Transient Source for the Highest Energy GALACTIC COSMIC RAYS

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and future collaboration with Marco Muzio & Diego Monzon

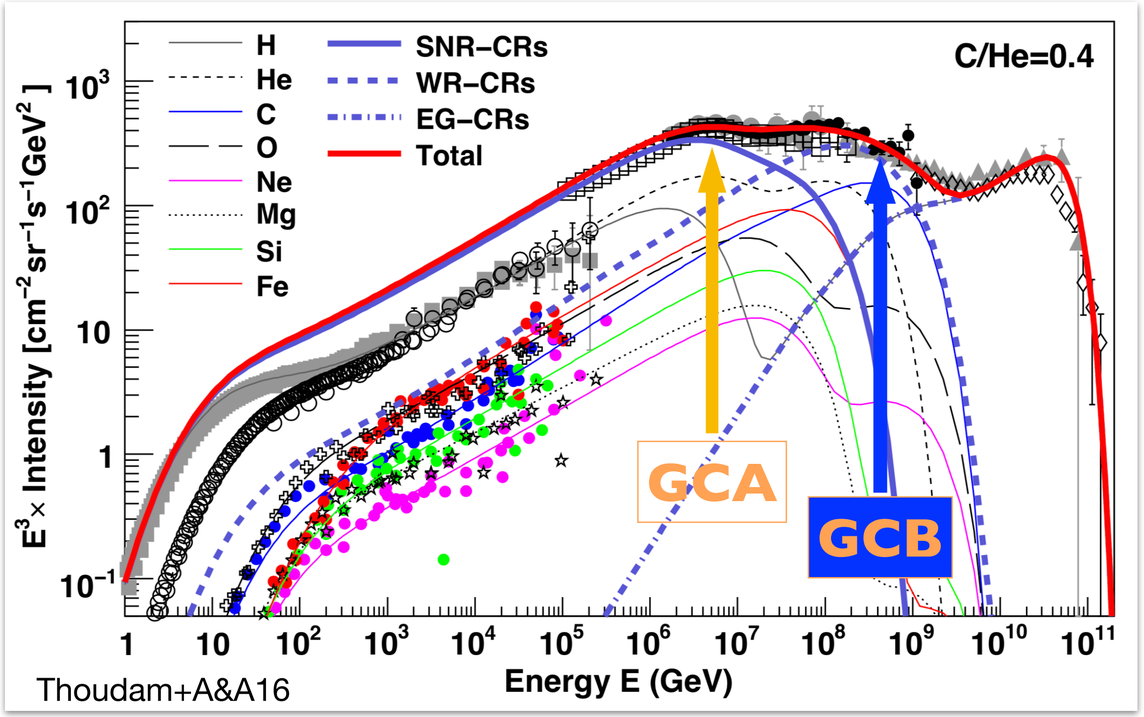
Identifying source of Galactic Component “B”

[term “B” coined by Hillas 2005]

- Supernova Remnant (SNR) acceleration is insufficient to explain highest energy GCRs
- Use Auger anisotropy data to determine direction and magnitude of Galactic B dipole

➡ favors transient source

- localize it
- identify possible relic
- power requirement & demographics



Proposals for GCB acceleration

- Acceleration in Galactic termination shock ➜
  - dipole direction: ≈ toward or away from GC (symmetry)
  - dipole magnitude: likely small (shock large & ≈ spherical)

- **Transient** (SN in star cluster (Bykov+17,18), W-R stellar wind, ccSN in binary pair) ➜
  - source most likely in the Galactic plane (*young* massive binary) ; not necessarily centered
  - flux, anisotropy ⇔ location/time of the event
    - unique SNR candidate

Find GCB anisotropy by subtracting extragalactic contribution

ApJ 2020; arXiv2002.06172

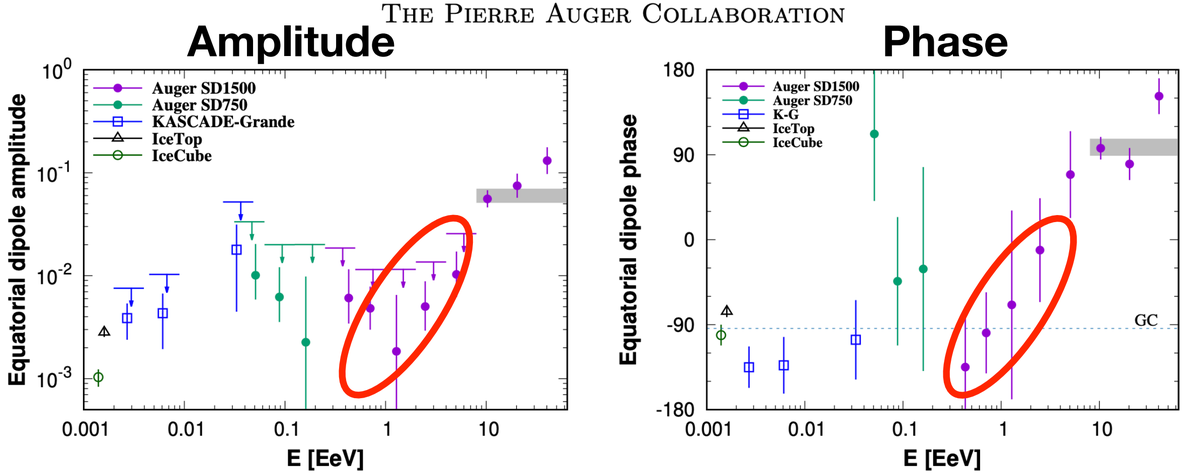
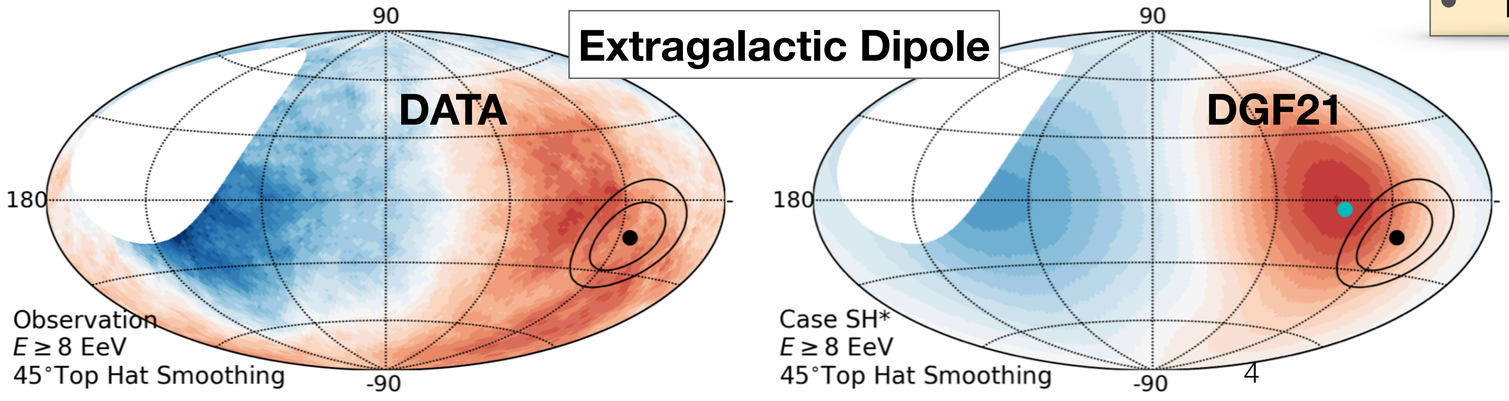
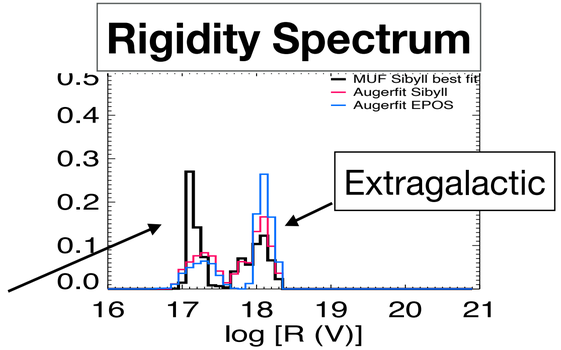


Figure 1. Reconstructed equatorial-dipole amplitude (left) and phase (right). The upper limits at 99% CL are shown for all the energy bins in which the measured amplitude has a chance probability greater than 1%. The gray bands indicate the amplitude and phase for the energy bin $E \geq 8$ EeV. Results from other experiments are shown for comparison (IceCube Collaboration 2012, 2016; KASCADE-Grande Collaboration 2019).

- Anisotropy above 8 EeV well-explained by Large Scale Structure and magnetic deflections in GMF and EGMF (Ding, Globus, Farrar ApJL 2021) [see Ding CR1:1415]
- Composition below 8 EeV (Auger) shows presence of heavy Galactic B component:
  - GCR fraction (0.5, 0.3, 0.1) in (1-2, 2-4,4-8) EeV bins
  - Peak GCR rigidity ~ $10^{17.2}$ eV
- **Determine the EGCR contribution to anisotropy at lower energies** (E-dep weak, from DGF21 analysis)
- **Residual is anisotropy of GCB**

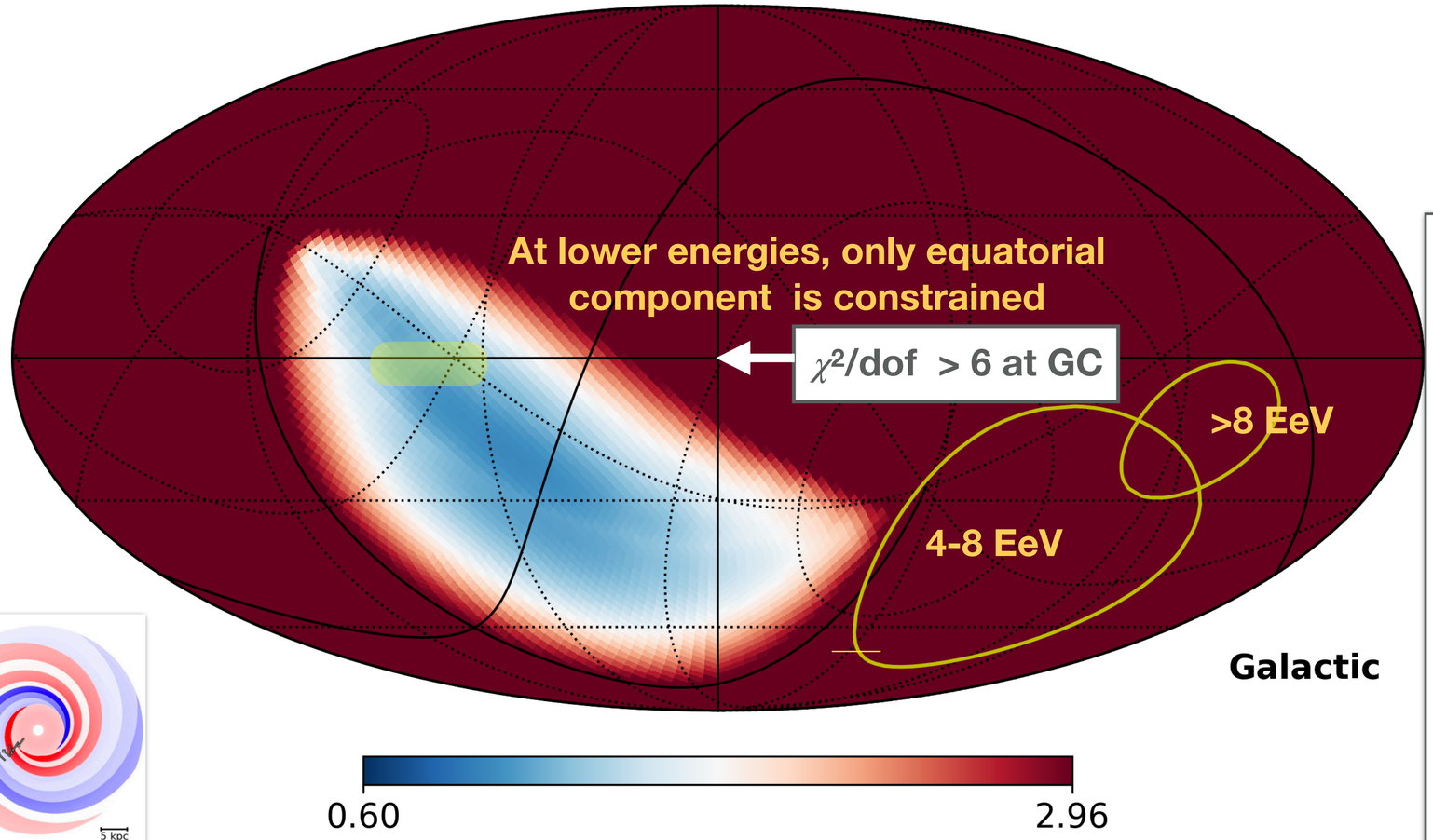


GCB: < lgR > = 17.2



GCB DIPOLE direction probability

χ^2 per observable of dipole components in 8 energy bins > 0.25 EeV



JF12 GMF def at R=10^{18} eV:
~ 7° in b, ~ 15° in L

GCB DIPOLE IS NOT AT THE GALACTIC CENTER!

Direction of GCB dipole consistent with being E-indept

Amplitude of Galactic dipole
$\alpha \approx 0.05$

Total dipole shifts towards GC as GCA takes over

Dipole from Transient Source

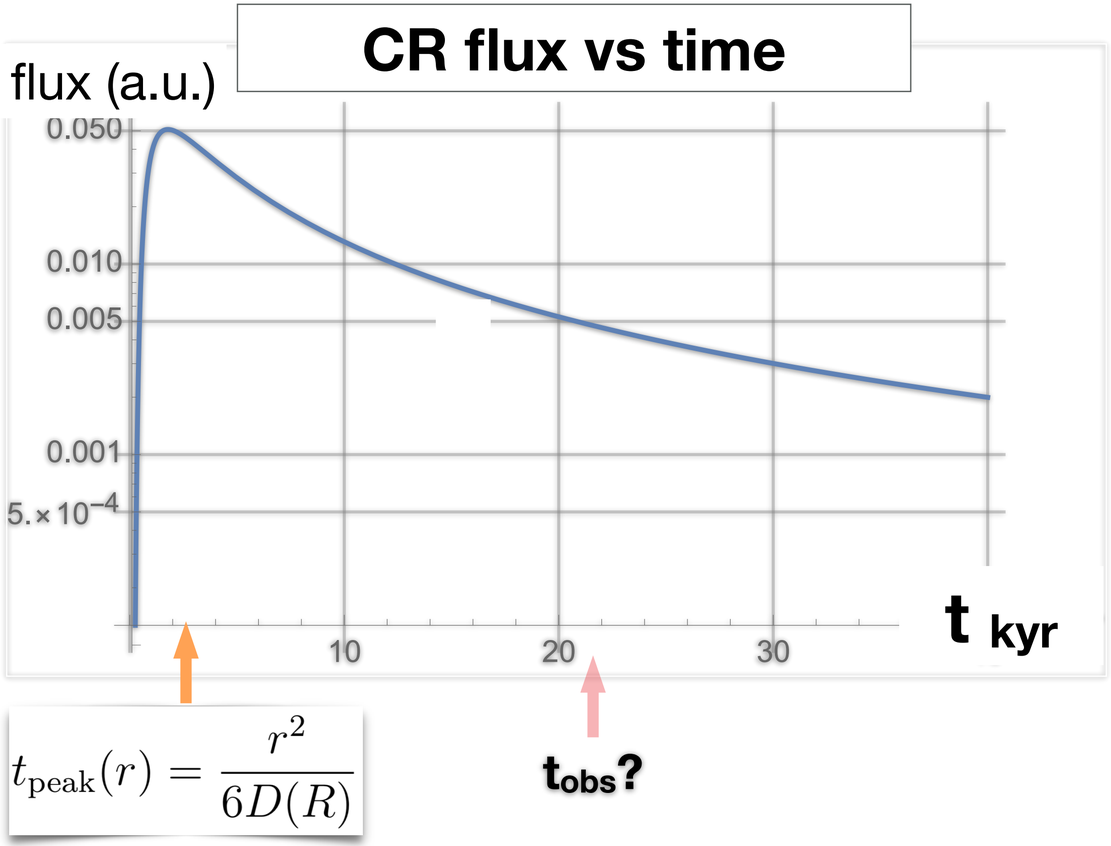
- CR propagation from a transient source in a homogeneous diffusive field **depends only on rigidity *R = E/Z*:**

$$n(r,t) = \frac{N_0\ e^{-r^2/(4\,D(R)\,t)}}{(8\pi\,D(R)\,t)^{3/2}}$$

- The dipole ***anisotropy*** depends ***only*** on source distance **r** and time since the event **t**, **not on D** (GRF + T. Piran, astro-ph/0010370):

α = r /(2 c t)

- ➜ GCB anisotropy is approximately independent of energy and composition
- Better approx: higher rigidity CRs escape more easily; E bins ≠ R bins mag **α** can depend weakly on E.
- Best: tracking to account for anisotropic diffusion (+Diego Monzon, M. Muzio)



Inferring source of GCB; Energy budget

1. **Fit to GCB anisotropy:**

$\alpha = r/(2\,c\,t) \approx 0.05 \Rightarrow 2\ t_{kyr}$ (1 kpc/3 kyr) **$\approx 20\ r_{kpc}$**

$t_{kyr} \approx 30\ r_{kpc}$

2. **Search for relic in direction of anisotropy:**

- Supernova remnant catalog http://www.mrao.cam.ac.uk/surveys/snrs ➜
- G65.3+5.7: **(r,t) = (0.8 kpc, 22.4 kyr)** ➜

  predicts **$\alpha \approx$ 0.053**
- associated PULSAR: PSRJ1931+30 (indicates core collapse SN)

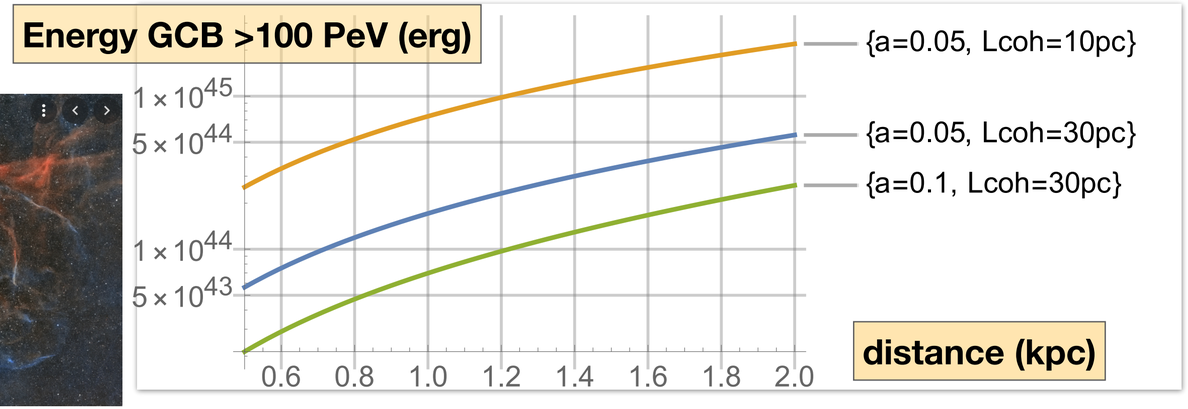
Energy emitted in CRs above 0.1 EeV:

- local CR flux $j = \frac{n\,c}{4\pi}$ ➜ n(r,t)
- local energy density of CR's with rigidity R

$$\epsilon_{\lg R} = \sum_Z \frac{4\pi}{c} Z\, 10^{\lg R}\, j(\lg E = \lg R + \lg Z)\, \Theta(E - E_{\min})$$

- CR energy emitted by source: $E_{\rm tot} = \sum_{\lg R} \epsilon_{\lg R}\ (8\pi\, D(R)\, t)^{-3/2}\ e^{r^2/(4\,D(R)\,t)}$

  D(R) from B (JF12) & Lcoh only ; used GAP08



Available energy in ccSN ~ 10^{54} erg ⇒ CR production uses small fraction

SOURCE demographics

- Explosion outflow must collide with external wind to increase max rigidity (via colliding shock flow)
  - (Bykov+17,18) suggest SN in young star cluster, but no SNR + star cluster in anisotropy direction
- New suggestion: core collapse SN in binary pair of massive stars.
  - massive stars are mostly in binaries.
  - typically have Wolf-Rayet wind (high velocity, intermediate mass)
  - pair separates after explosion so don't expect remnant pulsar to have a binary companion

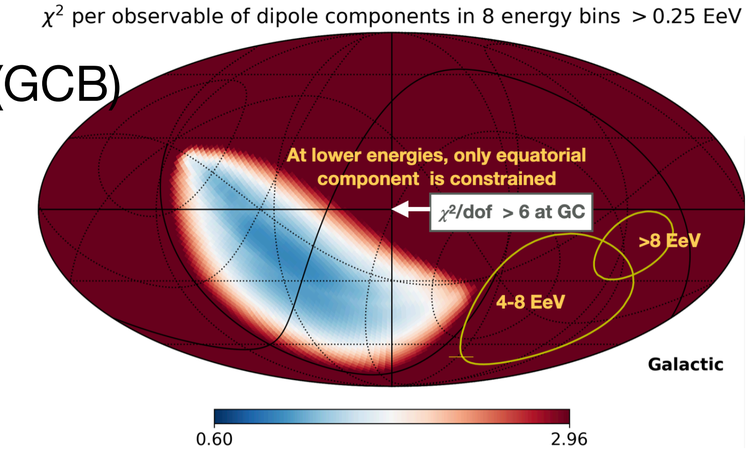
- 1 ccSN in MW /100 yr ⇒ 300 ccSNe in 30 kyr.
- ~4% of all SNe are within 2 kpc of us.
- ➜ ~12 ccSN within 2 kpc in 30 kyr time window.
- I event currently contributing ➜

10 - 100% of core collapse SNe produce High Energy CRs (E/Z >~100 PeV)

- reasonable, because most massive stars are in binaries.

- for the future: MC sim for distribution of anisotropies

CONCLUSIONS

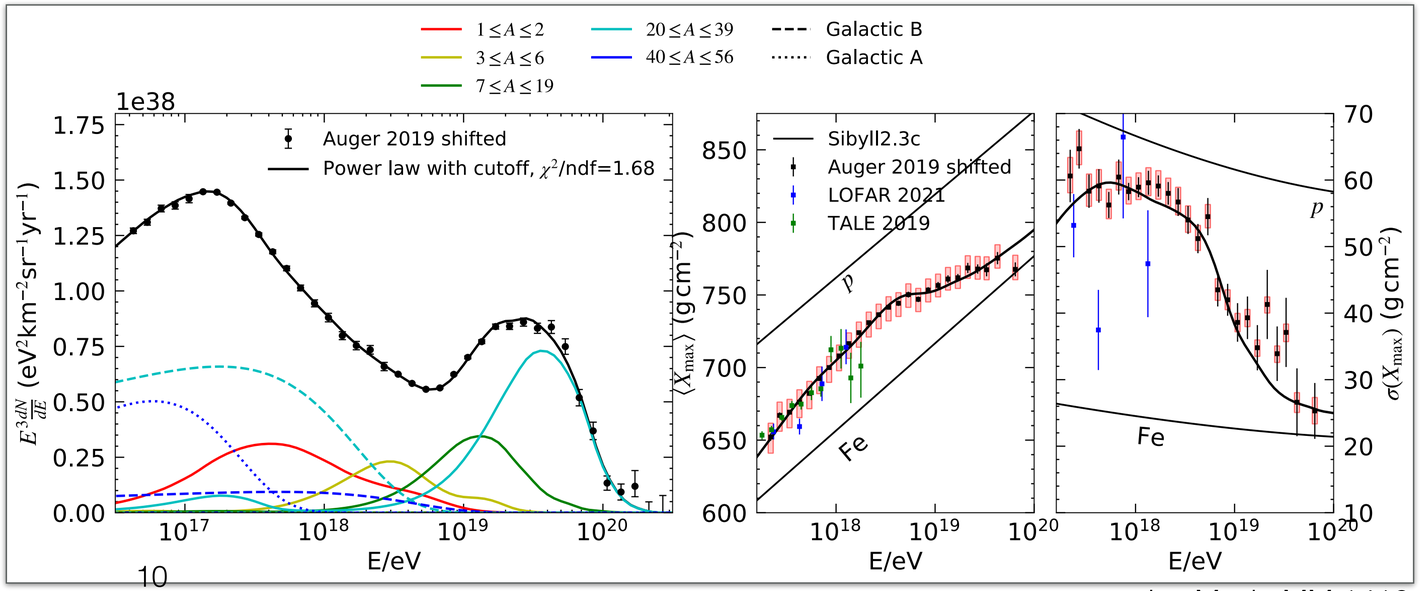


- We have measured the dipole anisotropy of the highest energy Galactic CRs (GCB)
  - < Rigidity > ≈ 0.15 EV, A up to ≈ 15
  - Dipole anisotropy **α** ≈ 0.05, towards B ≈ 0° (from theory), L ≈ 70° ±~15° (from data)
    - dipole toward GC excluded at > 6 σ
  - **Dipole anisotropy not toward GC**:
    - Galactic wind termination shock disfavored
    - ***favors transient source***
- Observed GCB Anisotropy strength and direction ➜ SNR G65.3+5.7 / PSR1931+30 (?)
  - 0.8 kpc away, 20+2.4 kyr ago excellent agreement with **α** ≈ 0.05
  - ≲ 10^{45} erg in CRs with E>100 PeV energy budget very comfortable (~10^{54} erg available)
- Proposed system:
  - core-collapse SN in massive binary ➜ converging shock flow: SN ejecta-Wolf-Rayet wind
  - population statistics: O(1) probability of seeing anisotropy and flux level observed

Next steps

with Diego Monzon and Marco Muzio joining in

- **Fit for composition/rigidity spectrum of GCB and high energy part of GCA (Muzio)**
  - Input: Auger spectrum and composition; high mass GCA from ARGO-YBT+LHAASO (joint), Tunka-25, Yakutsk, & TIBET-III
  - Knowing GCA/B composition in all energy bins >100 PeV ➜ *separate GCA & GCB dipole; predict total dipole evolution with energy* [compare to Kascade-Grande asymmetry (Ahlers19)]
- **More accurate mapping between GCB dipole direction and true source direction (Monzon)**
  - simulate trajectories in GMF
  - *Predict energy dependence of GCB anisotropy*
  - *More accurate anisotropy for G65.3+5.7*
- High precision timing of PSRJ1931+30
  - age: confirm/exclude association with SNR
  - measure magnetic field: magnetar?



see also Muzio MM:1410