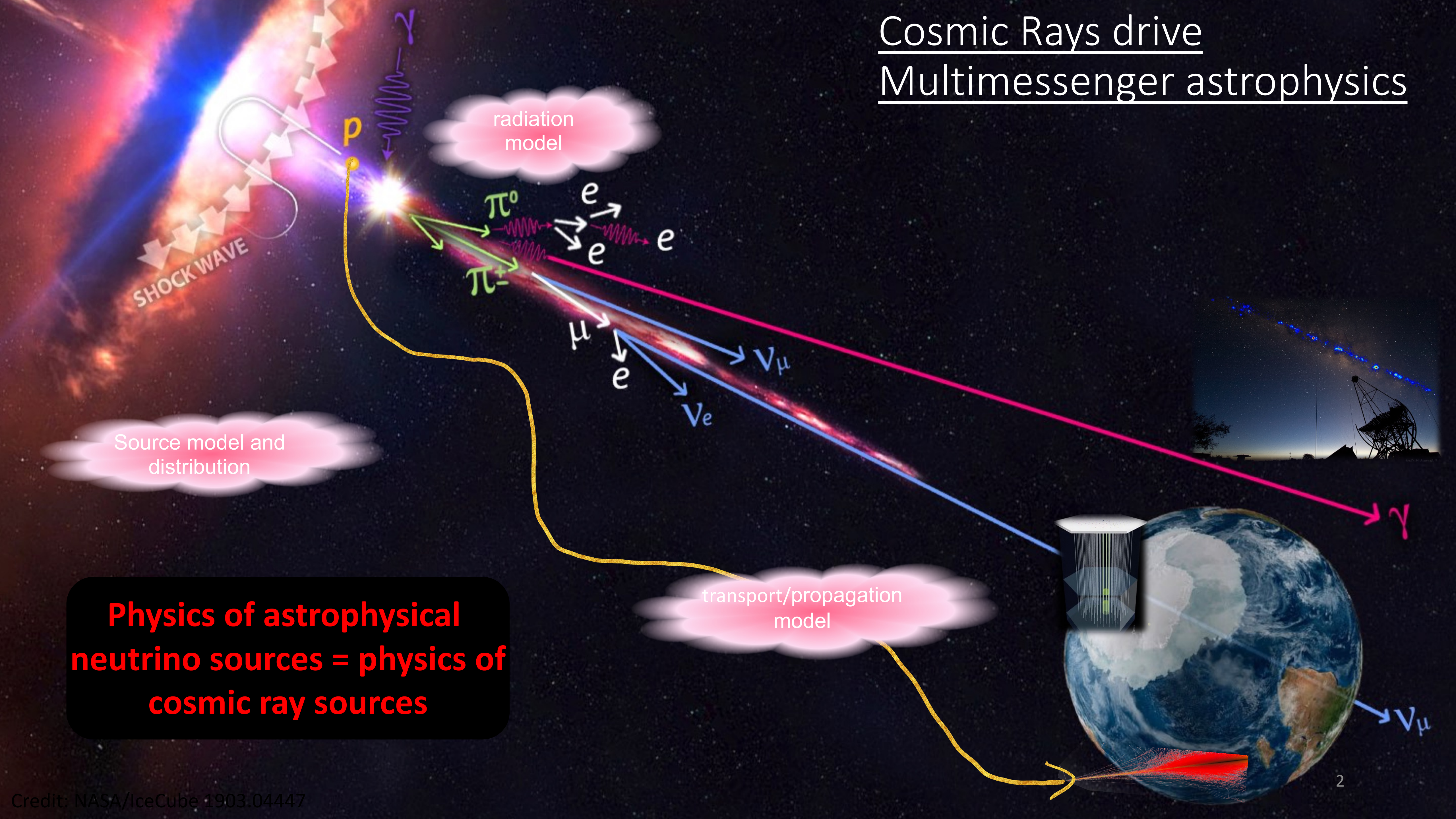
Treasure Maps for Detections of Extreme Energy Cosmic Rays

Anatoli Fedynitch

High-Energy Theory Group, Institute of Physics, Academia Sinica, Taipei

TU Dortmund Teilchenseminar, 2023/07/07

Cosmic Rays drive Multimessenger astrophysics

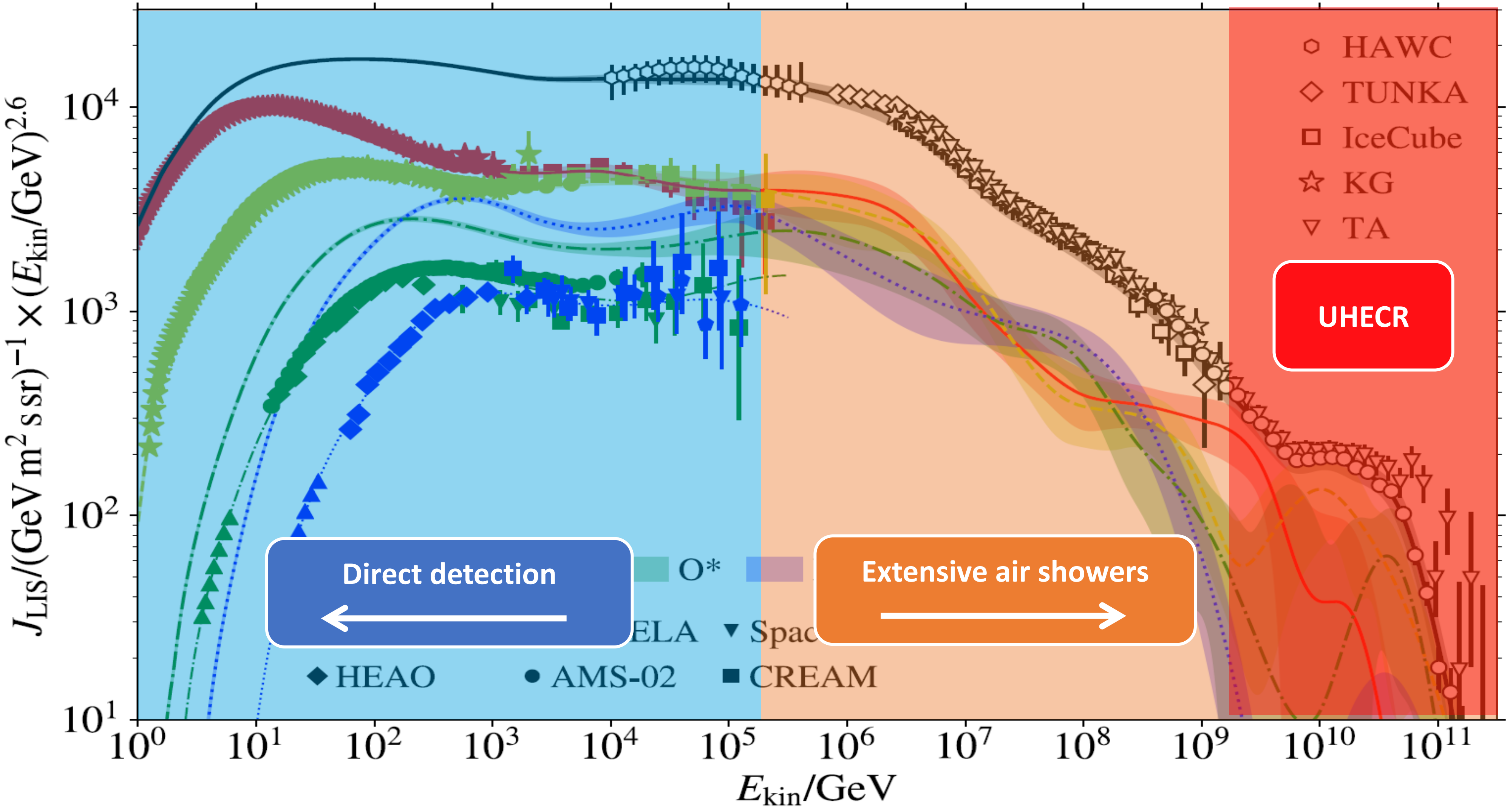


Physics of astrophysical neutrino sources = physics of cosmic ray sources

Credit: NASA/IceCube 1903.04447

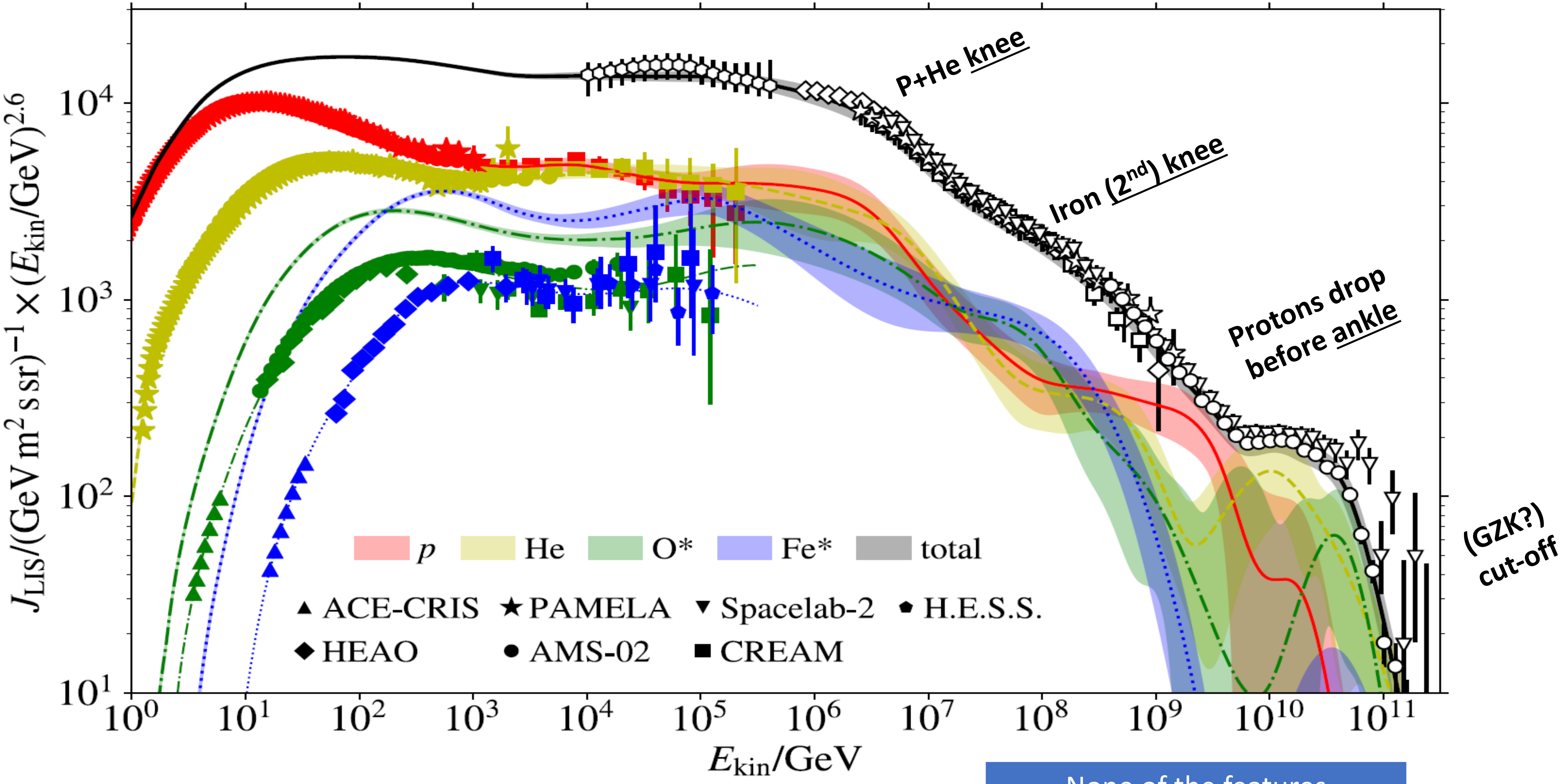
Cosmic Rays observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



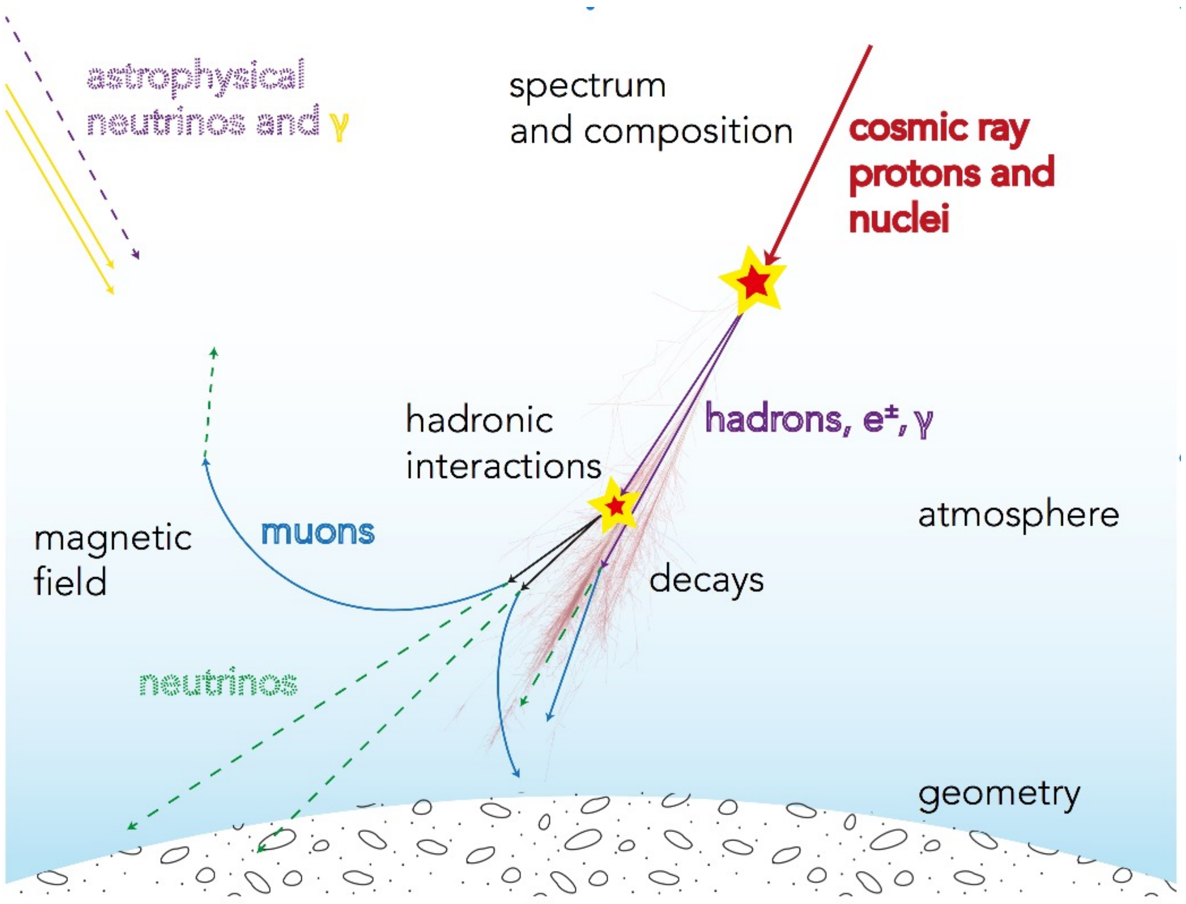
Cosmic Rays observations

Dembinski, AF, Engel, Gaisser, Stanev
PoS(ICRC2017)533



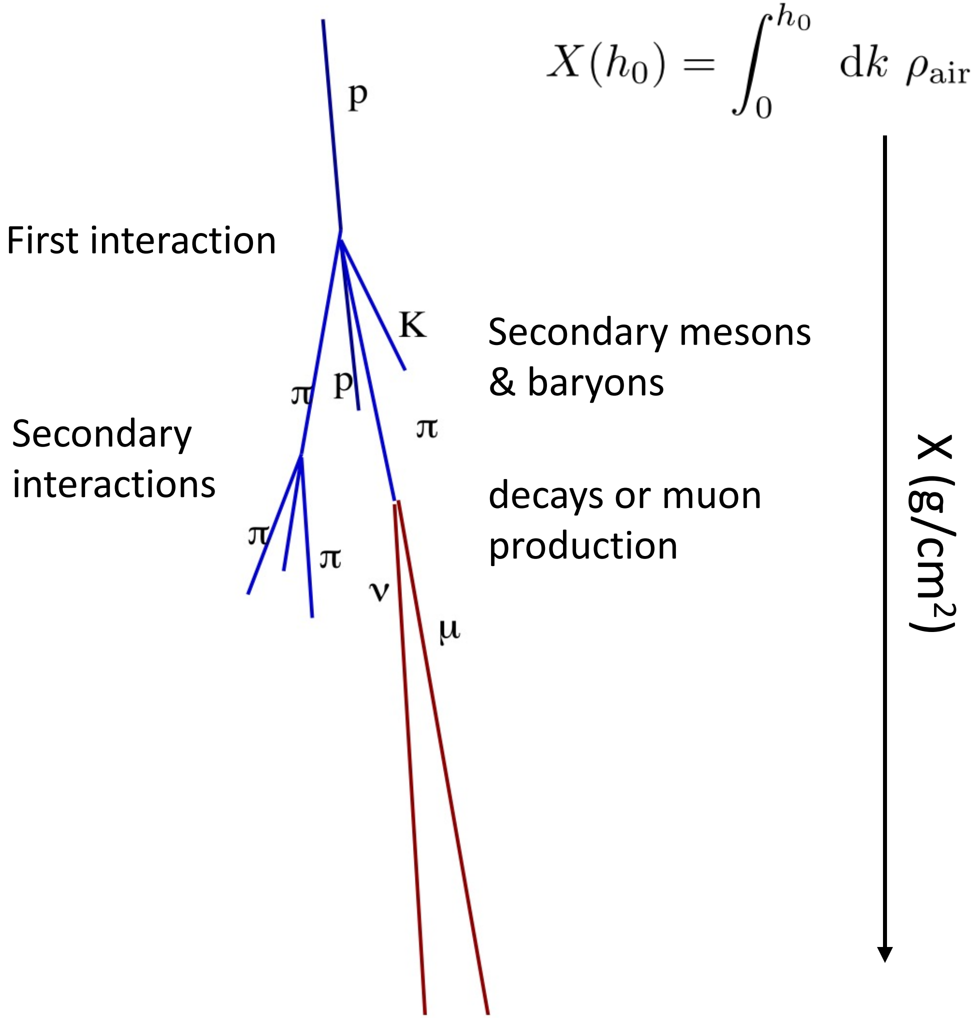
None of the features unambiguously explained!

Physics of extensive air (particle) showers from cosmic rays in the atmosphere



(Column-) depth

$$X(h_0) = \int_0^{h_0} \mathrm{d}k\ \rho_{\mathrm{air}}(\ell)$$



Pierre Auger Observatory in Malargüe (Argentina)

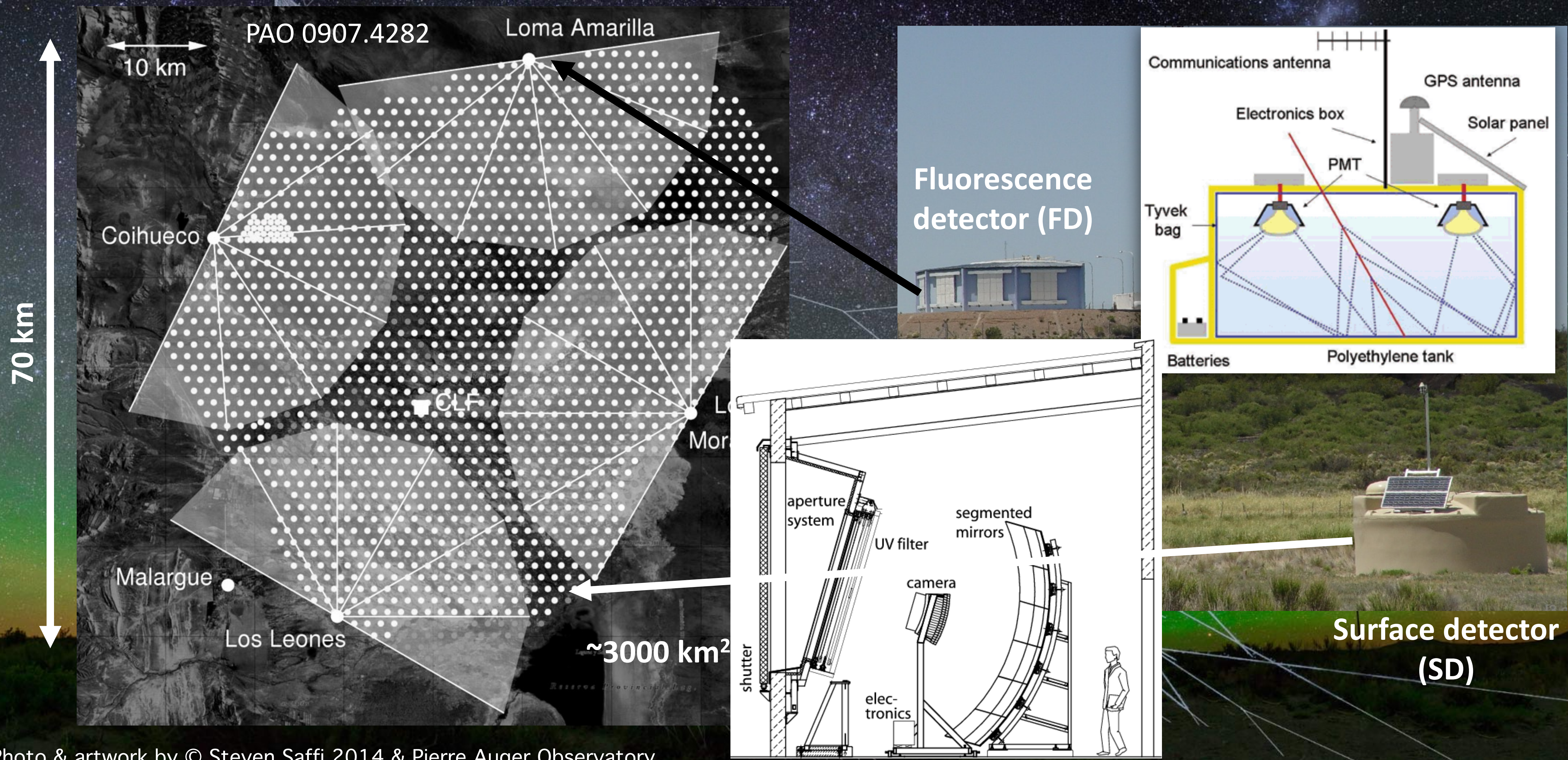
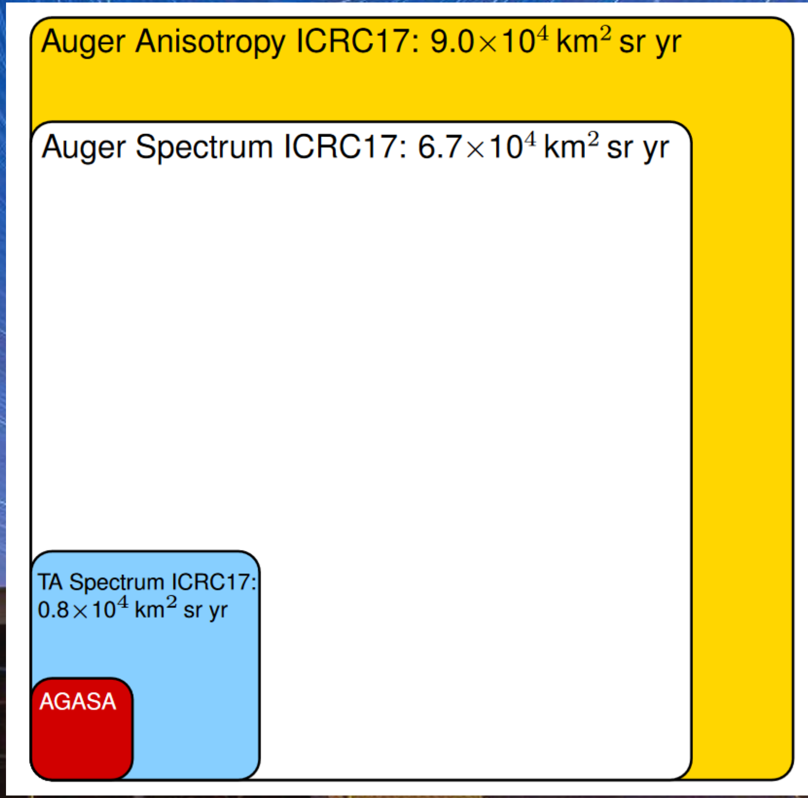


Photo & artwork by © Steven Saffi 2014 & Pierre Auger Observatory

Exposure



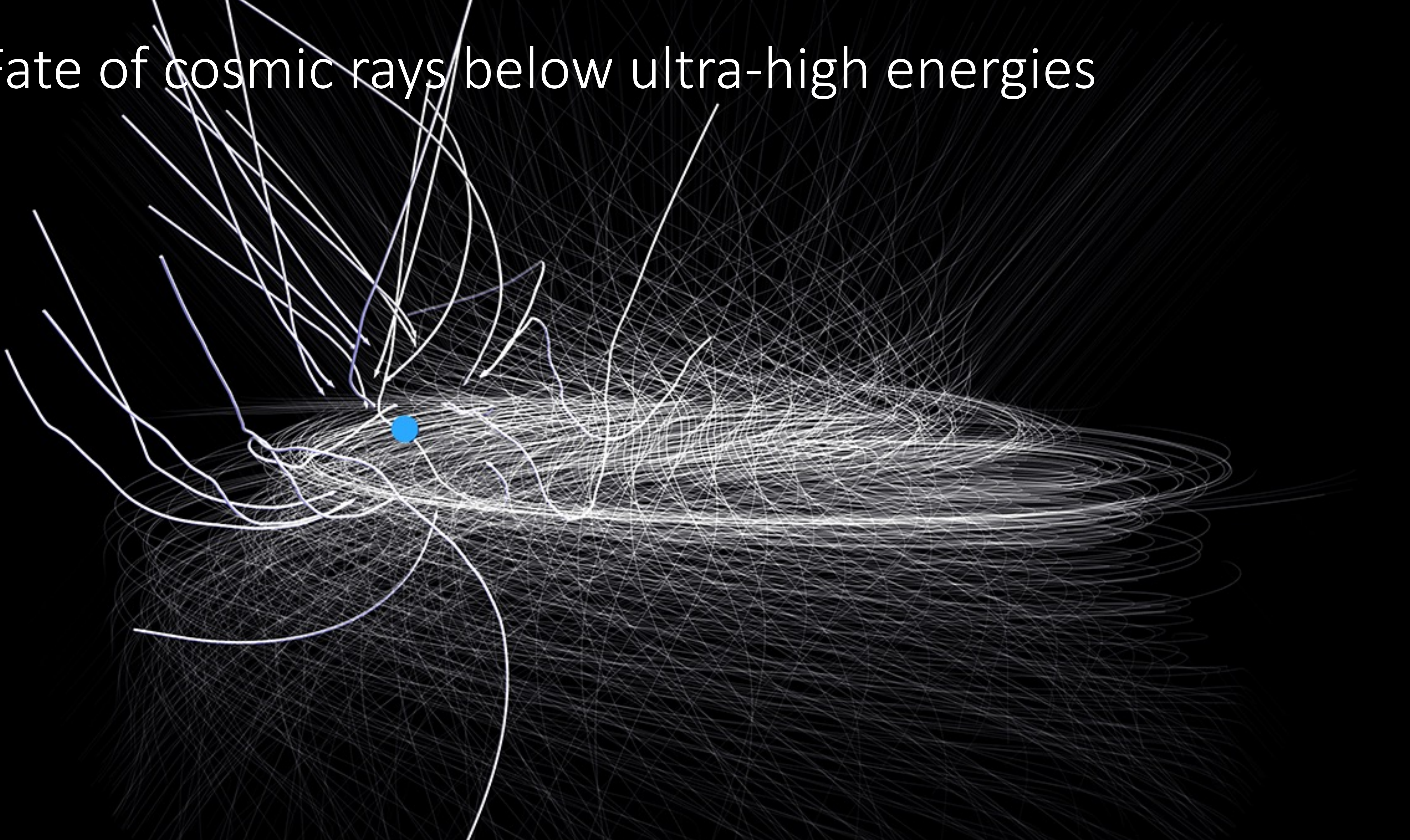
M. Unger, ICRC2017

Telescope array in Utah (USA)

Photos courtesy of the Telescope Array Collaboration

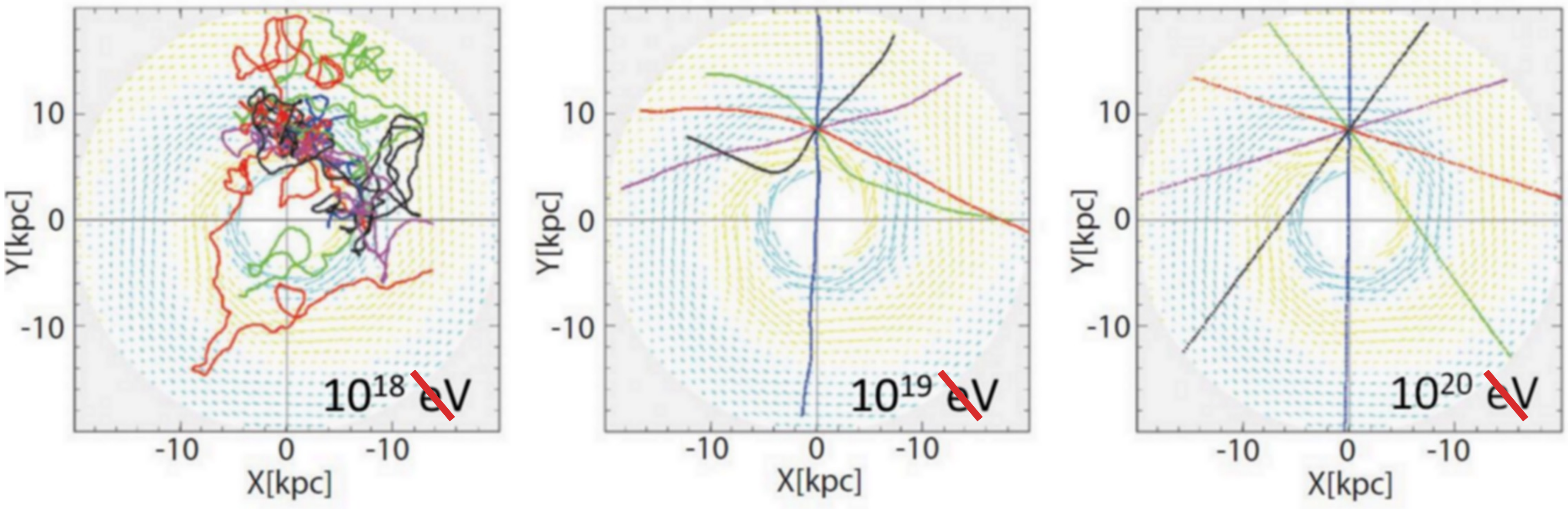
1. Physics challenges in UHECR source identification

Fate of cosmic rays below ultra-high energies



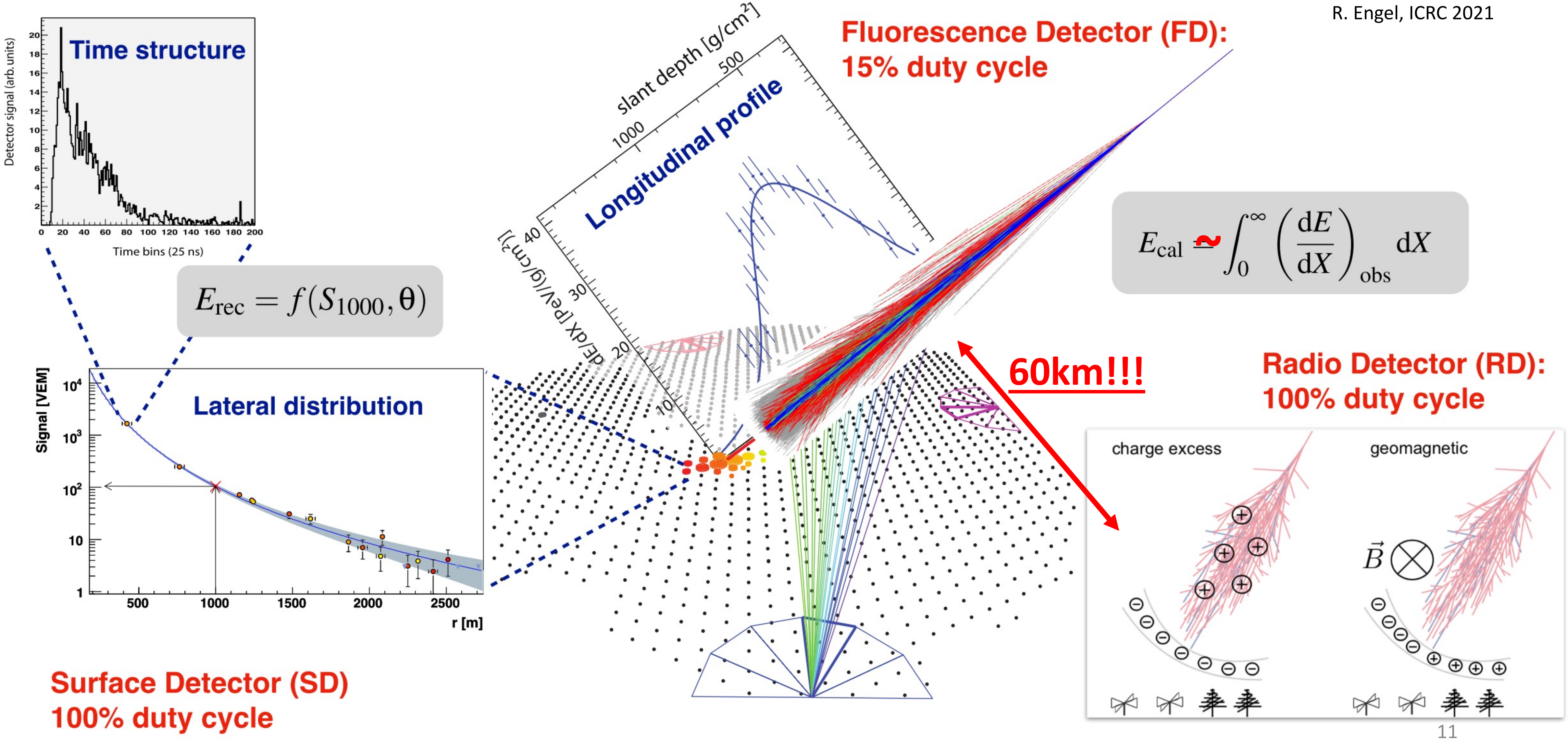
Deflections

Credit: Ebisuzaki? (RIKEN)



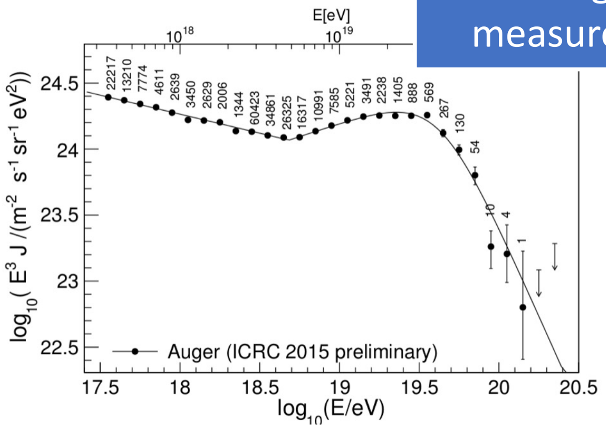
- Magnetic deflection in galactic and extragalactic magnetic fields is a function of **RIGIDITY (E/Z)**
- Anisotropic "by design"
- If an experiment measures the CR energy but not the charge (or mass number)
  - → Divide the energy by your favorite integer number between 1 and 20 😅😉

Hybrid air shower detection (Pierre Auger Observatory)

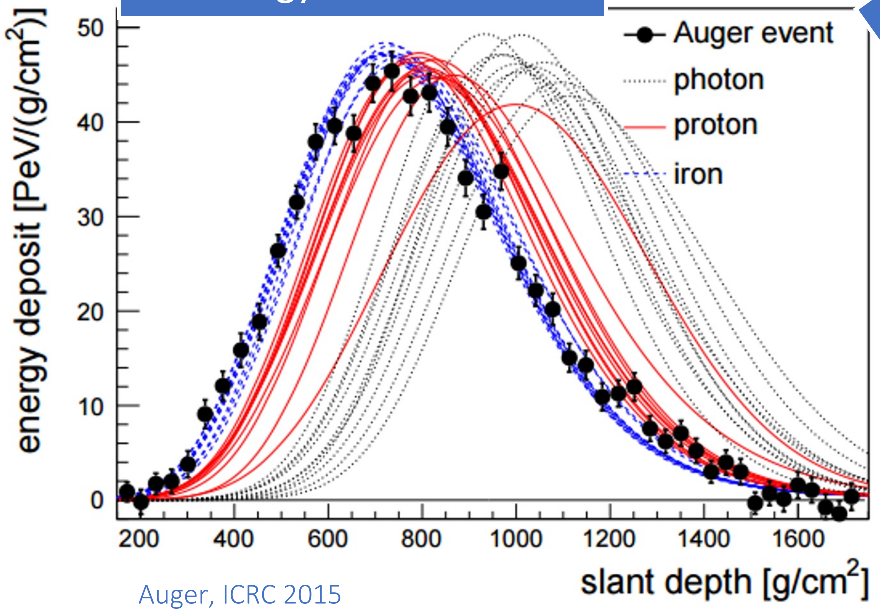


Template method for measuring average UHECR mass composition

Energy and spectrum measured calorimetrically

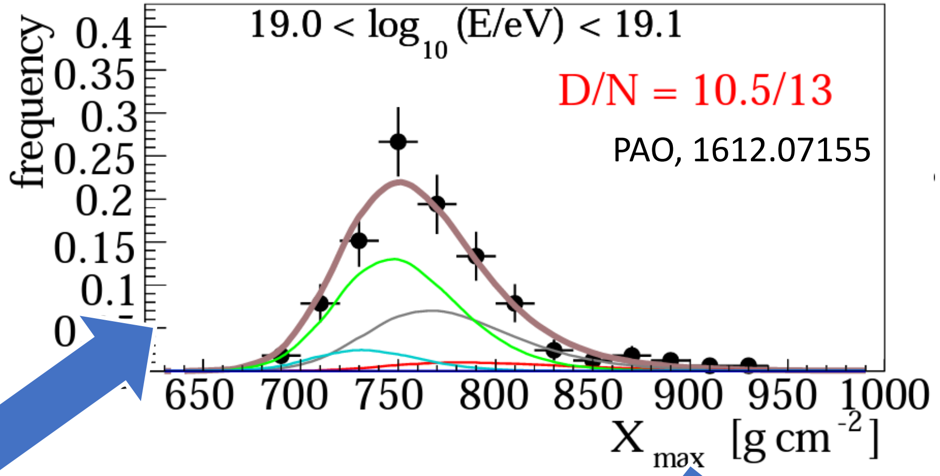


Simulated events of same energy + real event

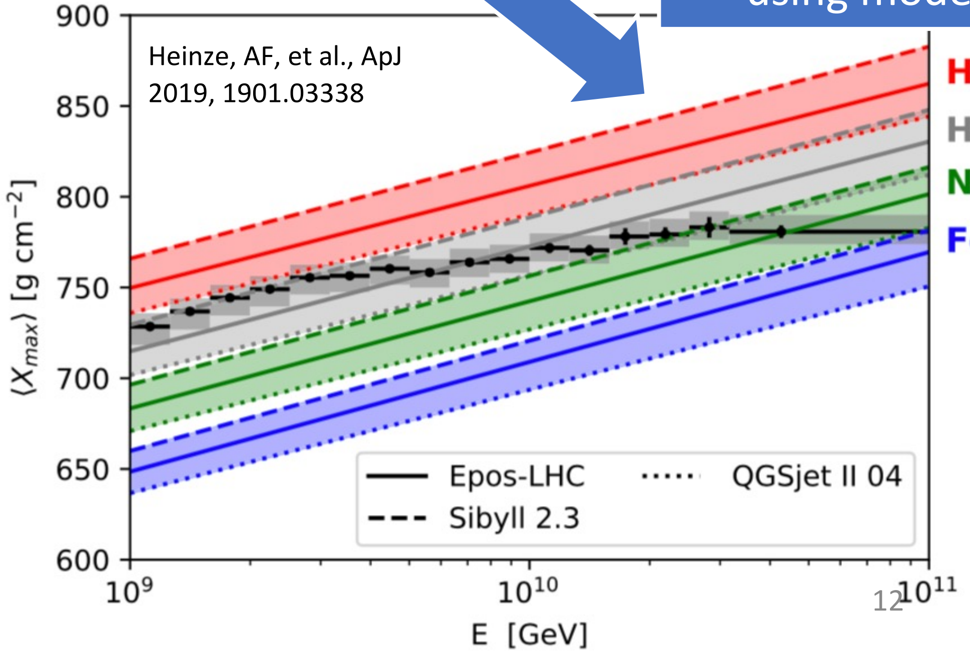


Auger, ICRC 2015

Group events in energy and histogram X_{max}



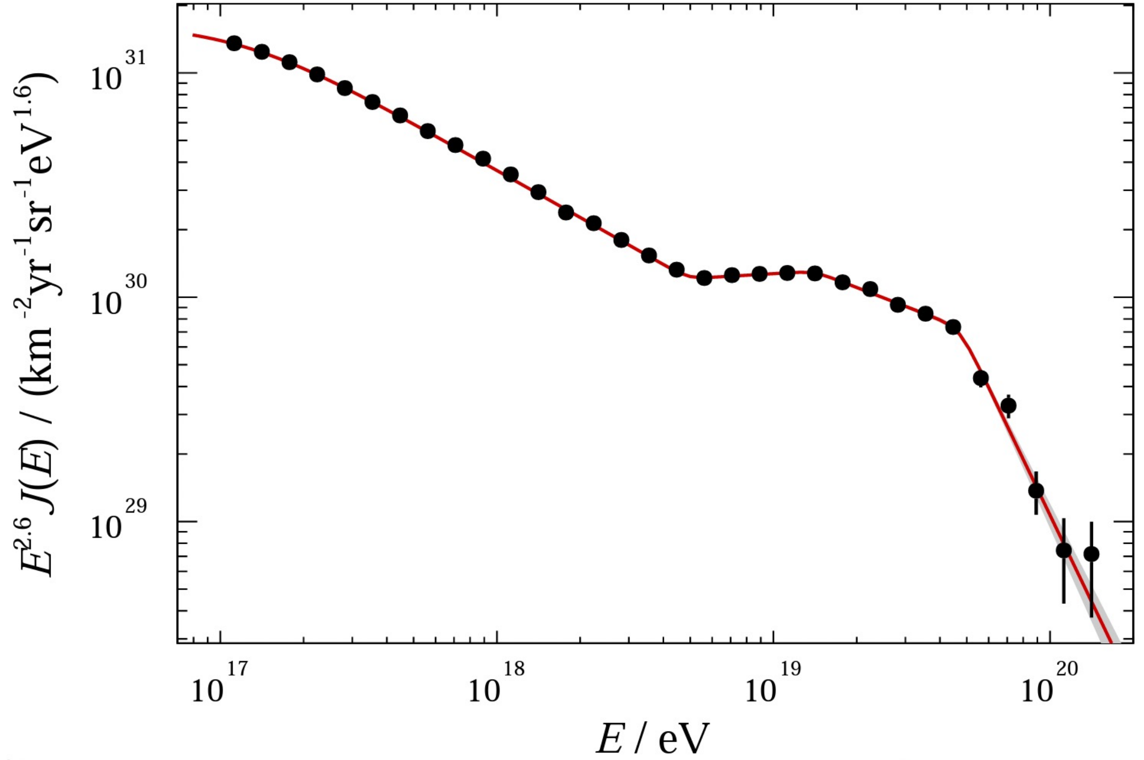
Conversion from Xmax dist to mass using models

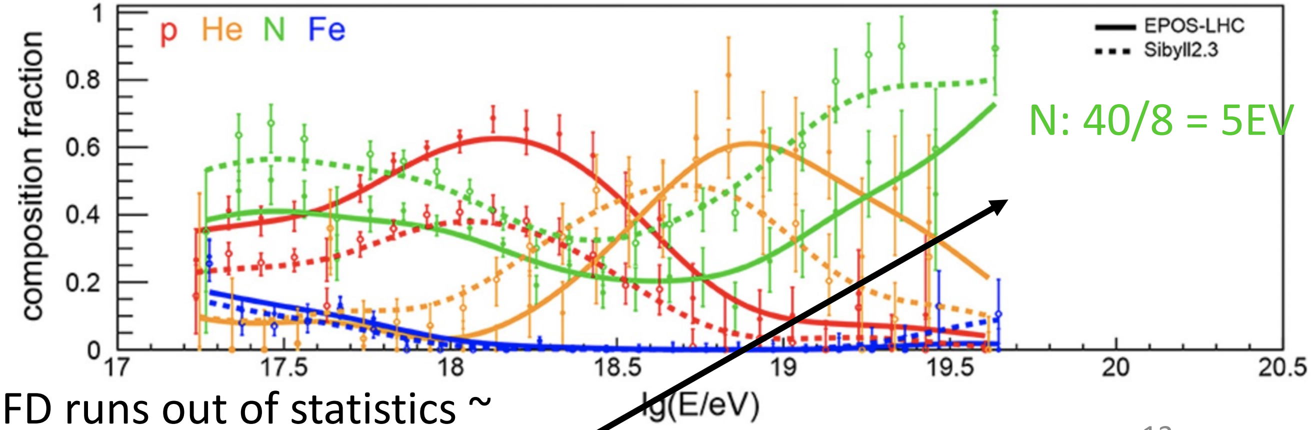


Current mass measurements not good enough

O. Deligny (PAO), CRIS 2022

- Template method (backup) gives "all-sky average" of masses, **not the mass of each event**
- The errors are still large ~lnA=1, because the impact on the shift of mean X_{max} is quite small
- The conversion from <Xmax> to <lnA> is model dependent (dashed vs solid line)
- Needs Fluorescence Detector FD (for X_{max})
  - Small duty cycle
  - Smaller exposure



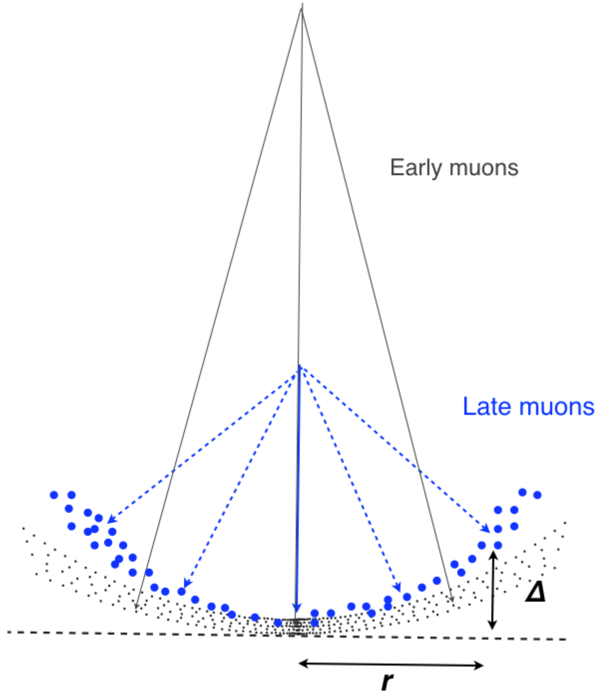


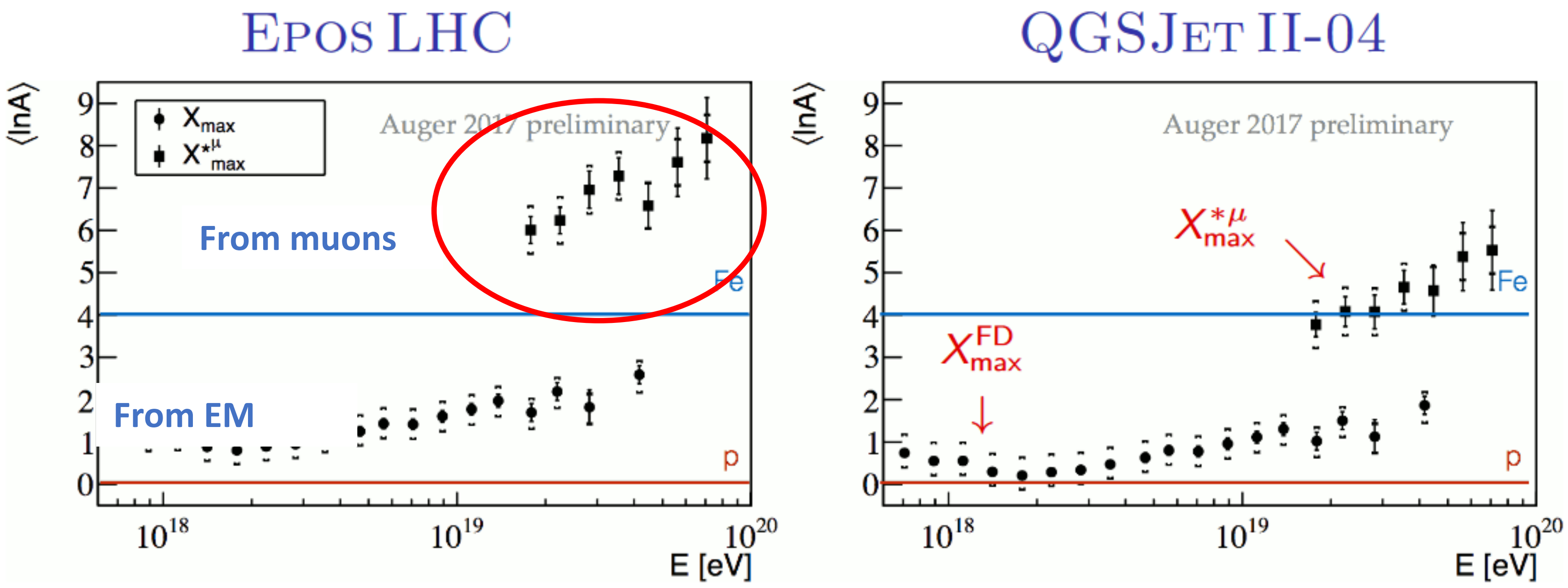
N: 40/8 = 5EV

FD runs out of statistics ~ 40 EeV (PAO), 10 EeV (TA)

Other means of mass determination

R. Prado, ISVHECRI 2018





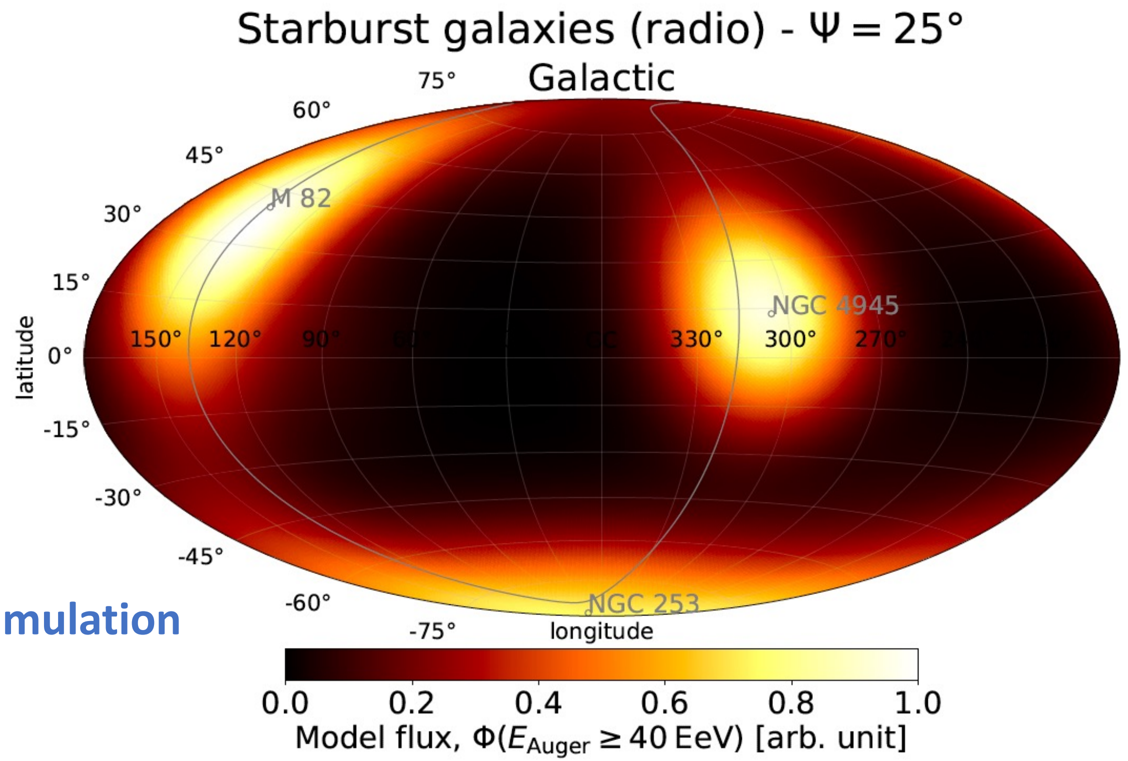
- Identify mass by surface detectors → higher energies
- Several issues, like the Muon Excess (review by Albrecht et al. 2105.06148)
- Big **improvements expected soon** but work in progress
- Auger Prime Upgrade in progress to solve some of these problems
- In 3 - 10 years?

Partial solution: Brute Force -- Explore higher energies.
High EeV = high EV?

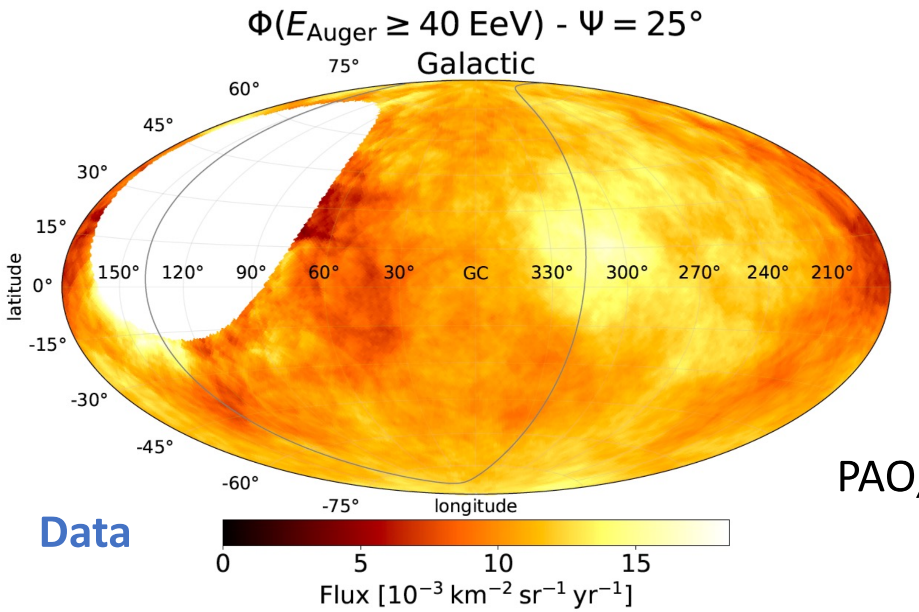
2. Conceptual challenges in UHECR source identification

Searching for clustering in the direction of potential sources

1. Assume that a catalog of sources astrophysical objects are the sources (here Starburst galaxies)
2. Assume isotropic and circular deflection scale here 25deg and an energy threshold
3. Assume that all sources have the same brightness (or so)
4. Test the compatibility of simulated pattern with observed one



Simulation



Data

PAO, 2206.13492

Common search radius at low rigidities misleading

THE ASTROPHYSICAL JOURNAL LETTERS, 833:L17 (5pp), 2016 December 20 GLOBUS & EICHLER

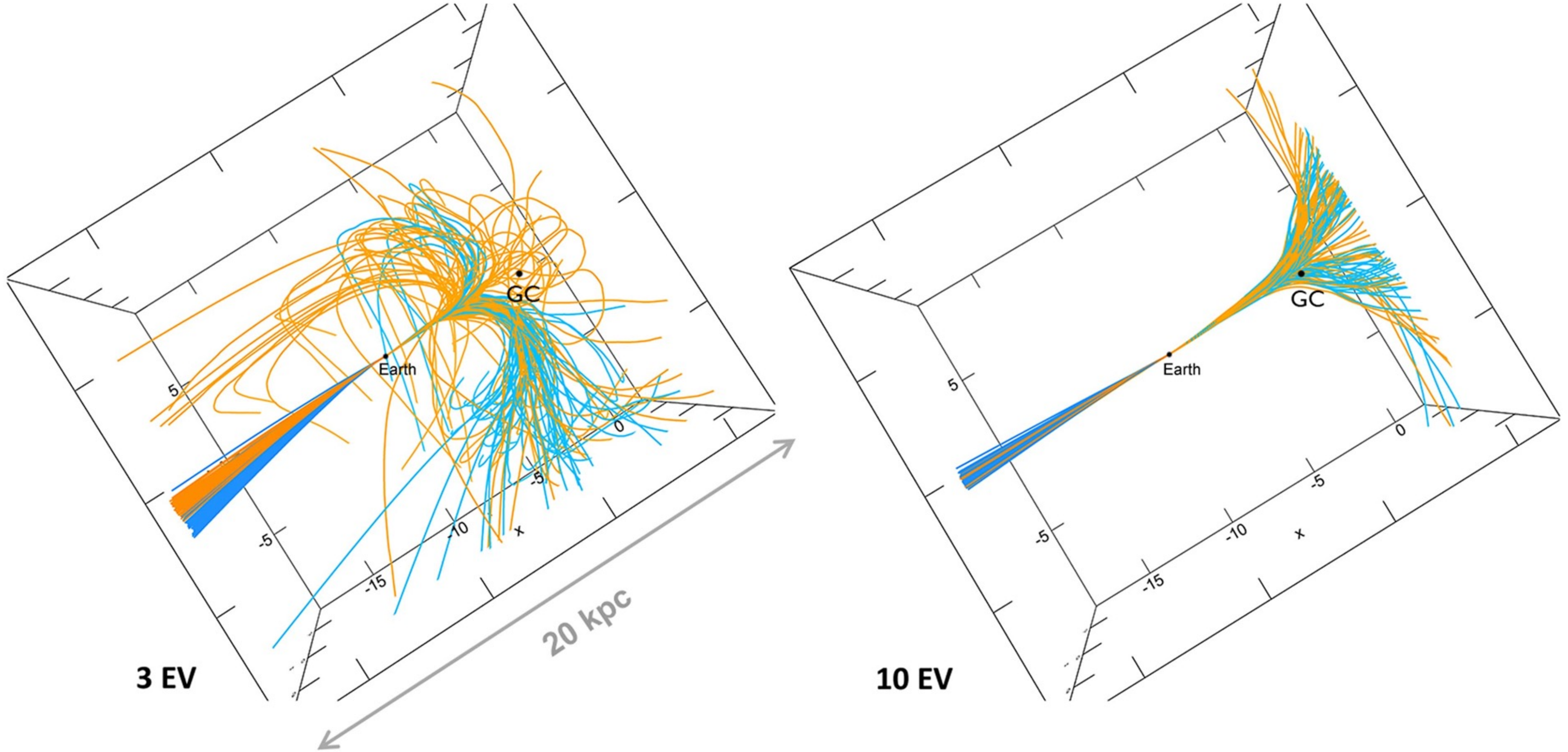
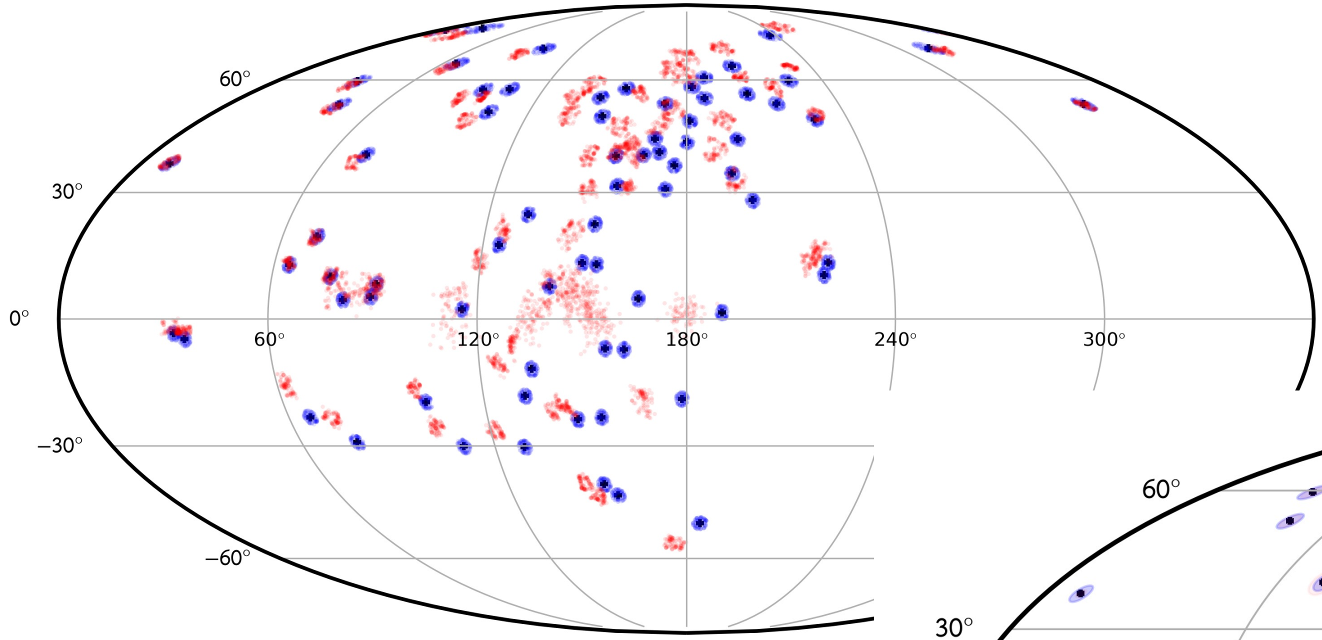
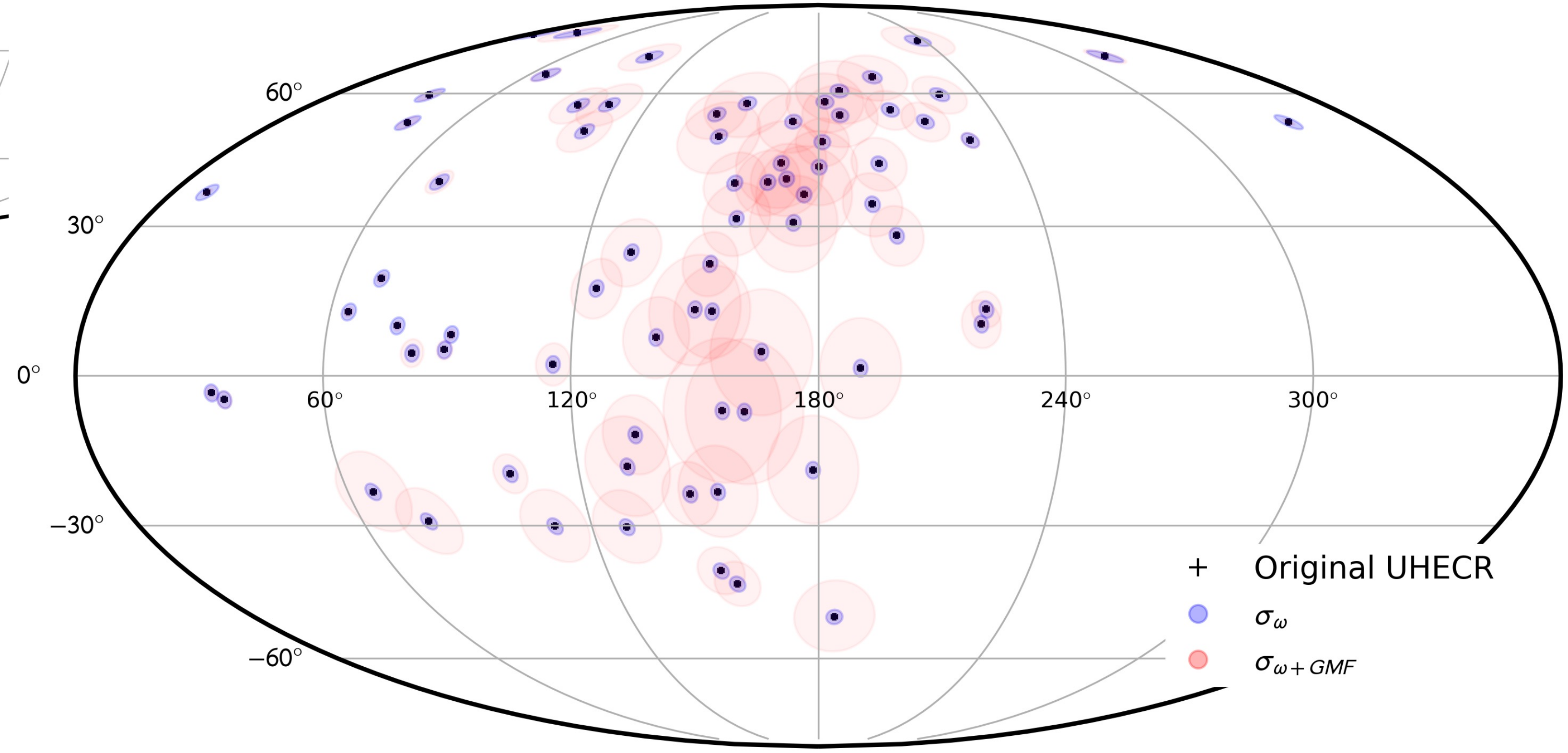


Figure 1. Trajectories of antiparticles corresponding to a spot of 3° square, after a backward propagation in the GMF in two different configurations of the magnetic turbulence (in orange and blue, respectively).

Deflections are anisotropic, individual, energy and composition dependent

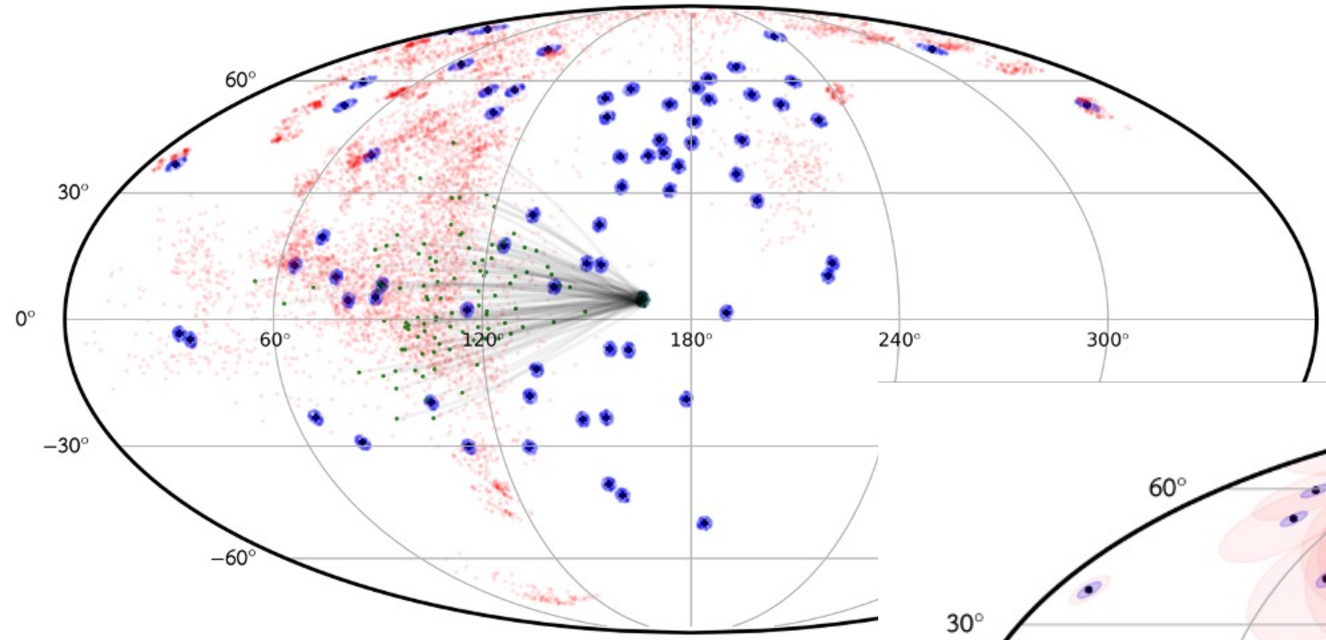
TA 2015 data, proton assumption, JF12



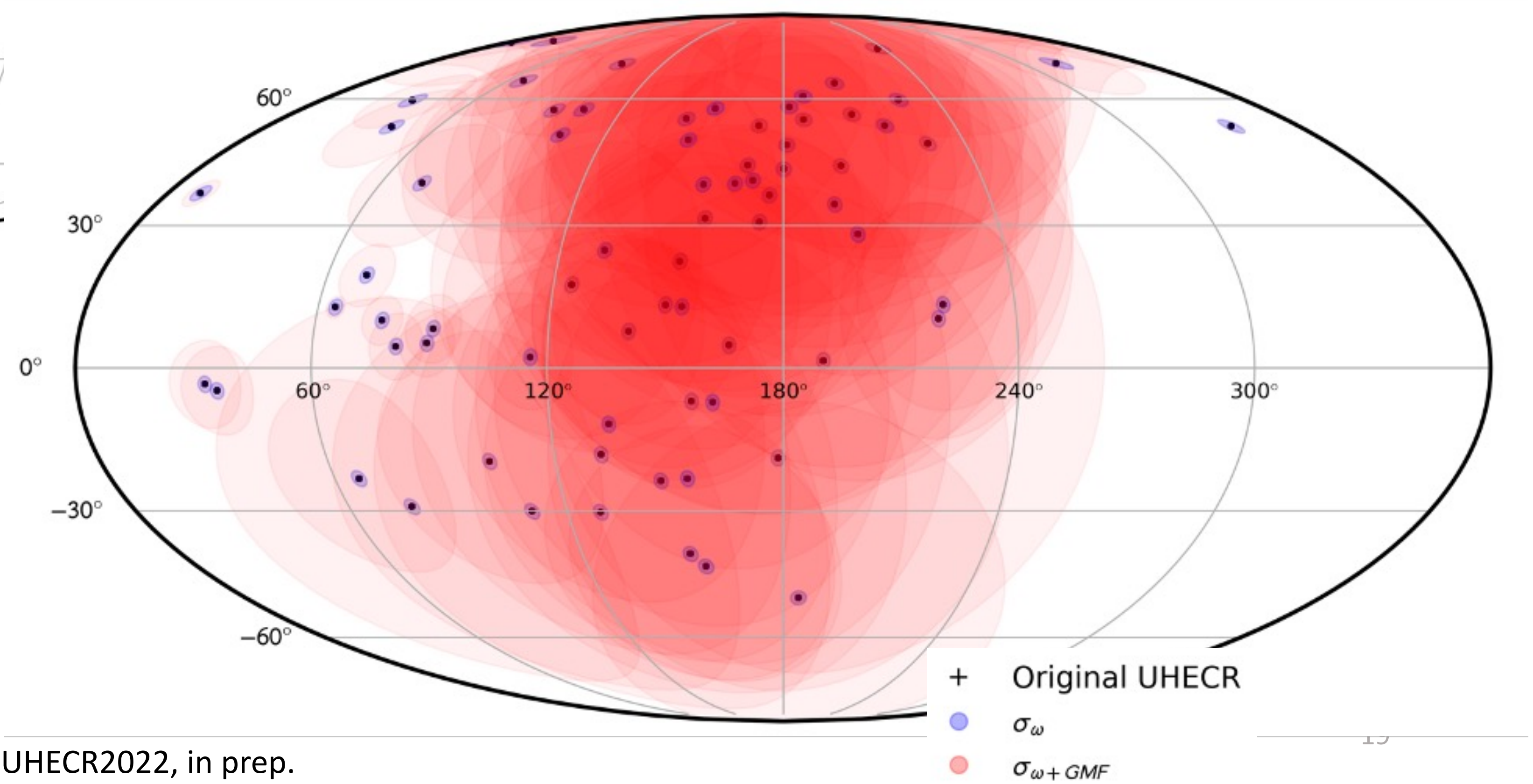


Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

Deflections are anisotropic, individual, energy and composition dependent



TA 2015 data, nitrogen assumption, JF12

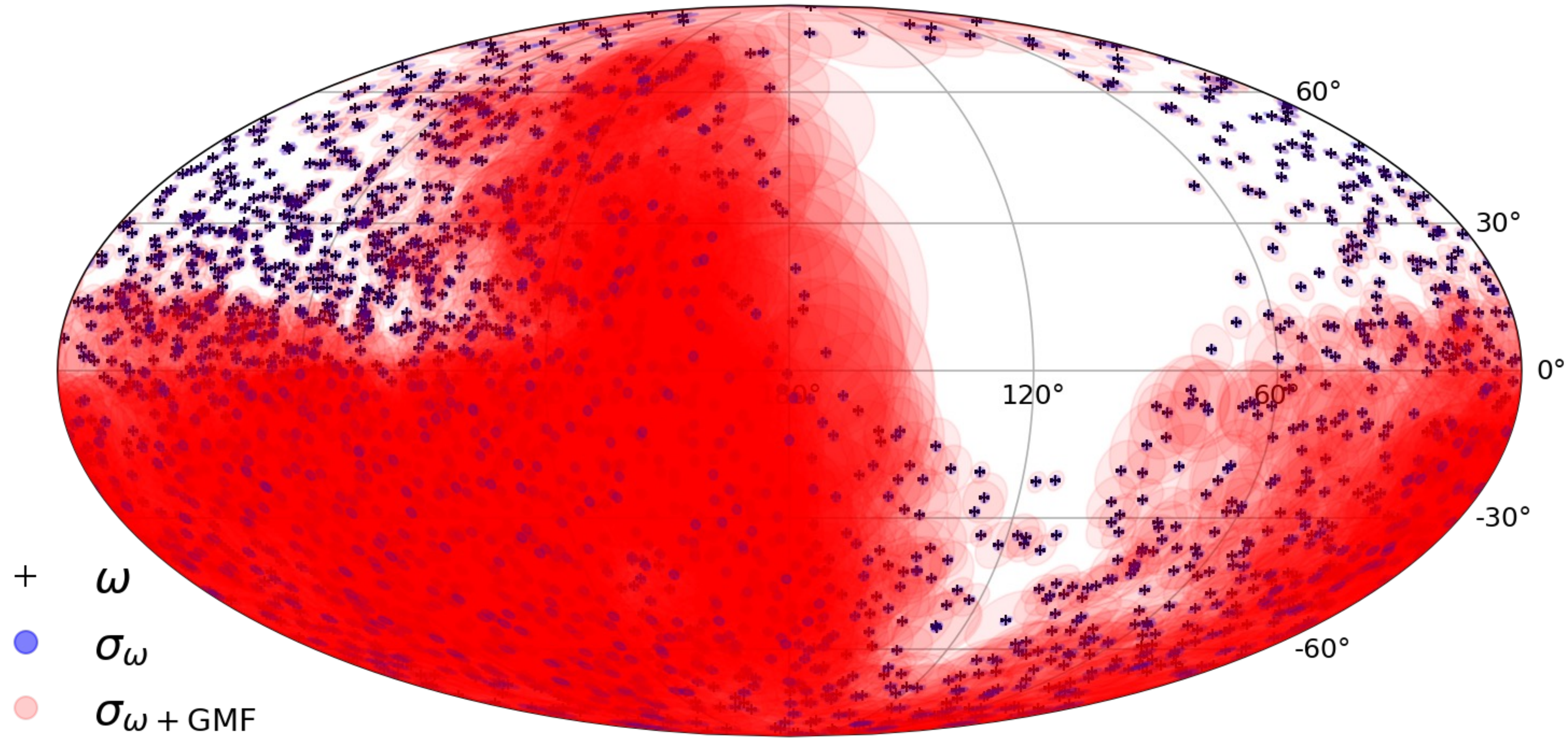


A simple, "circular" is a source of bias

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

Deflections are anisotropic, individual, energy and composition dependent

PAO 2022, proton assumption, JF12

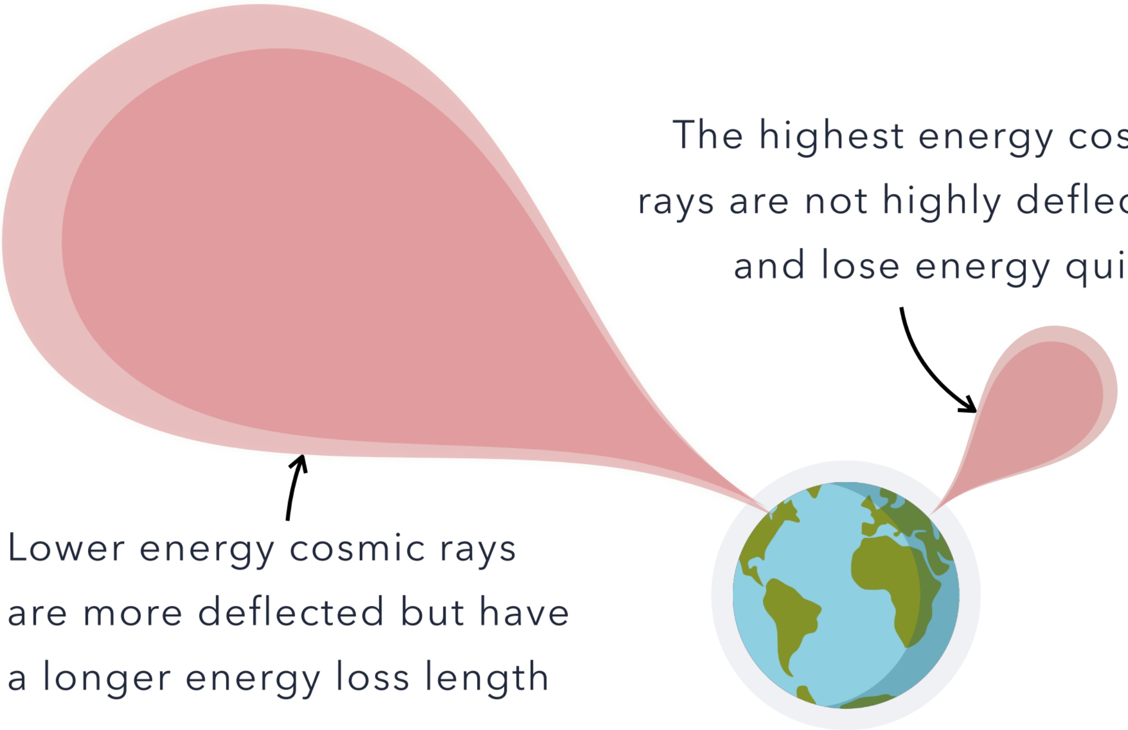


A simple, "circular" search radius is misleading

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

More realism: Bayesian inference and detailed modeling

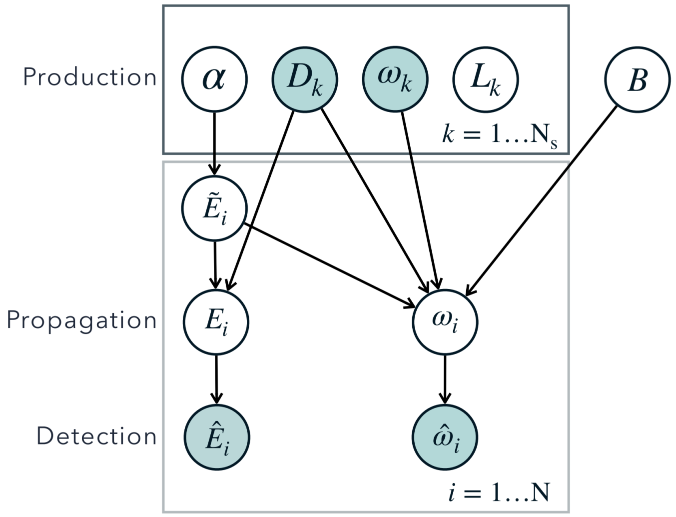
Francesca Capel & Mortlock, 1811.06464



The highest energy cosmic rays are not highly deflected and lose energy quickly

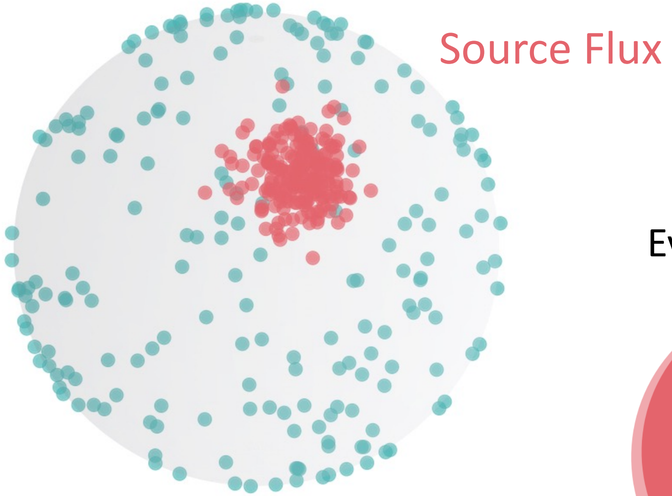
Lower energy cosmic rays are more deflected but have a longer energy loss length

Bayesian Hierarchical Model
(implemented in Python + STAN)



Source fraction:

$$f = \frac{F_s}{F_0 + F_s}$$



Evolution of:

Watson+2012

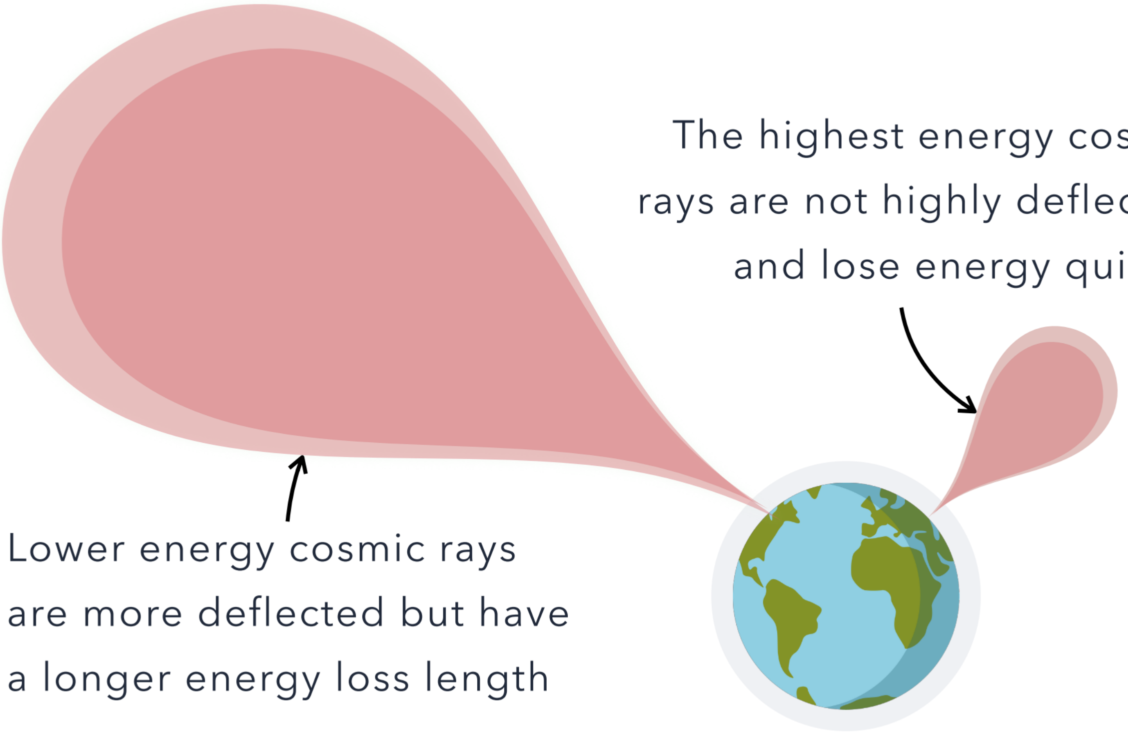
Soiaporn+2013

Khanin+2016

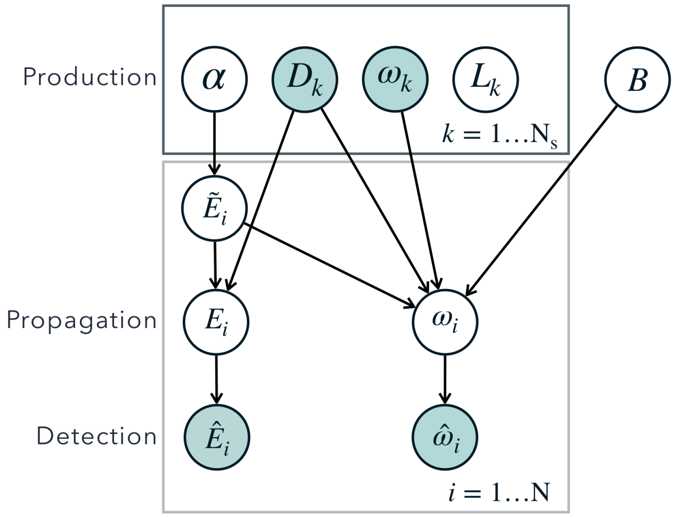
Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

More realism: Bayesian inference and detailed modeling

Francesca Capel & Mortlock, 1811.06464



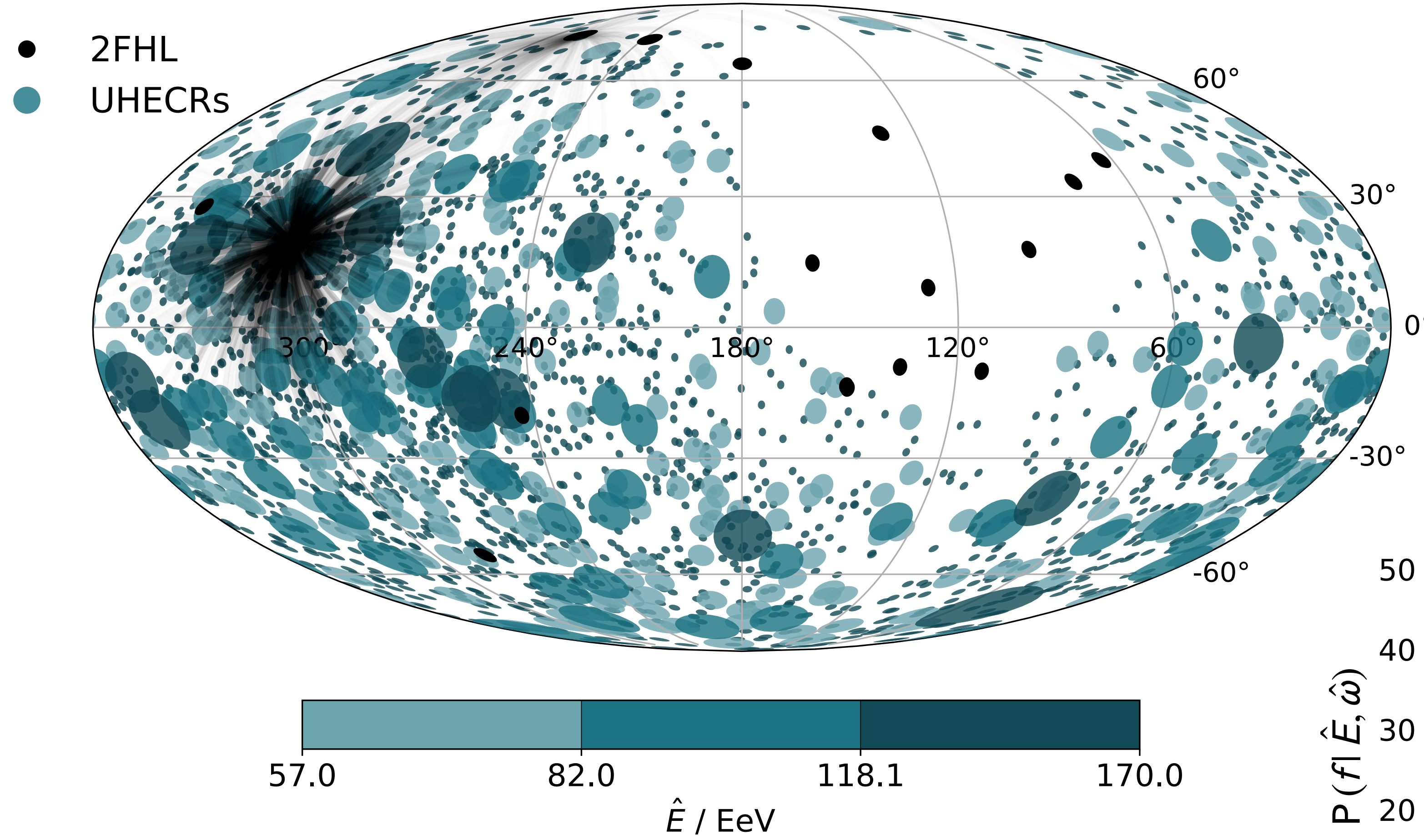
Bayesian Hierarchical Model
(implemented in Python + STAN)



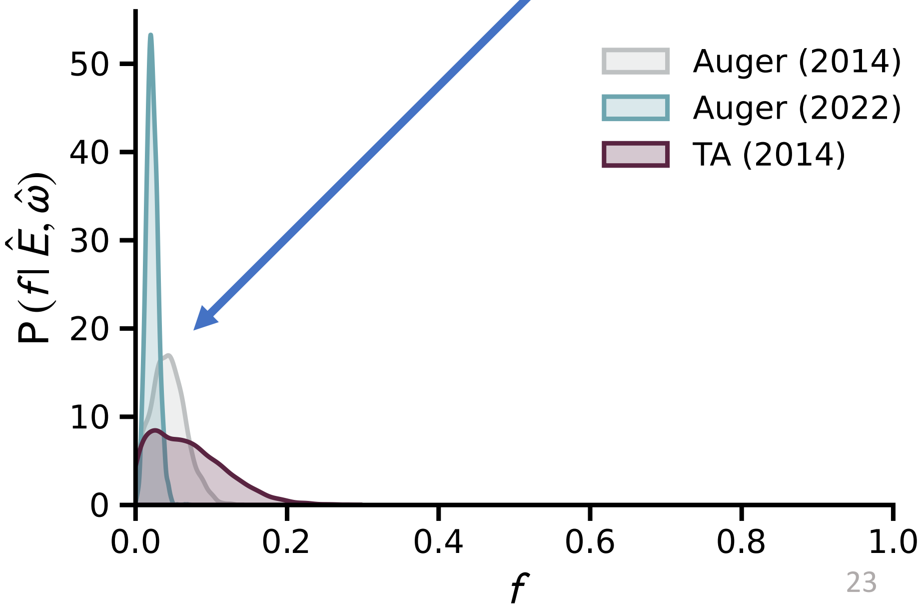
- Fits source associations of each cosmic ray with each source (summing these to obtain the total)
- **Physics model uncertainties** (such as B fields, source spectrum) latent (nuisance) parameters
- Machinery can absorb more realistic models compared to 1811.06464
- "Source fraction" is a catalog search/question, other questions can be asked ☺

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

Are source fraction and catalog searches really the right tool?



- Source association search using **2FHL catalog** < 250 Mpc
- Same physics model as Capel & Mortlock, 2019
  - simple deflection model, no GMF
  - assumes pure proton composition
  - **same per-source luminosity**
- "Clear source" (CenA) by eye but source fraction is small



More at ICRC… stay tuned

Keito Watanabe, Francesca Capel, AF, Hiroyuki Sagawa, UHECR2022, in prep.

This Bayesian inference model solves some conceptual issues

- No need for choosing threshold energy or search radius
  - Too low energy/rigidity events have large deflection radii associated → don’t contribute significantly

- Knowledge about the magnetic field, detector uncertainties etc. can be fed directly into the model

- Tells more than a simple couting excess:
  - Reconstructs source spectrum
  - magnetic field values
  - Etc

- **A simple, model independent, significant result might be a wrong expectation from UHECR research**

- **But if the dominant sources are transients? Not in any of the catalogs? Happened Myrs ago?**

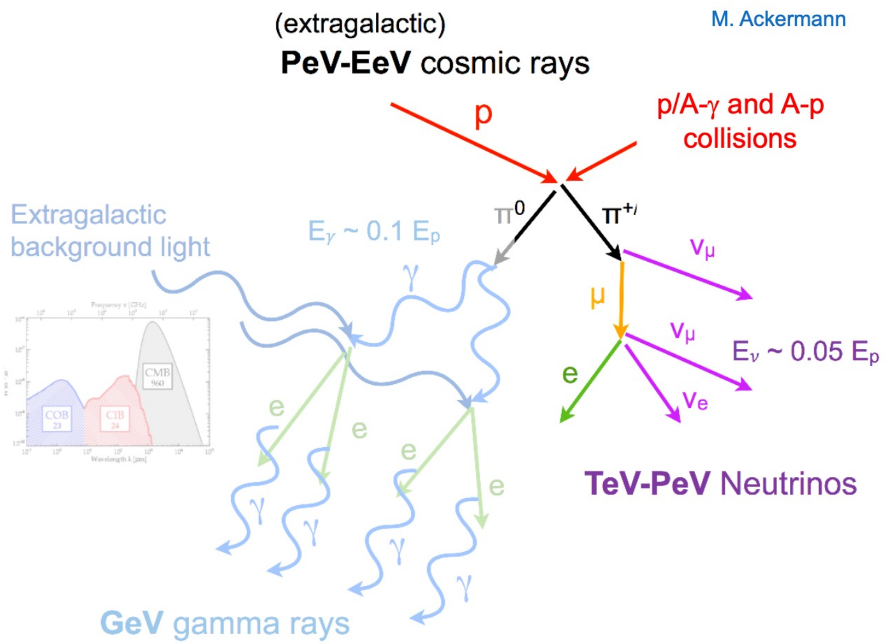
# 3. The EECR horizon
EE = extreme energy >> 100 EeV

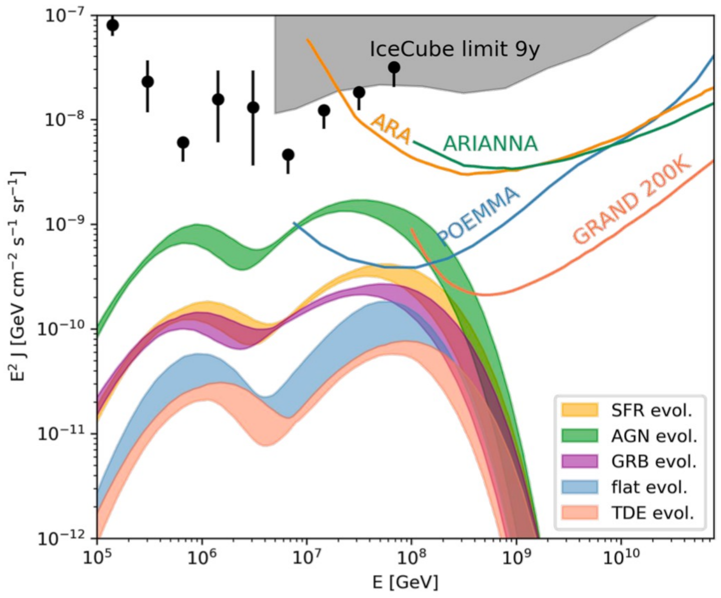
Astrophys. J., 945(1):12, 2023, 2210.15885

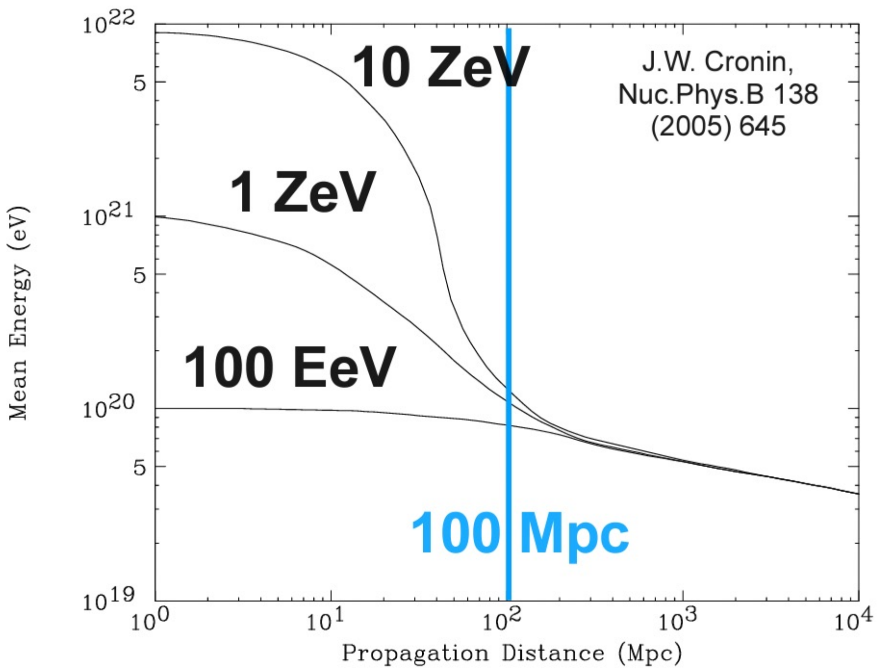
TREASURE MAPS FOR DETECTIONS OF EXTREME ENERGY COSMIC RAYS

Noémie Globus[1,2], Anatoli Fedynitch[3,4], Roger D. Blandford[5,6]

The GZK cutoff K. Greisen, PRL 16 (17): 748–750. (1966), G.T. Zatsepin and V.A. Kuz'min, JETP Letters. 4: 78–80 (1966)







$$p + \gamma_{\rm CMB} \to p + \pi^0 \to p + \gamma\gamma, \text{ and}$$
$$p + \gamma_{\rm CMB} \to n + \pi^+ \to p + \nu_{e,\mu}.$$

For Protons - expect
- cosmogenic neutrinos
- cosmogenic photons
- distant horizon

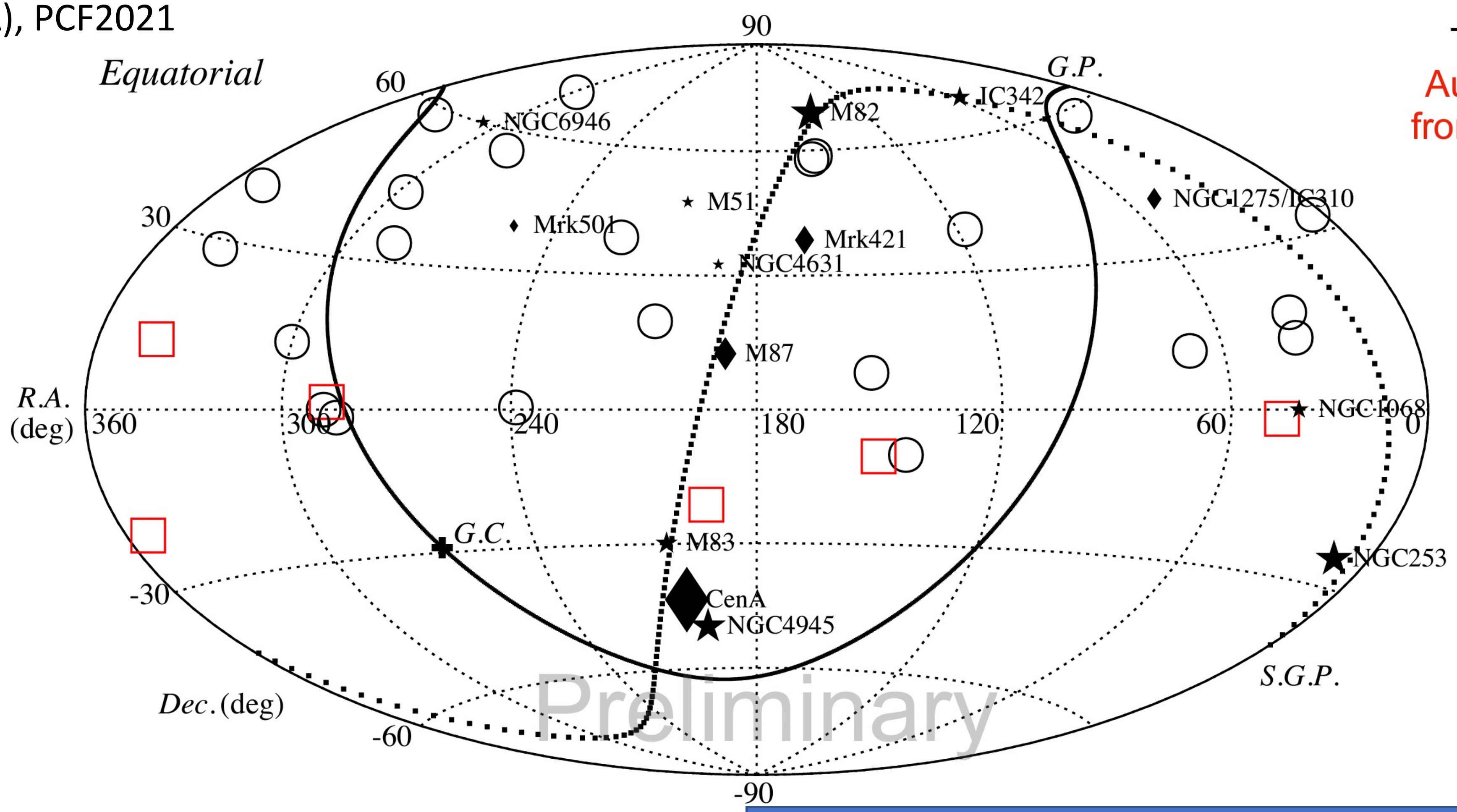
For nuclei - expect:
- disintegration via Giant Dipole Resonance
- fewer secondary messengers
- shorter horizon

Sky should become anisotropic!

UHECR sky > 100 EeV

T. Fujii, (TA), PCF2021

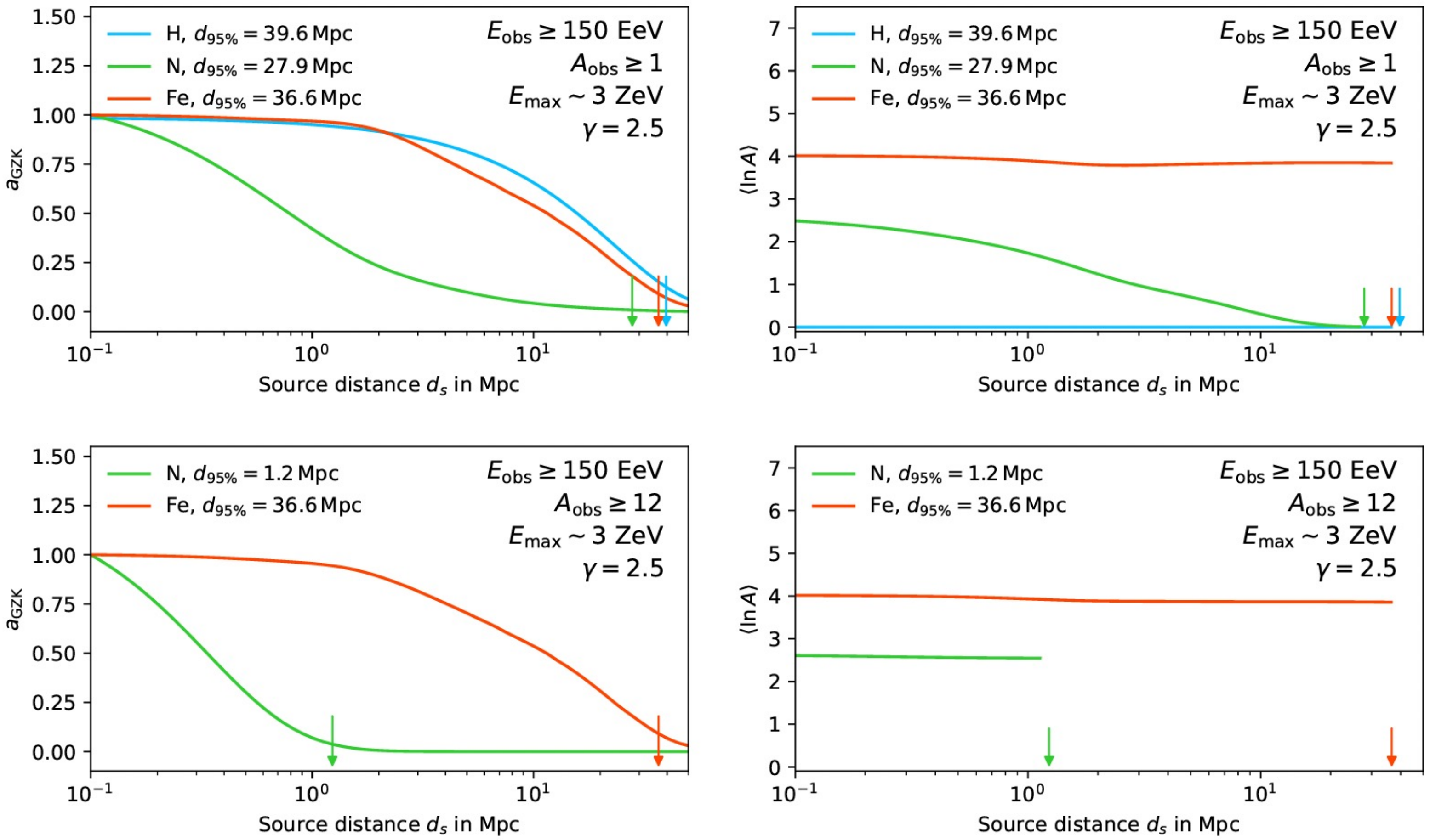
TA 11 years,
Auger 10 years
from ApJ, 804:15
(2015)



Highest energy observed by TA
~220 EeV! (UHECR snowmass)

Almost isotropic, no clustering, no obvious source associations & no ~EeV neutrinos → **TRANSIENTS??**

The EECR horizon for nuclei for E_{obs} > 150 EeV



Assume a source spectrum:

$$\frac{dN_s}{dE_s}(E_s, E_{s,\min}, E_{s,\max}) \propto \left(\frac{E_s}{E_{s,\min}}\right)^{-\gamma} e^{-\frac{E_s}{E_{s,\max}}}, E_s > E_{s,\min}$$

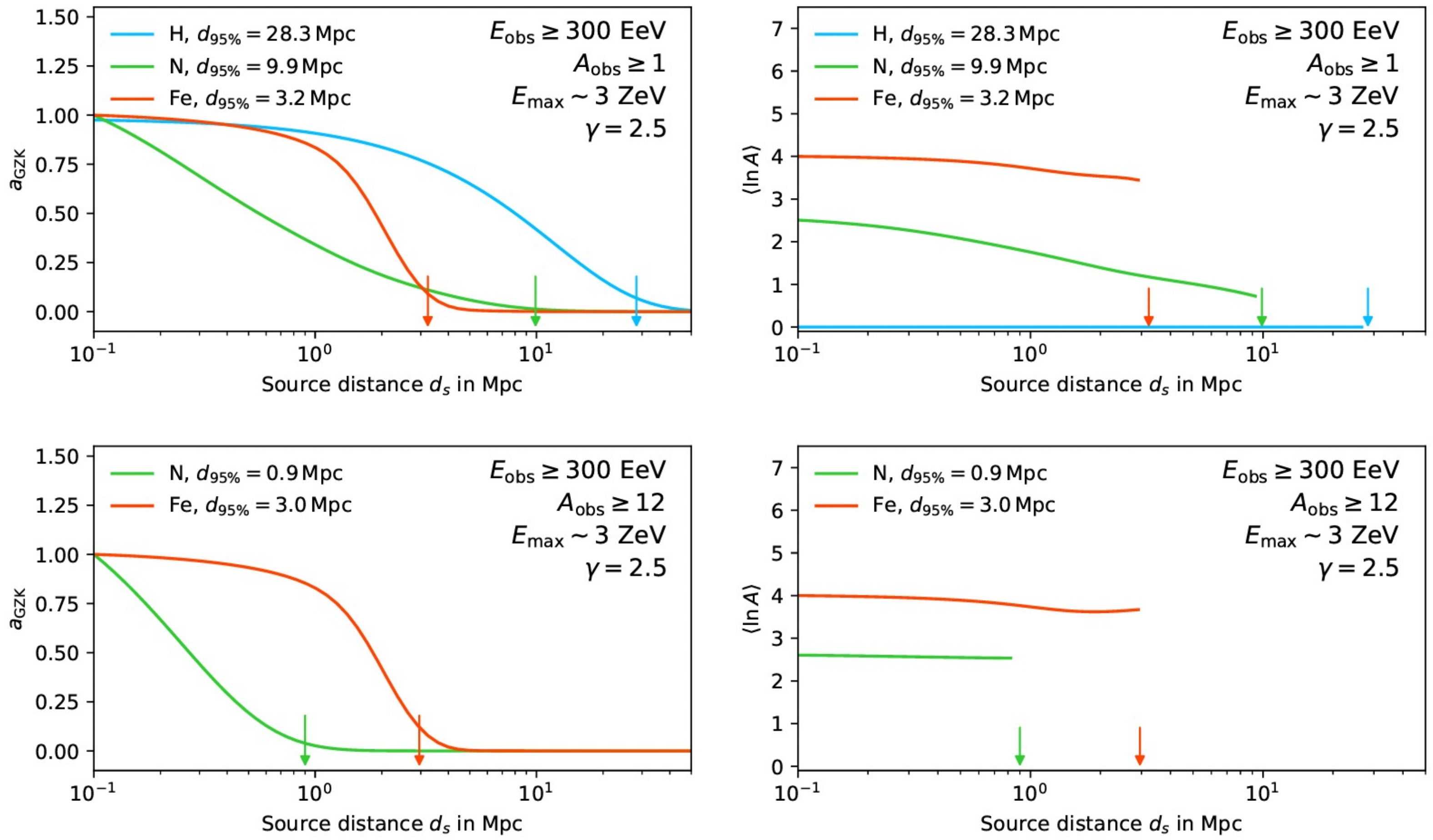
Loss of number in spectrum at Earth (dT/dE):

$$a_{\rm GZK}(A_s, d_s, E_{s,\max}, \gamma \mid A_{\rm obs}, E_{\rm obs}) = = \frac{\sum_{A_i \geq A_{\rm obs}} \int_{E_{\rm obs}}^{\infty} dE \frac{dT_{A_i}}{dE}(d_s, \gamma, E_{s,\max})}{\int_{E_{\rm obs}}^{\infty} dE_s \frac{dN_s}{dE_s}(E_s, E_{s,\max})}$$

Weak dependence on source spectrum choice for p & Fe. Stronger for Nitrogen.

Define 2x2 cases:
- Threshold E_{obs} = 150 EeV and 300 EeV
- Mass threshold A_{obs} = 1 (everything) or 12 carbon → composition sensitive observatory

The EECR horizon for nuclei for E_{obs} > 300 EeV



Assume a source spectrum:

$$\frac{dN_s}{dE_s}(E_s, E_{s,\min}, E_{s,\max}) \propto \left(\frac{E_s}{E_{s,\min}}\right)^{-\gamma} e^{-\frac{E_s}{E_{s,\max}}}, E_s > E_{s,\min}$$

Loss of number in spectrum at Earth (dT/dE):

$$a_{GZK}(A_s, d_s, E_{s,\max}, \gamma \mid A_{obs}, E_{obs}) = \frac{\sum_{A_i \geq A_{obs}} \int_{E_{obs}}^{\infty} dE \frac{dT_{A_i}}{dE}(d_s, \gamma, E_{s,\max})}{\int_{E_{obs}}^{\infty} dE_s \frac{dN_s}{dE_s}(E_s, E_{s,\max})}$$

Weak dependence on source spectrum choice for p & Fe. Stronger for Nitrogen.

GZK horizon for nuclei few MpC, for protons still ~30 Mpc → we can control the horizon by choosing the thresholds!

4. What can we expect to find in our neighborhood using EECR?

Following arxiv: 2210.15885

TREASURE MAPS FOR DETECTIONS OF EXTREME ENERGY COSMIC RAYS

Noémie Globus[1,2], Anatoli Fedynitch[3,4], Roger D. Blandford[5,6]

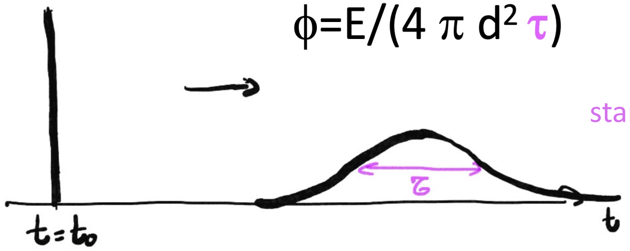
Define "find": Looking for multiplet candidates (simplicity)

Isotropic energy required to produce a EECR doublet at Earth

$$U_{\mathrm{iso},2} \sim 4.38 \cdot 10^{52} \mathrm{erg}\, (\tau_d / 10^3 \mathrm{yr}) d_{50}^2\, E_{200} (\mathcal{E}/\mathcal{E}_{\mathrm{PAO}})^{-1} a_{\mathrm{GZK}}^{-1} M^{-1} n_{\mathrm{yr}}^{-1}$$

The GMF and EGMF introduce a **temporal dispersion** (spread of the time delays distribution)

$\phi = E/(4\pi d^2 \tau)$



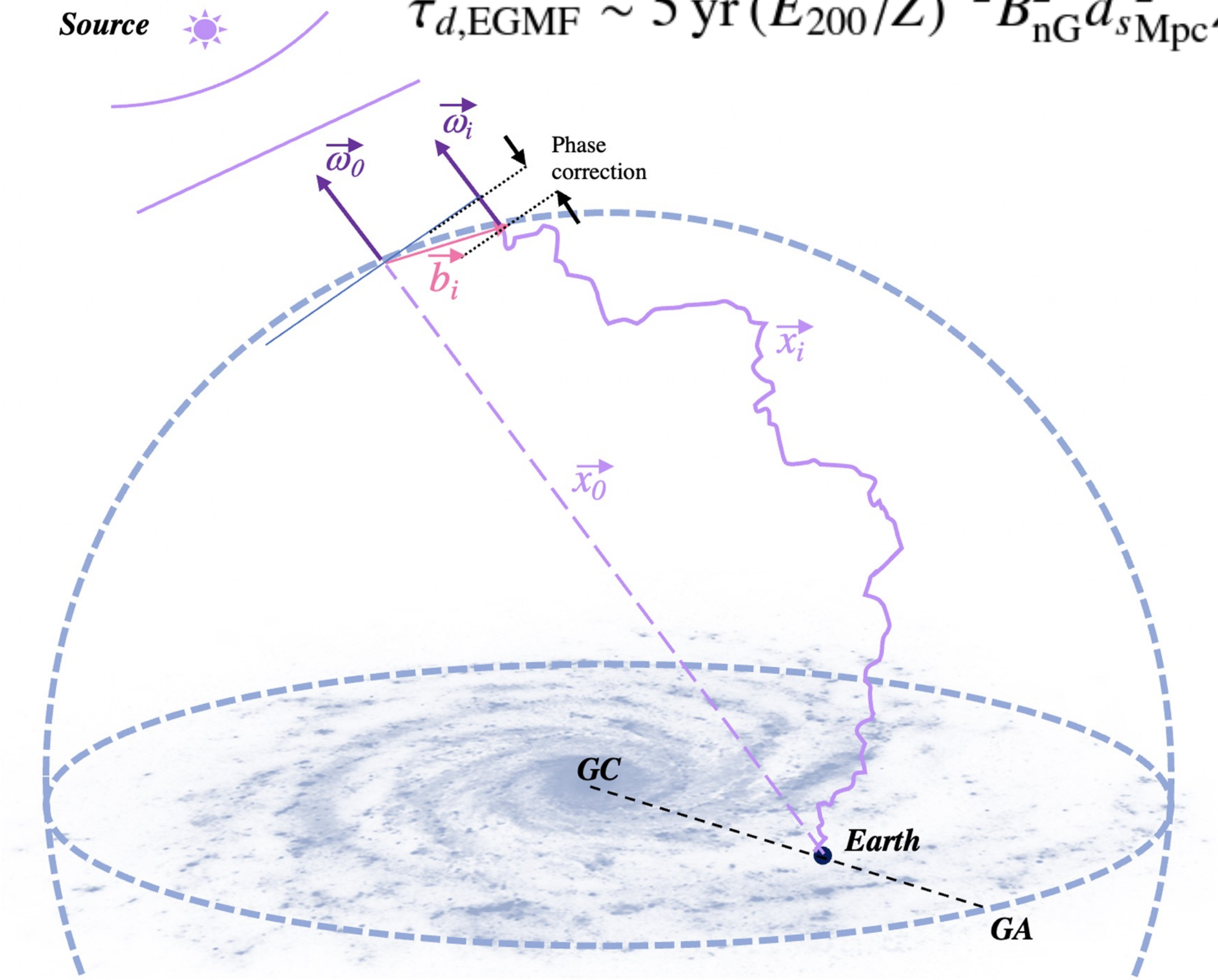
standard deviation

$$\tau_{d,\mathrm{EGMF}} \sim 5\,\mathrm{yr}\, (E_{200}/Z)^{-2} B_{\mathrm{nG}}^2 d_{s\,\mathrm{Mpc}}^{\;2} \lambda_{\mathrm{Mpc}}$$

$$\tau_{d,\mathrm{GMF}} = \sqrt{\frac{1}{N} \sum_i (t_i^2 - \mu^2)}$$

Geometric setup and correction (important when considering times)

$$\tau_{d,\mathrm{EGMF}} \sim 5\,\mathrm{yr}\,(E_{200}/Z)^{-2} B_{\mathrm{nG}}^2 d_{s\,\mathrm{Mpc}}^{\,2} \lambda_{\mathrm{Mpc}}$$



Correct for curvature of sampling sphere

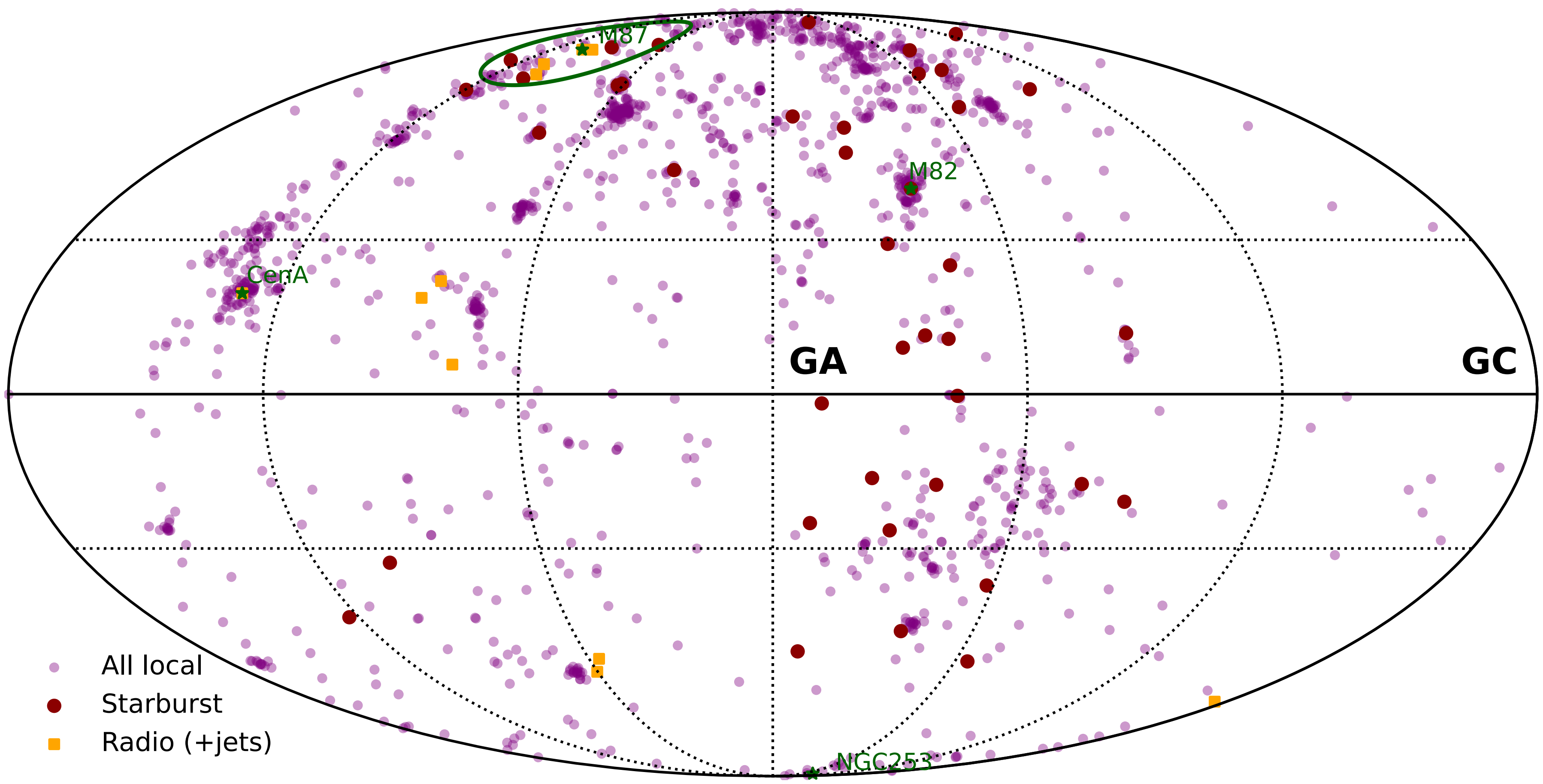
$$t_i = \vec{\omega_0} \cdot \vec{b}_i / c + t_{\mathrm{trajectory},i}$$

Simulation setup:

- Lots of CRPropa3 for galactic transport (backtracking) 5e8 per setup
- Extragalactic: analytical
- JF12(Planck) and TF17 magnetic fields
- Use Healpix with NSIDE=64, 1.7deg pixels
- **Thanks to all open source authors!!**

Total time dispersion (= loss of luminosity!) $\sqrt{\tau_{d,\mathrm{GMF}}^2 + \tau_{d,\mathrm{EGMF}}^2}$

Potential transient host galaxies → ALL GALAXIES



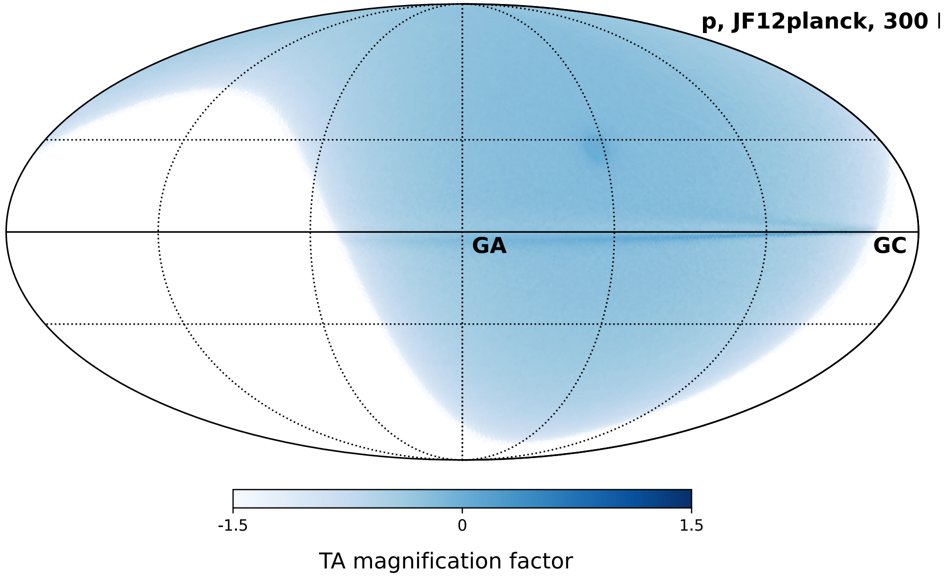
LVG, Karachetsev et al.
https://www.sao.ru/lv/lvgdb/introduction.php

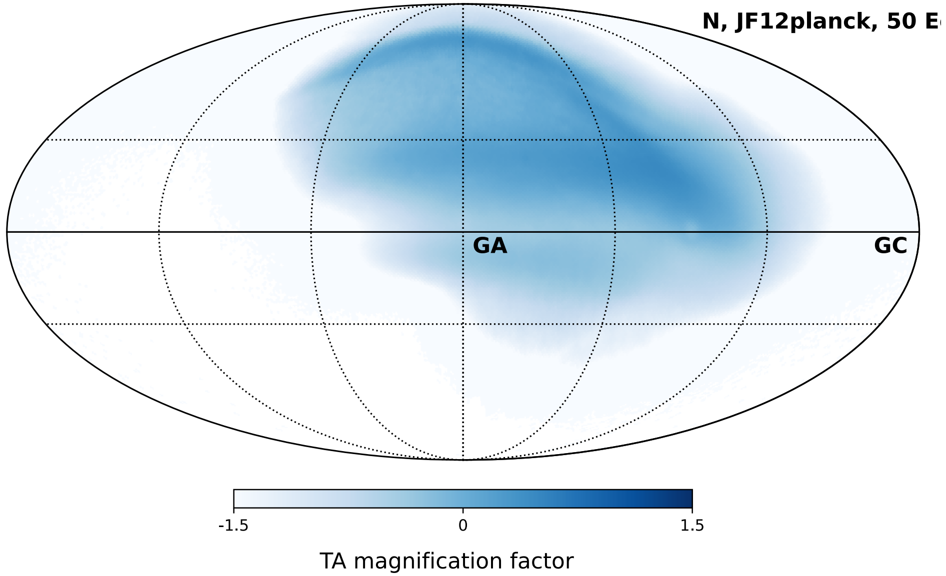
Local volume galaxies within: 2, 5, 10 ,20, 40 Mpc radius

Magnification Factors: North vs South

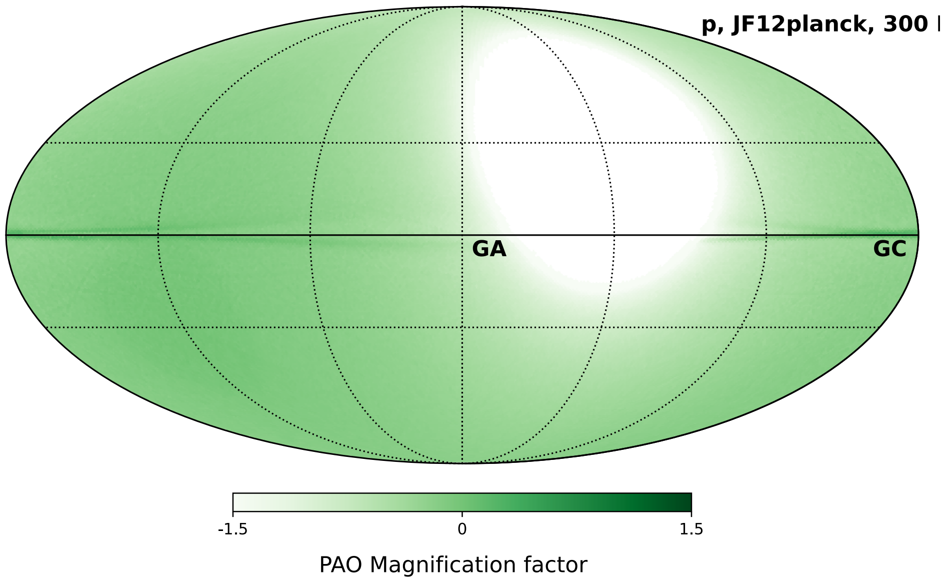
Pixels can be magnified and demagnified through magnetic lensing. Watch out the log scale!

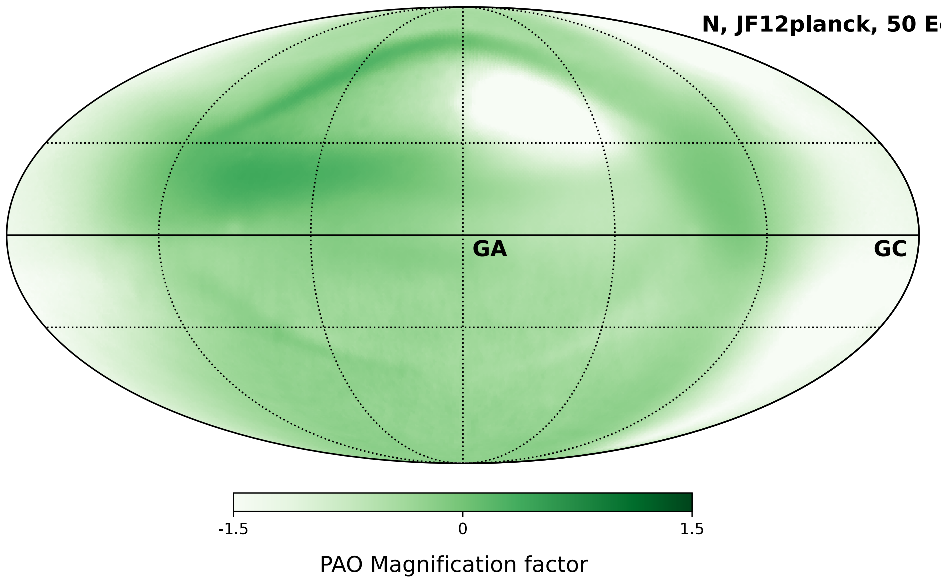
Telescope Array Exposure



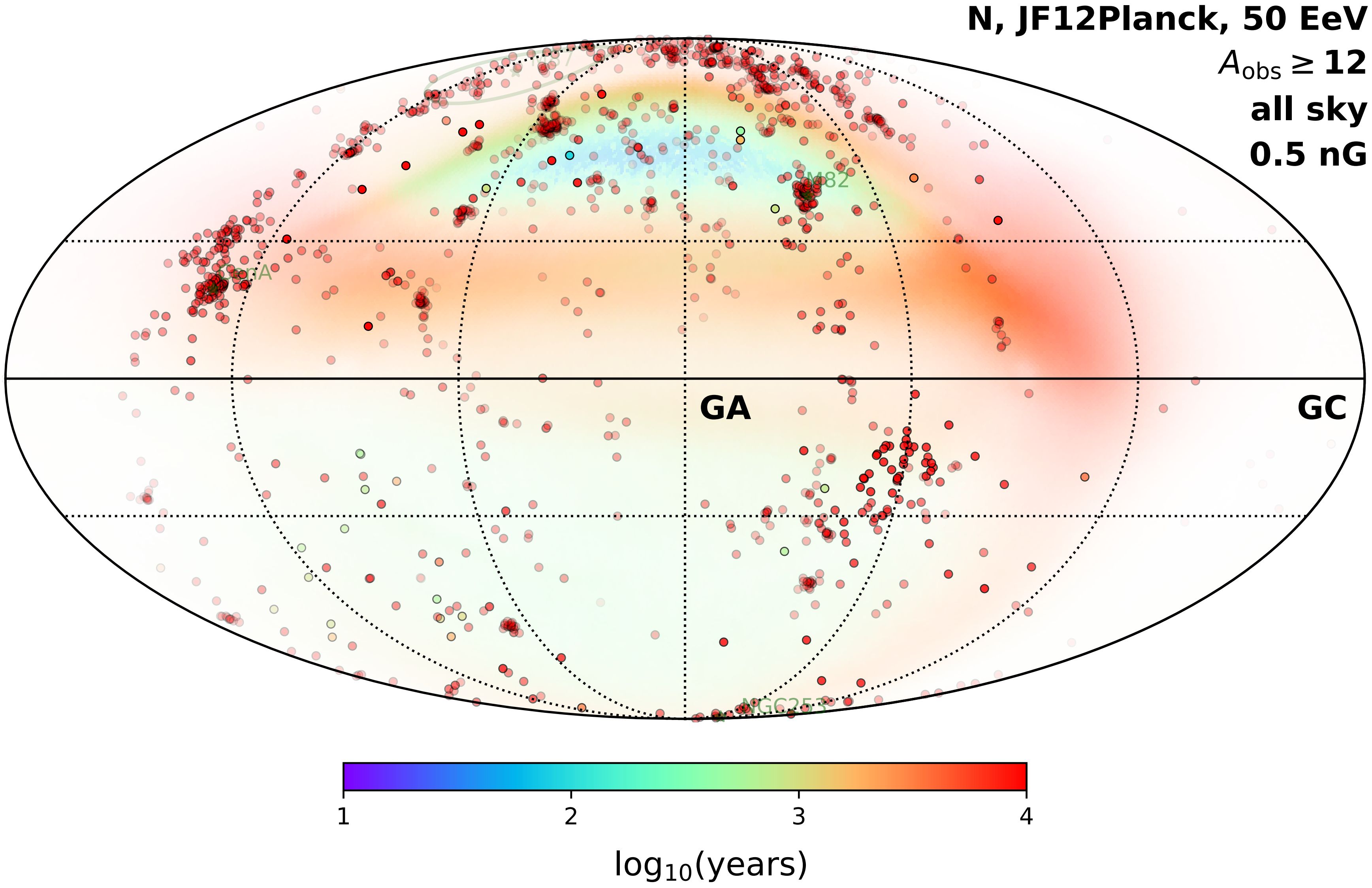


Pierre Auger Exposure





A treasure map (TM)



Transparency = magnification factor (exposure)

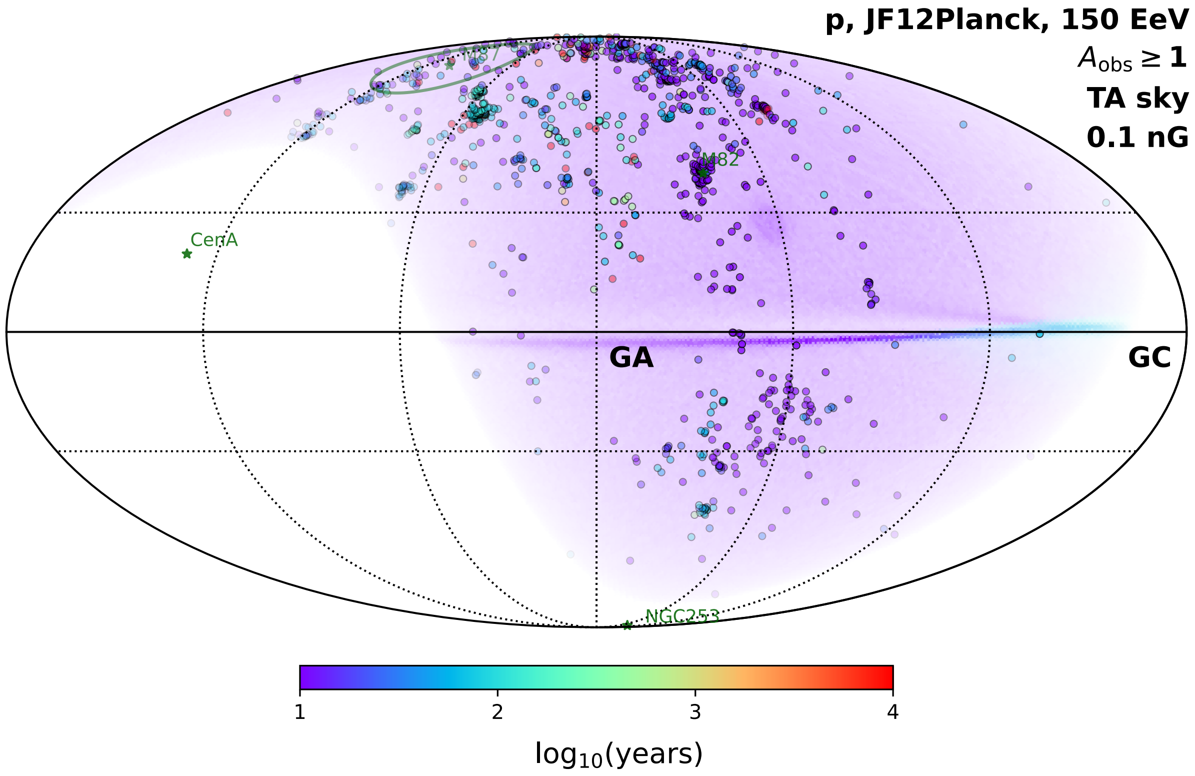
Background color: temporal dispersion due to GMF

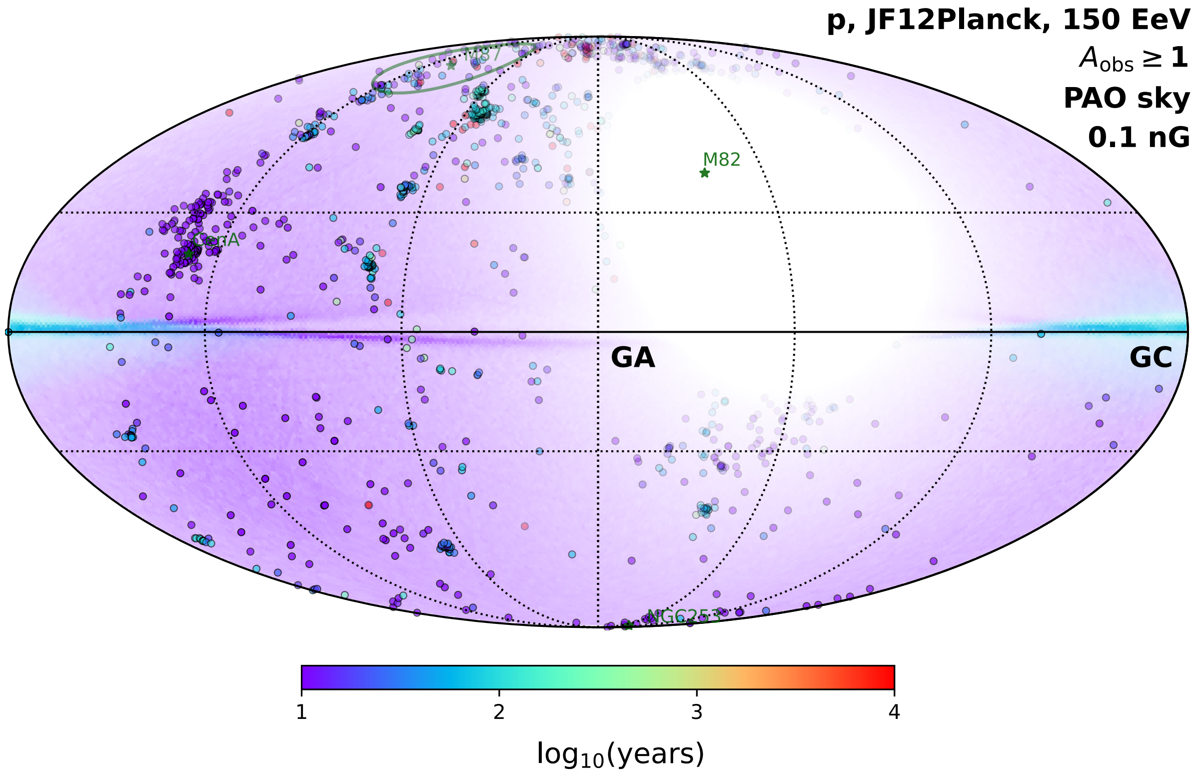
Markers: local galaxy catalog

Marker color: dispersion in GMF + EGMF in yrs (log scale)

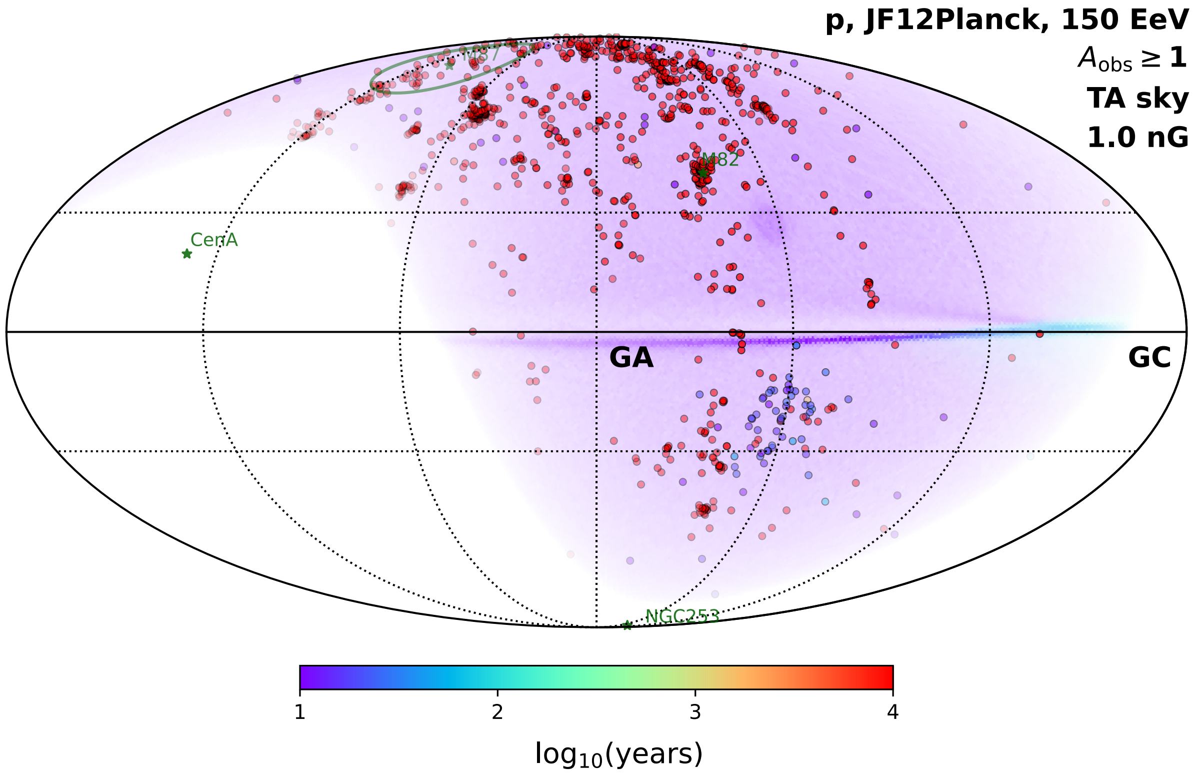
Dot trasparency: GZK horizon (sources fade out and not shown > $d_{95\%}$)

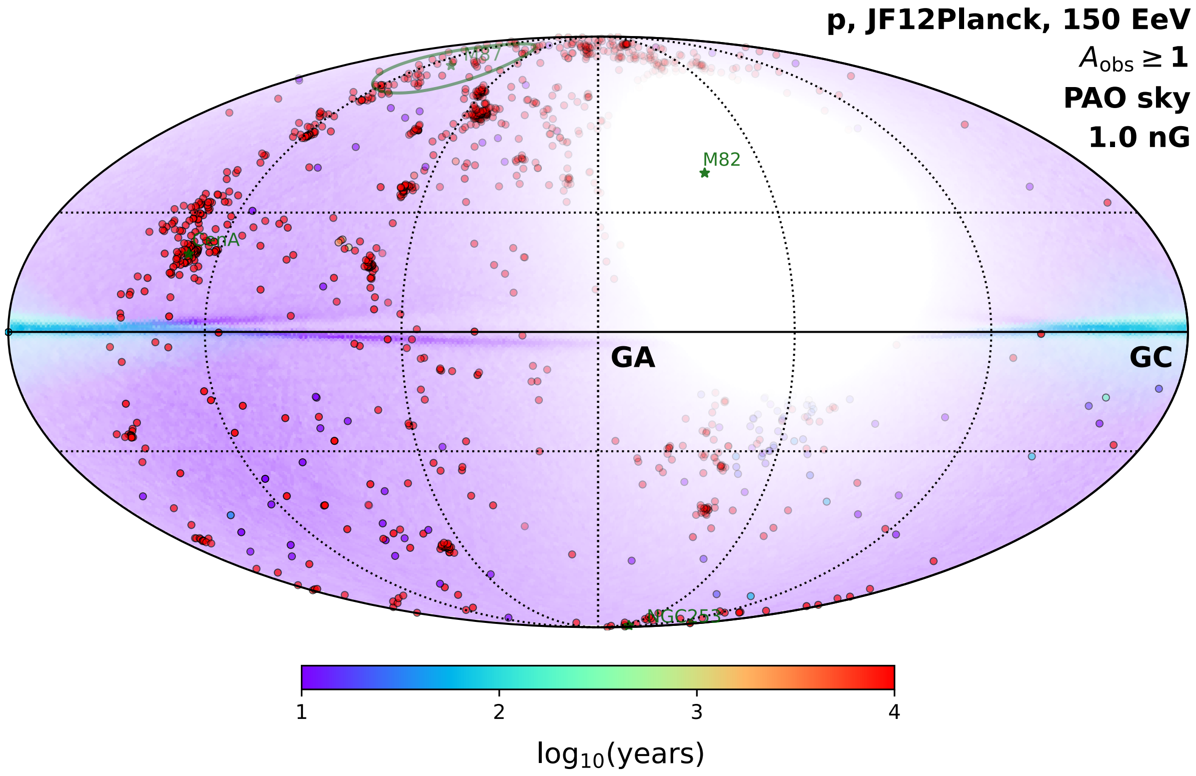
TMs for **protons** JF12 magnetic fields, <B_{EGMF}> = 0.1 nG



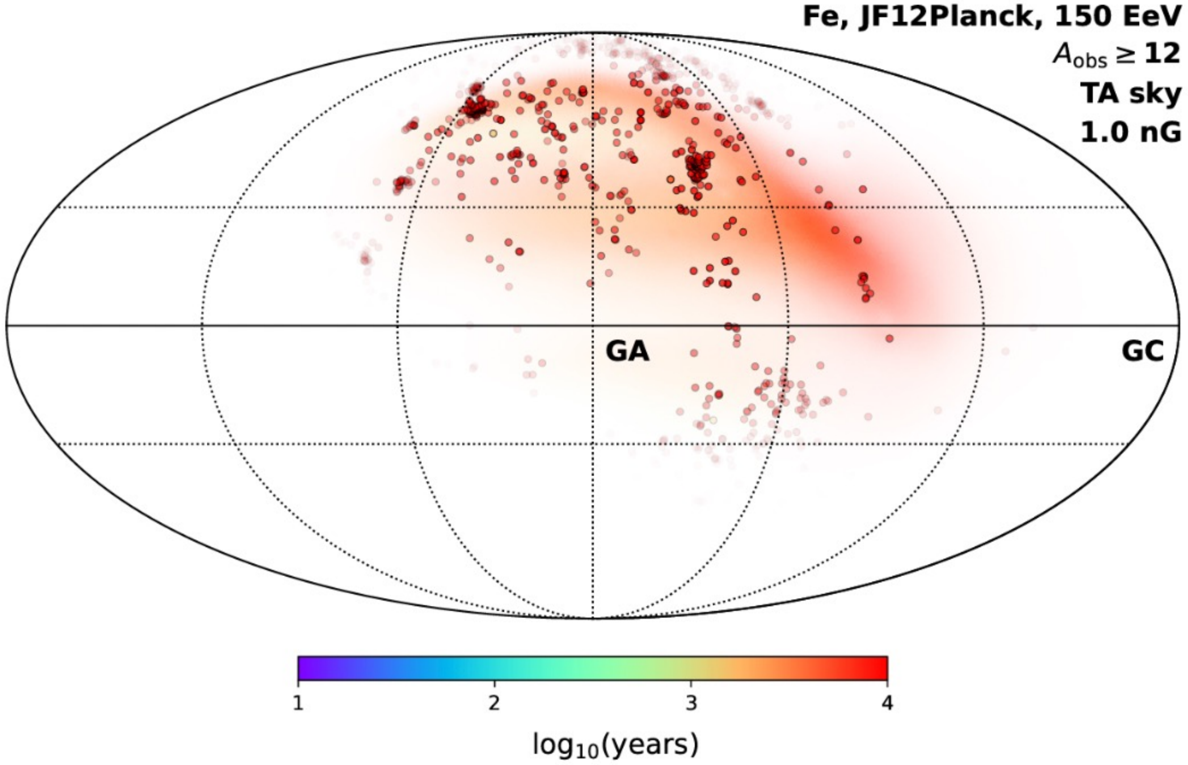


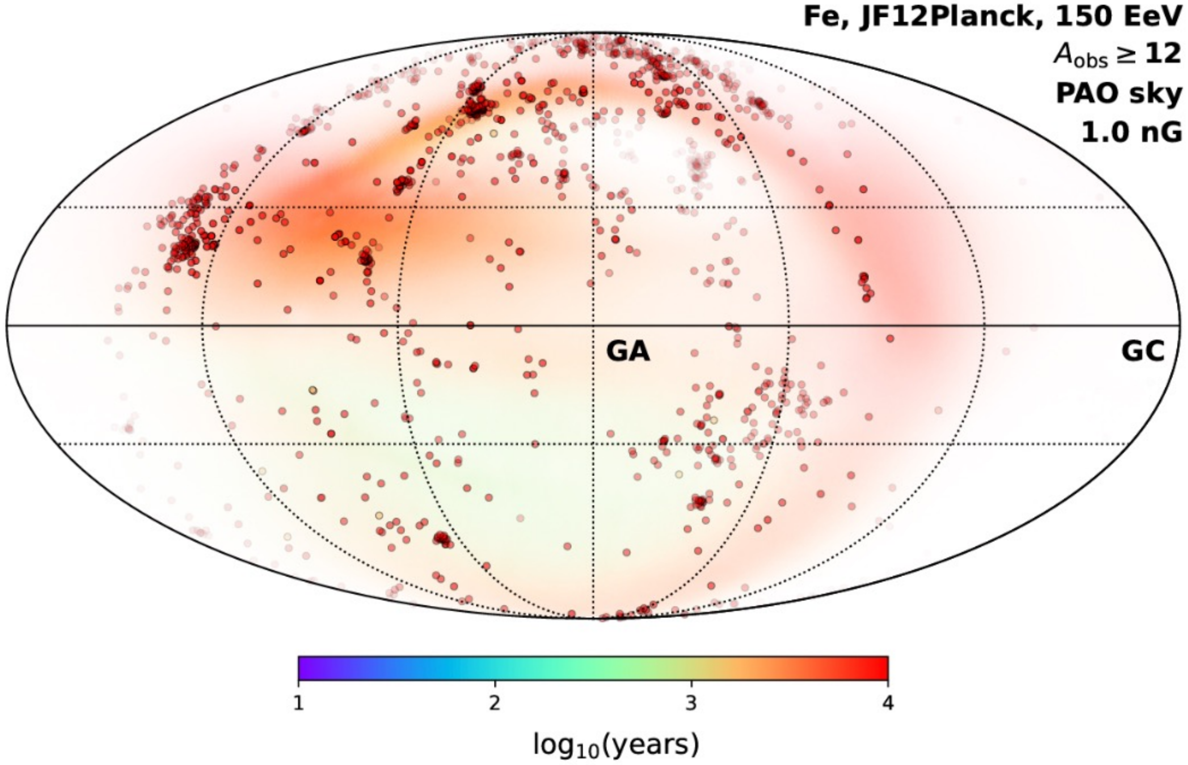
TMs for **protons** JF12 magnetic fields, <B_{EGMF}> = 1 nG



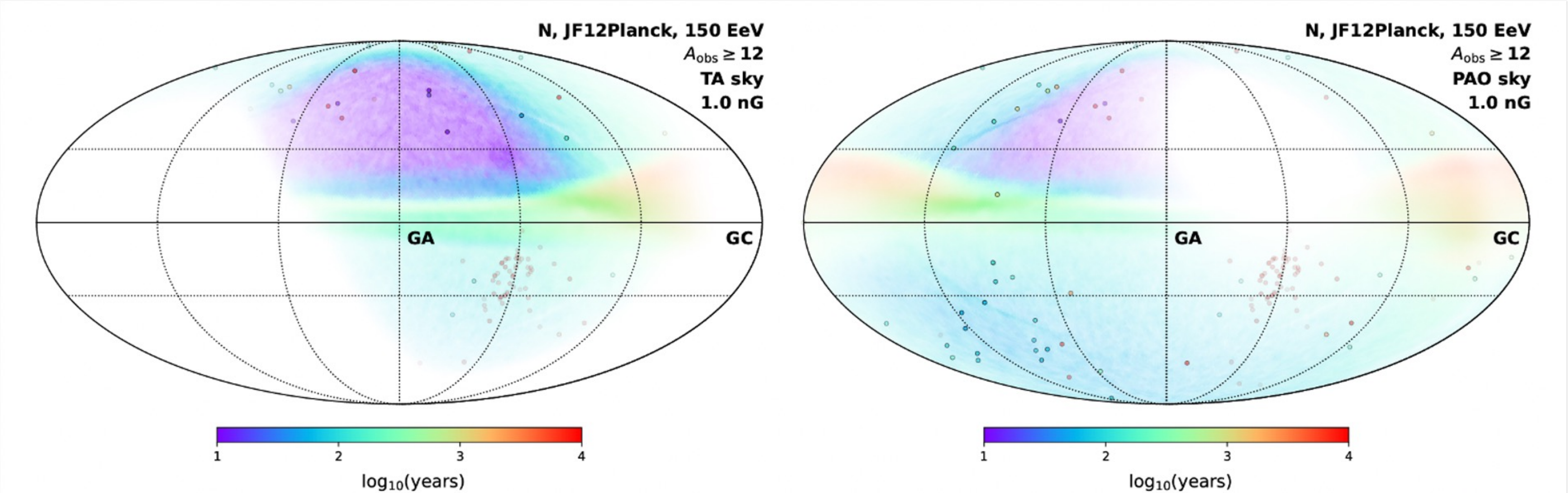


TMs for **iron** JF12 magnetic field, <B_{EGMF}> = 1.0 nG

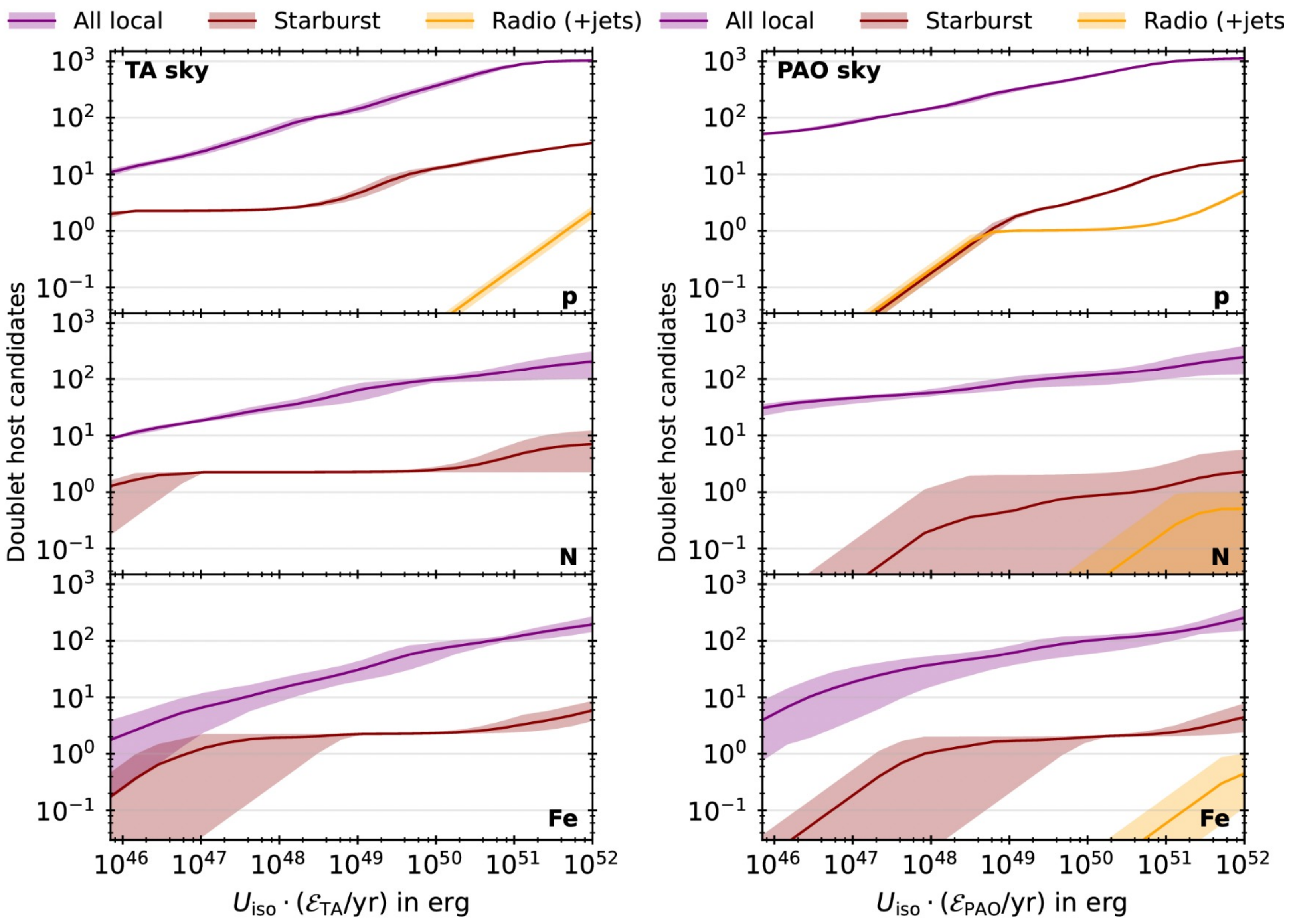




TMs for **nitrogen** JF12 magnetic field, $\langle B_{EGMF} \rangle$ = 1.0 nG



Counting the candidates



Including the effect of the:

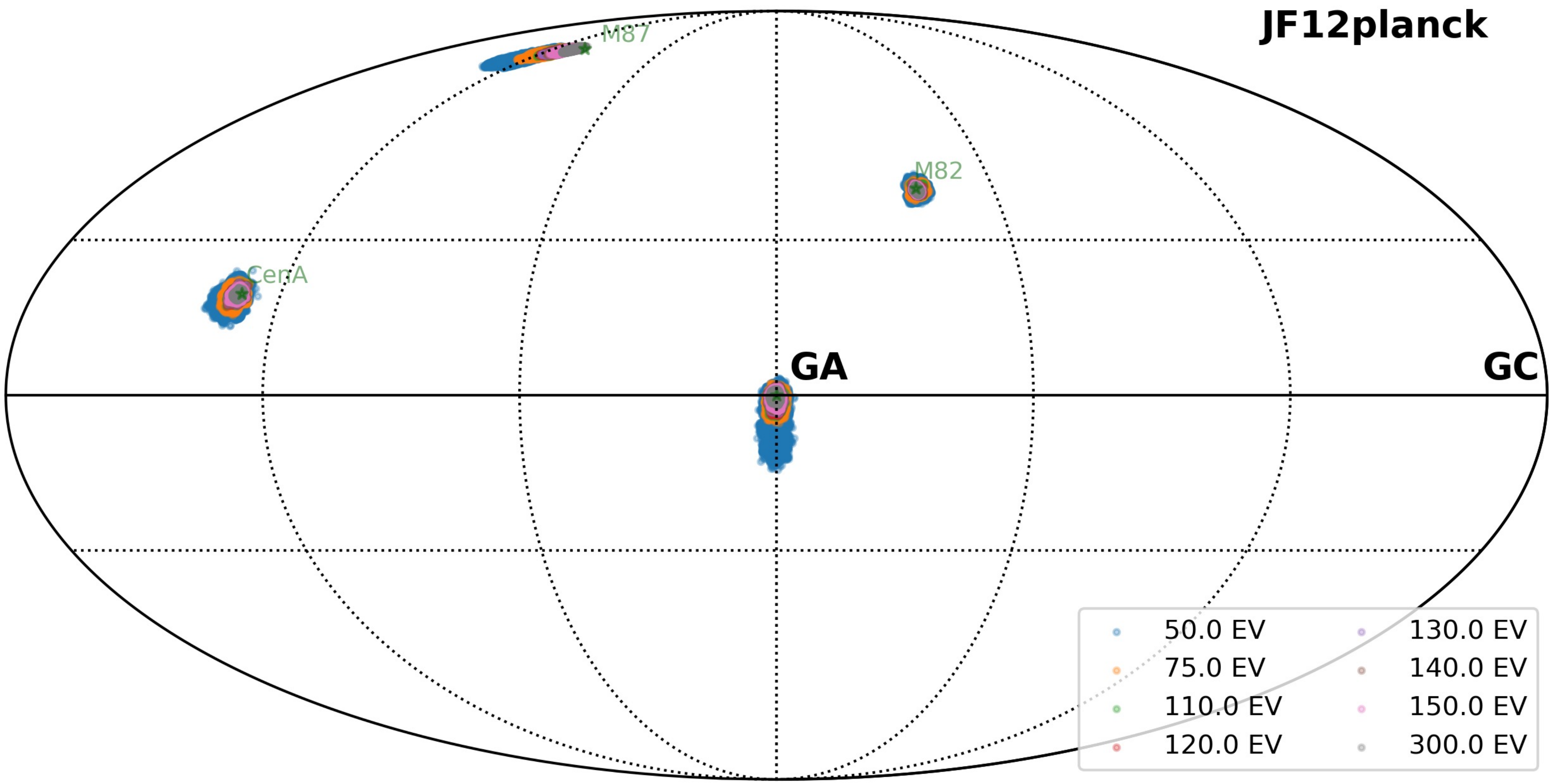
- The dispersion in GMF + EGMF (0.1 -10 nG)
- The 2x2 cases of A_{obs} and E_{obs}
- The GZK horizon
- The magnification factors

→ There are EECR source cadidates remaining

→ Comparing with volume-averaged GRB, TDE, … rates, no statistically guaranteed observation

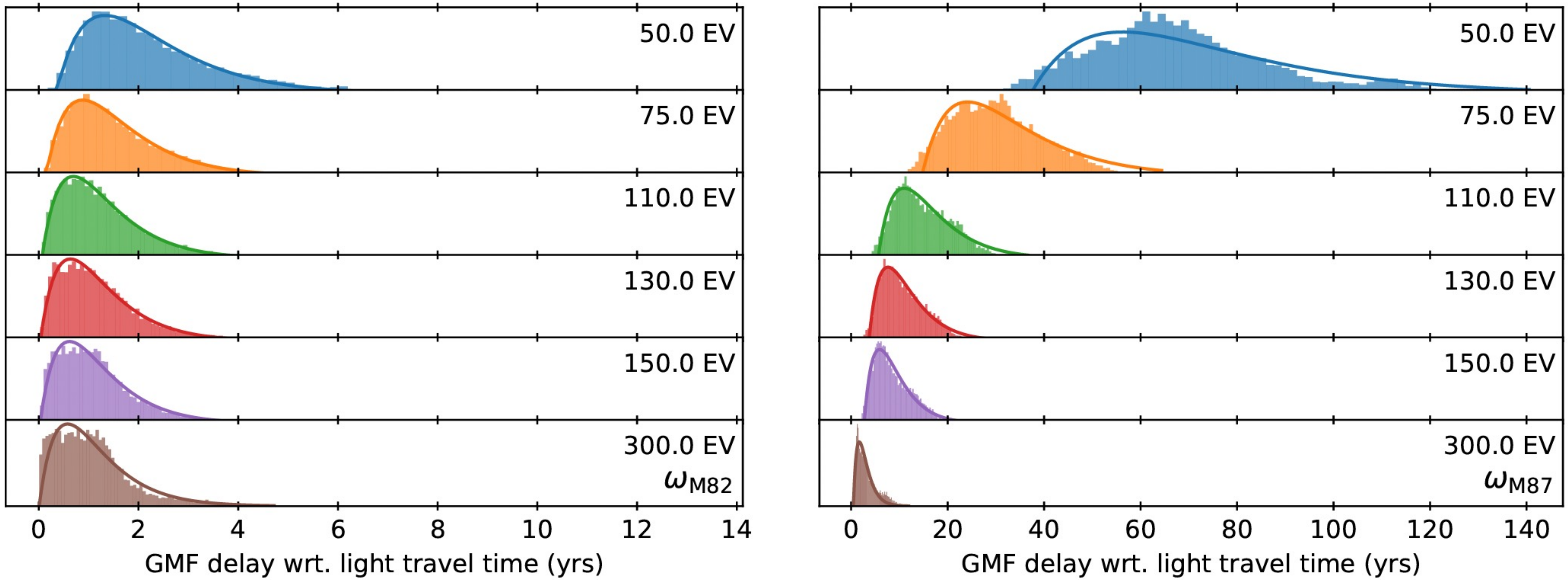
→ Radio-bright/jetted sources ~far away, transient luminosity suppressed

EECR transient spatial signature



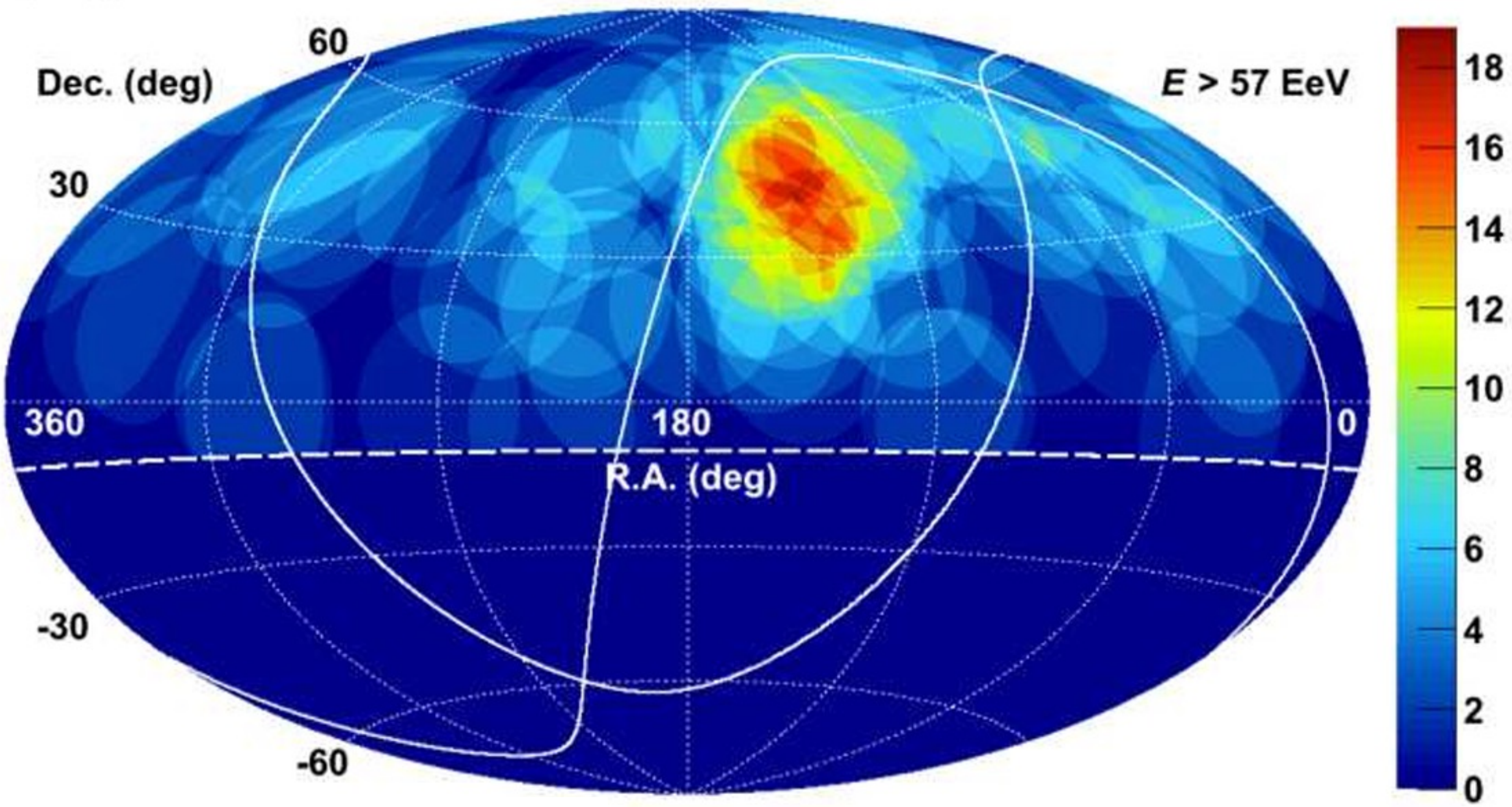
At very high **rigidity**, deflections are “under control”

EECR transient temporal signature



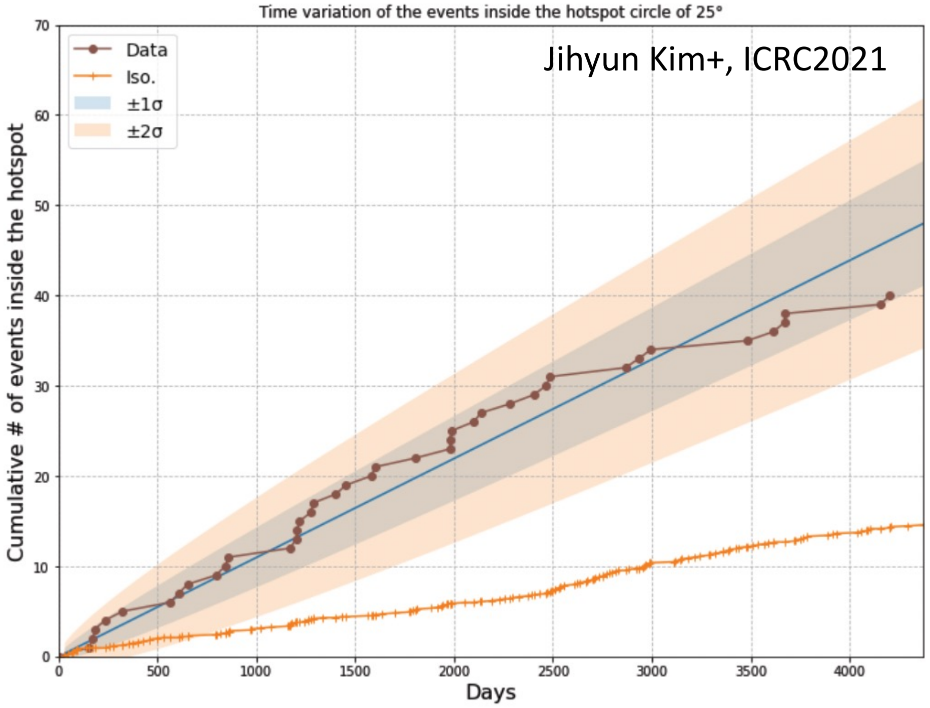
We expect strict ordering of cosmic ray arrival rigidities from the same source due to random deflections

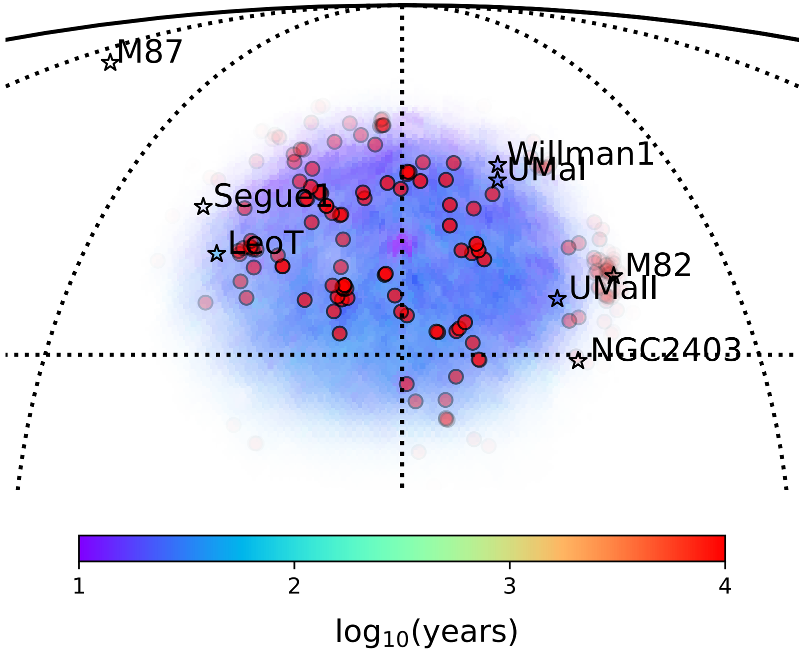
The TA hotspot



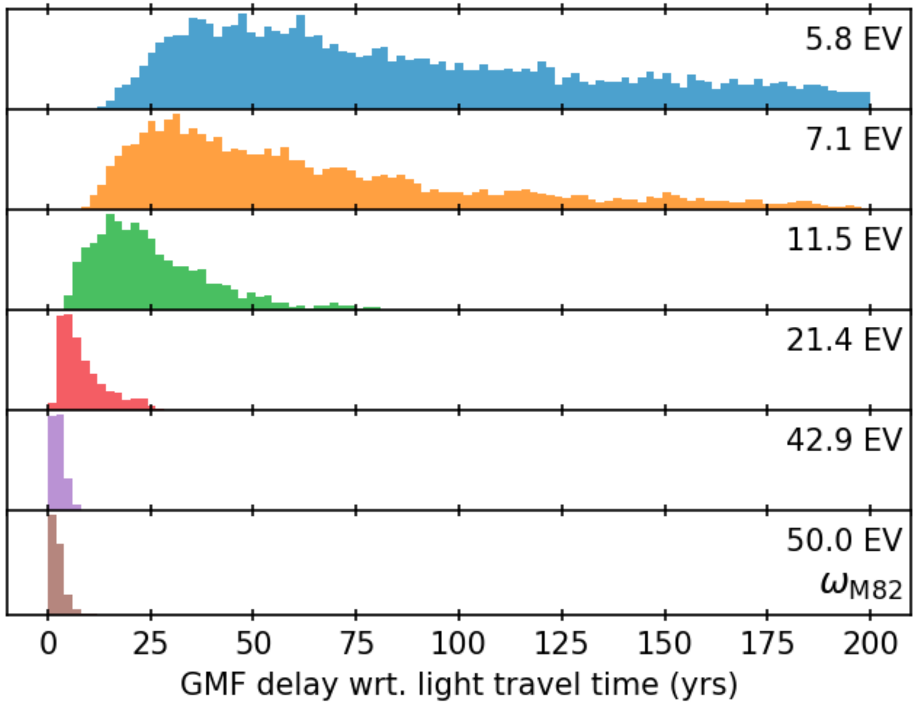
Clustering above 57 EeV: local significance 5-ish sigma, much smaller global. 20 degrees oversampling

Can the TA hotspot be a transient phenomenon?





TA hotspot located in magnetic window
→ short GMF delay, variability on year scale possible.



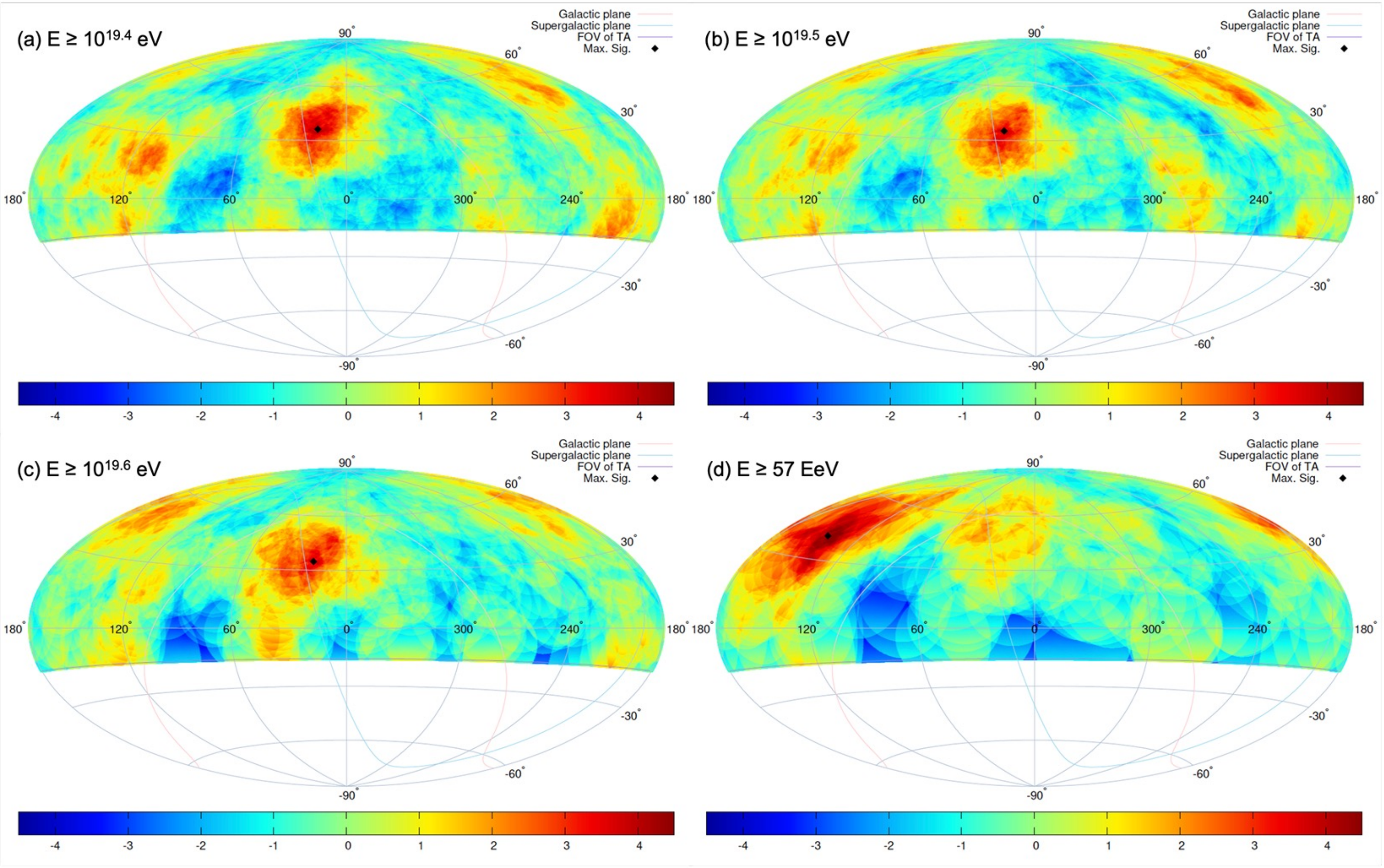
Summary

1. Identifying patterns generated nearby sources in data is challenging due to the **many "ingredients",** uncertainties and **unknown rigidities** of the observed UHECR events
2. We looked at the **issue of magnetic deflections** (again) with the motivation to investigate:
   - if there is a **meaningful science goal above the cutoff energies** (where defelctions are smaller)
   - whether a composition-sensitive observatory is needed (~excludes space observatories)
   - how many source host candidates are within an "energetically reasonable radius"
3. We characterized the **magnetic dispersion** in the galaxy and found that
   - **preferential directions in the Northern (TA's) hemisphere** with low magnetic dispersion
   - That **EGMF dispersion dominates for sources within the local group for B_{EGMF} > 0.1 nG**
4. If we would know the rigidity, EECR analyses should attempt to **use the temporal and spacial rigidity ordering to search for transient phenomena**
5. **Radio-bright/jetted, and Starburst galaxies are too far** or require extremely bright transients to be observed as multiplets

Master, PhD, and RA opportunities in my group anatoli@gate.sinica.edu.tw

The PPSC dilemma and why oversampling is concerning

INDICATIONS OF A COSMIC RAY SOURCE IN THE PERSEUS-PISCES SUPERCLUSTER 5

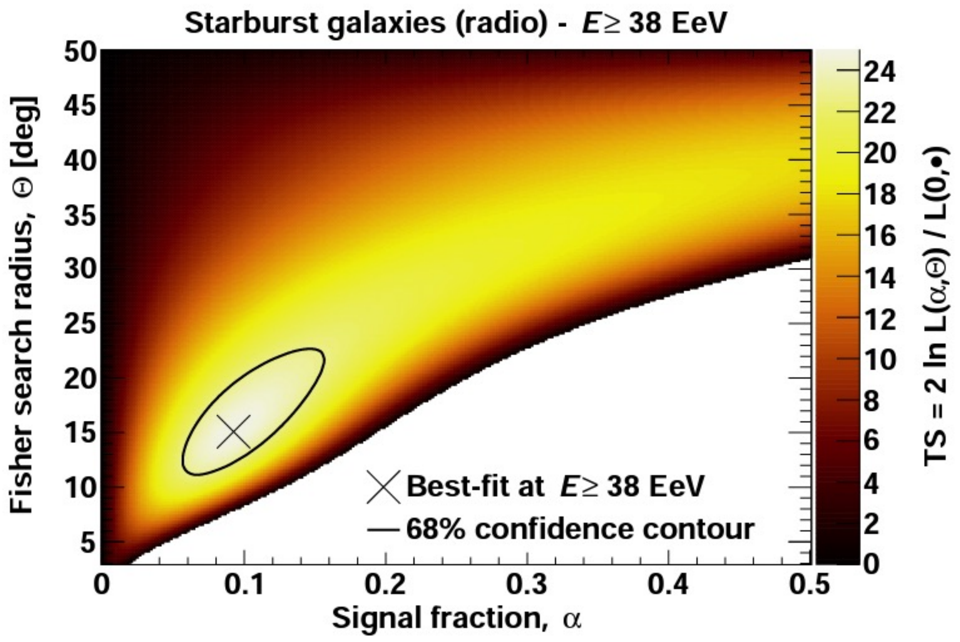


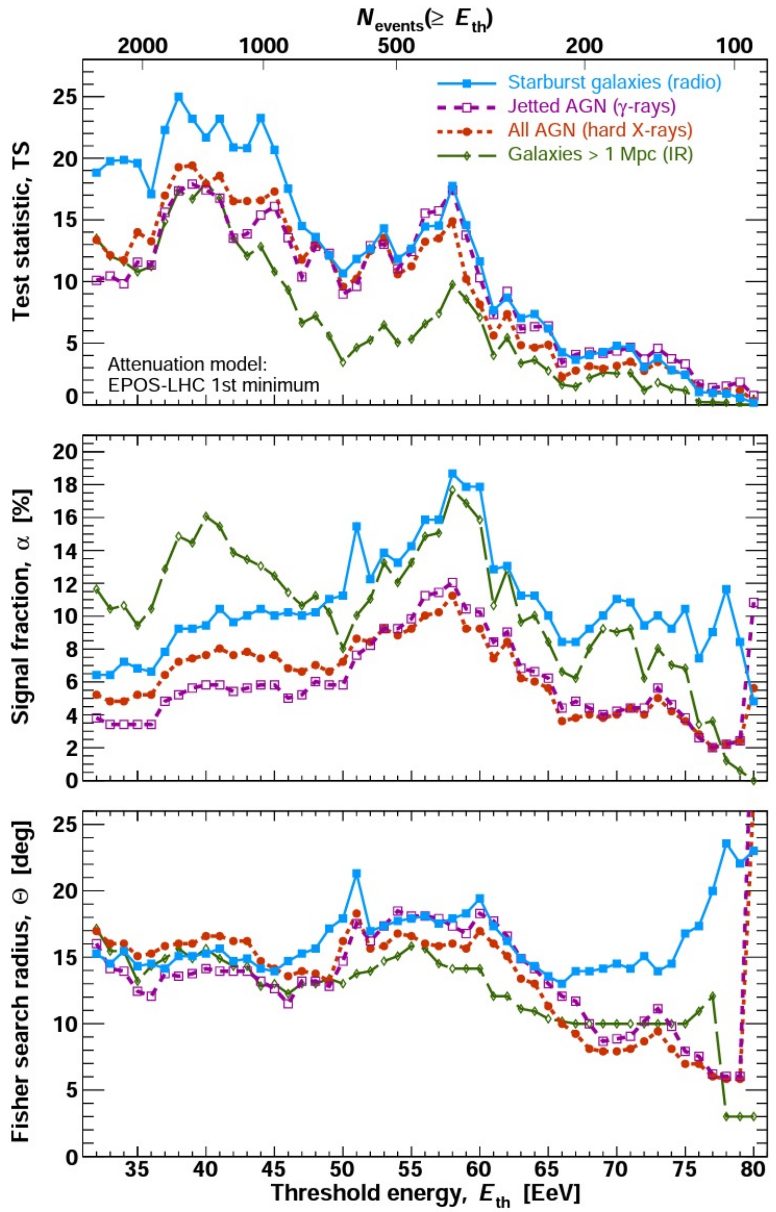
The TA Collaboration has observed a new excess of events in the arrival direction distribution. We found the excess over the isotropic background to have local significances of 4.4σ, 4.2σ, and 4.0σ for events of energy $E \geq 10^{19.4}$ eV, $E \geq 10^{19.5}$ eV, and $E \geq 10^{19.6}$ eV, respectively, by using the Li-Ma method and a 20°-radius circle oversampling analysis. This excess overlaps with

- Local significances above 25 – 39 EeV
- Implying PAO average composition, it's 3-6 EV range
- Fixed radius (to avoid trials). Why a circle?
- Behind the spot is the Perseus-Pisces supercluster @ ~70 Mpc

PAO – catalog searches

PAO, 2206.13492





- Catalog searches performed, varying threshold, search radius
- Tested assumptions for luminosity correlations
- Highest post-trial p-values in 10^{-3} – 10^{-4} range for all catalogs
- Search radius "circle" (vMF) because of the magnetic field uncertainty, and lack of knowledge about it
- PAO careful to interprete the result