UHECRs & Multimessenger Astrophysics part II

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N3AS
July 21, 2023

Key points from last time

- Measurements generally agree between Auger & TA; quality of data has vastly improved in past 15 years.
- Maximum energy is mainly determined by accelerators; energy loss in propagation ("GZK") has an impact but it's secondary.
- Composition of extragalactic component is mixed, starting as proton at lowest energy then becoming heavier with increasing energy.
    - LHC-tuned particle physics models do not correctly describe showers (relation between muons, X_{max} …)
- The mean rigidity (E/Z) is approximately constant, with peak about 5 EV (E = 5 EeV for protons) .
- Larmor radius is ~ 1 kpc (E_{EeV}/Z) / B_{uG} .

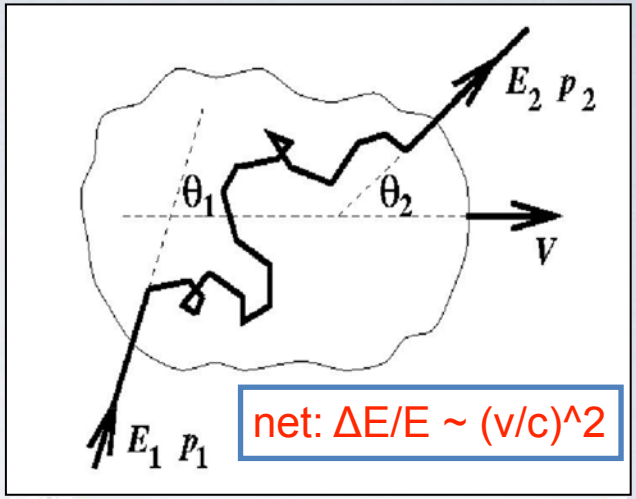
Today

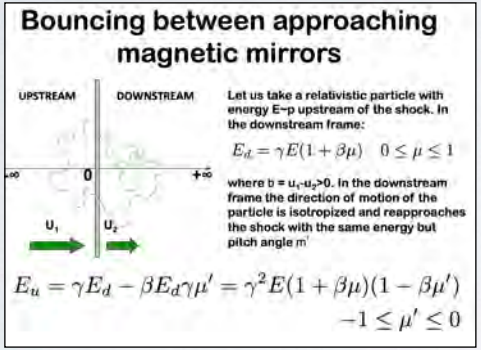
- Acceleration: “Hillas Criterion”, mechanisms
- Magnetic deflections
- What can be said about sources?
    - Arrival directions
    - Anisotropies
    - Indirect info from spectrum and composition data
- Using neutrinos to find sources — intro to IceCube

Acceleration

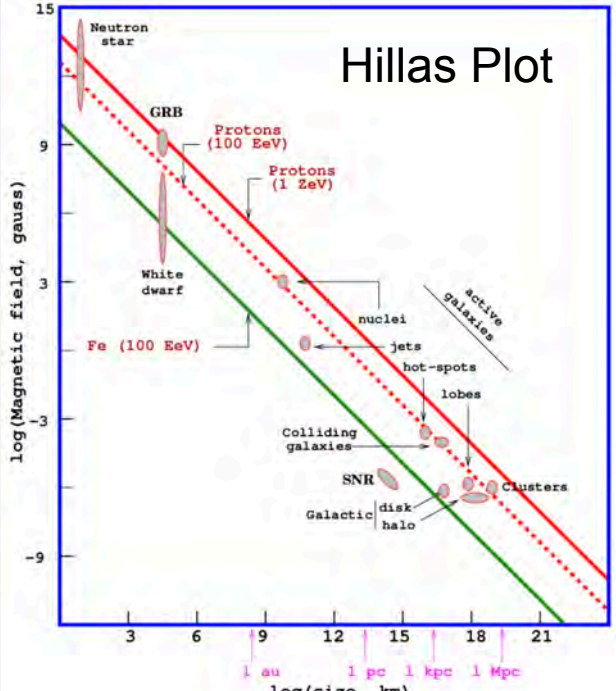
All variants on Fermi's Classic Mechanisms:

- "2nd Order Fermi"
- "1st Order Fermi" — Shock Acceleration: spectrum~$E^{-2.2}$





c.f., Blasi GSFC lecture



Accelerator must be able to retain the particle

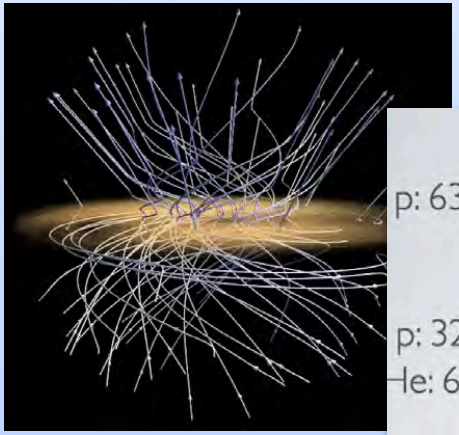
$R_{Larmor} \lesssim L$ (size of accelerating system)

➜ maximum rigidity. $E_{EeV}/Z \lesssim L_{kpc} B_{uG} \Gamma$

Also, minimum luminosity (Poynting):

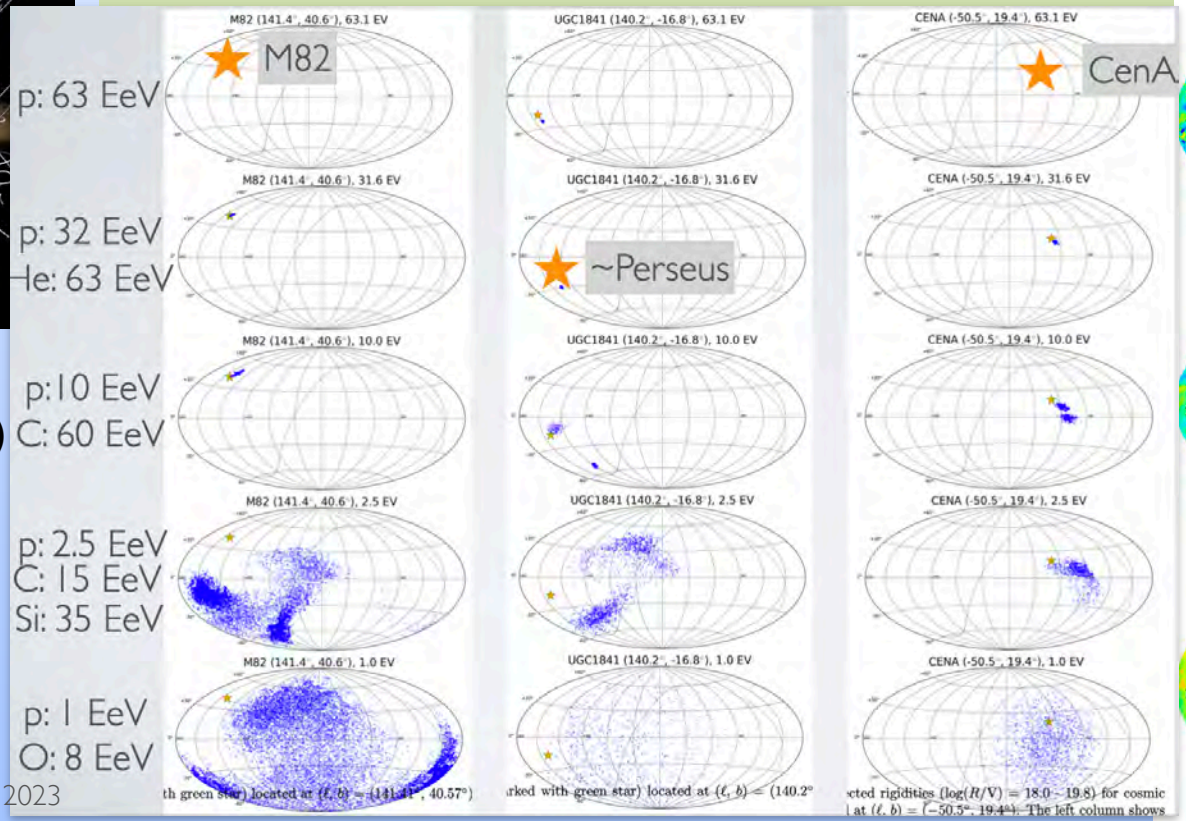
for p: $$L \sim \frac{1}{6} c \Gamma^4 B^2 R^2 \gtrsim 10^{45} \Gamma^2 E_{20}^2 \text{ erg s}^{-1}.$$

Magnetic deflections make source ID difficult

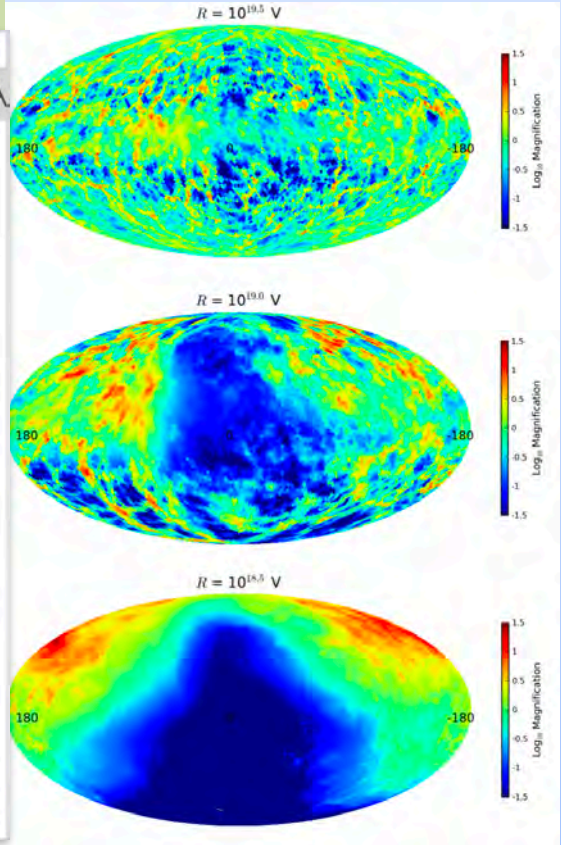


Larmor radius = 1.1 kpc (R_{EV} / $B_{\mu G}$)

Deflections in JF12 field model; GF+M.Sutherland, JCAP19

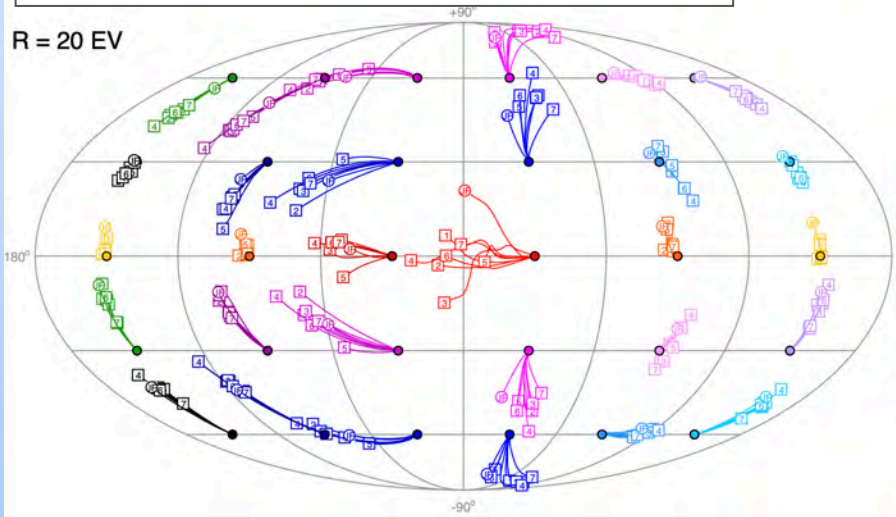


(de)Magnification too!

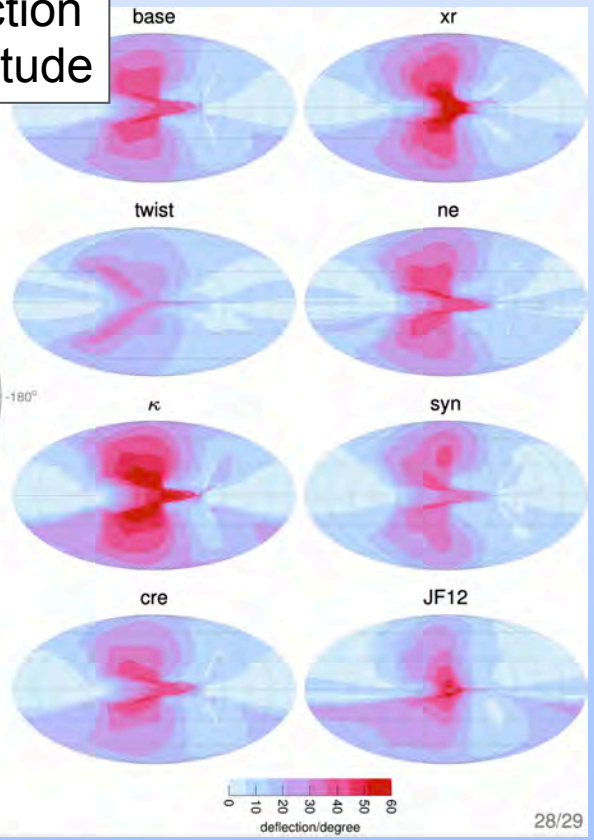


Magnetic deflections are large and uncertain at low rigidity

Source direction at E/Z = 20 EV



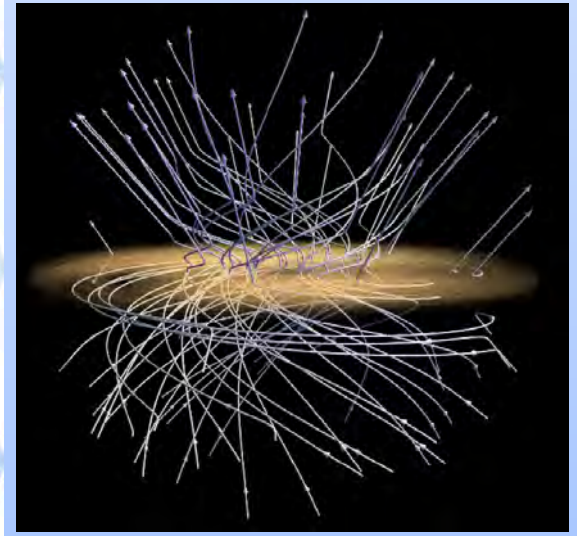
Deflection magnitude



Unger-Farrar 2023 Model Suite

M. Unger, CRA23 & MU+GF to appear soon

Larmor radius :
1.1 kpc (R_{EV} / $B_{\mu G}$)

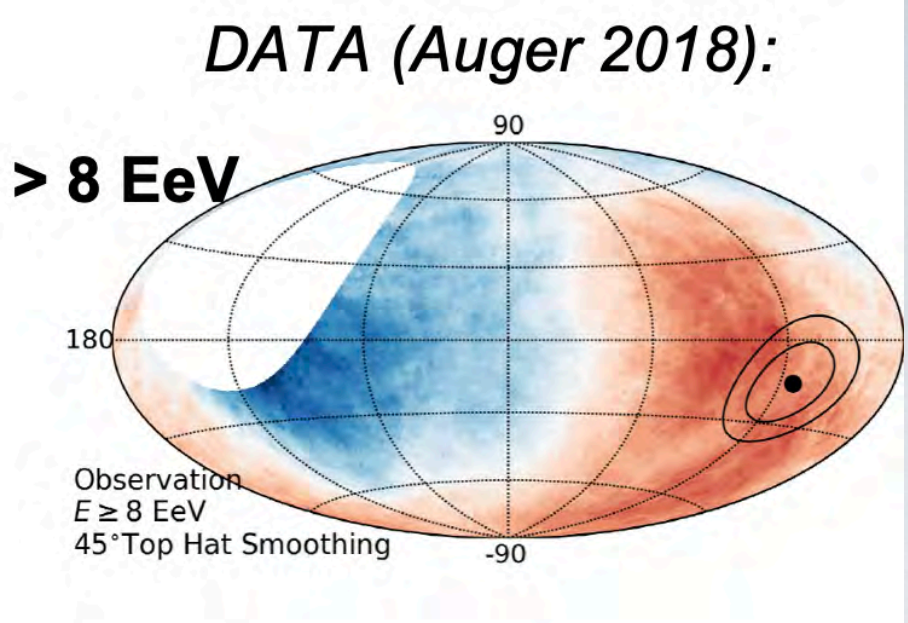


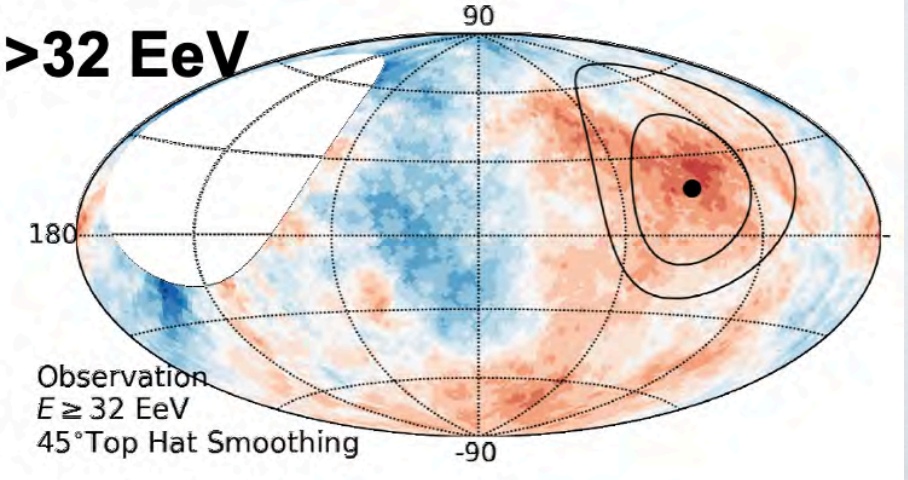
Arrival direction inhomogeneities

Clear Dipole anisotropy
amplitude >6% above 8 EeV

"Hot spot" in Cen A direction at high E

Correlations seen with
starburst galaxies and AGN
(ignoring magnetic deflections)



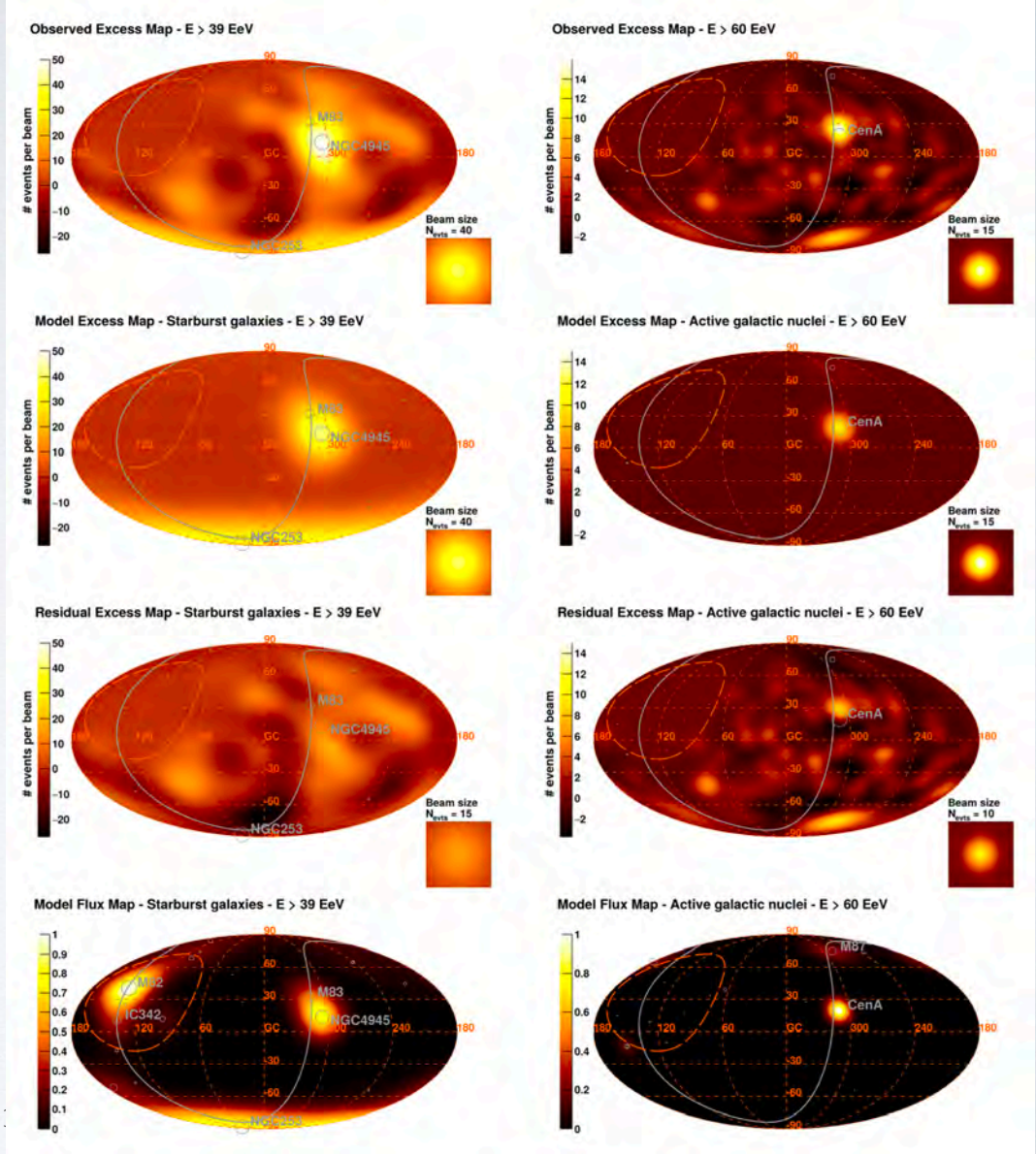


INDICATION OF ANISOTROPY IN ARRIVAL DIRECTIONS OF ULTRA-HIGH-ENERGY COSMIC RAYS THROUGH COMPARISON TO THE FLUX PATTERN OF EXTRAGALACTIC GAMMA-RAY SOURCES

THE PIERRE AUGER COLLABORATION
see the end matter for the full list of authors.

(Published in ApJL as DOI:10.3847/2041-8213/aaa66d)

TA has also reported hot spots, but so far they have failed to sustain 4σ



What can we deduce about UHECR sources?

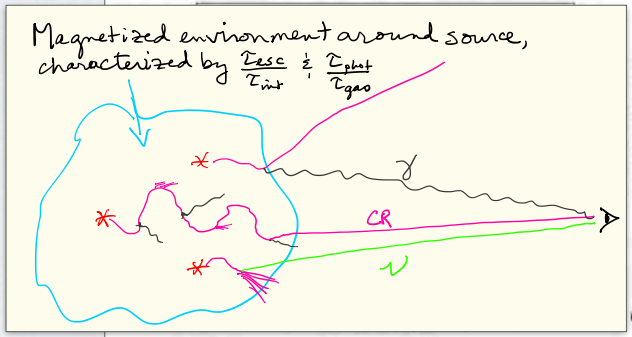
Indirect constraints on sources

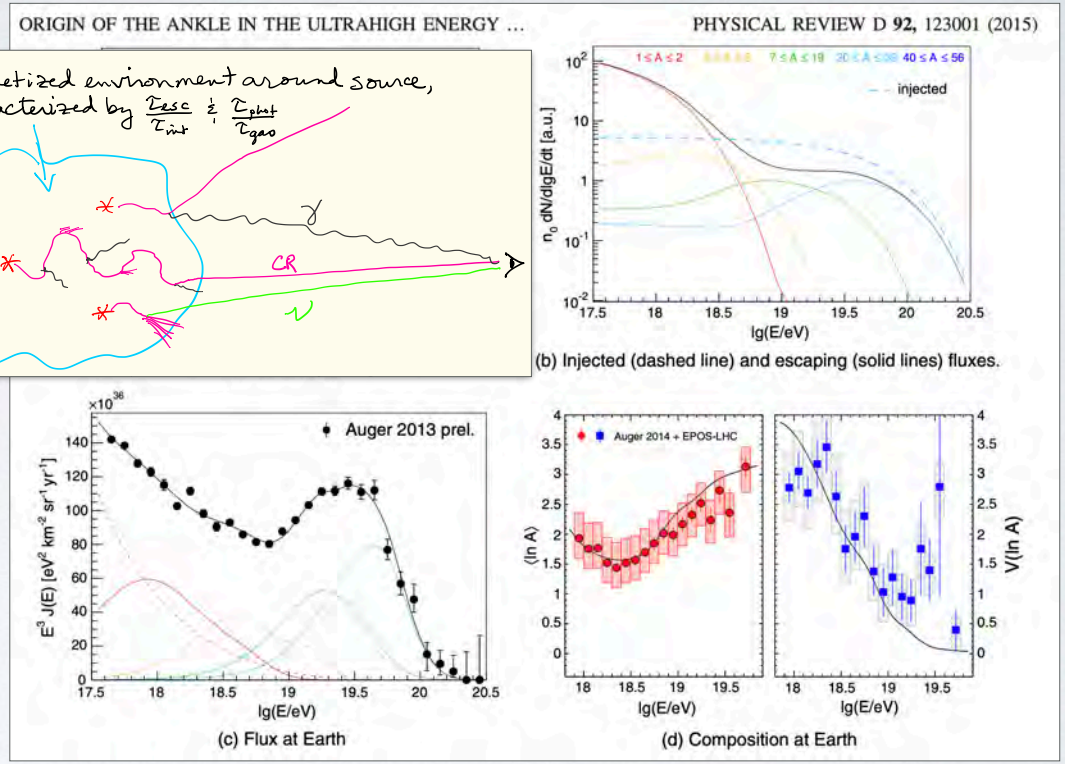
- Detailed fit to spectrum & composition ➜ processing in source environment [M. Muzio+GF, ApJL23]
- Large scale anisotropy [T. Bister+GF, in prep]
- [Hotspots]

UFA 2015 model proposed to explain light population below ankle

Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015



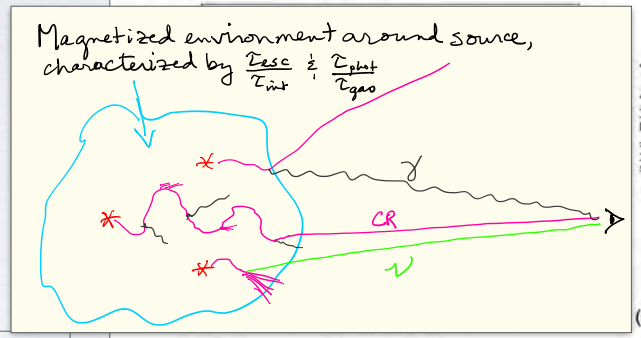


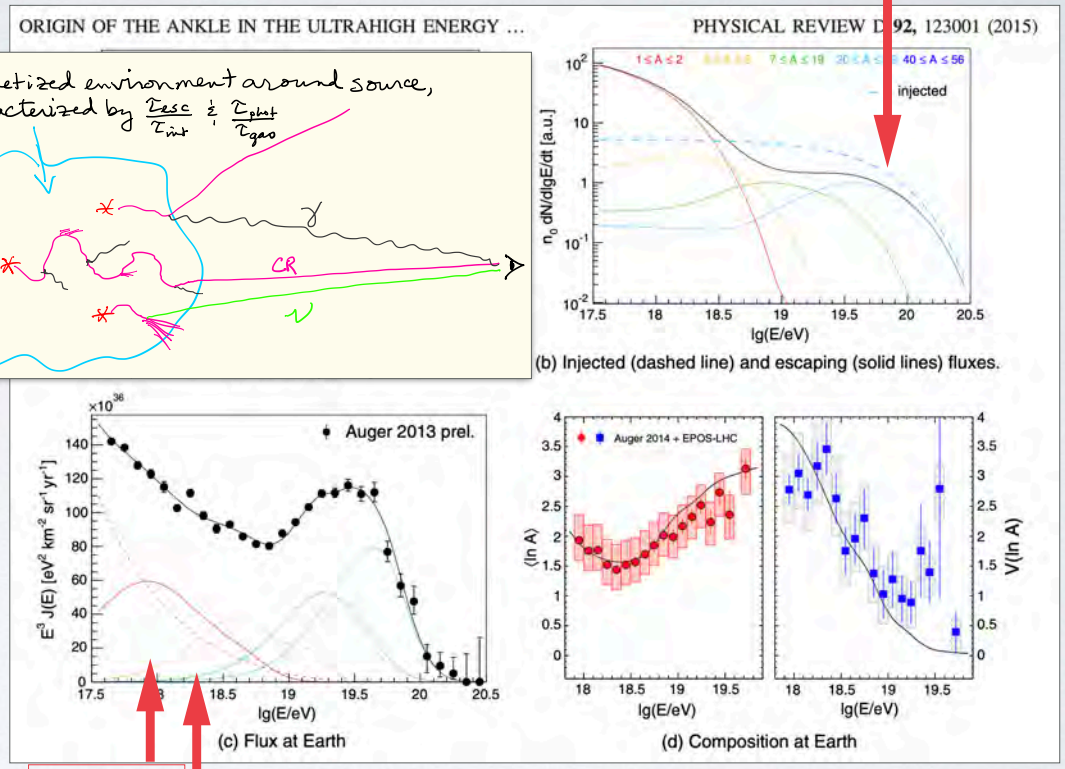
- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR

Cosmic Rays are Accelerated, then fragmented

Unger, GF & Anchordoqui 2015

Note large fraction of fragmented primaries





- Excellent fit to spectrum & composition
- Explains light population between between GCR & UHECR
- Smoking gun for UFA mechanism:

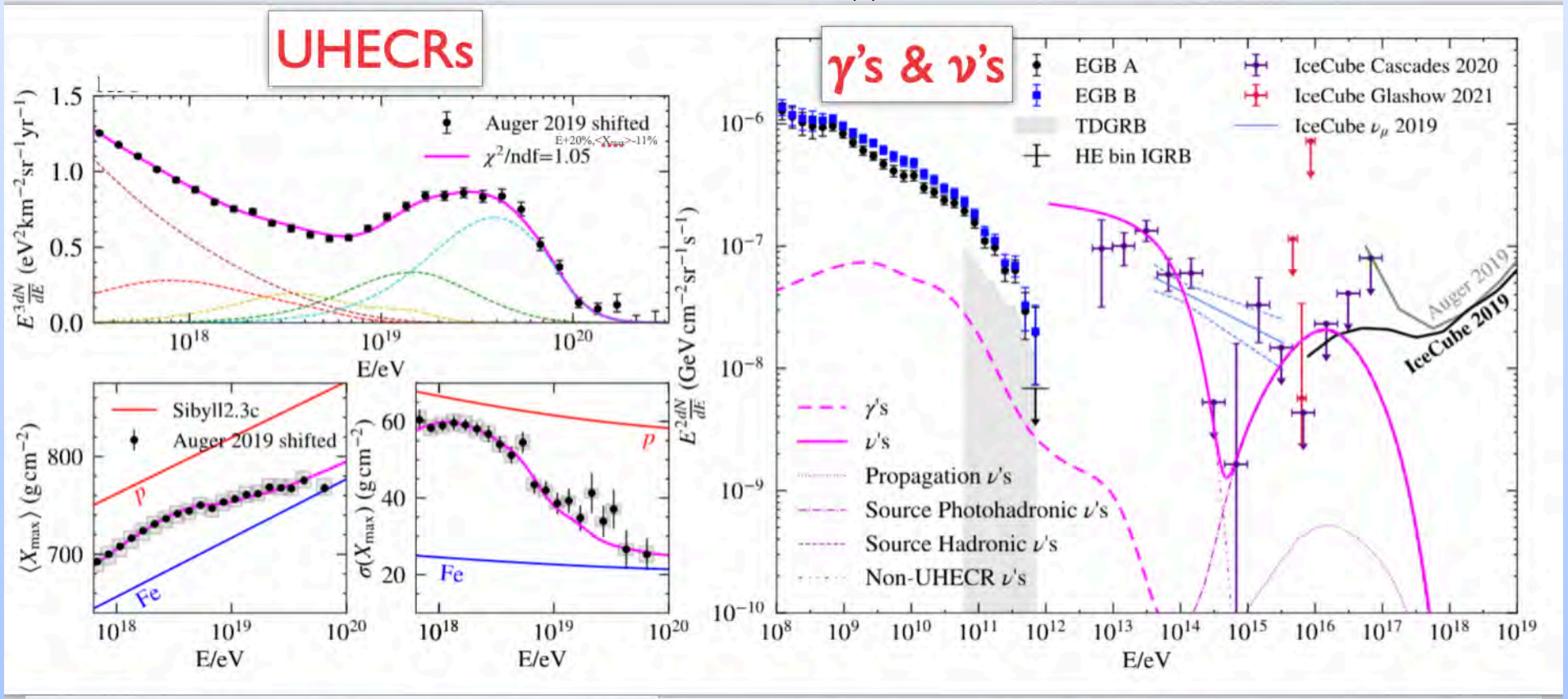
$E_p \sim E_{max} / A_{max}$ not E_{max} / Z_{max}

E_{max} / A_{max}

Peter's cycle protons would peak here

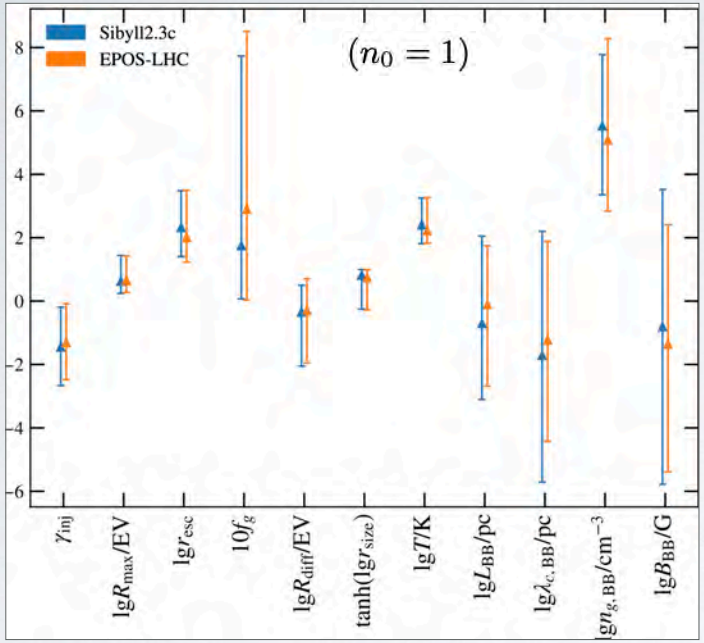
Constrains the source environment (T, B,…)!

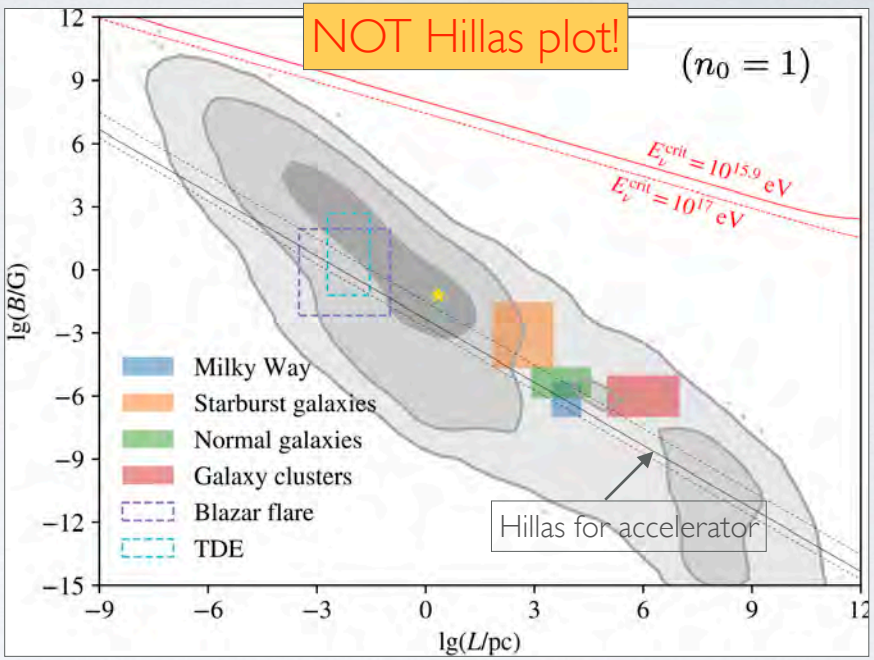
Muzio+GF ApJL23



$\gamma_{inj} = -1.45^{+1.25}_{-1.15}$ ➜ Diffusive Shock Accel. OK *(accelerator ≠ source)*

Constrain the **Surroundings** of UHECR Accelerators (M. Muzio+GF, ApJL2032)





btw: $\gamma_{inj} = -1.45^{+1.25}_{-1.15}$ ➜ Diffusive Shock Accel. OK *(accelerator ≠ source)*

$T_{surround}$ = 60 - 2000 K

{B_{rms} , L} of source** (not accelerator as in Hillas) **is constrained

black-body case $n_0 = 1$; the conversion for other n_0 values is $L = L_{BB}/n_0$, $B = n_0 B_{BB}$, $\lambda_c = \lambda_{c,BB}/n_0$, and $n_g = n_0\, n_{g,BB}$.

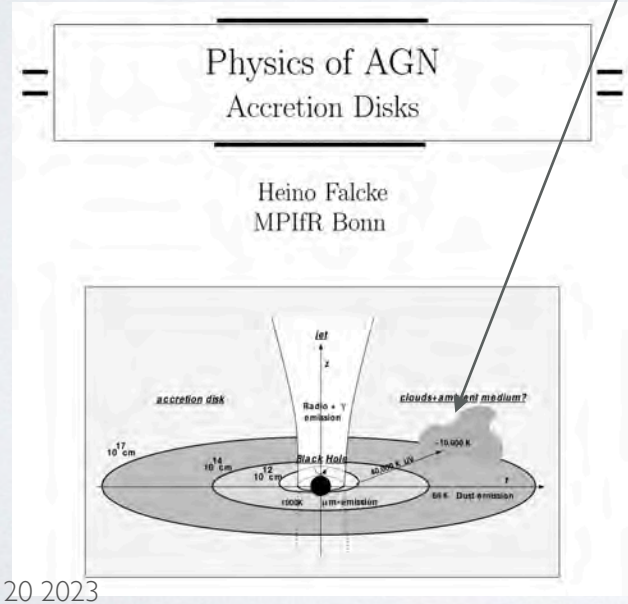
Muzio&GF arXiv:2209.08068

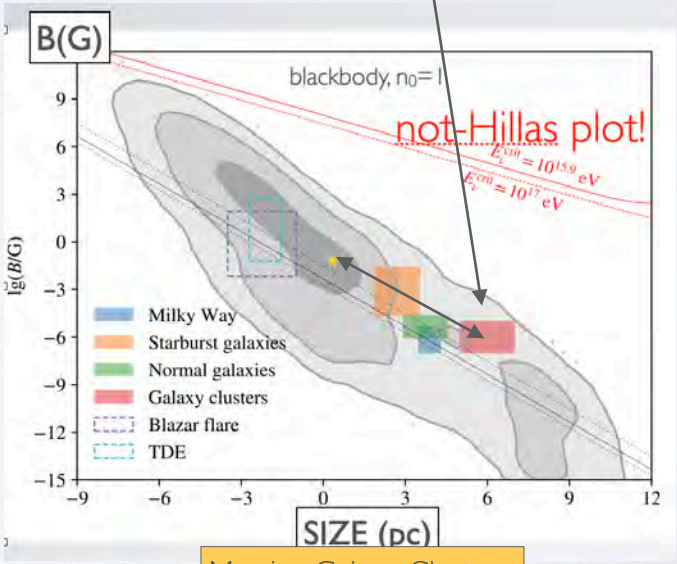
$T_{surround}$ = 60 - 2000 K excludes many candidate acceleration regions

~~Massive Galaxy Clusters~~ (2 x disfavored: T = $10^{7\text{-}8}$ K; n_0 = 1)

AGN:

- ~~radio lobes~~ (T ≈ few keV)
- ?internal shocks in jet? may be problematic; must also account for boost
- inner AGN disk: maybe ok (T=60-1000 K)
  - but nearby dangerous regions & must account boost



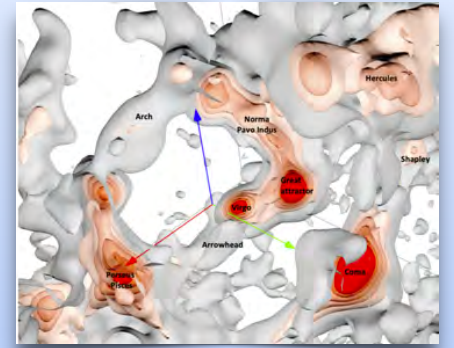


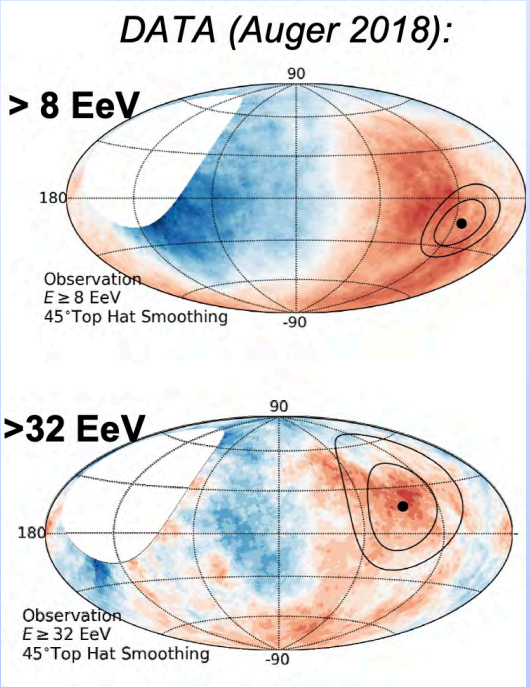
Massive Galaxy Clusters: poor fit to UHECRs

Source Density Constraint from Anisotropy

Teresa Bister + GF, to appear soon

- Ansatz: UHECR sources ~ large scale structure
  ➜ approximate illumination map
  + GMF deflections:
  Good accounting of dipole magnitude, direction & energy dependence.
  [Ding, Globus, GF ApJL 2021]

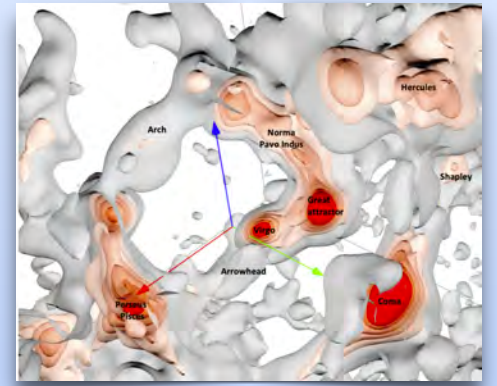




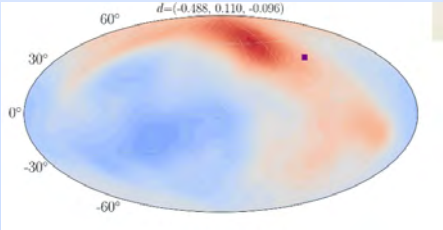
- New: [T. Bister+GF, in prep]
  - Self-consistent spectrum & composition
  - "Bias" of sources relative to LSS? (none seen)
  - Place constraints on source density

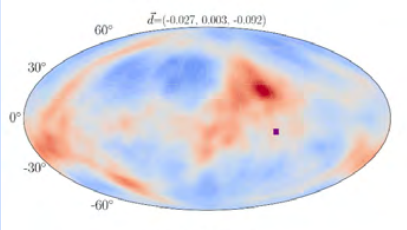
Modeling Anisotropy above 8 EeV

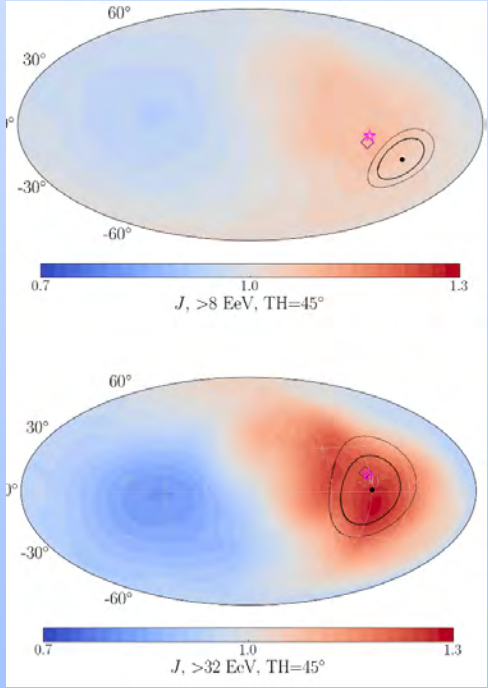
Teresa Bister + GF, in prep,

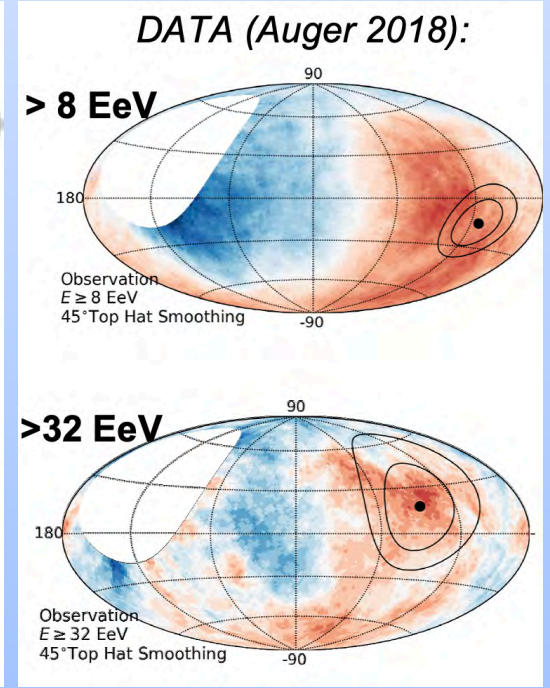


- LSS ➜ Illumination map
- propagate thru GMF
- good fit to dipole









More accurate treatment of approach of Ding, Globus, GF ApJL 2021

Extend to

- constrain "bias" between large scale distribution of mass and UHECR sources
- strong bound on UHECR source density > 10^{-3} Mpc^{-3}

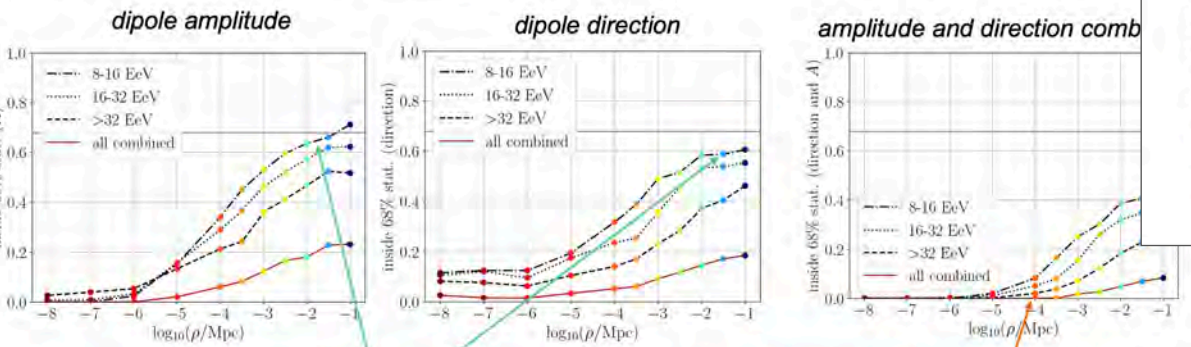
Source density < 10^{-3} Mpc^{-3} strongly disfavored

Teresa Bister + GF, to appear soon

Continuum model gives good fit to dipole. Create 1000 "source catalogs", source densities 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} Mpc^{-3}

Sampling source density: Dipole Amplitude and Direction

fraction within statistical uncertainty:



densities >10^{-2} / Mpc^3:

- behave as continuous model: 68% within 68% statistical
- combining direction & amplitude: almost independent ($0.68^2 = 0.46$)

densities <=10^{-4} / Mpc^3:
number of examples where dipole direction & amplitude fit at the same time: 0 / 1000

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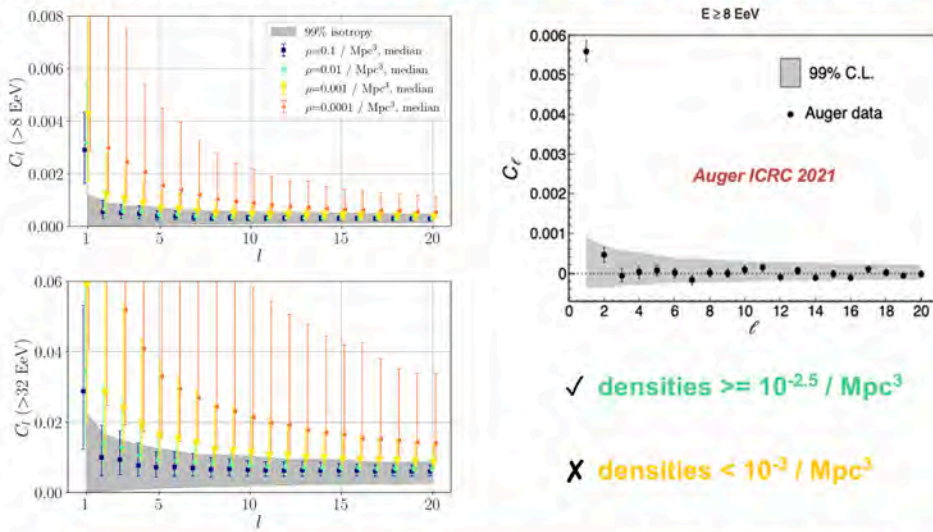
Sampling source density: Angular Power Spectrum



✓ densities >= $10^{-2.5}$ / Mpc^3

✗ densities < 10^{-3} / Mpc^3

c_l's are even more constraining on source density than dipole

Expect intermediate multipoles if source density < 10^{-3} Mpc^{-3}.

Unlikely to see observed dipole direction and magnitude for density < 10^{-3} Mpc^{-3}.

Data take-aways

- Auger & TA in agreement on both spectrum and composition
- Spectrum now very well measured; multiple breaks. Rigidity cuts off at ~ 5 EV.
- Lowest energy extragalactic CRs are protons and He.
- Composition becomes heavier with E, possibly reaching Fe

Interpretations

- Processing in region surrounding sources (UFA, MUF, …)
  - naturally explains sub-ankle extragalactic population
  - ➜ Spectral index can be consistent with DSA: escape from source environment hardens intrinsic spectrum of accelerator

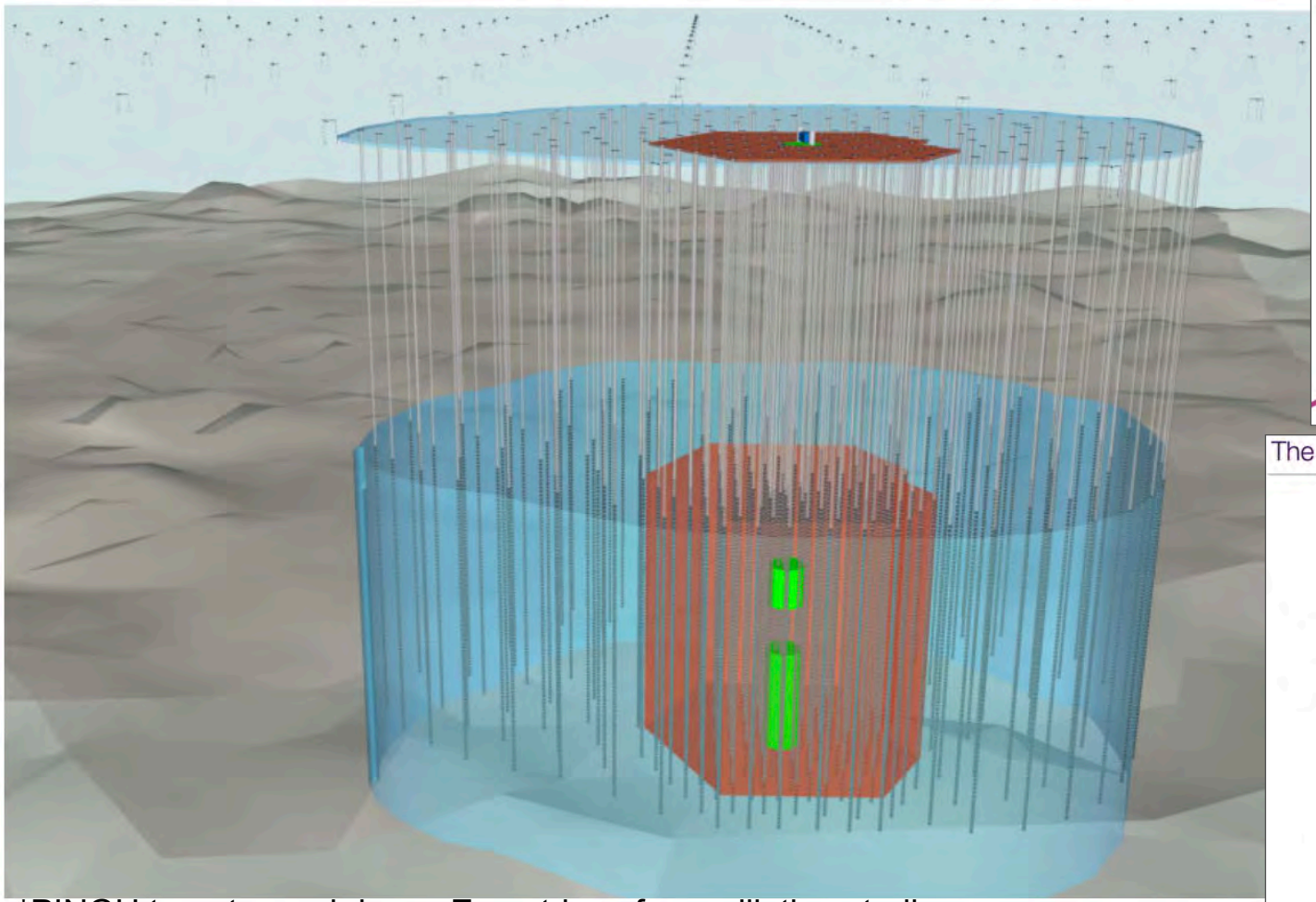
✦ Sources appear to be abundant and relatively weak

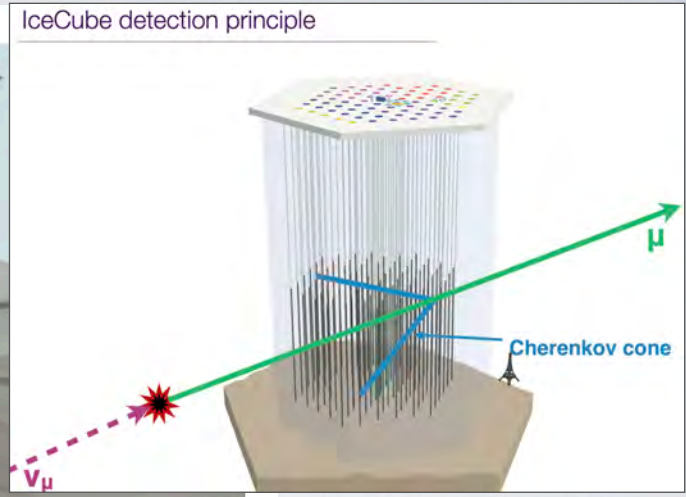
✦ Tidal disruption? (GF+Gruzinov, ApJ2009)

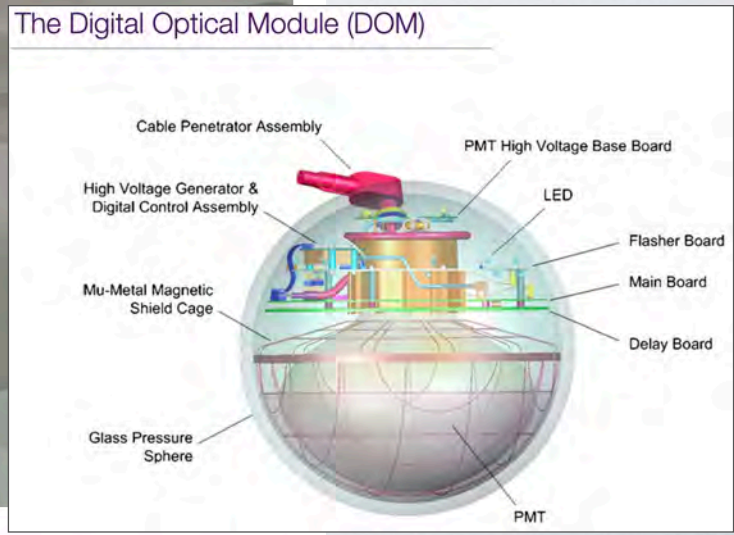
VHE Astrophysical Neutrinos IceCube

(coming: KM3Net, Antares in Mediteranean)

IceCube current (red) , Gen2 (blue) & DeepCore/PINGU* (green)



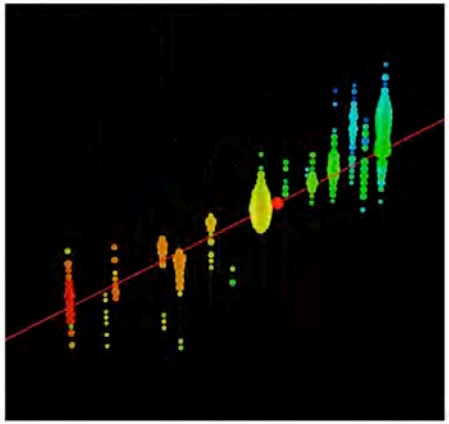




*PINGU targets much lower E neutrinos for oscillation studies

Three types of neutrino events:

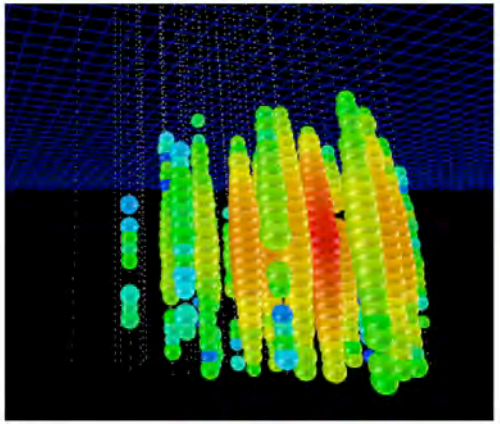
CC Muon Neutrino



track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

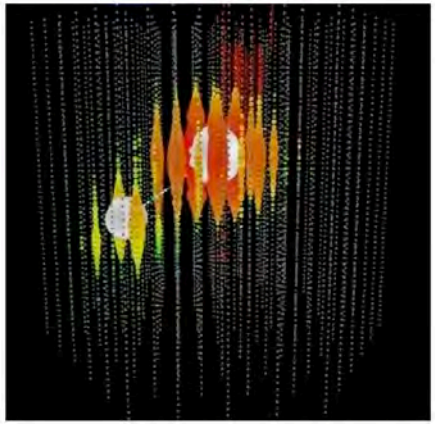
Neutral Current / Electron Neutrino



cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino



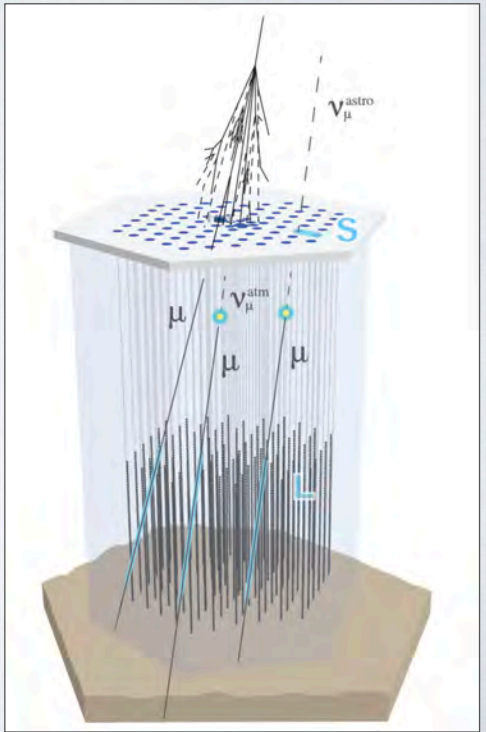
"double-bang" (≳10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

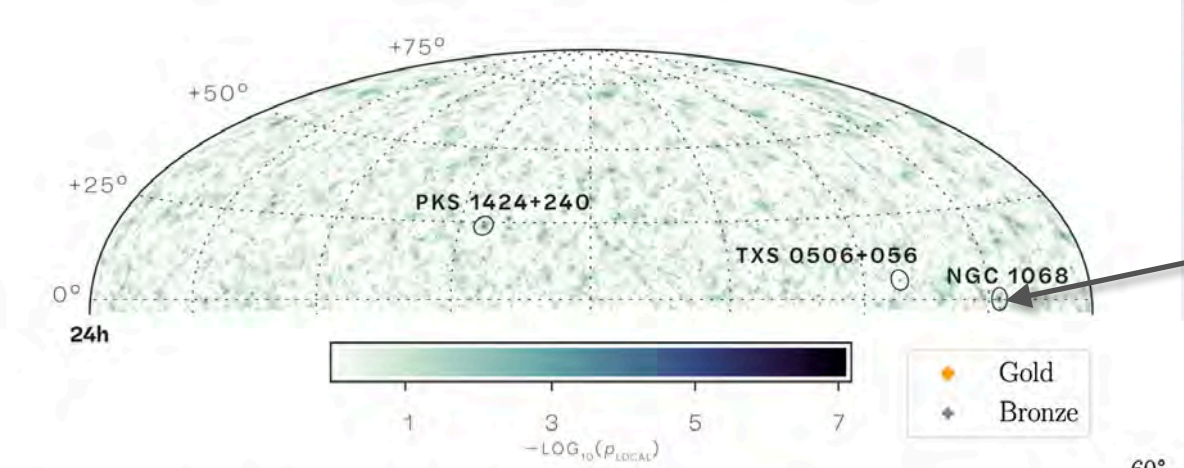
Darren R. Grant - University of Alberta

Neutrino Challenges

- Small interaction cross section (but grows with energy)
- Huge muon and neutrino background from CR interactions in atmosphere (>10^6 x signal)
  - use upward-going neutrinos
  - veto on accompanying muons or shower detected in IceTop

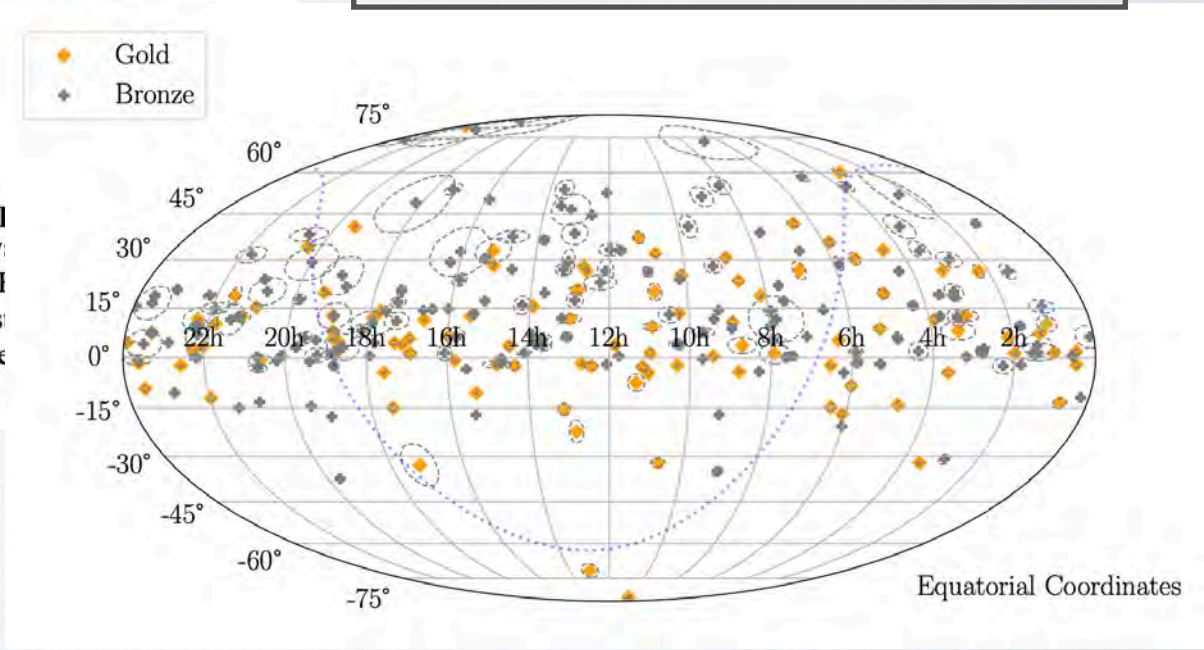


Neutrino Arrival Directions



statistically significant over density; nearby starburst galaxy

Figure 1: **Skymap of the scan for point sources in the Northern Hemisp**
represents the local p-value obtained from the maximum likelihood analy
spectral index as free fit parameter) at each location in the sky, shown in I
with Hammer-Aitoff projection. The black circles indicate the three mos
the source list search. The circle of NGC 1068 also coincides with the ove
Northern Sky.

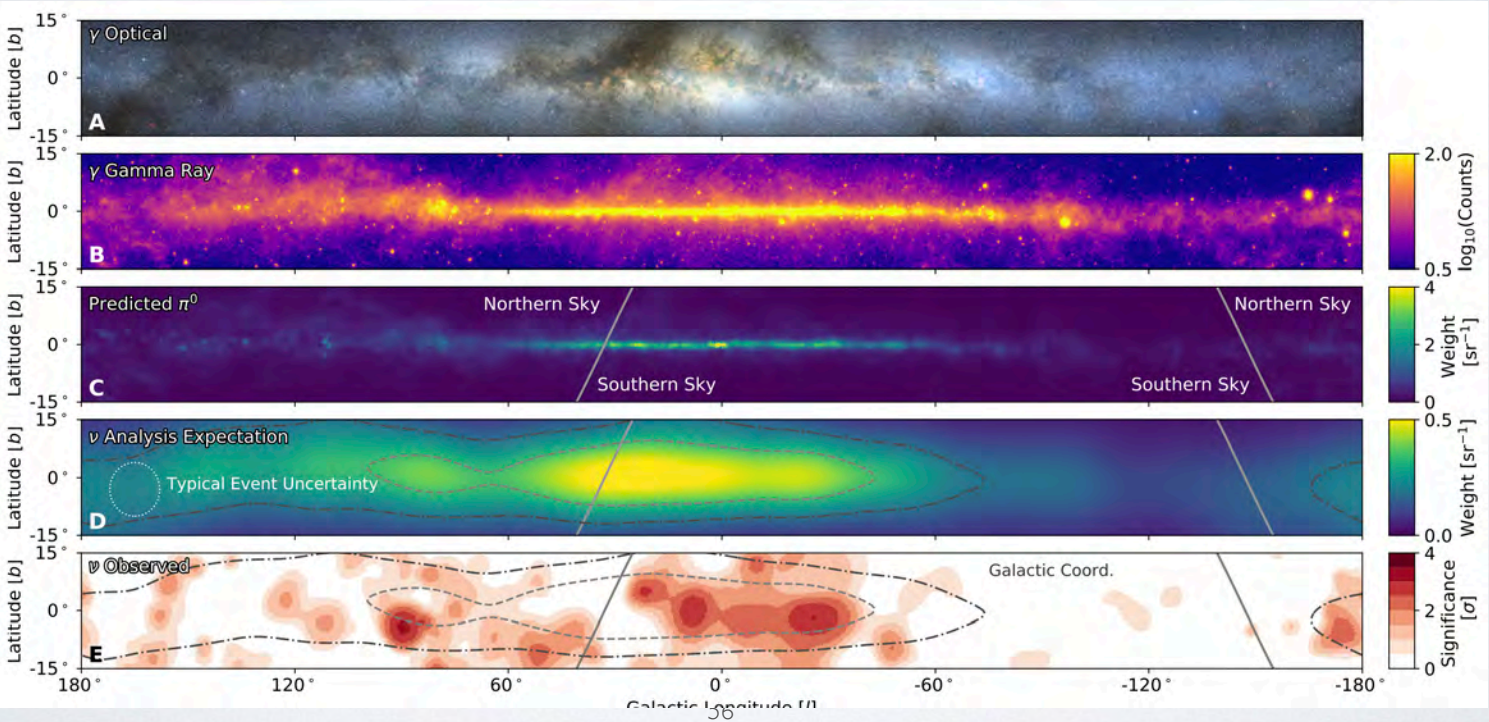


Neutrino correlations with transients (multi messenger astronomy)

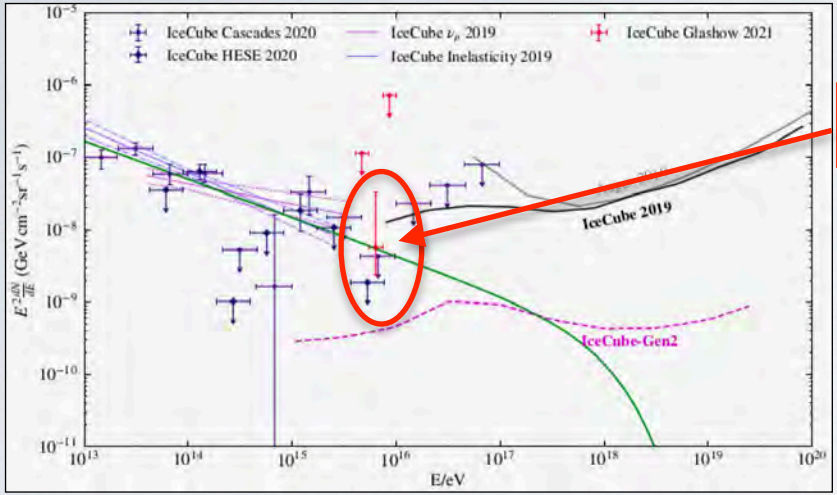
- Associations reported with
  - Blazar flares (Fermi TXS 0506+056, …)
  - ~3 Tidal Disruption Events
- Combination of temporal AND directional correlations reduces chance associations, but not fully accepted yet.
- IceCube places strong limits on GRB associations

Galactic Neutrinos Science 2023

Galactic Center is overhead for IceCube, so CR muon background (10^6 x bigger) is overwhelming
Use ML and cascade events to avoid muon contamination



Still Early Days for neutrino spectrum and composition



Glashow event: $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ hadrons

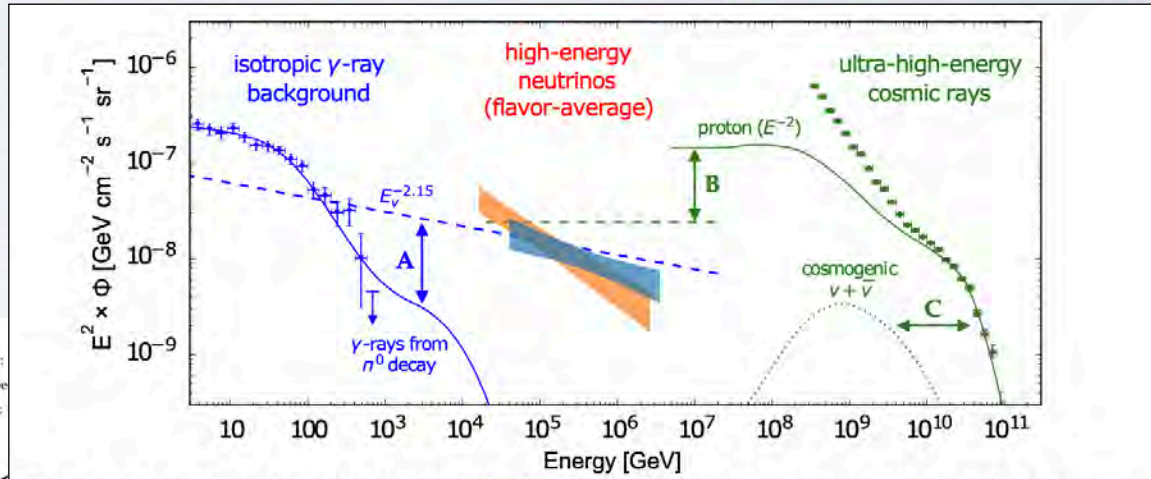
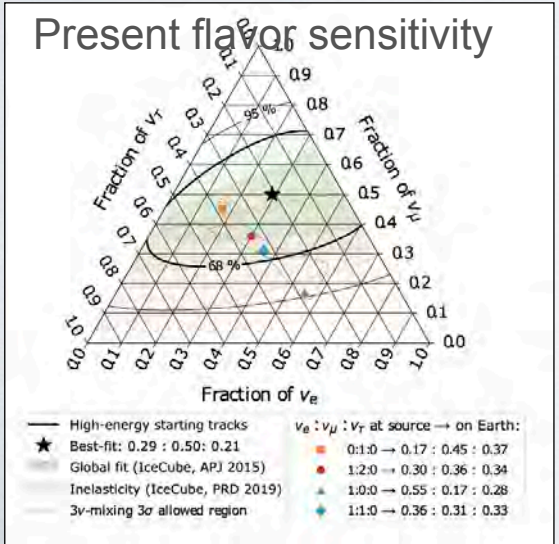
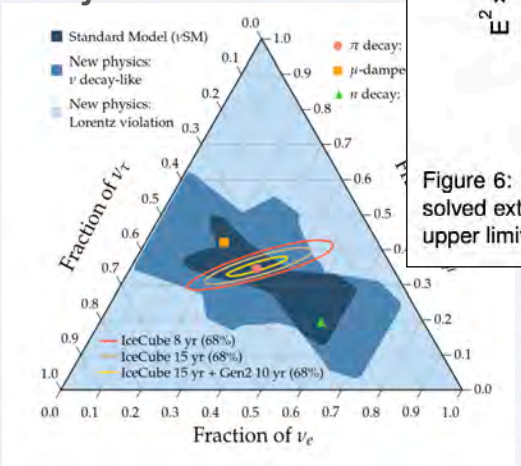


Figure 6: The per-flavor flux (ϕ) of neutrinos [21, 38] (orange and blue bands) compared to the flux of unresolved extragalactic γ-ray emission [32] (blue data) and UHE cosmic rays [59] (green data). We highlight two upper limits on the neutrino flux (dashed lines) predicted by multi-messenger models [52, 60].

Present flavor sensitivity



Projected Gen2



Energy per decade of energy is roughly the same in UHECRs, IceCube Neutrinos & diffuse gamma rays.

Enjoy the UHECR-VHE neutrino future!