The Millisecond Pulsar Contribution to the Rising Positron Fraction

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(Venter et al. 2015a,b)

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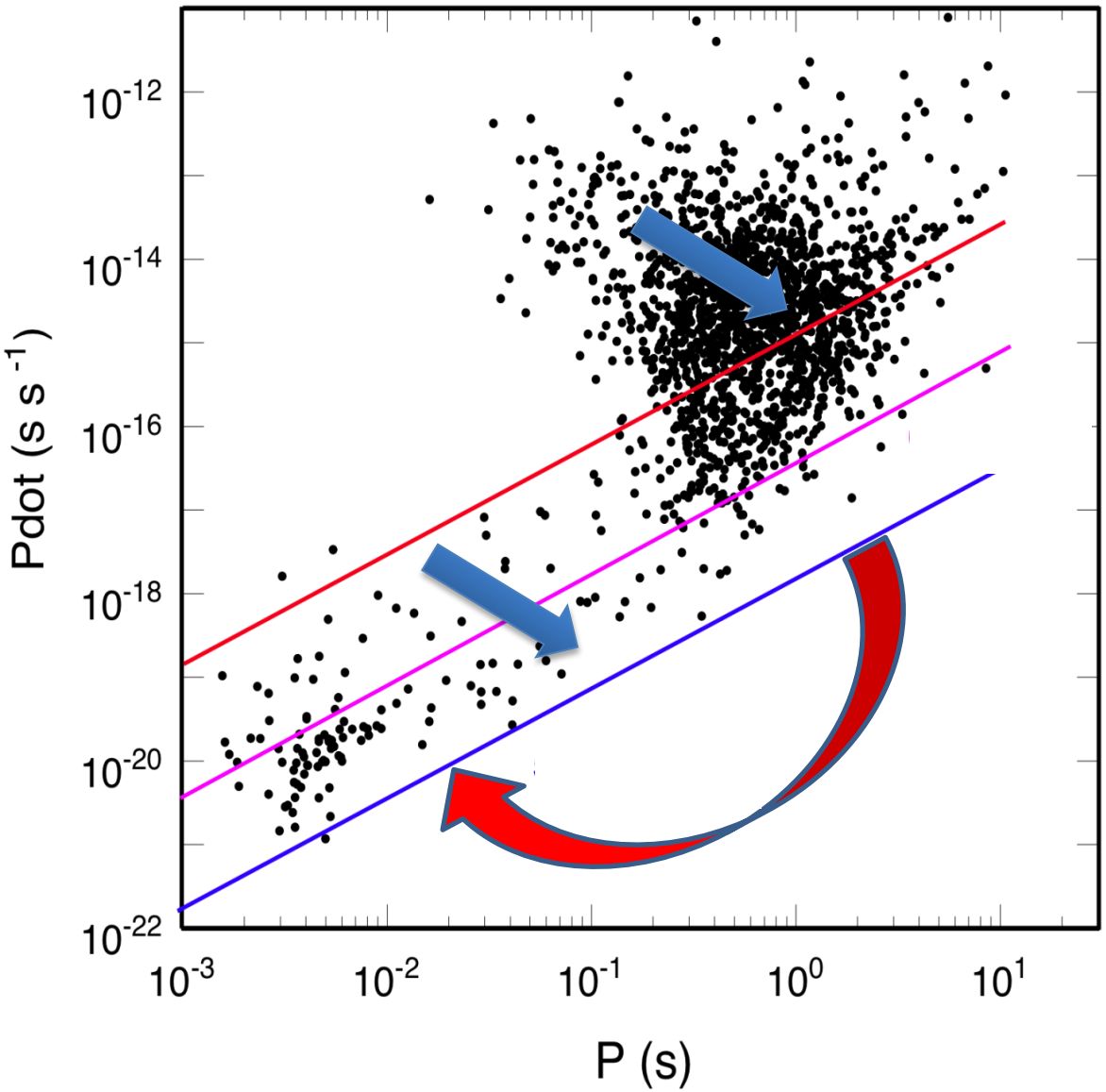
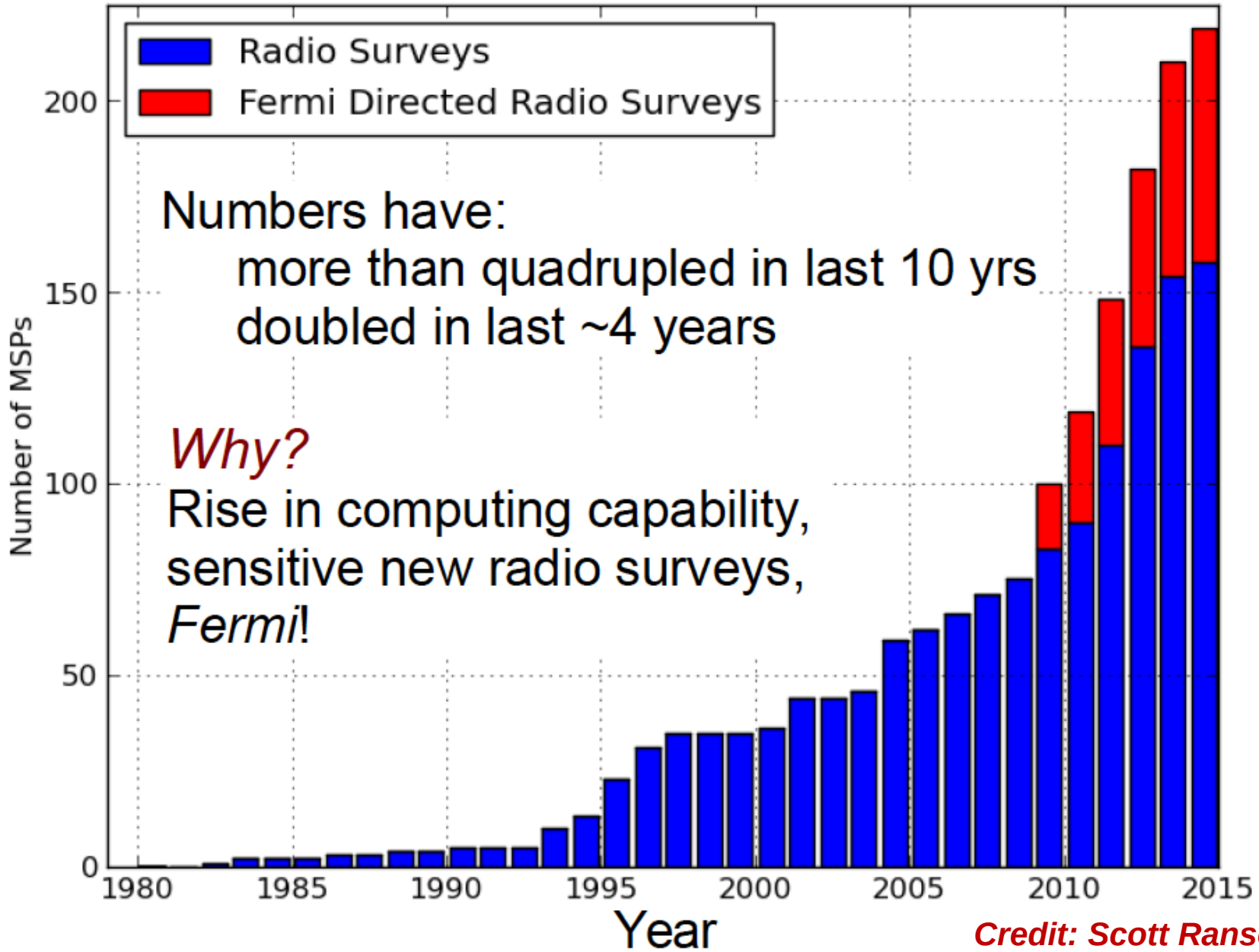
Recycled MSPs



- ~200 field MSPs
  - 160 binary (80%)
  - 40 isolated
- 144 in globular clusters
- ~70 γ-ray MSPs
- Very different characteristics from young PSRs
  - P = 1.5 – ~ 100 ms
  - $B \sim 10^8 - 10^{10}$ G
  - $T \sim 10^8 - 10^9$ yr
- "Recycled" pulsars spun-up by binary companion stars

New MSP Discoveries



Credit: Scott Ransom

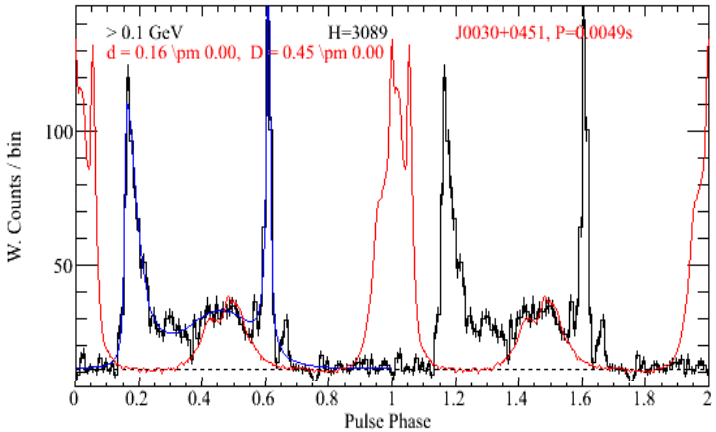
Motivation

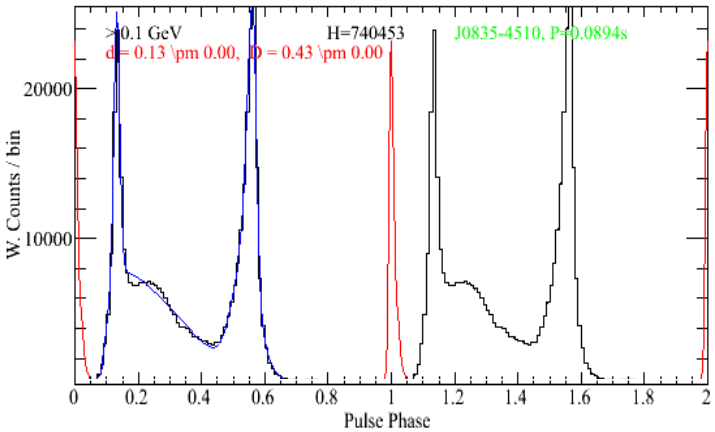
Similar MSP and Young-Pulsar LCs

Light curves of many MSPs show narrow peaks out of phase with radio peaks - indistinguishable from those of young pulsars

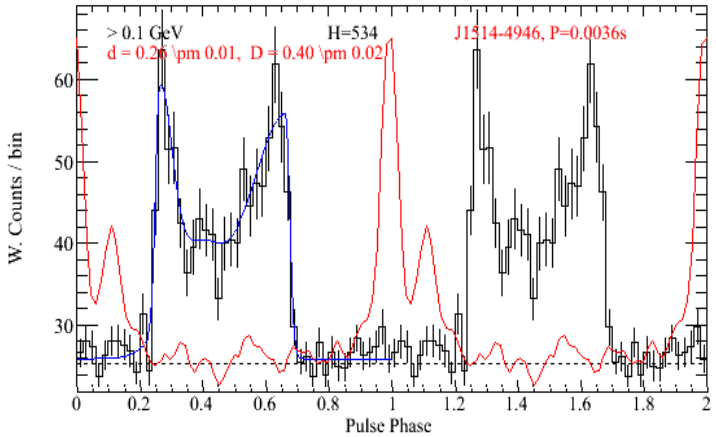
Millisecond pulsars

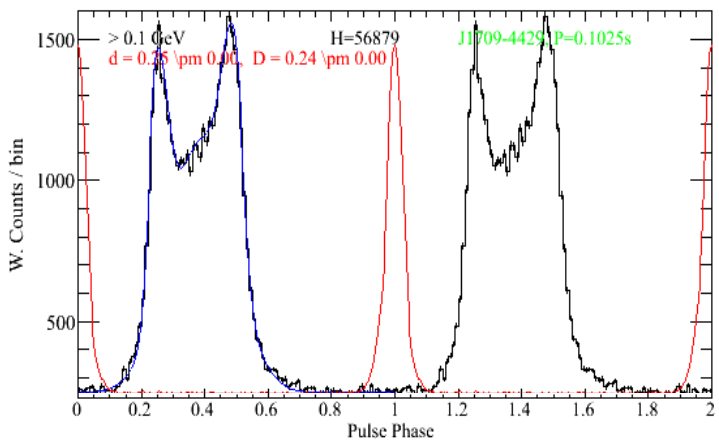
Young pulsars





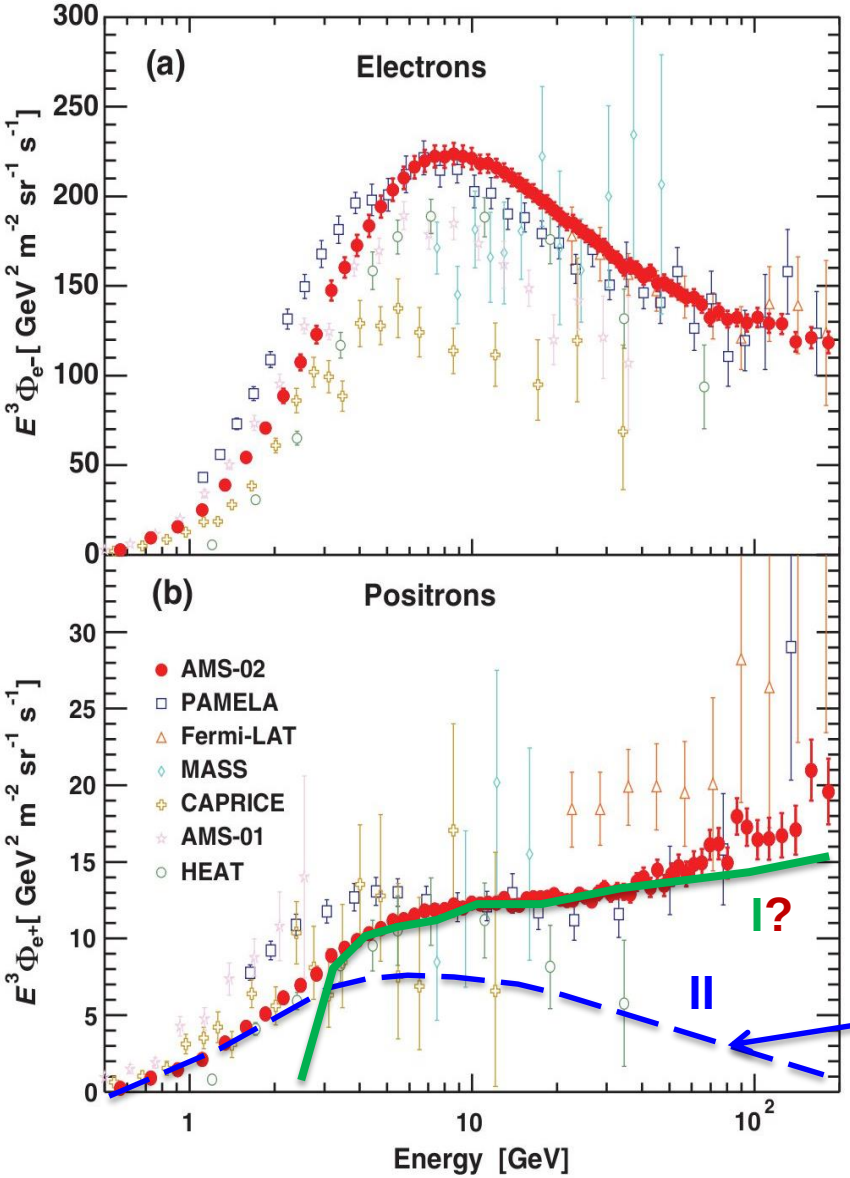
Narrow accelerator gaps

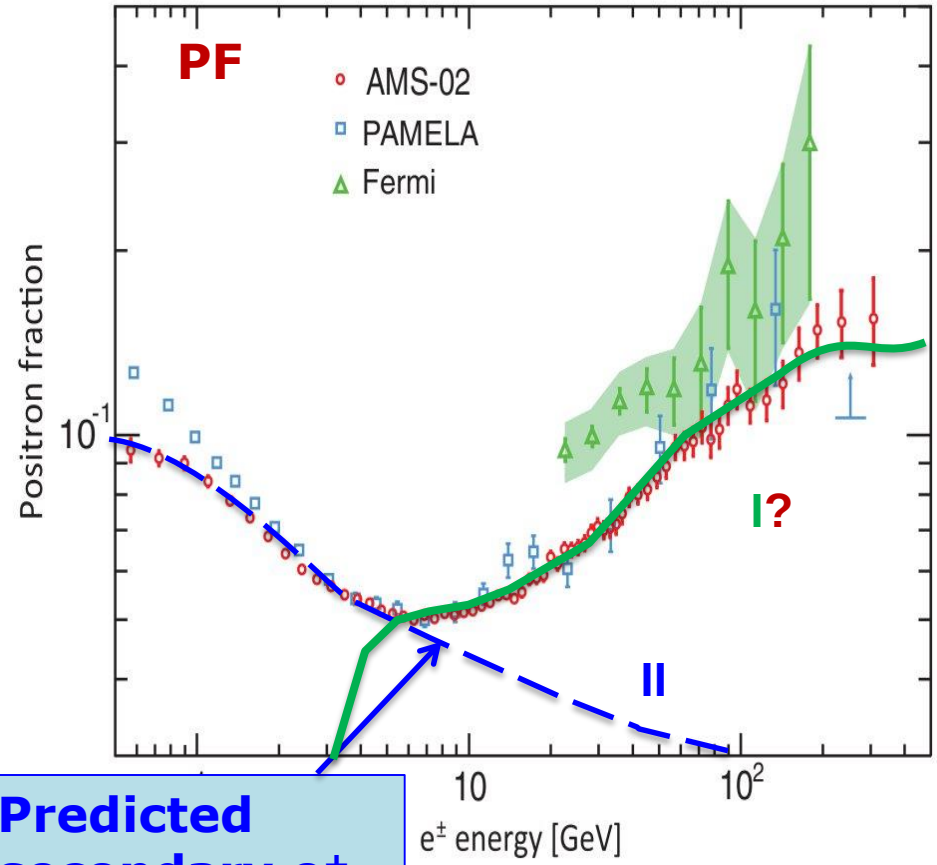




Screening by electron-positron pairs

Recent CR Measurements





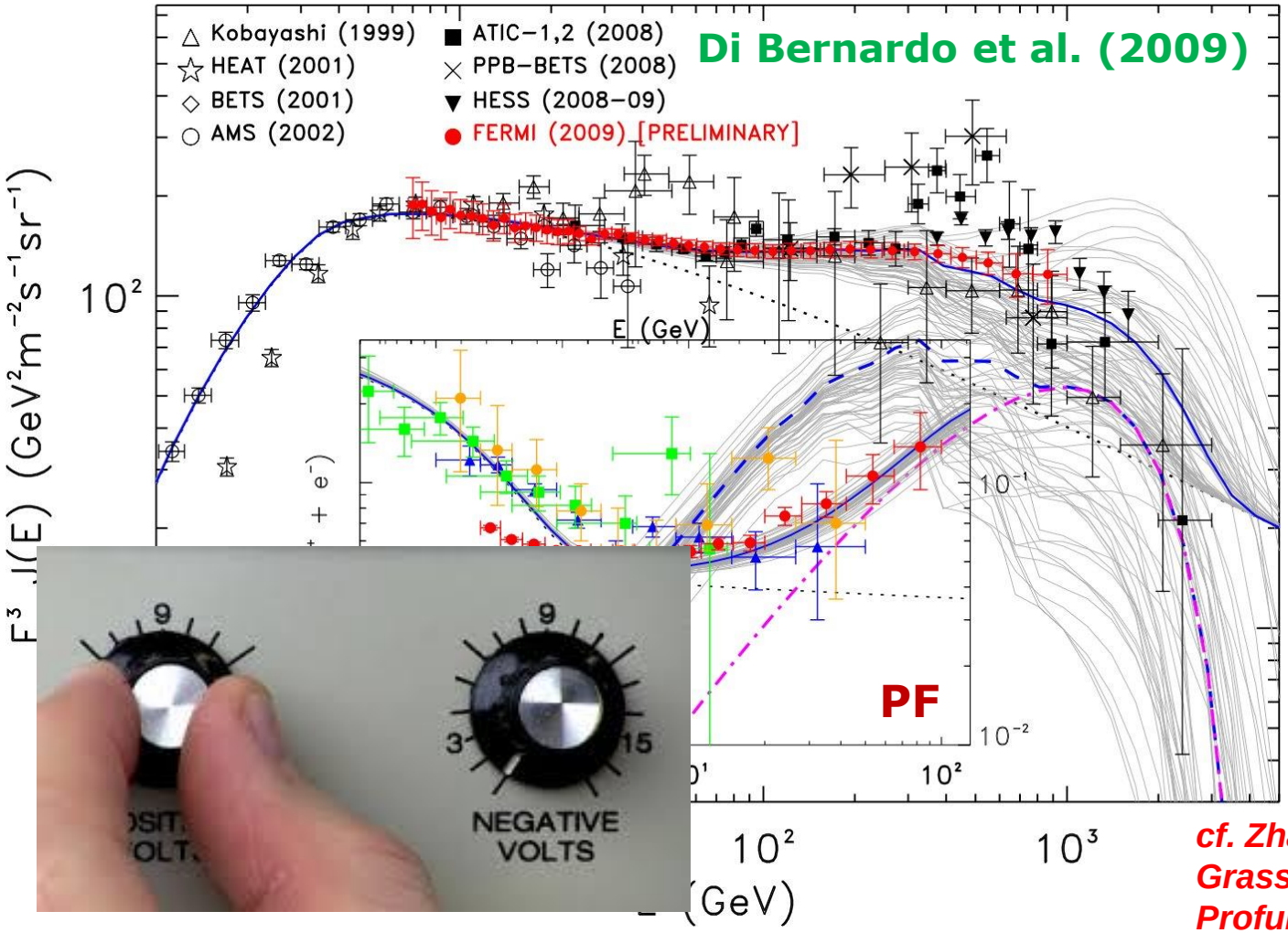
Predicted secondary e⁺ from CR interactions

Rising positron fraction!
→ Need primary e⁺ source(s)

Aguilar et al. (2013, 2014)

(Young) Pulsars as Sources of CRs

- **E.g., nearby canonical pulsars producing e^-e^+ pairs.**
- **OTHER sources: SNR, PWN, DM, …**



What about MSPs?
- **No surrounding nebula**
- **One layer of uncertainty removed.**

Two approaches:
- **Data fitting**
- **Bottom-up model**

cf. Zhang & Cheng (2001), Grasso et al. (2009), Profumo (2008), Gendelev (2010)

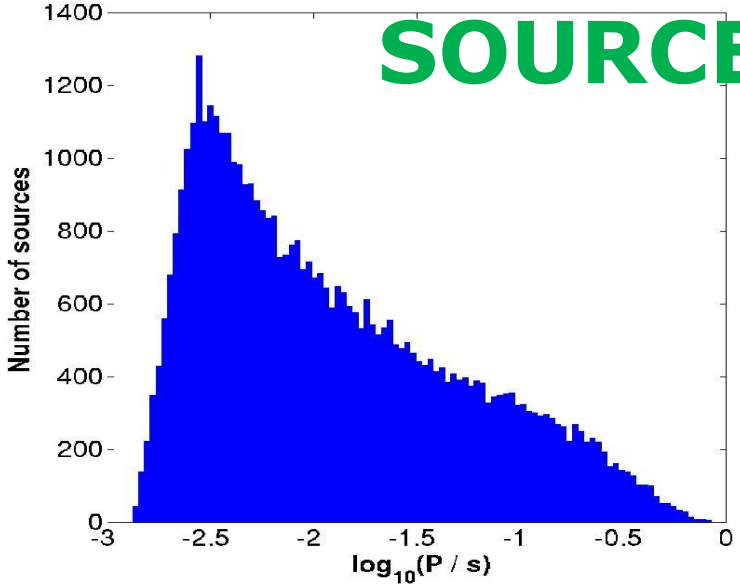
Summary: Motivation for Studying MSP Contribution

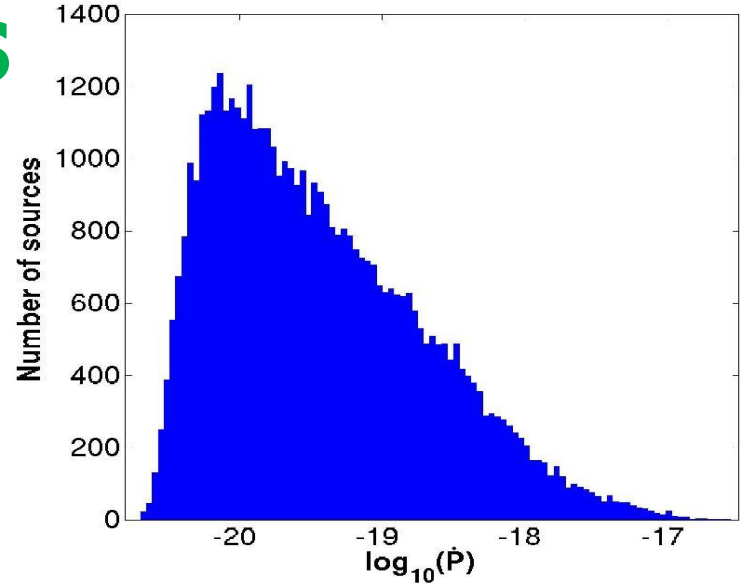
- Many new MSP detections: larger number of sources: N_{MSP}
- Light curves point to copious pair production: larger number of particles per source: M_+
- New black widows / redbacks: additional acceleration in shocks: η_{max}
- Simpler systems than young pulsars
  - ✓ No surrounding PWN, removing uncertainty in particle escape
  - ✓ Old systems – steady-state approach
  - ✓ Spherical symmetry of MSP spatial distribution

Model

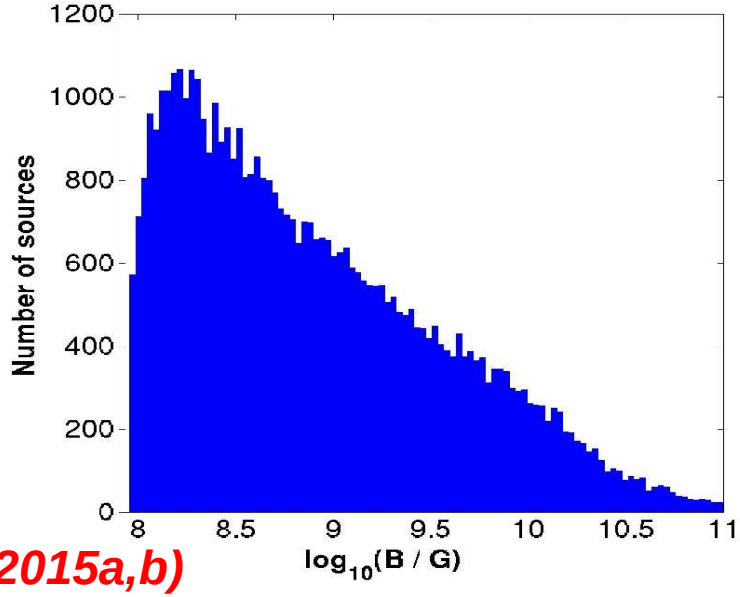
Galactic MSP Synthesis

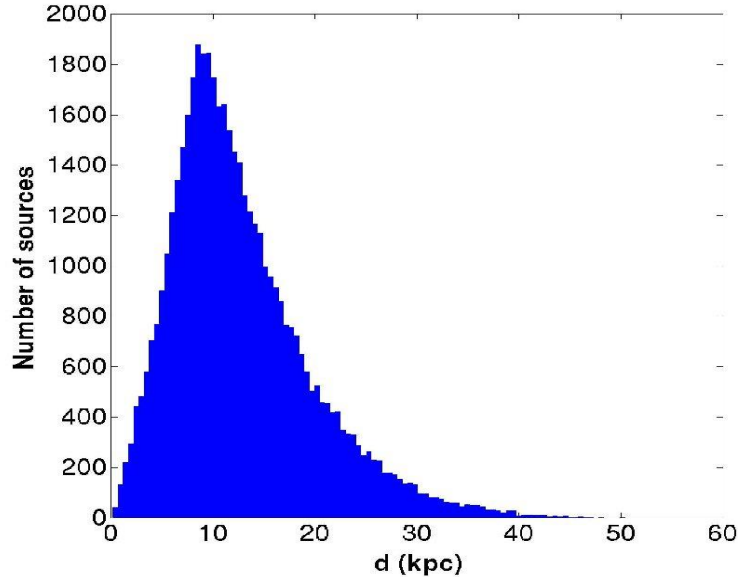
SOURCES





~50 000 MSPs in the Galaxy

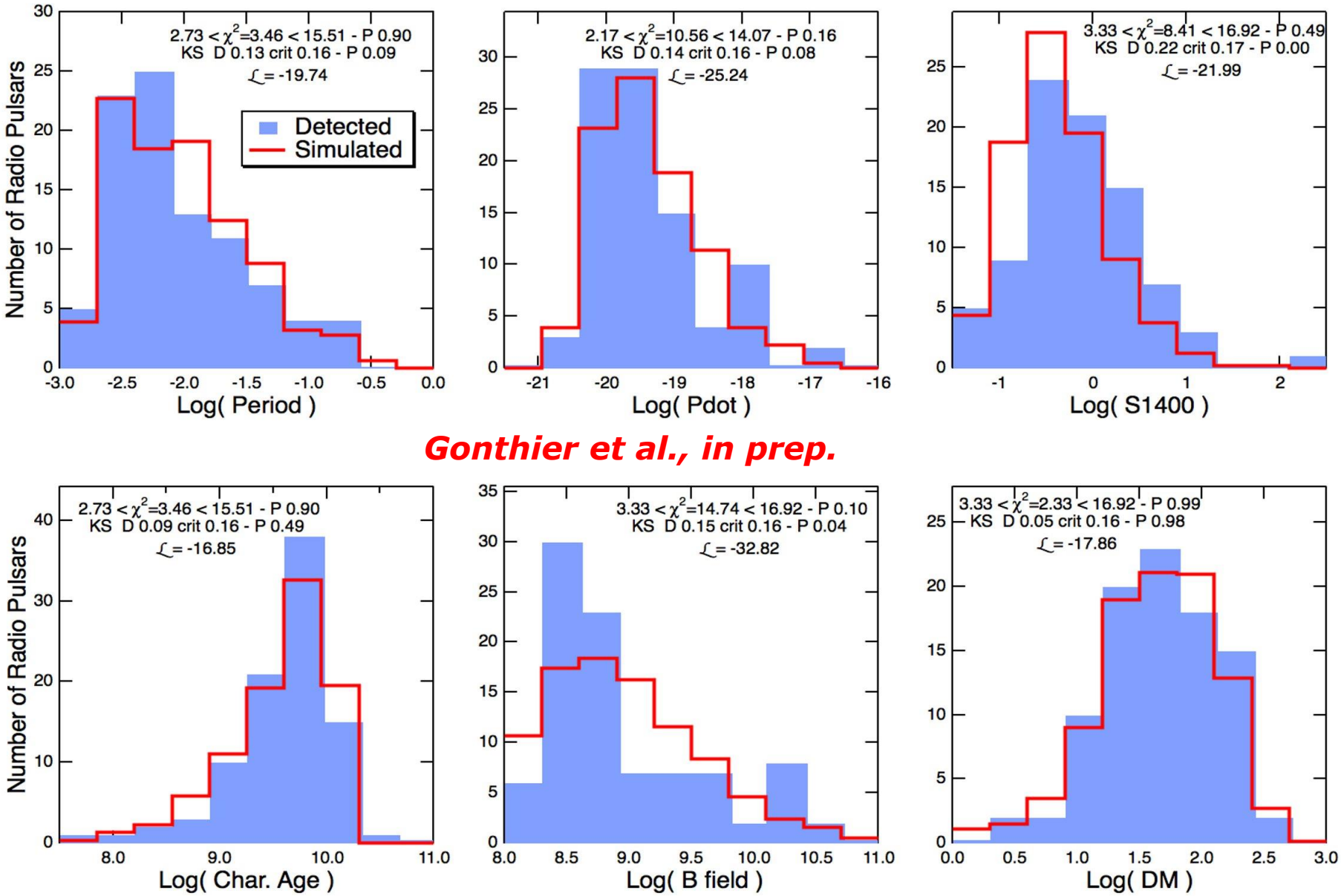




Gonthier et al., in prep.

Venter et al. (2015a,b)

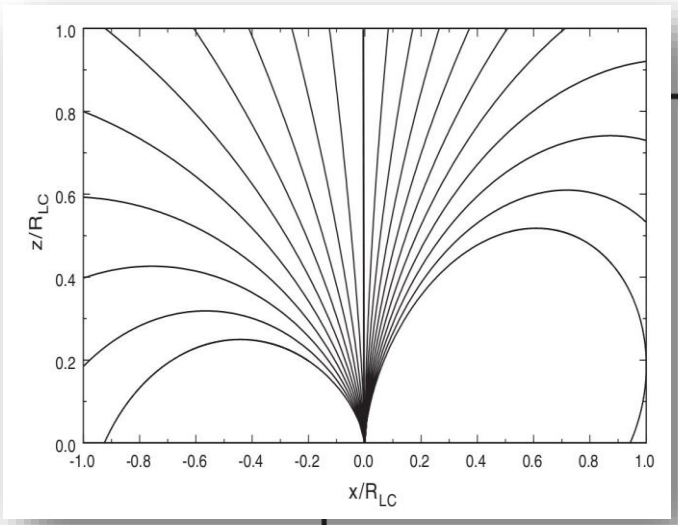
Galactic MSP Synthesis

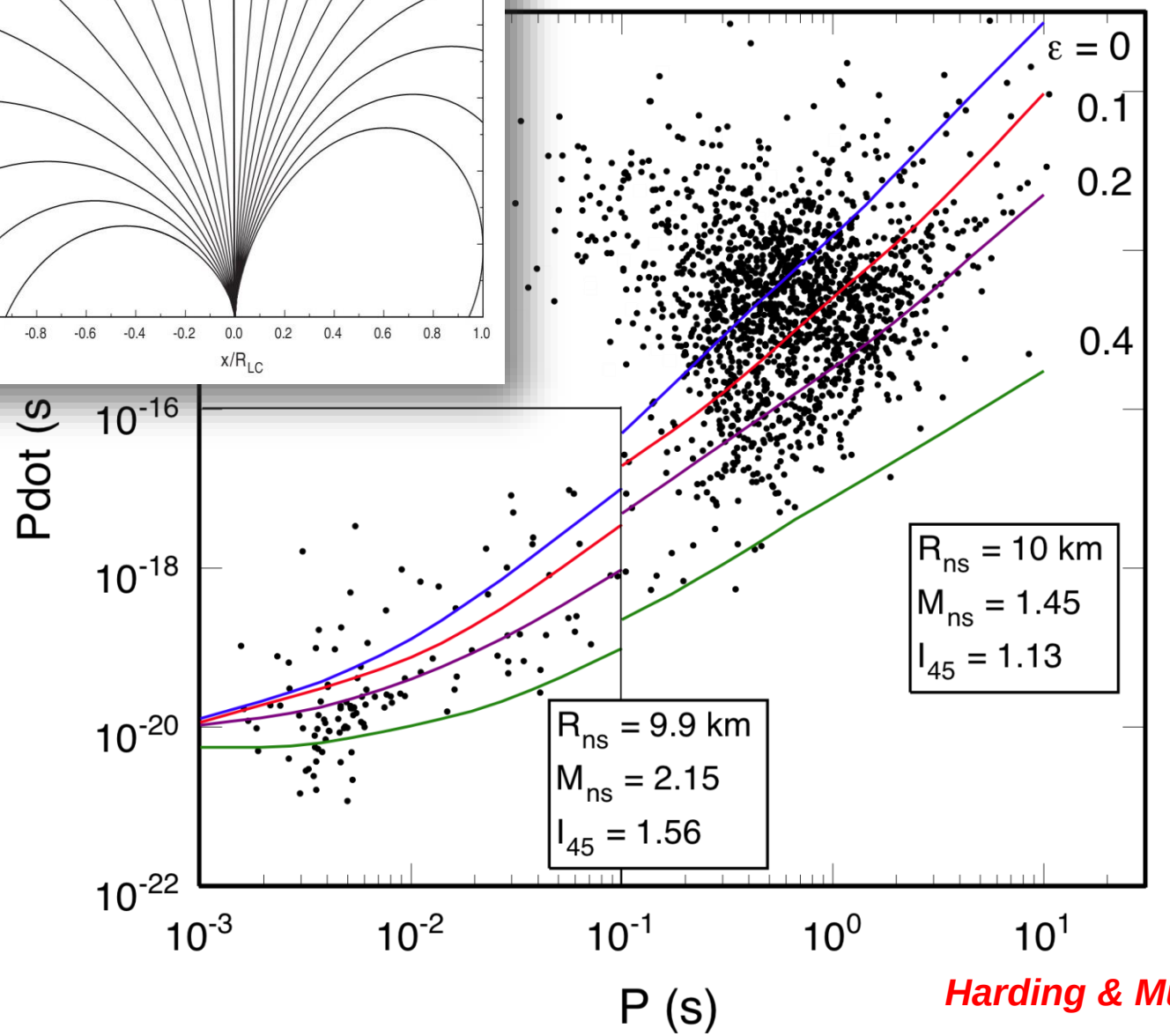


Gonthier et al., in prep.

Pair Death Lines for Offset PCs

SPECTRA





Need offset polar caps or non-dipolar fields for pair cascades in MSPs

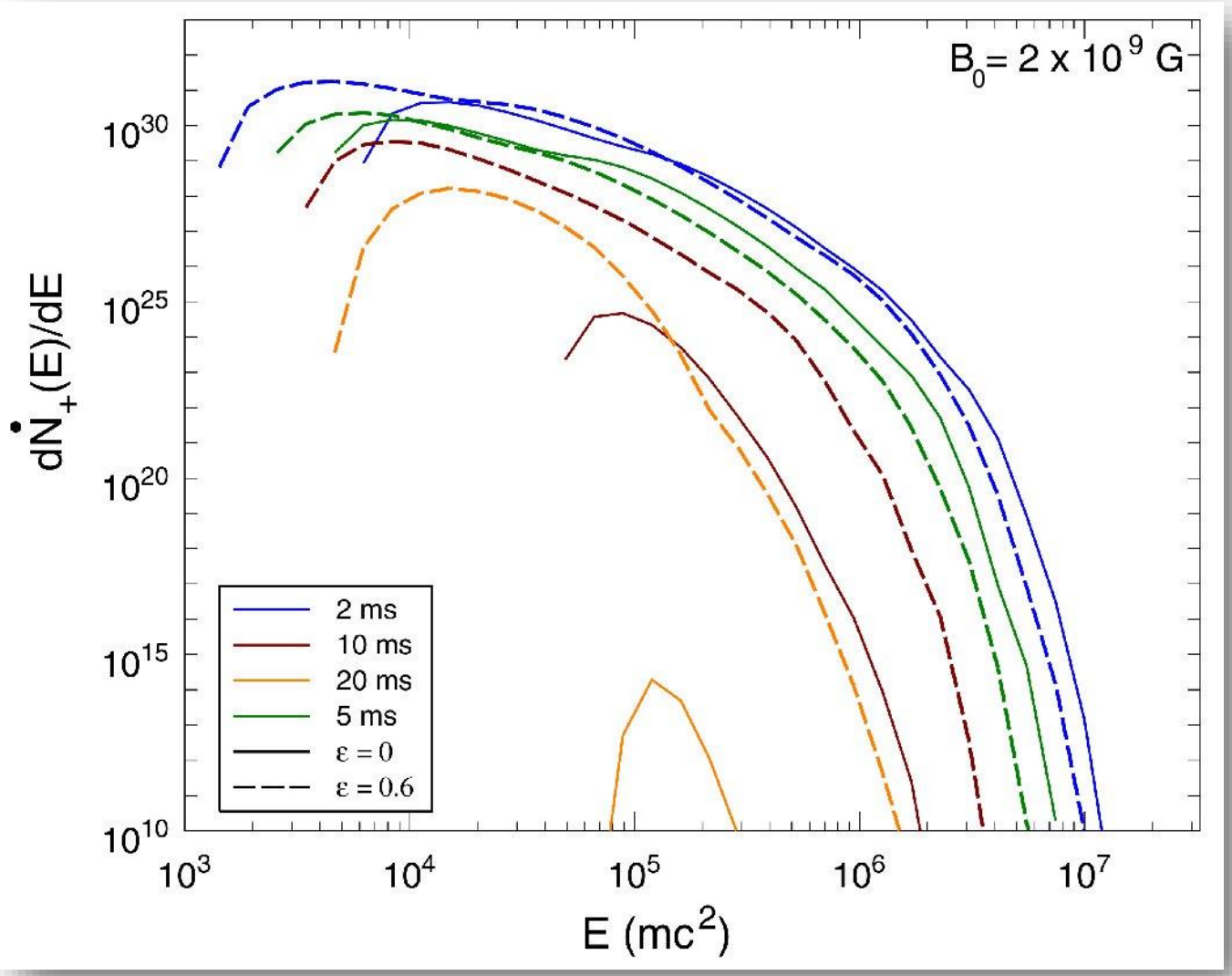
Offset parameter ε for MSPs:

0.0 – static dipole
0.1 – vacuum dipole
0.2 – force-free dipole
> 0.2 – multipoles

Harding & Muslimov (2011)

MSP Pair Cascade Spectra

Harding & Muslimov (2011a,b)

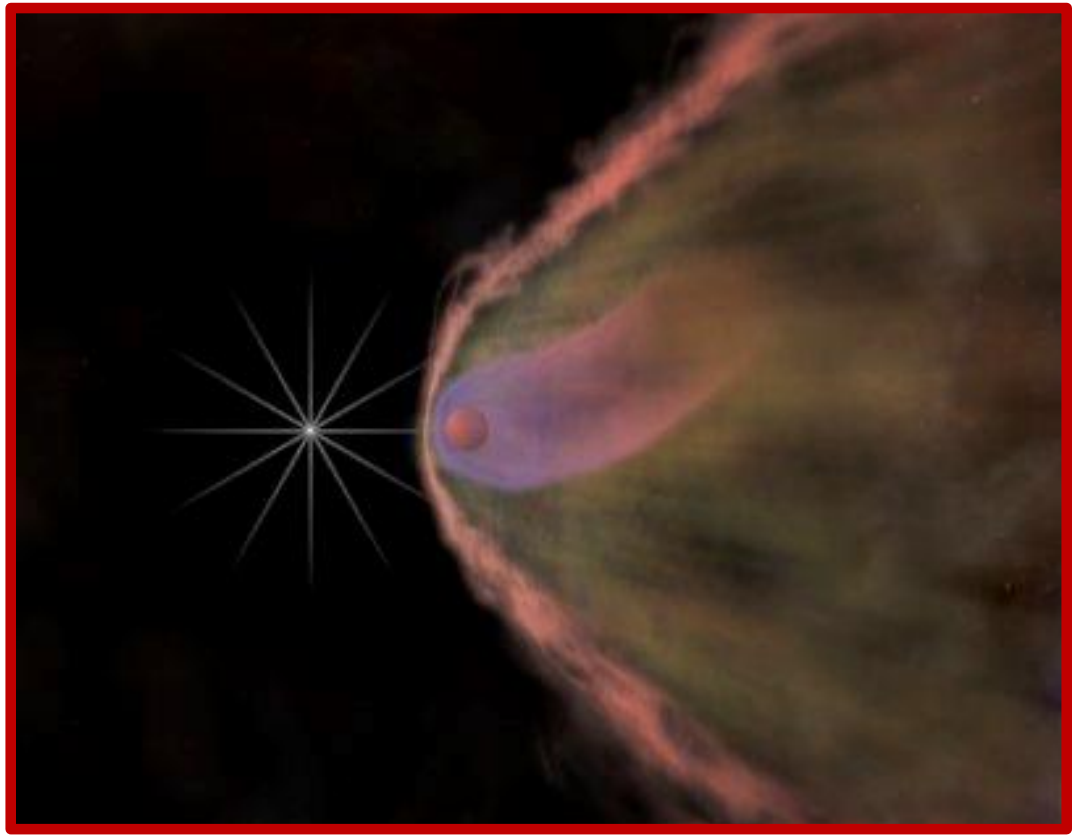


Consider two contributions:

1. **Direct injection of pair spectra from pulsar magneto-spheres**
2. **Injection of pair spectra after acceleration in binary shock**

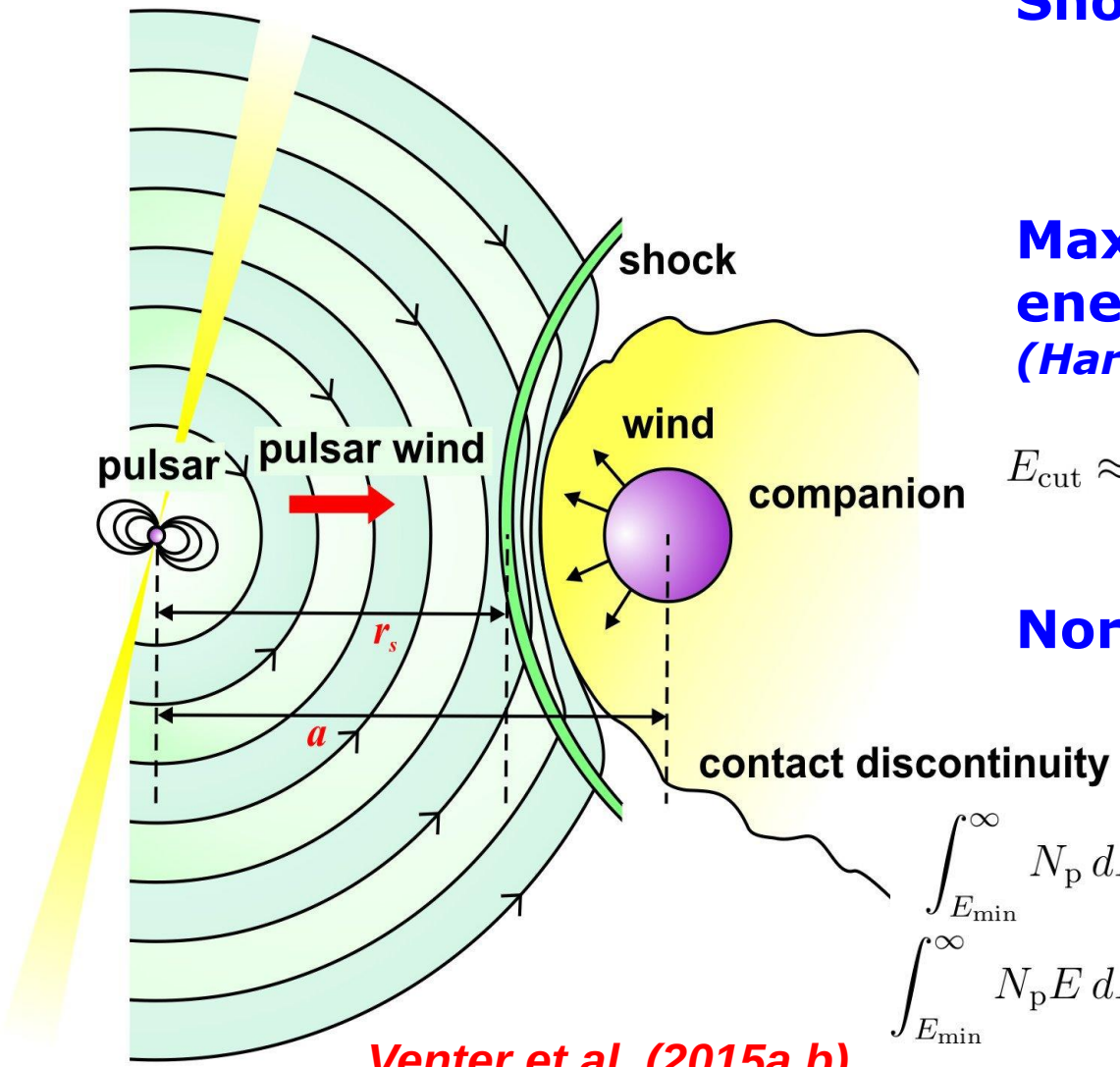
Black Widows & Redbacks

- MSPs with very low-mass binary companions
  - 10 – 80 Jupiter masses (~0.01 $M_\odot$)
- Tight binaries (P_b < 24 h)
- Radio eclipses common
- Pulsar wind ablates companion by exciting stellar winds
- Redbacks (cousins)
  - ~0.1 $M_\odot$ companions



Before *Fermi's* launch: 3 black widows, 1 redback
Now: >18 black widows, 8 redbacks – Total >26!

Particle Acceleration at the Binary Shock



Venter et al. (2015a,b)

Shock acceleration spectrum

$$N_{\rm p}(E) = Q_0 E^{-2} \exp\left(-\frac{E}{E_{\rm cut}}\right)$$

Maximum acceleration energy

(Harding & Gaisser 1990)

$$E_{\rm cut} \approx 2.6 B_8^{-1/2} P_{\rm ms} a_{11}^{-1/2} \left(\frac{3(\xi-1)}{\xi(\xi+1)}\right)^{1/2} \ {\rm TeV}$$

Normalization

Pair multiplicity

PC flux

$$\int_{E_{\rm min}}^{\infty} N_{\rm p}\, dE = [M_+(P, B_{\rm s}, \varepsilon) + 1]\, \dot{n}_{\rm GJ}(P, B_{\rm s}, \varepsilon)$$

$$\int_{E_{\rm min}}^{\infty} N_{\rm p} E\, dE = \eta_{\rm p,max} \dot{E},$$

Efficiency

Galactic CR Transport

- **Pair injection spectrum**
- **Spatial *E*-dependent diffusion (scalar here)**
- **SR & IC losses with KN limit**
- **Galactic background photons (CMB; IR; optical)**
- **Steady state**
- **Spherical symmetry**
- **Full transport equation**

$$\frac{\partial n_\mathrm{e}}{\partial t} = \vec{\nabla} \cdot \left(\mathcal{K} \cdot \vec{\nabla} n_\mathrm{e} \right) - \frac{\partial}{\partial E_\mathrm{e}} \left(\dot{E}_\mathrm{e} n_\mathrm{e} \right) + Q$$

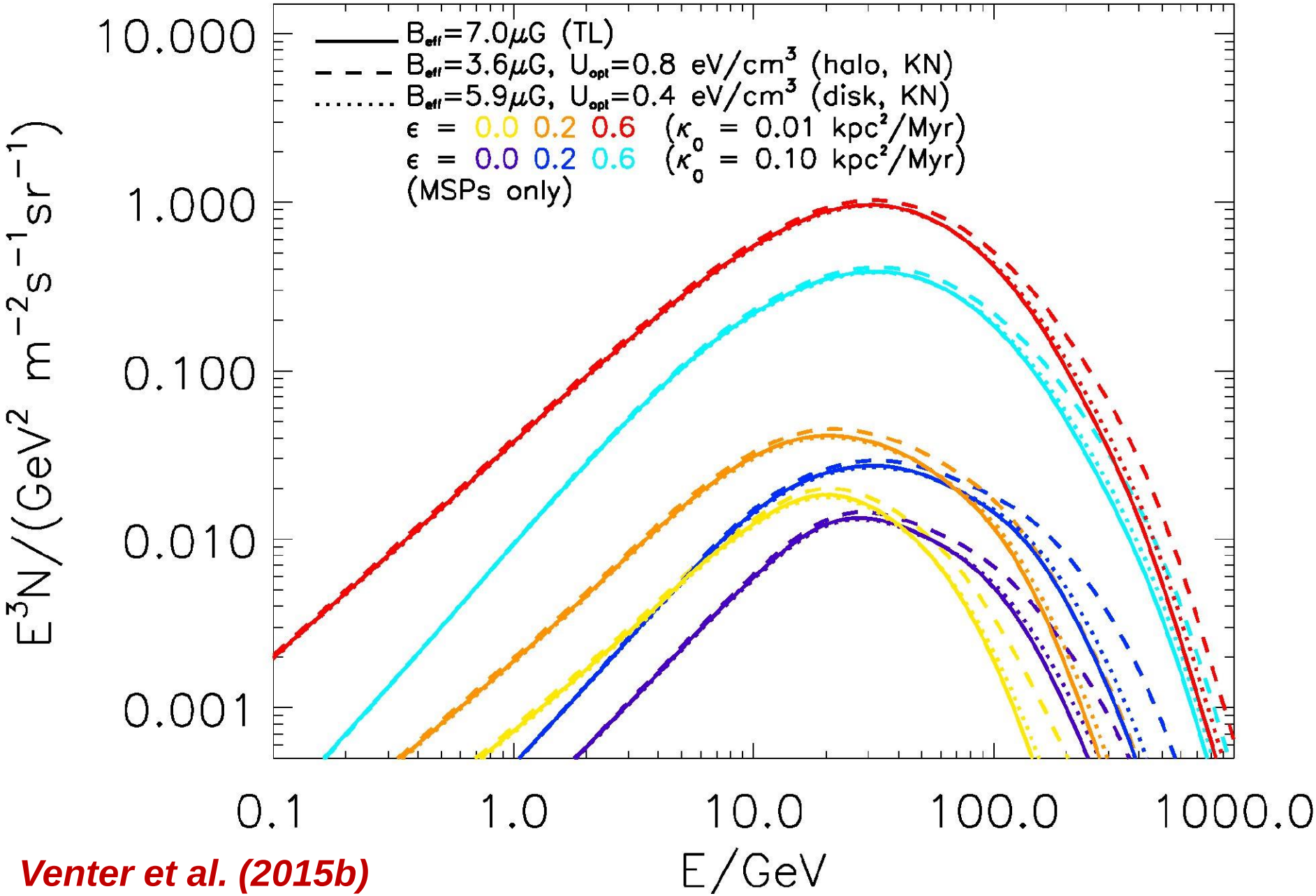
n_e	electron density per energy and volume
$\mathcal{K}$	spatial diffusion tensor
n_e	electron density per energy and volume
E_e	electron energy
$\dot{E}_\mathrm{e}$	radiation losses
Q	source term for the electron density in $(\mathrm{erg\ s\ cm}^3)^{-1}$

$$\kappa(E) = \kappa_0 \left(\frac{E}{E_\mathrm{norm}} \right)^{\alpha_\mathrm{D}}$$

Kopp et al. (2013)

Results

Galactic CR Transport: Losses



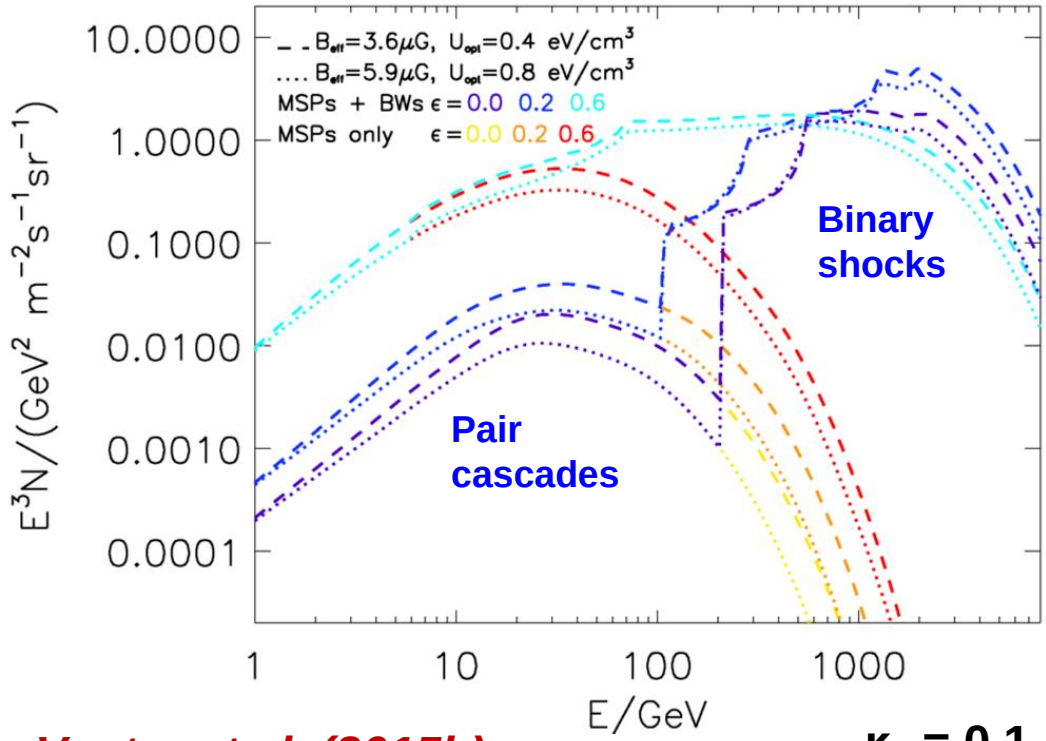
Venter et al. (2015b)

e^+ and e^- Spectra from MSPs

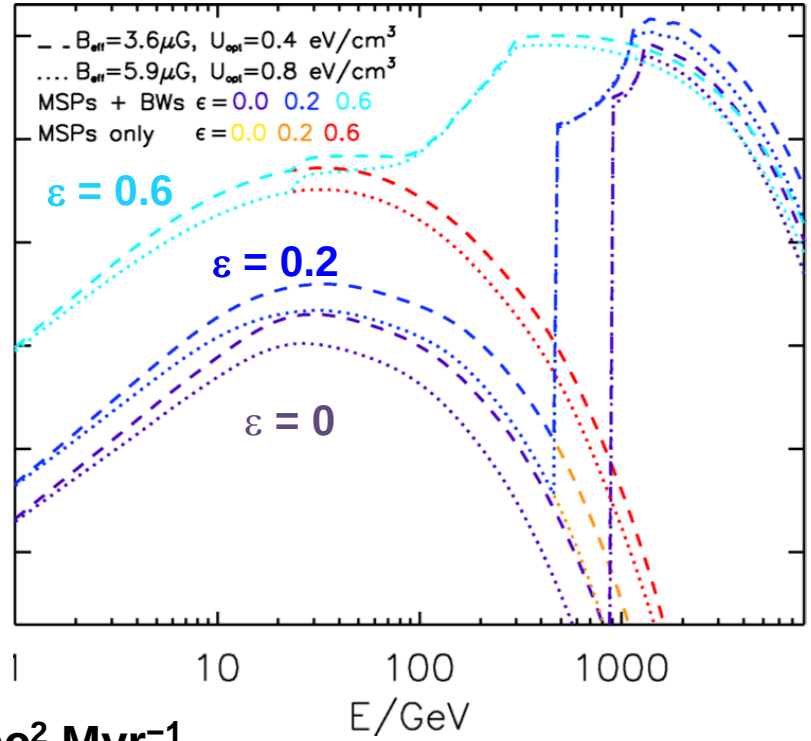
- **Pair cascades from magnetosphere contribute at lower energies**

- **Pairs accelerated in intra-binary shocks in Black Widow & Redback systems: larger contribution at high energies**

Efficiency $\eta_{p,max}$ = 0.1



Efficiency $\eta_{p,max}$ = 0.3



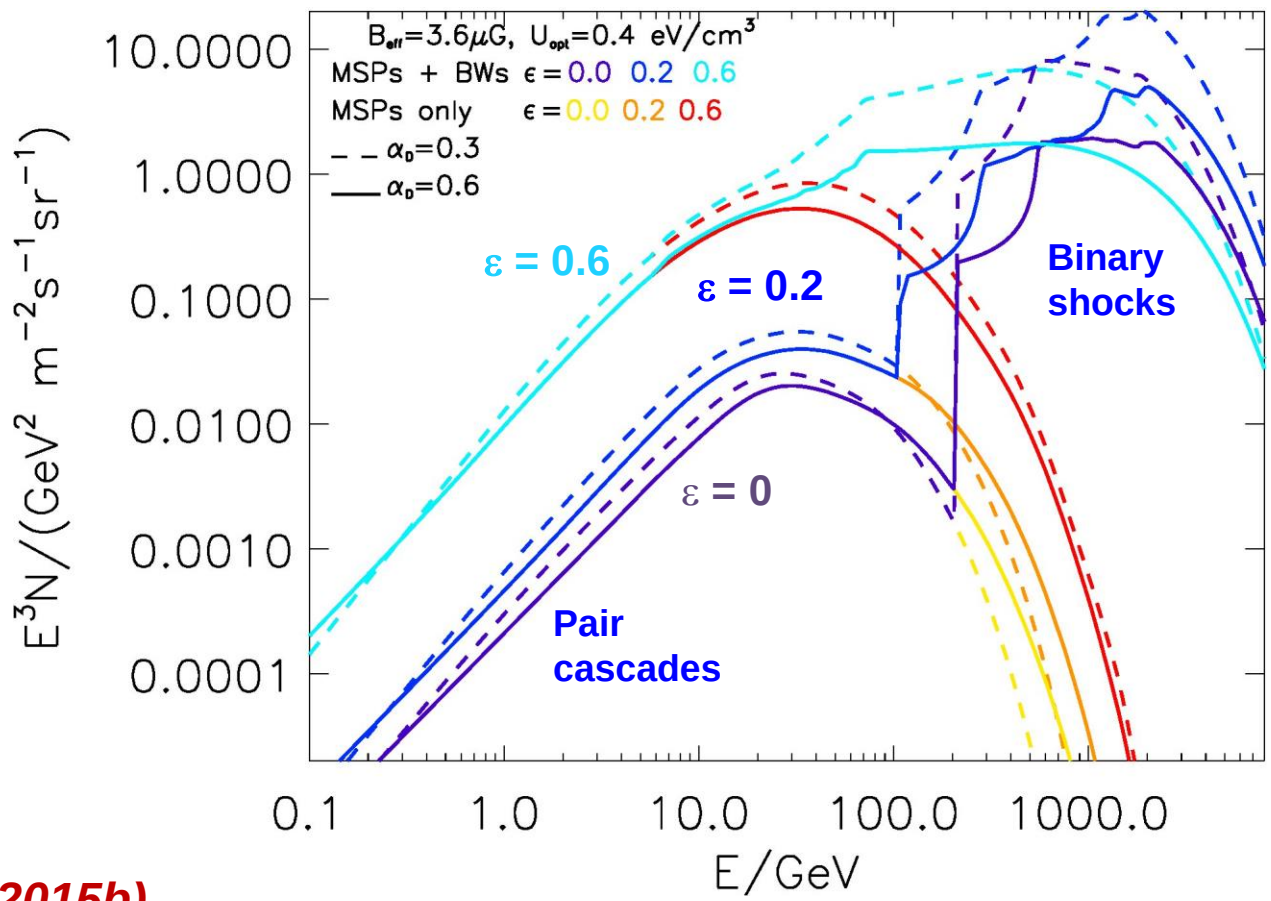
Venter et al. (2015b)

κ_0 = 0.1 kpc^2 Myr^{-1}

e^+ and e^- Spectra from MSPs

The effect of α_D: Smaller value similar to smaller diffusion at high energies – pile-up effect

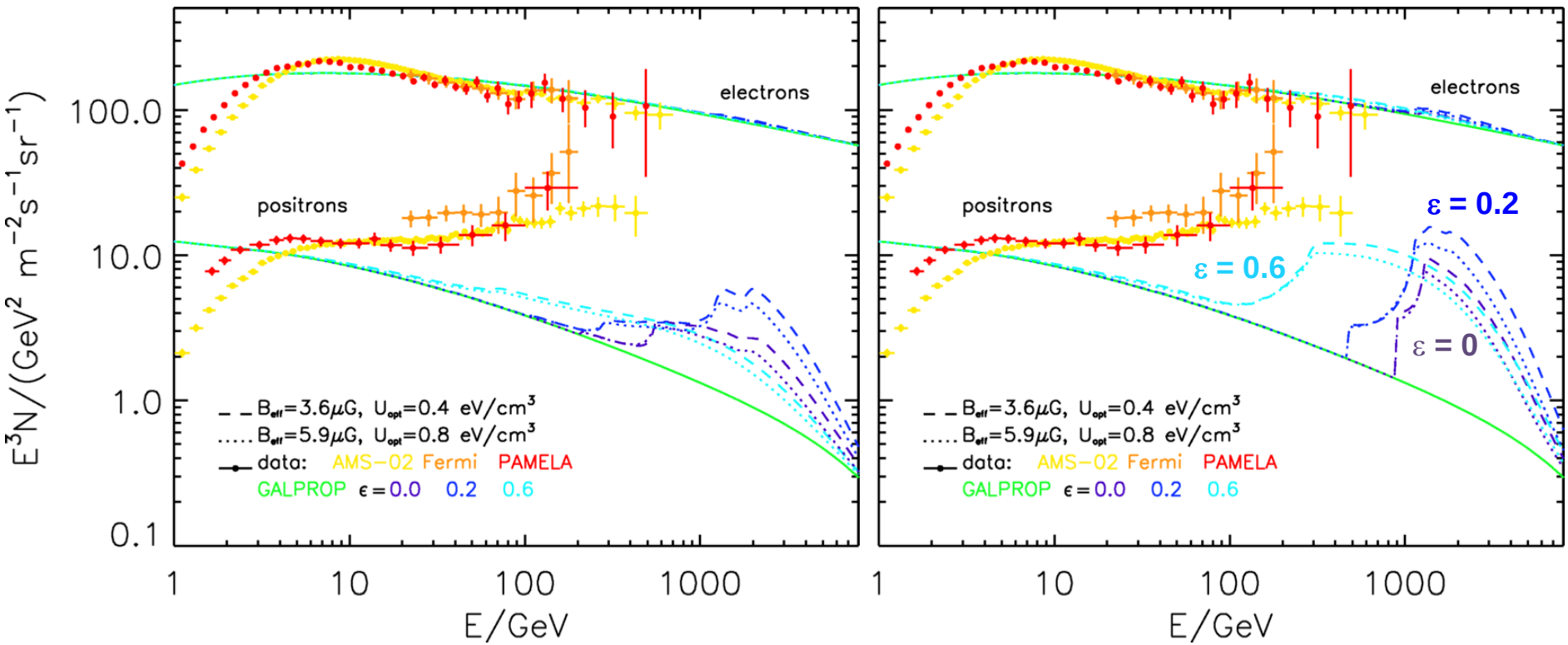
Efficiency $\eta_{p,max}$ = 0.1; κ_0 = 0.1 kpc^2 Myr^{-1}



Venter et al. (2015b)

MSP Contribution to CR e^+ and e^- Spectra

Efficiency $\eta_{p,max}$ = 0.1 **Efficiency $\eta_{p,max}$ = 0.3**



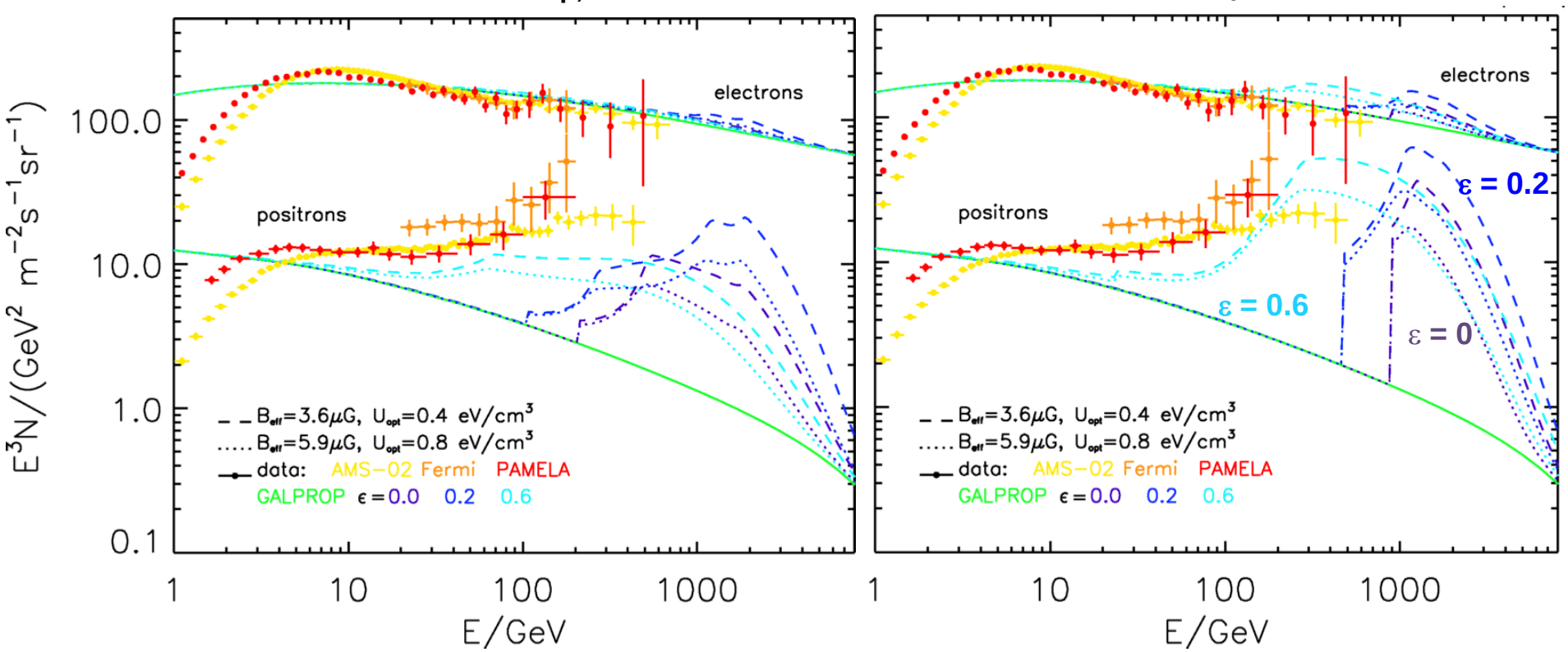
Venter et al. (2015b)

κ_0 = 0.1 kpc^2 Myr^{-1}

MSP Contribution to CR e^+ and e^- Spectra

Lowering diffusion coefficient by a factor of ten increases contribution – pile-up effect

Efficiency $\eta_{p,max}$ = 0.1 | **Efficiency $\eta_{p,max}$ = 0.3**

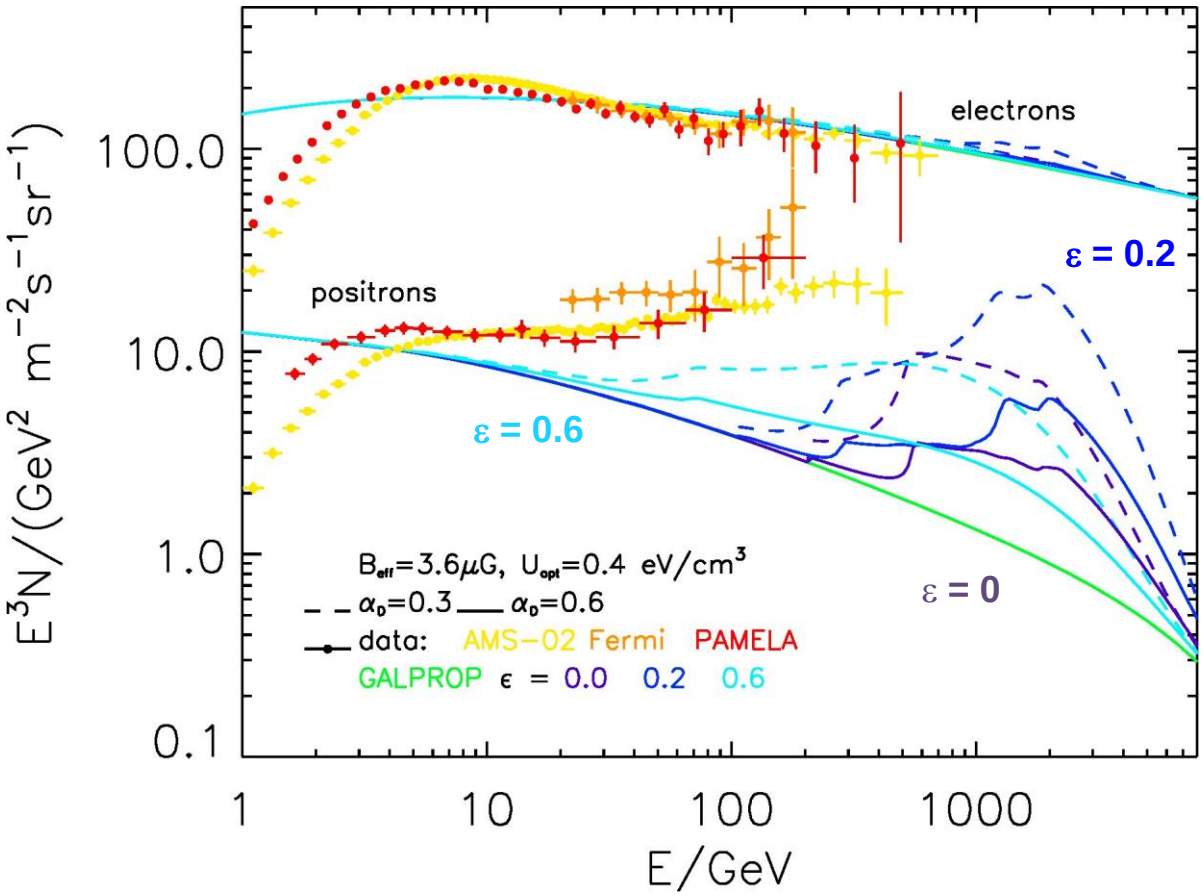


Venter et al. (2015b)

κ_0 = 0.01 kpc^2 Myr^{-1}

MSP Contribution to CR e^+ and e^- Spectra

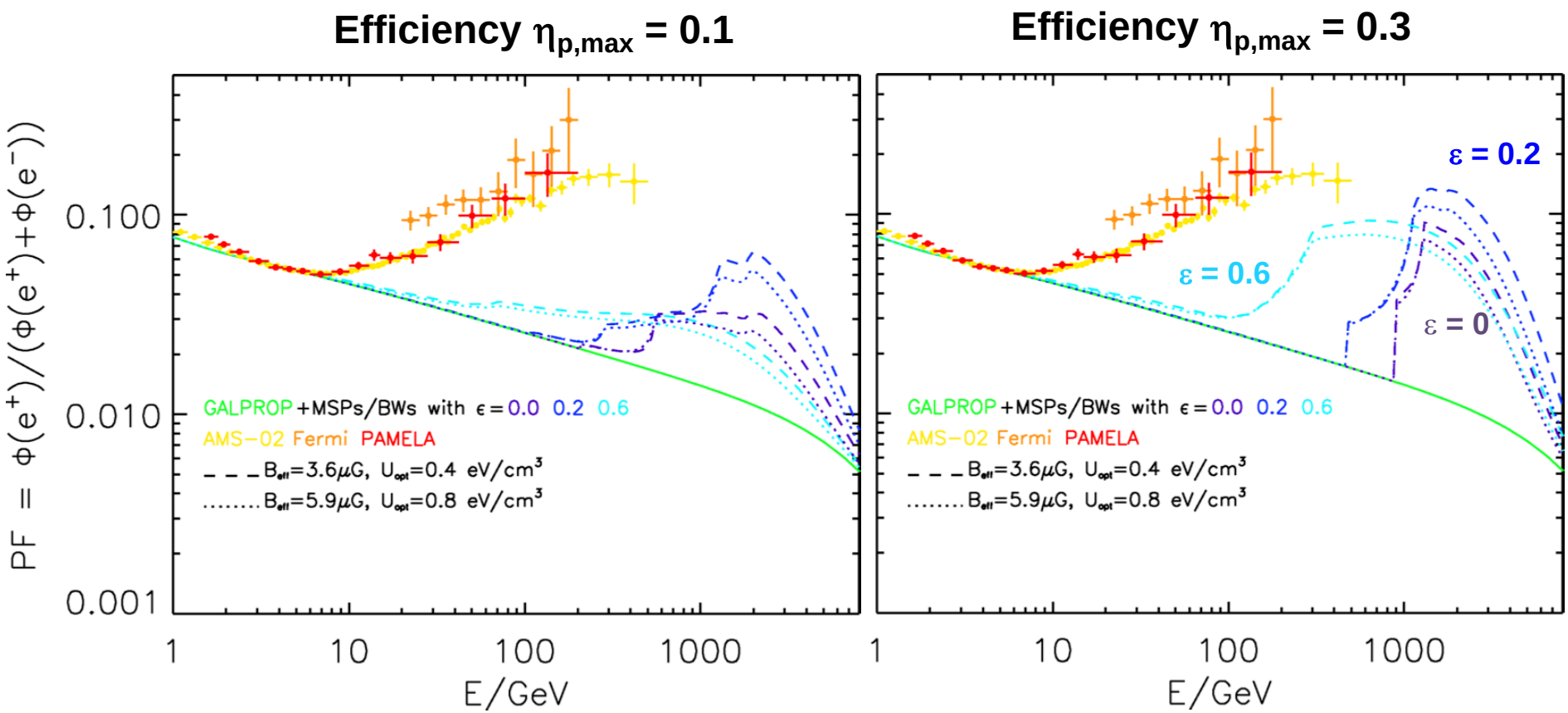
Different values of α_D



Venter et al. (2015b)

Efficiency $\eta_{p,max}$ = 0.1 κ_0 = 0.1 kpc^2 Myr^{-1}

MSP Contribution to Positron Fraction



Venter et al. (2015b)

κ_0 = 0.1 kpc^2 Myr^{-1}

MSP Contribution to Positron Fraction

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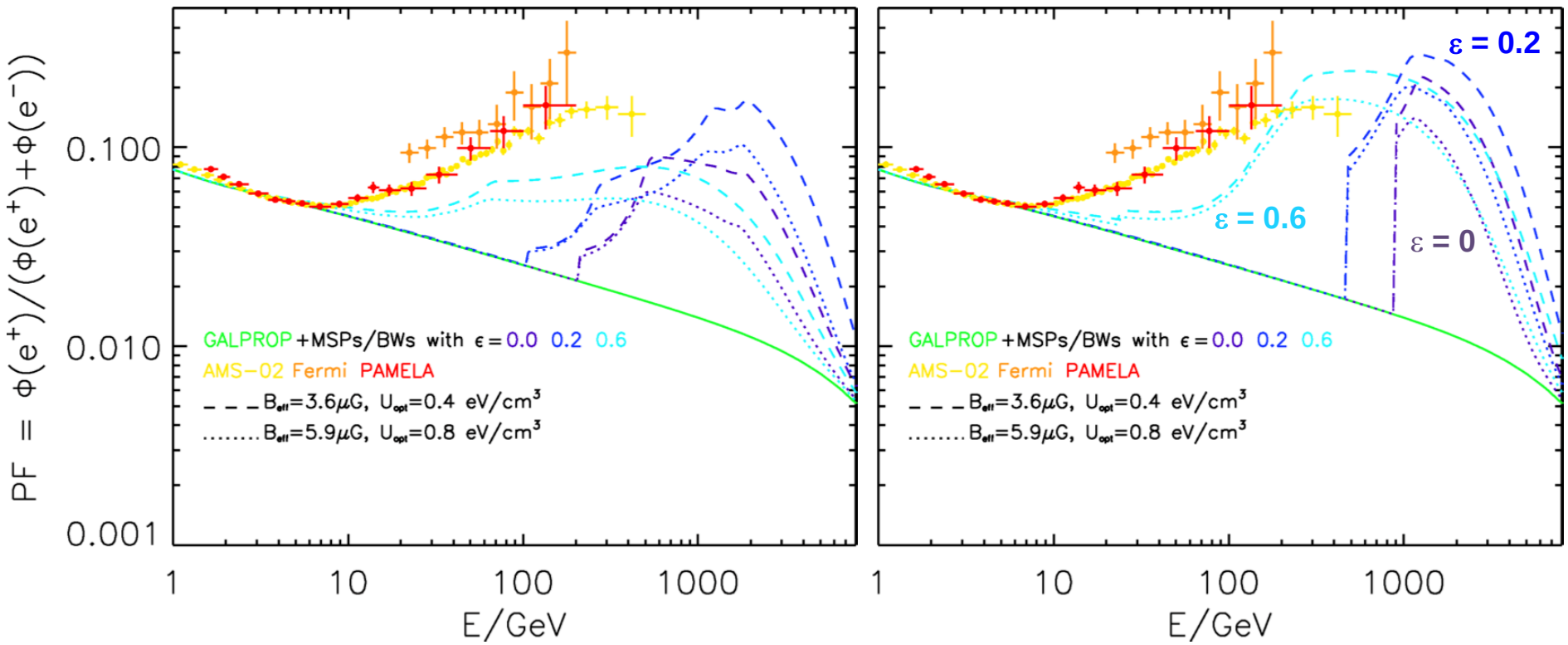
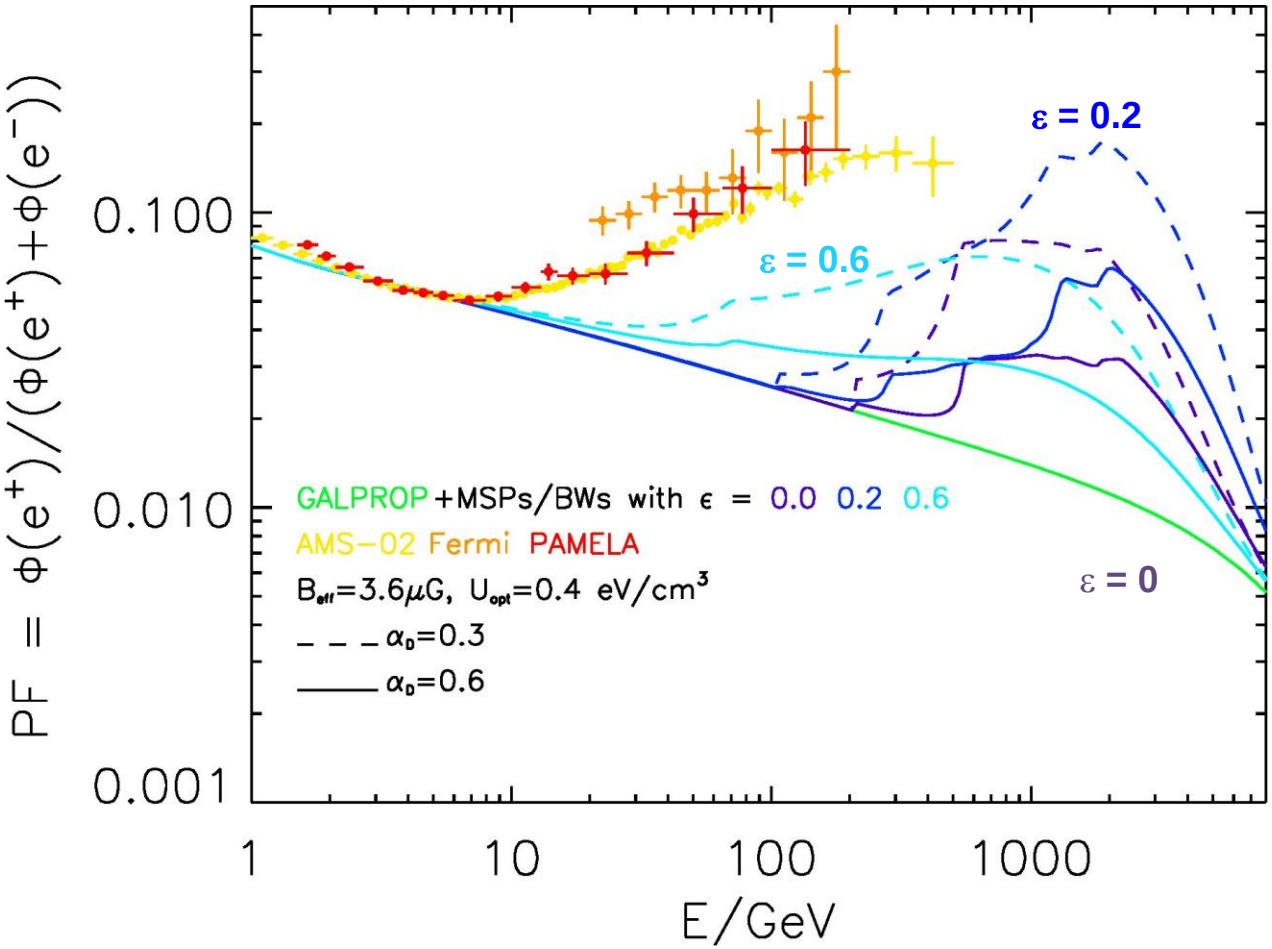


Venter et al. (2015b)

κ_0 = 0.01 kpc^2 Myr^{-1}

MSP Contribution to Positron Fraction

Different values of α_D



Venter et al. (2015b)

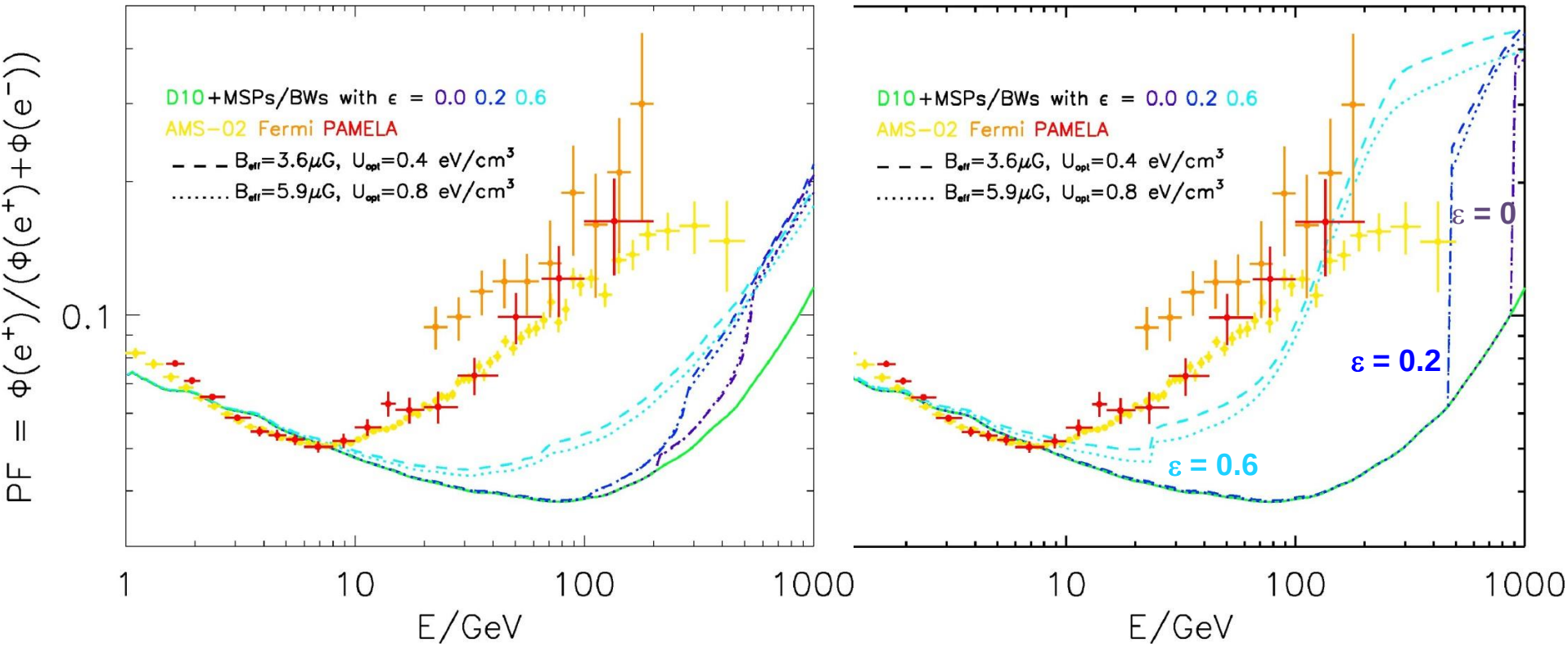
Efficiency $\eta_{p,max}$ = 0.1 κ_0 = 0.1 kpc^2 Myr^{-1}

MSP Contribution to Positron Fraction

Different 'background model': Delahaye et al. (2010)

Efficiency $\eta_{p,max}$ = 0.1
κ_0 = 0.1 kpc^2 Myr^{-1}

Efficiency $\eta_{p,max}$ = 0.3
κ_0 = 0.01 kpc^2 Myr^{-1}



Venter et al. (2015b)

Conclusions

Points for Discussion

- **Different realizations for Synthesis Population**
- **Limits on source parameters**
- **Contribution of other secondary sources**
- **Primary / secondary contributions**
- **Isotropy vs. pulsar origin of CR excess**
- **Implications of Galactic Centre γ-ray excess**

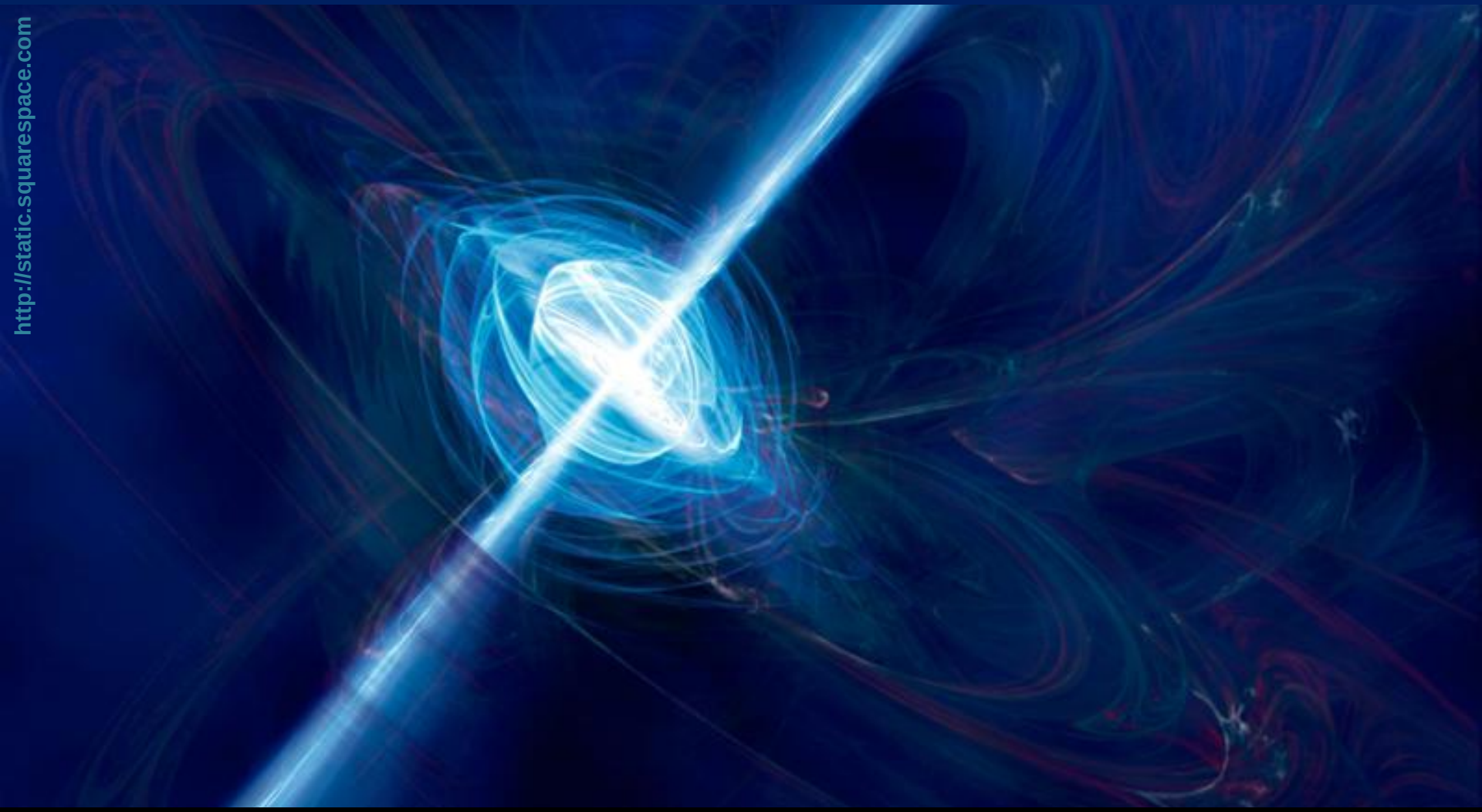
Conclusions

- **MSP pair cascades make up to ~ 15% contribution to CR positrons at 10 – 100 GeV, depending on background model**

- **Pairs accelerated in intra-binary shocks could make a significant contribution to positron fraction up to several TeV**

- **With the growing population of black widows and redbacks, present estimate is a lower limit**

THANK YOU!



"… the LORD … stretches out the heavens, lays the foundation of the earth, and forms the spirit of man within him…" (Zech. 12:1 NKJV).