Interpretation of the CALET Electron+Positron Spectrum by Astrophysical Sources

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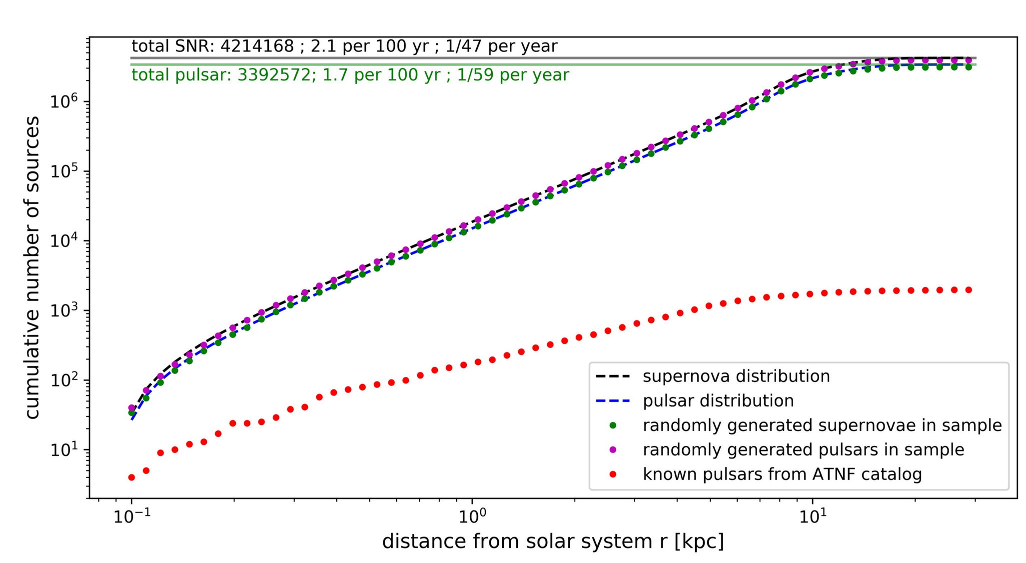
Abstract

The ISS-based Calorimetric Electron Telescope (CALET) is directly measuring the energy spec trum of electron+positron cosmic rays up to 20 TeV. Supernova remnants (SNR) are the most likely astrophysical sources to provide the majority of the electron flux, out of which a few nearby young SNR like Vela are expected to dominate in the TeV-region with potentially detectable spectral signatures. Another expected contribution to the spectrum is from pulsars as a primary positron-electron pair source for explanation of the positron excess. Complementary to the CALET all-electron spectrum, the positron-only spectrum measured by the magnet spectrometer AMS-02 below the TeV range provides detailed information on this component. An interpretation of the CALET and AMS-02 data by overlapping spectra from individual pulsar and SNR point sources is presented, combining sources known from electromagnetic wave observations with further randomly generated ones spread throughout the galaxy. Based on the study of a large number of samples with randomized source locations and emission spectra parameters, best fitting ranges and constraints for these parameters, as well as predictions for the spectrum beyond the so far measured energy range have been derived.

Constructing 85 random samples of the SNRs and pulsars in the Galaxy



Distribution of astrophysical sources as a function of distance from the solar system, about 7.5 million randomly generated sources

For each sample, properties of sources are randomly generated (pulsars first → add SNR to each pulsar → add more SNRs without pulsar):

- Position: SNR and pulsars follow spatial distribution from Ref. [1]
- Age: Flat distribution up to 200 Myr for spectrum down to 2 GeV
- Kinetic energy (SN explosion, pulsar rotation)
  - $Q_{SNR} = 10^{51\pm1}$ erg, log-Gaussian spread
  - $Q_{pulsar} = 10^{49.3\pm1.01}$ erg , log-Gaussian spread, fit to energies from ATNF catalog pulsars, calculate energy as $Q_{pulsar} = \dot{Q}\, T^2/\tau$; τ = 10 kyr
- Release delay time (time CR are trapped in pulsar wind nebula) for pulsar s up to 60 kyr in steps of 10 kyr (SNR: instant emission)

Known pulsars and associated SNR from ATNF catalog added, random sources in same distance and age bin removed if existing in the sample.

After fixing above source properties, the below source parameters are randomized and the averages adjusted, which is repeated until a good fit to AMS-02 and CALET data is found or 1000 trials have been completed:

- efficiency of electron CR acceleration ($\eta_{(SNR)}$, $\eta_{(pulsar)}$)
  → log-Gaussian spread with width 0.33, max. factor 10 from average
- spectrum power-law index ($\gamma_{i(SNR)}$, $\gamma_{i(pulsar)}$)
  → Gaussian spread with width 0.033, maximum 0.1 from average
- cut-off energy ($E_{cut(SNR)}$, $E_{cut(pulsar)}$)
  → scanned over fixed values (same for all SNR / pulsars)

Electron / Positron Flux propagated to Earth calculated for fixed grid of cut-off energies and spectra indices for fitting to AMS-02 and CALET by semi-analytical method from Ref. [2]:

$$\Phi(E) = \frac{Q_0 \eta}{\pi^{3/2} r_{dif}^3} E_0^{-\gamma_i} e^{-\frac{E_0}{E_{cut}}} \frac{b(E_0)}{b(E)} e^{-\frac{r^2}{r_{dif}^2}} \qquad r_{dif} = \sqrt{\int_E^{E_0} \frac{D(E')}{b(E')} dE'}$$

$$t_i(E, E_0) = \int_E^{E_0} \frac{1}{b(E')} dE' \qquad b(E) = b_{IC}(E) + b_{SYN}(E)$$

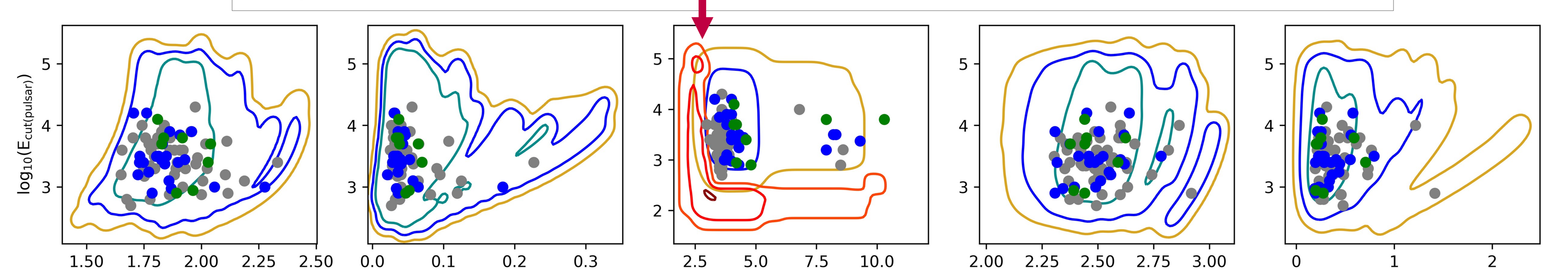
Energy loss coefficient includes synchrotron loss term $b_{SYN}(E)$ and inverse Compton loss term $b_{IC}(E)$, which includes Klein-Nishina effect

Propagation parameters taken from "A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra" (see neighboring poster)

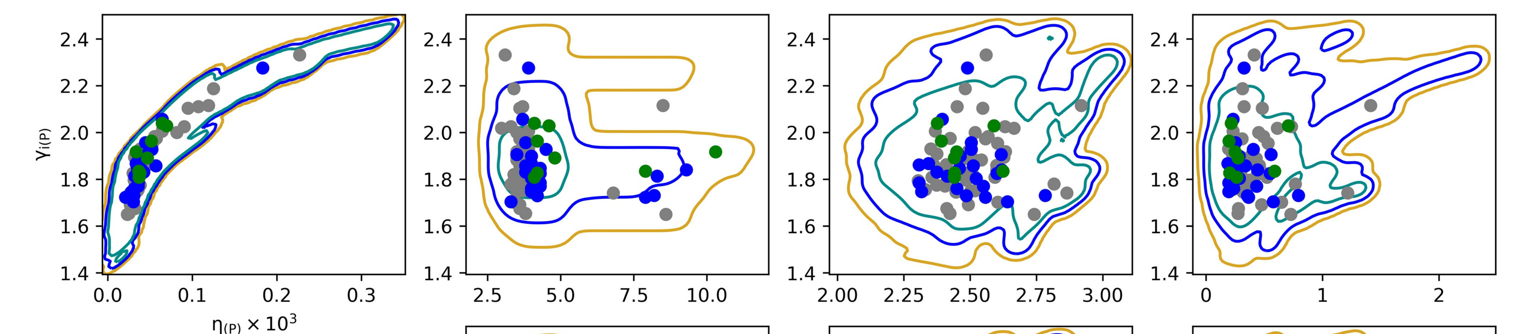
Main Result: Parameter space of average source spectrum parameters

This region in the $E_{cut(pulsar)} - E_{cut(SNR)}$ plane which was scanned,but in which χ^2 of all samples was found to be above the 90%CL threshold, can be considered disfavored.

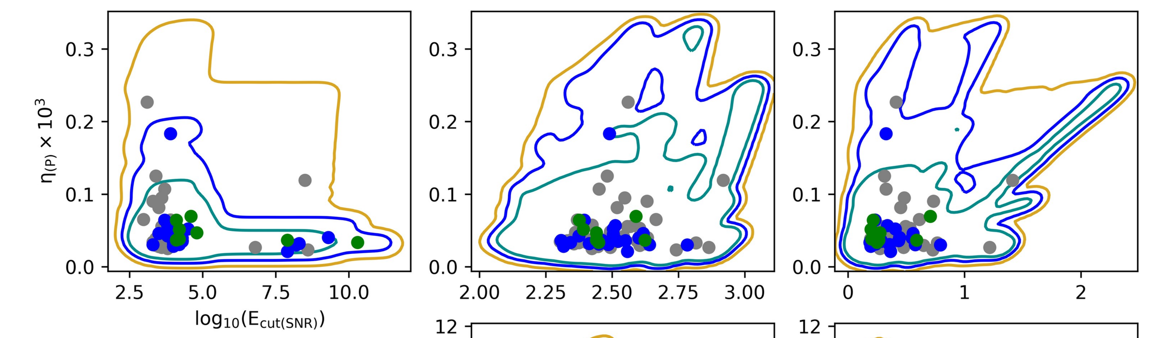
The pulsar cut-off energy covers a range of a few hundred GeV to around 100 TeV, with the best-fit cases between several hundred GeV and a few tens of TeV.



The pulsar source spectrum index is found to be generally harder than the SNR source spectrum index, covering a range of about 1.4 to 2.5, showing a strong correlation with the acceleration efficiency. $\eta_{(pulsar)}$ is found to be in the range of a few 10^{-5} , which is a realistic value for the acceleration efficiency.

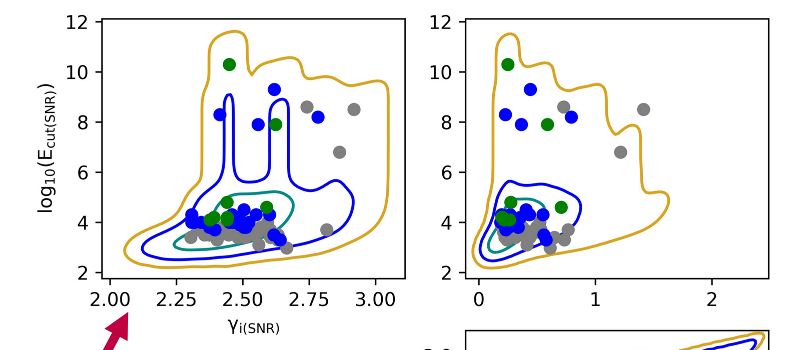


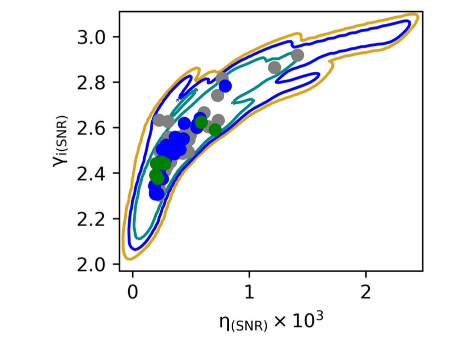
What is n? →To estimate possible outcomes of the CALET measurement above the current maximum energy, the number of events (n) that would be expected to be measured by CALET above 4.8 TeV was calculated for each sample, with detector livetime $2{\times}10^8$ seconds, 1040 cm² effective area and 80% reconstruction efficiency.



Parameter space covered by the well fitting models. Colored dots represent the best-fit locations, also indicating the prediction for events in CALET above 4.8 TeV. Gold-blue-cyan contours show theregions and sample density (by Gaussian kernel density estimation) where χ^2 <1 -limit, and red contours show the region where χ^2 > 90%-limit.

- best fit locations, n < 2
- best fit locations, 2 < n < 6
- best fit locations, n > 6
- n: expected events in CALET above 4.8 TeV
- 1 σ favored region KDE contour 0.01 level
- 1 σ favored region KDE contour 0.1 level
- 1 σ favored region KDE contour 0.5 level
- 90%CL disfavored region KDE contour 0.01 level
- 90%CL disfavored region KDE contour 0.1 level
- 90%CL disfavored region KDE contour 0.5 level





The SNR cut-off energy reaches from several hundred GeV to values of 10^{10} GeV. Such high cut-off values may not be realistic based on the magnetic confinement requirement in the acceleration region, but they indicate that the current electron and positron cosmic ray data provides no constraint on this parameter. However, the sampling indicates that the unbounded SNR cut-off requires the source index to be softer than 2.3, which may be understood from a harder index spectra cut-off only by energy loss creating spiky structures not compatible with the smoothness of the measurement.

The SNR source spectrum index covers a range of approximately 2 to 3, showing a strong correlation with the acceleration efficiency. A majority of samples clusters around $\eta_{(SNR)}$=5×10⁻⁴ or $5{\times}10^{47}$ erg of energy emitted in electron cosmic rays per SNR

Fitting of each sample's flux to CALET and AMS-02 data with examples

Data-sets used:

- CALET all-electron flux from ICRC2021 [3] from 10.6 GeV to 4.8 TeV
- AMS-02 positron-only flux [4] from 2 GeV to 1 TeV

Interpolated from pre-calculated fixed values as:

$$\Phi(\gamma_i) = \frac{\gamma_h - \gamma_i}{\gamma_h - \gamma_l} \Phi(\gamma_l) \left(\frac{E}{GeV}\right)^{\gamma_l - \gamma_i} + \frac{\gamma_i - \gamma_l}{\gamma_h - \gamma_l} \Phi(\gamma_h) \left(\frac{E}{GeV}\right)^{\gamma_h - \gamma_i}$$

Fit parameters:

- 6 source parameters → $\eta_{(SNR)}$, $\eta_{(pulsar)}$, $\gamma_{i(SNR)}$, $\gamma_{i(pulsar)}$, $E_{cut(SNR)}$, $E_{cut(pulsar)}$
- 4 Solar Modulation parameters
- 5 Systematic uncertainty weights (CALET)

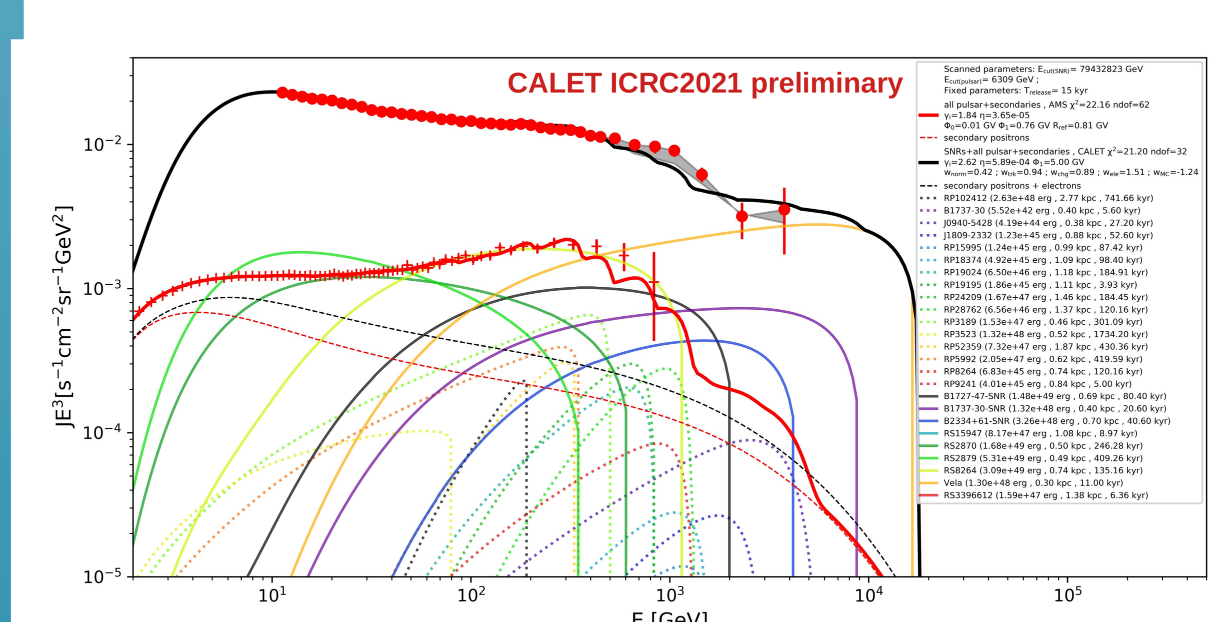
Each scanned in 10 logarithmic bins per decade, best fit values, 1σ region and 90% CL exclusion region from this scan shown above

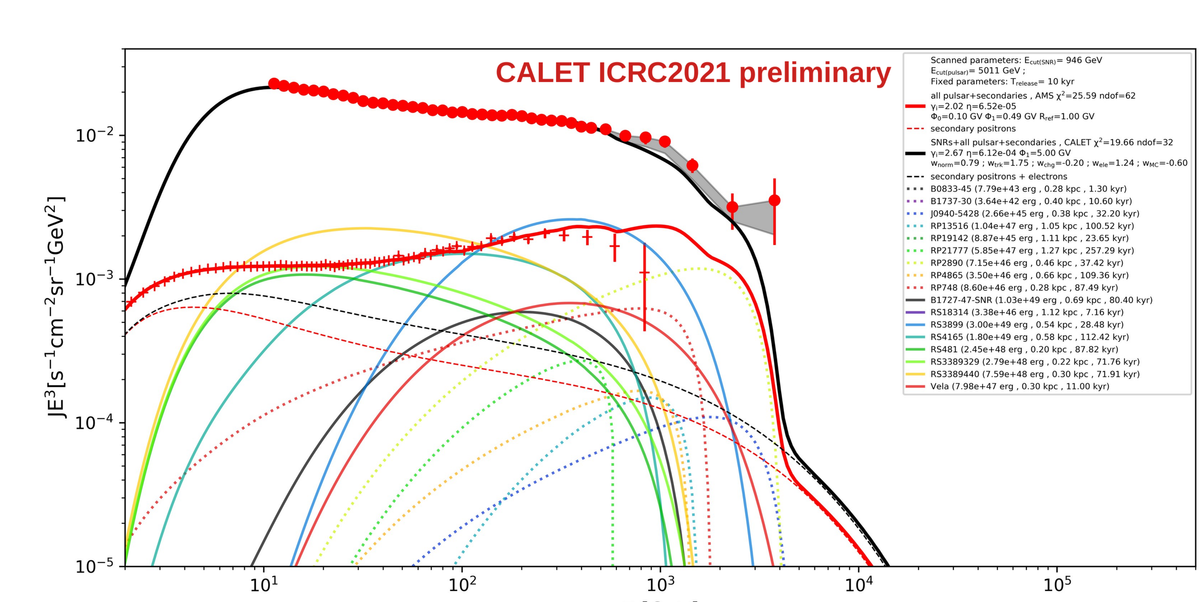
Rigidity and charge sign dependent solar modulation potential (inspired by Ref. [5]): $\Phi(R) = \Phi_0 + \Phi_{1\pm} \frac{1 + (R/R_r)^2}{(R/R_r)^3}$

For each systematic uncertainty source (normalization, tracking, charge selection, electron identification, Monte Carlo, model dependence), calculated energy dependent 1σ deviation $\Delta(E)$ → fit weight w for shift of fit function by $w\Delta(E)$ (gray area in fit plots below) → add squared weights to χ^2

Example fit with strong contribution from Vela in the TeV region, predicted number of events in CALET above 4.8 TeV: 9.4 (highest)

Example fit with sudden drop around 3-4 TeV, predicted number of events in CALET above 4.8 TeV: 0.04 (lowest)





Fit for two of the samples with the contributions of individual astrophysical sources contributing more than 5% to the flux at any energy shown. Details and parameter values in the legend. RP, RS denote randomly generated sources, others are known sources from the ATNF catalog.

References

[1] K. M. Ferrière, Rev. Mod. Phys. 73, 1031 (2001)

[2] K. Asano, et al., Astrophys. J. 926, 5 (2022).

[3] S. Torii, Y. Akaike, PoS ICRC2021, 105 (2021).

[4] M. Aguilar, et al., Phys. Rev. Lett. 122, 041102 (2019).

[5] I. Cholis et al., Phys. Rev. D 98, 063008 (2018).

Conclusion

The CALET all-electron and the AMS-02 positron-only flux measurements can be fit well by the overlapping spectra of randomly generated SNR and pulsar populations, if adjusting the average source spectrum parameters to the data by fitting, with the found fit parameters agreeing with common assumptions on the electron-positron cosmic ray origin. Future extensions of the CALET spectrum to higher energy may provide important information, as the current predictions for the above 4.8 TeV range leave a wide range of potential outcomes, with up to 9.4 events to be detected in CALET.

Acknowledgments

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