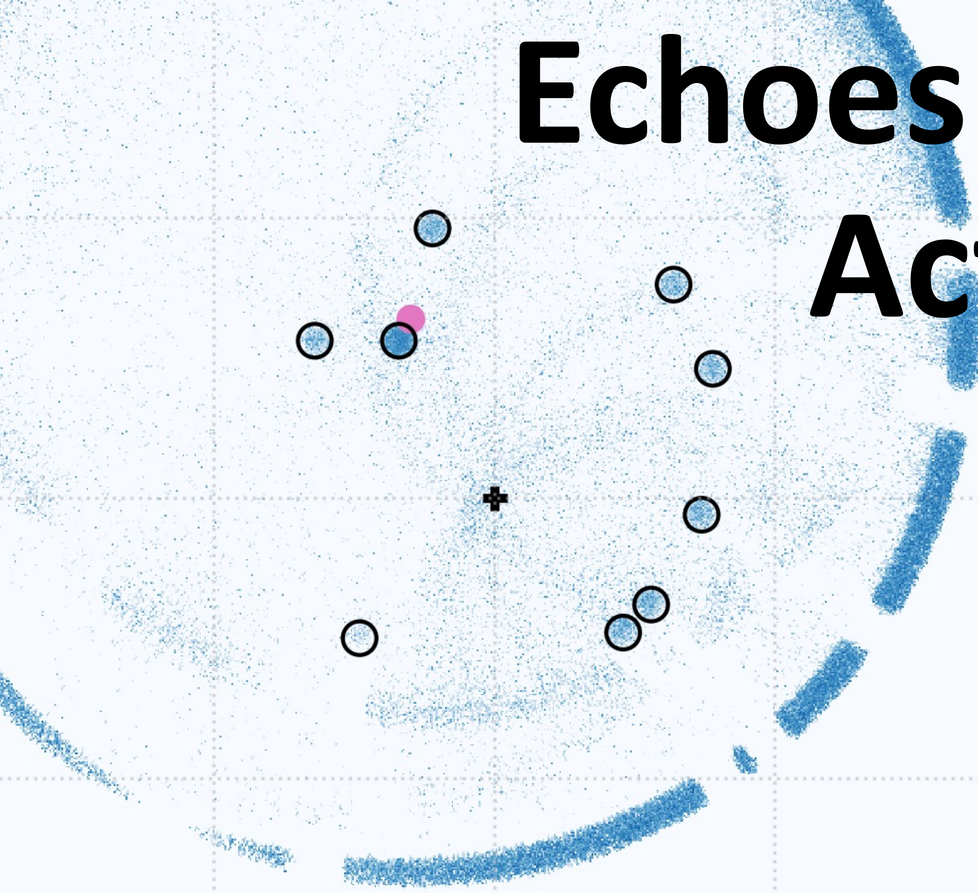
Echoes from Cen A's Active Past



Work done in collaboration with:

James Matthews (University of Cambridge/Oxford)

and

Tony Bell (University of Oxford)

Taylor et al. MNRAS 524 (2023)

Building on the results of Bell et al. MNRAS 448 (2022)

DESY.

Echoes from Subir's Past Activity

DESY.

My First Steps Exploring UHECR Propagation

Subir proposed for me to investigate the propagation of UHECR nuclei through extragalactic radiation fields as part of my PhD studies

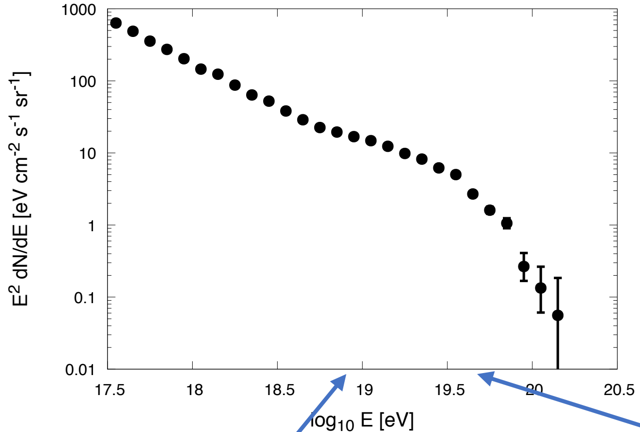
This topic proved to be extremely rich, introducing me to a range of topics:

- EBL (extra-galactic background radiation)
- the diffuse gamma-ray background
- cosmogenic neutrinos
- simplified analytic descriptions of more complicated Monte Carlo simulations

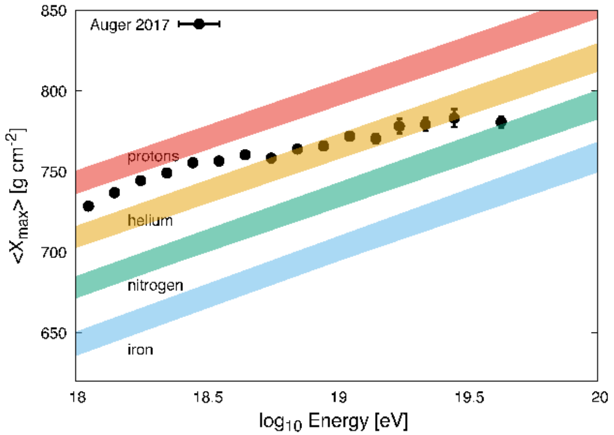
The breadth of topics he introduced me to put me in a position to lead research efforts myself in separate (but connected) disciplines

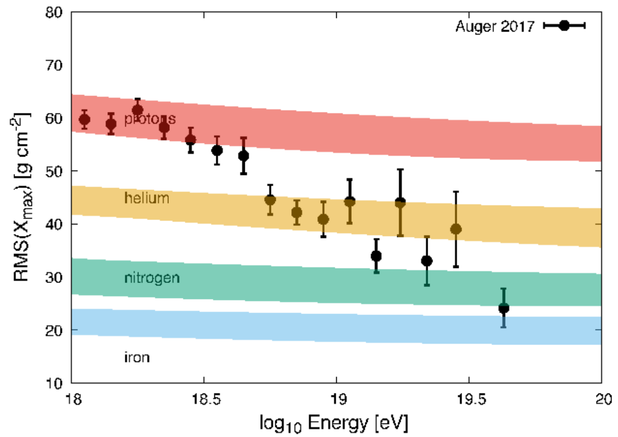
UHECR: The Observational Status

Spectrum

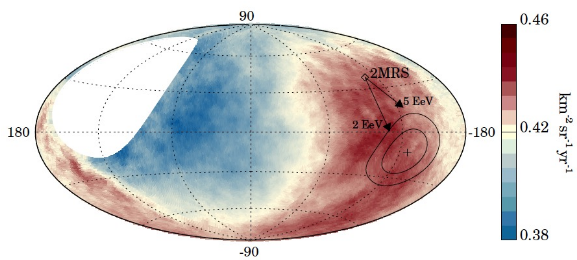


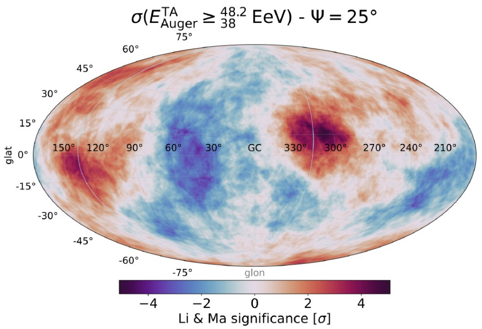
Composition





Anisotropy





Pierre Auger Collaboration. ApJ. 935 (2022)

Caccianiga et al. for the Auger and TA Collaborations. PoS (ICRC2023) 521

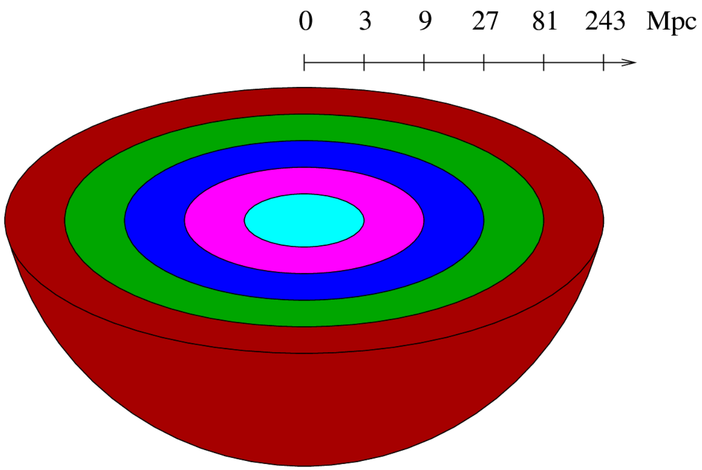
DESY.

Assumptions on Source Population

$$\frac{dN}{dV_C} \propto (1+z)^n$$

$$z < z_{max}$$

$$n = -6,\ -3,\ 0,\ 3$$



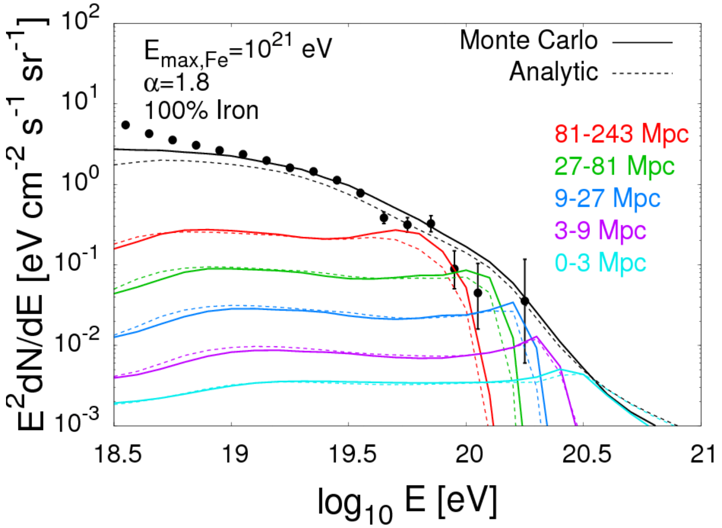
$$\frac{dN}{dE} \propto \sum_a f_a E^{-\alpha} e^{[-E/E_{Z_a,max}]}$$

$$E_{Z,max} = (Z/26) \times E_{Fe,max}$$

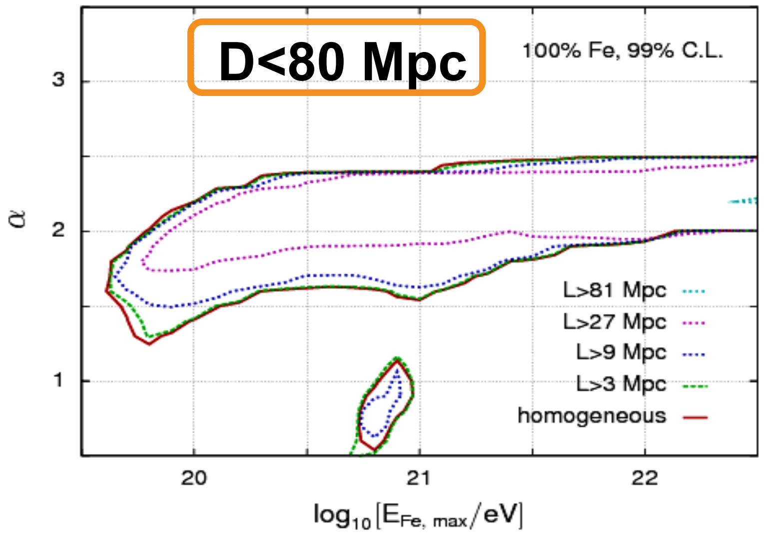
Note- magnetic field horizon effects are neglected in the following. This amounts to assuming: $d_s < (ct_H \lambda_{scat})^{1/2}$
ie. the source distribution may be approximated to be spatially continuous (also note, presence of t_H term comes from temporally continuous assumption)

DESY.

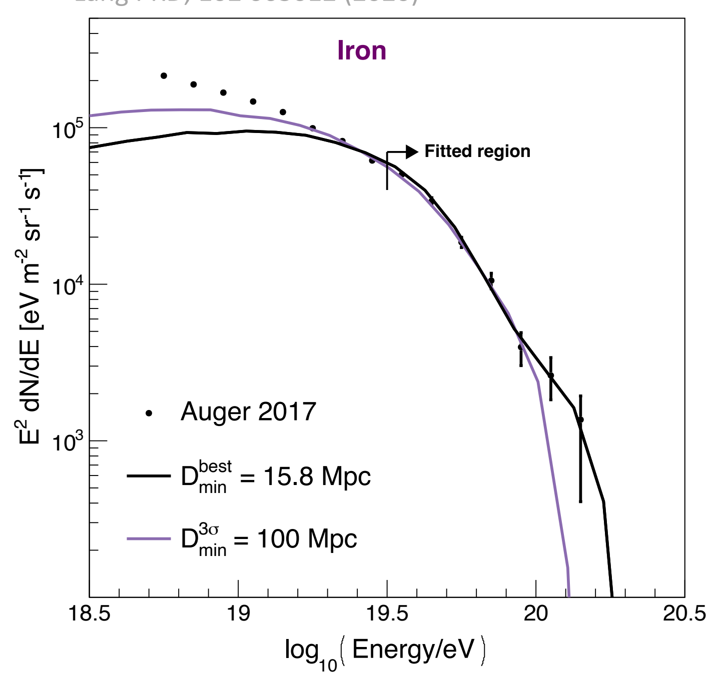
How Far is the Nearest Source?



Taylor PRD, 84 105007 (2011)



Lang PRD, 102 063012 (2020)

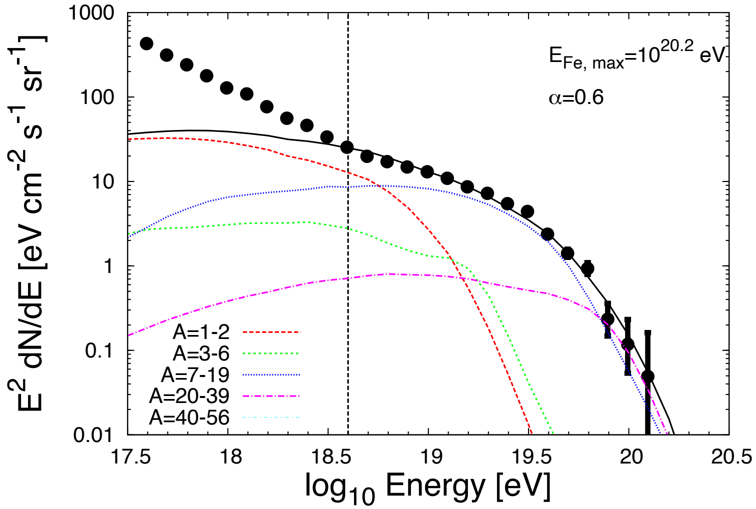


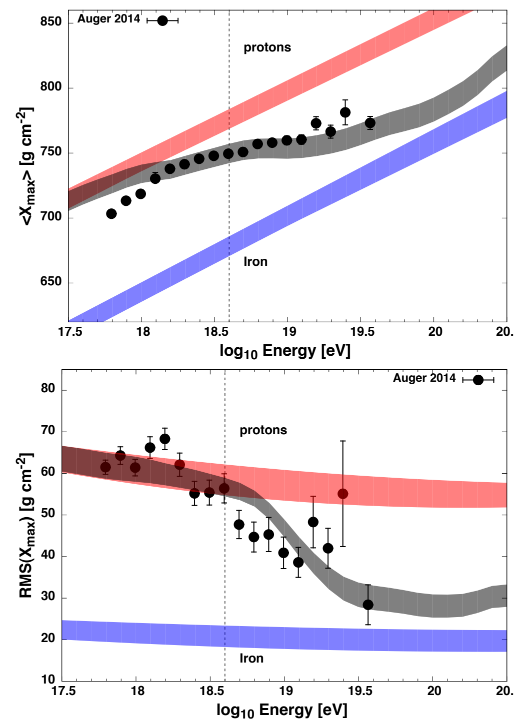
DESY.

Good Fit Solutions and their Stability

Focusing first on the spectrum and composition data

Taylor, PRD 92 (2015) 6





Evidence that either there aren't many such sources, or that these sources (spectrally) are copies of each other (ie. stability of solution issues) Ehlert PRD, 107 103045 (2020)

Proximity-Spectral Index Relation

Taylor, PRD 92 (2015) 6

Parameter	$n=-6$ Best-fit Value	$n=-6$ Posterior Mean & Standard Deviation	$n=-3$ Best-fit Value	$n=-3$ Posterior Mean & Standard Deviation	$n=0$ Best-fit Value	$n=0$ Posterior Mean & Standard Deviation	$n=3$ Best-fit Value	$n=3$ Posterior Mean & Standard Deviation
α	1.8	1.83 ± 0.31	1.6	1.67 ± 0.36	1.1	1.33 ± 0.41	0.6	0.64 ± 0.44
$\log_{10}\left(\frac{E_{\mathrm{Fe,max}}}{\mathrm{eV}}\right)$	20.5	20.55 ± 0.26	20.5	20.52 ± 0.27	20.2	20.38 ± 0.25	20.2	20.16 ± 0.18

note trend in index →

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note trend in index ↓

PAO, JCAP 04 (2017) 038

source evolution		γ	$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	D	$D(J)$	$D(X_{\mathrm{max}})$
$(1+z)^m$	$m=+3$	$-1.40^{+0.35}_{-0.09}$	$18.22^{+0.05}_{-0.02}$	179.1	7.5	171.7
	$m=0$	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
	$m=-3$	$+1.42^{+0.06}_{-0.07}$	$18.85^{+0.04}_{-0.07}$	173.9	19.3	154.6
	$m=-6$	$+1.56^{+0.06}_{-0.07}$	18.74 ± 0.03	182.4	19.1	163.3
	$m=-12$	$+1.79 \pm 0.06$	18.73 ± 0.03	182.1	18.1	164.0
	$z \leq 0.02$	$+2.69 \pm 0.01$	$19.50^{+0.08}_{-0.07}$	178.6	15.3	163.3

Local source solution calls upon a more acceptable spectral index

Proximity-Spectral Index Relation

Taylor, PRD 92 (2015) 6

Parameter	$n=-6$ Best-fit Value	$n=-6$ Posterior Mean & Standard Deviation	$n=-3$ Best-fit Value	$n=-3$ Posterior Mean & Standard Deviation	$n=0$ Best-fit Value	$n=0$ Posterior Mean & Standard Deviation	$n=3$ Best-fit Value	$n=3$ Posterior Mean & Standard Deviation
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PAO, JCAP 04 (2017) 038

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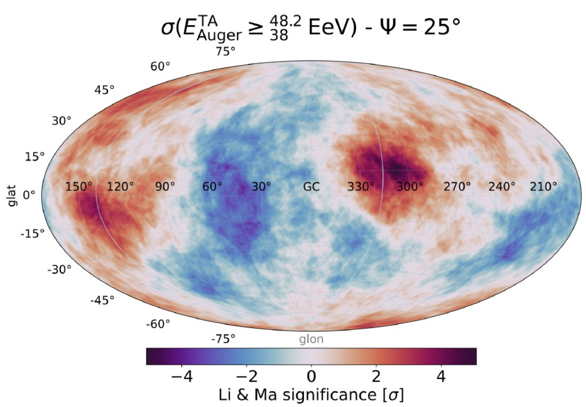
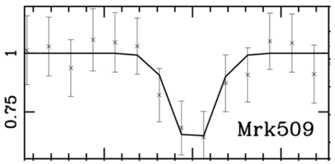
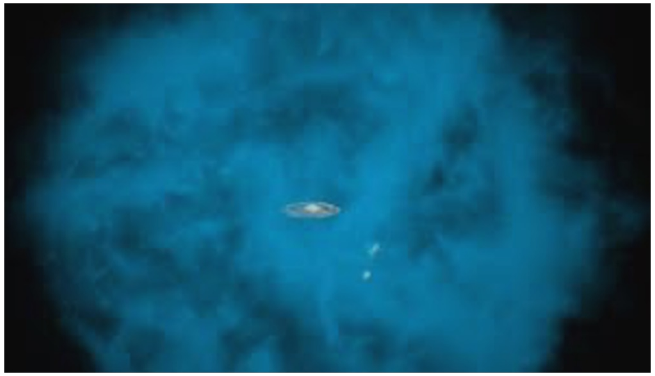


Local source solution calls upon a more acceptable spectral index- how to square this with the anisotropy data?

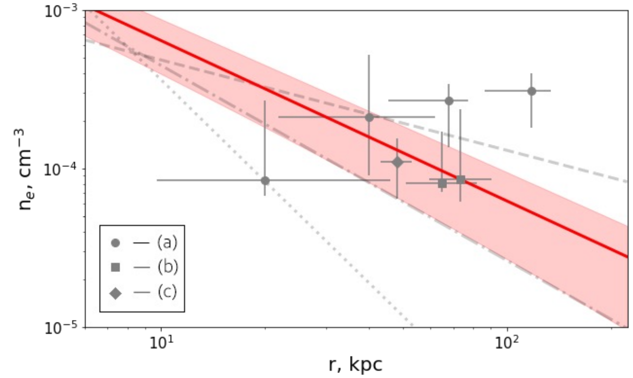
Large Thermal Pressure in Galactic Halo

X-ray observations of bright AGN indicate the presence of a hot local absorber.
Gupta ApJ, 756 (2012)

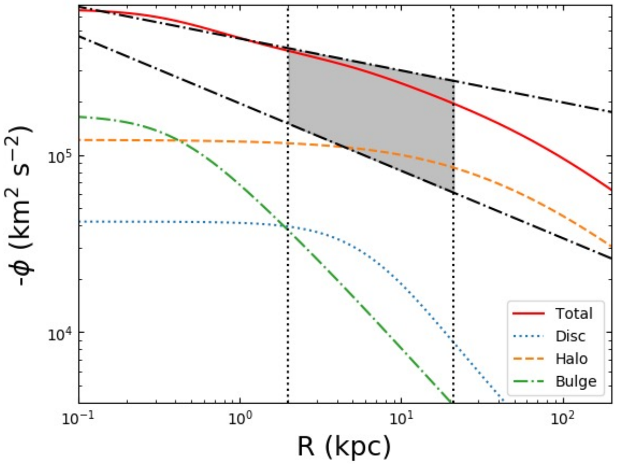


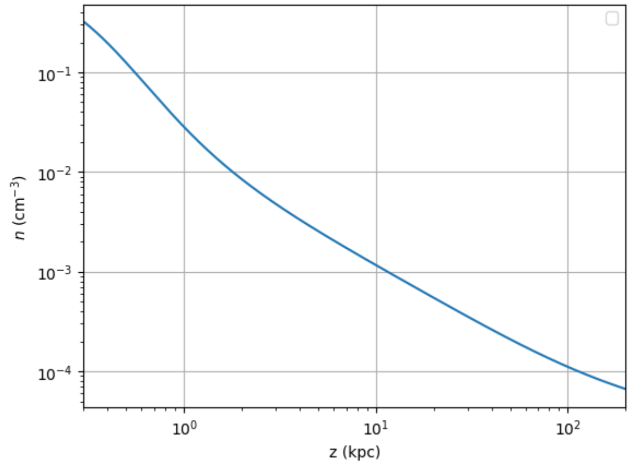


More recently, the ram pressure stripping of satellite galaxies + emission from the hot absorber have been collectively used to probe the halo gas density.
Faerman ApJ 835 (2017), Martynenko MNRAS, 511 (2022)



These results are consistent with expectations if the halo gas is in hydrostatic equilibrium Faerman ApJ 835 (2017), Tourmente 2207.09189, (2022)





Faerman ApJ, 893 (2020)

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

↓

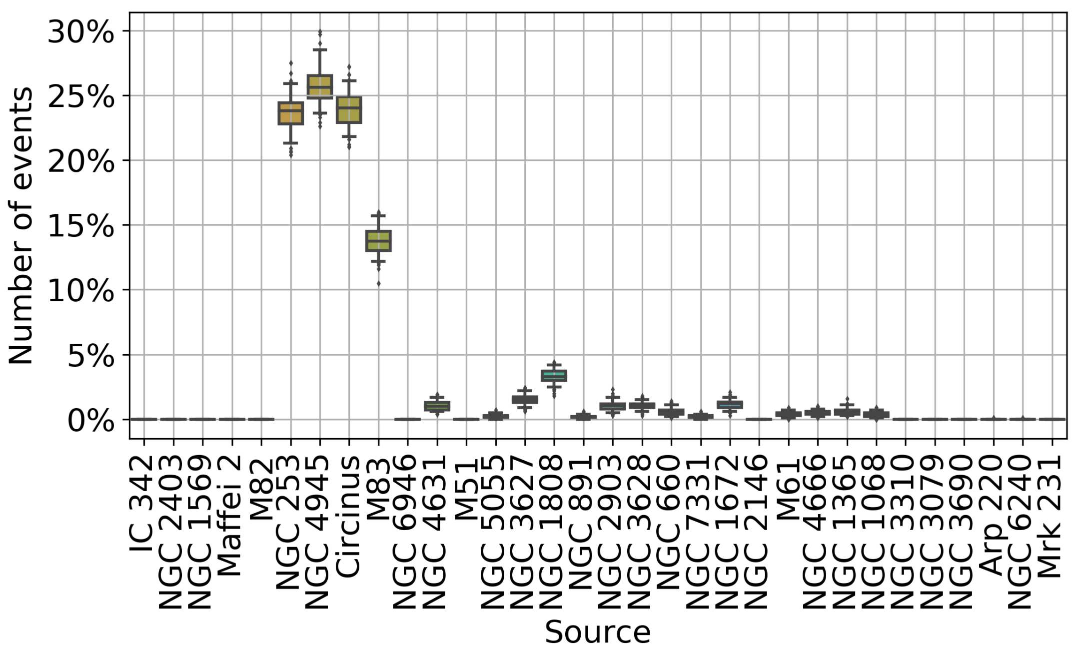
$$\mathbf{r_L(10\ EV) = 50\ kpc}$$

consistent with
Heesen A&A, 670 (2023)

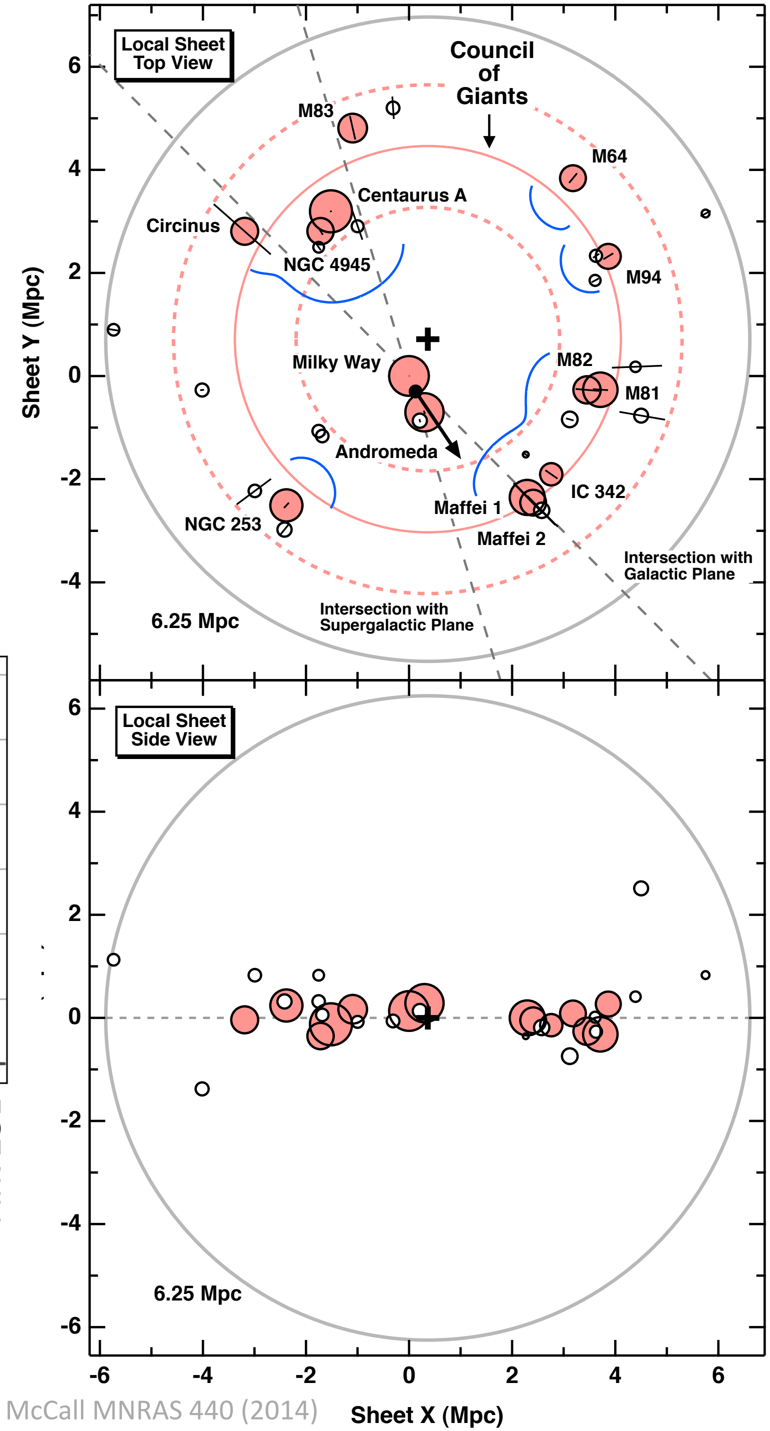
Our Local Extragalactic Neighbourhood

The local (<10 Mpc) extragalactic objects are structured, sitting in a roughly circular disk shape around the Milky Way

van Vliet MNRAS 510 (2021)



Bregman et al. ApJ 928 (2022)



McCall MNRAS 440 (2014)

Andrew Taylor

DESY.

The Uniqueness of Cen A within the Council of Giants

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

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

[AM Hillas (1984)]

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

$$\mathbf{L_B} = \mathbf{U_B} 4\pi \mathbf{R^2} \beta \mathbf{c}$$

Under the assumption of equipartition of energy between kinetic energy and magnetic field:

[Lovelace et al. (1976)]

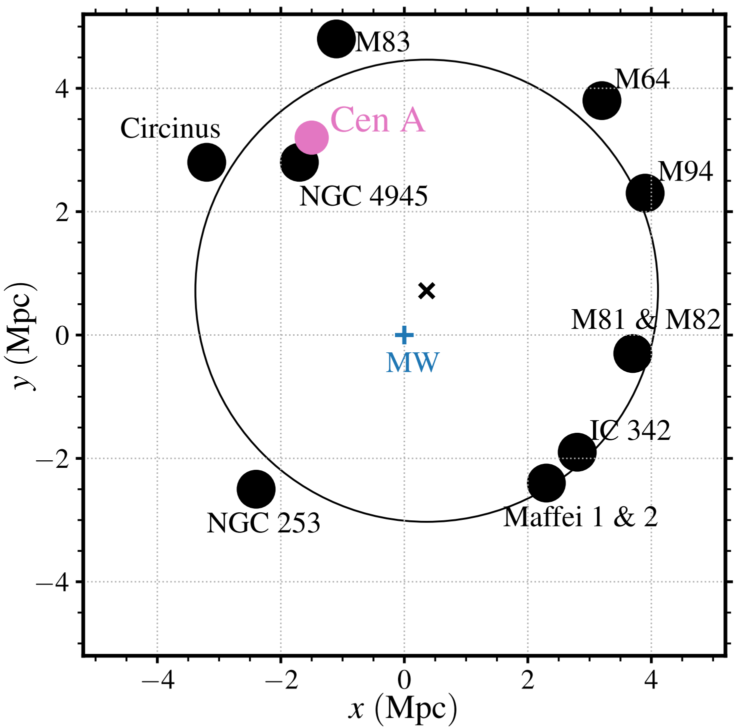
$$\mathbf{E_{max}} \lesssim \frac{\mathbf{Z}}{\eta} (\beta \mathbf{L_{KE}} \alpha \hbar)^{\mathbf{1/2}} \approx \mathbf{10} \ \frac{\mathbf{Z}}{\eta} \left(\frac{\beta \mathbf{L_{KE}}}{\mathbf{3 \times 10^{43} \ erg \ s^{-1}}} \right)^{\mathbf{1/2}} \mathbf{EeV}$$

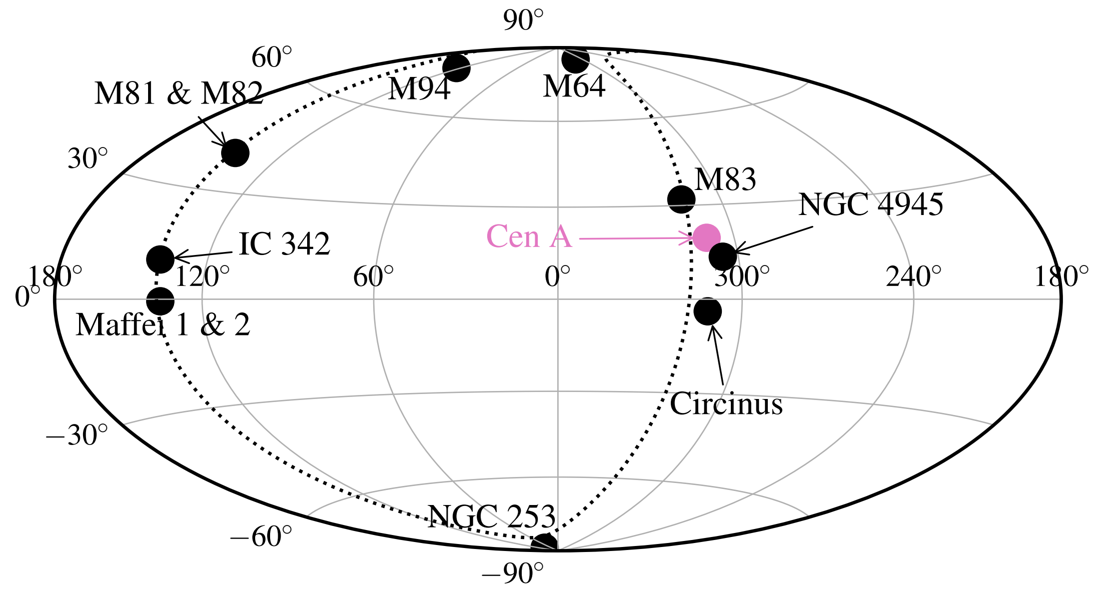
Local Extragalactic Structure
The Council of Giants

Cen A is unique within the council of giant structure are being the only object proving a kinetic luminosity capable of giving rise to multi EeV acceleration

Lovelace et al. (1976)

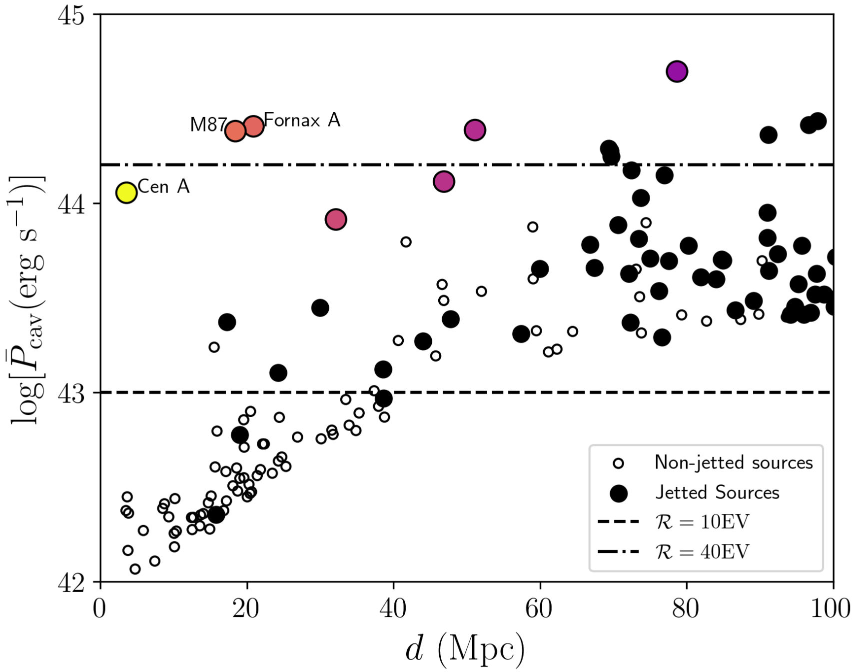
$$\mathbf{E_{max}} \lesssim \frac{\mathbf{Z}}{\eta}\left(\beta \mathbf{L_{KE}} \alpha \hbar\right)^{\mathbf{1/2}} \approx \mathbf{10}\ \frac{\mathbf{Z}}{\eta}\left(\frac{\beta \mathbf{L_{KE}}}{\mathbf{3 \times 10^{43}\ erg\ s^{-1}}}\right)^{\mathbf{1/2}} \mathbf{EeV}$$





Cen A's Past Activity

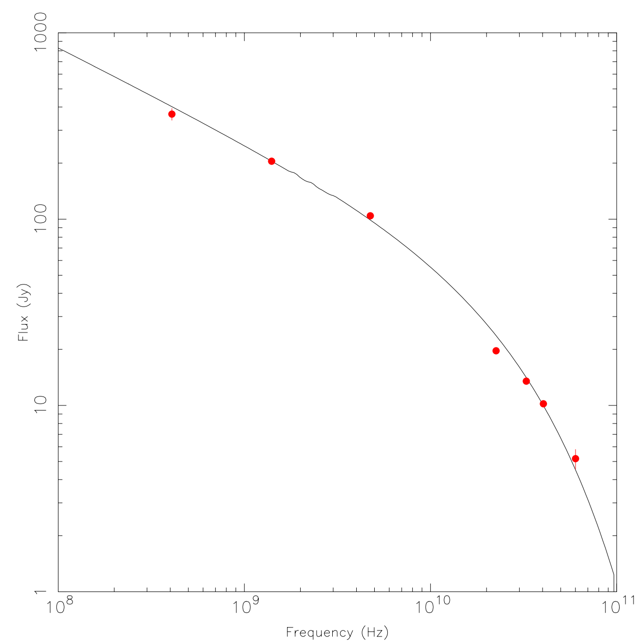
Matthews et al. MNRAS 479 (2018)



$$\mathbf{L_{jet} \sim 10^{44}\ erg\ s^{-1}}$$

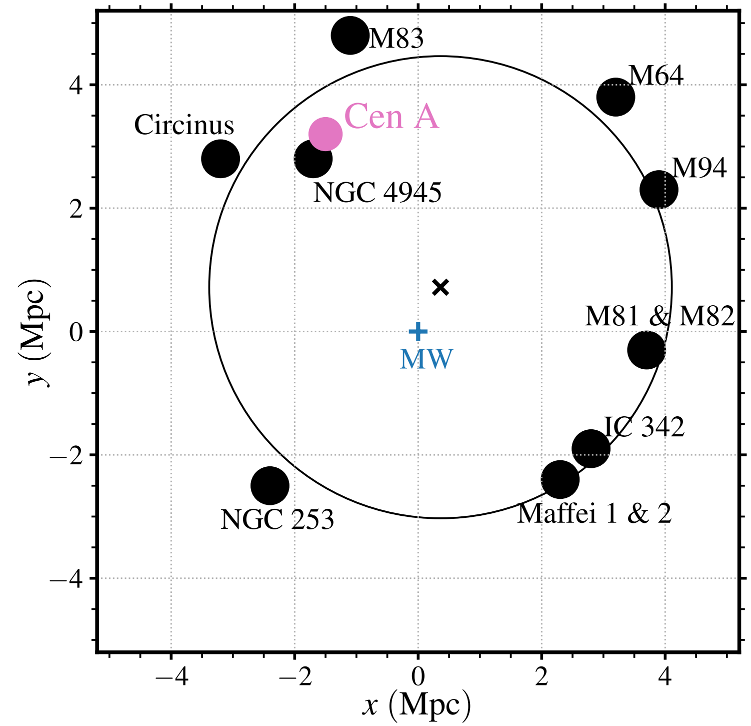
$$\mathbf{t_{act} \sim 20 - 30\ Myrs}$$

Hardcastle et al. MNRAS 393 (2009)



DESY.

Simulation Setup



- Particles initially fill 300 kpc region surrounding Cen A (isotropic momentum distribution)
- Large angle particle scattering occurs within the virial region (< 300 kpc) of all members of the council of giant system
- Outside the virial radii of these galaxies the particle propagation is treated as ballistic
- Fundamental parameter of problem- optical depth of scattering regions

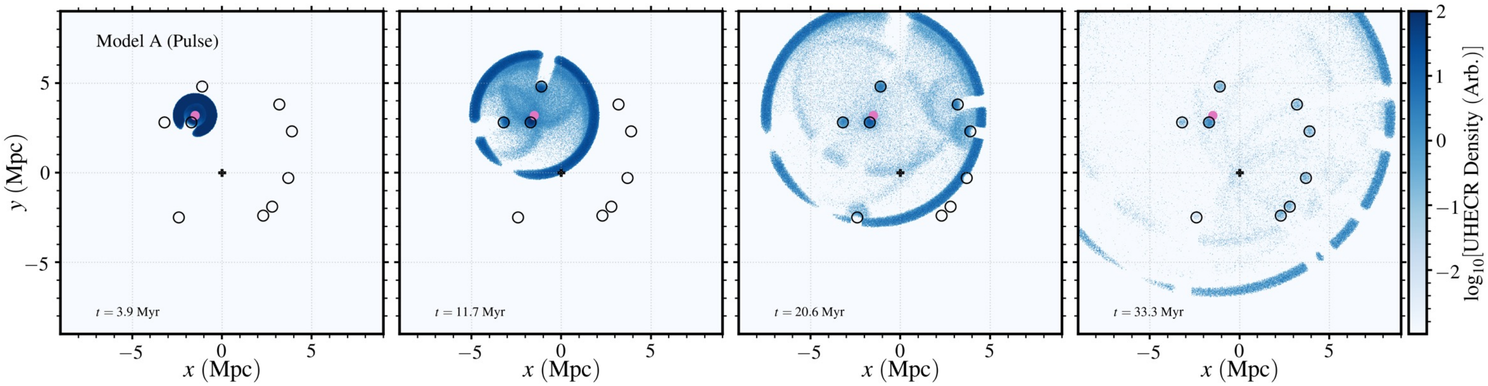
$$\tau = \frac{\mathbf{r_{vir}}}{\mathbf{l_{sc}}}$$

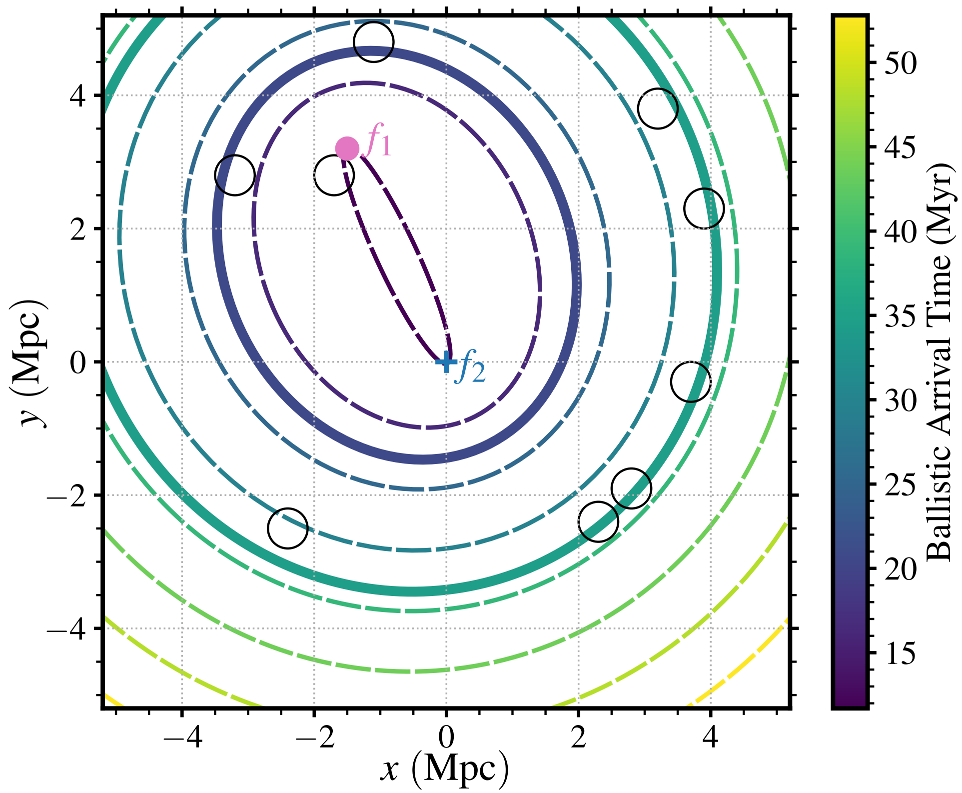
- Echo signals results are rather insensitive to optical depth of scattering regions, provided $\tau > \mathbf{1}$

- Only He and Fe injected into the system (fragile and robust species compared to crossing time of system)
- Particles photo-disintegrate en-route in extragalactic radiation fields
- 30 EeV particles being focused on
- Deflections from MW magnetized halo intentionally left out

DESY.

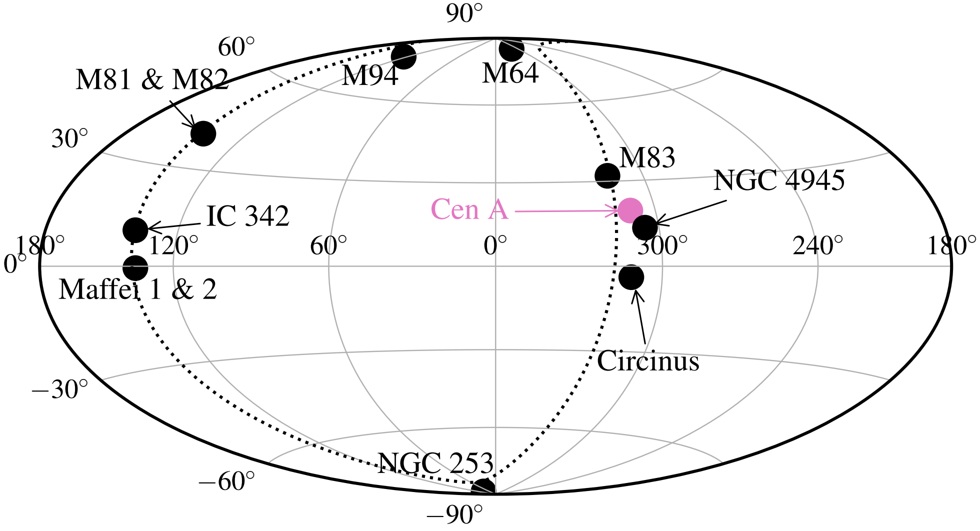
Simulations of UHECR Propagation Through the CoG Structure

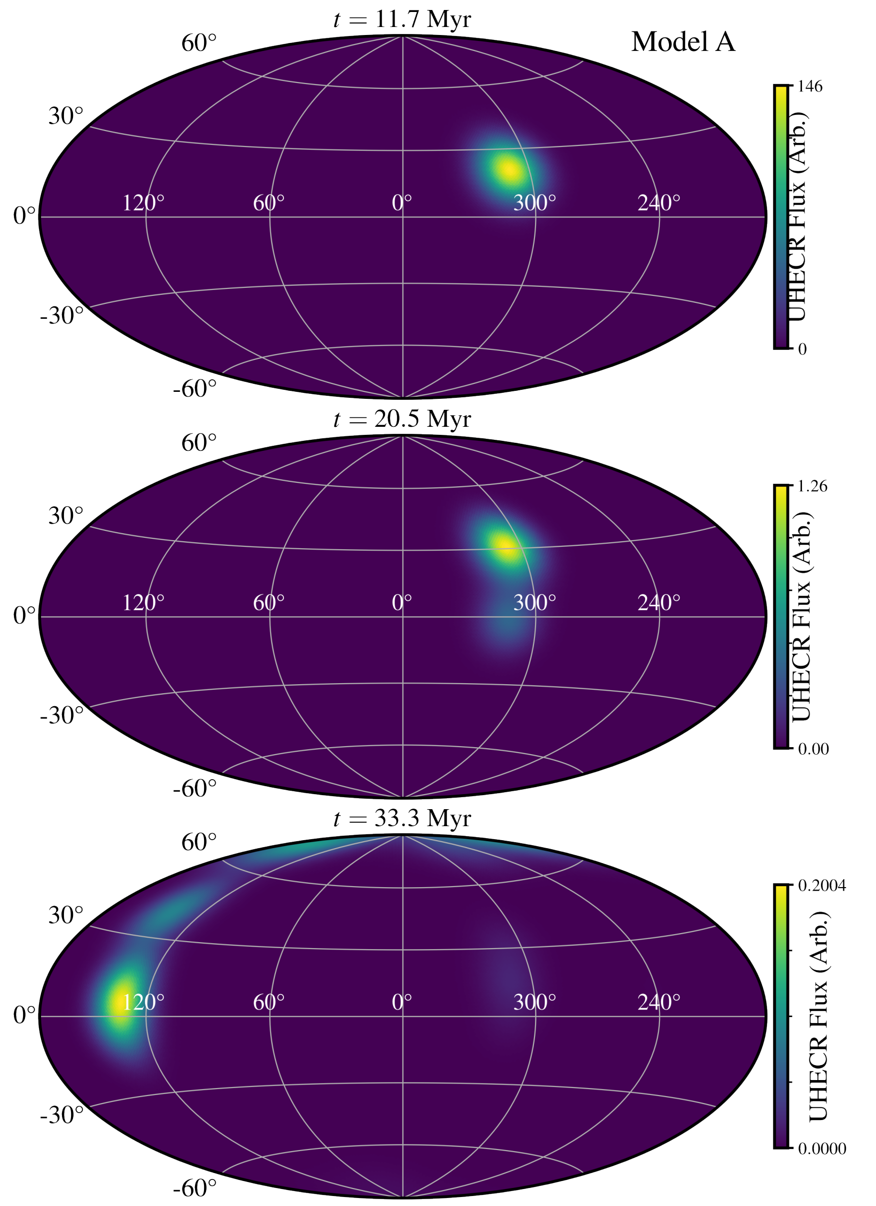




DESY.

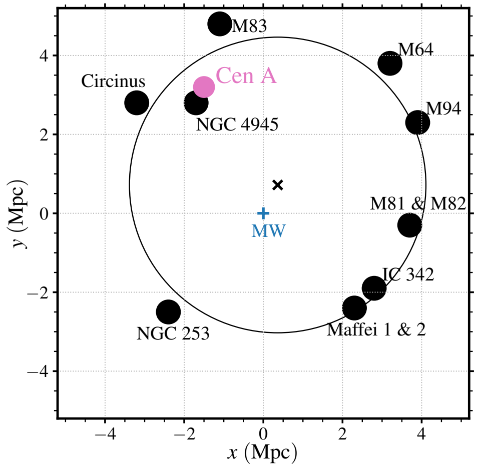
Milky Way Based Observers

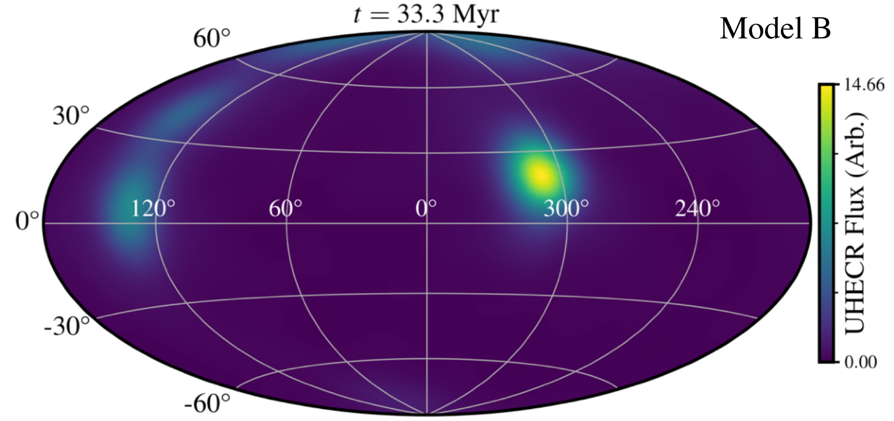


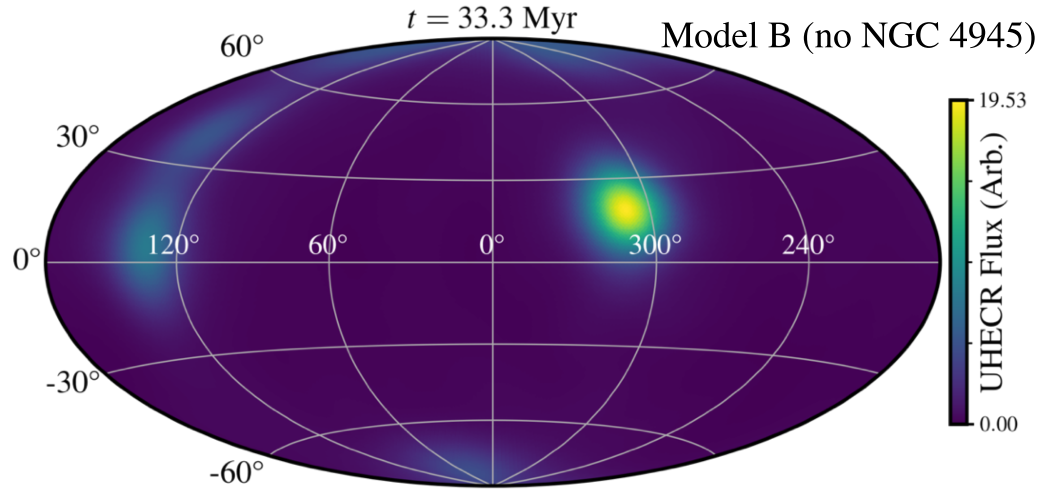


DESY.

The Presence of NGC 253 in the Skymaps?







DESY.

Particle Acceleration/Release Scenarios

Model B:
The UHECR output of Cen A is described by:

$$\mathbf{L = L_0 e^{-t/\tau_{dec}}}$$

$$\tau_{\mathbf{dec}} = \mathbf{3\ Myr}$$

The UHECR output of Cen A exponentially decays after the initial burst

Model C:
The UHECR leakage out of Cen A is rigidity dependent

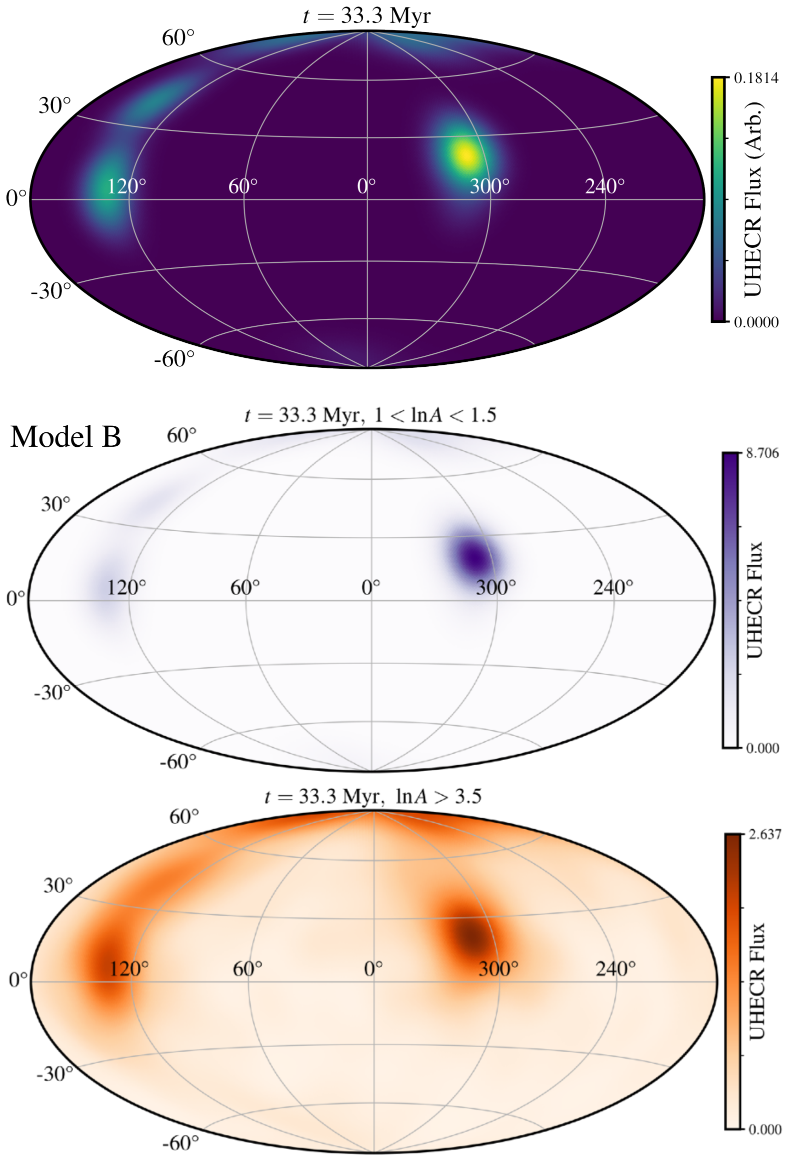
$$\tau_{\mathbf{esc}} = \tau_{\mathbf{10}} \left(\frac{\mathbf{(E/Z)}}{\mathbf{10\ EV}} \right)$$

$$\tau_{\mathbf{10}} = \mathbf{1.5\ Myr}$$

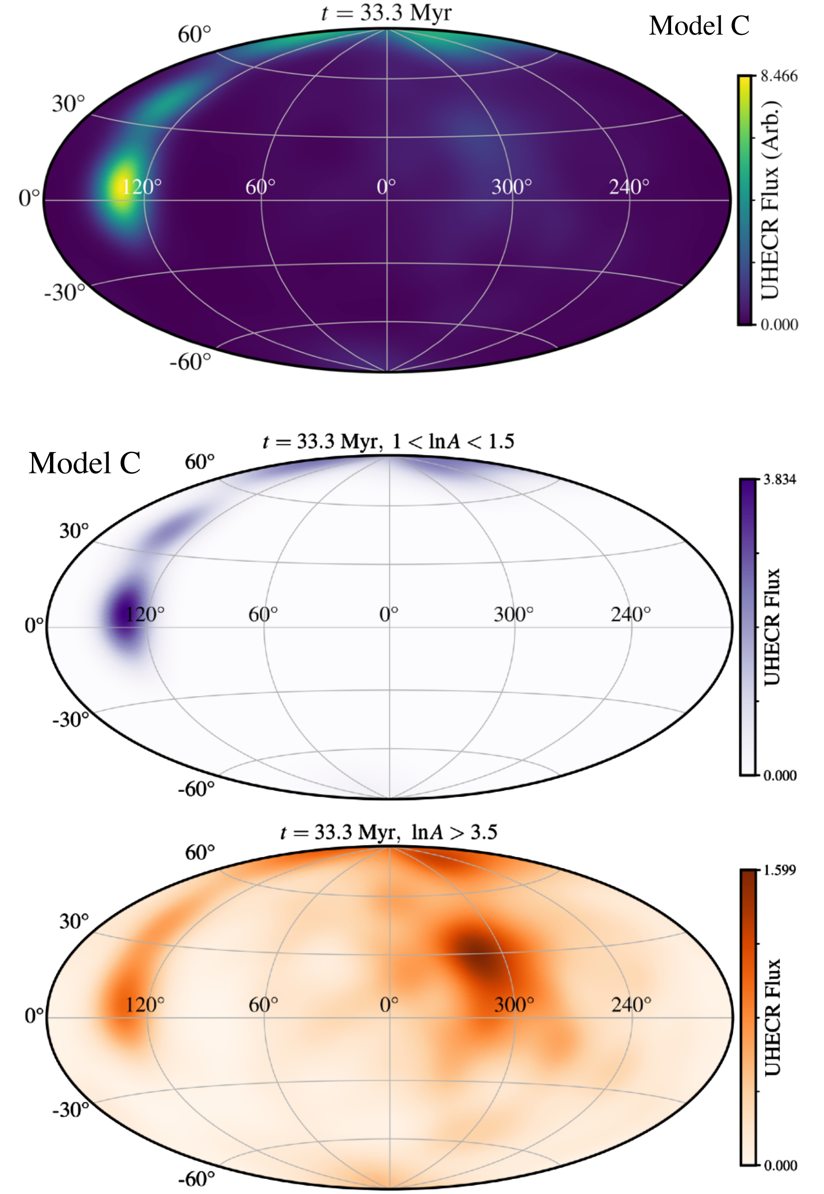
The UHECR escape from the source region in a rigidity dependent manner

Distinguishing Between Model B and Model C Results

Model B

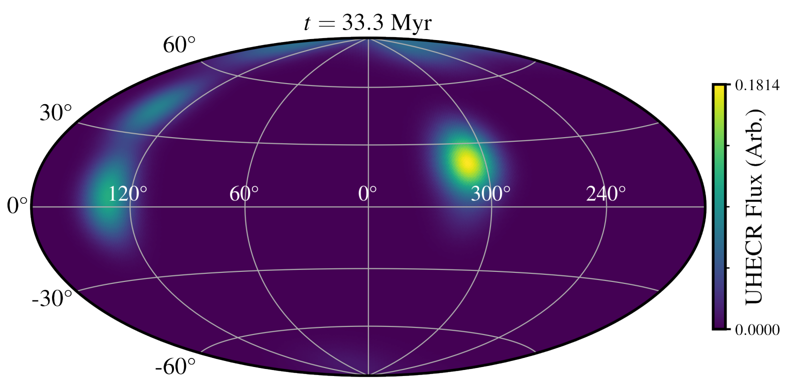


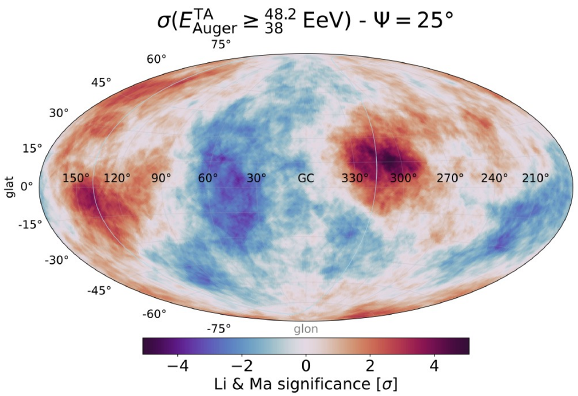
Model C



Conclusions

- Cosmic ray data is spectrally consistent with a local source scenario, whose spectral index is consistent with those expectations from Fermi diffusive shock acceleration theory
- Locally (within the Council of Giants) Cen A appears to be the only source capable of accelerating UHECR
- If strong deflections occur in the Council of Giant magnetised halos, this structure can be imprinted onto the arriving UHECR skymap
- Such an imprint may explain the correlation that PAO and TA have reported with local structure
- A key prediction of this scenario is a common composition of the echo regions





DESY.

A Few Words on the Influence Subir has had on me

Subir is an extremely sincere person- hard to convince of anything, and whose opinion is worth gold (perhaps for the same reason)

He set me out on the path of UHECR nuclei and the physical consequences of such a possibility 20 years ago! I am (we are) extremely fortunate that he pursues and encourages others to pursue the testing of theoretical ideas with the latest experimental results

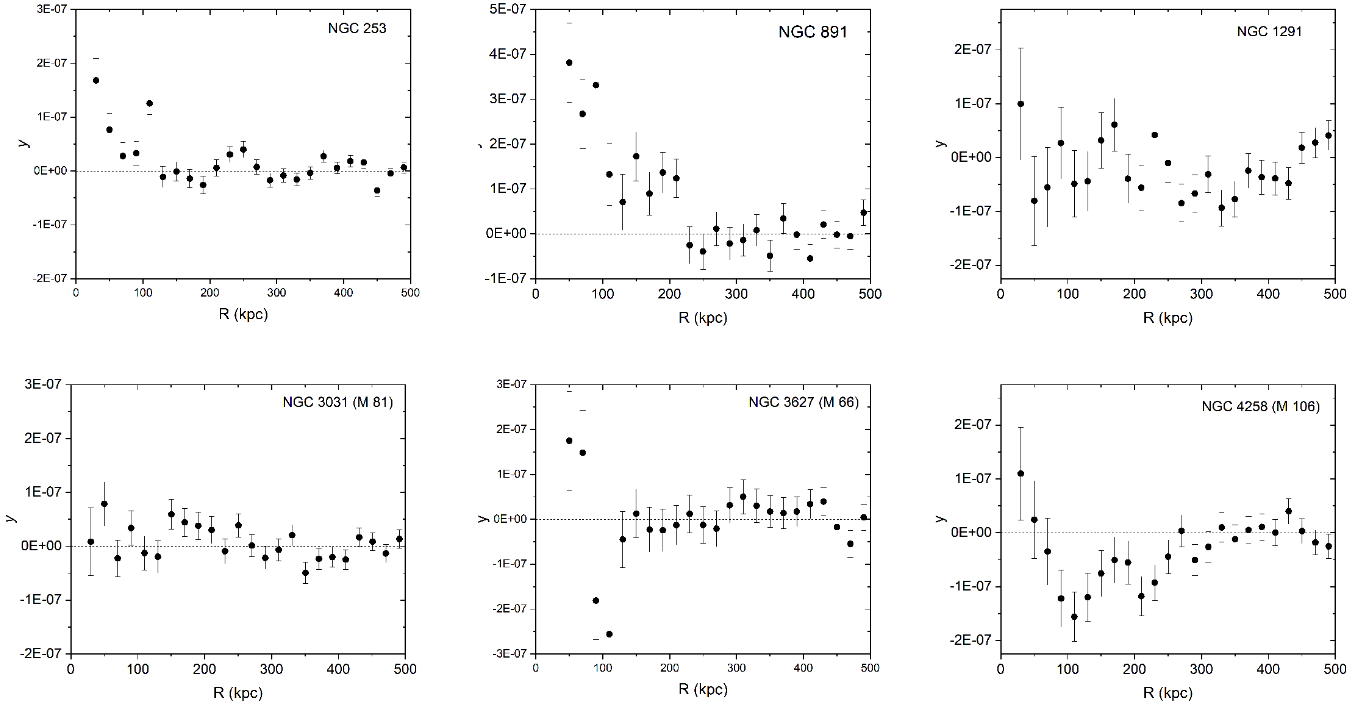
He also encouraged me to be outward (worldly) looking- encouraging me to go to a research school in Mexico (where I met my wife)

Extra Slides

DESY.

Extended Hot Gas Around CoG Members?

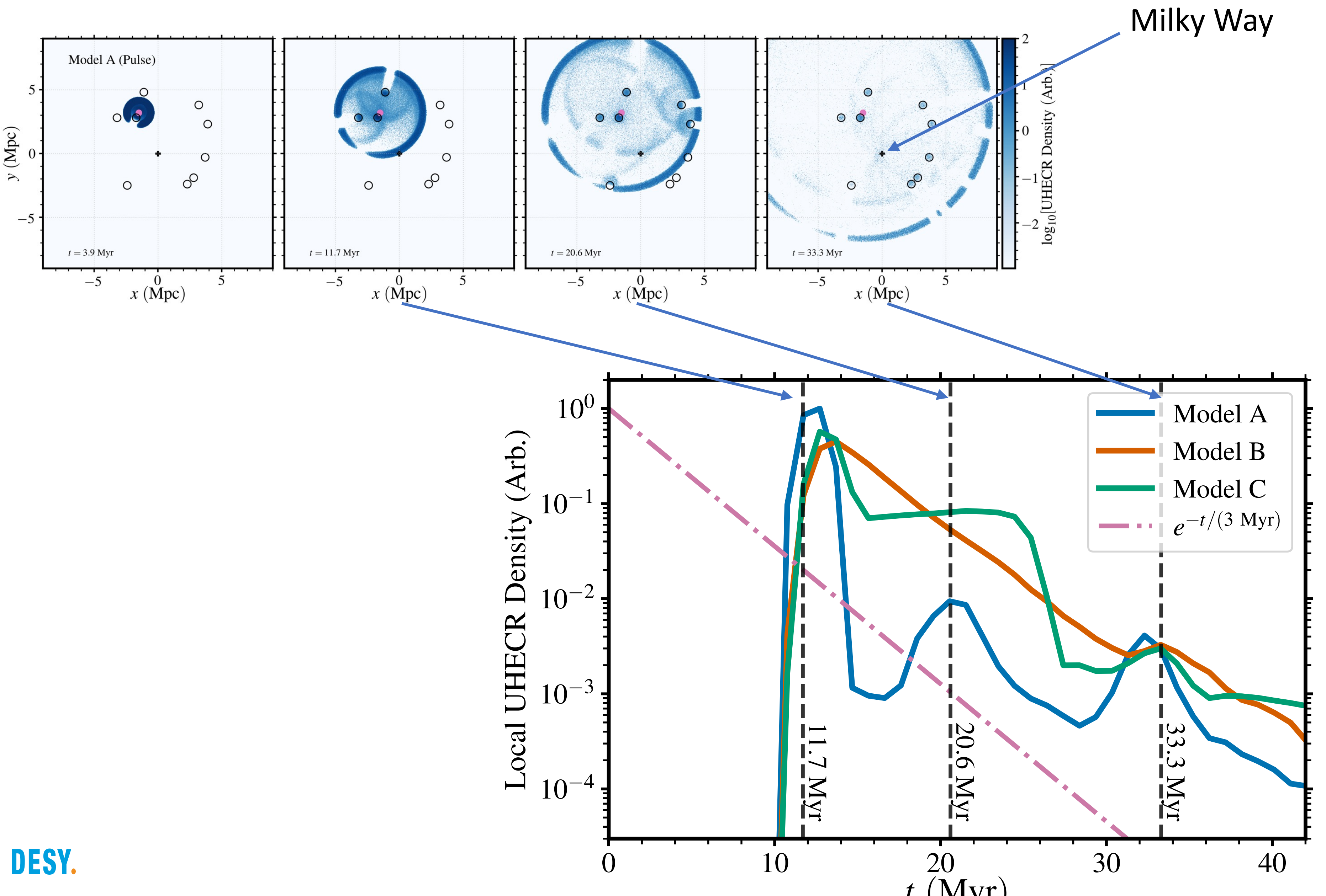
Bregman et al. ApJ 928 (2022)



Starburst Activity from CoG Members

Galaxy	l (°)	b (°)	Distance (Mpc)	M_* (10^{10} $M_\odot$)	$L_{12\mu m}$ ($10^9 L_\odot$)	est. SFR ($M_\odot$ yr^{-1})
NGC 253	97.36	−87.96	3.5	1.7	3.5	5.4
M64	315.68	84.42	5.0	11.5	1.3	2.3
M81	142.09	40.91	3.7	7.1	0.4	0.8
M82	141.41	40.57	3.5	1.3	7.8	10.7
M83	314.58	31.97	4.9	2.7	3.4	5.2
M94	123.36	76.01	4.5	3.8	0.9	1.6
NGC 4945	305.27	13.34	3.3	1.2	1.8	3.0
IC 342	138.17	10.58	3.4	2.7	2.1	3.5
Maffei 1	135.86	−0.55	3.3	6.2	–	–
Maffei 2	136.50	−0.33	3.4	1.2	0.9	1.5
Circinus	311.33	−3.81	4.3	1.5	6.2	8.8

Echo Waves



DESY.

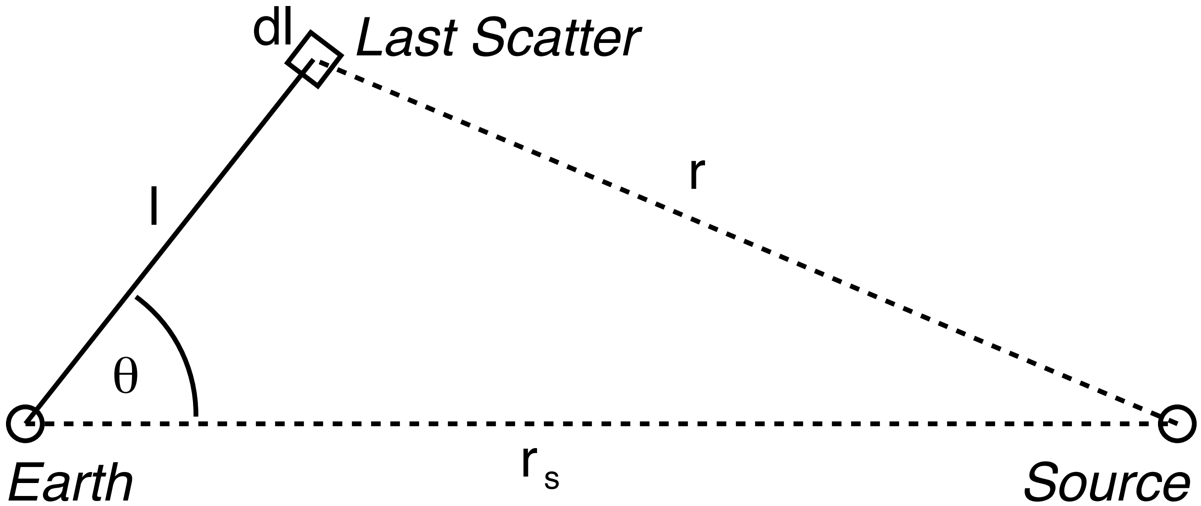
Steady State Distribution

$$\frac{\partial \mathbf{n}}{\partial \mathbf{t}} = \mathbf{D}\nabla^2\mathbf{n} + \mathbf{Q}$$

$$\mathbf{n} = \frac{\partial \mathbf{N}}{\partial^3 \mathbf{r}} = \int_0^\infty \frac{\mathbf{e}^{-\mathbf{x}^2/(4\mathbf{D}\mathbf{t})}}{(4\pi\mathbf{D}\mathbf{t})^{3/2}} \frac{\mathbf{d}\mathbf{t}}{\tau}$$

$$\mathbf{n} = \frac{1}{4\pi\mathbf{D}\mathbf{r}}$$

Why a Dipole Around the Observer?

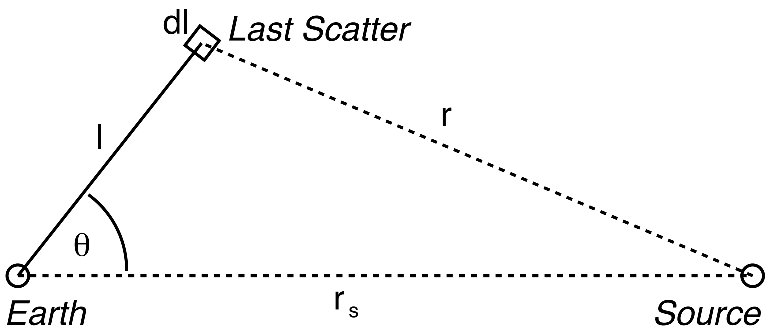


$$\mathbf{r^2 = l^2 + r_s^2 - 2lr_s}\cos\theta$$

DESY.

Why a Dipole Around the Observer?

$$\frac{\partial \mathbf{N}}{\partial \cos\theta} \propto \int \frac{\mathbf{e}^{-\mathbf{l}/\lambda_{\mathbf{scatt}}}}{\mathbf{r}(\mathbf{l})}\mathbf{dl}$$



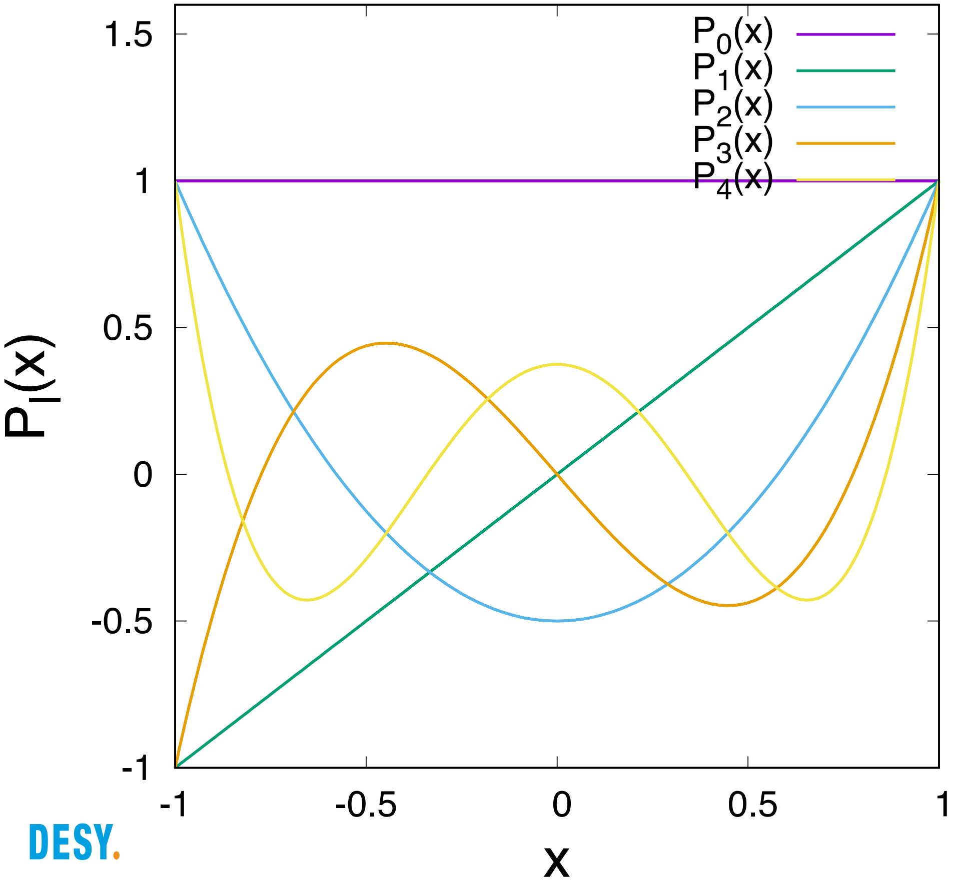
$$\approx \frac{\lambda}{\mathbf{r}(\mathbf{l})} = \frac{\lambda}{\mathbf{r_s}}\left(\mathbf{1} + \frac{\lambda}{\mathbf{r_s}}\cos\theta\right)$$

$$\propto \mathbf{1} + \delta\cos\theta$$

$$\delta = \frac{\lambda}{\mathbf{r_s}}$$

Expansion in Spherical Harmonic Basis Functions

$$\mathbf{a_n} = \int_{-1}^{1} \frac{\mathbf{dN}}{\mathbf{d}\cos\theta} \mathbf{P_n}(\cos\theta)\mathbf{d}\cos\theta$$

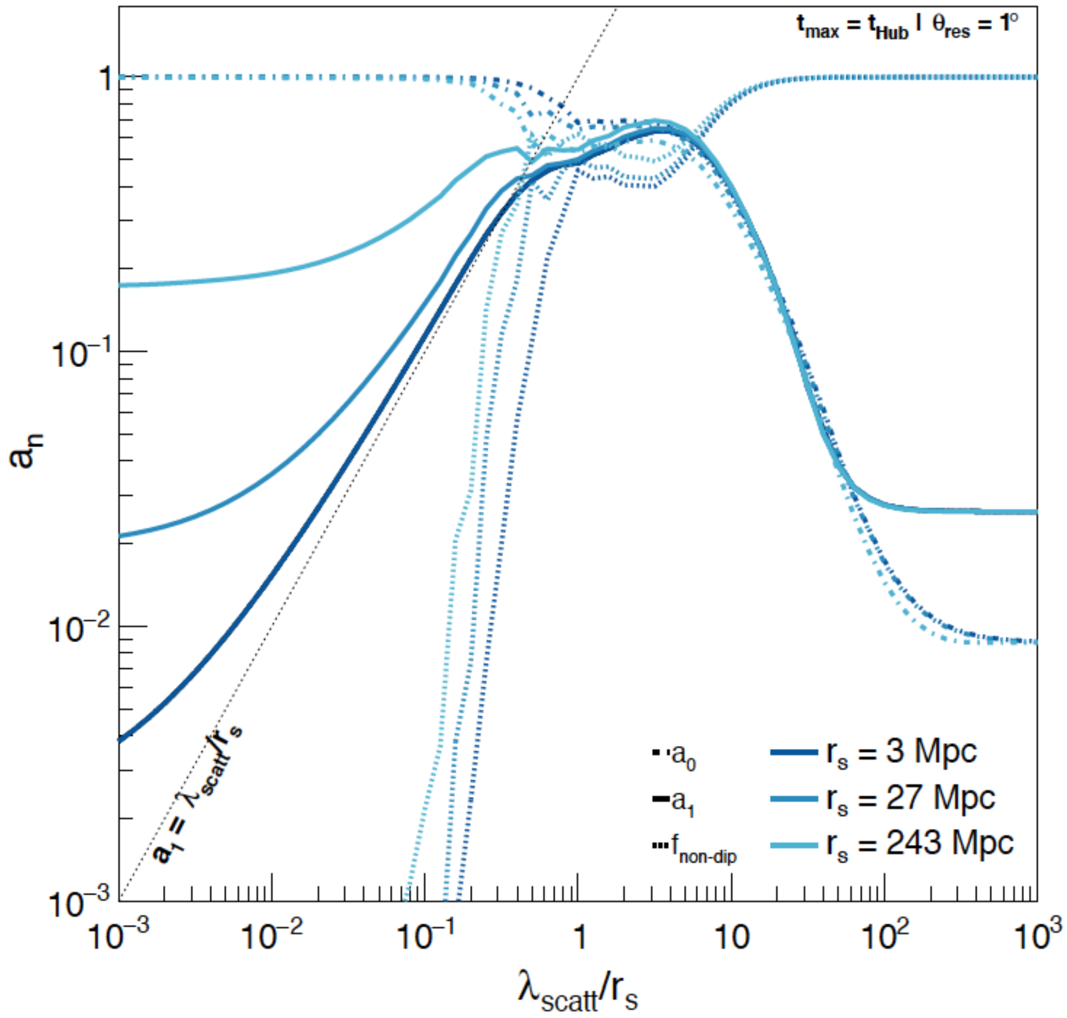


$$\mathbf{a_0} = \frac{\mathbf{1}}{\sqrt{\mathbf{1} + \frac{\delta^2}{\mathbf{3}}}} \approx \mathbf{1}$$

$$\mathbf{a_1} = \frac{\delta}{\sqrt{\mathbf{1} + \frac{\delta^2}{\mathbf{3}}}} \approx \delta$$

DESY.

Evolution of the Harmonic Coefficients



Dipole from an Ensemble of Sources

$$\mathbf{a_0^{(tot)}(E) = \frac{\sum_s a_0^{(s)} n_s(E, r_s)}{\sum_s n_s(E, r_s)}}$$

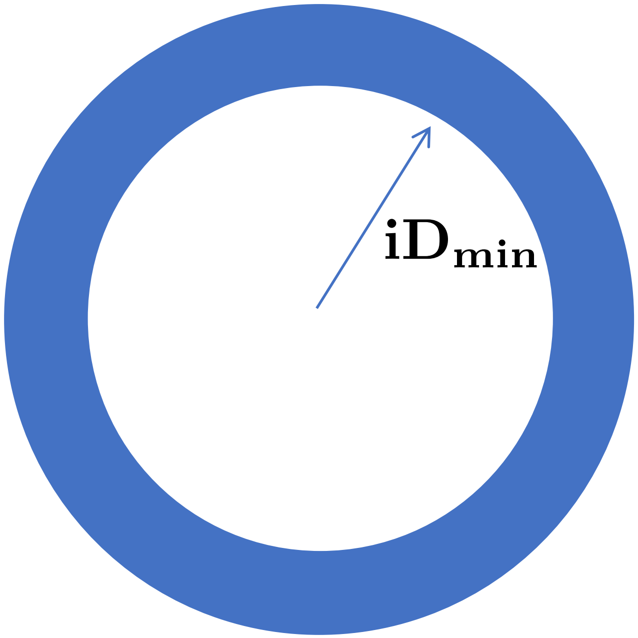
$$\mathbf{a_1^{(tot)}(E) = \frac{\sqrt{\sum_s \left(a_1^{(s)} n_s(E, r_s)\right)^2}}{\sum_s n_s(E, r_s)}}$$

Dipole from an Ensemble of Sources

$$\langle \mathbf{a_1^{(i)}} \rangle^2 = \frac{\mathbf{i^2 (a_1^{(s_i)} n_{s_i})^2}}{\mathbf{n_{tot}^2}}$$

$$\mathbf{n_{s_i}} \propto \frac{\mathbf{1}}{\mathbf{iD_{min}}}$$

$$\mathbf{a_1^{(s_i)}} = \frac{\lambda_{\mathbf{scatt}}}{\mathbf{iD_{min}}}$$



Dipole from an Ensemble of Sources

$$\langle \mathbf{a}_1^{(\mathbf{i})} \rangle^2 = \left(\frac{\mathbf{a}_1^{(1)} \mathbf{n}_1}{\mathbf{i}\mathbf{n}_{\mathbf{tot}}} \right)^2$$

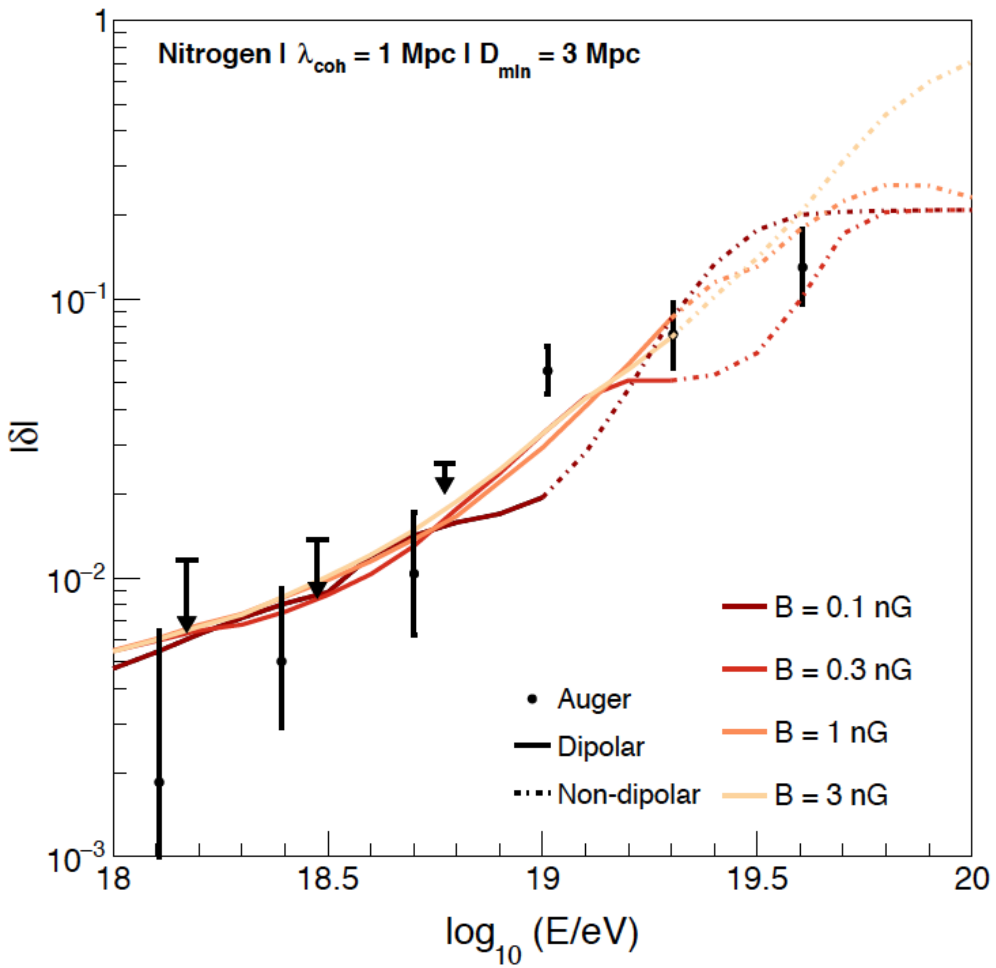
$$\langle \mathbf{a}_1^{(\mathbf{tot})} \rangle^2 = \sum_{\mathbf{i}} \left(\frac{\mathbf{a}_1^{(1)} \mathbf{n}_1}{\mathbf{i}\mathbf{n}_{\mathbf{tot}}} \right)^2$$

$$\delta = \langle \mathbf{a}_1^{(\mathbf{tot})} \rangle \approx \frac{\mathbf{a}_1^{(1)} \mathbf{n}_1}{\mathbf{n}_{\mathbf{tot}}}$$

$$\mathbf{a}_1^{(1)} = \delta_1$$

DESY.

The Evolution of the Dipole with Energy



- Dipole from nearest sources grows linearly with λ_{scatt} (for nearby sources steady-state approximation holds)
- Contribution of nearest source to total flux decays as $1/\lambda_{scatt}$
- At highest energies, harmonic power migrates to multi-pole terms….have the Auger collaboration seen this already?