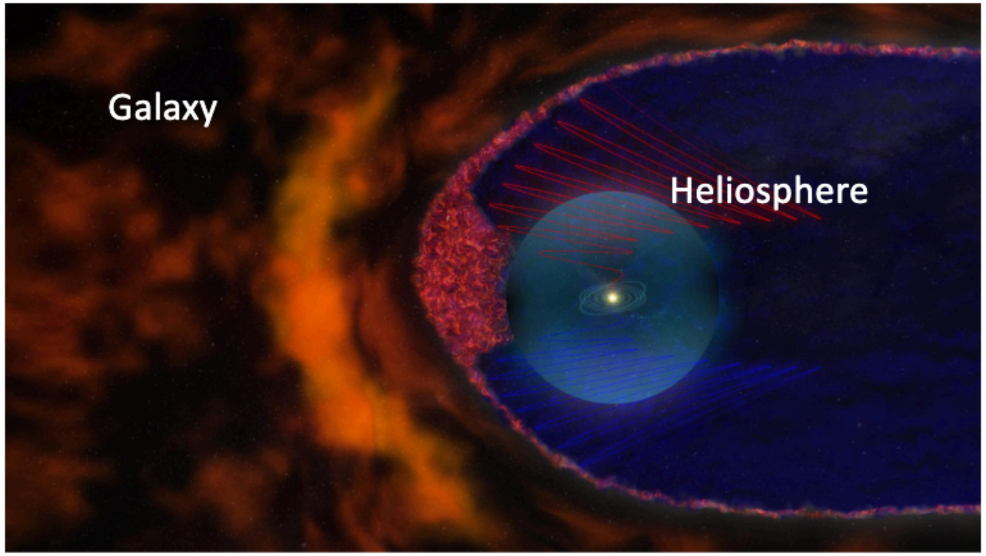
Galactic/Extragalactic Cosmic Ray Transition

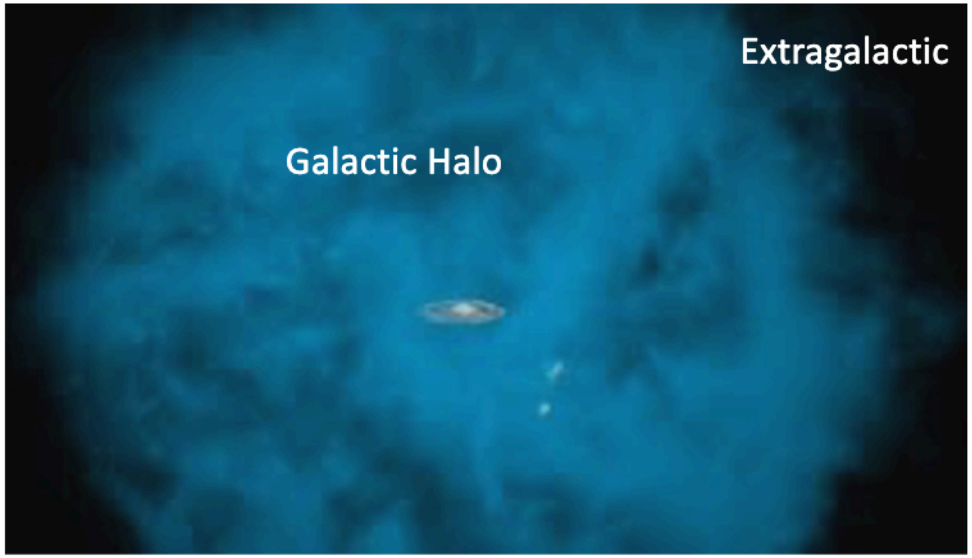
An Analogy Between

Gaisser, HAP Workshop, KIT (2015)

Heliosphere

Galactic Halo

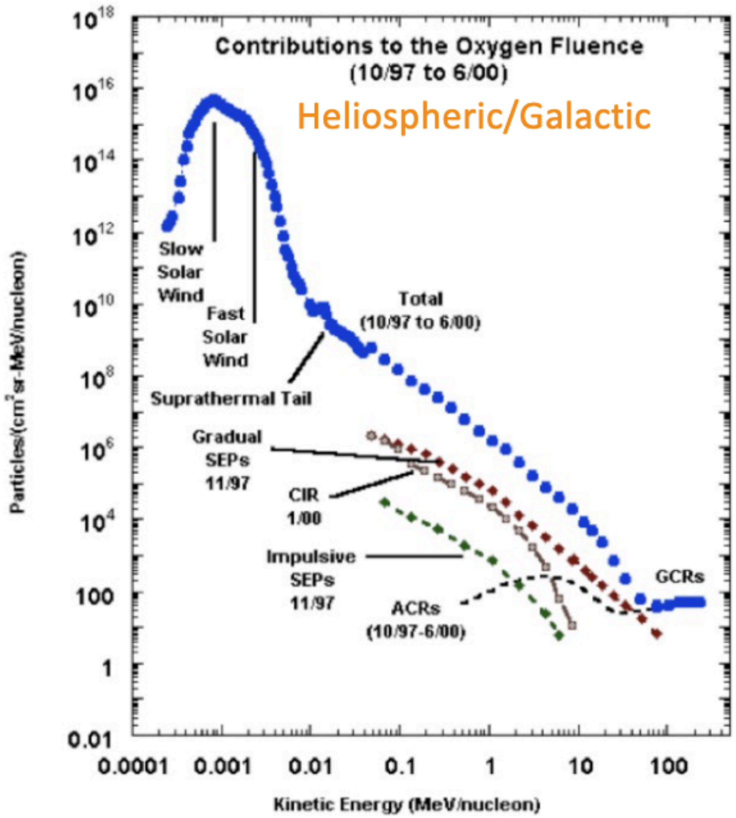




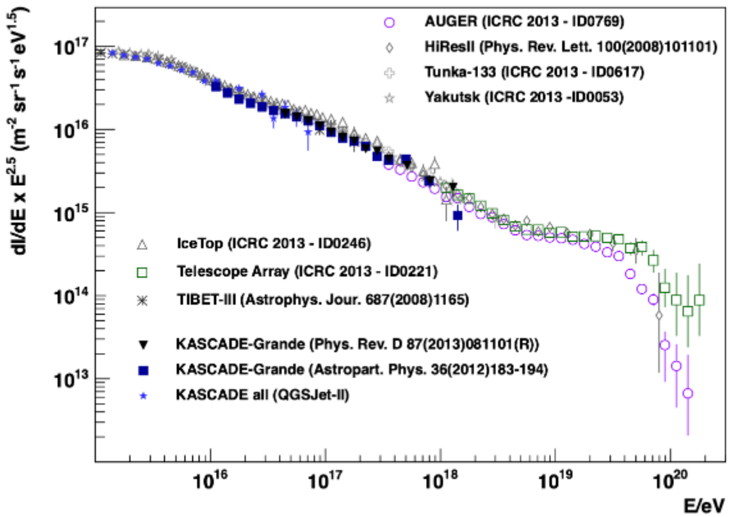
Galactic/Extragalactic Cosmic Rays

An Anology with the Transition from the Heliospheric to Galactic CR Spectrum

Gaisser, *Front.Phys.(Beijing)* 8 (2013) 748-758



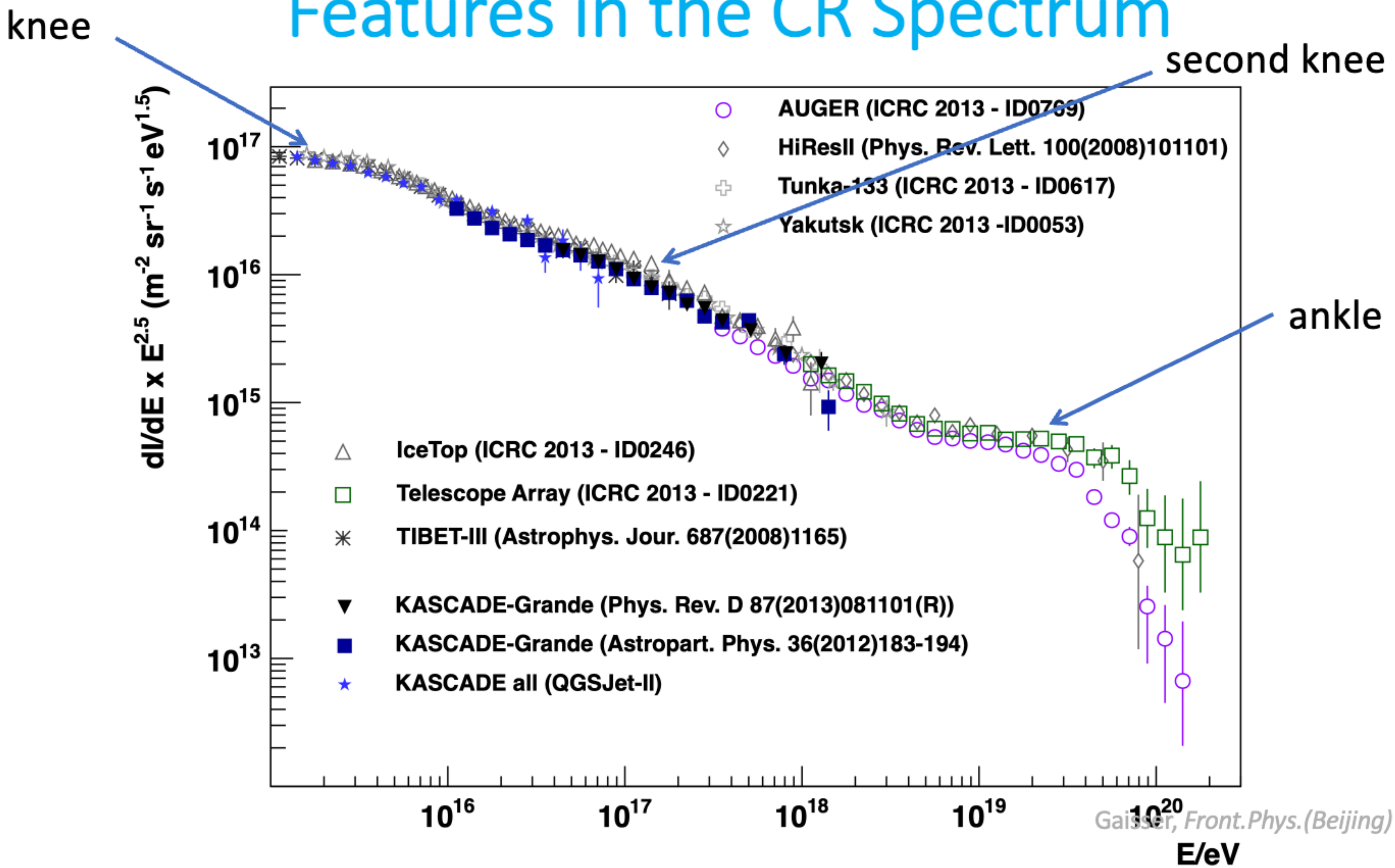
Galactic /Extragalactic



- Several kinds of events contribute
  - Typically power law with exponential cutoff
  - Different values of E_{max}
  - High energy events less frequent
- Overall spectrum is a power-law with a knee

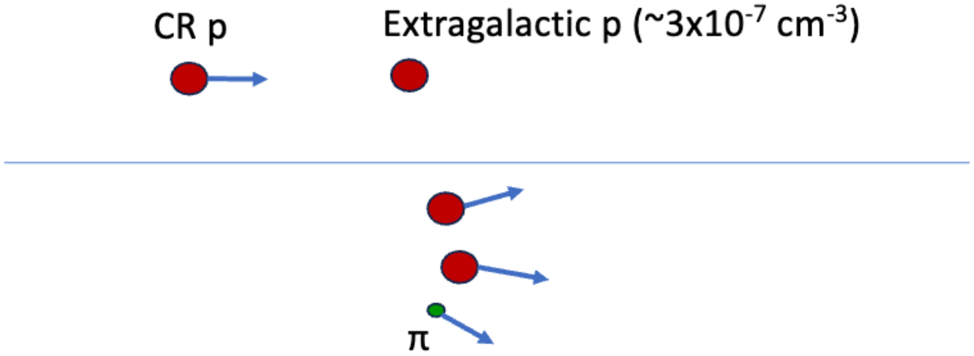
Gaisser, HAP Workshop, KIT (2015)

Features in the CR Spectrum



Gaisser, *Front.Phys.(Beijing)* 8 (2013) 748-758

Origins of the CR Spectrum?

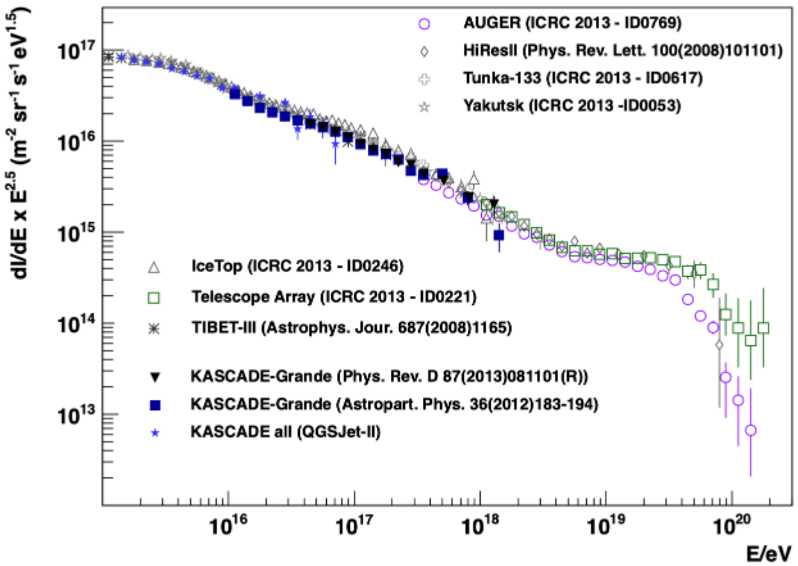


K. Brecher, G. R. Burbidge, ApJ 174 (1972) 253

V. L. Ginzburg, Astro. and Space Phys., Vol. 4, p.167 (1972)

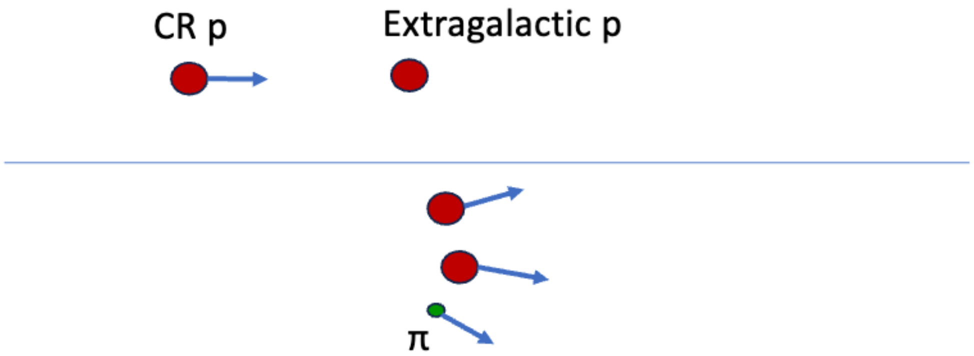
A.W. Strong, *Nucl.Part.Phys.Proc.* 297-299 (2018) 165-170

Back in the 1970s, there was a debate about whether **all** CRs could be extragalactic. Subsequent diffuse gamma-ray observations, however, constrained such a scenario.



Gaisser, *Front.Phys.(Beijing)* 8 (2013) 748-758

Origins of the CR Spectrum?



K. Brecher, G. R. Burbidge, ApJ 174 (1972) 253

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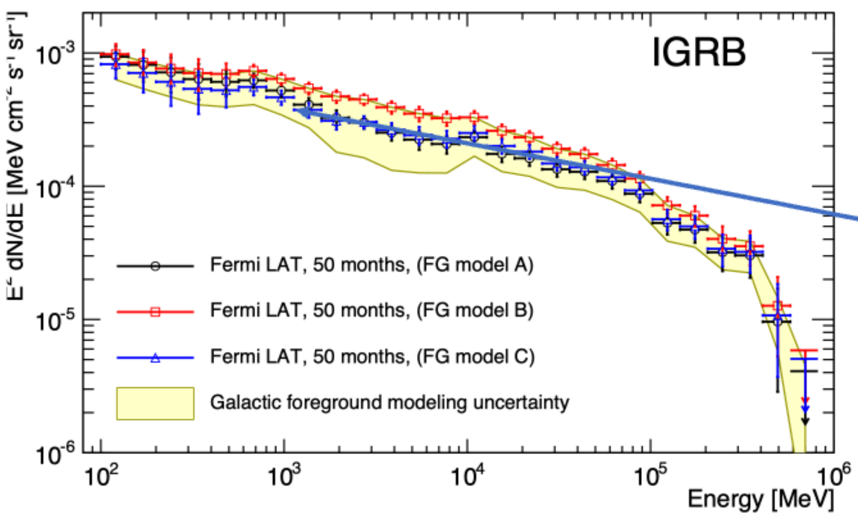
Isotropic Gamma-Ray Background



Ackermann et al., *Astrophys.J.* 799 (2015)

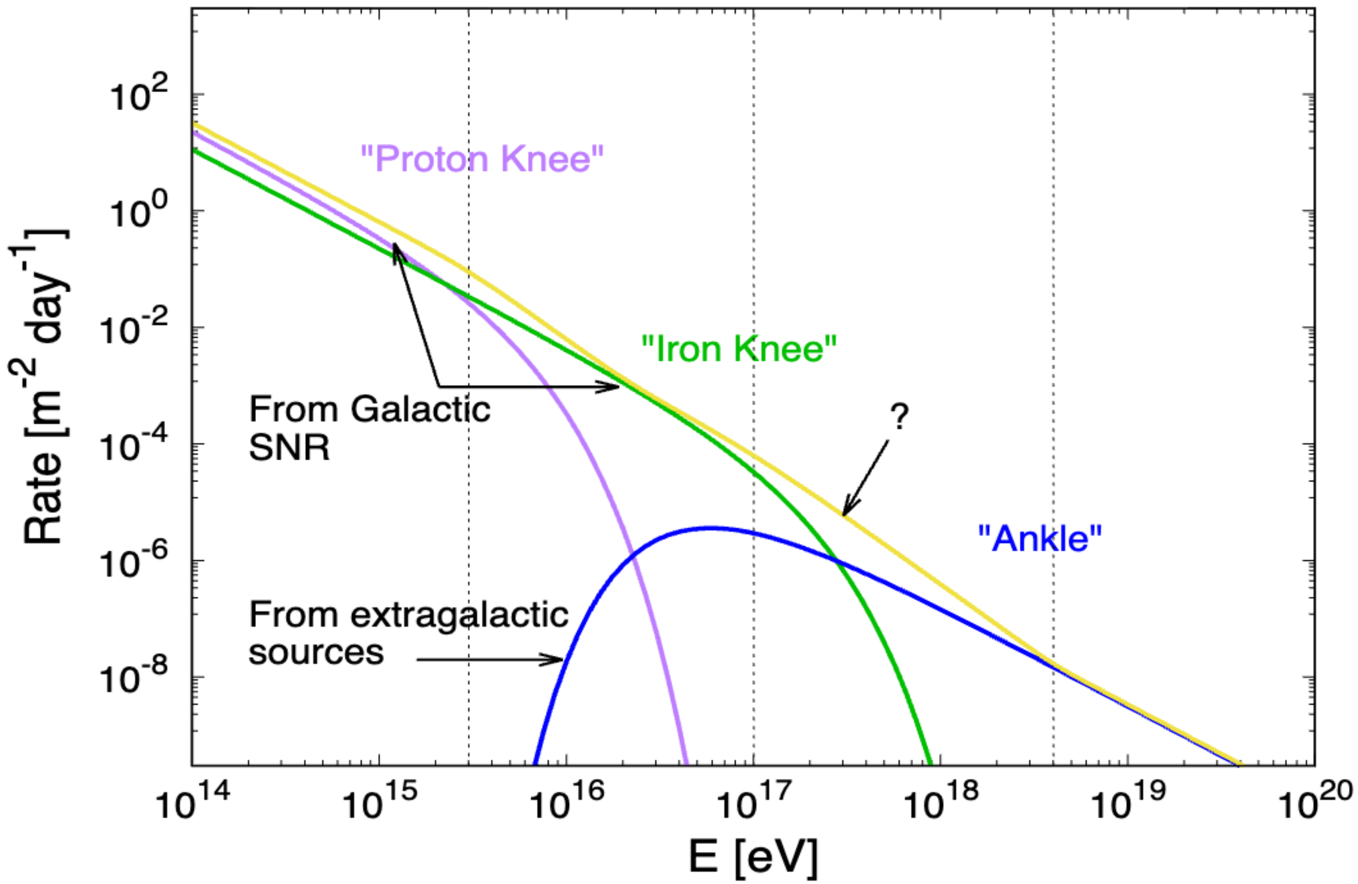
1 GeV Flux Expected for Model:

$$\mathbf{E_\gamma^2 \frac{dN}{dE_\gamma} \approx 2 \times 10^{-3}\ MeV cm^{-2} s^{-1} sr^{-1}}$$

1 GeV Diffuse Flux:

$$\mathbf{\approx 6 \times 10^{-4}\ MeV cm^{-2} s^{-1} sr^{-1}}$$

Origins of the CR Spectrum?



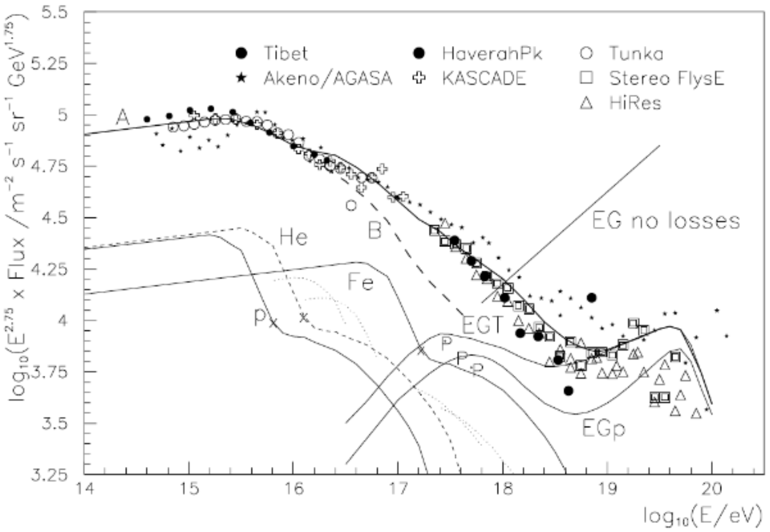
Instead, Galactic SNR, well motivated as a Galactic CR sources, became preferred option for powering the spectrum all the way up to the knee proton energy ($10^{15.5}$ eV)

However, even if SNR accelerate CRs up to the proton knee, **a new source class is needed to fill the energy gap between 10^{17} eV and 10^{18} eV**

Taylor et al., *Nature* **volume 531**, pages 43–44 (2016)

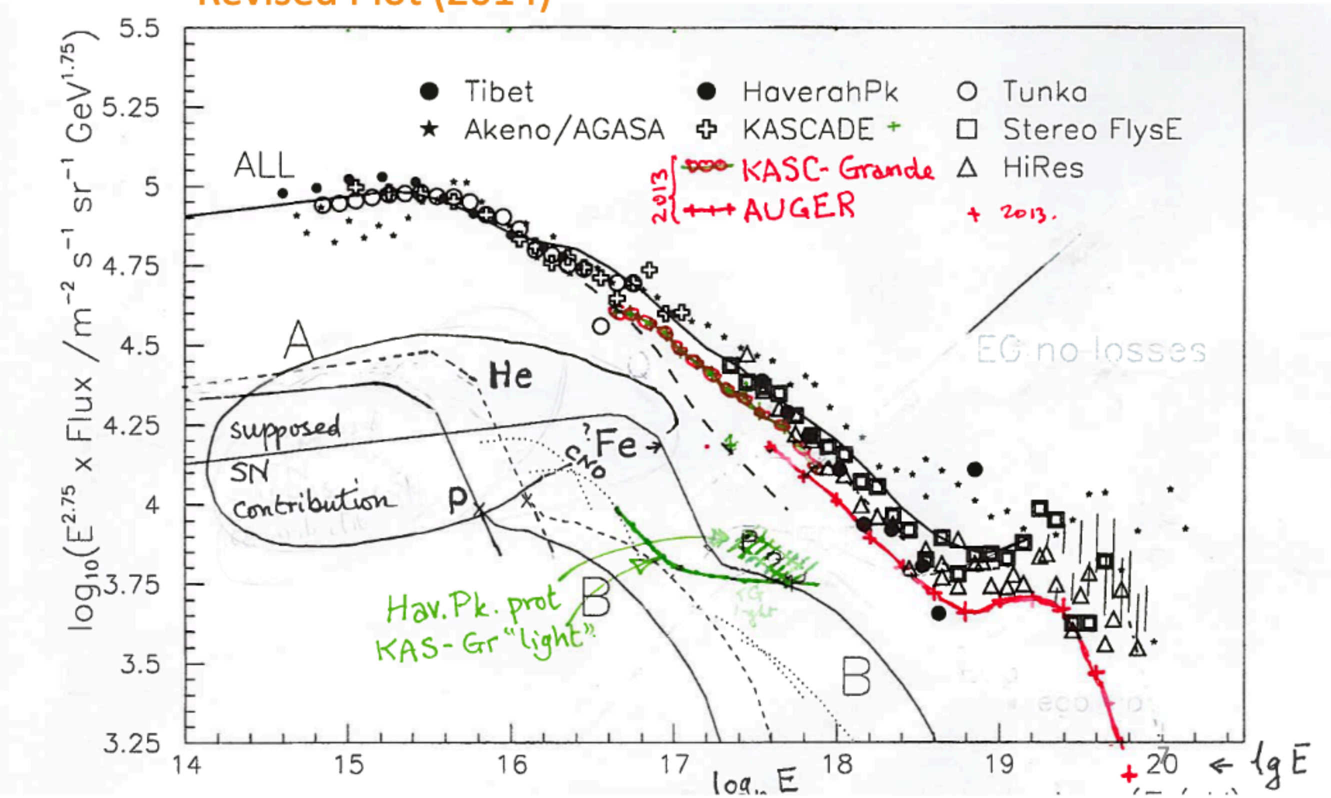
The Need for a Population B

Original Plot (2005)



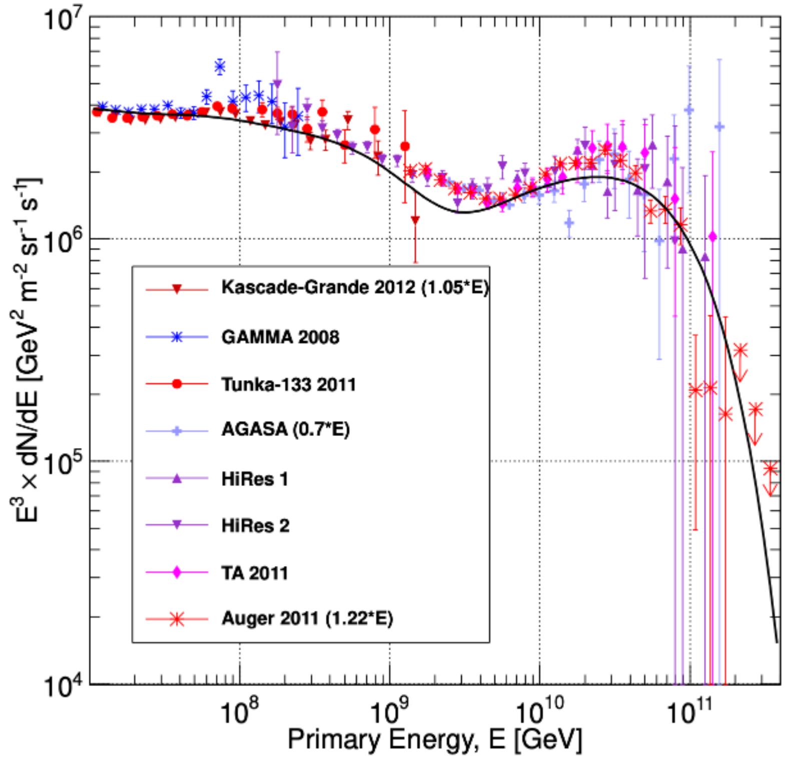
Hillas, 2005 *Nucl. Part. Phys.* **31** R95. (2005)

Revised Plot (2014)



Pop A → Pop 1
Pop B → Pop 2
Pop C → Pop 3

Hillas-Type 3 Population Fit to the Transition Region



Gaisser, Front. Phys., 2013, 8(6): 748–758 (2013)

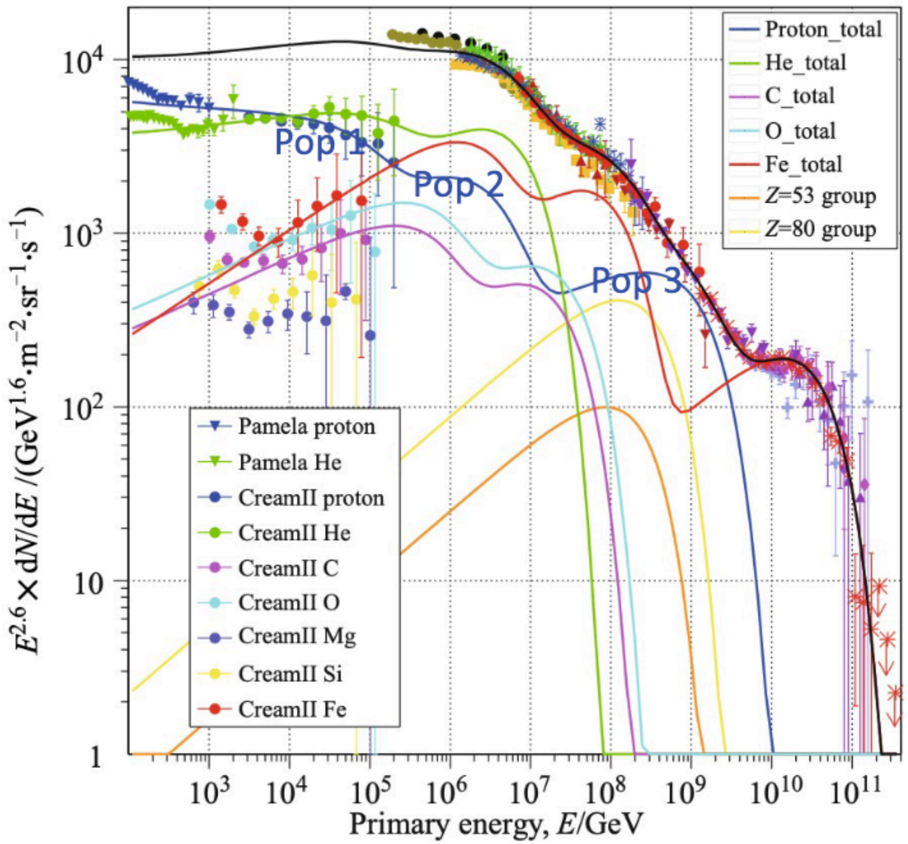
$$\frac{\mathbf{dN_{inj}}}{\mathbf{d\log E}} = \sum_{\mathbf{i}} \mathbf{a_i E^{-\gamma_i} e^{-(E/Z_i R_c)}}$$

		p	He	CNO	Mg-Si	Fe
Galactic	Pop. 1:	7860	3550	2200	1430	2120
	$R_c = 4$ PV	1.66	1.58	1.63	1.67	1.63
	Pop. 2:	20	20	13.4	13.4	13.4
	$R_c = 30$ PV	1.4	1.4	1.4	1.4	1.4
Extragalactic?	Pop. 3:	1.7	1.7	1.14	1.14	1.14
	$R_c = 2$ EV	1.4	1.4	1.4	1.4	1.4

Population B…But Whose Population B?

Pop A → Pop 1
Pop B → Pop 2
Pop C → Pop 3

Gaisser-Type 3 Population Fit to the Transition Region



Gaisser, Front. Phys., 2013, 8(6): 748–758 (2013)

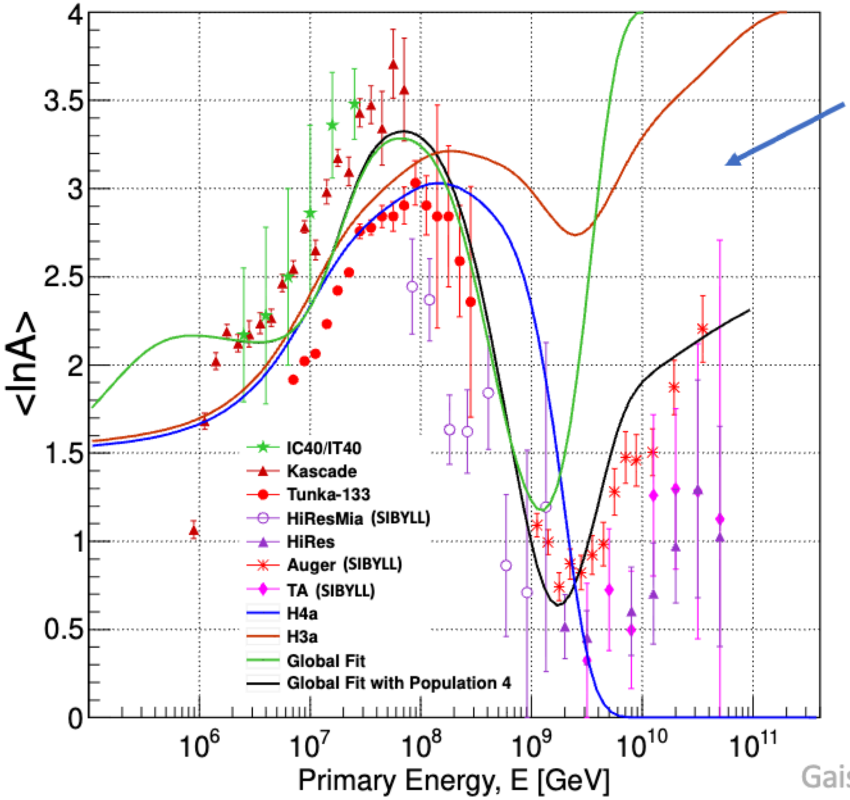
$$\frac{\mathbf{dN_{inj}}}{\mathbf{d\log E}} = \sum_{\mathbf{i}} \mathbf{a_i E^{-\gamma_i} e^{-(E/Z_i R_c)}}$$

Note: Pop A and Pop B max energy lowered by ~10-30 relative to Hillas' proposed scenario

	p	He	C	O	Fe	$50 < Z < 56$	$78 < Z < 82$
Pop. 1:	7000	3200	100	130	60		
$R_c = 120$ TV	1.66 1	1.58	1.4	1.4	1.3		
Pop. 2:	150	65	6	7	2.3	0.1	0.4
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3:	14				0.025		
$R_c = 1.3$ EV	1.4				1.2		
Pop. 2*:	150	65	6	7	2.1	0.1	0.53
$R_c = 4$ PV	1.4	1.3	1.3	1.3	1.2	1.2	1.2
Pop. 3*:	12				0.011		
$R_c = 1.5$ EV	1.4				1.2		

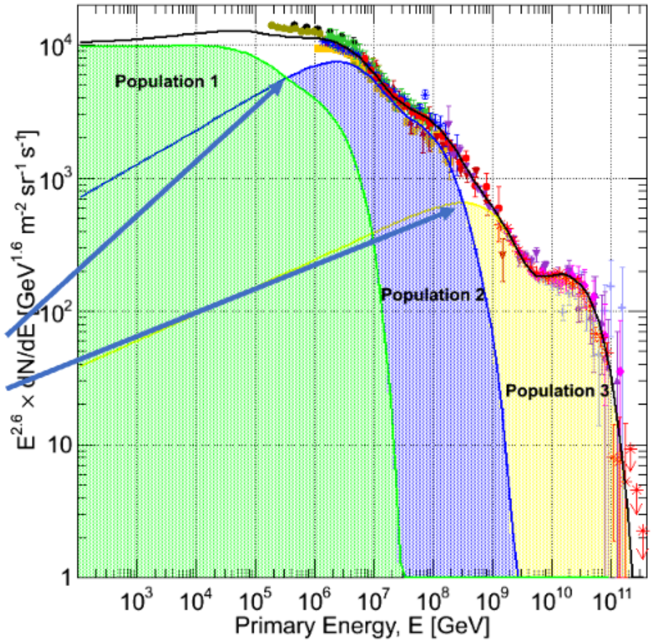
Note the Pop 2 proton component needs revising in light of recent LHAASO results: LHAASO Collaboration: 2511.05013

Constraints on at What Energy the Onset of Population B can Occur



Only two clear light-heavy-light-heavy “cycles” in composition observed in data between the knee and the highest energies.

This places a strong constraint on the spacing of the energy onset in dominance of the new spectral components

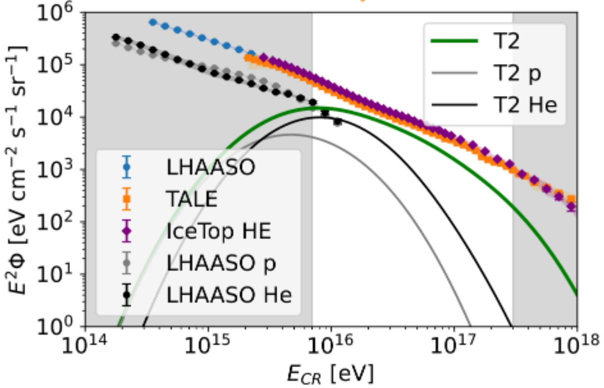


Gaisser, Front. Phys., 2013, 8(6): 748–758 (2013)

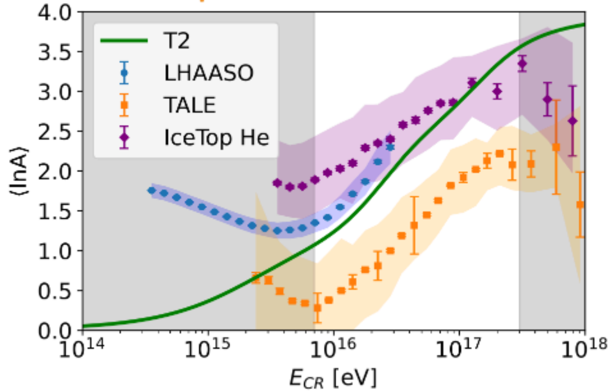
Kampert et al. **Astropart. Phys.** 35 10 660-678 (2012)

Hillas & Gaisser-Type Population B Candidates:

Proton Spectrum



Composition



Extreme Supernovae (Type IIn): Hillas-Type Pop B

Ekanger et al., 2602.06410

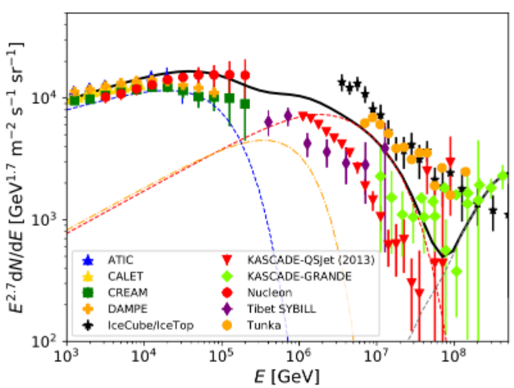
Christofari et al., Astropart. Phys. 123 102492 (2020)

Zirakashvilli et al., Astropart. Phys. 78 28–34 (2016)

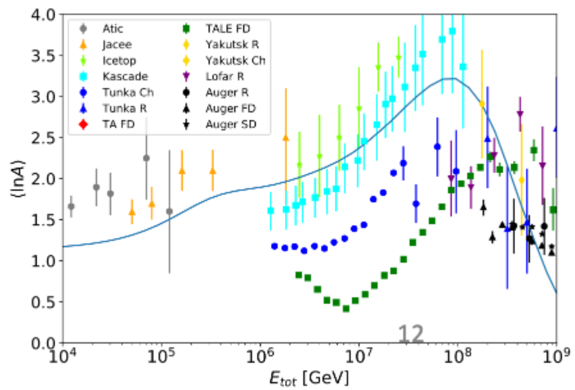
Supernovae in Massive Star Clusters: Gaisser-Type Pop B

Vieu et al., MNRAS 519, 136–147 (2023)

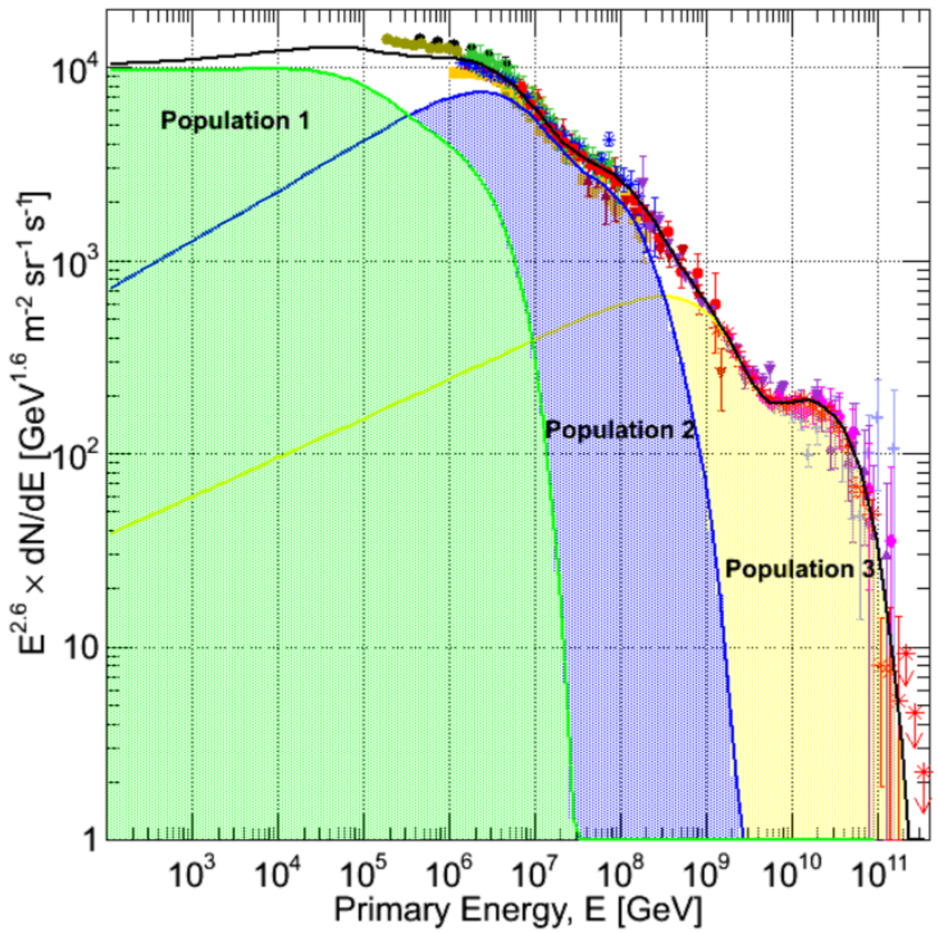
Proton Spectrum



Composition



The Power Needs of Gaisser-Type Population B



Gaisser, Front. Phys., 2013, 8(6): 748–758 (2013)

$$\mathbf{N_{ss} = Q_{CR}\tau_{esc.}}$$

$$\tau_{\mathbf{esc}} = \tau_{\mathbf{0}}(\mathbf{E/E_0})^{-\delta}$$

$$\delta = \mathbf{0.33}$$

$$\mathbf{L_A \approx 10^{41}\ erg\ s^{-1}}$$

$$\mathbf{L_B \approx 2 \times 10^{39}\ erg\ s^{-1}}$$

Particle Accelerator Limits

$$\mathbf{t_{acc}} = \eta \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{esc.}} = \frac{\mathbf{R}}{\mathbf{c}\beta}$$

[AM Hillas (1984)]

$$\mathbf{E_{max}} = \beta \mathbf{eBR}$$

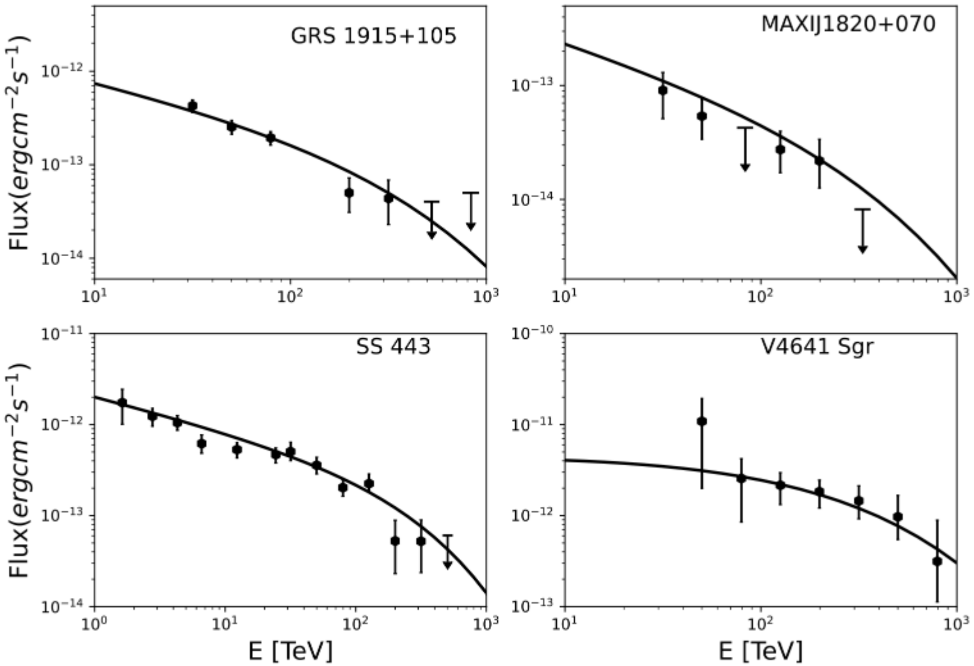
$$\mathbf{L_B} = \mathbf{U_B} 4\pi \mathbf{R^2} \beta \mathbf{c} = \eta_{\mathbf{B}} \mathbf{L_{KE}}$$

[Lovelace et al. (1976)]

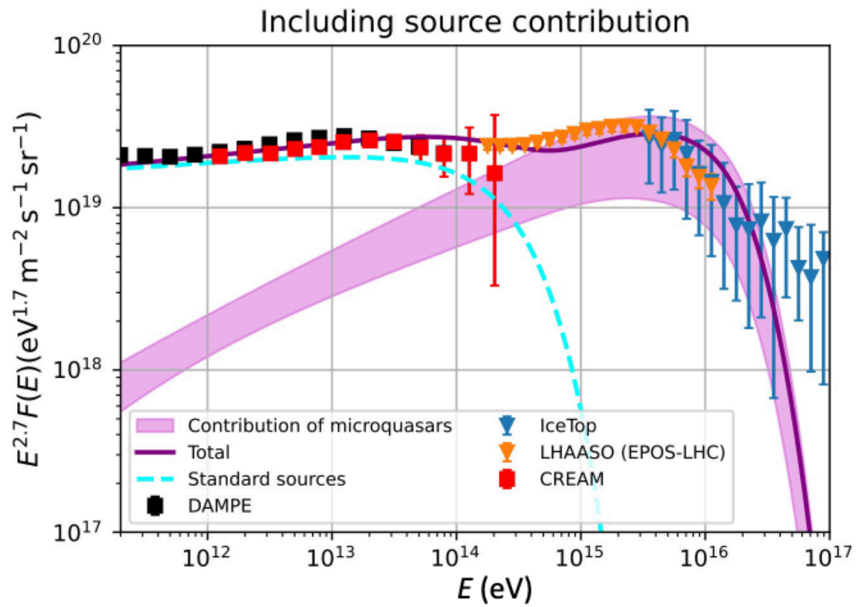
$$\mathbf{E_{max}} < \mathbf{2PeV} \left(\frac{\mathbf{L}}{\mathbf{10^{38}\ erg\ s^{-1}}} \right)^{\mathbf{1/2}} \left(\frac{\beta}{\mathbf{0.1}} \frac{\eta_{\mathbf{B}}}{\mathbf{0.1}} \right)^{\mathbf{1/2}}$$

Gaisser-Type Population B Candidates: **Microquasars**

$$\mathbf{E_{max} < 2PeV \left(\frac{L}{10^{38}\ erg\ s^{-1}}\right)^{1/2} \left(\frac{\beta}{0.1}\frac{\eta_B}{0.1}\right)^{1/2}}$$



Nie et al., 2602.07620



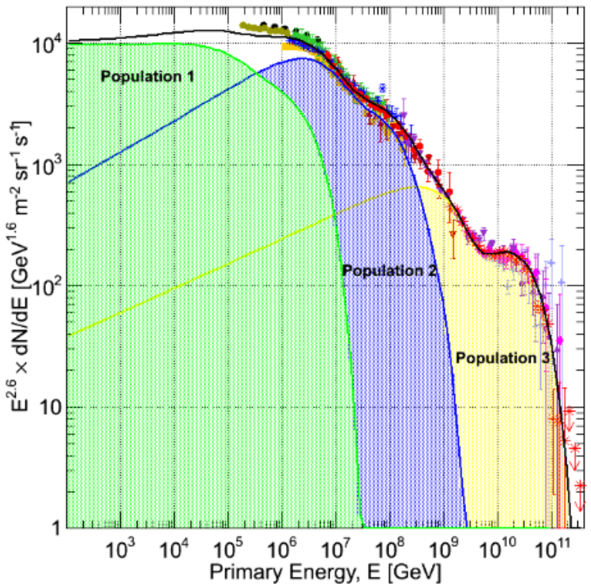
Kaci et al., 2510.01369

Star Cluster Winds

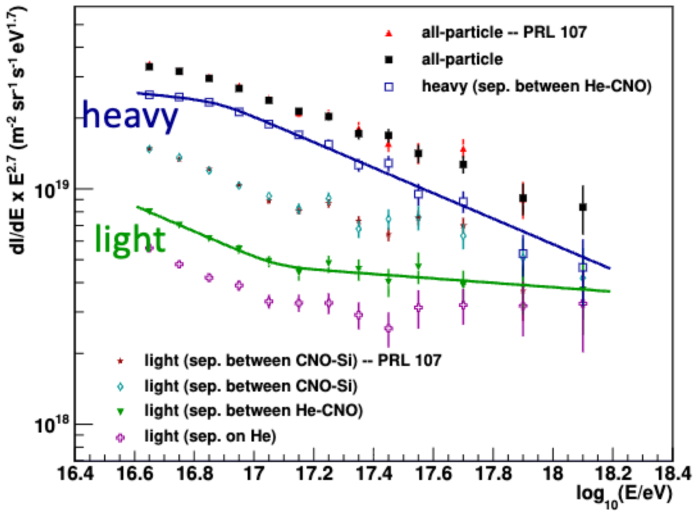
Morlino et al., MNRAS 504, 6096–6105 (2021)

LHAASO Coll., Science Bulletin 69 (2024) 449–457

Can Constraints be Placed on Population C?



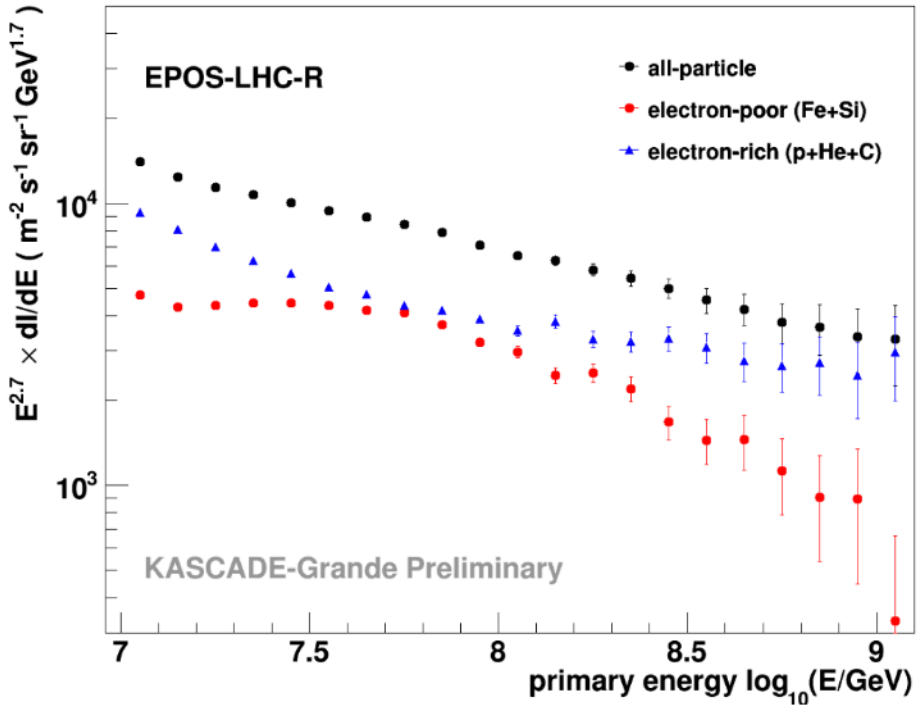
Population C Onset: Kascade-Grande Measurements & Analysis



Apel et al., Phys. Rev. D 87, 081101 (2013)

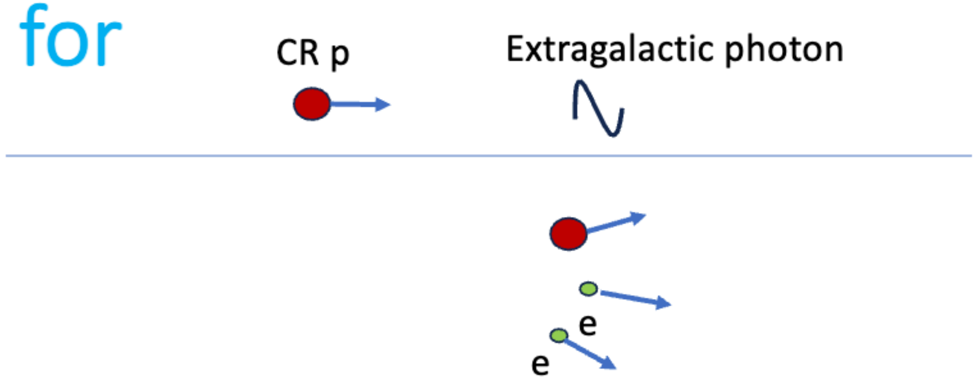
A subdominant component of light CRs is seen **$\gtrsim 10^{17}$ eV** ("light ankle")

A recent reanalysis of the Kaskade-Grande data with updated hadronic models finds the same feature (though at somewhat lower energies)

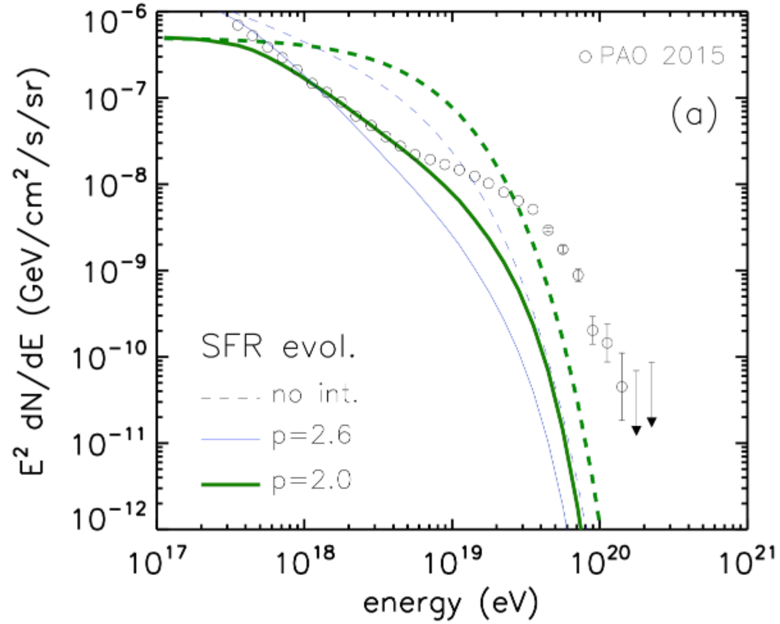


Kang et al., *PoS* ICRC2025 (2025) 297

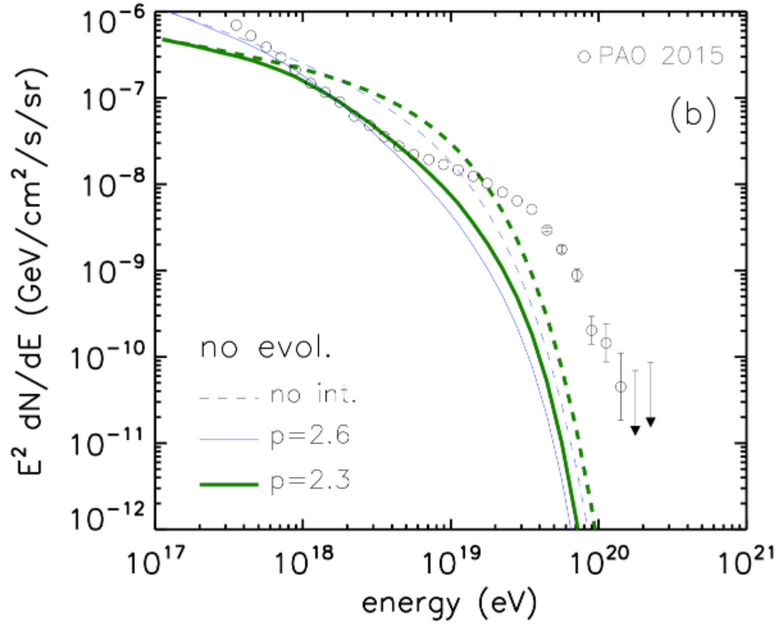
The Source Evolution Scenario for the >$10^{17.7}$eV CRs



SFR evolution scenario



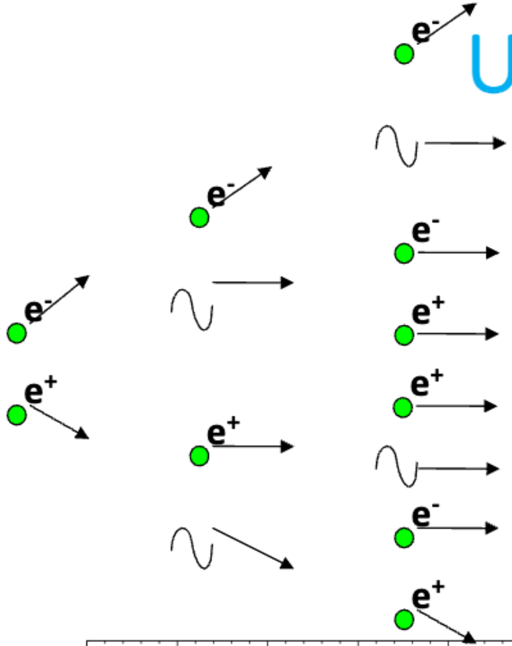
no evolution scenario

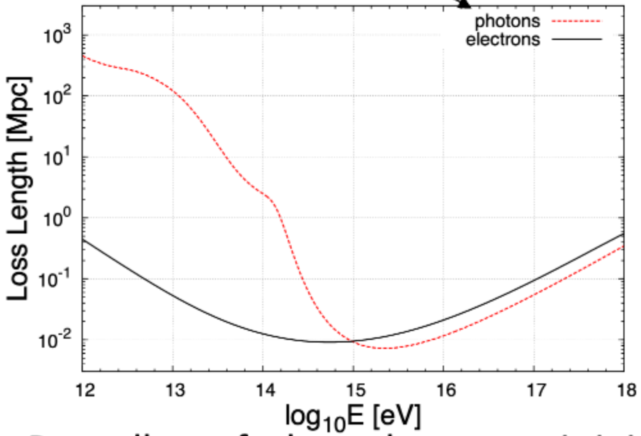


Liu et al., Phys.Rev.D 94 043008 (2016)

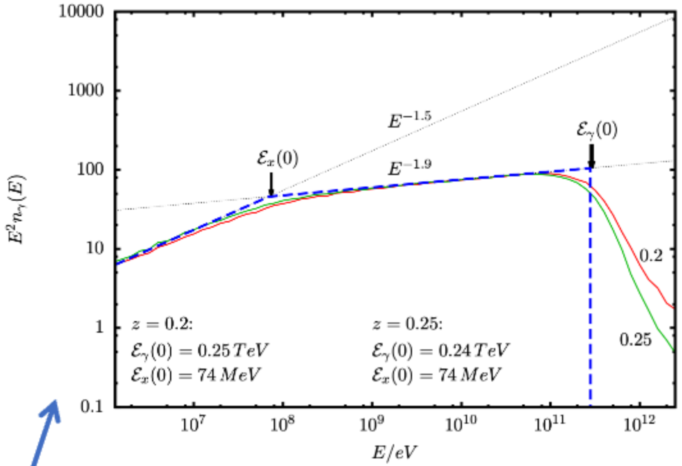
Universality of Cascade Spectra

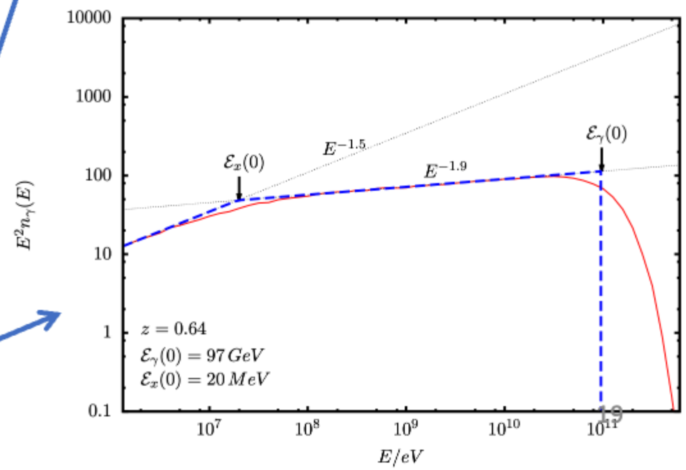
Aharonian et al., *Astrophys.J.Lett.* 423 (1994) L5-L8
Berezinsky *Phys.Rev.D* 94 (2016) 2, 023007





Regardless of where the energy is injected (ie independent of source z), the arriving flux possesses a universal shape

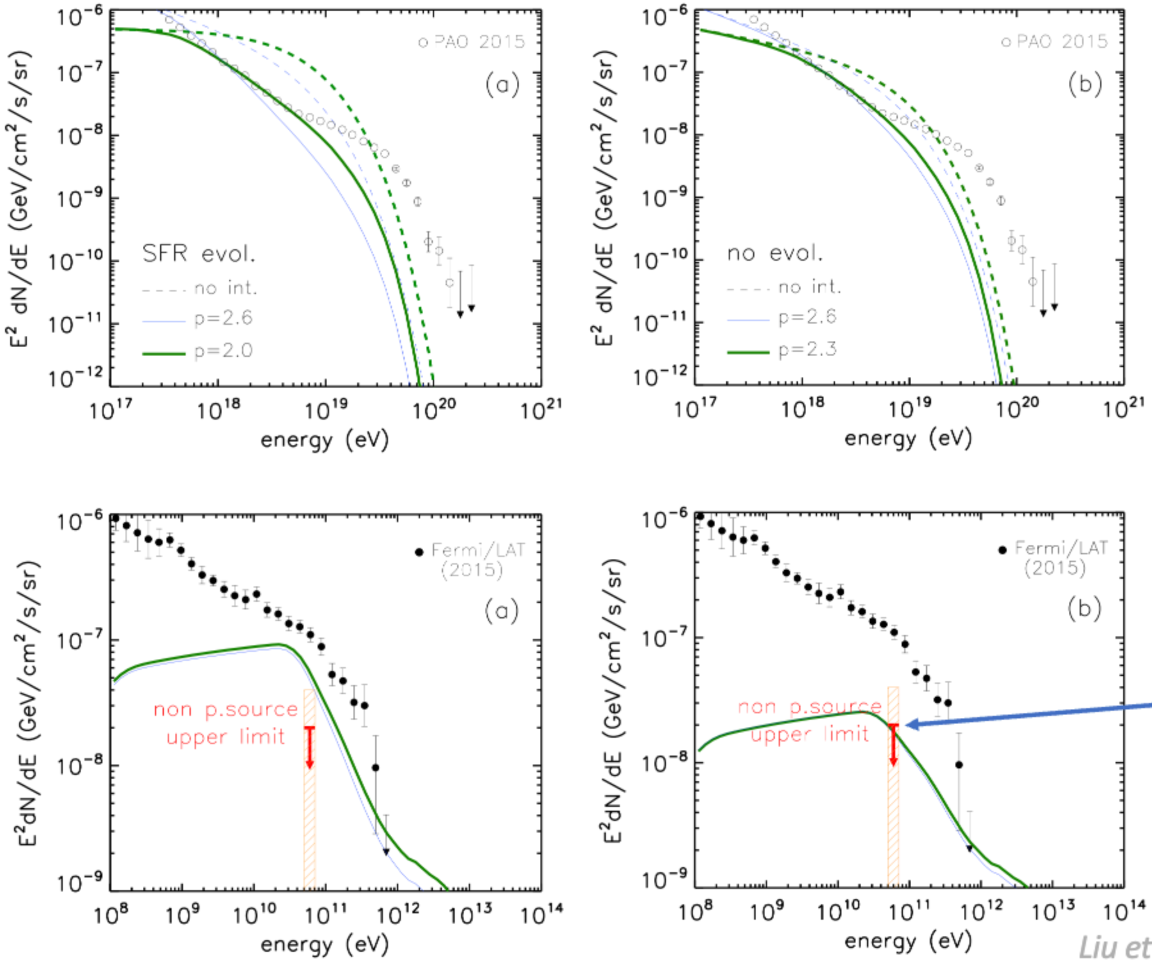




The Origin of Protons Below the Ankle

SFR evolution scenario

no evolution scenario



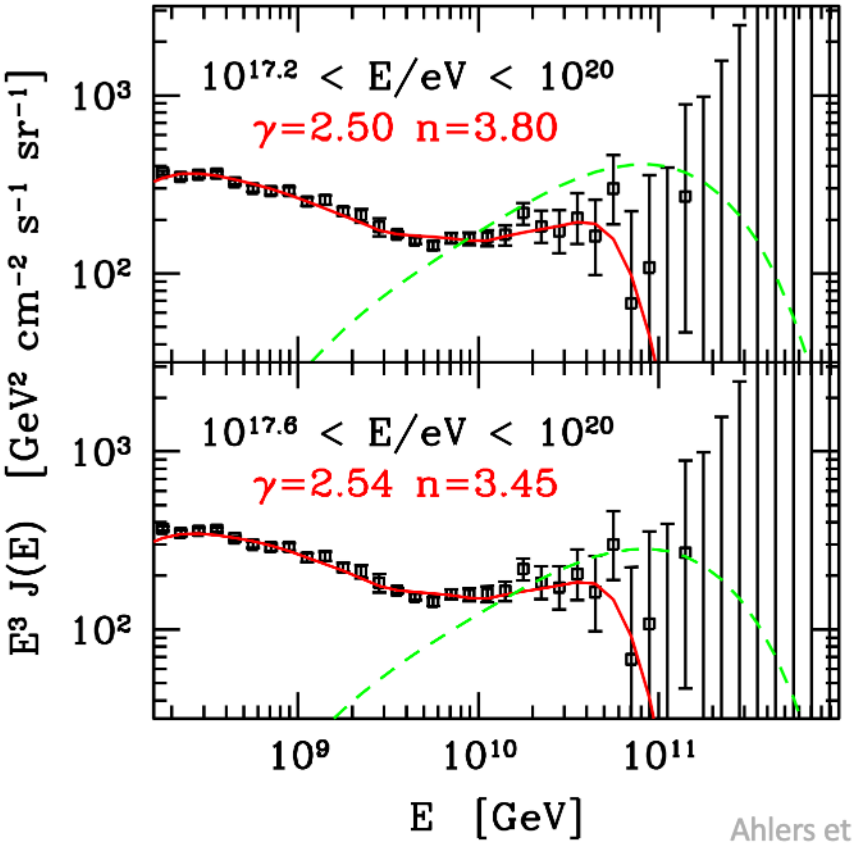
Note- IGRB contribution from cascade losses rather independent of source spectra

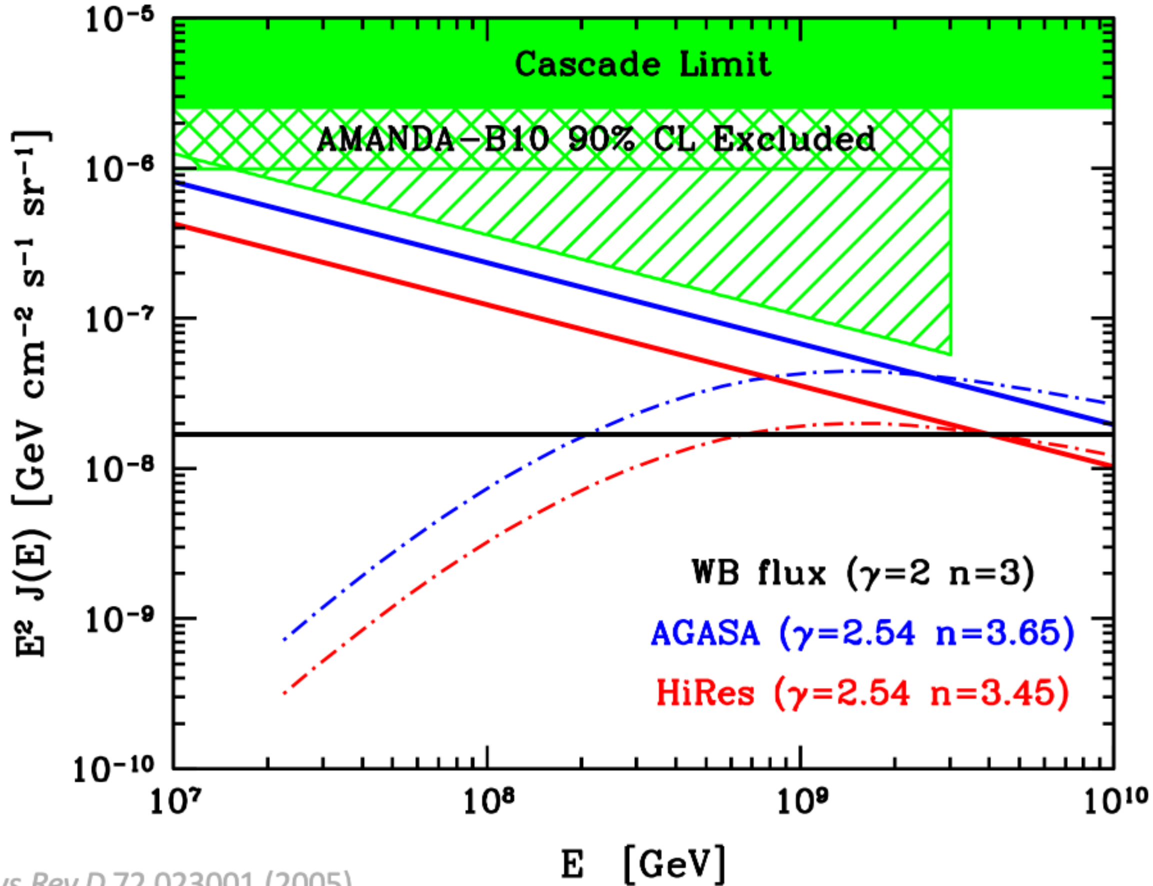
New upper limit once (resolved and unresolved) points sources removed

Liu et al., Phys.Rev.D 94 043008 (2016)

DESY.

Neutrinos as a Probe of Origin of Protons Below the Ankle

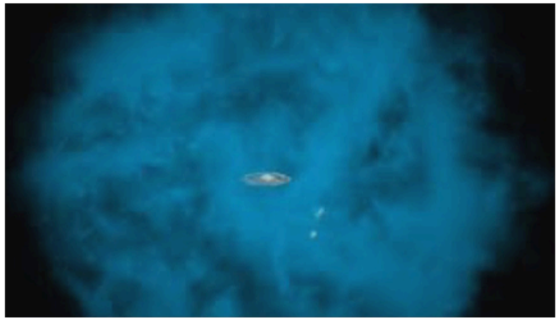




Ahlers et al. *Phys.Rev.D* 72 023001 (2005)

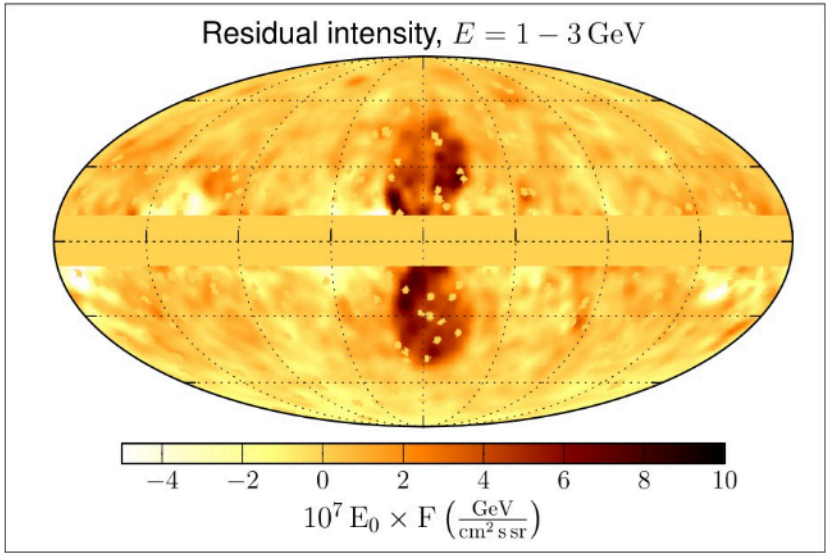
Ahlers et al. *Phys.Rev.D* 79 083009 (2009)

Are there Signatures of Galactic CR in the Galactic Halo Environment?

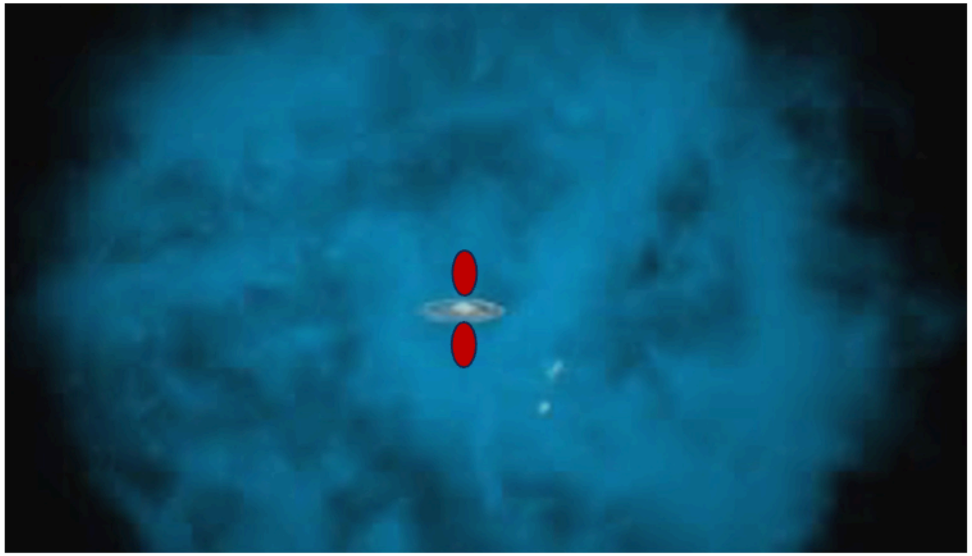


The Fermi/eROSITA Bubbles

- 2 Galactic gamma-ray emitting bubbles exist out to ~8 kpc above and below the Galactic plane
- These appear to be enshrouded in larger hot X-ray emitting bubbles, out to ~14 kpc



Ackermann et al. ApJ 793 (2014)

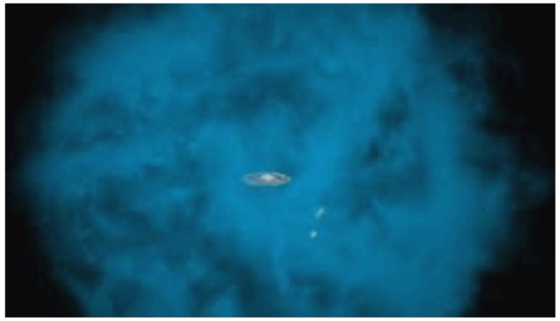


These results appear to indicate that non-thermal particle transport in the Milky Way halo, at least from the Galactic center region, possesses an advective component

Large Thermal Pressure in Galactic Haloes

X-ray observations of bright AGN indicate the presence of a hot local absorber.

Large Hot Halo



$$\mathbf{M = (0.8 - 3.5) \times 10^{11}\ M_\odot}$$

Zhang et al., 2511.17313

Gupta ApJ, 756 (2012)

King function

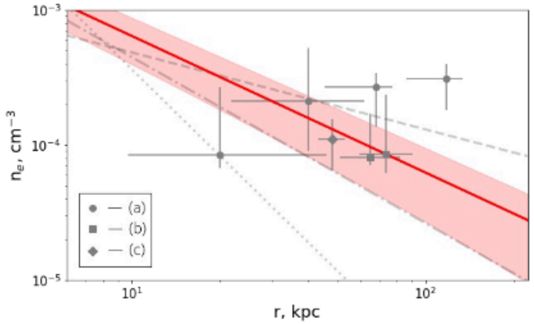
$$\mathbf{n = n_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-\frac{3}{2}\beta}}$$

$$\beta \approx \mathbf{0.4 \pm 0.1}$$

$$\mathbf{n \propto r^{-1}}$$

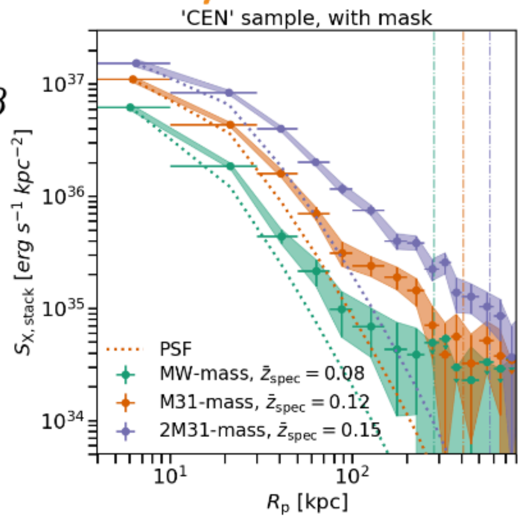
More recently, the ram pressure stripping of satellite galaxies + emission from the hot absorber have been collectively used to probe the halo gas density.

Ram pressure stripping



Faerman ApJ 835 (2017), Martynenko MNRAS, 511 (2022)

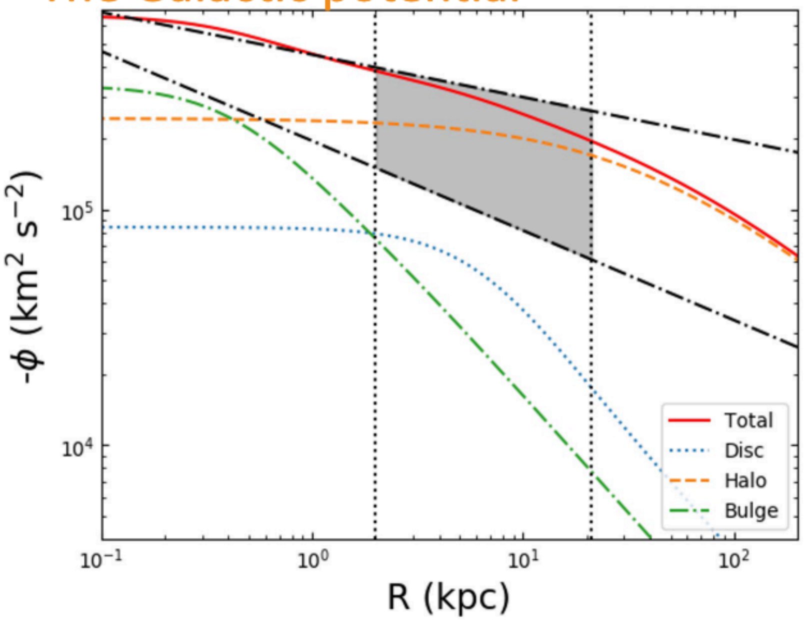
X-ray emission



Bregman et al. ApJ 928 (2022)
Zhang et al. for the eRosita collaboration- A&A (2024)

Inputs for Hydrodynamical Simulations

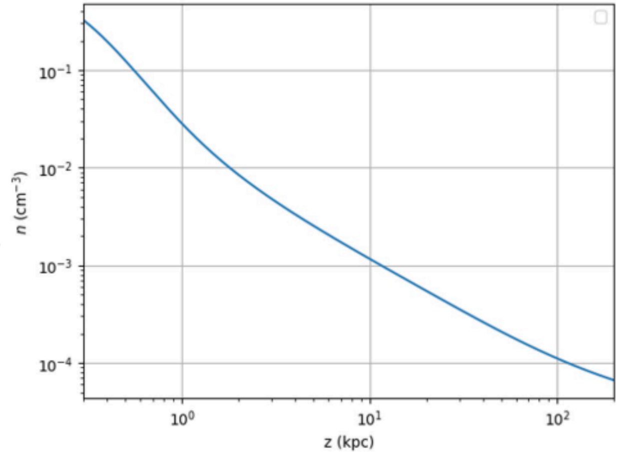
The Galactic potential



Tourmente et al. *MNRAS*, Vol 518, Iss. 4, (2023)

$$\mathbf{n = n_0 e^{-\frac{\Phi}{c_s^2}}}$$

Gas Density Distribution



Thermal gas temperature

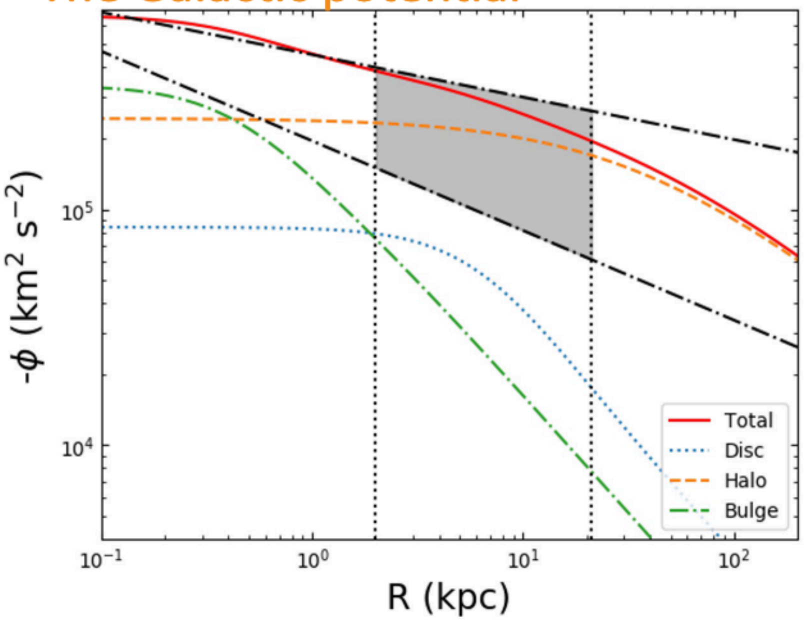
Isothermal temperature distribution adopted

$$\mathbf{kT = 0.4\ keV}$$

- For hydrodynamical simulations, gas density was started off with a hydrostatic equilibrium distribution
- Assumed a heating process exists throughout the simulation volume that keeps the gas hot (with an isothermal temperature)

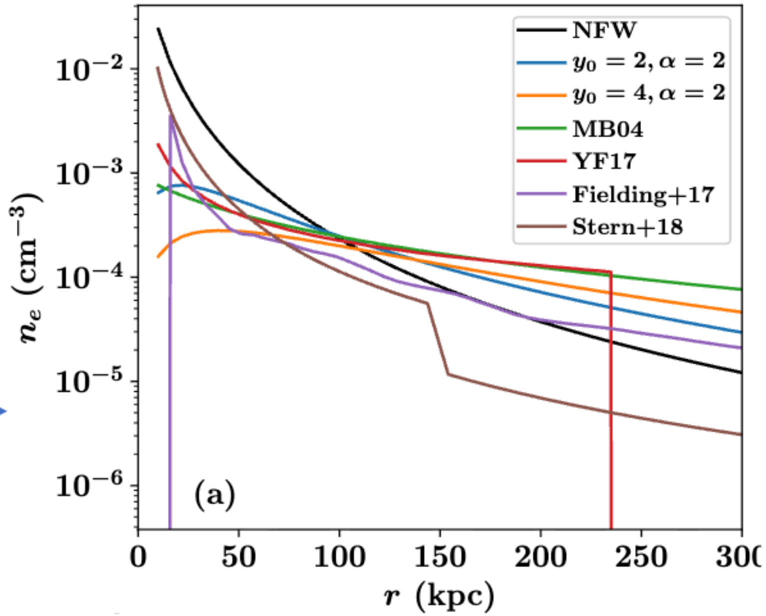
Inputs for Hydrodynamical Simulations

The Galactic potential



$$\mathbf{n = n_0 e^{-\frac{\Phi}{c_s^2}}}$$

Gas Density Distribution



Prochaska et al. MNRAS 485 (2019)

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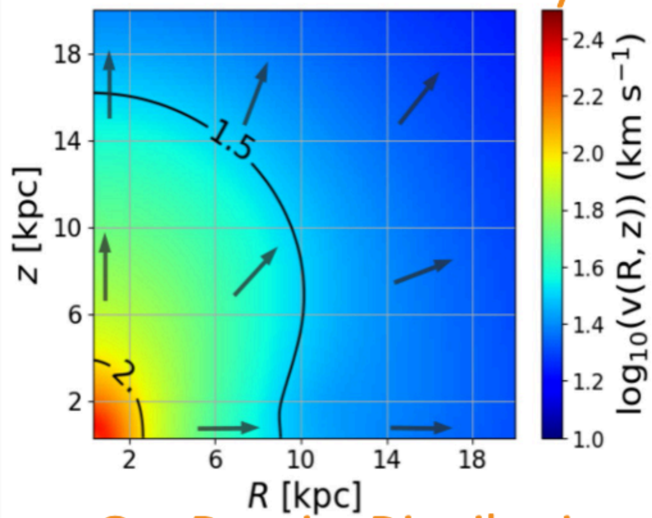
Subsonic Outflow Result for Isothermal Gas Using PLUTO

Resultant 2D velocity field simulation



Tourmente et al. *MNRAS*, Vol 518, Iss. 4, (2023)
Tourmente et al., 2507.20893

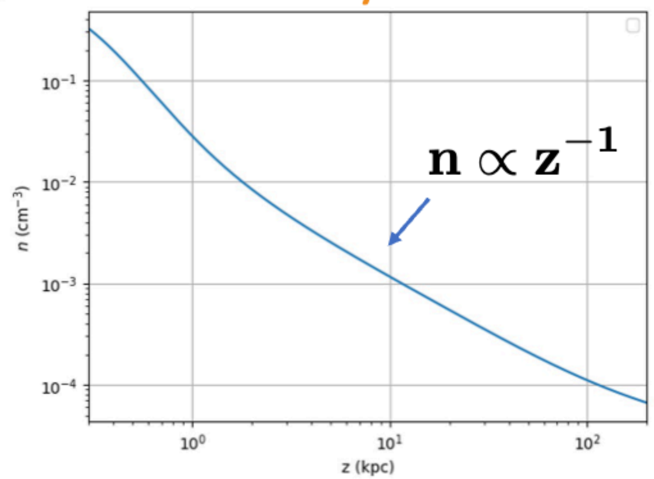
Galactic center source

velocity profile

$$\frac{\partial f}{\partial t} = \nabla \cdot (D\nabla f - \mathbf{v} f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[(\nabla \cdot \mathbf{v})\frac{p^3}{3} f\right] - \frac{f}{\tau_{\rm loss}} + \frac{Q}{p^2}$$

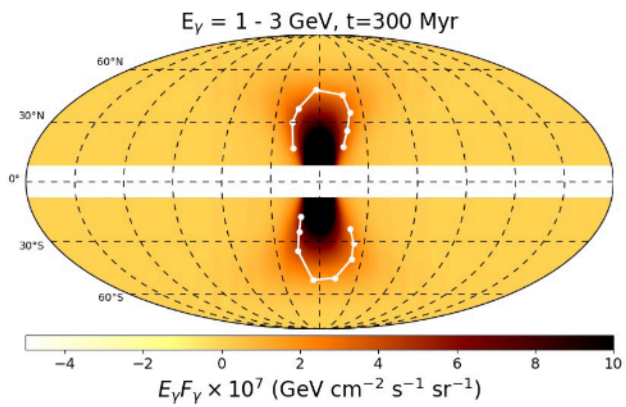
halo gas

Gas Density Distribution



Simulation results assuming constant source injection term present at the Galactic center

Gamma-Ray Skymap

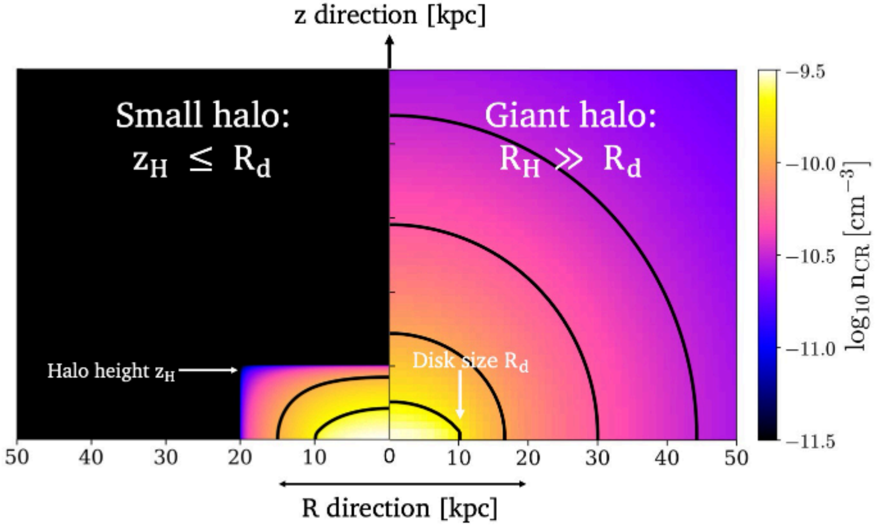


Secondary to Primary Cosmic Rays as a Probe of Galactic Halo Size (B/C)- LIMITATIONS

$$\frac{\partial f}{\partial t} = \nabla \cdot (D\nabla f - \mathbf{v}f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[(\nabla \cdot \mathbf{v})\frac{p^3}{3}f\right] - \frac{f}{\tau_s} + \frac{Q}{p^2}$$

Thanks to C. Li for these plots

(thanks for C. Li for preparing these plots!)



Hopkins et al, MNRAS 516 (2022) 3, 3470-3514

….the “halo size” does not really represent the scale-length of e.g. the magnetic energy or free-electron density profile; rather, the “halo size” in these models is more accurately defined as the volume interior to which CRs have an order-unity probability of scattering “back to” the Solar position.

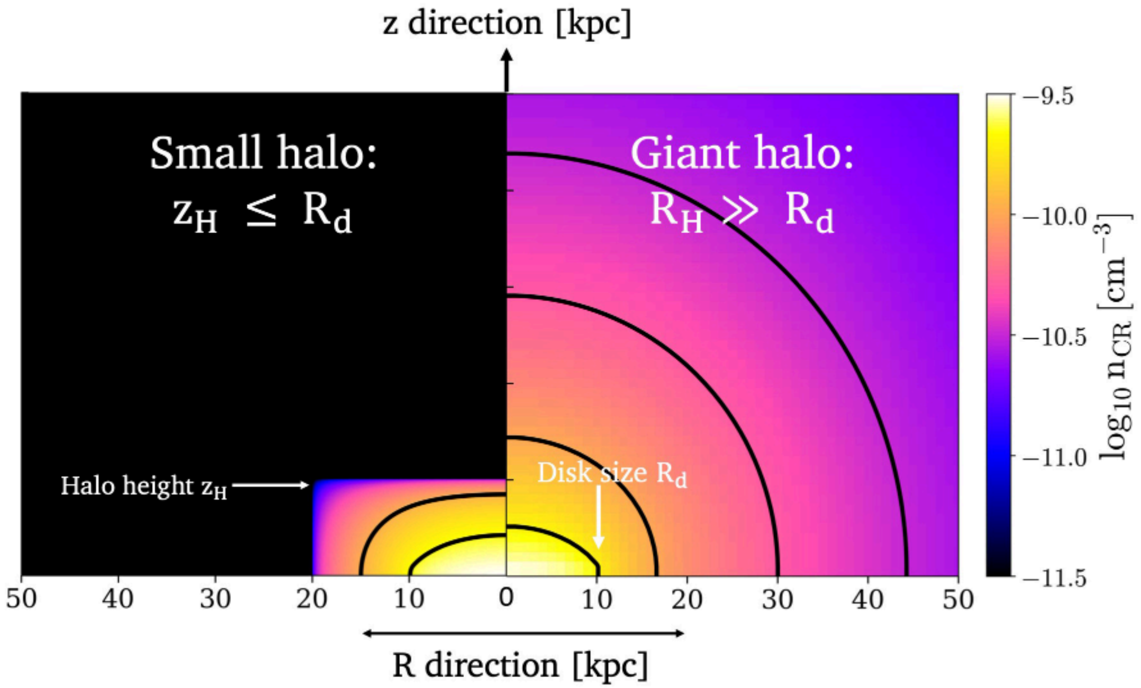
Shizuo Kakutani

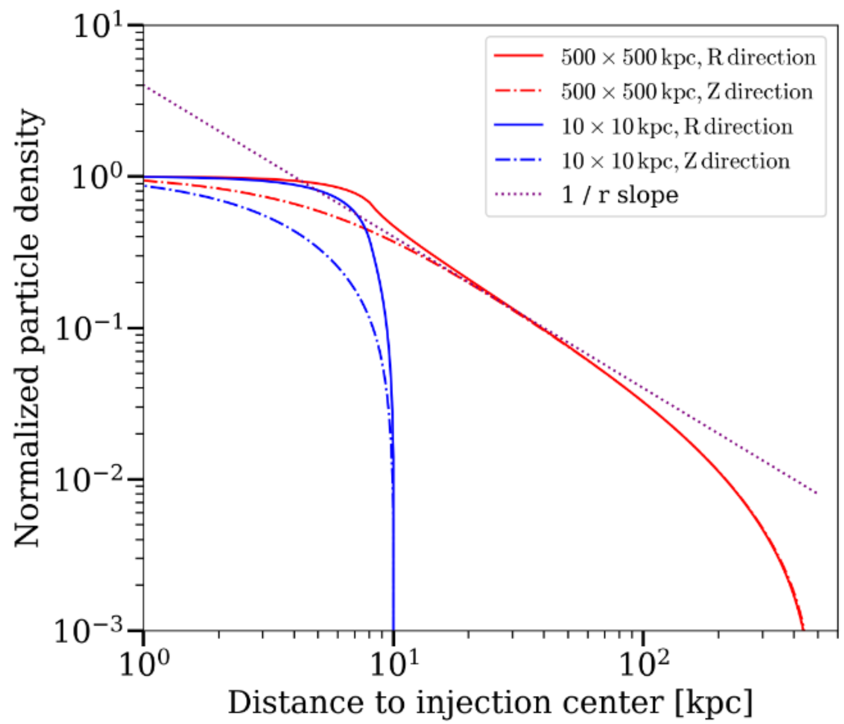
“A drunk man will eventually find his way home, but a drunk bird may get lost forever.”

Secondary to Primary Cosmic Rays as a Probe of Galactic Halo Size (B/C)- LIMITATIONS

$$\frac{\partial f}{\partial t} = \nabla \cdot (D\nabla f - \mathbf{v}f) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[(\nabla \cdot \mathbf{v})\frac{p^3}{3}f\right] - \frac{f}{\tau_s} + \frac{Q}{p^2}$$

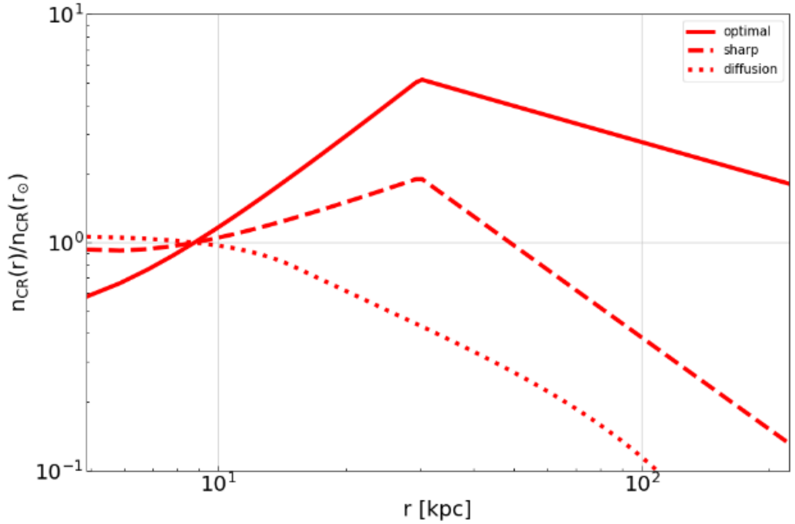
Thanks to C. Li for these plots
Hopkins et al, MNRAS 516 (2022) 3, 3470-3514





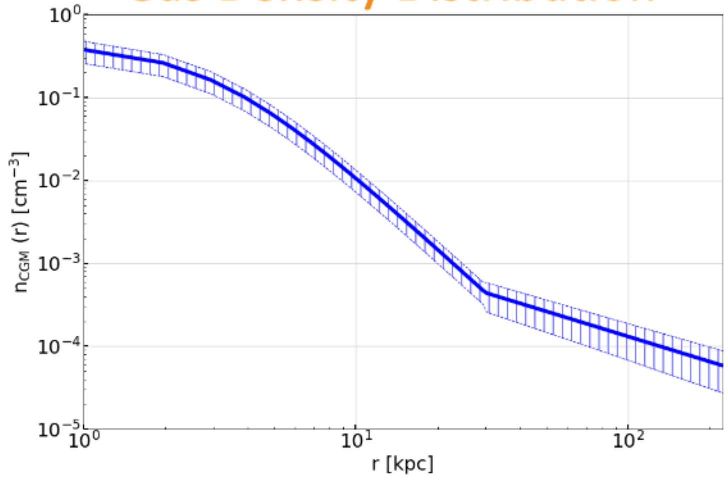
Neutrino Emission from the Galactic Halo?

CR Distribution

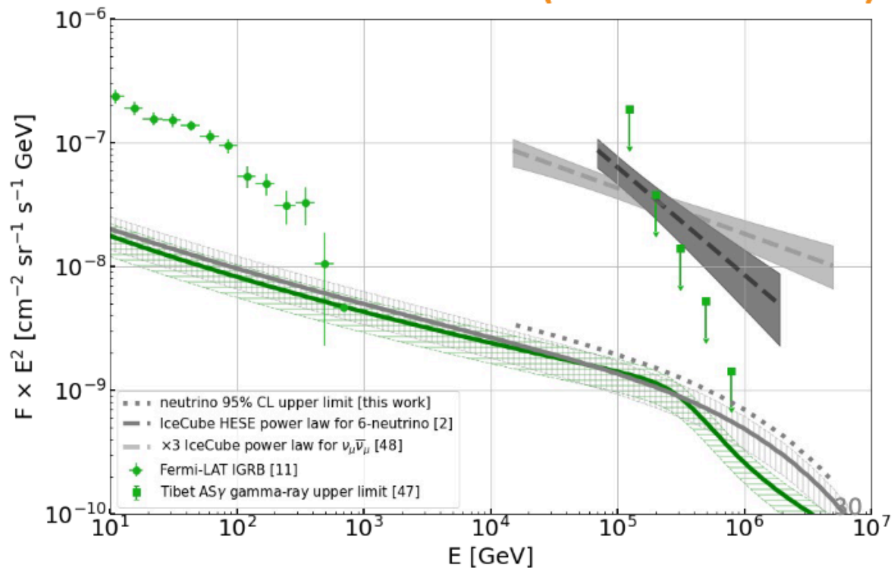


Kalashev et al., *JCAP* 03 (2023) 053

Gas Density Distribution



Halo Neutrino Flux (Diffusive Case)

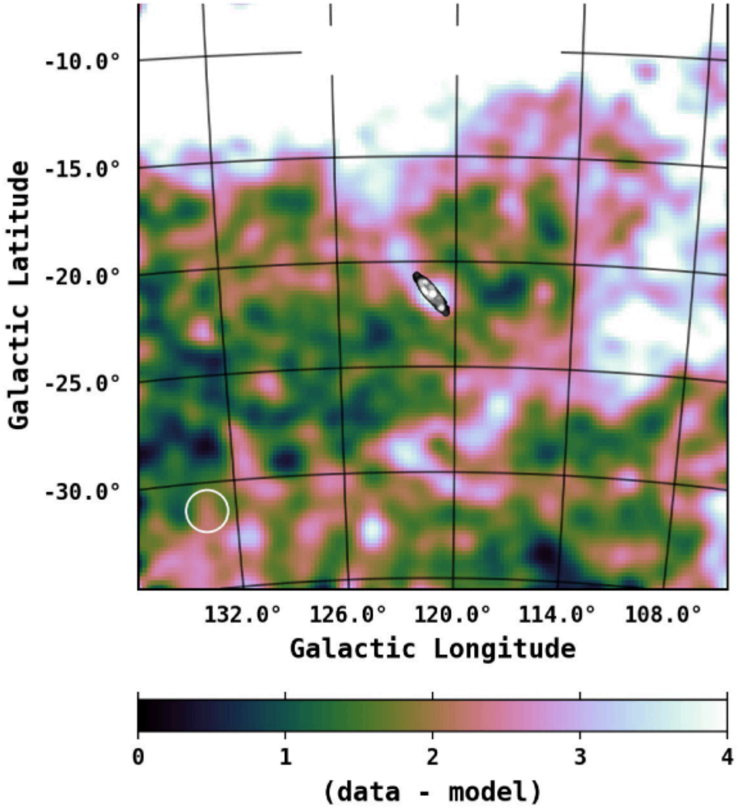


Understanding the CR transport process in the halo is key for these results

In this case, the circumgalactic neutrino flux contribution is comparable with the Galactic-disk contribution.

Probes of CR Escaping Nearby Galactic Haloes

Evidence for Diffuse Gamma-Rays Emission from M31's Galactic Halo

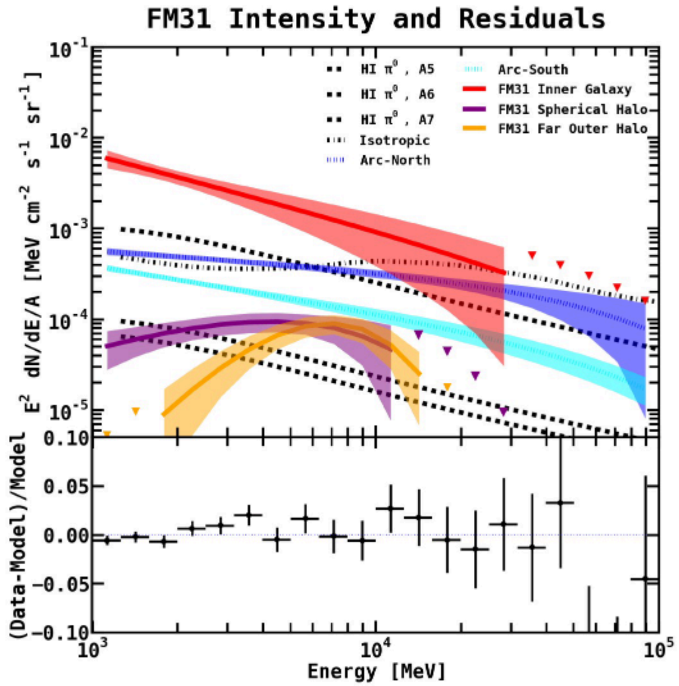


Suggests that emission extends out to tens of degrees (100s kpc)

Evidence that the escape of CRs from the Galaxy is not dictated solely by diffusive transport

Karwin et al., ApJ 880:95 48pp (2019)

Moskalenko paper



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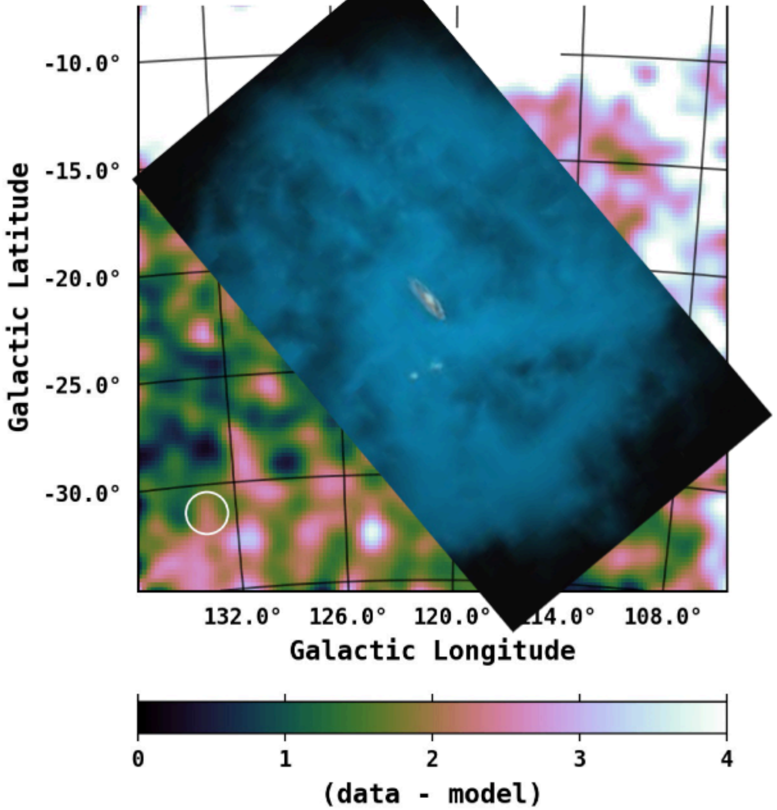

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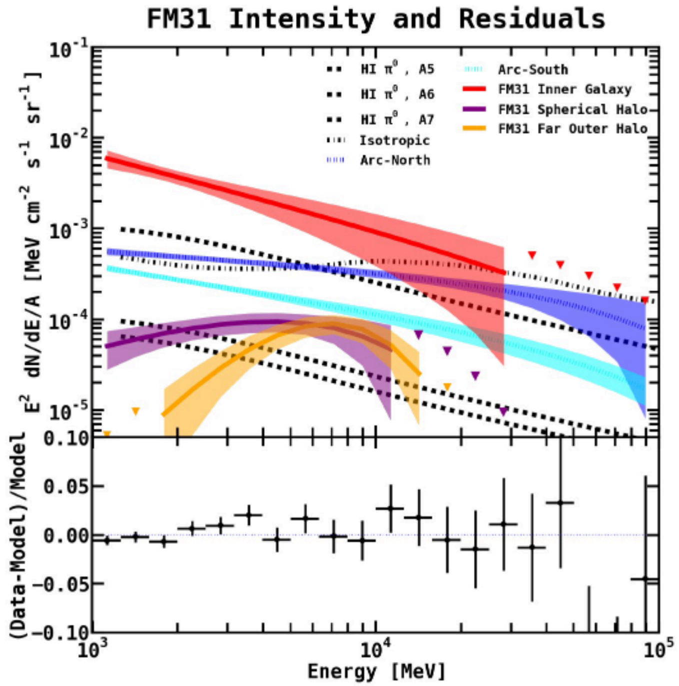
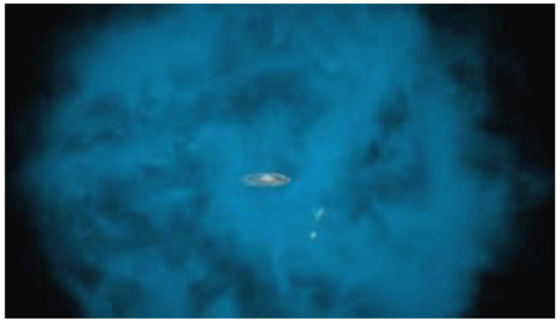


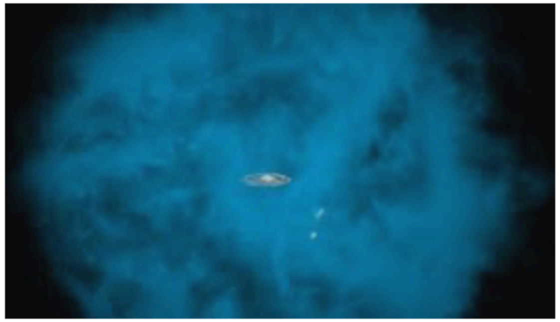
How Might the Galactic Halo Effect The Arrival of “Population C” CR?

“Population C”
CR source



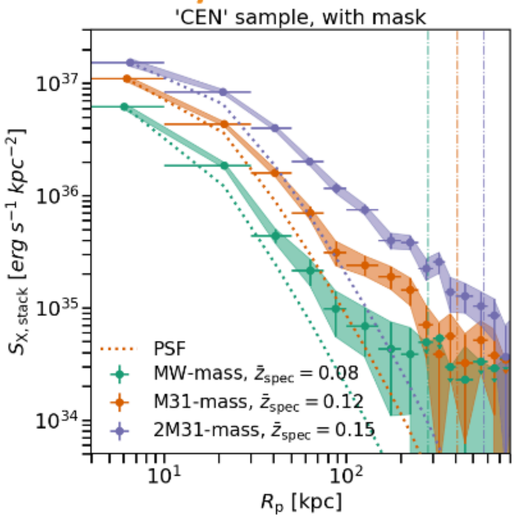
Large Thermal Pressure in Galactic Haloes

Large Hot Halo



Gupta ApJ, 756 (2012)

X-ray emission



Bregman et al. ApJ 928 (2022)
Zhang et al. for the eRosita collaboration-A&A (2024)

$$\mathbf{kT = 0.4\ keV}$$

$$\mathbf{n(100kpc) \approx 10^{-4} cm^{-3}}$$

Faerman ApJ, 893 (2020)

$$\mathbf{B(100\ kpc) \approx 0.2\ \mu G}$$

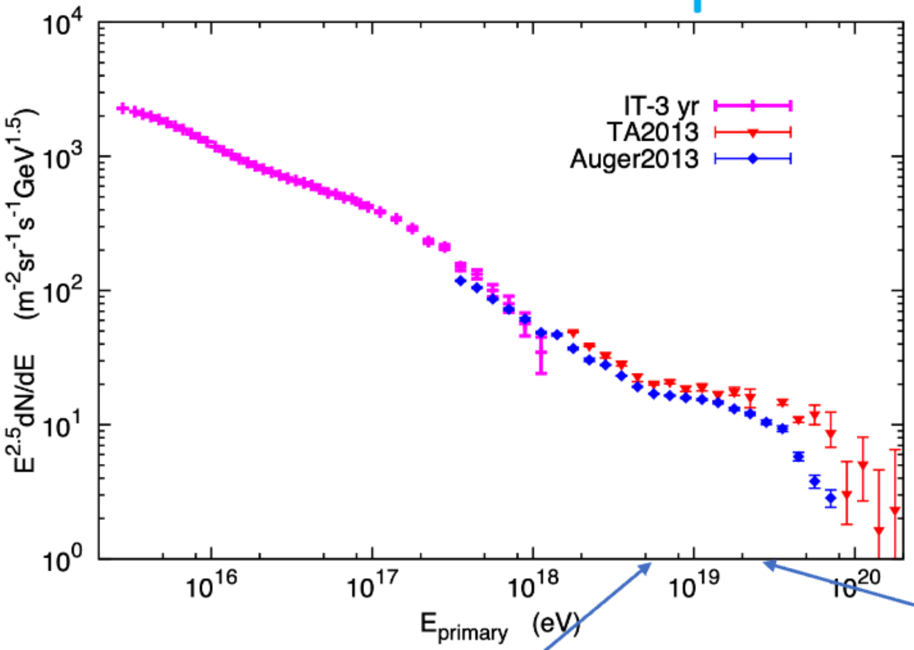
consistent with stacked measurement results:

Heesen A&A, 670 (2023)

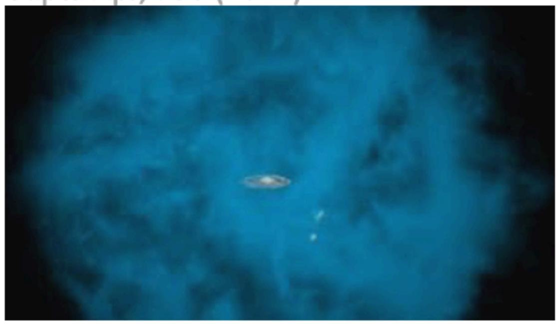
$$\mathbf{r_L(10\ EV) \approx 50\ kpc}$$

DESY.

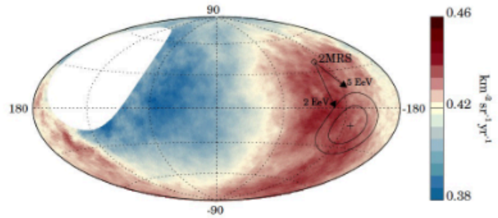
The Halo Imprint on the Extragalactic CRs

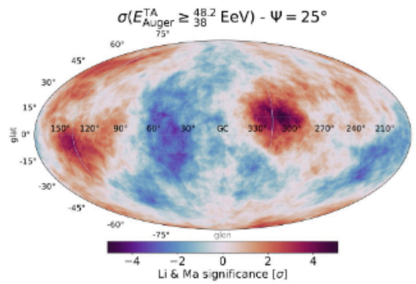


Gupta ApJ, 756 (2012)



Anisotropy





Auger Coll., Science Vol 357, Iss. 6357 1266-1270 (2017)

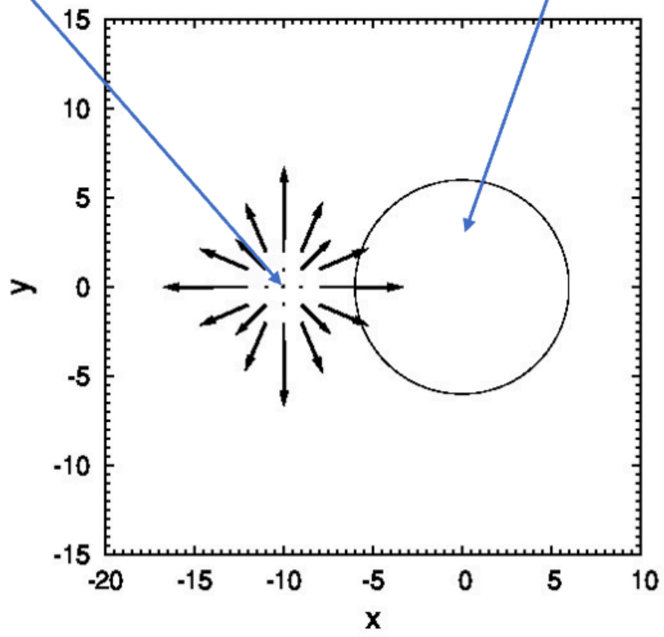
Caccianiga et al., Auger & TA Coll. PoS (ICRC2023) 521

Andrew Taylor

What "Arrives" is Not Necessarily What is Observed

Cosmic ray source

Reduced diffusion coefficient inside bubble region

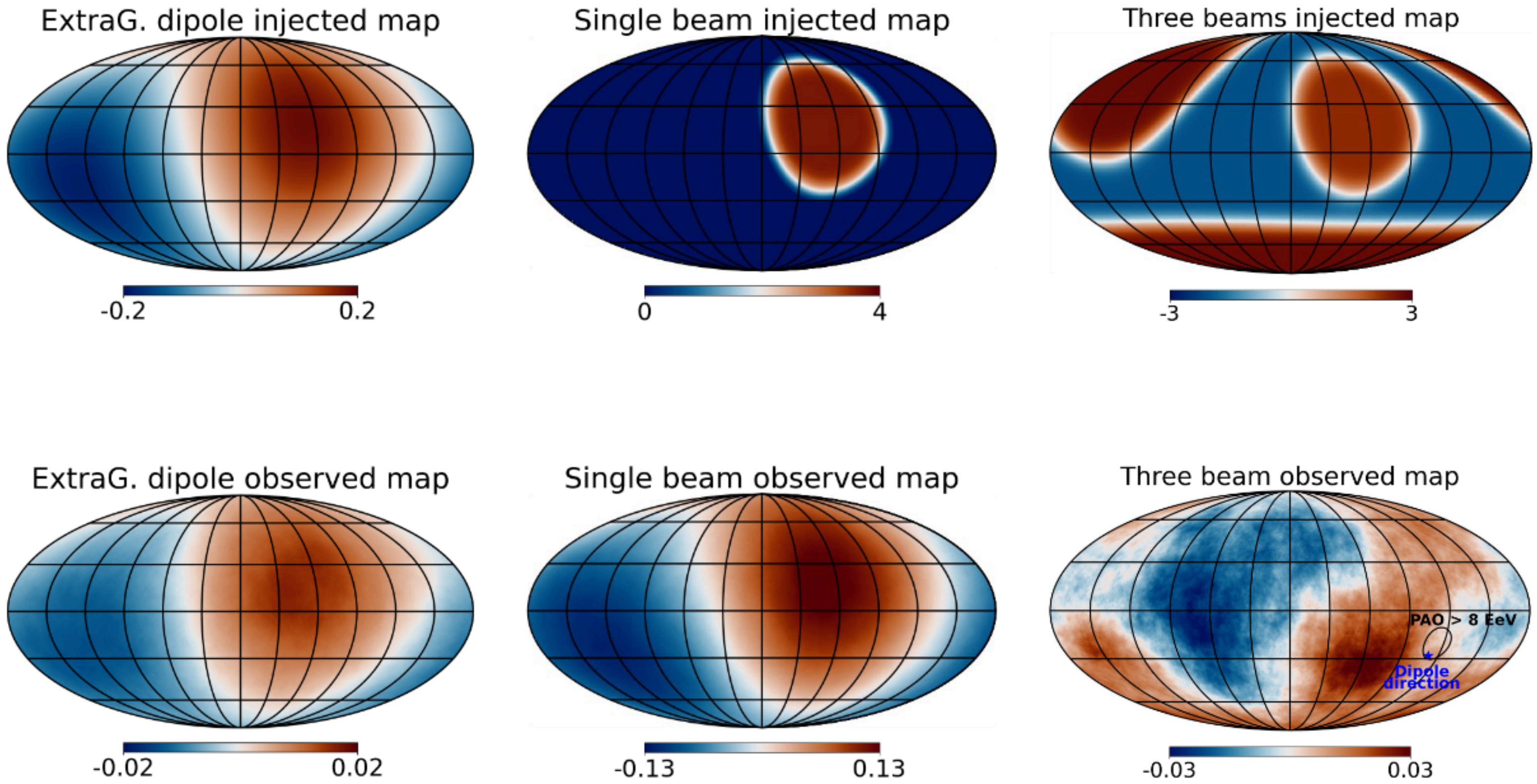


Arrows depict the CR current in different cell regions (D_{out}/D_{in} = 5 adopted for animation)

Injected and Observed Maps

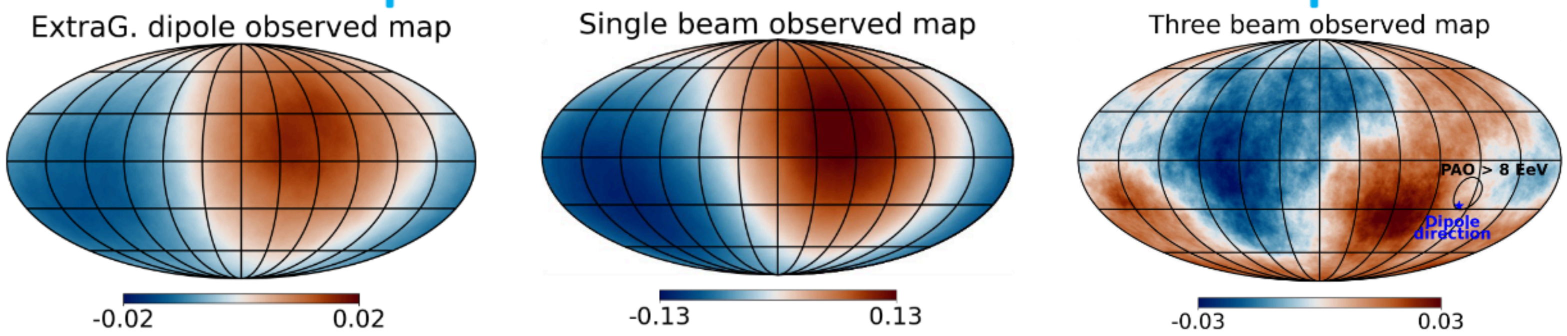
Injected:

Observed:

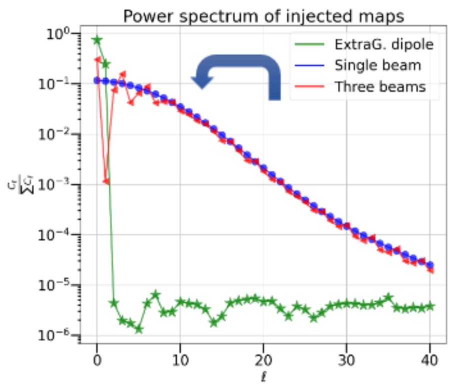


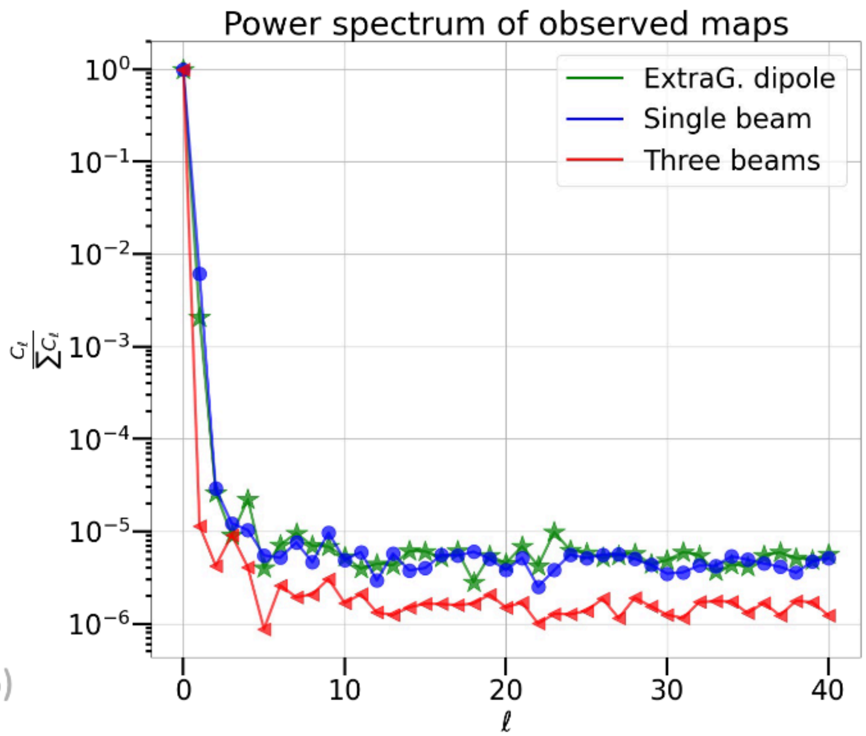
Shaw et al., *MNRAS*, Vol. 543, Iss. 4 (2025)

Power Spectra of Observed Maps



Shaw et al. (in prep.)



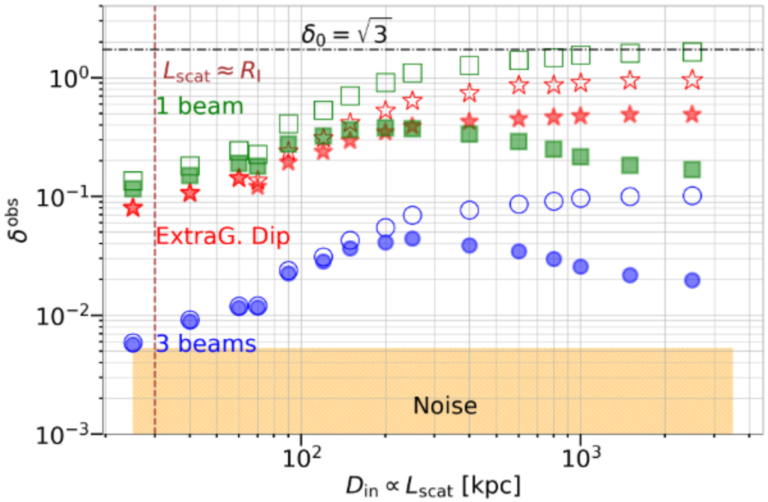


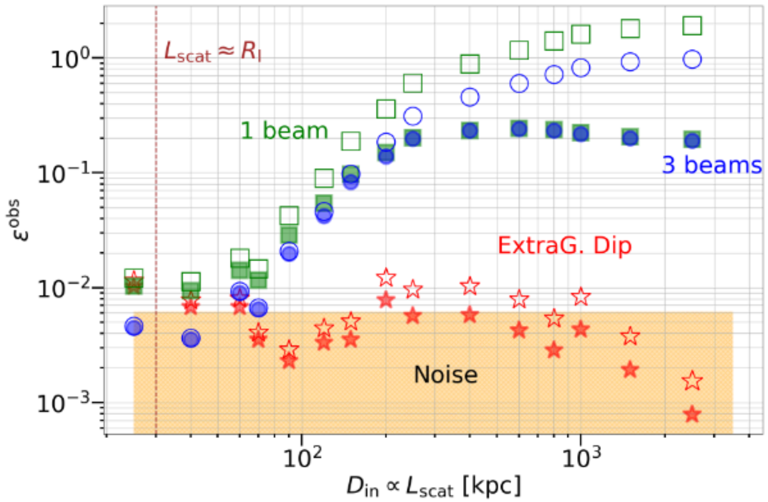
Shaw et al., *MNRAS*, Vol. 543, Iss. 4 (2025)

DESY.

The Importance of Measuring the Quadrupole Moment at EeV Energies

Shaw et al., *MNRAS*, Vol. 543, Iss. 4 (2025)

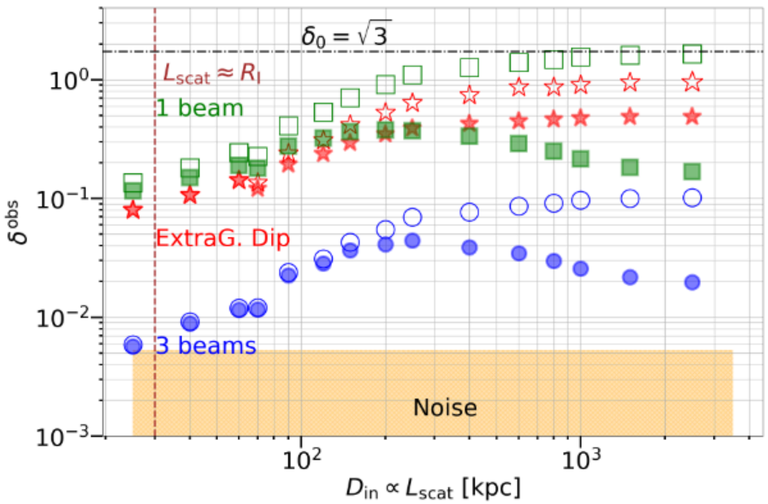


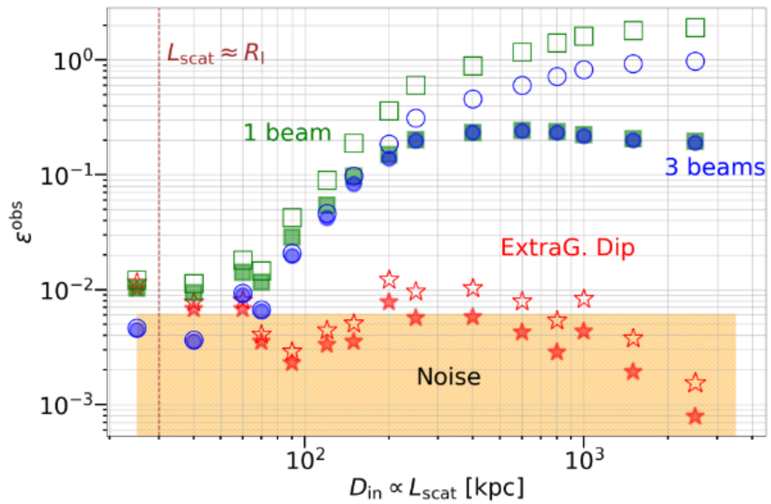


Note the difference in growth rates of dipole and quadrupole amplitude with L_{scat}

The Importance of Measuring the Quadrupole Moment at EeV Energies

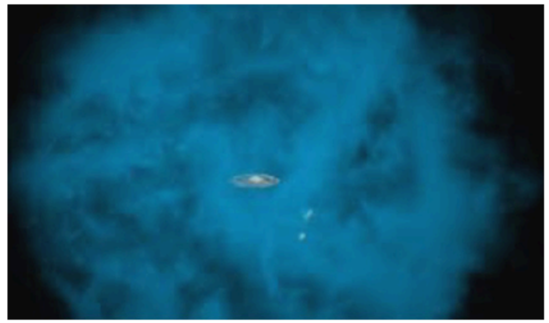
Shaw et al., *MNRAS*, Vol. 543, Iss. 4 (2025)





Note the difference in growth rates of dipole and quadrupole amplitude with L_{scat}

Hall Probe



Conclusions

- The transition from Galactic to Extragalactic occurs between 10^{17} eV and $10^{18.5}$ eV
- A Galactic "Population B" source class seems required to bridge the energy gap between the knee and the ankle, and CR composition data allow its E_{max} to be constrained
- The population 3 sources should not have a strong positive source evolution (local?)
- Secondary signatures from CR energy losses in the Galactic halo can be used to probe their presence (>10 kpc)
- The magnetisation of the Galactic halo can have implications for the penetration of Extragalactic CRs into the halo, which can be tested

What "Arrives" in Not Necessarily What is Observed

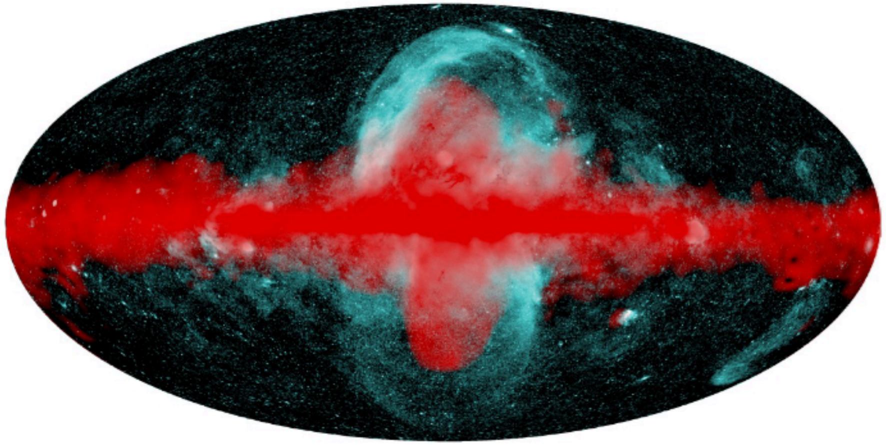
Cosmic ray source

Reduced diffusion coefficient inside bubble region

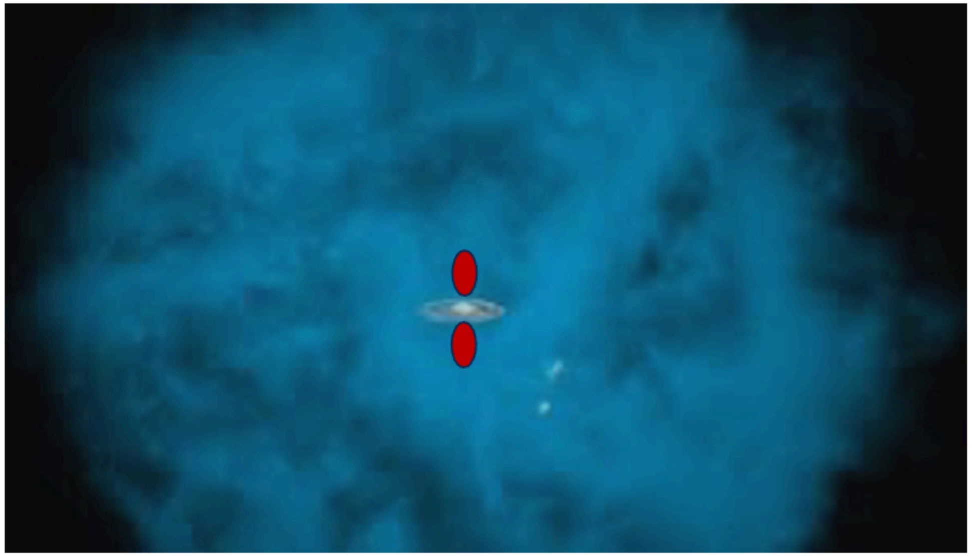
(D_{out}/D_{in} = 5 adopted for animation)

The Fermi/eROSITA Bubbles

- 2 Galactic gamma-ray emitting bubbles exist out to ~8 kpc above and below the Galactic plane
- These appear to be enshrouded in larger hot X-ray emitting bubbles, out to ~14 kpc

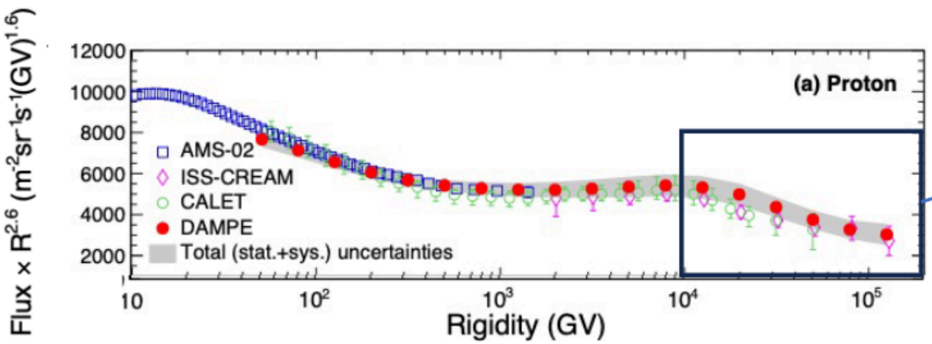


Predehl et al. Nature 588 (2020)

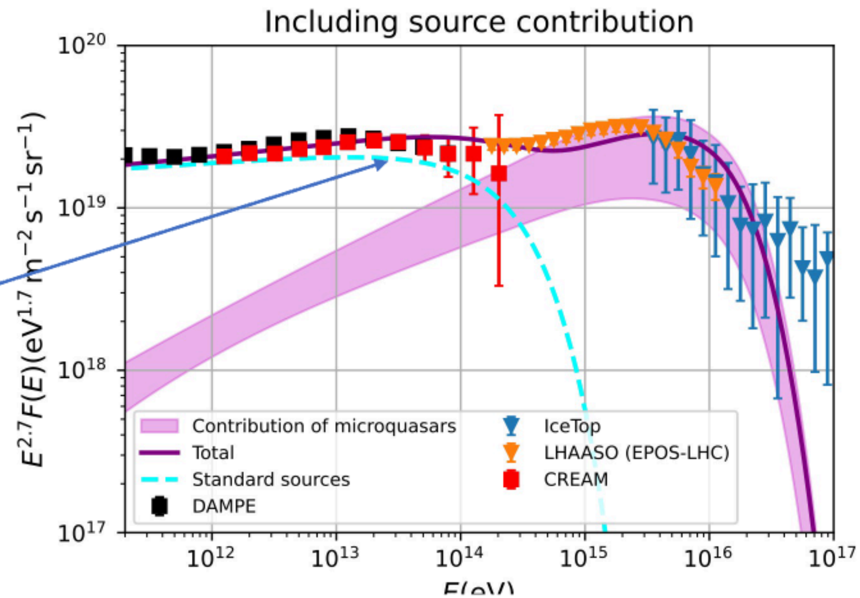


These results appear to indicate that non-thermal particle transport in the Milky Way halo, at least from the Galactic center region, possesses an advective component

Gaisser-Type Population B Candidates: **Microquasars**



DAMPE Coll. 2511.05409



Kaci et al., 2510.01369

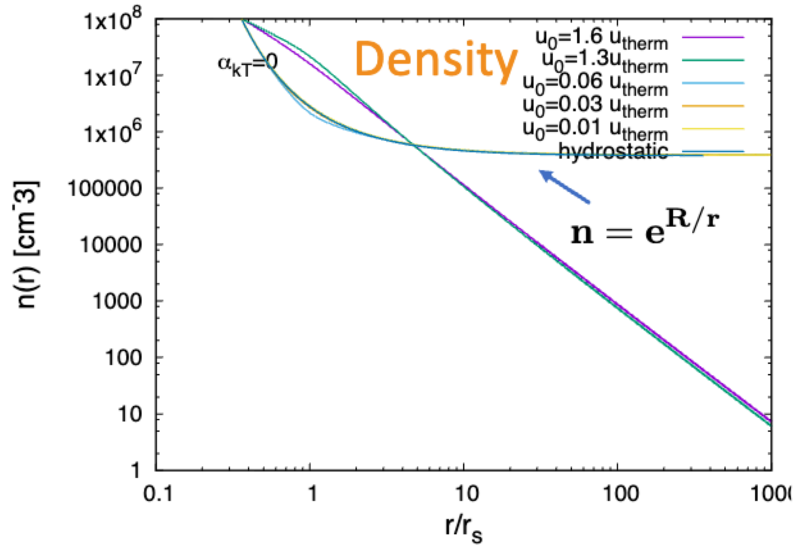
$$\mathbf{E_{max} < 2PeV \left(\frac{L}{10^{38}\ erg\ s^{-1}}\right)^{1/2} \left(\frac{\beta}{0.1}\frac{\eta_B}{0.1}\right)^{1/2}}$$

DESY.

Thermally Driven Outflows: 1/r (Point Source) Potential

Mass Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_\rho \quad \Rightarrow \quad \rho \mathbf{v} \mathbf{r}^2 = \text{const.}$$

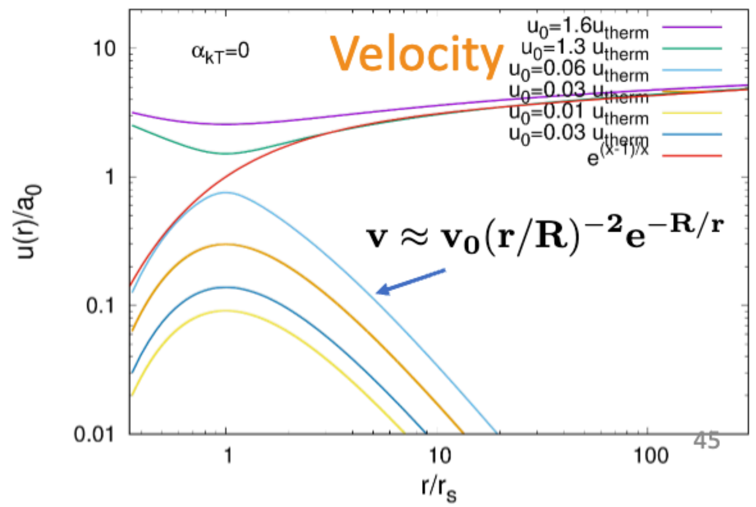


Momentum Continuity

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} + p\mathbf{I}) = -\rho \nabla \Phi_{\text{eff}}$$

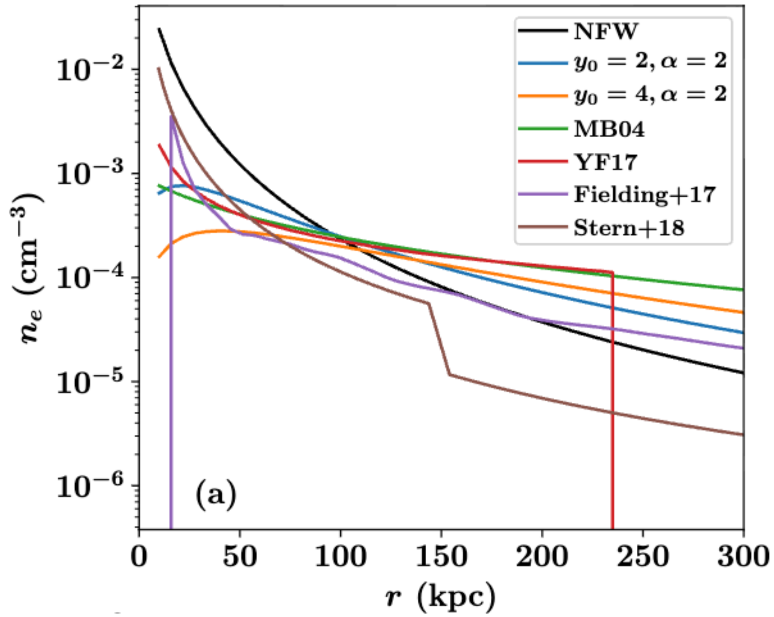
For a spherically symmetric (isothermal) thermally driven outflow

$$\Rightarrow \quad \frac{1}{v}\frac{dv}{dr} = \frac{1}{r}\left(\frac{2c_s^2 - r\frac{d\Phi}{dr}}{v^2 - c_s^2}\right)$$



Why Consider Slow Outflows?

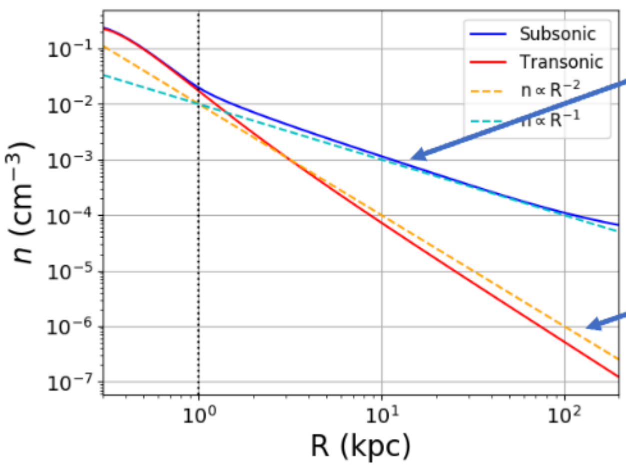
Although King function was adopted in eROSITA analysis, result is also consistent with hydrostatic equilibrium expectations for hot gas



Prochaska et al. MNRAS 485 (2019)

These profiles are consistent with expectations of the halo gas being in hydrostatic equilibrium

$$\mathbf{n = n_0 e^{-\frac{\Phi}{c_s^2}}}$$



Hydrostatic equilibrium scenario,

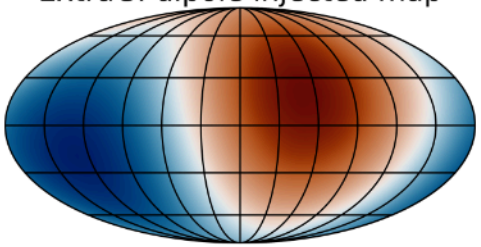
$$\mathbf{n \propto r^{-1}}$$

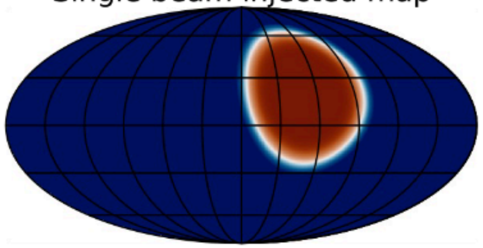
Supersonic wind scenario,

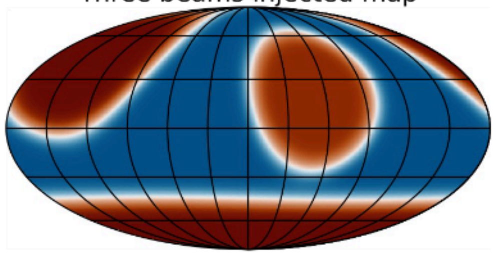
$$\mathbf{n \propto r^{-2}}$$

DESY.

Power Spectra of Injected Maps

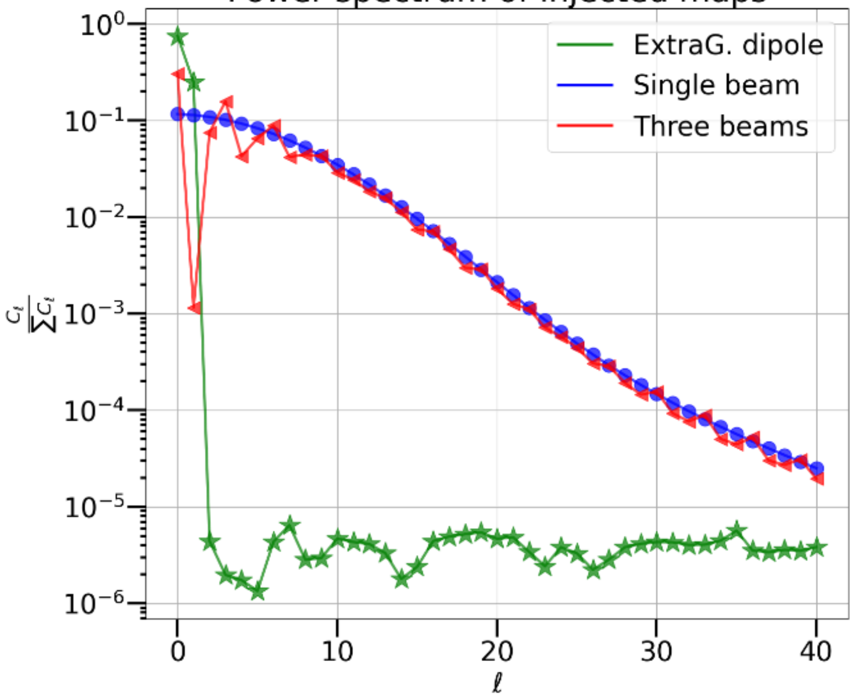






$$\mathbf{\Phi_l = \int_{-1}^{1} d\cos\theta \frac{dN}{N d\cos\theta} \frac{2l+1}{\sqrt{2}} P_l(\cos\theta)}$$

$$\mathbf{C_l = \frac{\Phi_l^2/(2l+1)}{\sum_n \Phi_n/(2n+1)}}$$



Shaw et al., *MNRAS*, Vol. 543, Iss. 4 (2025)

DESY.