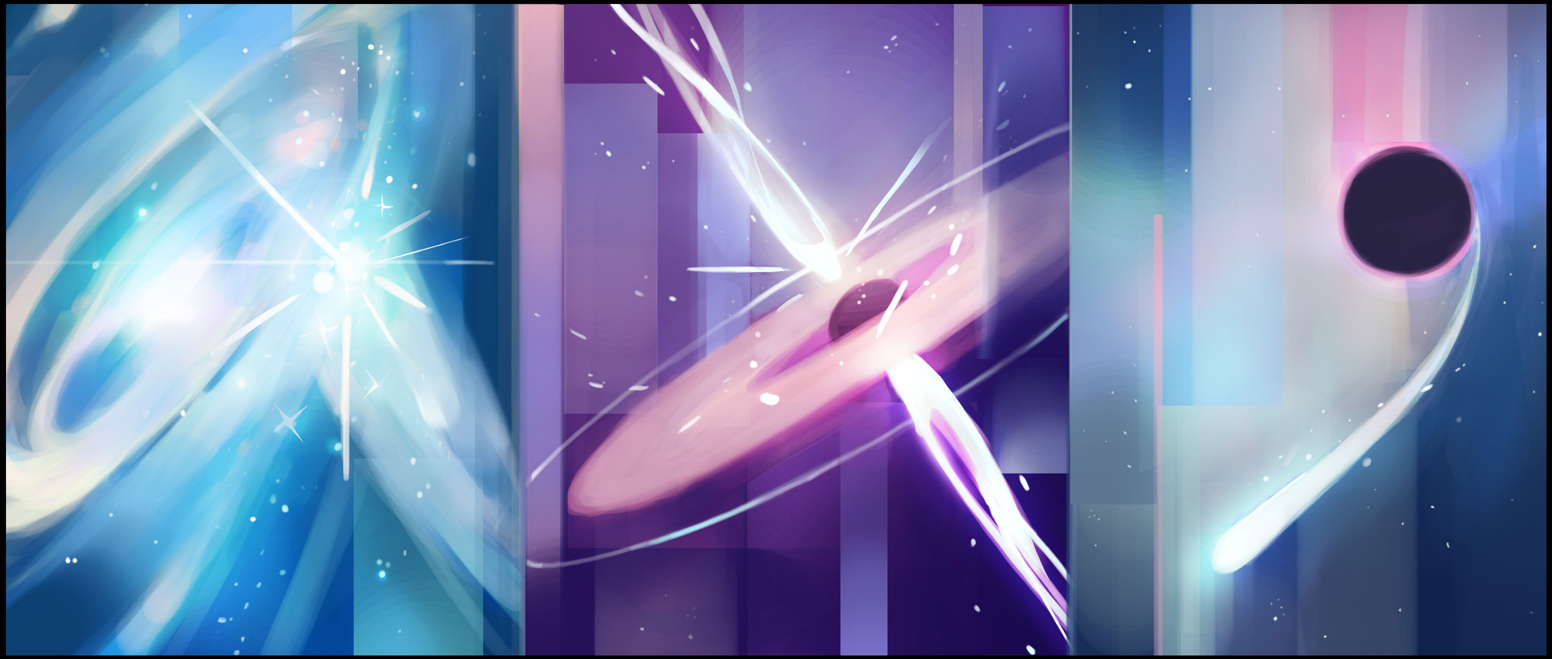
Astrophysical Black Holes:
A Rapidly Moving Field

Hong Kong, June 23-26, 2023

Black Holes as Cosmic Accelerators

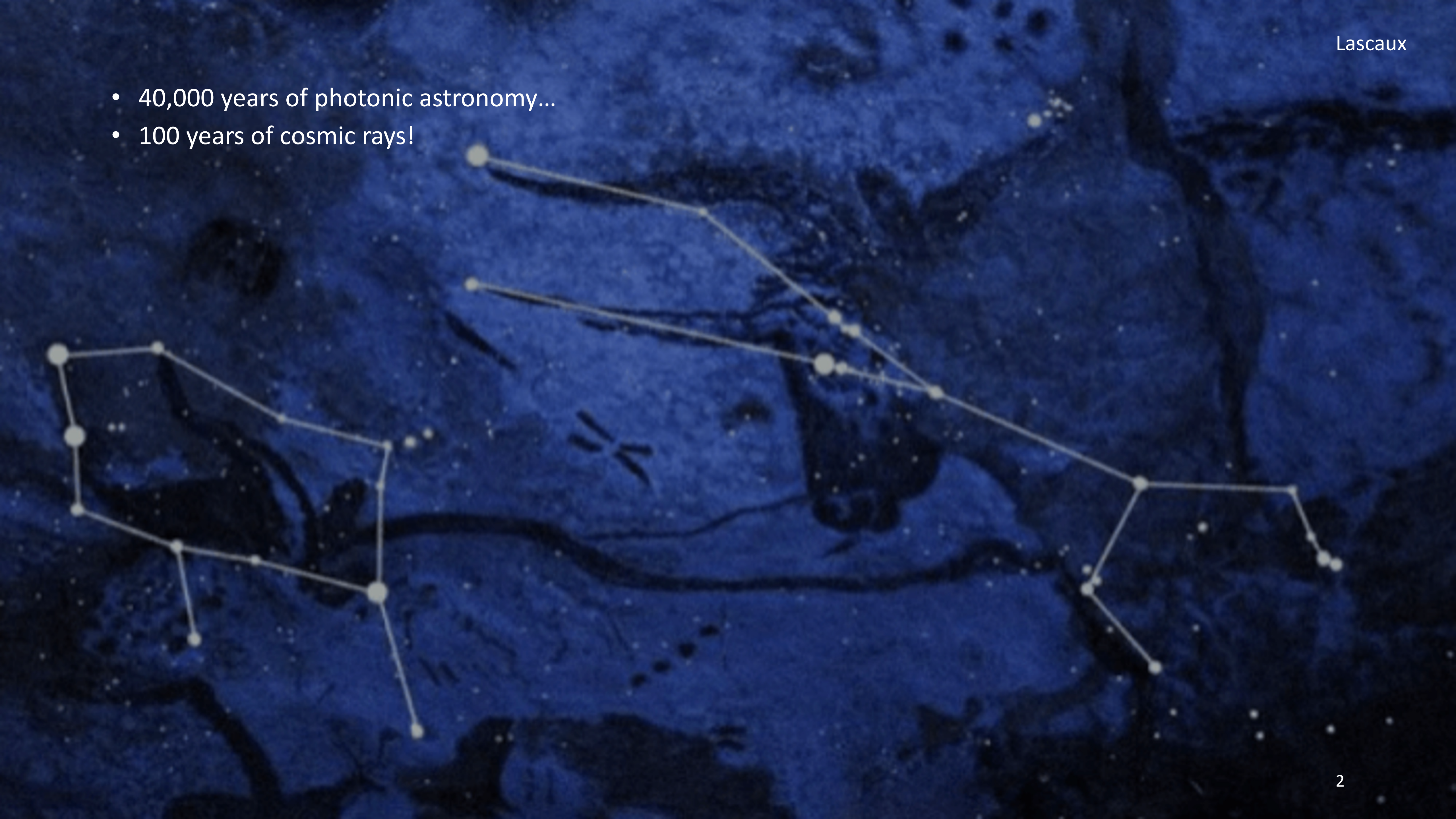
Noémie Globus



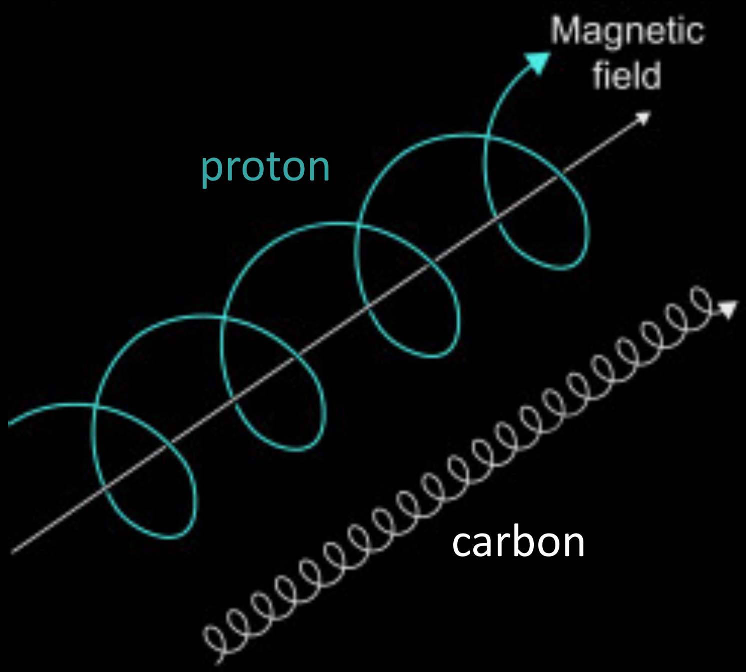
UC SANTA CRUZ located on the unceded territory of the Awaswas-speaking Uypi Tribe

Lascaux

- 40,000 years of photonic astronomy…
- 100 years of cosmic rays!

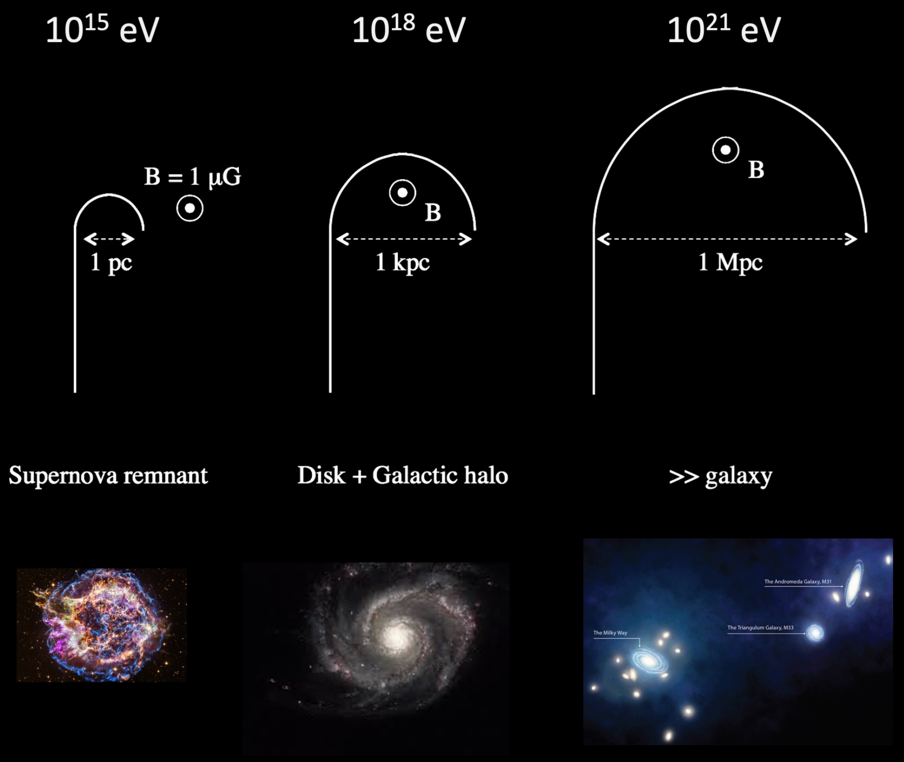


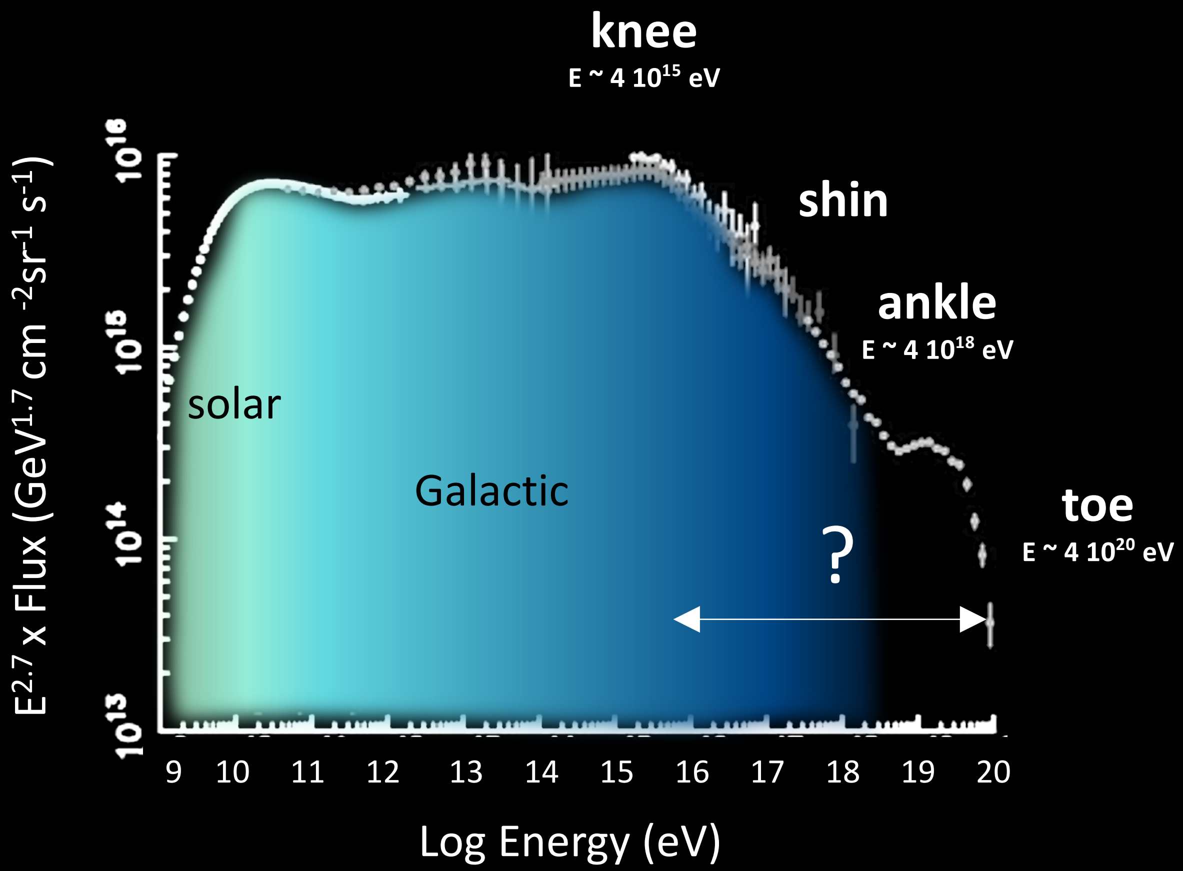
Cosmic rays are not "rays"



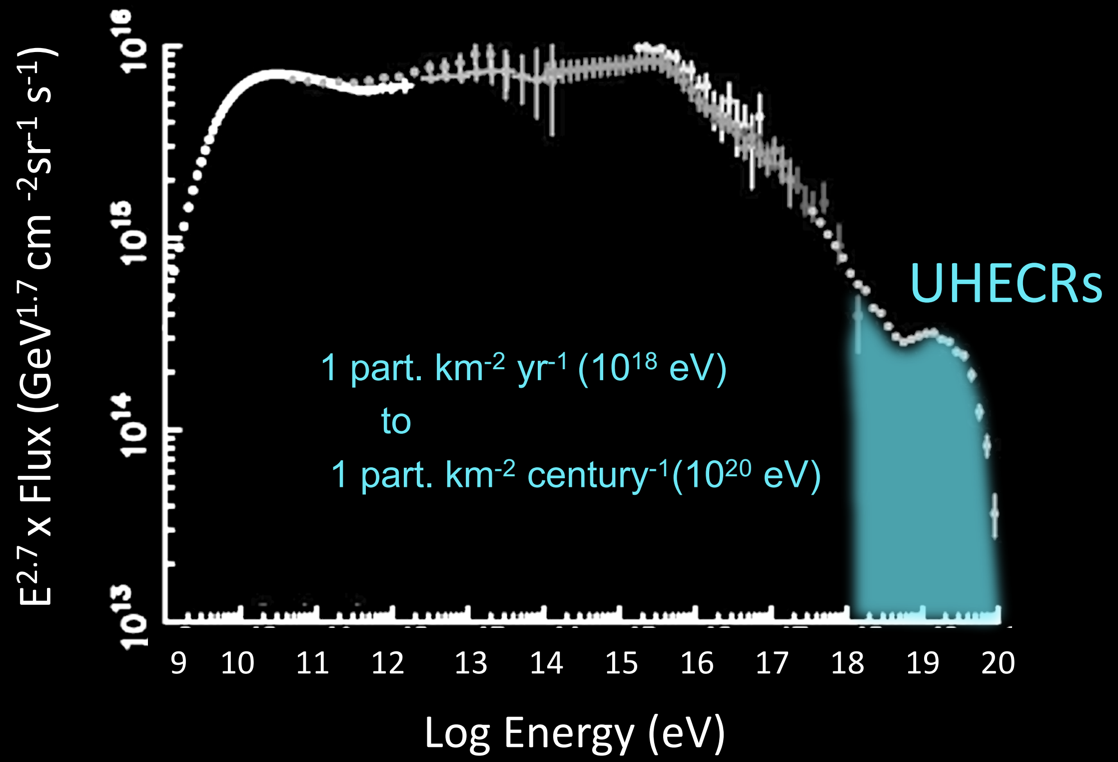
rigidity: $R=E/Z$
gyroradius: $r_g = R/B$

“Anatomy” of the cosmic-ray spectrum

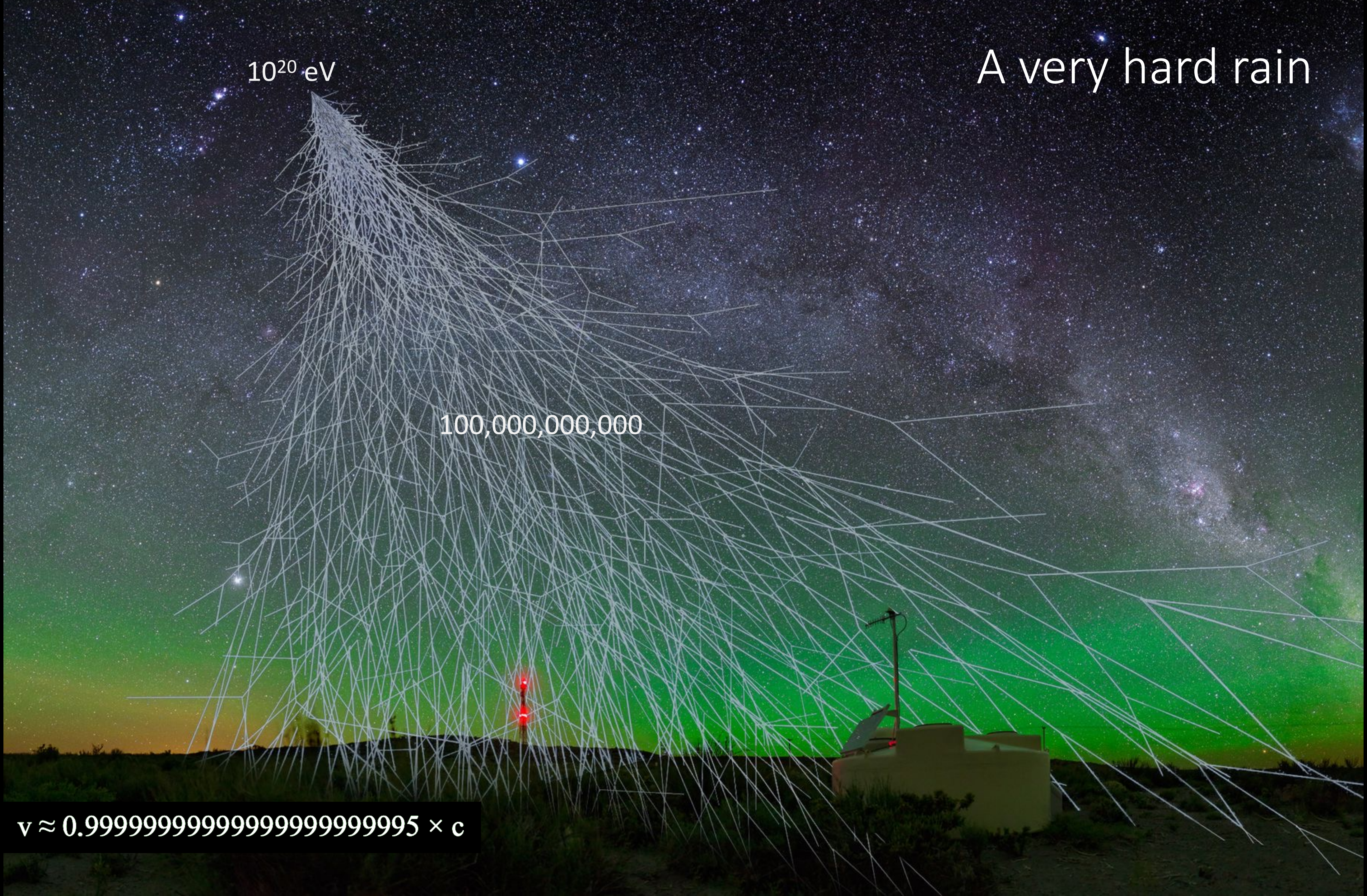




In pursuit of the extremely rare... ultra high energy cosmic rays!



A very hard rain

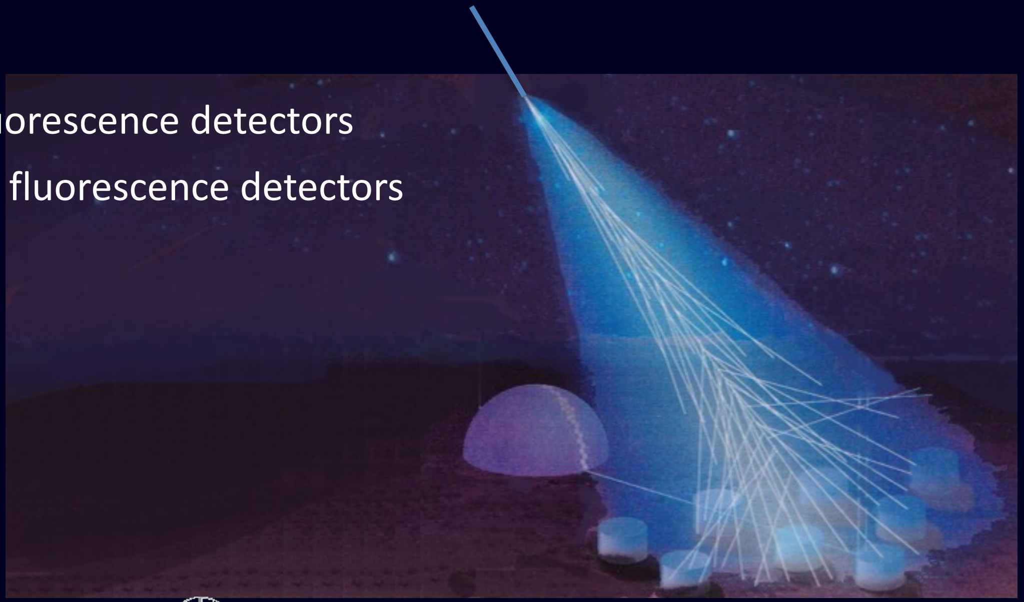


$v \approx 0.99999999999999999999995 \times c$

The two giants

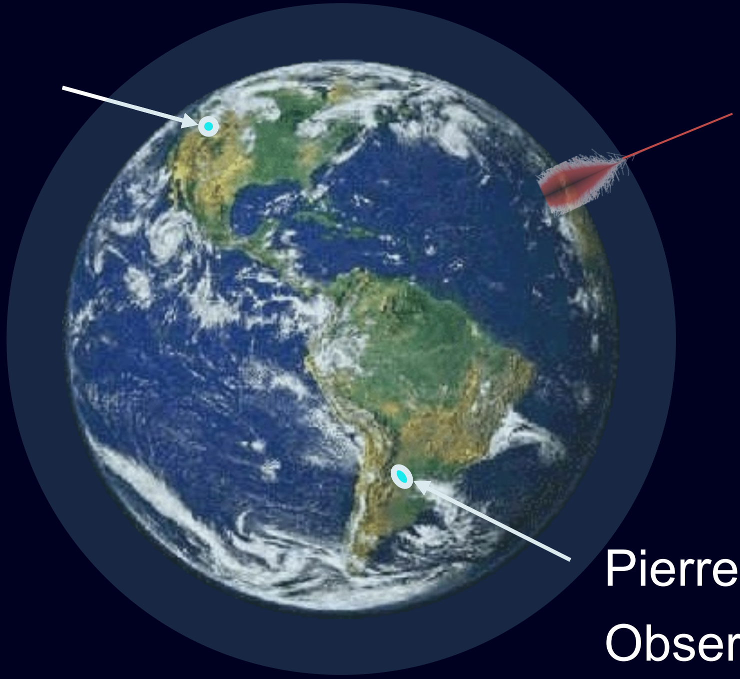
Auger ($10^{18.5}$- >10^{20} eV) : surface 3000 km^2, 1600 detectors, spacing 1500 m, 4 fluorescence detectors

Telescope Array ($10^{18.5}$- >10^{20} eV) : surface 700 km^2, 500 scintillator detectors, 3 fluorescence detectors

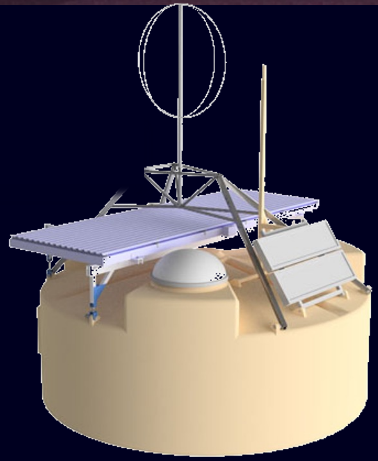


Telescope Array
Utah, USA
(5 countries)

Upgrade: TAx4



Pierre Auger Observatory
Argentina
(19 countries)

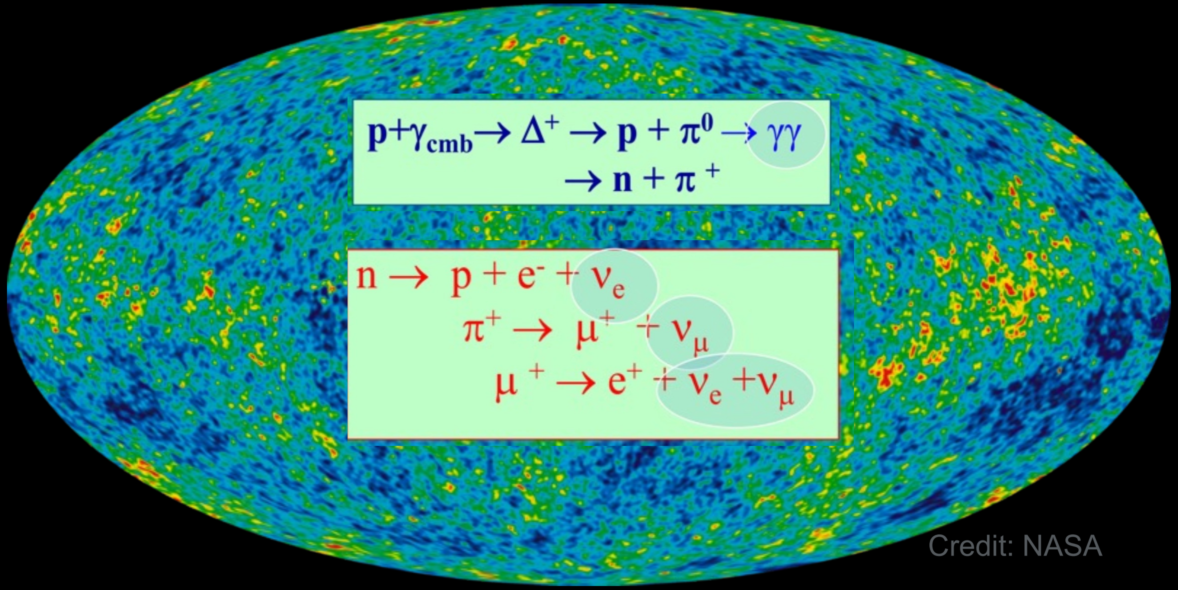


Upgrade: AugerPrime
SSD + radio

Observables: energy, arrival direction, composition

Source spectrum ≠ observed spectrum

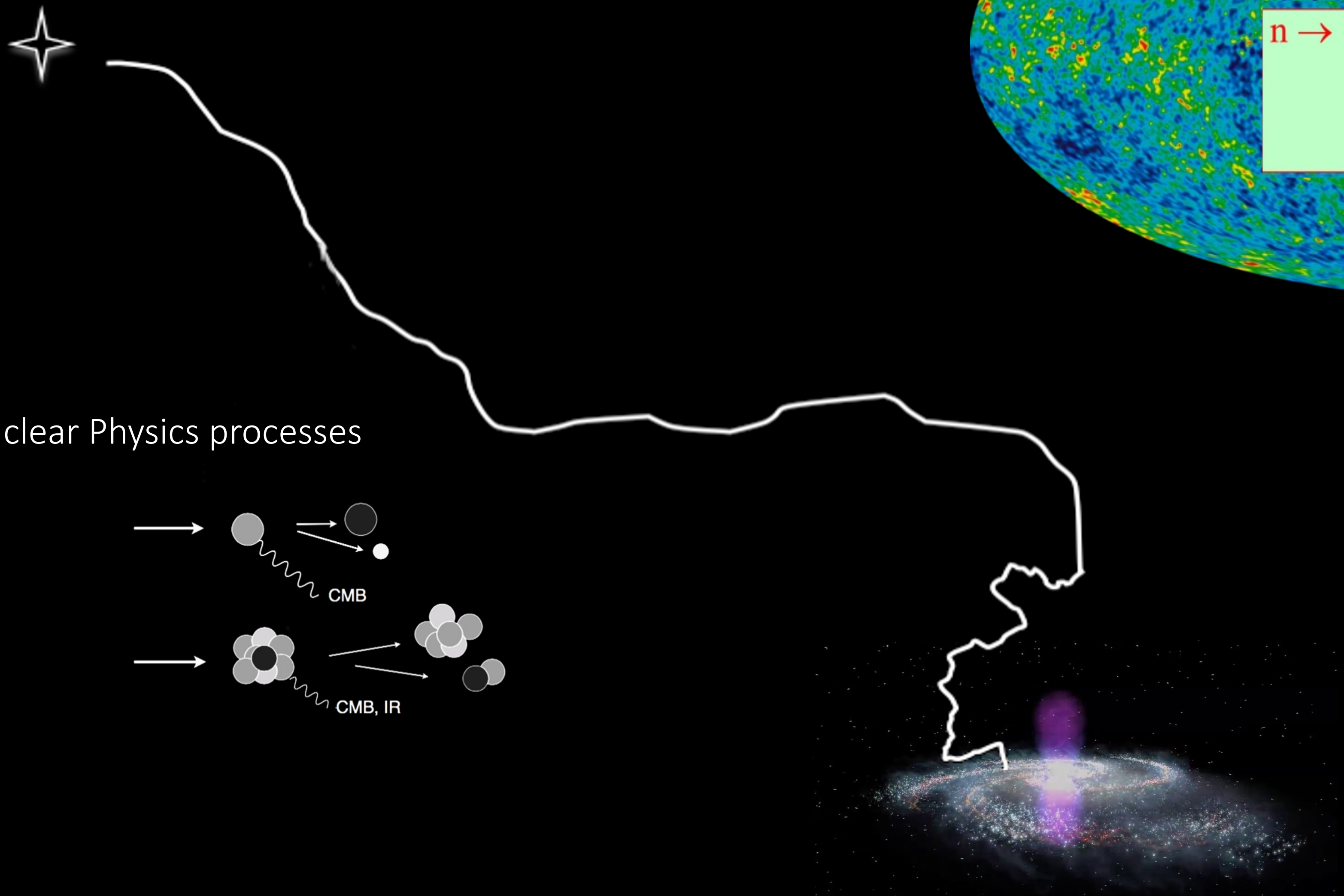
Greisen-Zatsepin-Kuzmin (GZK) effect, 1966



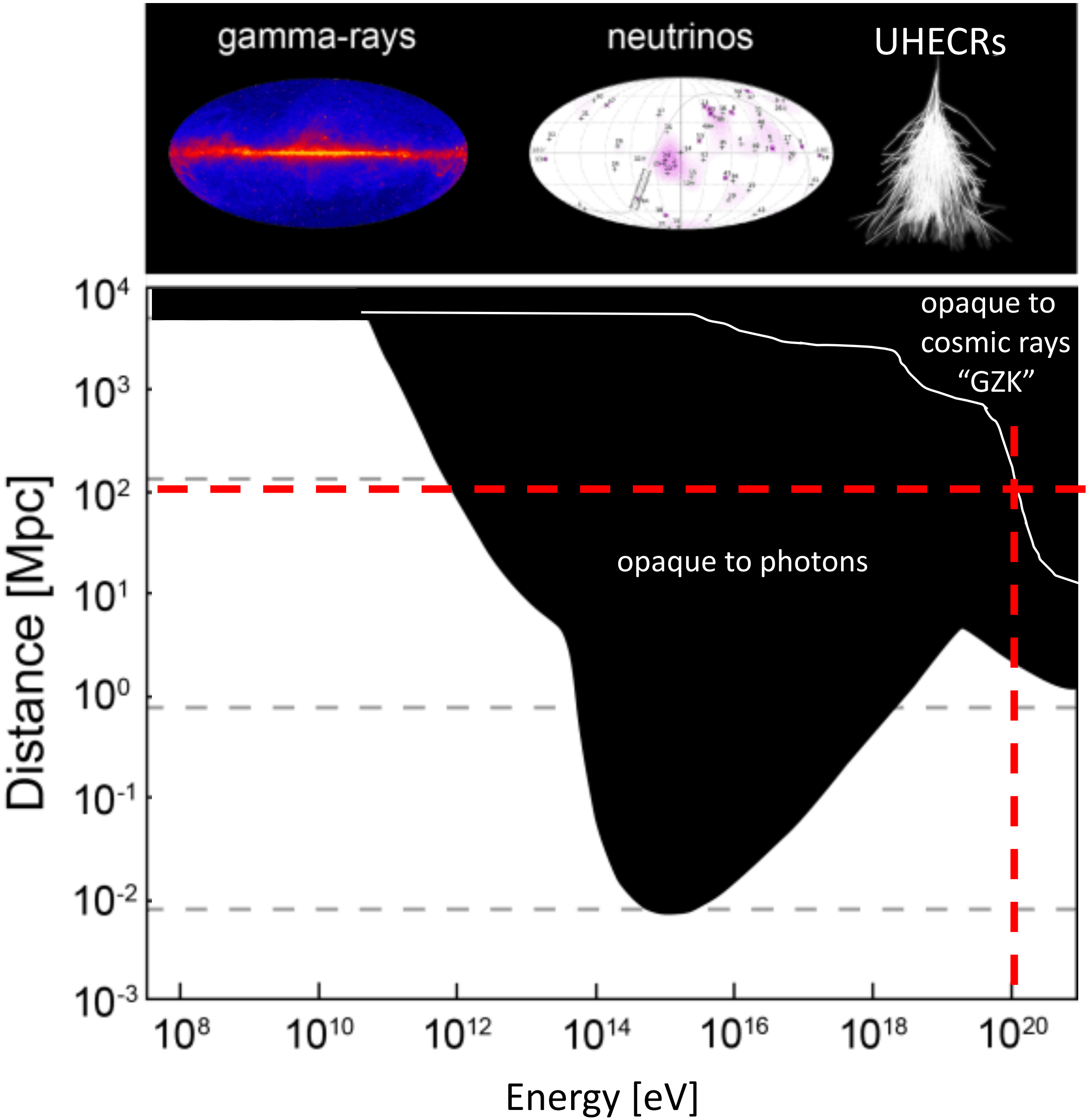
Credit: NASA

Extragalactic sources

Nuclear Physics processes

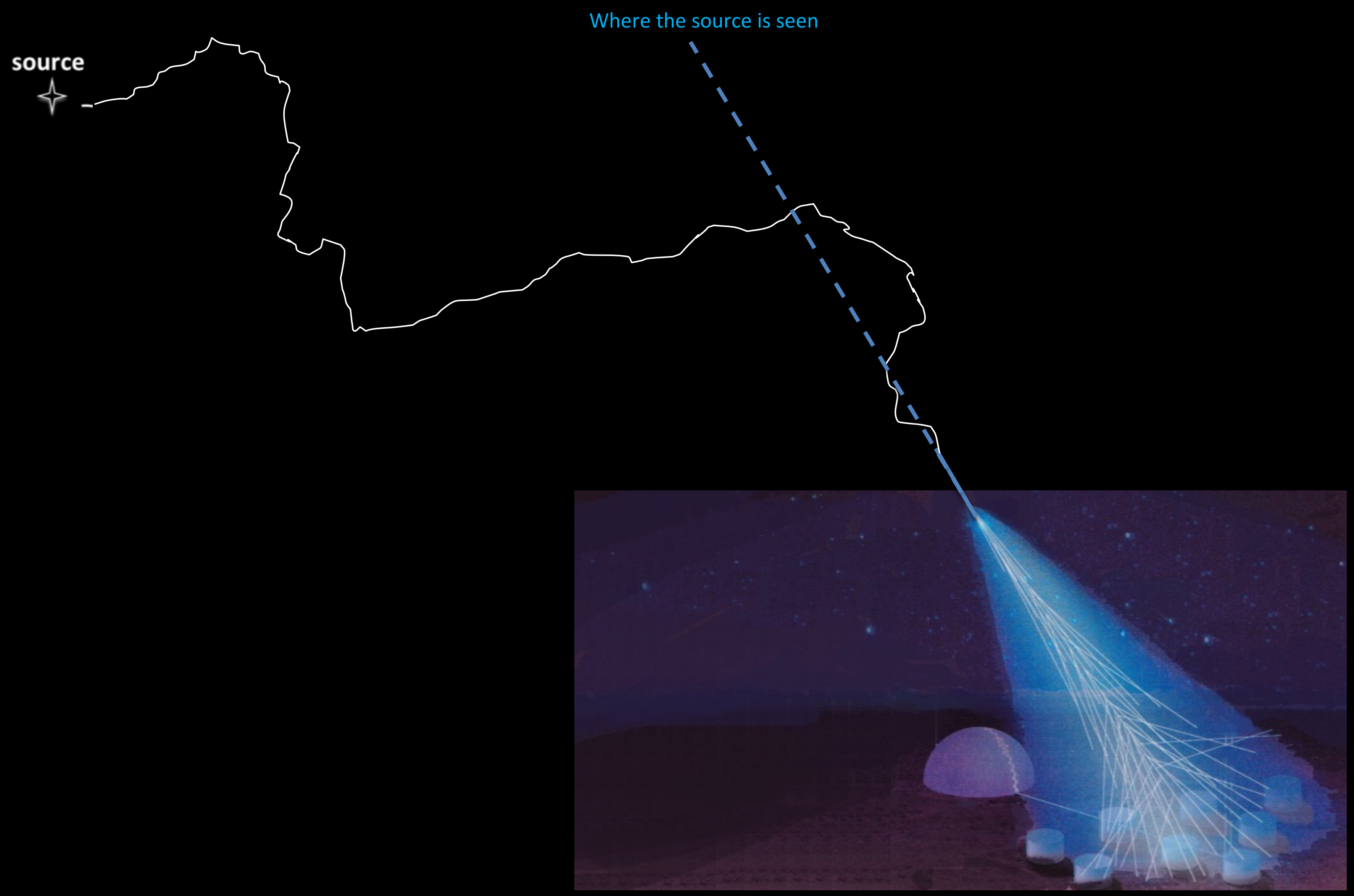


Consequence: UHECR observable universe

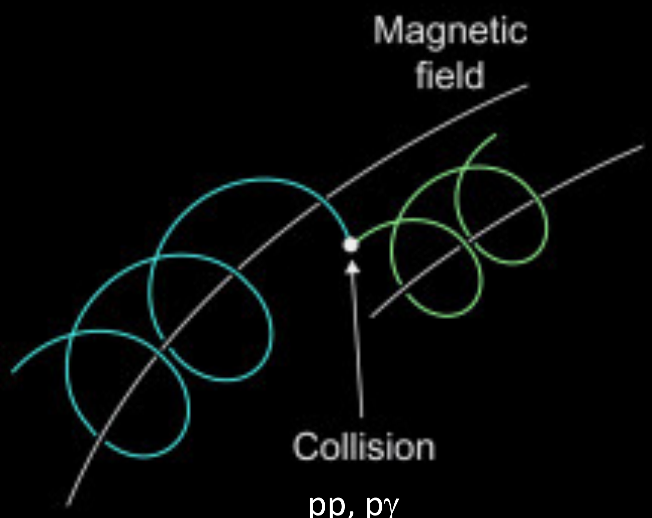


100 Mpc!
local universe!
sources?

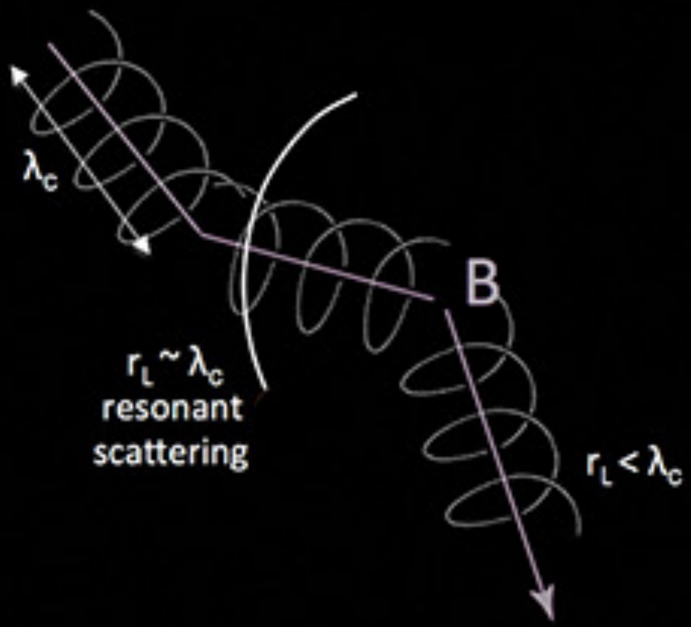
Source direction ≠ observed direction



Cosmic-ray transport

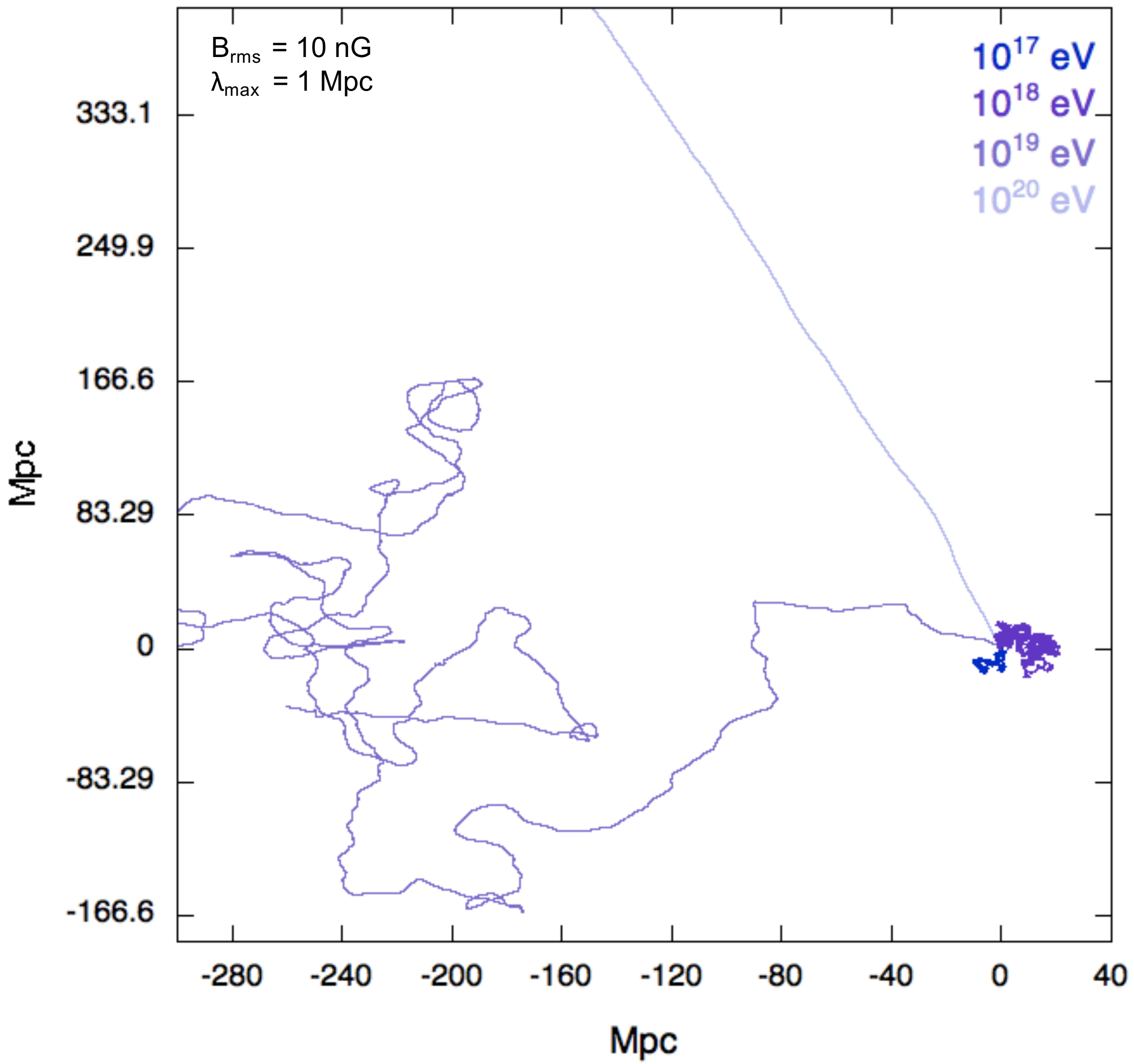


energy loss



diffusion

Diffusion in the extragalactic magnetic field

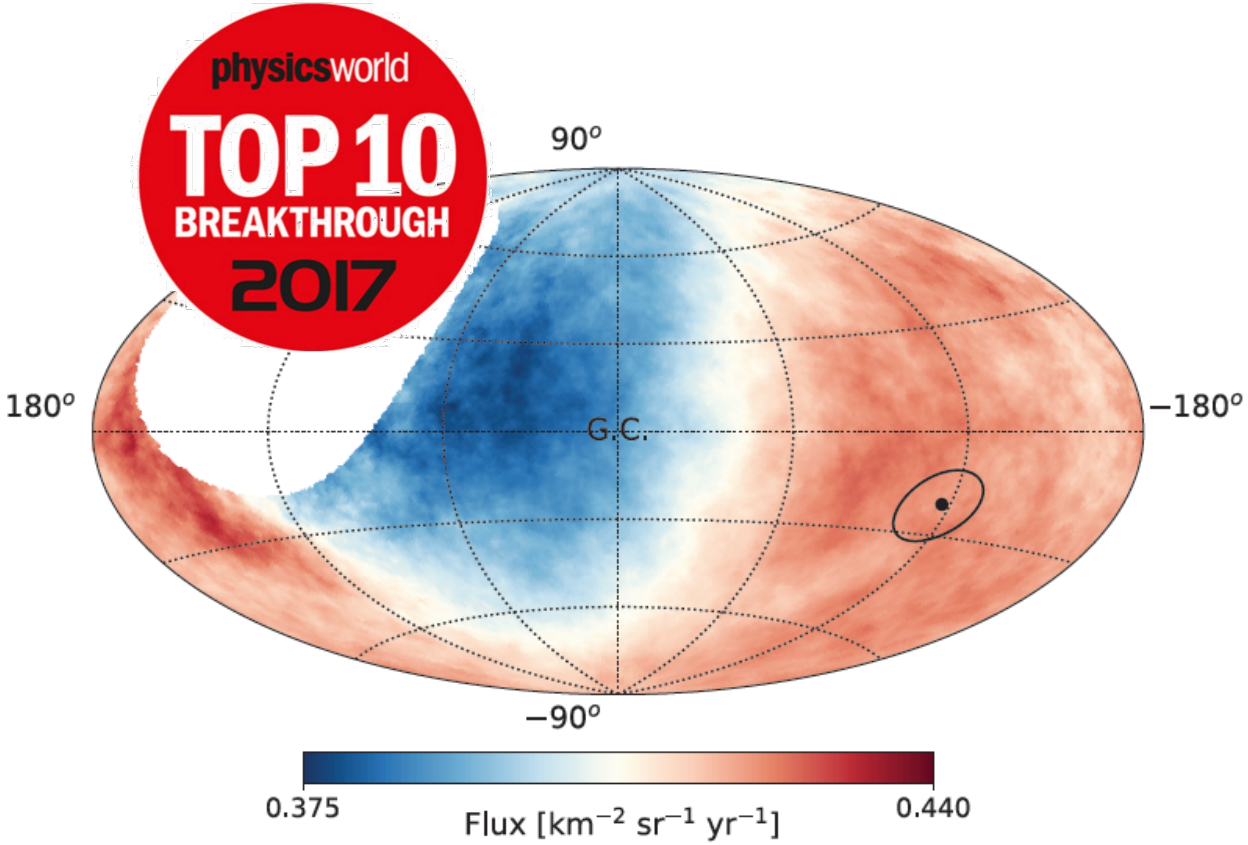


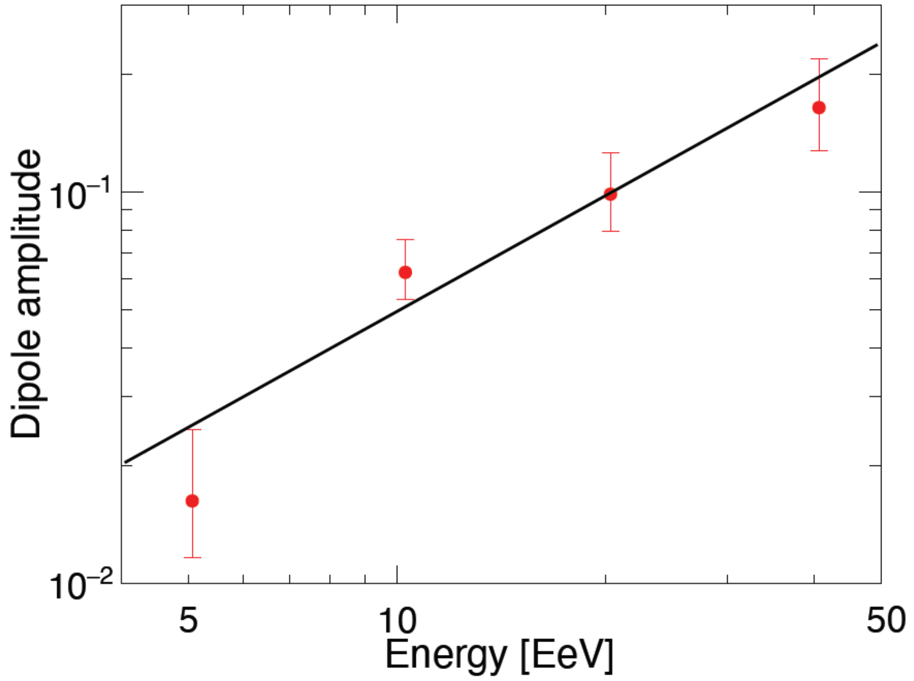
Globus, Allard and Parizot 2008


© Pierre-Paul Feyte

2017: Discovery of a large-scale cosmic-ray anisotropy!

Pierre Auger Collaboration

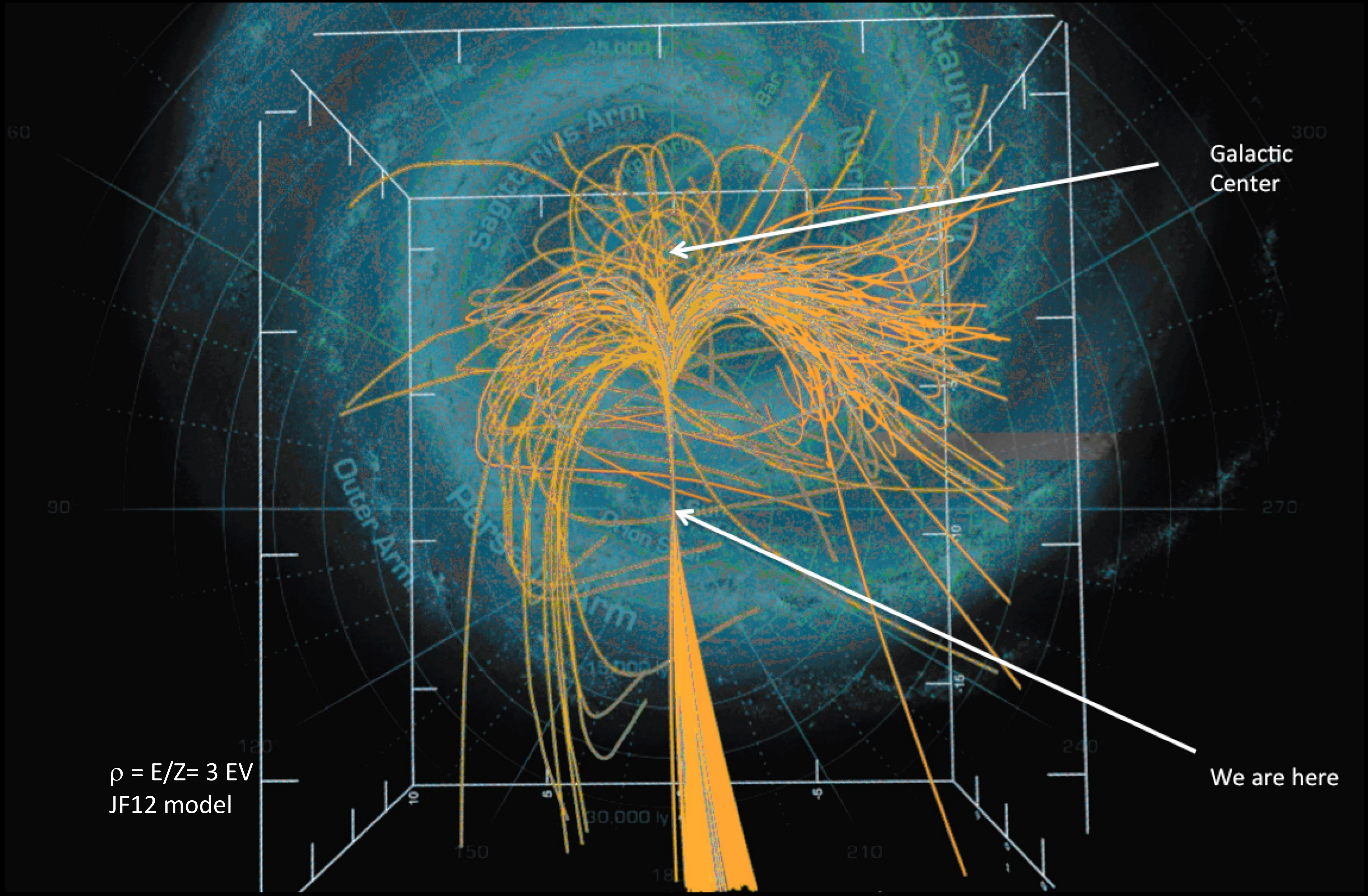




significant above 8 10^{18} eV

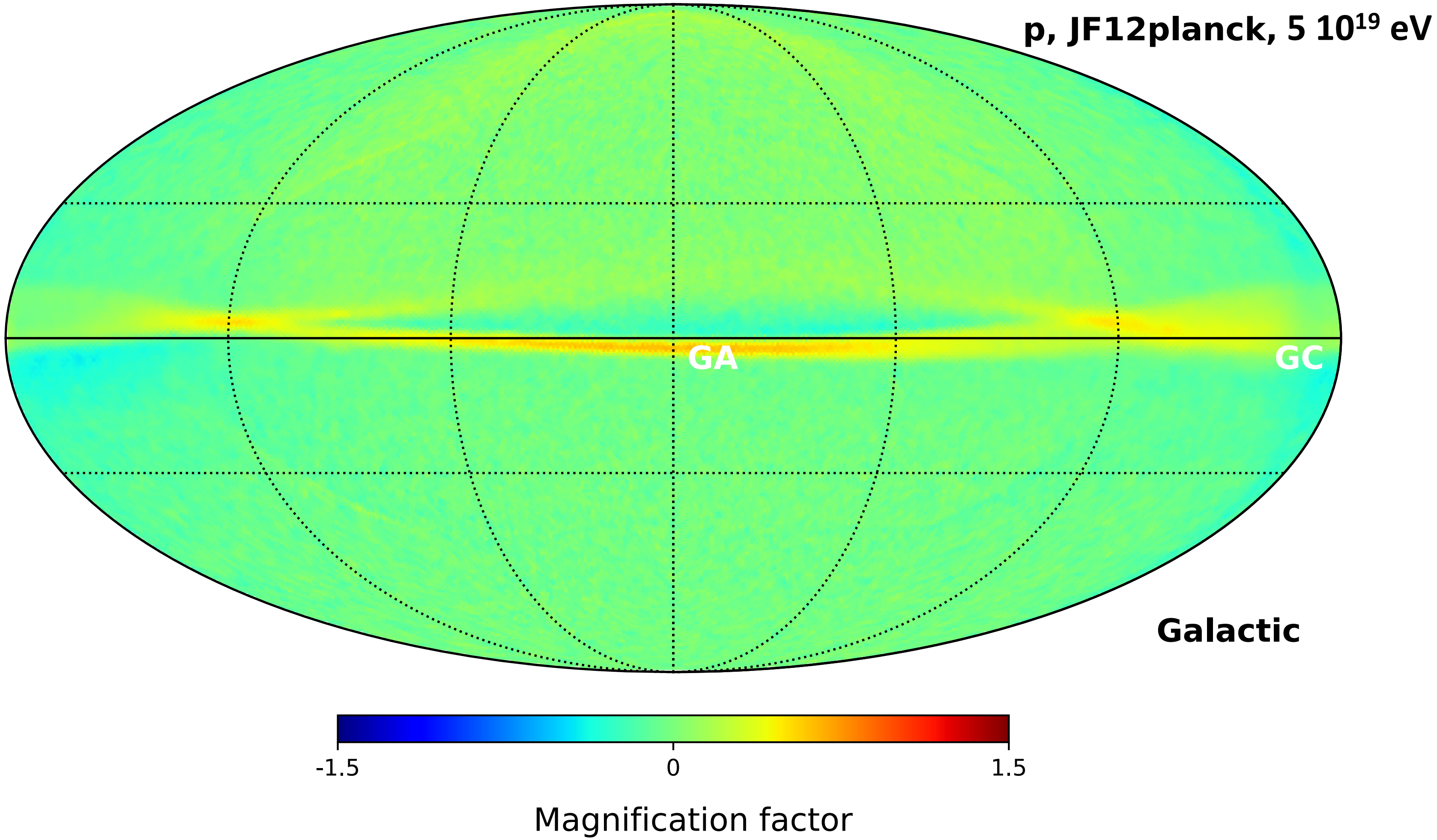
Lensing by the Galactic Magnetic field

Globus and Eichler, 2016



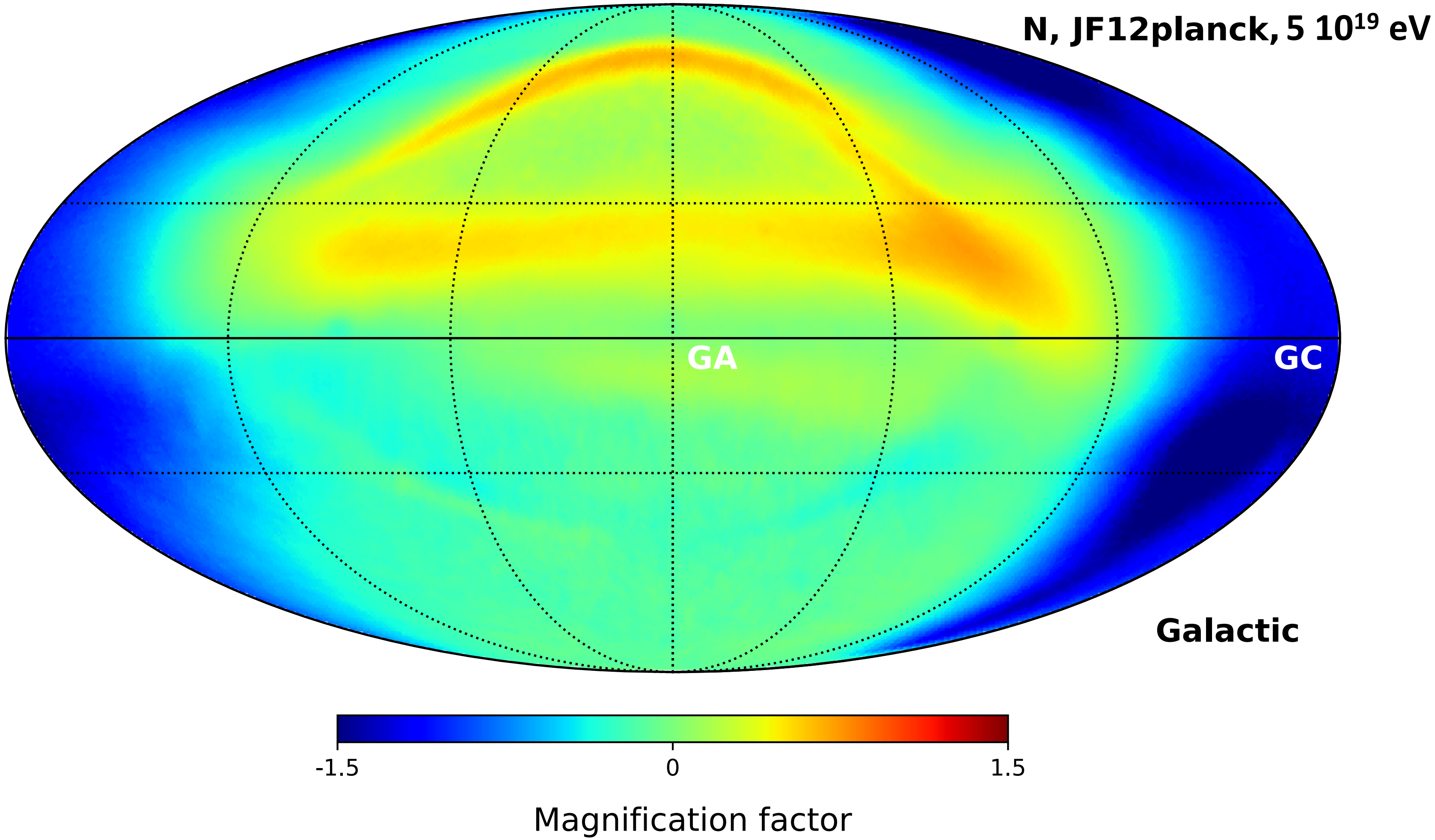
ρ = E/Z= 3 EV
JF12 model

Magnification factor (log scale!)



Globus, Fedynitch and Blandford, 2023 ApJ 945 12

Magnification factor (log scale!)



Globus, Fedynitch and Blandford, 2023 ApJ 945 12

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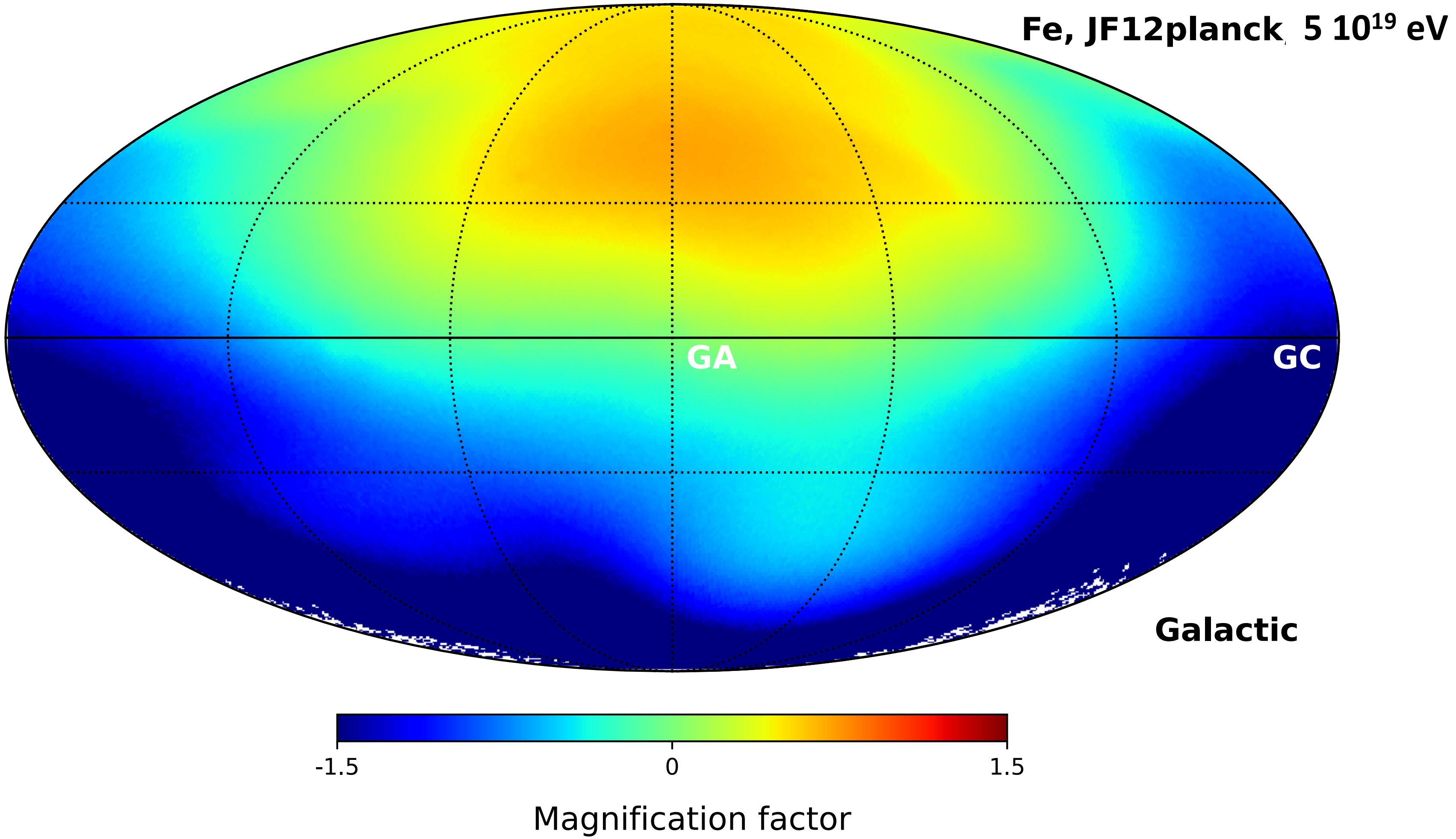
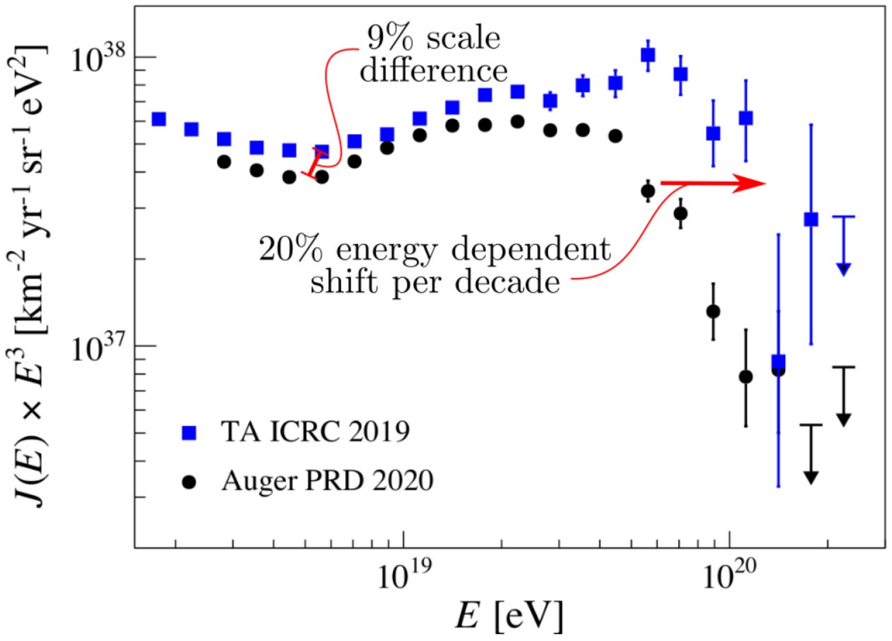


Globus, Fedynitch and Blandford, 2023 ApJ 945 12

UHECRs: status on the spectrum

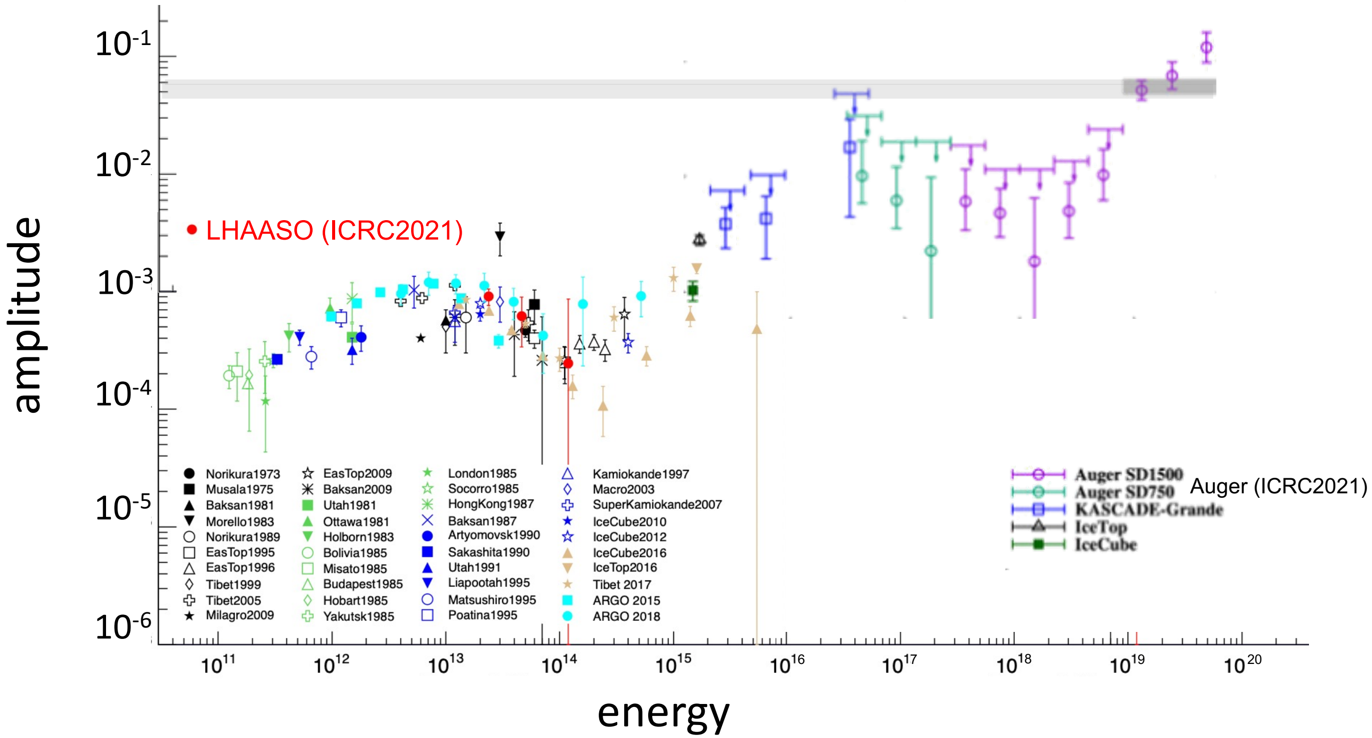
Two features “ankle” and “toe” (cutoff) firmly established

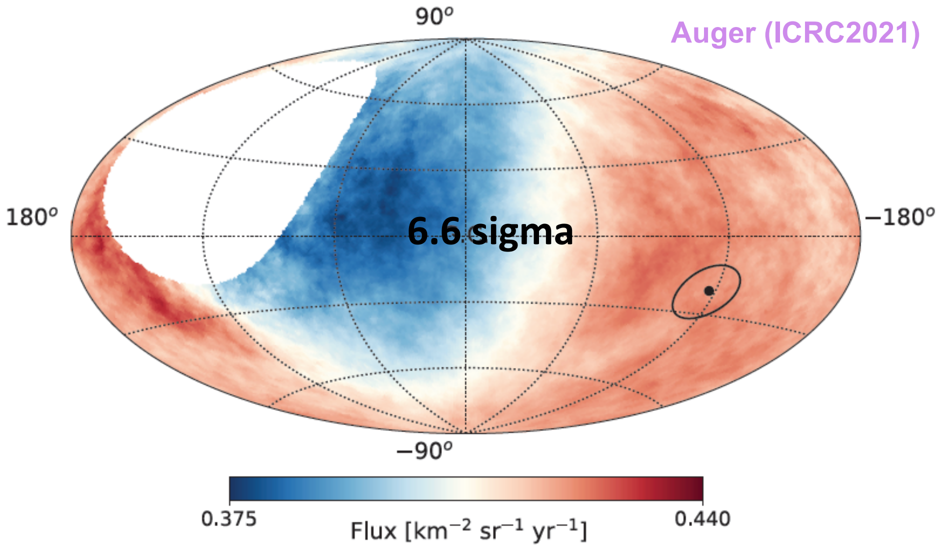
Discrepancies in the energy scales of the two experiments

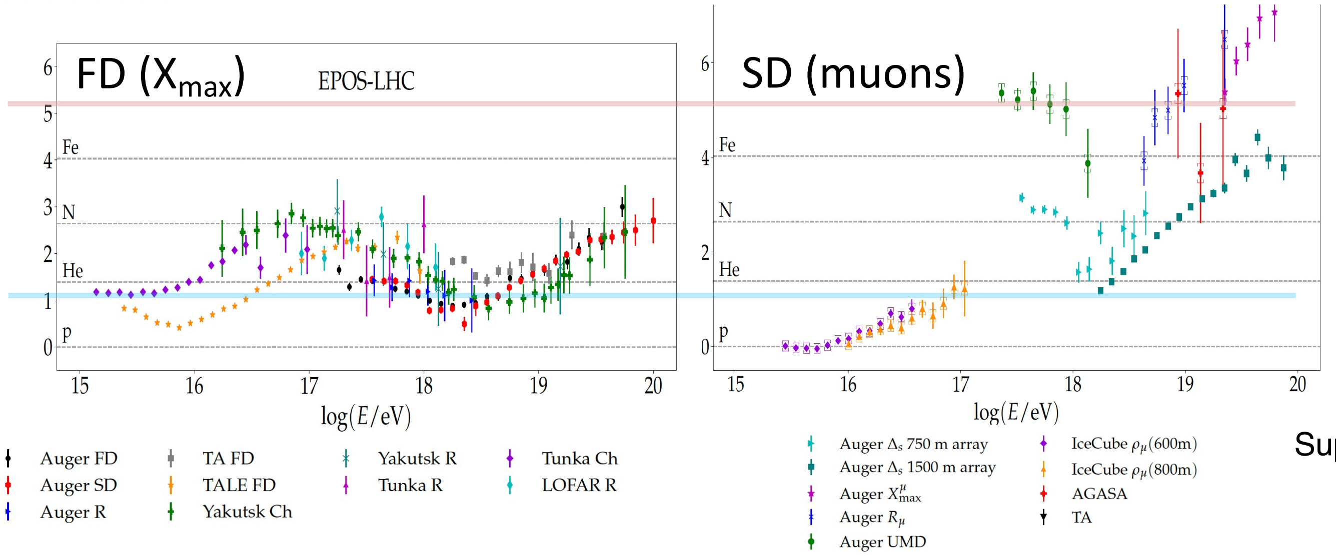


Auger@TA station

UHECRs: anisotropy and composition





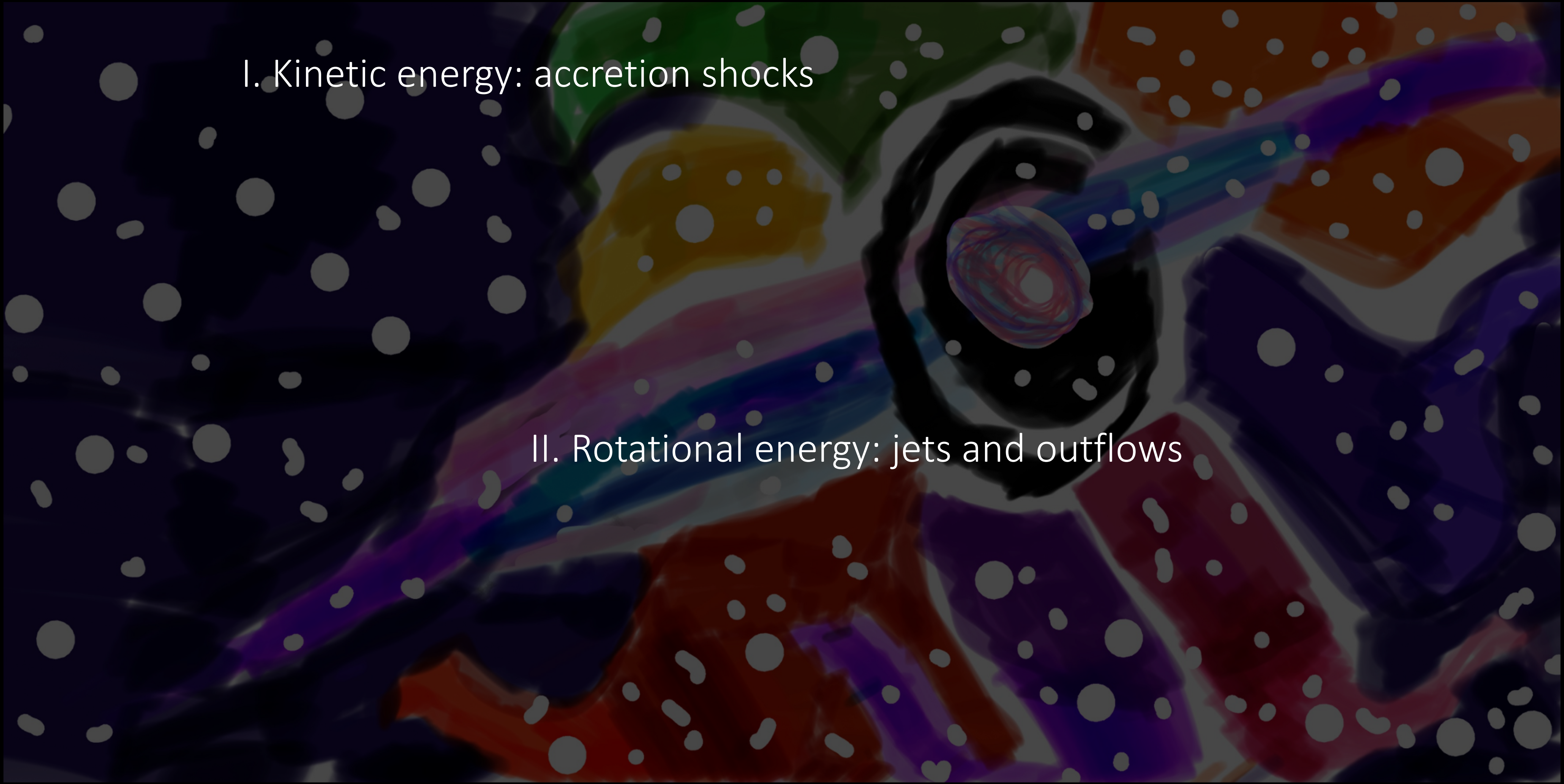


Supanitsky 2022

What are the sources?


by Lou

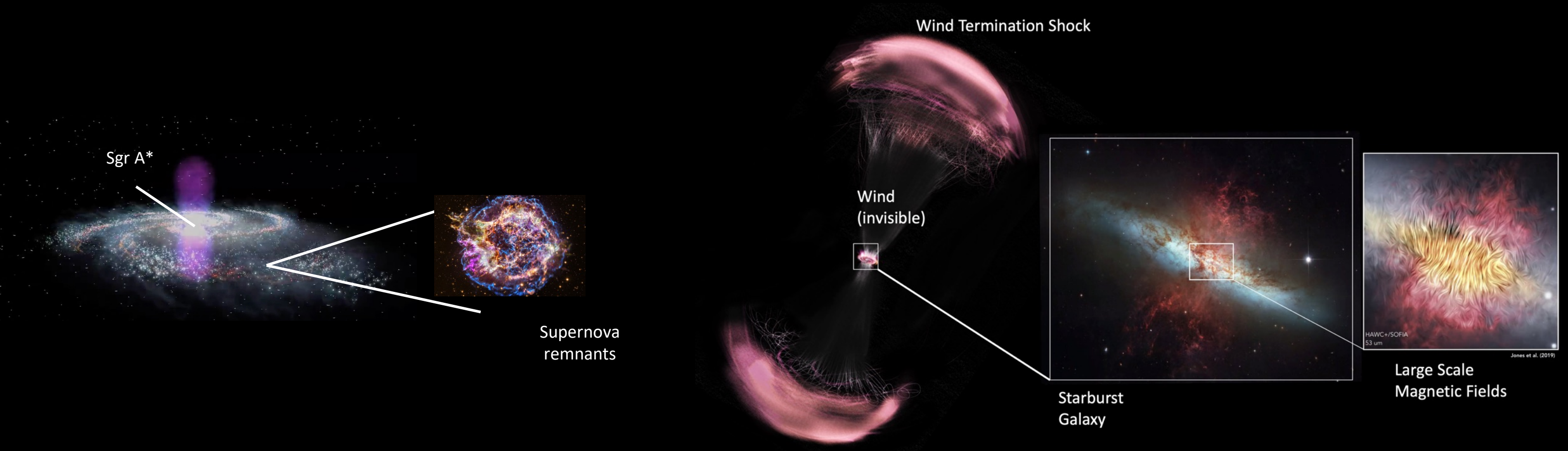
Black holes as cosmic accelerators:

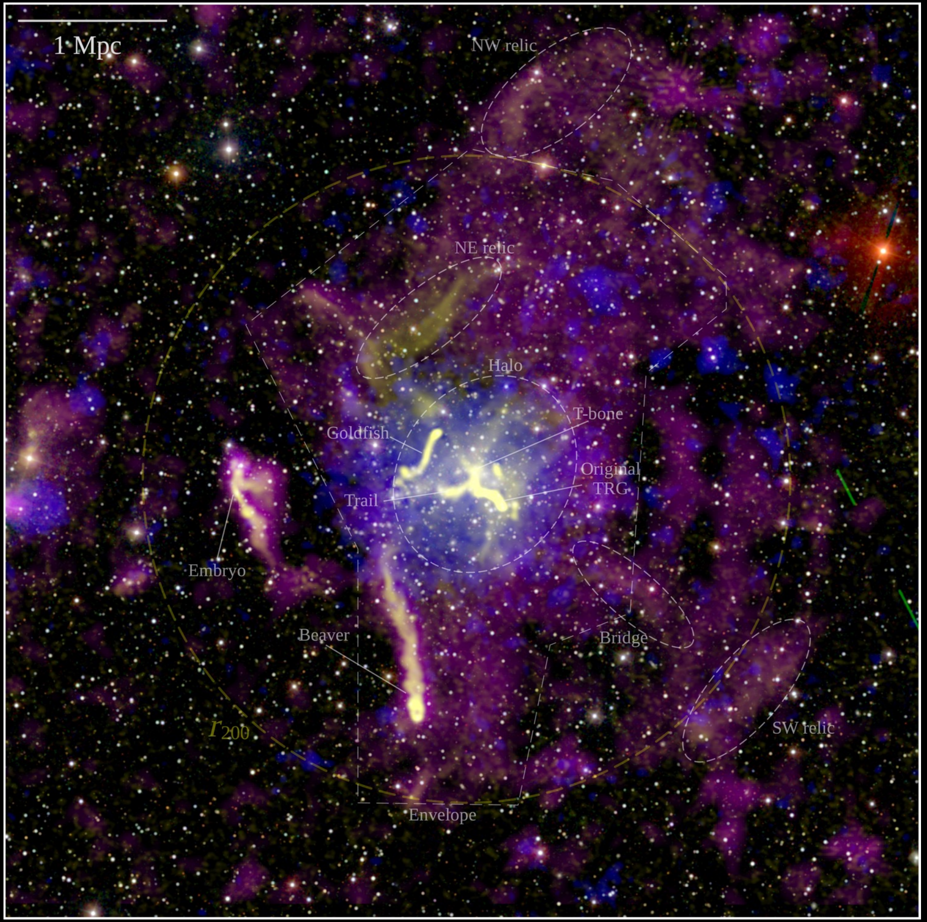


by Lou

I. Kinetic energy: Hierarchical model for DSA

PeV EeV ZeV



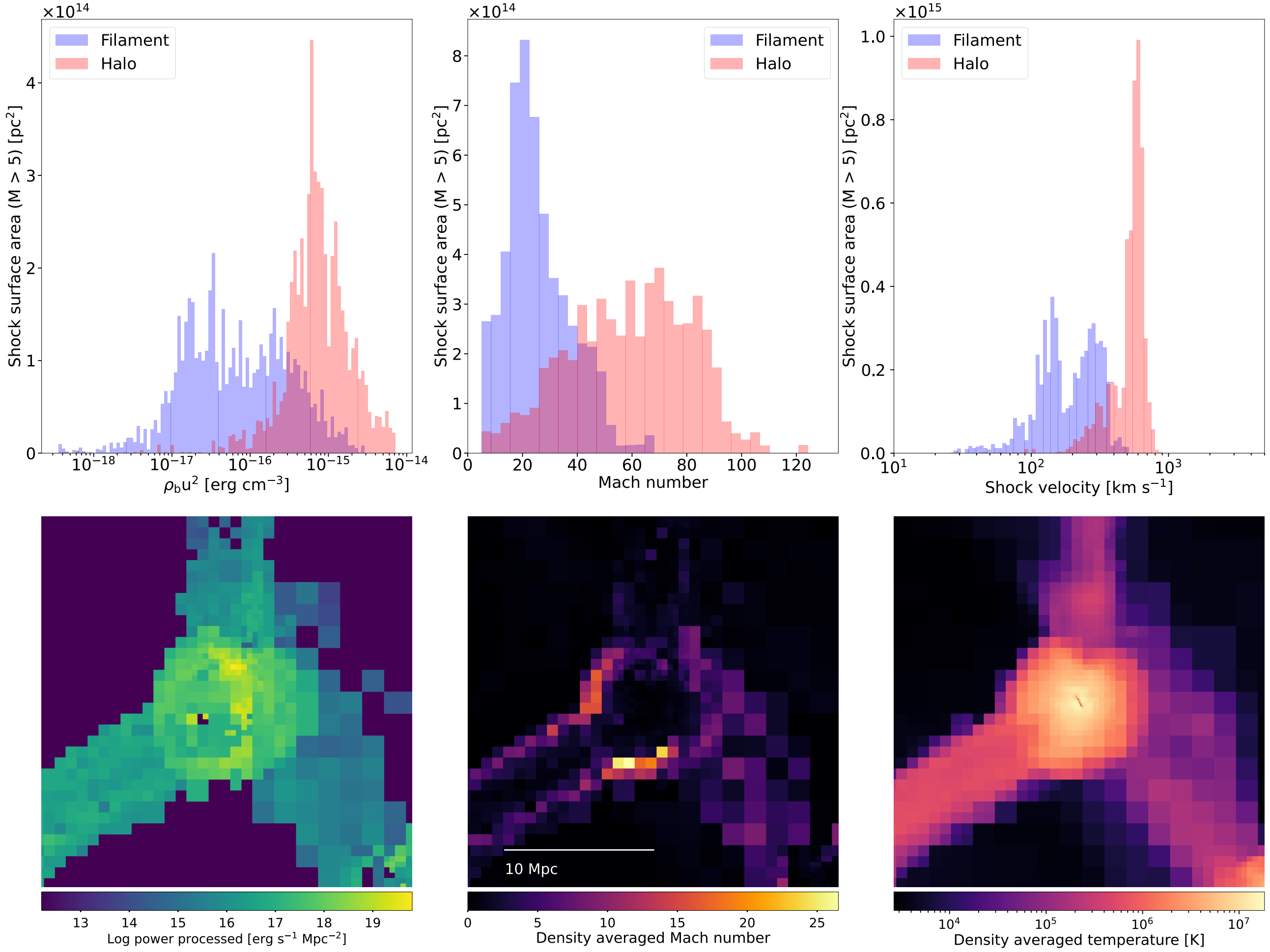


Merging cluster Abell 2255

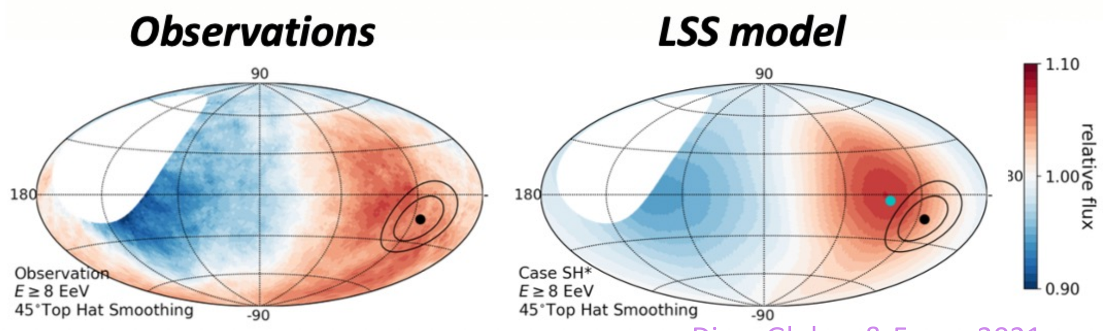
“Particle acceleration at astrophysical shocks”, Blandford and Eichler 1987

Modeling the acceleration at Cluster Accretion Shocks

Common but invisible (radio?); tap accretion energy; transfer mediated by DSA; Neutrinos not expected



- Injection of pre-existing population of cosmic-rays into filament shocks, cluster accretion shocks
- **Cluster "Halo" component**: high metallicity (selection effect), hard spectrum (upstream: escaping cosmic rays)
- **Filament component**: softer spectrum (downstream of the shock)
- High Mach numbers and emissivity (**few times 10^{44} erg Mpc^{-3} yr^{-1}**)
- Mechanism: magnetic **"bootstrap"** (Blandford)
- **Connection with UHECR anisotropies**



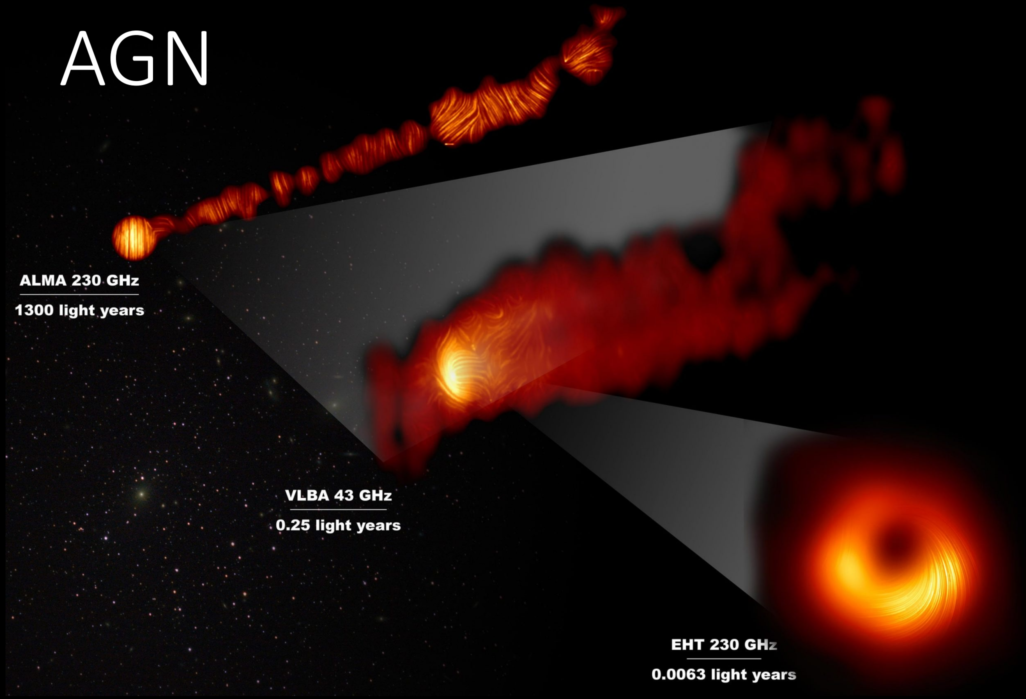
Ding, Globus & Farrar 2021

Simeon, Globus, Barrow, Mukhopadhyay & Blandford in prep.

II. Rotational energy (or: why do we Kerr?)

Large scale magnetic fields B
Magnetospheric electric fields E due to spinning black hole } = **EMF (Blandford & Znajek 1977)**

AGN



TDE

GRB

GRB Credit: Ore Gottlieb

II. Rotational energy (or: why do we Kerr?)

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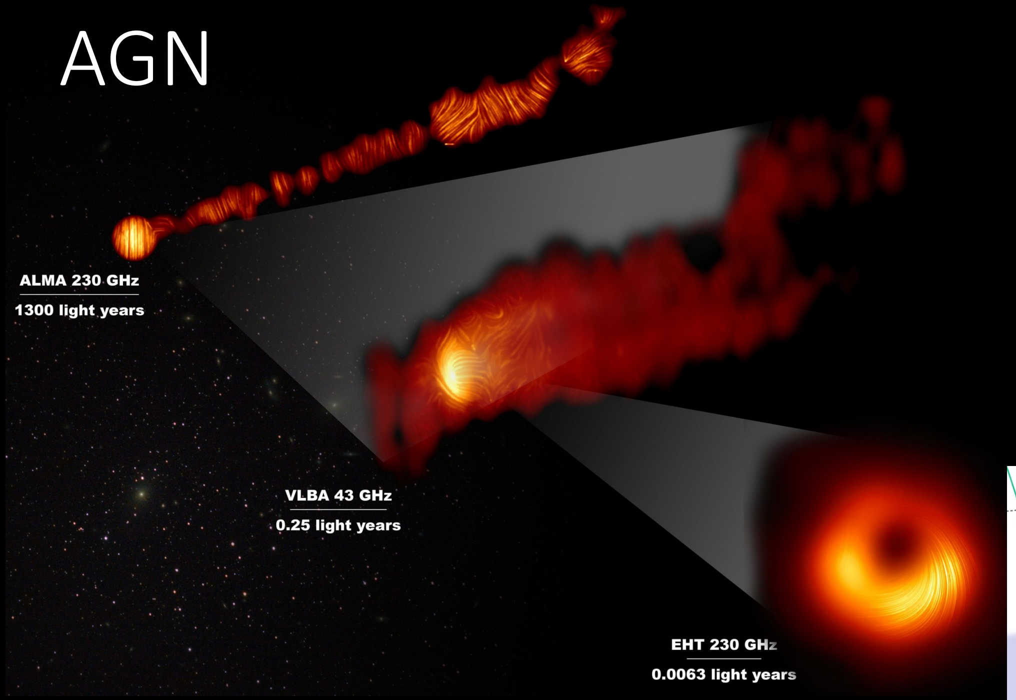
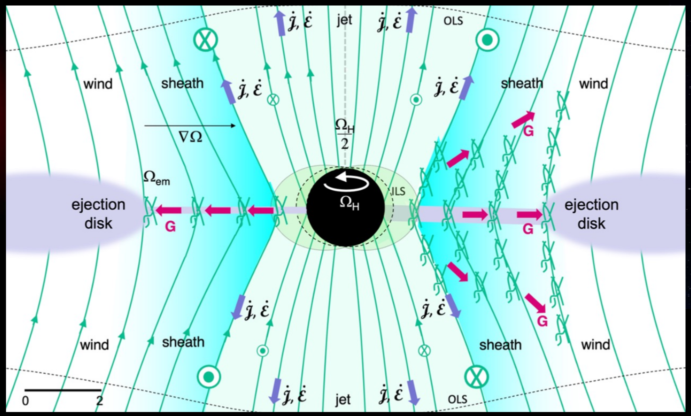
AGN



Open questions
- E x B sign depends on load!
- ”ergomagnetosphere” powering disk wind?

TDE

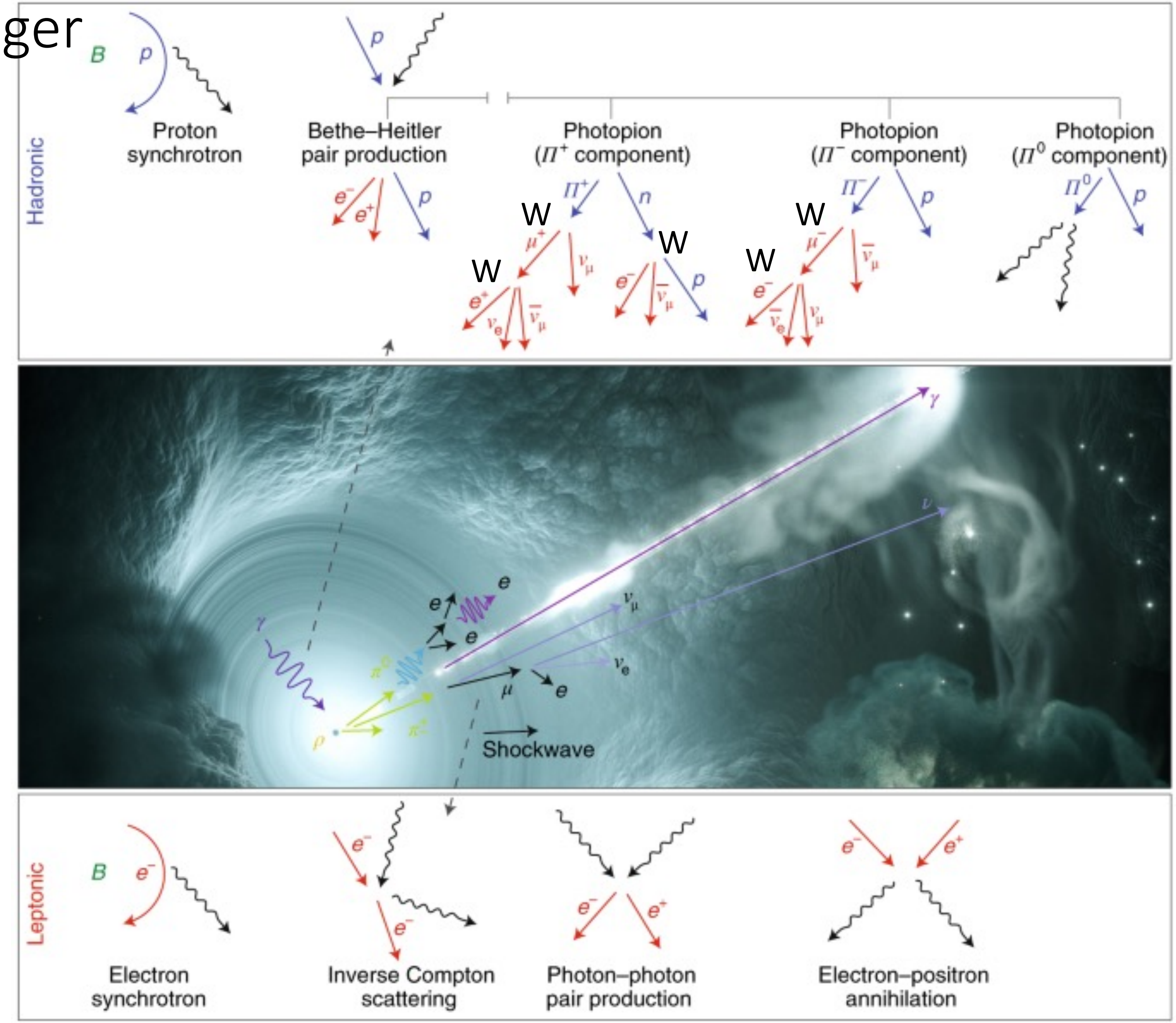


Blandford & Globus 2022

GRB

GRB Credit: Ore Gottlieb

Multimessenger



N

+ GDR for nuclei

(actually: they need to survive…)

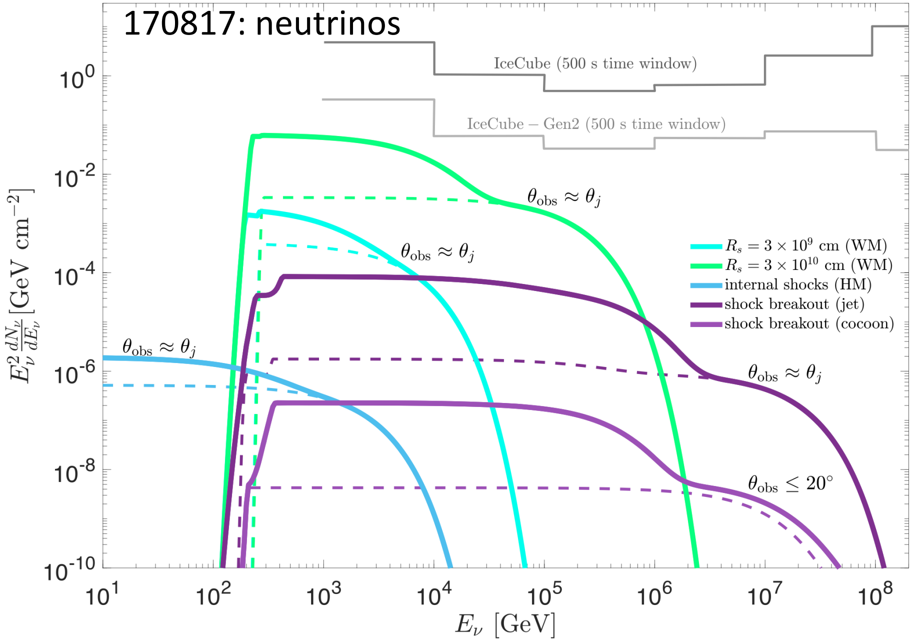
GRB jets: internal shocks, shock breakout…

Before "breakout"

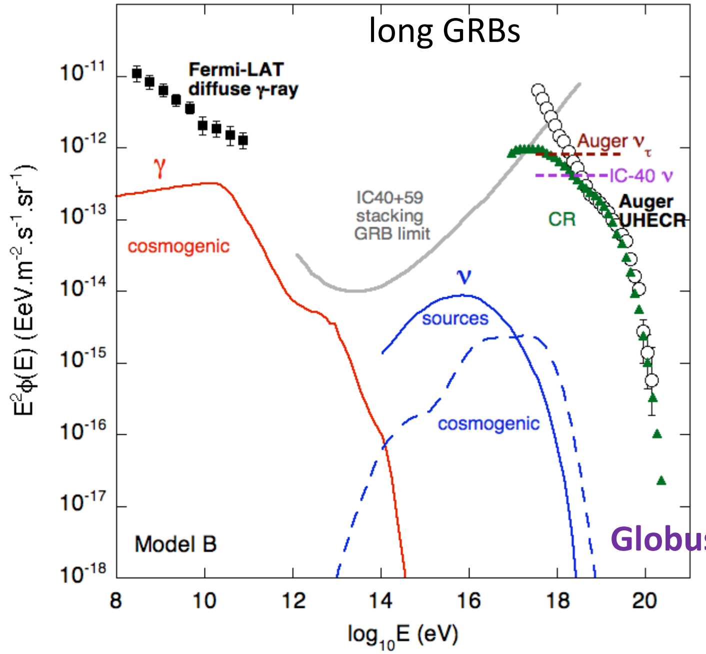
- Cosmic-ray acceleration at internal (mildly-relativistic) shocks in an opaque environments **only possible if the jet is highly magnetized** (formation of collisionless subshocks). **Cosmic rays won't escape, but neutrinos are emitted (e.g., Gottlieb & Globus 2021)**

After "breakout"

- Cosmic-ray acceleration at collisionless internal **mildly-relativistic shocks (external shocks responsible for the afterglow are inefficient accelerators)**
- Long-duration GRBs have sufficient power to accelerate cosmic rays to ultra-high energies, but their local rate implies large baryon loading;
- **Too rare to account for the UHECR flux (but local contribution possible: Eichler, Globus, Kumar et al. 2016)**
- **Rate of LLGRBs 100-1000 the rate of long GRBs?**
- UHECR acceleration at GRB internal shocks (**Globus et al. 2015**): **most protons are secondary particles (escaping as neutrons)-> sub-ankle protons?**



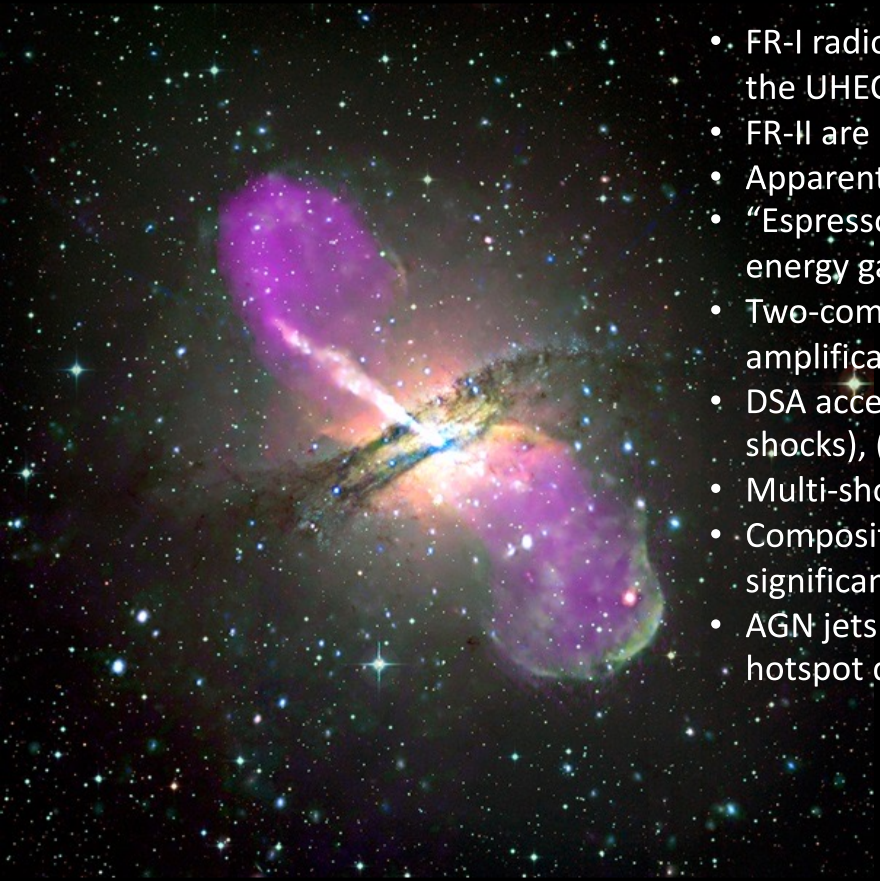
Gottlieb & Globus 2021



Globus et al. 2015

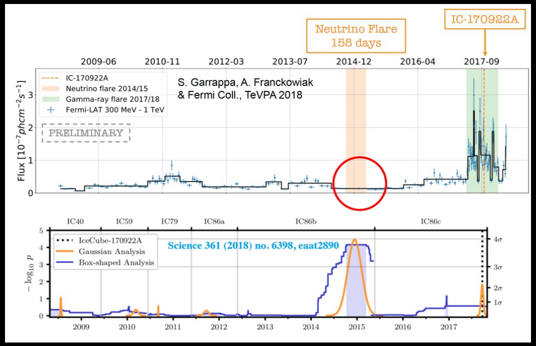
AGN jets: shear acceleration, backflows…

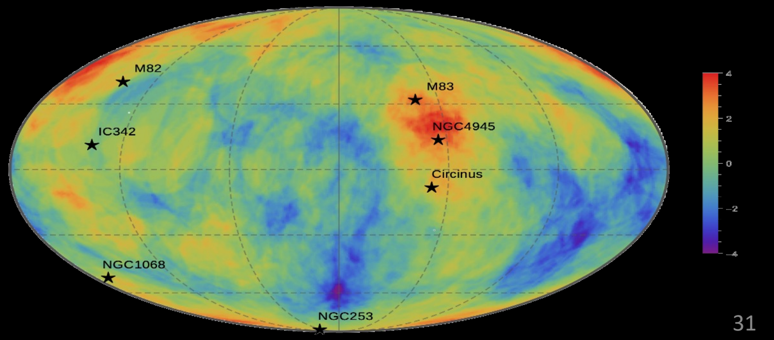
Rare but powerful; ultimately tap some rotational energy (unipolar inductors); transfer mediated by shear or DSA; Multimessenger (gamma-ray, neutrino) signatures; anisotropies



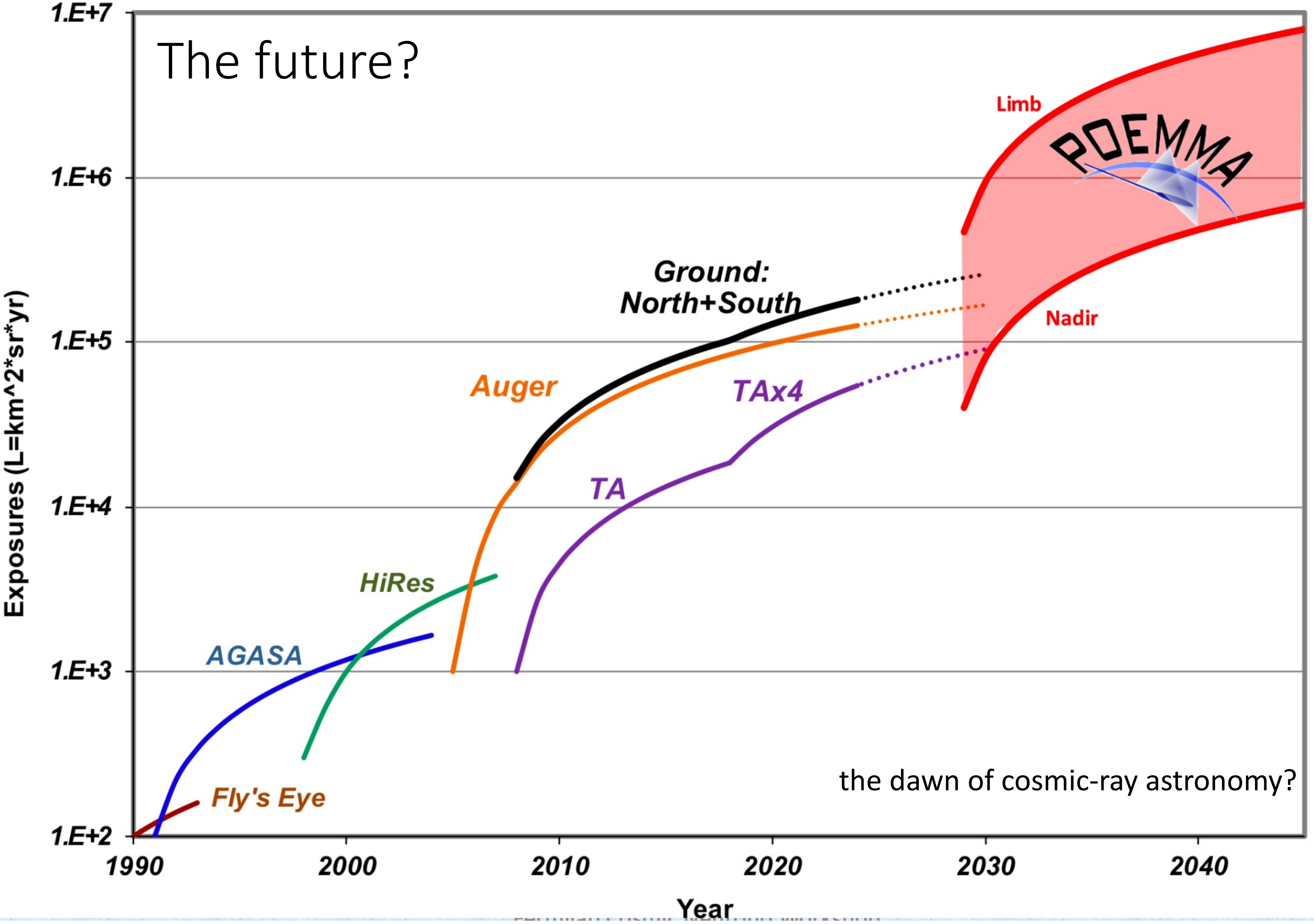
Centaurus A

- FR-I radio galaxies and misaligned BL Lac objects located within the GZK horizon have sufficient emissivity to power the UHECRs
- FR-II are disregarded (overproduce cosmogenic gamma-rays, Globus et al. 2017)
- Apparent jet power: 10^{43}– 10^{44}erg s^{-1} (which could exceed 10^{46}erg s^{-1} and large Lorentz factors during flaring episodes)
- “Espresso” (Caprioli 2015): assuming $\Gamma \sim 30$, a one-shot boost of a factor of $\sim \Gamma^2$ in energy, can transform the highest-energy galactic CRs at 100 PeV in the highest-energy UHECRs at 100 EeV.
- Two-component outflow (disk wind and force-free jet) : shocks, instabilities at the interface -> leads to B amplification?
- DSA acceleration sites: shock at the interface between the wind and the jet, lobes and backflows (mildly relativistic shocks), (e.g., Bell et al. 2019, Cerutti and Giacinti 2023)
- Multi-shock acceleration from stars crossing the jets (Müller and Araudo 2023)
- Composition: depend on the injection model; internal entrainment in the jets of Centaurus A will contribute with a significant amount of ^{4}He, ^{16}O, ^{12}C, ^{14}N, and ^{20}Ne (Wykes et al. 2015)
- AGN jets are rare in the local universe. Predictions possible in term of UHECR anisotropies. Cen A hot spot? TA hotspot due to UHECR reverberation? (Bell and Matthews 2021)





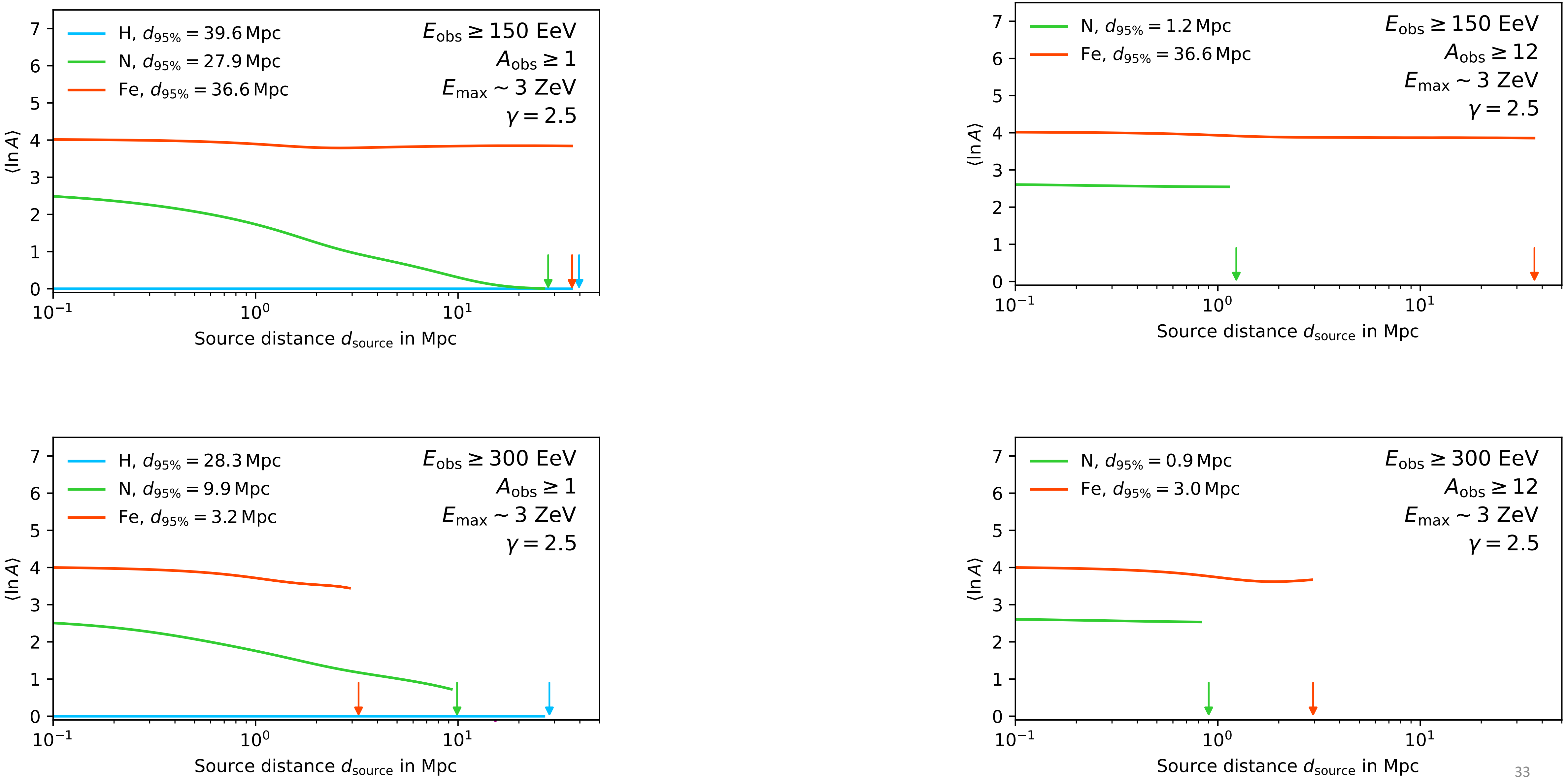
The future?



the dawn of cosmic-ray astronomy?

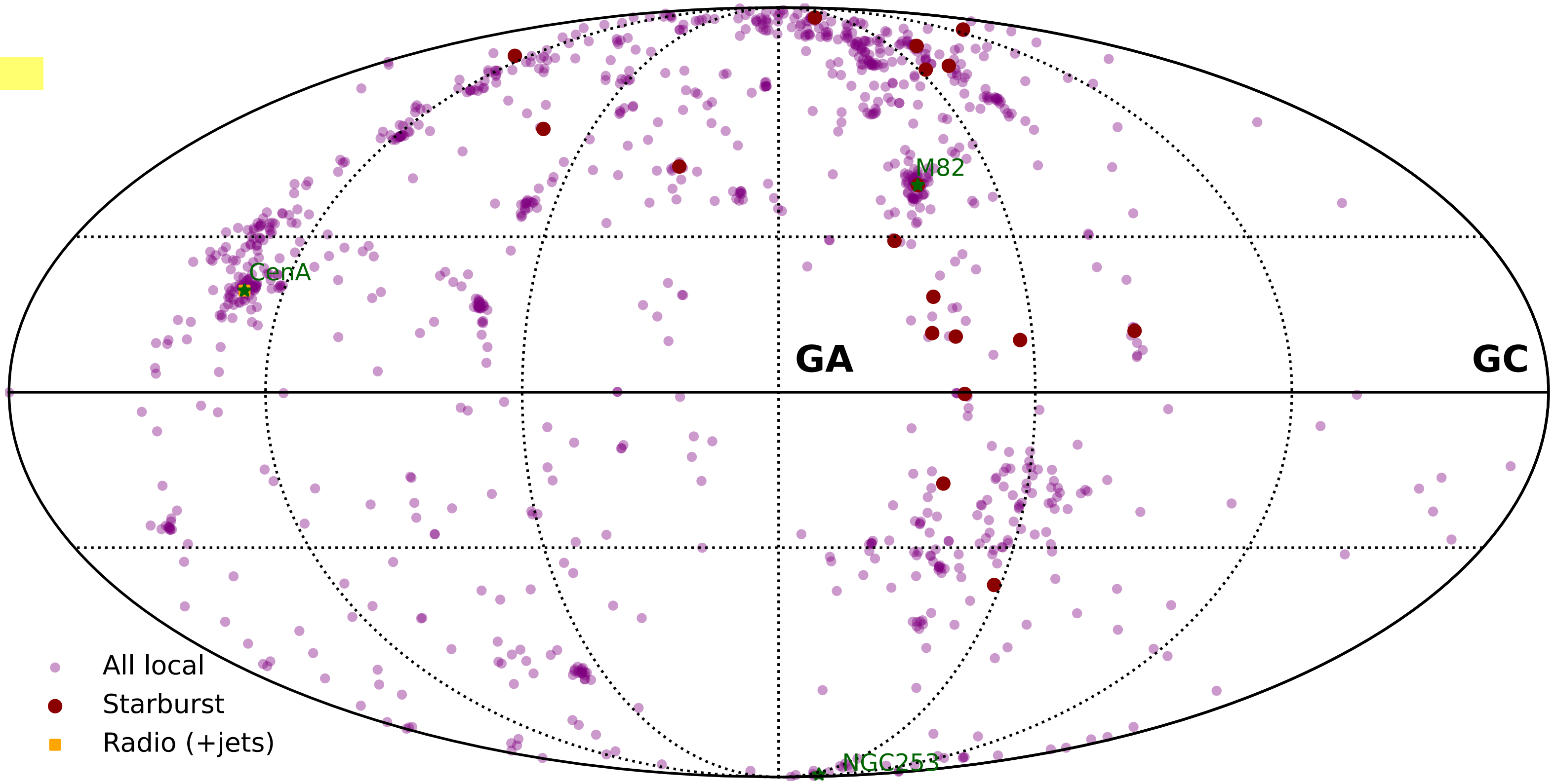
On the importance of detecting "extreme energy cosmic rays"

Globus, Fedynitch and Blandford, 2023 ApJ 945 12



Possible source candidates < 10 Mpc

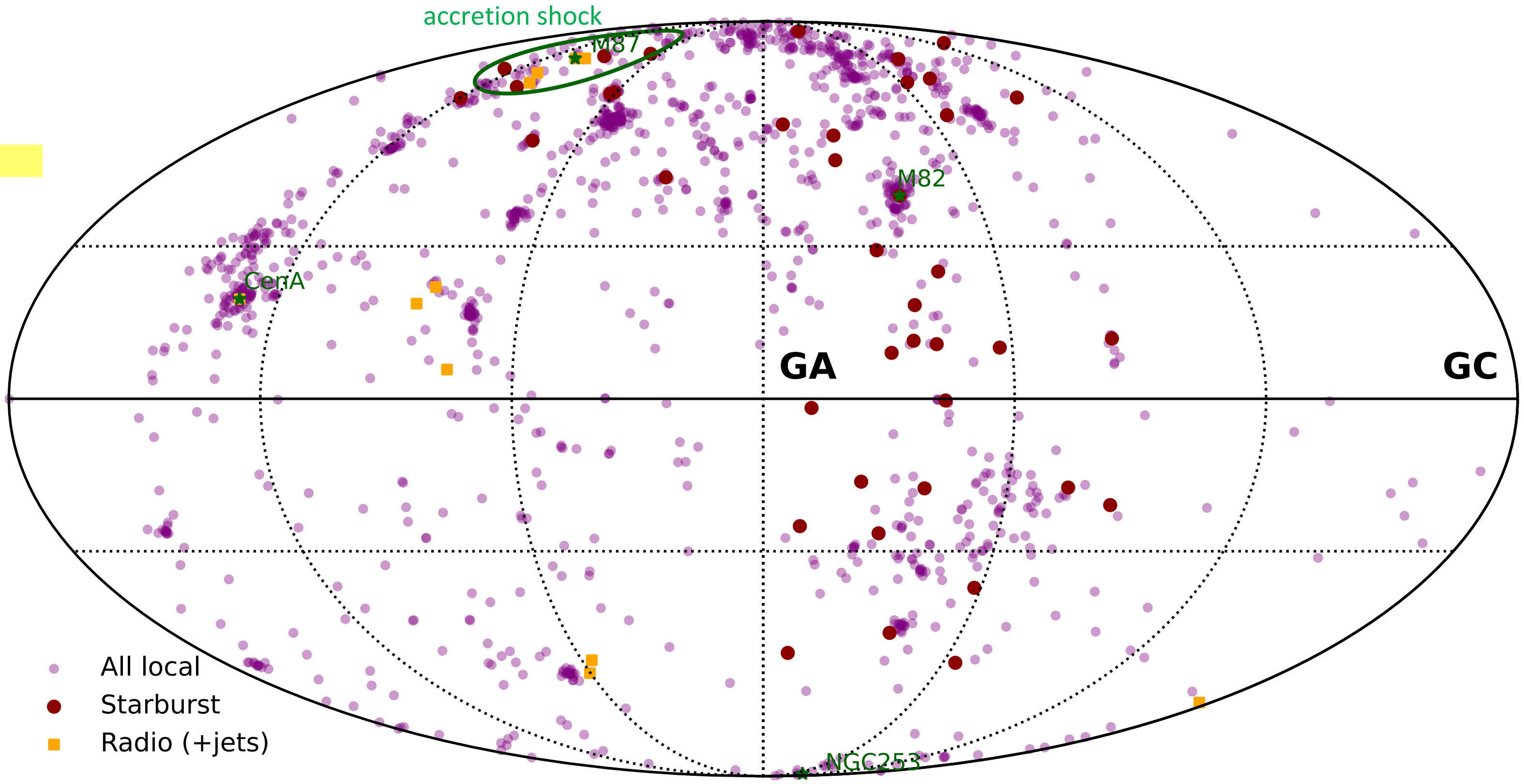
d_{max} (Mpc)	All local	SBG	Radio+jets
2	129	2	0
5	440	10	1
10	1076	18	1
20	1393	34	5
40	1419	40	11



All local: Updated Nearby Galaxy Catalog maintained by Karachentsev et al. 2013
SBG Catalog by Lunardini et al. 2019
Radio(+ jets) AGN Catalog by van Velzen et al. 2012

Possible source candidates < 40 Mpc

d_{max} (Mpc)	All local	SBG	Radio+jets
2	129	2	0
5	440	10	1
10	1076	18	1
20	1393	34	5
40	1419	40	11



All local: Updated Nearby Galaxy Catalog maintained by Karachentsev et al. 2013
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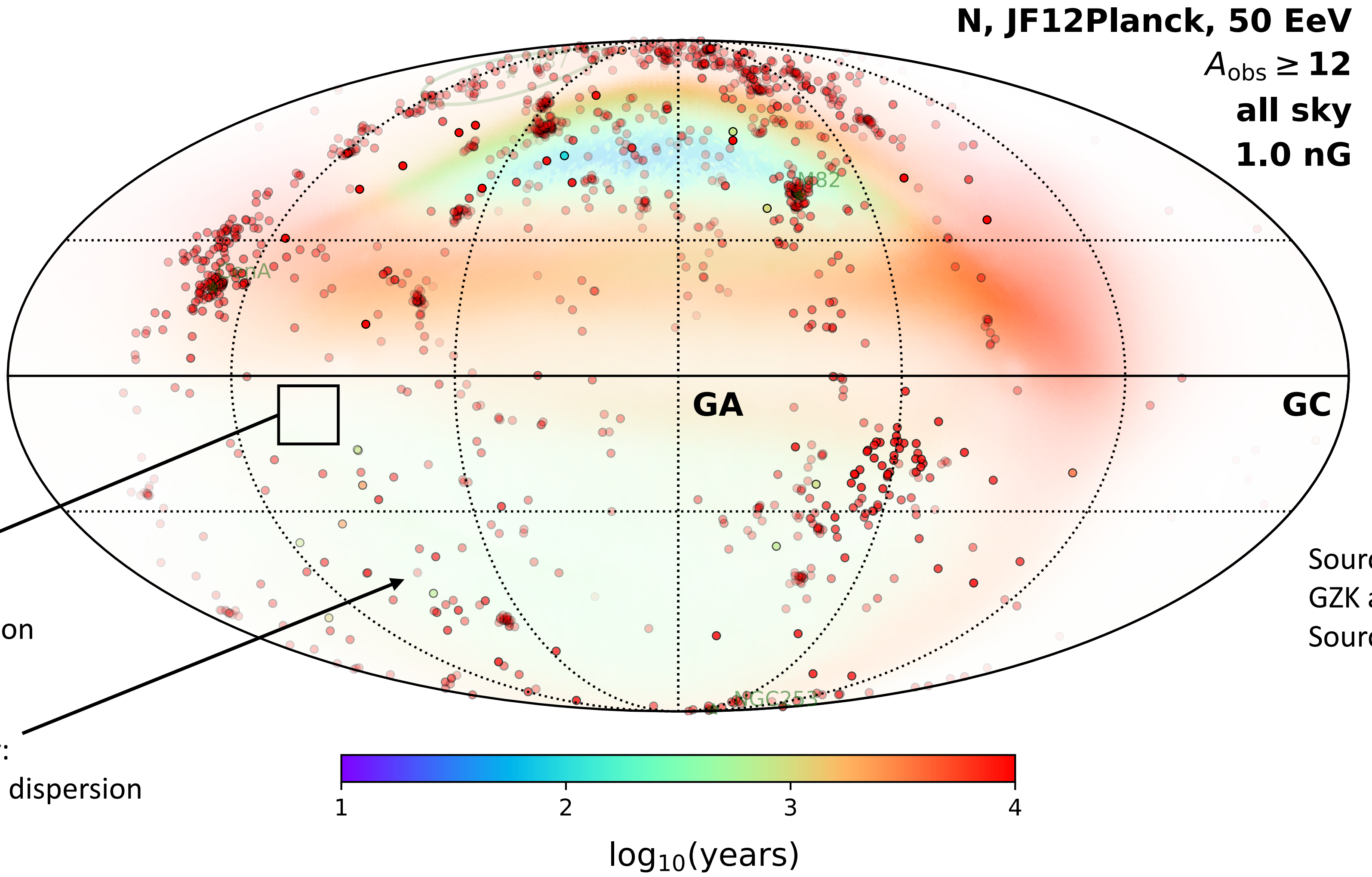
“Treasure maps”: nitrogen at 5 10^{19} eV

Globus, Fedynitch and Blandford, 2023 ApJ 945 12



GMF model
mass at detection
detector FoV
EGMF

Background transparency:
magnification factor

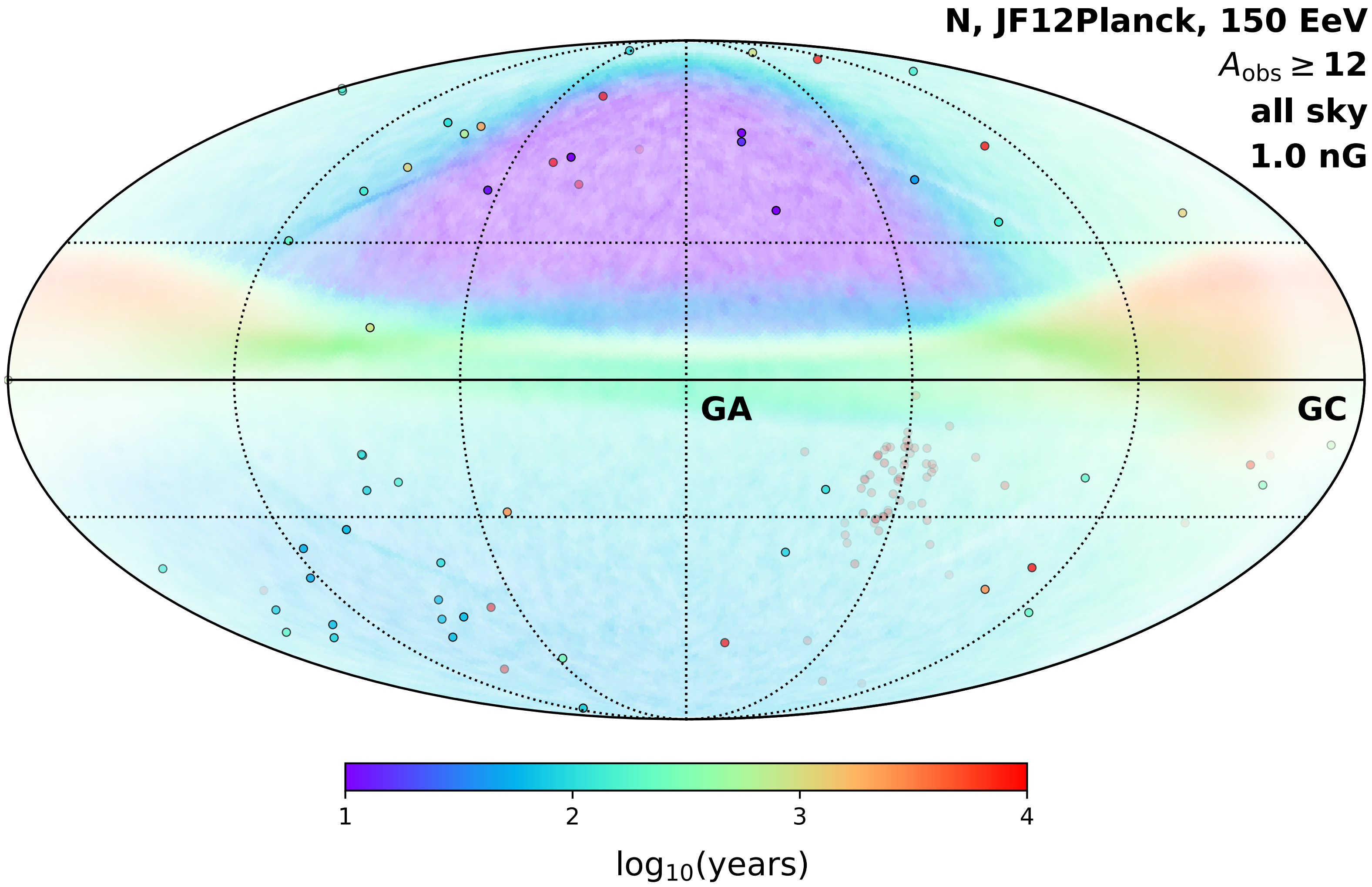
Background color:
GMF temporal dispersion

Source candidate color:
GMF + EGMF temporal dispersion

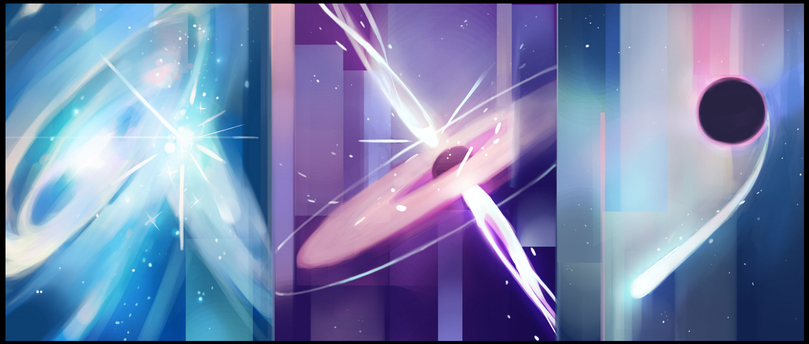
Source transparency:
GZK attenuation
Source beyond $d_{95\%}$ are not shown

“Treasure maps ”: nitrogen at 1.5 10^{20} eV

Globus, Fedynitch and Blandford, 2023 ApJ 945 12



Summary: black holes as (ultra-high energy) cosmic accelerators



- After 60 years the problem of the origin of UHECRs (particles with energies up to ~50 Joules) remains unsolved.
- Surely one of the biggest challenges in high energy astrophysics and potentially a contributor to particles physics.
- The origin of the highest energy cosmic rays in our local Universe could be a natural consequence of the mechanism that efficiently extracts the power from spinning black holes (Blandford & Znajek 1977). A "hierarchical" model where UHECRs are re-accelerated at accretion shocks is another possibility.
- More events at the highest energies (e.g., > 150 EeV) and a composition-sensitive experiment (on an event-by-event basis) could rule out many currently viable source models.