Astroparticles from the extragalactic universe

Séminaire du DAp
2020-01-14

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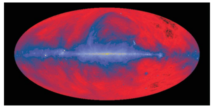
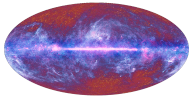
Extragalactic multi-wavelength sky

see http://www.chromoscope.net/

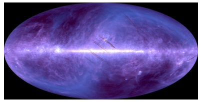
Radio band from ground (Parkes, Bank) → ***relativistic electrons***



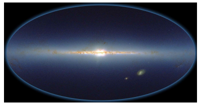
Microwave from *Planck* (2009-2012) → ***dust emission, relativistic electrons***



Far infrared from *AKARI* (2006-2011) → ***dust emission***

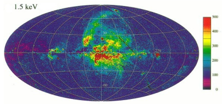


Near infrared from ground (2MASS) → ***starlight, dust emission***



Optical band from ground mosaic → ***starlight, dust absorption***

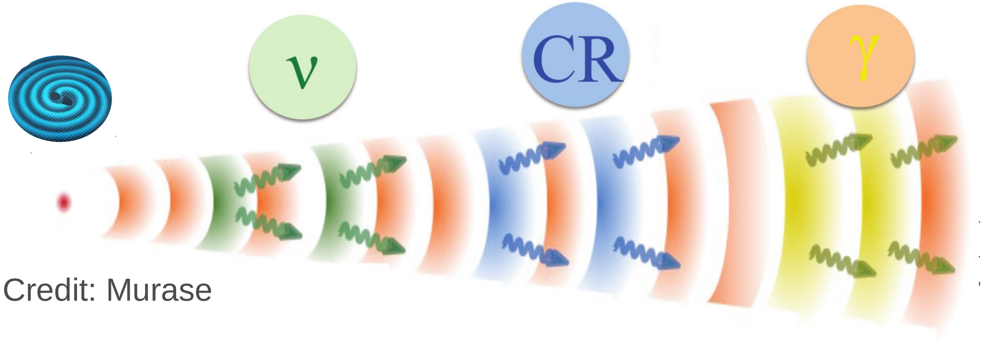
X rays from *ROSAT* (1990-1999) → ***relativistic electrons***



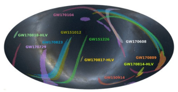
A story to the millennials

Extragalactic multi-messenger sky

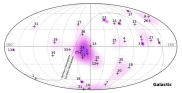
see http://www.chromoscope.net/



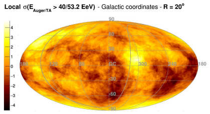
Credit: Murase



Gravitational-wave events
from LIGO & Virgo (since 2015)
→ ***motion of compact objects***

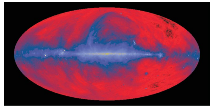


PeV ν background from
IceCube & ANTARES (since 2013)
→ ***relativistic hadrons***



EeV cosmic-ray background from
Auger & Telescope Array (since 1999)
→ ***most relativistic hadrons***

Radio band from ground (Parkes, Bank)
→ ***relativistic electrons***



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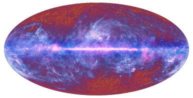

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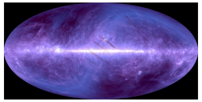

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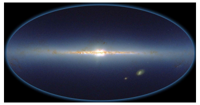

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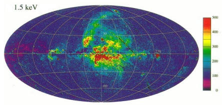
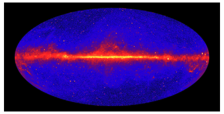
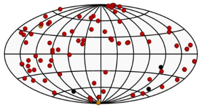


γ rays from *Fermi*-LAT (2008-now)
→ ***relativistic electrons & hadrons***



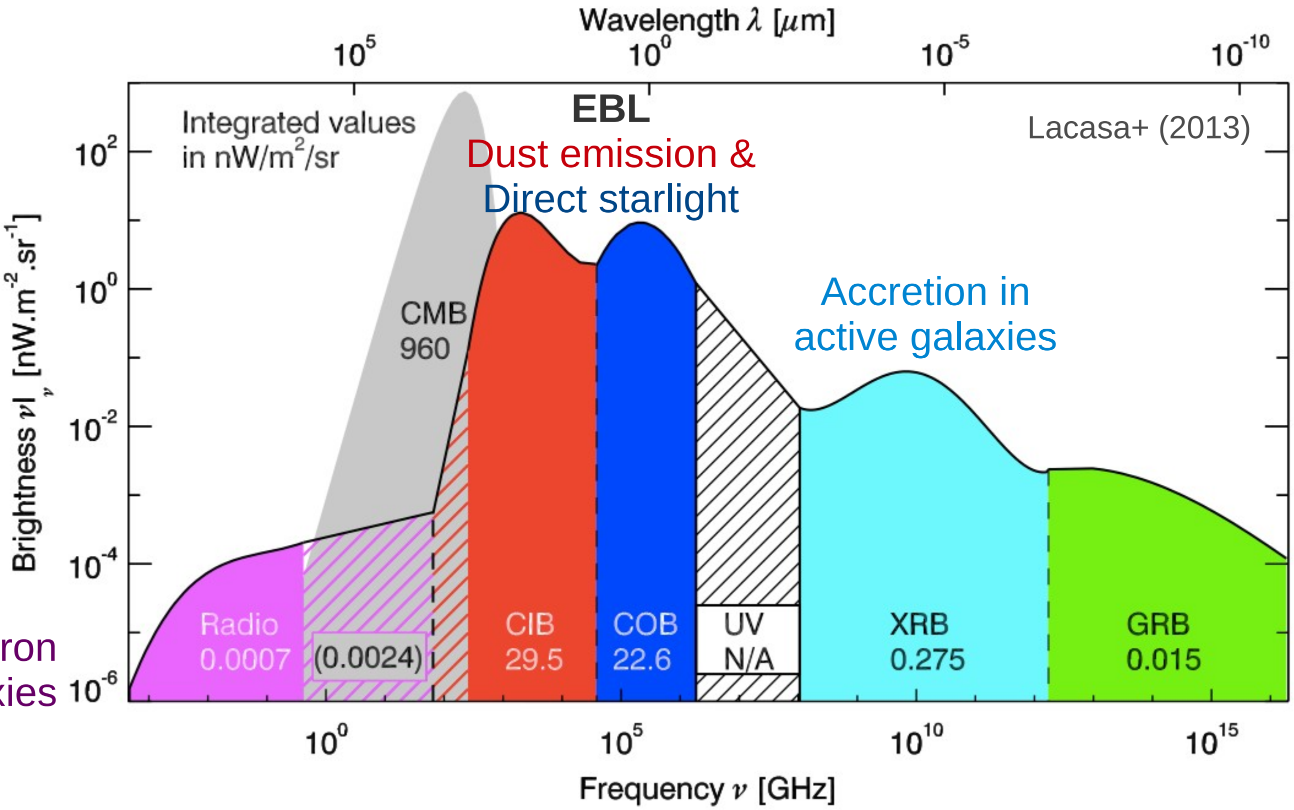
TeV γ rays from IACTs (2005-now)
→ ***relativistic electrons & hadrons***



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)



Extragalactic night sky: electromagnetic & hadronic spectra

Extragalactic electromagnetic background

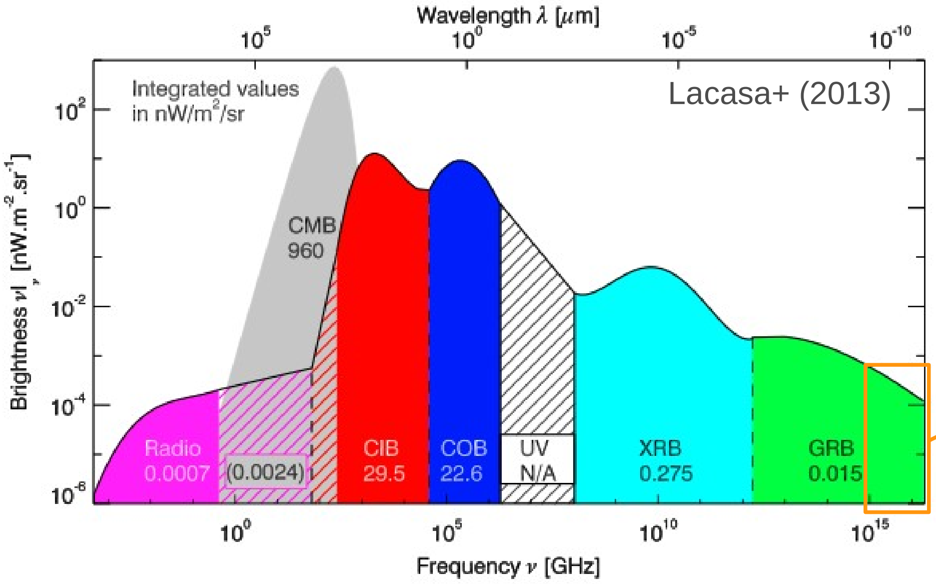
Diffuse backgrounds measured
from radio to γ rays, up to ~ 100 GeV
→ sources: *known and (rather well) understood*

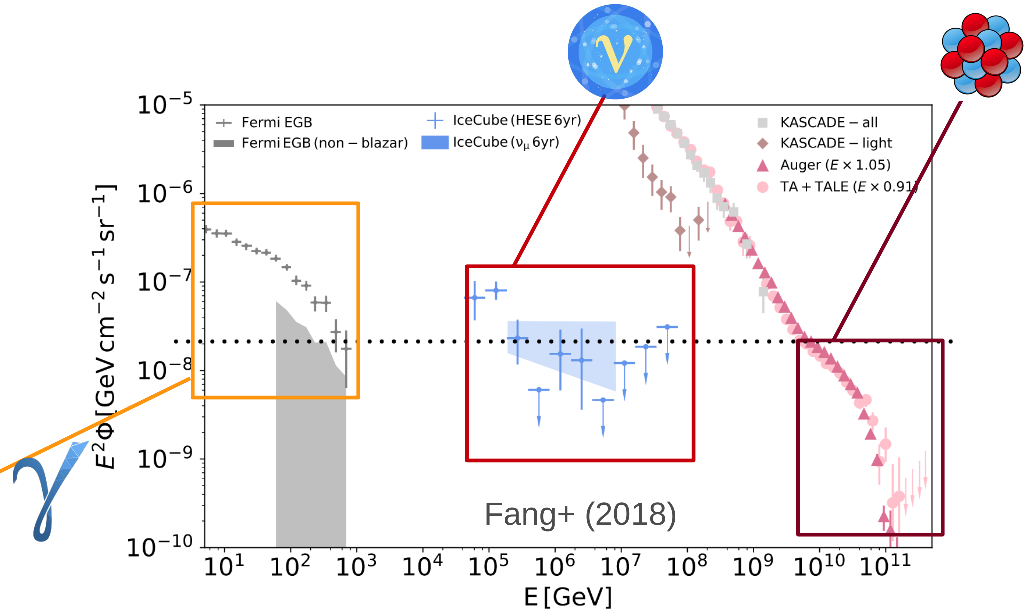
Beyond ~ 100 GeV, background not measured
→ sources: *partly known & understood*

Extragalactic hadronic background

Diffuse backgrounds measured in:
- PeV neutrinos (few dozens of events)
- EeV cosmic rays (mostly isotropic sky)

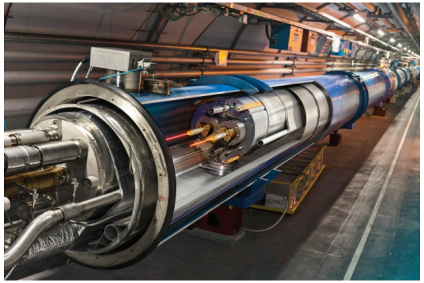
→ sources: *unknown & far-from being understood*!





Most extreme accelerators in the universe?

Taking man-kind realizations as a reference



LHC energy / proton: ~ 10 TeV ≡ 10^**13** eV

“Linear” rate (2 beams x protons / beam x c/2πR):
~ 10^**19** protons / sec

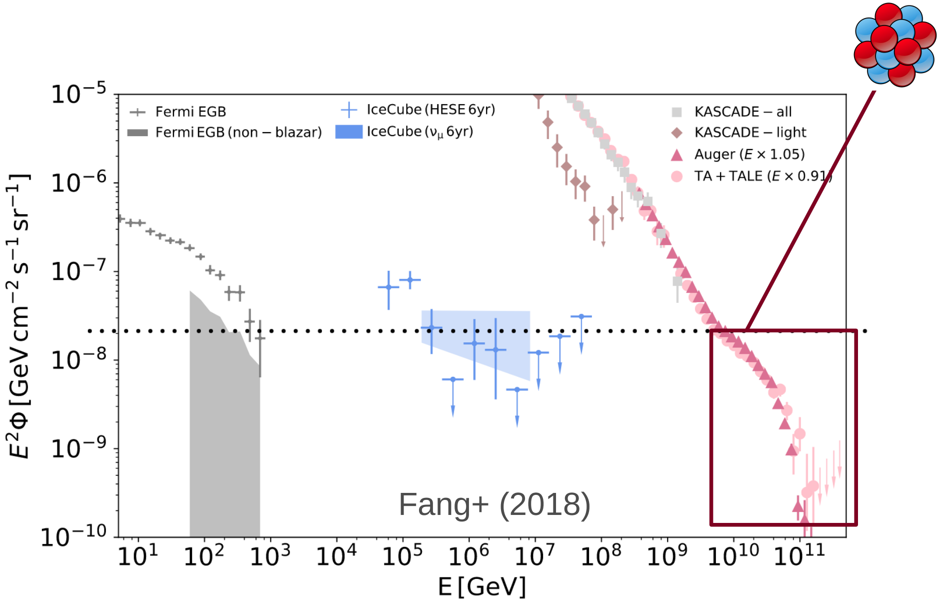
Extragalactic UHECR

Energy / UHECR above the ankle: ~10 EeV ≡ 10^**19** eV

Production rate density for $\overline{E}$ ~ 10 EeV (Auger+ 2017):
~ 10^30 UHECR / Mpc³ / sec

“Bright” galaxy number density < 0.1 /Mpc³

Production rate per galaxy: ~ 10^**31** UHECR / sec



What are we looking for?

Accelerators *trillion times more luminous* and reaching *million times higher energies* than the LHC

Where? Among most violent electromagnetic sources.

Detecting the highest-energy “rays”

Extensive atmospheric showers

Electromagnetic showers

Bremsstrahlung ($e^{+/-}$) and pair production (γ)

Interaction length ~ 25 g / cm²

Stops after 30-40 generations (ionization losses)
→ *hard to distinguish $e^{+/-}$ from γ primaries*
(1 X_0 out of 30)

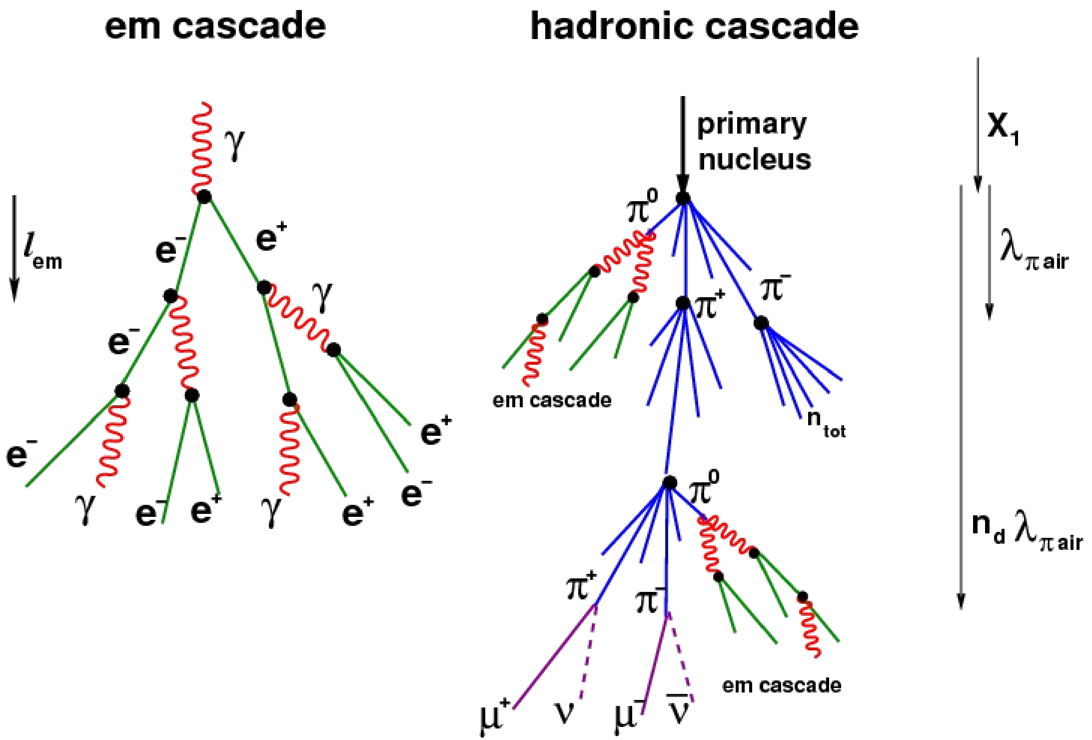
Hadronic showers

Production of pions, π^0 decay, $\pi^{+/-}$ cascades

$\pi^{+/-}$ decay in μ/ν after 5-6 generations (< 0.1 TeV)
with π-air interaction length ~ 120 g / cm²

First interaction of proton/iron at ~90/5 g / cm²

→ *heavy-light discrimination*



Mollerach & Roulet (2017)

γ-ray showers

Stereoscopic imaging of Cherenkov from $e^{+/-}$

O(10%) duty cycle, ~ 2000m above sea level

Cameras with O(1000) PMTs and ns sampling

Energy resolution ~ 10%. Angular resolution ~ 0.1°.

Lead experiments: H.E.S.S. (Namibia),
MAGIC (Canary), VERITAS (Arizona)

Sampling the secondary particles

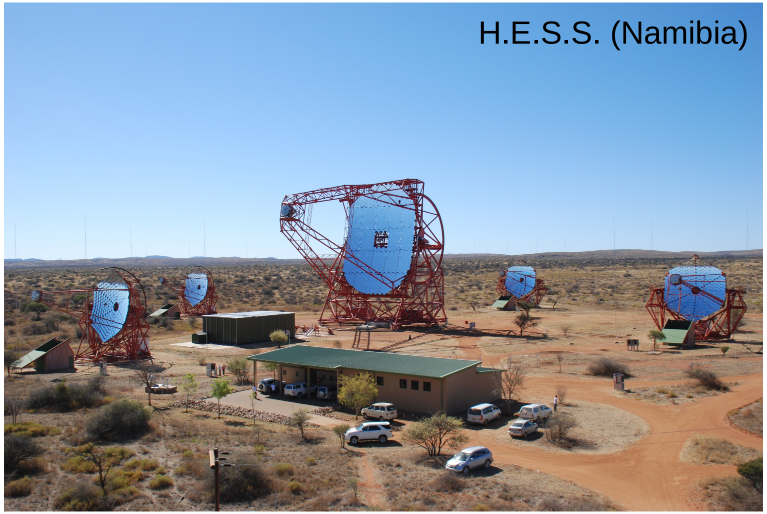
O(100%) duty cycle, ~ 4000m above sea level

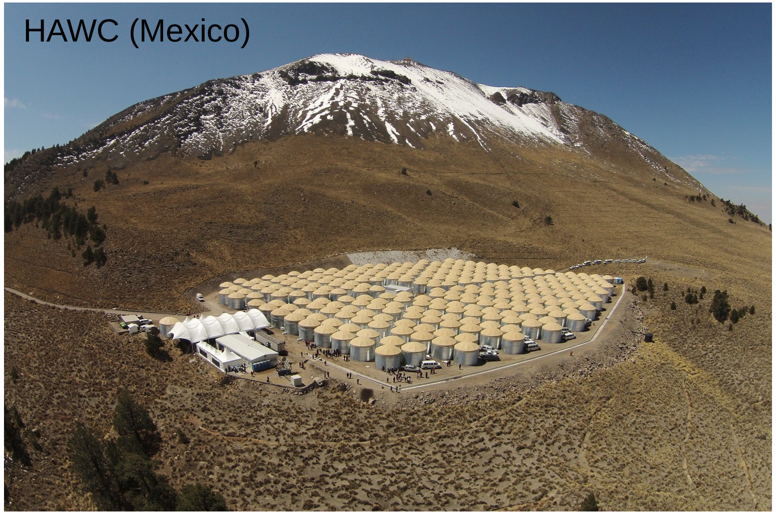
Water-Cherenkov tanks equipped with 3 PMTs

Energy resolution ~ 50%. Angular resolution ~ 0.5°.

Lead experiment: HAWC (Mexico)

Full-sky flux > 1 TeV ~ few **/ m² / hour** ↔ Effective area: **10^4 – 10 ^5 m²**





Cosmic-ray showers

Leading the field: Pierre Auger Observatory

West Argentina, 1,400m above sea level

Full-sky flux > 10 EeV ~ few **/ km² / year**
→ area = **3,000 km²** (Luxembourg / Rhode Island!)

Energy resolution ~ 10%. Angular resolution ~ 1°.

Imaging Flurorescence Telescopes

27 PMT cameras in 5 buildings, ~10% duty cycle

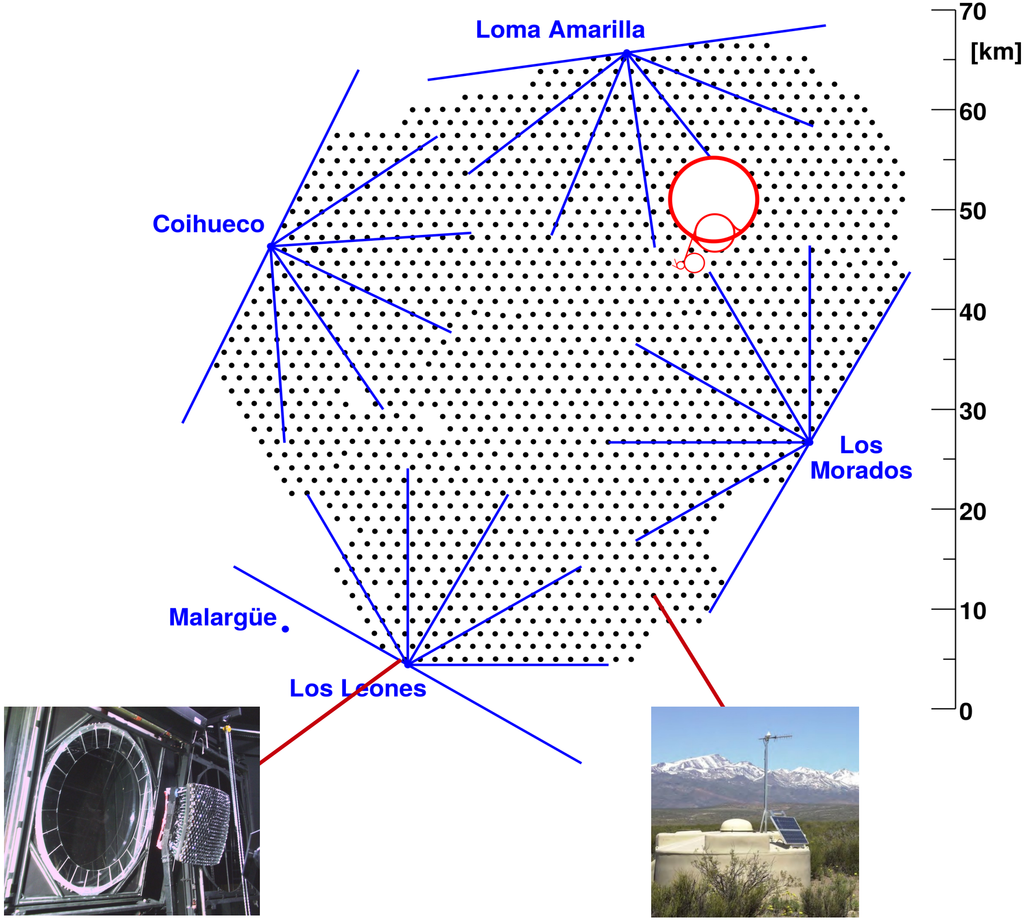
4 main sites: 6 eyes / site – 30°×30° FoV

Sampling Particle (μ/e) Detectors

1600 water-Cherenkov tanks, ~100% duty cycle

spaced by 1,500m, 3 PMTs per tank

+ many other sub-component not discussed here

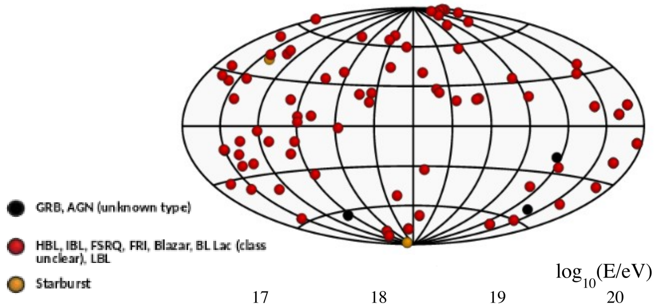


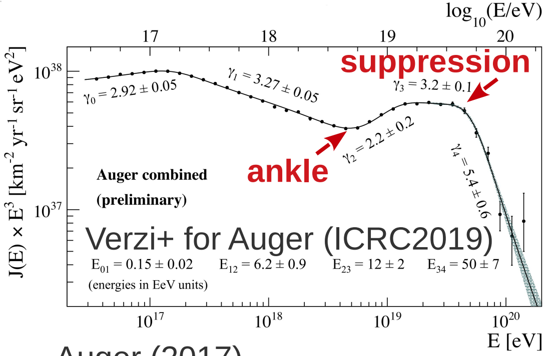
A selection of major results

> 80 extragalactic sources in TeV γ-rays

- **“constant” emitters**: starburst galaxies (NGC 253, M82)
  → *likely hadronic accelerators*
- **“persistent” emitters**: radio galaxies (e.g. Cen A) and blazars (e.g. Mkn 421). Down to minute-timescale variability measured
  → *likely leptonic accelerators* (at least during flares)
- **“transient” emitters**: 3 γ-ray bursts above ~ 100 GeV
  (in 2018-07 and 2019-01, 2019-08)

TeVCat, Aug. 2019





Cosmic-ray diffuse emission

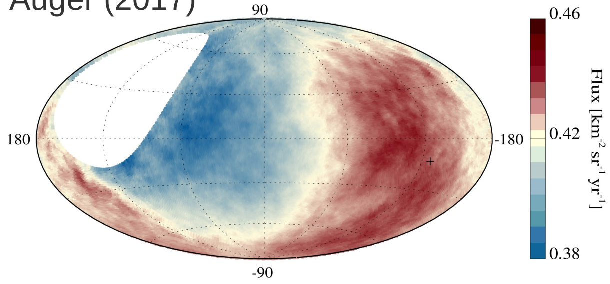
Lack of EeV neutrals → *top-down scenarii excluded*

Precision spectral measurement over > 3 energy decades

Composition measurements (<40 EeV) and spectrum in line with *acceleration-limited scenarios*

Detection of a **dipolar anisotropy beyond the ankle**
→ 1st observational *evidence of extragalactic origin*

Auger (2017)



Open questions in extragalactic astroparticle physics

adapted from CTA (2019) and Alves Batista, JB+ (2019)

Origin of Cosmic Particles

- What are the mechanisms for cosmic particle acceleration?
- What are the sites of particle acceleration in the universe?

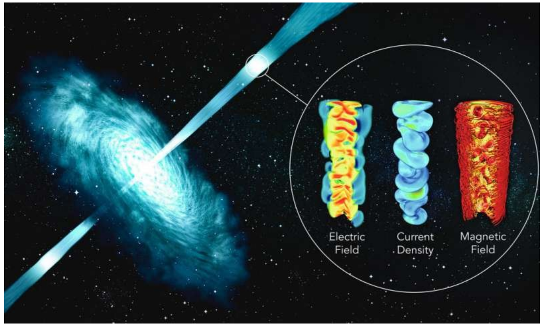
Extreme Environments

- What physical processes are at work close to neutron stars and black holes?
- What are the characteristics of relativistic jets, winds and explosions?

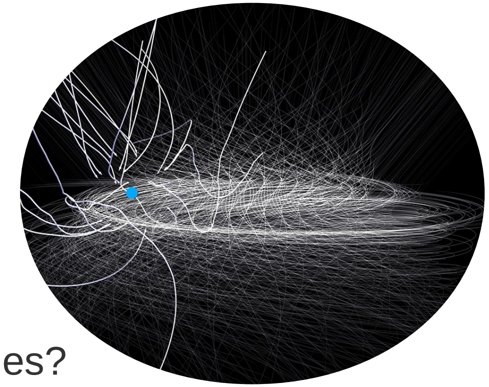
Propagation and Frontiers in Physics

- What is the charge of the highest-energy cosmic rays? How are they affected by magnetic fields?
- How intense are radiation and magnetic fields in cosmic voids?
- Do quantum gravity or axion-like particles affect propagation of astroparticles?

Alves, Zrake, Fiuza (2018)

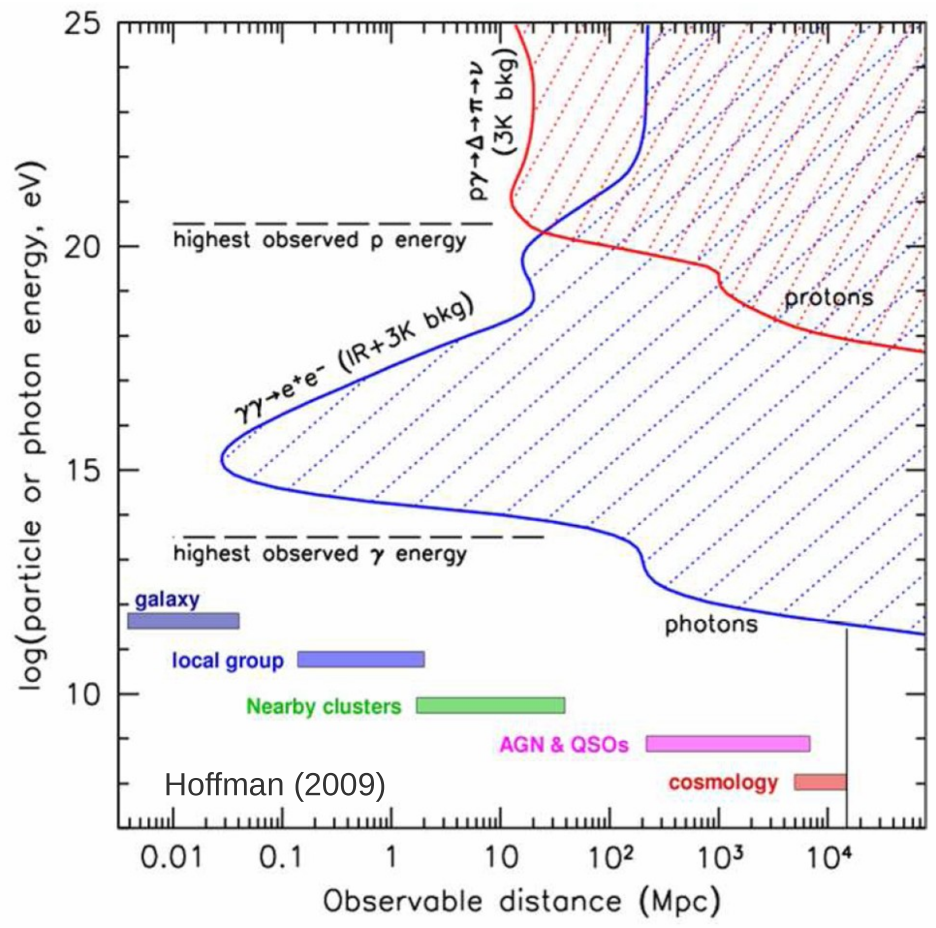


Farrar & Sutherland (2015)



Cosmic propagation at the highest energies

Cosmic-ray horizon and γ-ray imprint

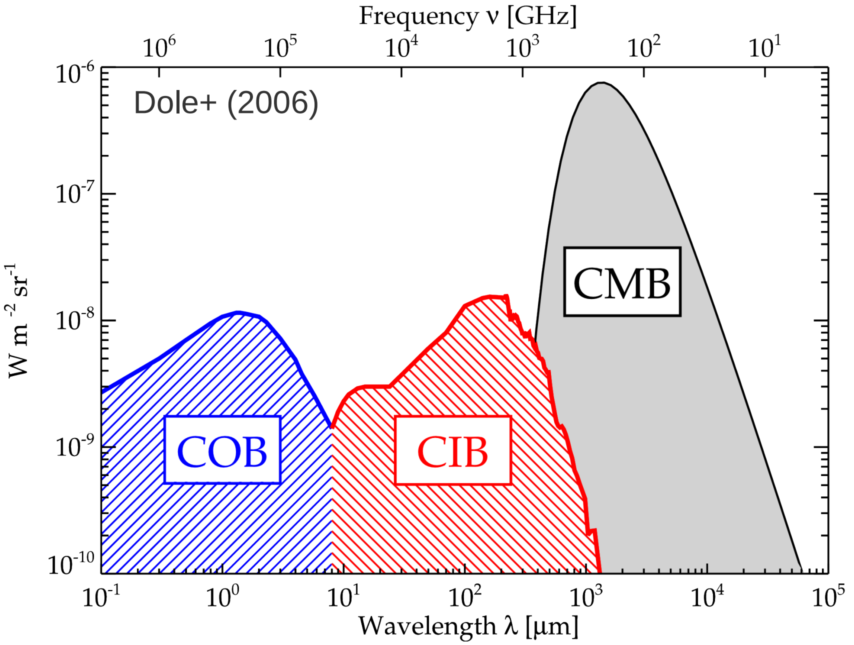


p + γ(EBL/CMB) → p/n + π (or p + $e^{+/-}$)

→ $2m_p\, m_\pi / 4E_{EBL/CMB}$ ~ **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**)



Cosmic-ray horizon

 # evolution along propagation:

Aloiso, Berezinsky, Grigorieva (2013)

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

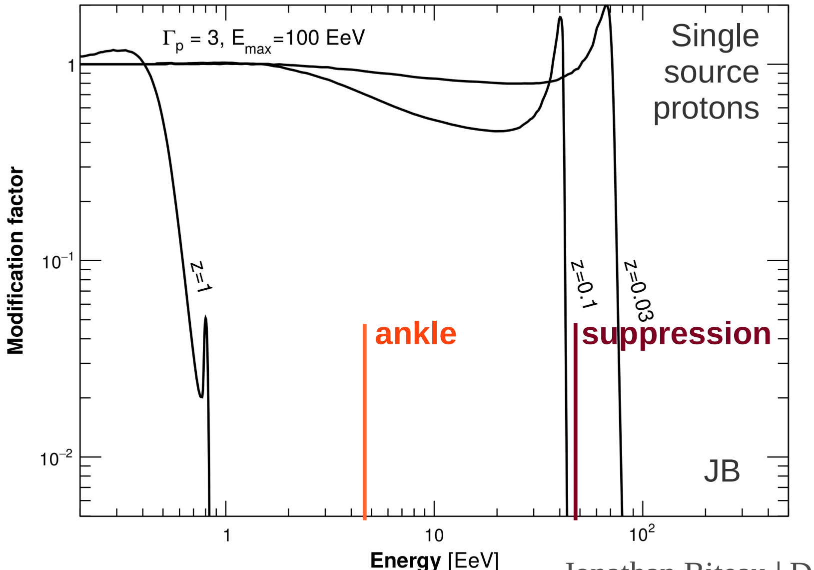
Energy losses: $e^{+/-}$ or π production — Absorption: photo-disintegation — Injection: source or cascade

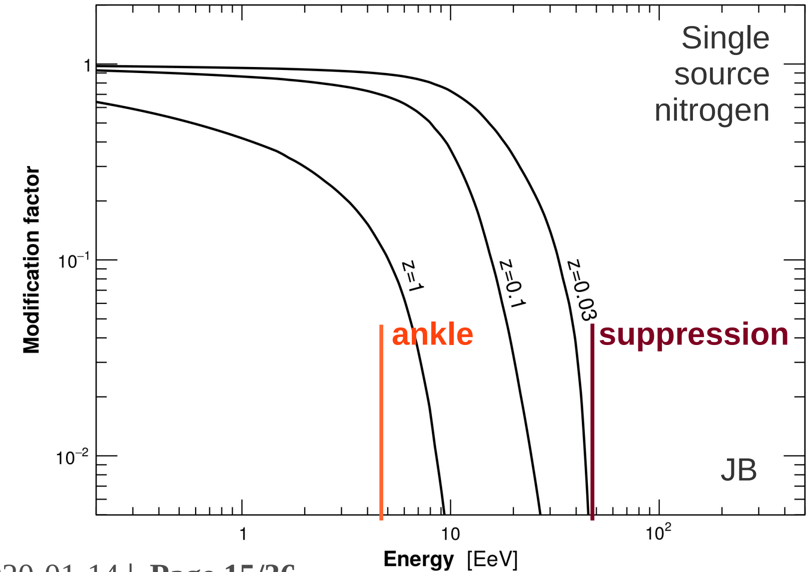
Propagation of protons

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

Propagation of nuclei

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





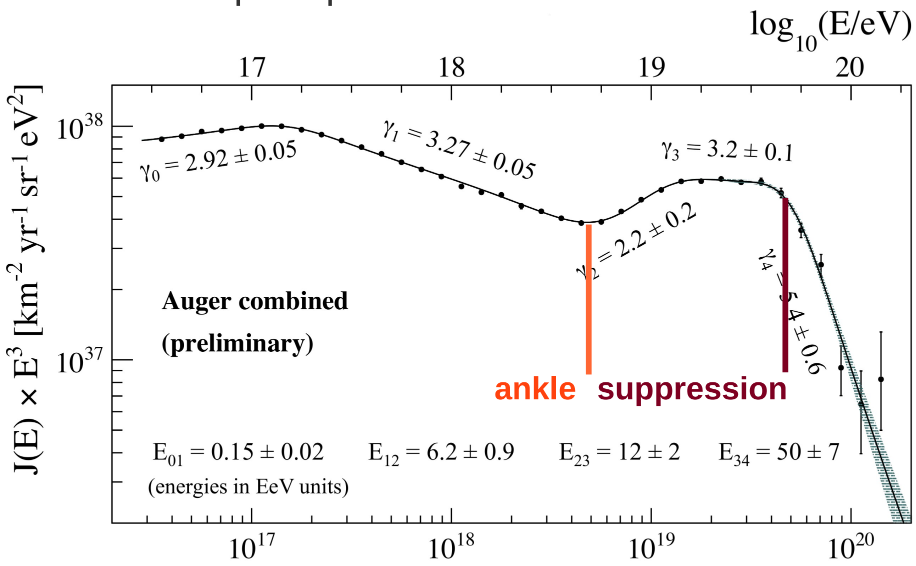
Cosmic-ray observations

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

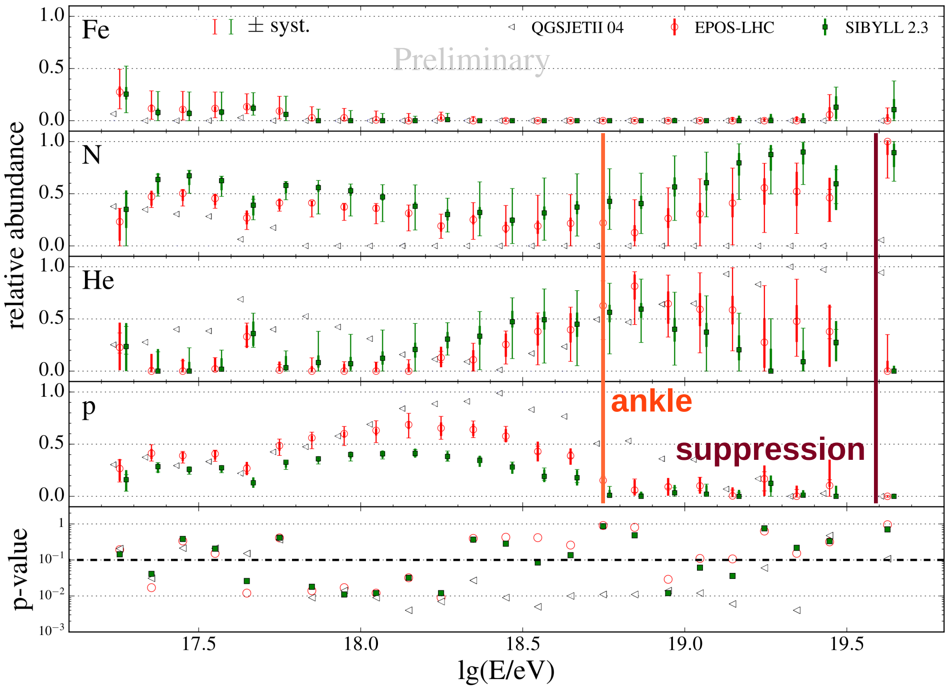


Verzi+ for Auger (ICRC2019)

But mixed composition

Inference: p → He → CNO sequence

→ in line with E_{max} ~ a few EeV x (Z or A)

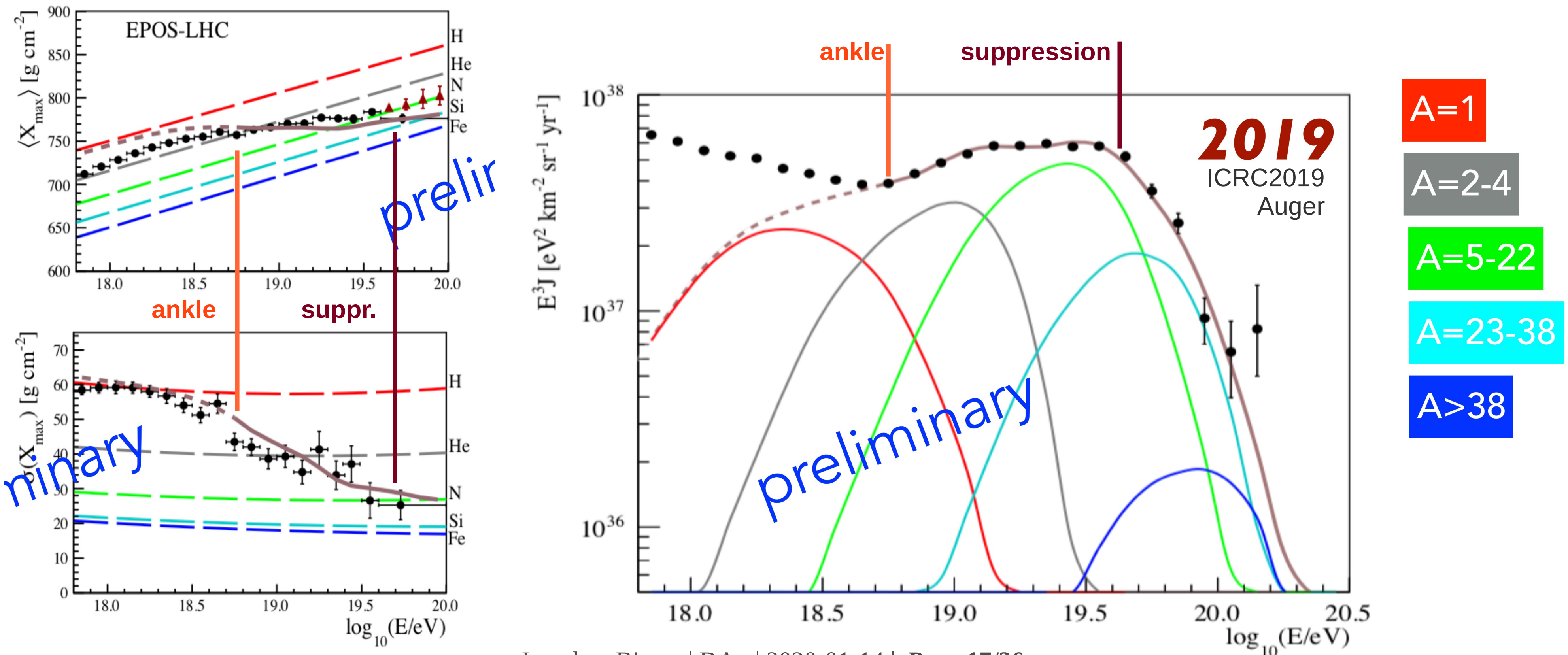


Bellido+ for Auger (ICRC2017)

Cosmic-ray models

The mixed model e.g. Auger (2017)

Homogeneous source distribution + hard escape spectrum (p<2)

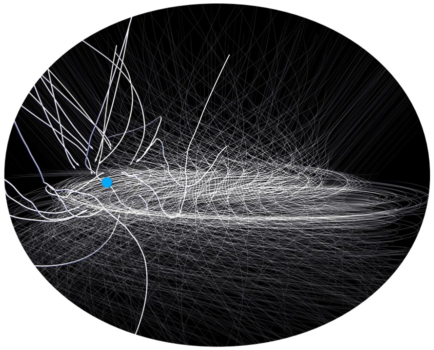


Cosmic rays and magnetic fields

Magnetic fields everywhere

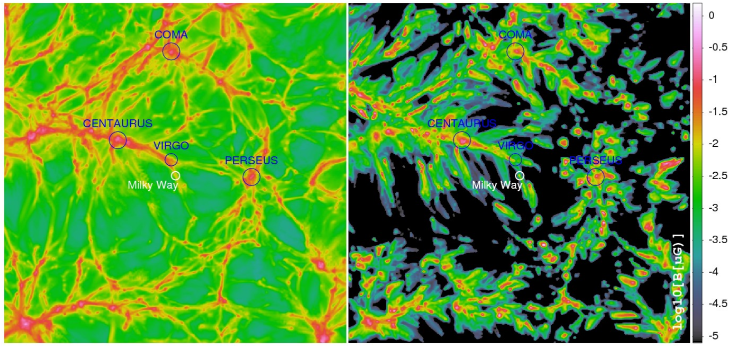
Galactic ~ μG from Faraday/synchrotron (± 0.5 dex)

Local intergalactic ~ nG (± 1 dex) – Extragalactic ~ pG? (± >3 dex)

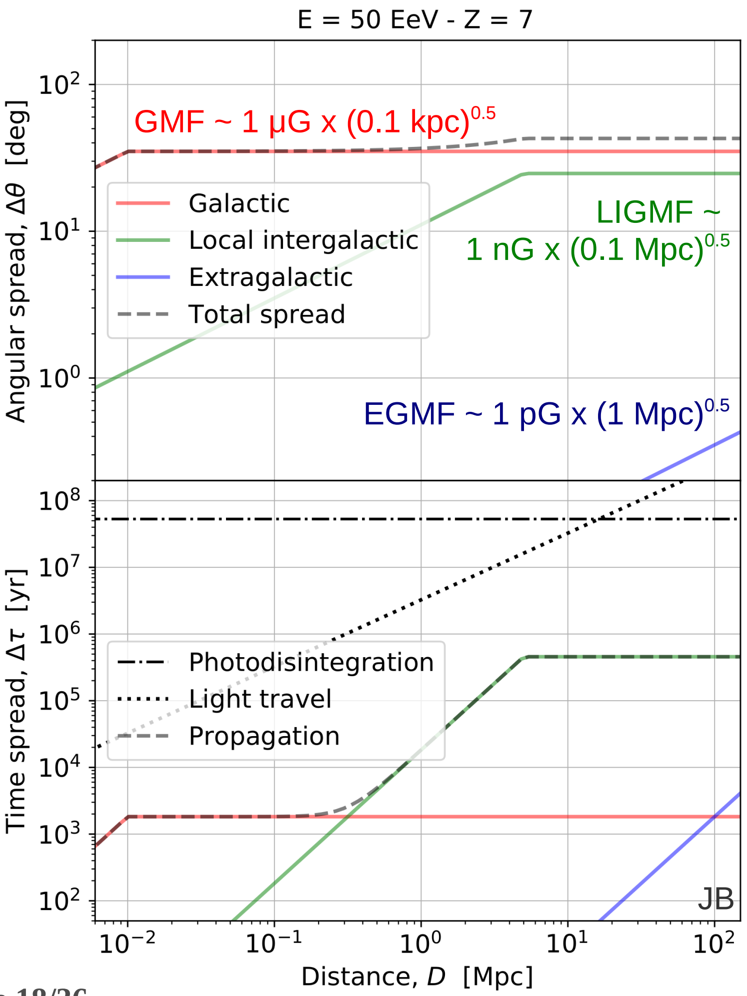


Farrar & Sutherland (2015)

Primordial seed Astrophysical seed



Hackstein+ (2018)



Impact of charged nature

Spectrum unaffected (*propagation theorem*)
if Δ(sources) << attenuation/diffusion length

Angular and time spread → transients appear kyr-Myr steady

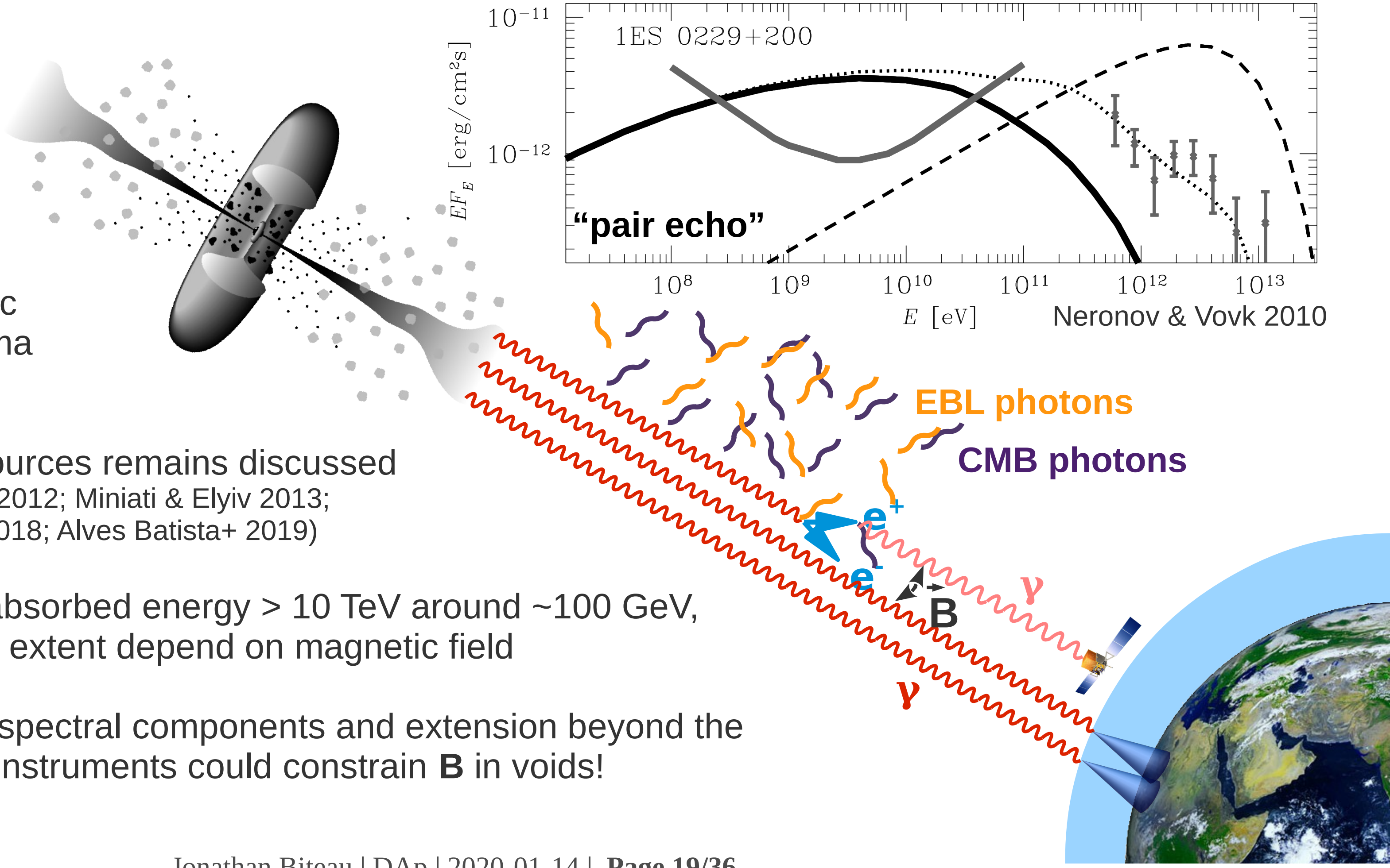
γ-ray cascades in magnetic fields

Secondary γ rays?

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

A) either upscatter
CMB photons

B) or heat the intergalactic
medium through plasma
instabilities



Neronov & Vovk 2010

B) viability for all/some sources remains discussed
(Broderick+ 2012; Schlikeiser+ 2012; Miniati & Elyiv 2013;
Sironi & Gianios 2014; Vafin+ 2018; Alves Batista+ 2019)

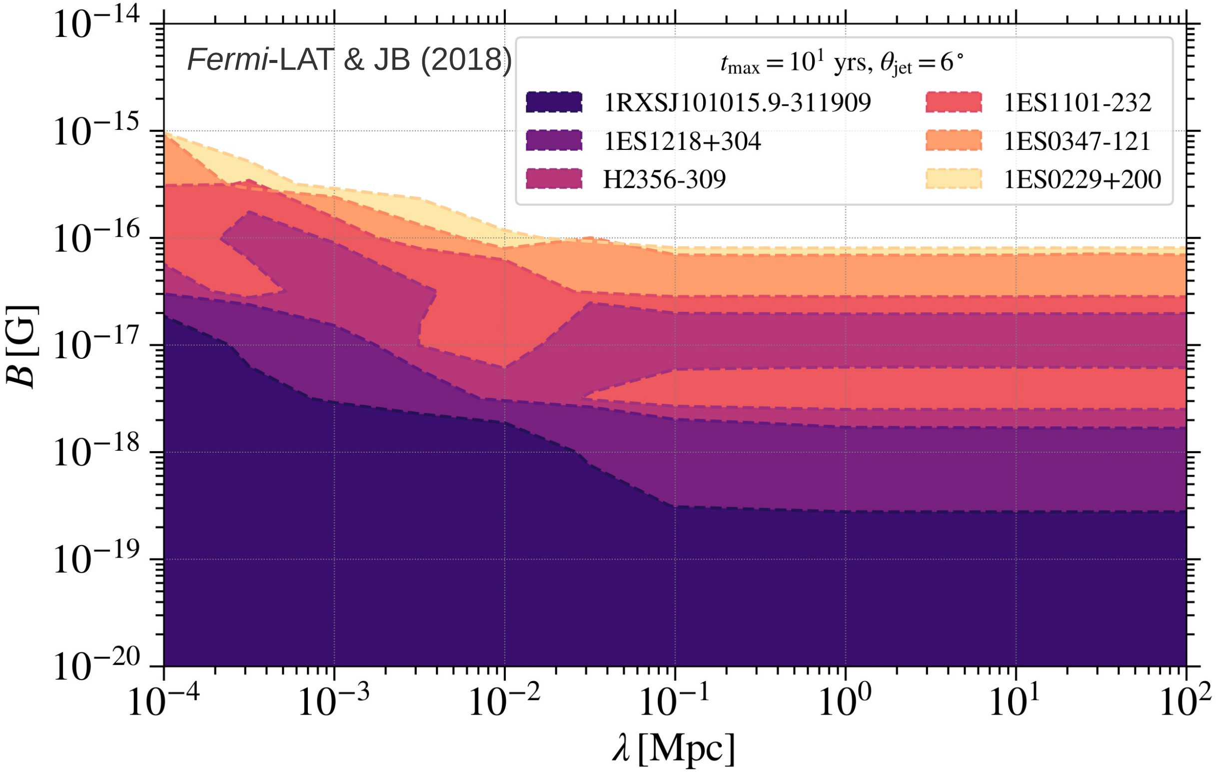
If A), reprocessing of all absorbed energy > 10 TeV around ~100 GeV,
→ amplitude and angular extent depend on magnetic field

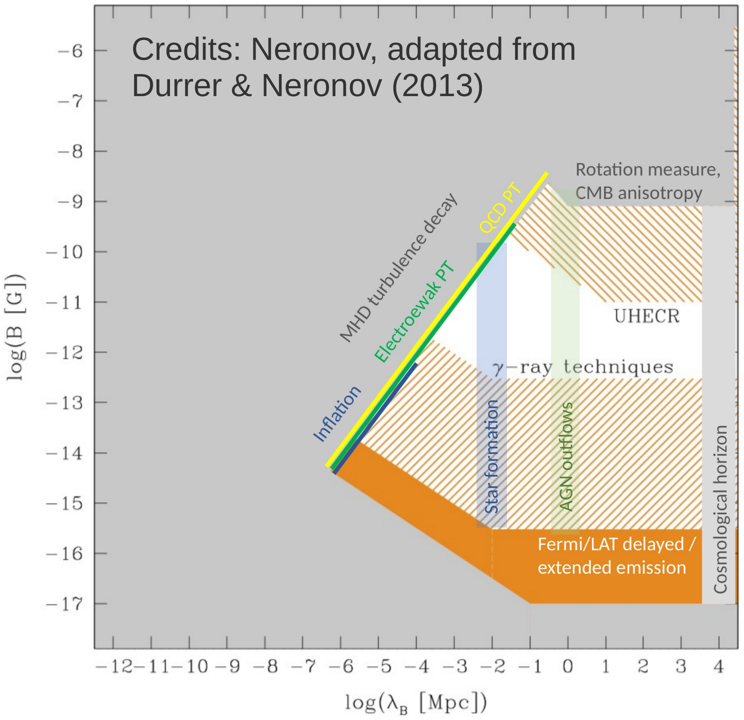
Searches for low-energy spectral components and extension beyond the angular resolution of the instruments could constrain **B** in voids!

Constraints on cosmic magnetic fields

Constraints from GeV-TeV measurements (assuming no beam instabilities)

→ latest constraints jointly fit the angular extent and the spectral component





Magnetic fields in voids: < nG (CMB constraints) and > fG (*Fermi*-LAT/HESS/VERITAS)

Gamma-ray absorption in photon fields

Absorption, exp(-τ), with:

$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon' \frac{\partial n}{\partial \epsilon'}(\epsilon', z) \int_1^{-1} d\cos\theta \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma}(E_\gamma \times (1+z), \epsilon, \cos\theta)$$

Cosmology — EBL photons — Particle physics

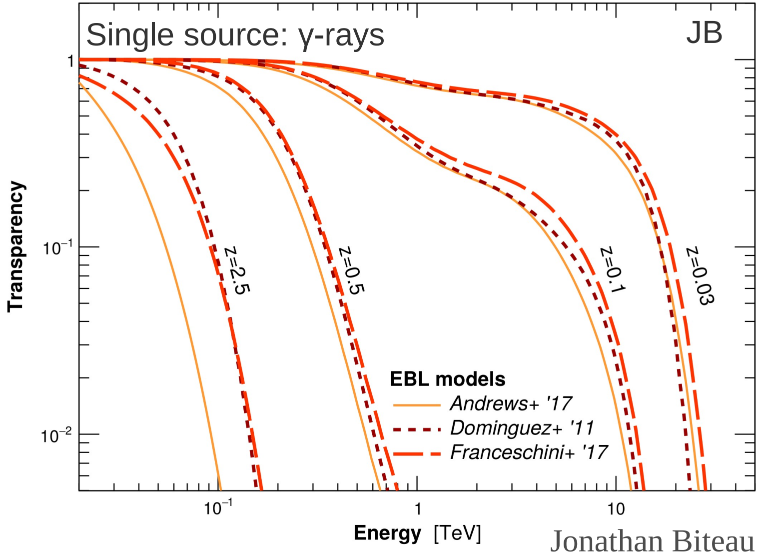
Target photon field

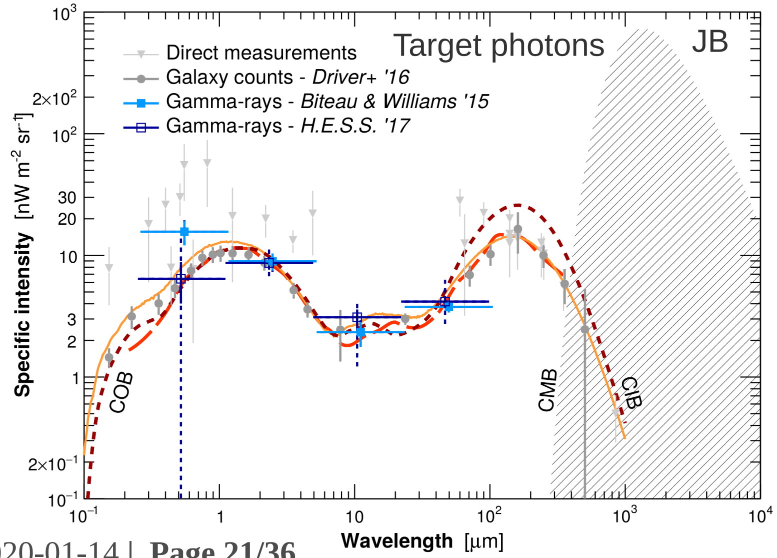
EBL underconstrained by direct measurements (bright foregrounds)

Single-source γ-ray spectra: inflections trace the EBL spectrum

γ-ray imprint

Local (z < 0.5) EBL measurement with 20-30% accuracy, matches galaxy counts (±20% at most λ)





Evolution of absorption at z > 0.5

Cosmic star-formation history (CSFH)

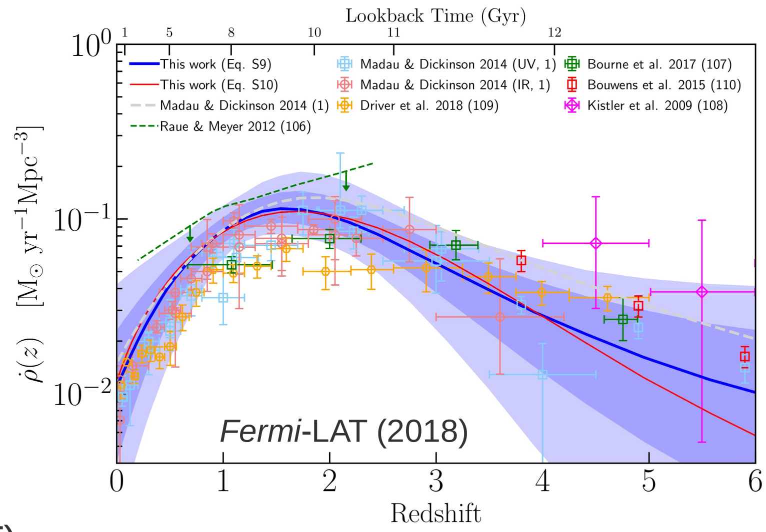
EBL photon density dictated by luminosity density (emissivity)

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

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

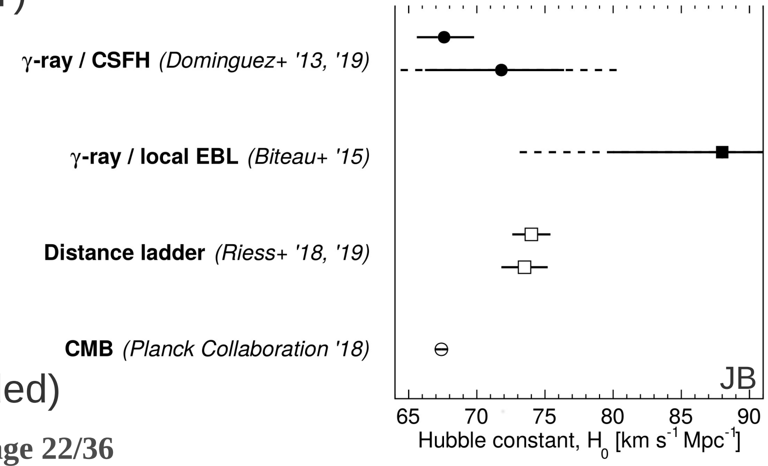
Absorption distance element ~ H_0^{-1} & emissivity ~ H_0^3

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)



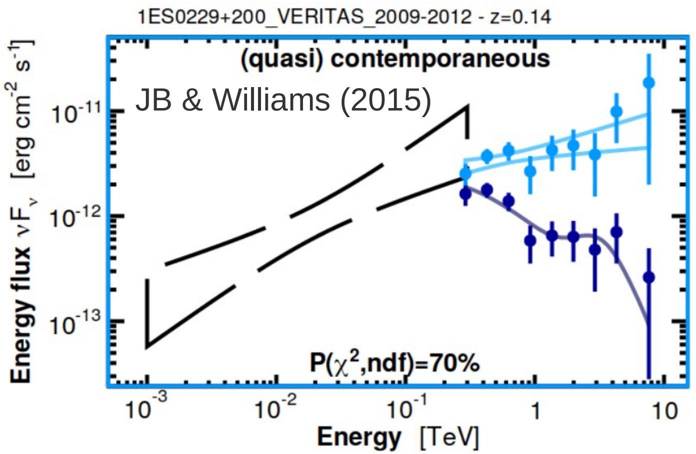
γ-ray and cosmic-ray sources

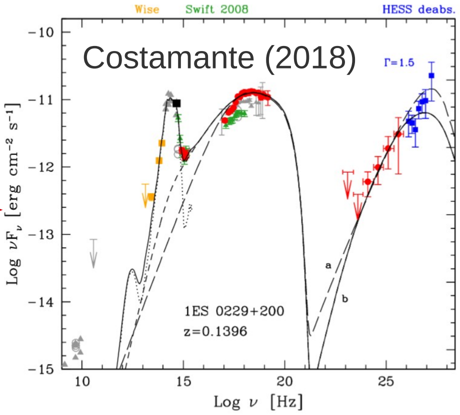
Inferring the astrophysics of accelerators

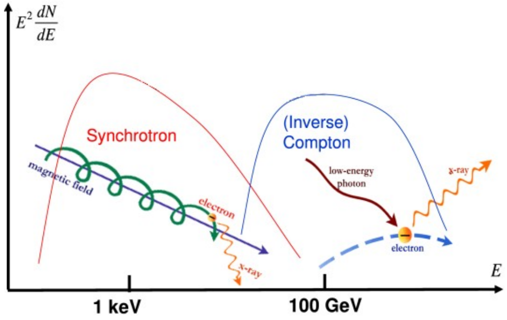
Observations: γ-ray and multi-wavelength bands

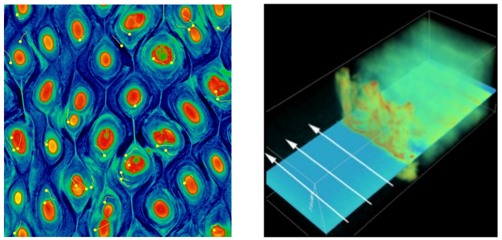
GeV-TeV data: harness of the γ-ray emission, location of peak energy

Combined with optical – X-ray data: common or distinct origin

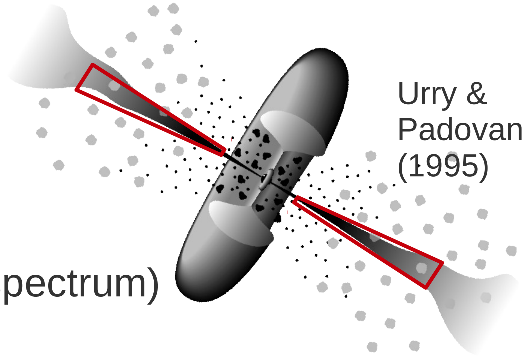








Sironi & Spitkovski (2011)



Urry & Padovani (1995)

Models: radiative processes, acceleration and environment

Low-energy component: synchrotron from $e^{+/-}$

High-energy component: Compton from $e^{+/-}$, p synchroton, pγ / pp

→ R, B, Γ (luminosity + peak location) → shock / magnetic reconnection (B, p/e spectrum)

Lessons learned on extreme sources' properties

Example: extreme blazars

Active galaxies with 1st component peaking > 1 keV (*extreme-synchrotron* blazars, ~200 known w/o bias)
and/or 2nd component peaking > TeV (*extreme-TeV* blazars, ~14 known with bias)

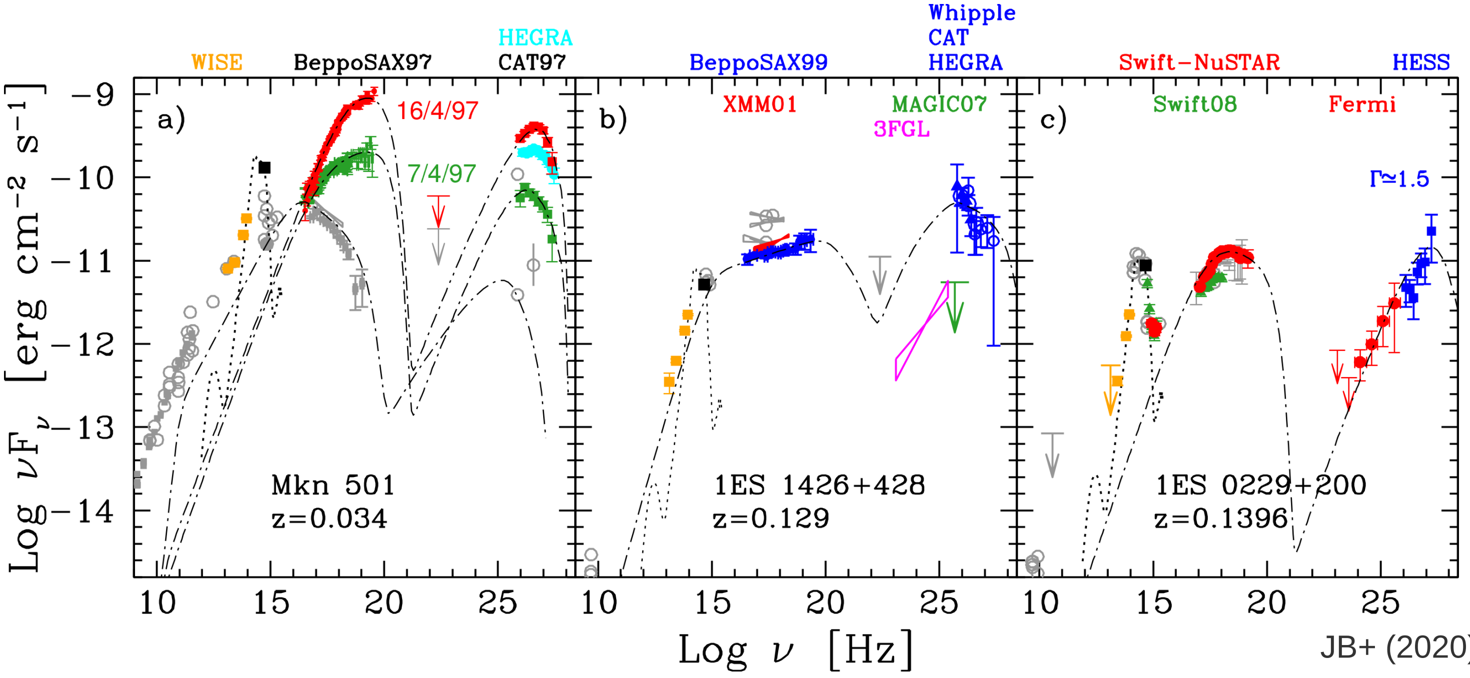
Hard TeV emission up to a few TeV → ideal targets for CIB constraints, IGMF studies, as well as exoticas

Small-amplitude variations & slow flux variability:

→ best candidates for **hadronic emission** among blazars

High synchrotron peak frequency: fast accelerators (low t_{acc} / t_{Larmor})

→ best candidates for **UHECR acceleration** among blazars



JB+ (2020)

Lessons learned on extreme sources' properties

Modeling extreme TeV blazars

- Spherical cow: **SSC conical**

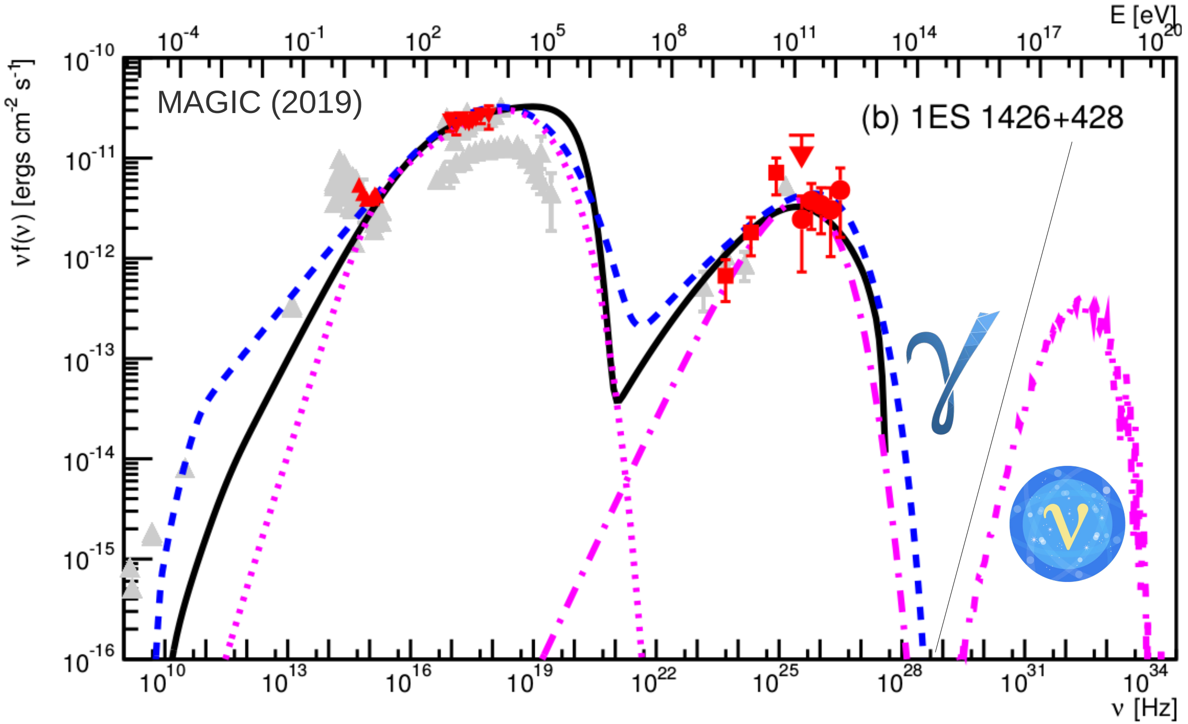
  low magnetization → shocks favored
  but out-of-equipartition: high-jet power

- Two flows **spine-layer**

  jet power / 10-100 wrt SSC but struggle
  to produce high peak frequency
  due to losses

- Mixed flavor: **proton synchrotron**

  low ν flux beyond IceCube reach;
  proton break beyond the UHECR ankle



Only the brightest

What photons tell us

A bestiary of of accelerators:

- pulsars and magnetars: $r \sim 10^7$ cm, $B > 10^{10}$ G, $\Gamma \sim 1$

...

- jets of active nuclei: $r \sim 10^{17}$ cm, $B > 10^{-3}$ G, $\Gamma > 10$

...

- clusters: $r \sim 10^{25}$ cm, $B > 10^{-6}$ G, $\Gamma \sim 1$

Hillas: only the highest energy

Confinement: large B-field, size, and shock velocity

$$B \times (r \times \Gamma) \times v_{shock} > (E / Ze)$$

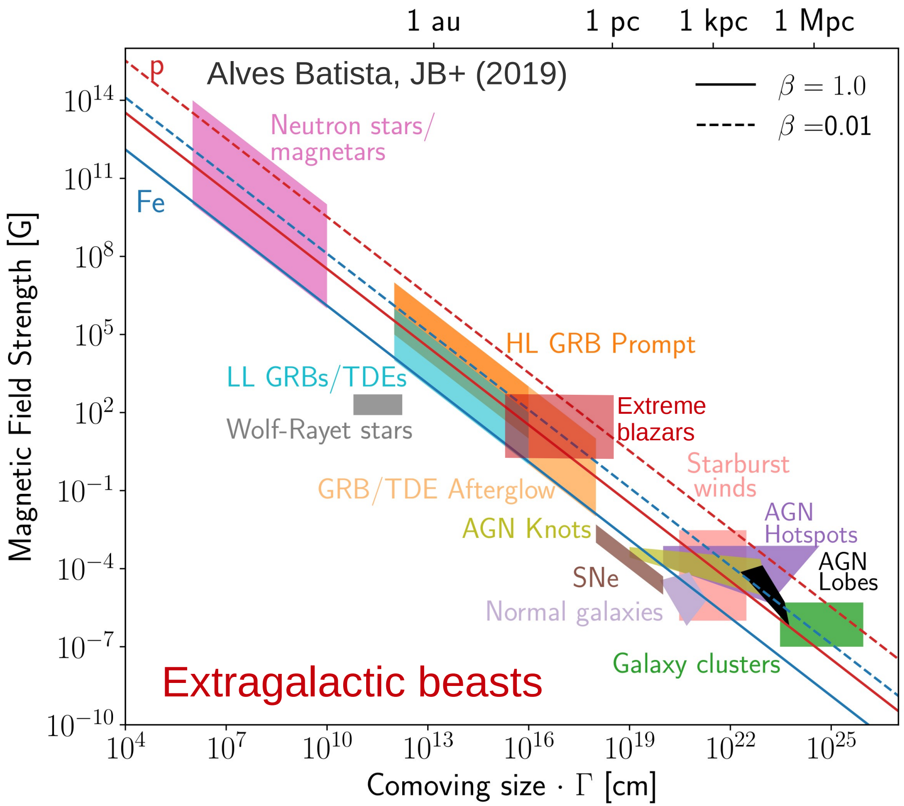
Hillas-Lovelace-Waxman: only the brightest

In an expanding plasma, magnetic luminosity:

$$L_B > 10^{45} \text{ erg/s} \times (E/Z / 10 \text{ EV}) \times (\Gamma^2 c / 100 v_{shock})$$

Large magnetic luminosity → large synchrotron emission

→ UHECR sources hidden among brightest photon emitters



Only the numerous

What cosmic rays tell us

To reproduce the UHECR flux above the ankle:

number density x luminosity > 10^30 UHECR / Mpc³ / s

No significant self-clustering above flux suppression:

number density > 10^-5 / Mpc³ (if deflections < 30°)

Sorting galaxies and transients

Account for spread in time Δτ ~ 10^5 years:

number density = burst rate x Δτ

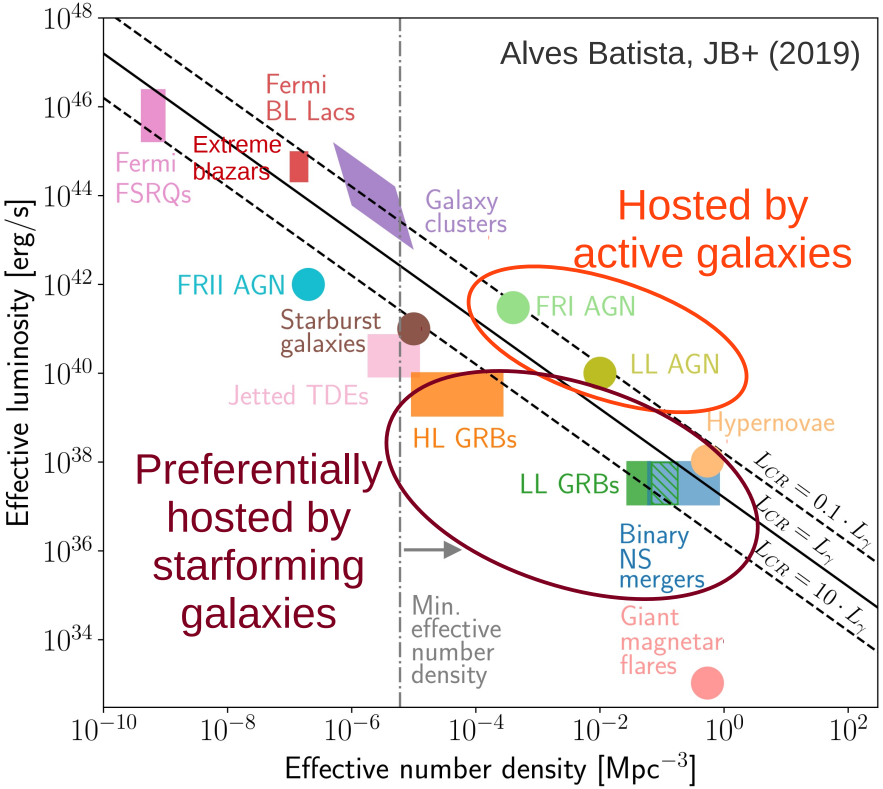
luminosity *= burst duration / Δτ

Seaching for ultra-high-energy accelerators

If scaling of cosmic-ray & electromagnetic luminosities:

→ select the brightest host galaxies within few 100's Mpc

→ check if the all-sky flux patterns match



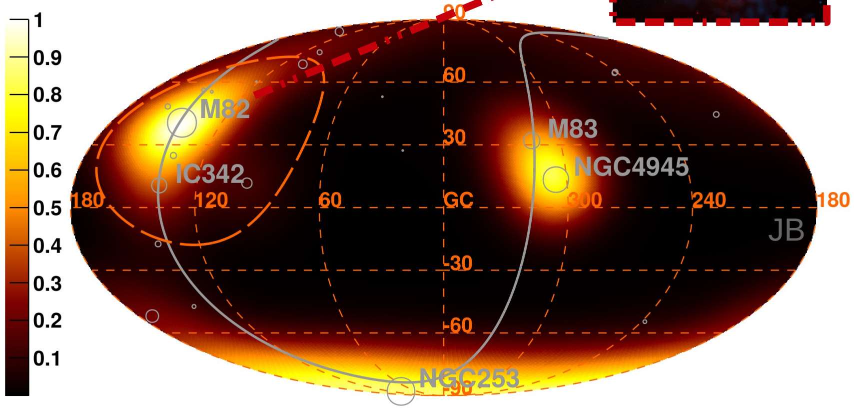
Starforming and active galaxies in the local universe

Starburst galaxies

= starforming galaxies with high star formation rate

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)

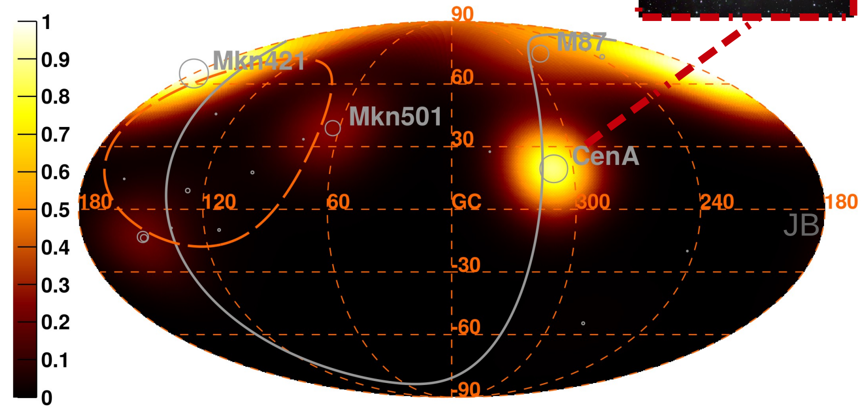
Radio luminosity to trace UHECR emission

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)

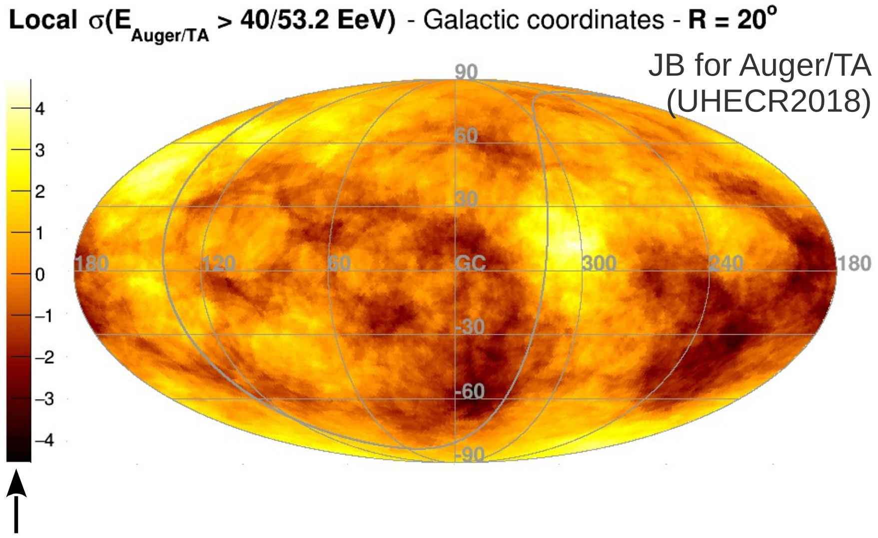
γ-ray luminosity to trace UHECR emission

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

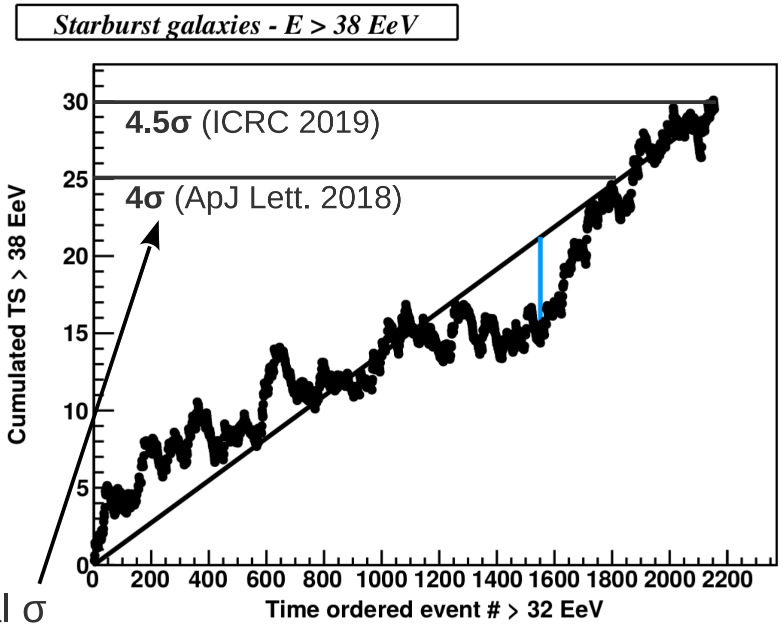


Local σ

Catalog-based searches

Assumption: UHECR flux ∝ electromagnetic flux × propagation effects

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



Global σ

Quite promising excess, stay tuned!

The most extreme accelerators
and how to find them

The road so far...

	Known knowns	Known unknowns
Origin of Cosmic Particles		
• What are the mechanisms for cosmic particle acceleration?	Shocks, magnetic reconnection	Which dominates where? Others?
• What are the sites of particle acceleration in the universe?	Entire bestiary, from pulsars to clusters	UHECR sources ν sources
Extreme Environments		
• What physical processes are at work close to neutron stars and black holes?	Importance of magnetosphere	Competition of acceleration/losses
• What are the characteristics of relativistic jets, winds and explosions?	Constraints on size, B-field, velocity	Favored geometry, hadronic content
Propagation and Frontiers in Physics		
• What is the charge of the highest-energy cosmic rays? How are they affected by magnetic fields?	Increasing < 40 EeV ~ Galactic with fixed Z	Charge > 40 EeV LSS, extragalactic
• How intense are radiation/magnetic fields in cosmic voids?	COB, B < nG	CIB, B > fG
• Do exotic processes affect propagation of astroparticles?	Above Planck scale Not outside DM space	Tighter parameter space

Charge of the highest-energy cosmic rays

Auger Prime

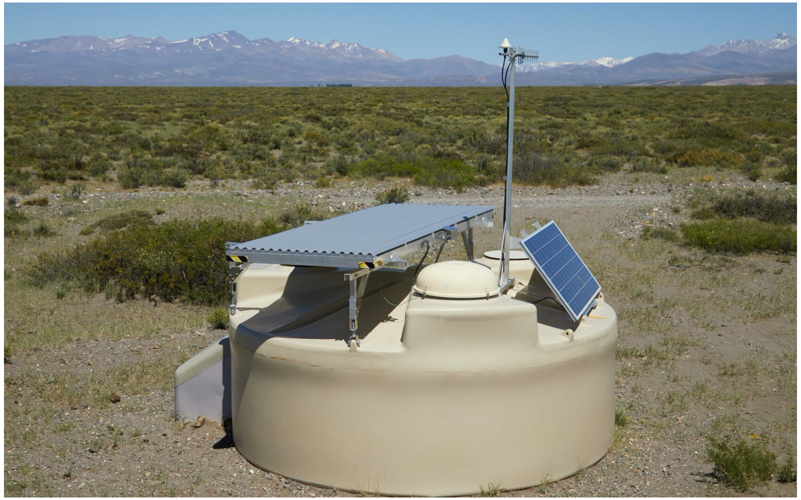
Upgrade of 1,600 surface array detectors

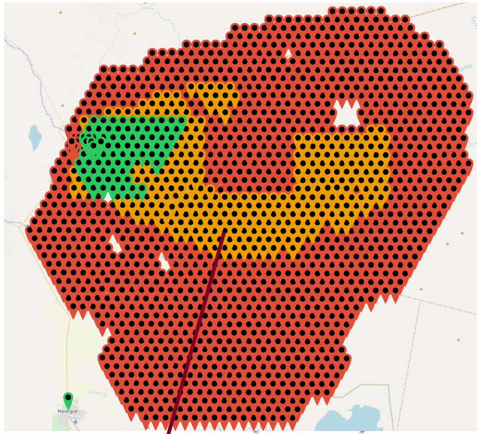
Equipped (in particular) with scintillators

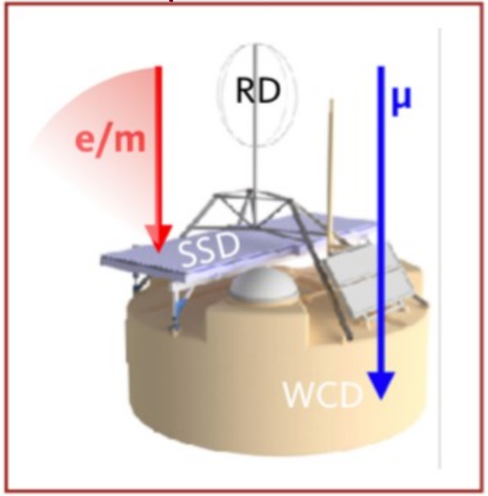
Discrimination of e/μ components

Composition-dependent observables with 100% duty cycle

Castellina for Auger (ICRC2019)







Known unknowns

Which dominates where? Others?

UHECR sources

ν sources

Competition of acceleration/losses

Favored geometry, hadronic content

Charge > 40 EeV

LSS, extragalactic

CIB, B > fG

Tighter parameter space

Cosmic magnetism

Upcoming multi-wavelength facilities

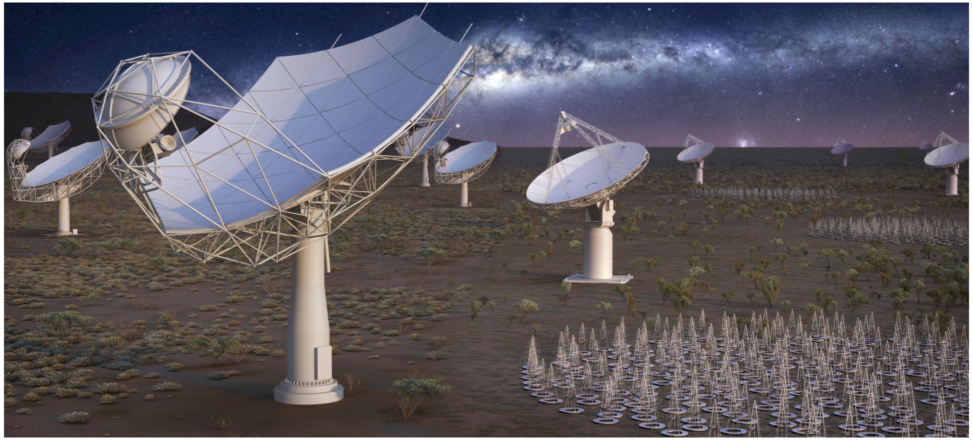
At all wavelengths, for all messengers

At radio frequencies: SKA

Based in Australia and South Africa

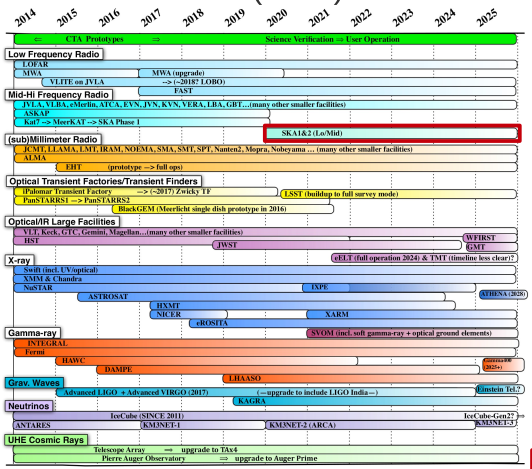
Constraints on magnetic fields

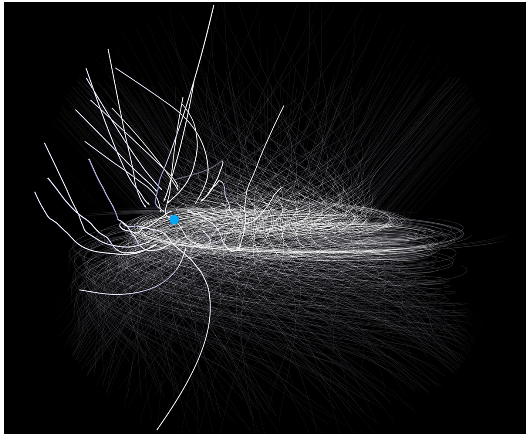
Galactic, clusters and intergalactic (FRBs, Vaza+ 2018)



Credit: SKA Collaboration

CTA Consortium (2019)





Farrar & Sutherland (2015)

Known unknowns

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Tighter parameter space

Environment of accelerators

Cherenkov Telescope Array

Upcoming γ-ray observatory

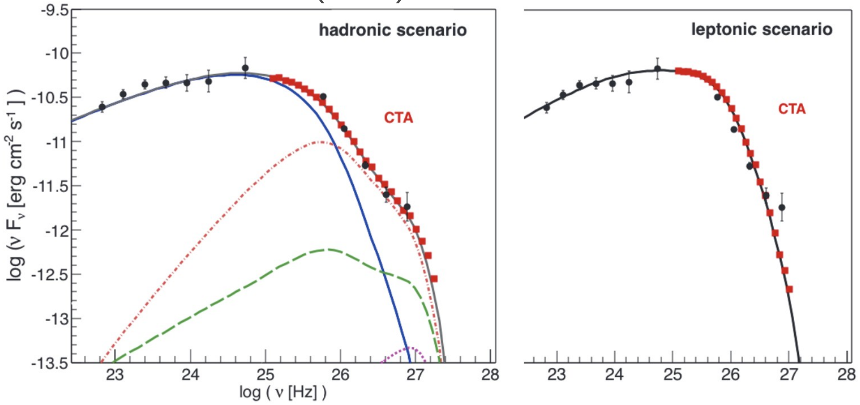
2 sites: Chile & Canary Islands

10-fold increased sensitivity

Full Galactic-plane and
¼ extragalactic-sky surveys

Unprecedented quality γ-ray data

CTA Consortium (2019)



Credit: CTA Consortium

Known unknowns

Which dominates where? Others?

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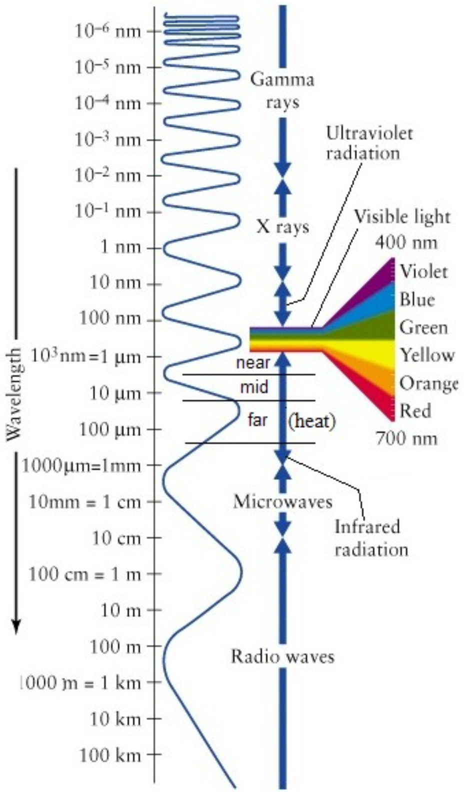
Charge > 40 EeV
LSS, extragalactic

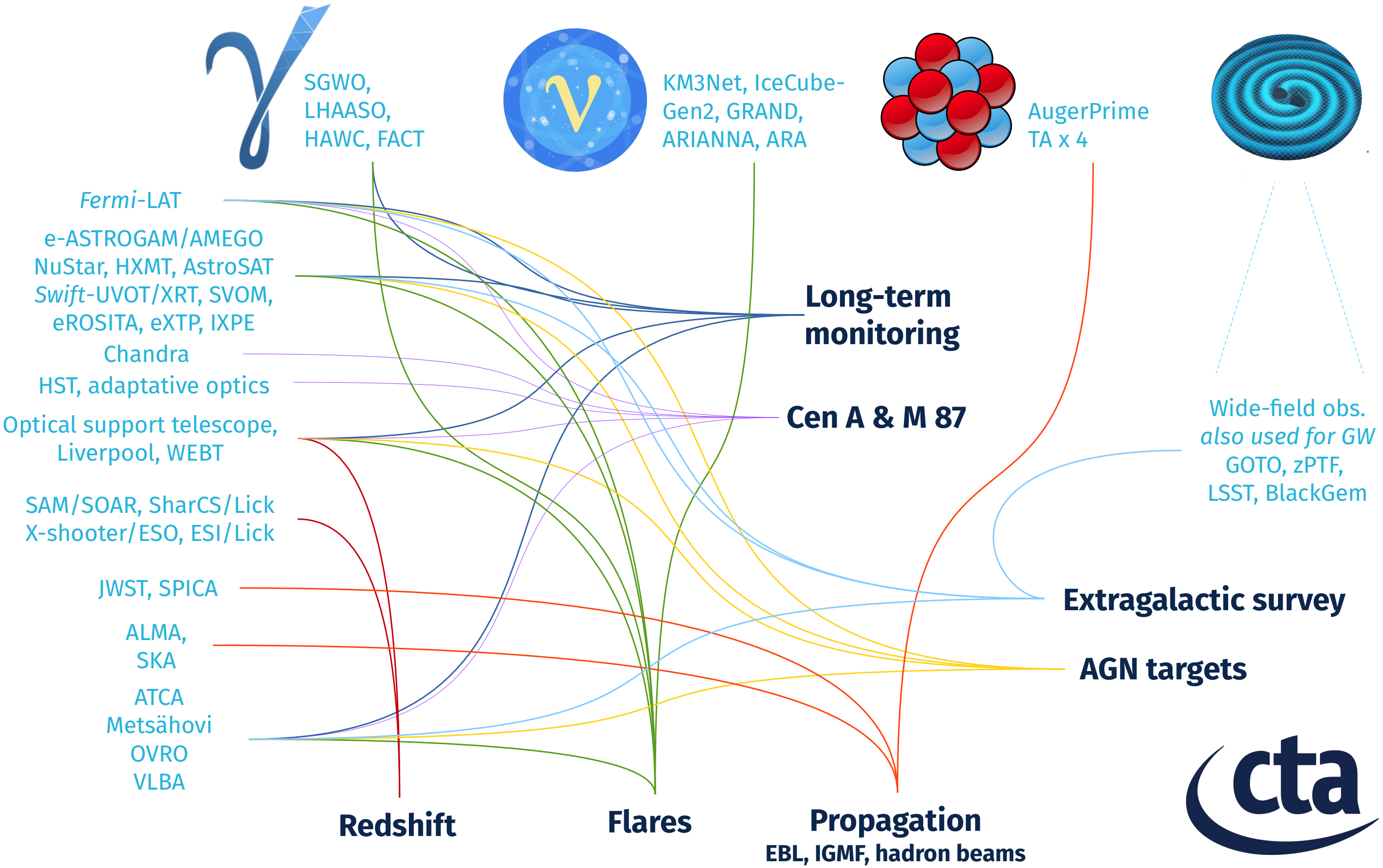
CIB, B > fG

Tighter parameter space

The key for the future: Synergies

example of extragalactic synergies of CTA





My bet with you:
the 2020's will unveil the sources of all these components