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The Cosmic-Ray Positron Excess and the Constraints on Milky Way Pulsars

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THE UNIVERSITY OF CHICAGO

The Positron Excess Backstory…

- For the past ~25 years, cosmic ray telescopes and satellites such as:
  - **A**lpha **M**agnetic **S**pectrometer (AMS-01)
  - **H**igh **E**nergy **A**ntimatter **T**elescope (HEAT)
  - **P**ayload for **A**ntimatter **M**atter **E**xploration and **L**ight-nuclei **A**strophysics (PAMELA)

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Positron fraction: the ratio of the *flux* of positrons to the combined flux of electrons plus positrons present in the interstellar medium (ISM) (i.e. in space)

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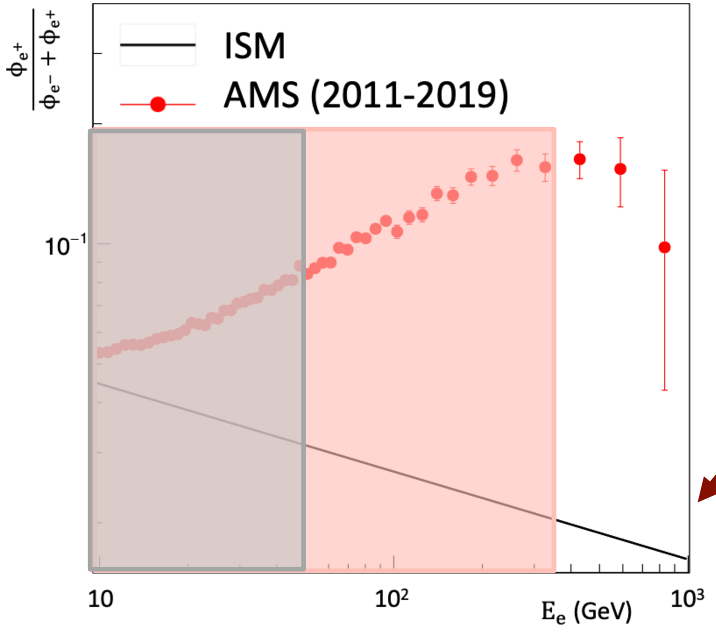
Up to ~50 GeV:
Could still be explained with annihilating Dark Matter (DM) models.

Excess seen to ~350 GeV and higher:
DM Models **ruled out** by experiments such as the Fermi gamma-ray space telescope.

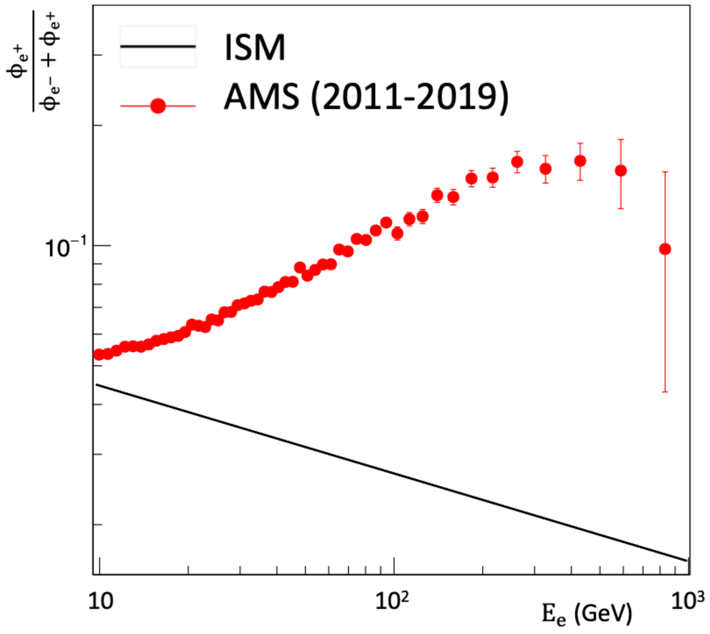


Primary observations from AMS-02

Secondary predictions from the interstellar medium

The Positron Excess Backstory…

AMS-02: 2019
(tension up to ~1 TeV)



The Positron Excess Backstory…

What is the *dominate source* that experiments are attuned to that is responsible for the observed excess?

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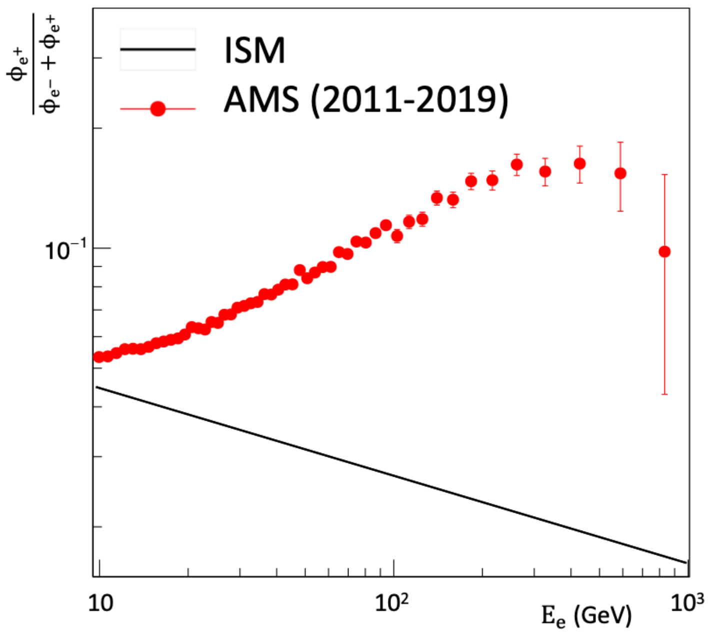

And under what *constraints* can this source contribution provide the best fit to explain this tension?

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Pulsar Populations

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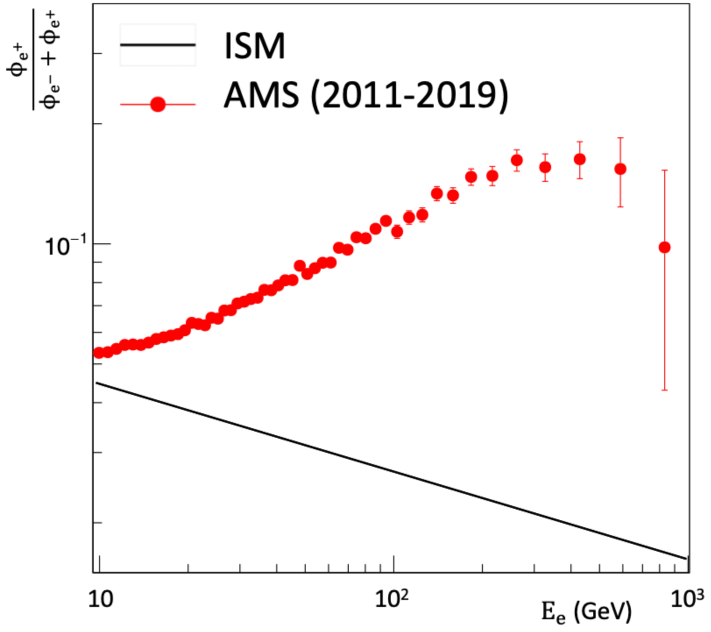

And under what *constraints* can this source contribution provide the best fit to explain this tension?

Enter…the Pulsars (Magnetized Spinning Neutron Stars)

- The highly favored solution to solve the ongoing tension is to consider contributions from *pulsars*.

- Pulsars are a great source of high energy positrons and electrons because:

  - Relatively young to middle-aged and local pulsars produce high gamma ray fluxes the via inverse Compton scattering of positrons and elections.
  - This can be observed in experiments such as **H**igh **A**ltitude **W**ater **C**herenkov (HAWC) as TeV Halos around the pulsars, when said pulsars inject high energy particles (including positrons) into the interstellar medium.

Therefore, the TeV halos such as those observed by HAWC are very likely the dominant producer of positrons involved in this excess.

Cosmic Ray Propagation…

- *In fact,* the high energy positrons that are injected into the ISM emit also 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/diffusion-loss equation to model their propagation through the ISM.

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Propagation equation

r **= distance from the pulsar**
E_e **= electron/positron energy**
t **= cosmic time since pulsar birth**

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Diffusion

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,r,t) = \underbrace{\vec{\nabla}\cdot\left[D(E_e)\vec{\nabla}\frac{dn_e}{dE_e}(E_e,r,t)\right]}_{} + \frac{\partial}{\partial E_e}\left[\frac{dE_e}{dt}(E_e,r)\frac{dn_e}{dE_e}(E_e,r,t)\right] + \delta(r)Q(E_e,t)$$

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Energy Losses

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Source

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Positron/electron differential number density term

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, we looked at both **M**onte **C**arlo simulations (MC) that give the distance of an MC source as well as its age (*unknown pulsars*), as well as those found in the **A**ustralia **T**elescope **N**ational **F**acility (ATNF) catalog (*known pulsars*).
- One can extract the pulsar contribution to the positron flux ratio for many free parameters.

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

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Spectral Index which indicates particle flux density

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Cutoff energy of the injected spectrum

Questions to answer:

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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 local pulsars could explain the positron excess under certain energy budget conditions (~10%). HAWC agrees with this through observations of TeV halos.

These updates that will be shown further constrain what precise characteristics the local pulsar populations have, to provide the best fit contribution to the positron flux.

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.
  - **Spectral Index**: indicator of particle flux density in the power-law distribution concerning frequencies of positrons and electrons.
  - **Magnetic Field**: magnitude in the ISM and contributing to energy losses.
  - **Pulsar Injection Time**: time at which we start to allow for pulsar injection (end of pulsar wind nebula phase).
  - **Spin-down Fluxes**: rates 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 and/or radio waves.
  - **Beaming fractions for Radio and Gamma sources**: fractions of MC sources that are considered to be detected (either by gamma rays or in radio waves) and catalogued in ATNF.
  - **Efficiency**: percent of rotational kinetic energy loss from injection. (energy budget)
  - **Pulsar Birth Rate**: rate per century of the number of pulsars born.
  - **Cut-off Energy**: the injected spectral cut-off energy.

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Fixed, but dependent upon the Spin-down Time

1 per century

Fixed

Used to normalize to a good fit at ~20 GeV

Degenerate with the efficiency

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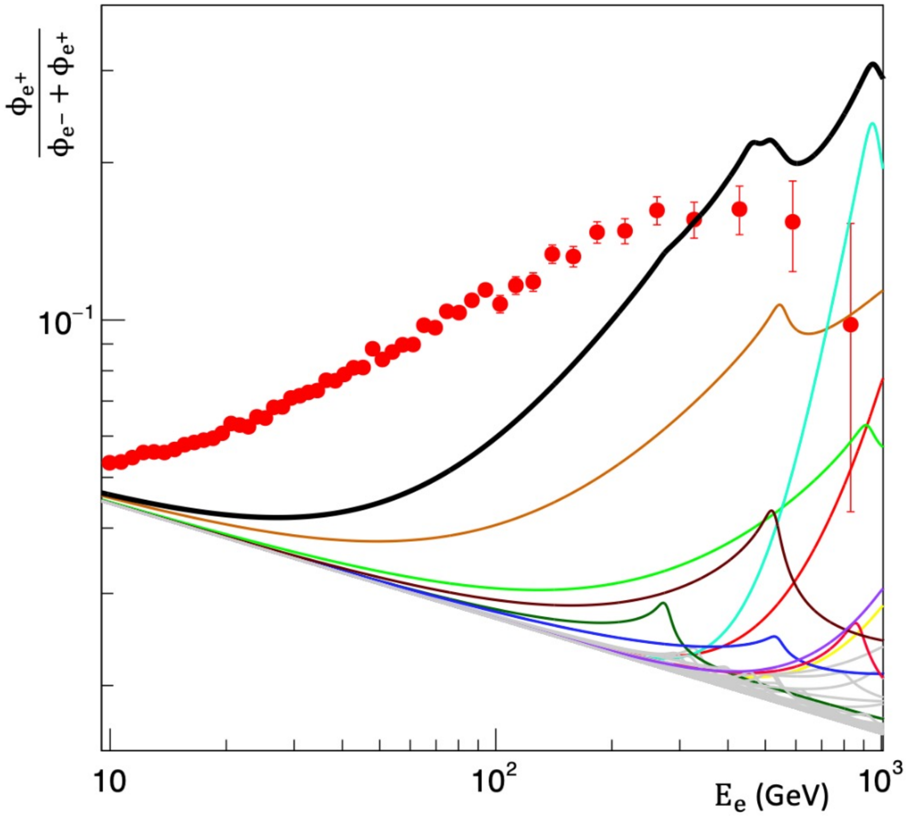
Contributions From Known Pulsars…

- Used 103 known (ATNF) pulsars up to 10^6 years in characteristic age *and* within 3 kpc of Earth (local).



Pulsar Name	P (s)	d (kpc)	τ_c (yr)	Color (Fig. 1)
J1302-6350	0.048	2.63	3.22×10^5	Light Blue
J1057-5226	0.197	0.093	5.25×10^5	Orange
J0117+5914	0.101	1.77	2.65×10^5	Red
J0633+1746	0.237	0.190	3.32×10^5	Light Green
J2032+4127	0.143	1.33	1.91×10^5	Violet
J0908-4913	0.107	1.00	1.02×10^5	Yellow
J2030+4415	0.227	0.720	5.45×10^5	Brown
J1846+0919	0.226	1.53	3.50×10^5	Pink
J1745-3040	0.367	0.200	5.36×10^5	Blue
J1530-5327	0.279	1.12	9.34×10^5	Green

Top 10 most contributing sources

Main Parameter choices (Default case):

Spectral index = 1.5

Cut-off energy = 50TeV

Efficiency = 0.15

B Field (ISM) = 3μG

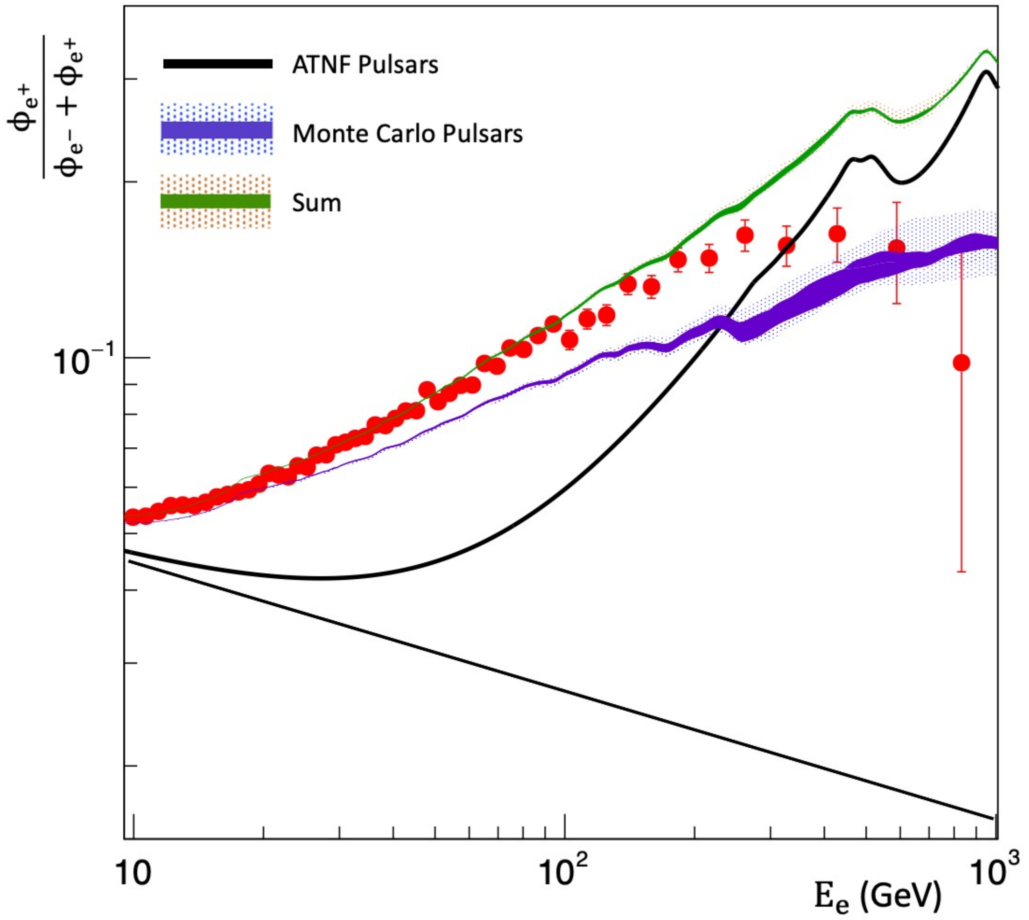
Pulsar Injection time = 3 x 10^4 years

Spin-down time = 10^4 years

Contributions From Unknown Pulsars and the Total Contribution…

- Sampled from spatial distributions, Monte Carlo Realizations obtain pulsars with ages and distances (younger than 10^6 years and within 3 kpc of Earth, respectively.)

- Pulsars between 10^6 and 10^7 years do contribute as well, but we used an average output for this range as there was a negligible degree of variation from realization-to-realization.

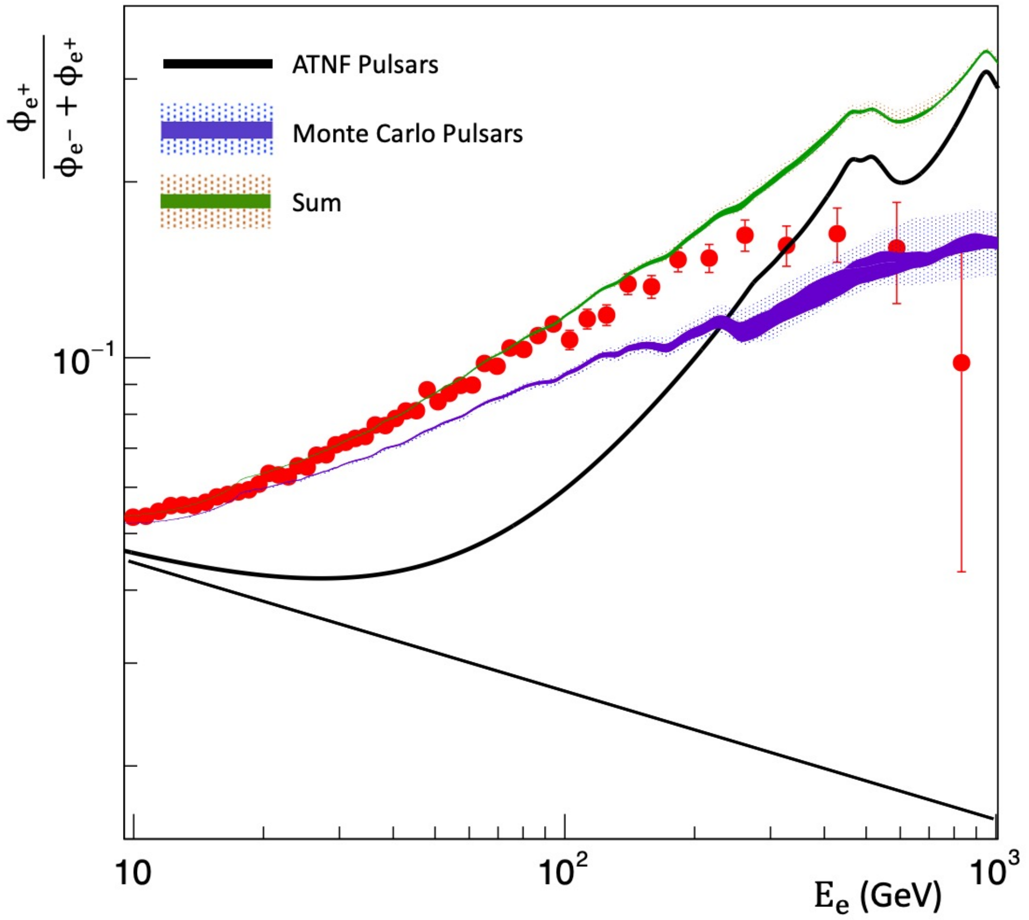


Contributions From Unknown Pulsars and the Total Contribution…

Note: We assumed *all* MC generated pulsars would have the same spin-down time and period which, in reality, would not typically be the case.

- Bands of 30 source-realizations (light blue = MC, orange = sum)
- 1σ band (purple = MC, green = sum)

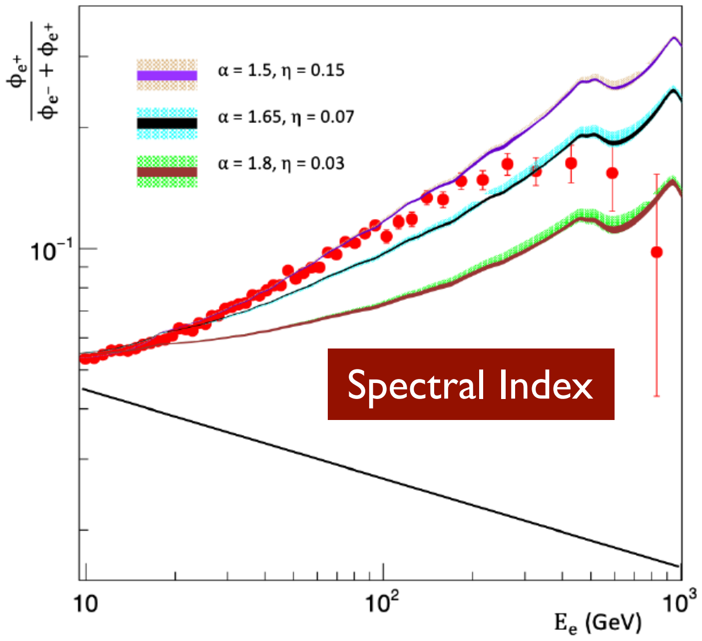
- Low energies: **MC contributions dominate** (unknown, little variation)
- High energies: **ATNF contributions dominate** (known, effects vary)

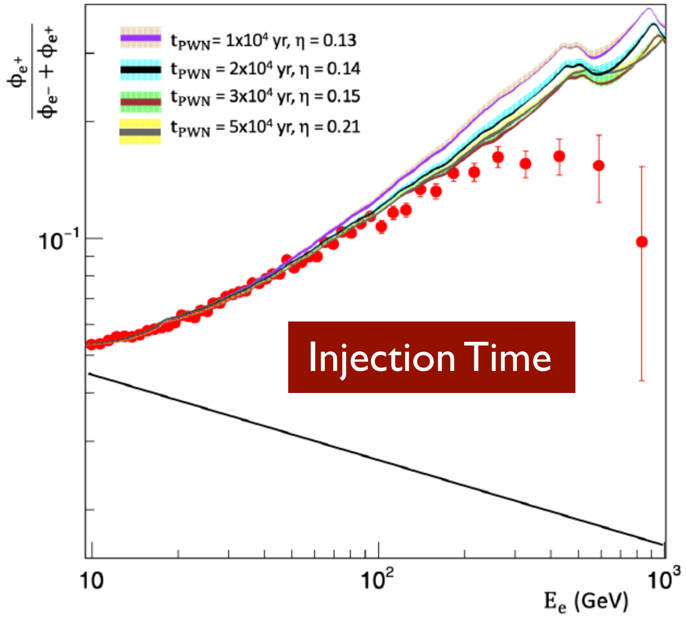


Parameter choices (Default case):

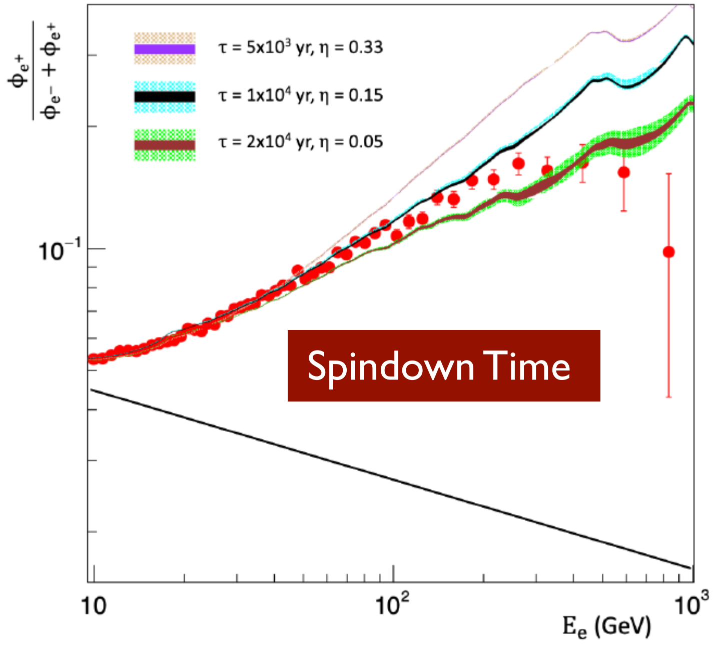
Spectral index = 1.5
B Field (ISM) = 3μG
Cut-off energy = 50TeV
Pulsar Injection time = 3×10^4 years
Efficiency = 0.15
Spin-down time = 10^4 years
Radio beam fraction = 0.28
Gamma-ray beam fraction = 0.62
Radio spin-down flux = 2.66×10^{41} erg/kpc^2/yr
Gamma-ray spin-down flux = 4.22×10^{42} erg/kpc^2/yr
Pulsar birth rate = 0.01 yr^{-1}

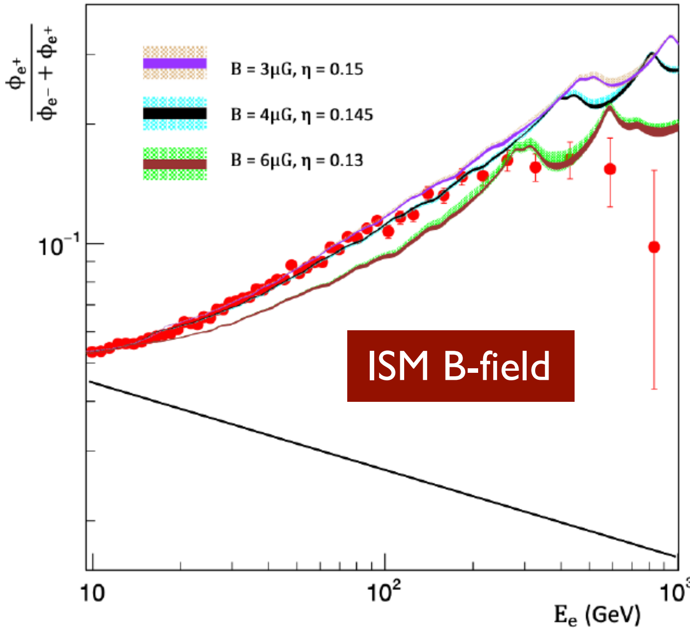
Parameter Variations…





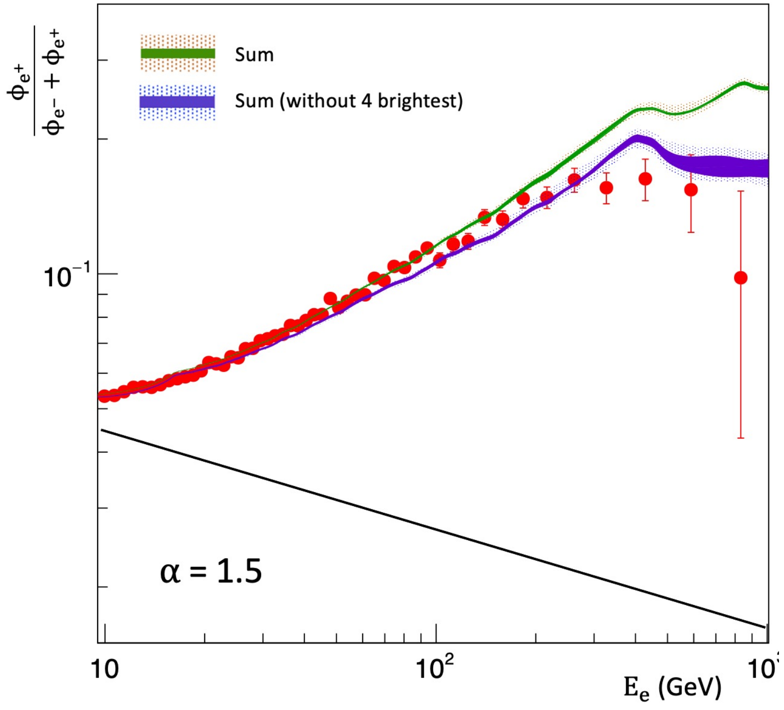
- Helps to further constrain what a good fit would be when varying one parameter from the default case at a time.

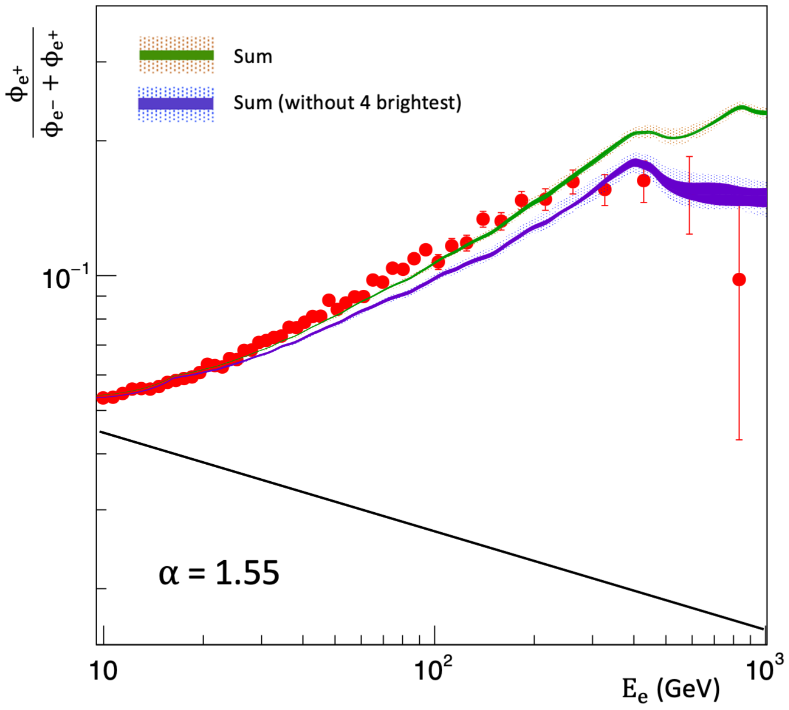




Best Fit…(Considering all Free Parameters)

- Top line gives the total contribution including all 103 ATNF sources.
- Bottom suppresses the top 4 most contributing ATNF sources.





- The positron fraction at energies below a few hundred GeV comes from many pulsar sources (insensitive to age and location)
- At higher energies, it is impossible to reliably predict the positron fraction (dominated by a few sources) and can vary for a given set of choice parameters.

Main Parameter choices:

B Field (ISM) = $4\mu G$ Spin-down time = 10^4 years Efficiency (alpha of 1.5) = 0.1 or 0.11 (suppressed)

Cut-off energy = 10TeV Pulsar Injection time = 5 x 10^4 years Efficiency (alpha of 1.55) = 0.08 or 0.09 (suppressed)

Summary and Conclusions

- **Pulsar populations do provide a highly likely solution to the positron excess problem as indicated via observations of "TeV Halos" around them.**
- **Furthermore, pulsars within 3 kpc of Earth and younger than a million years contribute the most.**
- **In varying many free parameters, we have further constrained what pulsar characteristics of both known and unknown pulsar sources must have in order to provide the best fit to AMS data.**
- **In particular, the positron fraction at low energies seems to come from many sources, is largely insensitive to age and location, can agrees well with the data for reasonable parameters.**
- **However, at high energies, we see that the specific choice of free parameters greatly influences the positron fraction and making it impossible to reliably predict. (this is dominated by only a few sources)**
- **This also makes it harder to draw reliable conclusions pertaining to the Milky Way's broader pulsar population.**
- **The ArXiv submission can be found at: arXiv:2205.05200 [astro-ph.HE] Final results will soon be published in JCAP.**

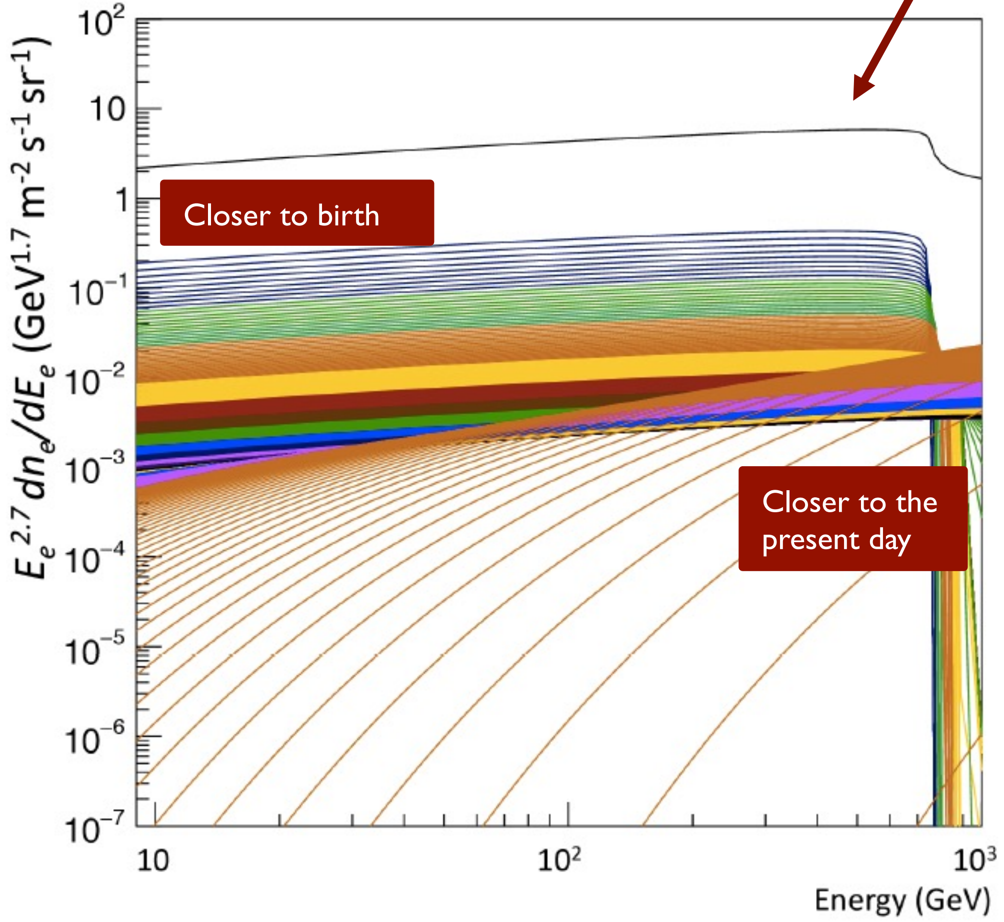

Thank You!


Questions?

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 secondary productions of positrons and electrons, as well as to account/combine with primary productions of electrons.

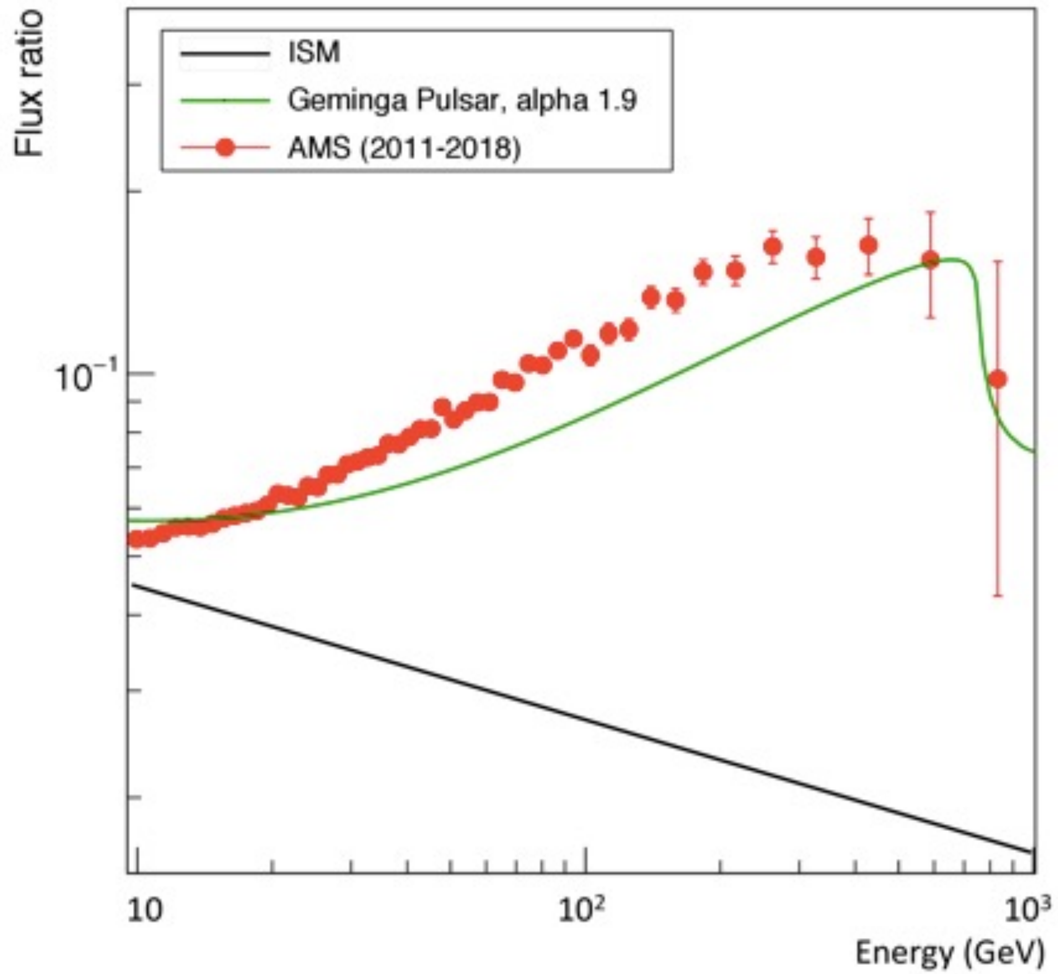
Process of obtaining pulsar contribution:

Geminga contribution

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

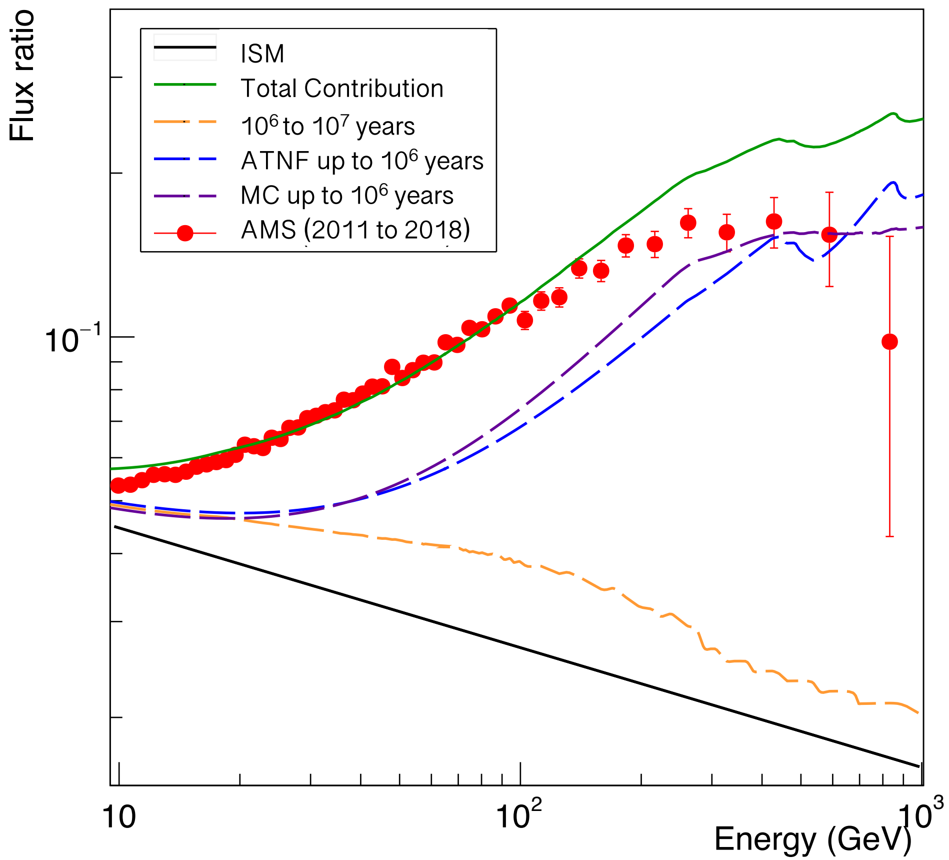
The Geminga contribution is the "halved" amount plotted in the previous slide.

The positron fraction *is* the flux ratio.



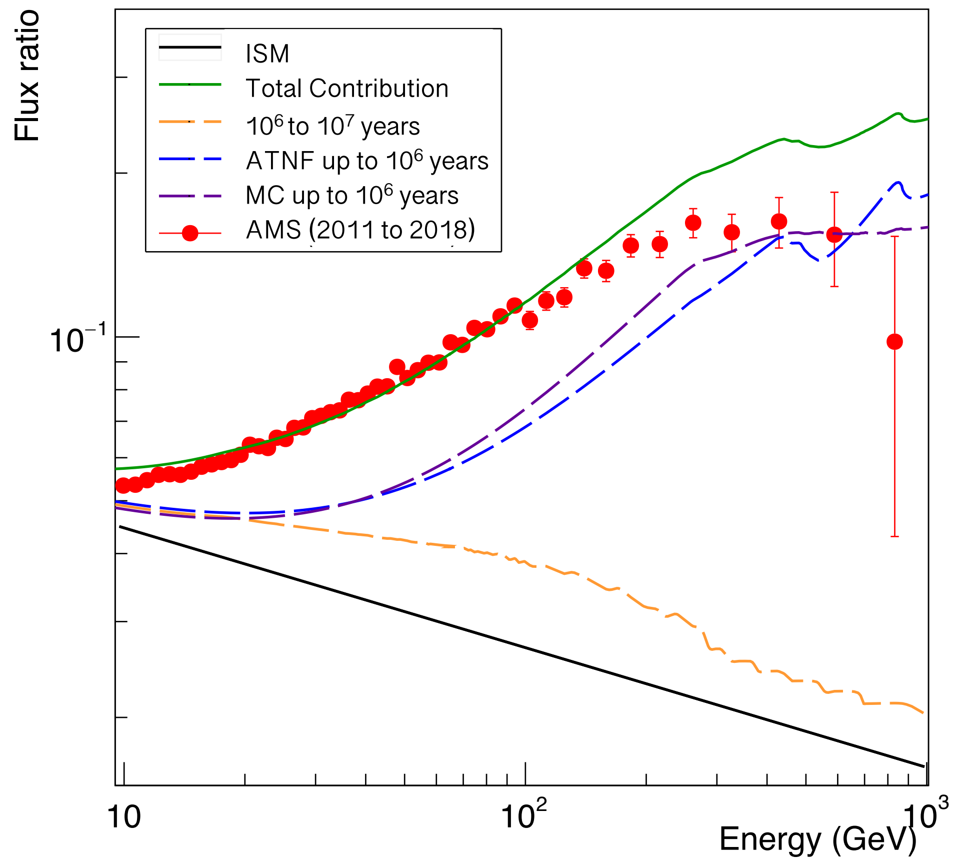
INITIAL RESULTS…

- 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.



INITIAL RESULTS…

- Initial 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.



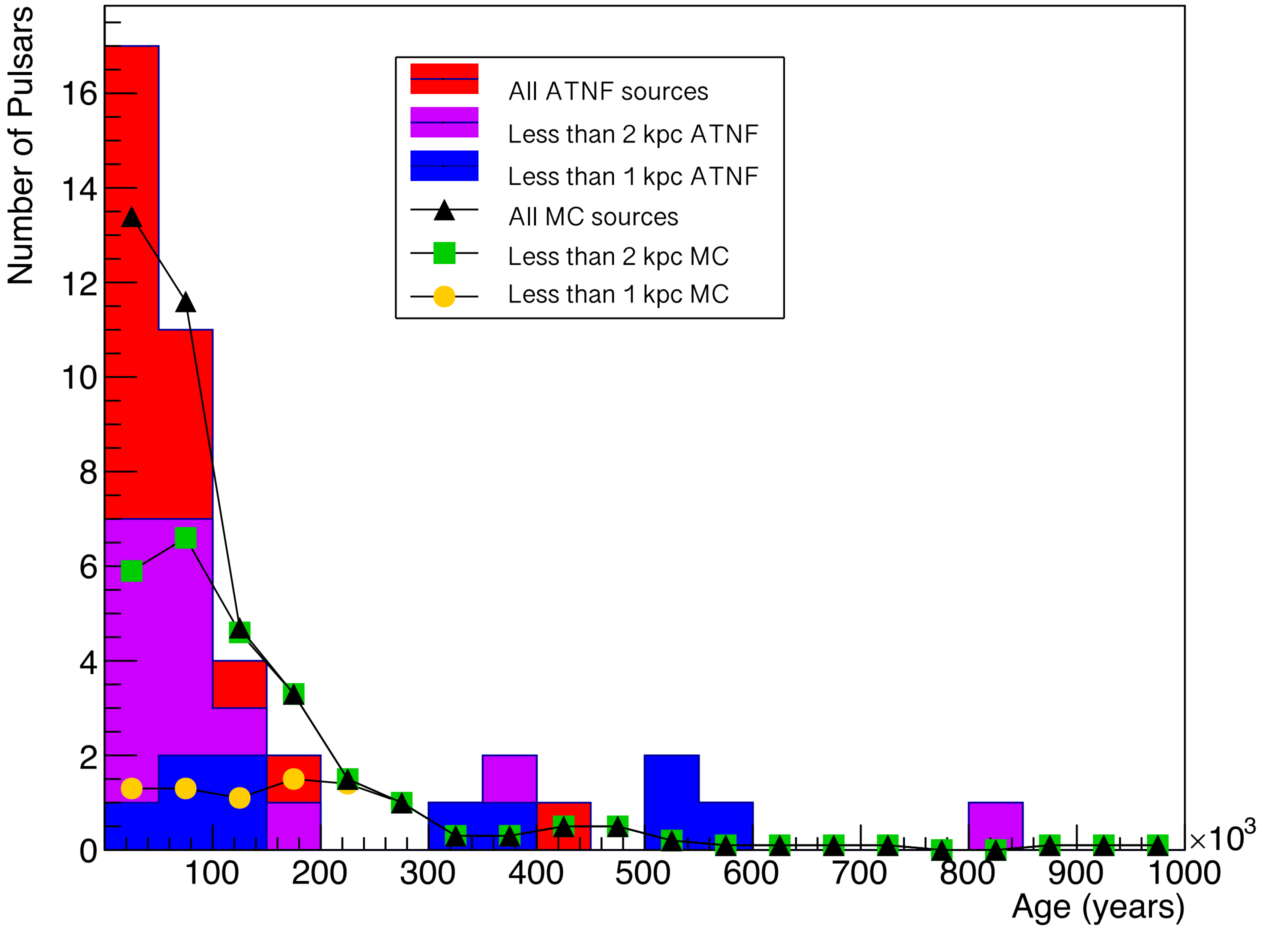
*Note that the three dashed lines *exclude* pulsar sources further than 3 kpc away from Earth. Our analysis showed that they contribute negligibly.

Process of obtaining Poisson probability:

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

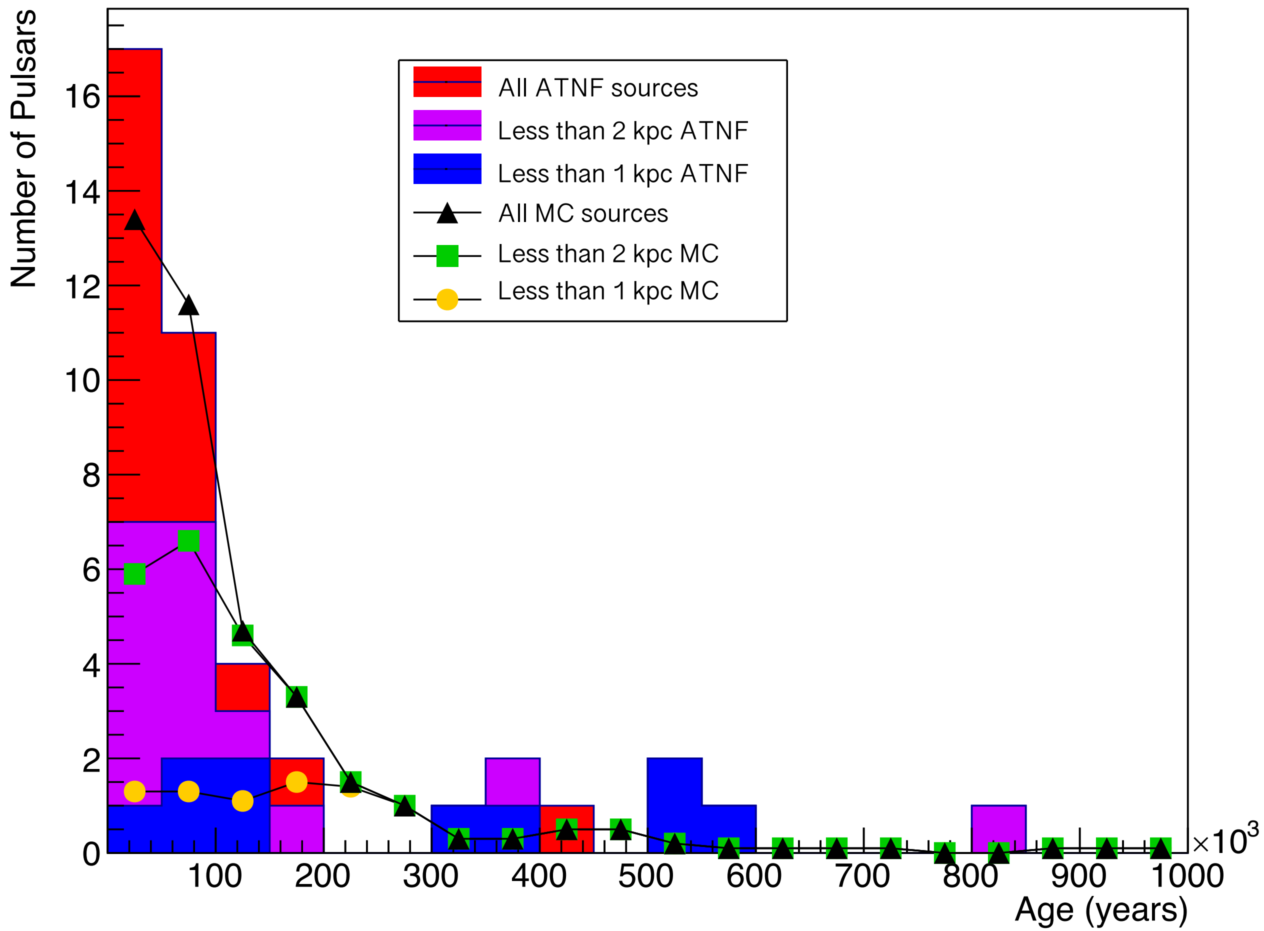
Histogram: ATNF (k(i))
Scatter Plots: Average of 10 MCs ($\lambda(i)$)

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



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}	$\boxed{3.25 \times 10^{-26}}$	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.