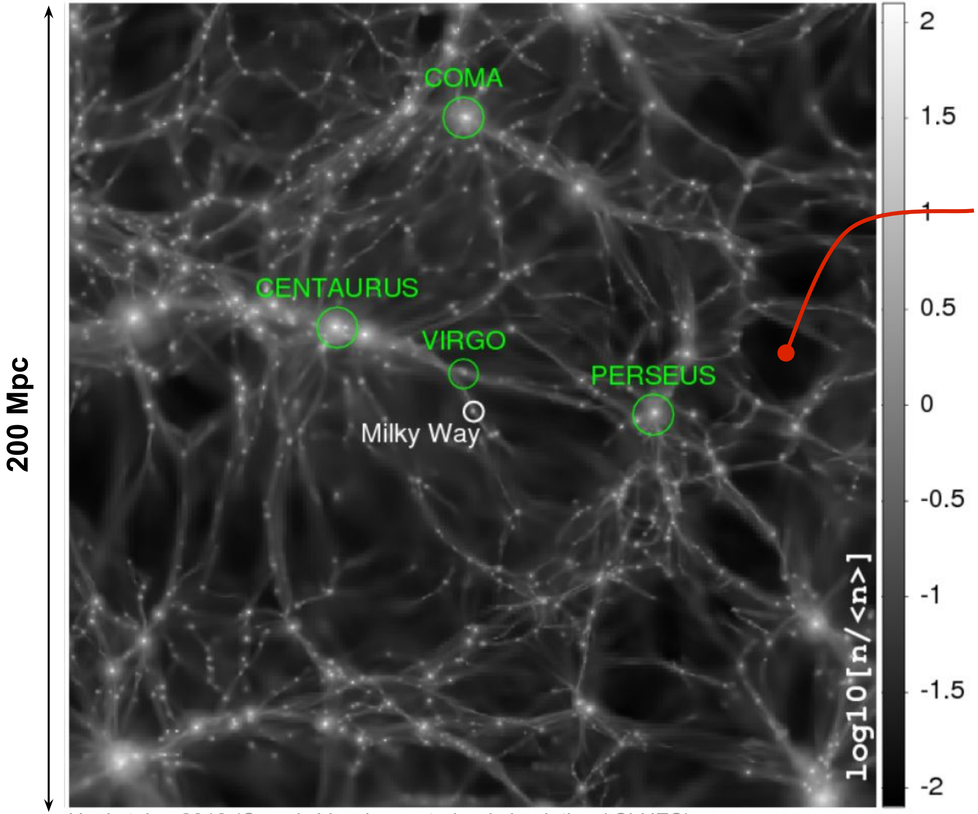
Probing Extragalactic Magnetic and Radiation Fields with Gamma Rays

2022-06-27, Irfu/DPhP

Jonathan Biteau, IJCLab / Université Paris Saclay

What's in voids?

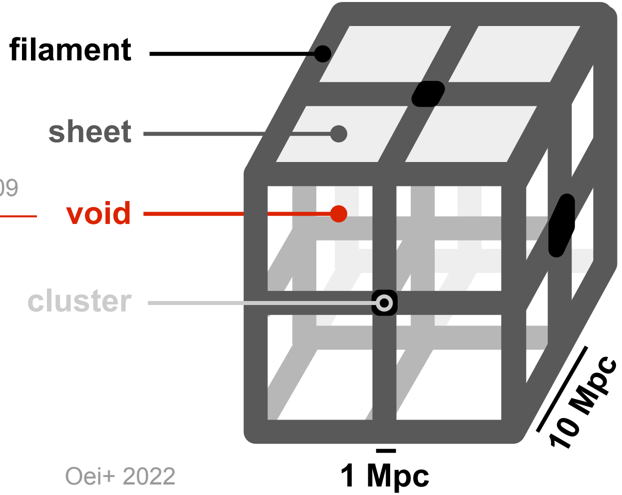


Hackstein+ 2018 (Cosmic V-web constrained simulation / CLUES)

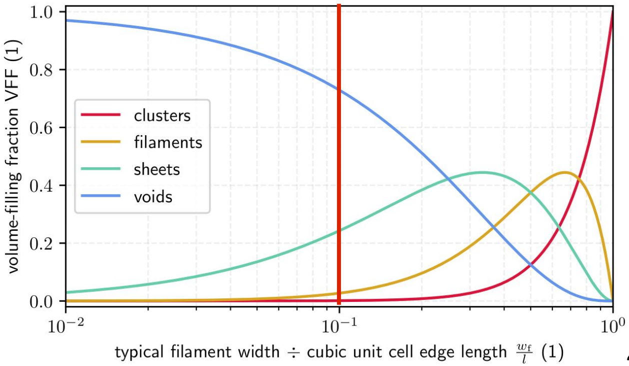
· 70-80% of the volume?
Forero-Romero+ 2009

· Significant fraction of baryons
Driver 2021

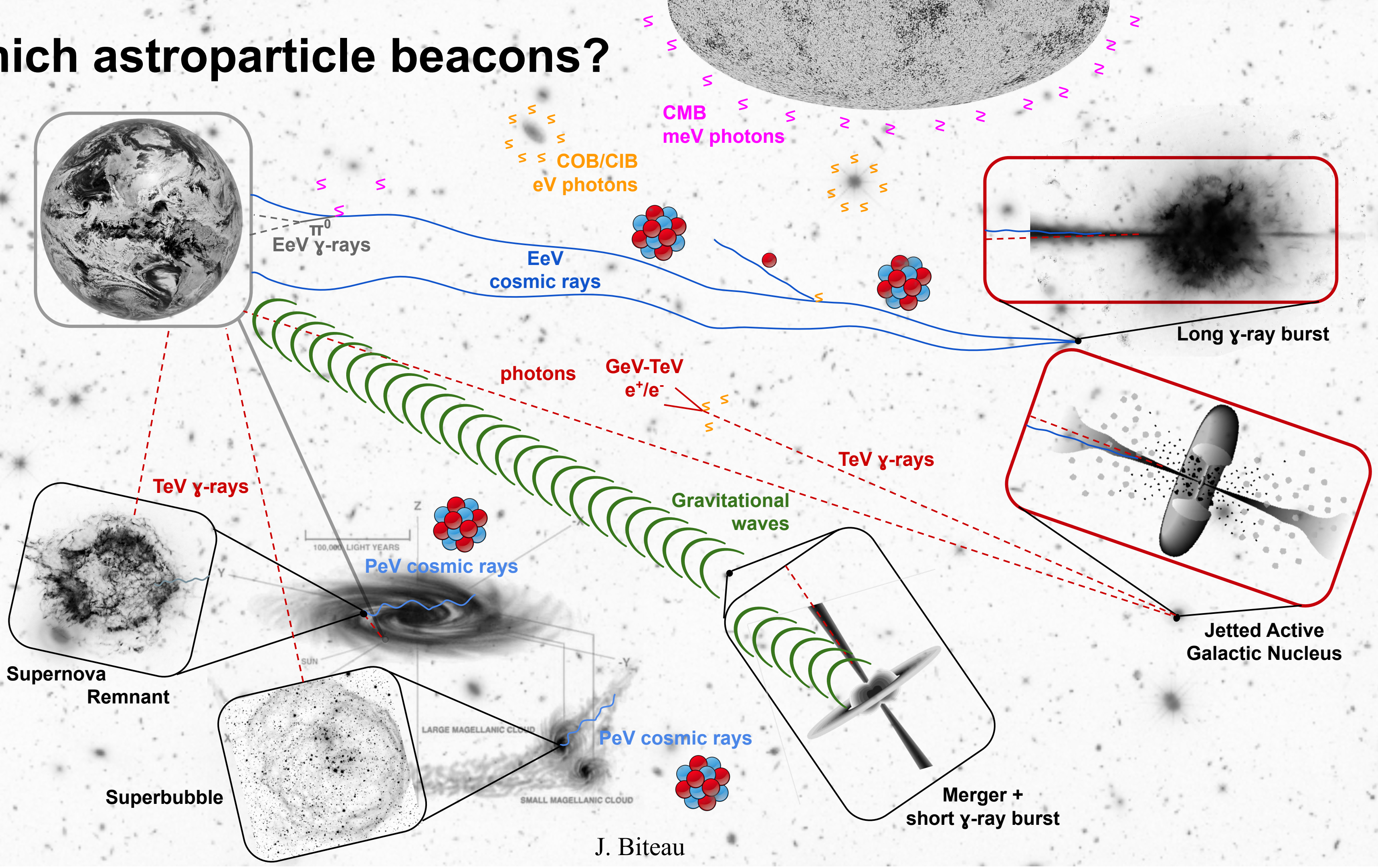
· Probed here with **astroparticles**



Oei+ 2022



Which astroparticle beacons?



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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

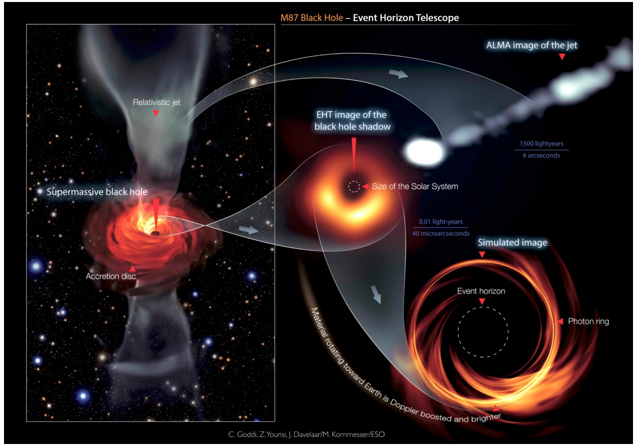
Escape

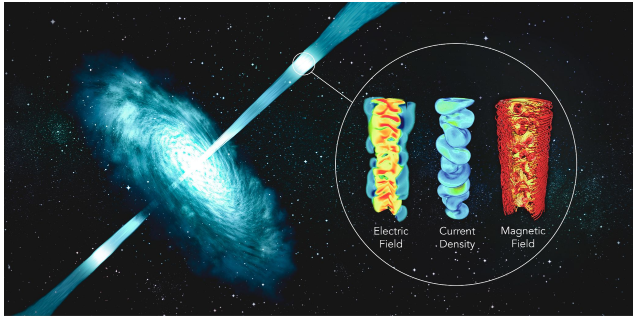
Multiscale magnetic fields and photon fields, target material
→ phenomenological model of particle/photon flow & of environment

Propagation

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

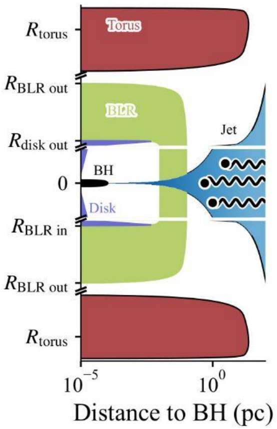
Highlight: the active galaxy M87 **Credits:** Goddi+, ESO

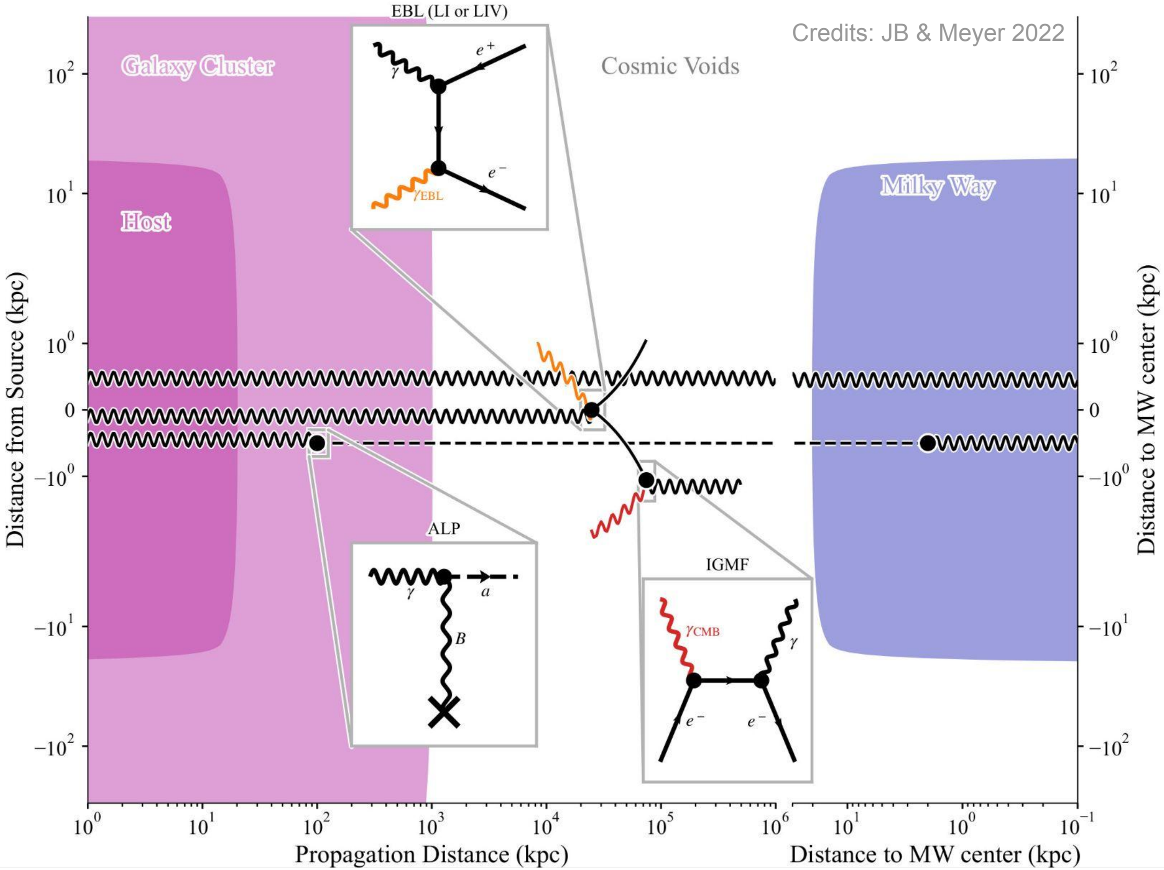




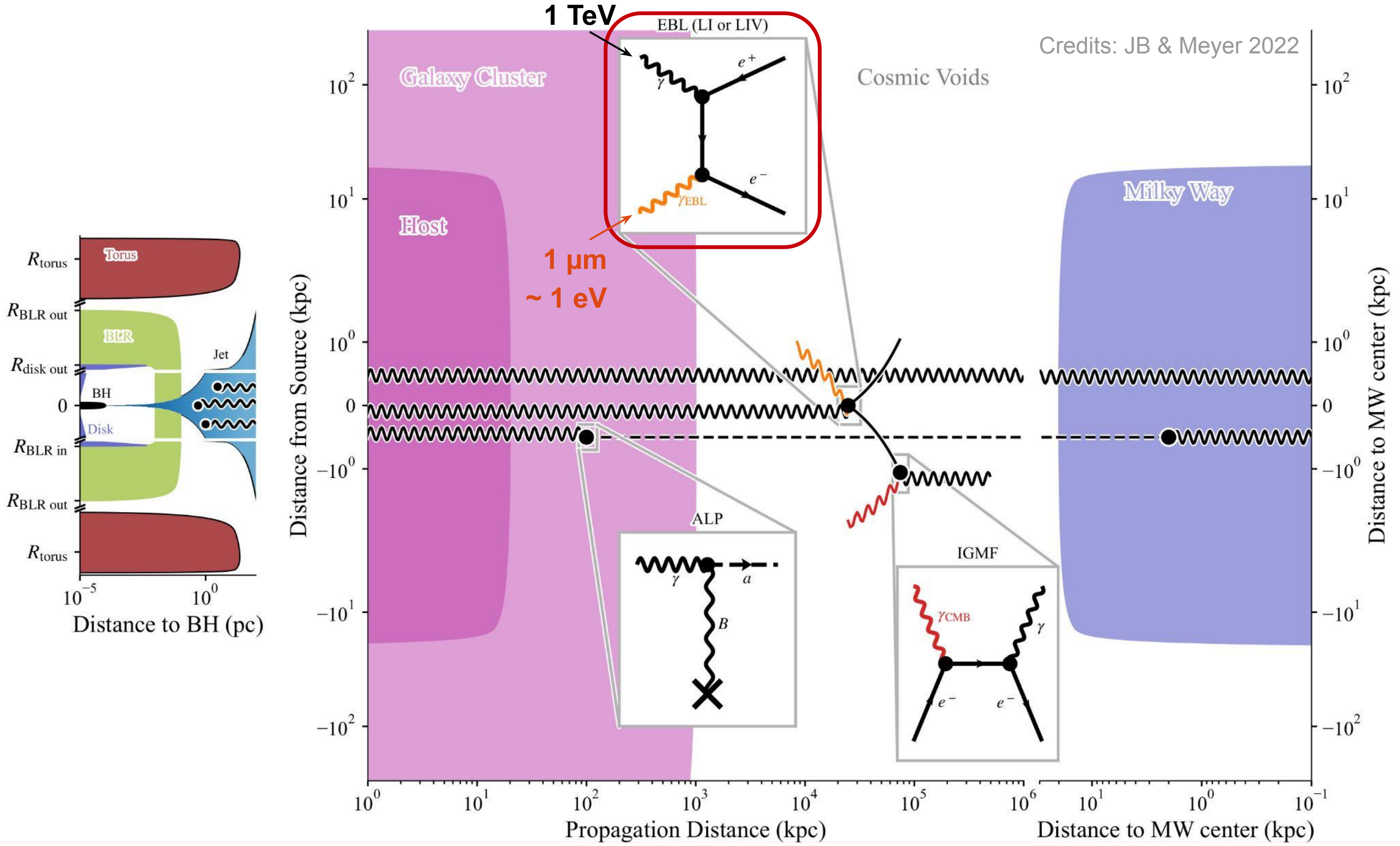
Credits: Stewart, SLAC

ɣ-ray propagation from sources down to Earth

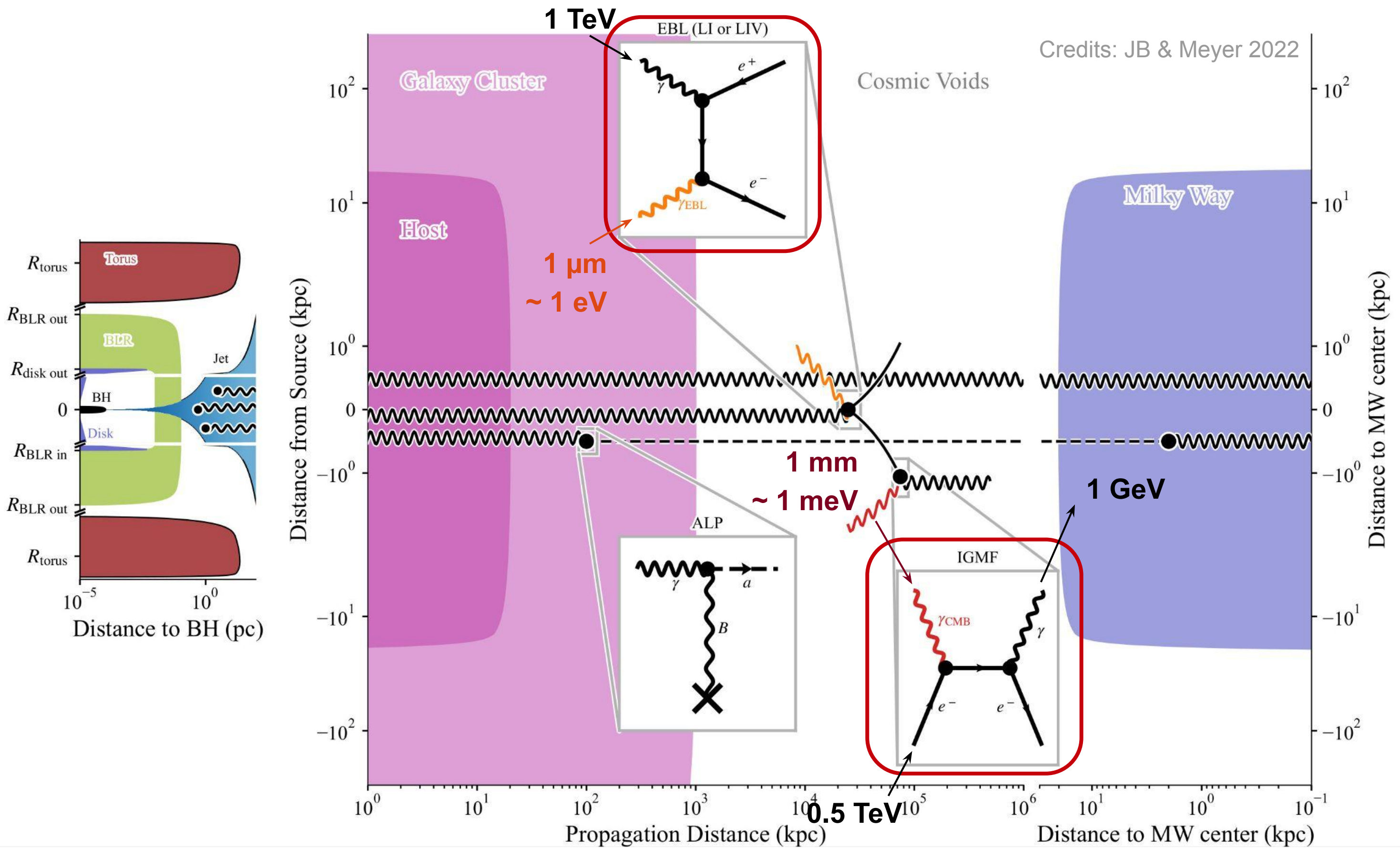




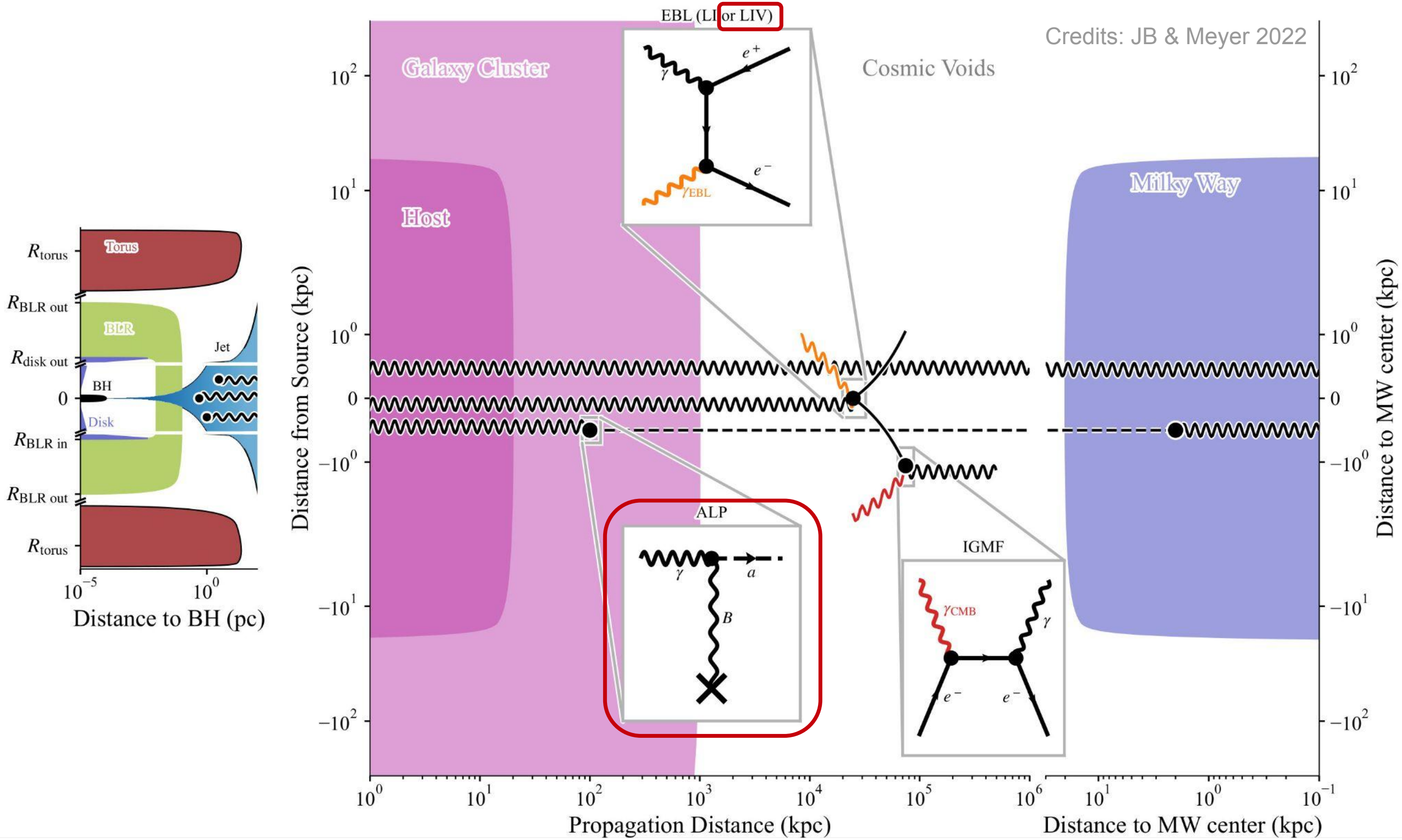
ɣ-ray propagation from sources down to Earth



ɣ-ray propagation from sources down to Earth



ɣ-ray propagation from sources down to Earth

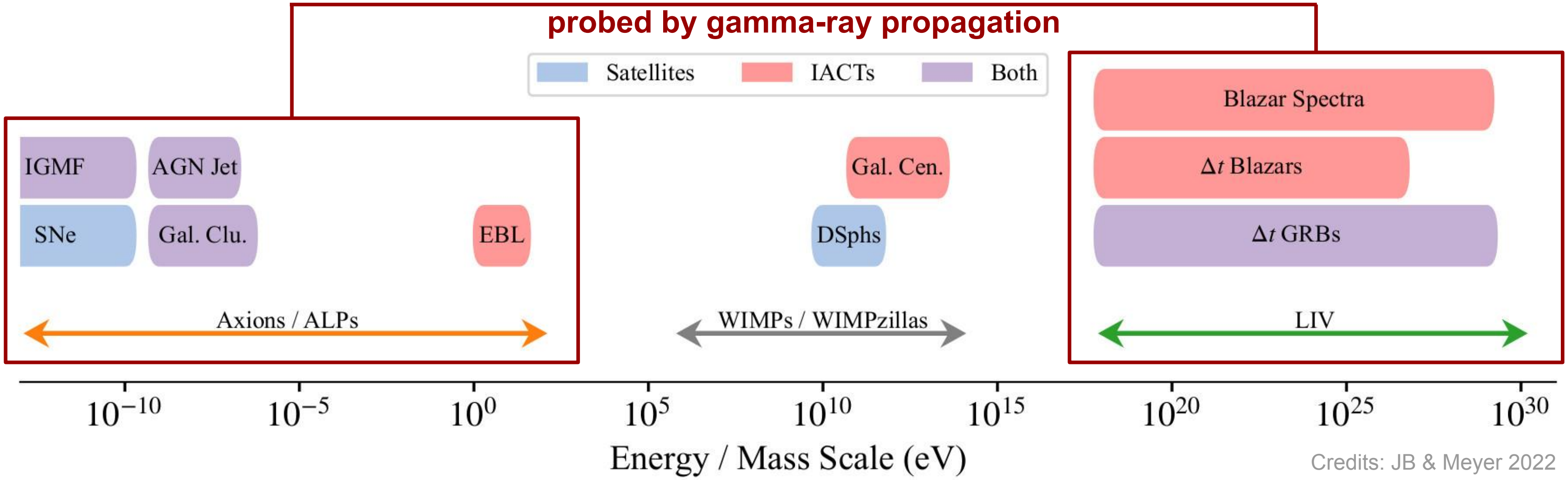


Aparté: ɣ-ray propagation and fundamental physics

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

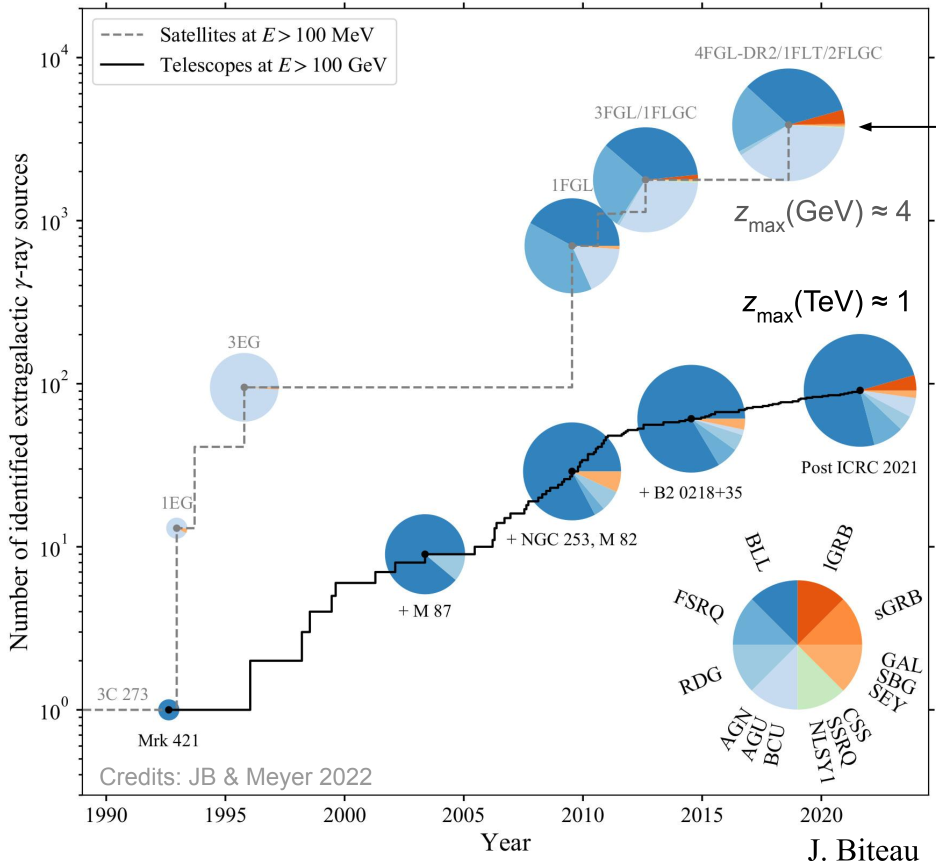
- Top-down processes (*heavy axion-like particles* /*or WIMPs*/): decay /*or self annihilation*/ into photons
- Mixing with light axion-like particles (ALP): CTA will start probing ALP dark-matter parameter space CTA 2021
- LIV linearly modified dispersion relation (CPT-odd): Planck scale ~excluded by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

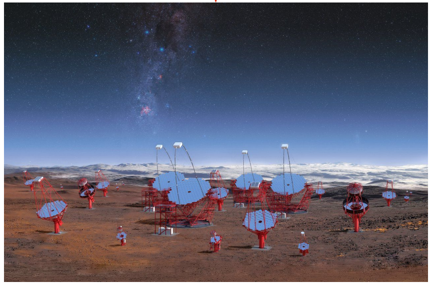
⇒ *High-risk / high-gain themes. Notes: ALP constraints dependent upon B-field morphology in jet*



Credits: JB & Meyer 2022

Status of extragalactic ɣ-ray astronomy





cta cherenkov telescope array

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ɣ-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

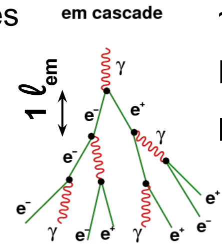
Telescope-based: 100 GeV - 100 TeV

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

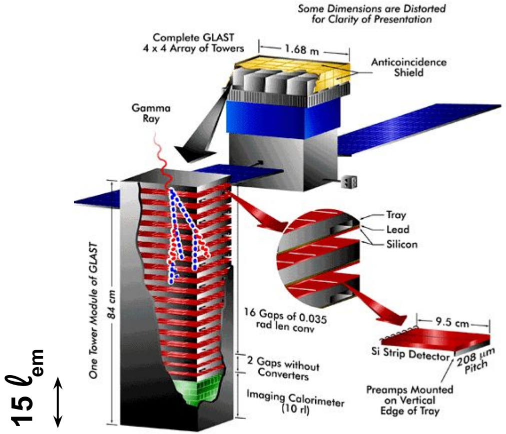
~1000 PMTs / camera

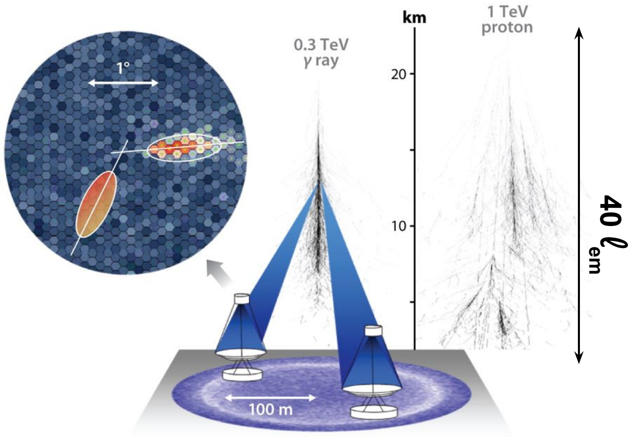
Field of view ~ 5°

Lead: HESS, MAGIC, VERITAS



Mollerach & Roulet (2017)





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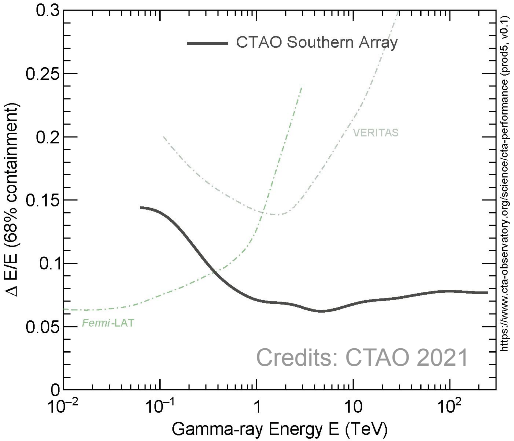
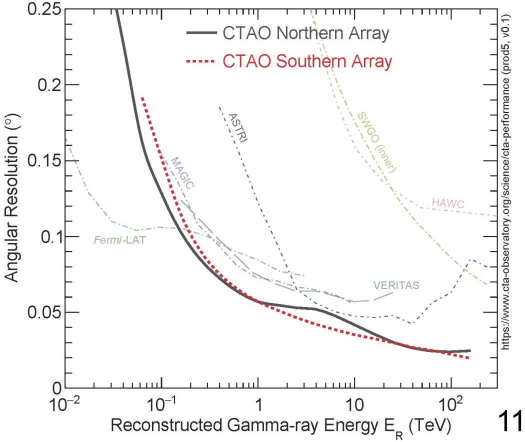
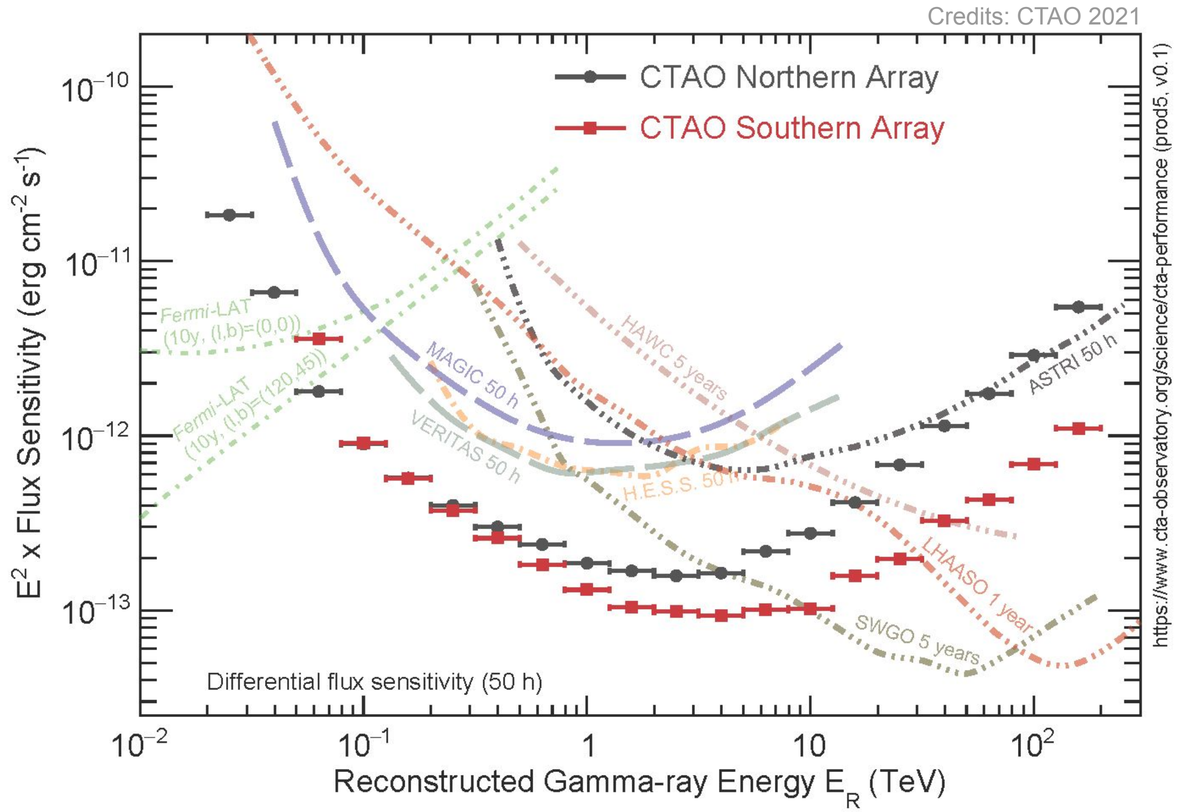
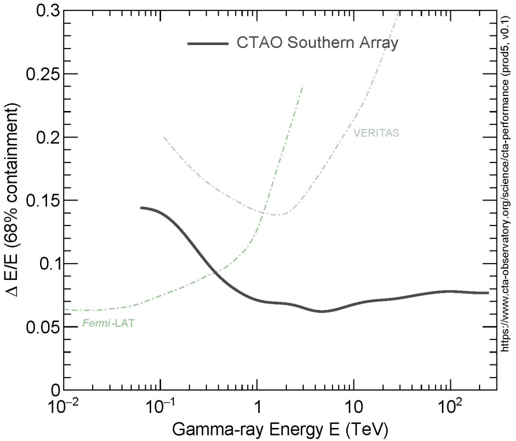
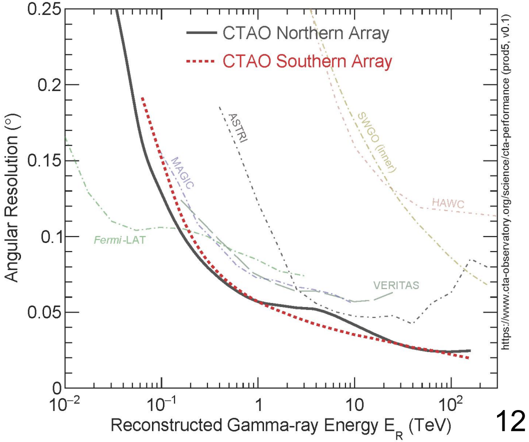




Upcoming: the Cherenkov Telescope Array







The magnetic content of voids

A gamma-ray view

2022-06-27, Irfu/DPhP

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

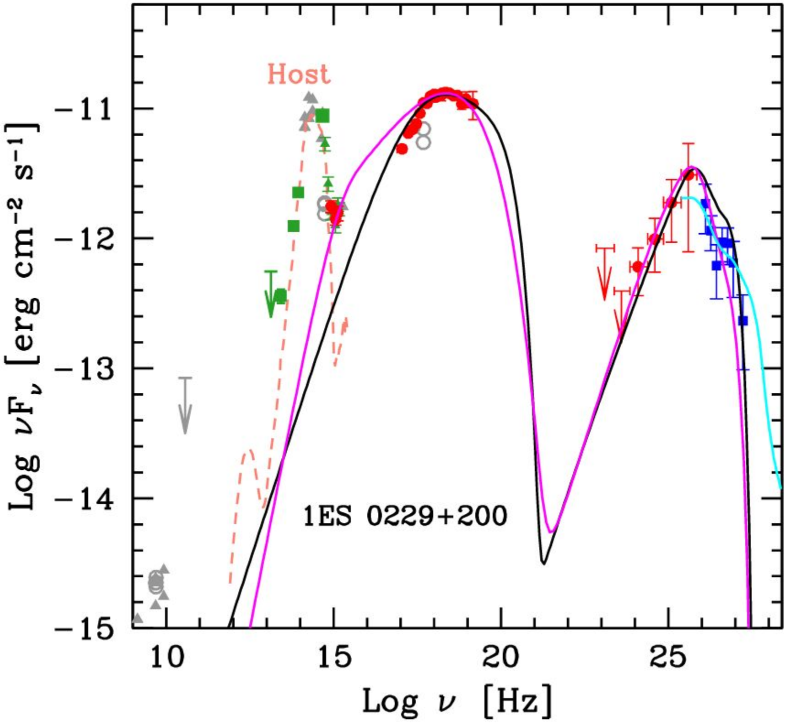
Intrinsic emission expected to be faint in the GeV band

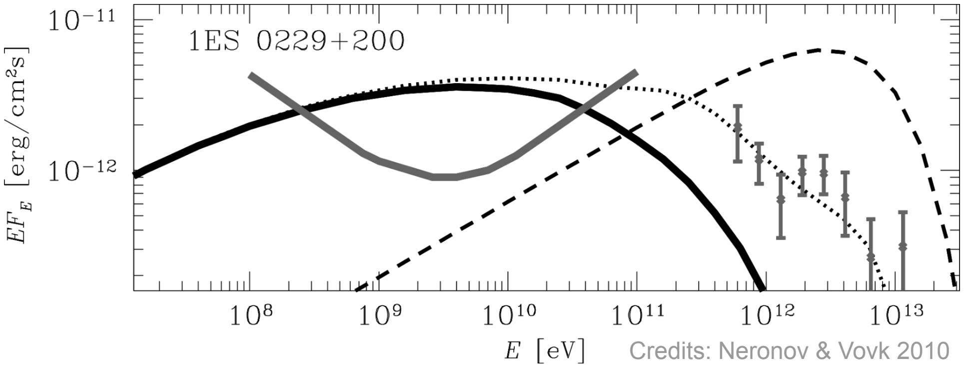
Reprocessed emission?

None in 2010 within point spread function

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

Credits: JB+ 2020





Credits: Neronov & Vovk 2010

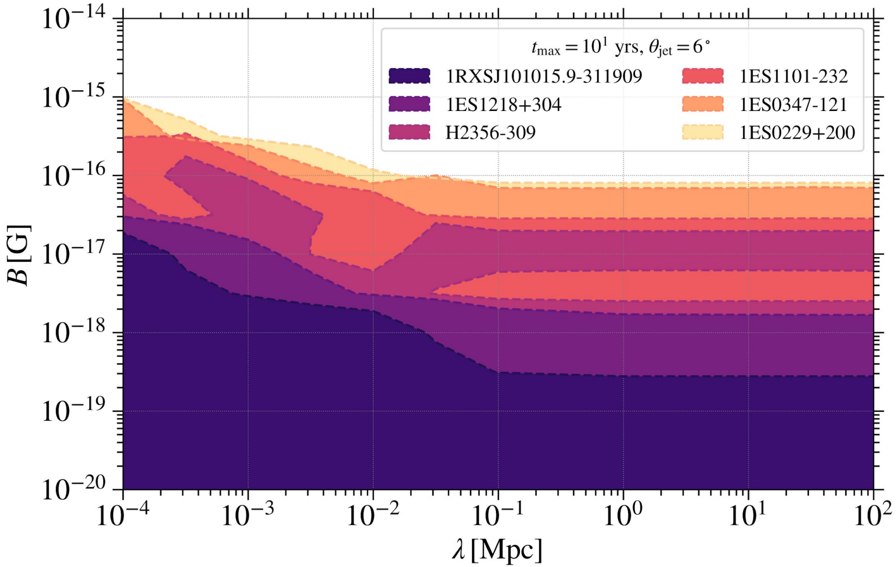
Most up-to-date constraints

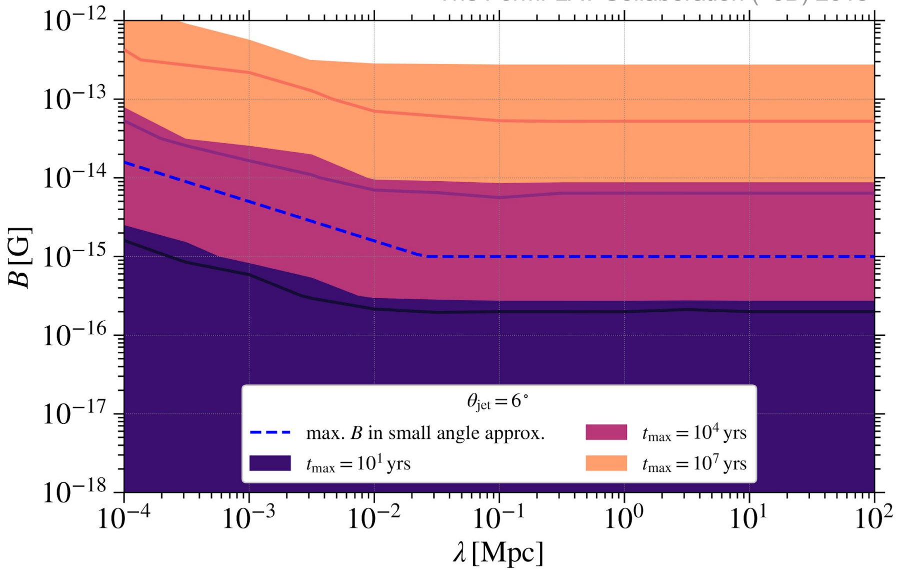
Search for extended sources in the GeV band

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)

The *Fermi*-LAT Collaboration (+JB) 2018





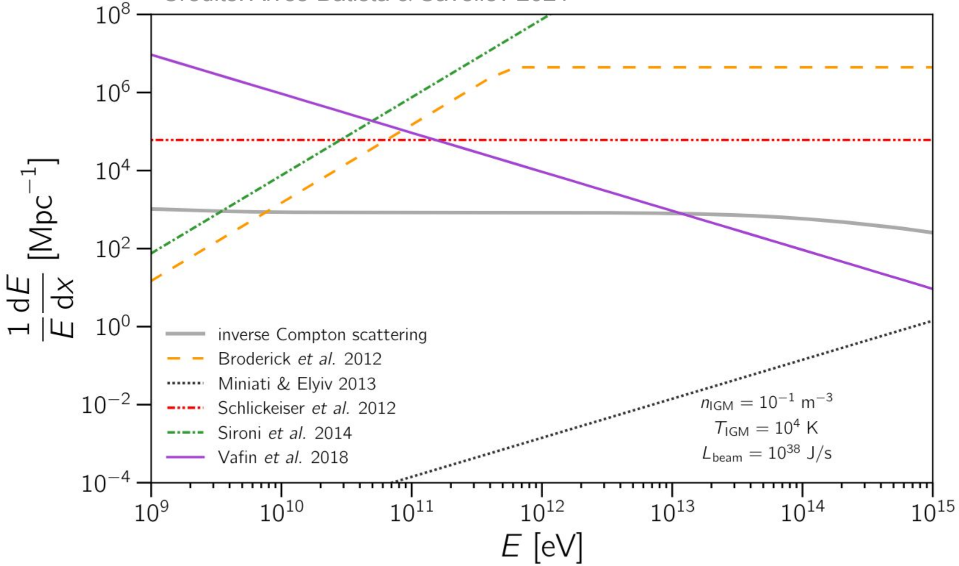
Alternative cooling

Plasma instabilities faster than inverse Compton?

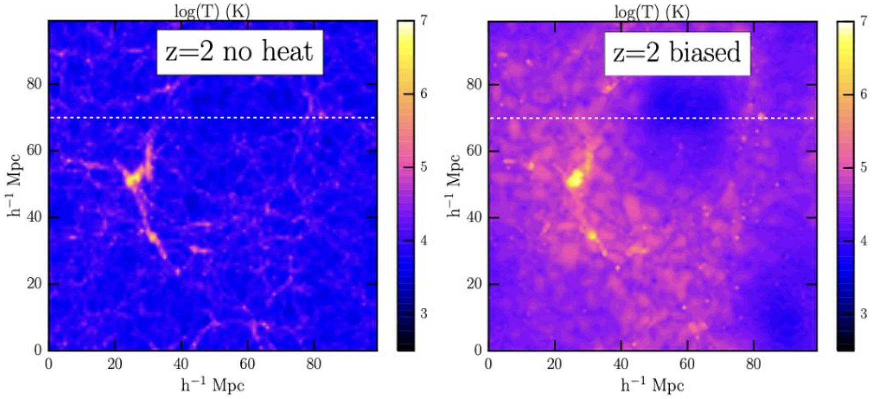
Yes, on paper… Analytics / simulations limited by several order-of-magnitude extrapolations ⇒ unclear if viable

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

Credits: Alves-Batista & Saveliev 2021



Credits: Lamberts+ 2022

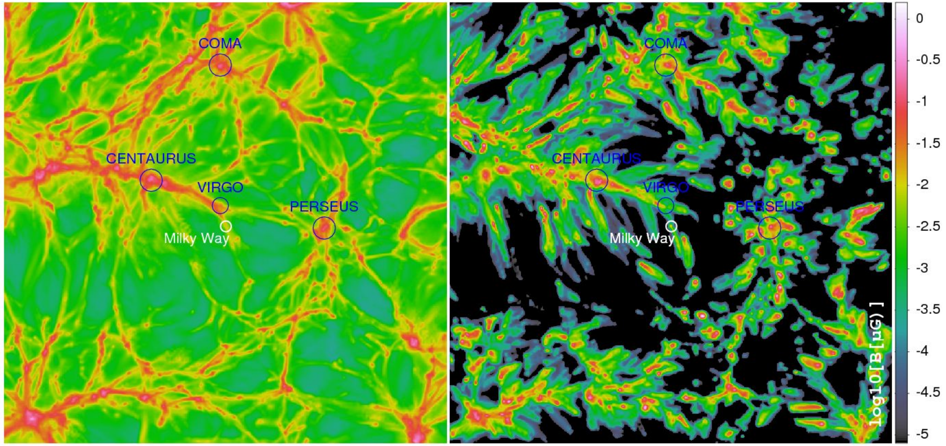


Magnetic fields in voids

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



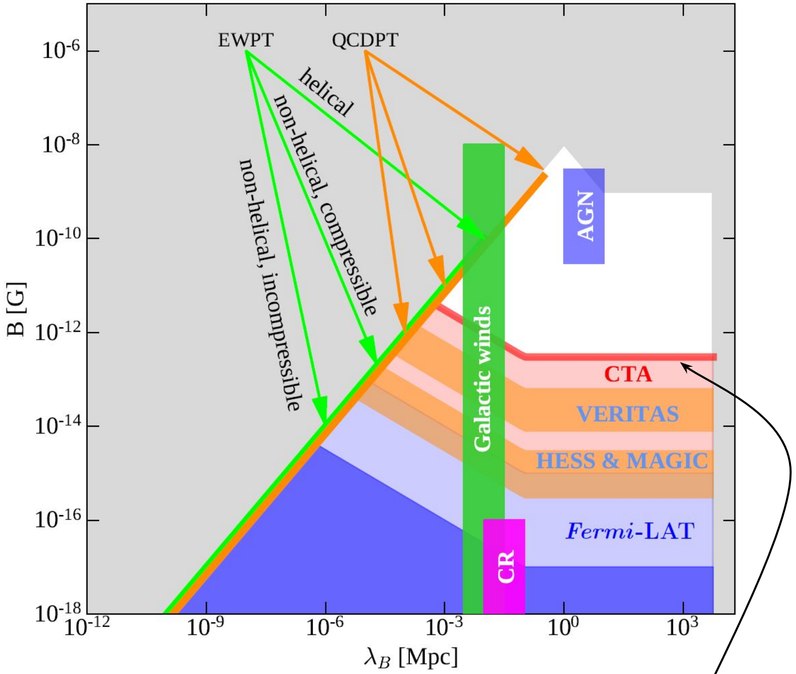
Credits: Hackstein+ 2018

Primordial origin simulation
B(void) < 1 nG?

Astrophysical origin simulation
B(void) < 1 pG?

In practice… largely unknown!

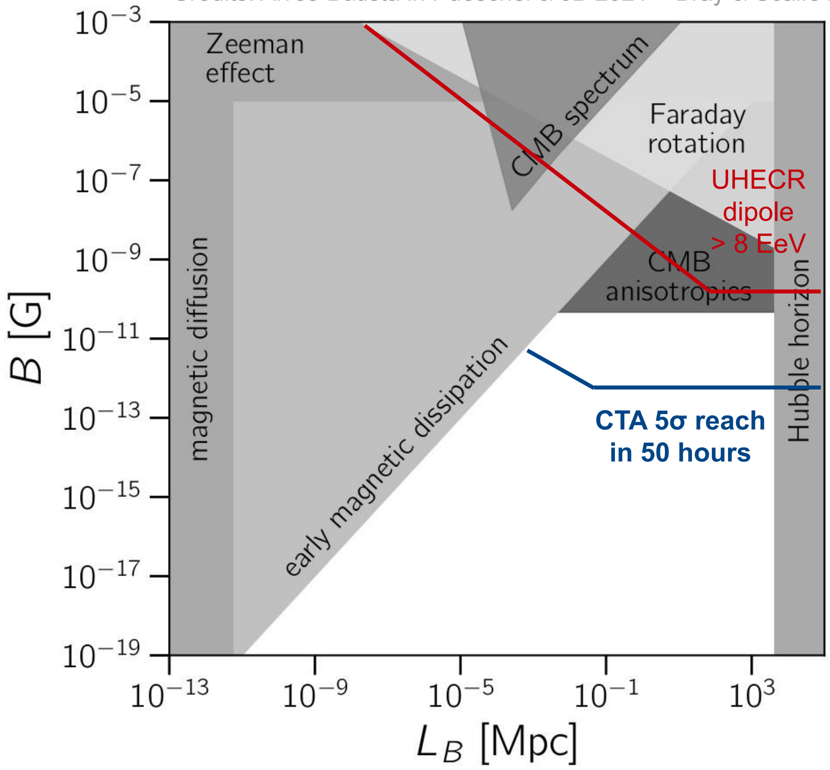
Credits: CTA Consortium 2021



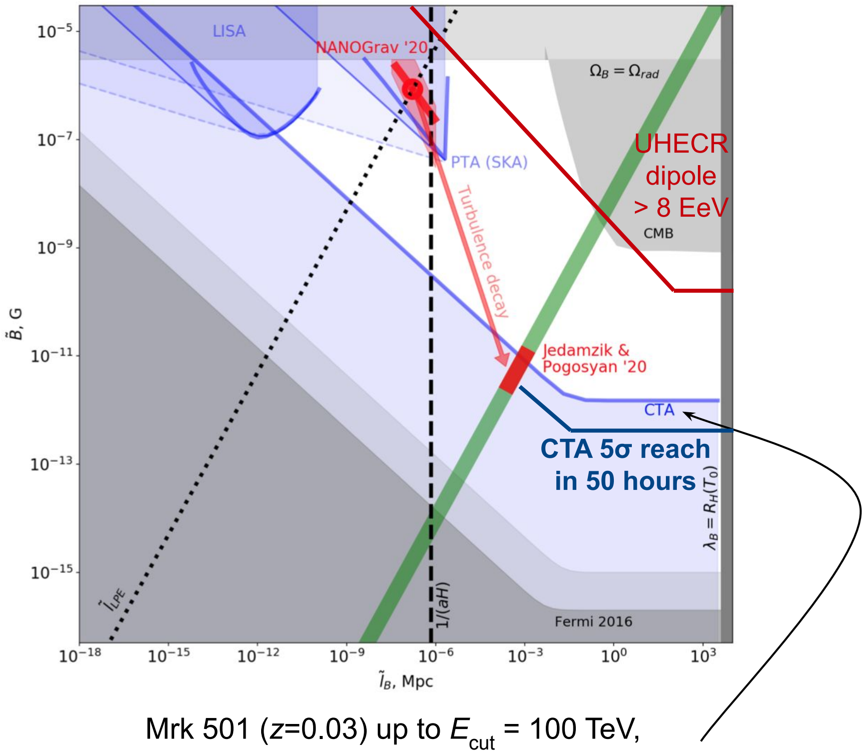
1ES 0229+200 (z=0.14) up to E_{cut} = 10 TeV,
50h of CTAO-North to reach 5σ

Multi-wavelength and multi-messenger constraints

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



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



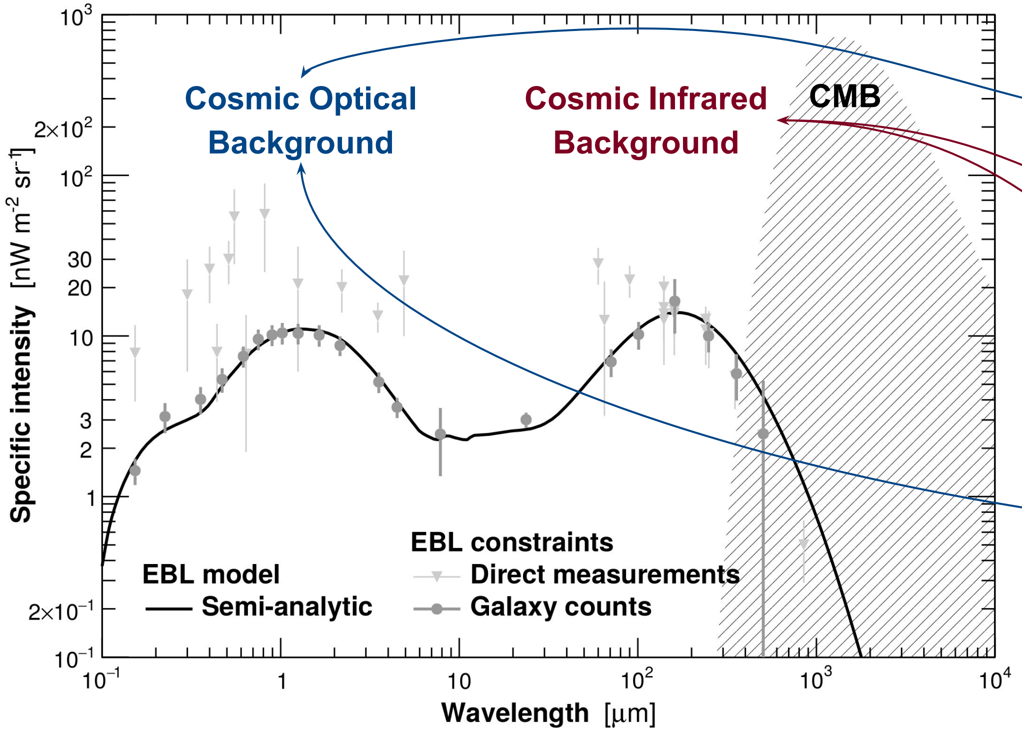
Mrk 501 (z=0.03) up to E_{cut} = 100 TeV,
350h of CTAO-North to reach 5σ

The light content of voids

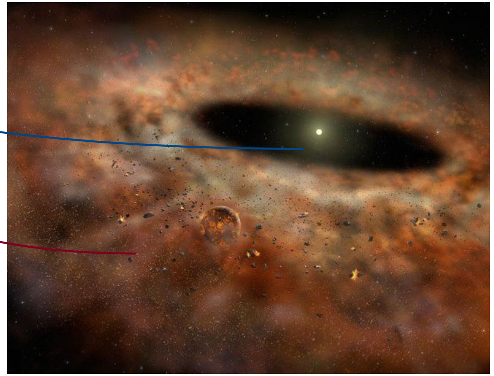
A gamma-ray view

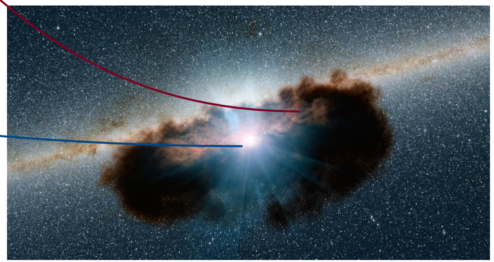
Jonathan Biteau, IJCLab / Université Paris Saclay

The extragalactic background light



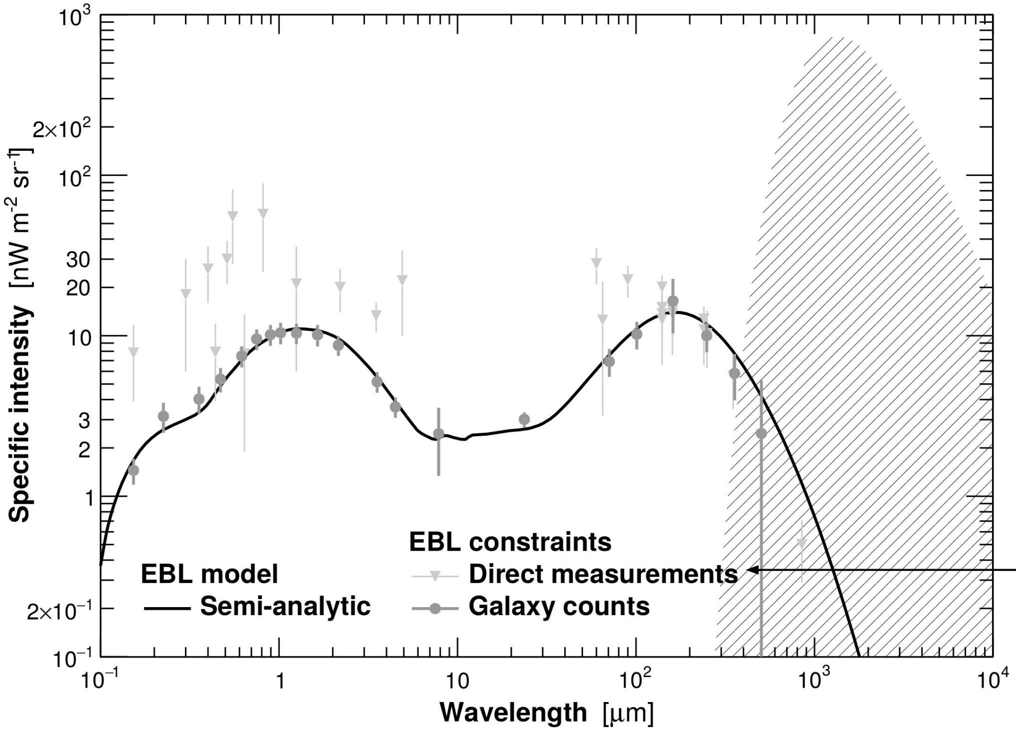
Credits: Gemini Obs./AURA/Lynette Cook



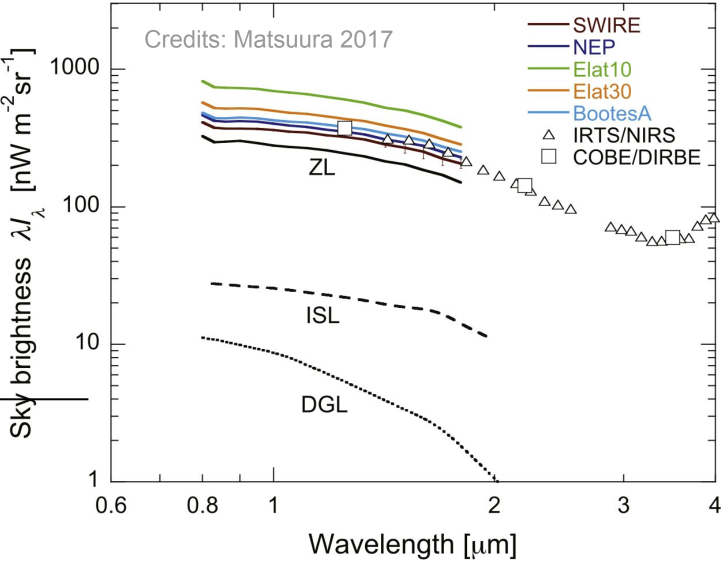


Credits: NASA/JPL-Caltech

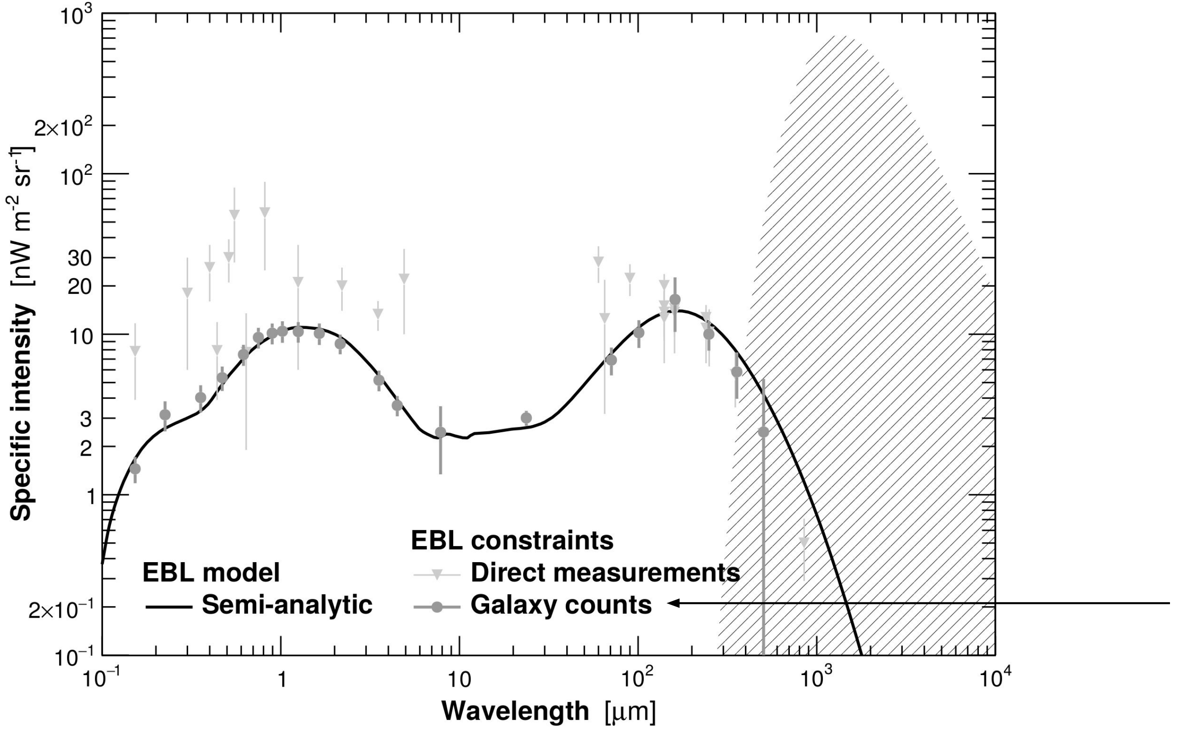
Direct measurements

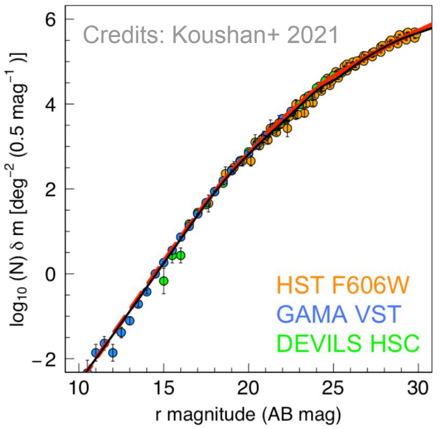


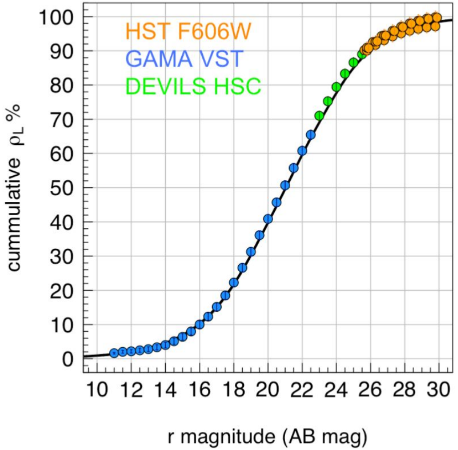
- ZL = Zodiacal light
- ISL = Integrated star light
- DGL = Diffuse Galactic light
- EBL = Extragalactic background light
  = COB + CIB here



Galaxy counts



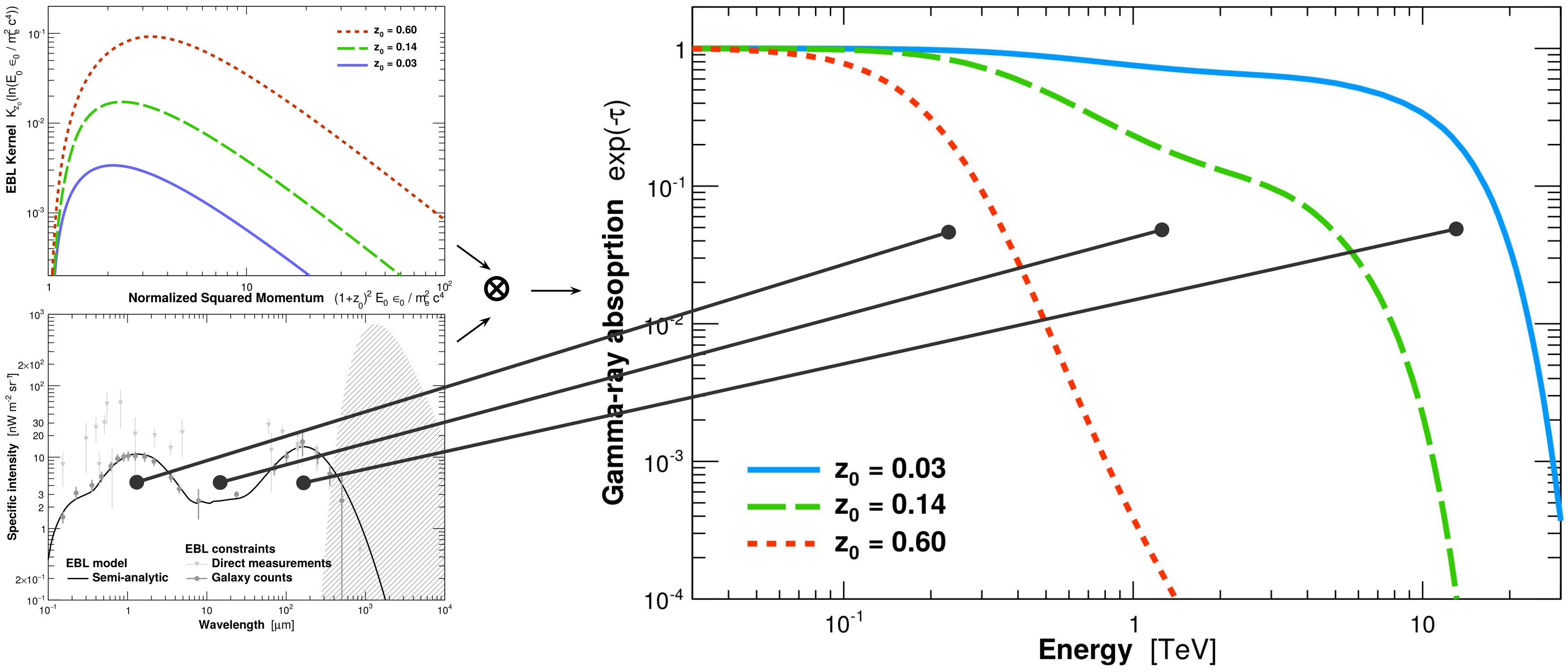




The gamma-ray technique

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

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

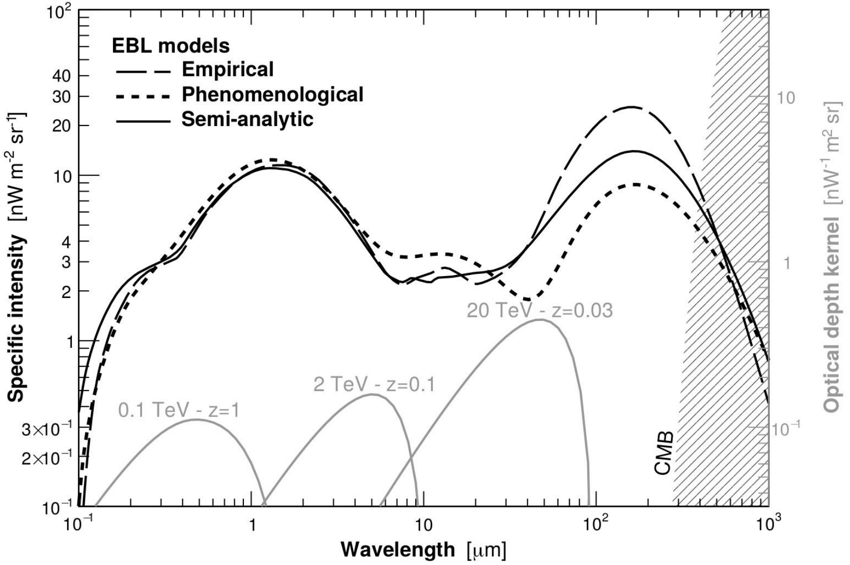


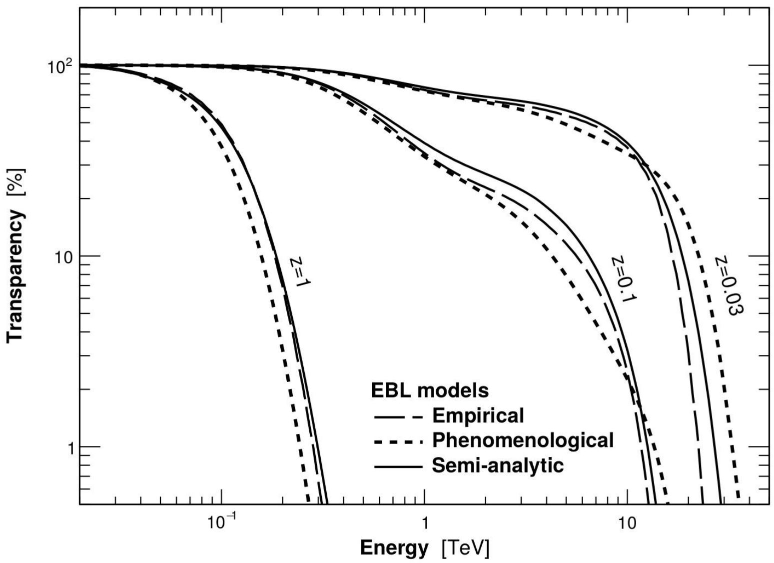
The models and the gamma-ray technique

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

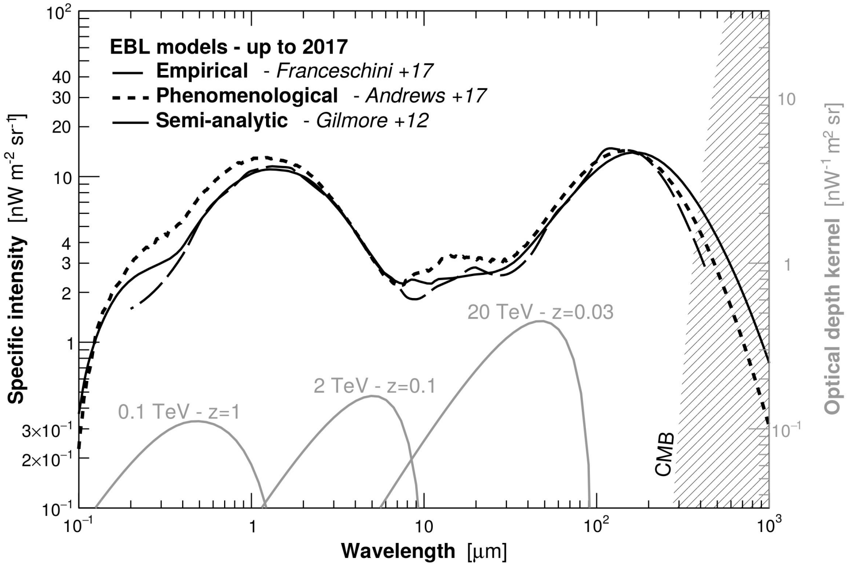


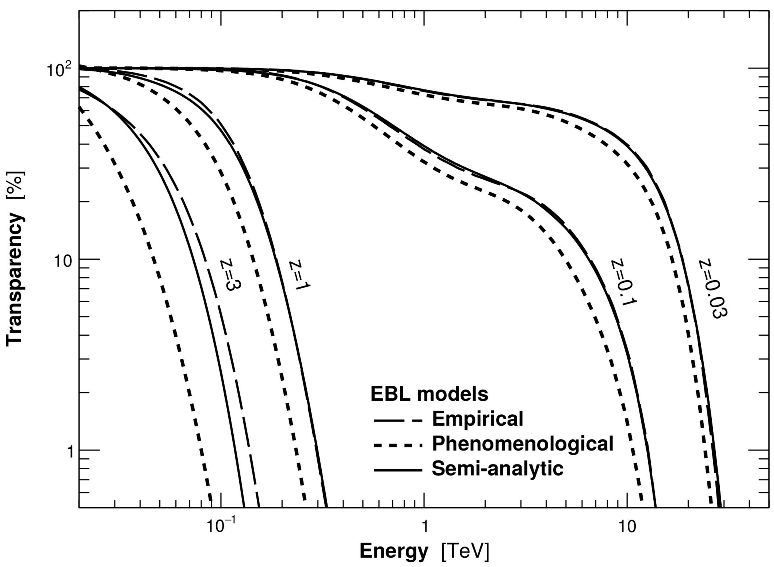


The models and the gamma-ray technique

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

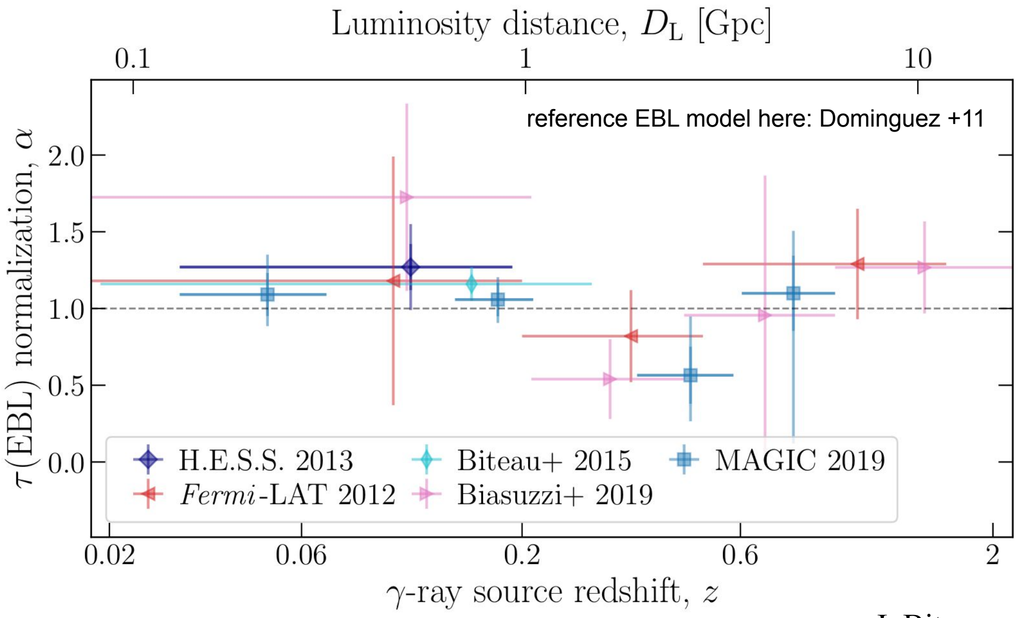


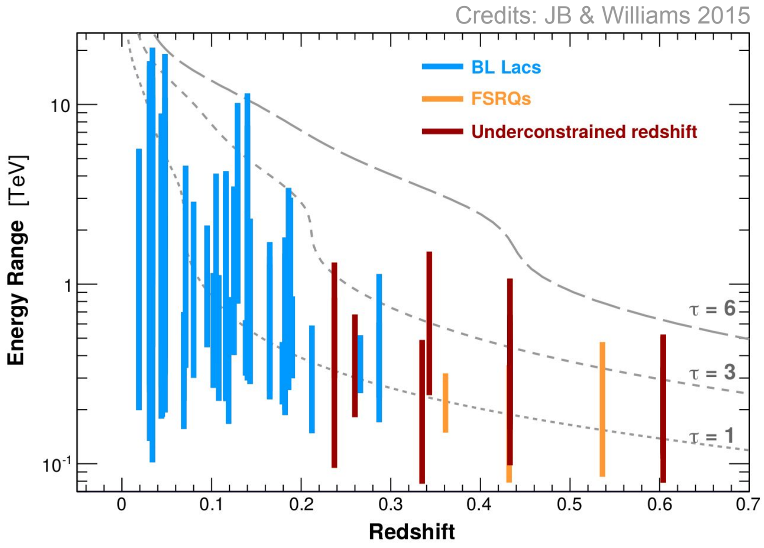


Status: gamma-ray inference vs model

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)





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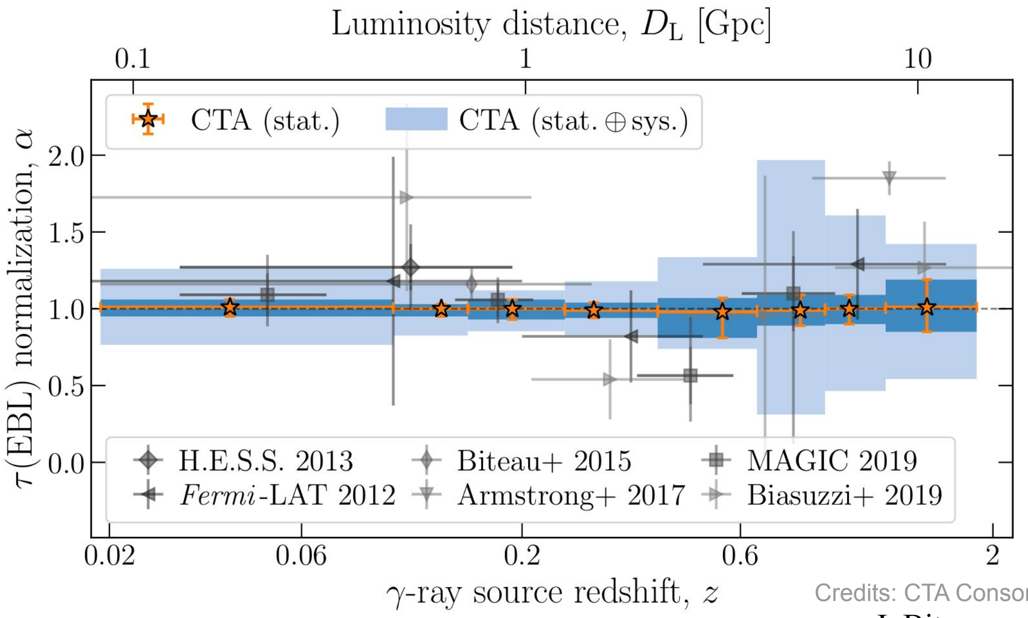
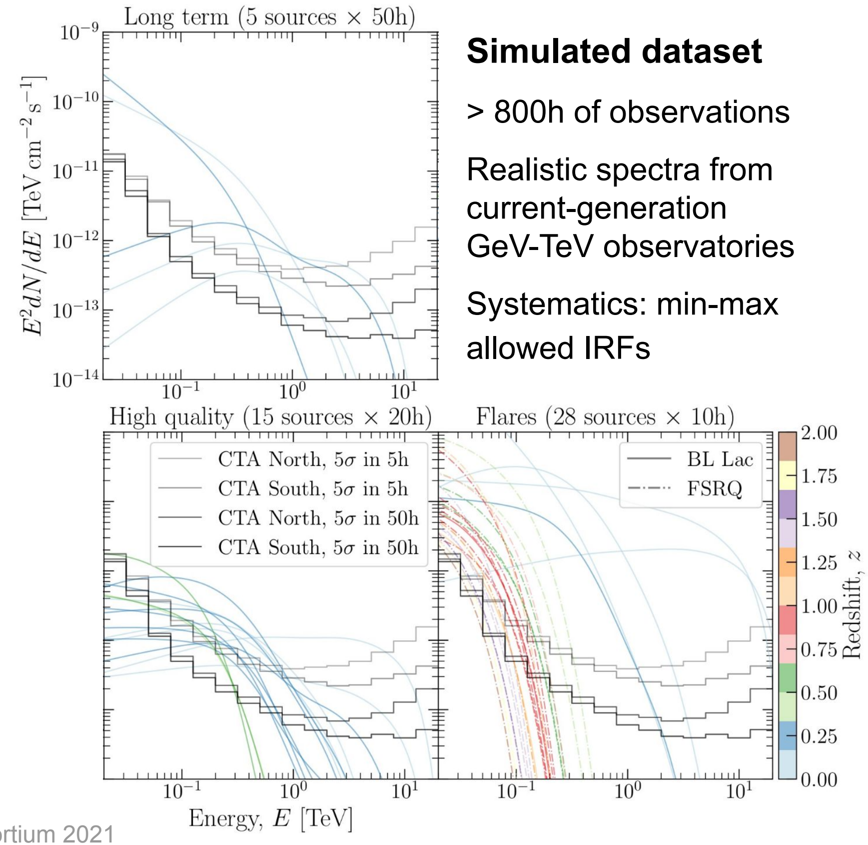
Expectations from CTA

Reconstructed EBL level wrt to a reference model

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





Credits: CTA Consortium 2021

Simulated dataset

> 800h of observations

Realistic spectra from current-generation GeV-TeV observatories

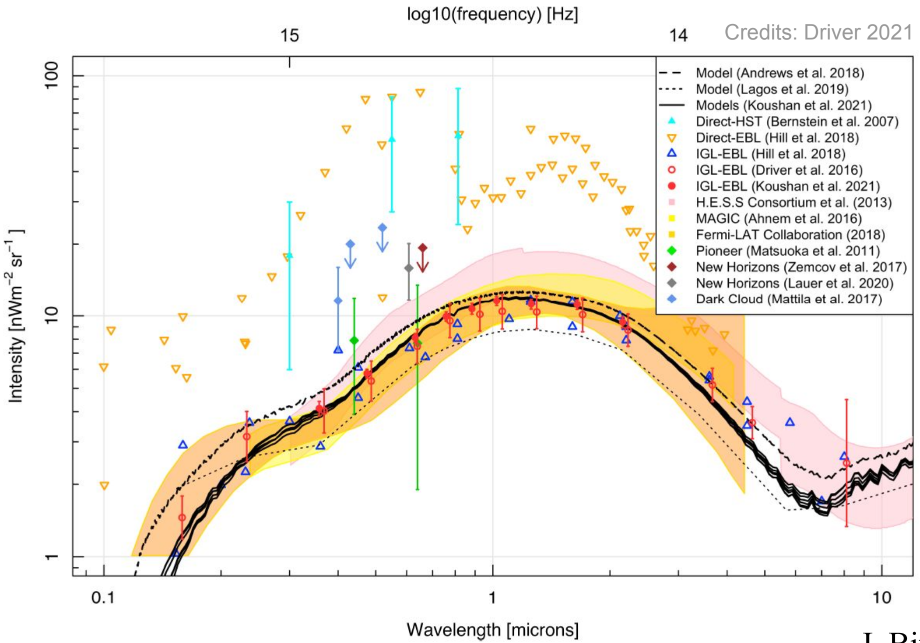
Systematics: min-max allowed IRFs

Wavelength-resolved measurements from ɣ-ray spectra

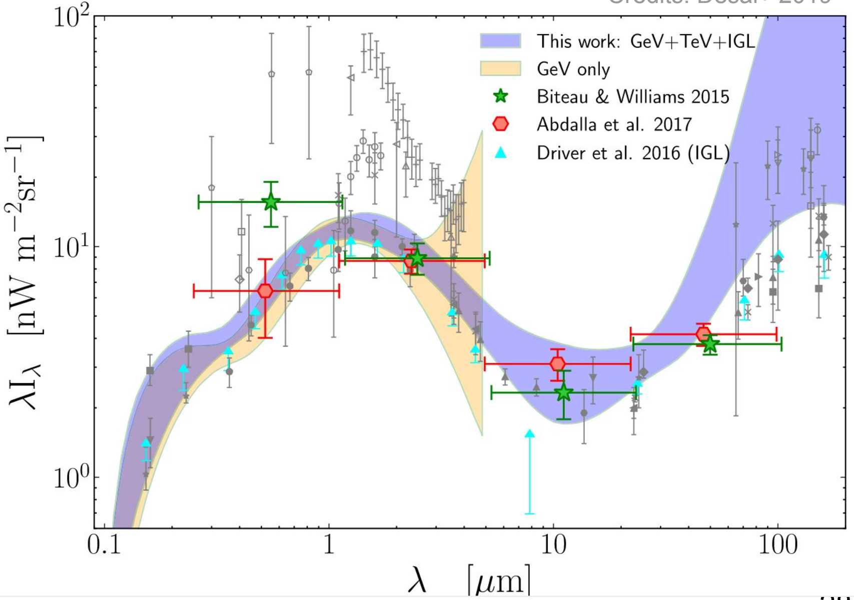
Direct measurements vs galaxy counts… and the ɣ-ray referee?

- ɣ-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)

Credits: Driver 2021



Credits: Desai+ 2019

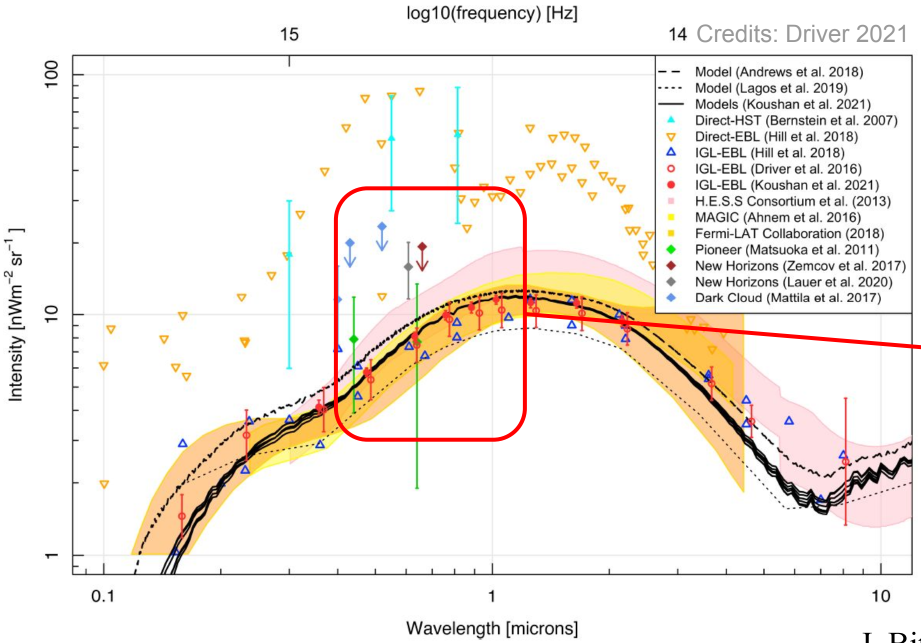


The “optical controversy”

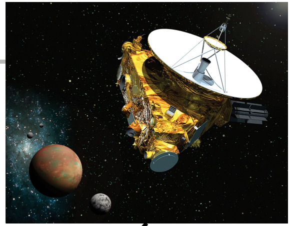
Spacecrafts out of the Solar System at [this link]

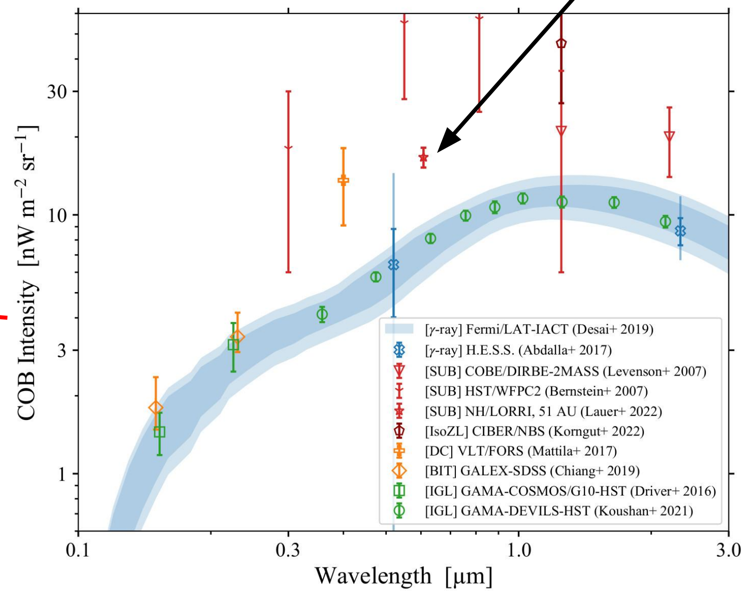
Recent news: New Horizons / LORRI

- 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



Credits: Driver 2021



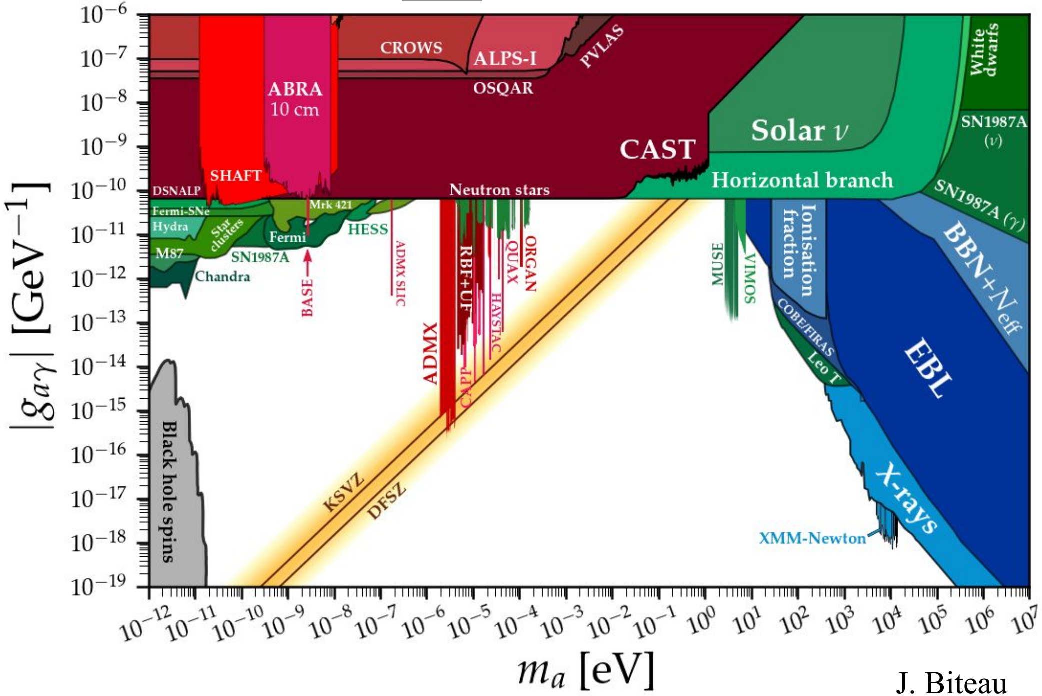


Constraints on decaying axions

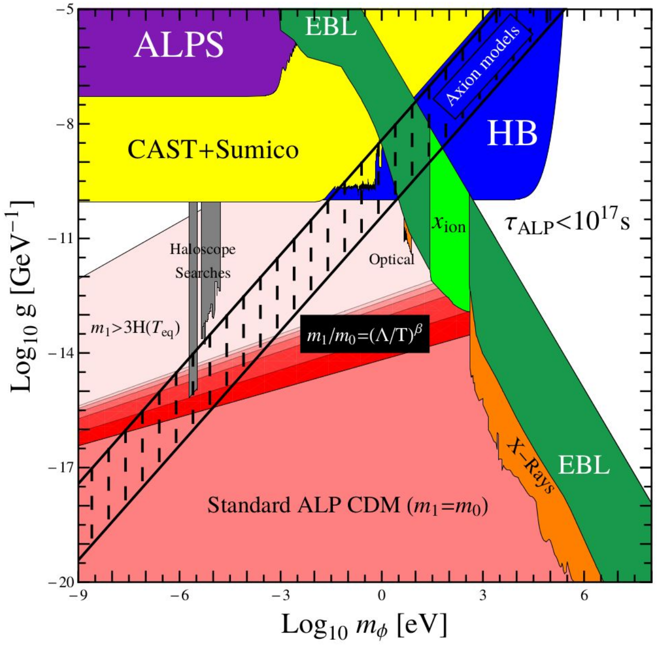
Exotic contributions to the night-sky brightness?

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

Credits: O'Hare 2020 at this link



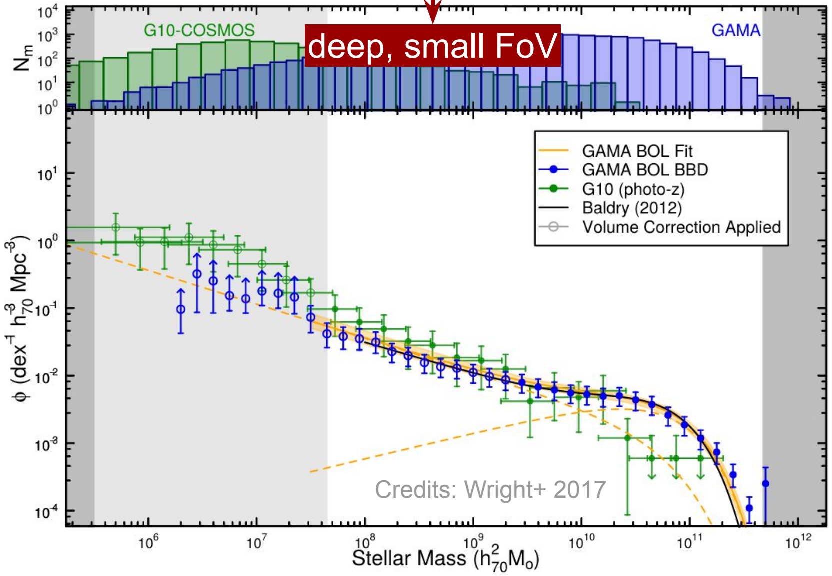
Credits: Arias+ 2012

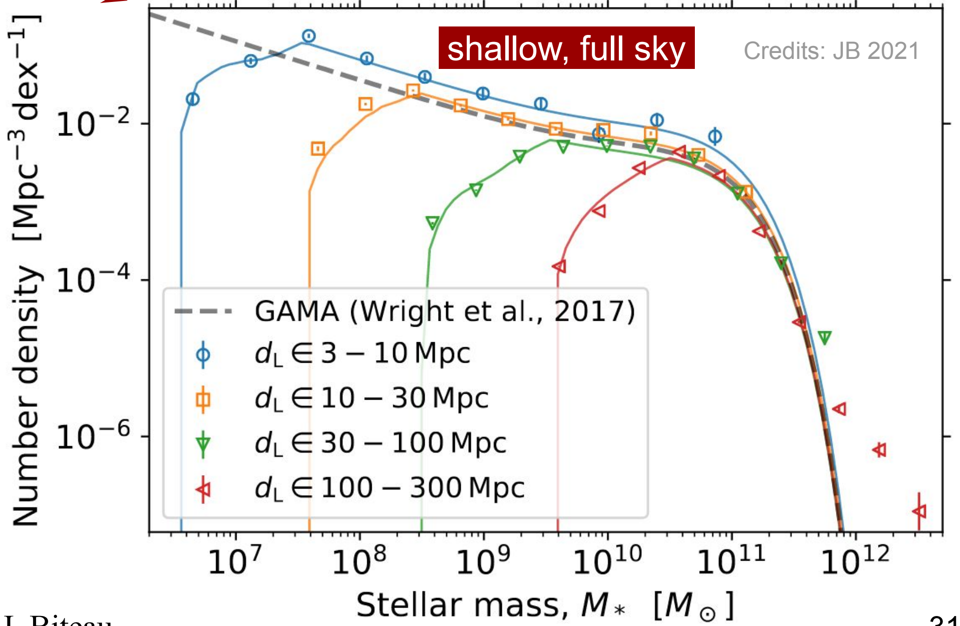


Constraints on faint galaxies / halo light

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?

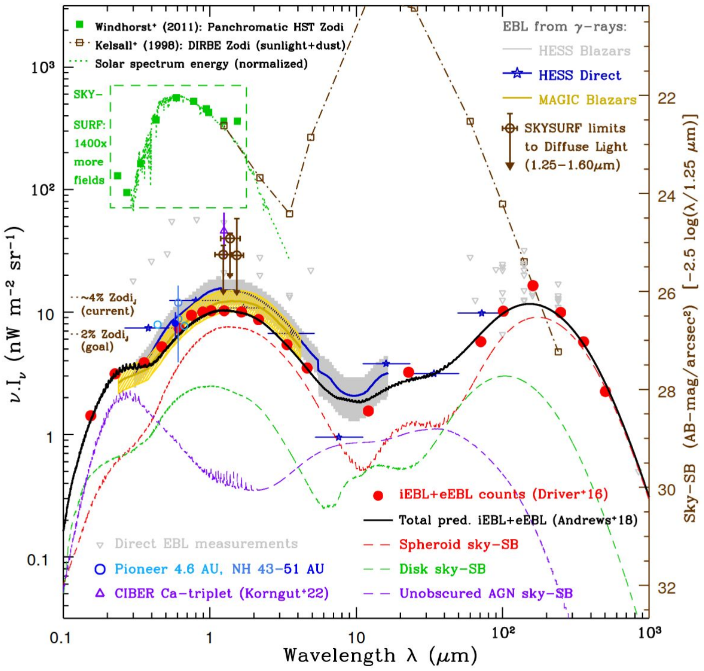




A new Inter-Planetary Dust component?

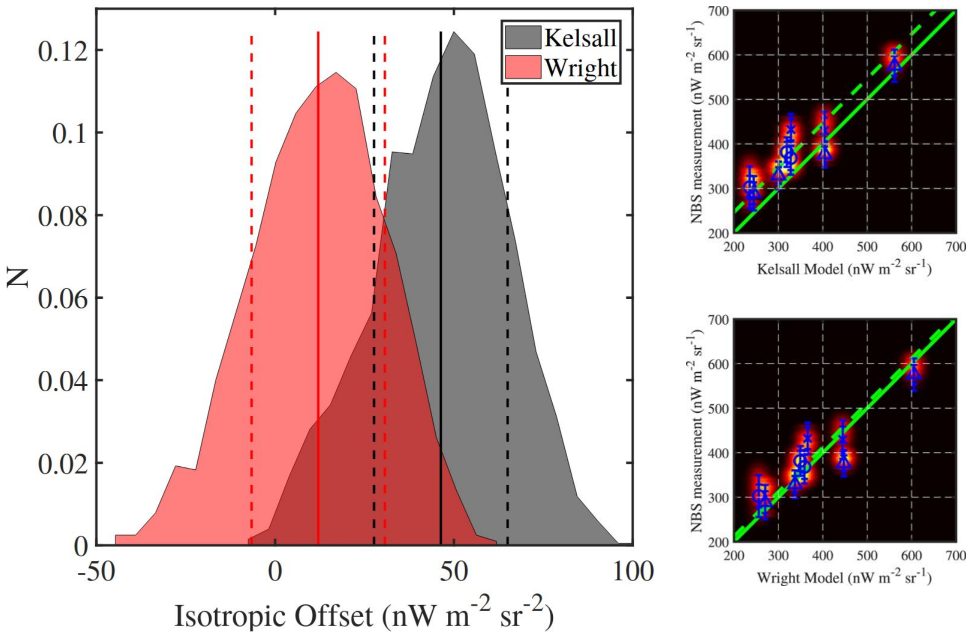
Spherical cloud of cometary dust (Kuiper Belt, Oort Cloud)?

- 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 ɣ-ray propagation

Absorption on EBL: precision and validity?

- $\pm20\%_{stat}$ $\pm20\%_{sys}$ $\rightarrow$ $\pm5\%_{stat}$ $\pm12\%_{sys}$ (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* ~ 2

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

⇒ Accuracy on H_0? (Dominguez+ 2019)

Where are the secondaries?

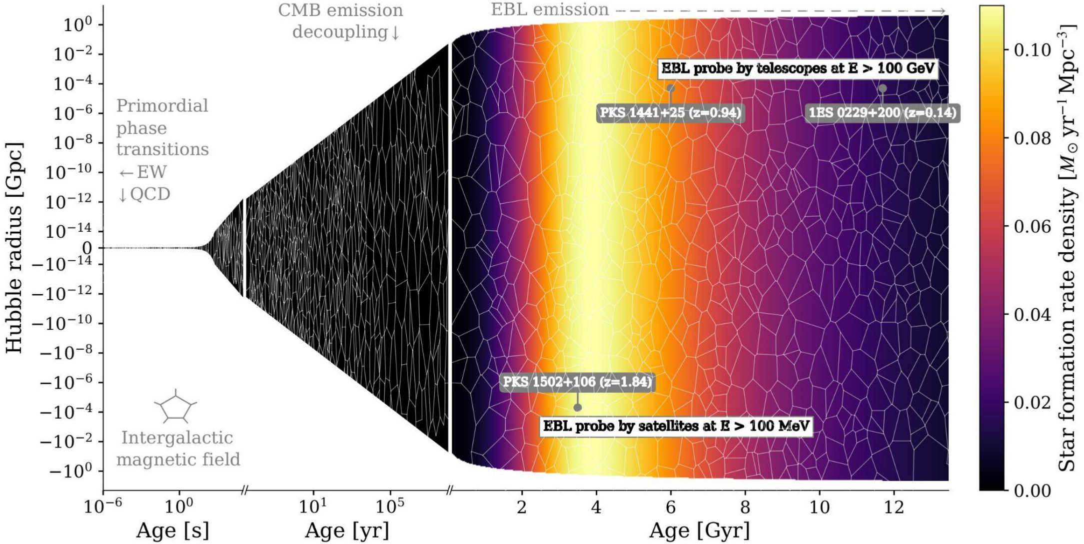
- Lead hypothesis: magnetic fields in voids

⇒ primordial phase transitions? structure formation?

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

⇒ numerical challenge with unsettled status (Vafin+ 2018)

Credits: JB & Meyer 2022



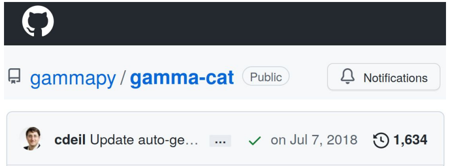
Addressing the optical controversy before CTA?

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

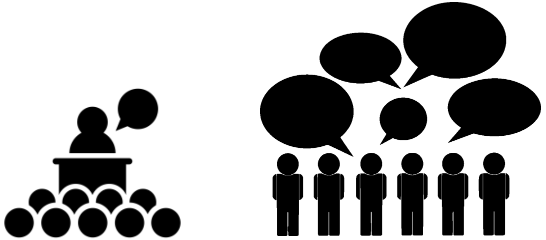
- All published extragalactic TeV spectral points
  ⇒ exported to **gamma-cat** format (**to be revived?**)
- More modest effort: Gamma 2022 (Gréaux+, IJCLab)



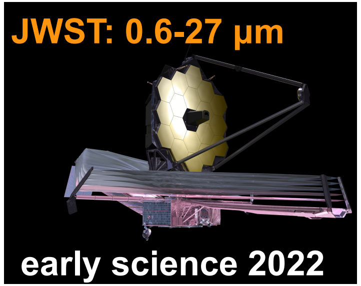
The three communities around a single table?

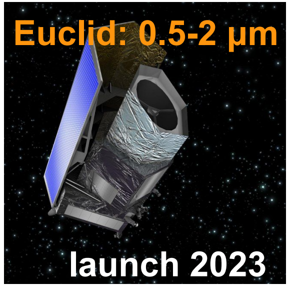
- New 4σ evidence from direct observation beyond Pluto
- New 5%-resolution measurement of galaxy counts
- Upcoming TeV measurement with 2-3× previous archival data

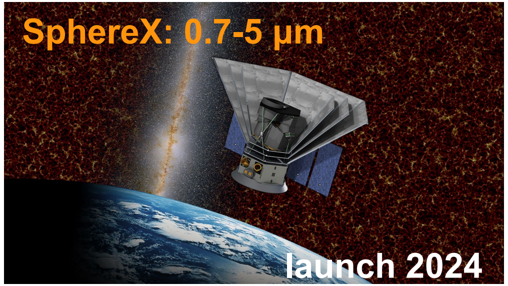
⇒ **EBL workshop (3-5 days) in Paris area in 2023/24?**



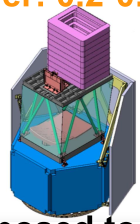
Gamma-ray cosmology in the upcoming CTA era







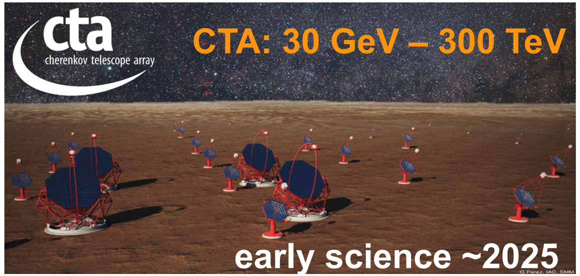
Messier: 0.2-0.9 μm



proposed to ESA-F

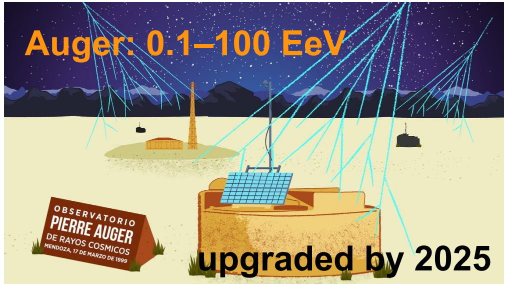
Light in voids and faint galaxies

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



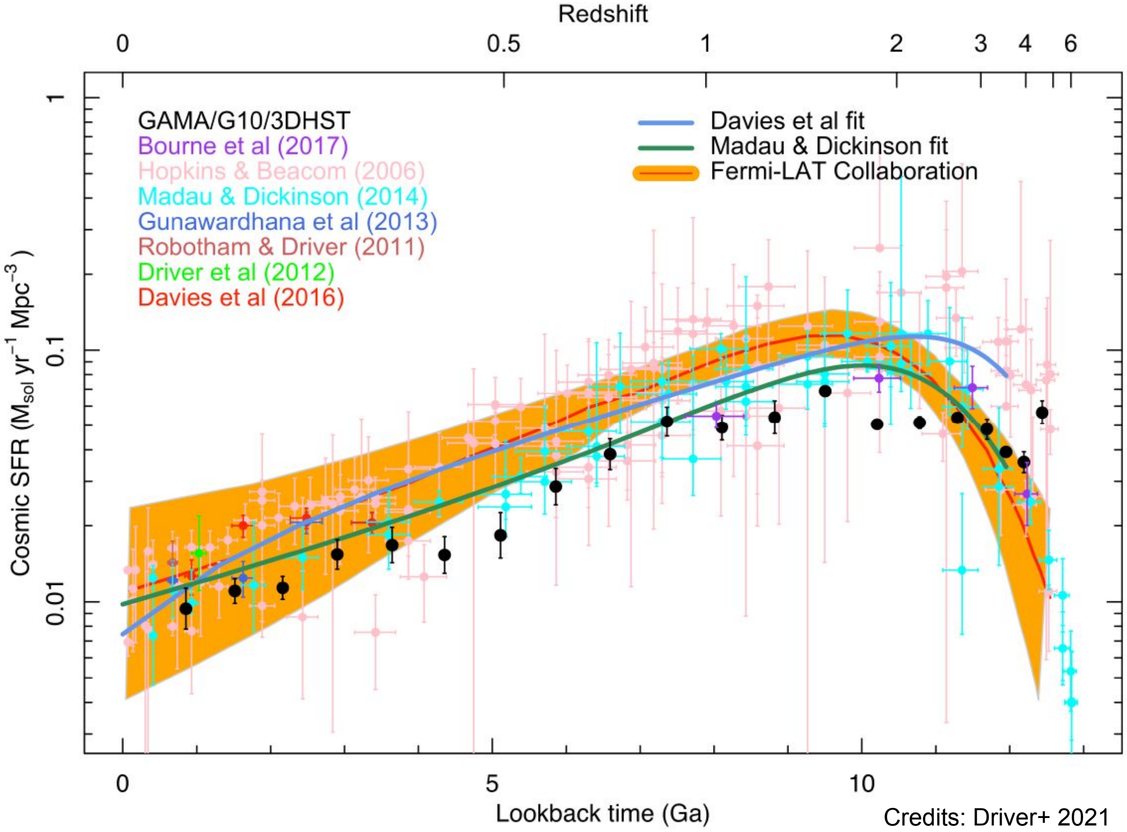
Cosmic magnetism

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



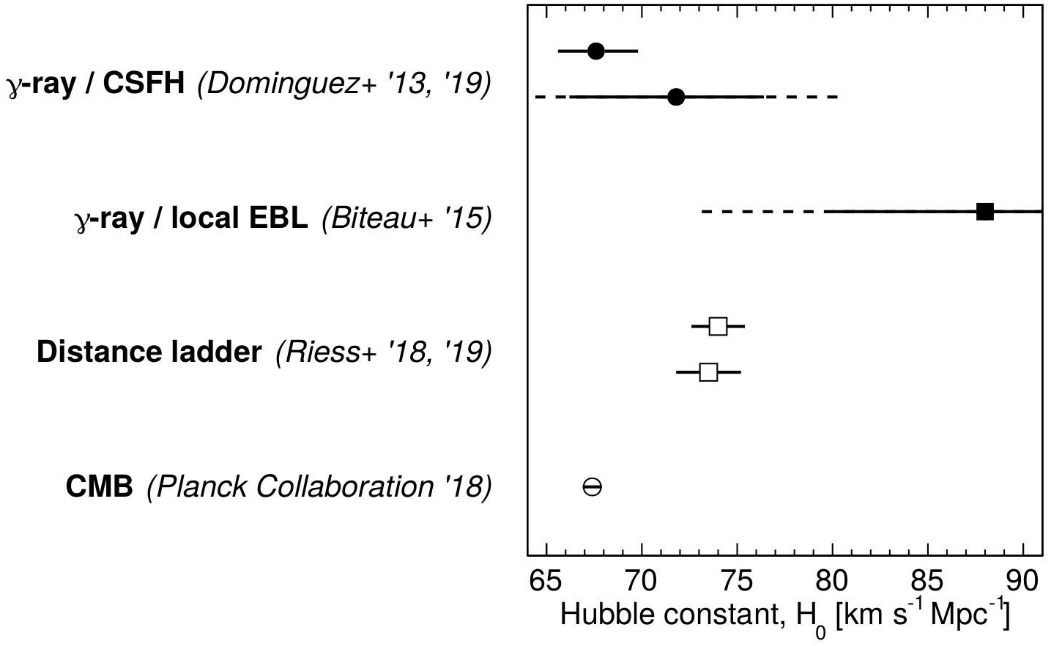
Backup

Cosmic star-formation history



Credits: Driver+ 2021

Hubble constant



Credits: Pueschel & JB 2021

How to:

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

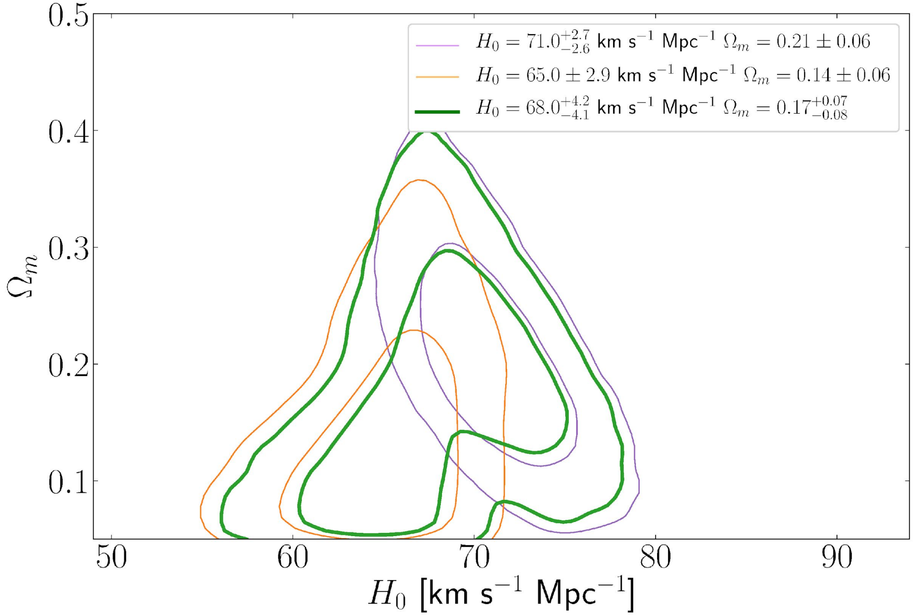
$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} \Gamma_{\gamma\gamma}^{-1}(E(1+z), z) \frac{\mathrm{d}\ell(z)}{\mathrm{d}z} \mathrm{d}z$$

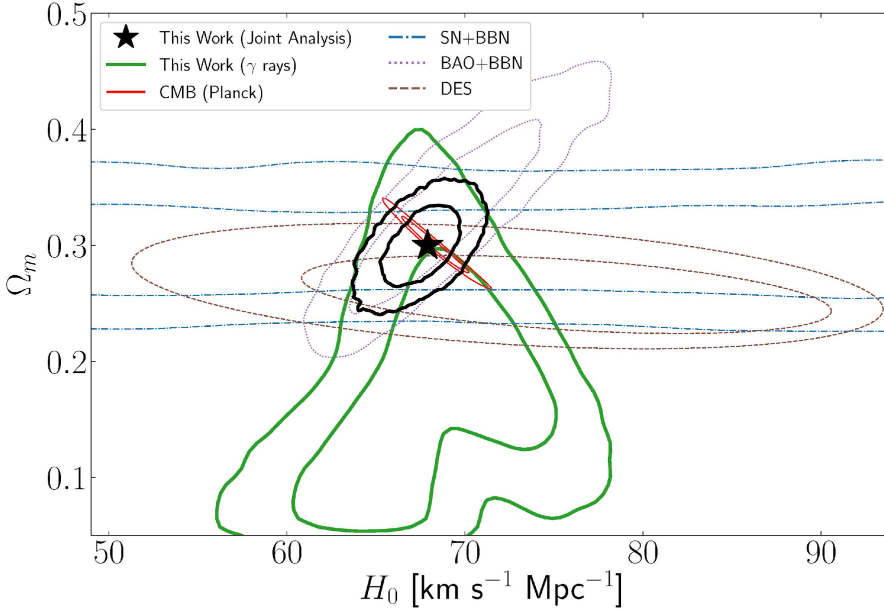
$$\Gamma_{\gamma\gamma}^{-1}(E', z) = \int_0^{\infty} \mathrm{d}\epsilon' \frac{\mathrm{d}n(\epsilon', z)}{\mathrm{d}\epsilon'} \int_{-1}^{1} \mathrm{d}\cos\theta' \frac{1-\cos\theta'}{2} \sigma_{\gamma\gamma}(\beta') \Theta(\epsilon' - \epsilon'_{\rm th})$$

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

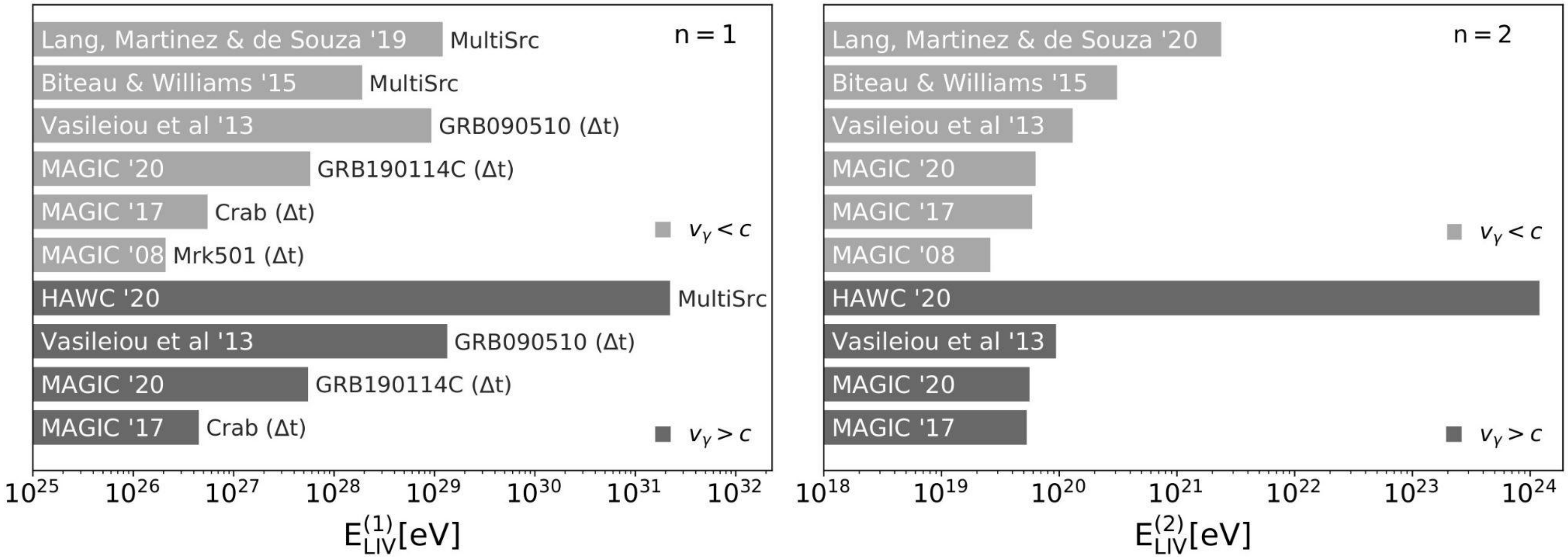
Hubble constant: ɣ-ray inference

Dominguez et al. 2019



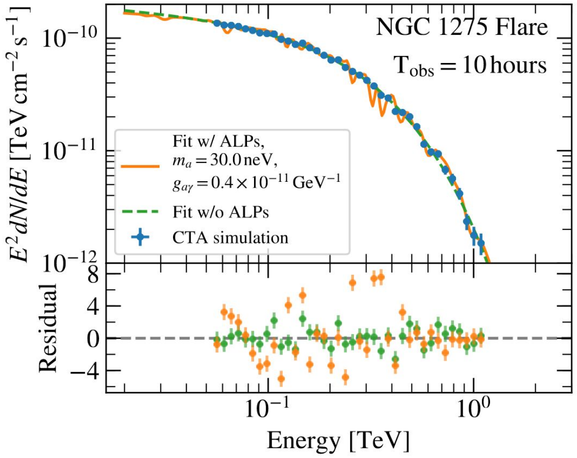


Lorentz invariance violation: status

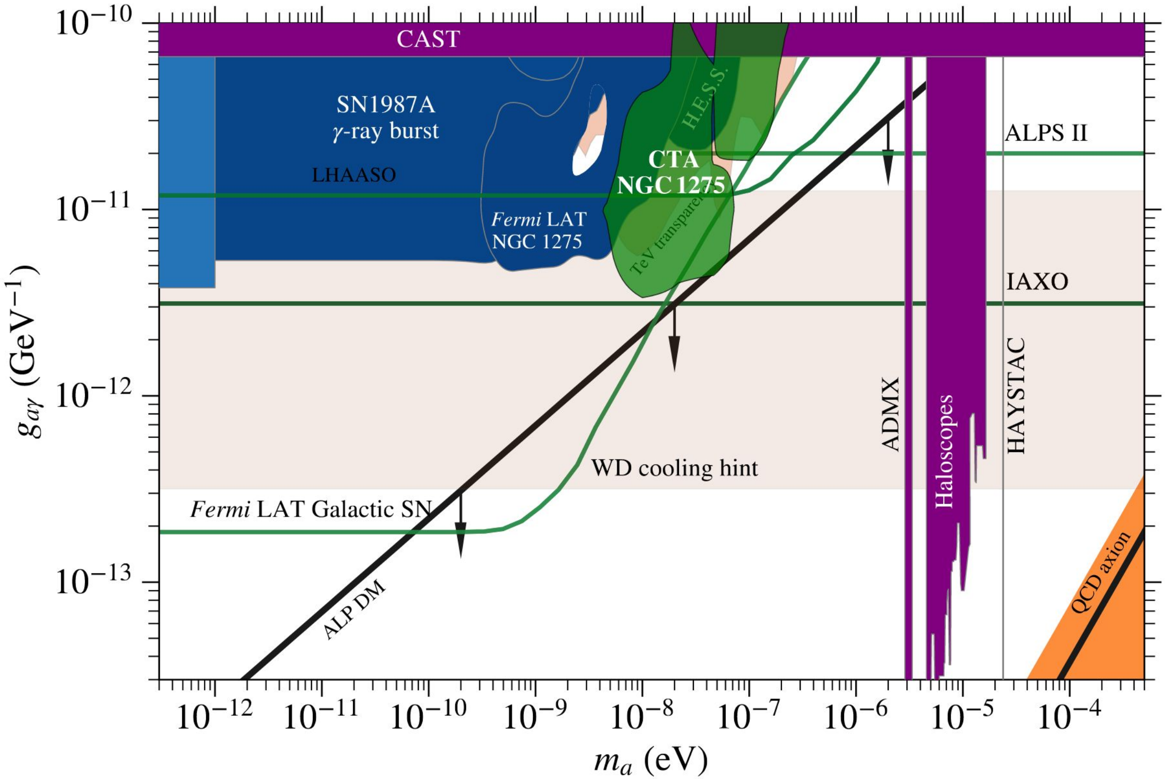


Credits: H. Martinez-Huerta
in Pueschel & JB 2021

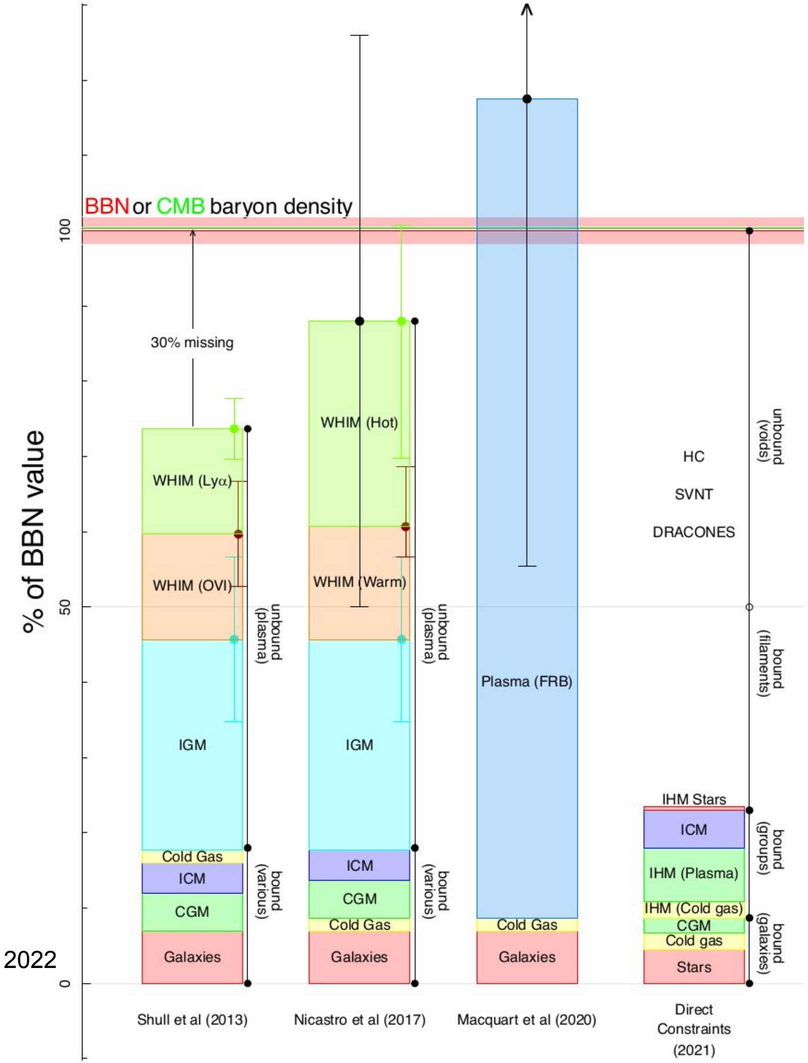
Axion-like particles: perspectives



CTA Consortium 2020



Missing baryons



Credits: Driver 2022

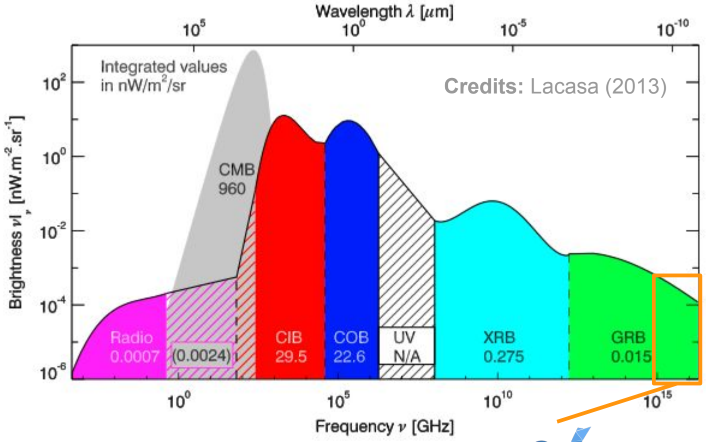
The multi-wavelength and multi-messenger night skies

The “gentle” universe
Cosmic Microwave, Infrared and Optical Backgrounds

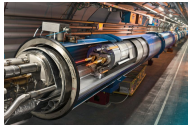
→ 6 energy decades covered

The “violent” universe
From gravitational waves to ultra-high energy cosmic rays

→ 35 energy decades covered



How violent does it get?

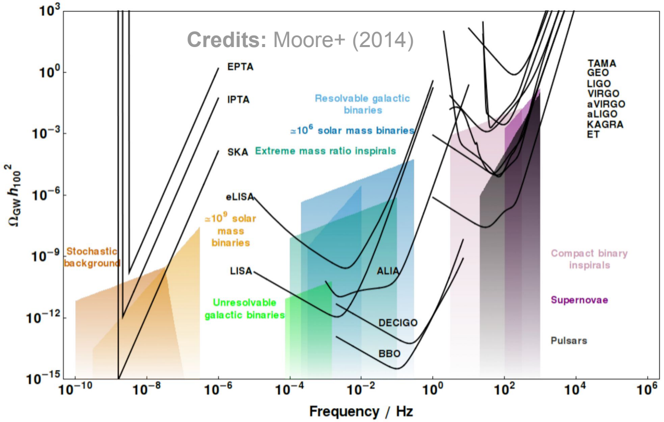


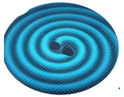
LHC

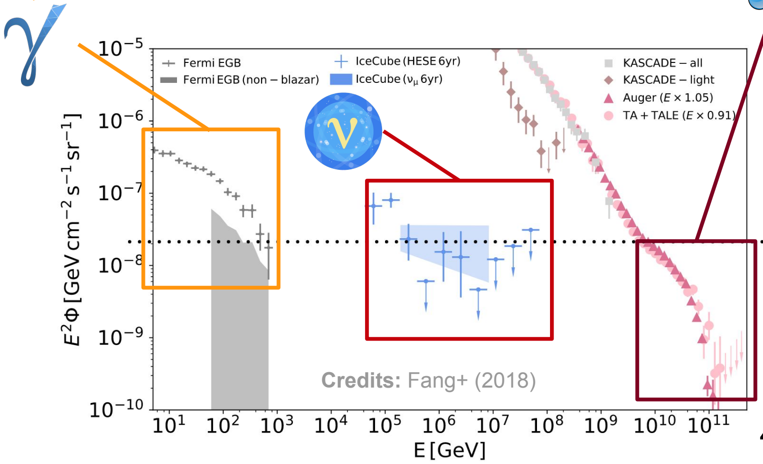
*E*max ~ 10^**13** eV
rate ~ 10^**19** part./sec

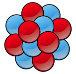
Most extreme sources

*E*max ~ 10^**20** eV
rate ~ 10^**31** part./sec









The quest for UHECR origins

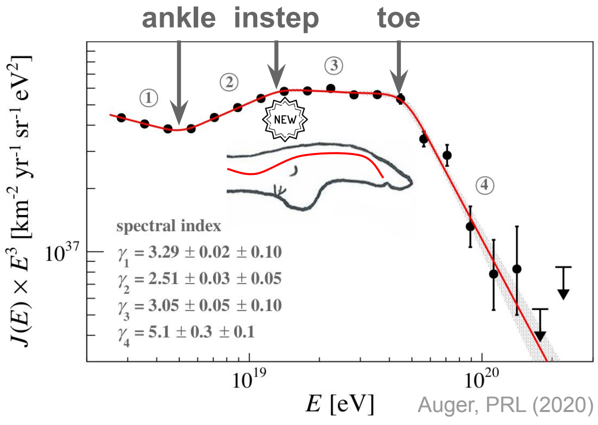
Ultra-high energy cosmic rays (UHECR)

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**

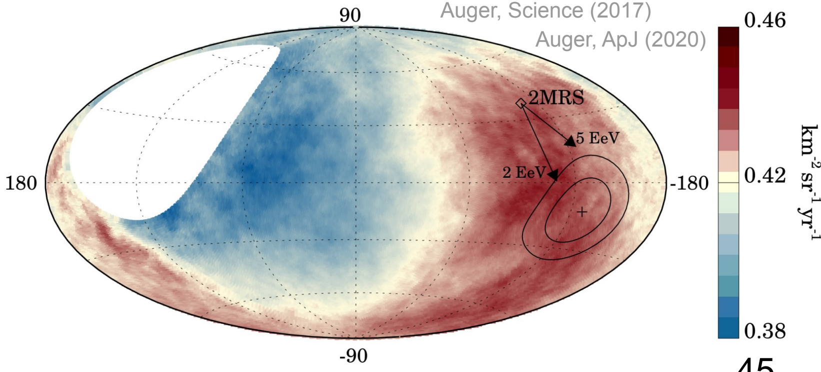
Anisotropy observables
→ break down the flux (and composition) vs **arrival direction**: **pinpoint sources?**

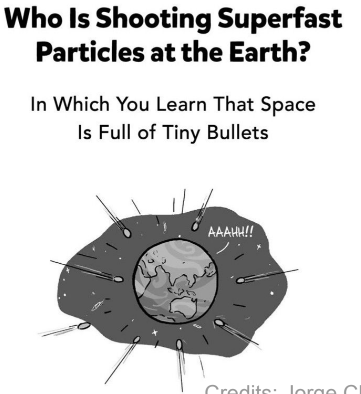


Auger, PRL (2020)

Auger dipole > 8 EeV (>6σ)

Auger, Science (2017)
Auger, ApJ (2020)

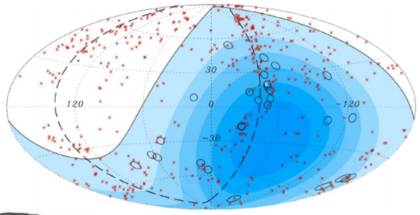


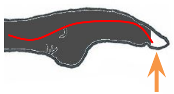


Credits: Jorge Cham & Daniel Whiteson

Some landmarks in Auger anisotropy studies

Auger, Science 2007





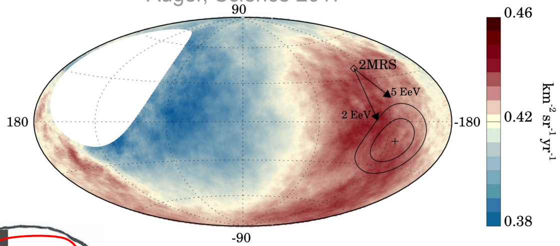
First steps: hint

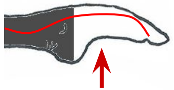
20 out of 27 evts within 3° of nearby galaxies → ~3σ

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

~ 27 evts ≥ 57 EeV

Auger, Science 2017





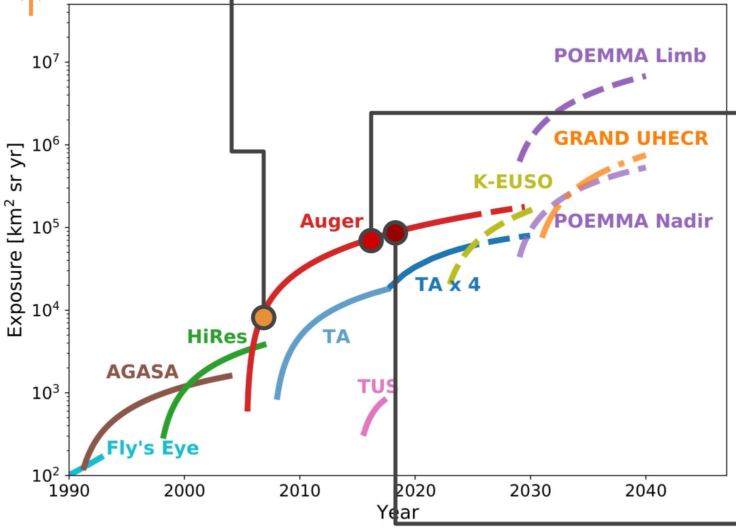
Maturity: discovery

6σ dipolar-like flux

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

~ 32,000 evts ≥ 8 EeV

Alves Batista+ 2019

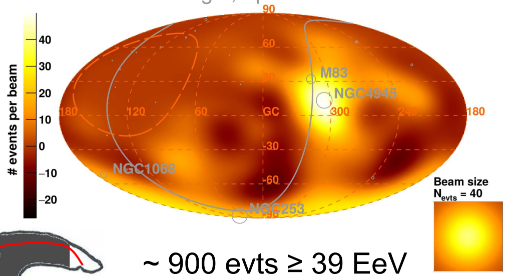


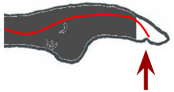
Revival: a trail?

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

3σ level for other types of galaxies

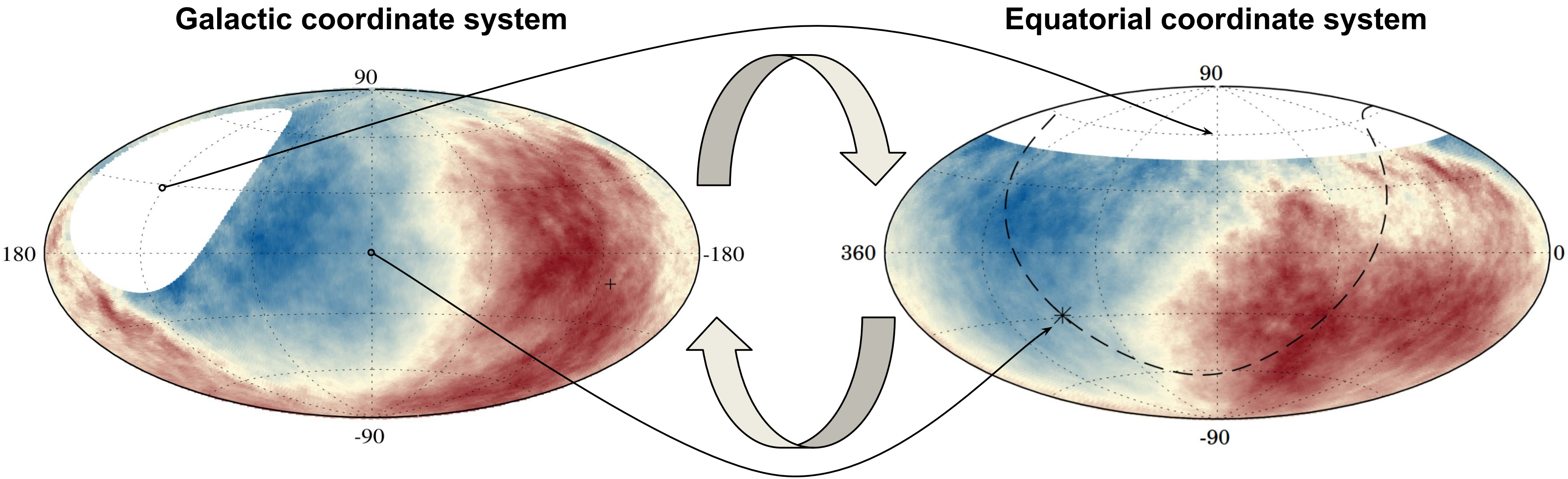
Auger, ApJL 2018



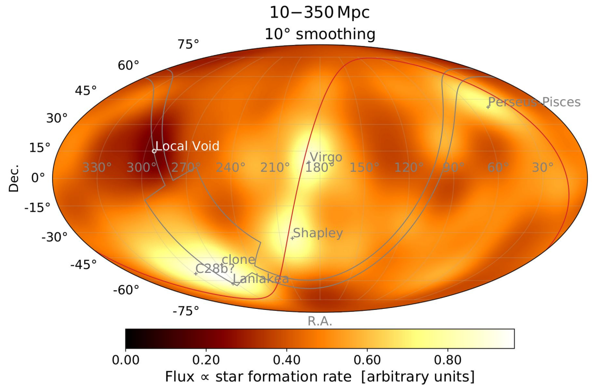


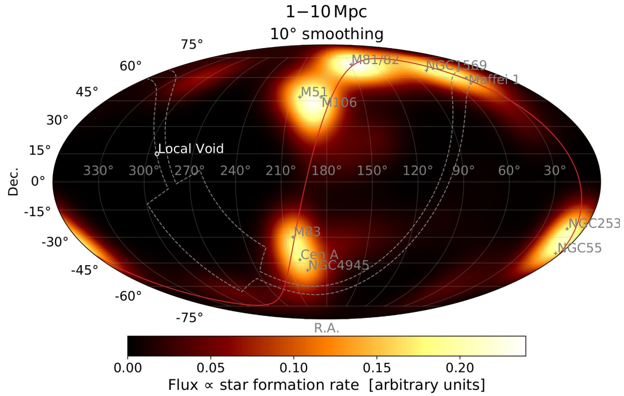
~ 900 evts ≥ 39 EeV

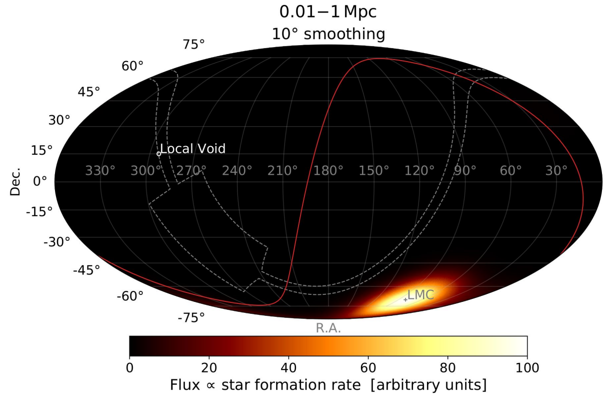
! skymaps in next slide !



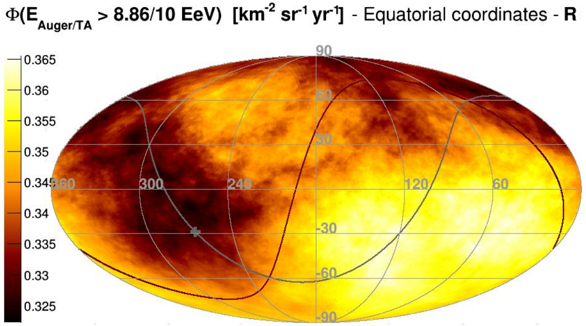
Mapping of SFR on the sphere



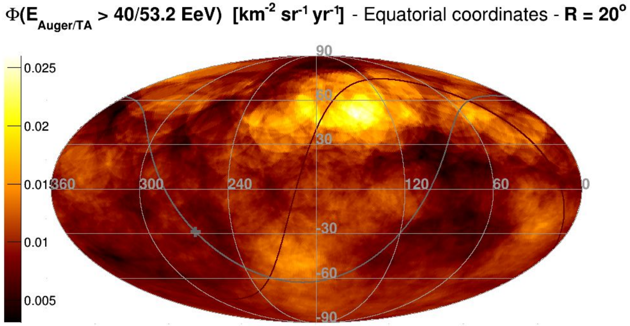




UHE sky around the instep



UHE sky around the toe



Biteau+ for Auger & Telescope Array Collab., 2019

SFR sky vs UHE sky

- Local Universe:
  - · Local Void ~ UHE underdensity ✓
  - · Local clusters and supercluster hardly seen at UHE ❌

  → UHECR can't escape B++
- Local Sheet ~ UHE toe region ✓
- LMC not seen at UHE ❌

  → intrahalo bursts too short to be seen, missed most of the time

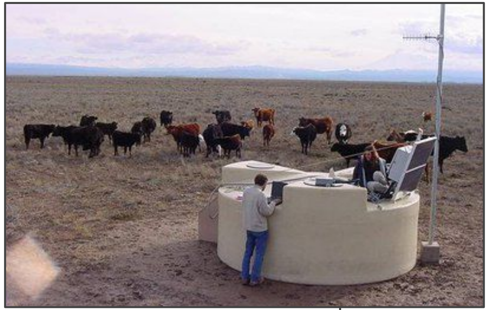
The largest UHECR observatory ever built

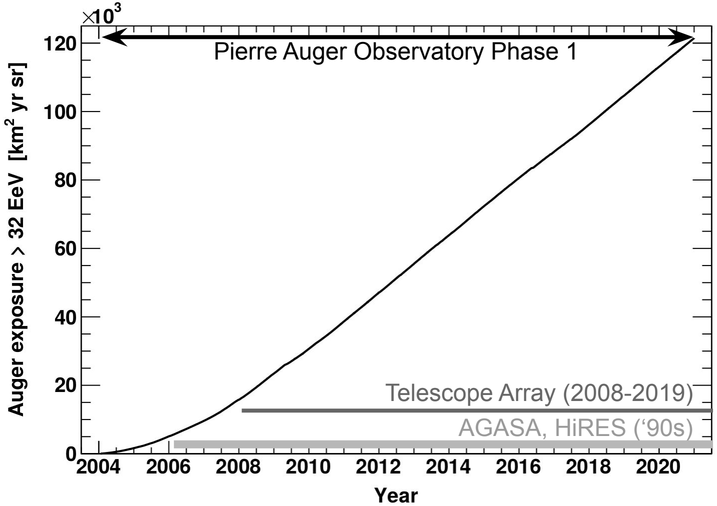
The Pierre Auger Observatory

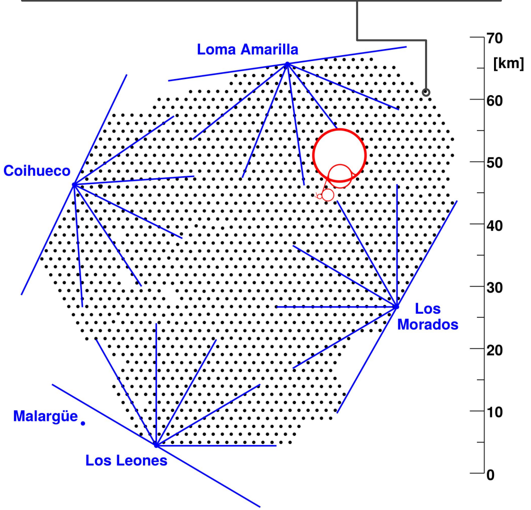
West Argentina at 1,400m a.s.l., **spread over 3,000 km²** (~ Luxembourg or Rhode Island)

1600 water Cherenkov detectors (12t each) to measure secondary particles in air showers
→ **85% of the sky covered** with angular resolution < 1° above the ankle

Exposure at the highest energies (loosest cuts): **120,000 km² yr sr in 2004-2020**
→ **40-70x larger than previous generation** experiments (AGASA, HiRES)
→ **9x larger than complementary Northern hemisphere** experiment (Telescope Array)

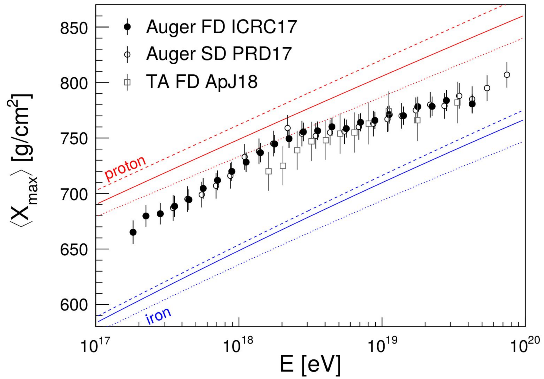


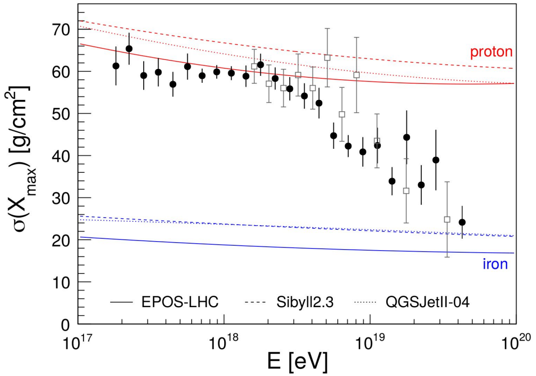




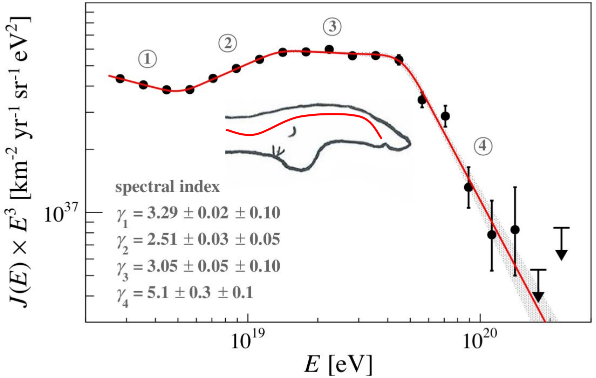
UHECR observables

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

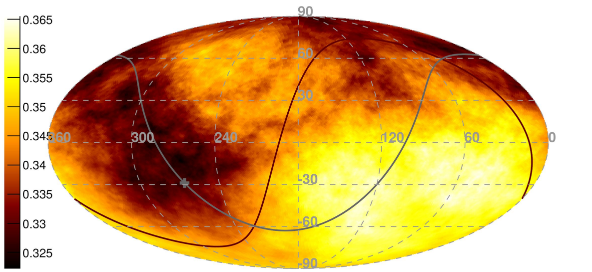




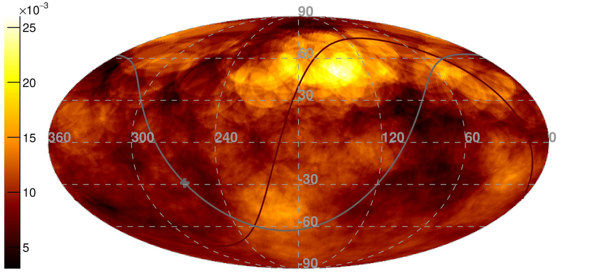
Auger, PRL 125, 121106 (2020)



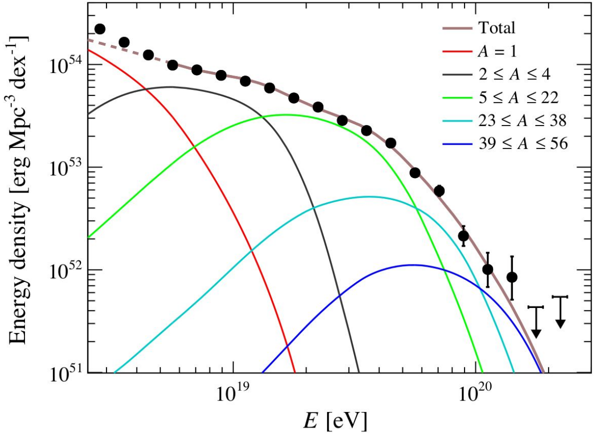
$\Phi(E_{Auger/TA}$ > 8.86/10 EeV) [km^{-2} sr^{-1} yr^{-1}] - Equatorial coordinates - R = 45°



$\Phi(E_{Auger/TA}$ > 40/53.2 EeV) [km^{-2} sr^{-1} yr^{-1}] - Equatorial coordinates - R = 20°



Biteau+ for Auger & Telescope Array Collab., EPJ Web Conf., 210:01005, 2019

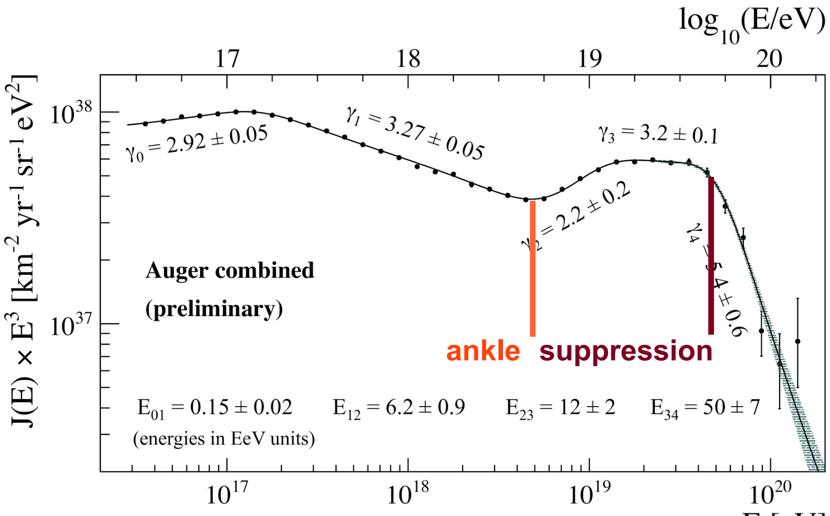


Multi-dimensional UHECR flux dependences: energy, composition, direction

Cosmic-ray observations

The dip model: pure protons Berezinki (2006)

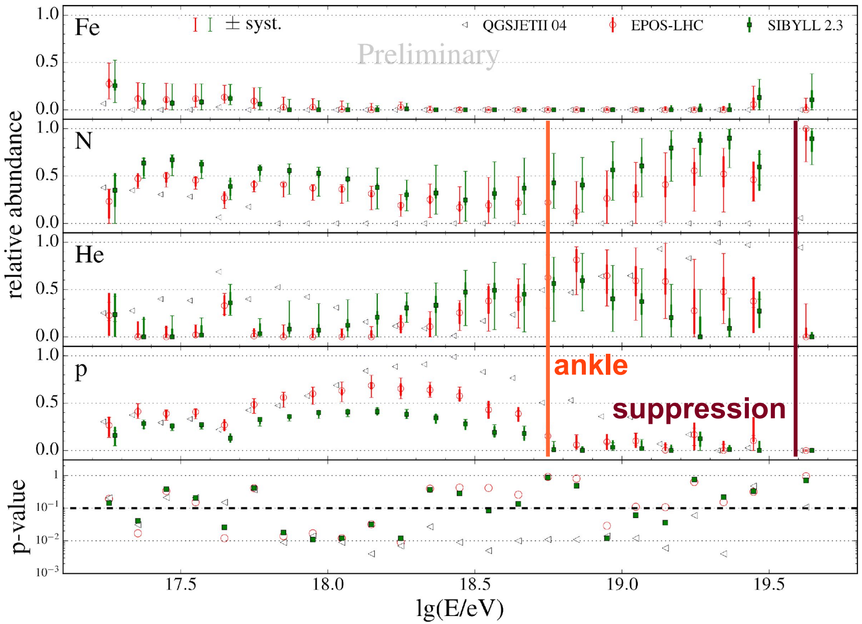
Attempt to explain the ankle and suppression with a purely proton composition
→ quite successful at reproducing the spectrum down to ~ 10^18 eV
→ based on pure protons



Verzi+ for Auger (ICRC2019)

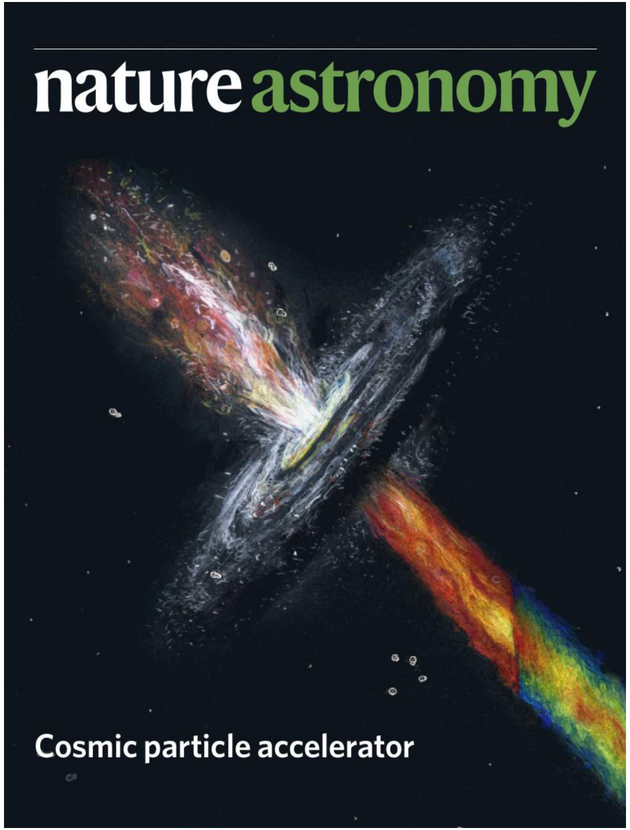
But mixed composition

Inference: p → He → CNO sequence
→in line with E_{max} ~ a few EeV x (Z or A)



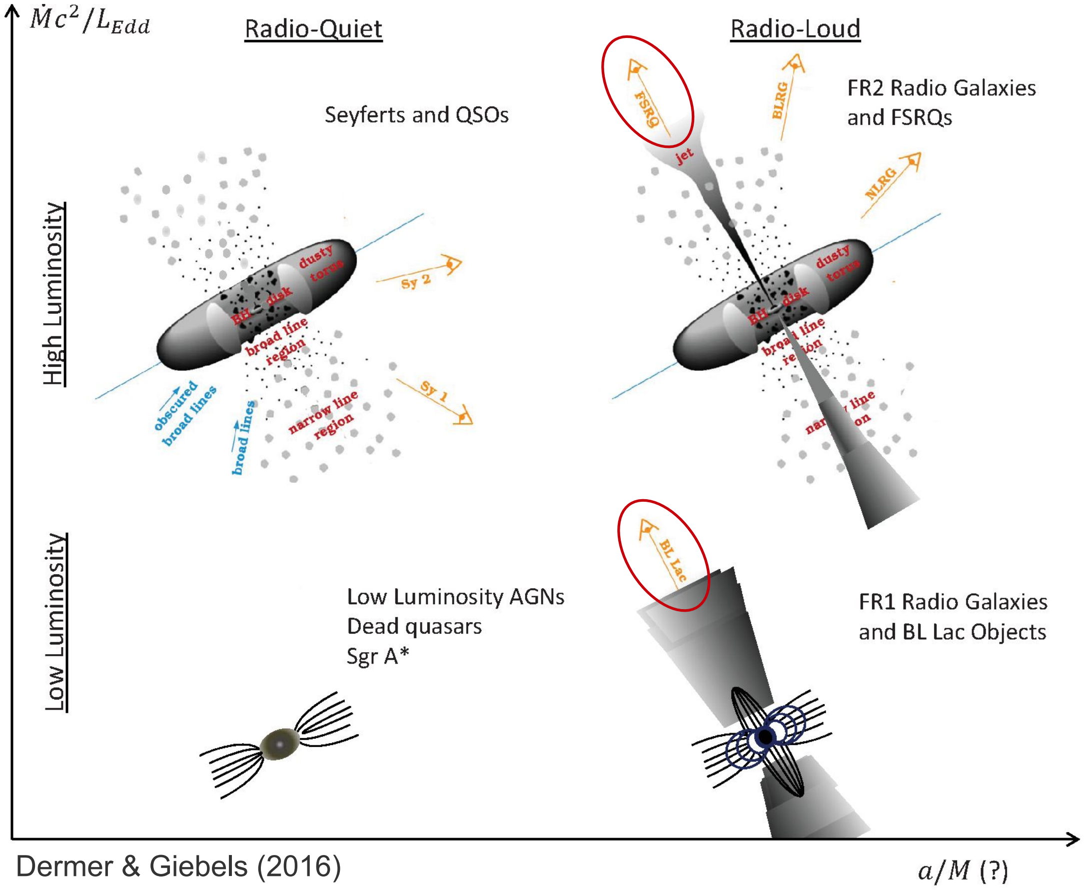
Bellido+ for Auger (ICRC2017)

Extreme blazars



See JB+ 2020

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

Some of Fermi's lessons on blazars

Detections

- 2863 sources at |b| > 10° 4LAC, Fermi-LAT 2019
  - > 79% are AGNs
    - ~98% of these AGNs are blazars
      - 24% FSRQs, 38% BL Lacs, 38% unclear

Blazar sequence?

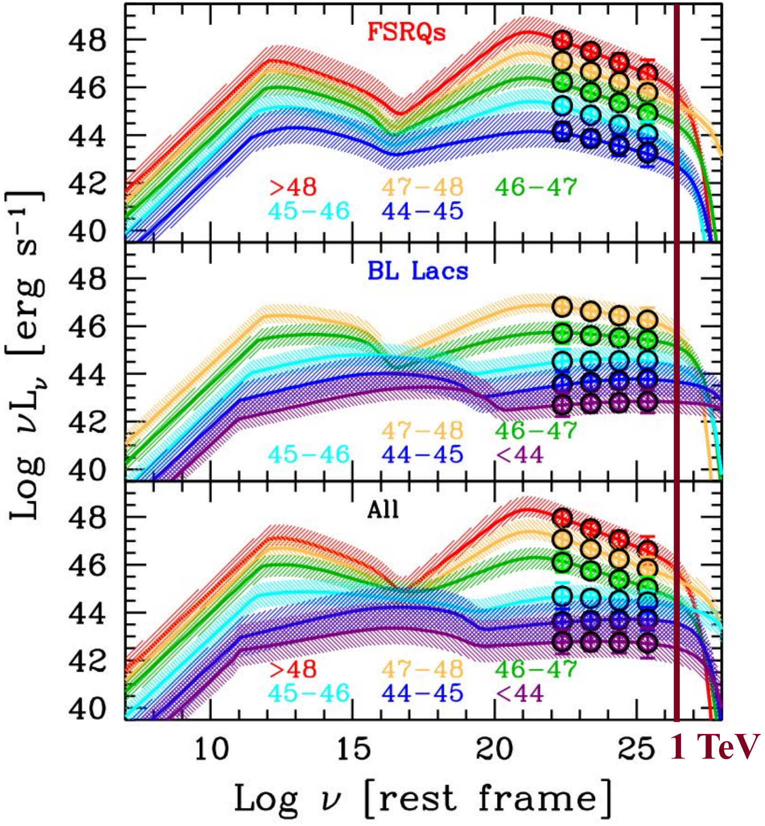
- Inferred anti-correlation of peak power with peak frequency
- Initially: (biased?) X-ray/radio selection Fossati et al. (1998)
- Confirmed with Fermi-only selection Ghisellini et al. (2017)

→ links maximum energy, jet power and accretion rate
(FSRQ / BL Lac lines = reprocessed disk emission)

Extreme blazars

The high-energy frontier of the sequence
→ two dozen known to date Biteau et al. (2020)

Ghisellini et al. (2017)

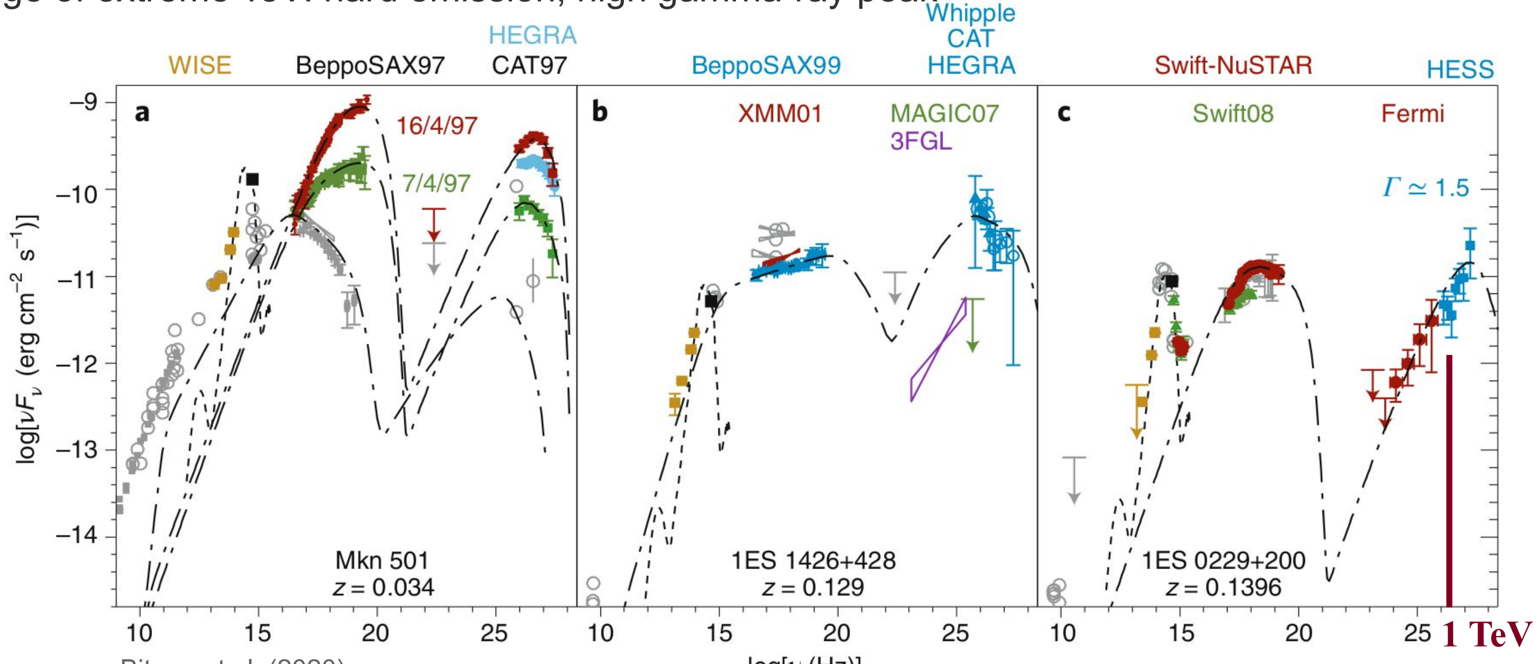


Broad-band emission of extreme blazars

Extreme-synchrotron & extreme-TeV blazars

Extreme blazars: synchrotron peak $h\nu \geq$ keV (~2x10^{17} Hz) OR gamma-ray peak $h\nu \geq$ TeV (~2x10^{26} Hz)

Challenge of extreme TeV: hard emission, high gamma-ray peak



Biteau et al. (2020)

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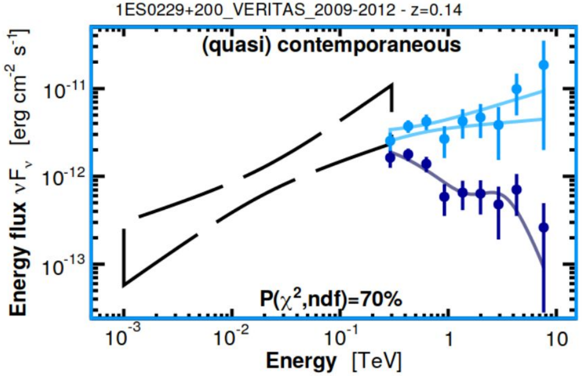
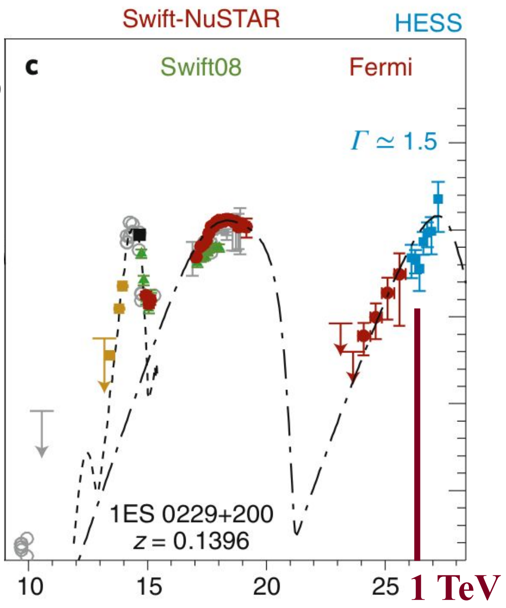
Challenge of extreme TeV: hard emission, high gamma-ray peak

Observed ≠ Intrinsic

- X-rays: photoelectric effect → sharp transitions, ~ easy to de-absorb
- gamma-rays: pair production → smooth absorption with energy, with order of magnitude uncertainty on target photon field 10 yrs ago!



Biteau & Williams (2015)



Extreme-TeV blazars as cosmological beacons

Absorption on the line of sight - *observed since 2012*

- γ(TeV) + γ(eV) → $e^+ + e^-$
  → 0.1-10 eV target photon field: extragalactic background

light

- Extreme-TeV emission > 10 TeV: unique integral probe of EBL
  at ~0.1 eV (mid- to far-infrared), complementarity with JWST!

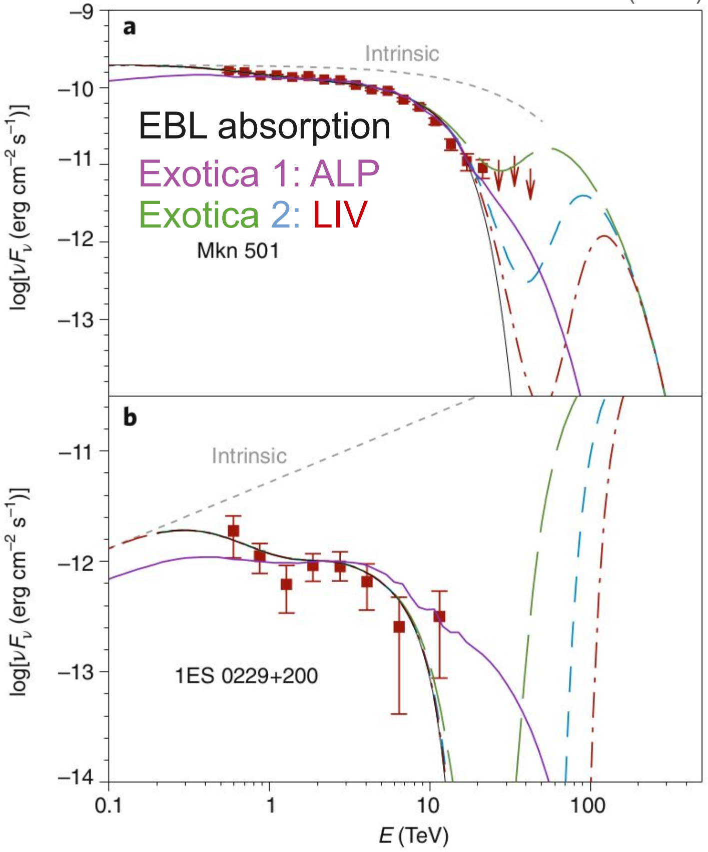
Cooling of e^+/e^- pairs - *not observed, tight constraints*

- Either plasma instabilities
  → intergalactic medium heating
- Or inverse Compton on CMB (secondary γ-rays >1 GeV)
  → probe of intergalactic *B*-fields up to pG level CTA (2021)

Exotic physics - *not observed, tight constraints*

- Lorentz invariance violation (LIV) or axion-like particles (ALPs)

Biteau et al. (2020)



Recent example of advanced (beautiful!) model

Micro- & macro-physics in magnetic reconnection

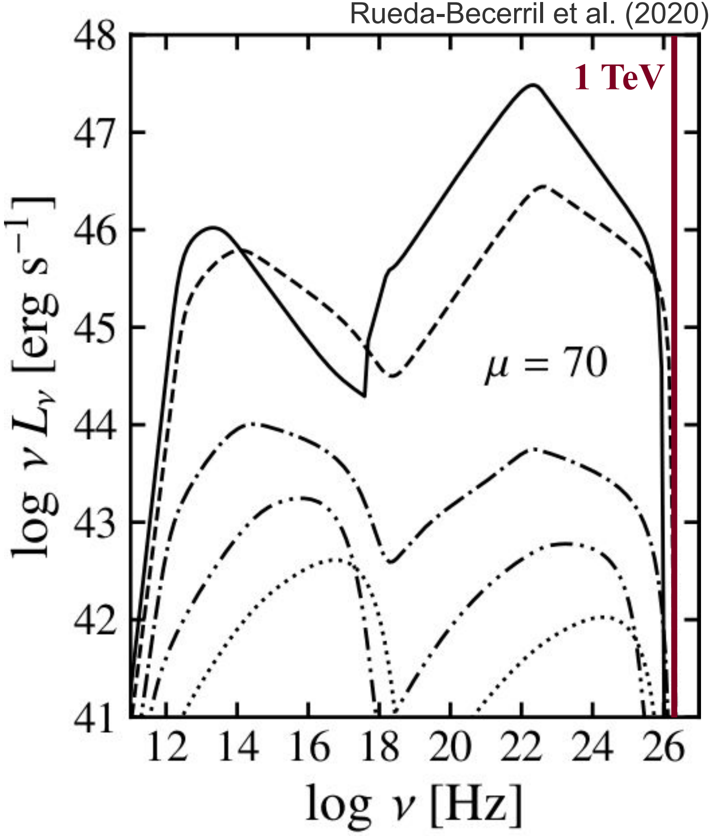
Observations: bulk Lorentz factor, Γ → Accretion rate, Jet power

MHD theory: μ = Γ(1+σ) const. → Jet power, Magnetization, σ

Reconnection simulations: σ↗, p↘ → Magnetization, σ, Acceleration index, p

Accretion rate, Jet power, Magnetization, σ, Acceleration index, p, Radiative processes → Maximum energy

Rueda-Becerril et al. (2020)



Explanatory power

Overall reproduction of blazar sequence:

(Γ↘, higher σ, harder p) ⇒ Power↘ - Frequency↗

Limitation: no emission > 1 TeV!

Orthodox model of extreme blazars

Acceleration processes

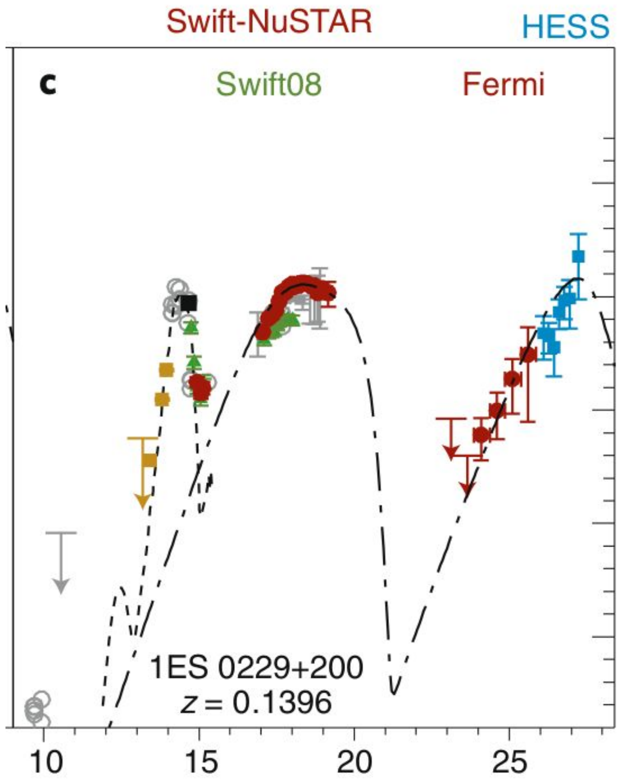
- Hard photon spectrum → hard particle spectrum with p < 2
  most of the energy carried by rarer high-energy particles!
  → shocks (p=2) with backreaction (p<2)
  → magnetic reconnection (p<2 allowed)

Leptonic radiative processes

- High synchrotron peak → weak energy losses
  ***Low magnetic field** responsible for e^+/e^- synchrotron ~ mG*
- Gamma-ray peak = Synchrotron Self Compton
  *Two peak frequencies correlated, **high bulk Γ (~50)***
- Limitation: particle energy density / B-field energy density ~10^5

At odds with scenario in previous slide (high σ, low Γ)

→ Explaining extreme-TeV blazars is indeed challenging!

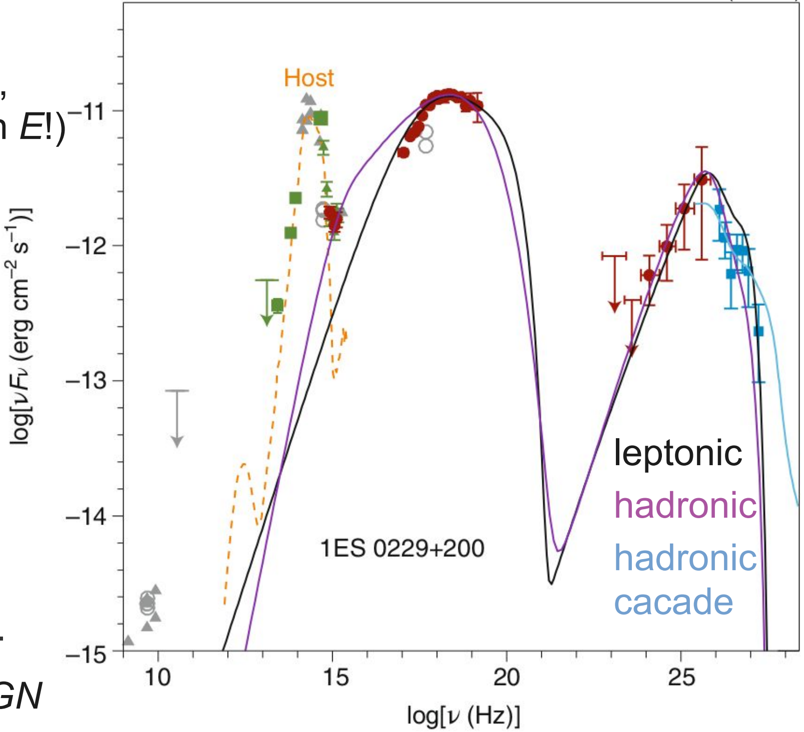


Heterodox models of extreme-TeV blazars

Lepto-Hadronic radiative processes

- co-accelerated leptons (synchrotron peak) and protons
- γ-ray peak from proton synchrotron (*ok if slow variability*), with p ~ 1.3-1.7 and E_{max} ~ 10^{19} eV $(B/100G)^{-1/2}$ (ultra-high *E*!)
  → *jet close to Eddington accretion limit*
- line-of sight cascade from UHECR
  → *GeV emission remains to be explained*

Biteau et al. (2020)



Escaping astroparticles from extreme-TeV blazars

- Neutrino: flux beyond reach (pγ and pp sub-dominant)
- Ultra-high energy cosmic rays (UHECRs):
  highest synchrotron peak of extreme blazars
  → low t_{acc} / t_{Larmor} = fastest accelerators among AGN pop.

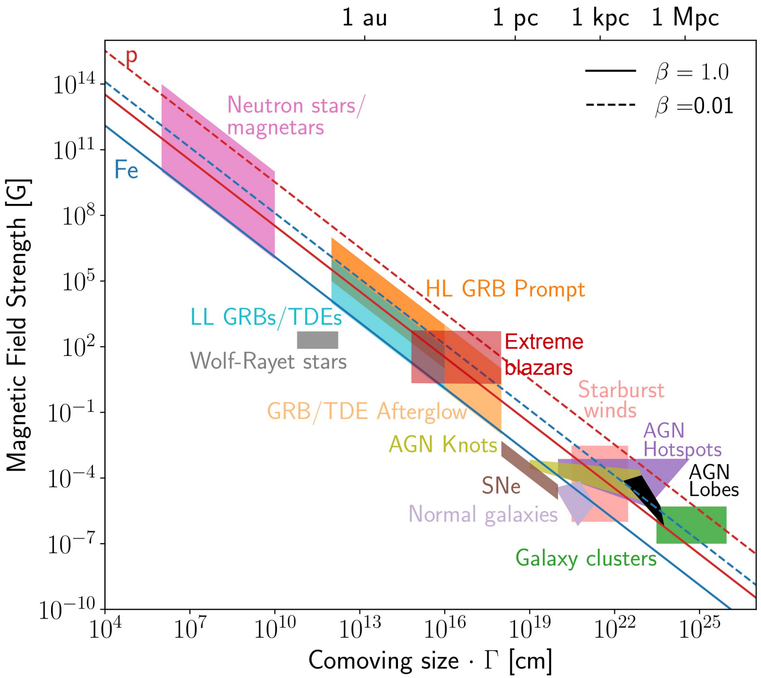
Extreme-TeV = best UHECR-source candidates among AGN

UHECR accelerators?

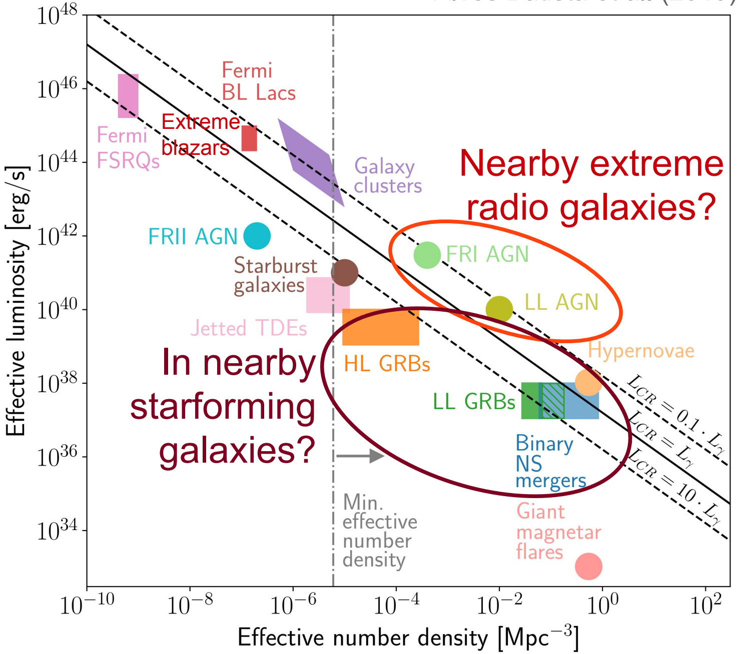
Extreme blazars and necessary conditions for being an UHECR source

Confinement (Hillas condition) ✓, Number density (anisotropies) ✗, Distance (<100 Mpc) ✗

→ *nearby extreme radio galaxies? Only if they accelerate heavy nuclei (e.g. expresso model,* Caprioli (2015)*)*



Alves Batista et al. (2019)

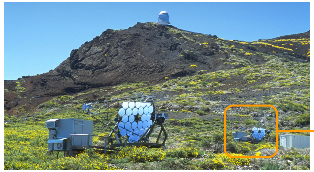


Tell-tale sign for UHECR acceleration with CTA

20-30 GeV energy threshold + 10× increased sensitivity + improved energy resolution

- Nice potential to distinguish hadronic & leptonic scenarios.
- Nearby extreme radio galaxies discovery?

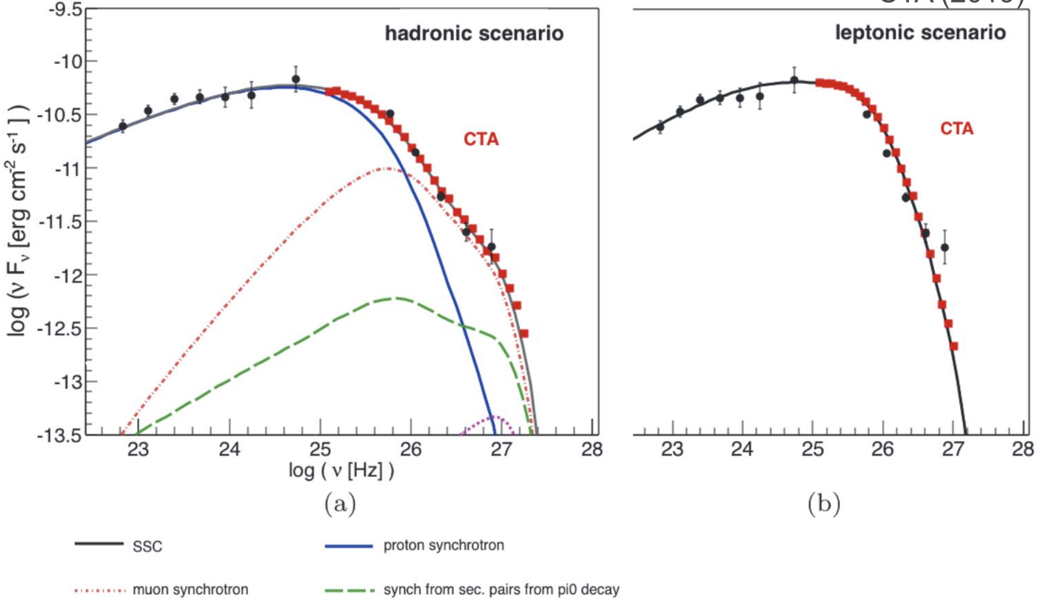
HEGRA (‘90s)



MAGIC (‘00s,’10s)

CTA (‘20s,’30s, ‘40s)

CTA (2019)



Arrival of ɣ-rays near Earth

Satellite-based: 100 MeV - 1 TeV

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

Tracker with SSDs, CsI(TI) with photodiodes

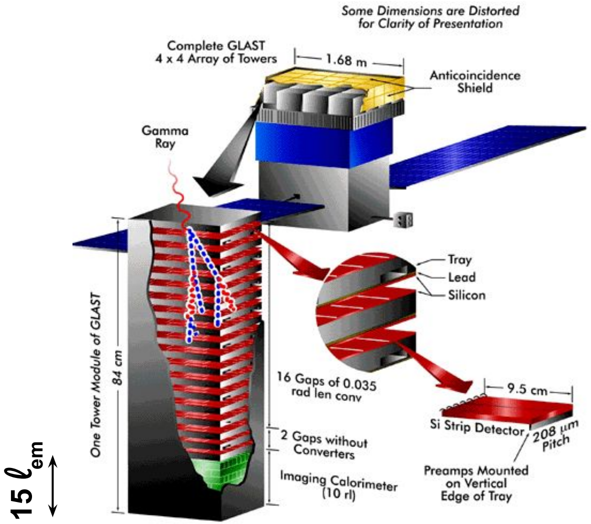
Lead experiment: *Fermi*-LAT

Telescope-based: 100 GeV - 100 TeV

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

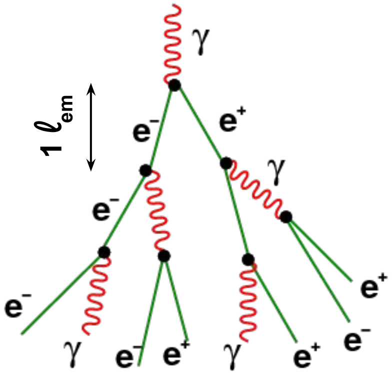
Cameras with O(1000) PMTs and ns sampling

Lead experiments: HESS, MAGIC, VERITAS



em cascade

Mollerach & Roulet (2017)



Performance > 10 GeV
energy resolution ~ 10%
angular resolution ~ 0.1°