Image Credit: ESA

# Every Nearby Pulsar is Surrounded by Inhibited Diffusion

arXiv:2503.17442

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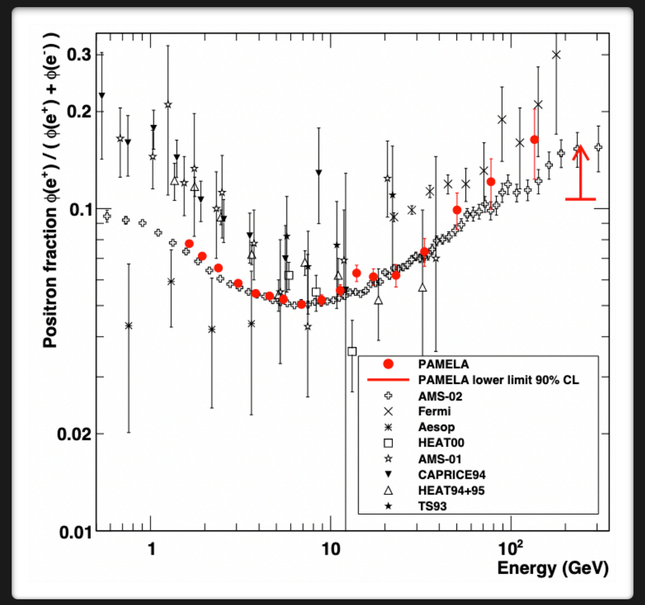
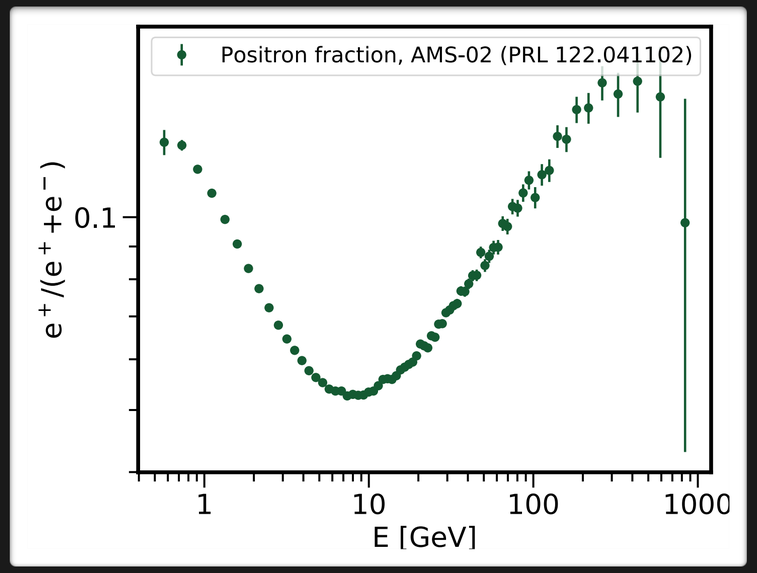
# Cosmic-Ray Positron Excess

PAMELA
2006




Unexpected rise in positron fraction above about 20 GeV

AMS-02
2013

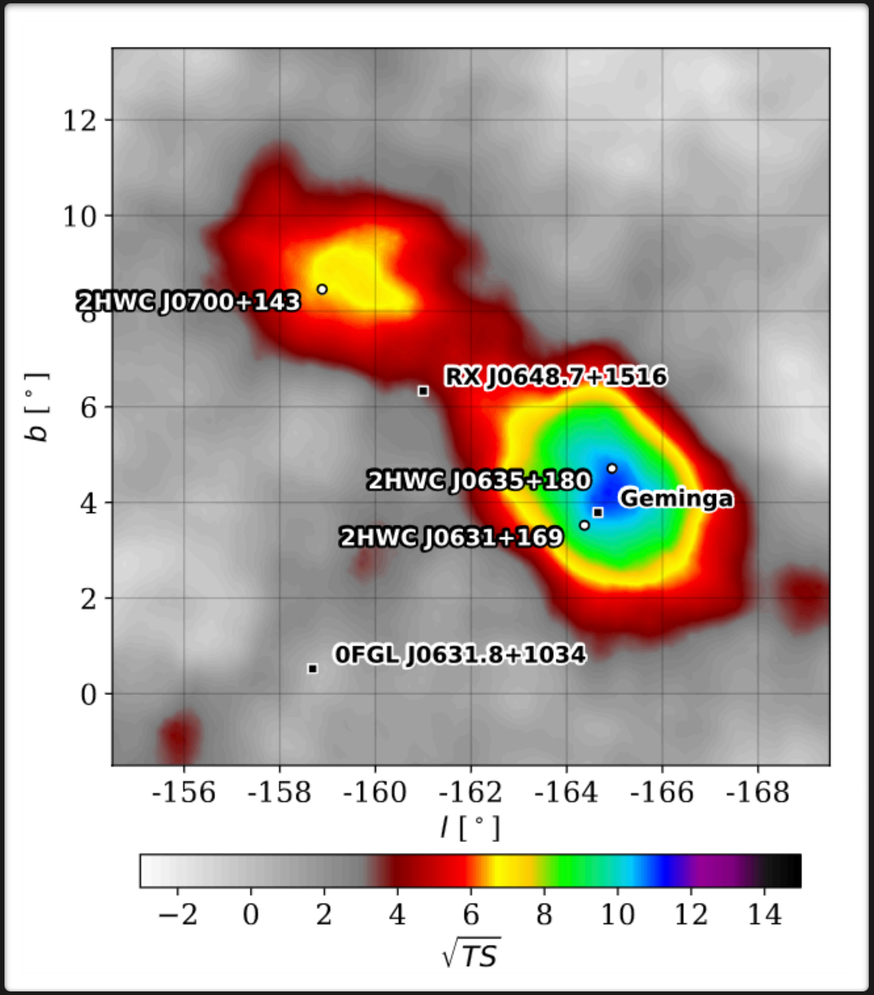



Possible explanations:

- Dark matter
- Pulsars

# Positron Excess: TeV Halos

2017: HAWC discovers extended gamma-ray halos around pulsars (TeV halos)




HAWC Collaboration, arXiv:1702.02992

**Using HAWC to Discover Invisible Pulsars**

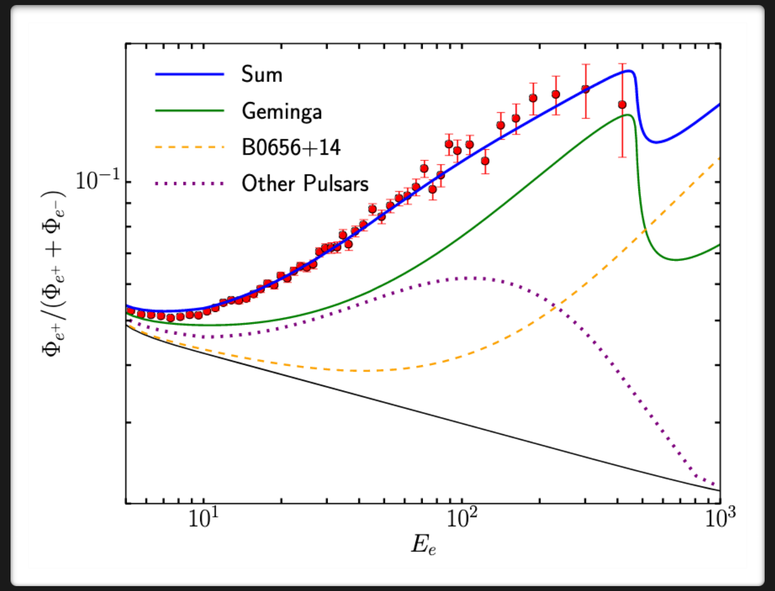
Tim Linden,[1,*] Katie Auchettl,[1,†] Joseph Bramante,[2,‡] Ilias Cholis,[3,§] Ke Fang,[4,5,¶] Dan Hooper,[6,7,8,**] Tanvi Karwal,[3,††] and Shirley Weishi Li[1,‡‡]

Linden et al., arXiv:1703.09704

**HAWC Observations Strongly Favor Pulsar Interpretations of the Cosmic-Ray Positron Excess**

Dan Hooper,[a,b,c] Ilias Cholis,[d] Tim Linden[e] and Ke Fang[f,g]

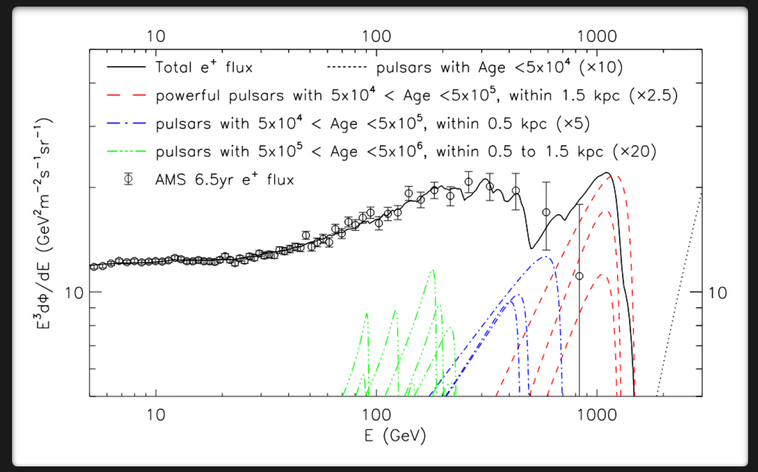
Hooper et al., arXiv:1702.08436



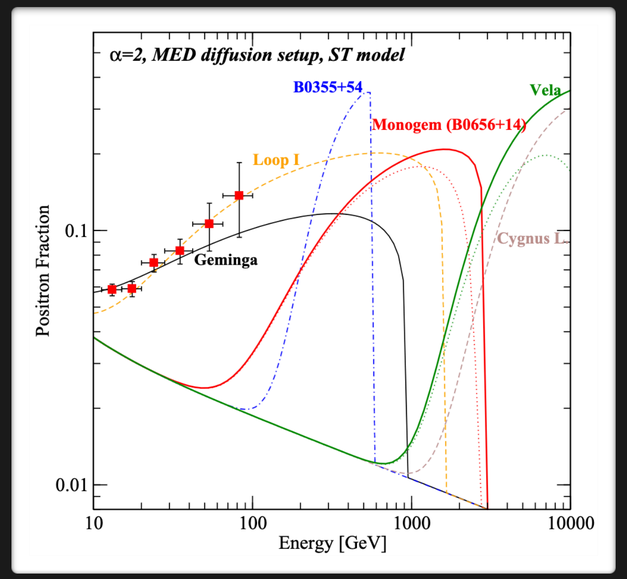
# Pulsars Produce Highly-Energetic $e^+e^-$

Many open questions:

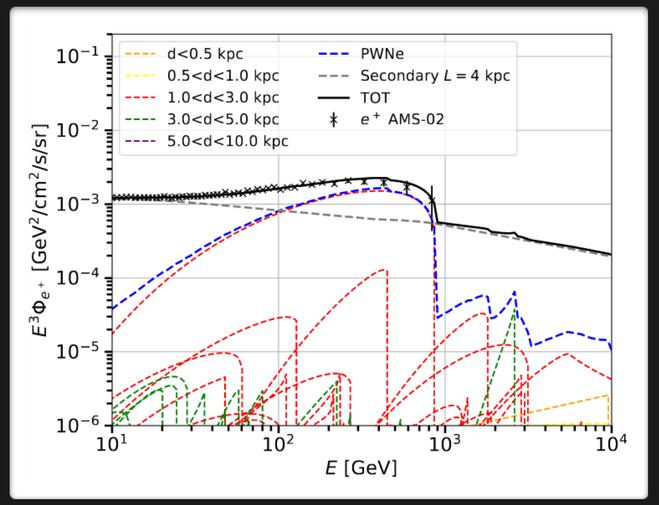
- How many nearby pulsars produce positron excess?
- What is their $e^+e^-$ spectrum?
- Do all pulsars have TeV halos?
- …



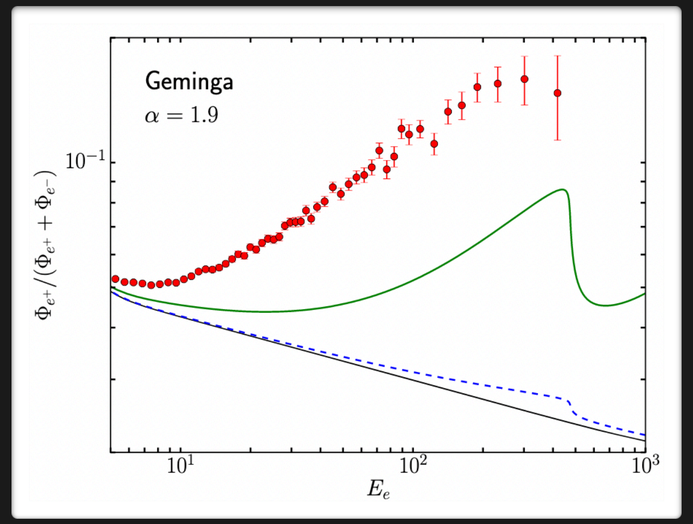

Cholis & Krommydas, arXiv:2111.05864




Profumo, arXiv:0812.4457




Orusa et al., arXiv:2107.06300



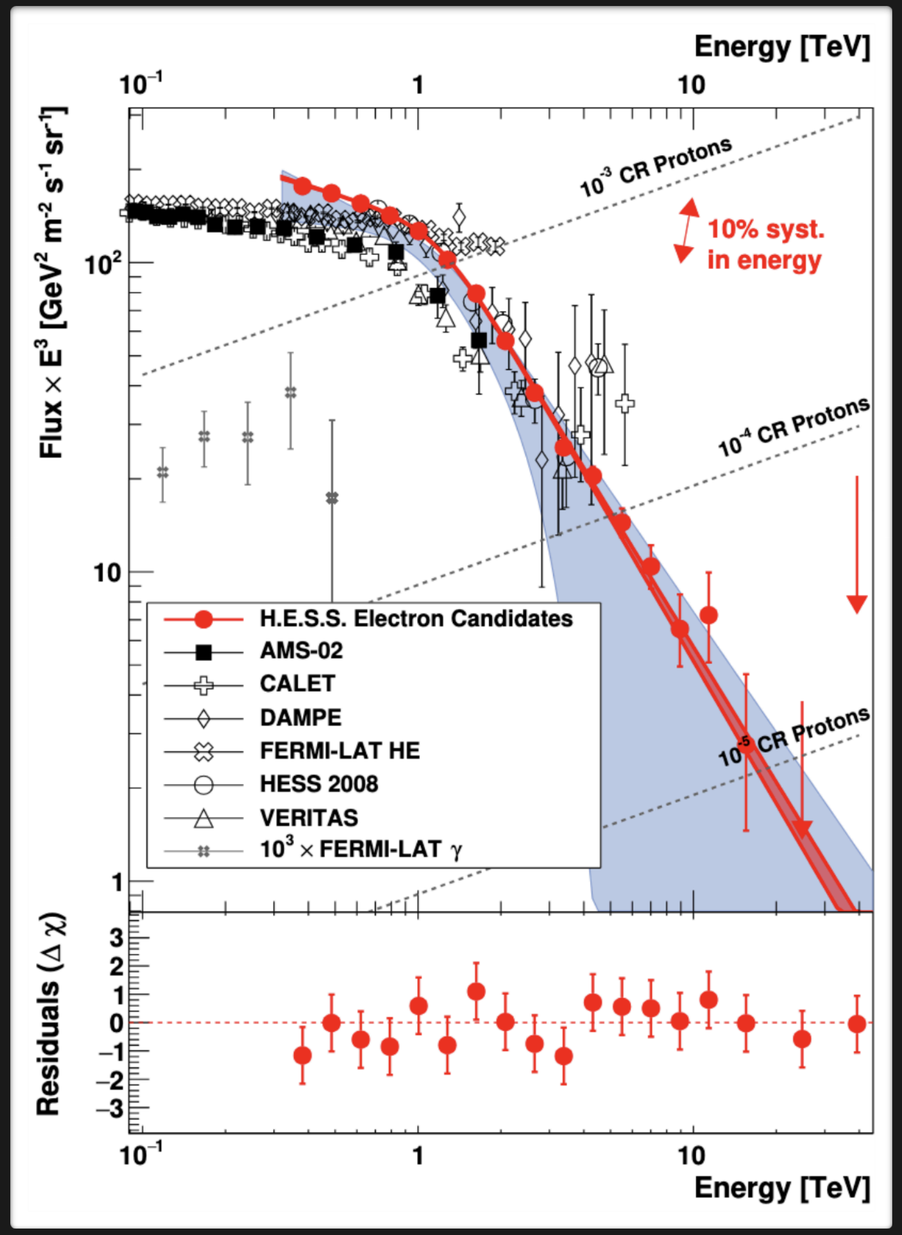

Hooper et al., arXiv:1702.08436

# Recent H.E.S.S. $e^+e^-$ Data

H.E.S.S. measures cosmic-ray electron+positron flux up to several tens of TeV

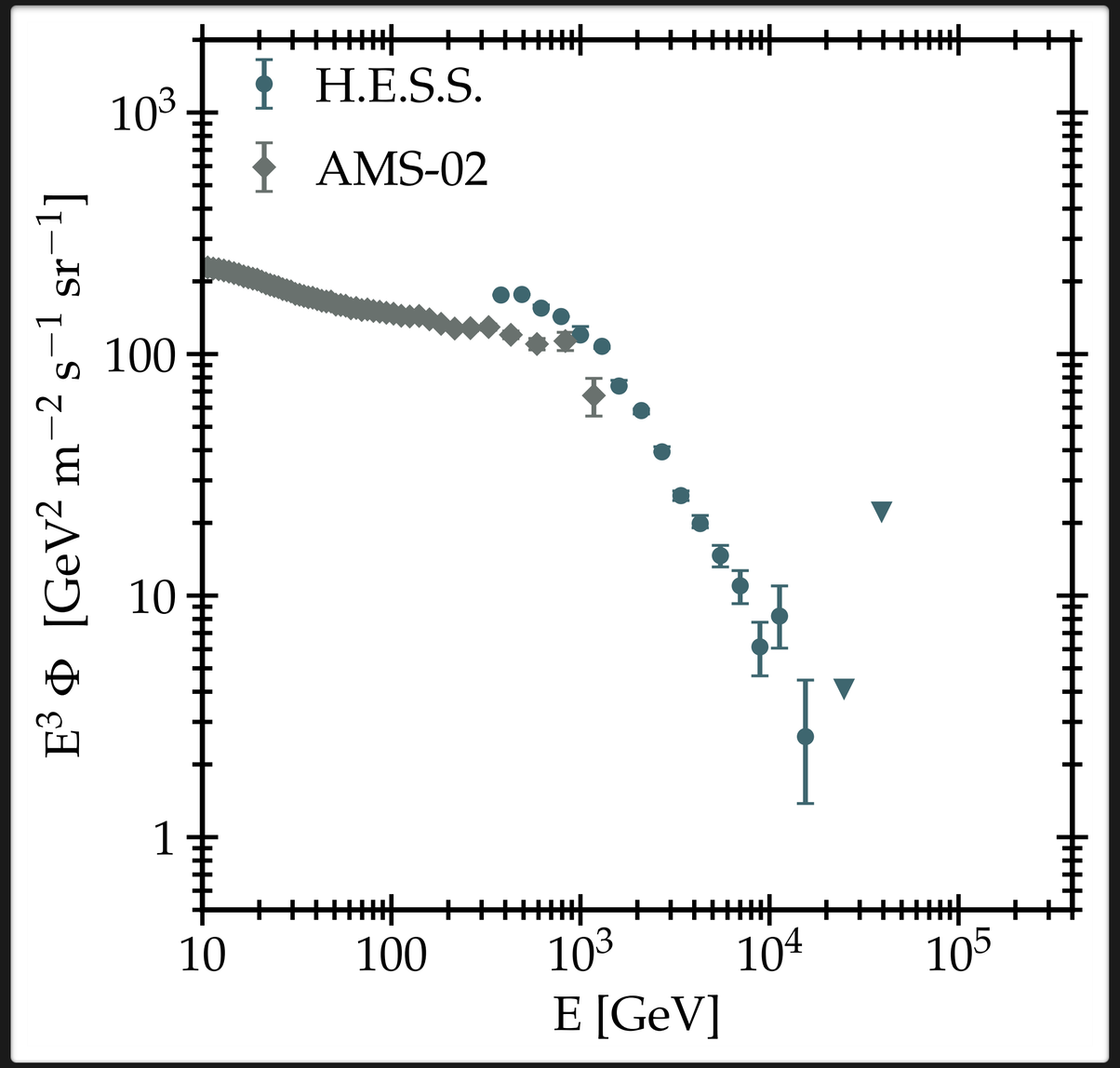
[arXiv: 2411.08981]

Flux falls smoothly and steeply above ~ 1 TeV



# One-Zone Diffusion Overproduces Data

Flux falls smoothly above ~ 1 TeV



# One-Zone Diffusion Overproduces Data

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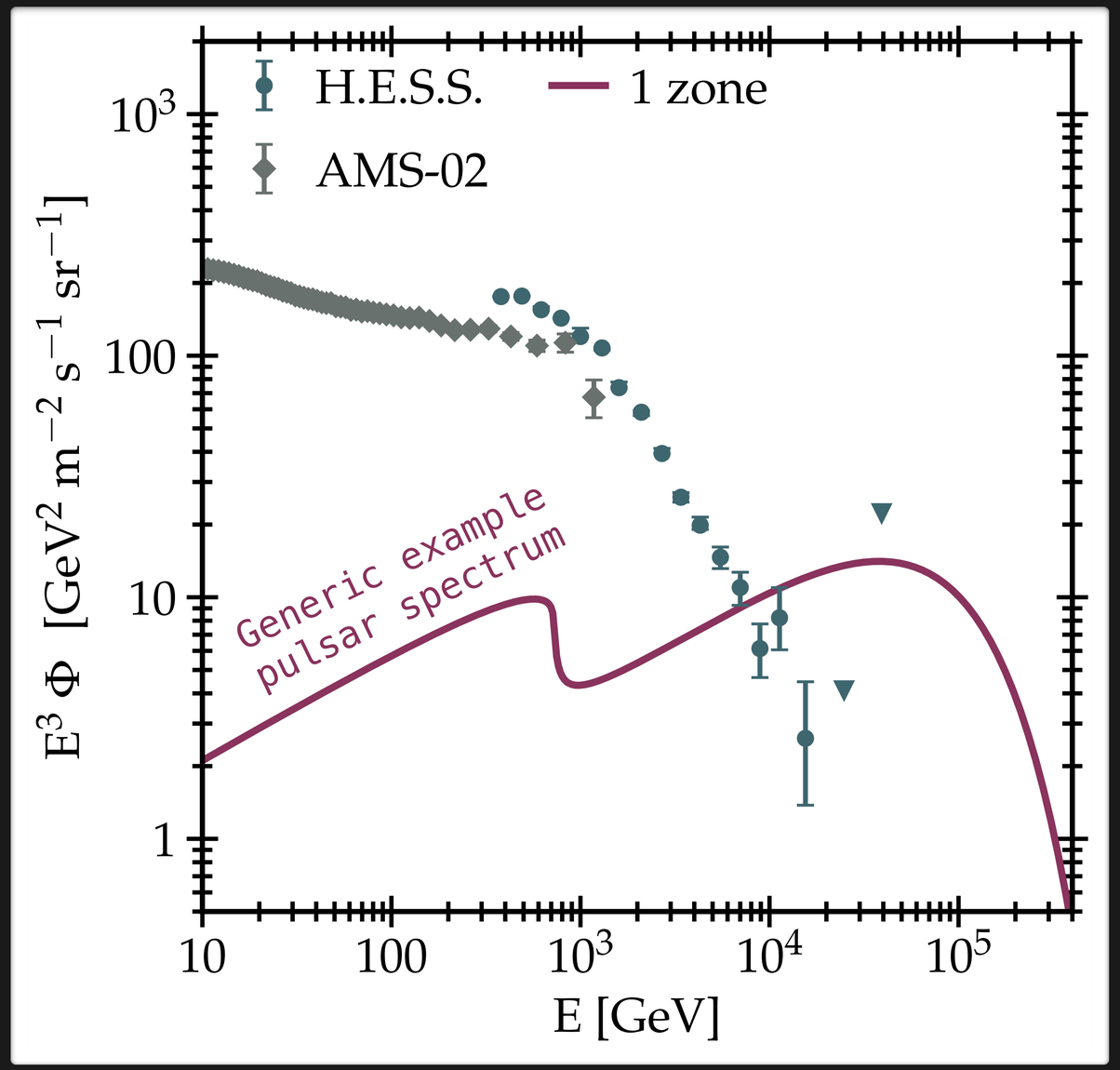
$\gamma$-ray observations show that pulsars produce $e^+e^-$ at TeV energies

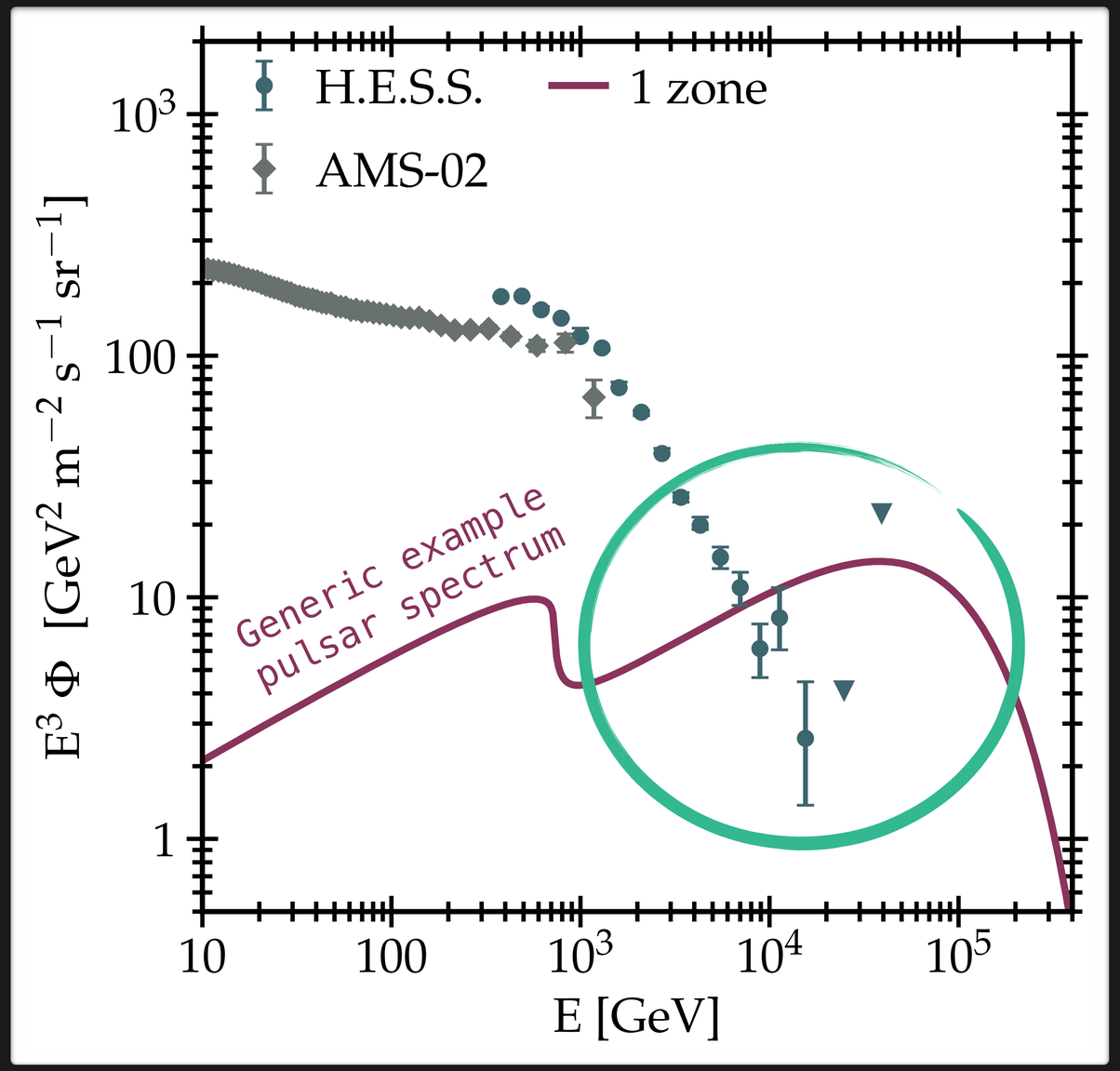


# One-Zone Diffusion Overproduces Data

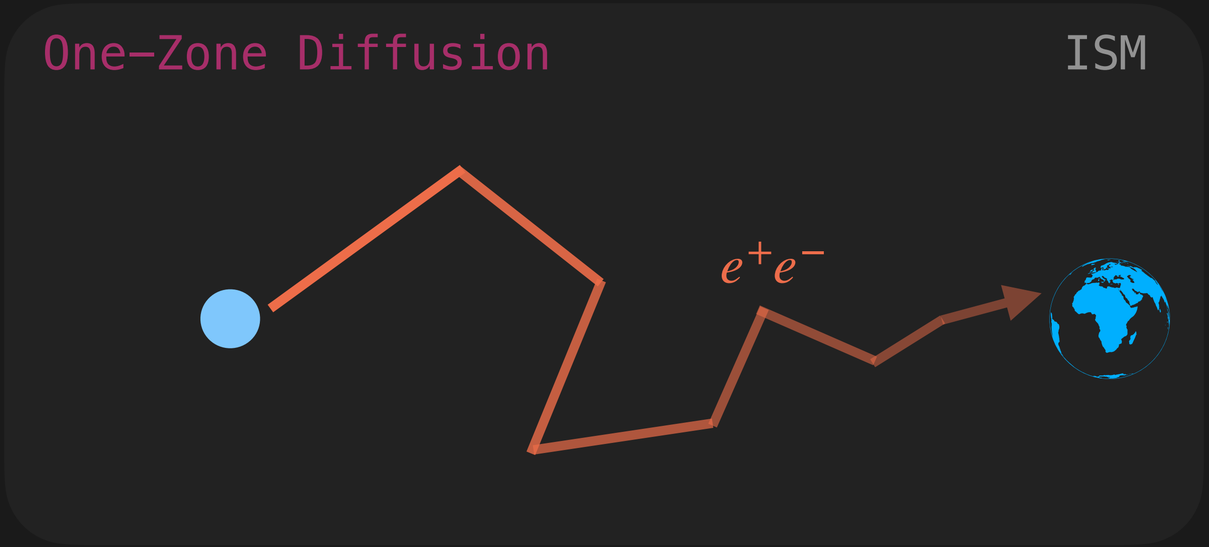
Flux falls smoothly above ~ 1 TeV

$\gamma$-ray observations show that pulsars produce $e^+e^-$ at TeV energies

Simple pulsar models overproduce data at tens of TeV



# Inhibited Diffusion Zones




$e^+e^-$ escape pulsar efficiently

Fang et al, arXiv:1906.08542
Osipov et al (2020)
Mitchell & Gelfand, arXiv:2208.11026
Schroer et al, arXiv:2305.08019

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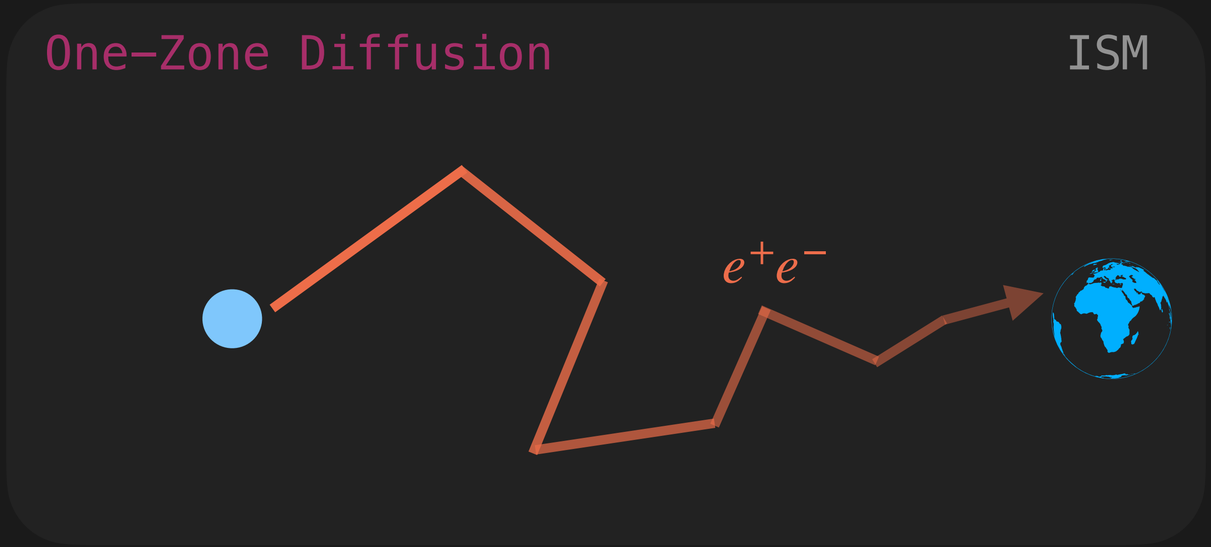
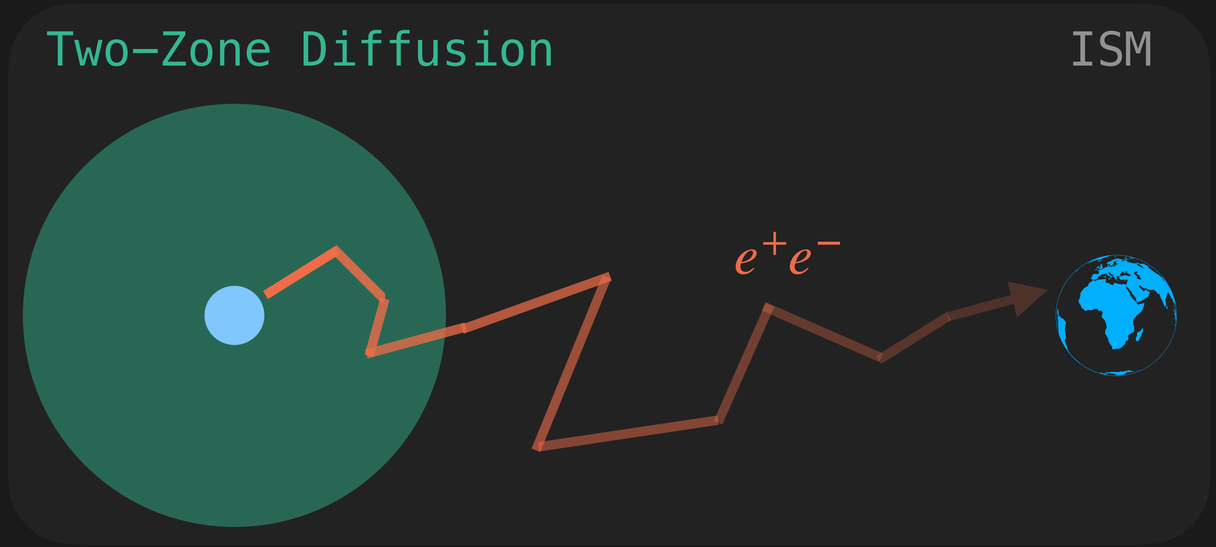



$e^+e^-$ escape pulsar efficiently

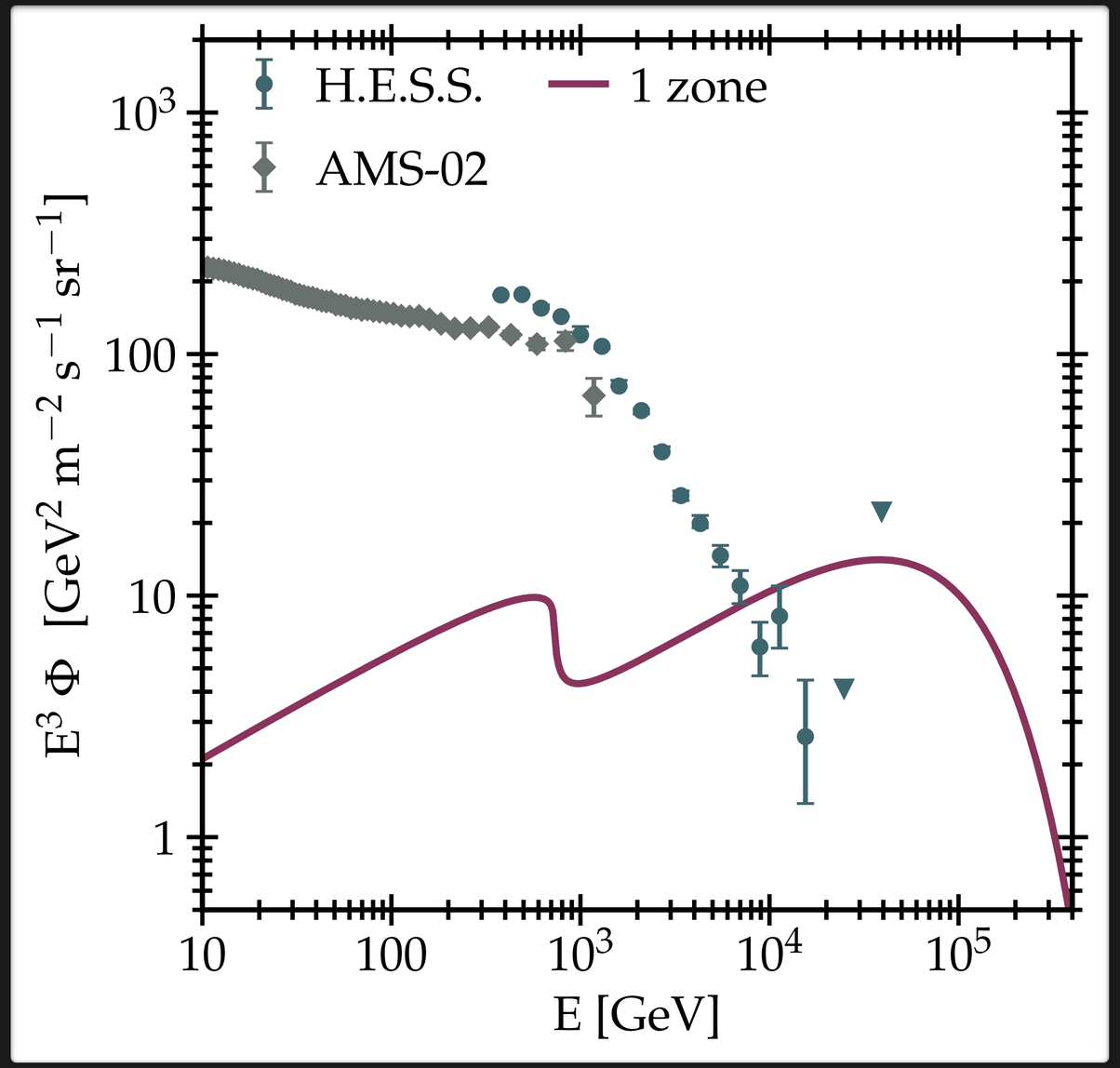
Inhibited diffusion zone around pulsar slows down diffusion compared to interstellar medium

Mechanism of turbulence not well-understood

Fang et al, arXiv:1906.08542
Osipov et al (2020)
Mitchell & Gelfand, arXiv:2208.11026
Schroer et al, arXiv:2305.08019

# Two-Zone Diffusion Models Confine $e^+e^-$

Inhibited diffusion traps $e^+e^-$ around pulsar, where they lose energy



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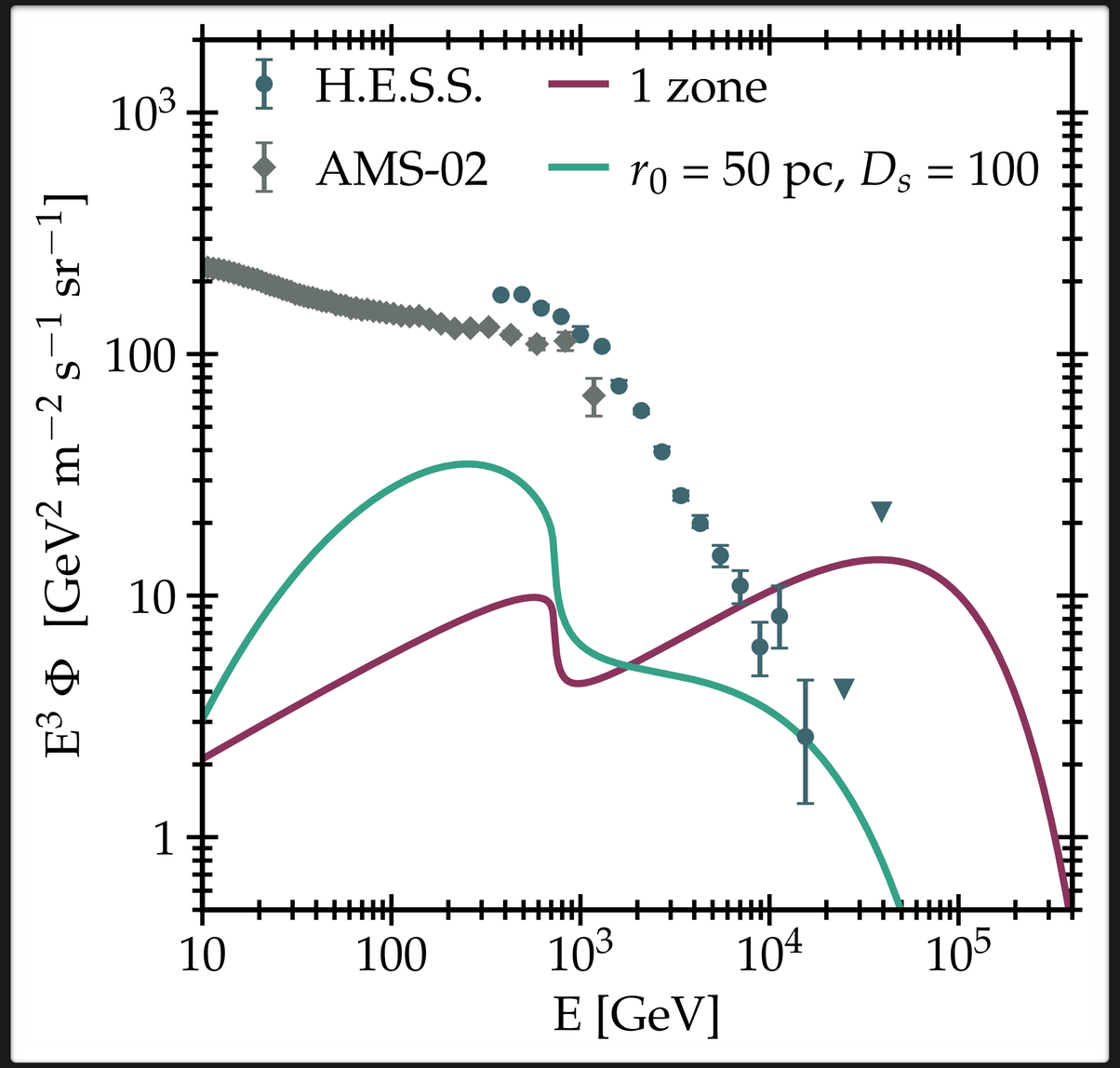
↓

High-energy flux is suppressed



# Two-Zone Diffusion Models Confine $e^+e^-$

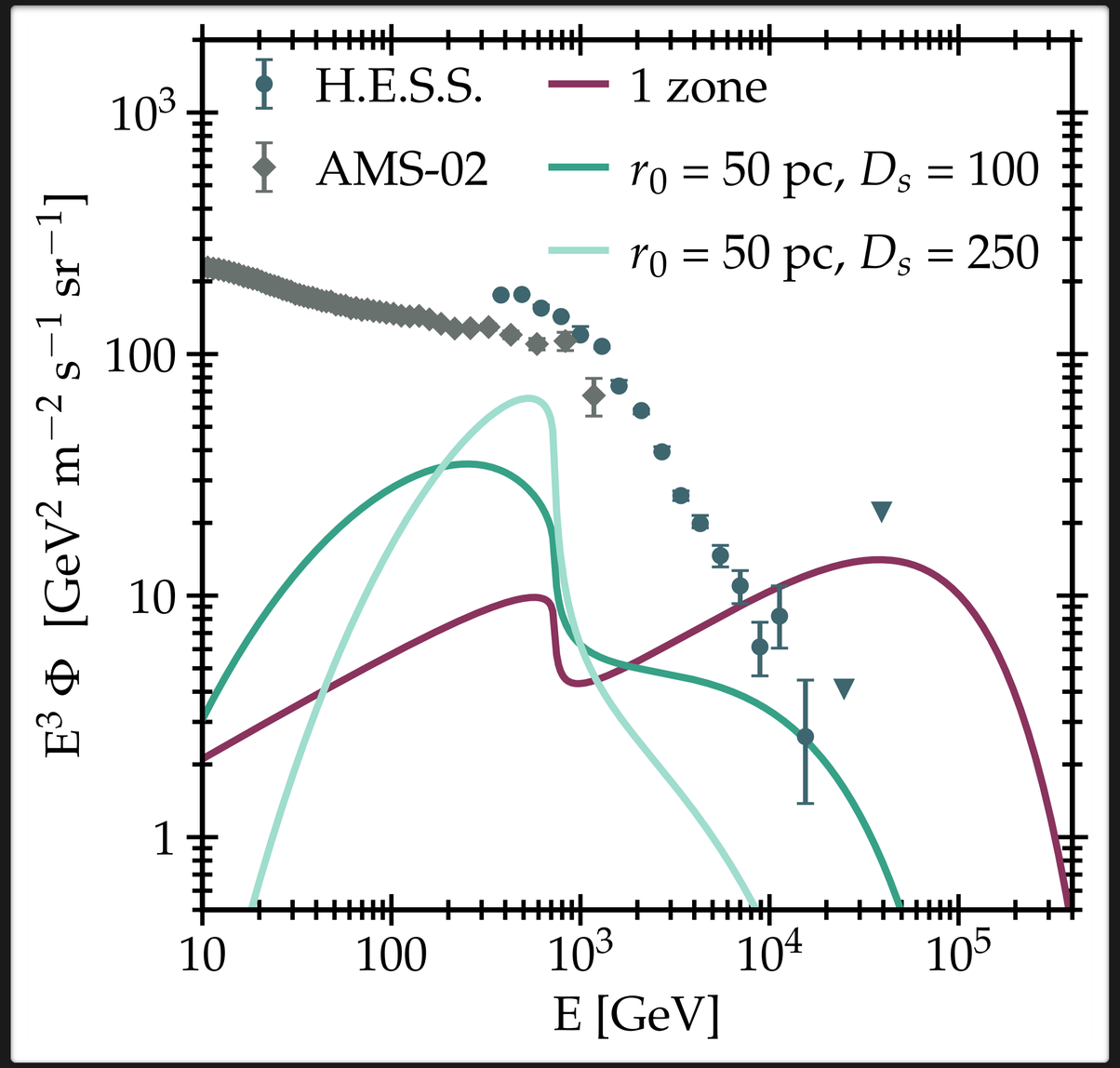
Inhibited diffusion traps $e^+e^-$ around pulsar, where they lose energy

↓

High-energy flux is suppressed

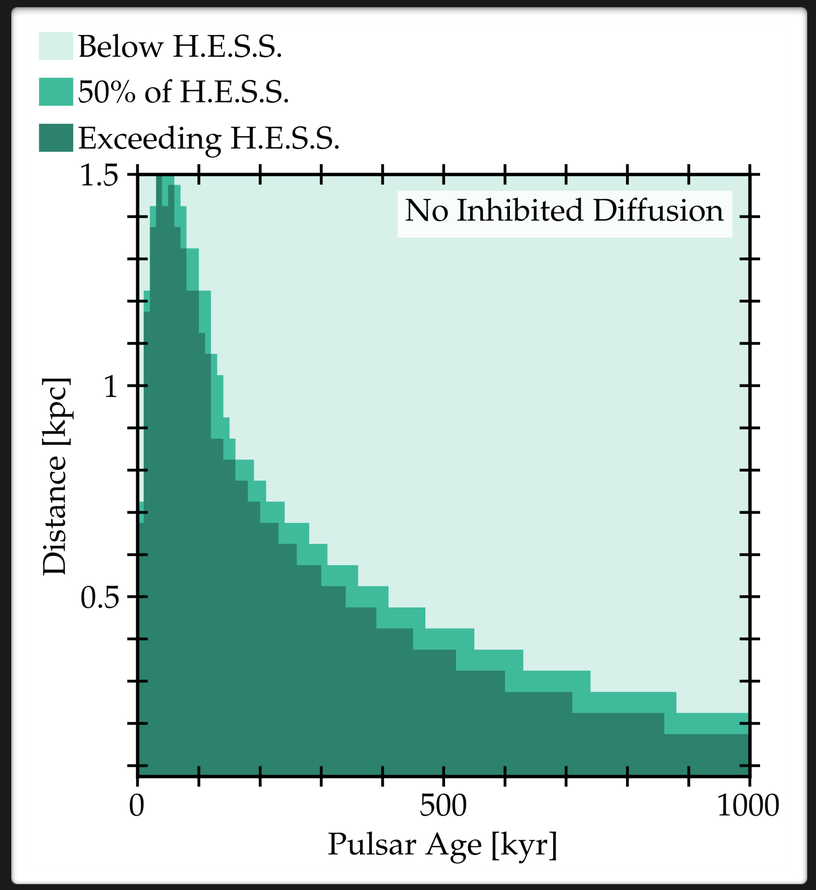
↓

Consistent with H.E.S.S. $e^+e^-$



# Individual Pulsars vs H.E.S.S.

## Pulsars within 1.5 kpc and 1 Myr from ATNF Catalog



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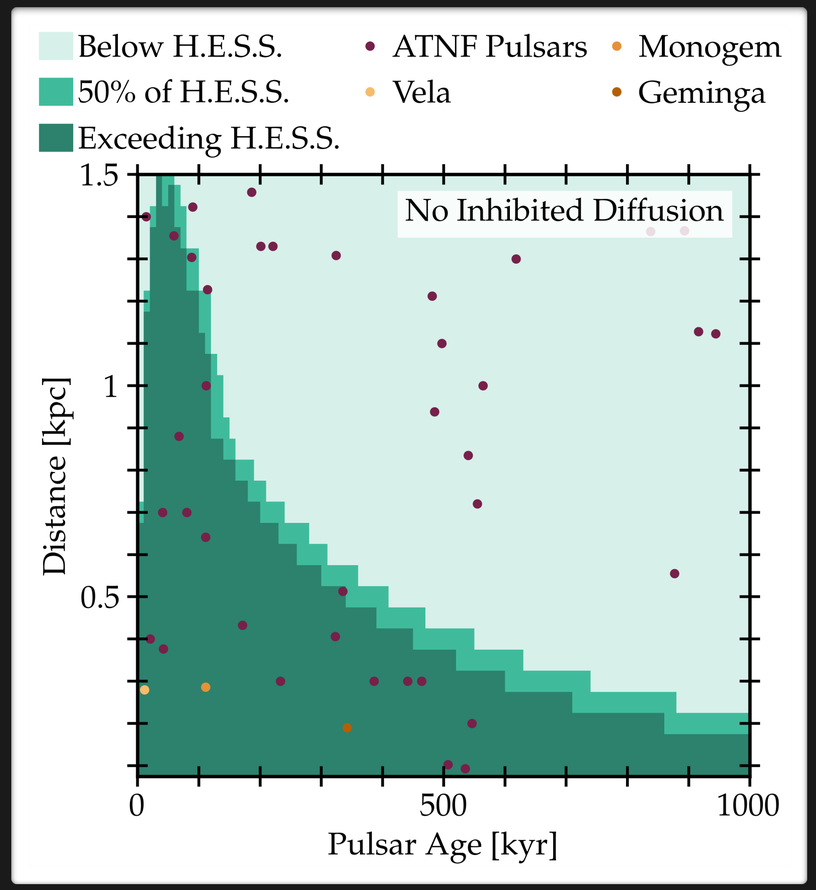


One-zone diffusion

21 pulsars

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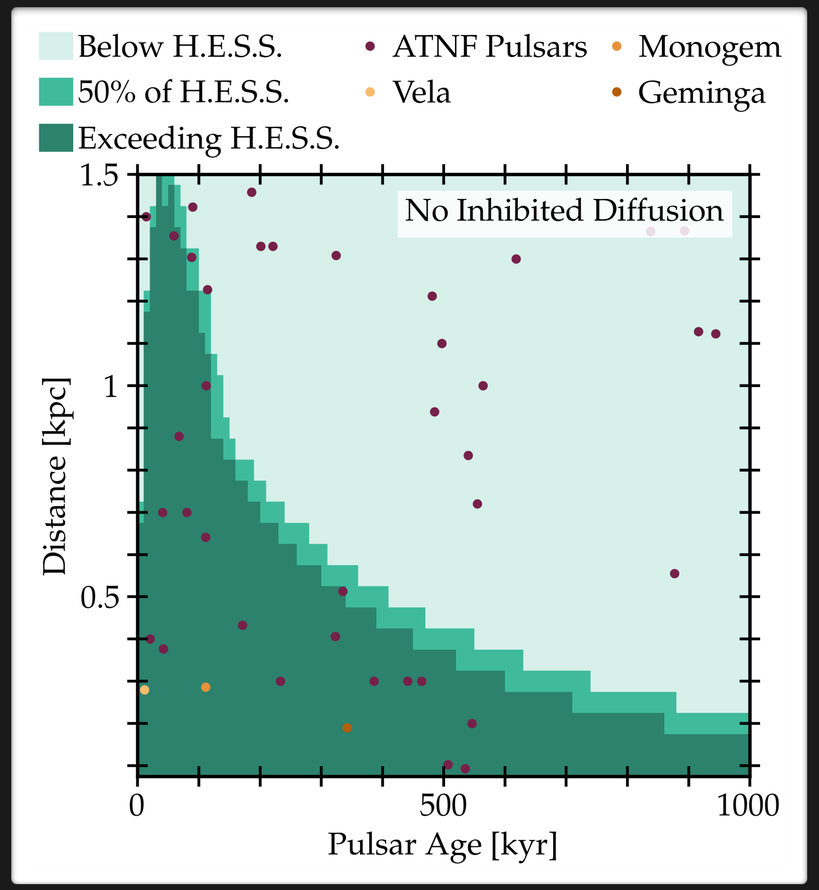


One-zone diffusion

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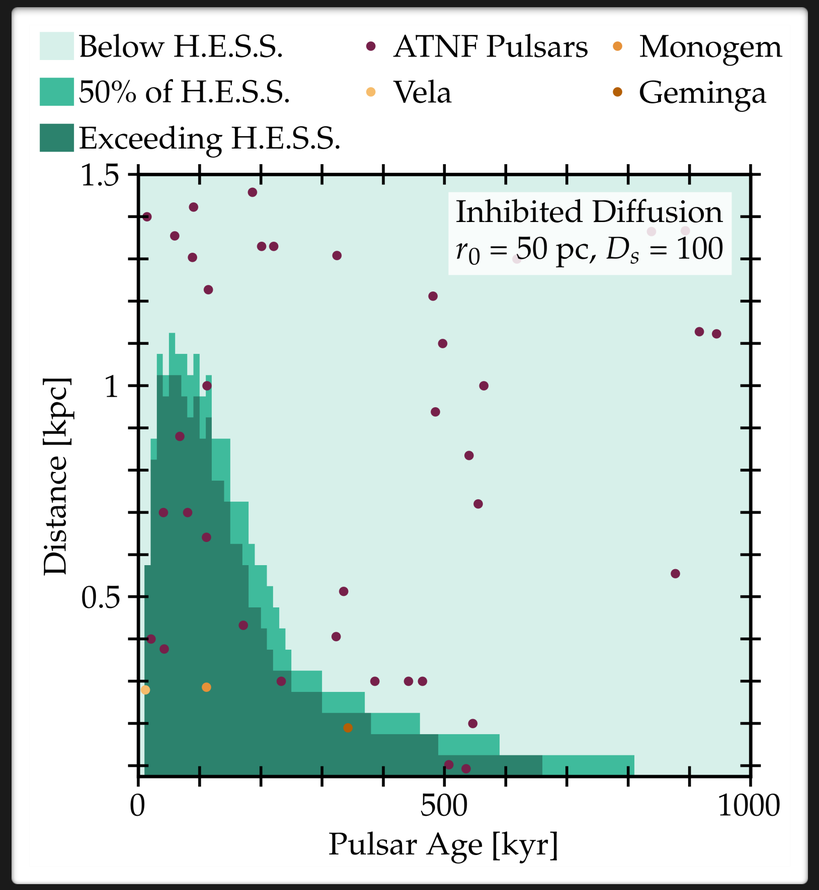
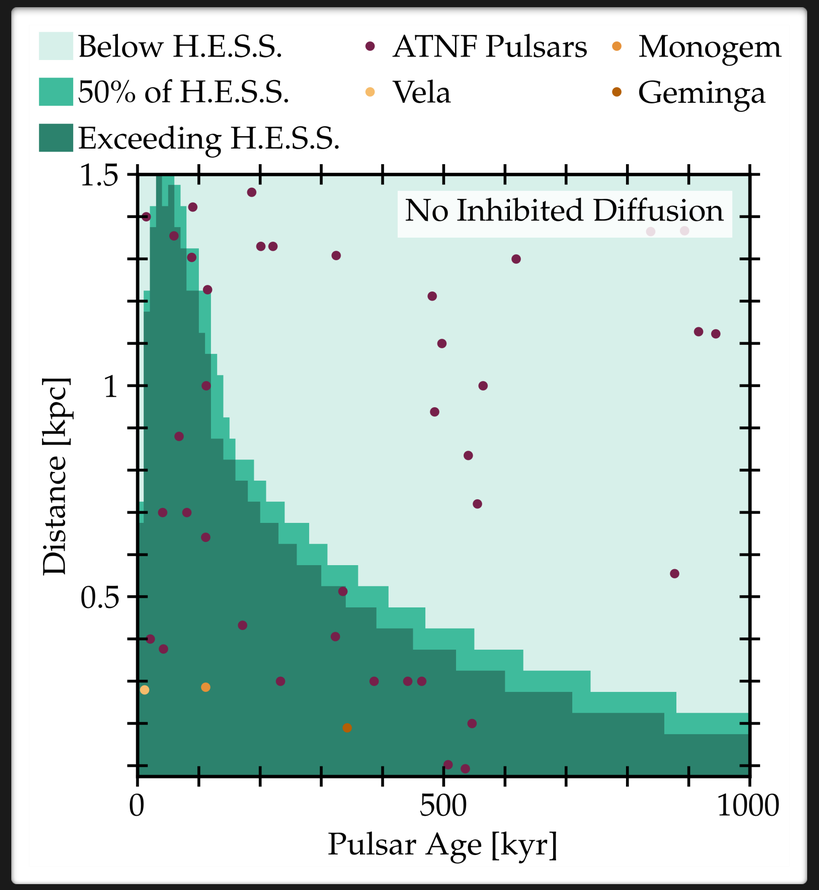



Two-zone diffusion
Ds = 100

12 pulsars

# Individual Pulsars vs H.E.S.S.

## Pulsars within 1.5 kpc and 1 Myr from ATNF Catalog




One-zone diffusion

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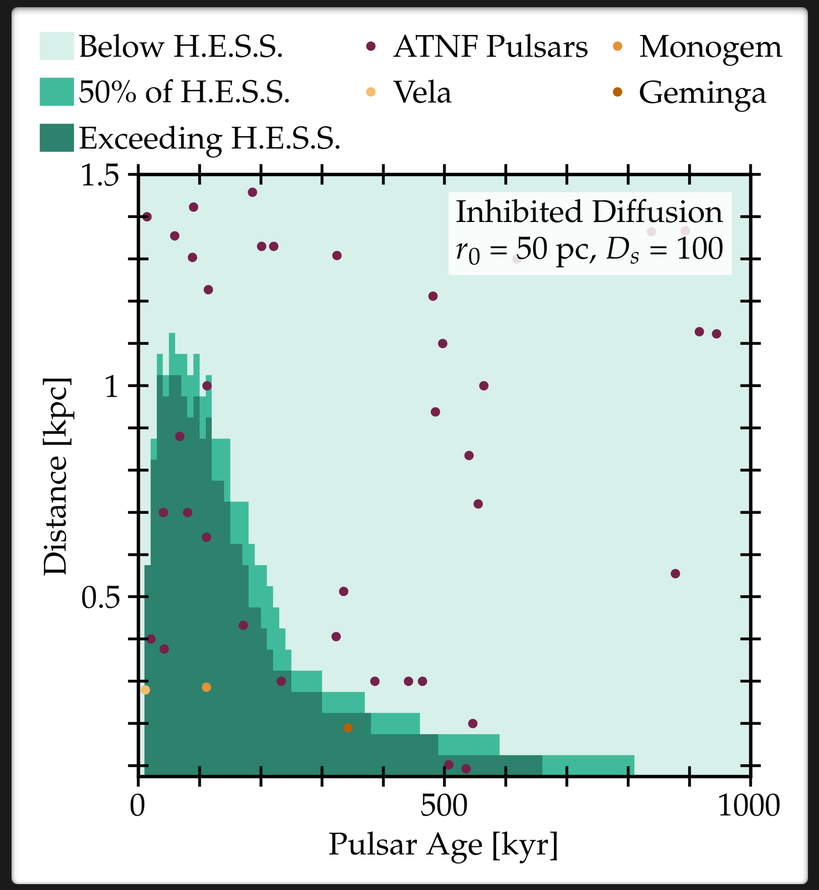


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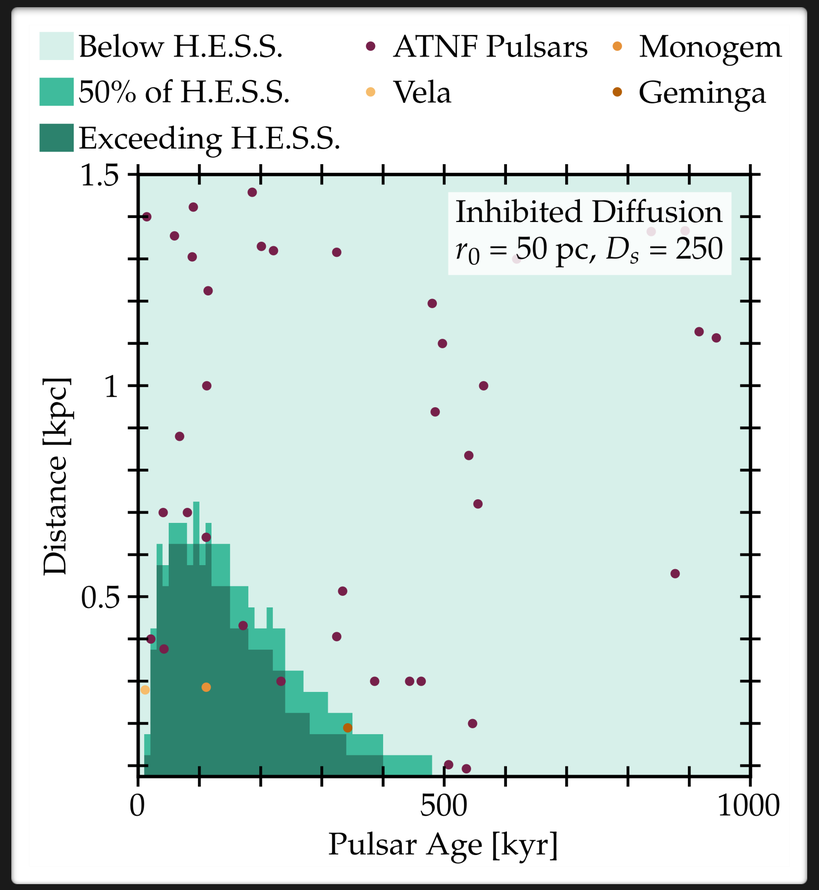
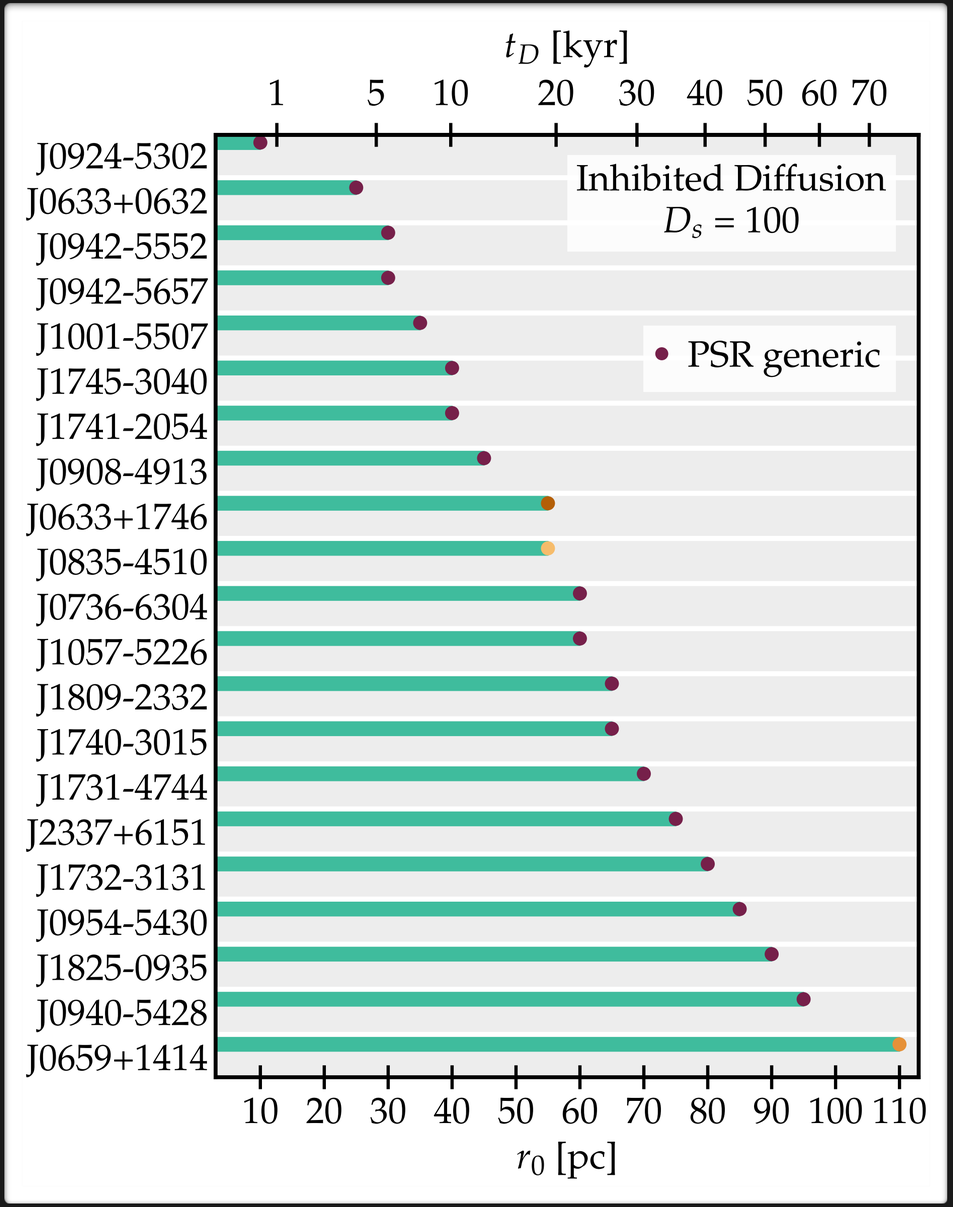



Two-zone diffusion
Ds = 250

3 pulsars

# Uncertainties in the Pulsar Model

- Generic pulsar model based on Geminga – 21 pulsars

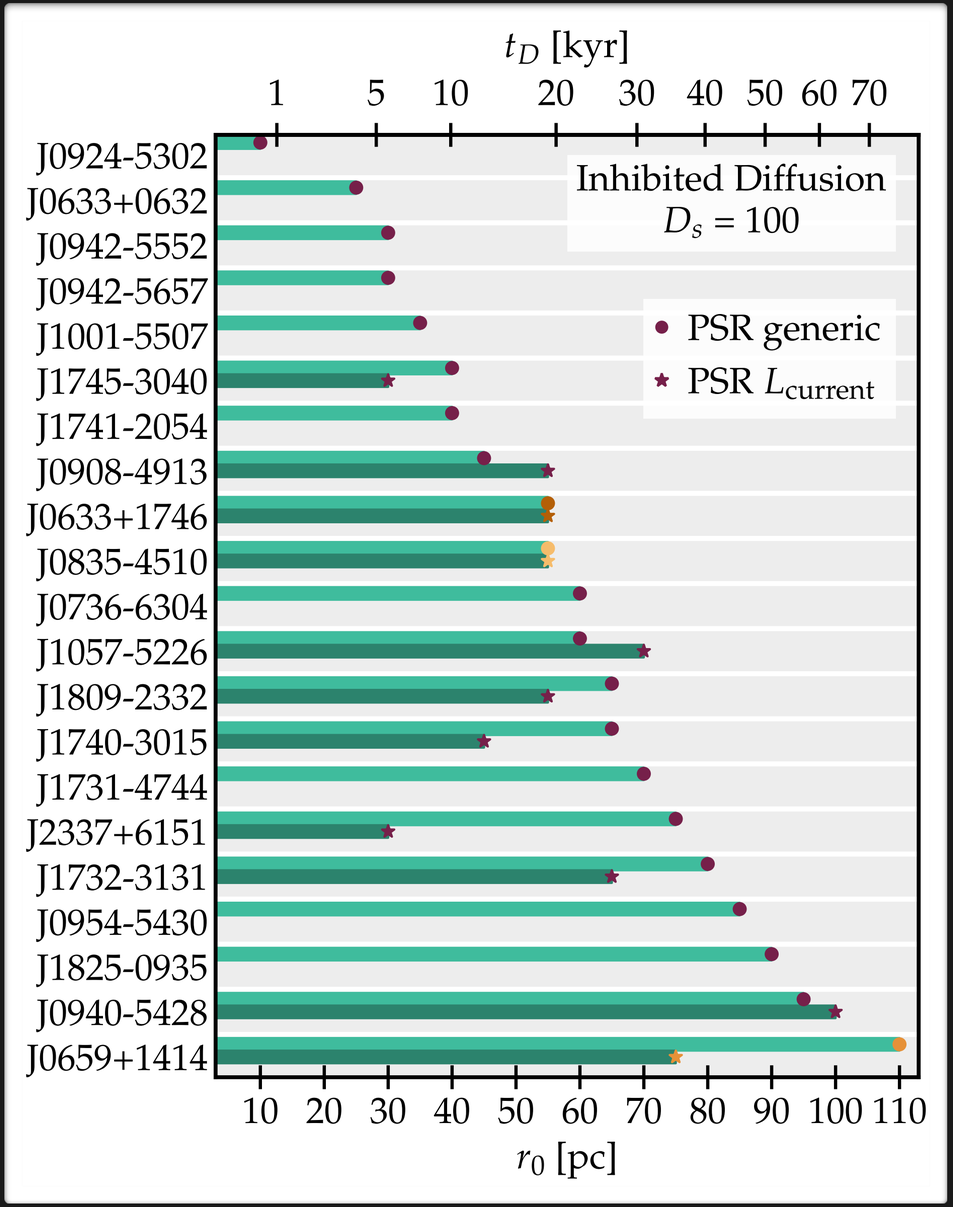


# Uncertainties in the Pulsar Model

- Generic pulsar model based on Geminga – 21 pulsars

Alternative models:

- ★ Individual ATNF spin down power – 11 pulsars



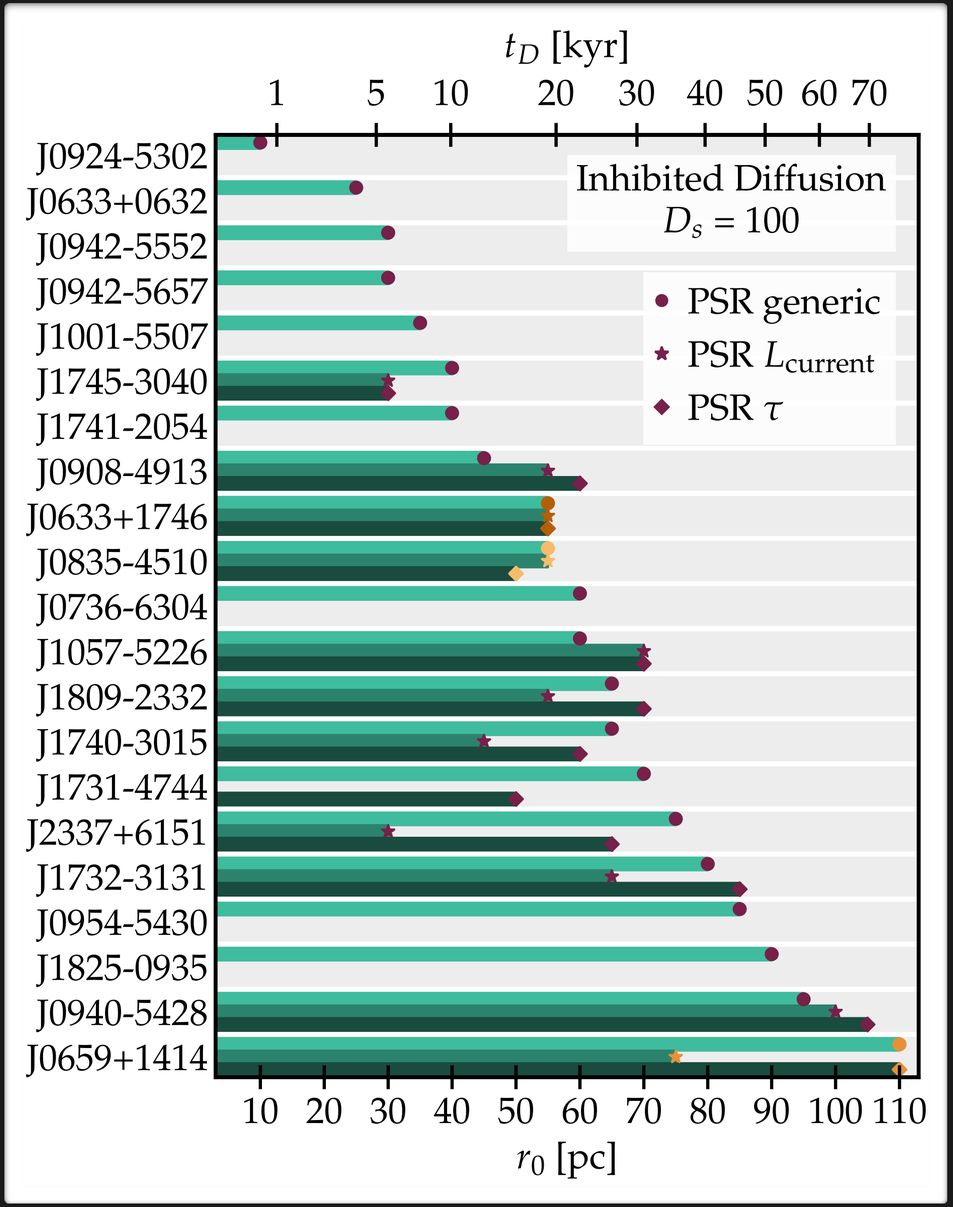
# Uncertainties in the Pulsar Model

- Generic pulsar model based on Geminga – 21 pulsars

Alternative models:

- ★ Individual ATNF spin down power – 11 pulsars
- ❖ Individual ATNF spin down power and time scale – 12 pulsars

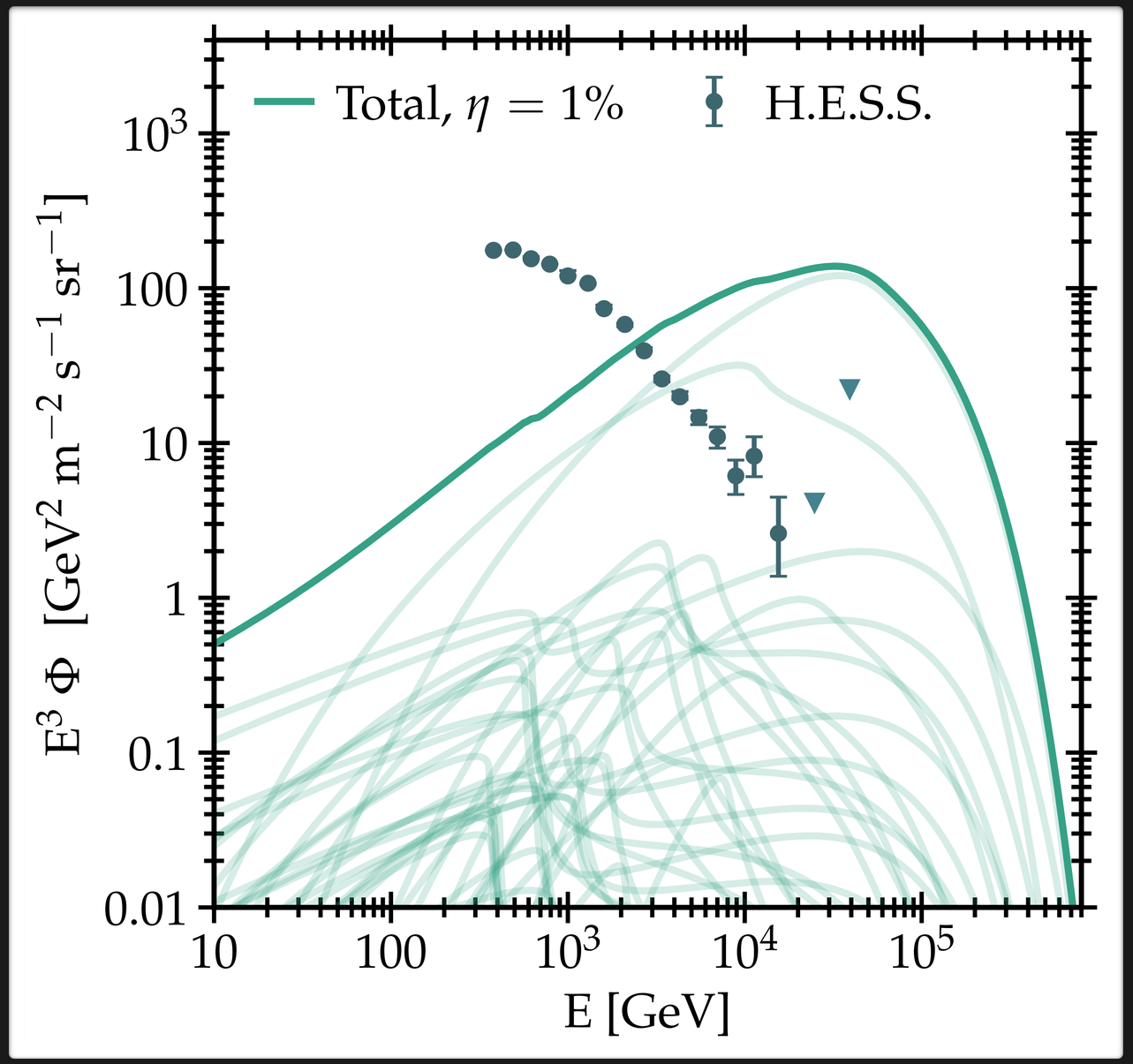
Pulsars that *individually* overproduce H.E.S.S. data



# Combined Pulsars vs H.E.S.S.

We only compare *individual* pulsars to H.E.S.S.

In reality, there are contributions from many pulsars and other sources – results are conservative



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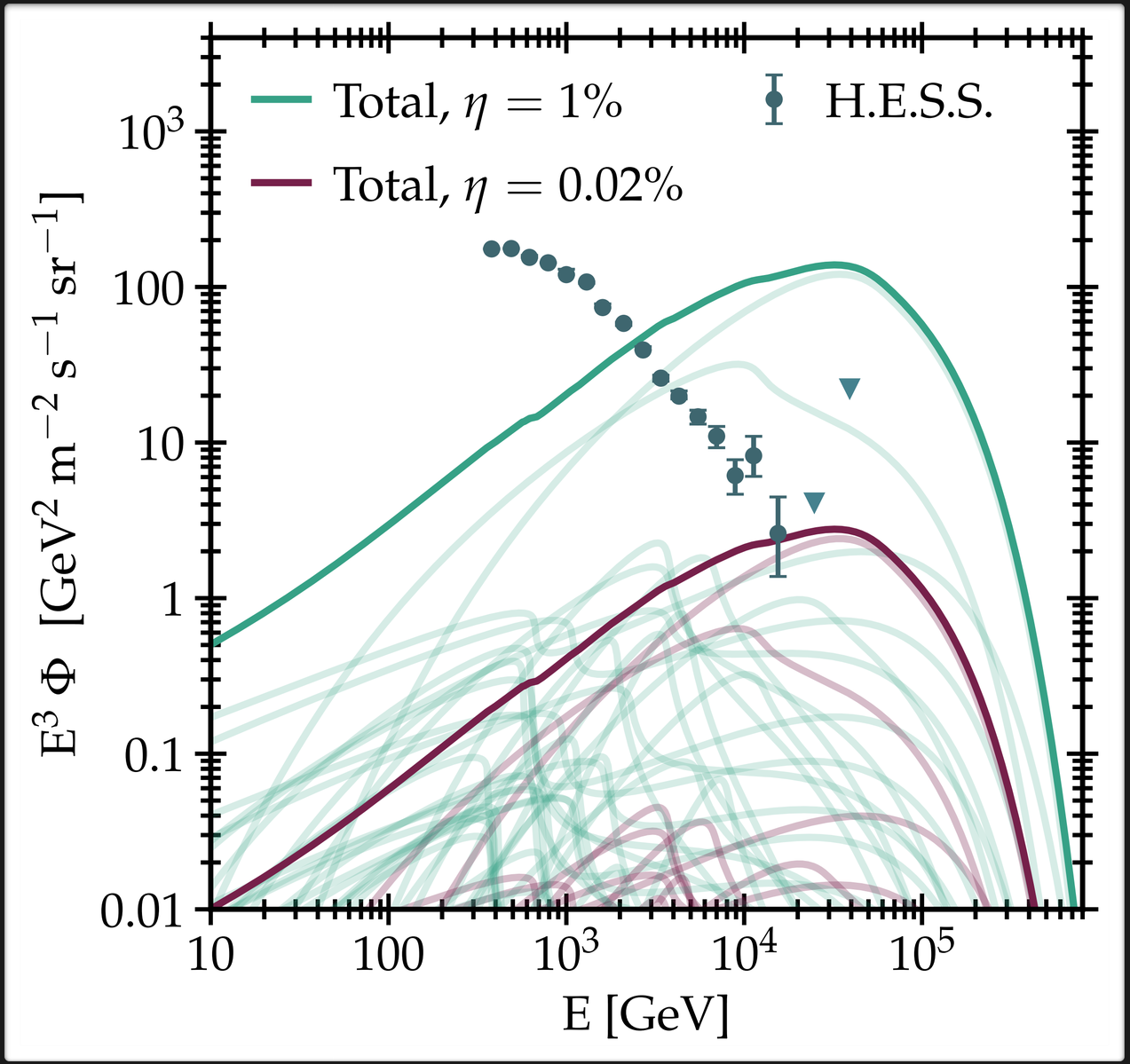
We only compare *individual* pulsars to H.E.S.S.

In reality, there are contributions from many pulsars and other sources – results are conservative

Combined pulsars would need very low efficiency of $\eta = 0.02\%$ to not overproduce H.E.S.S. – inhibited diffusion is likely very common



# Detection of Inhibited Diffusion

List of the 21 pulsars that individually overproduce H.E.S.S. in one-zone diffusion

Inhibited diffusion zones detected around many pulsars – more will likely follow with further observations

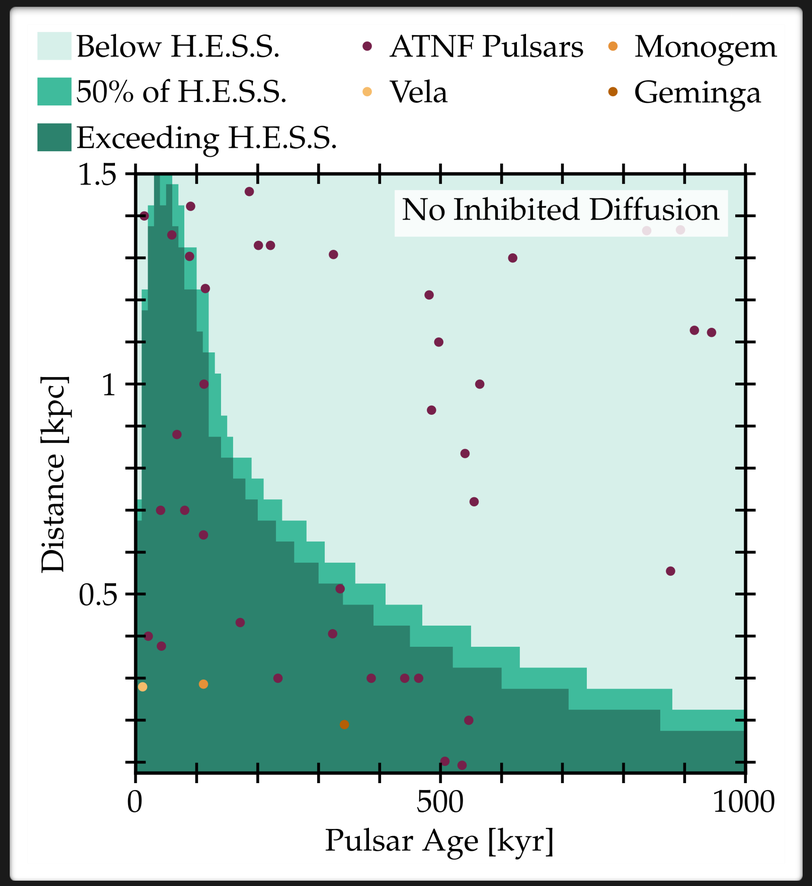
| Pulsar | Age [kyr] | Distance [pc] | Inhibited Diffusion Zone |
|---|---|---|---|
| J0633+0632 | 59.2 | 1355 | PWN [51] |
| J0633+1746 | 342 | 190 | TeV halo [22] |
| J0659+1414 | 111 | 286 | TeV halo [22] |
| J0736-6304 | 507 | 103 | TeV halo candidate [45][a] |
| J0835-4510 | 11.3 | 280 | TeV halo [27] |
| J0908-4913 | 112 | 1000 | SNR, PWN [52] |
| J0924-5302 | 335 | 513 | – |
| J0940-5428 | 42.2 | 377 | – |
| J0942-5552 | 464 | 300 | – |
| J0942-5657 | 323 | 406 | – |
| J0954-5430 | 171 | 433 | PWN candidate [53] |
| J1001-5507 | 441 | 300 | – |
| J1731-4744 | 80.4 | 700 | – |
| J1732-3131 | 111 | 641 | – |
| J1740-3015 | 20.6 | 400 | PWN, TeV halo [54] |
| J1741-2054 | 386 | 300 | PWN [55, 56] |
| J1745-3040 | 546 | 200 | SNR candidate [57] |
| J1809-2332 | 67.6 | 880 | SNR, PWN [58] |
| J1825-0935 | 233 | 300 | – |
| J2337+6151 | 40.6 | 700 | SNR [59] |

# Summary and Conclusions

We find ~ 10 to 20 nearby pulsars that individually overproduce H.E.S.S. $e^+e^-$ data

–

Inhibited diffusion is likely very common around pulsars




Inhibited diffusion zones around pulsars are bright

–

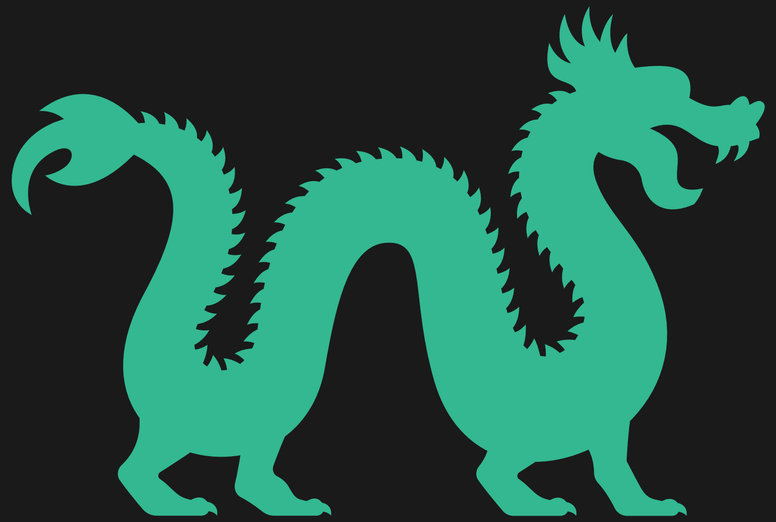
(Misaligned) pulsars are detectable

Recent HAWC paper:

*Extended TeV Halos May Commonly Exist around Middle-Aged Pulsars*

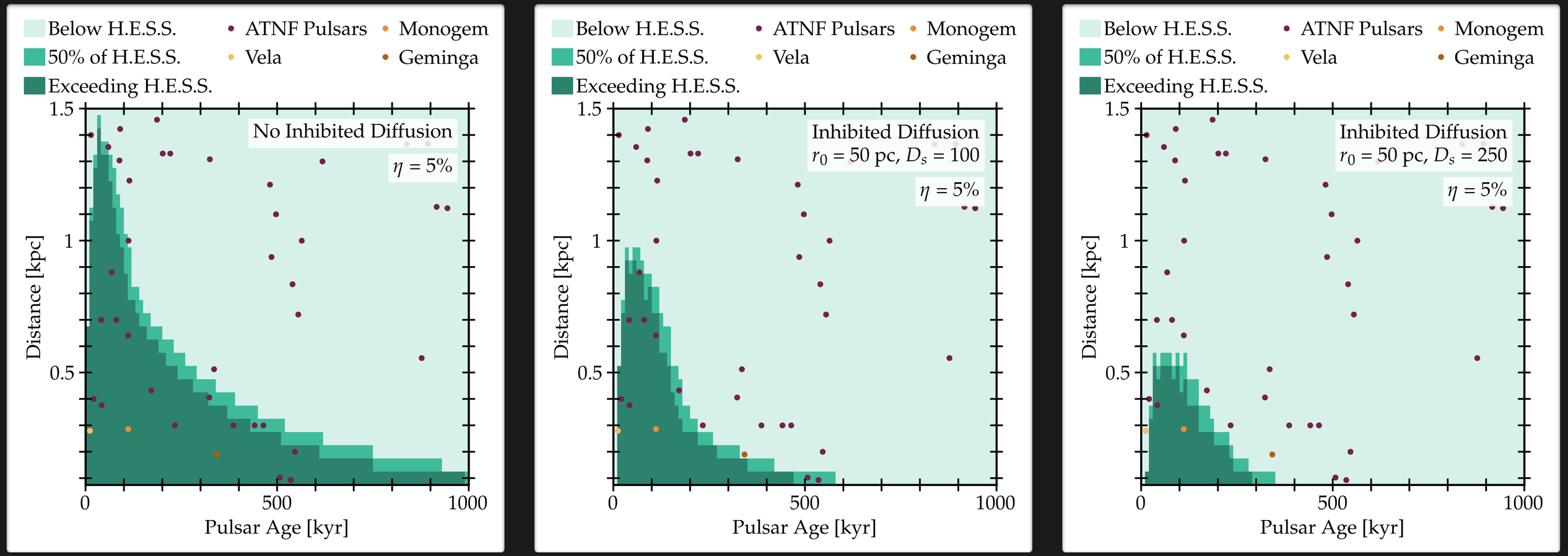
[arXiv:2505.00175]

# Additional Slides



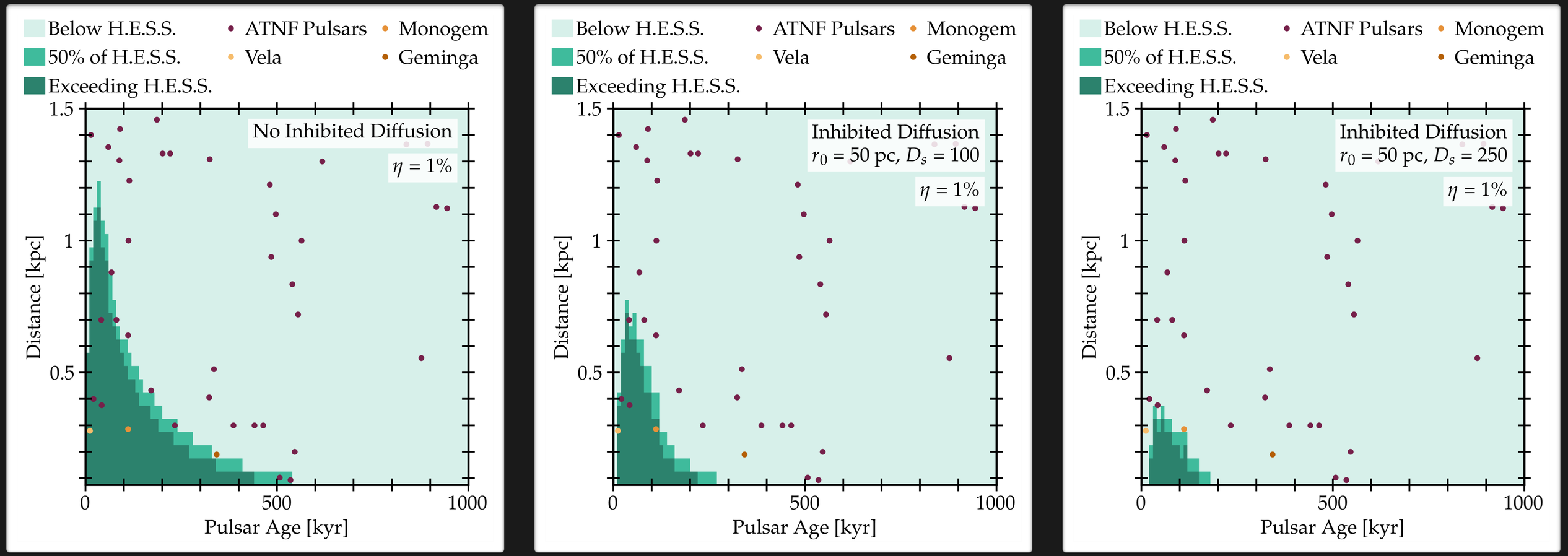
# Individual Pulsars vs H.E.S.S. – 5%

Comparison of individual ATNF pulsars with an efficiency of 5% (instead of 10%)



# Individual Pulsars vs H.E.S.S. – 1%

Comparison of individual ATNF pulsars with an efficiency of 1% (instead of 10%)



# Pulsars vs H.E.S.S. – Extrapolated

Comparison of individual ATNF pulsars including H.E.S.S. flux extrapolated above ~ 20 TeV