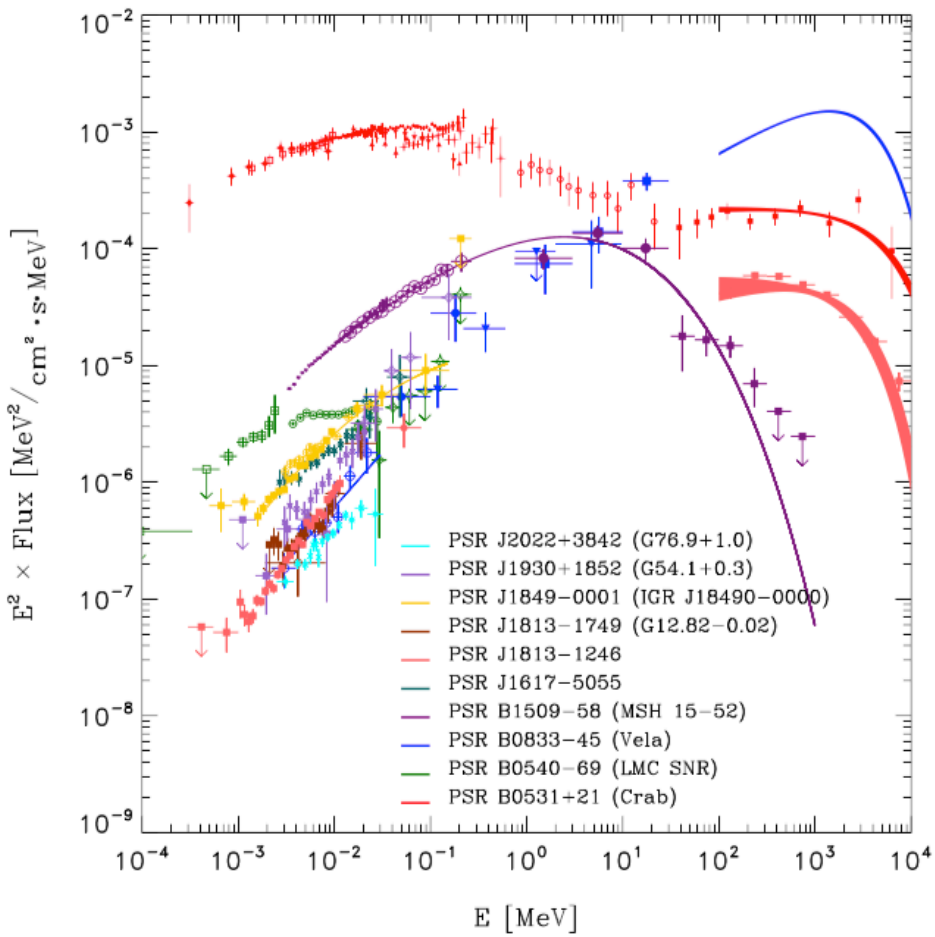
Pulsars and Magnetars at 0.1 – 100 MeV Energies

Alice K. Harding

NASA Goddard

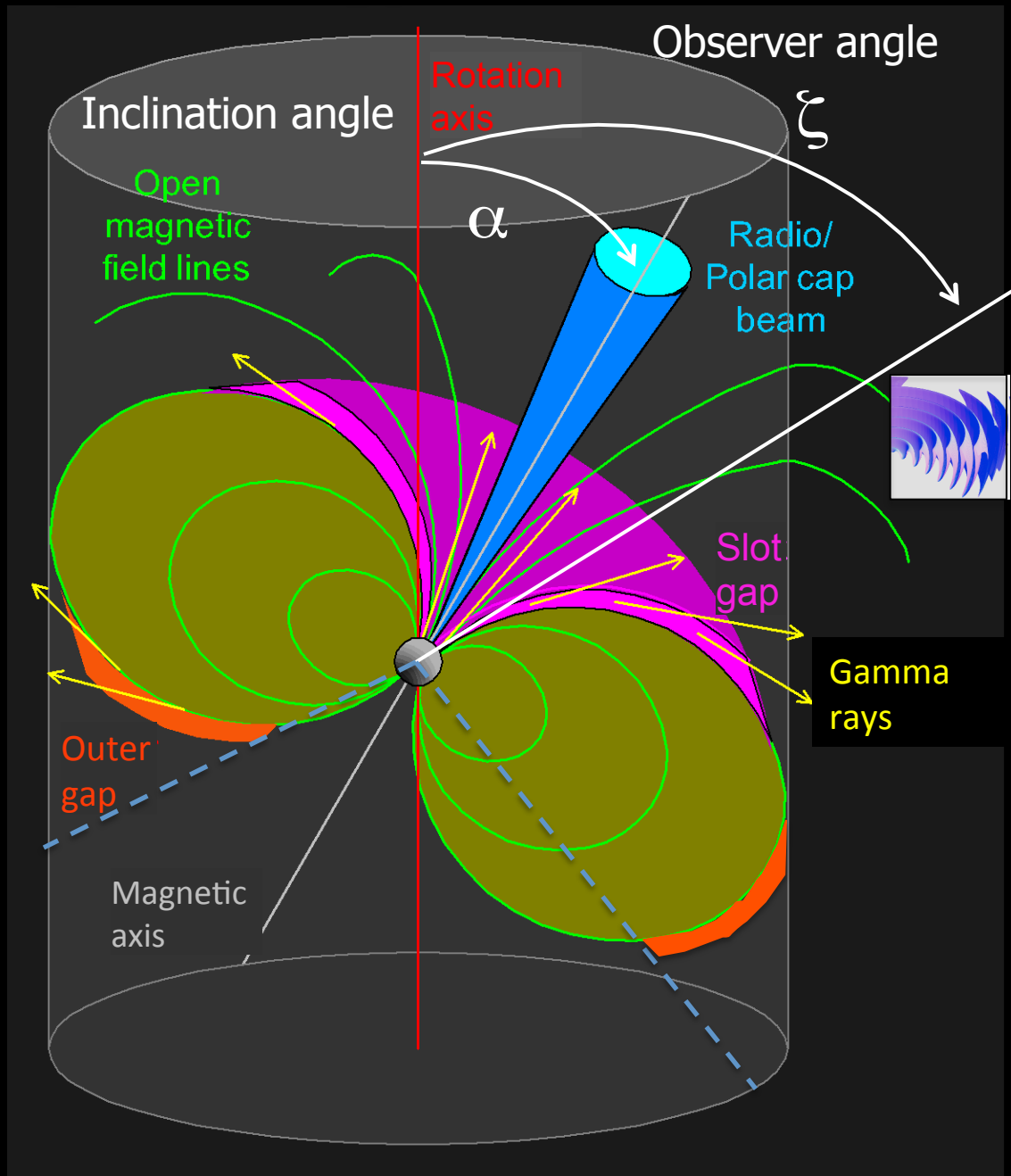
Soft γ-ray pulsar population



Kuiper & Hermsen 2015

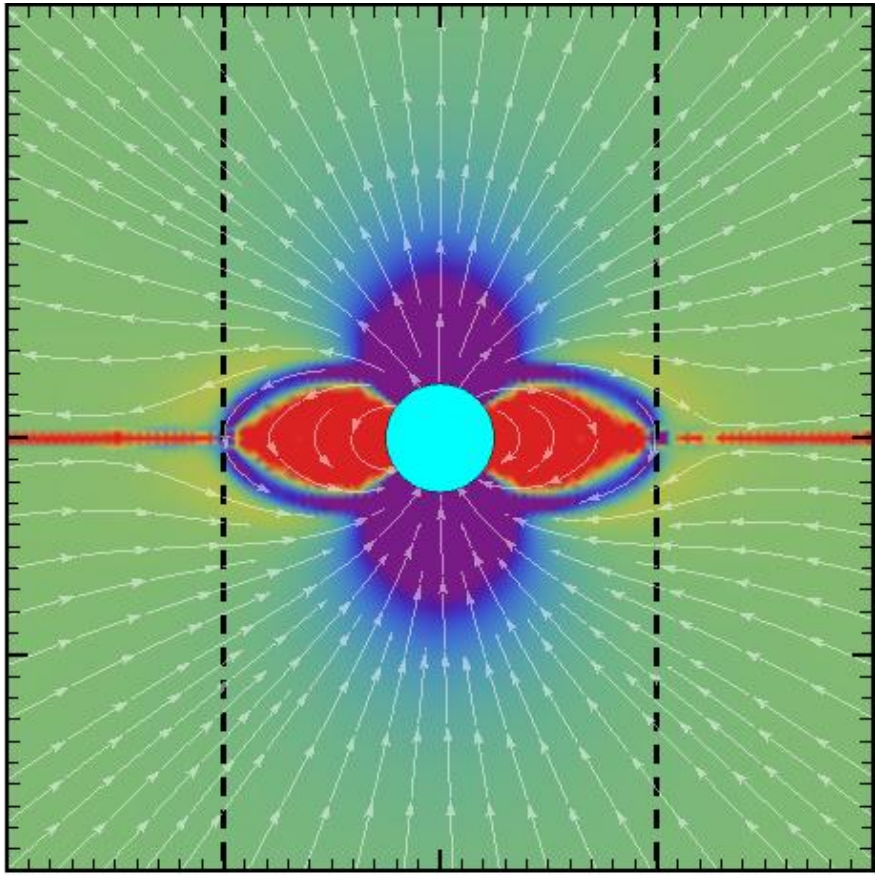
- Pulsars seen only in hard X-ray but not with Fermi
- 11 "MeV pulsars" are known, Edot > 10^{36} erg/s
- emission may probe a different part of the magnetosphere than GeV
- look for high energy spectral cutoff

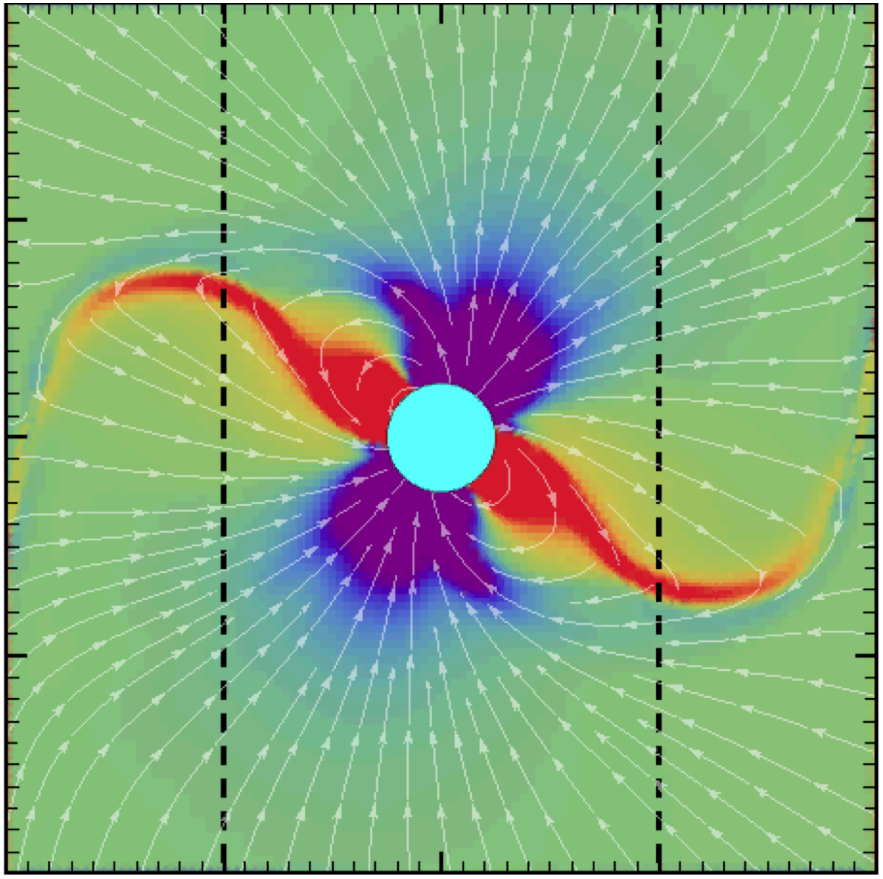
High energy emission models



MHD pulsar magnetospheres

- Contain open and closed field regions
- Contain different signs of charge
- Current sheet forms along spin equator
- Current flows out of polar regions and returns along equatorial current sheet



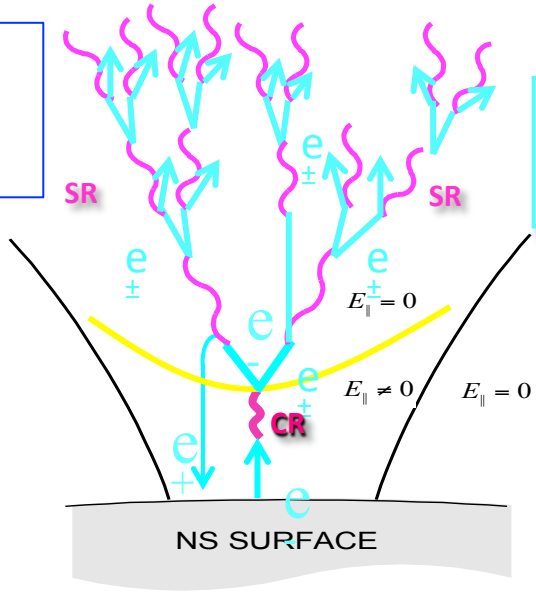


Kalapotharakos et al. 2012

Color: charge density, Streamlines: magnetic field

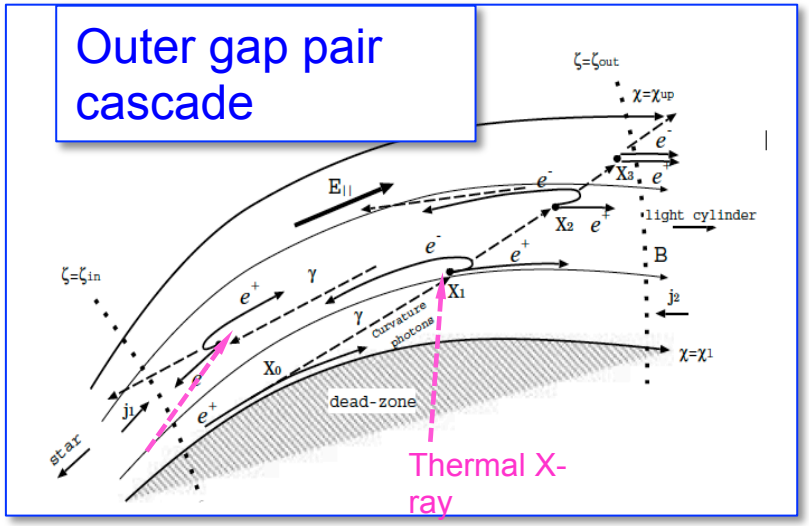
X-ray/soft γ-ray radiation from pairs

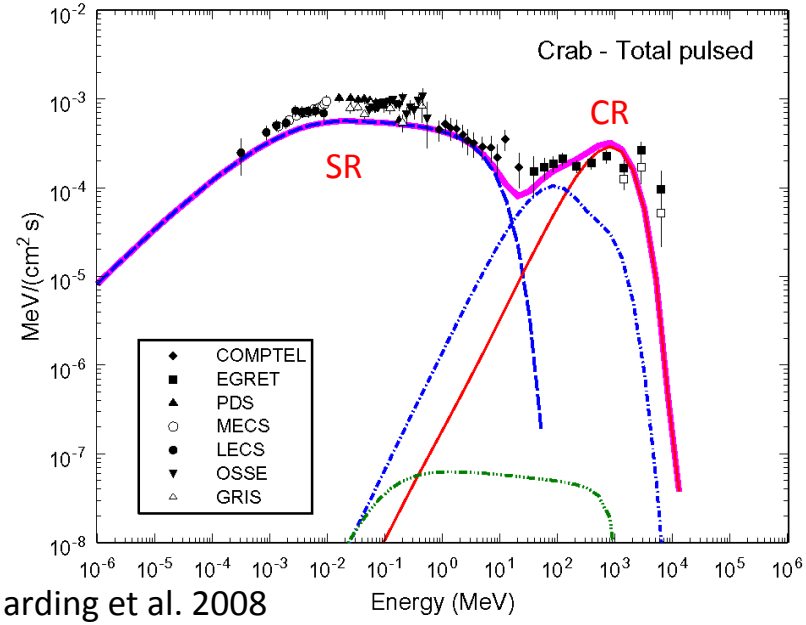
Polar cap pair cascade



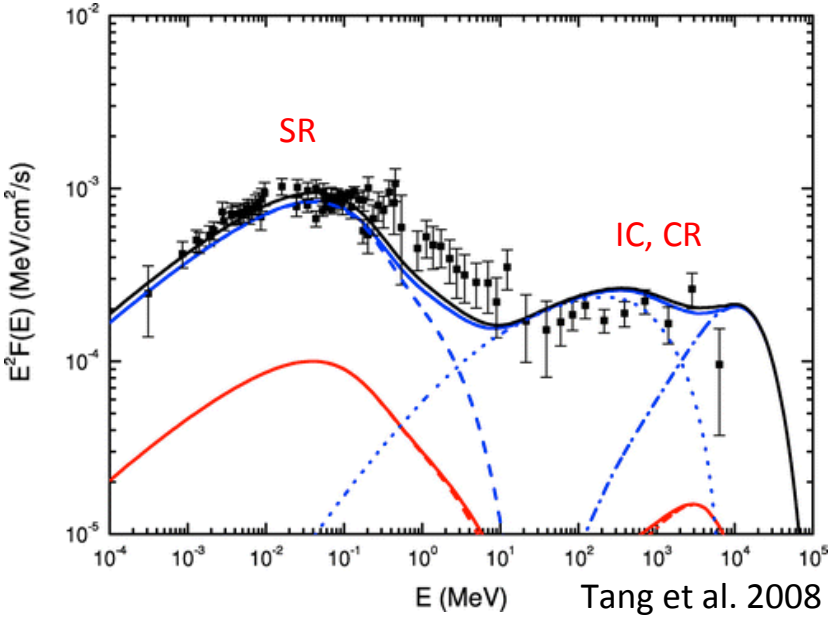
γ + B → e±

Outer gap pair cascade



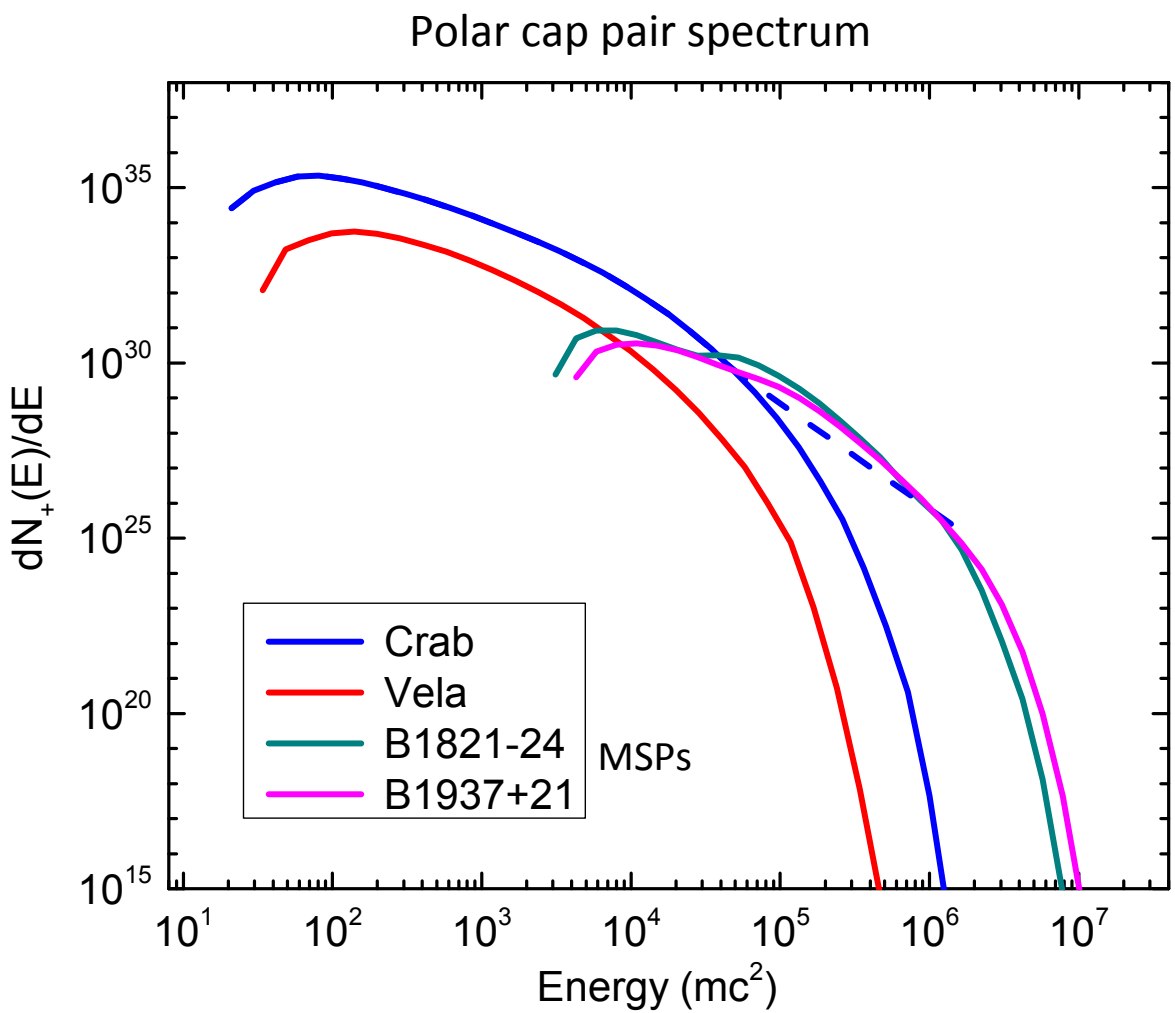


Harding et al. 2008



Tang et al. 2008

Pair cascade spectrum

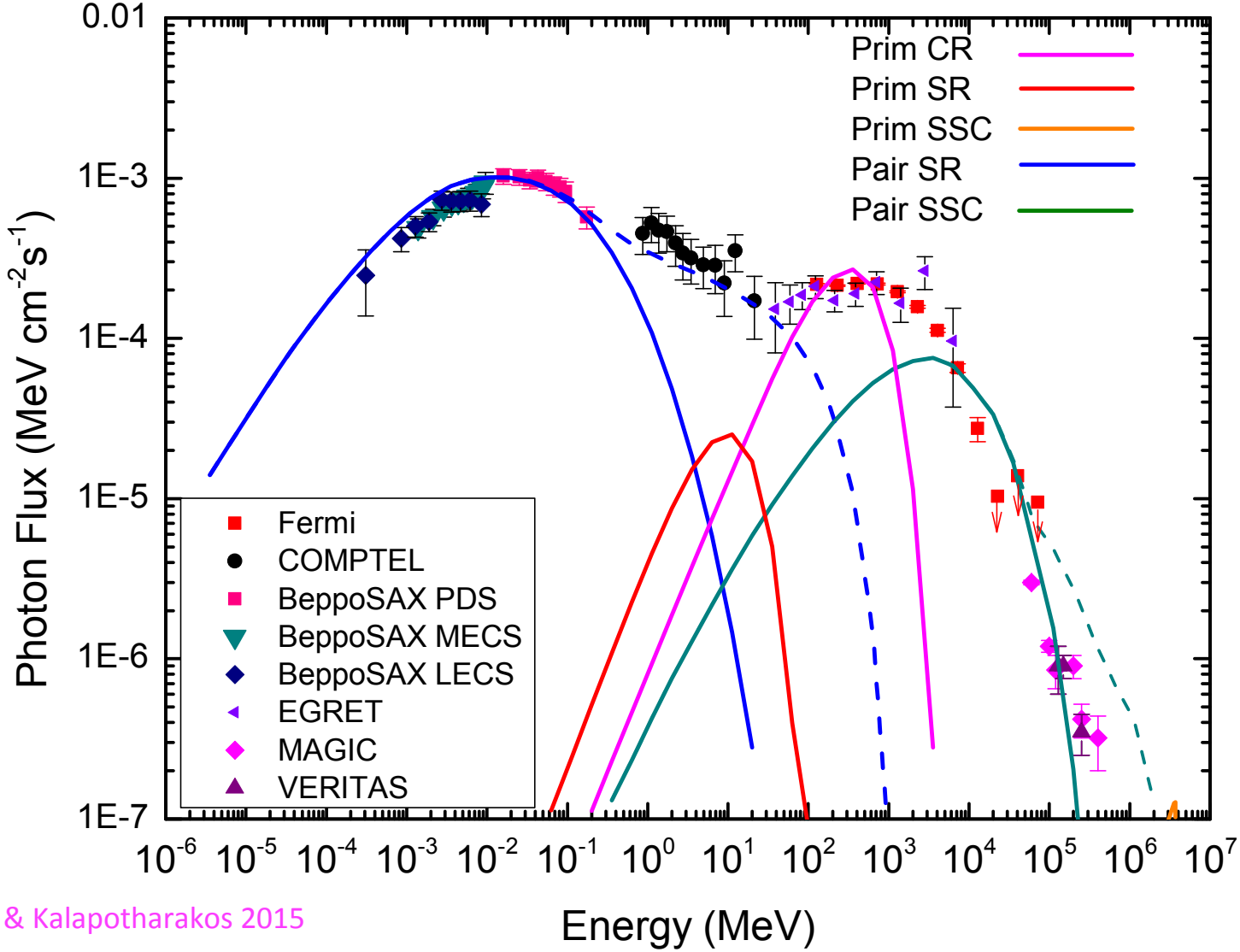


MeV γ-rays are a signature of the pair spectrum

Spectral model for Crab pulsar

Radiation from outer magnetosphere and current sheet

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

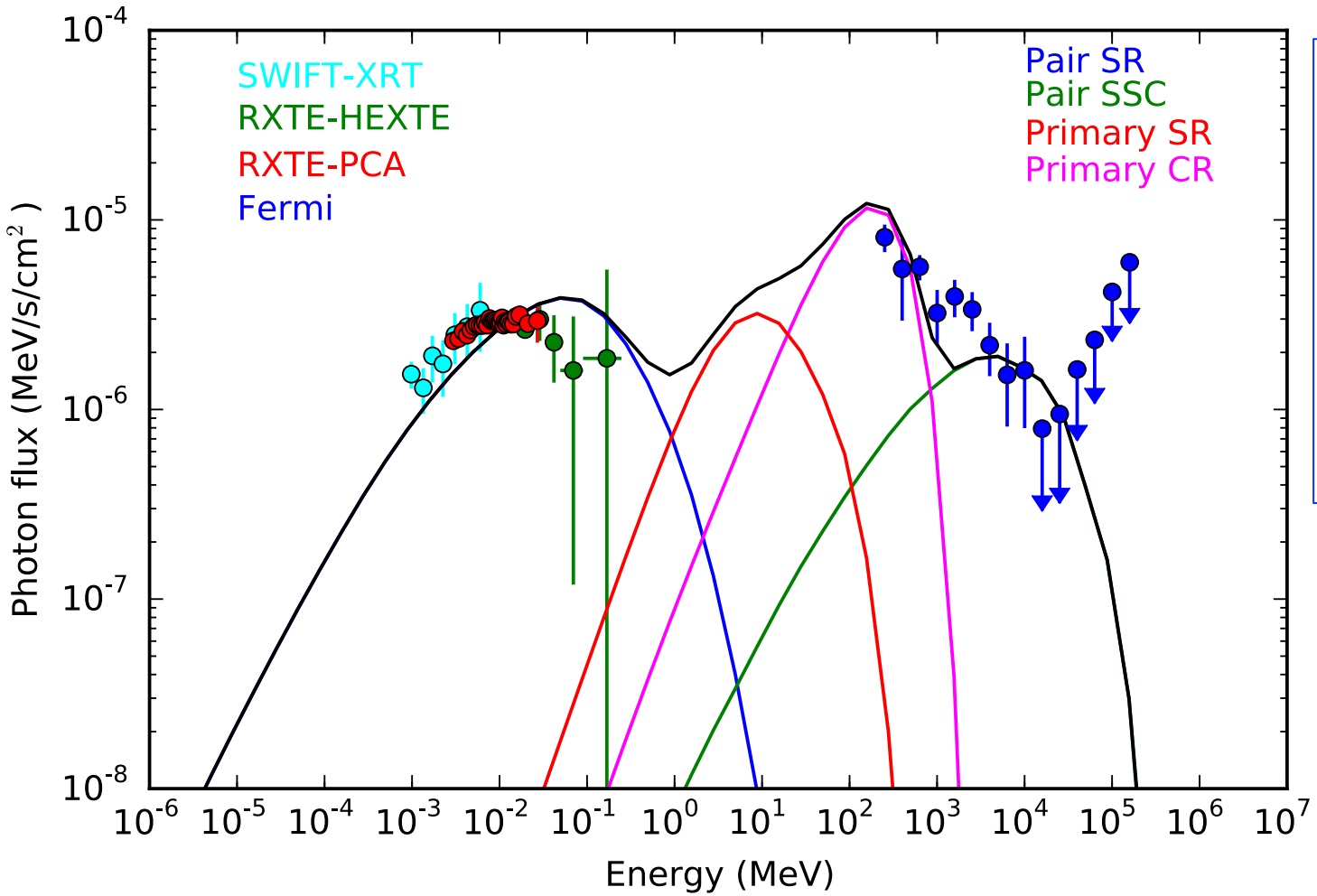


Harding & Kalapotharakos 2015

Model for Crab-like pulsar B0540-69

Harding & Kalapotharakos 2015

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



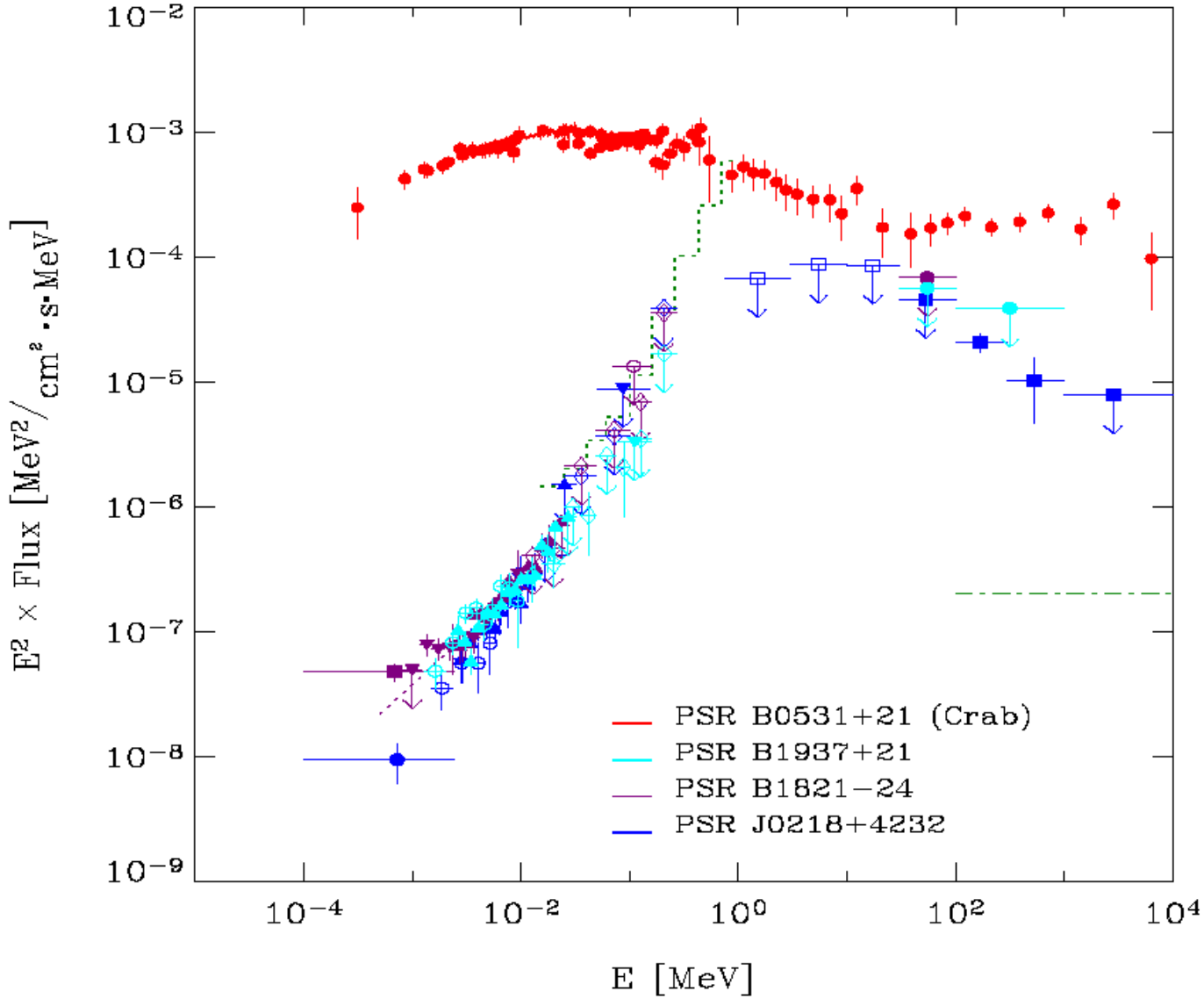
Twin J0537-6910 is an MeV pulsar – not a γ-ray pulsar

Is lack of CR component for MeV pulsars due to different viewing angle?

Fermi data – Ackermann et al. 2015

HE spectra of millisecond pulsars

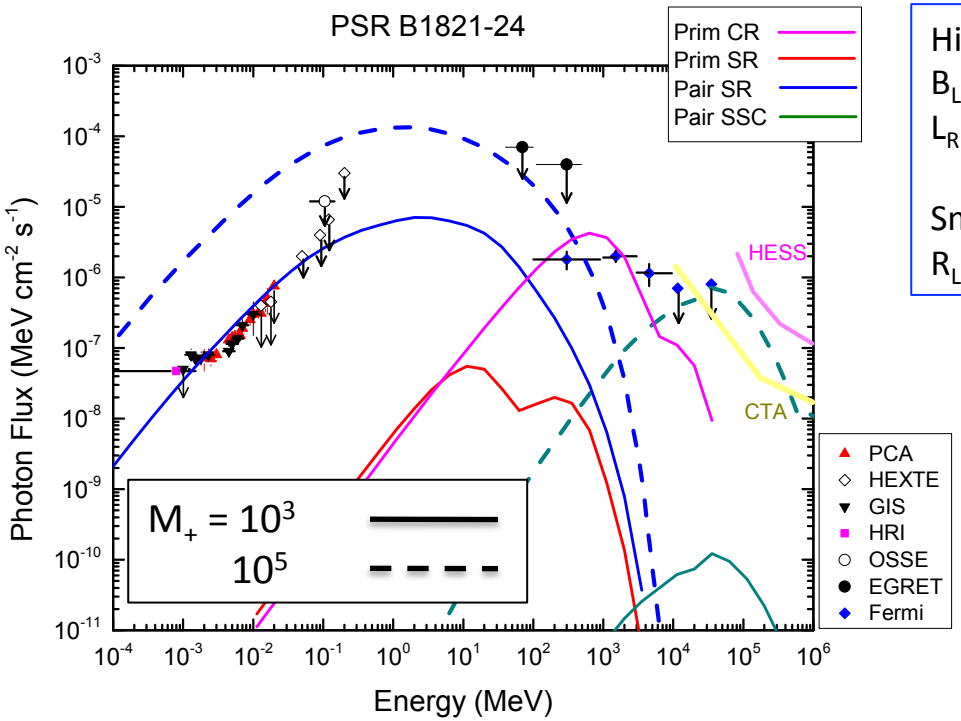
Kuiper & Hermsen2003



Spectral models for MSPs

Harding & Kalapotharakos 2015

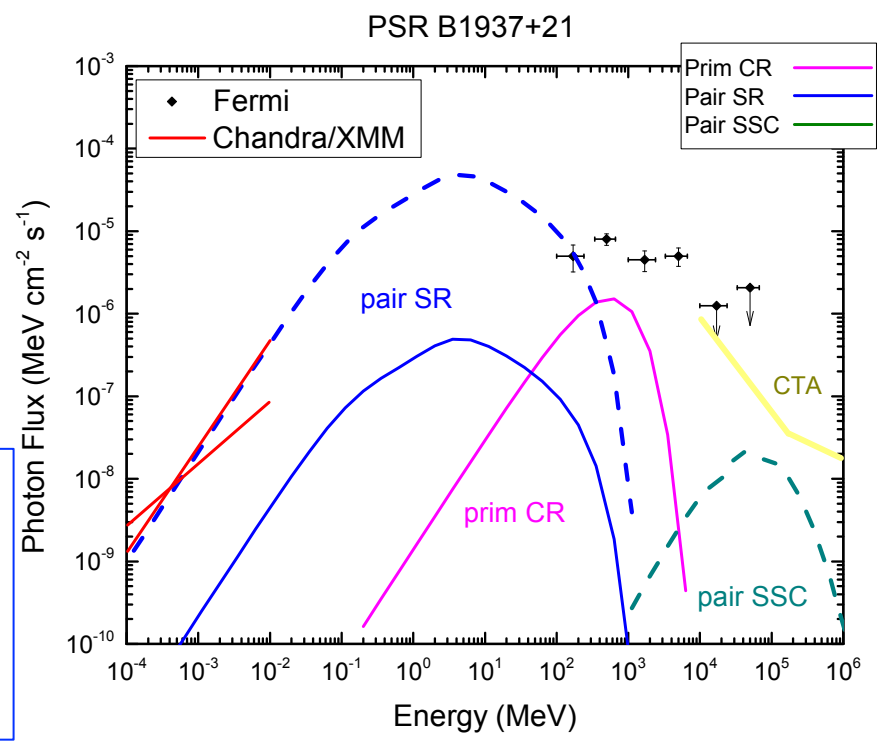
$\alpha = 45^0, \zeta = 80^0$



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

Small
$R_{LC} = 1.4 \times 10^7$ cm

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



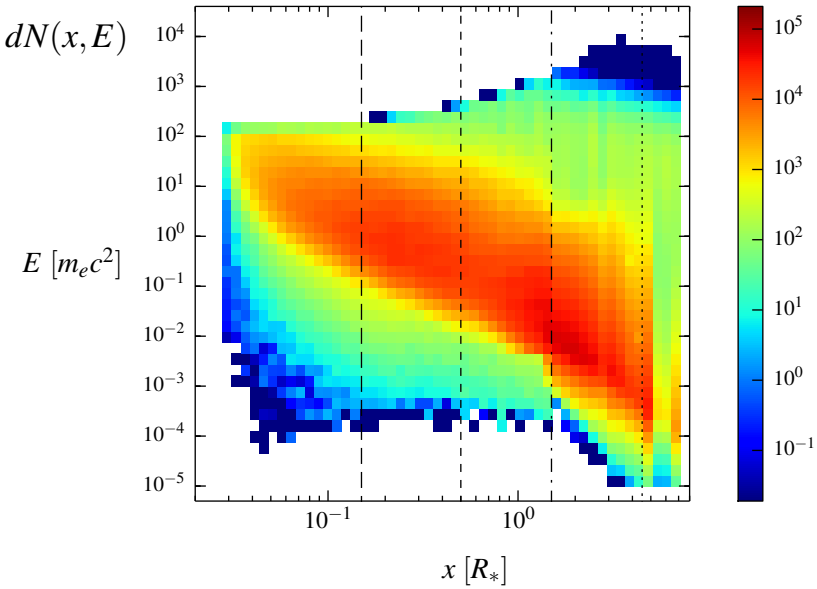
SR spectra peak ~1-10 MeV

SSC peak ~ 100 GeV but lowered by KN reductions

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

Small
$R_{LC} = 7.6 \times 10^6$ cm

Polar cap pair cascade spectra



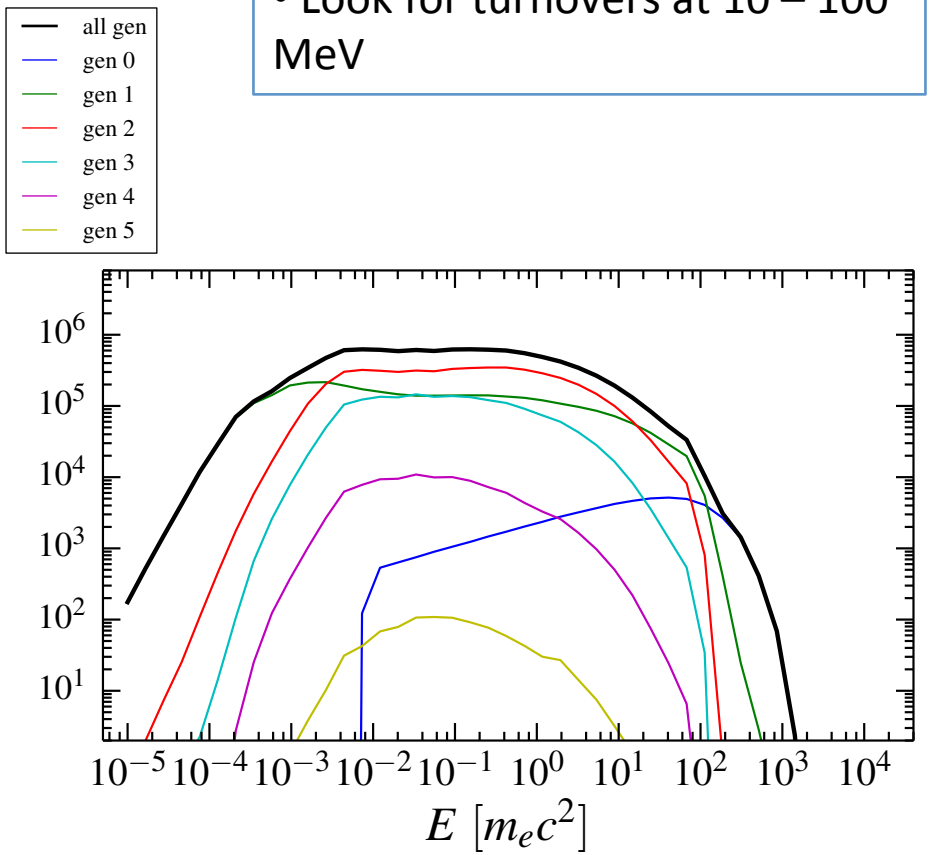
$\gamma_{\rm esc}$

- Pair cascade photon spectra have HE turnovers below 100 MeV
- Look for turnovers at 10 – 100 MeV

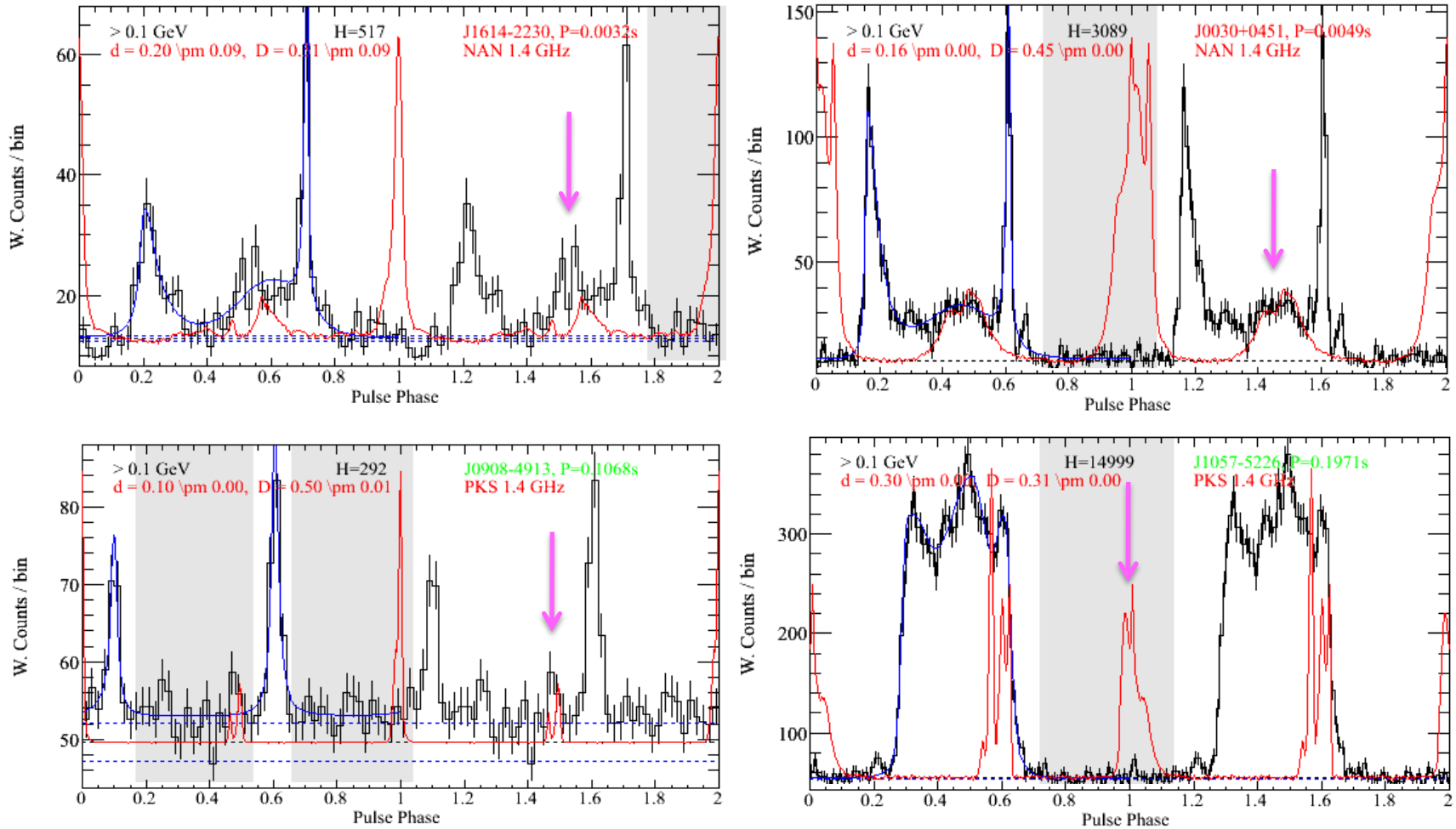
Timokhin & Harding 2015

Emission appears from 100 keV – 100 MeV

$E\,f(E)$

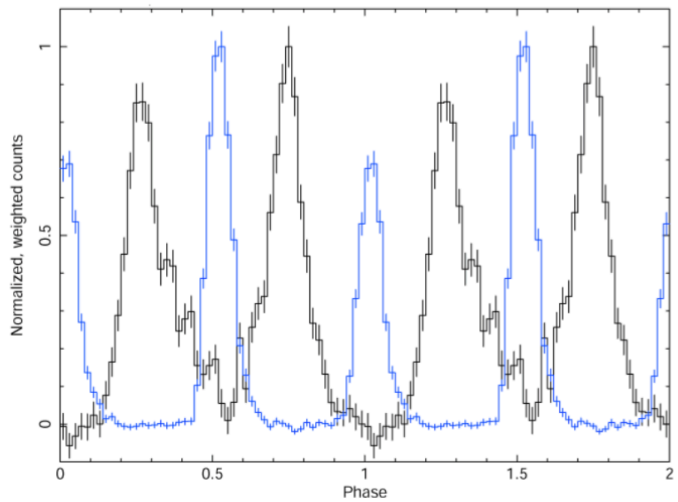


Polar cap emission – hints from Fermi?



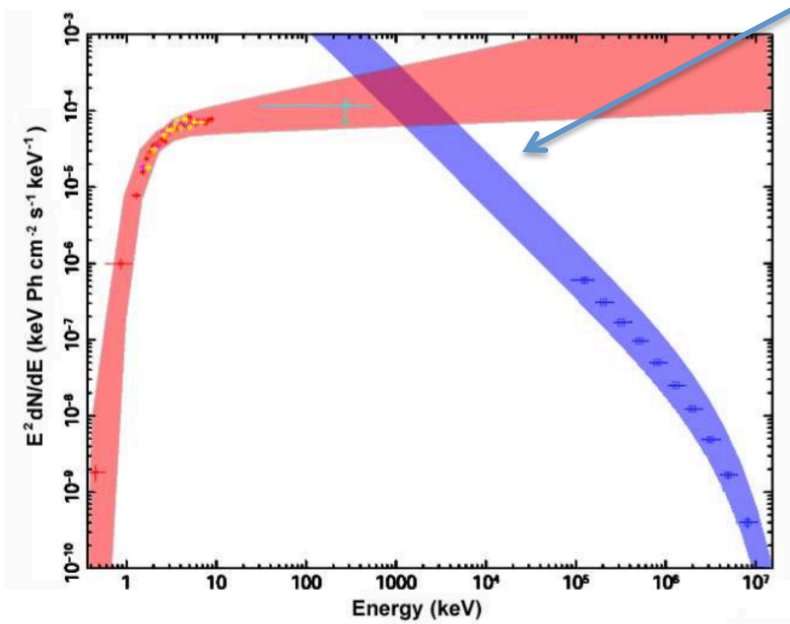
PSR J1813-1246 – polar cap emission?

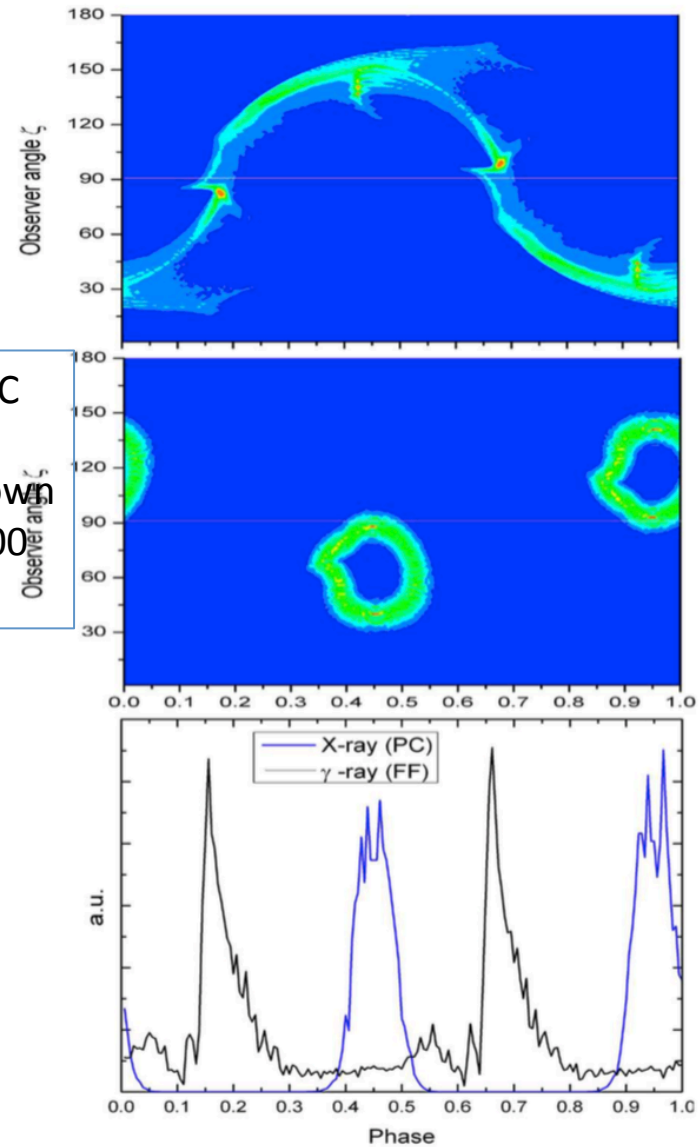
Marelli et al. 2014 Fermi and XMM



γ-rays from current sheet

X-rays from PC cascade Spectrum shown cutoff ~ 10-100 MeV





Polarization of pulsar emission

Synchrotron (SR) and curvature radiation (CR)

- Polarization degree

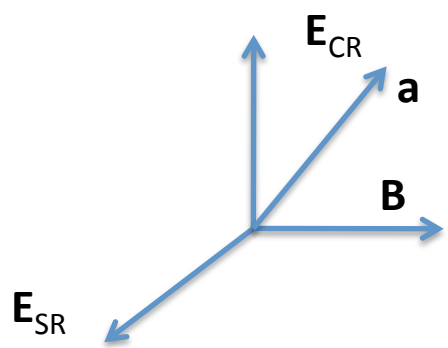
$$p(\varepsilon) = \frac{P_2(\varepsilon) - P_1(\varepsilon)}{P_2(\varepsilon) + P_1(\varepsilon)} = \frac{K_{2/3}(\varepsilon/\varepsilon_c)}{\int_{\varepsilon/\varepsilon_c}^{\infty} K_{5/3}(x)dx},$$

$$\varepsilon << \varepsilon_c \Rightarrow 0.5$$
$$\varepsilon = \varepsilon_c \Rightarrow 0.75$$
$$\varepsilon >> \varepsilon_c \Rightarrow 1.0$$

- Position angle

CR: E vector || to electron acceleration vector

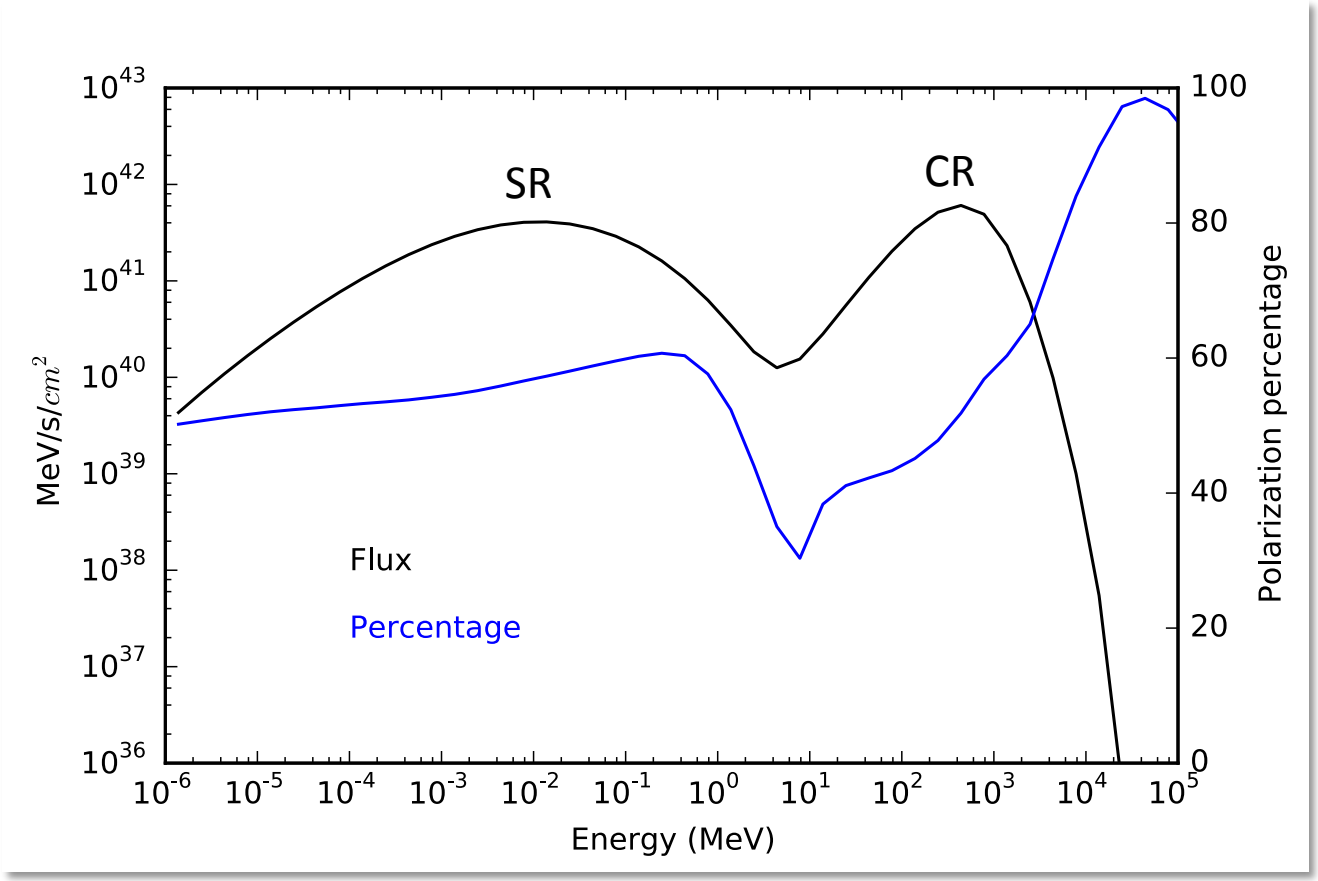
SR: E vector is perpendicular to B and electron acceleration



Phase-averaged polarization

Transition between synchrotron and curvature radiation occurs at 1 – 100 MeV in Crab-like pulsars

Look for drop in polarization degree at transition



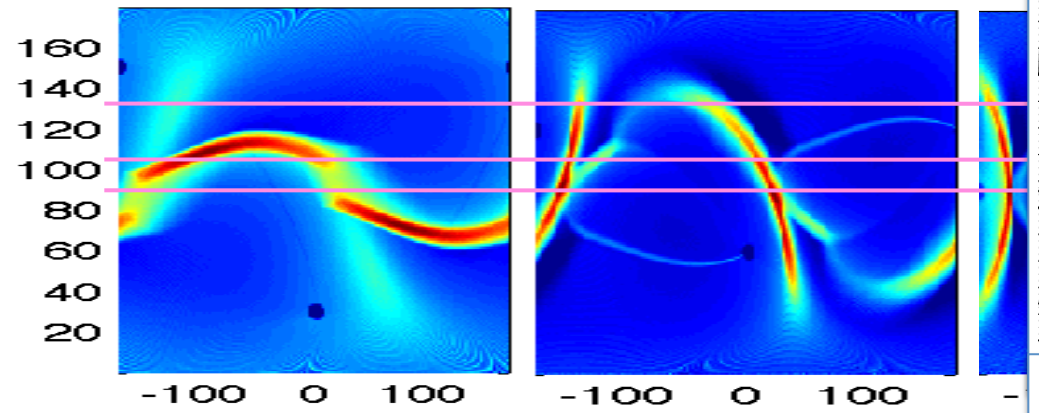
Emission sky maps

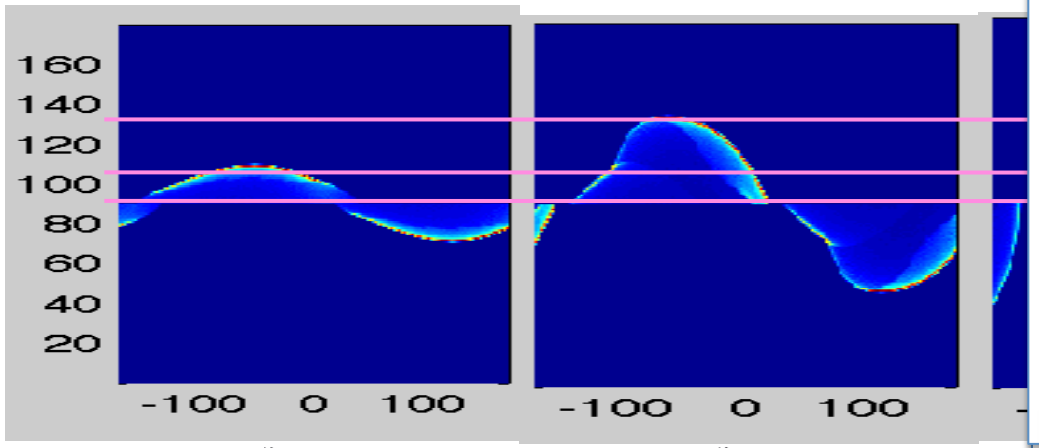
Pulsar inclination

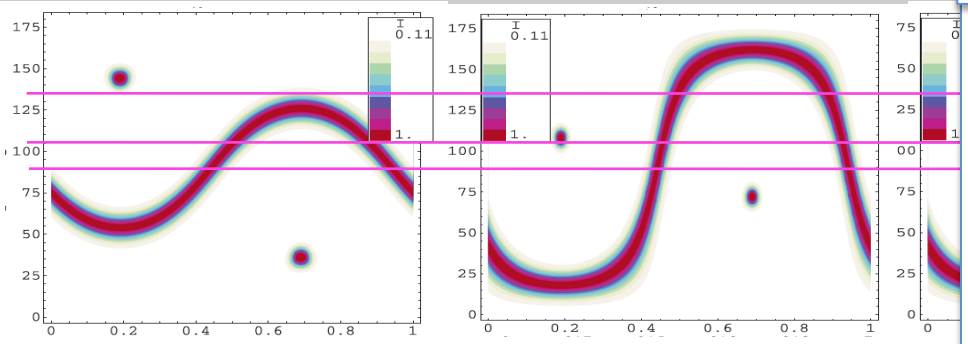
Slot gap

Outer gap

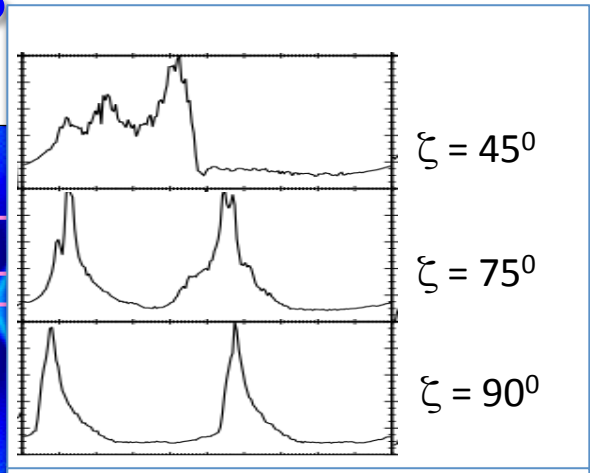
Current sheet
(Petri 2011)

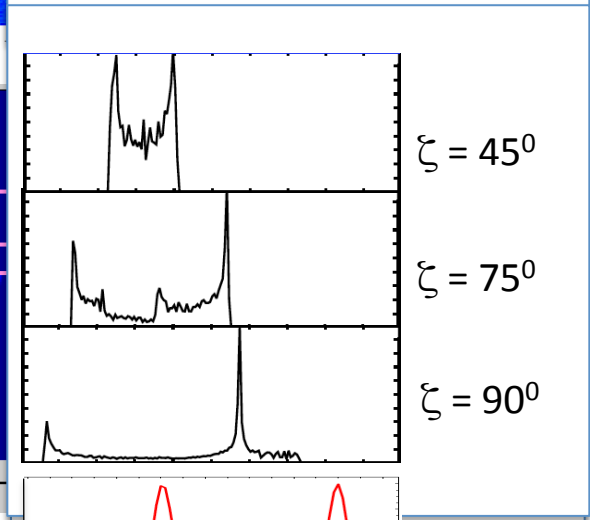


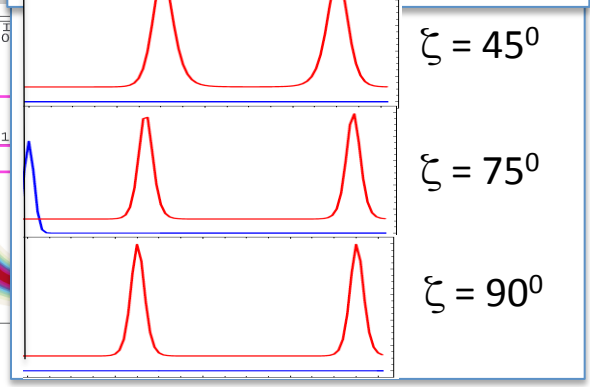




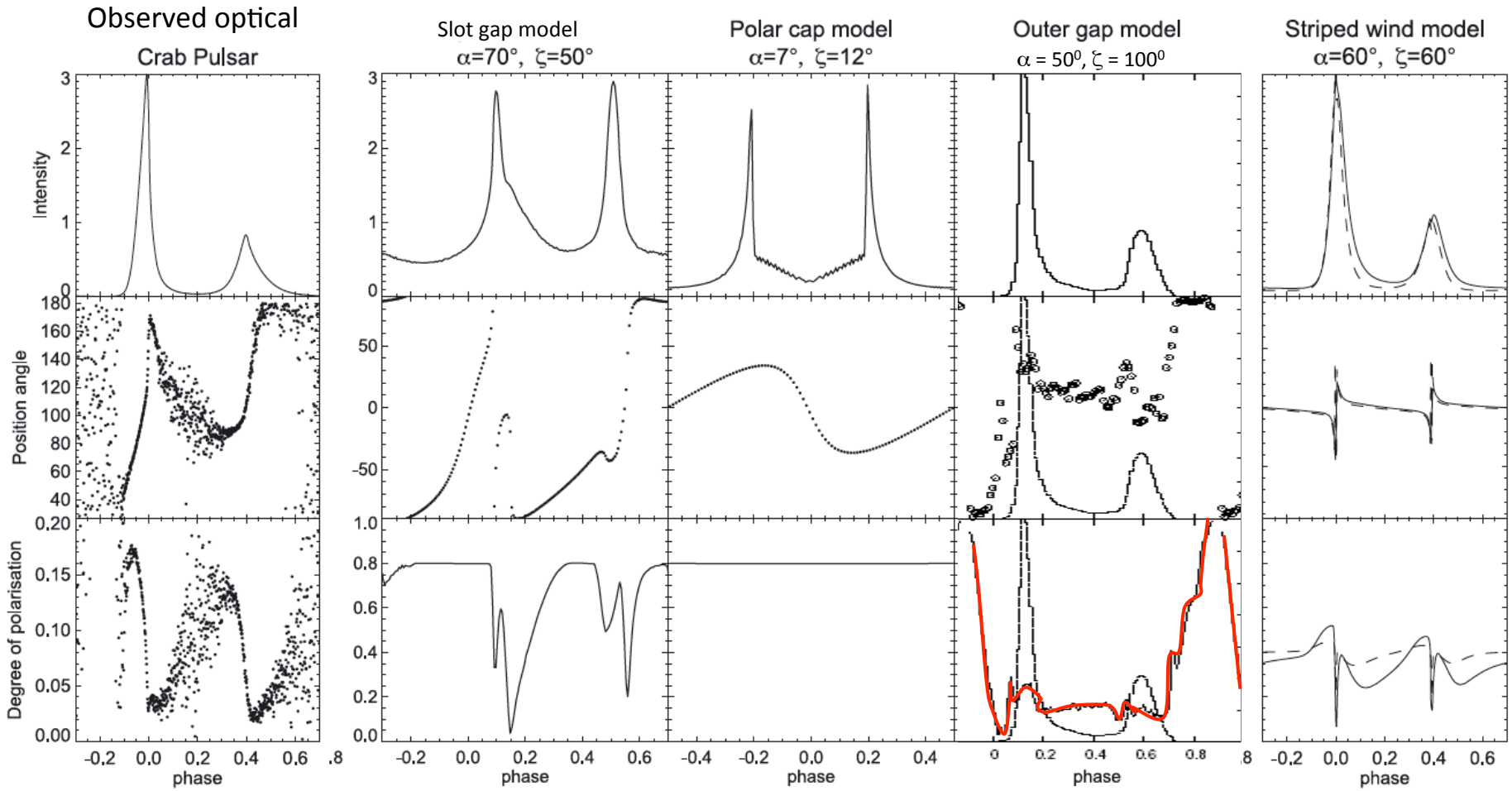
Phase





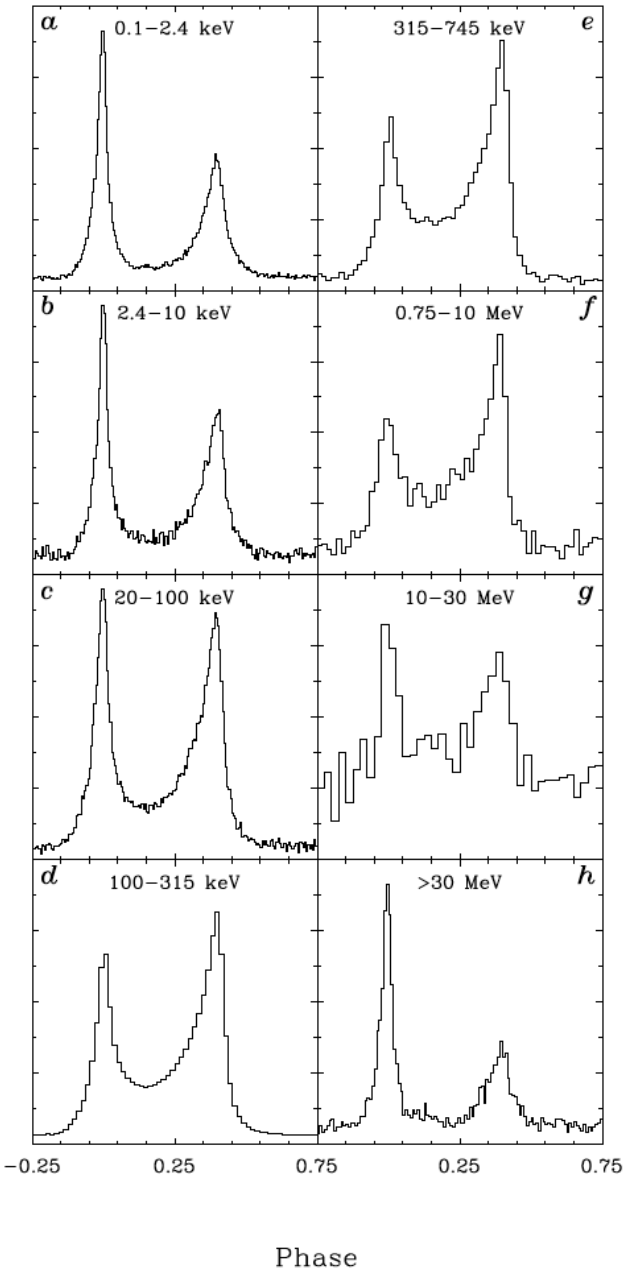


Crab pulsar: models vs. data



Slowikowska et al. 2009 Dyks, Harding & Rudak 2004 Takata & Chang 2007 Petri & Kirk 2005

Crab energy evolution

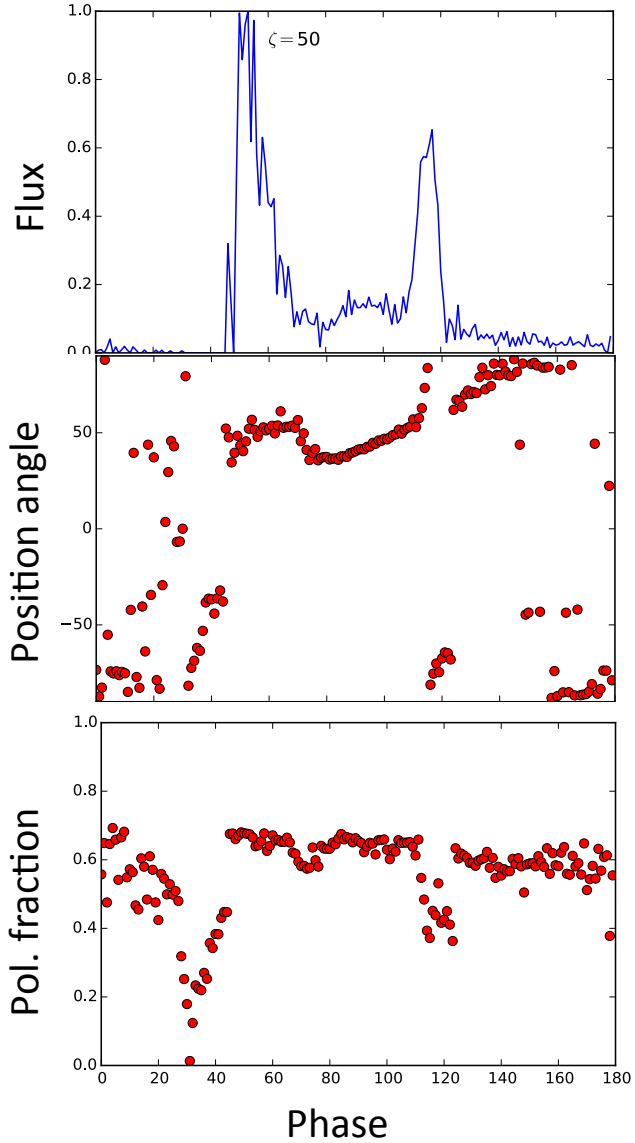


- Light curve undergoes shape between 100 keV and 50 MeV
- Bridge emission is highest around 500 keV
- Polarization measurements may show emission mechanism transition

Energy-dependent polarization

Slot gap

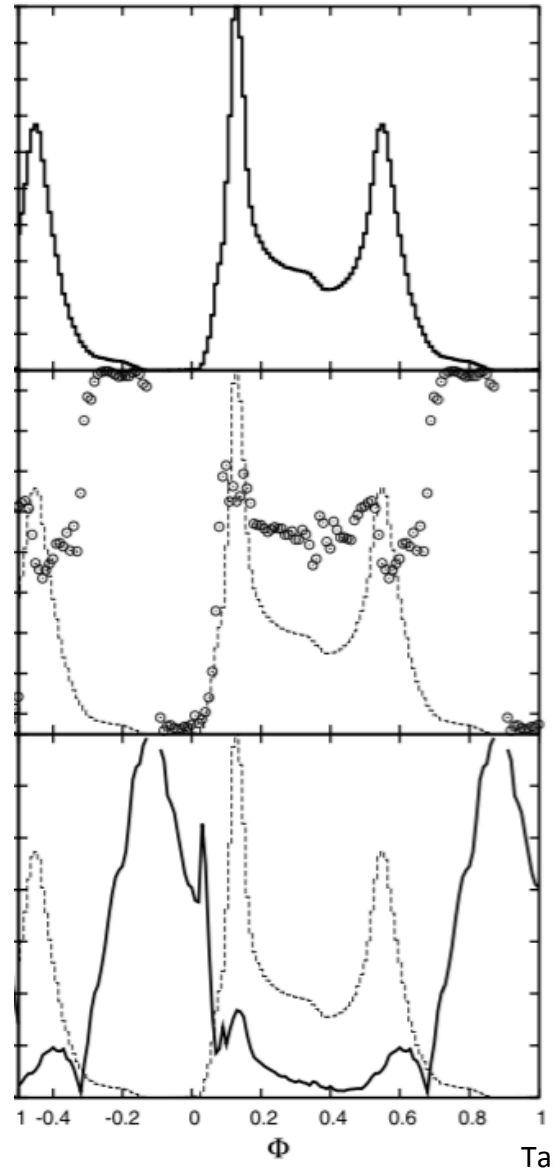
0.1 – 10 MeV



Harding & Kalapotharakos 2016

20 - 100 keV

Outer gap

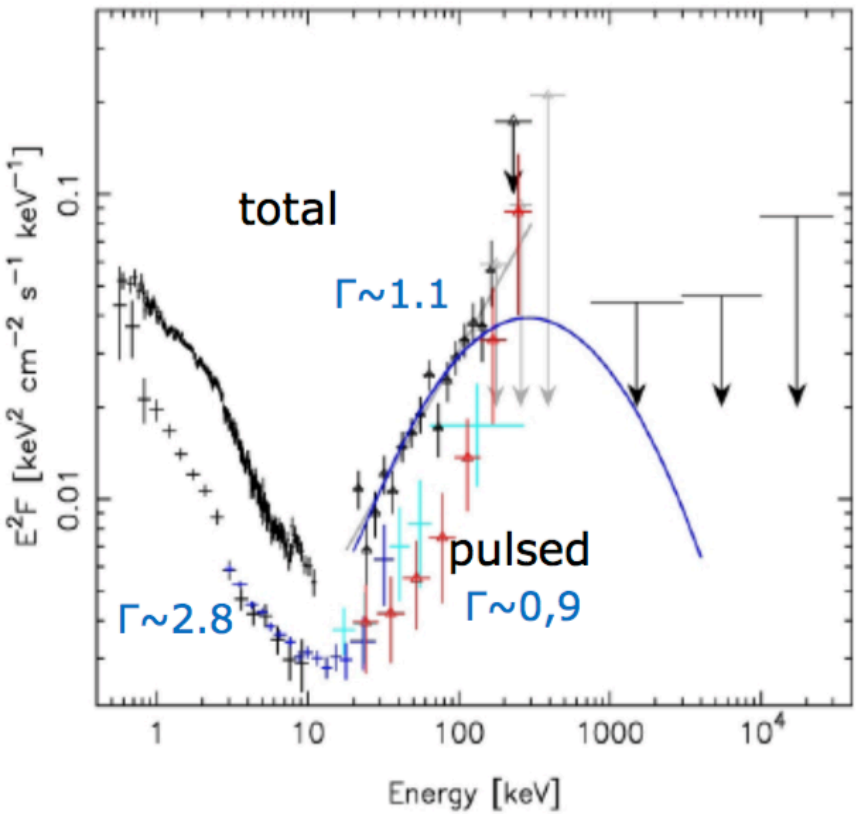


Takata et al. 2007

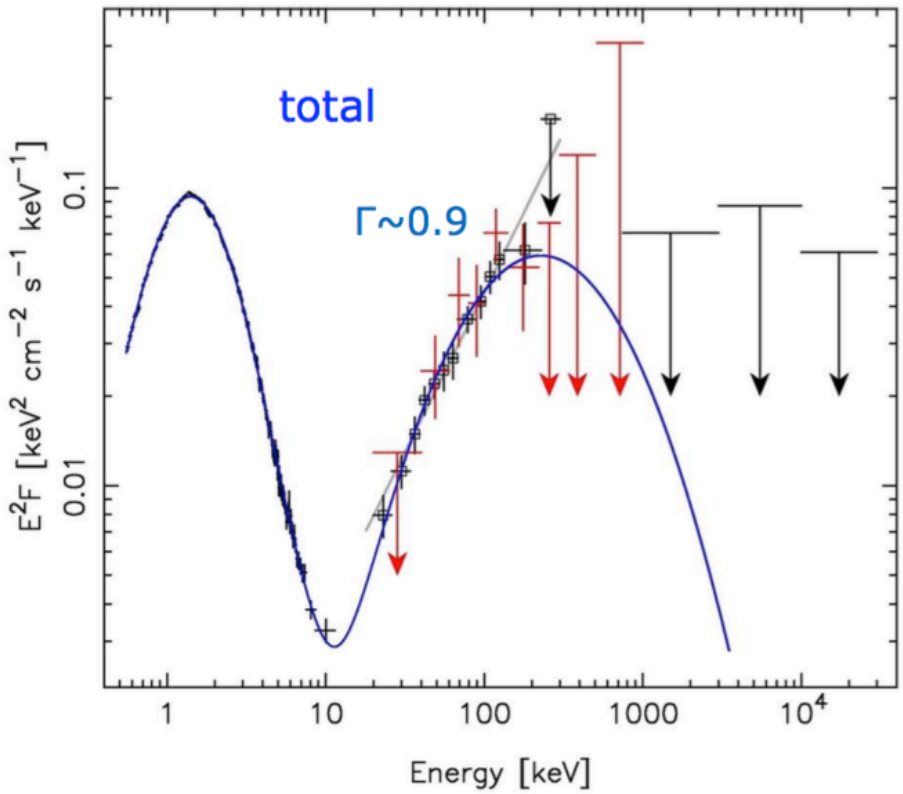
Magnetar quiescent emission

Low-energy thermal plus hard high-energy components up to 200 keV
Seen by INTEGRAL (den Hartog et al. 2008)

AXP 1RXS J170849-400910



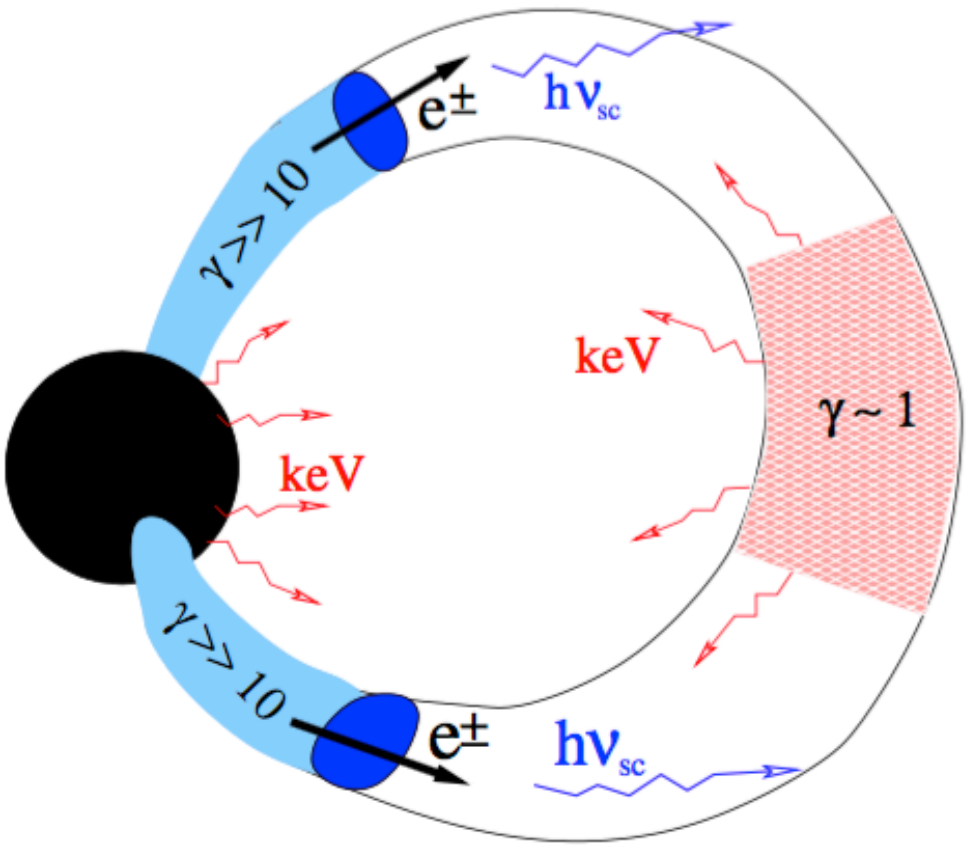
AXP 4U 0142+61

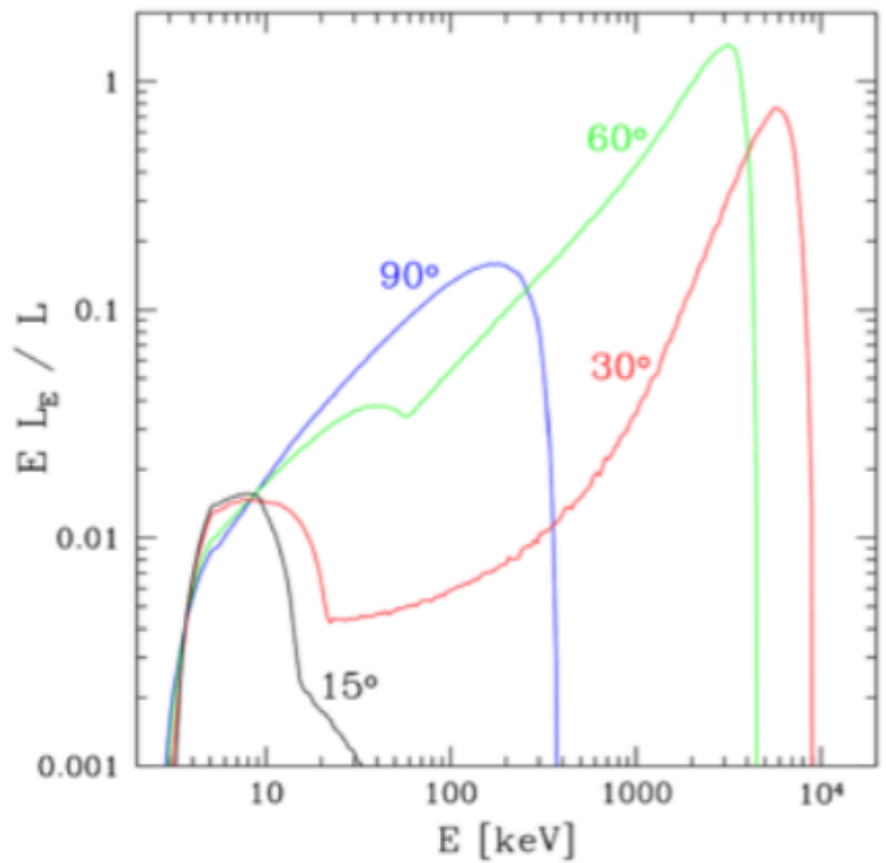


Magnetar quiescent emission theory

Cyclotron resonant upscattering and pair/splitting cascade

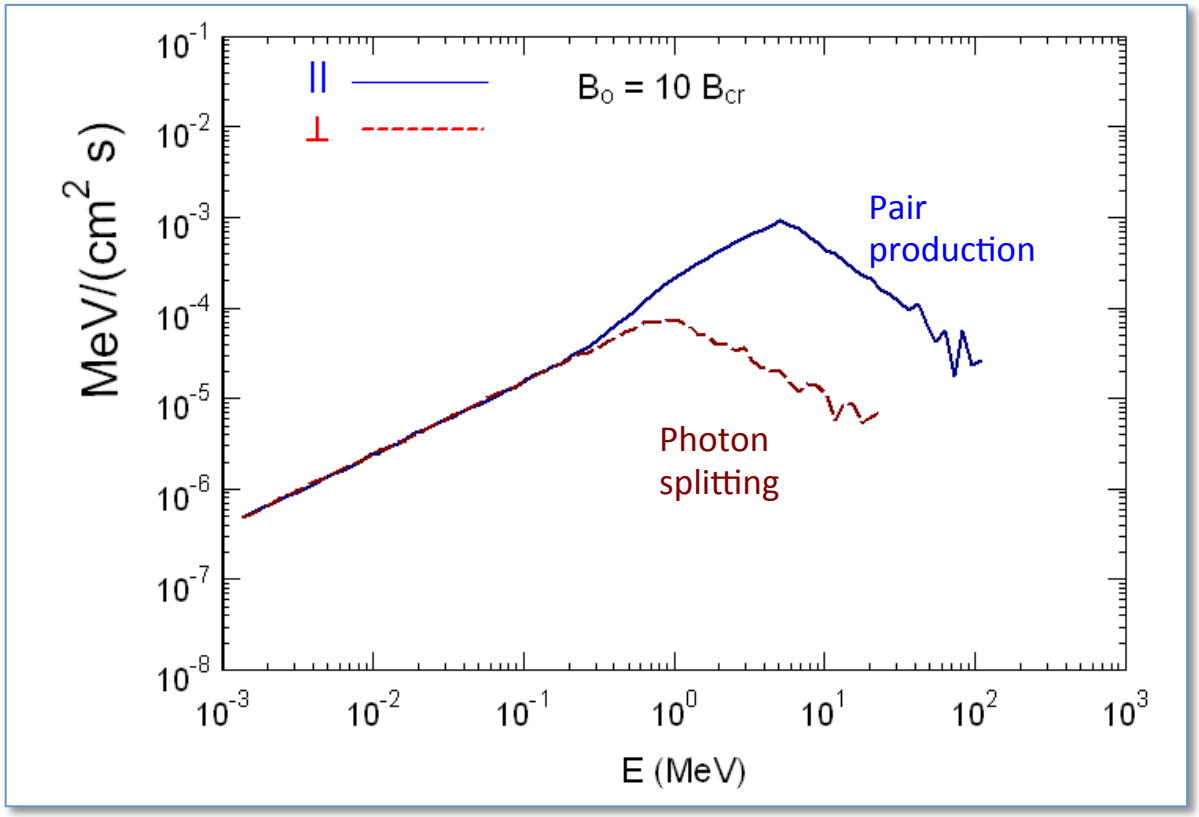
Baring & Harding (2004), Beloborodov (2013)





Magnetars – signature of photon splitting?

- Photon splitting threshold at lower energy than pair production threshold



Look for 100% polarization near the cutoff

Summary

- Rotation-powered pulsars
  - Young 'MeV' pulsars
  - Millisecond pulsars

    } Peak in SED
  - Polar cap emission
  - Polarization – SR-CR transition, pol. vs. phase
- Magnetars
  - Cutoff in quiescent hard component
  - Photon splitting signature: 100% polarization at cutoff