Status of the multi-messenger extragalactic backgrounds

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The de Chéseaux - Olbers paradox

Why is the sky not covered by stars ?

Riddle from T. Digges (1576) in his translation of Copernicus' *De revolutionibus orbium coelestium*.

Formulated by de Chéseaux (1744), popularized by Olbers (1823):

$$\Phi_{total} = \int dr\ \Phi_{star} \times N_{star}(r; r+dr) \text{ with } \Phi_{star} \propto 1 / r^2 \text{ and } N_{star}(r; r+dr) \propto r^2$$

In a **static unbounded universe** (Descartes, Newton):

$$\Phi_{total} \rightarrow \infty !$$

Triggered many cosmological ideas

Absorbing medium? Heat up and reradiate (Herschel, Kelvin)

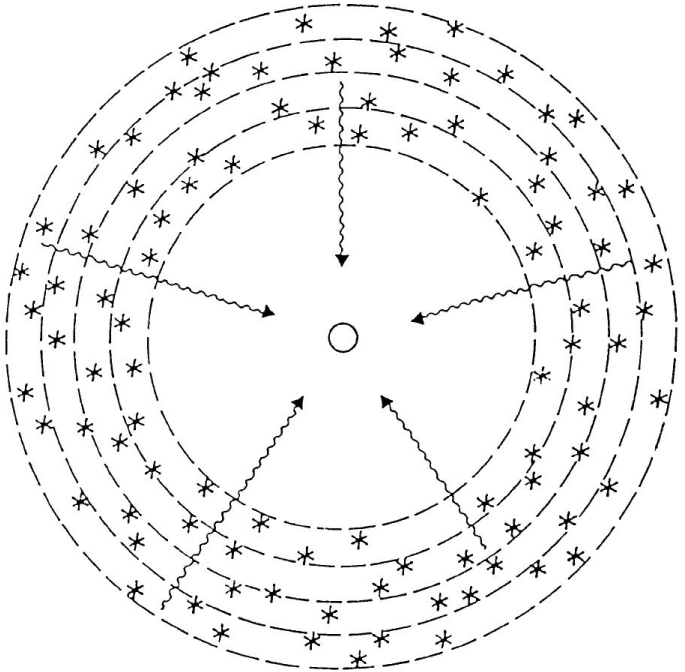
Hierarchical structures (fractal)? (Kant, Herschel, Fournier d'Albe...)

Looking back in time! (Poe)

"The only way we could comprehend the voids which our telescopes find in innumerable directions would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us."

(Edgar Allan Poe, *Eureka*, 1848)

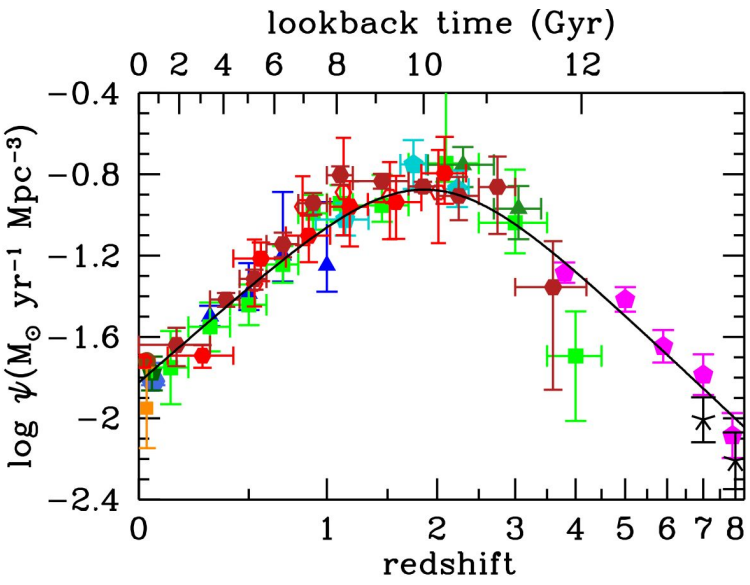
"Infinity of the sphere of stars" (Halley, 1721) at this link



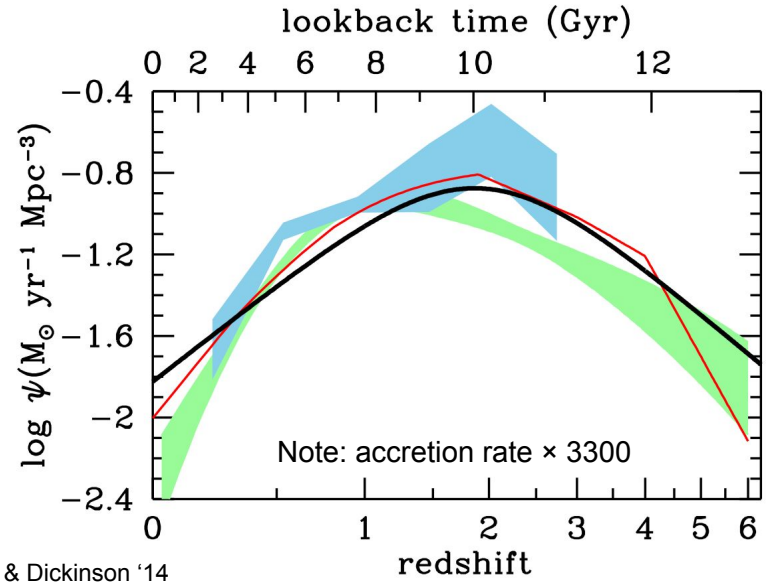
Credits: Harrison '90

A finite astrophysical history

Star formation history



Black-hole accretion history



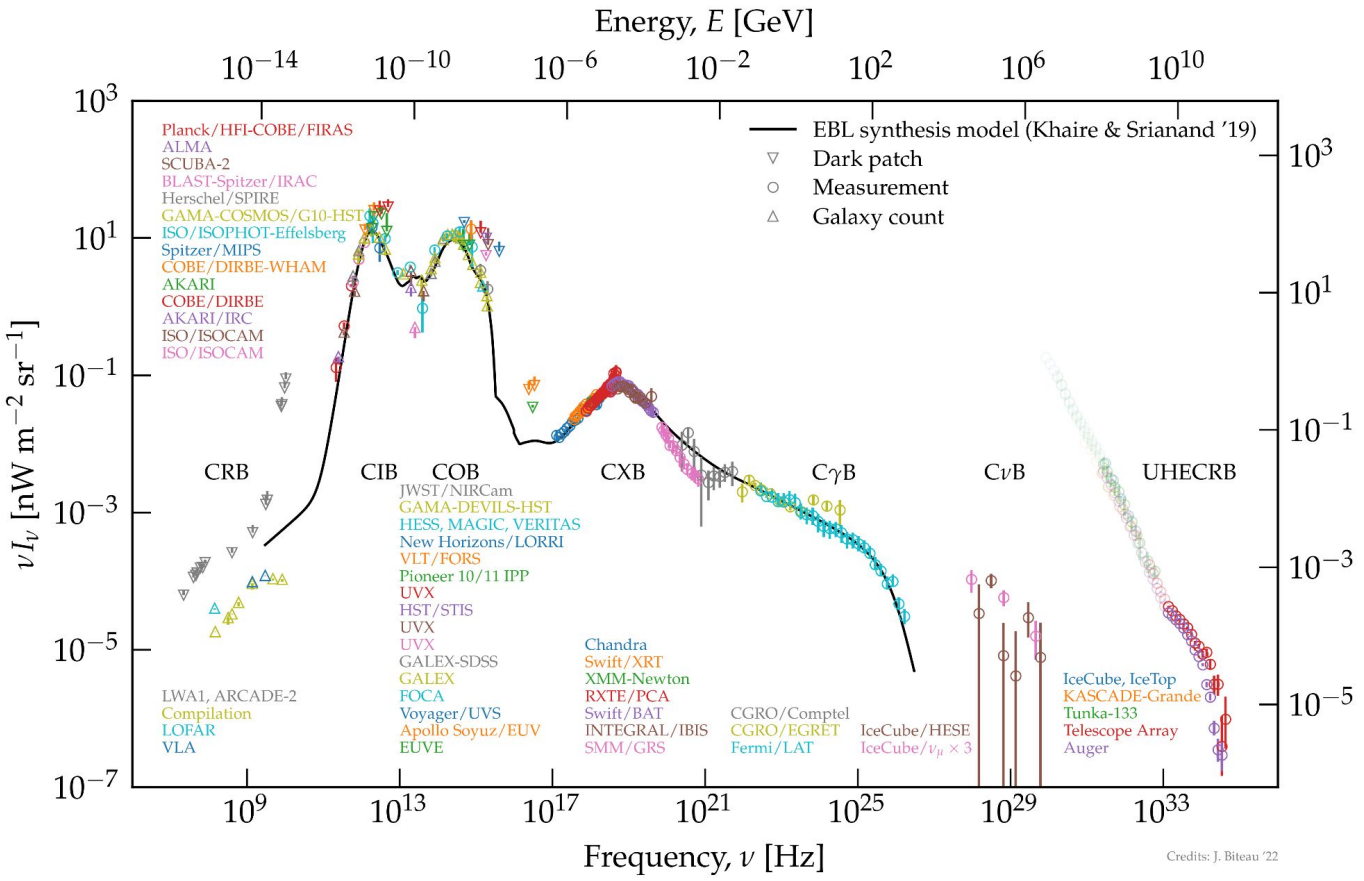
Credits: Madau & Dickinson ‘14

Modern version of the riddle: How dark is the night sky?

i.e. what is the radiation / astroparticle content of the universe?

Photon/particle equivalent of the cosmic baryon budget.

The multi-messenger extragalactic backgrounds



All measurements of extragalactic backgrounds from radio to ultra-high energies

I will make the **code, data and models public by summer '23**

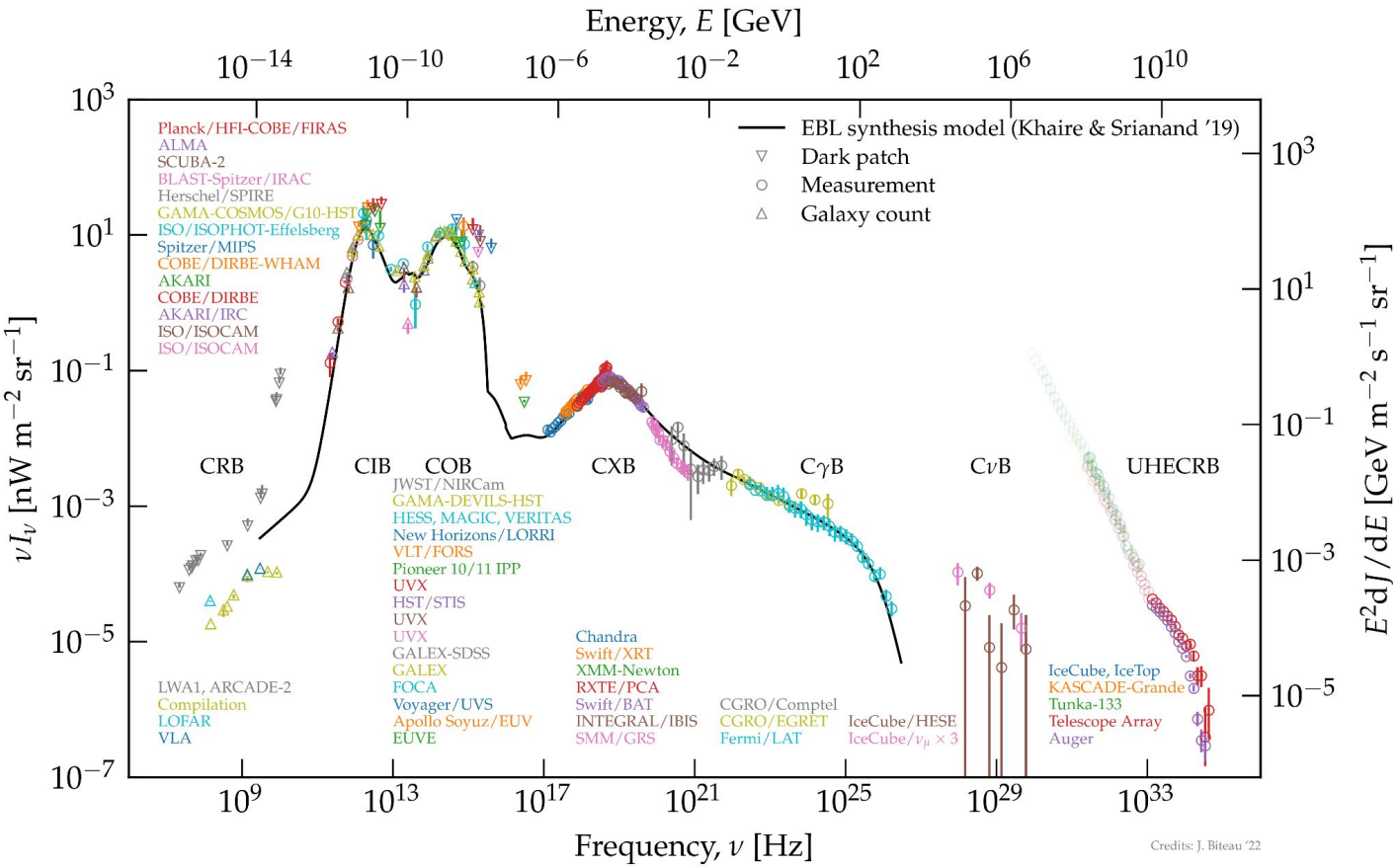
Credits

Dataset: partly from Hill+ '18

Code: adapted from Evoli 21

See also: reviews from Cooray '16 and Driver '21

The multi-messenger extragalactic backgrounds



Disclaimers on this review

Focus on monopoles
no deep coverage of: dipole, smaller angular scales, autocorrelation, cross-correlations

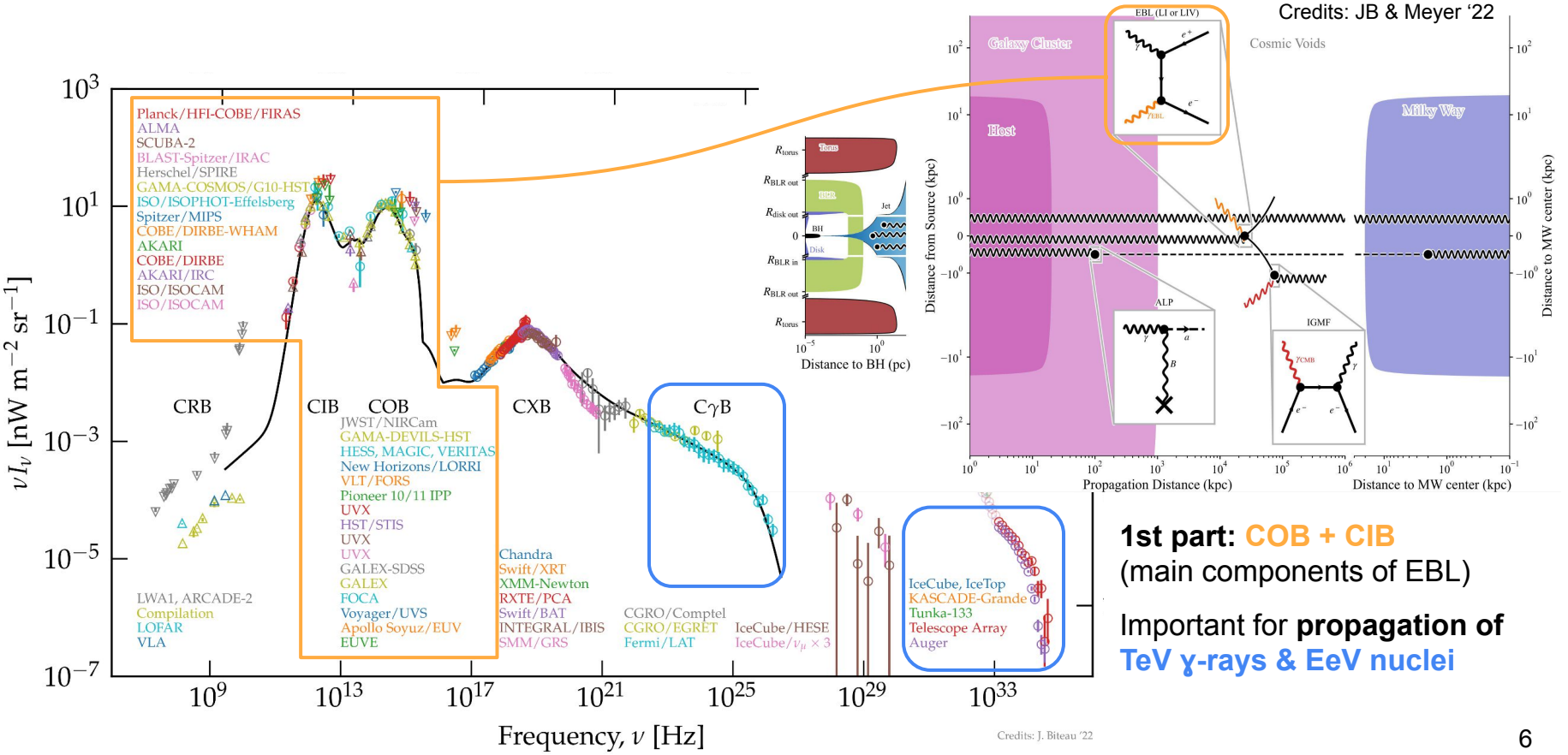
Gravitational waves not covered here

Radio to optical
data and model sets **quite complete**

>UV
a few measurements and **a bunch** of models **to be added**

Your feedback is highly valued!

The extragalactic backgrounds are linked



Credits: J. Biteau '22

1st part: COB + CIB
(main components of EBL)

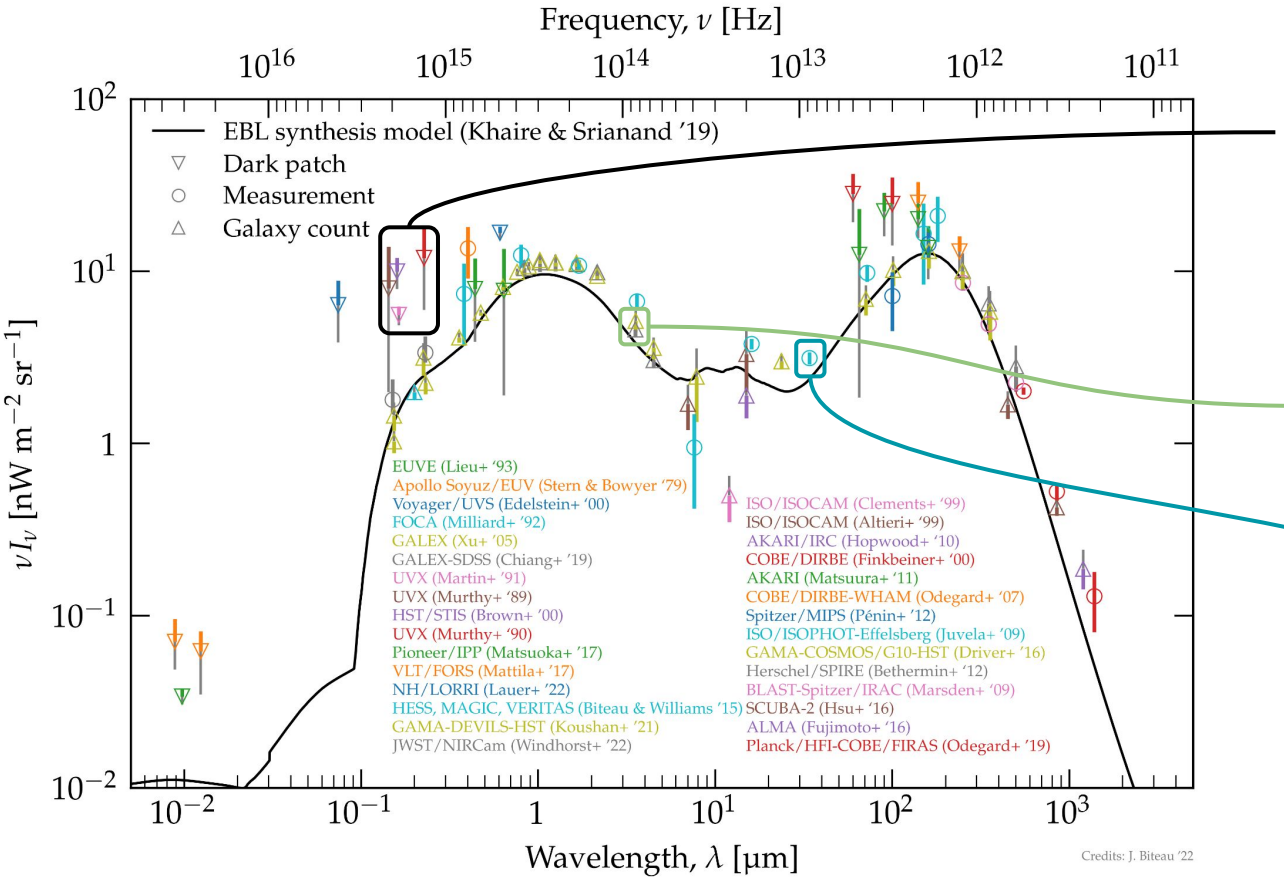
Important for **propagation of TeV γ-rays & EeV nuclei**

Part I - COB and CIB

Part II - CRB, CXB and CGB

Part III - CνB and UHECRB

Measurements of the COB and CIB

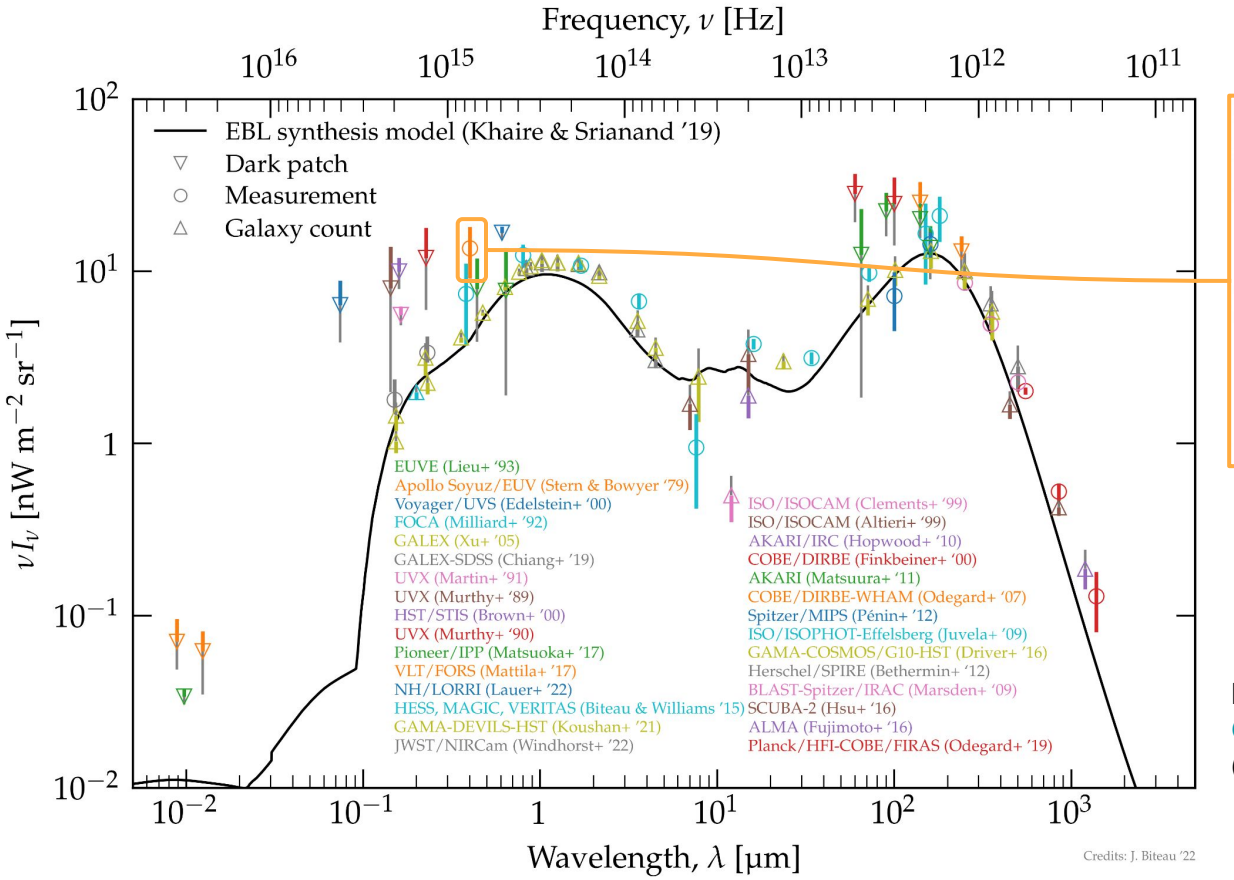


Some direct estimates in dark patches of the sky

Integrated galaxy light (galaxy counts)

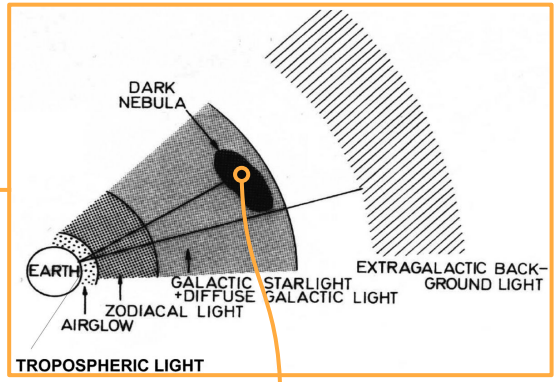
Some constraints from ɣ-rays + galaxy counts

COB & CIB: dark-patch estimates



Credits: J. Biteau '22

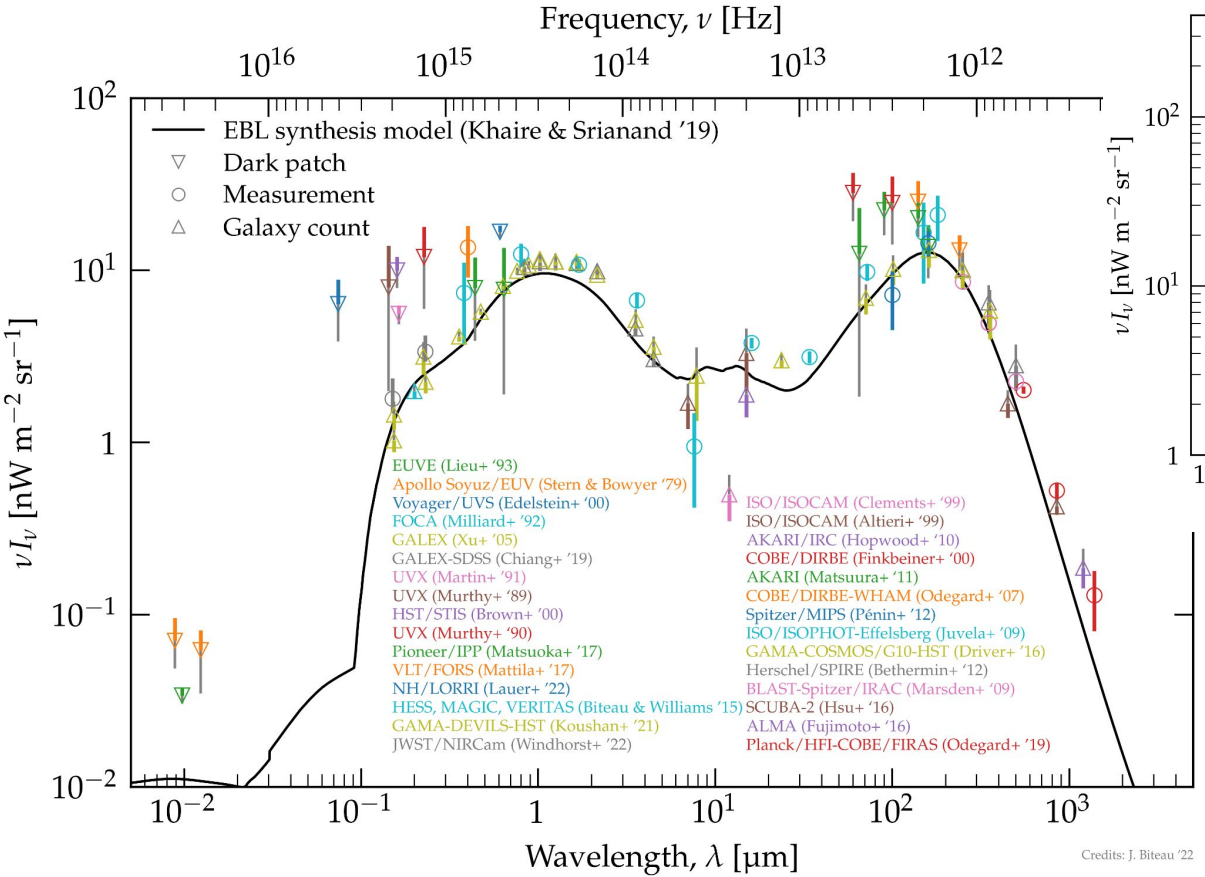
Credits: Mattila+ '17

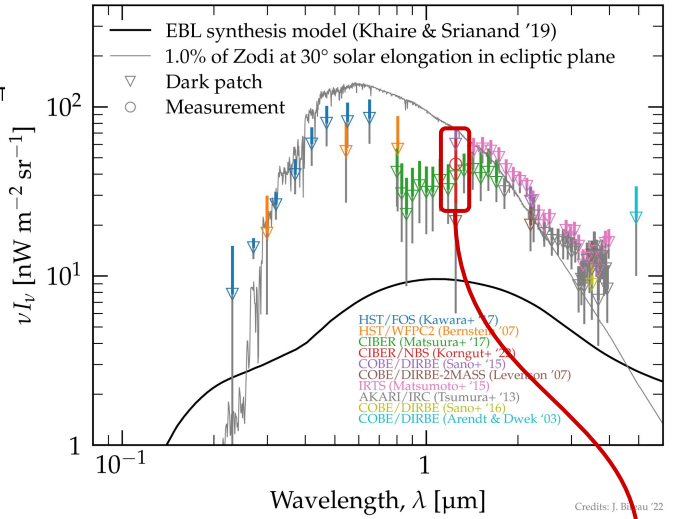


opaque molecular cloud
Lynds 1642 at d = 0.2 kpc

Note: similar JWST proposal using Galilean satellites, approved for 24.3h (2021jwst.prop.2134T)

COB & CIB: the Zodi contaminant

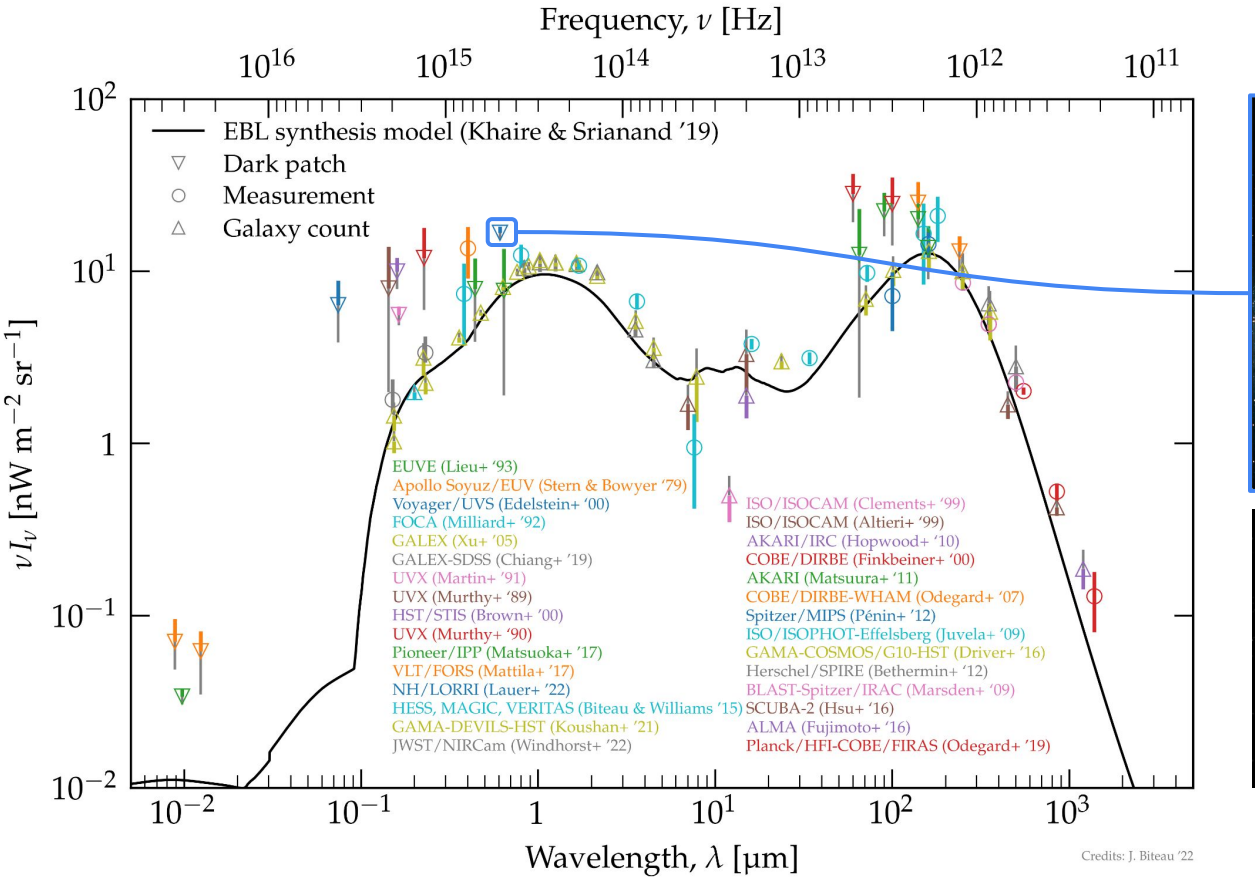




Dark-patch estimates in 0.3-5μm roughly consistent with 1% Zodi

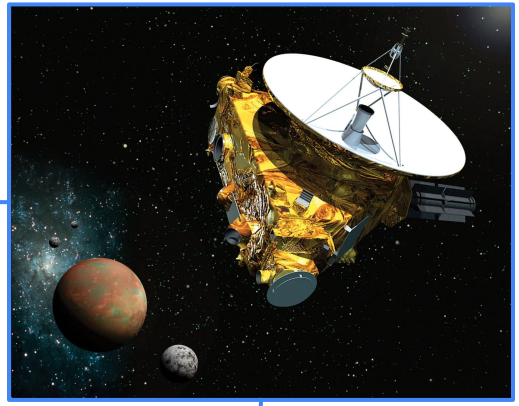
Ca-II absorption lines by CIBER
→ unaccounted for (Kelsall+ '98) faint spherical Zodi component

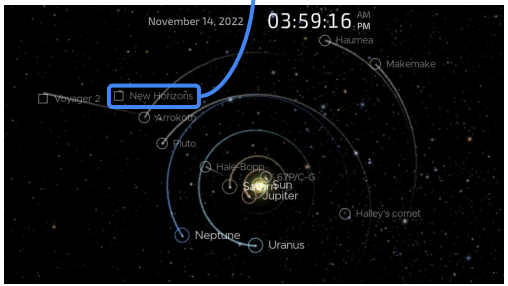
The optical controversy from New Horizons



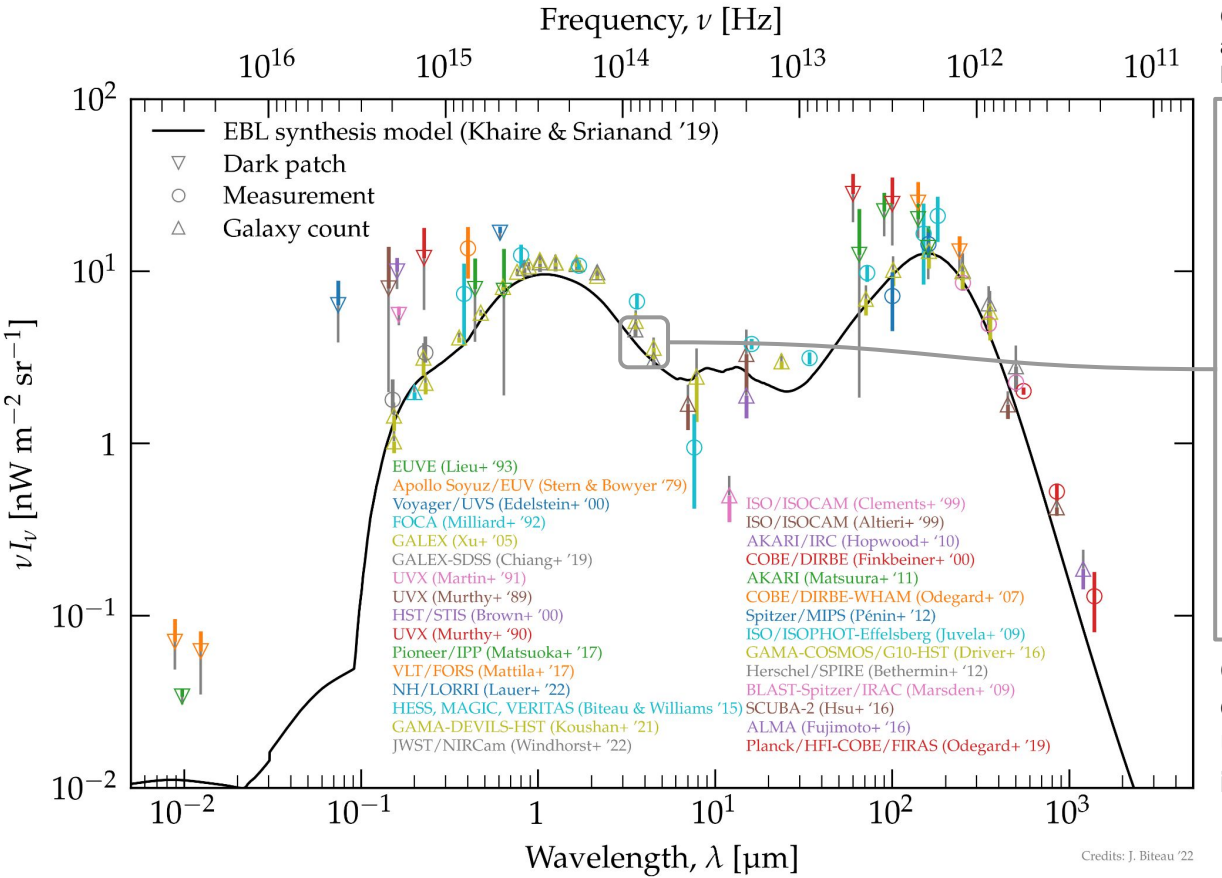
Credits: J. Biteau '22

Credits: NASA; Note: Brian May's song



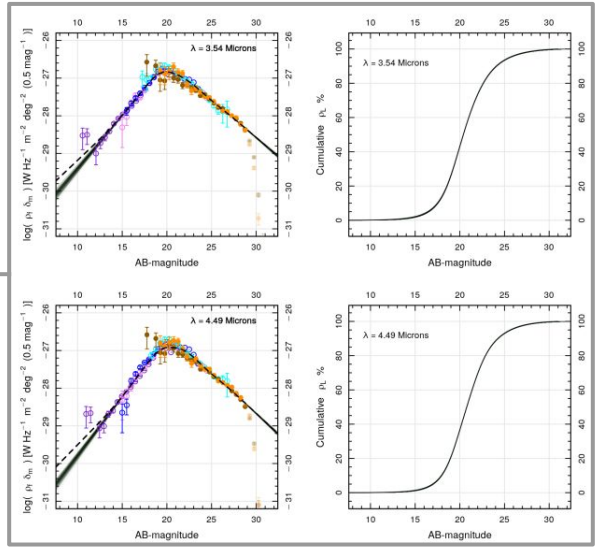


COB & CIB: integrated galaxy light



Credits: J. Biteau '22

Credits: Windhorst+ '22 (JWST's PEARLs program) also Windhorst+ '21, '22 (HST's SKYSURF program), Driver+ '16, Koushan+ '21 (GAMA/HST)



Current limitation (± 5-10%):
cosmic variance → future: 1%

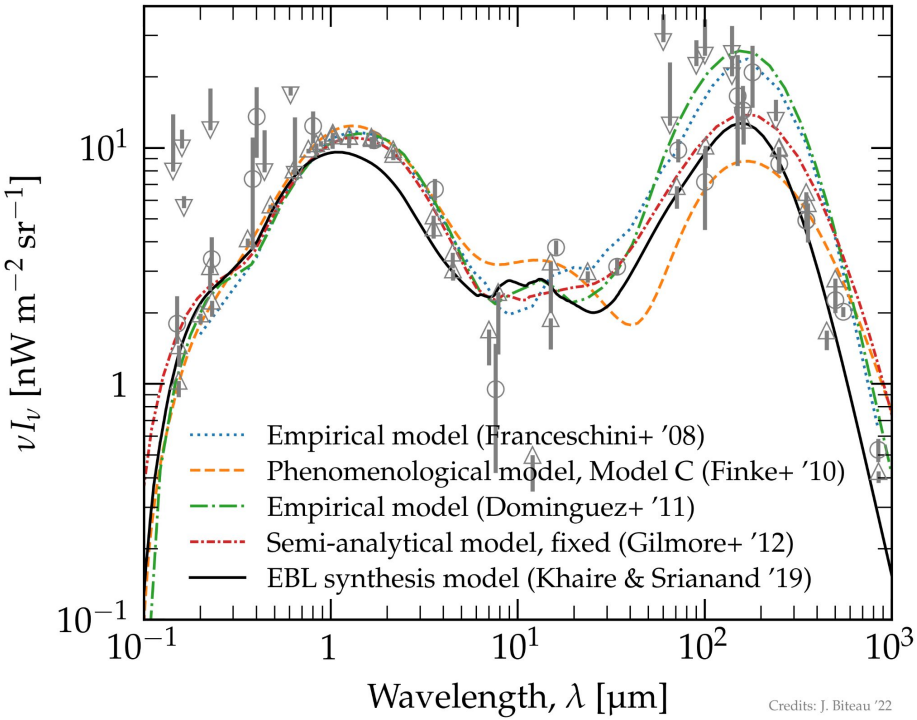
Unknowns (<30%):
intra-halo, -group, -cluster light

Models of the COB and CIB: prior to γ-ray measurements

Three main categories of models:

- **Empirical models**
  from observed luminosity functions of galactic populations, extrapolate them to high-*z*
- **Phenomenological models**
  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with simplified equations wrt N-body sims, including sub-grid recipes for baryonic feedback

All models aim at matching observations, in particular galaxy counts (**unknowns = 0**)



Models of the COB and CIB: post γ-ray measurements

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  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
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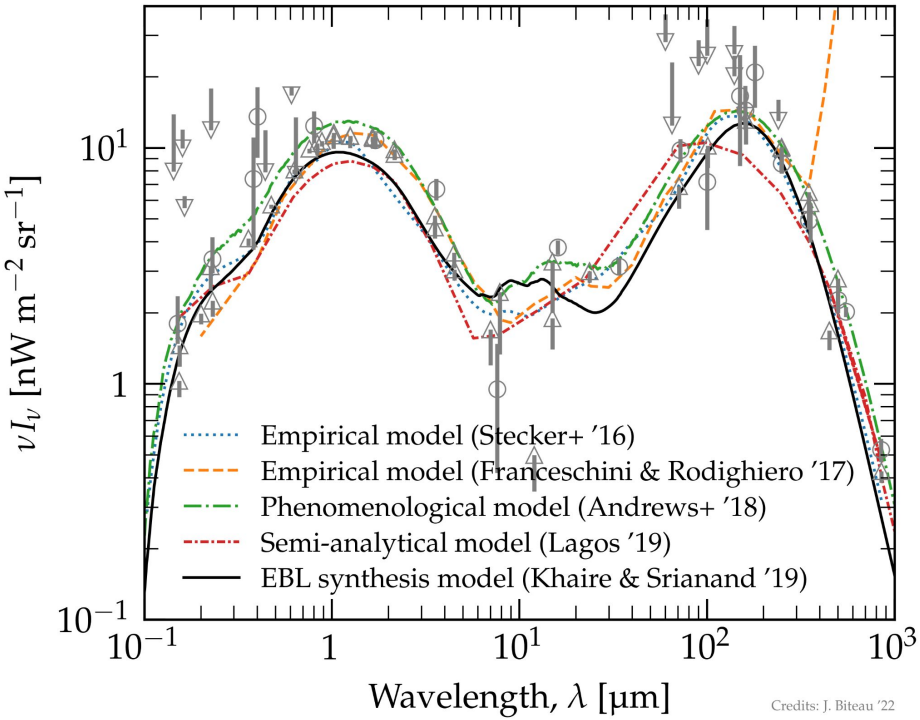

Models of the COB and CIB: most recent

Three main categories of models:

- **Empirical models**
  from observed luminosity functions of galactic populations, extrapolate them to high-*z*
- **Phenomenological models**
  from initial mass function (distribution of stellar mass at 0 age), cosmic star formation history and stellar population synthesis models
- **Semi-analytical models**
  from cosmological simulations with simplified equations wrt N-body sims, including sub-grid recipes for baryonic feedback

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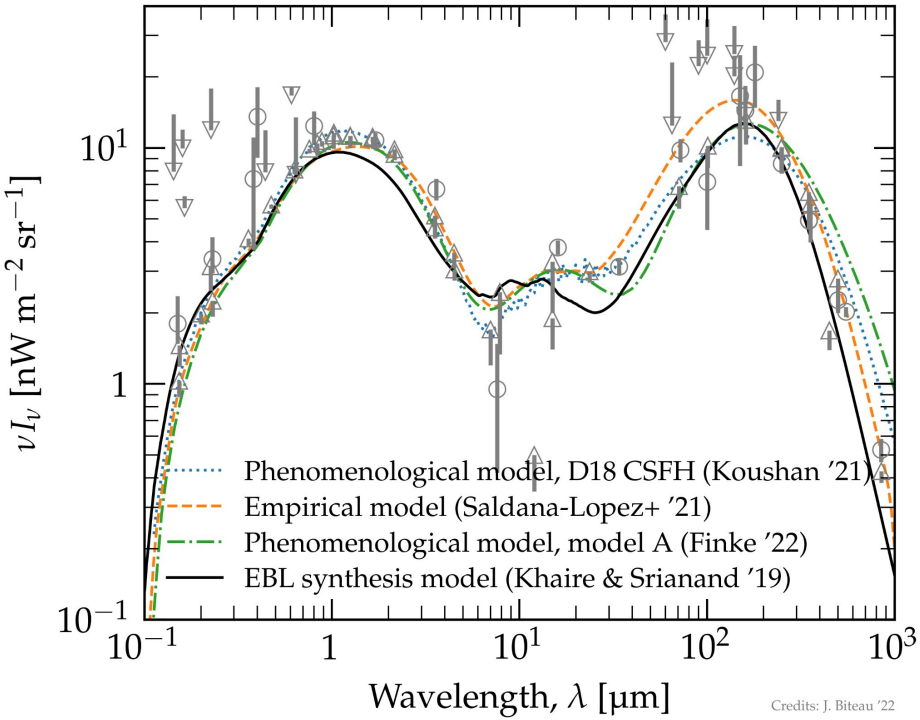

Models of the COB and CIB: possibly best of each type

Three main categories of models:

- **Empirical models**
  from observed luminosity functions
  of galactic populations,
  extrapolate them to high-*z*
- **Phenomenological models**
  from initial mass function
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All models aim at matching observations,
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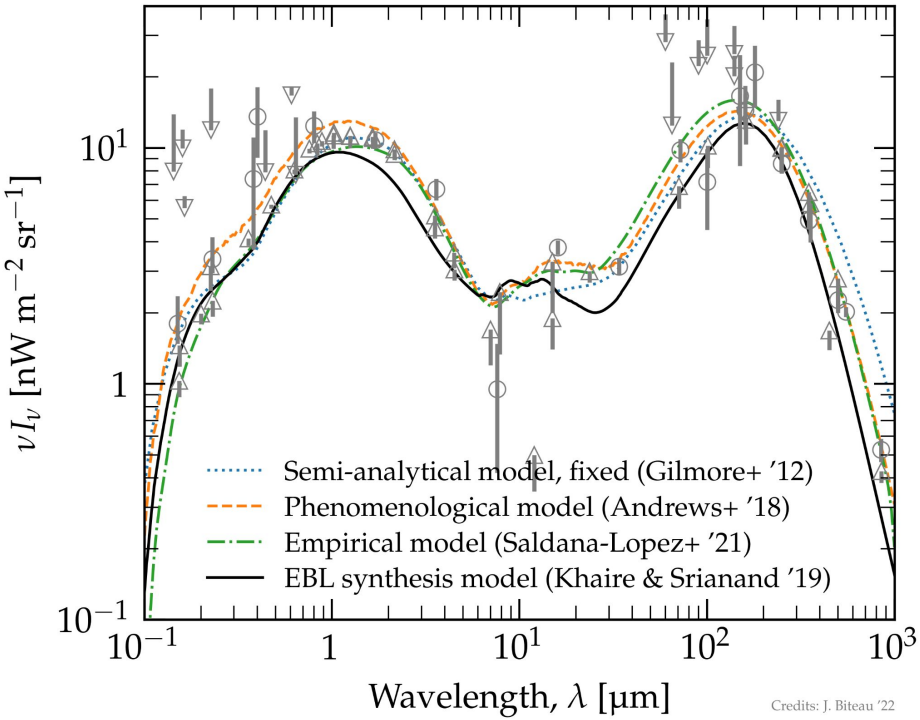
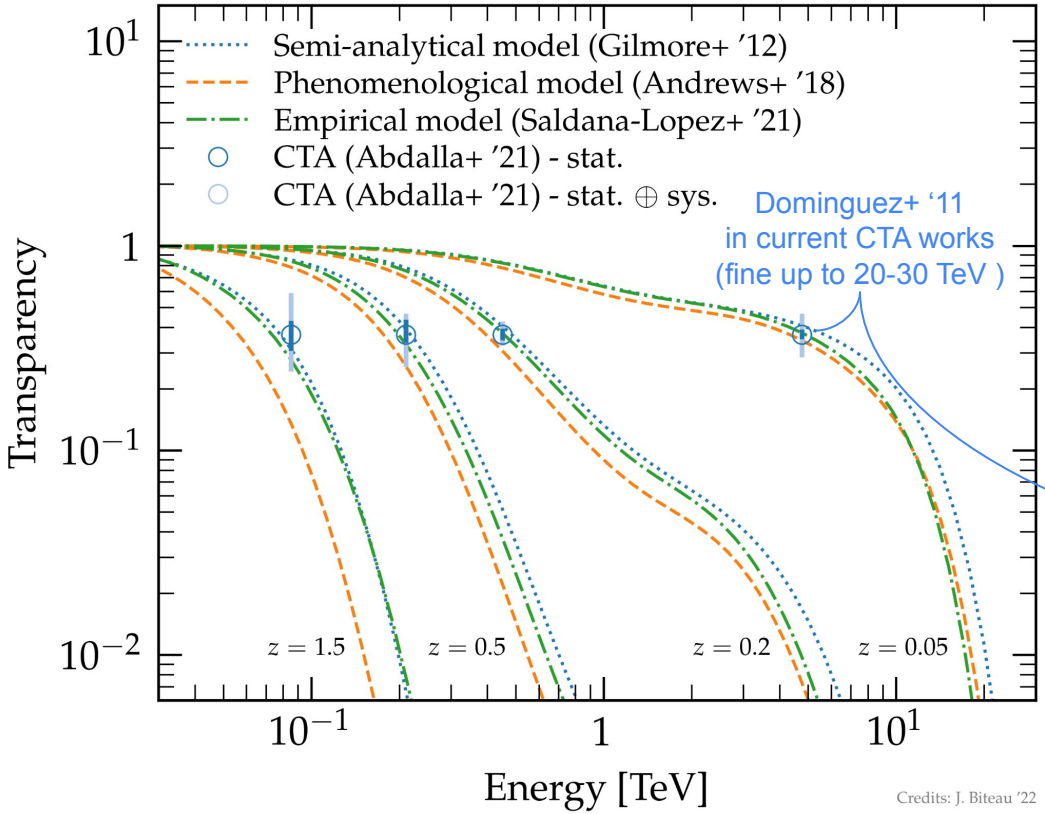
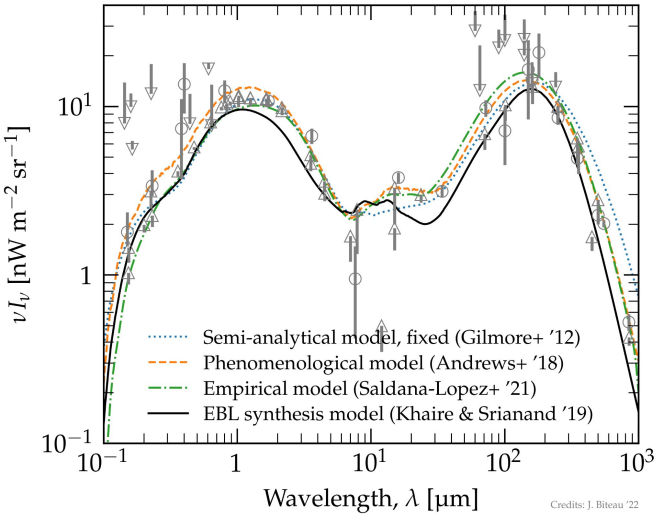
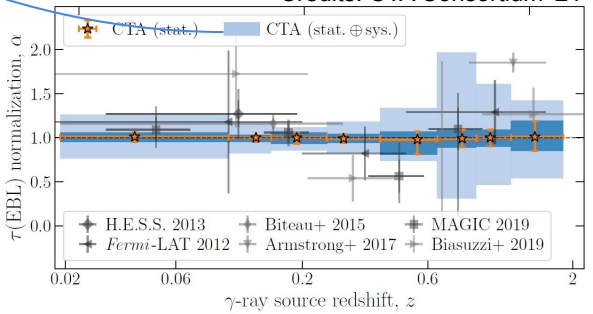


Impact on gamma-ray absorption





Credits: CTA Consortium '21



Status of the COB and CIB as of 2022

Measurements

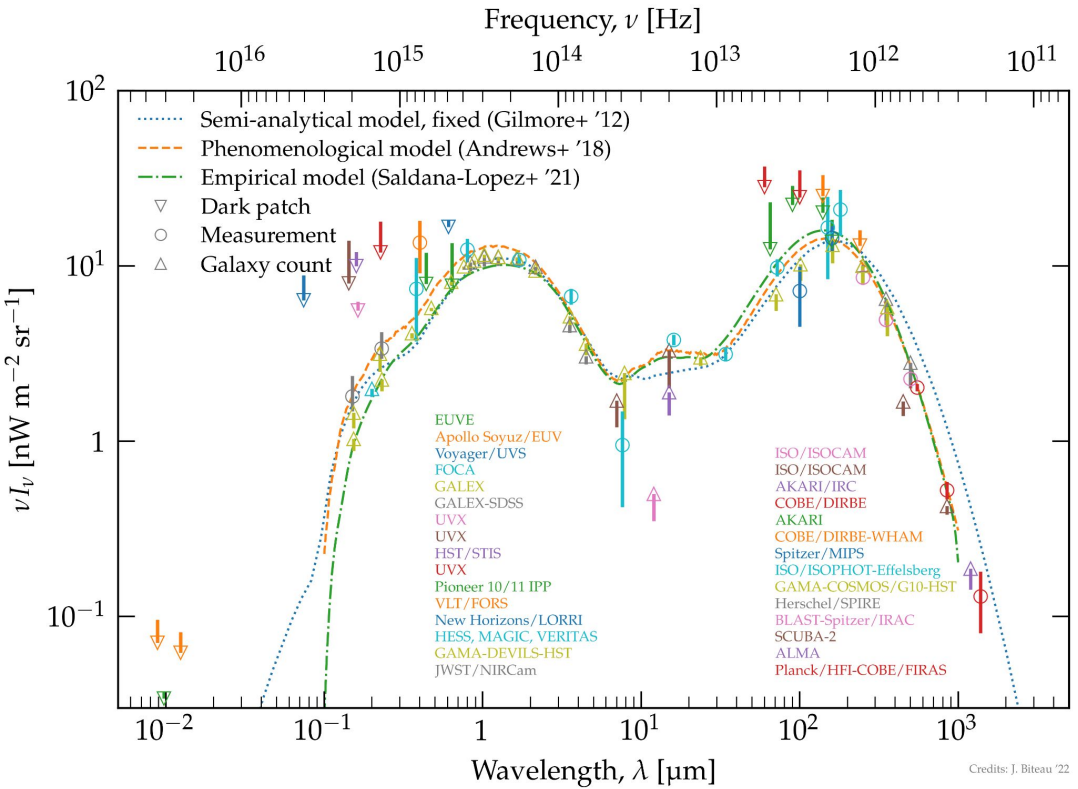
- ❏ Galaxy counts: 5-10% accuracy, 1% in coming years?
- ❏ Dark-patch estimates suggest unaccounted Zodi component. Puzzle from New Horizons.
- ❏ γ-ray measurements still lack accuracy to solve the puzzle.

Models

- ❏ Impressive convergence over the past ten years.

CTA and precursors

- ❏ Beat the systematics.
- ❏ Solve the optical controversy.
- ❏ Measure AGN & PAH contributions.

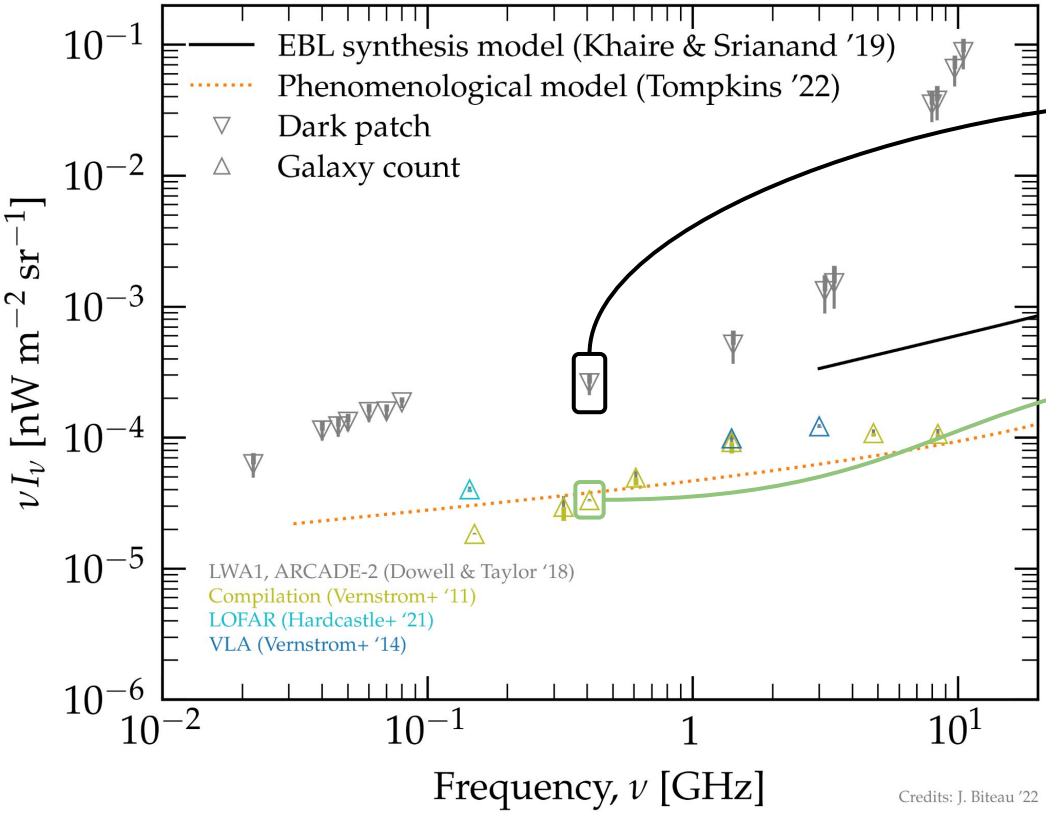


Part I - COB and CIB

Part II - CRB, CXB and CGB

Part III - CνB and UHECRB

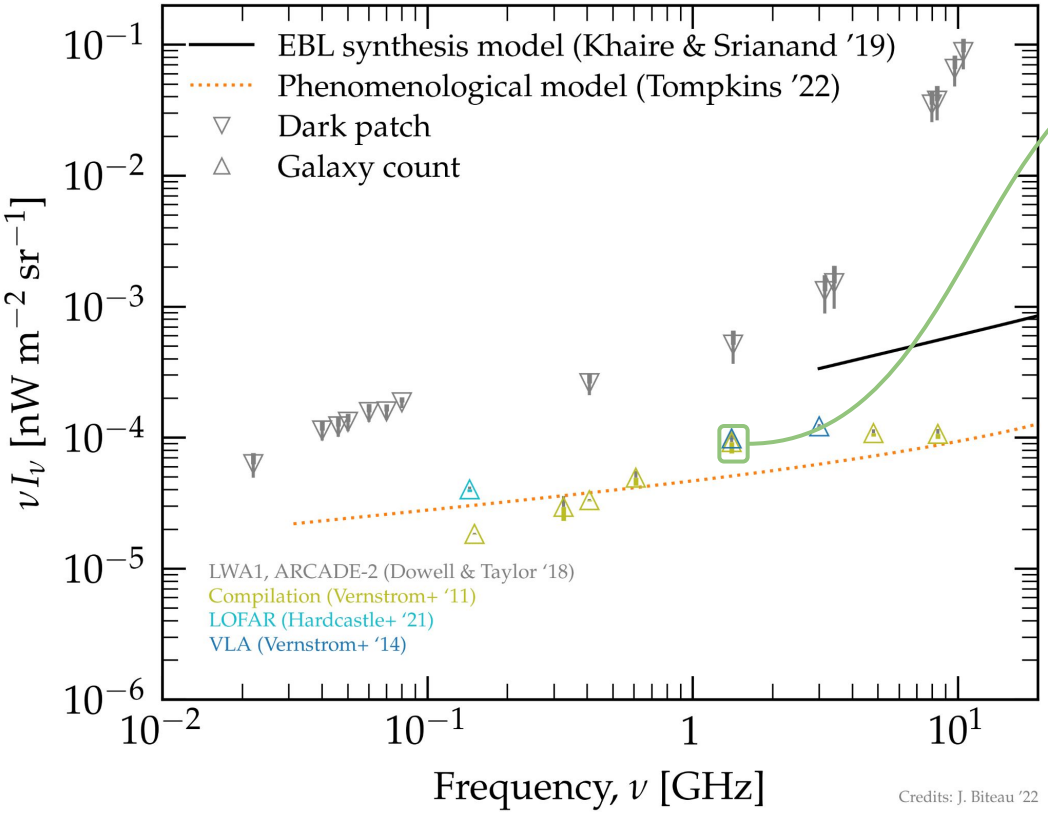
The Cosmic Radio Background



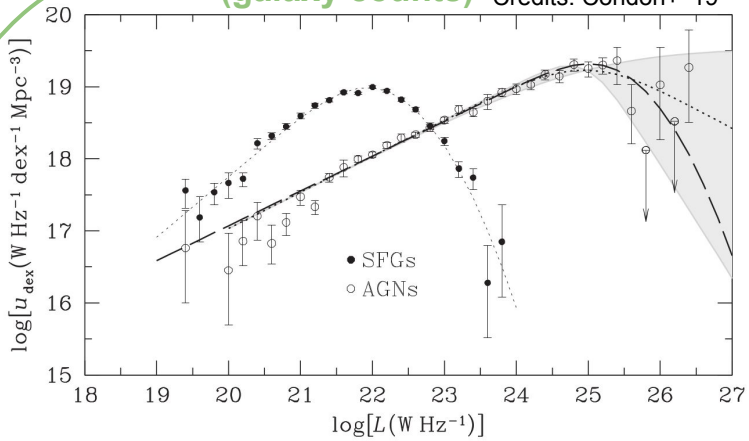
Some direct estimates in dark patches of the sky

Integrated galaxy light (galaxy counts)

The Cosmic Radio Background



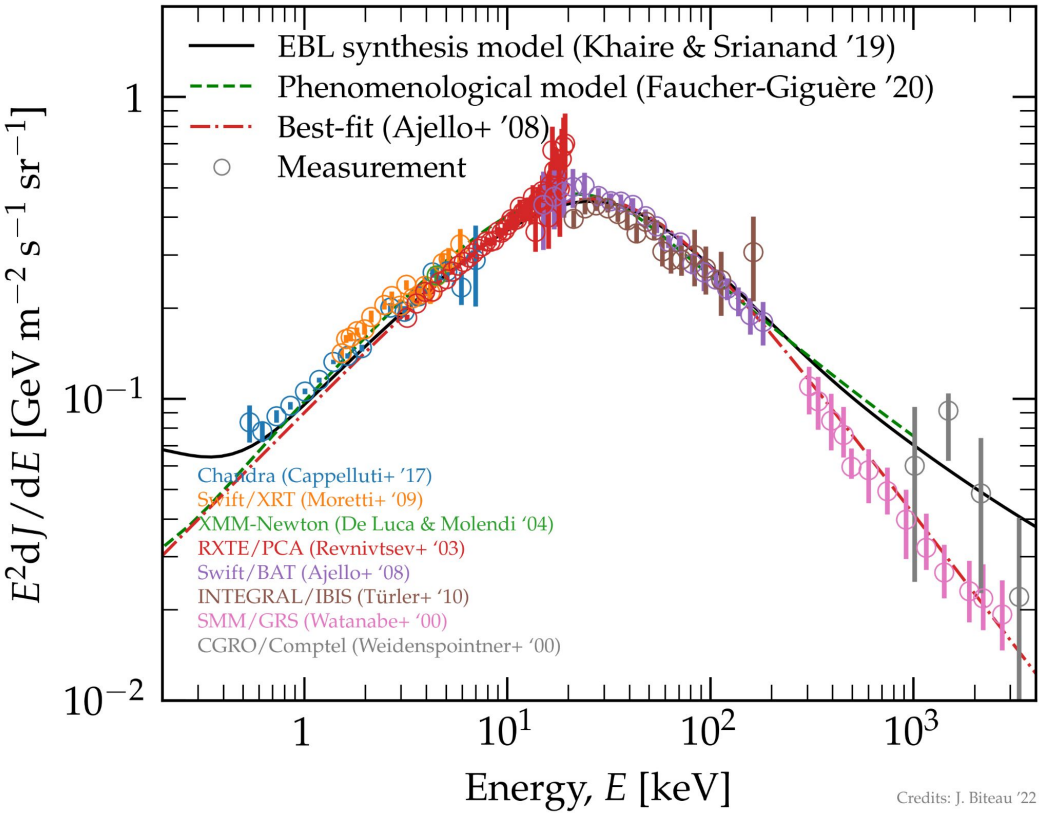
Integrated galaxy light (galaxy counts) Credits: Condon+ '19

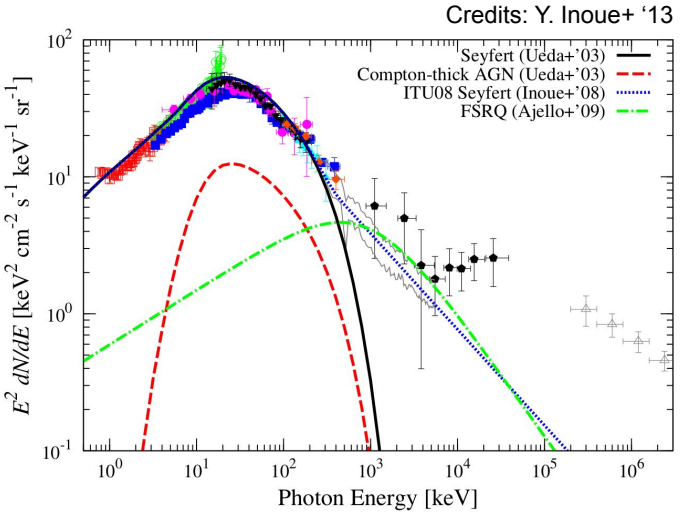


Tension with direct estimates (see Singal+ 2018)**:**

- Small sky coverage / Zero point?
- Galactic halo (X-ray IC counterpart)?
- Extragalactic unknown pop.?

The Cosmic X-ray Background

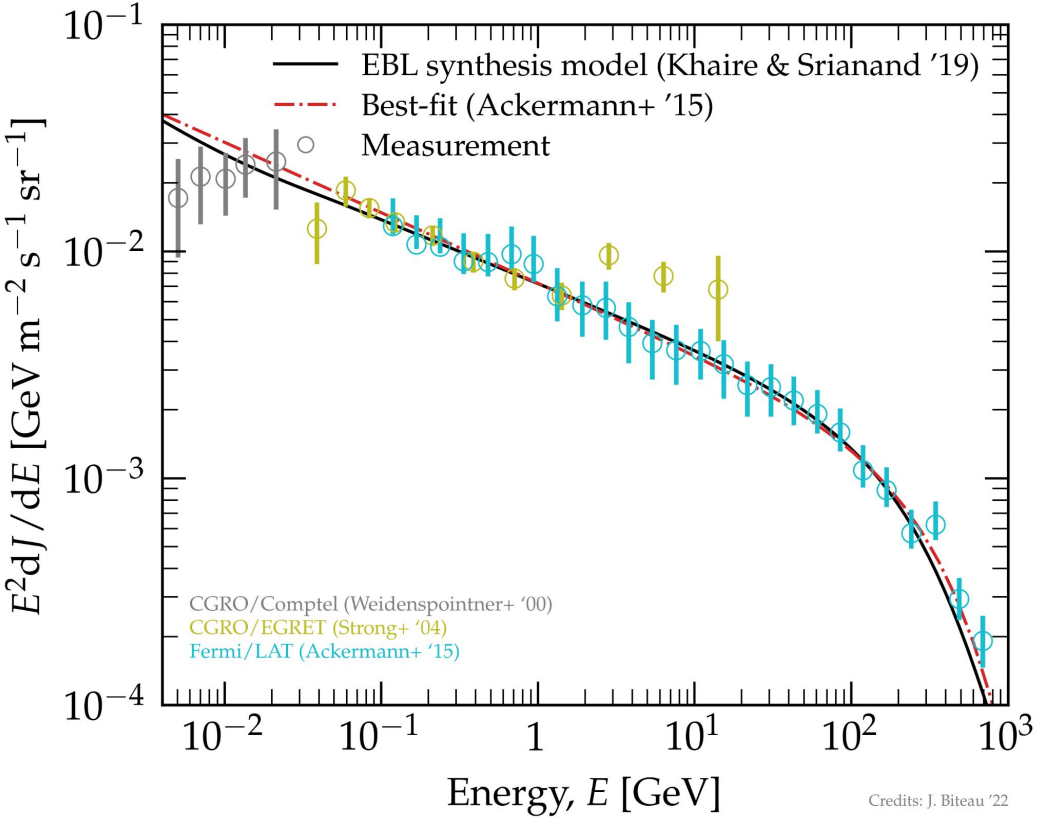


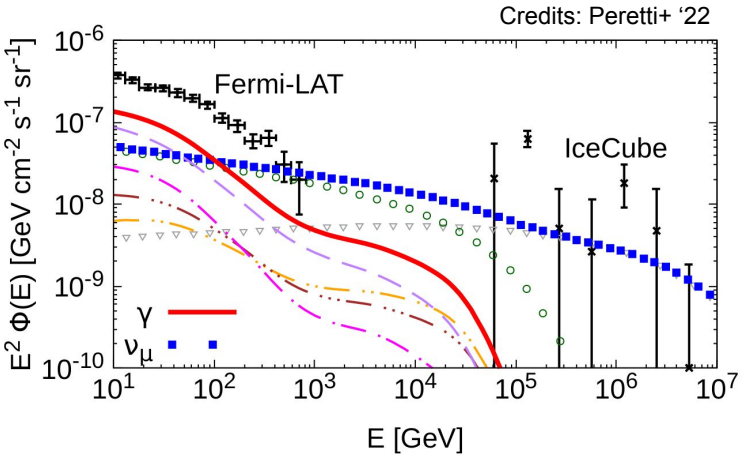


Cross-correlation of X-ray / MeV

- eROSITA
- e-ASTROGAM / AMEGO

The Cosmic γ-ray Background





Mostly jetted AGN

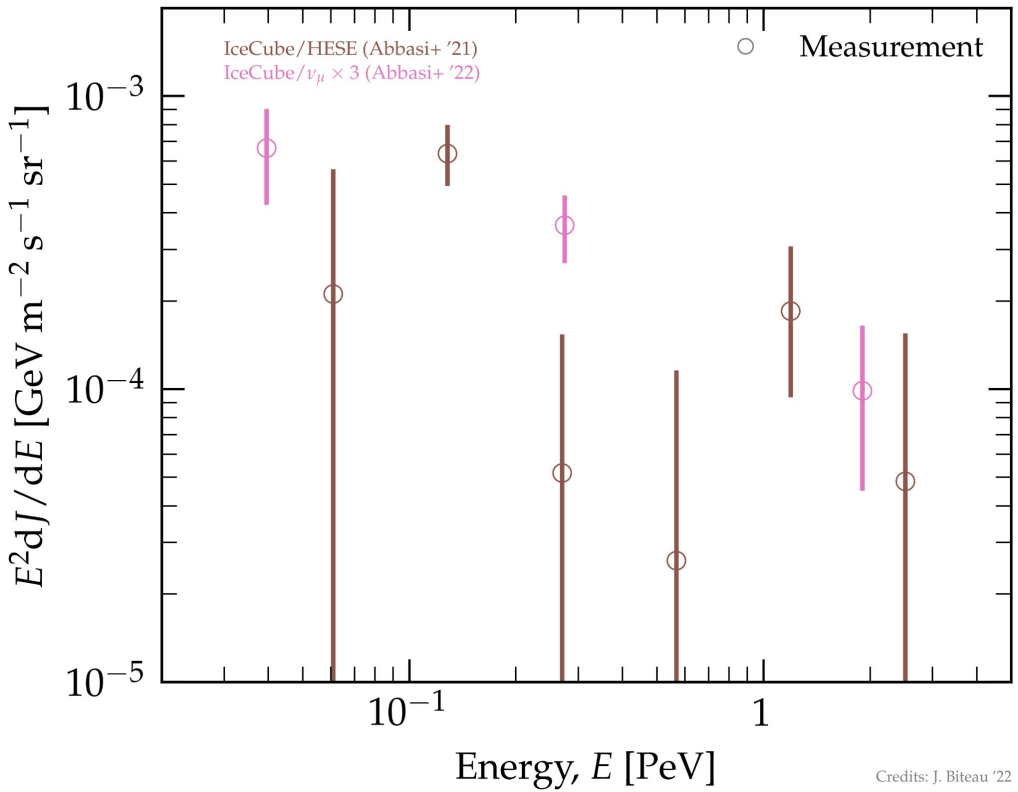
with a non-negligible contribution from starburst galaxies

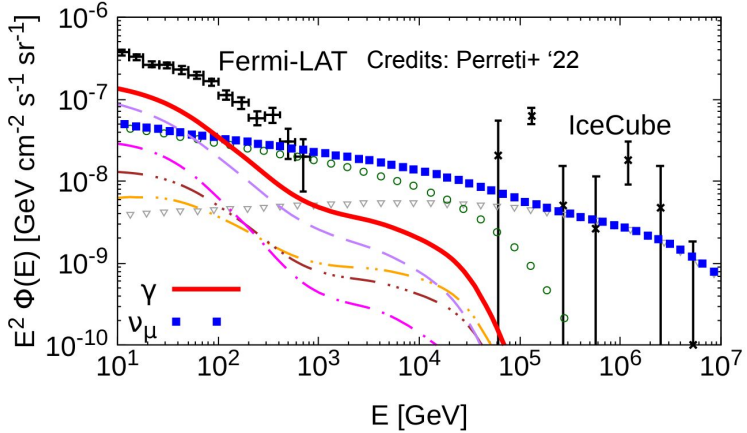
Part I - COB and CIB

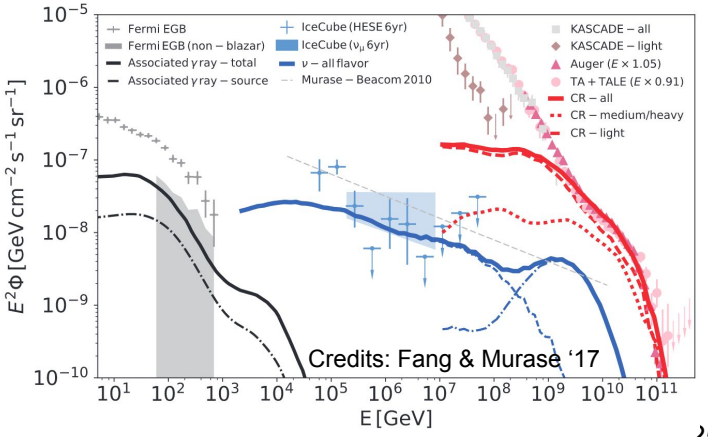
Part II - CRB, CXB and CGB

Part III - CνB and UHECRB

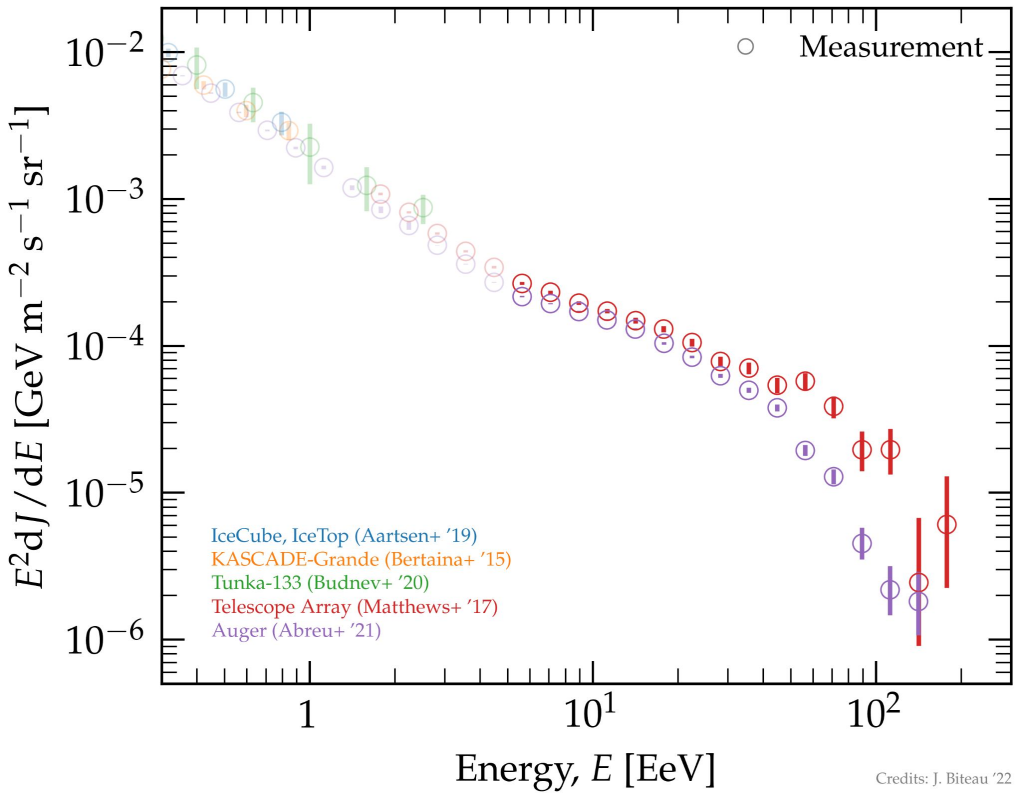
The Cosmic ν Background





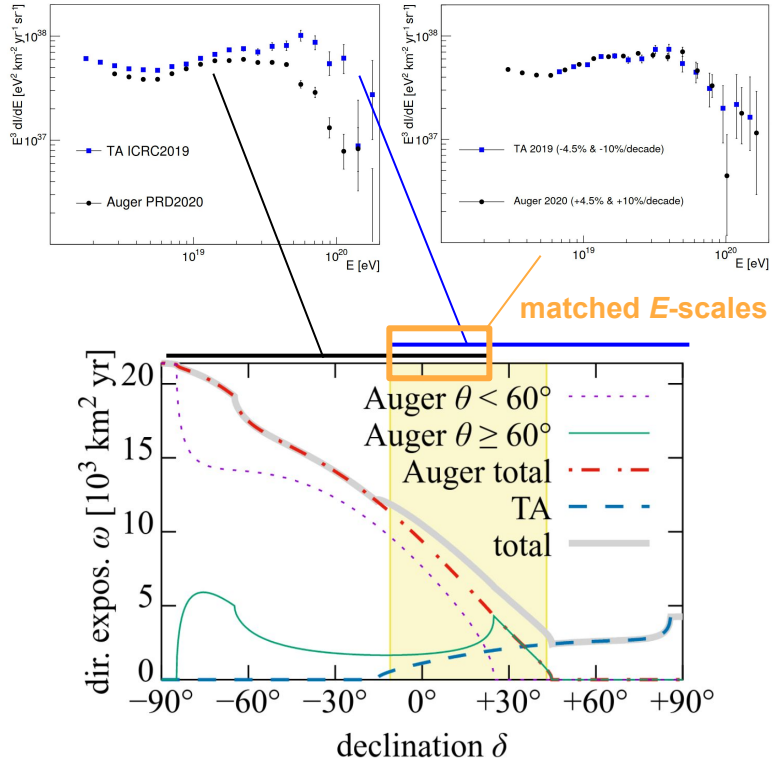


The UHECR Background



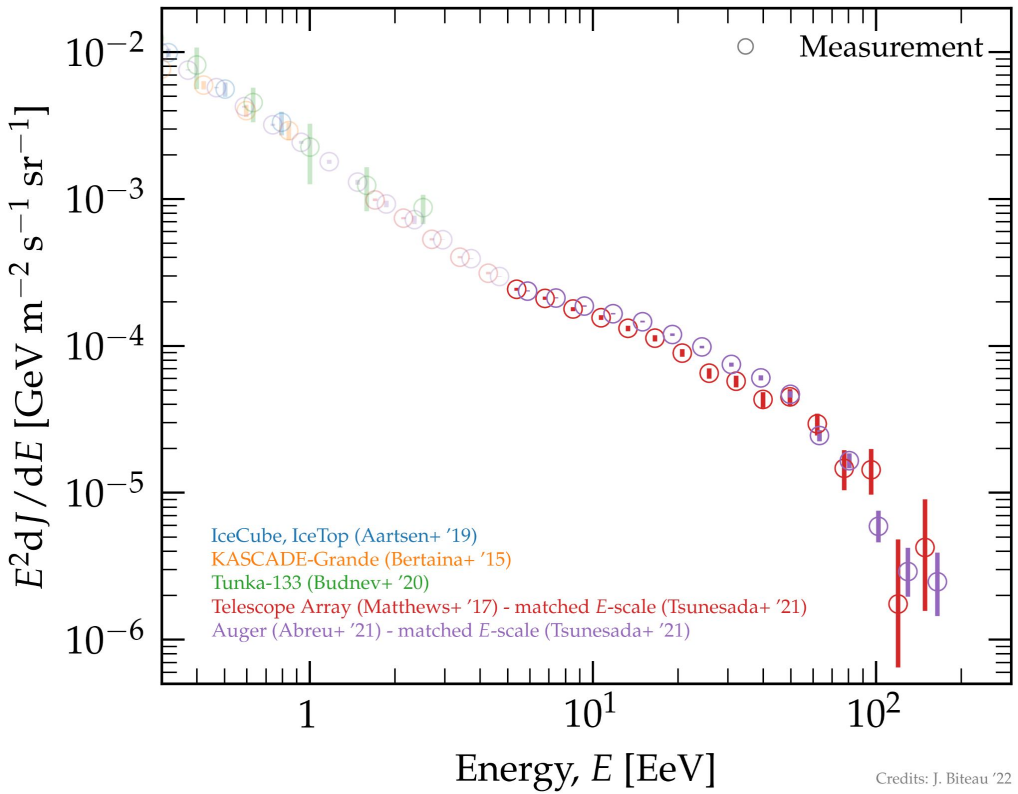
Credits: J. Biteau '22

Credits: Tsunesada+ '21



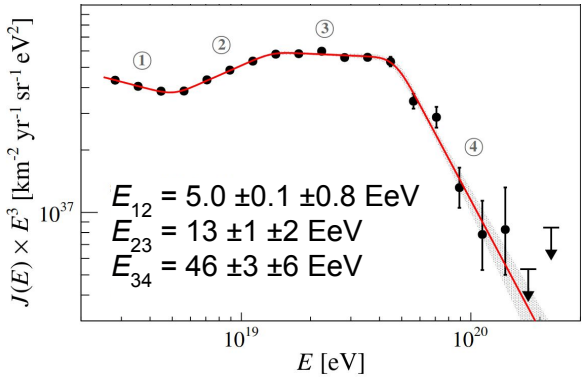
Credits: Tinyakov+ '21

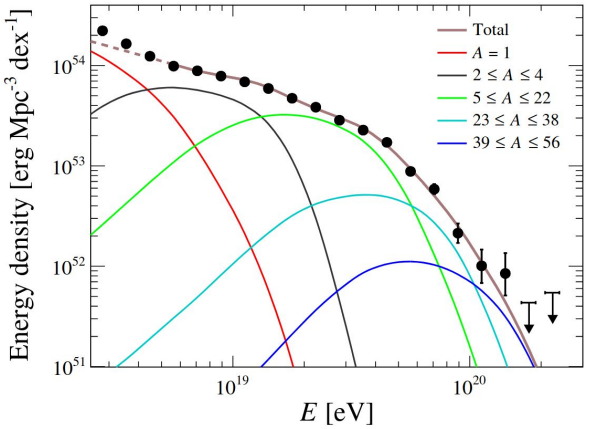
The UHECR Background



Credits: J. Biteau '22

Credits: Auger Collab. '20

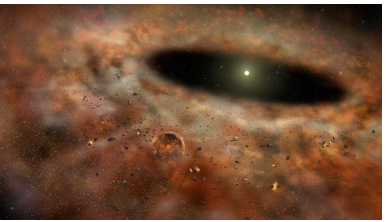




Tentative summary

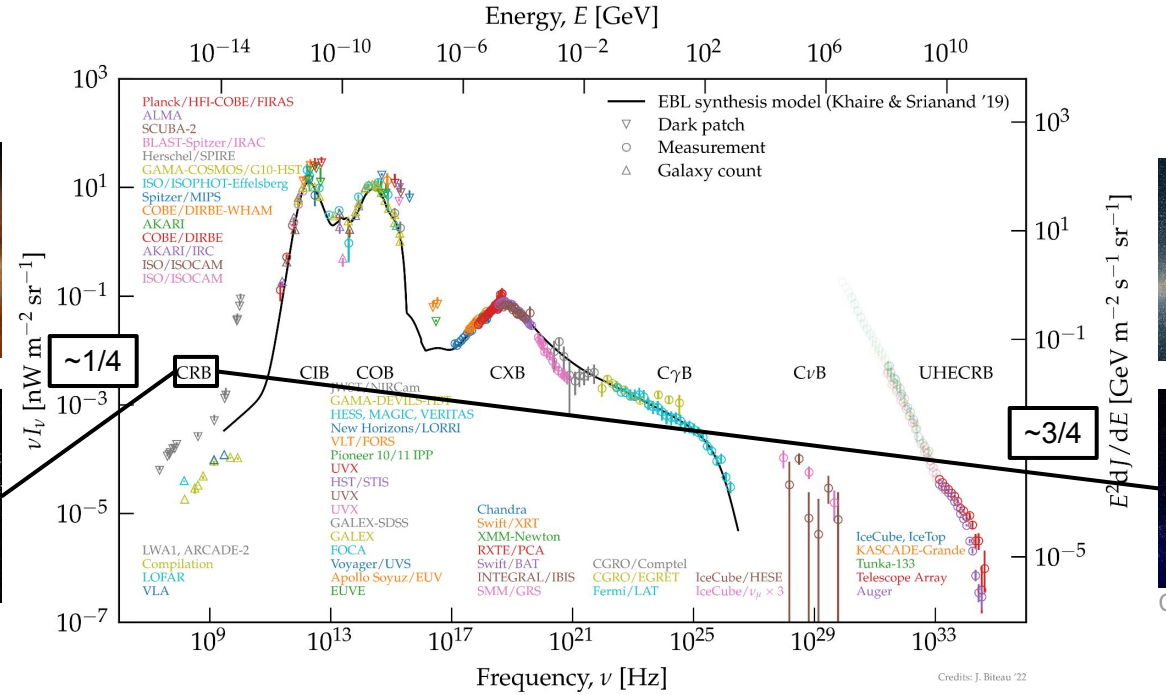
The multi-messenger extragalactic backgrounds

Star formation

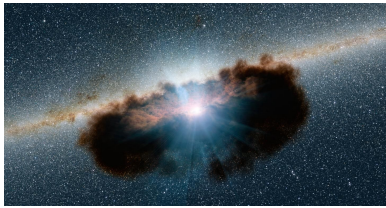


Credits: Gemini Obs./AURA/Cook

Credits: NASA



Black-hole accretion

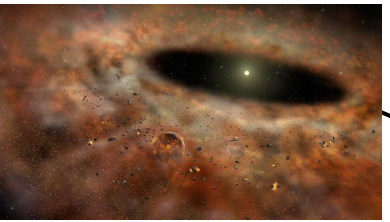


Credits: NASA/JPL-Caltech

Credits: ESA/NASA/AVO/Padovani

The multi-messenger extragalactic backgrounds

Star formation



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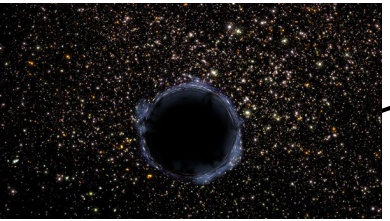
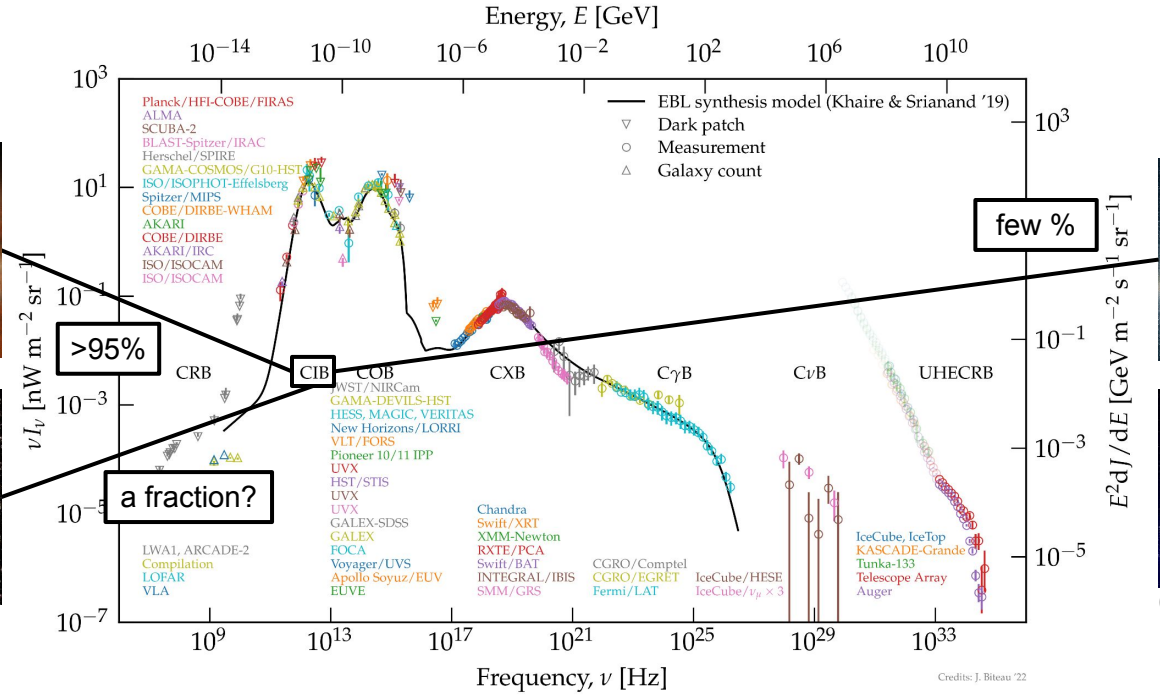
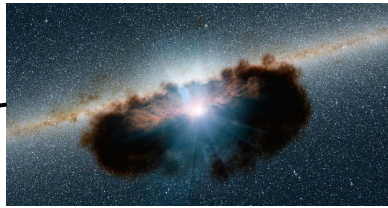


Credits: NASA/ESA/Bacon (STScI)



Black-hole accretion

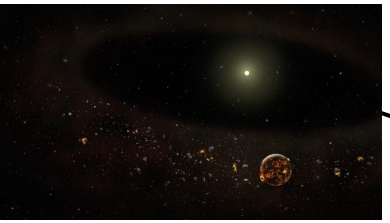


Credits: NASA/JPL-Caltech

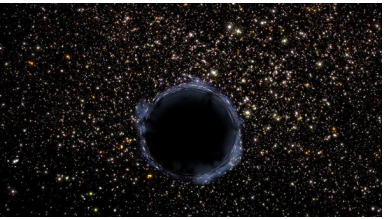
Credits: ESA/NASA/AVO/Padovani

The multi-messenger extragalactic backgrounds

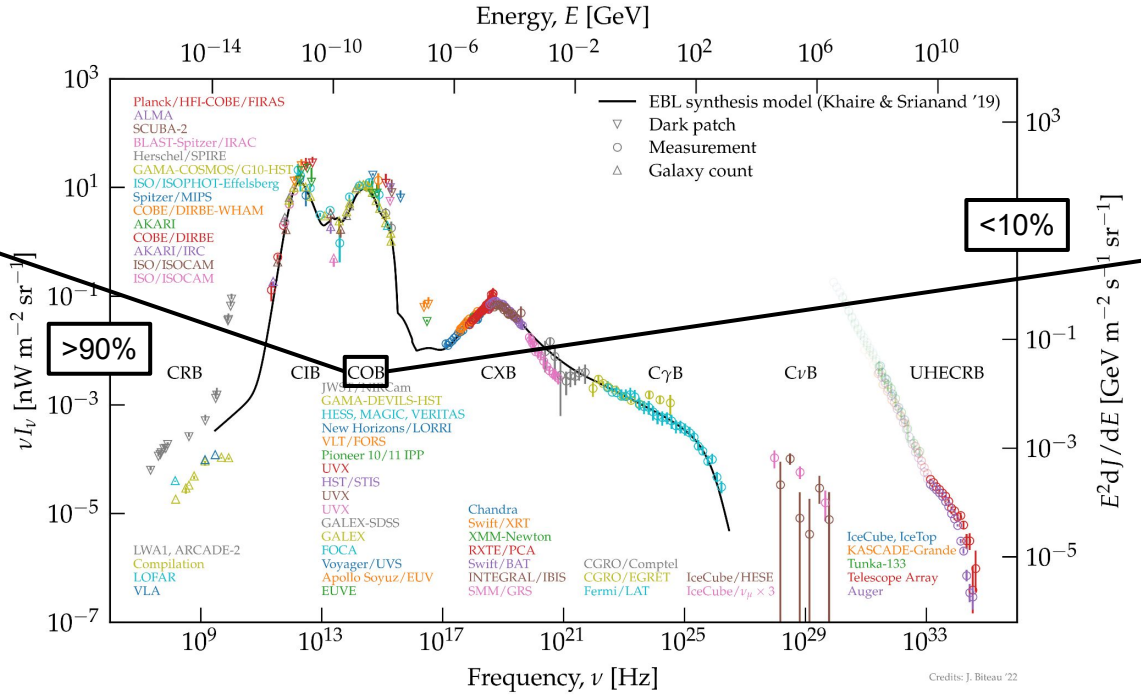
Star formation



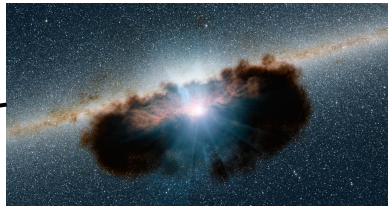
Credits: Gemini Obs./AURA/Cook



Credits: NASA/ESA/Bacon (STScI)



Black-hole accretion

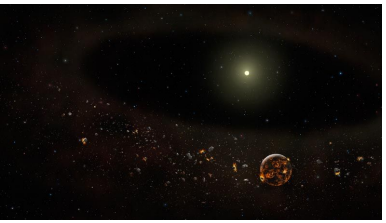


Credits: NASA/JPL-Caltech

Credits: ESA/NASA/AVO/Padovani

The multi-messenger extragalactic backgrounds

Star formation



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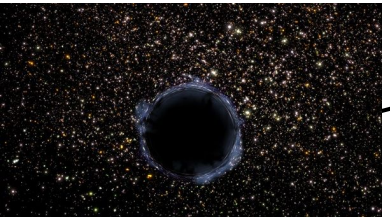
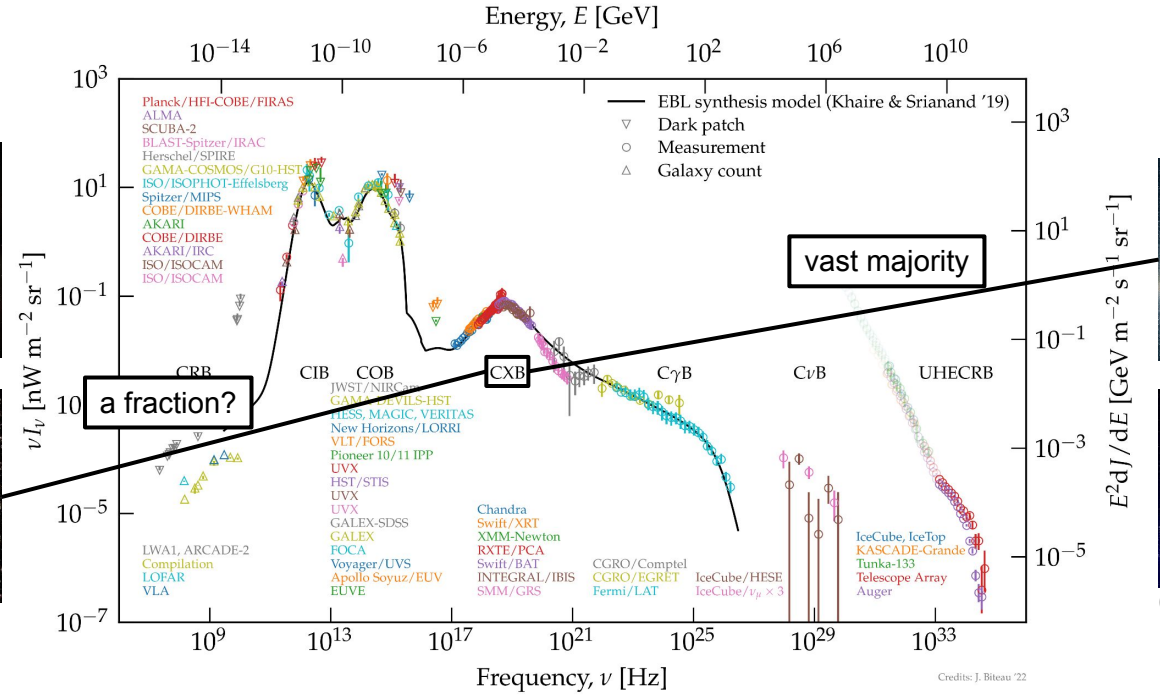


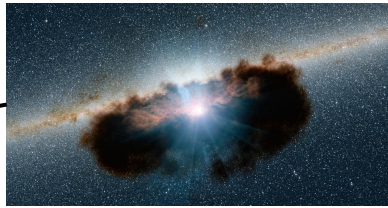
Credits: NASA/ESA/Bacon (STScI)



a fraction?

vast majority

Black-hole accretion

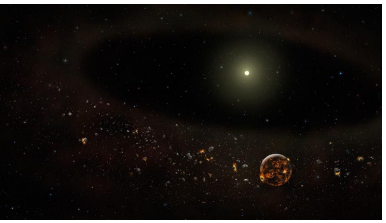


Credits: NASA/JPL-Caltech

Credits: ESA/NASA/AVO/Padovani

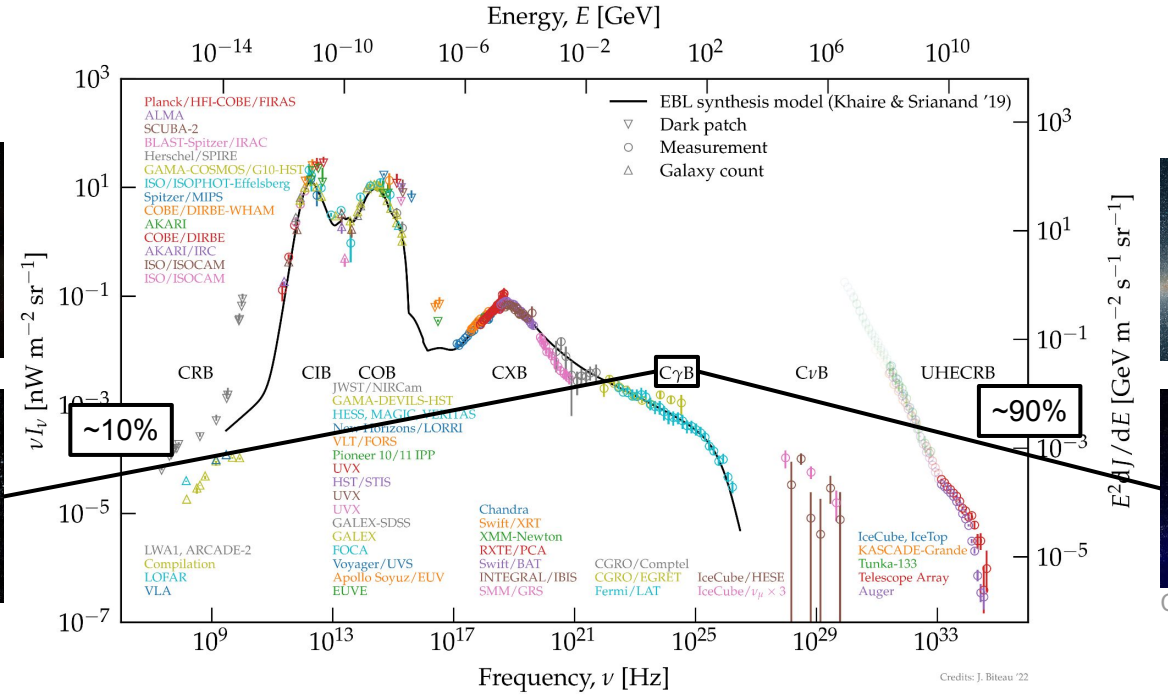
The multi-messenger extragalactic backgrounds

Star formation

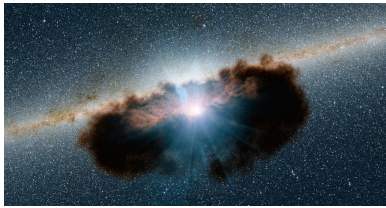


Credits: Gemini Obs./AURA/Cook

Credits: NASA



Black-hole accretion

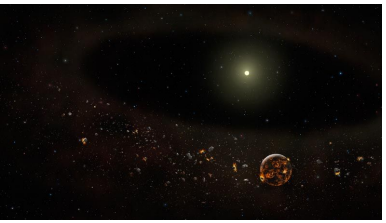


Credits: NASA/JPL-Caltech

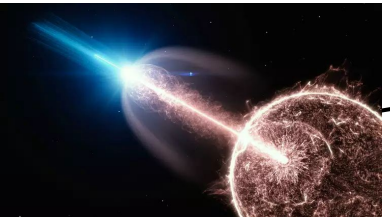
Credits: ESA/NASA/AVO/Padovani

The multi-messenger extragalactic backgrounds

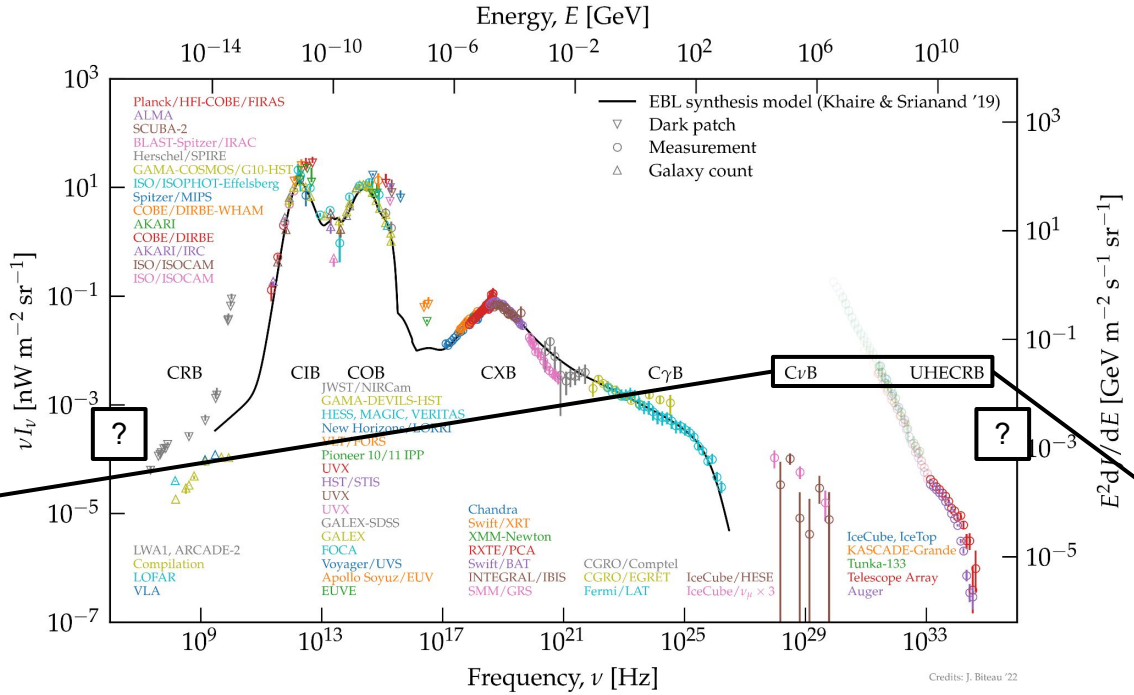
Star formation



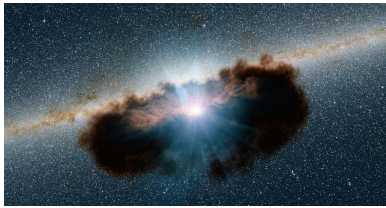
Credits: Gemini Obs./AURA/Cook



Credits: DESY, Sci. Com. Lab



Black-hole accretion



Credits: NASA/JPL-Caltech

Credits: ESA/NASA/AVO/Padovani

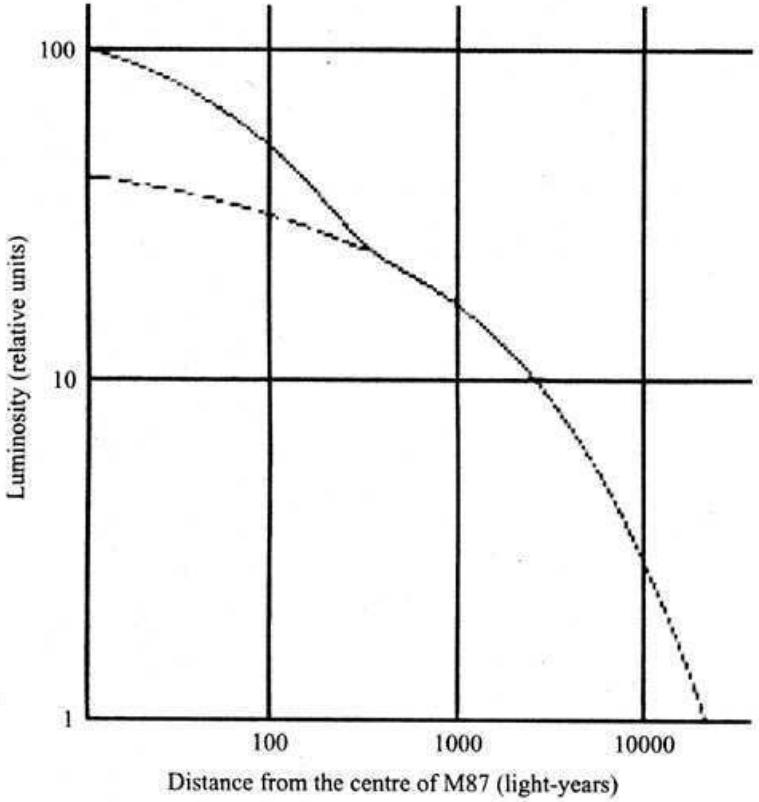
Backup

Active Galactic Nuclei (AGN)

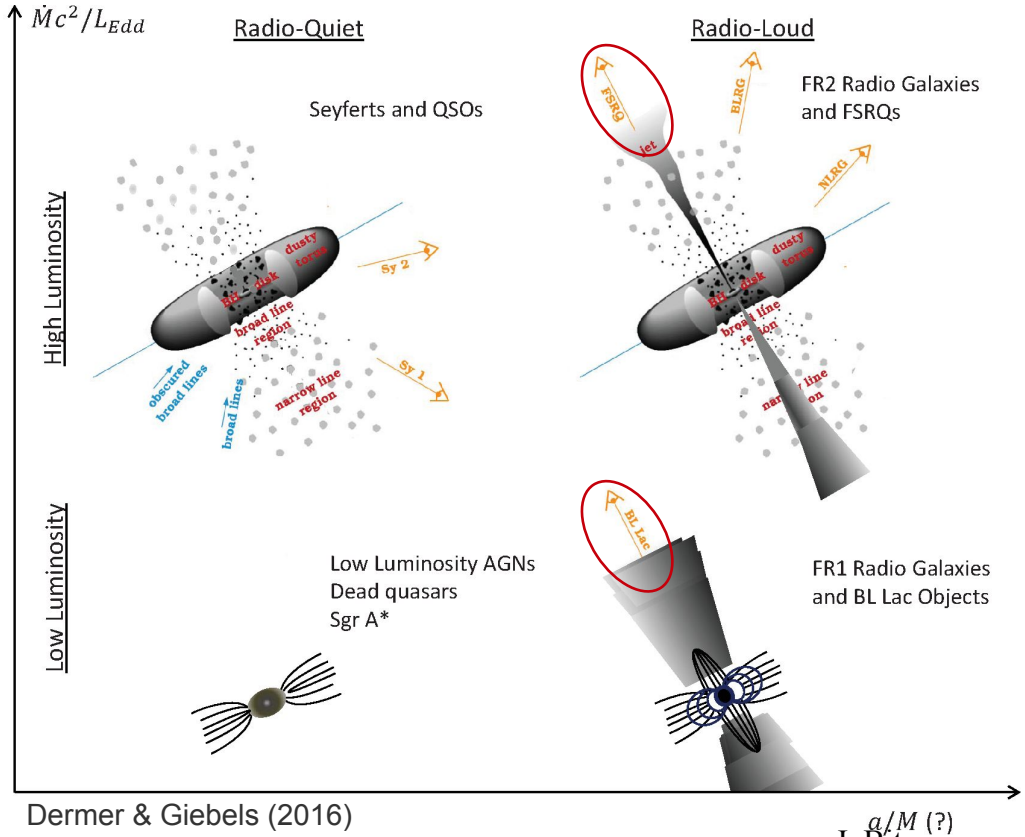
Historical landmarks

- 1920's: extragalactic objects exist (Hubble, 1924)
- 1940's: spiral galaxies with bright nuclei (Seyfert, 1943)
- 1950's:
  - Discovery of 1st radio galaxies (Cen A, M 87, Cygnus A), polarized emission
  - Discovery of quasars (quasi-stellar radio sources)
- 1960's:
  - Quasar 3C 273 at z=0.16!
  - X-ray detection of 3C 273, M 87, Cen A
- 1970's:
  - VLBI observation of superluminal speeds in jets
  - CCD: M 87 resolved core = bridge with Seyfert
  - BL Lacs (variable stars ?!) and FSRQs = blazars
- 1980's:
  - 1st large X-ray surveys (Einstein telescope)
  - Active Galactic Nuclei (AGN) = radio galaxies, Seyfert galaxies, quasars & blazars

Kembhavi & Narlikar (1999)



The various flavors of AGN



Dermer & Giebels (2016)

AGN unification scheme

Antonucci (1993), Urry & Padovani (1995)

- AGN composed of
  - Black hole (billion Msun)
  - Accretion disk + torus
  - Broad-line regions reprocess ~10% of disk emission
  - (Jets)
- Jets: high black hole spin?
- Viewing angle → observed properties
  e.g. blazars = radio galaxies with jets along line of sight
- Blazars: ideal probes of jet physics
  - FSRQs (strong emission lines) = high accretion rate
  - BL Lacs (weak emission lines) = low accretion rate

The quest for UHECR origins

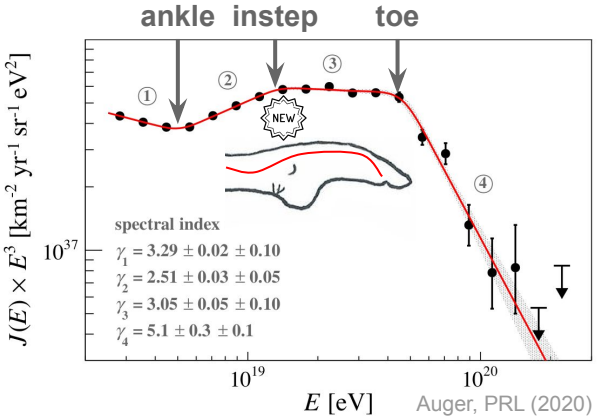
Ultra-high energy cosmic rays (UHECR)

Long thought to be of **extragalactic origin > 5 EeV** (0.8 J!), marking the **ankle**

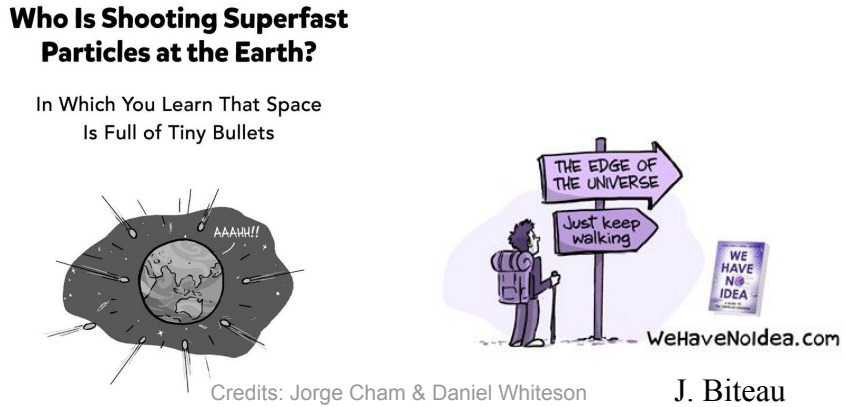
Observed spectral features: **instep at 10-15 EeV**, **toe at 40-50 EeV**
→ markers of Peters cycle (**acceleration**) and UHECR horizon (**propagation**) based on joint spectral-composition modeling

Spectral and composition observables integrated over the sphere
→ help constrain **source distance** distribution & source **escape spectrum**

Anisotropy observables
→ break down the flux (and composition) vs **arrival direction**: **pinpoint sources?**

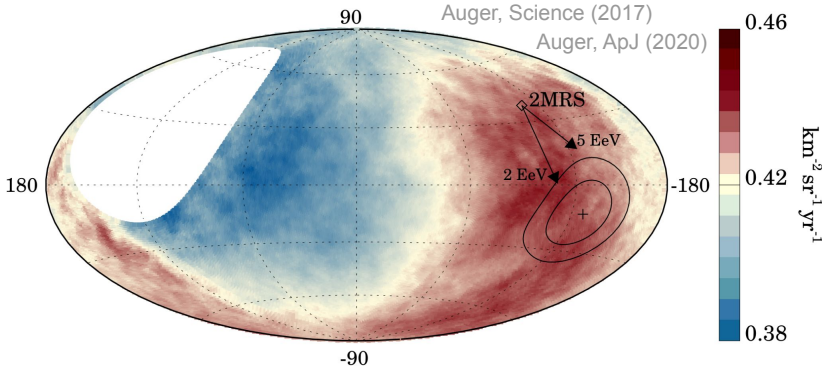


Auger, PRL (2020)



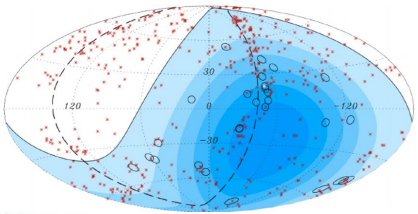
Credits: Jorge Cham & Daniel Whiteson

Auger dipole > 8 EeV (>6σ)



Some landmarks in Auger anisotropy studies

Auger, Science 2007



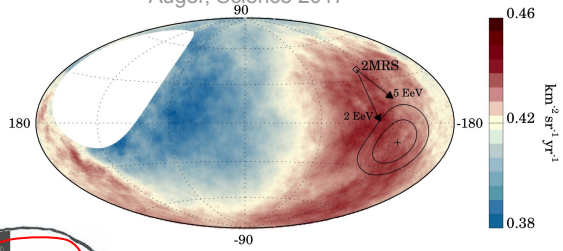
First steps: hint

20 out of 27 evts within 3° of nearby galaxies → ~3σ

10 evts in particular clustered in the **Centaurus region**

~ 27 evts ≥ 57 EeV

Auger, Science 2017



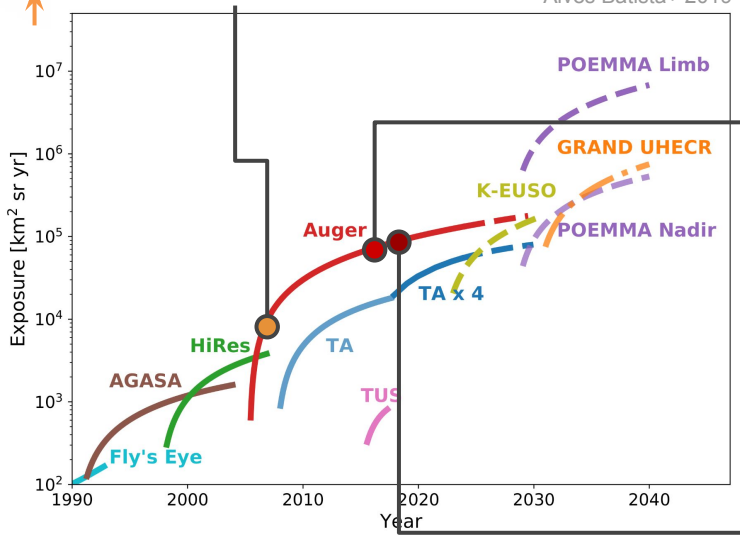
Maturity: discovery

6σ dipolar-like flux

In line with nearby **galaxy stellar mass distribution** (2MRS)

~ 32,000 evts ≥ 8 EeV

Alves Batista+ 2019

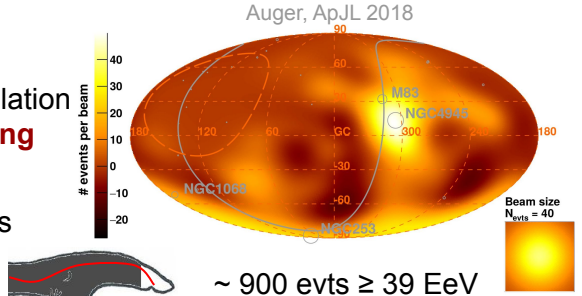


Revival: a trail?

4σ evidence for correlation with nearby **starforming galaxies**

3σ level for other types of galaxies

Auger, ApJL 2018



~ 900 evts ≥ 39 EeV

Status of UHECR sky from the Pierre Auger Observatory

Anisotropy search in the toe region with Auger phase 1 data spanning 2004-2020 (17 years!)

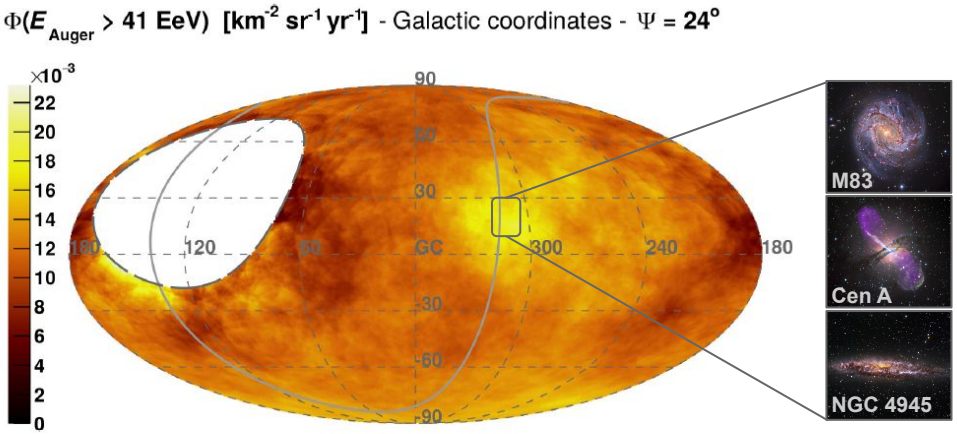
~4σ from search in Centaurus region, confirmed by catalog-based searches.

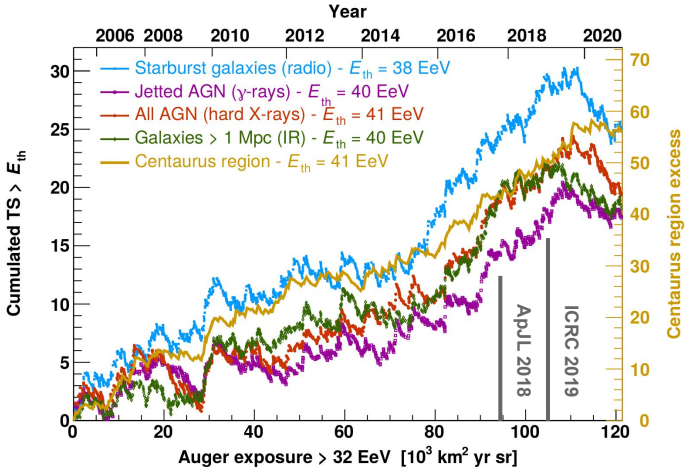
Largest signal from starburst galaxies but **no compelling evidence for catalog preference**

For all these searches: most significant signal at E_{th} **~ 40 EeV** on top-hat scale **Ψ ~ 25°** with signal fraction **α ~ 10%**

Evolution of signal: compatible with **linear growth within expected variance, 5σ reach expected in late 2025**

Most important evidence for UHECR anisotropy around the toe from a single observatory → **UHECR source ID is near?**





Plausible ultra-high energy accelerators

Hillas: only the highest-energy

Confinement, i.e. large B-field, size, and shock velocity:
$B \times (r \times \Gamma) \times \beta_{shock} > (E / Ze)$.

Hillas-Lovelace-Waxman: only the brightest

In an expanding plasma, magnetic luminosity:
$L_B > 3 \times 10^{44}$ erg/s $\times (E/Z / 10$ EeV $)^2 \times (\Gamma^2/\beta_{shock} / 10)$.

Arrival directions: only the numerous

UHECR flux above the ankle:
number density x luminosity > 10^{30} UHECR / Mpc³ / s

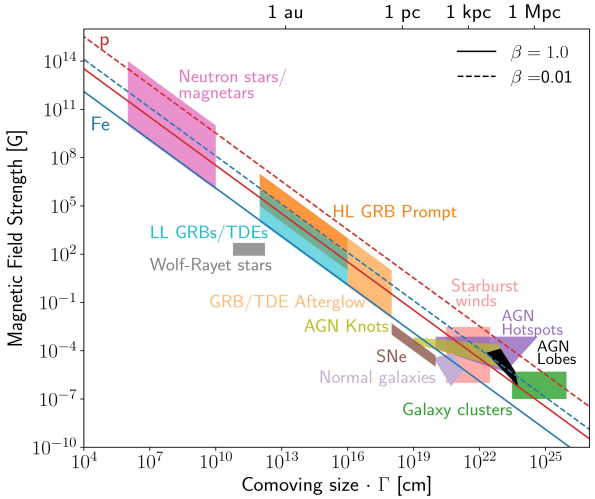
No significant self-clustering above flux suppression:
number density > 10^{-5} / Mpc³ (if deflections < 30°)

Work hypothesis: transient UHECR sources

Active Galactic Nuclei *vs* Gamma-ray bursts

Only the numerous, escape → low-luminosity preferred

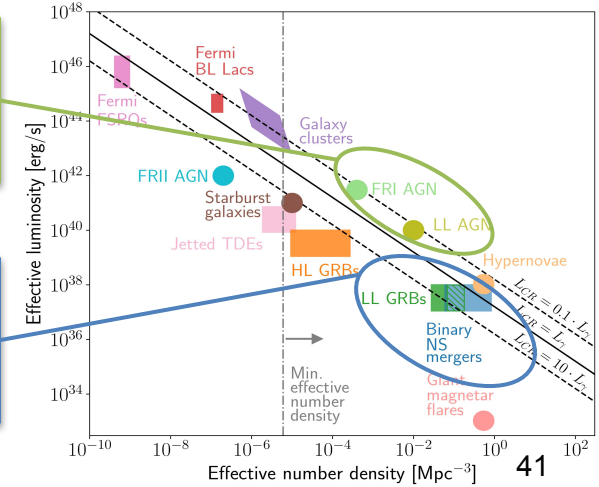
Only the brightest → constrains the min luminosity



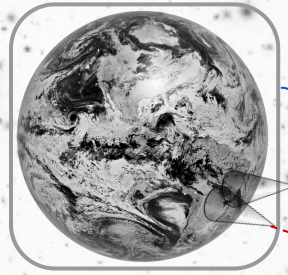
Alves Batista+, Front.Astron.Space Sci. 6 (2019) 23

Jetted AGNs
· mostly hosted by elliptical galaxies
· traced by non-thermal emission (radio, X rays, γ rays)

Long GRBs
· mostly hosted by star-forming galaxies
· star-formation rate traced by thermal emission (UV, Hα, FIR)



Which sources, which galaxies?

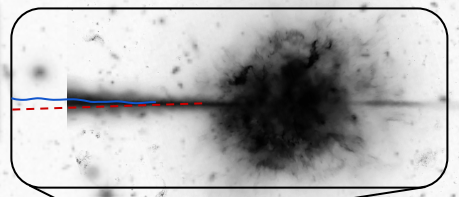


CMB
meV photons

EBL
eV photons

EeV-ZeV
cosmic rays

Attenuation weights:
from best-fit escape spectrum
of spectral-composition
modeling

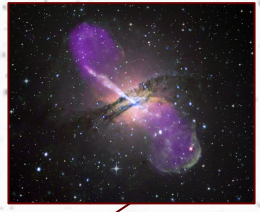


Long gamma-
ray burst

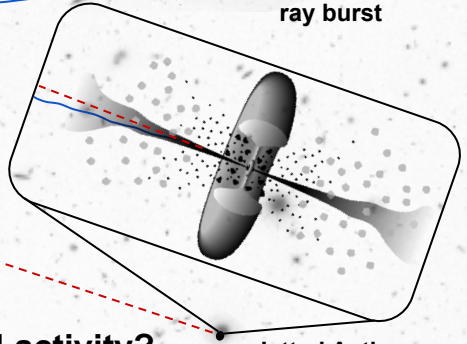
M82, starburst

NGC 4151,
non-jetted AGN

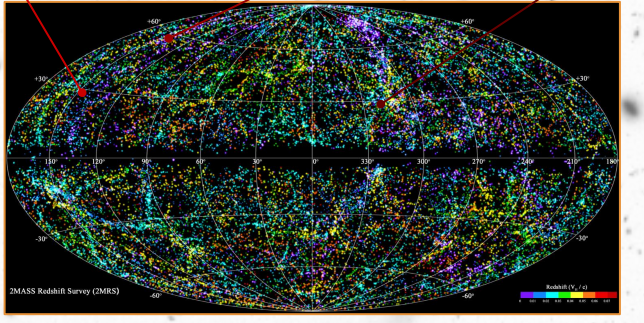
Cen A, jetted AGN



electromagnetic
emission



Jetted Active
Galactic Nucleus

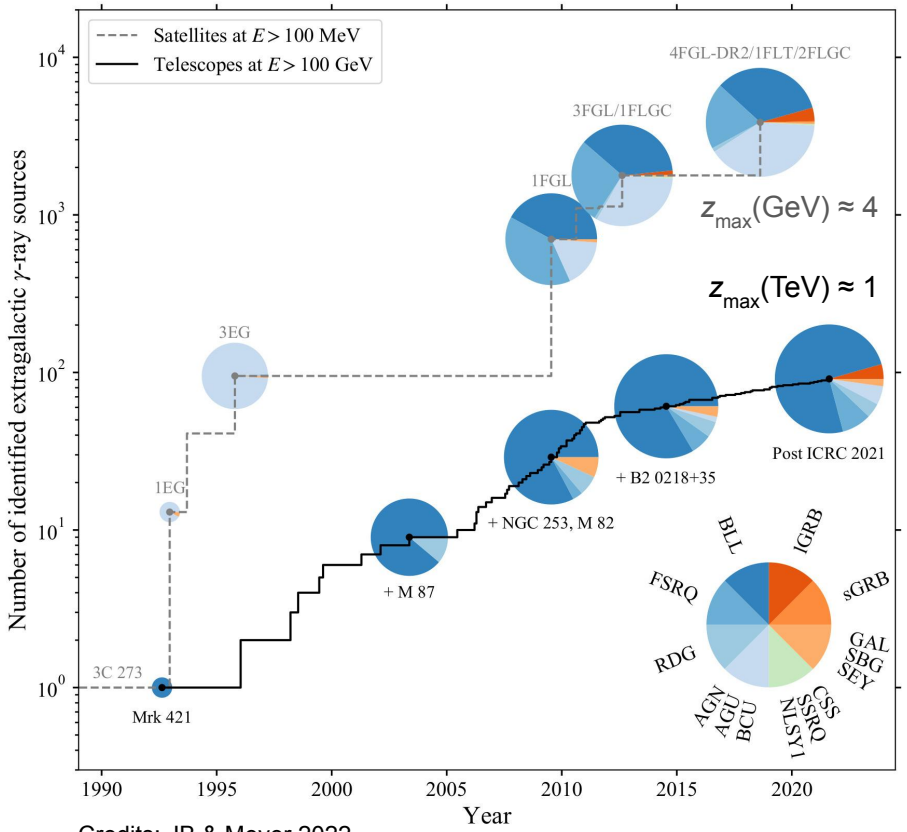


UHECR flux ∝ star formation / AGN activity?

Star formation (e.g. long GRB):
- integral = **stellar mass**: **infrared**
- **instantaneous**: **radio / Hα**

Jetted / non-jetted **AGN** (e.g. radio galaxies, blazars / Seyferts):
- **accretion** w. or w./o. jets: **hard X-rays**
- **jets**: **γ-rays, radio**

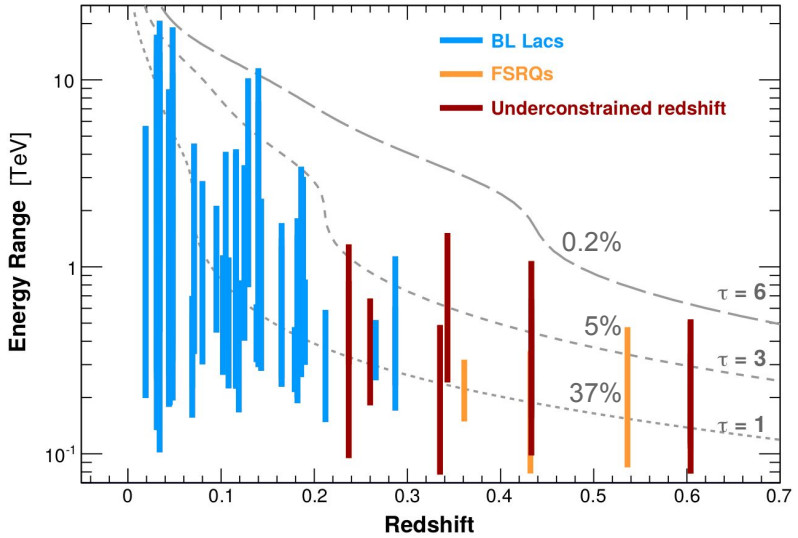
Which γ-ray beacons?



Credits: JB & Meyer 2022

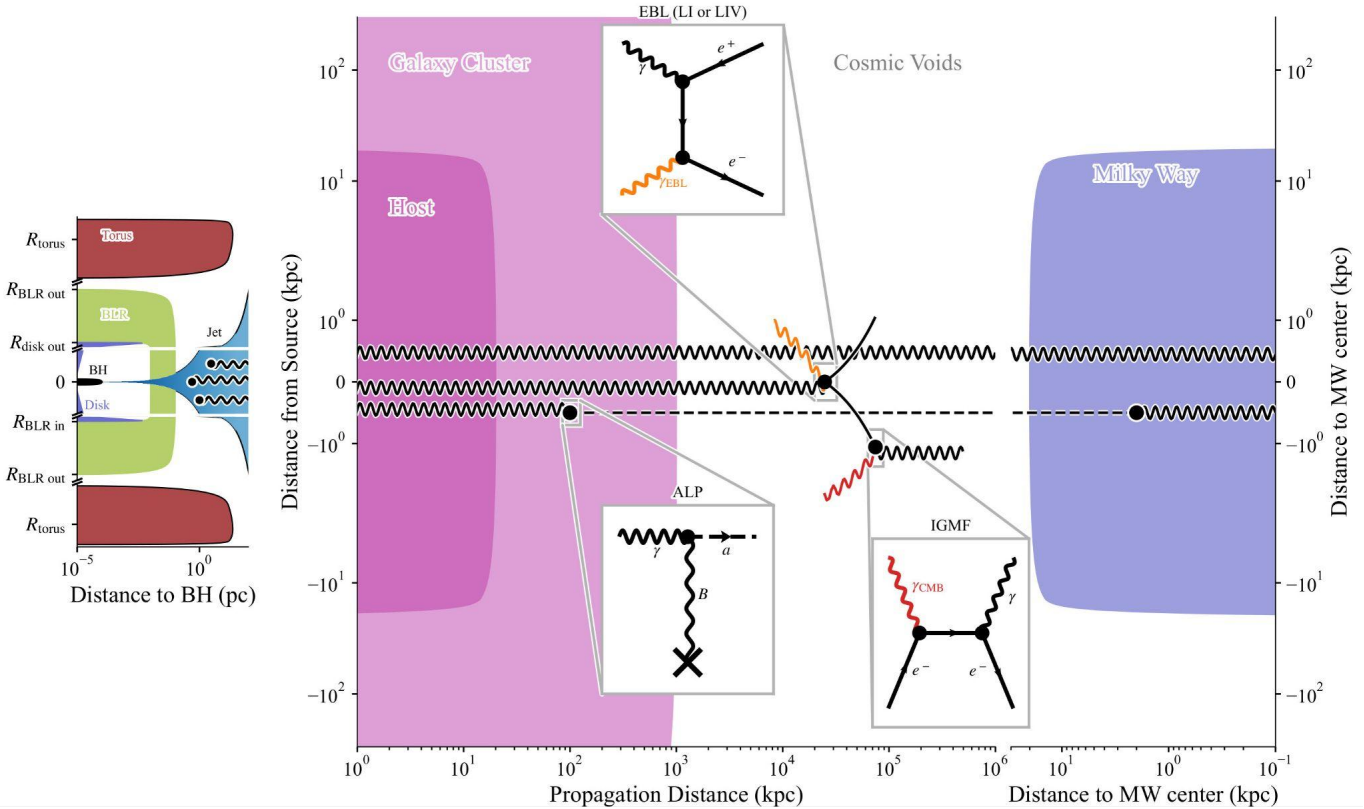
AGNs and GRBs with $E > 100$ GeV… and z!

- Space-based: ~40% of spectro. z @ $E >$ 30 GeV
  see P. Goldoni's z-catalog at this link
- Ground-based: ~80% of spectroscopic z
  → only a third / half of current data used so far!



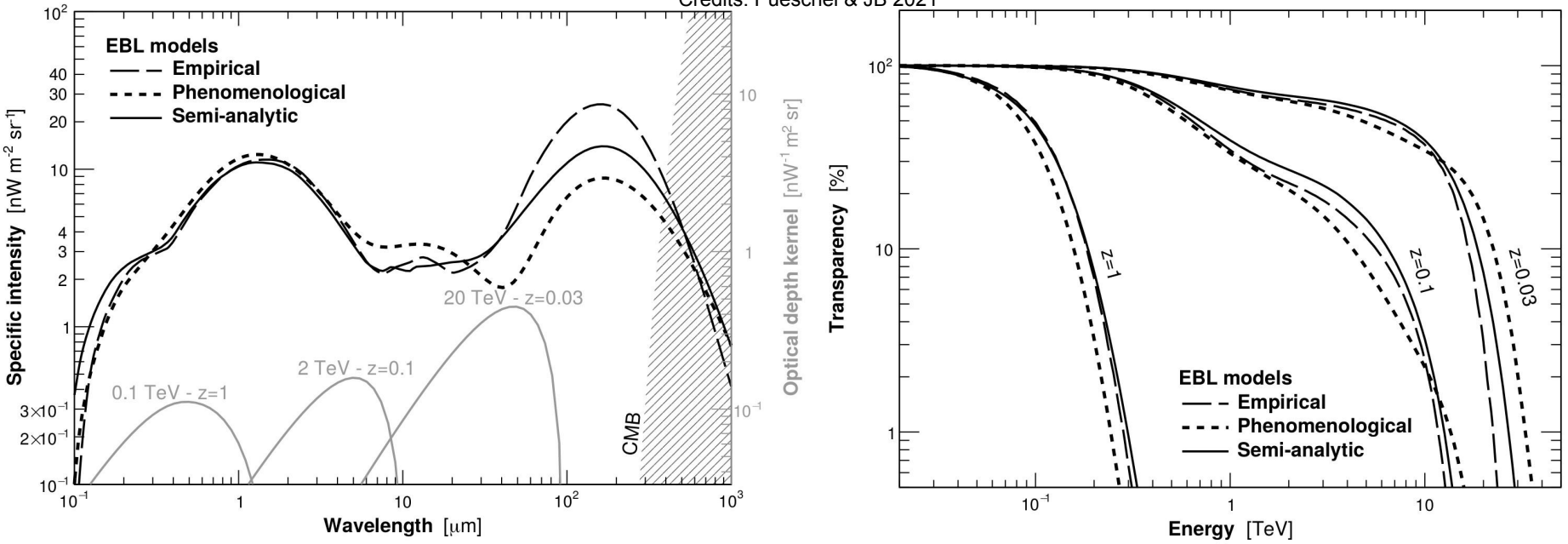
Credits: JB & Williams 2015

ɣ-ray propagation from sources down to Earth



Imprint from the extragalactic background light

Credits: Pueschel & JB 2021

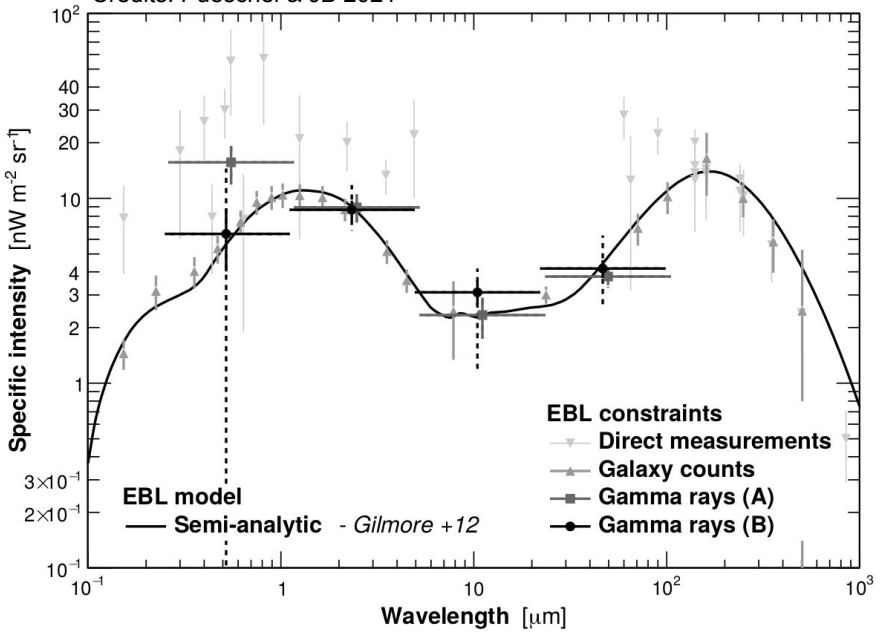


EBL: direct estimates / galaxy counts / γ-rays

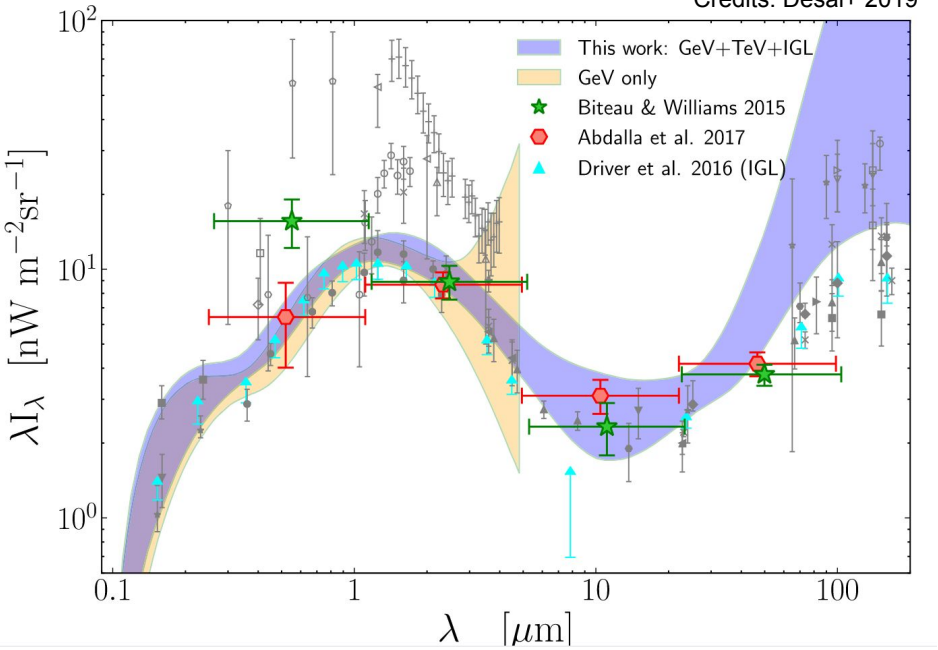
Three independent communities with different conclusions…

Direct: bright foreground contamination… Galaxy counts: all known galaxy emission… γ-rays: all EBL, incl. galaxies

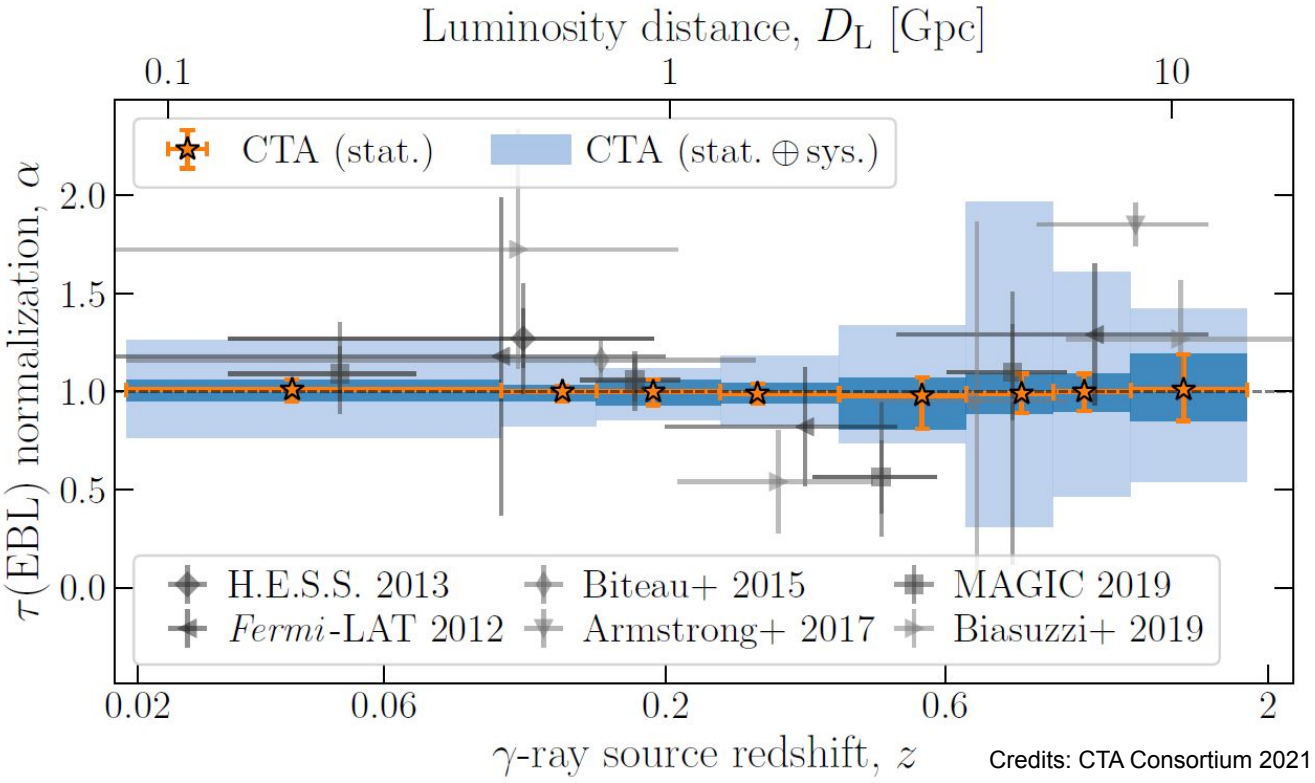
Credits: Pueschel & JB 2021



Credits: Desai+ 2019



EBL (and SFR): expectations from CTA

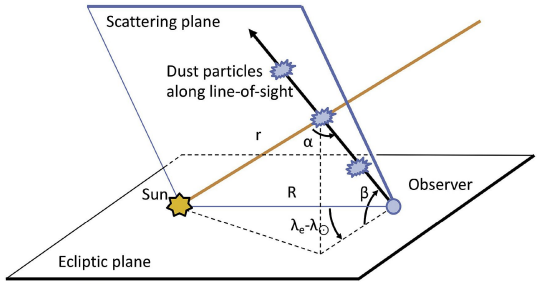


Credits: CTA Consortium 2021

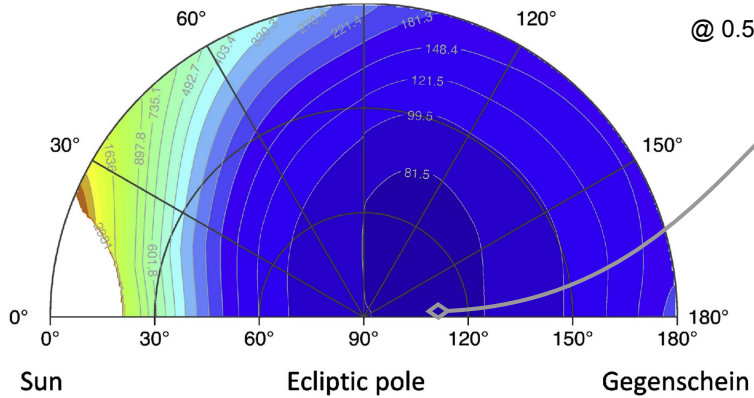
Contaminants

Zodiacal light, integrated star light, diffuse galactic light (cirrus)

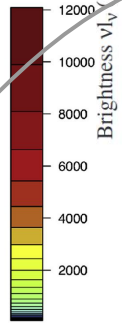
- To compare to maxima of COB at ~1μm and CIB at ~100μm around 10^{-9} nW m^{-2} sr^{-1}

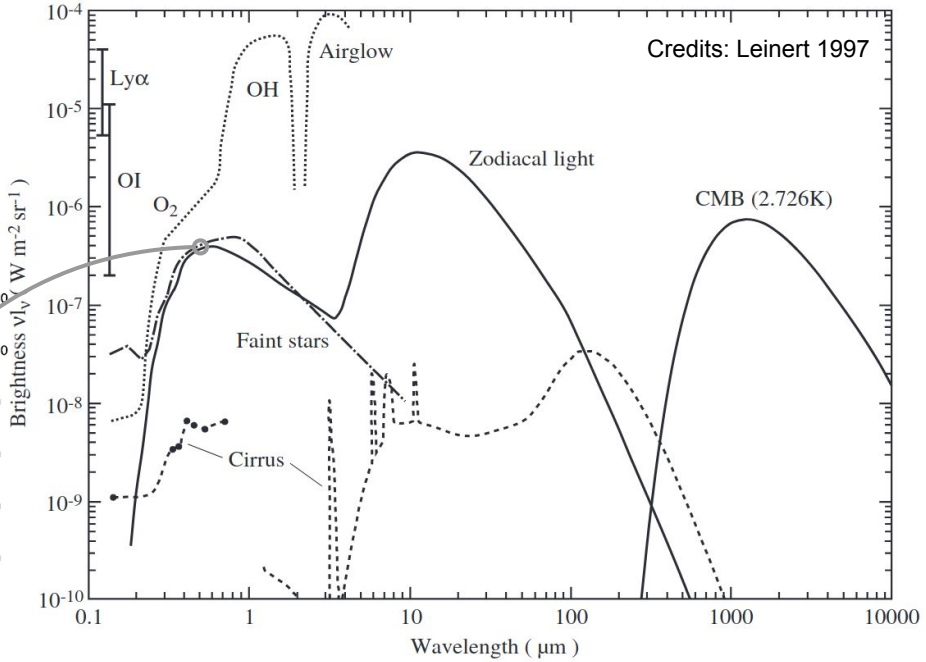


Credits: Lasue 2020



@ 0.55 μm





The “optical controversy”

Spacecrafts out of the Solar System at this link

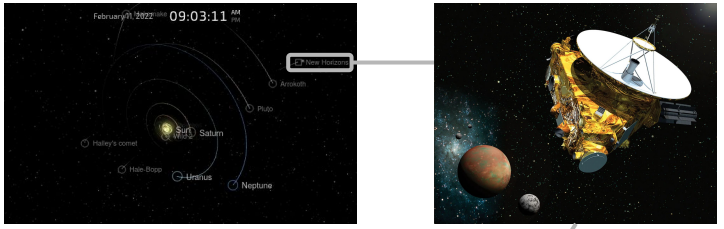
Direct, galaxy counts… and the ɣ-ray referee?

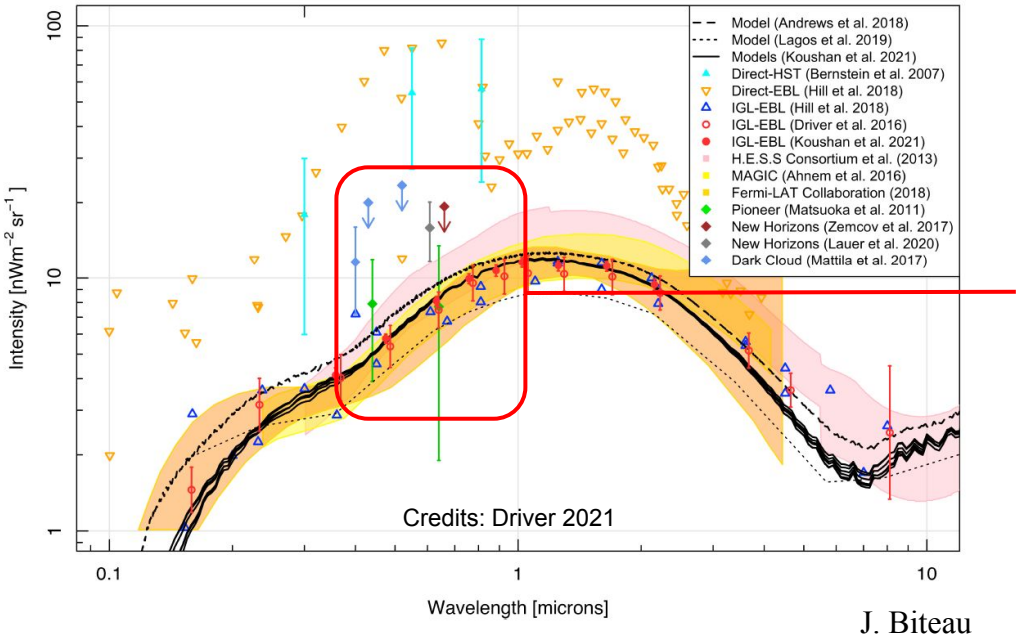
- IGL / Direct @ 0.6μm: 8.1±0.3 nW m^{-2} sr^{-1} / 16.4±1.5 nW m^{-2} sr^{-1}

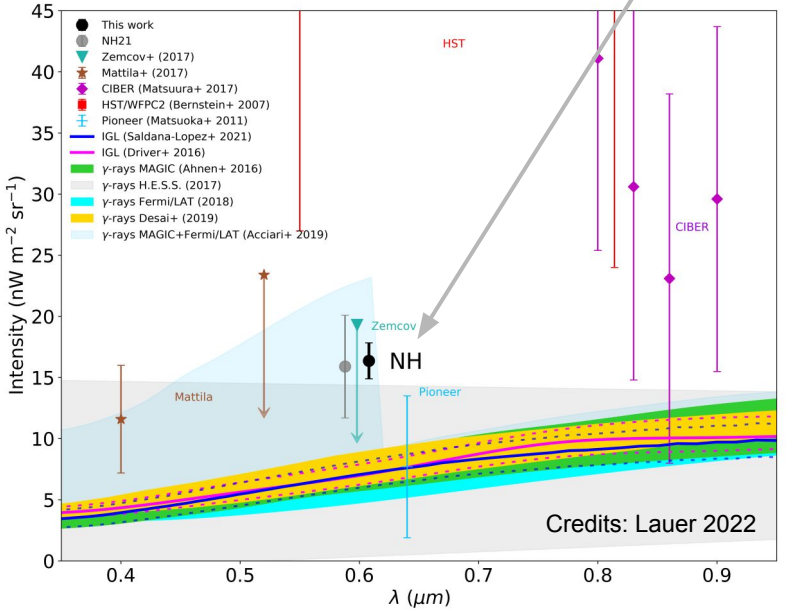
Koushan+ 2021, Lauer+ 2022

- ɣ-ray around 0.6μm: < 15-25 nW m^{-2} sr^{-1}

JB, HESS, VERITAS

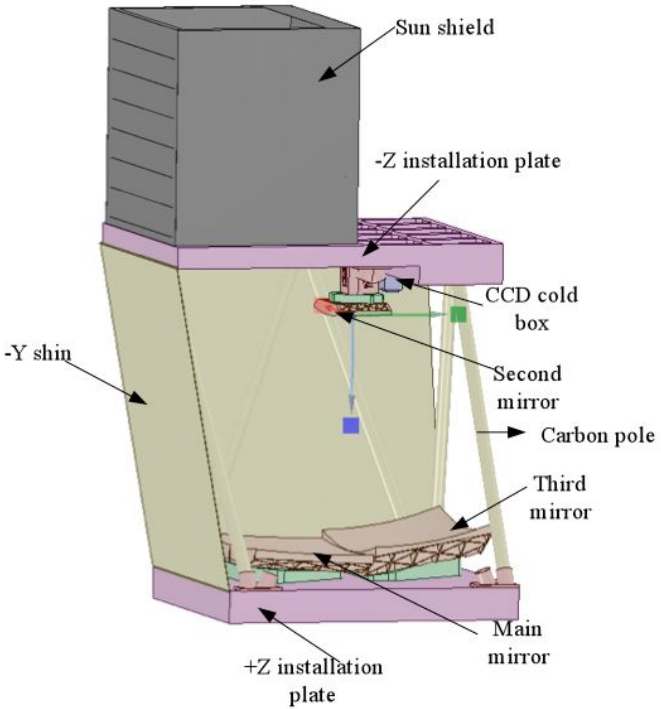






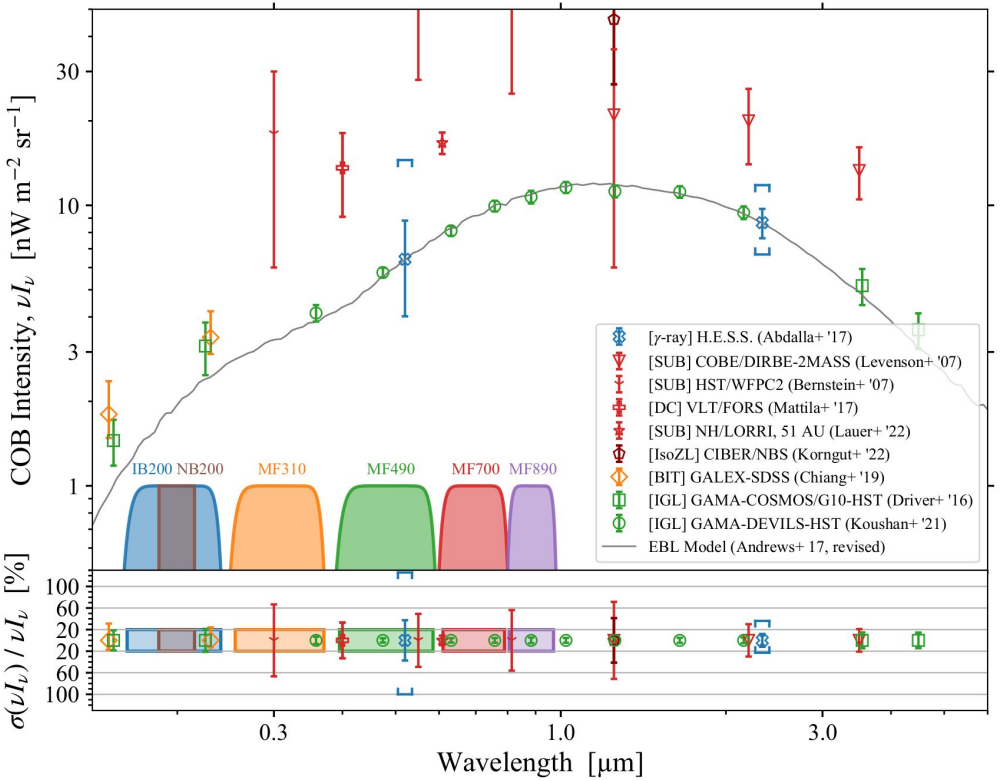
The MESSIER satellite project

Credits: D. Valls-Gabaud



Proposed as ESA-F mission (2022)

Credits: JB+ in MESSIER's White Book (in prep., 2023)

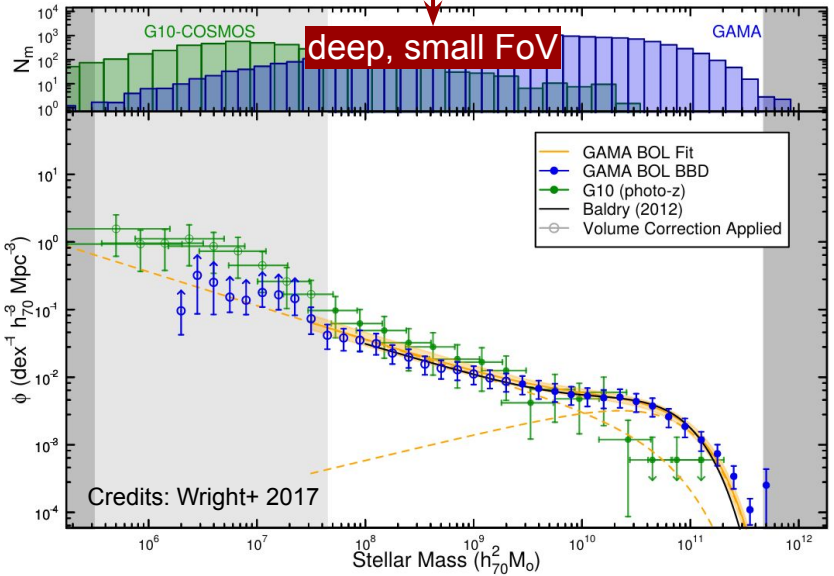


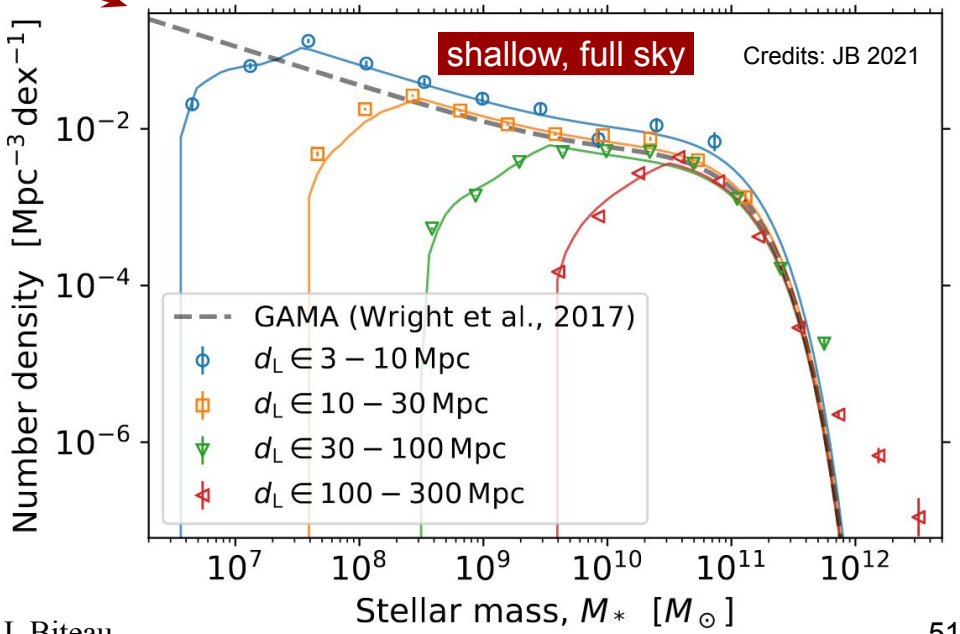
Constraints on faint galaxies / halo light

Have we resolved only half the optical light in the Universe?

- K-band (2.2μm) = Stellar mass (old & young stars within containment radius)
- Down to ~10^7 $M_\odot$ at z~0.1 and in the local Universe.

Low mass, high z, large radii?

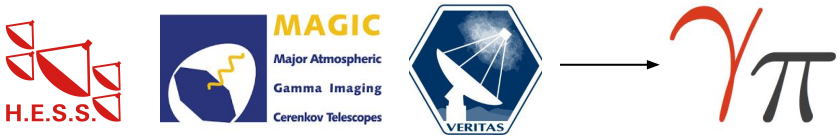




Addressing the optical controversy with ɣ-rays before CTA?

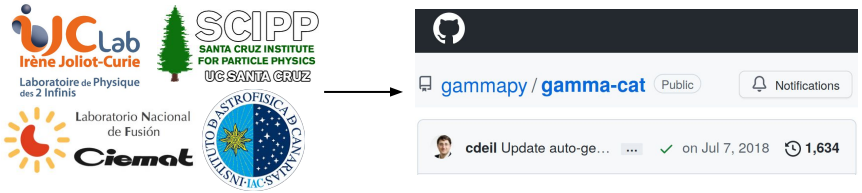
Event-level data from current generation

- Sharing of datasets and instrument response
  ⇒ natural way to account for e.g. energy resolution
- Hard (politically) but **certainly the best**! (S. Pita, APC)



Archival spectral data from current & past

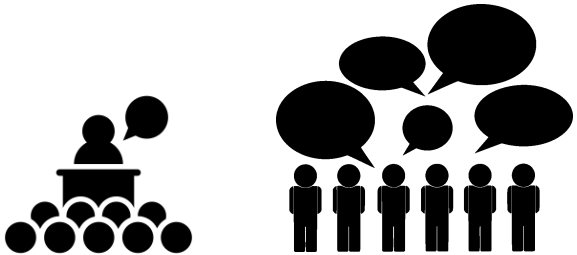
- All published extragalactic TeV spectral points
  ⇒ exported to **gamma-cat** format (**to be revived?**)
- More modest effort: see Gamma 2022 (L. Gréaux, IJCLab)



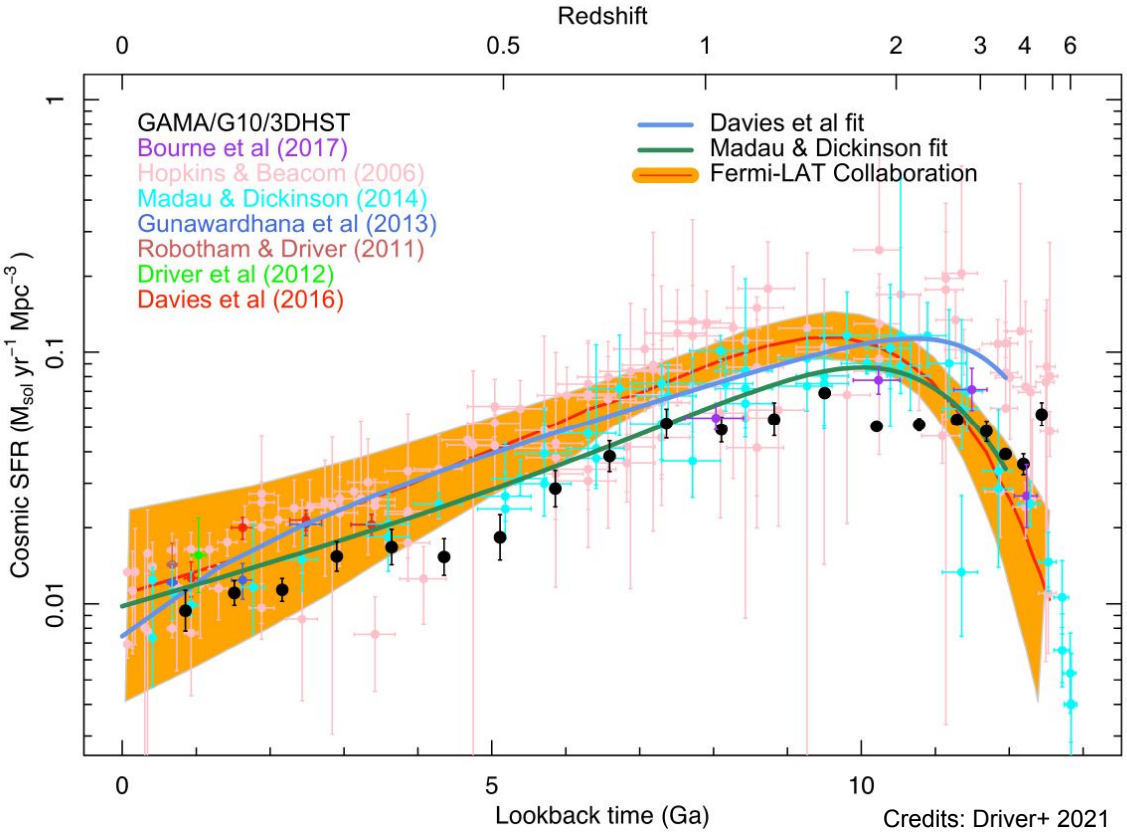
The three communities around a single table?

- New 4σ evidence from direct observation beyond Pluto
- New 5%-resolution measurement of galaxy counts
- Upcoming TeV measurement with >2× previous archival data

⇒ **EBL workshop (3-5 days?) in Paris area in 2023/24?**



Cosmic star-formation history



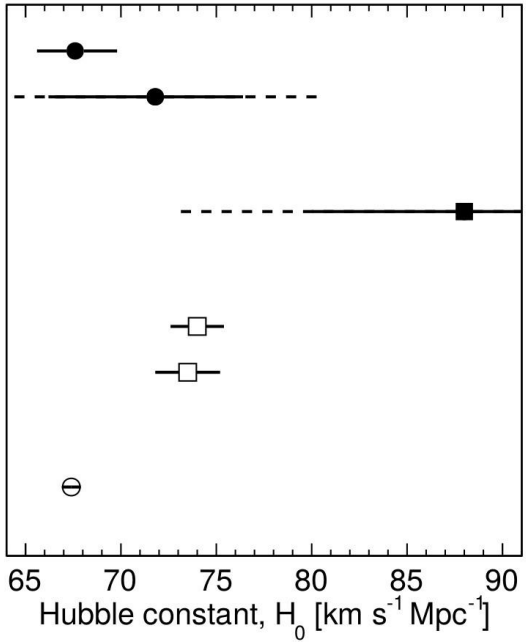
Hubble constant

γ-ray / CSFH *(Dominguez+ '13, '19)*

γ-ray / local EBL *(Biteau+ '15)*

Distance ladder *(Riess+ '18, '19)*

CMB *(Planck Collaboration '18)*



Credits: Pueschel & JB 2021

How to:

$$F_{\rm obs}(E) = F_{\rm emitted}(E(1+z_0)) \times \exp[-\tau_{\gamma\gamma}(E,z_0)]$$

$$\tau_{\gamma\gamma}(E,z_0) = \int_0^{z_0} \Gamma_{\gamma\gamma}^{-1}(E(1+z),z)\frac{{\rm d}\ell(z)}{{\rm d}z}{\rm d}z$$

$$\Gamma_{\gamma\gamma}^{-1}(E',z) = \int_0^{\infty} {\rm d}\epsilon' \frac{{\rm d}n(\epsilon',z)}{{\rm d}\epsilon'} \int_{-1}^{1} {\rm d}\cos\theta' \frac{1-\cos\theta'}{2} \sigma_{\gamma\gamma}(\beta')\Theta(\epsilon'-\epsilon'_{\rm th})$$

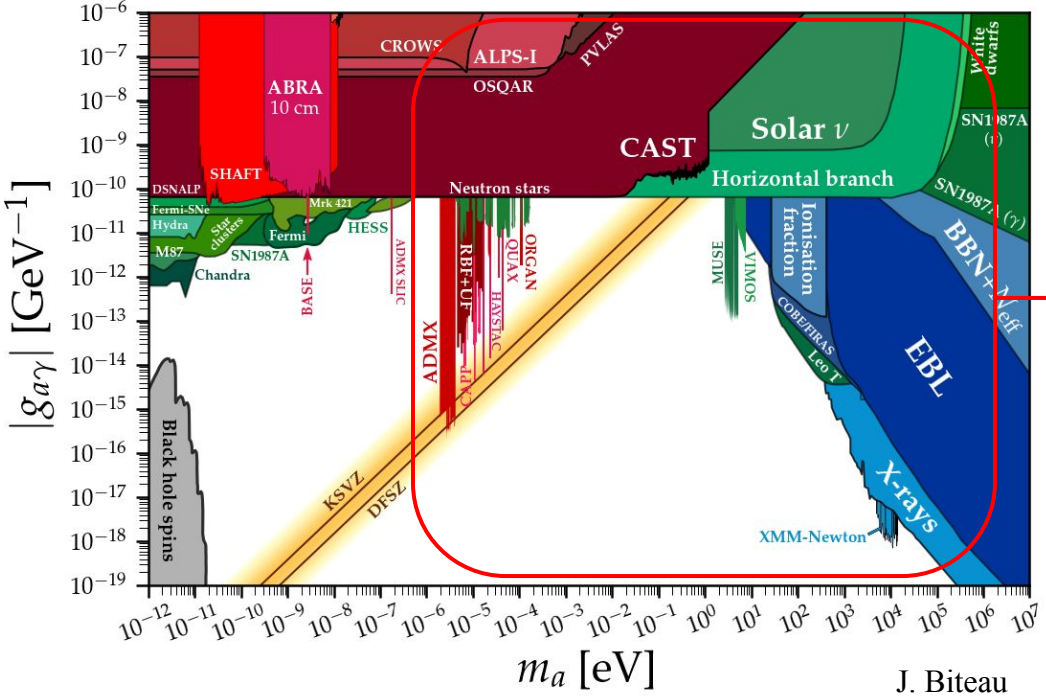
$$\partial n/\partial\epsilon = (1+z)^3/c \times \int_z^{\infty} {\rm d}z'\, {\rm d}\ell/{\rm d}z' \times j(\epsilon',z')/\epsilon'$$

Constraints on decaying axions

Exotic contributions to the night-sky brightness?

- Top-down process: decay of heavy (eV) axion-like particles. Update of ALP constraints from EBL TBD!

Credits: O'Hare 2020 at this link



Credits: Arias+ 2012