Modeling Pulsar Broadband Emission

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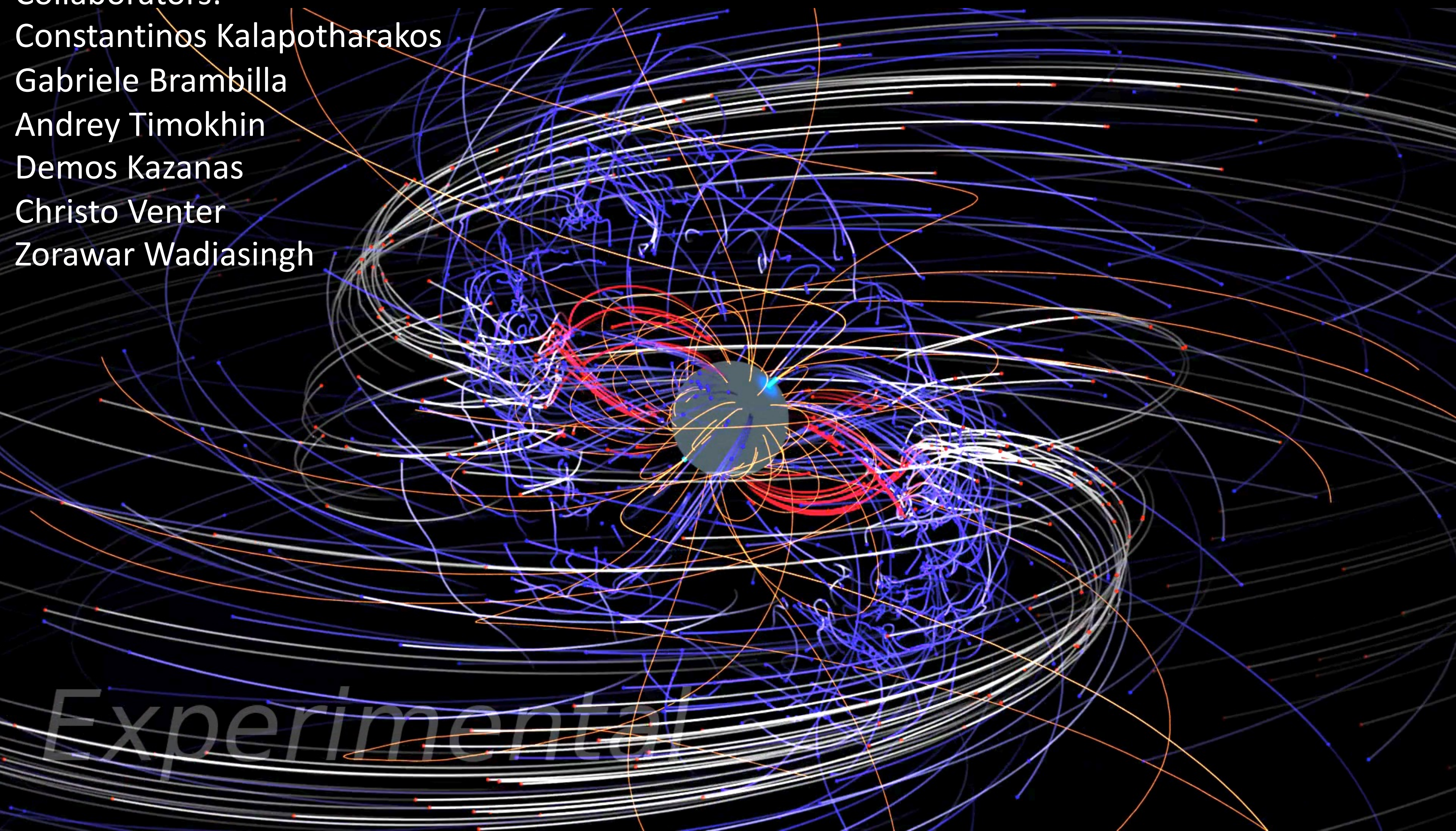
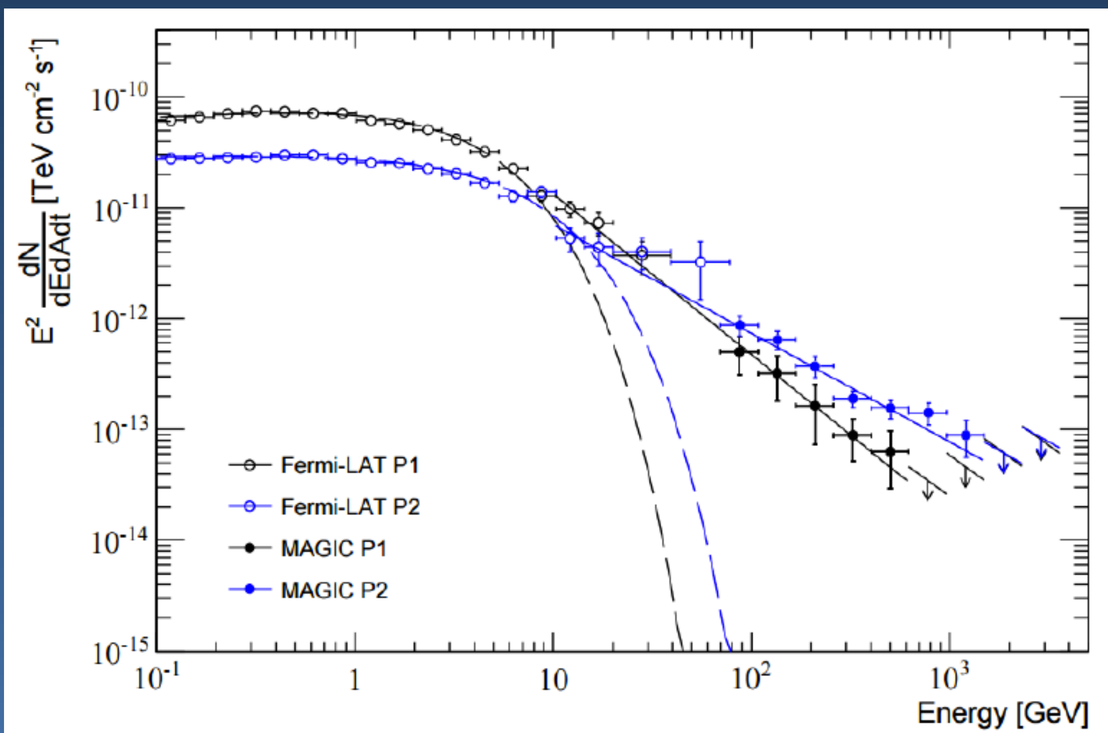


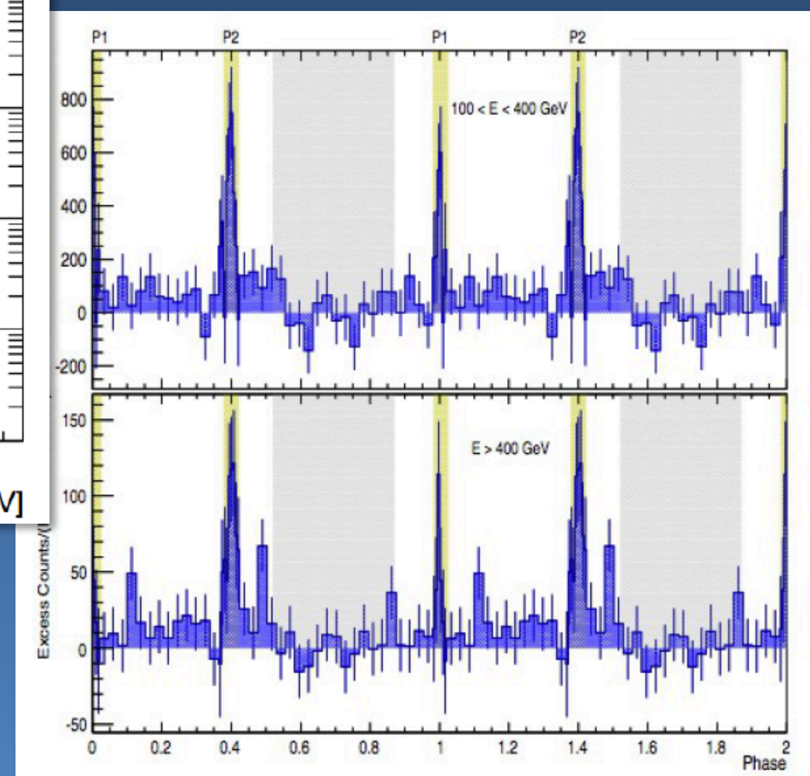
Detection of Crab pulsar up to 1 TeV

MAGIC - Aliu et al. 2008, 2011
Veritas - Aleksic et al. 2011

MAGIC 40 GeV – 1 TeV (Ansoldi et al. 2016)

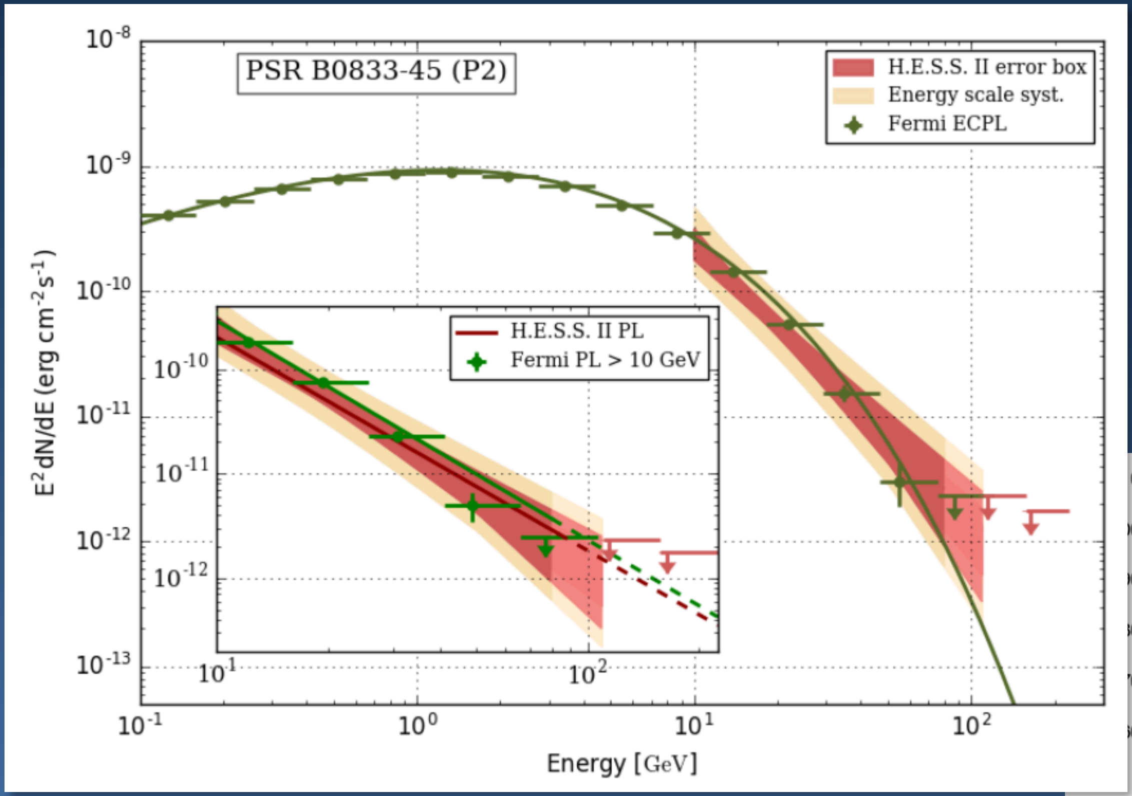


Both peaks detected!



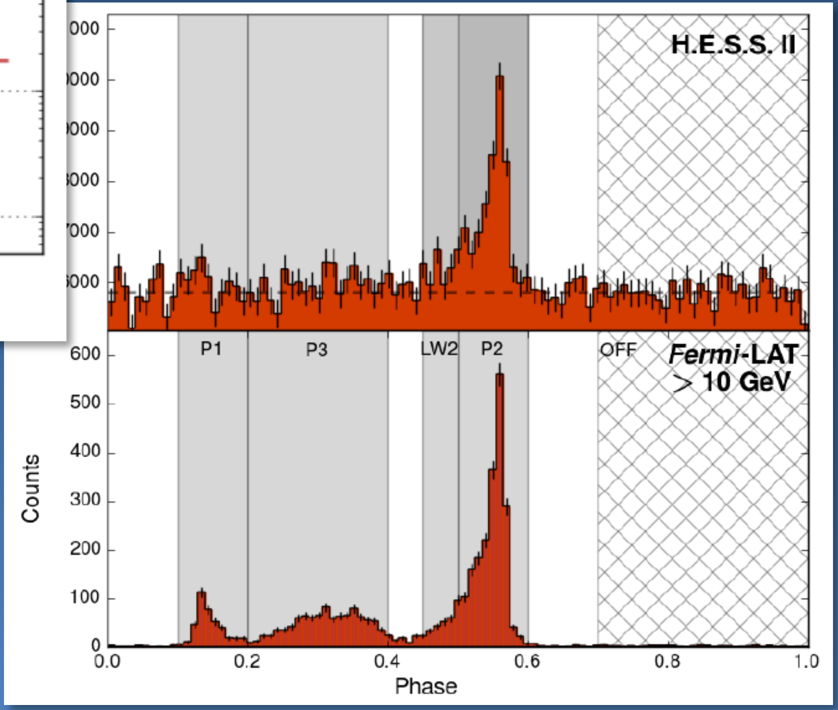
Vela pulsar – HESS II

10 – 100 GeV (Abdalla et al. 2018)



Continuation of Fermi spectrum (curved sub-exponential) or power law?

Curvature favored by HESS II at > 3.0σ

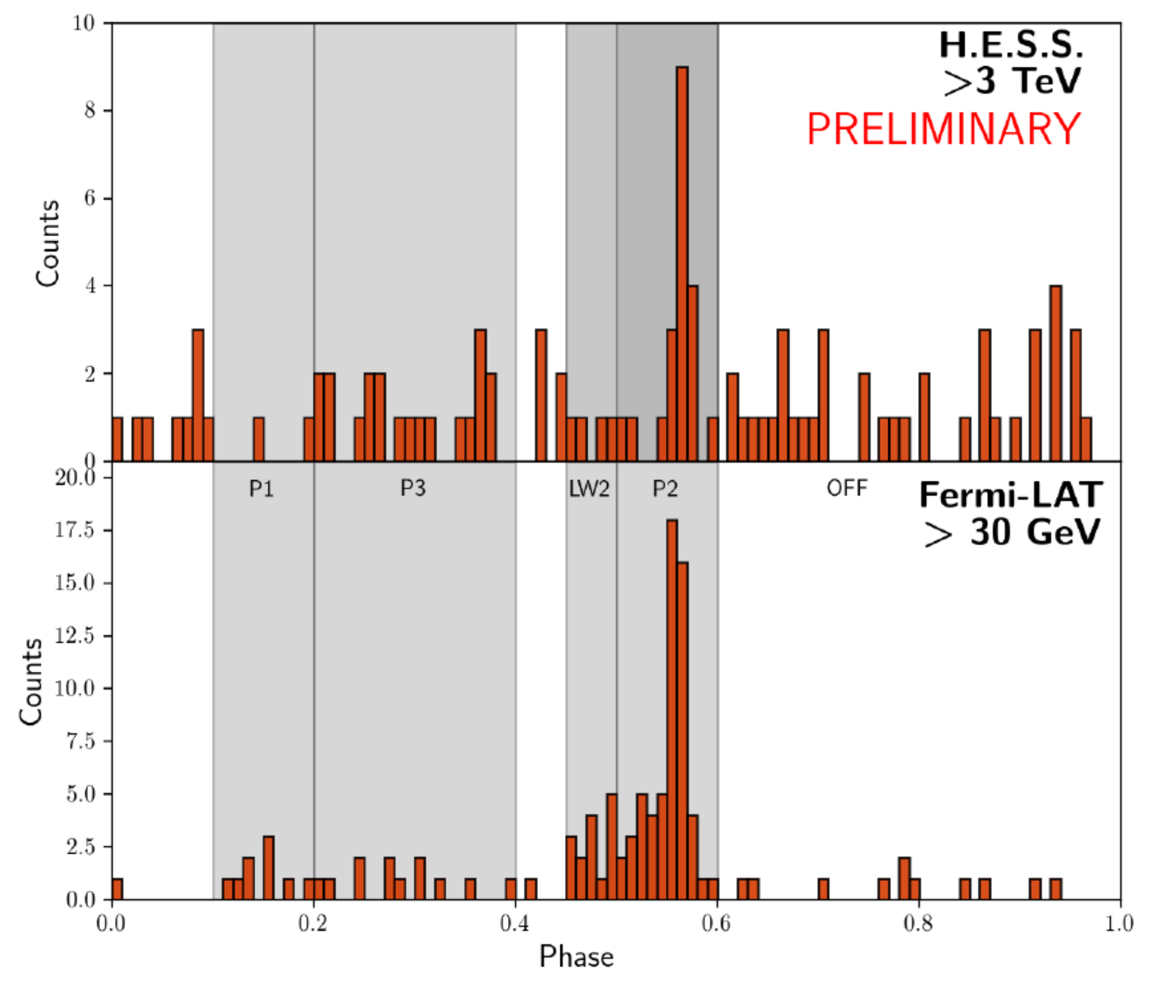


Fundamental difference with Crab – VHE emission only seen in peak 2

Vela pulsar – HESS II

2004 – 2016: 60 hours in stereoscopic mode

3 - > 7 TeV!! 5.6σ (Djannati-Atai 2018)   20 TeV!? (Rudak 2018)

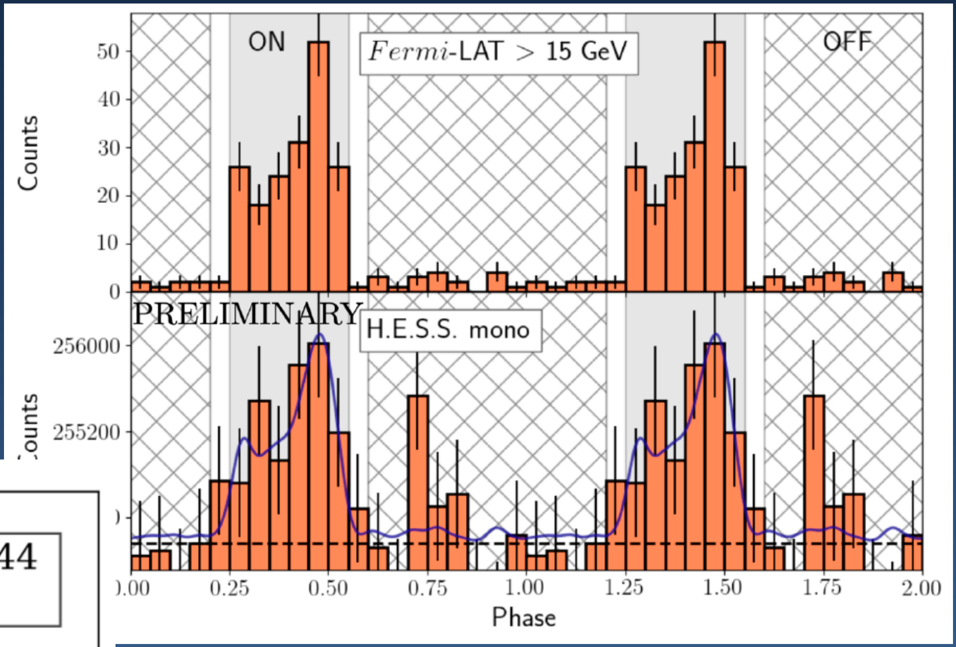


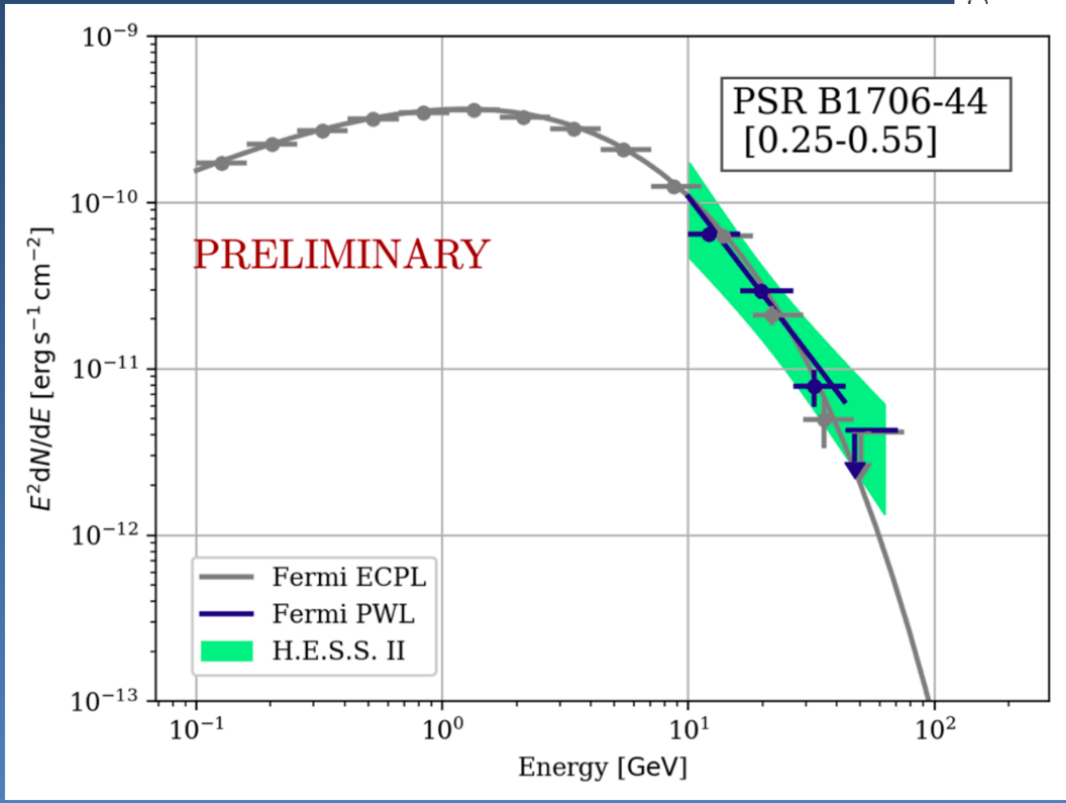
Additional component distinct from GeV spectrum?

B1706-44 - HESSII

Spir-Jacob et al. 2019

10 – 70 GeV

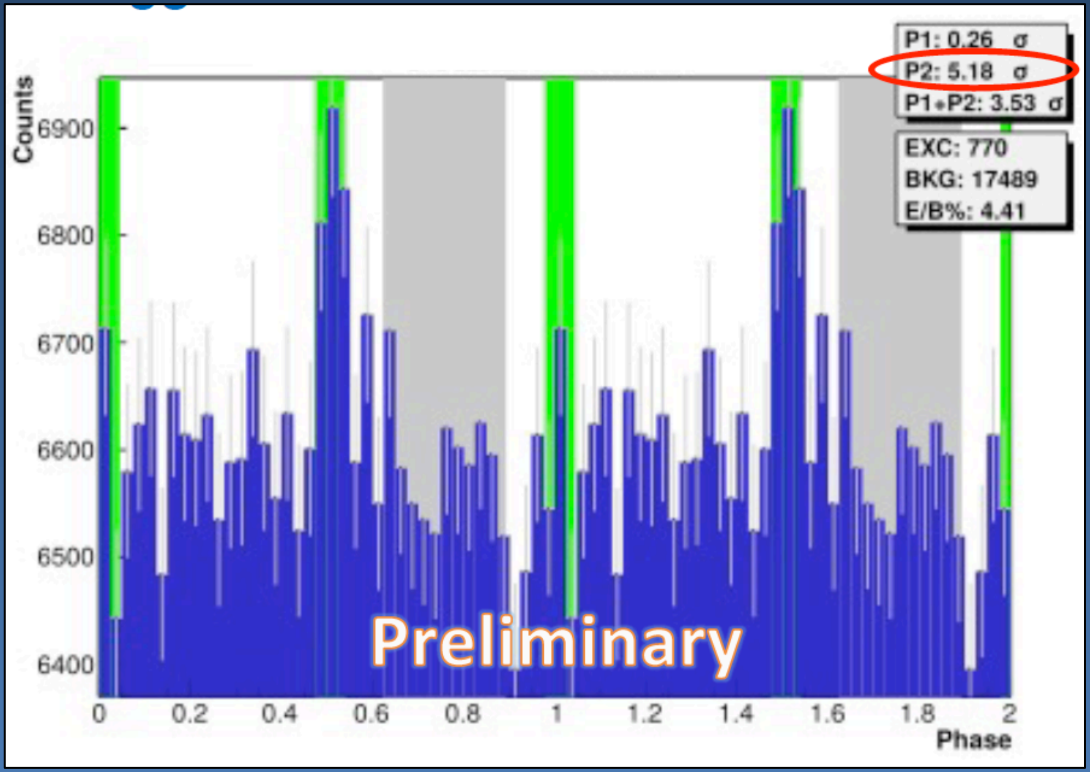




Geminga - MAGIC

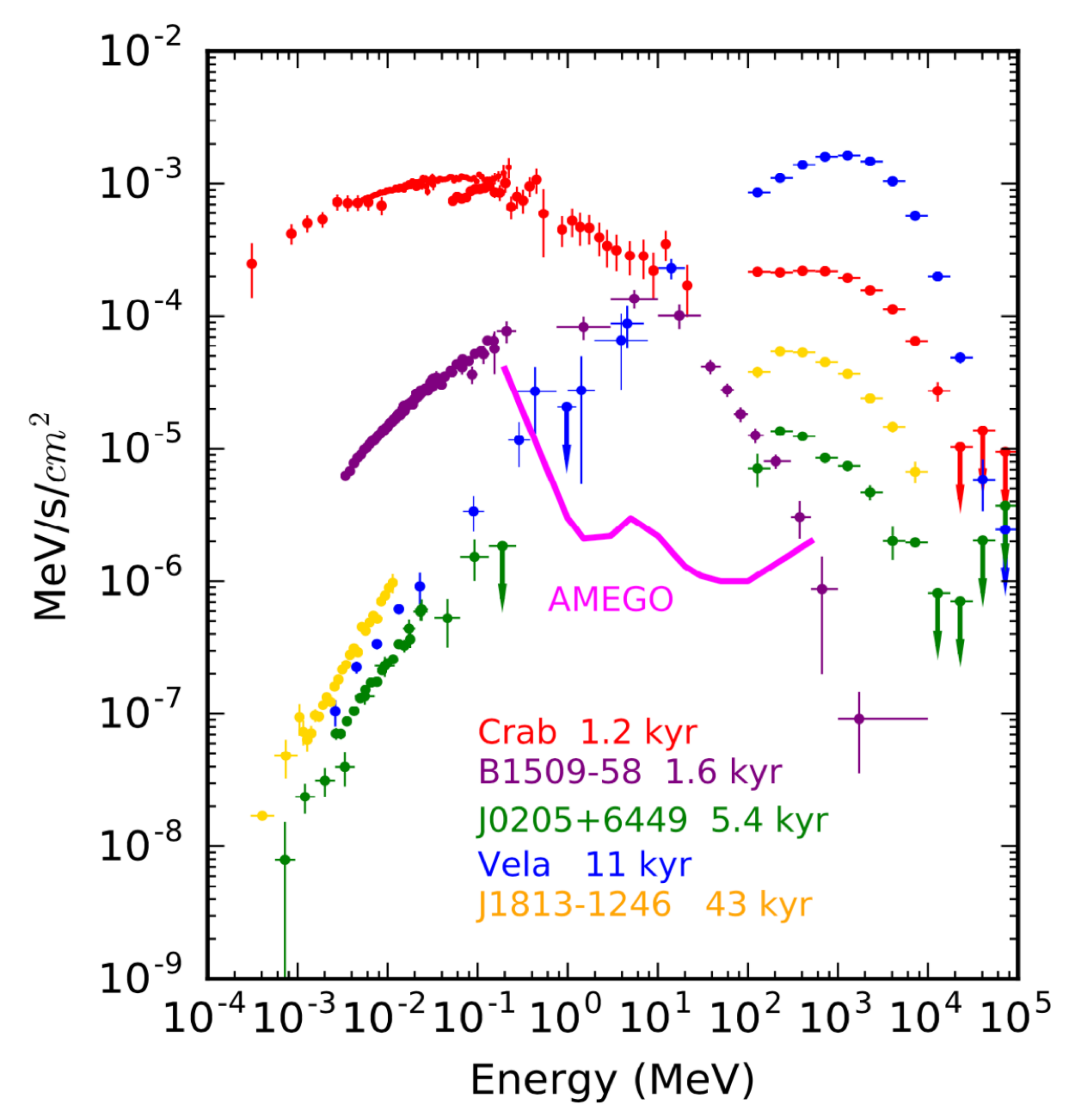
Lopez et al. 2019

P2 > 30 GeV



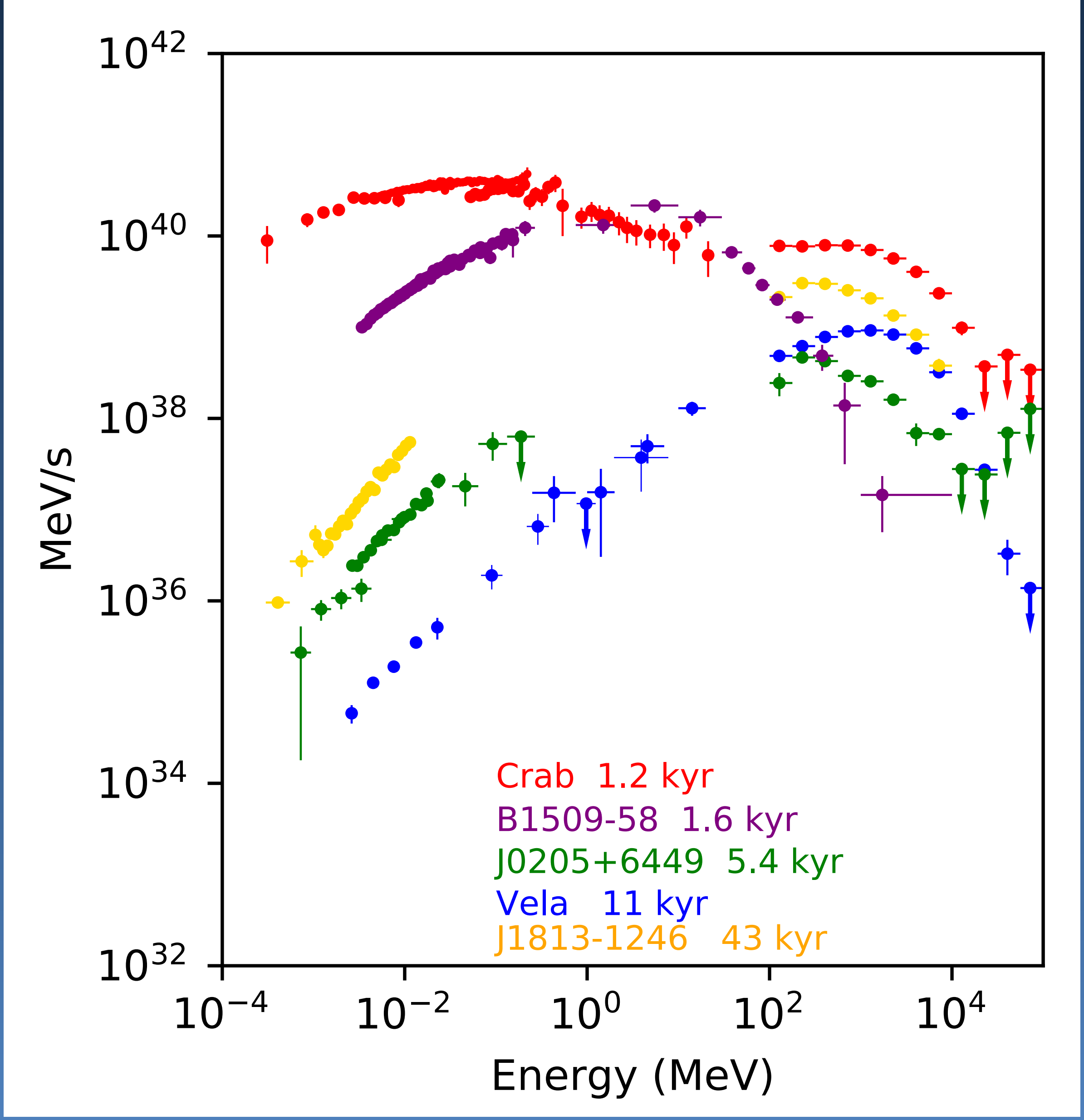
Broadband spectra of young pulsars

Data from Kuiper & Hermsen 2015



- No correlation between GeV and X-ray emission flux
- Younger pulsars have higher X-ray flux relative to GeV flux

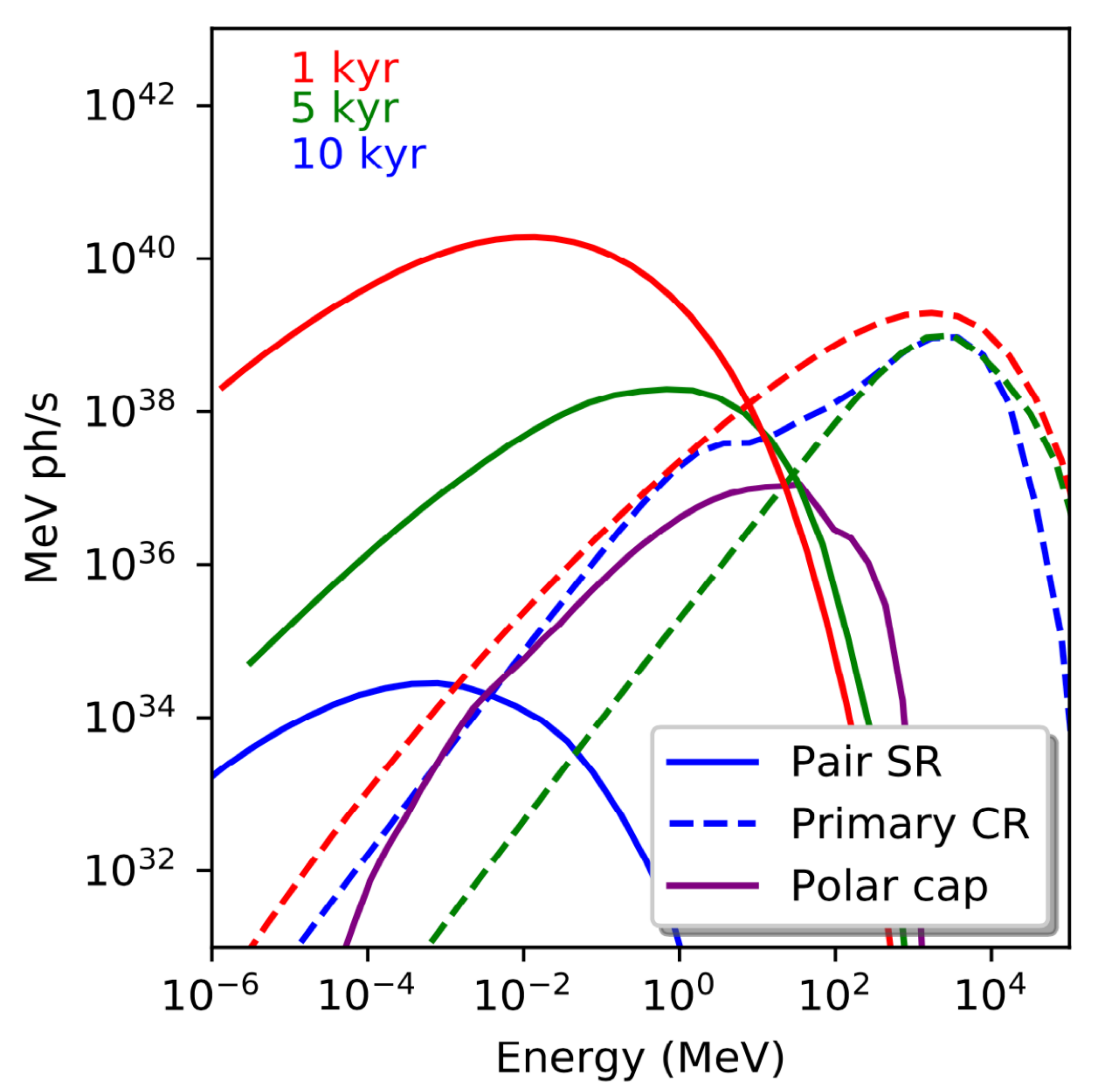
Broadband spectra of young pulsars



- Less than 2 decades spread in GeV luminosity
- More than 5 decades spread in X-ray luminosity

Spectral models for young pulsars

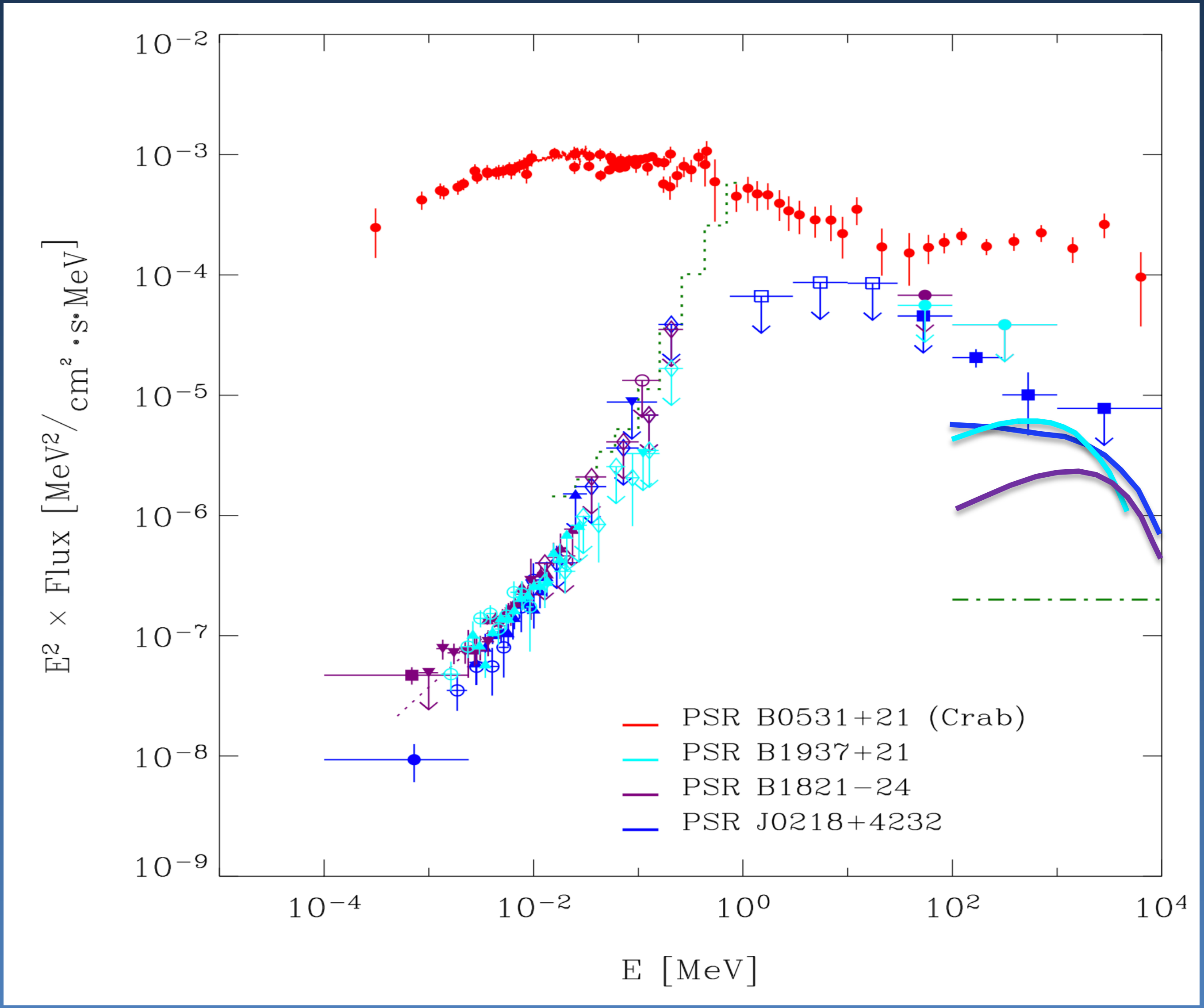
Harding et al. 2019



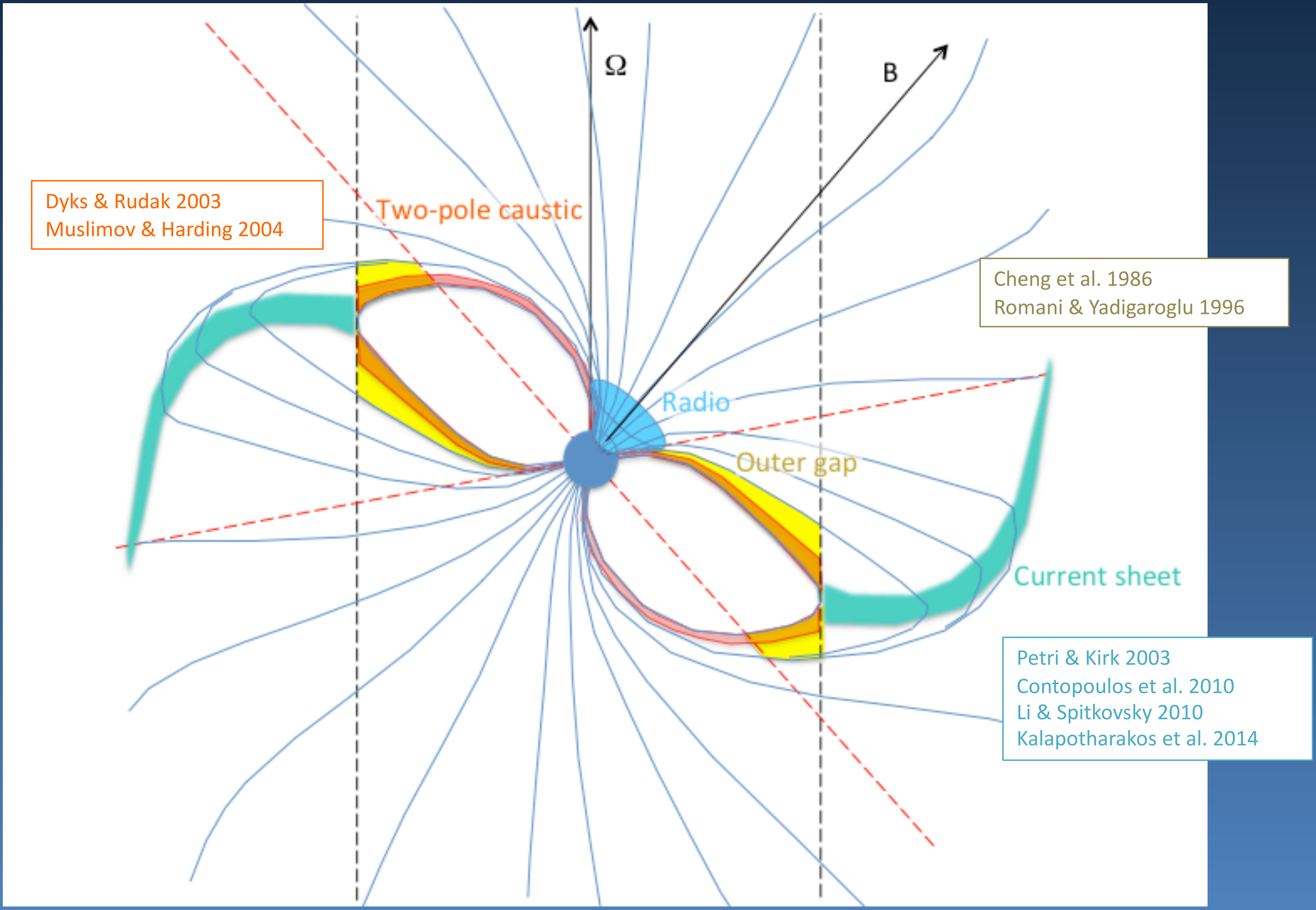
- Much less spread in GeV than in X-ray emission with age
- X-ray emission possibly correlated with pair multiplicity and B_{LC}

Broadband spectra of millisecond pulsars

Kuiper et al. 2003

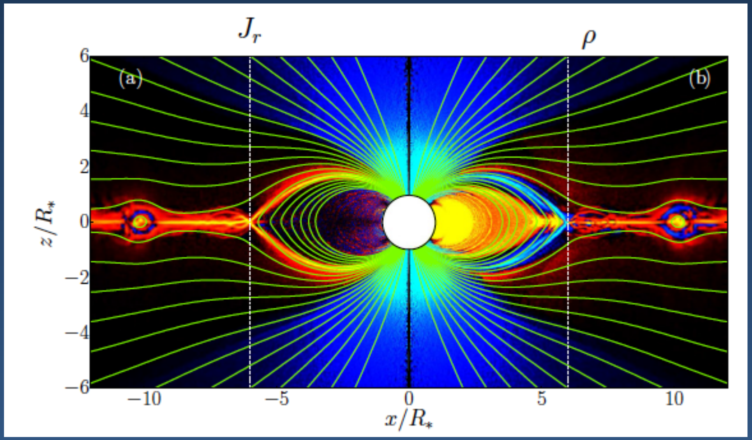


High-energy emission models

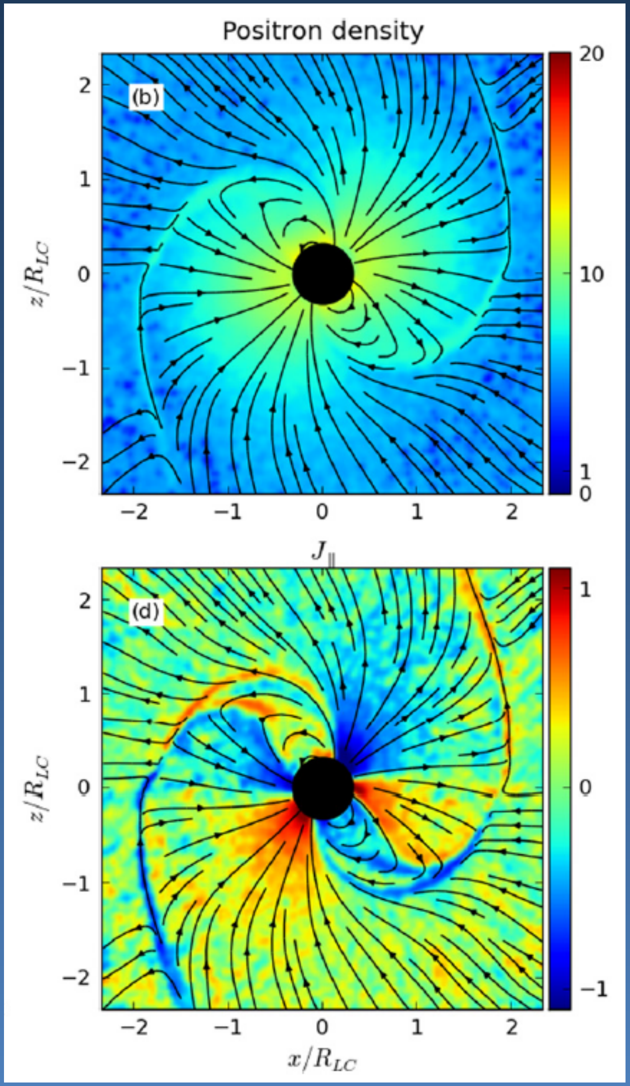


Particle-in-cell simulations

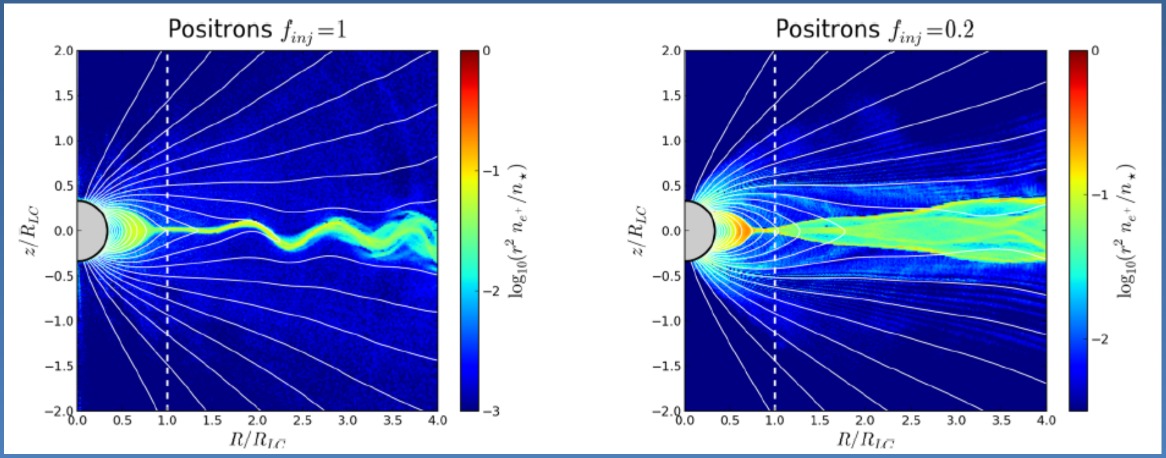
Aligned rotator - Chen & Beloborodov 2014



Oblique rotator - Philippov et al. 2015



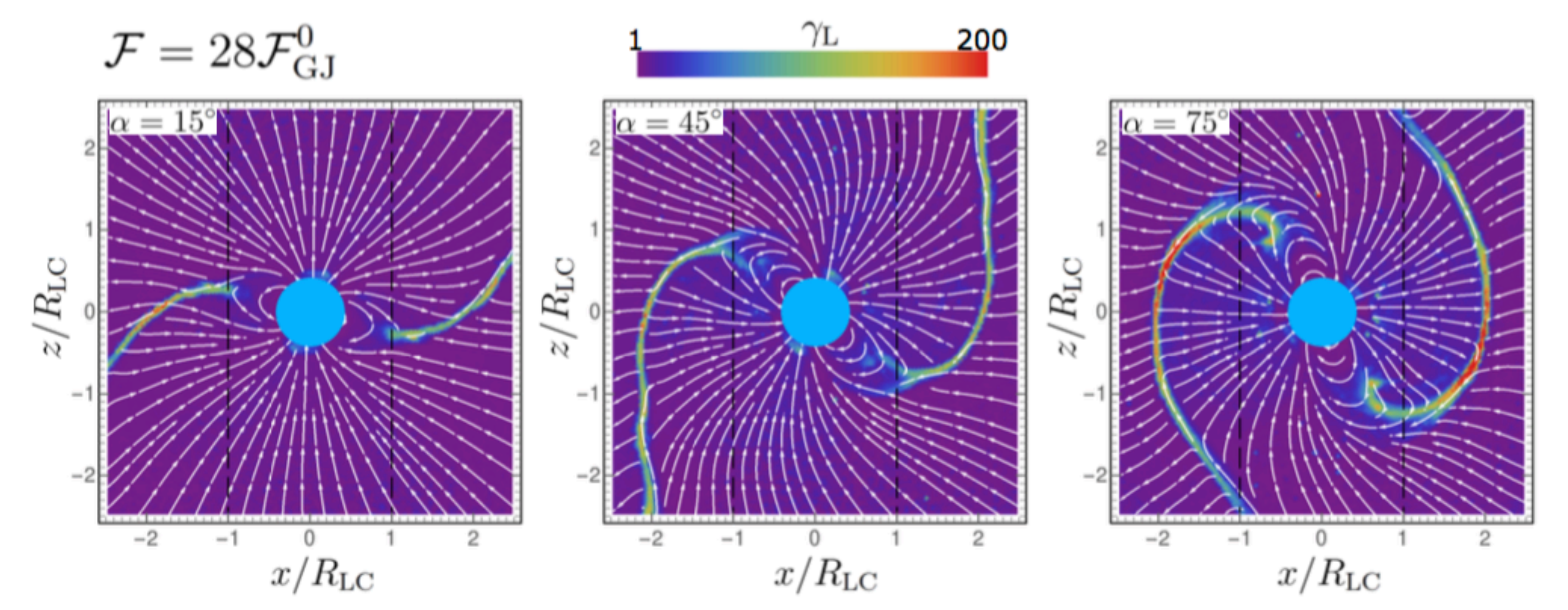
Cerutti et al. 2015



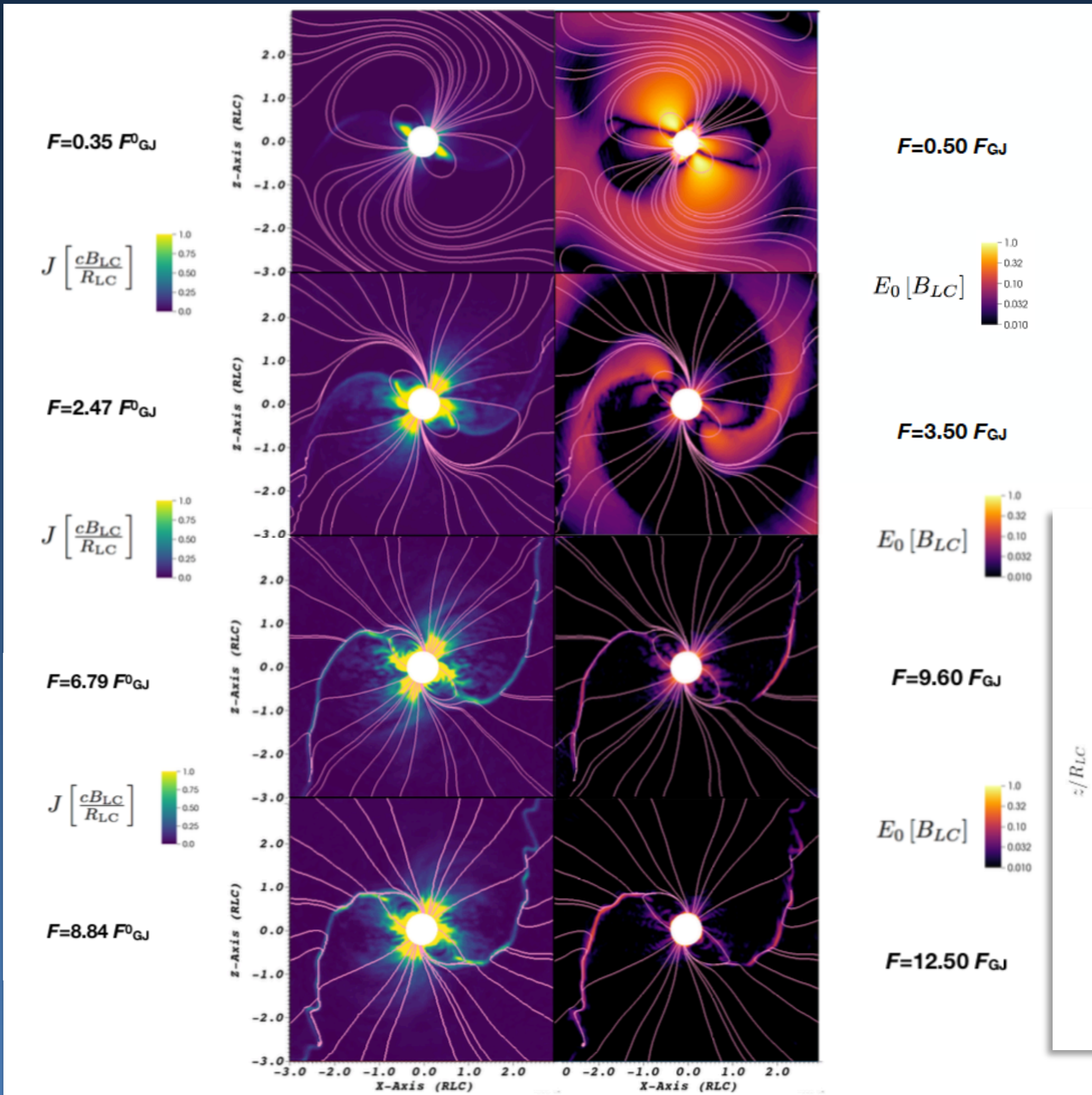
PIC models - acceleration

Global particle-in-cell simulations (Kalapotharakos+ 2018)

Most particle acceleration occurs in and near the current sheet and separatrices

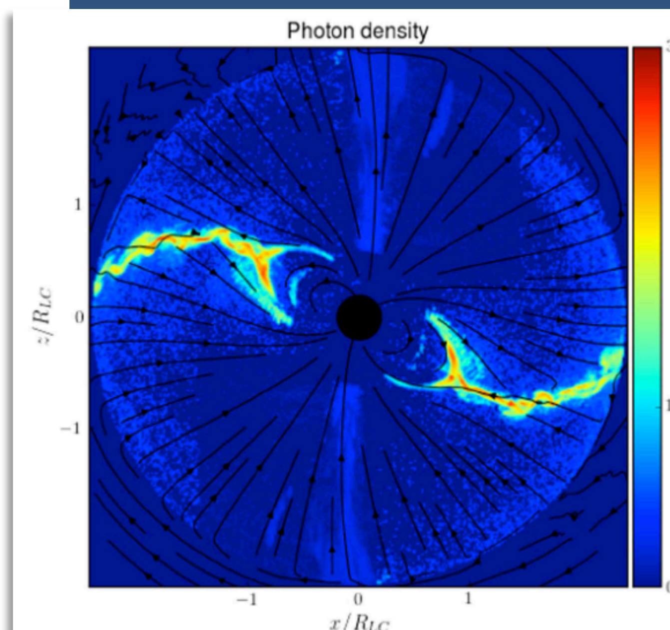


Current and E_0 with injection rate



Brambilla et al. 2018

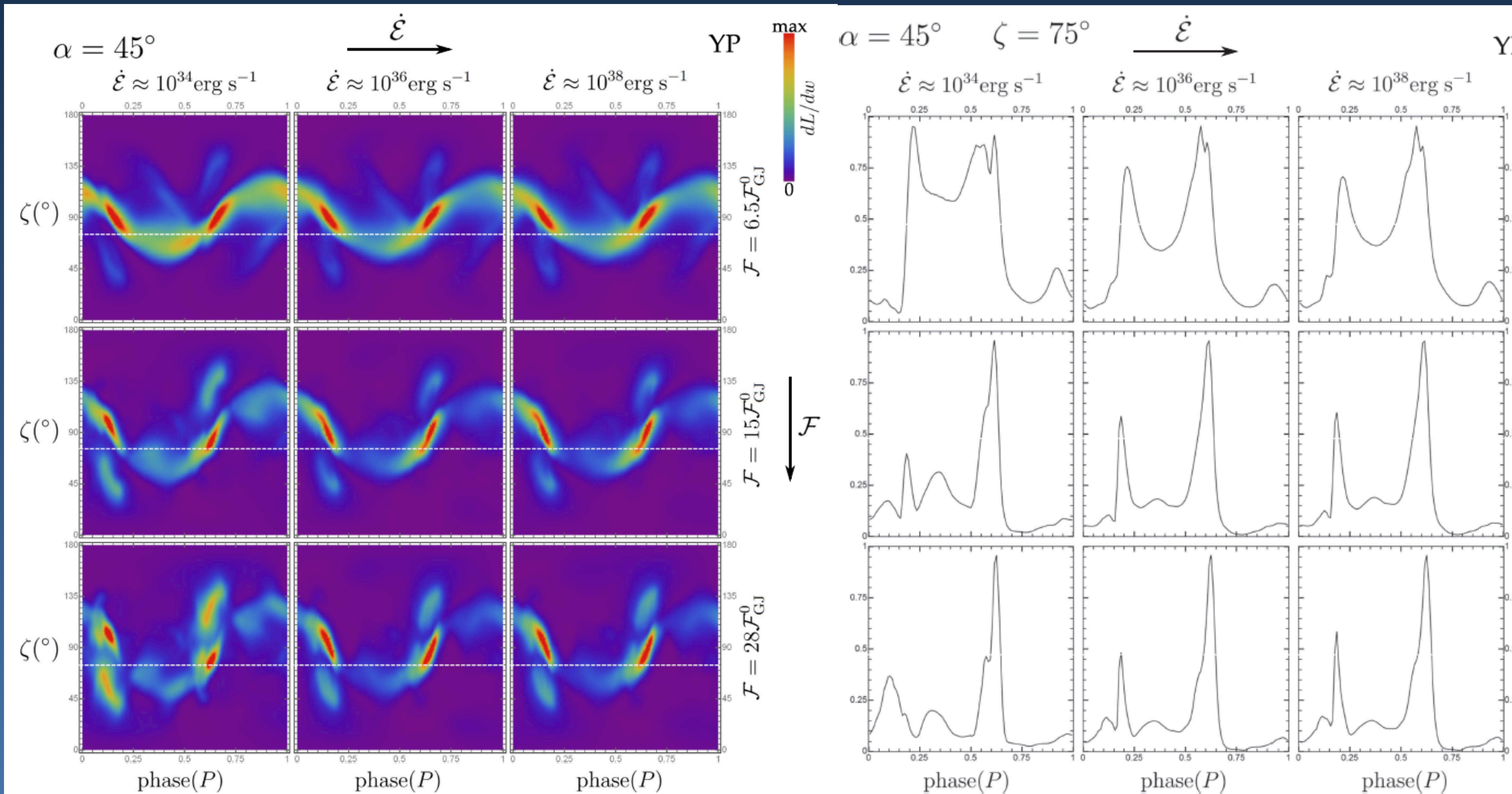
As pair injection rate increases – region of accelerating electric field shrinks to current sheet



Philippov & Spitkovsky 2018

High energy light curves

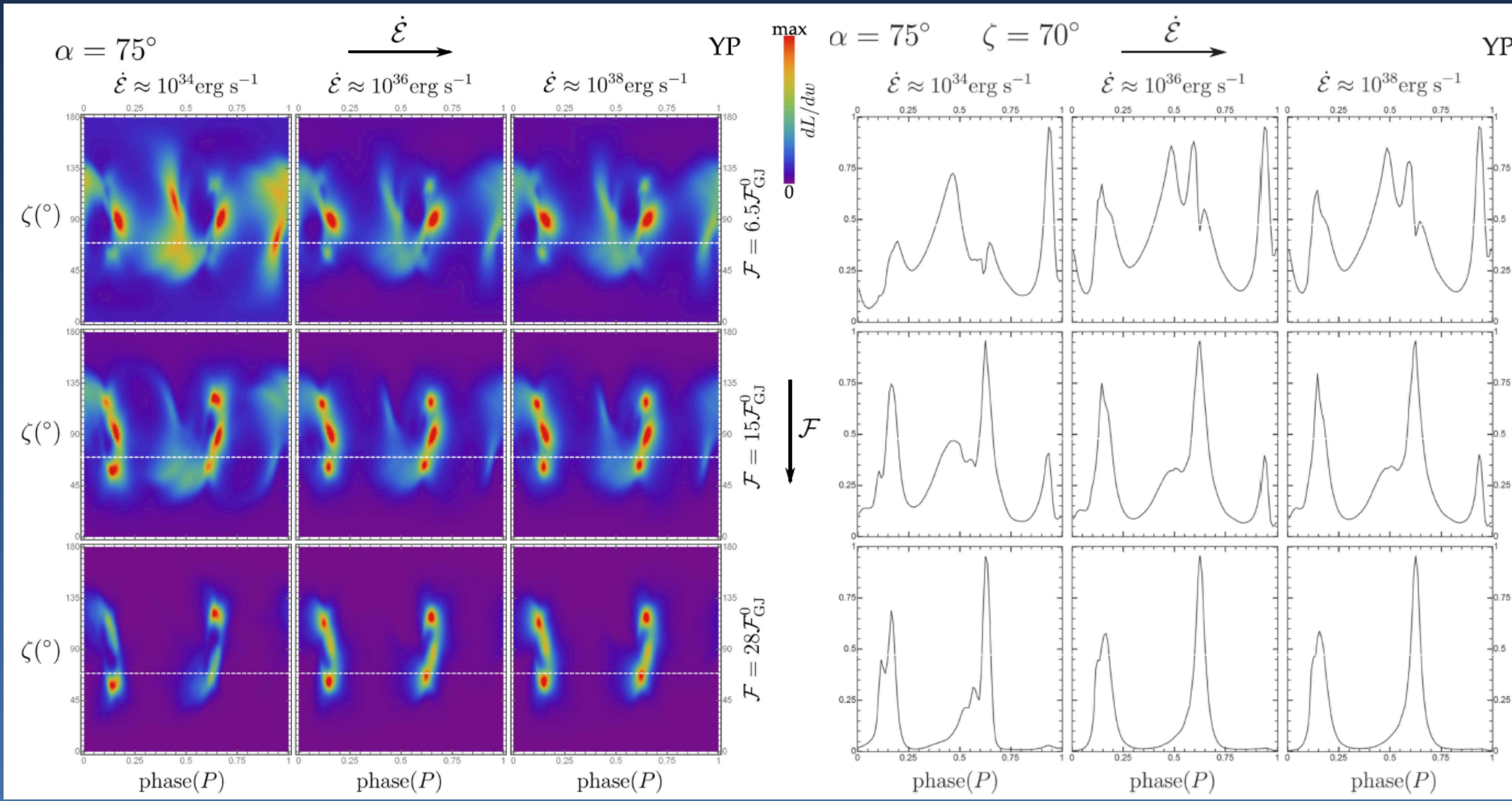
Kalapotharakos et al. 2018



B field – and resulting particle energies – scaled up to realistic pulsar fields

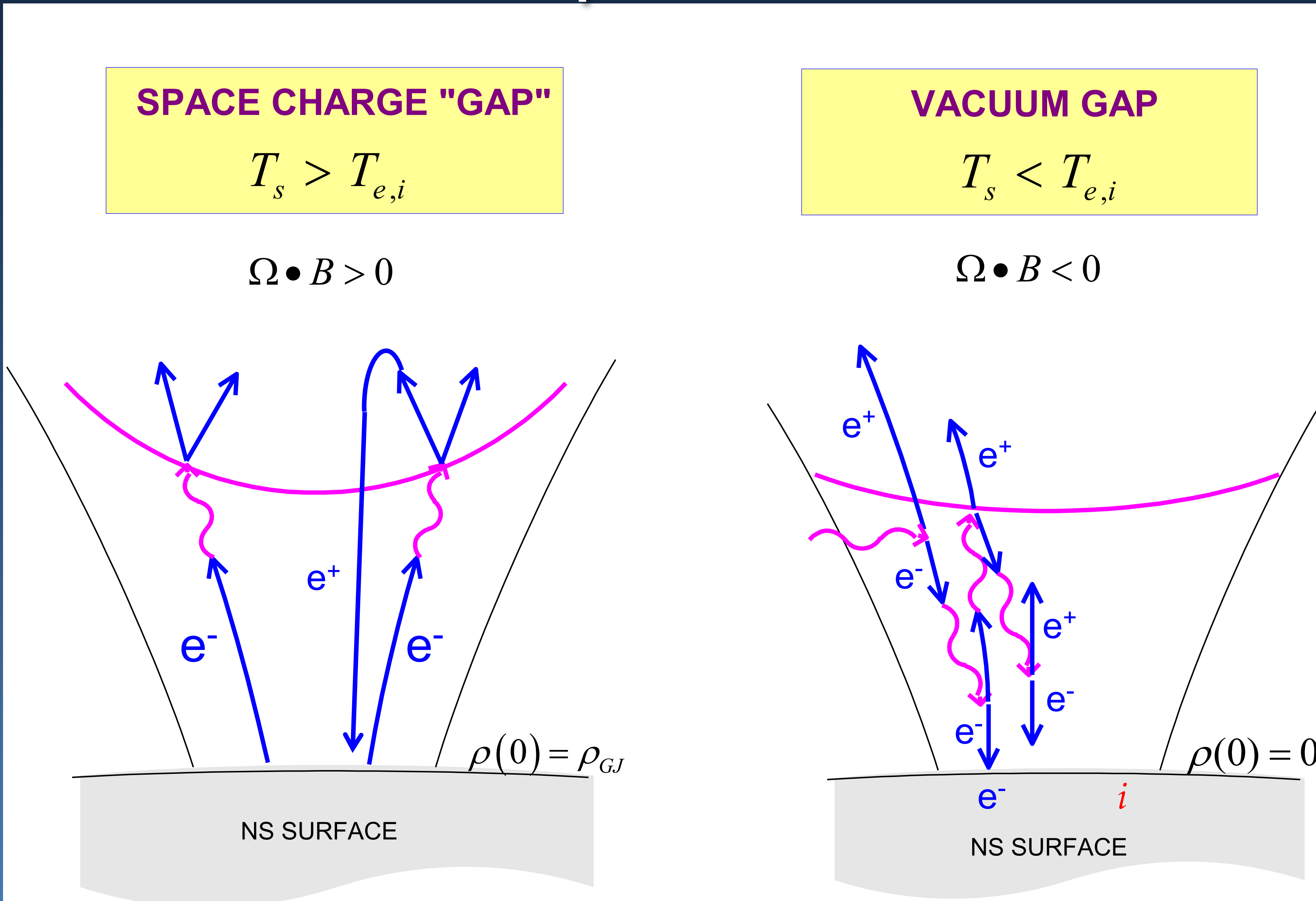
High energy light curves

Kalapotharakos et al. 2018



Fermi pulsars have high pair injection near force-free magnetosphere

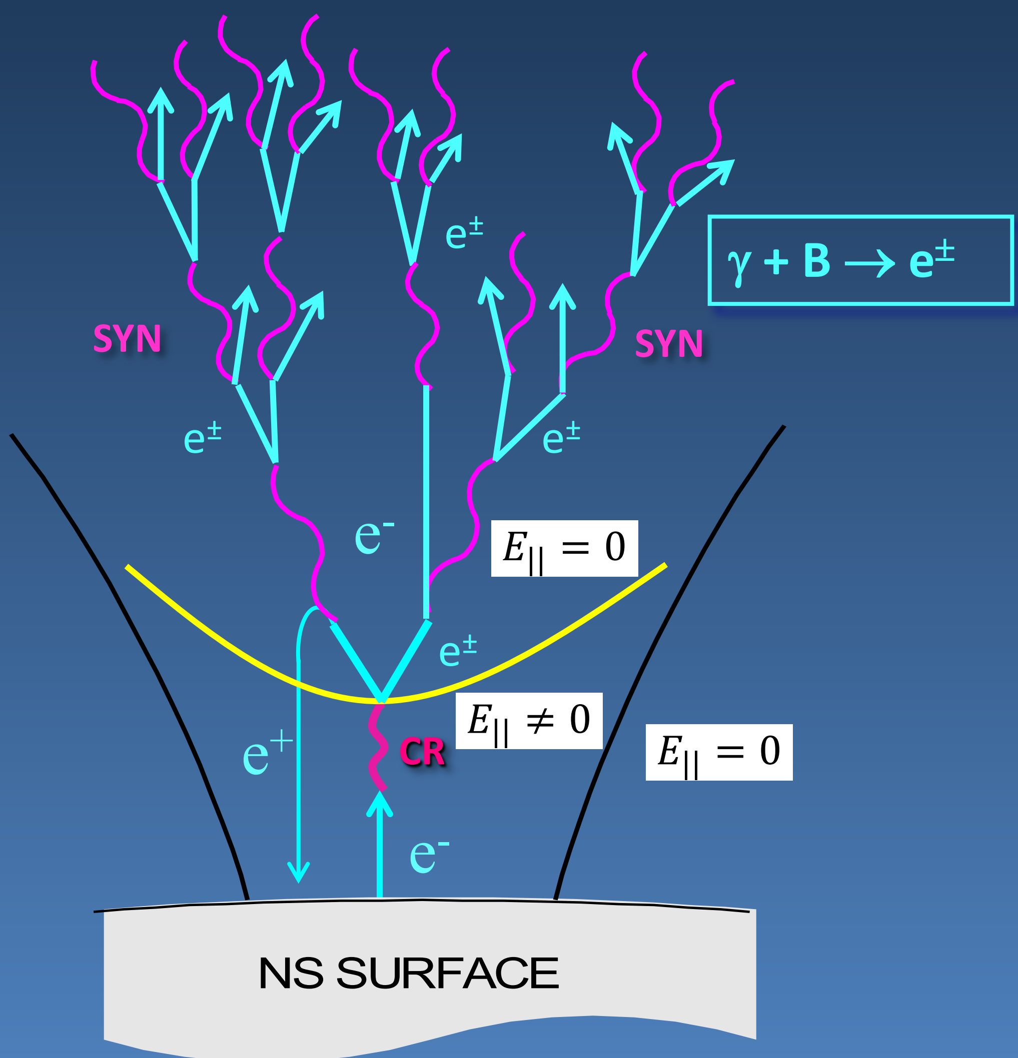
Polar cap accelerators



$$\nabla \cdot E = -4\pi(\rho - \rho_{GJ})$$

$$\nabla \cdot E = 4\pi\rho_{GJ}$$

Polar cap pair cascades



Pair cascades above the PC are necessary for coherent radio emission

Cascades are time-varying

Timokhin 2010, Timokhin & Arons 2013

Pair cascades produce an abundance of charged particles to supply charges to magnetosphere

$$M_{\pm} \sim 10^3 - 3\times10^5$$

Timokhin & Harding 2015

Pairs from polar cap cascades

Timokhin & Arons 2013

Sub-Goldreich-Julian currents – $0 < J/J_{GJ} < 1$

NO pair cascades

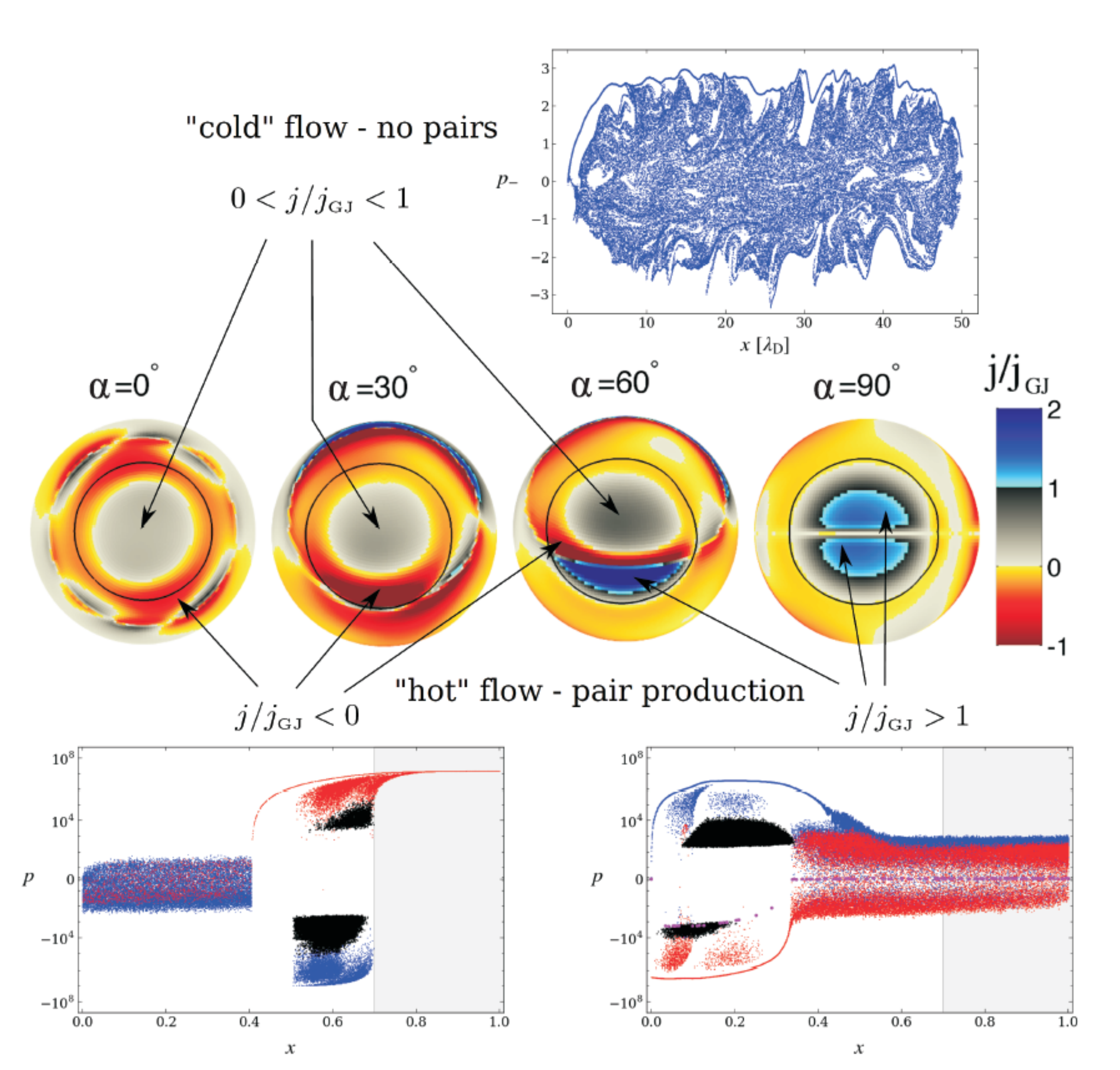
Super- Goldreich-Julian currents – $J/J_{GJ} > 1$

Pair cascades

Anti-Goldreich-Julian currents - $J/J_{GJ} < 0$

Pair cascades

Credit: Andrey Timokhin



Time-dependent pair cascades

Timokhin 2010, Timokhin & Arons 2013

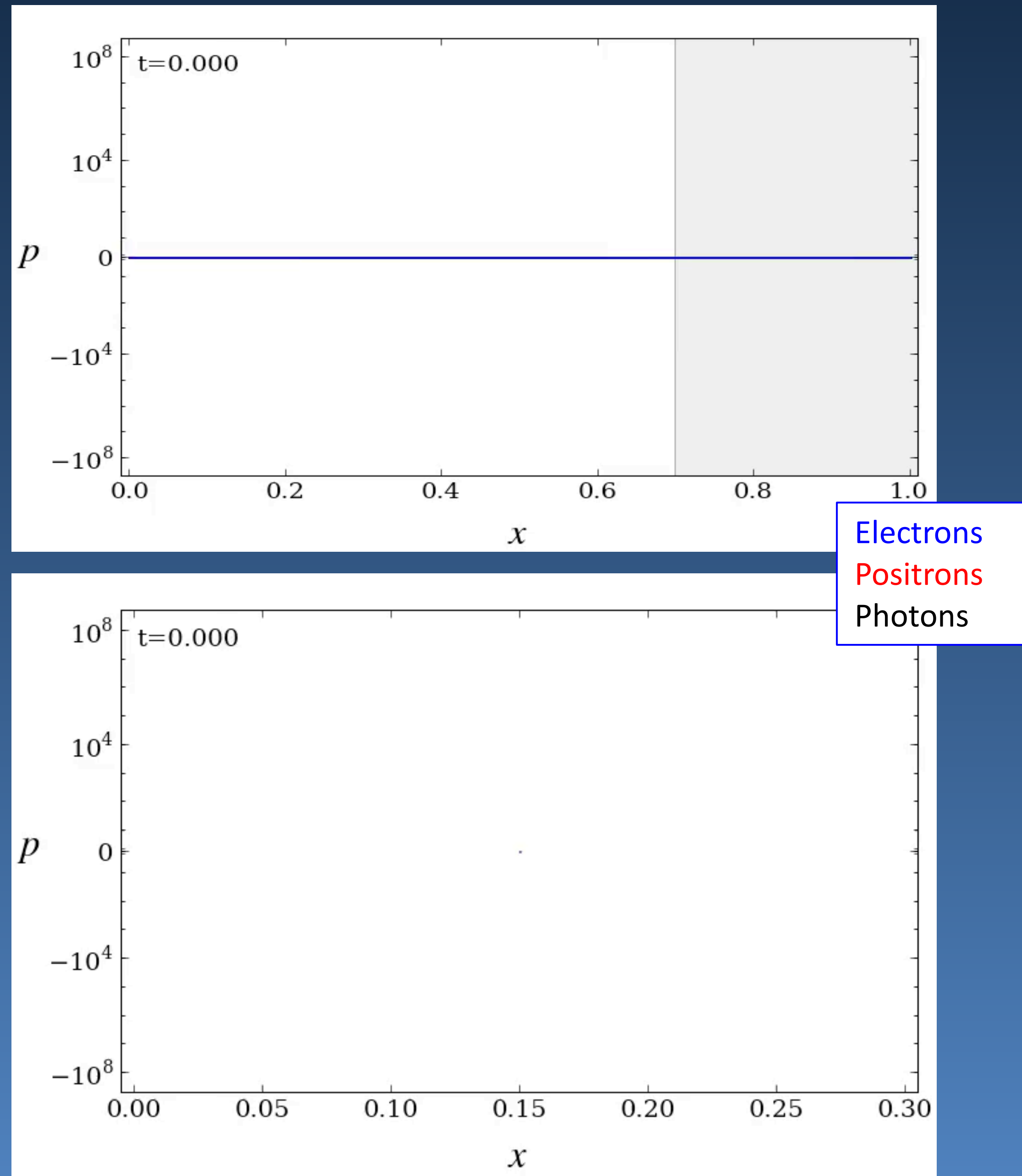
Steady state cascades requires finely-tuned current → not compatible with global models

SCLF gap

Arbitrary current produces time-variable bursts of pairs and photons

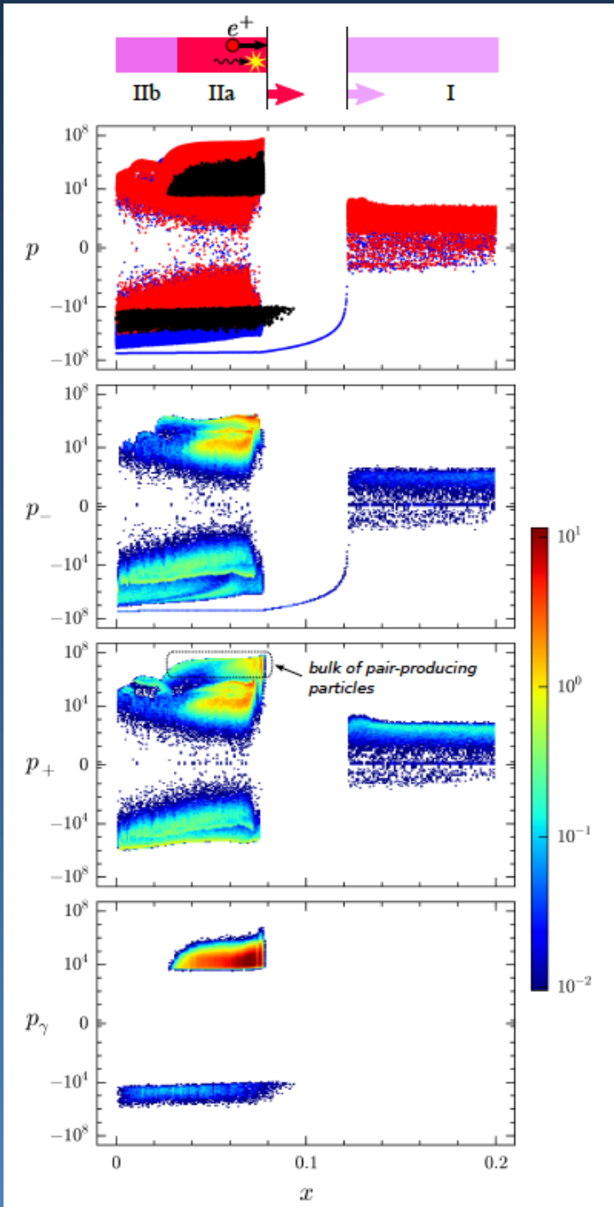
Vacuum gap

From Andrey Timokhin

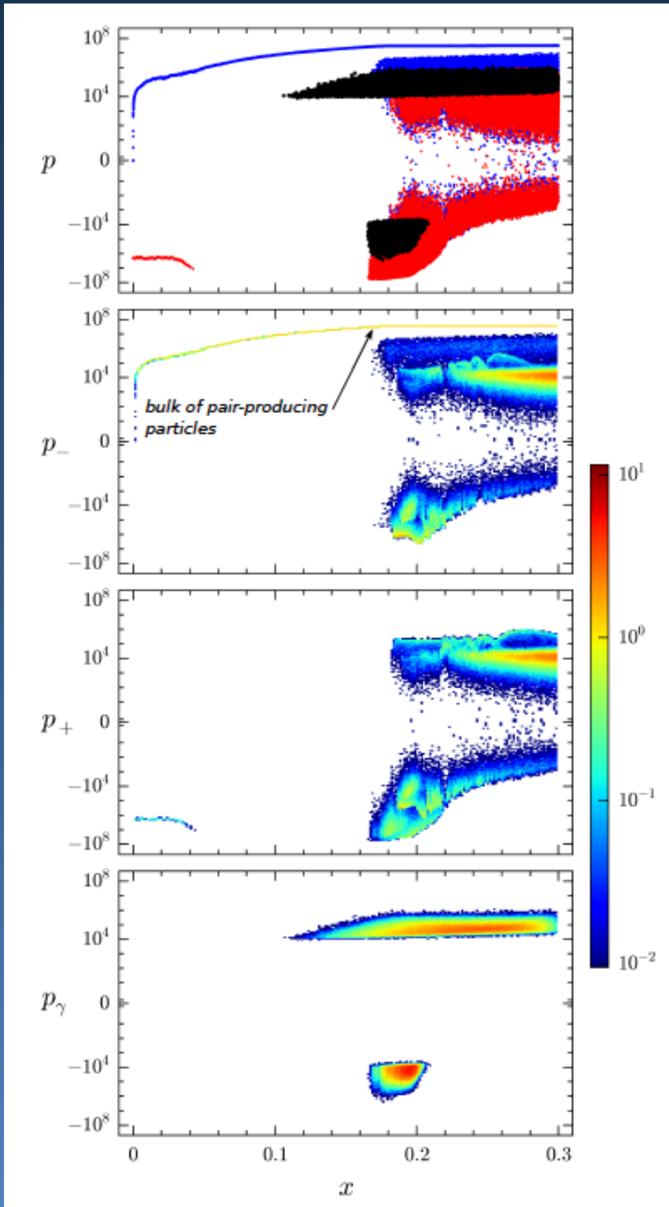


Time-averaged pair yield

I. No charges from NS



II. Free charge flow from NS



Type I gaps
(vacuum)

Cascade on-time:

$\tau_{cas} \sim h_{gap}/c$

$f_\kappa \sim h_{gap}/R_0 \sim 10^{-3}$

Average multiplicity:

$$\langle M_\pm \rangle < 10^3$$

Type II gaps
(Space-charge limited flow)

Cascade on-time:

$\tau_{cas} \sim R_0/c$

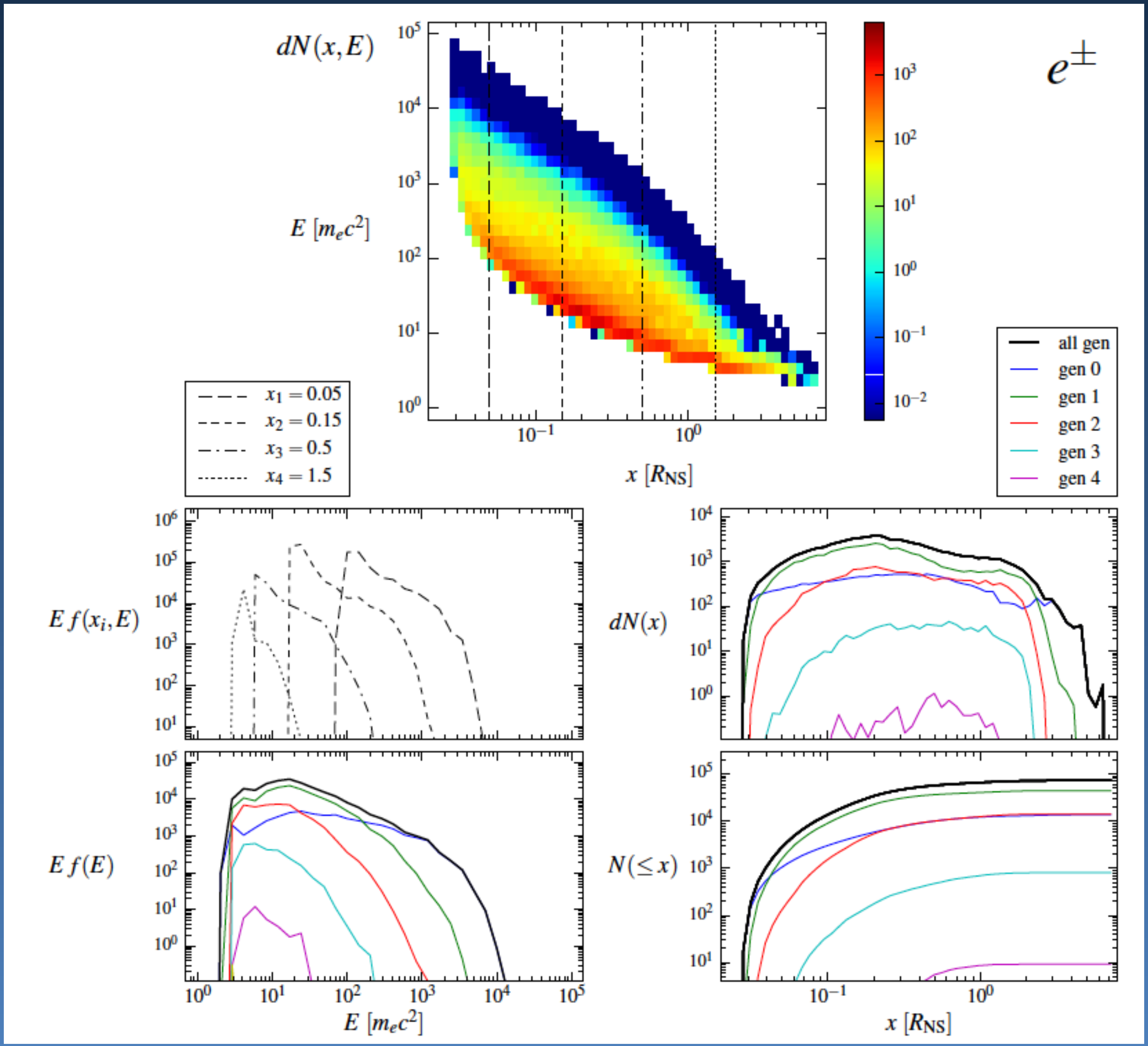
$f_\kappa \sim 0.5$

Average multiplicity:

$$\langle M_\pm \rangle \approx 10^5$$

Numerical full pair cascade simulation

Timokhin & Harding 2015



Crab pulsar

At peak of cycle:
$M_+ = 8 \times 10^4$
(each polar cap)

Full cascade code:

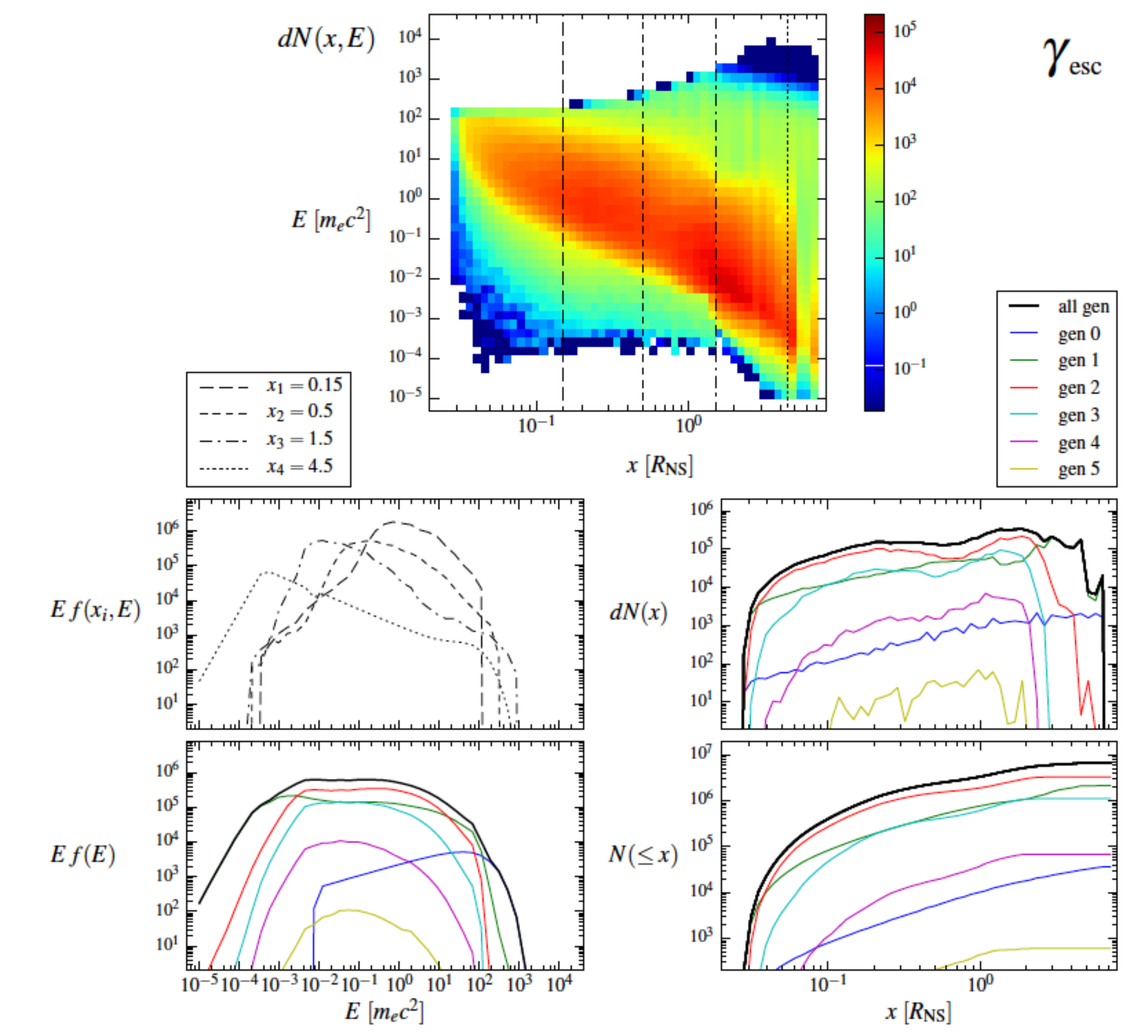
- CR and IC of primaries
- Magnetic pair production with high B, threshold modifications
- SR of pairs:

Asymptotic quantum SR for $n > 20$
Exact QED SR for $n < 20$

- Recursive routine handles large generation #s

Numerical full pair cascade simulation

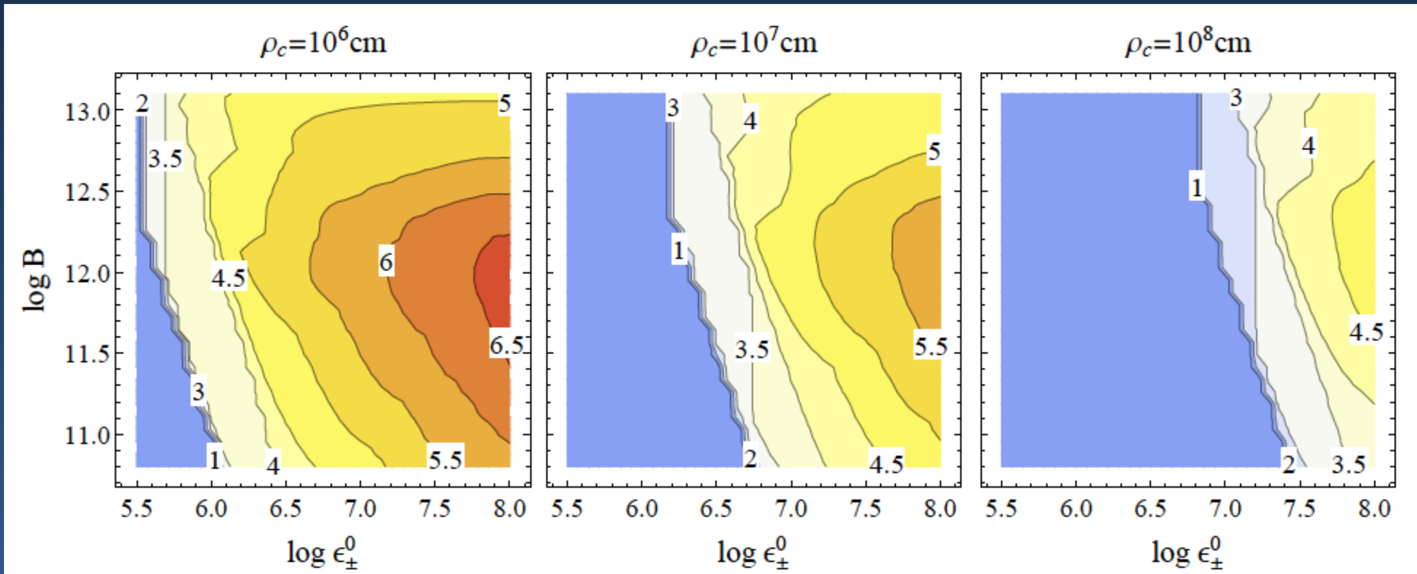
Timokhin & Harding 2015

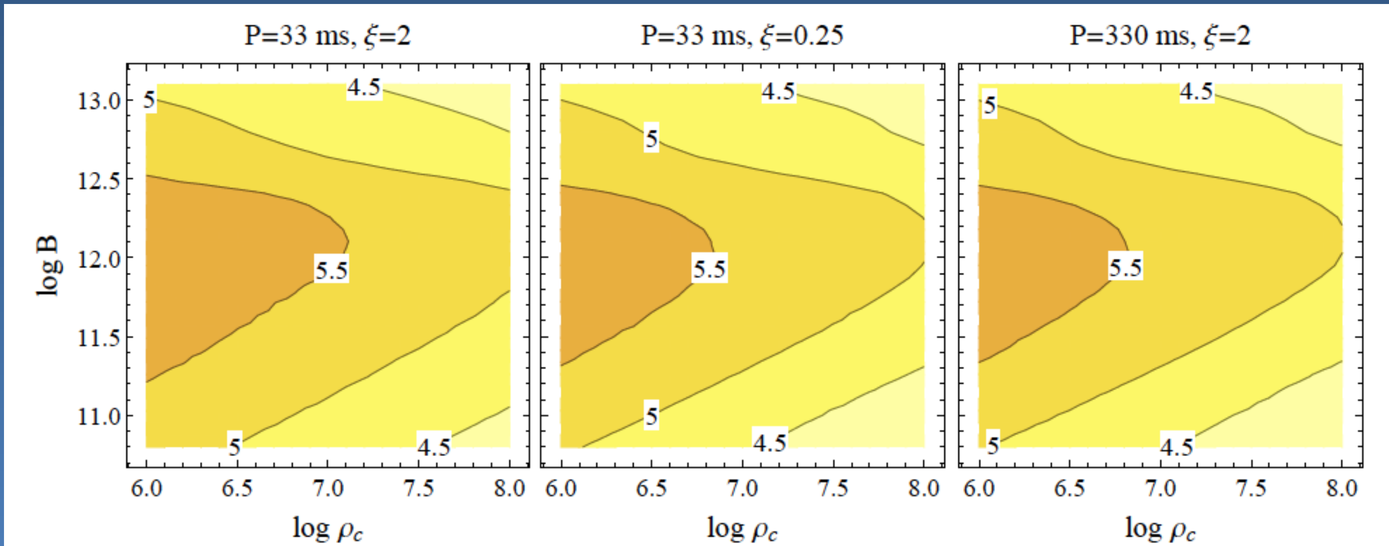


Cascade photon spectra turn over at E < 100 MeV

Maximum pair multiplicity

Timokhin & Harding 2015





CR of primaries plus SR from pairs

Multiplicity most sensitive to primary particle energy and field curvature

Maximum multiplicity ~ $10^{5.5}$ at B ~ 10^{12} G

Weakly dependent on pulsar period since

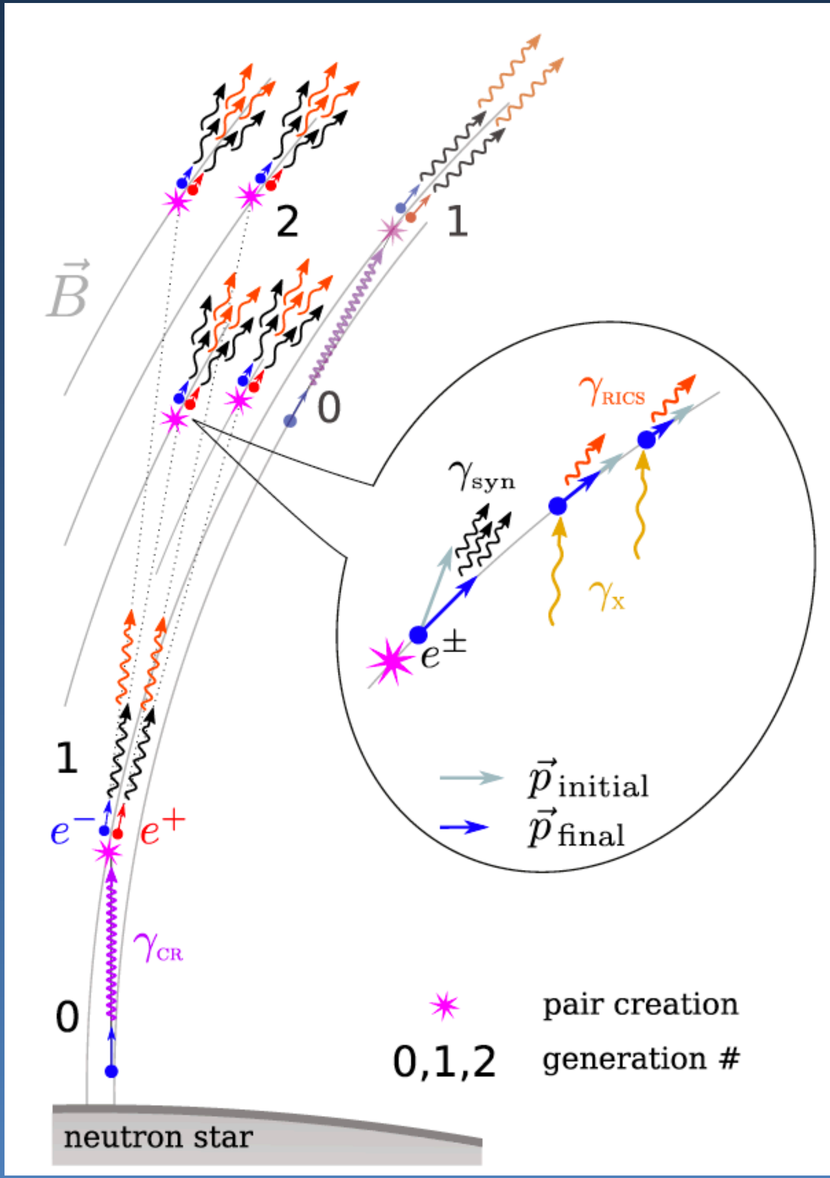
$$\epsilon_\pm^0 \sim 5\times10^7\ \rho_{c,7}^{4/7}$$

in cascades

Maximum pair multiplicity

Timokhin & Harding 2019

Curvature radiation plus resonant inverse Compton



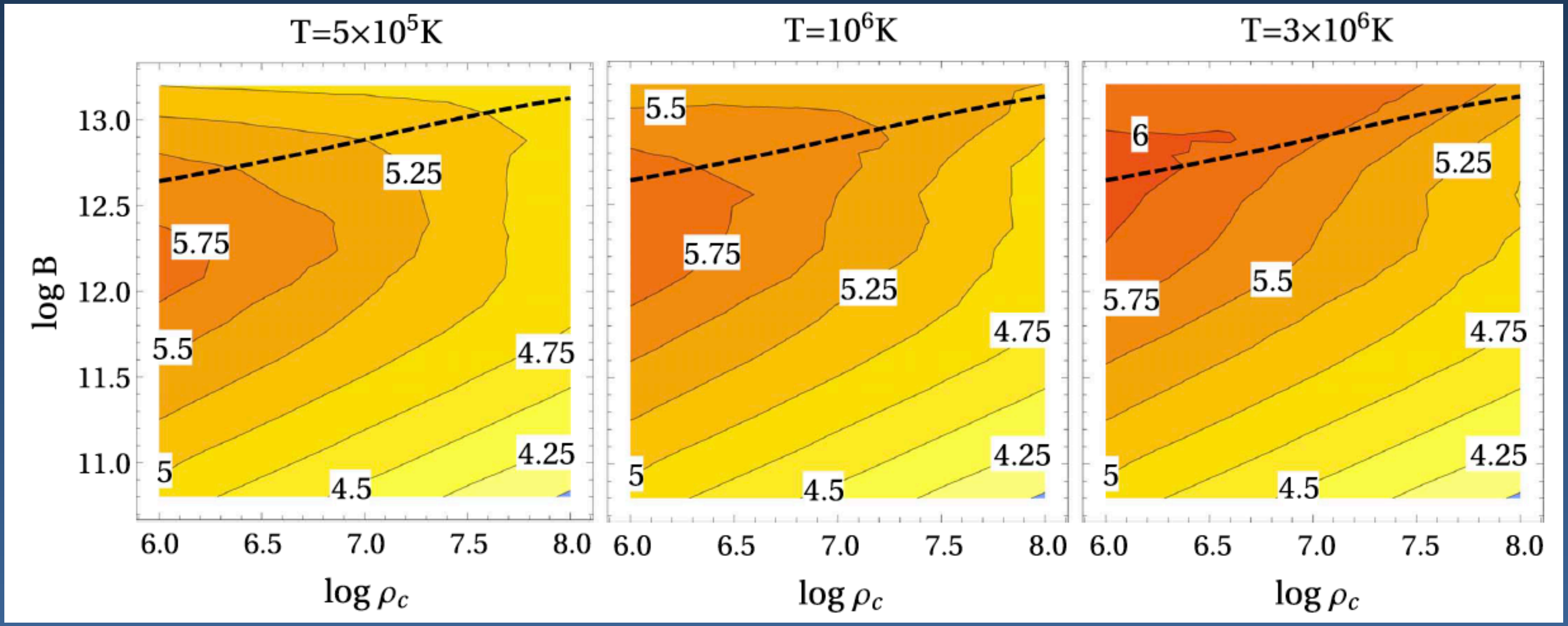
SR turns perpendicular pair into more pairs

RICS turns parallel pair momentum into more pairs

Maximum pair multiplicity

Timokhin & Harding 2019

Curvature radiation of primaries plus SR and resonant inverse Compton of pairs

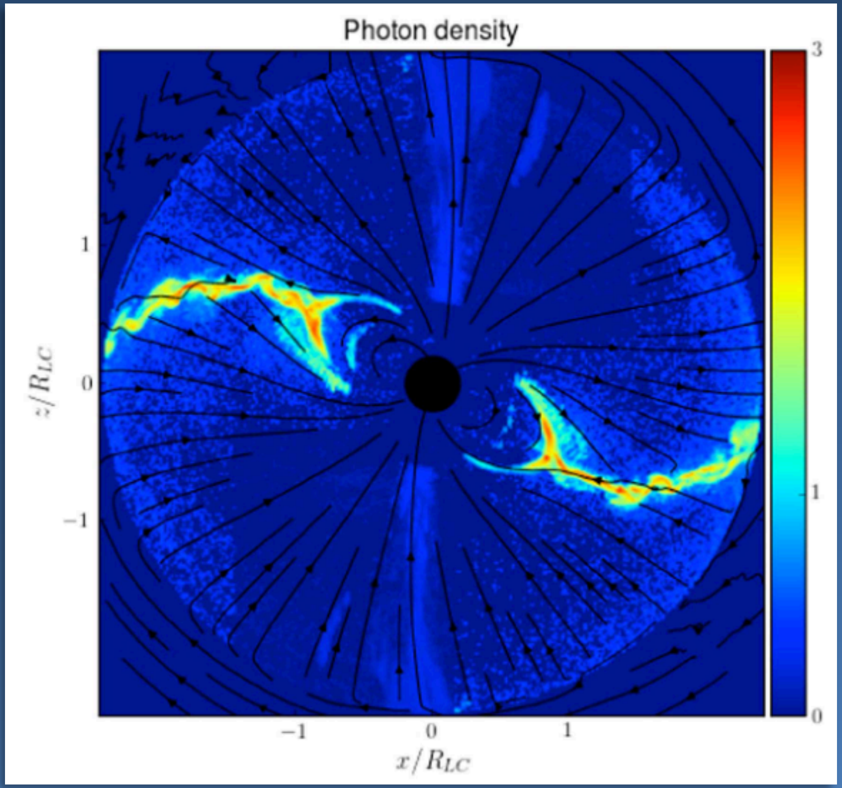


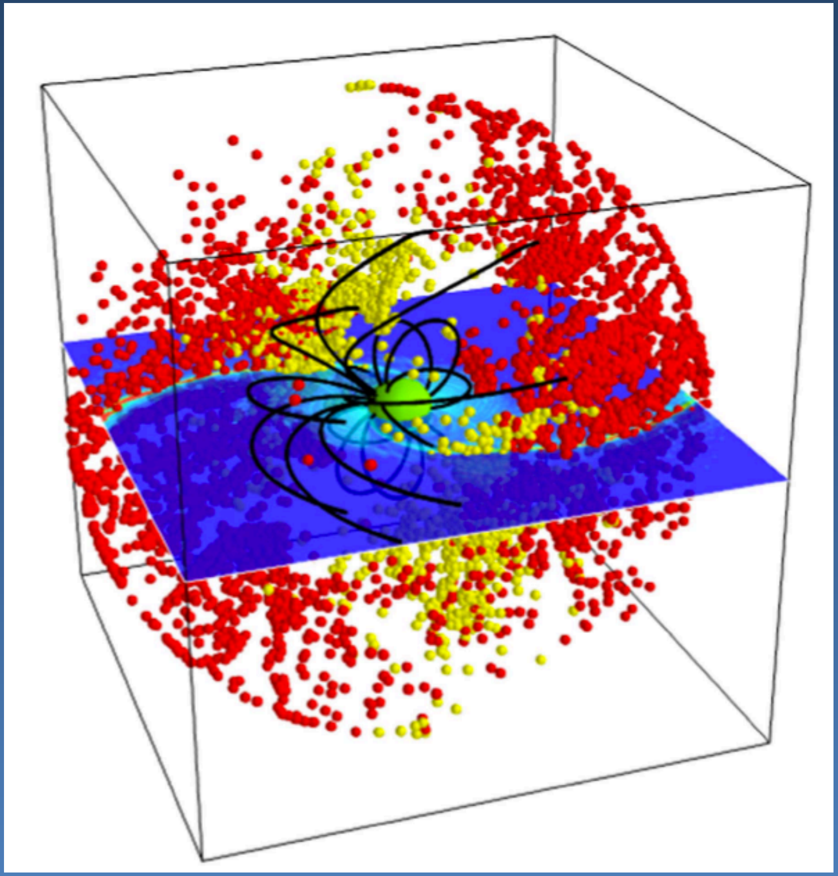
Inclusion of RICS for pairs increases cascade pair multiplicity by only a factor a of ~ 2

Pairs from Y-point and current sheet

Most photons produced around Y-point and current sheet
Counterstreaming photons produce pairs by γ–γ process

Philippov & Spitkovsky 2018

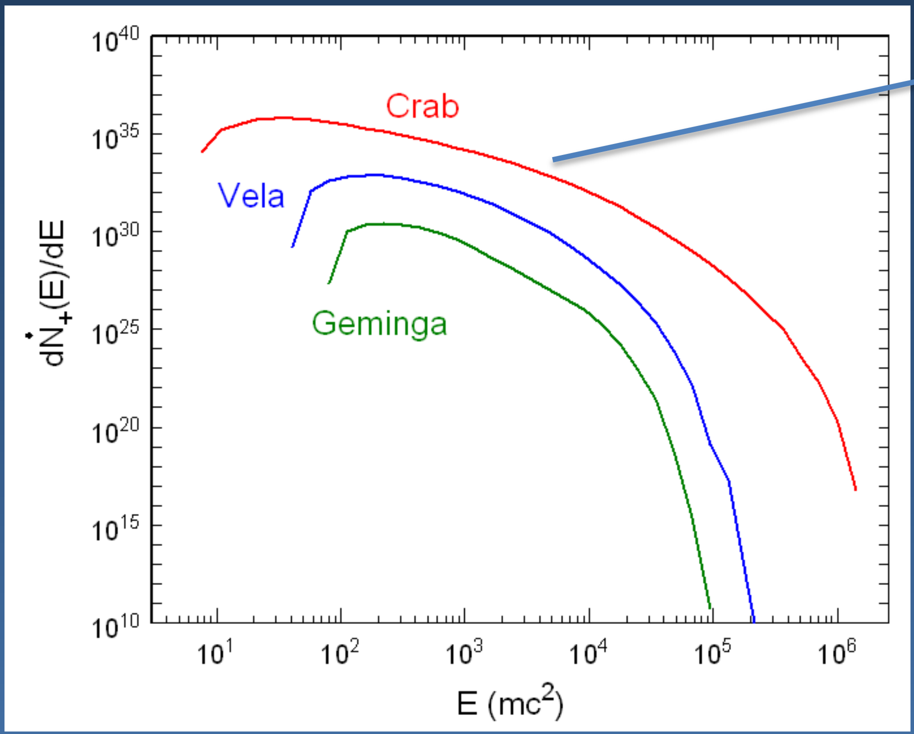




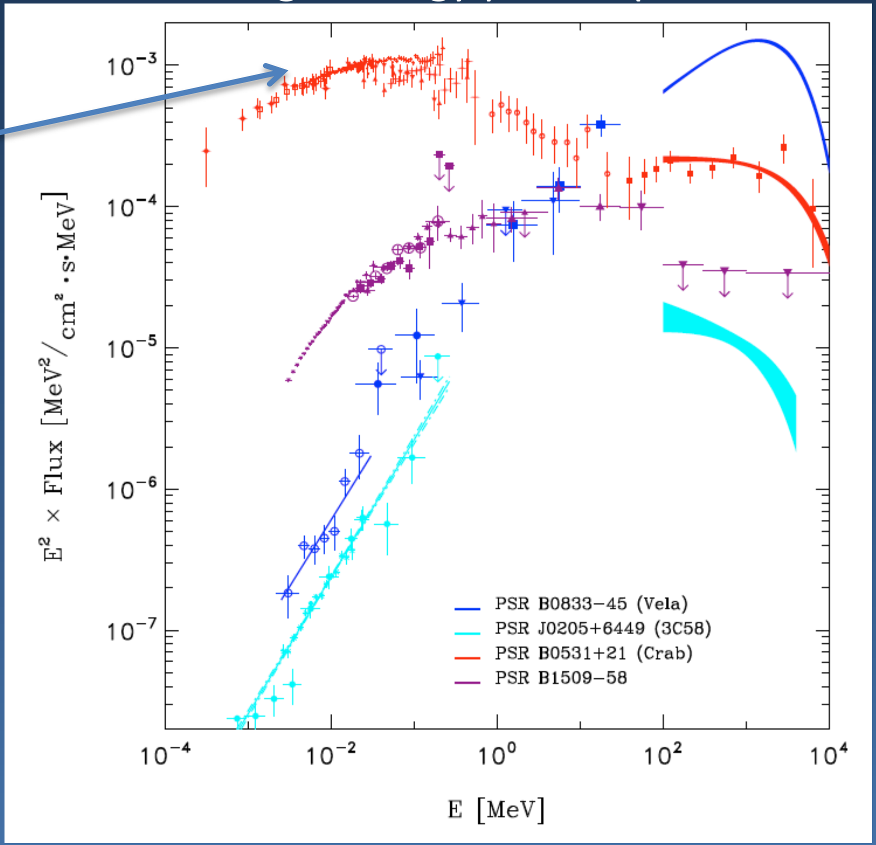
VHE: Synchrotron self-Compton emission?

Essential ingredients: 1) Energetic particles
2) High synchrotron emission level

Pair cascade spectrum (polar cap)



High-energy pulsar spectra

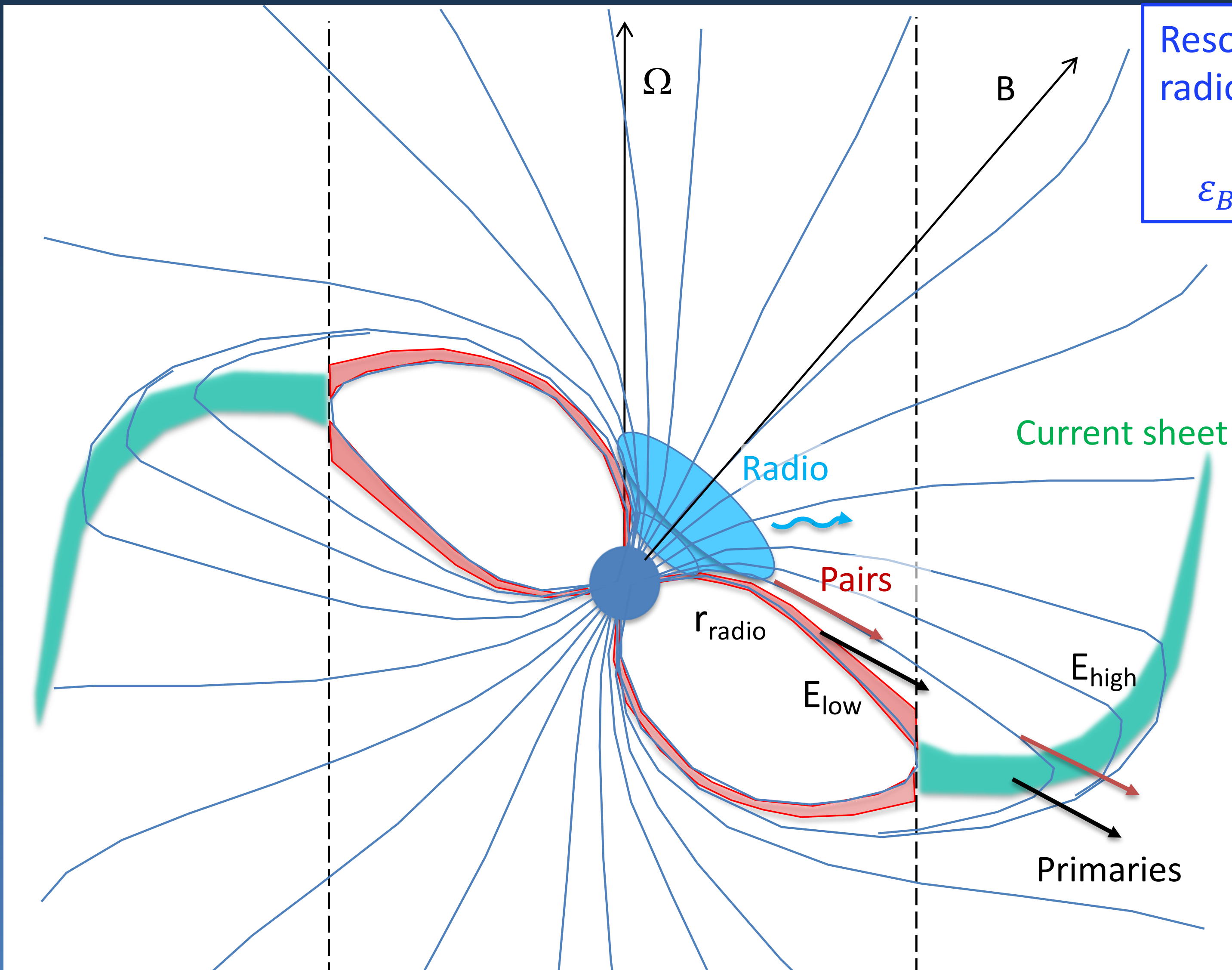


Energetic pair spectrum and high non-thermal X-rays produce high level of SSC

SSC emission from middle-aged pulsars will be much lower

Simulation of radiation

Harding & Kalapotharakos 2015



Resonant absorption of radio photons when

$$\varepsilon_B = \gamma \varepsilon_R (1 - \beta cos\theta)$$

Petrova & Lybarski 1998

Force-free magnetic field 0.2 to 2 R_{LC}

Connect to vacuum retarded dipole below 0.2 R_{LC}

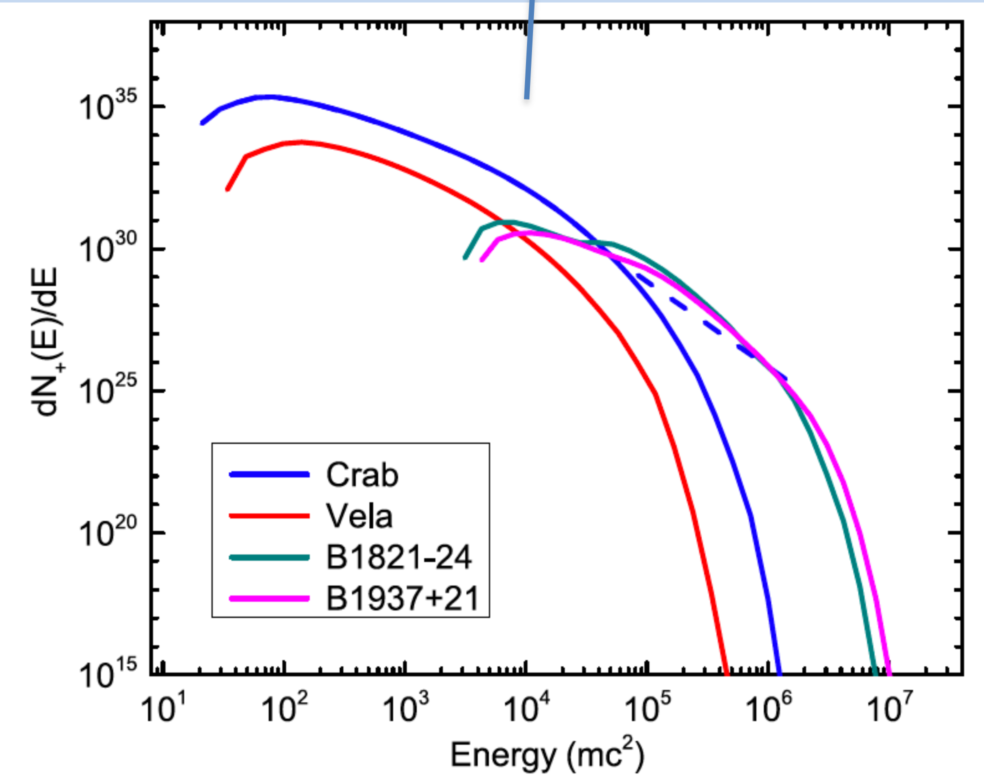
$$\boldsymbol{v} = \left(\frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2 + E_0^2} + f \frac{\boldsymbol{B}}{B} \right) c$$

Synchrotron self-Compton emission

$$\frac{N(\varepsilon_s,\vec{r})}{d\varepsilon_s d\Omega_s} = c\int dE\; n_\pm(\mathrm{E}) \int d\Omega \int d\varepsilon\; n_\gamma(\varepsilon,\Omega)\, \frac{d\sigma(\varepsilon',\vec{r},\Omega')}{d\varepsilon' d\Omega'} (1-\beta\cos\theta)$$

Synchrotron emissivity

Pair cascade spectrum (polar cap)



$$n_\gamma(\varepsilon,\vec{r},\Omega) = \frac{1}{c}\int d\vec{r}_s \frac{\epsilon_{SR}(\varepsilon,\vec{r},\Omega)}{(r^2-r_s^2)}$$

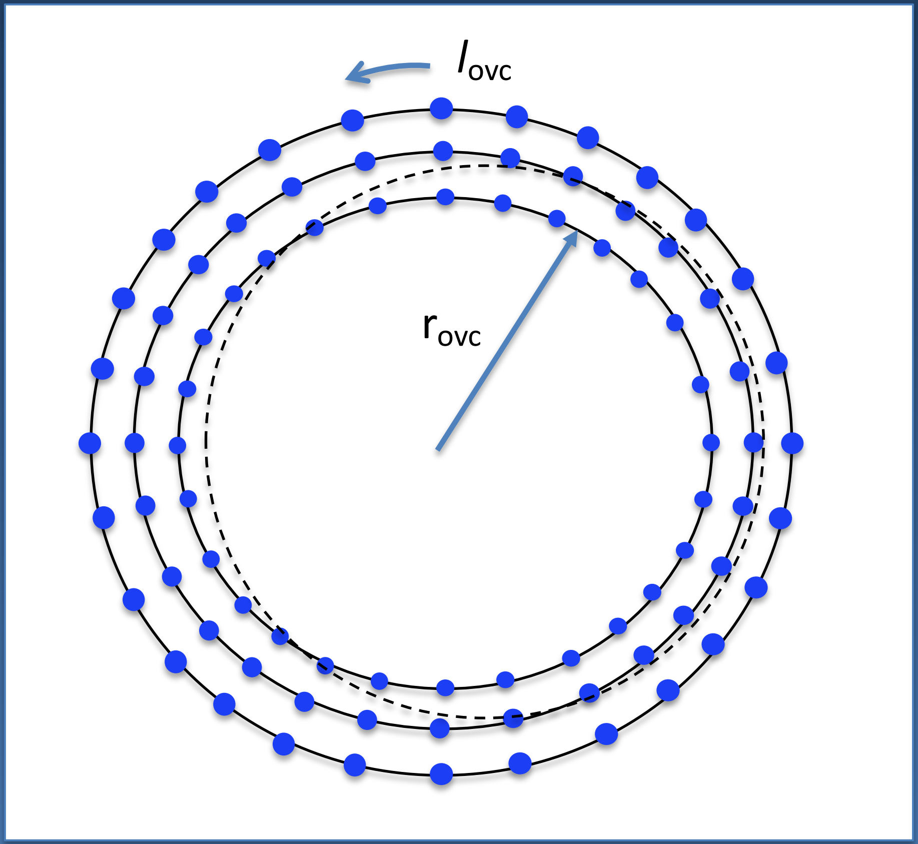
Synchrotron photon density (anisotropic)

Need two trajectories for each particle: one to create the SR emissivity, one to compute the SSC/IC emission

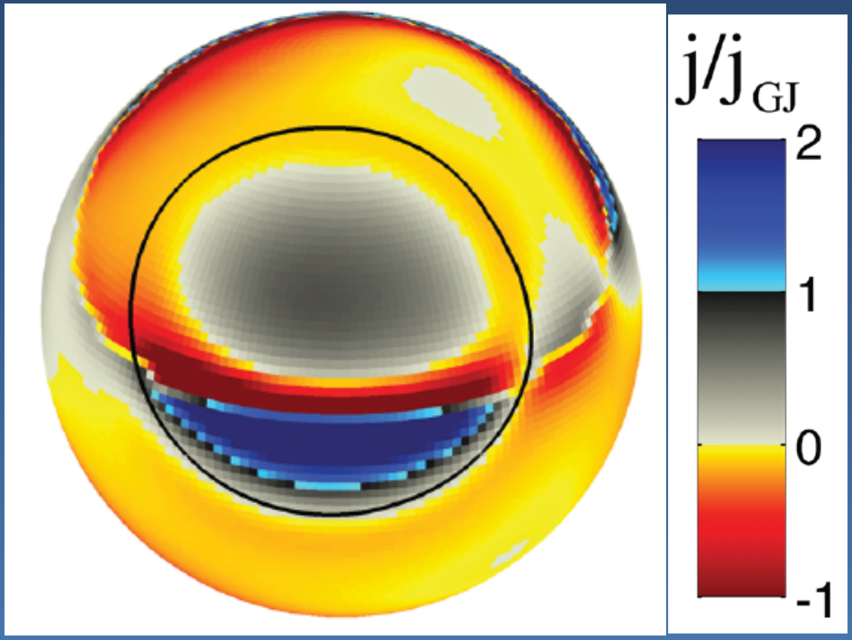
Primary IC uses this same SR photon density

Particle trajectories on polar cap

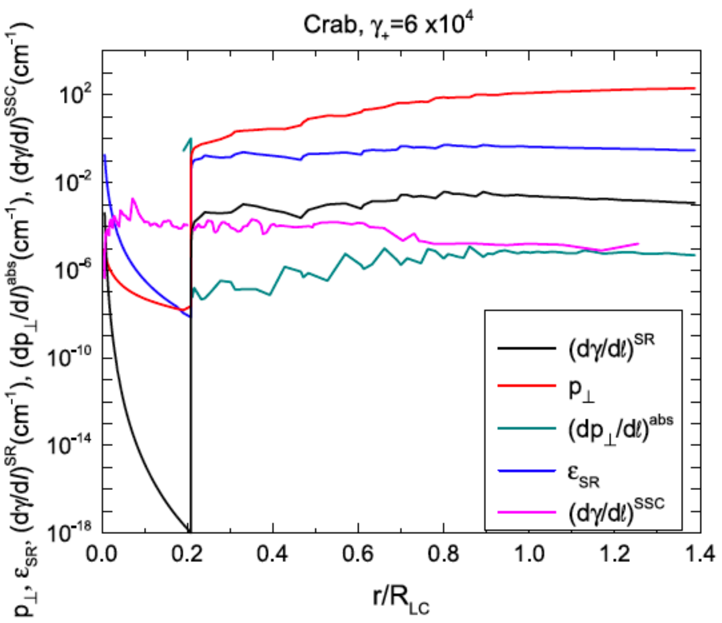
Open volume coordinates: r_{ovc}, l_{ovc}

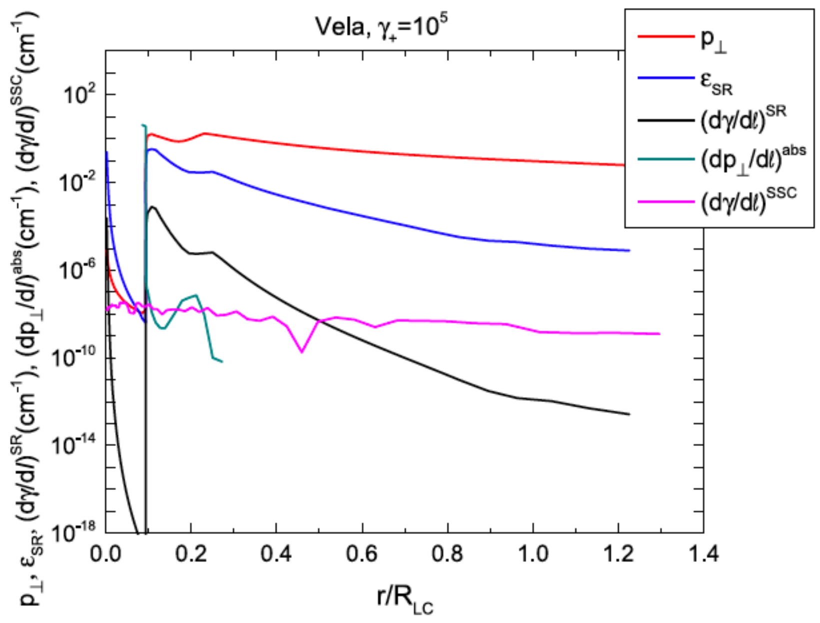


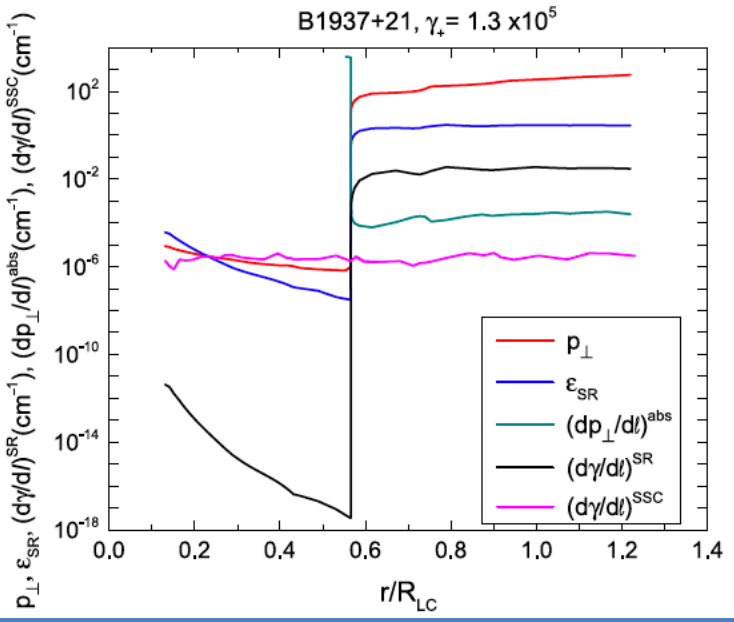
Pair injection for $j/j_{GJ} > 1$ and < 0



Particle dynamics - pairs



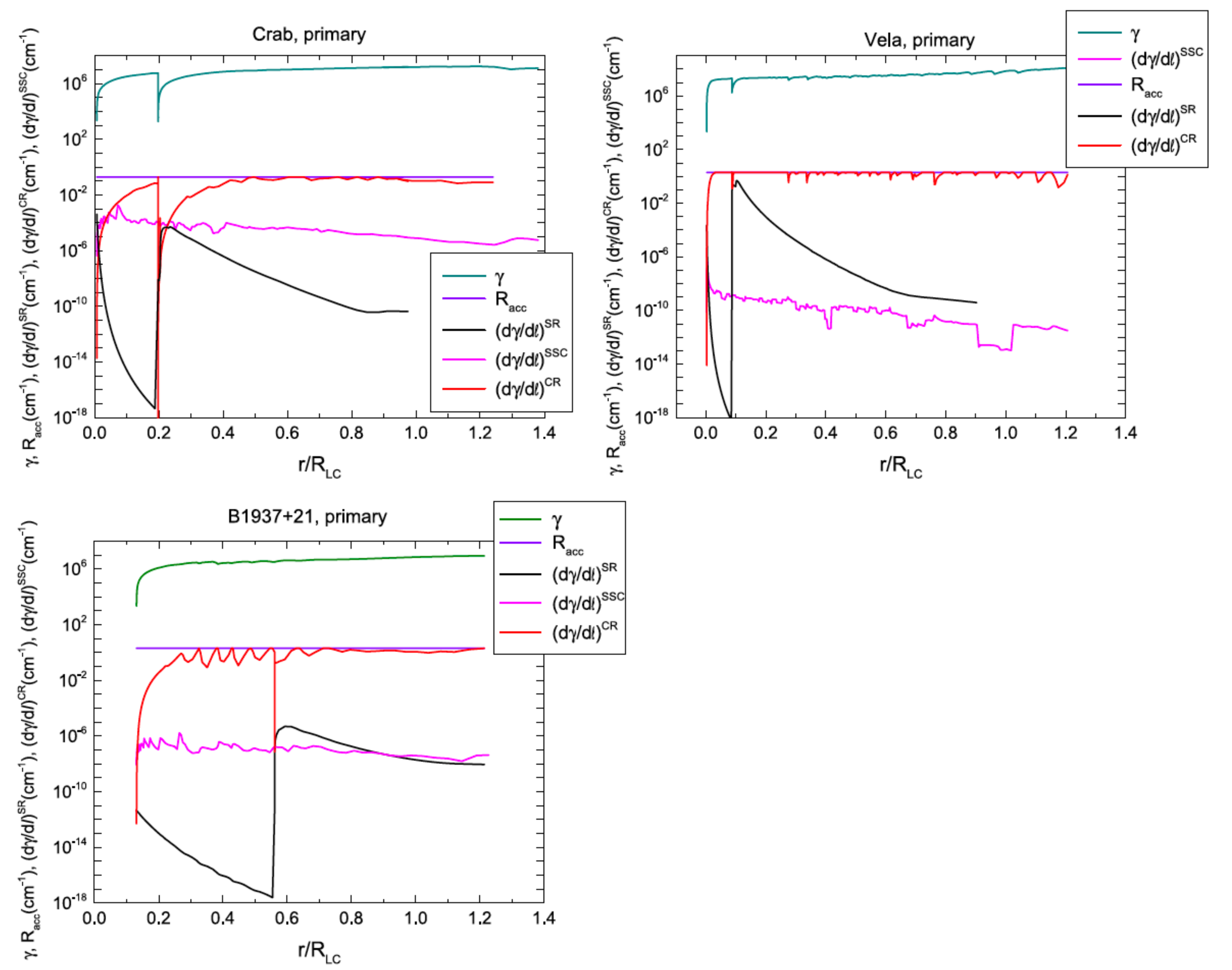




$$\frac{d\gamma}{dt} = \frac{eE_\parallel}{mc} - \frac{2e^4}{3m^3c^5}B^2\,p_\perp^2 - \frac{2e^2\gamma^4}{3\rho_c^2} + \left(\frac{d\gamma}{dt}\right)^{\rm abs} - \left(\frac{d\gamma}{dt}\right)^{\rm SSC}$$

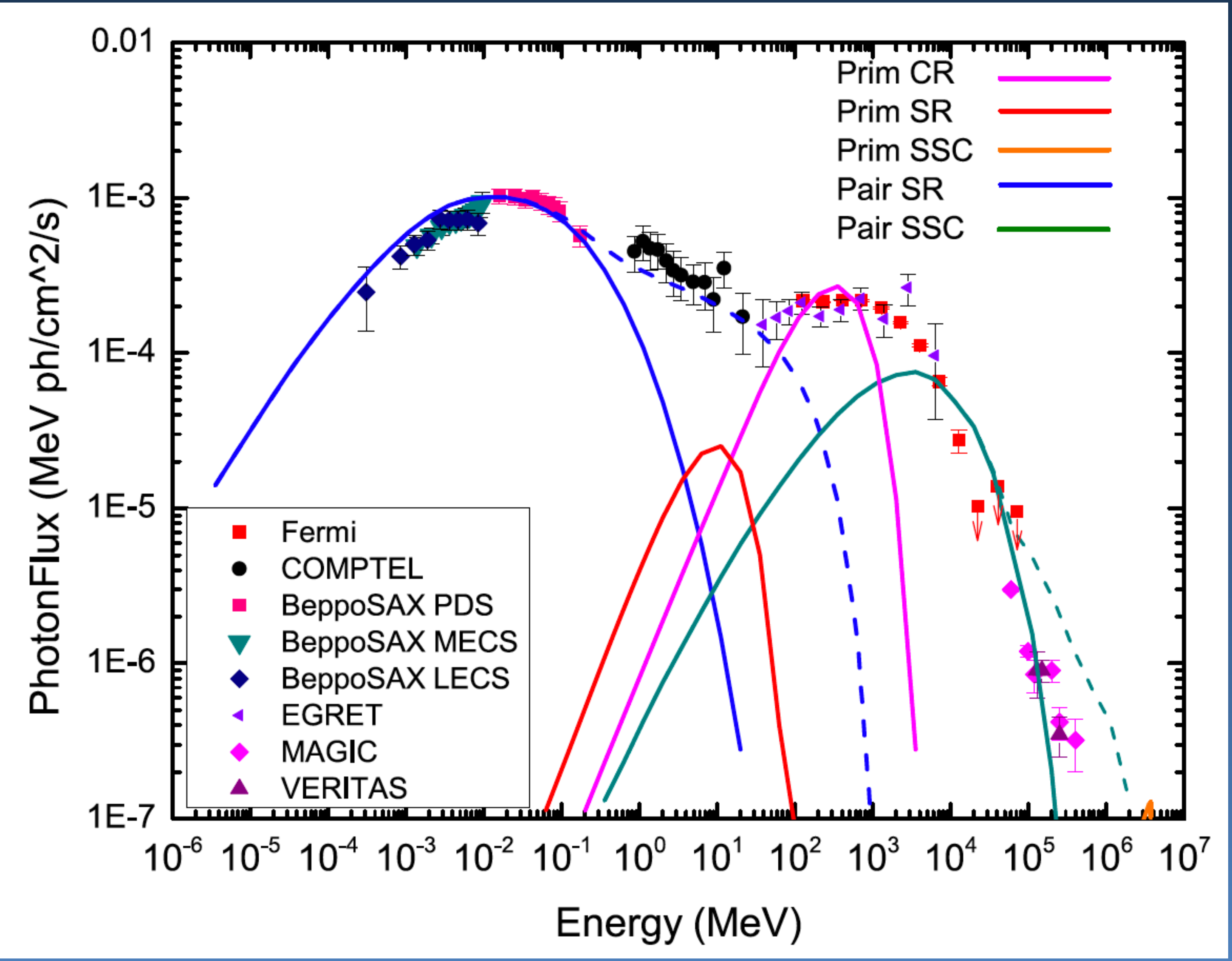
$$\frac{dp_\perp}{dt} = -\frac{3}{2}\frac{c}{r}p_\perp - \frac{2e^4}{3m^3c^5}B^2\,\frac{p_\perp^3}{\gamma} + \left(\frac{dp_\perp(\gamma)}{dt}\right)^{\rm abs}$$

Particle dynamics - primaries



SSC emission from Crab pulsar

Harding & Kalapotharakos 2015 $\alpha = 45^0$, $\zeta = 60^0$, $M_+ = 3 \times 10^5$



High
$B_{LC} = 1 \times 10^6$ G
$L_R = 2200$ mJy kpc^2

Small
$R_{LC} = 1.5 \times 10^8$ cm

All good for SR and SSC

SSC from Crab-like pulsar B0540-69

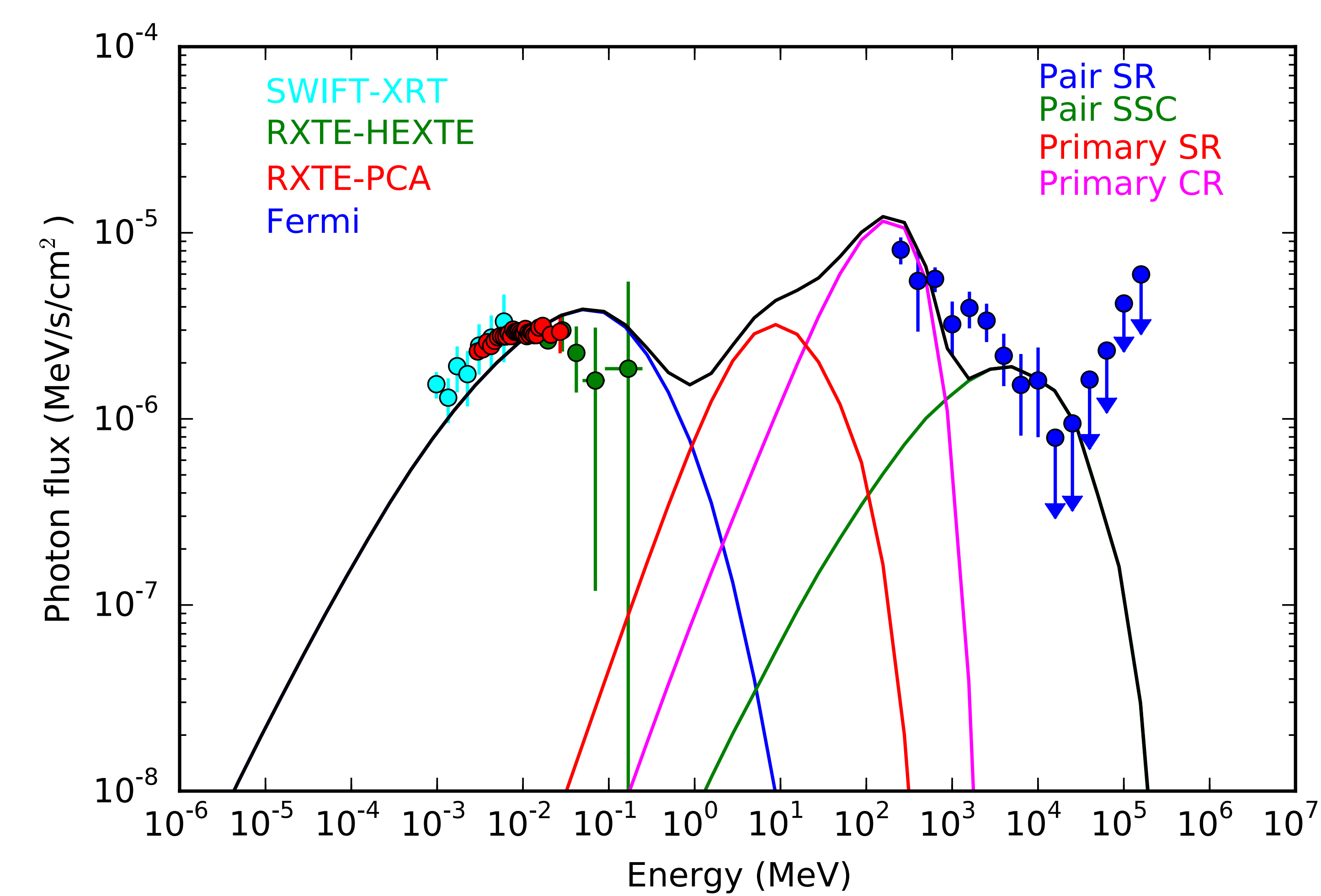
$\alpha = 45^0$, $\zeta = 70^0$, $M_+ = 3 \times 10^5$

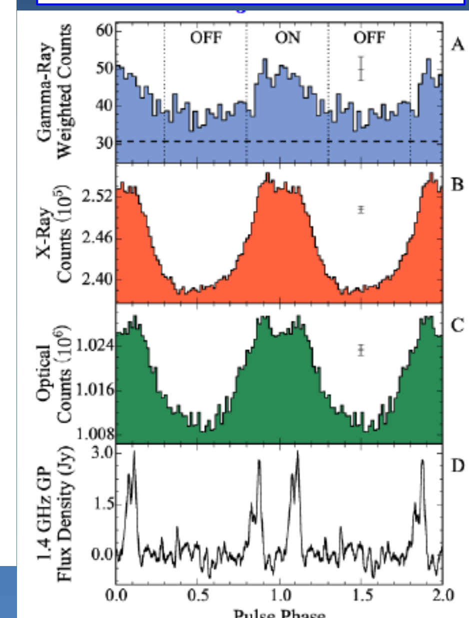
High
$B_{LC} = 3.6 \times 10^5$ G

Small
$R_{LC} = 1.5 \times 10^8$ cm

But
$L_R = 1000$ mJy kpc^2

So, smaller SR and SSC



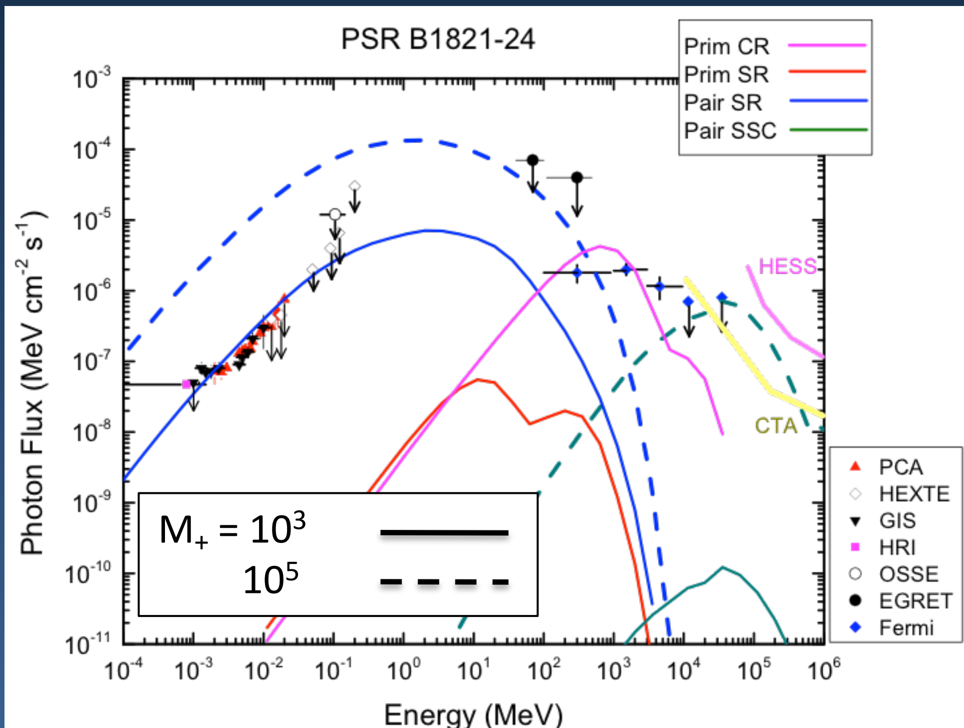


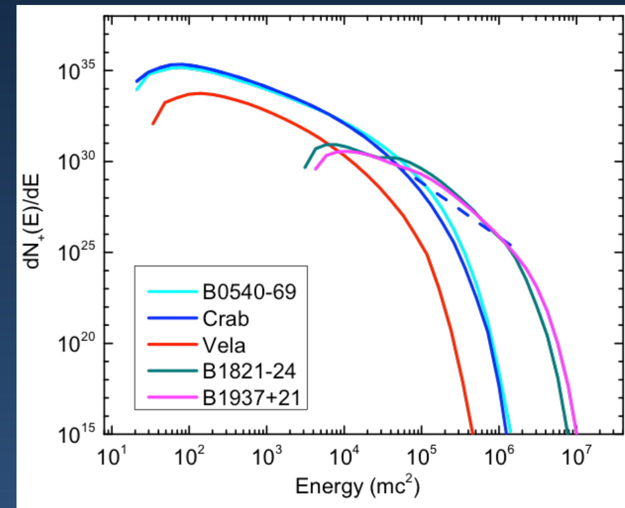
Fermi data – Ackermann et al. 2015

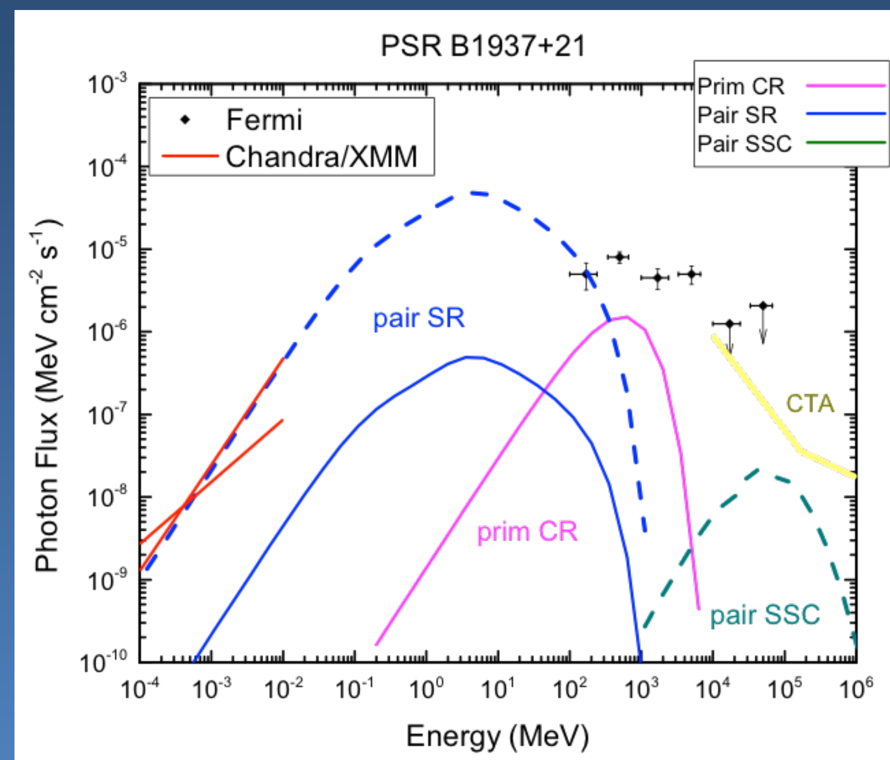
SSC emission from MSPs

Harding & Kalapotharakos 2015

$\alpha = 45^0, \zeta = 80^0$





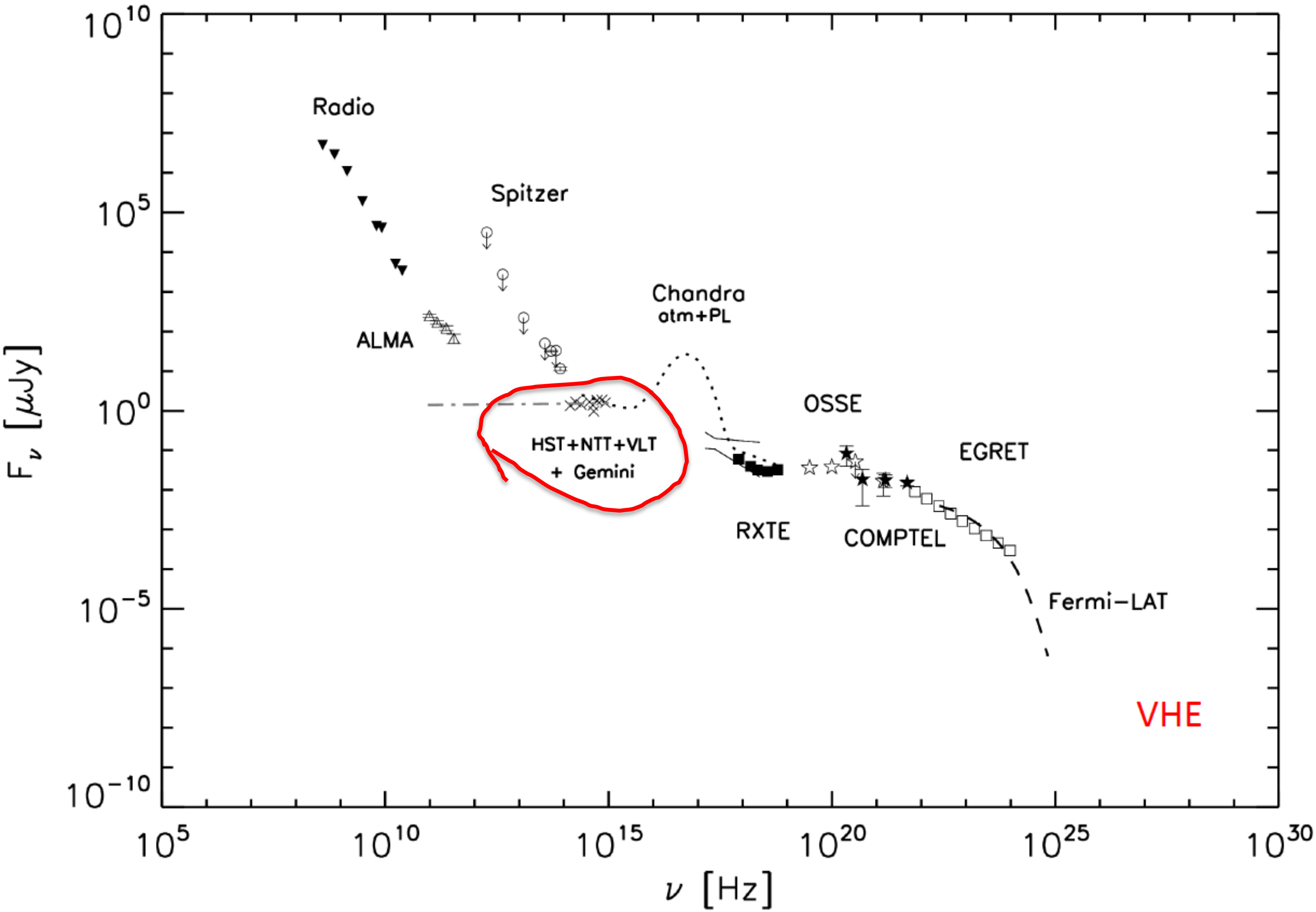


SR spectra peak ~1-10 MeV

SSC peak ~ 100 GeV but lowered by KN reductions

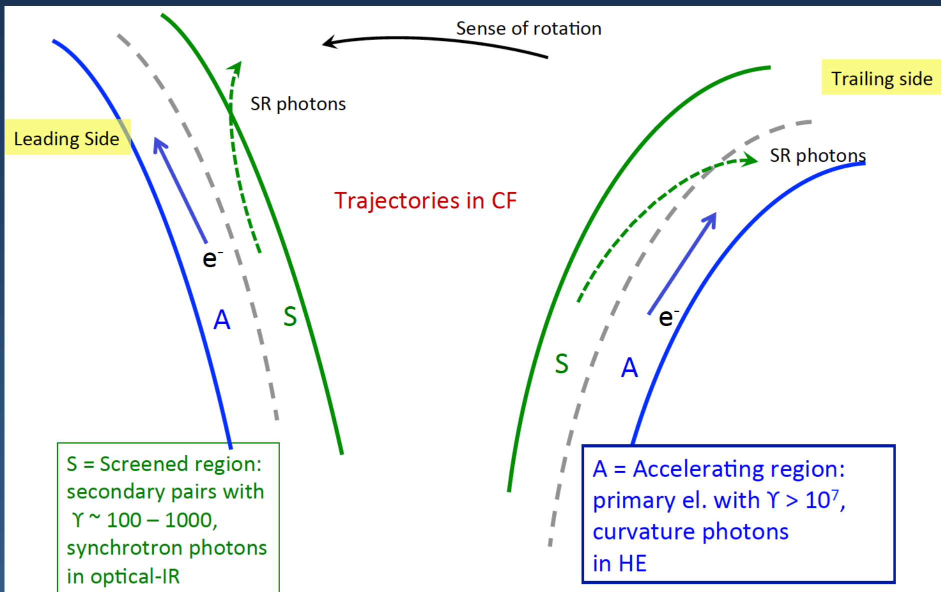
$\alpha = 75^0, \zeta = 70^0$

Spectral energy distribution of the Vela pulsar



ICS model for Vela TeV emision

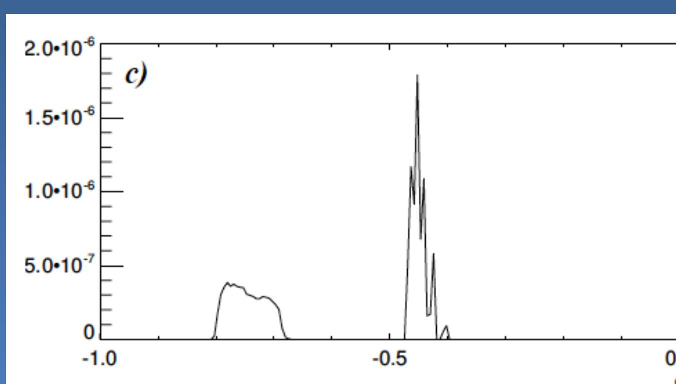
Rudak & Dyks 2017

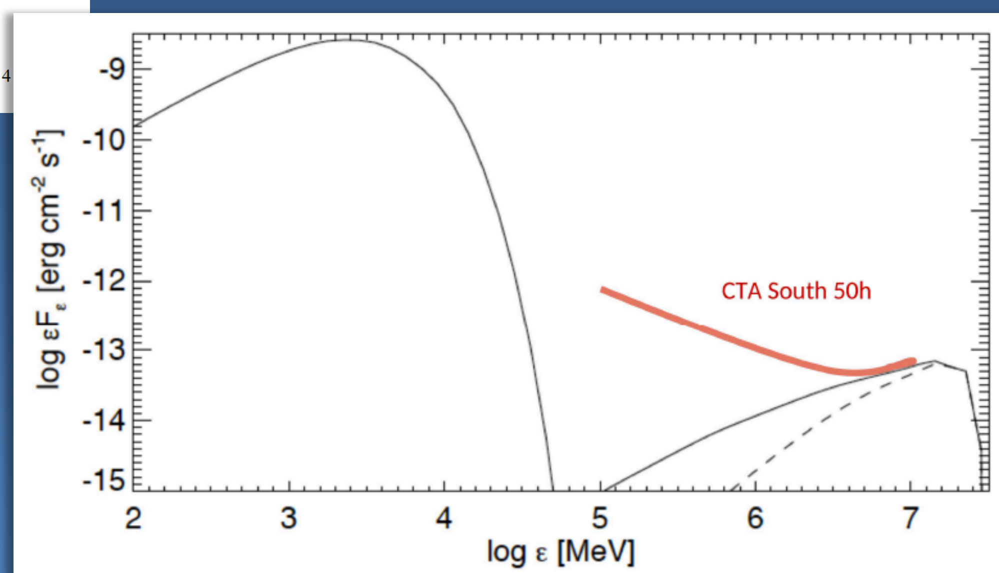


Cartoon version of the outer gap structure used in the calculations

Outer gap model

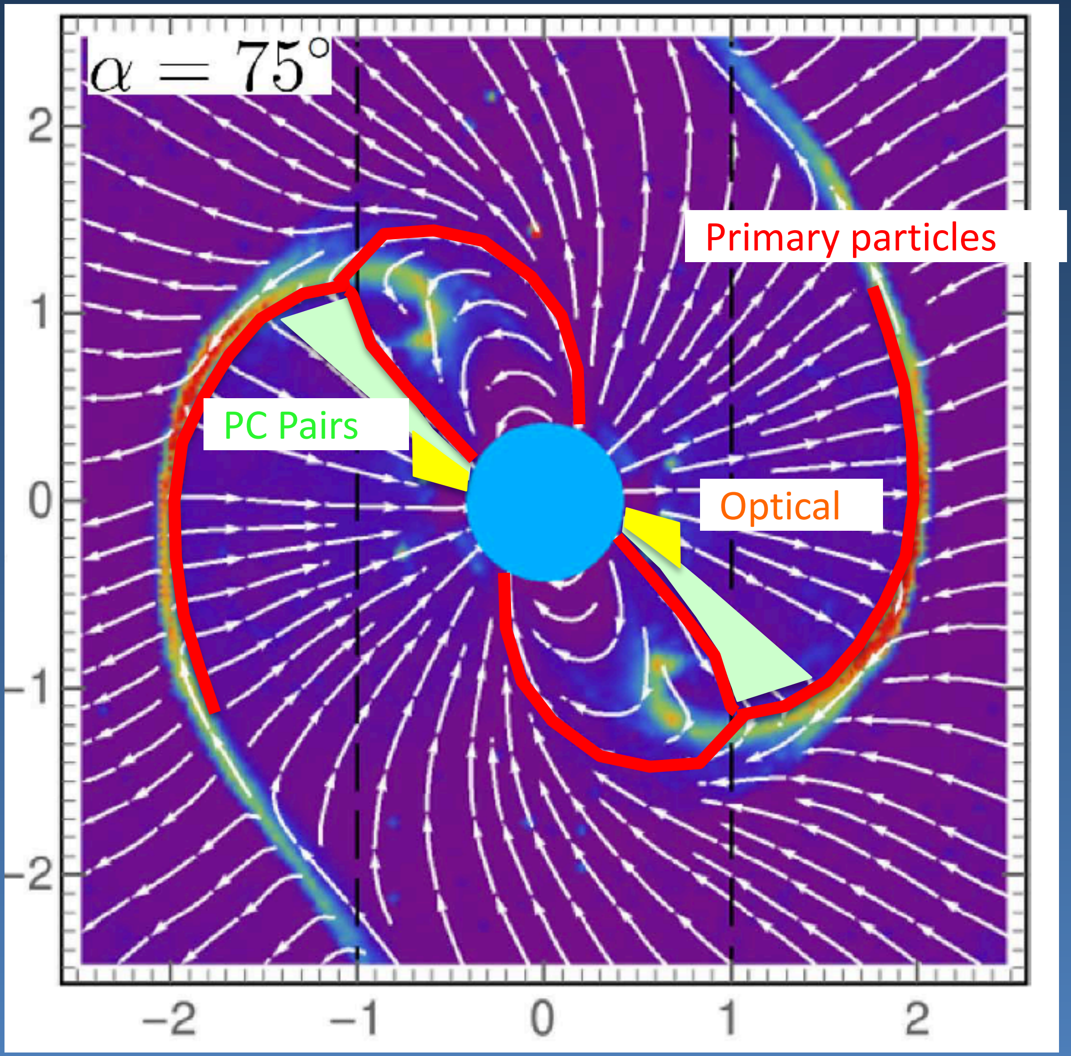
- Emission inside light cylinder
- PC pairs produce SR optical/UV
- Accelerated primaries scatter optical/UV photons





Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018



Near force-free magnetosphere

- PC pairs produce SR optical/UV at lower altitude
- Primary particles (mostly positrons) produce synchro-curvature and scatter optical/UV to produce 10 TeV ICS emission
- Pairs scatter optical/UV to produce SSC hard X-ray emission

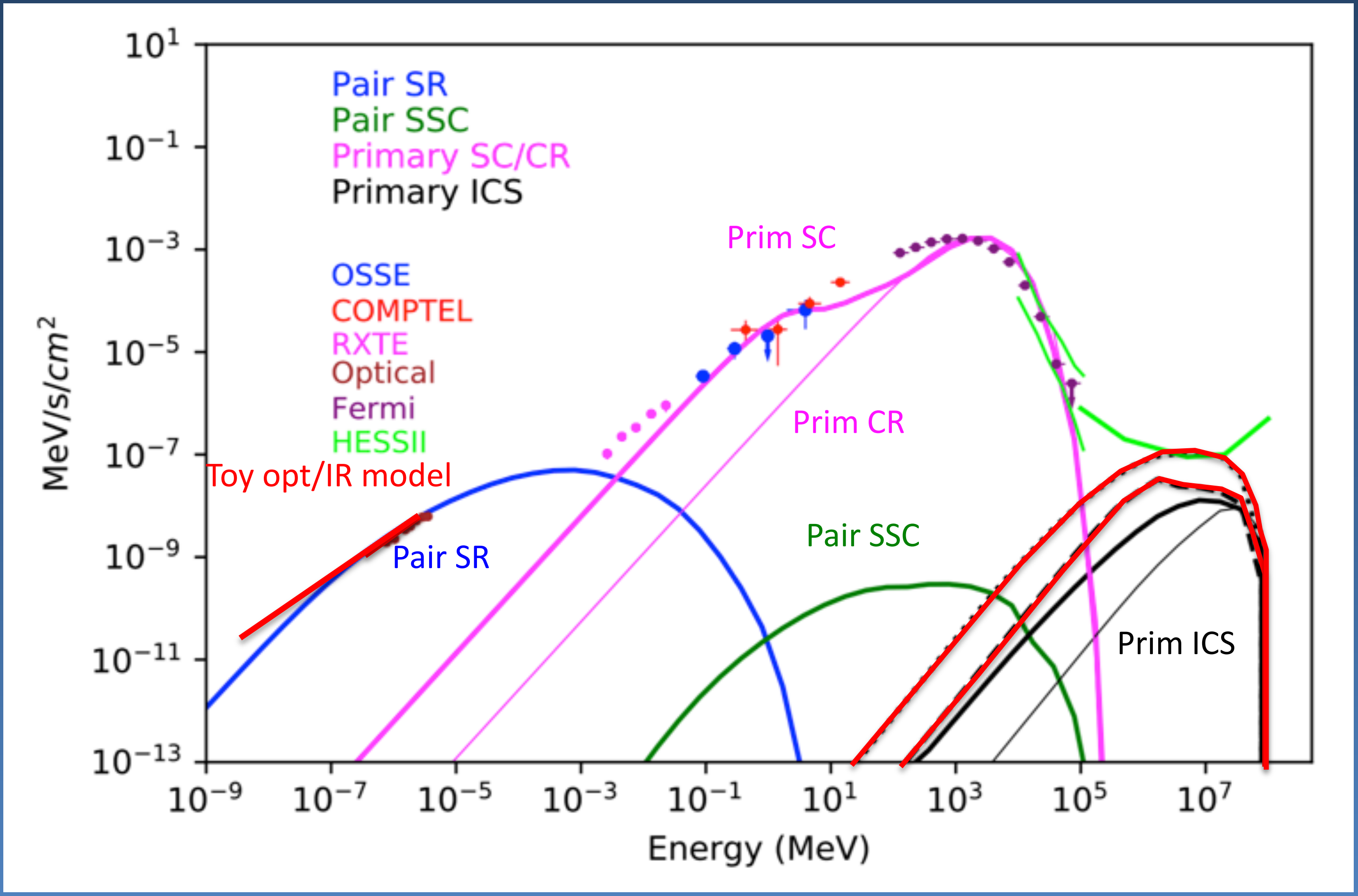
Modeling TeV+ emission from Vela

Harding, Kalapotharakos, Venter & Barnard 2018

$P = 0.089$ s, $B_0 = 4 \times 10^{12}$ G, $d = 0.25$ kpc

$\alpha = 75$, $\zeta = 65$, pair $M_+ = 6 \times 10^3$

- Detectable component from primary ICS around 10 TeV!
- Pair SR matches optical spectrum

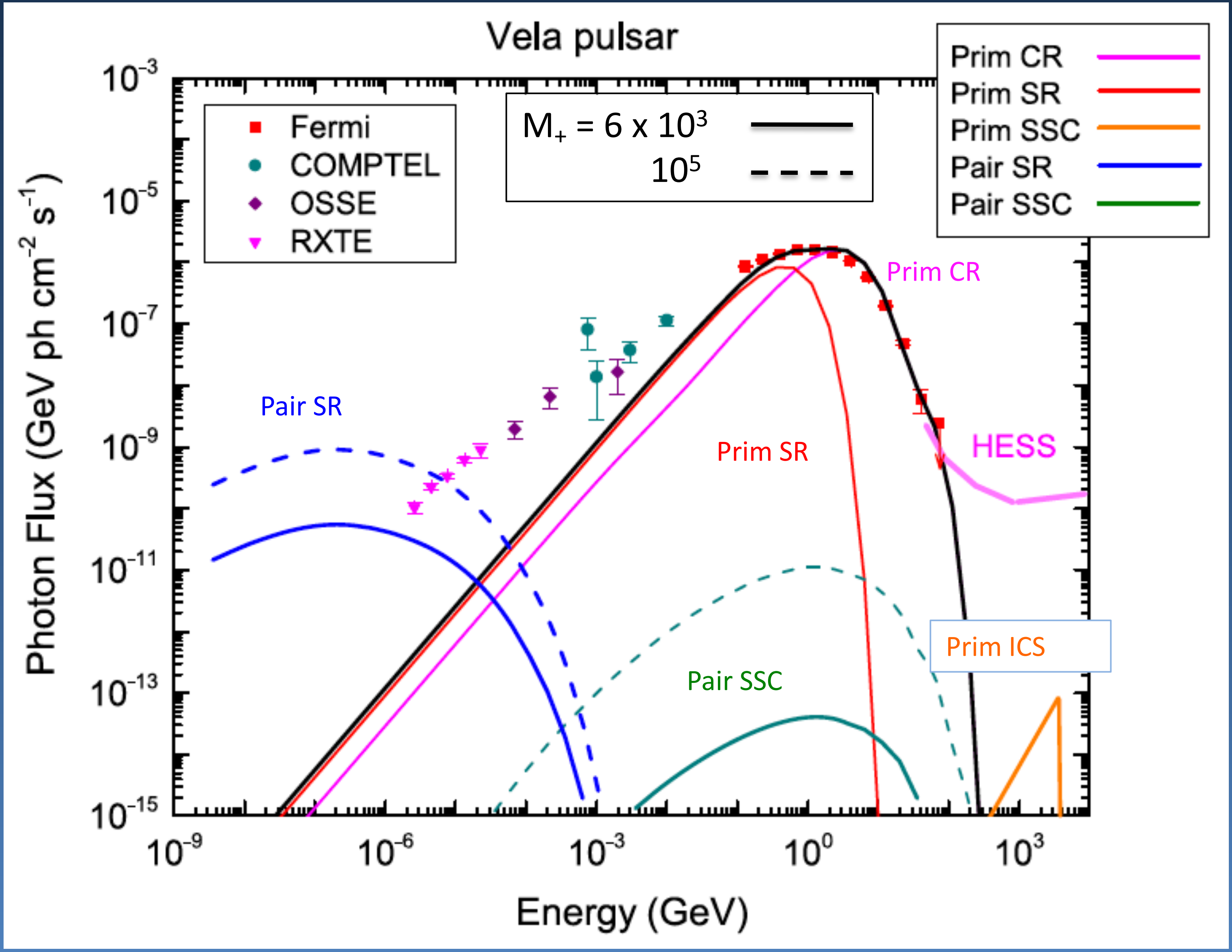


Pulsed emission at 10 TeV requires higher particle energy → GeV emission is CR

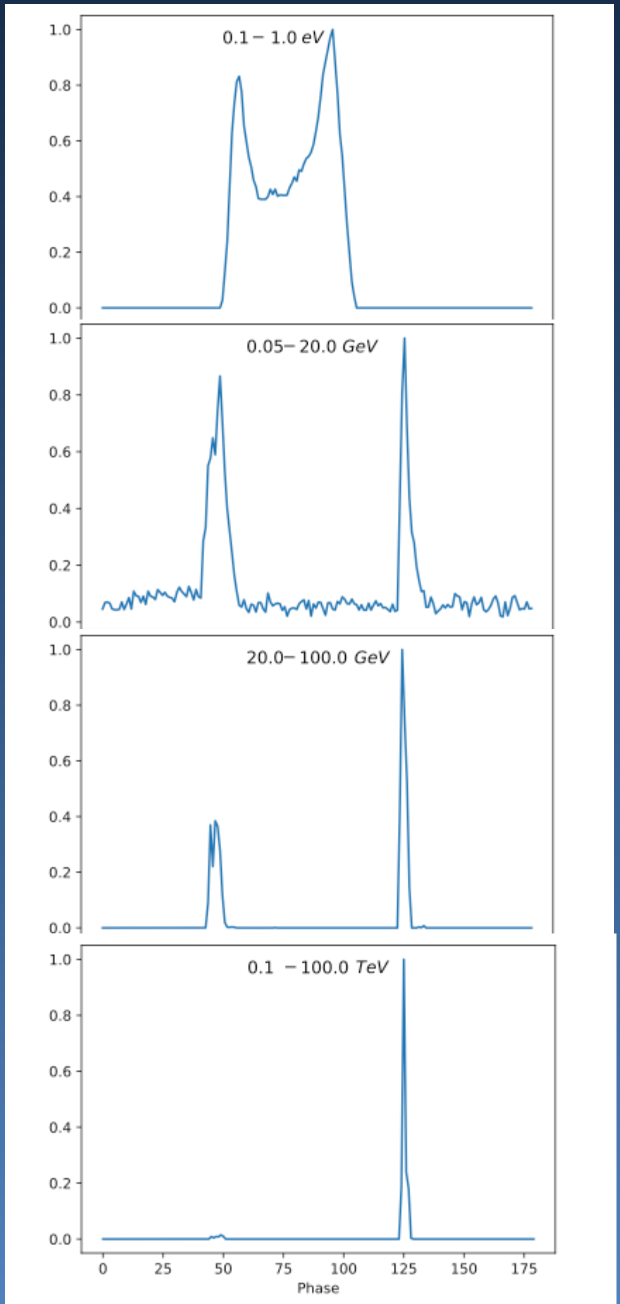
SSC emission from Vela pulsar

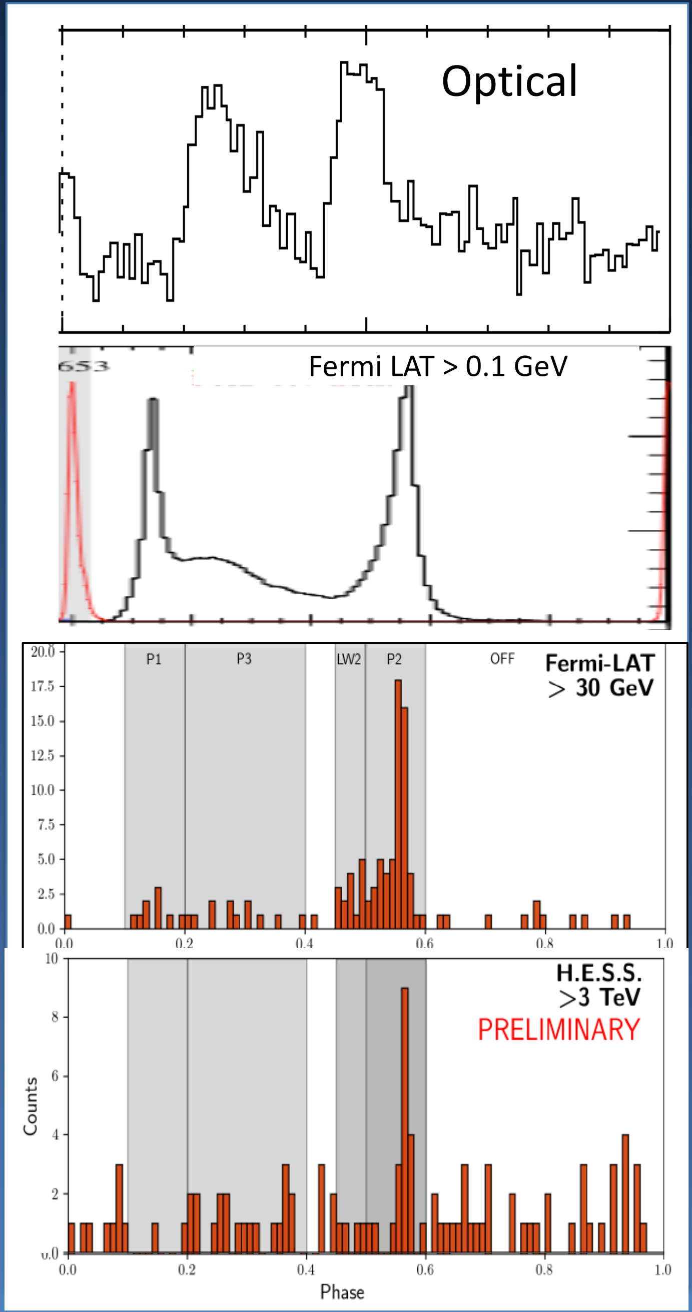
Harding & Kalapotharakos 2015

$\alpha = 75^0$, $\zeta = 60^0$



Model light curves





Harding, Kalapotharakos, Venter & Barnard 2018

Fermi P2/P1 increases with energy – higher γ particles produce P2

P2 only at > 3TeV – ICS from highest γ particles

Large model γ-ray/radio phase lag due to azimuthally symmetric emission in current sheet

What's important?

TeV+ emission from primary IC:

- Particle energies at least 10 TeV
- High flux of optical/UV emission (Not necessarily correlated with pair multiplicity!)
- Small distance between optical/UV and primaries in current sheet

SSC emission from pairs:

- High pair multiplicity
- High B_{LC}
- Lower pair energies – SR SED peak below 1 MeV – to avoid KN reduction

Summary and future prospects

- Fermi and ACTs are providing ground-breaking results
- Recent progress in global modeling of pulsar magnetospheres
  - Identified location of particle acceleration and high-energy emission – mostly current sheet
  - Good match between predicted and observed emission properties
- Unresolved questions
  - How to scale PIC model energies up to real pulsar energies
  - What is the GeV radiation mechanism (CR, SR, ICS, SSC)?
    Spectra of VHE emission components critical
  - What is the primary source(s) of pairs?
  - How to incorporate pair microphysics into global models