Interpretation of the CALET Electron+Positron Flux Anisotropy Measurement by Emission from the Vela SNR

17aE523-5

JPS annual meeting
The University of Tokyo
2026/9/17

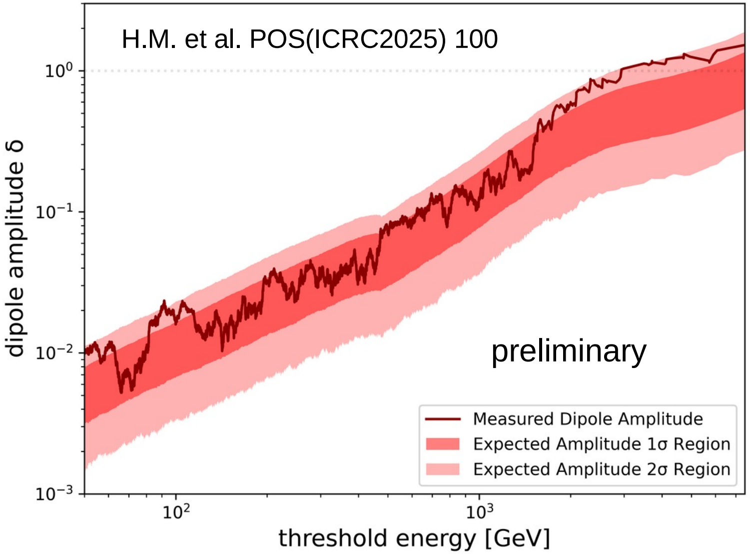
Holger Motz

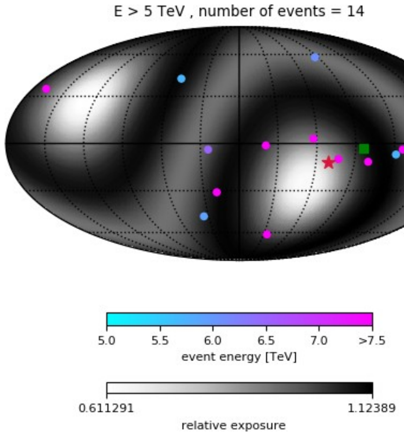
Waseda University, Faculty of Science and Engineering,
Global Center for Science and Engineering

Introduction

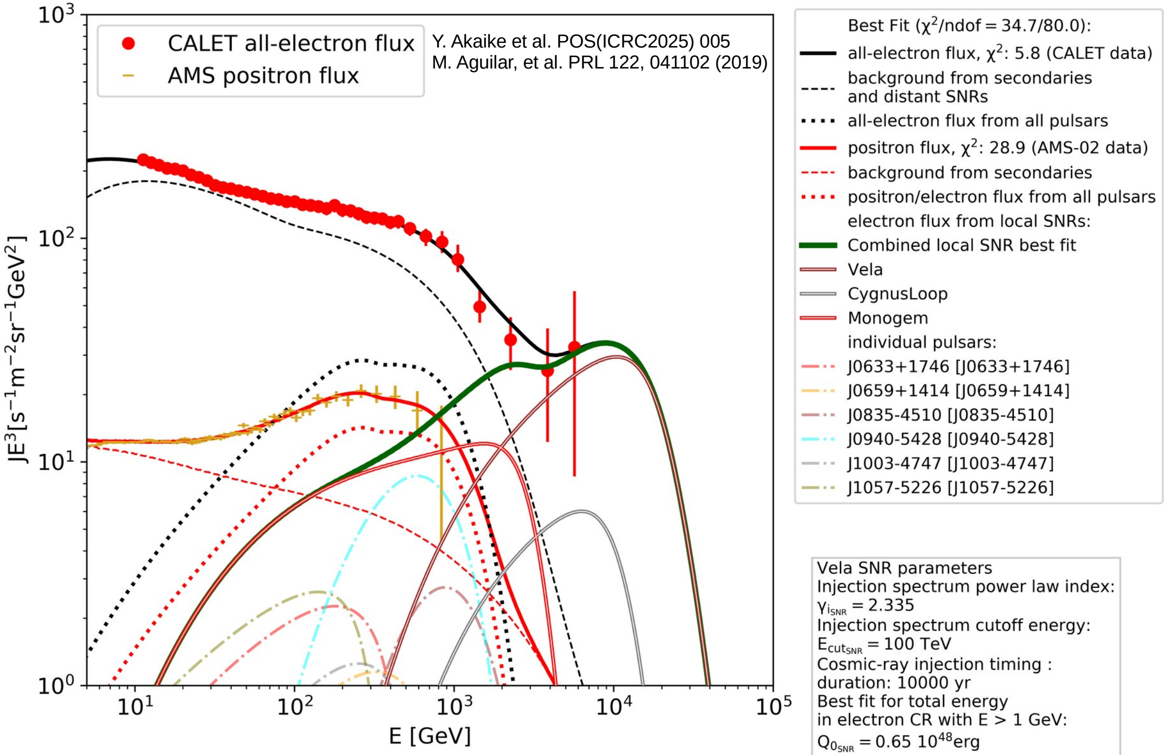
- CALET has measured an O(1) dipole amplitude above 5 TeV threshold energy in the electron +positron flux
- The dipole direction aligns with the direction towards Vela.
- Fermi-LAT 2017 [S. Abdollahi, et al. PRL 118, 091103] puts strict limits on dipole anisotropy below ~ 1 TeV, but no limits (except by CALET) exist in the TeV region.

Study the predicted dipole amplitude from Vela
(and other nearby SNR: Cygnus Loop, Monogem)

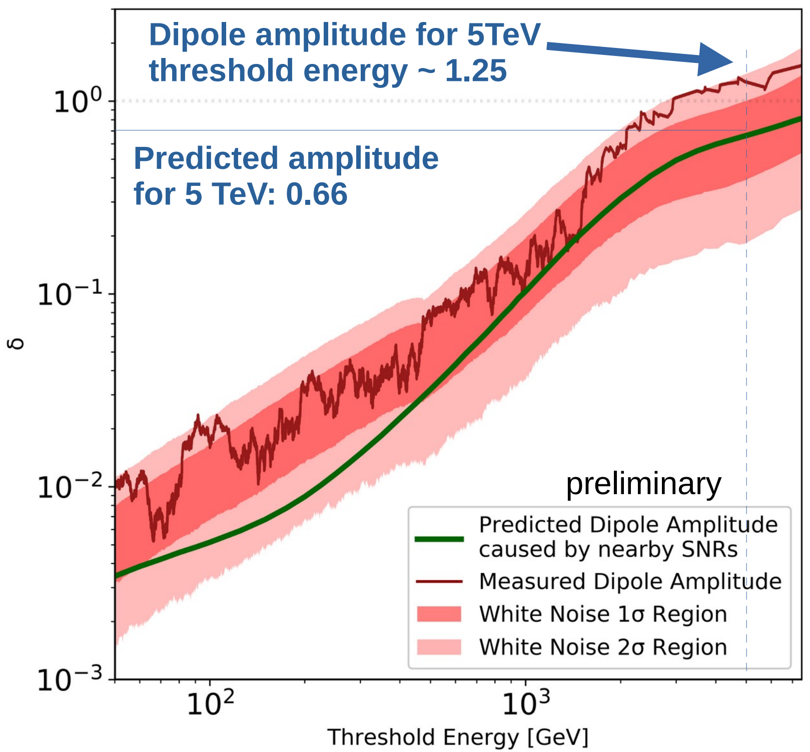

H.M. et al. POS(ICRC2025) 100



Example Fit and Anisotropy



Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.335$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
duration: 10000 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 0.65\ 10^{48}$erg

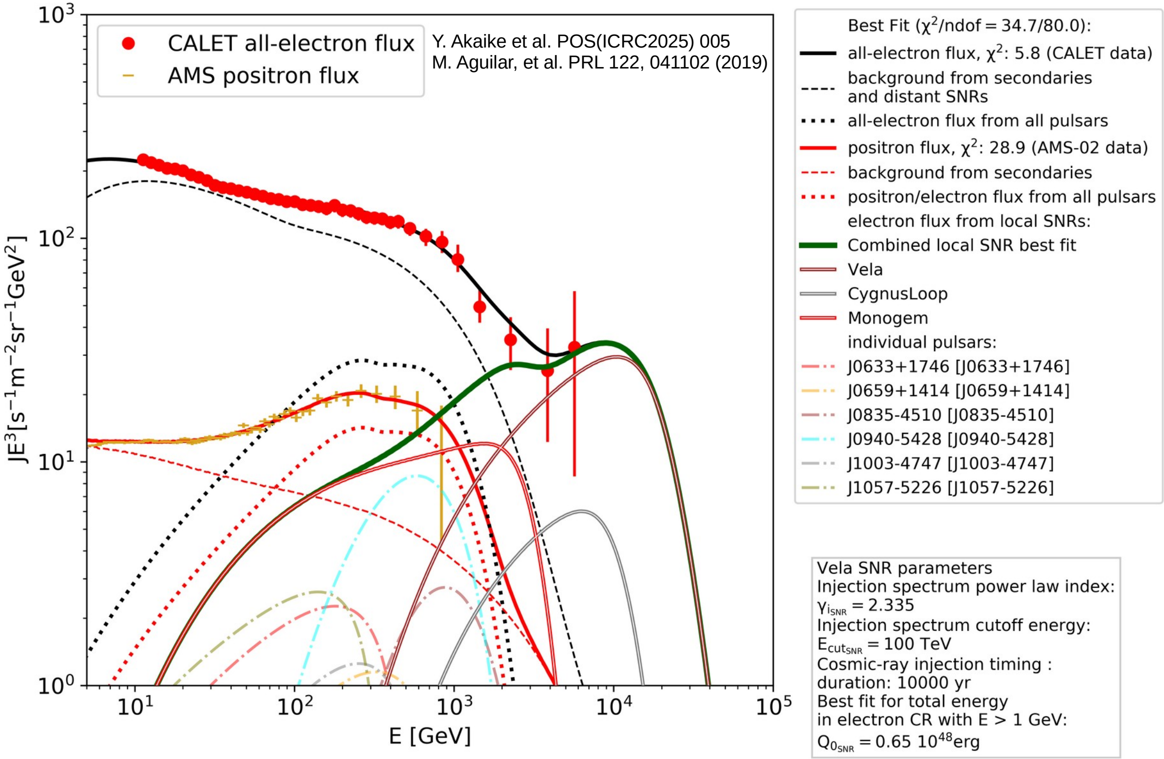


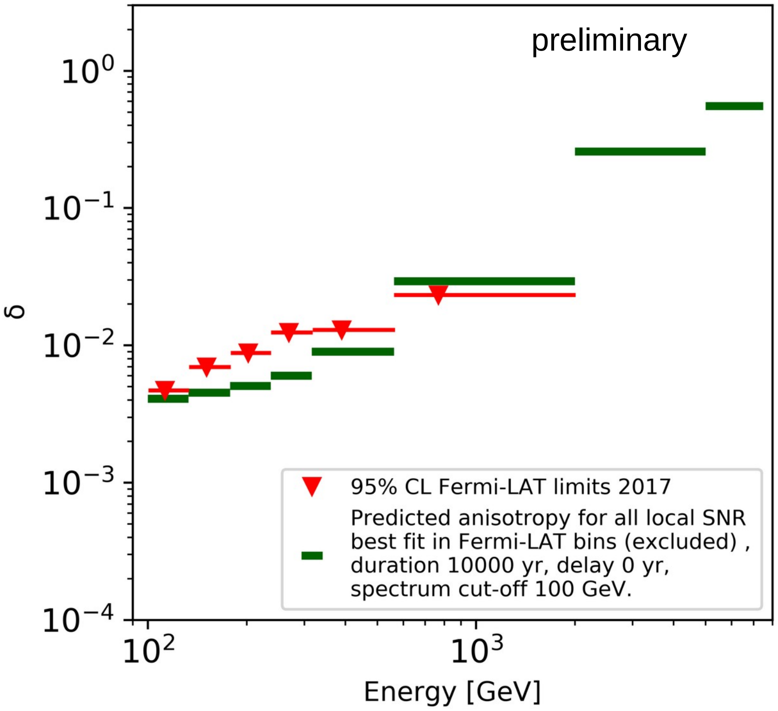
Dipole amplitude for 5TeV threshold energy ~ 1.25

Predicted amplitude for 5 TeV: 0.66

- Model fit from [Y. Akaike et al. POS(ICRC2025) 005] with propagation conditions and injection power law index from [H.M., POS(ICRC2021)100], model also used also in [O. Adriani et al. PRL 131, 191001 (2023)].
- Power law parametrization for distant SNR, individual pulsars from ATNF catalog, secondaries from DRAGON nuclei calculation, nearby SNR flux calculated with DRAGON on fine spatial grid to extract anisotropy
- Fit to CALET all-electron and AMS-02 positron only data, free background parameters and Vela normalization corresponding to total energy emitted as electron CR – changed from $0.8 \cdot 10^{48}$ erg in PRL(2023) to $0.65 \cdot 10^{48}$ erg in ICRC(2025) by new CALET electron data.
- **The predicted anisotropy in this model is large but does not exceed the white noise expectation in the CALET measurement.**

Example Fit and Anisotropy





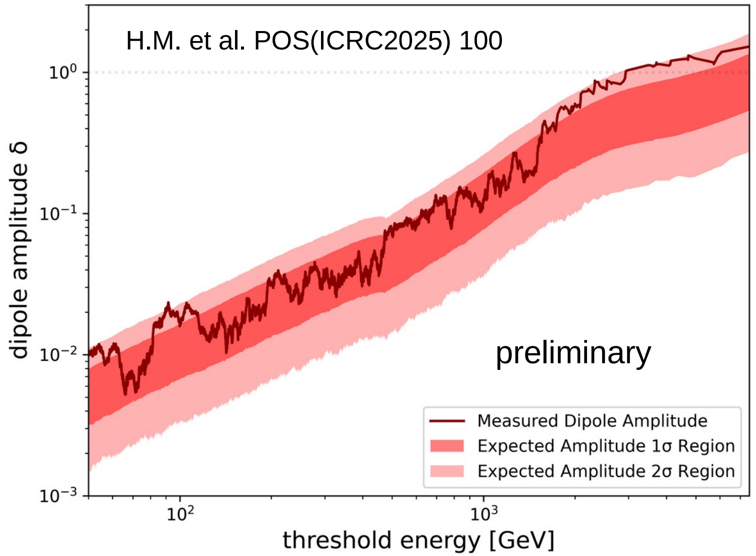
- Model fit from [Y. Akaike et al. POS(ICRC2025) 005] with propagation conditions and injection power law index from [H.M., POS(ICRC2021)100], model also used also in [O. Adriani et al. PRL 131, 191001 (2023)].
- **This model is also excluded by the Fermi-LAT anisotropy limit** [S. Abdollahi, et al. PRL 118, 091103] .

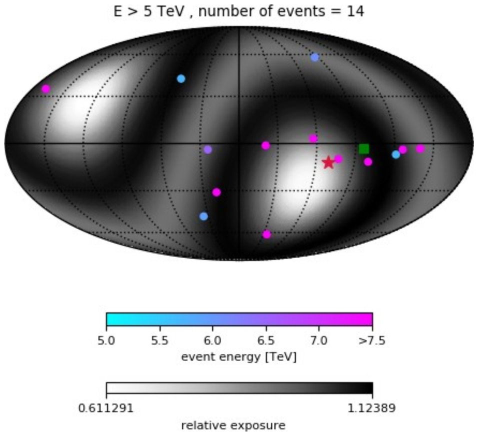
Introduction

- CALET has measured an O(1) dipole amplitude above 5 TeV threshold energy in the electron +positron flux
- The dipole direction aligns with the direction towards Vela.
- Fermi-LAT 2017 [S. Abdollahi, et al. PRL 118, 091103] puts strict limits on dipole anisotropy below ~ 1 TeV, but no limits (except by CALET) exist in the TeV region.

Study the predicted dipole amplitude from Vela
(and other nearby SNR: Cygnus Loop, Monogem)

→ **Investigated question: If choosing propagation conditions freely (favorable for anisotropy, independent of trying to explain nuclei spectra) and choose a hard injection index of 2.0 (so that the contribution of Vela raises sharply above ~ 1 TeV to avoid Fermi-LAT limits), and a spectral cut-off at 100 TeV, can the excess of the measured dipole amplitude above the white noise band be explained by emission from Vela?**





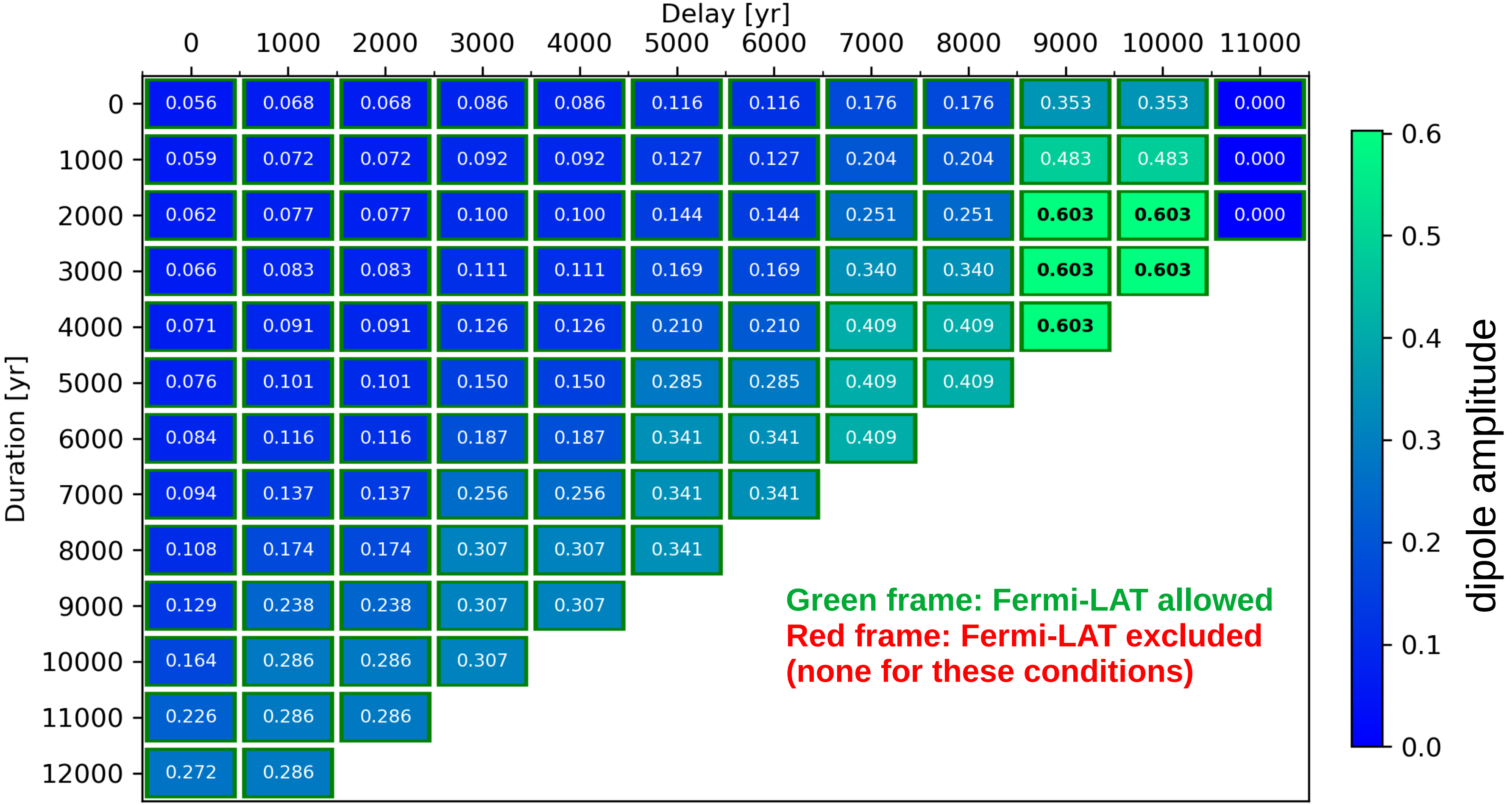
Propagation / Emission Model and Parameter Space Scan

- **Toy model for emission:** constant emission for a variable duration after a variable delay period
- **Simple propagation model:** Kolmogorov turbulence (δ=1/3), variable diffusion coefficient normalization D_0

$$D(E) = D_0 \left(\frac{E}{4\,GeV} \right)^{\delta}$$

- Scan delay, duration in steps of 1 kyr, and D_0 in [1,2,3,4,5] 10^{28} m^2/s
- Search for parameters with dipole amplitude above 5 TeV being closest to 1.25 and passing the Fermi-LAT limit.
- Vela-only case at first (ignore Cygnus Loop and Monogem)

Scan Results for $D_0 = 5 \cdot 10^{28}$ cm^2/s

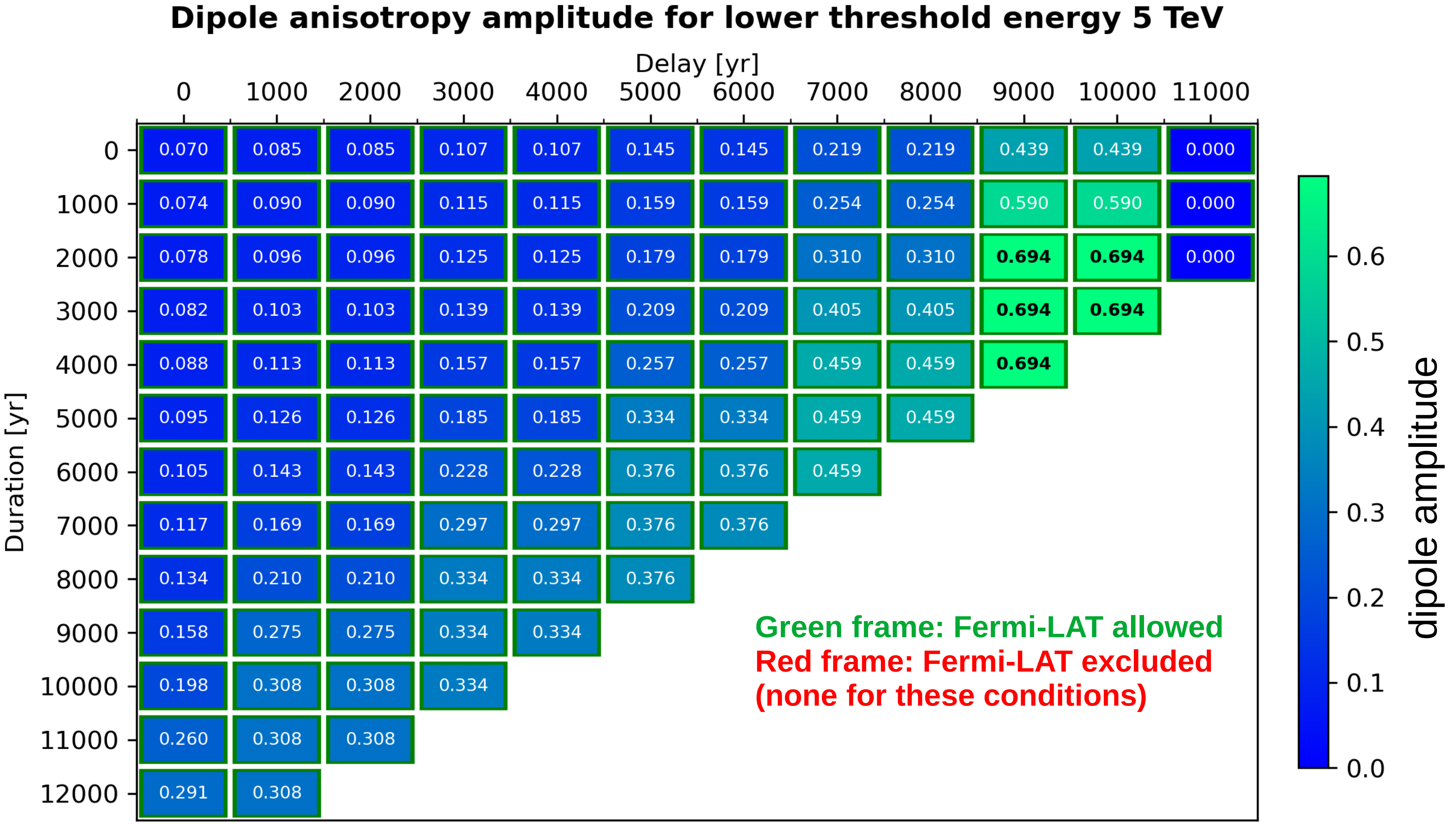


Dipole anisotropy amplitude for lower threshold energy 5 TeV

	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	0.056	0.068	0.068	0.086	0.086	0.116	0.116	0.176	0.176	0.353	0.353	0.000
1000	0.059	0.072	0.072	0.092	0.092	0.127	0.127	0.204	0.204	0.483	0.483	0.000
2000	0.062	0.077	0.077	0.100	0.100	0.144	0.144	0.251	0.251	**0.603**	**0.603**	0.000
3000	0.066	0.083	0.083	0.111	0.111	0.169	0.169	0.340	0.340	**0.603**	**0.603**	
4000	0.071	0.091	0.091	0.126	0.126	0.210	0.210	0.409	0.409	**0.603**		
5000	0.076	0.101	0.101	0.150	0.150	0.285	0.285	0.409	0.409			
6000	0.084	0.116	0.116	0.187	0.187	0.341	0.341	0.409				
7000	0.094	0.137	0.137	0.256	0.256	0.341	0.341					
8000	0.108	0.174	0.174	0.307	0.307	0.341						
9000	0.129	0.238	0.238	0.307	0.307							
10000	0.164	0.286	0.286	0.307								
11000	0.226	0.286	0.286									
12000	0.272	0.286										

Green frame: Fermi-LAT allowed
Red frame: Fermi-LAT excluded
(none for these conditions)

Scan Results for $D_0 = 4 \cdot 10^{28}$ cm^2/s

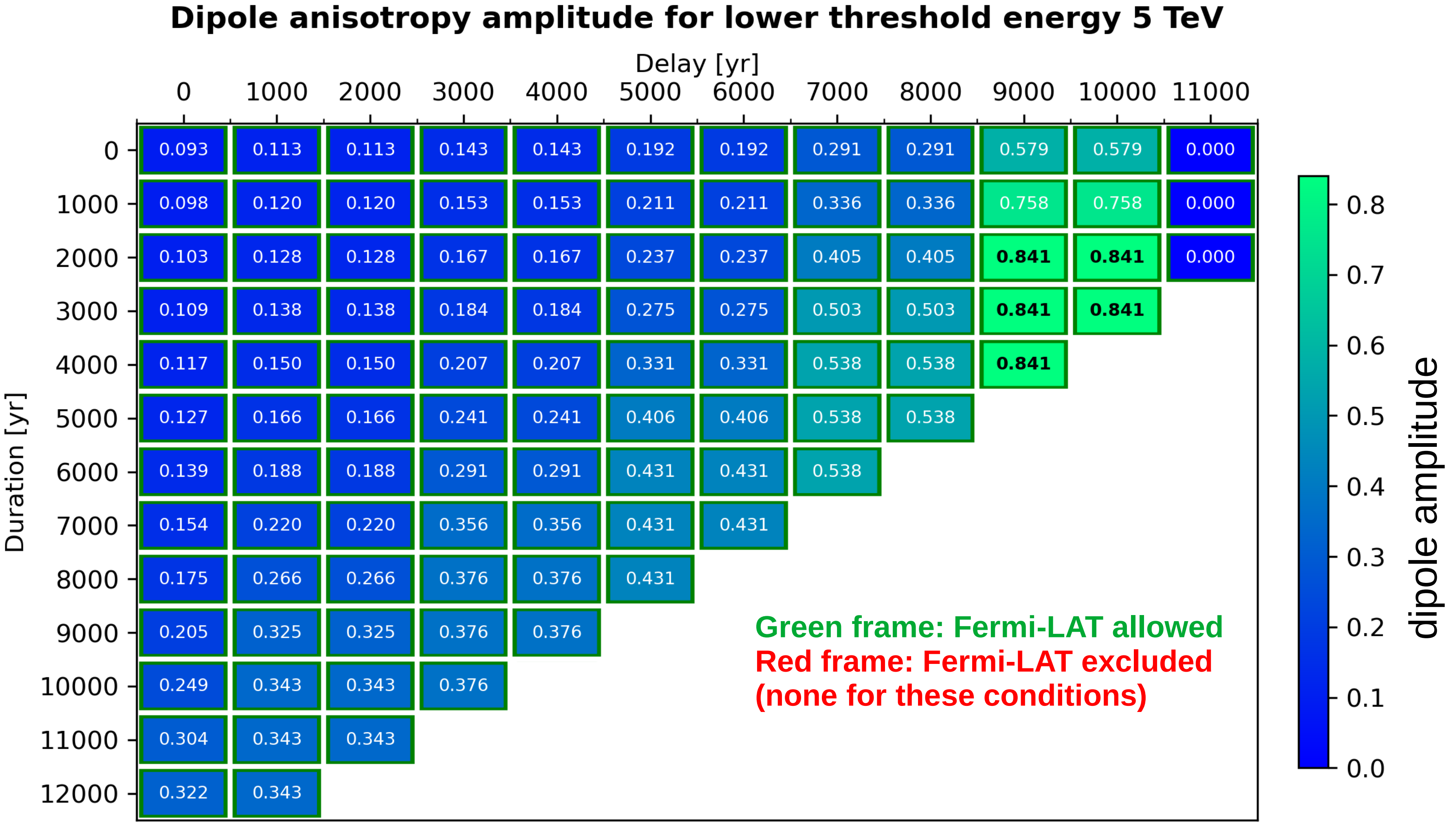


Dipole anisotropy amplitude for lower threshold energy 5 TeV

	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	0.070	0.085	0.085	0.107	0.107	0.145	0.145	0.219	0.219	0.439	0.439	0.000
1000	0.074	0.090	0.090	0.115	0.115	0.159	0.159	0.254	0.254	0.590	0.590	0.000
2000	0.078	0.096	0.096	0.125	0.125	0.179	0.179	0.310	0.310	**0.694**	**0.694**	0.000
3000	0.082	0.103	0.103	0.139	0.139	0.209	0.209	0.405	0.405	**0.694**	**0.694**	
4000	0.088	0.113	0.113	0.157	0.157	0.257	0.257	0.459	0.459	**0.694**		
5000	0.095	0.126	0.126	0.185	0.185	0.334	0.334	0.459	0.459			
6000	0.105	0.143	0.143	0.228	0.228	0.376	0.376	0.459				
7000	0.117	0.169	0.169	0.297	0.297	0.376	0.376					
8000	0.134	0.210	0.210	0.334	0.334	0.376						
9000	0.158	0.275	0.275	0.334	0.334							
10000	0.198	0.308	0.308	0.334								
11000	0.260	0.308	0.308									
12000	0.291	0.308										

Green frame: Fermi-LAT allowed
Red frame: Fermi-LAT excluded
(none for these conditions)

Scan Results for $D_0 = 3\cdot10^{28}\ \mathrm{cm}^2/\mathrm{s}$

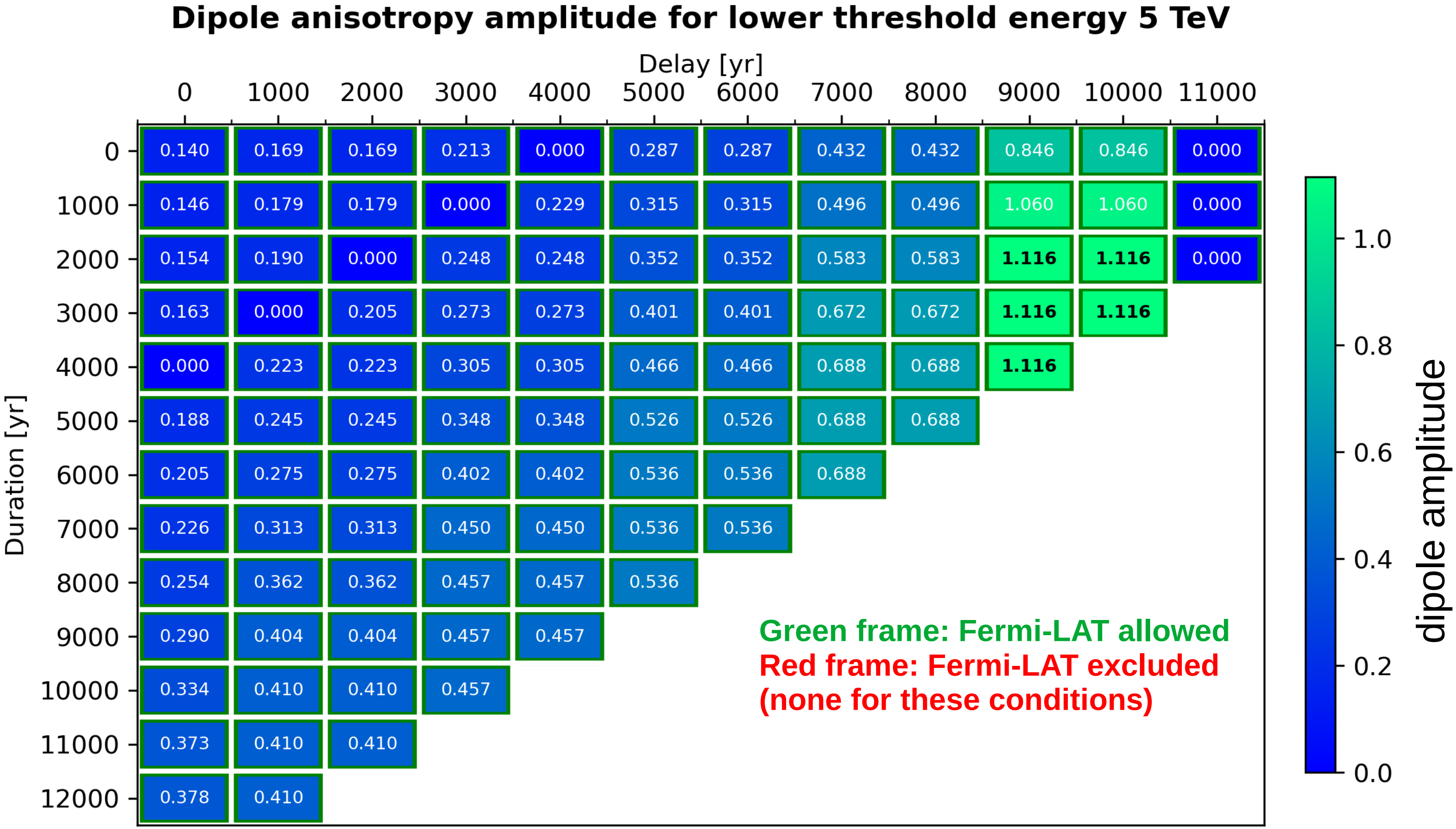


Dipole anisotropy amplitude for lower threshold energy 5 TeV

	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	0.093	0.113	0.113	0.143	0.143	0.192	0.192	0.291	0.291	0.579	0.579	0.000
1000	0.098	0.120	0.120	0.153	0.153	0.211	0.211	0.336	0.336	0.758	0.758	0.000
2000	0.103	0.128	0.128	0.167	0.167	0.237	0.237	0.405	0.405	**0.841**	**0.841**	0.000
3000	0.109	0.138	0.138	0.184	0.184	0.275	0.275	0.503	0.503	**0.841**	**0.841**	
4000	0.117	0.150	0.150	0.207	0.207	0.331	0.331	0.538	0.538	**0.841**		
5000	0.127	0.166	0.166	0.241	0.241	0.406	0.406	0.538	0.538			
6000	0.139	0.188	0.188	0.291	0.291	0.431	0.431	0.538				
7000	0.154	0.220	0.220	0.356	0.356	0.431	0.431					
8000	0.175	0.266	0.266	0.376	0.376	0.431						
9000	0.205	0.325	0.325	0.376	0.376							
10000	0.249	0.343	0.343	0.376								
11000	0.304	0.343	0.343									
12000	0.322	0.343										

Green frame: Fermi-LAT allowed
Red frame: Fermi-LAT excluded
(none for these conditions)

Scan Results for $D_0 = 2\cdot10^{28}$ cm^2/s

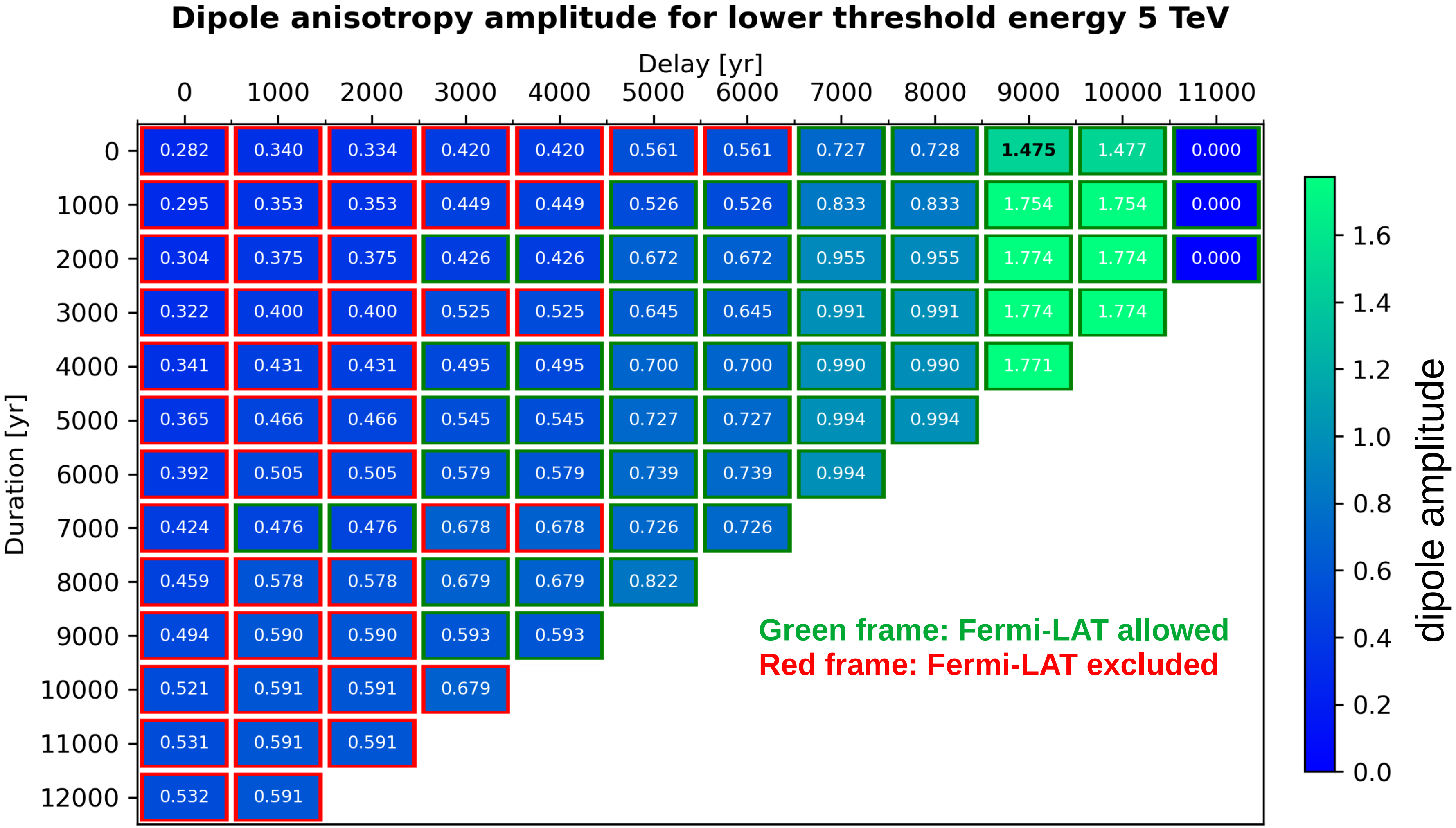


Dipole anisotropy amplitude for lower threshold energy 5 TeV

	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	0.140	0.169	0.169	0.213	0.000	0.287	0.287	0.432	0.432	0.846	0.846	0.000
1000	0.146	0.179	0.179	0.000	0.229	0.315	0.315	0.496	0.496	1.060	1.060	0.000
2000	0.154	0.190	0.000	0.248	0.248	0.352	0.352	0.583	0.583	**1.116**	**1.116**	0.000
3000	0.163	0.000	0.205	0.273	0.273	0.401	0.401	0.672	0.672	**1.116**	**1.116**	
4000	0.000	0.223	0.223	0.305	0.305	0.466	0.466	0.688	0.688	**1.116**		
5000	0.188	0.245	0.245	0.348	0.348	0.526	0.526	0.688	0.688			
6000	0.205	0.275	0.275	0.402	0.402	0.536	0.536	0.688				
7000	0.226	0.313	0.313	0.450	0.450	0.536	0.536					
8000	0.254	0.362	0.362	0.457	0.457	0.536						
9000	0.290	0.404	0.404	0.457	0.457							
10000	0.334	0.410	0.410	0.457								
11000	0.373	0.410	0.410									
12000	0.378	0.410										

Green frame: Fermi-LAT allowed
Red frame: Fermi-LAT excluded
(none for these conditions)

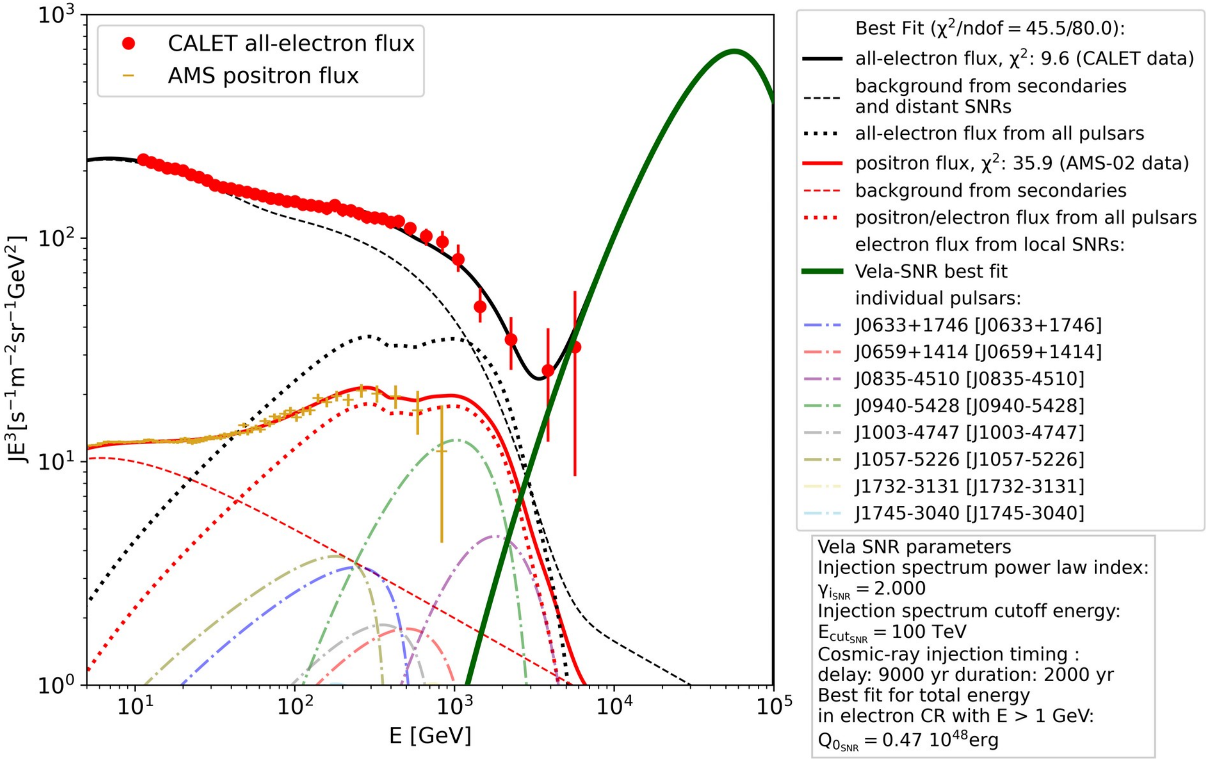
Scan Results for $D_0 = 1\cdot10^{28}$ cm^2/s



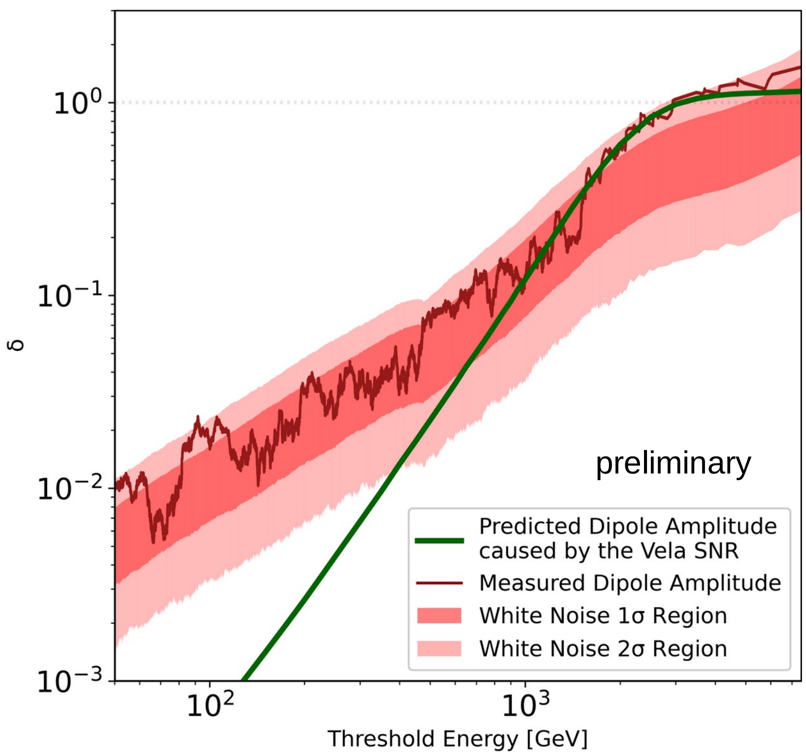
	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	🟥 0.282	🟥 0.340	🟥 0.334	🟥 0.420	🟥 0.420	🟥 0.561	🟥 0.561	🟩 0.727	🟩 0.728	🟩 **1.475**	🟩 1.477	🟩 0.000
1000	🟥 0.295	🟥 0.353	🟥 0.353	🟥 0.449	🟥 0.449	🟩 0.526	🟩 0.526	🟩 0.833	🟩 0.833	🟩 1.754	🟩 1.754	🟩 0.000
2000	🟥 0.304	🟥 0.375	🟥 0.375	🟩 0.426	🟩 0.426	🟩 0.672	🟩 0.672	🟩 0.955	🟩 0.955	🟩 1.774	🟩 1.774	🟩 0.000
3000	🟥 0.322	🟥 0.400	🟥 0.400	🟥 0.525	🟥 0.525	🟩 0.645	🟩 0.645	🟩 0.991	🟩 0.991	🟩 1.774	🟩 1.774	
4000	🟥 0.341	🟥 0.431	🟥 0.431	🟩 0.495	🟩 0.495	🟩 0.700	🟩 0.700	🟩 0.990	🟩 0.990	🟩 1.771		
5000	🟥 0.365	🟥 0.466	🟥 0.466	🟩 0.545	🟩 0.545	🟩 0.727	🟩 0.727	🟩 0.994	🟩 0.994			
6000	🟥 0.392	🟥 0.505	🟥 0.505	🟩 0.579	🟩 0.579	🟩 0.739	🟩 0.739	🟩 0.994				
7000	🟥 0.424	🟩 0.476	🟩 0.476	🟥 0.678	🟥 0.678	🟩 0.726	🟩 0.726					
8000	🟥 0.459	🟥 0.578	🟥 0.578	🟩 0.679	🟩 0.679	🟩 0.822						
9000	🟥 0.494	🟥 0.590	🟥 0.590	🟩 0.593	🟩 0.593							
10000	🟥 0.521	🟥 0.591	🟥 0.591	🟥 0.679								
11000	🟥 0.531	🟥 0.591	🟥 0.591									
12000	🟥 0.532	🟥 0.591										

Green frame: Fermi-LAT allowed
Red frame: Fermi-LAT excluded

Fit for $D_0 = 2 \cdot 10^{28}$ cm^2/s 9kyr delay, 2kyr duration

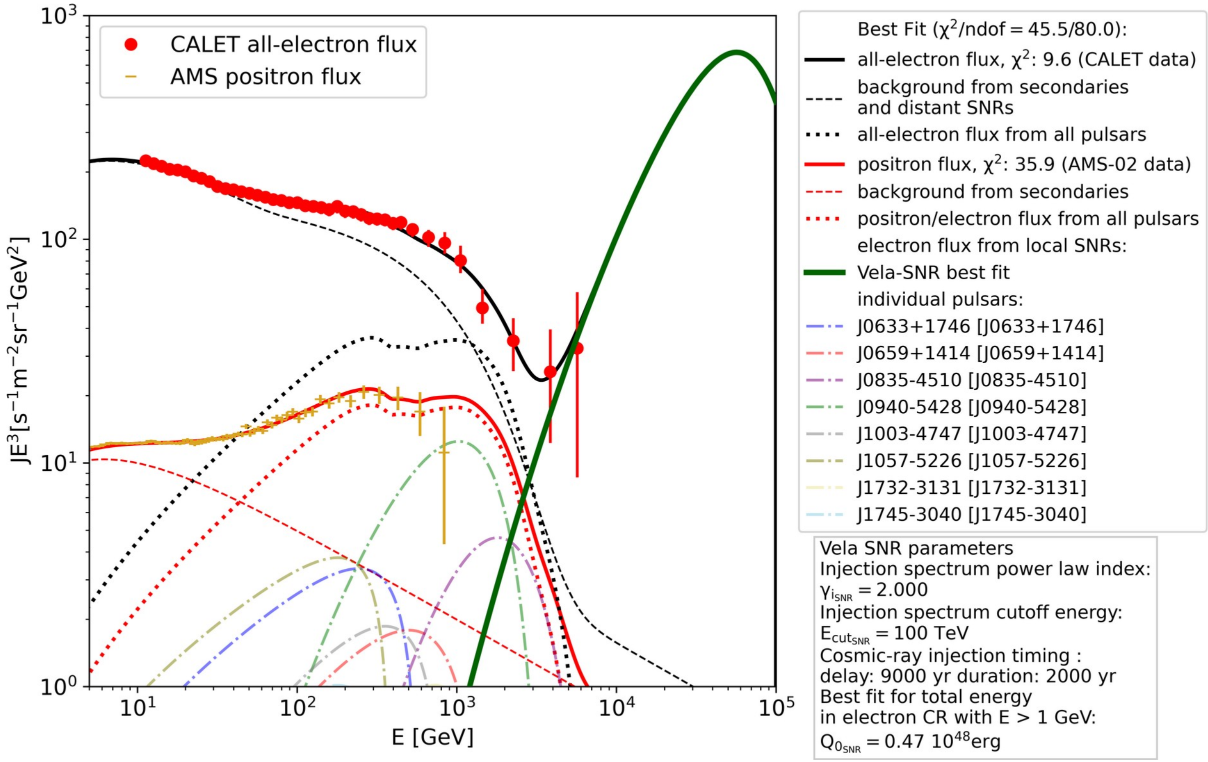


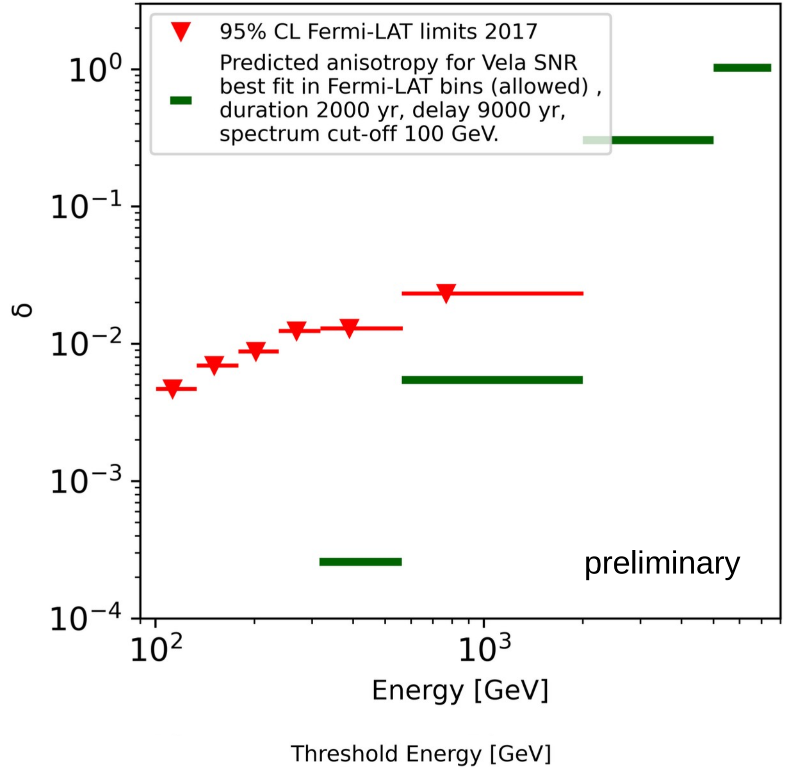
Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.000$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
delay: 9000 yr duration: 2000 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 0.47\ 10^{48}$erg



This model explains the increase of the measured amplitude over the white noise expectation band for threshold energy above 1 TeV

Fit for $D_0 = 2 \cdot 10^{28}$ cm^2/s
9kyr delay, 2kyr duration

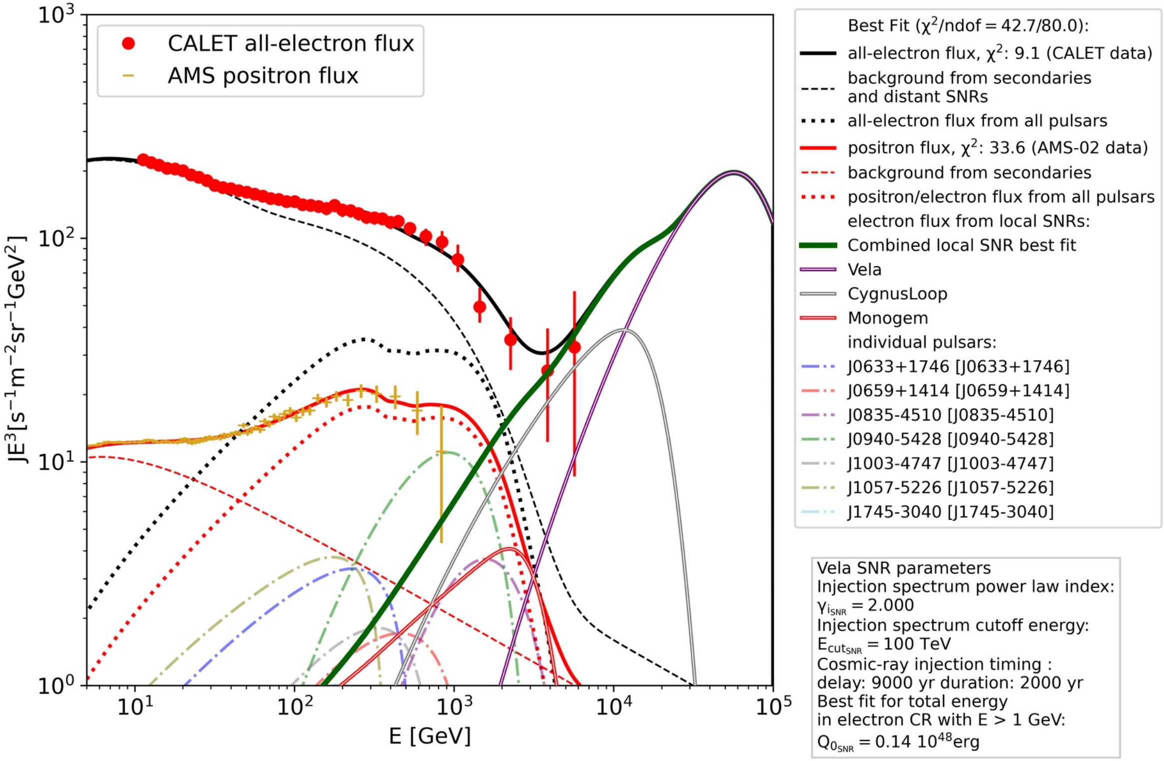




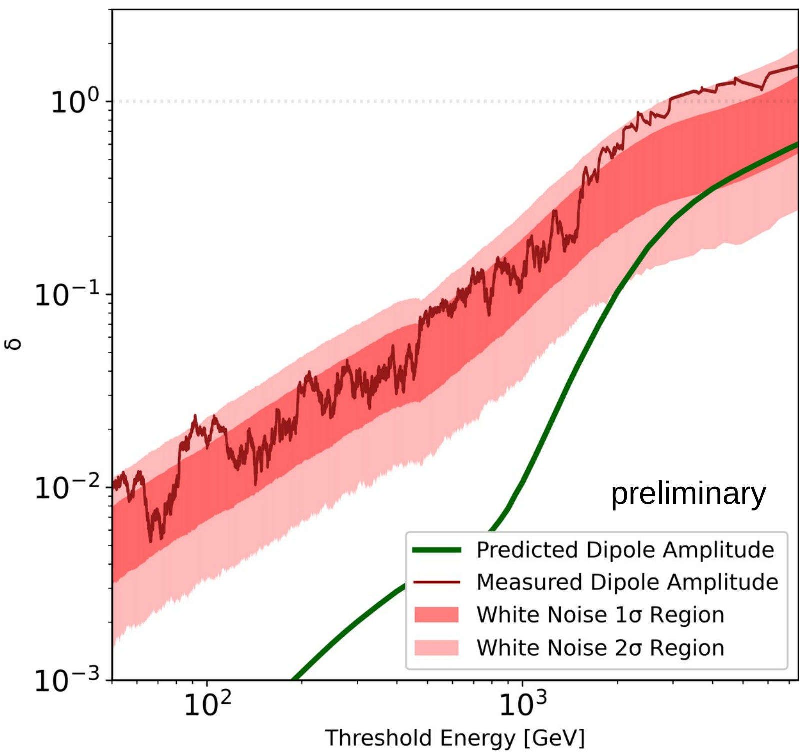
Contribution from Vela significant only above 1 TeV
→ the model is well clear of the Fermi-LAT limit

Adding Cygnus Loop and Monogem

($D_0 = 2\cdot10^{28}$ cm^2/s, 9kyr delay, 2kyr duration)

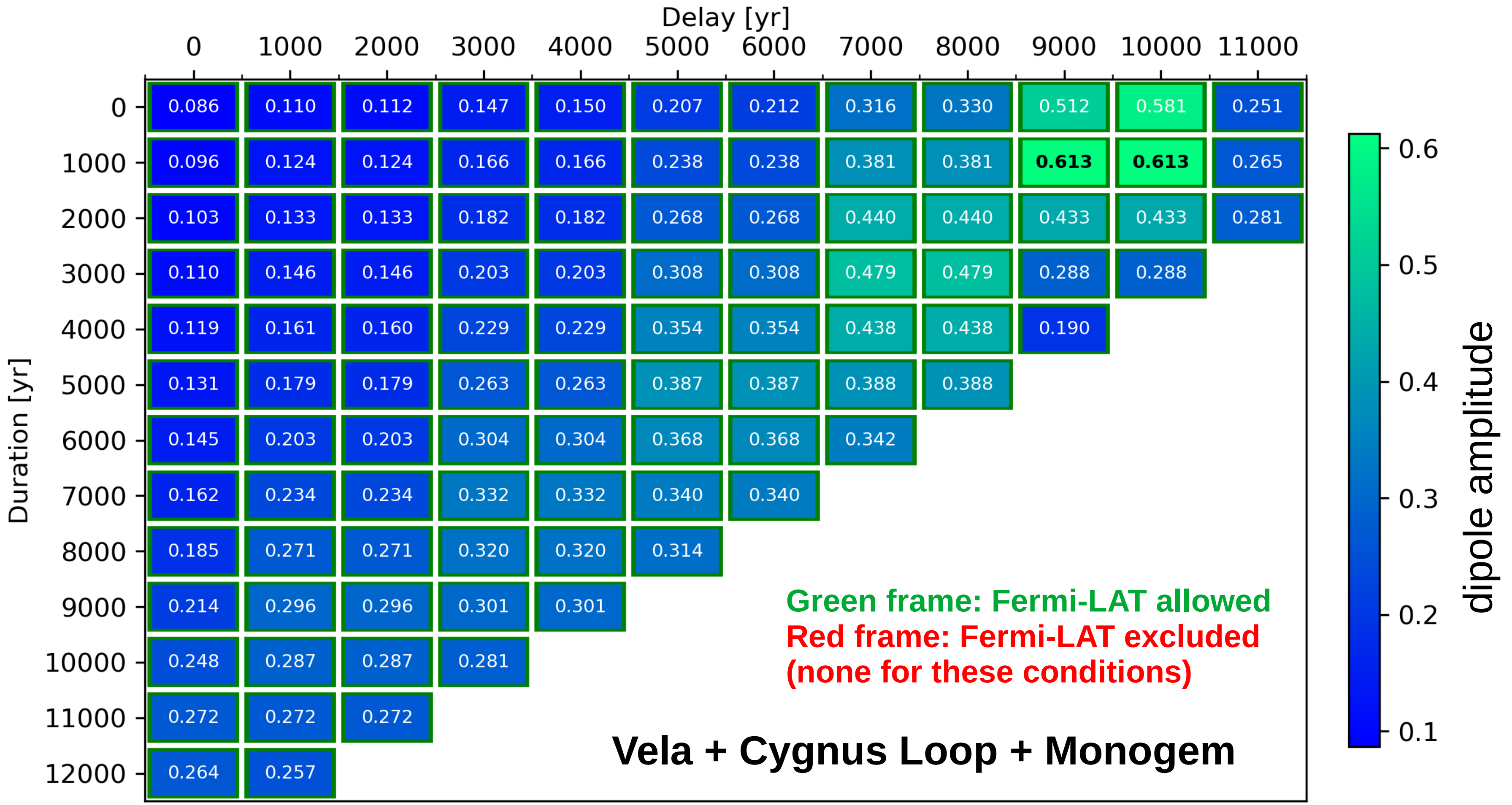


Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.000$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
delay: 9000 yr duration: 2000 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 0.14\ 10^{48}$erg



The influence of Cygnus Loop (opposite direction of Vela) reduces the dipole amplitude above 5 TeV from 1.116 to 0.433 in this case.

Scan Results for $D_0 = 2\cdot 10^{28}\ \mathrm{cm^2/s}$



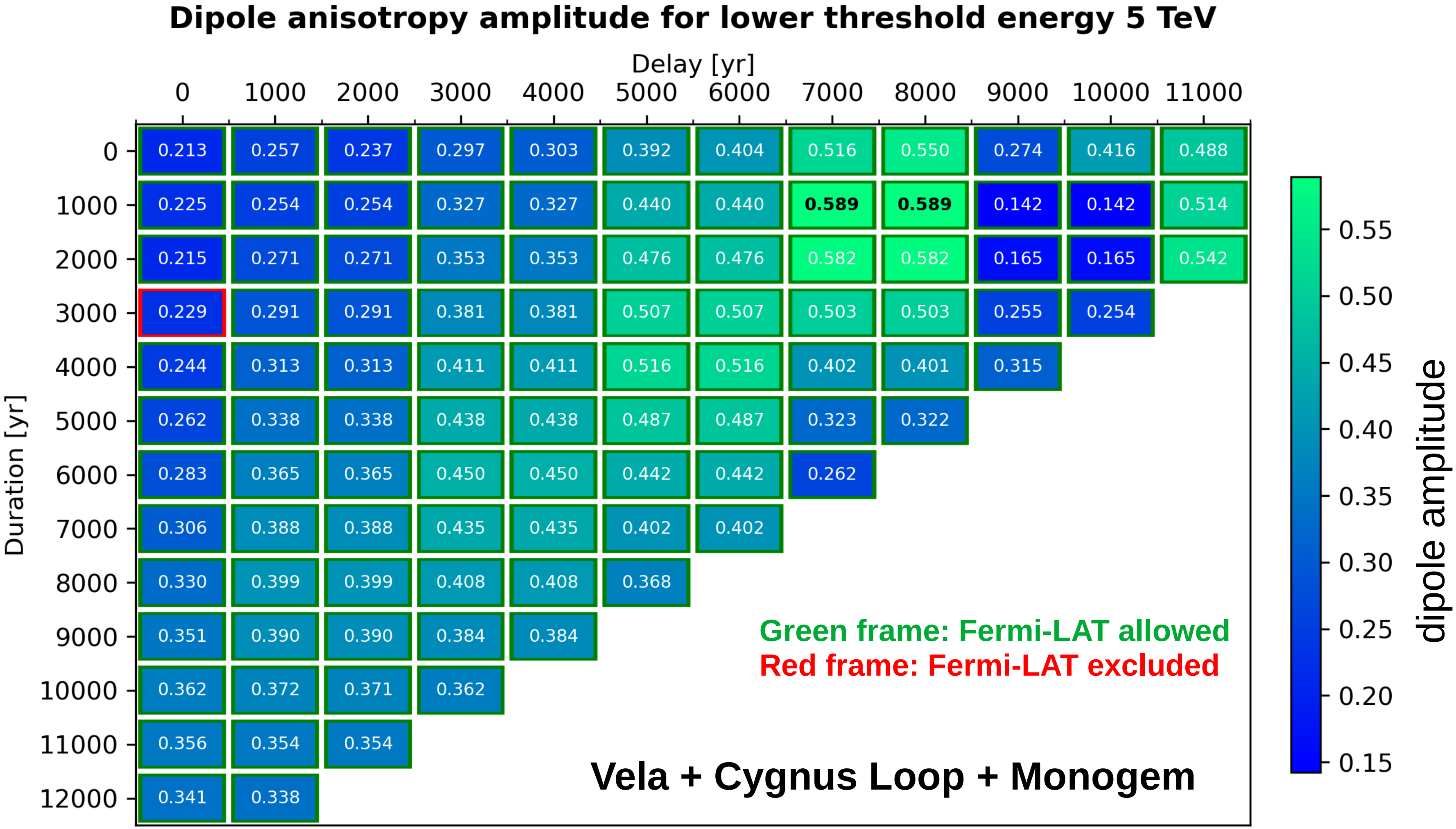
Dipole anisotropy amplitude for lower threshold energy 5 TeV

	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	0.086	0.110	0.112	0.147	0.150	0.207	0.212	0.316	0.330	0.512	0.581	0.251
1000	0.096	0.124	0.124	0.166	0.166	0.238	0.238	0.381	0.381	**0.613**	**0.613**	0.265
2000	0.103	0.133	0.133	0.182	0.182	0.268	0.268	0.440	0.440	0.433	0.433	0.281
3000	0.110	0.146	0.146	0.203	0.203	0.308	0.308	0.479	0.479	0.288	0.288	
4000	0.119	0.161	0.160	0.229	0.229	0.354	0.354	0.438	0.438	0.190		
5000	0.131	0.179	0.179	0.263	0.263	0.387	0.387	0.388	0.388			
6000	0.145	0.203	0.203	0.304	0.304	0.368	0.368	0.342				
7000	0.162	0.234	0.234	0.332	0.332	0.340	0.340					
8000	0.185	0.271	0.271	0.320	0.320	0.314						
9000	0.214	0.296	0.296	0.301	0.301							
10000	0.248	0.287	0.287	0.281								
11000	0.272	0.272	0.272									
12000	0.264	0.257										

Green frame: Fermi-LAT allowed
Red frame: Fermi-LAT excluded
(none for these conditions)

Vela + Cygnus Loop + Monogem

Scan Results for $D_0 = 1\cdot10^{28}$ cm^2/s



Dipole anisotropy amplitude for lower threshold energy 5 TeV

	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000	11000
0	0.213	0.257	0.237	0.297	0.303	0.392	0.404	0.516	0.550	0.274	0.416	0.488
1000	0.225	0.254	0.254	0.327	0.327	0.440	0.440	**0.589**	**0.589**	0.142	0.142	0.514
2000	0.215	0.271	0.271	0.353	0.353	0.476	0.476	0.582	0.582	0.165	0.165	0.542
3000	0.229	0.291	0.291	0.381	0.381	0.507	0.507	0.503	0.503	0.255	0.254	
4000	0.244	0.313	0.313	0.411	0.411	0.516	0.516	0.402	0.401	0.315		
5000	0.262	0.338	0.338	0.438	0.438	0.487	0.487	0.323	0.322			
6000	0.283	0.365	0.365	0.450	0.450	0.442	0.442	0.262				
7000	0.306	0.388	0.388	0.435	0.435	0.402	0.402					
8000	0.330	0.399	0.399	0.408	0.408	0.368						
9000	0.351	0.390	0.390	0.384	0.384							
10000	0.362	0.372	0.371	0.362								
11000	0.356	0.354	0.354									
12000	0.341	0.338										

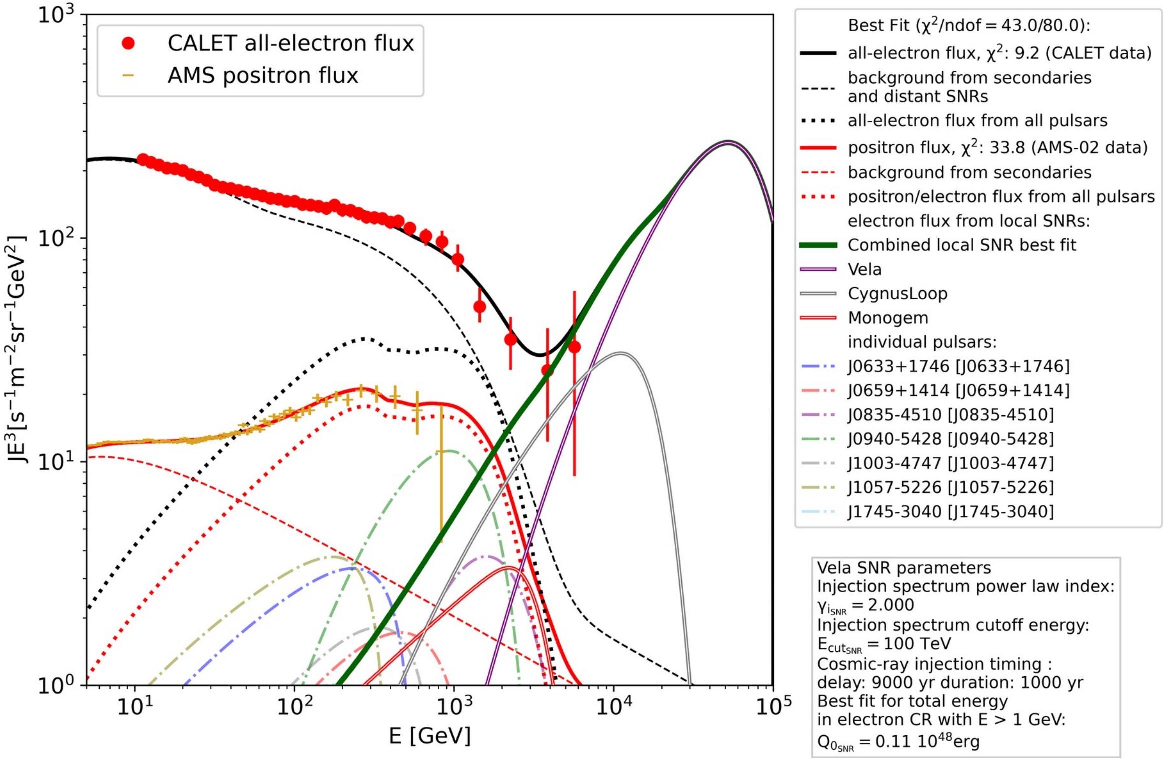
Green frame: Fermi-LAT allowed

Red frame: Fermi-LAT excluded

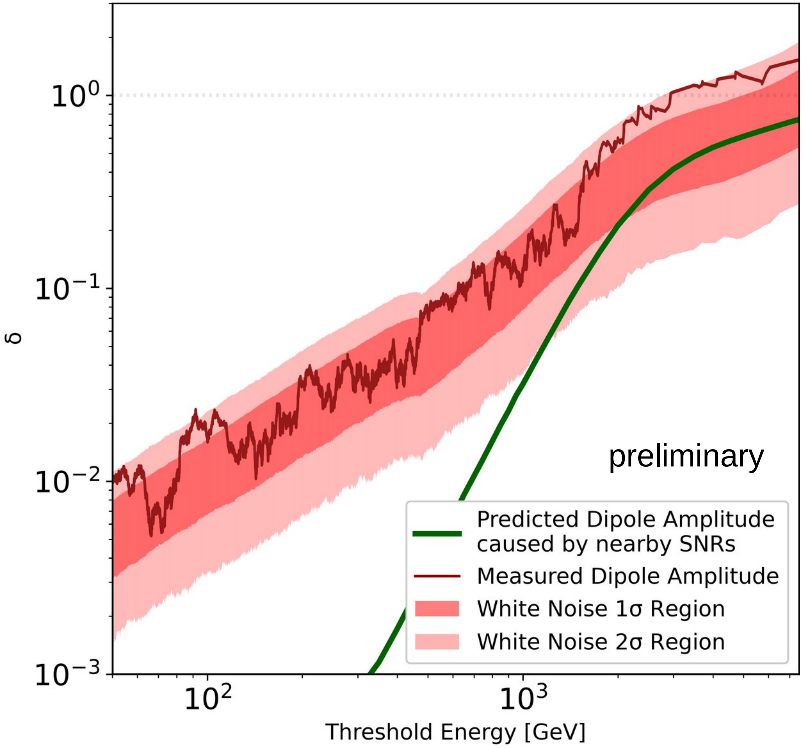
Vela + Cygnus Loop + Monogem

Best Anisotropy for 3-SNR Case

($D_0 = 2 \cdot 10^{28}$ cm^2/s, 9kyr delay, 1kr duration)



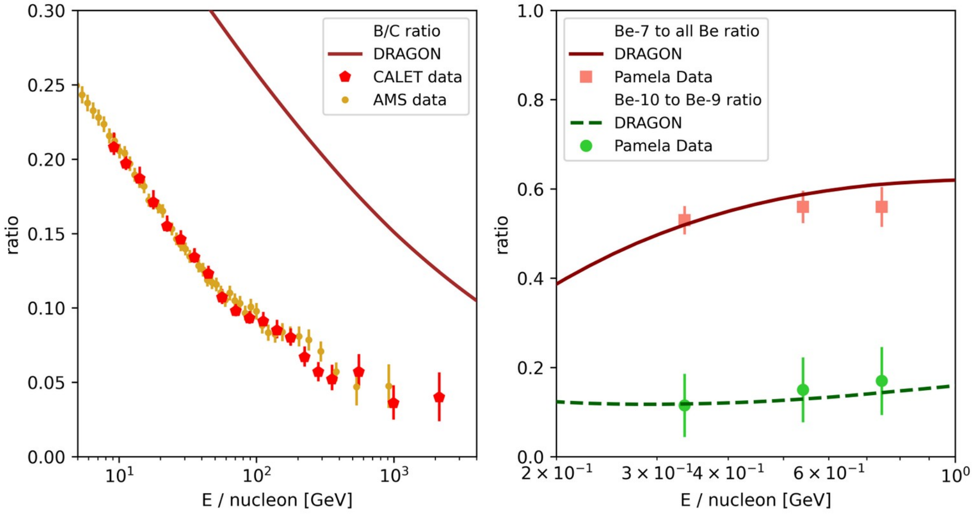
Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.000$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
delay: 9000 yr duration: 1000 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 0.11\ 10^{48}$erg



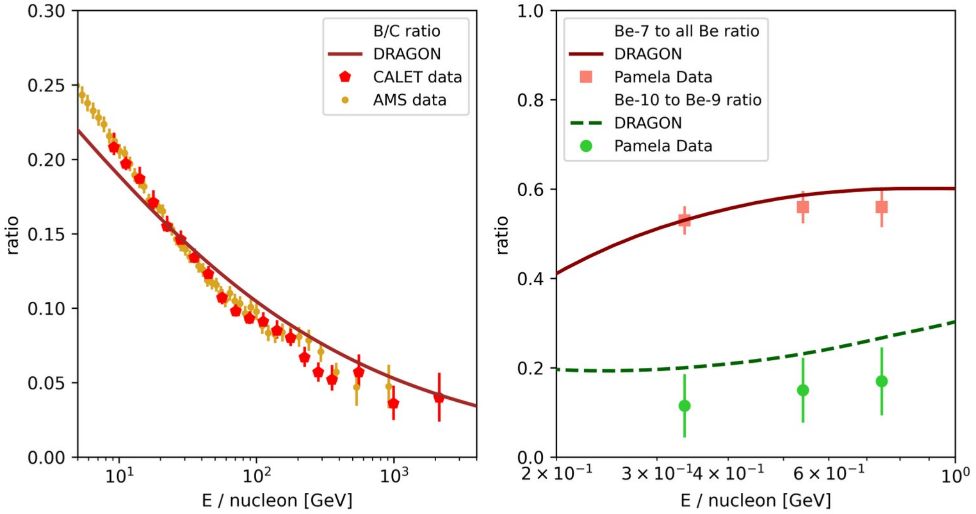
Changing the emission duration 2kyr → 1kyr increases the dipole amplitude from 0.433 to 0.613

B/C-Ratio and Be-Ratios for $D_0 = 2 \cdot 10^{28}$ cm²/s

Diffusion zone half height L = 4 kpc



Diffusion zone half height L = 1 kpc

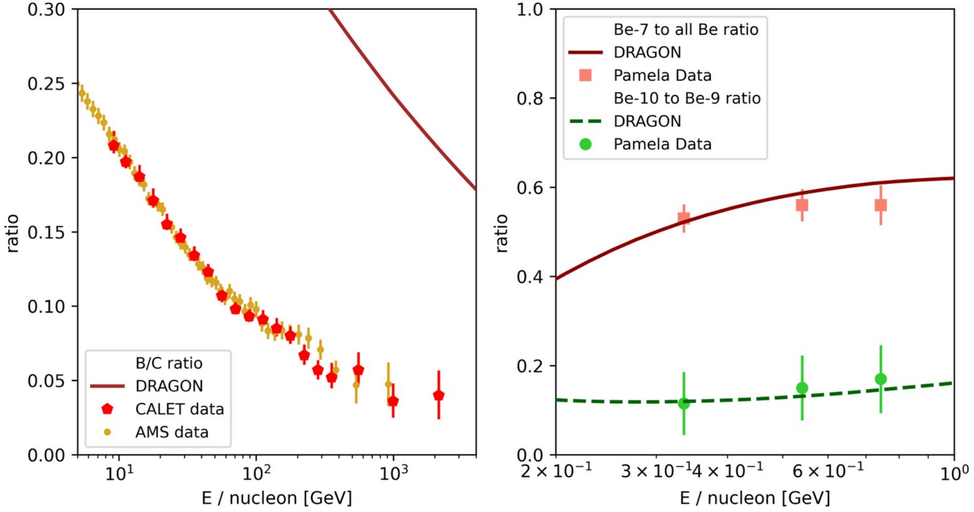


The low diffusion coefficient causes overproduction of secondaries unless the diffusion zone is very thin, but that creates tension with the Berillium-7 ratio
→ Reduced diffusion around SNRs only could solve this (future work)

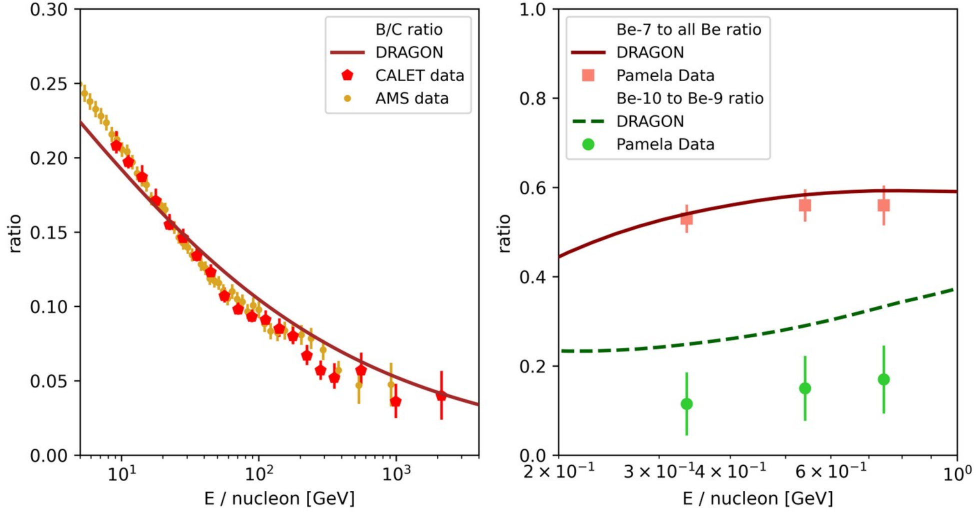
B/C ratio:
CALET PRL 129, 251103 (2022)
AMS-02 PRL 120, 021101 (2018)
Be ratios:
Francesco Nozzoli, Cinzia Cernetti,
Universe 7 (2021) 6, 183

B/C-Ratio and Be-Ratios for $D_0 = 1{\cdot}10^{28}$ cm^2/s

Diffusion zone half height L = 4 kpc



Diffusion zone half height L = 0.45 kpc



The tension is even larger for $D_0 = 1{\cdot}10^{28}$ cm^2/s

B/C ratio:
CALET PRL 129, 251103 (2022)
AMS-02 PRL 120, 021101 (2018)
Be ratios:
Francesco Nozzoli, Cinzia Cernetti,
Universe 7 (2021) 6, 183

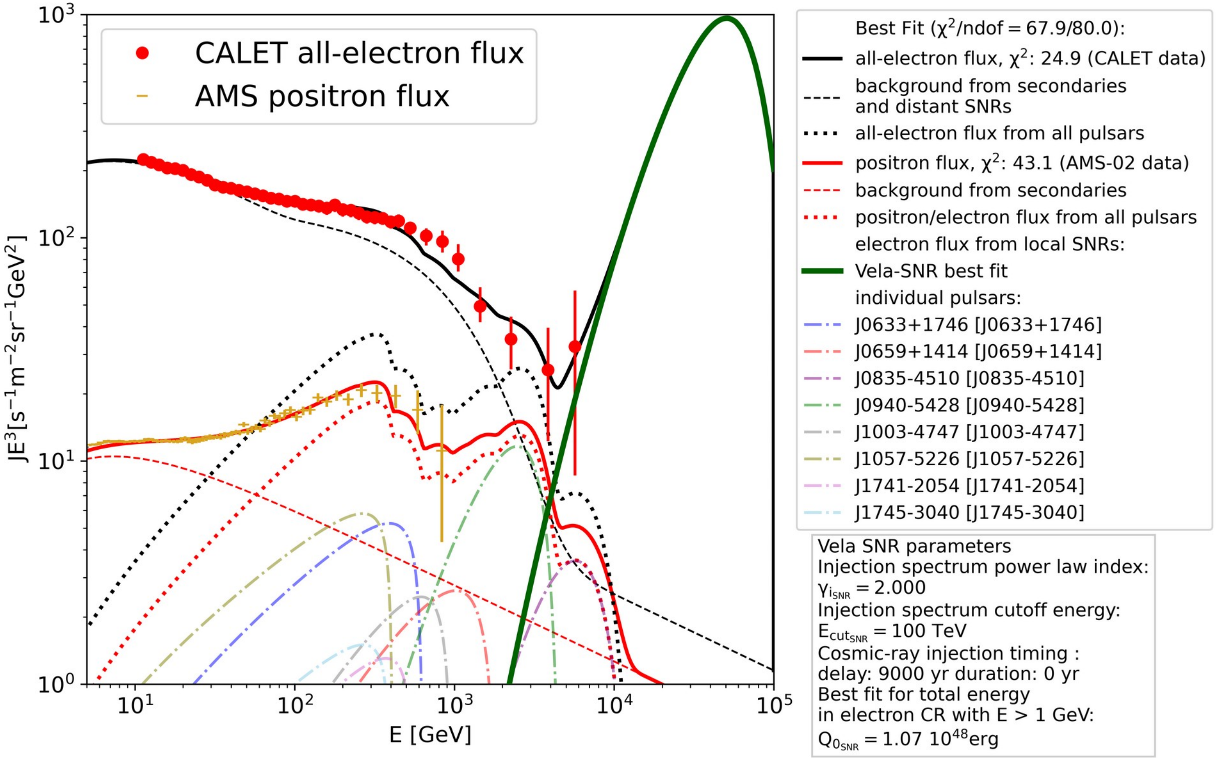
Conclusion and Outlook

- The observed dipole anisotropy towards Vela with amplitude O(1) could be attributed to emission from the Vela SNR for a strongly delayed emission with a hard injection index and very low diffusion coefficient if Vela is dominant in the TeV region.
- If assuming the same properties for Cygnus Loop and Monogem, the dipole amplitude towards Vela depends strongly on the exact release timing and is ~0.6 at most for the scanned cases.
- This study used a very simple toy model for emission and propagation condition
  → **preliminary results requiring refinement**
- Study better motivated time dependent CR acceleration and escape models to achieve this interpretation in a more realistic way.
- Calculate nearby SNR contribution with reduced diffusion coefficient around the source only, to reconcile the model with global propagation models explaining the nuclei spectra data.

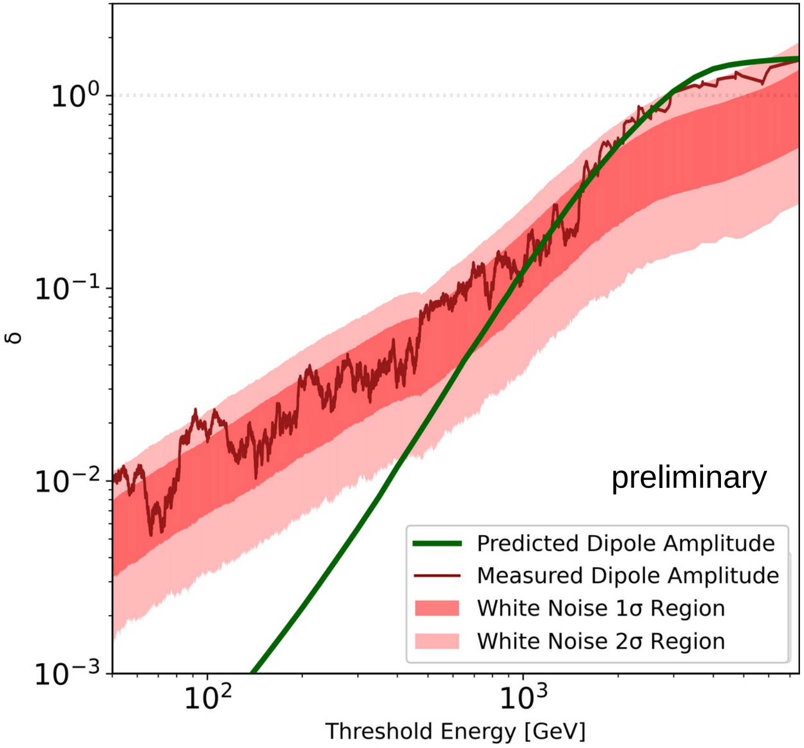
This work is supported by Waseda University Grant for Special Research Projects No. 2026R-035.

Backup Slides

Fit for $D_0 = 1 \cdot 10^{28}$ cm^2/s , 9kyr delay

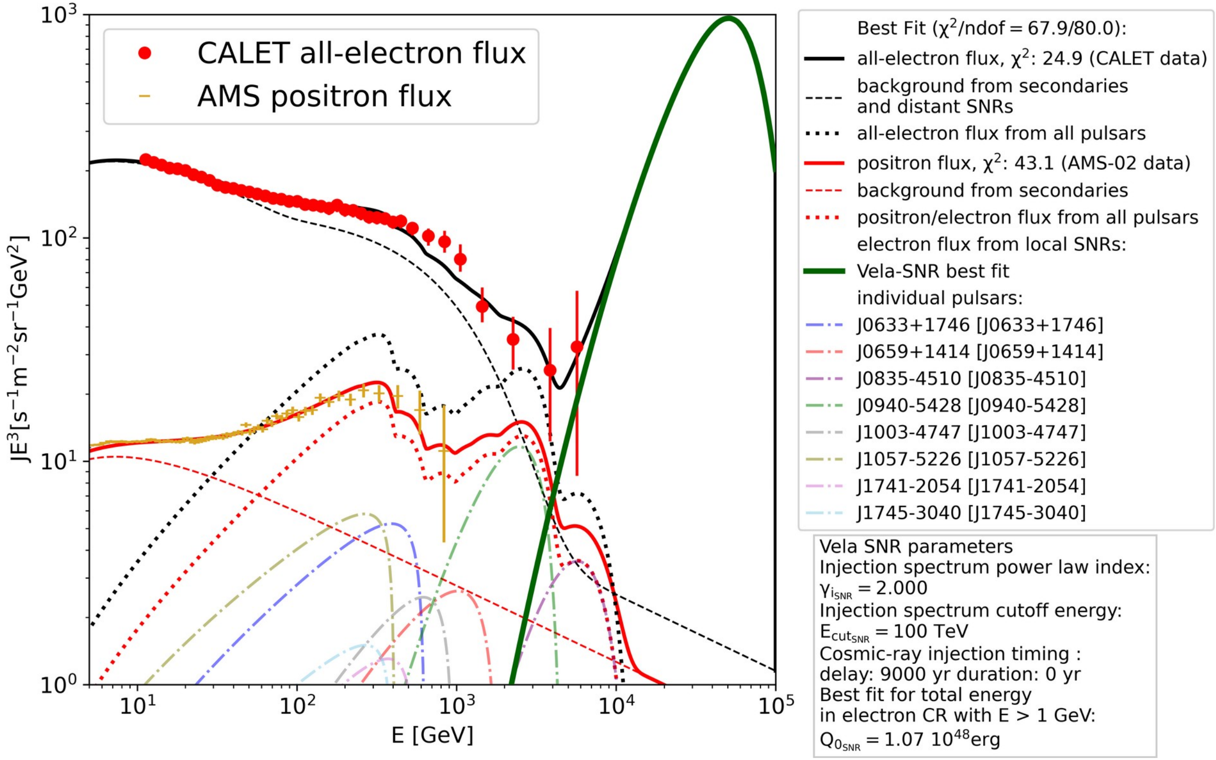


Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.000$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
delay: 9000 yr duration: 0 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 1.07\ 10^{48}$erg

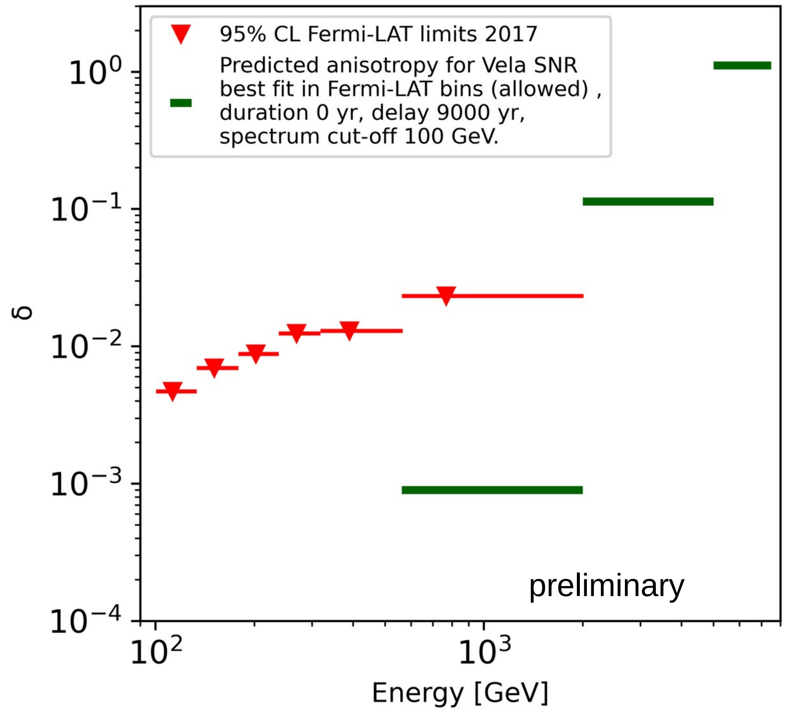


This model explains the increase of the measured amplitude over the white noise expectation band for threshold energy above 1 TeV

Fit for $D_0 = 1 \cdot 10^{28}$ cm^2/s , 9kyr delay



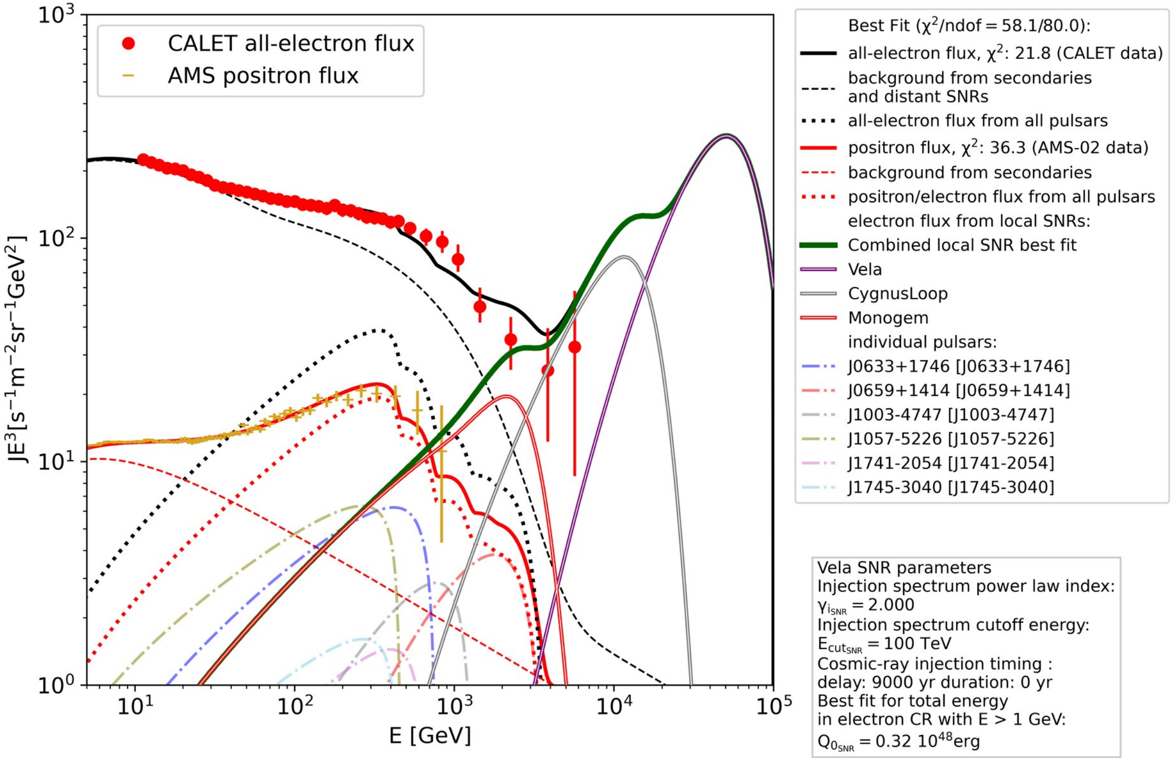
Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.000$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
delay: 9000 yr duration: 0 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 1.07\ 10^{48}$erg



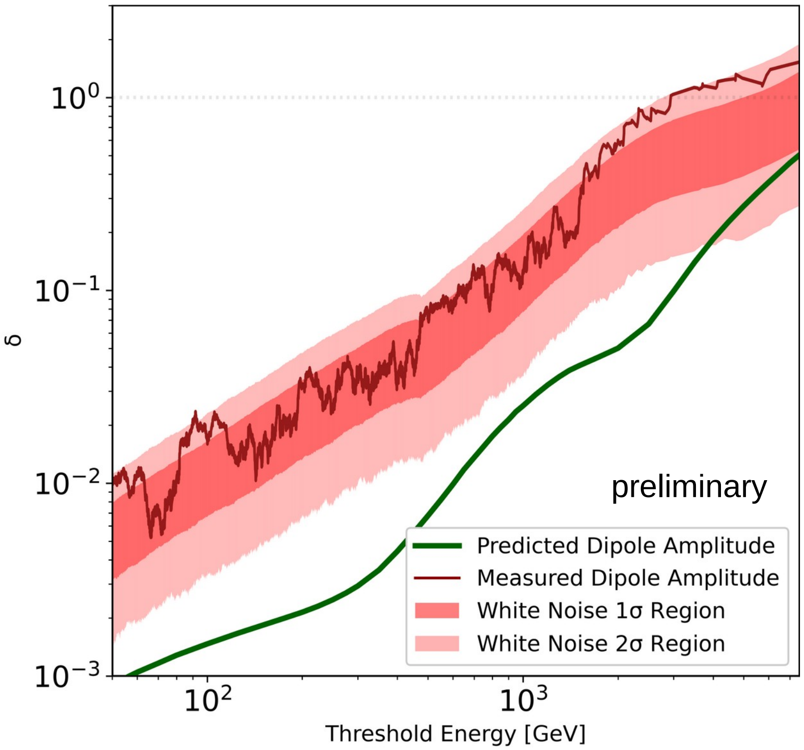
Contribution from Vela significant only above 1 TeV →
the model is well clear of the Fermi-LAT limit

Adding Cygnus Loop and Monogem

($D_0 = 1\cdot10^{28}$ cm^2/s, 9kyr delay)

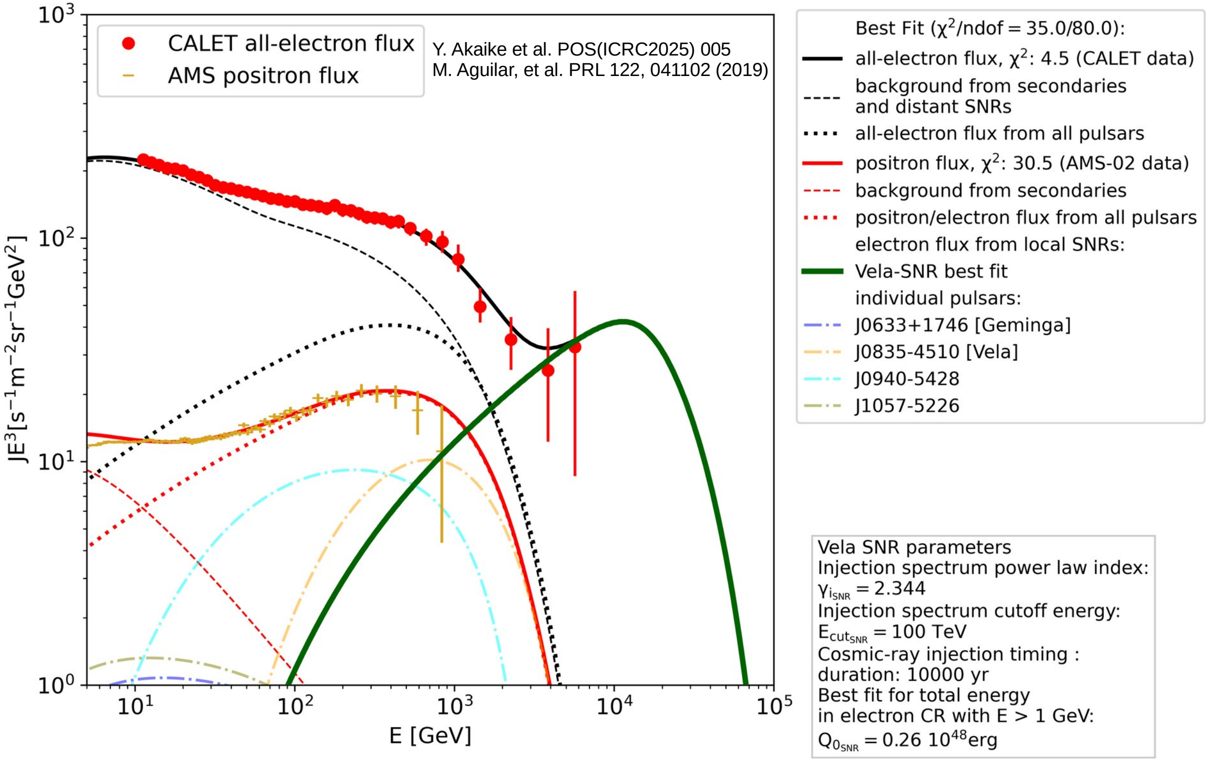


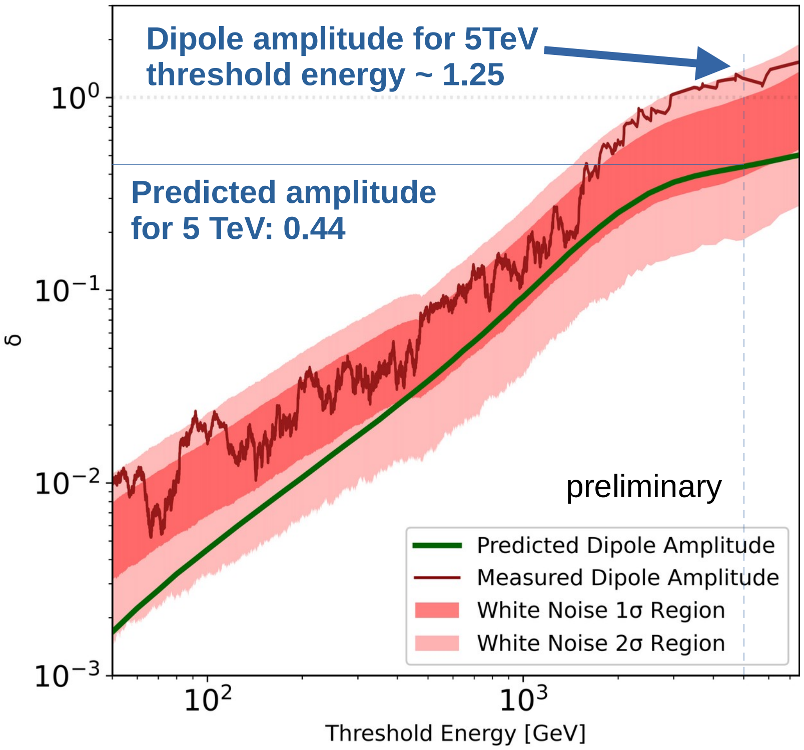
Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.000$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
delay: 9000 yr duration: 0 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 0.32\ 10^{48}$erg



The influence of Cygnus Loop (opposite direction of Vela) reduces the dipole amplitude above 5 TeV from 1.475 to 0.274 in this case.

Fit and Anisotropy for Conditions Explaining most Nuclei Spectra



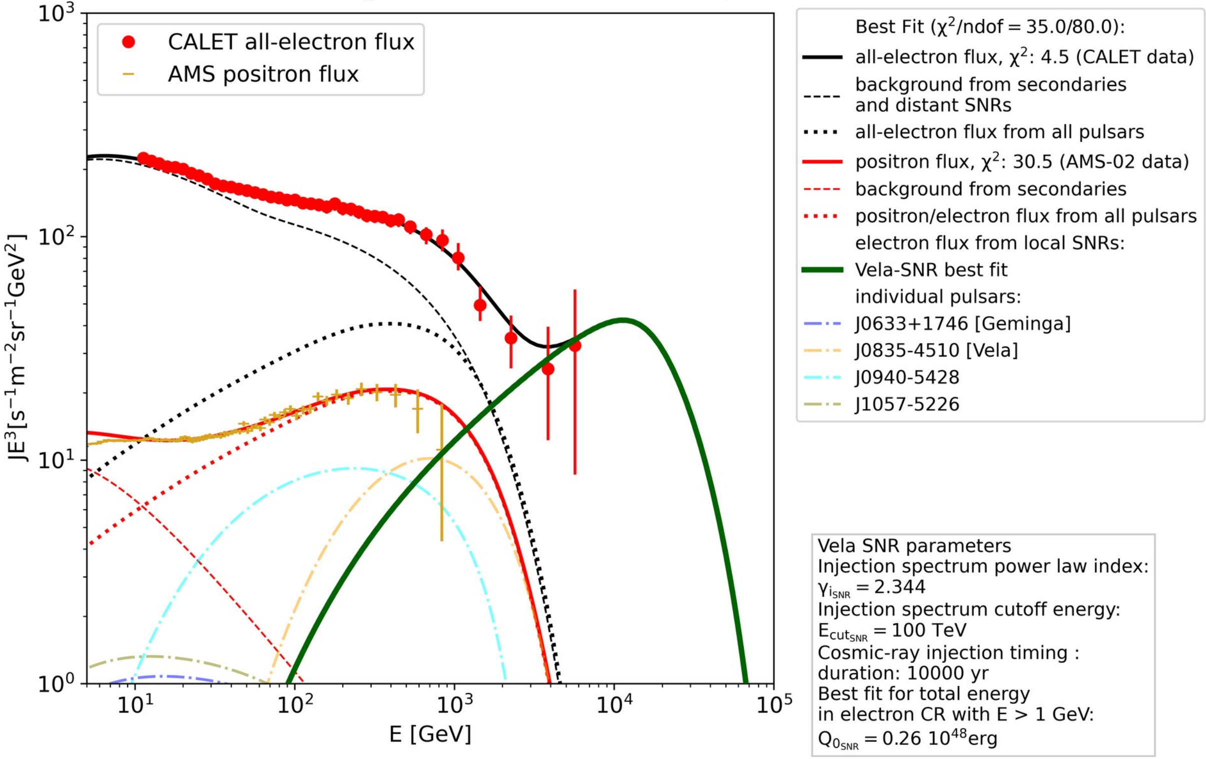


Dipole amplitude for 5TeV threshold energy ~ 1.25

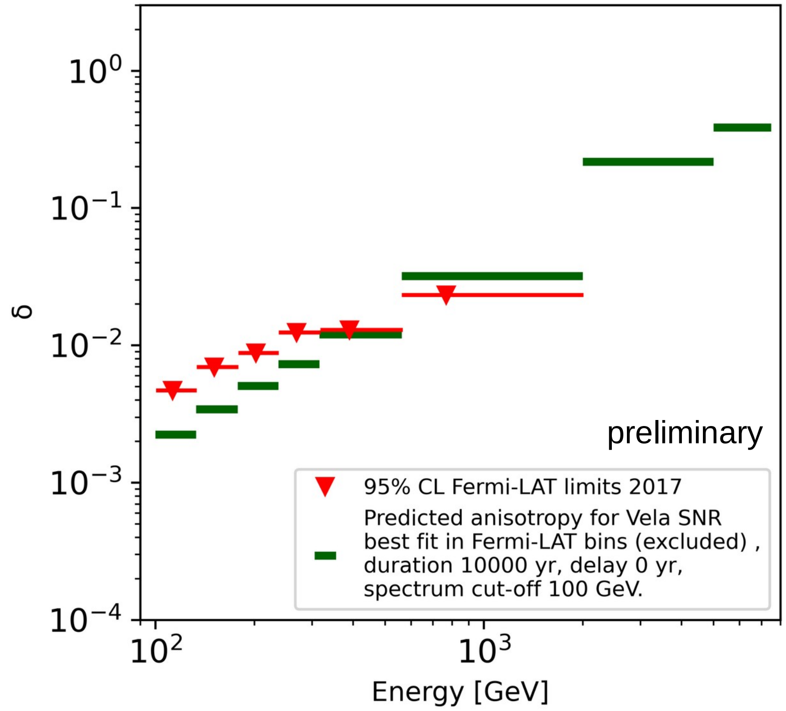
Predicted amplitude for 5 TeV: 0.44

- Fit an anisotropy with propagation conditions and injection power law index from [H.M. POS(ICRC2023)068 “A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra”]

Fit and Anisotropy for Conditions Explaining most Nuclei Spectra

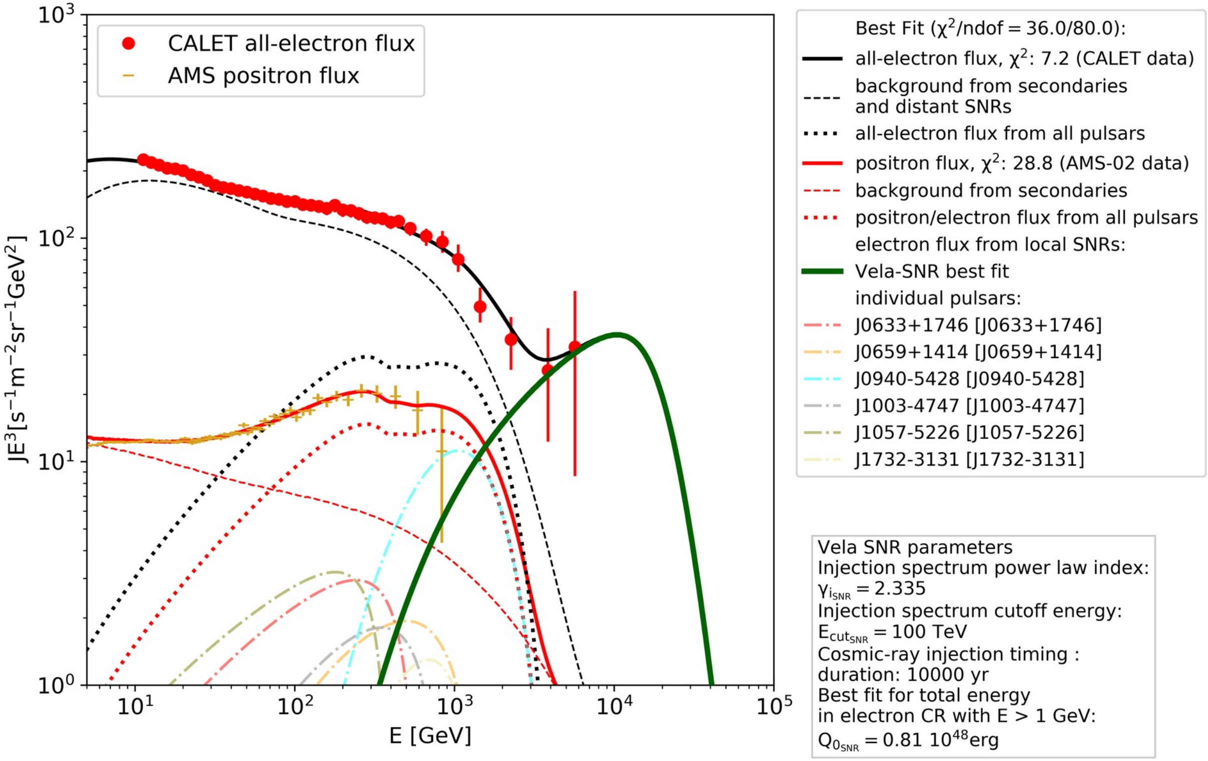


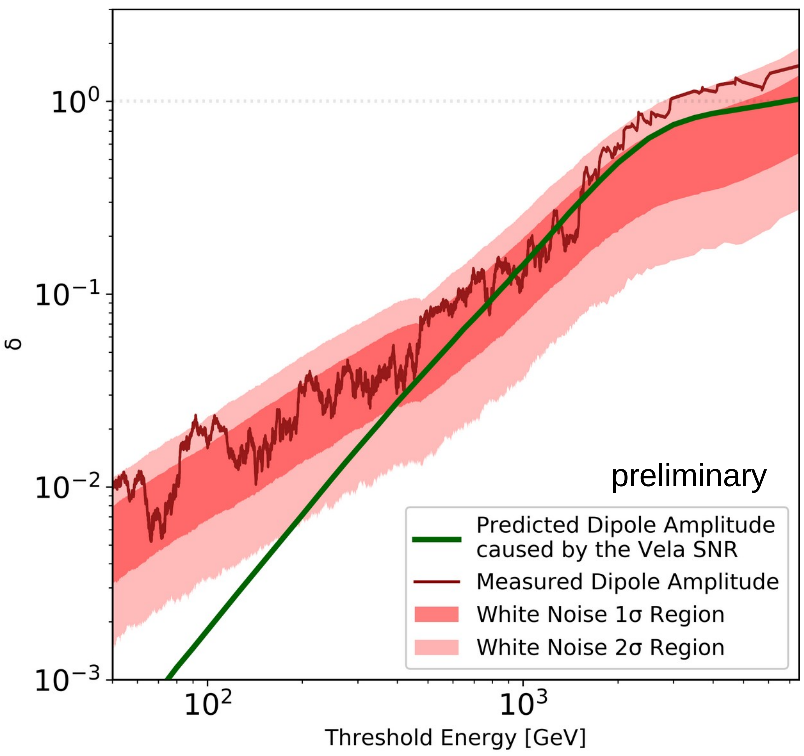
Vela SNR parameters
Injection spectrum power law index:
$\gamma_{i_{SNR}} = 2.344$
Injection spectrum cutoff energy:
$E_{cut_{SNR}} = 100$ TeV
Cosmic-ray injection timing :
duration: 10000 yr
Best fit for total energy
in electron CR with E > 1 GeV:
$Q_{0_{SNR}} = 0.26\ 10^{48}$erg



The fit with this propagation model and these injection conditions is also excluded by Fermi-LAT

Fit and Anisotropy with PRL(2023) Conditions (Vela only)

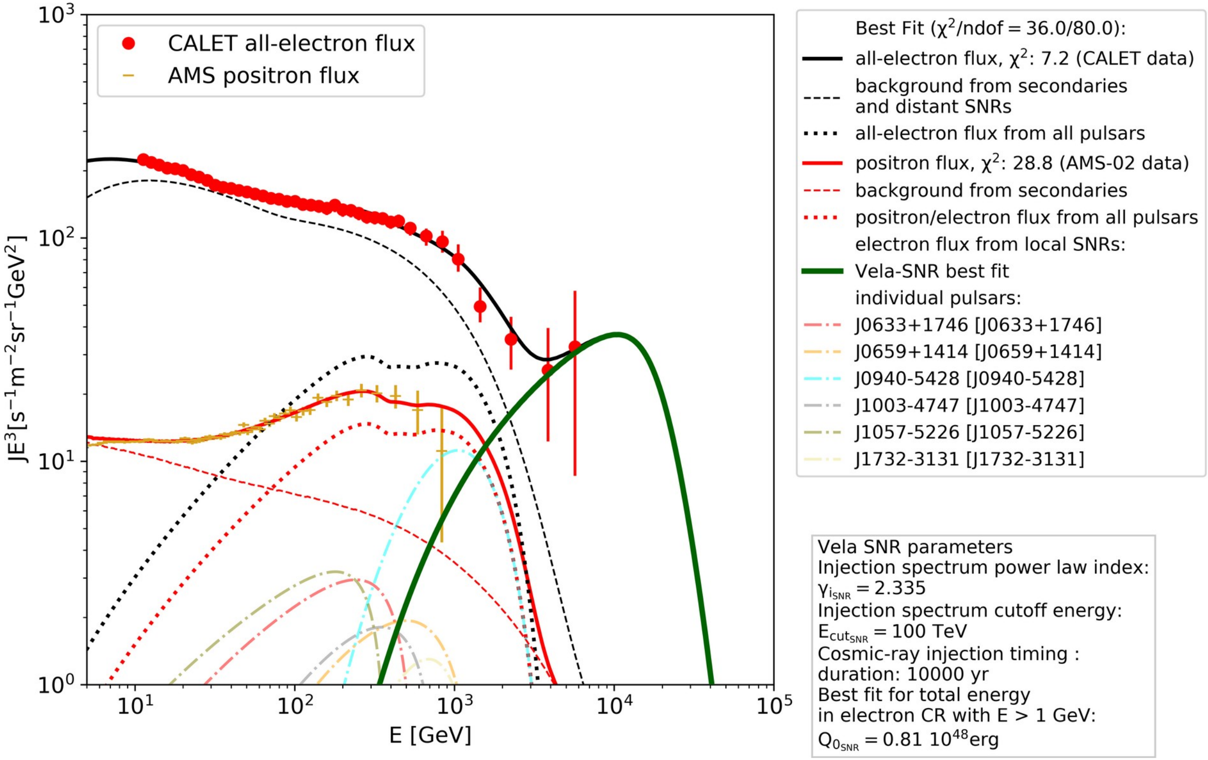


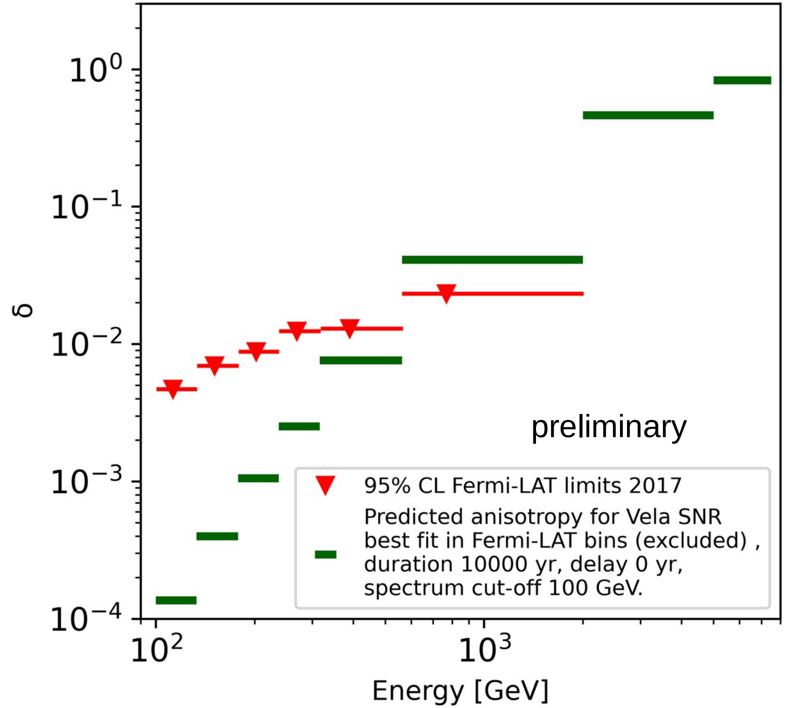


Model parameters from POS(ICRC2021)100
Dipole amplitude for E>5TeV: 0.92

PRL(2023): O. Adriani et al. (CALET collaboration)
Phys. Rev. Lett. 131, 191001 (2023)

Fit and Anisotropy with PRL(2023) Conditions (Vela only)





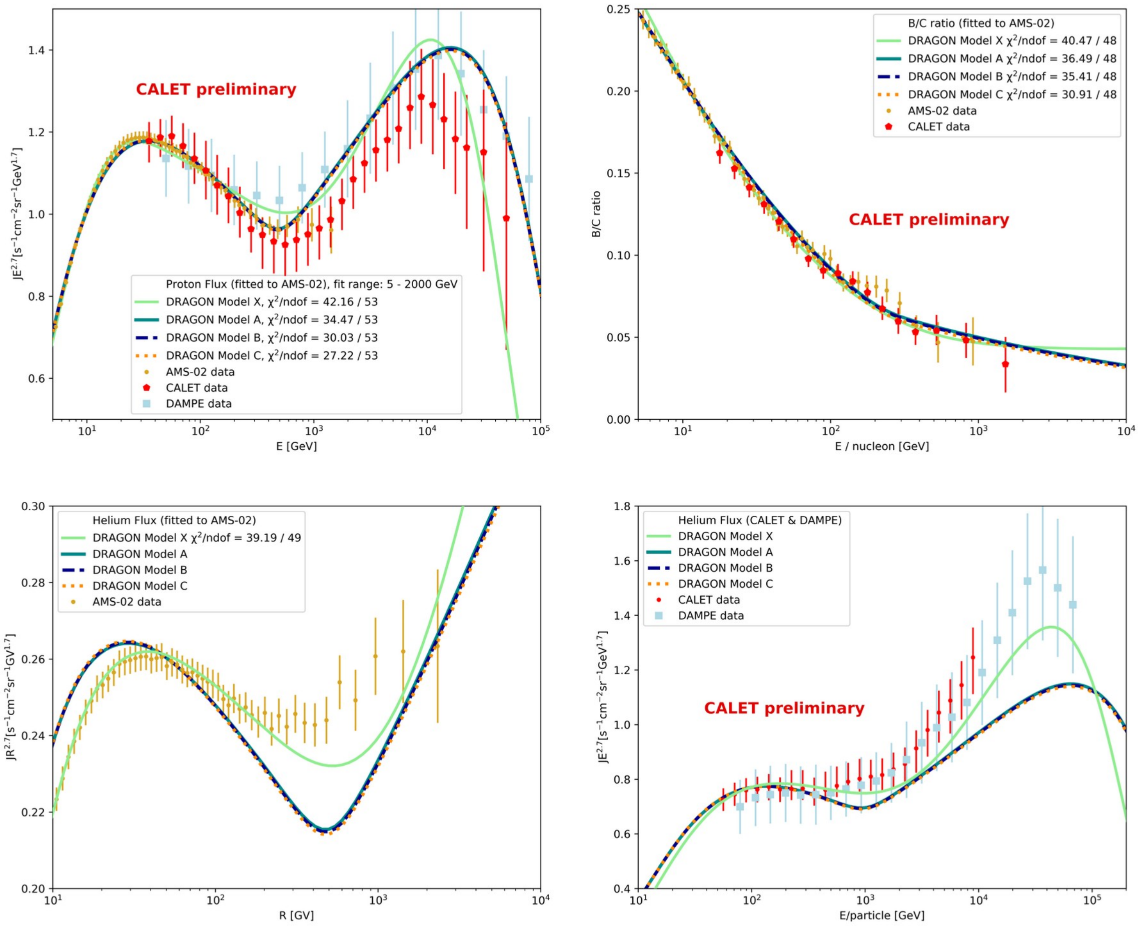
Model excluded by Fermi-LAT

Propagation Models from ICRC2021

δ=0.5 (Kraichnan Turbulence)

Model / Parameter	A	B	C	X
D_0 $[10^{28}\mathrm{cm}^2/\mathrm{s}]$	0.66	1.32	1.78	0.16
r_s [kpc]	4.5	4.5	4.5	3.0
L [kpc]	3	6	9	6
z_s [kpc]	1.8	3.5	5.3	0.6
R_b [TV]	0.5	0.5	0.5	1.0
δ_h	0.2	0.2	0.2	0.01
s	0.05	0.05	0.05	0.3
v_a [km/s]	0	0	0	18
γ_i	2.34	2.34	2.34	2.335
R_{cut} [TV]	100	100	100	30
$D_{0(sol)}$ $[10^{28}\mathrm{cm}^2/\mathrm{s}]$	2.68	5.35	7.22	1.31
Φ_0 [GV]	0.32	0.34	0.36	0.89
Φ_1 [GV]	2.0	2.0	2.0	0.37
$\Phi(10\ \mathrm{GV})$[GV]	0.43	0.45	0.47	0.91

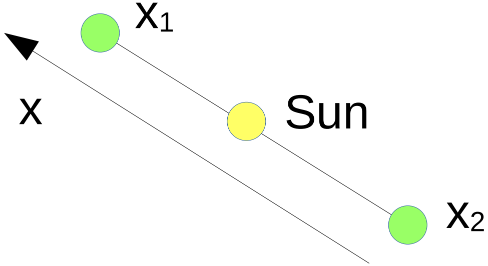
$$D(r, z, R) = D_0 \max\left\{e^{(r-r_n)/r_s}, 1\right\} \max\left\{e^{(z-z_n)/z_s}, 1\right\} \left(\frac{R}{R_0}\right)^{\delta_l} \left(1 + \left(\frac{R}{R_b}\right)^{\frac{\delta_l-\delta_h}{s}}\right)^{-s}$$



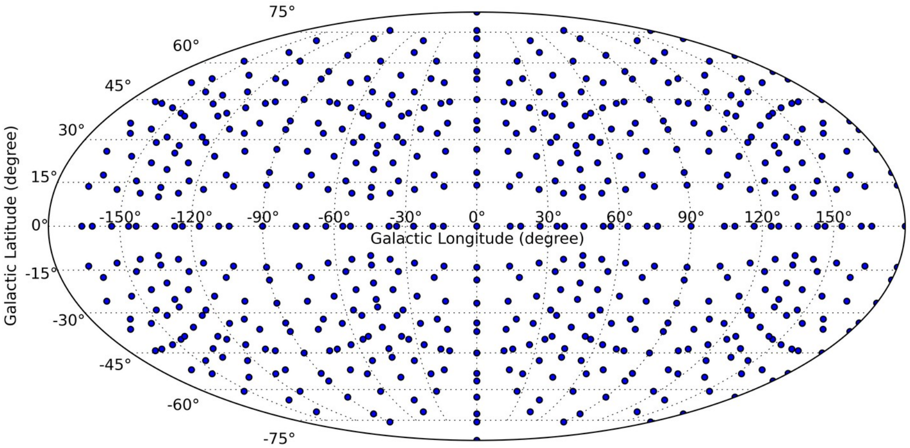
Anisotropy with DRAGON

- Directional flux calculated from differences in cosmic ray density ***F***:

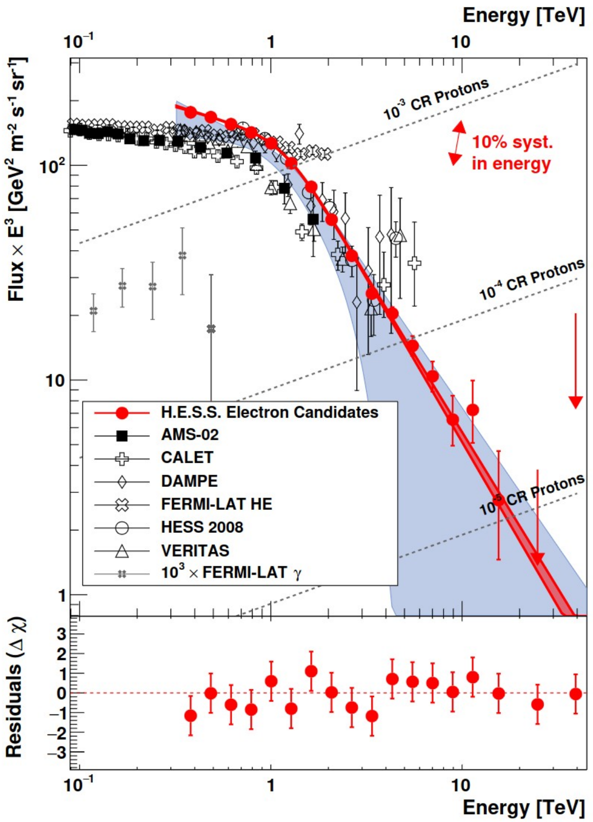
$$\Phi_{dir} = \Phi_{avg}\left(1 + \frac{3D}{c}\frac{(F_{x1} - F_{x2})/|x_1 - x_2|}{F_{Sun}}\right)$$



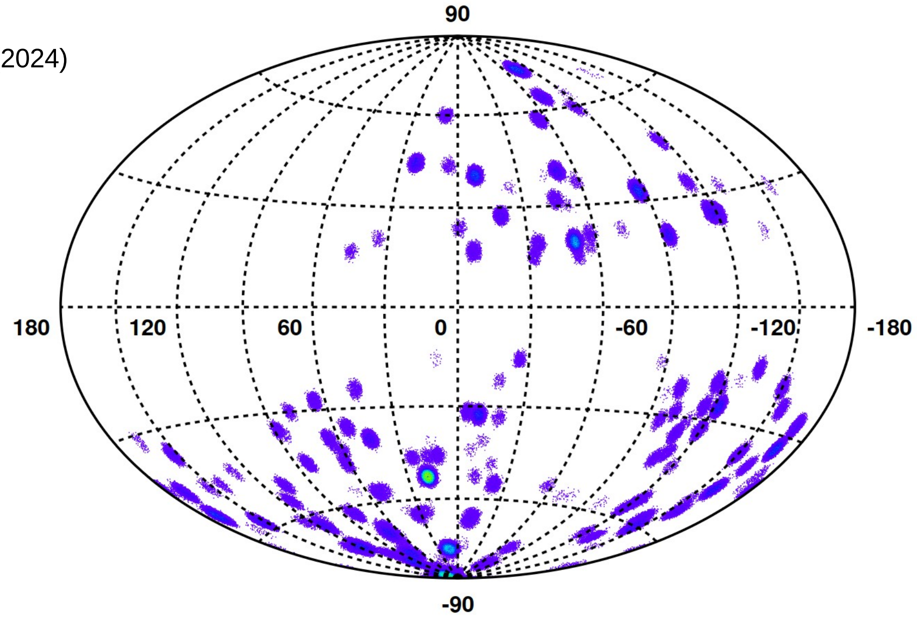
Non-equidistant spatial grid
=> Dense grid around Sun:
Anisotropy in 642 directions



HESS electron flux measurement and observation region



Phys. Rev. Lett. 133, 221001 (2024)



The HESS electron flux/upper limit is from observations mostly pointed away from the Vela direction → models with strong anisotropy can circumvent this limit