Investigating the Properties of Astrophysical Cosmic-ray Sources based on the CALET Electron+Positron Spectrum

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Introduction

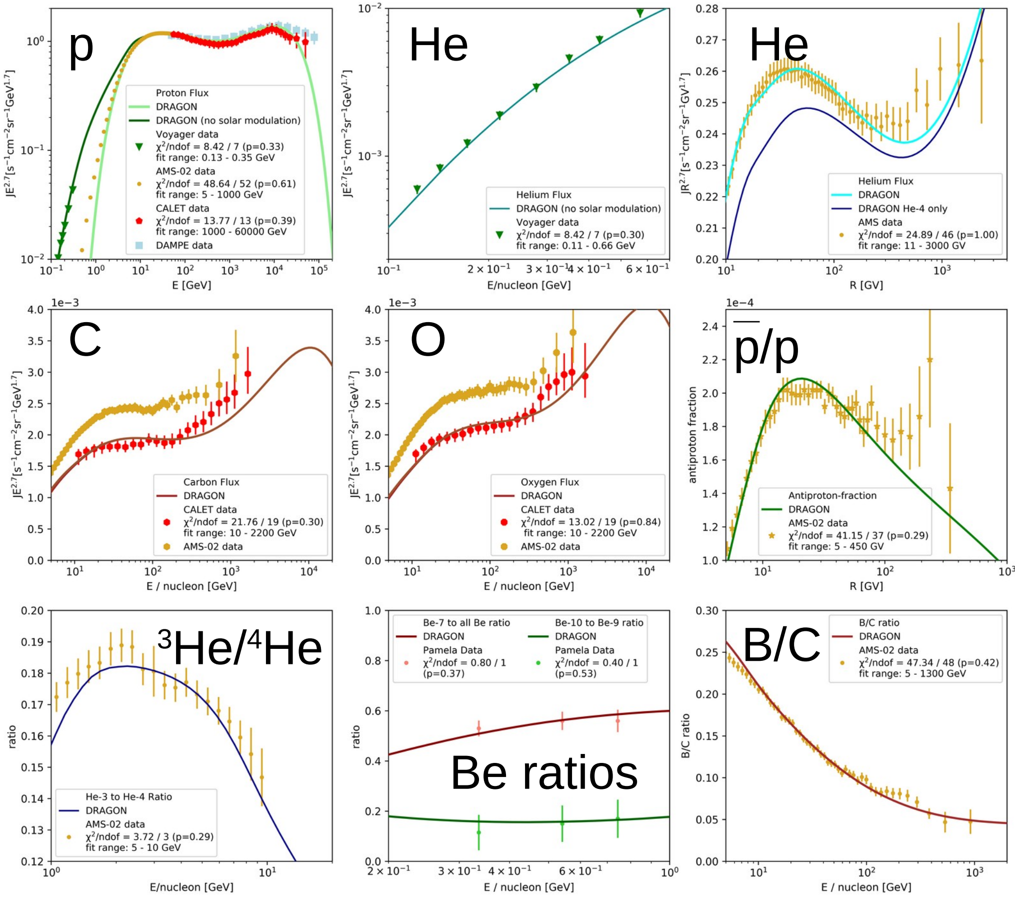
- Common assumption: Cosmic rays originate from shock-wave acceleration in supernova remnants (SNR)
  - Source spectrum index (before propagation) around two
  - About 10^{51} erg kinetic energy per supernova, conversion into cosmic rays with few percent efficiency
  - Electrons one order of magnitude lower than proton flux: 10^{48} erg in electron cosmic rays per SNR

- Investigated main question: Is the measured electron spectrum compatible with these assumptions?

- Data:
  - CALET all-electron flux shown at ICRC2021 over the full energy range from 10.6 GeV to 4.8 TeV
  - AMS-02 positron-only flux from 2 GeV to 1 TeV

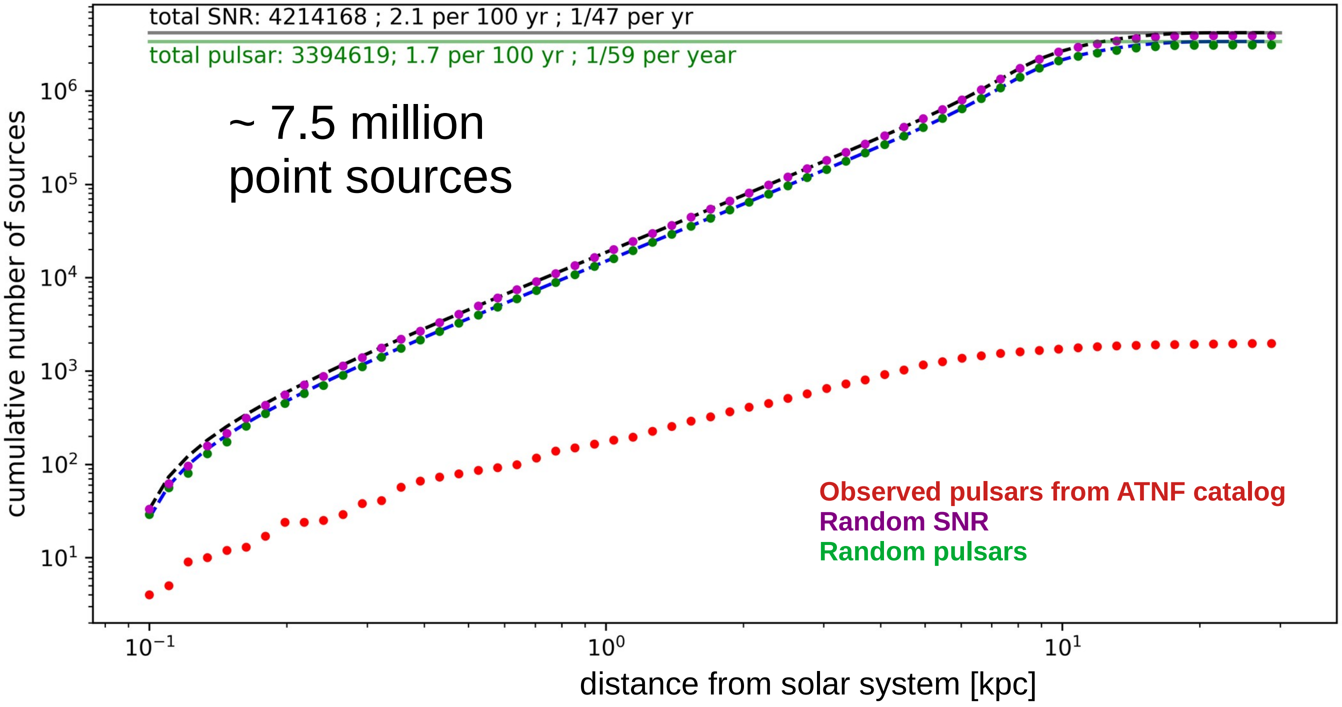
- Concept:
  - Calculate flux from random samples of individual SNRs and pulsars throughout the galaxy
  - Fit to the data by adjusting the average of source spectrum power-law indices $\gamma_{i(SNR)}$ and $\gamma_{i(pulsar)}$ and acceleration efficiencies $\eta_{(SNR)}$ and $\eta_{(pulsar)}$, scan cut-off energies $E_{cut(SNR)}$ and $E_{cut(pulsar)}$ in discrete values

Propagation Model



- Calculation of nuclei spectra with DRAGON tuned to explain measurements of AMS-02, CALET and Voyager.
- A common injection spectrum for all primary nuclei species is assumed, structures (hardening, softening) in the observed spectra are due to propagation effects from rigidity and position dependence of diffusion coefficient.
- Secondary electron and positron component of background for the dark matter limit fit also taken from this DRAGON calculation.
- Reference: HM, A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra, POS ICRC2023 068

Pulsar and SNR Sample Creation



For each of the studied samples, source properties are randomly generated (pulsars first → add SNR to each pulsar → add more SNRs without pulsar)

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

$$Q_{pulsar} = \dot{Q}\, T^2 / \tau \quad ; \quad \tau = 10\,kyr$$

Release delay time (time CR are trapped in pulsar wind nebula) for pulsars 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.

Spatial distribution and SN rate:

The interstellar environment of our galaxy, K. Ferriere, Rev.Mod.Phys. 73, 1031-1066 (2001) (same model as used in DRAGON for determining the propagation parameters)

Pulsar birth rate:

The galactic population of young γ-ray pulsar, Kyle P. Watters and Roger W. Romani, 2011 ApJ 727 123

Calculating the Flux at Earth from Pulsars and SNR

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

$$D(E) = D_{0(@sol)} \left(\frac{E}{E_0}\right)^{\delta_l} \left(1 + \left(\frac{E}{E_{bl}}\right)^{\frac{\delta_l - \delta}{s_l}}\right)^{s_l} \left(1 + \left(\frac{E}{E_{bh}}\right)^{\frac{\delta - \delta_h}{s_h}}\right)^{-s_h}$$

$b(E) = b_{IC}(E) + b_{SYN}(E)$ (IC takes Klein-Nishina effect into account)

source spectrum parameters: efficiency η, index γ, cut-off energy E_{cut}

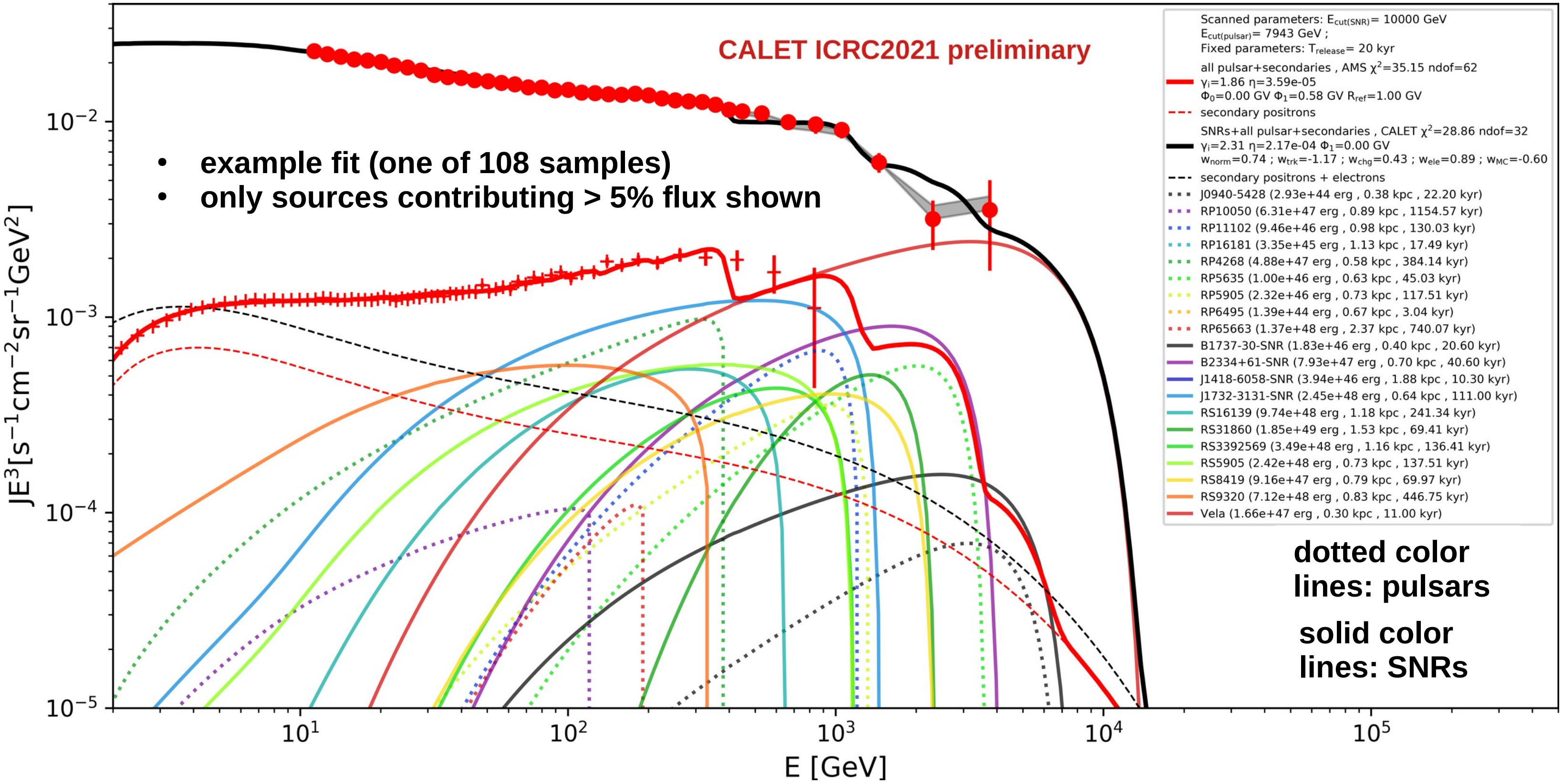
source properties: total energy Q_0, distance r, diffusion time t_{dif}

propagation parameters: $D_0, \delta, \delta_l, \delta_h, E_{bl}, E_{bh}, s$

- Calculation method adopted from K. Asano et al. 2022 ApJ 926 5

semi-analytic calculation for 7.5 million sources not feasible inside the fitting procedure
→ combined flux of all sources pre-calculated for several indices
→ interpolation used in the fitting procedure to quickly get the flux for any index value
→ injection spectrum cut-off energies are scanned parameters (10 bins per decade on log scale)

Fit to CALET and AMS-02



- Source spectrum index spread with Gaussian distribution (σ=0.033)
- Efficiency spread with log-Gaussian distribution (σ=0.33), max factor 10
- Distributions re-rolled until good fit (or 1000 attempts)
- Free parameters:
  - average SNR index $\gamma_{i(S)}$
  - average SNR efficiency η_S
  - average pulsar index $\gamma_{i(P)}$
  - average pulsar efficiency η_P
  - solar modulation (4)
  - weights for energy dependent systematic uncertainties of CALET spectrum (5)
- Scanned parameters:
  - pulsar cut-off $E_{cut(pulsar)}$
  - SNR cut-off $E_{cut(SNR)}$

Charge sign and rigidity depended solar modulation potential based on Ilias Cholis, Dan Hooper, Tim Linden Phys. Rev. D 93, 043016 (2016) “A Predictive Analytic Model for the Solar Modulation of Cosmic Rays”

$$\Phi = \Phi_0 + \Phi_{1\pm} \left(\frac{1+(R/R_0)^2}{((R/R_0)^3)} \right)$$

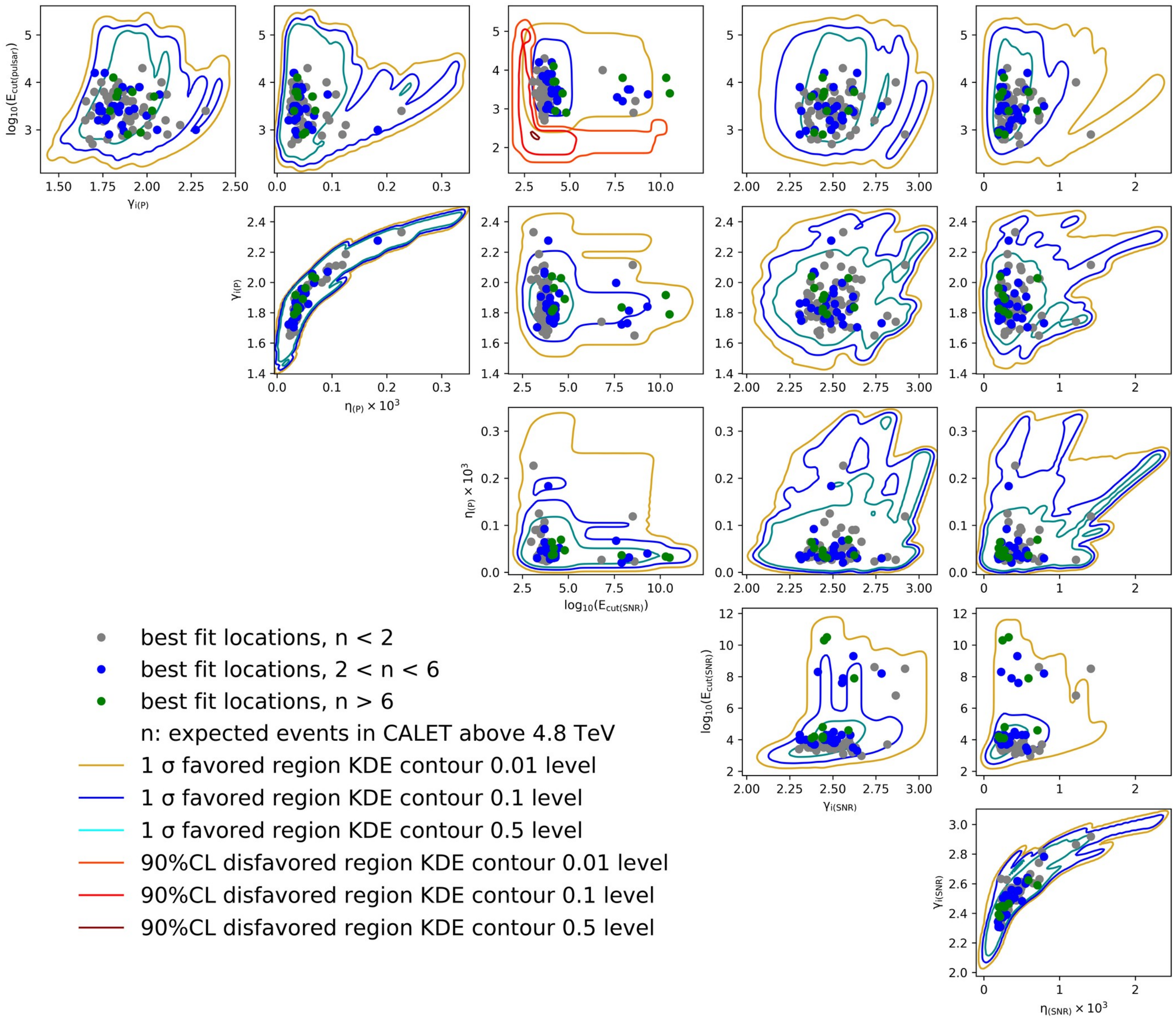
4 parameters:
Φ_0, Φ_{1+} (positive charge),
Φ_{1-} (negative charge), R_0

Parameter Space

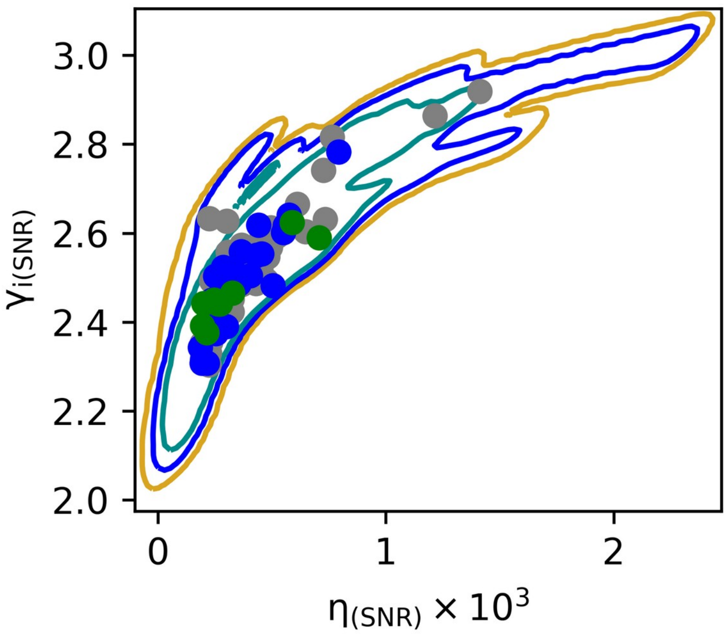
Parameter space covered by the 108 well fitting models.

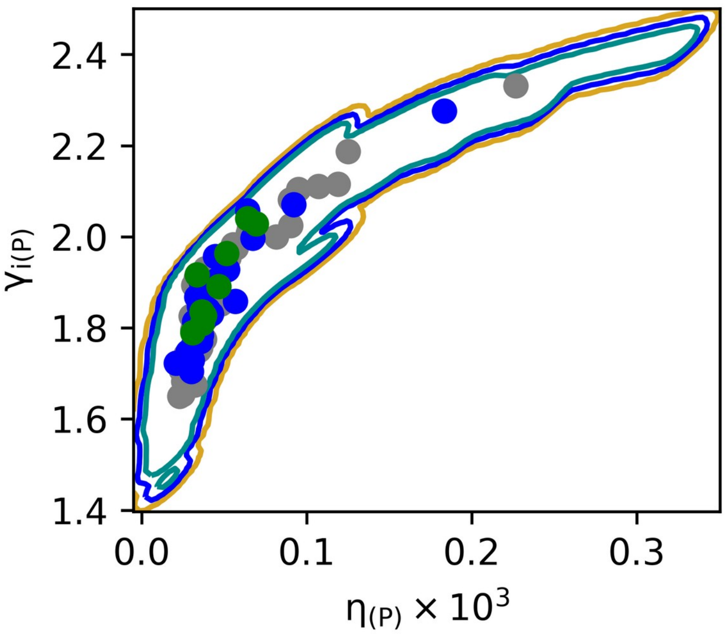
Colored dots represent the best-fit locations, also indicating the prediction for events in CALET above 4.8 TeV.

Gold-blue-cyan contours show the regions and sample density (by Gaussian kernel density estimation) where χ^2 <1 - limit, and red contours show the region where χ^2 > 90%-limit.



Correlation Efficiency – Index

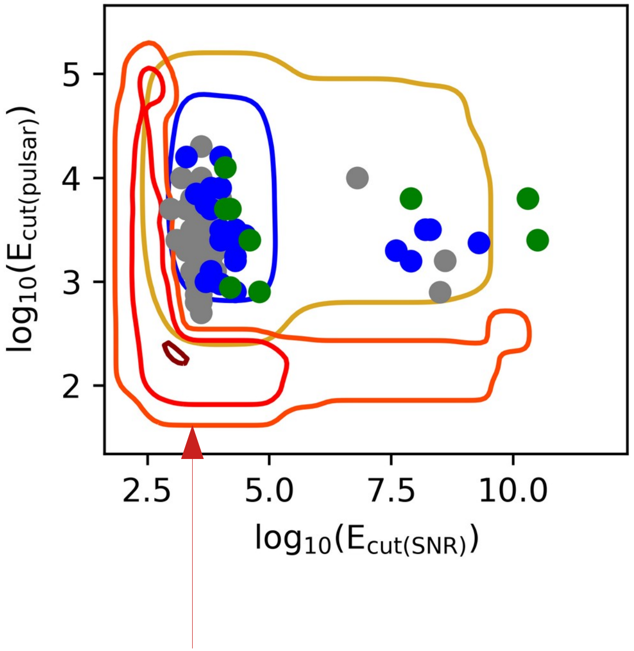


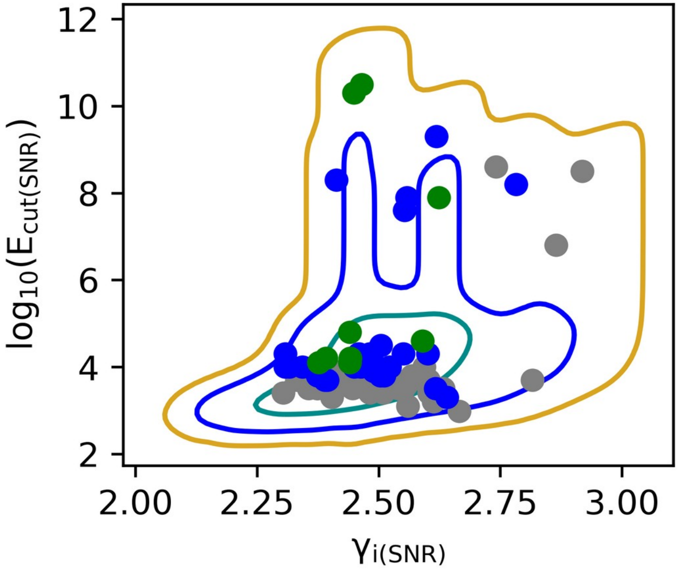


- SNR source spectrum index covers a range of approximately 2 to 3
- strong correlation with acceleration efficiency
- A majority of samples clusters around $\eta_{(SNR)}$=5×10⁻⁴ or 5×10⁴⁷ erg of energy emitted in electron cosmic rays per SNR

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

Cut-off Energy Ranges





This red 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.

SNR cut-off energy from several hundred GeV to ~10^{10} GeV.

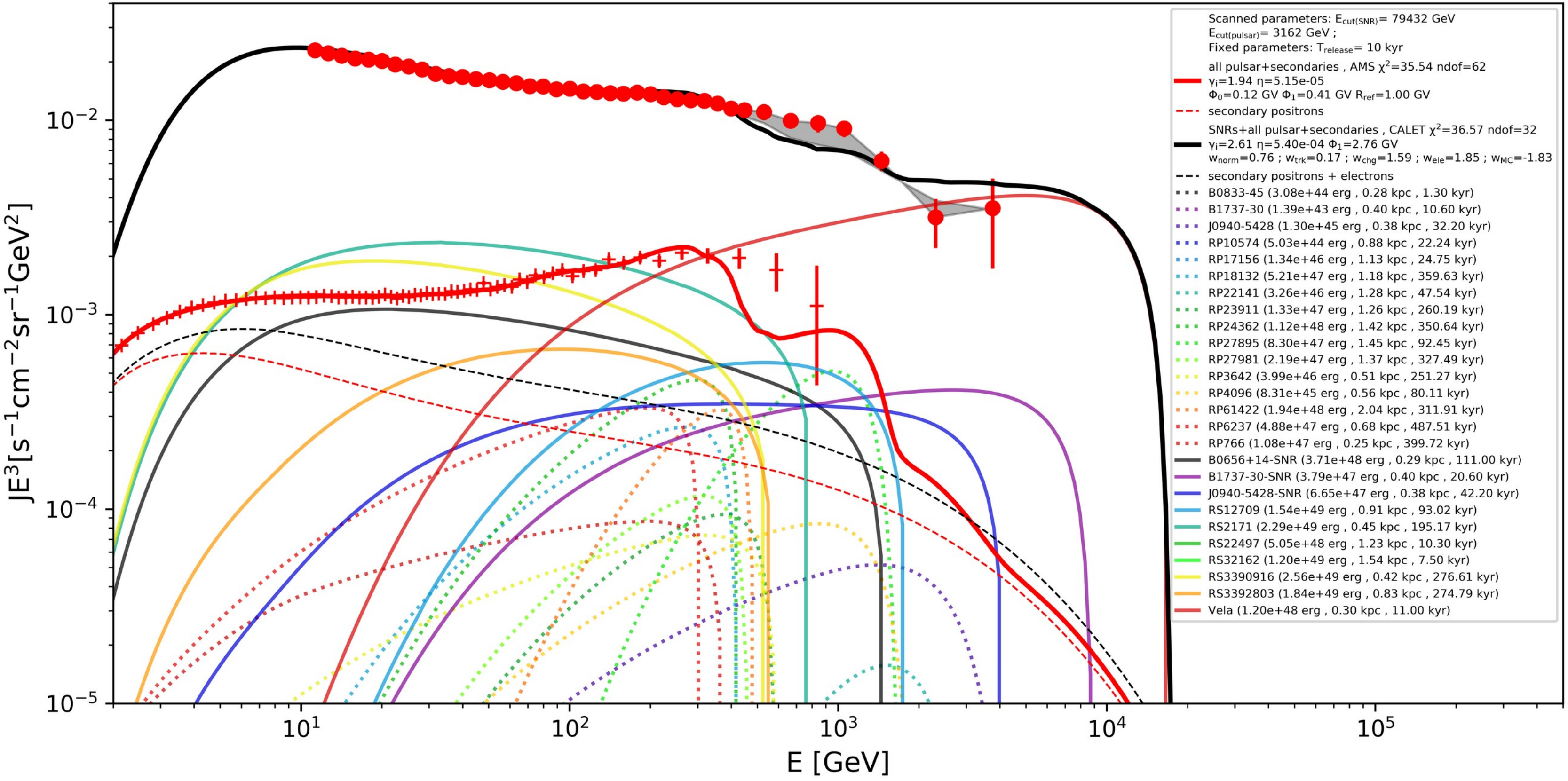
Highest values not realistic (magnetic confinement requirement) but no constraint from current electron and positron cosmic ray data on this parameter.

The unbounded SNR cut-off requires the source index to be softer than 2.3

Harder spectra would be cut-off only by energy loss → spiky structures not compatible with the smoothness of the measurement

Predictions for CALET above 4.8 TeV

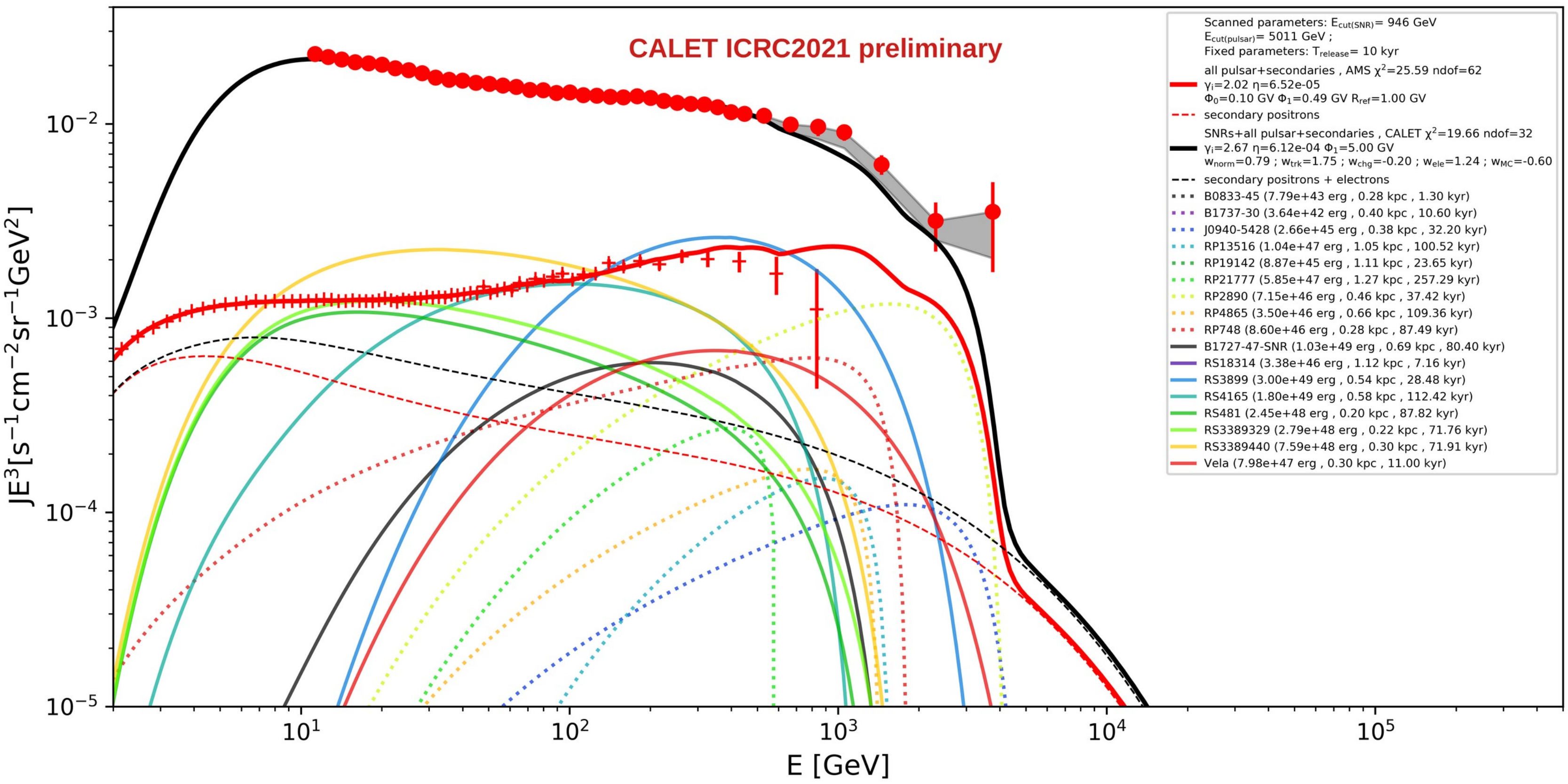
Example fit with strong contribution from Vela in the TeV region, predicted number of events in CALET above 4.8 TeV: 11.9 (highest):



- detector live-time 2×10^8 seconds
- 1040 cm^2 effective area
- 80% analysis efficiency

Predictions for CALET above 4.8 TeV

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



- detector live-time 2×10^8 seconds
- 1040 cm^2 effective area
- 80% analysis efficiency

Conclusions

- The CALET all-electron and the AMS-02 positron-only flux 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.
- The found fit parameters from 108 studied samples agree with the 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 11.9 events expected to be detected in CALET with $2\ 10^8$ seconds of live-time.

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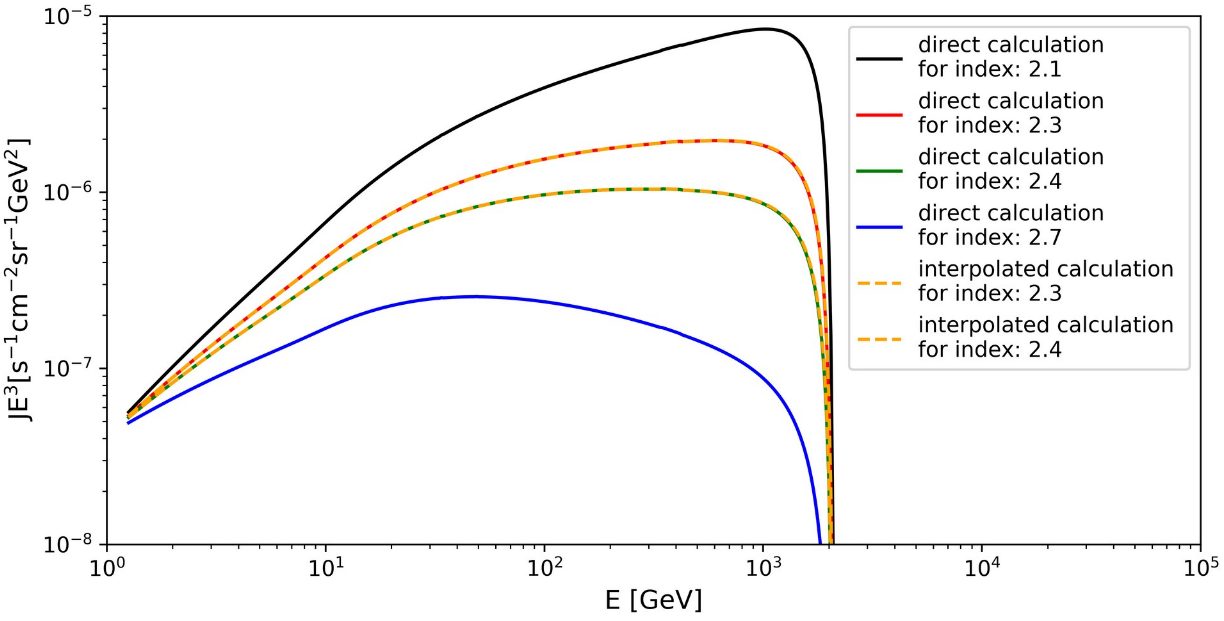
Backup Slides

Spectrum Interpolation (Index)

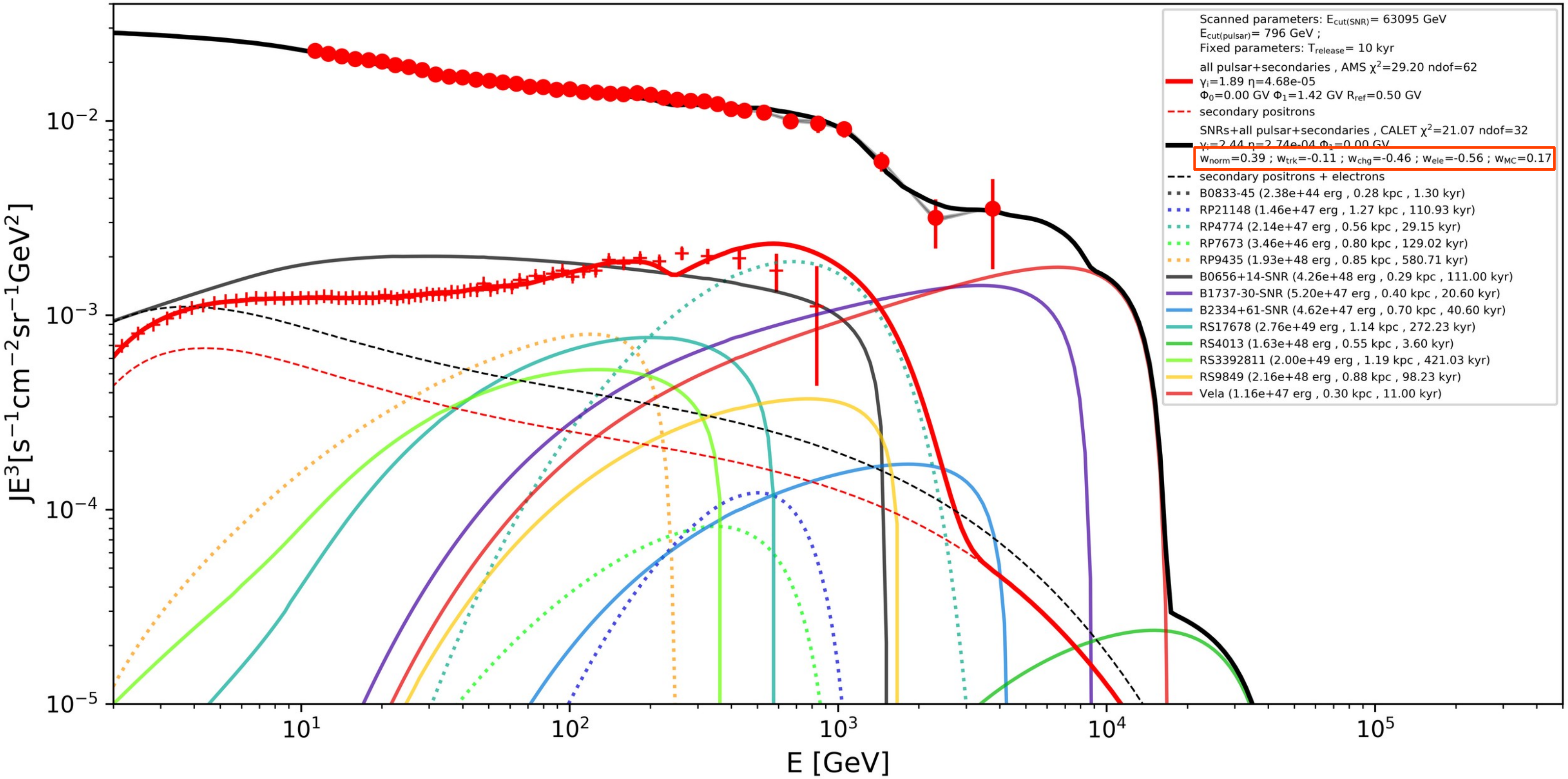
- Calculating the propagated spectrum for 7.5 million sources takes several minutes → not feasible to put this through a minimizer
- Solution: Calculate spectrum for selected values, compensate for the index difference and interpolate to get intermediate values:



$$F(\gamma)=\frac{\gamma_2-\gamma}{\gamma_2-\gamma_1}F(\gamma_1)\left(\frac{E}{GeV}\right)^{\gamma_1-\gamma}+\frac{\gamma-\gamma_1}{\gamma_2-\gamma_1}F(\gamma_2)\left(\frac{E}{GeV}\right)^{\gamma_2-\gamma}$$

Treatment of systematic errors

- The spectrum measured by CALET has systematic errors with known energy dependence
- Instead of adding the systematic error quadratically to the systematic error, the data is shifted systematically by the function Δ calculated in the same way as those in the S.M. of Phys. Rev. Lett. 120, 261102 (2018) with the normalization coefficients as fitted nuisance parameters
- The systematic uncertainties of Normalization, Tracking, Charge Selection, Electron Identification and Monte Carlo are fitted in this way,
- The squared weight of each uncertainty is added to the total χ^2 of the fit, while the fitting function is shifted as represented by the gray area.



$$\chi^2_{CALET} = \left(\sum_i \frac{\left(\phi_i + \sum_k \Delta_k w_k - J_i\right)^2}{\sigma_i^2} \right) + \sum_k w_k^2$$

i: data point index
k: uncertainty type index