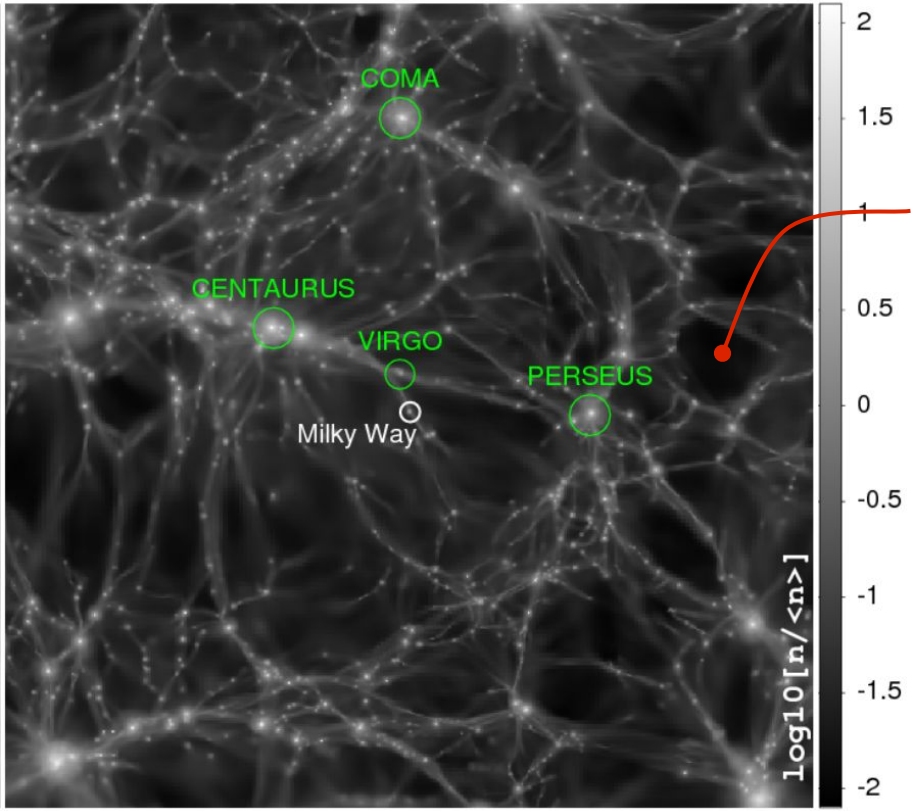
Probing Extragalactic Magnetic and Radiation Fields with Gamma Rays

Jonathan Biteau, IJCLab / Université Paris Saclay

What's in voids?



Hackstein+ 2018 (Cosmic V-web constrained simulation / CLUES)

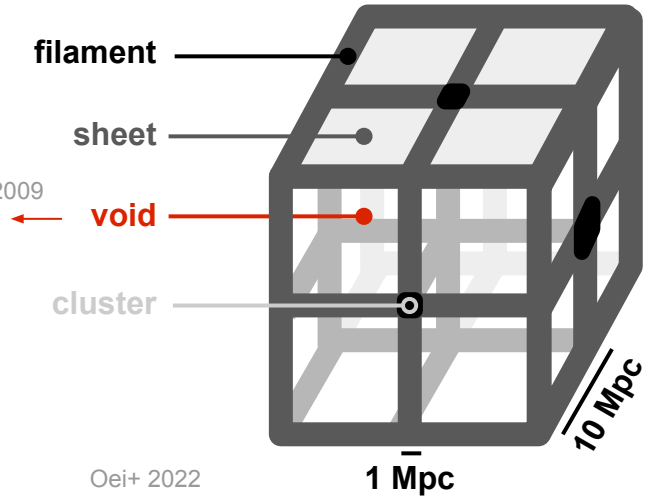
· 70-80% of the volume?

Forero-Romero+ 2009

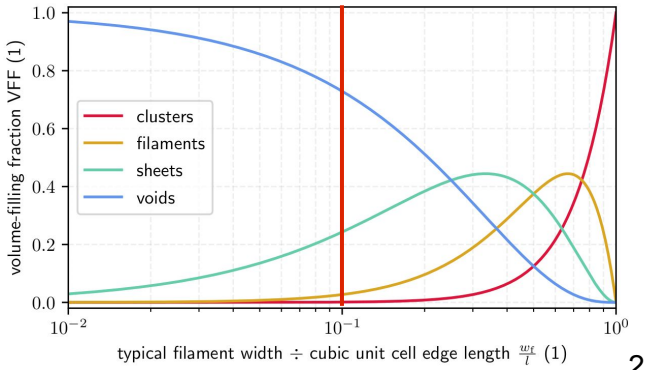
· Significant fraction of baryons

Driver 2021

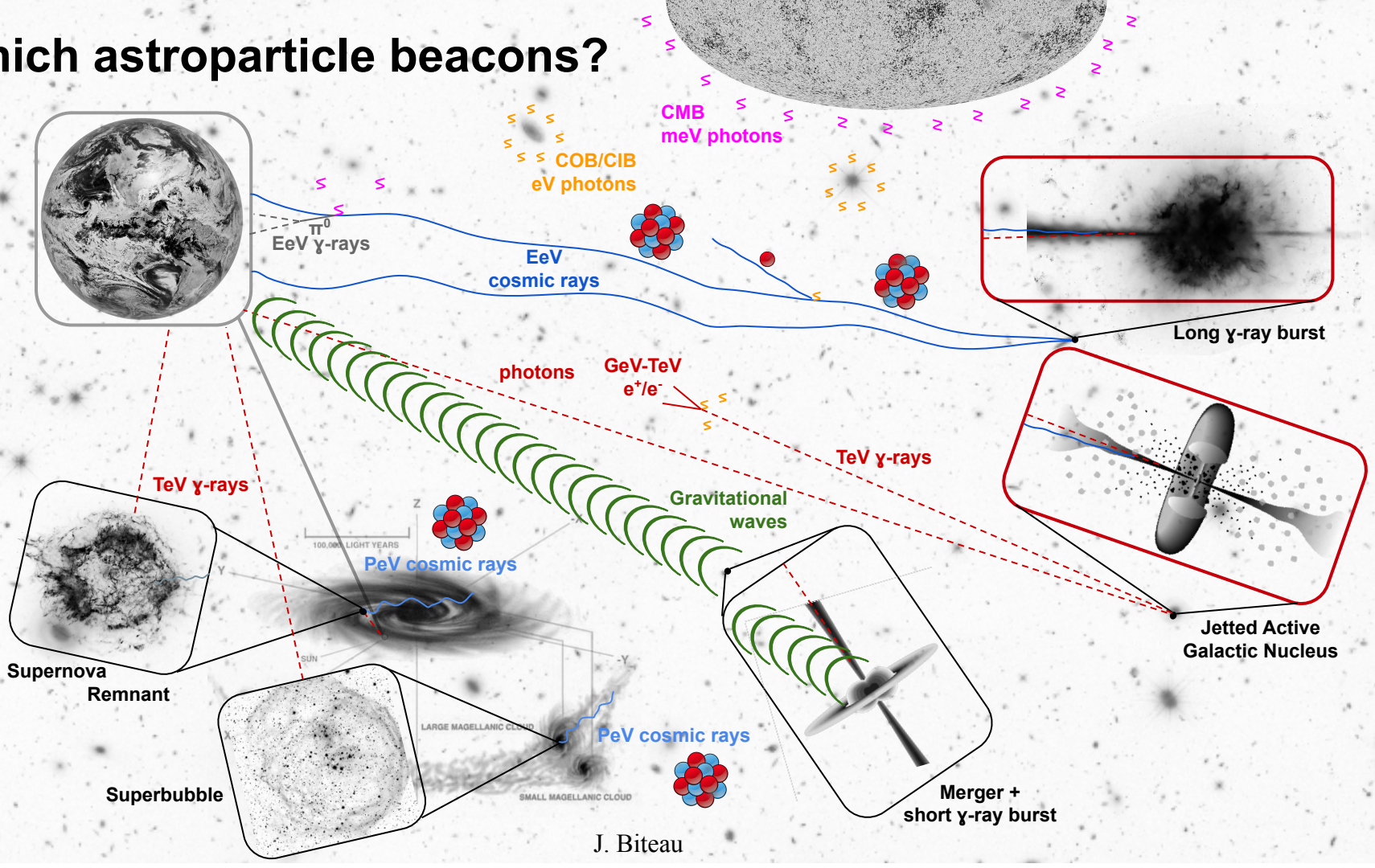
· Probed here with **astroparticles**



Oei+ 2022



Which astroparticle beacons?



Physics of extragalactic beacons of astroparticles

Central engine
Compact objects: black holes, neutron stars (accretion-ejection, merging)
→ dense matter, general relativity (GR), GR magnetohydrodynamics

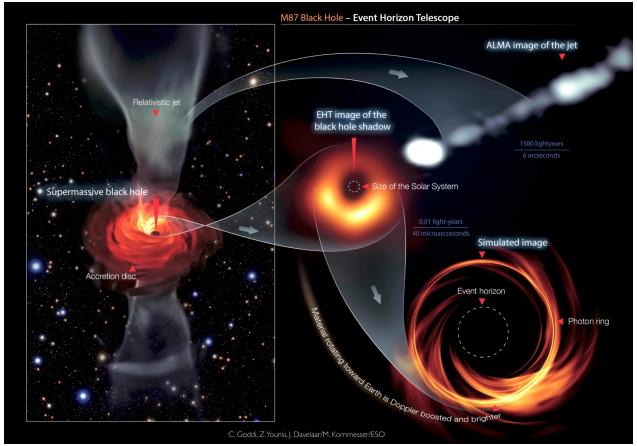
Acceleration
Relativistic shocks, magnetic reconnection
→ particle-in-cell simulations from first principles

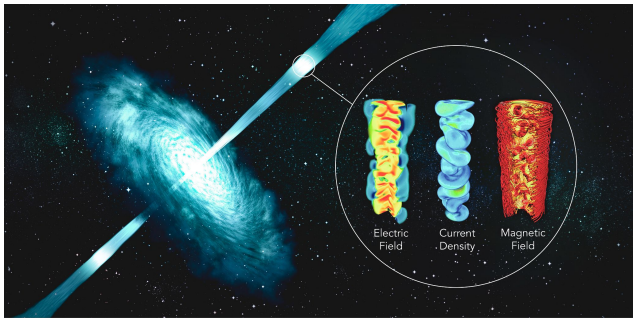
Radiative processes
Synchrotron, Inverse-Compton, Pion decay, Nuclear cascades
→ phenomenological model of particle flow + radiative microphysics

Escape
Multiscale magnetic fields and photon fields, target material
→ phenomenological model of particle/photon flow & of environment

Propagation
On interstellar (kyrs), intergalactic (Myrs) or cosmic (Gyrs) scales
→ probe of fundamental physics & diffuse electromagnetic fields

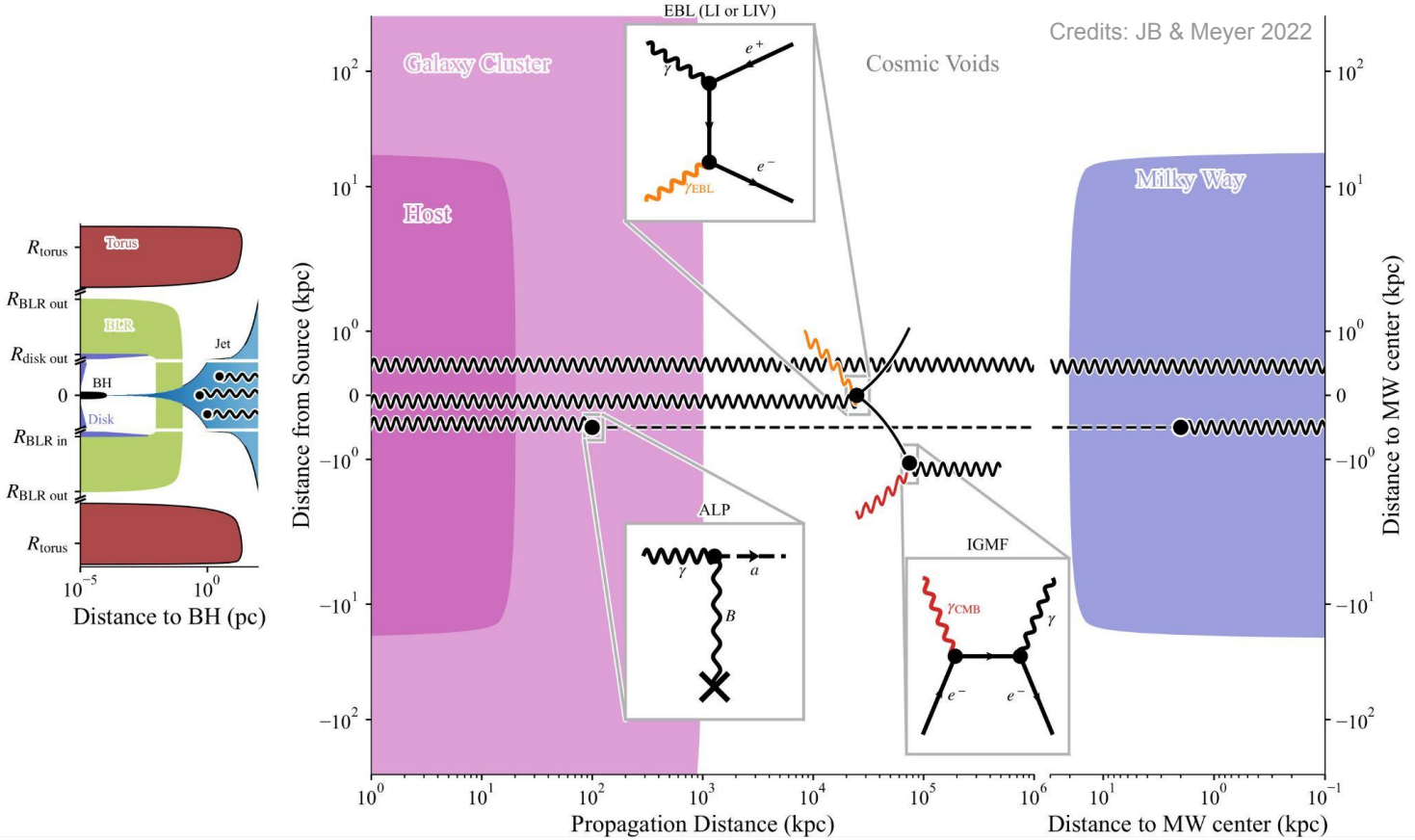
Highlight: the active galaxy M87 **Credits:** Goddi+, ESO



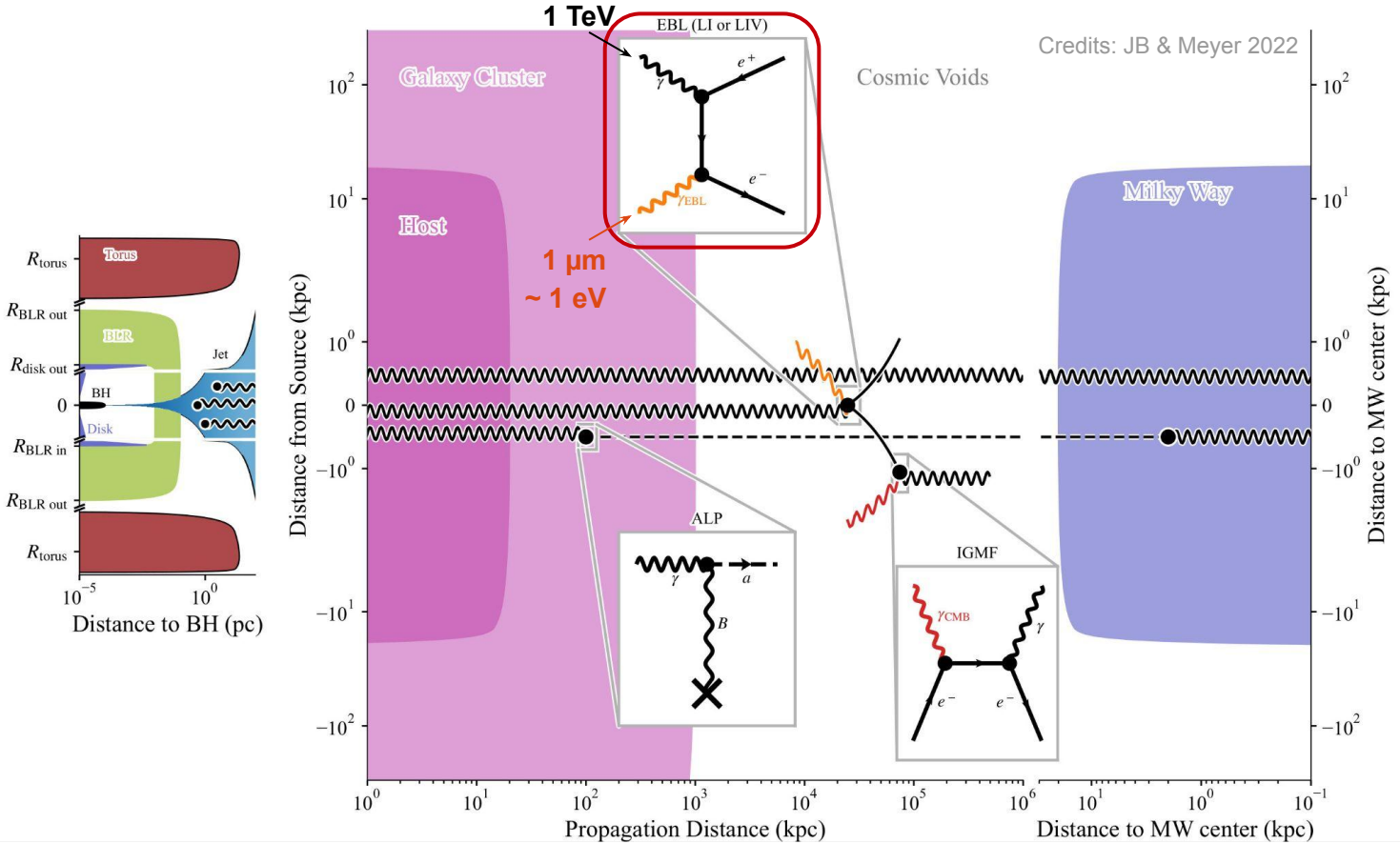


Credits: Stewart, SLAC

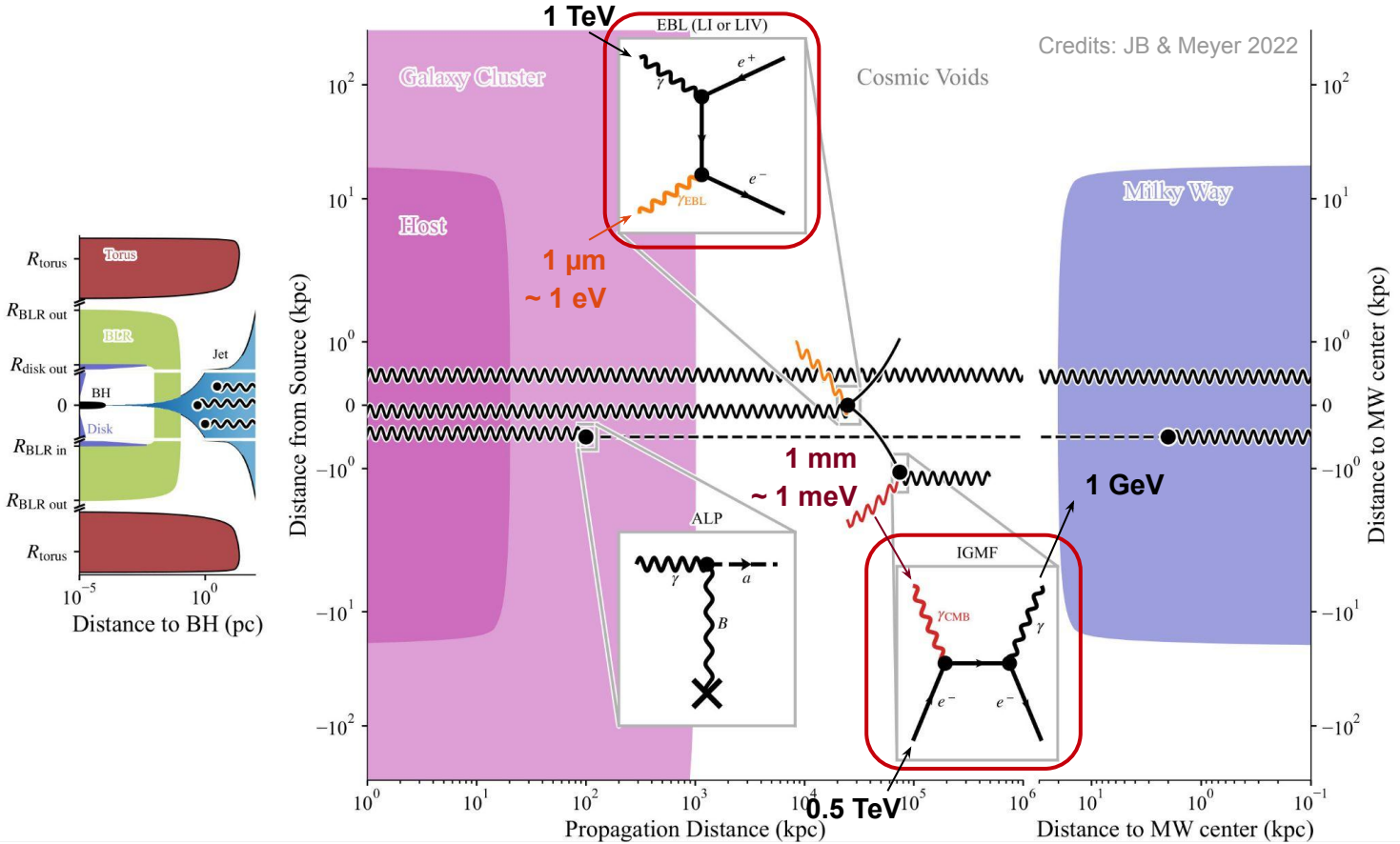
γ-ray propagation from sources down to Earth



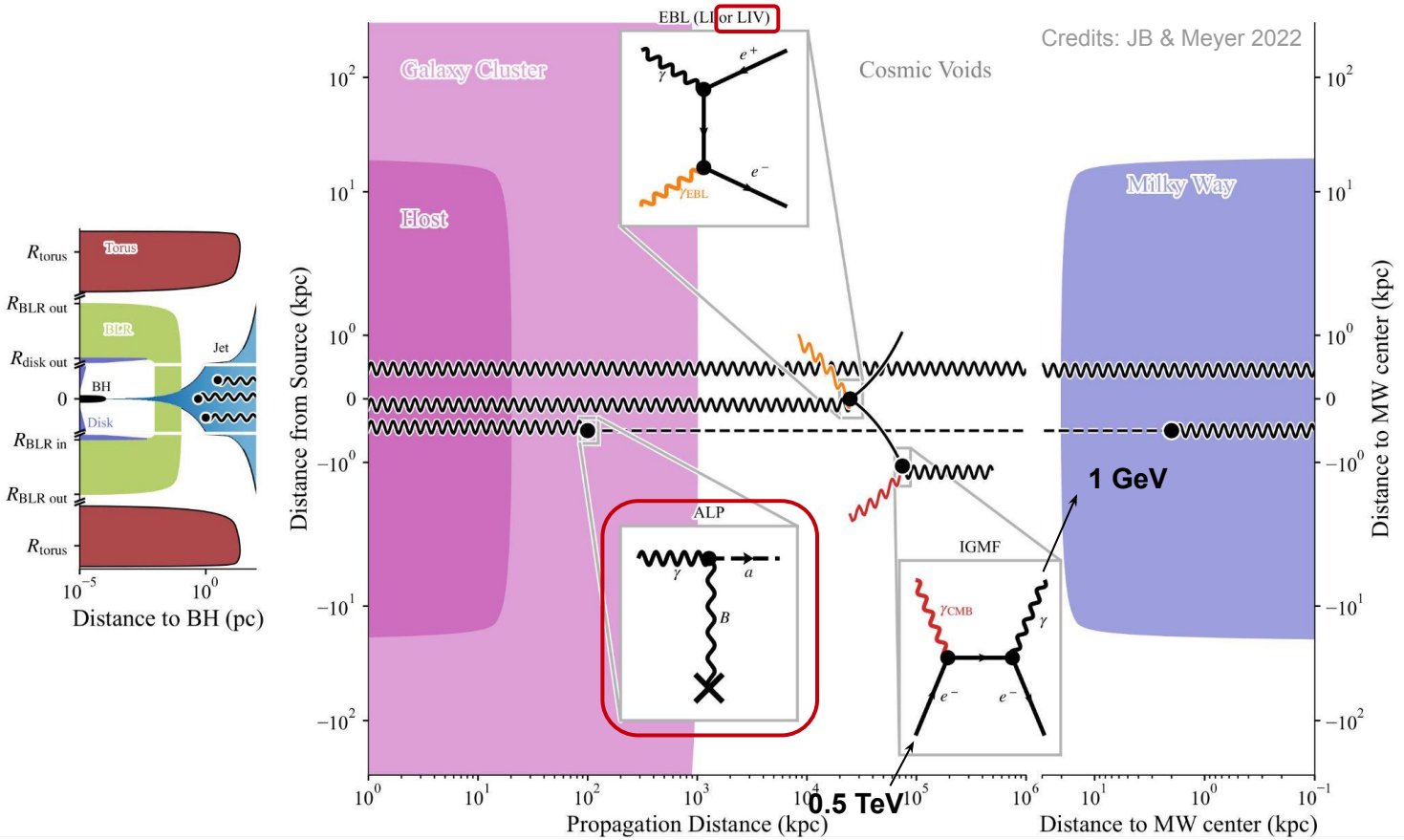
γ-ray propagation from sources down to Earth



γ-ray propagation from sources down to Earth



γ-ray propagation from sources down to Earth

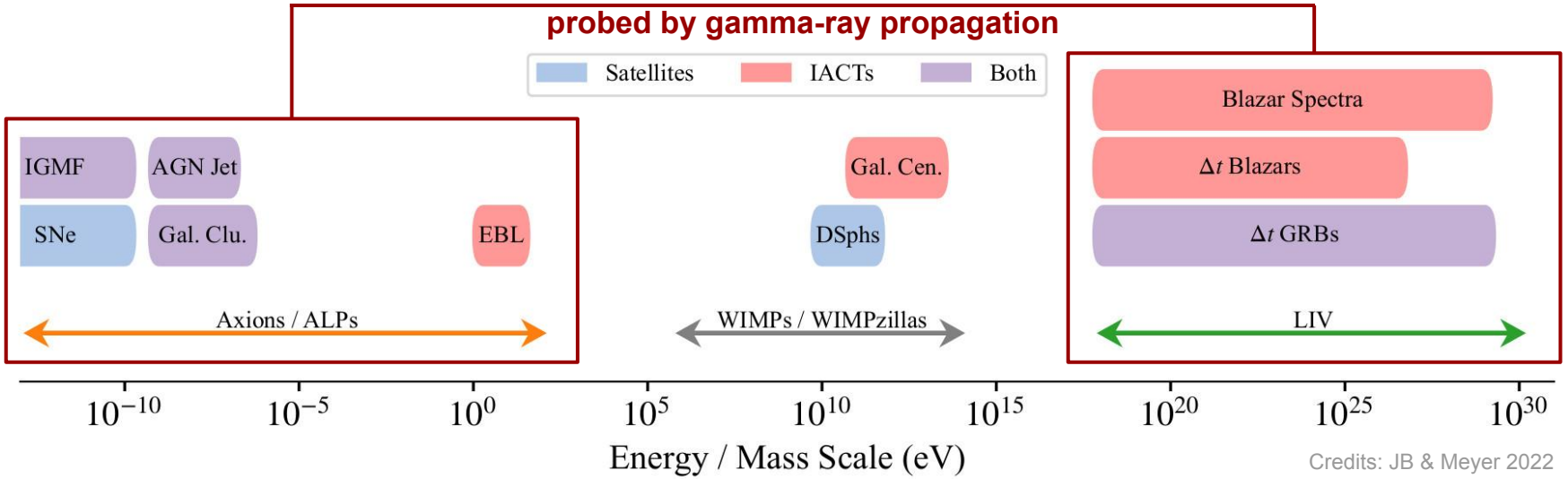


Aparté: γ-ray propagation and fundamental physics

Dark matter: what is that? Theories beyond QFT and GR: is there anything to observe?

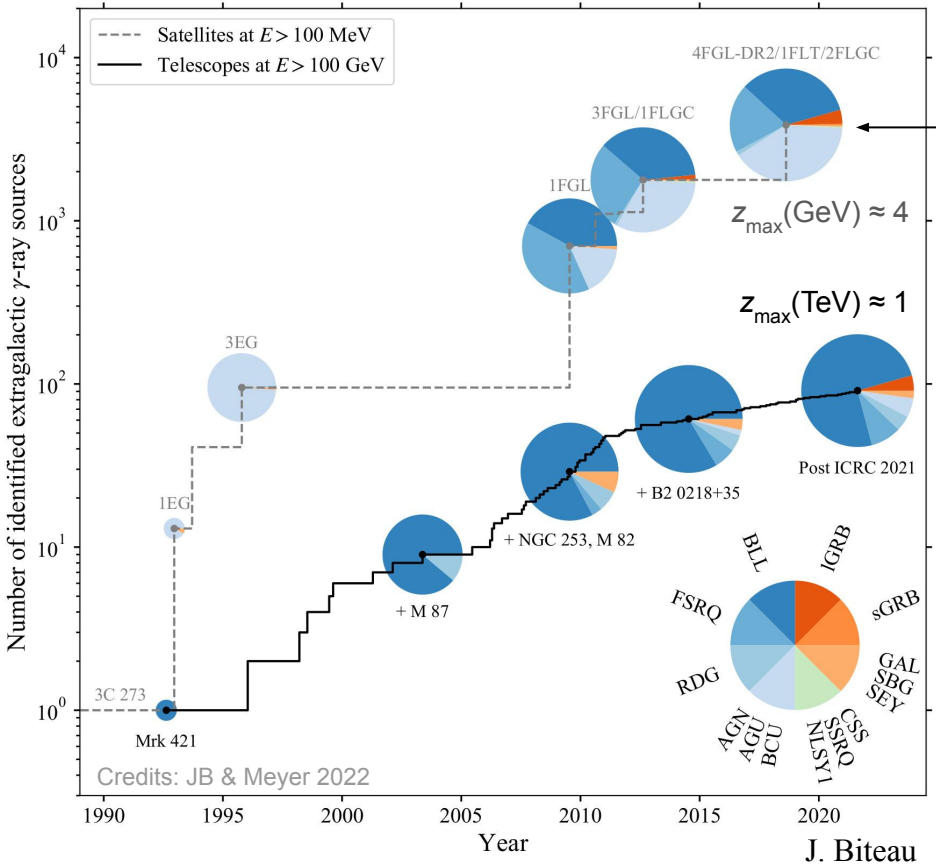
- Top-down processes (*heavy axion-like particles* /*or WIMPs*/): decay /*or self annihilation*/ into photons
- Mixing with light axion-like particles (ALP): CTA will start probing ALP dark-matter parameter space CTA 2021
- LIV linearly modified dispersion relation (CPT-odd): Planck scale ~excluded by spectra & Δt!

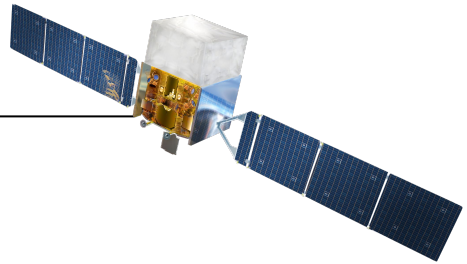
⇒ *High-risk / high-gain themes. Notes: ALP constraints dependent upon B-field morphology in jet*

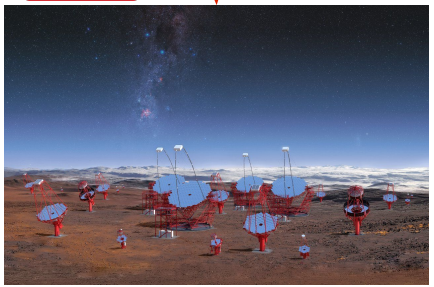


Credits: JB & Meyer 2022

Status of extragalactic γ-ray astronomy







γ-ray observation techniques

Satellite-based: 100 MeV - 1 TeV

O(100%) duty cycle, ~ 550 km altitude

SSDs + CsI(Tl) / photodiodes

Field of view > 0.5π sr

Lead: *Fermi*-LAT

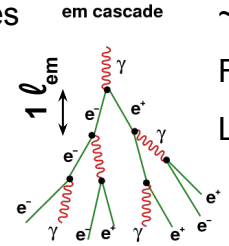
Telescope-based: 100 GeV - 100 TeV

O(10%) duty cycle, ~ 2 km above sea level

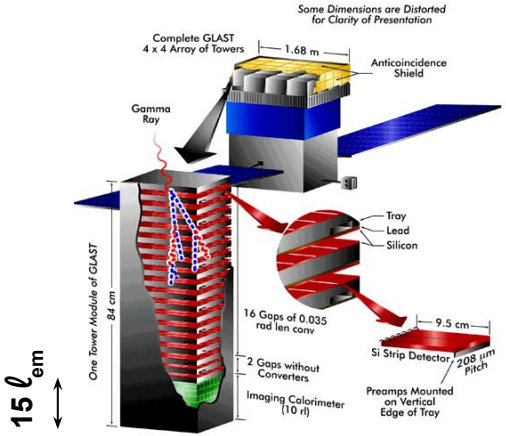
~1000 PMTs / camera

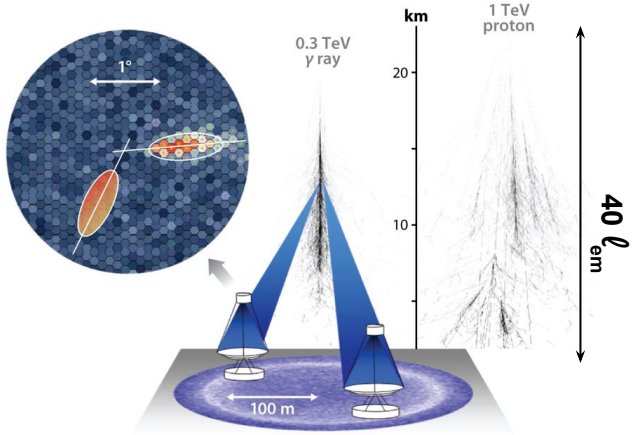
Field of view ~ 5°

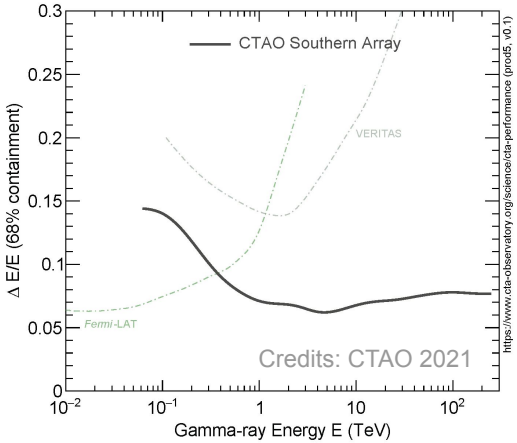
Lead: HESS, MAGIC, VERITAS

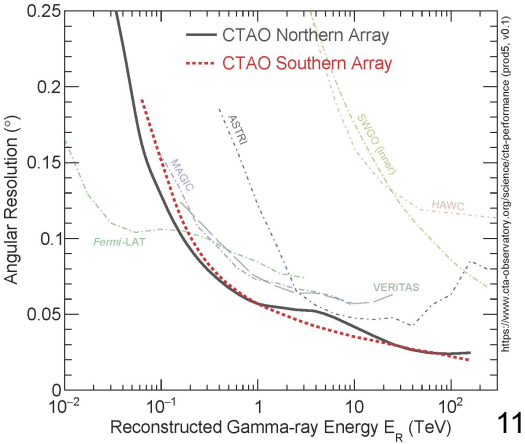


Mollerach & Roulet (2017)

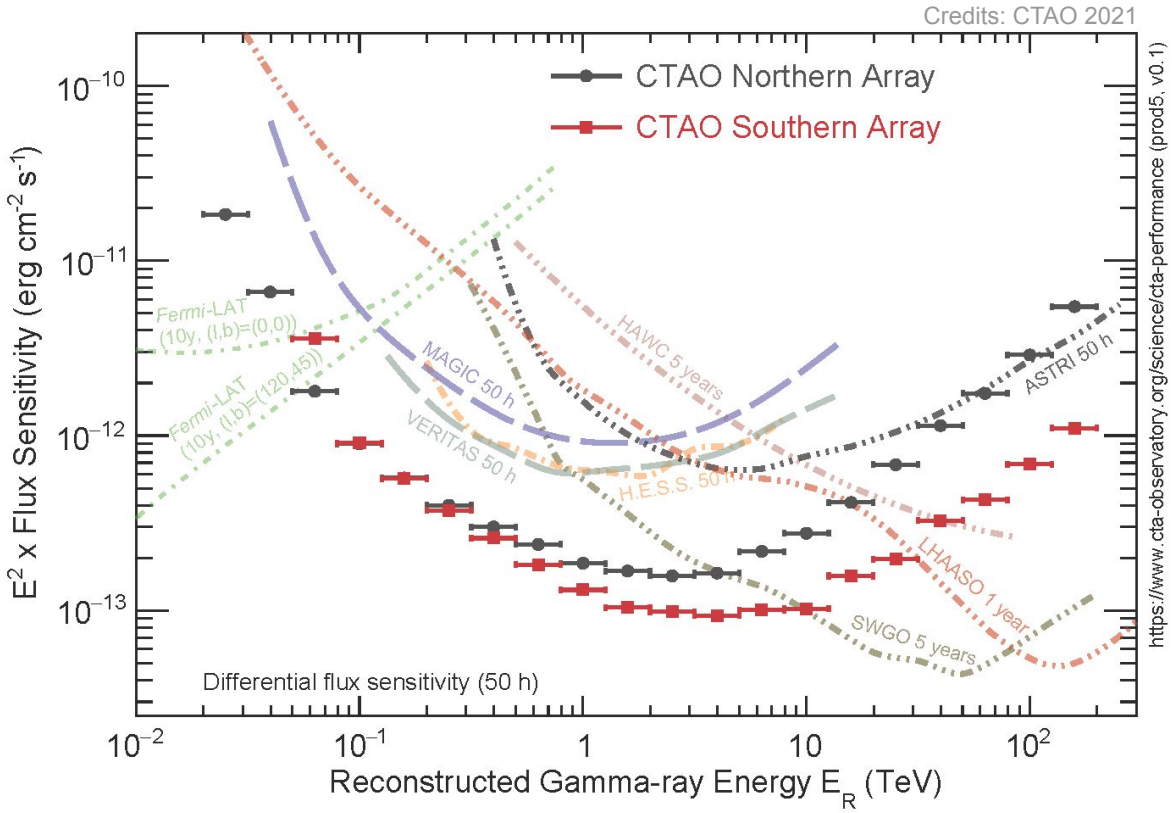


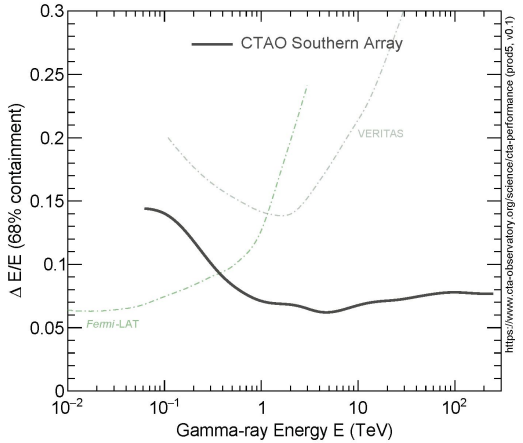


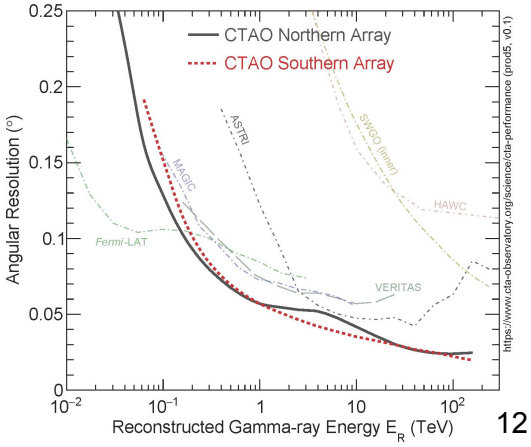




Upcoming: the Cherenkov Telescope Array







The magnetic content of voids

A gamma-ray view

Jonathan Biteau, IJCLab / Université Paris Saclay

Absence of secondary signal

Discovery of extreme TeV blazars in 2006

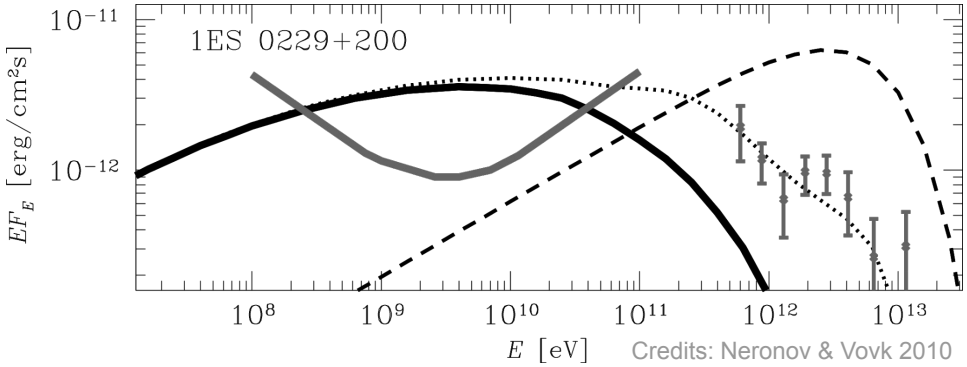
Hard TeV photon spectrum when corrected for absorption

Intrinsic emission expected to be faint in the GeV band

Reprocessed emission?

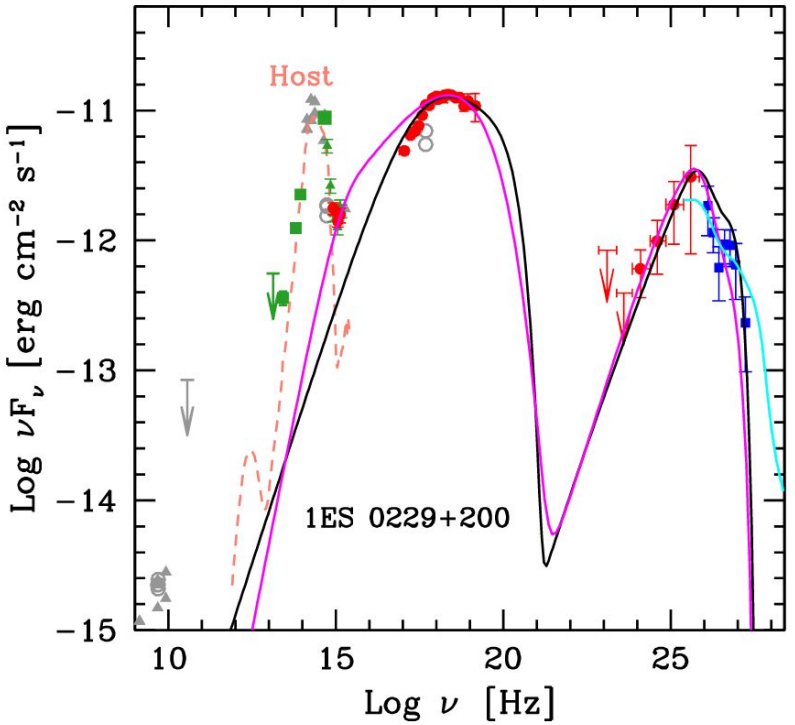
None in 2010 within point spread function

⇒ **minimum *B*-field needed to spread out the signal**



Credits: Neronov & Vovk 2010

Credits: JB+ 2020

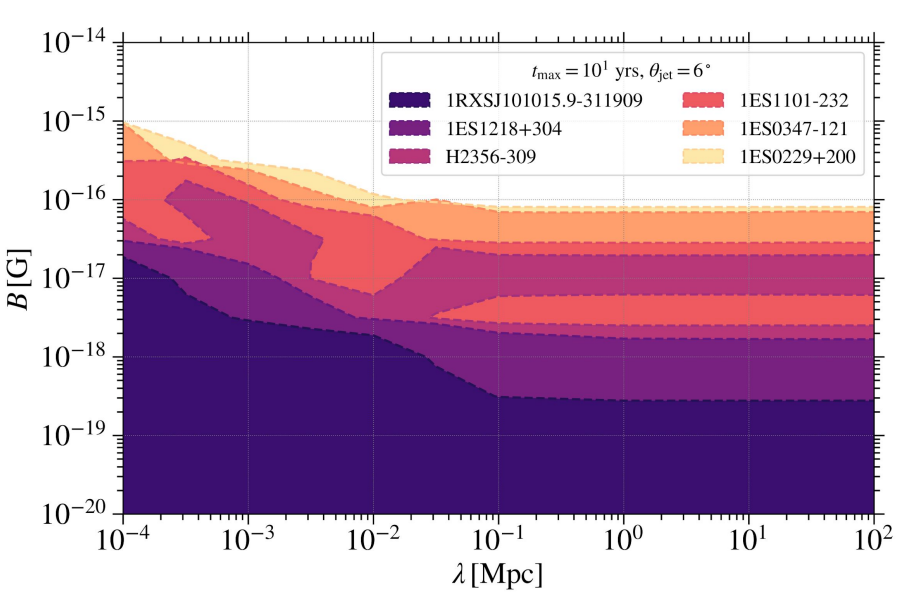


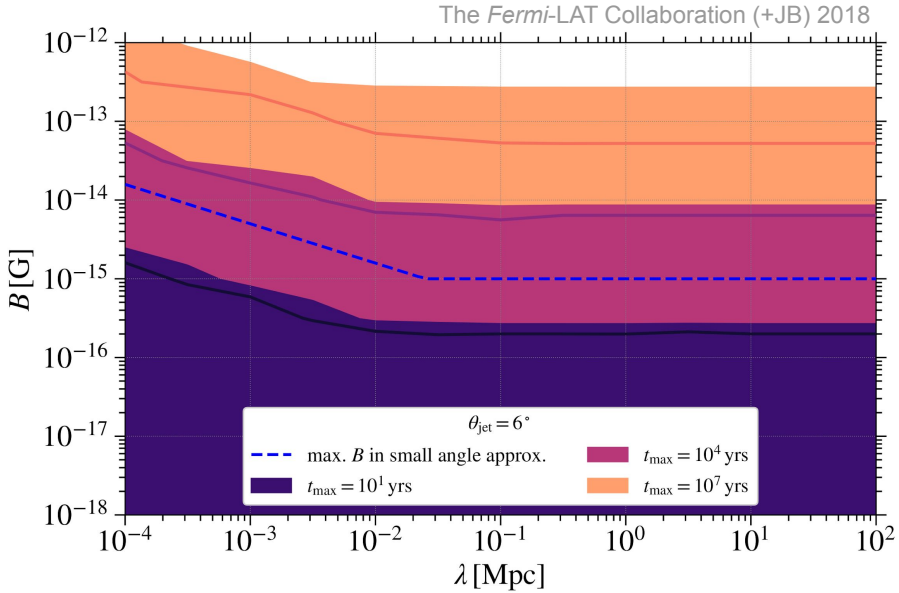
Most up-to-date constraints

Search for extended sources in the GeV band

Extreme-TeV blazars observed by *Fermi*-LAT ~ point source → joint likelihood: TeV/GeV spectra + *GeV morphology*

Constraints on magnetic fields in voids: ***B* > 0.1-1 fG** (minimal assumptions)





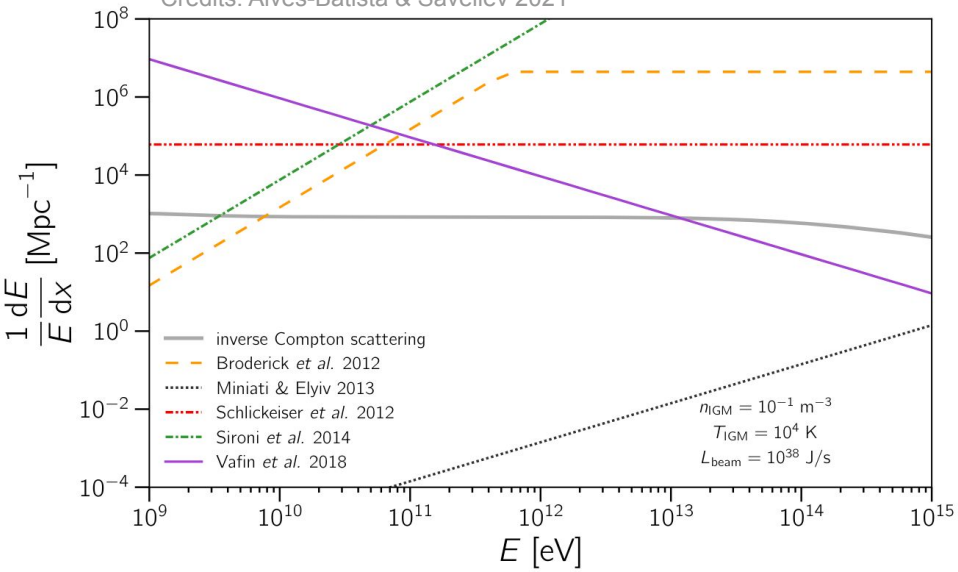
Alternative cooling

Plasma instabilities faster than inverse Compton?

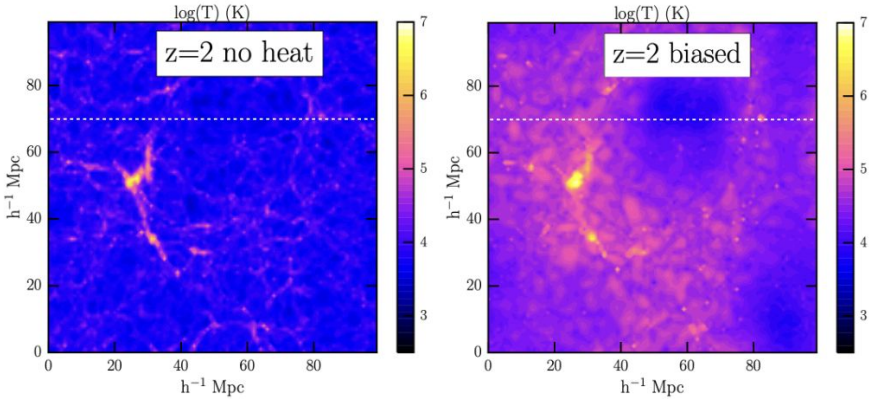
Yes, on paper… Analytics / simulations limited by several order-of-magnitude extrapolations ⇒ unclear if viable

Possible heat source for intergalactic medium, observable through temperature history of the universe (Lyα forest)?

Credits: Alves-Batista & Saveliev 2021



Credits: Lamberts+ 2022

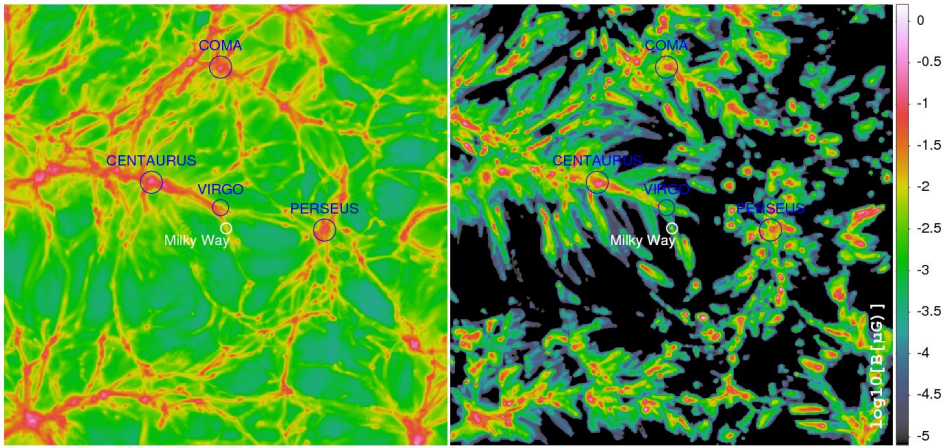


Magnetic fields in voids

Status and expectations (if low plasma instabilities)

Current-generation (GeV+TeV - TeV extension): B > 10-100 fG

5σ CTA-discovery potential up to 300 fG



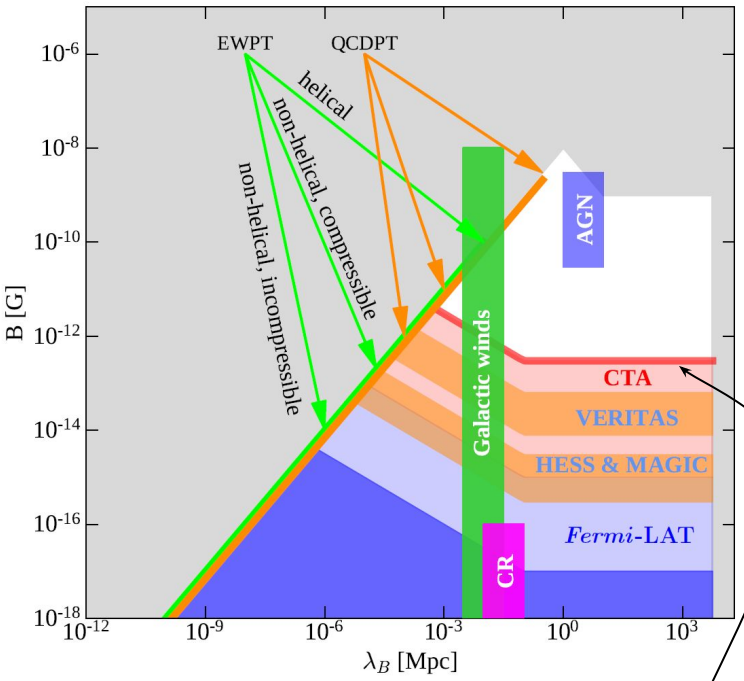
Credits: Hackstein+ 2018

Primordial origin simulation
B(void) < 1 nG

Astrophysical origin simulation
B(void) < 1 pG

In practice… largely unknown!

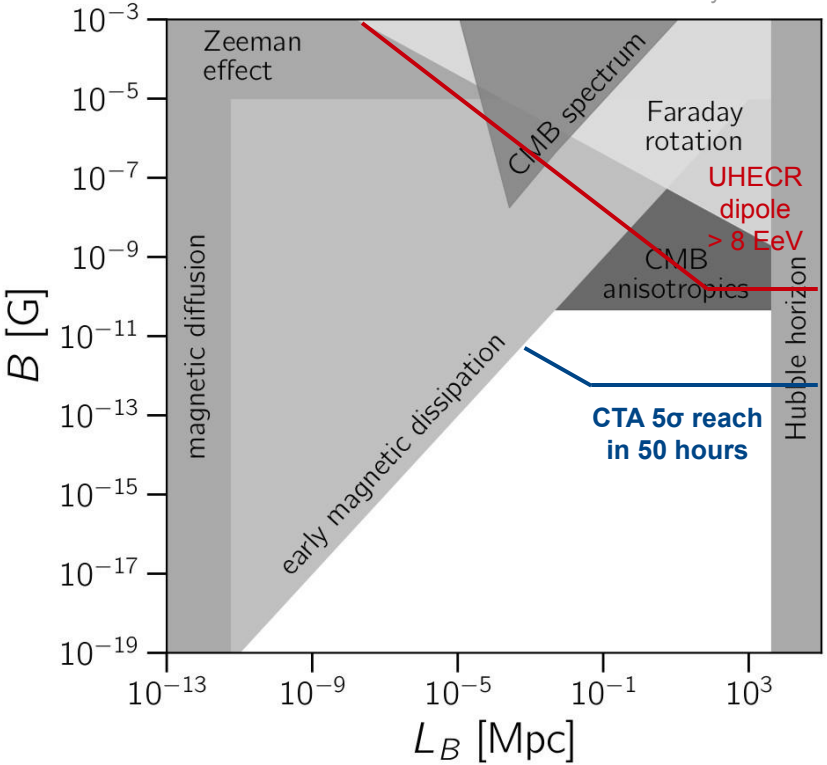
Credits: CTA Consortium 2021



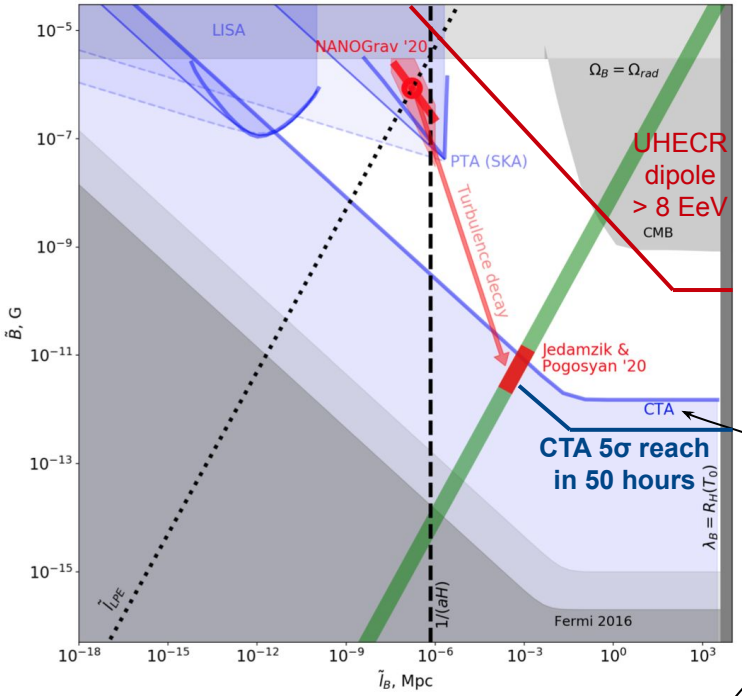
1ES 0229+200 (z=0.14) up to E_{cut} = 10 TeV,
50h of CTAO-North to reach 5σ

Multi-wavelength and multi-messenger constraints

Credits: Alves-Batista in Pueschel & JB 2021 + Bray & Scaife 2018 (UHECR)



Credits: Neronov+ 2021+ Bray & Scaife 2018 (UHECR)



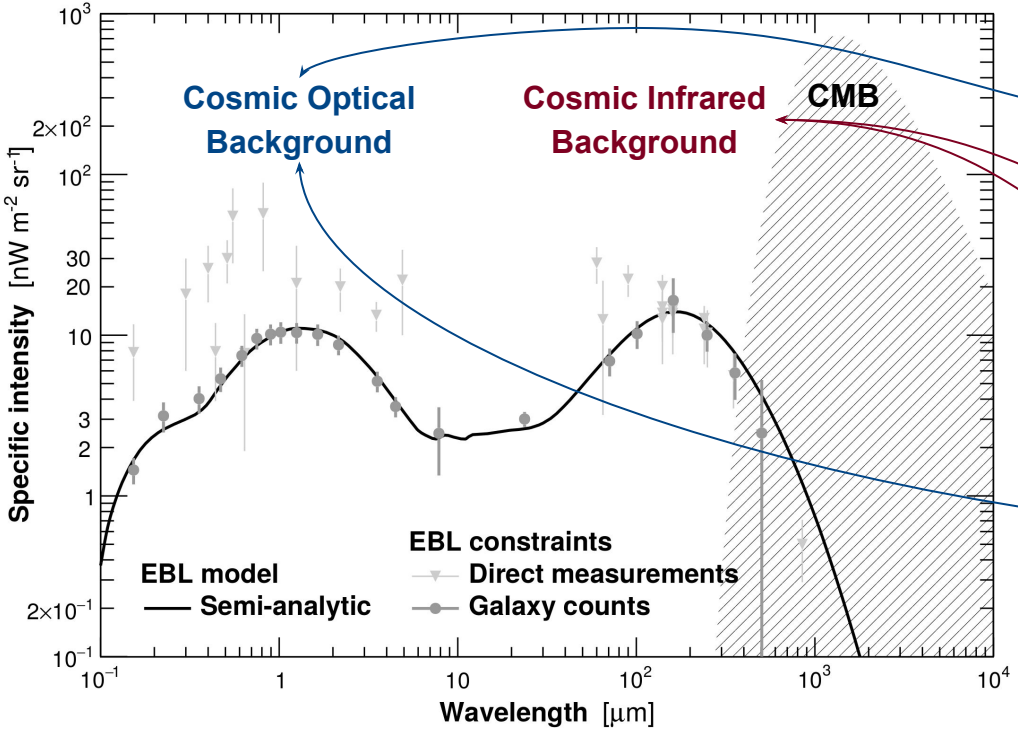
Mrk 501 (z=0.03) up to E_{cut} = 100 TeV,
350h of CTAO-North to reach 5σ

The light content of voids

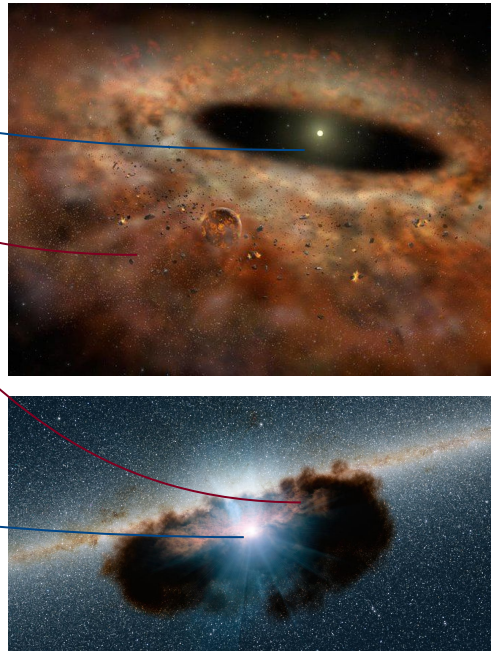
A gamma-ray view

Jonathan Biteau, IJCLab / Université Paris Saclay

The extragalactic background light

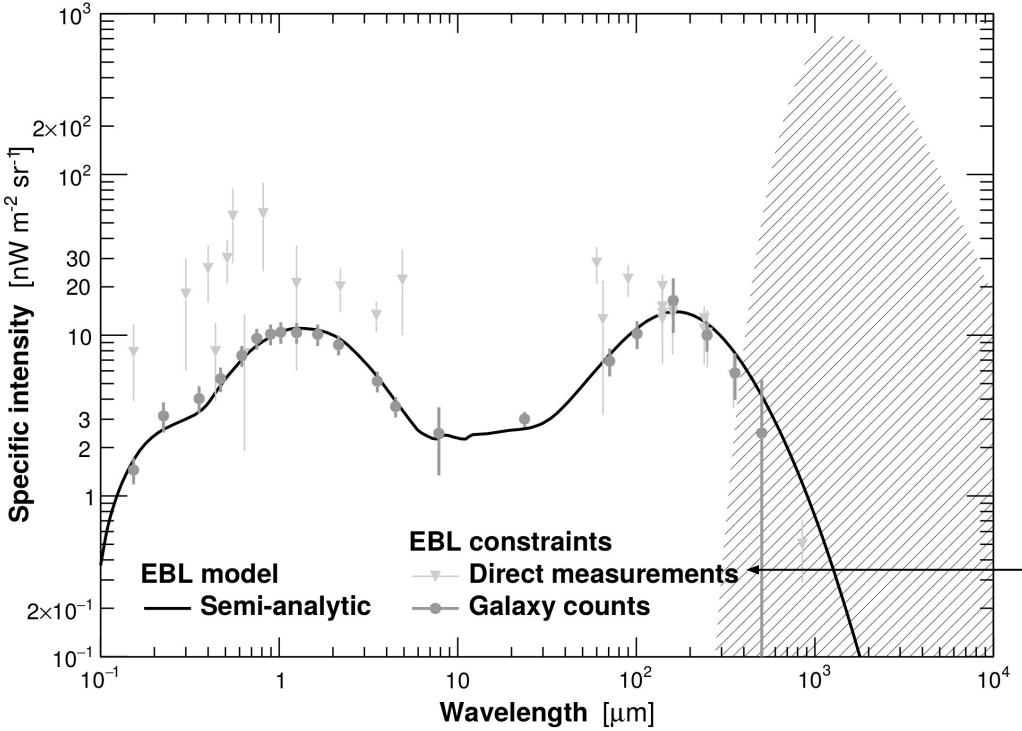


Credits: Gemini Obs./AURA/Lynette Cook

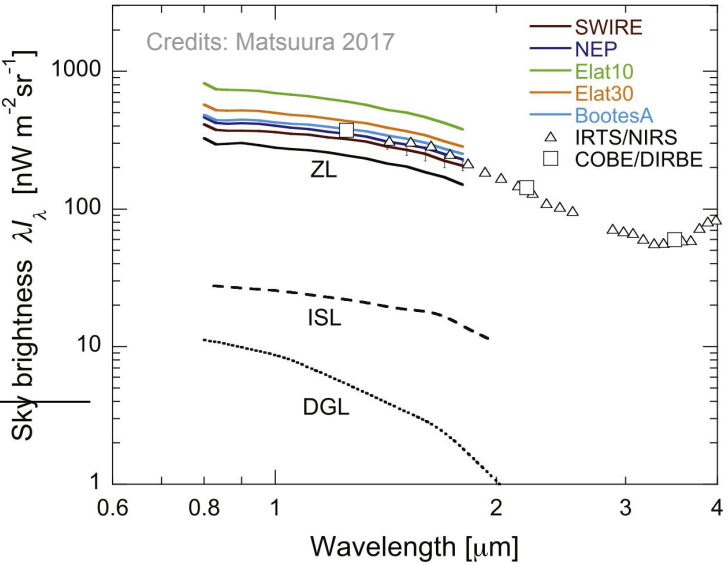


Credits: NASA/JPL-Caltech

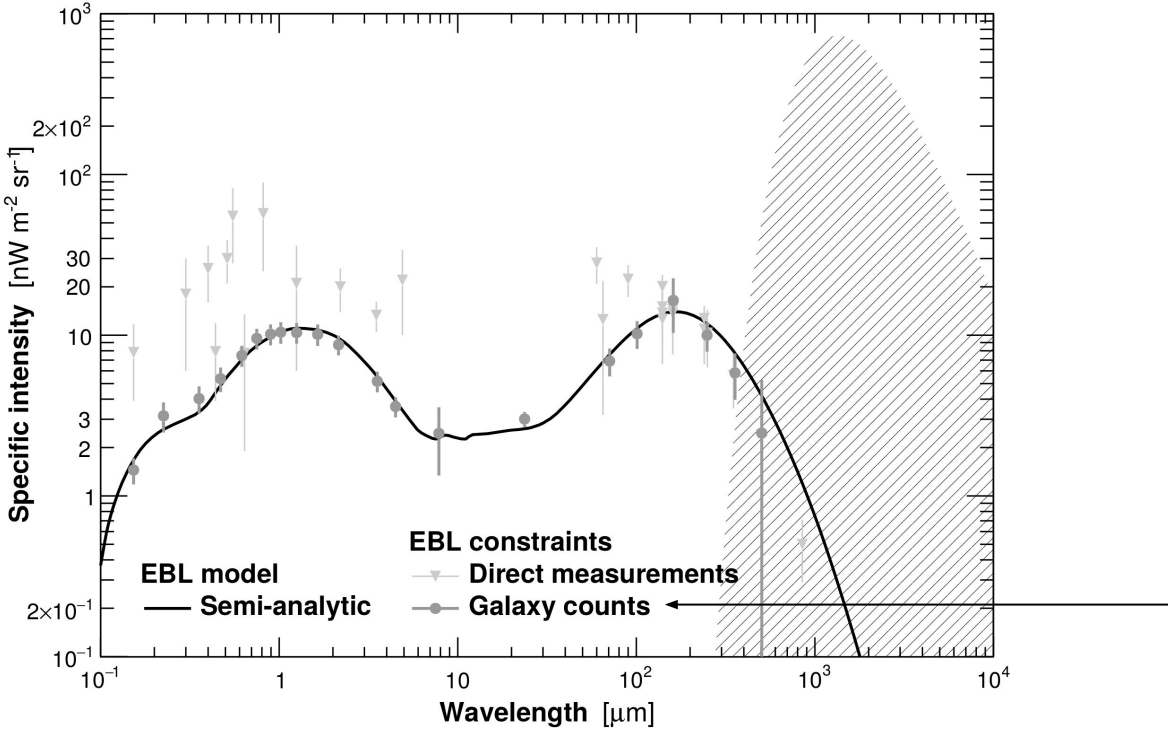
Direct measurements

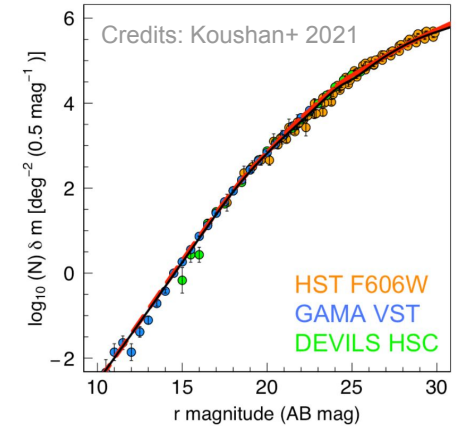


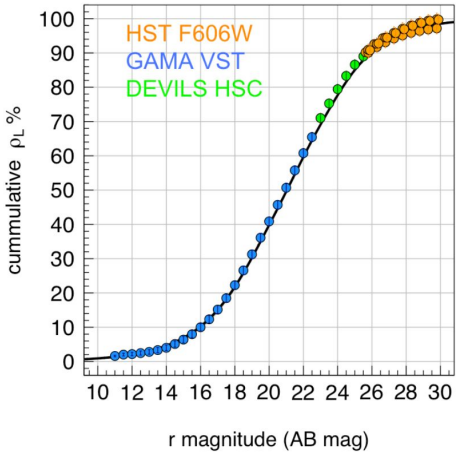
- ZL = Zodiacal light
- ISL = Integrated star light
- DGL = Diffuse Galactic light
- EBL = Extragalactic background light
  = COB + CIB here



Galaxy counts



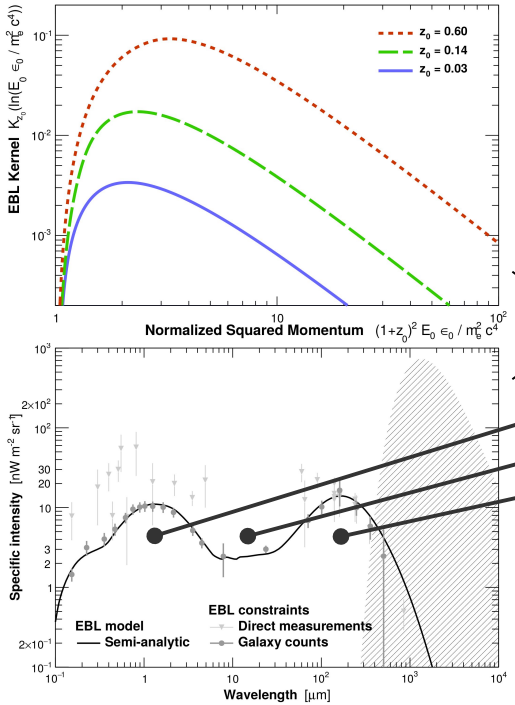


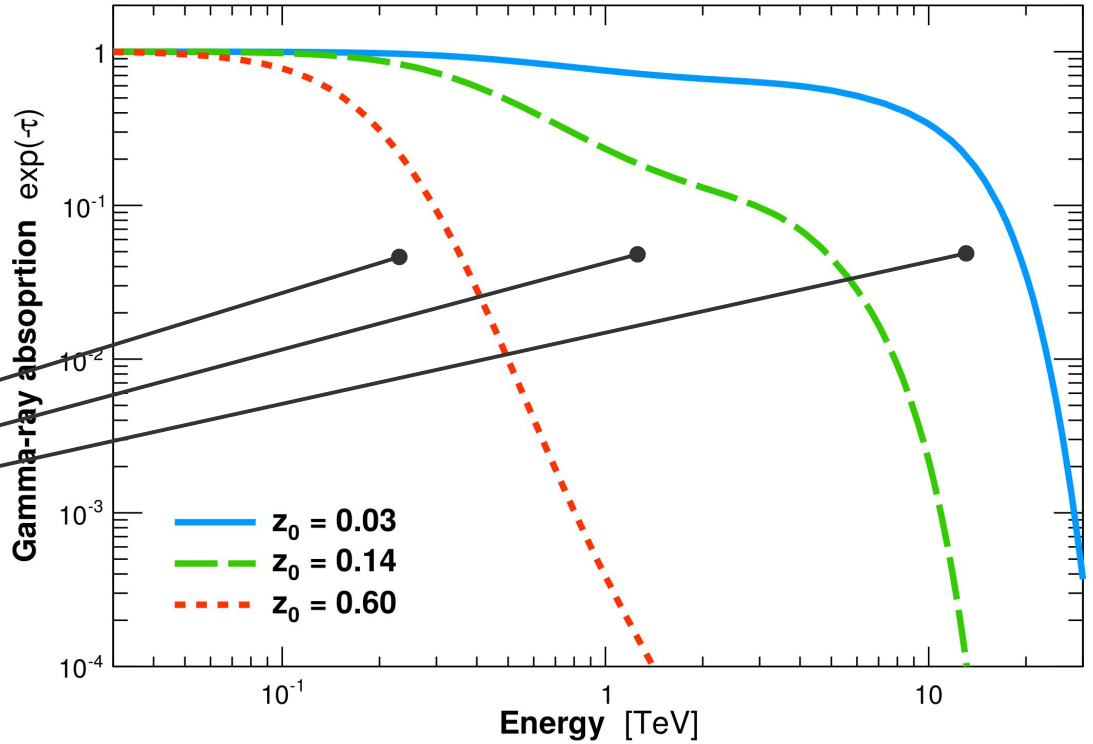


The gamma-ray technique

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

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



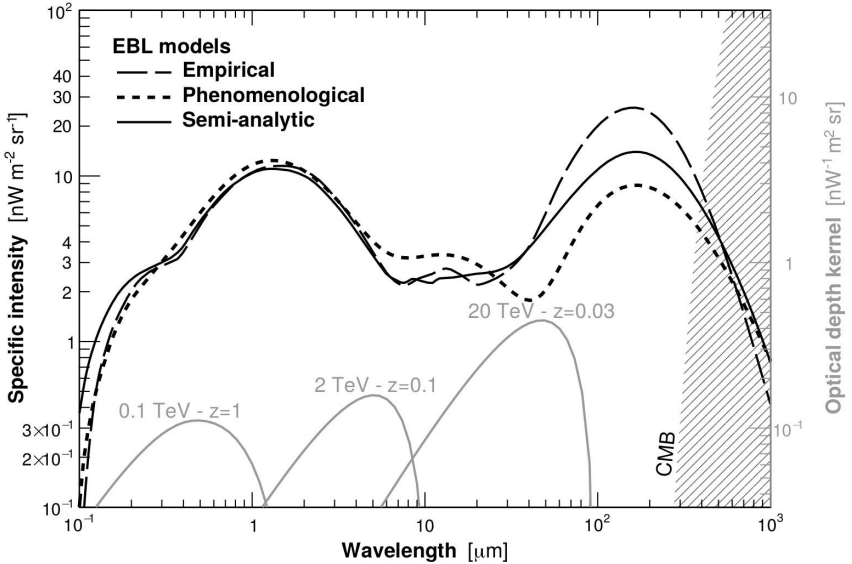


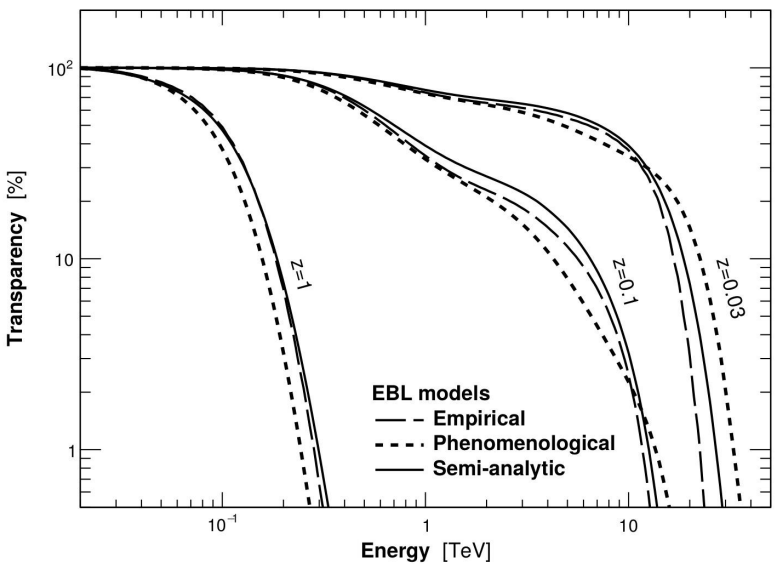
The models and the gamma-ray technique

Models of the COB + CIB (= extragalactic background light, EBL)

- Empirical models: extrapolate on local data — here Dominguez +11
- Phenomenological models: SFR + population synthesis — here Finke+ 10
- Semi-analytic models: N-body simulations — here Gilmore+ 12

Credits: Pueschel & JB 2021

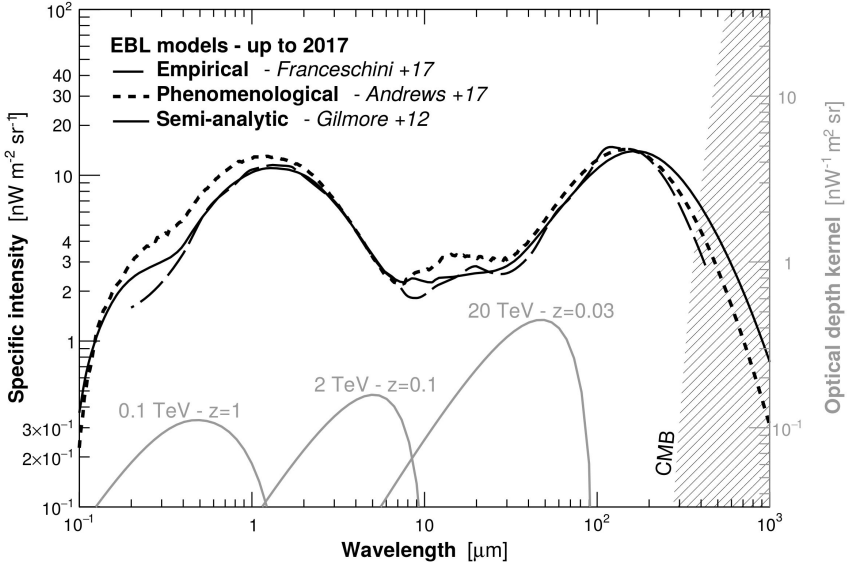


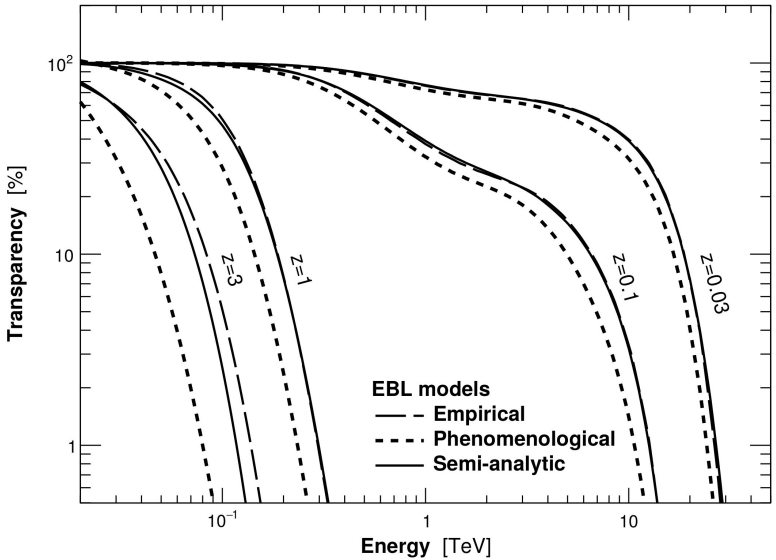


The models and the gamma-ray technique

Models of the COB + CIB (= extragalactic background light, EBL)

- Empirical models: extrapolate on local data — here Franceschini +17
- Phenomenological models: SFR + population synthesis — here Andrews+ 17
- Semi-analytic models: N-body simulations — here Gilmore+ 12

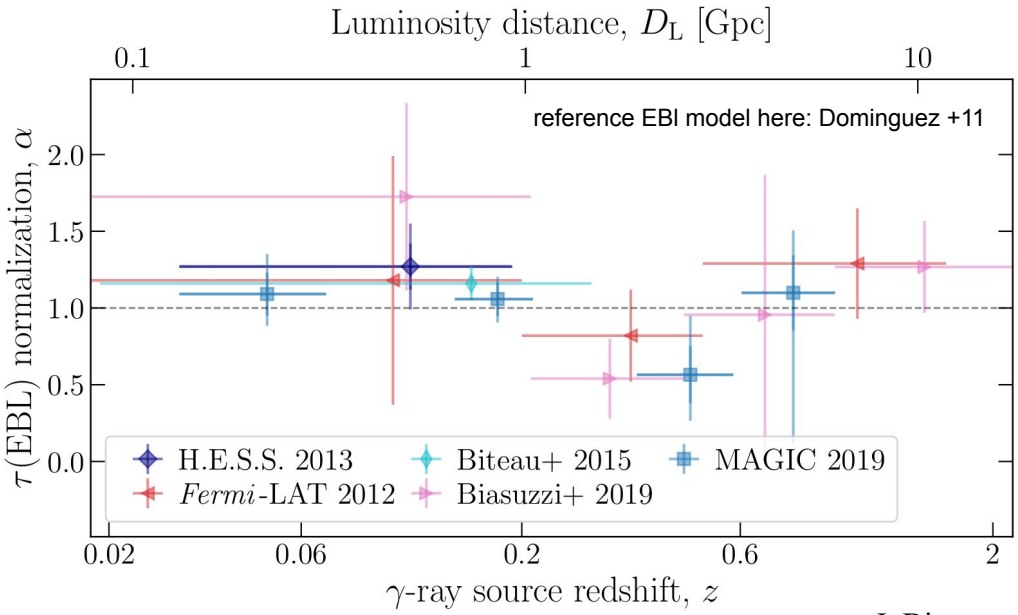


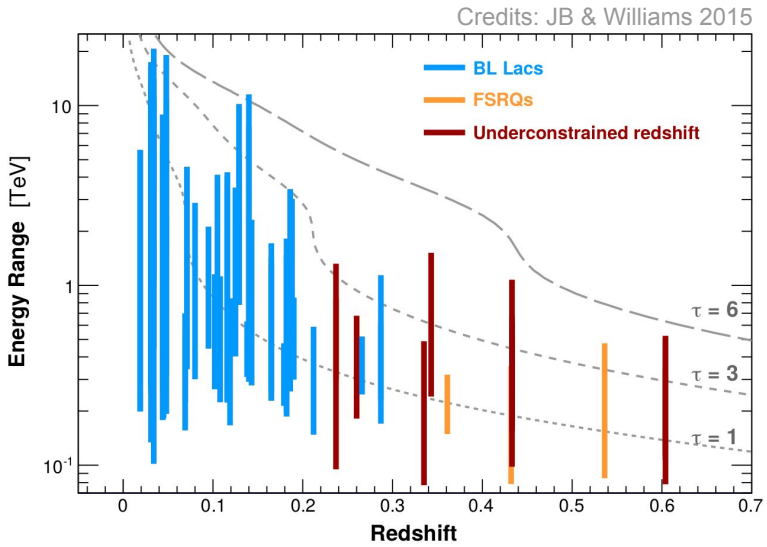


Status: gamma-ray inference vs model

Model: $\Phi(E, z) = \Phi_{int}(E \mid \theta_{int}) \exp(-\alpha\, \tau(E,z))$, **applied to spectra of AGN/GRBs with *E* > 100 GeV… and *z*:**

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

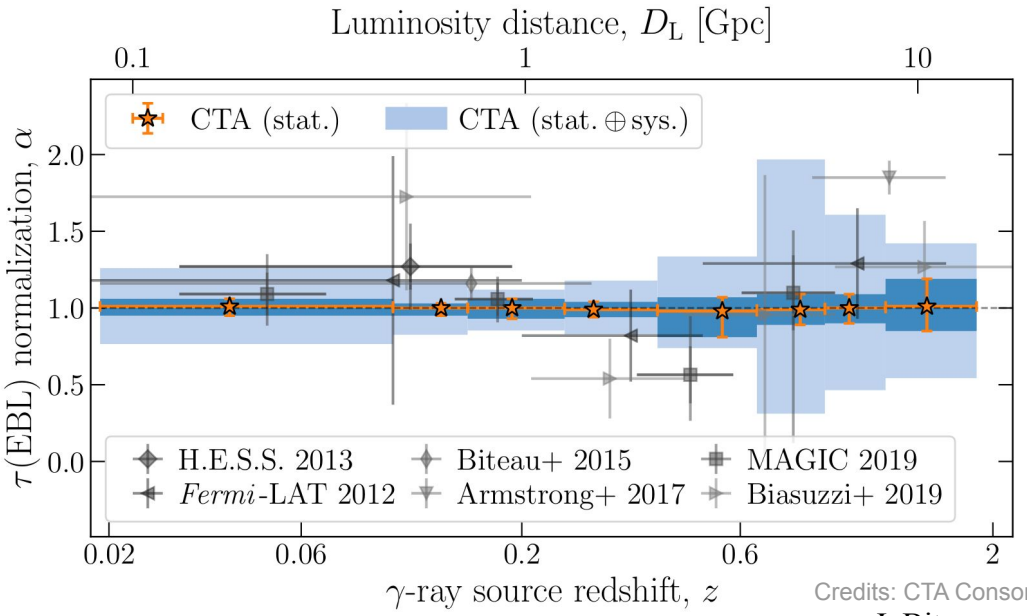


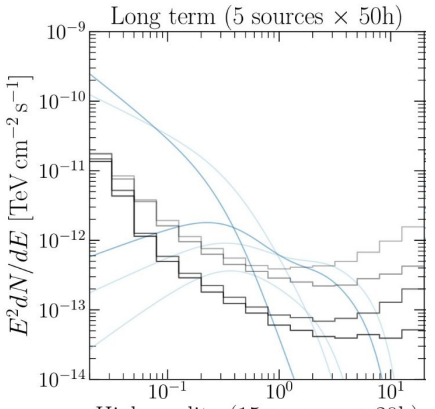


Expectations from CTA

Reconstructed EBL level wrt to a reference model

- Out to z ~ 2, with at least five spectra per bin
- Uncertainty down to ±5%$_{stat}$ ±12%$_{sys}$ (vs. ±20%$_{stat}$ ±20%$_{sys}$ today)



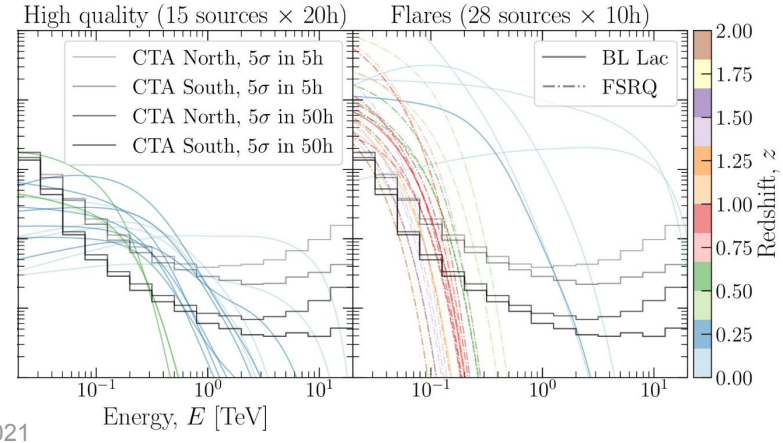


Simulated dataset

> 800h of observations

Realistic spectra from current-generation GeV-TeV observatories

Systematics: min-max allowed IRFs

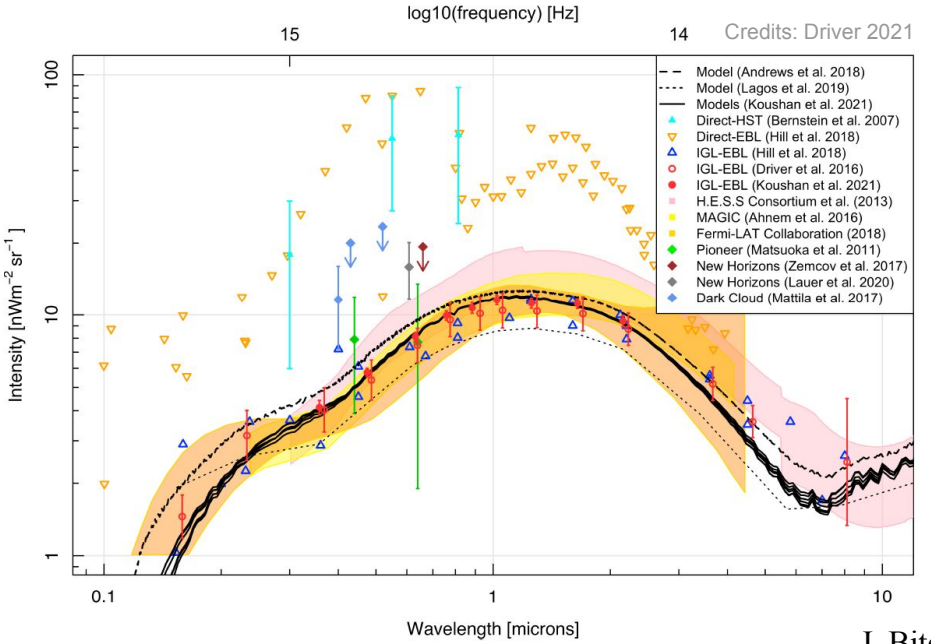


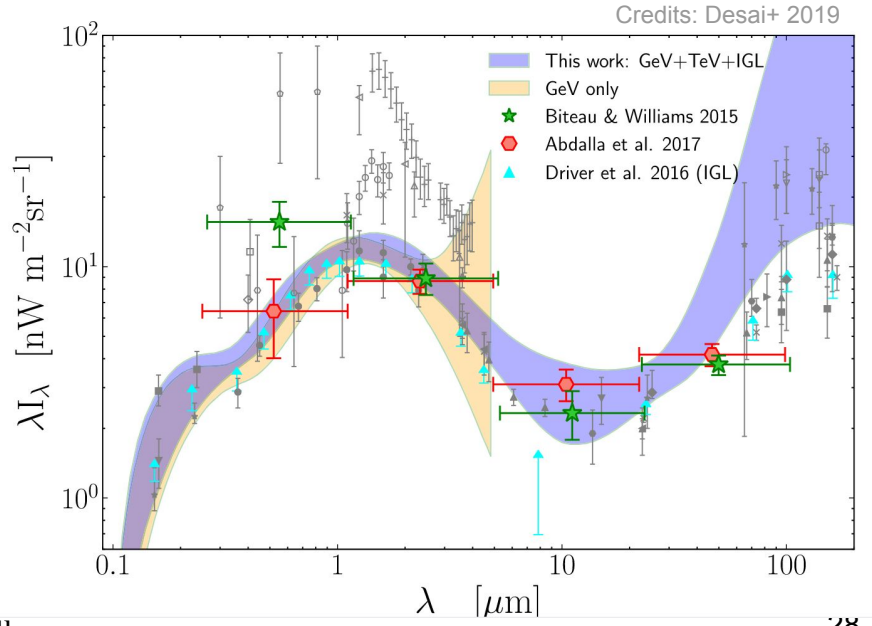
Credits: CTA Consortium 2021

Wavelength-resolved measurements from γ-ray spectra

Direct measurements vs galaxy counts… and the γ-ray referee?

- γ-ray "specific" intensity around 0.6μm: < 15-25 nW m^{-2} sr^{-1} (JB+ 2015, HESS 2017, VERITAS 2019, MAGIC 2019)
- Galaxy counts / Direct measurements @ 0.6μm: 8.1±0.3 nW m^{-2} sr^{-1} (Koushan+ 2021) / 16±4 nW m^{-2} sr^{-1} (Lauer+ 2020)



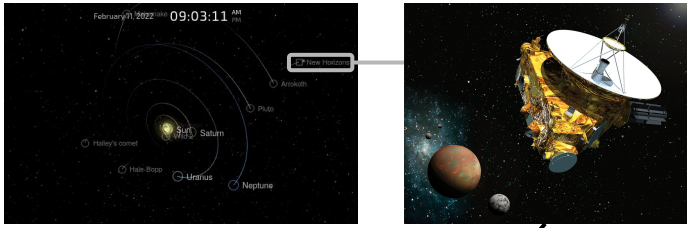


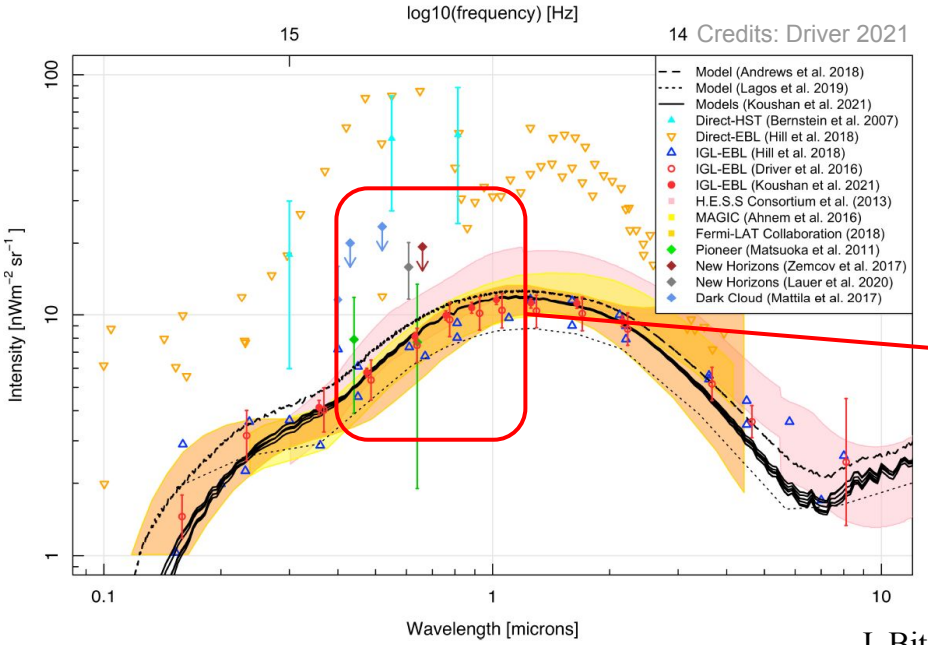
The “optical controversy”

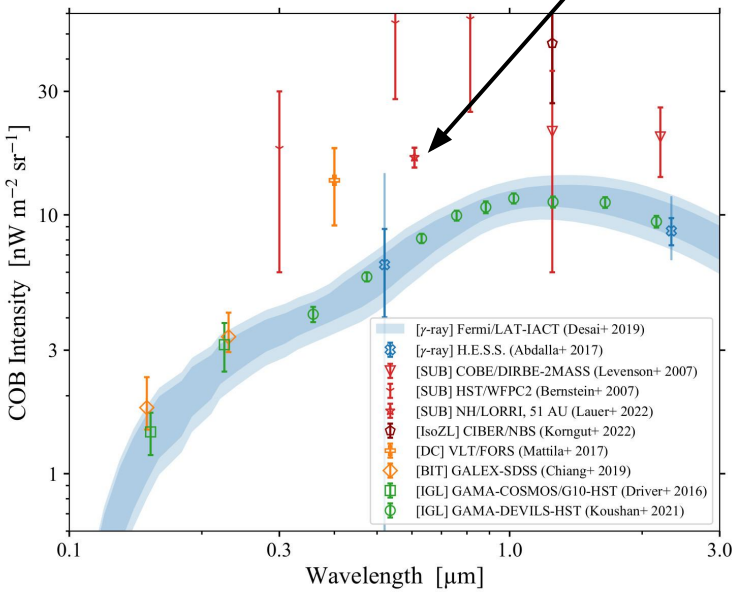
Spacecrafts out of the Solar System at this link

Recent news: New Horizons / LORRI

- Darkest, reliable field: 16.4±1.5 nW m^{-2} sr^{-1} (Lauer+ 2022)
- If of extragalactic origin: galaxy counts = half of EBL @ 0.6μm





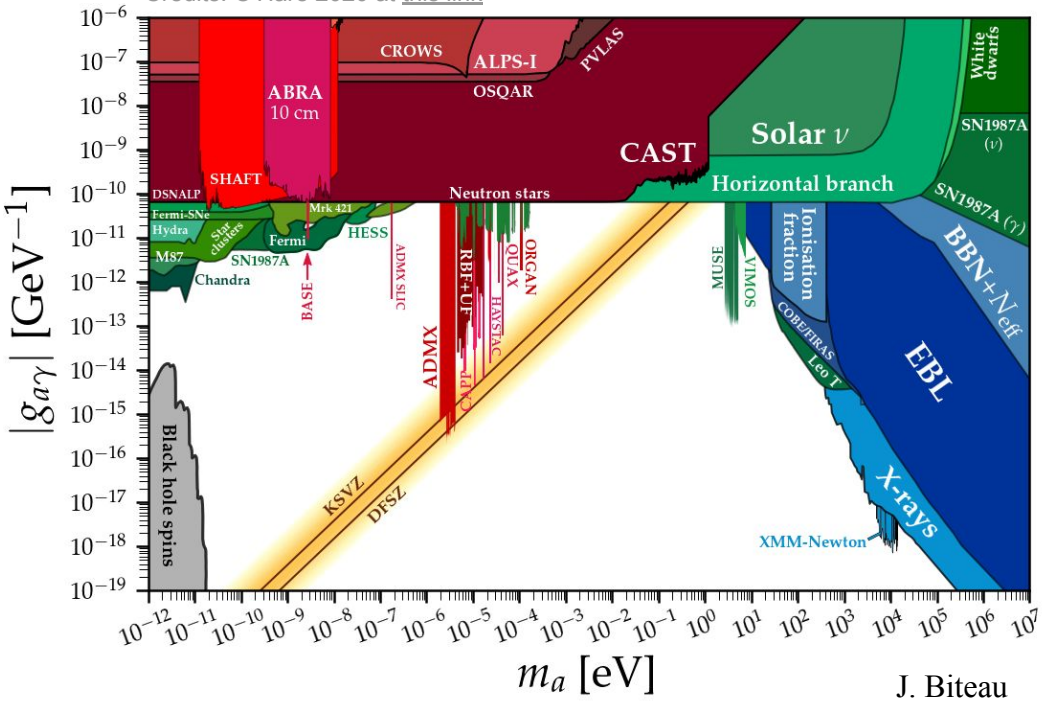


Constraints on decaying axions

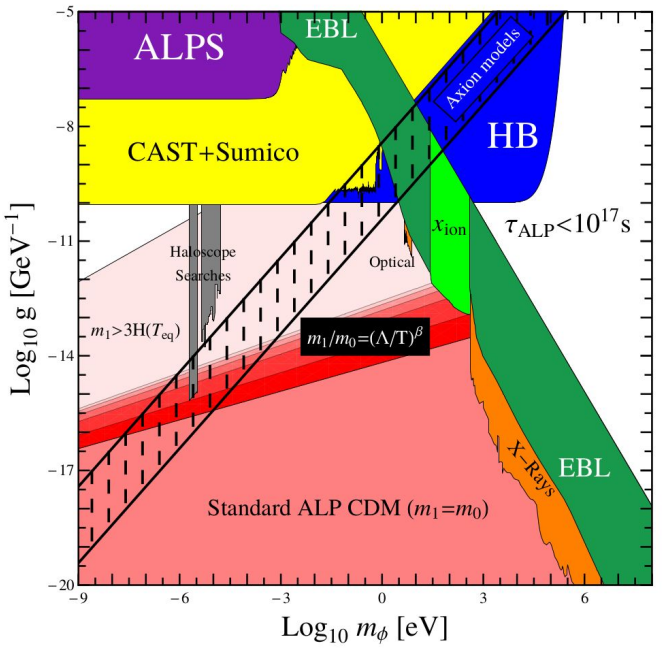
Exotic contributions to the night-sky brightness?

- Top-down process: decay of heavy (eV) axion-like particles (unlikely DM explanation though, Nakayama & Yin 2022) .

Credits: O'Hare 2020 at this link



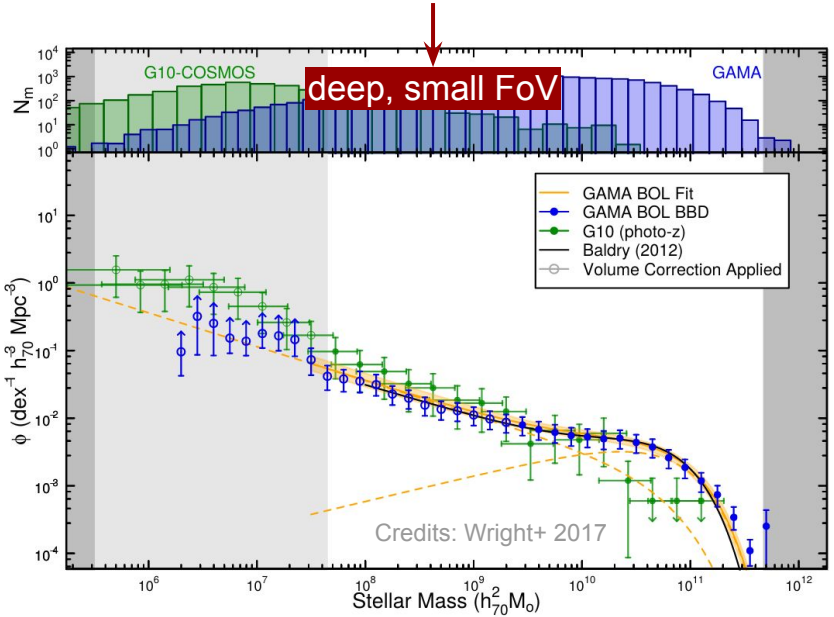
Credits: Arias+ 2012

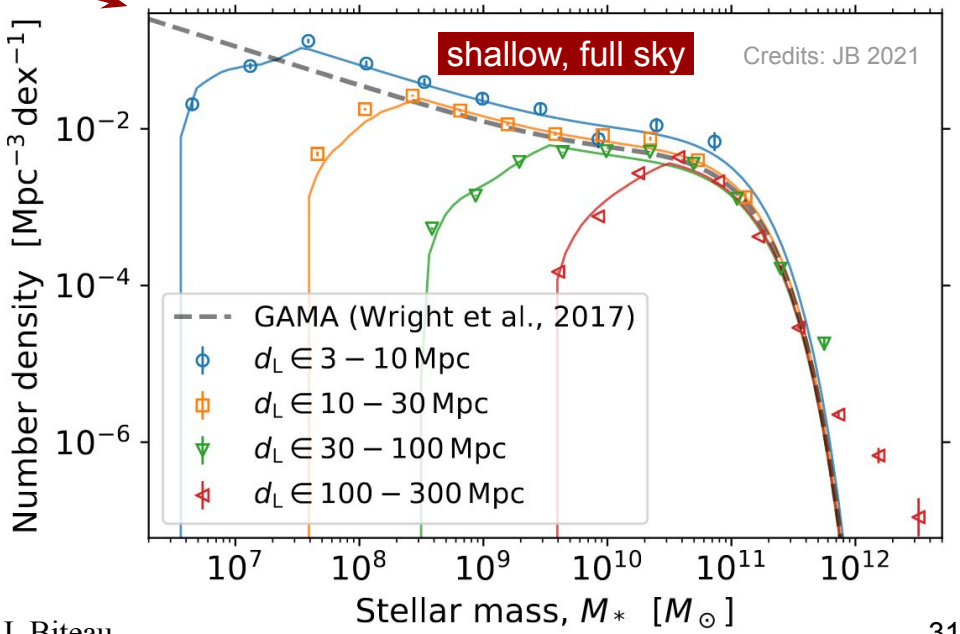


Constraints on faint galaxies / halo light

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?

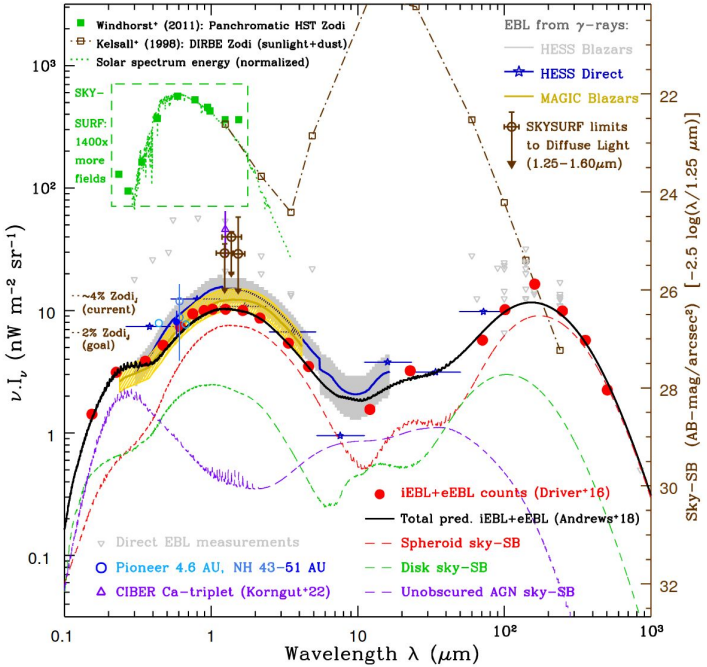




A new Inter-Planetary Dust component?

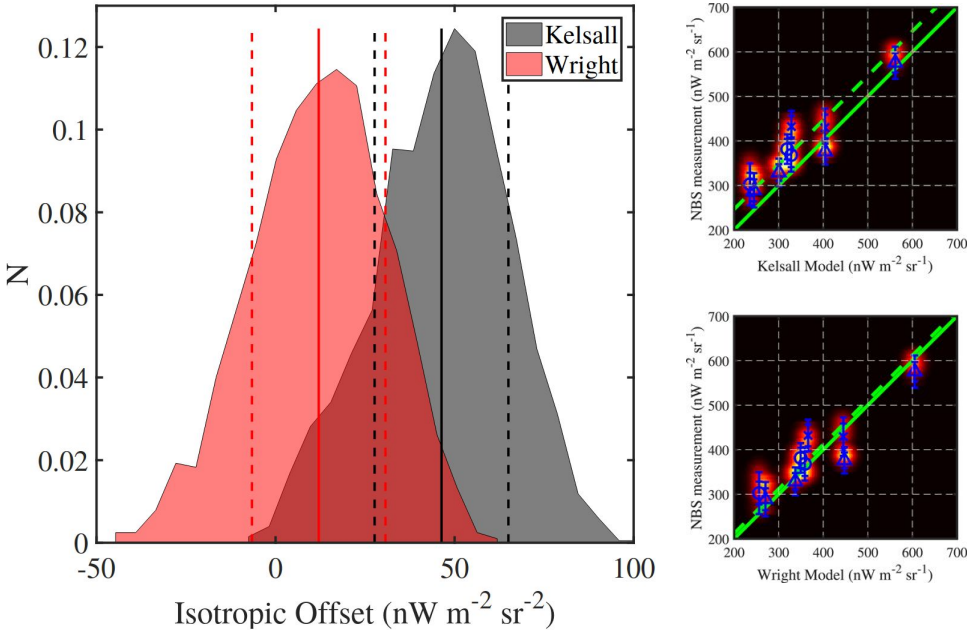
Spherical cloud of cometary dust (Kuiper Belt, Oort Cloud)?

- Ca II observations by CIBER rocket and SKYSURF reanalysis of HST data → reassessment of ZL models needed?



Credits: Carleton+ 2022 (HST / SKYSURF)

Credits: Korngut+ 2022 (CIBER / NBS)



Current status & looking ahead

Status of γ-ray propagation

Absorption on EBL: precision and validity?

- $\pm 20\%_{stat}$ $\pm 20\%_{sys}$ → $\pm 5\%_{stat}$ $\pm 12\%_{sys}$ (CTA 2021)

- Impact of intrinsic emission model?

⇒ ongoing: fully Bayesian approach to tackle intrinsic and instrument-induced uncertainties

Evolution of the EBL?

- CTA: EBL evolution out to $z \sim 2$

⇒ Cosmic SFR with better precision than *Fermi*-LAT? (*Fermi*-LAT 2018)

⇒ Accuracy on H_0? (Dominguez+ 2019)

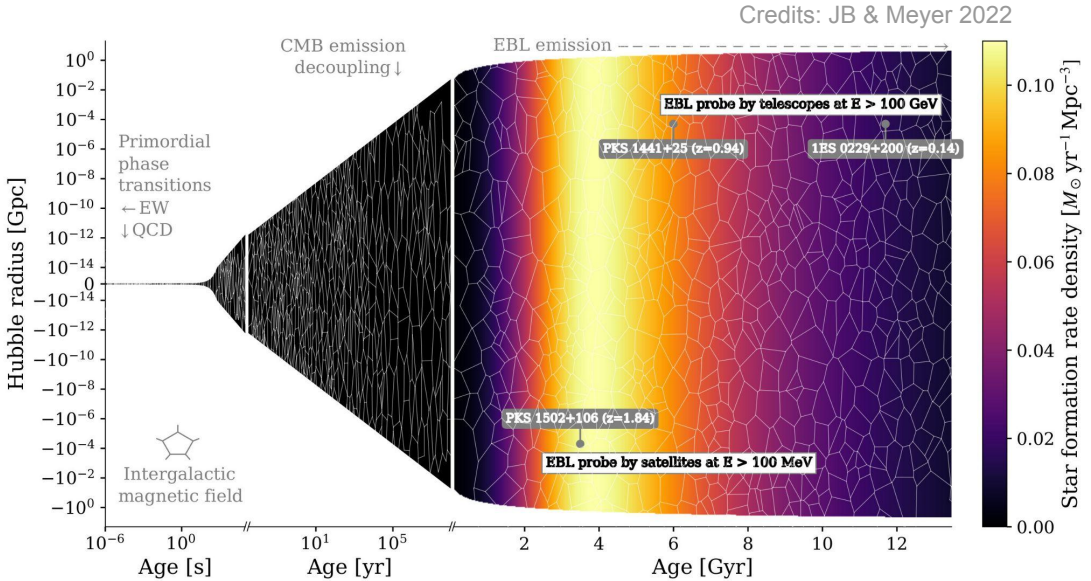
Where are the secondaries?

- Lead hypothesis: magnetic fields in voids

⇒ primordial phase transitions? structure formation?

- Challenger: plasma instabilities in pair beam (Broderick+ 2012)

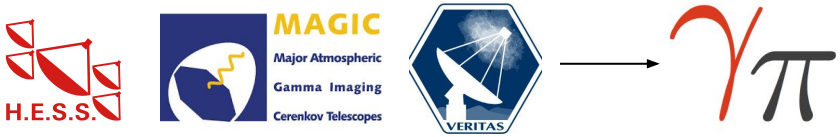
⇒ numerical challenge with unsettled status (Vafin+ 2018)



Addressing the optical controversy before CTA?

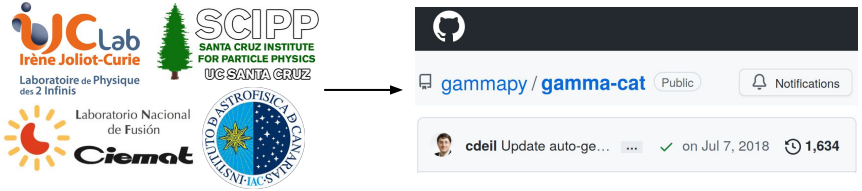
Event-level data from current generation

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



Archival spectral data from current & past

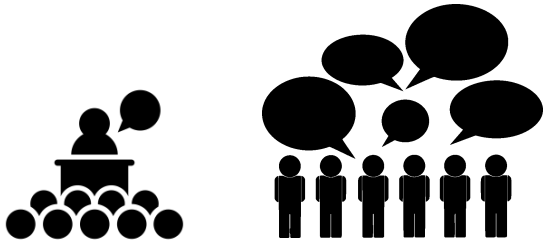
- All published extragalactic TeV spectral points
  ⇒ exported to **gamma-cat** format (**to be revived?**)
- More modest effort: Gamma 2022 (Gréaux+, IJCLab)



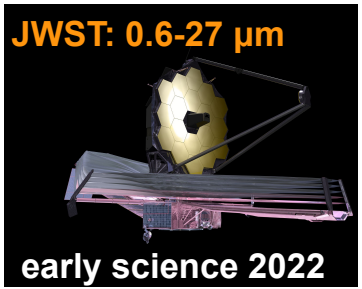
The three communities around a single table?

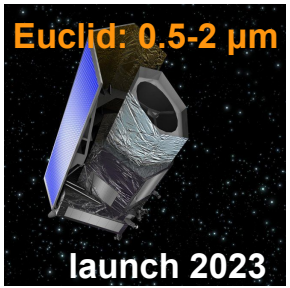
- New 4σ evidence from direct observation beyond Pluto
- New 5%-resolution measurement of galaxy counts
- Upcoming TeV measurement with 2-3× previous archival data

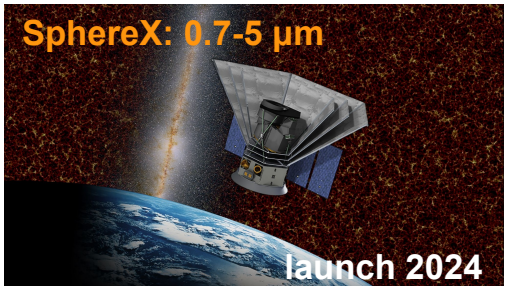
⇒ **EBL workshop (3-5 days) in Paris area in 2023/24?**



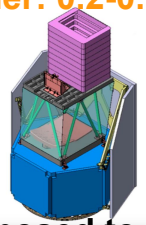
Gamma-ray cosmology in the upcoming CTA era







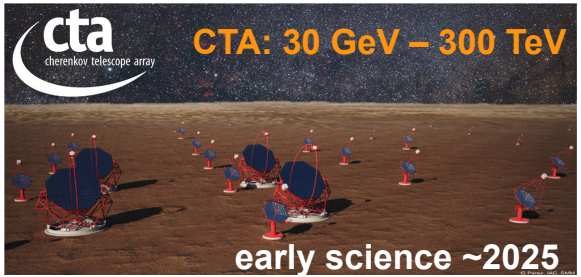
Messier: 0.2-0.9 μm



proposed to ESA-F

Light in voids and faint galaxies

- Low-end of the galaxy luminosity function
- Redshift surveys ∩ Broadband intensity mapping
- Low-surface brightness universe
- Gamma-ray absorption



Cosmic magnetism

- Gamma-ray halo and spectral bump
- UHECR deflections in the cosmic web
- Synchrotron mapping and Faraday rotation