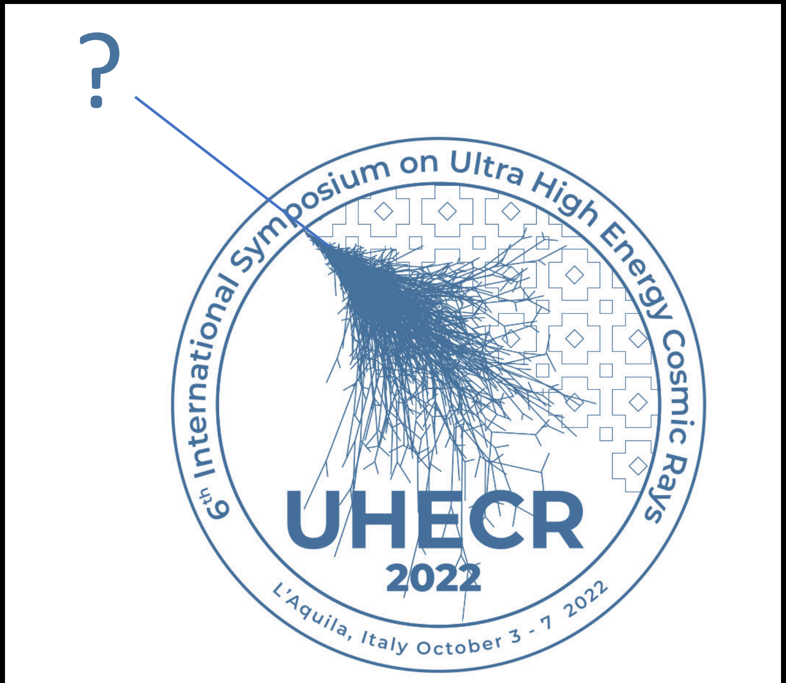
Ultra-High Energy Cosmic-Ray Sources

Noémie Globus



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

Ultra-High Energy Cosmic-Ray Sources

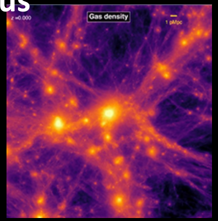
Noémie Globus

Lou

Extragalactic sources

Continuous

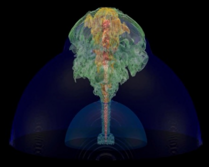
Starburst galaxies



Accretion shocks

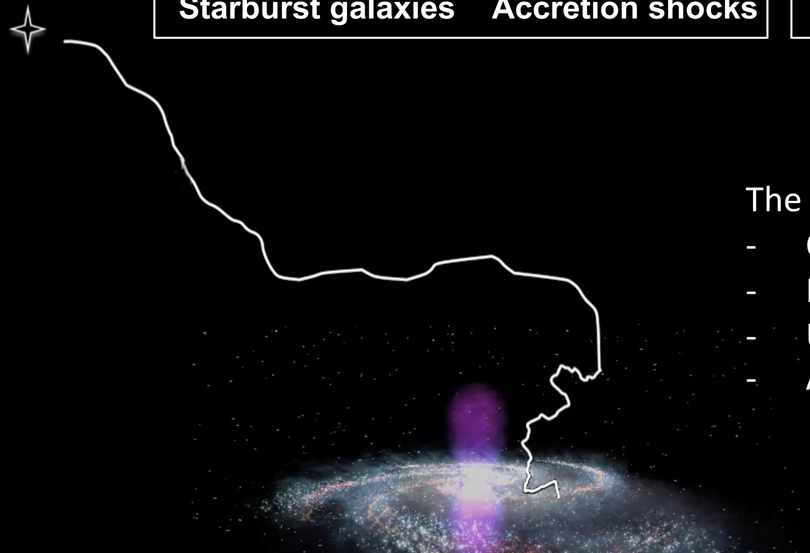
transients

AGN jets



GRB, TDE jets

?



The sources need to account for:

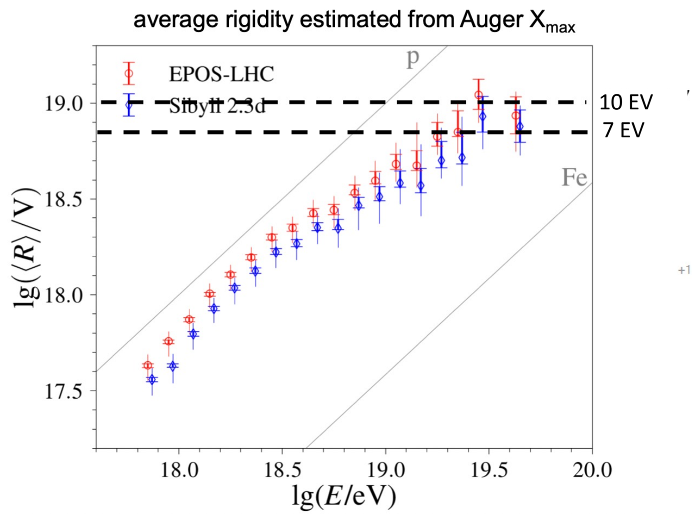
- Observed spectrum and composition
- Maximum energy (rigidity)
- UHECR emissivity > 10^{18} eV: ~ a few 10^{44} erg Mpc^{-3} yr^{-1}
- Anisotropy measurements

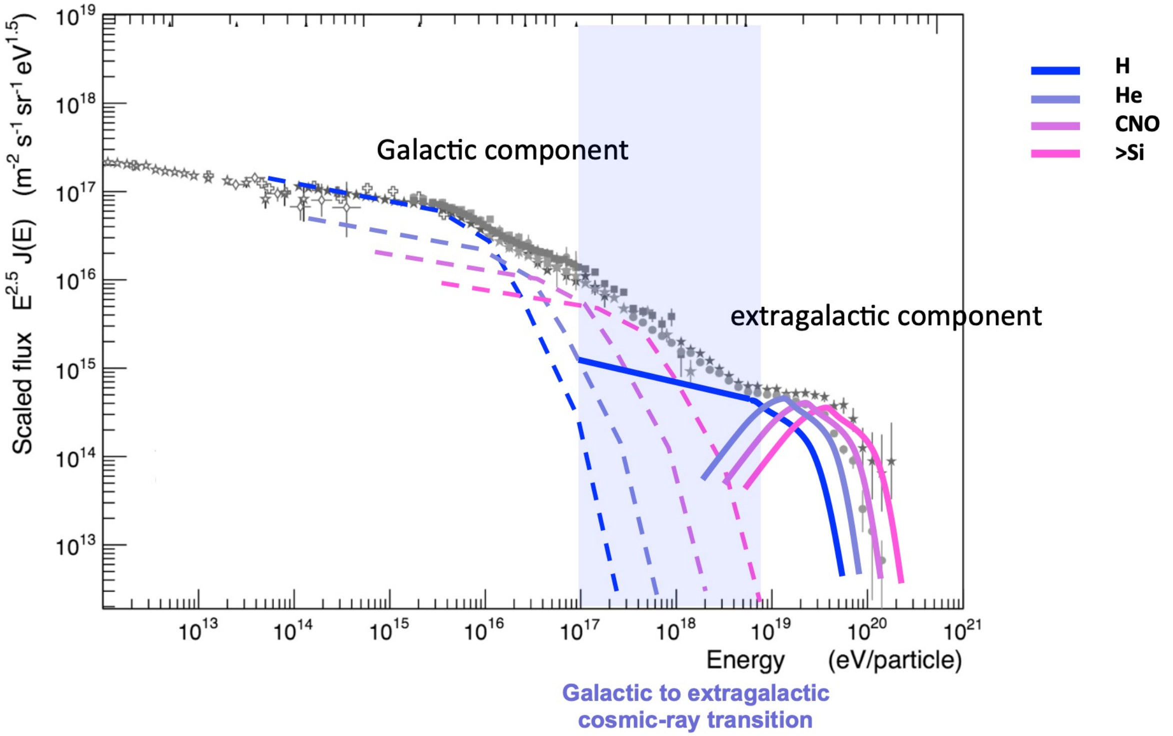
Galactic sources

Galactic center outflows

Local transient

UHECRs are a mix of elements





The evolution of the composition strongly suggest that the composition is becoming heavier as the energy increases

—> most likely explanation: dominant sources of UHECR do not accelerate protons to the highest energies

—> This implies a low maximum energy per nucleon (a few EeV to 10^{19} eV, well below the pion production threshold with CMB photons) and hard source spectral indexes required, for example: $N(E) \propto E^{-\beta}$, $\beta \sim 1.5$, $E_{max}(Z)=Z\, E_{max}^{proton}$, $E_{max}^{proton} \sim 5\ 10^{18}$ eV

—> allows to reproduce the high energy composition trend;

—> high energy cut-off explained by the combined effect of the maximum energy at the sources and the interaction of nuclei with photon backgrounds;

—> strong implications for UHE cosmogenic neutrinos predictions (Globus et al., 2017, ApJ 839L, 22, arXiv:1703.04158; Decerprit & Allard, 2011, A&A 535A, 66)

Origin of sub-ankle protons?

One possibility: radiation dominated acceleration site

—> At UHECR acceleration at gamma-ray bursts internal shocks (Globus et al. 2015), most protons are secondary particles (escaping as neutrons) .

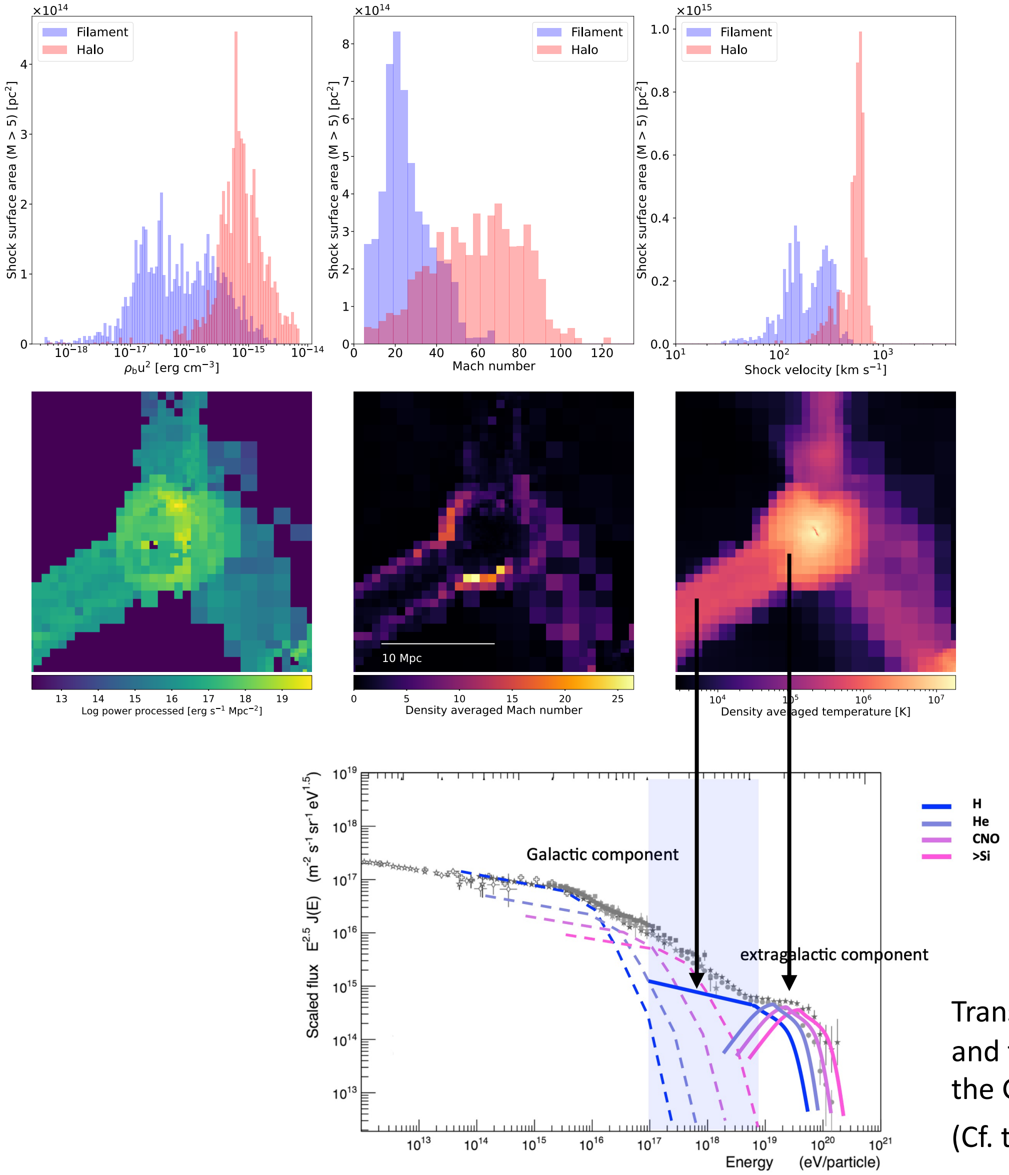
—> This is a generic feature of acceleration models in high radiation density environment see also Unger, Farrar & Anchordoqui 2015

—> Subcomponent of hierarchical model? See R. Blandford's talk

Origin of 10 EV cosmic rays? (EECRs or trans-GZK) – this talk

UHECRs from large-scale structure accretion shocks

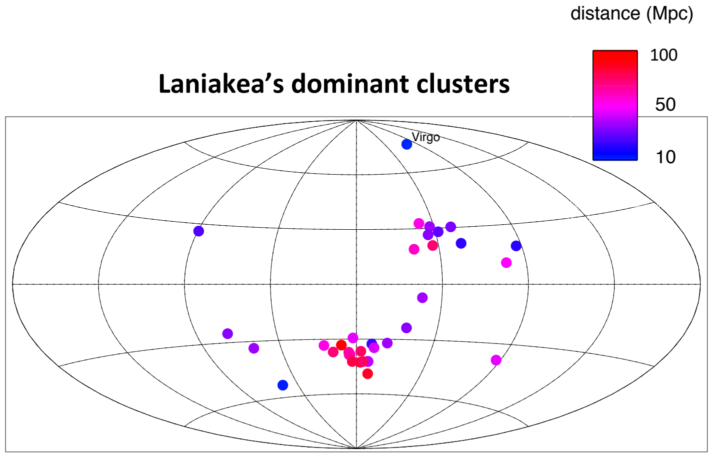
Cf. talk by R. Blandford



Common but invisible (may appear in radio?); ultimately tap accretion energy; transfer mediated by (Non-Relativistic) Diffusive Shock Acceleration; Neutrinos not expected

- Injection of pre-existing population of galactic cosmic-rays into filament shocks, and cluster accretion shocks
- Cluster “Halo” component: high metallicity (selection effect), hard spectrum (upstream of the shock: escaping cosmic rays)
- Filament component: softer spectrum (downstream of the shock)
- Geometry is important!
- High Mach numbers and emissivity (few times 10^{44} erg Mpc^{-3} yr^{-1})
- Mechanism: magnetic “bootstrap”
- Can be considered as continuous sources; connection with UHECR anisotropies

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



Transition: contribution from Filament component and from re-acceleration of galactic cosmic rays at the Galactic Wind Termination Shock

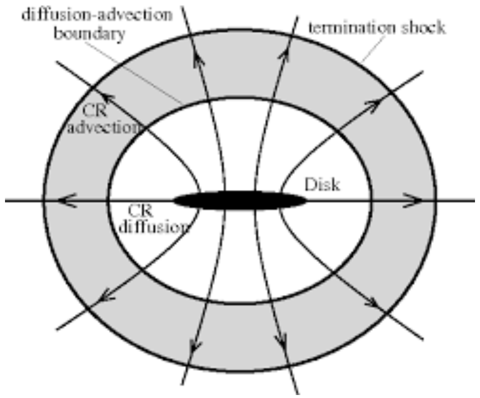
(Cf. talk by E. Peretti)

Starburst galaxies (GWTS)

AGN-driven wind observations:

- Radio jets (relativistic)
- X-ray winds (WA thousands km/s, UFO semi-relativistic)
- ionized gas outflows (v=1000-3000 km/s)
- atomic gas outflows (v=100-1000 km/s)
- molecular gas outflows (100-2000 km/s)

Spherical model:

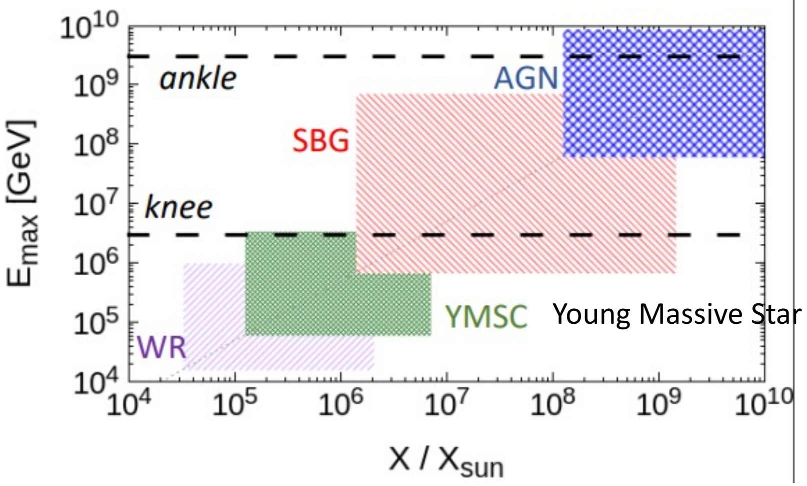


the maximum rigidity for SB-driven wind is ~0.5 EV, for AGN-driven wind is ~10 EV

Possible association with TA hotspot

SB/AGN driven winds could be sources of PeV neutrinos

M82



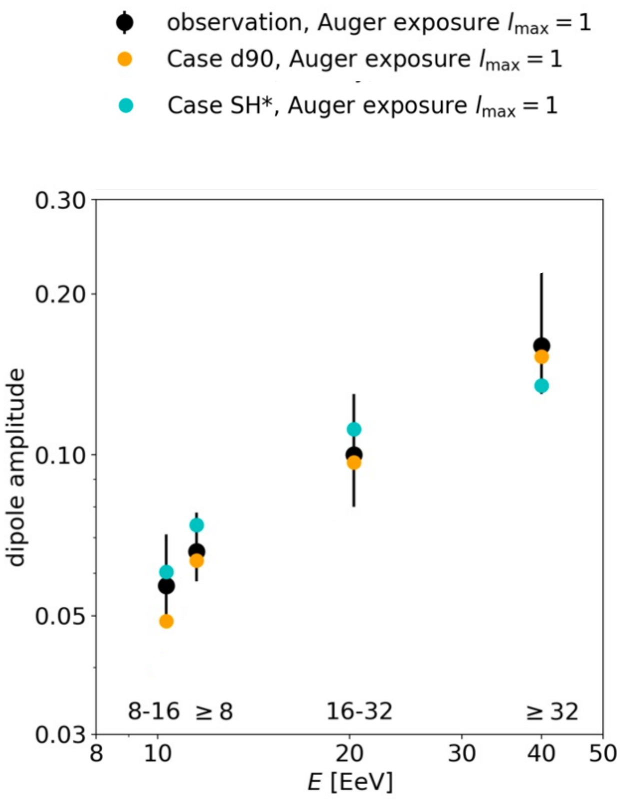
Young Massive Star Clusters

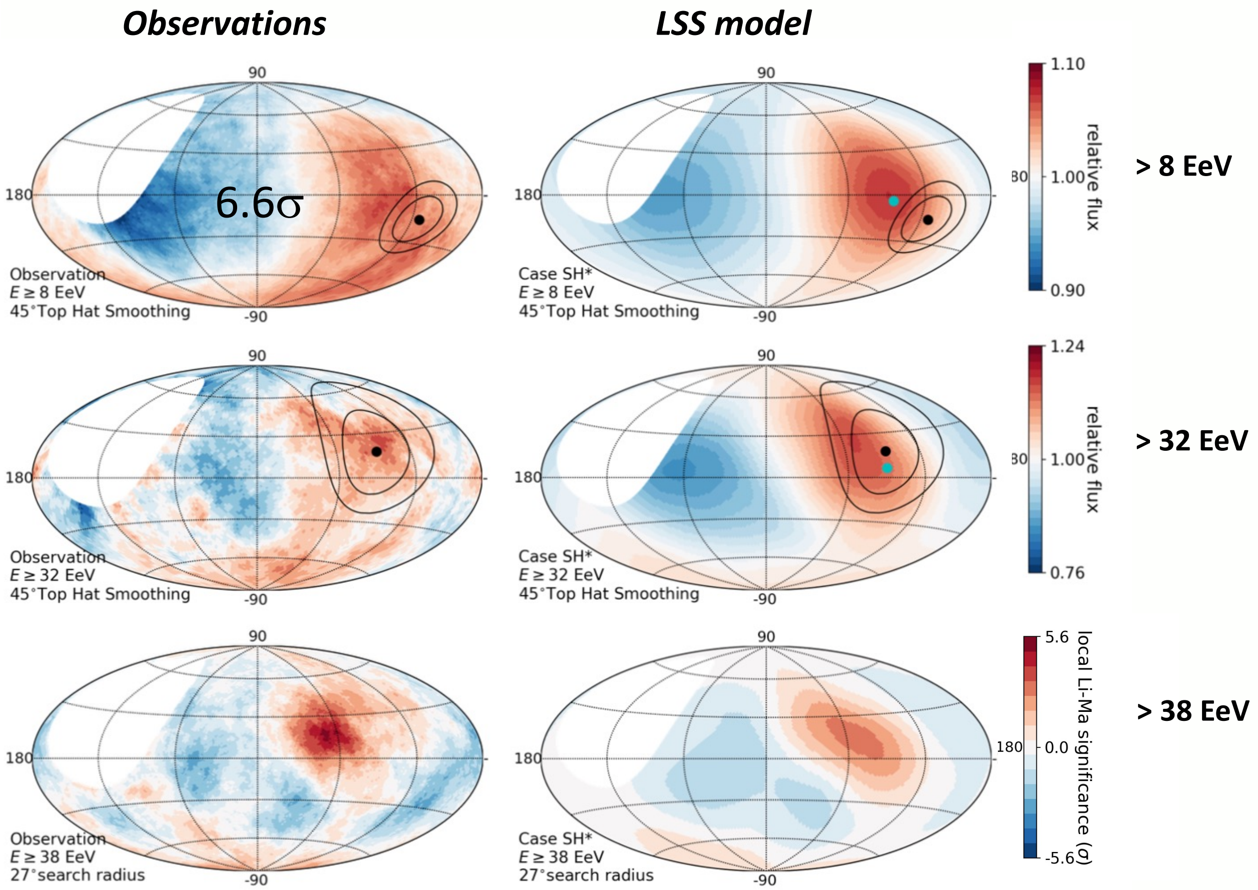
Cf. talk by E. Peretti

UHECRs from many sources following the large-scale structure

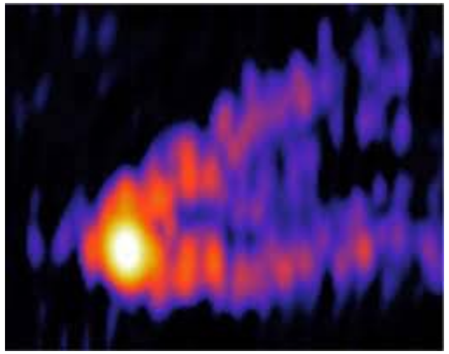
Cf. talk by G. Farrar

Ding, Globus & Farrar 2021

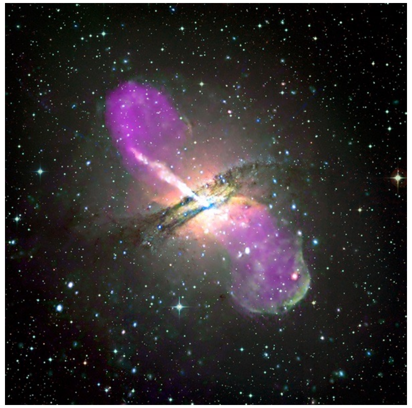




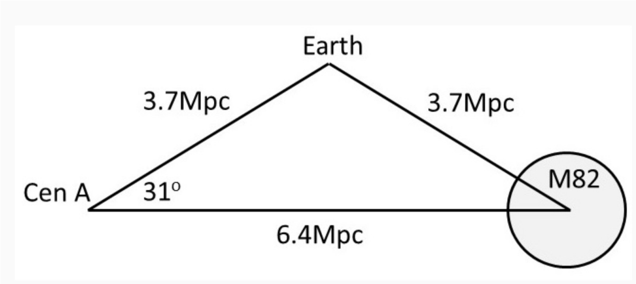
UHECRs from active galactic nuclei



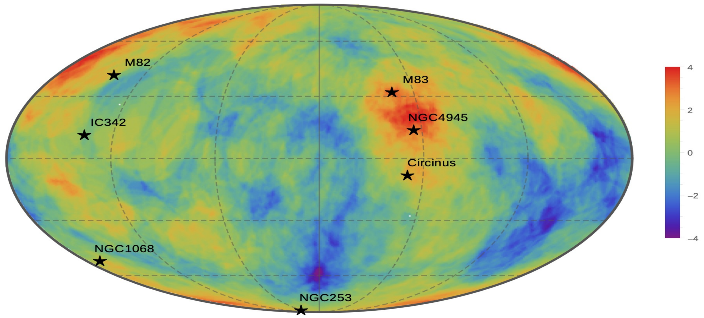
M87



Cen A



Bell & Matthews (2021)



Rare but powerful; tap rotational energy (unipolar inductors) or accretion energy; transfer mediated by shear acceleration, DSA, reconnection; Multi-messenger (gamma-ray, neutrino) signatures

- FR-I radio galaxies and misaligned BL Lac objects located within the GZK horizon have sufficient emissivity to power the UHECRs
- FR-II are disregarded (overproduce cosmogenic gamma-rays)
- Apparent jet power: 10^{43}–10^{44}erg s^{-1} (which could exceed 10^{46}erg s^{-1} and large Lorentz factors during flaring episodes)
- Two-component outflow (disk wind and ergospheric-driven jet) : shear and instabilities expected leading to magnetic field amplification
- DSA acceleration sites: shock at the interface between the wind and the jet, lobes and backflows (mildly relativistic shocks), multi-shock acceleration from star crossing the jets (cf. talk by A. Müller)
- Composition: depend on the injection model; internal entrainment in the jets of Centaurus A will contribute with a significant amount of ^{4}He, ^{16}O, ^{12}C, ^{14}N, and ^{20}Ne (Wykes et al. 2015)
- AGN jets are rare in the local universe. Predictions possible in term of UHECR anisotropies. Cen a hot spot? Is TA hotspot due to UHECR reverberation? Cf. talk by A. Taylor
- Flaring source. Doublets?

Gamma-ray bursts jets

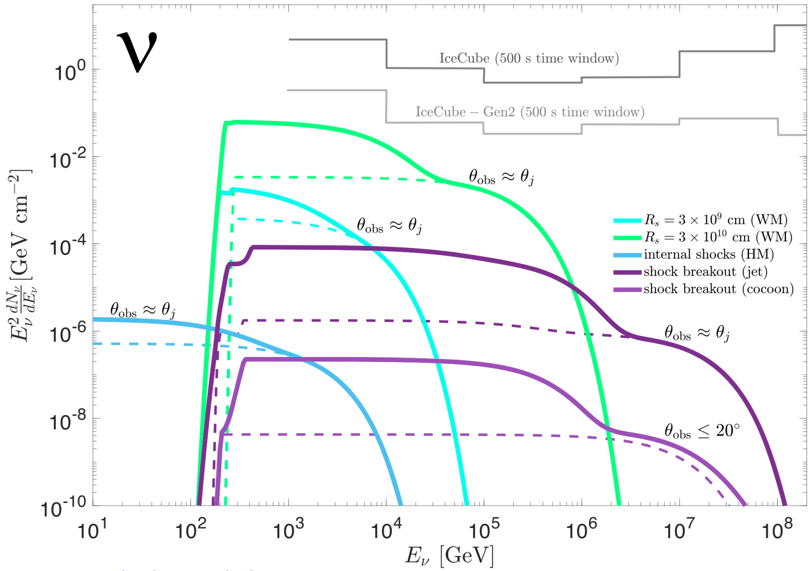
Rare but powerful; tap rotational energy (unipolar inductors) or accretion energy; transfer mediated by shear acceleration, DSA, reconnection; Multi-messenger (gamma-ray, neutrino) signatures

Before breakout of the ejecta:

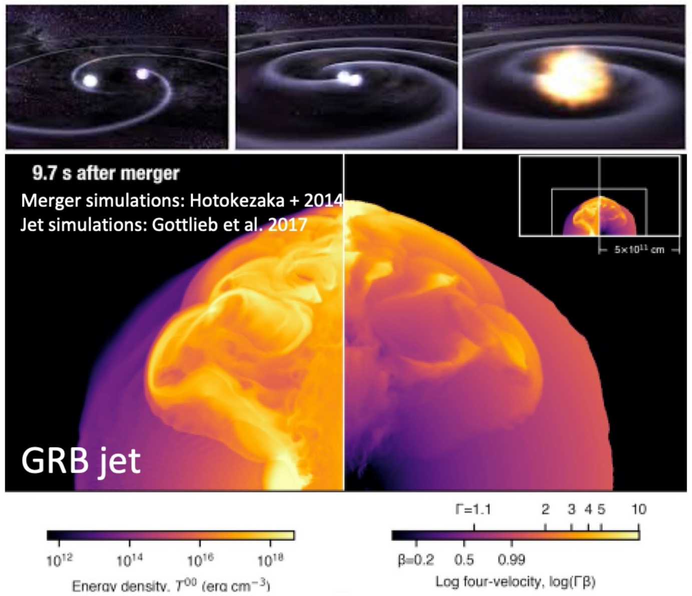
- UHECR acceleration at internal (mildly-relativistic) shocks in an opaque environment? Possible if the jet is highly magnetized (formation of collisionless subshocks). But the UHECRs won't escape --> neutrinos are emitted

After breakout of the ejecta:

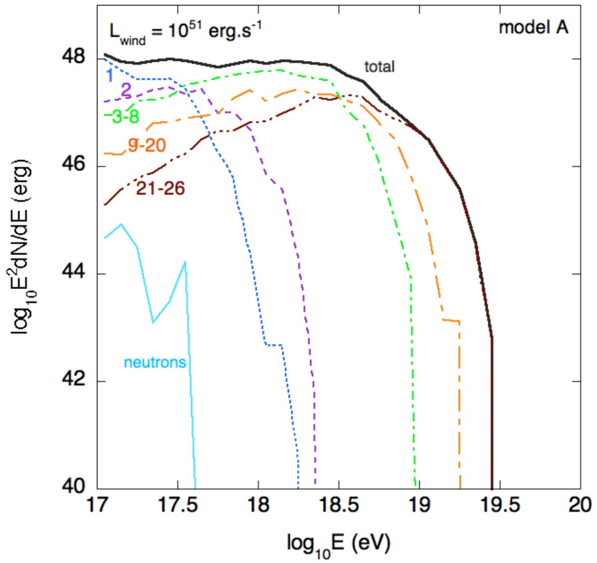
- UHECR acceleration at collisionless internal (mildly-relativistic) shocks
- Long-duration GRBs have sufficient power to accelerate cosmic rays to ultra-high energies, but their local photon luminosity density in photons, ~ 6 10^{42} erg Mpc^{-3} yr^{-1}, implies large baryon loading
- Rate of LLGRBs more important? (100-1000 the rate of long GRBs?)
- UHECR acceleration at GRB internal shocks (Globus et al. 2015): most protons are secondary particles (escaping as neutrons)
- The composition injected at the shock must be ~ 5-10 times galactic CR metallicity to account for the observations
- Impulsive source. Doublets?

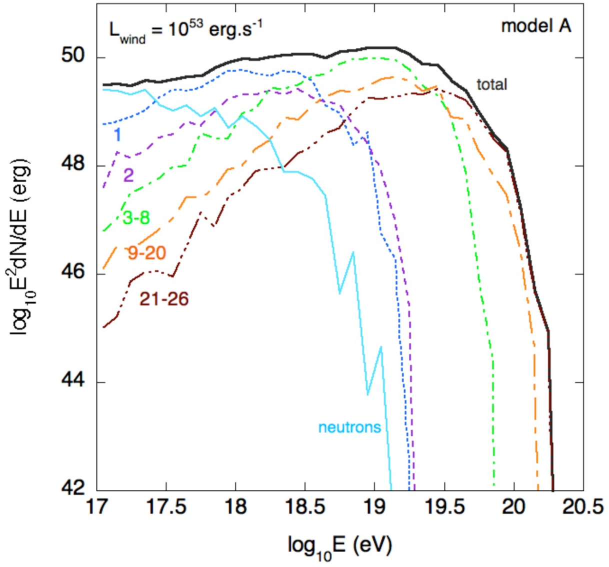


Gottlieb & Globus 2021



UHECRs





Globus et al., 2015

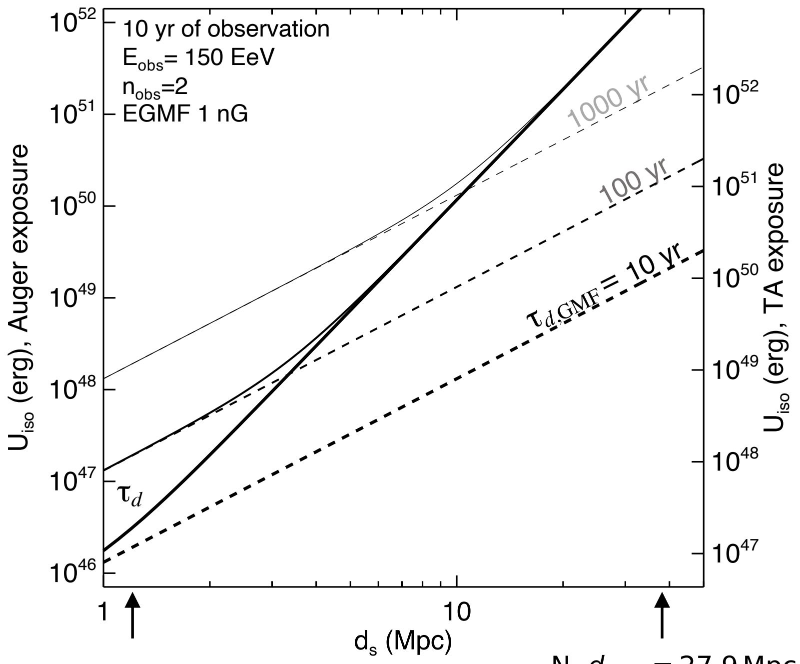
Necessary condition for detecting EECRs doublets from a transient source

To observe $n_2 = 1$, doublet of EECR with E_{obs}, A_{obs}, the isotropic equivalent energy in the EECR flare must be: $U_{\rm iso} \sim 4.38 \cdot 10^{52} {\rm erg}\, (\tau_d/10^3 {\rm yr}) d_{50}^2 n_2 E_{200} (\mathcal{E}/\mathcal{E}_{\rm PAO})^{-1} n_{\rm yr}^{-1}$

The $\tau_{d,\rm GMF}$'s in the example below are assumed. In our study the $\tau_{d,\rm GMF}$'s are calculated for each directional pixel independently with a Monte Carlo method.

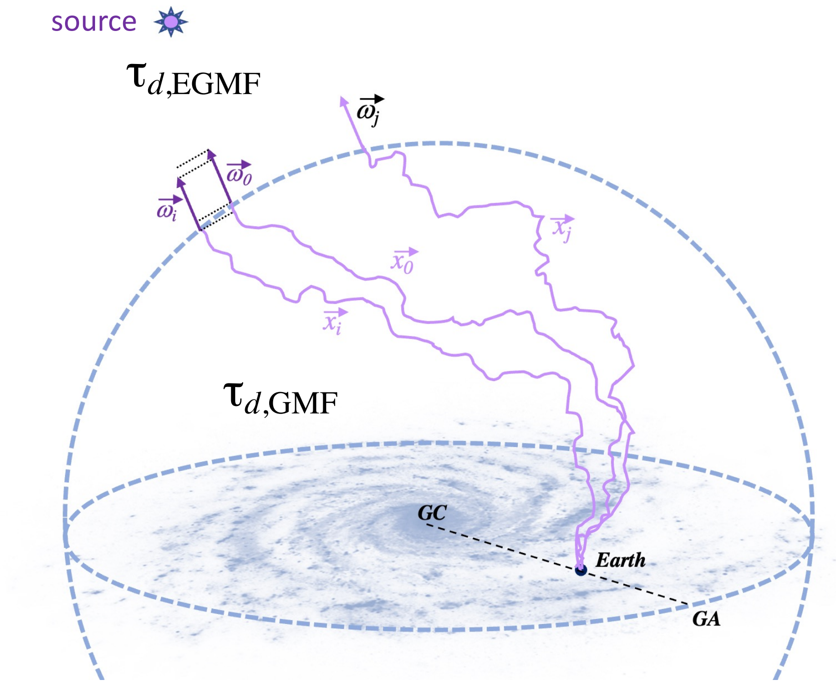
Adding the EGMF contribution: $\tau_{d,\rm EGMF} \sim 5\,{\rm yr}\,(E_{200}/Z)^{-2} B_{\rm nG}^2 r_{\rm Mpc}^2 \lambda_{\rm Mpc}$

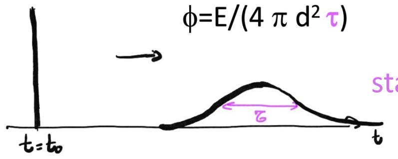
Finally, $\tau_d = \sqrt{\tau_{d,\rm GMF}^2 + \tau_{d,\rm EGMF}^2}$



N, $d_{95\%} = 1.2$ Mpc
$A_{obs} > 12$

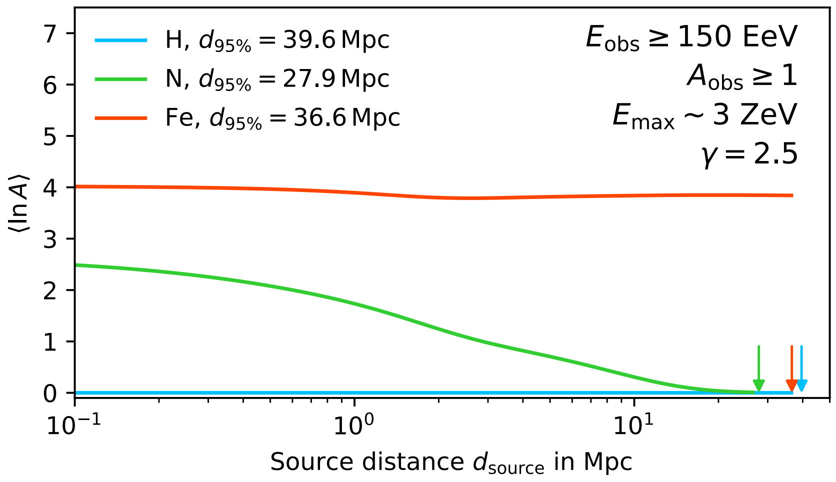
N, $d_{95\%} = 27.9$ Mpc
$A_{obs} > 1$

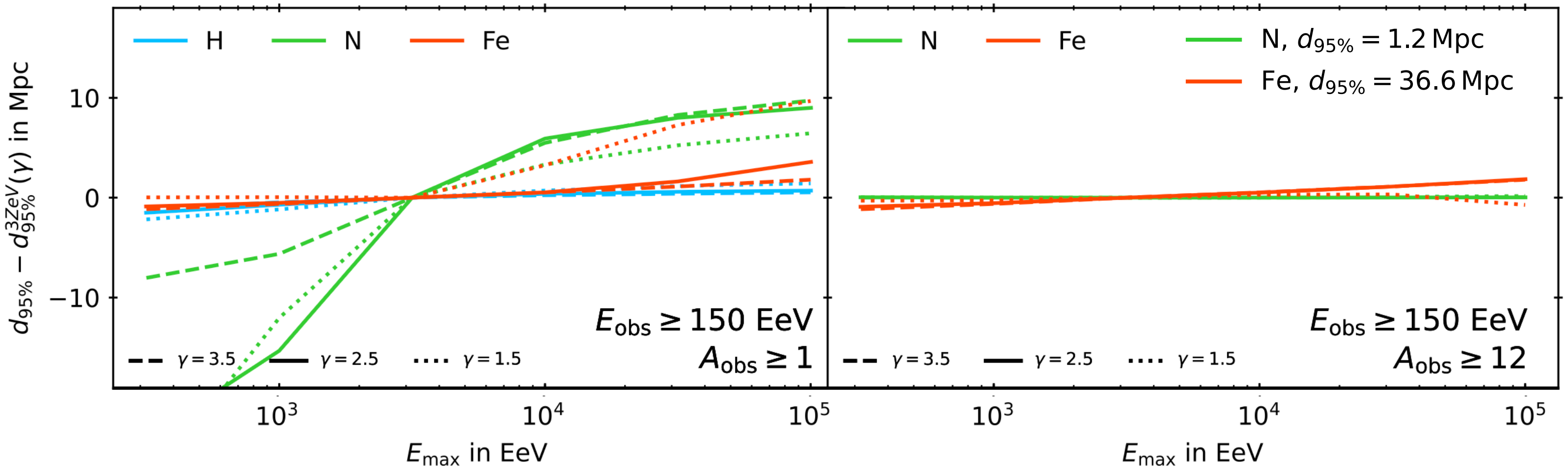




$\tau_{d,\rm GMF} = \sqrt{\frac{1}{N}\sum_i (t_i^2 - \mu^2)}$

Possible source candidates (local supercluster ~40 Mpc)



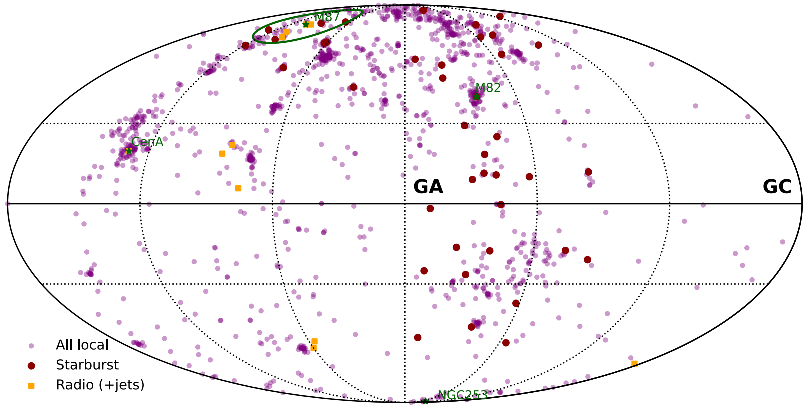


The “selected horizon” depends on the mass number of the doublets detected at Earth.

The GZK horizon structure is essentially the same for protons and Fe nuclei

This is not the case for intermediate mass elements that, if detected as such, needs to come from our local group.

Each host candidate for an impulsive source has a weight, depending on magnification factor and “opacity” (GZK attenuation)

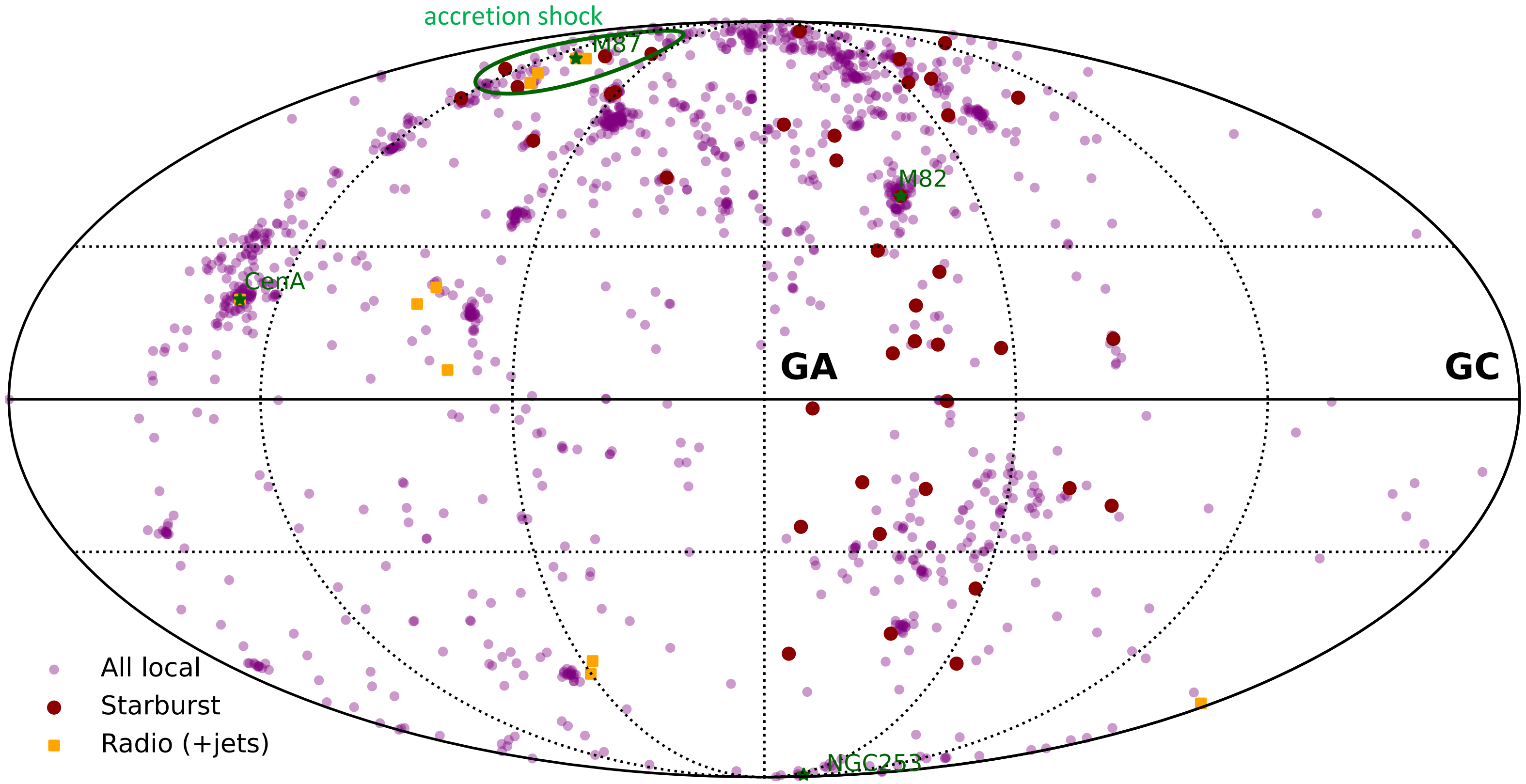


Catalogs:

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

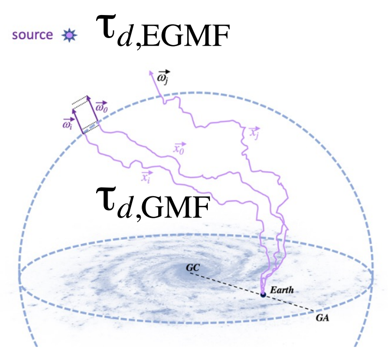
Possible source candidates < 40 Mpc

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



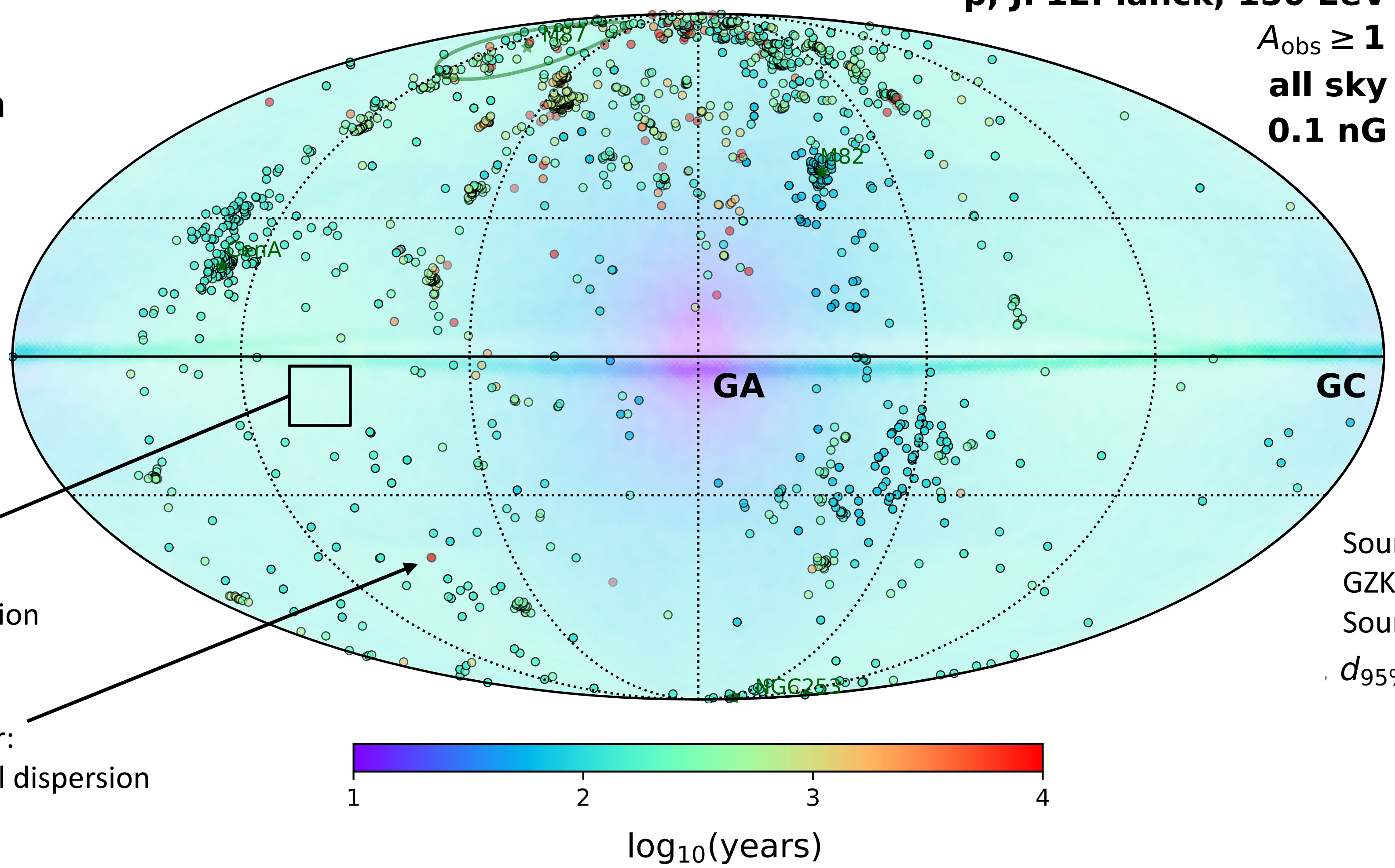
“treasure maps” combining temporal dispersion, GZK attenuation, detector FoV

temporal dispersion



Background color:
GMF temporal dispersion

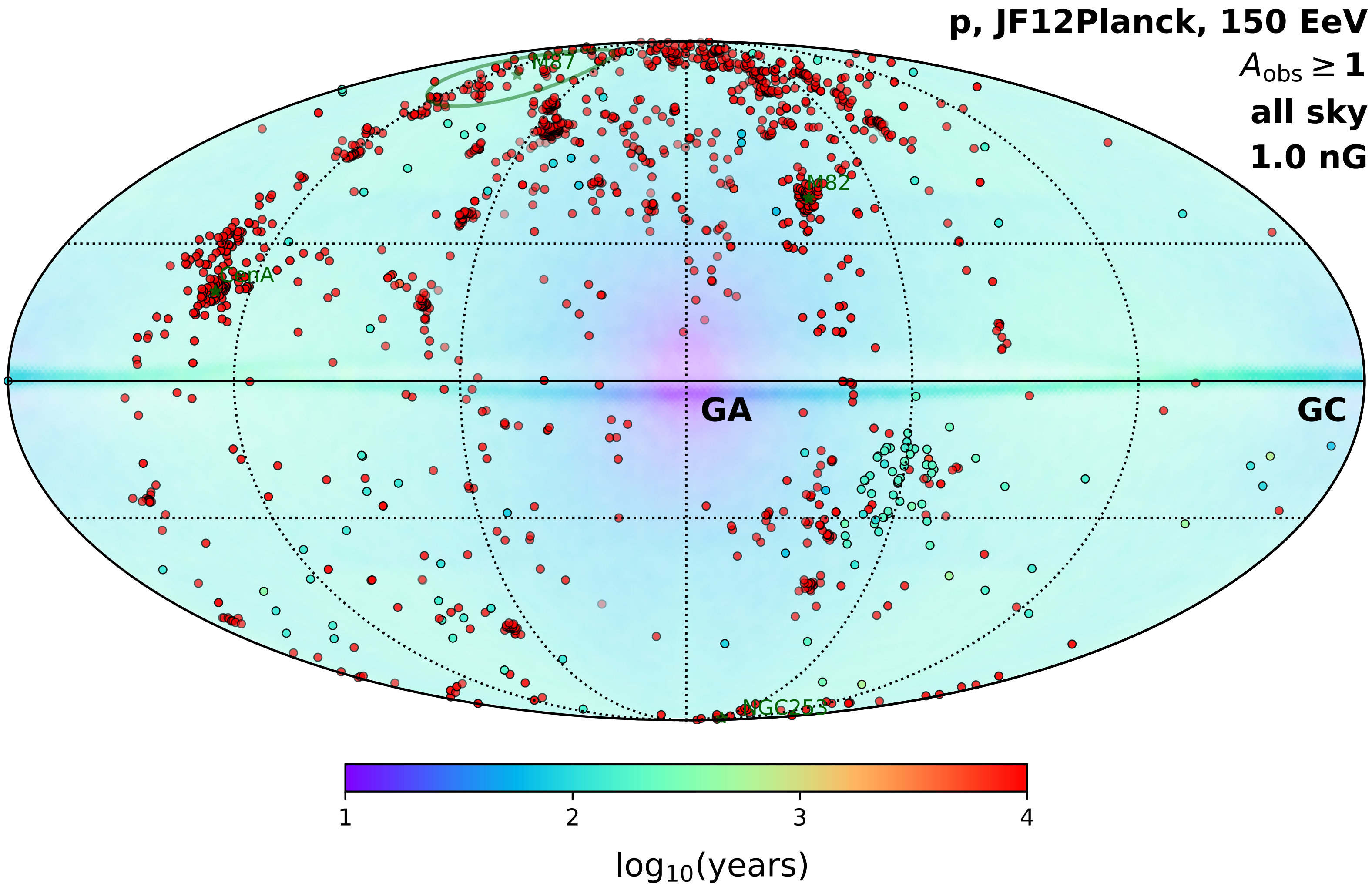
Source candidate color:
GMF + EGMF temporal dispersion



p, JF12Planck, 150 EeV GMF model
$A_{\mathrm{obs}} \geq 1$ horizon selection
all sky detector FoV
0.1 nG EGMF

Source transparency:
GZK attenuation
Source beyond $d_{95\%}$ are not shown
$d_{95\%} = 39.6$ Mpc

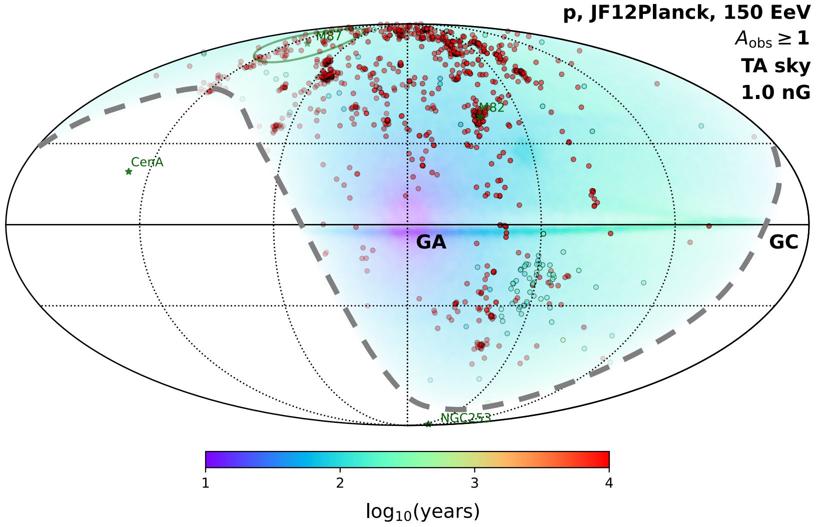
“treasure maps” combining temporal dispersion, GZK attenuation, detector FoV

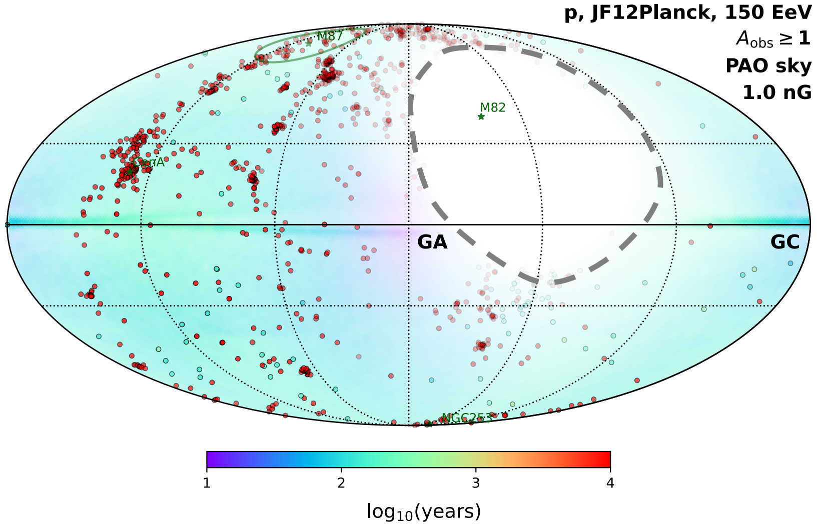


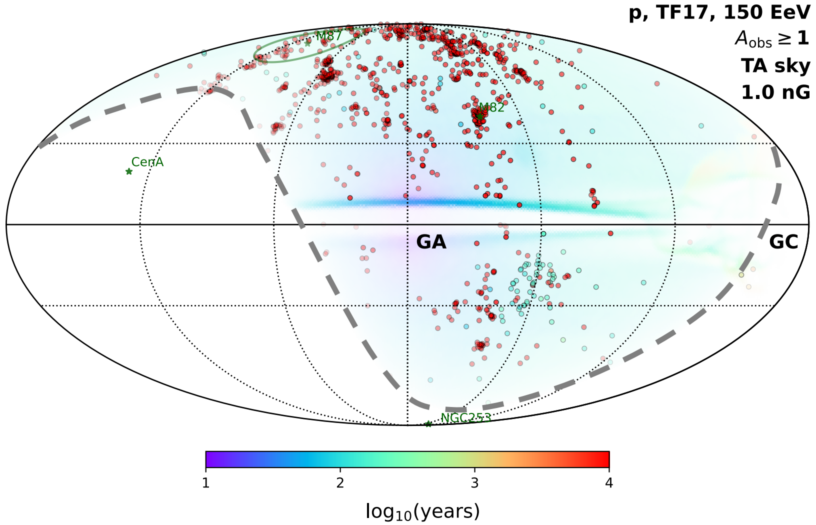
EGMF “fiducial”

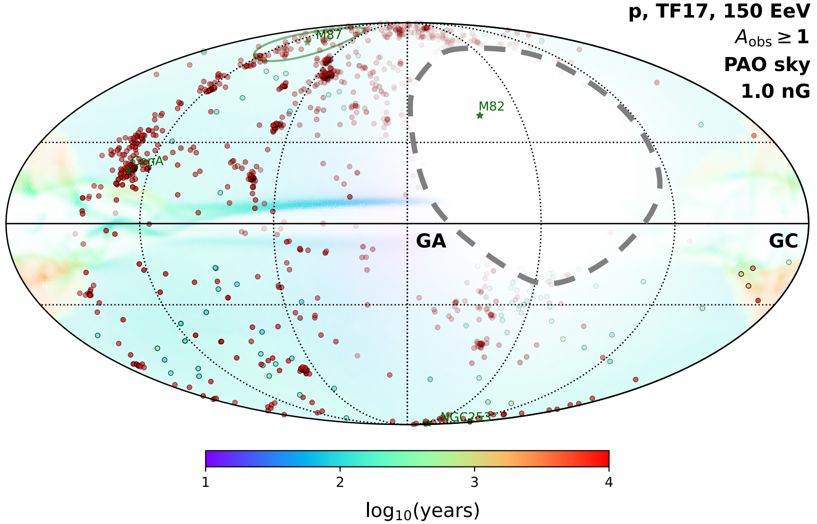
p, JF12Planck (top) and TF17 (bottom)

$d_{95\%} = 39.6\,\mathrm{Mpc}$





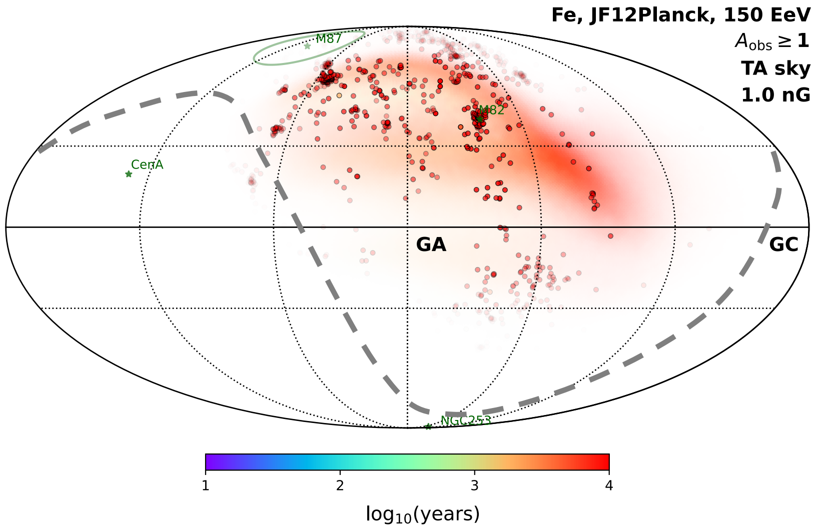


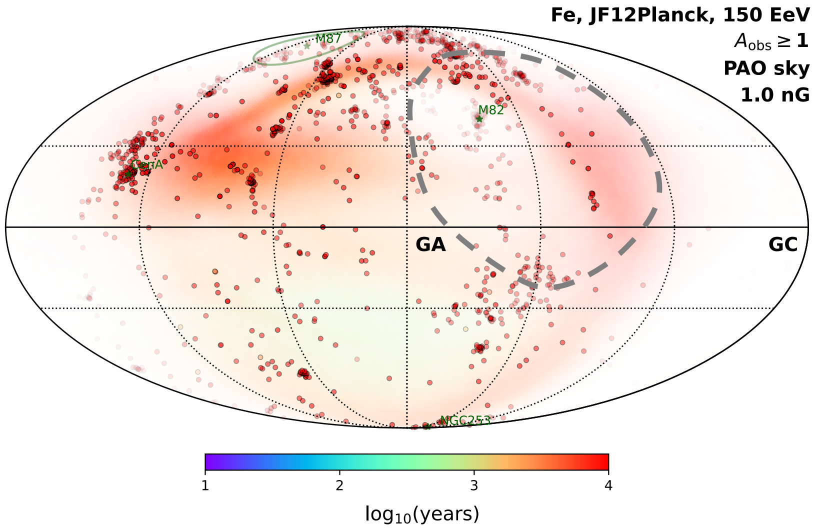


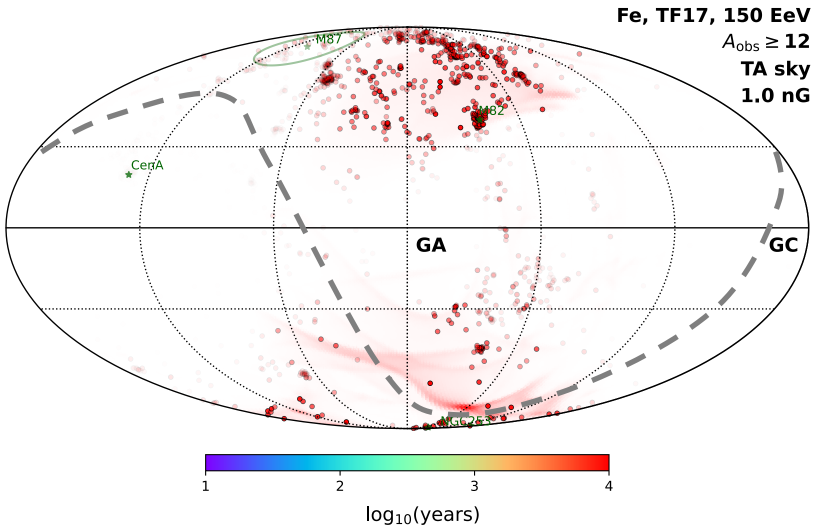
Globus & Fedynitch, in prep.

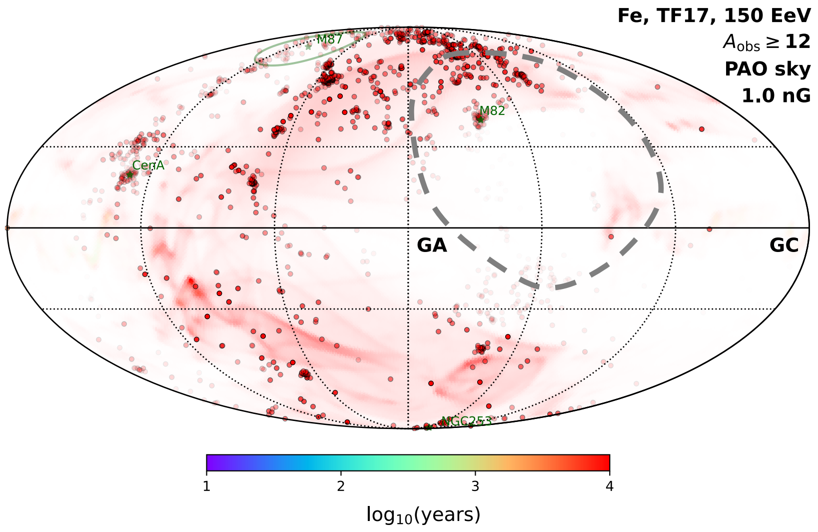
Iron, JF12Planck (top) and TF17 (bottom)

$d_{95\%} = 36.6\,\mathrm{Mpc}$

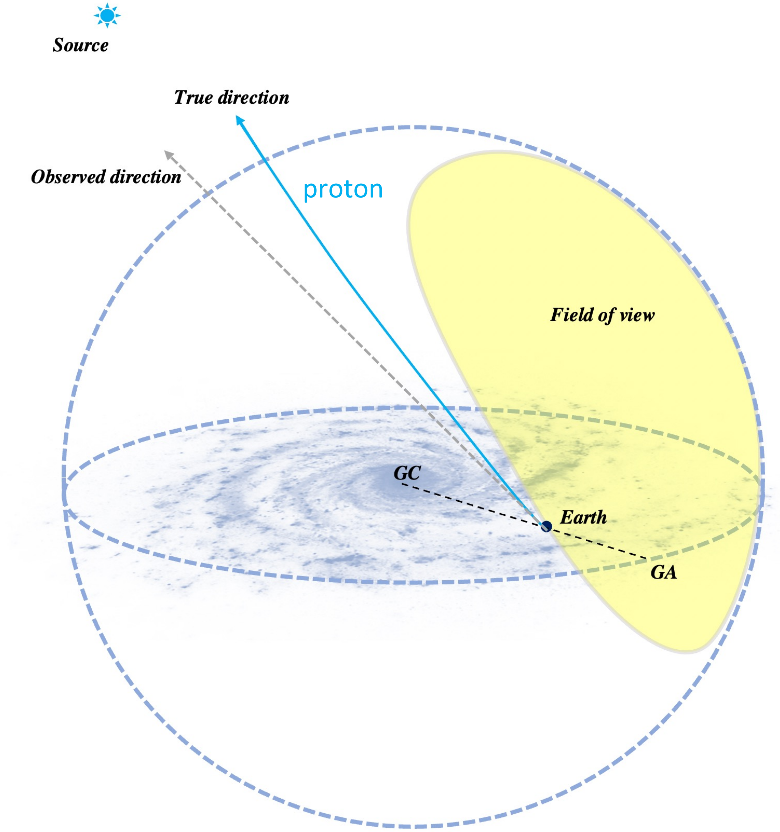


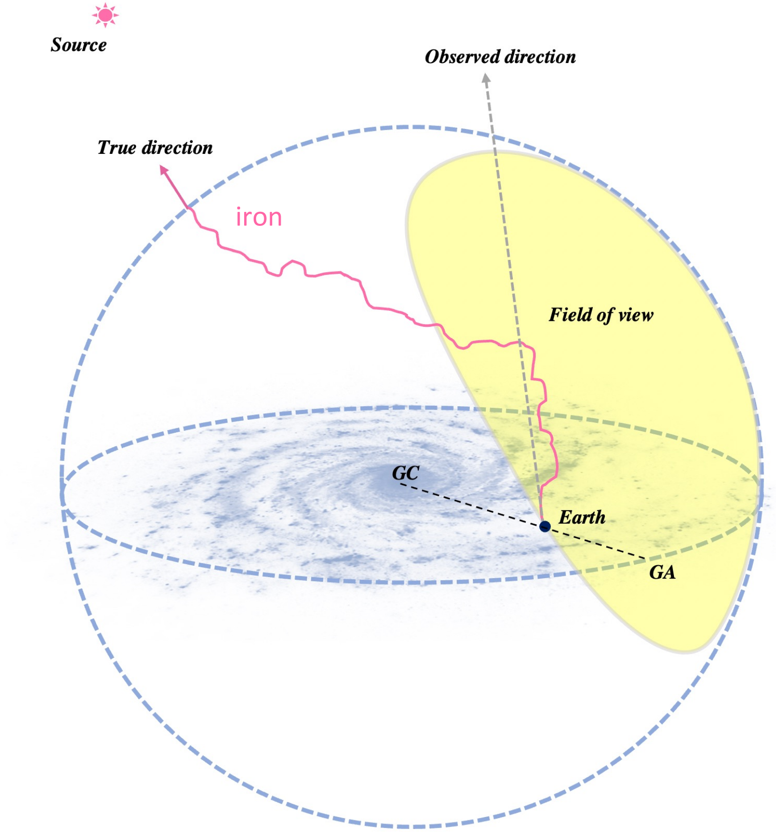






Globus & Fedynitch, in prep.





Galactic Magnetic Field modeling:
Cf. talk by Ferrière, Unger

Slides removed due to unpublished results: Number of host candidates for doublets.

“Darkening” the Ultra-High Energy Cosmic-Ray Sky?

- After 60 years the problem of the origin of UHECRs still remain unsolved.
- Fundamental particles with energies up to 100 Joules!
- Surely one of the biggest challenges in high energy astrophysics and potentially a contributor to elementary particles physics.
- We need more events at the highest energies > 150 EeV and a composition-sensitive experiment (on an event-by-event basis).
- We already have a few events at 150 EeV (and even higher!).
- Discovery of higher energy particles > 150 EeV, and doublets of events with a composition-sensitive detector could rule out many currently viable source models.

The prospects for solving this problem are bright.