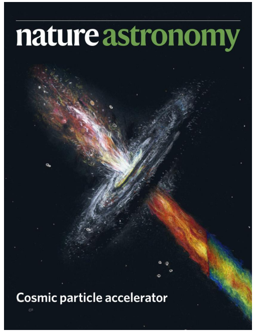
Extreme blazars and gamma-ray cosmology with CTA

https://www.nature.com/articles/s41550-019-0988-4.epdf

(Biteau et al. 2020)

https://arxiv.org/abs/2010.01349

(CTA 2020)



IJC Lab Seminar
2020-10-12

Jonathan Biteau, Université Paris Saclay / IJC Lab (IPNO)

Outline

Active galactic nuclei and blazars: brief overview

Extreme observational properties of blazars

From observations to intrinsic emission: gamma-ray cosmology

Challenges in modeling extreme blazars: multi-messenger emitters?

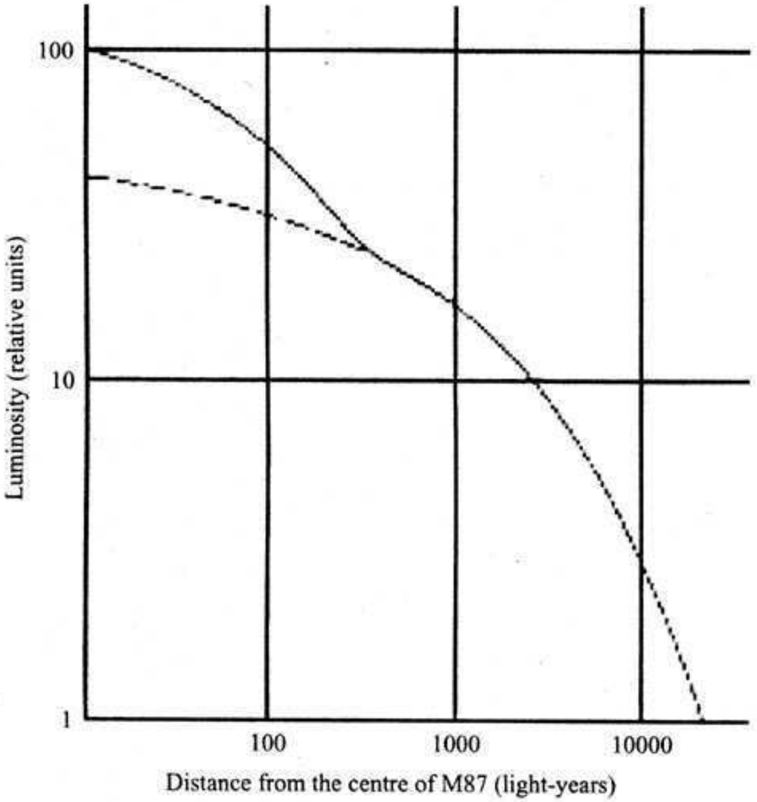
Observational roadmap: multi-wavelength observatories & CTA

Active Galactic Nuclei (AGN)

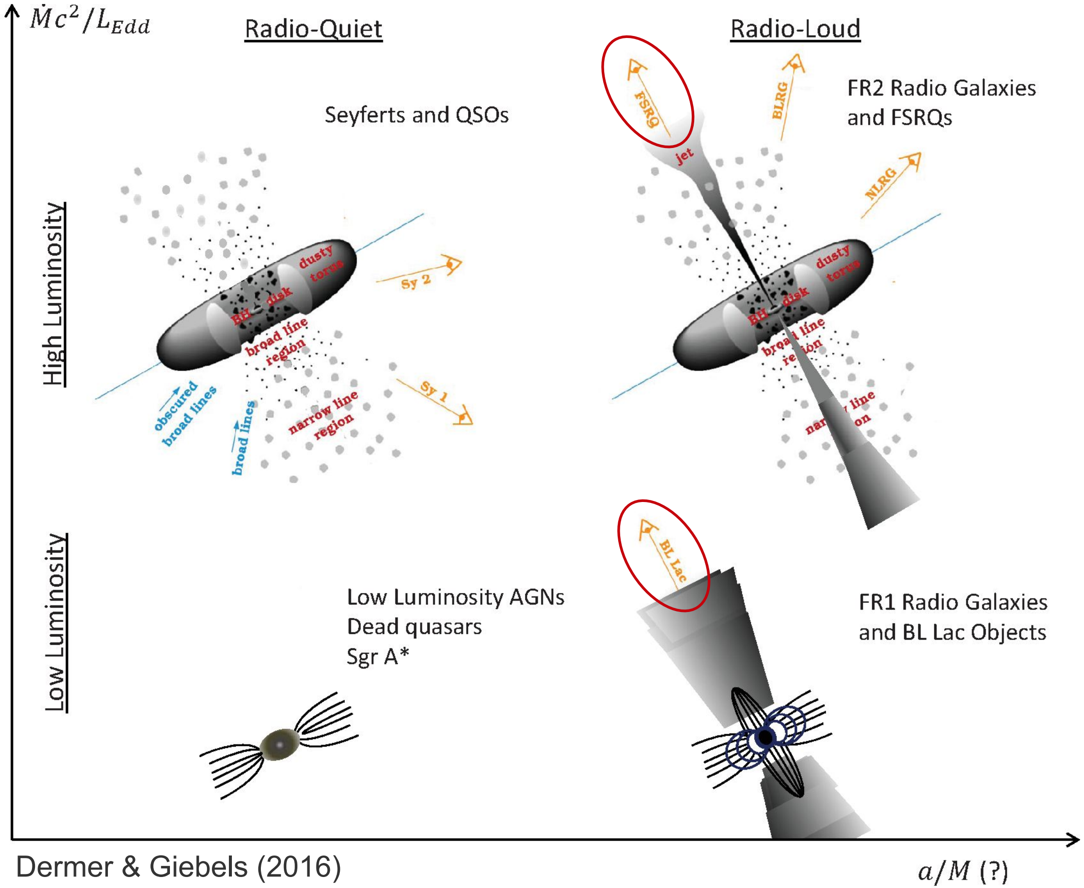
Historical landmarks

- 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

Some fundamental questions in AGN physics

Jet formation: Accretion - Ejection

Blandford-Znajek (*B*-field in ergosphere) or Blandford-Payne (*B*-field in disk)?

Jet composition: Baryons & Leptons

Pure e^+/e^- jet excluded for stability but which e/p ratio, and baryon origin?

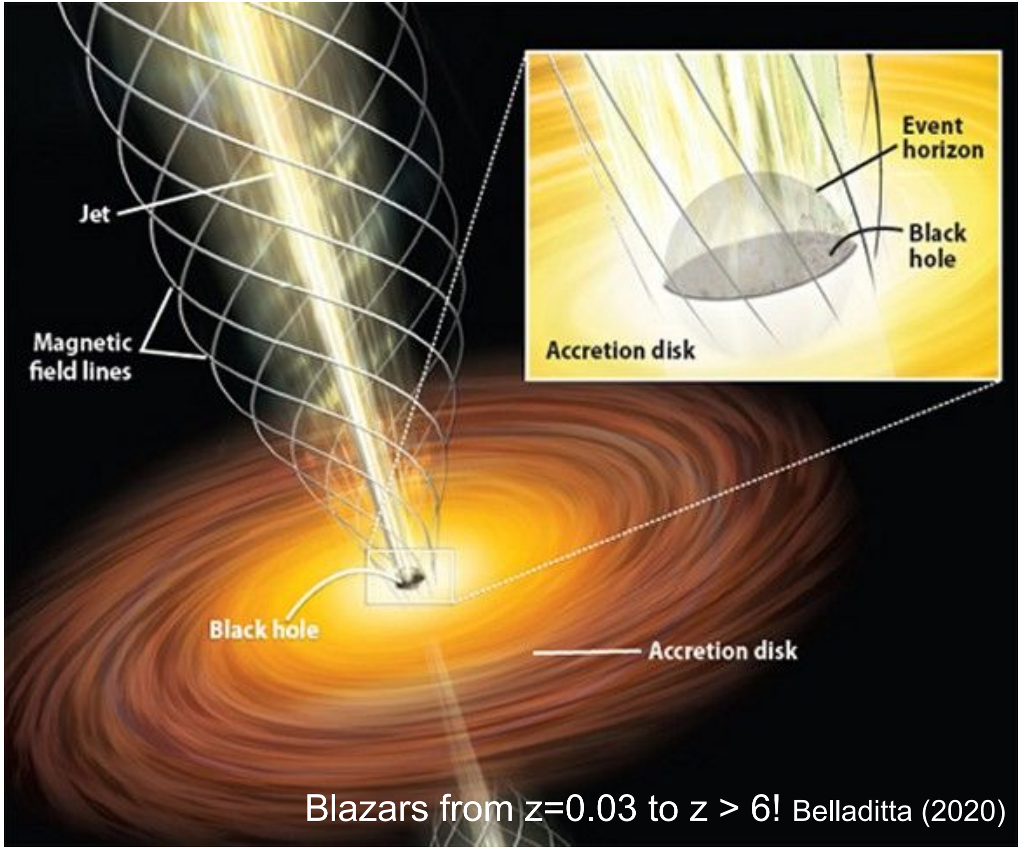
Jet bulk acceleration

Poynting dominated at basis → bulk motion at $\Gamma \sim 10$ beyond pc scales

Particle acceleration

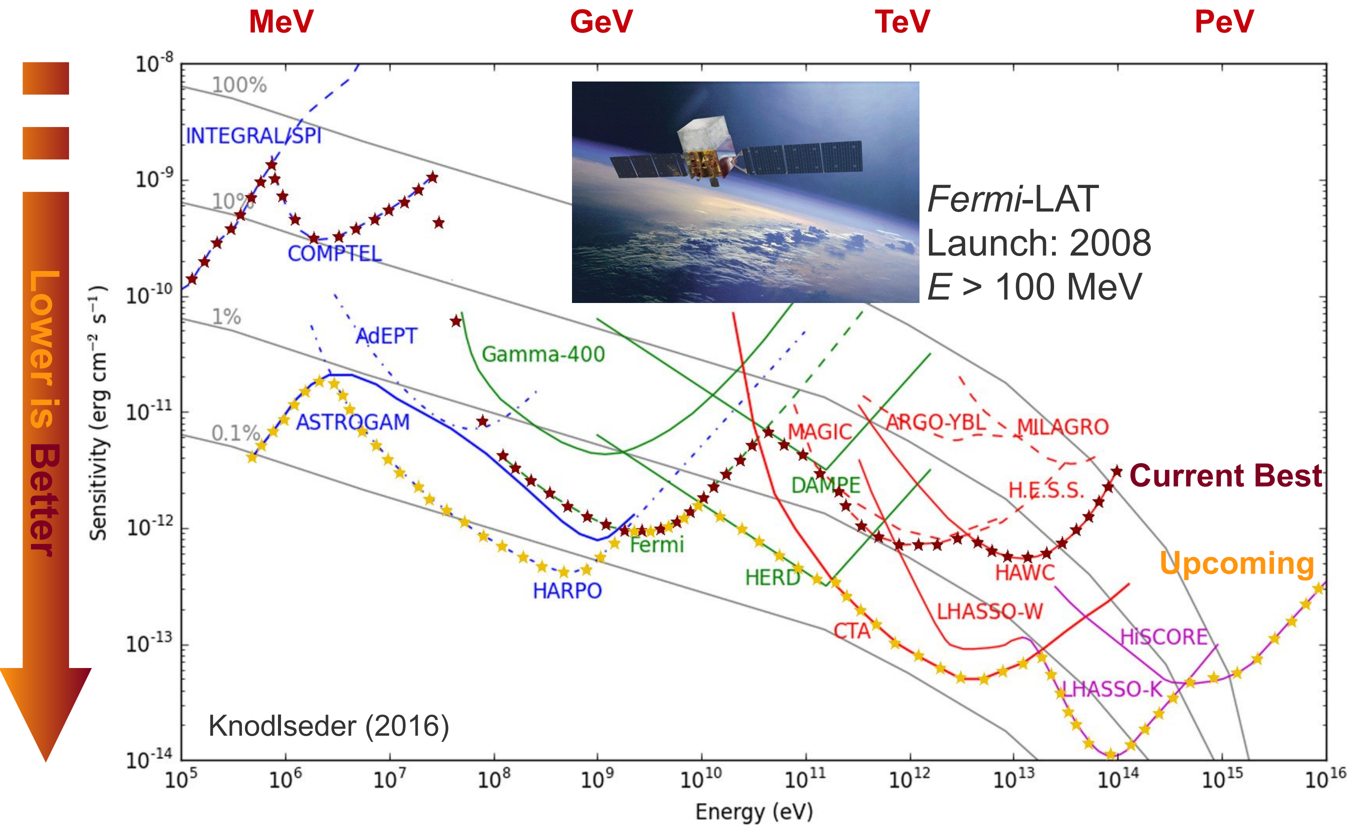
Transfer of magnetization / bulk motion to leptons (& baryons?) up to $\gamma > 10^5$:

- Shock acceleration?
- Magnetic reconnection?
- Others?

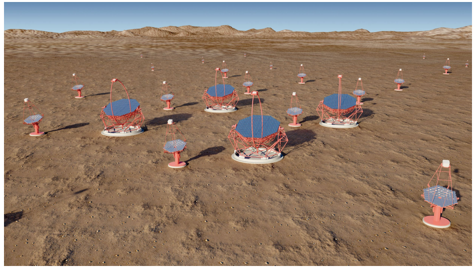


Extreme observational properties of blazars

Probing the gamma-ray emission of blazars



H.E.S.S.
Start: 2004 (CT1-4), 2012 (CT5)
$E > 100$ GeV



CTA
Early science: 2023
$E > 20$ GeV

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

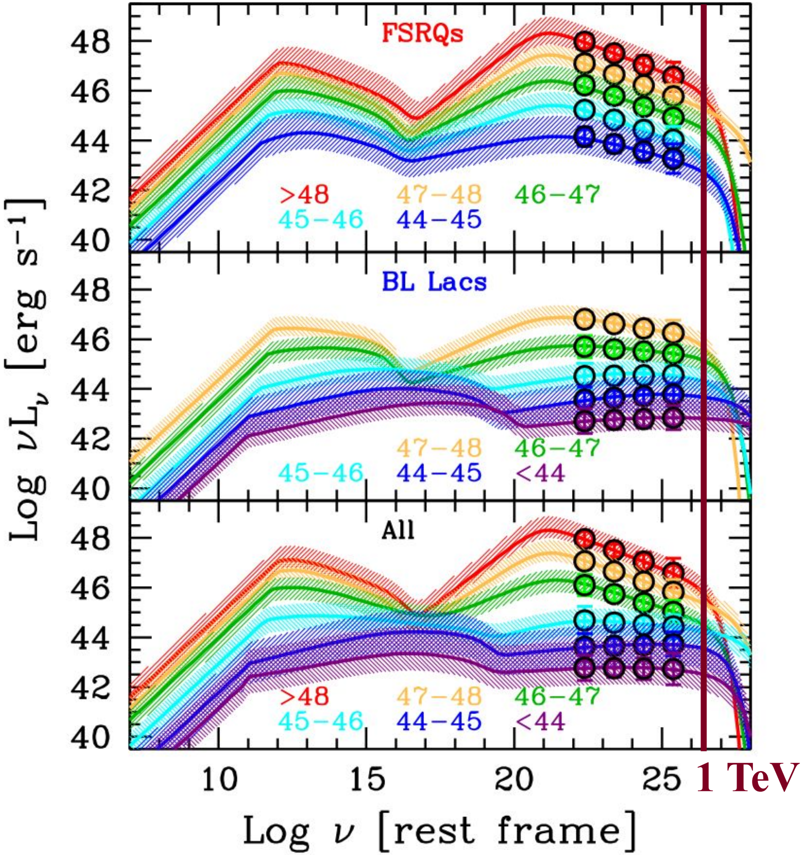
- Inferred anti-correlation of peak power with peak frequency
- Initially: (biased?) X-ray/radio selection Fossati et al. (1998)
- Confirmed with Fermi-only selection Ghisellini et al. (2017)

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

Extreme blazars

The high-energy frontier of the sequence

Ghisellini et al. (2017)

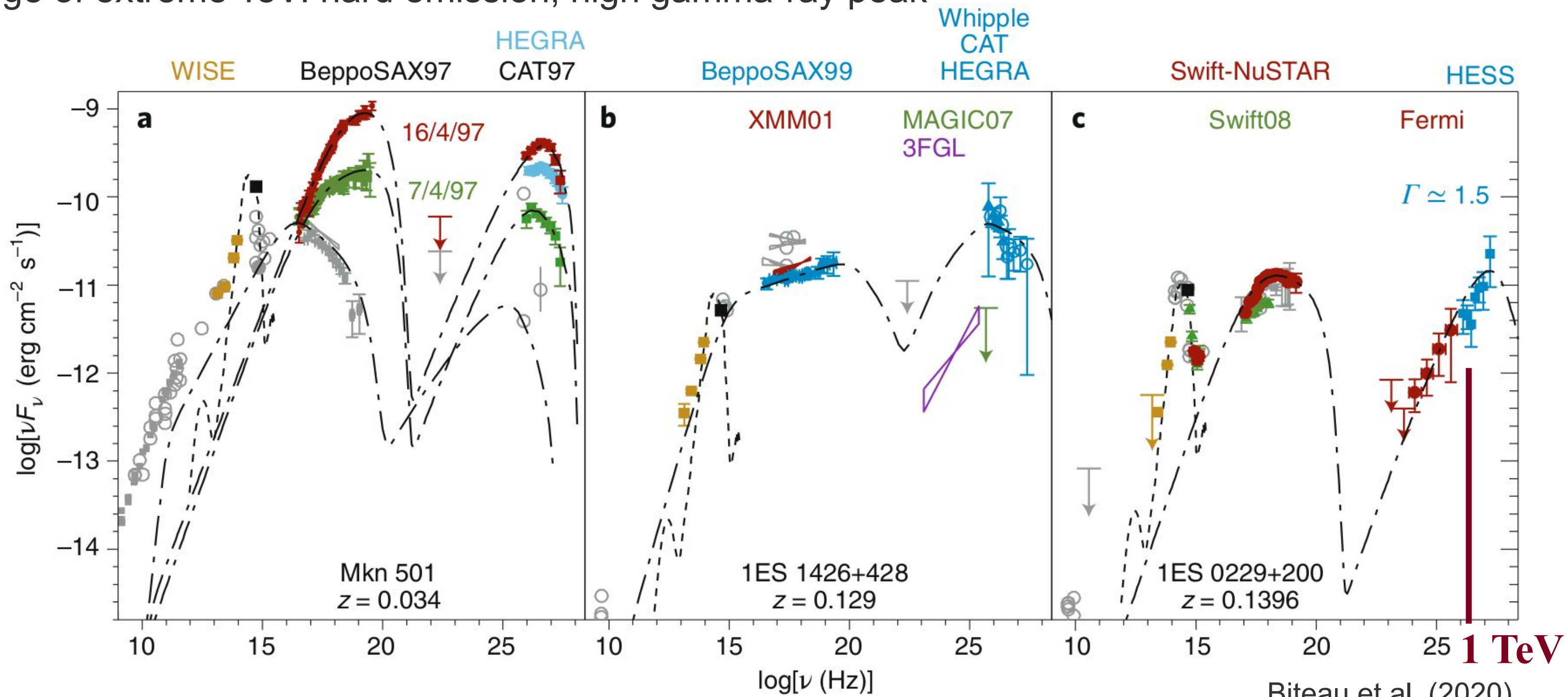


Broad-band emission of extreme blazars

Extreme-synchrotron & extreme-TeV blazars

Extreme blazars: synchrotron peak ν ≥ keV (~2x10^{17} Hz) OR gamma-ray peak ν ≥ TeV (~2x10^{26} Hz)

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



Biteau et al. (2020)

Broad-band emission of extreme blazars

Extreme-synchrotron & extreme-TeV blazars

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

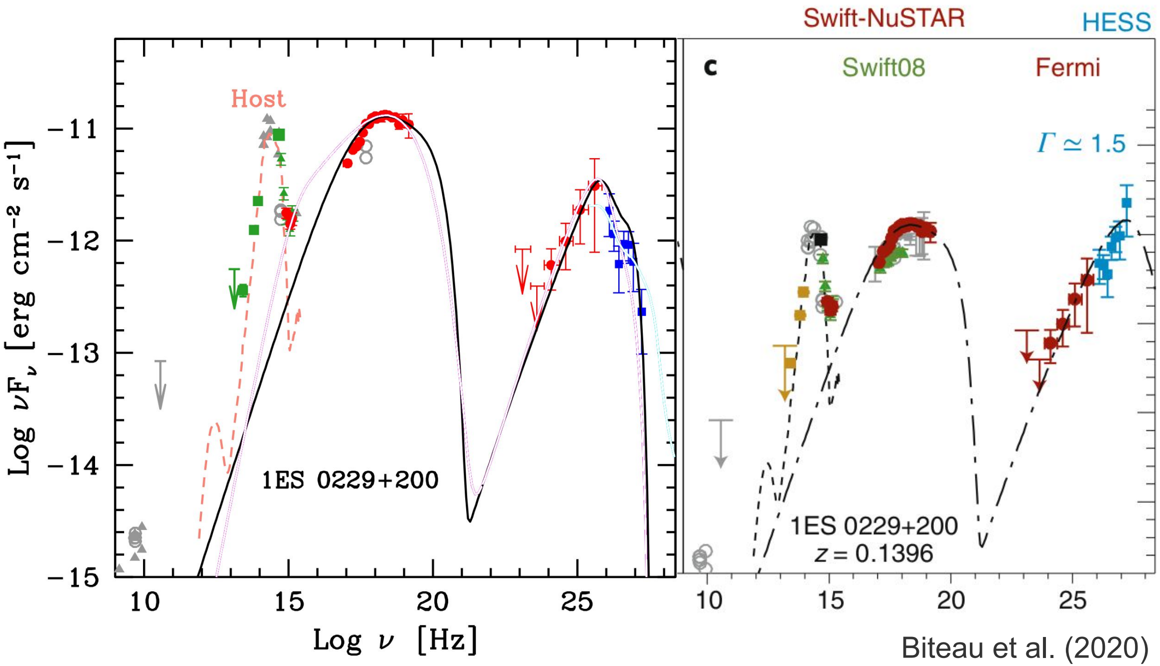
Observed ≠ Intrinsic

- X-rays: photoelectric abs.

→ sharp transitions, relatively easy to extract from fit

- gamma-rays: pair production

→ smooth absorption with energy, order of magnitude uncertainty on target photon field 10 years ago.

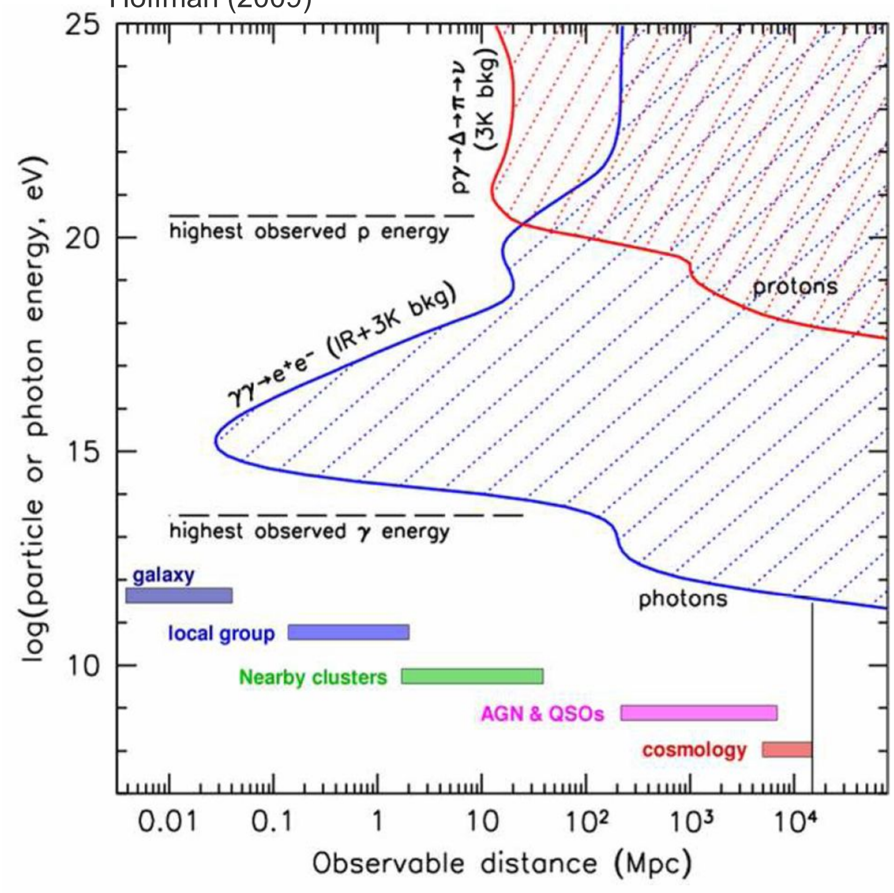


Biteau et al. (2020)

From observations to intrinsic emission: gamma-ray cosmology

Cosmic-ray horizon and γ-ray imprint

Hoffman (2009)

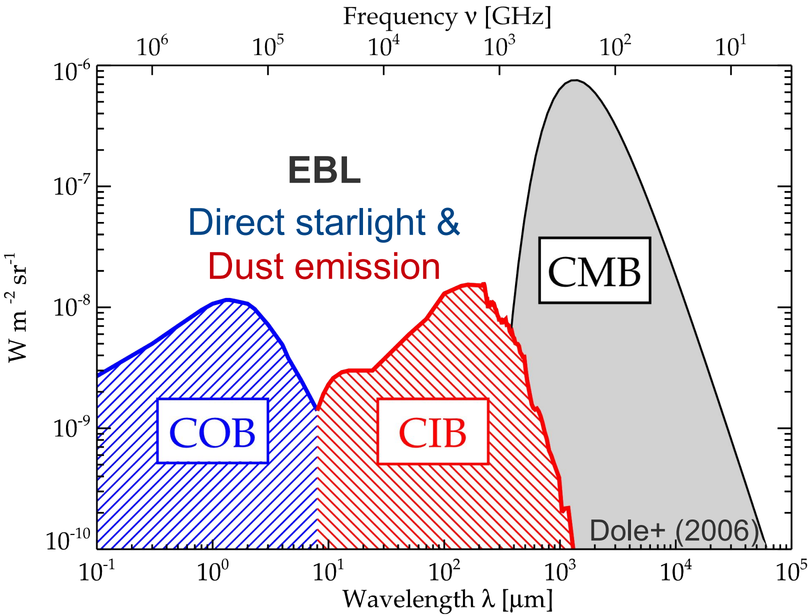


p + γ(EBL/CMB)→ p/n + π (or p + $e^{+/-}$)

→ $2m_p m_\pi / 4E_{EBL/CMB}$ ~ **50 EeV** x ($\lambda_{CMB / EBL}$ / **1000 μm**)

γ + γ(EBL/CMB) → $e^+ e^-$

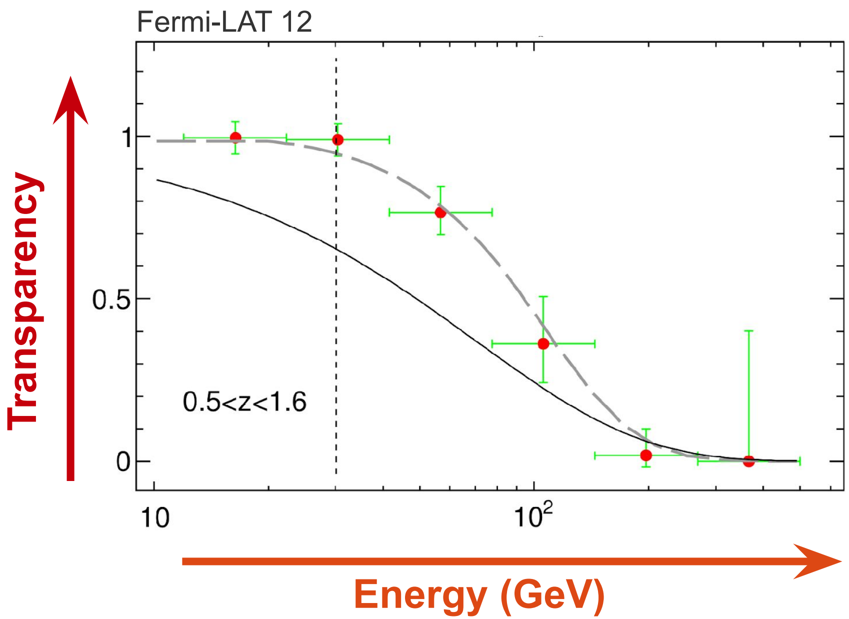
→ $(2m_e)^2 / 4E_{EBL/CMB}$ ~ **1 TeV** x ($\lambda_{CMB / EBL}$ / **1 μm**)

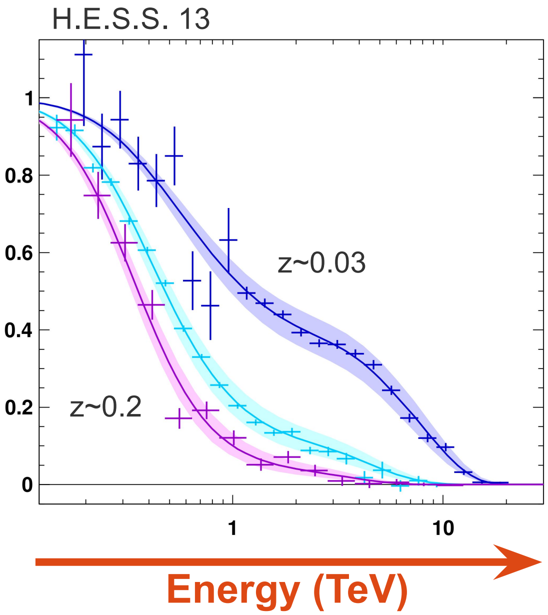


Reconstruction of EBL imprint

Example of model dependent approaches

- Reconstruct normalization α of EBL optical depth wrt galaxy-counts models $\Phi_{\rm obs} = e^{-\alpha\tau(E_0,z_0)}\,\Phi_{\rm intr}$
- Imprint now detected at > 11σ. α compatible with 1 (20-30% precision), i.e. inferred EBL ~ galaxy counts.





EBL constraining power vs redshift

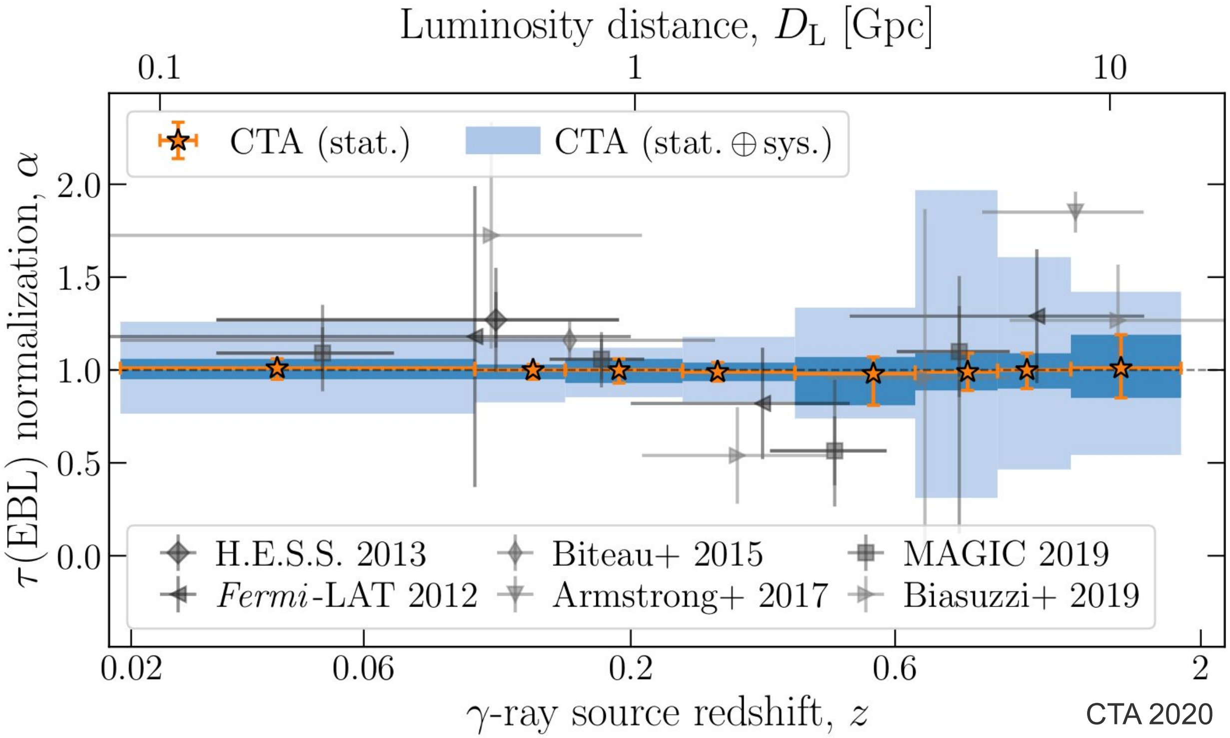
Current generation

- Ground-based telescopes dominant at $z < 1$
- Fermi-LAT dominant at $1 < z < 2$
- 1st constraints on Cosmic star formation rate, H_0, Ω_M

CTA

- Simulation of >800h of blazar observations
- Measurement up to $z < 2$
- Best precision at $z \sim 0.2$: $\pm 5\%_{(stat)}$ $\pm 12\%_{(syst)}$

Constraints limited by instrument systematics



CTA 2020

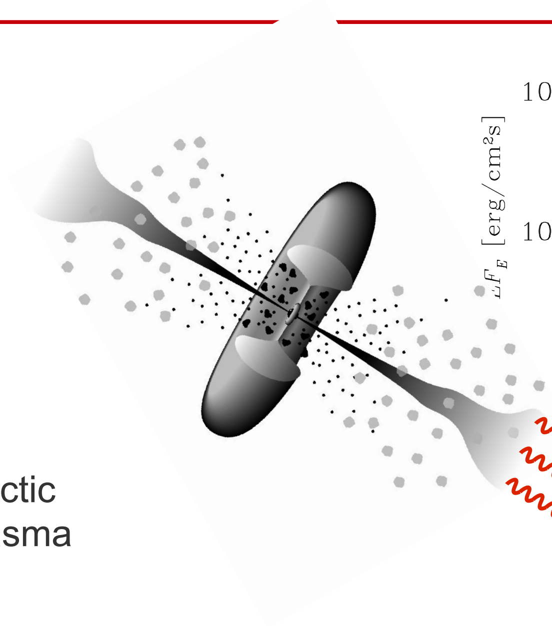
γ-ray cascades in magnetic fields

Secondary γ rays

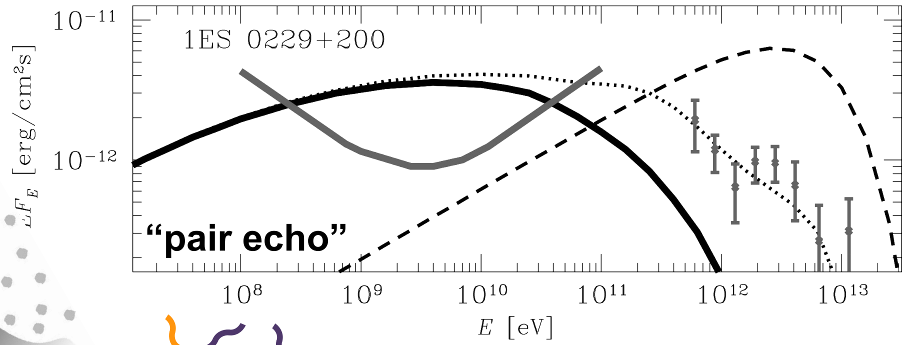
Fate of $e^{+/-}$ pairs:

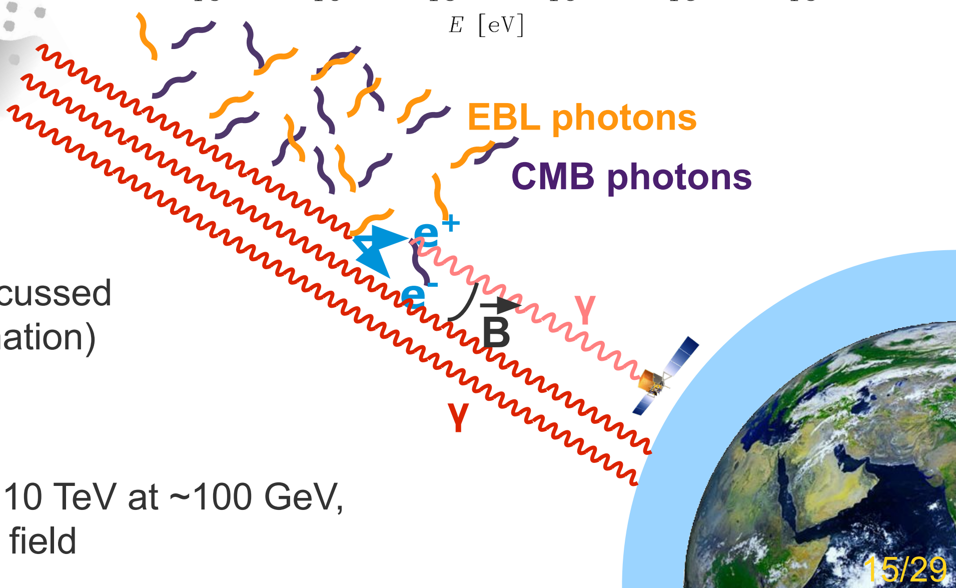
A) either upscatter
CMB photons

B) or heat the intergalactic
medium through plasma
instabilities



Neronov & Vovk 2010





Scenario B) viability for all/some sources remains discussed
→ heating of intergalactic medium (dwarf galaxy formation)
(Broderick+ 2012; Schlikeiser+ 2012; Miniati & Elyiv 2013;
Sironi & Gianios 2014; Vafin+ 2018; Alves Batista+ 2019)

If Scenario A), reprocessing of all absorbed energy > 10 TeV at ~100 GeV,
→ amplitude and angular extent depend on magnetic field

Constraints on cosmic magnetic fields

IGMF origin

• Either of astrophysical original (pollution from outflows) of first-order primordial phase transition

• IGMF seed needed to explain μG central fields observed in galaxies & galaxy clusters

Current generation

• Ground-based: no extended component
→ fG range excluded

• Fermi-LAT: no extension + no GeV bump
→ sub-fG range excluded

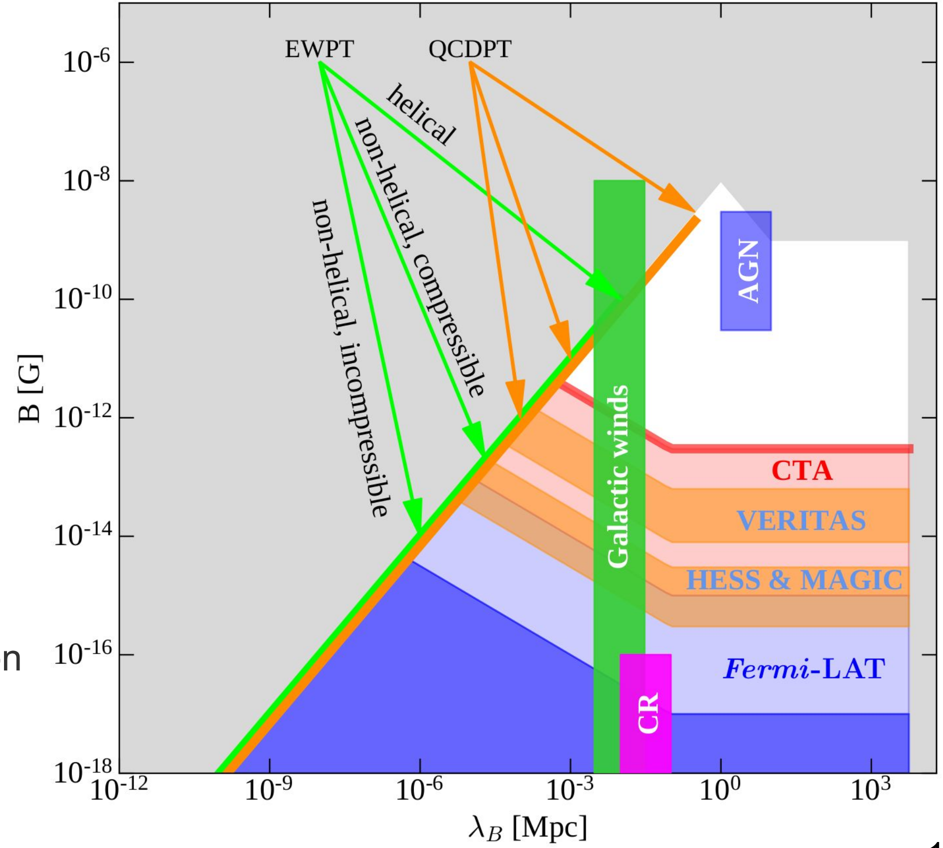
CTA

• Simulation of ~50h of extreme blazar observation

• 5σ detection possible up to nearly 1 pG

Constraints limited by blazar activity time scale

CTA 2020



Extreme-TeV blazars probing fundamental physics

Exoticas affecting gamma-ray propagation

• Axion-like particles (ALP): ~ QCD axions with free photon coupling, couple to gamma rays within *B*-field.

• Lorentz Invariance Violation (LIV): modified dispersion relation → modified pair-creation threshold → universe virtually gamma-ray transparent > 10s TeV

ALP signatures

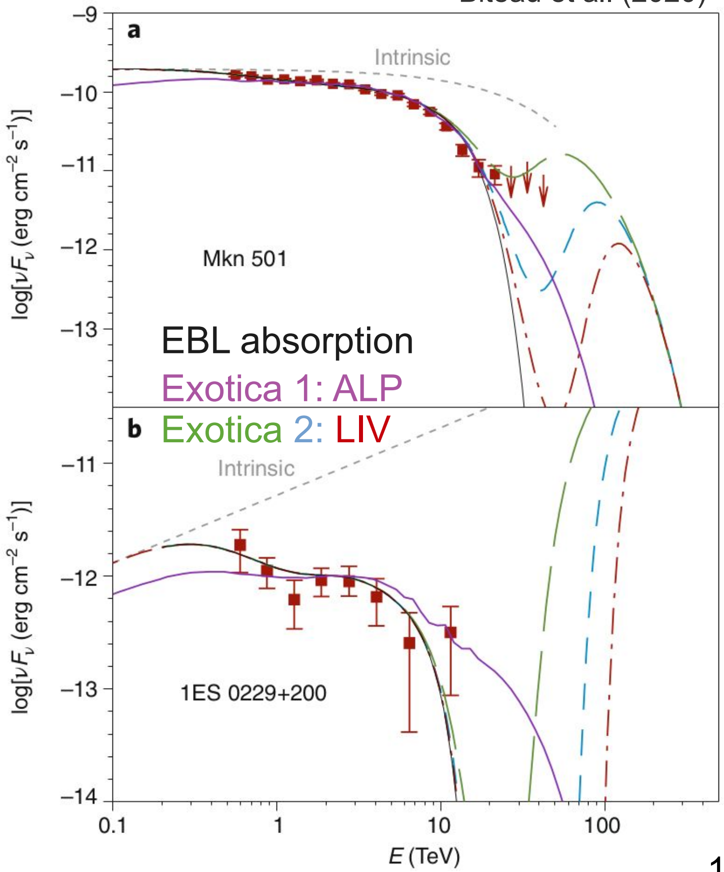
• Propagation as ALP instead of gamma rays: increased transparency at high optical depth

• Strong-mixing regime: oscillatory features imprinted on gamma-ray spectra (strongest bounds to date)

LIV signature

• Full transparency at high gamma-ray energies
→ 1st order modification: probe of Planck scale
→ 2nd order modification: probe of ZeV scale

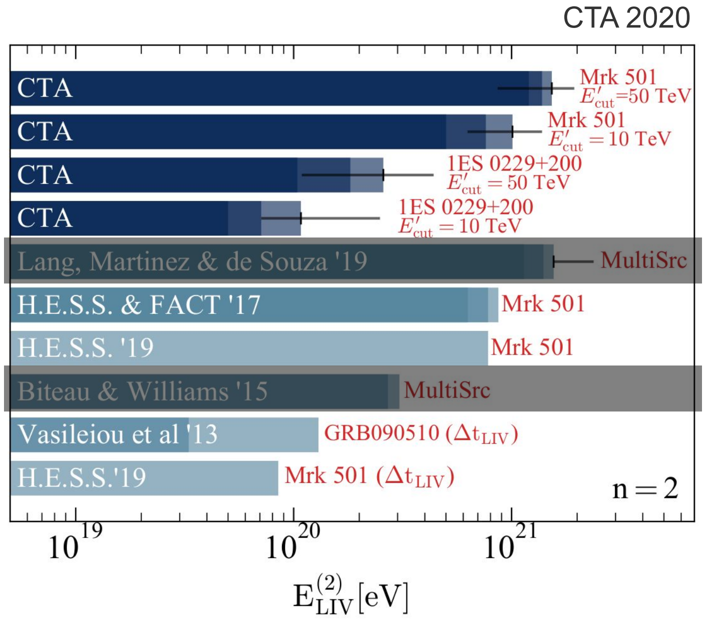
Biteau et al. (2020)

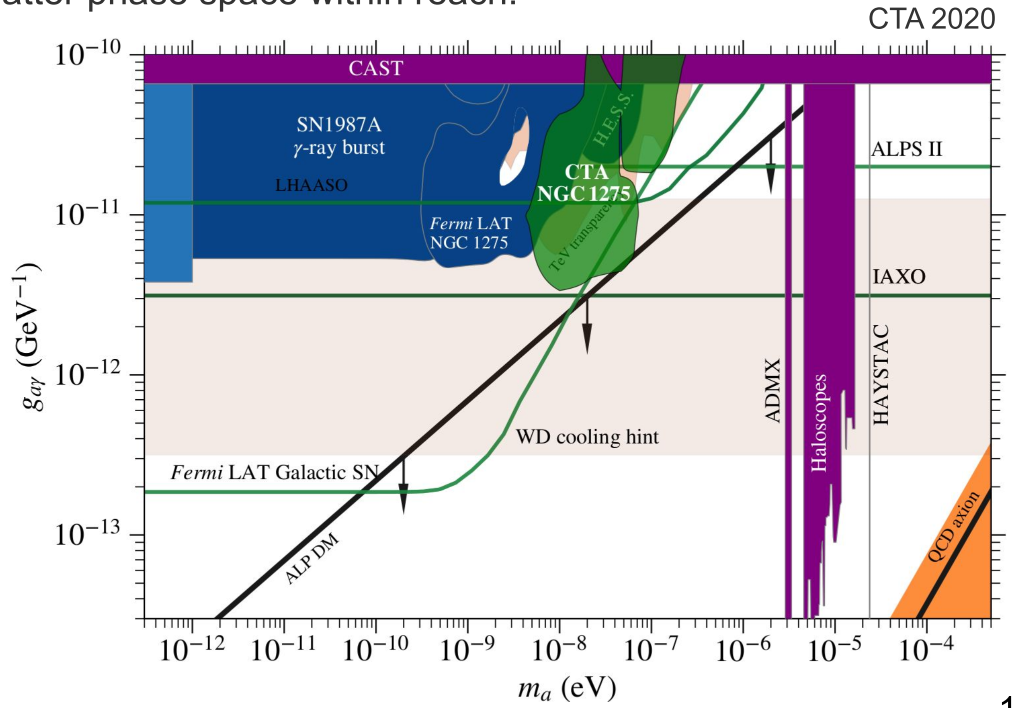


Current and future constraints on ALPs and LIV

No exotic effect observed thus far, but nice potential (tighter bounds) for CTA

- LIV: single-source simulations (10h-50h), factor of 2-3 improvement wrt H.E.S.S.
- ALP: single source simulation (10h), dark matter phase space within reach!



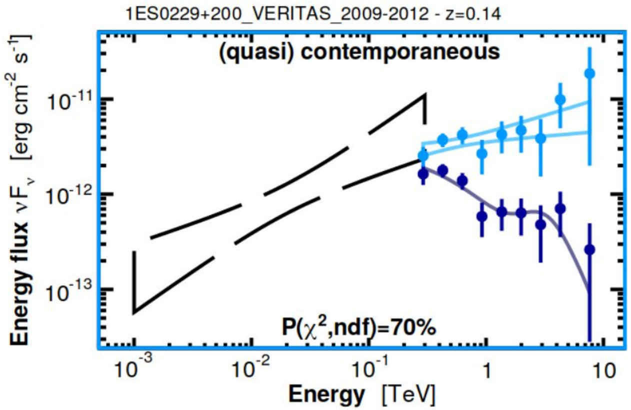


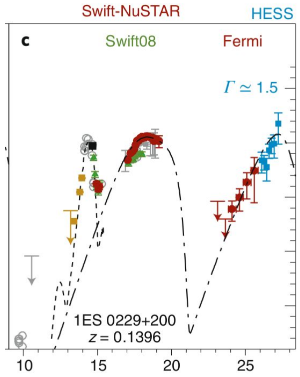
Challenges in modeling extreme blazars: multi-messenger emitters?

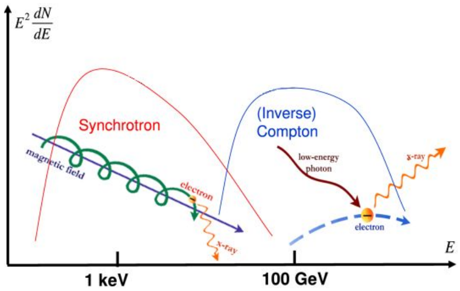
Astrophysics of blazars

Inference approach:

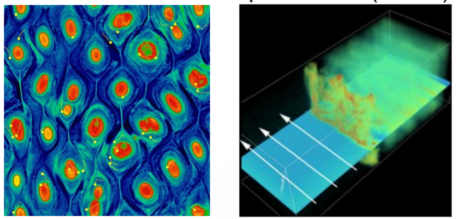
Near-infrared to TeV Observations → Intrinsic emission → Radiative model
→ parameters of parent particles (index, max energy): acceleration process
→ environmental parameters (size, bulk Lorentz factor, B-field): AGN model

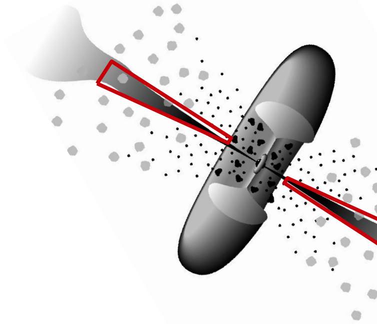






Sironi & Spitkovski (2011)





Urry & Padovani (1995)

Major challenge: bridging the micro- / macro-physics gap

→ Particle-in-cell acceleration simulations: at best 10,000 plasma skin depth
→ Blazar emission regions: 1mpc -1 pc (10^{15}-10^{18} cm)

>6 order of magnitude gap, radiative processes, environment properties

Recent example of advanced (beautiful!) model

Micro- & macro-physics in magnetic reconnection

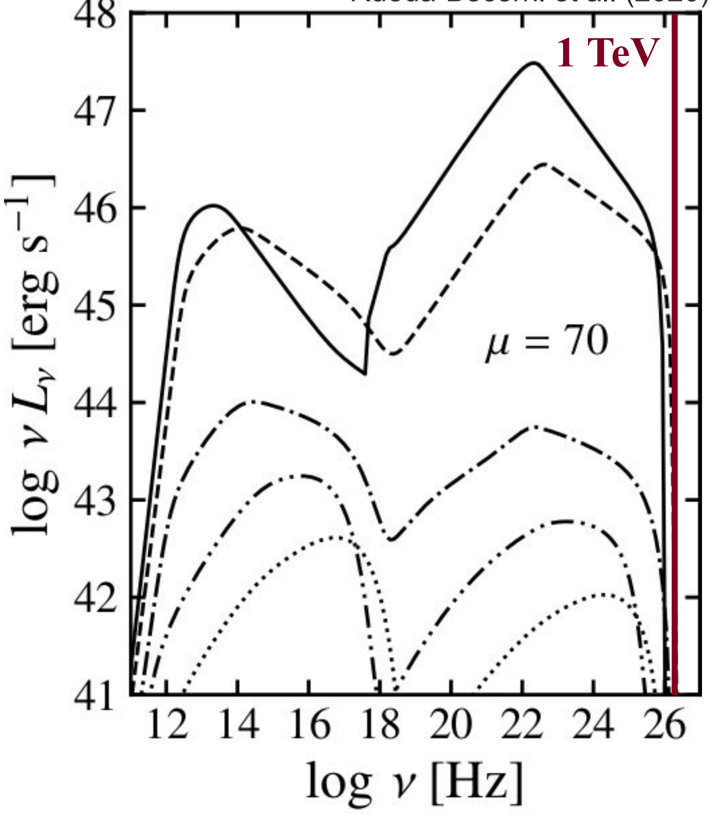
Observations: bulk Lorentz factor, Γ → Accretion rate, Jet power

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 (index - synchro peak correlation)
- Power↘ - Frequency↗ = Γ↘, low σ↗, p↘ (harder) & vice-versa

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*

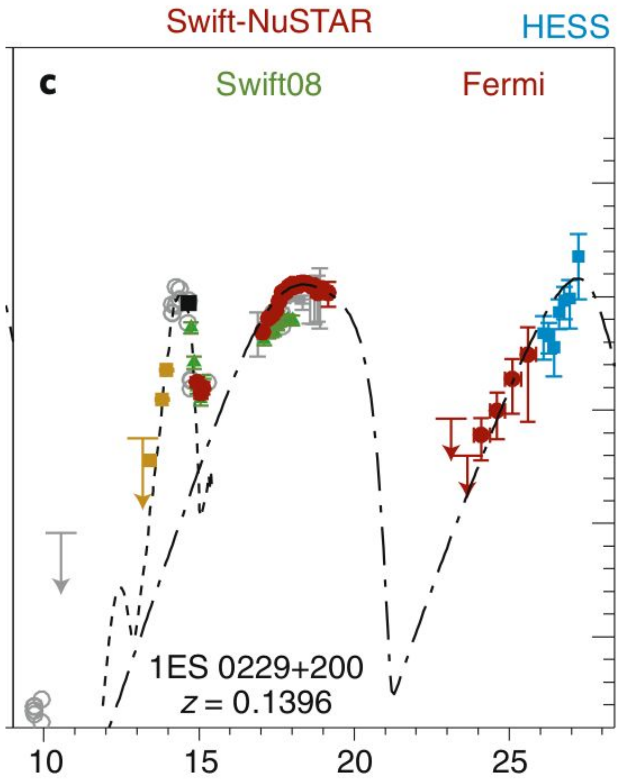
• Gamma-ray peak = Synchrotron self Compton

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 (gamma-ray peak, mostly ok if steady source)

• γ-rays from proton synchrotron, with p~1.3-1.7 and $E_p > 10^{19}$ eV $(B/100G)^{-1/2}$

→ *jet close to Eddington accretion limit*

• line-of sight cascade from UHECR

→ *GeV emission remains to be explained*

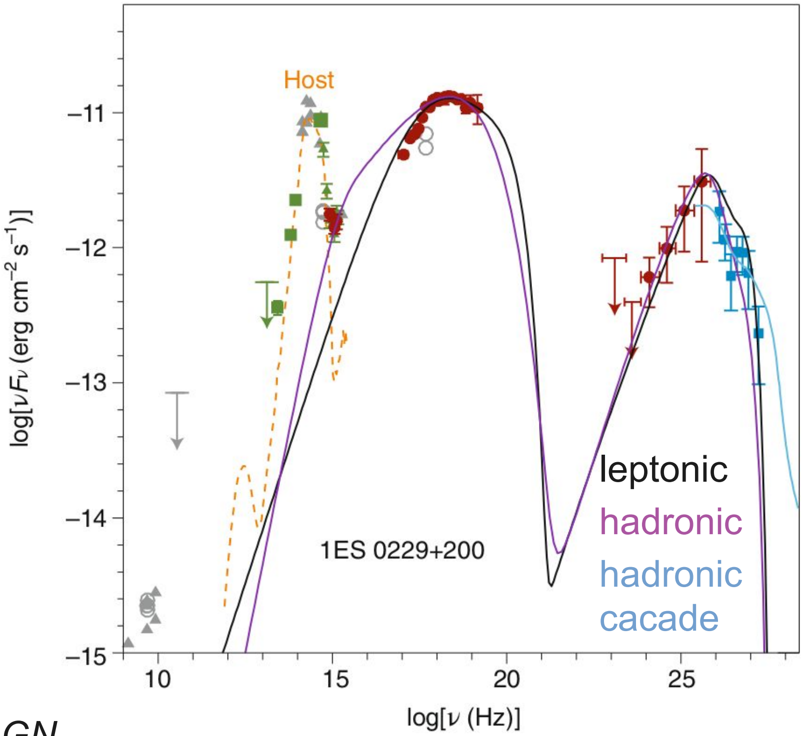
Escaping astroparticles

• Neutrino: flux beyond reach (pγ and pp sub-dominant)

• UHECRs: high synchrotron peak of extreme blazars: low t_{acc} / t_{Larmor} = fast accelerators

Extreme-TeV = best UHECR-source candidates among AGN

Biteau et al. (2020)

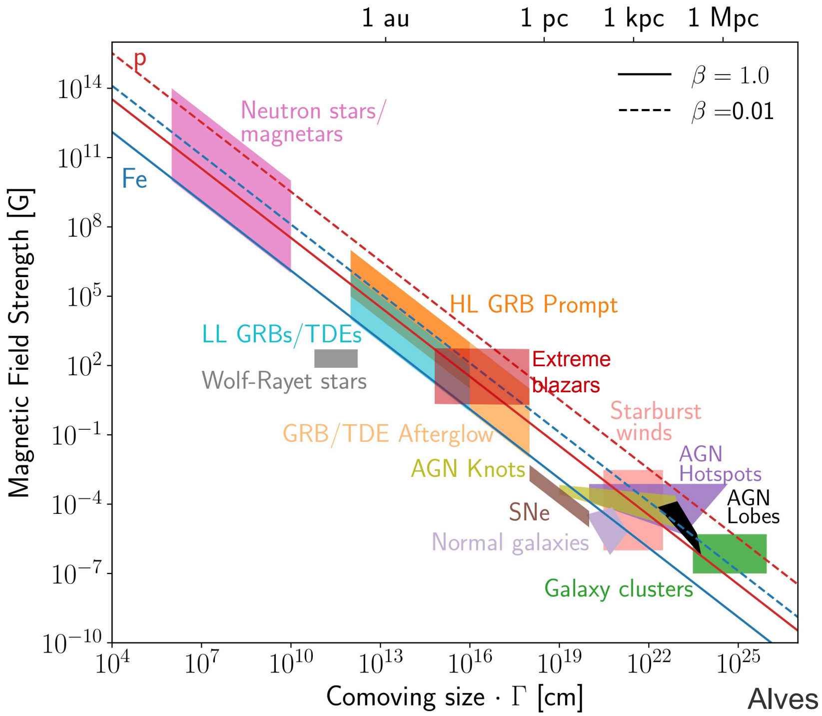


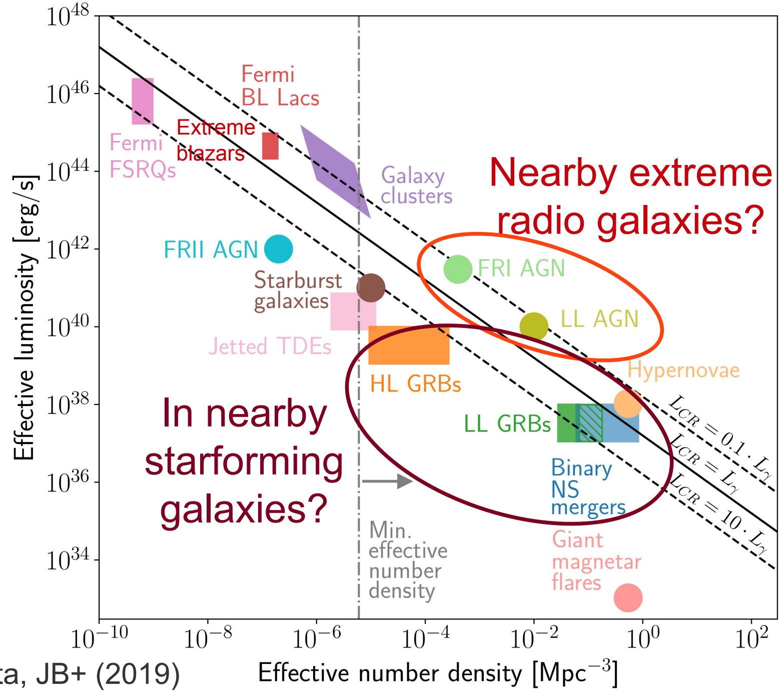
UHECR accelerators?

Extreme blazars and necessary conditions for being an UHECR source

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

→ *nearby extreme radio galaxies could do the job, need to accelerate heavy nuclei*



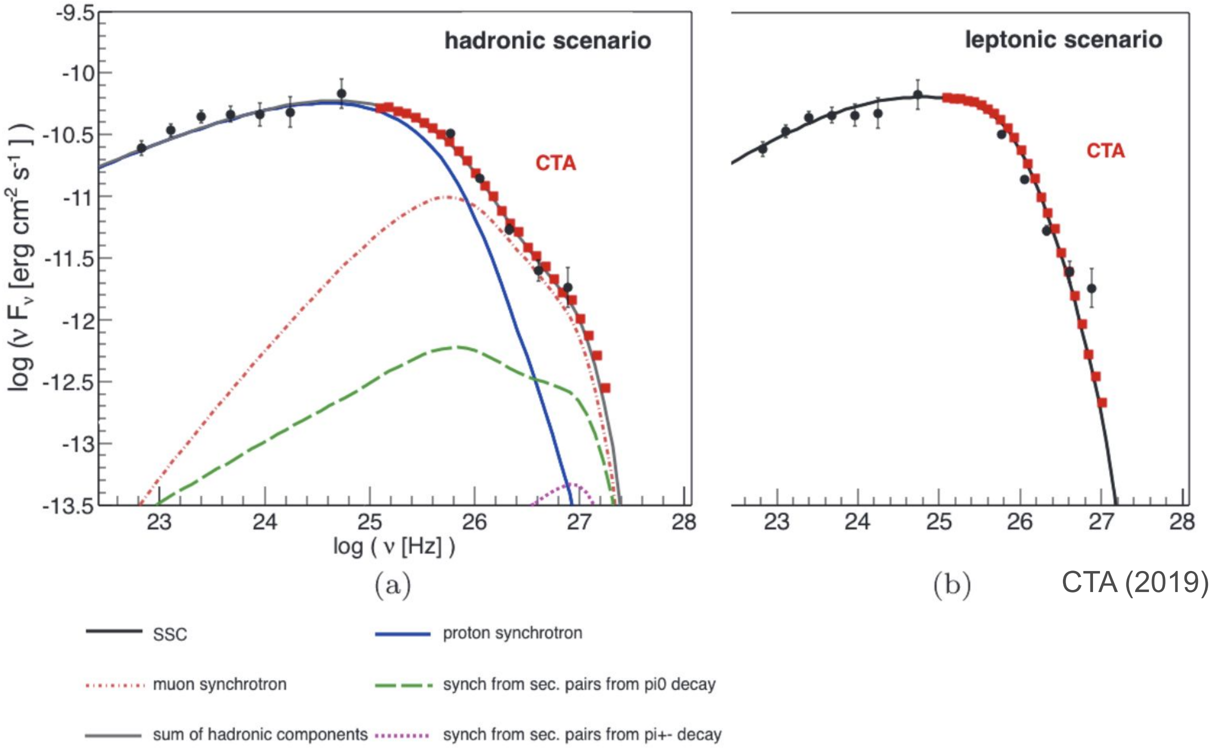


Alves Batista, JB+ (2019)

Tell-tale sign for UHECR acceleration with CTA

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

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



CTA (2019)

Observational roadmap:
CTA & multi-wavelength observatories

Upcoming synergies for extreme blazars

X-rays

• eROSITA: launched mid 2019, full-sky survey.

• IXPE: launch in 2021, polarimetry.

• SVOM/MXT: launch in 2021, successor of Swift-XRT.

MeV-GeV gamma rays

• AMEGO/e-ASTROGAM: launch? Crucial need to fill MeV gap.

GeV-TeV gamma-rays

• LHAASO & SWGO: start mid 2019 & ?, wide field of view.

• CTA: preliminary science in 2022, unprecedented sensitivity, survey of a quarter of the extragalactic sky.

IJC Lab: technical involvement in CTA-NectarCAM

Focal-plane calibration

• XY movable screen behind the camera window

• Single p.e. light pulses (~5 ns)
→ low intensity gain

• Lambertian reflector towards mirrors for optical point-spread measurement

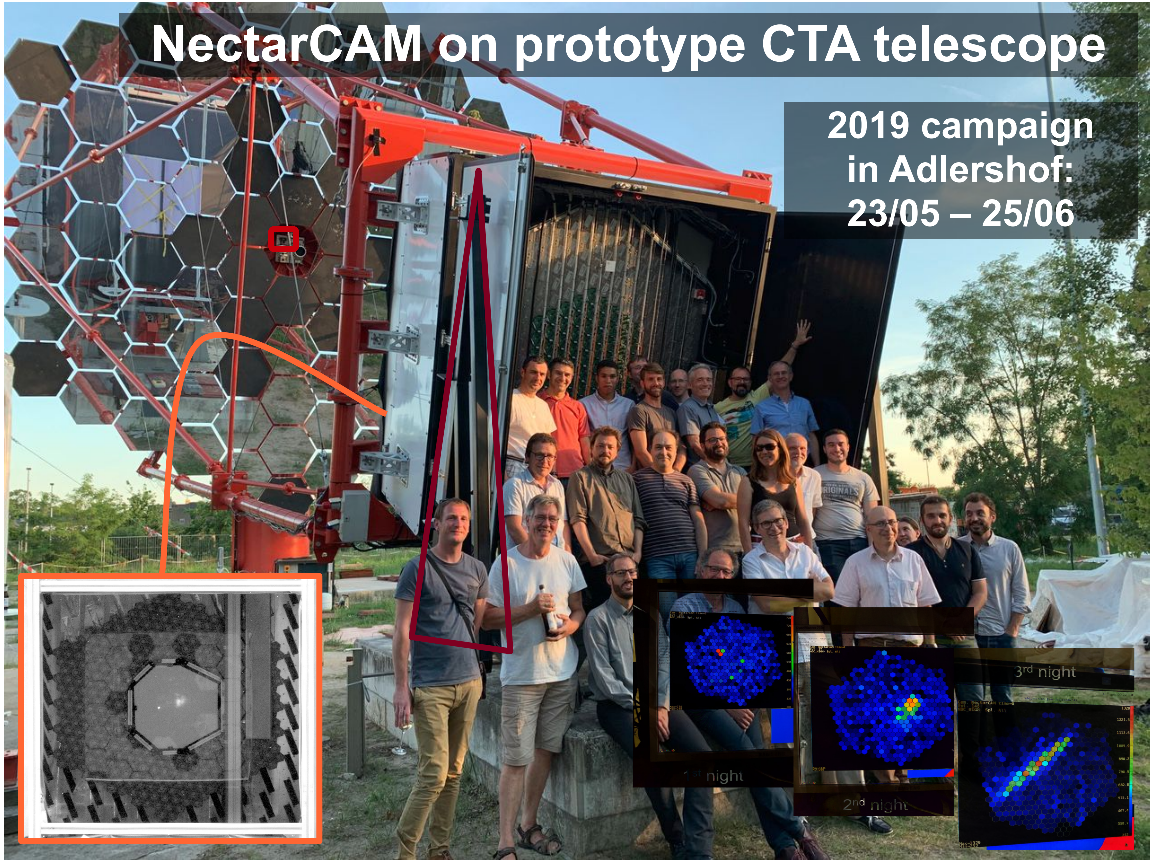
Flat-field light source

• Mechanical integration of LUPM boards + alignment system
→ high intensity gain

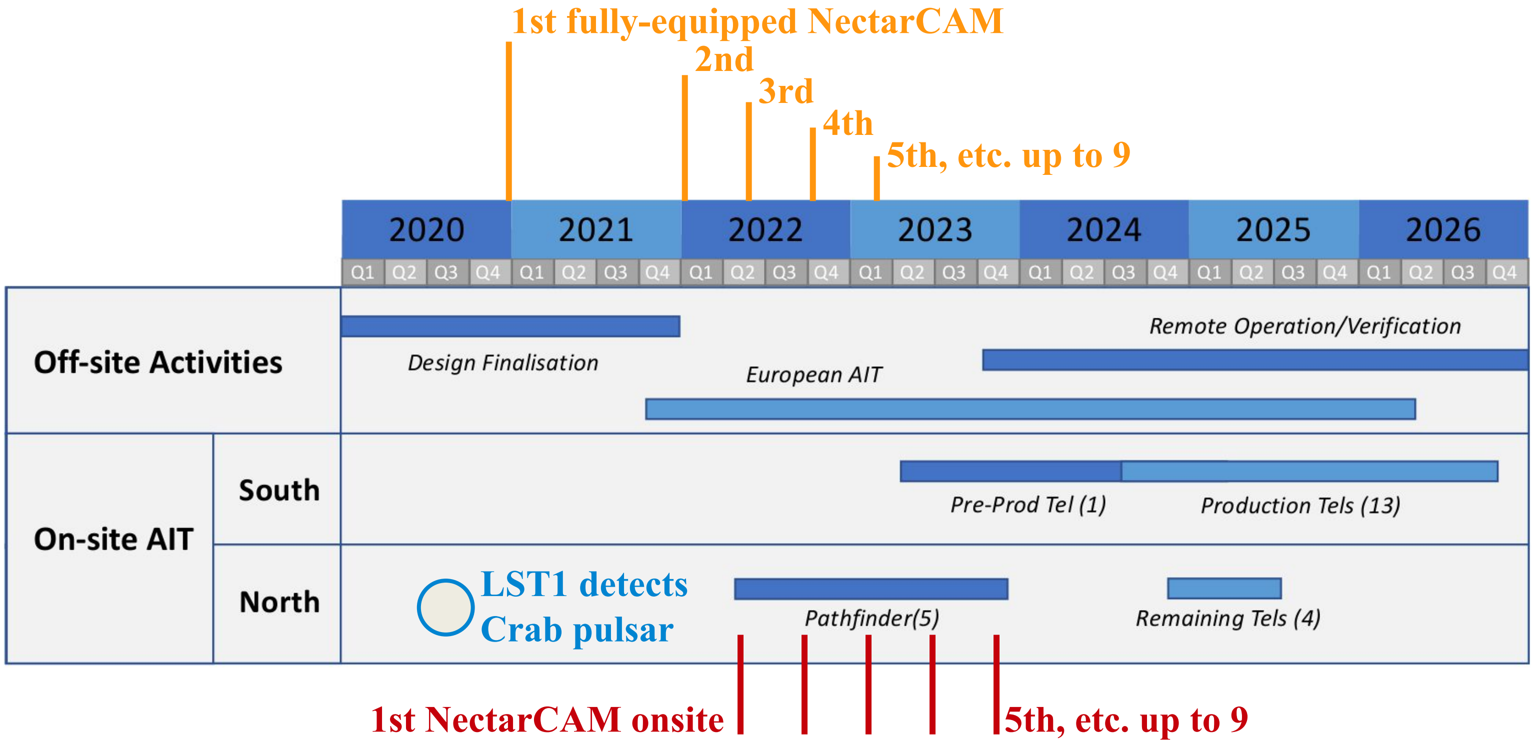
Camera mounting/maintenance

• Trolley - Telescope connection

• Onsite tent for annual check up



From camera integration to observations



2022: Observations with more than 2 telescopes begins. 2023: CTA > H.E.S.S. / MAGIC / VERITAS

- Goal: **data analysis, observation proposals**. A2C CTA-position ranking 👍. Collaborators welcome 🙂 !


The CTA-North Site: Our Northern Eye on the High-Energy Universe
A preview
La Palma
0:05 / 2:53
Scroll for details

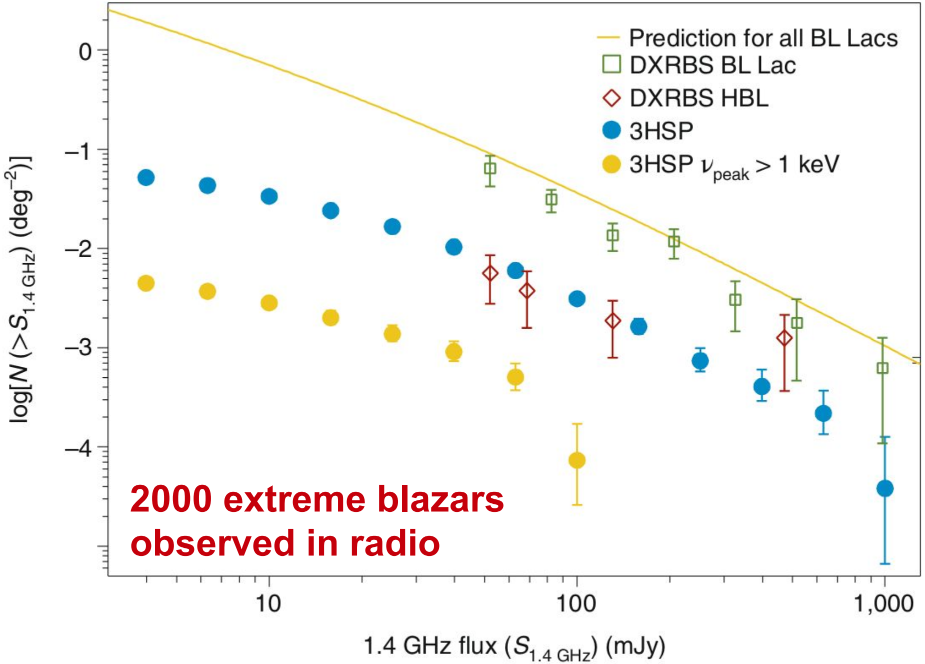
Backup slides

The population of extreme blazars

Breaking it down

- O(**1%**) of galaxies have an AGN
  - O(**10%**) of AGNs have jets
    - … proportion of BL Lacs?
      - O(**1%**) of BL Lacs are HBLs
        - O(**10%**) of HBLs are extreme

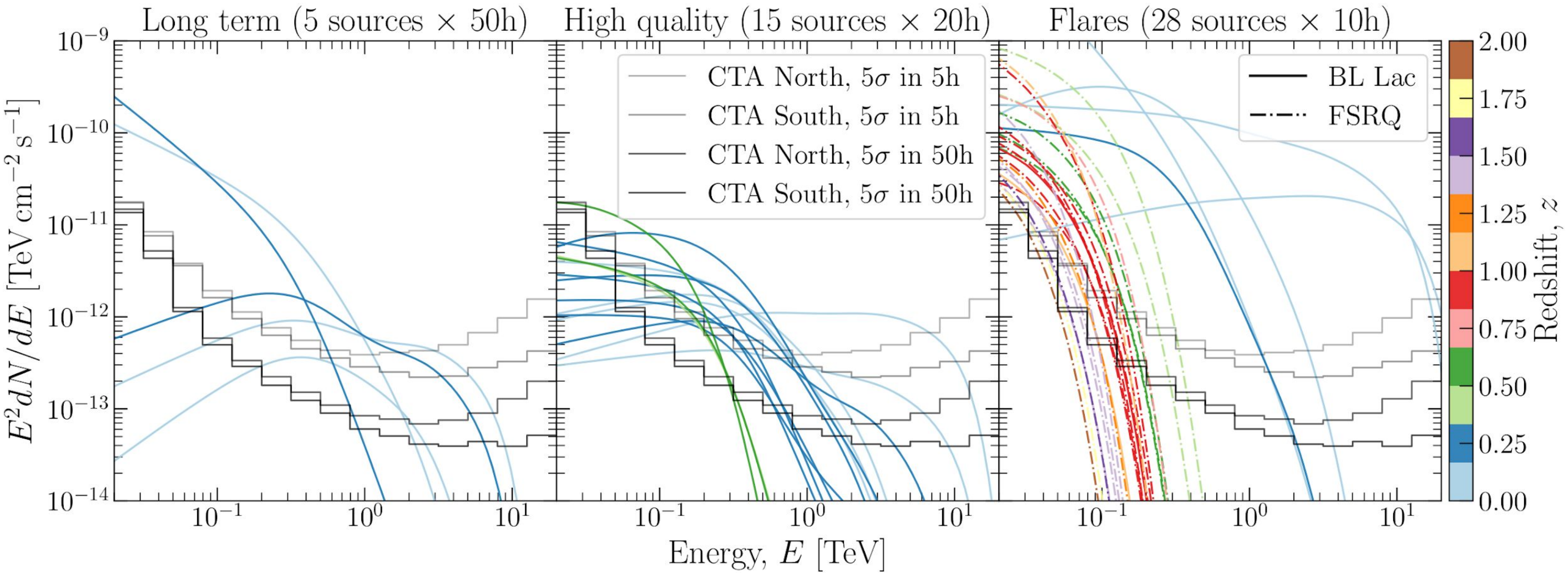
Biteau et al. (2020)



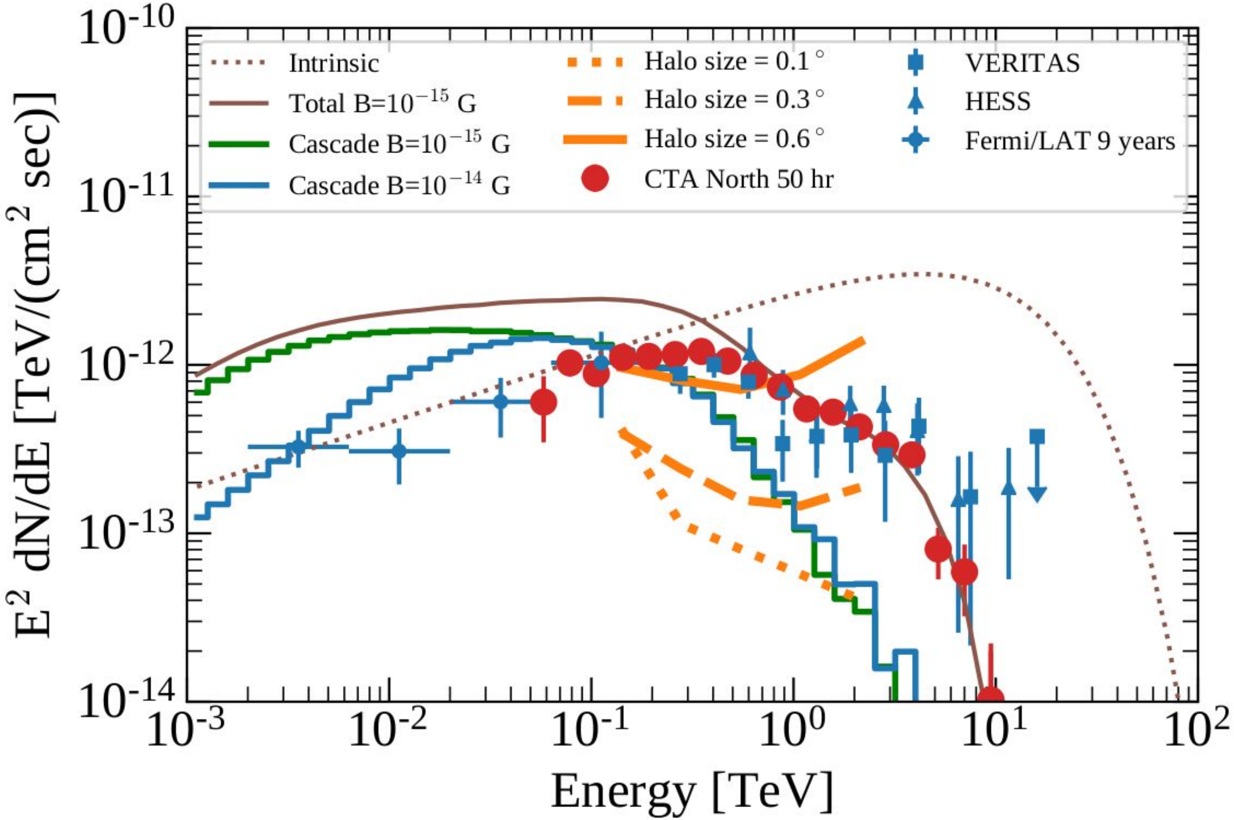
How do we know?

- Full-sky infrared surveys, with radio and X-ray follow-up observations
- Limitation: no large extragalactic survey with sufficient TeV sensitivity to characterize the extreme-TeV population

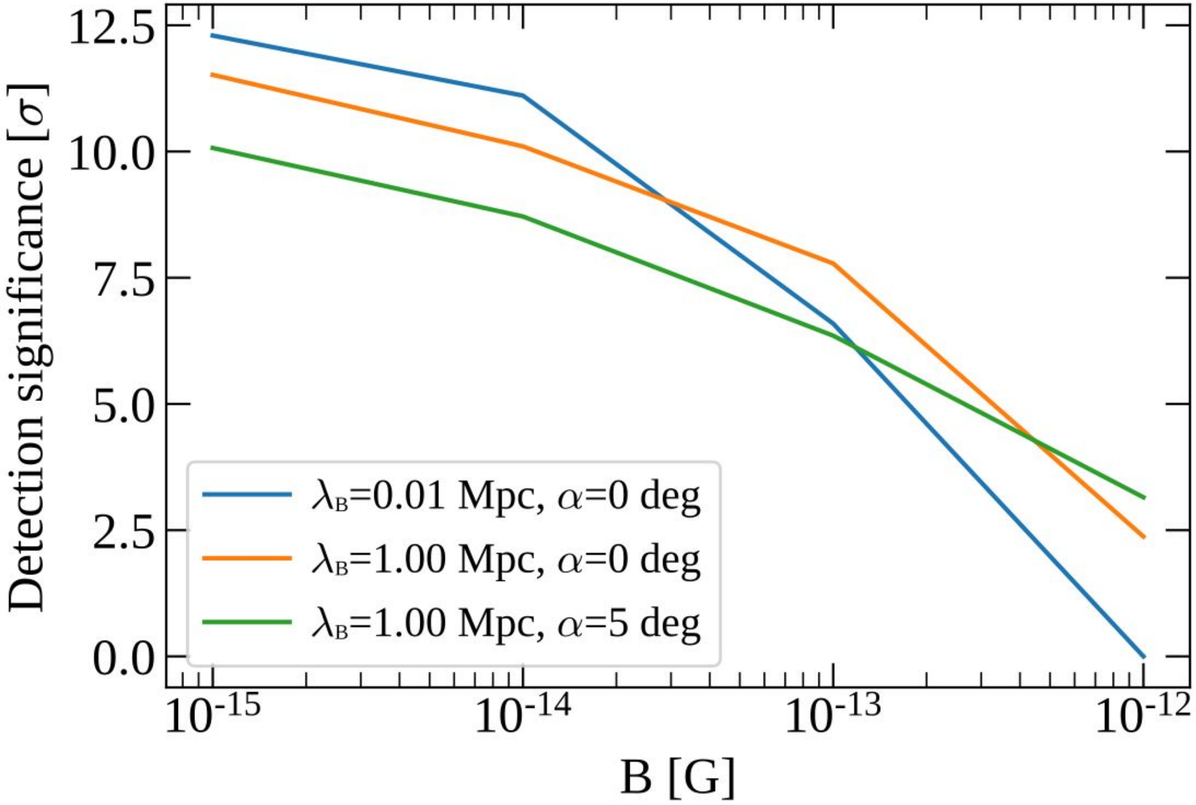
EBL absorbed spectra for CTA



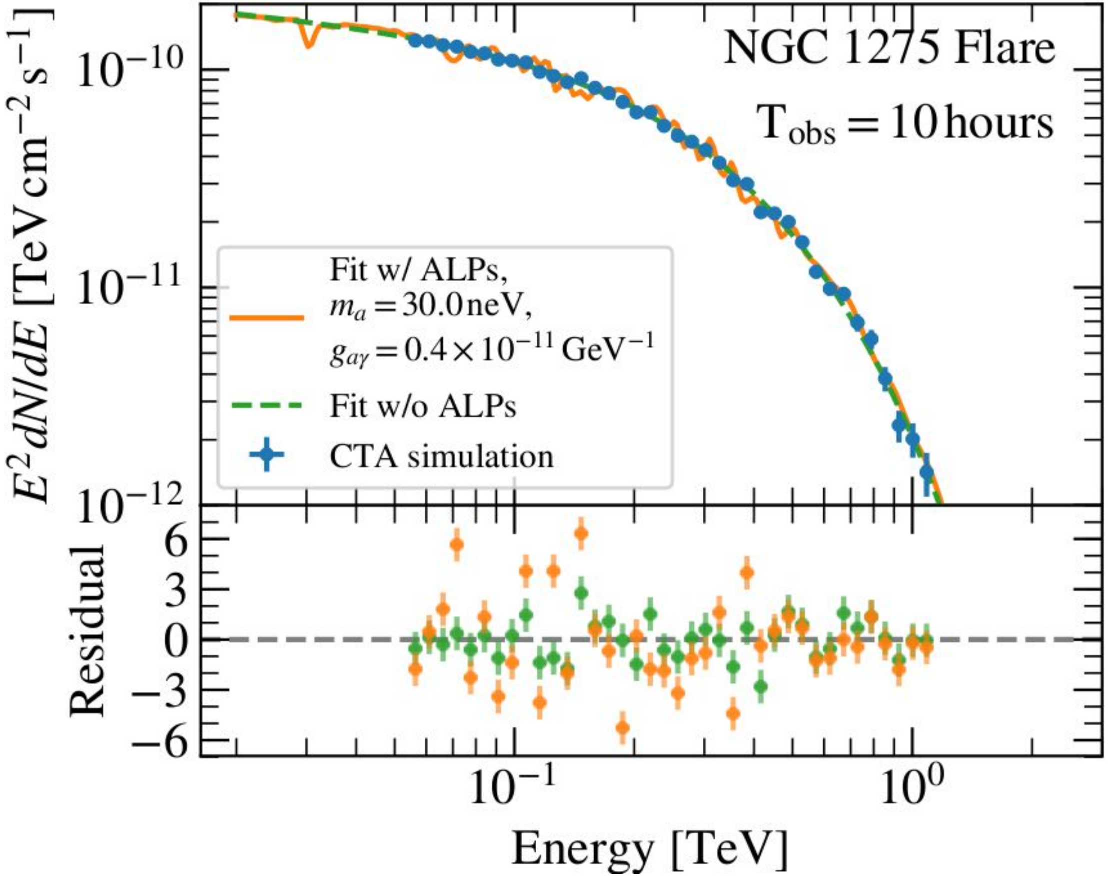
IGMF probe: simulated spectrum



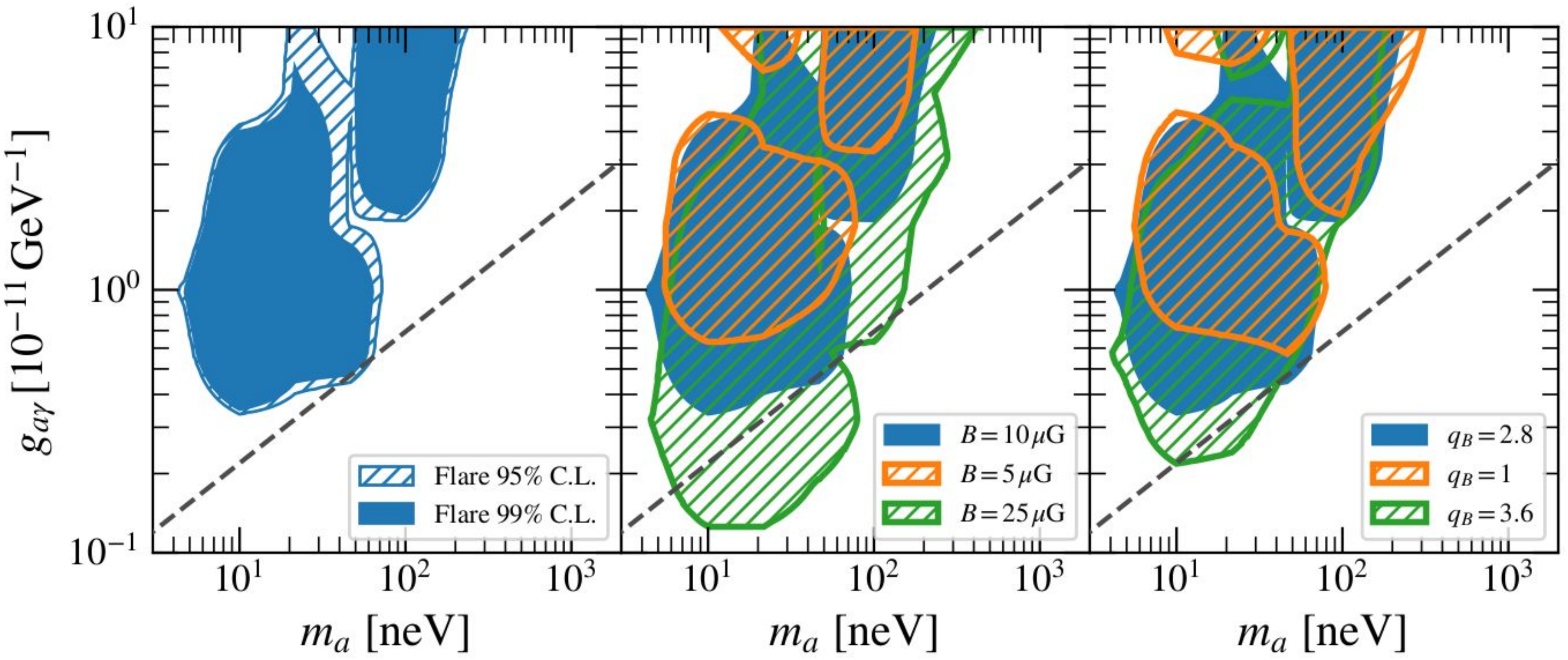
IGMF: impact of astrophysical parameters



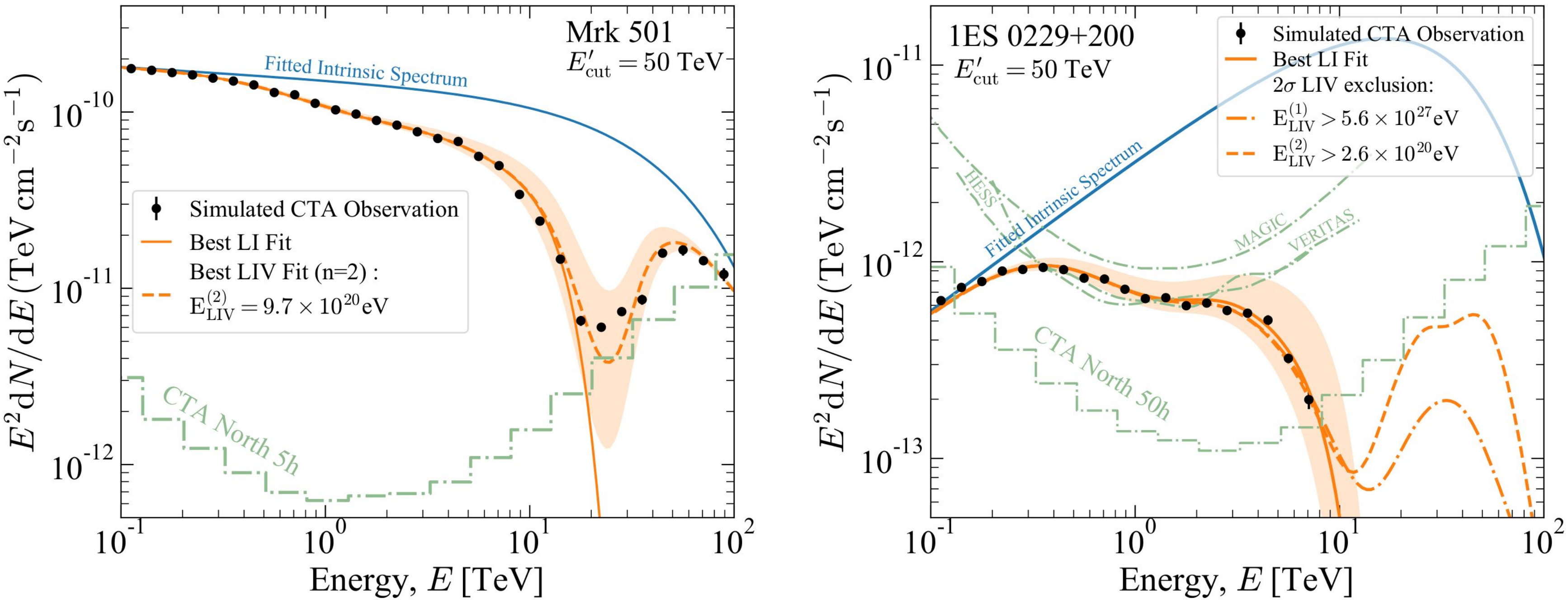
ALP: simulated spectrum



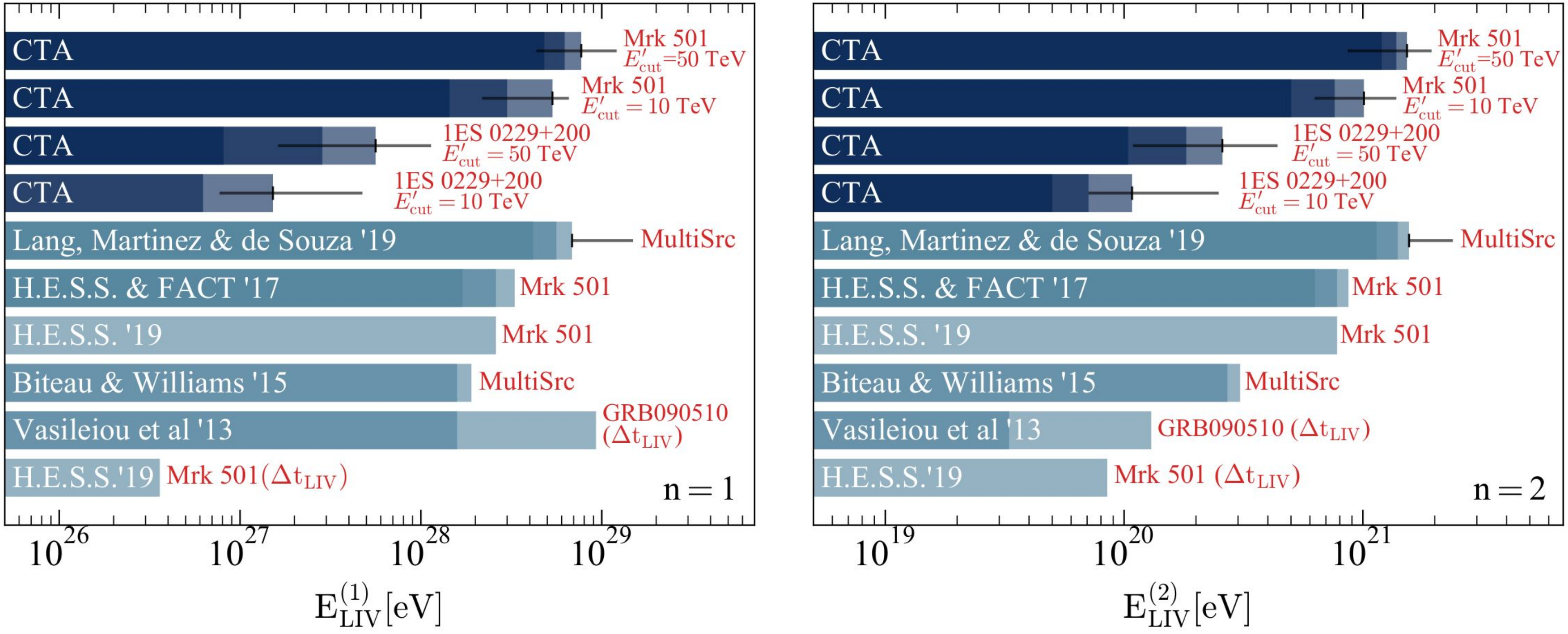
ALP: impact of astrophysical parameters



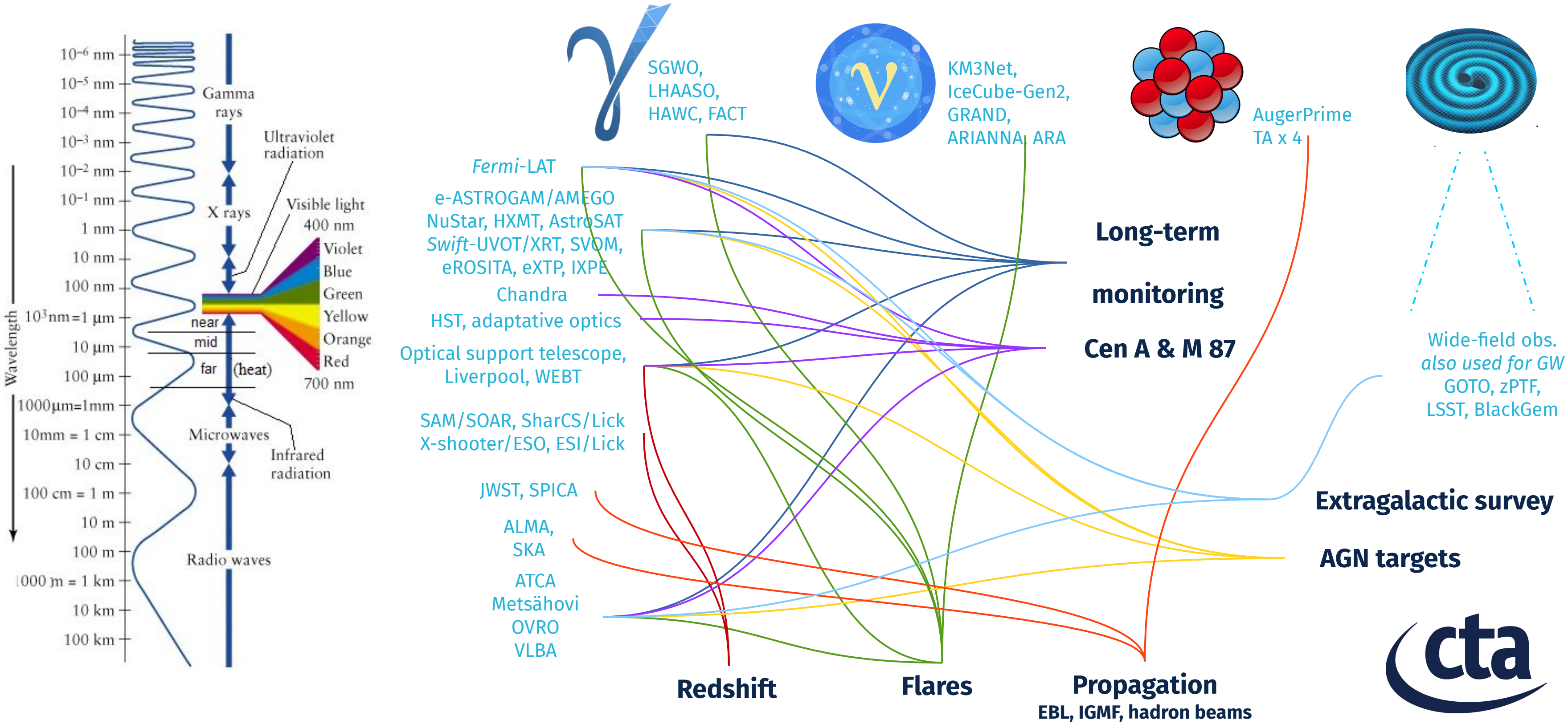
LIV: simulated spectra



LIV: constraints



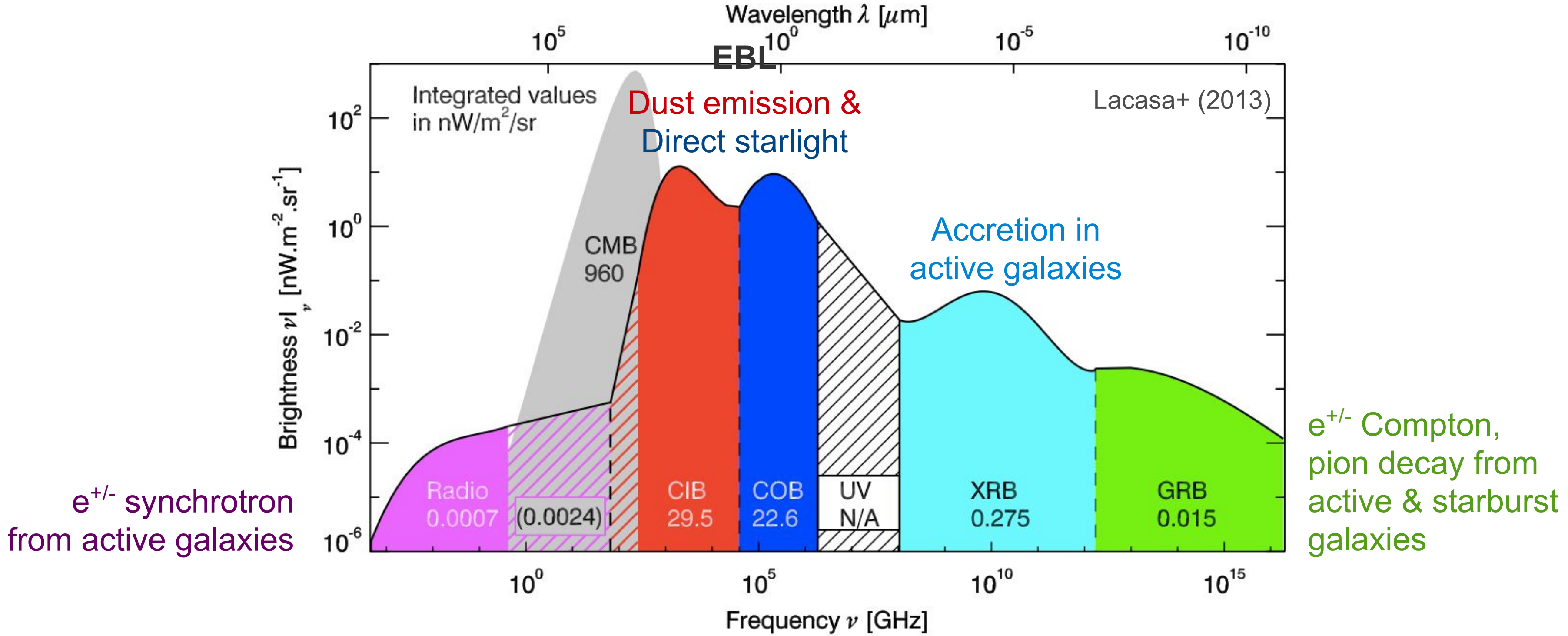
The key for the future: Synergies



Extragalactic night sky: electromagnetic spectrum

All the galaxies in the universe

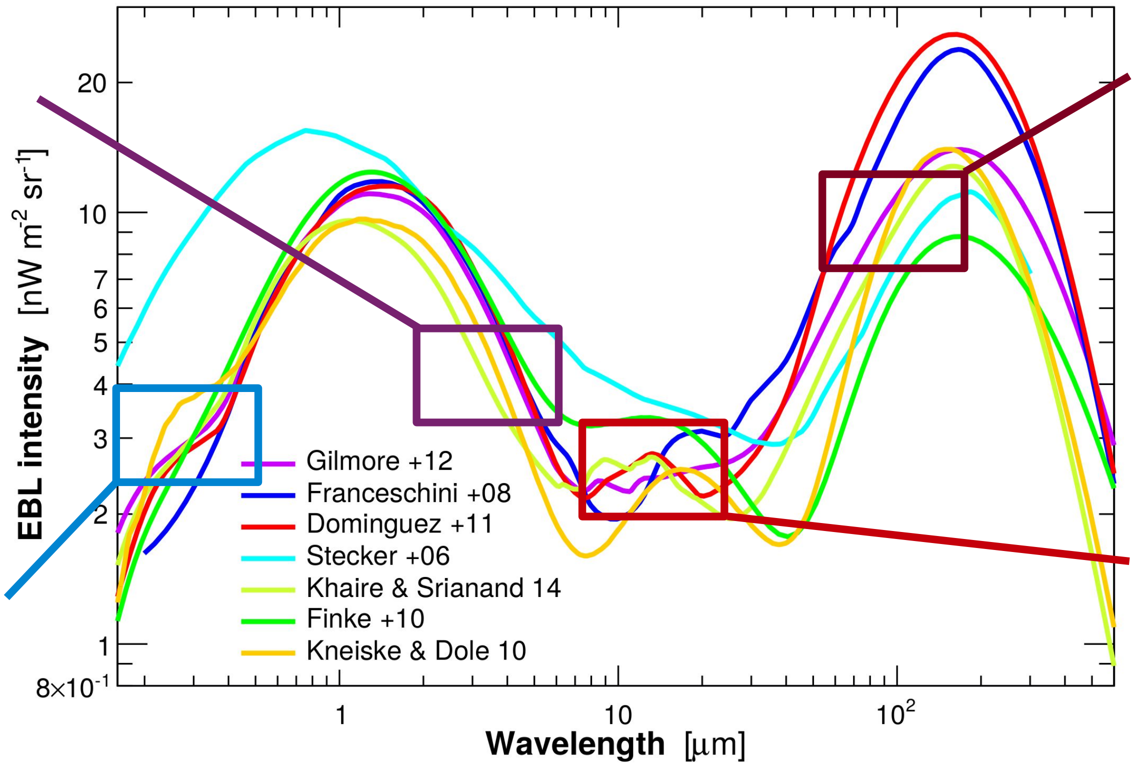
Emission from star-forming galaxies (e.g. starburst galaxies) & active galaxies (e.g. radio-galaxies, blazars)



Old and New Models of the EBL

1-10 μm region
Signature of reionization sources?
e.g. Cooray & Yoshida 2004

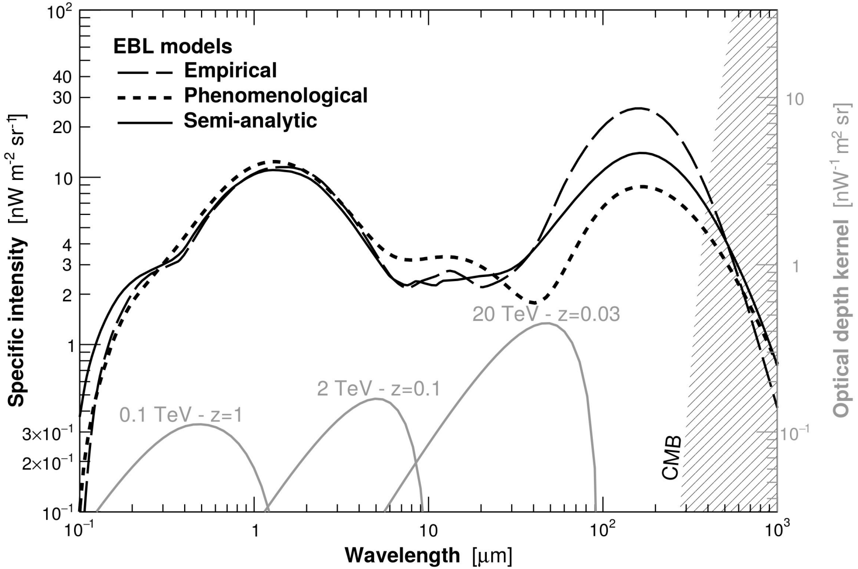
UV background
Largely underconstrained by theory and experiments
Haardt & Madau 2012

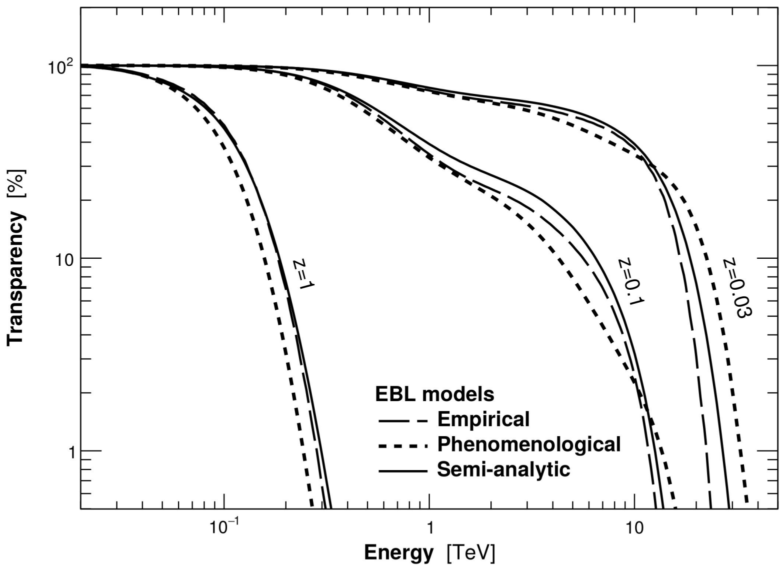


100 μm region
Probe of Lorentz Invariance Violation
e.g. JB & Williams 2015

10-30 μm region
Amount of polycyclic aromatic hydrocarbons?
e.g. Dominguez+ 2011

Gamma-ray absorption in photon fields





Model independent EBL results

Results

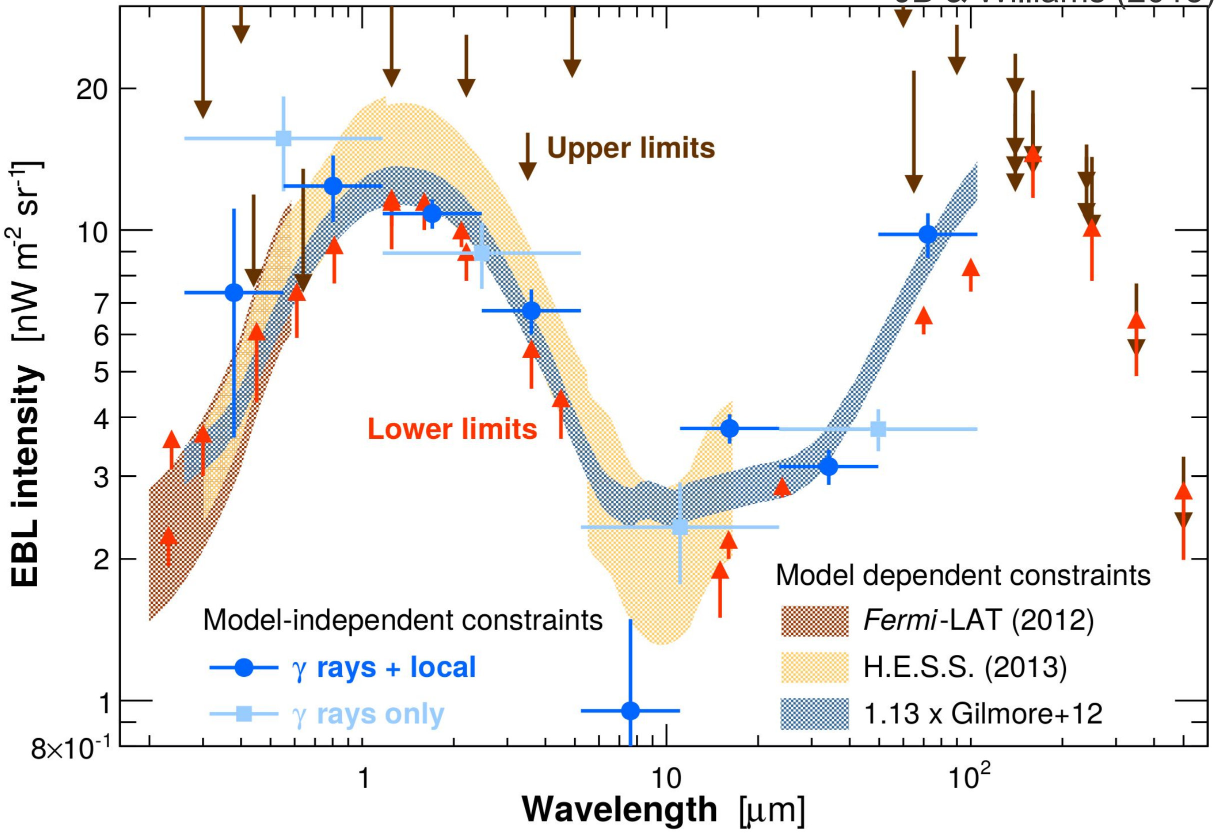
. 11σ detection both for model-dependent & independent methods

. Study of 7 models, 4 ruled out, 3 ~as good as model-independent

. EBL (0.1 - 1000 µm): 62±12 nW m-2 sr-1 6.5±1.2% of the CMB

. No significant tension with galaxy counts

JB & Williams (2015)



Evolution of absorption at z > 0.5

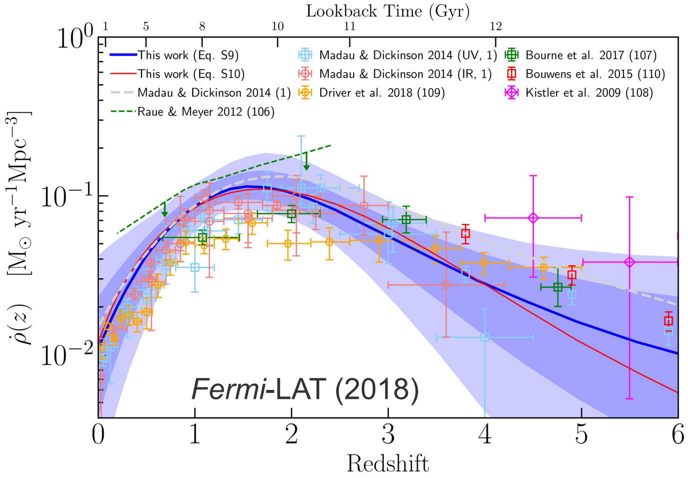
Cosmic star-formation history (CSFH)

EBL photon density dictated by luminosity density (emissivity)

$$\partial n/\partial \epsilon = (1+z)^3 \int_z^\infty \mathrm{d}z' \, \partial t/\partial z' \times j(\epsilon', z')/\epsilon'$$

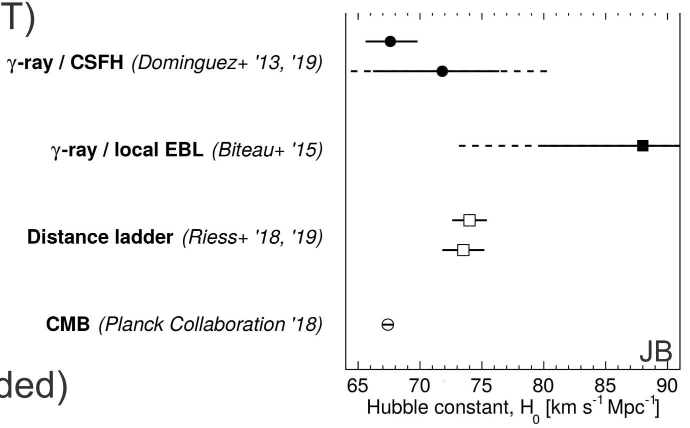
For given emissivity per SFR unit and dust extinction
luminosity density traces CSFH (important for CCSNe MeV ν)

$$\rho(z) = K_\epsilon \times 10^{0.4 A_\epsilon} \times j(\epsilon, z)$$



Fermi-LAT combined constraints from sources up to z ~ 2:
- UV density at z > 4 ~ lowest values from Lyman-break galaxies
- starts constraining faint end of luminosity function at z > 6 (JWST)

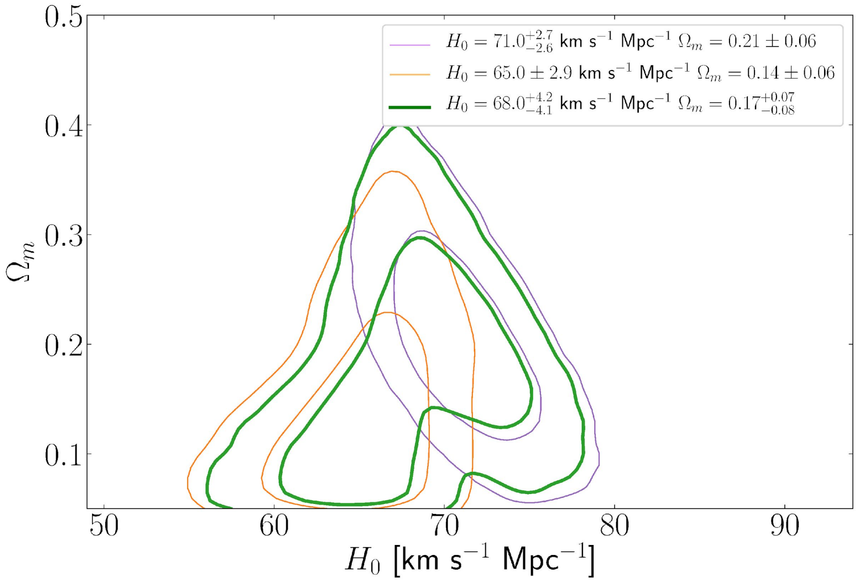
Cosmological parameters

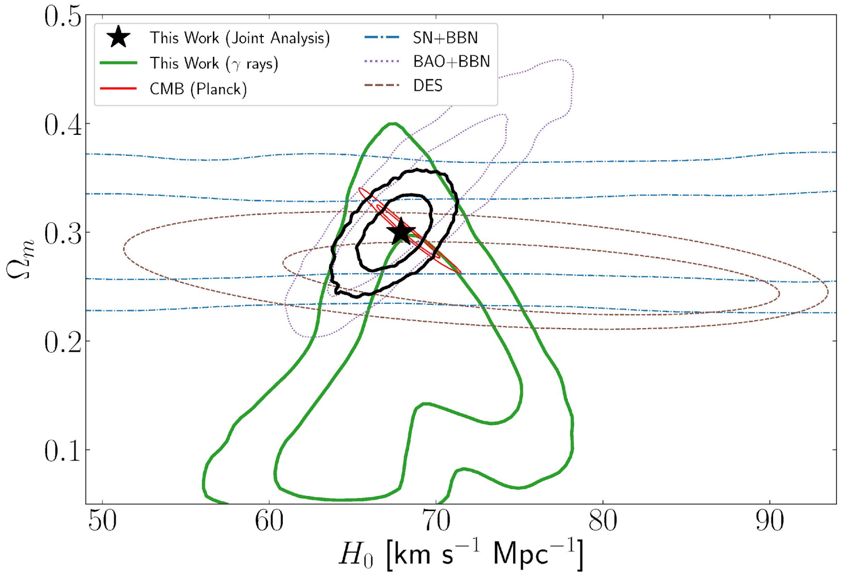


Absorption distance element ~ H_0^{-1} & emissivity ~ H_0^3
At z =0, local γ-ray / EBL constraints ~ H_0^{-1}
→ first quantitative γ-ray constraints on h_0: ± 0.1
For a constrained evolution, γ-ray / CSFH constraints ~ H_0^2
→ recent LAT constraints on h_0: ± 0.03 (independent checks needed)

Constraints on Cosmological Parameters

Dominguez *et al.* (2019)





Extragalactic night sky: electromagnetic & hadronic spectra

Extragalactic electromagnetic background

Diffuse backgrounds measured
from radio to γ rays, <u>up to ~ 100 GeV</u>
→ sources: *known and (rather well) understood*

<u>Beyond ~ 100 GeV</u>, background not measured

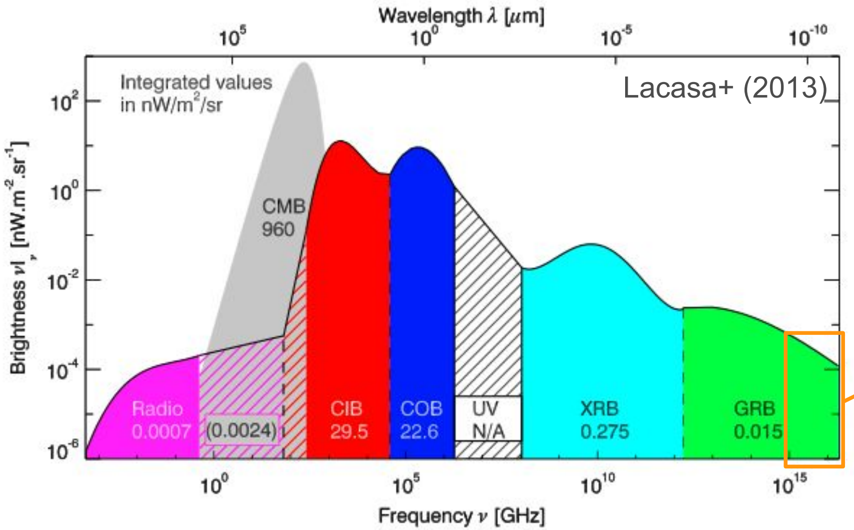
→ sources: *partly known & understood*

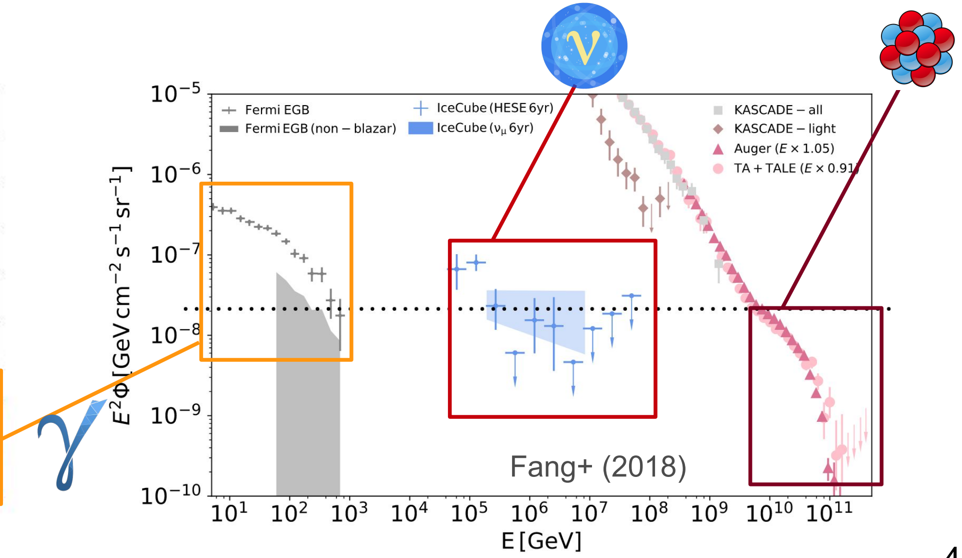
Extragalactic hadronic background

Diffuse backgrounds measured in:

- PeV neutrinos (few dozens of events)
- EeV cosmic rays (mostly isotropic sky)

→ sources: *unknown & far-from being understood*!





Cosmic-ray horizon

evolution along propagation:

Aloiso, Berezinsky, Grigorieva (2013)

$$\frac{\partial n_{A_0}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}\left[n_{A_0}(\Gamma,t) b_{A_0}(\Gamma,t)\right] + \frac{n_{A_0}(\Gamma,t)}{\tau^{\rm tot}_{A_0}(\Gamma,t)} = Q_{A_0}(\Gamma,t).$$

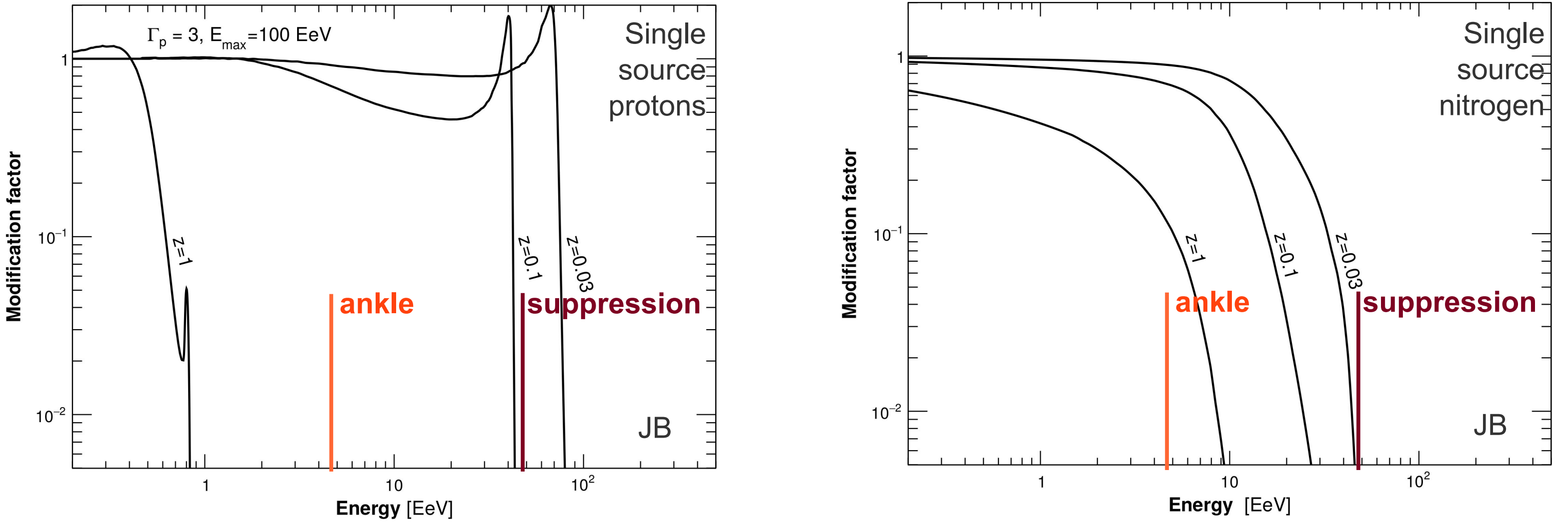
Energy losses: $e^{+/-}$ or π production | Absorption: photo-dissociation | Injection: source or cascade

Propagation of protons

No absorption term → sharp wall at ~ 100 EeV for D ~ 100 Mpc, pile-up feature

Propagation of nuclei

Dominated by single-nucleon photo-disso → ~ exp. attenuation at ~20/50 EeV for D ~ 100/10 Mpc



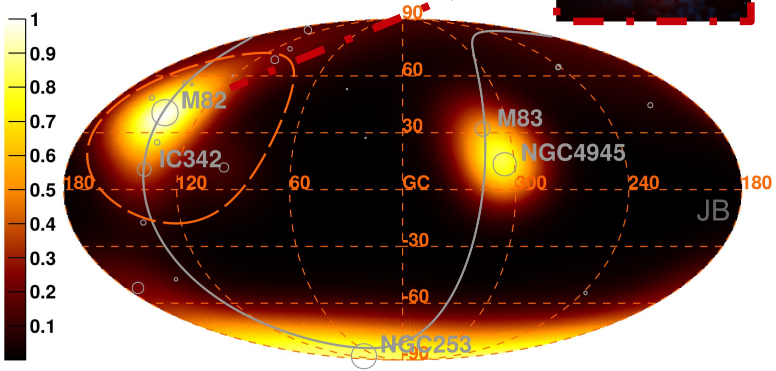
Starforming and active galaxies in the local universe

Starburst galaxies

= starforming galaxies with high SFR

As more probable hosts of transient sources.

Starburst galaxies - Scenario A > 50EeV



Starburst galaxies from radio master catalog within 250 Mpc, with flux > 0.3 Jy Mostly nearby (90% of flux < 10 Mpc)

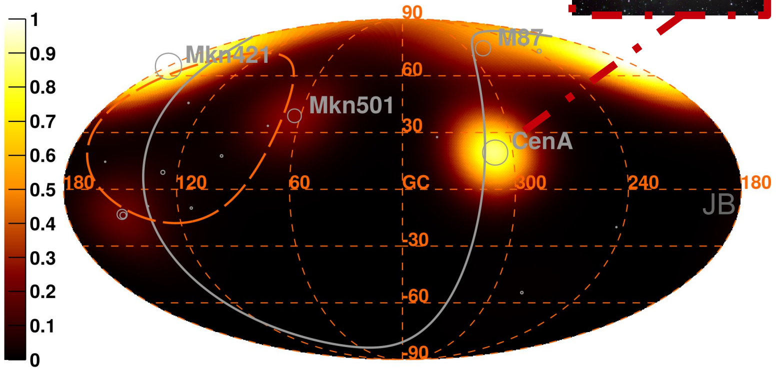
Radio luminosity to trace UHECR emission

Active galaxies

= radio galaxies & blazars

As hosts of the most powerful, persistent relativistic Jets

Active galactic nuclei - Scenario A > 50EeV



Active galaxies from *Fermi*-LAT (3FHL, > 10 GeV) within 250 Mpc more distant (90% of flux < 100 Mpc)

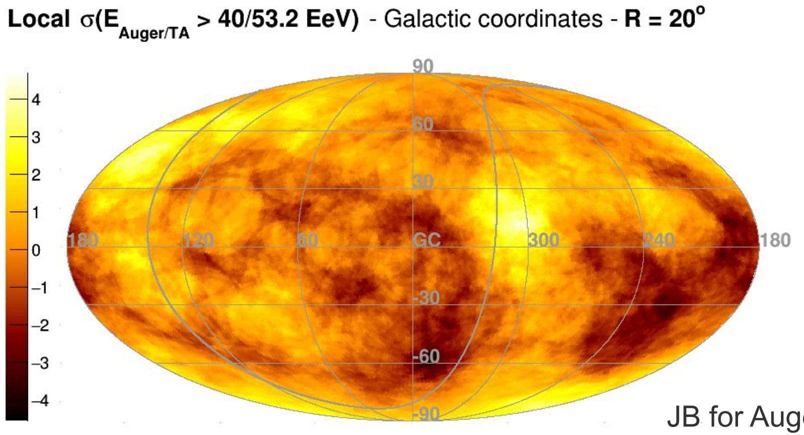
γ-ray luminosity to trace UHECR emission

Cosmic-ray anisotropies at high rigidities

Blind searches for self-clustering

Auger-only: 2.0σ at E_{Auger}> 38 EeV

Auger + TA: South/North: 2.2/1.5σ at E_{Auger}> 40 EeV



JB for Auger/TA
(UHECR2018)

Catalog-based searches

Assumption: UHECR flux electromagnetic flux
× propagation effects

Active / **starforming** galaxies: **3.1 / 4.5σ** on θ ~ 15°