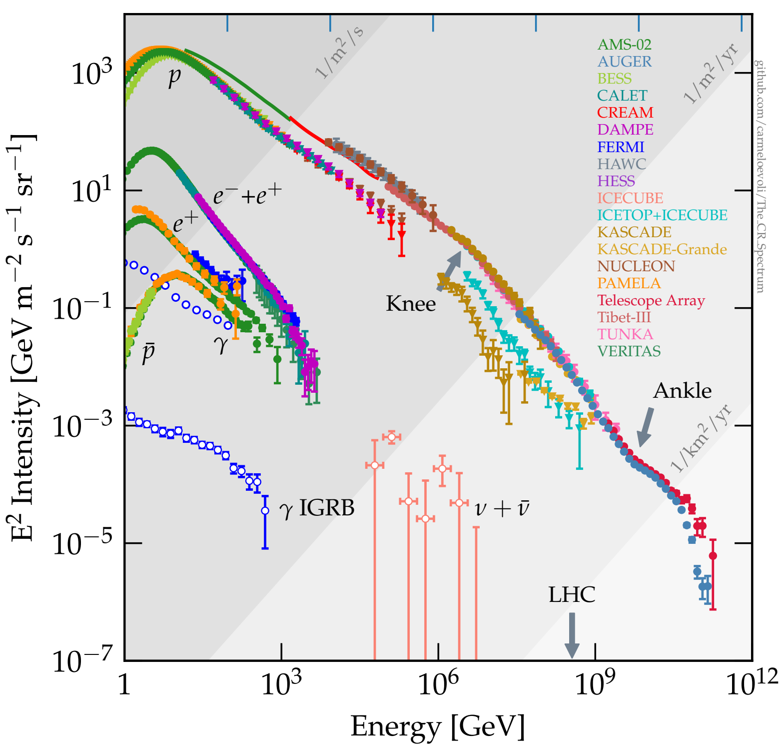
Galactic Sources (of cosmic rays)

Pierre Cristofari

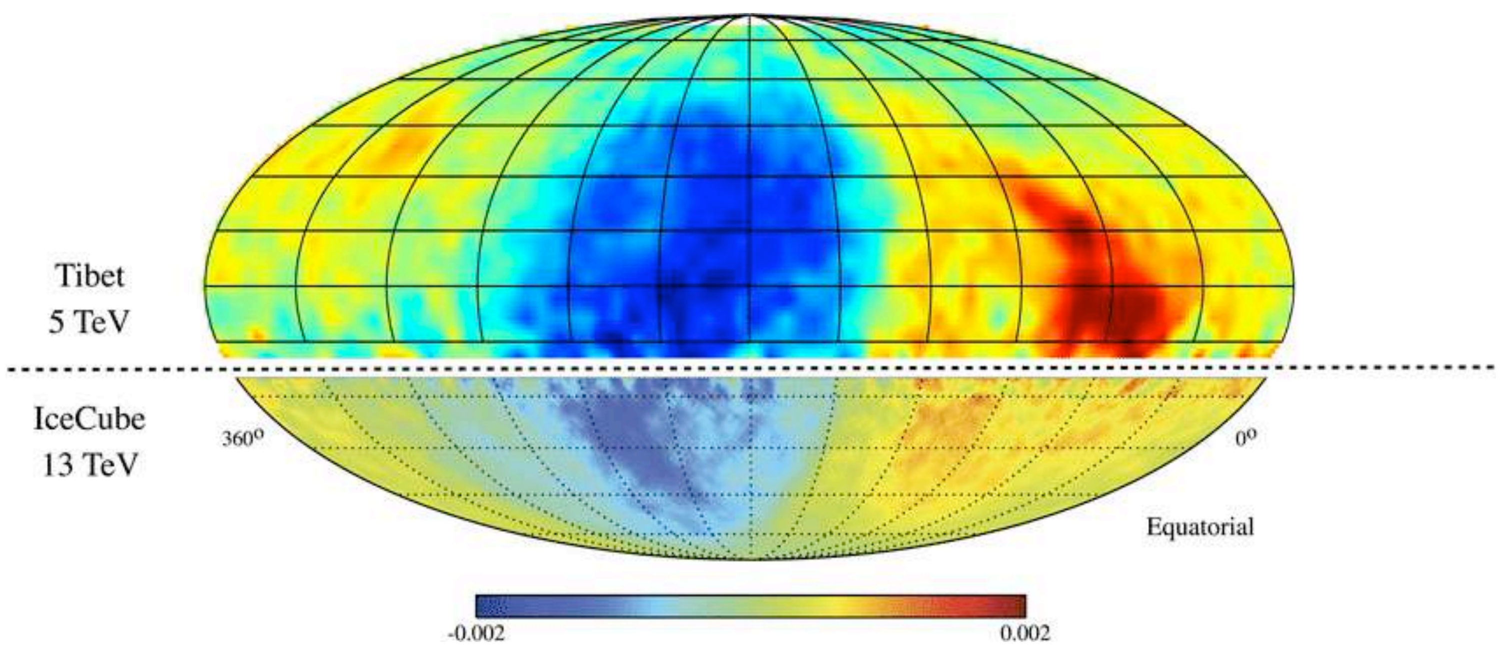
ISAPP 2026

Cosmic ray observables

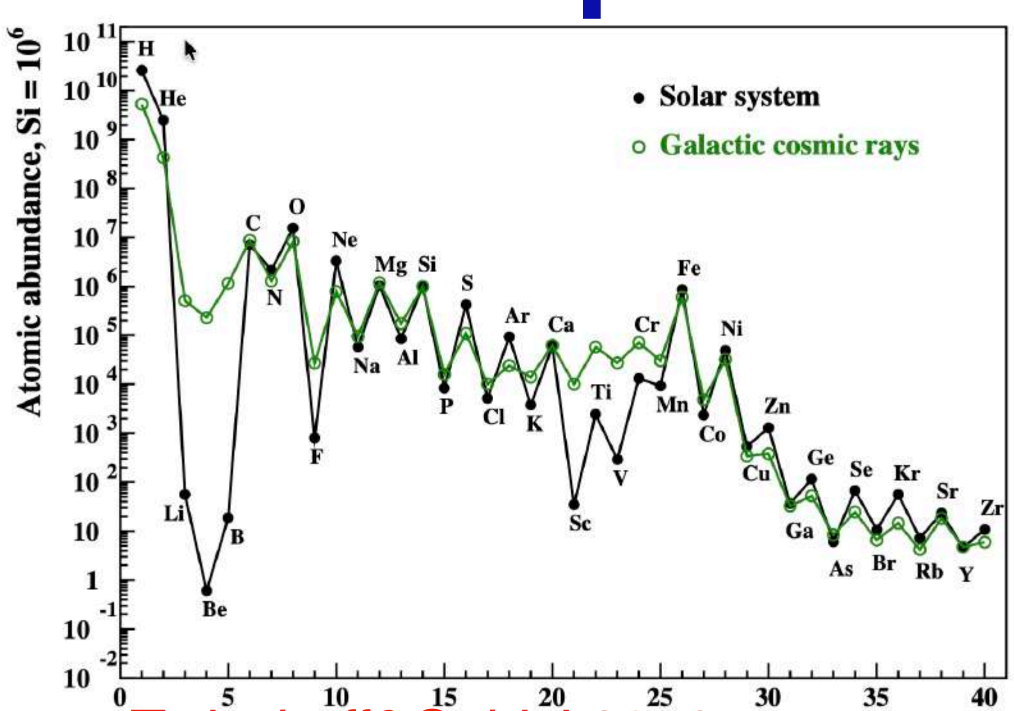
1. Local interstellar spectrum



2. Anisotropies

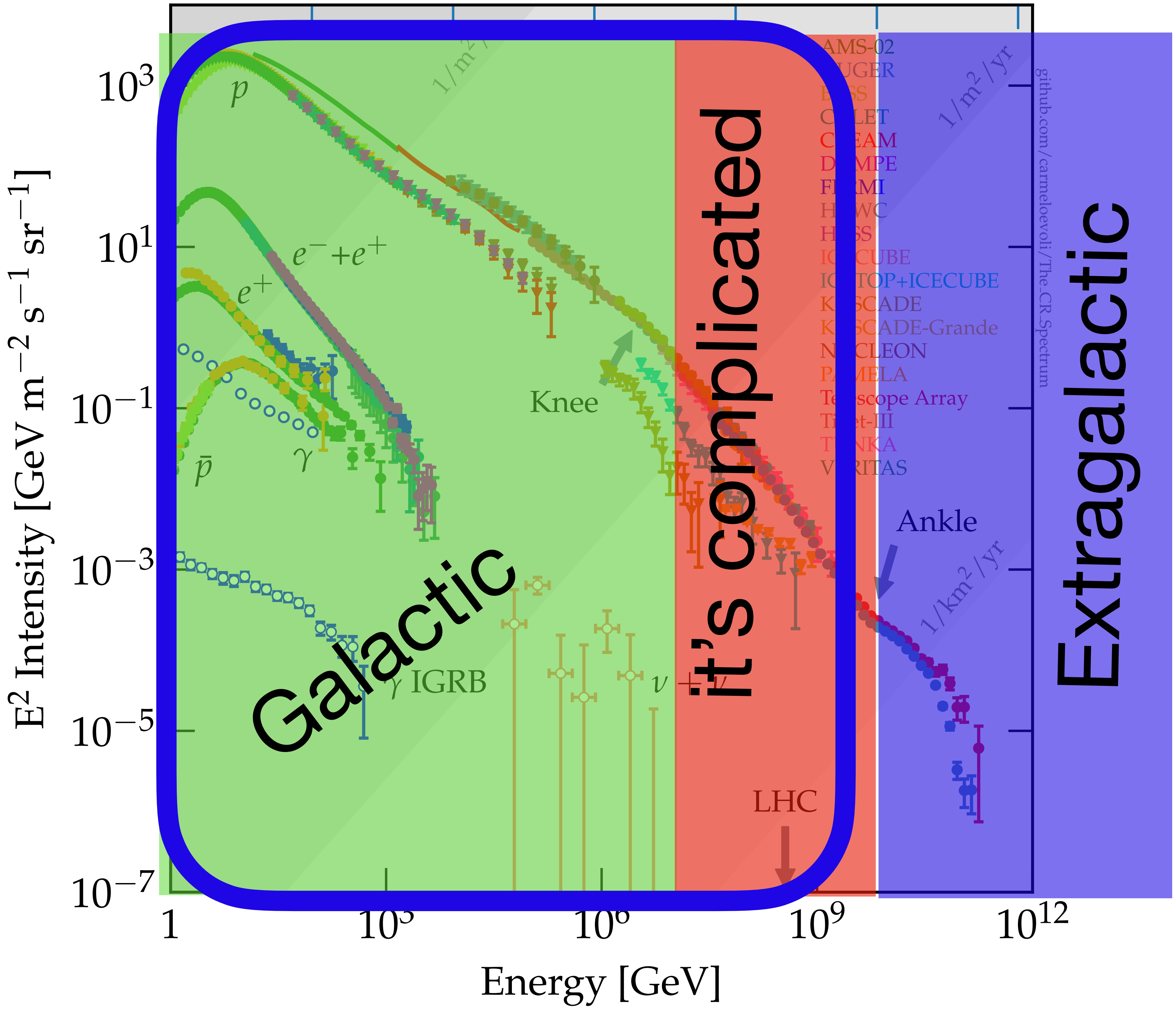


3. CR composition



Tatischeff&Gabici 2018

The Local Interstellar Spectrum



Reviews: Allard+ 2005, Berezinsky 2007, Aloisio+ 2012, Parizot 2014, Kachelrieß 2019 Evoli 2021

Cosmic ray composition

Stefano Gabici's lectures

Measurements B/C

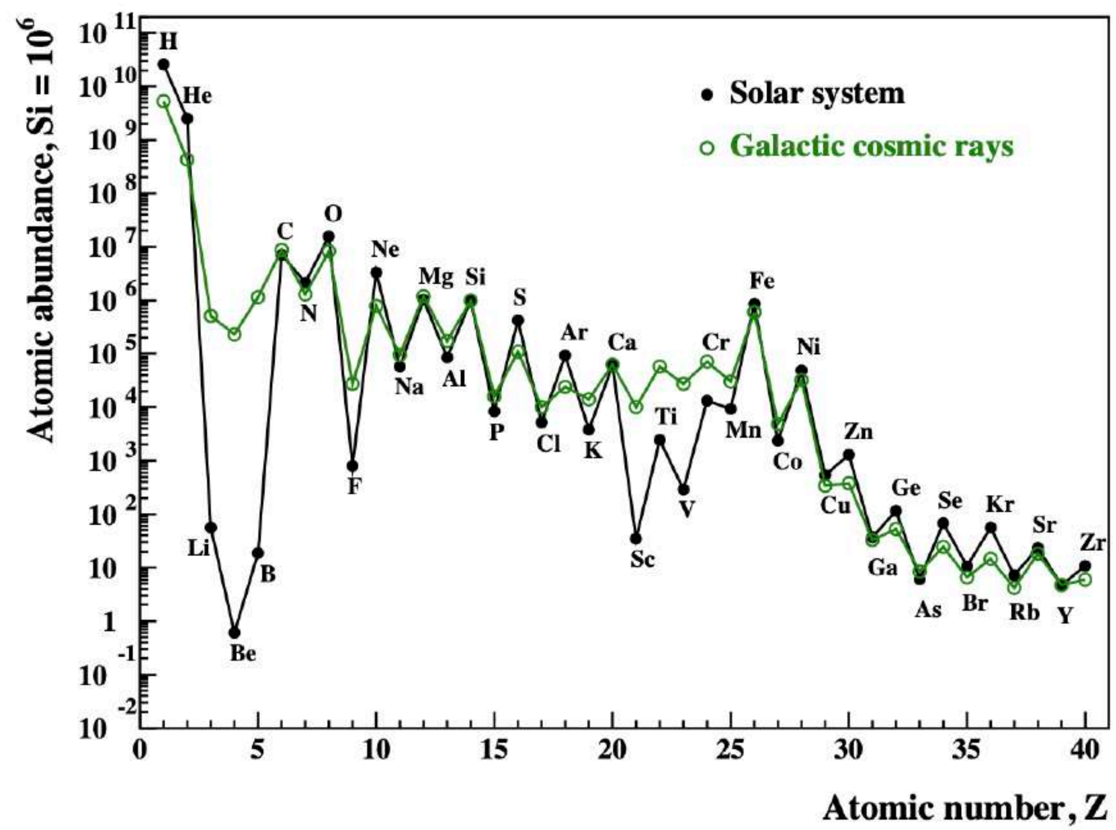
Boron: secondary product of spallation $^{12}\mathrm{C} + \mathrm{p} \rightarrow ^{11}\mathrm{B} + \mathrm{p} + \mathrm{p}$

$$q_\mathrm{B} \sim n_\mathrm{C} \sigma n_0 c$$

$$n_\mathrm{B} \sim q_\mathrm{B} \tau_\mathrm{disk}$$

$$\boxed{\frac{n_\mathrm{B}}{n_\mathrm{C}} \sim \sigma n_0 c \tau_\mathrm{disk} \sim \frac{\sigma}{\mu m_p} \Lambda}$$

$$\boxed{\Lambda \approx 40 \frac{n_\mathrm{B}}{n_\mathrm{C}} \ \mathrm{g/cm^2}}$$

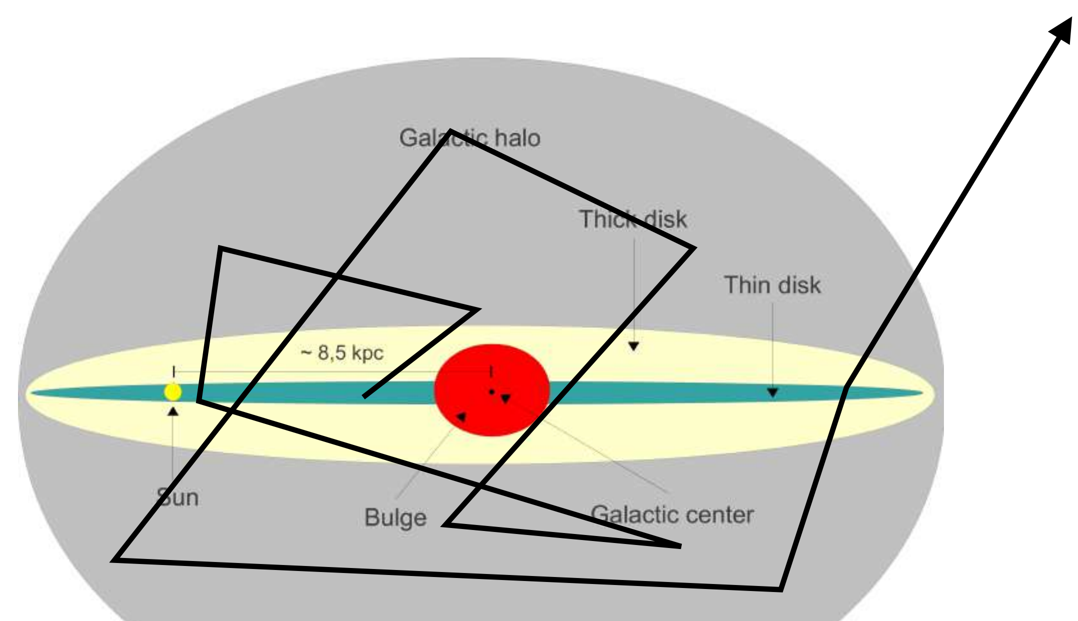


^{10}Be/^{9}Be

$$\tau(^{10}\mathrm{Be}) \sim 1.4 \ \mathrm{Myr}$$

$$\frac{^{10}\mathrm{Be}}{\mathrm{Be}} \sim \frac{\tau(^{10}\mathrm{Be})}{\tau_\mathrm{esc}} \frac{q(^{10}\mathrm{Be})}{q(\mathrm{Be})}$$

$$\tau_\mathrm{esc} \approx 10 - 20 \ \mathrm{Myr}$$



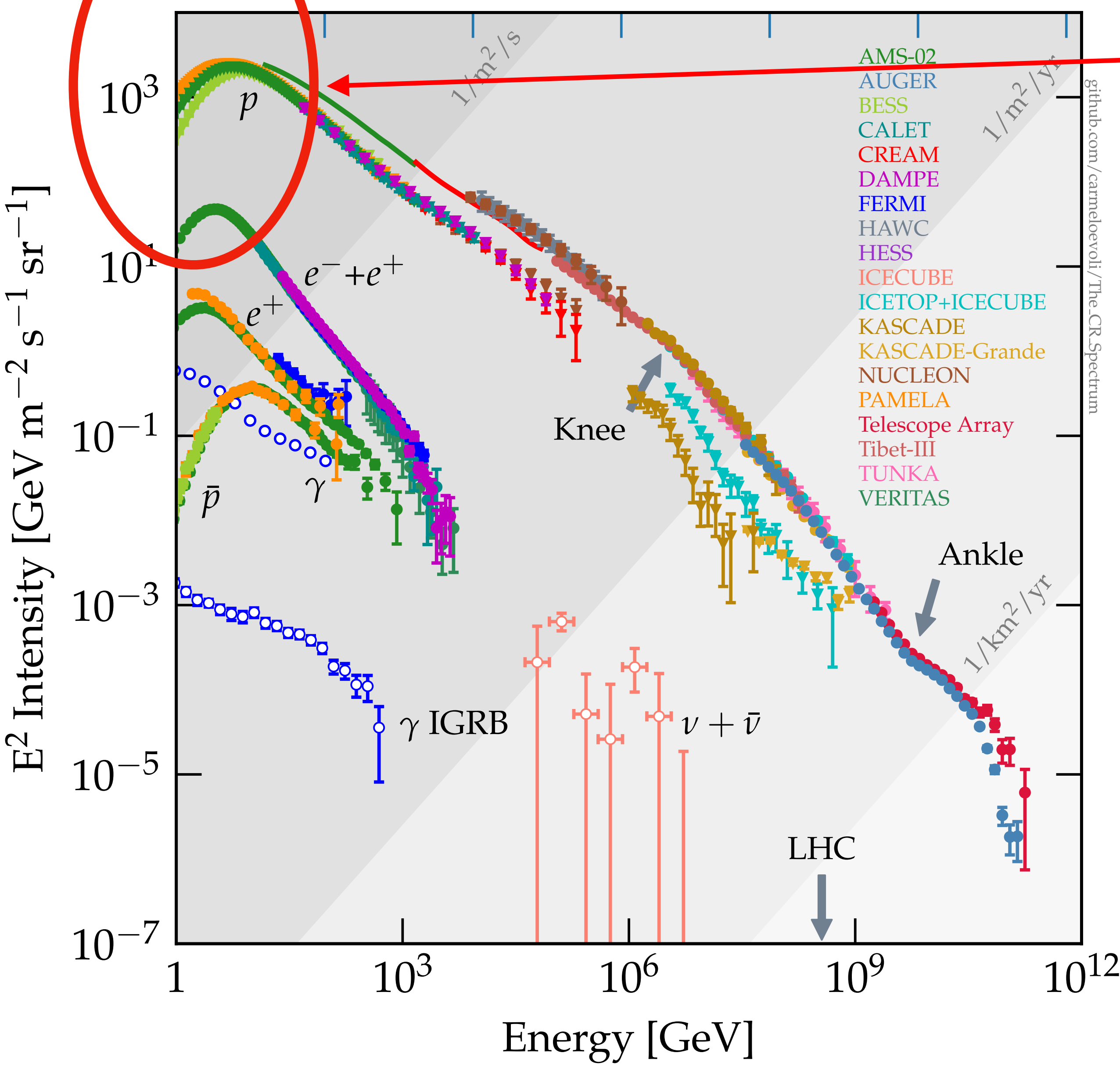
Surface density of disk
$X_\mathrm{disk} \lesssim 10^{-3} \ \mathrm{g/cm^2}$

CRs injected in Disk and propagate in Halo

Multiple crossing of Disk

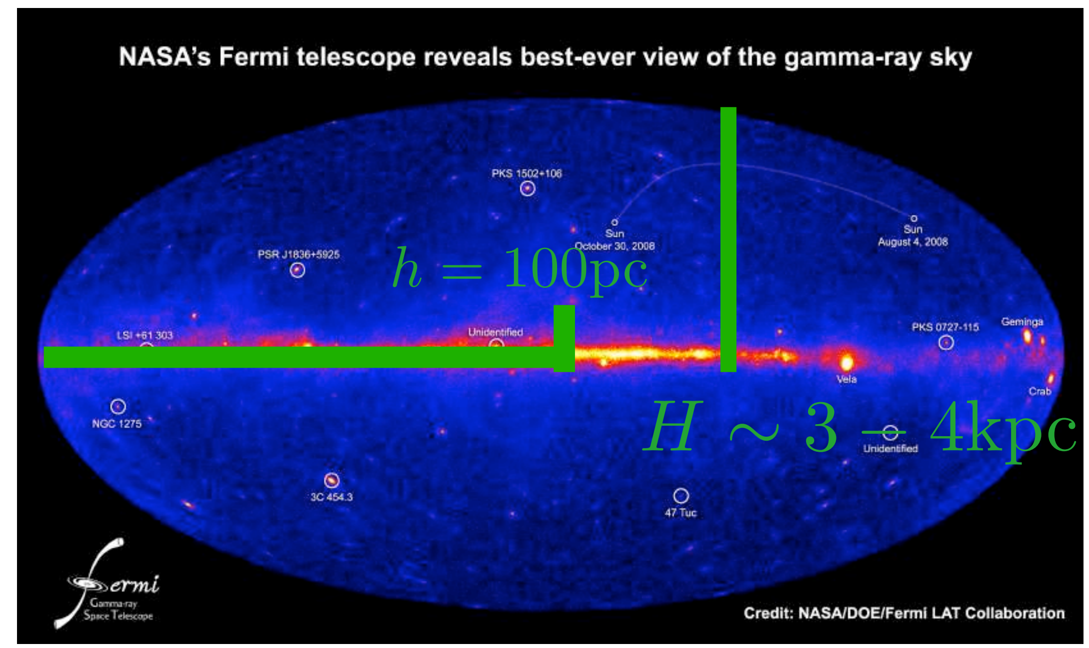
Tatischeff & Gabici 2018

The Local Interstellar Spectrum



Bulk of CR energy

$$w_{\rm CR} \sim 1{\rm eV} \quad \sim \frac{B^2}{8\pi} \sim \rho u_{\rm th}^2$$



Fermi-LAT: CRs fill the disk

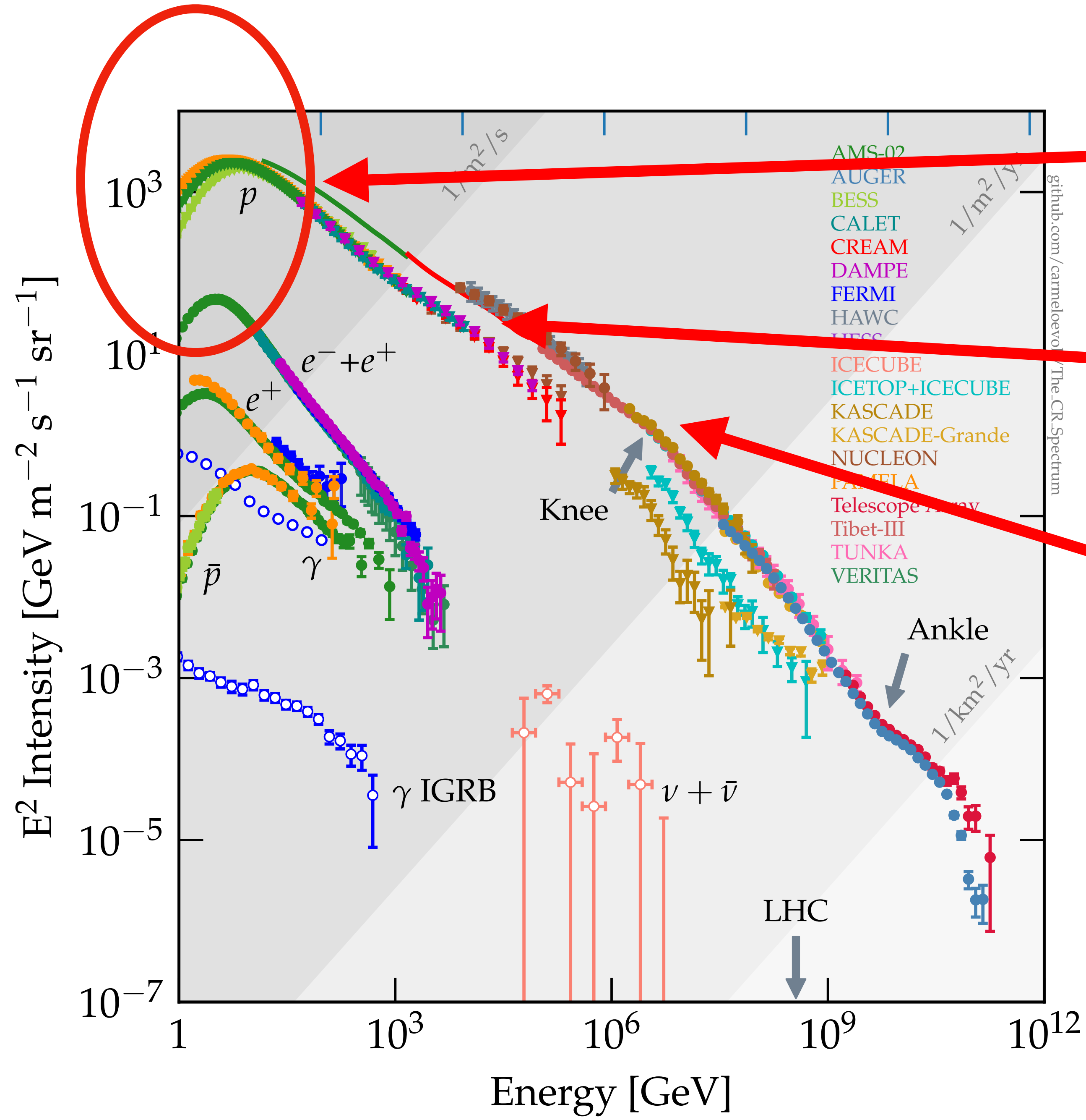
$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

$$W_{\rm CR} = w_{\rm CR} \times V \approx 7 \times 10^{54} \left(\frac{R}{15{\rm kpc}}\right)^2 \left(\frac{h}{100{\rm pc}}\right) {\rm erg}$$

Evoli 2021

The Local Interstellar Spectrum



Bulk of CR energy

$$w_{\rm CR} \sim 1{\rm eV} \sim \frac{B^2}{8\pi} \sim \rho u_{\rm th}^2$$

$$\propto E^{-2.7}$$

« Galactic sources must reach the knee »

Supernova remnants?

Something connected with supernovae (SNe in specific environments, superbubles)?

Something not connected with supernovae (massive stars, microquasars)?

Evoli 2021

Supernovae

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

Galactic supernovae - Ter Haar 1950?

Supernovae

If you convert a fraction of the total explosion energy of SNe into CRs, you can explain the CR energy density

Modern version of the estimate (not Baade&Zwicky)

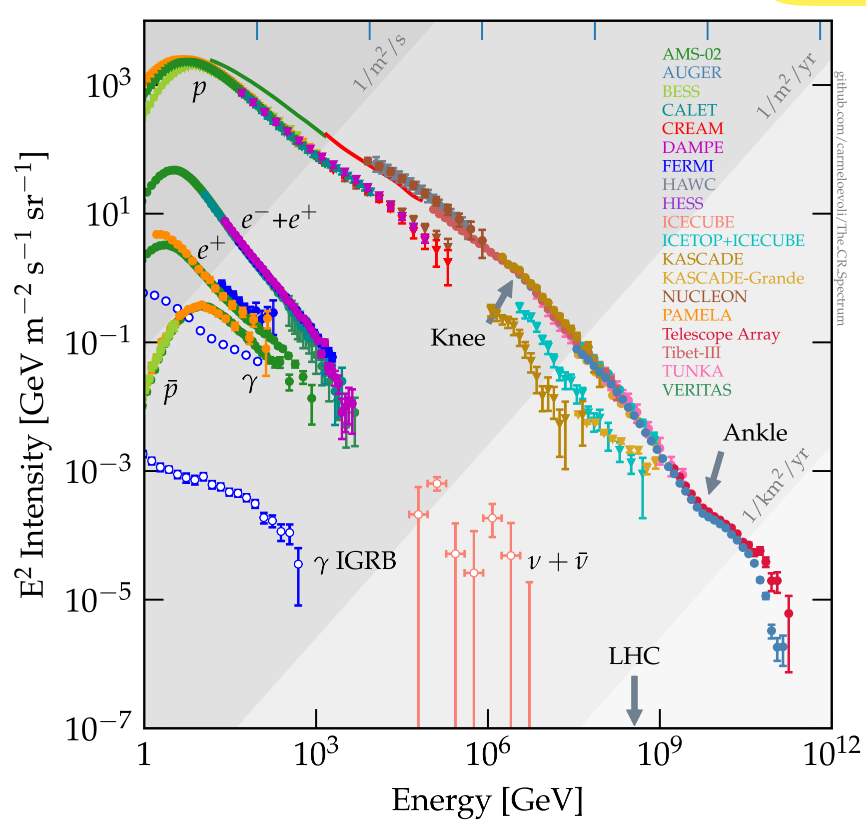
$$V_{\rm halo} = 2\pi R^2 H$$

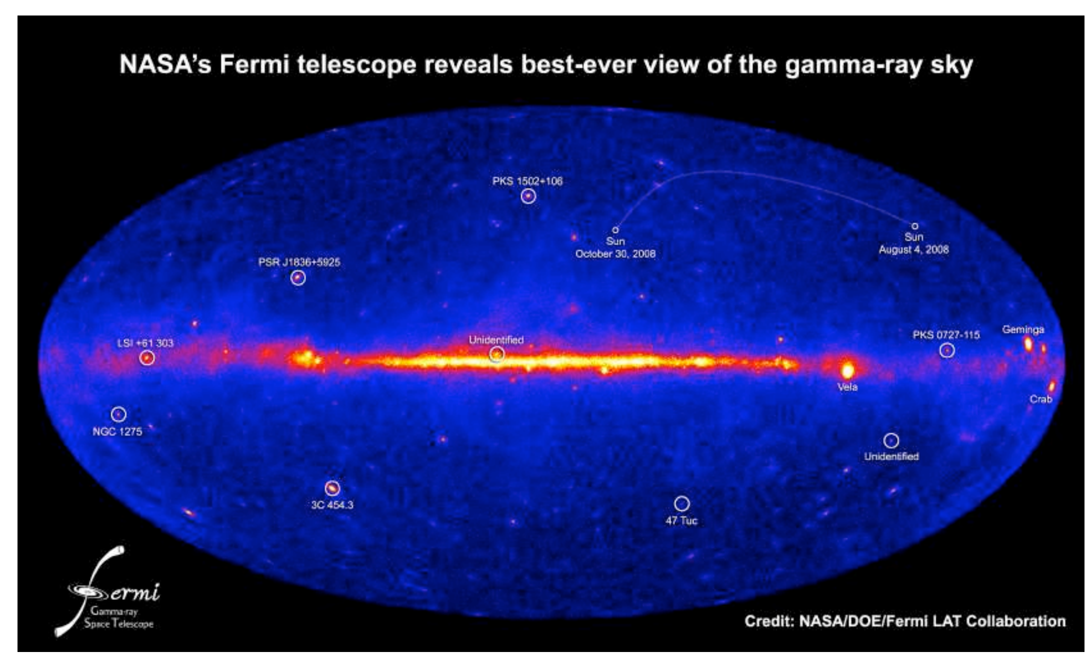
$$\tau_{\rm esc} \sim 10^7 {\rm yr}$$

$$W_{\rm SN} \approx 10^{42} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)\left(\frac{\nu_{\rm SN}}{3/{\rm century}}\right)\,{\rm erg\,s^{-1}}$$

$$W_{\rm CR} \sim \frac{u_{\rm CR} V_{\rm halo}}{\tau_{\rm esc}} \approx 10^{41}\,{\rm erg\,s^{-1}}$$

$$\boxed{W_{\rm CR} = \eta \times W_{\rm SN}}$$



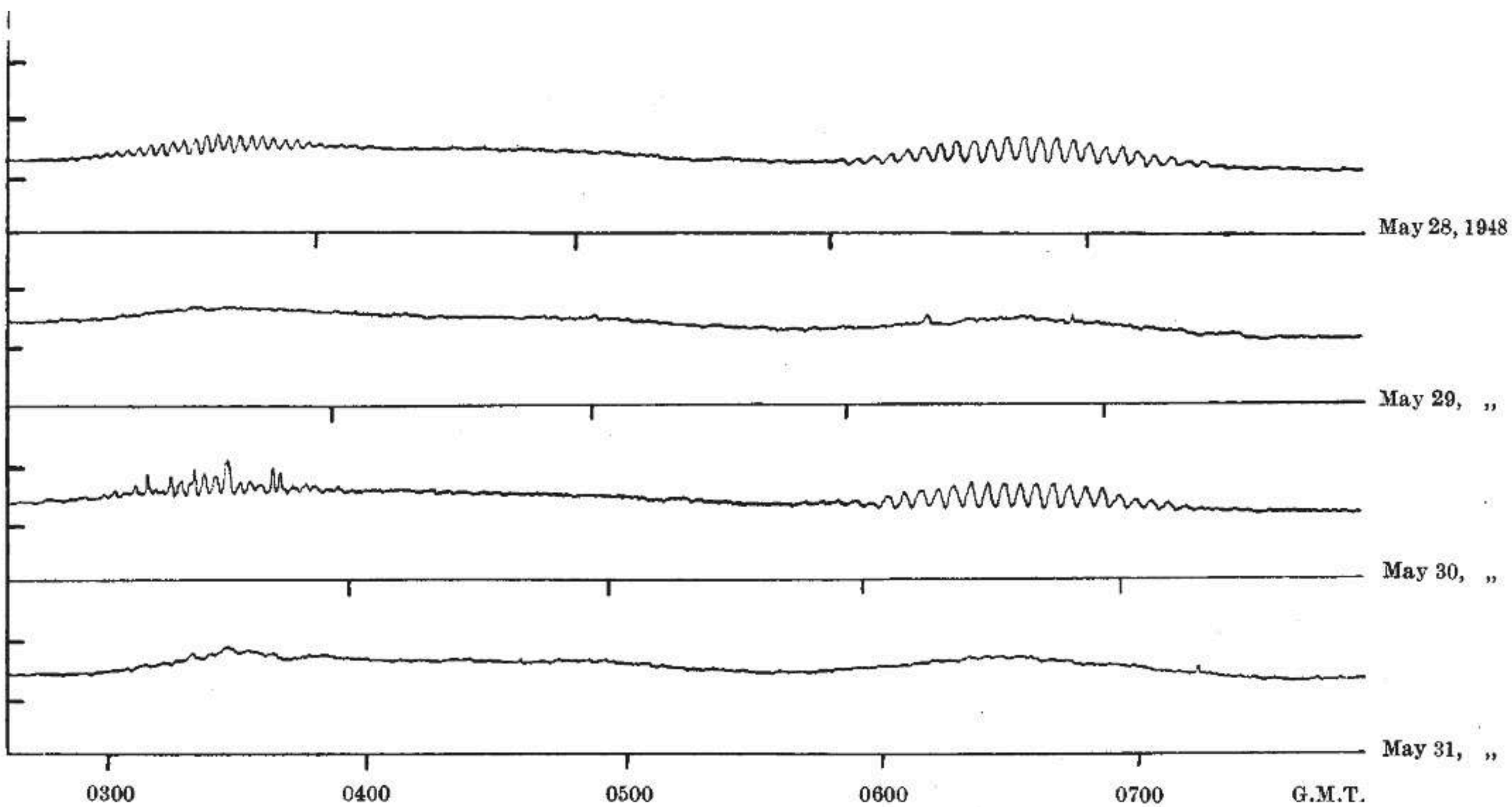


Supernovae (SNe) → Supernova remnants (SNRs)

More than the SN explosion, the shock wave expanding after the SN explosion

Observations of non-thermal particles at SNR shells (Radio -> electrons)

Ryle& Smith 1948 (Radio, Cassiopea A)



Records of galactic radiation using the spaced aerial system (units of intensity are 5×10^{-22} watts/m.^{2}/(c./s.)). May 28, aerials parallel ; (2) May 29, aerials mutually perpendicular ; (3) May 30, aerials parallel ; (4) May 31, aerials mutually perpendicular

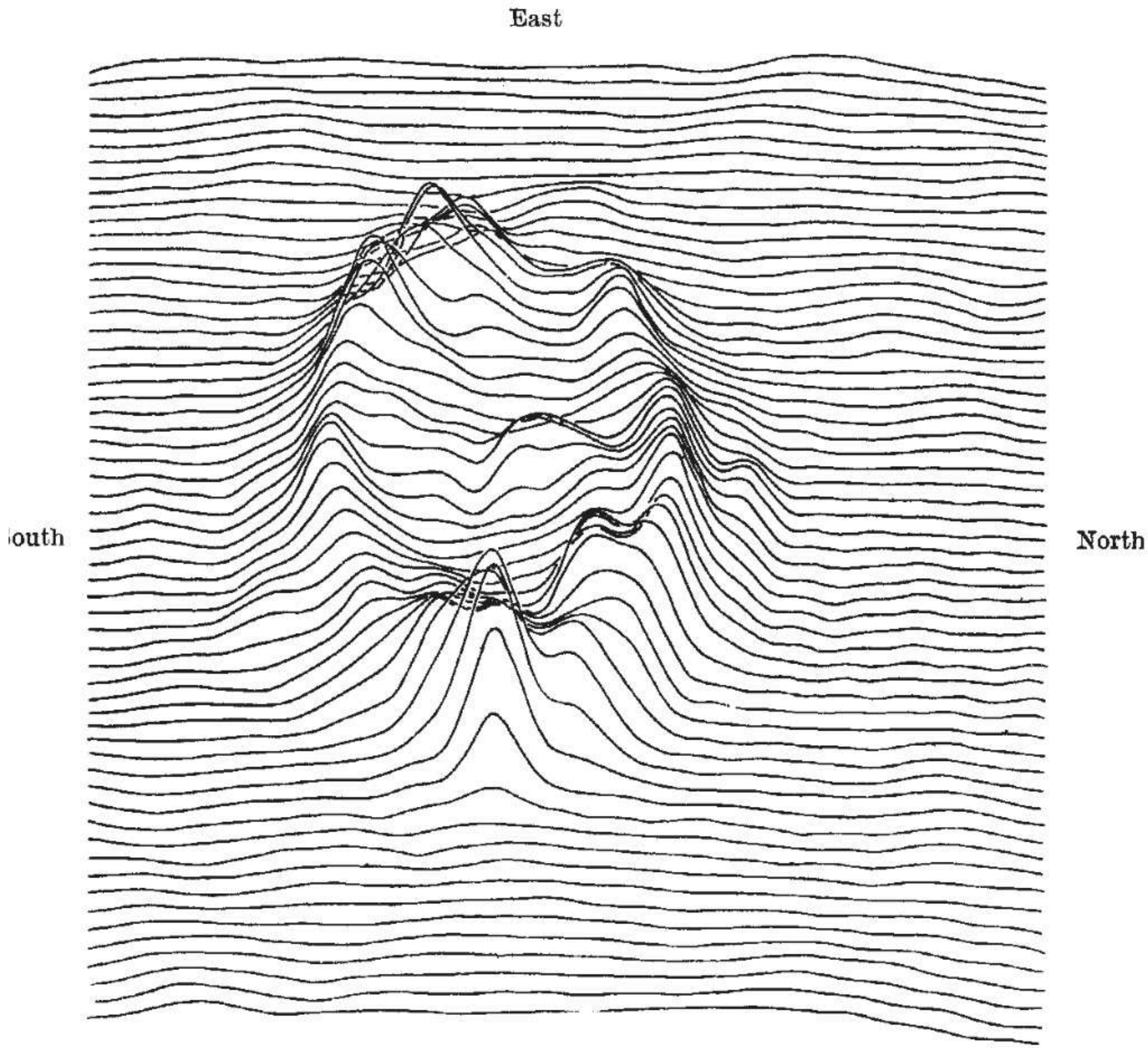


Fig. 4. Profiles of Cassiopeia A as presented by the automatic curve-plotter

Ryle et al. 1965 (Cas A)

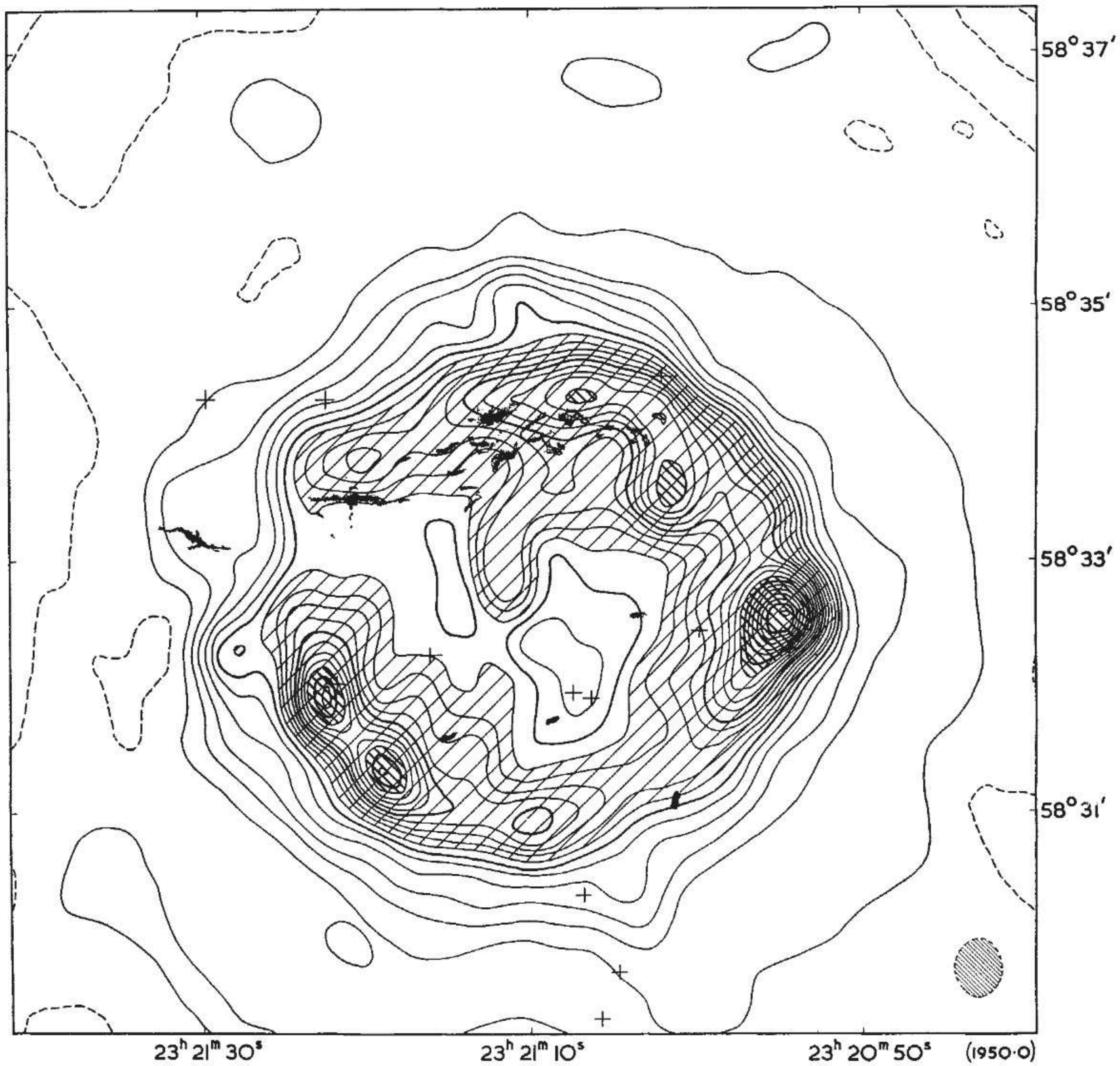
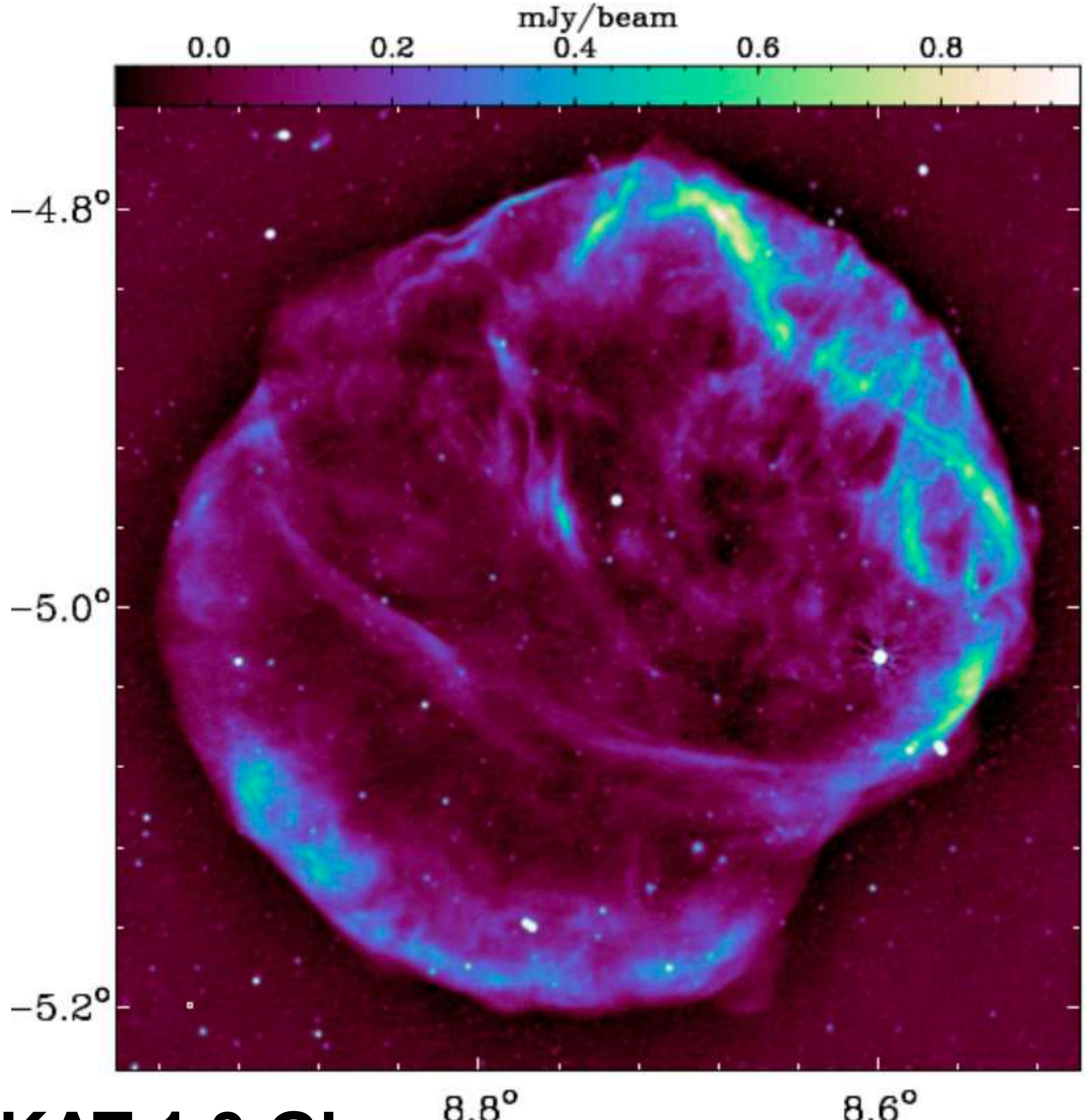


Fig. 5. Contour map of Cassiopeia A showing also the main optical filaments. The contour interval is 3,000° K. The positions of some of the brighter stars in the field are indicated by crosses

Ryle et al. 1965 (Cas A)

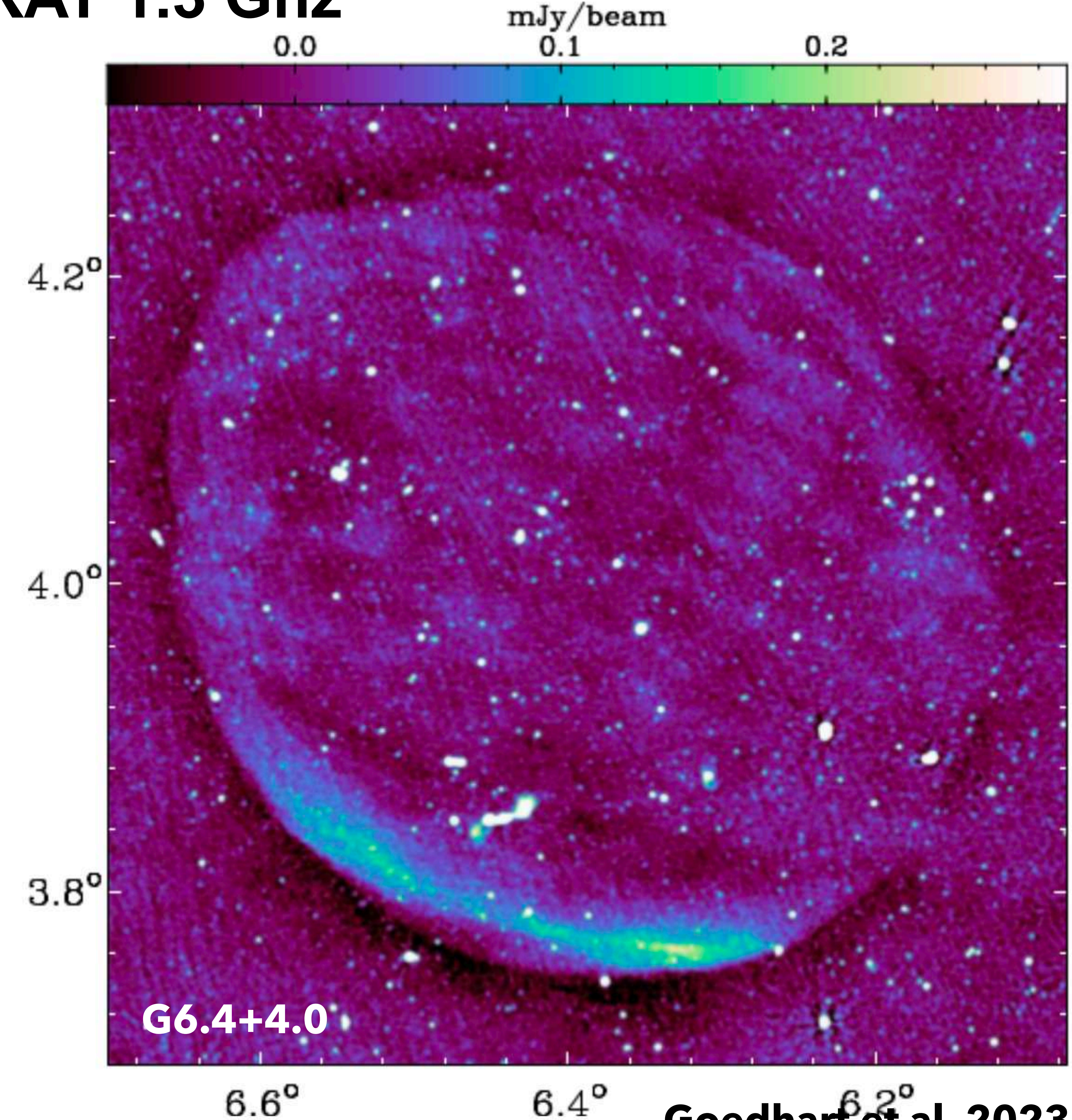
Radio observations of SNRs



MeerKAT 1.3 Ghz

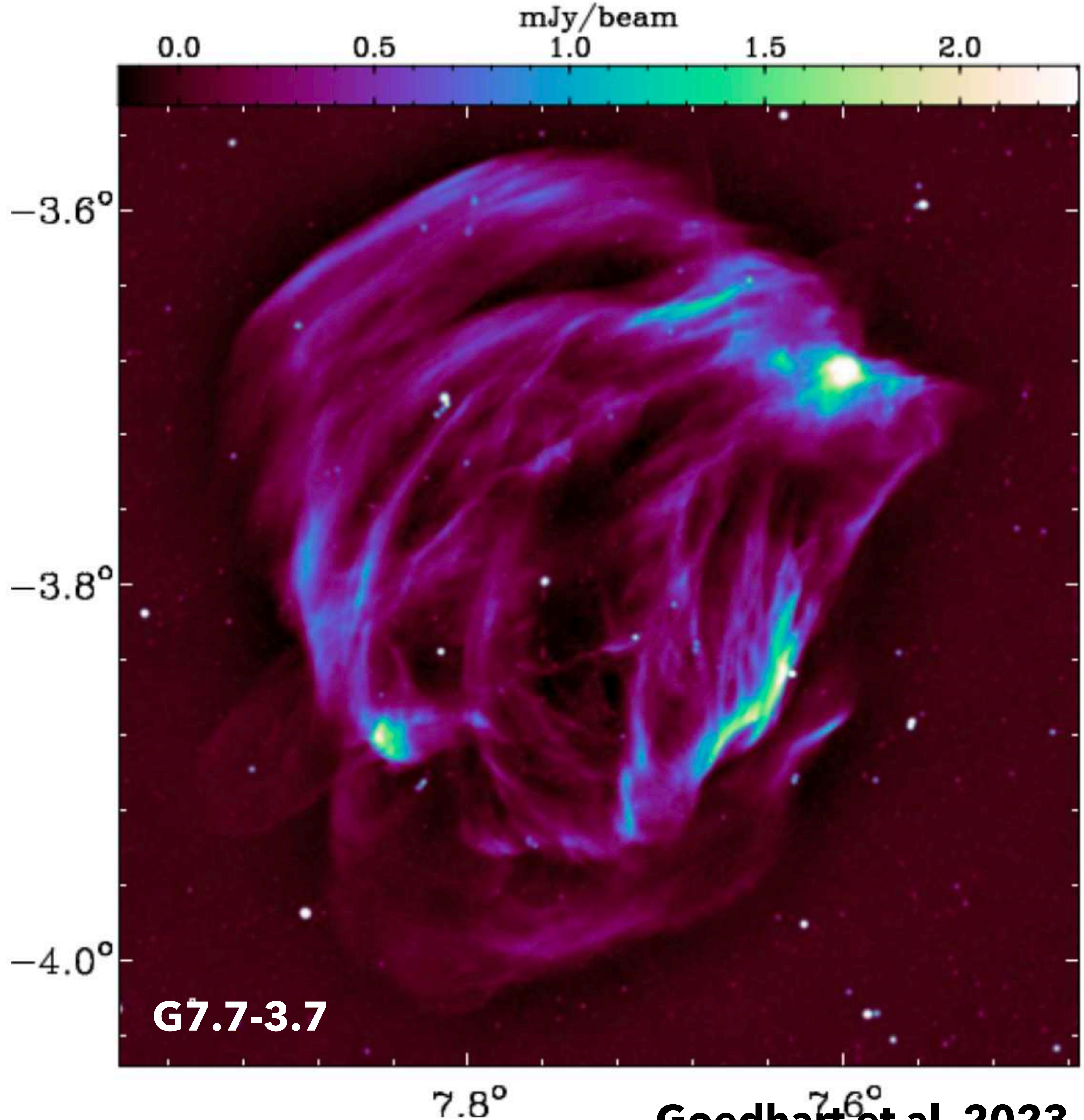
Cotton et al. 2023

MeerKAT 1.3 Ghz



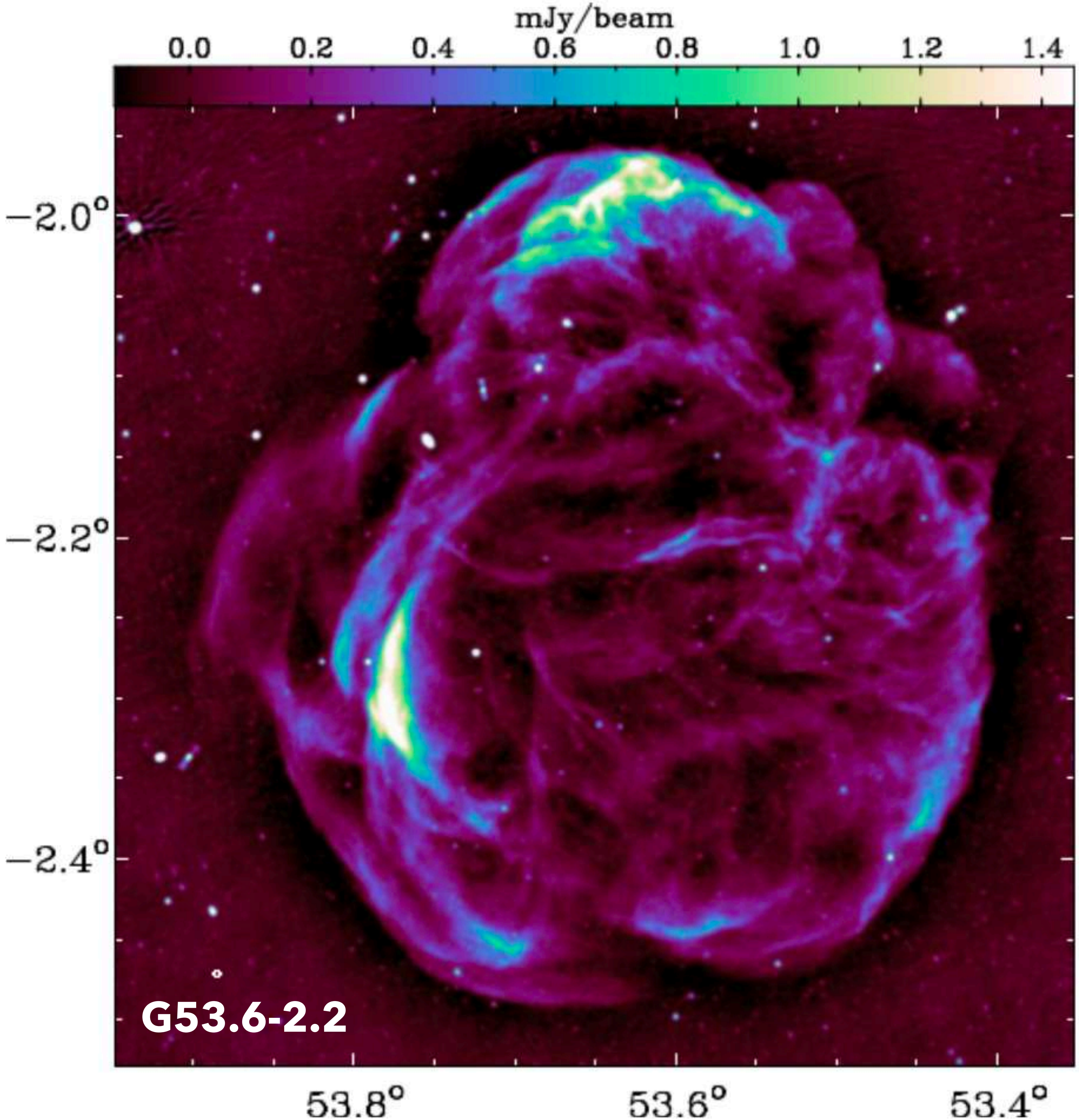
Goedhart et al. 2023, Cotton et al. 202

MeerKAT 1.3 Ghz



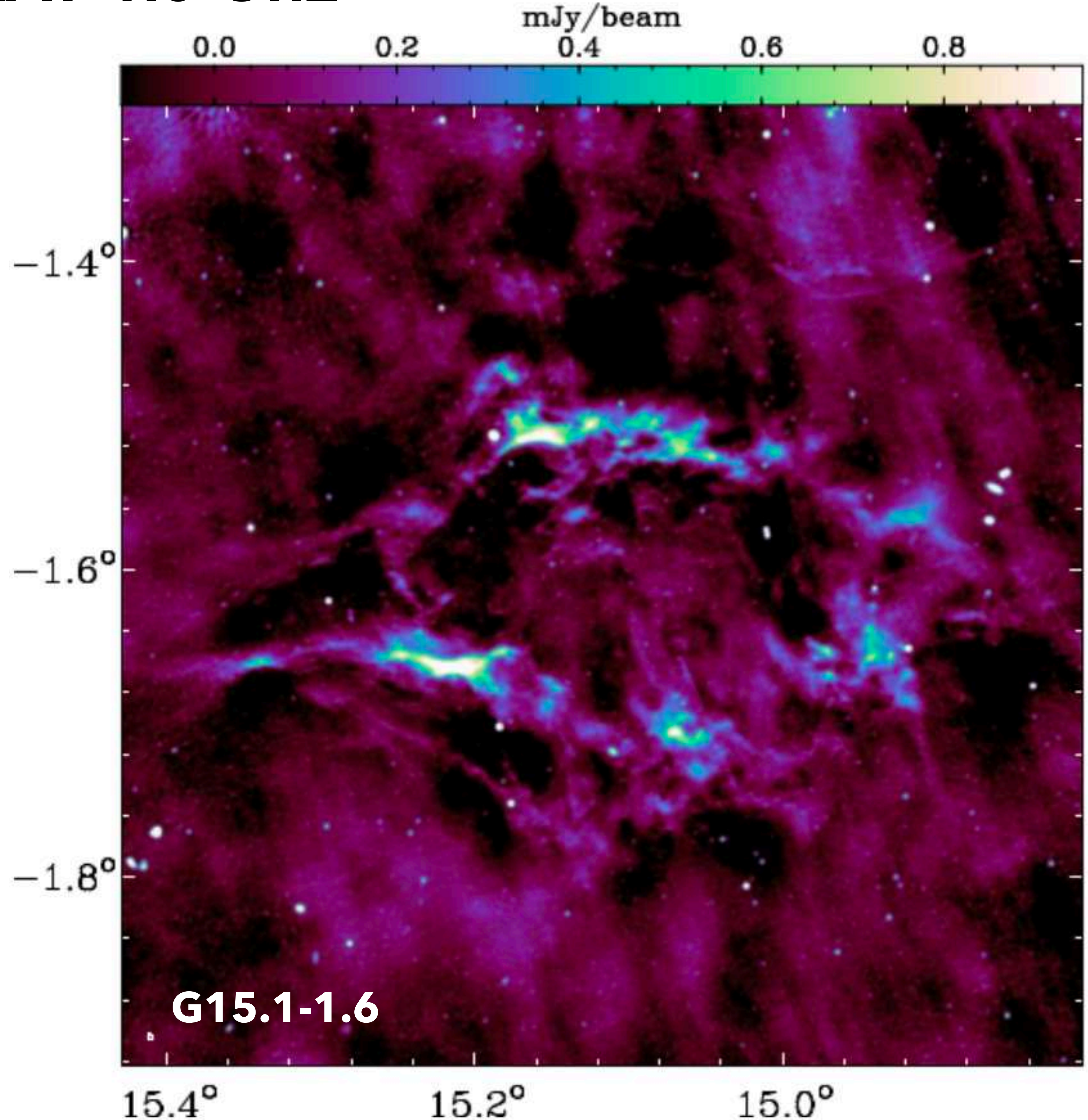
Goedhart et al. 2023, Cotton et al. 202

MeerKAT 1.3 Ghz

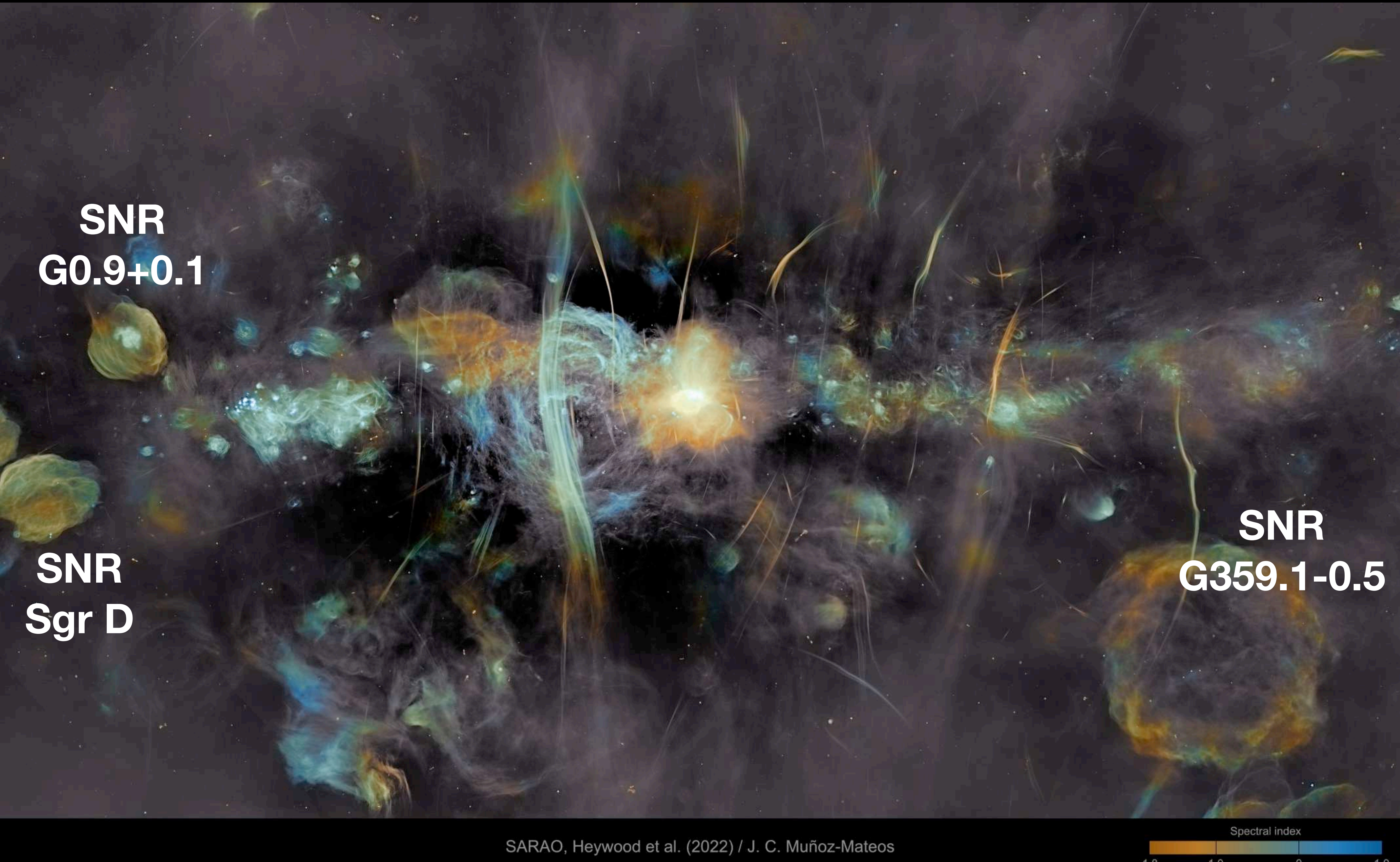


Goedhart et al. 2023, Cotton et al. 202

MeerKAT 1.3 Ghz

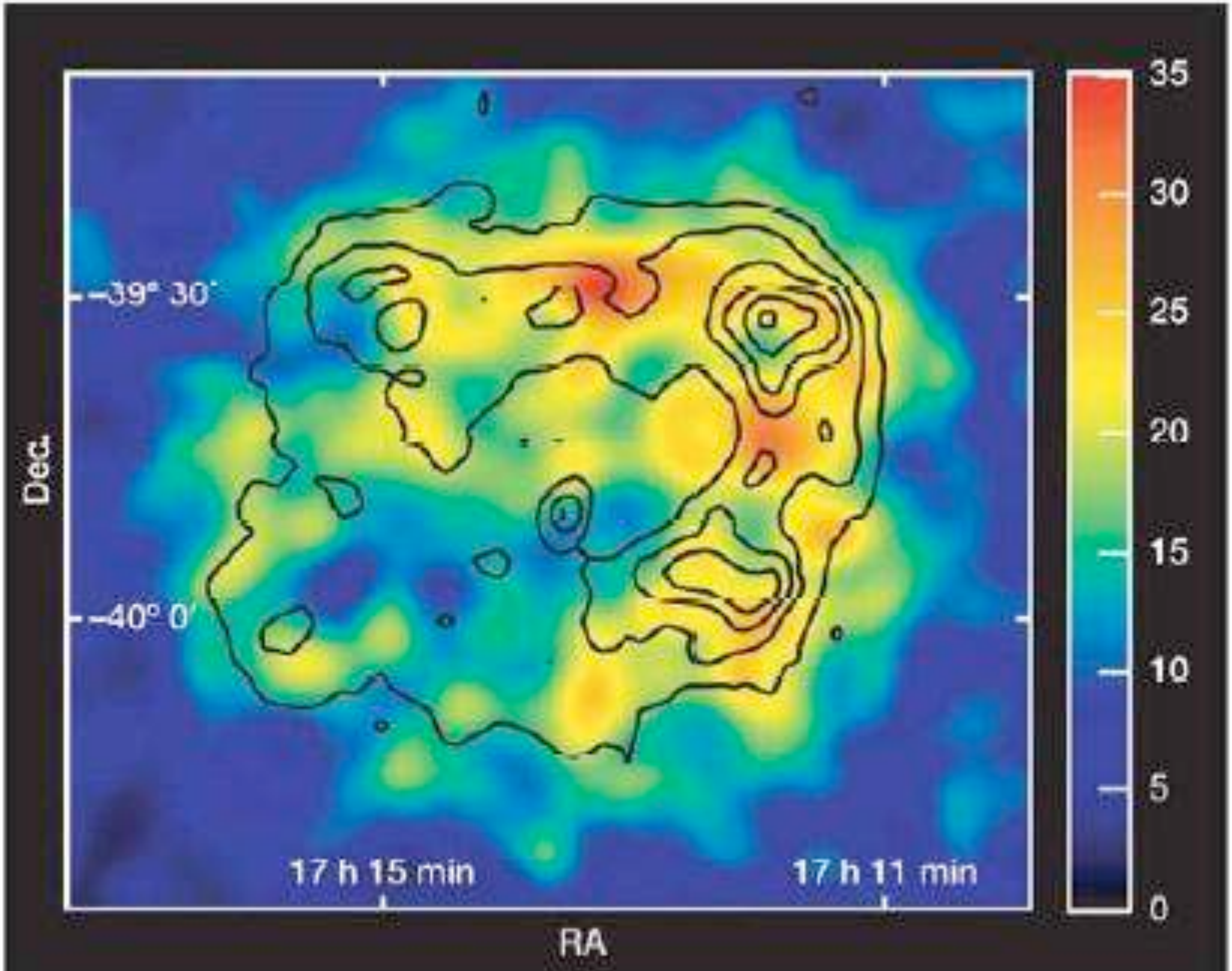


Goedhart et al. 2023, Cotton et al. 202

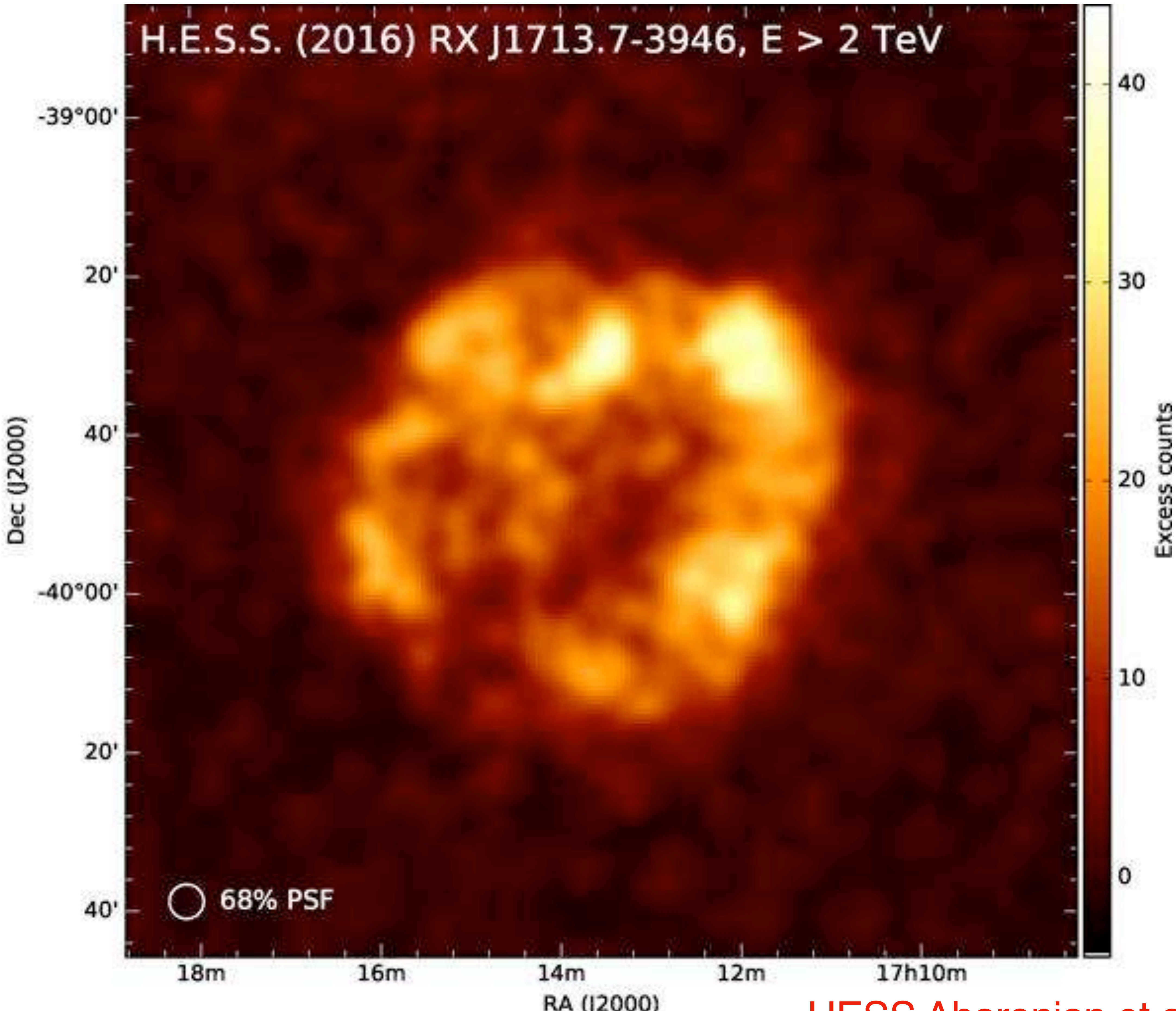


SARAO, Heywood et al. (2022) / J. C. Muñoz-Mateos

MeerKAT 2023

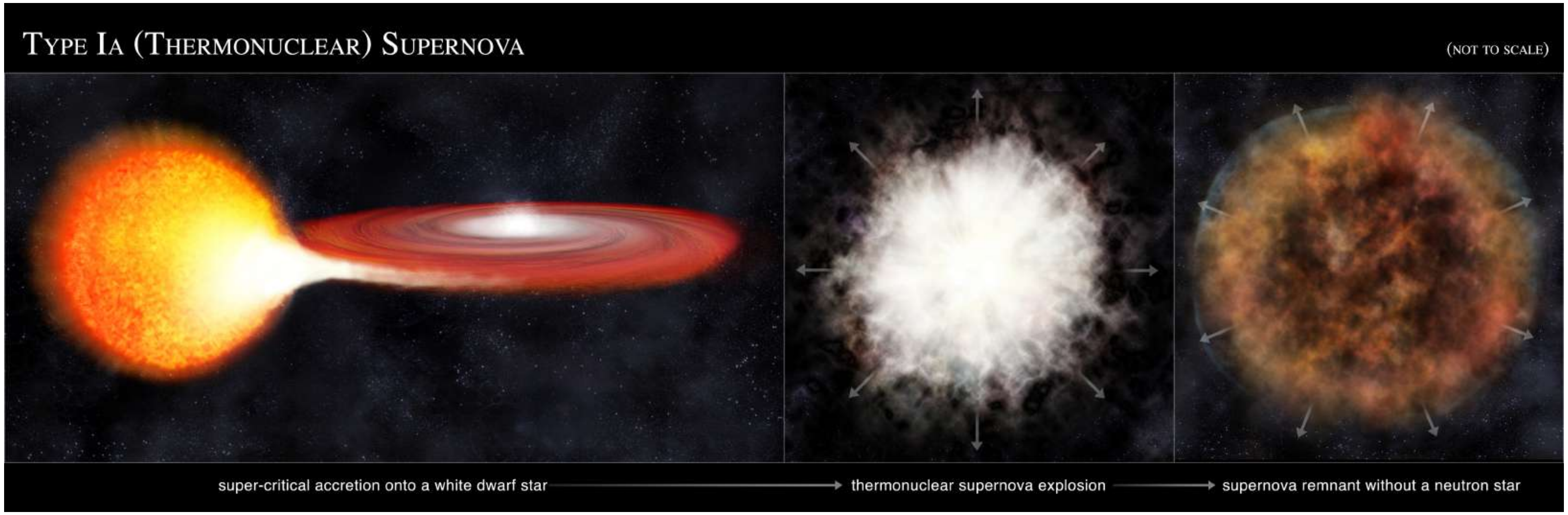


HESS Aharonian et al. 2004



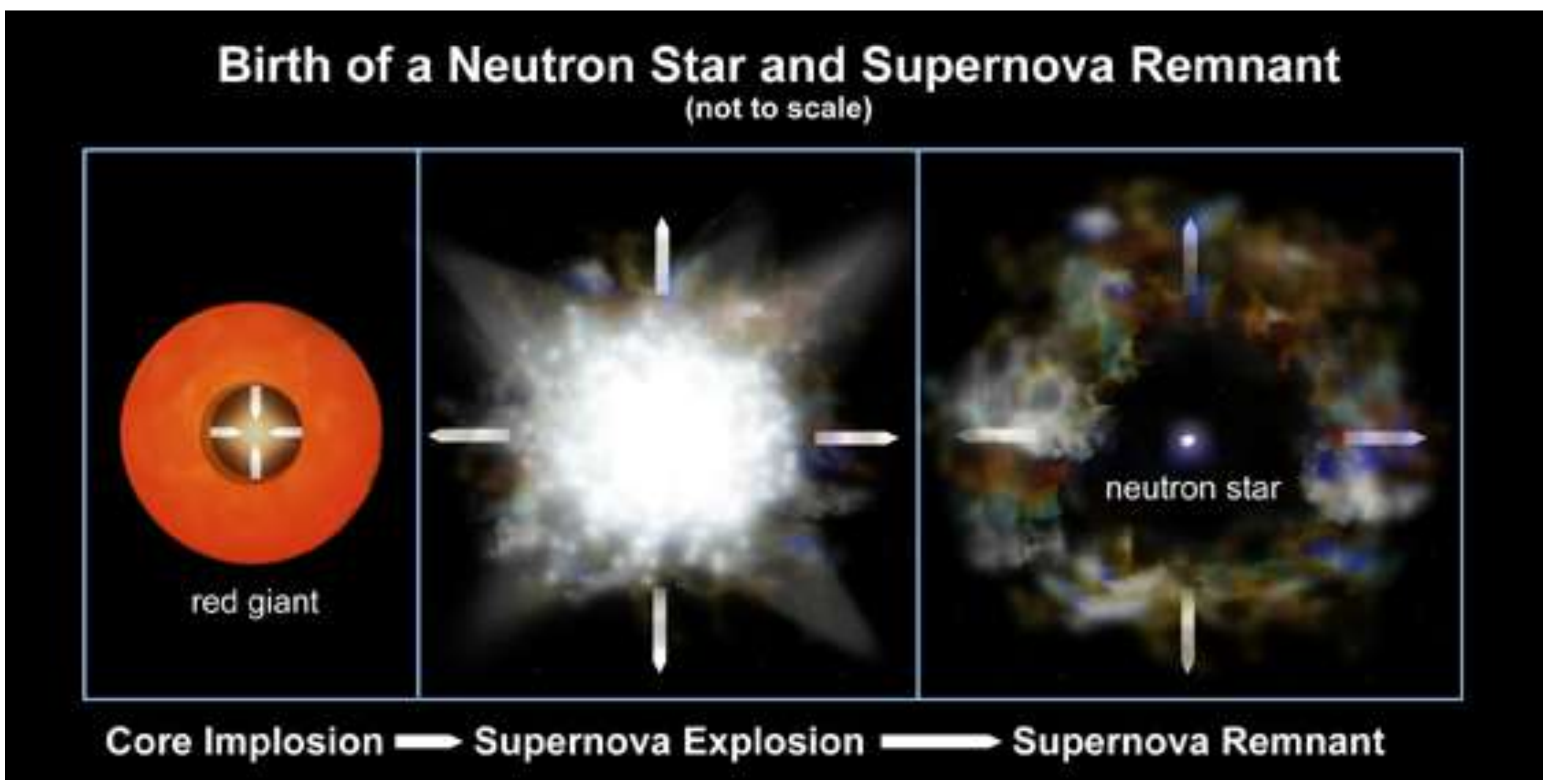
HESS Aharonian et al. 2016

Thermonuclear (Type Ia) & Core collapse supernovae



$$M_{\rm ej} = 1.4 M_\odot$$

$$E_{\rm SN} = 10^{51} {\rm erg}$$



Any other Type

$$M \geq 8 M_\odot$$

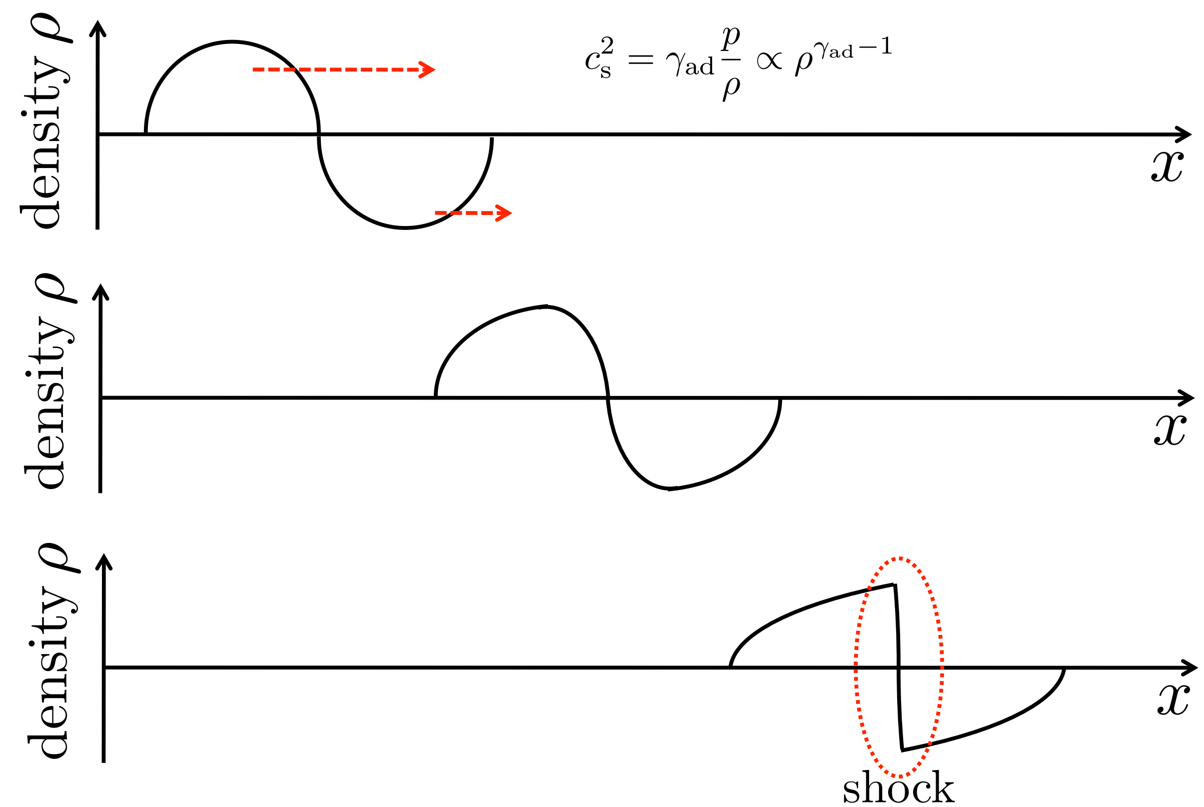
$$M_{\rm ej} \sim 1 - 10 M_\odot$$

$$E_{\rm SN} \sim 0.5 - 5 \; 10^{51} {\rm erg}$$

https://chandra.harvard.edu

Strong shock waves

Small perturbation in a fluid can form sound waves



Mass: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

Momentum: $$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = -\frac{\nabla P}{\rho}$$

Energy: $$\frac{d}{dt}\left(\frac{P}{\rho^\gamma}\right) = 0$$

Perturb it! $\delta\vec{v},\ \delta P,\ \delta\rho$

→ **If some part of the gas moves faster than sound, the gas ahead cannot "know" what is coming**

→ **Material piles up into a very thin compression front**

Strong perturbation: a discontinuity appears!

At SNRs: $$\mathcal{M} = \frac{u}{c_s} \gg 1$$

Strong shock waves

Mass: $$\rho_1 u_1 = \rho_2 u_2$$

Momentum: $$\rho_1 u_1^2 + P_1 = \rho_2 u_2^2 + P_2$$

Energy: $$\frac{1}{2}\rho_1 u_1^3 + \rho_1 u_1 \left(\epsilon_1 + \frac{P_1}{\rho_1}\right) = \frac{1}{2}\rho_2 u_2^3 + \rho_2 u_2 \left(\epsilon_2 + \frac{P_2}{\rho_2}\right)$$

Internal energy

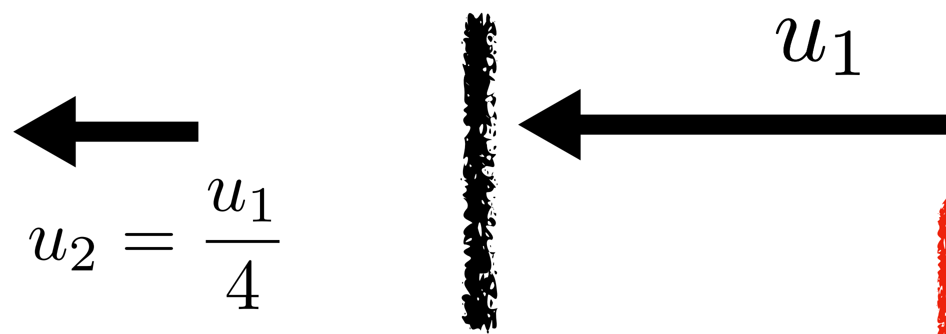
Specific enthalpy

Compression factor: $r = \dfrac{u_1}{u_2} = \dfrac{\rho_2}{\rho_1}$

$\mathcal{M} = \dfrac{u_1}{c_s} \gg 1$ **+ manipulations:** $\longrightarrow$ $$r^2 - 1 = \frac{2\gamma}{\gamma - 1}(r - 1)$$

$$\boxed{r = \frac{2\gamma}{\gamma - 1} - 1 = \frac{\gamma + 1}{\gamma - 1} \xrightarrow{\gamma = 5/3} 4}$$

Strong shock waves



$$r = \frac{2\gamma}{\gamma - 1} - 1 = \frac{\gamma + 1}{\gamma - 1} \xrightarrow{\gamma = 5/3} 4$$

1. Moderate compression of the gas

2. Makes the downstream gas subsonic: $\mathcal{M}_2^2 = \frac{u_2^2}{c_{s,2}^2} = \frac{\rho_2 u_2^2}{\gamma P_2} = \frac{\gamma - 1}{2\gamma} \xrightarrow{\gamma = 5/3} \frac{1}{5} < 1$

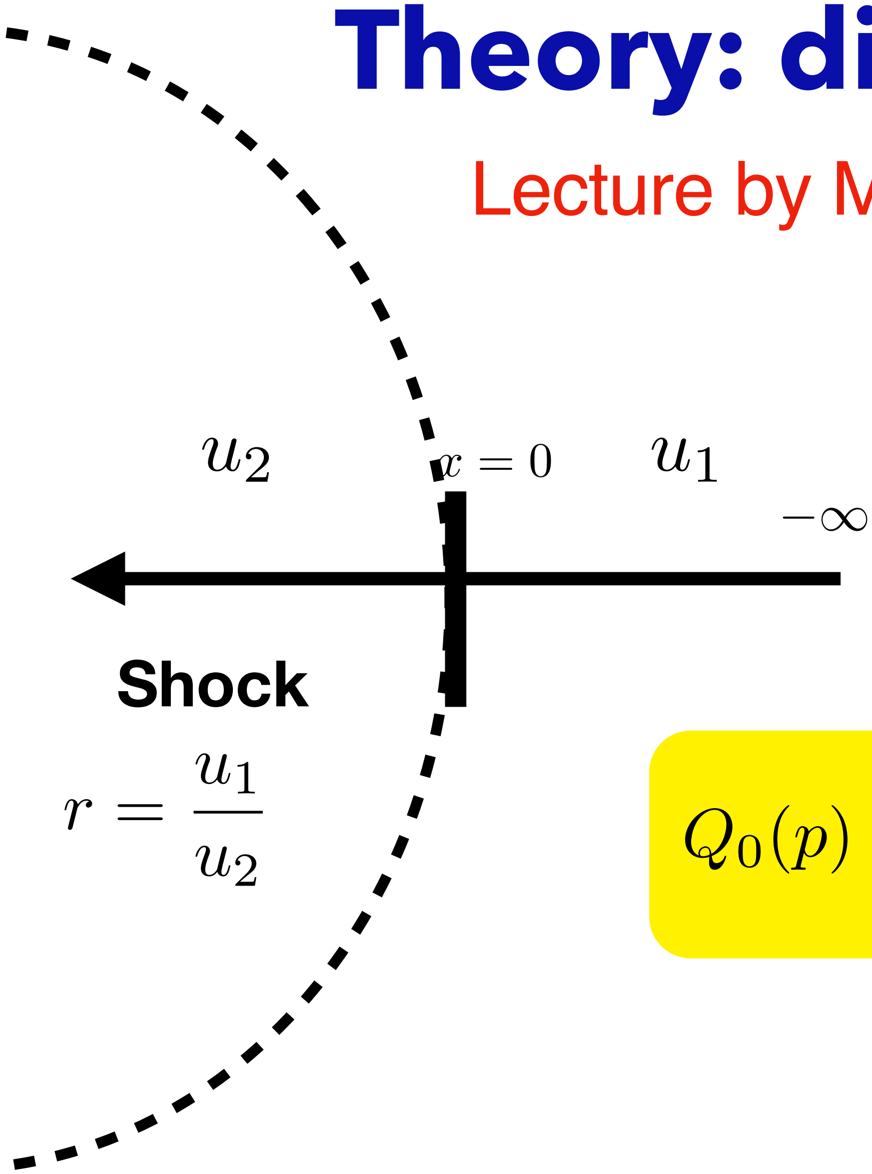
3. Heats significantly the gas (downstream)

$$kT_2 = \frac{2(\gamma - 1)}{(\gamma + 1)^2} m_p u_1^2 \xrightarrow{\gamma = 5/3} \frac{3}{16} m_p u_1^2 \sim \left(\frac{u_1}{1000\,\mathrm{km/s}} \right)^2 \mathrm{keV}$$

Theory: diffusive shock acceleration (DSA)

Lecture by Martin Lemoine

Well documented since the 1970s: Axford 1977, Krymskii 1977, Bell 1978, Blandford&Ostriker1978



$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f(x,p)}{\partial p} = -Q(x,p)$$

$$Q_0(p) = \frac{\eta n_0 u_1}{4\pi p_{\mathrm{inj}}^2}\delta(p - p_{\mathrm{inj}})$$

$$f_0(p) = s\frac{\eta n_1}{4\pi p_{\mathrm{inj}}^3}\left(\frac{p}{p_{\mathrm{inj}}}\right)^{-s}$$

$$\mathcal{M} \gg 1 \qquad s = \frac{3r}{r-1} \to 4$$

The 1D test-particle theory at strong colisionless shocks is well known

Open questions:

1. **Which particles (electrons/protons)?**
2. **Maximum energy of accelerated particles?**
3. **Efficiency of particle acceleration? How do particles get injected in the process**
4. **Spectrum of accelerated particles at the shock?**
5. **Total spectrum released in the ISM? Escape of particles, diffusion around sourc**

Reviews: Blasi 2013, Gabici 20

Theory: diffusive shock acceleration (DSA)

Well documented since the 1970s: Axford 1977,
Krymskii 1977, Bell 1978, Blandford&Ostriker1978

For any acceleration mechanism:

$$f(p) \propto A \left(\frac{p}{p_0} \right)^{-\alpha} \exp\left[\frac{p}{p_{\mathrm{max}}} \right]$$

NB: deviations from power-laws (curvature) are predicted and expected, but on 1st order this is enough (given current observations, etc.)

Reviews: Blasi 2013, Gabici 20

Acceleration mechanisms

	Spectrum	Efficiency	Emax
Fermi 2			
Fermi1 non-relat.			
Fermi1 Relativistic			
Magnetic reconnection			
Gaps			
Shear			
...			

Acceleration mechanisms

	Spectrum	Efficiency	Emax
Fermi 2	$\propto p^{\frac{1}{\alpha \tau_{\rm esc}} - 1}$	$+$	?
Fermi1 non-relat.	$\propto p^{-4}$	$+++$	?
Fermi1 Relativistic	$\propto p^{-4.2}$	$+$	?
Magnetic reconnecti			
Gaps			
Shear		?	

Supposed to be « universal » (test-particle) and we easily get deviation from power-law + harder/steeper spectra!

Diffusive shock reacceleration

Bell (1978, MNRAS, II.)

6. Effect of a shock front on pre-existing cosmic rays

« In previous sections the injection of particles into the acceleration mechanism has been considered as taking place at low energy […] An alternative source for the injection of particles is the cosmic ray population which already exists in the upstream gas. »

(…)

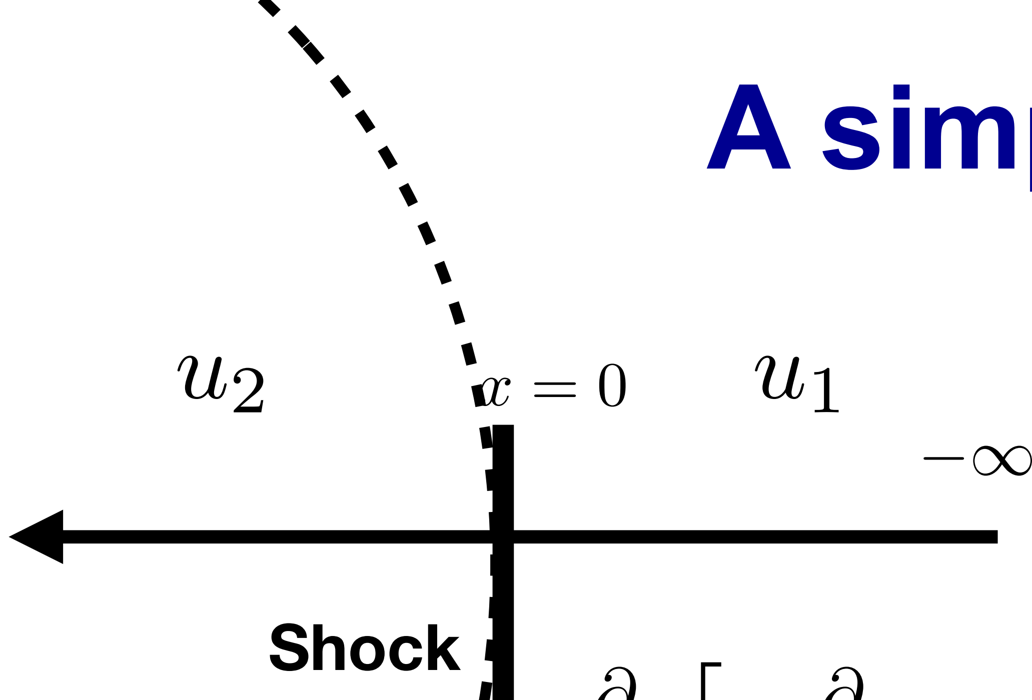
Pohl et. al (2015, A&A)

Reacceleration of electrons in SNRs

Blasi (2017, MNRAS), Bresci et al. (2019, MNRAS)

The role of reacceleration on secondary nuclei.
-> Anti-proton-to-proton and Boron-to-Carbon ratios

A simple description



$$\frac{\partial}{\partial x}\left[D\frac{\partial}{\partial x}f(x,p)\right] - u\frac{\partial f(x,p)}{\partial x} + \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}x}p\frac{\partial f(x,p)}{\partial p} = -Q(x,p)$$

$$Q_0(p) = \frac{\eta n_0 u_1}{4\pi p_{\mathrm{inj}}^2}\delta(p - p_{\mathrm{inj}})$$

$$g(p) = f(-\infty, p)$$

Boudary condition -> upstream infinity of the shock

$$r = \frac{u_1}{u_2}$$

$$s = \frac{3r}{r-1}$$

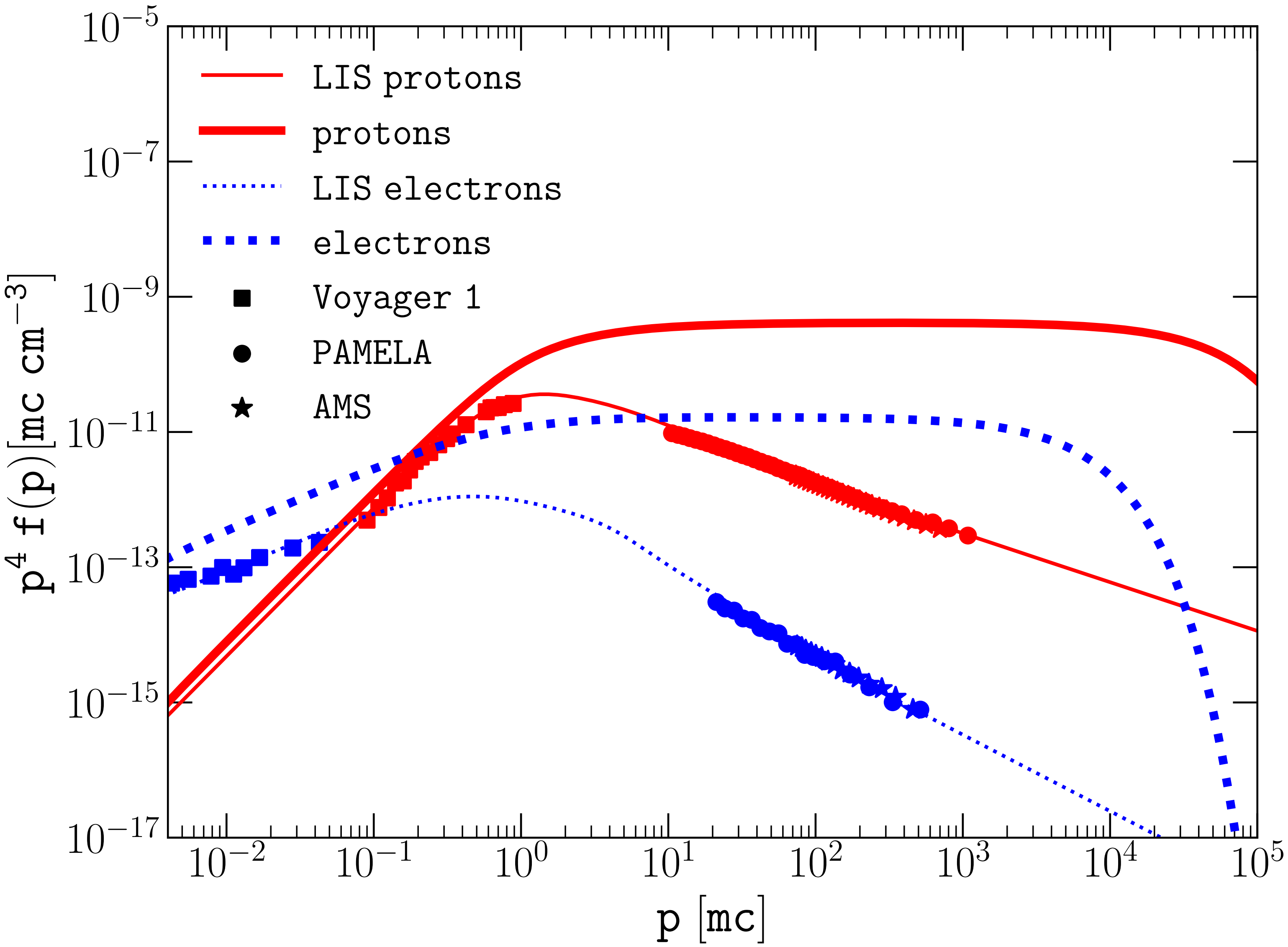
$$f_0(p) = \cancel{s\frac{\eta n_1}{4\pi p_{\mathrm{inj}}^3}\left(\frac{p}{p_{\mathrm{inj}}}\right)^{-s}} + s\int_{p_0}^{p}\frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^s g(p')$$

« Classic » diffusive shock acceleration

Reacceleration

Blasi (2004)

Reacceleration of Galactic CRs



$$f_0^{\mathrm{reac}}(p) = s \int_{p_0}^{p} \frac{\mathrm{d}p'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$

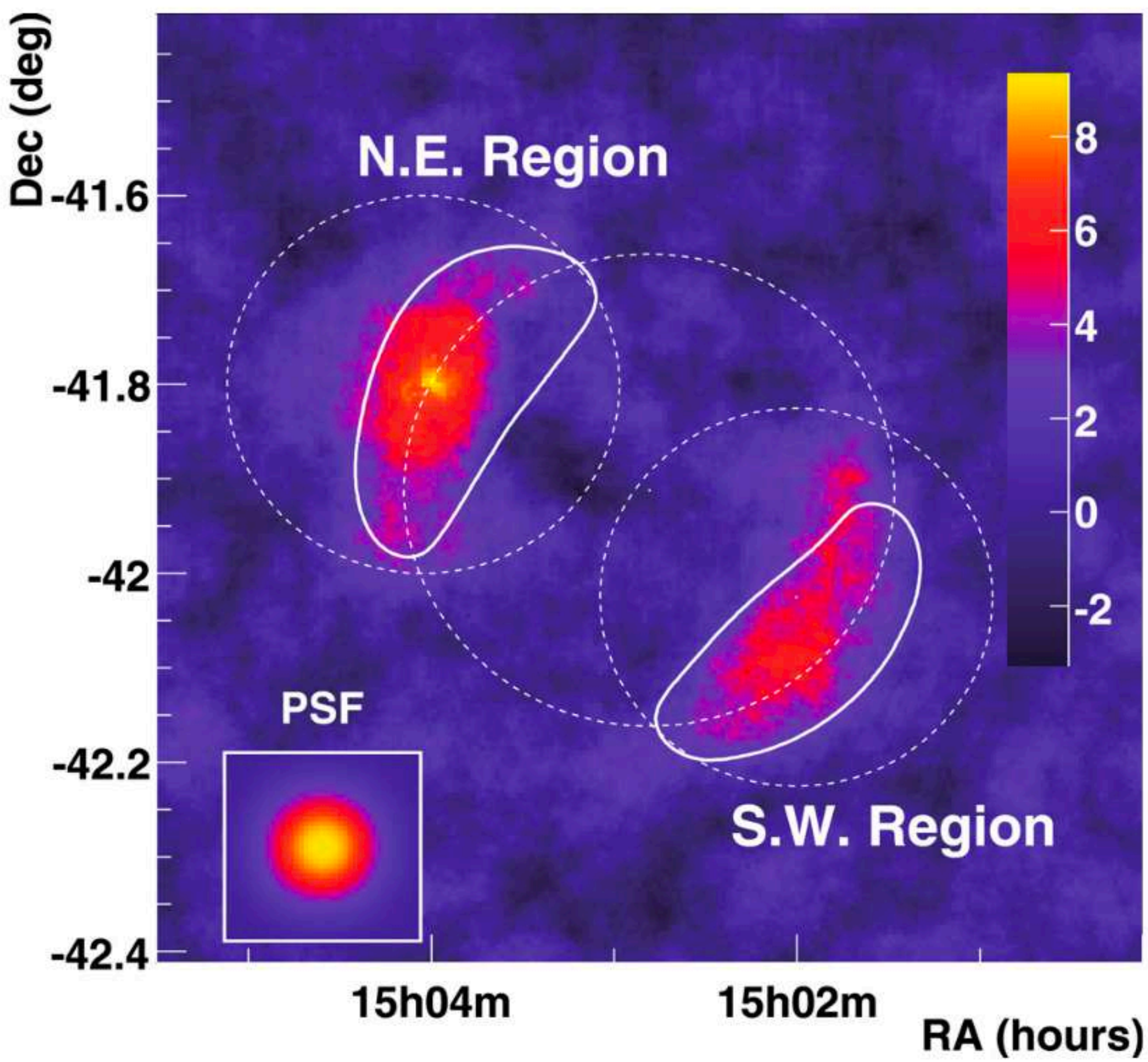
$$s = 4$$

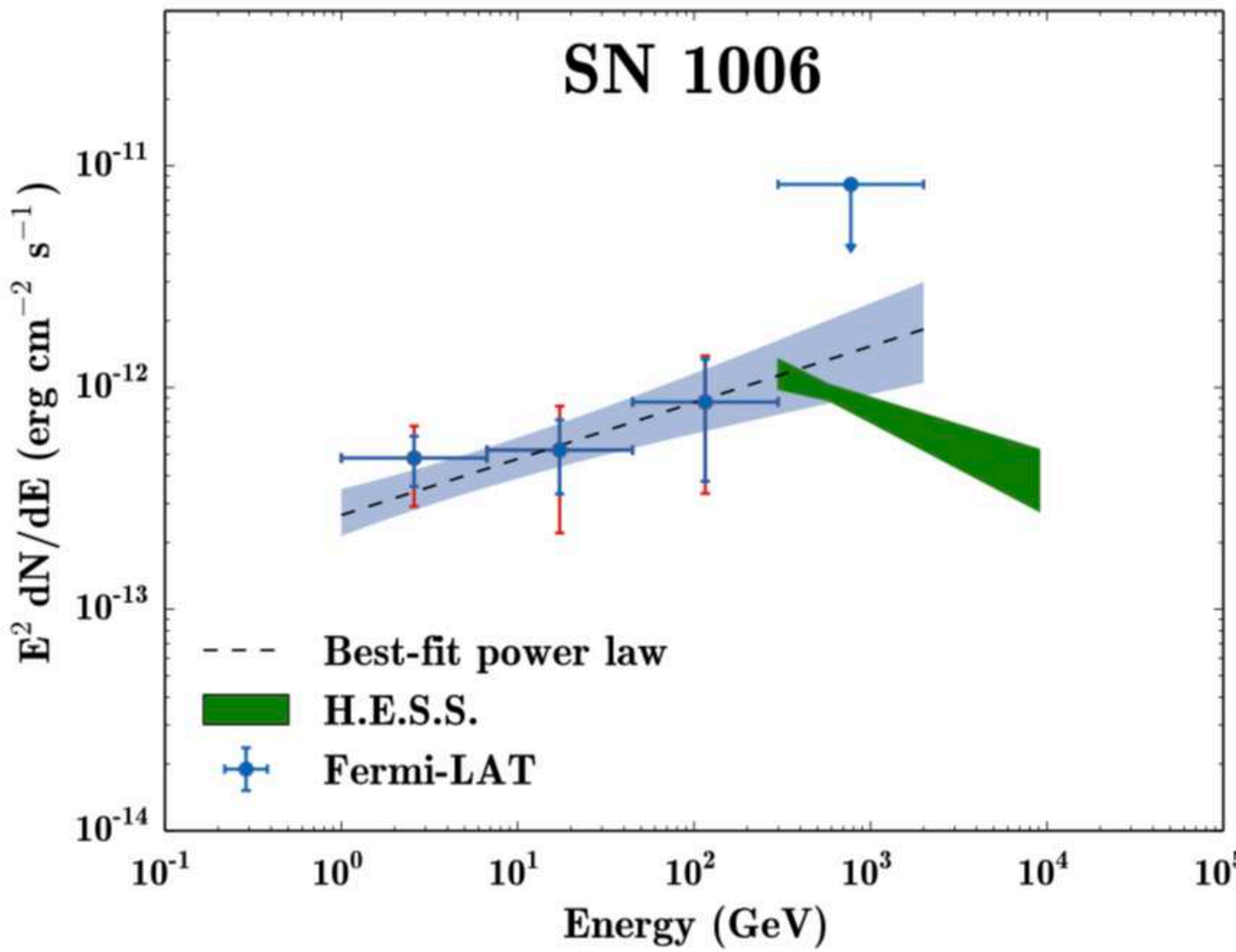
$$p_0 \lesssim 1 \text{ GeV}$$

Maximum energy of reaccelerated particles?

Bisschoff et al. (2019)
Aguilar et al. (2019)
Cummings et al. (2016)
Adriani et al. (2011)

SN 1006





$$R_{\rm sh} \approx 7 - 8 \text{ pc}$$

$$d \approx 1.8 - 2 \text{ kpc}$$

$$u_{\rm sh} \approx 4.3 \; 10^8 \text{cm/s}$$

$$n_0 \sim 10^{-2} - 10^{-1} \text{ cm}^{-3}$$

H.E.S.S. (2010)

Condon (2017)

Reaccelerated particles at SN 1006

$$f_0^{\rm reac}(p) = s \int_{p_0}^{p} \frac{{\rm d}p'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$

Maximum energy of reaccelerated particles?

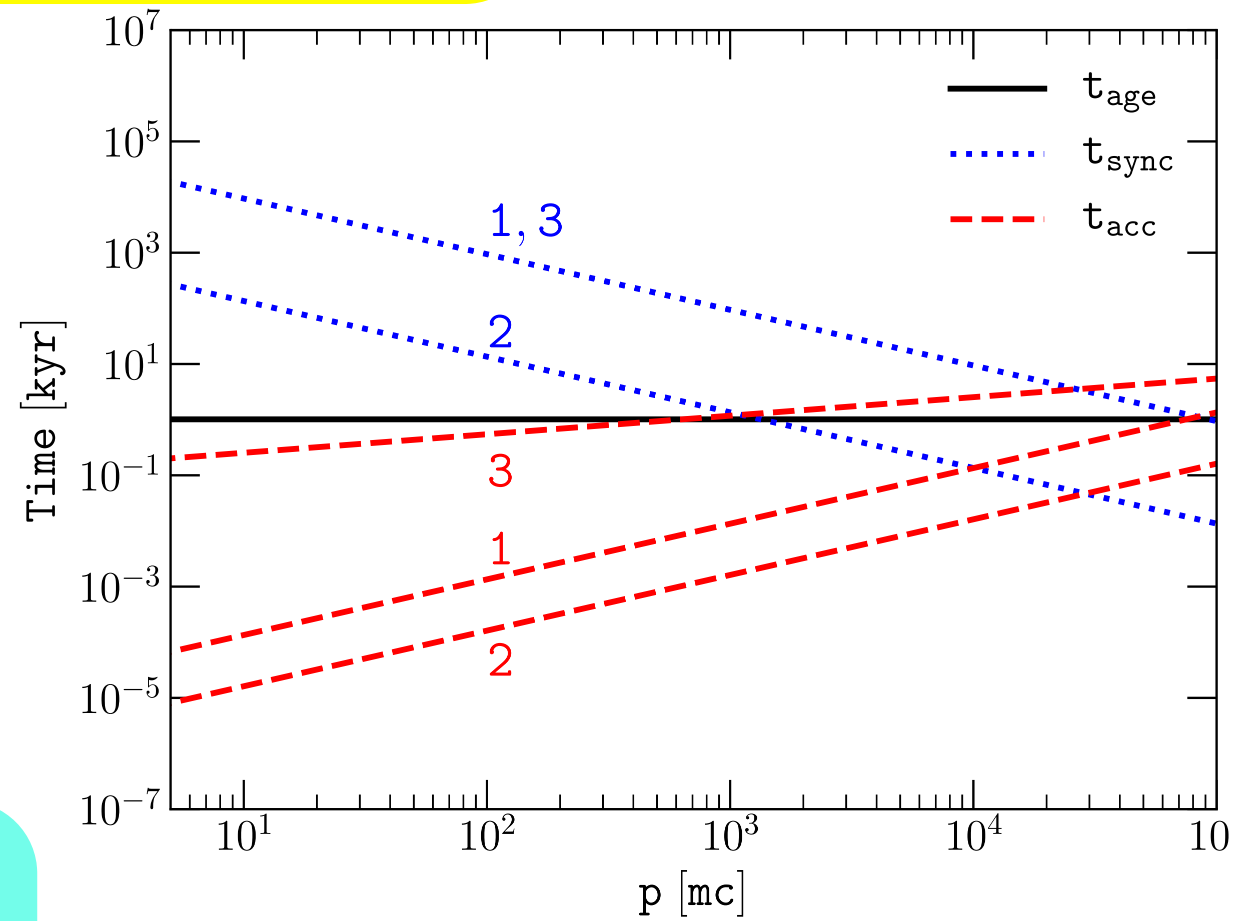
~~Protons?~~

$$n_0 \sim \cancel{10^{-2} - 10^{-1}}\ {\rm cm}^{-3}$$

Maximum energy of reaccelerated electrons?

$$\tau_{\rm acc} = \min(\tau_{\rm sync}, t_{\rm age})$$

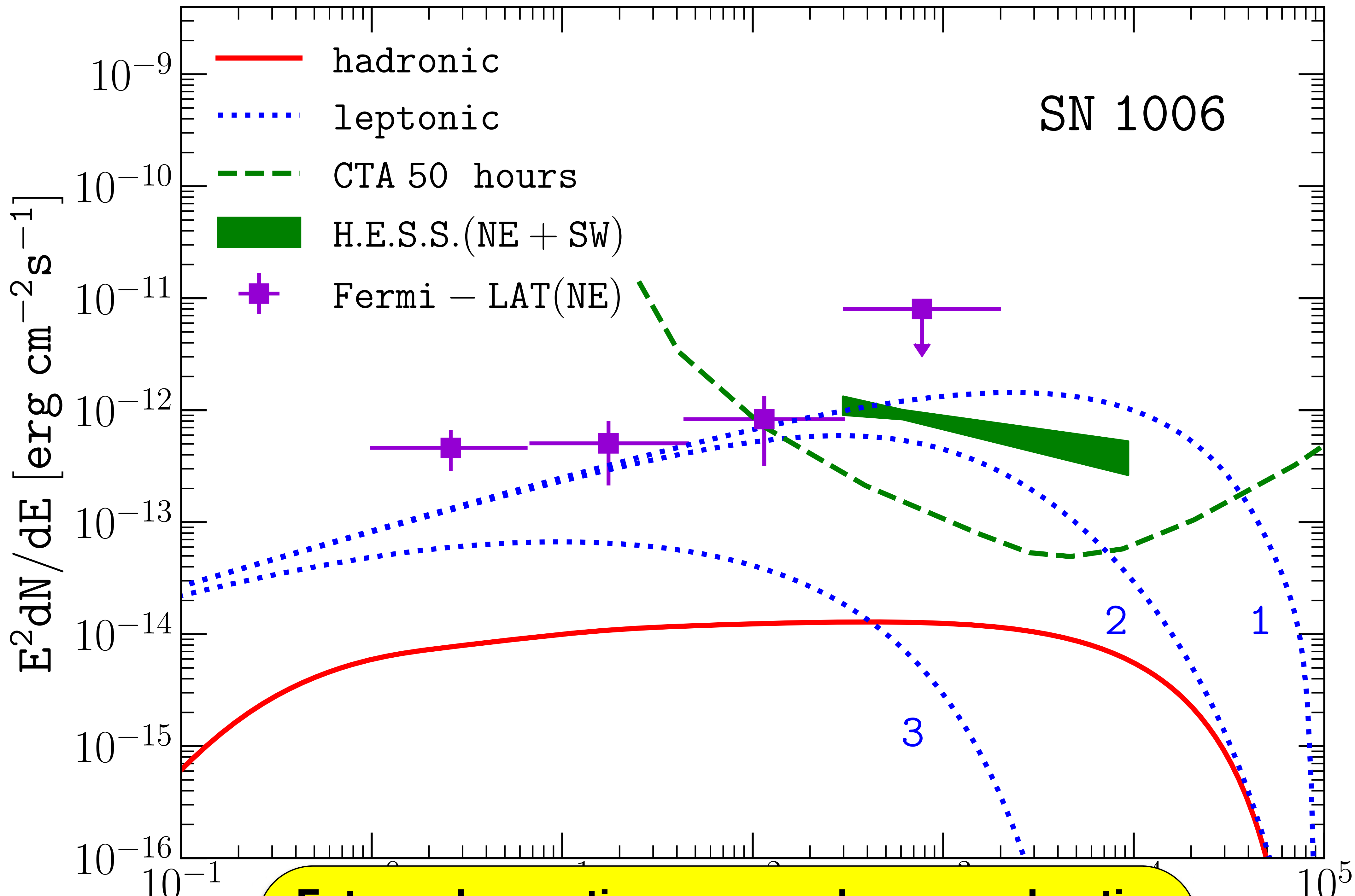
$$\tau_{\rm acc} = \frac{3}{u_1 - u_2} \int_0^p \frac{{\rm d}p'}{p'} \left(\frac{D_1(p')}{u_1} + \frac{D_2(p')}{u_2}\right)$$



1. $D(p) \propto p$ $\quad B_2 = 12\mu G$
2. $D(p) \propto p$ $\quad B_2 = 100\mu G$
3. $D(p) \propto p^{1/3}$ $\quad B_2 = 12\mu G$

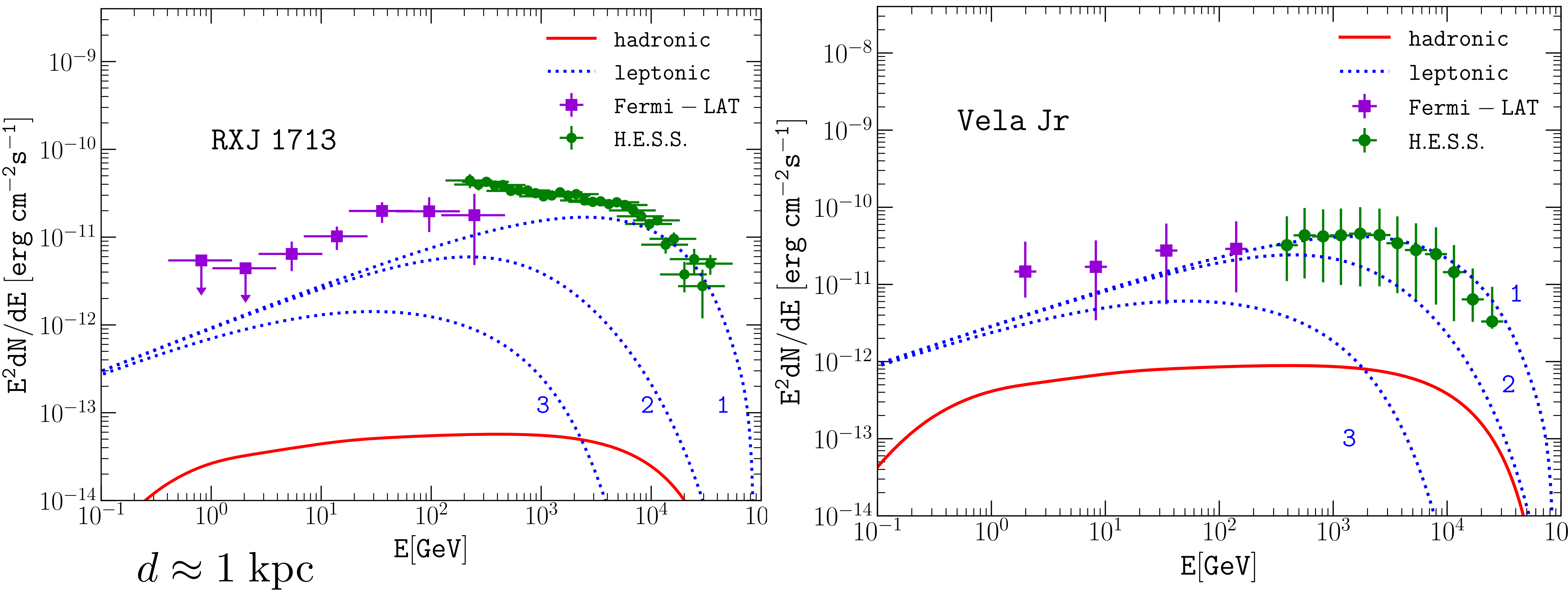
$$B_2 = rB_1$$

Gamma rays from SN 1006



Future observations can probe reacceleration and constrain the diffusion coefficient

RXJ1713 and Vela Jr



$d \approx 1$ kpc

$n_0 \approx 10^{-2}\mathrm{cm}^{-3}$

$R_{\mathrm{sh}} \approx 10$ pc

$u_{\mathrm{sh}} \approx 4\ 10^8$ cm/s

$d \approx 0.750$ kpc

$n_0 \approx 10^{-1}\mathrm{cm}^{-3}$

$R_{\mathrm{sh}} \approx 12$ pc

$u_{\mathrm{sh}} \approx 3\ 10^8$ cm/s

Gamma rays from reaccelerated particles ~somewhat at the level of gamma rays from 'freshly' accelerated particles

Reaccelaration over the SNR lifetime

$$R_{\mathrm{sh}} \propto t^{2/5}$$
$$u_{\mathrm{sh}} \propto t^{-3/5}$$
$$p_{\max} = p_{\mathrm{M}} t^{-\alpha}$$

$$N(p) = \int_{t_0}^{T_{\mathrm{SN}}} \mathrm{d}t \; n(p,t) 4\pi R_{\mathrm{sh}}^2(t) u_{\mathrm{sh}}(t)$$

Number of freshly accelerated particles

$$n_{\mathrm{acc}}(p,t) \propto \eta \; n_0 \; u_{\mathrm{sh}}(t) \; p^{-2} \exp\left[-\frac{p}{p_{\max}(t)}\right]$$

Number of reaccelerated particles

$$n_{\mathrm{reac}}(p,t) \propto p^2 \; f_0^{\mathrm{reac}}(p)$$
$$\propto p^2 \; s \int_{p_0}^{p} \frac{\mathrm{d}p'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$
$$\propto p^{-2} \exp\left[-\frac{p}{p_{\max}(t)}\right]$$

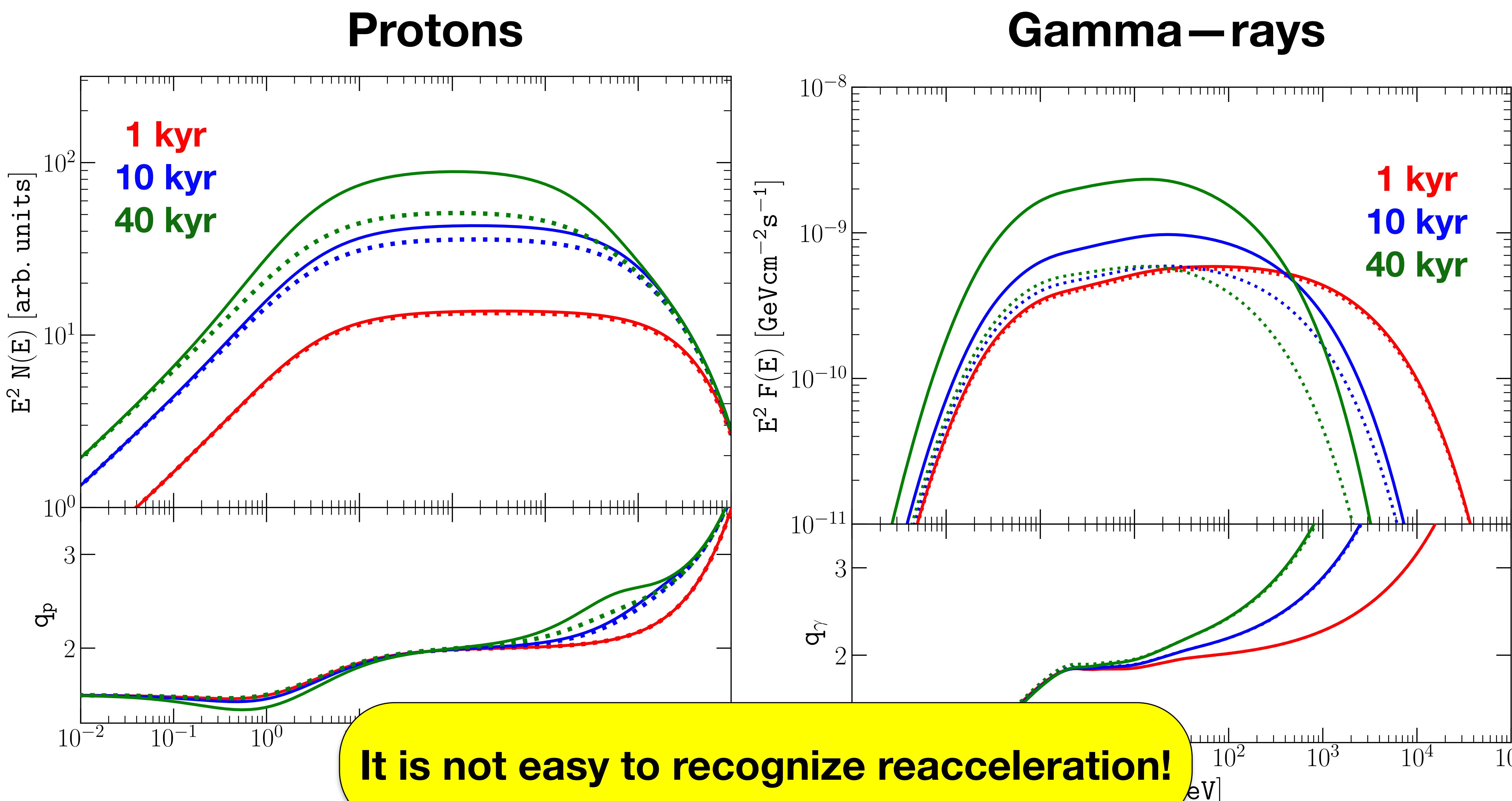
Total integrated spectrum

$$N_{\mathrm{acc}}(p) \propto \xi E_{\mathrm{SN}} \; p^{-2} \ln\left(\frac{p_{\mathrm{M}}}{p}\right)$$

Total integrated spectrum

$$N_{\mathrm{reac}}(p) \propto V_{\mathrm{SN}} \left(\frac{T_{\mathrm{SN}}}{t_0}\right)^{6/5} p^{-2} \exp\left[-\frac{p}{p_{\max}(T_{\mathrm{SN}})}\right]$$

Reacceleration over the SNR lifetime



It is not easy to recognize reacceleration!

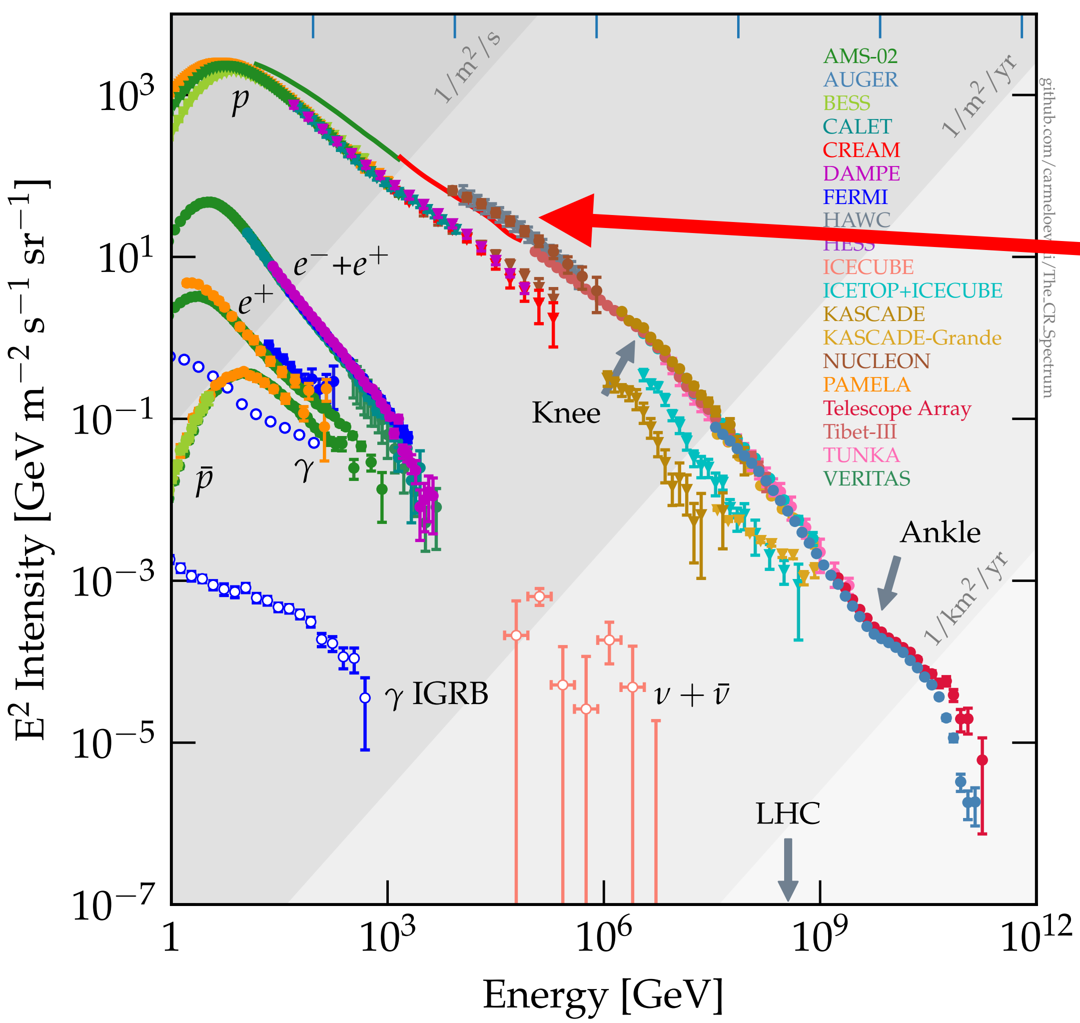
Diffusive shock acceleration (DSA)

Test-particle limit, spectrum of particles accelerated at a strong shock (compression factor 4)

$$f(p) \propto p^{-4}$$

$$f(E) \propto E^{-2}$$

$$E \gg m_p c^2$$



$$\propto E^{-2.7}$$

Propagation of CRs in the Galaxy

$$\frac{B}{C} \propto \frac{1}{D(E)} \propto E^{-0.3-0.6}$$

$$E^{-2.7} = E^{-0.3\ldots0.6} \times N(E)$$

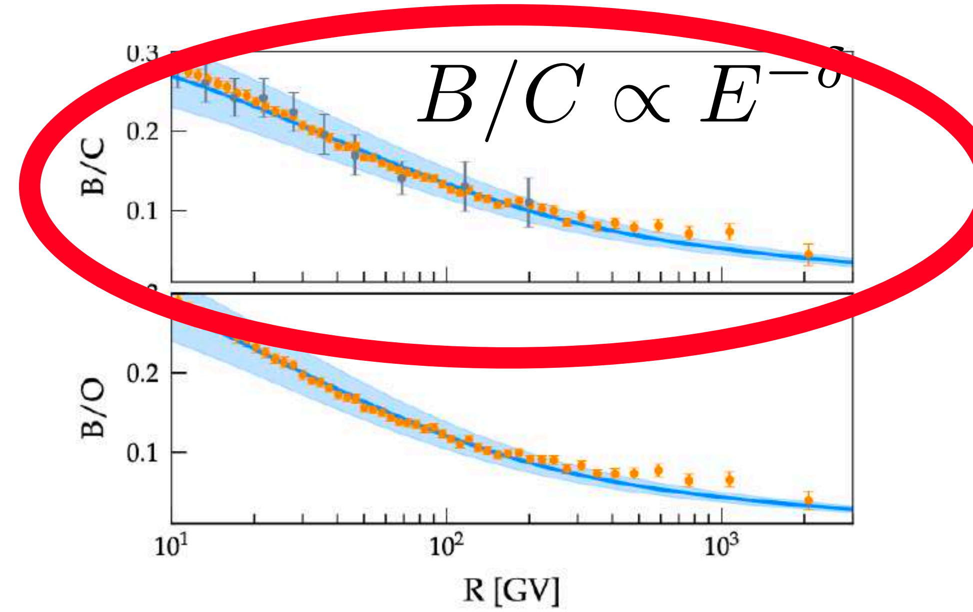
$$N(E) \propto E^{-2.1\ldots2.4} \neq E^{-2}$$

Problem faced by the SNR hypothesis

1. Diffusive shock acceleration predicts E^{-2} at SNRs

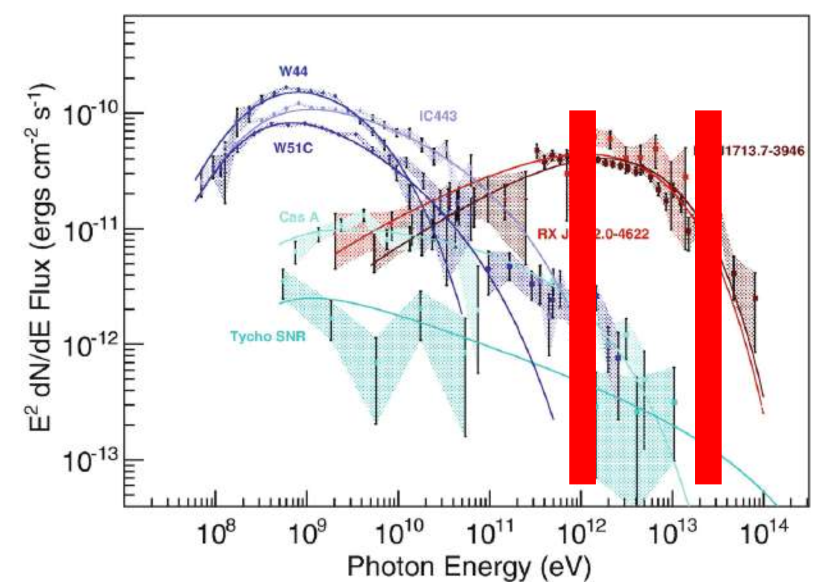
$$E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$$

Injection Propagation



2. Non-thermal emission from radio to gamma

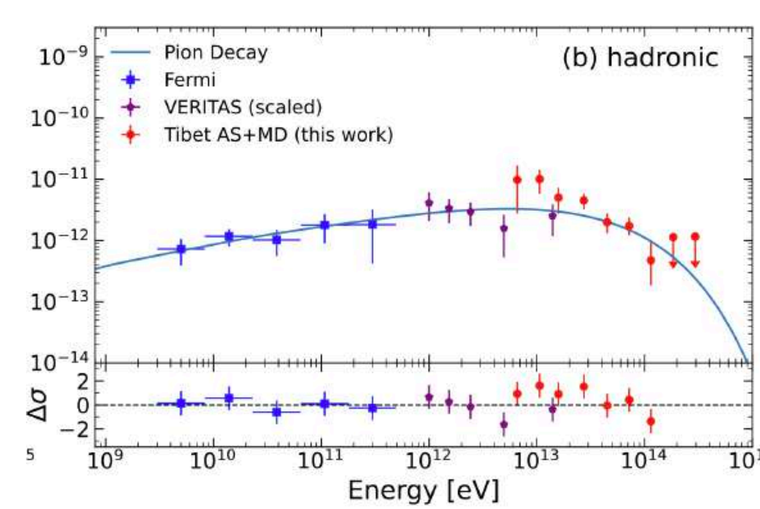
VHE domain steep spectra?
Particle content: protons/electrons?



Funk (2017)

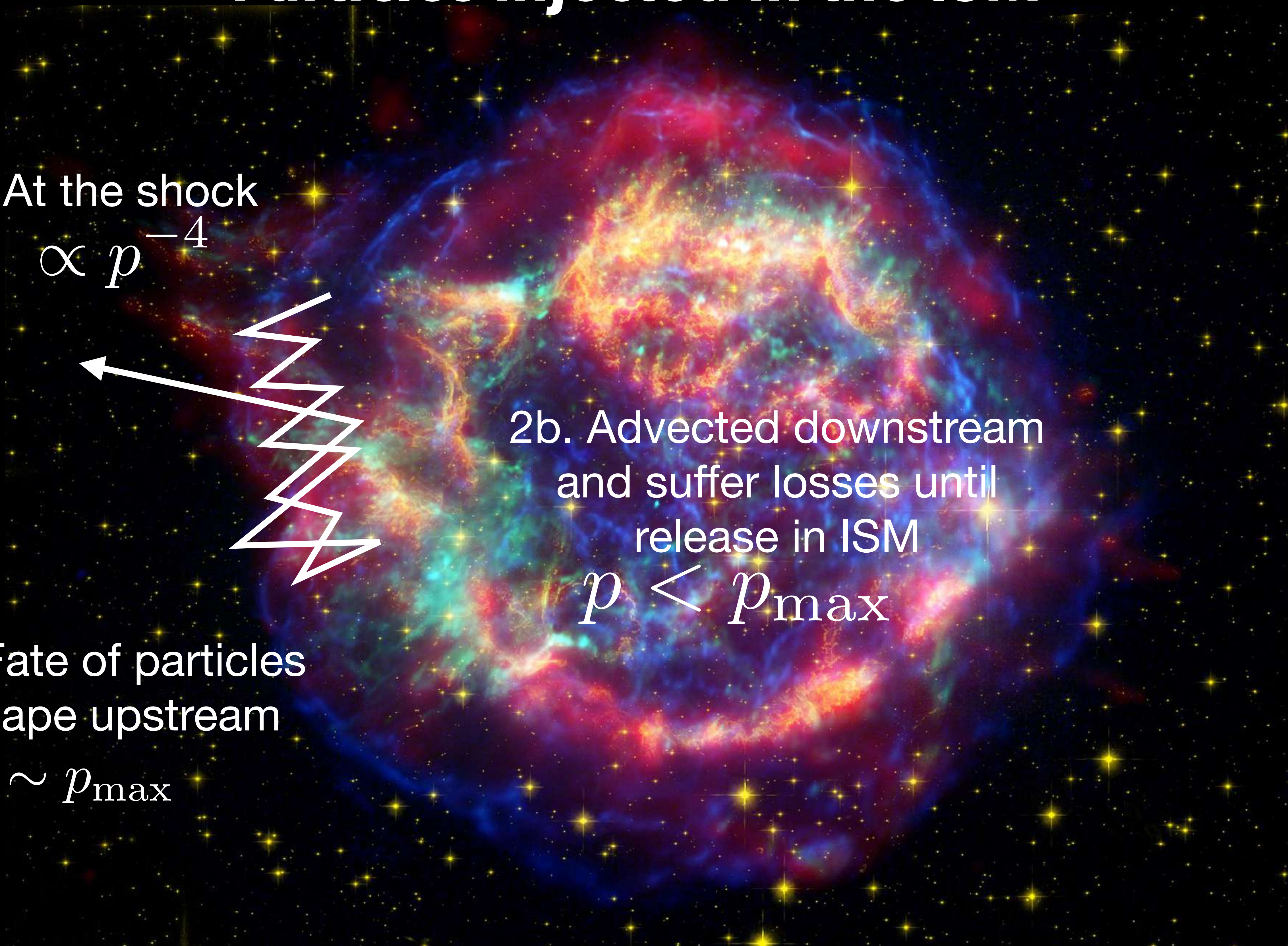
3. SNR Pevatron? (magnetic field amplification)

NO SNR pevatron?



SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

Particles accelerated at the shock ≠ Particles injected in the ISM



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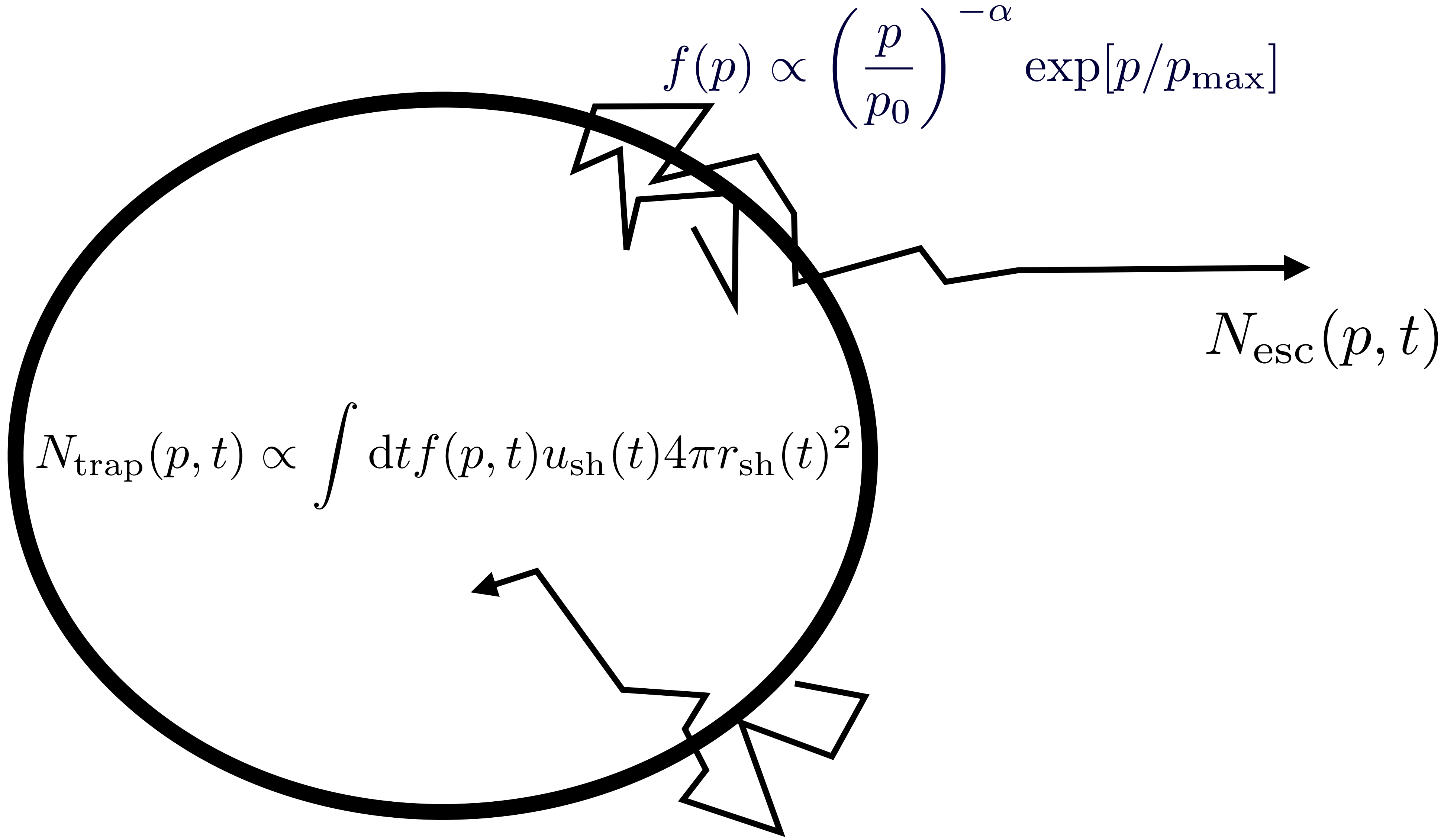


$$N_{\rm tot} = N_{\rm trap} + N_{\rm esc}$$

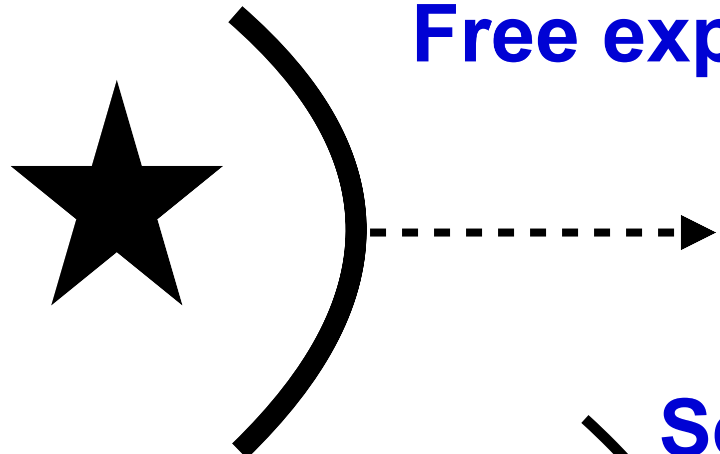
$$N_{\rm tot} = \int_{t_0}^{t_{\rm end}} \mathrm{d}t \ldots$$

When it ends..

When particle acceleration starts～ SN explosion

The evolution of supernova remnants

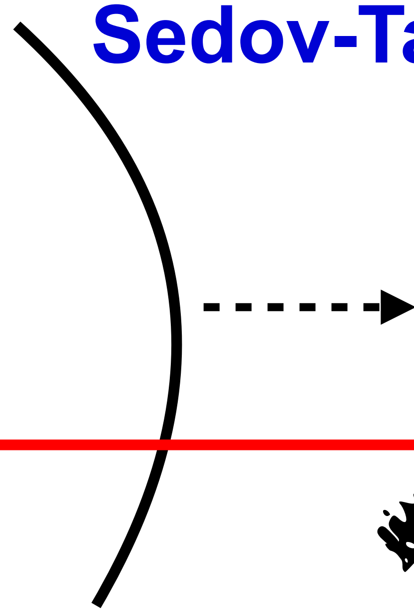
$M_{\rm ej} = 1.4 M_\odot$
$E_{\rm SN} = 10^{51} {\rm erg}$
$n_0 = 1 \ {\rm cm}^{-3}$



Free expansion phase

$M_{\rm ejecta} \gg M_{\rm swept-up}$

$t_{\rm end} \sim 0.3 \ {\rm kyr}$

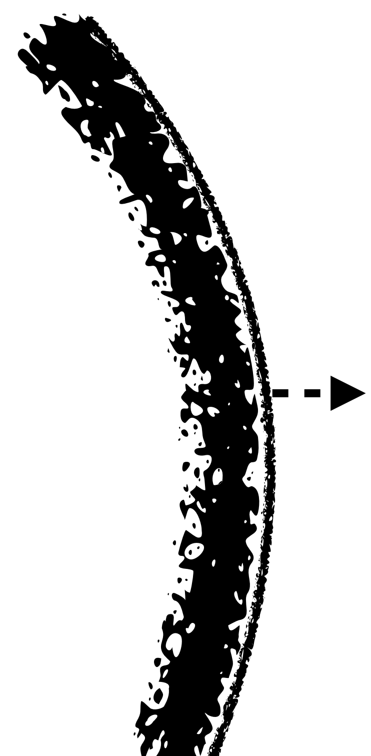


Sedov-Taylor (adiabatic) phase

$M_{\rm ejecta} \lesssim M_{\rm swept-up}$

$t_{\rm end} \sim 20 \ {\rm kyr}$

Particle acceleration



Radiative phase

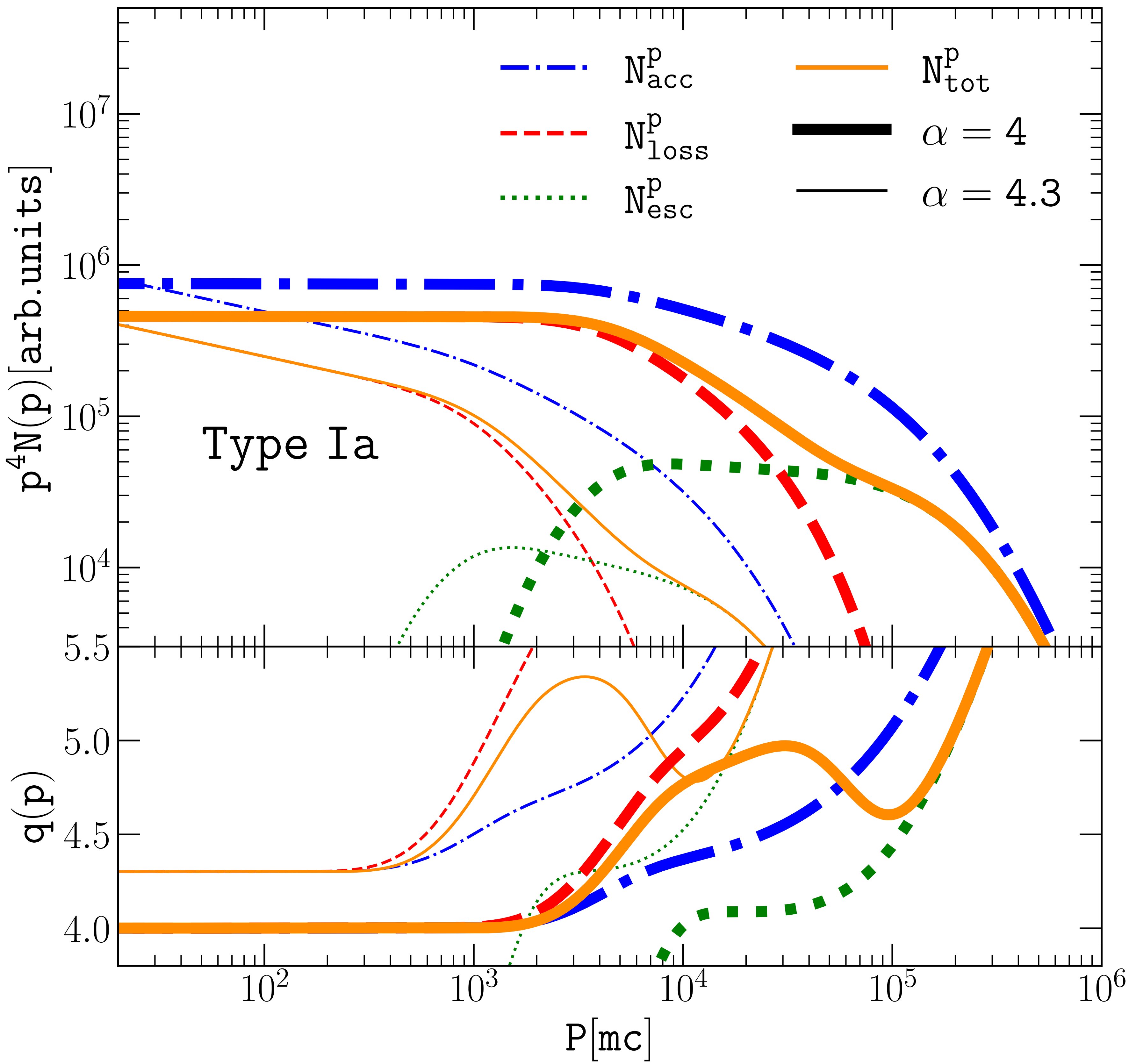
?

$\cancel{\tau_{\rm cooling} \lesssim t_{\rm age}}$

$\cancel{t_{\rm end} \sim 100 - 200 \ {\rm kyr}}$

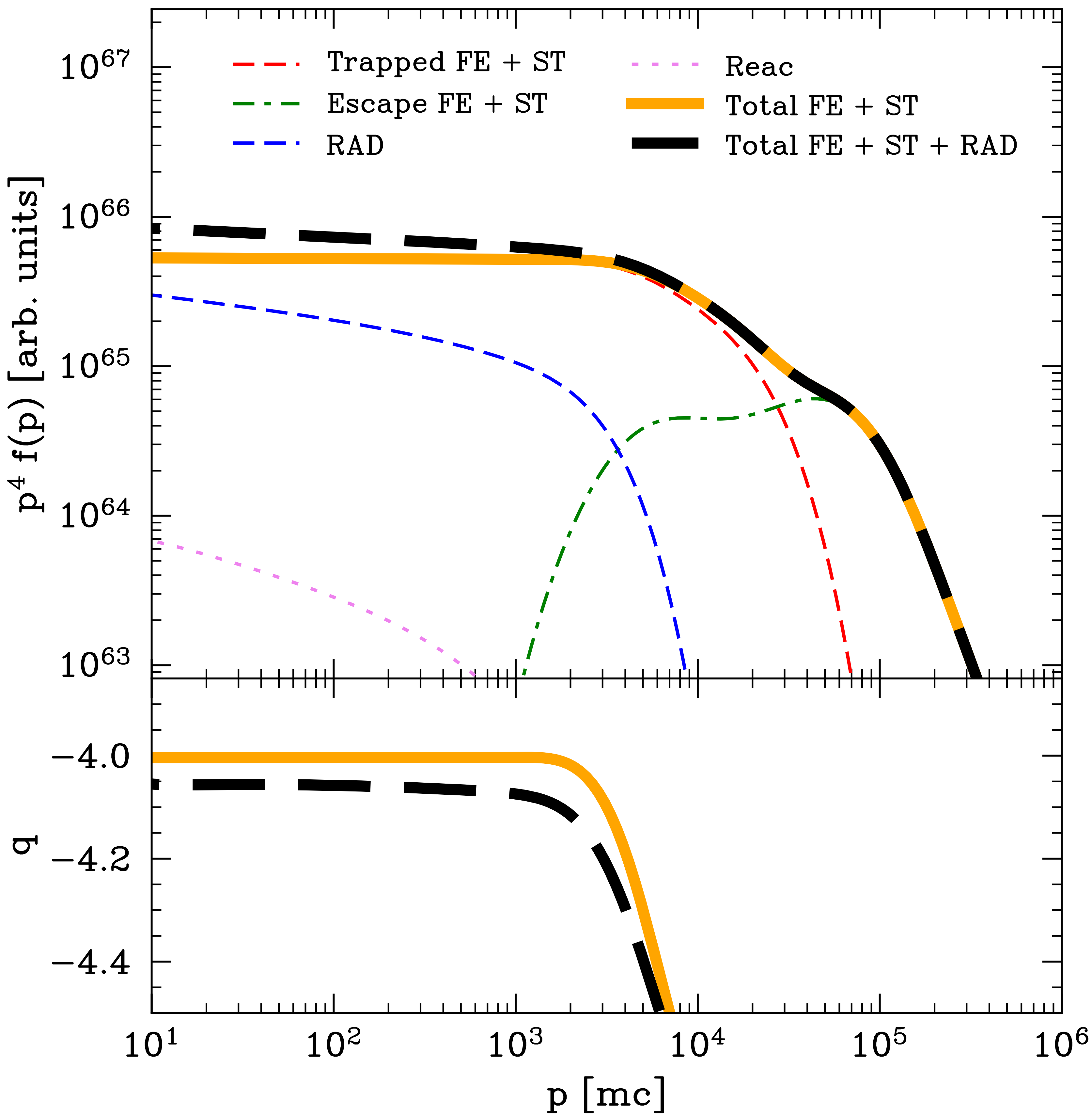
$\cancel{t_{\rm end} \sim 20 - 300 \ {\rm kyr}}$ **????**

accelerated ≠ injected



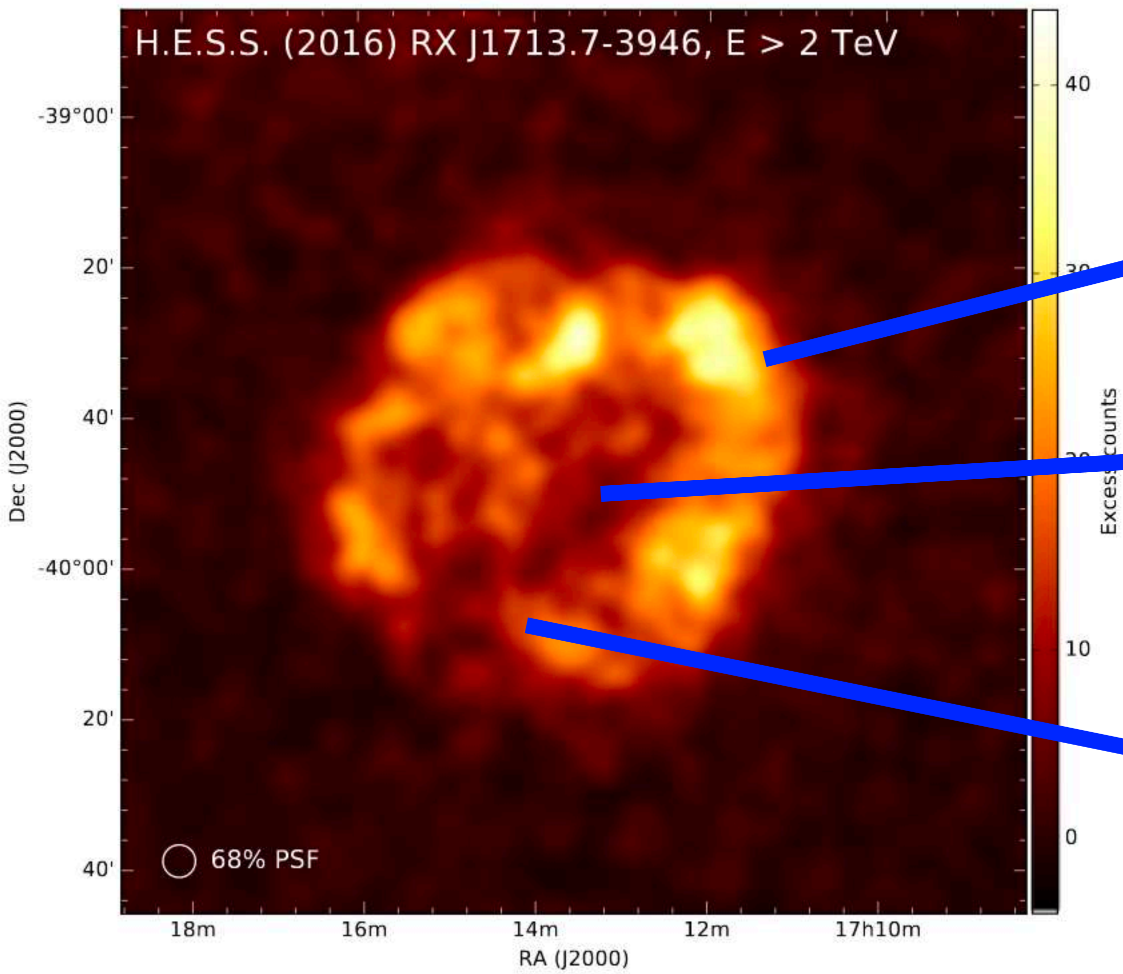
PC, Blasi, Caprioli 2021

accelerated ≠ injected



PC 2025

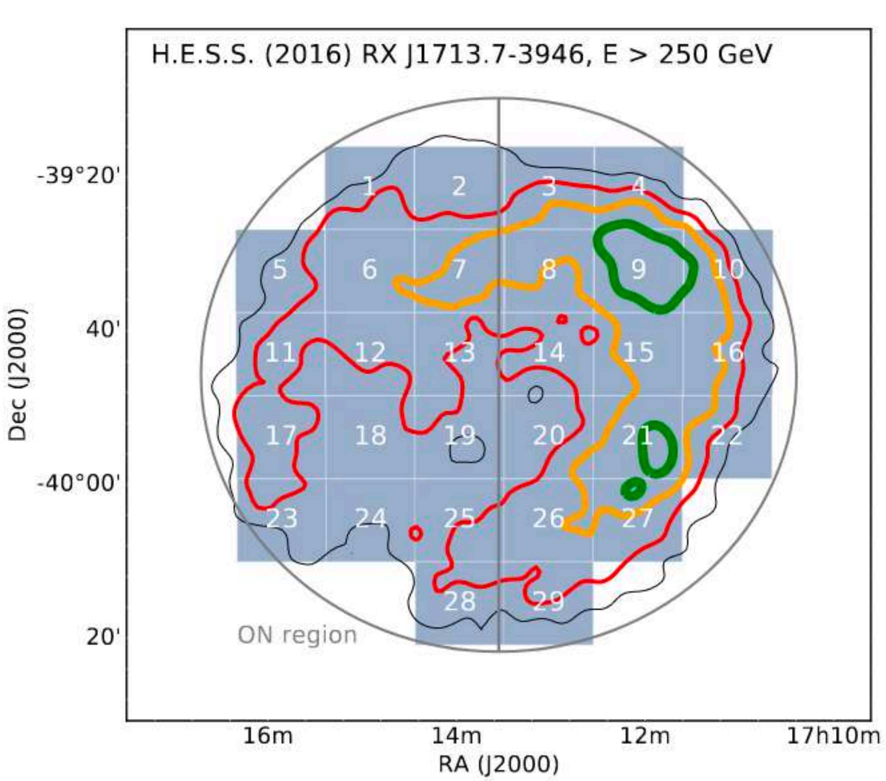
The particle content

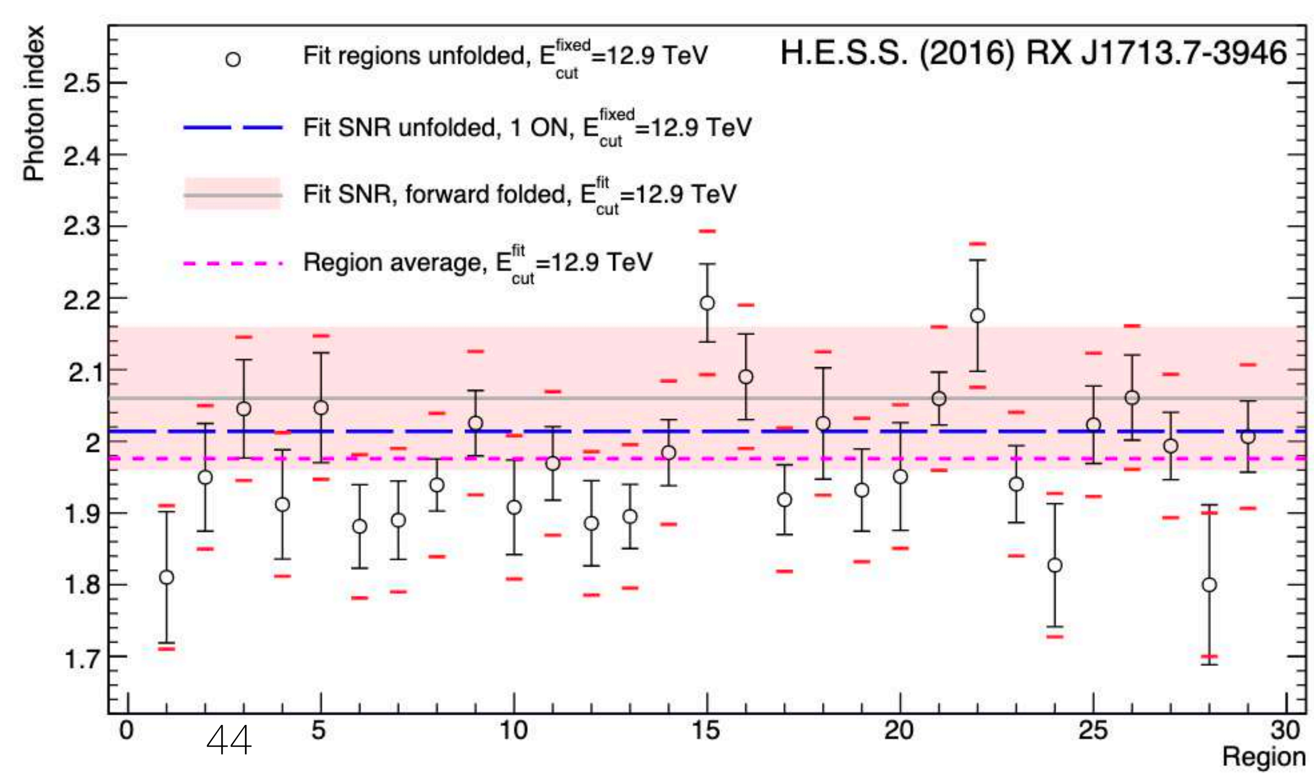


Particles at the shock?

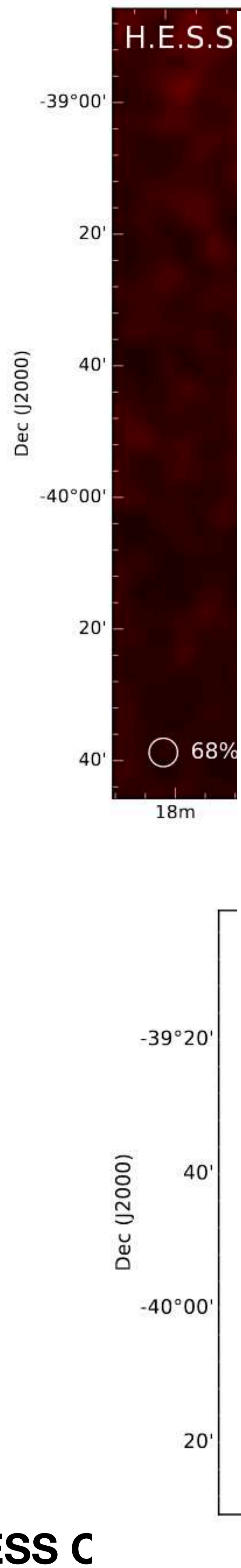
Inside the SNR? losses?

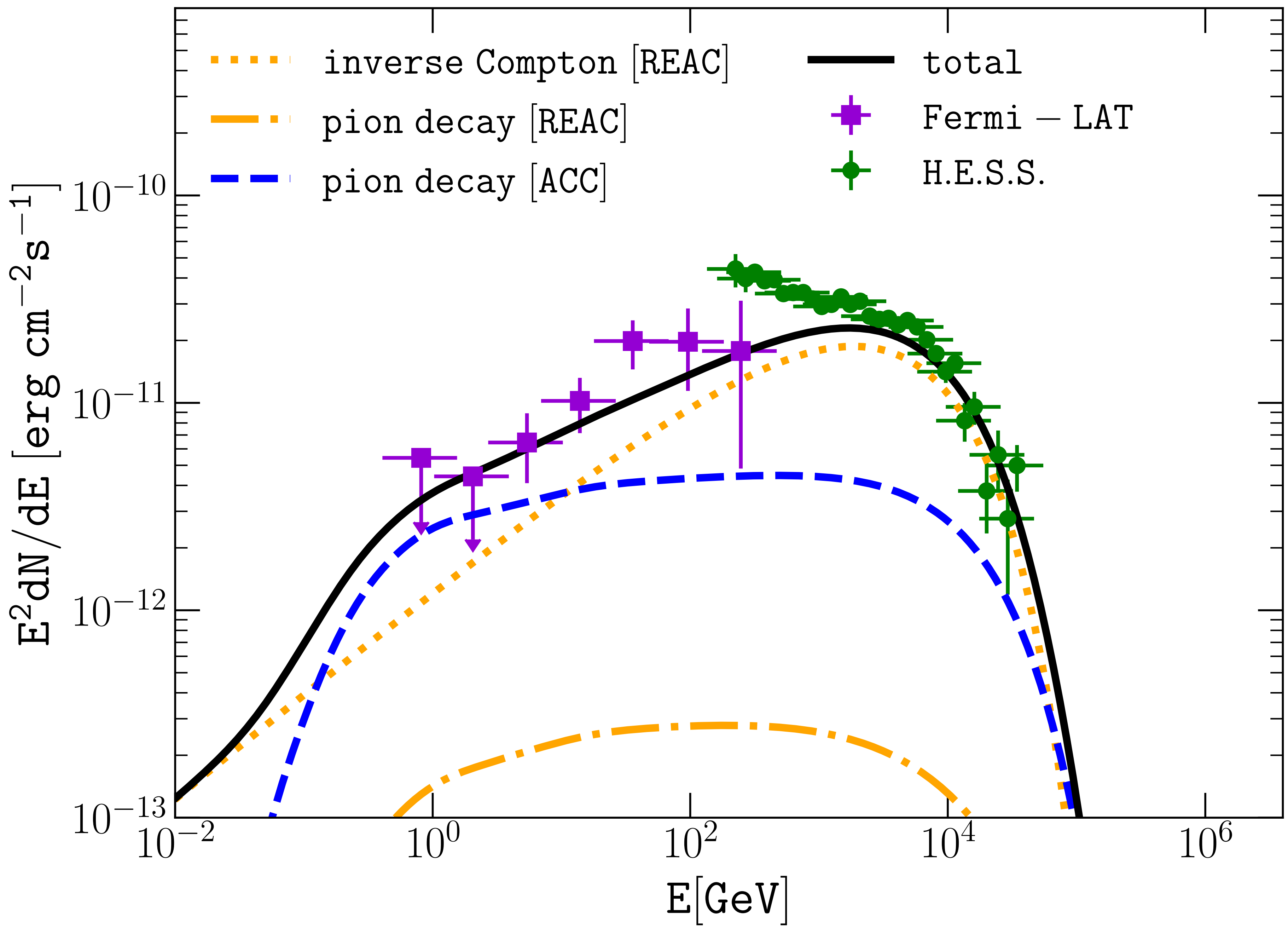
Accelerated/reaccelerated

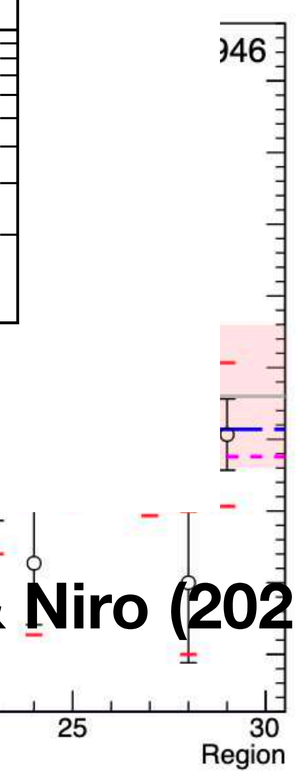




The particle content







ock?

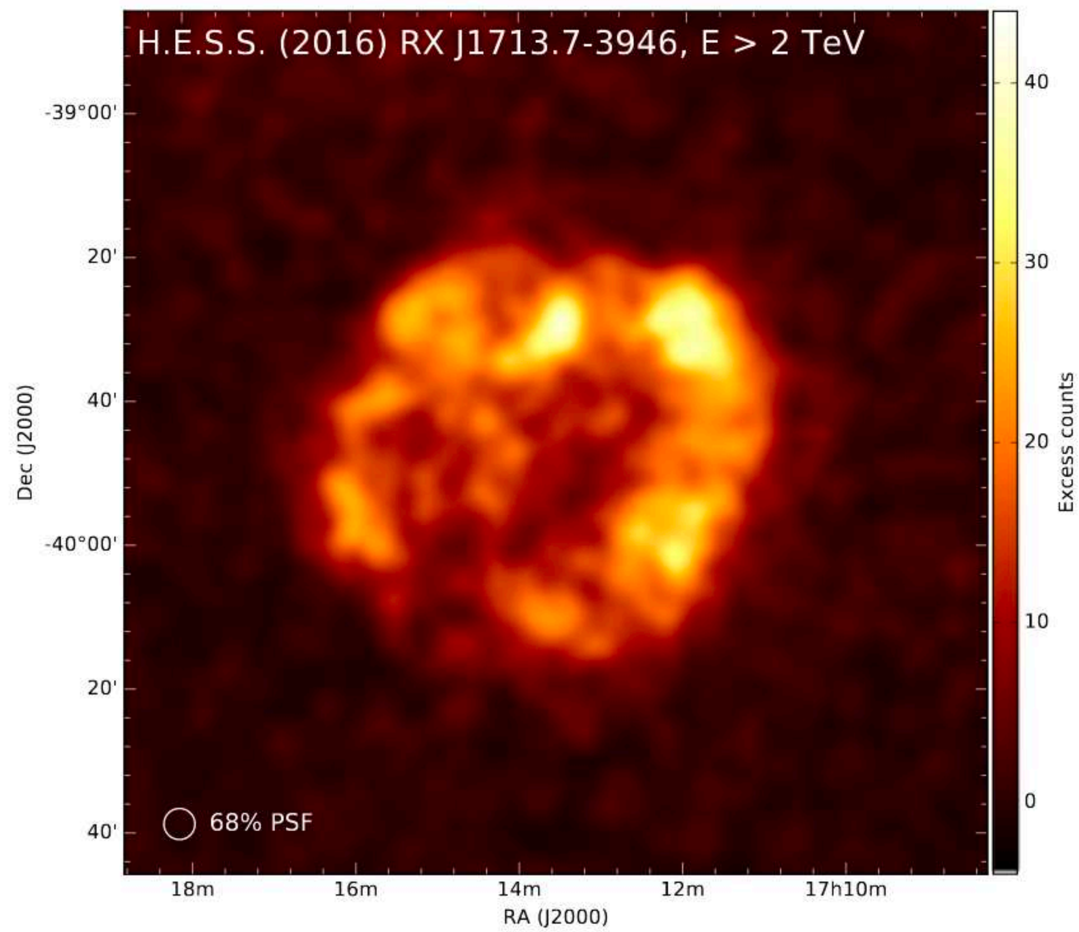
ated

PC, Gabici & Niro (2021)

HESS C

The example of RXJ1713: Hadronic or Leptonic?

20 years of discussion on the nature of the emission hadronic/leptonic/mix?



Muraishi et al. 2000, Aharonian et al. 2004, Aharonian et al. 2006, Aharonian et al. 2007, Uchiyama et al. 2007, Berezhko & Völk 2008, Tanaka et al. 2008, Ellison & Vladimirov 2008, Morlino et al. 2009, Stefano Gabici et al. 2009, Fang et al. 2009, Acero et al. 2009, Zirakashvili & Aharonian 2010, Ellison et al. 2010, Casanova et. 2010, Abdo et al. 2011, Yuan et al. 2011, Gabici et al. 2011, Finke & Dermer 2012, Ellison et al. 2012, Fukui et al. 2012, Yang & Liu 2013, Sano et al. 2013, Cristofari et al. 2013, Gabici et al. 2014, H.E.S.S. Collaboration et al. 2016, Acero et al. 2016, Tsuji et al. 2019, Tanaka et al. 2020, Sano et al. 2020, Celli et al. 2018, Pais & Pfrommer 2020, Tateishi et al. 2021, Tang & Liu 2021, Fukui et al. 2021, Cristofari et al. 2021, Fujita et al. 2022, Picquenot et al. 2024

HESS Collab (2016)

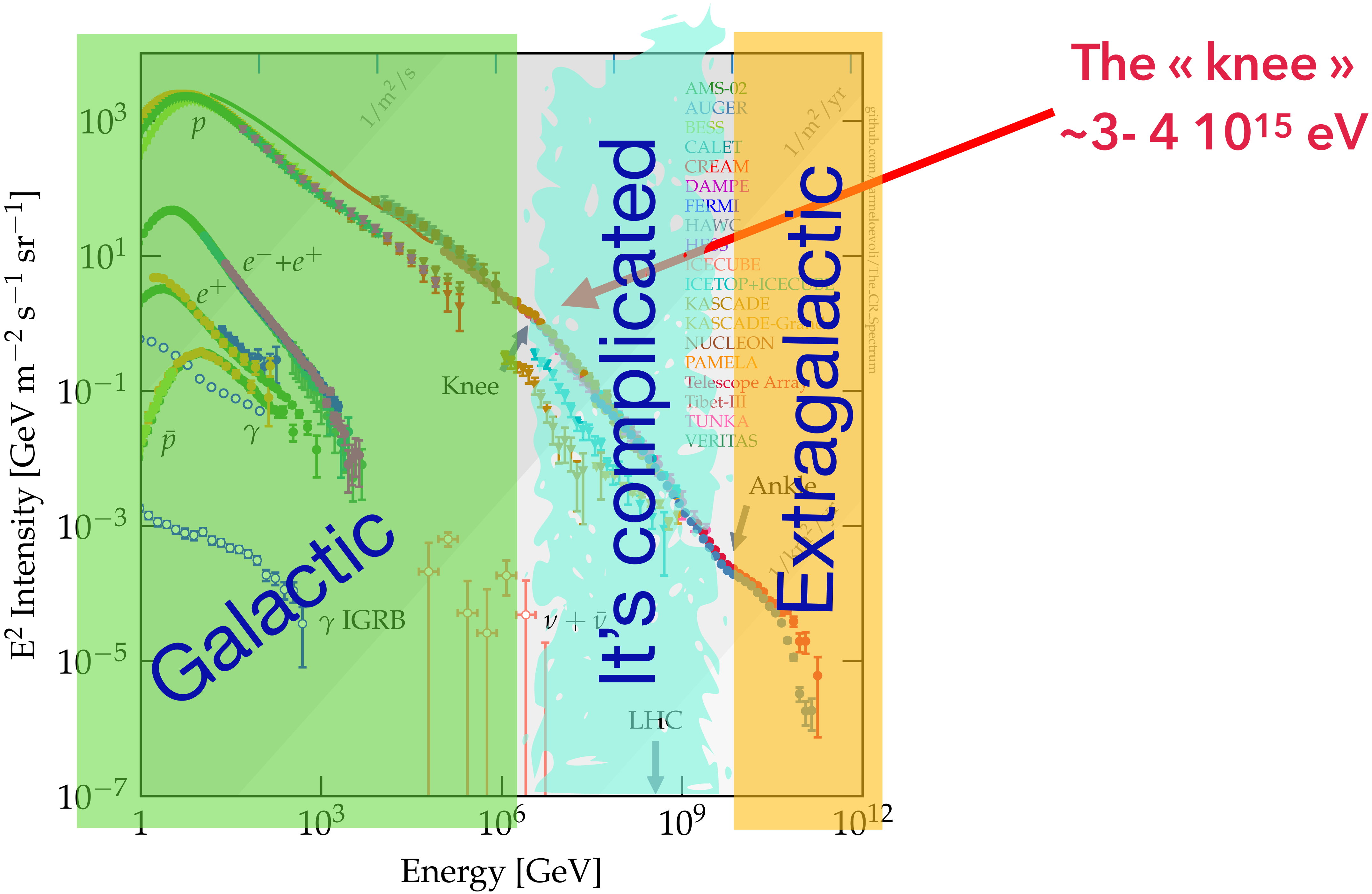
The hunt for PeVatrons

10^{15} eV

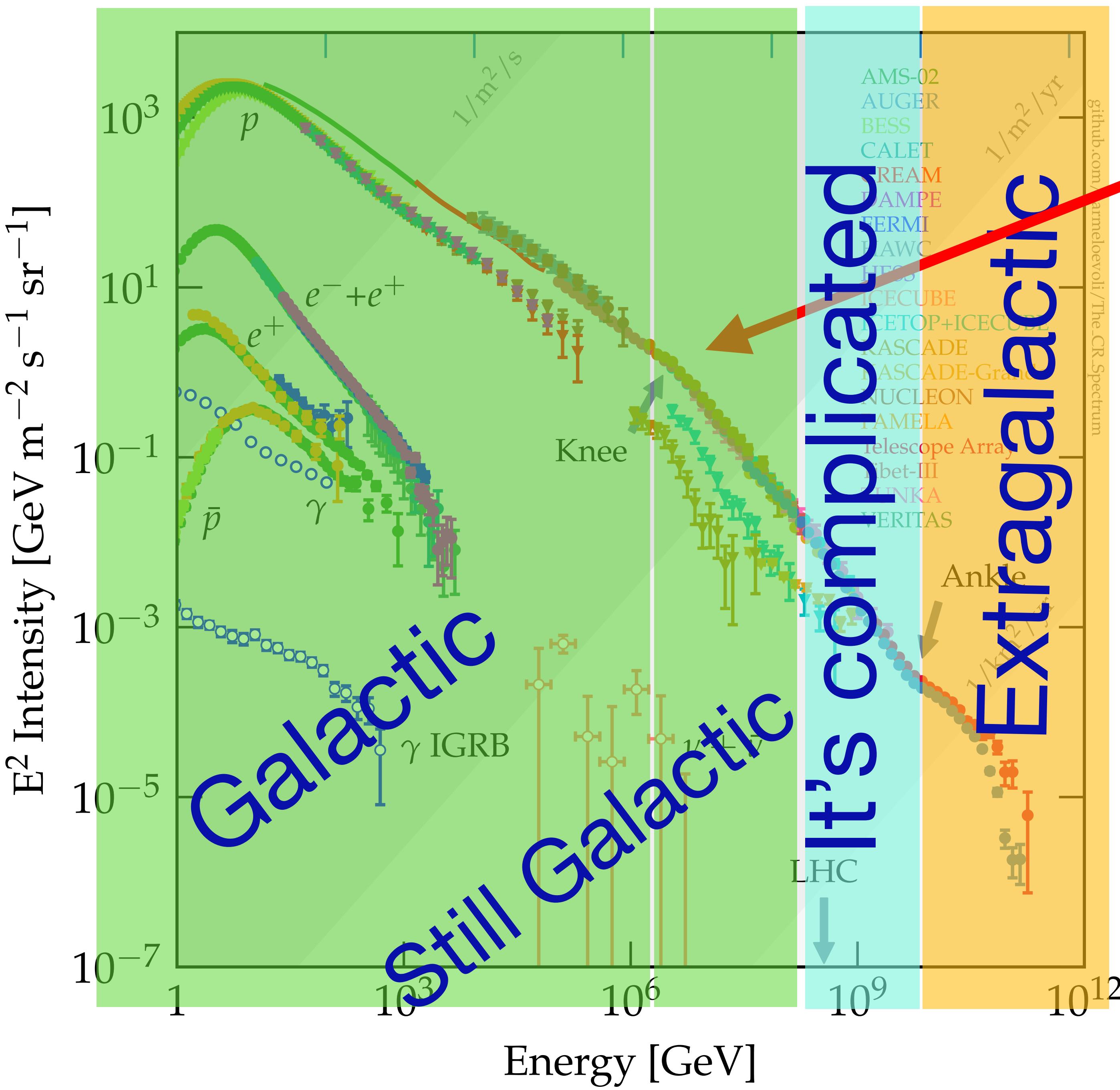
1. Not easy to achieve

2. The origin of Galactic cosmic rays

The Local Interstellar spectrum

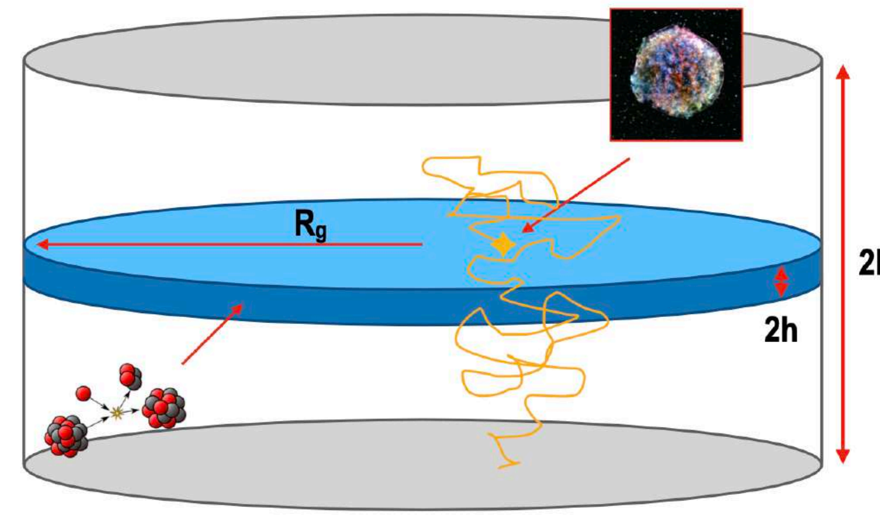


The Local Interstellar spectrum



The « knee »

~3- 4 10^{15} eV



Consensus: Protons are injected in the disk and diffusively propagate in a magnetized halo

$$R_{\rm L} \lesssim H$$

$$E \lesssim 10^{18} Z^{-1} \left(\frac{H}{3\ \rm kpc}\right) \rm eV$$

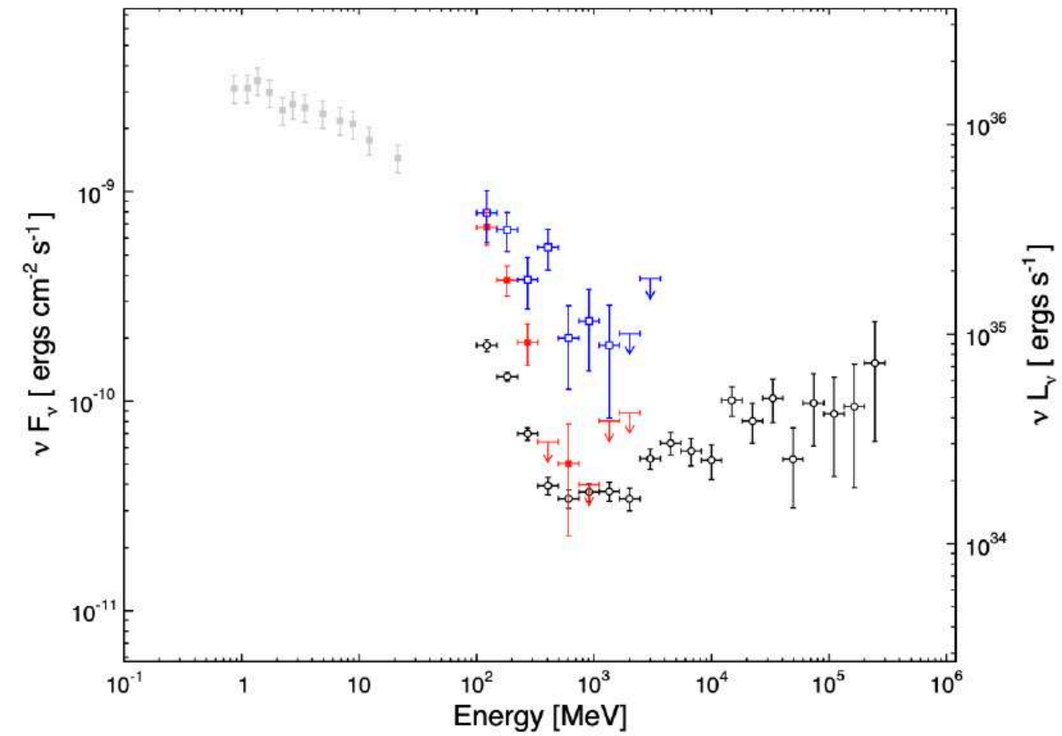
Finding the « superpevatrons »?

~ 10^{17} - 10^{18} eV

Morrison, Olbert & Rossi 1954, Ginzburg & Syrovatskii 1964, Evoli et al. 2018, 2019

Pevatrons in the last 10 years

1. Crab electron pevatron (Fermi-LAT 2010): Flares 100 MeV due to PeV electrons



2. Galactic center Sgr. A* J1745-290 (H.E.S.S. 2016)

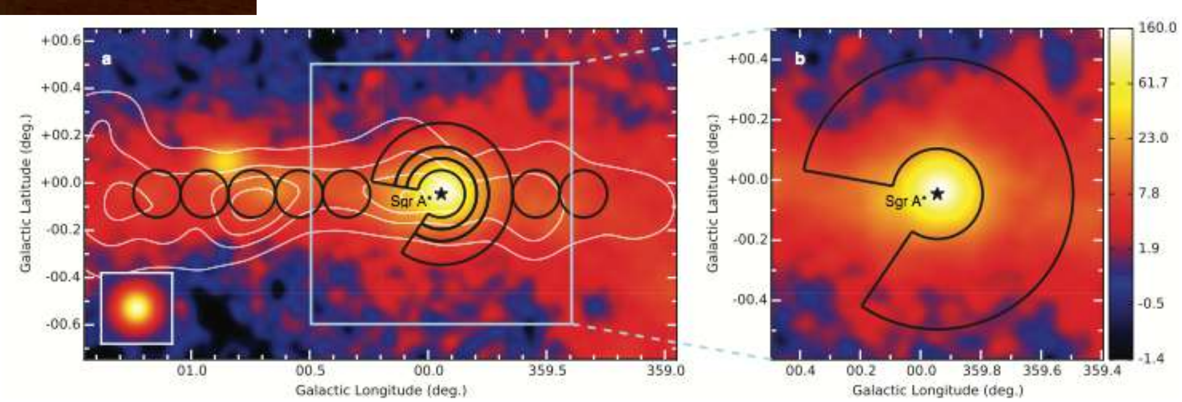
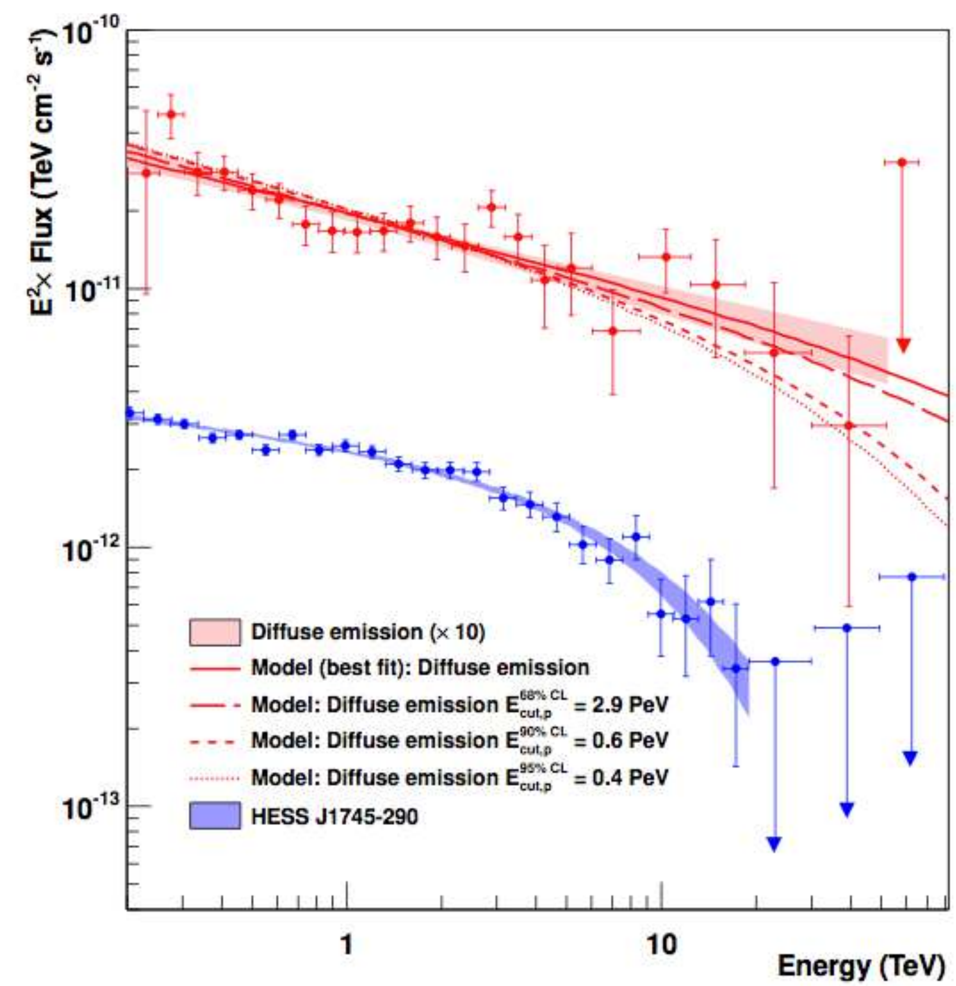


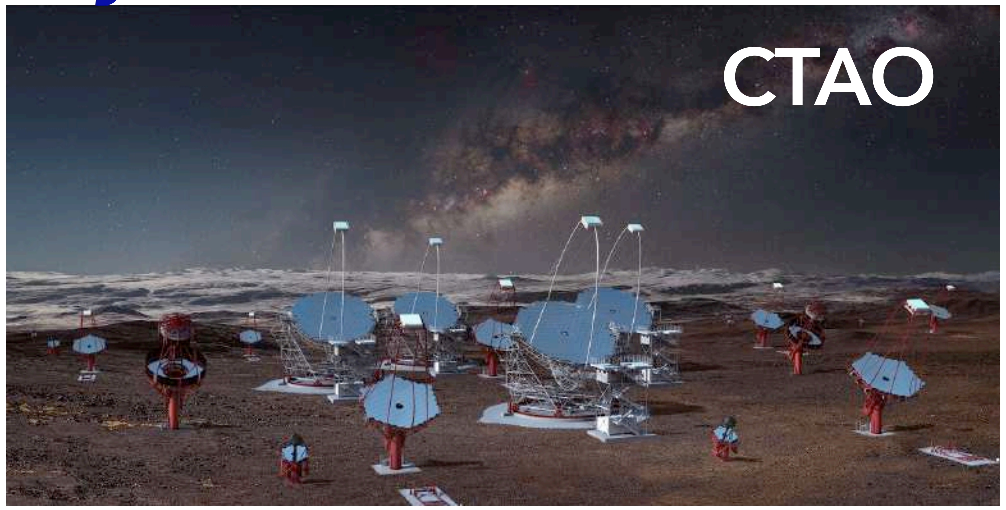
Figure 1: **VHE γ-ray image of the Galactic Centre region.** The colour scale indicates counts per 0.02°×0.02° pixel.



Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pevatrons



Pevatrons in the last 10 years

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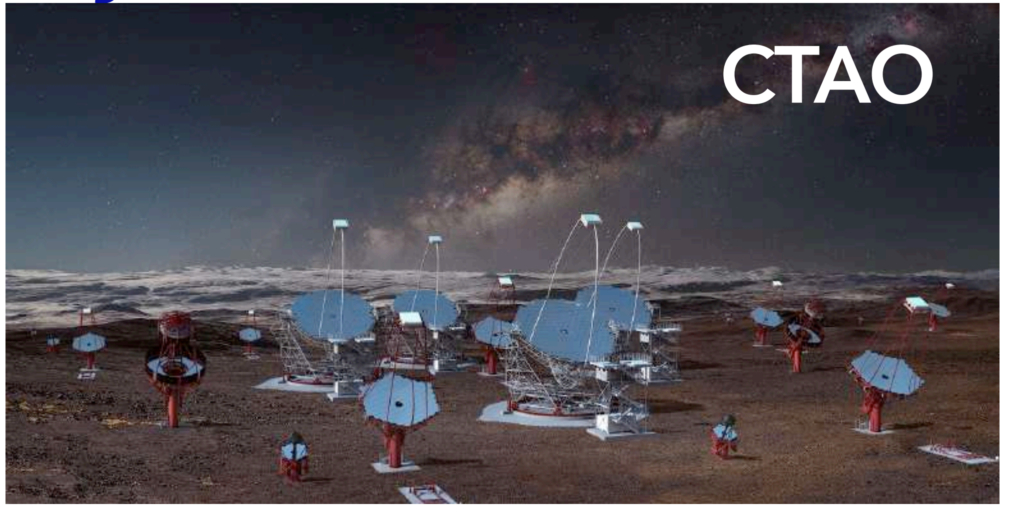

100 TeV gamma rays ⟷ PeV protons

Hadronic interactions :
Pion decay

CR ISM

$$p + p \to p + p + \pi^0$$

$$\pi^0 \to \gamma + \gamma$$

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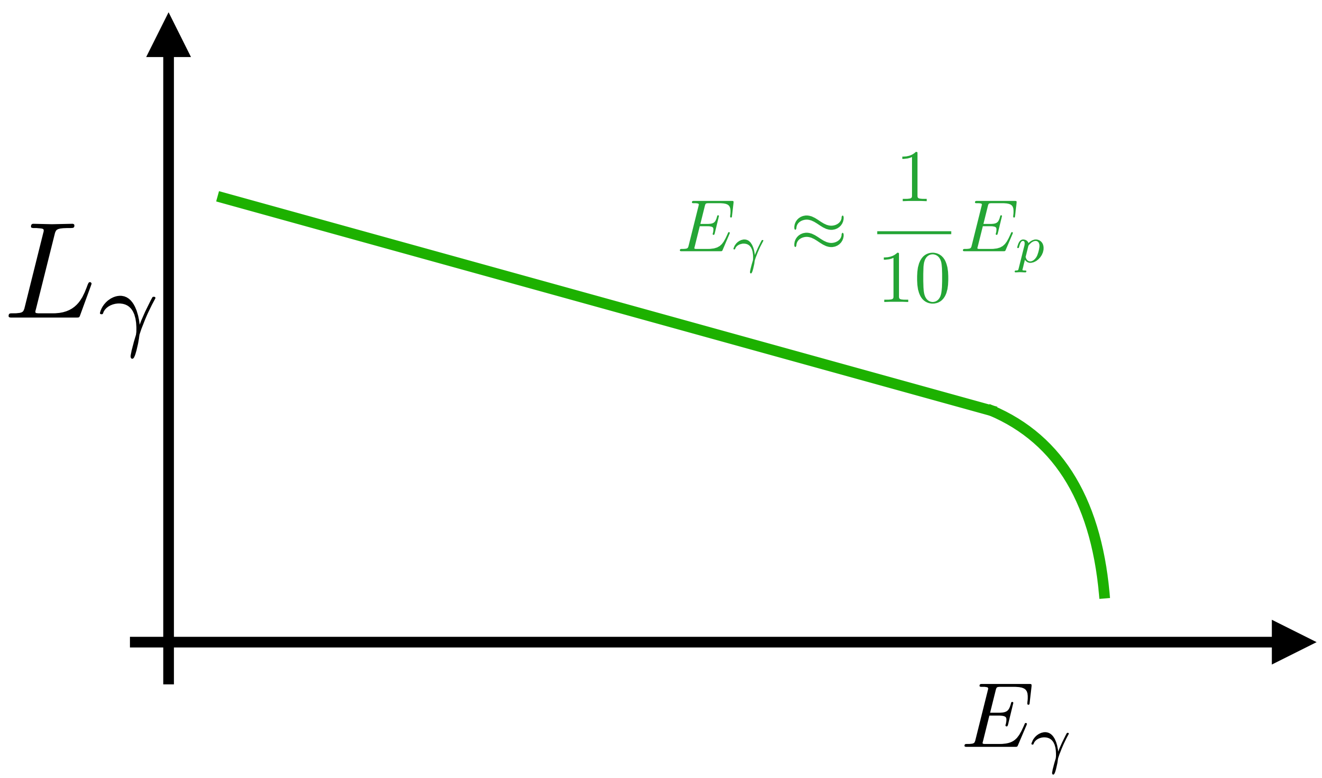

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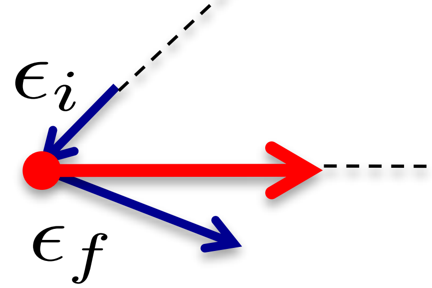
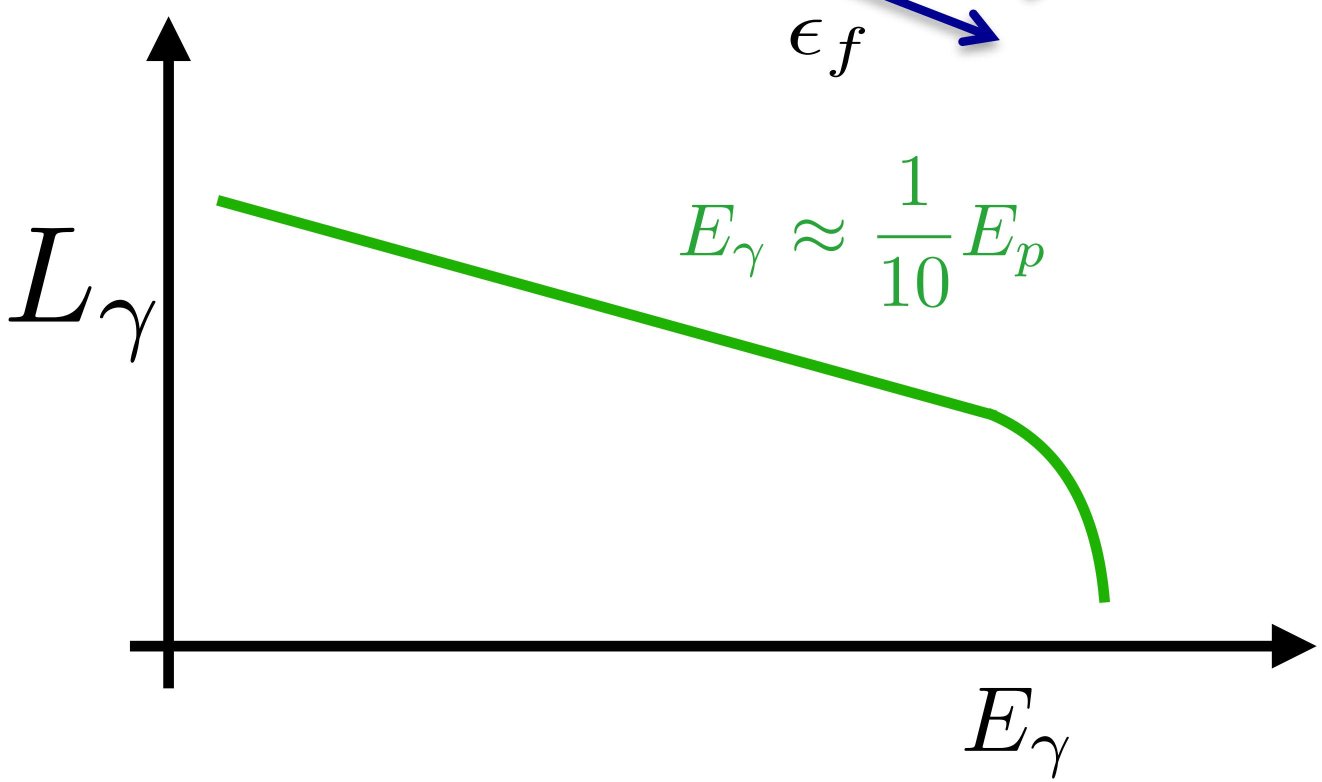
Leptonic interactions :

Inverse Compton scattering





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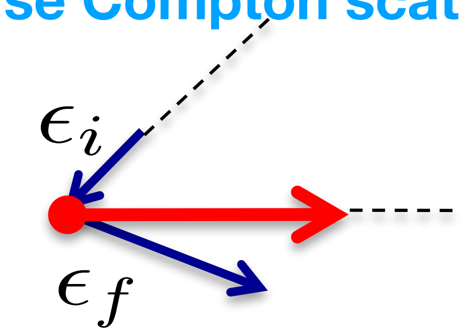

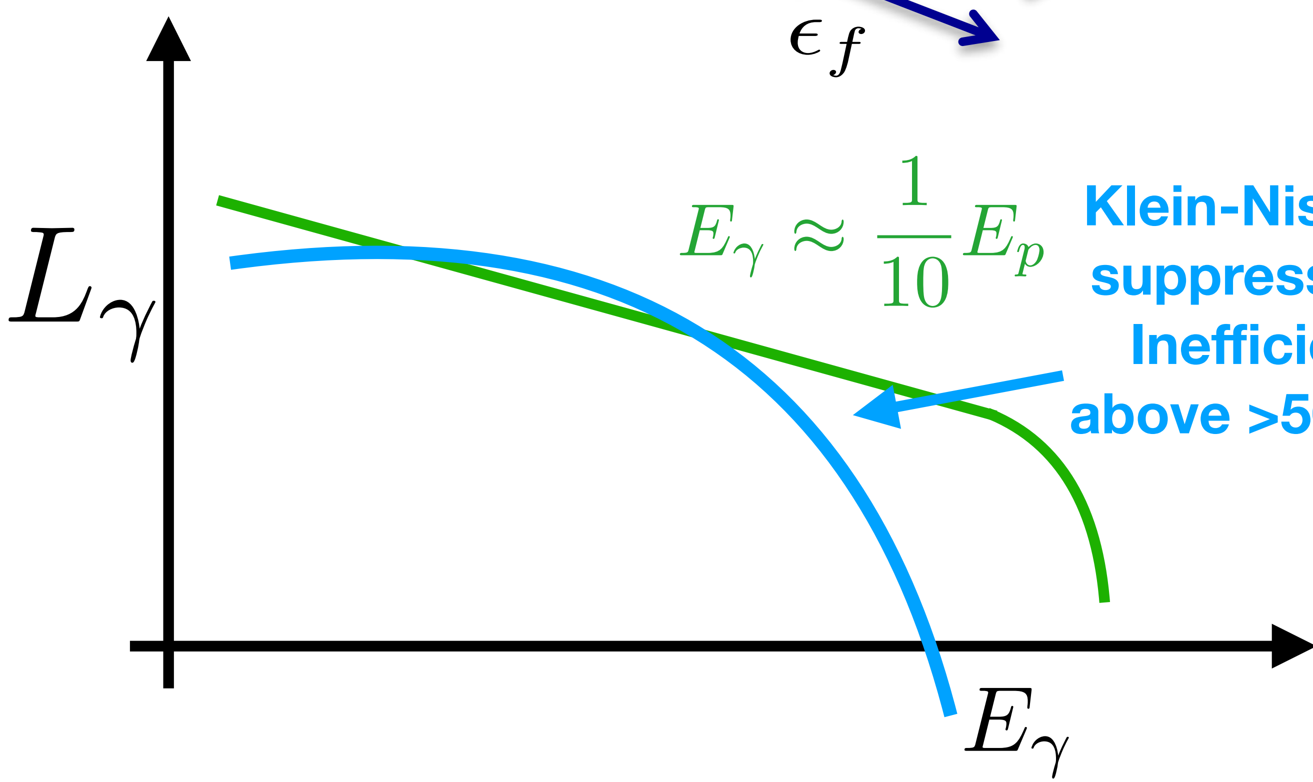

Klein-Nishina suppression: Inefficient above >50 TeV

Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pevatrons

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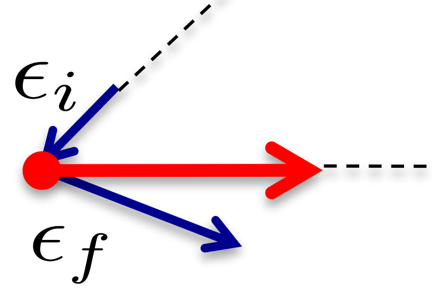
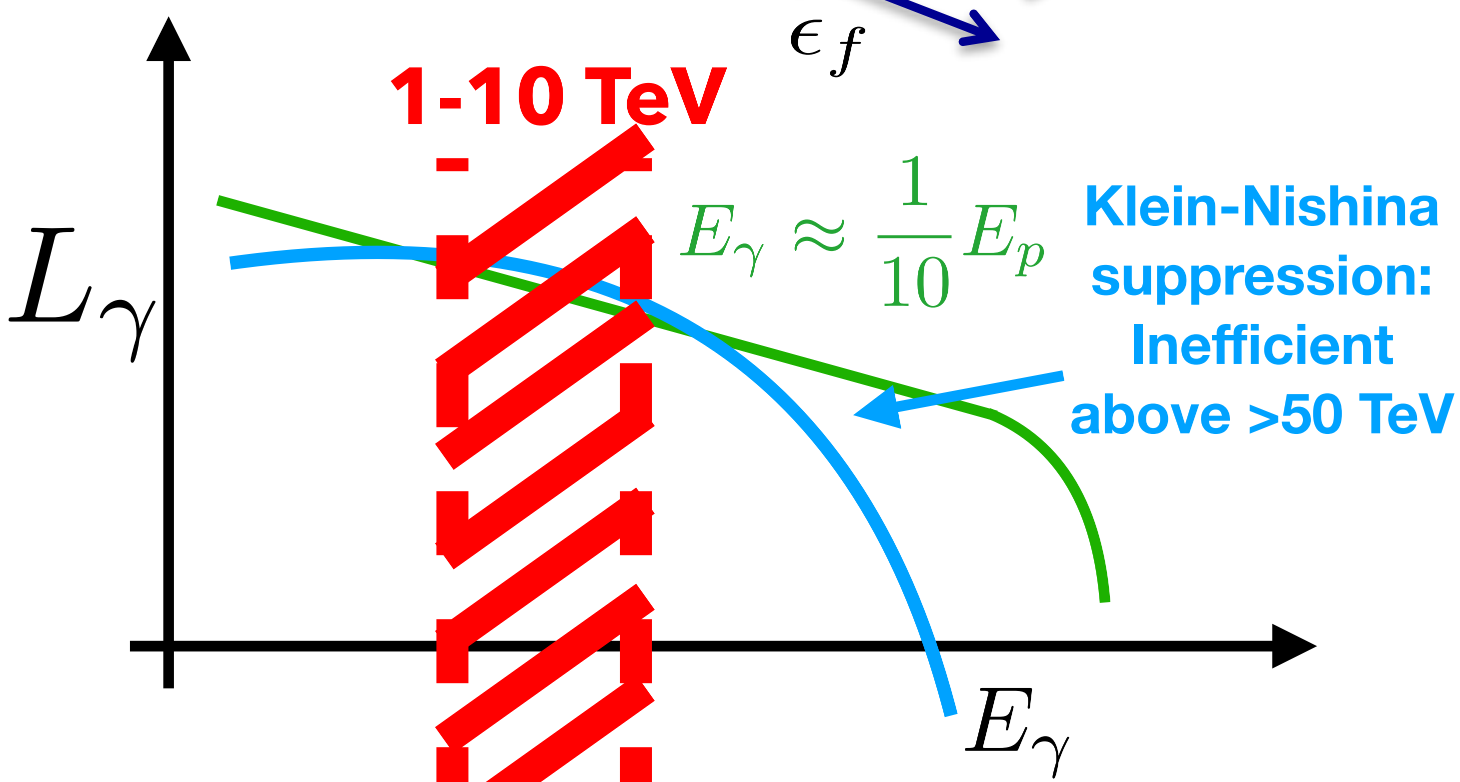
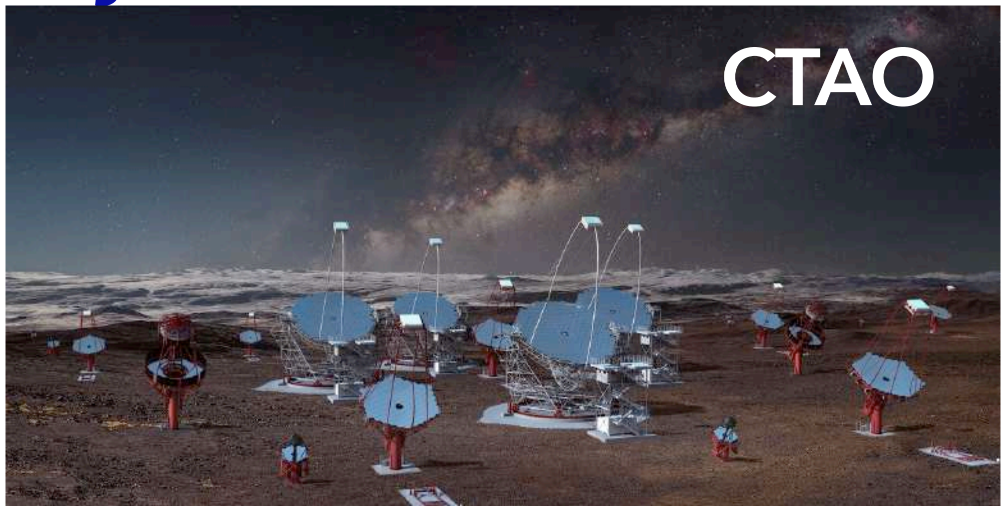




Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pevatrons



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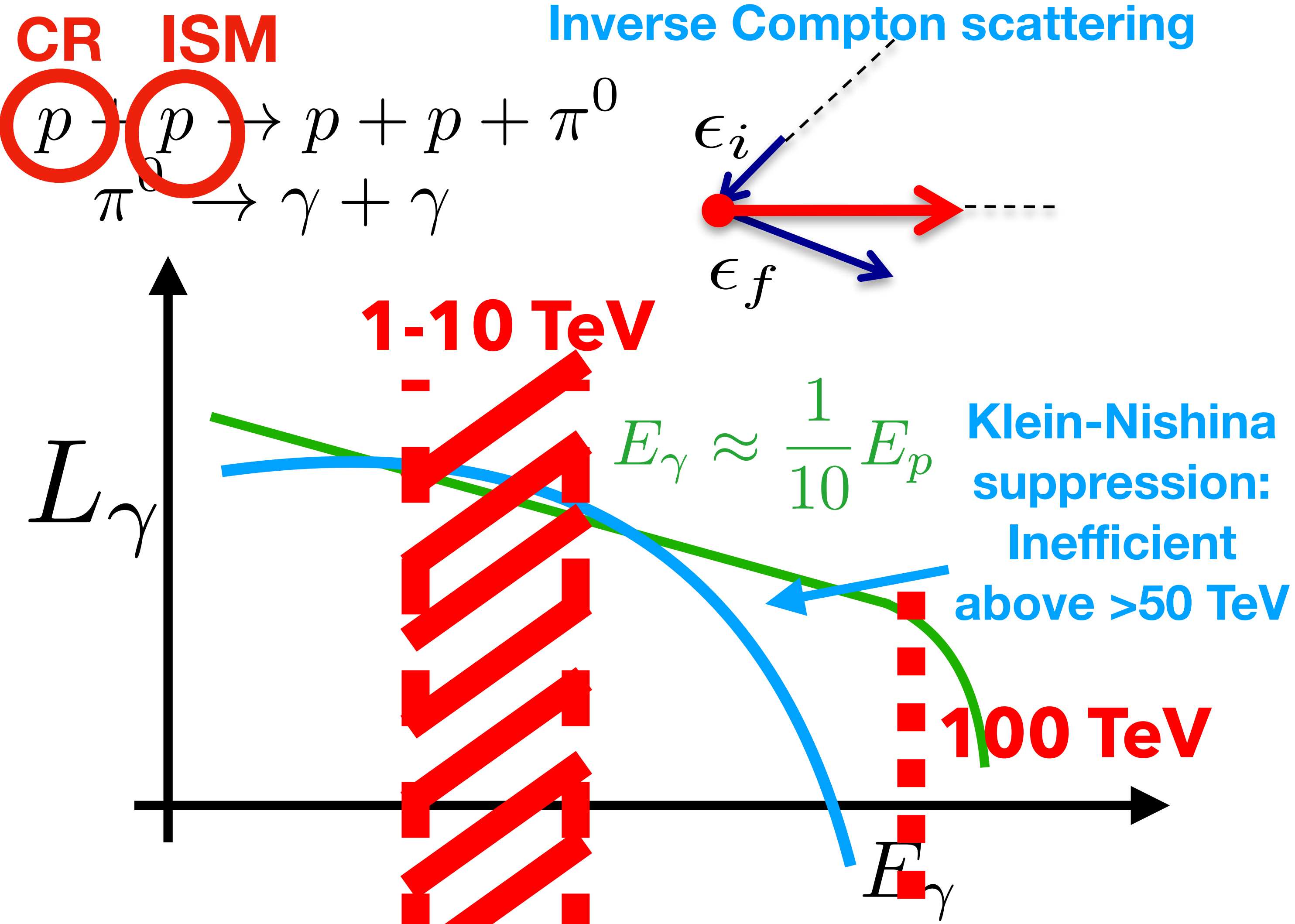
Pion decay

Leptonic interactions :
Inverse Compton scattering



Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pevatrons

100 TeV gamma rays ⟷ PeV protons

Supernova remnant RXJ1713

Hadronic interactions :
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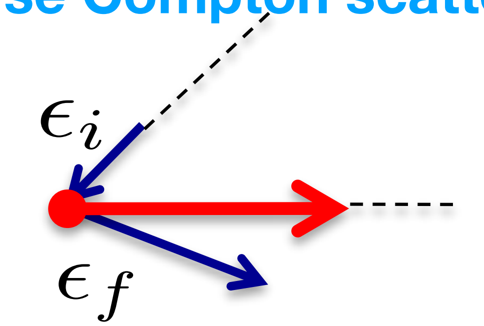
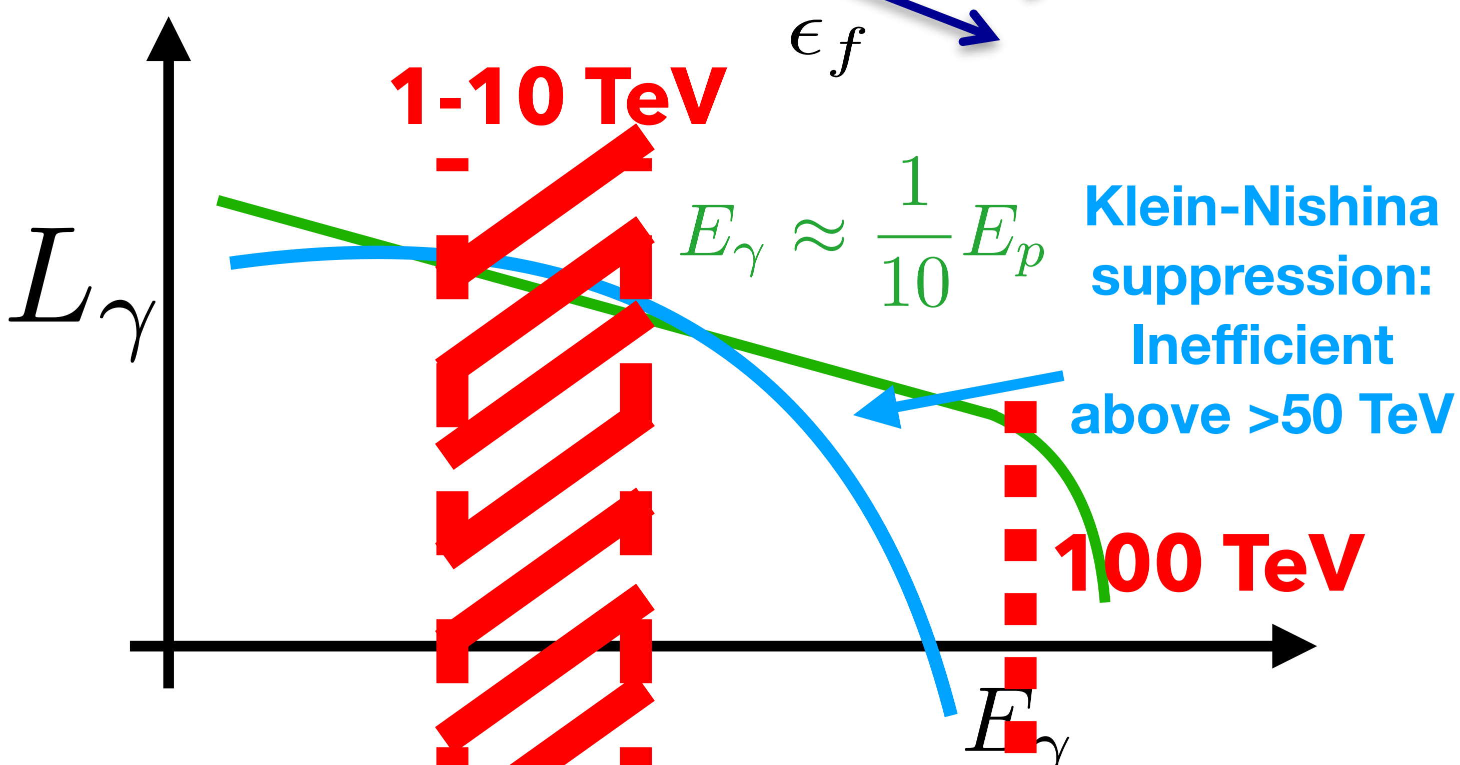
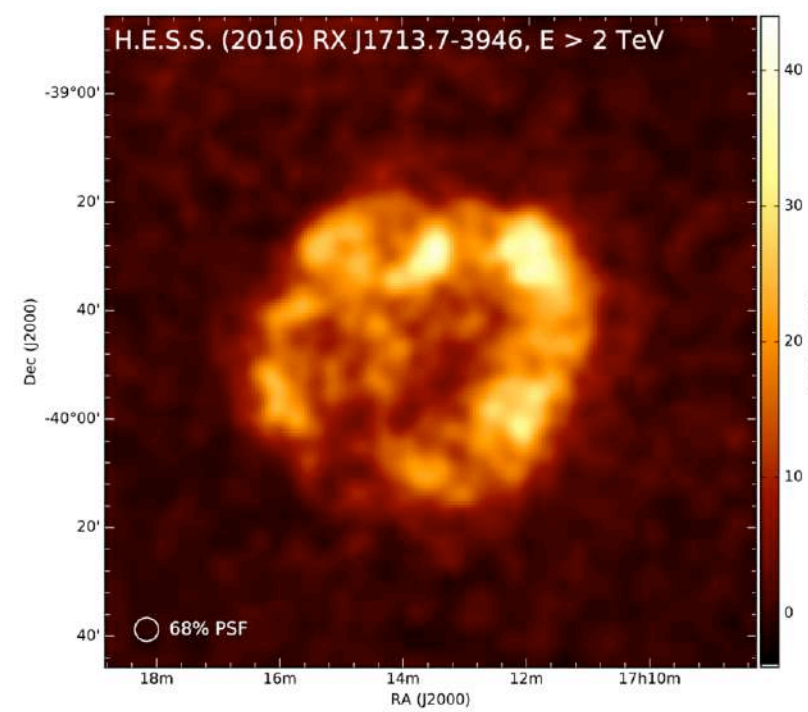
Leptonic interactions :
Inverse Compton scattering







Preferred candidates for bulk of CR protons

Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pevatrons

~~100 TeV gamma rays ⟷ PeV protons~~

~~Supernova remnant RXJ1713~~

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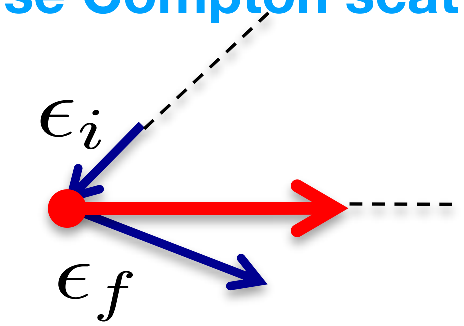

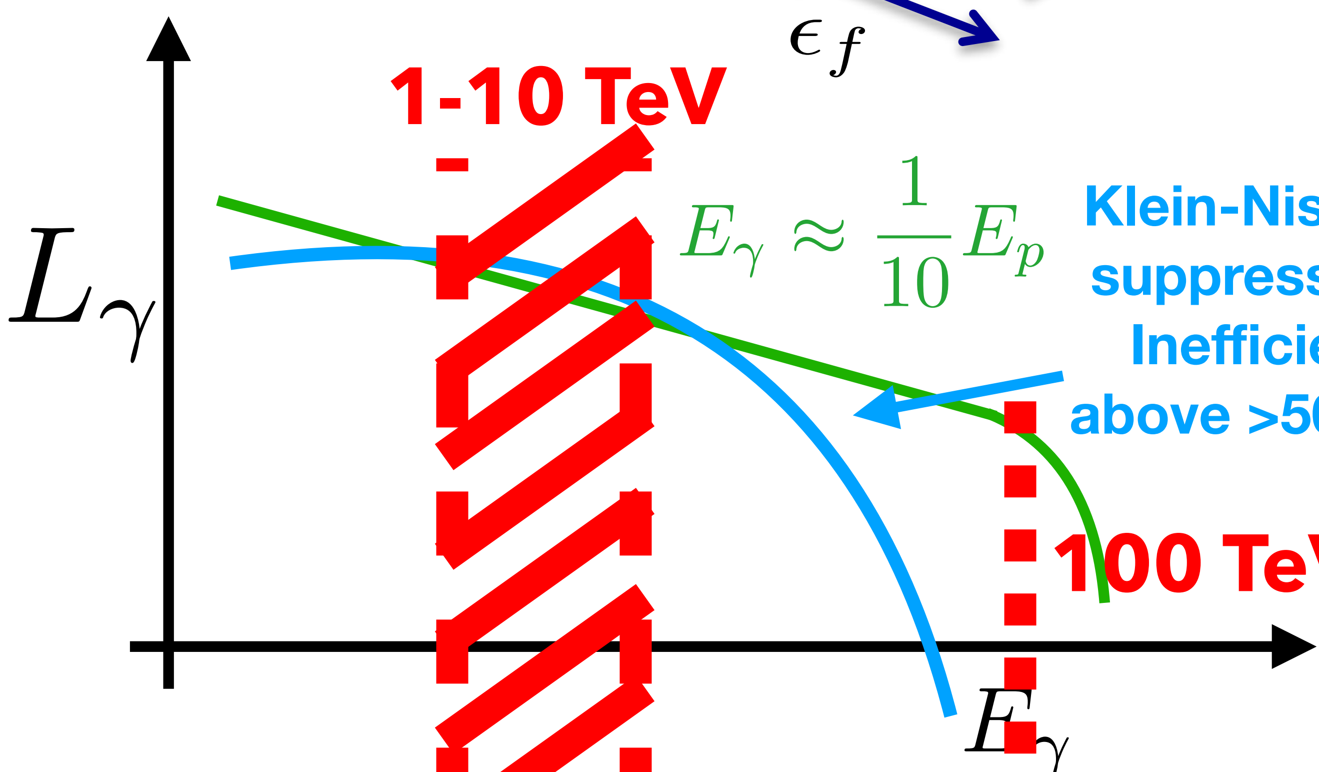

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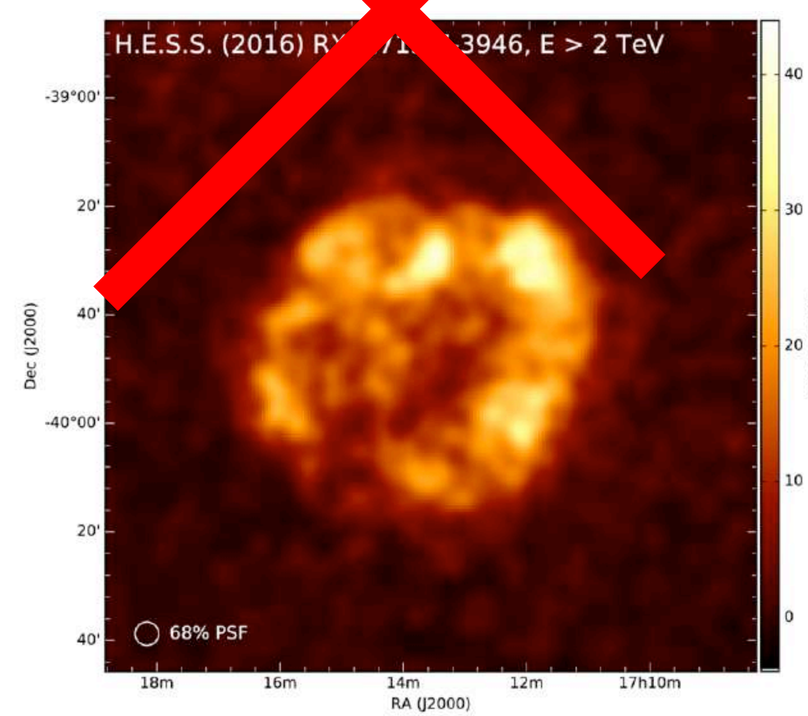


Preferred candidates for bulk of CR protons

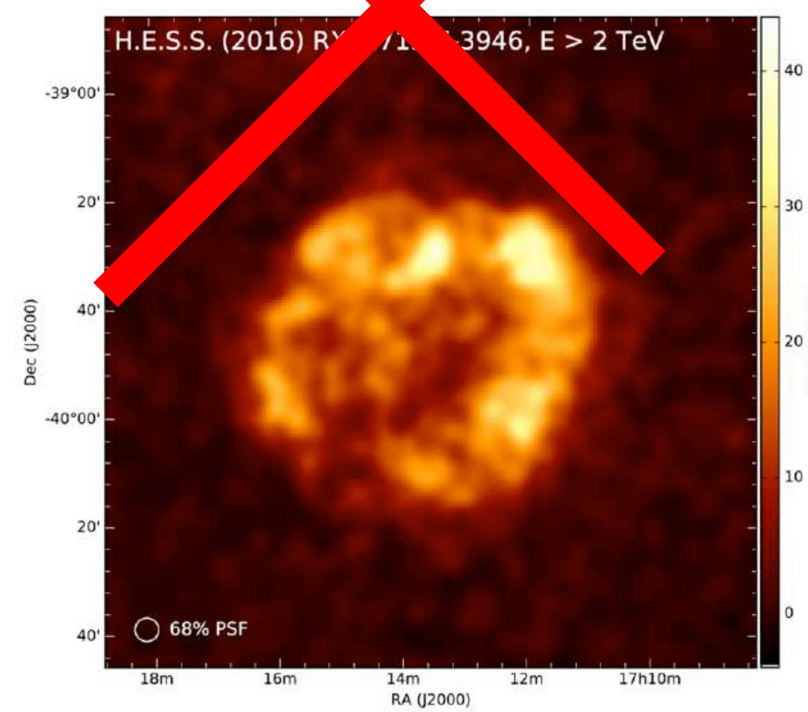
Pevatrons in the last 10 years

« Science with CTA 2017 »

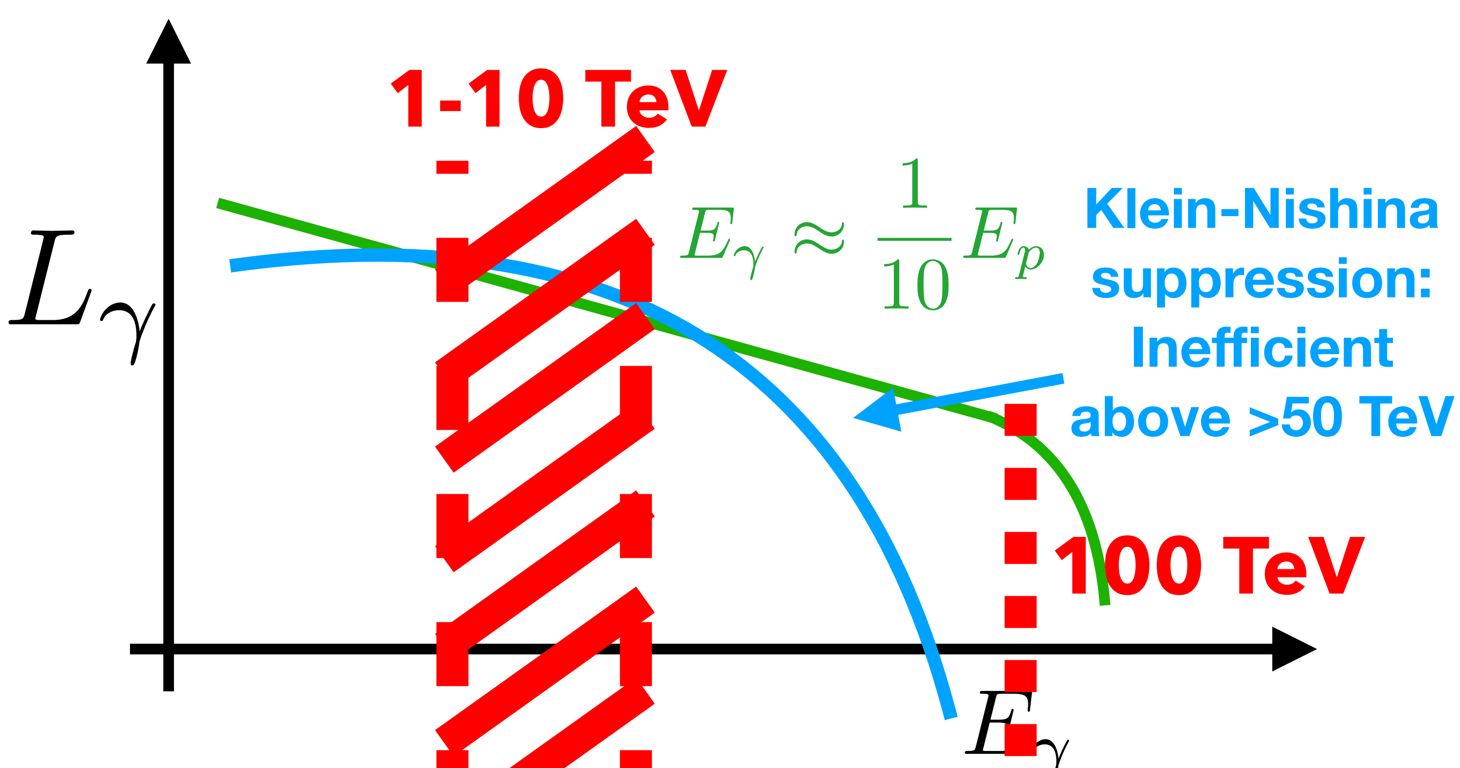
Key Science project: detection of pevatrons

~~100 TeV gamma rays ↔ PeV protons~~

~~Supernova remnant RXJ1713~~



Preferred candidates for bulk of CR protons

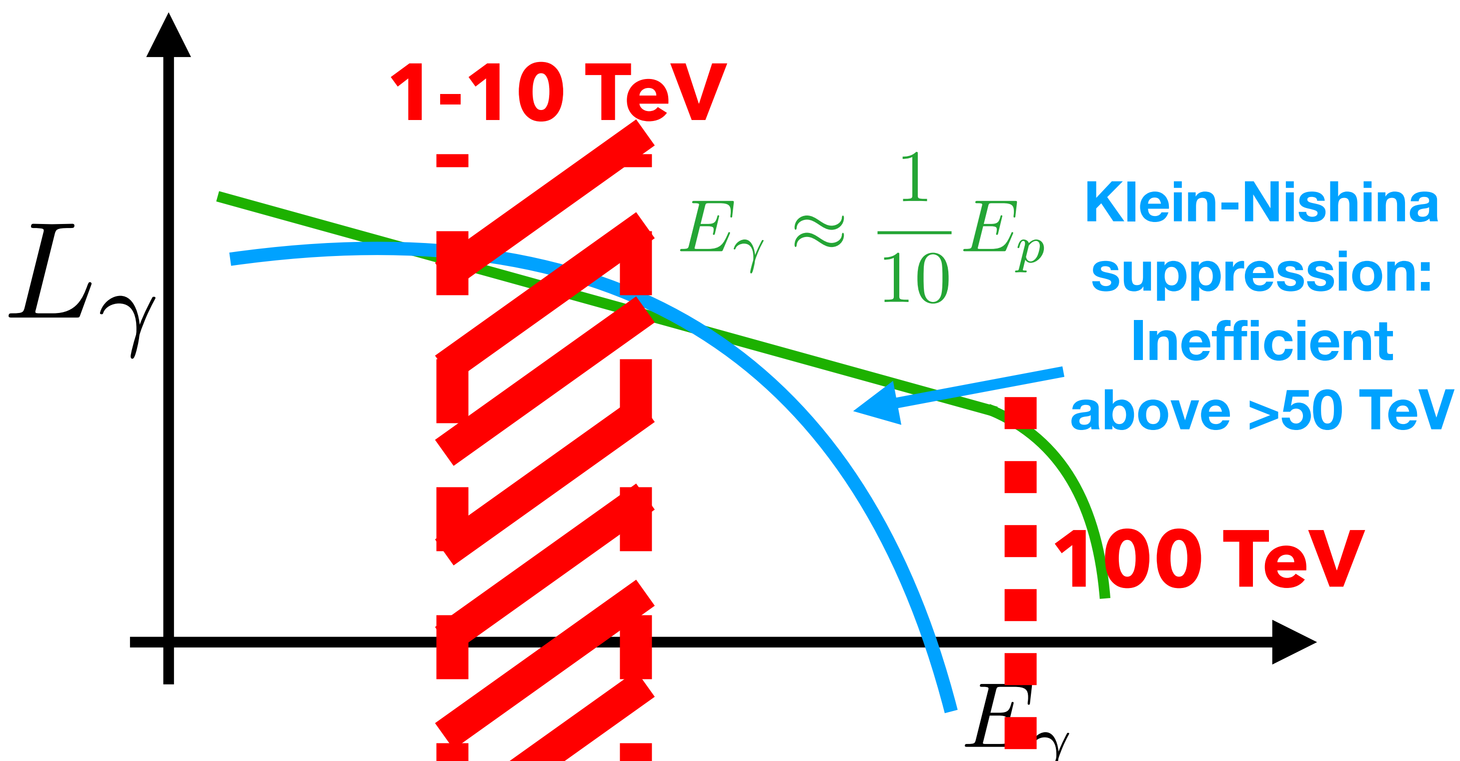


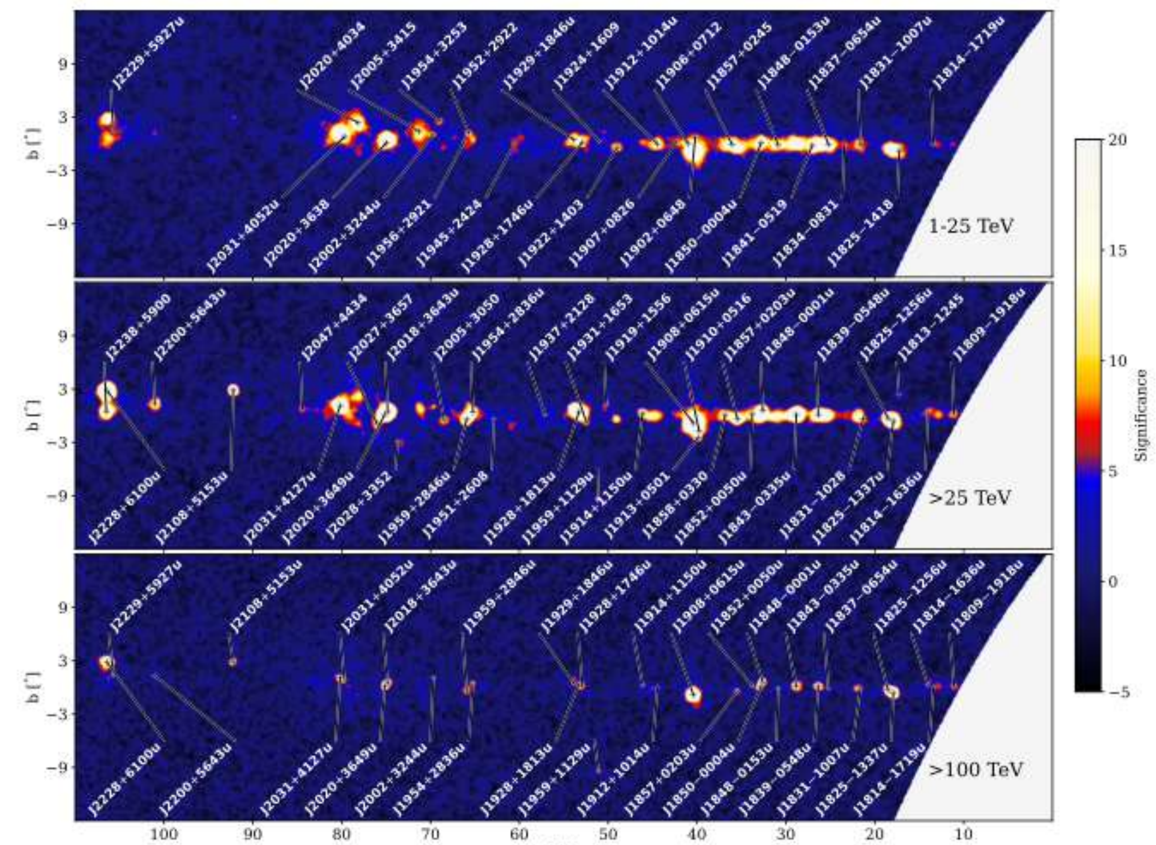
Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pev

~~100 TeV gamma rays ↔ PeV protons~~





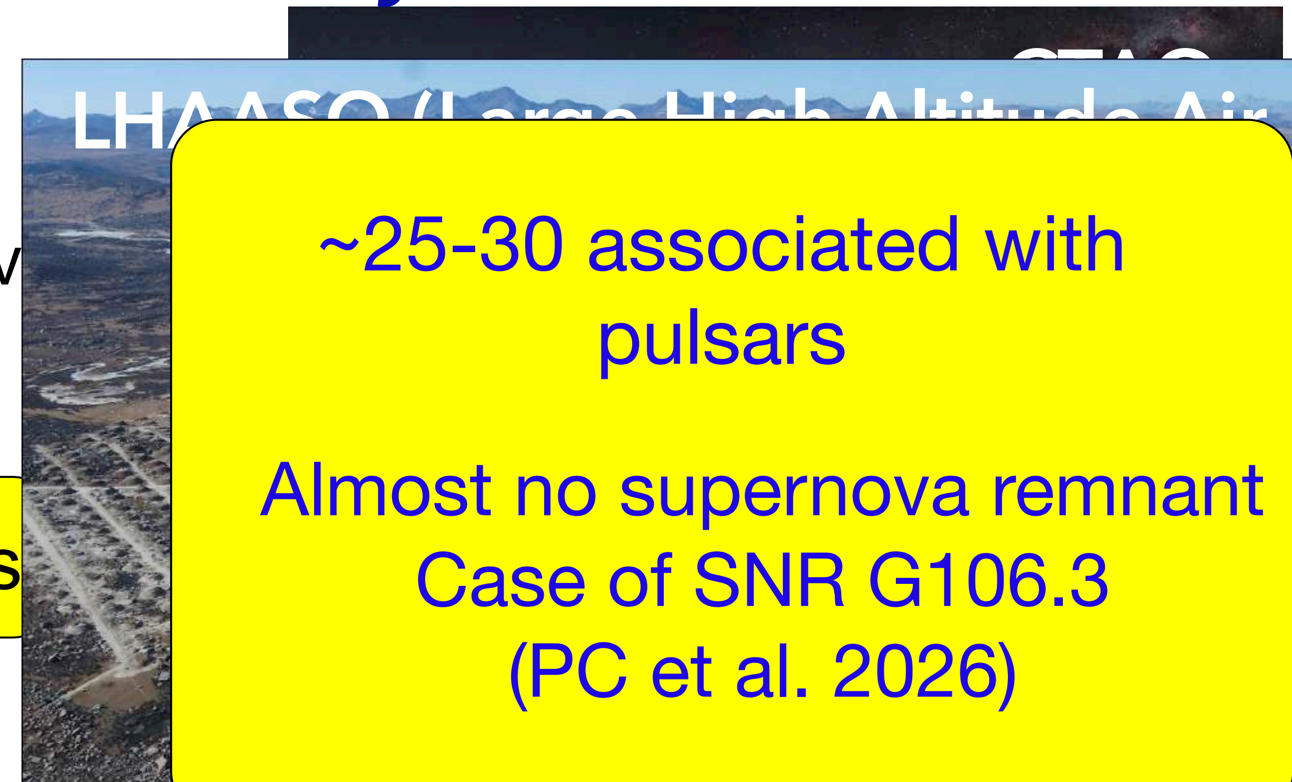
LHAASO catalog Cao et al. 2024
43 sources >100 TeV

Pevatrons in the last 10 years

« Science with CTA 2017 »

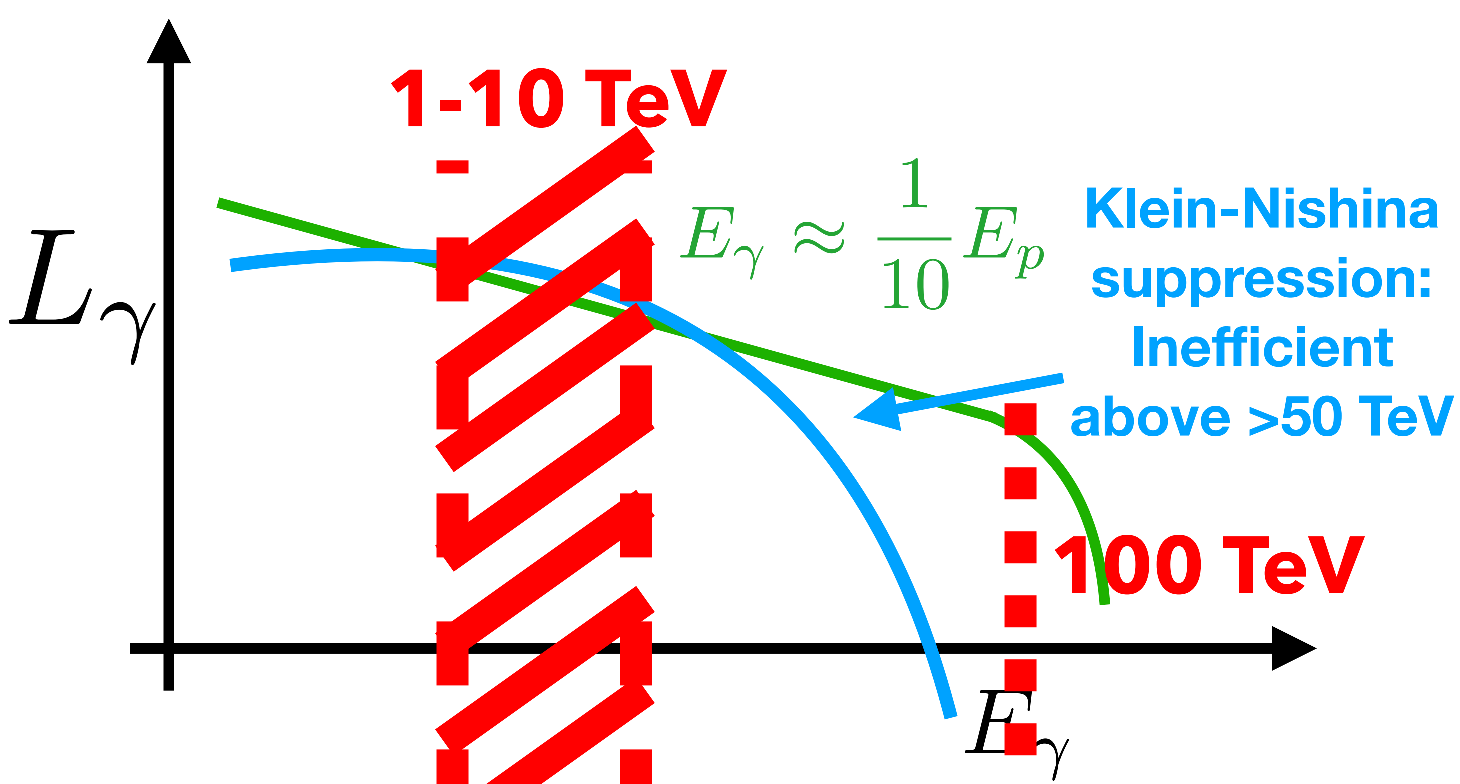
Key Science project: detection of pev

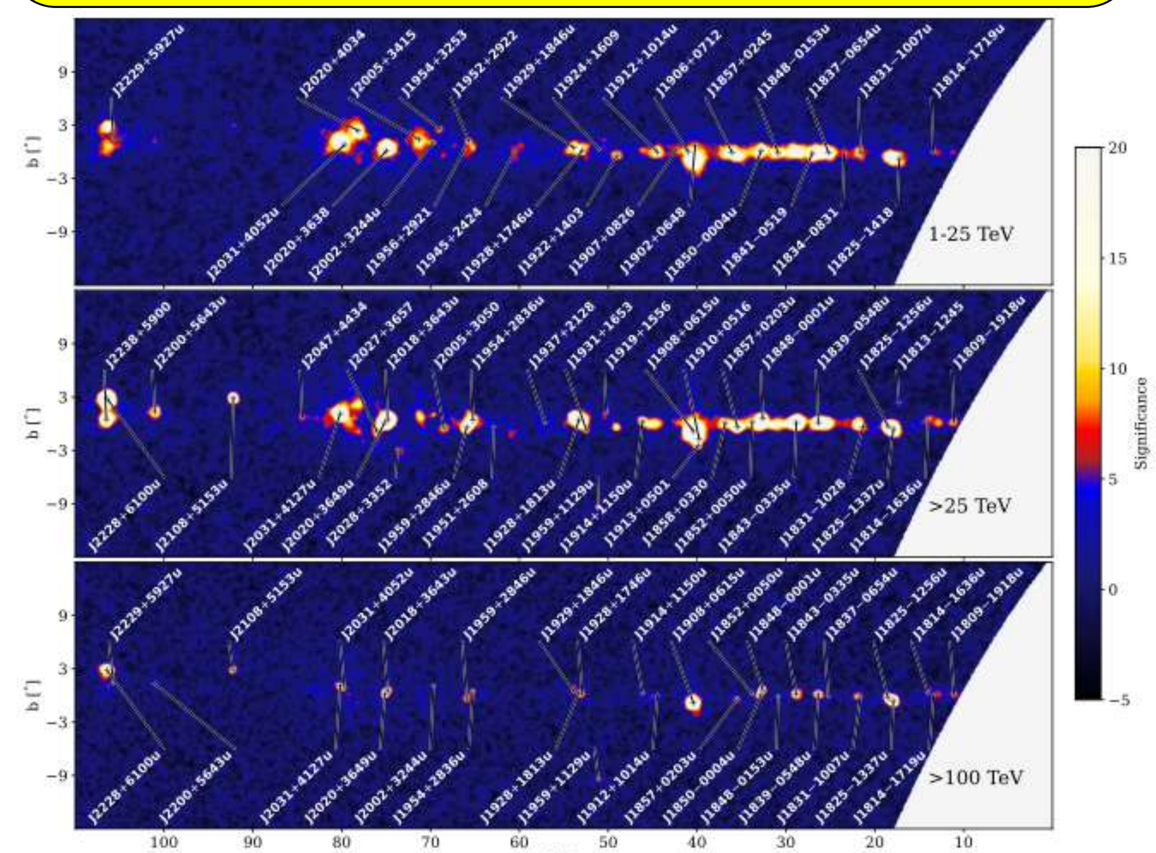
100 TeV gamma rays ⟷ PeV protons



~25-30 associated with pulsars

Almost no supernova remnant
Case of SNR G106.3
(PC et al. 2026)





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Pevatrons in the last 10 years

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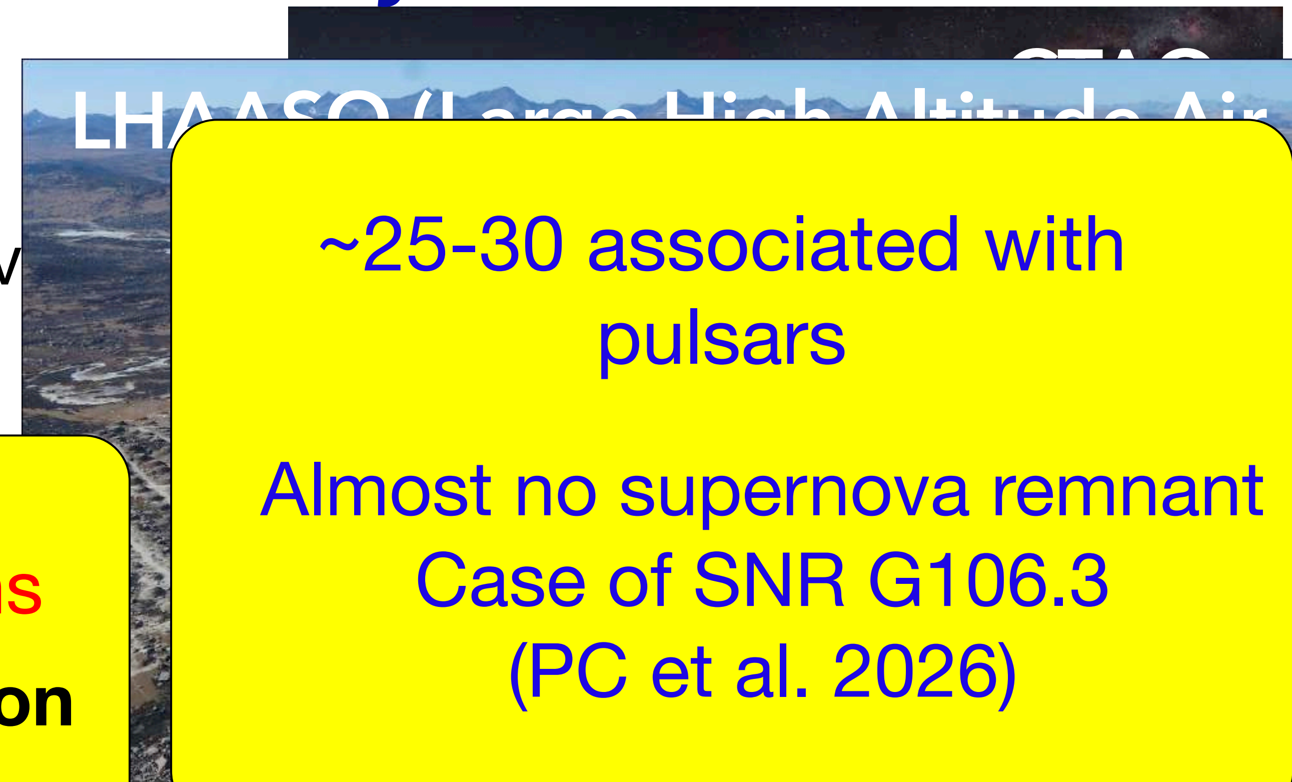
Key Science project: detection of pev



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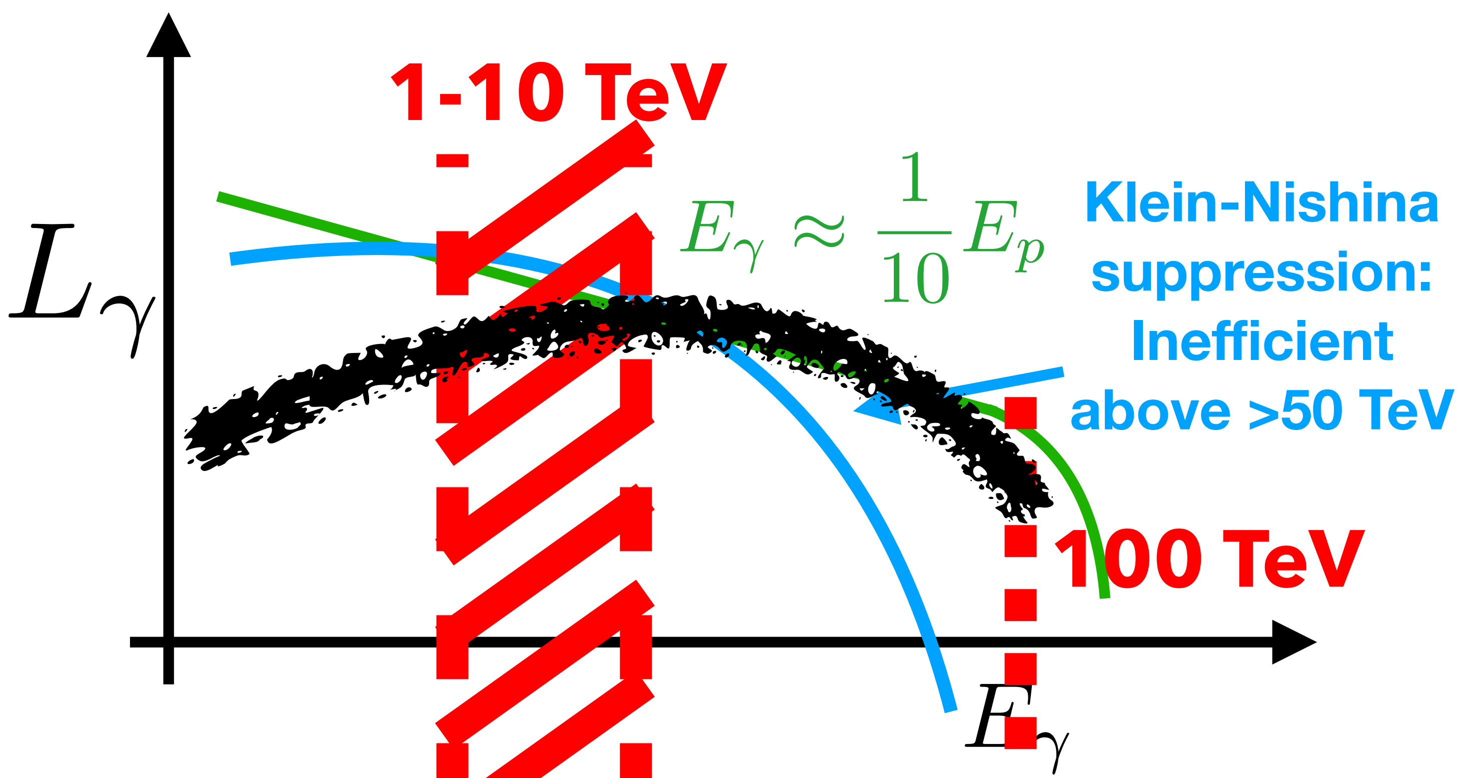
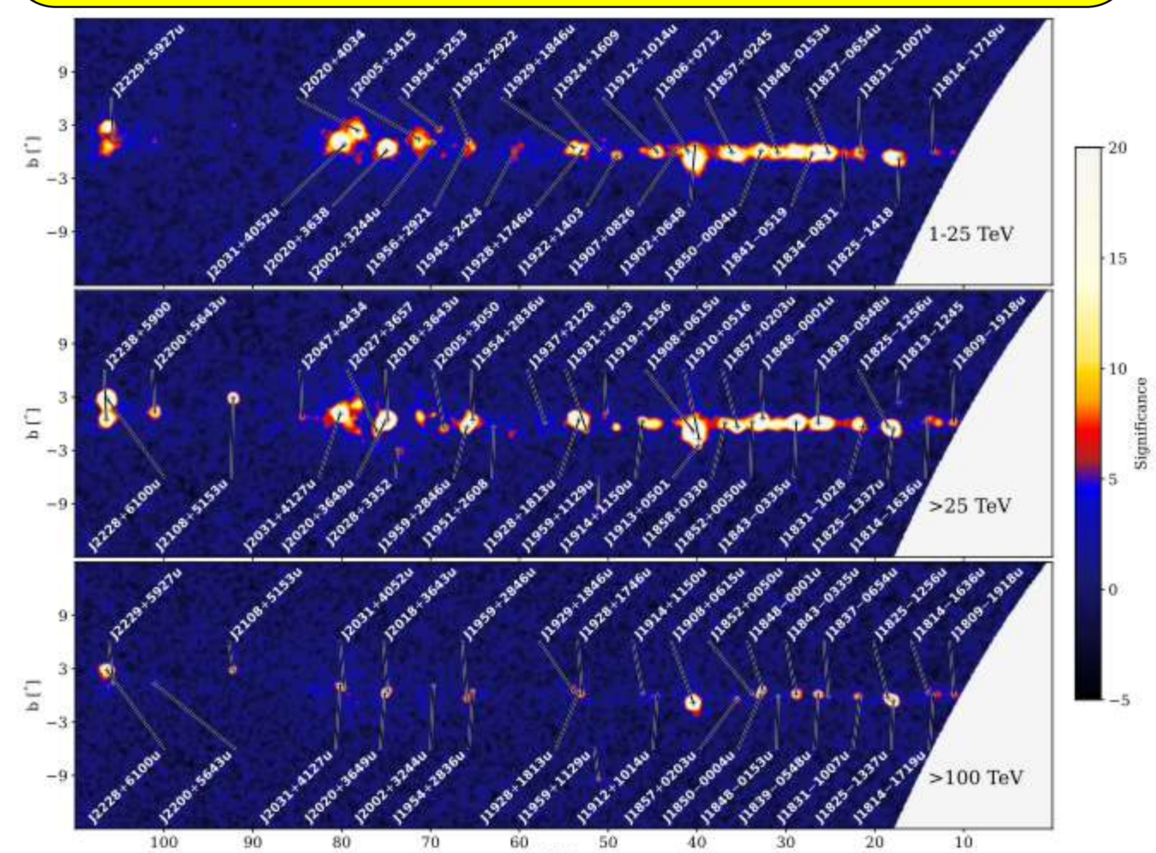
100 TeV gamma rays ⟷ Electrons

Hard spectra for electron with radiation dominated environment





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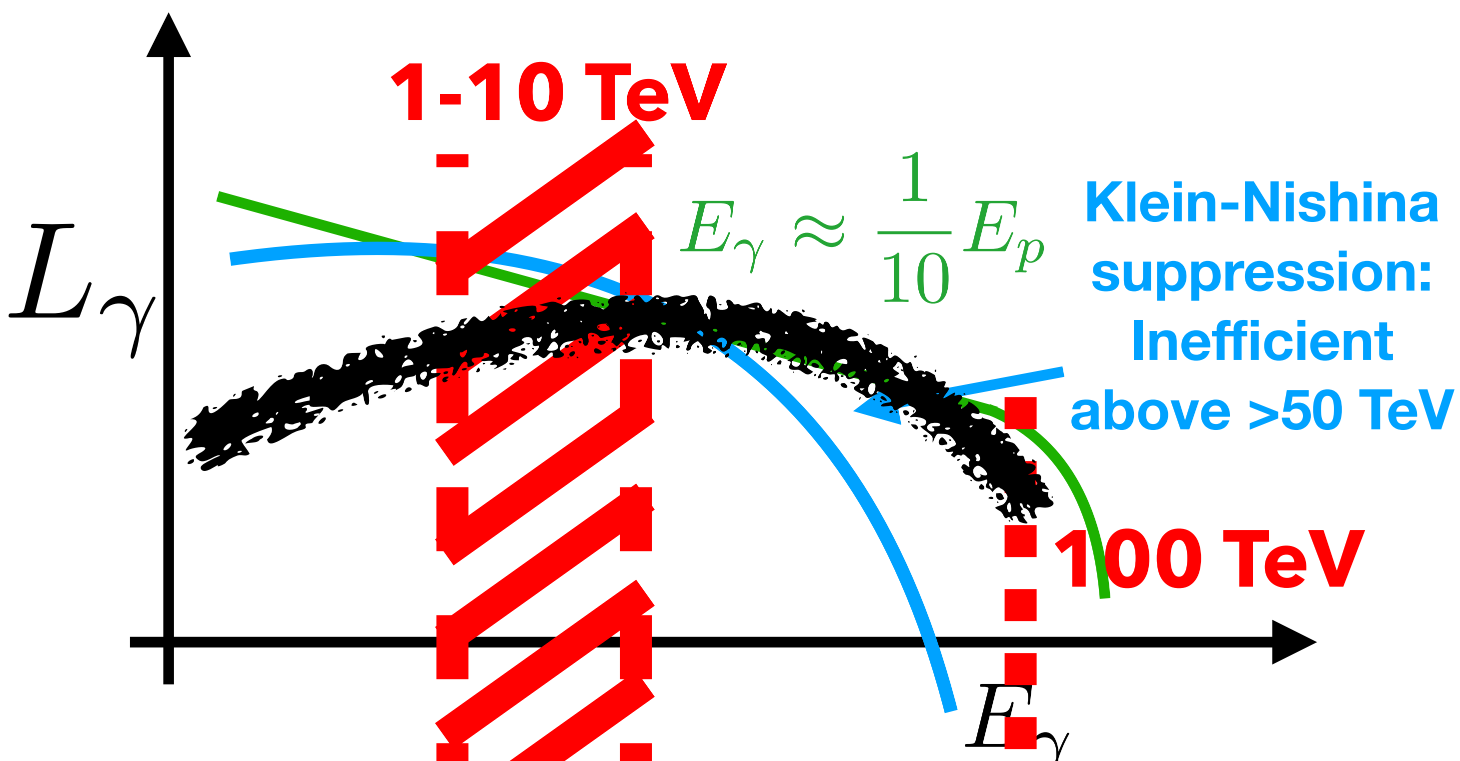
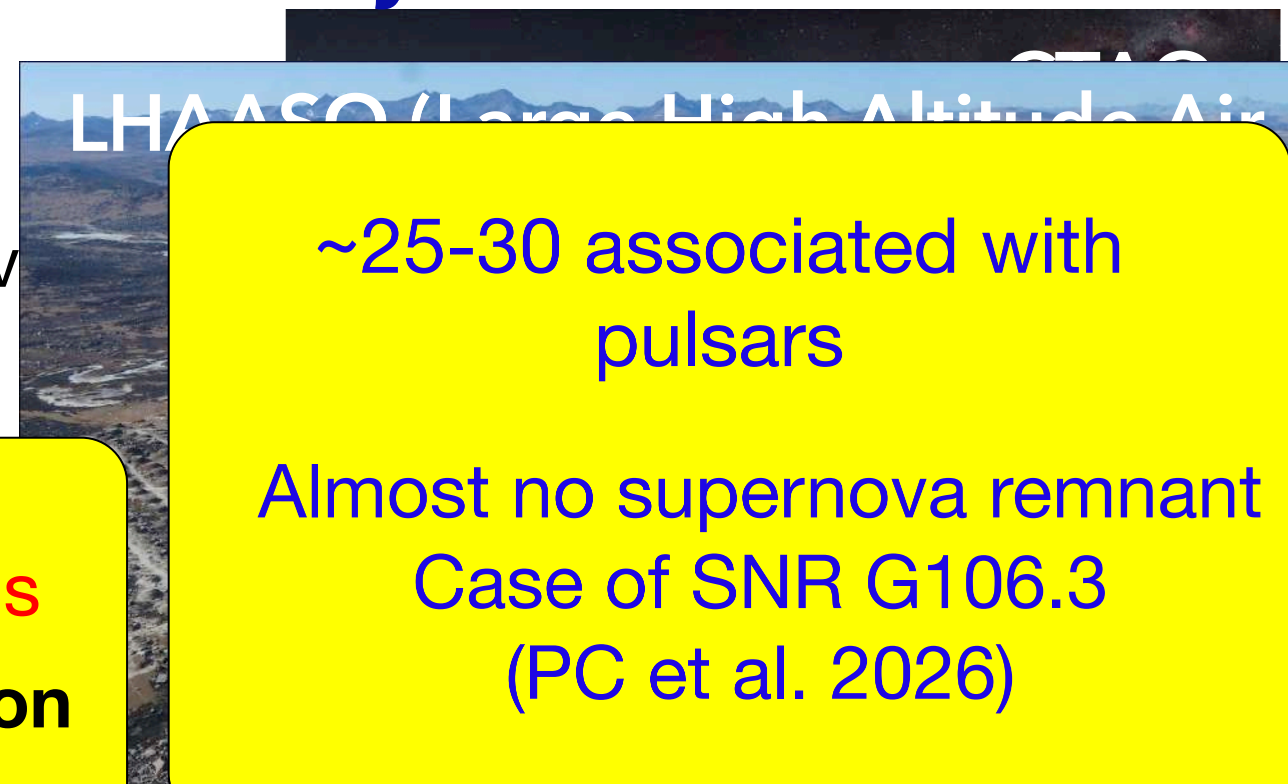
100 TeV gamma rays ⟷ Electrons

Hard spectra for electron with radiation dominated environment

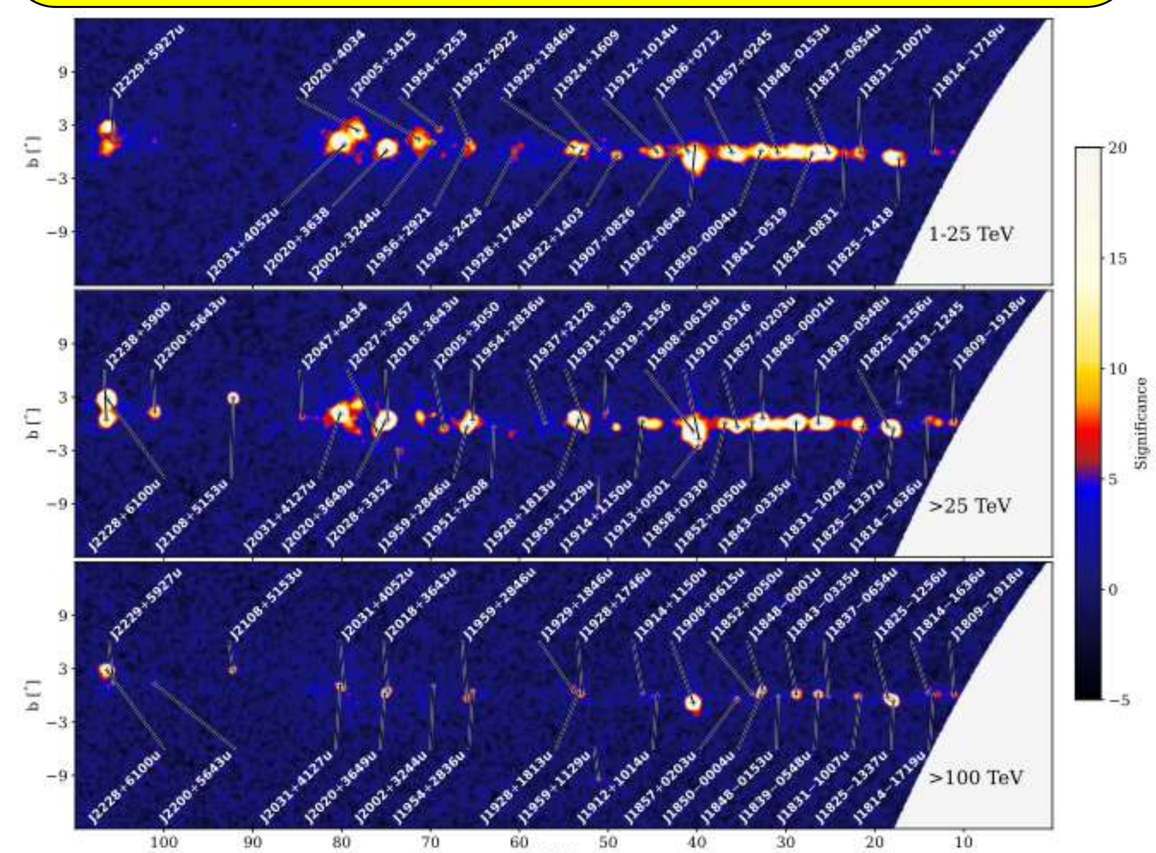
Vannoni et al. (2007), Brehaus et al. (2021)++





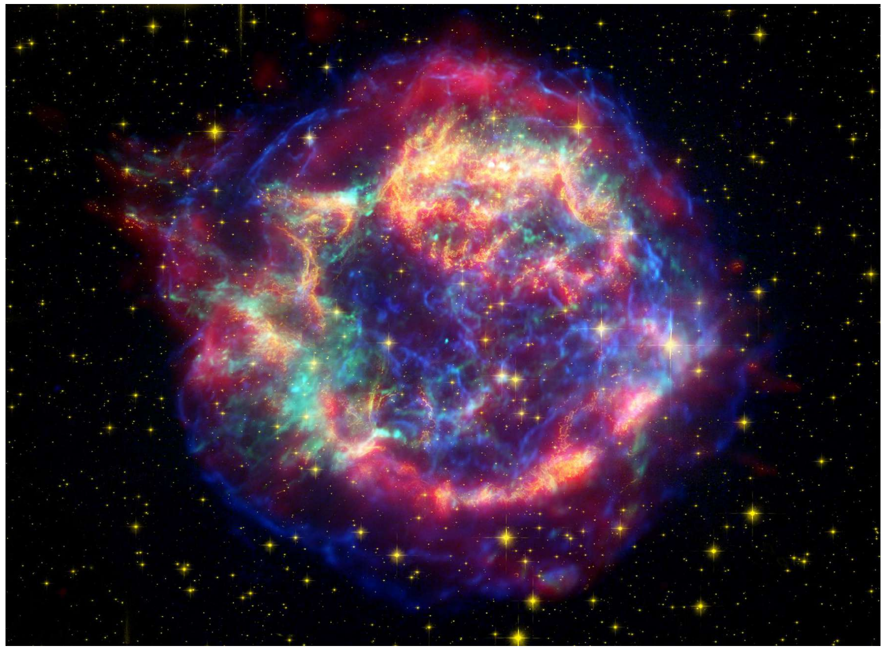
~25-30 associated with pulsars

Almost no supernova remnant
Case of SNR G106.3
(PC et al. 2026)

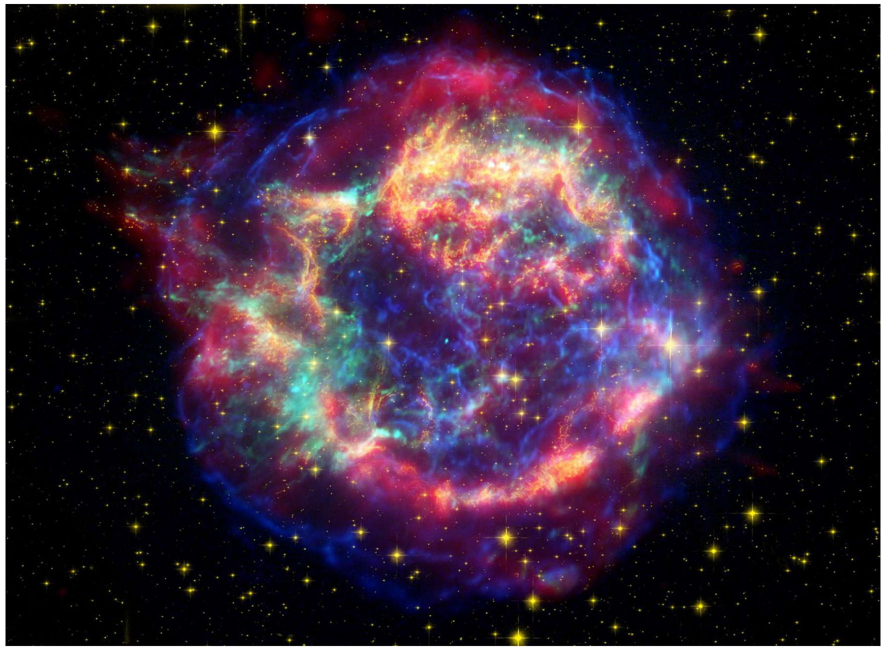


LHAASO catalog Cao et al. 2024
43 sources >100 TeV

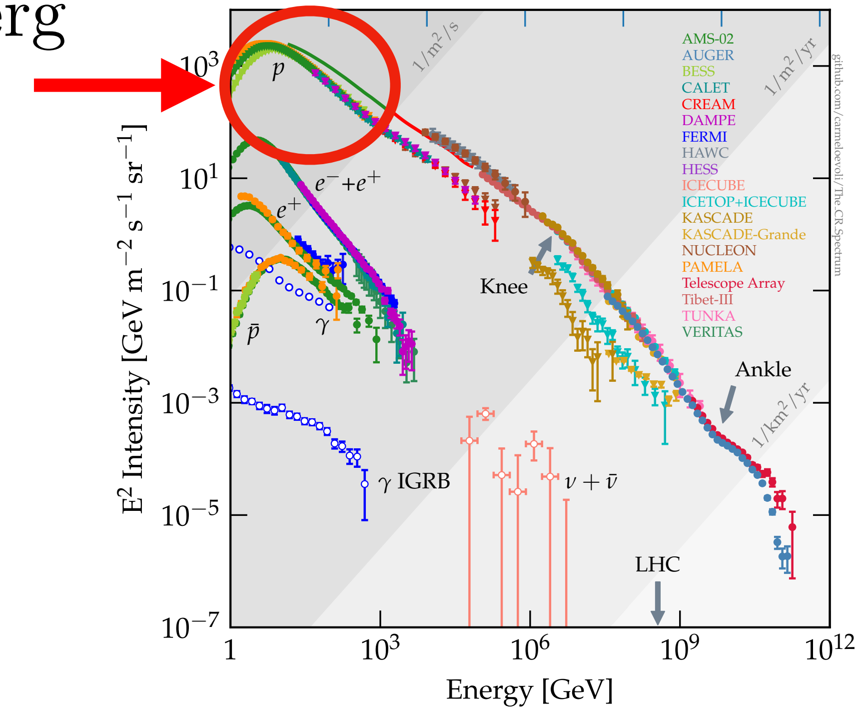
Supernova remnant pevatrons



Supernova remnant pevatrons



$$10\% \times 3/\text{century} \times 10^{51}\text{erg}$$
$$w_{\text{CR}} \sim 1\text{eV.cm}^{-3}$$



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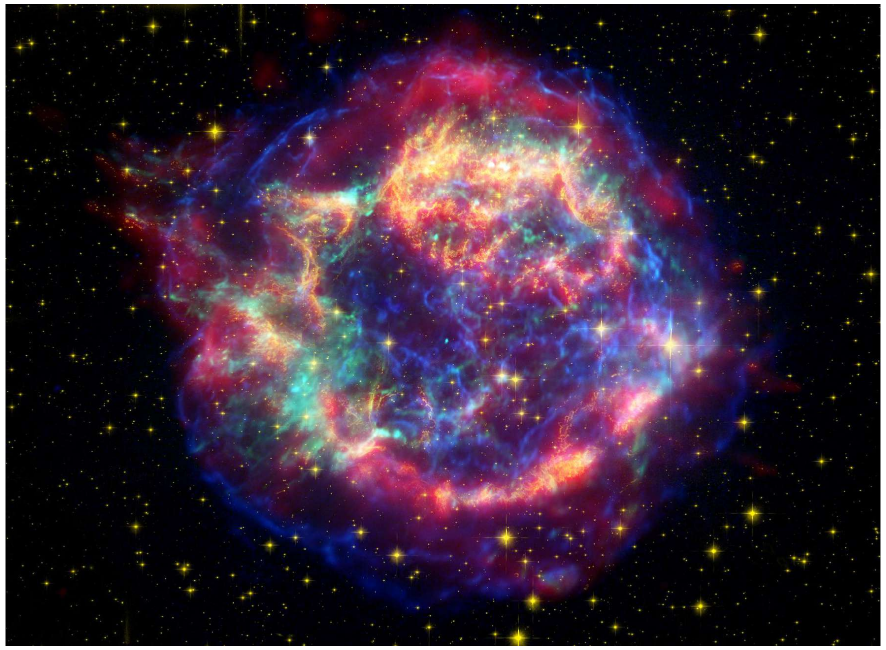
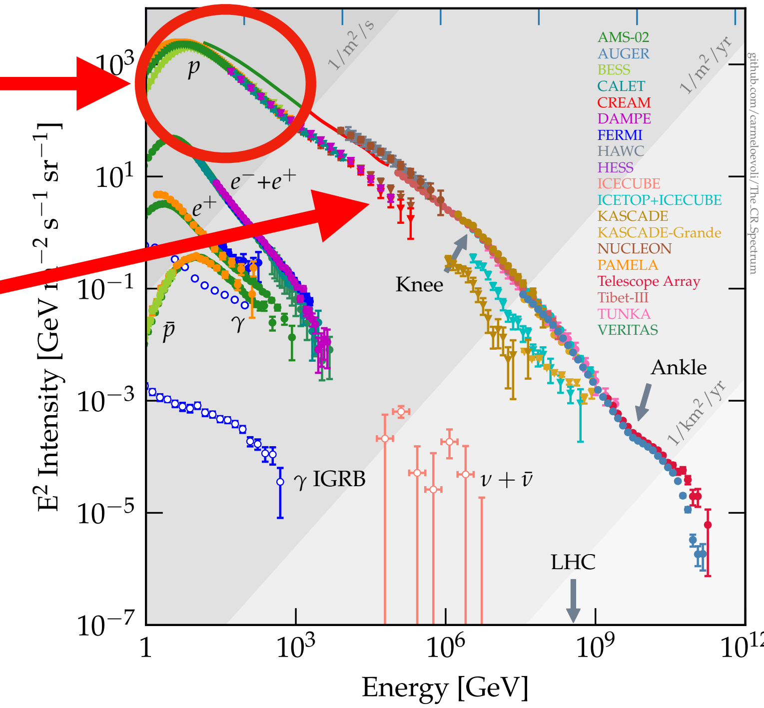


Slope (DSA)
$$\propto E^{-2.7}$$



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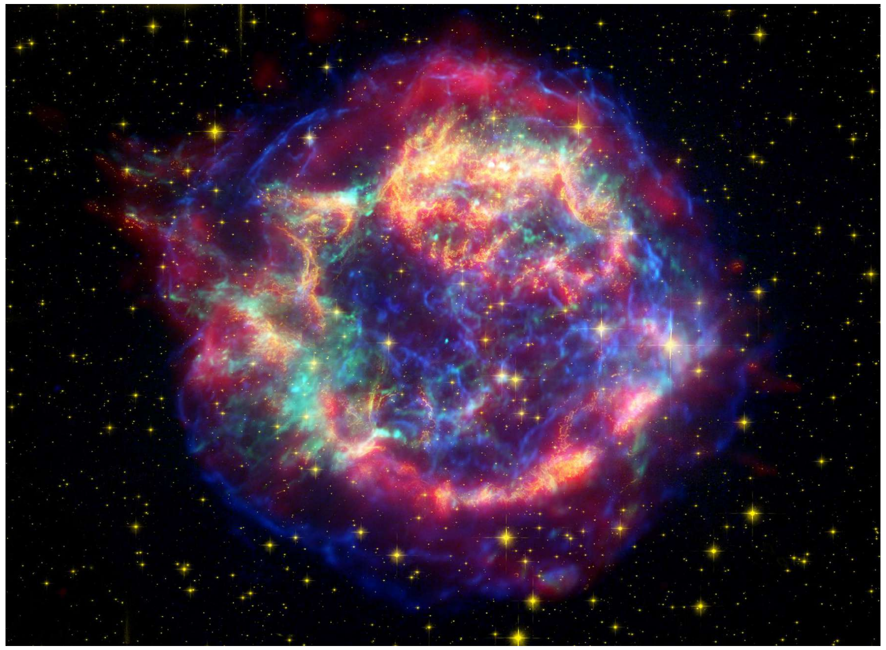

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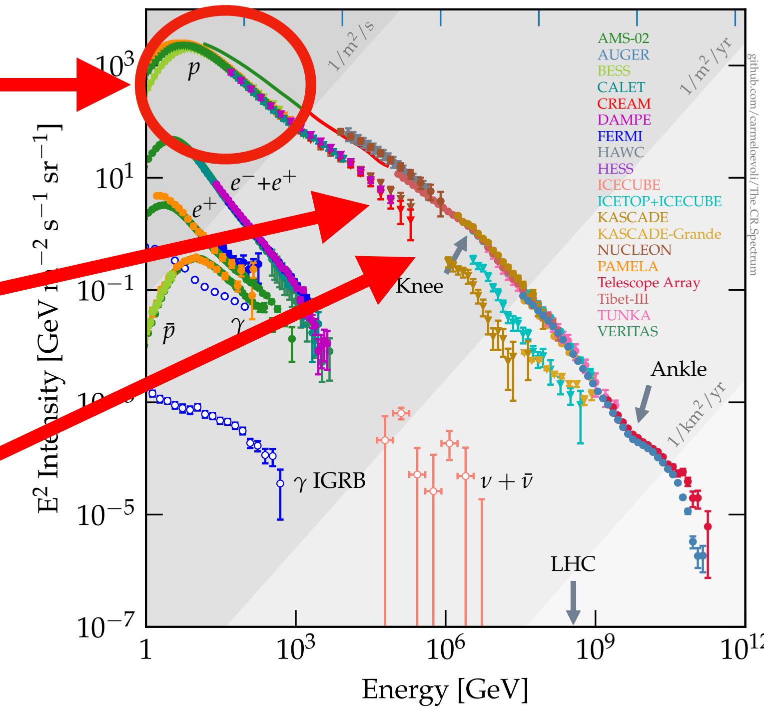
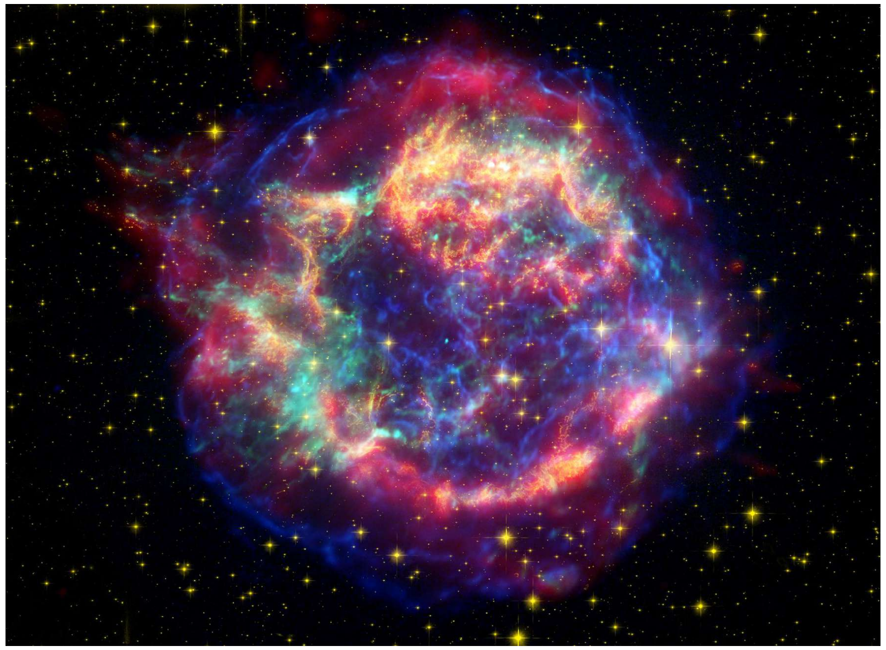
Knee?



Supernova remnant pevatrons



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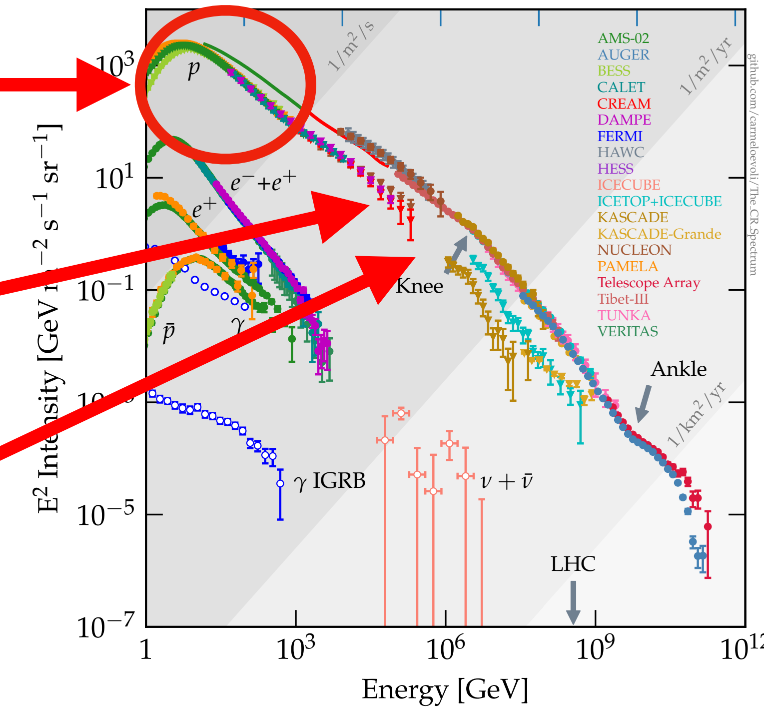
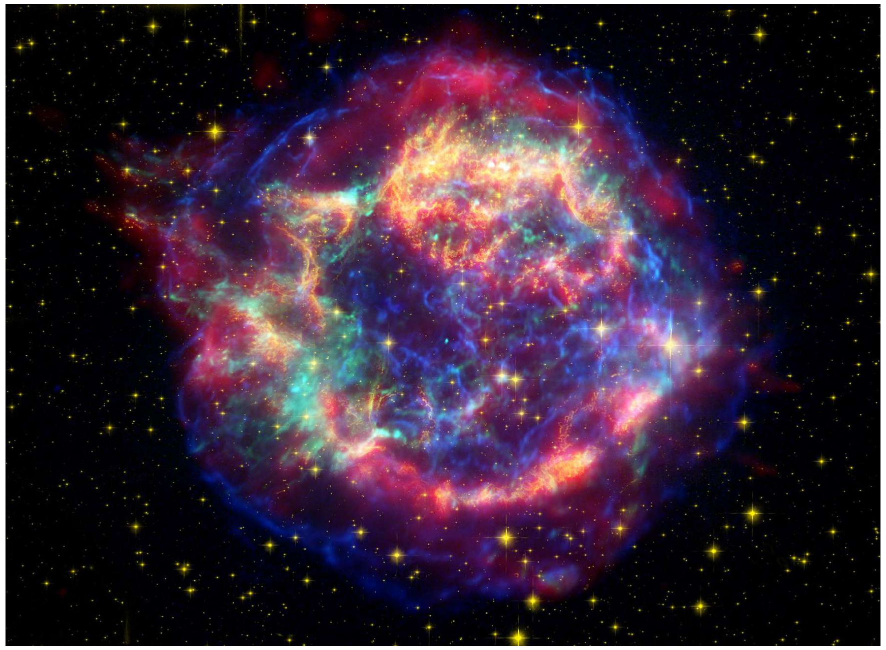


Hillas criterion

$$E_{\max} \approx \xi \left(\frac{R_{\mathrm{sh}}}{\mathrm{pc}}\right)\left(\frac{u_{\mathrm{sh}}}{1000\mathrm{km/s}}\right)\left(\frac{B}{\mu\ \mathrm{G}}\right)\mathrm{TeV}$$

Supernova remnant pevatrons



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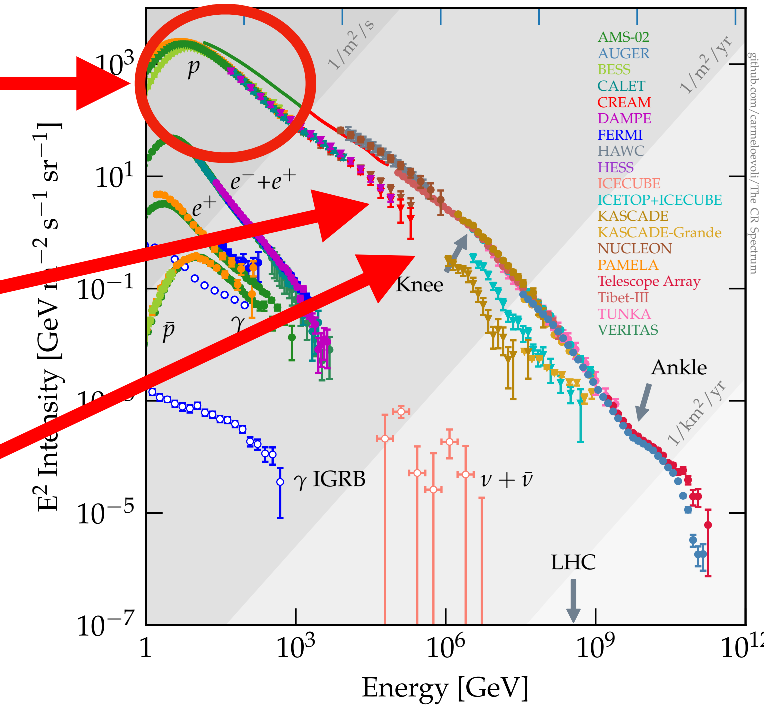

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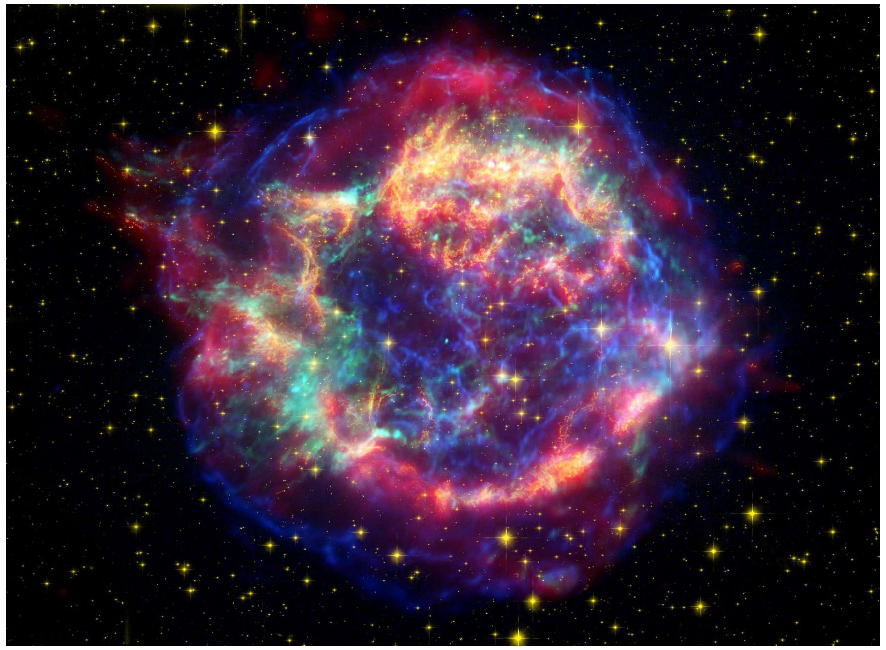

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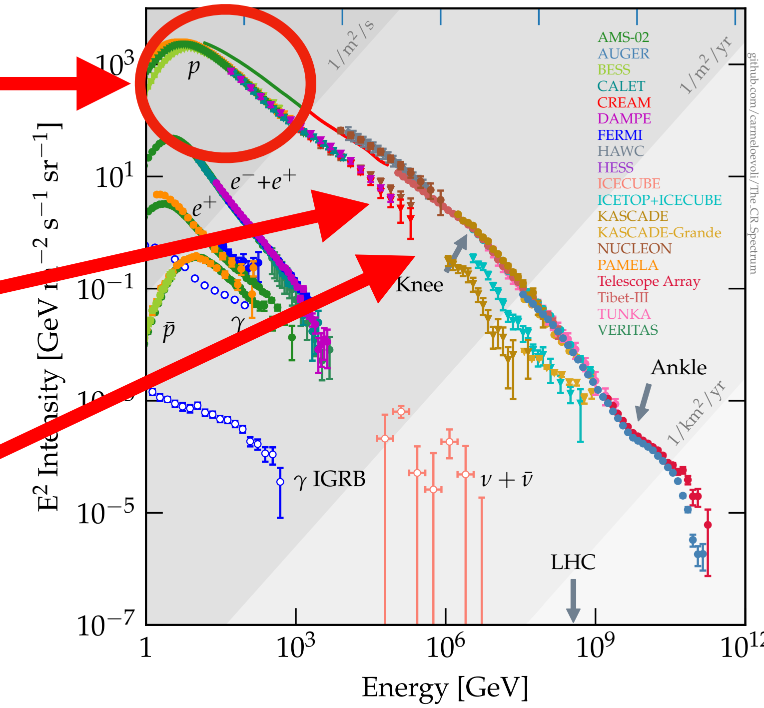

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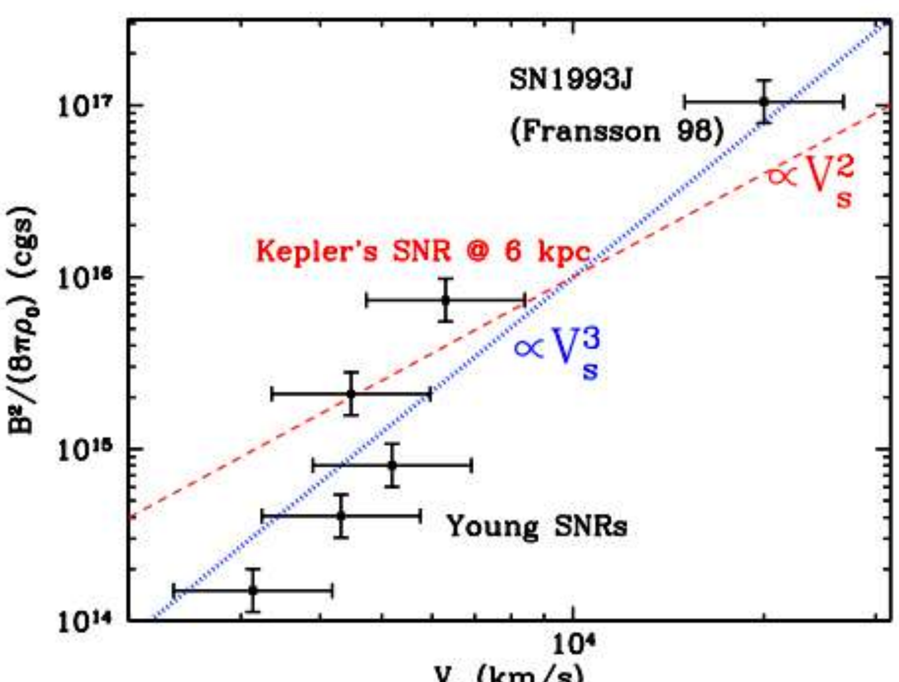
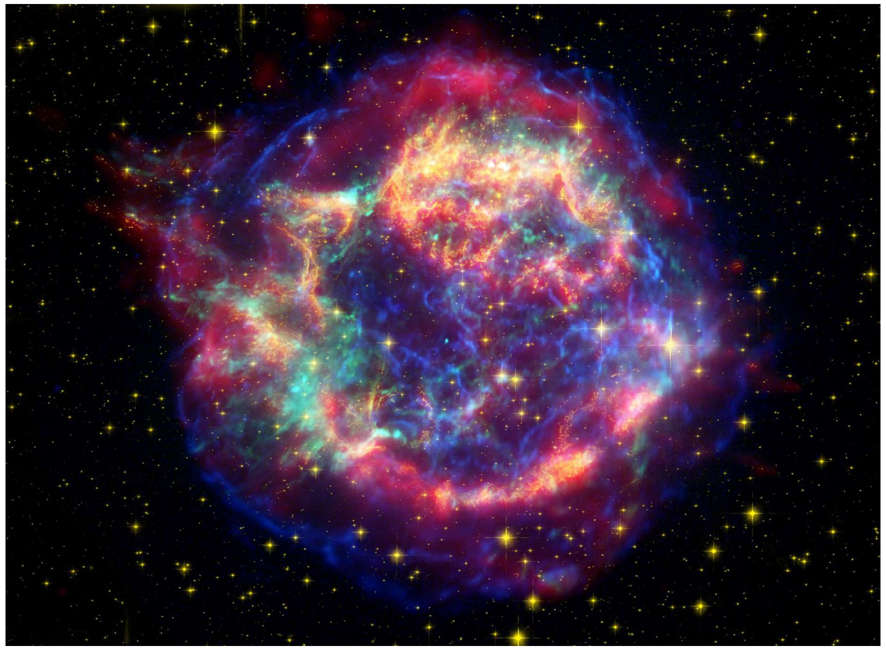


Supernova remnant pevatrons



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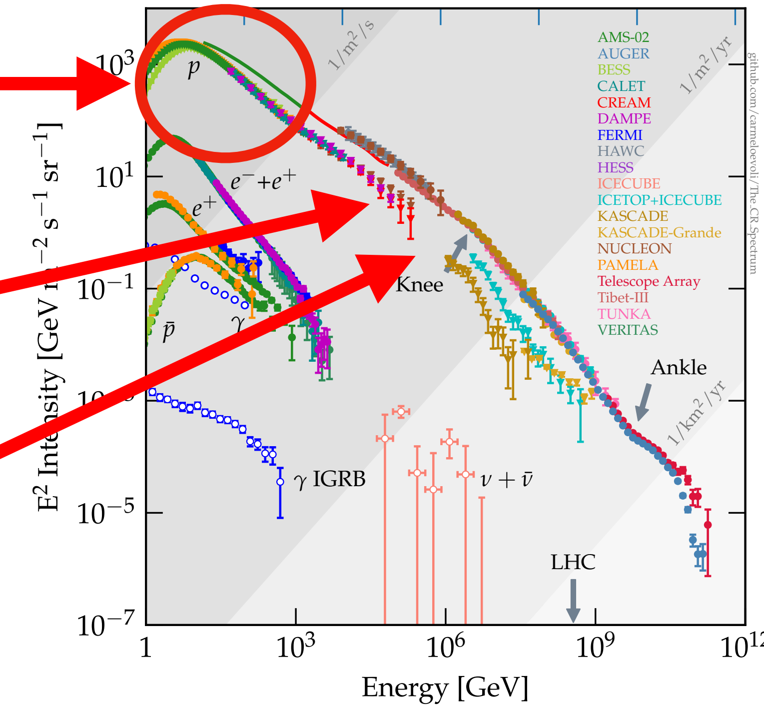

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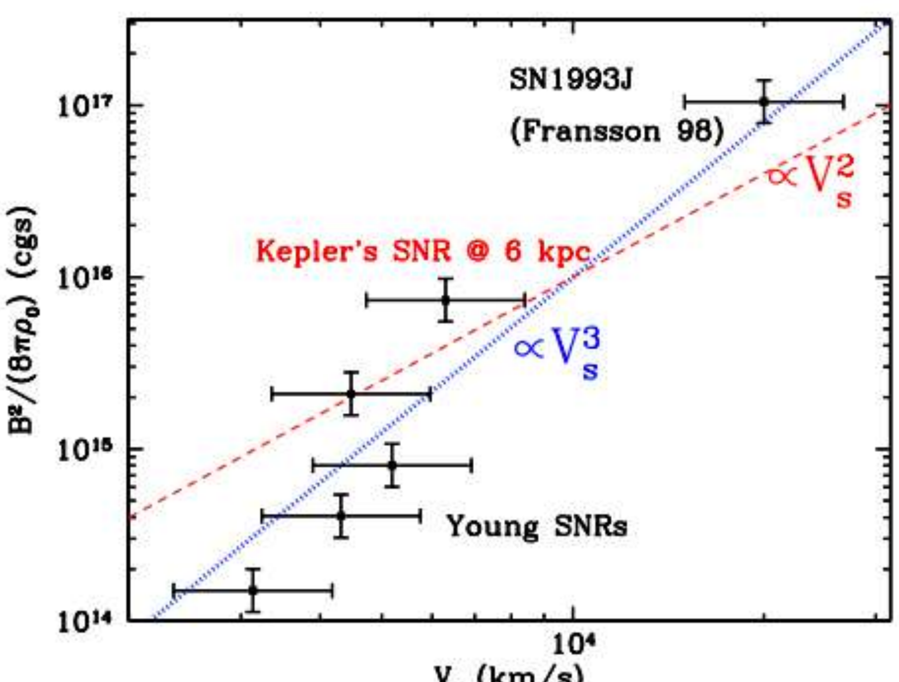


Growth of the non-resonant streaming instability

$$p_{\max}(t) \approx \frac{r_{\mathrm{sh}}(t)}{10}\,\frac{\xi e\sqrt{4\pi\rho(t)}}{\Lambda}\left(\frac{u_{\mathrm{sh}}(t)}{c}\right)^2$$

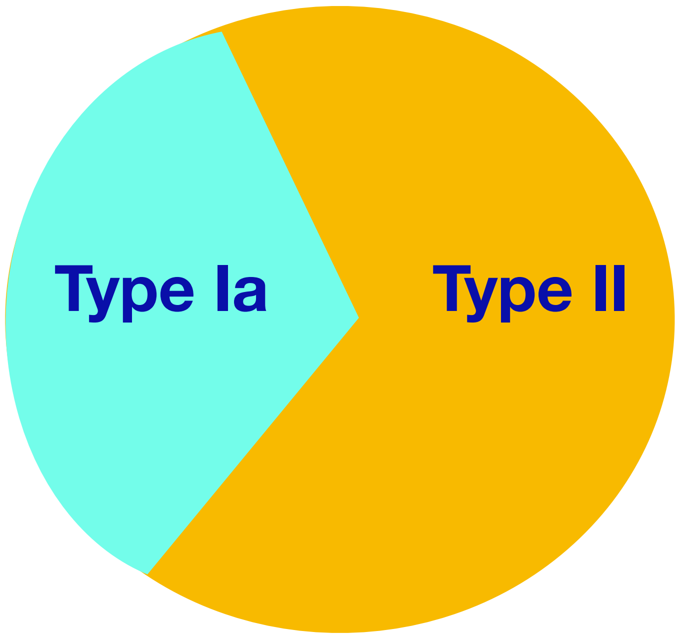
Different for different SNRs/SNe

Bell (2004), Bell et al. (2013), Schure et al. (2014)

Supernova remnant pevatrons

non-resonant streaming instability

$$p_{\max}(t) \approx \frac{r_{\rm sh}(t)}{10} \frac{\xi e \sqrt{4\pi\rho(t)}}{\Lambda} \left(\frac{u_{\rm sh}(t)}{c} \right)^2$$



Bell (2004), Bell et al. (2013), Schure et al. (2014)

Supernova remnant pevatrons

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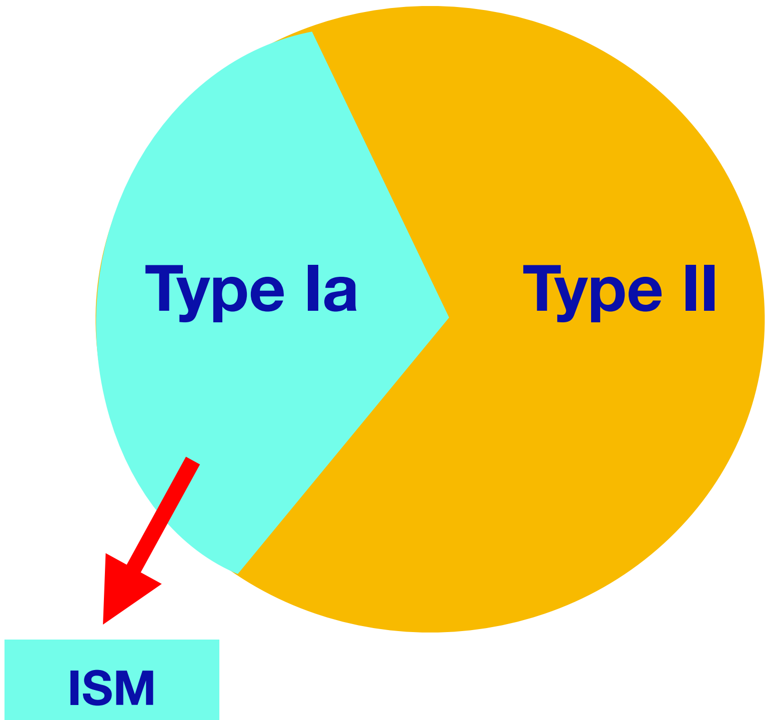

Bell (2004), Bell et al. (2013), Schure et al. (2014)

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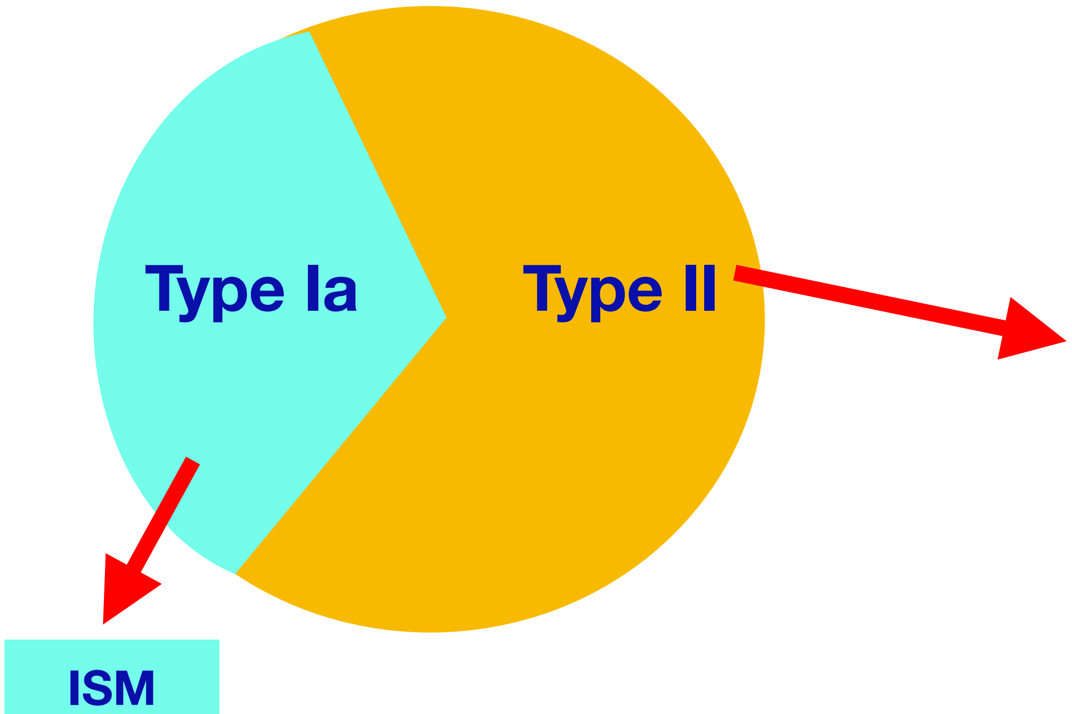
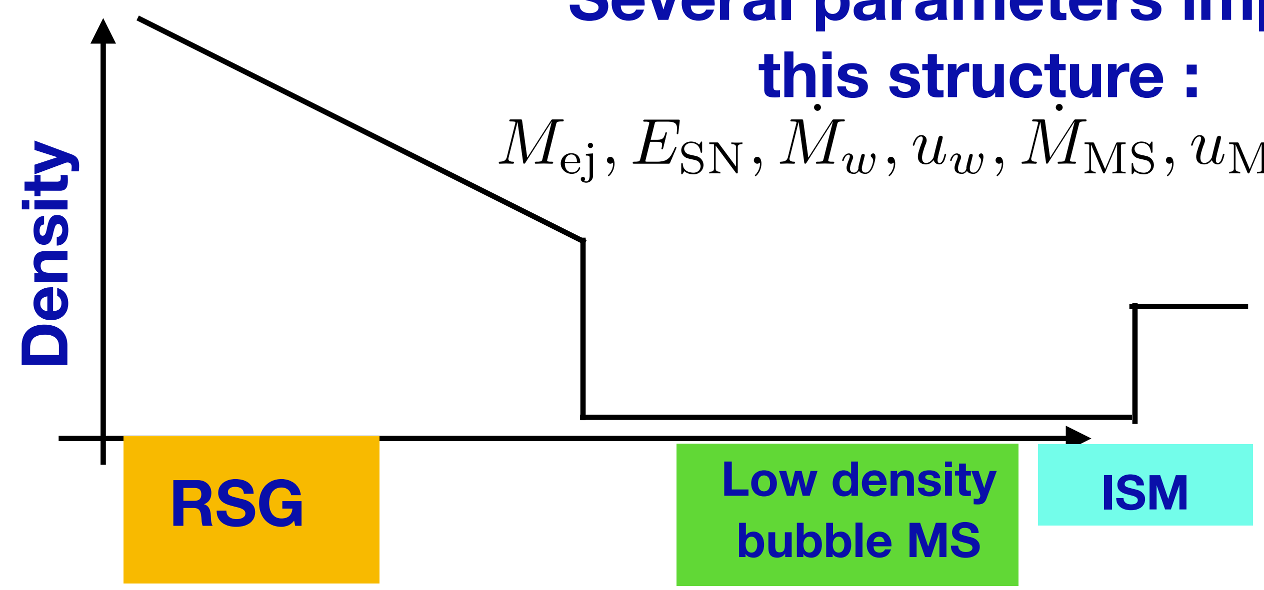


Several parameters impact this structure :

$M_{\rm ej}, E_{\rm SN}, \dot{M}_w, u_w, \dot{M}_{\rm MS}, u_{\rm MS}, t_{\rm RSG}$



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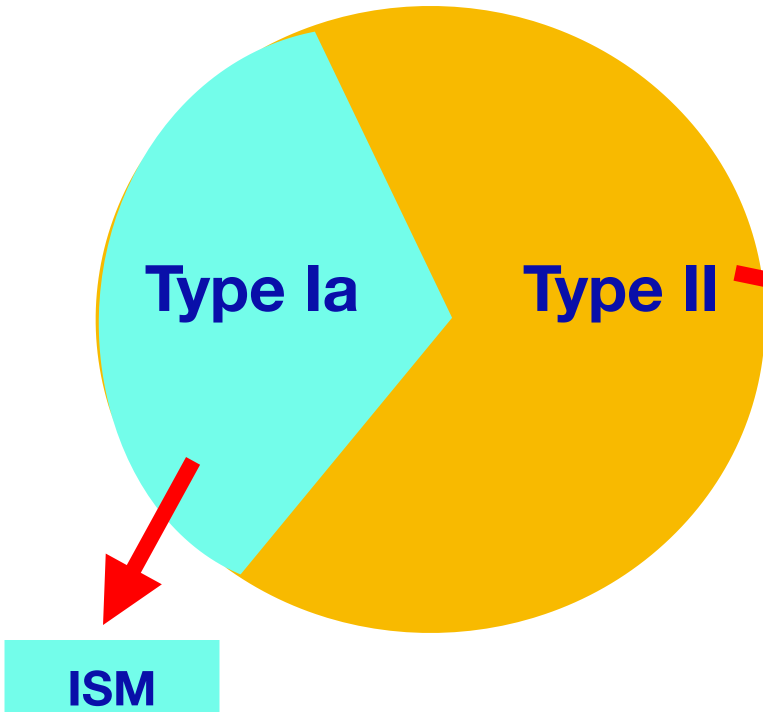

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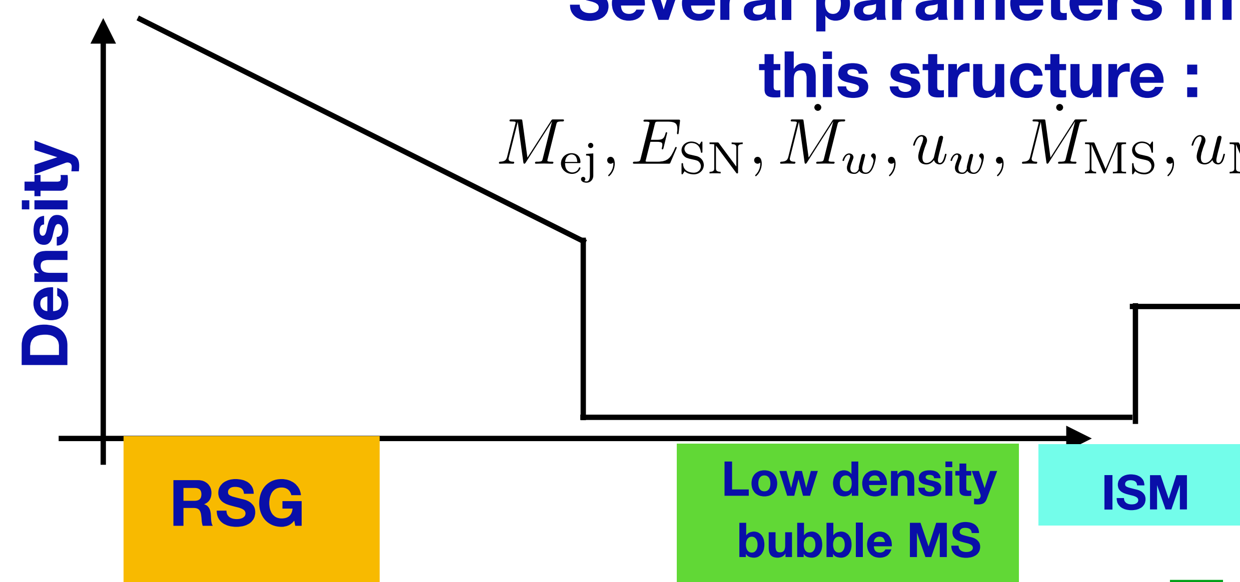
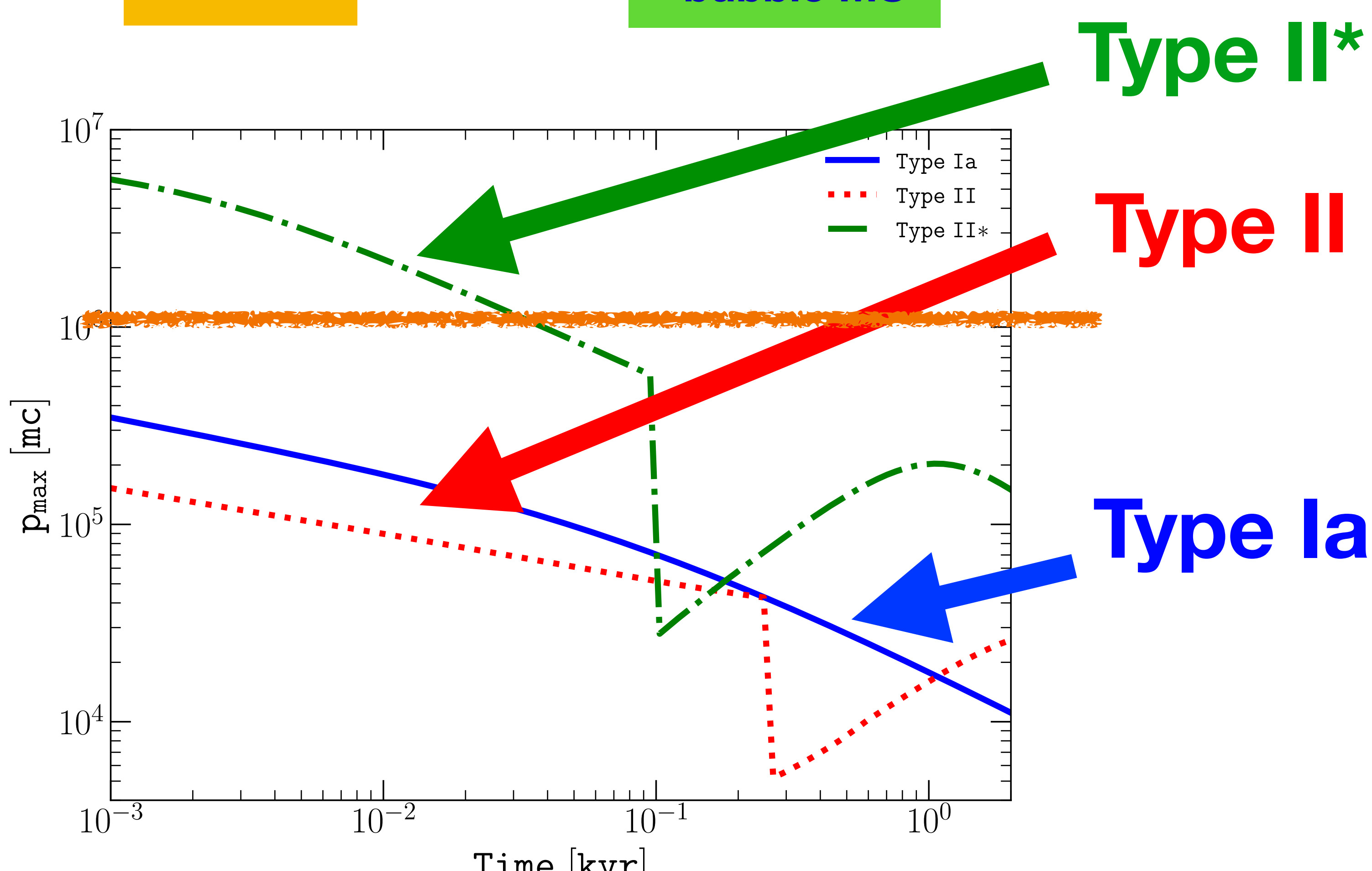


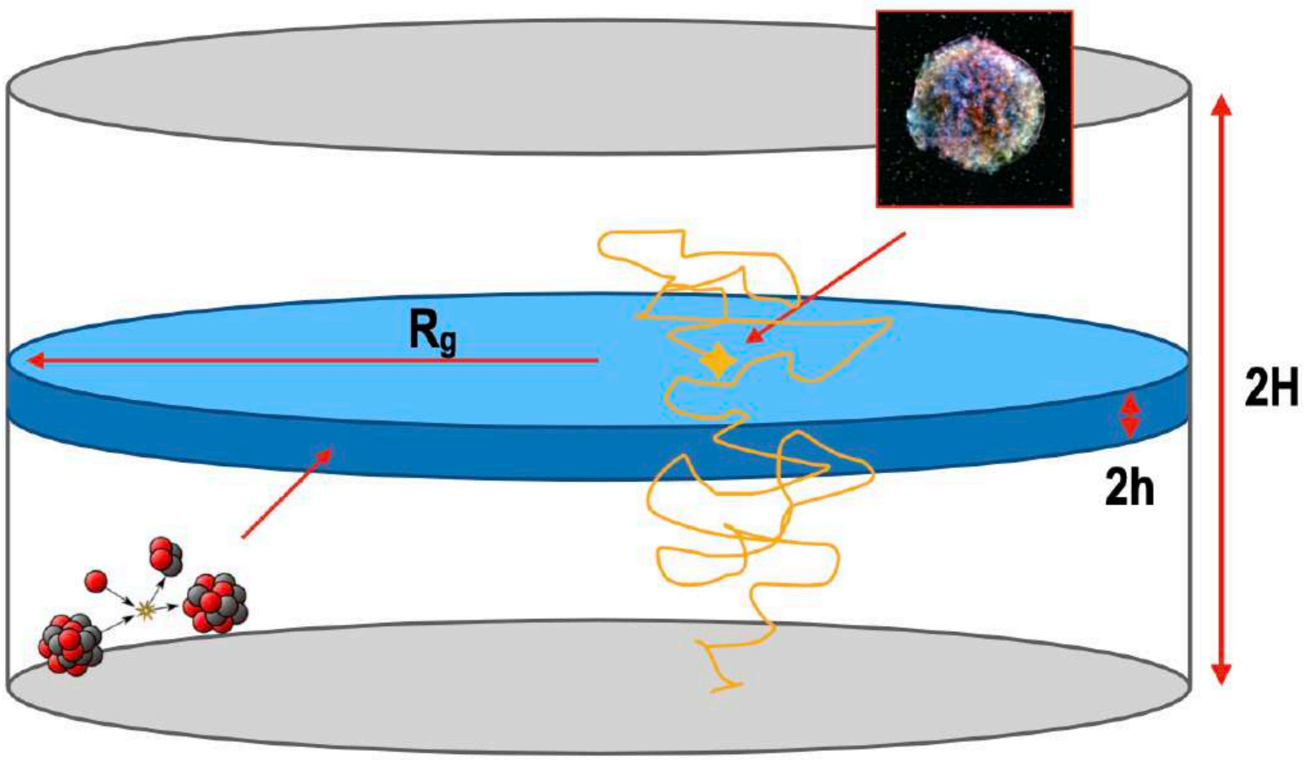


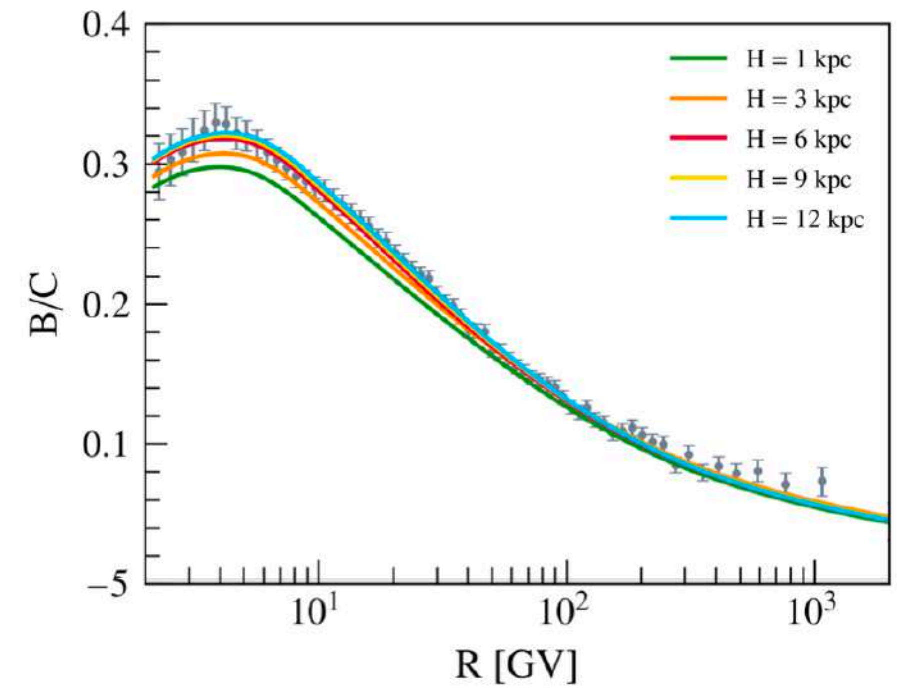
Typical SNRs : not pevatrons
Young and peculiar SNRs: pevatrons

Bell (2004), Bell et al. (2013), Schure et al. (2014)

The case of supernova remnants

Consensus: Protons are injected in the disk and diffusively propagate in a magnetized halo





Secondary-to-primary ratio: properties of transport

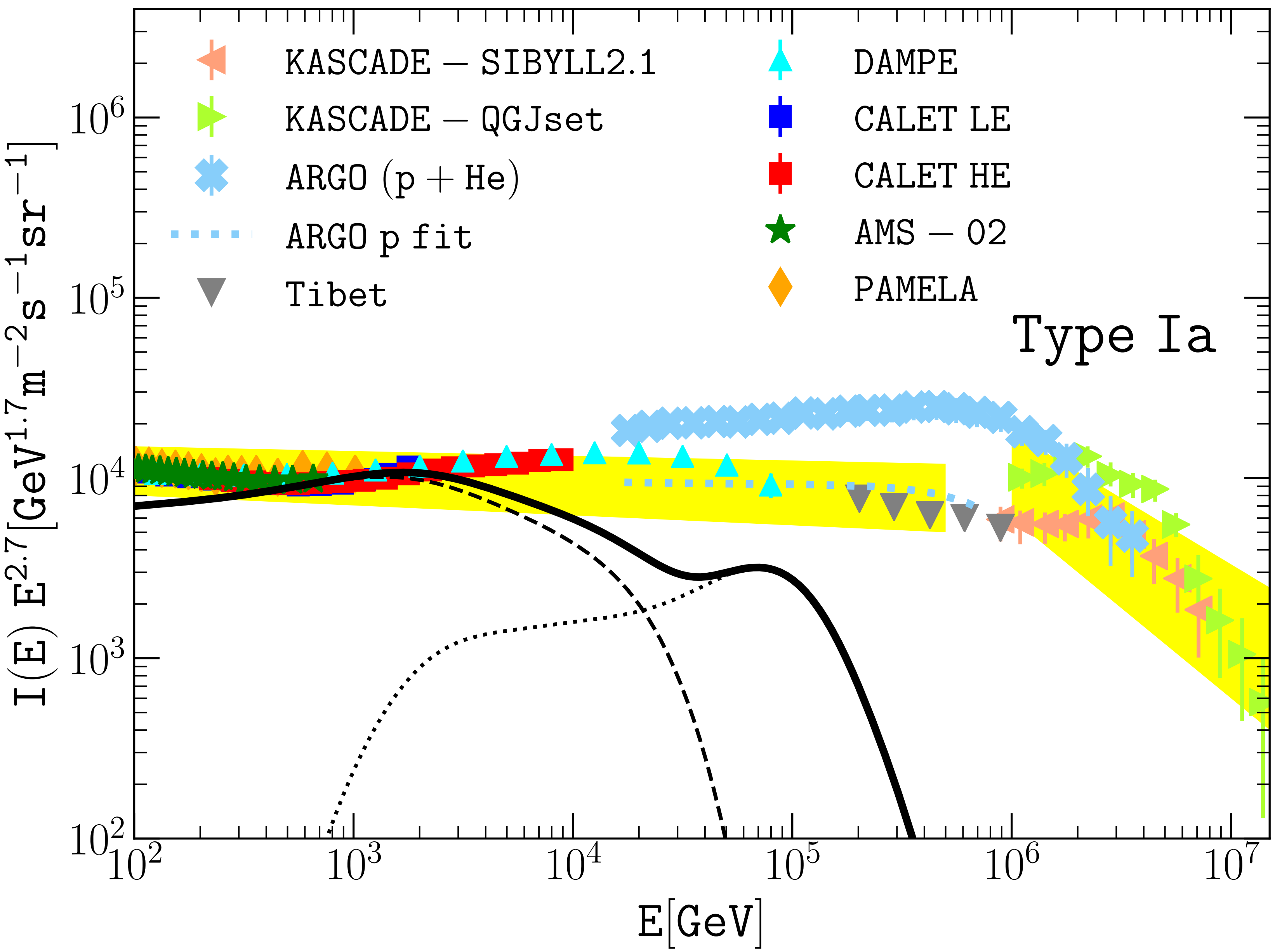
$$\underbrace{E^{-(2.4..2.1)}}_{\text{Injection}} \times \underbrace{E^{-(0.3..0.6)}}_{\text{Propagation}} = E^{-2.7}$$

$$\underbrace{-\frac{\partial}{\partial z}\left[D(p)\frac{\partial f}{\partial z}\right]}_{\text{Diffusion}} \underbrace{+ u\frac{\partial f}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f}{\partial p}}_{\text{Advection}} \underbrace{+ \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\text{ion}} f\right]}_{\text{Ionisation losses}} = \underbrace{q(p,z)}_{\text{Injection from SNRs}}$$

Morrison, Olbert & Rossi 1954, Ginzburg & Syrovatskii 1964, Evoli et al. 2018, 2019

The case of supernova remnants

Protons after propagation:



PC, Blasi& Amato (2020)

The case of supernova remnants

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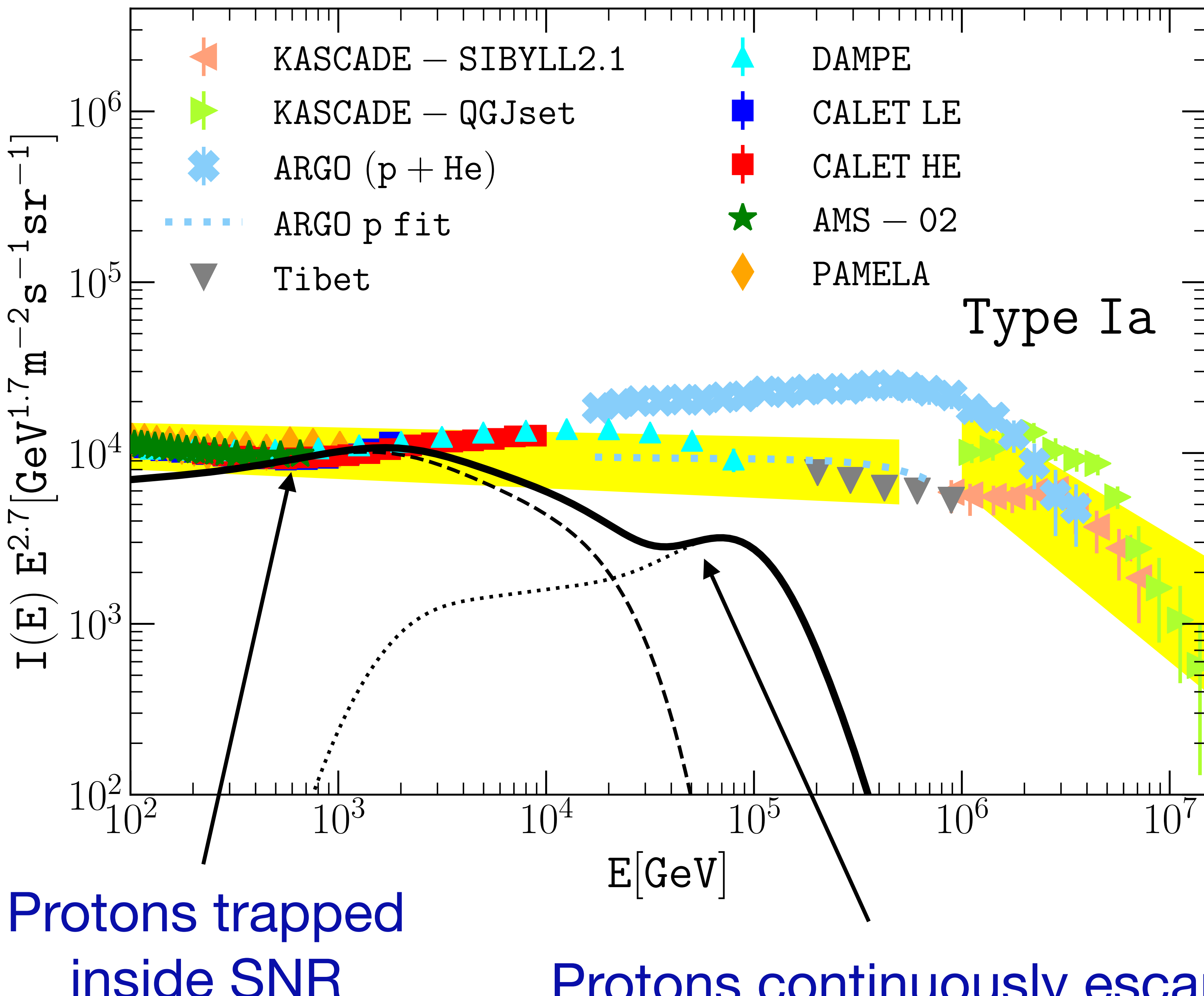


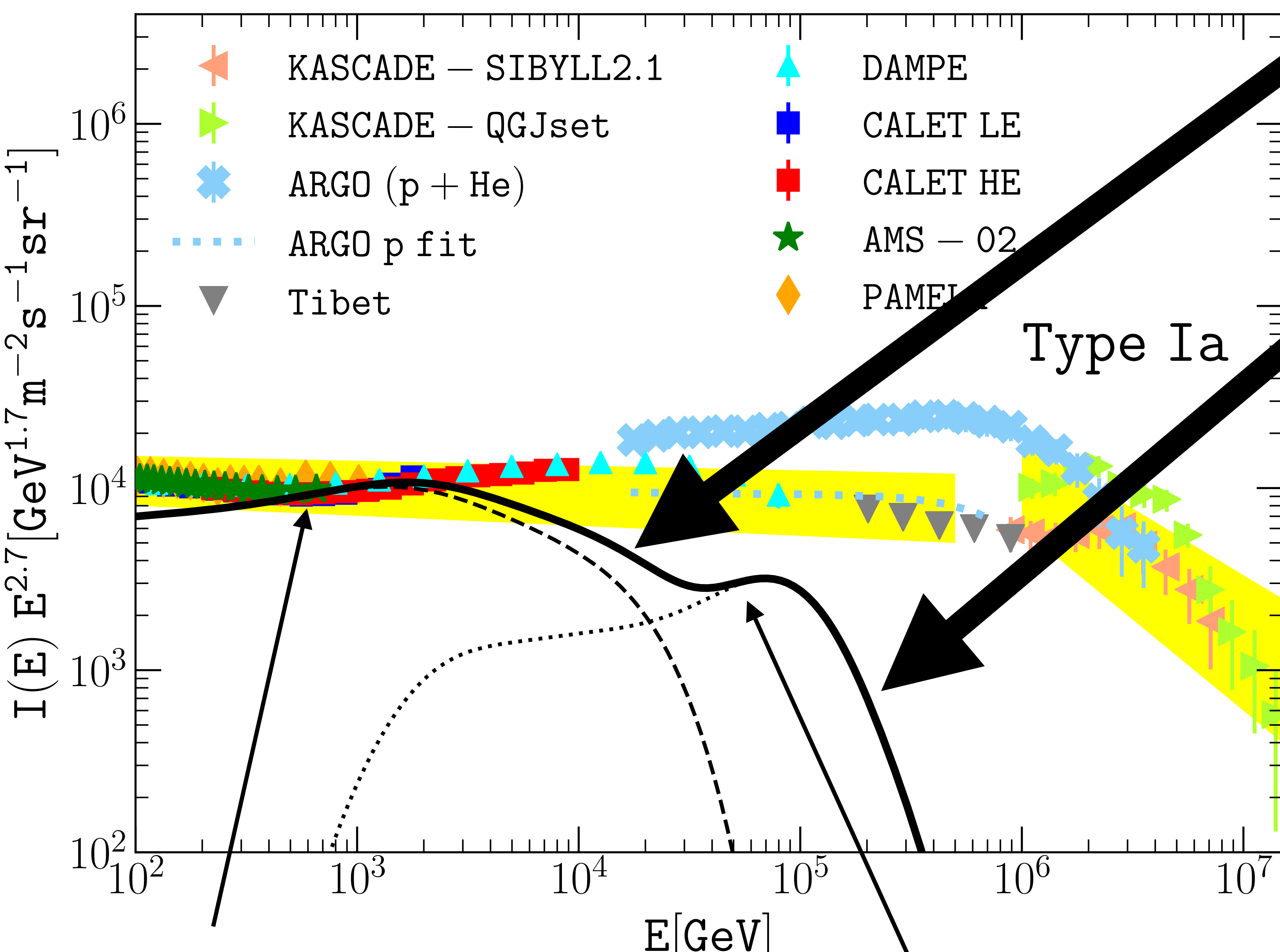
PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:

$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$

$E_{\mathrm{max}} \propto \xi_{\mathrm{CR}}$



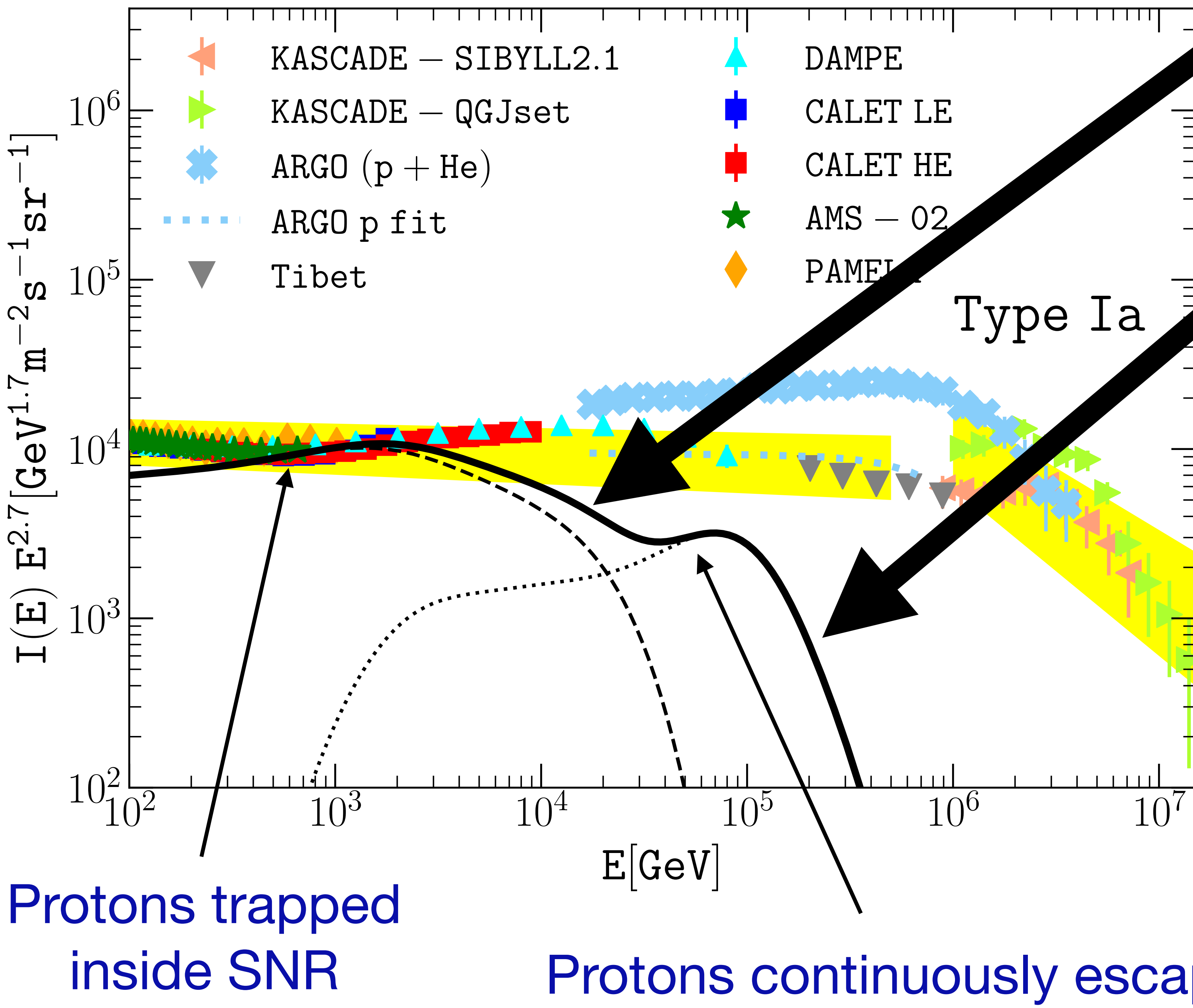
Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:



$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$

$E_{\mathrm{max}} \propto \xi_{\mathrm{CR}}$

$\nu_{\mathrm{Ia}} = 1/\mathrm{century}$

PC, Blasi& Amato (2020)

The case of supernova remnants

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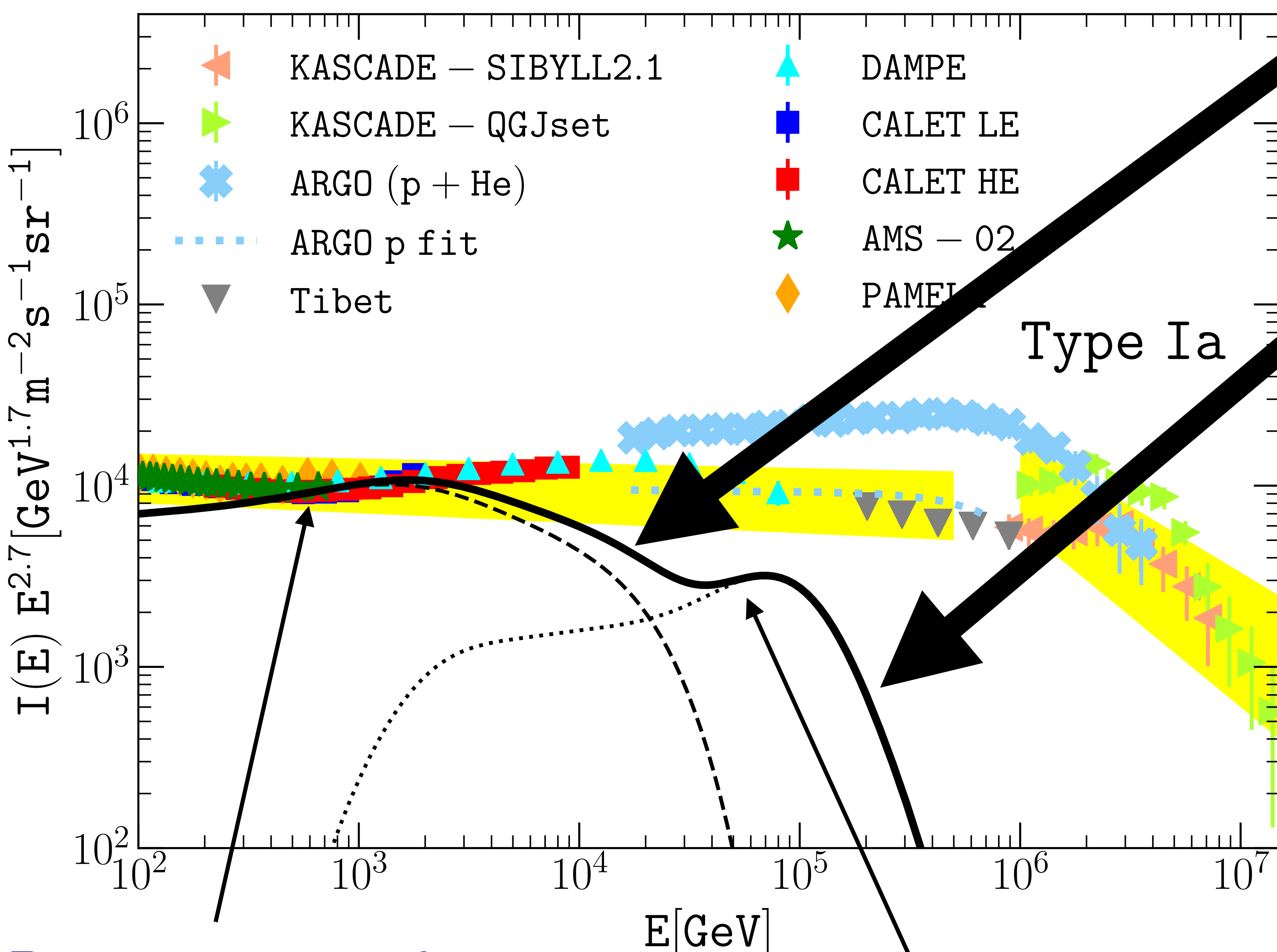

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$E_{\max} \propto \xi_{\mathrm{CR}}$

$\nu_{\mathrm{Ia}} = 1/\mathrm{century}$

$\xi_{\mathrm{SN}} = 0.1$

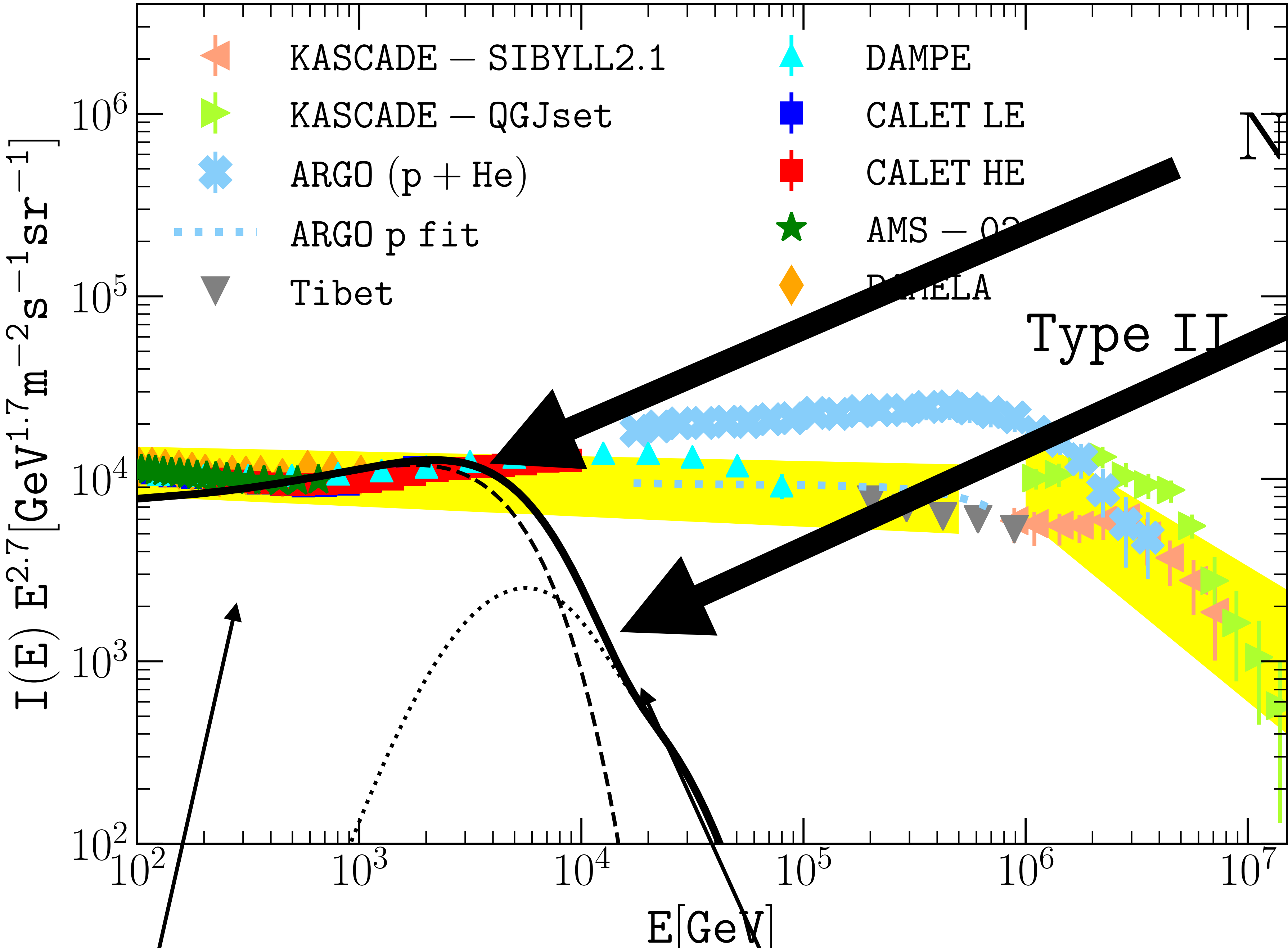
Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:



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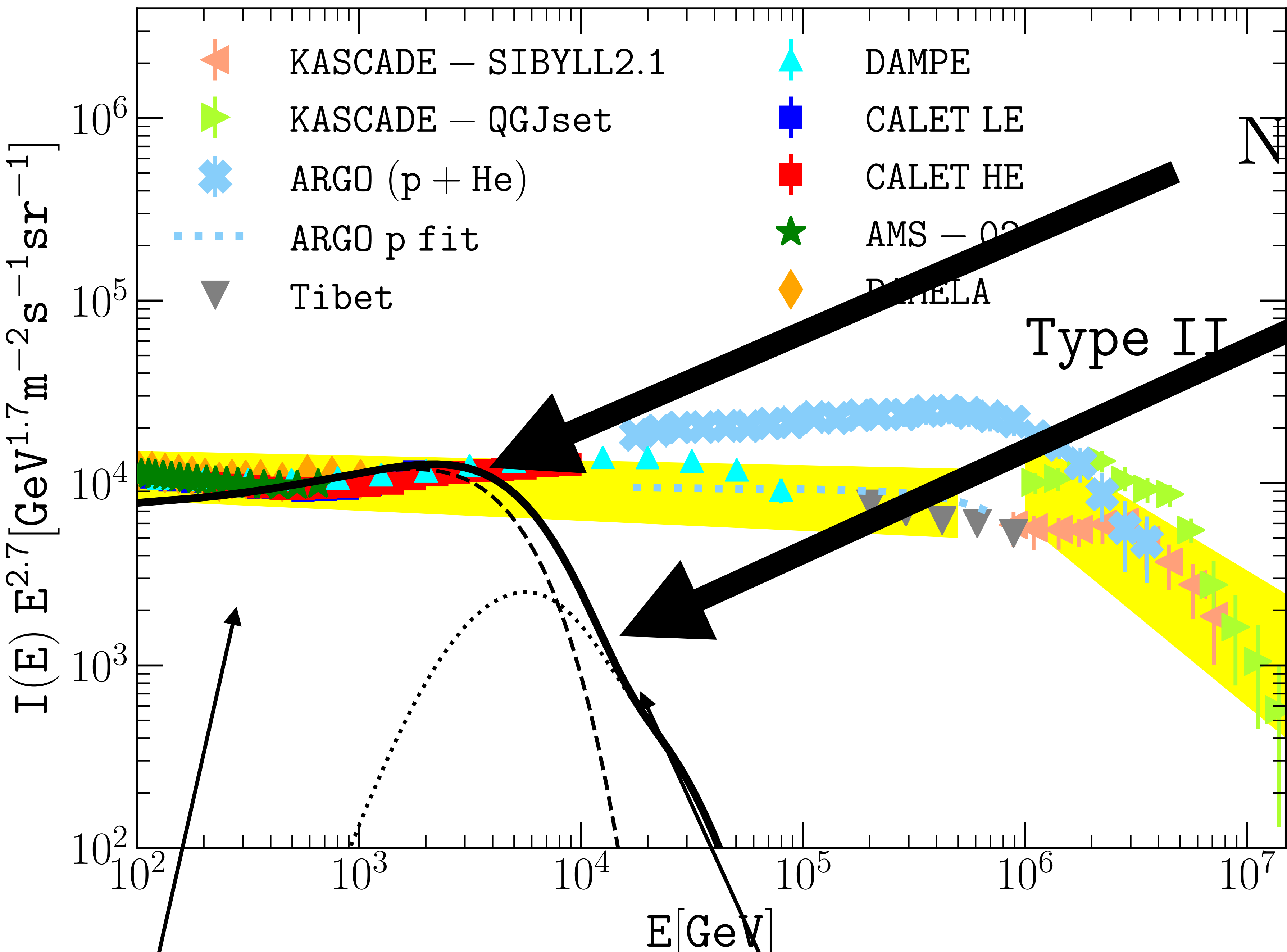

$\mathrm{Norm} \propto \xi_{\rm CR} \times \nu_{\rm SN}$

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$\nu_{\rm II} = 2/\mathrm{century}$

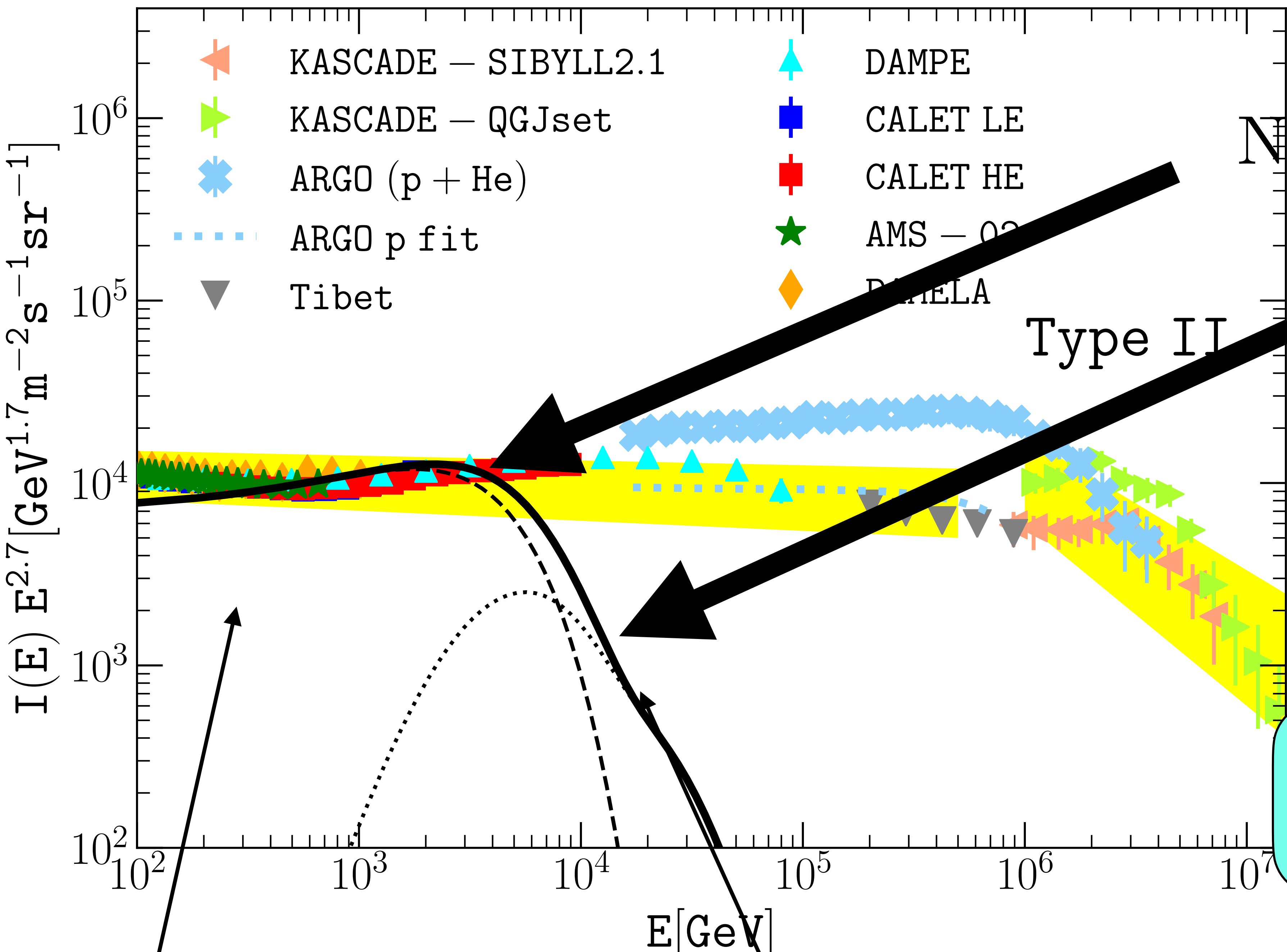
Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:



$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$

$E_{\max} \propto \xi_{\mathrm{CR}}$

$\nu_{\mathrm{II}} = 2/\mathrm{century}$

$\xi_{\mathrm{SN}} = 0.06$

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

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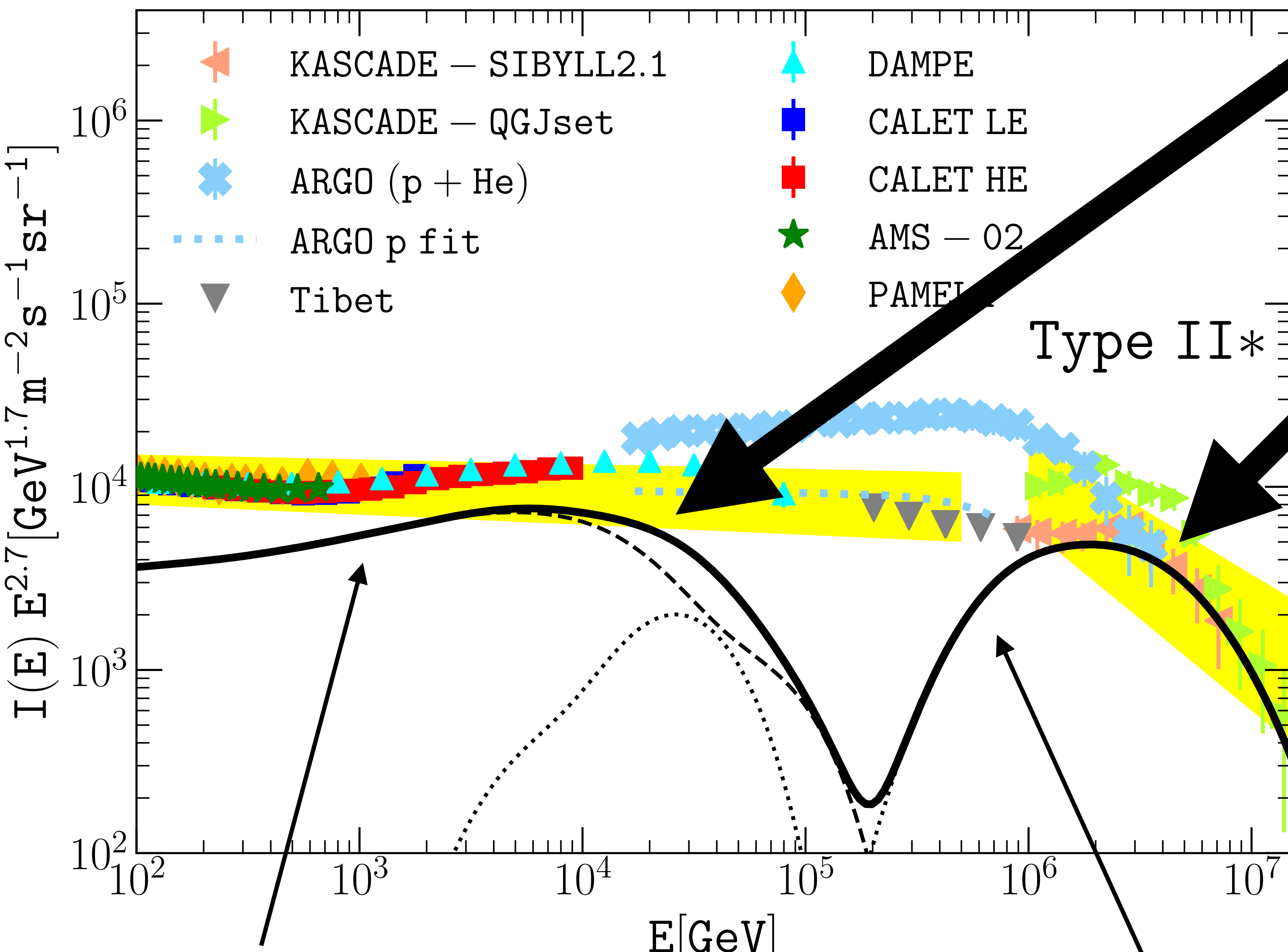

Protons trapped inside SNR

Protons continuously escaping

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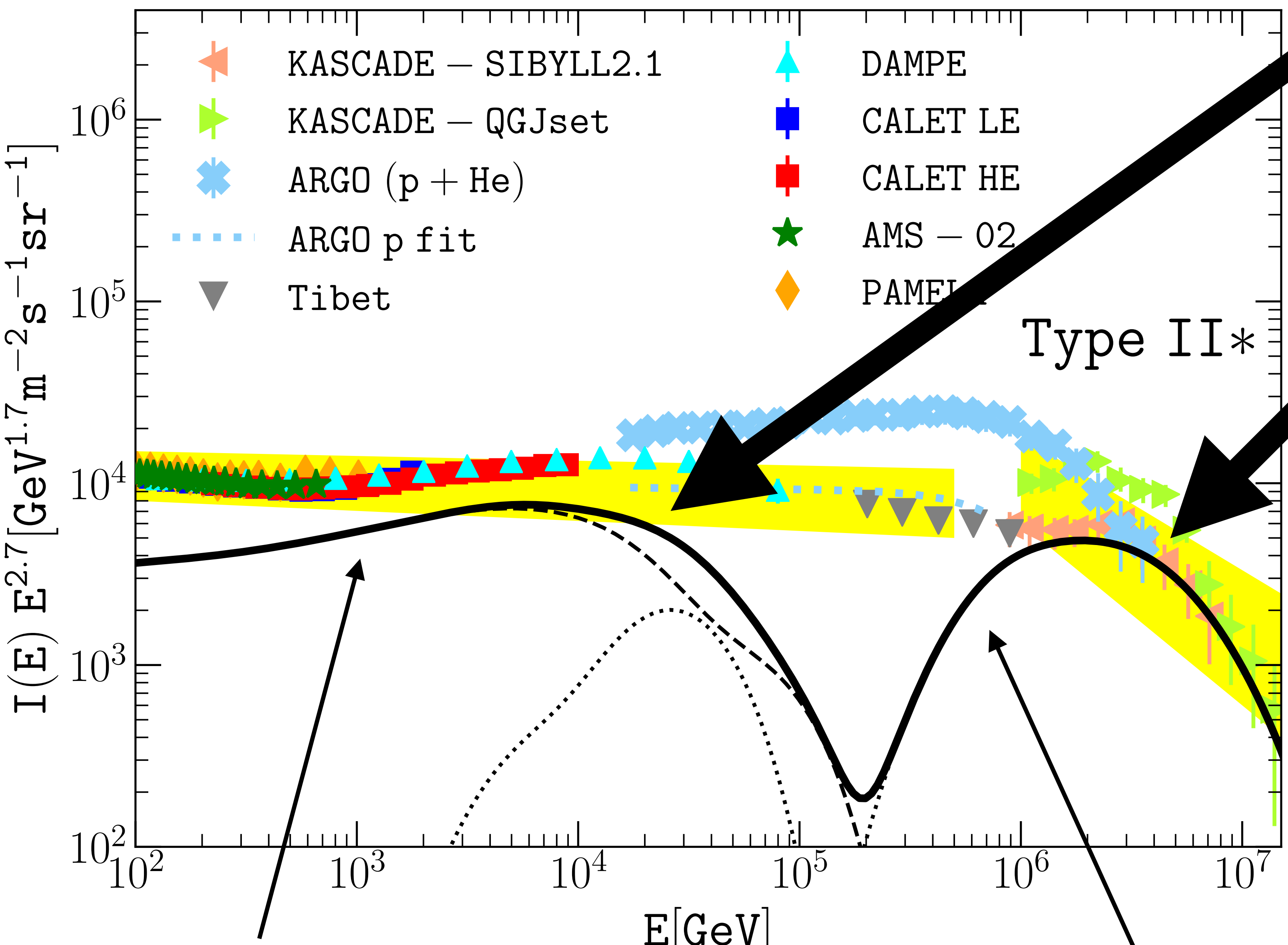
The case of supernova remnants

Protons after propagation:

$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

$$E_{\mathrm{max}} \propto \xi_{\mathrm{CR}}$$

$$\xi_{\mathrm{CR}} \sim 5 - 10\%$$



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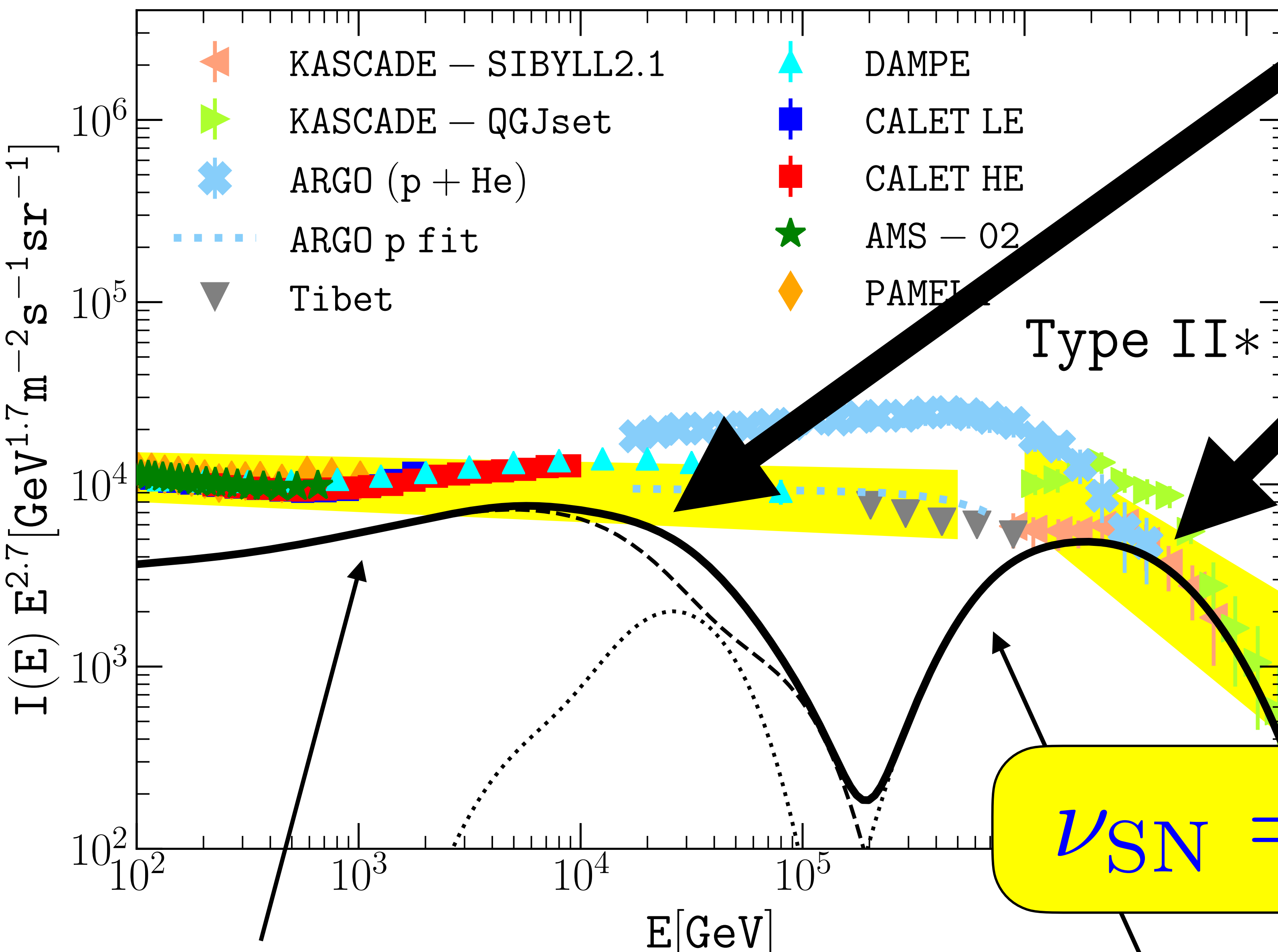

$\xi_{\mathrm{CR}} \sim 5 - 10\%$

Reach PeV and not overproduce the CR spectrum:

$\nu_{\mathrm{SN}} = 1\% \times 3/\mathrm{century}$

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

1. Possible to account for PeV protons with rare unusual SNRs (1-5% 3/century, hard to catch!) - specific environments and diversity of SNe investigated in several works (Gabici et al. 2019, Kamijina& Ohira 2024, Das et al. 2024, Vieu et al. 2023, Bykov et al. 2024 + many more, (Sushsch et al. 2025), SNe close to stellar clusters (Vieu&Reville 2024)?)

The case of supernova remnants

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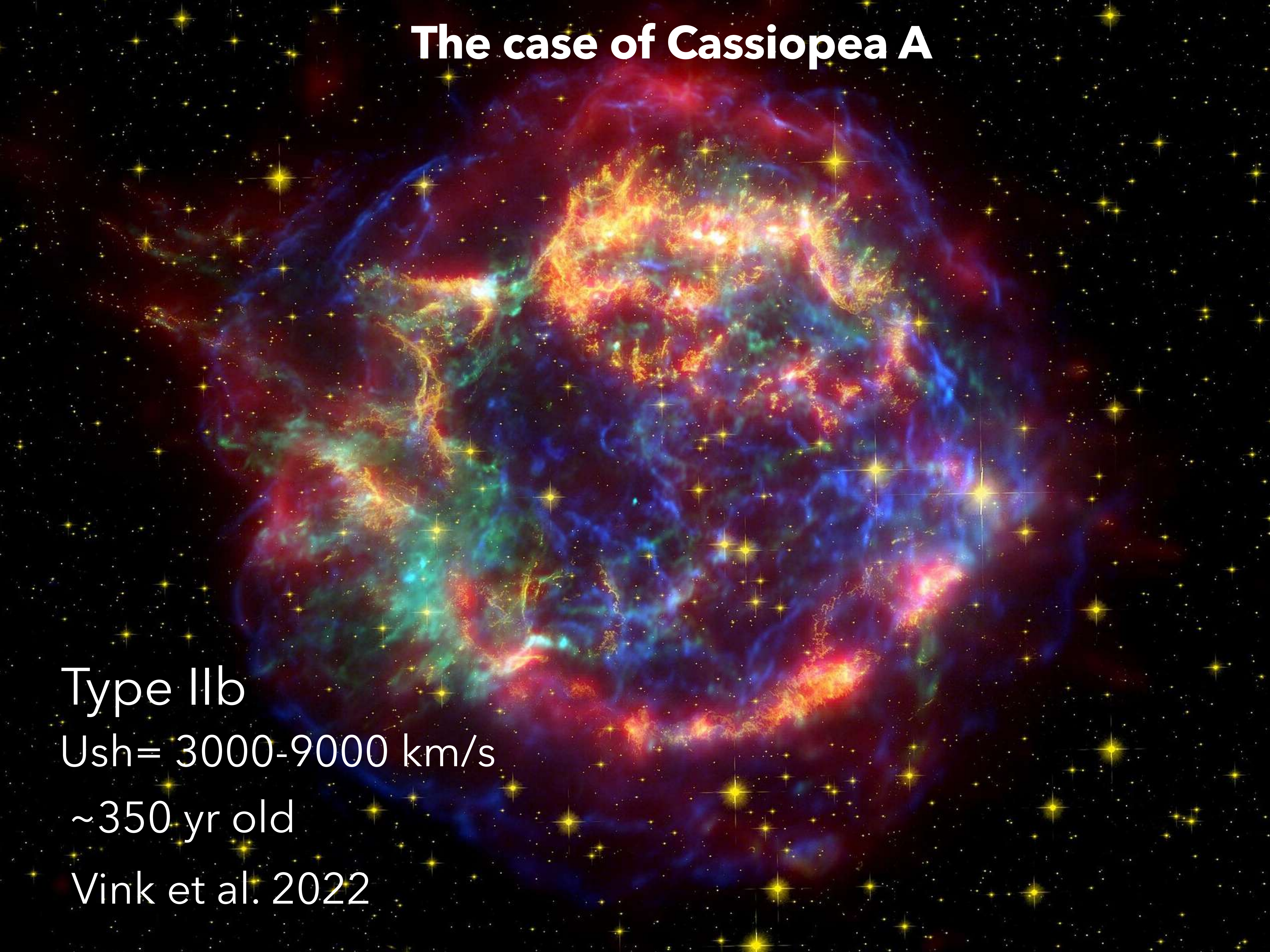
The case of Cas A

The case of G106.3+2.7

The case of Cassiopea A



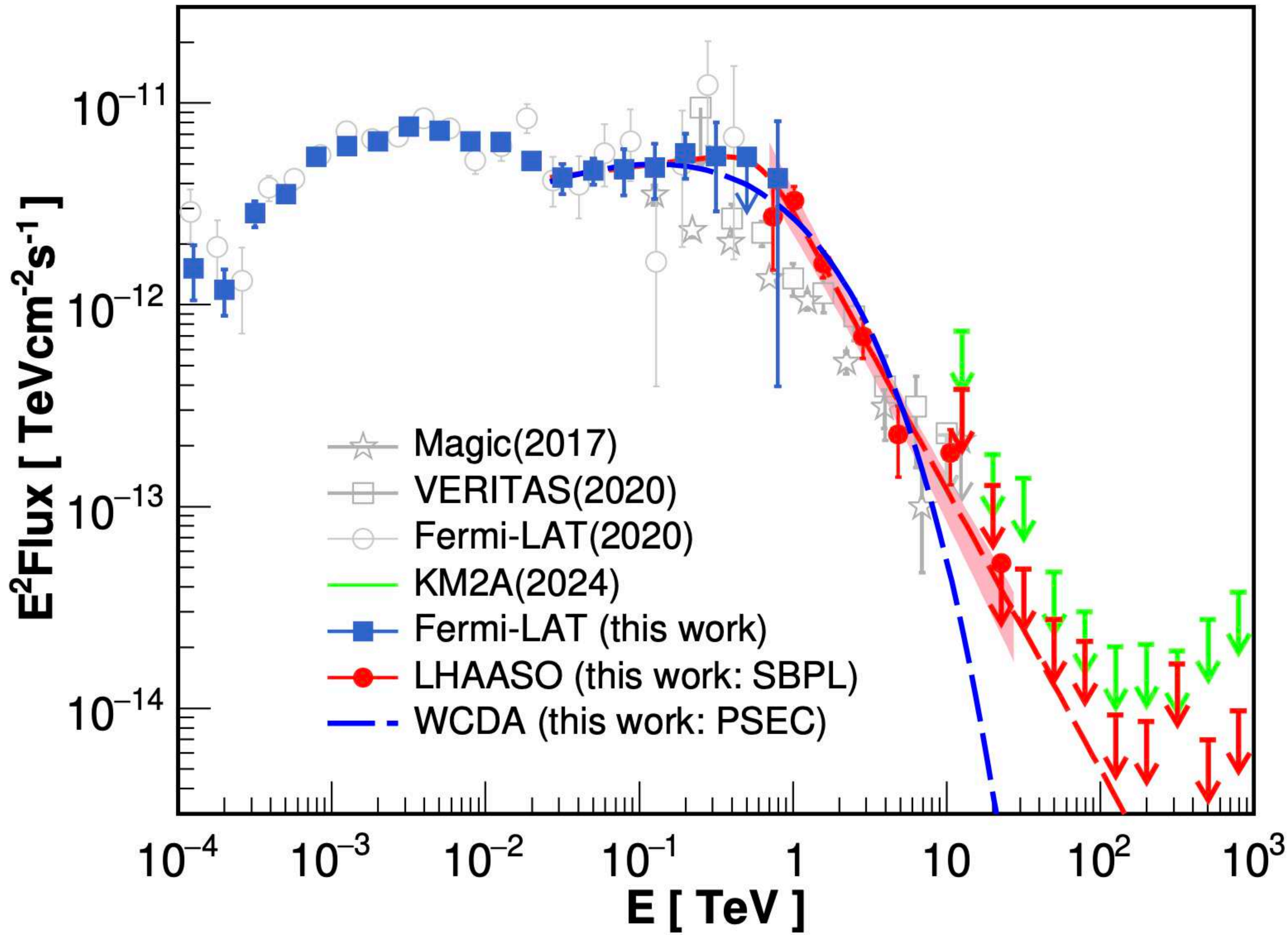
Type IIb

Ush= 3000-9000 km/s

~350 yr old

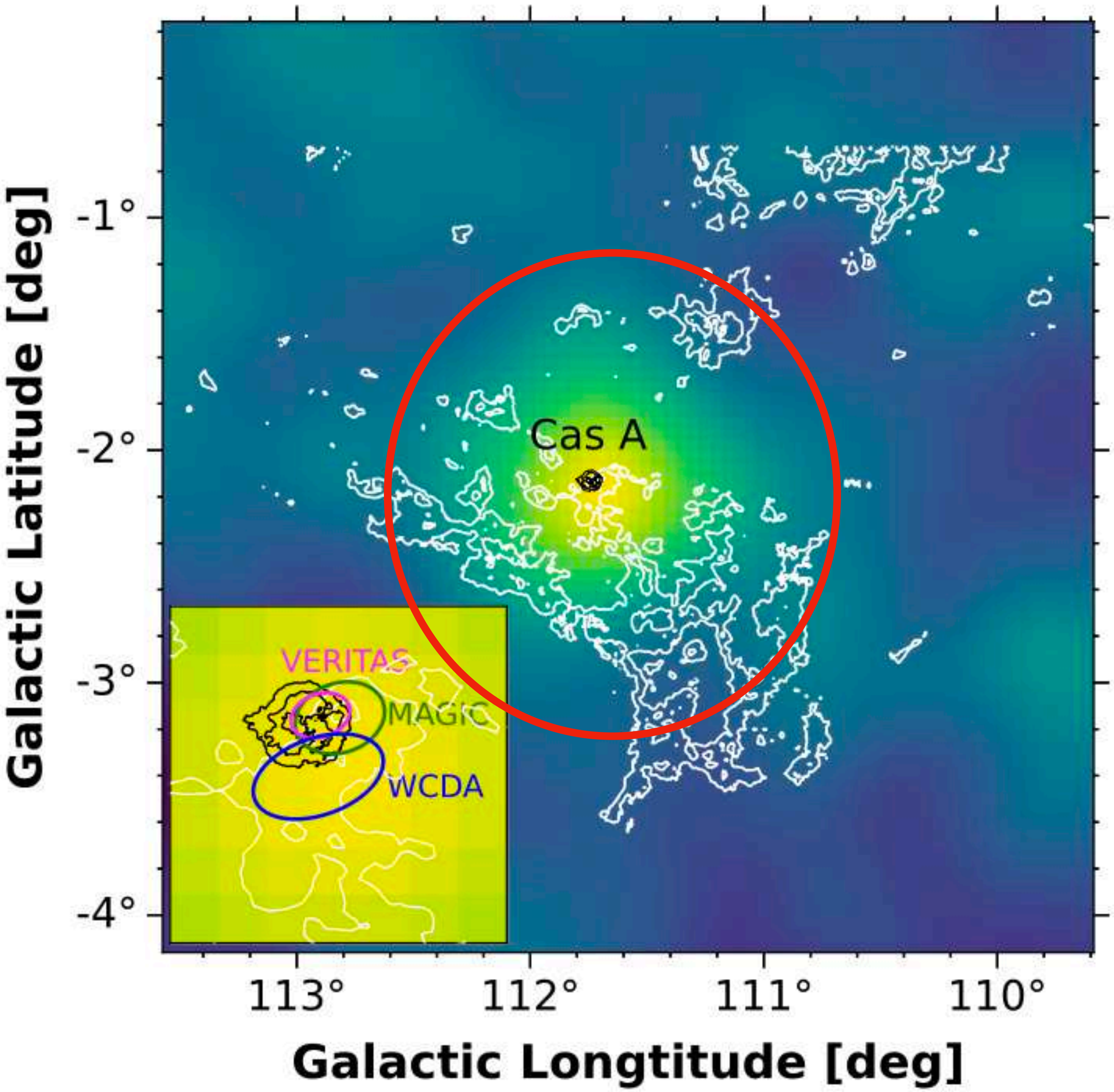
Vink et al. 2022

The case of Cassiopea A



Cao et al. 2025

The case of Cassiopea A



Maximum distance PeV particle diffusing and escaping around SNR:

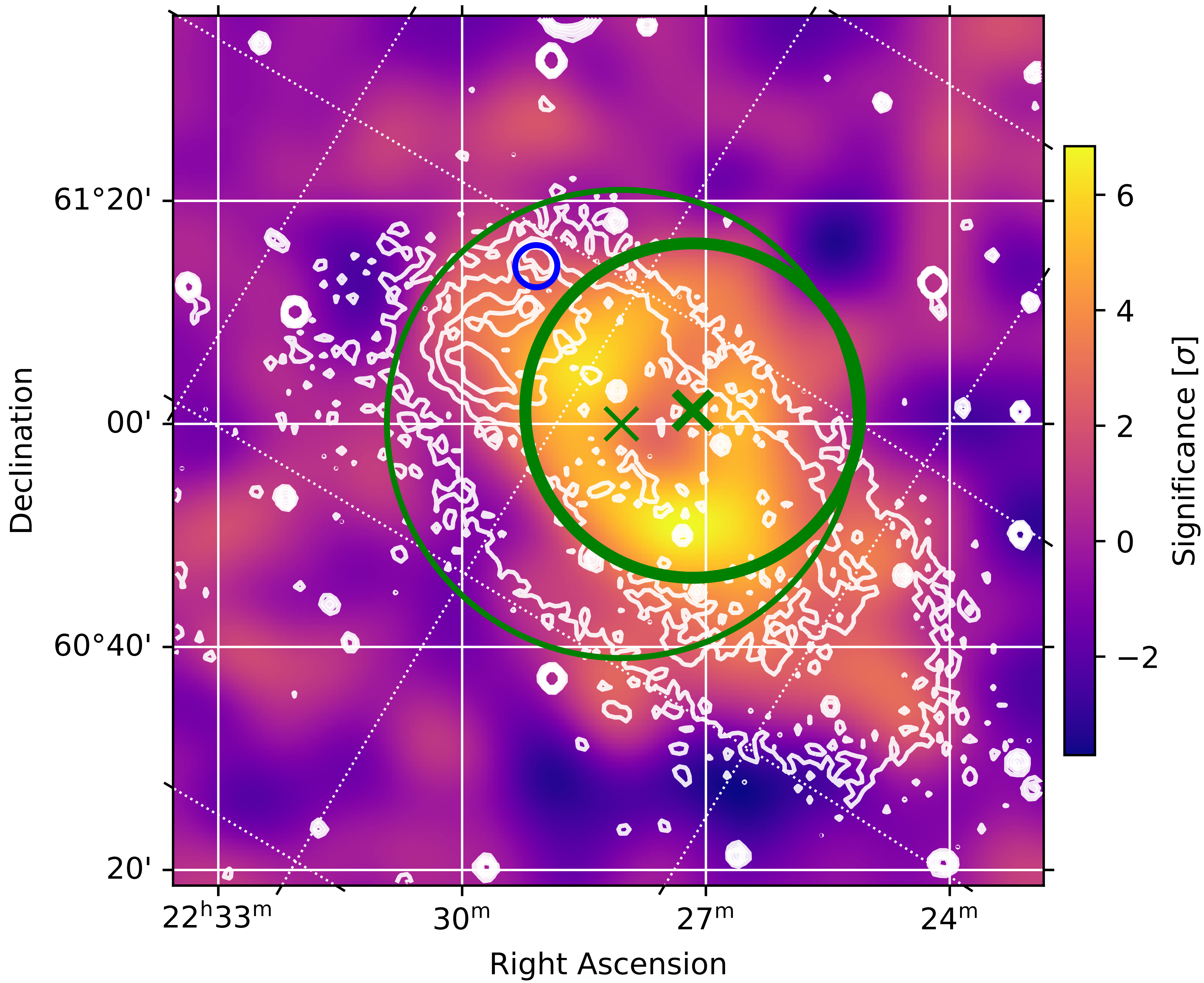
$$\mathrm{dist} \sim 100\mathrm{pc}$$

LHAASO probed 2° (120pc)

All particle content accelerated in the past and escaped already probed by LHAASO

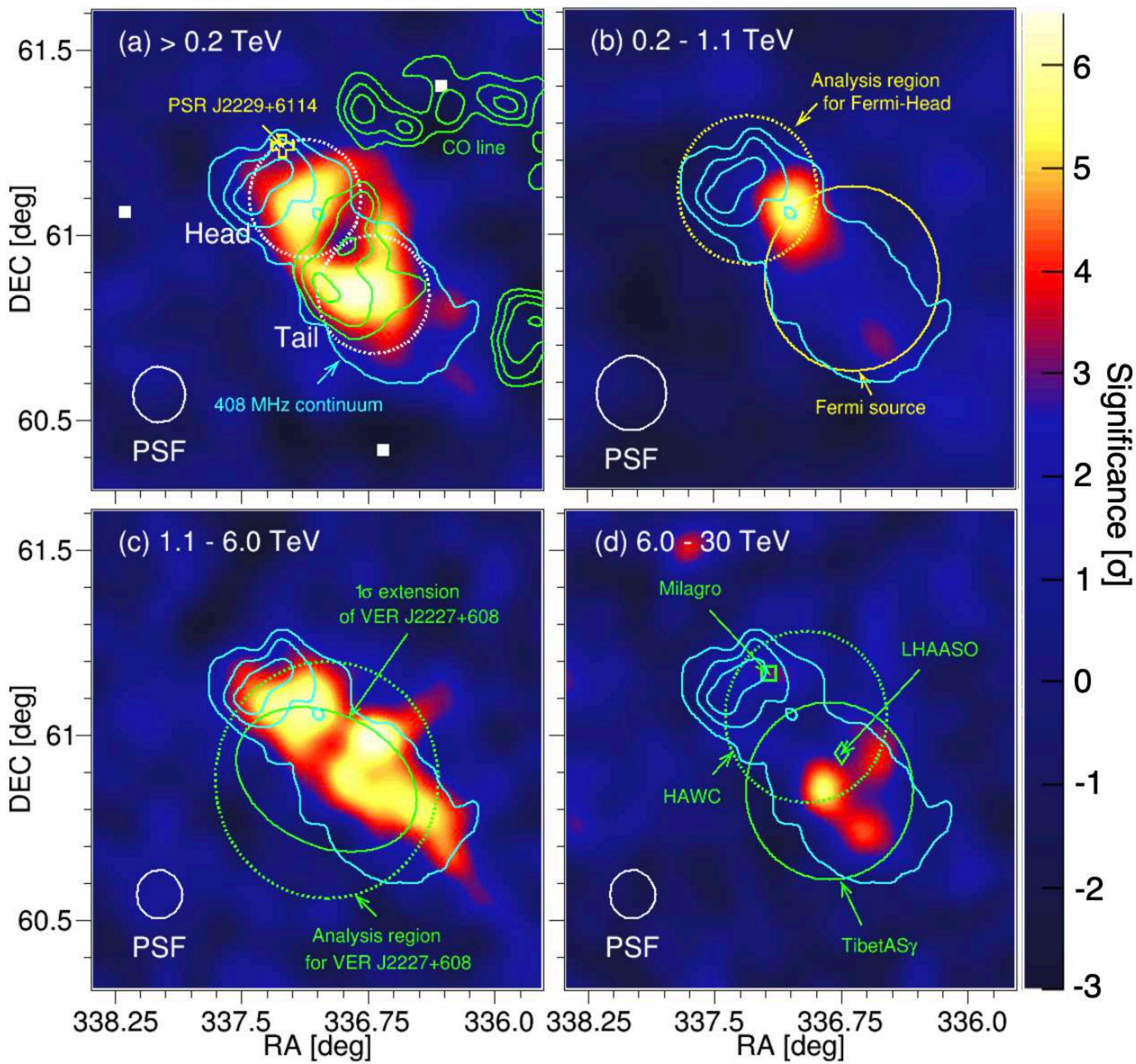
Cao et al. 2025
Blasi 2025

The case of G106.3+2.7

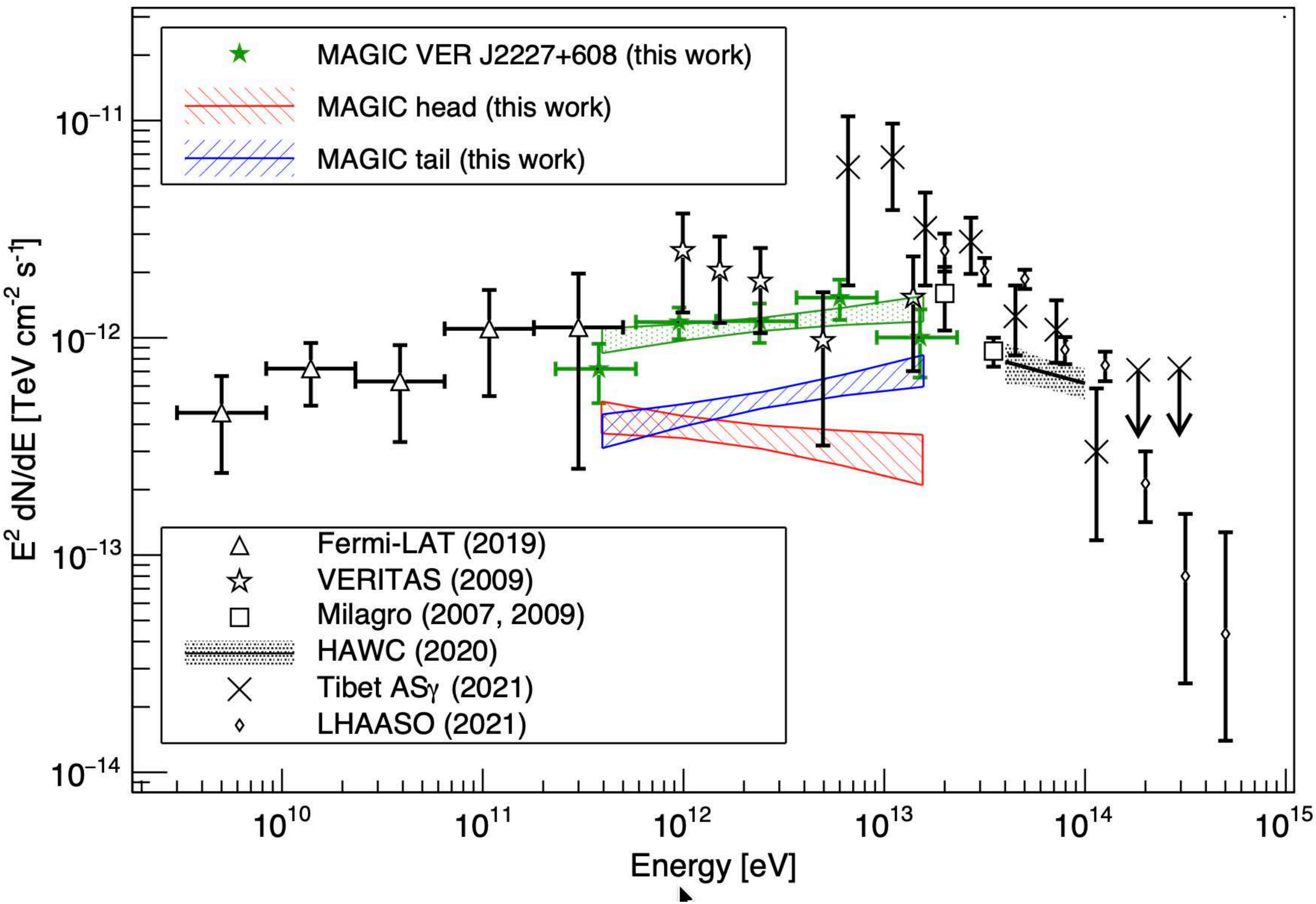


The case of G106.3+2.7

MAGIC Collaboration et al.: MAGIC observations in the vicinity of SNR G106.3+2.7

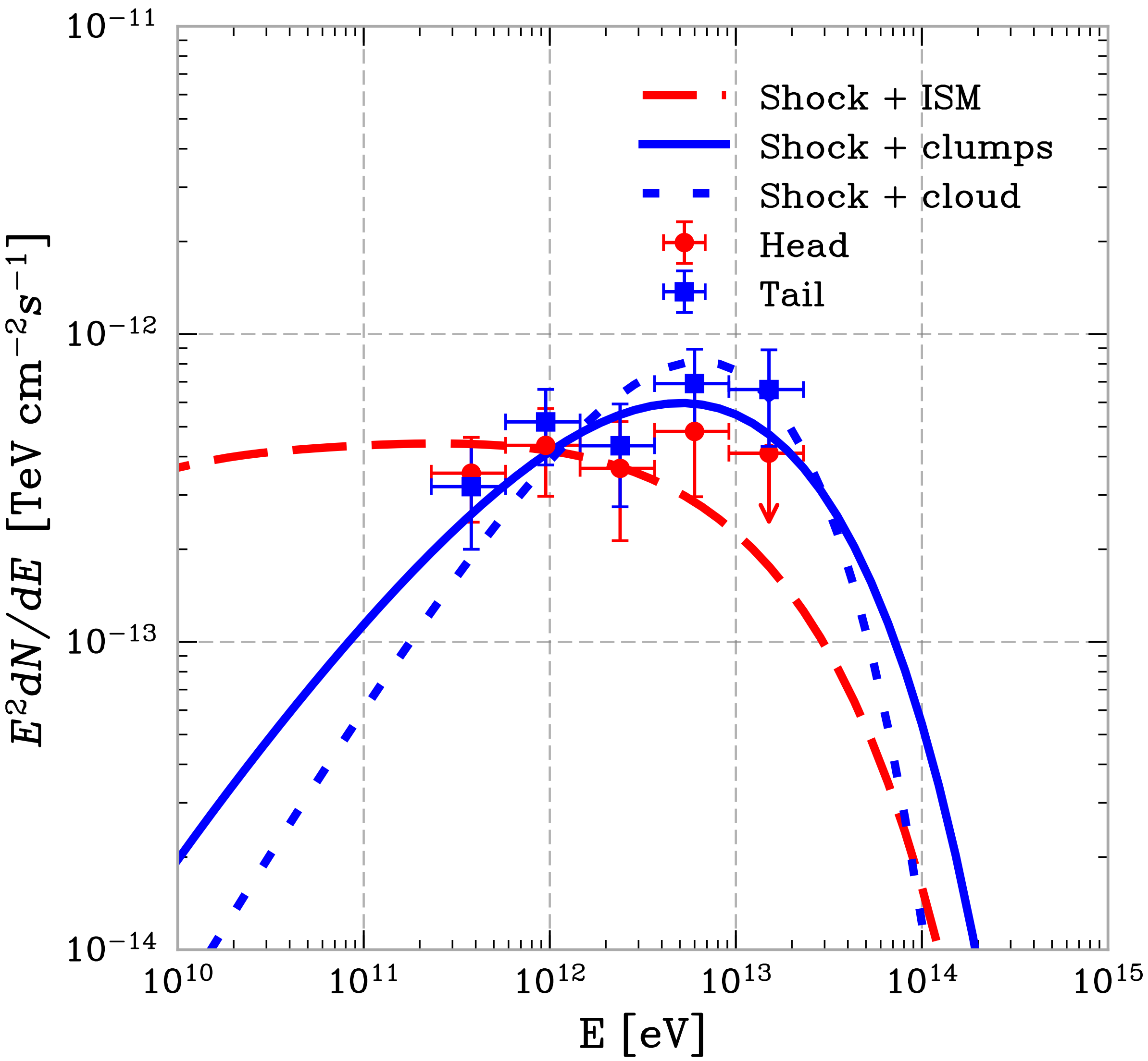


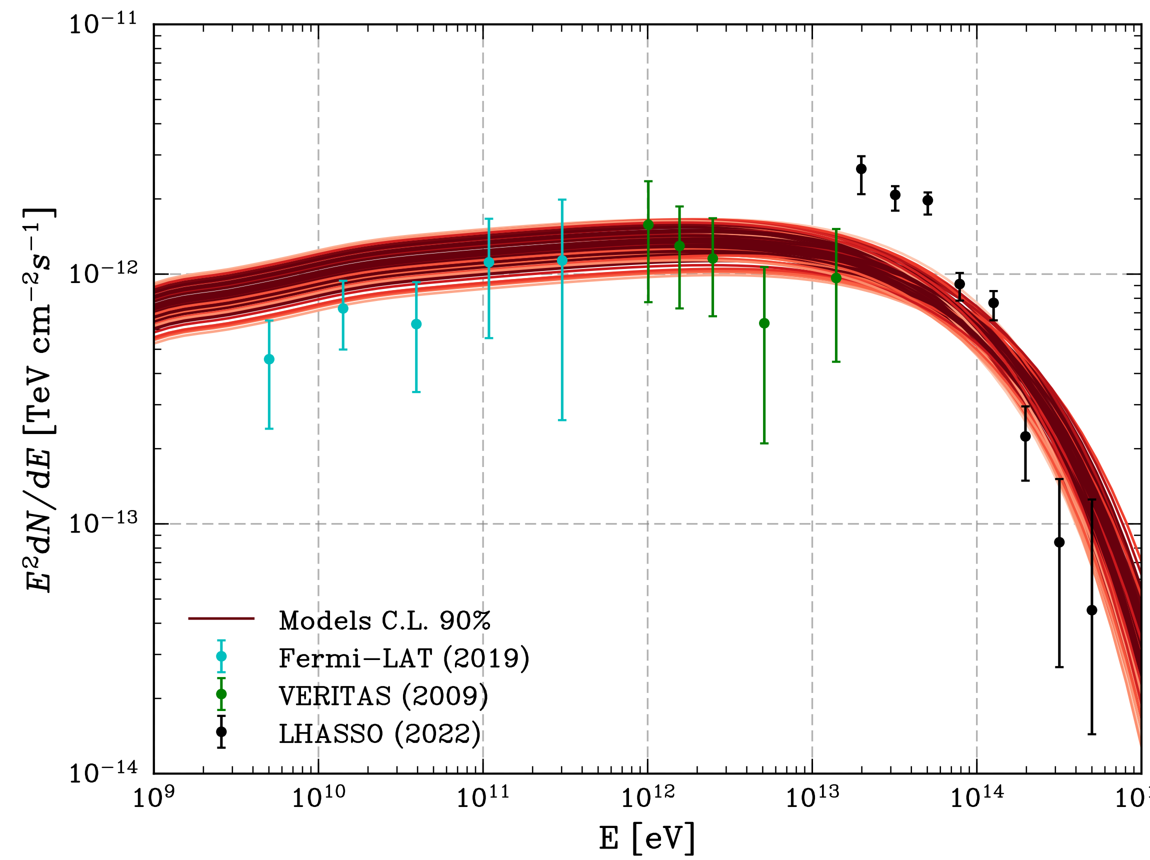
The case of G106.3+2.7



MAGIC 2022

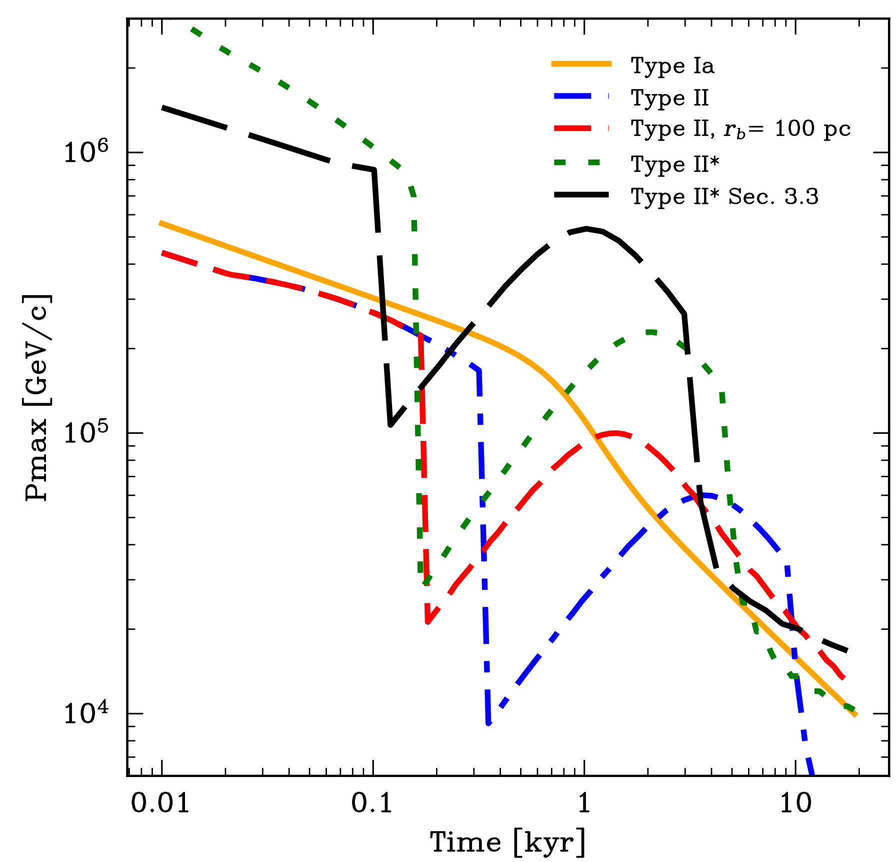
The case of G106.3+2.7





TeV emission -> ok with SNR

100 TeV emission -> need for very usual SNR



Recent LHAASO observations: gamma Cygni (G78.2+2.1) and G150.3+4.5

Ultra-high-energy γ-ray imprints from PeV particles accelerated by supernova remnants

Authors and affiliations appear at the end of the paper.

The quest for the origin of cosmic ray (CRs) is a fundamental issue in astrophysics (*1, 2*). Shocks of supernova remnants (SNRs) have been considered as the dominant contributors to Galactic CRs below the spectral knee near ~ 3 petaelectronvolt (PeV). Whether SNRs are efficient accelerators of particles beyond PeV energies has long been debated (*3, 4*). Here we report observations of very-high-energy γ-ray emission up to hundreds of TeV from two middle age shell-type SNRs, G150.3+4.5 and γ-Cygni, with the Large High Altitude Air Shower Observatory (LHAASO). Two (or three) distinct morphological/spectral components with convex spectral shapes are observed in both sources, with the low-energy one being more extended than the high-energy one. The likely association of the high-energy component with molecular clouds at similar distances, and the weakness/absence of pulsar wind nebulae (PWNe) inside these SNRs (*5, 6*) clearly indicate for the first time that the highest energy emission is produced by collision of hadronic CRs up to PeV energies with the clouds. These results are compatible with the classic model prediction that PeV particles accelerated near the end of the free expansion phase of SNR evolution can illuminate nearby molecular clouds (MCs) to produce strong γ-ray emission (*7, 8*).

Recent LHAASO observations:
gamma Cygni (G78.2+2.1) and G150.3+4.5

Table 1: Fitting locations and 39% containment radii of multiple source components of the two SNRs.

Source	Component	GL (°)	GB (°)	R_{39} (°)	TS
G150.3+4.5	A	150.41 ± 0.09	4.69 ± 0.10	1.26 ± 0.07	466
	B	150.96 ± 0.04	3.83 ± 0.04	0.22 ± 0.04	172
γ-Cygni	A	78.11 ± 0.07	2.23 ± 0.05	0.59 ± 0.03	632
	B	78.13 ± 0.05	2.24 ± 0.03	0.26 ± 0.02	499
	C	78.27 ± 0.10	2.66 ± 0.05	Point Source	182

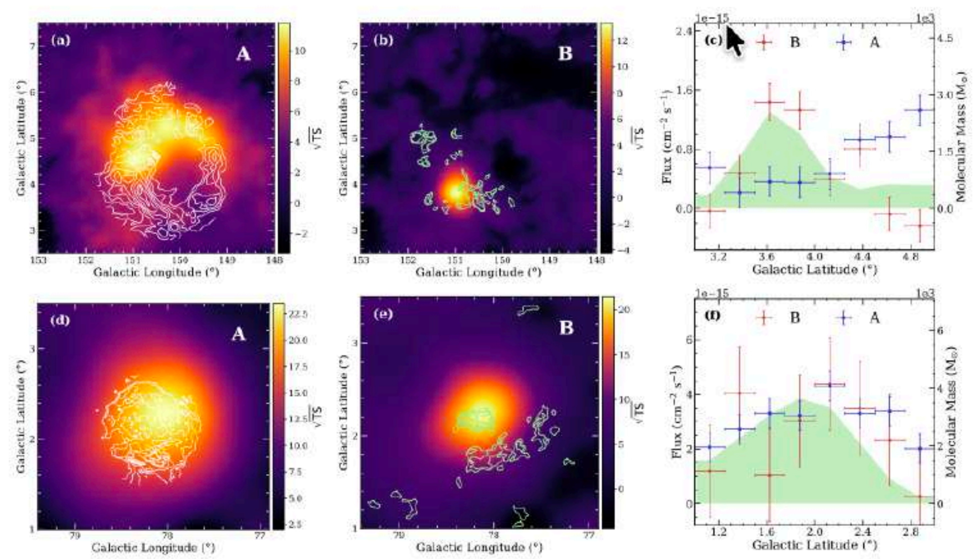
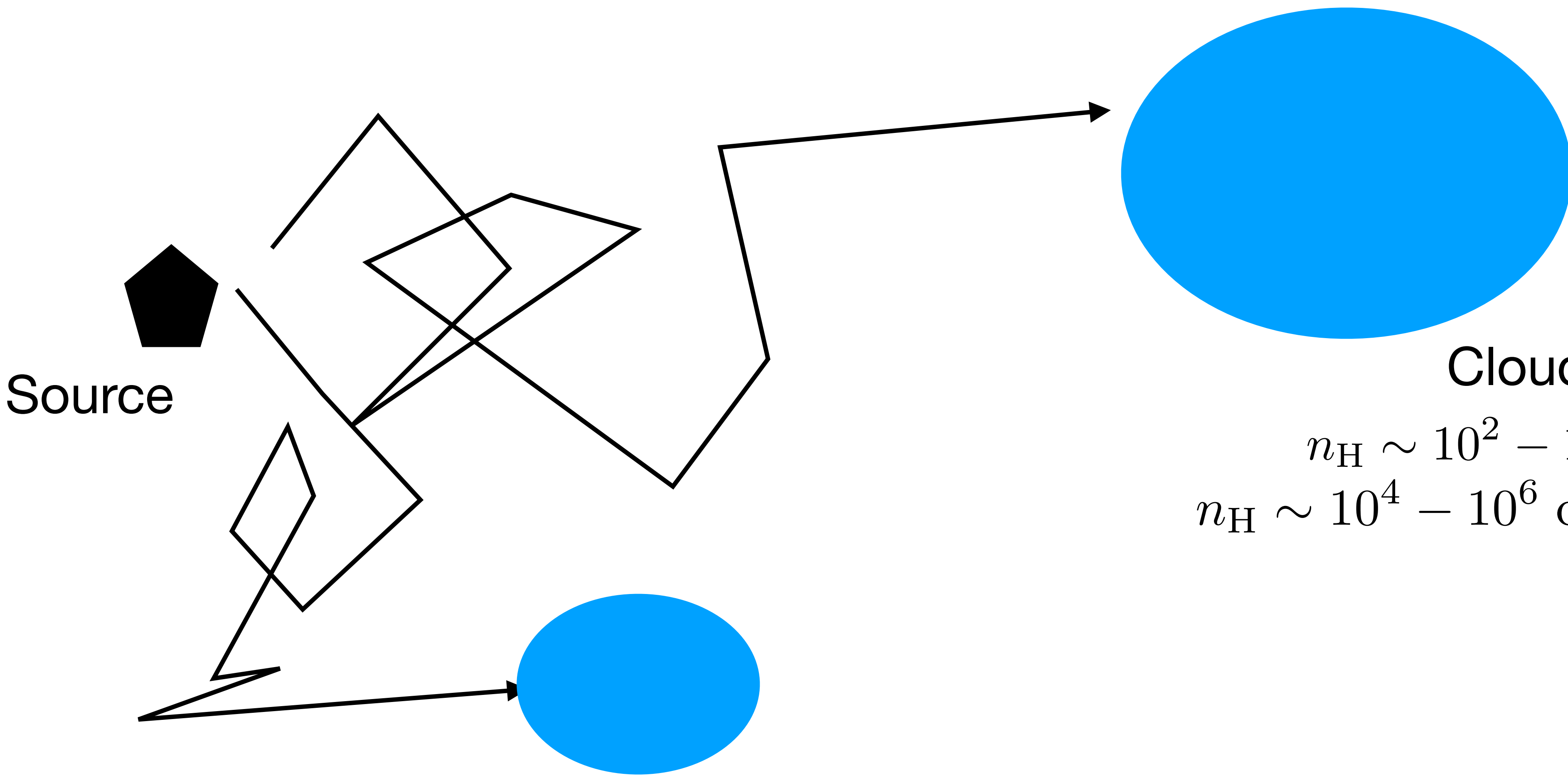


Figure 2: Significance maps of gamma-ray emission components for G150.3+4.5 (top) and γ-Cygni (bottom). Panels (a, b) and (d, e) correspond to components A and B, respectively. Radio continuum contours (white) (*15, 20*) or CO molecular gas contours (green) (*16, 26*) are overlaid. CO emission is integrated over velocities of -9 to -6 km s^{-1} for G150.3+4.5 (*16*) and -17 to -11 km s^{-1} for γ-Cygni (*26*). Panels (c, f) present 1D latitude profiles of integrated fluxes (blue: A; red: B) and molecular mass (0.25° belts) over longitudes 149.5°–151.5° (G150.3+4.5) and 77°–79° (γ-Cygni); fluxes of A are rescaled by 3×10^{-3} and 10^{-2}, respectively.

Hints for hadronic gamma rays up to PeV from clouds around middle age SNRs

Using clouds around sources



$$n_{\rm H} \sim 10^2 - 10^3 \ {\rm cm}^{-3}$$
$$n_{\rm H} \sim 10^4 - 10^6 \ {\rm cm}^{-3} (\text{dense cores})$$

Target-> hadronic gamma rays. Clouds can be used to probe escape and diffusion

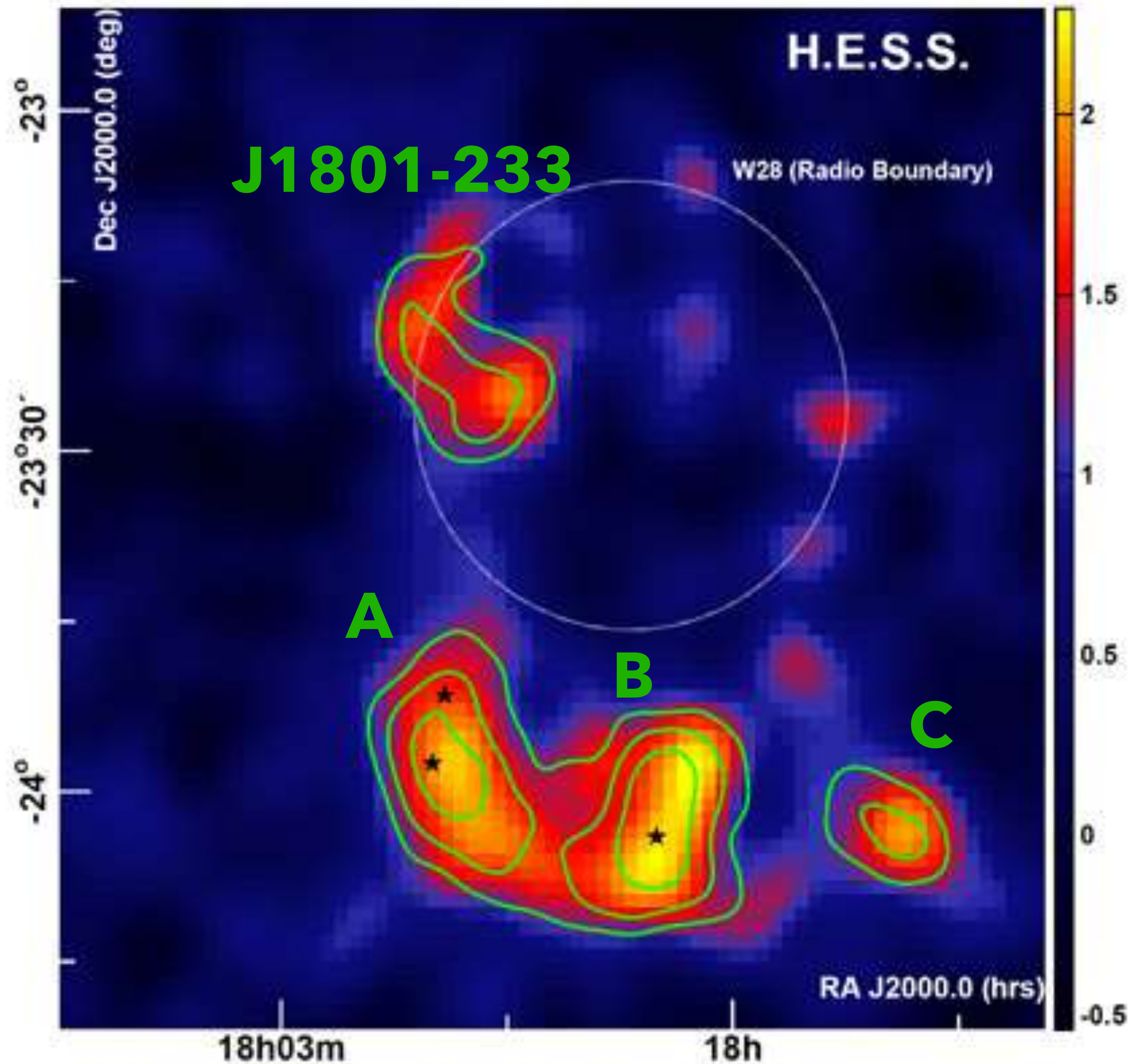
$$D(10{\rm GeV}) \approx 10^{28} - 3 \times 10^{28} {\rm cm}^2 {\rm s}^{-1}$$

Case of W28:

$$D_{\rm local} \approx 10^{26} - \times 10^{27} {\rm cm}^2 {\rm s}^{-1}$$

CR driven turbulence reducing diffusion?

Aharonian& Atoyan 1996, Gabici& Aharonian 2007, Gabici et al. 2009, Celli et al. 2018


H.E.S.S.
J1801-233
W28 (Radio Boundary)
A
B
C
Dec J2000.0 (deg)
-23°
-23°30'
-24°
RA J2000.0 (hrs)
18h03m
18h
2
1.5
1
0.5
0
-0.5

Gamma rays from Molecular clouds illuminated by CRs

t = 32000 yr

100 GeV

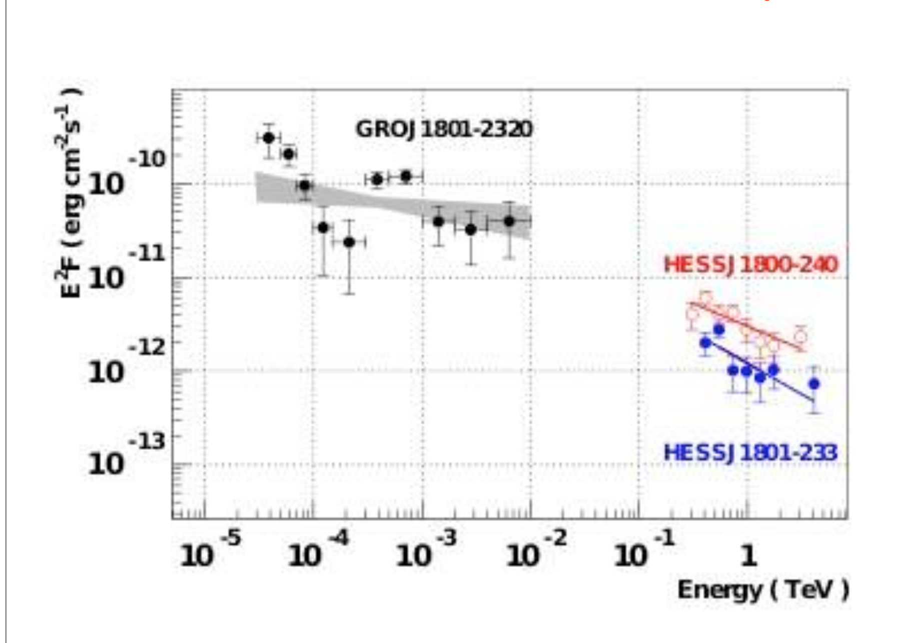
10 TeV

$$d = 1\ kpc$$
$$d_{snr/cl} = 100\ pc$$
$$M_{cl} = 10^4 M_\odot$$
$$D_{PeV} = 3\ 10^{29} cm^2/s$$

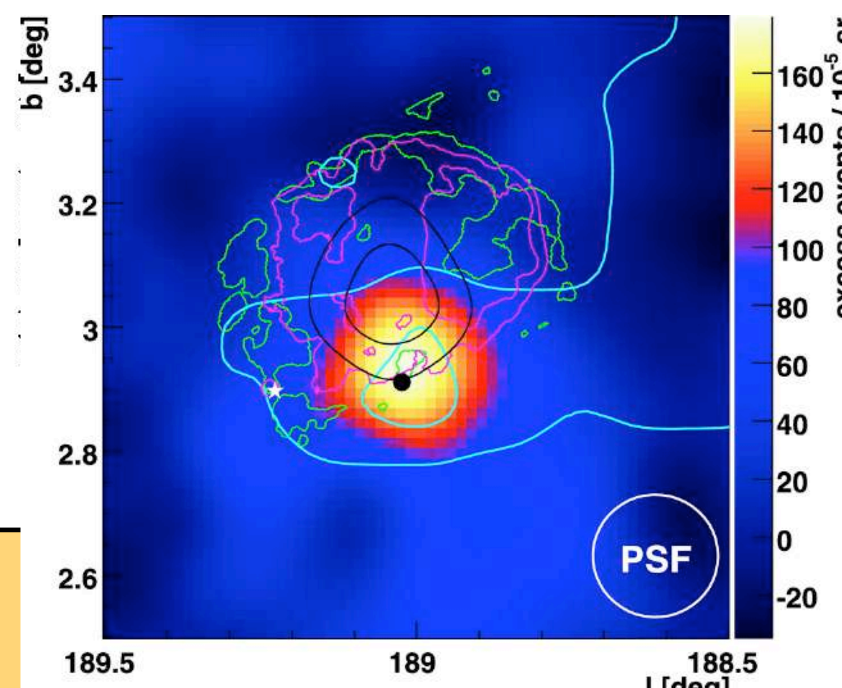
SNR

Cloud

HESS: clouds in W28 field



MAGIC: IC443 (see Torres2008)



Gabici&Aharonian(2007)

Gamma rays from Molecular clouds illuminated by CRs

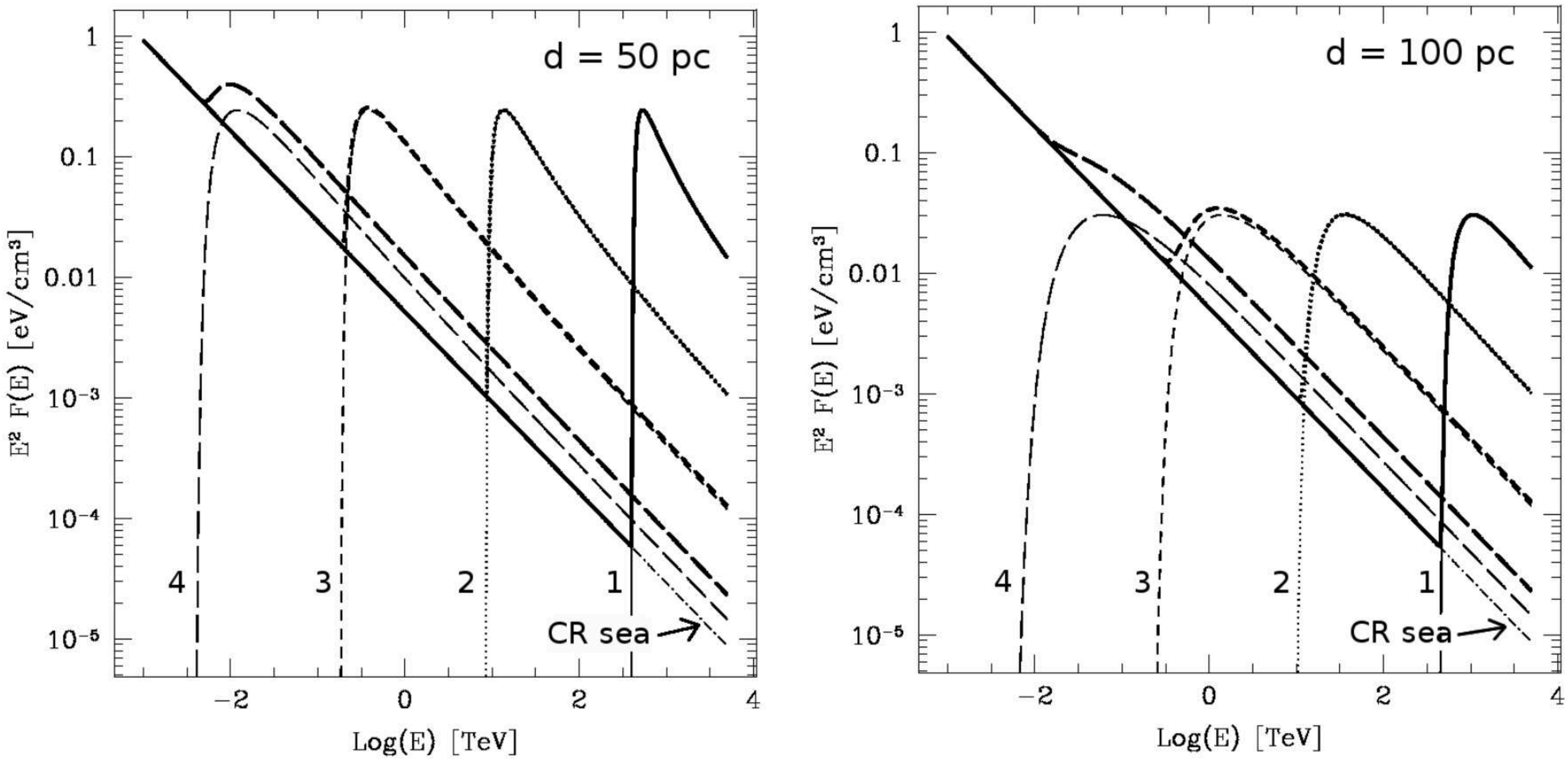
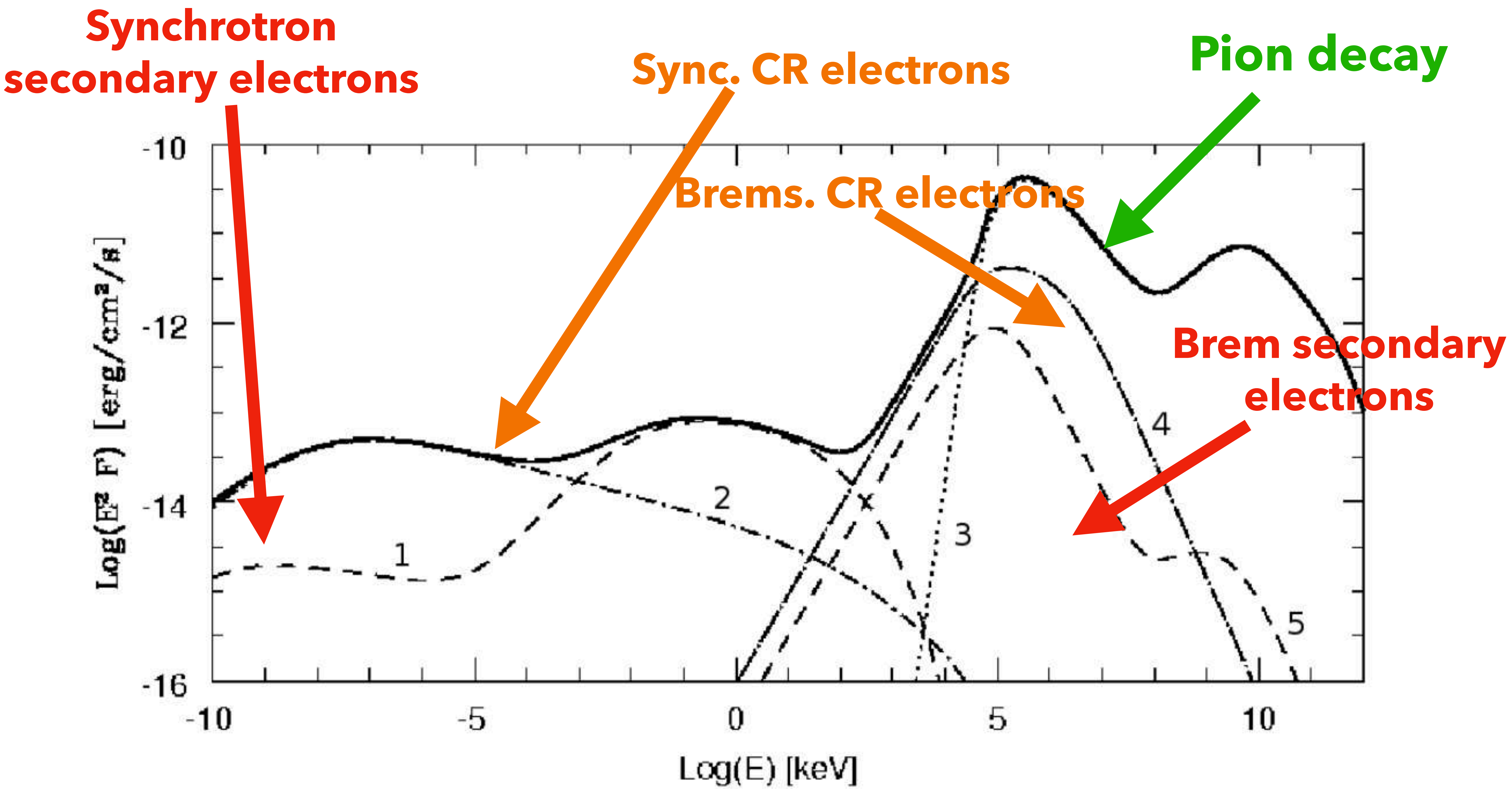


Figure 1. Spectrum of CRs at the location of the molecular cloud. The cloud is located at 50 pc (left) and 100 pc (right panel) from a SNR. The thin dot–dashed line shows the Galactic CR spectrum, while the thin solid (curve 1), dotted (2), short–dashed (3) and long-dashed (4) lines represent the spectrum of CRs coming from the SNR for 500, 2000, 8000 and 32000 years after the supernova explosion, respectively. The thick lines show the total CR spectrum at the cloud location.

Gamma rays from Molecular clouds illuminated by CRs



Secondaries play a major role to shape the MWL signal!

Figure 3. Broad band spectrum for a molecular cloud of mass $10^5 M_\odot$, radius 20 pc, density ~ 120 cm^{-3}, magnetic field 20μG. The molecular cloud is at 100 pc from a SNR that exploded 2000 yr ago. The distance of the cloud is 1 kpc. The dotted line shows the emission from π^0–decay (curve 3), the dot-dashed lines represent the synchrotron (curve 2) and Bremsstrahlung (curve 4) emission from background CR electrons that penetrate the molecular cloud and the dashed lines the synchrotron (curve 1) and Bremsstrahlung (curve 5) emission from secondary electrons.

Looking for Pevatrons with secondary electrons?

$$p + p \to \pi^0 + \pi^+ + \pi^- + \cdots$$

$$\pi^0 \to \gamma + \gamma$$

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

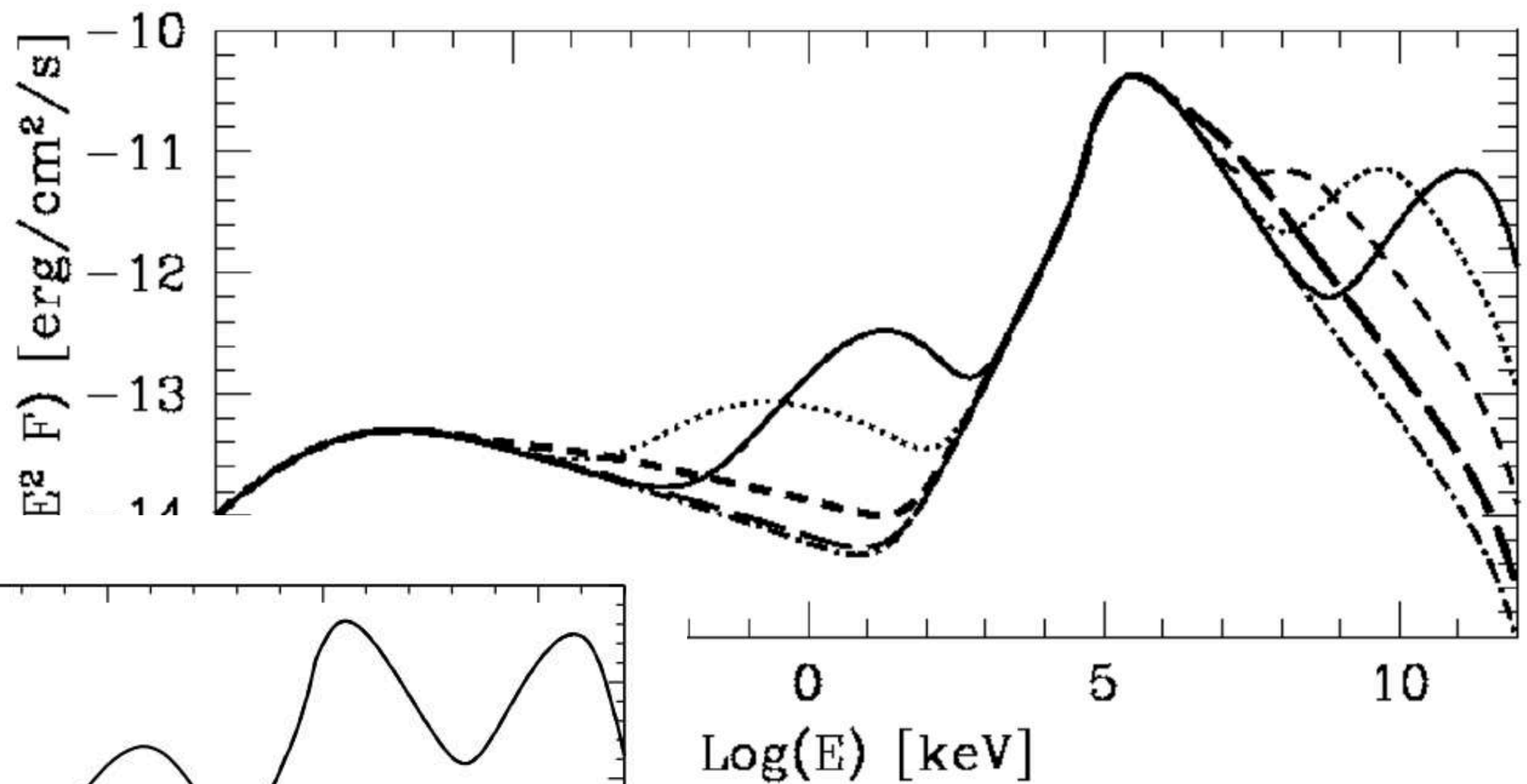
$$\mu^\pm \to e^\pm + \nu_e + \nu_\mu$$

$$\boxed{\epsilon_{\rm syn} \sim 20 \left(\frac{B}{30\,\mu{\rm G}}\right)\left(\frac{E}{100\,{\rm TeV}}\right)^2 {\rm keV}}$$

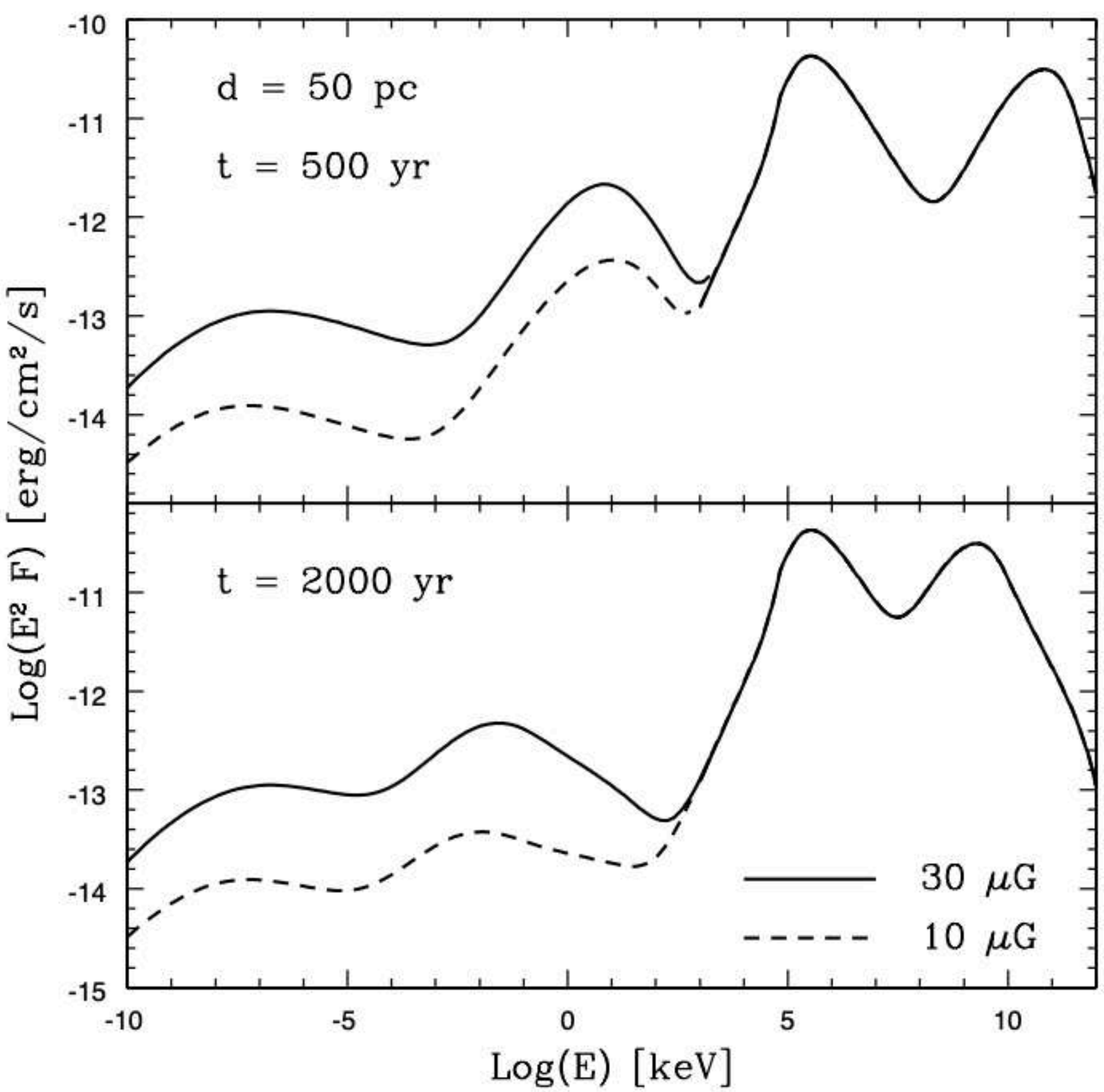
Detection of pevatrons in the X-ray domain?

Gabici et al. 2009

Gamma rays from Molecular clouds illuminated by CRs



ɔr the same giant molecular cloud considered in Fig. 3. The solid, dotted,
a time 500, 2000, 8000 and 32000 years after the explosion. The dot–dashed
R in its proximity.



ɪf the MWL signal!

Very elegant, but still senstitive to the magnetic field

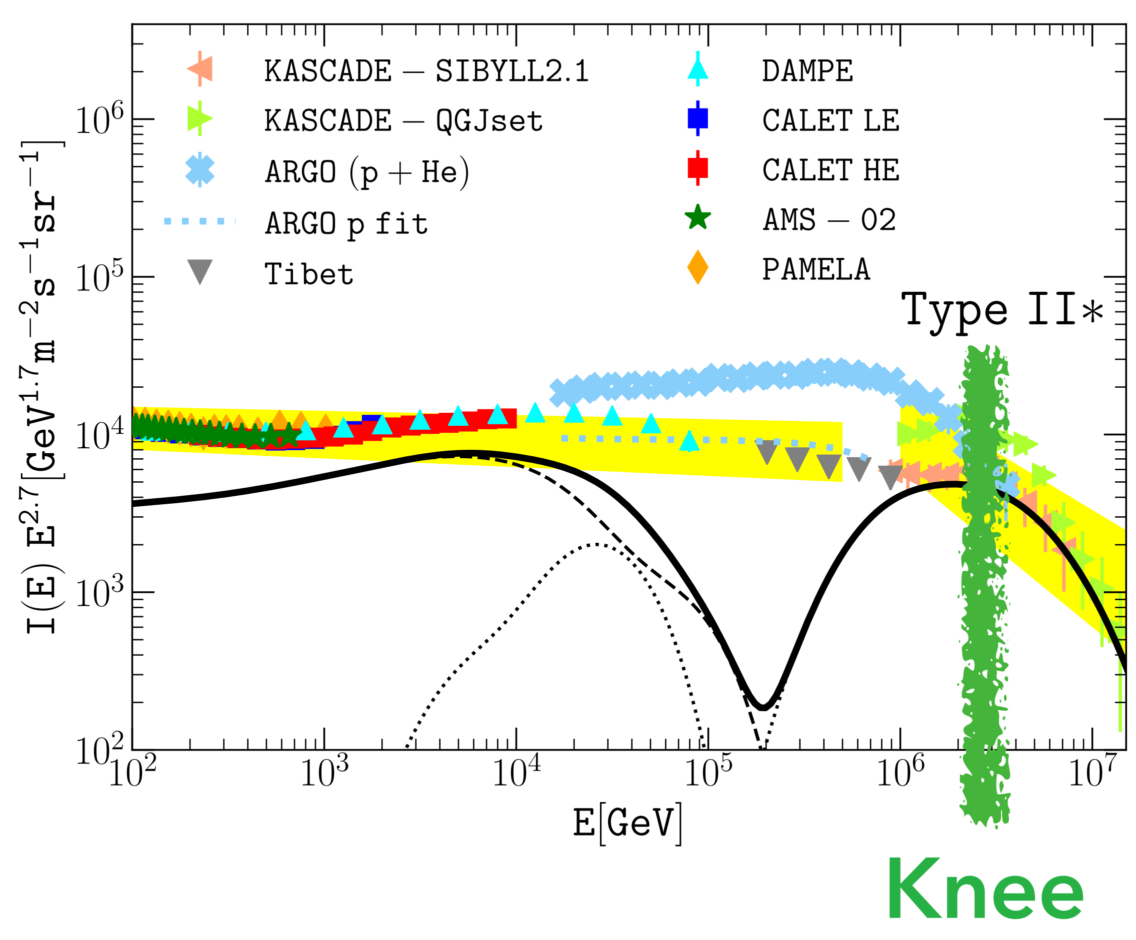
Gabici et al. 2009

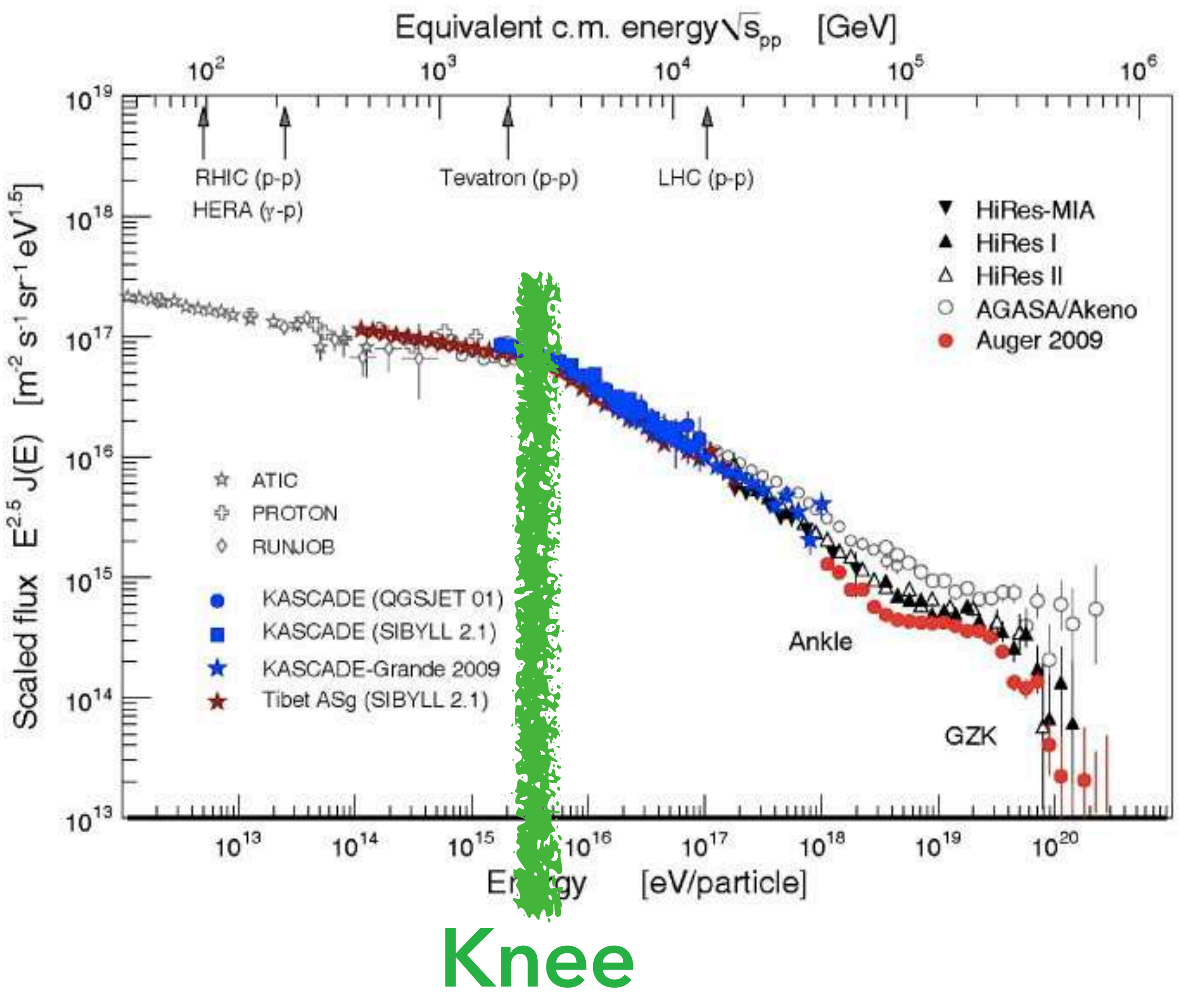
The case of supernova remnants

1. Possible to account for PeV protons with rare unusual SNRs (1-5% 3/century, hard to catch!) - specific environments and diversity of SNe investigated in several works (Gabici et al. 2019, Kamijina& Ohira 2024, Das et al. 2024, Vieu et al. 2023, Bykov et al. 2024 + many more, (Sushsch et al. 2025), SNe close to stellar clusters (Vieu&Reville 2024)?)

2. Issues above the knee: Exponential cut-off (expected from escape of protons

3. Issues below the knee





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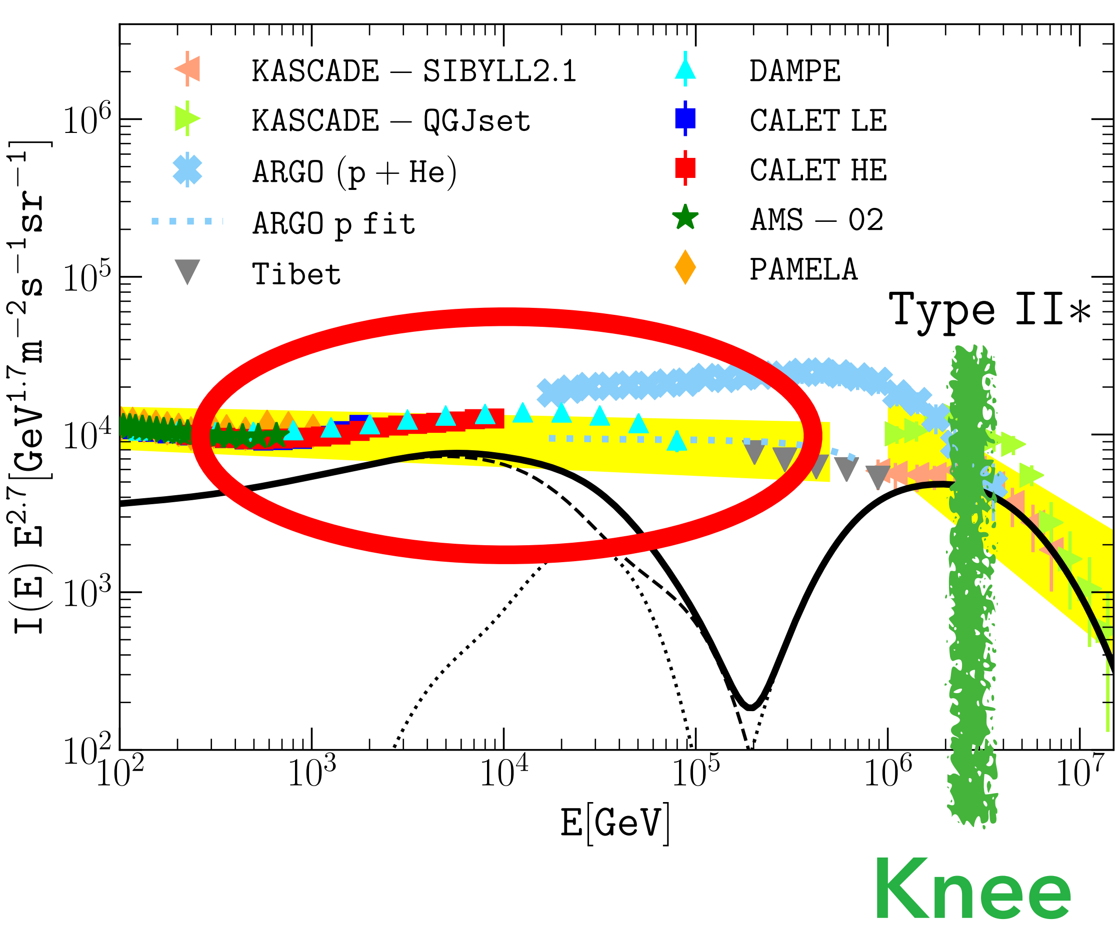

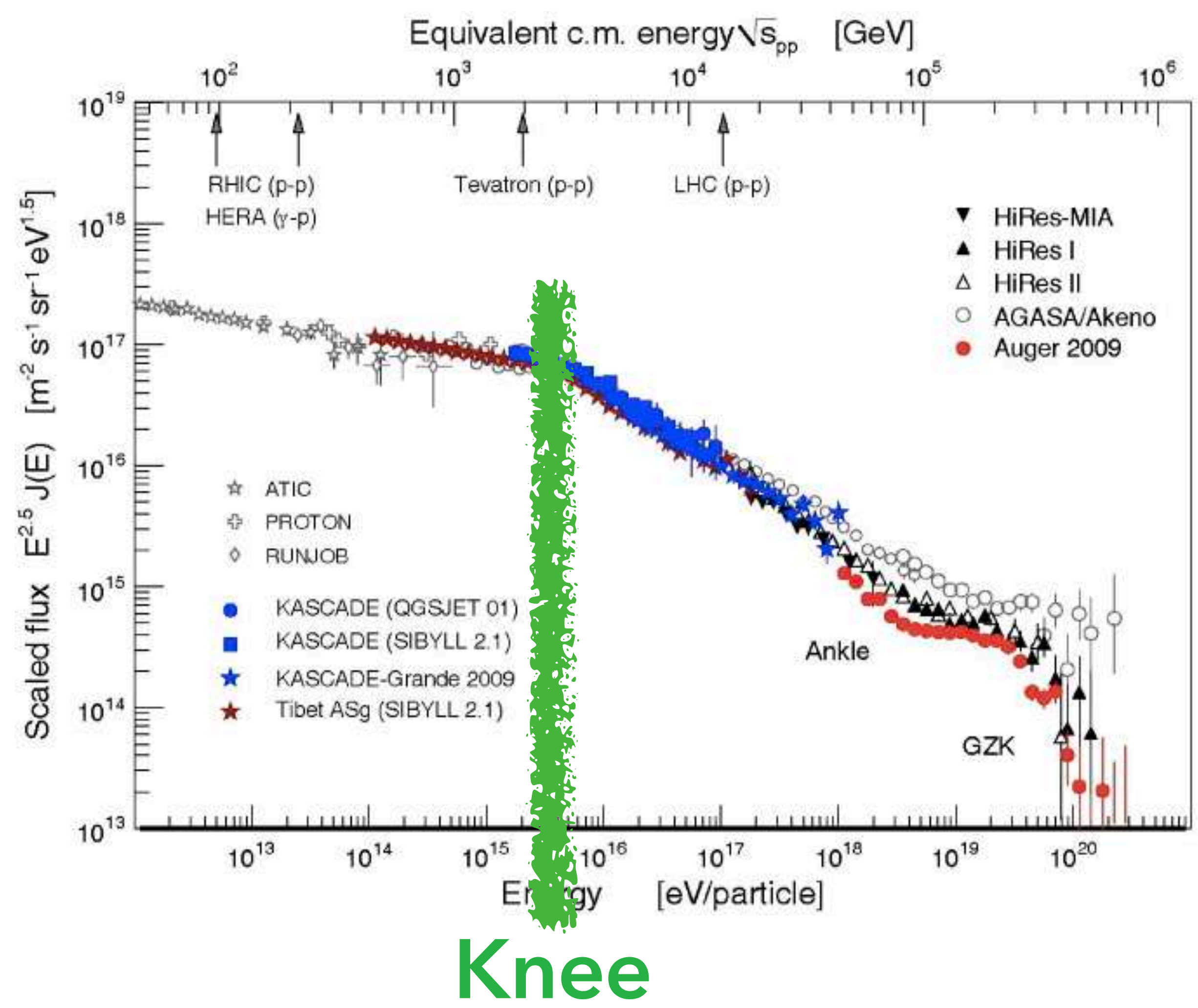

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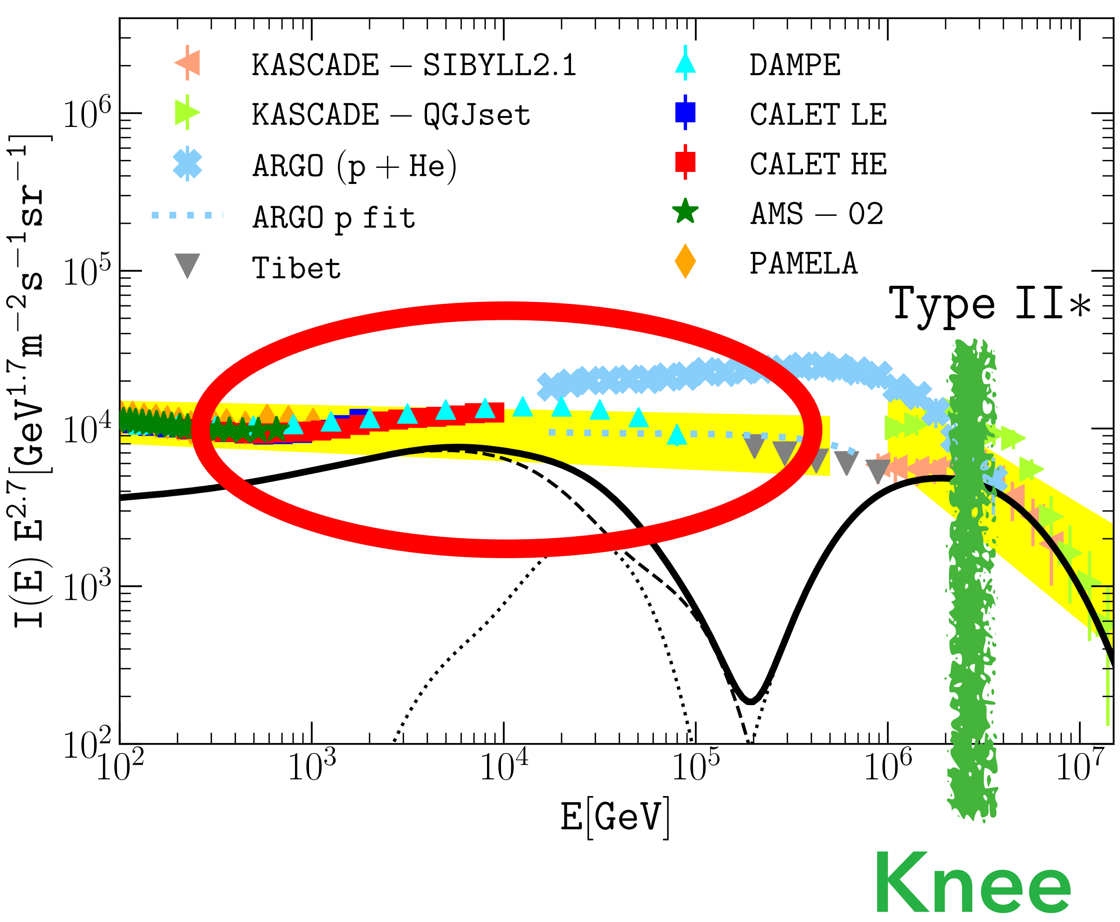

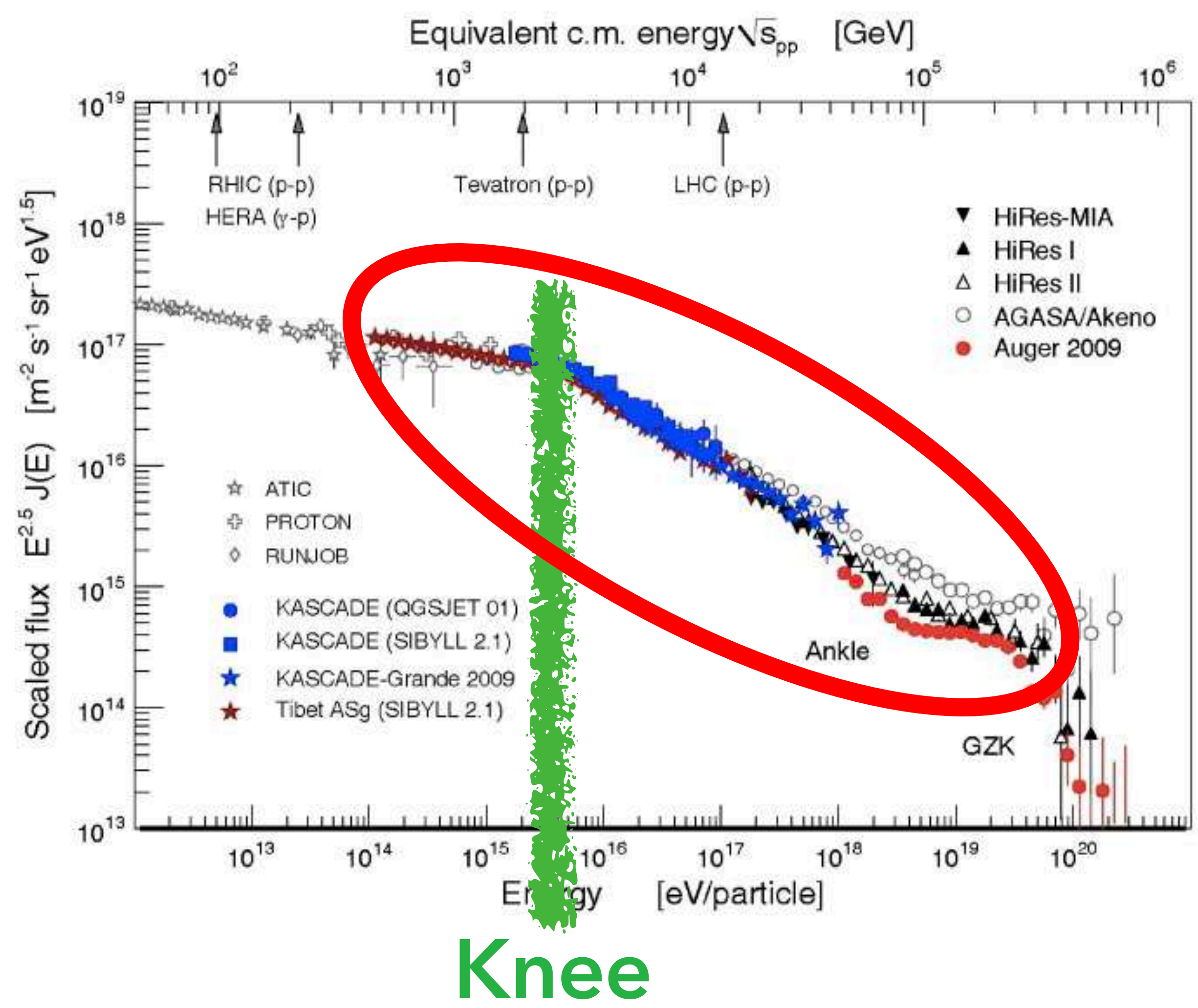

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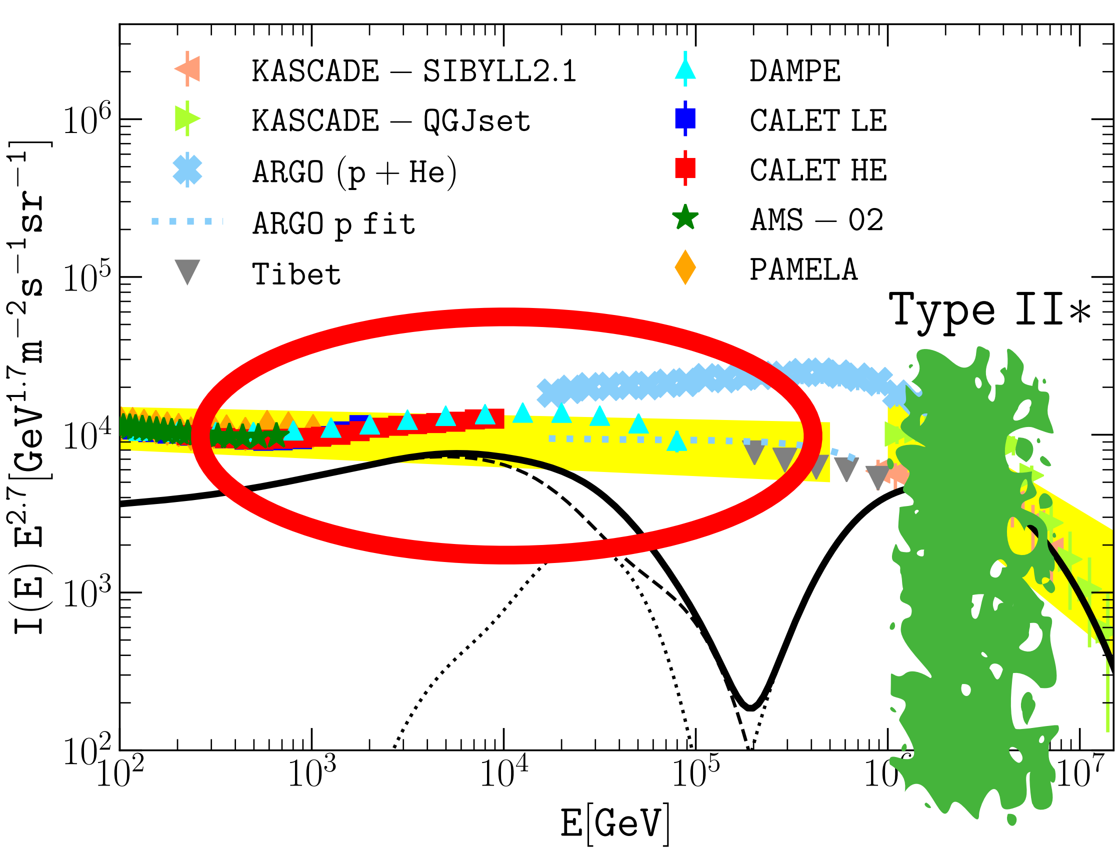
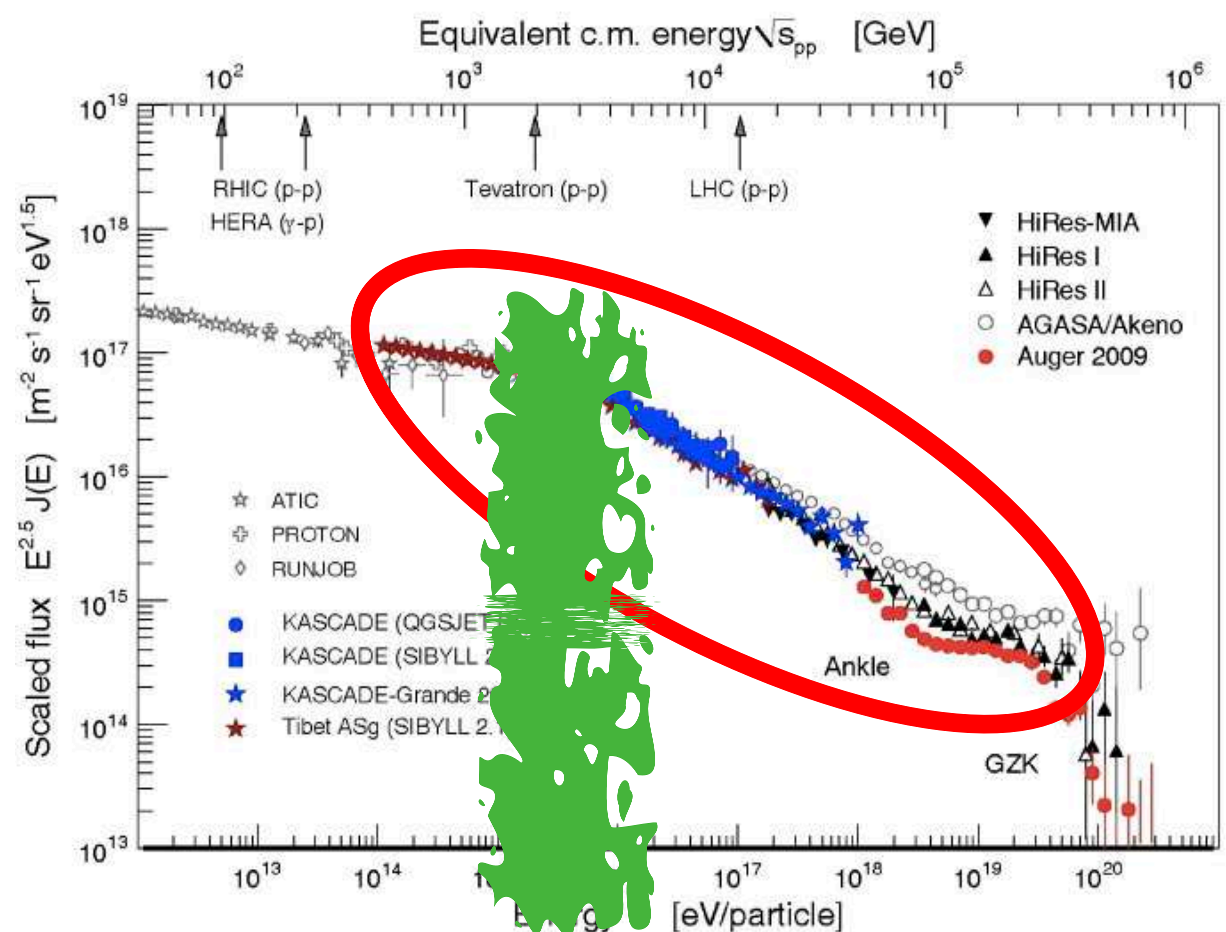
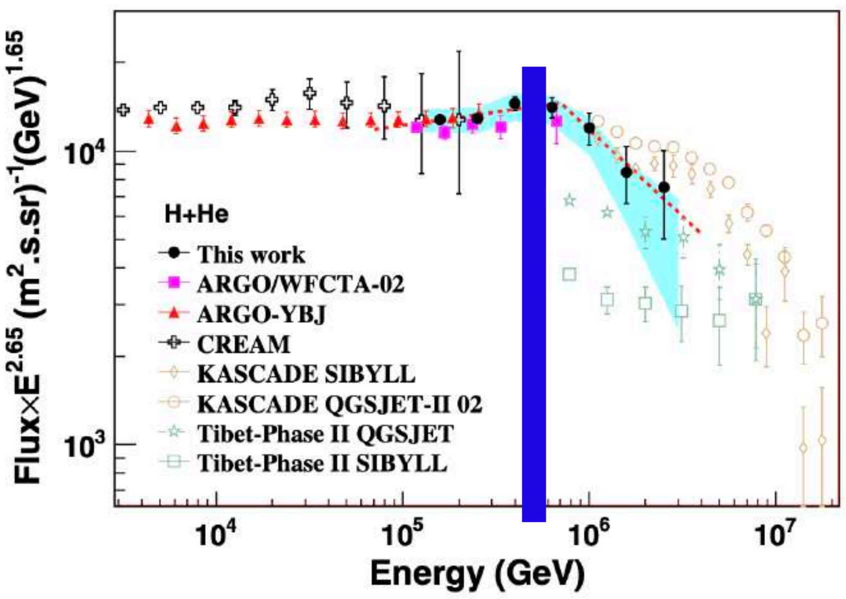


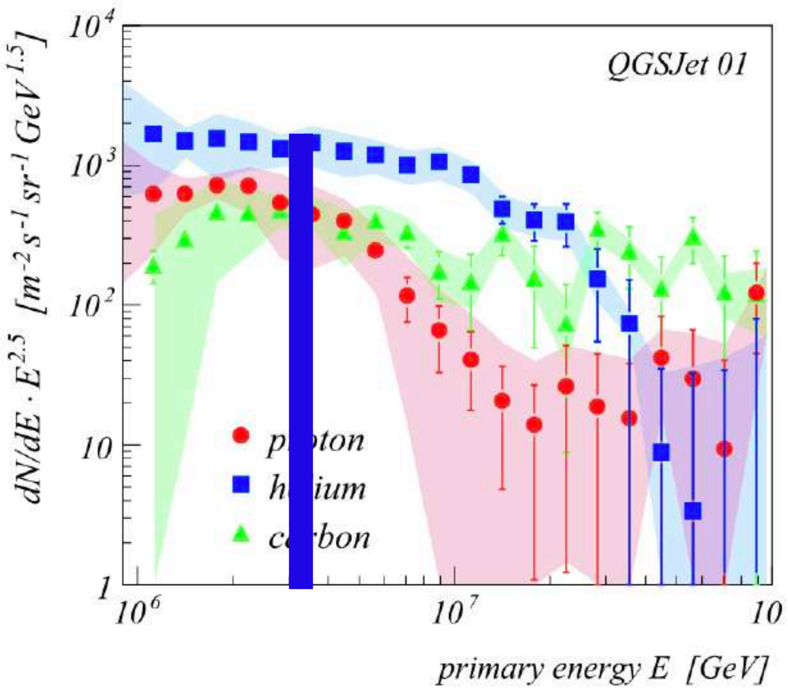
Knee



Knee

The proton « knee »





ARGO-YBJ

~700 TeV

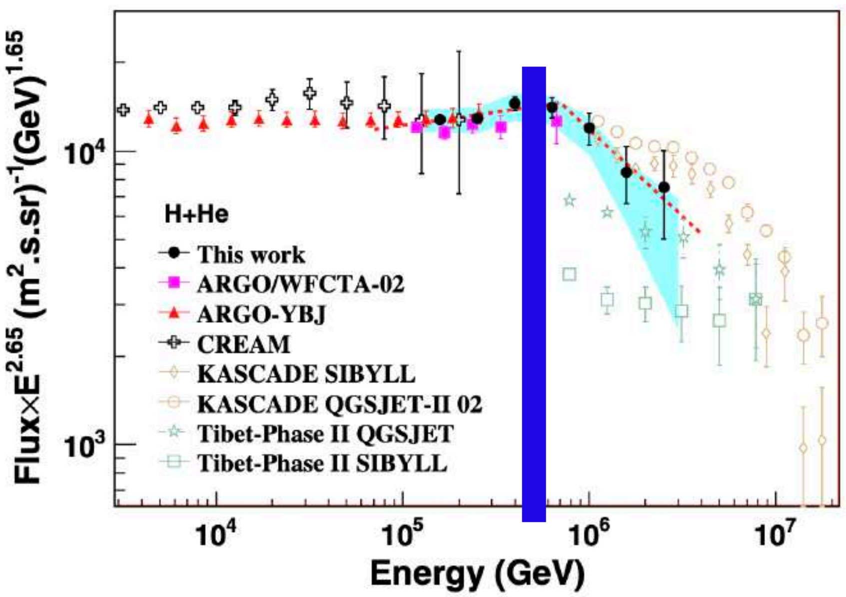
Bartoli et al. 2015

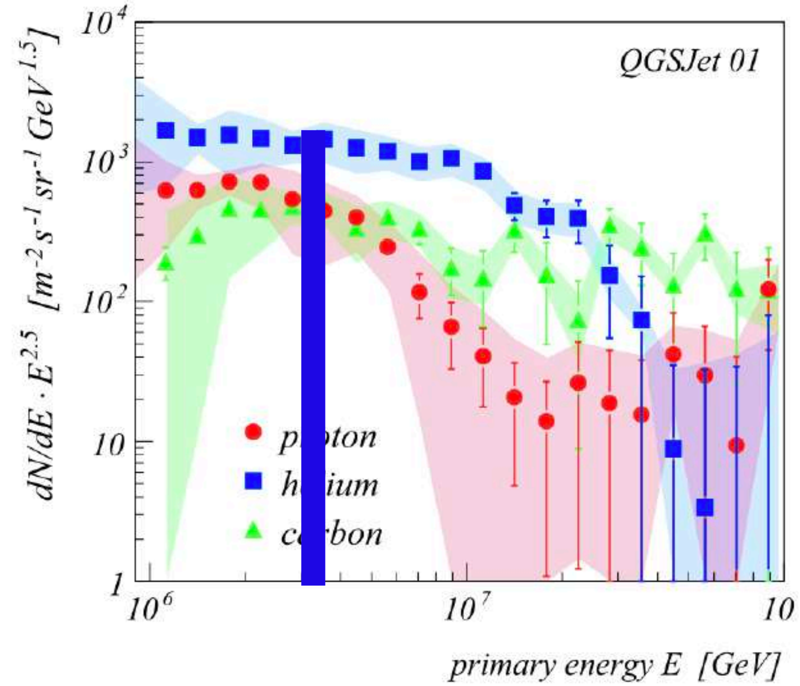
KASCADE

~3-4 PeV

Antoni et al. 2005

The proton « knee »





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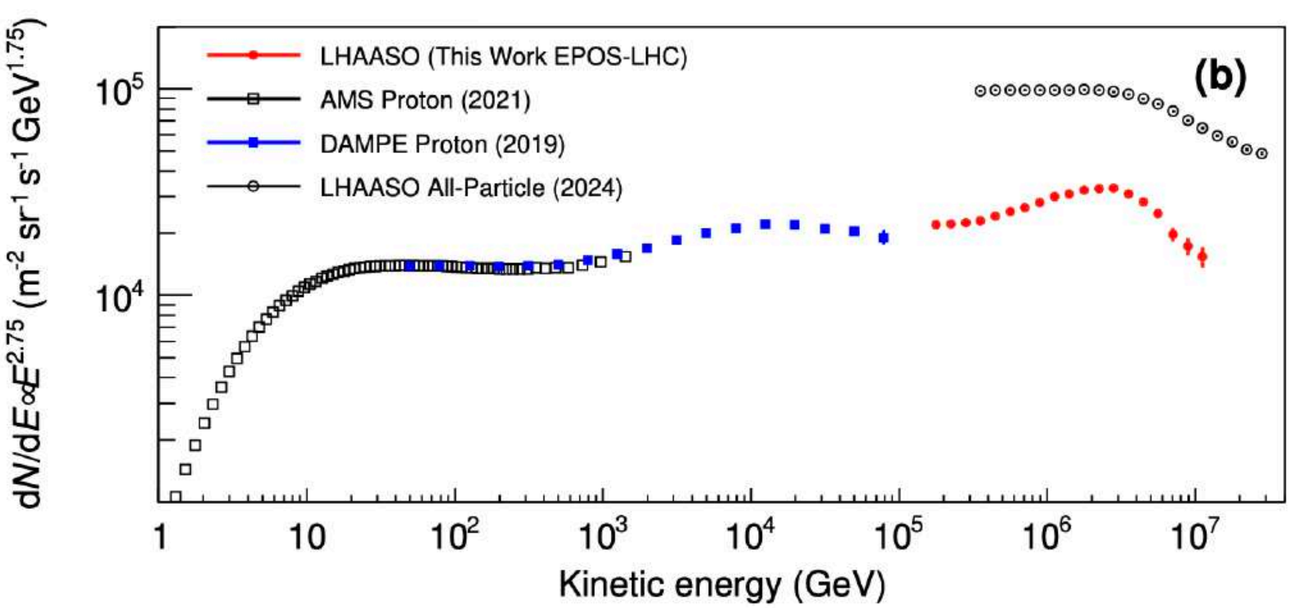
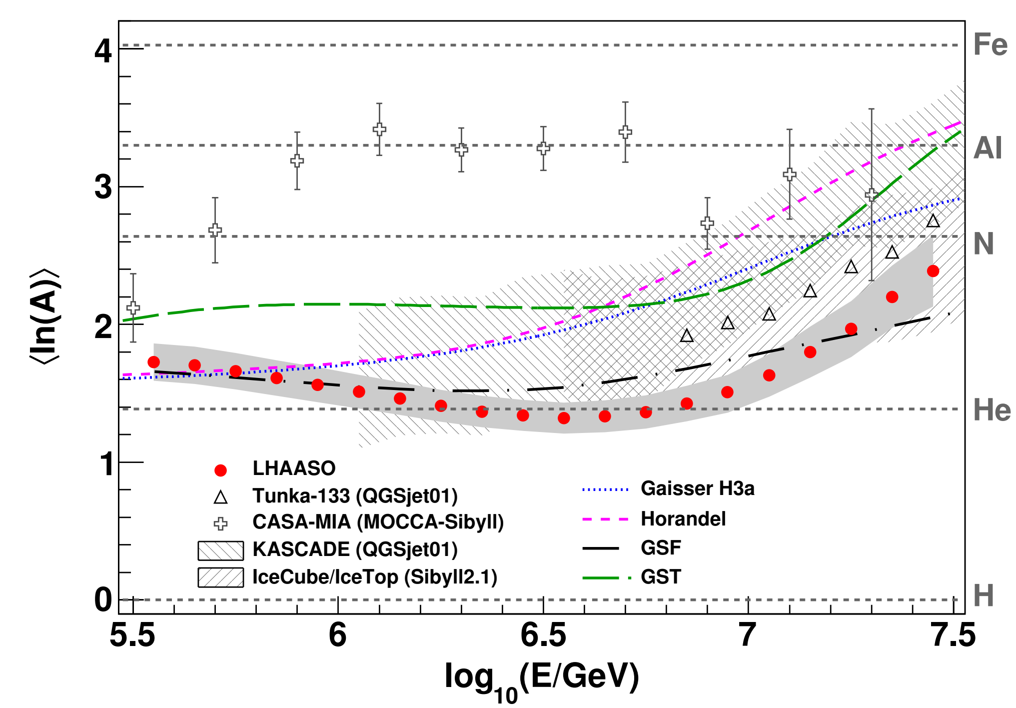


LHAASO Cao et al. 2025 ~3 PeV

Hints for rigidity-dependent knee

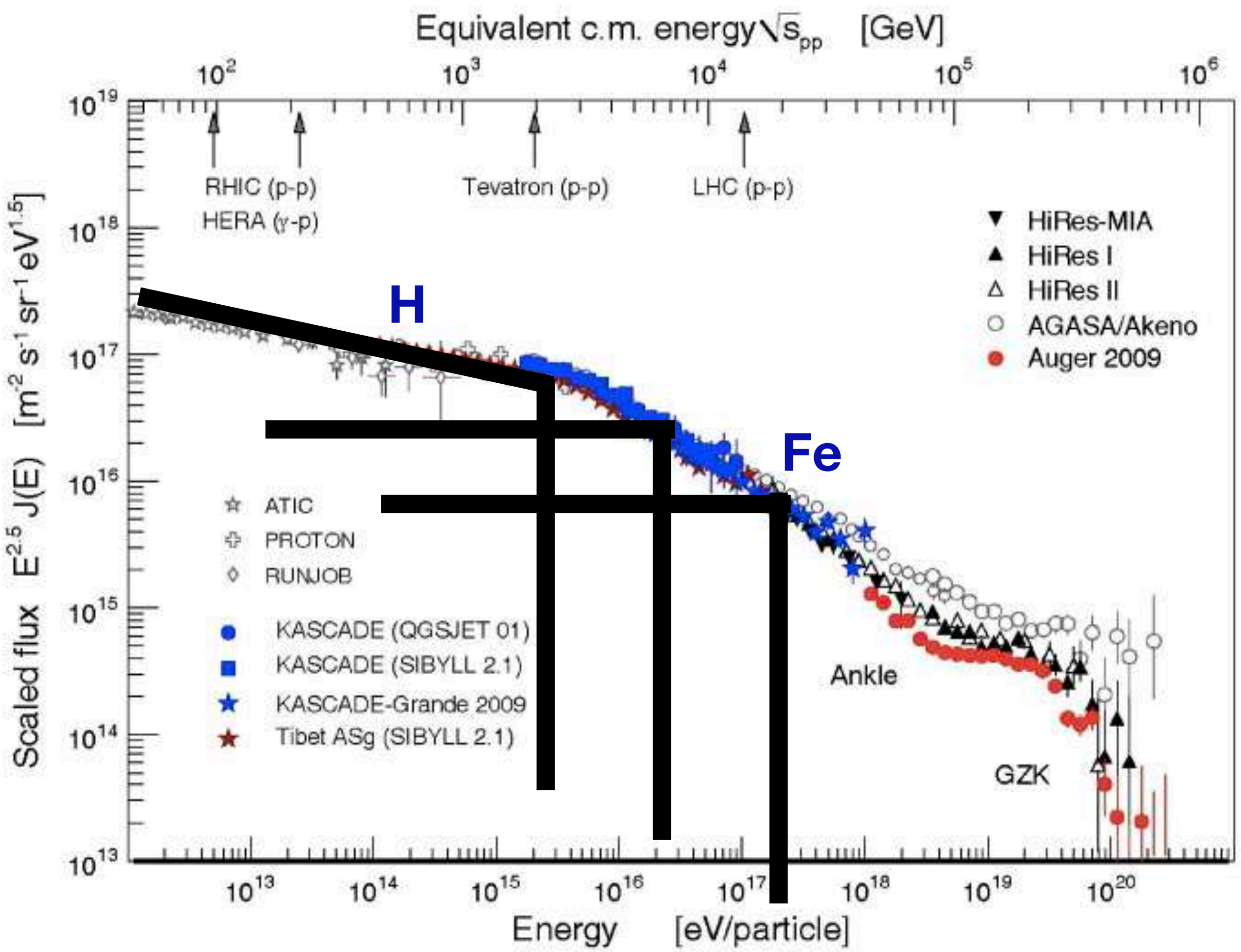


LHAASO Cao et al. 2024

The « knee »

Source of Galactic CRs must accelerate up to AT LEAST the knee!

~100 PeV



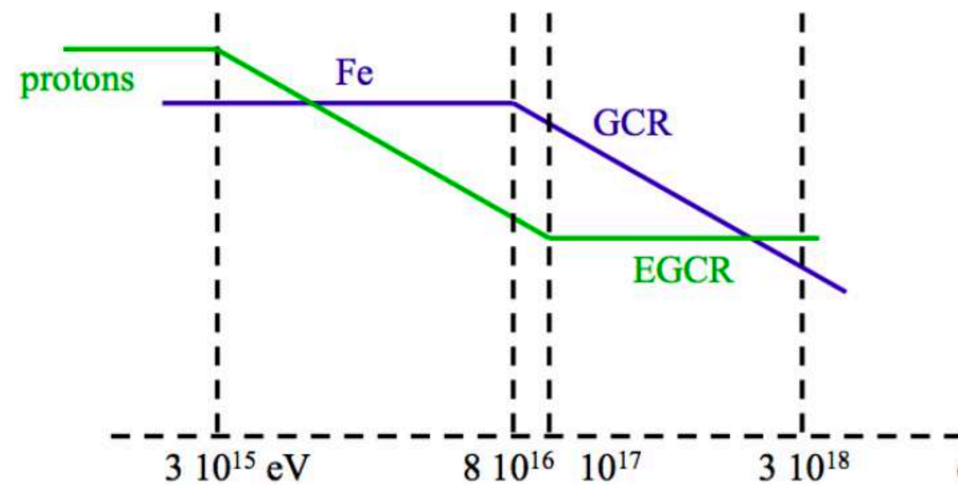


Figure 4: Sketch of the GCR/EGCR transition, with the proton and Fe components indicated (respectively in green and in blue on the color version of the figure). In ordinate, the CR flux is multiplied by E^x, where x is the logarithmic slope of the CR spectrum below the knee. (See also Fig. 3).

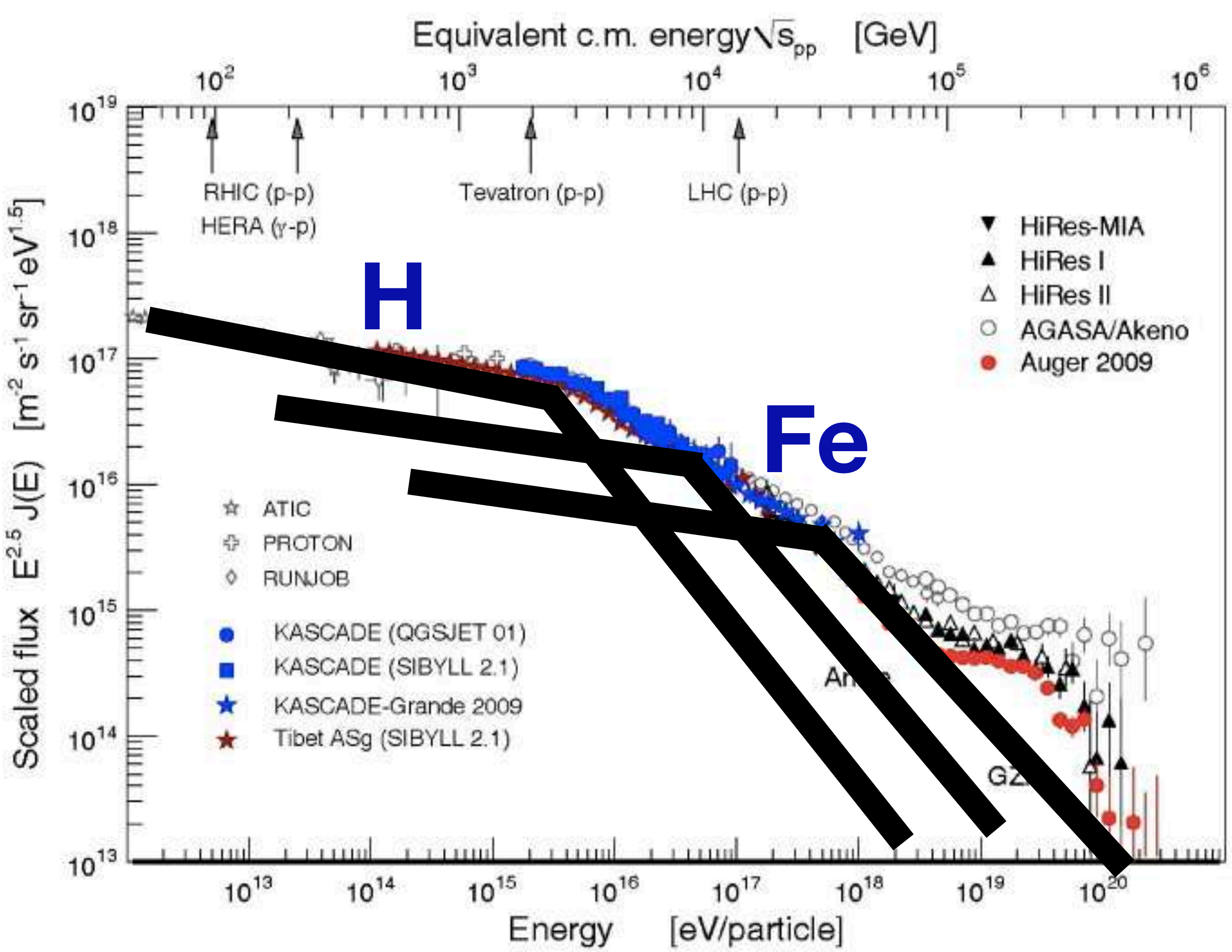
Z dependent knee ⟷ DSA depends on rigidity

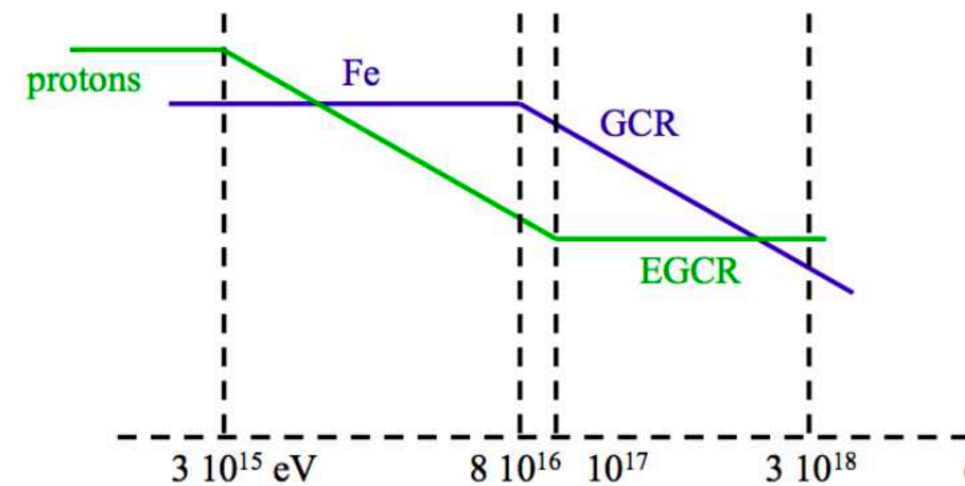
Hillas 2006, Parizot 2014

The « knee »

Source of Galactic CRs must accelerate up to AT LEAST the knee!

~100 PeV





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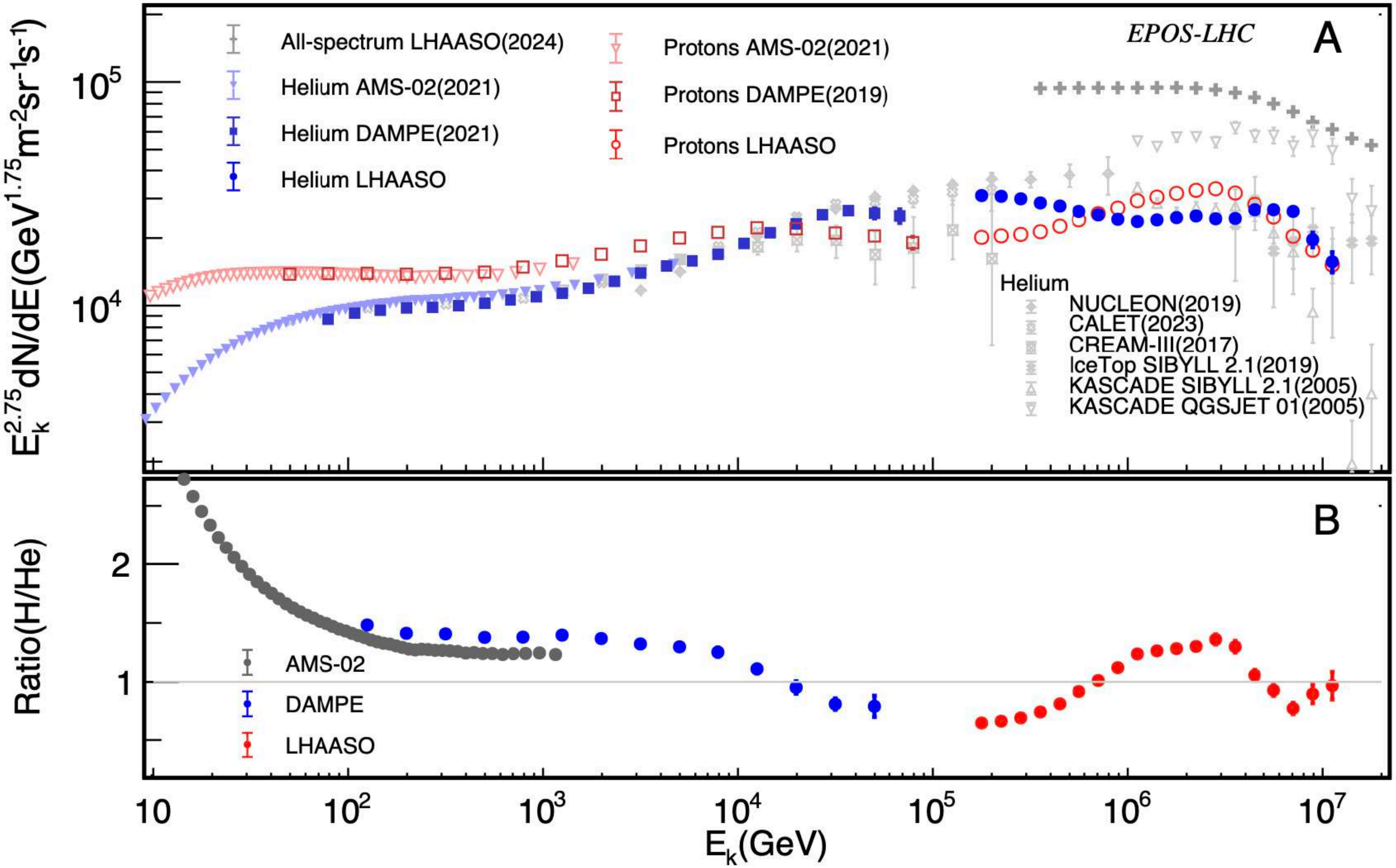
Smooth transition from Galactic to extraGalactic

Hillas 2006, Parizot 2014

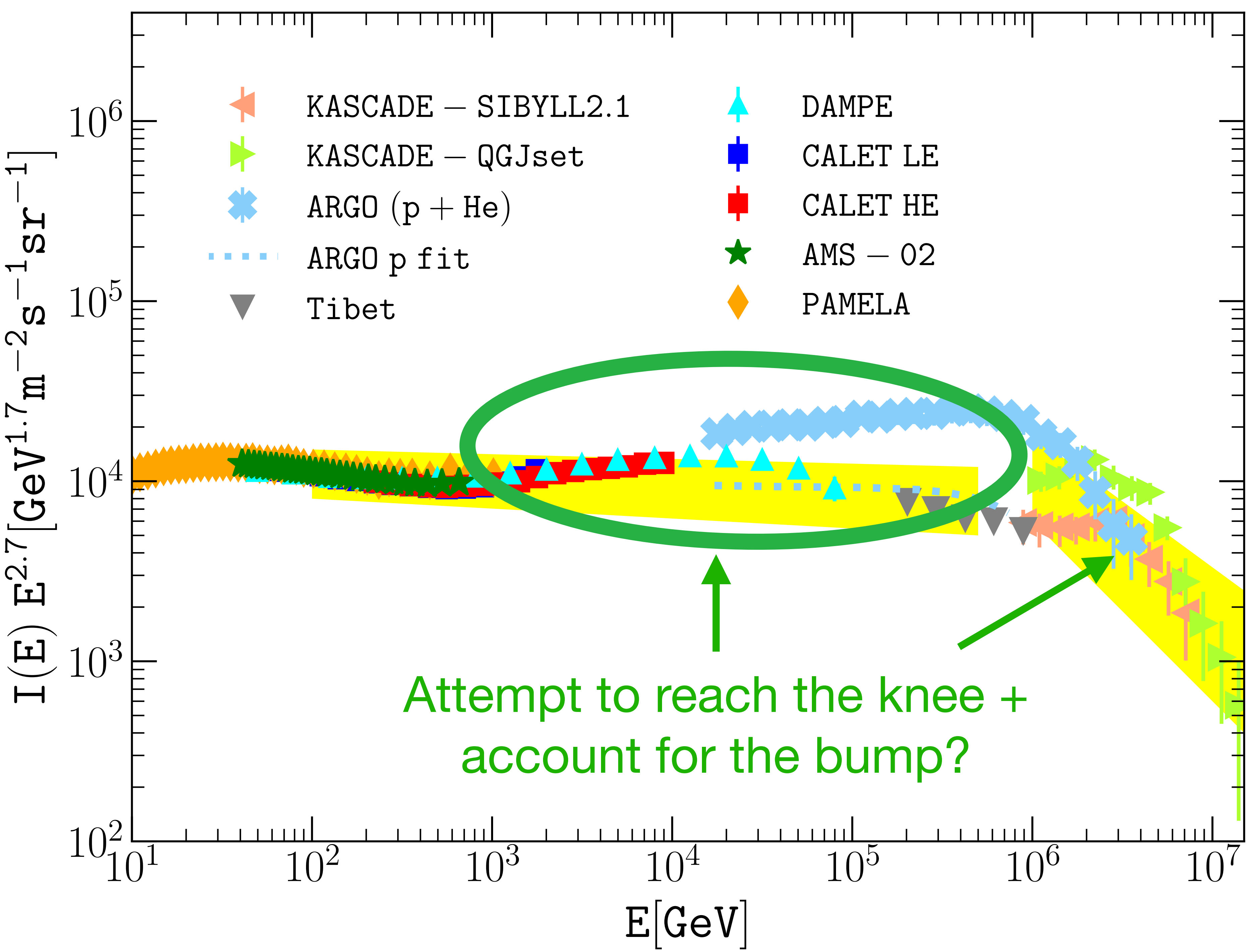
The proton and Helium « knee »



Complex behavior (not like the smooth all-particle spectrum)
Interpretation: Several sources of Galactic cosmic rays (not only one)

LHAASO Cao et al. 2026

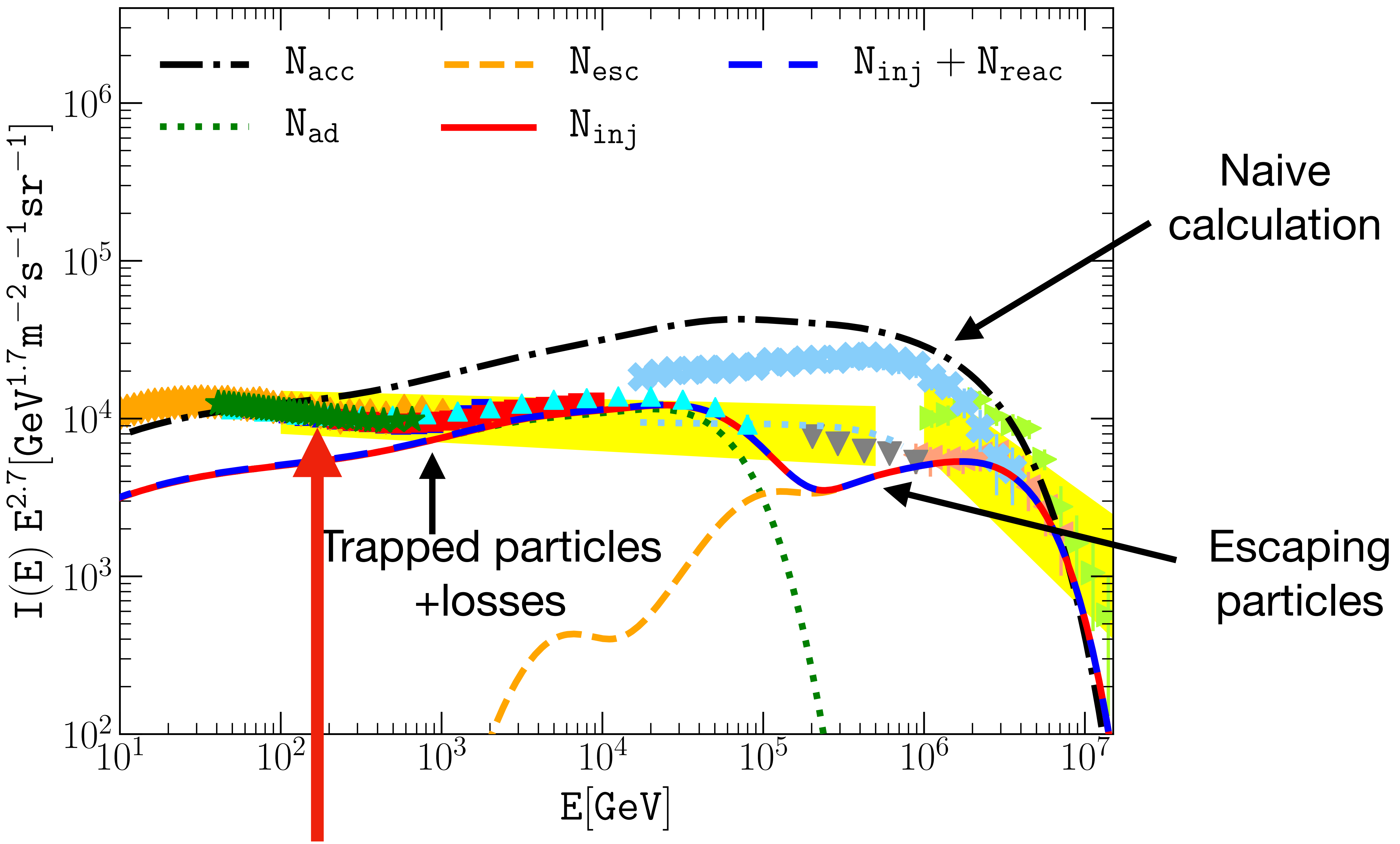
And ... below the knee?



With only one object?

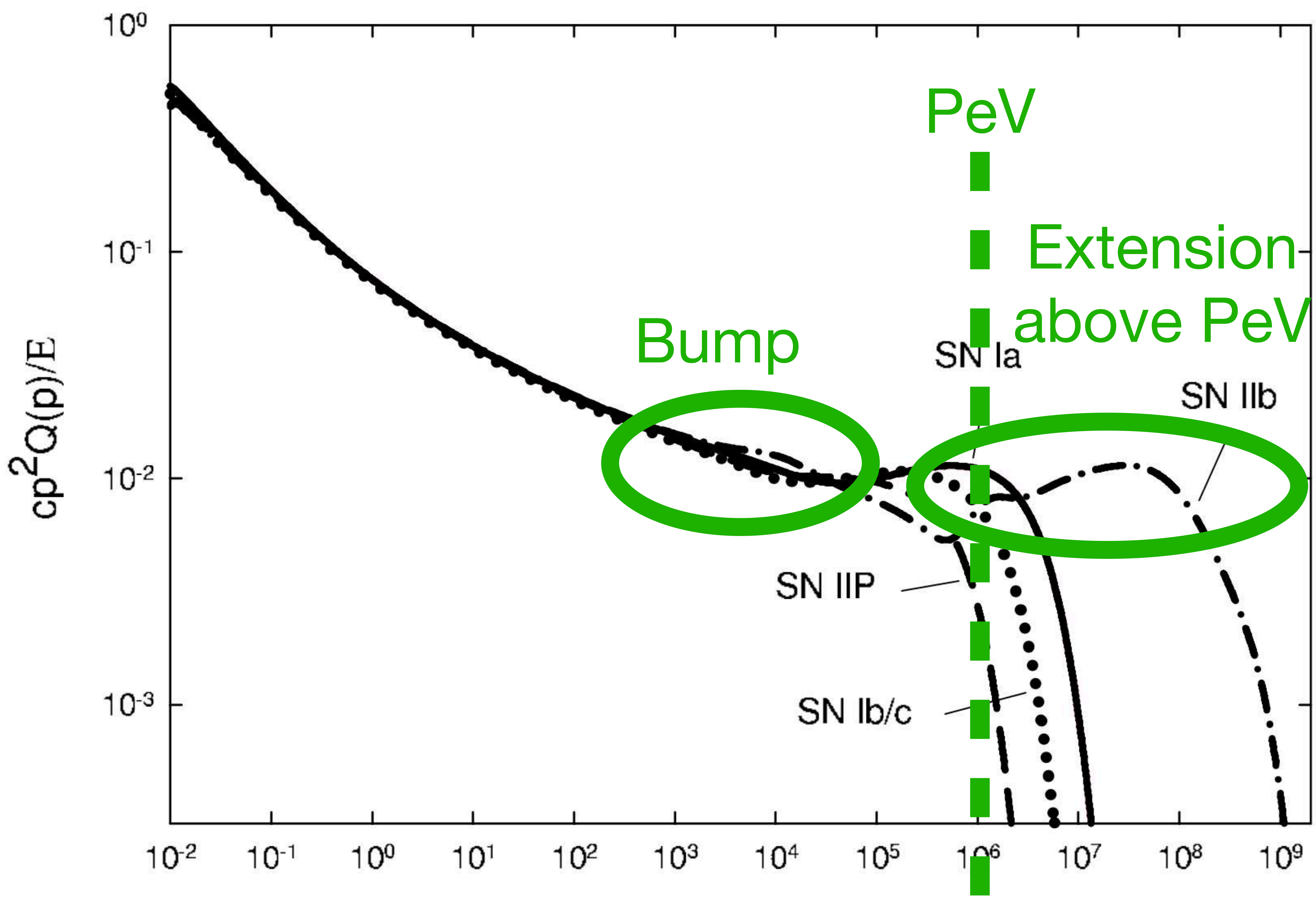
Type II $*$ $[E_{SN} = 1 - 10\ 10^{51} \mathrm{erg}]$

$\dot{M} = 10^{-4} M_\odot/\mathrm{yr} \qquad \xi = 5\%$



Major problem: no room for other SNRs/ other accelerators

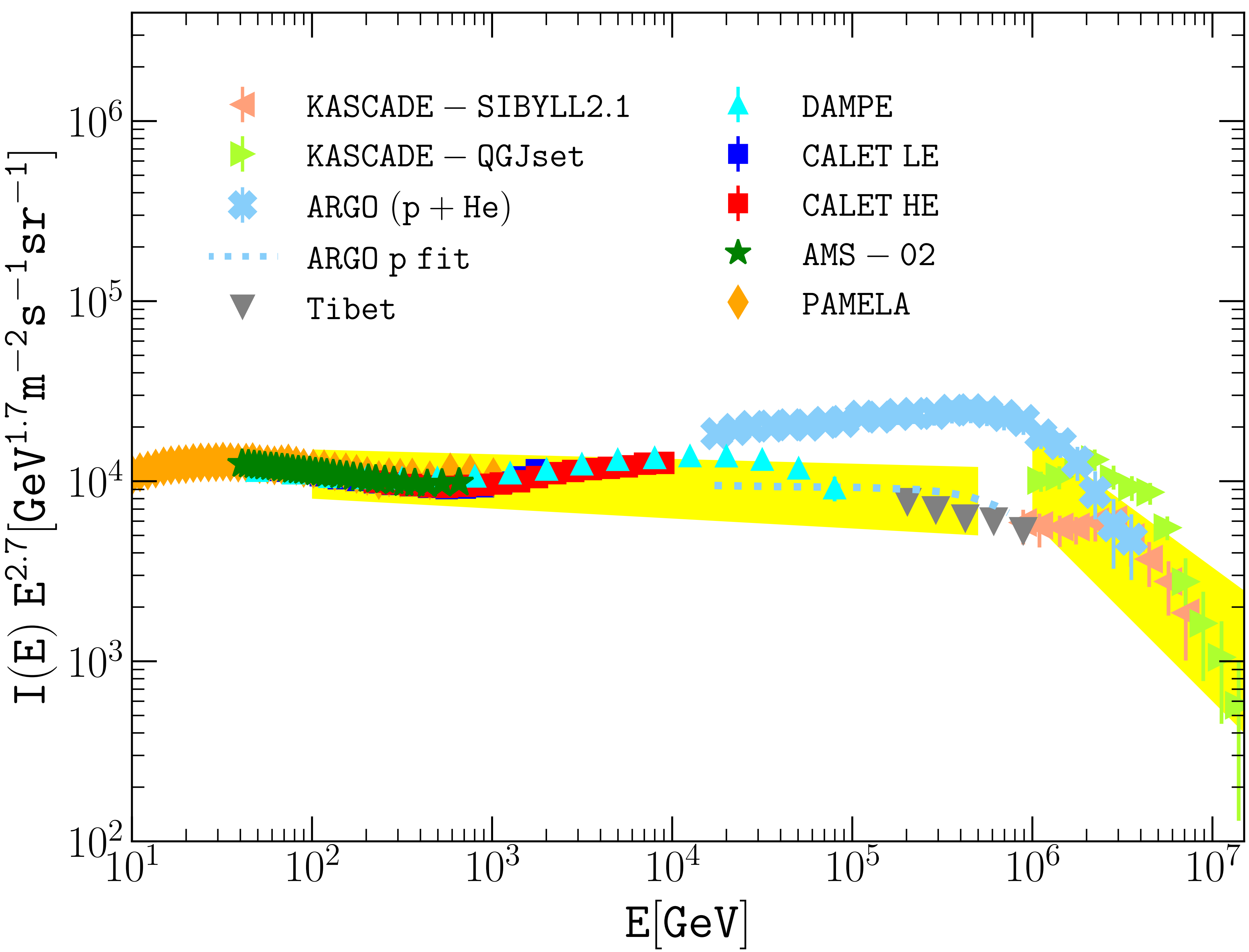
And ... below the knee?



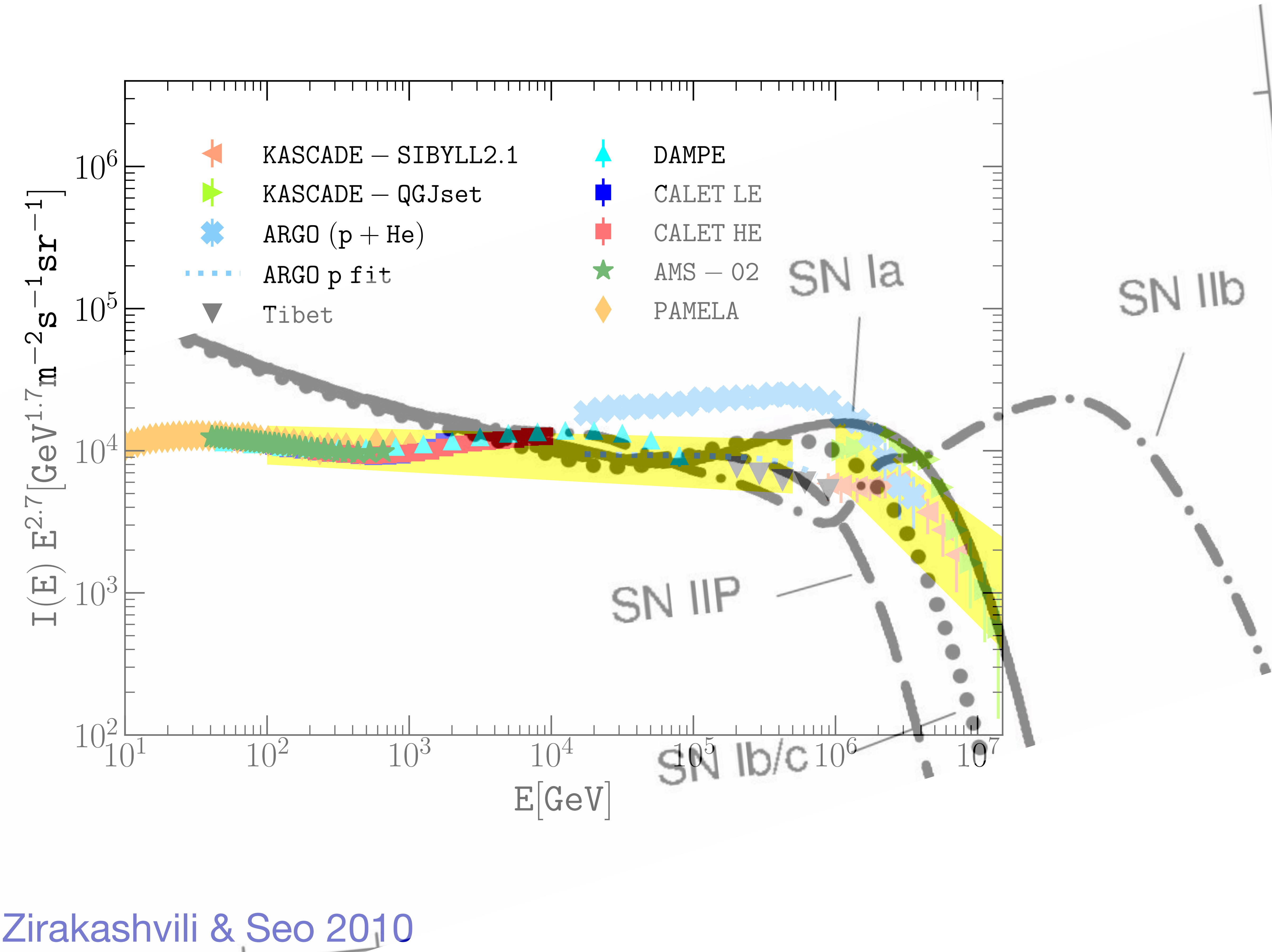
With several ‘components’

Ptuskin, Zirakashvili & Seo 2010

And … below the knee?

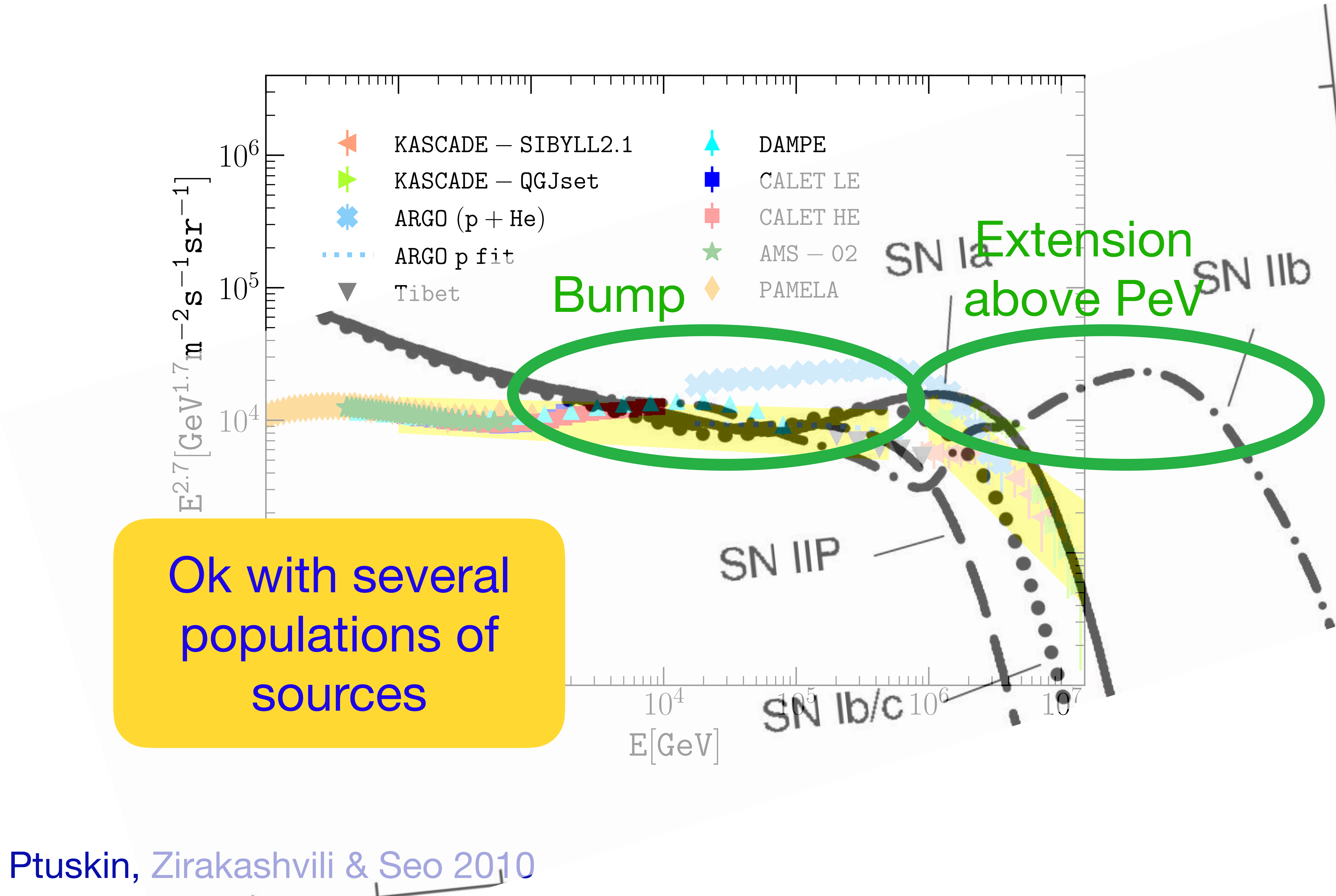


And … below the knee?



Ptuskin, Zirakashvili & Seo 2010

And … below the knee?



Ok with several populations of sources

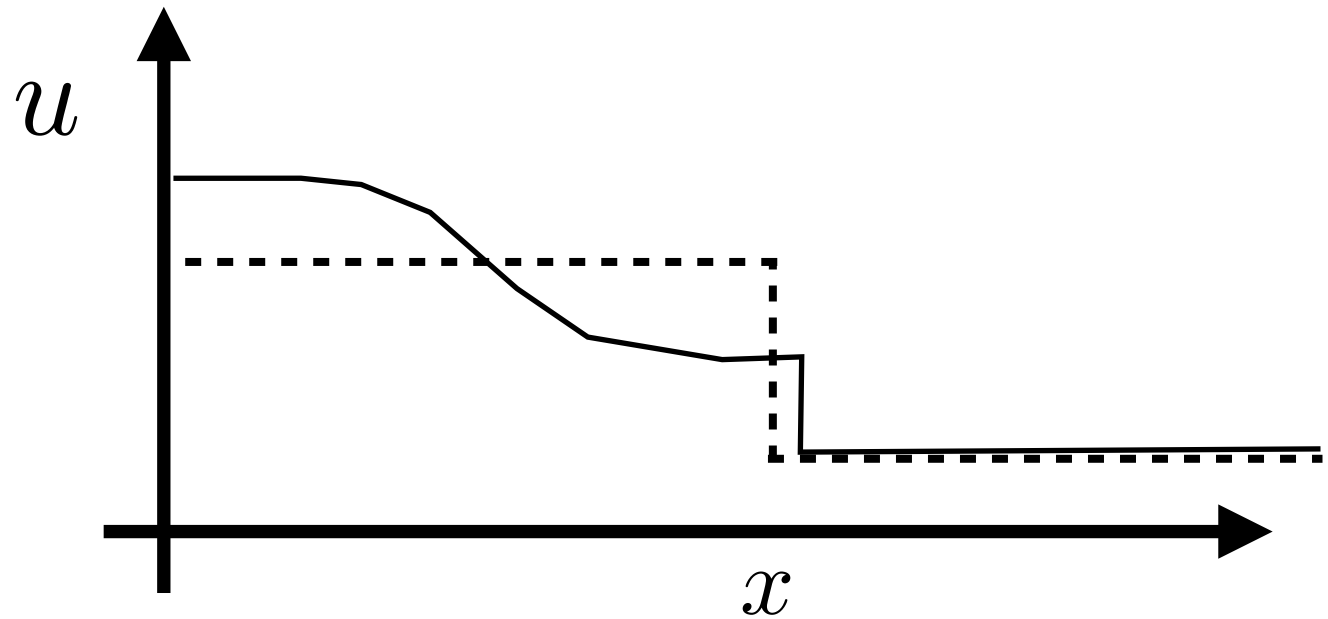
Ptuskin, Zirakashvili & Seo 2010

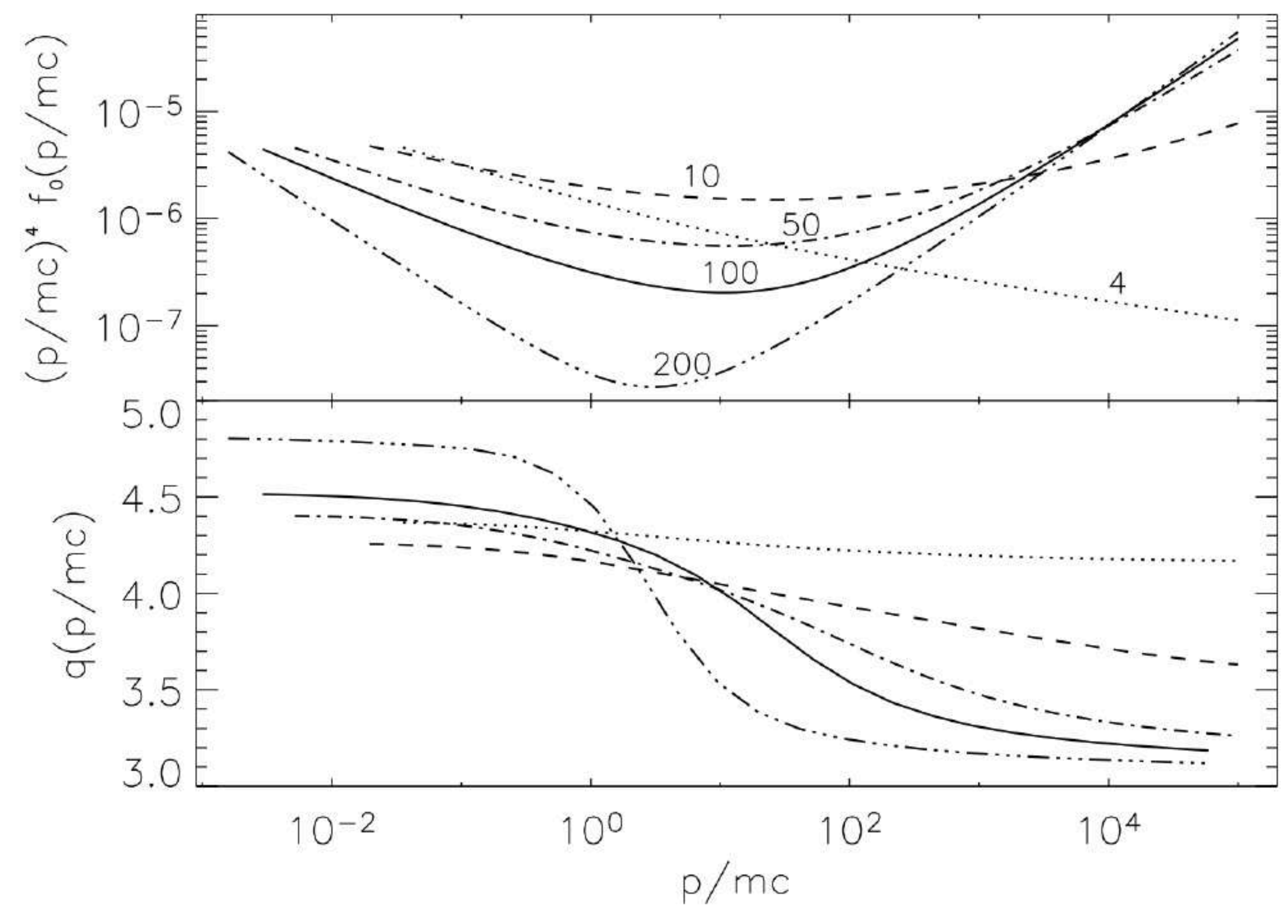
Spectrum at the shock?

Until now: fixed slope at the shock produced steeper summed injected spectrum.

$$f(p) \propto p^{-\alpha} \qquad\qquad f(p) \propto p^{-\alpha(t)} \quad \alpha \neq 4$$

Non-linear effects: efficient particle acceleration acting on the shock structure





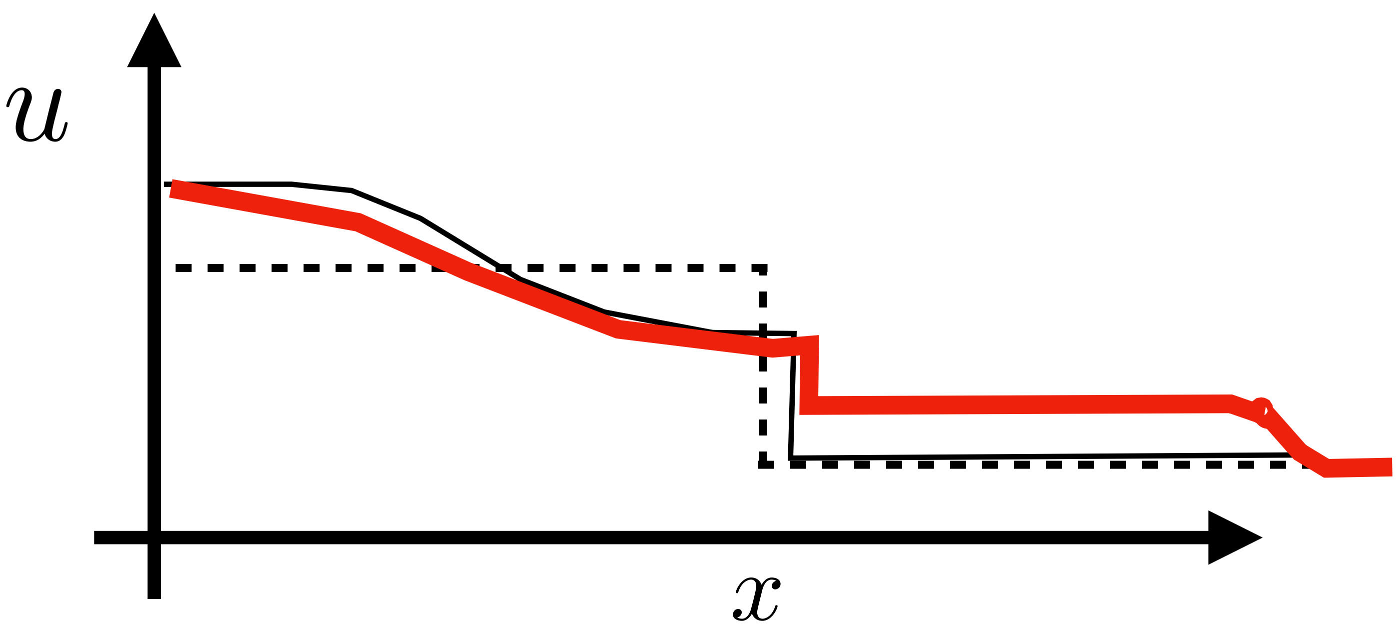
Drury& Völk (1980,1981), Bell (1987)
Jones & Ellison (1991), Ellison, Möbius & Paschamnn (1990), Ellison, Baring & Jones (1995, 1995) Kang & Jones (1997, 2005) Kang, Jones & Gieseler (2002), Malkov (1997), Malkov, Diamond & Völk (2000)
Blasi (2002), Amato & Blasi (2005,2006)

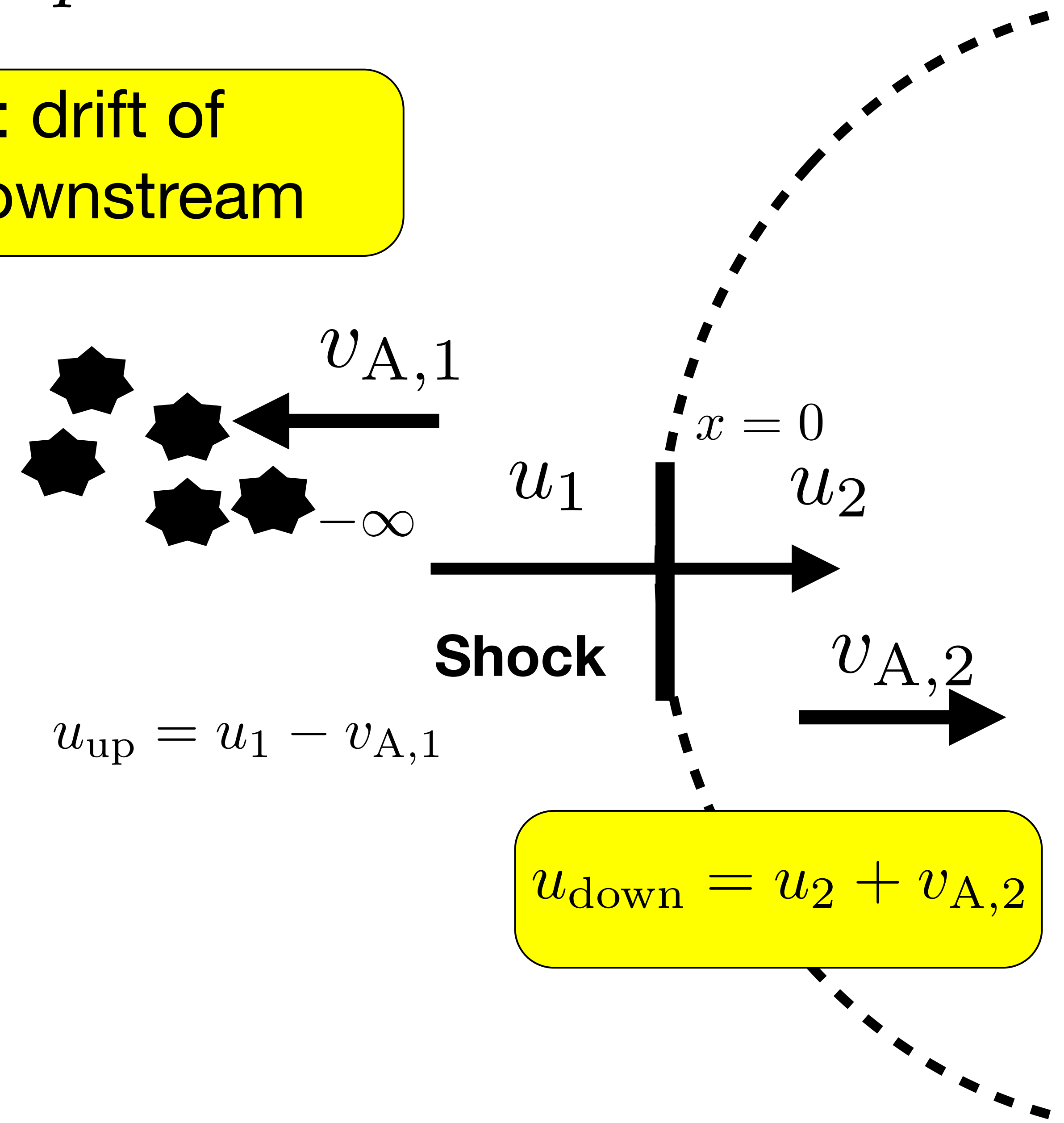
Spectrum at the shock?

Until now: fixed slope at the shock produced steeper summed injected spectrum.

$$f(p) \propto p^{-\alpha} \qquad\qquad f(p) \propto p^{-\alpha(t)} \quad \alpha \neq 4$$

Non-linear effects: drift of scattering centers downstream





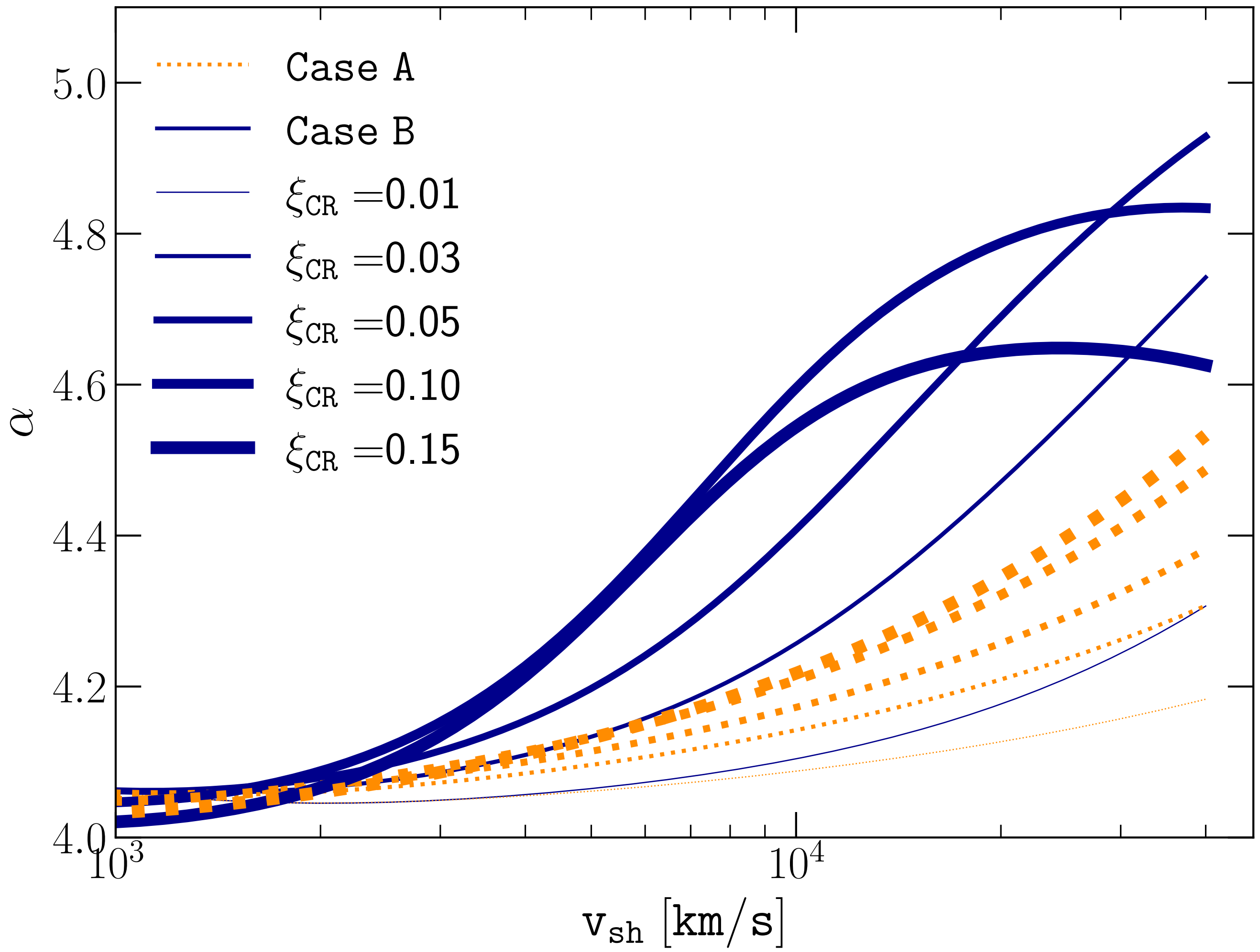
Zirakashvili & Ptuskin (2008)

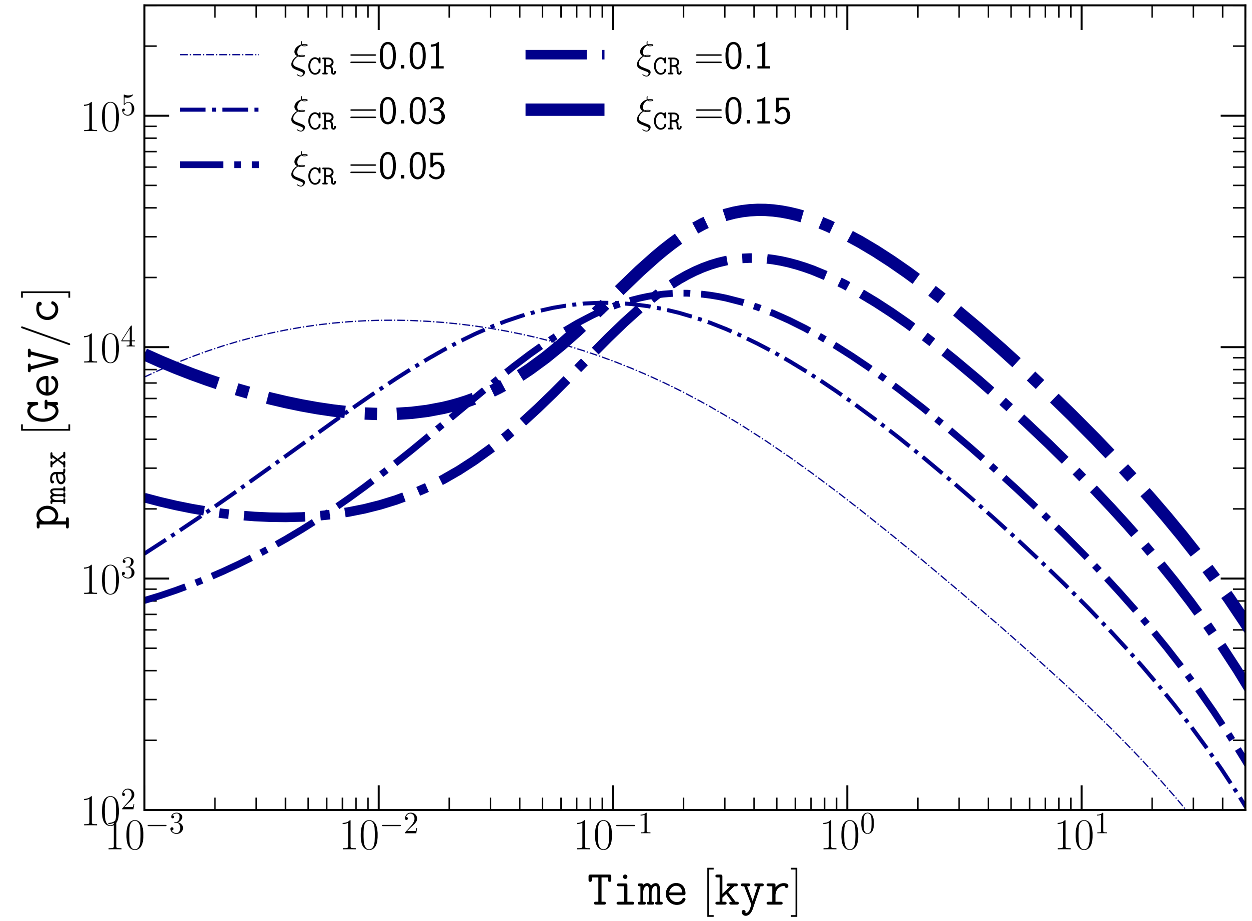
Drury (1983), Caprioli, Haggerty & Blasi (2020), Diesing & Caprioli (2021), PC, Blasi & Caprioli (submitted 2022)

Spectrum at the shock?

$$v_{A,2} = R_{\rm tot} \frac{\delta B_2}{\sqrt{4\pi\rho}}$$

Bell: current from all particles
(maximum value B)





Bell: current escaping
particles upstream infinity

Consequences on pmax!

Drury (1983), Caprioli, Haggerty & Blasi (2020), Diesing & Caprioli (2021), PC, Blasi & Caprioli (submitted 2022)

Radiative supernova remnants

$M_{\rm ej} = 1.4 M_\odot$
$E_{\rm SN} = 10^{51} {\rm erg}$
$n_0 = 1 \ {\rm cm}^{-3}$

Free expansion phase

$M_{\rm ejecta} \gg M_{\rm swept-up}$

$t_{\rm end} \sim 0.3 \ {\rm kyr}$

Sedov-Taylor (adiabatic) phase

$M_{\rm ejecta} \lesssim M_{\rm swept-up}$

$t_{\rm end} \sim 20 \ {\rm kyr}$

Particle acceleration

Radiative phase

?

$\tau_{\rm cooling} \lesssim t_{\rm age}$

$t_{\rm end} \sim 100 - 200 \ {\rm kyr}$

$t_{\rm end} \sim 20 - 300 \ {\rm kyr}$ **????**

The Green catalog (from Dave A. Green)

310 SNRs (+21 since 2019 mostly reclassifying HII regions)

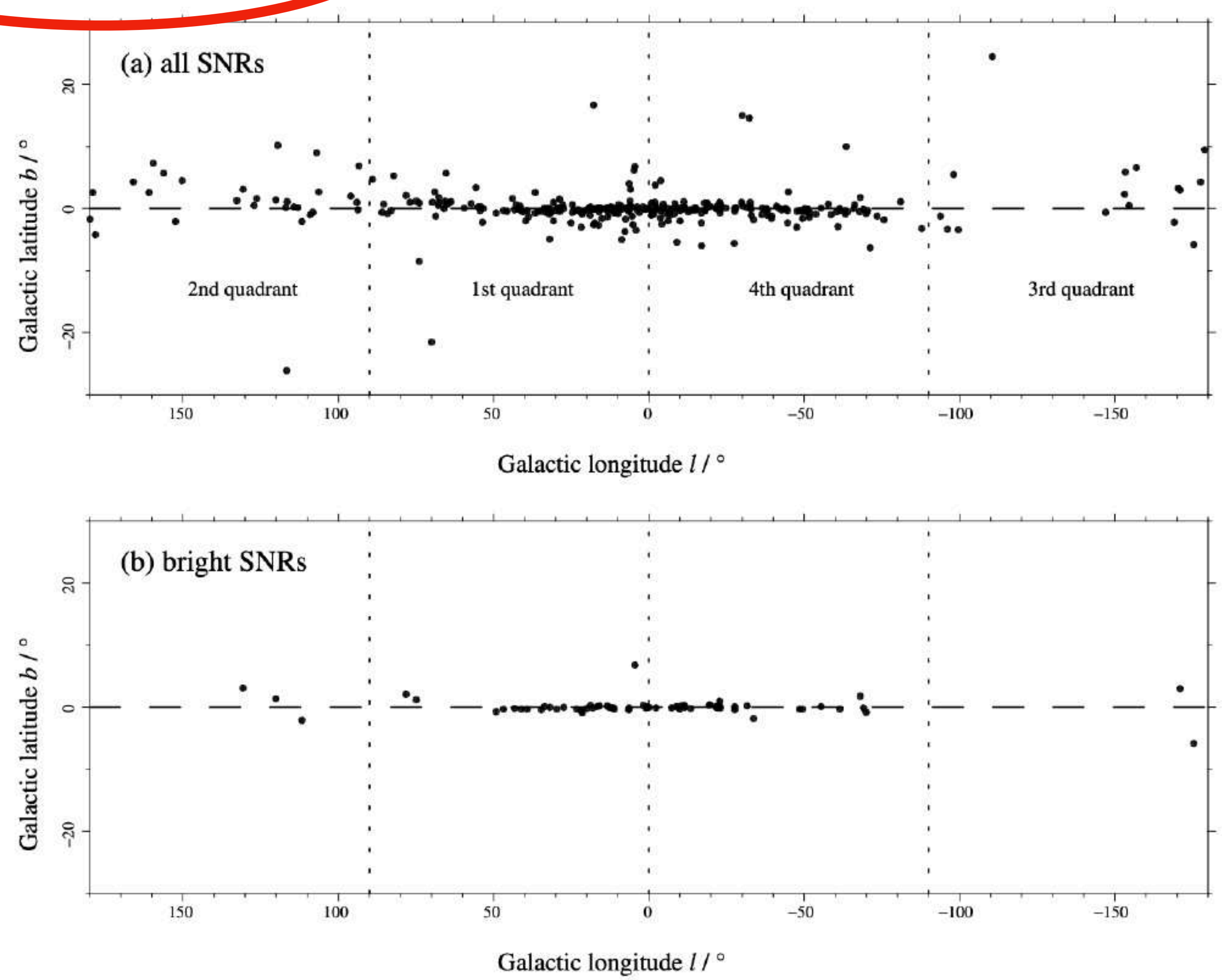


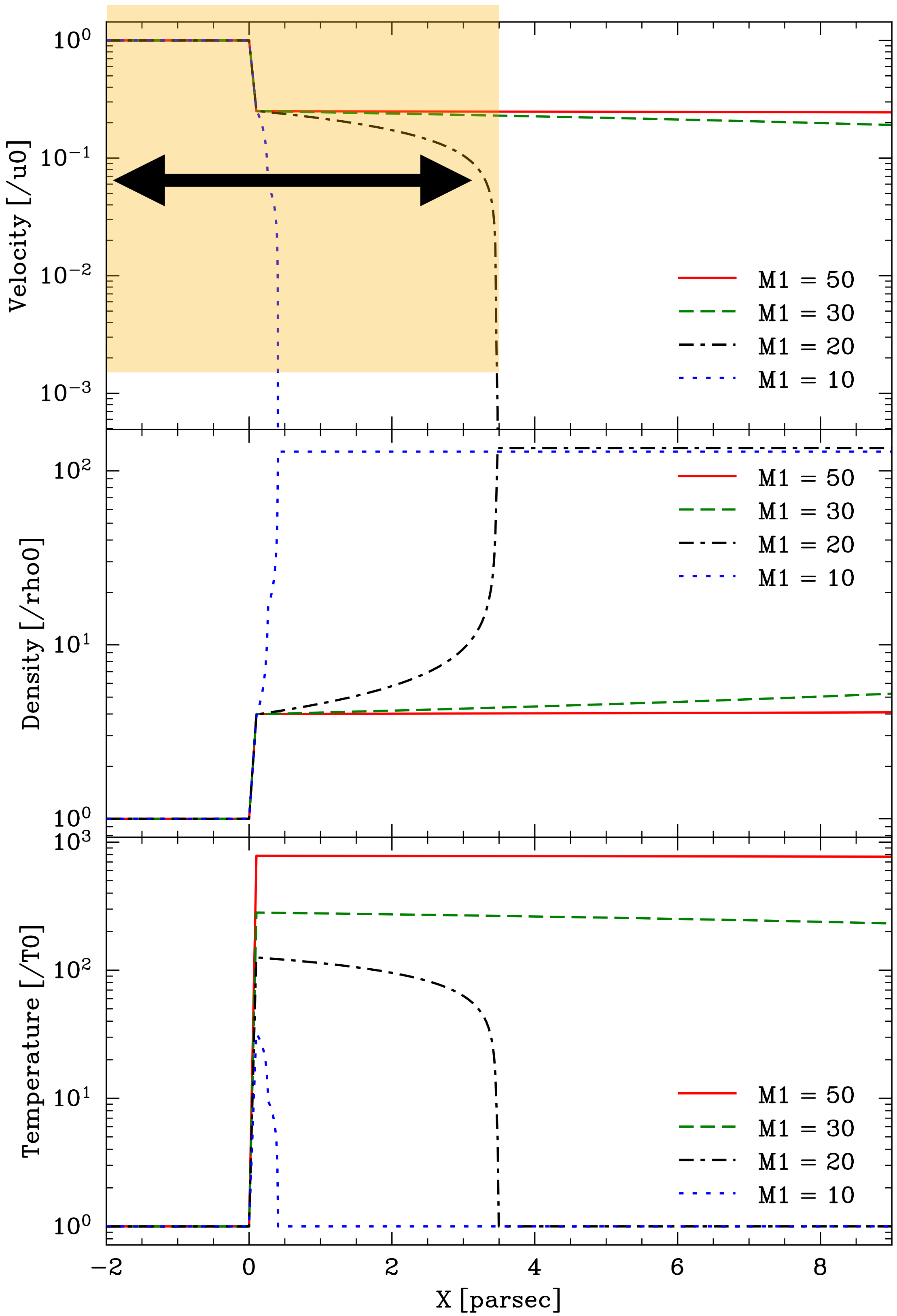
Figure 3. Distribution of SNRs with Galactic latitude and longitude: (top) all remnants; (bottom) the 66 'bright' remnants. Note that the latitude and longitude scales are different.

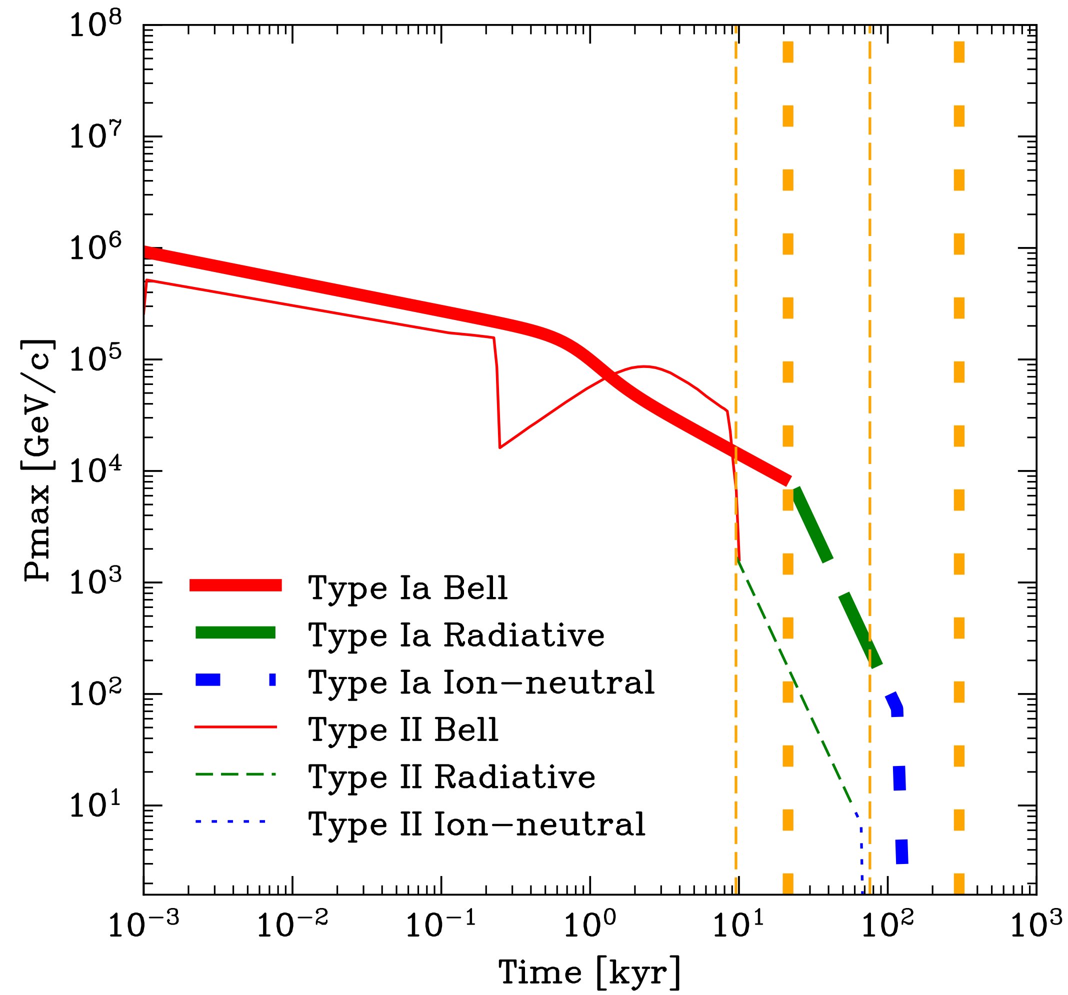
Naïve estimate: $\nu_{\rm SN} \times T_{\rm end} \approx 3/\text{century} \times 50\ \text{kyr} = 1500$

Green 2025 A&A

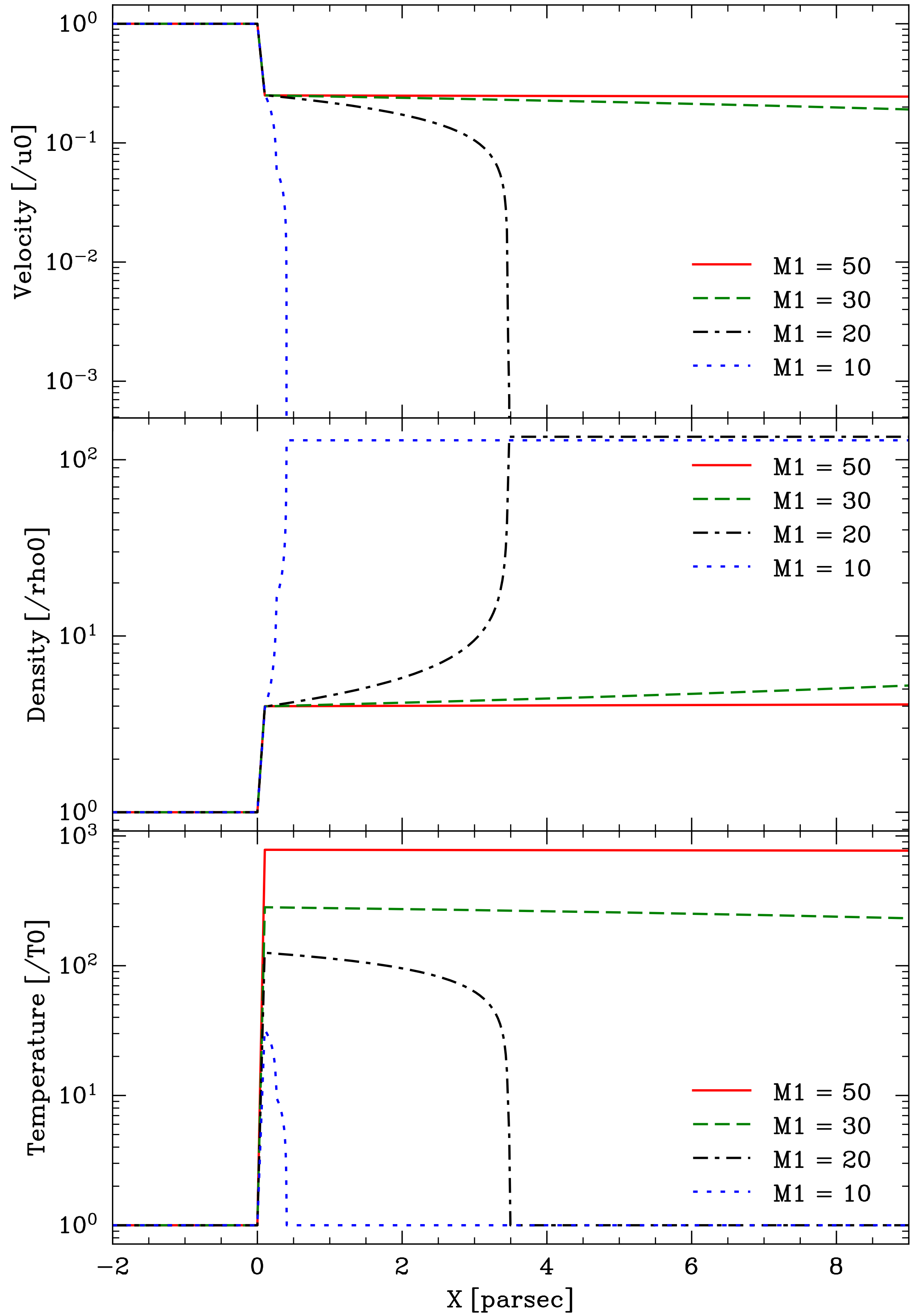
$p_{\max}$?

$r_{\rm L} \lesssim L_{\rm cool}$





$$f_0(p) = \frac{3r_{\rm sub}}{r_{\rm sub}-1}\frac{\eta n_1}{4\pi p_{\rm inj}^3}\exp\left[\int_{p_{\rm inj}}^{p}\frac{3R_{\rm tot}(p)}{R_{\rm tot}(p)-1}\frac{{\rm d}p'}{p'}\right]$$



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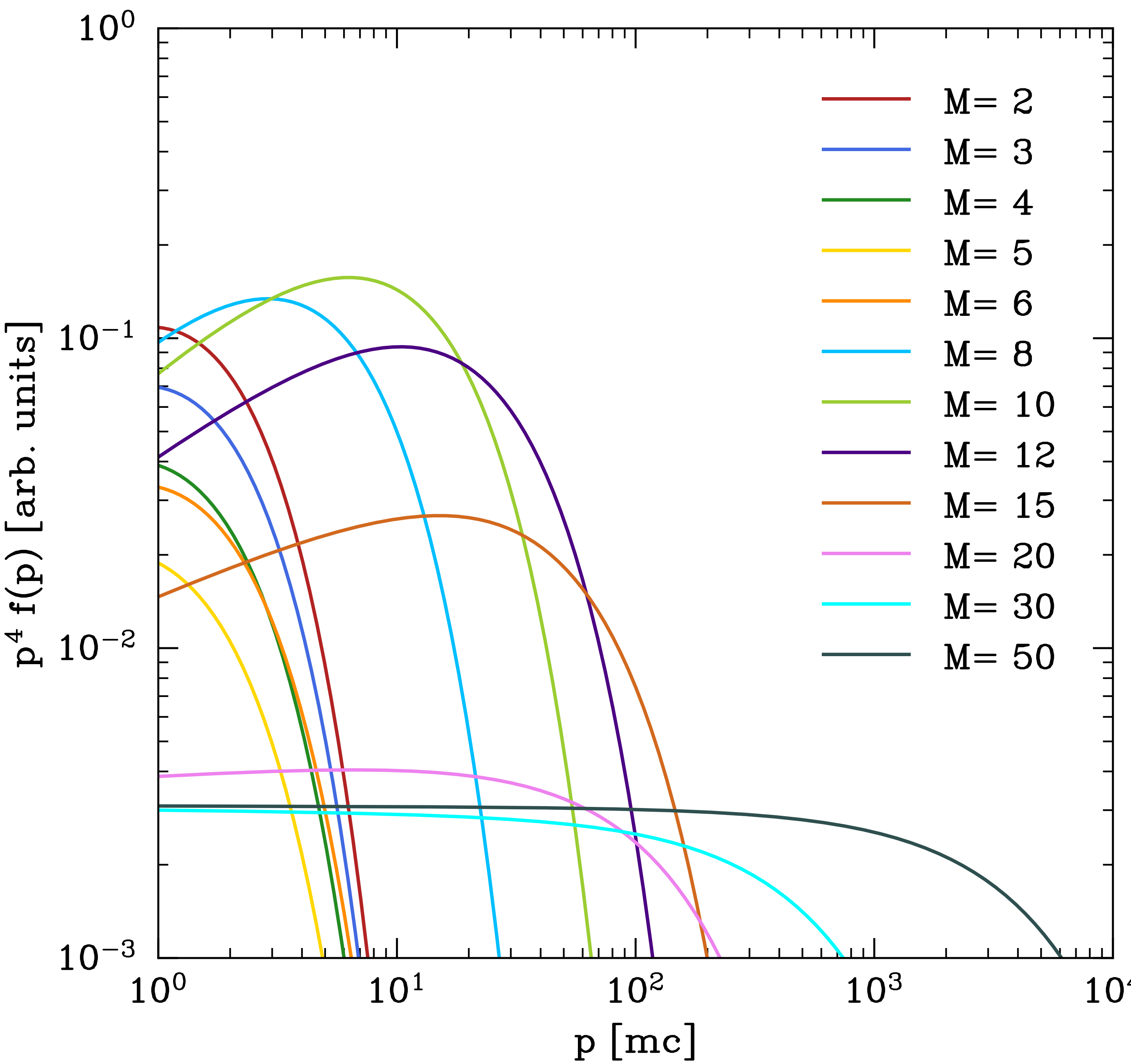
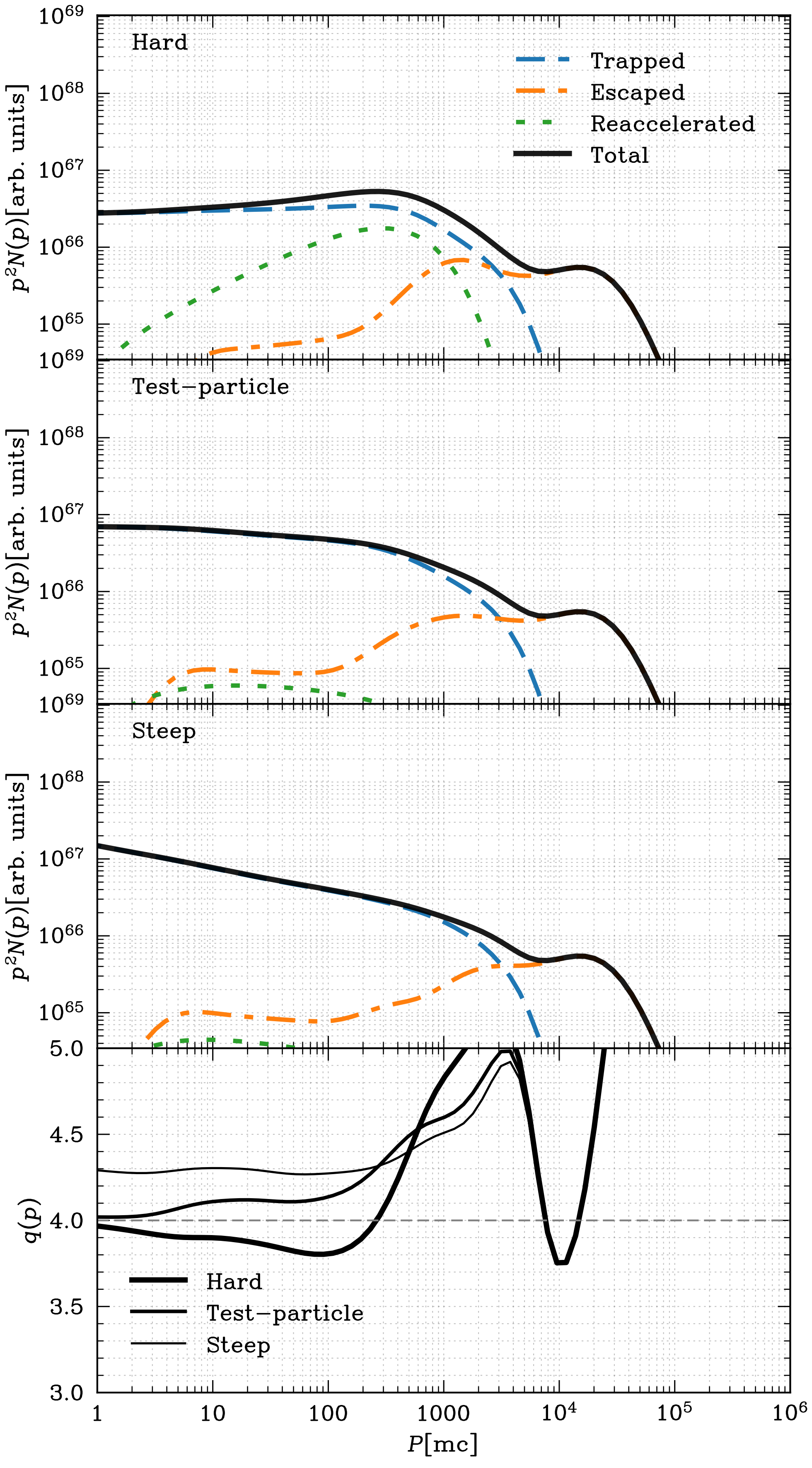


Type Ia SNR

Cumulative proton spectrum



Unknown:
duration of radiative phase
Pmax (ion-neutral damping, cooling?)
efficiency of injection
Slope of accelerated particles
...

RS Ophiuchi in gamma rays: radiative nova shocks

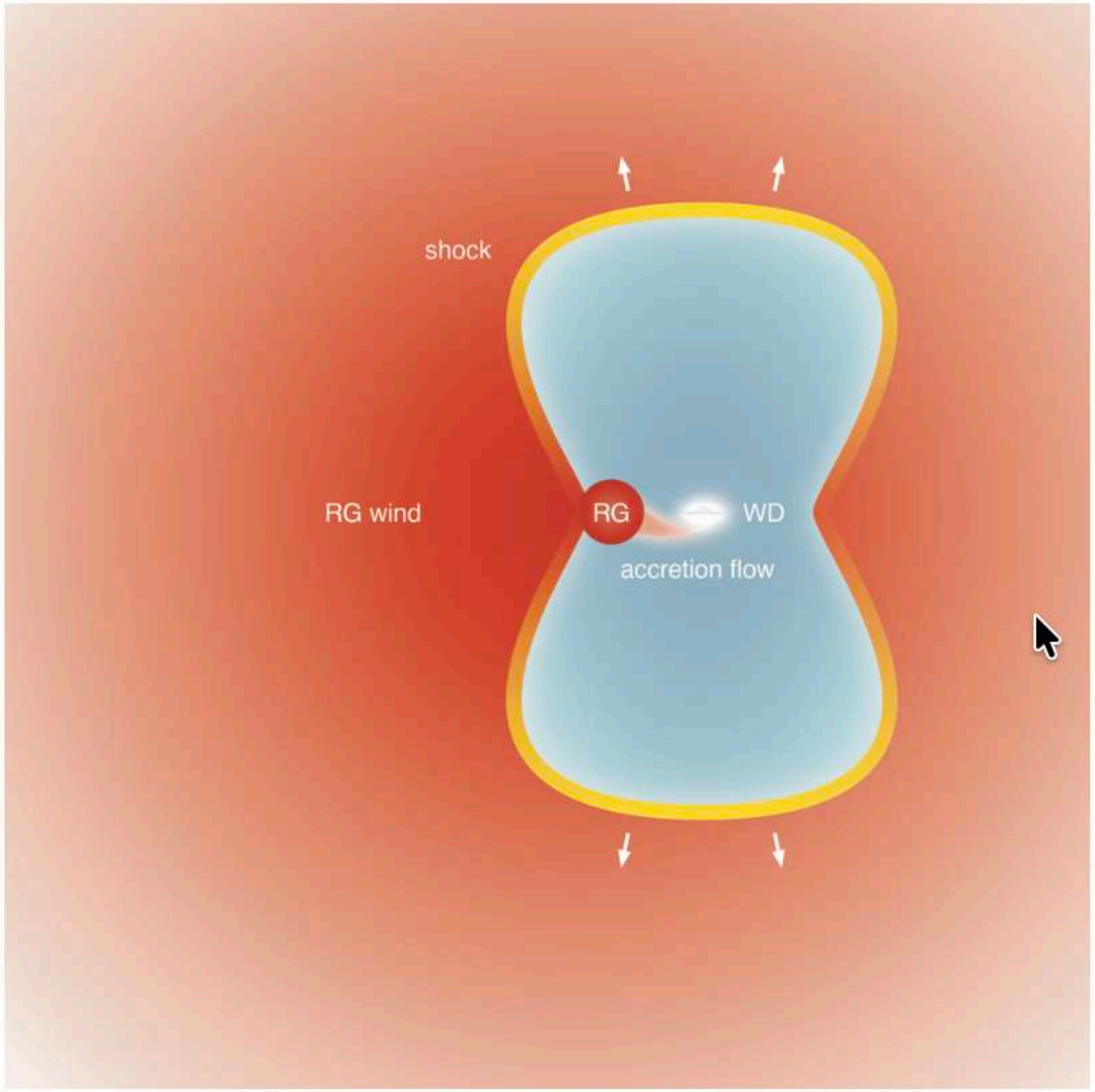
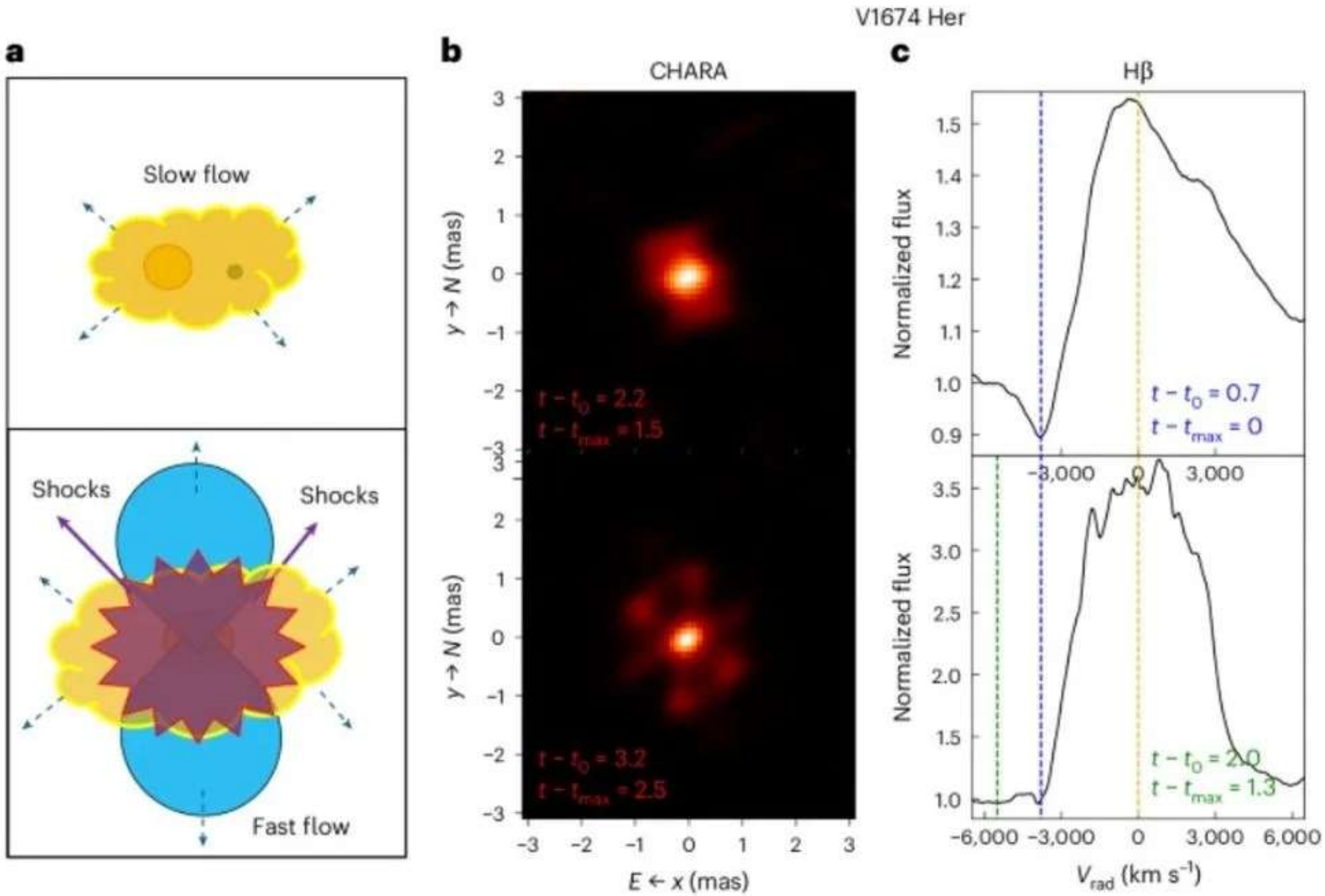


Figure S2: **Schematic of external shock model.** The explosion originates near the surface of the white dwarf (WD). Within one day, the shock is expanding as a bipolar blast wave moving orthogonal to the accretion disk, into the wind of the red giant (RG). The colour gradient of the shock indicates the expansion velocity, whilst the red gradient of the surrounding medium indicates the density of the RG wind. Material internal to the shock is shown in blue. Figure is not to scale.

Aharonian et al. 2022

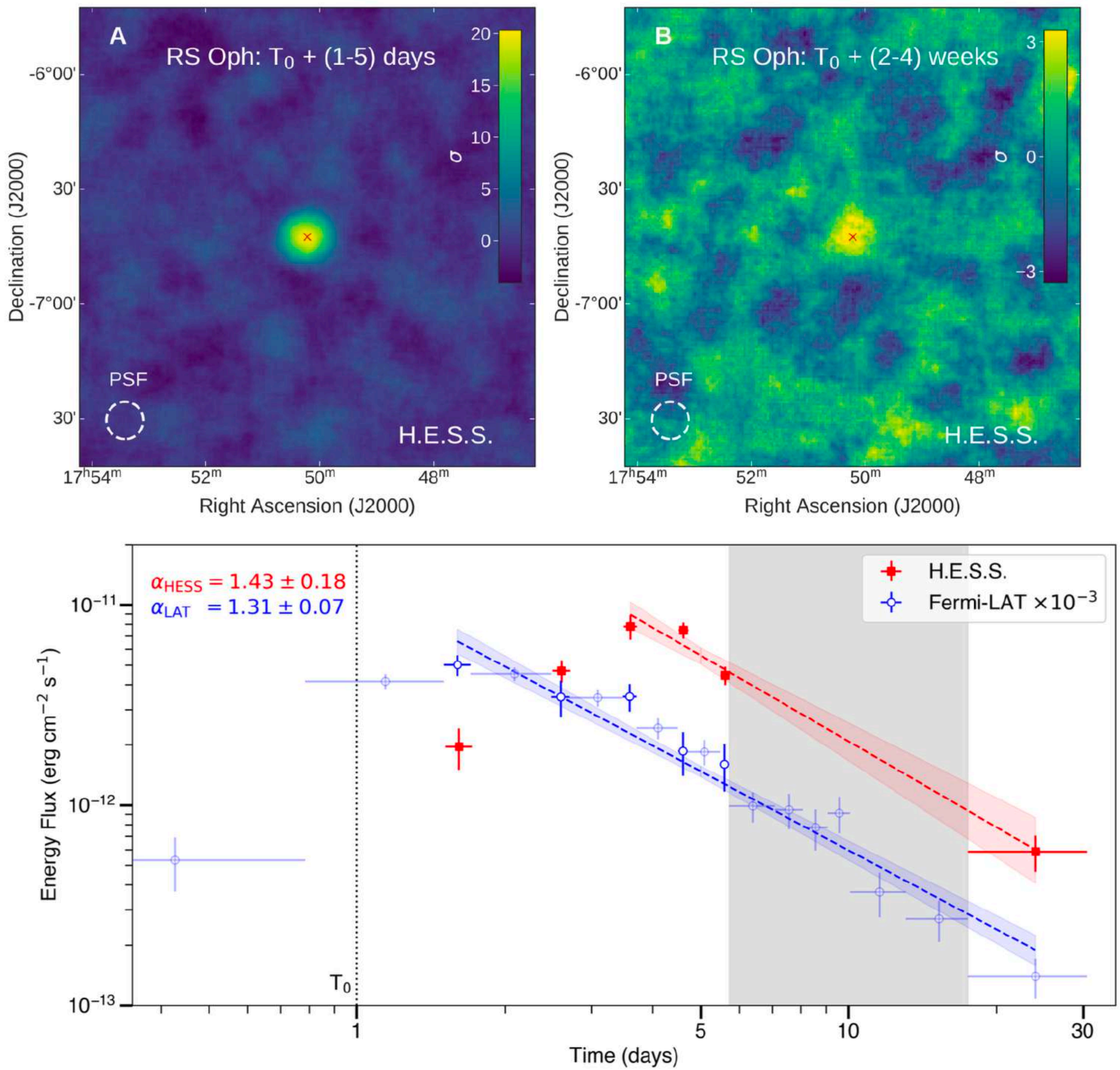
Artist view, wiki

Direct imaging V1674 Her

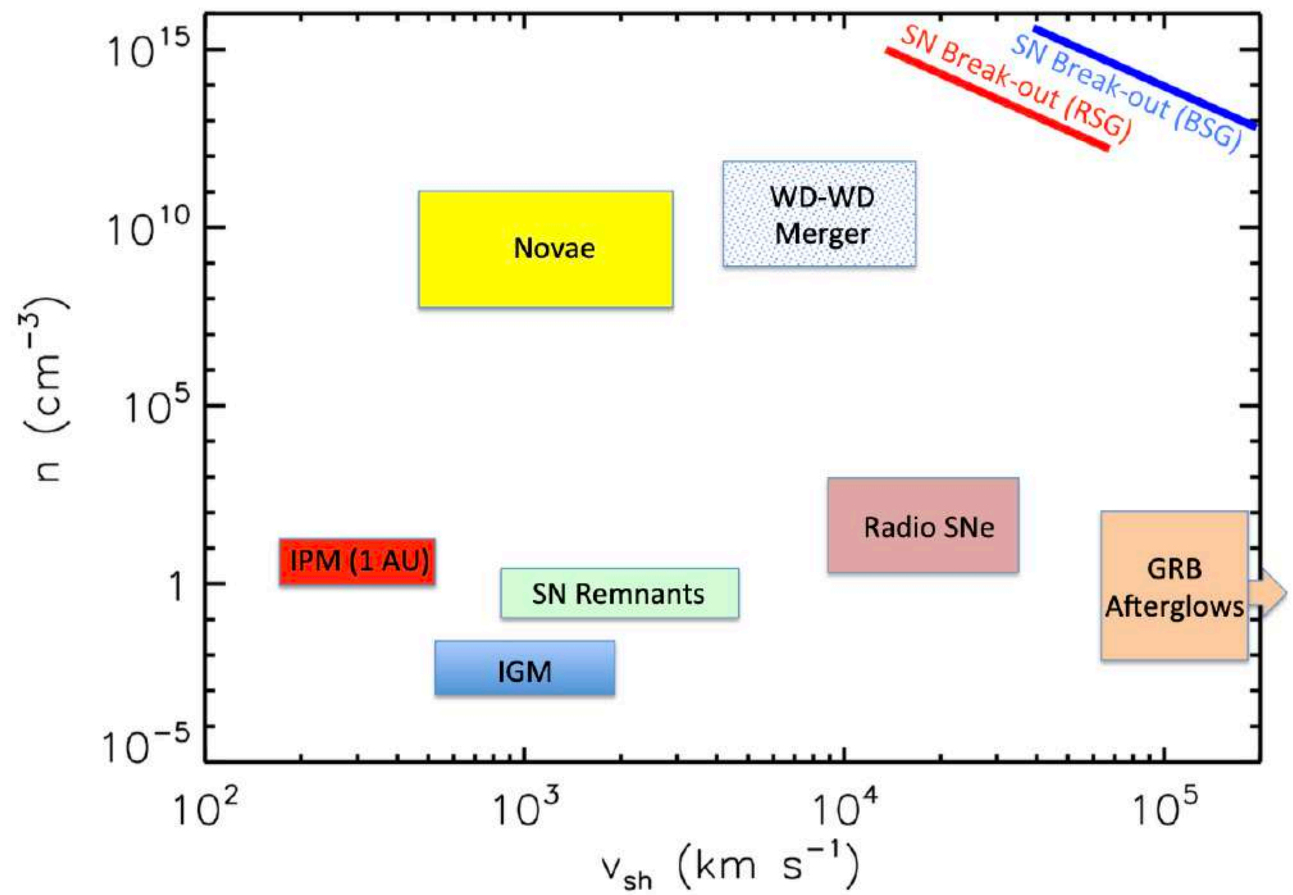


Aydi et al. 2025

RS Ophiuchi in gamma rays: radiative nova shocks



RS Ophiuchi in gamma rays: radiative nova shocks



SNRs: $n \sim 0.01 - 100 \text{ cm}^{-3}$ $v_{\rm sh} \sim 100 - 10^4 \text{ km/s}$

Novae: $n \sim 10^8 - 10^{10} \text{ cm}^{-3}$ $v_{\rm sh} \sim 100 - 3000 \text{ km/s}$

$$t_{\rm cool} \sim \frac{3kT_{\rm sh}}{2n\Lambda(T)} \qquad T_{\rm sh} \approx \frac{3\mu m v_{\rm sh}^2}{16k}$$

$$10^7 \text{ K} \rightarrow \Lambda(T) \sim 10^{-22} \text{erg cm}^3\text{s}^{-1}$$

$$t_{\rm cool} \approx 3\times 10^6 \left(\frac{T}{10^7\text{K}}\right)\left(\frac{10^{10}\text{cm}^{-3}}{n}\right)\text{s}$$

Days to weeks

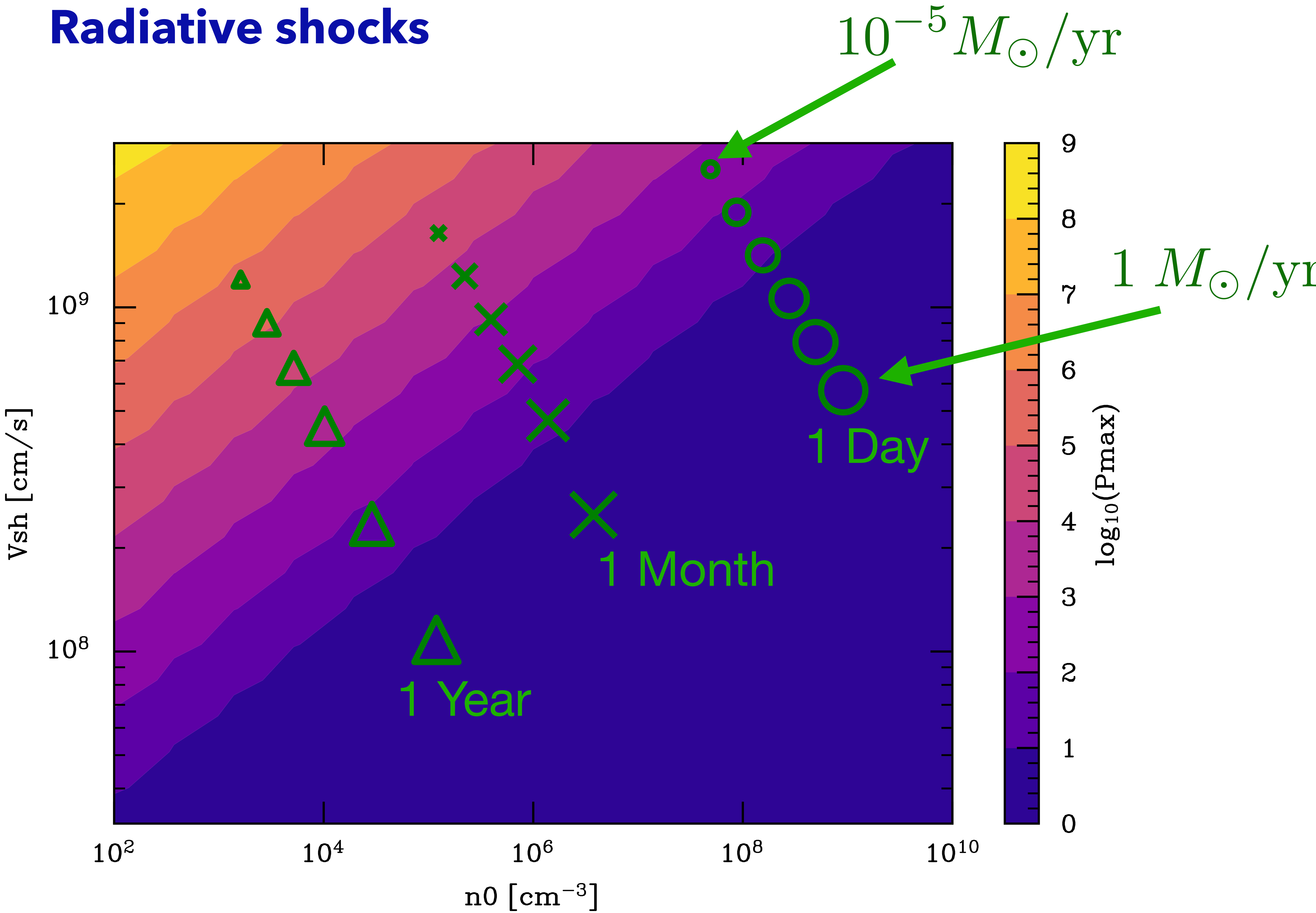
$$t_{\rm cool} \propto \frac{v_{\rm sh}^2}{n}$$

$$t_{\rm acc} \lesssim t_{\rm cool}$$

To allow particle acceleration: high energy probe fresh acceleration

Metzger et al. 2015

Radiative shocks

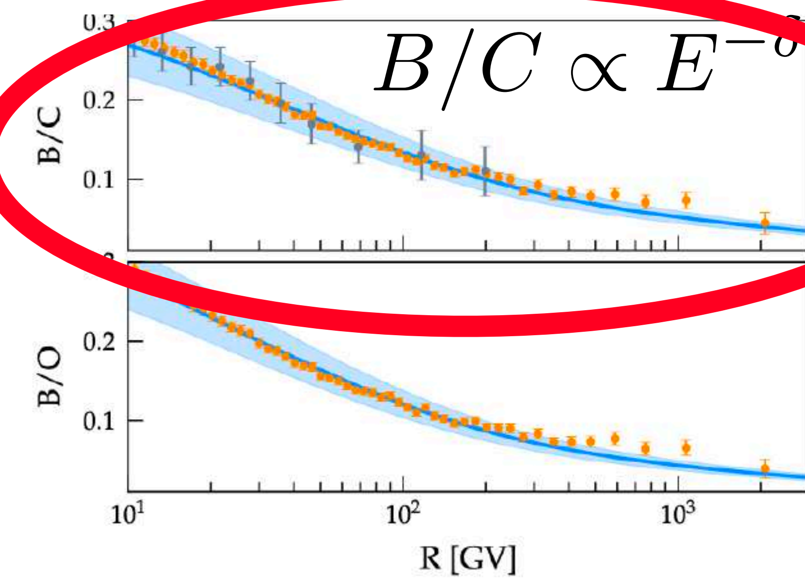


Problem faced by the SNR hypothesis

1. **Diffusive shock acceleration predicts E^{-2} at SNRs**

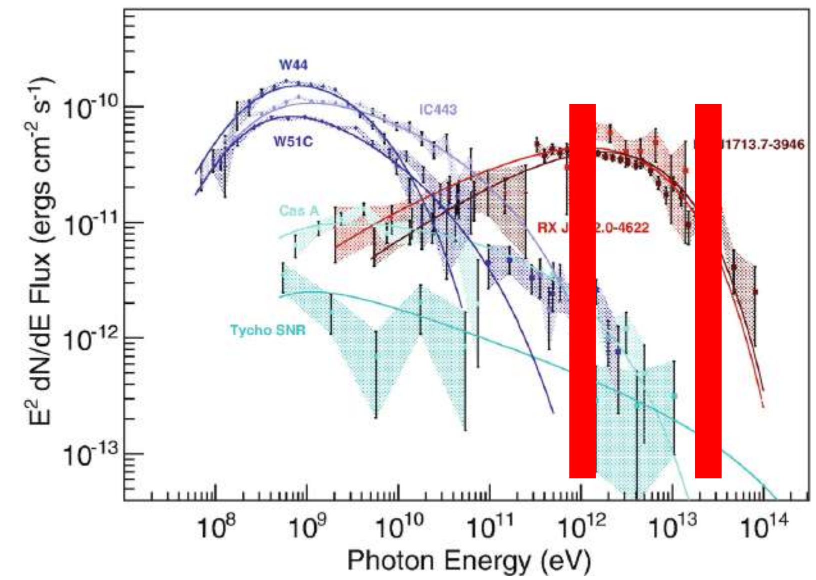
$$E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$$

Injection **Propagation**



2. **Non-thermal emission from radio to gamma**

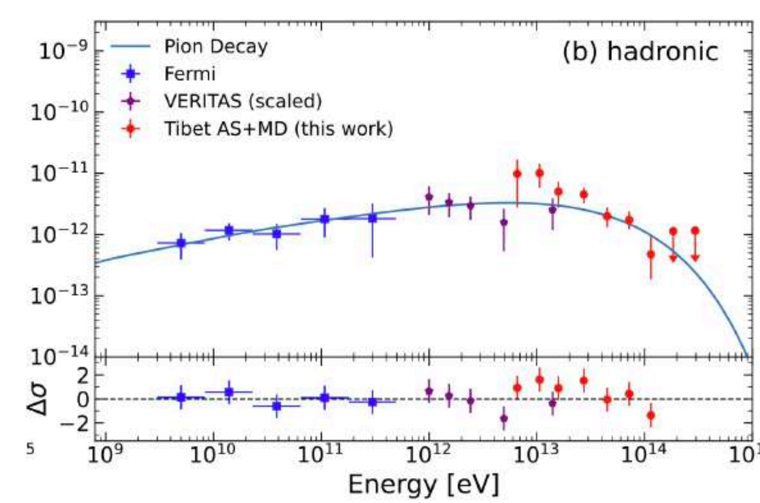
VHE domain steep spectra?
Particle content: protons/electrons?



Funk (2017)

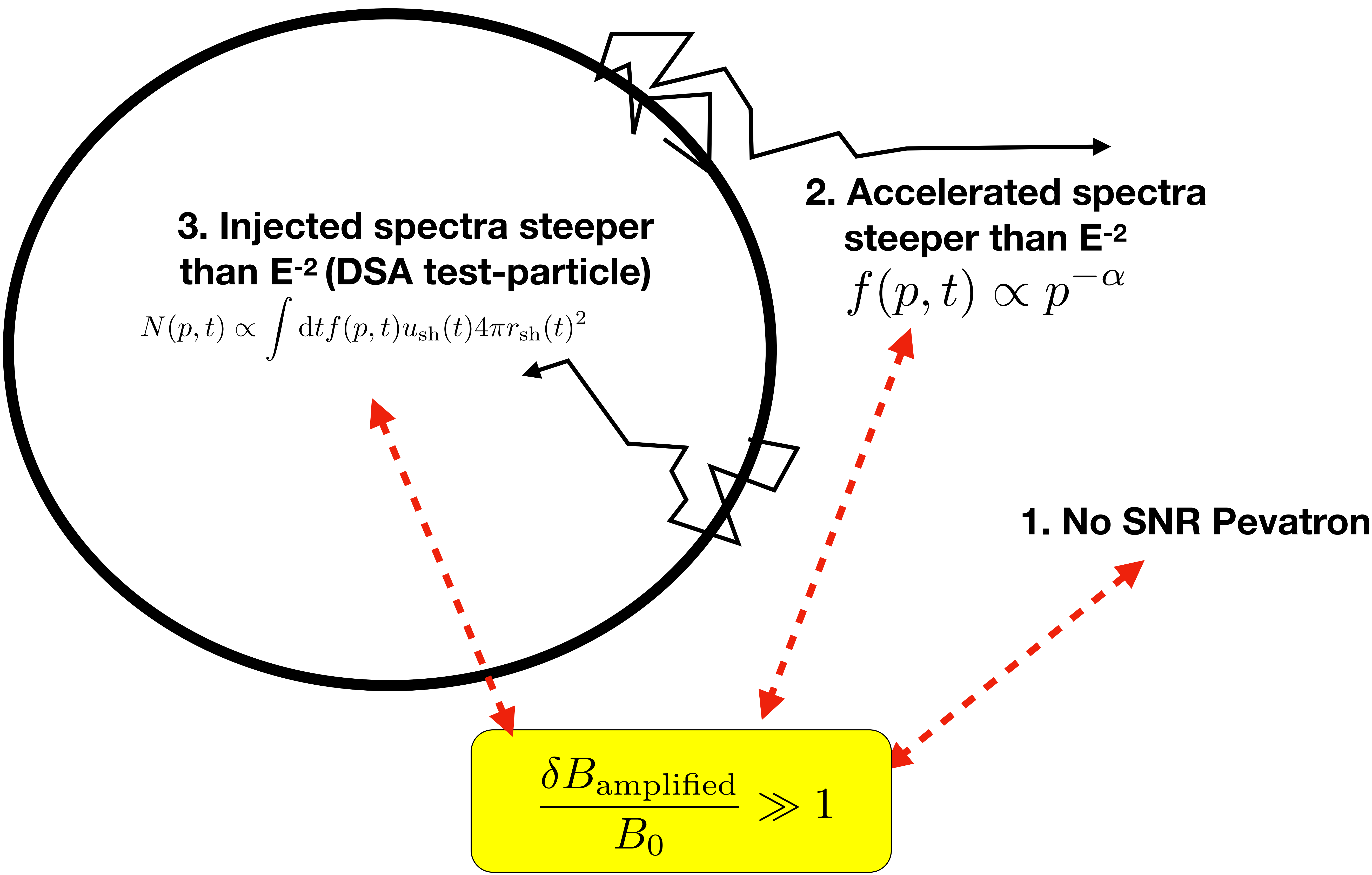
3. **SNR Pevatron? (magnetic field amplification)**

NO SNR pevatron?

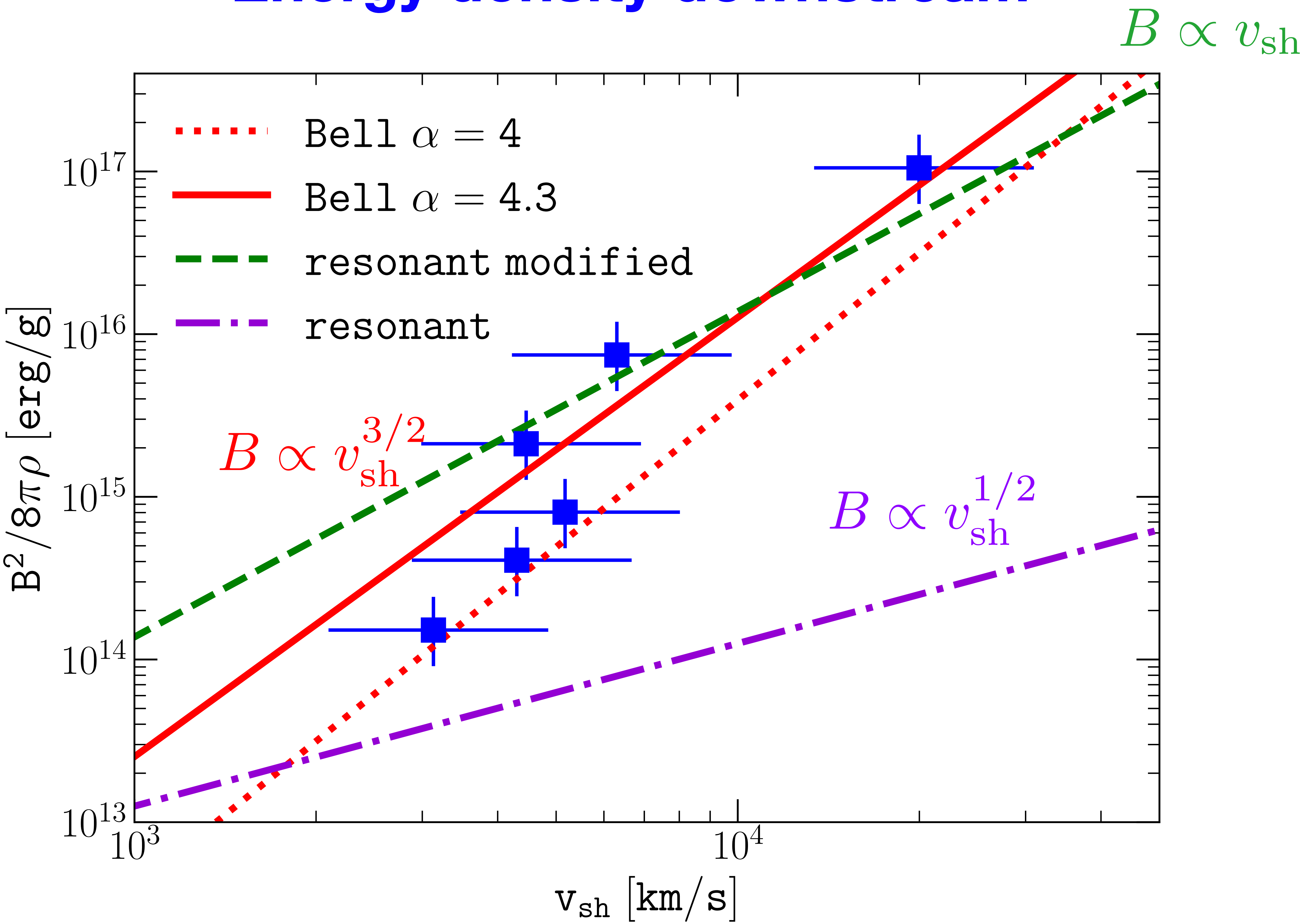


SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

Supernova remnants: Three issues



Energy density downstream

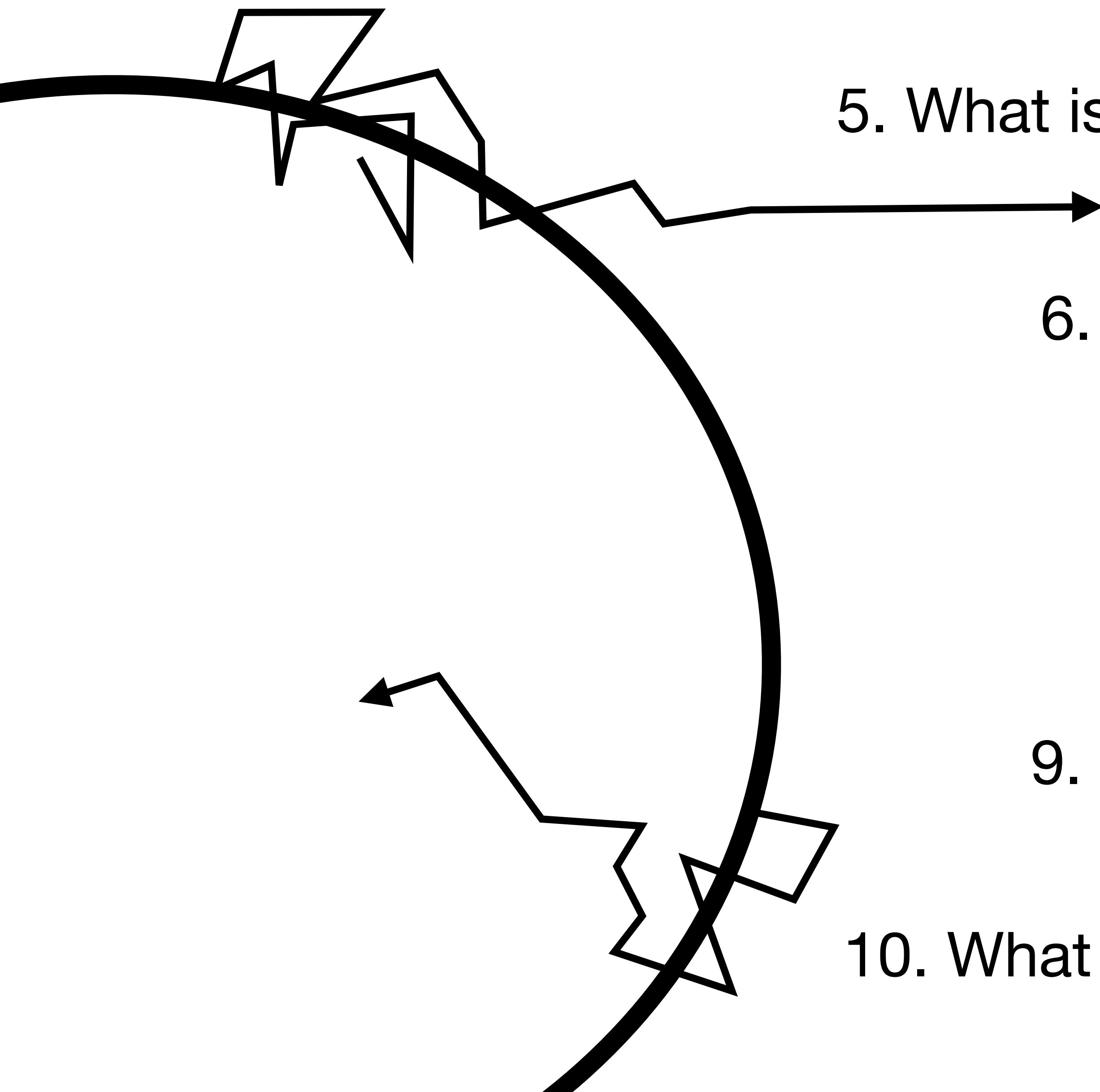


Vink 2012

Conclusions: need to answer these questions

All connected !

1. How are particles **injected** in the accelerator?
2. What is the **efficiency** of particle acceleration?
3. What is the **spectrum of accelerated** particles at the shock?
4. **Protons? Electrons?** Ratio?
5. What is the effect of losses on the **trapped** particles?
6. **How long** does the acceleration phase last?
7. How do particles **escape** the SNR?
8. How is the **magnetic field amplified**?
9. What is the **maximum energy** of accelerated particles?
10. What is the role of pre-existing CRs (**reacceleration**?)



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