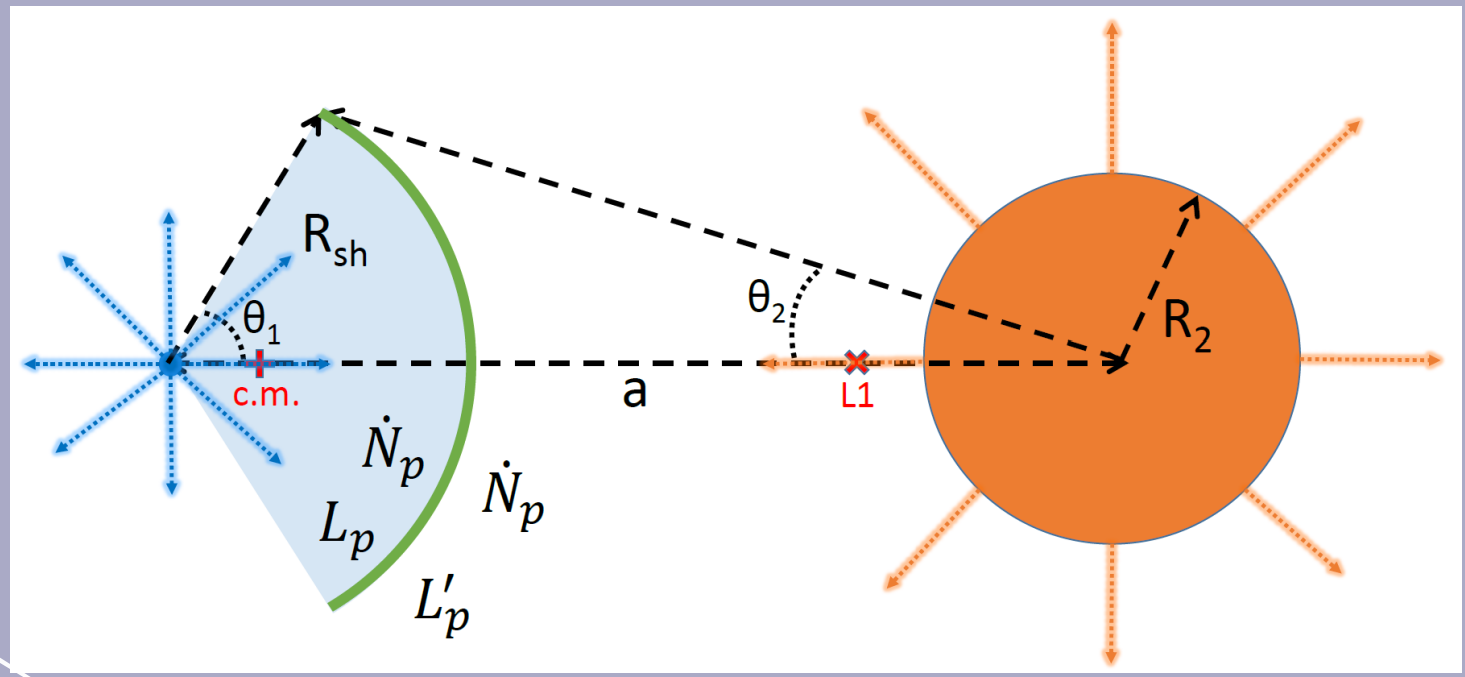
Compact binary millisecond pulsars and the positron excess



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PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

Compact Binary Millisecond Pulsars

A growing, nearby population of millisecond pulsars

"Spiders" (blackwidows, BWs; redbacks, RBs):

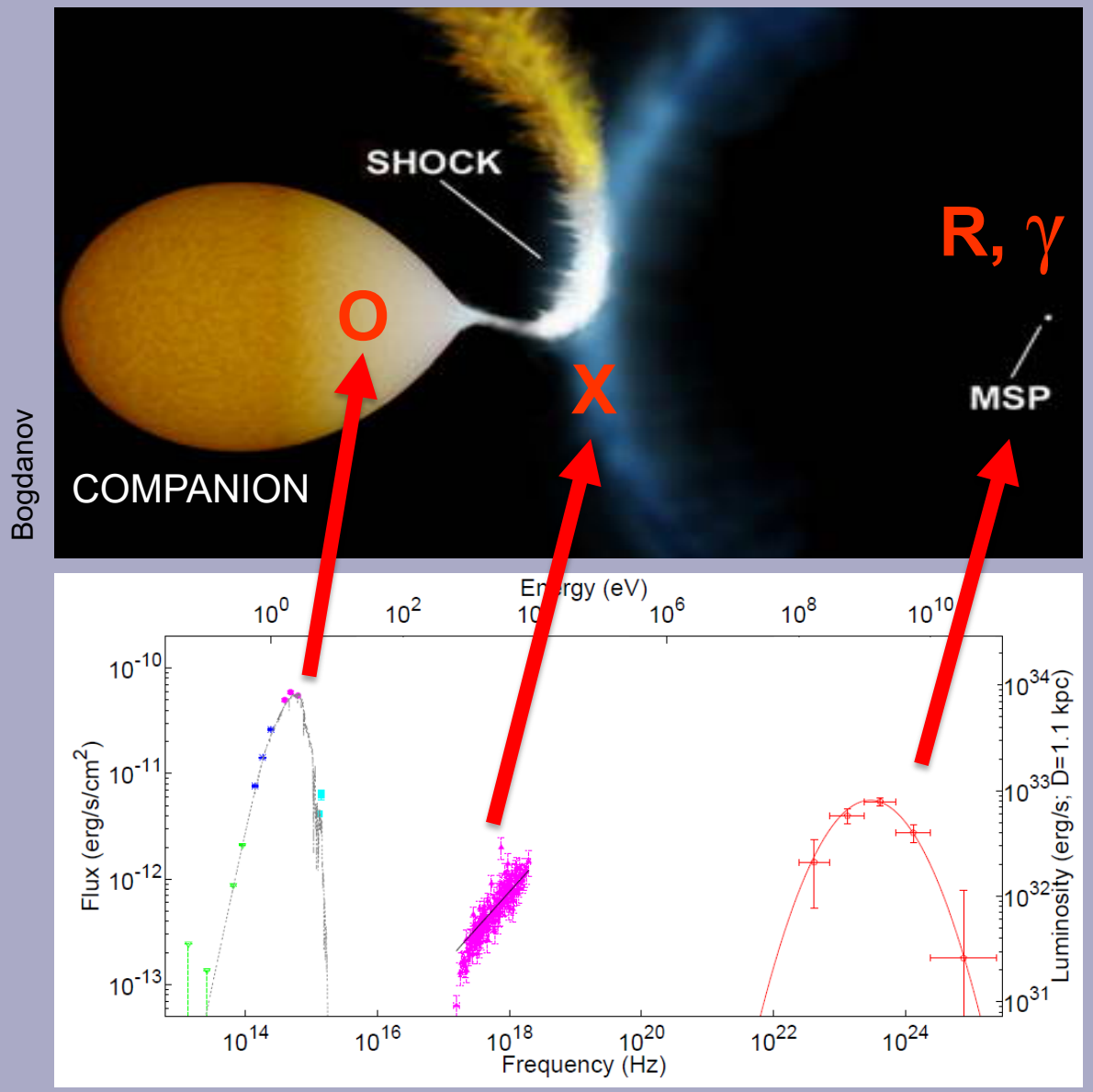
- Millisecond pulsar

(wind, γ-rays, spin-down luminosity: L_{sd}~10^{34}-10^{35} erg/s)

- Binary, compact orbit ($P_{orb} \leq 1$ day; $a \sim R_{Sun}$)
- Non/semi-degenerate companion star

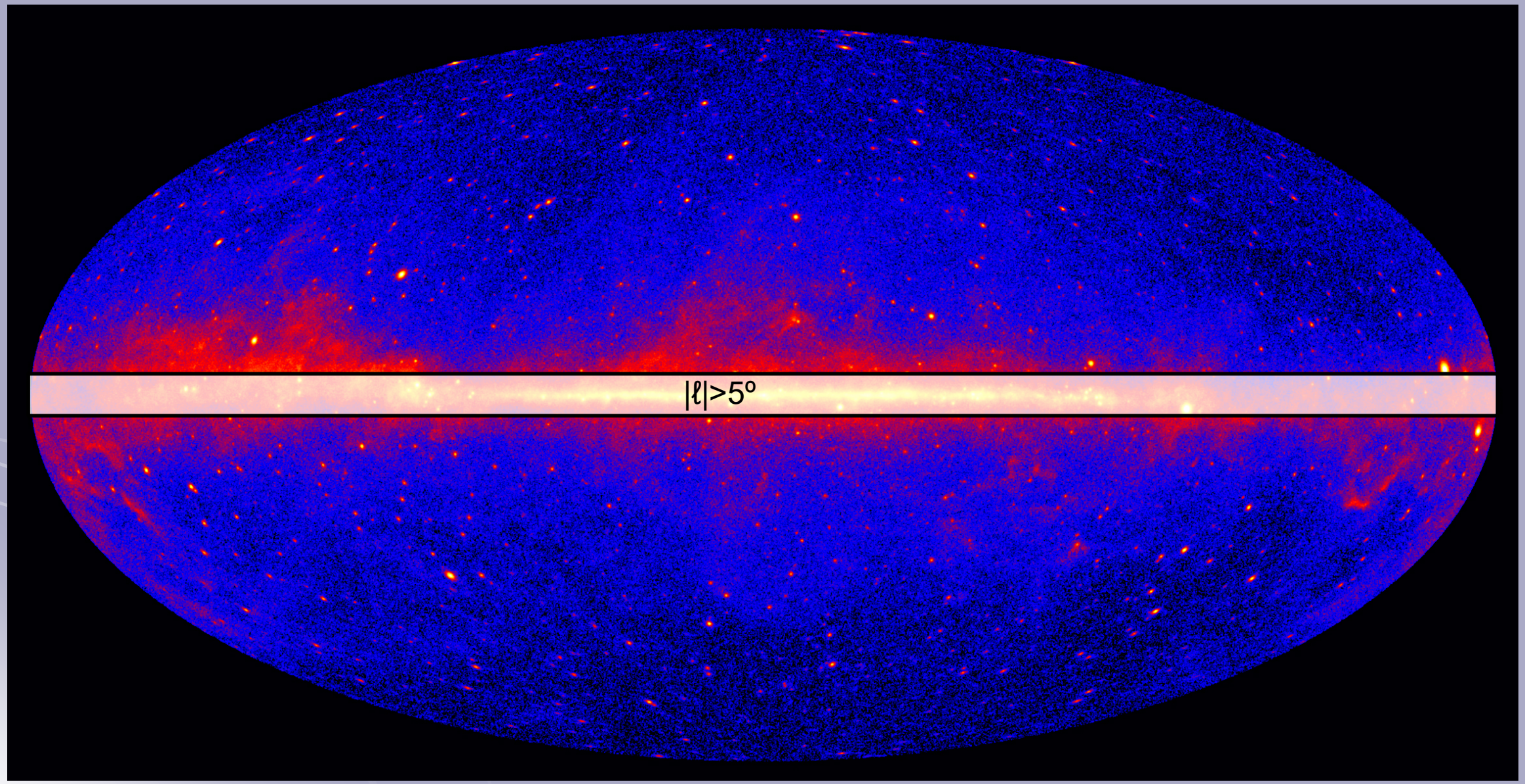
(low/very-low mass, RBs / BWs: ~0.1 / 0.01 M_{Sun})

•Accreting past: maximum neutron star mass
(van Kerkwijk+11, Linares+18)
•Transitional MSPs: disk-wind-magnetosphere
(Archibald+09, Papitto+13)
•Evolution: link with low-mass X-ray binaries
(Chen+13, Benvenuto+12)
•**Intra-binary shock: particle accel., cosmic rays**
(Bogdanov+11, Venter+15, Linares & Kachelriess 2021)



A Spider Revolution

A booming field thanks to Fermi-LAT driven discoveries

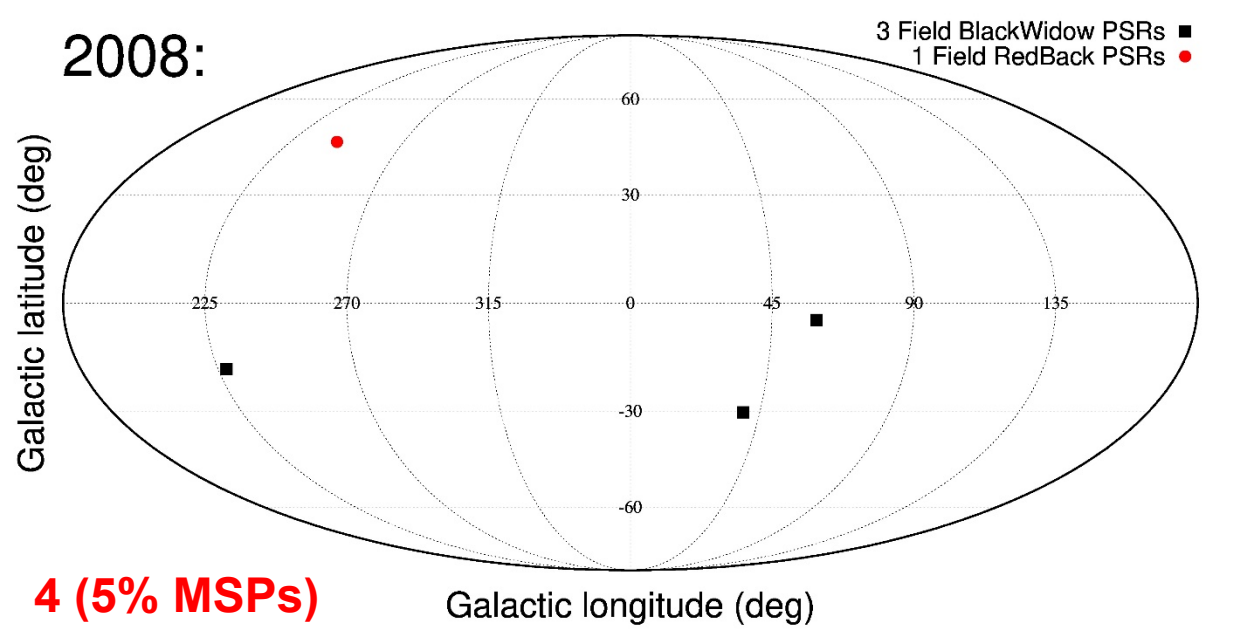


Fermi-LAT, 5 years, E> 1 GeV

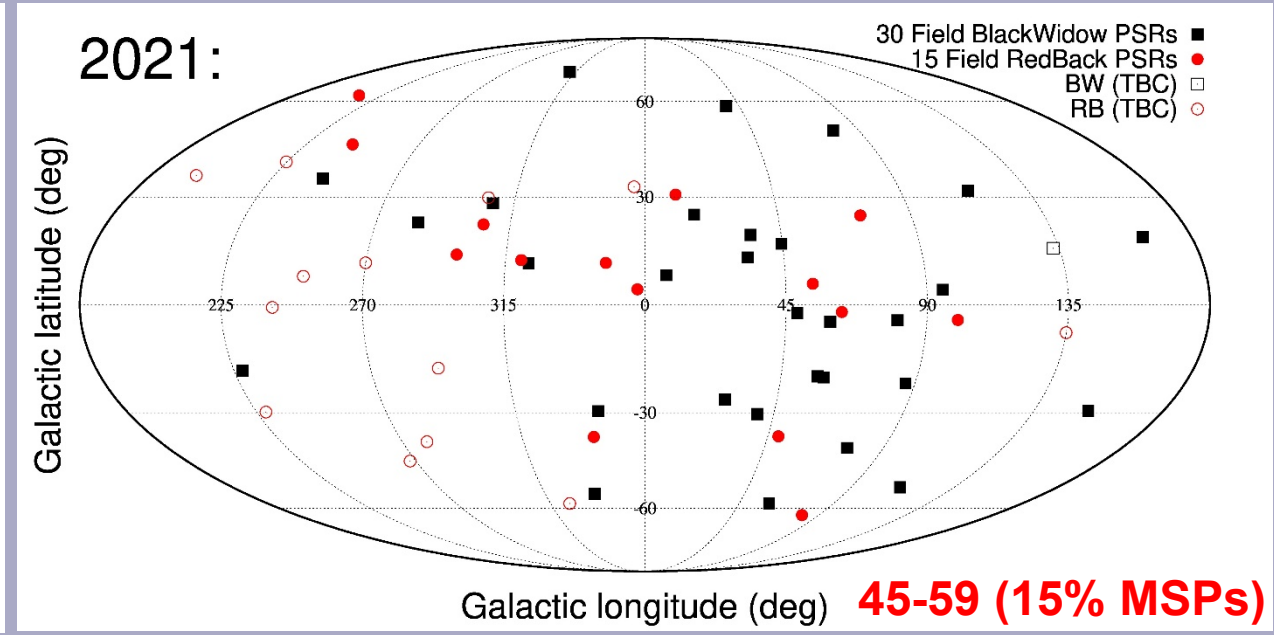
Credit: NASA/DOE/Fermi LAT Collaboration

A Spider Revolution

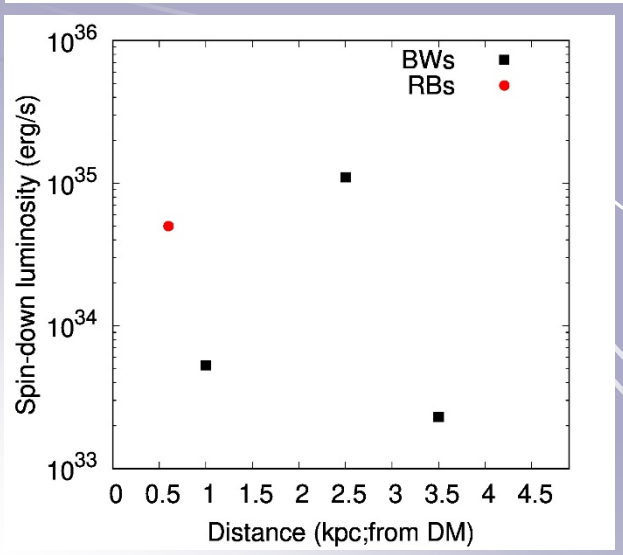
A booming field thanks to Fermi-LAT driven discoveries



4 (5% MSPs)



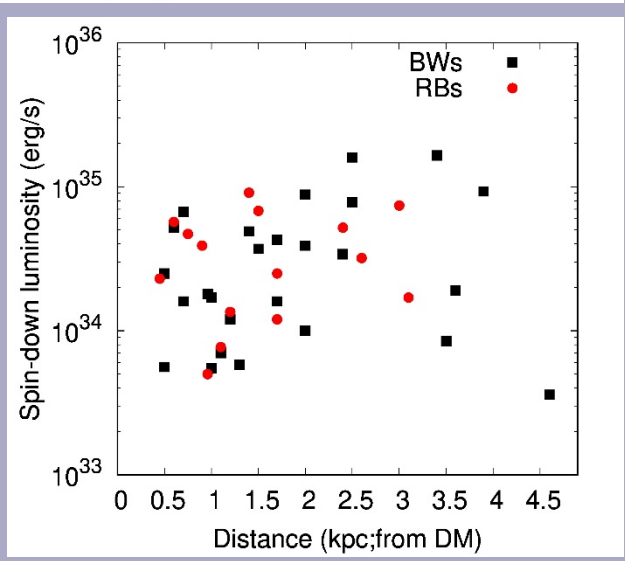
45-59 (15% MSPs)



Field population x10 in ~10 years!

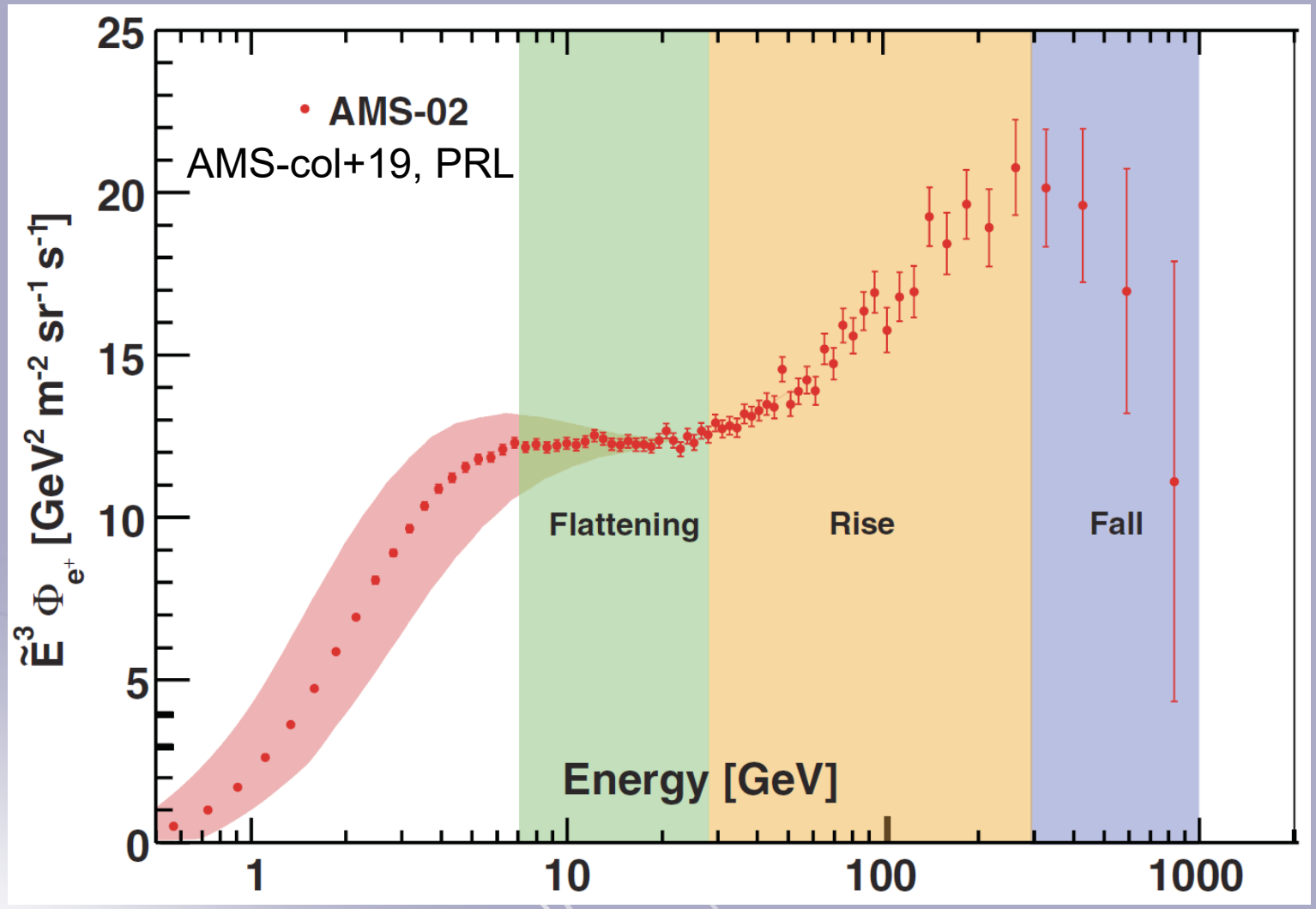
d ~ **0.5**-5 kpc; L_{sd} ~ 10^{34}-10^{35} erg/s

(Hessels, Roberts, Ray, Ransom+ PSC;
Kong, Romani, Salvetti, …)



Positrons from Pulsars

Natural electron-positron sources



Copious pair cascades:

can PSRs explain e^+ excess?

- Young nearby PSRs can't

(<15-20% of obs. flux; Xi+19, DiMauro+19)

- Bow shock PWNe might, IF very efficient at $L_{sd} \rightarrow L_p$

(30-50%; Blasi+11, Bykov+17)

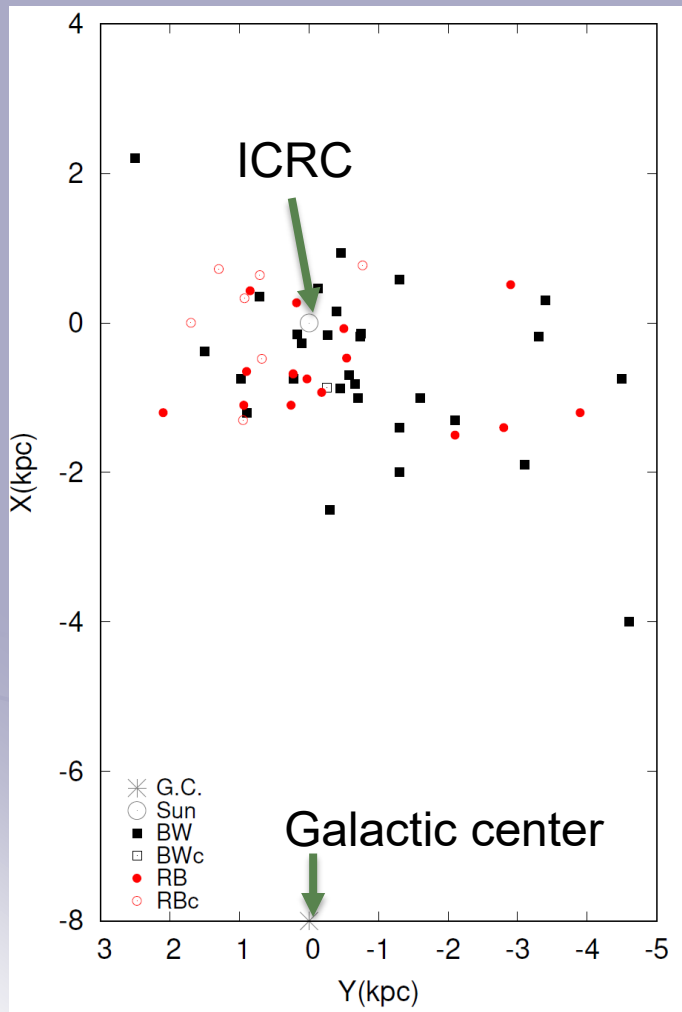
- Normal MSPs can't

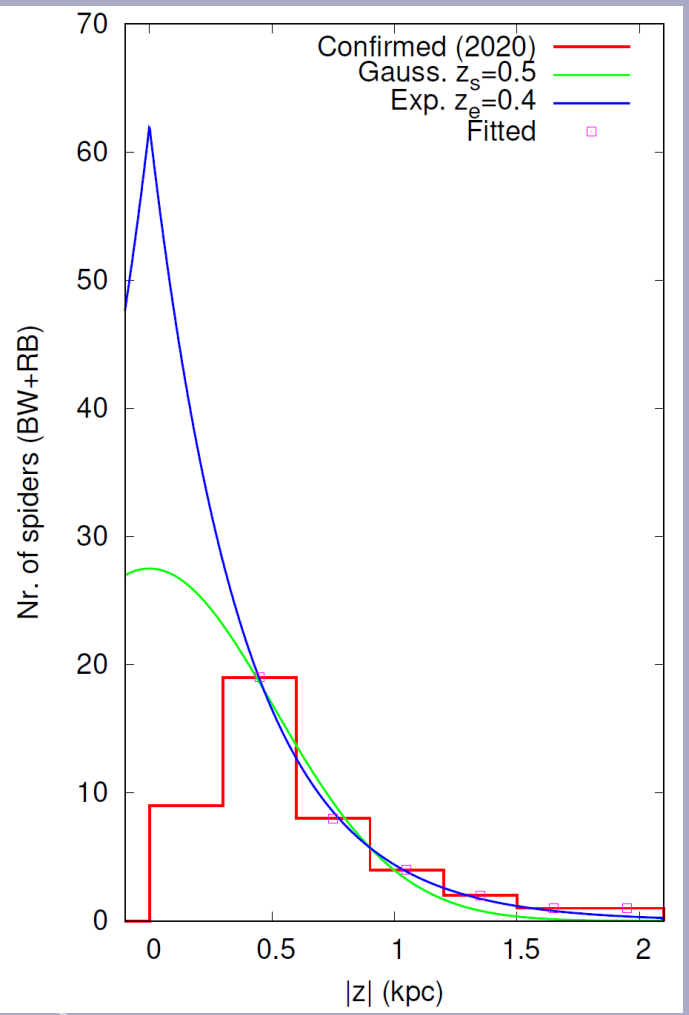
(cut-off above ~1 TeV; Venter+15)

→ Contribution from spiders?

Spiders in the Galaxy

From the tip to the size of the iceberg





Updated catalog: 52 known spiders
(24 in Venter+15)

Exp. scale height: z_e = 0.4+/-0.1 kpc
(bias against z→0 corrected; agree with LMXBs and MSPs; Grimm+02,Cordes+97,Story+07)

20-50 “hidden” spiders (|z|≤0.5 kpc)

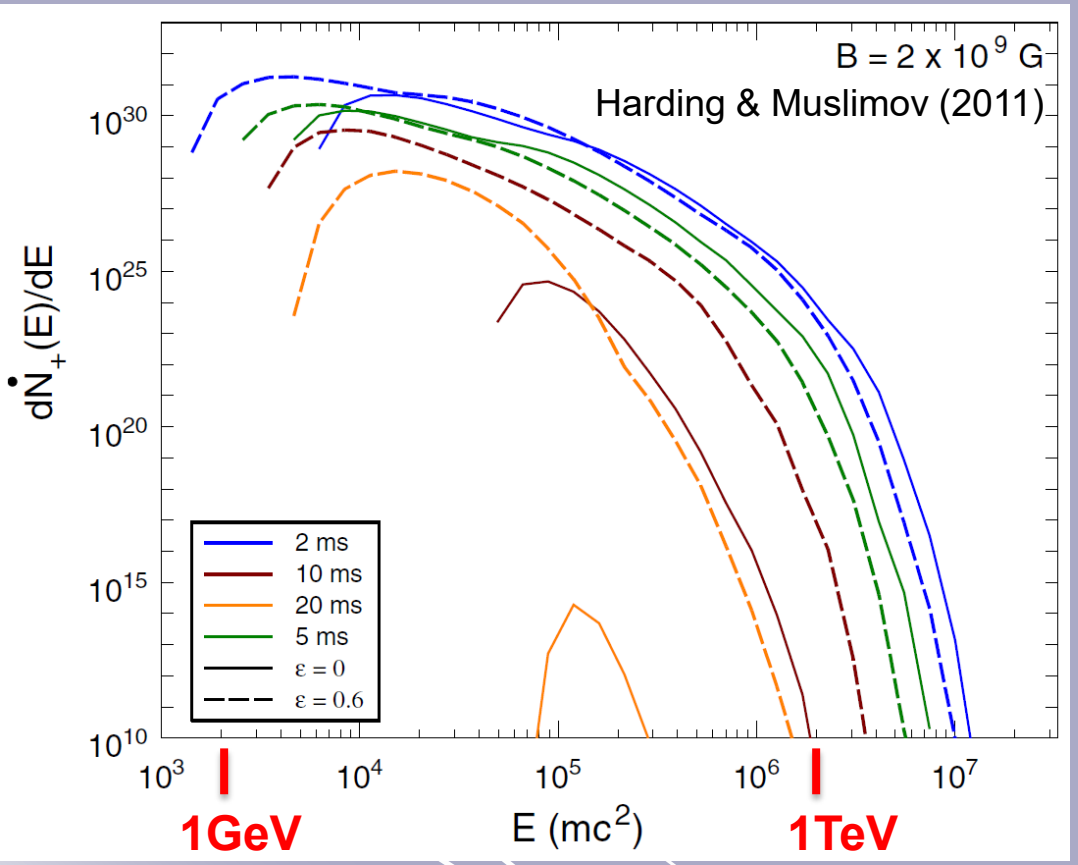
2-3 “hidden nearby” spiders (d<1kpc) close to the plane (|ℓ|<5º)

→ Total: 2-7 thousand spiders:
we simulate 5000 additional Spiders

Nr. DENSITY: $$n(R,z) = n_c \, e^{-R/R_e} e^{-|z|/z_e}$$

Positrons from Spiders

A third built-in accelerator



Magnetosphere:

1ary: GJ

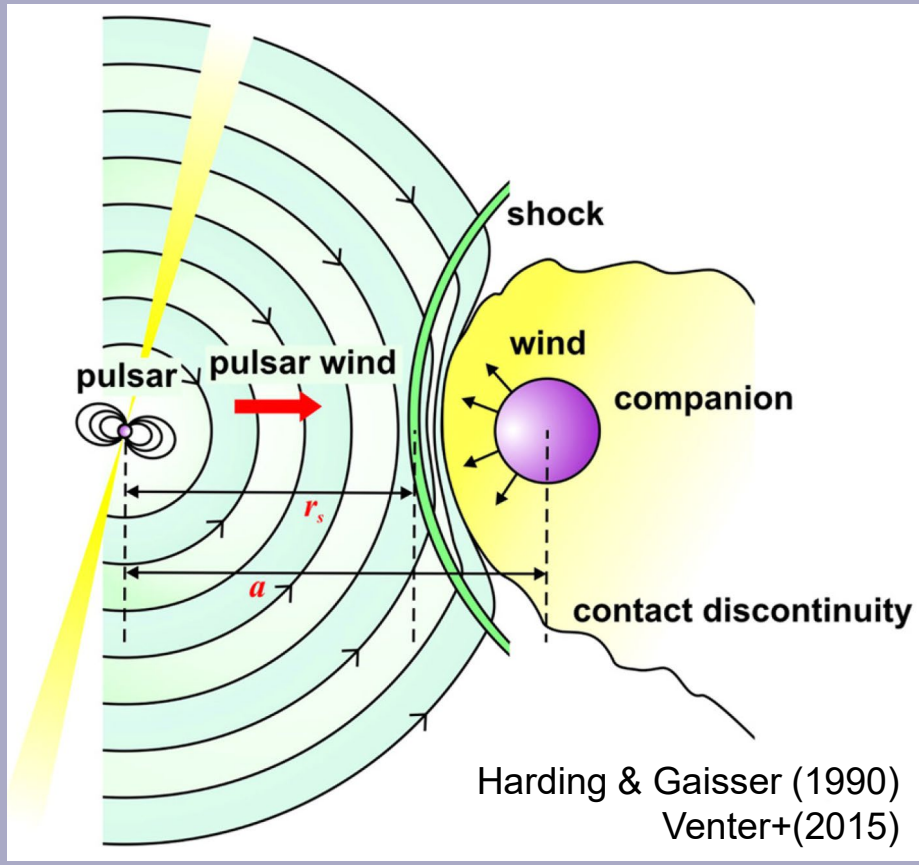
2ary: cascades

Wind:

Magnetic → kinetic

Intrabinary shock:

3ary: reaccelerated!



E_{min} = 1-50 GeV

Power law index ~3

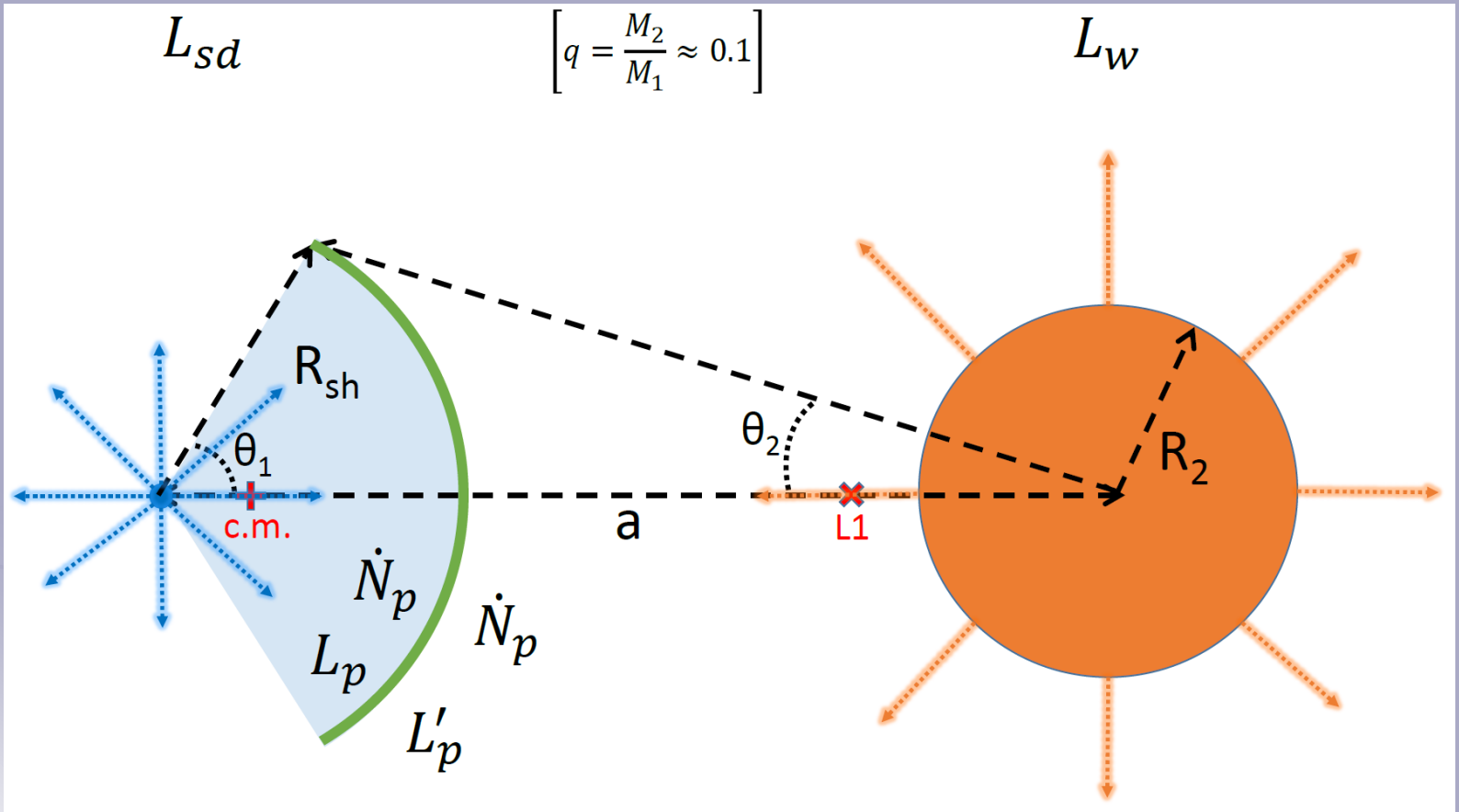
E_{top} = 1-10 TeV

Power law index ~2

Steady CR sources (Gyr >> diffusion)

Intrabinary Shock Reacceleration

A simple self-consistent model of the "tertiary" pair spectra

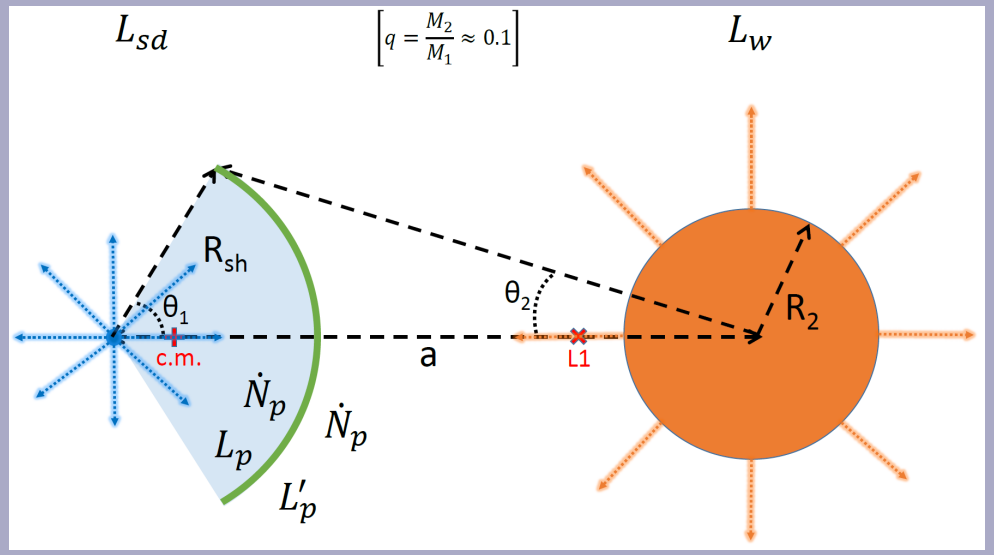


Parameters:

- $\mathbf{E_{min}}$: minimum pair energy after shock reacceleration (1-50 GeV)
- $\mathbf{\Omega_1}$: fraction of PSR sky covered by the shock (25-100% = pairs intercepted)
- $\mathbf{f_w}$: fraction of the intercepted PSR wind that launches companion's wind (10-50%)
- $\boldsymbol{\sigma}$: fraction of intercepted spin-down luminosity available for shock acceleration (0-30%)

Intrabinary Shock Reacceleration

Two regimes: power-limited vs. synchrotron-limited



$$\dot{N}_{\rm p} = 2\Omega_1 \times 8.5 \times 10^{33}\,{\rm s}^{-1} \left(\frac{L_{\rm sd}}{10^{35}\,{\rm erg\,s}^{-1}}\right)^{0.91}$$

$$L_{\rm p} = 2\Omega_1 \times 3.2 \times 10^{32}\,{\rm erg\,s}^{-1} \left(\frac{L_{\rm sd}}{10^{35}\,{\rm erg\,s}^{-1}}\right)^{0.86}$$

2$^{\rm ary}$ (input) pair rate & luminosity scale with L_{SD} (Harding & Muslimov 2011)

$$L'_{\rm p,max} = L_{\rm p} + \sigma\Omega_1 L_{\rm sd} + \Omega_2 L_{\rm w}$$

$$\dot{N}_{\rm p} = \dot{N}'_{\rm p} \simeq \frac{K}{E_{\rm min}}$$

Normalization

- Post-shock pair spectrum (**Fermi 1st order, strong non-rel. shock**):

$$Q(E) = \frac{{\rm d}N}{{\rm d}E\,{\rm d}t} = KE^{-2}$$

- Maximum energy in the post-shock (tertiary) pair spectra (E_{top}) limited by:

-Synchrotron losses (cut E>E_{cut})

$$E_{\rm cut} = 68\ {\rm TeV} \left(\frac{B_{\rm sh}}{\rm G}\right)^{-1/2} \sqrt{\frac{(\xi-1)}{\xi(\xi+1)}}$$

OR

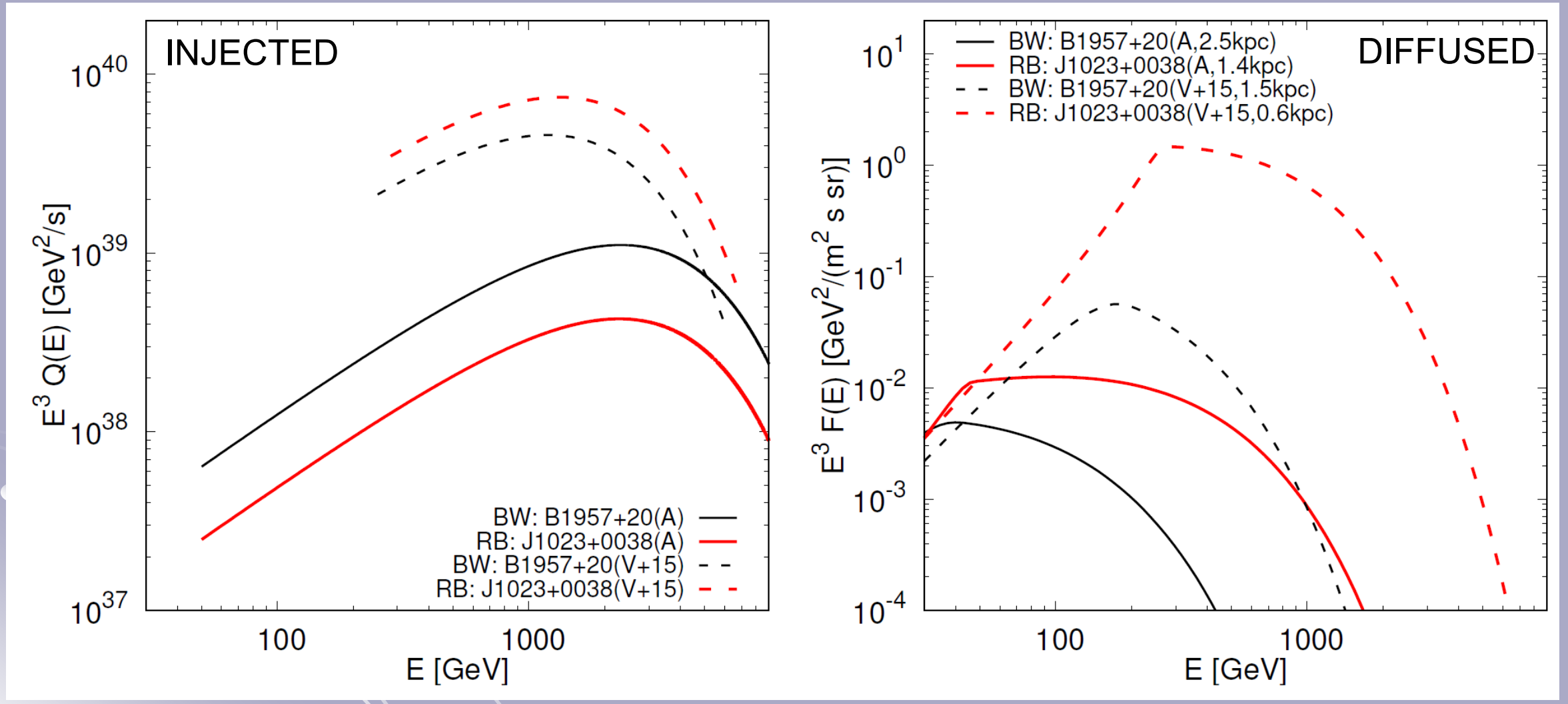
-Kinetic luminosity (accelerate to E<E_{max})

$$E_{\rm max} = E_{\rm min} {\rm e}^{L'_{\rm p,max}/K}$$

→Cut-off at E_{top}=min(E_{max};E_{cut})~1-10 TeV

Results I: e^+ injection

Injected and diffused positron spectra



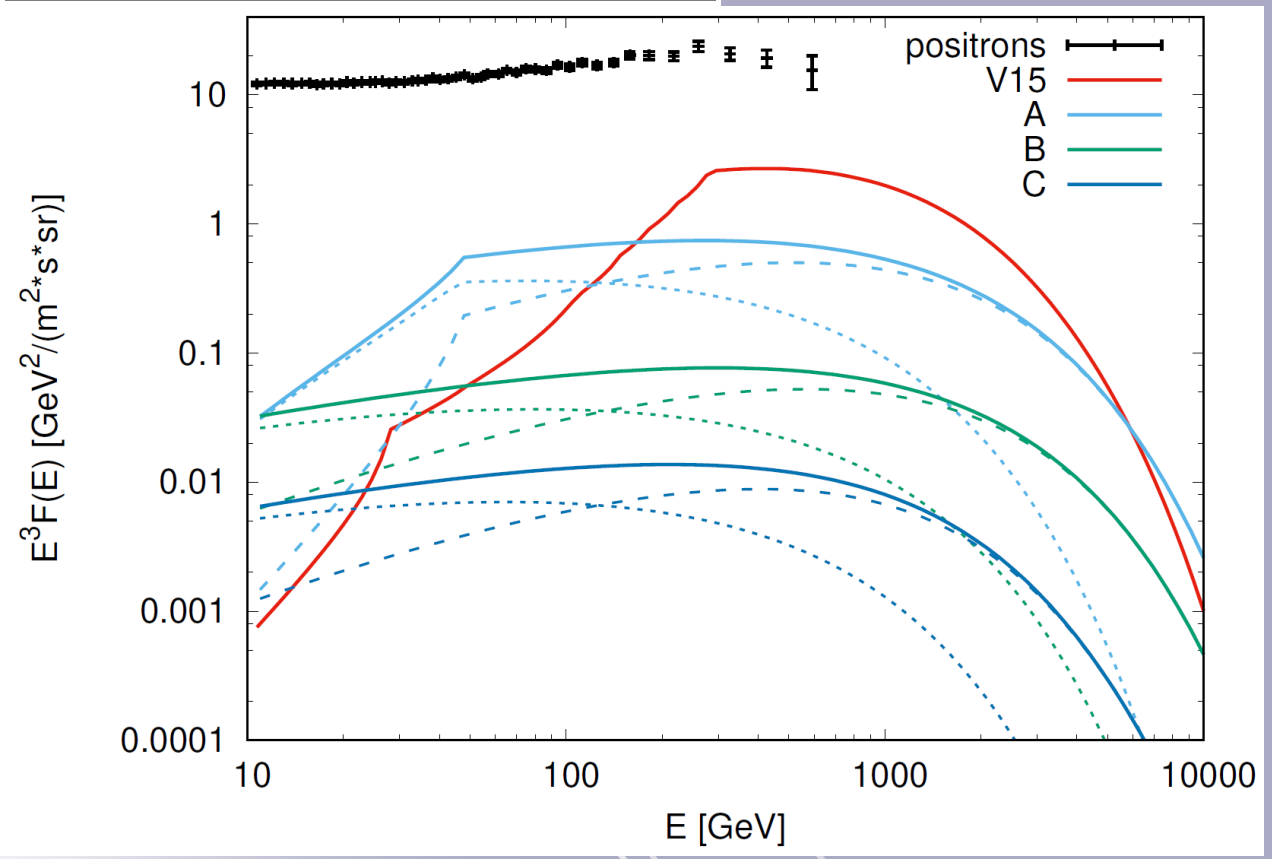
L_p = 0.1-10% L_{sd}

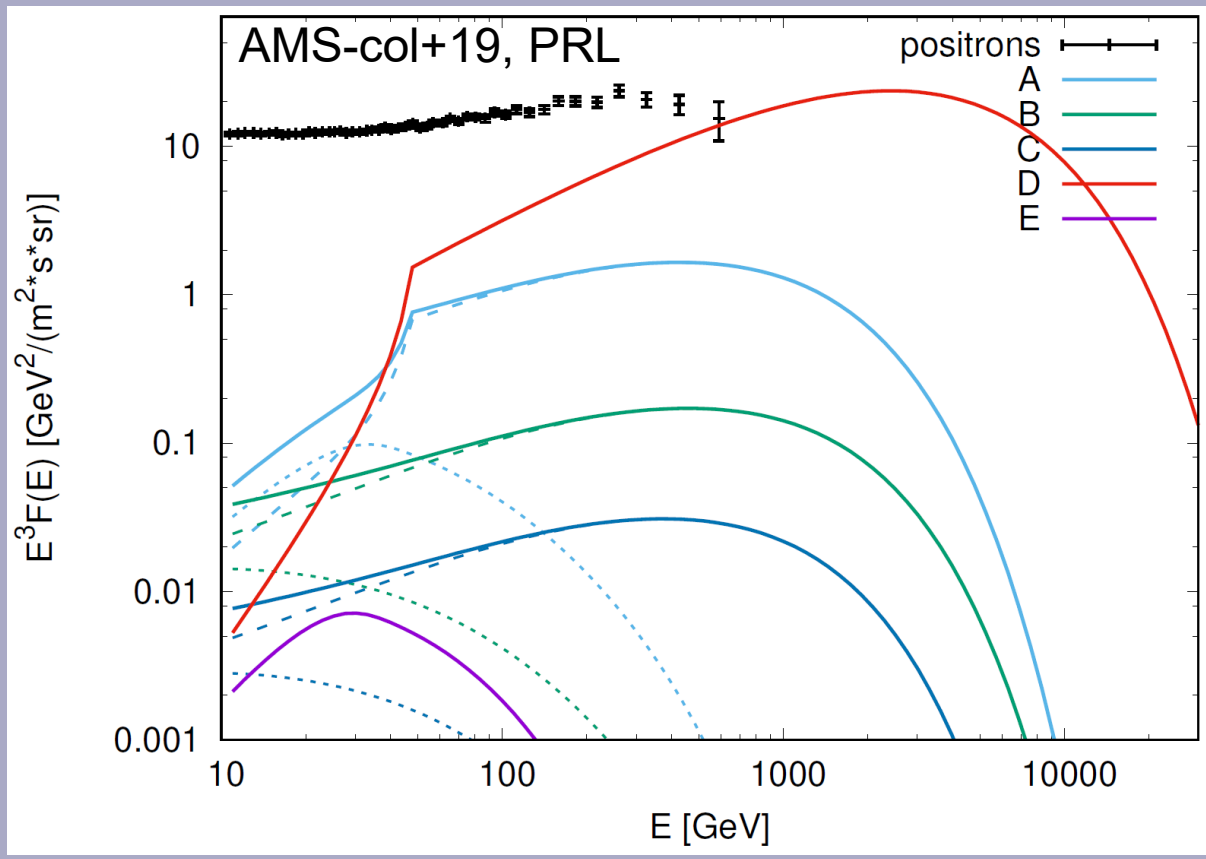
$\beta=4\times10^{-17}$ GeV/s, $\delta=1/3$. Isotropic: $D_0=3\times10^{28}$ cm^2/s
Anisotropic: $D_{\perp0}=2\times10^{26}$ cm^2/s, $D_{\parallel0}=5\times10^{28}$ cm^2/s

Results II: e^+ flux

Comparison with AMS measurements

Label	Nr.	Sample	E_{min} (GeV)	Ω_1	f_w	σ
V15	24	known in 2015	30–1850	1.0	- (0?)	- ?
A′	52	currently known	50	1.0	0.5	0.3
A″	5000	simulated outside 1 kpc	50	1.0	0.5	0.3
B′	52	currently known.	10	0.5	0.2	0.15
B″	5000	simulated outside 1 kpc	10	0.5	0.2	0.15
C′	52	currently known.	4	0.25	0.1	0.0
C″	5000	simulated outside 1 kpc	4	0.25	0.1	0.0
D	1	plane perpendicular	50	1.0	0.5	0.3
E	1	plane parallel	50	1.0	0.5	0.3





Isotropic diffusion:

Minor contributions from the current and full spider population

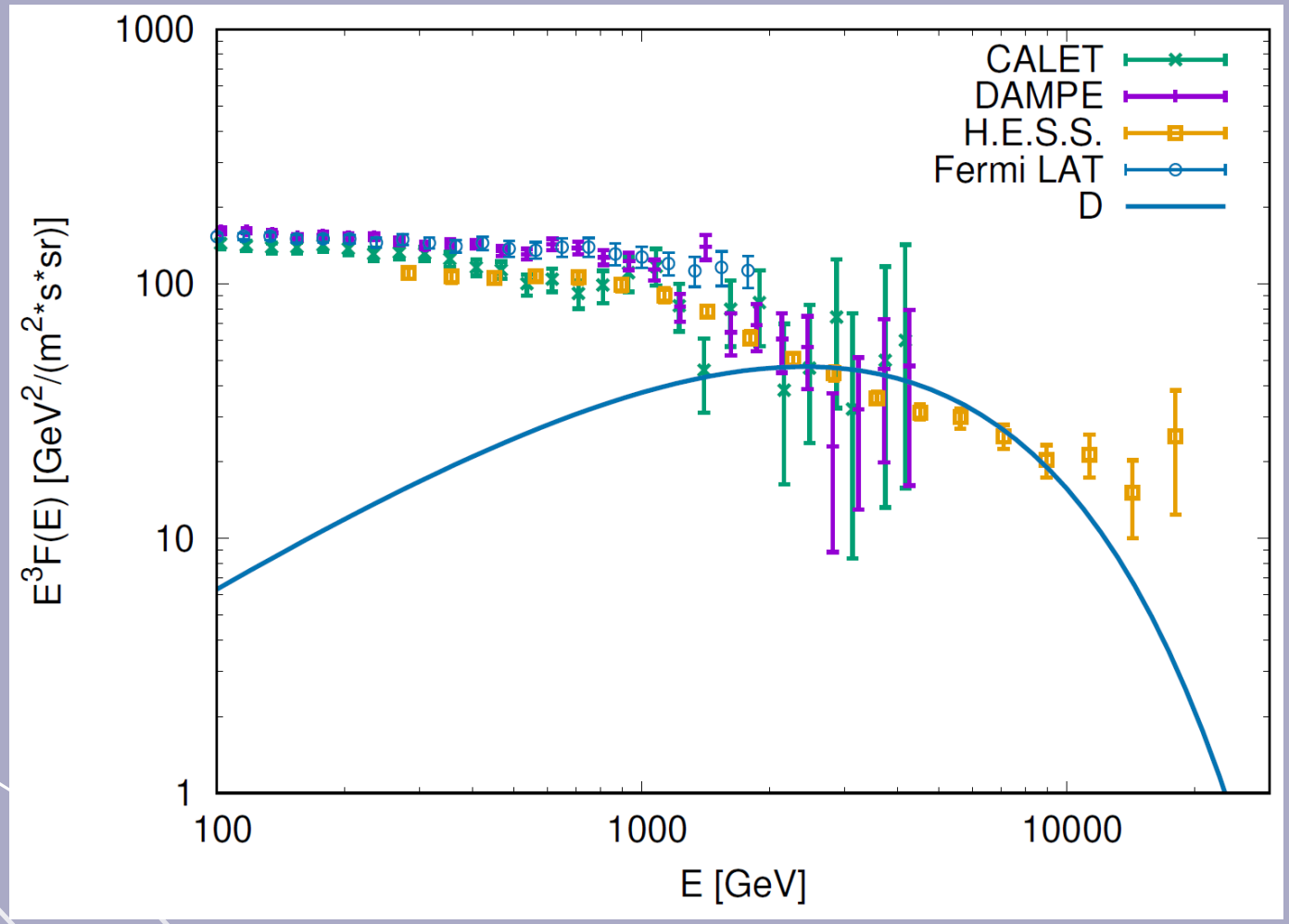
Anisotropic diffusion:

One spider at d=0.5kpc could give a major contribution if line of sight mostly parallel to Galactic B field

Results III: combined e^+ e^- flux

Comparison with current measurements

Adriani+18, DAMPE/HESS/Fermi-LAT collaborations (2017)



Nearby spider along Galactic magnetic field lines:

combined electron positron flux agrees with current measurements

Summary

- Spiders: a growing nearby population of e+/e- accelerators (10% of L_{sd}, up to ~10 TeV)
- Current population unlikely to be a major e+ contributor
- One single nearby spider could be a major e+ contributor

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Cosmic ray positrons from compact binary millisecond pulsars

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Received November 2, 2020
Accepted December 13, 2020
Published February 15, 2021