FERMILAB-SLIDES-21-079-T

Updated Constraints on Pulsar Explanations for Positron Excess

Olivia Meredith Bitter
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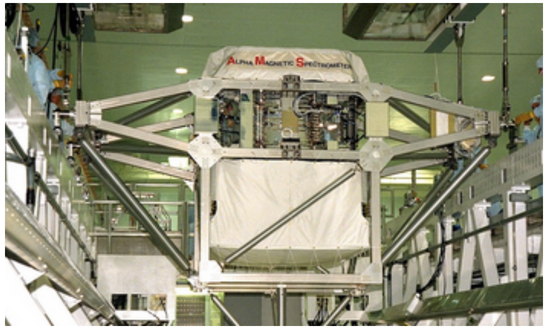
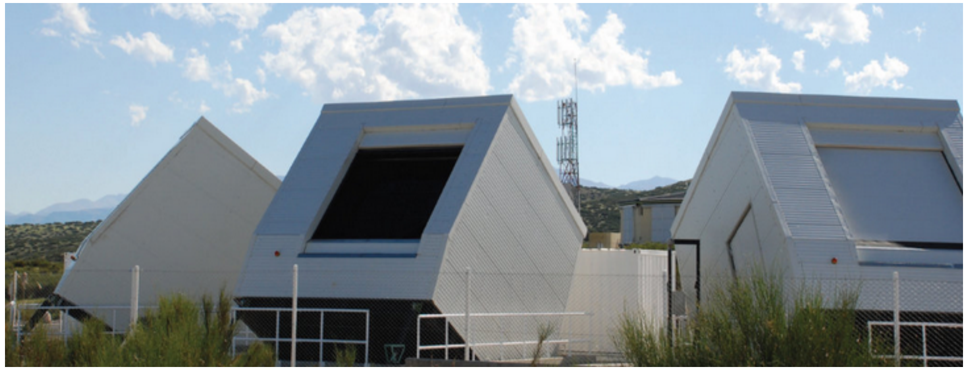
THE UNIVERSITY OF CHICAGO

THE POSITRON EXCESS STORY…

- Since the early 2000s, many cosmic ray telescopes and modules such as AMS-01, HEAT, and PAMELA have all indicated a substantial deviation in the observed **positron fraction** compared to the standard predictions of secondary productions of cosmic rays.
  - **positron fraction or flux ratio:** the ratio of the *number* of positrons to the combined number of electrons plus positrons present in the interstellar medium (ISM) - space between the astronomical bodies.
- These observations were *first* seen at energies roughly between 1 - 100 GeV.
- More recently, data from AMS-02 has shown that this tension is more noticeable up to at least 1TeV.



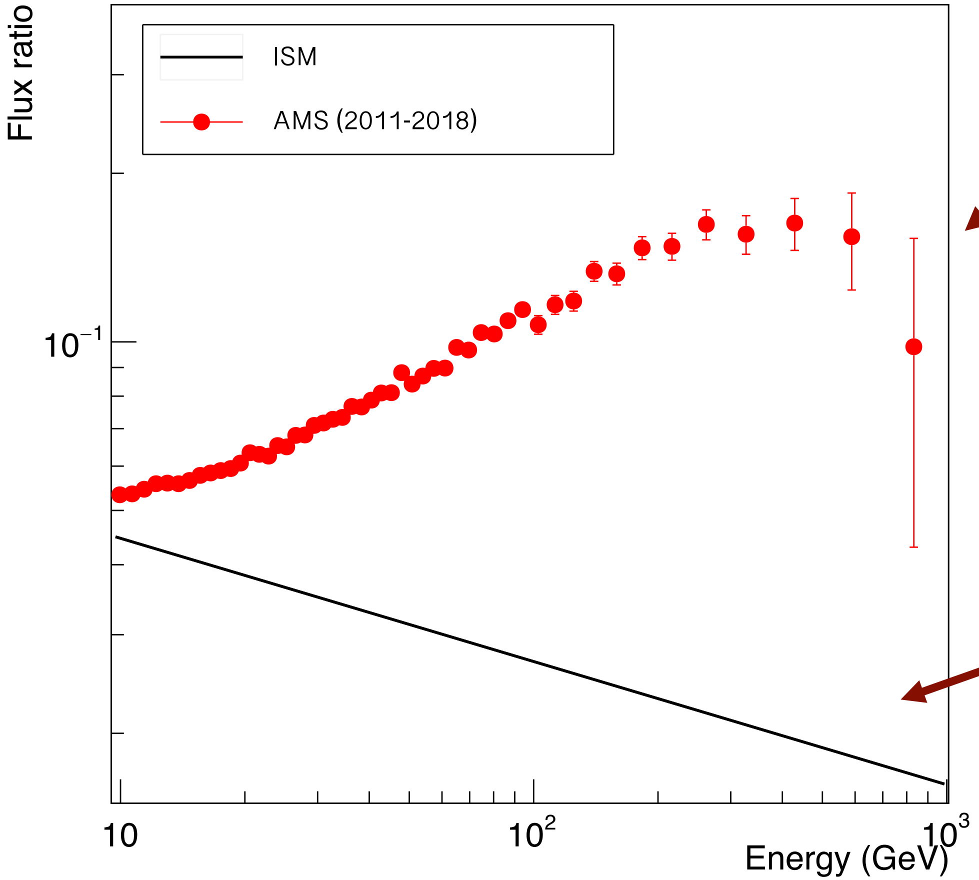


THE POSITRON EXCESS STORY…

Goals to answer:

What *source* could explain this tension?

And under what *constraints* can the contribution provide the best fit?



Observations from ASM-02

Predictions of the interstellar medium

ENTER THE PULSARS…

- One plausible solution to solve this ongoing tension is to consider **pulsars** - spinning neutron stars that are magnetized.
- Pulsars are a great source of high energy positrons and electrons because:
  - Relatively young and nearby pulsars have high gamma ray emissions as *seen* in experiments such as HAWC (High Altitude Water Cherenkov).
  - The gamma ray emission is produced by high energy particles such as positrons that are injected from pulsars into the interstellar medium.

COSMIC RAY PROPAGATION…

- More *specifically*, the high energy positrons that are injected into the ISM from pulsars, emit gamma rays through inverse Compton scattering and synchrotron radiation.
- It causes the injected electrons and positrons to loss energy, impacting their observed spectrum as seen on Earth. (This spectrum can be extracted via the standard propagation equation).

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r = Distance from our galactic center
E_e = electron/positron energy
t = cosmic time since pulsar birth

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,r,t) = \vec{\nabla}\cdot\left[D(E_e)\vec{\nabla}\frac{dn_e}{dE_e}(E_e,r,t) - \vec{v}_c\frac{dn_e}{dE_e}(E_e,r,t)\right]$$

$$+\ \frac{\partial}{\partial E_e}\left[\frac{dE_e}{dt}(r)\frac{dn_e}{dE_e}(E_e,r,t)\right] + \delta(r)Q(E_e,t)$$

Propagation equation

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Convection velocity responsible for Galactic wind

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Source term to describe how the positrons enter ISM

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Positron number density

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Diffusion coefficient index to describe the way the particles move in ISM

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,r,t) = \vec{\nabla}\cdot\left[D(E_e)\vec{\nabla}\frac{dn_e}{dE_e}(E_e,r,t) - \vec{v}_c\frac{dn_e}{dE_e}(E_e,r,t)\right]$$

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COSMIC RAY PROPAGATION…

- The differential number density term from the previous equation is *most useful* to describe the distribution of a single pulsar source.
- For the purpose of this study, these are Monte Carlo simulations (MC) that give both the distance of an MC source from Earth as well as its age.
- One can extract the pulsar contribution to the positron flux ratio for many free parameters.

Diffusion length scale

$$\frac{dn_e}{dE_e}(E_e, r, t) = \frac{Q_o E_e^{2-\alpha}}{8\pi^{3/2} E_e^2 L_{\mathrm{dif}}^3(E_e, t)} \exp\left[\frac{-E_o}{E_c}\right] \exp\left[\frac{-r^2}{4L_{\mathrm{dif}}^2(E_e, t)}\right]$$

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Normalization term

$$\frac{dn_e}{dE_e}(E_e, r, t) = \frac{Q_o E_o^{2-\alpha}}{8\pi^{3/2} E_e^2 L_{\mathrm{dif}}^3(E_e, t)} \exp\left[\frac{-E_o}{E_c}\right] \exp\left[\frac{-r^2}{4L_{\mathrm{dif}}^2(E_e, t)}\right]$$

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Spectral Index which indicates particle flux density

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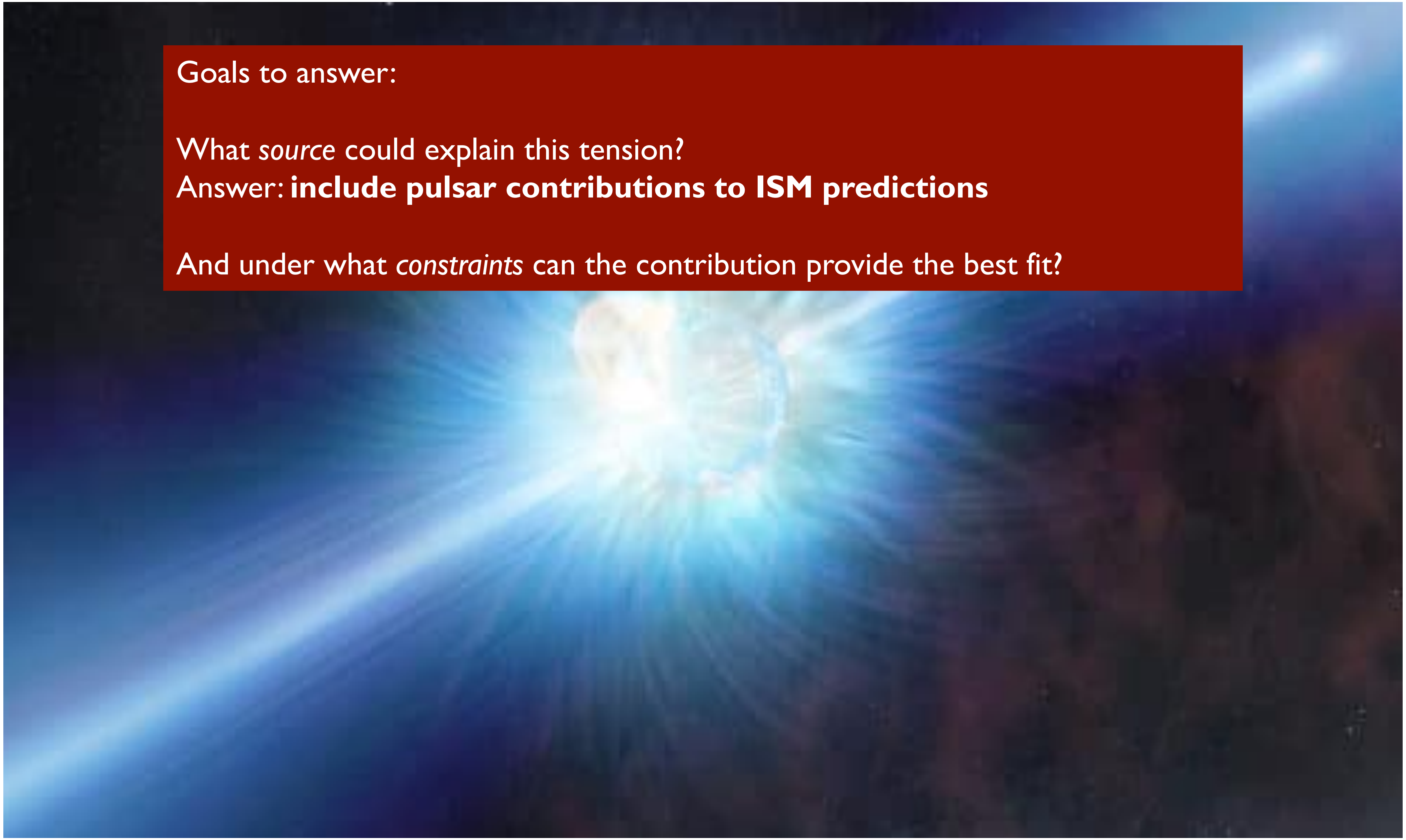
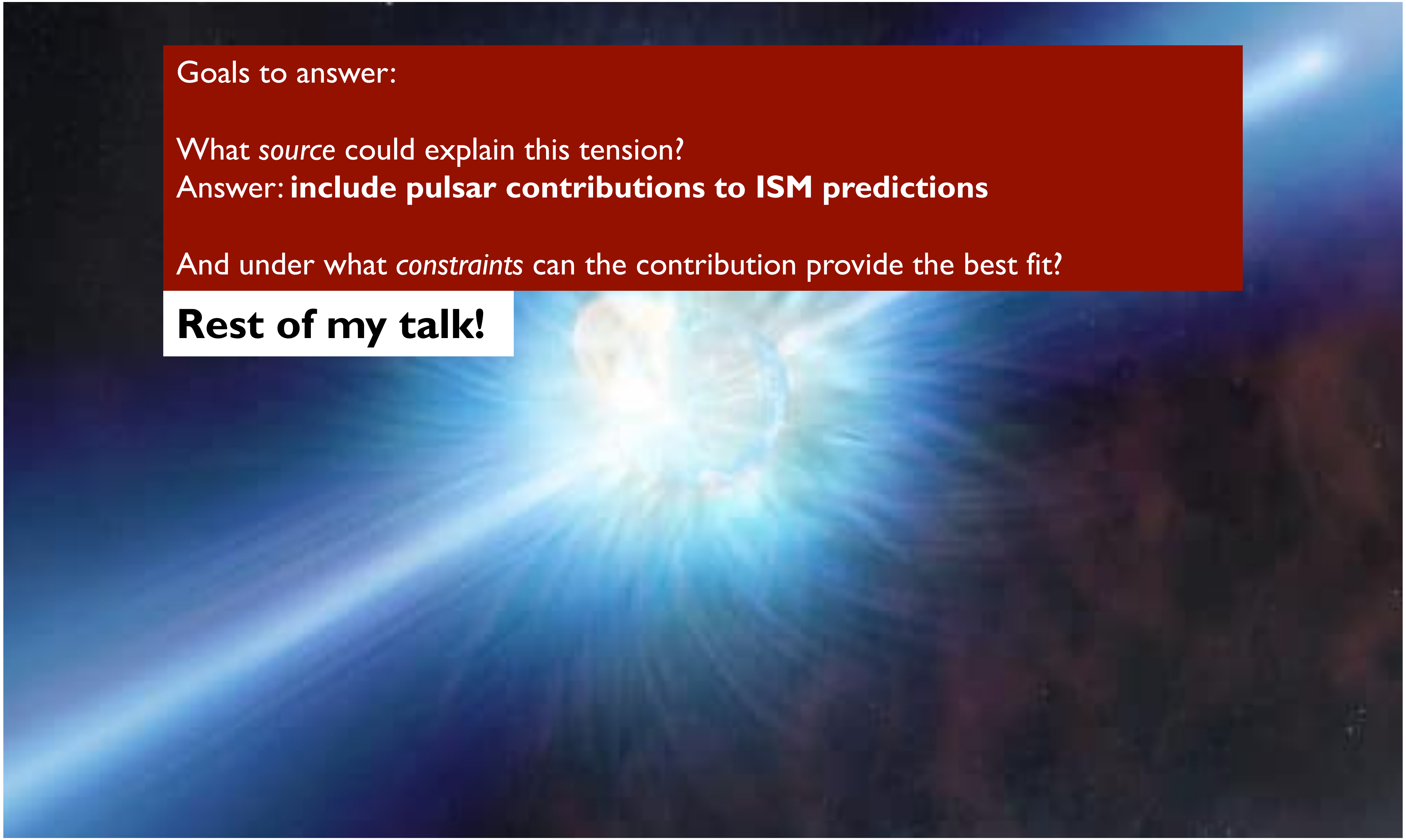
Goals to answer:

What *source* could explain this tension?
Answer: **include pulsar contributions to ISM predictions**

And under what *constraints* can the contribution provide the best fit?





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Rest of my talk!

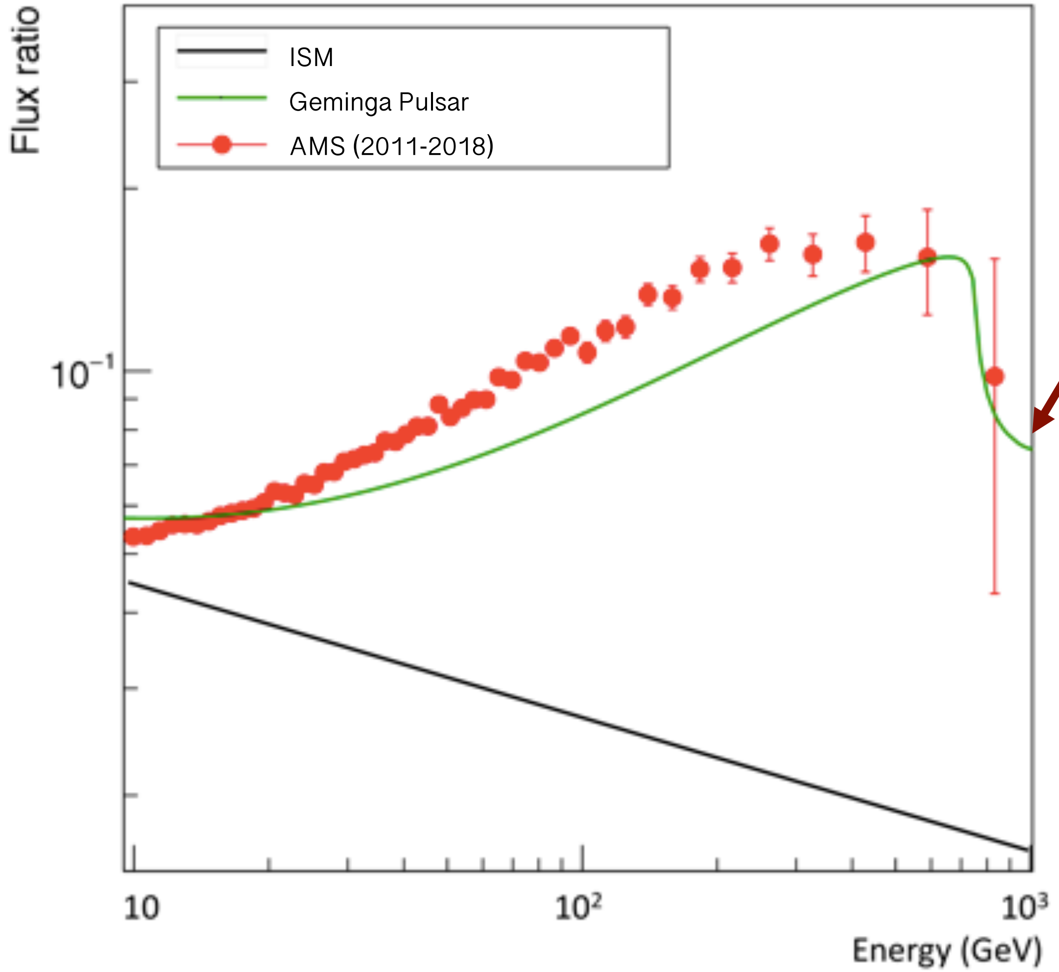
The following results and analysis builds upon previous work done by Hooper, Linden, and collaborators*.

They already proposed that young and nearby (to Earth) pulsars could best explain the positron excess.

These are updates to further constrain what characteristics pulsars *should have* in order to contribute the most to the positron flux excess.

*Previous publications include: arXiv:1304.1840 [astro-ph.HE], arXiv:0810.1527 [astro-ph], arXiv:1705.09293 [astro-ph.HE], arXiv:1711.07482 [astro-ph.HE], arXiv:1702.08436 [astro-ph.HE], arXiv:1304.1791 [astro-ph.HE].

INCLUDING THE PULSAR CONTRIBUTION…



Contribution from *only* the Geminga pulsar in green (it is both nearby and young).

Note: The above contribution used a *specific* set of free parameters: an efficiency of 29%, a spectral index of 1.9 and a spectral energy of 50 TeV.

THE FREE PARAMETERS…

- The free parameters which constitute the characteristics exhibited by pulsars within a given population. The main ones that affect the pulsar flux contributions are:

  - **Spin-down Time**: time between injections of particles into the ISM.
  - **Spin-down Flux:** rate of rotational kinetic energy lose per distance from Earth squared – this is used as a threshold for determining MC sources already detected by gamma rays.
  - **Efficiency**: percent of rotational kinetic energy loss from injection.
  - **Spectral Index**: indicator of particle flux density in the power-law distribution concerning frequencies of positrons and electrons.
  - **Pulsar Birth Rate**: rate per century of the number of pulsars born.
  - **F_{beam} Radio and F_{beam} Gamma:** fractions of MC sources that are considered to be detected (either by gamma rays or in radio) and catalogued in ATNF.

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Focus

- **Spin-down Time**: time between injections of particles into the ISM.
- **Spin-down Flux:** rate of rotational kinetic energy lose per distance from Earth squared – this is used as a threshold for determining MC sources already detected by gamma rays.

Used to normalize to a good fit

- **Efficiency**: percent of rotational kinetic energy loss from injection.

Fixed

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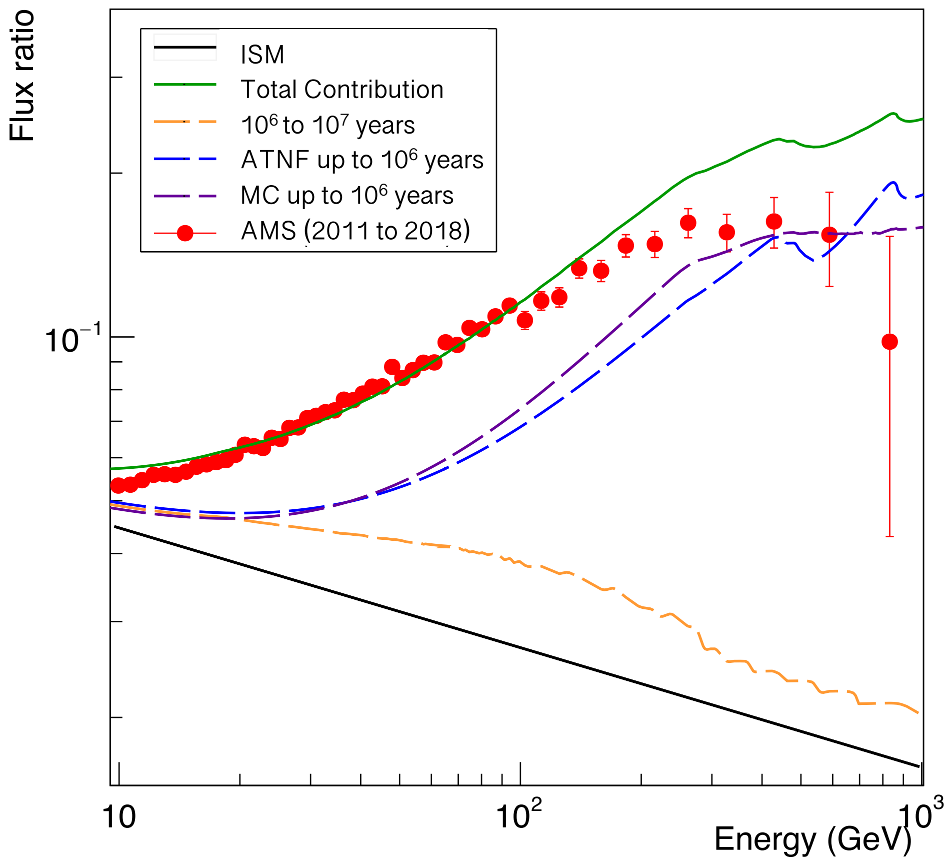
PRELIMINARY RESULTS…

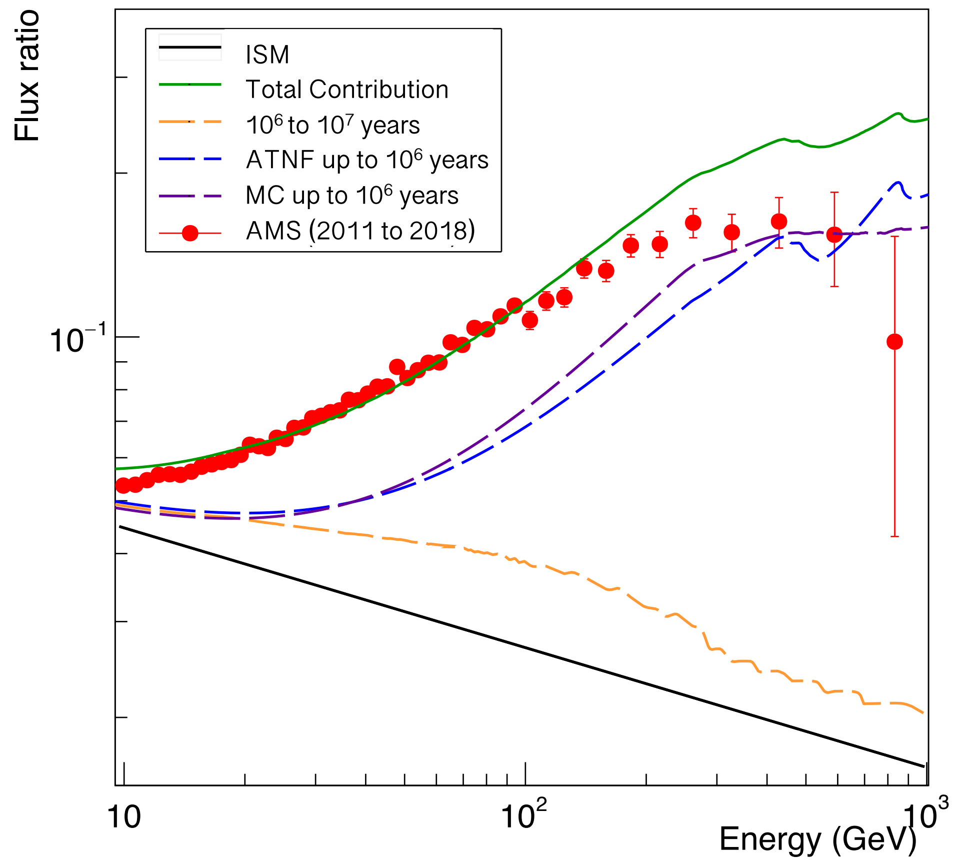
- Preliminary analysis has further constrained that:
  - Pulsars *younger* than a million years and *within* 3 kpc of Earth to contribute the most.*
  - But pulsars between a million years to ten million years old are still included as they raise the ISM prediction threshold. (orange dashed line)
- Also, included are all *known* pulsar sources *younger* than a million years and *within* 3 kpc of Earth. (blue dashed line).
- And, the Monte Carlo simulations that cover sources *not yet known*. (purple dashed line)
- Note that for each energy bin, the three dashed lines on the right add up to the solid green line.



*Note that the three dashed lines *exclude* pulsar sources further than 3 kpc away from Earth. Our analysis showed that they contribute negligibly.

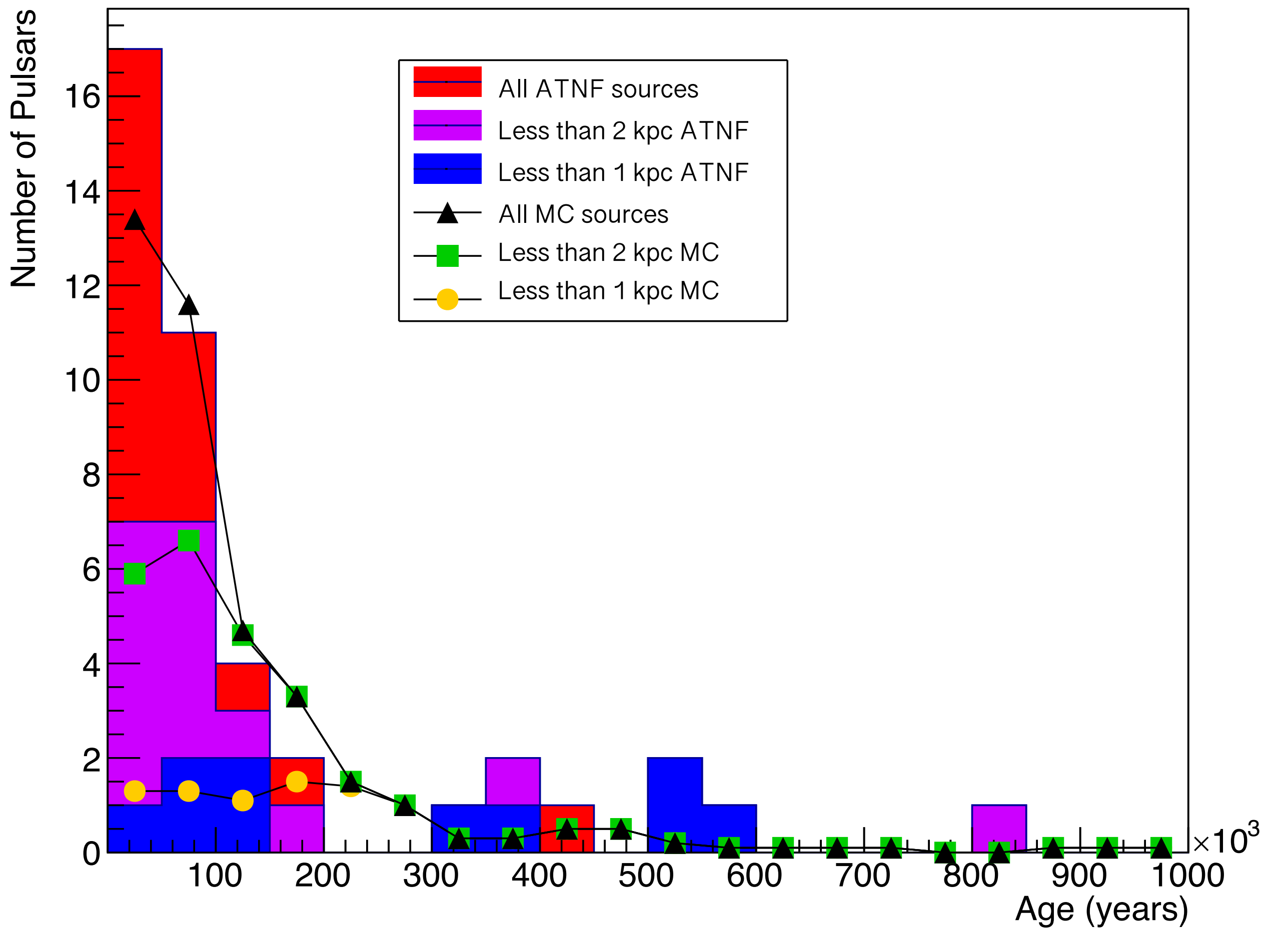
PRELIMINARY RESULTS…

- Best fit so far…
  - An example contribution showing how the three considerations add to give a total pulsar contribution to the flux ratio.
  - Free parameters:
    - **spin-down time of 1 x 10^4 years**
    - **spin-down flux of 5 x 10^{42} ergs/kpc^2/yr**
    - **efficiency of 1.8%**
    - **spectral index of 1.9**
    - **pulsar birth rate of 1 per century**
    - **F_{beam} radio of 15% and F_{beam} gamma of 50%**
  - Past 100 GeV, the deviation indicates that further adjusting of parameters is needed to provide a better fit.
  - One should note that this result is a "simple case" where it assumes that *all* MC generated pulsars have the same spin-down time and period which, in reality, would not be the case.



PRELIMINARY RESULTS…

- Another look at the same conclusion statistically…
  - The histogram shows the distribution of the gamma ray sources in ATNF broken up by distance range.
  - The line plots that are overlaid are the *average values* of 10 MC source distributions that follow the same parameters as shown in the plot on the previous slide.



PRELIMINARY RESULTS…

- The table lists the Poisson probability or likelihood of the "focus" parameters (spin-down time and spin-down flux) to show *quantitatively* which set is more favored to explain the positron excess.

Spin-down Timescales

Spin-down Flux

	5×10^3 years	1×10^4 years	2×10^4 years	5×10^4 years
1×10^{42} ergs/kpc^2/yr	6.63×10^{-27}	4.74×10^{-33}	8.77×10^{-56}	3.91×10^{-97}
5×10^{42} ergs/kpc^2/yr	1.15×10^{-36}	3.25×10^{-26}	7.17×10^{-30}	1.96×10^{-58}
1×10^{43} ergs/kpc^2/yr	5.57×10^{-44}	9.63×10^{-30}	1.72×10^{-28}	8.12×10^{-48}
5×10^{43} ergs/kpc^2/yr	4.37×10^{-50}	1.44×10^{-43}	8.49×10^{-35}	8.29×10^{-28}

Best likelihood *so far* for the given combination of parameters. There is agreement on what these parameters should be from both numerical and graphical analysis.

CONCLUSIONS

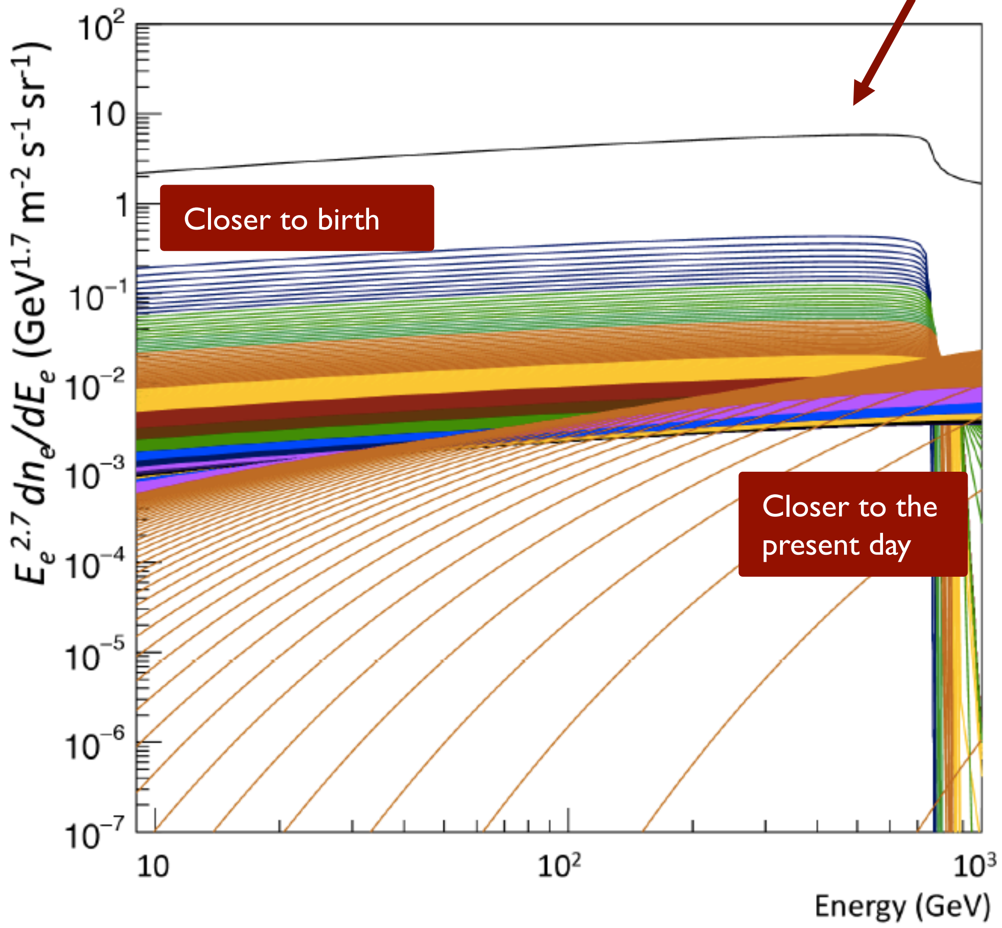
- Pulsar populations do provide a **very plausible solution** to the positron excess problem.
- Furthermore, sources **within 3 kpc** of Earth and **younger than a million years old** contribute the most.
- In the preliminary results, **a simple case** of fixing most free parameters – the only two that change being **the spin-down time and spin-down flux**.
  - With these assumptions, the full contribution from all three considerations add to provide a **very good fit to AMS data**.
- Further work will seek to constrain the free parameters **more precisely.**
- **Final results soon be published.**


THANK YOU!


BACK UP SLIDES

Process of obtaining pulsar contribution:

Geminga differential number density



Time profiles: shows the differential number density after every 10,000 years. One adds the profile's value per energy bin to obtain the black line at the top of the plot

$$Q(E_e, t) = \delta(t) Q_0 E^{-\alpha} \exp(-E_e/E_c)$$

Source description

For each energy bin:
Take **half** of the black line and **add** it to the ISM positron contribution and also to the ISM electron contribution

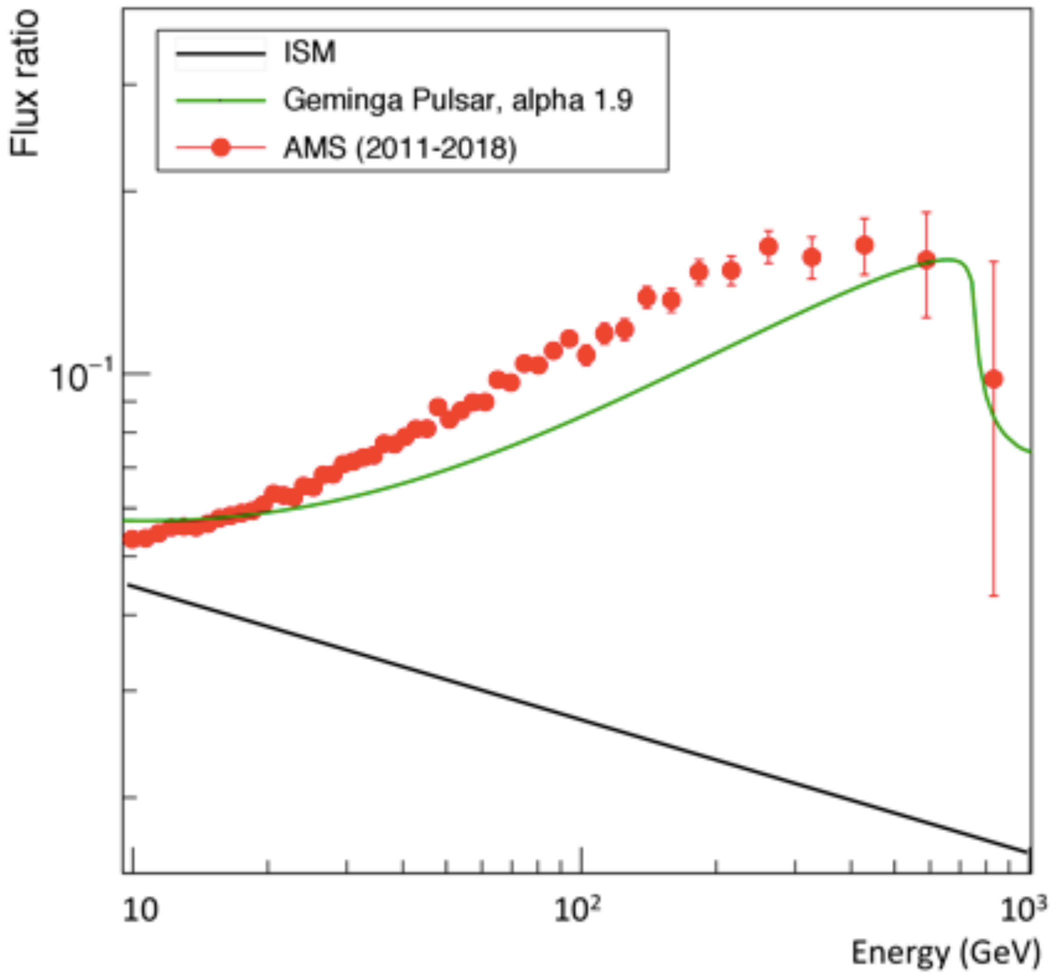
Process of obtaining pulsar contribution:

Geminga contribution

$$\text{Positron fraction} = \frac{\text{ISM positron} + \textbf{Geminga} \text{ contrbutions}}{(\text{ISM positron} + \textbf{Geminga}) + (\text{ISM electron} + \textbf{Geminga}) \text{ contrbutions}}$$

The Geminga contribution is the "halved" amount plotted in the previous slide.

The positron fraction *is* the flux ratio.

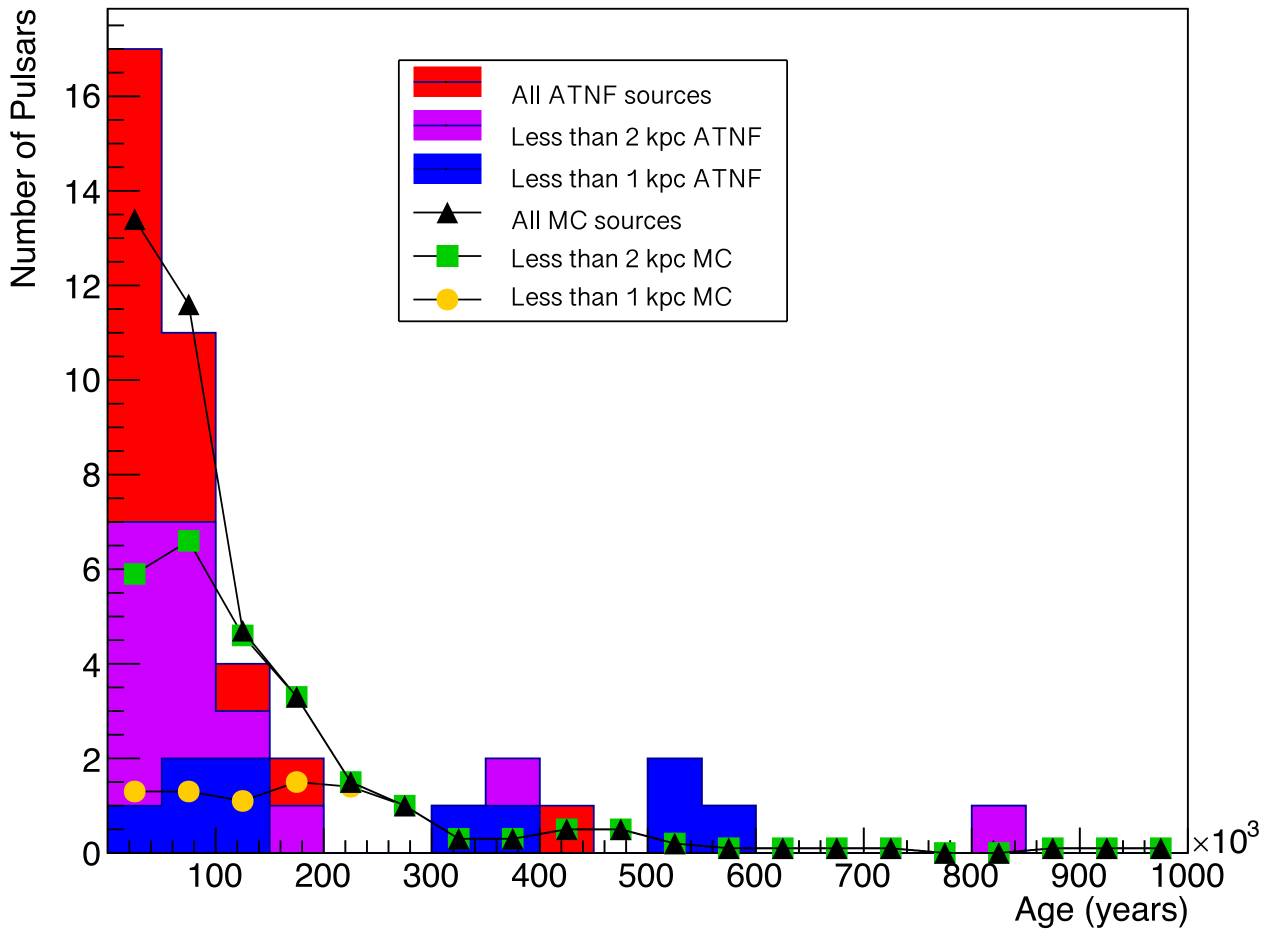


Process of obtaining Poisson probability:

$$\text{Probability or Likelihood} = \prod \frac{\lambda(i)^{k(i)} e^{-\lambda(i)}}{k(i)!}$$

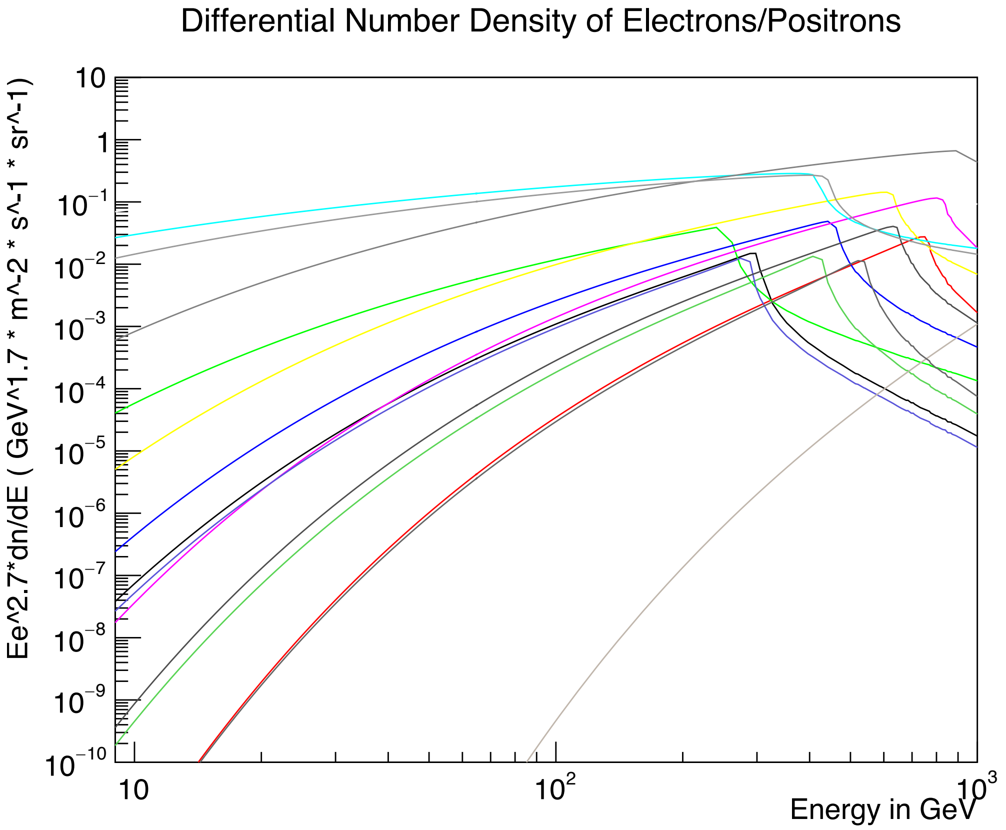
Histogram: ATNF (k(i))
Scatter Plots: Average of 10 MCs ($\lambda(i)$)

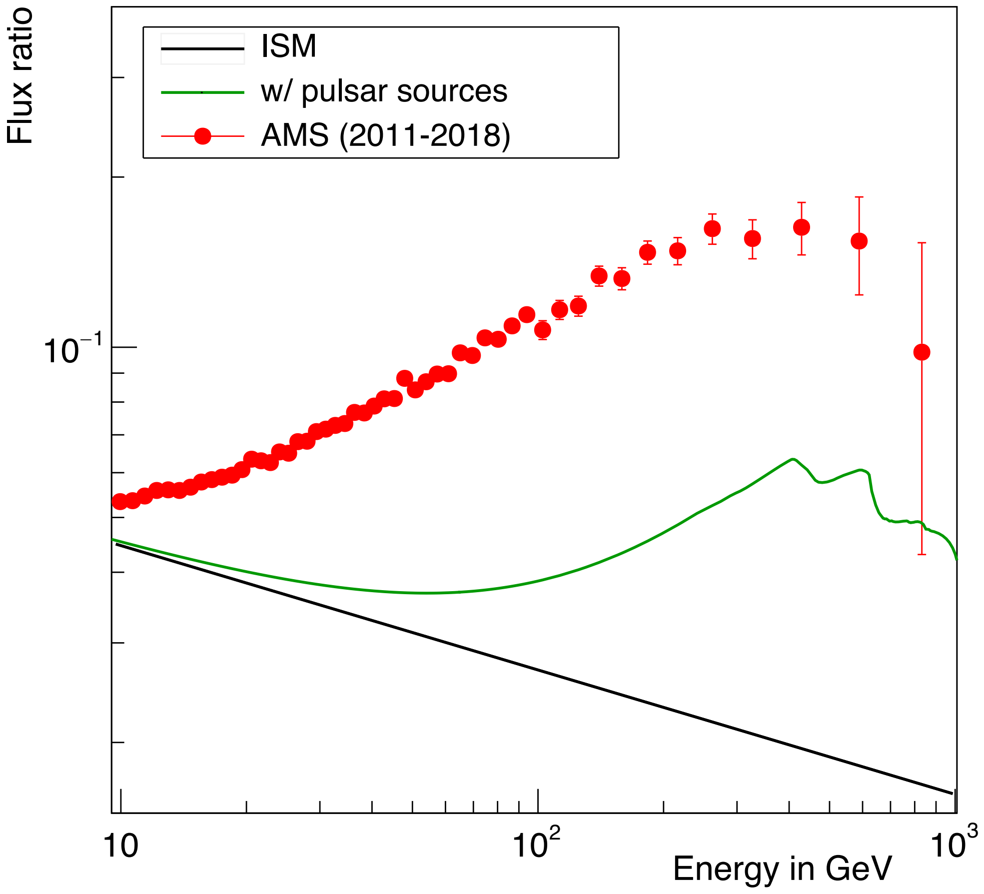
Note that this is done for each distance consideration, not just per energy bin. Hence, the index goes up to 60 terms.



Pulsar ages and their characteristics:
(a sample MC of pulsars from 10^5 years to 10^6 years)

Age differences cause the extra "humps" in contributions. – impacts at what energy the pulsar can provide a substantial contribution.



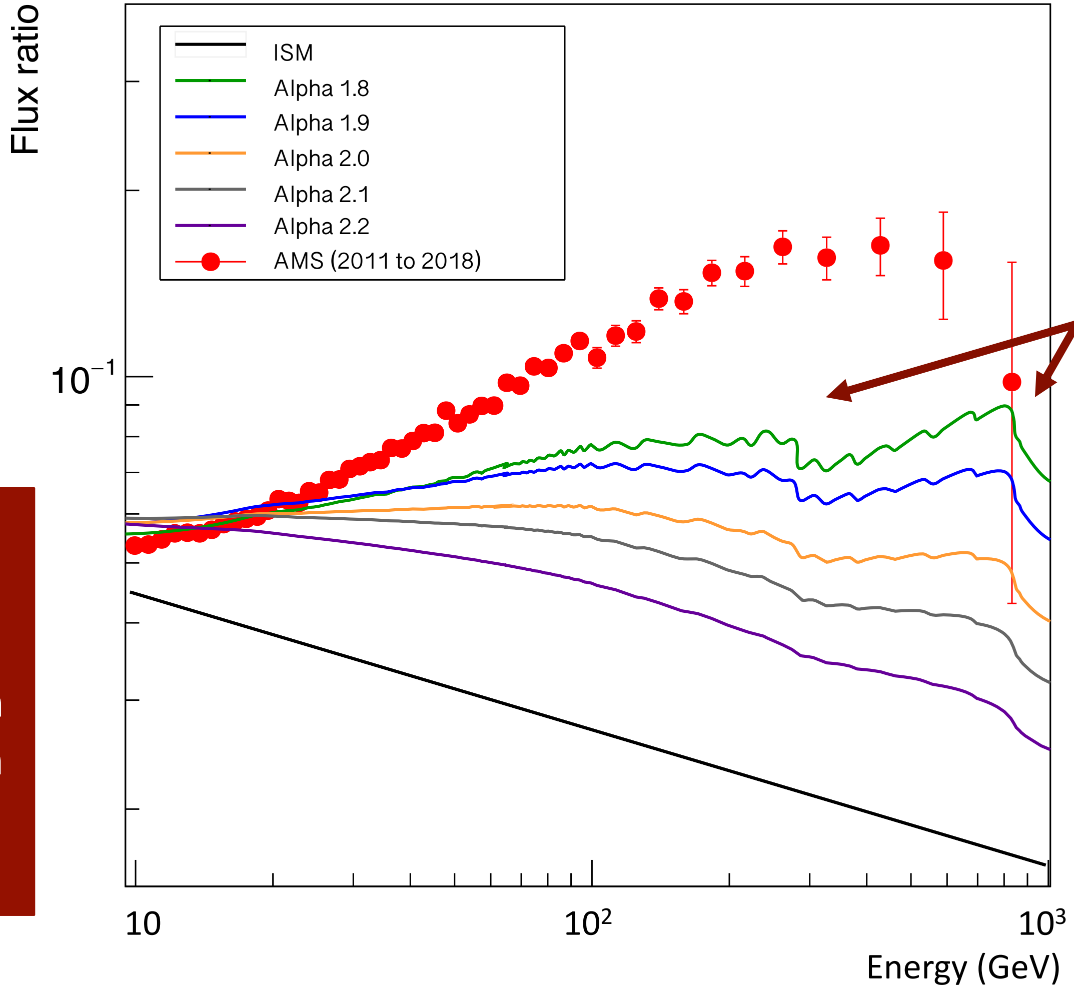


This reasoning is the same for known ATNF sources.

After about ~ 3 x 10^5 years, the sources drop off at higher energies.

Pulsar ages and their characteristics:
(a sample MC of pulsars from 10^5 years to 10^6 years)

Example: Monogem versus Geminga (+ one million to ten million threshold MC sources) with a spin-down time of 10^4 years. The spectral indices range from 1.8 to 2.2. The pulsar birth rate is 0.673 per century.



Monogem age: 1.1 x 10^5 years old
Geminga age: 3.7 x 10^5 years old

Note that the saw-tooth effect here is due to lower statistics in combination with the chosen parameters.

For a low spectral index (alpha), one can see that Monogem's age compared to Geminga's age produces two "humps" in the contribution.