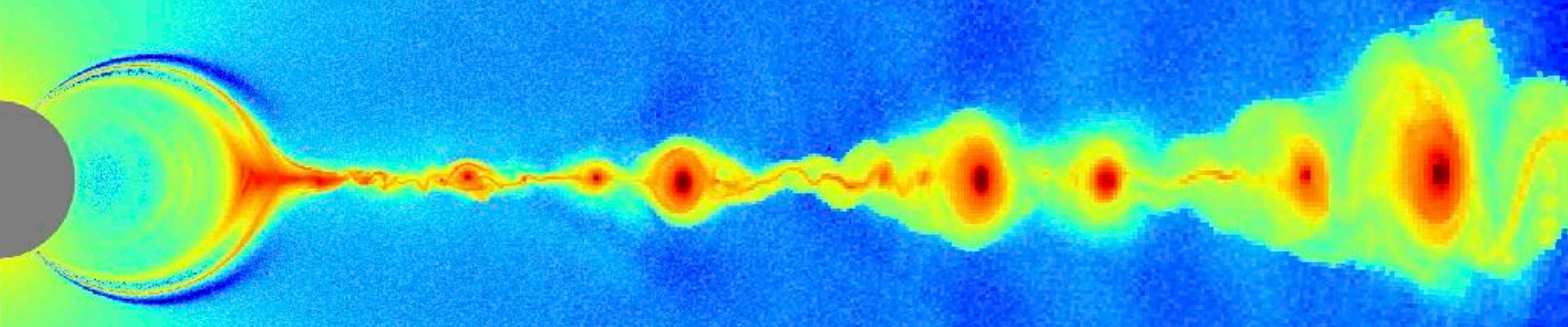
NASA PhysPAG Cosmic Ray Science Interest Group Meeting

Tuesday January 18



Pulsars as cosmic-ray sources

Claire Guépin

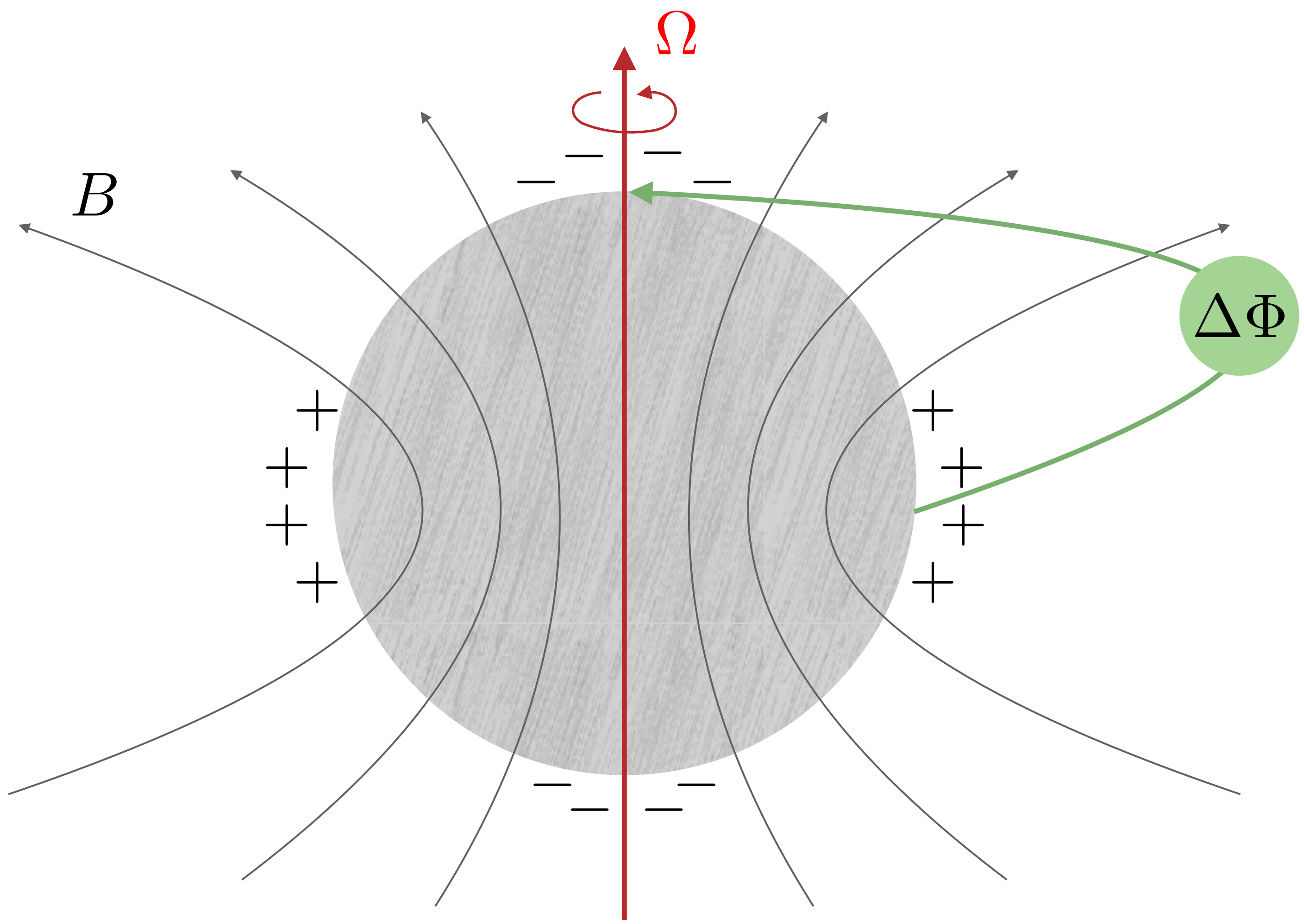
Neil Gehrels fellow, University of Maryland, College Park

& NASA Goddard Space Flight Center, Greenbelt

Physical properties

highly magnetized + rapid rotation → expected charge extraction from the surface

observed non-thermal radiation → acceleration of leptons



Schematic view of an aligned rotator

Introduction - Pulsars as cosmic-ray sources

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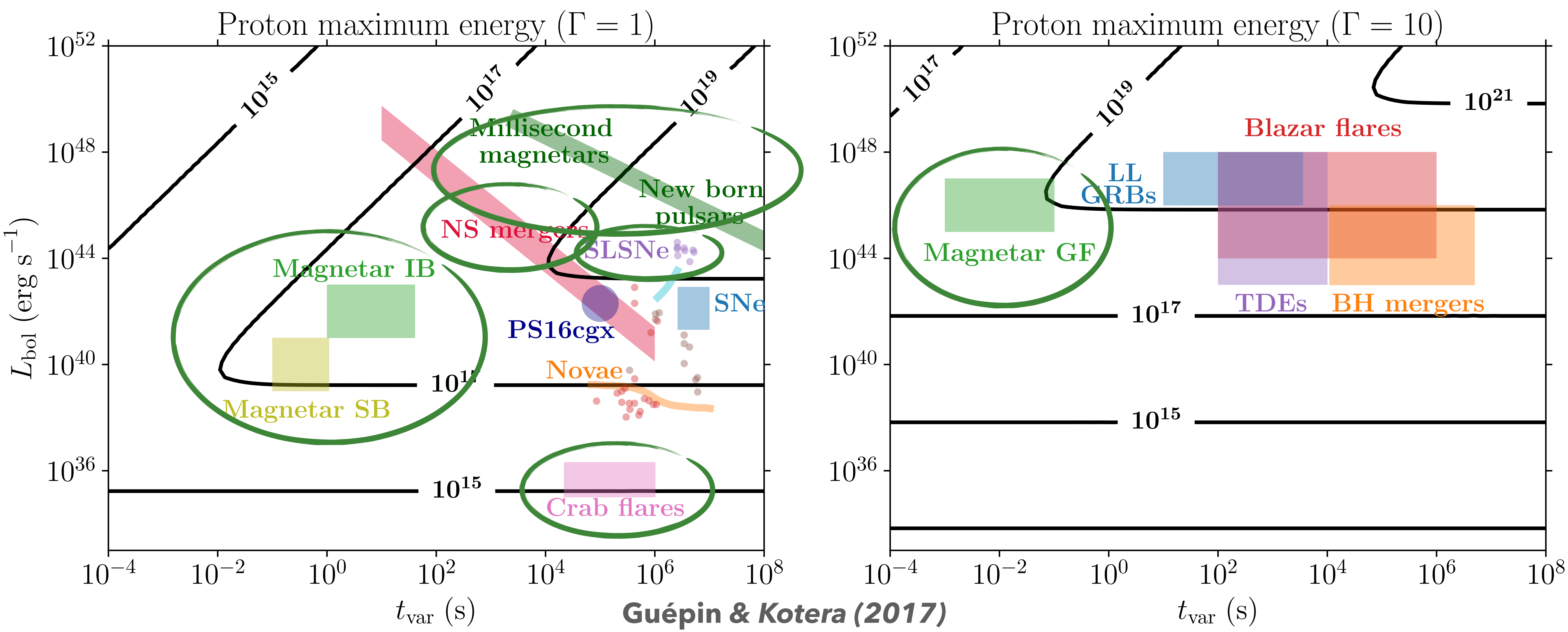
Pulsars as cosmic-ray sources

Venkatesan et al. (1997), Blasi et al. (2000), Arons (2003), Fang et al. (2012a), Fang et al. (2013a), Lemoine et al. (2015), Kotera et al. (2015)



Guépin & *Kotera (2017)*

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Acceleration of protons in pulsar magnetospheres, first principles simulations

C. Guépin, B. Cerutti, K. Kotera (2020)

Pulsars as pevatrons and diffuse TeV emission in the Galactic Center region

C. Guépin, L. Rinchiuso, K. Kotera, E. Moulin, T. Pierog and J. Silk (2018)

Acceleration of protons in pulsar magnetospheres

Previous work

Chen & Beloborodov (2014), Philippov & Spitkovsky (2018)

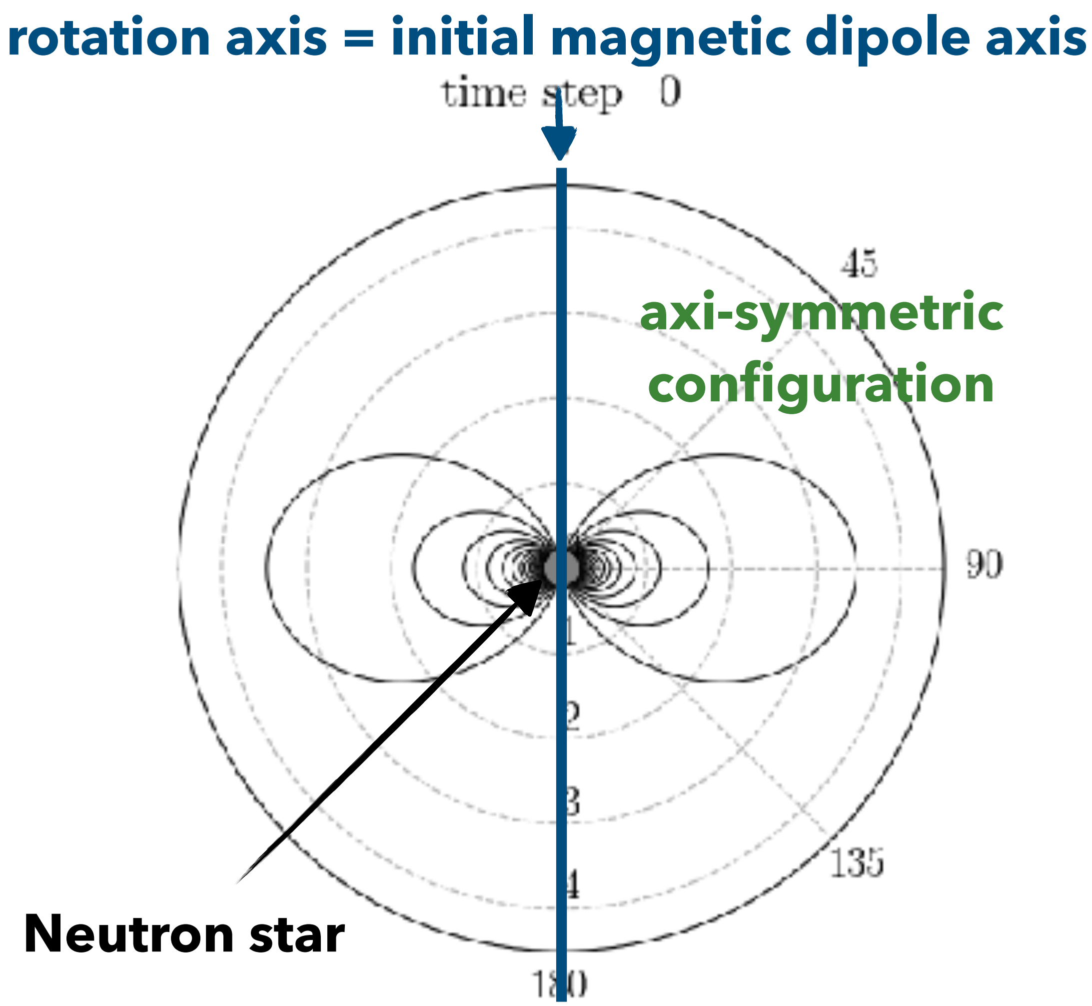
Our work

C. Guépin, B. Cerutti, K. Kotera (2020)

Particle in cell (PIC) simulations Zeltron **(Cerutti et al., 2013)**

→ ***compromise between kinetic and macroscopic scales***

- neutron star radius $\sim 10\,\mathrm{km} \rightarrow 100\,\mathrm{cm}$
- magnetic field $\sim 10^9\,\mathrm{G} - 10^{13}\,\mathrm{G} \rightarrow 10^5\,\mathrm{G}$
- millisecond rotation $R_{\mathrm{LC}}/R_\star = 5$
- proton mass / electron mass ratio $(m_p/m_e)/100$
- separation macroscopic / kinetic scales



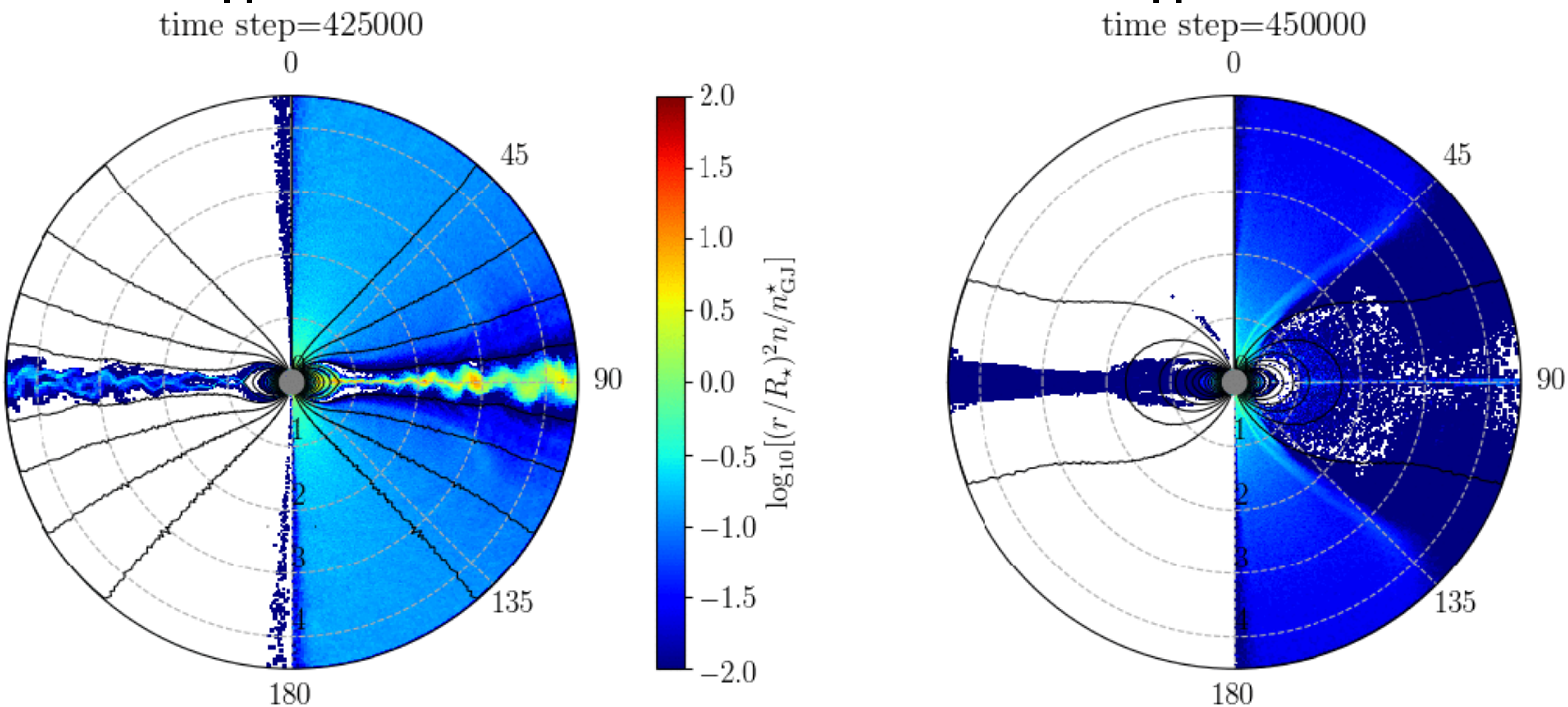
Acceleration of protons in pulsar magnetospheres

- Injection of protons and electrons at the surface

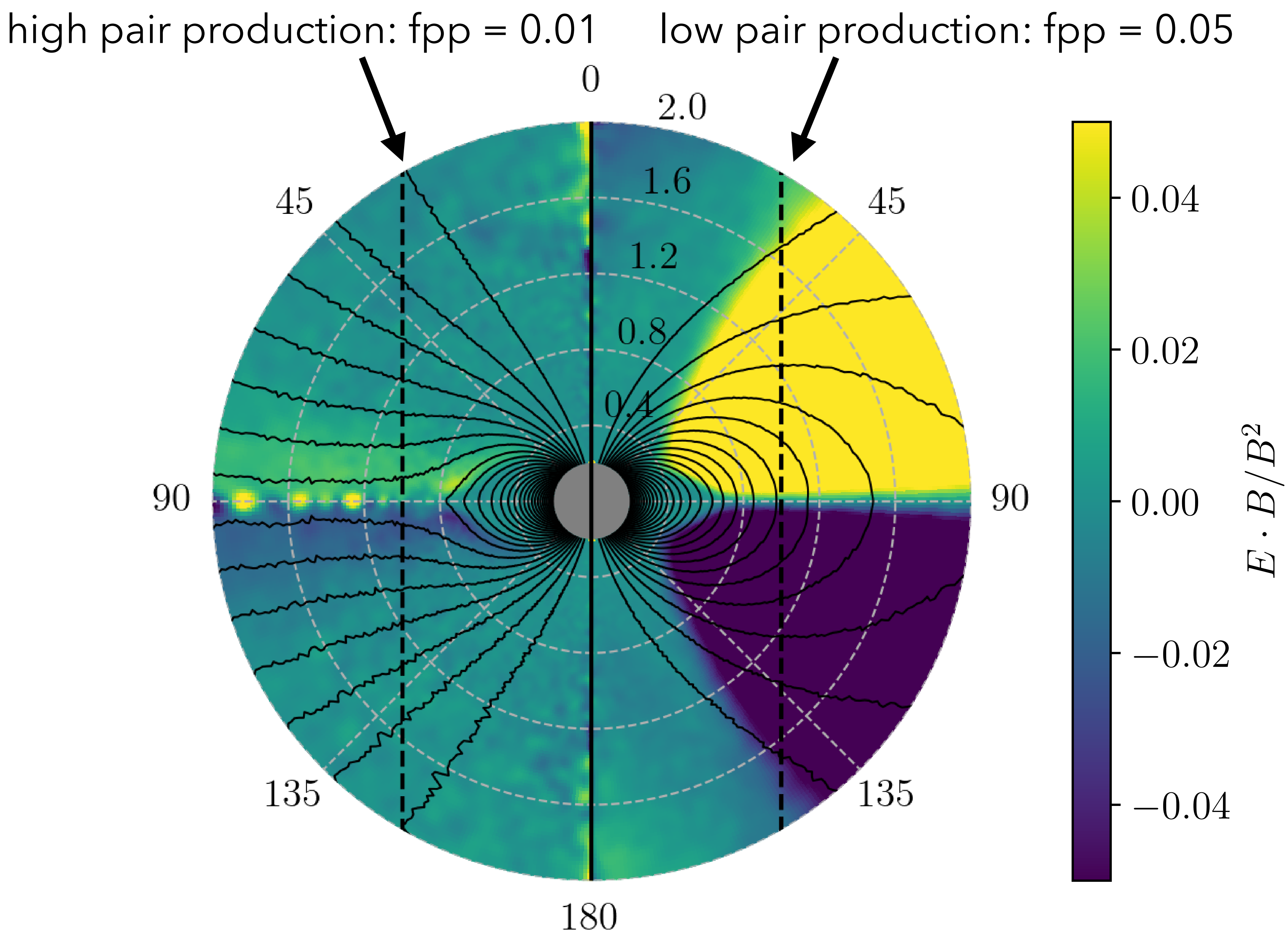
Main processes impacting magnetosphere structure and particle acceleration

- Injection of electrons and positrons: local **pair production** criterion, $\gamma_{\rm min,pp} = f_{\rm pp}\,\gamma_{0,e}$

fpp = 0.01 **fpp = 0.05**



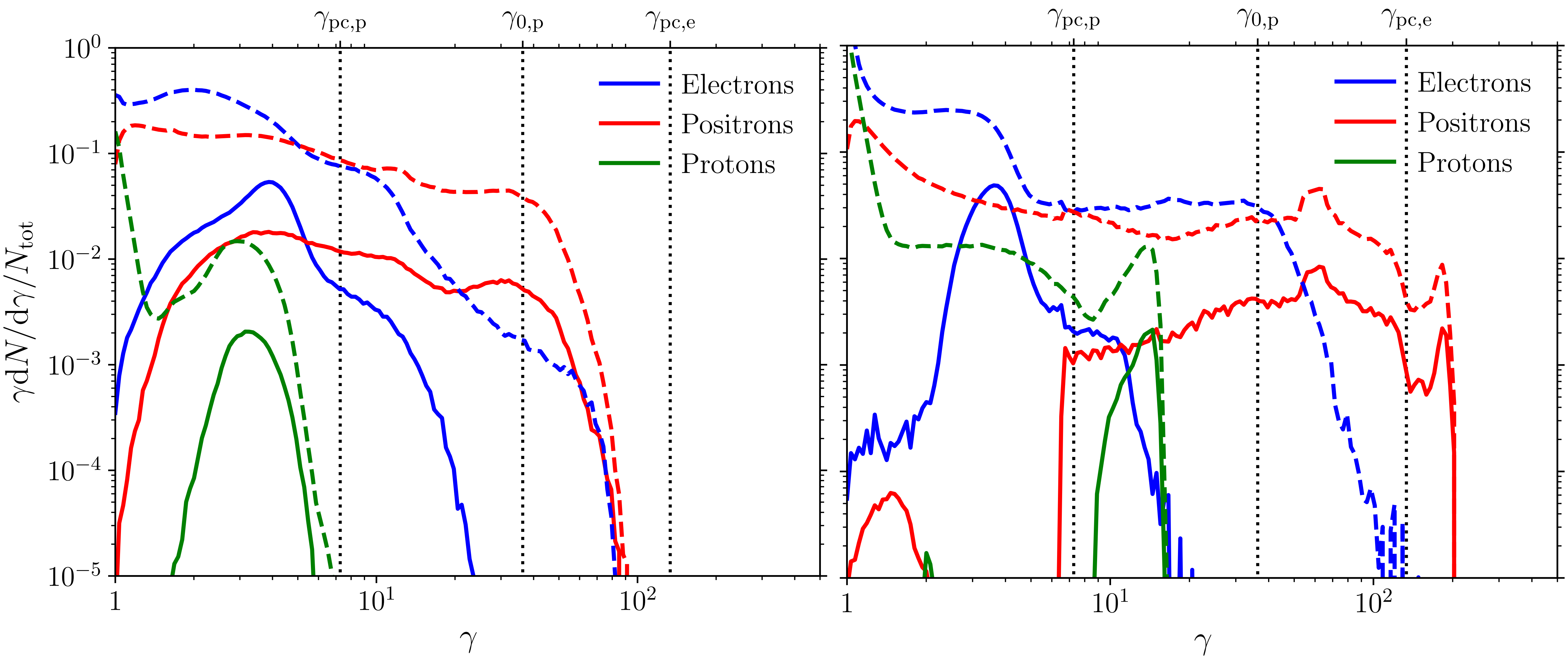
Particle acceleration



Proton, electron and positron spectra

Dashed lines: total, solid lines: escaping

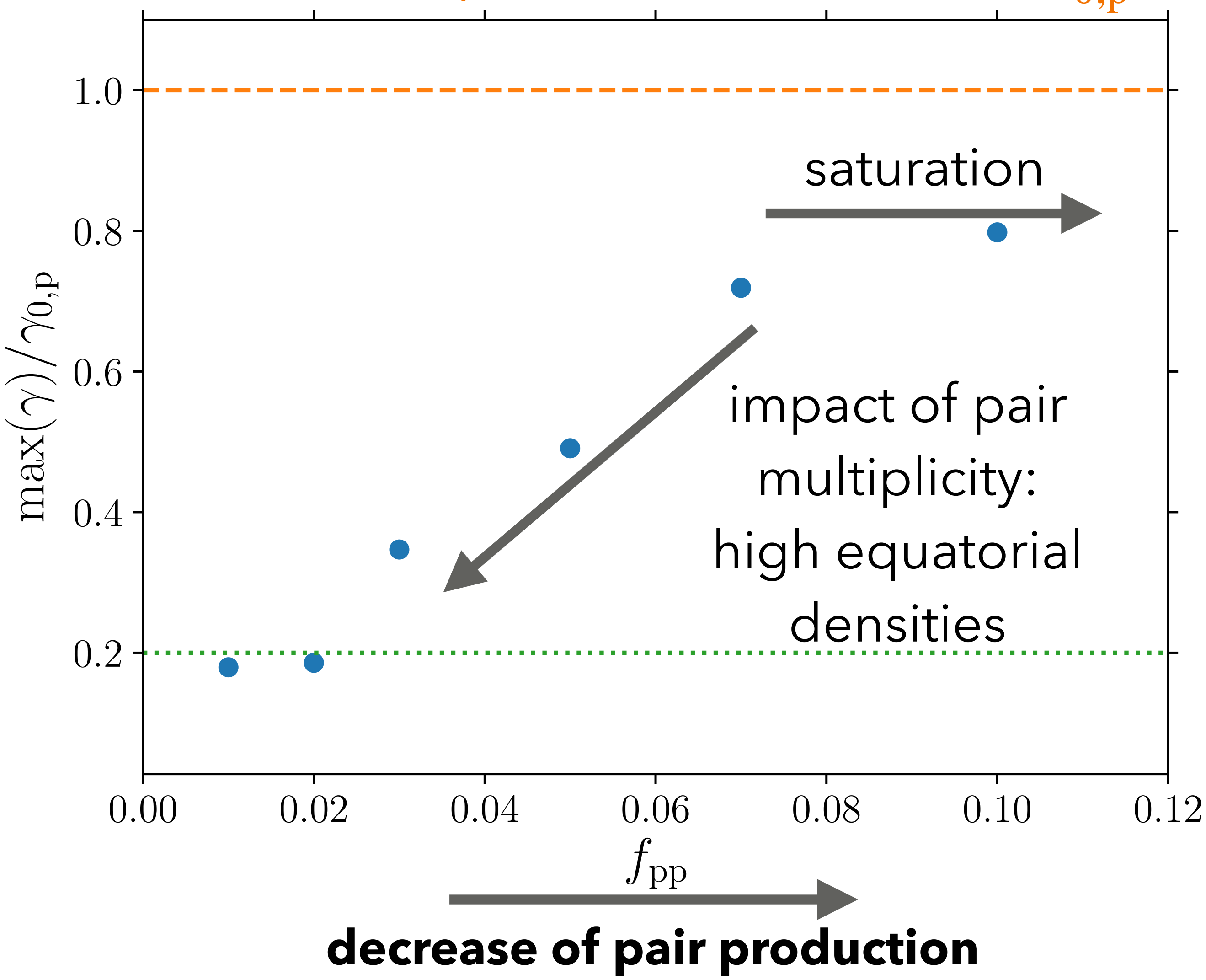
high pair production: fpp = 0.01 **low pair production: fpp = 0.05**



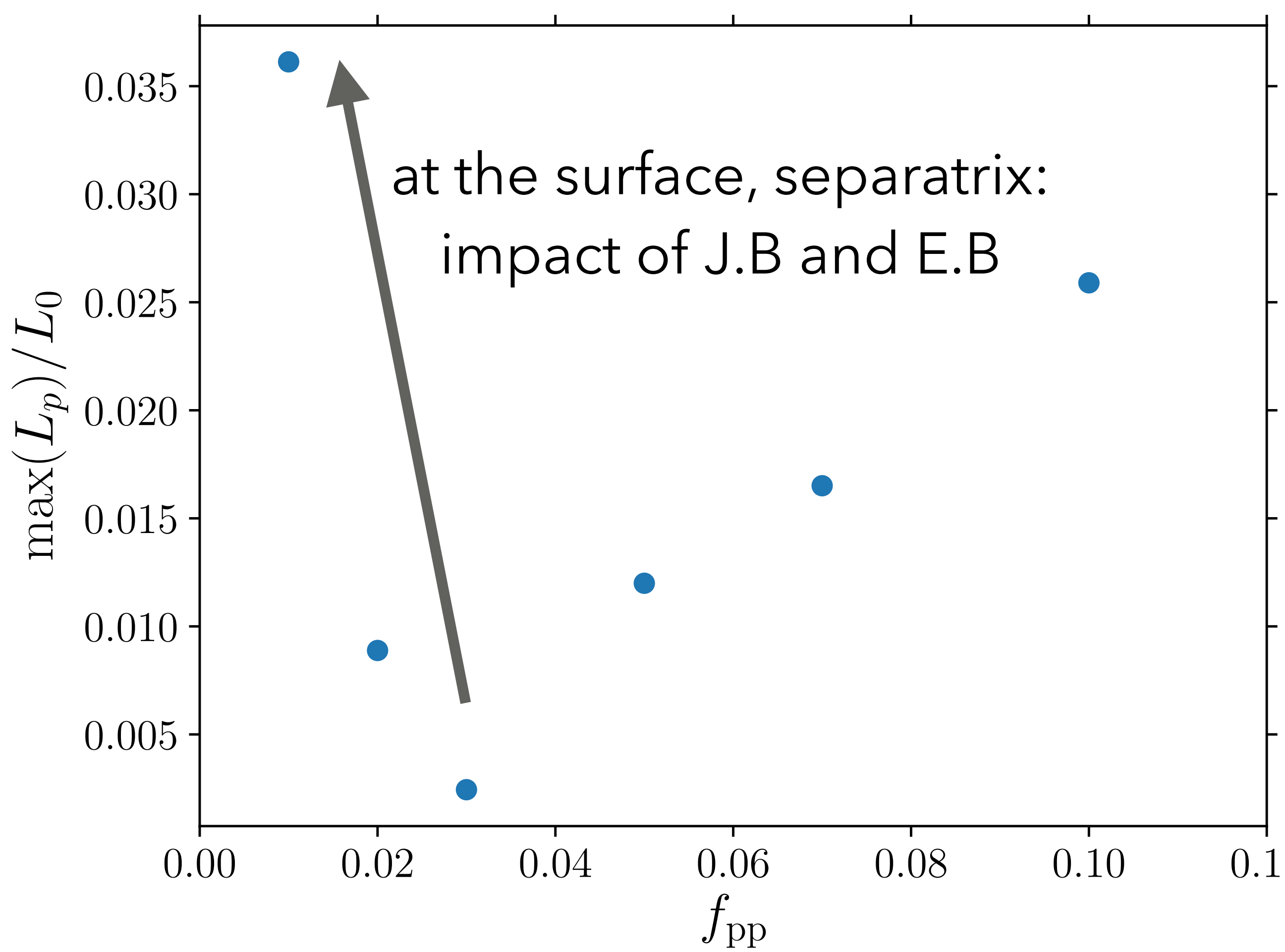
Acceleration of protons in pulsar magnetospheres

Proton acceleration: maximum energy and luminosity

maximum proton Lorentz factor: $\gamma_{0,\mathrm{p}}$



spin-down luminosity: L_0



Simulation results: $\gamma_{p,\max} = 5 - 75\ \%\ \gamma_{0,\mathrm{p}}$ and $L_{p,\max} = 0.2 - 4\ \%\ L_0$

Millisecond pulsars, using theoretical estimates of $\gamma_{0,\mathrm{p}}$ and L_0:

$$E_{\mathrm{p}} \simeq 5 \times 10^{15} - 2 \times 10^{16}\,\mathrm{eV}\ \ B_{\star,9} R_{\star,6}^{2} P_{-3}^{-1}$$

$$L_{\mathrm{p}} \simeq 3 \times 10^{34} - 5 \times 10^{35}\,\mathrm{erg\,s^{-1}}\ \ B_{\star,9}^{2} R_{\star,6}^{6} P_{-3}^{-4}$$

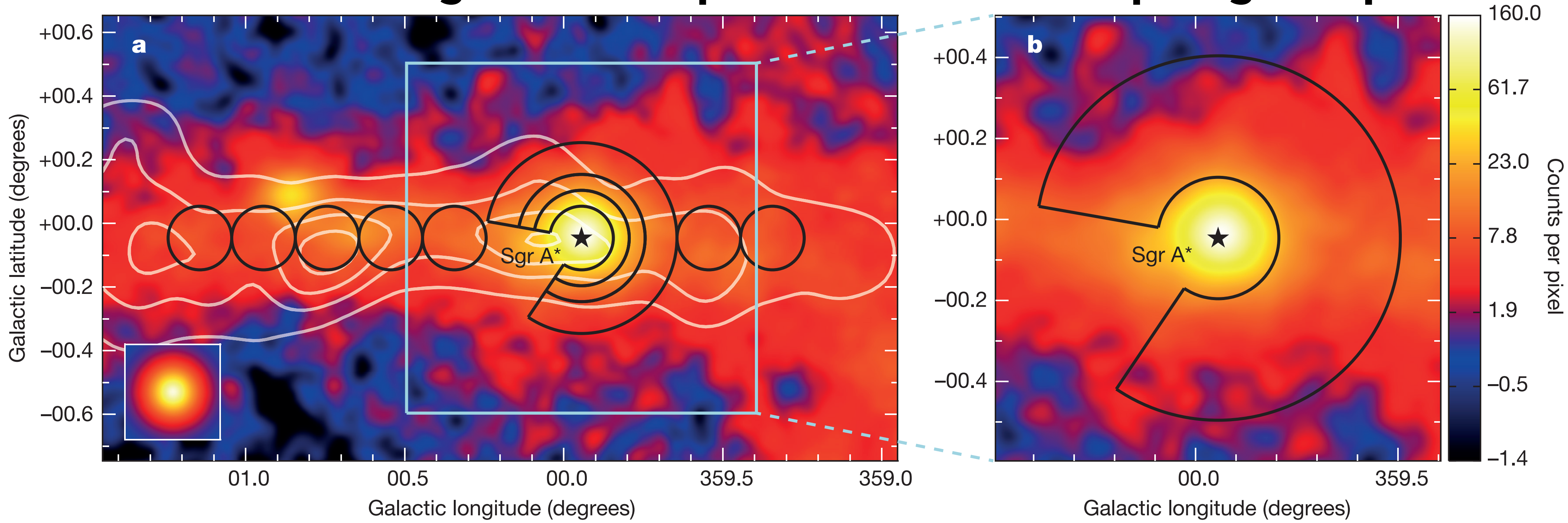
C. Guépin, L. Rinchiuso, K. Kotera, E. Moulin, T. Pierog and J. Silk (2018)

Diffuse emission in the galactic center (GC) region

- Fermi-LAT, GeV range
- H.E.S.S., TeV range

→ **radial profile**

different regions: radial profile **inner 50 pc region: spectrum**



HESS Collaboration (2016)

Pulsars as pevatrons

C. Guépin, L. Rinchiuso, K. Kotera, E. Moulin, T. Pierog and J. Silk (2018)

Diffuse emission in the galactic center (GC) region

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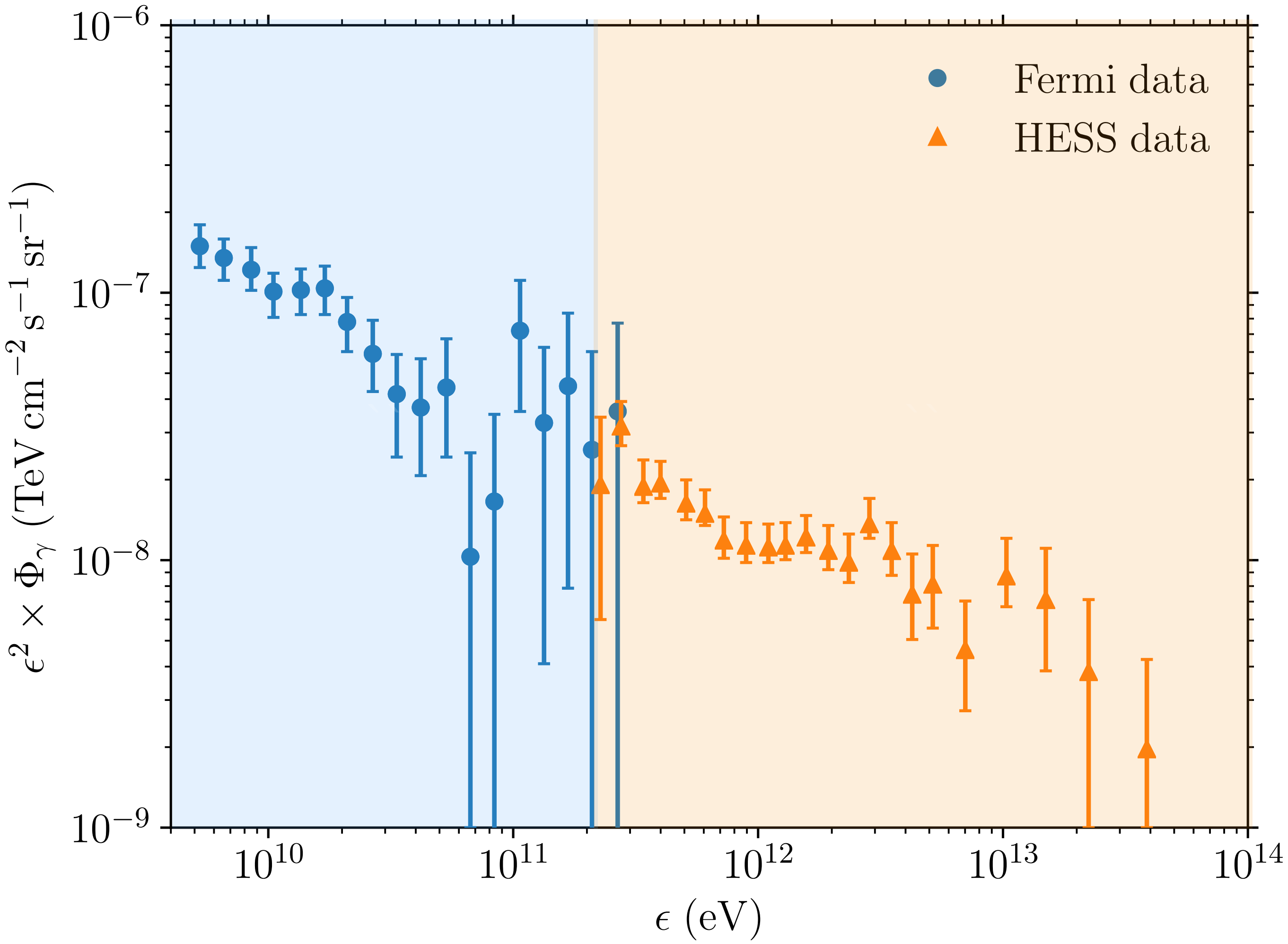
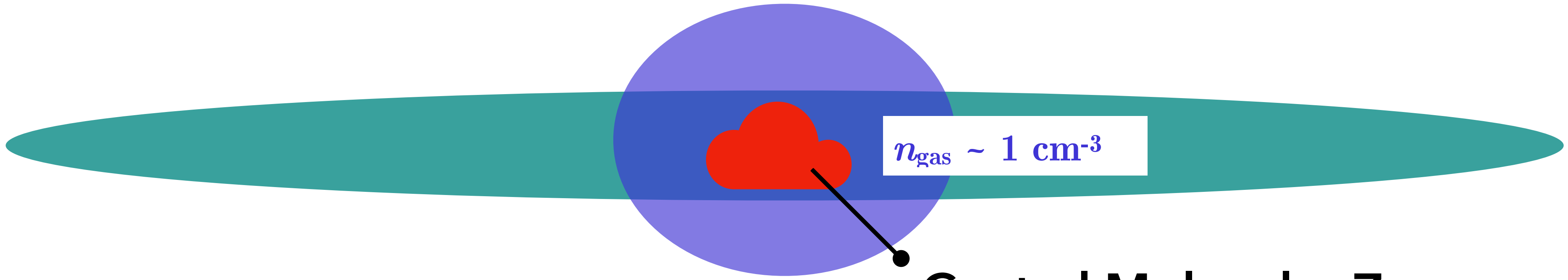
→ **radial profile**, **spectrum**

Spectrum in the inner 50 pc region

HESS collaboration (2016) and Gaggero et al. (2017)



Pulsars as pevatrons



Bulge millisecond pulsar (MSP) distribution

$$F_b(r_s, \theta, \phi) = \frac{(3-\alpha_b)N_b}{4\pi r_{max}^{3-\alpha_b}} r_s^{-\alpha_b} \quad \text{for } 0 < r_s < r_{max}$$

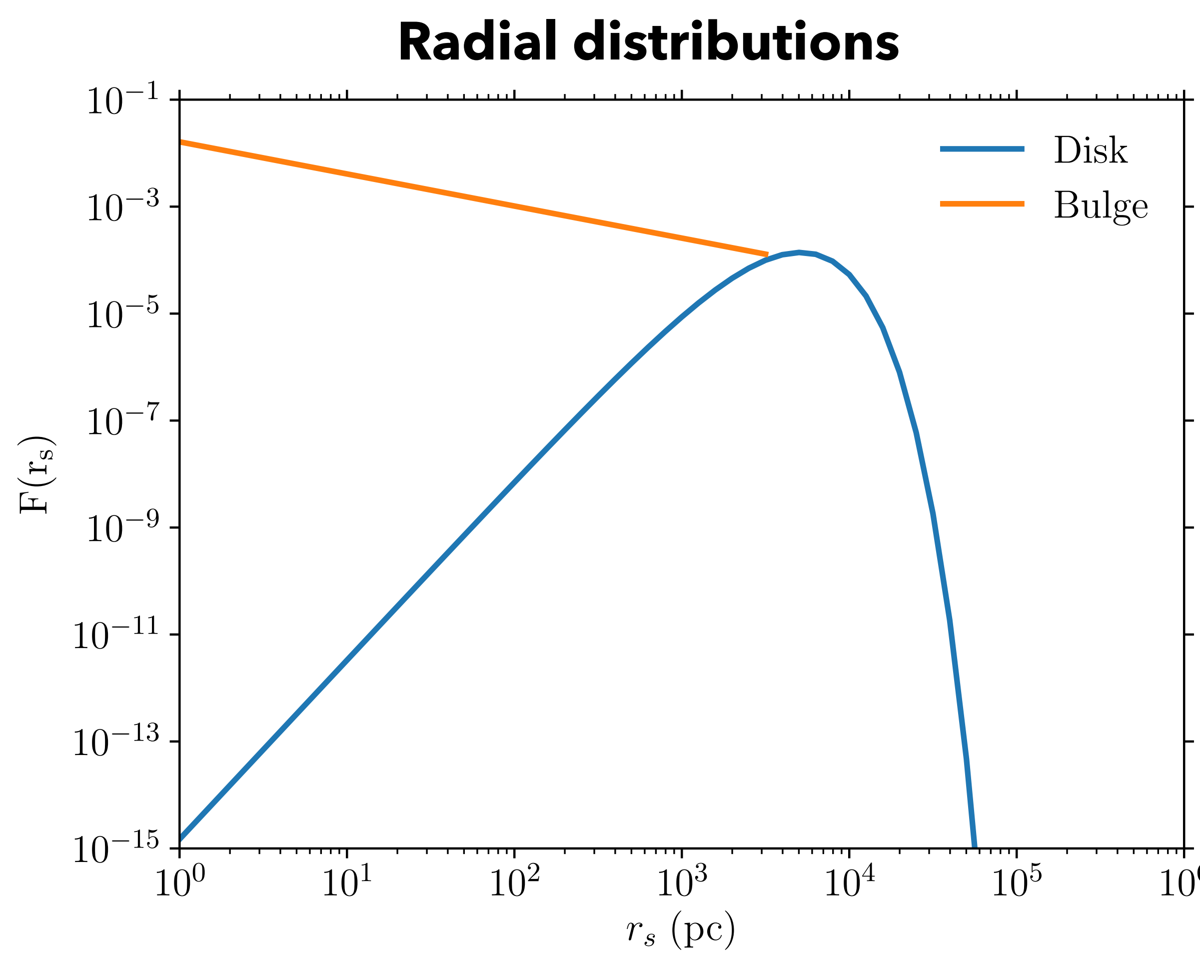
N_b = [800-3600] for $L_\gamma \in [10^{33}, 10^{36}]$ erg s^{-1},

- **but** also N_b ~ 4 × 10^4 for $L_\gamma > 10^{32}$ erg s^{-1}
- **or** no evidence for bulge

Disk MSP distribution

$$F_d(r_s, \theta, z) = \frac{r_s^n \exp(-r_s/\sigma) \exp(-|z_s|/z_0) N_d}{4\pi z_0 \sigma^{n+2} \Gamma(n+2)}$$

N_d = [4000-16000] for $L_\gamma \in [10^{33}, 10^{36}]$ erg s^{-1}



r_s distance from Galactic Center

Our scenario

Hypothesis: protons accelerated by MSP population

- acceleration efficiency
- injection from individual objects
- diffusion of protons in interstellar medium
- integrate over spatial, initial spin, magnetic field and age distributions
- interaction with molecular clouds: $pp \to \pi^0 \to \gamma\gamma$

predictions for **radial profile** and **spectrum** of gamma-rays

$L_\gamma(\epsilon > 1\,\mathrm{TeV}, r)$ $\epsilon^2 \Phi_\gamma(\epsilon)$ in the inner 50 pc region

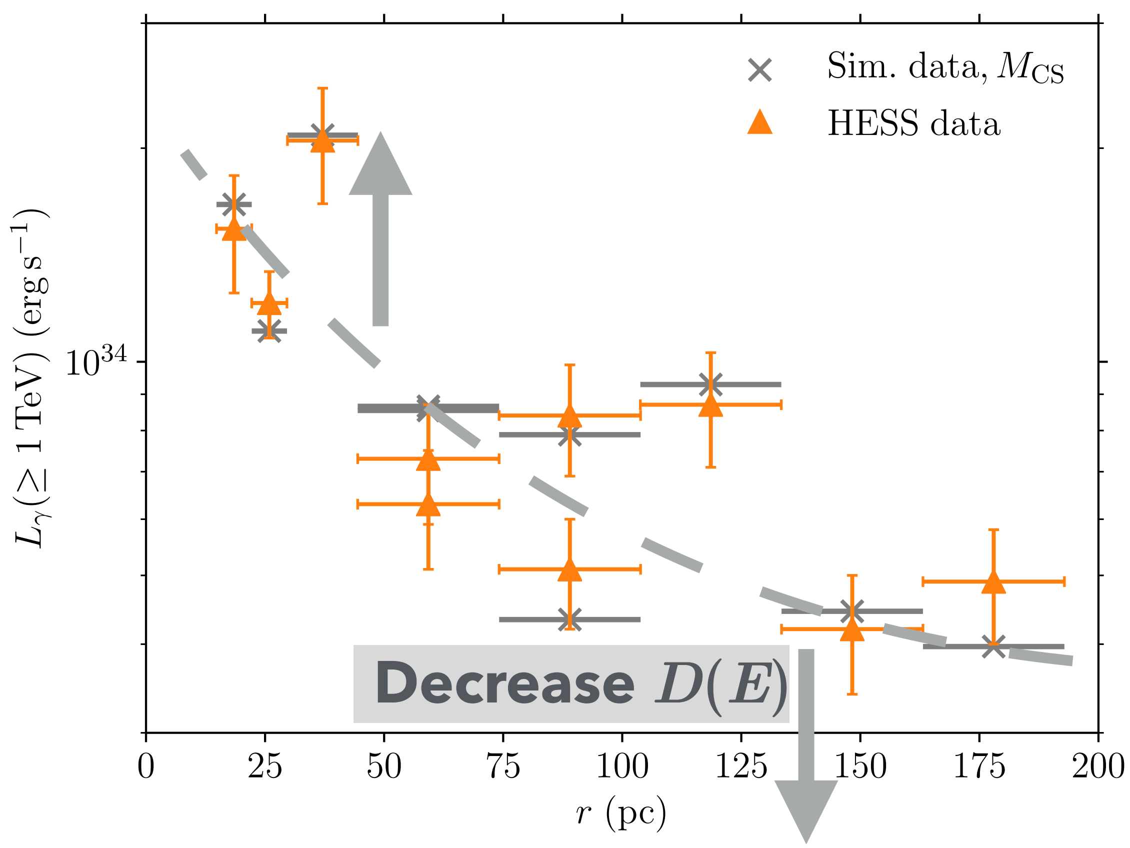
Pulsars as pevatrons

With following parameters

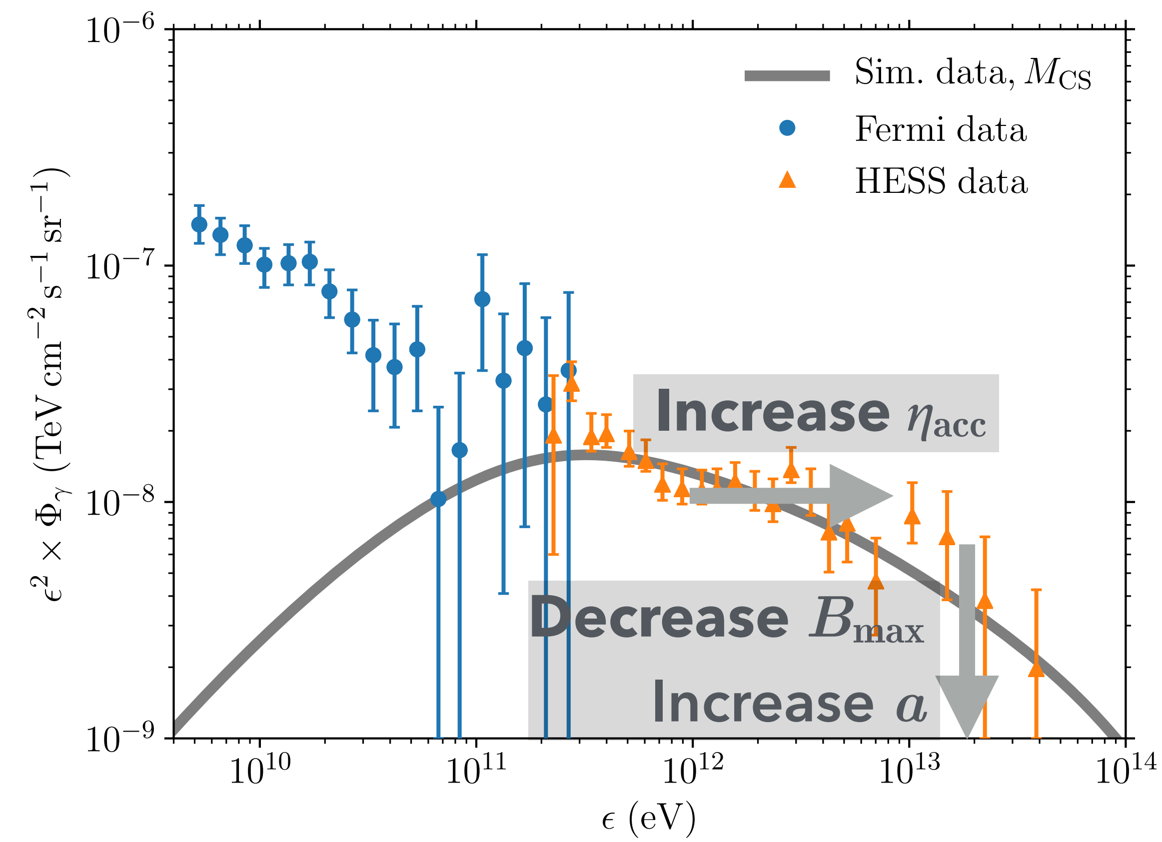
- hard injection spectrum E^{-1} from pulsars
- spatial distribution: **bulge component**
- log-normal initial spin distribution
- power law dipole magnetic field distribution $\propto B^{-a}$ with $a = 1$ $B_{\max} \geq 10^{11}$ G
- uniform age distribution

$\eta_p N_b \sim 10^6$, $\eta_{acc} \sim 0.03$, $\kappa \sim 10^3$ η_p: baryon loading

different regions: **radial profile**



inner 50 pc region: **spectrum**



Conclusions - Pulsars as cosmic-ray sources

- pulsars candidates for production of cosmic rays
- PIC simulations: focus on aligned dipole (initial condition), millisecond periods
- pulsar magnetospheres can accelerate protons
- support analytical estimes, millisecond pulsars are potential PeVatrons
- large-scale observable consequences, e.g. Galactic center diffuse gamma rays

Prospects

- proton **injection** from the neutron star surface: impact of local (EM fields) and non-local (pair production) effects
- **escape** of proton & electron-positron spectra from the magnetosphere: impact of mass ratio, magnetic field, rotation period, and other parameters
- **propagation** of proton/electron-positron spectra in the wind, termination shock (TS)
  - possible contribution to the development of instabilities at TS
  - impact on propagation and **emissions** (e.g. gamma-ray halos, Geminga)