Constraining the sources of ultra-high-energy cosmic rays

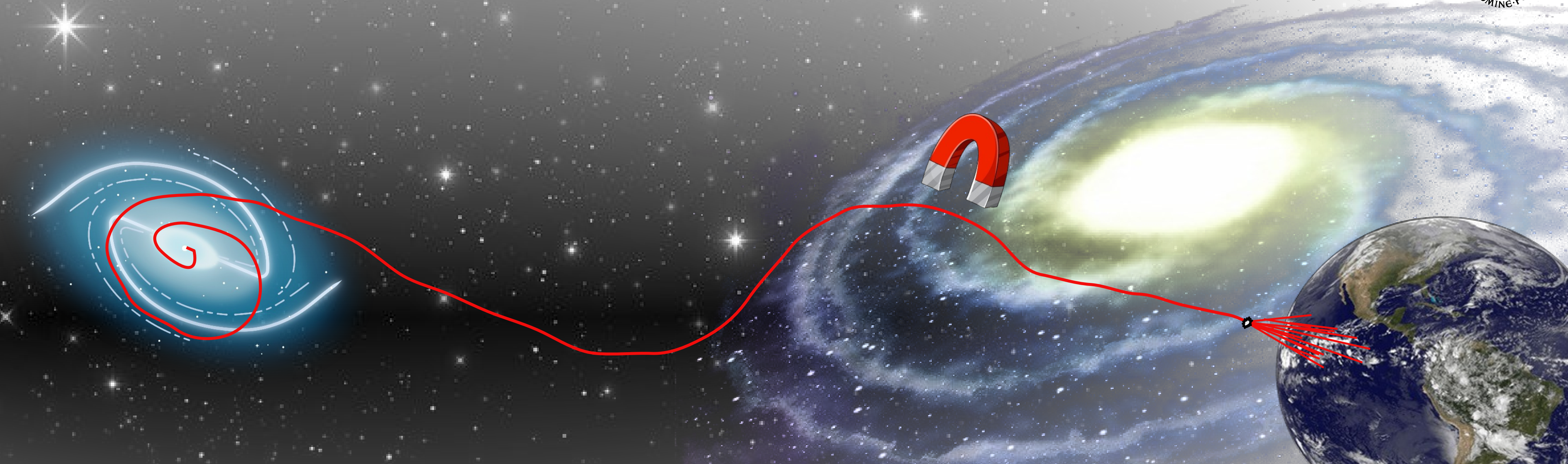
Teresa Bister

Topical lectures, July 2026

PIERRE AUGER OBSERVATORY

Nikhef

Radboud University



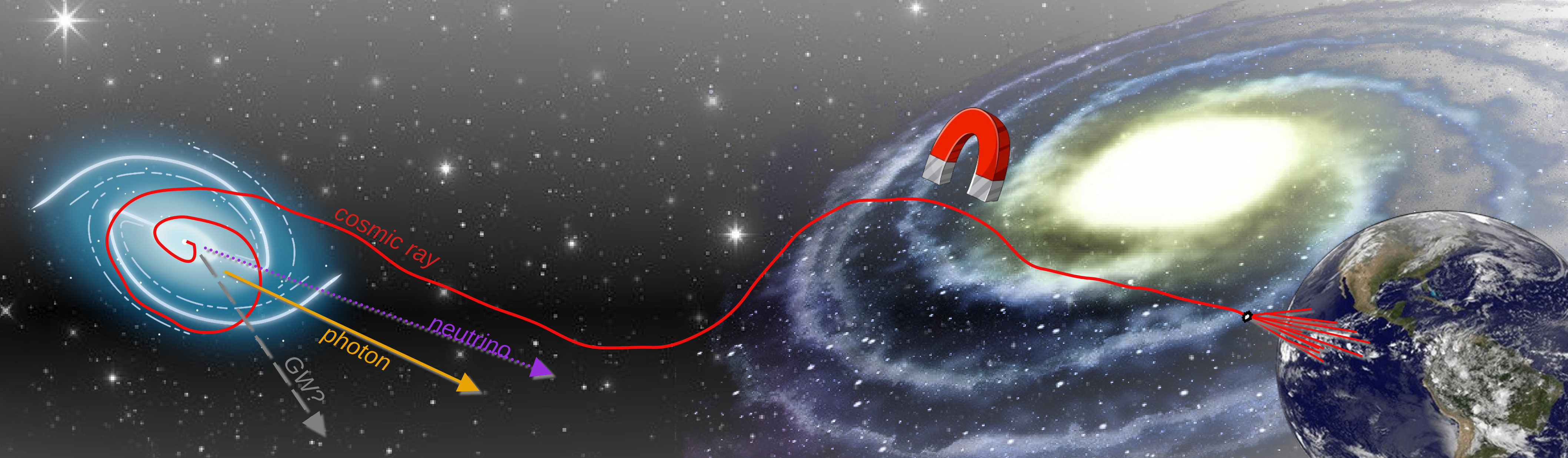
Journey of an ultra-high-energy cosmic ray

generation by powerful extragalactic sources

propagation, interactions with background fields

deflections in extra-galactic & Galactic magnetic field

generation of air shower in the atmosphere → detection



Overview

1. sources

2. constraints

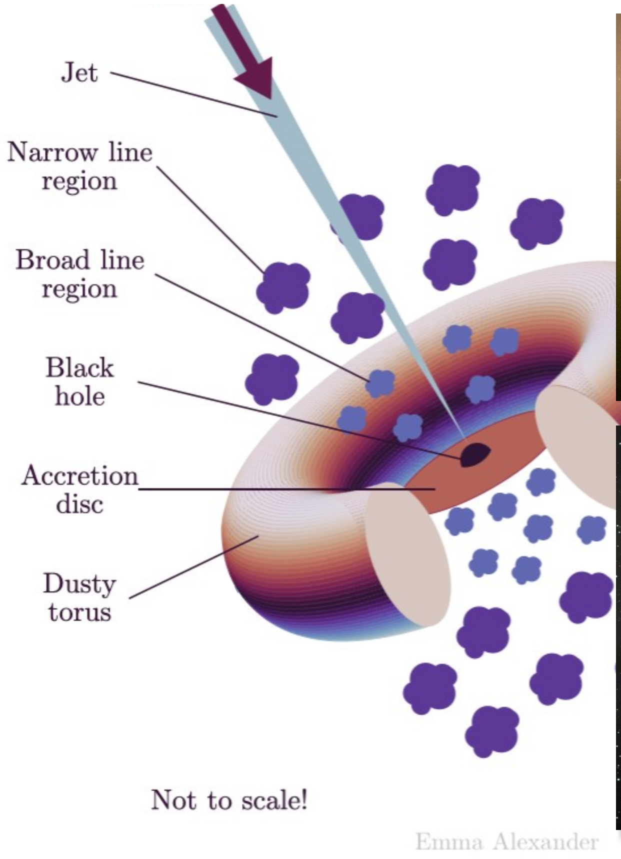
	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
$E_{\max}$							
emissivity							
diversity							
evolution							
arrival directions							
density							
neutrinos							

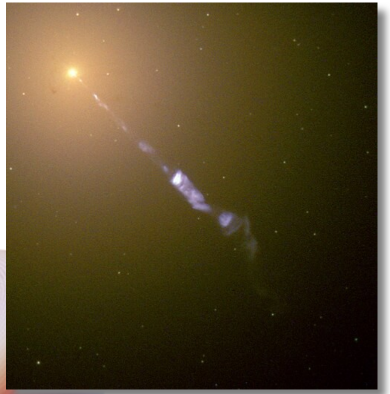
Active Galactic nuclei (AGNs)

steady source

variable emission

- **most powerful sources in the Universe**
  - ~1% of galaxies are active
  - ~10% of those are jetted
- driven by a **central supermassive black hole**
  - infalling matter and gas heated up
    - ➔ forms accretion disk
    - ➔ rotational energy from spinning black hole can launch collimated, relativistic plasma jets (v~c)
- broad, non-thermal **continuum spectrum,** spanning from radio to TeV gamma rays
  - brightest gamma-ray sources in the sky
- **different types:**
  - radio quiet (e.g Seyfert galaxies)
  - radio loud (e.g. radio galaxies, blazars)





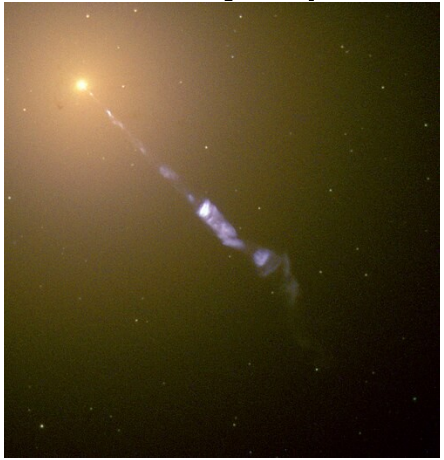
AGN unification theme

steady source

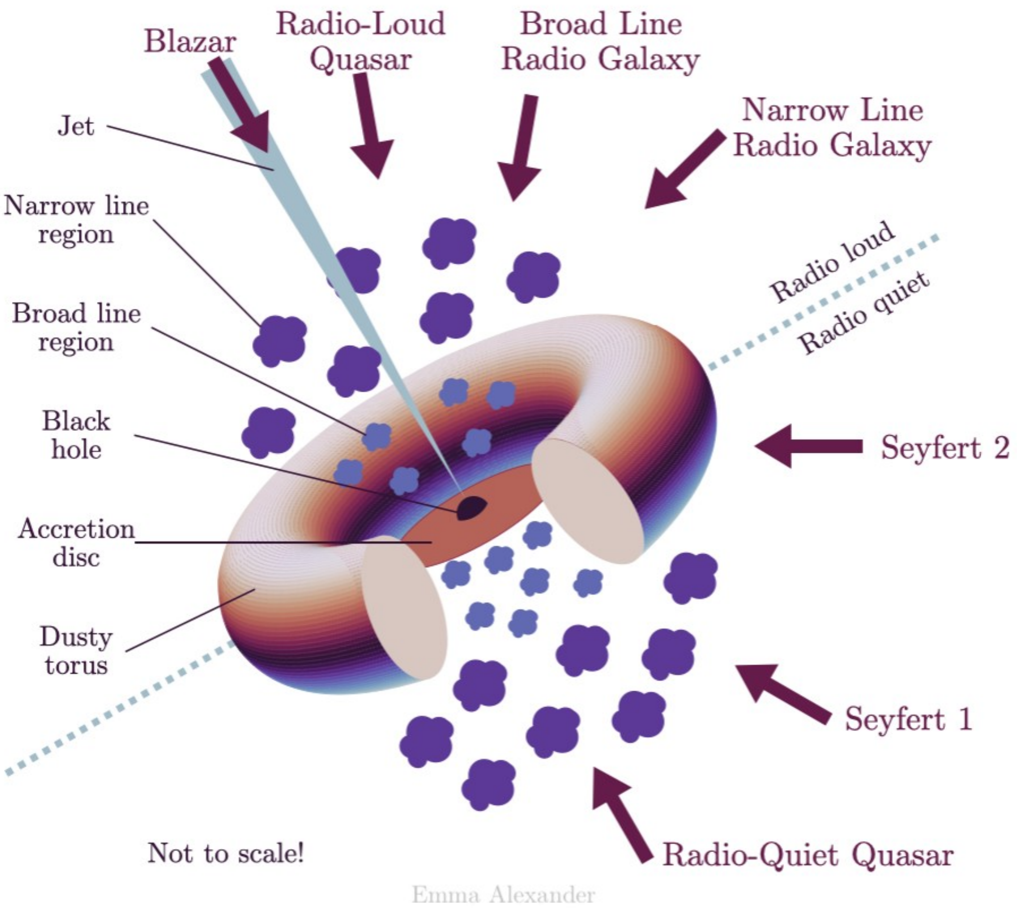
variable emission

- historical classification by spectrum features, later understood: **viewing angle dependency**
  - e.g. side view can see thermal continuum emission of disk
  - face-on view: almost featureless, polarized synchrotron spectrum: **blazar**
    - first thought to be irregular Galactic stars!
    - interesting UHECR source candidate if acceleration along jet

M87: radio galaxy



Mkn 421: blazar

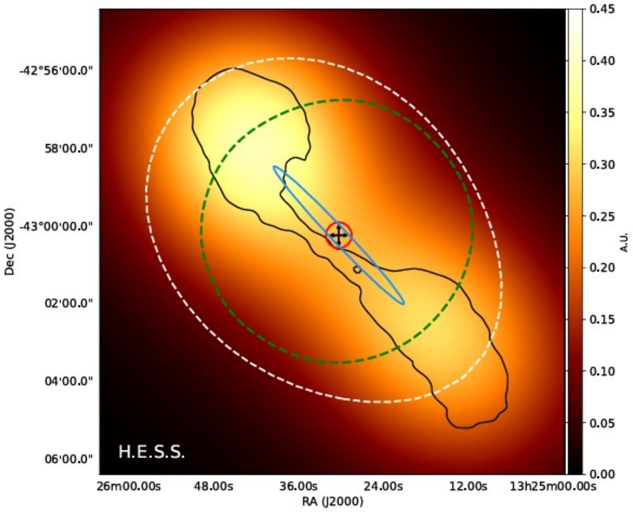


Centaurus A

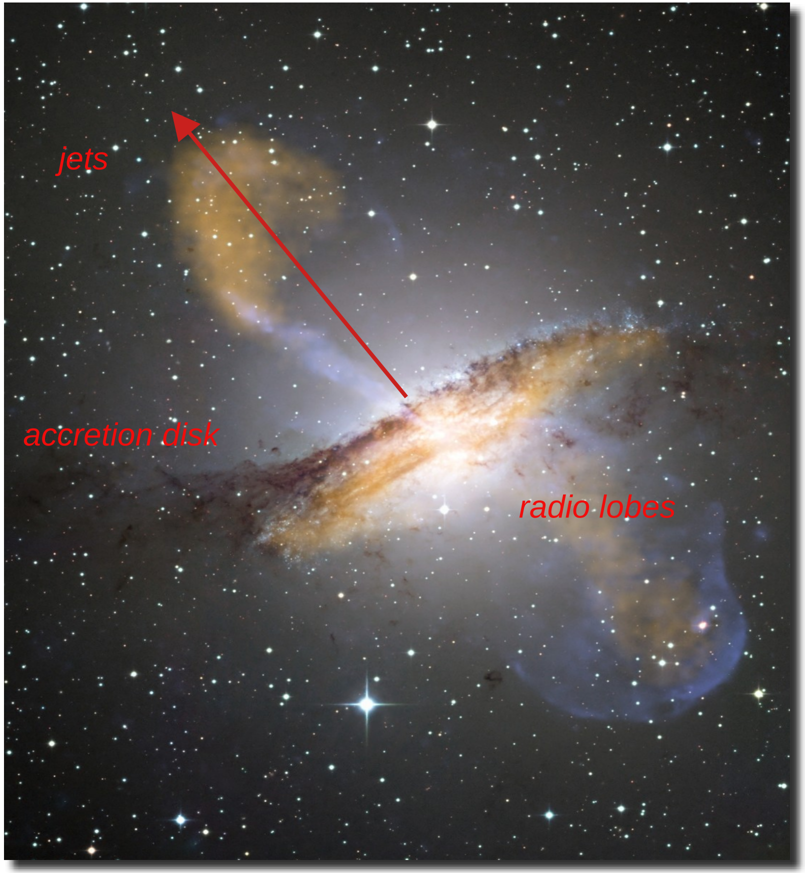
steady source

variable emission

- closest powerful radio galaxy to Earth
  - **distance of ~3.8 Mpc**
    - expected from AGN density: nearest one at ~ 50 Mpc!
  - energetic radio lobes, angle to the jet ~12°-45°
- detected up to very high energies (~TeV) with HESS
  - spectrum well modeled when including hadronic interactions
- flux excess of cosmic-rays >40 EeV seen in direction of Cen A!



radio emission measured by HESS (colorbar)



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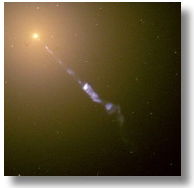
							

Starburst Galaxies (SBGs)

steady source

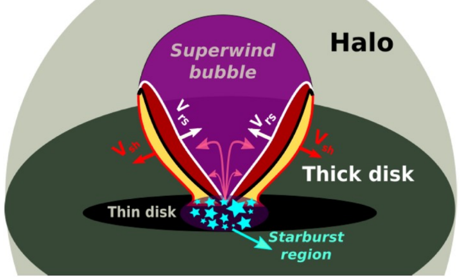
steady emission

- SBGs are galaxies with a **high starformation rate (SFR)**
  - ~1% of all galaxies are SBGs
  - SFR ~ 10-100 M_{sun} / yr, in a normal galaxy 1-3 M_{sun} / yr
  - 10x **more supernovae** (up to 1 / yr)

- hosts of transient events like **gamma-ray bursts**
  - correlated with supernova rate

- often contain **Galactic superwind + shocks**
  - driven by supernovae outflows
  - could accelerate cosmic rays (further)

Romero et al 2018



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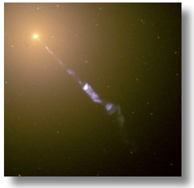


transient sources

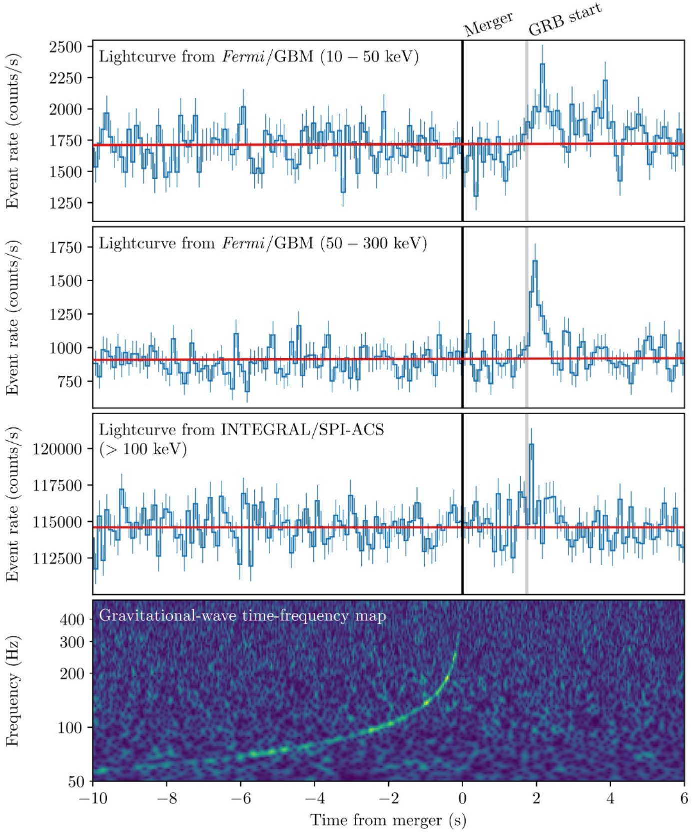
2. constraints

Binary neutron star mergers

- **merger of two neutron stars, emission of gravitational waves**
  - merger product can be neutron star or black hole
  - emitters of heavy elements through r-process (rapid neutron capture)
  - note: *black hole* mergers are not cosmic-ray sources because all baryonic matter stays inside black hole, energy only emitted via gravitational waves

- emission of **short gamma-ray burst** (~2 seconds)
  - confirmed by **multimessenger observation** of simultaneous gravitational wave GW170817 with LIGO/Virgo & short GRB with Fermi-LAT, INTEGRAL, Chandra, Hubble…

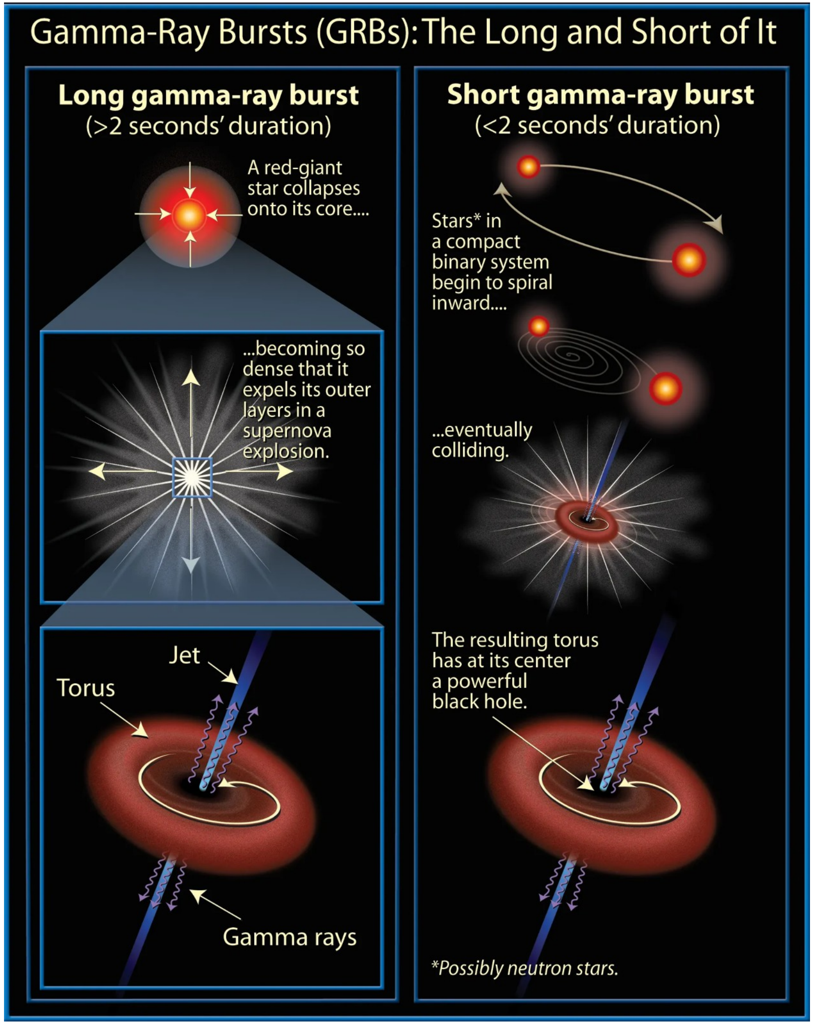
- expected **neutrino source**, but so far no coincidences (also not geometrically expected yet)



Long Gamma-ray bursts

transient source

- long GRBs >2s occur when massive stars collapse into black hole
  - launching **powerful relativistic jets**
  - **highest energetic events**, releasing ~10^{50} ergs → whole sun mass
  - briefly outshine their whole host galaxy
- often afterglow over whole electromagnetic spectrum
- daily, ~1-2 are detected by satellite detectors like Fermi

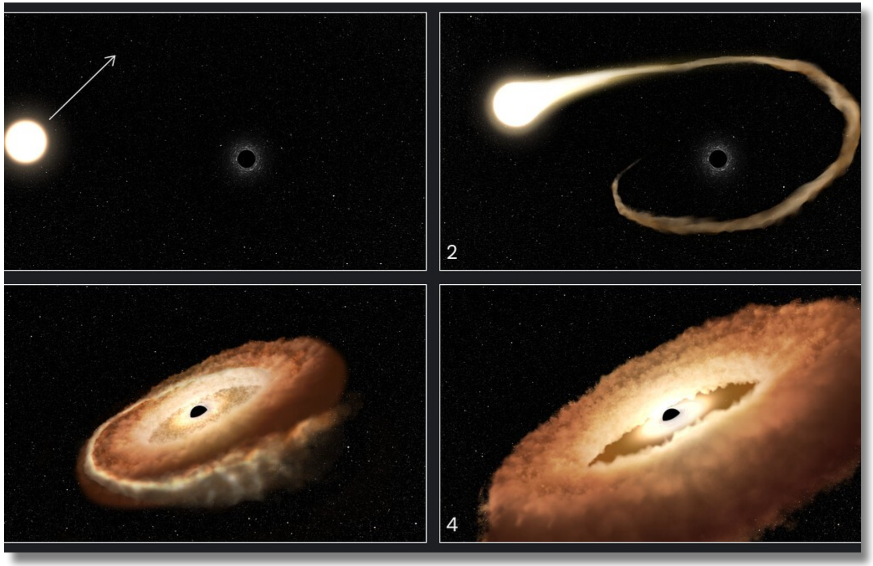


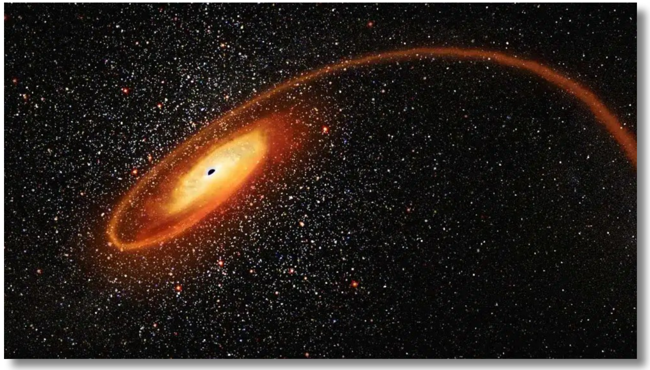
Tidal disruption events (TDEs)

transient source

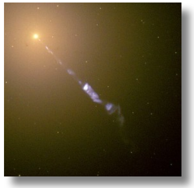
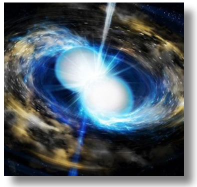
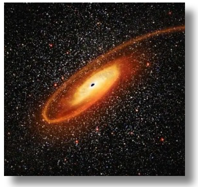
- stars torn apart by supermassive black hole
- only ~150 confirmed TDEs
- can launch relativistic outflow or **jet**
  - less than 1% jetted (~5 measured)
  - **jetted TDEs** form shock that could accelerate particles to the highest observed energies

- became especially interesting for cosmic-ray acceleration when IceCube saw **correlation of TDEs with neutrinos**
  - IceCube-191001A with AT2019dsg, IceCube-200530A with AT2019fdr
  - but, with updated data and systematics, this correlation vanished (Icecube: IceCat-2, 2026)





Hillas criterion - E_{max}

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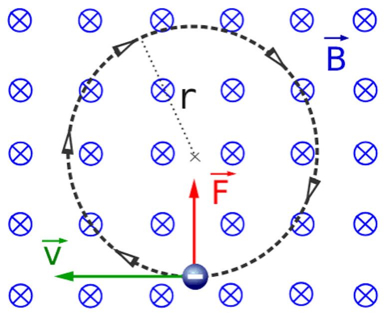
E_{max}							
emissivity							
diversity							
evolution							
arrival directions							
density							
neutrinos							

UHECR acceleration & source candidates

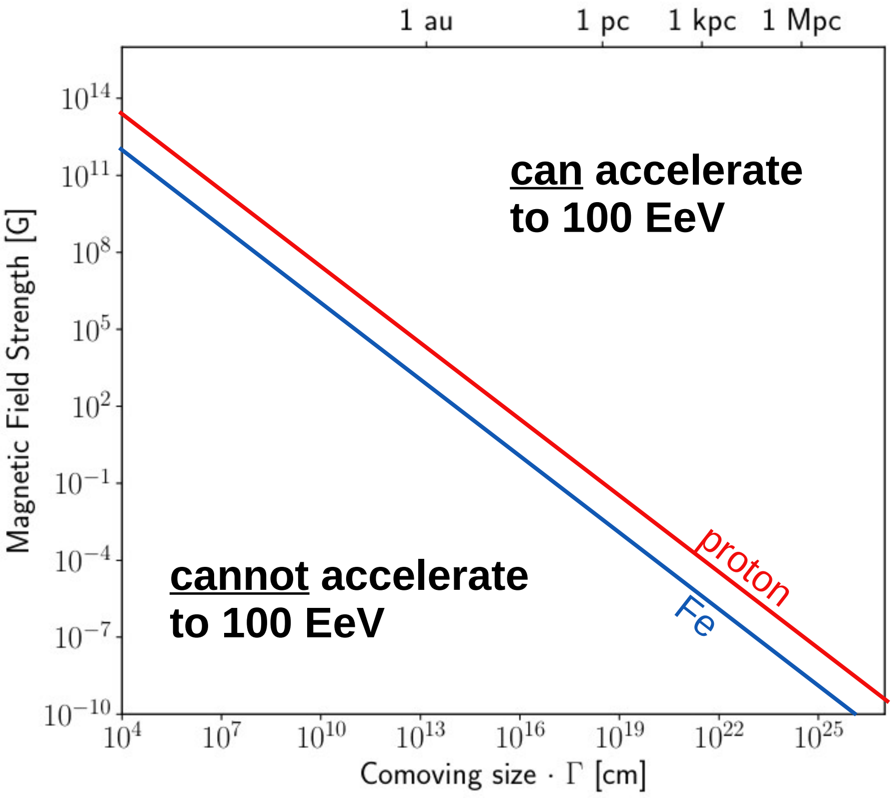
Hillas plot:
a source must be able to confine cosmic rays: if Larmor radius becomes bigger than source, they escape



Lorentz force == centripetal force:

$$E_{\text{max}} = ZecBR_{\text{source}}$$

$$E_{\text{max}} \sim 10^{17} \text{ eV } Z \left(\frac{B}{1\,\mu\text{G}}\right)\left(\frac{R_{\text{source}}}{0.1\ \text{kpc}}\right)$$



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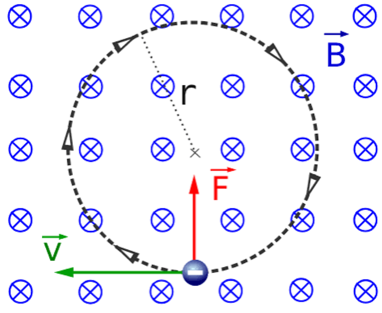

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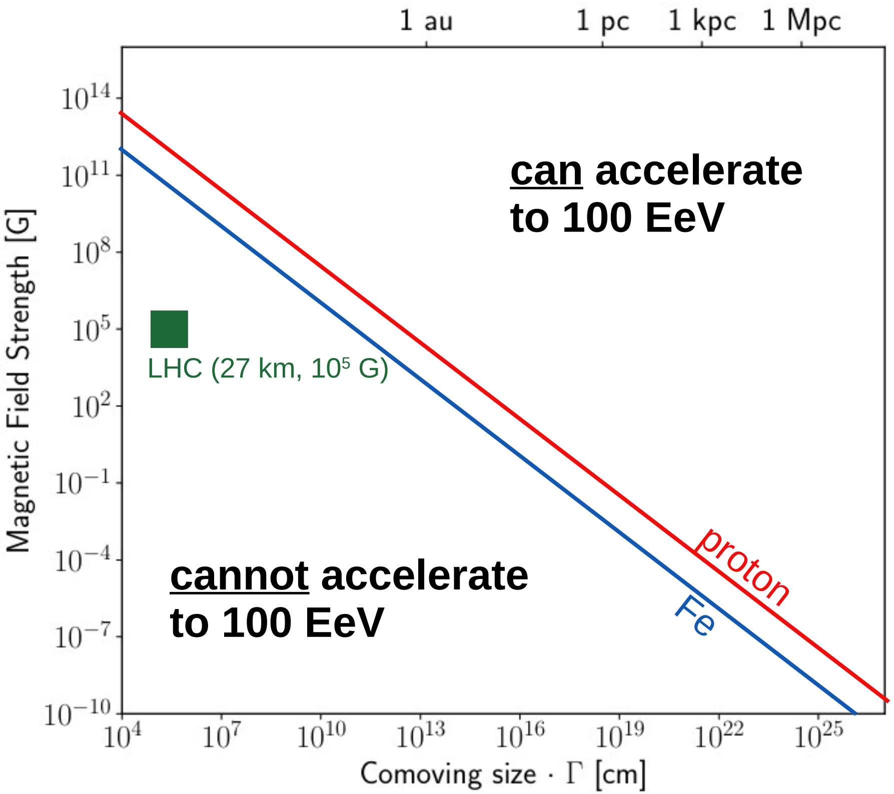

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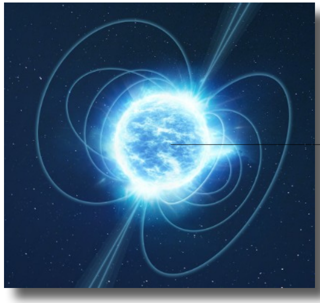
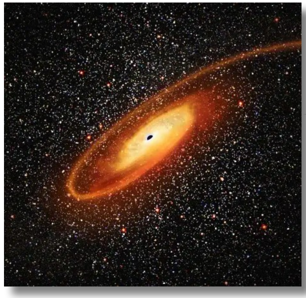
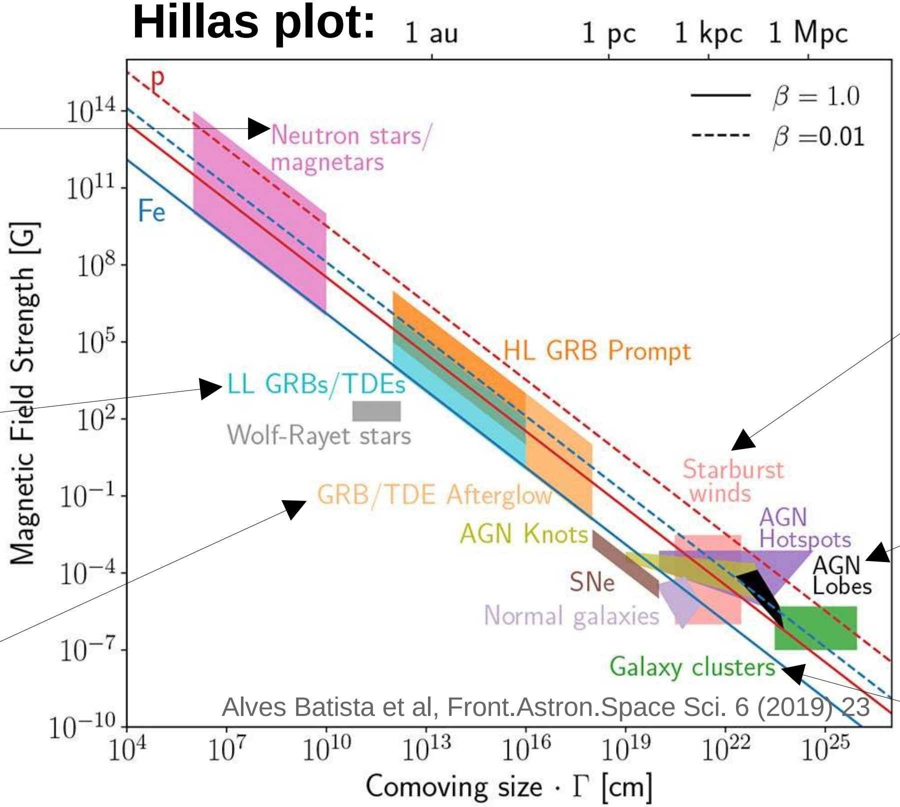




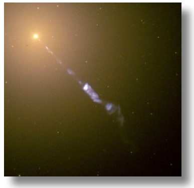
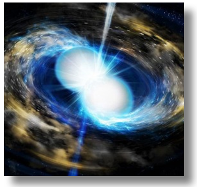
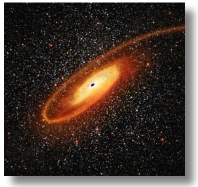
Hillas plot:



note: only a necessary condition
e.g. in SBGs, losses could be
too large to reach E_{max} = 100 EeV

A. Condorelli et al. PRD 107 (2023) 083009,
L.A. Anchordoqui PRD 97 (2018) 063010.,
G.E. Romero et al. A&A 616 (2018) A57.

Hillas criterion - E_{max}

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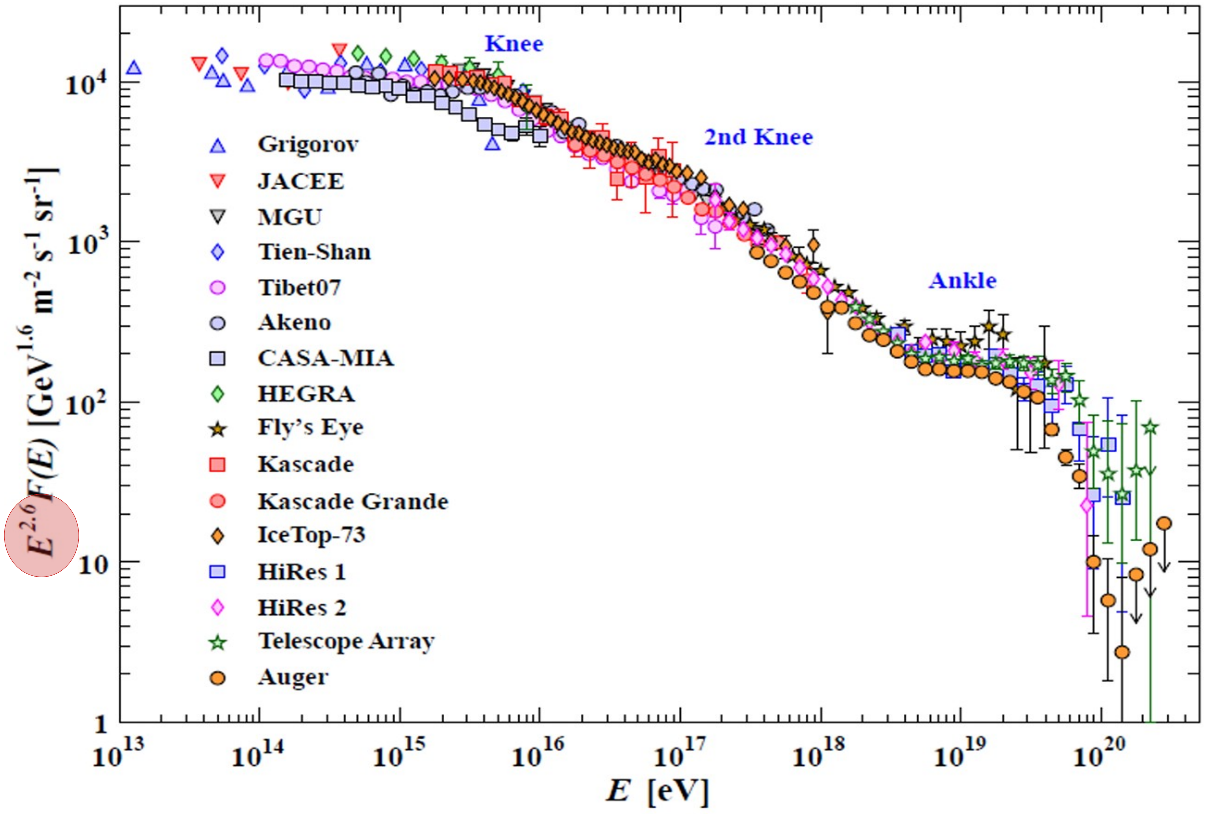
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity							
diversity							
evolution							
arrival directions							
density							
neutrinos							

Cosmic-ray energy spectrum

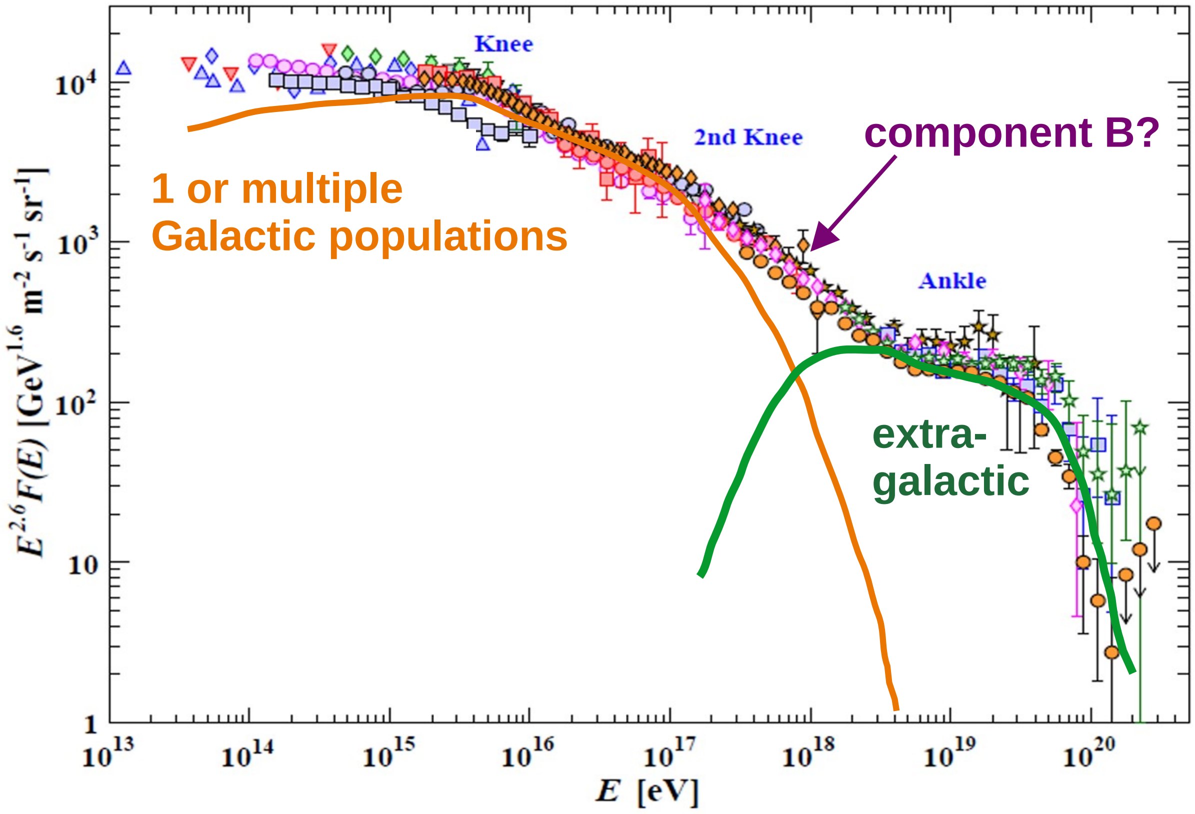
- steeply falling spectrum!
- **features in energy spectrum, very significant:**



Cosmic-ray energy spectrum

- steeply falling spectrum!

- **features in energy spectrum, very significant:**
- **knee**: ~$10^{15.5}$ eV, maximum Galactic protons?
- **2^{nd} knee**: ~$10^{16.9}$ eV, maximum Galactic iron?
- **ankle:** ~$10^{18.5}$ eV, transition to extragalactic?
- **cutoff:** ~$10^{19.7}$ eV, maximum energy of sources?



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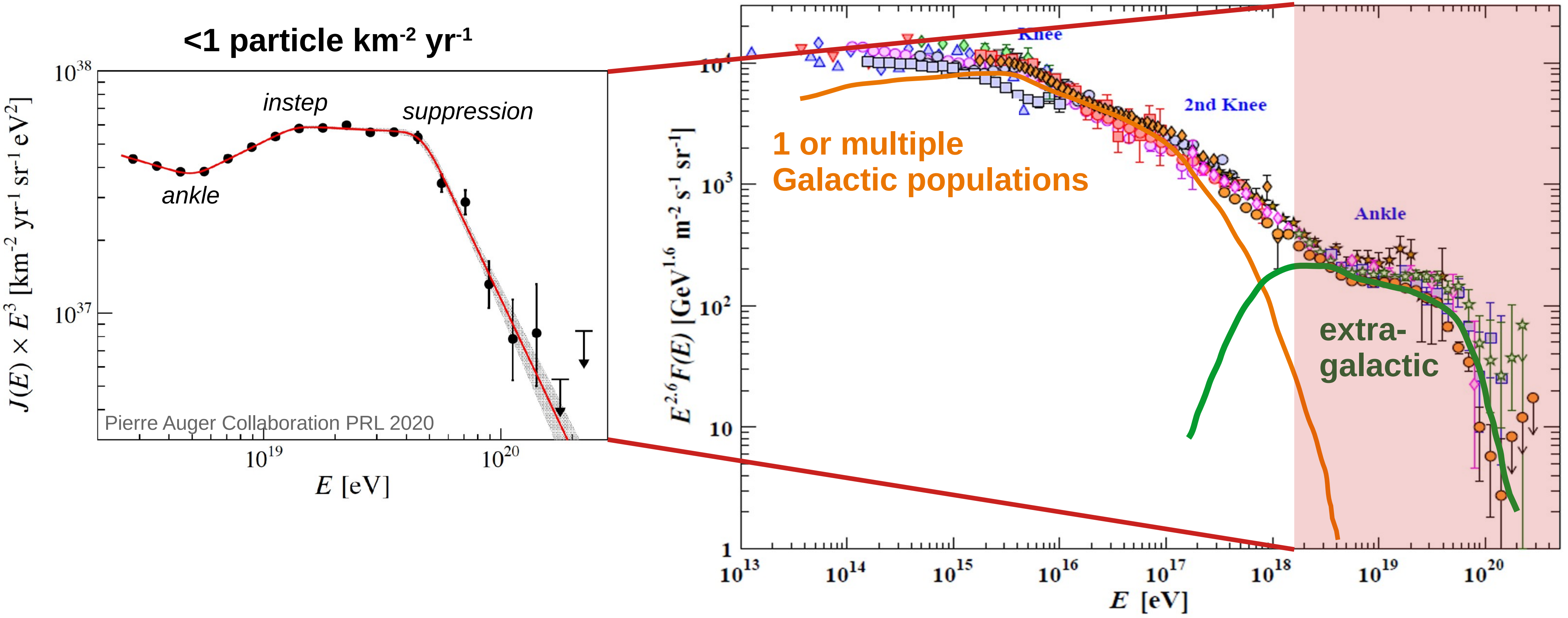
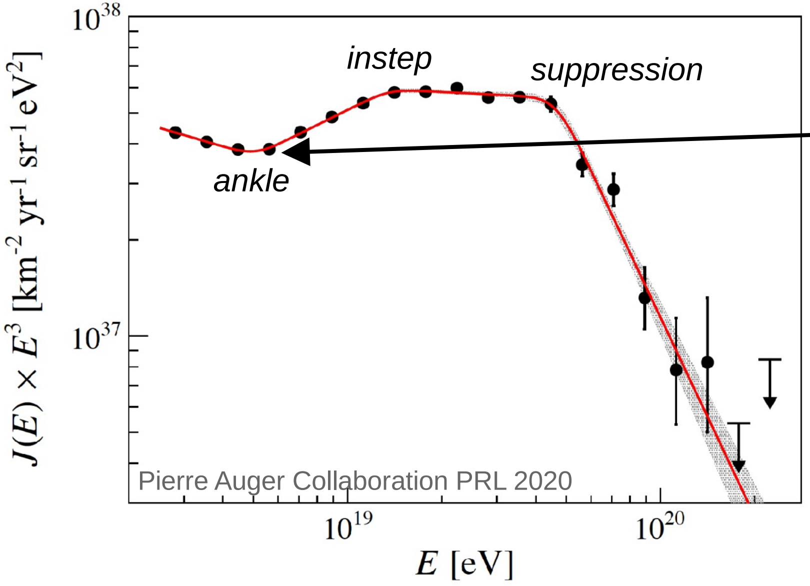


Cosmic-ray energy density

<1 particle km^{-2} yr^{-1}



energy density: $U_E = \frac{4\pi}{c}\int E\,J(E)\,\mathrm{d}E$

at the ankle:

$$E_0^3 \cdot J_0 = 10^{37.3}\ \mathrm{eV}^2\ \mathrm{km}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{yr}^{-1}$$

simplified calculation of energy density:
integrate over E^{-2} spectrum above the ankle

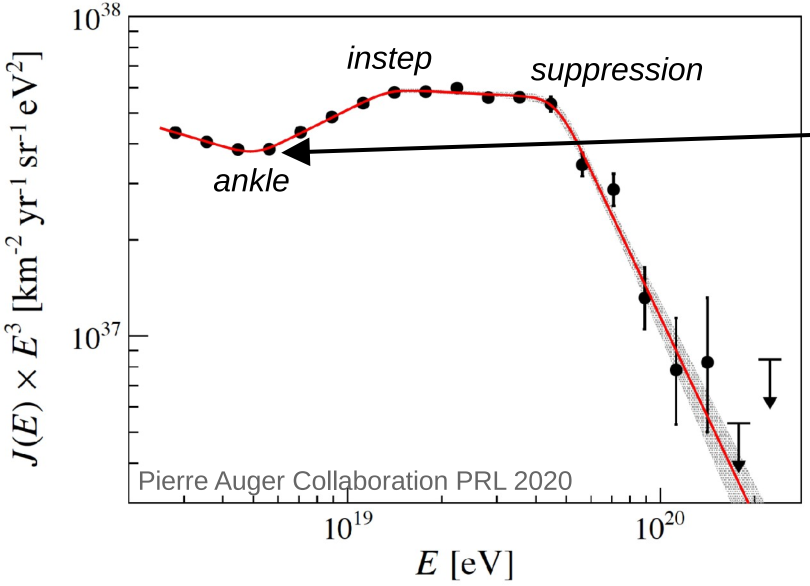
$$U_{\mathrm{UHECR}} \approx \frac{4\pi}{c} E_0^2 J_0 \ln(E_{\max}/E_{\min}) \sim \frac{4\pi}{c} E_0^2 J_0 \ln(10)$$

$$\approx 10^{-8}\ \mathrm{eV\ cm}^{-3} \quad \approx 6 \times 10^{53}\ \mathrm{erg\ Mpc}^{-3}$$

partly taken from F. Oikonomou Bad Honnef 2025

Cosmic-ray energy production rate

<1 particle km^{-2} yr^{-1}



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calculate necessary **energy production rate** to generate observed spectrum:

$$\dot{\varepsilon}_{\mathrm{UHECR}} \approx \frac{U_{\mathrm{UHECR}}}{\chi_{\mathrm{loss,UHECR}}/c}$$

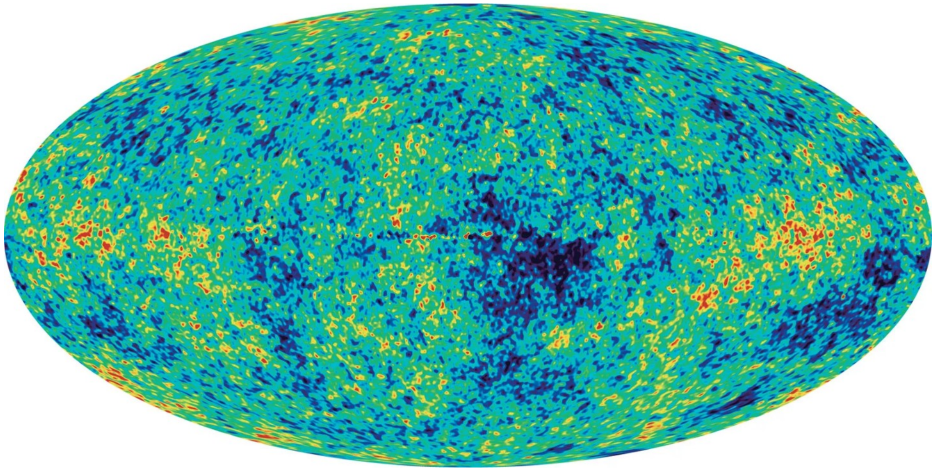
→ *What is the energy loss length of UHECRs?*

partly taken from F. Oikonomou Bad Honnef 2025

UHECR propagation

GZK cutoff

→ predicted 1966



background photons: mostly CMB

photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$ $\qquad$ $\pi^0 \rightarrow \gamma + \gamma$

$p + \gamma_{bg} \rightarrow n + \pi^+$ $\qquad$ $\pi^+ \rightarrow \nu_\mu + \mu^+$

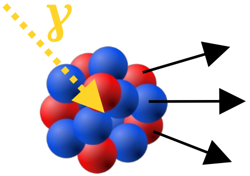
$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

(similar for nuclei)

Bethe-Heitler pair production

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A, Z) + e^- + e^+$

photodisintegration



$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1, Z) + n$

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1, Z\text{-}1) + p$

...

nuclear decays

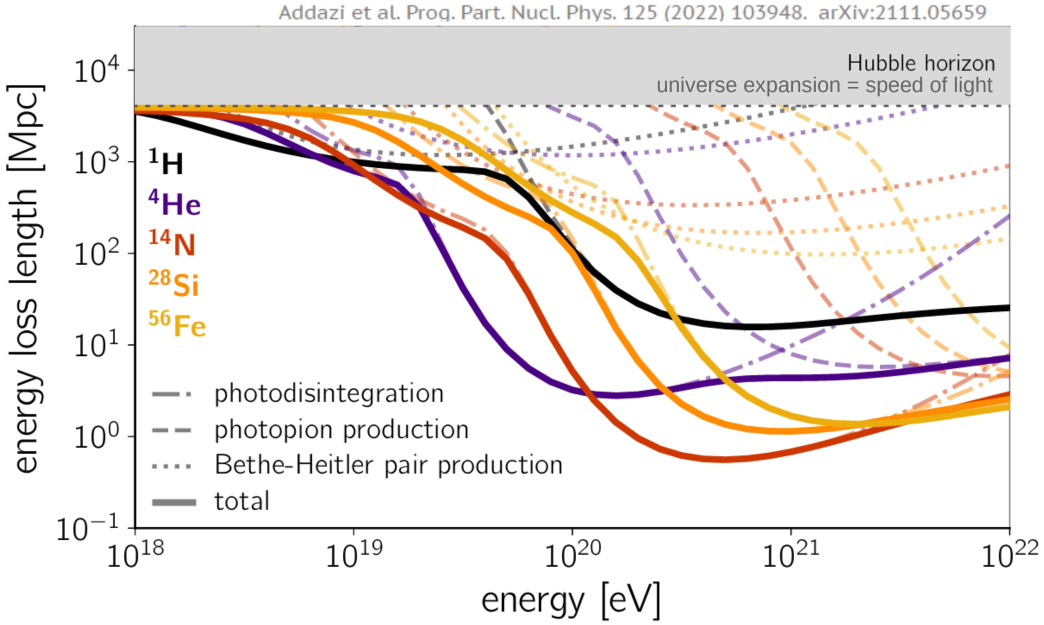
$\text{nucleus}(A, Z) \rightarrow \text{nucleus}(A\text{-}4, Z\text{-}2) + \alpha$

$\text{nucleus}(A, Z) \rightarrow \text{nucleus}(A, Z{+}1) + e^- + \underline{\nu_e}$

$\text{nucleus}(A, Z) \rightarrow \text{nucleus}(A, Z\text{-}1) + e^{-+} + \nu_e$

$\text{nucleus}(A, Z)^* \rightarrow \text{nucleus}(A, Z) + \gamma$

UHECR propagation



limited distance from which we can detect UHECRs due to interactions with background photons!

above the ankle: $\chi_{\text{loss}} \lesssim 1$ Gpc

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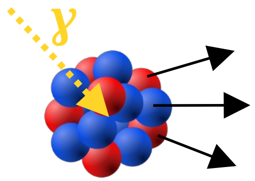


nucleus(A, Z) + $\gamma_{bg} \rightarrow$ nucleus(A-1, Z) + n

nucleus(A, Z) + $\gamma_{bg} \rightarrow$ nucleus(A-1, Z-1) + p

...

nuclear decays

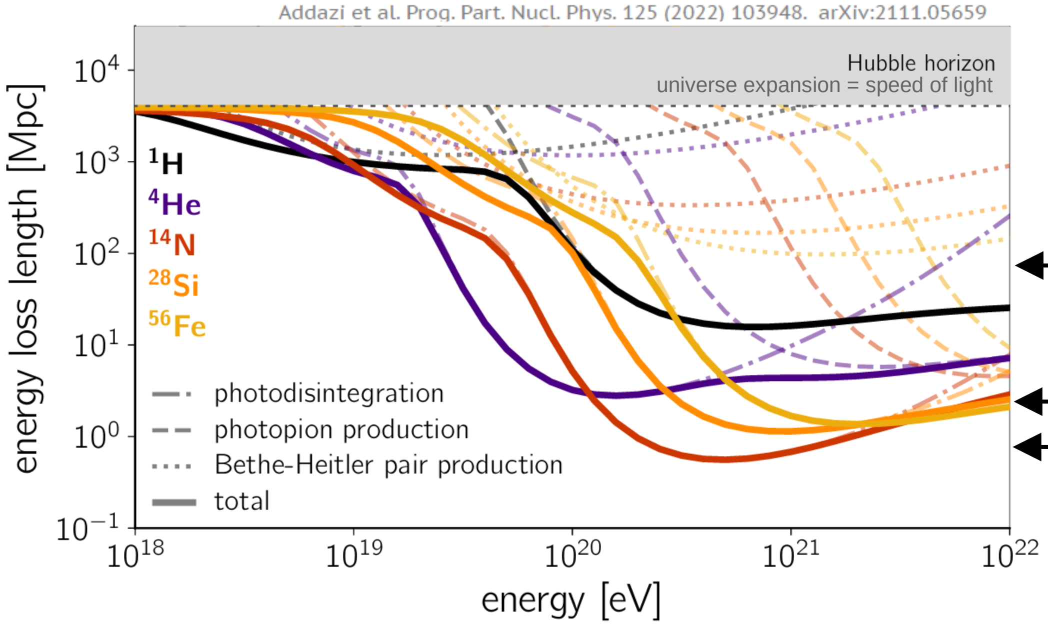
nucleus(A, Z) $\rightarrow$ nucleus(A-4, Z-2) + α

nucleus(A, Z) $\rightarrow$ nucleus(A, Z+1) + e^- + $\bar{\nu}_e$

nucleus(A, Z) $\rightarrow$ nucleus(A, Z-1) + e^+ + ν_e

nucleus(A, Z)* $\rightarrow$ nucleus(A, Z) + γ

UHECR propagation



nearest blazar ~100 Mpc

nearest radio galaxy: Centaurus A, 4 Mpc

nearest galaxy Andromeda ~0.8 Mpc

limited distance from which we can detect UHECRs due to interactions with background photons!

above the ankle: $\chi_{loss} \lesssim$ 1 Gpc

Cosmic-ray energy density

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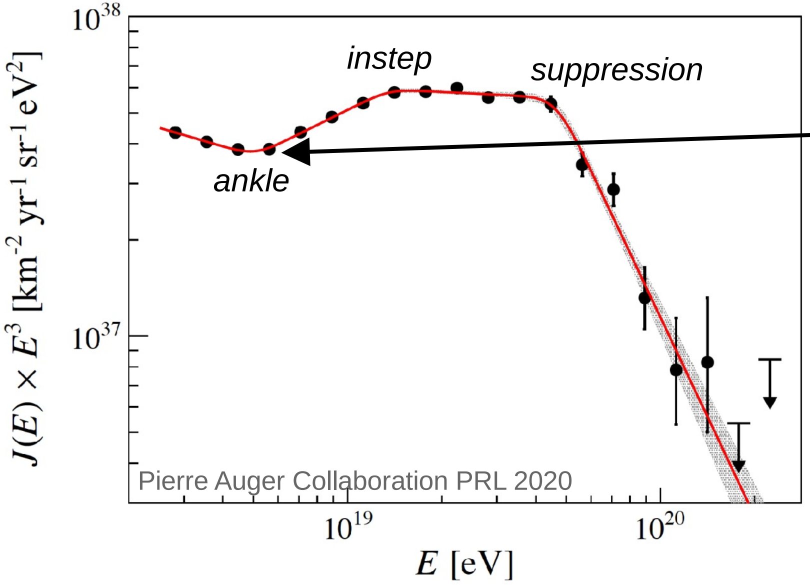

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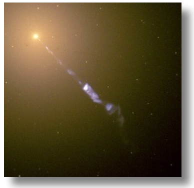
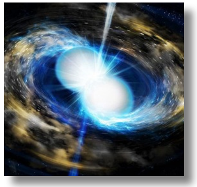
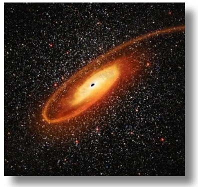
calculate necessary **energy production rate** to generate observed spectrum:

$$\boxed{\dot{\varepsilon}_{\mathrm{UHECR}} \approx \frac{U_{\mathrm{UHECR}}}{\chi_{\mathrm{loss,UHECR}}/c} = \frac{U_{\mathrm{UHECR}}}{1\,\mathrm{Gpc}/c} \approx 2 \times 10^{44}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{year}^{-1}}$$

exact with Auger combined fit: 5x10^{44} erg Mpc^{-3} yr^{-1}

partly taken from F. Oikonomou Bad Honnef 2025

Emissivity of source candidates

	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓			

energy production rate for **steady sources** is*:

emitted power [erg / s]   x   number density [Mpc^{-3}]

goal: 5×10^{44} erg Mpc^{-3} yr^{-1}

<u>rough estimates:</u>

AGN: 10^{50} erg yr^{-1} x 10^{-5} Mpc^{-3} = 10^{45} erg Mpc^{-3} yr^{-1}

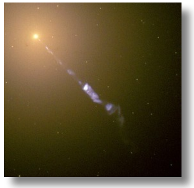
blazars: 10^{55} erg yr^{-1} x 10^{-7} Mpc^{-3} x 1% = 10^{46} erg Mpc^{-3} yr^{-1}

Cen A: 10^{50} erg yr^{-1} x $1 / (4\ \mathrm{Mpc})^{3}$ = 10^{48} erg Mpc^{-3} yr^{-1}

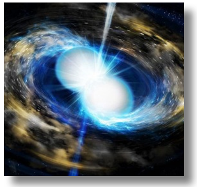
SBGs: 10^{49} erg yr^{-1} x 10^{-4} Mpc^{-3} = 10^{45} erg Mpc^{-3} yr^{-1}

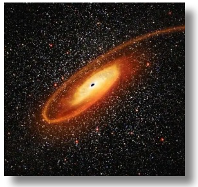
*neglecting jet angle influence

Emissivity of source candidates









	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?

energy production rate for **transient sources** is:

emitted power [erg] x beam-corrected rate density [$Mpc^{-3}\,yr^{-1}$]

goal: 5×10^{44} erg Mpc^{-3} yr^{-1}

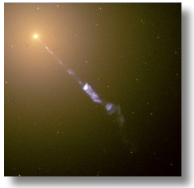
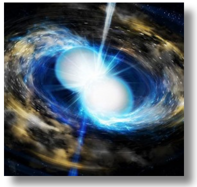
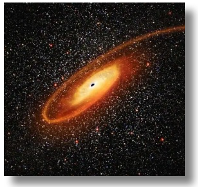
<u>rough estimates:</u>

short GRBs: 10^{50} erg x 10^{-7} yr^{-1} Mpc^{-3} = 10^{43} erg Mpc^{-3} yr^{-1} → uncertainty due to limited measurements

long GRBs: 10^{50} erg x 10^{-5} yr^{-1} Mpc^{-3} = 10^{45} erg Mpc^{-3} yr^{-1} → large variations

jetted TDEs: 10^{52} erg x 10^{-9} yr^{-1} Mpc^{-3} = 10^{43} erg Mpc^{-3} yr^{-1} → uncertainty due to limited measurements

Overview

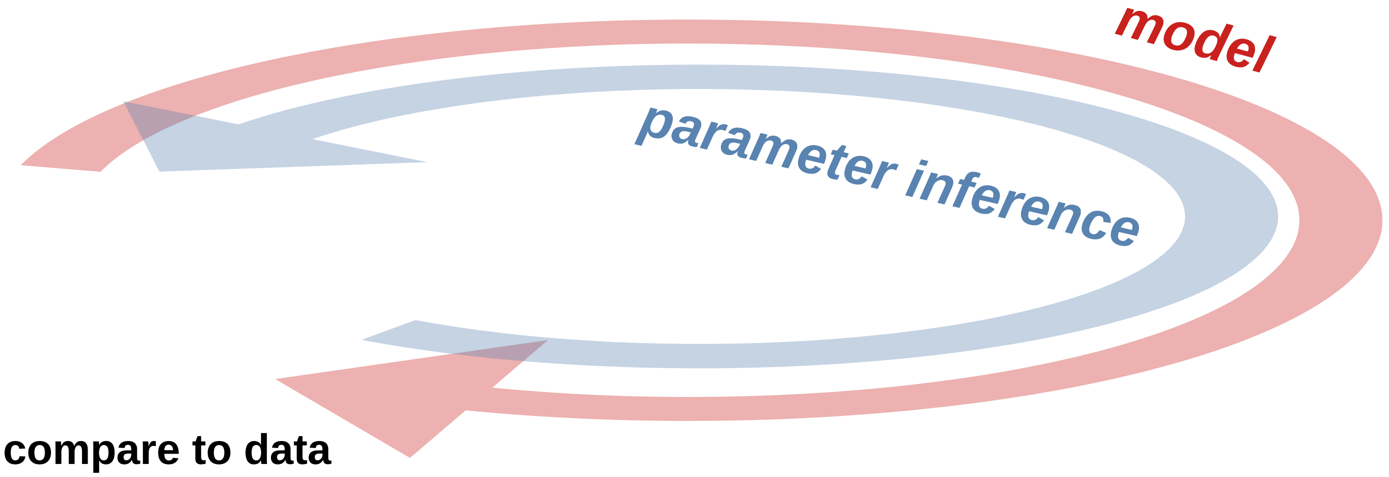
      

	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
diversity							
evolution							
arrival directions							
density							
neutrinos							

need to fit a model to the measured spectrum and mass composition to see if these source population properties can be constrained

The combined fit: how does it work?

main aim: learn more about the sources of UHECRs

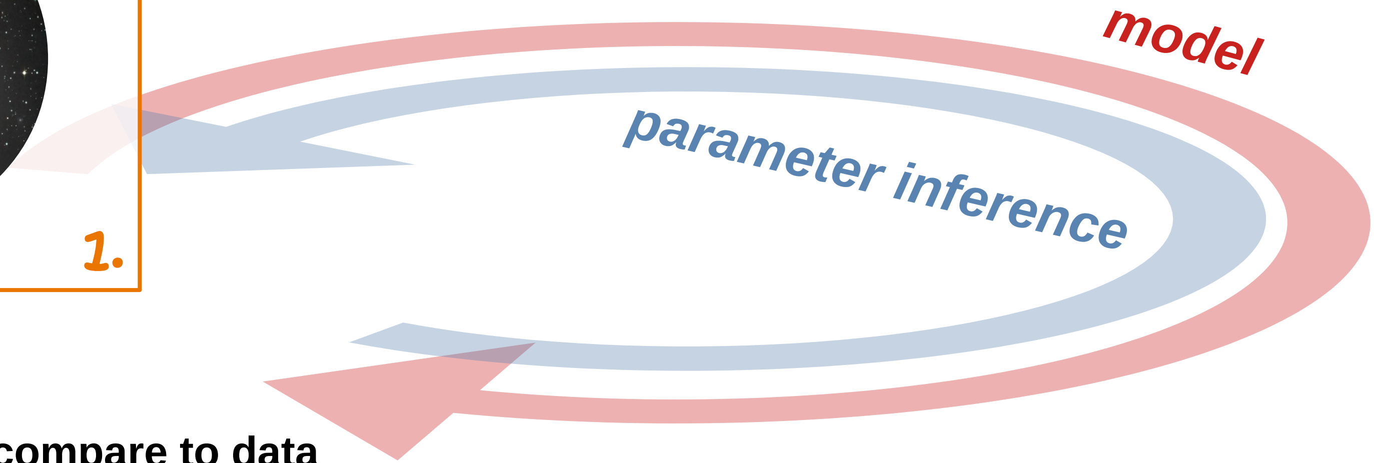


The combined fit: how does it work?

sources emit UHECRs

1.

main aim: learn more about the sources of UHECRs

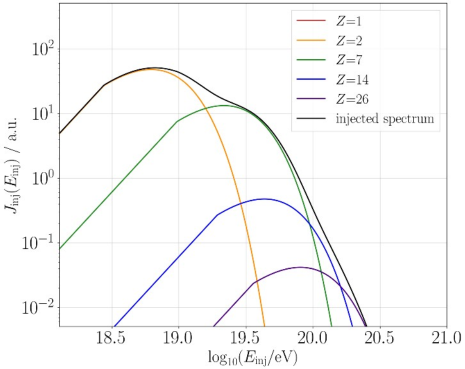


compare to data

The combined fit: how does it work?

sources emit UHECRs

2. injection



usual assumptions:

- **maximum energy prop. to charge number Z: "Peters cycle"**
- shape: power-law + cutoff:

spectral index

rigidity cutoff

$$\widetilde{Q}_A(E) = \widetilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \leq Z_A R_{\mathrm{cut}} \\ \exp\left(1 - \frac{E}{Z_A R_{\mathrm{cut}}}\right), & E > Z_A R_{\mathrm{cut}} \end{cases}$$

element contributions

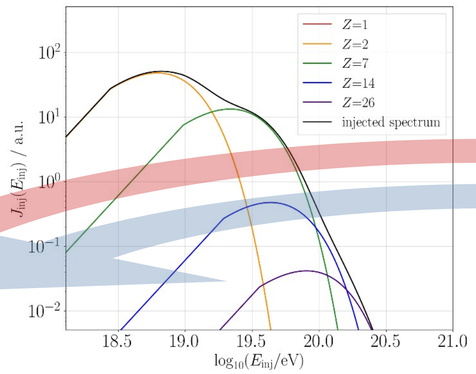
- model 5 representative elements (H, He, N, Si, Fe)

compare to data

The combined fit: how does it work?

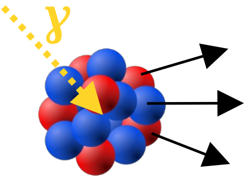
sources emit UHECRs

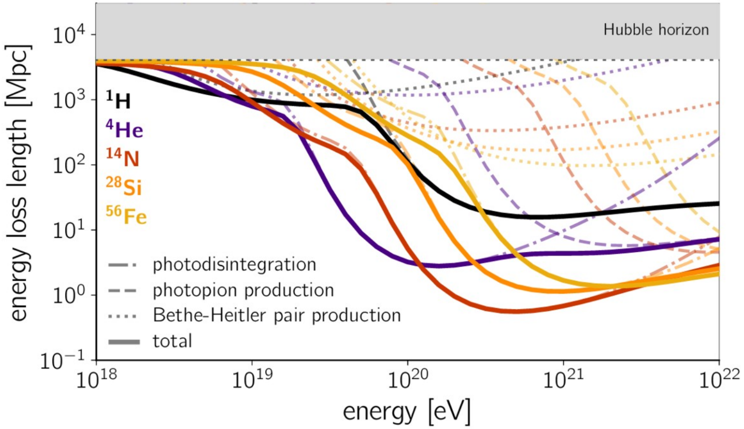
injection



3.

propagation through extragalactic space



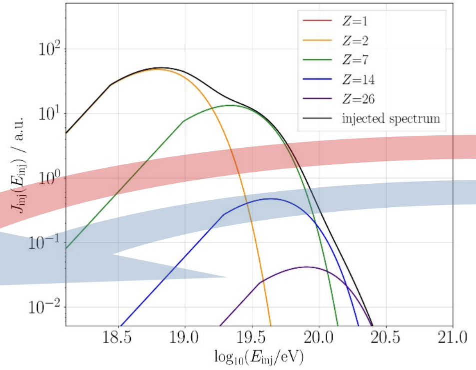


compare to data

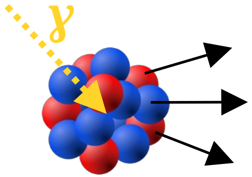
The combined fit: how does it work?

sources emit UHECRs

injection



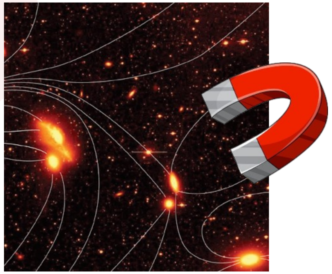
propagation through extragalactic space



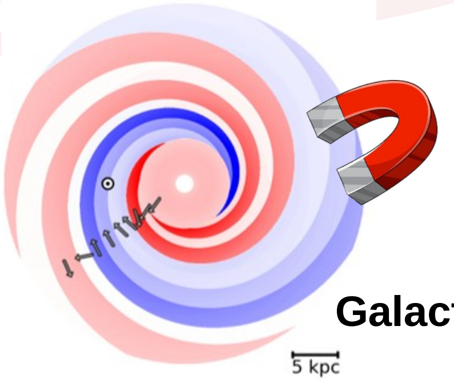
4. & 5.

→ tomorrow

extragalactic magnetic field



both deflect particles proportionally to Z/E = 1/R („rigidity“)



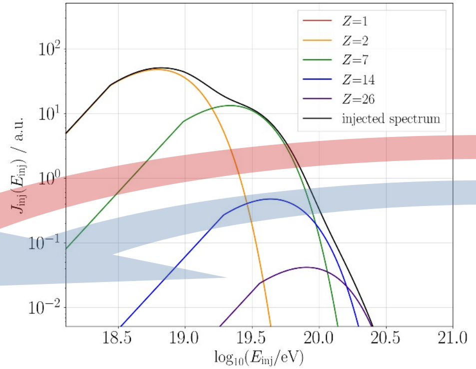
Galactic magnetic field

compare to data

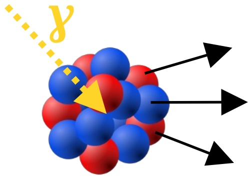
The combined fit: how does it work?

sources emit UHECRs

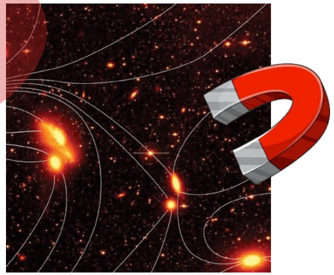
injection



propagation through extragalactic space



extragalactic magnetic field

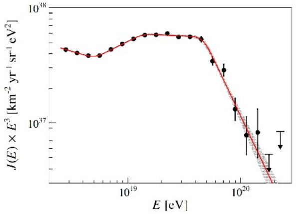


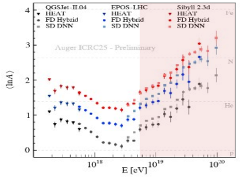
6.

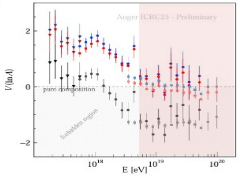
compare to data

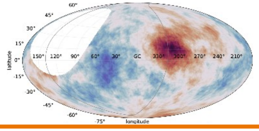
- energy spectrum
- mass composition
- arrival directions

likelihood









$$\log \mathcal{L} = \log \mathcal{L}_E + \log \mathcal{L}_{\rm Xmax} + \log \mathcal{L}_{\rm AD}$$

$$\mathcal{L}_E = \prod_e \frac{(p^e)^{k^e}}{k^e!} \exp\left(-p^e\right)$$

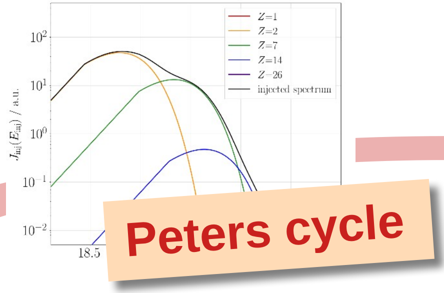
$$\mathcal{L}_{\rm Xmax} = \prod_{\tilde{e}} k^{\tilde{e}}! \prod_x \frac{(p^{\tilde{e},x})^{k^{\tilde{e},x}}}{k^{\tilde{e},x}!}$$

$$\mathcal{L}_{\rm AD} = \prod_e \prod_p {\rm pdf}^{e,p}(v^{e,p})$$

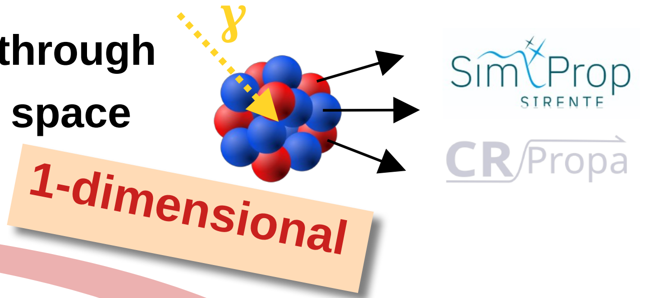
Combined fit of spectrum and composition

source distribution

injection



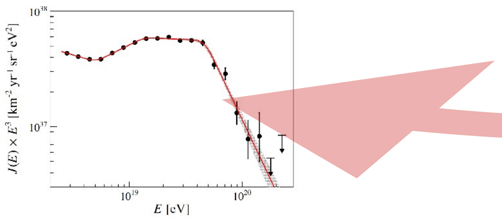
propagation through extragalactic space

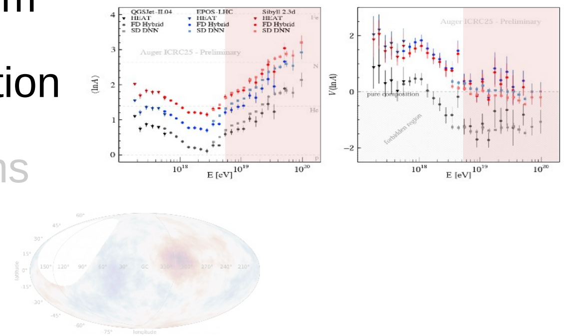


extragalactic magnetic fields

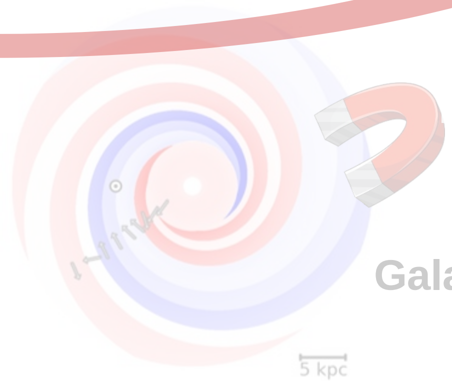
compare to data

- energy spectrum
- mass composition
- arrival directions





Galactic magnetic fields

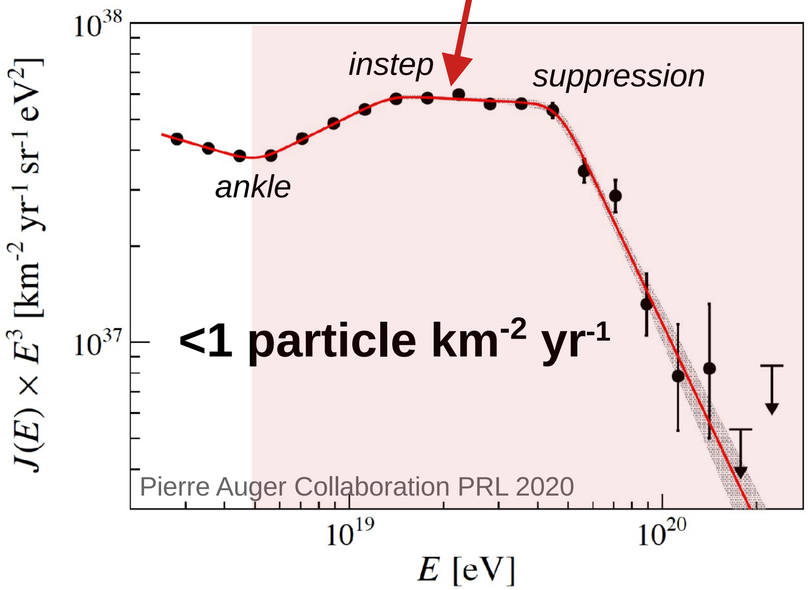


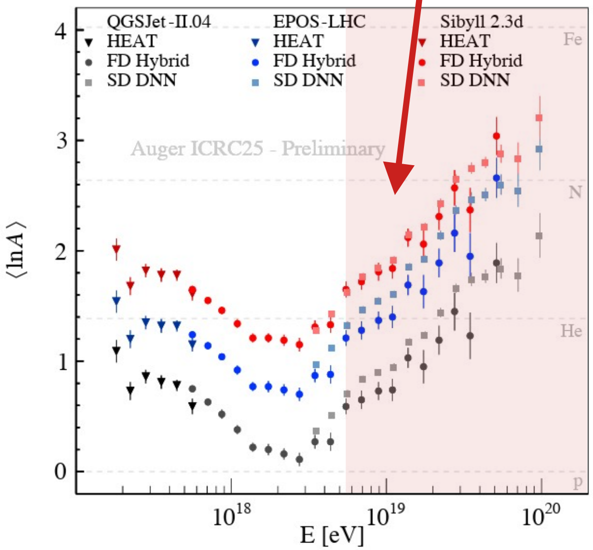
Energy spectrum and mass composition

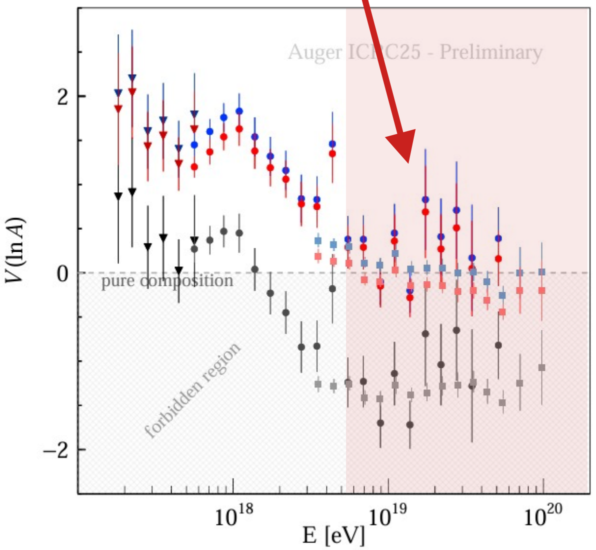
pronounced features in the energy spectrum

mass composition becomes **progressively heavier above the ankle**

composition becomes **purer** with energy







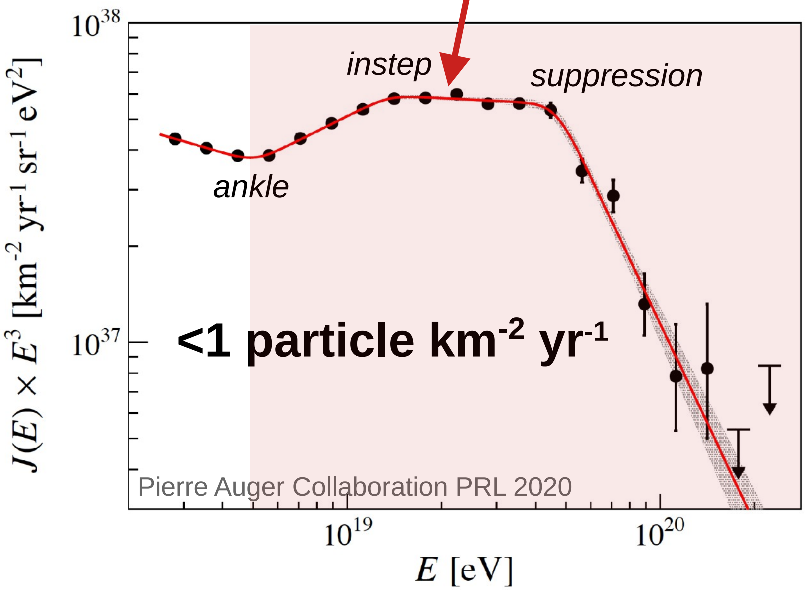
Energy spectrum and mass composition

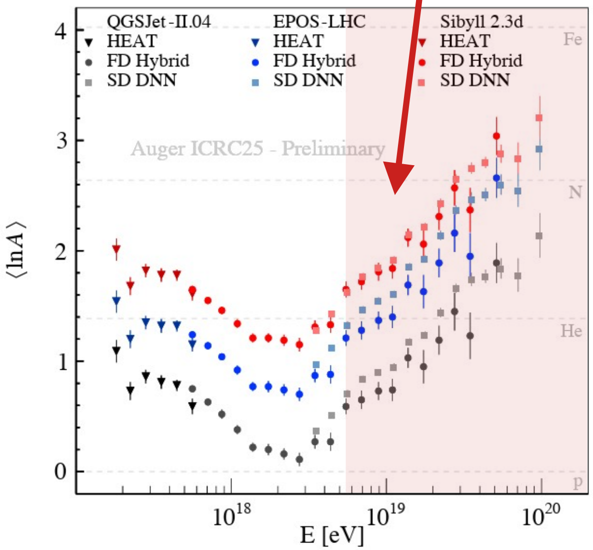
What can we learn about the sources from this data?

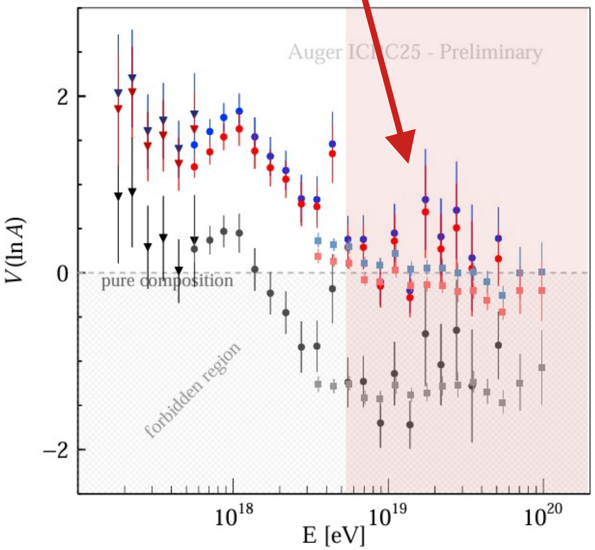
pronounced features in the energy spectrum

mass composition becomes **progressively heavier above the ankle**

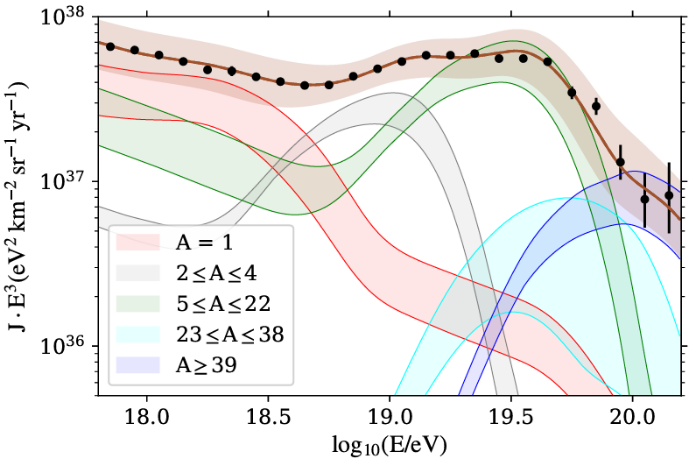
composition becomes **purer** with energy







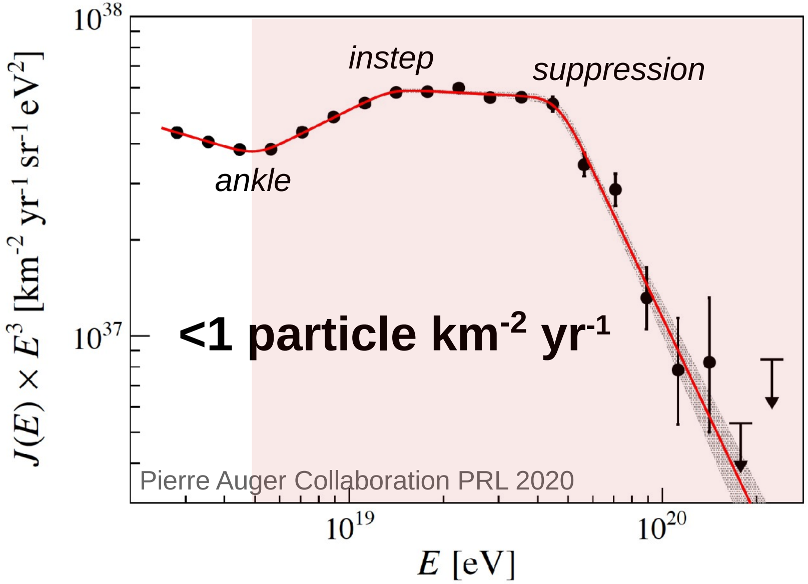
Energy spectrum and mass composition

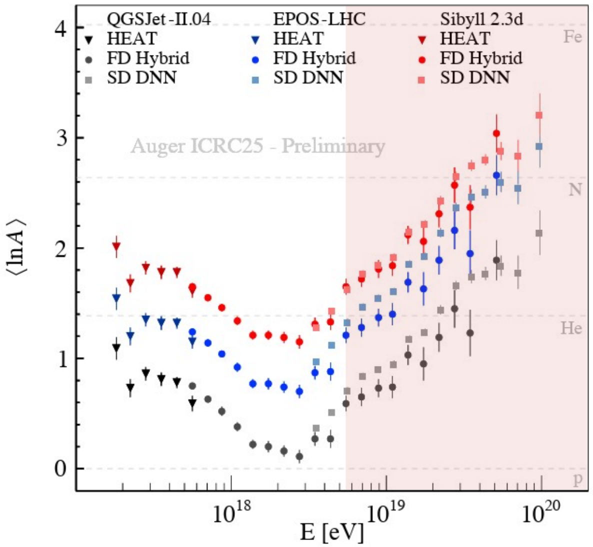


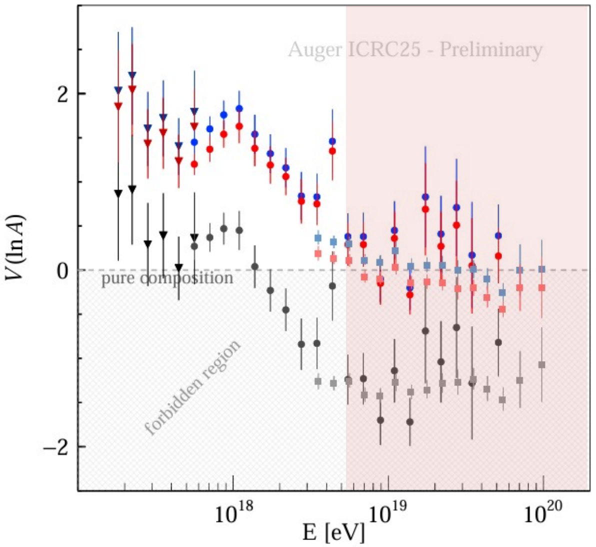
combined fit to energy spectrum & mass composition data:

- **homogeneous & extragalactic** sources dominating above ankle
- **acceleration ∝ Z** → mass composition gets heavier
- constrains spectrum and composition emitted at sources:
  - hard spectrum & fast change of mass groups, mixed composition

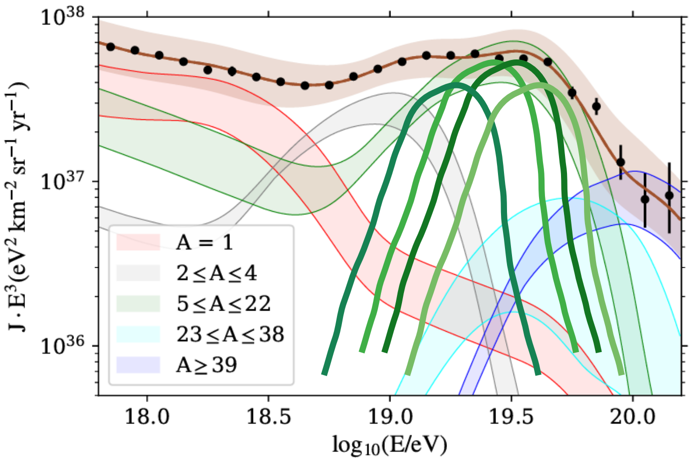
Pierre Auger Collaboration, JCAP 2023







Energy spectrum and mass composition

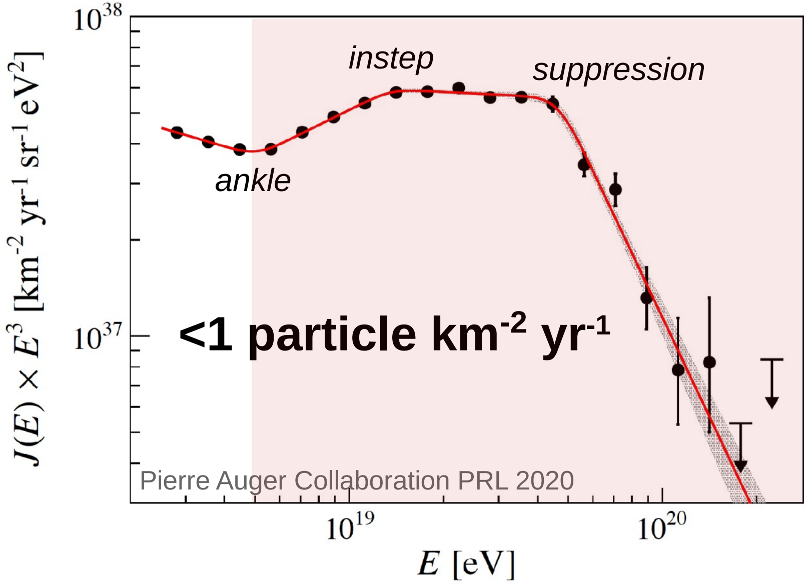


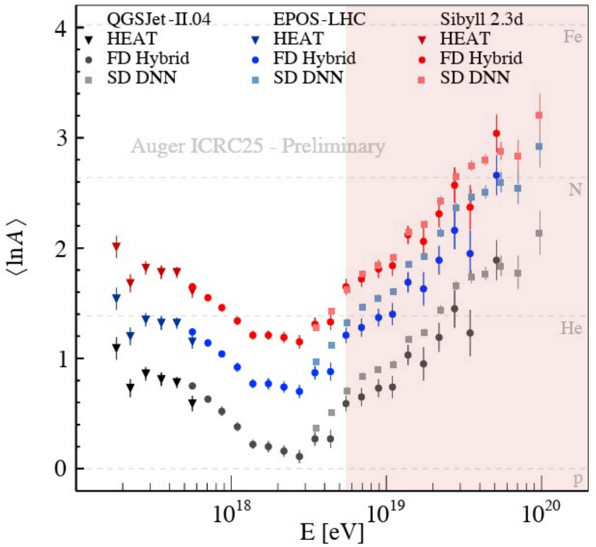
combined fit to energy spectrum & mass composition data:

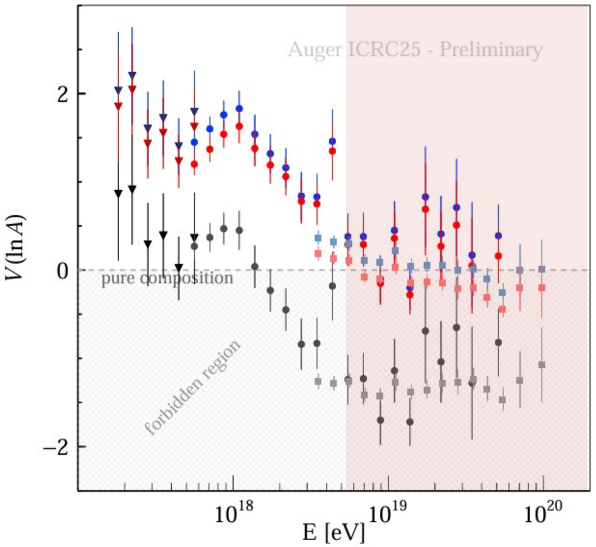
- **homogeneous & extragalactic** sources dominating above ankle
- **acceleration ∝ Z** → mass composition gets heavier
- constrains spectrum and composition emitted at sources:
  - hard spectrum & fast change of mass groups, mixed composition & **identical sources within factor of a few!**

Pierre Auger Collaboration, JCAP 2023

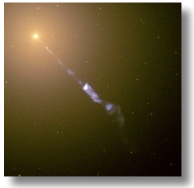
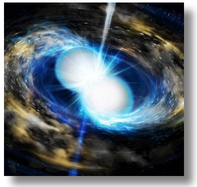
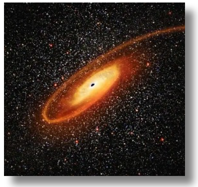
Ehlert, Oikonomou, Unger, PRD 2023







Source classes with low population diversity?

	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
low population diversity	✗	✗	✓	✗	✓	✗	✗

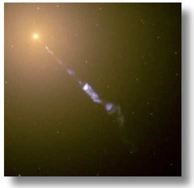
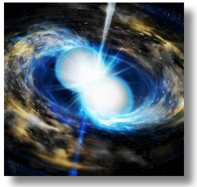
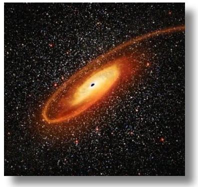
Ehlert, et al 2023
Eichmann et al 2022

Mollerach & Roulet 2024
Bister 2025

Farrar 2024, 2025:
acceleration driven gravitationally,
neutron stars always similar mass
$(2.7\,M_\odot \pm 5\%)$

- This small source diversity is still a topic of debate!
- No complete simulations of CR acceleration in any of the source candidates exist yet
- Could there be something wrong with the measurements or interpretation?

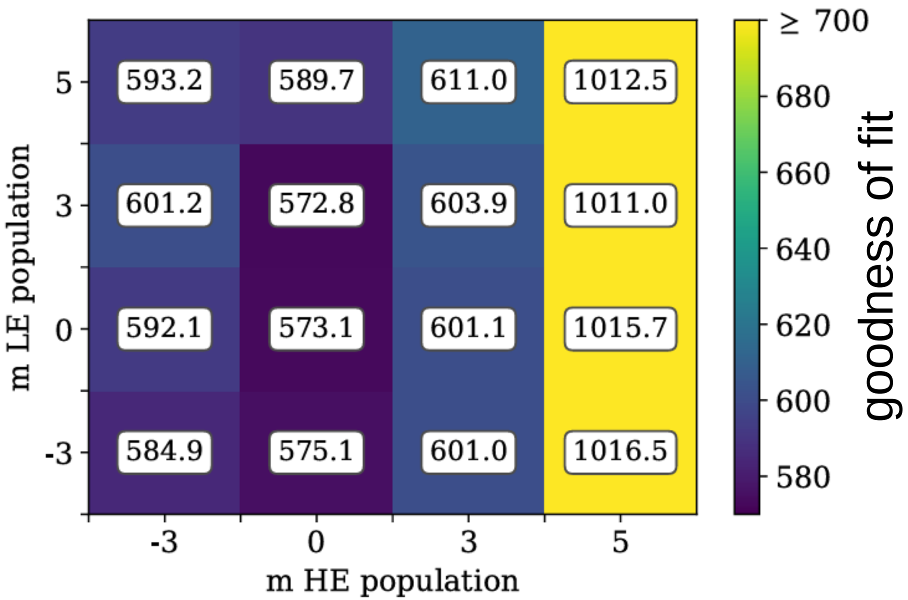
Overview

	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
low population diversity	✗	✗	✓	✗	✓	✗	✗
evolution							
arrival directions							
density							
neutrinos							

Model predictions for the source evolution

test cosmological source evolution $\psi(z) \propto (1+z)^m$ z: redshift



Model predictions for the source evolution

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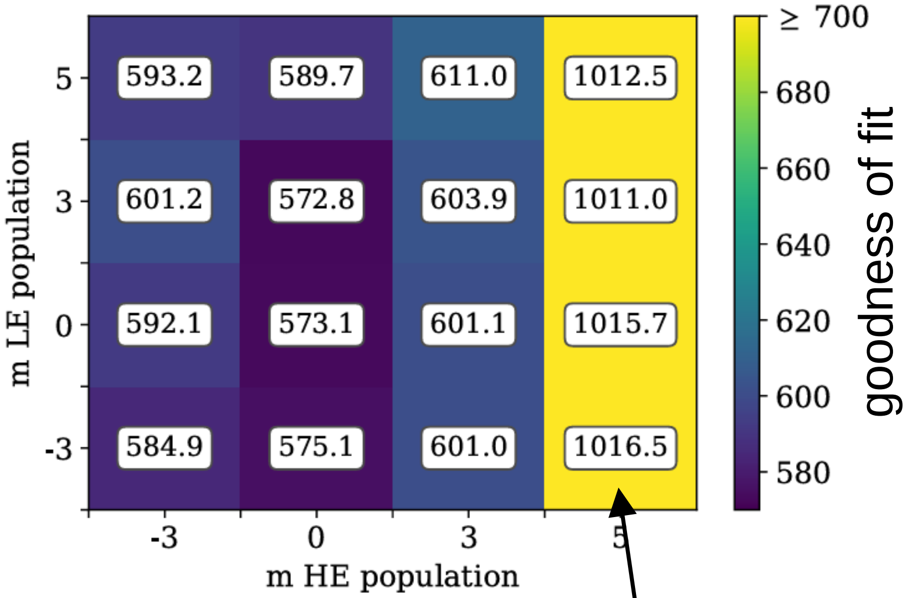
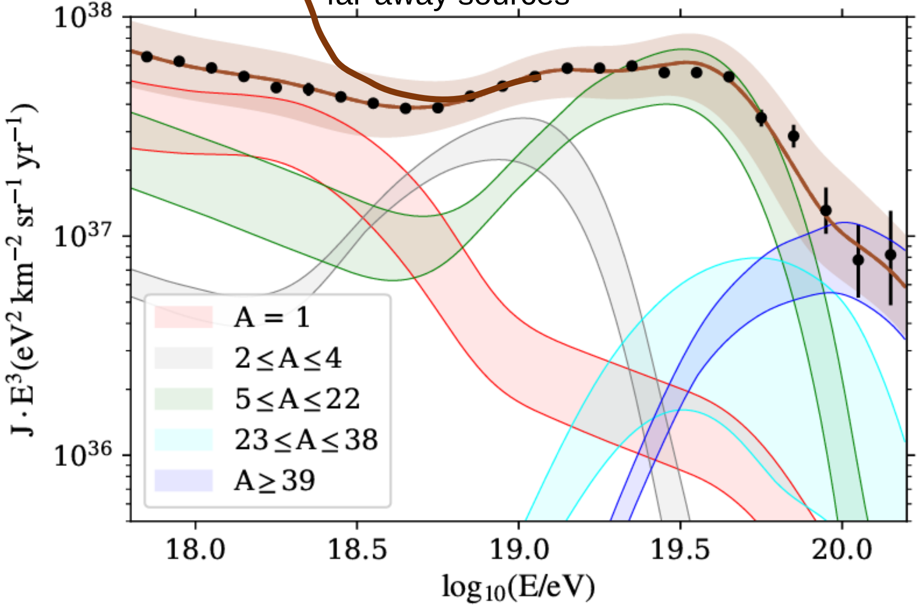


strong evolution of high-energy population disfavored

if too strong evolution:
too many decay products from far-away sources



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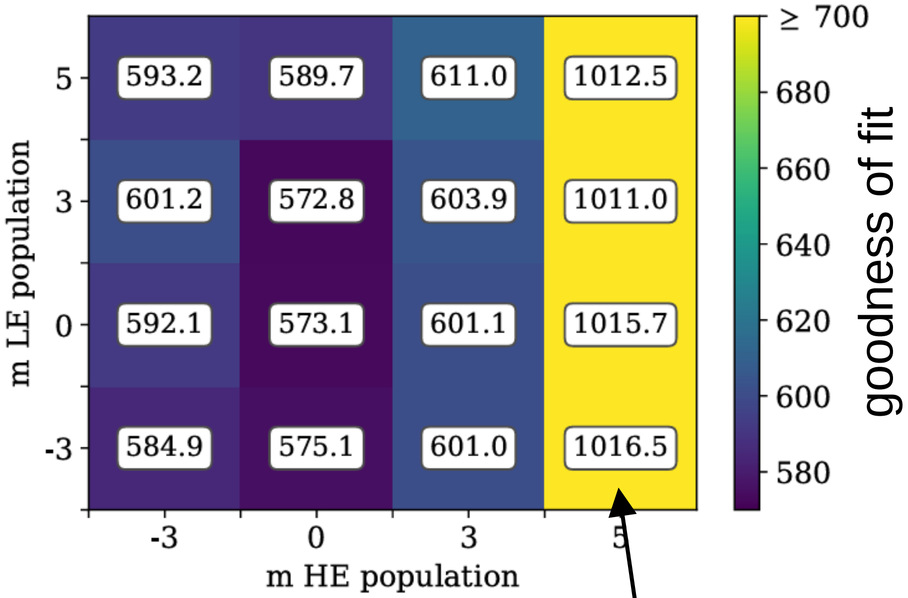
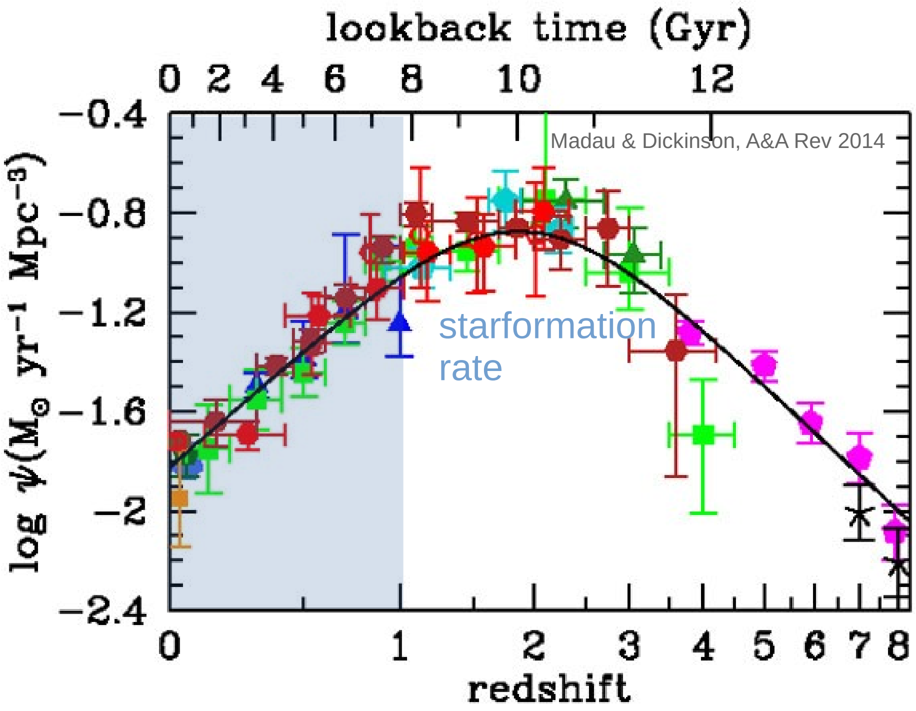
Model predictions for the source evolution

test cosmological source evolution $\psi(z) \propto (1+z)^m$





strong evolution of
high-energy population
disfavored

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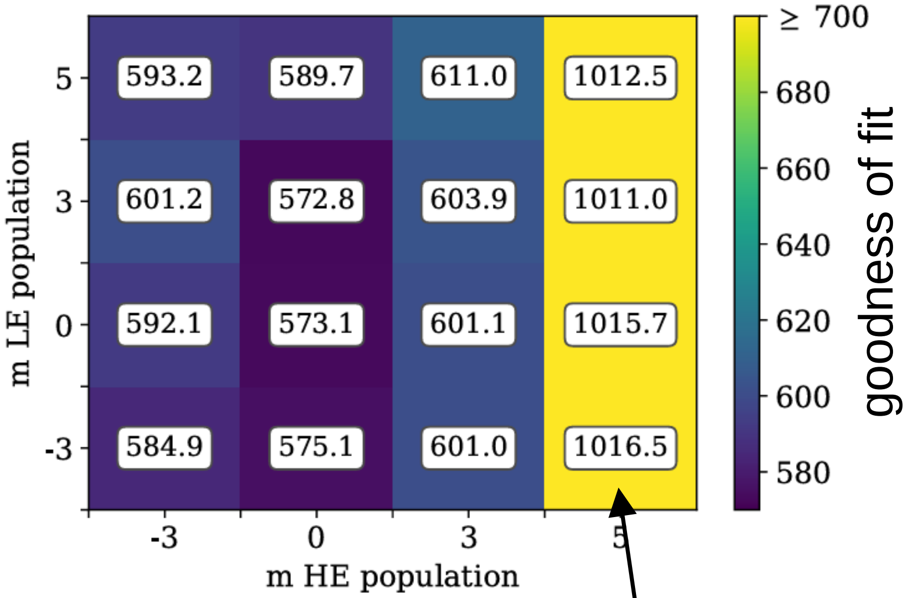
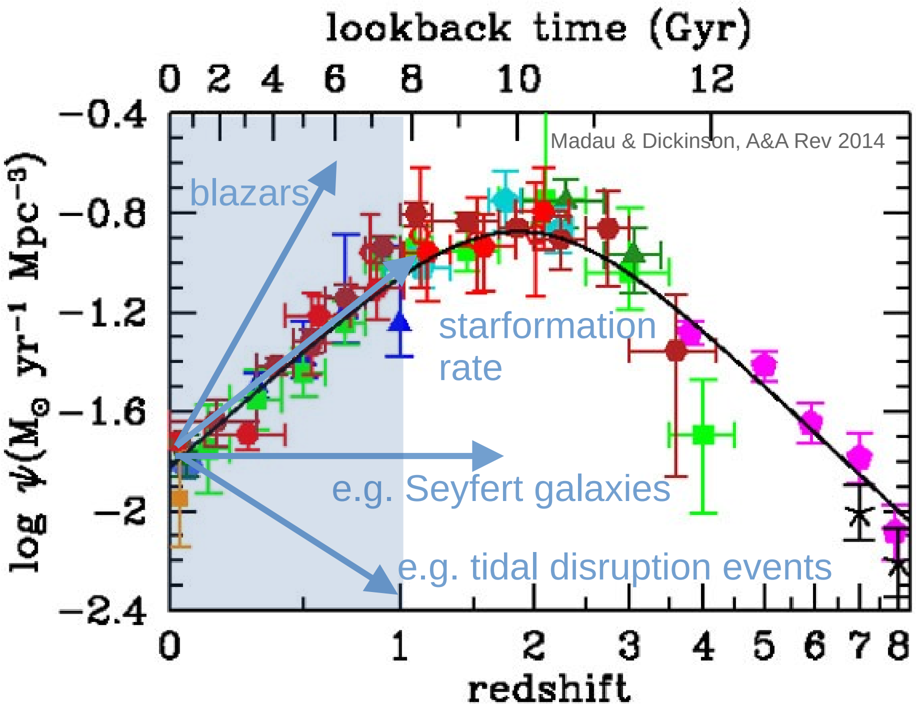
Model predictions for the source evolution

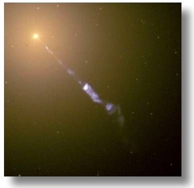
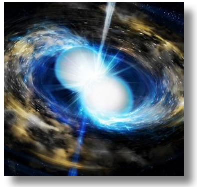
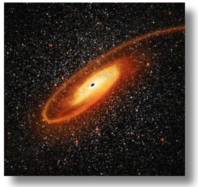
test cosmological source evolution $\psi(z) \propto (1+z)^m$





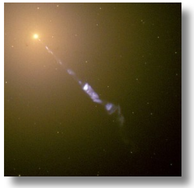
strong evolution of high-energy population disfavored

Source evolution

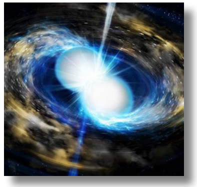
      

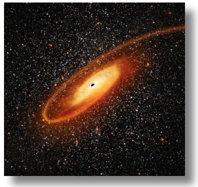
	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
low population diversity	✗	✗	✓	✗	✓	✗	✗
not too strong evolution	(✓)	(✗)	✓	✓	✓	✓	✓

Overview









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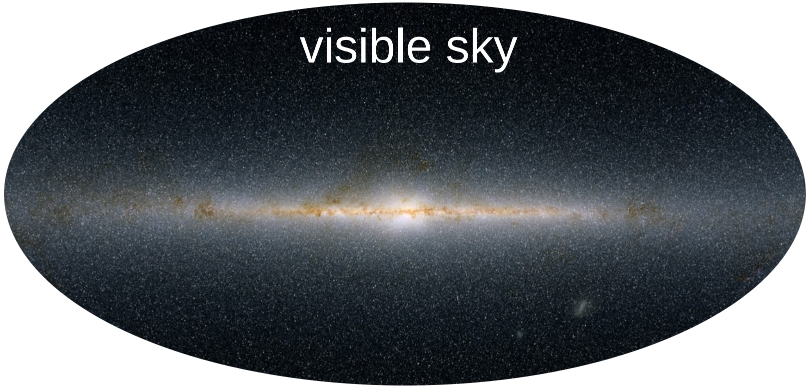
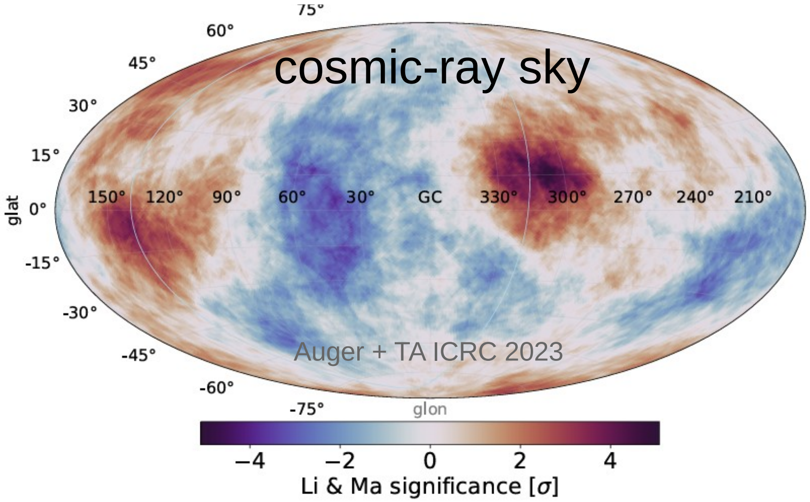
arrival directions							
density							
neutrinos							

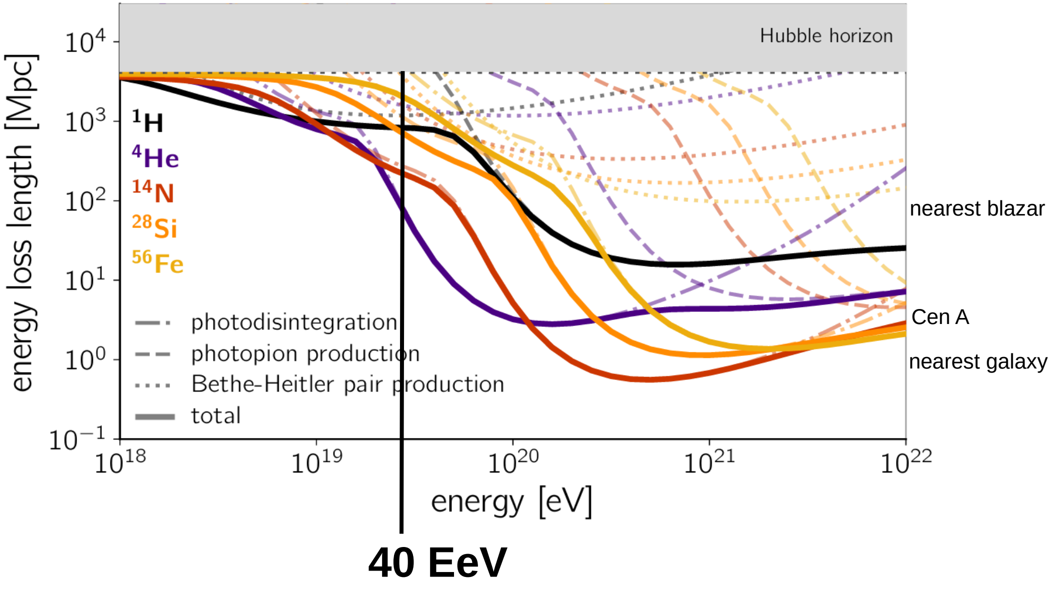
The UHECR sky >40 EeV



cosmic-ray sky very different from visible sky:

- no clear point sources
- no flux from Galactic center
- overdensities could be imprints of local sources?





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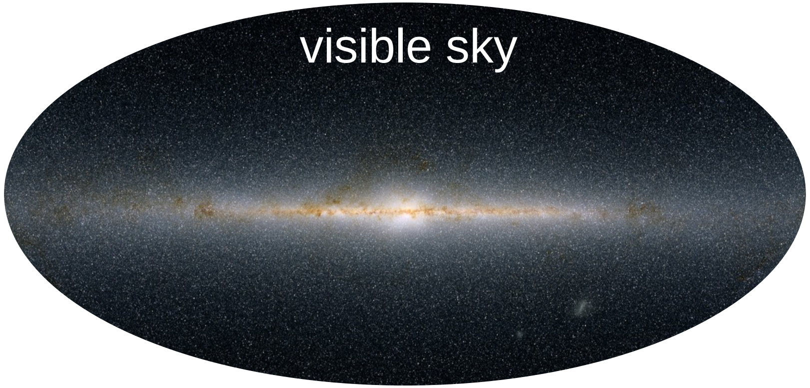
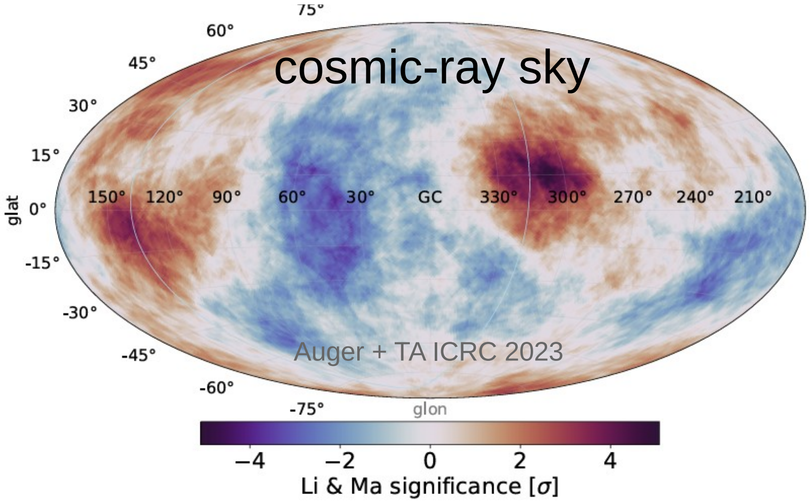
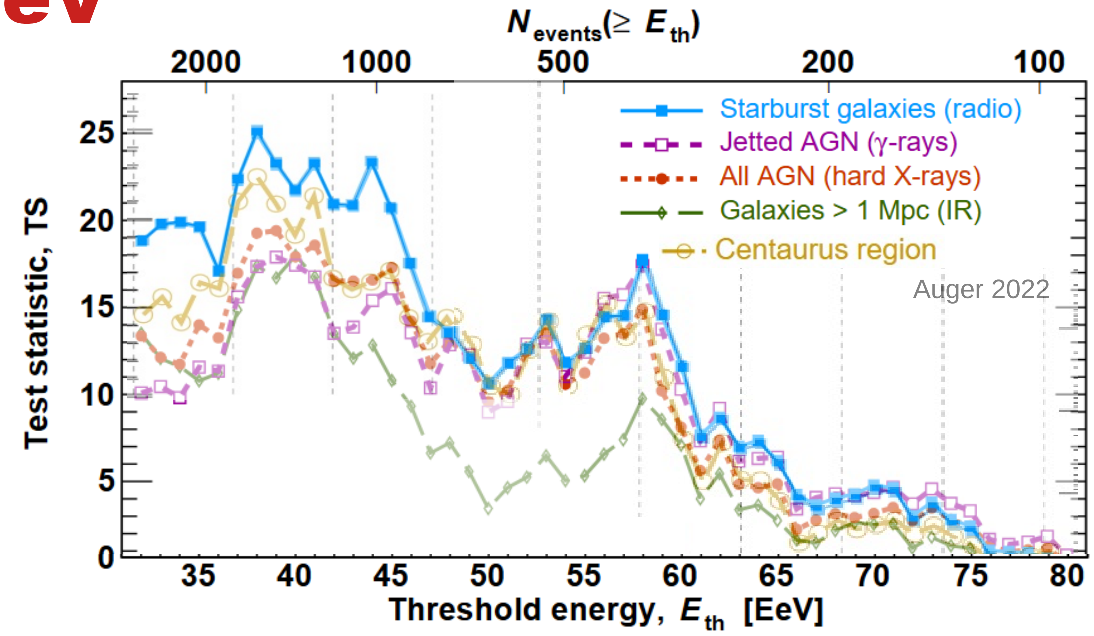
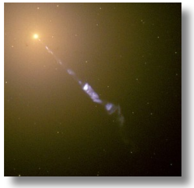




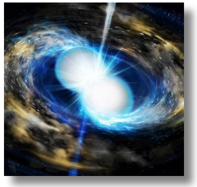


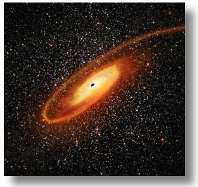
- **best correlation: with starburst galaxies**
  - i.e. also with transient events happening more often in starburst galaxies

Overview









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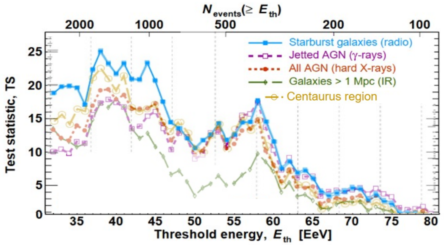

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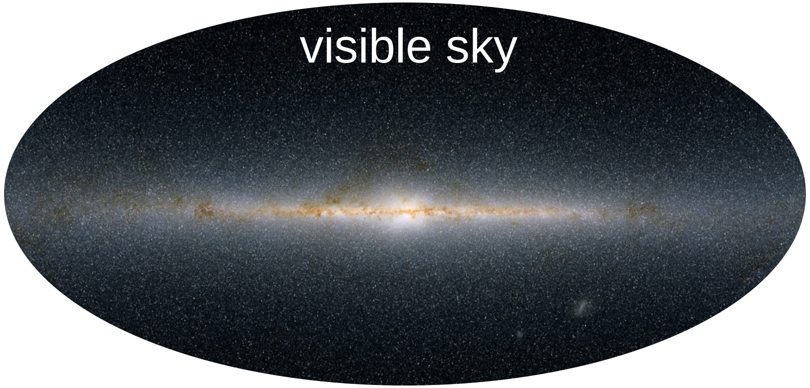
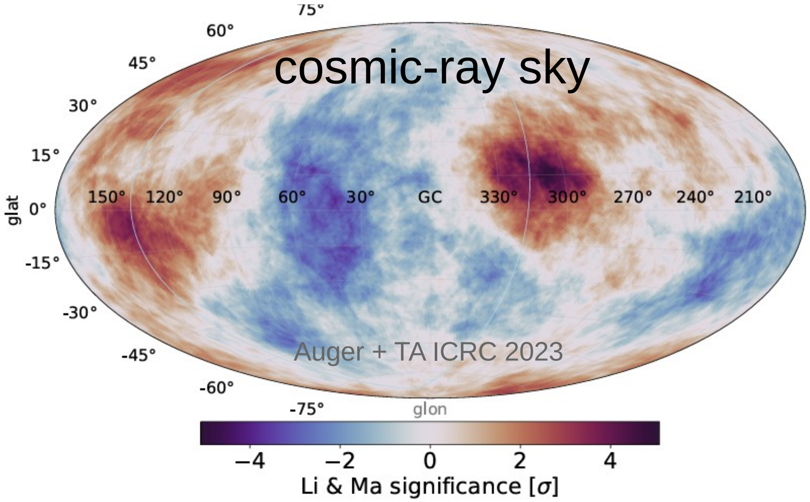
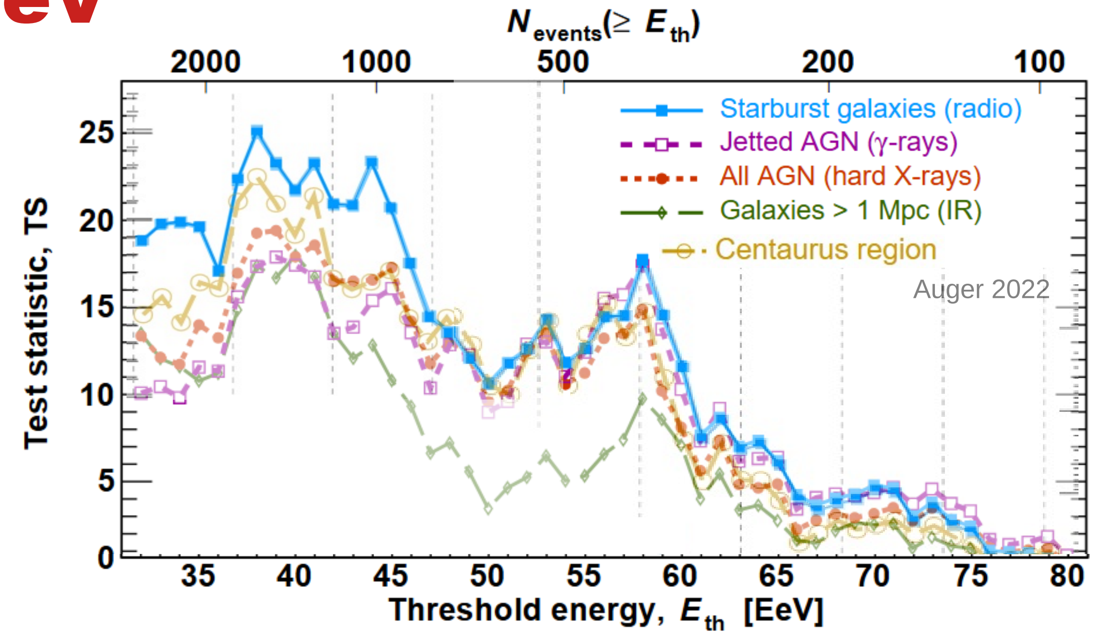
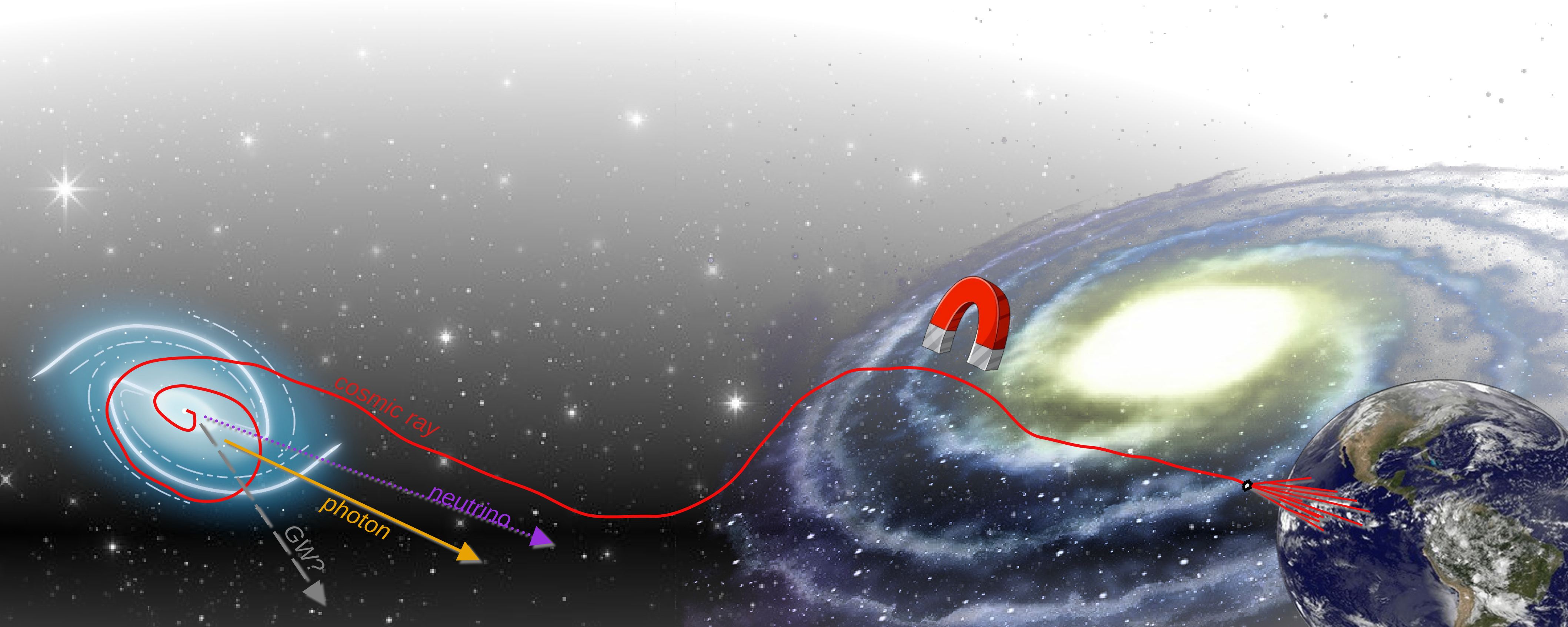






- **best correlation: with starburst galaxies**
  - i.e. also with transient events happening more often in starburst galaxies
- **but: also correlation with all galaxies, i.e. general matter**
- and: **magnetic field deflections not taken into account!**

Cosmic magnetic field deflections



Cosmic magnetic fields: basics

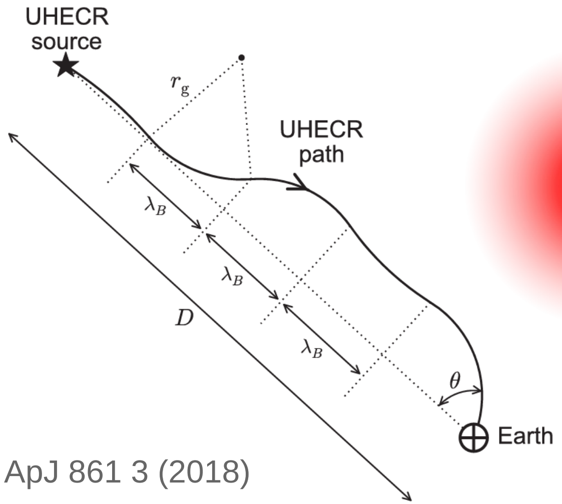
due to lack of precise model, often the most simple approximation is used:

→ **a random walk**

→ **leads to „blurring / beam widening“**

$$\theta_{\rm rms} \approx \frac{\sqrt{D\ \lambda_B}}{2}\ \frac{ZecB_\perp}{E}$$

$$\approx 0^\circ\!.84 Z\left(\frac{D}{10\ \rm Mpc}\right)^{\frac{1}{2}}\left(\frac{\lambda_B}{1\ \rm Mpc}\right)^{\frac{1}{2}} \times \left(\frac{B_\perp}{10^{-9}\ \rm G}\right)\left(\frac{E}{10^{20}\ \rm eV}\right)^{-1}$$



Bray & Scaife ApJ 861 3 (2018)

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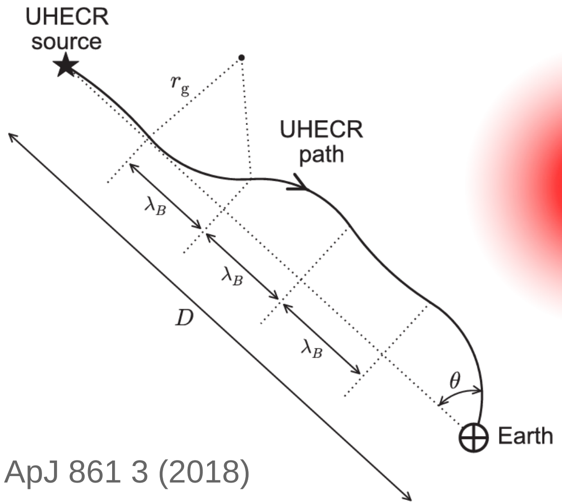
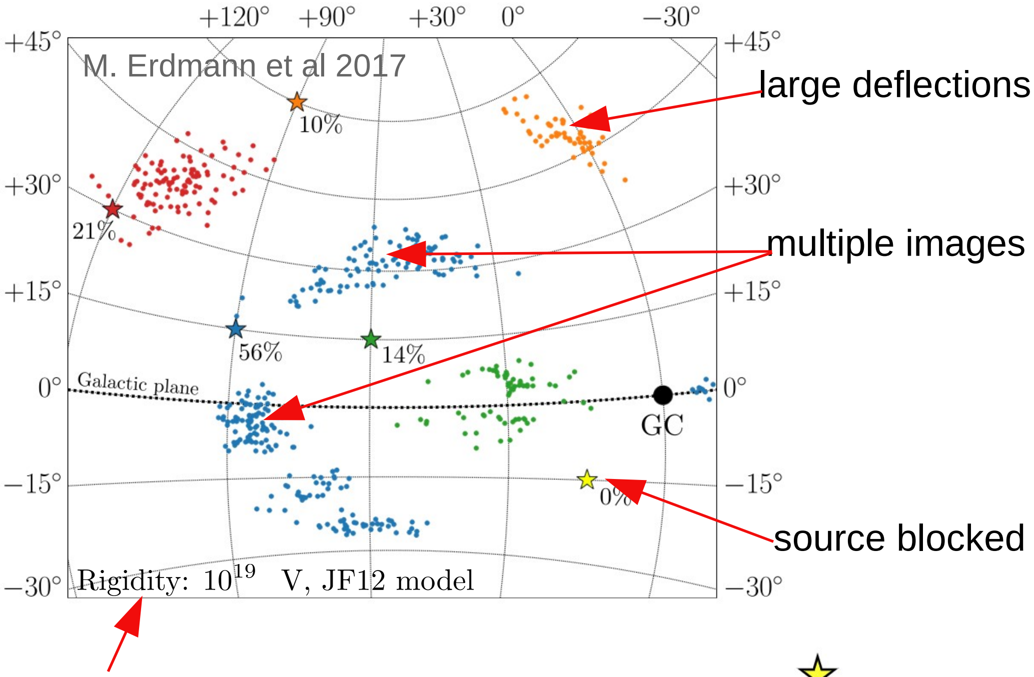
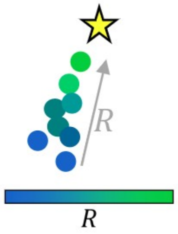


Bray & Scaife ApJ 861 3 (2018)

more realistic, complicated picture:



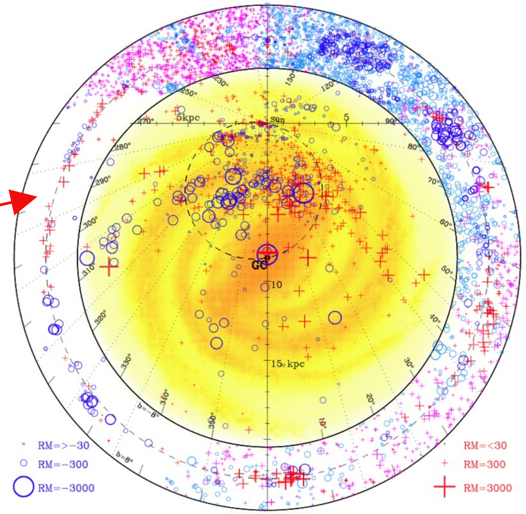
- **„rigidity“: energy / charge**
- deflection size proportional to inverse rigidity



The Galactic magnetic field: measurements

nnly indirect measurements of the GMF are possible:

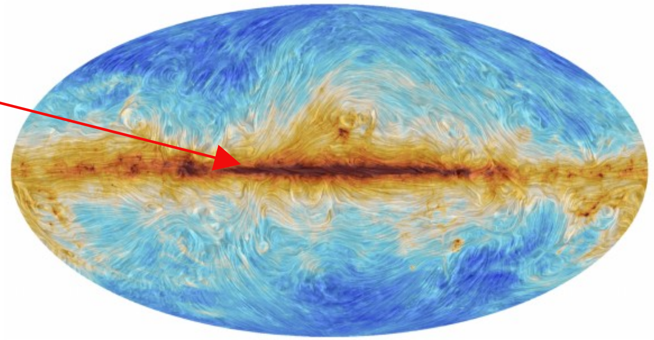
- **e.g. Faraday rotation** $\Delta\theta \propto \lambda^2 \int n_e(\boldsymbol{x})\, \boldsymbol{B}(\boldsymbol{x}) \cdot \mathrm{d}\boldsymbol{l} = \lambda^2\,\mathrm{RM}$
  - polarized radiation e.g. from pulsars
  - alternating structure in Galactic disk region: spiral arms
  - line of sight component



[Han et al., 2017]

- **Polarization by dust grains** (Planck satellite)
  paramagnetic alignment of dust grains

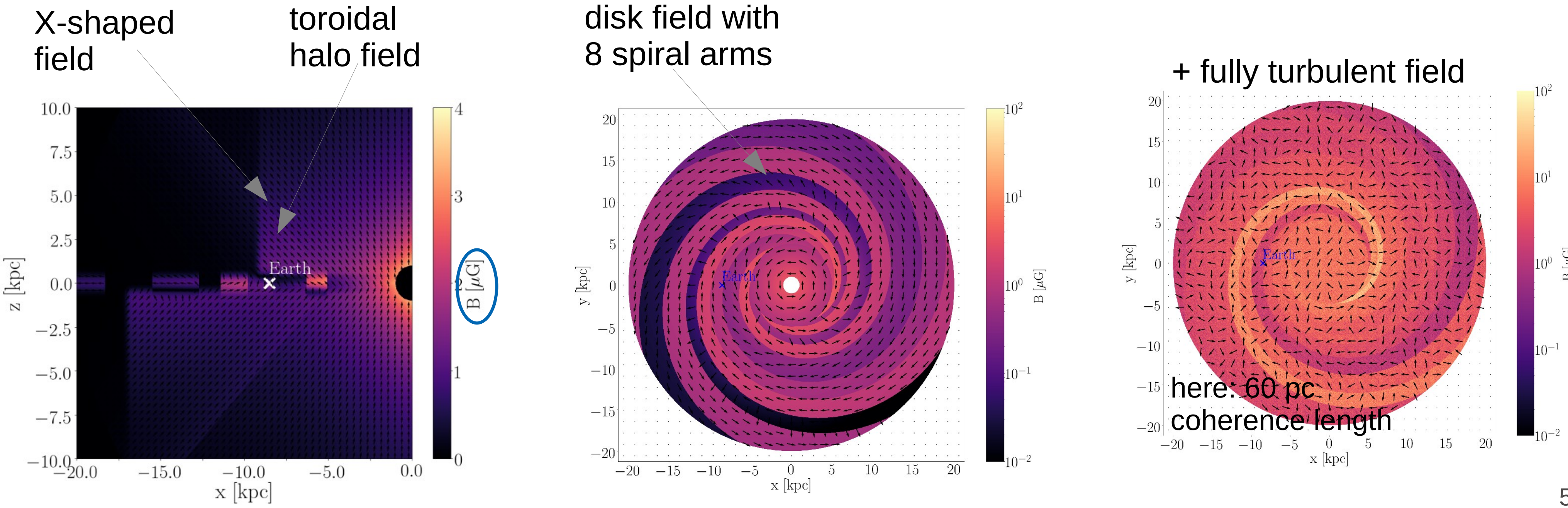
- **Synchrotron radiation** of electrons,
  Zeeman splitting of light from molecular clouds
  …



[Aghanim et al., 2016]

The Galactic magnetic field: models

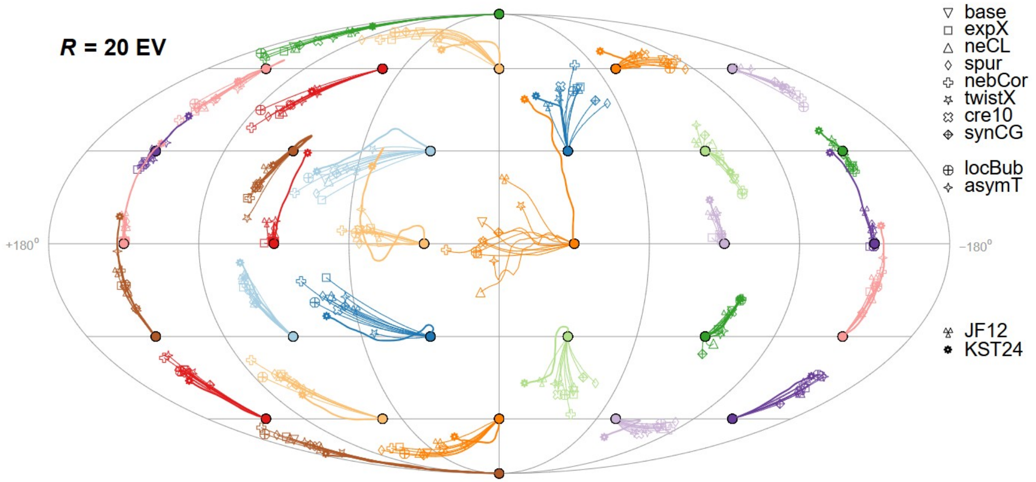
- older models available: e.g. *Jansson & Farrar 2012* (***JF12***), *Pshirkov et al. 2011* (***PT11***)…
- recently, **new models were fit to updated data:** *Unger & Farrar (2023), Korochkin, Semikoz, Tinyakov (2024):* include the local bubble & Fan region
- models often consist of **several parts** (here JF12 as example), strengths ~μG



Influence of the GMF on UHECRs

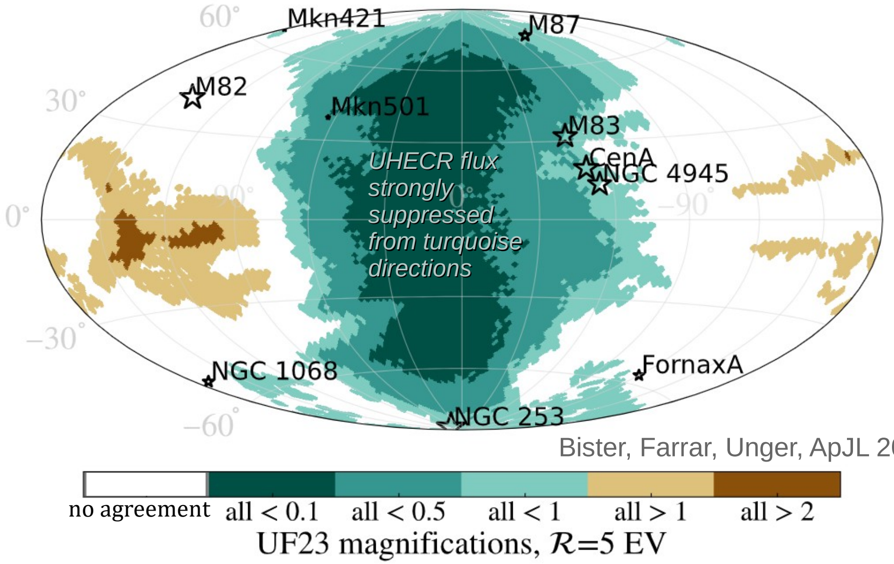
GMF effect on UHECRs: deflection and (de-)magnification:

deflection $\propto Z / E := 1 / R$



T. Bister, Universe 2025

flux (de-)magnification



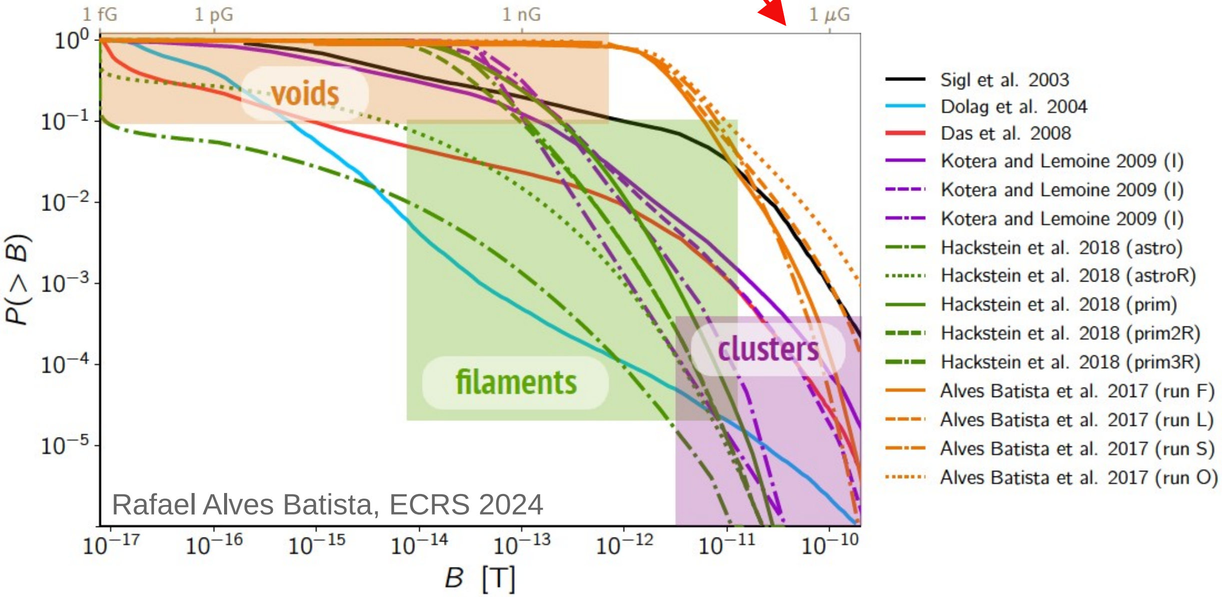
Bister, Farrar, Unger, ApJL 2025

- in last three years: **<u>>10 new models released</u>**
  - based on varying assumptions about electron distribution, parameterization...

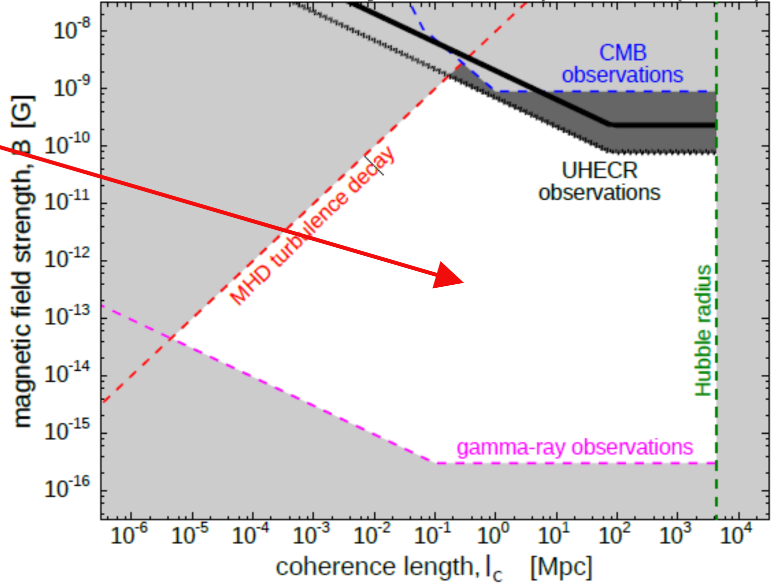
➔ finally some agreement between models, enables estimate of systematic uncertainty

The extragalactic magnetic field

- **quite little is known about the EGMF**
  - observations challenging
- **origin**: primordial or astrophysical?
- **models differ significantly**

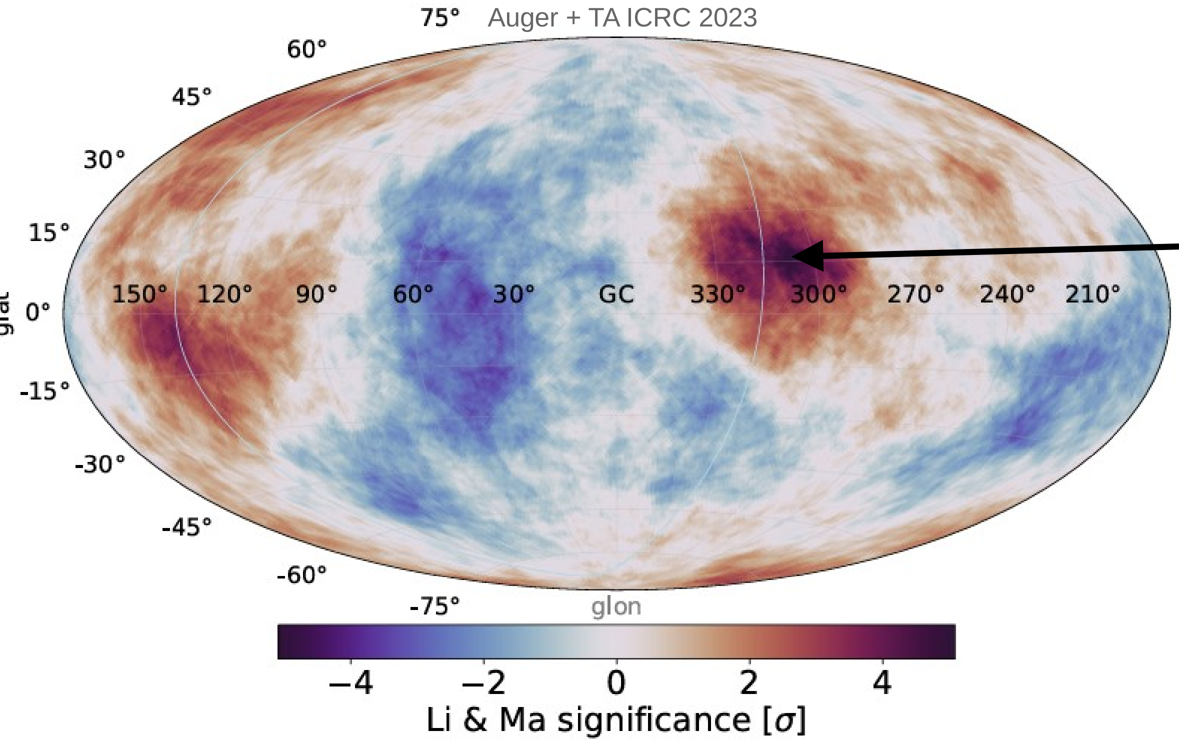


Bray & Scaife ApJ 861 3 (2018)



- often **neglected** or only assumed to be **turbulent**
  - then: only beam-widening
    (& suppression of low-energy particles)

Is there a local source?

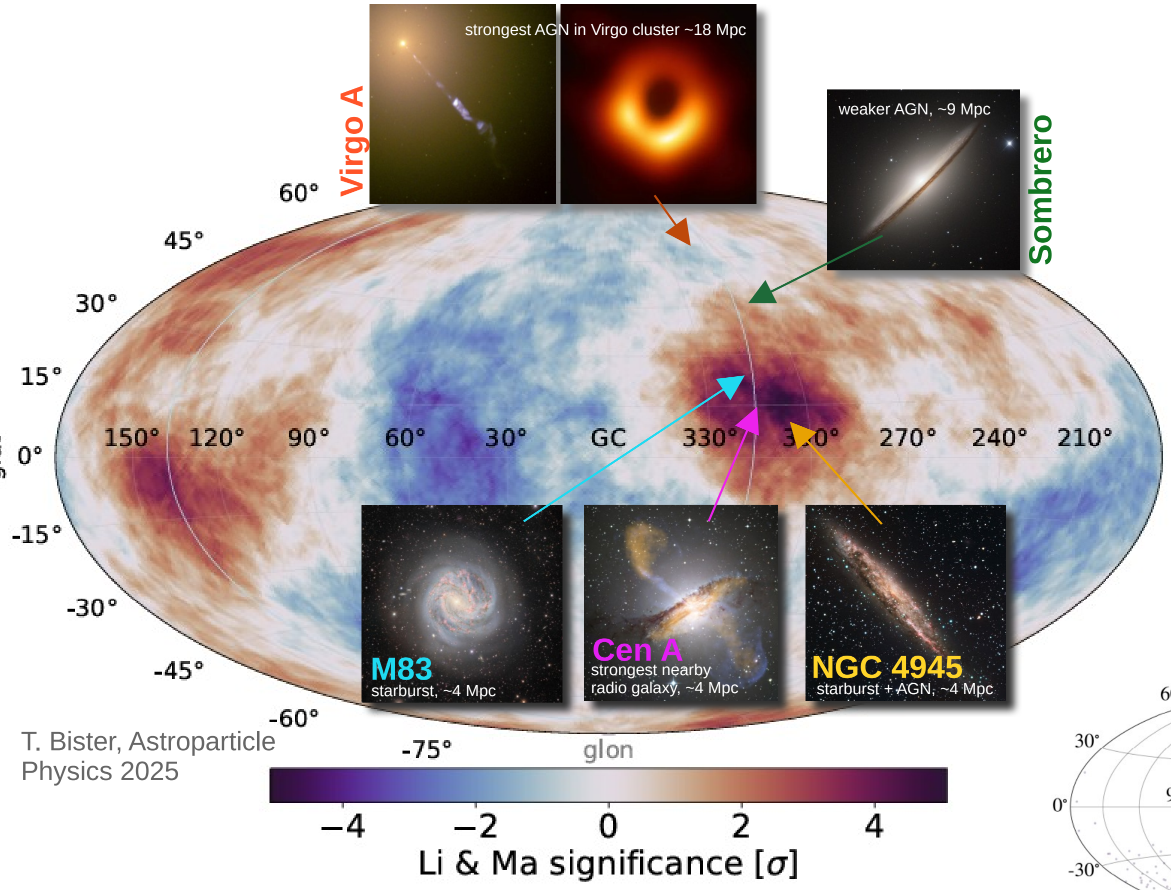


- at $\gtrsim$ 40 EeV, propagation length $\lesssim$ 200 Mpc
  - ➔ warmspots imprints of nearby sources?
- most significant flux excess: **„Centaurus region excess“**

Which source can actually explain the excess direction, strength, and size considering magnetic field deflections?

IceCube

Is there a local source?



T. Bister, Astroparticle Physics 2025

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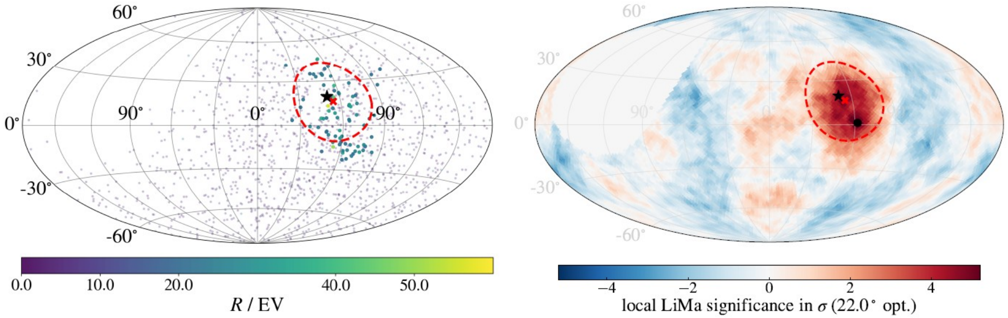

example simulation

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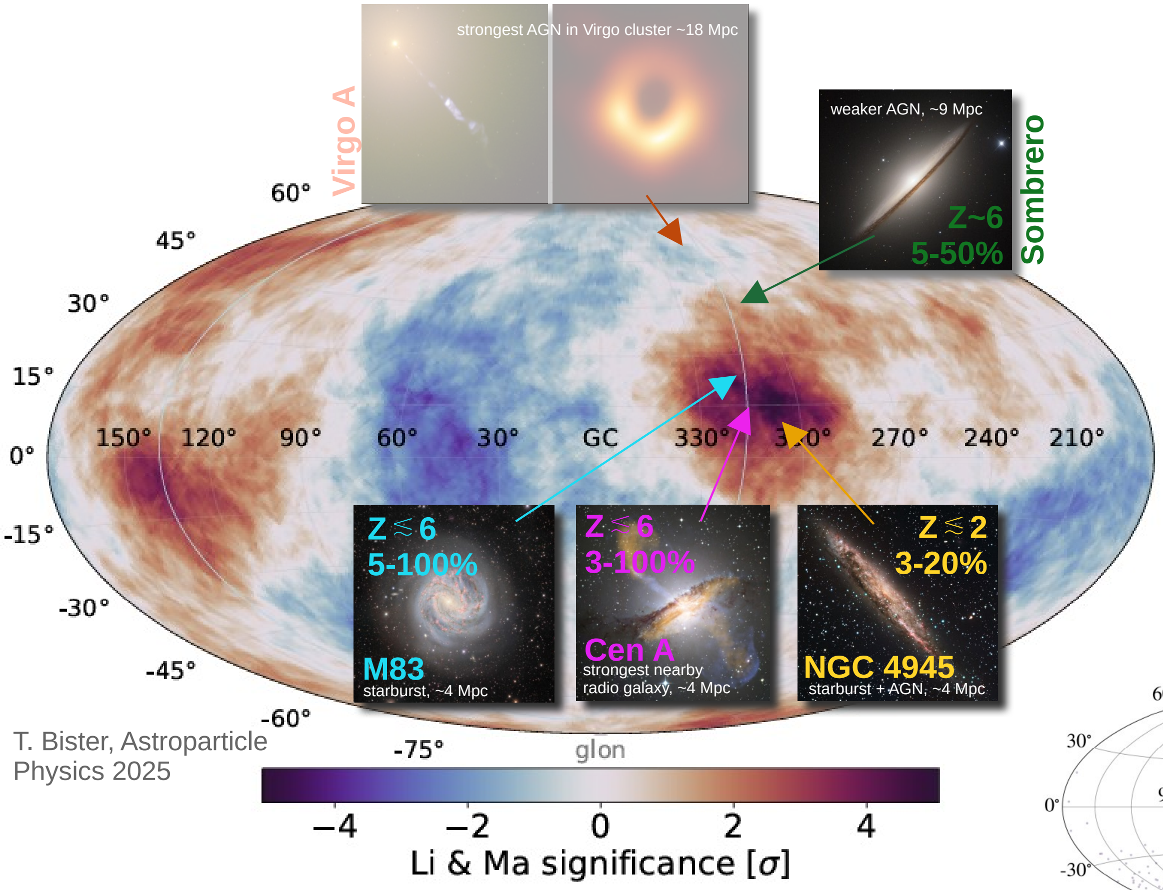

T. Bister, Astroparticle Physics 2025

- at ≳ 40 EeV, propagation length ≲ 200 Mpc
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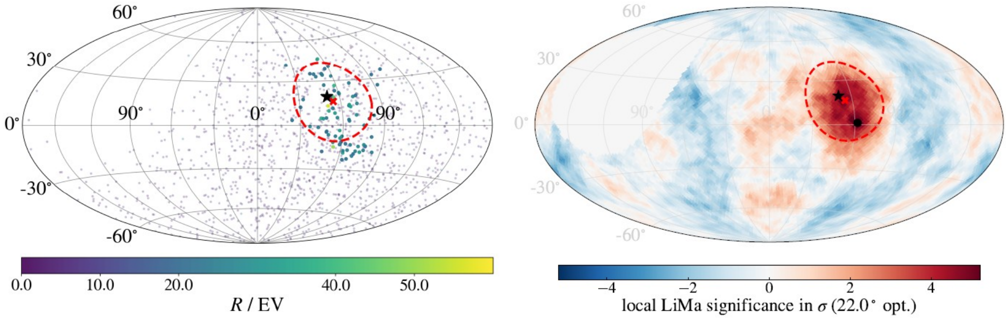

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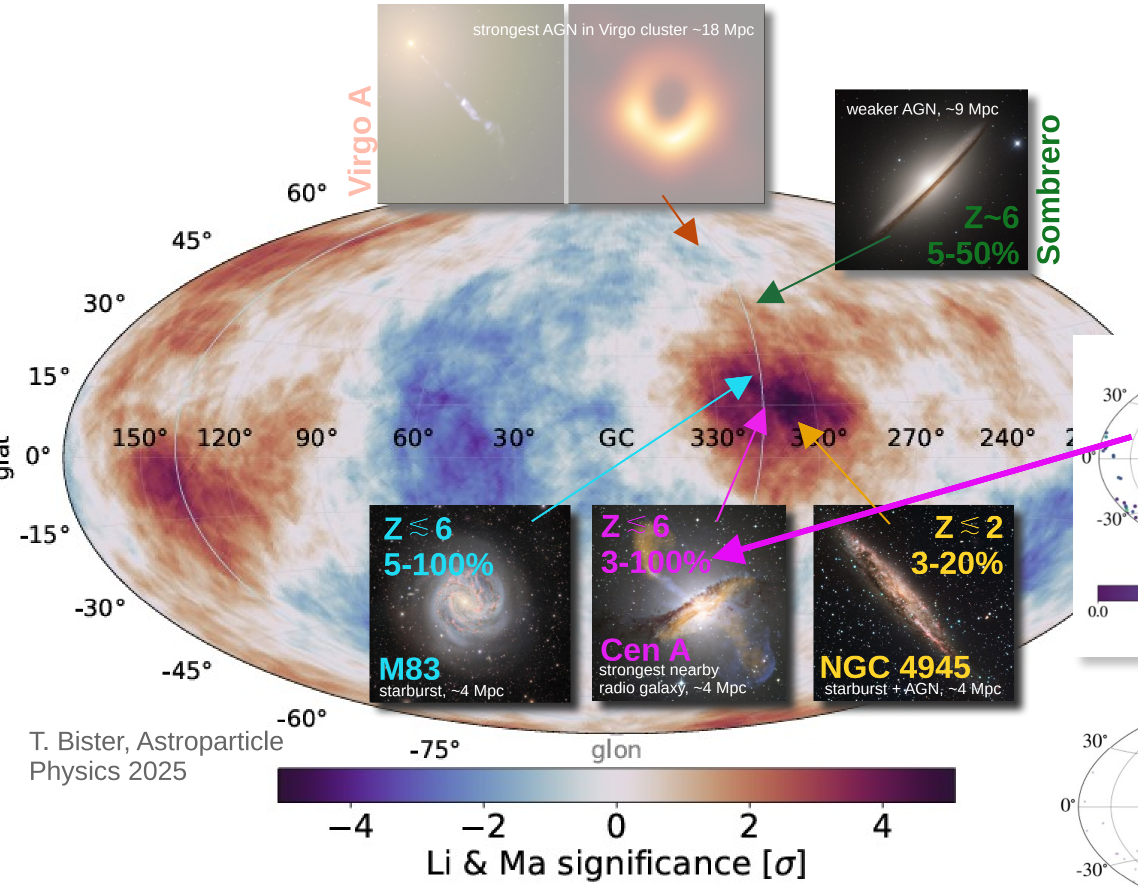

T. Bister, Astroparticle Physics 2025

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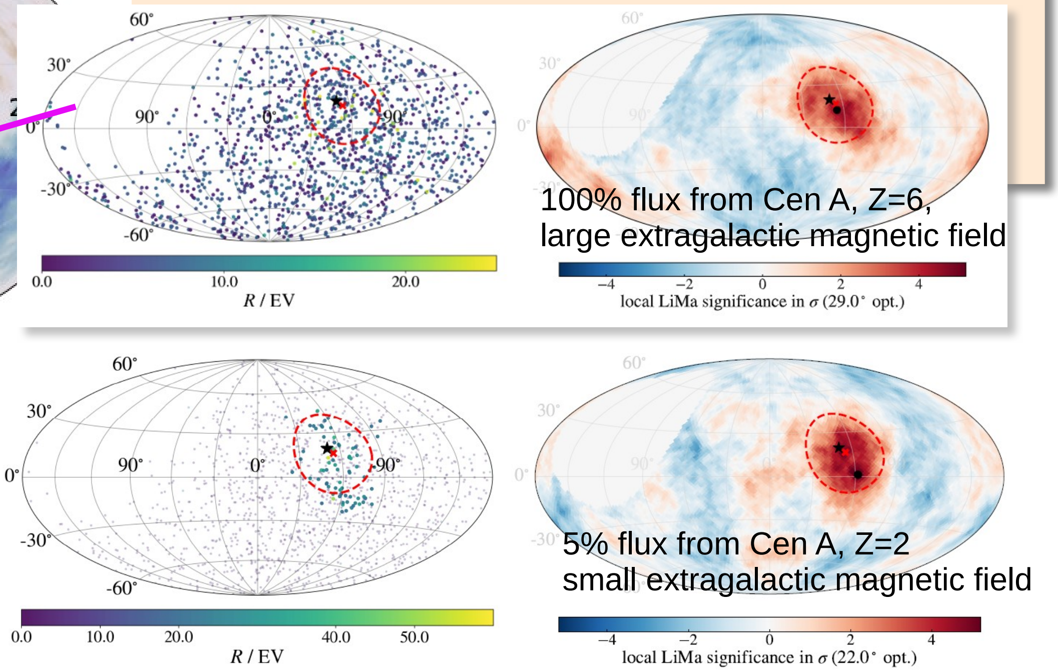
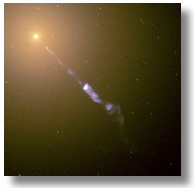
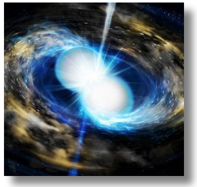


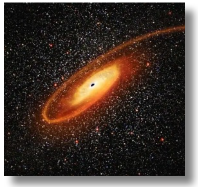
example simulations

Overview









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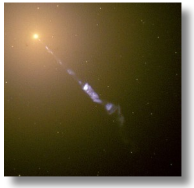



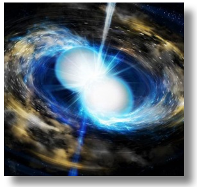

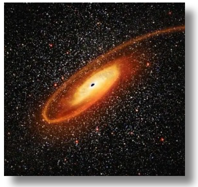

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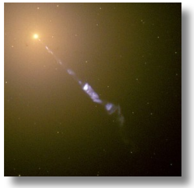
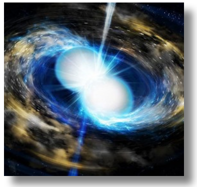
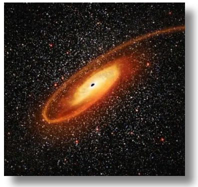
not too strong evolution	(✓)	(✗)	✓	✓	✓	✓	✓
arrival directions > 40 EeV	✓	✗	✓	✓	**currently working on this!**		

Can we explain the observed arrival directions by transient events?

What rate and magnetic field strength do we need?

Overview

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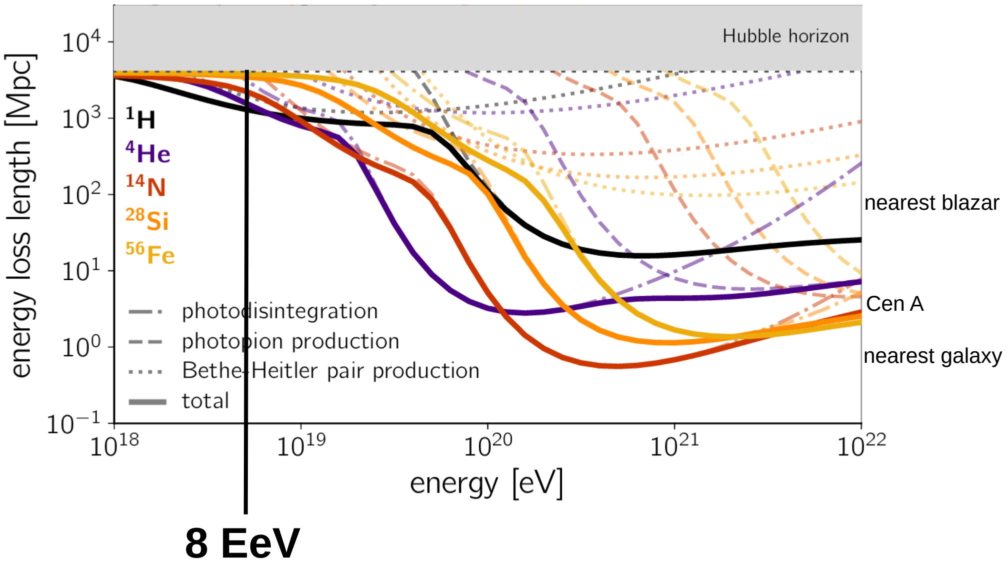
Can we explain the observed arrival directions by transient events?

What rate and magnetic field strength do we need?

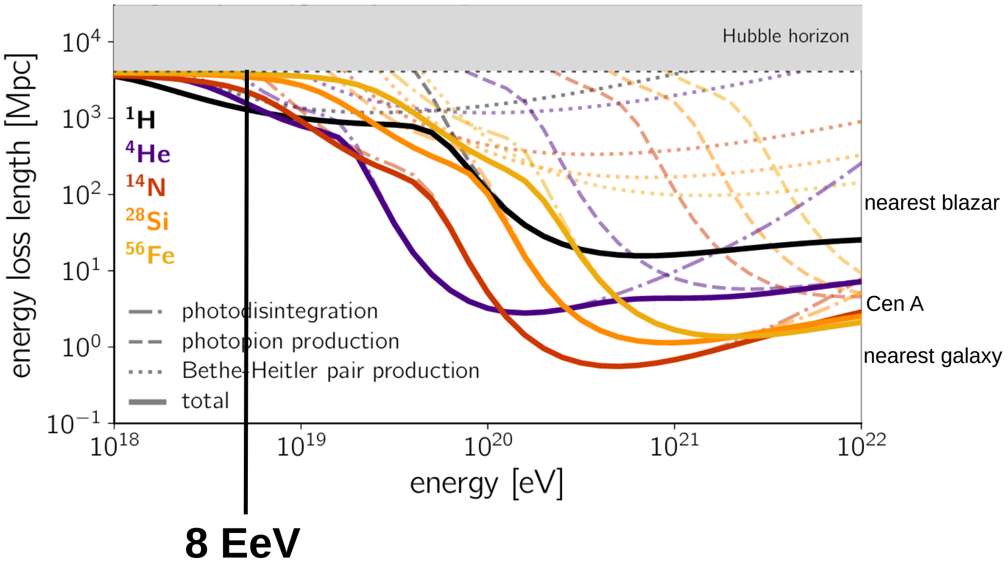
What about the arrival directions at lower energies?

UHECR arrival directions >8 EeV



do not expect local sources,
instead imprint of *large-scale structure*

UHECR arrival directions >8 EeV



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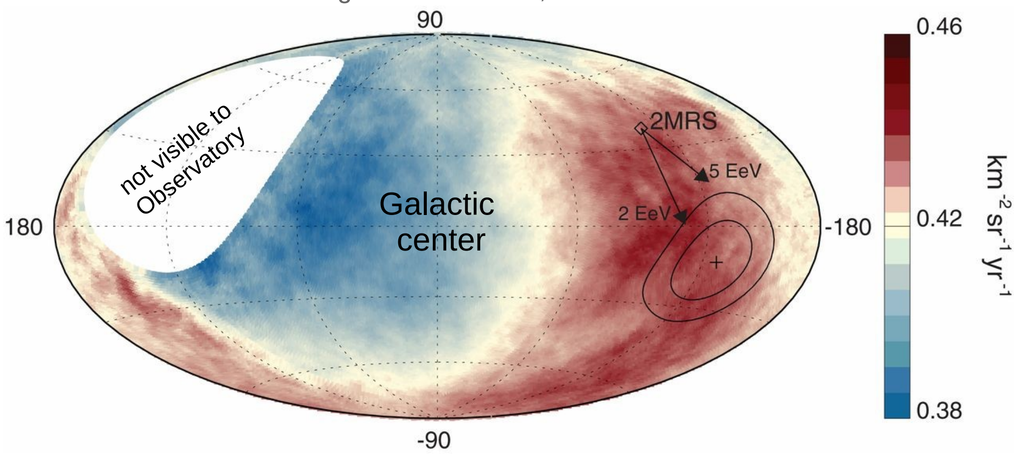
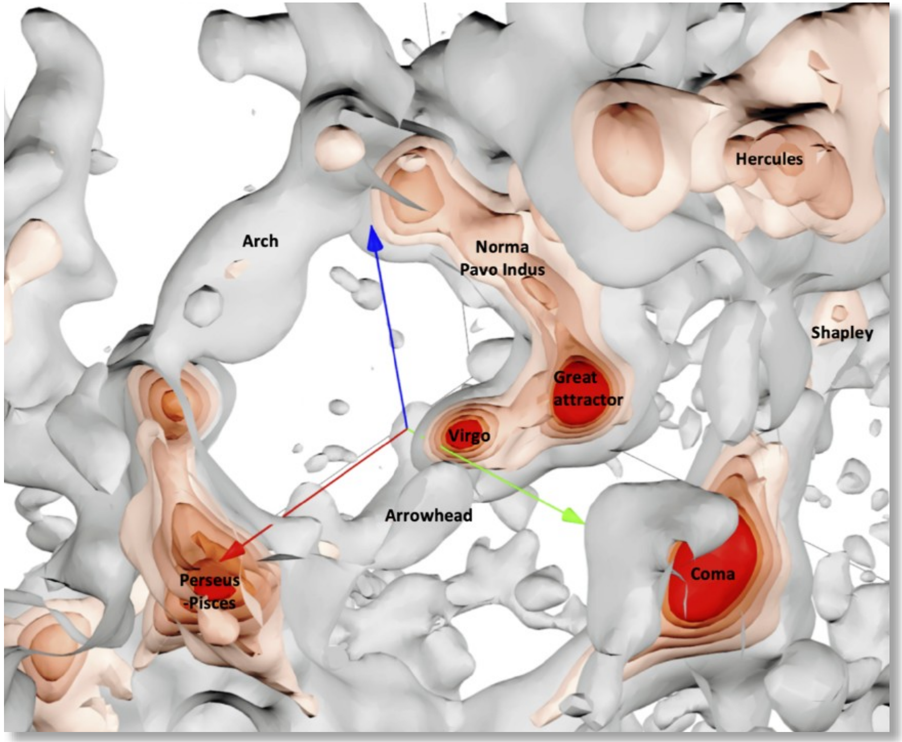
The Pierre Auger Collaboration, Science 2017

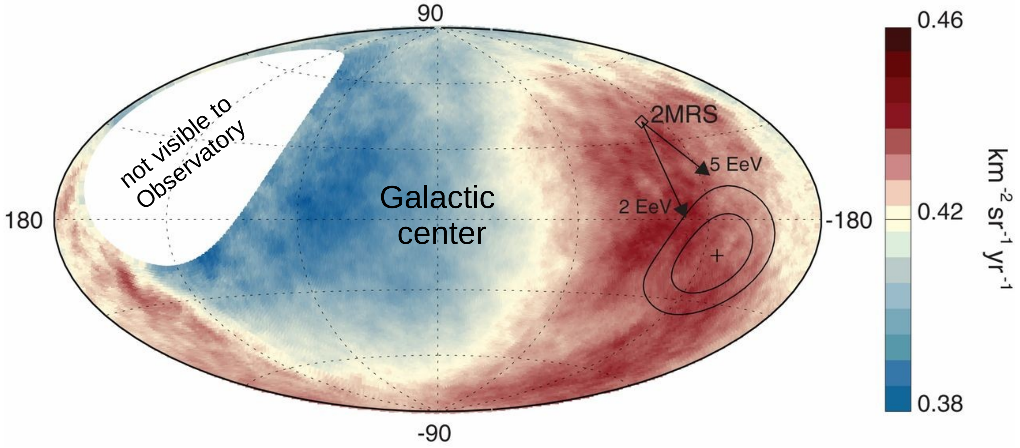


- **dipole** >6.8σ, no quadrupole
- amplitude ~ 7%, rising with the energy
- not aligned with Galactic center
  - ➔ **sources extragalactic!**
  - ➔ **follow large-scale structure?**

What does the sky look like in cosmic rays?



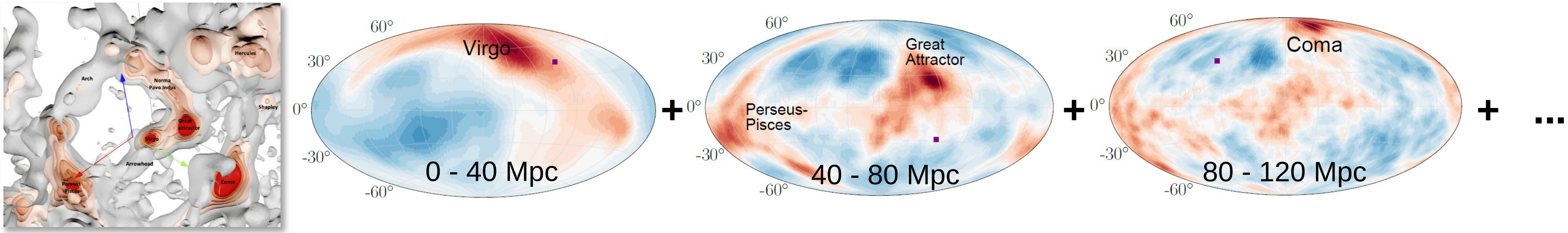
The Pierre Auger Collaboration, Science 2017



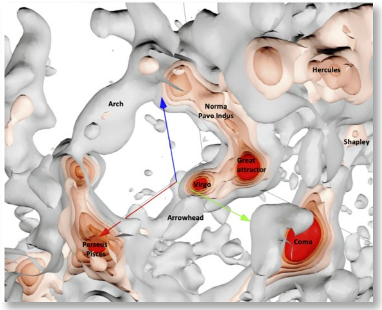
- **dipole** >6.8σ, no quadrupole
- amplitude ~ 7%, rising with the energy
- not aligned with Galactic center
  - ➔ **sources extragalactic!**
  - ➔ **follow large-scale structure?**

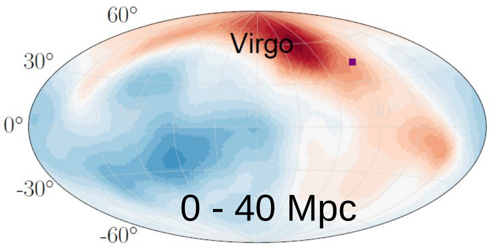
Bister & Farrar, ApJ 966 71 (2024)

Model to explain the dipole



Model to explain the dipole





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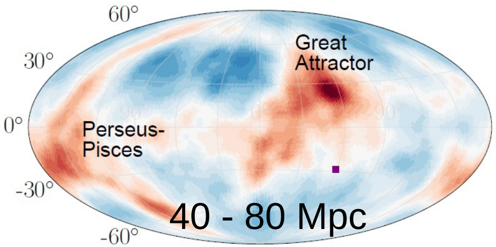

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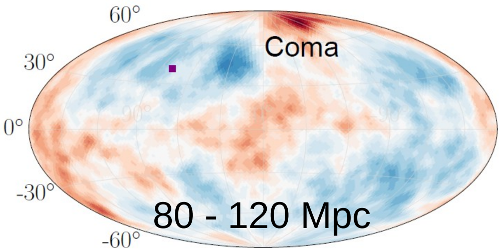
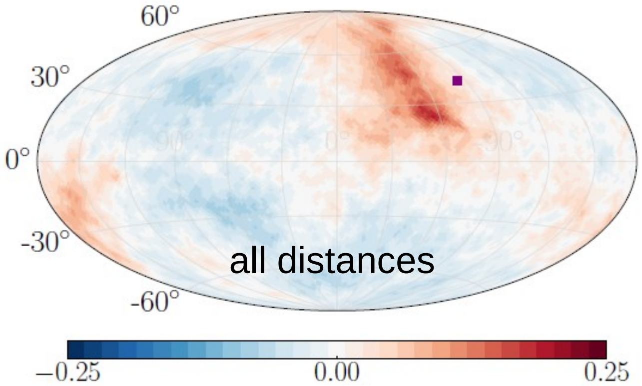
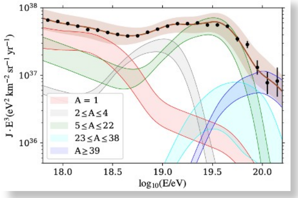


+ ...

=



modeled flux at the edge of our Galaxy



taking into account interactions
& fitting a model for source emission

Bister & Farrar, ApJ 966 71 (2024)

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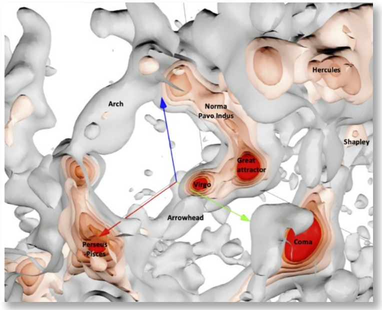

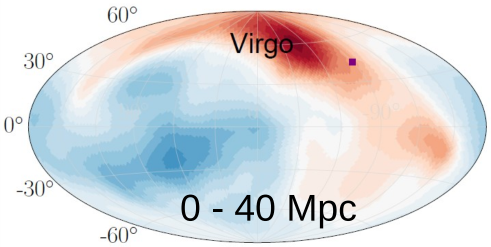

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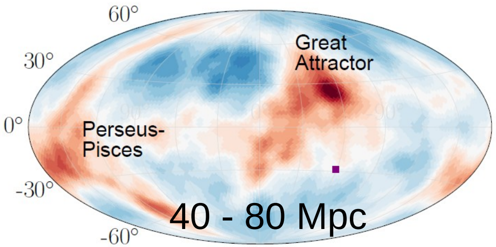

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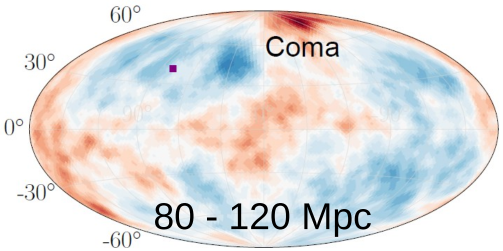

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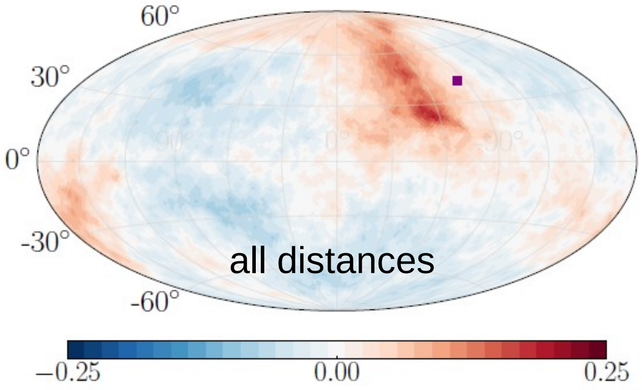
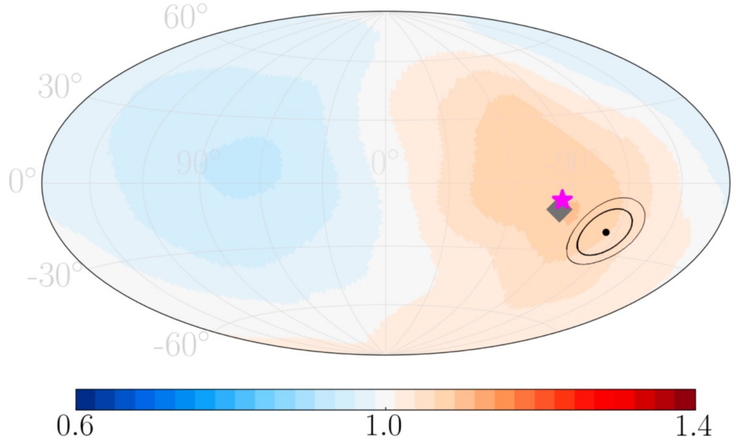
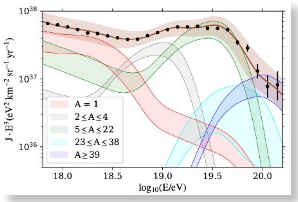


modeled flux at the edge of our Galaxy

Galactic magnetic field model



modeled flux at Earth reproduces dipole ✓



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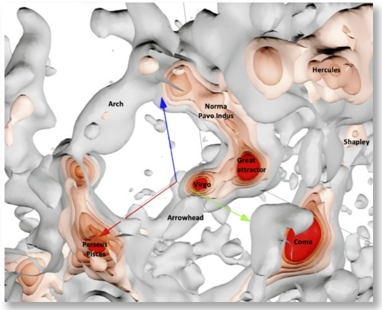
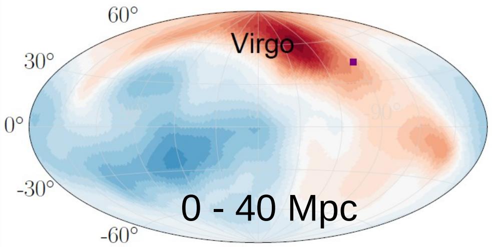
Model to explain the dipole





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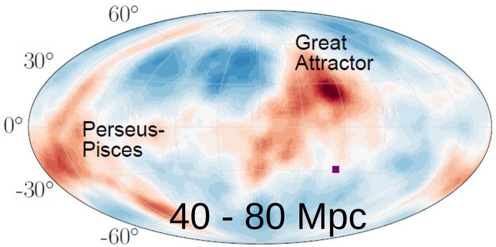

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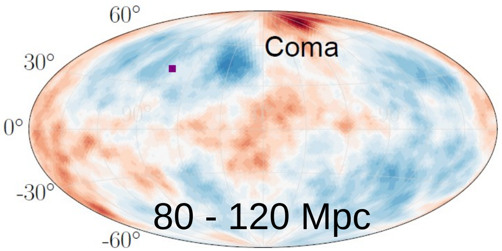

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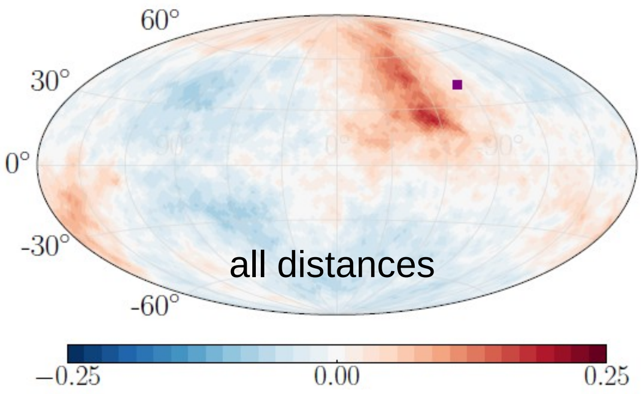

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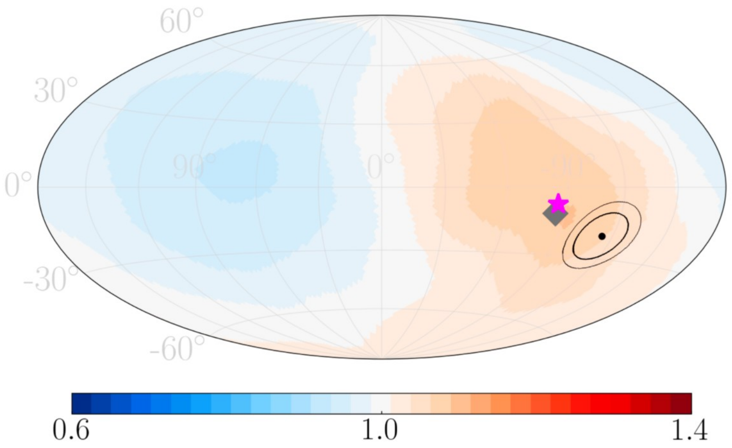
Galactic magnetic field model



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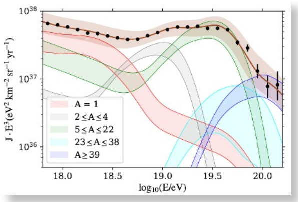

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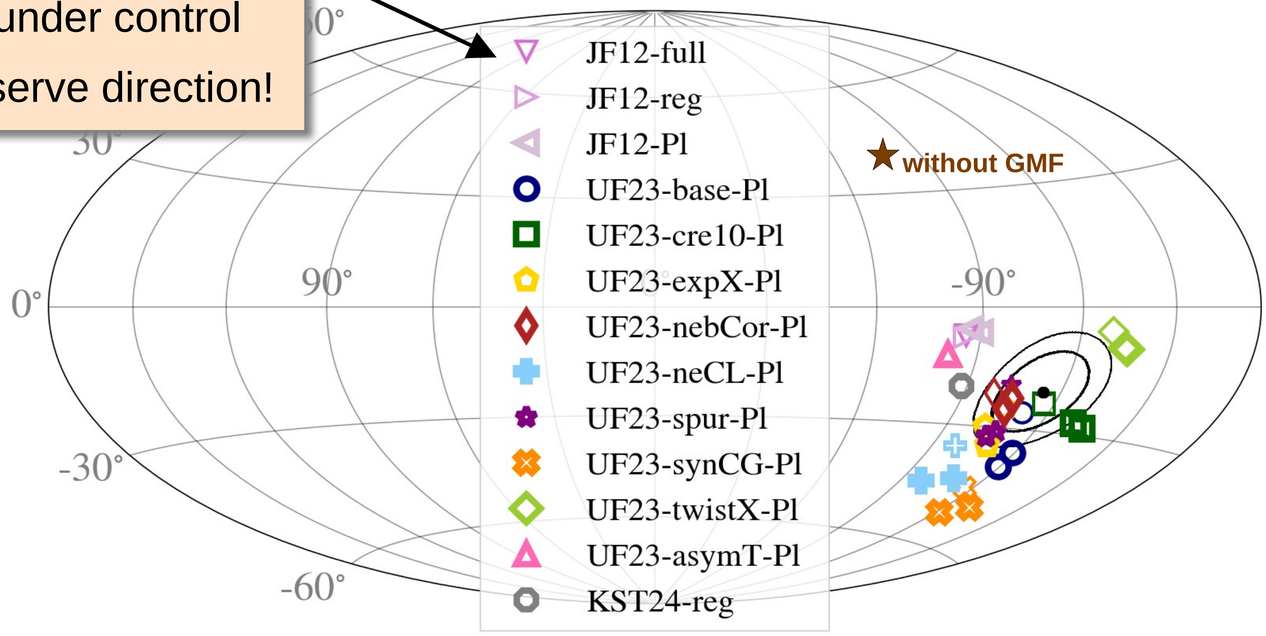
UHECR sources likely follow extragalactic matter distribution

Bister, Farrar, Unger
ApJL 975 L21 (2024)

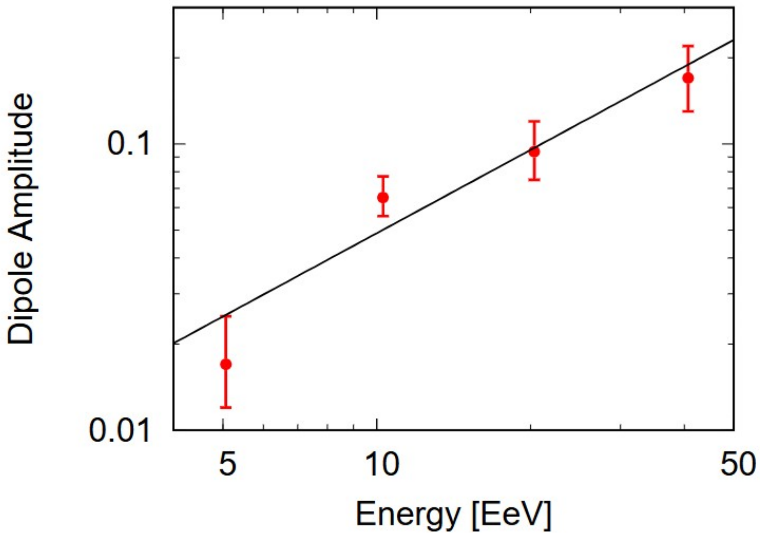
What more can we do?

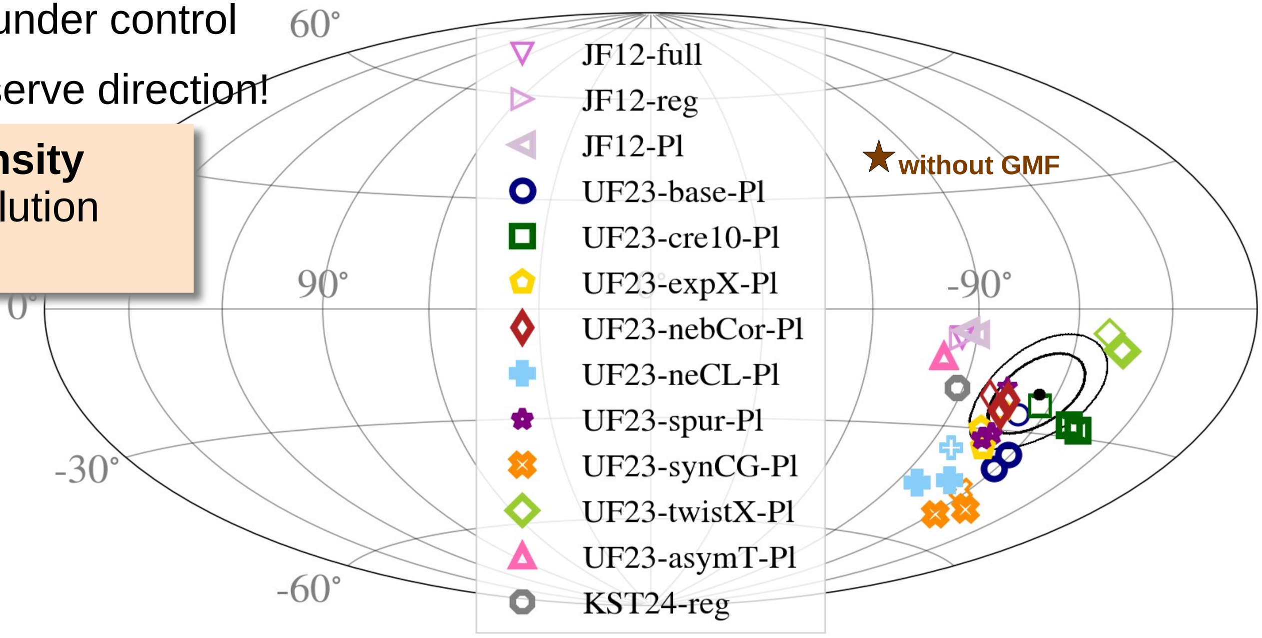
- compare **different Galactic magnetic field models**
  - agreement, systematic uncertainty under control
  - GMF is necessary to reproduce observe direction!



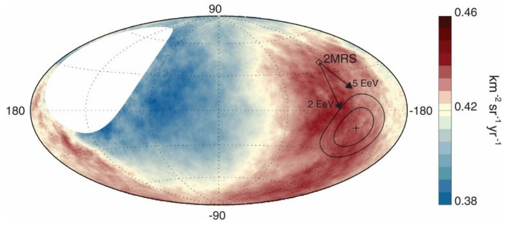
What more can we do?

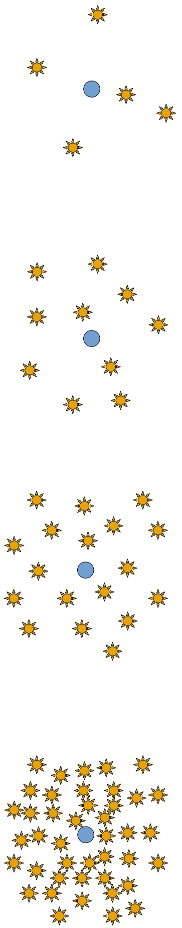
- compare **different Galactic magnetic field models**
  - agreement, systematic uncertainty under control
  - GMF is necessary to reproduce observe direction!
- learn more about **source number density of sources** from dipole amplitude evolution & absence of quadrupole





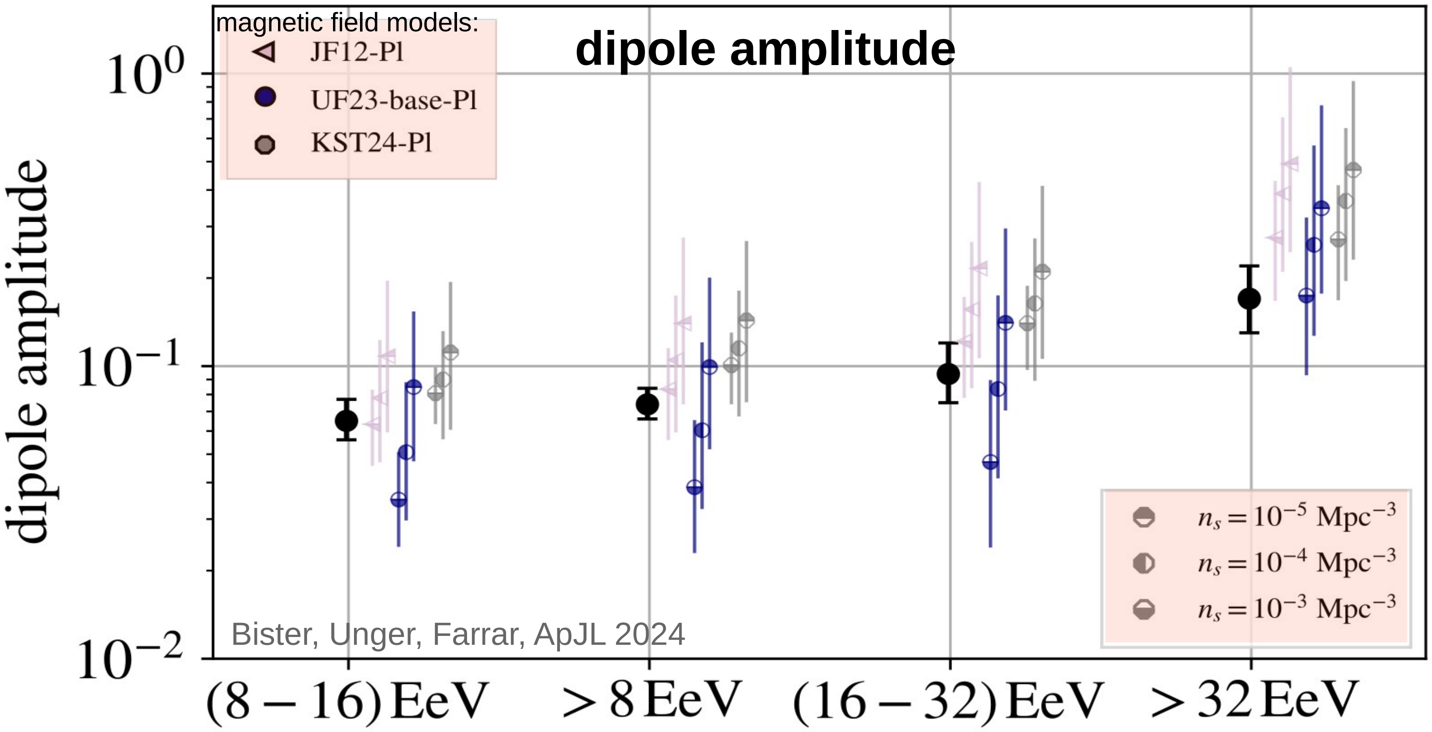
Source number density





smaller density
→ larger multipole moments (on average)

larger density
→ smoother, smaller multipole moments (on average)



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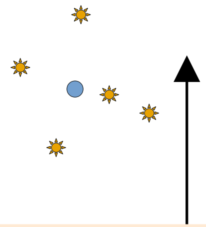
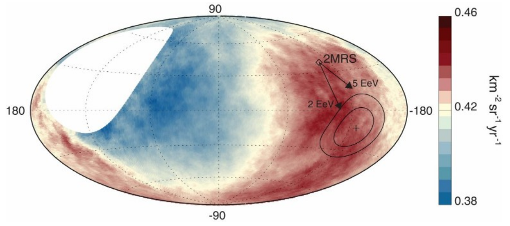




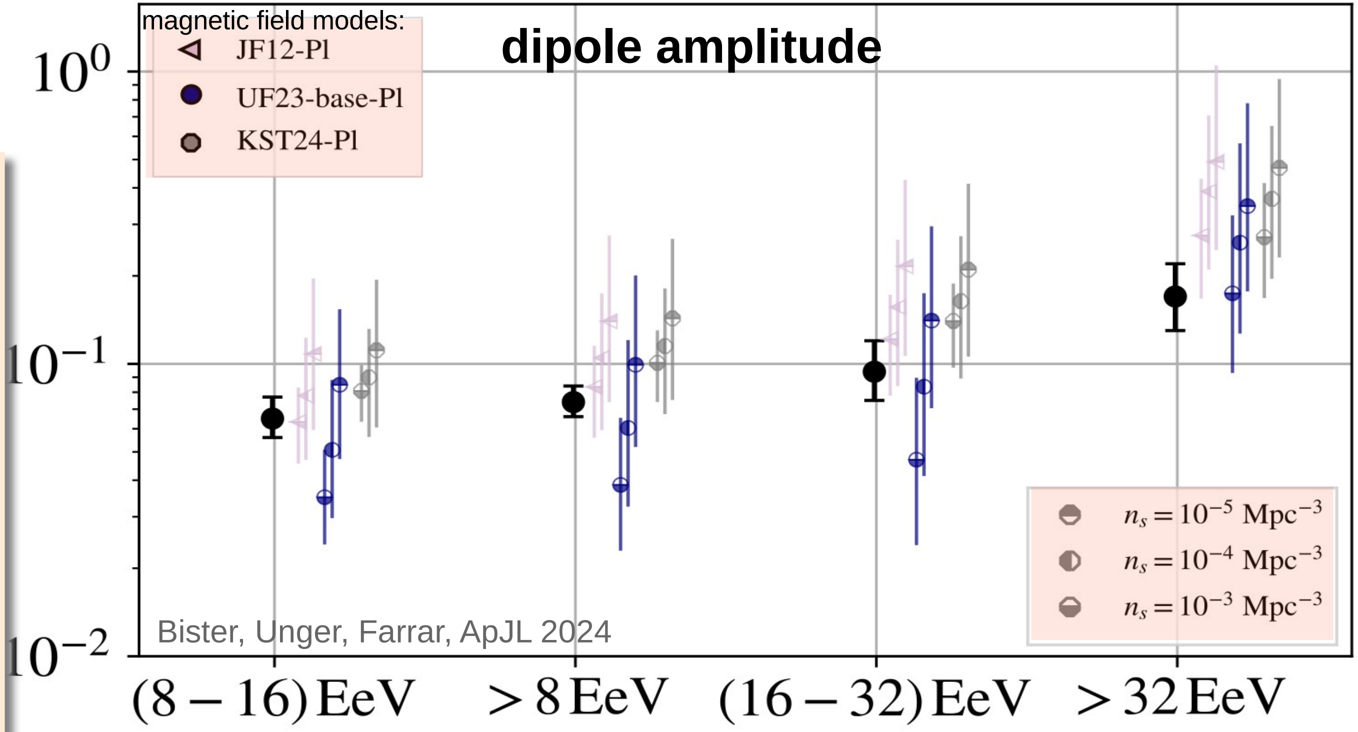
smaller density
→ larger multipole moments
(on average)

densities of **~(10^{-3} - 10^{-5}) Mpc^{-3}**
work best for most GMF models

for comparison:

normal galaxies	~10^{-2} Mpc^{-3}
starburst galaxies	~10^{-5} Mpc^{-3}
active galactic nuclei	~10^{-6} Mpc^{-3}
blazars	~10^{-7} Mpc^{-3}

- **UHECR sources quite common at $\gtrsim$ 8 EeV!**
- **or: strong extragalactic magnetic fields**



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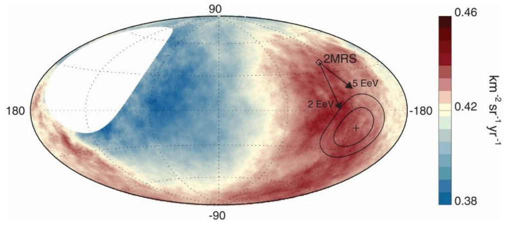

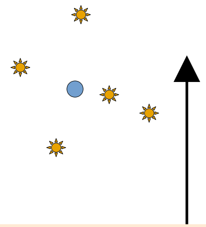

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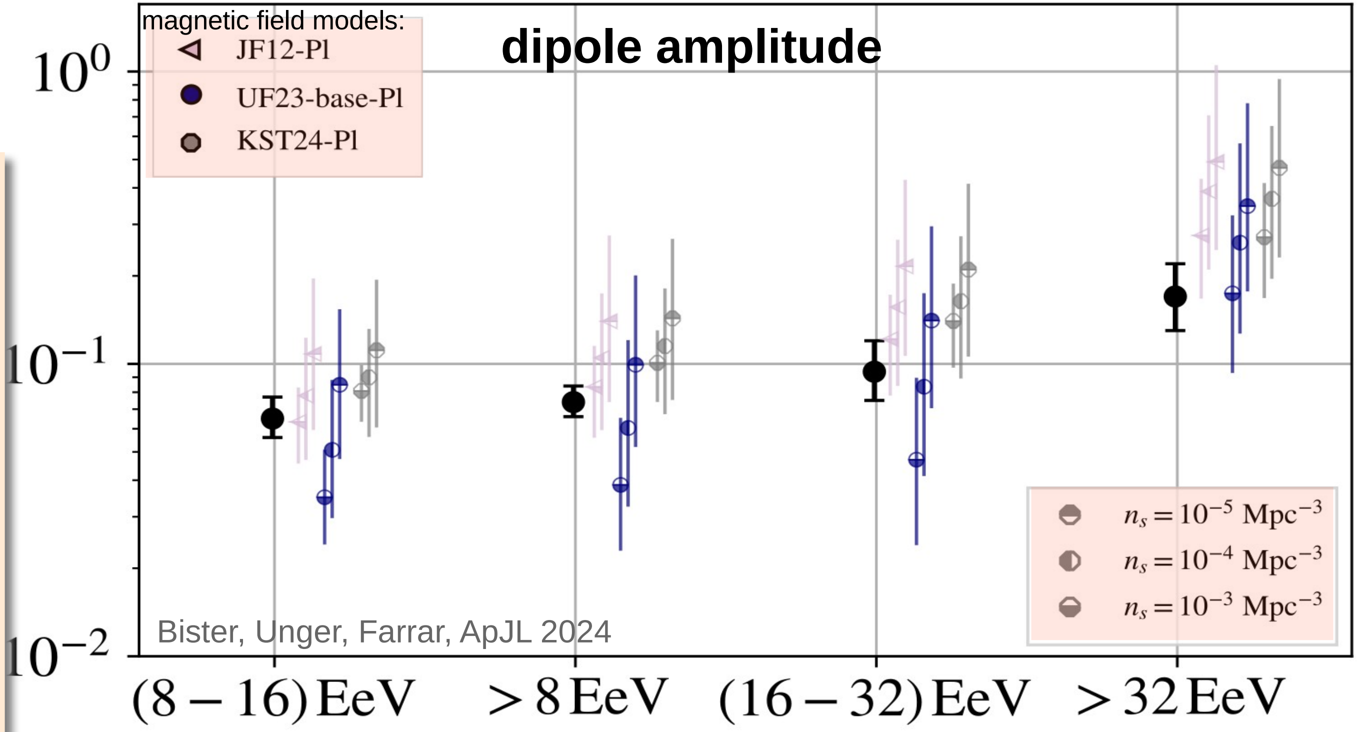
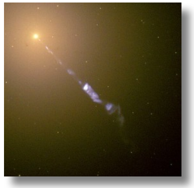
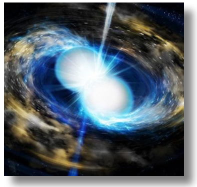


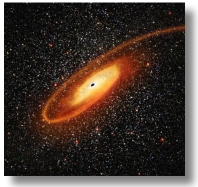
similar conclusions also from non-observed clustering of highest-energy events [Auger 2014]

Overview





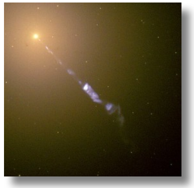
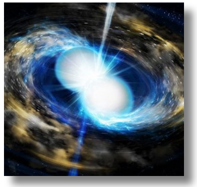
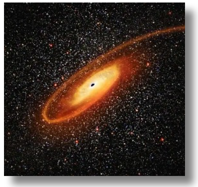




	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
low population diversity	✗	✗	✓	✗	✓	✗	✗
not too strong evolution	(✓)	(✗)	✓	✓	✓	✓	✓
arrival directions > 40 EeV	✓	✗	✓	✓	?	?	?
not too small density	✓	✗ too rare!	?	✓	(✓)	(✓)	(✓)

still a question:
Can Cen A alone produce the dipole?
What anisotropy would „Cen A“-like sources induce?

Overview

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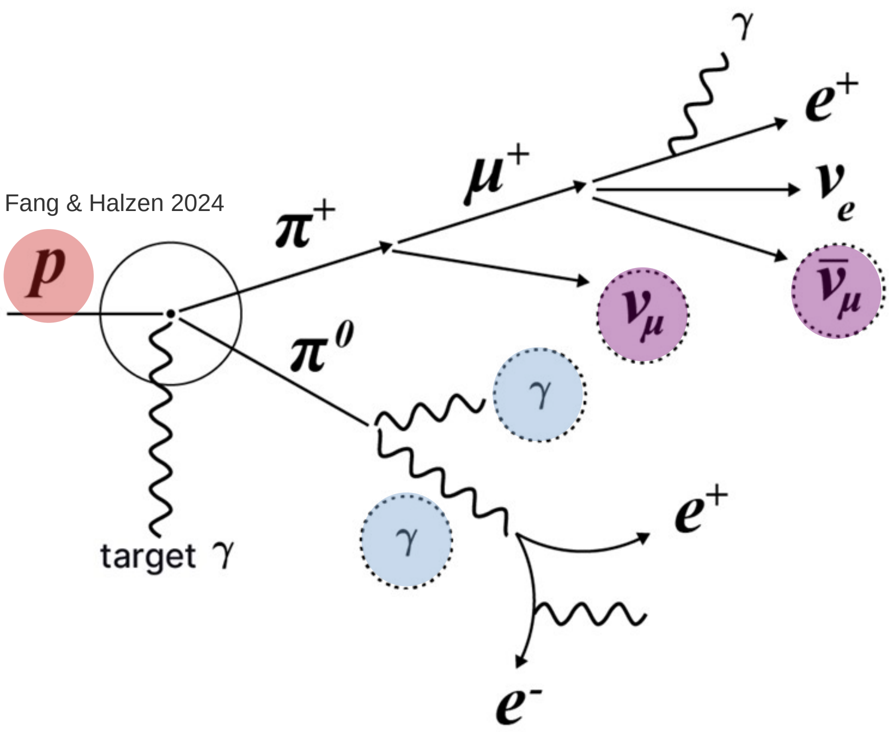
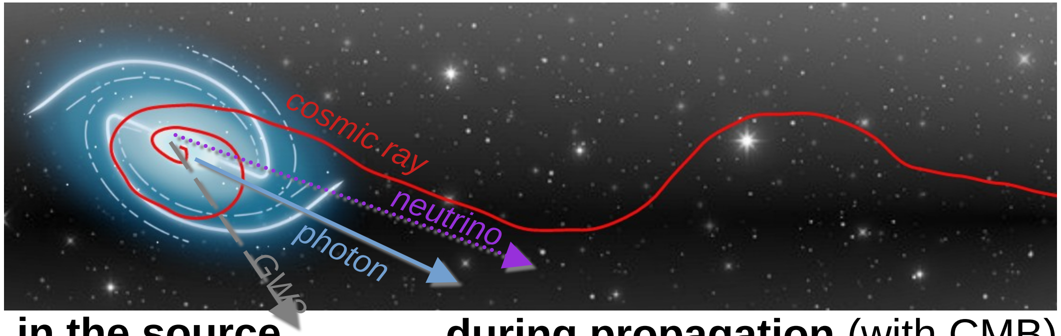
not too strong evolution	(✓)	(✗)	✓	✓	✓	✓	✓
arrival directions $>$ 40 EeV	✓	✗	✓	✓	?	?	?
not too small density	✓	✗	?	✓	(✓)	(✓)	(✓)
neutrinos							

Multimessenger astroparticle physics

Fang & Halzen 2024





in the source
→ ***astrophysical***

during propagation (with CMB)
→ ***cosmogenic***

Multimessenger astroparticle physics

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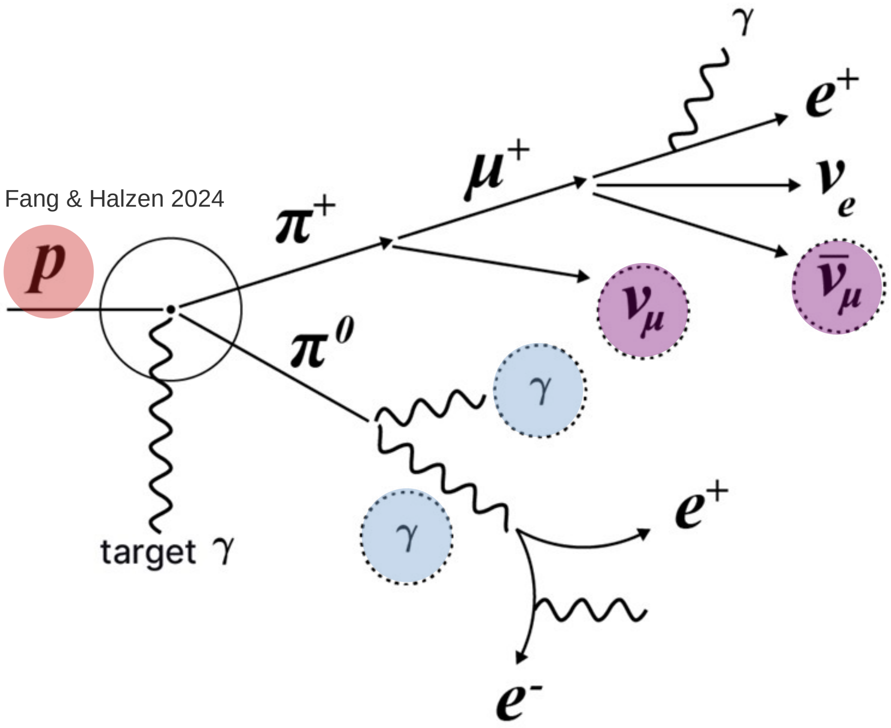

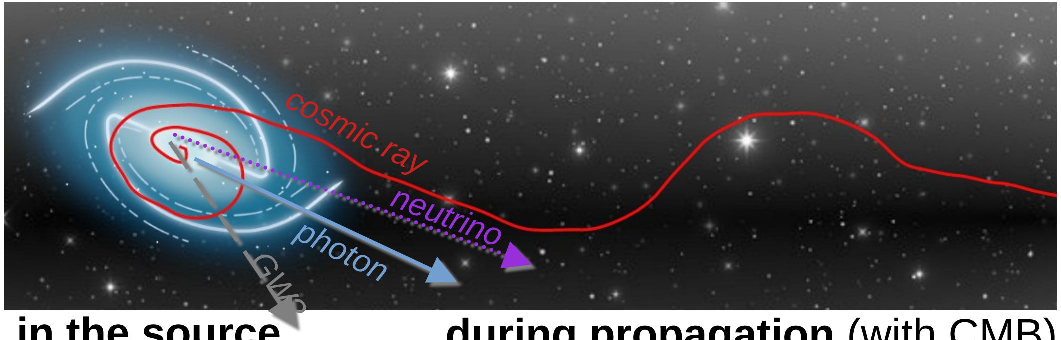

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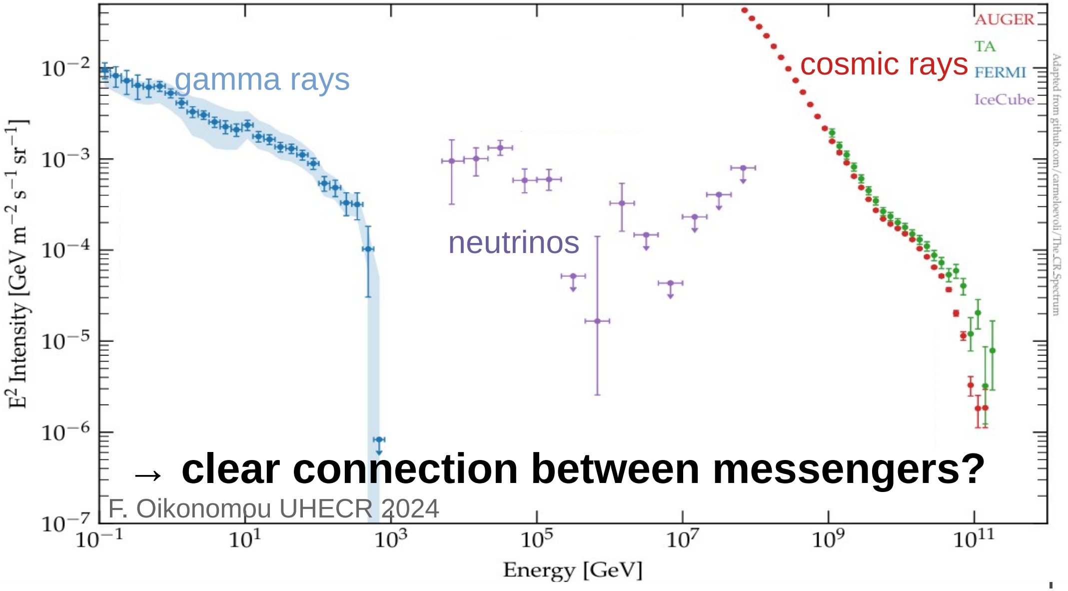
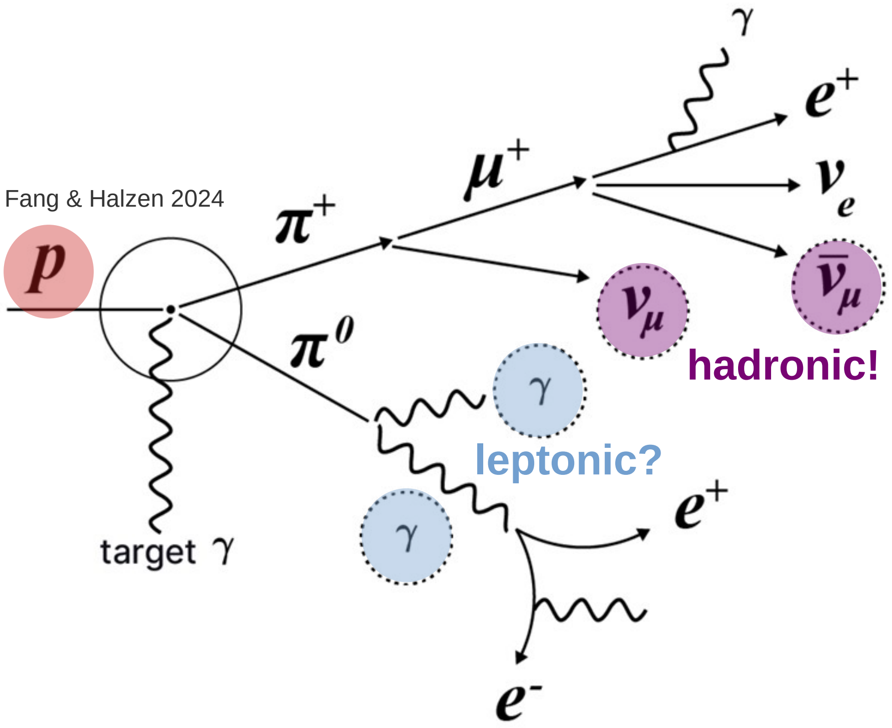
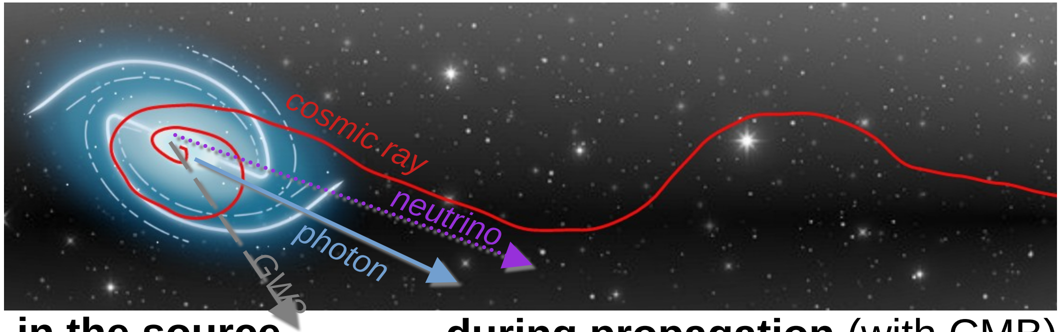


→ clear connection between messengers?

F. Oikonomou UHECR 2024

Multimessenger astroparticle physics





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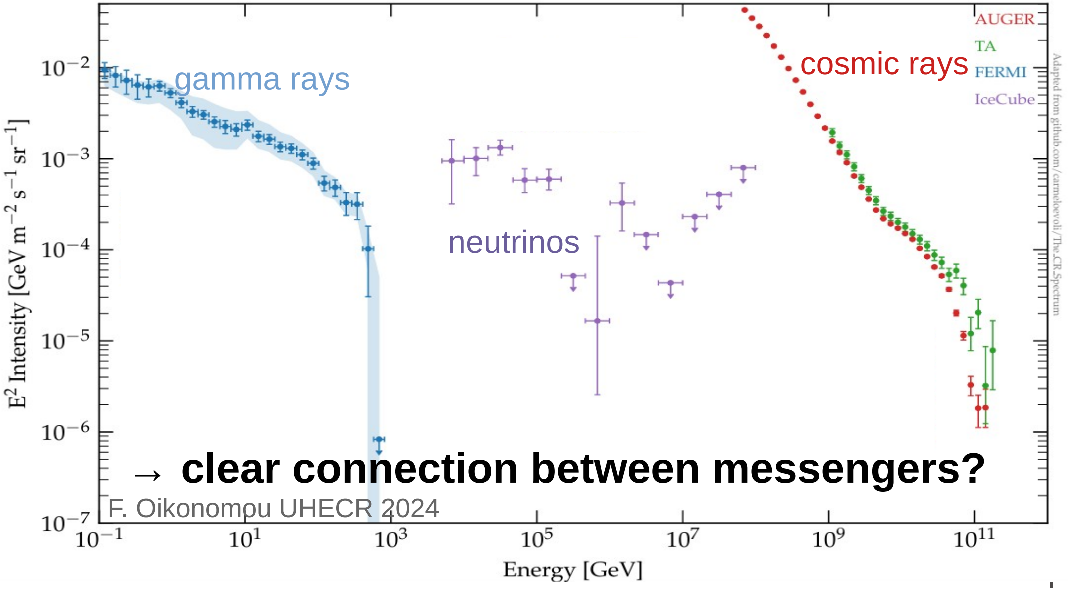
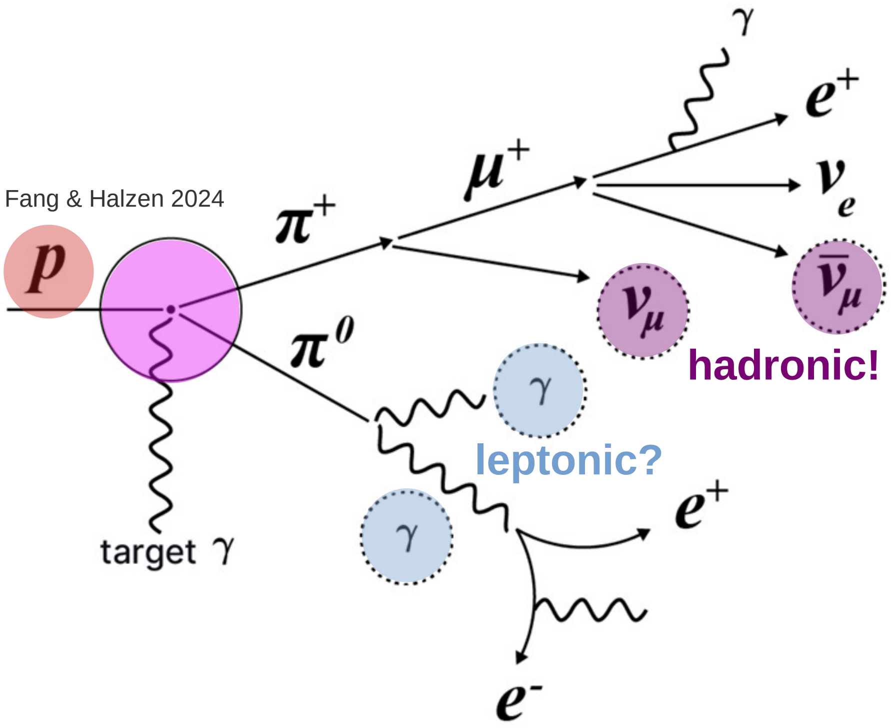


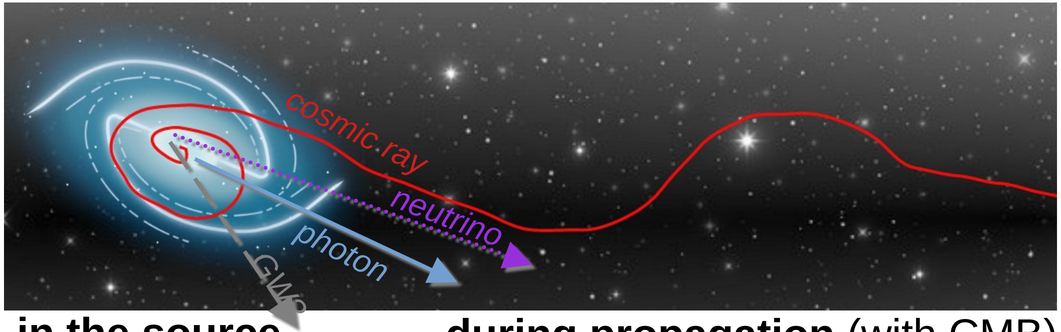
→ clear connection between messengers?

- **We are especially interested in neutrinos because they signal hadronic processes**
- **gamma-rays can also be produced through leptons**

Multimessenger astroparticle physics

Fang & Halzen 2024





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during propagation (with CMB) → ***cosmogenic***

- **We are especially interested in neutrinos because they signal hadronic processes**
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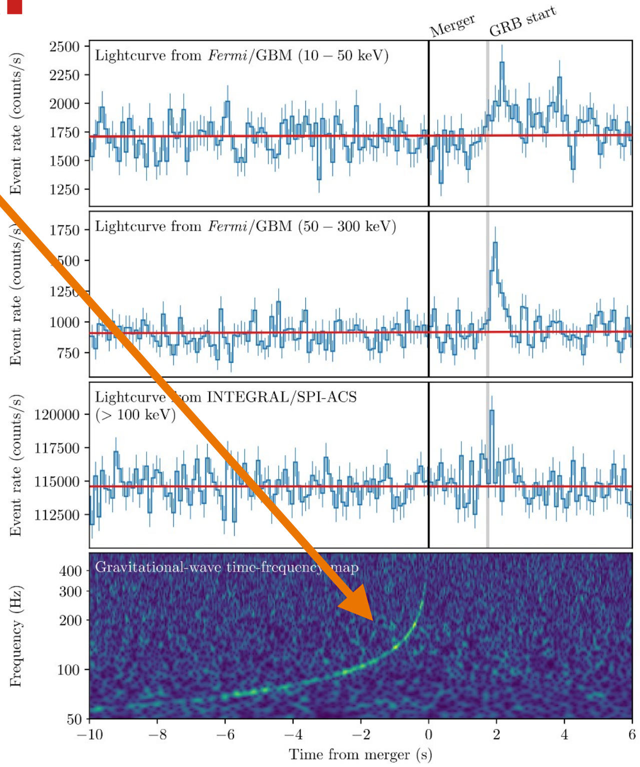
but, cross-correlation not straight forward:

- **neutrinos need a target** to be produced
  - **cosmic-rays may not be able to escape dense sources and lose energy!**
- also: sources of the UHECRs we measure have to be in our vicinity
  - neutinos can traverse the whole universe

Multimessenger observations so far

- 1987: neutrinos from **supernova** (photons)
- 2017: gravitational wave GW 170817 from **binary neutron star merger** in coincidence with photons from **short gamma-ray burst**



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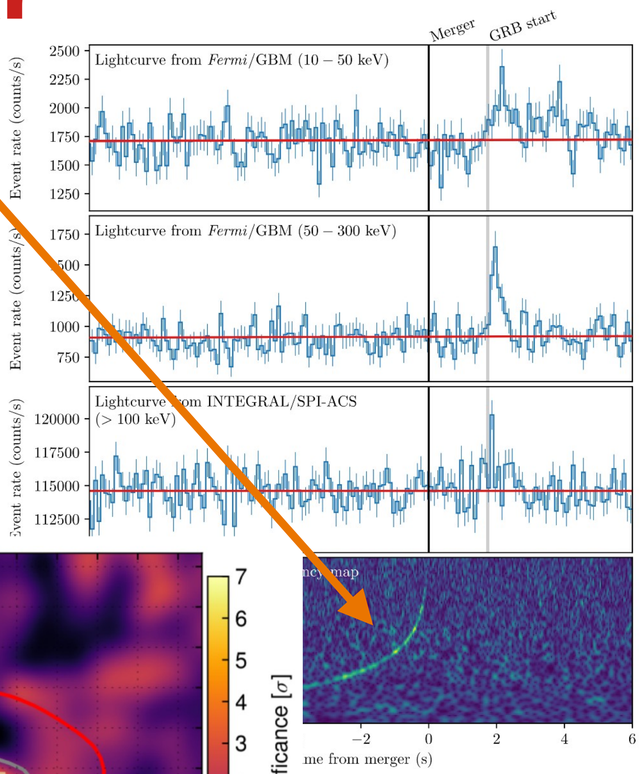

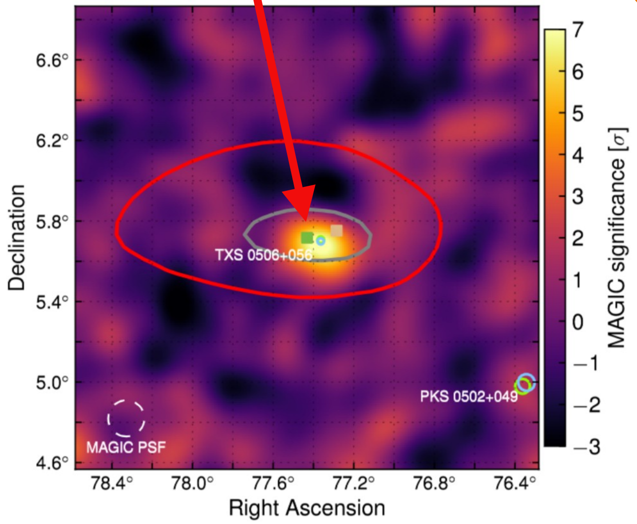

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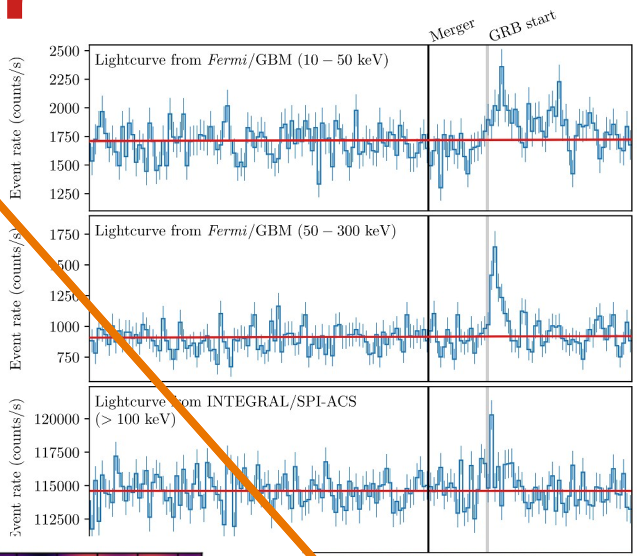

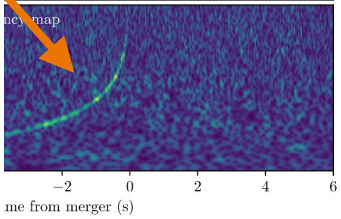

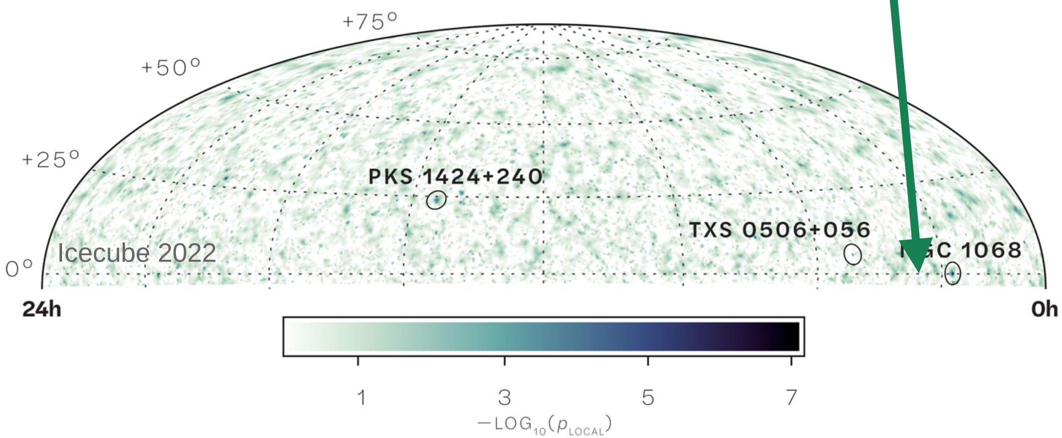

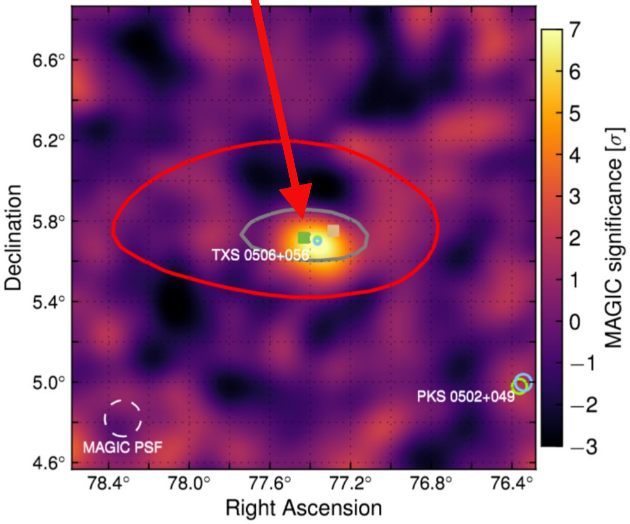

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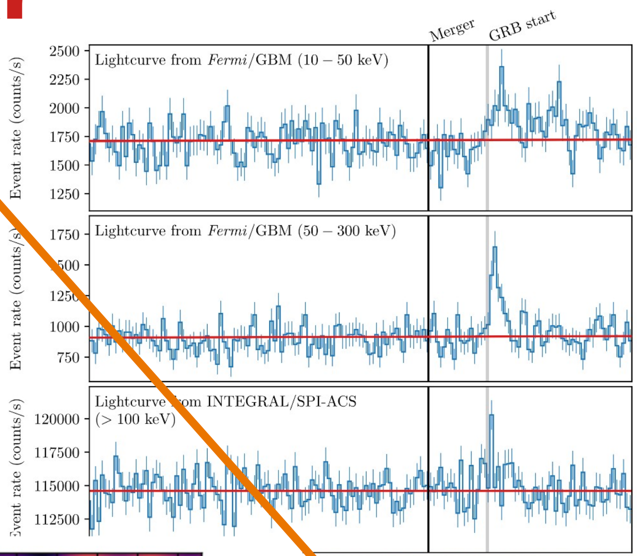
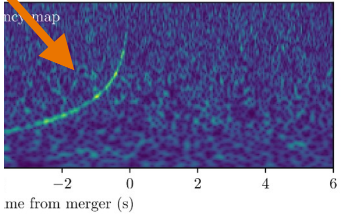
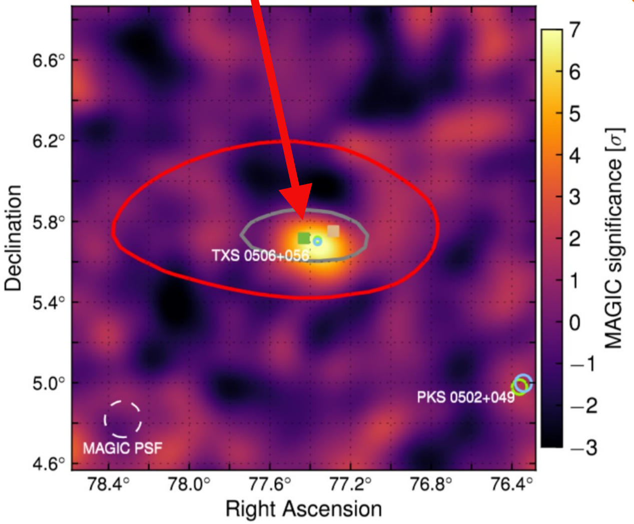
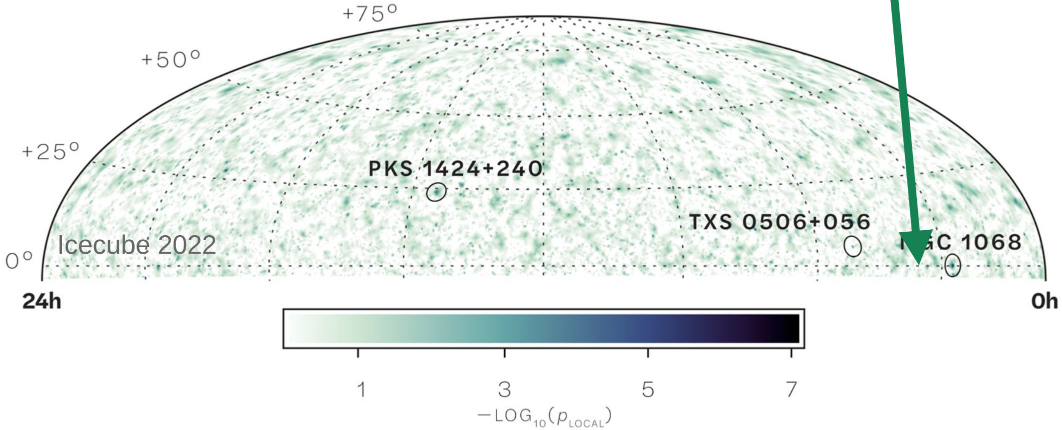
- 2022: 79 neutrinos events associated with low-luminosity active galaxy / SBG NGC1068 (photons), ~4σ
- 2023: **Galactic center** neutrino flux (~10%) detected

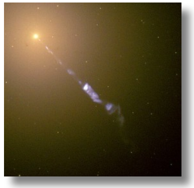
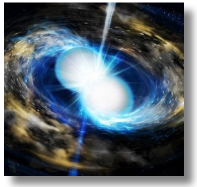
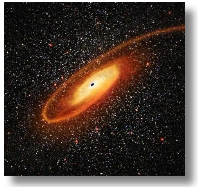






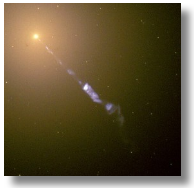


Overview

	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
diversity	✗	✗	✓	✗	✓	✗	✗
evolution	(✓)	(✗)	✓	✓	✓	✓	✓
arrival directions > 40 EeV	✓	✗	✓	✓	?	?	?
not too small density	✓	✗	?	✓	(✓)	(✓)	(✓)
Is it a neutrino source?	✓	✓	?	(✓)	?	?	?

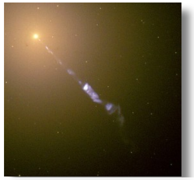
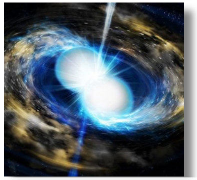
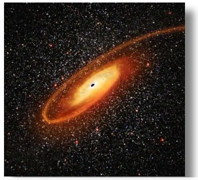
Overview - 10 years ago



	AGNs	blazars	Cen A	SBGs	BNS mergers	long GRBs	jetted TDEs
E_{max}	✓	✓	✓	?	✓	✓	✓
emissivity	✓	✓	✓	✓	?	(✓)	?
diversity	✗	✗	✓	✗	✓	✗	✗
evolution	(✓)	(✗)	✓	✓	✓	✓	✓
arrival directions > 40 EeV	✓	✗	✓	✓	?	?	?
not too small density	✓	✗	?	✓	(✓)	(✓)	(✓)
Is it a neutrino source?	✓	✓	?	(✓)	?	?	?

but without properly considering magnetic field deflections

Outlook

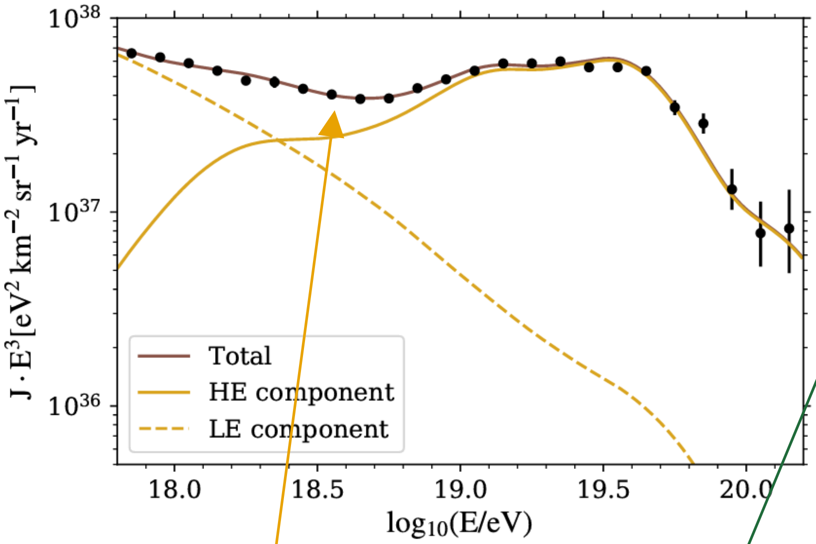
- **We have understood a lot more about the sources of UHECRs in the last years!**
- **But, there are still open questions...**
  - Can Cen A as a single source really work, can it reproduce the dipole, where would we expect contibutions of „Cen A like“ sources?
  - Which transient source classes can describe the arrival directions well?
  - Are UHECR sources really „standard candles“ with small population diversity? Or is there something wrong in the systematics or modeling?
  - Can we learn something about the source density or locations using the highest energy events? Or through their mass composition?
  - Where does the transition from extragalactic to Galactic sources occur?
  - Can we learn more about the extragalactic magnetic field? Or constrain the Galactic magnetic field with cosmic rays?
  - ...

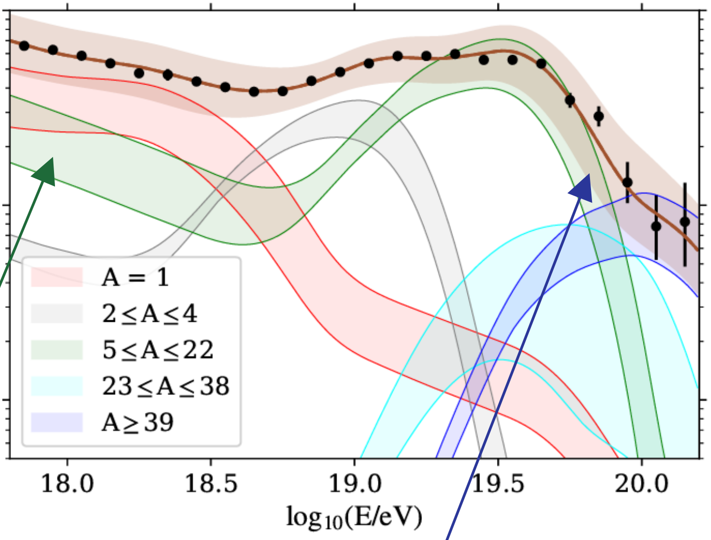
Backup

Pierre Auger Collaboration JCAP05(2023)024

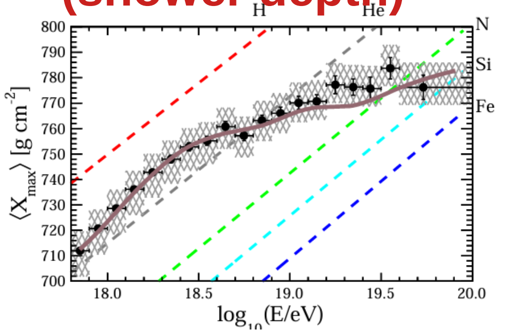
Combined fit: model predictions on Earth

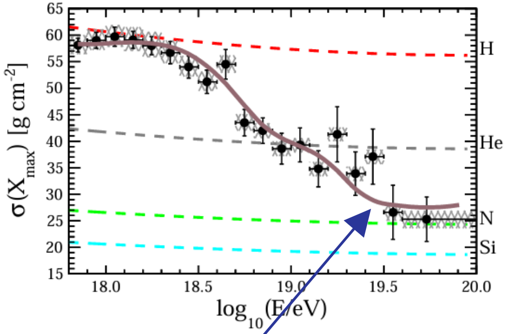
energy spectrum





mass composition (shower depth)





ankle: transition between two populations

conclusions stable with regards to **systematic effects**

transition between element groups

to describe composition getting heavier
+ small mixing + pronounced features in spectrum

Combined fit model predictions: source injection

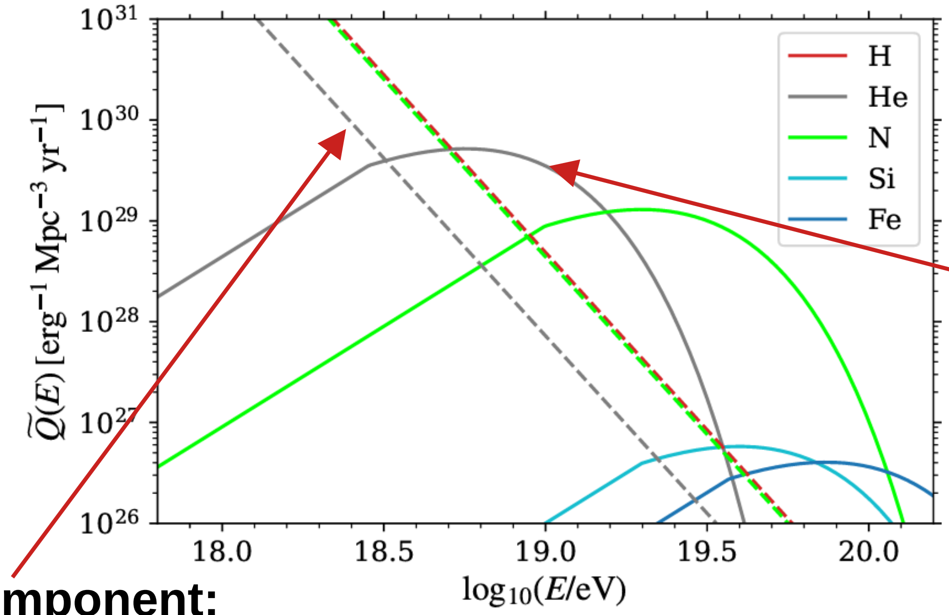
Peters cycle
+ broken exponential cutoff

spectral index

rigidity cutoff

$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \leq Z_A R_{\rm cut} \\ \exp\left(1 - \frac{E}{Z_A R_{\rm cut}}\right), & E > Z_A R_{\rm cut} \end{cases}$$

element contributions



high-energy component:

→ intermediate mass composition (not compatible with all-protons)

→ low rigidity cutoff O(1 EeV)

→ very hard spectrum ɣ < 0

→ shock acceleration: ɣ ~ +2

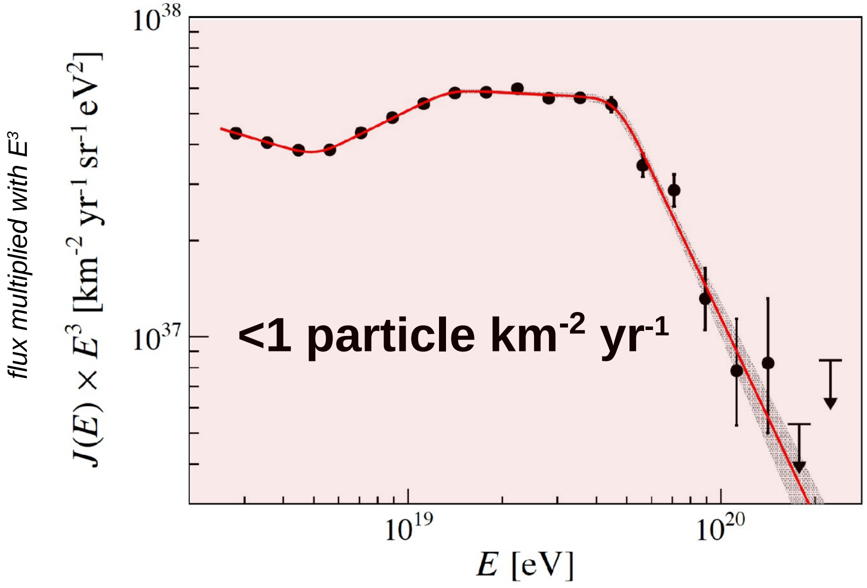
Why?

low-energy component:

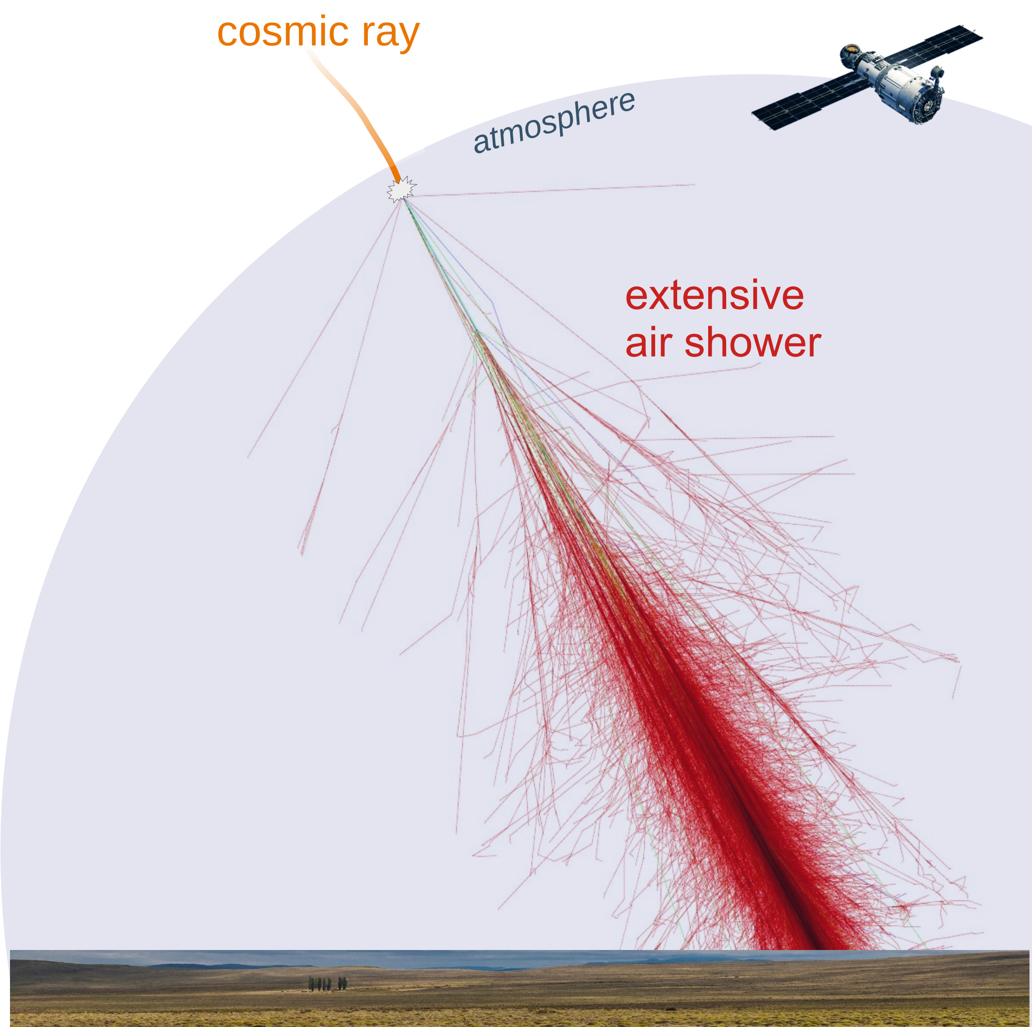
→ H+He+N, very soft spectrum ɣ~3.5

→ rigidity cutoff unconstrained

Measurement of UHECRs



- features in spectrum (e.g. suppression) give information about sources
- need huge observatories for statistics
  - measure air showers

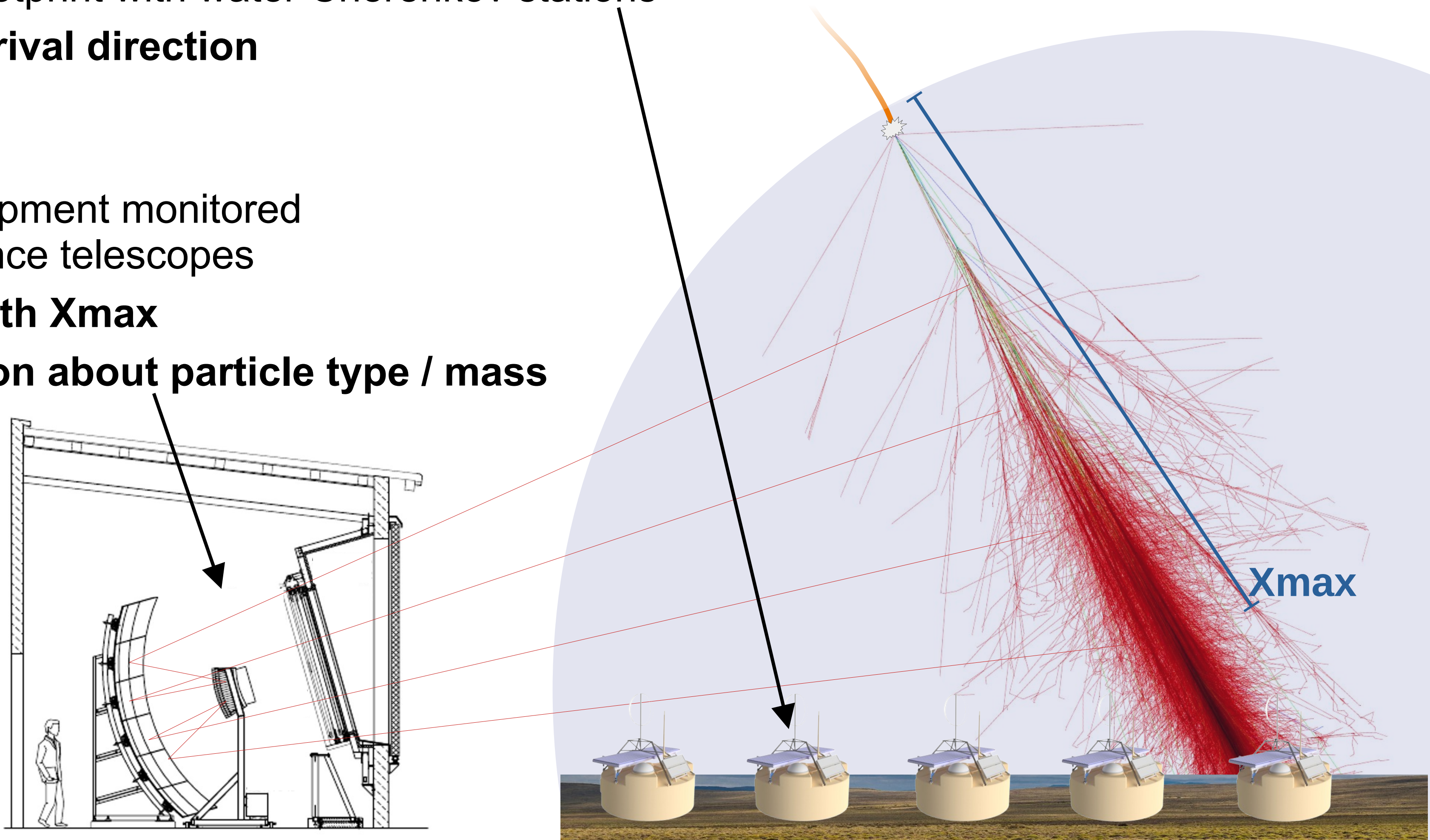


Measurement of UHECRs at the Pierre Auger Observatory

- detection of footprint with water Cherenkov stations
  - → **energy + arrival direction**

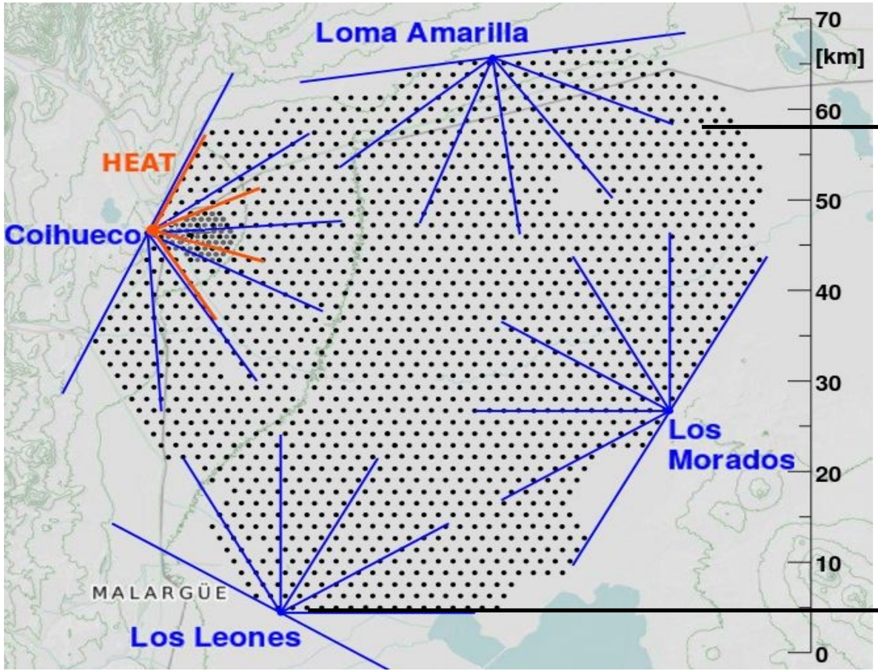
- in dark nights:

  shower development monitored
  with fluorescence telescopes
  - → **shower depth Xmax**
    - → **information about particle type / mass**



The Pierre Auger Observatory

- largest observatory for UHECRs in the world (3000 km^2)
- located in Argentina, close to Malargüe

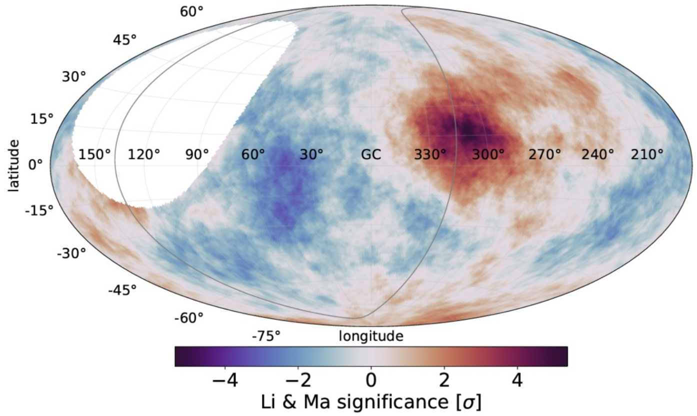


hybrid detection:

1660 water cherenkov detectors (SD)

27 fluorescence telescopes (FD)

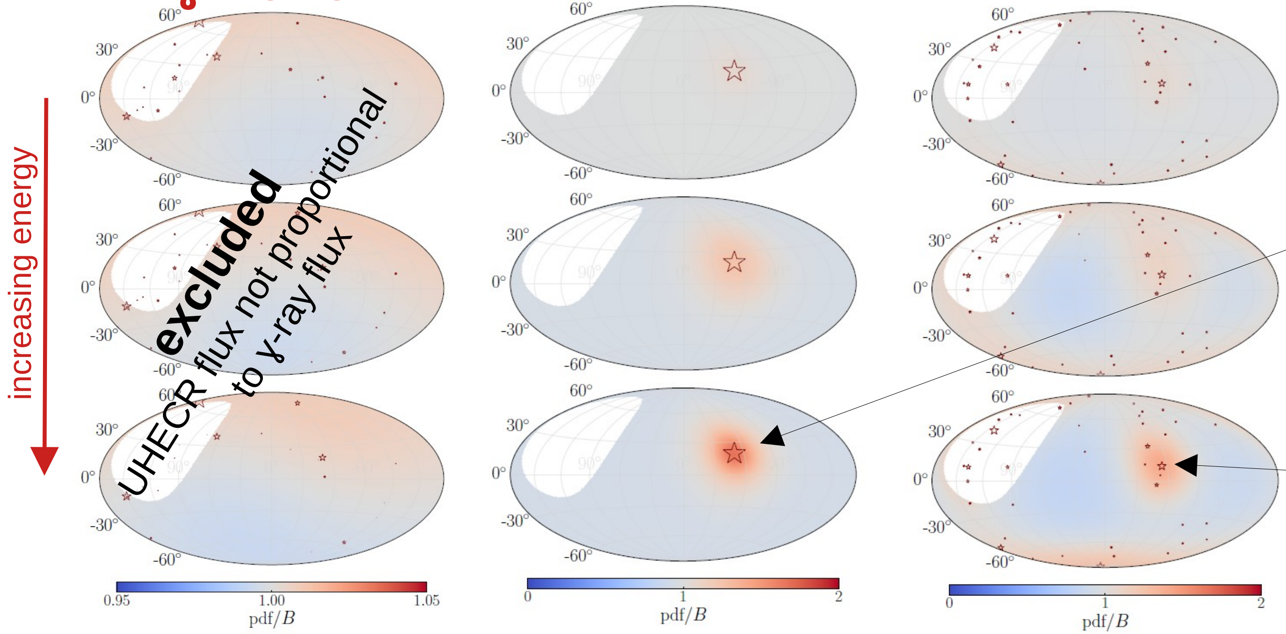
Best-fit model: arrival directions



γ-AGNs

Centaurus A

Starburst Galaxies



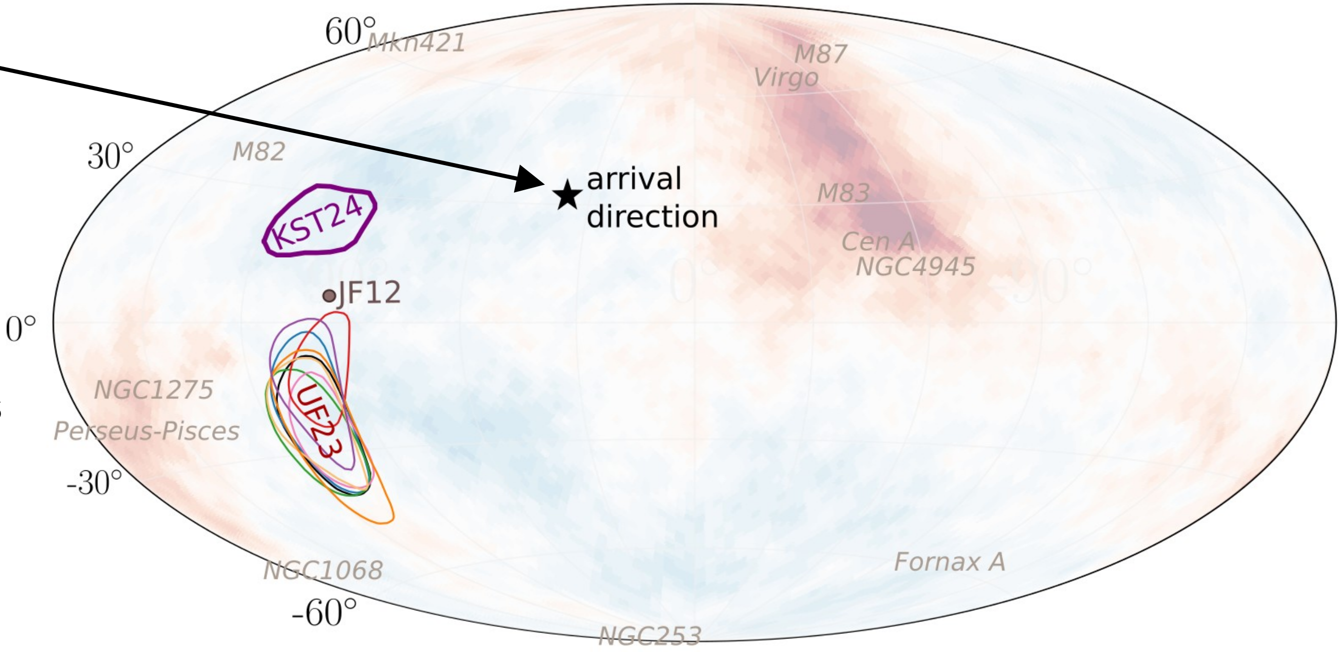
- **starburst galaxy model favored with 4.5σ significance over homogeneous model!**
- mostly due to Centaurus A / NGC 4945 region

Where do the highest energy cosmic rays come from?

background: imprint of matter distribution from Bister & Farrar ApJ 966 71 (2024)

backtracking **Amaterasu event** with E=244 EeV
TA Science 382 (2023)

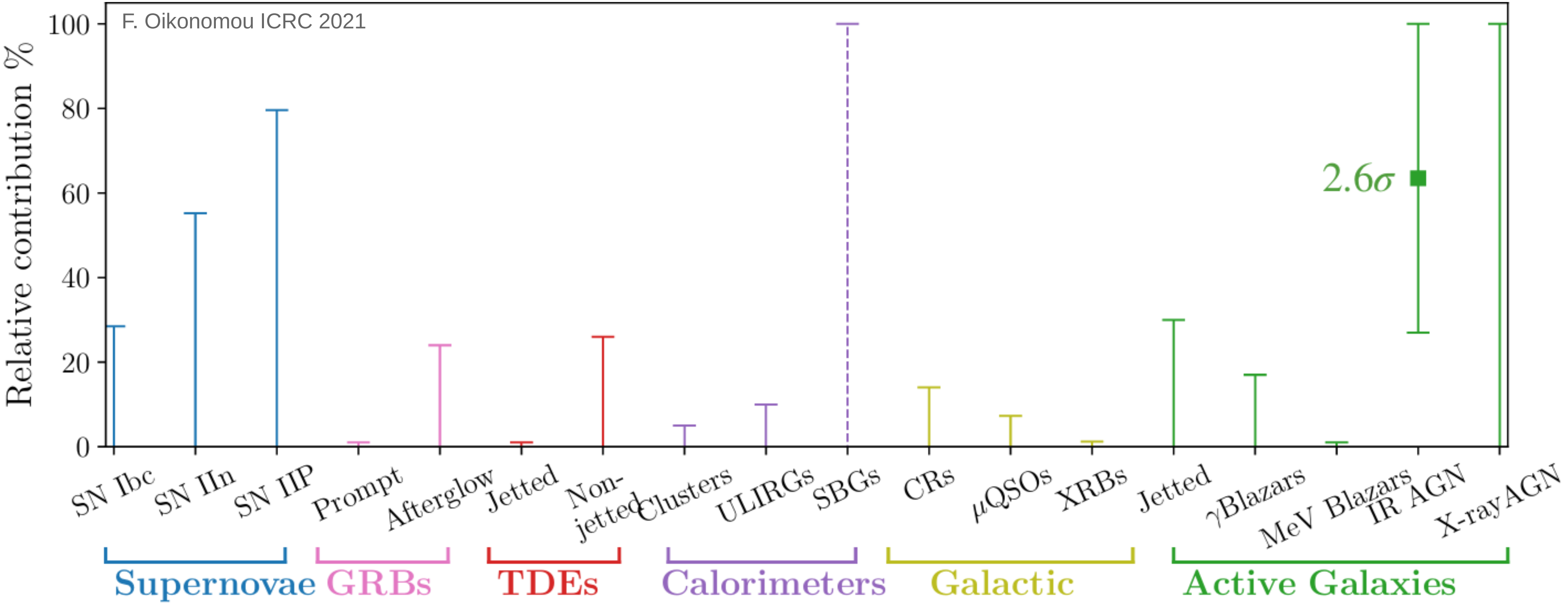
- assumption: Fe at source
  - ➔ source within ~ 8-50 Mpc
- ➔ source direction not close to any powerful source candidates
- ➔ rather close to local void
  - ➔ why?



- similar conclusions for all highest energy Auger + TA events: TA PRL 133 (2024) Auger ICRC 2025
  - ➔ not easy to find powerful source candidates
    - ➔ **ultraheavy particles? transients? strong extragalactic magnetic field?**

Contribution to the total neutrino flux

identified by IceCube: a blazar, a low-luminosity AGN / SBG, Galactic center



- **probably not only one source class producing all neutrinos**
- **connection to cosmic rays not very clear, also due to target and distance problem**