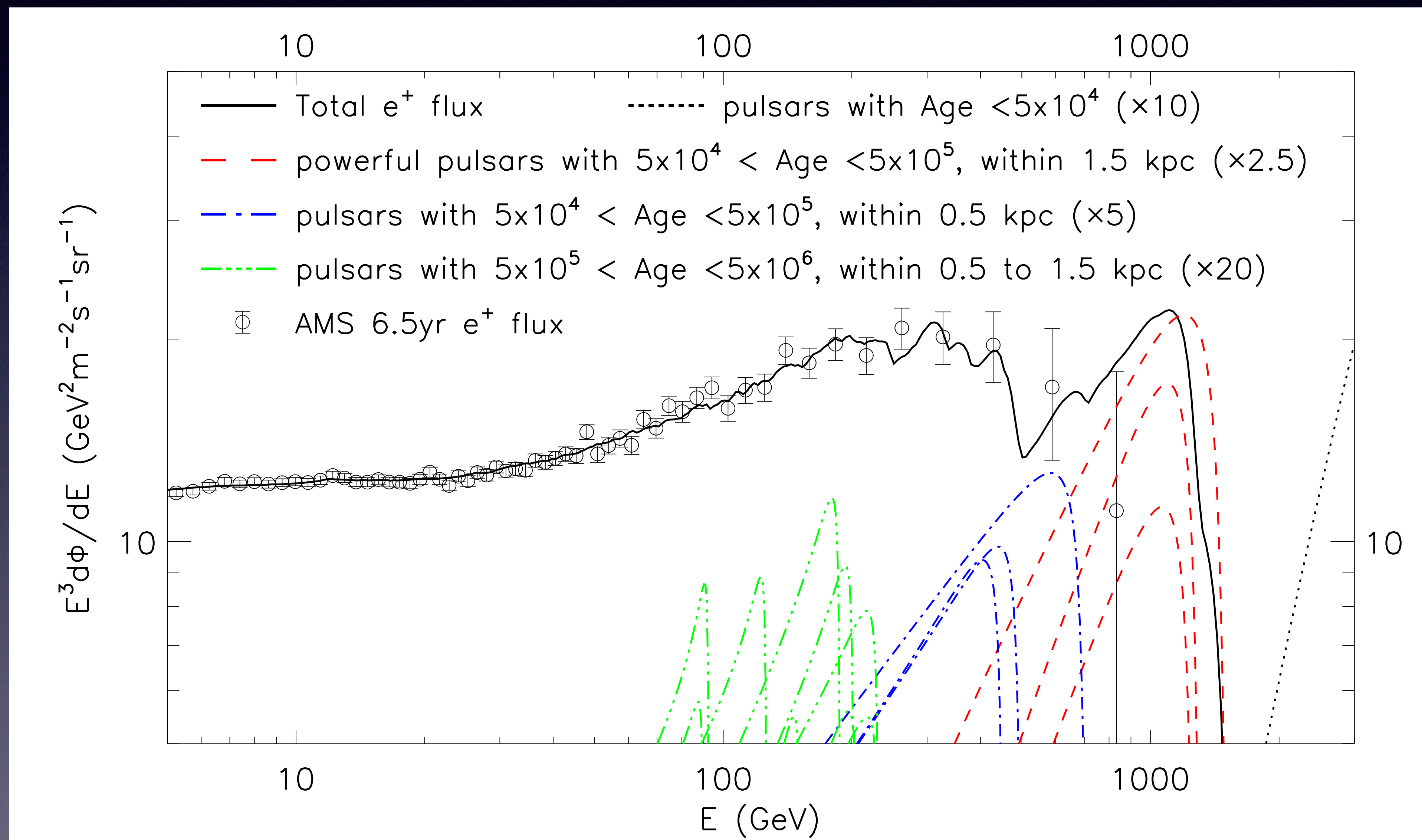
Cosmic rays as a new probe to study the properties and evolution of Milky Way pulsars



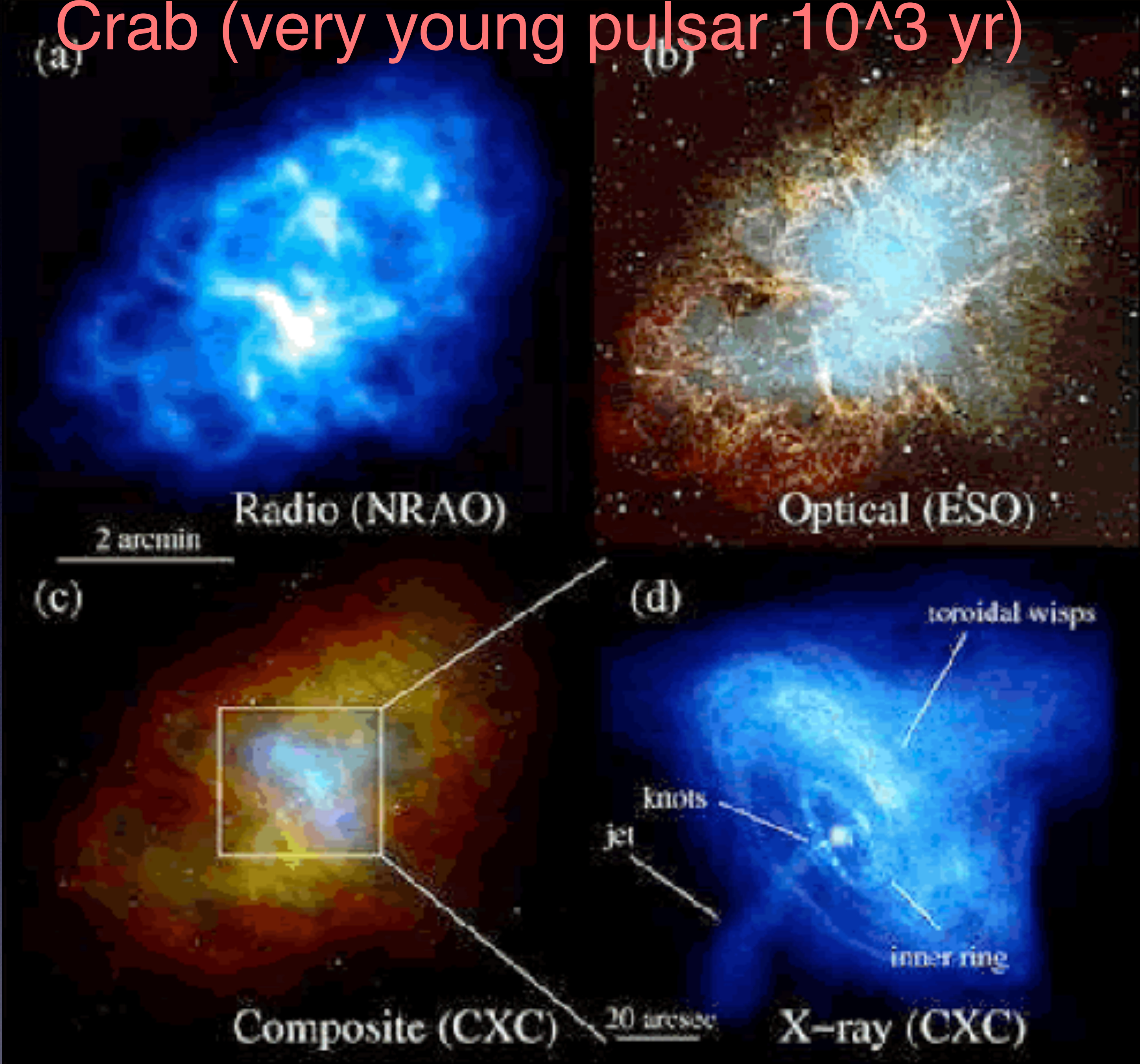
In collaboration with Tess Hoover (OU) and Iason Krommydas (NTUA)

*Cholis, Krommydas, PRD **105** 023015 (2022)*

Ilias Cholis, 19/7/2022

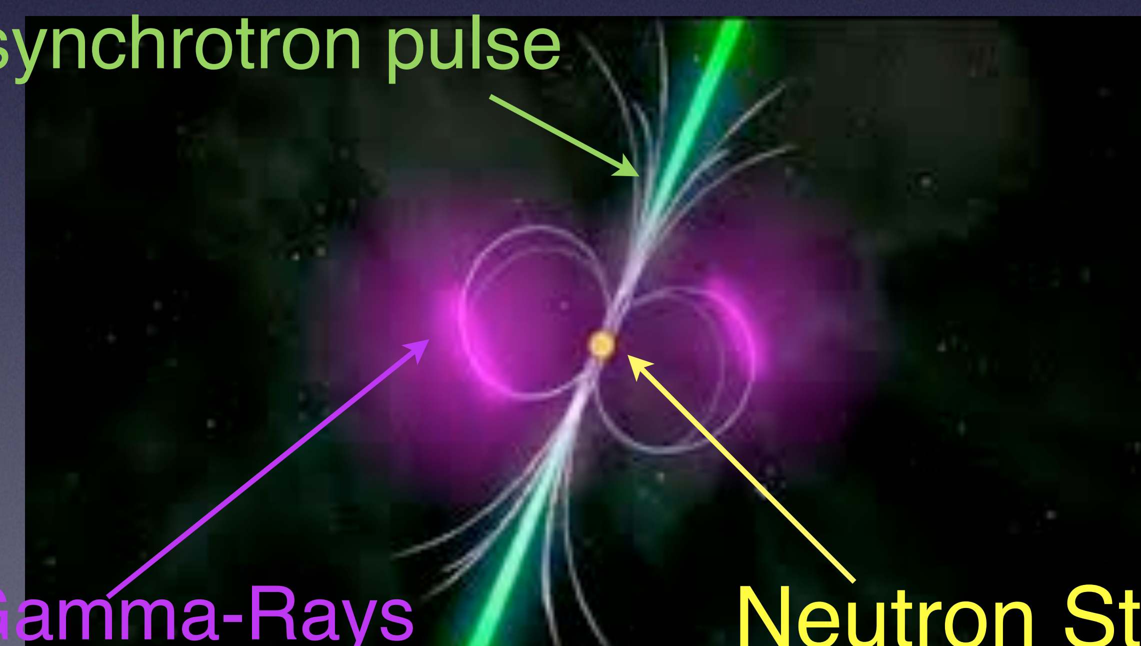
Milky Way Pulsars as sources of high-energy cosmic rays

Crab (very young pulsar 10^3 yr)



Pulsars loose their spinning energy into EM radiation and cosmic rays. This "spin-down" power evolves with time and can be modeled as,

$$\dot{E}(t) = \dot{E}_0 \left(1 + \frac{t}{\tau_0}\right)^{-\frac{\kappa+1}{\kappa-1}}$$



Through many different observations Pulsars are known sources of cosmic-ray electrons and positrons.

Milky Way Pulsars as sources of high-energy cosmic rays

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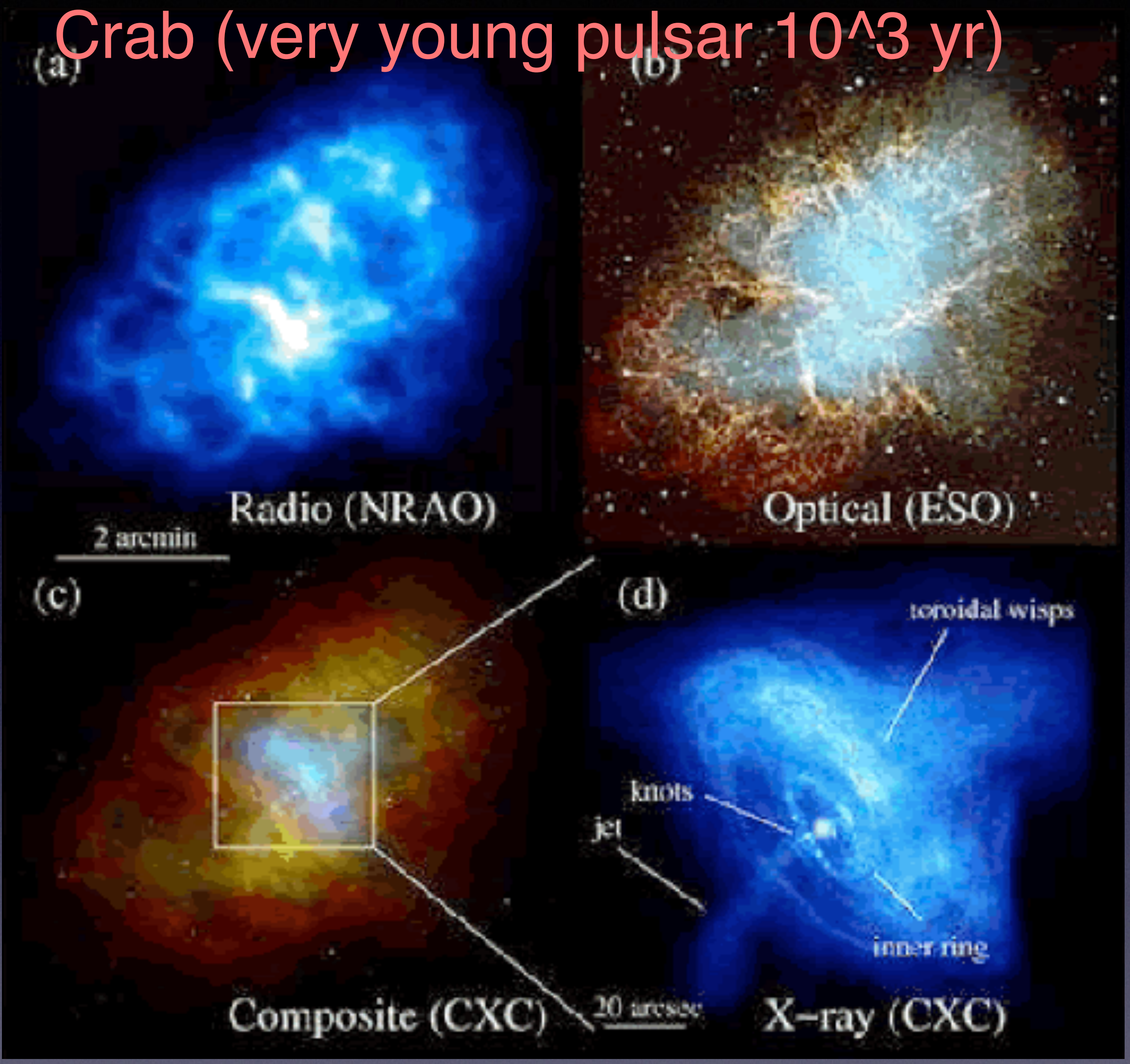


Pulsars loose their spinning energy into EM radiation and cosmic rays. This "spin-down" power evolves with time and can be modeled as,

$$\dot{E}(t) = \dot{E}_0 \left(1 + \frac{t}{\tau_0}\right)^{-\frac{\kappa+1}{\kappa-1}}$$

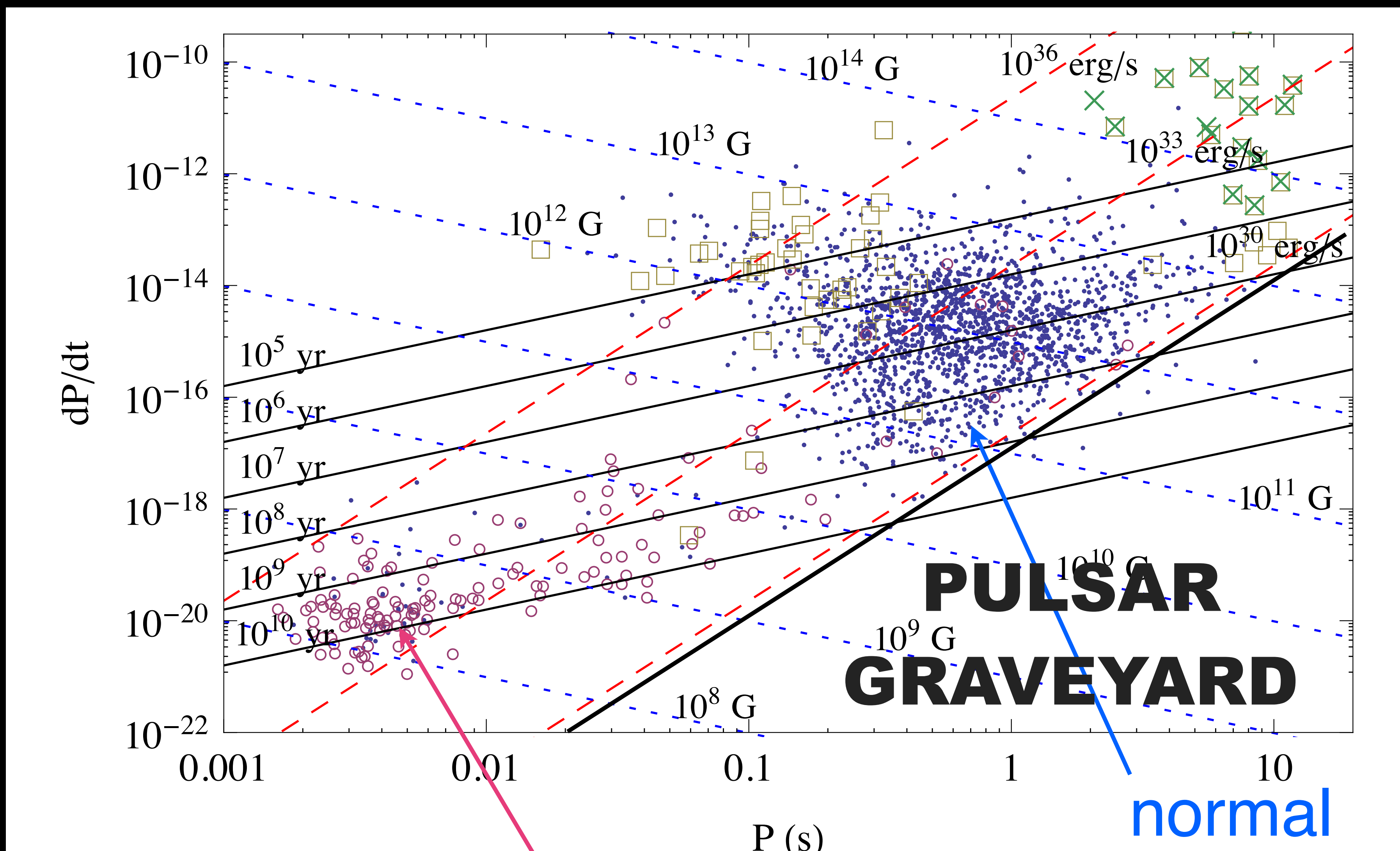
The total energy released from a single pulsar over a time $t \gg \tau_0$ is its initial rotational kinetic energy:

$$E_{tot} \simeq E_0 = \frac{1}{2} I_0 \Omega_0^2$$

Through many different observations Pulsars are known sources of cosmic-ray electrons and positrons.

A bit about Pulsars in General

Basic model assumes magnetic dipole radiation (κ=3)



$$\tau = \frac{P}{(\kappa - 1)\dot{P}} \times \left[1 - \left(\frac{P_0}{P}\right)^{\kappa-1}\right]$$

$$K = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}$$

Measured only in about a dozen very young and energetic pulsars

milli-second (recycled) pulsars:
NEED A COMPANION

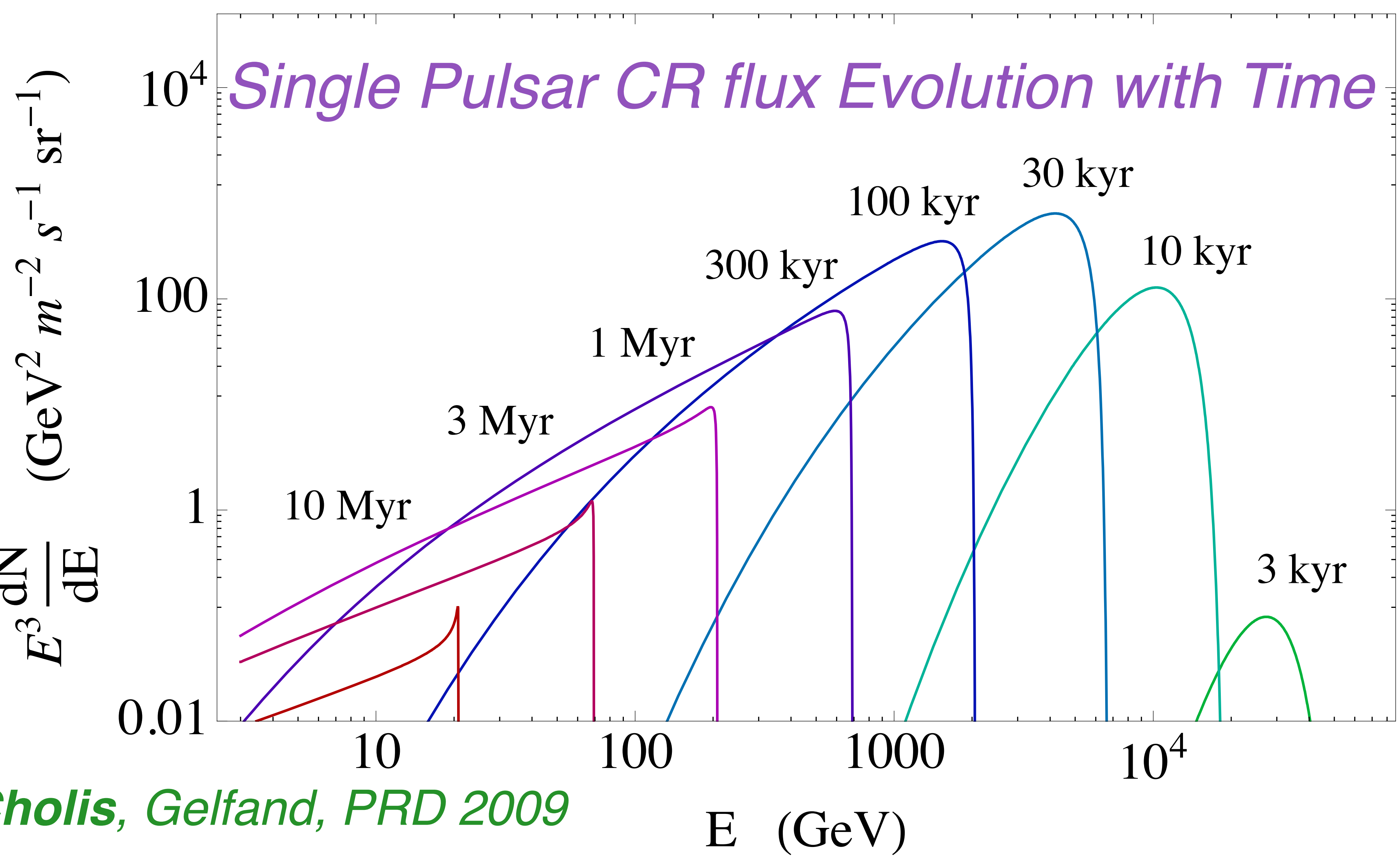
$$\dot{E} = -\frac{B_s^2 R_s^6 \Omega^4}{6c^3} \approx 10^{31} B_{12}^2 R_{10}^6 P^{-4}\,\mathrm{erg\ s^{-1}}$$

$$\dot{P} = 3.3 \times 10^{-15}\,(B/10^{12}\,\mathrm{G})^2\,(P/0.3\,\mathrm{s})^{-1}$$

Modeling the Pulsars

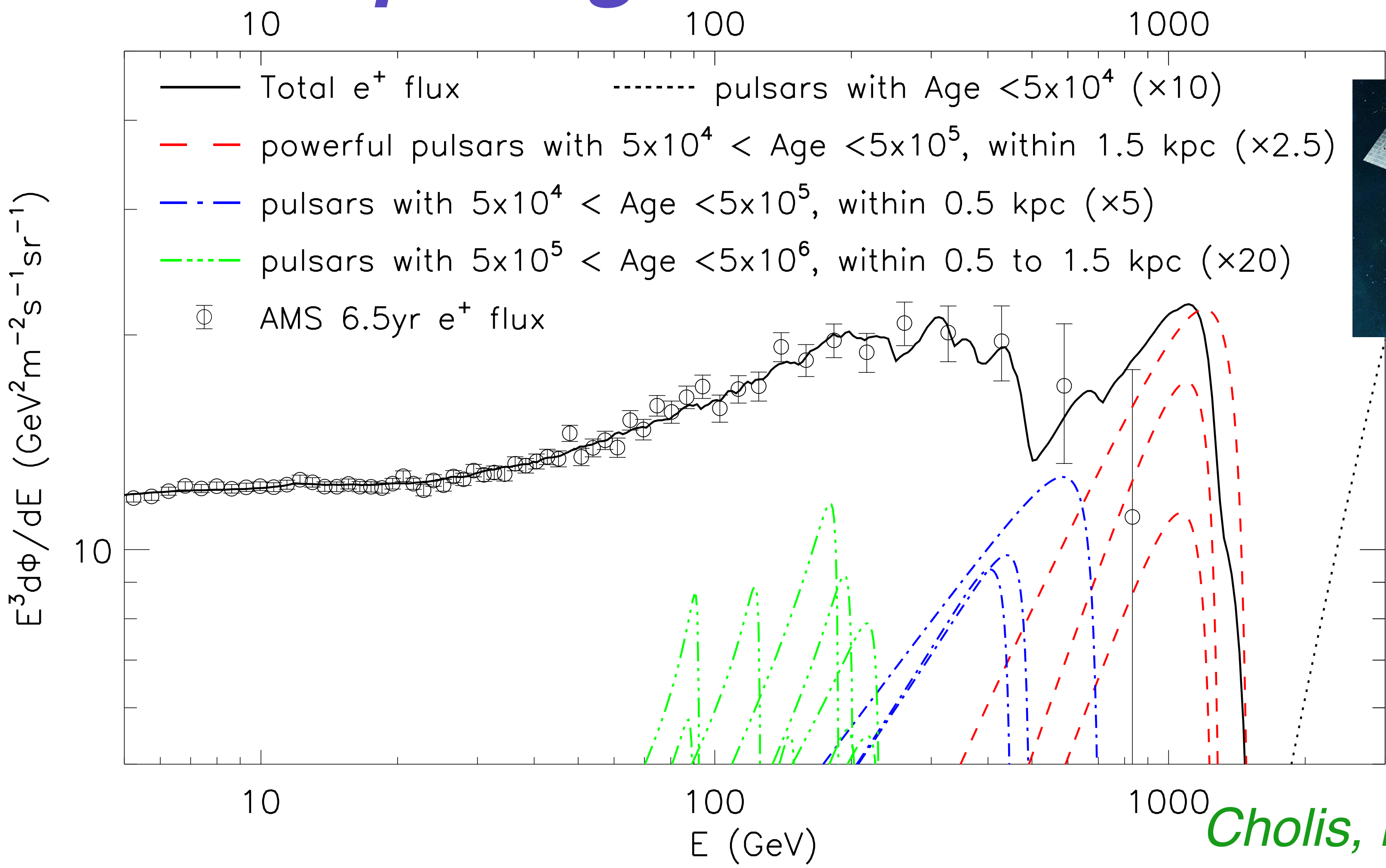
The pulsar spins down with $\tau_0 \sim 10$ kyr << *Time for cosmic rays to propagate to us.*

Pulsars are ~Time-bombs of Cosmic-Rays

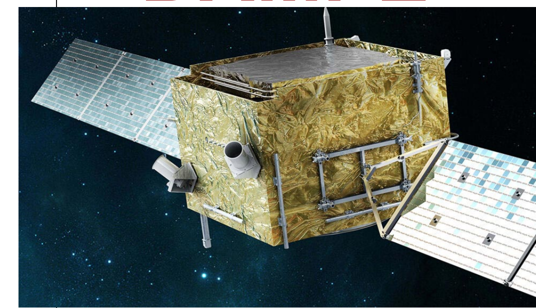


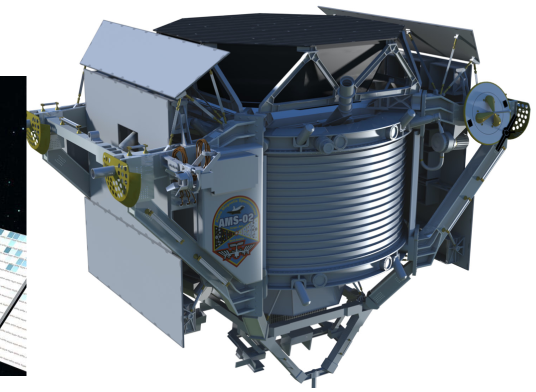
*Malyshev, **Cholis**, Gelfand, PRD 2009*

Comparing to Observations



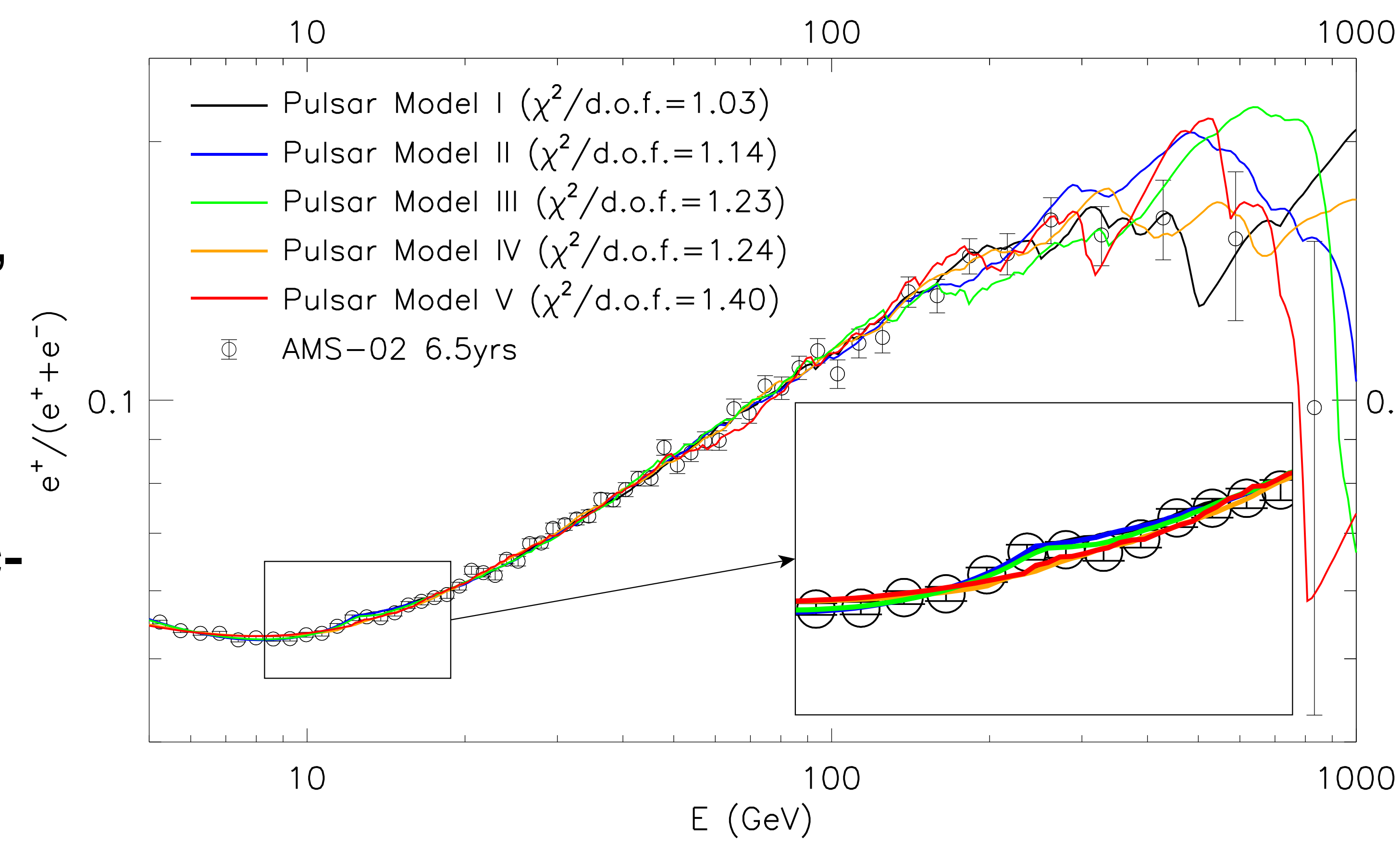
DAMPE





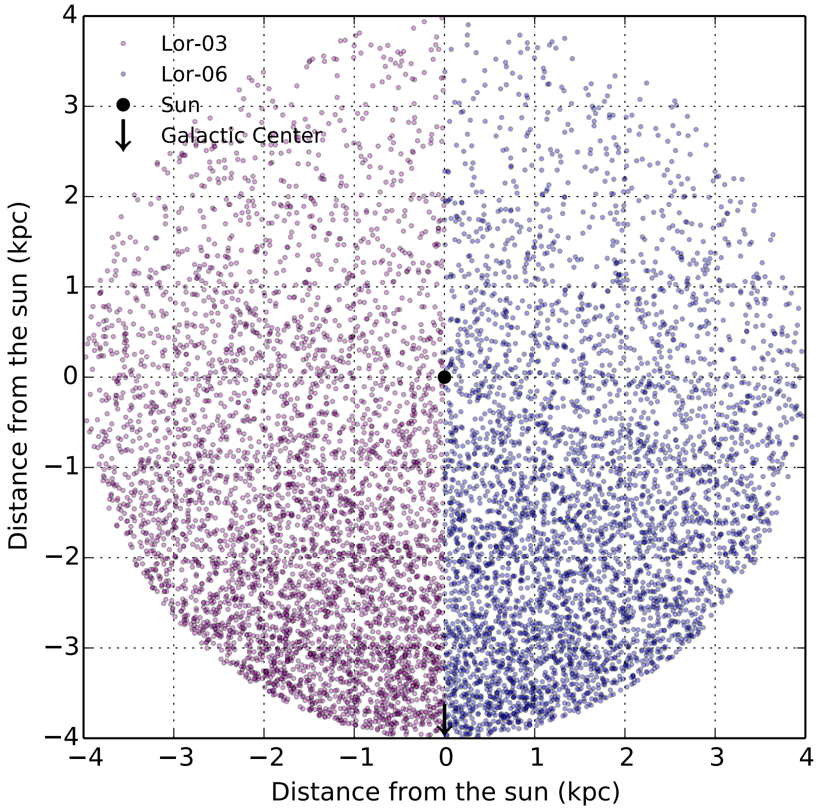
AMS-02

*Cholis, Krommydas, PRD **105** 023015 (2022)*



While pulsars are not the only source of cosmic-ray electrons and positrons, adding their contribution we can test various hypotheses on the properties of Milky Way pulsars using the recently released (2017-2021) cosmic-ray energy spectral measurements.

Study the Pulsar Properties through the Observed Cosmic-Ray Spectra

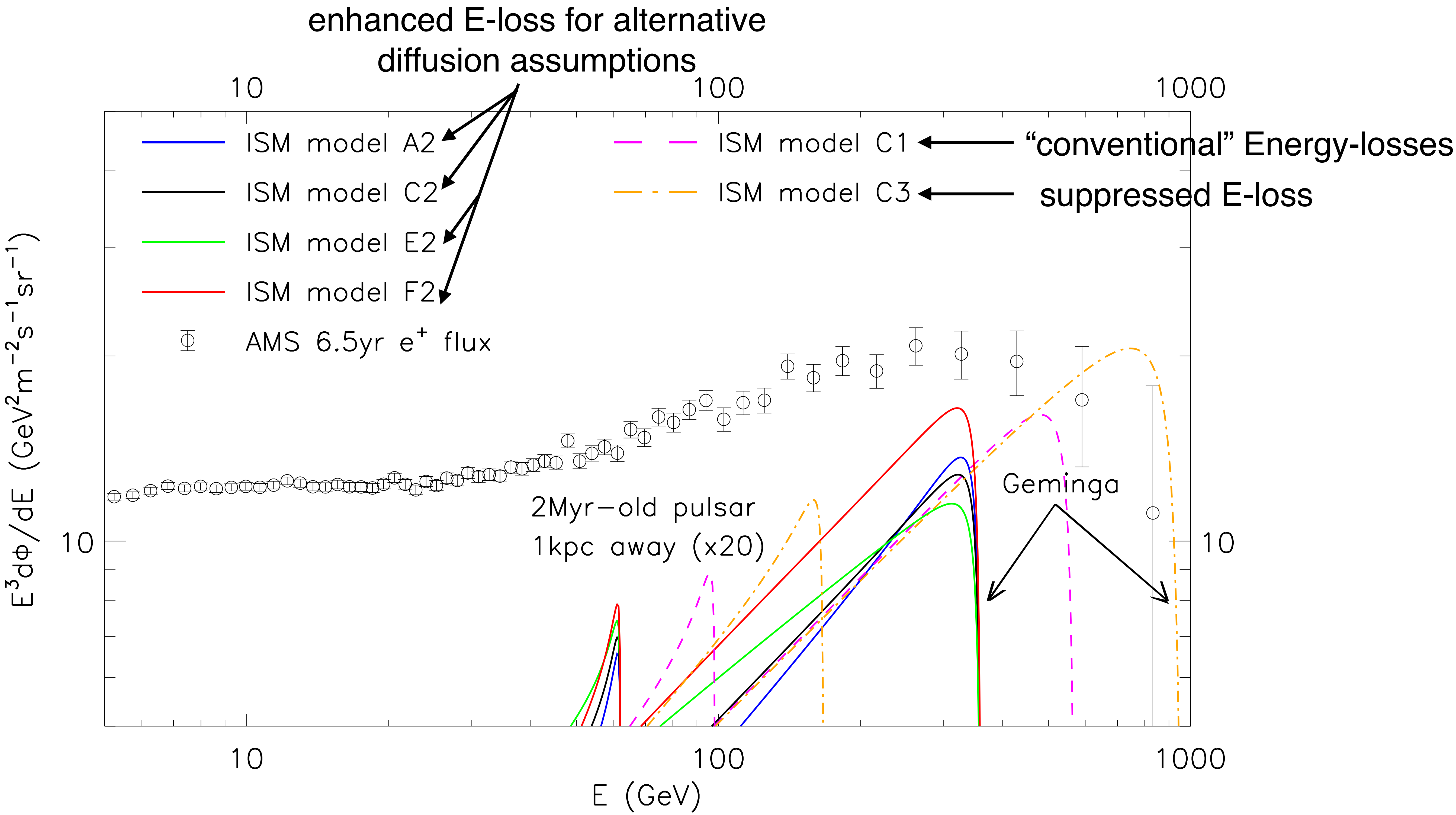


One has to include all uncertainties, pertaining to

- The Neutron Stars distribution in space
- The initial conditions of the Neutron Stars (as a distribution of properties) in terms of their initial spin-down power
- The uncertainties on their time evolution, i.e. κ & τ_0
- How many cosmic-ray electrons and positrons they produce/inject into the interstellar medium and with what spectrum
- How these electrons/positrons propagate from there to us (ISM physics & Heliospheric Physics)

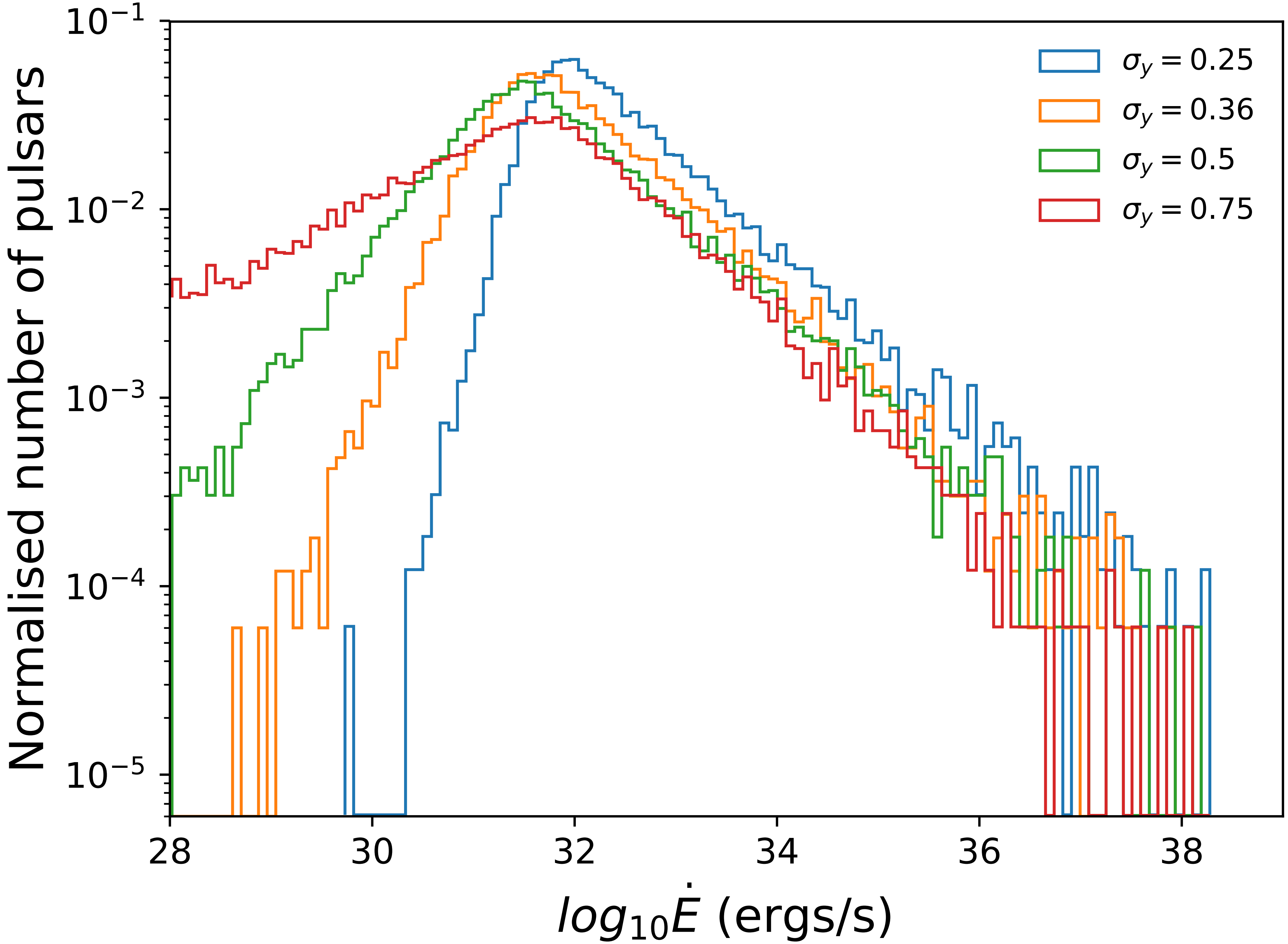
We have produced over 7K unique Milky-Way pulsar simulations. Each simulation contains anywhere between 5K to 18K unique pulsars within 4 kpc from the Sun.

The impact of ISM assumptions on the propagation of cosmic-rays



*Cholis, Krommydas, PRD **105** 023015 (2022)*

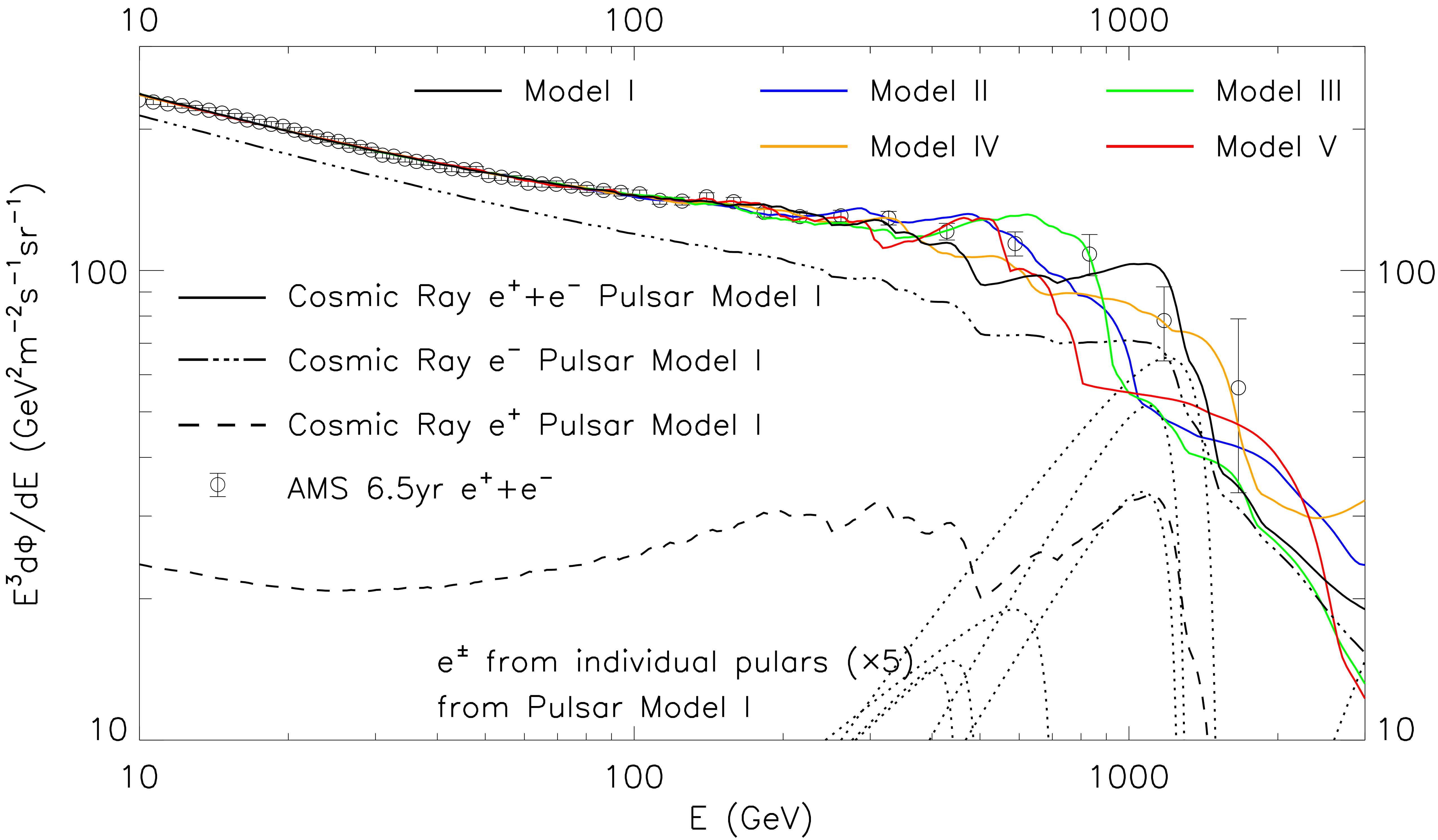
Alternative assumptions on the (i.e. observable) luminosity of pulsars



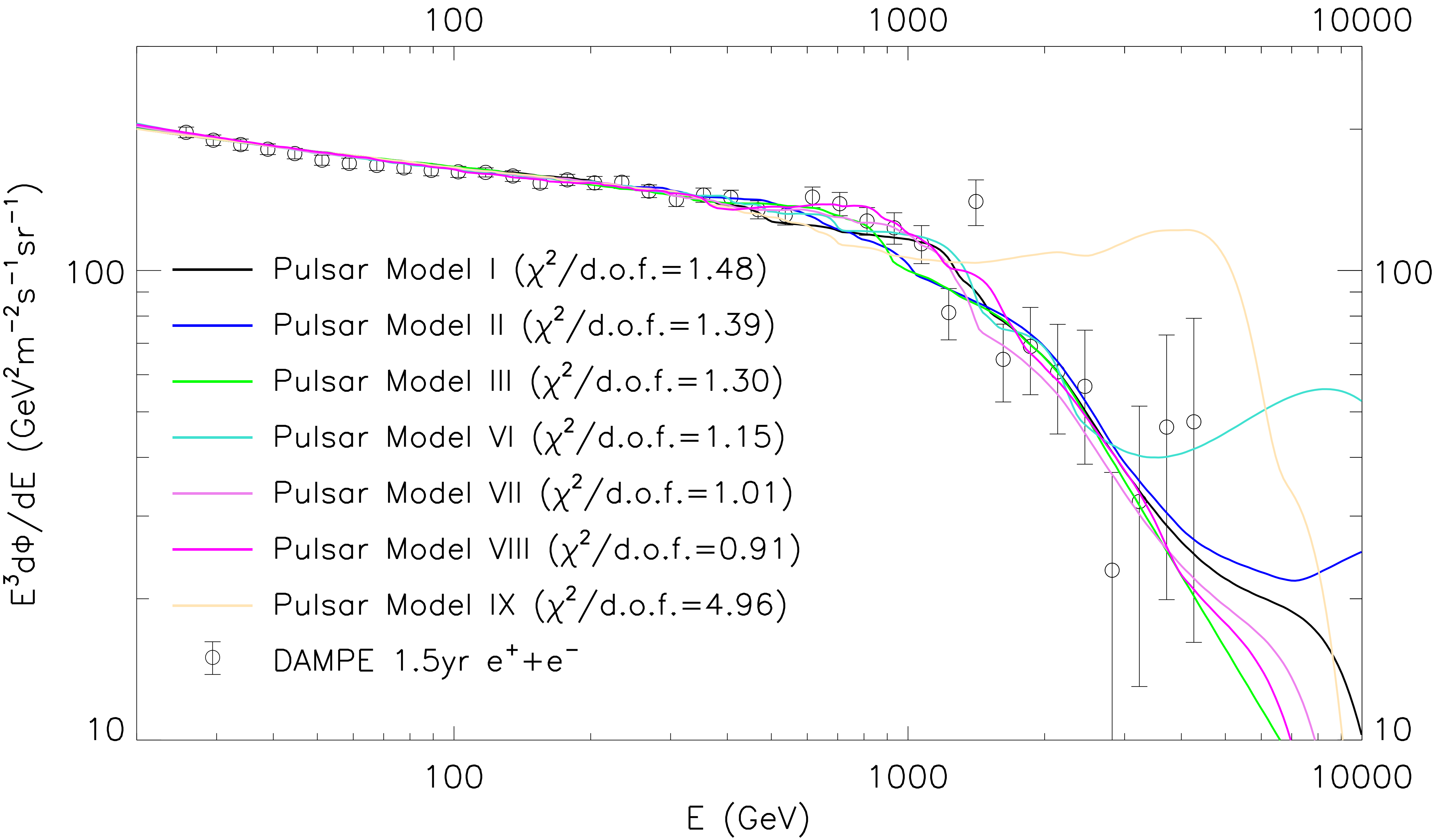
*Cholis, Karwal, Kamionkowski, PRD **98** 063008 (2018)*

Total Lepton Flux from AMS-02:

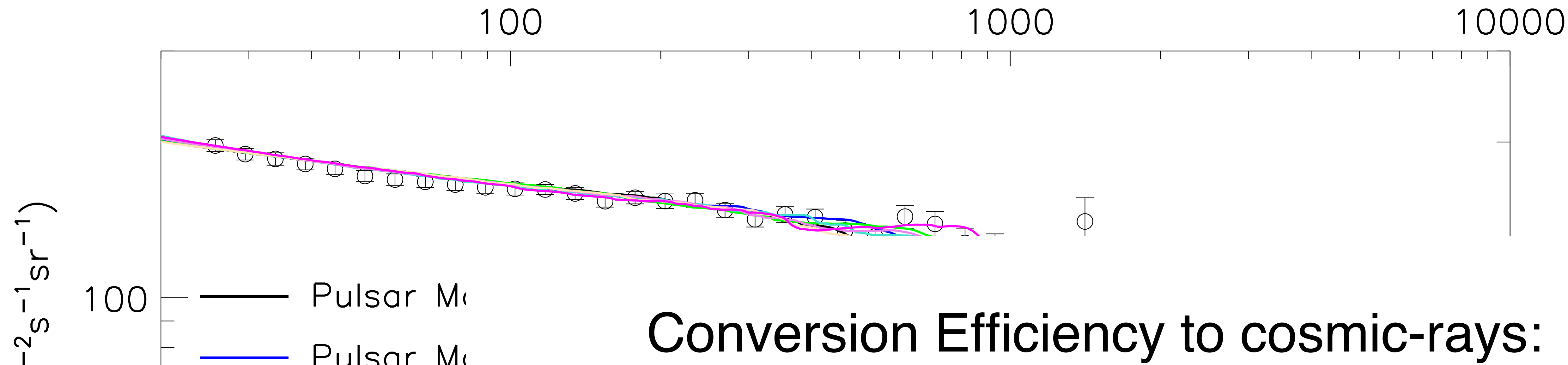
*Cholis, Krommydas, PRD **105** 023015 (2022)*



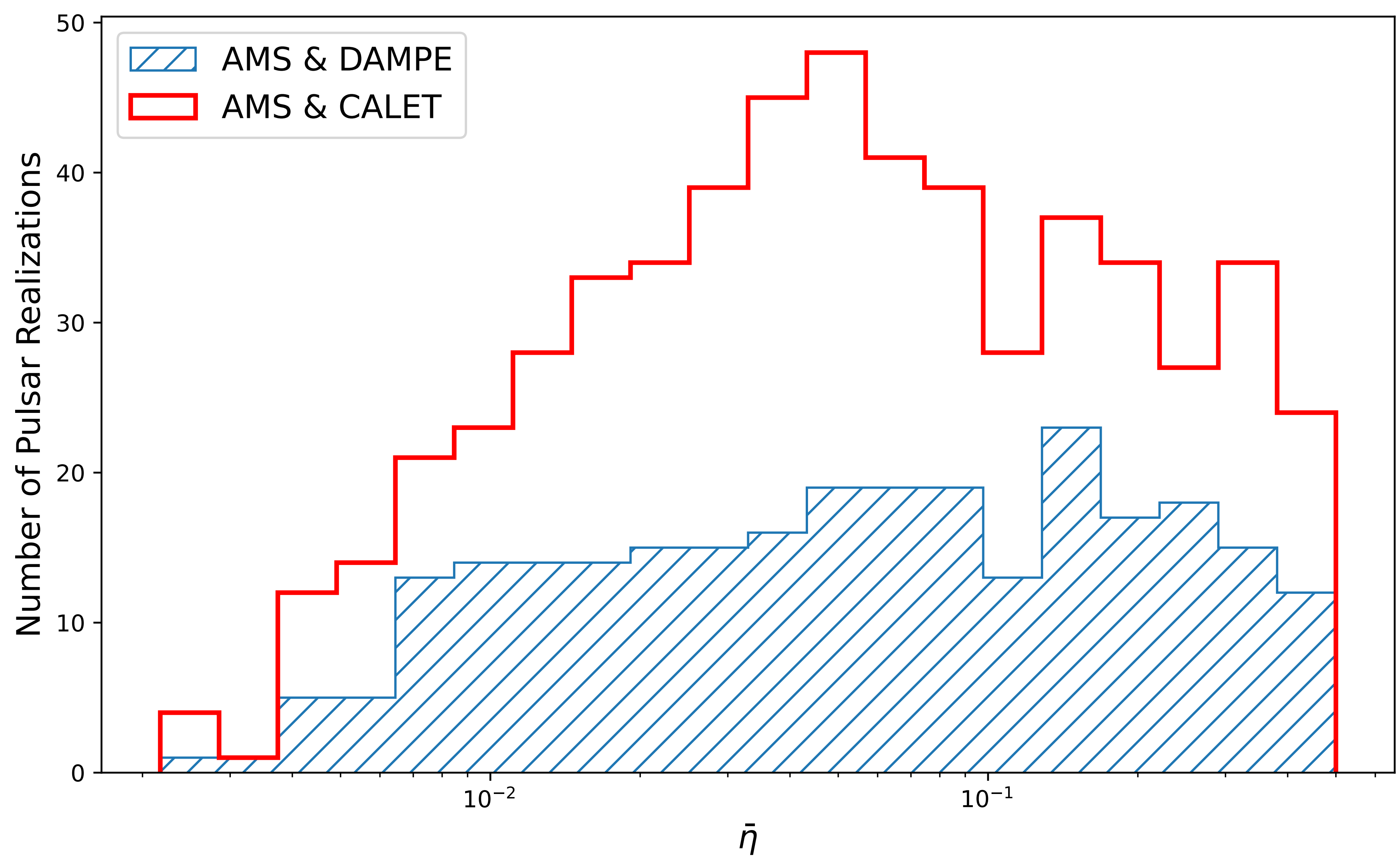
Total Lepton Flux from DAMPE (probing the youngest pulsars):



Total Lepton Flux from DAMPE (probing the youngest pulsars):

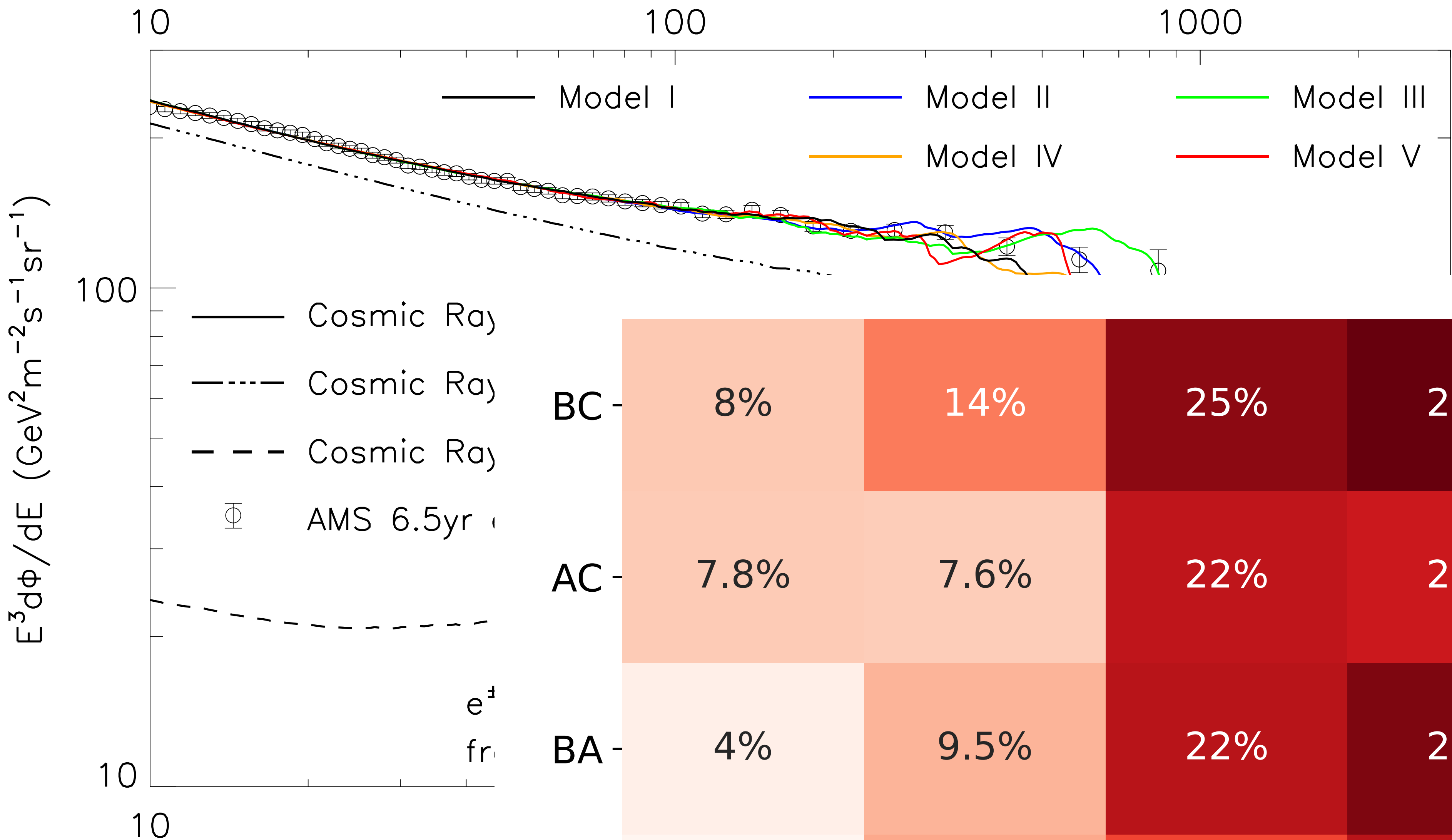


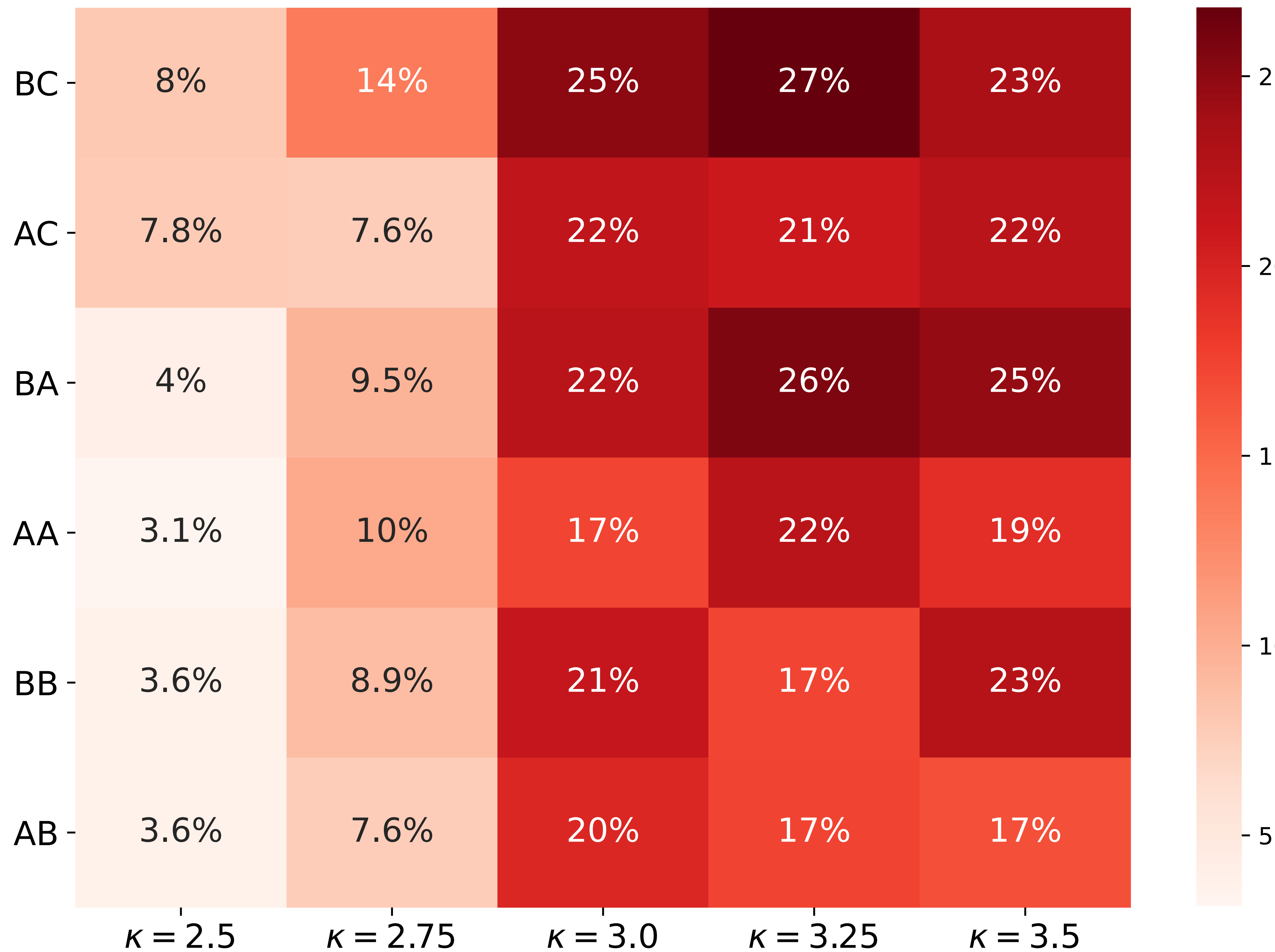
Conversion Efficiency to cosmic-rays:



Total Lepton Flux:

*Cholis, Krommydas, PRD **105** 023015 (2022)*

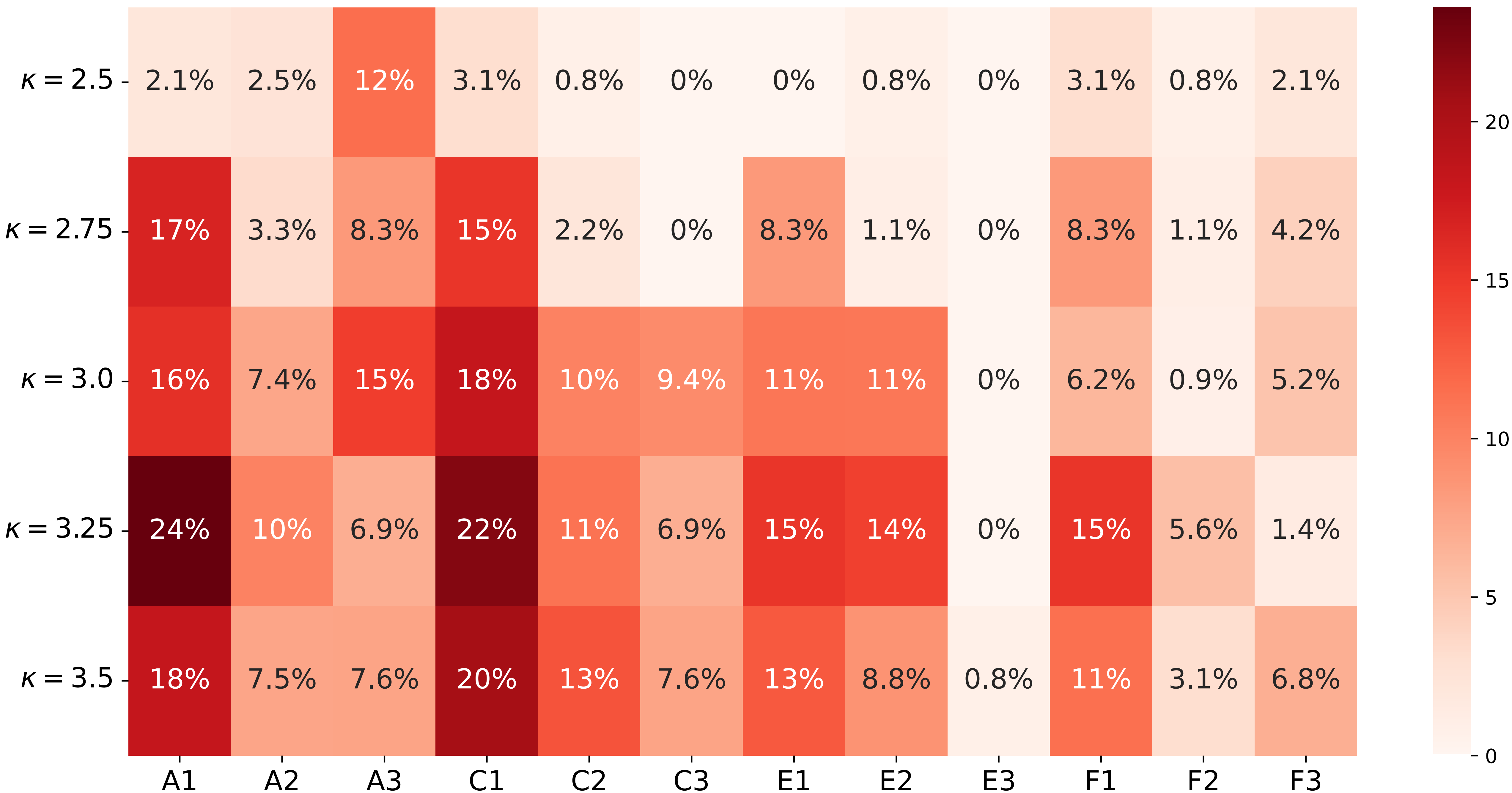




Pulsars have a time-evolving braking index that allows them to retain some of their rotational energy.

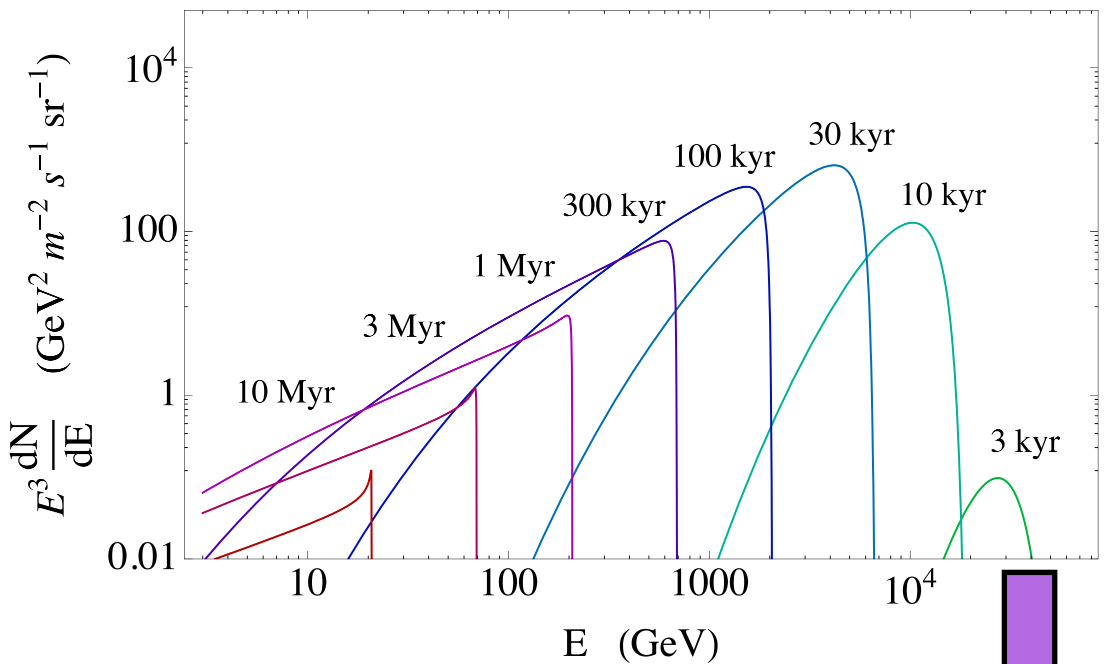
The impact on ISM assumptions

We can also invert the question on what we can learn about the ISM if pulsars are prominent sources of cosmic-ray electrons and positrons:



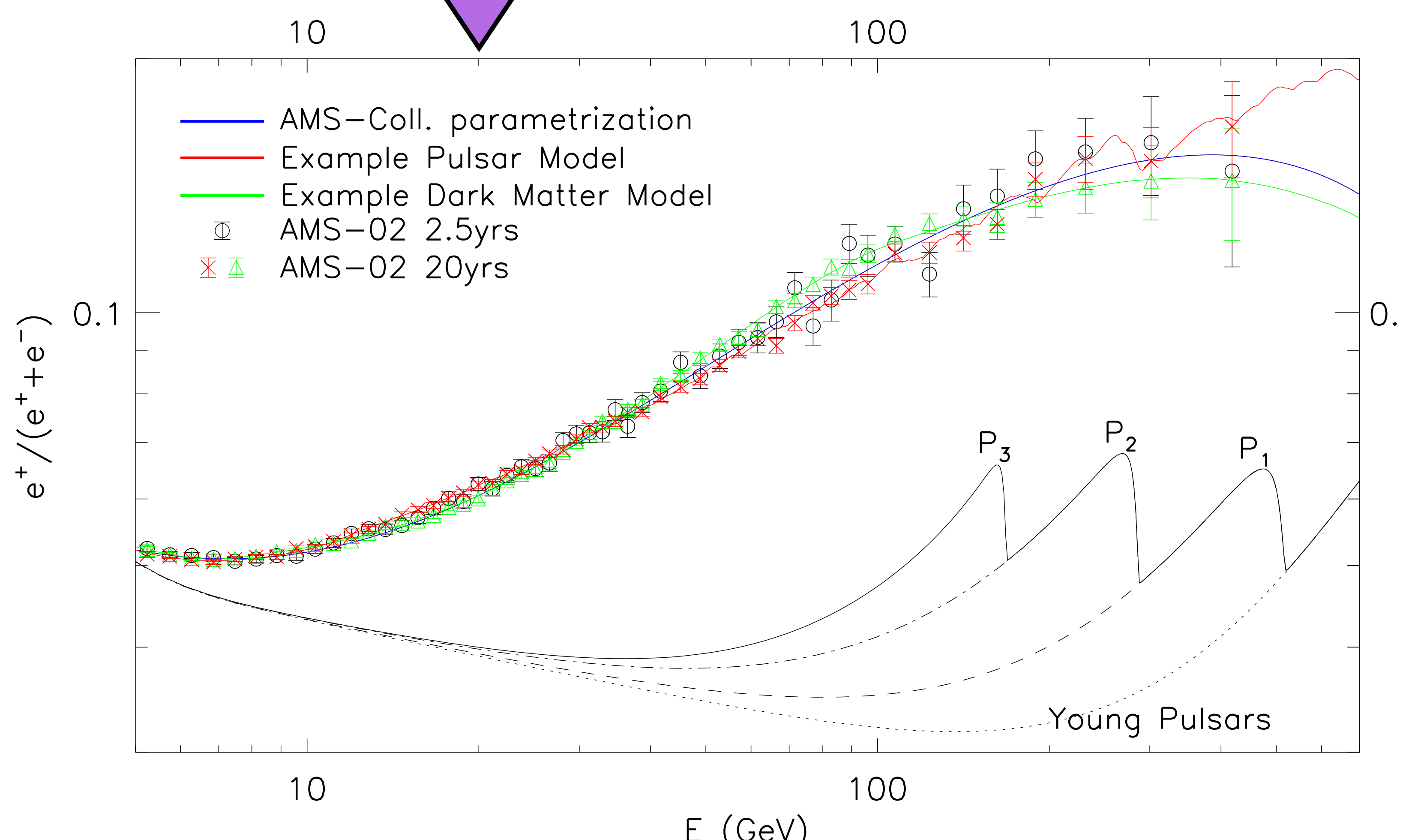
Next Goal: Pulsars VS Dark Matter

Single Pulsar CR flux Evolution with Time



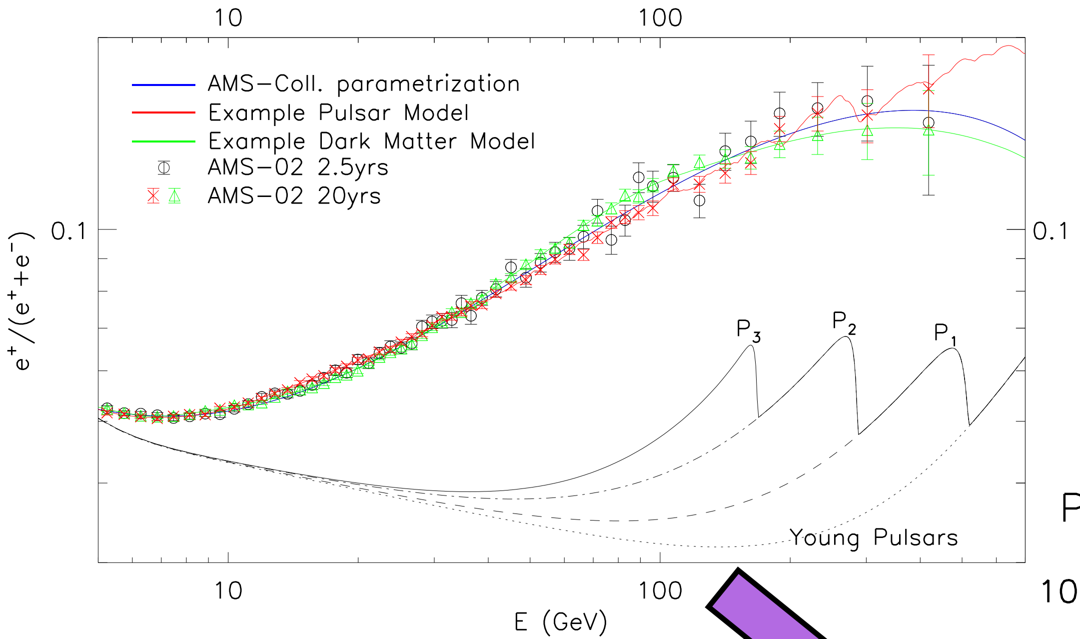
See positive/negative bumps at higher energy electrons & positrons.

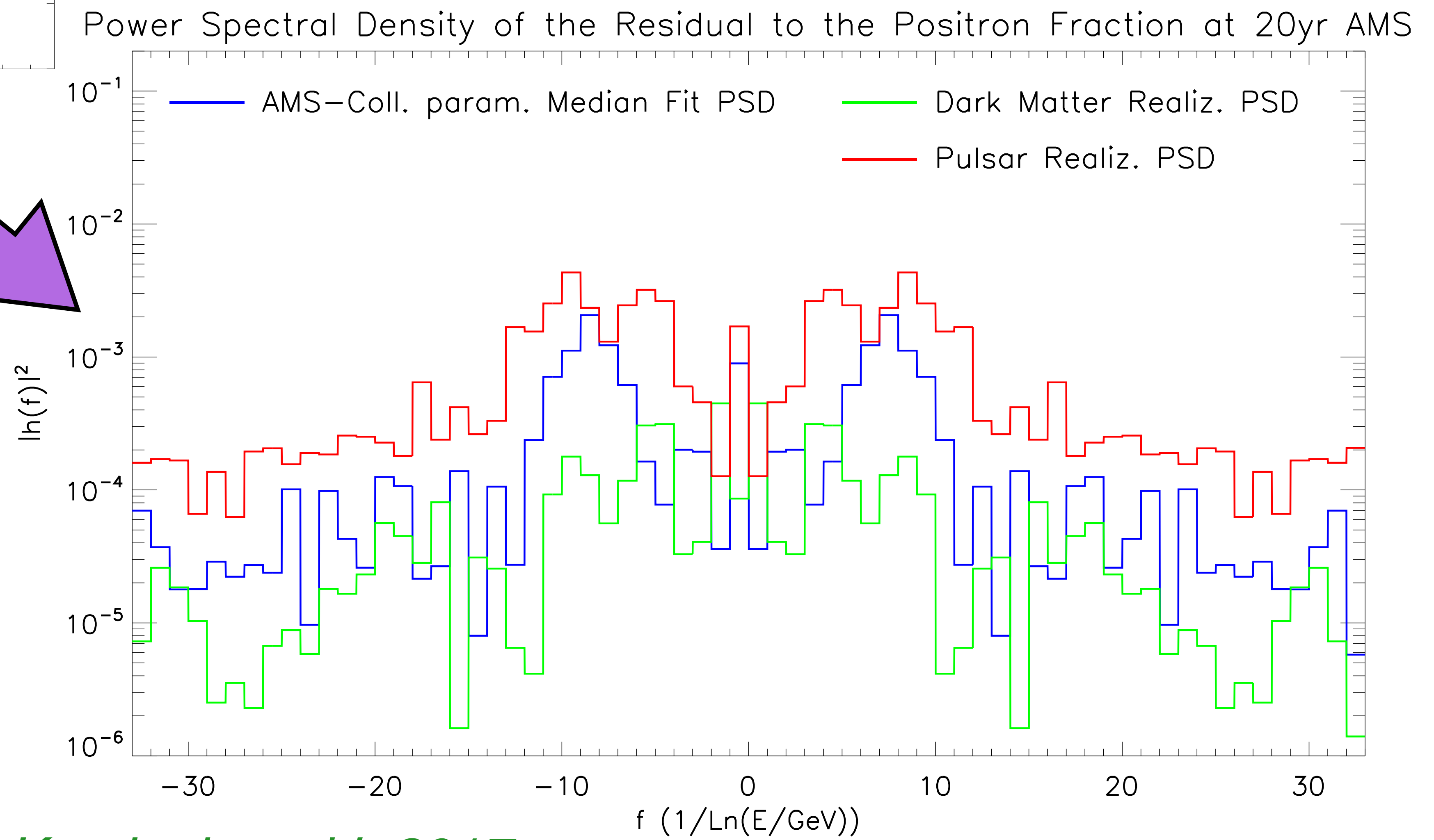
One bump/cut-off: DM
Many features: pulsars



***Cholis**, Karwal, Kamionkowski, 2017*

Technique to Differentiate: Power-Spectrum on the Cosmic-Ray Spectrum





***Cholis**, Karwal, Kamionkowski, 2017*

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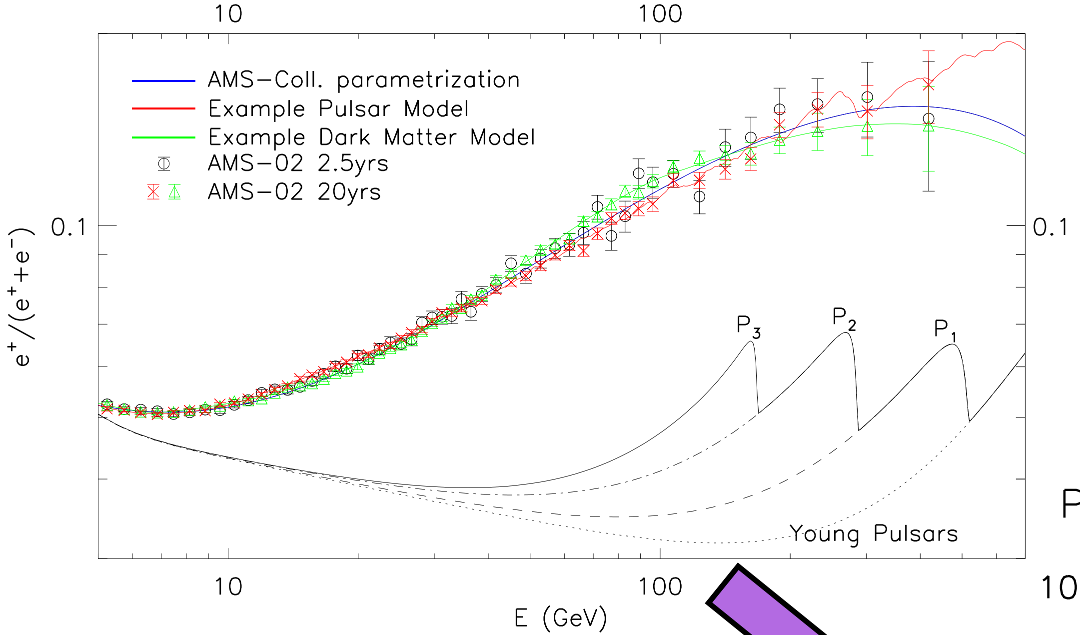
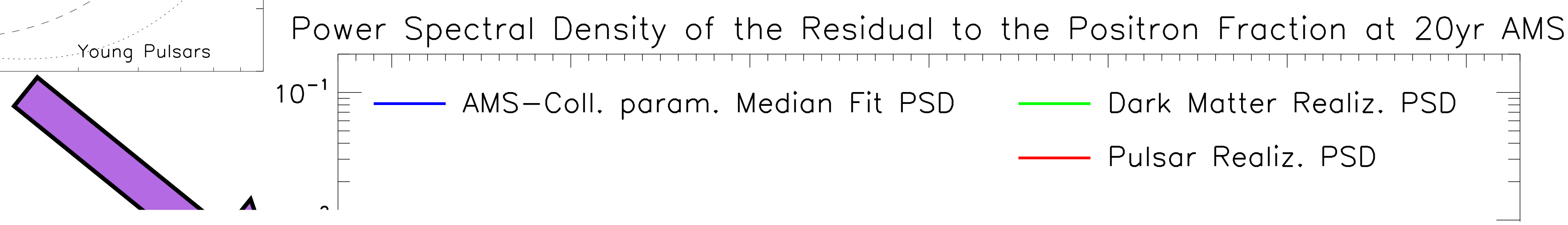
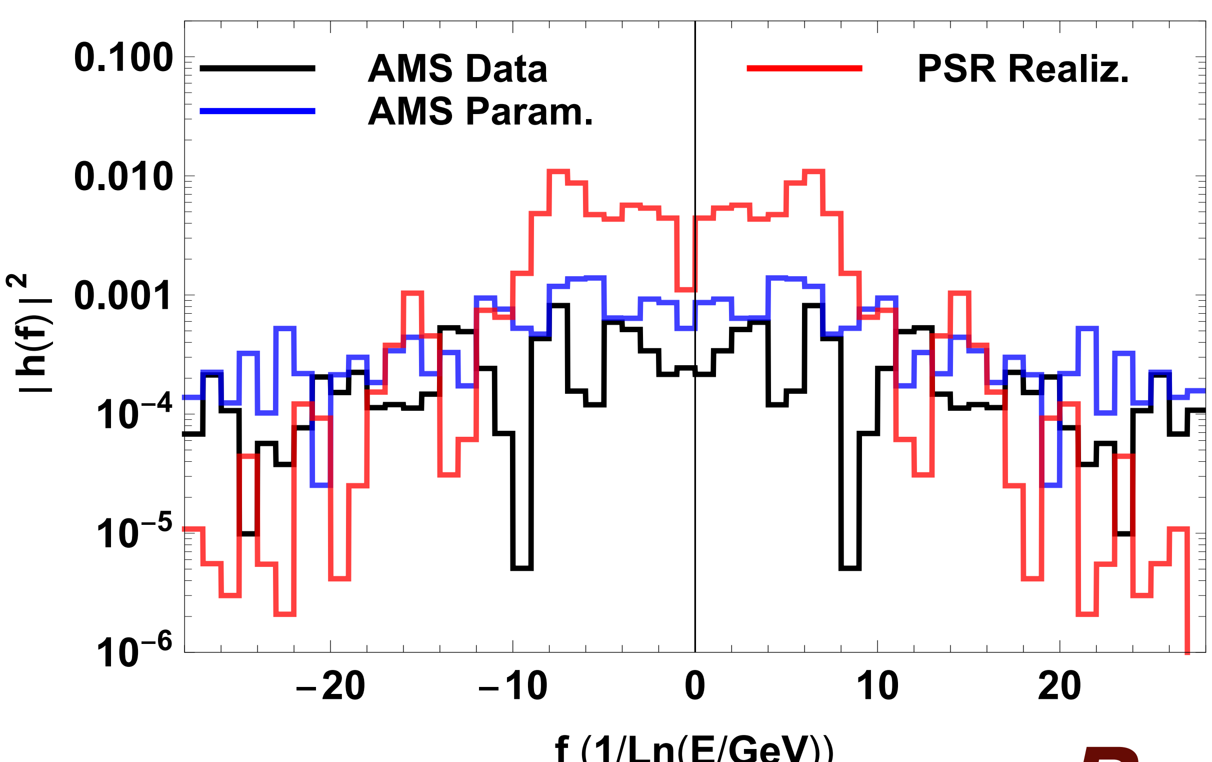
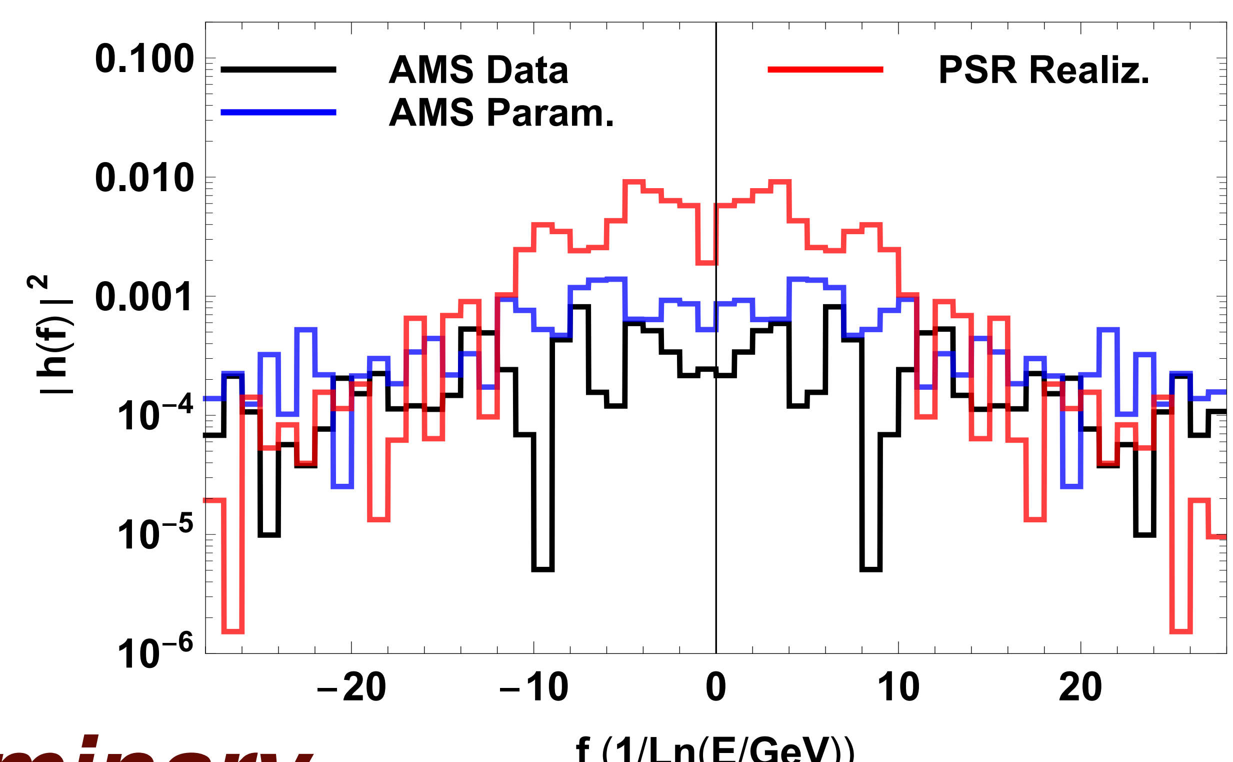






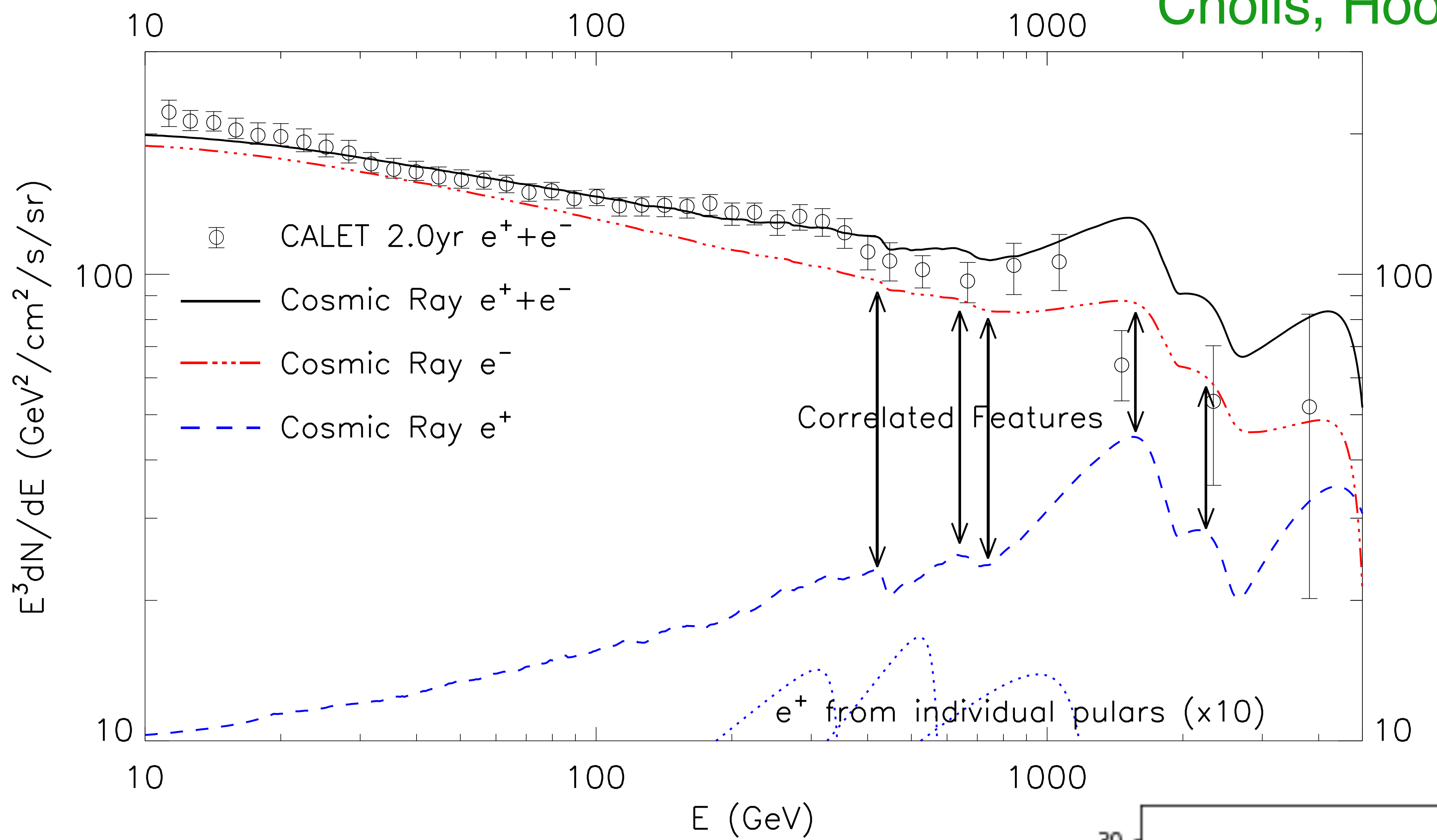


Preliminary

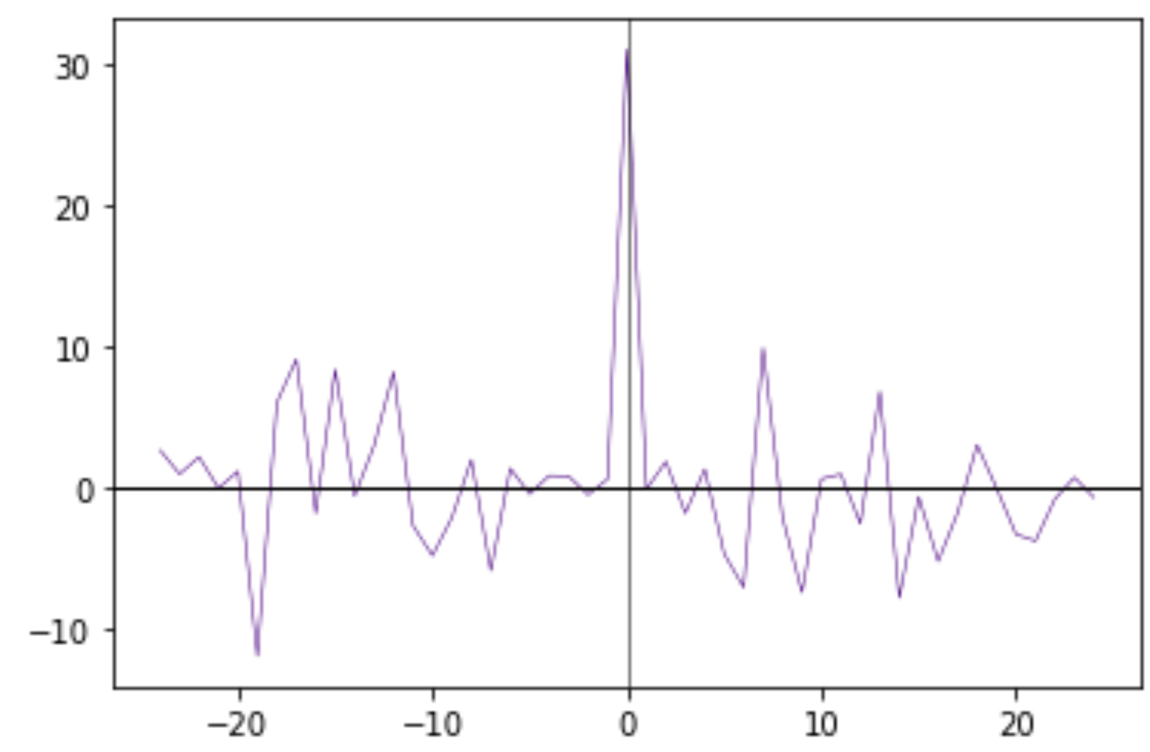
Cholis, Hoover (in prep. 2022)

Performing Cross-correlation of electrons and positrons

Cholis, Hoover (in prep. 2022)



Preliminary



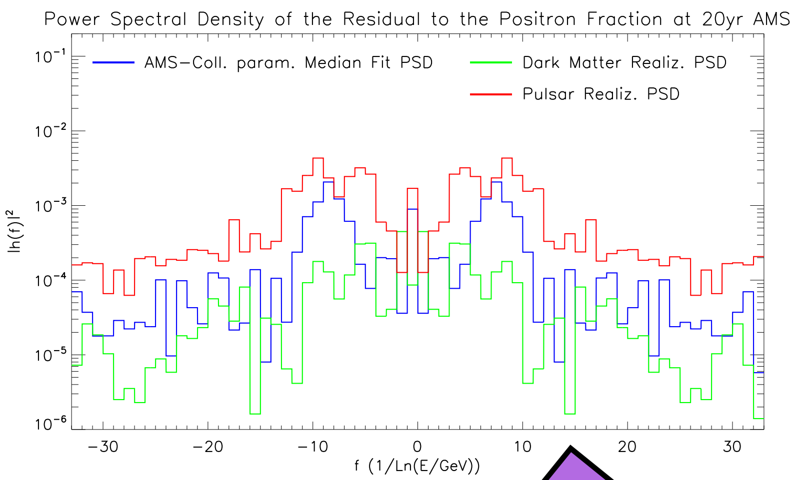
Can get a positive signal in the cross-correlation of the two cosmic-ray species… which we find indications for

Conclusions and what comes next

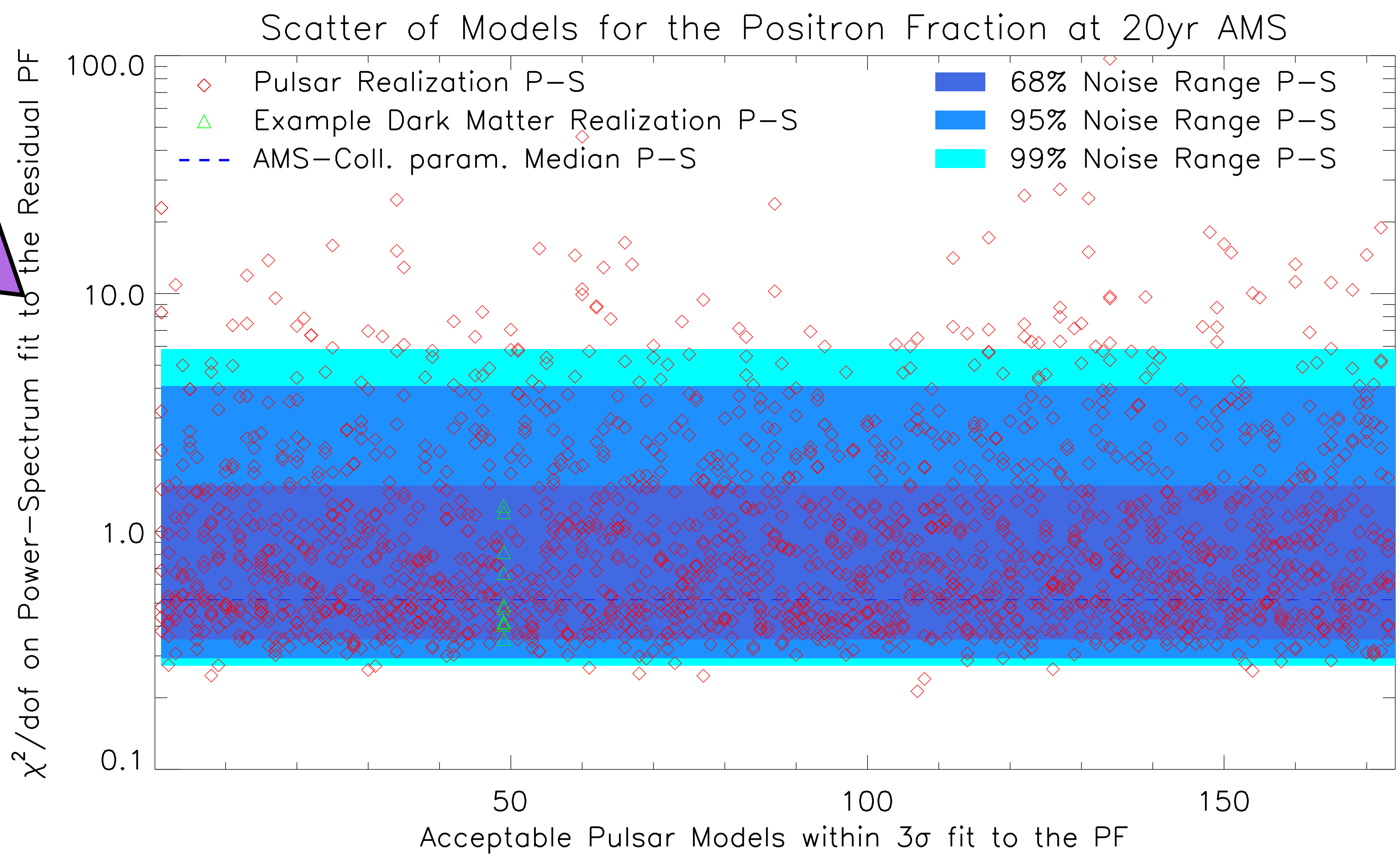
- Performed simulations on the Milky Way pulsars population, accounting for the various astrophysical modeling uncertainties.
- Tested simulations to recent cosmic-ray measurements to probe the averaged properties of pulsars at times well after EM observations are sensitive to provide us information on their evolution
- We find clear preference for braking index $\kappa \geq 3$
- We find that pulsars have quite uniform properties as sources of cosmic-ray electrons and positrons (fraction of E and spectrum) and likely release of $O(10\%)$ of their rotational energy to cosmic-rays in the ISM.
- We find at ~12 GeV an interesting spectral feature that suggests a new subpopulation of sources at (contribution from inner spiral arm or from dark matter)
- Early Stages of performing power-spectral calculations (auto-correlation)
- Cross-correlating the electron and the positron energy spectra for coinciding features in the measurements (we find some first hints)

Additional Slides

Power-Spectrum on the Cosmic-Ray Spectrum
Is it a robust Test?



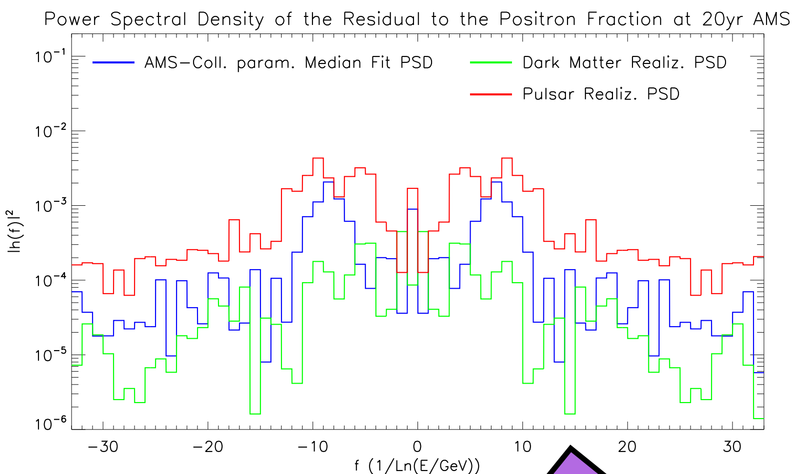
We run many simulations (900)

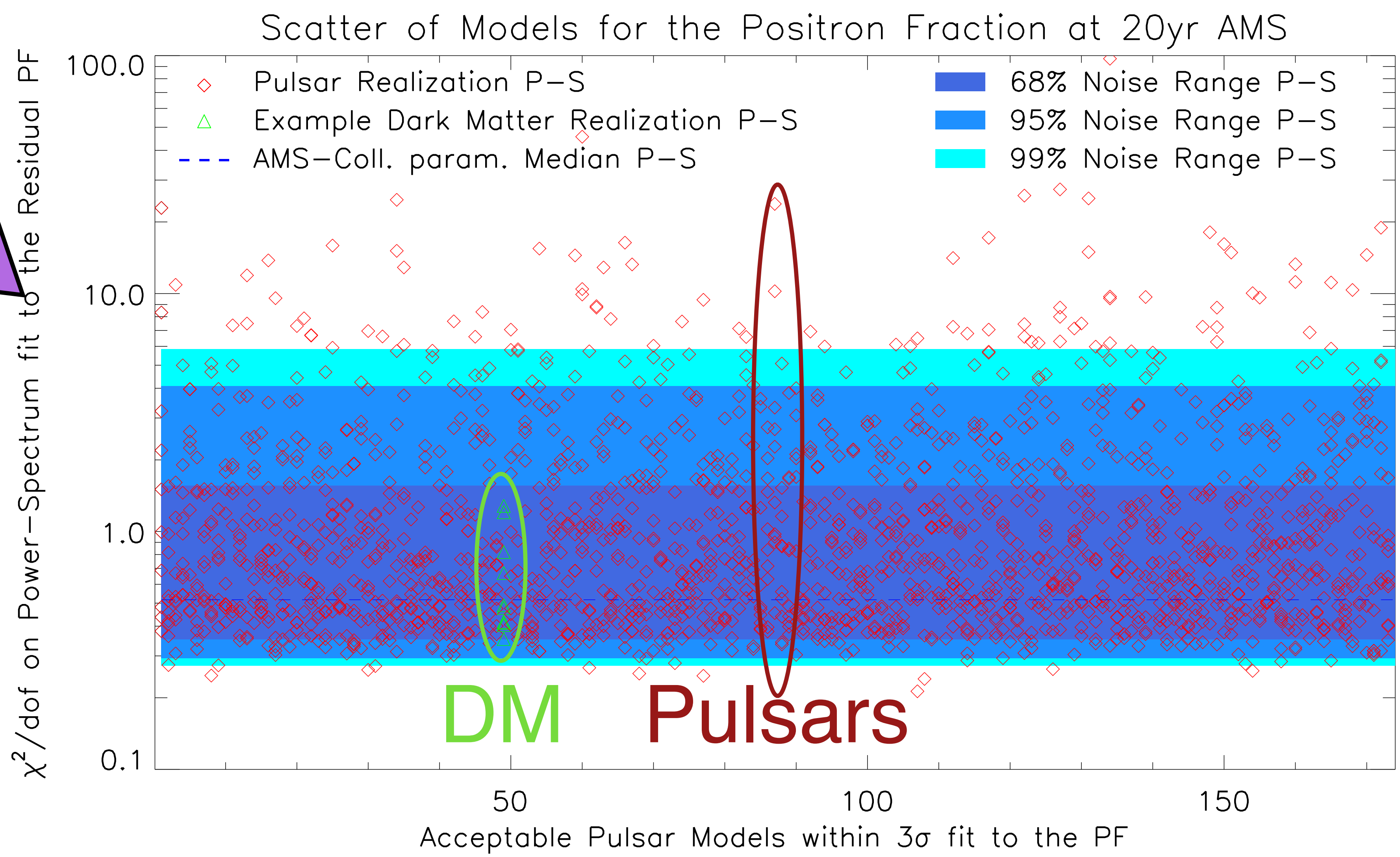


***Cholis**, Karwal, Kamionkowski, 2017*

Power-Spectrum on the Cosmic-Ray Spectrum

Is it a robust Test? Probably Yes.



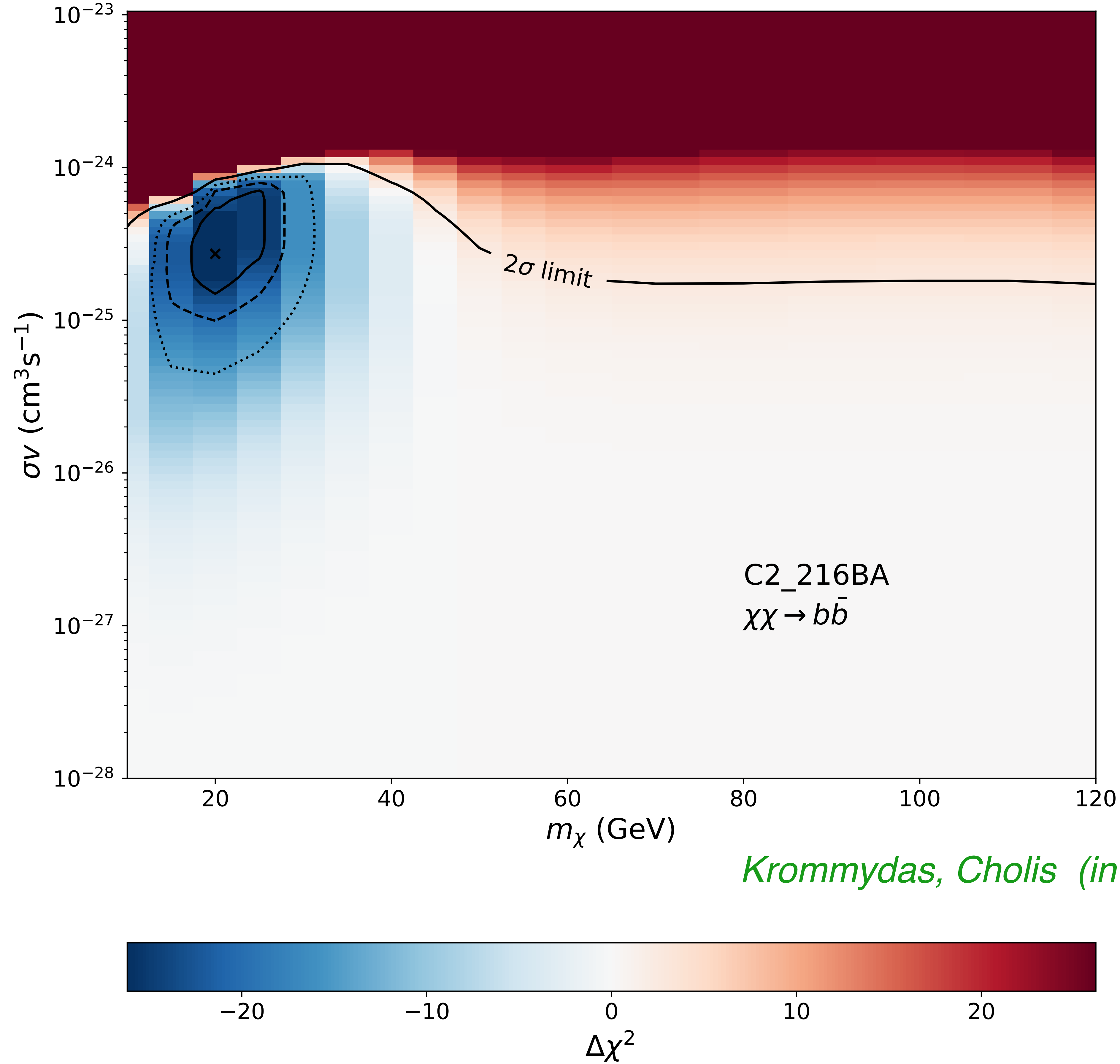


In 10-20 years we have a chance to observe a signal in the Power-Spectrum with AMS, and future experiments. Yet, uncertainties need to be further tackled.

***Cholis**, Karwal, Kamionkowski, 2017*

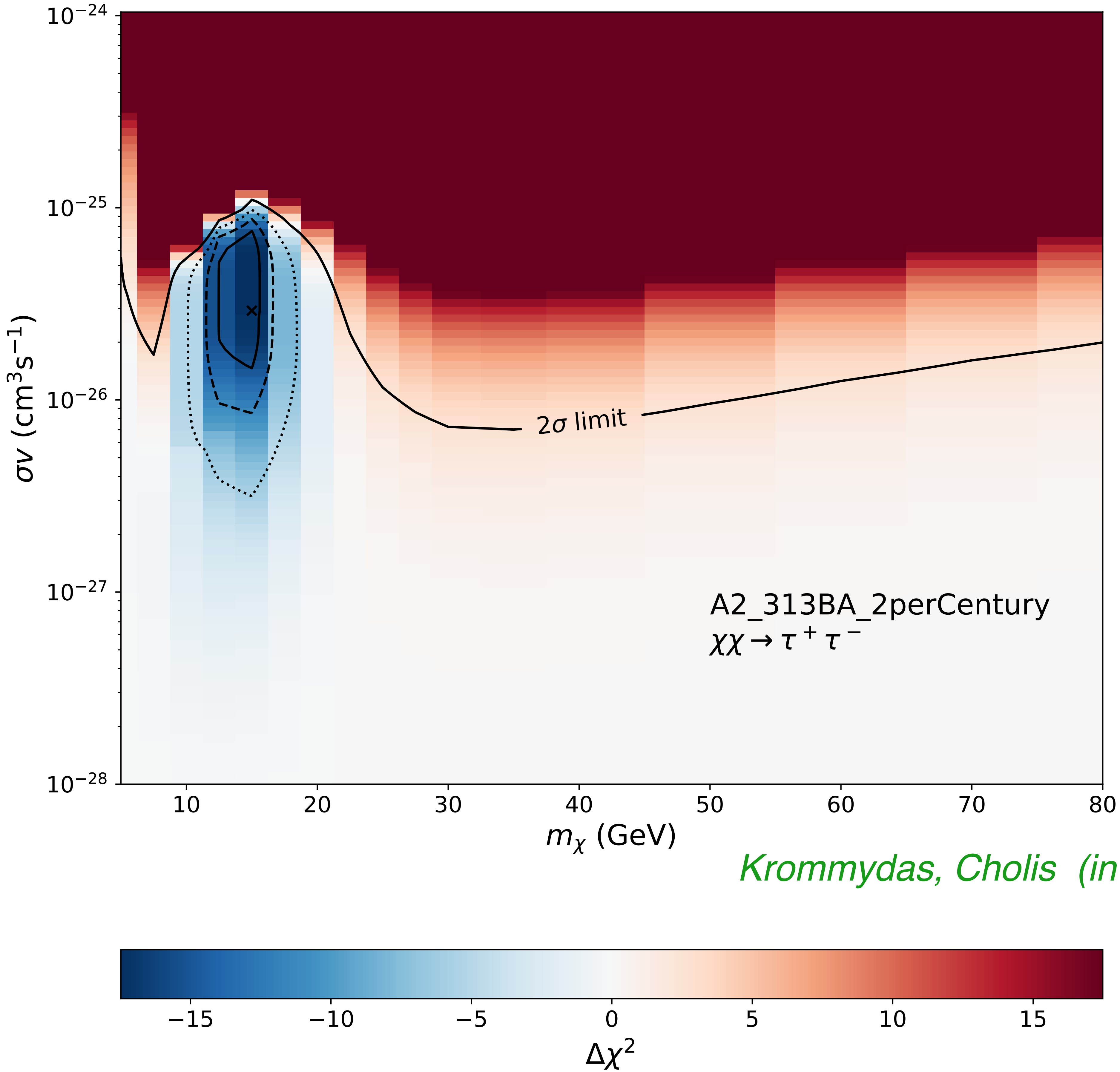
On the ~12 GeV feature:

Preliminary



Krommydas, Cholis (in prep. 2022)

On the ~12 GeV feature: Preliminary



Krommydas, Cholis (in prep. 2022)