A Synchrotron-Self Compton Model for Pulsar Emission

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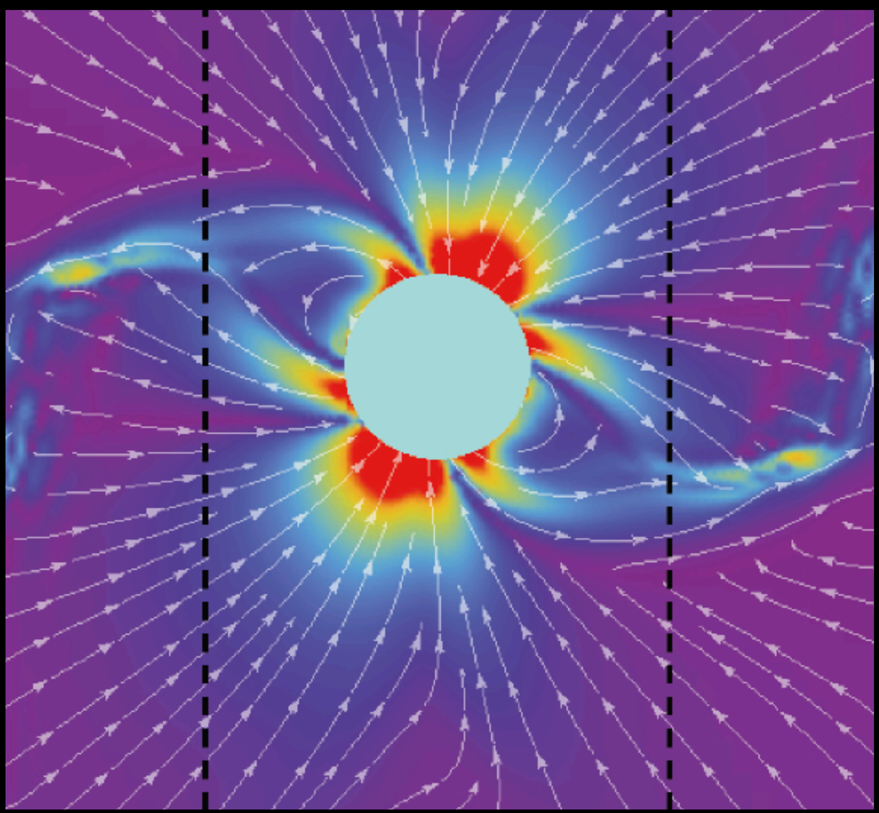
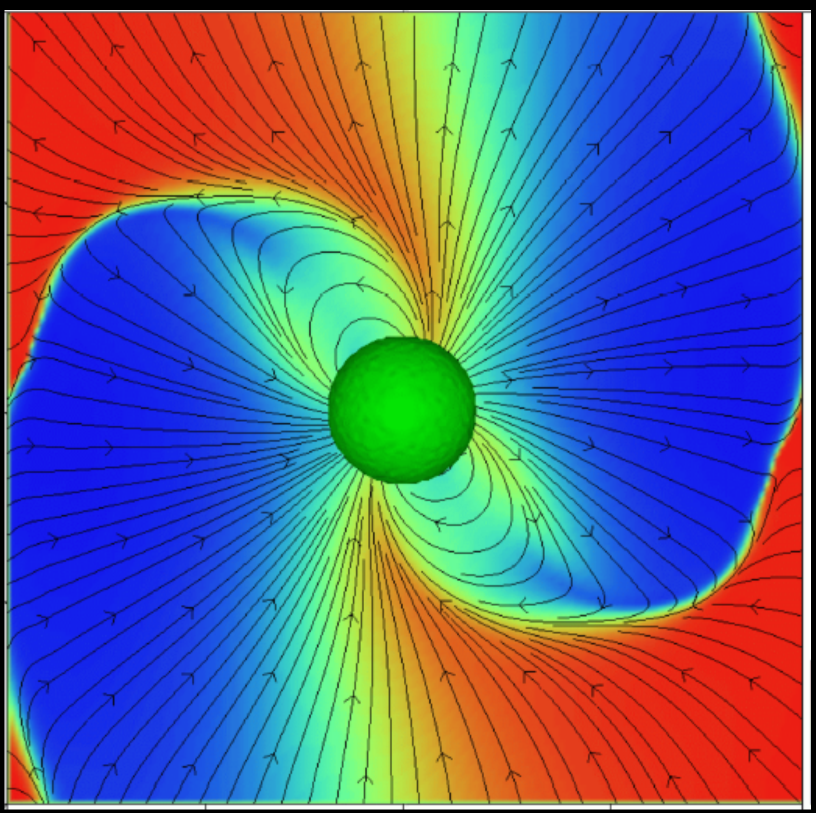
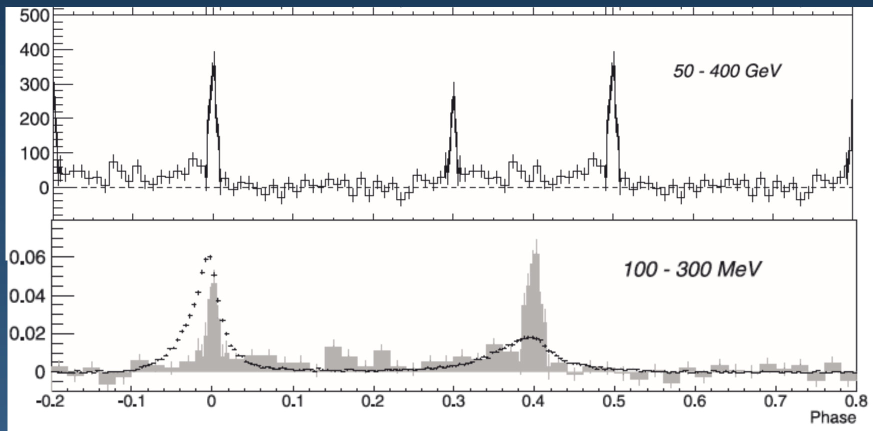


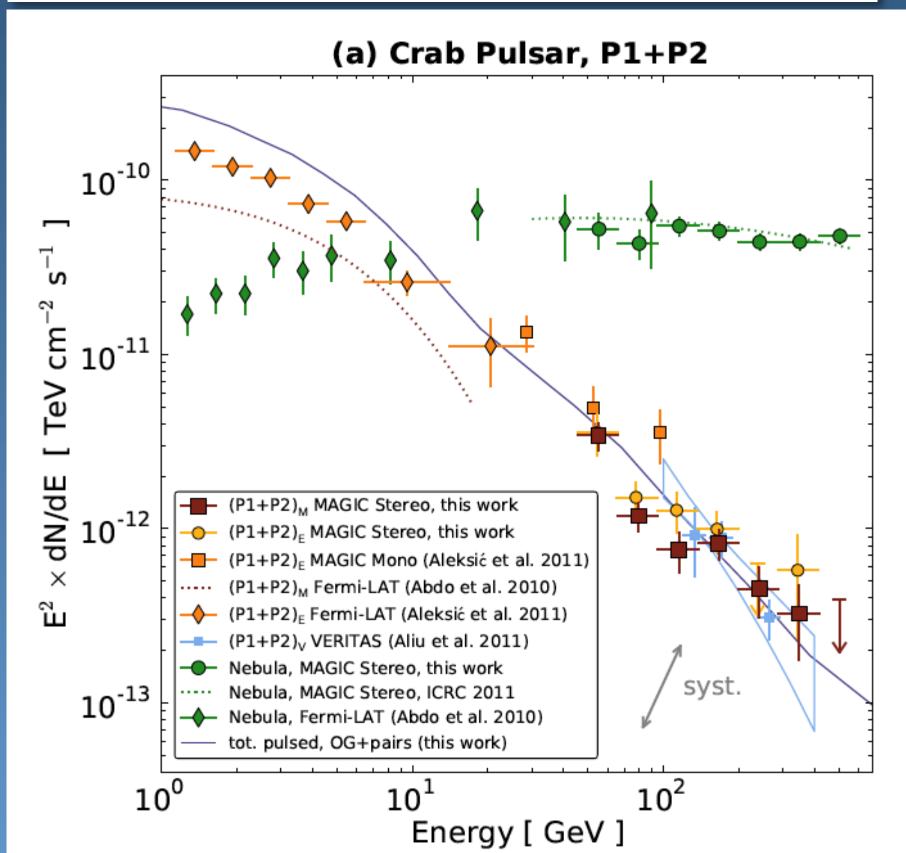


VERITAS and MAGIC detection of the Crab pulsar



Pulsed emission up to at least 400 GeV and possibly 1 TeV!

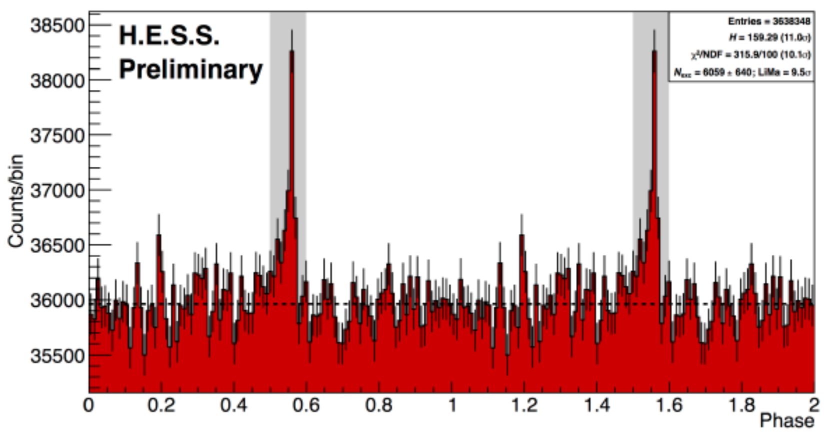
Aliu et al. 2011
Aleksic et al. 2011, 2012, 2014
Ansoldi et al. 2015



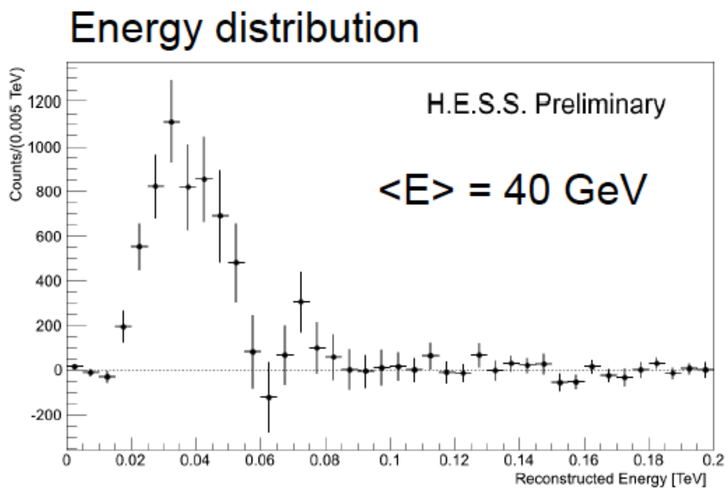
- Cutoff of combined spectrum is not simple exponential
- Extension of Fermi spectrum or separate component (inverse Compton)?
- Is the Crab unique or do other pulsars have > 100 GeV emission as well?

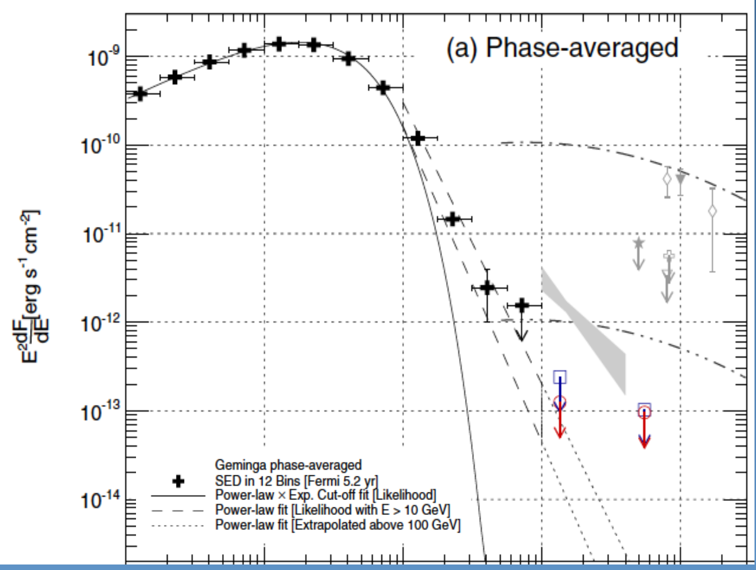
VHE emission from other pulsars?

Vela detected by HESS (Stegmann 2014, talk by B. Rudak)



Energy distribution



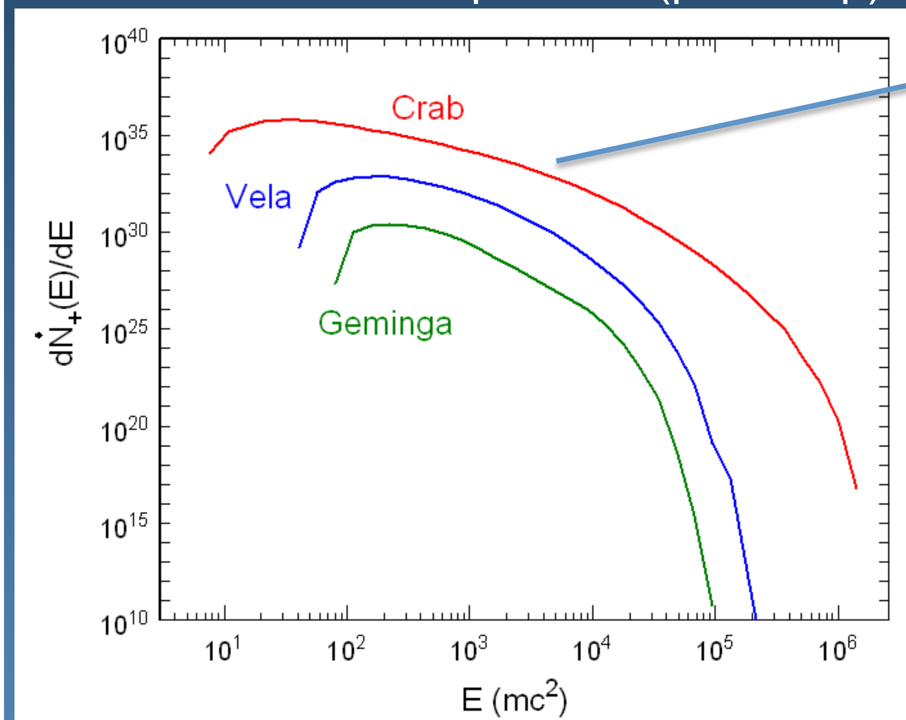


Geminga not detected by VERITAS (Aliu et al. 2015)

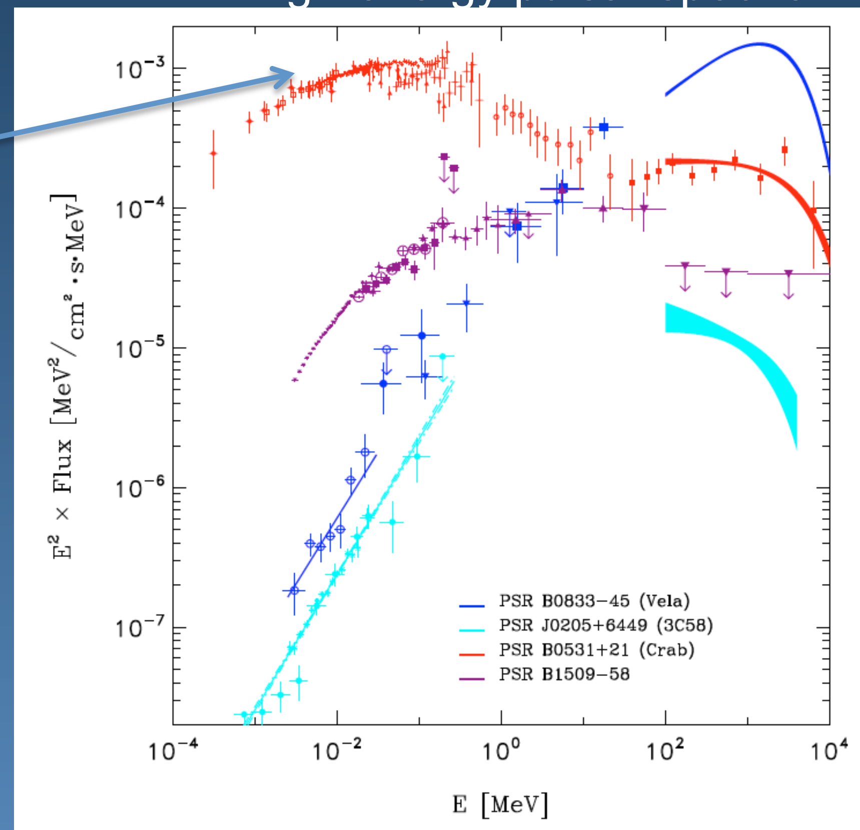
Synchrotron self-Compton emission

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

Pair cascade spectrum (polar cap)



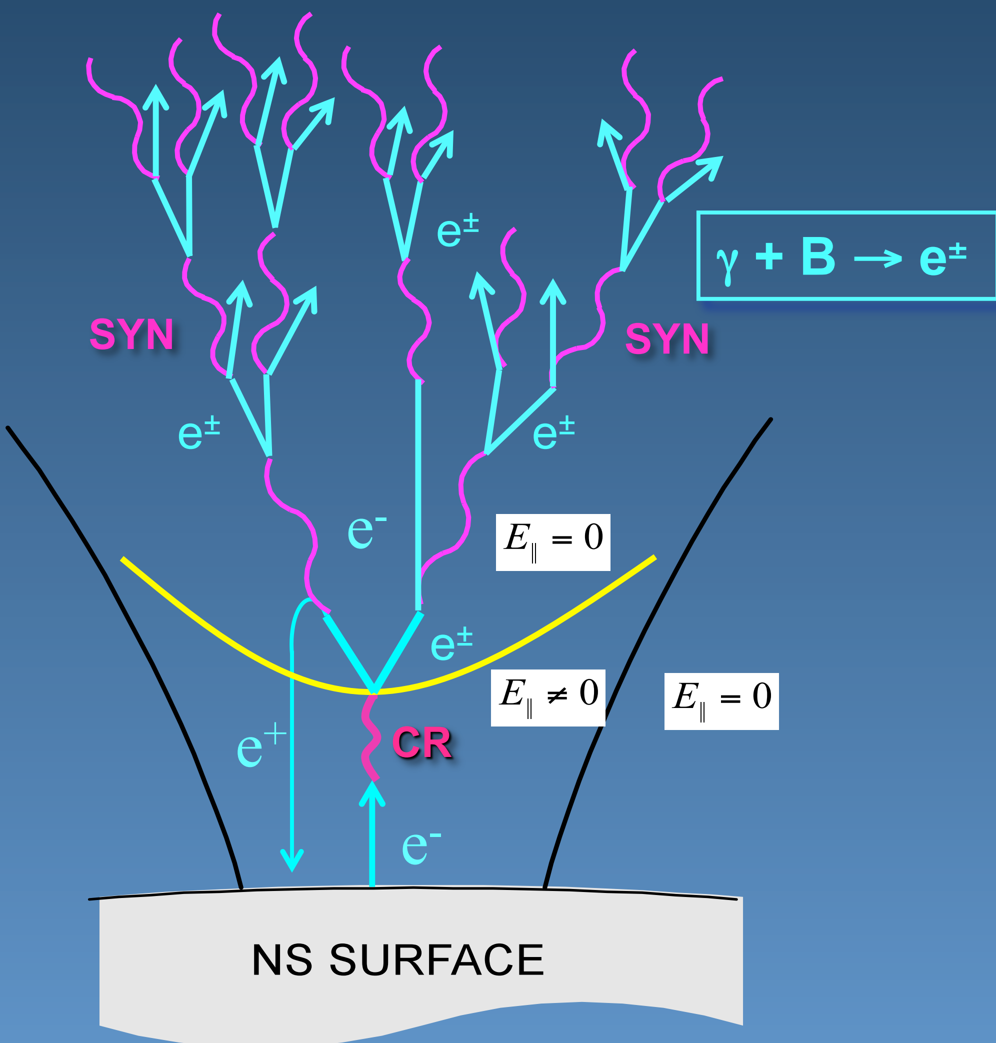
High-energy pulsar spectra



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

SSC emission from middle-aged pulsars will be much lower

Polar cap pair cascades



Pair cascades above the PC are necessary for coherent radio emission
Cascades are likely time-varying

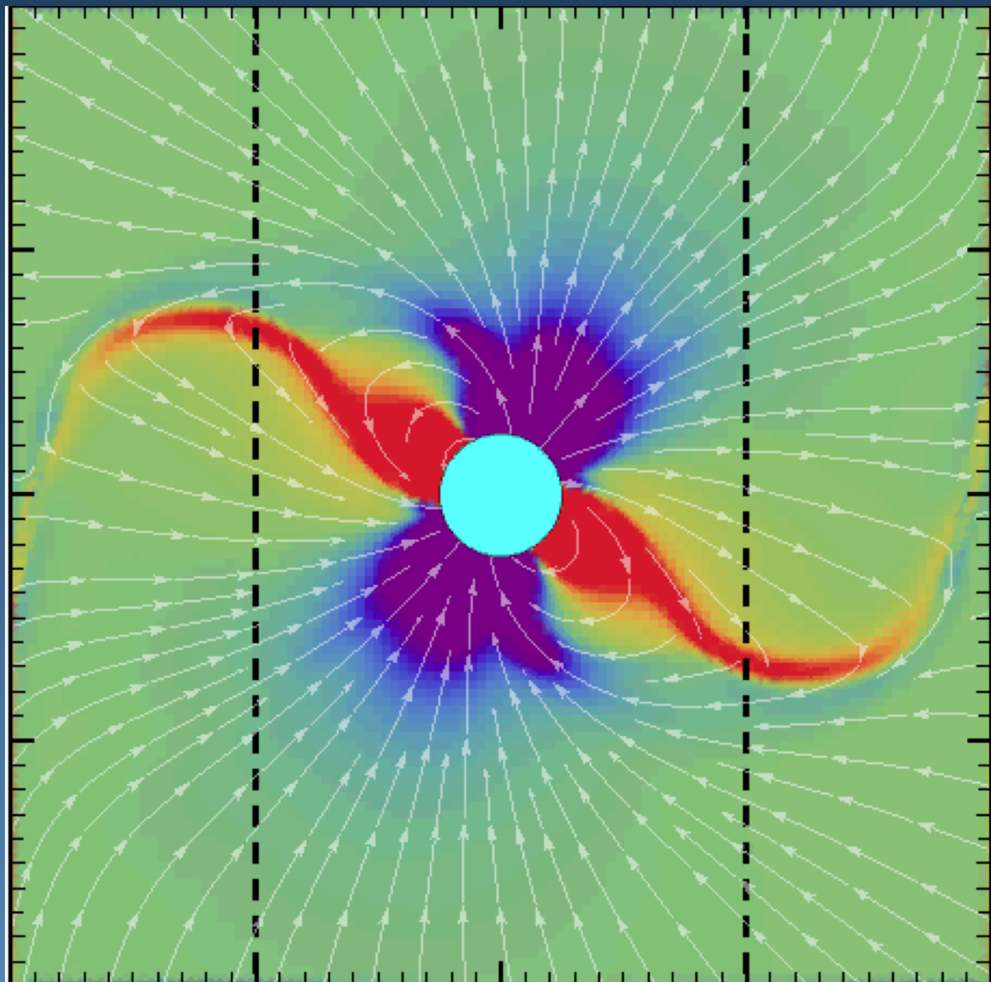
Timokhin 2010, Timokhin & Arons 2013

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

$$M_\pm \approx 10^3 - 10^5$$

Timokhin & Harding 2015

Force-free magnetosphere geometry



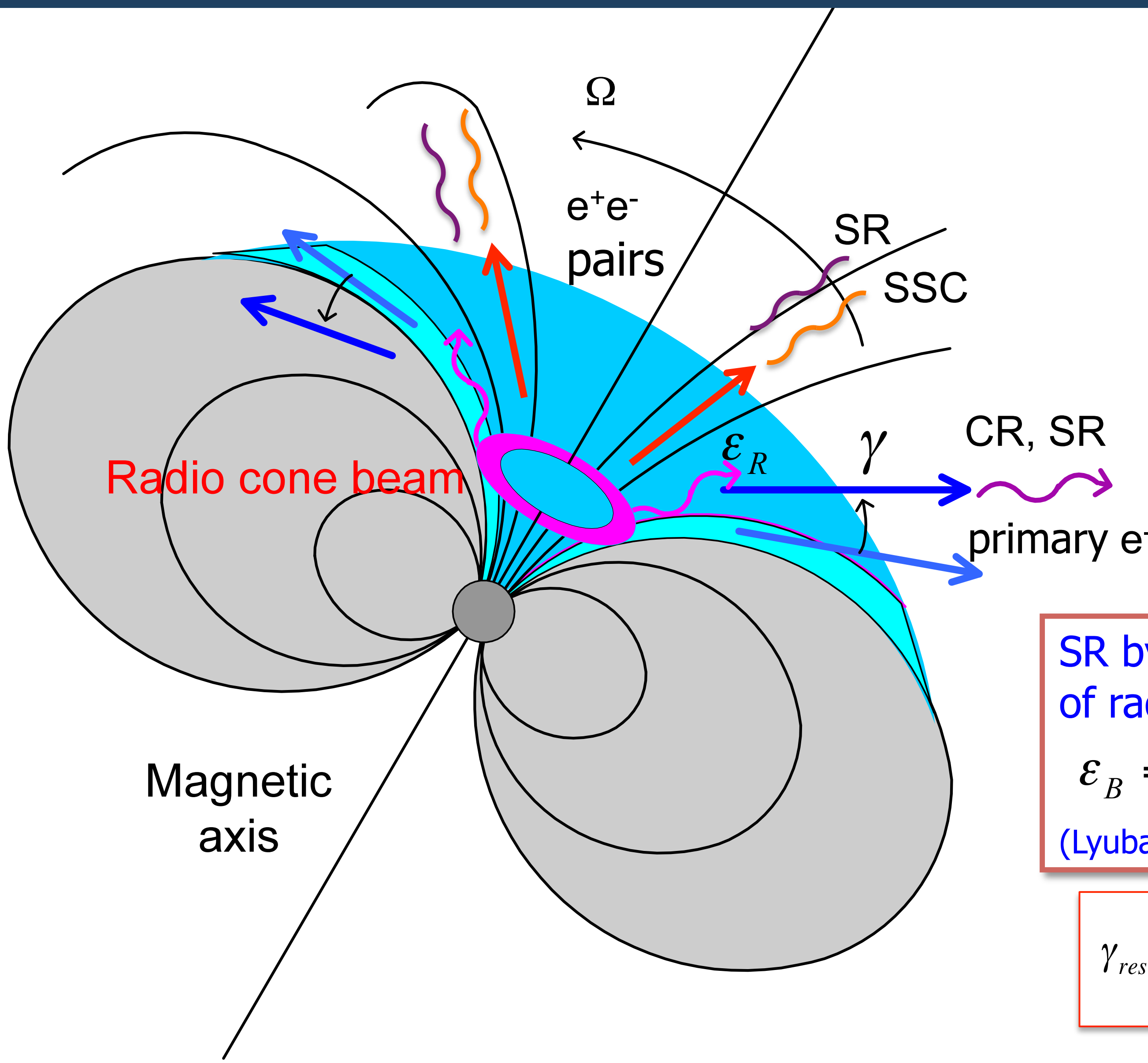
Kalapotharakos et al. 2012
Color: charge density, Streamlines: magnetic field

- 3D Cartesian grid with resolution 0.02 R_{LC} from r = 0.2 - 2 R_{LC}
- Match with dipole down to "real" pulsar surface
- Inject primary e^- and pairs at points on surface between r_{ovc} = 0.95 – 0.99 (e^-) and 0.91 – 0.95 (pairs)

Particle trajectories in force-free magnetic field, R_* to $2R_{LC}$

$$\beta = \frac{\mathbf{E} \times \mathbf{B}}{B^2 + E_0^2} + f\,\frac{\mathbf{B}}{B} = 1$$

Simulation of pulsar radiation



Primaries and pairs emit curvature (CR), synchrotron (SR) and SSC

SR by resonant absorption of radio photons when

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

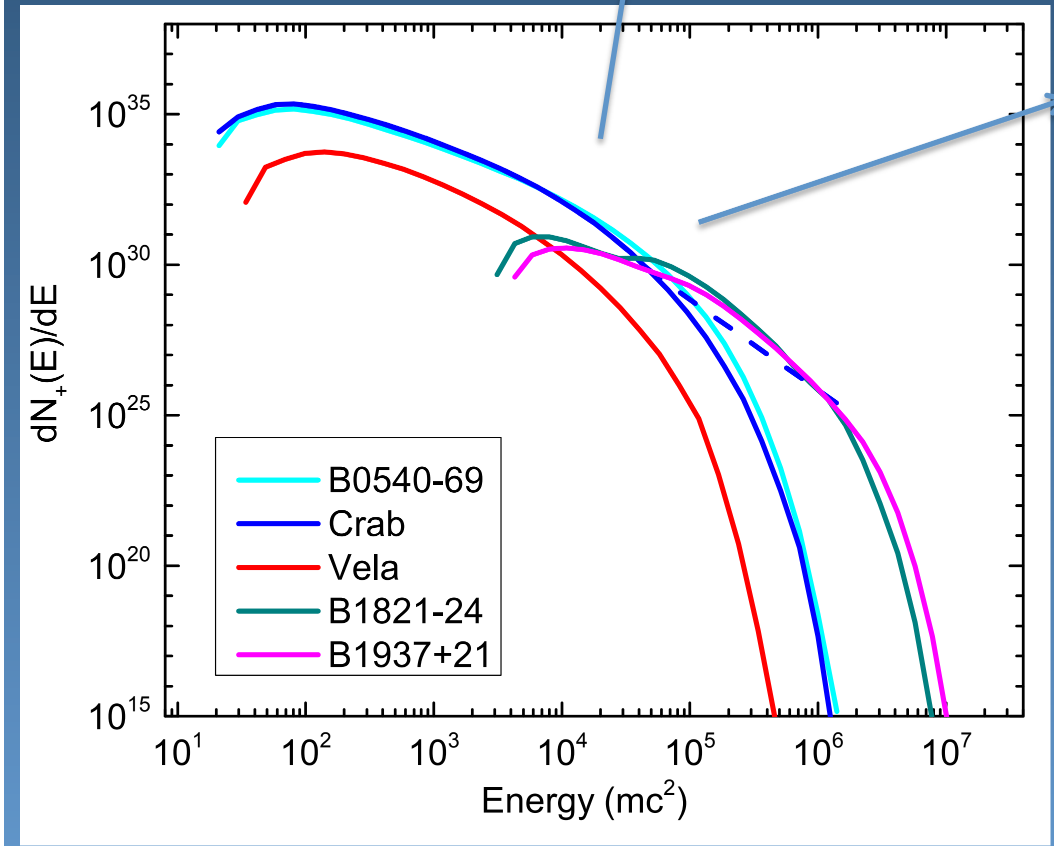
(Lyubarski & Petrova 1998)

$$\gamma_{res} = 3 \times 10^3 \frac{B_6}{\varepsilon_{R,GHz}(1 - \beta\cos\theta)}$$

Synchrotron self-Compton emission

$$\frac{d\dot{N}_{SSC}(\varepsilon_s)}{d\varepsilon_s d\Omega_s} = \int dE\, n_\pm(E) \int d\Omega \int d\varepsilon\, n_\gamma(\varepsilon,\Omega) \frac{d\sigma_{KN}(\varepsilon,\Omega)}{d\varepsilon d\Omega}(1-\beta\cos\theta)$$

Pair cascade spectrum (polar cap)



Synchrotron photon density

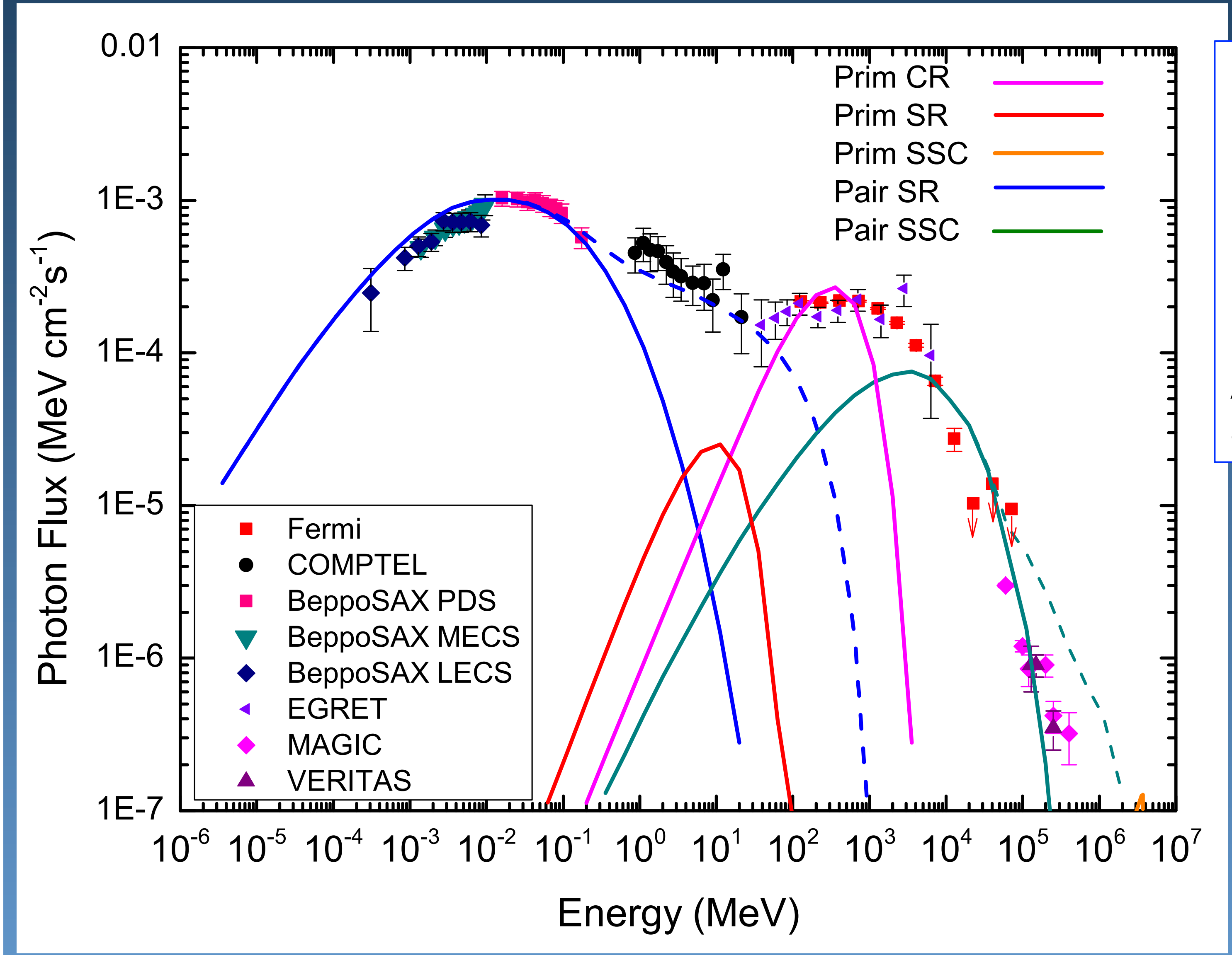
$$n_\gamma(\varepsilon,\Omega) = \frac{1}{c}\int dr\, r^2 \frac{\varepsilon_{SR}(\varepsilon,\Omega,r)}{r_s^2}$$

SSC calculation in two steps:

1. SR emission, SR photon density
2. SSC emission

SSC emission from Crab pulsar

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



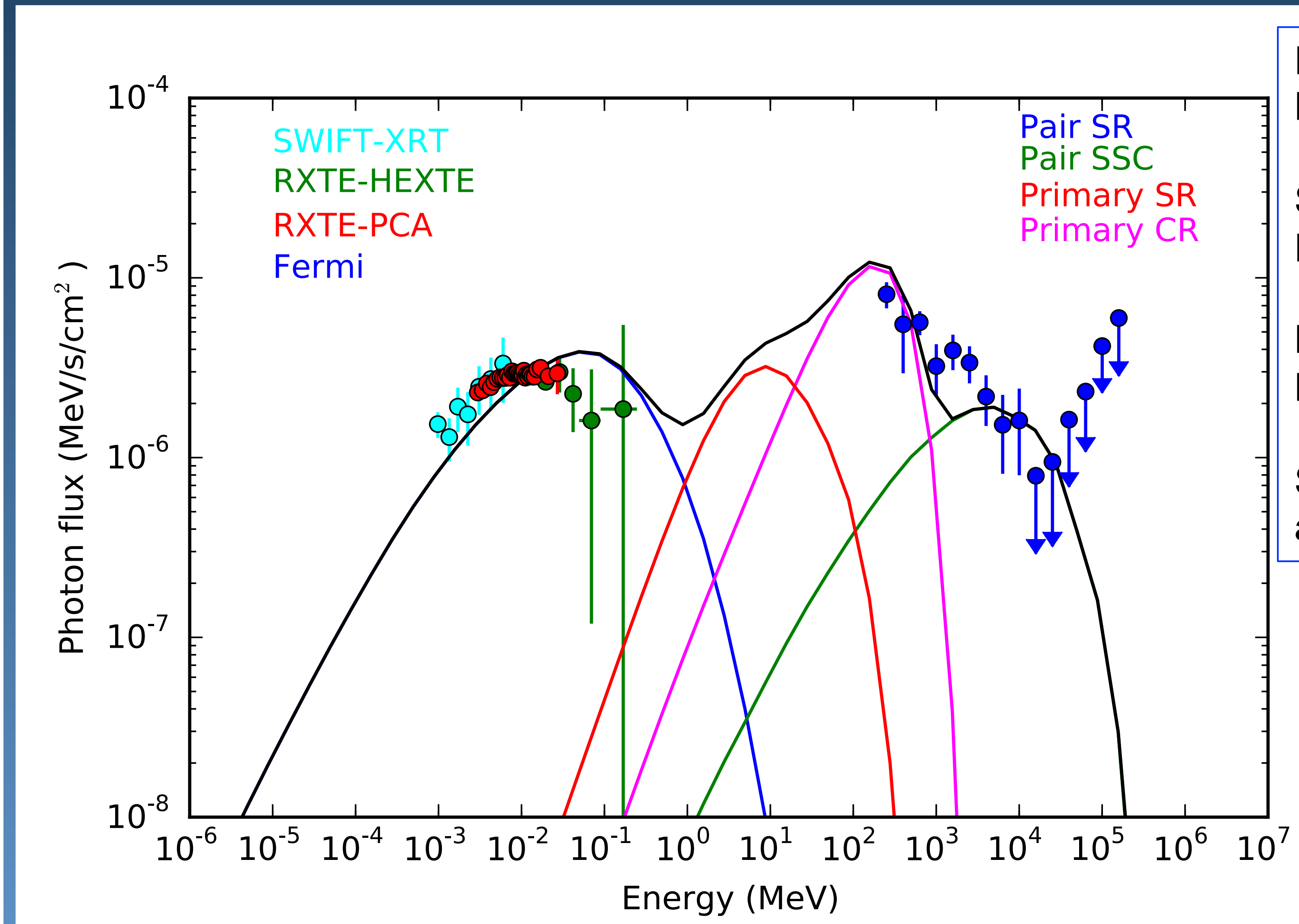
High
$B_{LC} = 1 \times 10^6$ G
$L_R = 2200$ mJy kpc^2

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

All good for SR and SSC

SSC from Crab-like pulsar B0540-69

Harding & Kalapotharakos 2015 $\alpha = 45^0$, $\zeta = 70^0$, $M_+ = 3 \times 10^5$



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

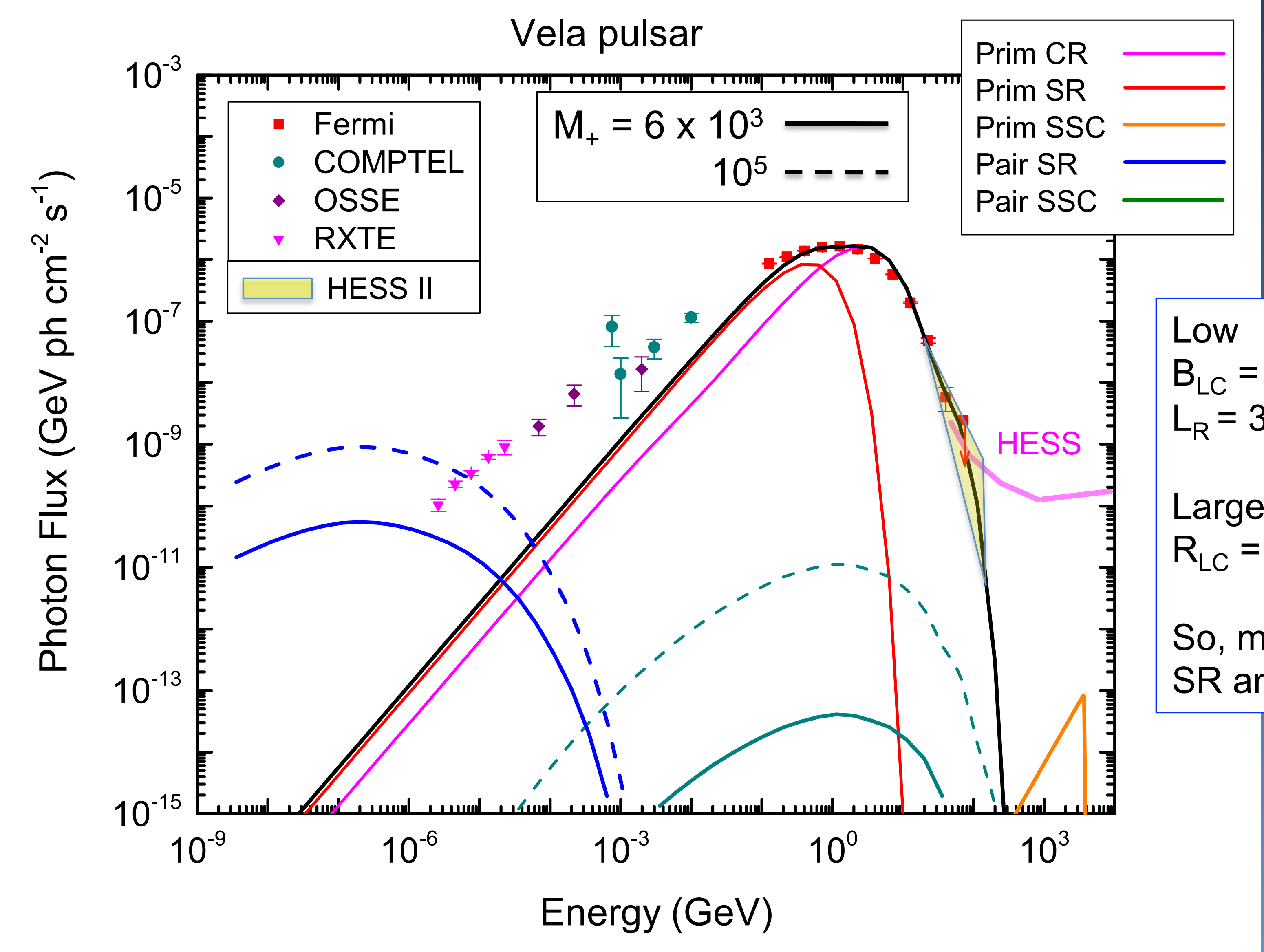
So, smaller SR and SSC

Fermi data – Ackermann et al. 2015, see poster by Martin

SSC emission from Vela pulsar

Harding & Kalapotharakos 2015

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



Low
$B_{LC} = 4 \times 10^4$ G
$L_R = 392$ mJy kpc^2

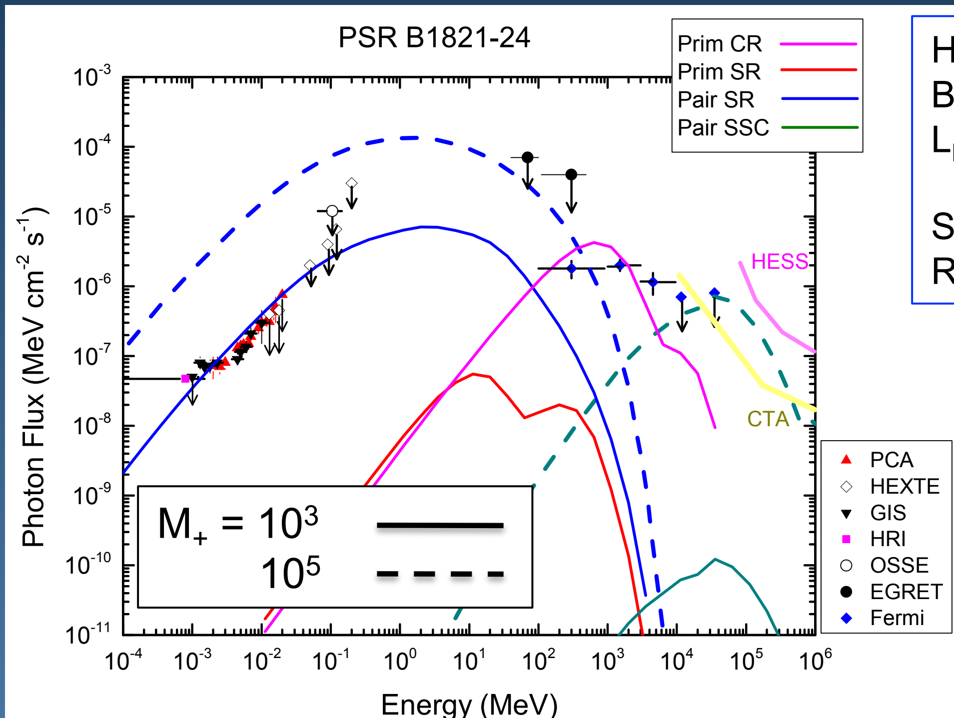
Larger
$R_{LC} = 4.3 \times 10^8$ cm

So, much smaller SR and SSC

SSC emission from MSPs

Harding & Kalapotharakos 2015

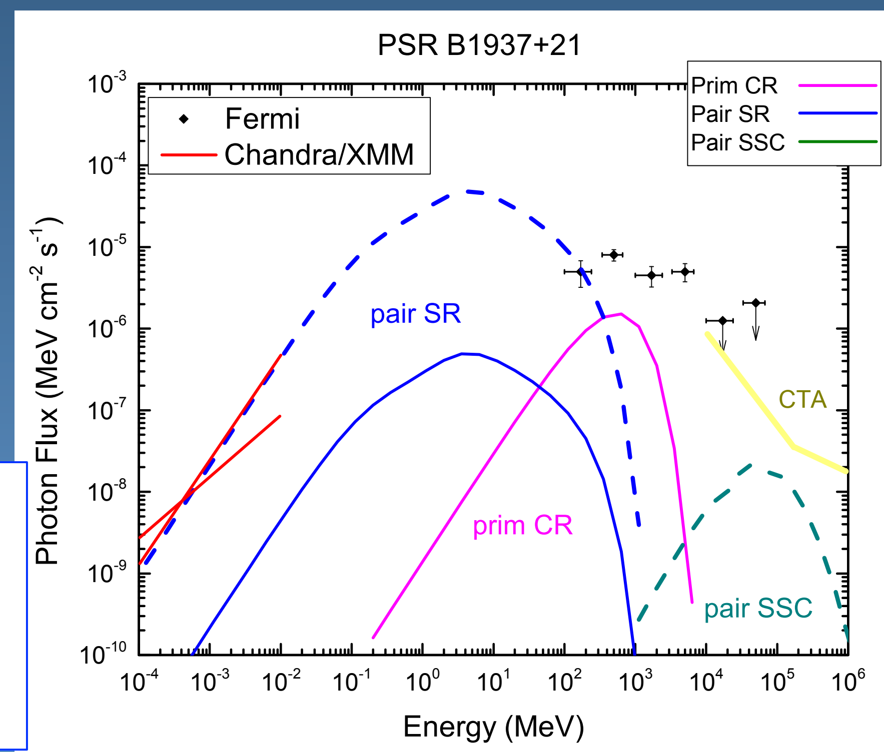
$\alpha = 45^0$, $\zeta = 80^0$



High
B_{LC} = 7.3 x 10^5 G
L_R = 1210 mJy kpc^2

Small
R_{LC} = 1.4 x 10^7 cm

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



SR spectra peak ~1-10 MeV

SSC peak ~ 100 GeV but lowered by KN reductions

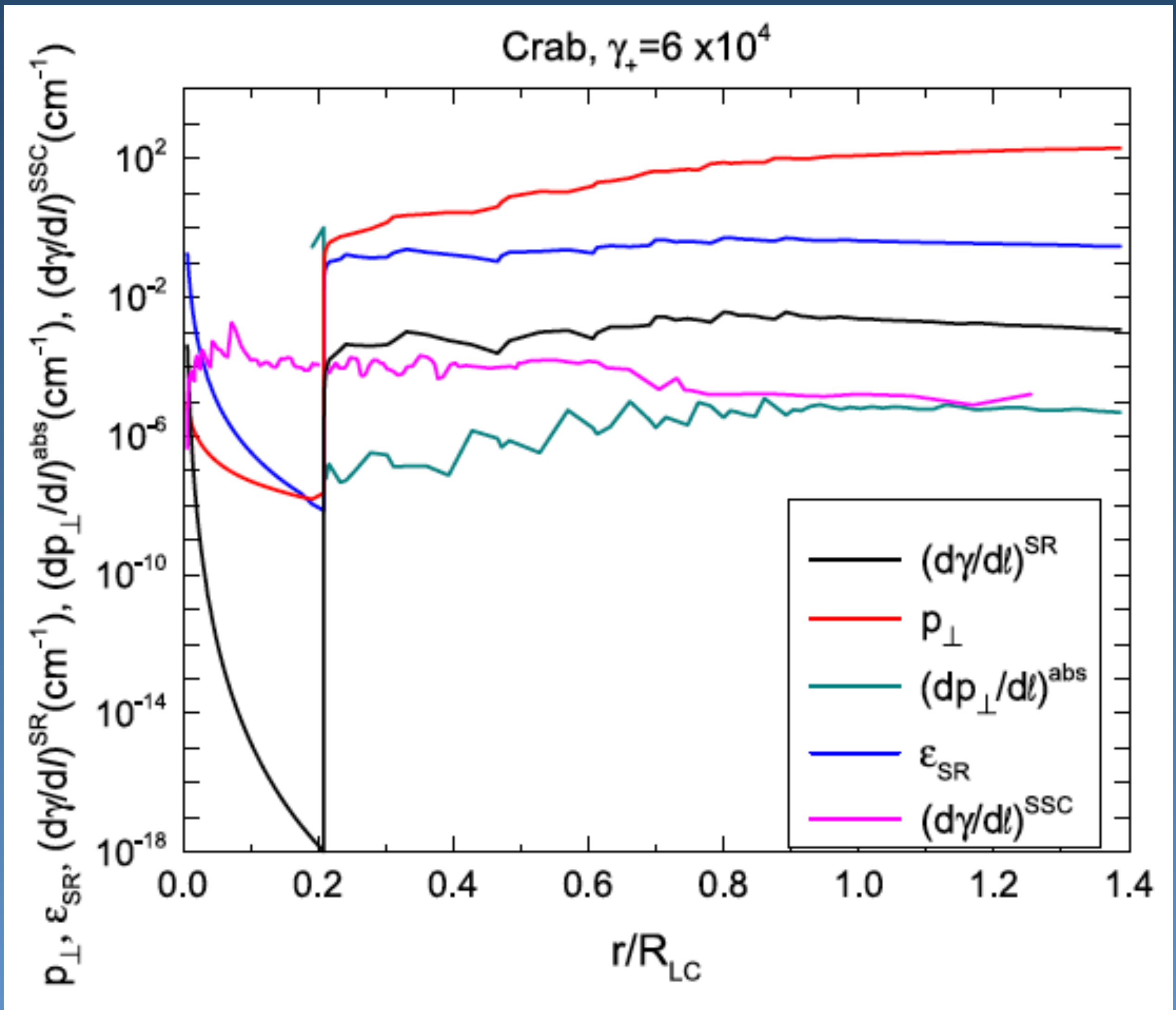
High
B_{LC} = 1 x 10^6 G
L_R = 6000 mJy kpc^2

Small
R_{LC} = 7.6 x 10^6 cm

Summary

- Synchrotron radiation from pairs can produce non-thermal X-rays in Crab-like pulsars and MSPs
- Prediction of synchrotron peak ~1-10 MeV in MSPs is testable with Compton or pair telescopes
- SSC from pairs produce VHE emission in Crab and Crab-like pulsars (high B_{LC} and M_{+})
- VHE possibly detectable from MSPs but only for high pair multiplicity
- No detectable SSC from Vela-like pulsars
- Next step: use E-field distribution from global models (see talks by Kalapotharakos and Philippov, poster by Brambilla) and self-consistent pairs

Particle trajectories



Resonant absorption →
relativistic $p_\perp$ → SR