Search for Signatures of Nearby Supernova Remnants with CALET

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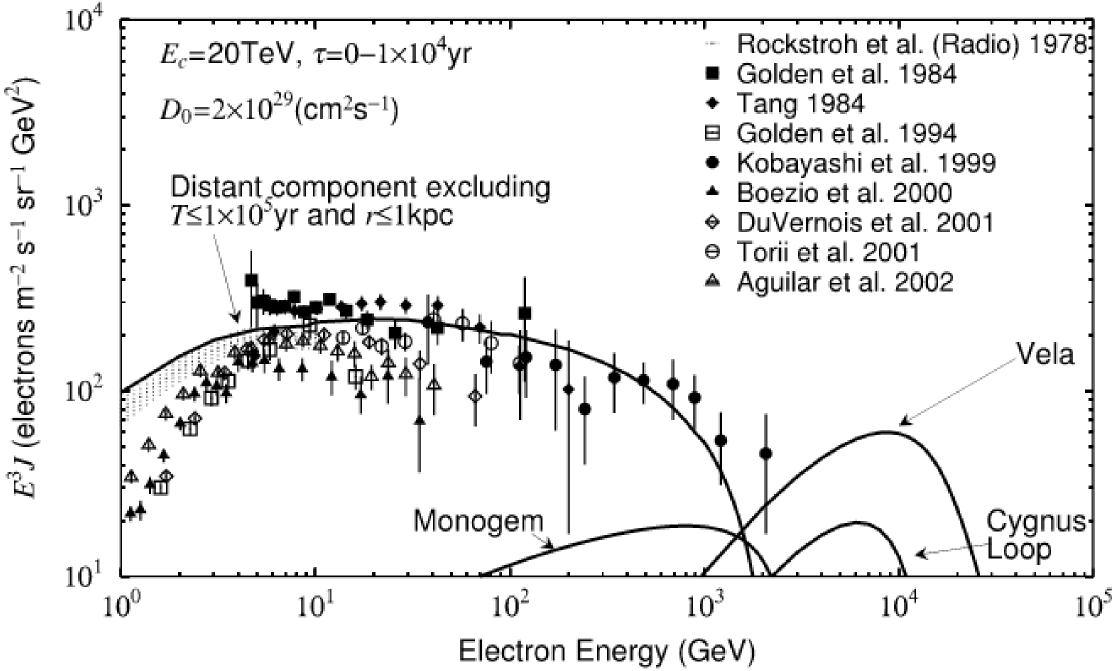
Introduction



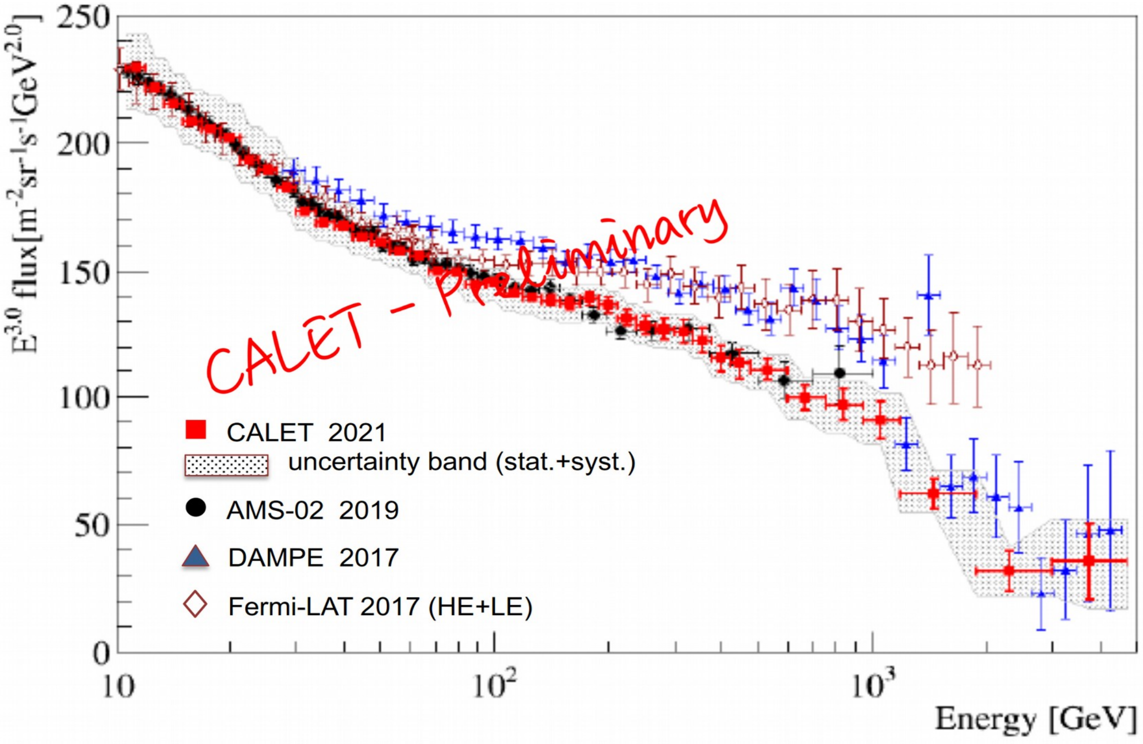
- In the TeV region of the electron CR spectrum, we expect only three supernova remnants to significantly contribute:

  Vela, Monogem, Cygnus Loop

- The estimated energy emitted as electron CR (above 1 GeV) is on the order of 10^{48} erg (total 10^{51} erg, proton CR 10^{50} erg → electron 1/100)

  (T. Kobayashi et al 2004 ApJ 601 340, “The Most Likely Sources of High-Energy Cosmic-Ray Electrons in Supernova Remnants”)

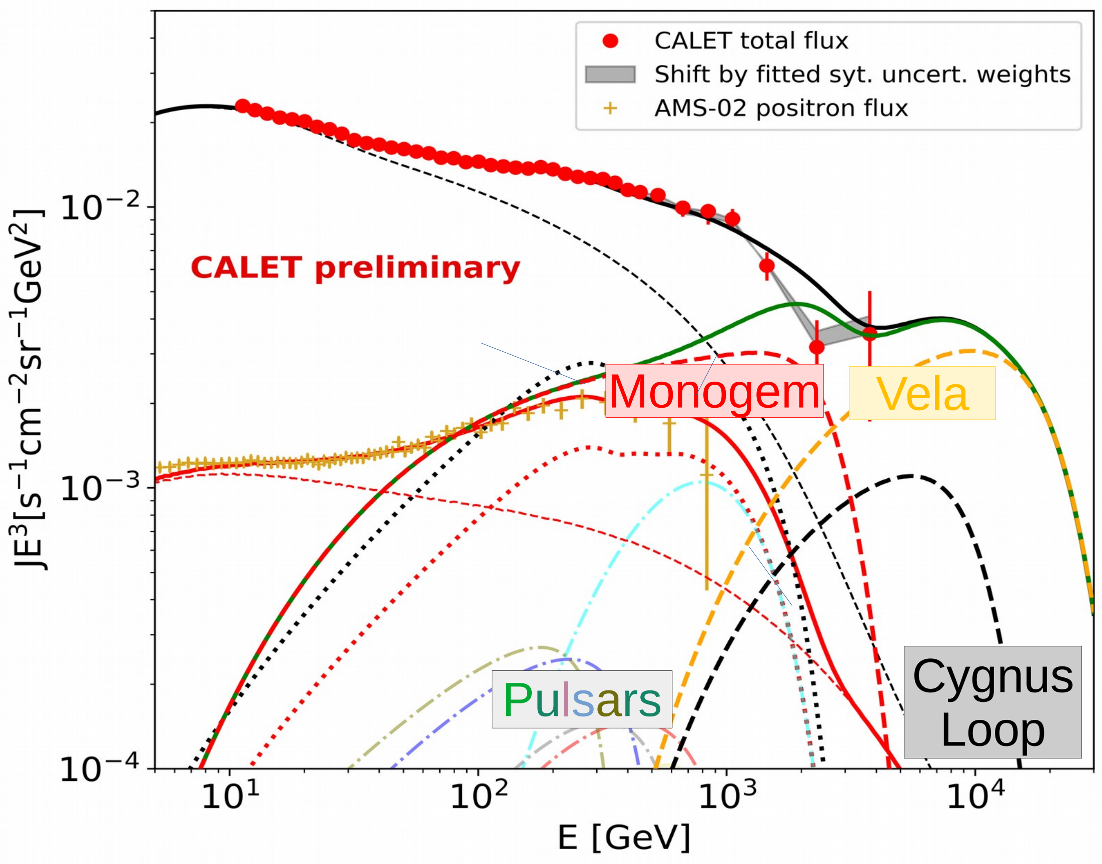
Goals of this Study



Use the latest CALET all-electron spectrum (S.Torii,Y. Akaike et al. PoS(ICRC2021)105) to:

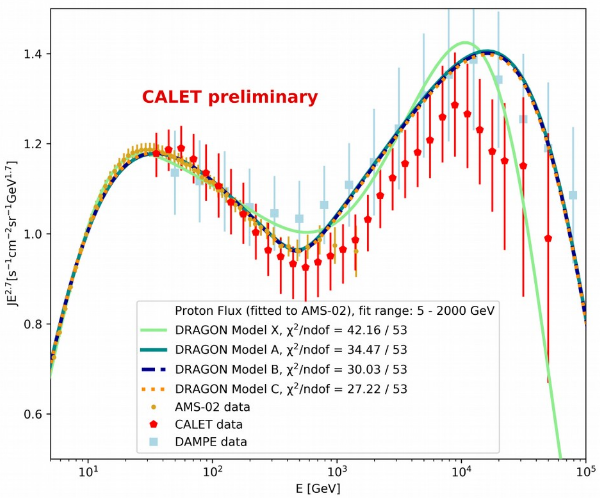
- Check if it agrees with the 10^{48} erg hypothesis for Q_0
- Constrain the preferred range of emitted energy further
- Set limits on this value for Vela and nearby SNR

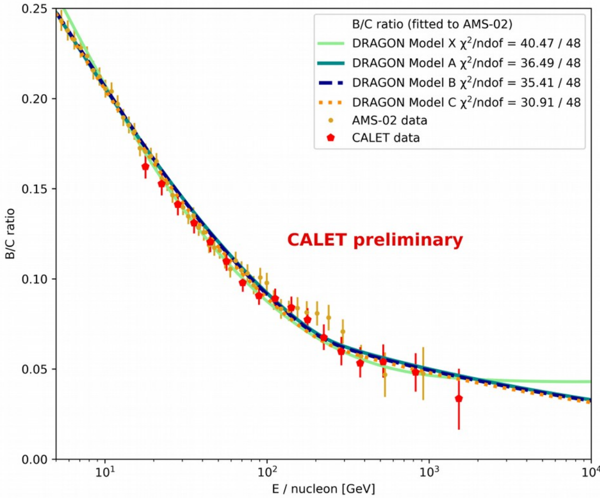
Method Overview

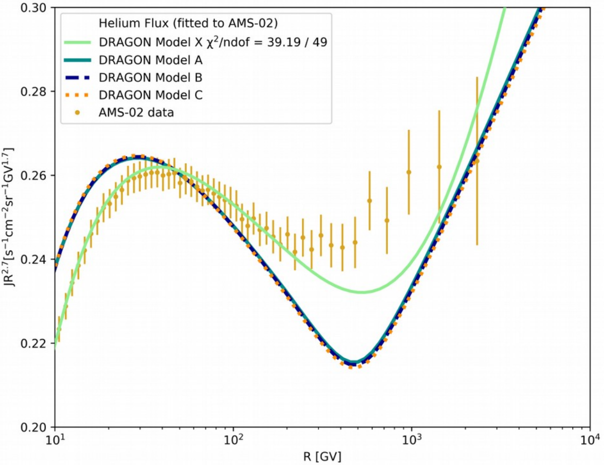


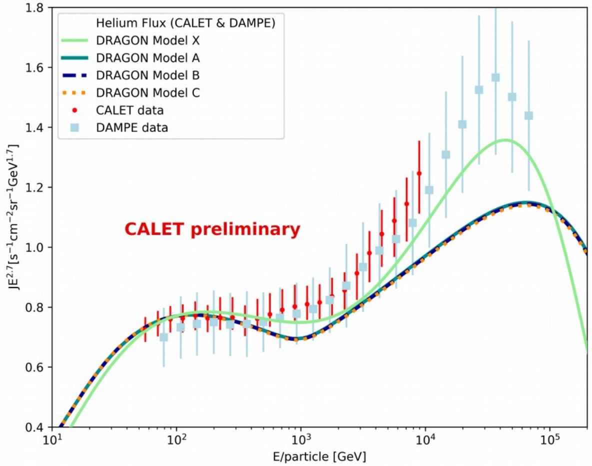
- Calculate the signatures of the nearby SNRs with DRAGON (D. Gaggero, et al., Phys.Rev.Lett. 111, 021102 (2013) numerical CR propagation calculation package, features non-equidistant spatial grid advantageous for calculation of flux from point sources)
- Combine them with a flexible parametrization of the background which includes pulsars as the source of the positron excess (guaranteed background from AMS-02 positron), and secondaries, and distant SNRs
- Fit the model to the CALET all-electron spectrum and AMS-02 positron only data.

Propagation Models









Four models covering a wide range in diffusion coefficient normalization:

X – very low diffusion ($D_{0(sol)}$=1.31 10^{28} cm^2/s)

A – low diffusion ($D_{0(sol)}$=2.68 10^{28} cm^2/s)

B – medium diffusion ($D_{0(sol)}$=5.35 10^{28} cm^2/s)

C – high diffusion ($D_{0(sol)}$=7.22 10^{28} cm^2/s)

Calculation of nuclei spectra with DRAGON and comparison to CALET & AMS-02 measurements

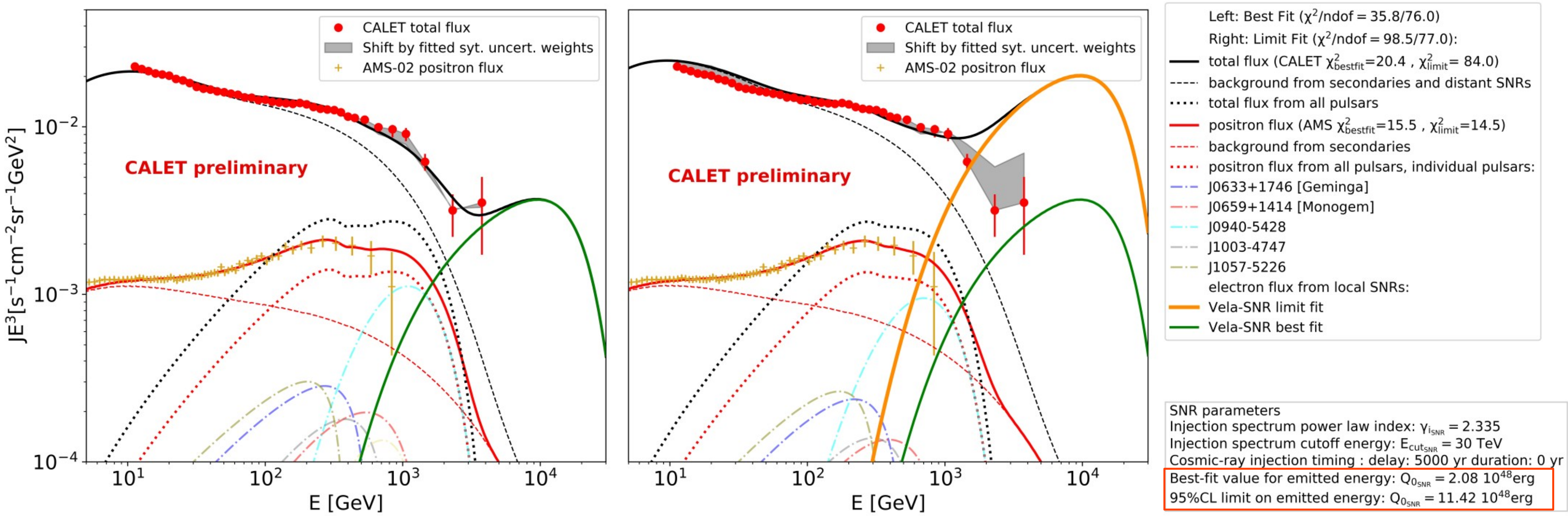
Spectral hardening by change of slope in diffusion coefficient → single power law injection spectrum → index assumed general property of acceleration, also used for nearby SNR electron spectra

Model X simultaneously explains proton and helium spectra with same injection spectral index (position dependent diffusion + diffusive re-acceleration)

Studied Parameter Space

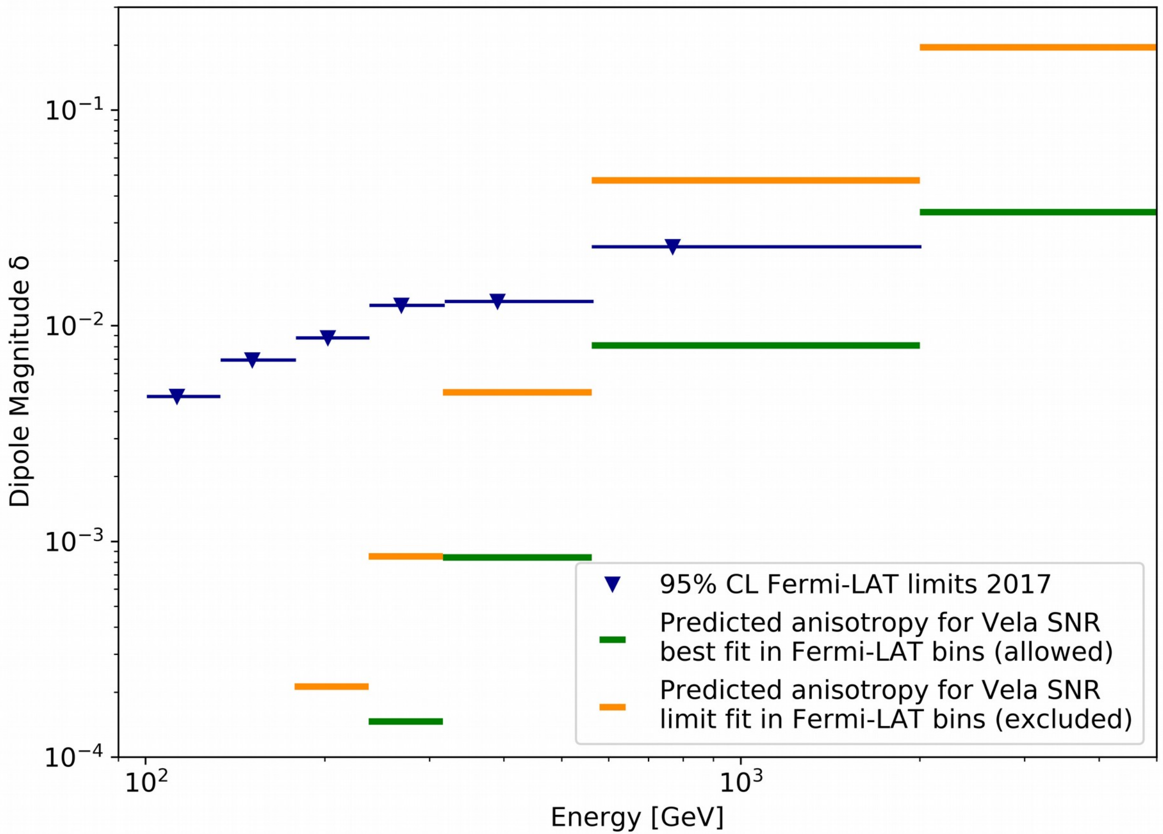
- 4 Propagation Models: X,A,B,C
- 2 Generic scenarios for the release of the cosmic rays from the SNR:
  - Continuous for a duration
  - Burst-like with a delay
- Values for duration/delay: 0, 1, 2, 5, 10 kyr
- Range of cut-off energies: 10, 20, 30, 50, 100, 200 TeV
- 2 Studies: Vela-only and three nearby SNR (Vela, Monogem, Cygnus Loop)

Fit with only Vela as nearby SNR



- Example Case: 5000 year delay then burst-like release, 30 TeV cut-off, propagation Model X
- **Best fit:** Flexible scale factor for the Vela spectrum to find best value for $Q_{0,SNR}$
- Flexible parameters of background (secondaries, distant SNR, pulsars)
- **Limit Fit:** Increase ($Q_{0,SNR}$) until the fit is excluded at 95% CL → limit value of $Q_{0,SNR}$

Comparison of Predicted Anisotropy with Fermi-LAT Anisotropy Limit



Predicted anisotropy for the best fit (green) below the **Fermi-LAT limit**
→ allowed

Predicted anisotropy for the limit fit (orange) above **Fermi-LAT limit**
→ Fermi-LAT anisotropy limit is better than the CALET spectrum limit on $Q_{0,SNR}$

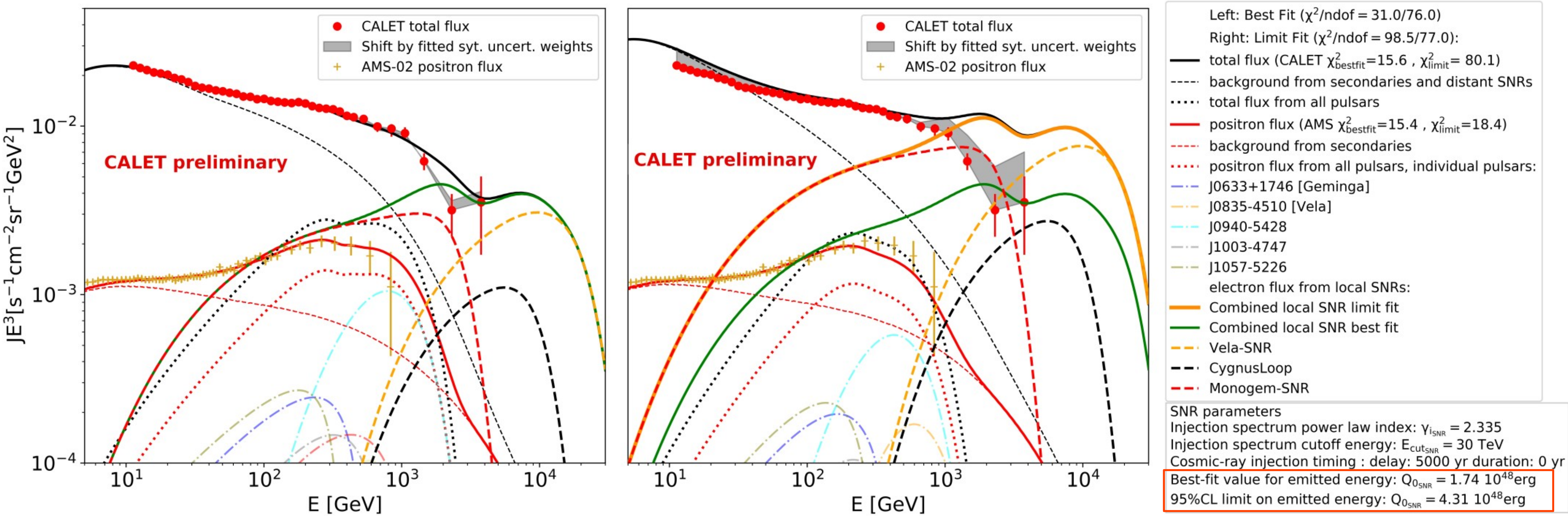
Fermi-LAT anisotropy limits from :
S. Abdollahi, et al. ,
Phys. Rev. Lett. 118, 091103 (2017).

Results with only Vela

Model	duration [kyr]					delay [kyr]			
	0	1	2	5	10	1	2	5	10
	Best-Fit Q_0 [10^{48} erg]								
X	0.37 – 0.58	0.44 – 0.58	0.43 – 0.65	0.52 – 0.76	0.93 – 1.33	0.54 – 0.79	0.47 – 0.67	1.84 – 2.59	2875 – 4037
A	0.35 – 0.49	0.34 – 0.48	0.33 – 0.48	0.33 – 0.46	0.42 – 0.59	0.36 – 0.51	0.32 – 0.46	0.42 – 0.60	5.68 – 8.10
B	0.55 – 0.78	0.52 – 0.77	0.50 – 0.71	0.44 – 0.62	0.37 – 0.53	0.51 – 0.72	0.45 – 0.65	0.37 – 0.54	0.55 – 0.77
C	0.70 – 1.01	0.92 – 1.01	0.62 – 1.02	0.57 – 0.83	0.41 – 0.61	0.58 – 0.92	0.58 – 0.85	0.43 – 0.65	0.37 – 0.51
	95%CL-Limit Q_0 [10^{48} erg]								
X	1.83 – 2.44	1.92 – 2.56	2.04 – 2.71	2.63 – 3.47	4.62 – 6.10	2.59 – 3.41	2.35 – 3.10	10.6 – 13.9	21365 – 28612
A	1.40 – 1.75	1.39 – 1.74	1.38 – 1.74	1.40 – 1.79	1.87 – 2.43	1.50 – 1.91	1.37 – 1.73	2.00 – 2.62	41.3 – 56.2
B	2.06 – 2.48	1.98 – 2.38	1.90 – 2.29	1.68 – 2.05	1.60 – 2.00	1.92 – 2.34	1.75 – 2.12	1.57 – 1.94	3.19 – 4.17
C	2.73 – 3.27	2.60 – 3.12	2.48 – 2.97	2.11 – 2.54	1.73 – 2.13	2.47 – 2.97	2.25 – 2.70	1.74 – 2.11	1.88 – 2.42

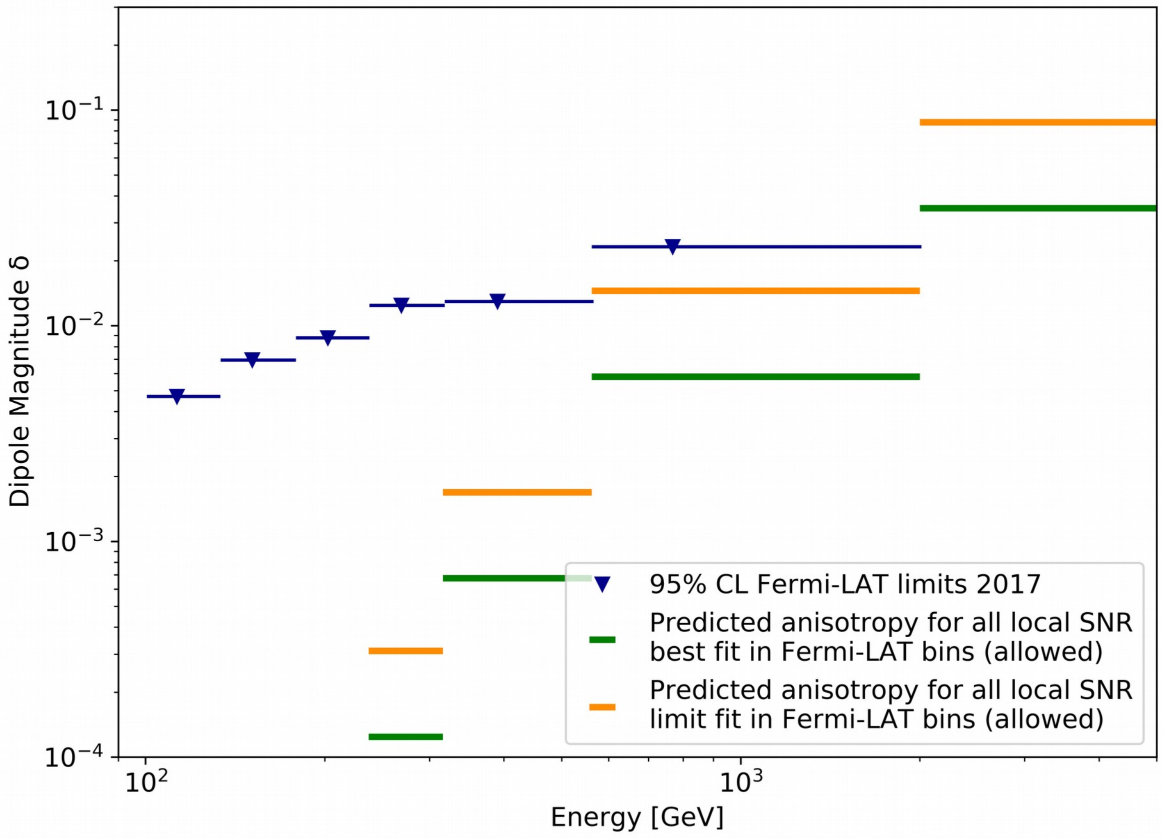
- Each cell shows the range of Q_0 for variation of the cut-off energy (mostly 10 TeV - high, 200 TeV – low)
- **Best fit values** for most conditions are several 10^{47} erg
- Exception: Delayed emission (5-10 kyr), slow diffusion (Model X, A) → above 10^{48} erg
- Fermi-LAT anisotropy: Model X, A all allowed, Model B partly, Model C excluded
- **Limit values** for most conditions are a few 10^{48} erg , exception cases: above 10^{49} erg
- For all cases, limits from Fermi-LAT anisotropy are better than these limits from the CALET spectrum

Fit with all three nearby SNR



- Example Case: 5000 year delay then burst-like release, 30 TeV cut-off, propagation Model X
- Monogem and Cygnus Loop SNR added
- All three SNR assumed to have same Q_0 and injection conditions
- Difference in spectra from position and age dependence

Comparison of Predicted Anisotropy with Fermi-LAT Anisotropy Limit



Predicted anisotropy for the best fit (green) below the **Fermi-LAT limit**
→ allowed

Predicted anisotropy for the limit fit (orange) also below the **Fermi-LAT limit**
→ CALET spectrum limit on $Q_{0,SNR}$ is better than the Fermi-LAT anisotropy limit

Fermi-LAT anisotropy limits from :
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Results with all three nearby SNR

Model	duration [kyr]					delay [kyr]			
	0	1	2	5	10	1	2	5	10
	Best-Fit Q_0 [10^{48} erg]								
X	0.33 – 0.50	0.35 – 0.57	0.36 – 0.55	0.44 – 0.71	0.70 – 1.21	0.43 – 0.70	0.41 – 0.67	1.38 – 2.23	2.05 – 3.17
A	0.27 – 0.40	0.27 – 0.37	0.26 – 0.39	0.25 – 0.37	0.31 – 0.45	0.28 – 0.41	0.25 – 0.38	0.31 – 0.45	1.08 – 1.70
B	0.40 – 0.61	0.40 – 0.59	0.38 – 0.57	0.34 – 0.50	0.29 – 0.45	0.39 – 0.56	0.35 – 0.51	0.30 – 0.44	0.39 – 0.58
C	0.54 – 0.81	0.52 – 0.86	0.50 – 0.73	0.43 – 0.66	0.33 – 0.50	0.51 – 0.71	0.43 – 0.68	0.35 – 0.53	0.29 – 0.40
	95%CL-Limit Q_0 [10^{48} erg]								
X	1.38 – 1.89	1.44 – 1.97	1.52 – 2.09	1.85 – 2.55	2.67 – 3.58	1.85 – 2.55	1.70 – 2.34	3.94 – 5.05	4.82 – 5.63
A	1.32 – 1.05	1.05 – 1.33	1.05 – 1.33	1.07 – 1.38	1.34 – 1.77	1.12 – 1.44	1.03 – 1.32	1.41 – 1.89	4.62 – 6.43
B	1.48 – 1.78	1.45 – 1.75	1.40 – 1.70	1.26 – 1.55	1.20 – 1.50	1.40 – 1.70	1.29 – 1.56	1.17 – 1.45	1.83 – 2.44
C	1.91 – 2.30	1.89 – 2.26	1.81 – 2.17	1.58 – 1.90	1.33 – 1.63	1.78 – 2.13	1.64 – 1.96	1.32 – 1.59	1.34 – 1.75

- Each cell shows the range of Q_0 for variation of the cut-off energy (mostly 10 TeV - high, 200 TeV – low)
- **Best fit values** for most conditions are several 10^{47} erg (generally a bit lower than for Vela alone)
- Exception: Delayed emission (5-10 kyr), slow diffusion (Model X, A) → above 10^{48} erg
- Fermi-LAT anisotropy: Model X, A all allowed, Model B mostly allowed, Model C a few cases allowed (dipole anisotropy from the three SNR partly cancels each other)
- **Limit values** for most conditions are a few 10^{48} erg , exception cases: around 5×10^{48} erg
- For these exception cases, limits from the CALET spectrum are better than Fermi-LAT anisotropy limits

Result Summary and Outlook

- CALET data is compatible with the hypothesis of 10^{48} erg for the emitted energy in electron CR above 1 GeV
- For a wide range of propagation conditions and injection timing:
  - Best fits for the emitted energy are several 10^{47} erg
  - Limits are a few 10^{48} erg
- Exception Cases: Delayed emission (5-10 kyr), slow diffusion → only highest energy electrons from Vela can arrive at Earth
  - A few 10^{48} erg best fit energy (if considering all three SNR)
  - ~ 5×10^{48} erg limits (if considering all three SNR)

  These limits are better than those from Fermi-LAT Anisotropy
- Future extension of CALET electron spectrum beyond 5 TeV should constrain the parameter space significantly, possibly show a signature of Vela

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