Constraints on the Emission of Electron Cosmic Rays by the Vela SNR from CALET Data

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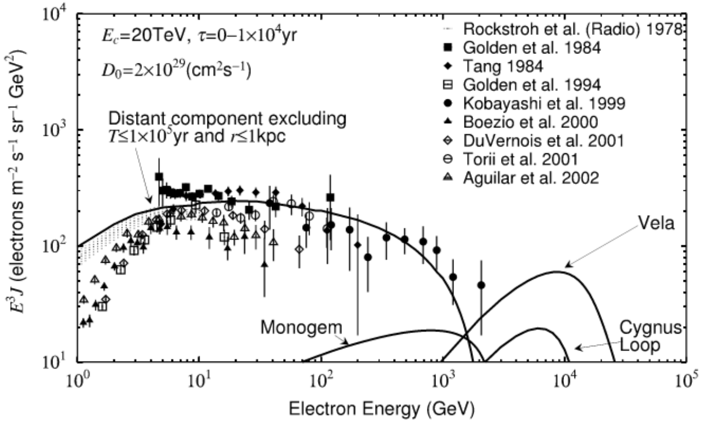
Introduction

- T. Kobayashi et al 2004 ApJ 601 340, “The Most Likely Sources of High-Energy Cosmic-Ray Electrons in Supernova Remnants” establishes that the Vela SNR (age 12kyr, distance 0.3 kpc) should be the dominating source for the electron flux in the TeV region, with a total energy in the order of 10^{48} erg emitted as CR electrons above 1 GeV energy.



→ What is the best fitting value for this total energy Q_0 and the limits on it from currently published CALET data, assuming propagation conditions based on the recent CR nuclei measurements?

- Vela dominates in the TeV region, but also contributes in the range of several 100 GeV, overlapping with the source of the positron excess → minimum background guaranteed by the positron flux → combined analysis of CALET electron+positron and AMS-02 positron-only data

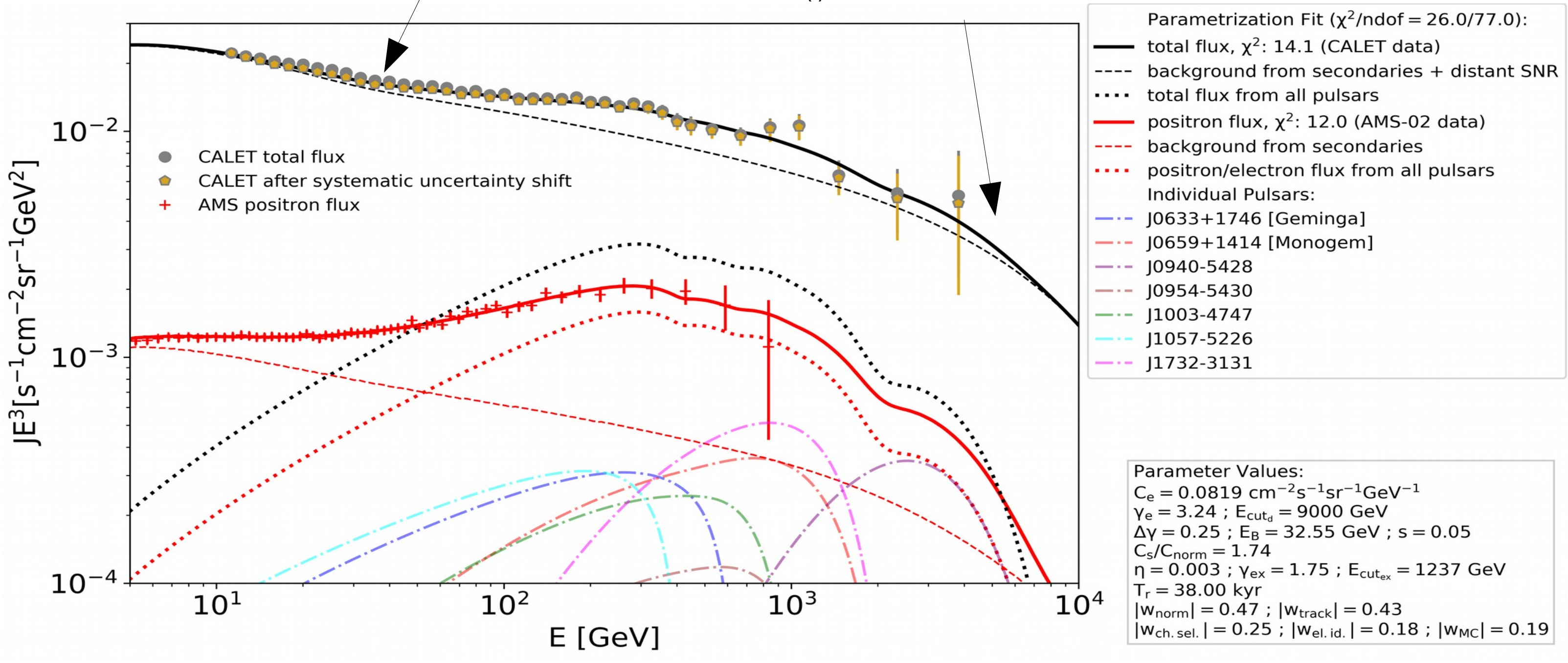
Model for Electron/Positron Spectra

Primary electron spectrum with low-energy spectral break and exponential cut-off, secondary electrons, secondary positrons, extra pulsar source for positron excess

$$\Phi_{ele} = C_e E^{-(\gamma_e - \Delta\gamma_e)} \left(1 + \left(\frac{E}{E_B}\right)^{\frac{\Delta\gamma_e}{s}}\right)^s e^{-\left(\frac{E}{E_{cut_d}}\right)} + C_s \Phi_{s(e^-)} + \Phi_{ex} \;;\; \Phi_{pos} = C_s \Phi_{s(e^-)} + \Phi_{ex} \;;\; \Phi_{tot} = \Phi_{ele} + \Phi_{pos}$$

Smooth break in the **primary electron spectrum**

Exponential cut-off of **primary electron spectrum** from energy loss, not well constrained by data → scan values of **$E_{cut(d)}$ in [1 TeV, 10 TeV]**



Combined model is fitted to **CALET data** and AMS-02 positron flux for E>10GeV (solar modulation treated by force field approximation with potential Φ = 0.5 GV)

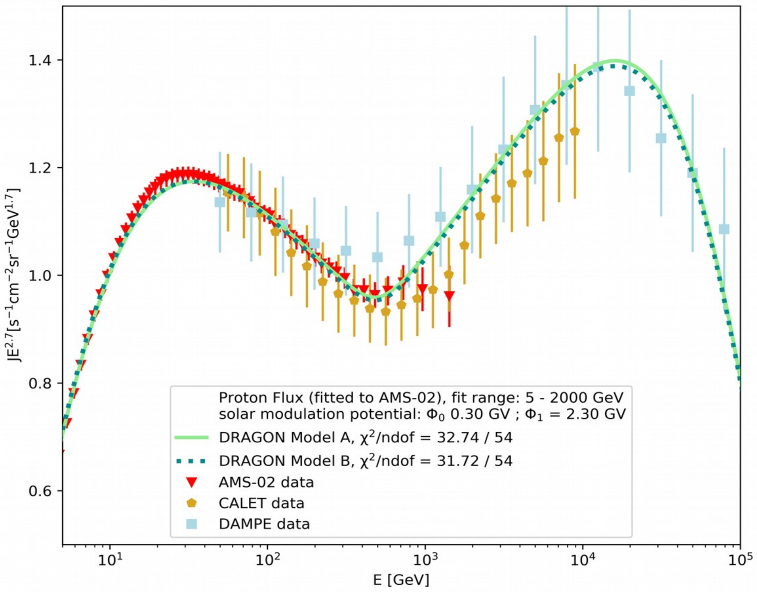
Weights for systematic uncertainties with known energy dependence of CALET spectrum fitted as extra (nuisance) parameters

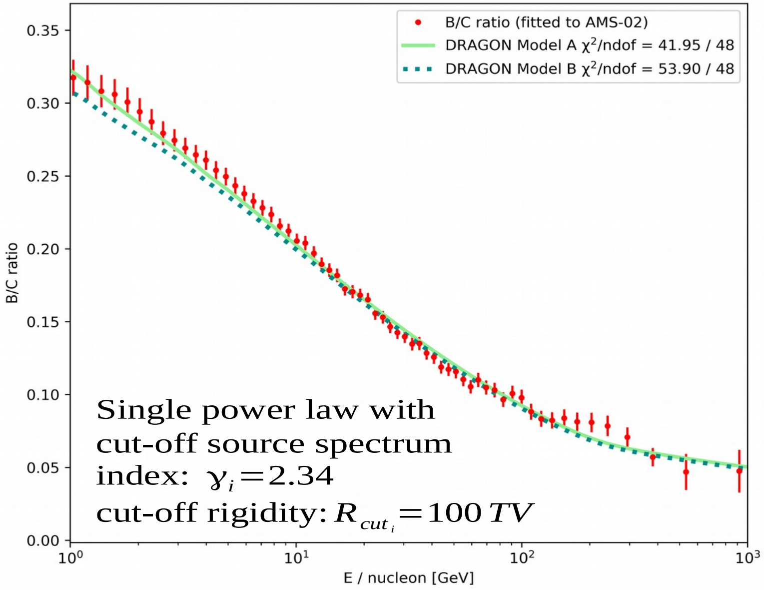
CALET data (2018):
O. Adriani et al.
Phys. Rev. Lett. 120, 261102

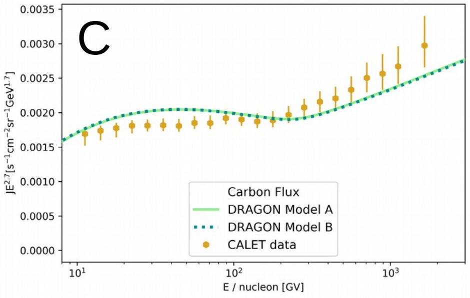
AMS-02 data (2019):
M. Aguilar et al.
Phys. Rev. Lett. 122, 041102

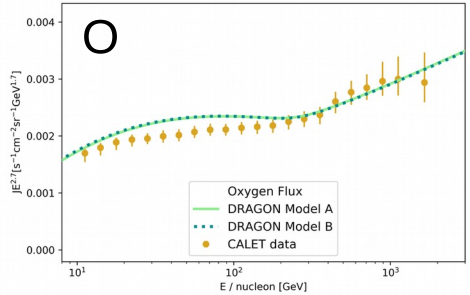
Propagation Model(s)

- Calculation with DRAGON tuned to explain nuclei measurements (proton flux and B/C ratio), general agreement with CALET C and O spectra
- Spectral hardening at ~0.5 TeV explained by break in diffusion coefficient, softening at 10 TeV by exp. cut-off of source spectrum at 100 TV
- Flux of secondary electrons and positrons interpolated and used in fitting with free parameter re-scaling factor
- Propagation parameters consistently used also for pulsar and Vela SNR spectra calculation









Diffusion coefficient depends on position (increasing exponentially with galactic radius r and distance from plane z) and rigidity R (soft break)

$$D(r) = D(r_n)\, e^{(r-r_n)/r_s} \text{ for } r > r_n \;\; ; \;\; D(r_n) \text{ for } r < r_n$$

$$D(z) = D(r, z_n)\, e^{(z-z_n)/z_s} \text{ for } z > z_n \;\; ; \;\; D(r, z_n) \text{ for } z < z_n$$

$$D(r,z,R) = D(r,z,4\,GV)\left(\frac{R}{R_0}\right)^{\delta_l} \Big/ \left(1+\left(\frac{R}{R_b}\right)^{\frac{\delta_l-\delta_h}{s}}\right)^{s}$$

$r_n = 2.0\,kpc$ (bulge)
$r_s = 4.5\,kpc$
$z_n = 0.15\,kpc$ (thin disk)
z_s : depends on model

Model A:
$D_0 = 0.65 \cdot 10^{28}\, cm^2/s \;\; @ r_n, z_n, 4\,GV$
$\delta = 0.5\, (R > 500\,GV \rightarrow 0.2)$
$L = \pm 3\,kpc \;\; ; \;\; z_s = 1.8\,kpc$

Model B:
$D_0 = 1.32 \cdot 10^{28}\, cm^2/s \;\; @ r_n, z_n, 4\,GV$
$\delta = 0.5\, (R > 500\,GV \rightarrow 0.2)$
$L = \pm 6\,kpc \;\; ; \;\; z_s = 3.5\,kpc$

Calculating the Flux from Pulsars

- Information about position, age and spin-down rate of pulsars from astronomical observations
- Large uncertainty on the acceleration and escape mechanism of cosmic rays from pulsars
  → use available information but fit parameters of injected cosmic ray spectrum:

Analytic solution of propagation equation for instantaneous point source (Green's function) [e.g. Eur. Phys. J. C. 76:229 (2016)] adapted to propagation model with break in diffusion coefficient

$$\phi_{pulsar} = \frac{Q_0 \eta}{\pi^{3/2} r_{dif}^3} E^{-\gamma} \left(1 - \frac{E}{E_{max}}\right)^{\gamma-2} e^{-\frac{E/E_{cut}}{1-E/E_{max}} - \frac{r^2}{r_{dif}^2}}$$

$$r_{dif} = 2\sqrt{\frac{D(E)\, t_{dif}}{1-\delta(E)} \frac{E_{max}}{E} \left[1 - \left(1 - \frac{E}{E_{max}}\right)^{(1-\delta(E))}\right]} \;;\quad E_{max} = \frac{1}{b_0 t_{dif}}$$

$$D(E) = D_0 \left(\frac{E}{E_0}\right)^{\delta_l} \Big/ \left(1 + \left(\frac{E}{E_b}\right)^{\frac{\delta_h - \delta_l}{s}}\right)^{s} \;;\quad \delta(E) = \frac{d[\log(D(E))]}{d[\log(E)]}$$

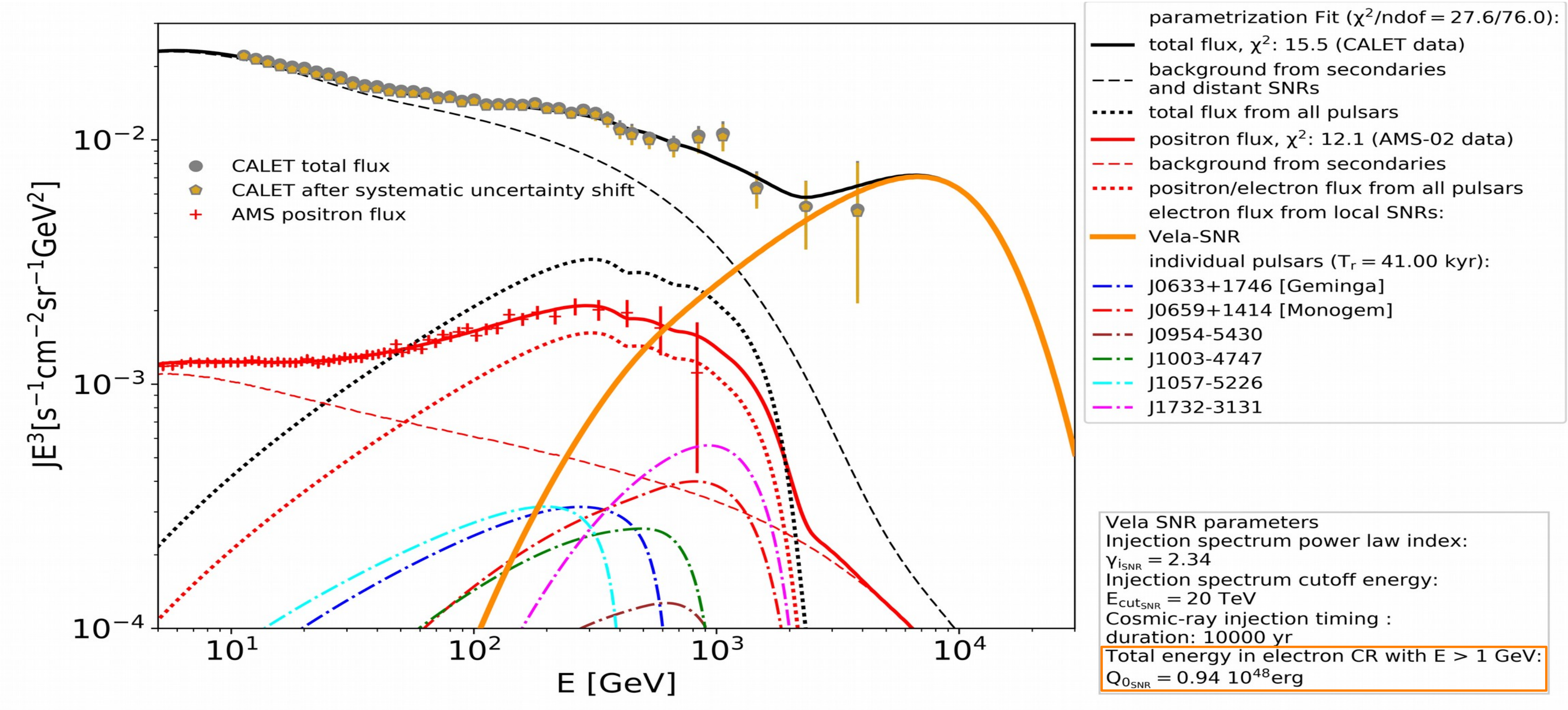
free parameters: efficiency η, index γ, cutoff energy E_{cut}

determined parameters: $D_0, \delta_l, \delta_h, E_B, s, b_0$ (from propagation model)

total energy Q_0, distance r, diffusion time t_{dif} (from ATNF catalog)

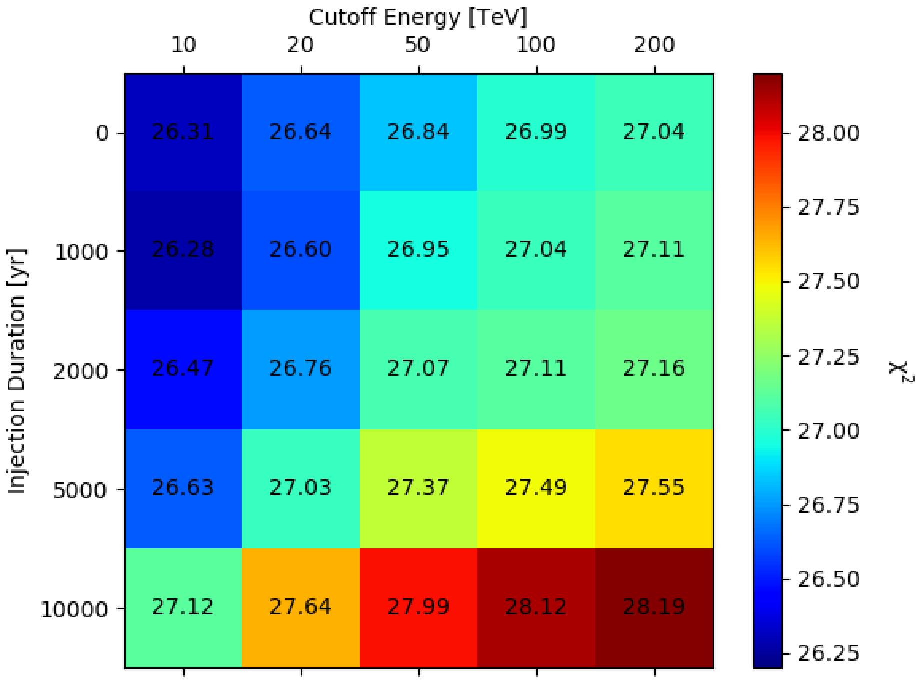
- Position dependent diffusion coefficient is approximated by value for the position of the solar system (Model A: D_0 = 2.636 10^{28} cm^2/s
  Model B: D_0 = 5.353 10^{28} cm^2/s)
- Instantaneous (burst-like) release of the cosmic rays is assumed
- Free parameters assumed to be the same for all pulsars
- Pulsars which can contribute more than 5% to the flux for any case and at any energy are considered in the fitting
- The diffusion time is equal to the age of the pulsar minus the duration for which the electrons and positrons are trapped in the pulsar wind nebula (T_R)
- T_R is optimized in the fitting by scanning in steps of 1 kyr

Adding the Vela SNR's Spectrum

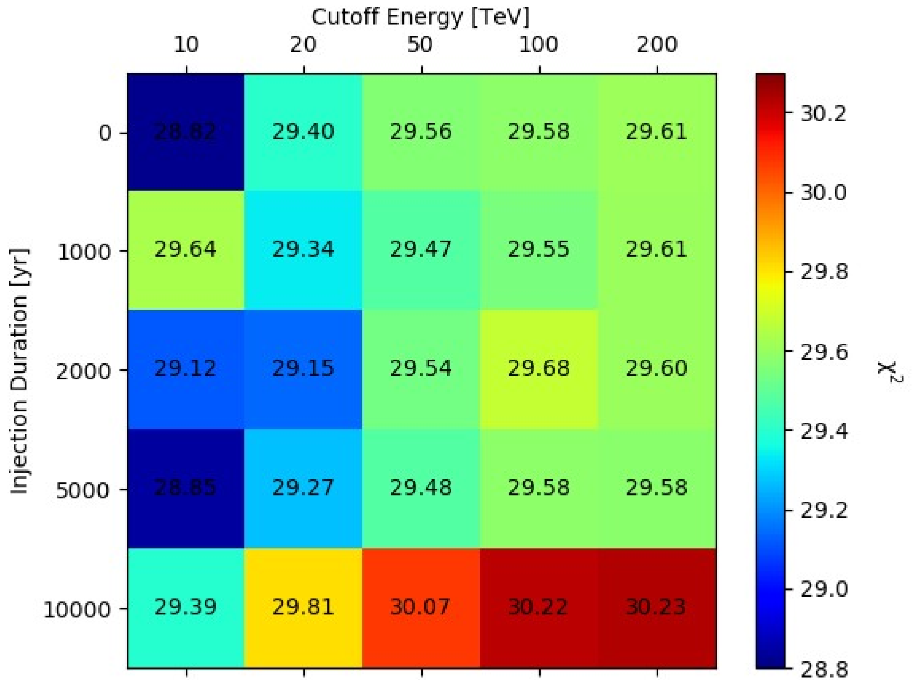


- Vela SNR flux as calculated with DRAGON is added to the best fit multi-pulsar model after $E_{cut(d)}$ changed to 1 TeV and the normalization **Q_0** (released energy in electron cosmic rays above 1 GeV) fitted as a free parameter for the SNR (index same as nuclei in the propagation model, injection duration 10 kyr and cut-off 20 TeV fixed parameters)

Dependence of χ^2 on Vela SNR's Injection Duration and Cut-off



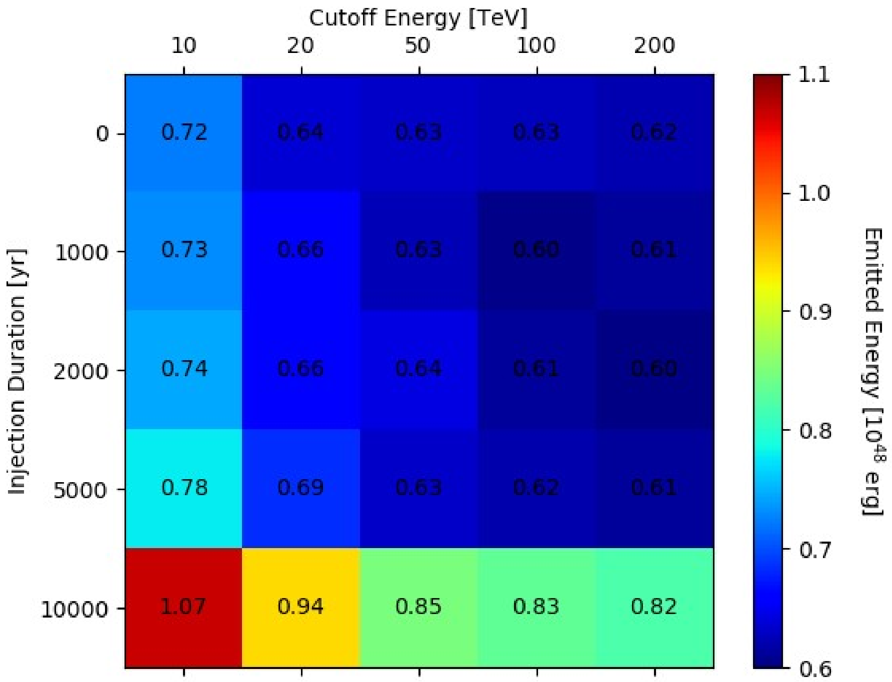
Propagation Model A



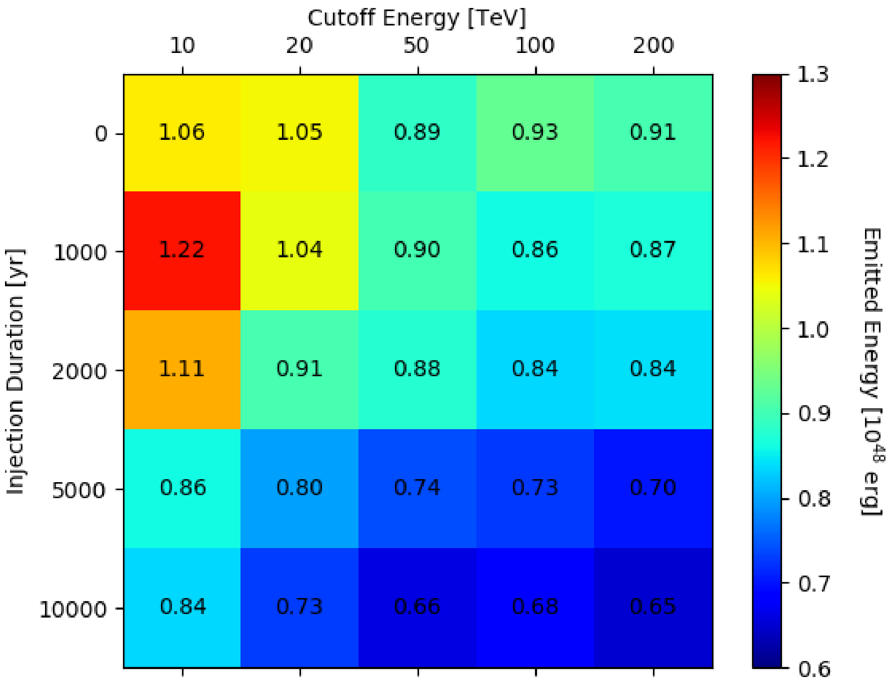
Propagation Model B

ndof = 76 → good fit for all cases, independent on injection duration and cut-off

Dependence of Best-Fit Q_0 on Vela's Injection Duration and Cut-off

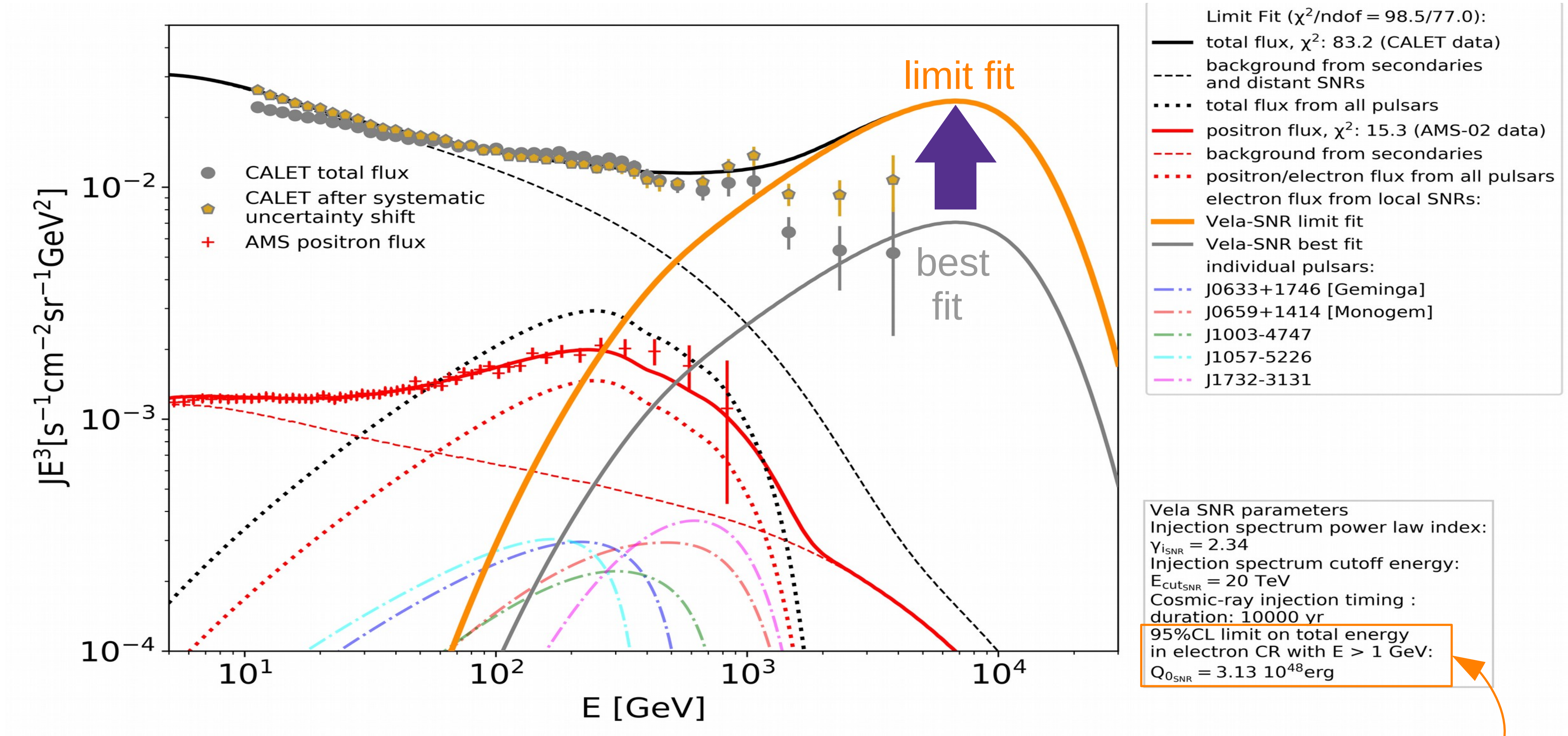


Propagation Model A



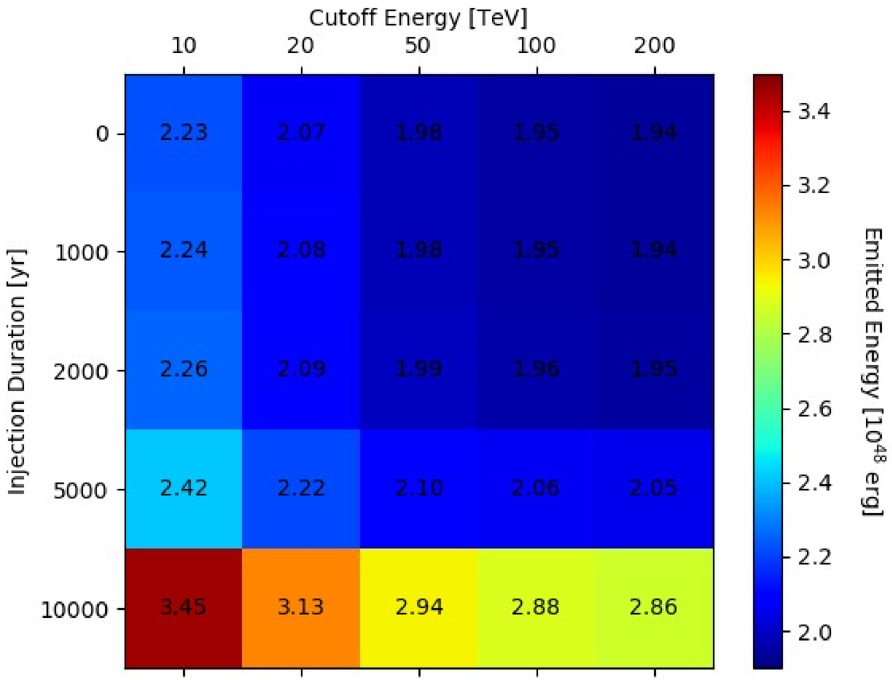
Propagation Model B

Limit on Cosmic Rays from Vela

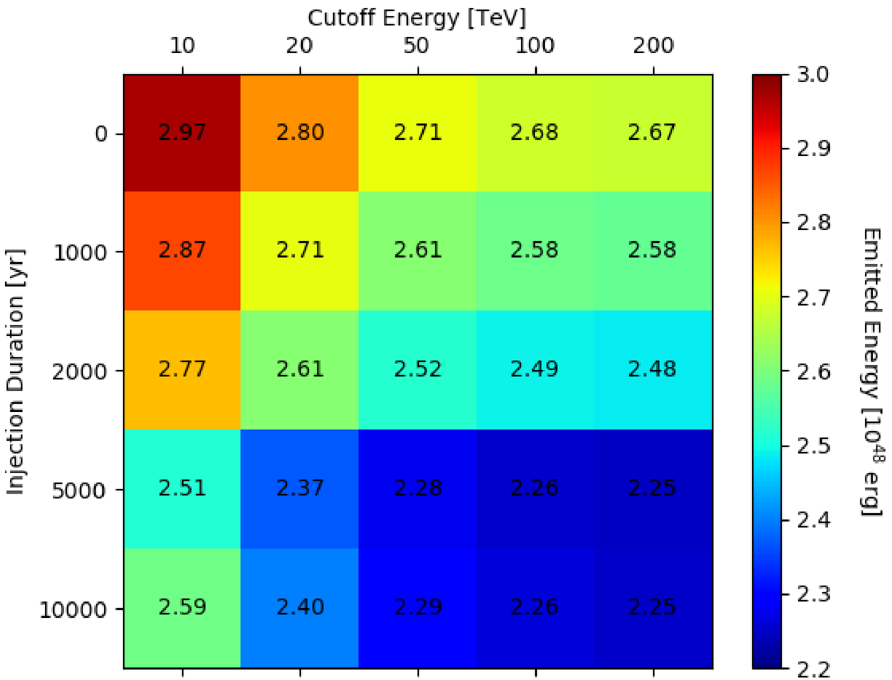


- Starting from the best fit (grey line), the injected energy is increased in steps until the fit is excluded at 95% CL (final fit: orange line) → limit on the injected energy Q_0

Dependence of Limit Q_0 on Vela's Injection Duration and Cut-off



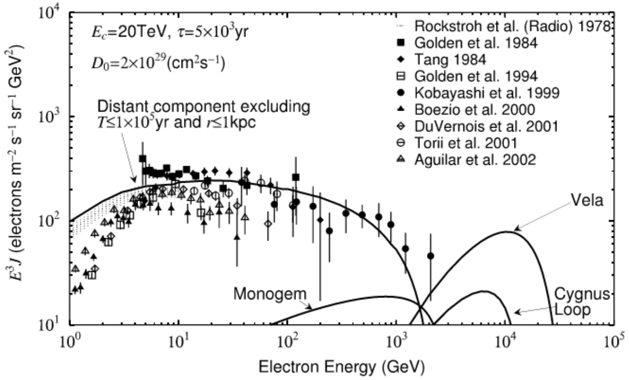
Propagation Model A

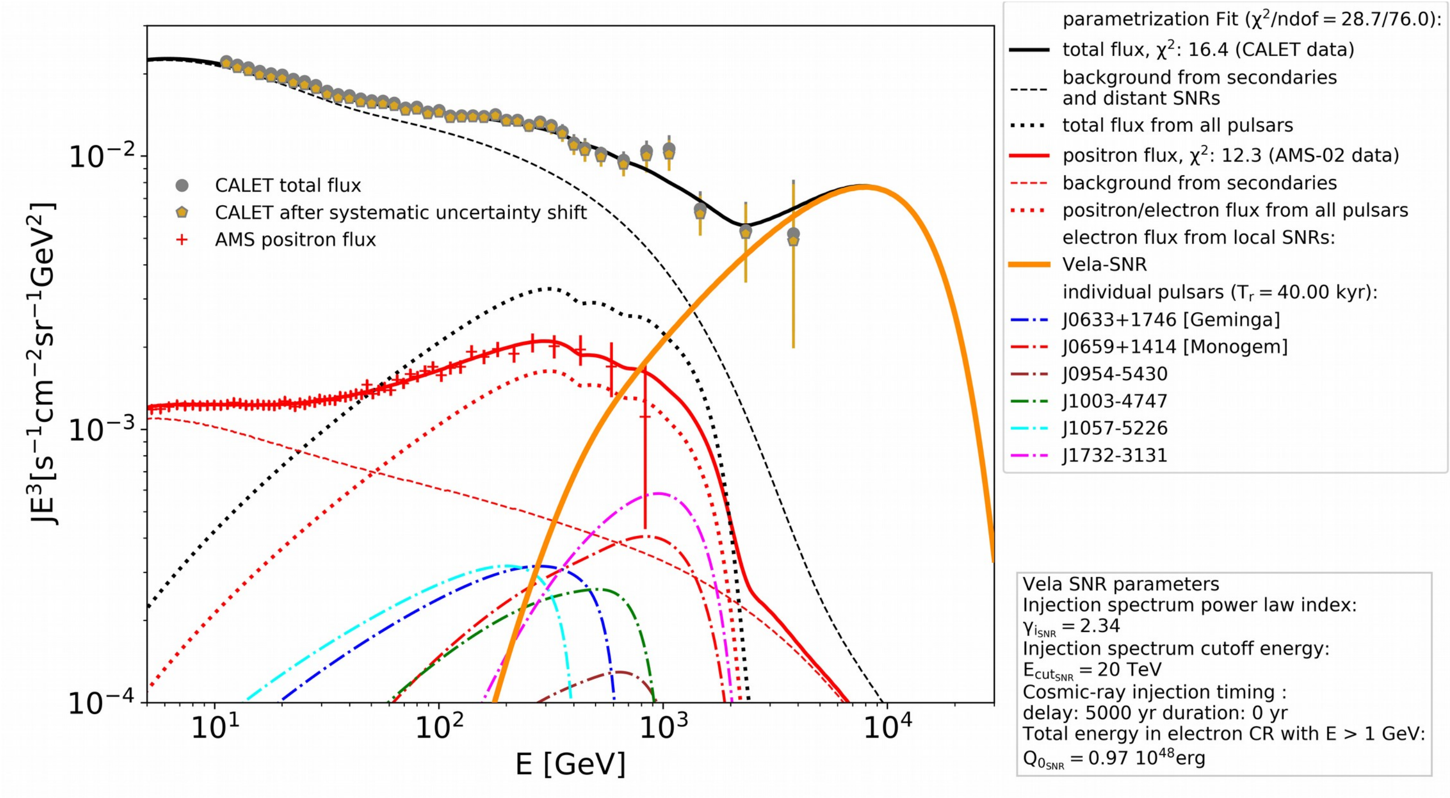


Propagation Model B

Delayed Release of Cosmic Rays

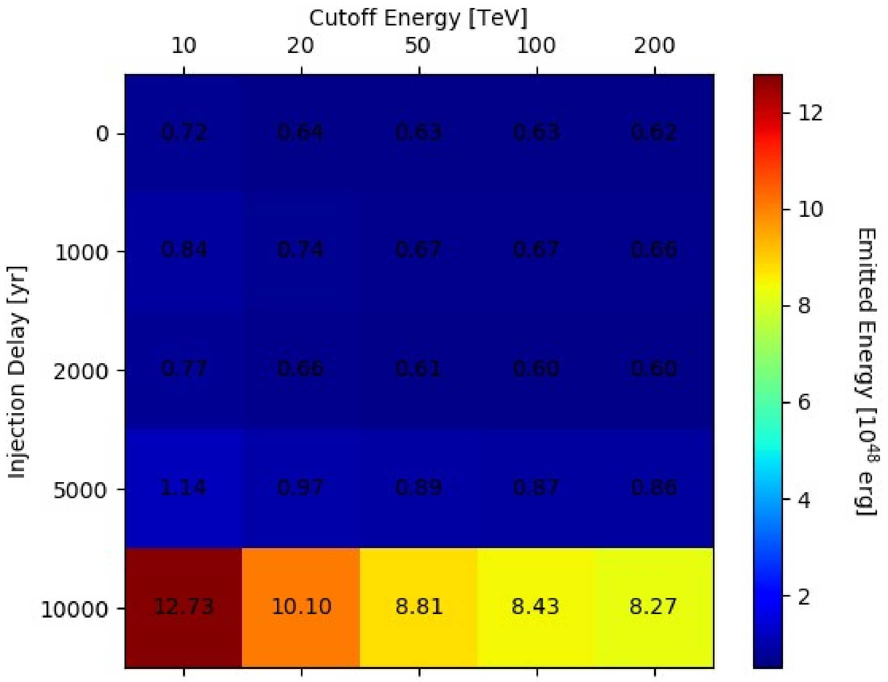
- Alternative scenario:
  burst-like release of cosmic rays with a few thousand years delay after the supernova explosion



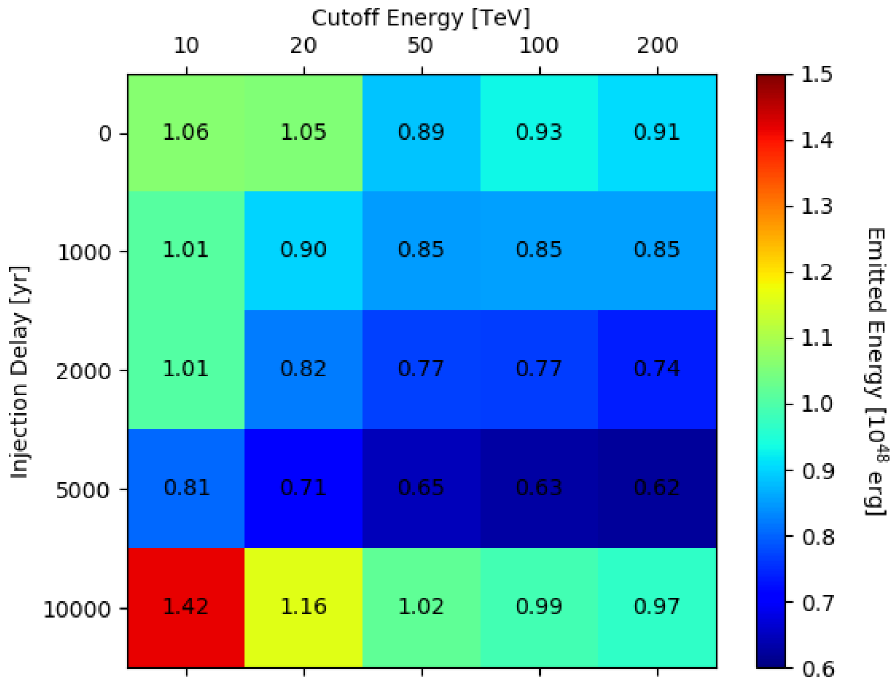


- Shown example case:
  Injection delay 5 kyr , cut-off energy 20 TeV

Dependence of Best-Fit Q_0 on Vela's Injection Delay and Cut-off



Propagation Model A



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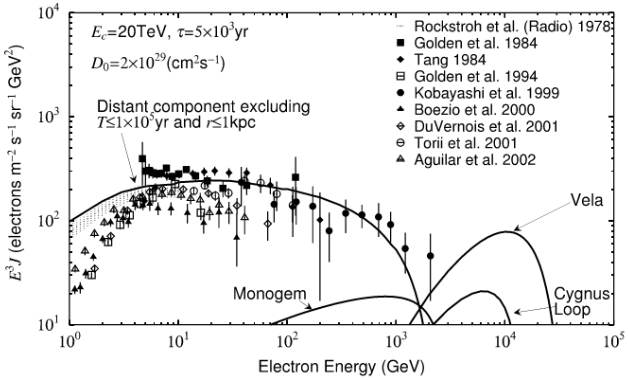
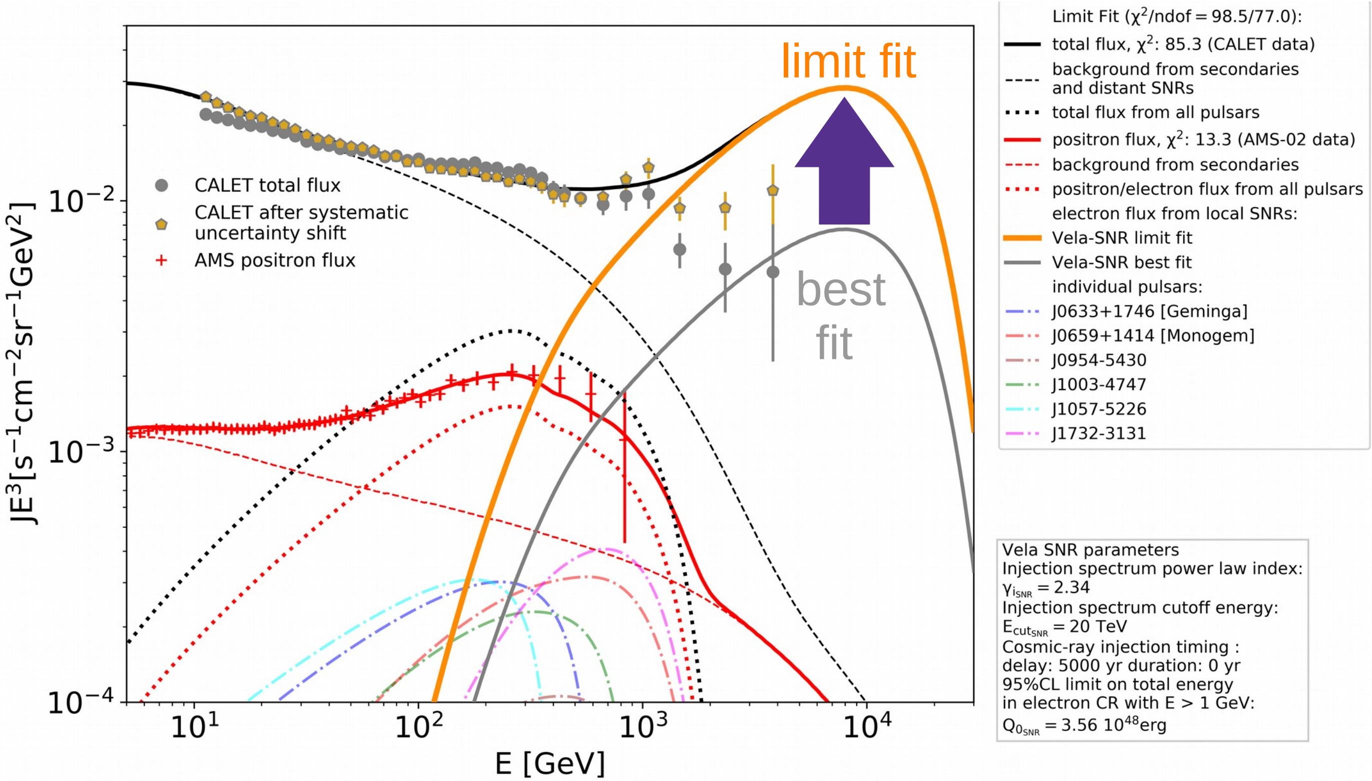
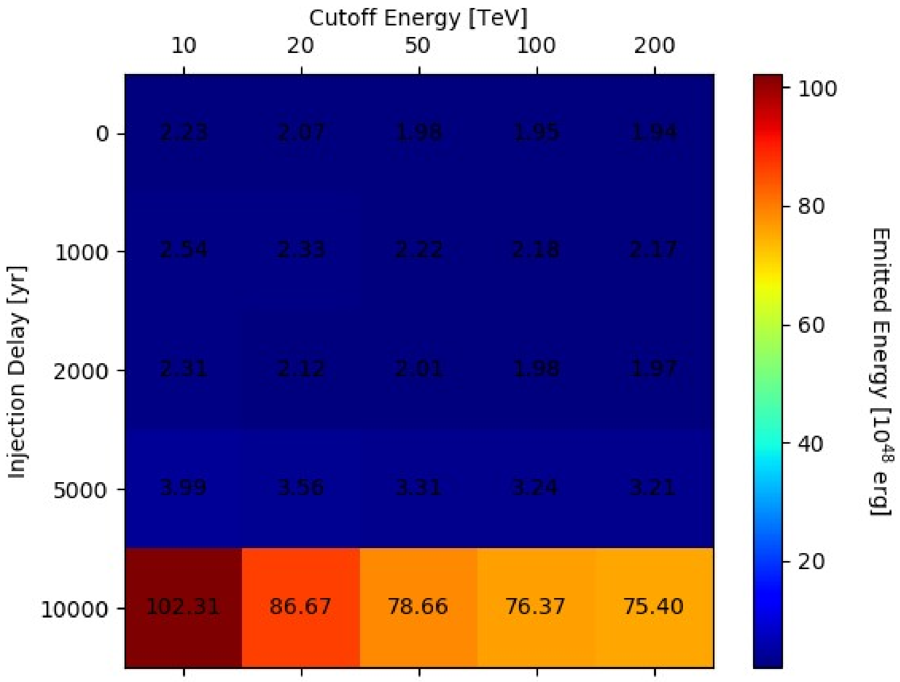


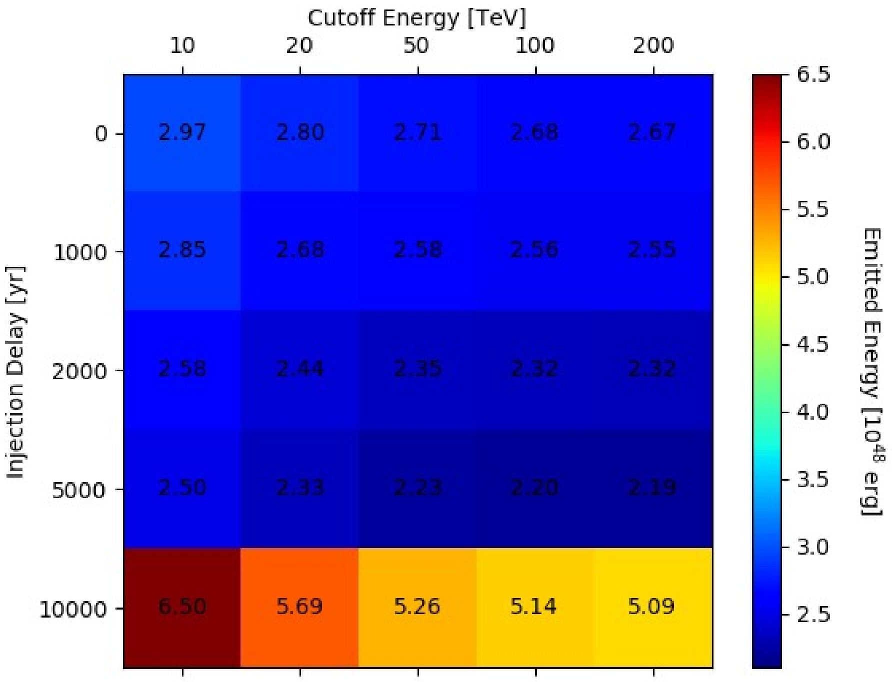


- Shown example case:
  Injection delay 5 kyr , cut-off energy 20 TeV

Dependence of Limit Q_0 on Vela's Injection Delay and Cut-off



Propagation Model A



Propagation Model B

Summary and Outlook

- The CALET all electron spectrum can provide strong constraints on the emission of cosmic rays by the Vela SNR depending on the emission timing, duration and propagation conditions.
  - Range of best fitting total energy: ~0.6×10^{48} erg to ~1.2×10^{48} erg
  - Range of upper limits: ~1.9×10^{48} erg to ~4.0×10^{48} erg
  - Exception: Burst-like emission after 10 kyr
- Further improvements:
  - Study of more scenarios including energy dependent emission timing
  - Combination with analysis of flux anisotropy

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