Pulsars and the highest energy multi-messengers

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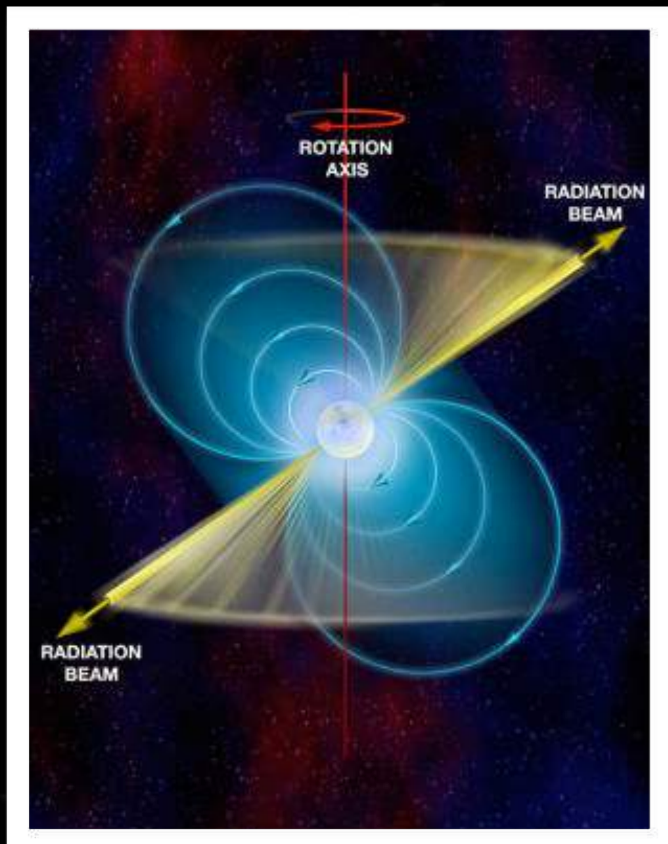
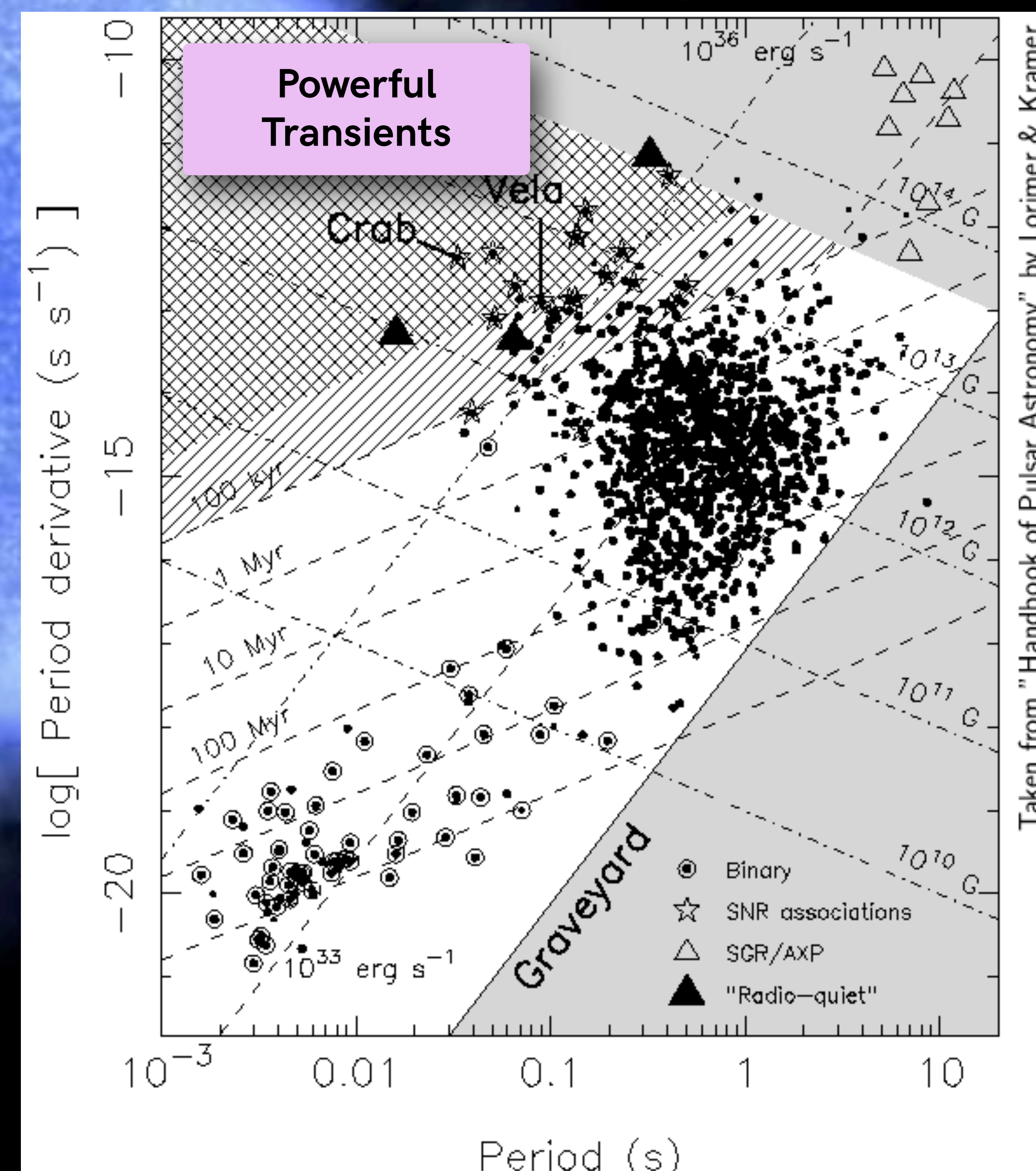
Pulsars



- neutron star
- fast rotation, period P
- strong magnetic field B
- spins down by electromagnetic losses

supernova

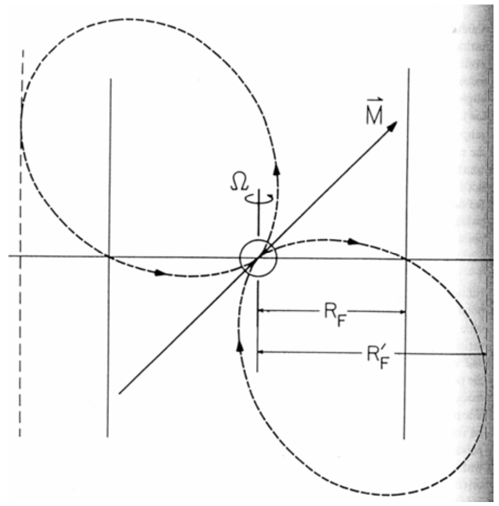


Particle acceleration in pulsars

Charge density

Induced electric field

$$\mathbf{E} = -\frac{\mathbf{v}}{c}\times\mathbf{B} = -\frac{1}{c}(\mathbf{\Omega}\times\mathbf{r})\times\mathbf{B}$$



Implies a charge density (Goldreich-Julian 69)

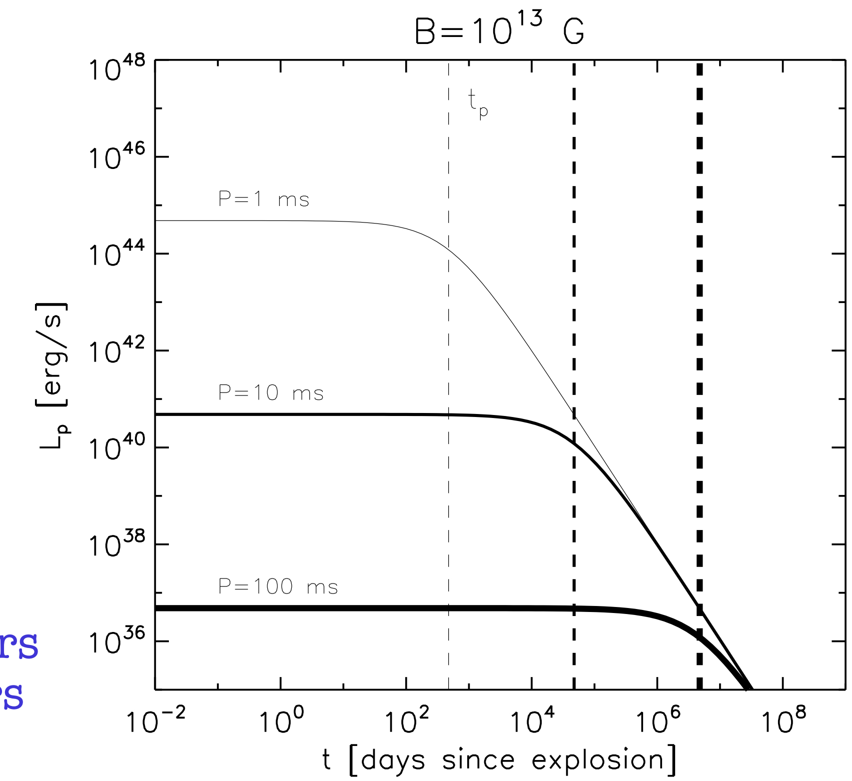
$$\rho = \frac{1}{4\pi}\nabla\cdot\mathbf{E} \approx -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c} \equiv \rho_{GJ}$$

e.g.
Blasi et al. (2000)
Arons et al. (2003)
Bednarek & Bartosik (2006)

outflow energetics

total energy $\quad E_\mathrm{p} = \frac{I\Omega_\mathrm{i}^2}{2} \sim 1.9\times10^{52}\,\mathrm{erg}\,I_{45}P_{\mathrm{i},-3}^2$

neutron star luminosity $\quad L_\mathrm{p}(t) = \frac{E_\mathrm{p}}{t_\mathrm{p}}\frac{1}{(1+t/t_\mathrm{p})^2}$



t_p ~ a few years for ms pulsars

conversion of pulsar electromagnetic into kinetic energy

particles accelerated to maximum Lorentz factor:

$$\gamma_\mathrm{M} \simeq \frac{L_\mathrm{p}}{\dot{N}mc^2}$$

Goldreich-Julian charge density

maximum energy:

$$E_0 \sim 1.5\times10^{20}\,\mathrm{eV}\,A_{56}\,\eta\,\kappa_4^{-1}P_{\mathrm{i},-3}^{-2}B_{13}R_{\star,6}^3$$

fraction of luminosity into particle kinetic energy

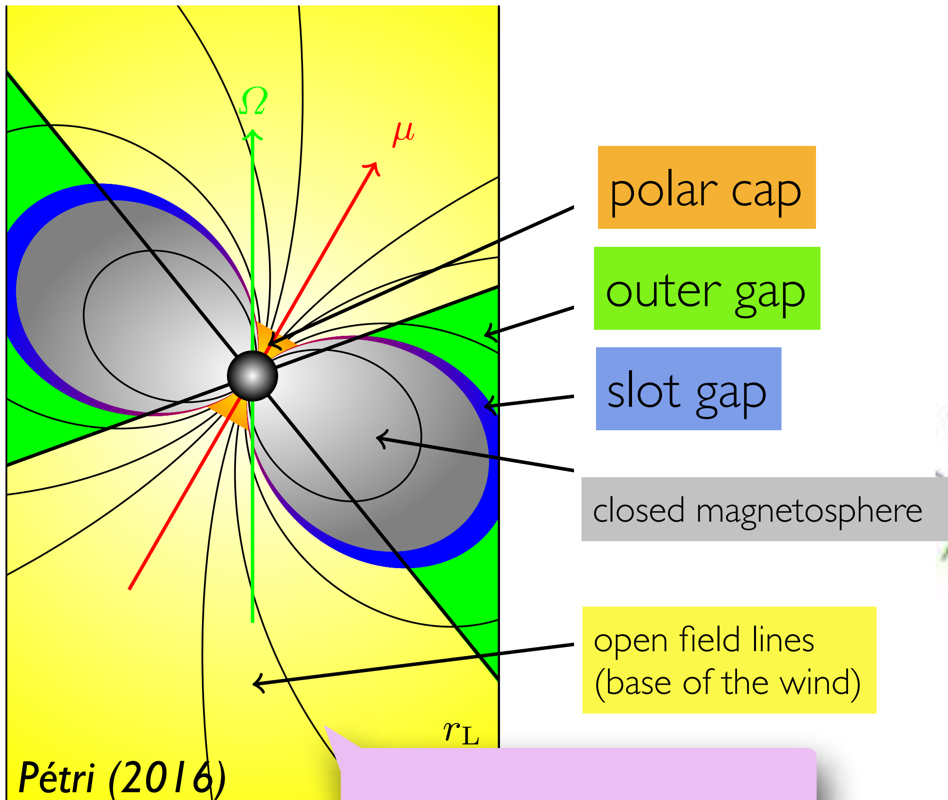
pair multiplicity

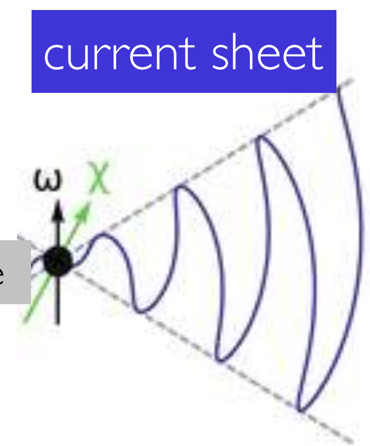
Lemoine, KK & Pétri (2015)

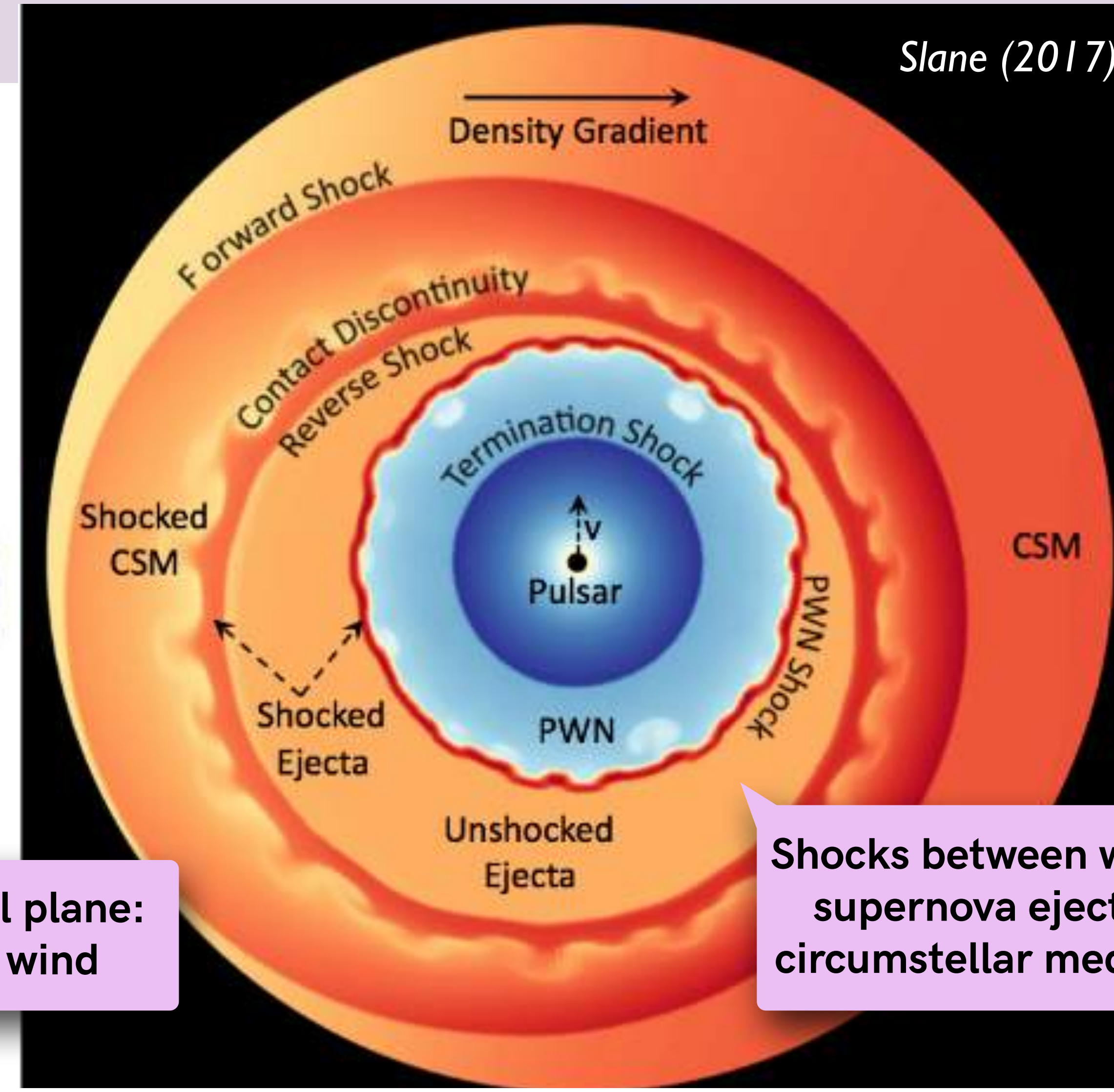
Pulsars born with ms periods and magnetars are good candidates of UHECR sources

Particle acceleration in pulsars

Acceleration region?







Gaps close to stars

equatorial plane: striped wind

Shocks between wind/ supernova ejecta/ circumstellar medium

reviews: Harding (2007), Hirotani (2008)

Acceleration mechanism?

- « linear » E∝r — e.g., *Chen et al. 92, Arons 03*
- Fermi @ TS — e.g., *Lemoine, KK, Pétri 15*
- reconnection wind region and/or close to TS in striped wind or in nebula? — e.g., *Sironi & Spitkovsky 12*, *Lemoine, KK, Pétri 15*

Ion acceleration in pulsar magnetospheres   PIC simulations

Guépin, Cerutti, KK (2020)

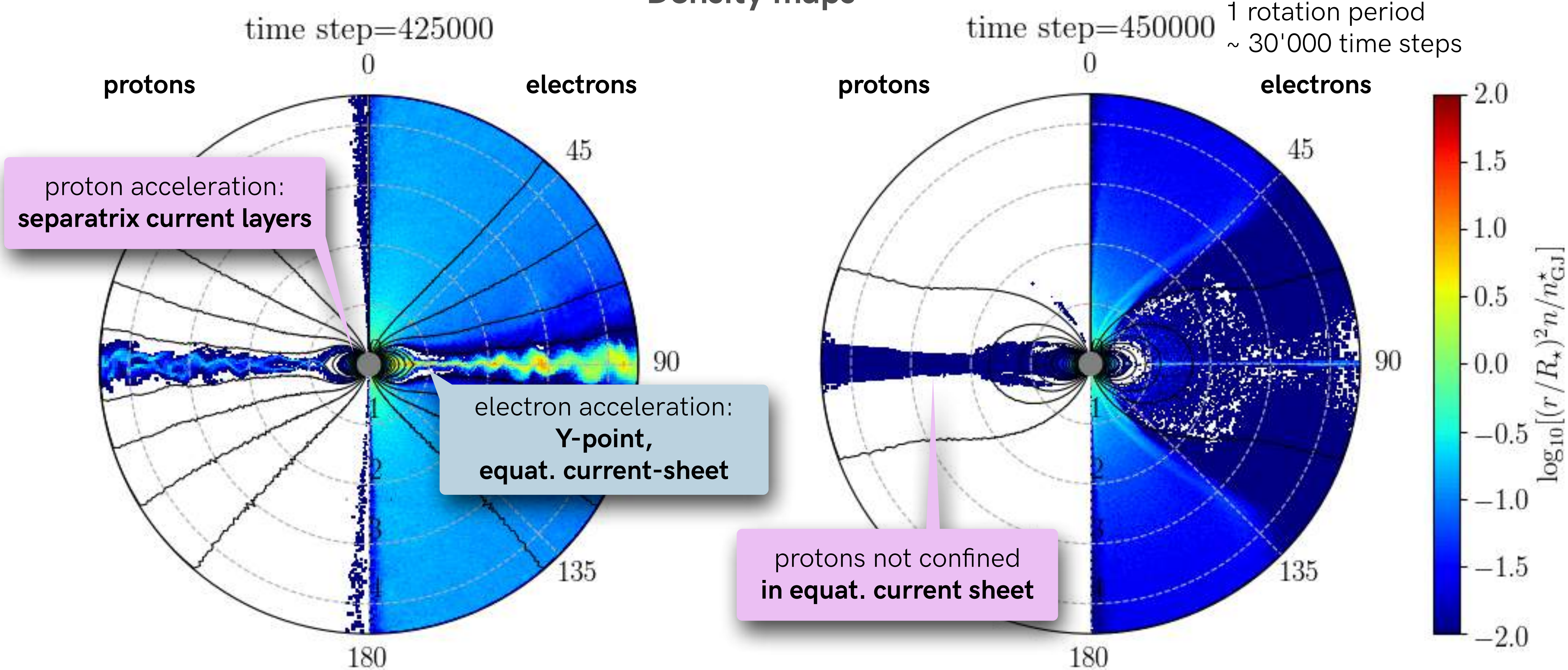
Zeltron *Cerutti et al. (2013)*

Magnetosphere configuration: **aligned dipole**

Injection of protons and electrons allowed at the surface, limited by the GJ density

Main variable: pair production "strength", local, $\gamma_{min,pp} = f_{pp}\, \gamma_{0,e}$

Density maps



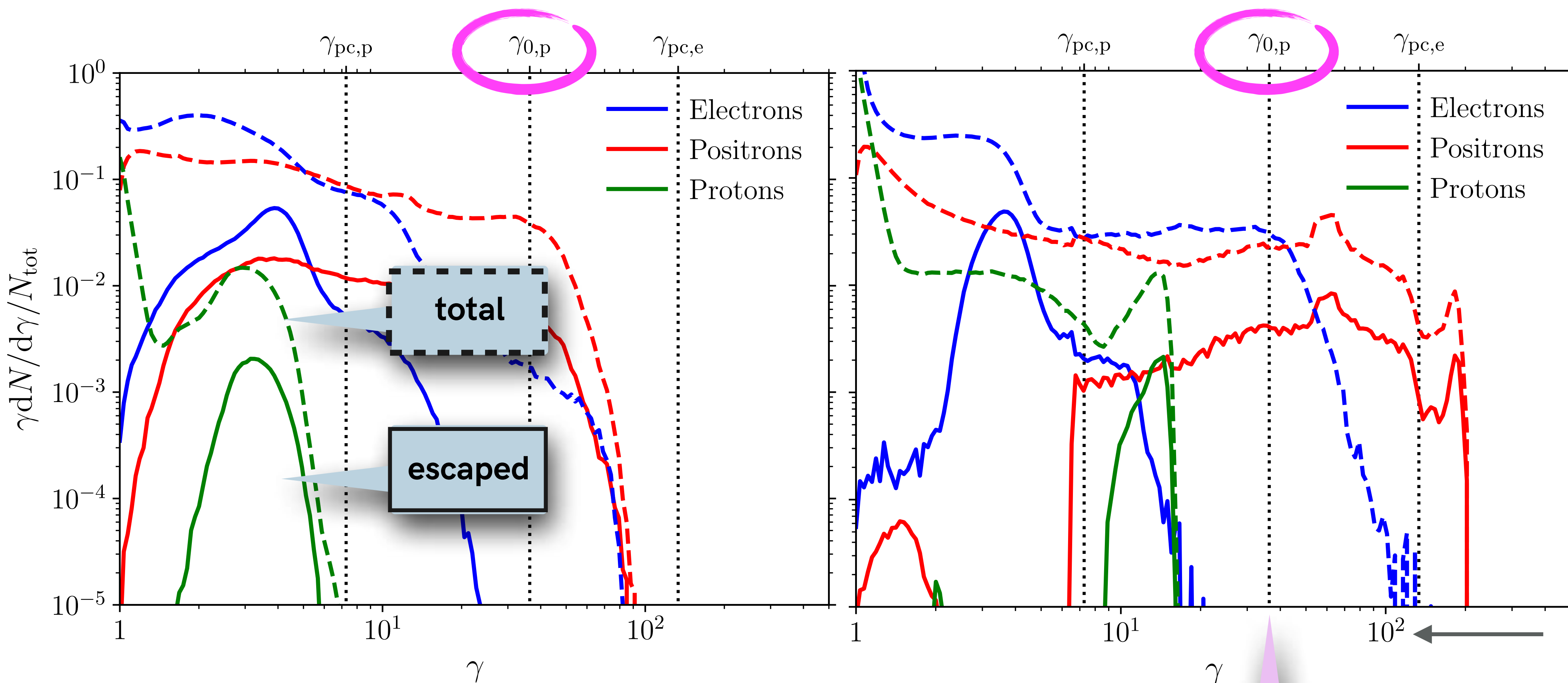
high pair production (f_{pp} = 0.01)

low pair production (f_{pp} = 0.01)

Protons can be accelerated and can escape

Guépin, Cerutti, KK (2020)

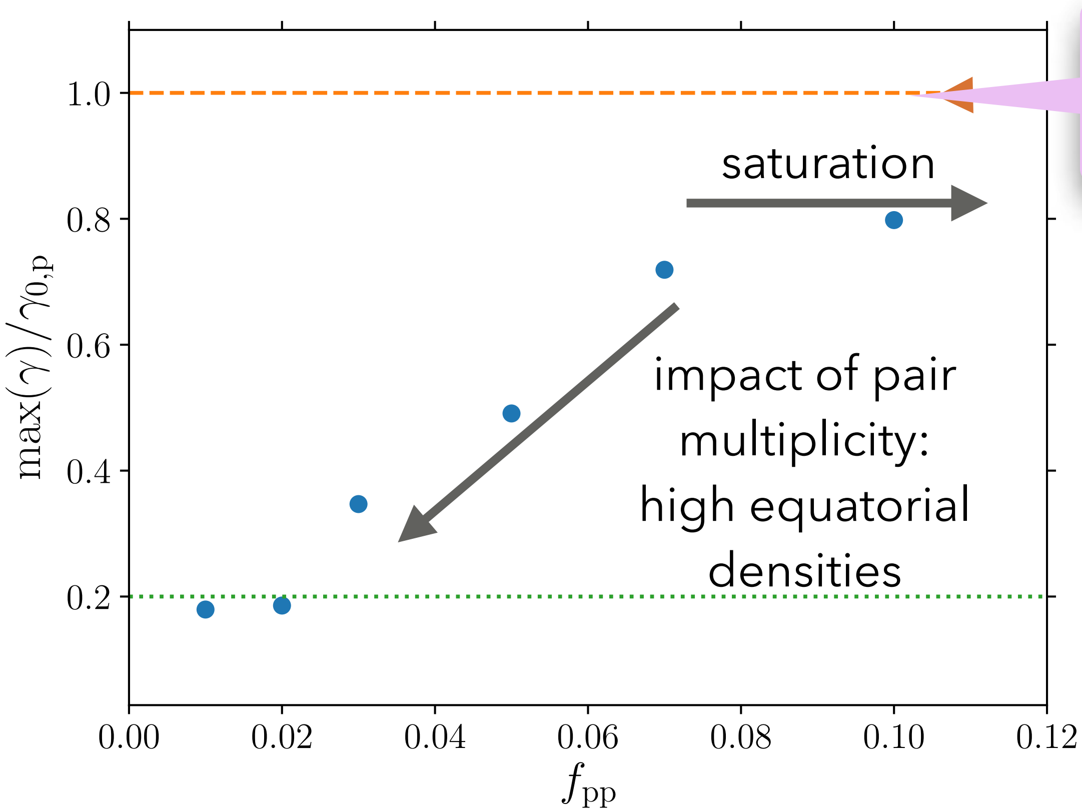
high pair production (f_{pp} = 0.01)



low pair production (f_{pp} = 0.01)

values in simulation: to be rescaled

acceleration through **full potential drop** from pole to equator $|\Phi| = R^2 B / 2 R_{LC}$



$$\gamma_0 = 3.3 \times 10^{10}\, m_{r,1836}^{-1}\, B_{\star,12}\, R_{\star,6}^2\, P_{-3}^{-1}$$

Simulations: $5 - 85\%\ \gamma_0$

Newborn pulsars with ms rotation period:

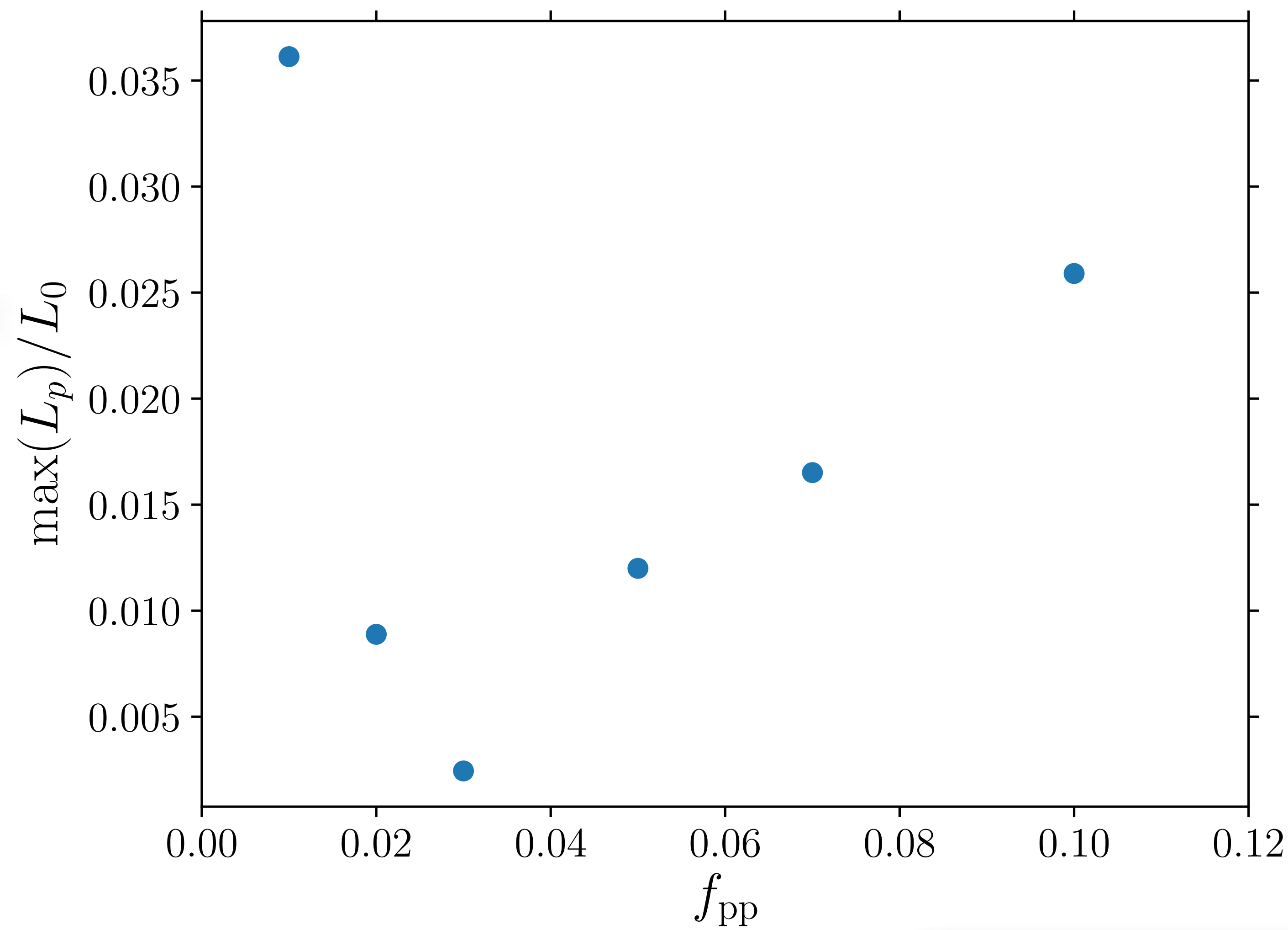
$$E_p \simeq 5\times10^{19} - 2\times10^{20}\ \mathrm{eV}\, B_{\star,13} R_{\star,6}^2 P_{-3}^{-1}$$

Proton luminosity in pulsars

Guépin, Cerutti, KK (2020)

Energy dissipation in protons

L_0 spin-down luminosity (e.g., ***Spitkovsky 2006***)



few % of spin-down luminosity required to produced observed UHECRs.
e.g., Fang, KK, Olinto (2013a)

Simulation results: $L_p = 0.2 - 4\% L_0$

Newborn pulsars with ms rotation period:

$$L_{\rm p} \simeq 3 \times 10^{42} - 5 \times 10^{43}\,{\rm erg\,s^{-1}}\,B_{\star,13}^2 R_{\star,6}^6 P_{-3}^{-4}$$

Interaction backgrounds for high-energy cosmic rays

nebula non-thermal γ

Amato et al. (2003)
Lemoine, KK, Pétri (2015)

SN thermal γ

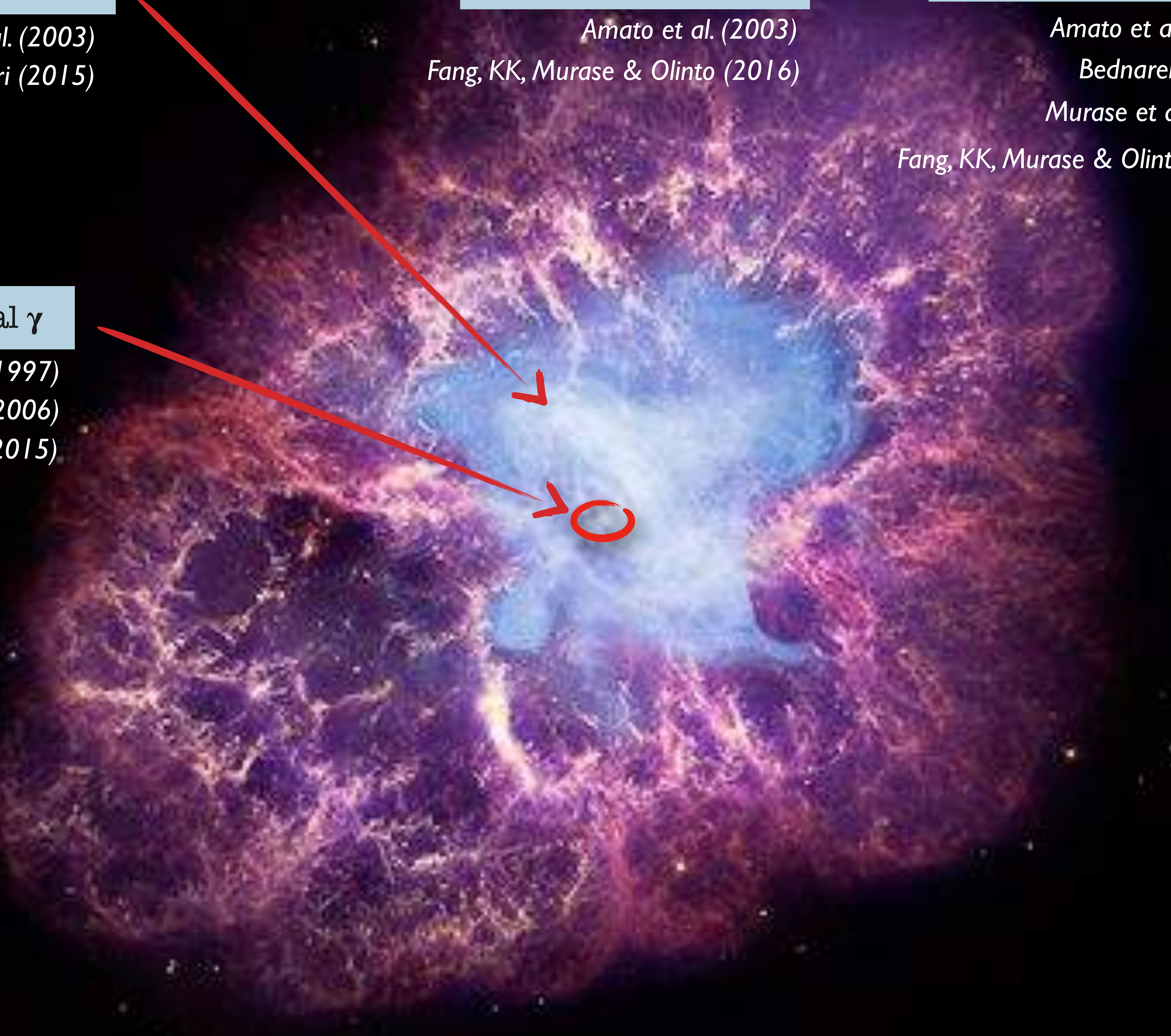
Amato et al. (2003)
Fang, KK, Murase & Olinto (2016)

SN ejecta matter

Amato et al. (2003)
Bednarek (2003)
Murase et al. (2009)
Fang, KK, Murase & Olinto (2015, 2016)

star's thermal γ

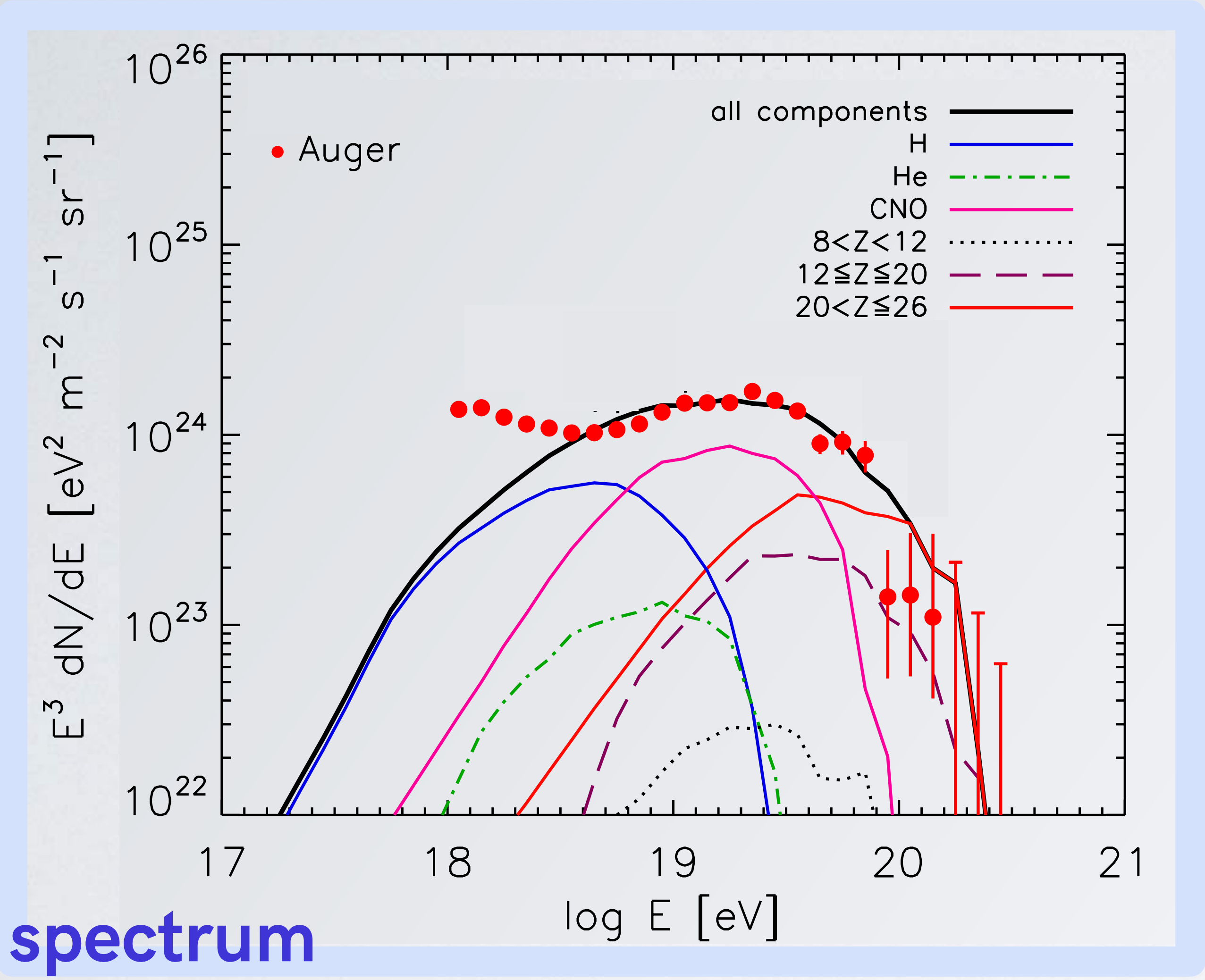
Bednarek & Protheroe (1997)
Link & Burgio (2006)
KK, Amato & Blasi (2015)

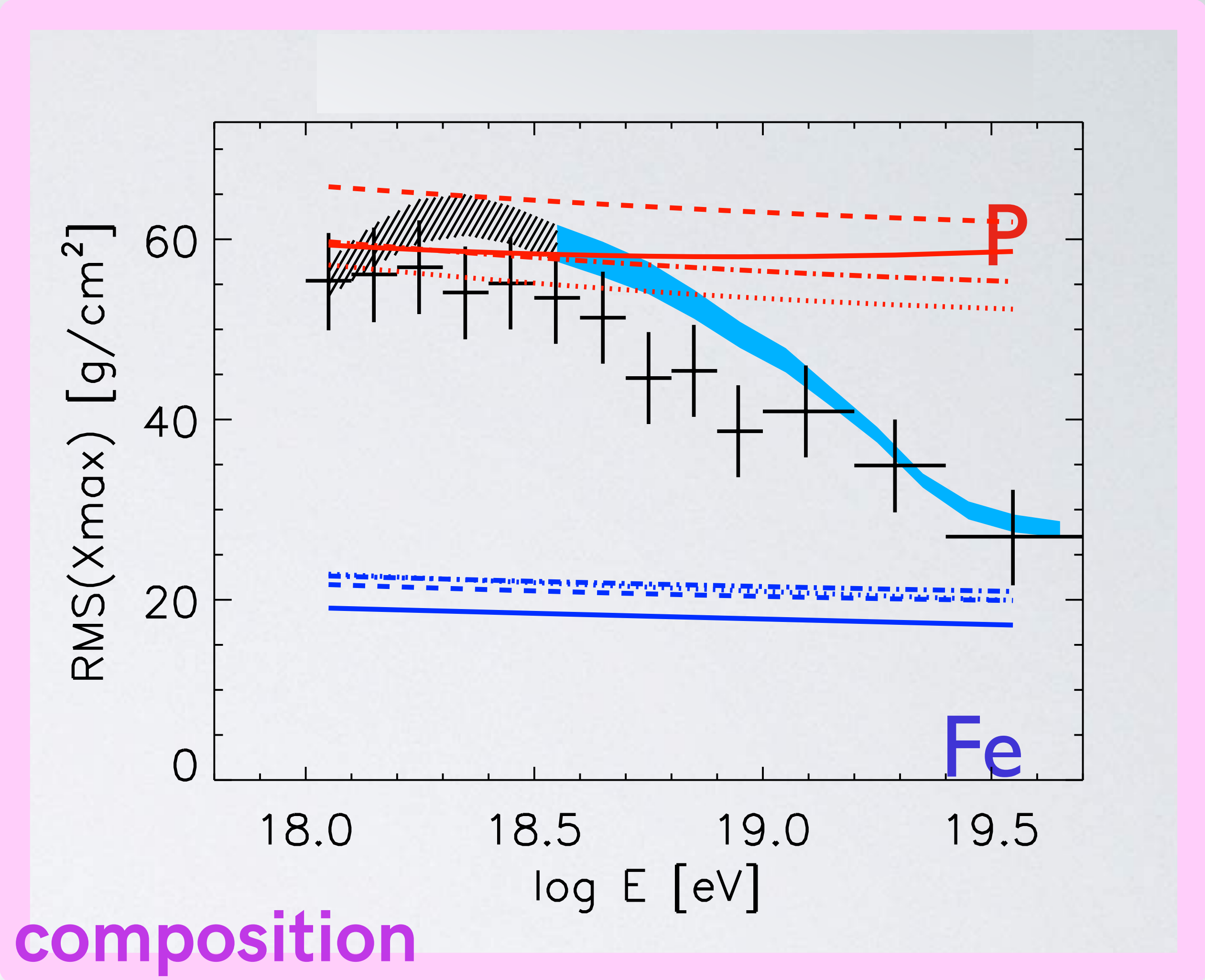


Properties of escaping UHECRs

Fang, KK, Olinto 2012
Fang, KK, Olinto, 2013
KK, Amato, Blasi 2015

after interaction on **supernova ejecta + propagation** in the intergalactic medium

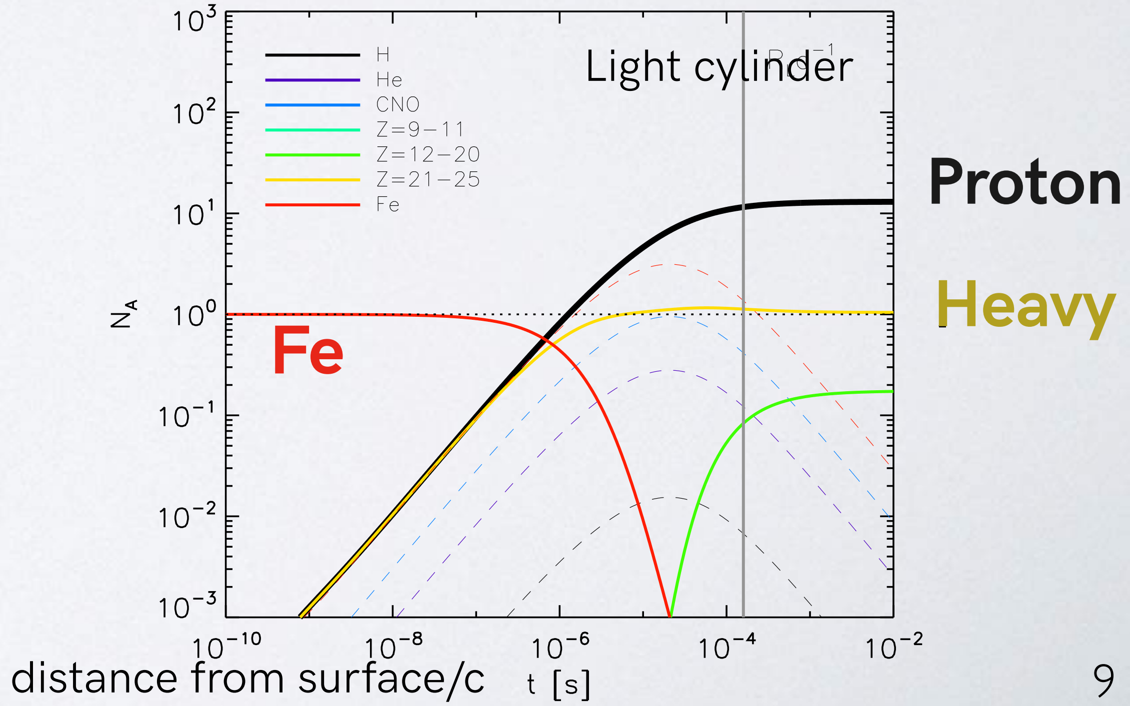




uniform source emissivity evolution
accelerated: 50%P, 30%CNO, 20%Fe

100% Fe @ injection

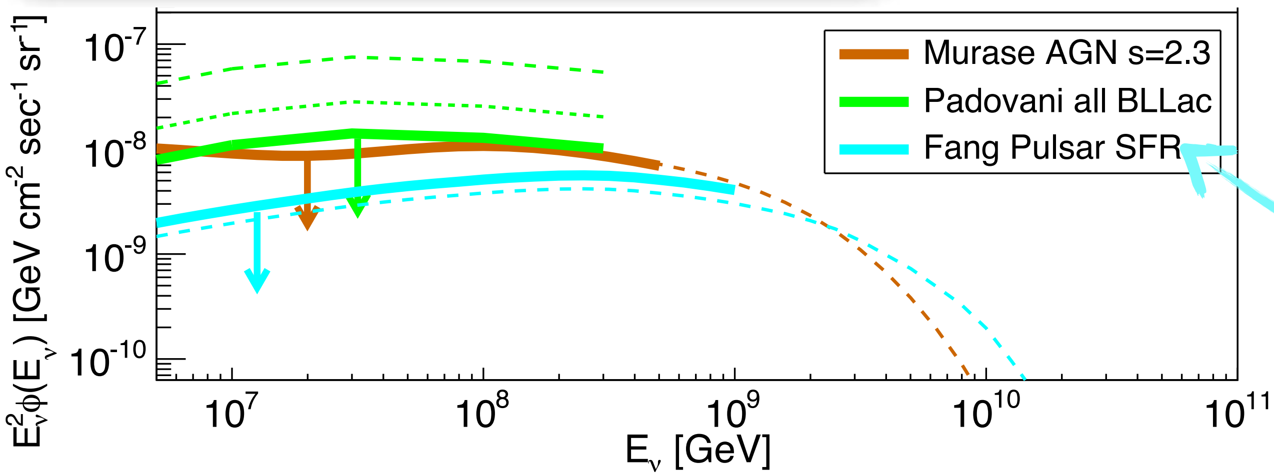
then interaction on neutron star thermal radiation can lead to right composition *KK, Amato, Blasi 2015*



IceCube constraints on pulsars as sources of HECRs

model dependent 90% C.L. limits

Aartsen et al. 2016



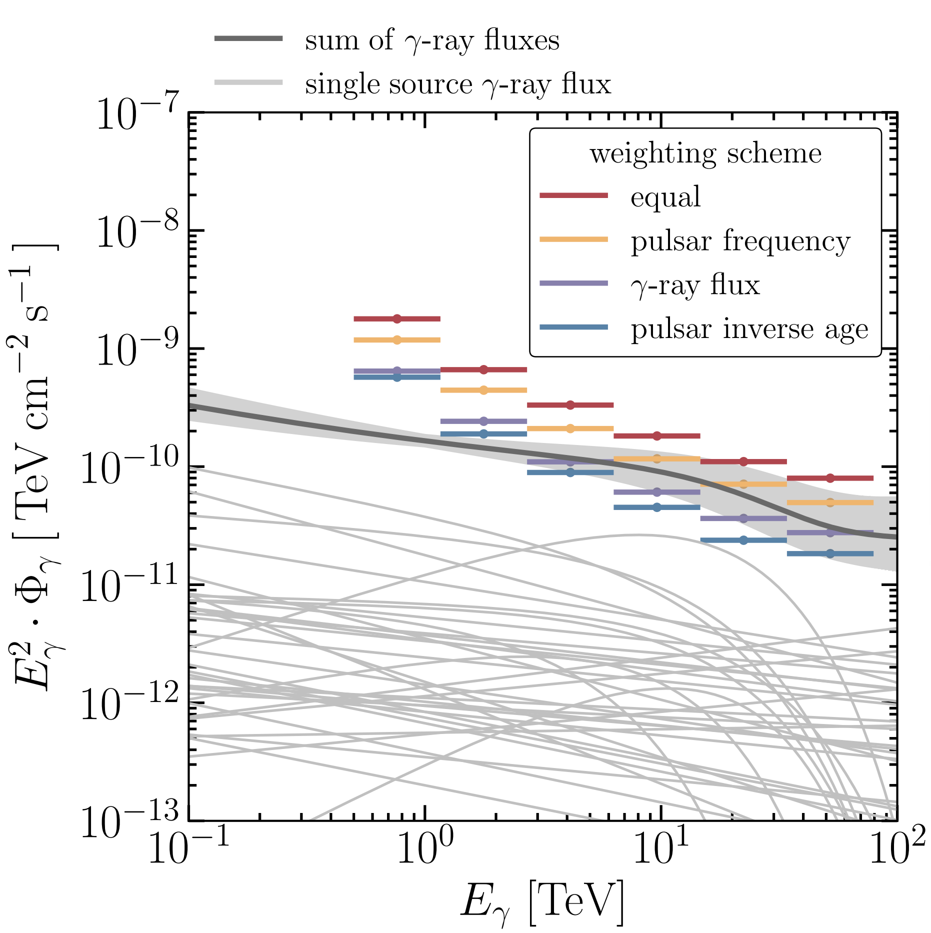
population of pulsars with realistic (P,B) distribution

ν Model	Event rate per livetime (Expected number of events in 2426 days of effective livetime)	p-value	MRF (Model Rejection Factor)
Murase *et al.* [45] $s = 2.3$, ξ_{CR}=100	$7.4^{+1.1}_{-1.8}$	$2.2^{+9.9}_{-1.4}$%	0.96 ($\xi_{CR} \leq 96$)
Murase *et al.* [45] $s = 2.0$, ξ_{CR}=3	$4.5^{+0.7}_{-0.9}$	$19.9^{+20.2}_{-9.2}$%	1.66 ($\xi_{CR} \leq 5.0$)
Fang *et al.* [48] SFR	$5.5^{+0.8}_{-1.1}$	$7.8^{+14.4}_{-3.7}$%	1.34
Fang *et al.* [48] uniform	$1.2^{+0.2}_{-0.2}$	$54.8^{+1.7}_{-2.7}$%	5.66
Padovani *et al.* [46] $Y_{\nu\gamma} = 0.8$	$37.8^{+5.6}_{-8.3}$	<0.1%	0.19 ($Y_{\nu\gamma} \leq 0.15$)

MRF = ratio of expected average upper limit to expected signal

Population of newborn pulsars as sources of UHECRs following star formation rate excluded at 90% C.L.

Fang, KK, Murase & Olinto 2013
Aartsen et al. 2016



No significant correlation between IceCube neutrinos and PWN locations

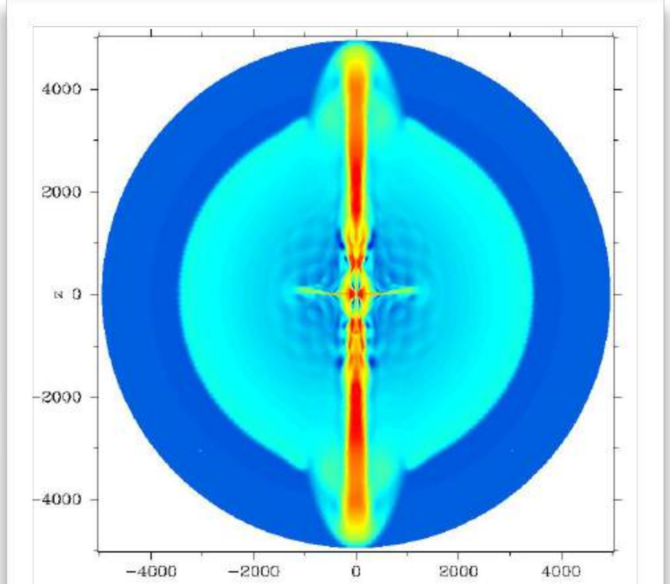
90% C.L. upper limits on hadronic gamma-ray emission from 35 stacked Pulsar Wind Nebulae

Aartsen et al. 2020

IceCube constraints on pulsars/magnetars as sources of UHECRs

Fang, KK, Murase & Olinto 2016
for magnetars: see also Murase et al. 2009

magnetar jet puncturing SN ejecta



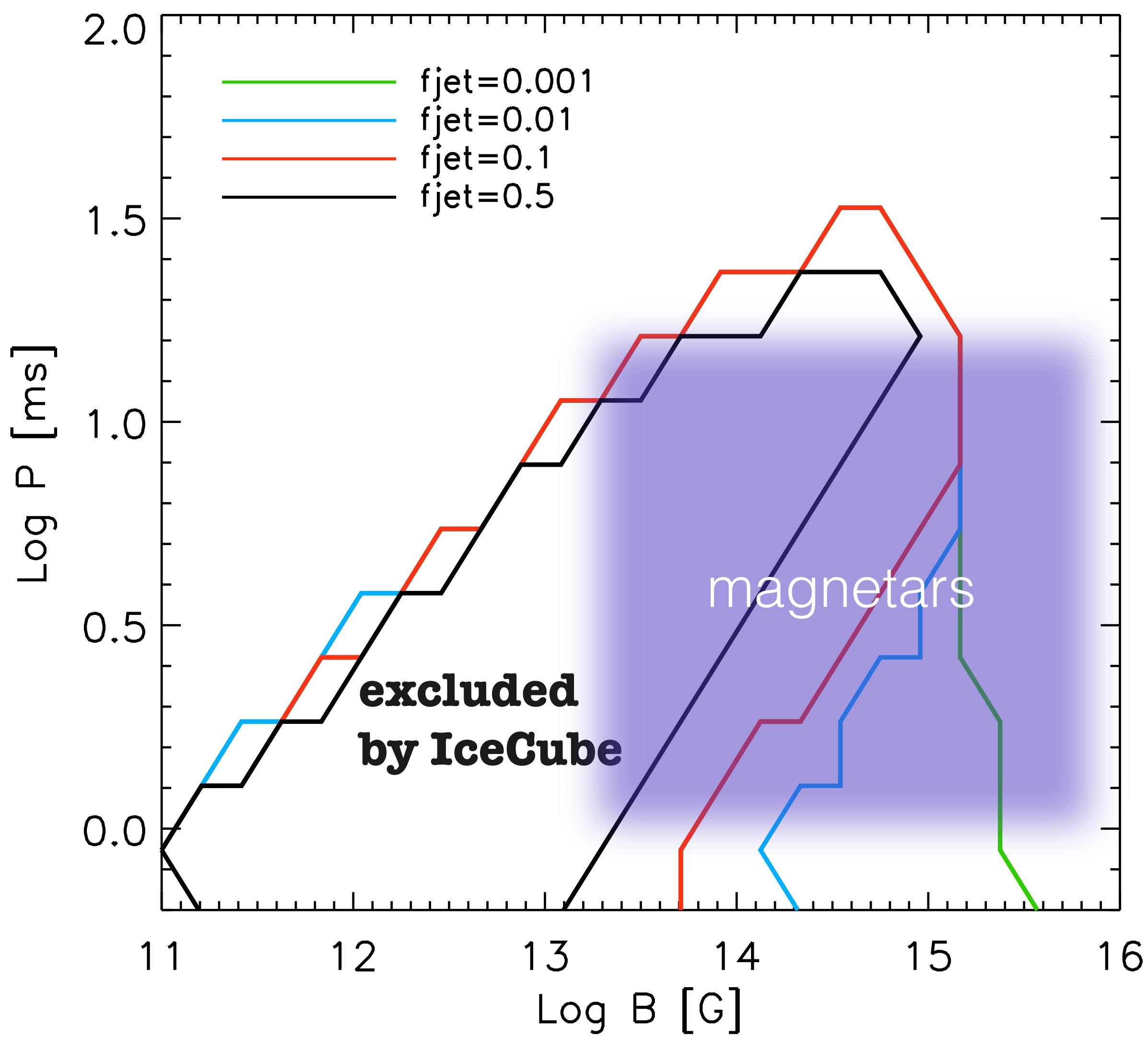
Komissarov & Barkov (2007)

f_{jet} = "jet fraction"

fraction of accelerated particles that can escape without crossing a dense environment

neutrino fluxes @ break energy,
if normalized to UHECR spectrum

population of neutron stars
with same characteristics (P,B)



magnetars not excluded if escape fraction > 10%
UHECR production and escape possible

Superluminous supernovae due to central pulsars

observable X-ray and gamma-ray emissions

KK, Phinney & Olinto 2013
Murase et al. 2015

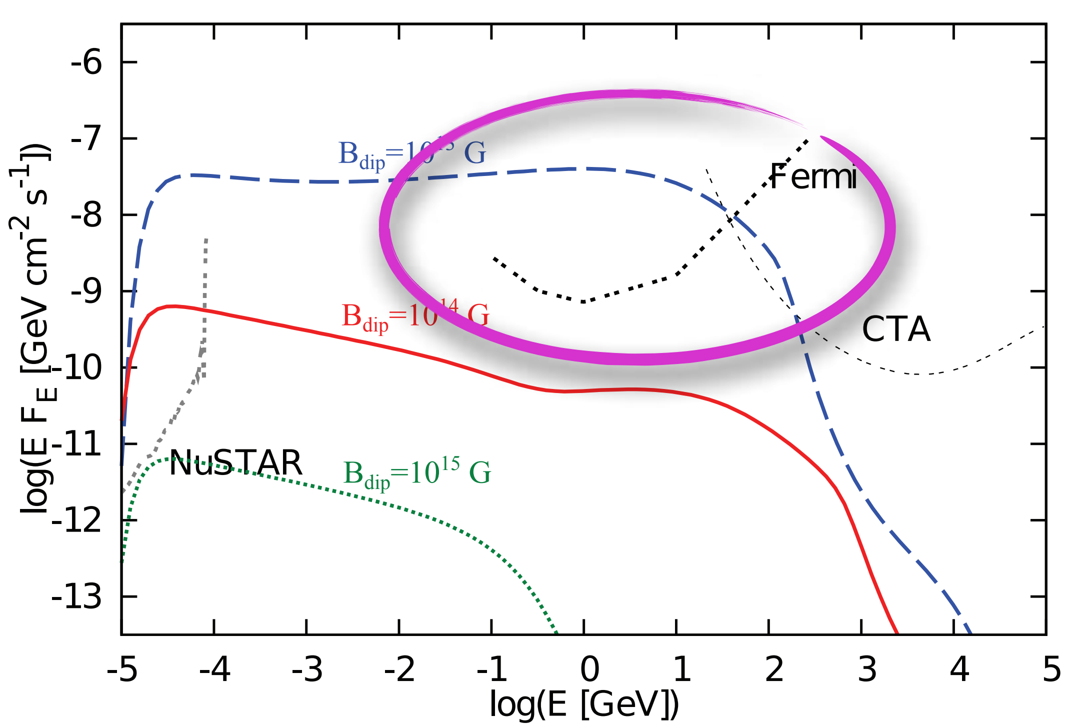
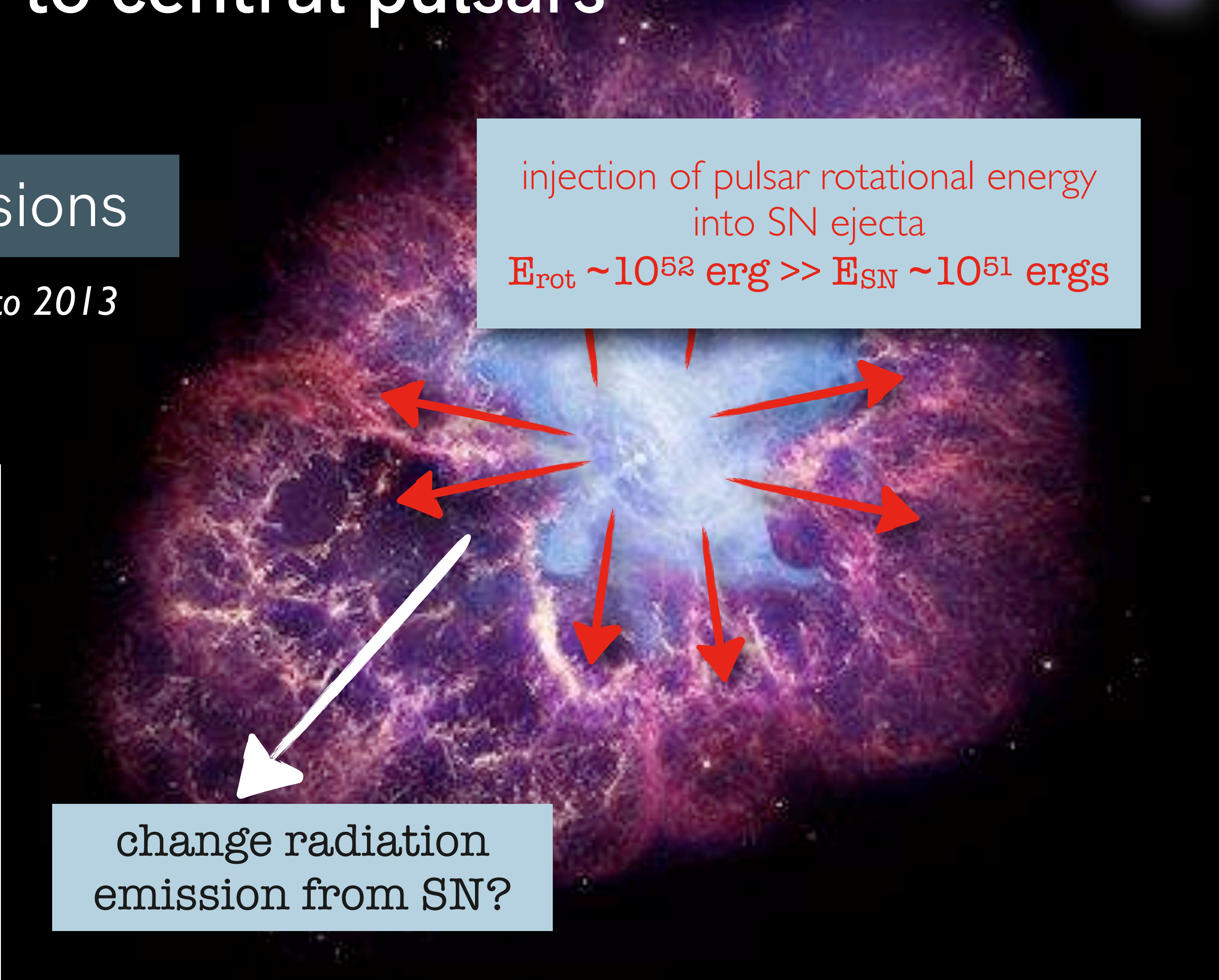


FIG. 7.— High-energy photon spectra of the early PWN embedded in the SN ejecta for $P_i = 2$ ms at $t = 10^{7.5}$ s $\simeq 316$ d. Different magnetic field strengths are considered. Detections with CTA are possible for $B_{\rm dip} = 10^{13}$ G.

Murase et al. 2015



systematic search with Fermi LAT @ location of SLSNe

strong constraints on central object *Renault-Tinacci, KK, et al. for the Fermi Coll., 2018*

Search for superluminous supernovae with Fermi-LAT

Renault-Tinacci, KK, Ando, Neronov,
for the Fermi Coll., 2018

sample of 39 SLSNe
Fermi Pass-8 data
3+1 and 7+1 bands in E: 0.6-600 GeV
4 different time windows

- Individual analysis

  only source detected above 3-sigma level: SN2011ke
  constraints on SLSNe luminosities: <~10^{44} erg/s

- Joint likelihood analysis (stacking)

- constraints on (P, B) of central object!

$$L_{\gamma,\epsilon} \sim \xi \beta_{\rm ej} \eta_e \frac{L_{\rm rot}}{4} \sim 6.0 \times 10^{42}\,{\rm erg\,s^{-1}}\,\xi\, P_{-3}^{-5} B_{13}^{2} R_6^6 I_{45}^{1/2} M_{\rm ej,5}^{-1/2}$$

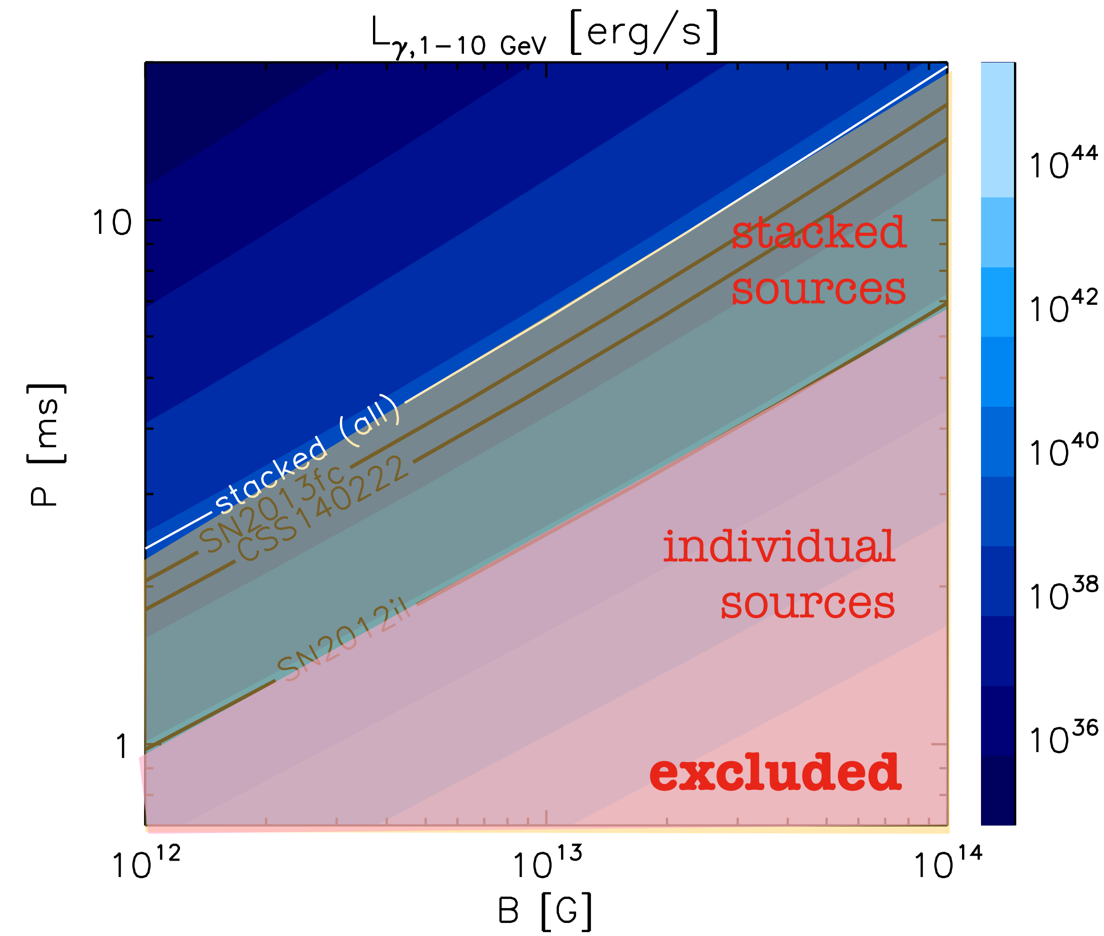


Table 4: Luminosities from joint likelihood analysis measurements with the 7+1 energy band set and all sources.

Time window	$\mathrm{Sig}_{0.6-600.0\,\mathrm{GeV}}$ σ units	$L_{0.6-10.2\,\mathrm{GeV}}$ erg s^{-1}	$L^{\mathrm{sum}}_{0.6-600.0\,\mathrm{GeV}}$ erg s^{-1}	$\mathrm{Sig}^{\mathrm{best\,bnd}}_{\mathrm{E1-E2}}$ σ units	E1 GeV	E2 GeV
$t_{\rm peak}$ to $t_{\rm peak}+3$ months	0.1	$< 2.0\times10^{39}$	$2.3\times10^{38}{}^{+2.0\times10^{39}}_{-1.8\times10^{38}}$	2.9	171.50	600.00
$t_{\rm peak}$ to $t_{\rm peak}+6$ months	0.0	$< 1.6\times10^{39}$	$2.5\times10^{38}{}^{+1.5\times10^{39}}_{-2.3\times10^{38}}$	2.8	171.50	600.00
$t_{\rm peak}$ to $t_{\rm peak}+1$ year	0.2	$< 7.2\times10^{38}$	$< 9.5\times10^{38}$	1.5	67.04	171.50
$t_{\rm peak}$ to $t_{\rm peak}+2$ years	0.0	$< 6.6\times10^{38}$	$1.2\times10^{38}{}^{+6.0\times10^{38}}_{-1.2\times10^{38}}$	3.8	67.04	171.50
SN off-peak period	1.6	$< 3.5\times10^{38}$	$9.6\times10^{37}{}^{+4.6\times10^{38}}_{-8.8\times10^{37}}$	2.2	26.21	67.04

Pulsars and the highest energy multi-messengers

What's your targeted physics in next decades?

More precise understanding of ion acceleration in neutron star magnetospheres

Pulsars and more multi-messengers:

Association with UHE neutrinos

Association with GW (if association with BNS: Fang & Metzger 2017)

Association with FRBs (e.g., Mottez & Zarka 2014, Decoene et al., arXiv:2012.00029)

What do we need to accomplish?

Dedicated PIC simulations (magnetosphere configs., emission mechanisms, escape…)

Detection of UHE neutrinos to probe directly UHECR acceleration:
UHE neutrino detectors (GRAND, PUEO, RNO, …)

Efficient transient multi-messenger network (e.g., AMON)