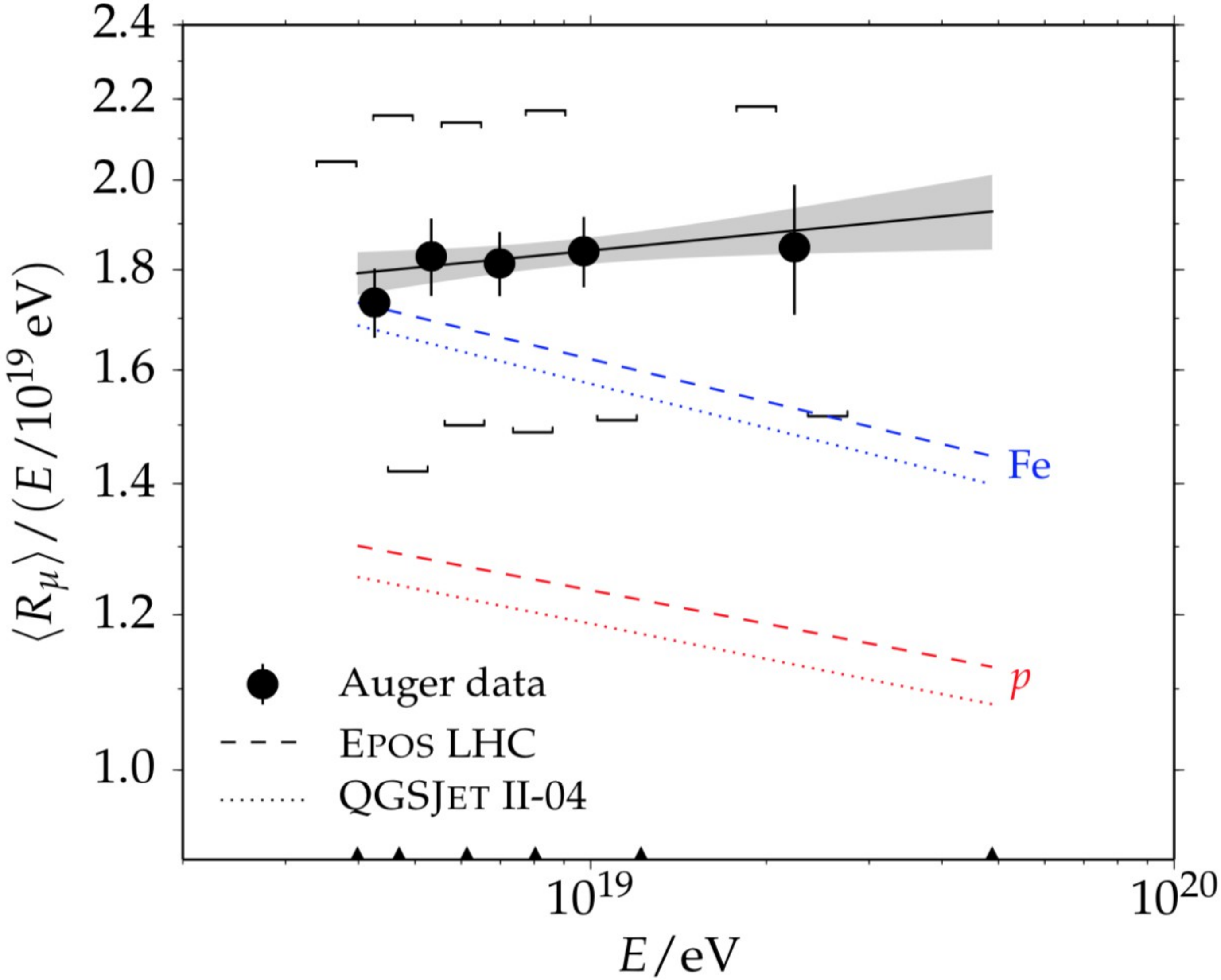
my opinion:

Uncertainties on hadronic interactions are still large (and possibly/probably underestimated).

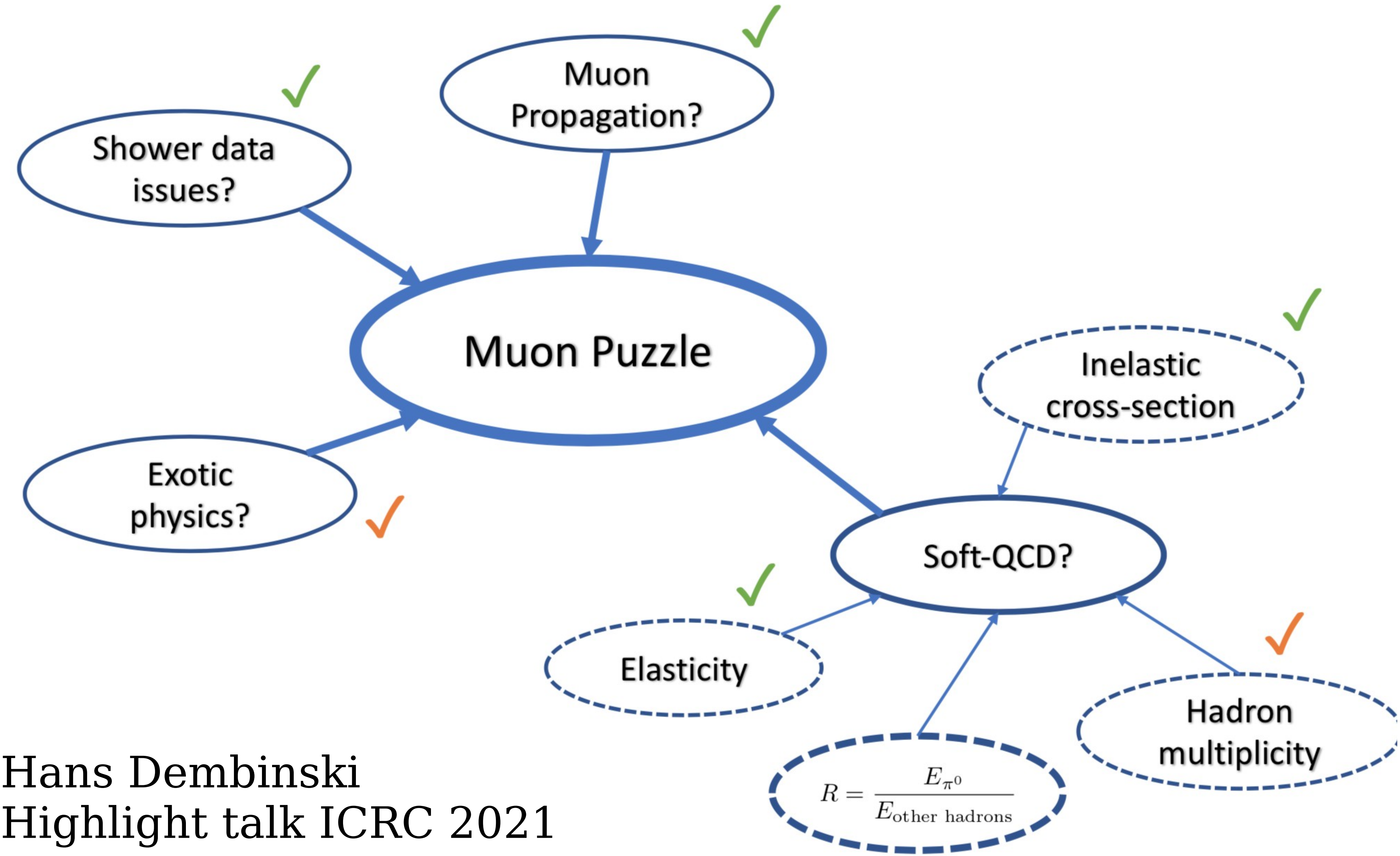
Dedicated efforts (experimental and theoretical) can significantly reduce these uncertainties.
This a very important and valuable program for
High energy astrophysics
and
Particle Physics

However: necessary to construct
Observational programs that
"minimize" the dependence on hadronic interactions
[multiple variables, self consistency, ...]

The “Muon problem” in Ultra High Energy Cosmic Rays



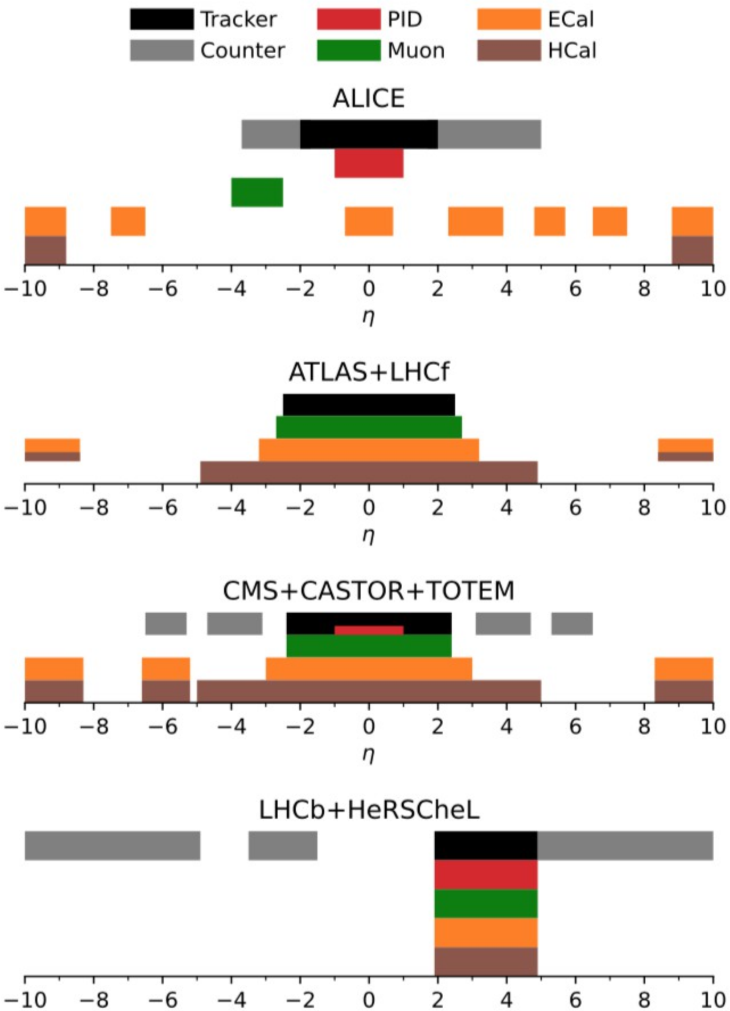
Attempts to explain muon puzzle



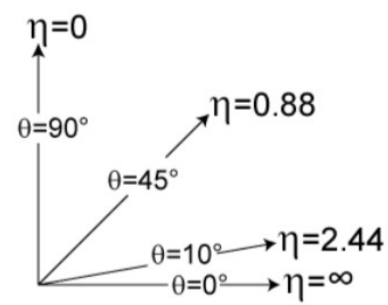
Hans Dembinski
Highlight talk ICRC 2021

LHC experiments and Muon Puzzle

arXiv:2105.06148



pseudorapidity η



η related to emission angle

Image credit: JabberWok - Wikipedia CC BY-SA 3.0

- Most LHC experiments focus on |η| < 2 region
    - Detectors well instrumented here
- Forward capabilities |η| > 2
    - ALICE, TOTEM: counters
    - CMS-CASTOR: Calorimeters for eγ and hadrons
    - LHCb: full tracking and PID at 2 < η < 5
    - LHCf: neutral particles η > 8

Summary & outlook

- Muon Puzzle in air showers
  - Excess in mean muon number observed with 8σ over simulation
  - Early onset around 40 PeV ($\sqrt{s} \sim 8$ TeV) in reach of LHC
  - Muon number fluctuations consistent with model predictions; constrains exotic explanations
- Origin of muon discrepancy
  - Most likely an issue in forward **soft-QCD**
  - Very sensitive to energy ratio *R* in forward region $\eta \gg 2$
    - Constrained only by few LHC experiments: CMS-CASTOR, LHCb, LHCf
    - Key to Muon Puzzle: statistical hadronization in high-density collisions?
  - Sensitive to charged particle spectra
    - Well constrained by LHC p-p data now, still large model spread for p-O
    - Important also for X_{max} prediction

$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- LHC measurements with p-O collisions in 2023/24
  - Will resolve large model spread in charged particle density
  - Need to study hadron composition & strangeness production over wide η range
- More precise muon data from enhanced and new air shower experiments
  - AugerPrime PoS(ICRC2021)270
  - IceCube surface extension and Gen2 PoS(ICRC2021)314
  - TAx4 PoS(ICRC2021)203
  - NEVOD-DECOR extension
  - GRAND PoS(ICRC2021)1181
  - GCOS PoS(ICRC2021)027

Muons and radio: great match

Muon energy spectrum: additional information

Pierre Auger Collaboration
"Measurement of the Fluctuations in the Number of Muons in Extensive Air Showers with the Pierre Auger Observatory,"
Phys. Rev. Lett. **126**, no.15, 152002 (2021)
[arXiv:2102.07797 [hep-ex]].

We present the first measurement of the fluctuations in the number of muons in extensive air showers produced by ultrahigh energy cosmic rays.
We find that the measured fluctuations are in good agreement with predictions from air shower simulations.
This observation provides new insights into the origin of the previously reported deficit of muons in air shower simulations and constrains models of hadronic interactions at ultrahigh energies.

Our measurement is compatible with the muon deficit originating from small deviations in the predictions from hadronic interaction models of particle production that accumulate as the showers develop.

Fundamental Open Problems:

1. Galactic / extragalactic transition

2. Spectrum + Composition

   from the Knee to the “end of the spectrum”

3. Measure and understand Anisotropies

4. Hadronic Interactions

Open Problems for Cosmic Ray Astrophysics

Ensemble of Galactic sources:

[*] What is the shape of the source spectrum
[*] What is the source spectrum for *electrons*
[*] Do positron accelerator exist ?
[*] What is the maximum energy of Galactic sources
[*] What generates the "Knee"
[*] Do different classes of object contribute to the flux
[*] What classes of objects ?

Ensemble of extragalactic sources:

[*] What is the shape of the extragalactic source spectrum
[*] What is the maximum energy
[*] More than one class of events ?
[*] Source identification [CR astronomy]
....

Strategies for future CR studies

Two main directions:

[1.] Highest Energies, Very large Exposures

pursue the dream of Cosmic Ray Astronomy
[look for surprises, exotic, ...]

[2.] Lower energies [TeV - EeV]
Higher statistics
Better control of systematics
Redundant measurements.
Clarify open problems
Knee, Ankle, Galactic/extragalactic, ...