Exploring Hidden Emission from Neutron Stars

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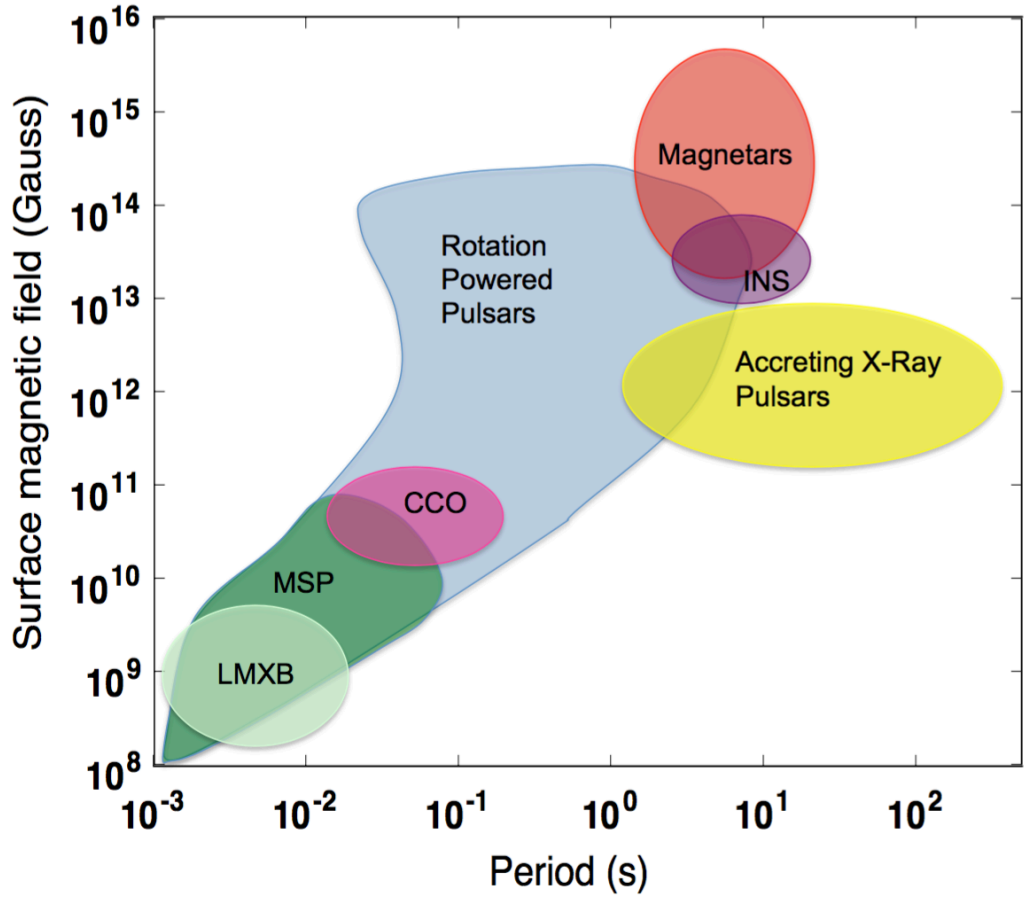
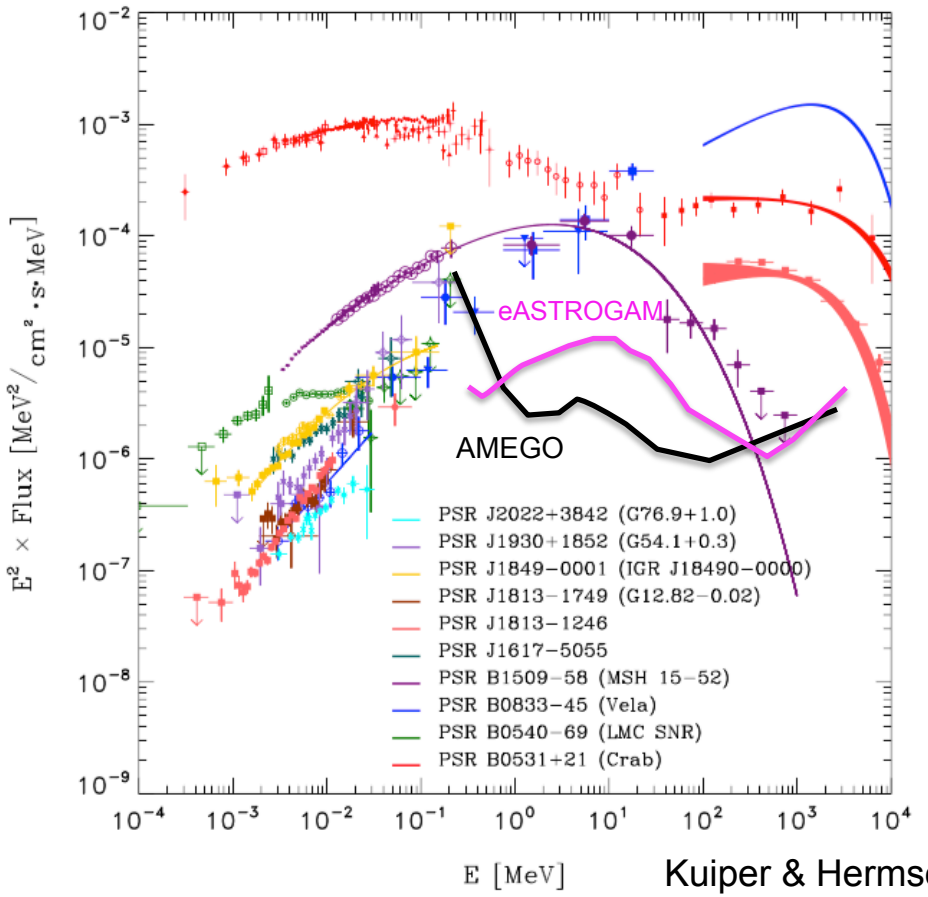
The neutron star zoo

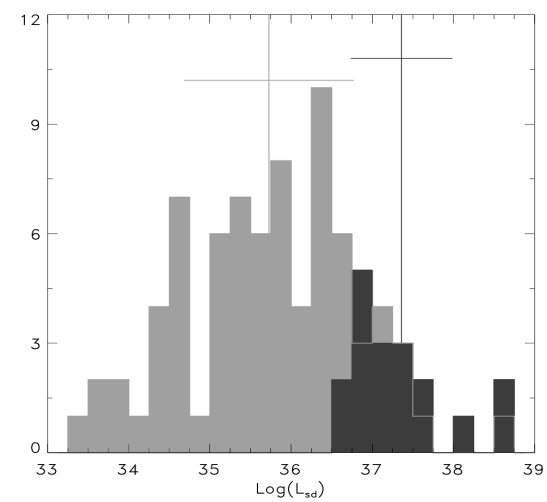


Hard X-ray pulsar population

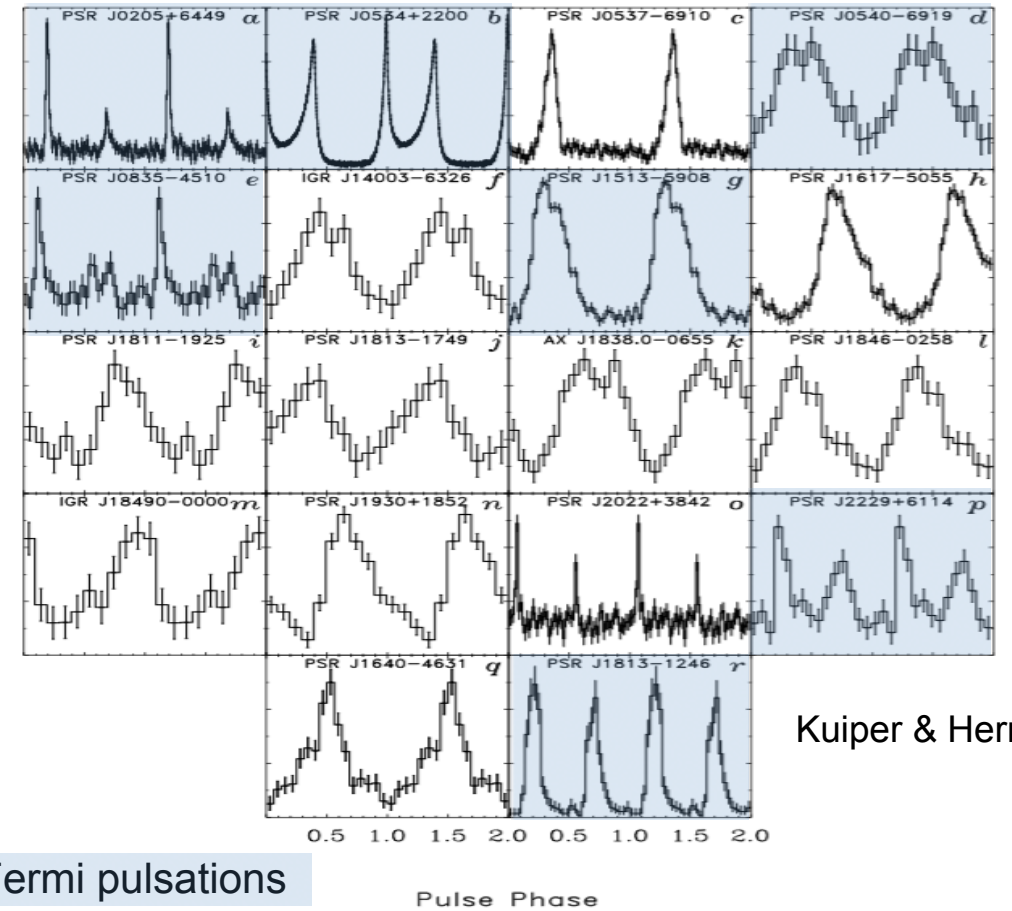


Kuiper & Hermsen 2015

- Pulsars seen only in hard X-ray – not at GeV
- 11 "MeV pulsars" are known, Edot > 10^{36} erg/s
- emission may probe a different part of the magnetosphere than GeV



Light curves of MeV pulsars



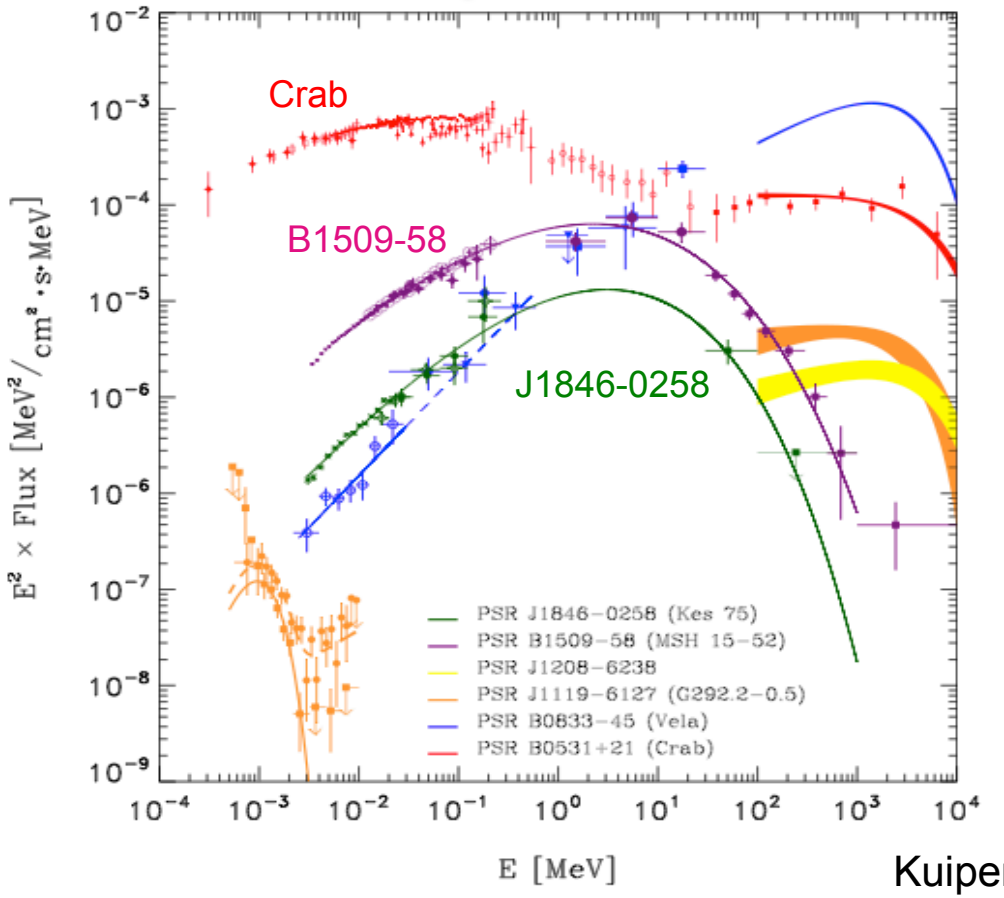
Fermi pulsations

- All MeV pulsars with no Fermi pulsations have broad single peaks – with the exception of J2022+3842

- J1513-5908 and J0540-6919 have Fermi pulsations but very soft SED

Kuiper & Hermsen 2015

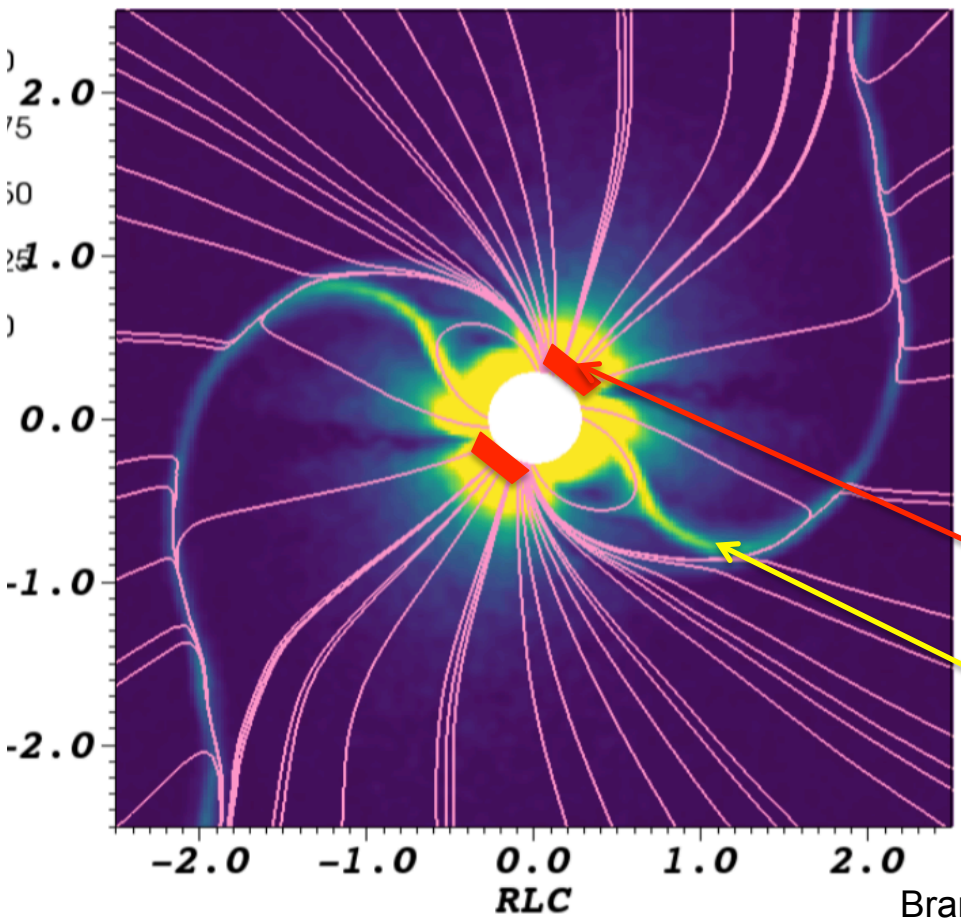
Spectra of MeV pulsars



- Broad SED peaking at 1-10 MeV
- No GeV component??

Kuiper et al. 2017

Radiation modeling of MeV pulsars



Harding & Kalapotharakos 2017

- Particle trajectories in force-free magnetosphere
- Synchrotron radiation from pairs
- Curvature radiation from primaries
- Emission from 0.7 – 2.0 R_{lc}

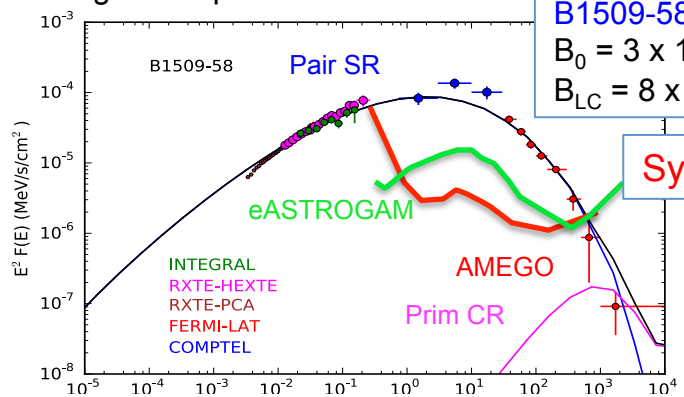
Pair production site

Radiation site

Brambilla et al. 2018

Model spectra for MeV pulsars

Harding & Kalapotharakos 2017



B1509-58
$B_0 = 3 \times 10^{13}$ G
$B_{LC} = 8 \times 10^4$ G

Synchrotron only!

Peak of synchrotron SED

$$E_{SR} \approx \gamma_{e^\pm}^2 B_{LC}$$

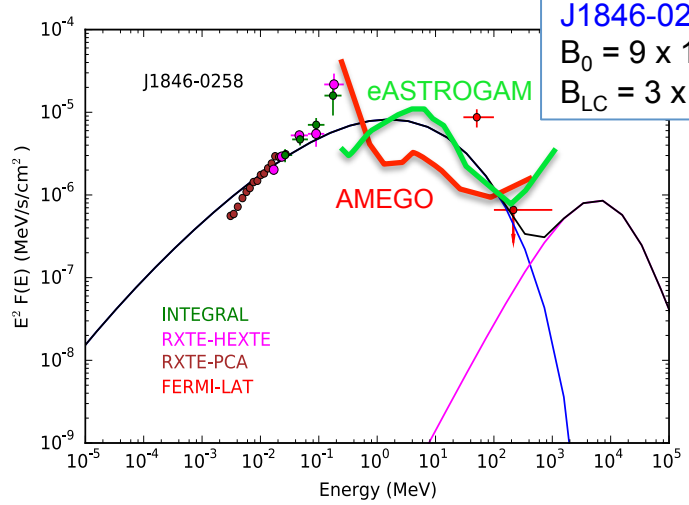
Pairs from polar cap,

$$E_{SR} \propto B_0 B_{LC}$$

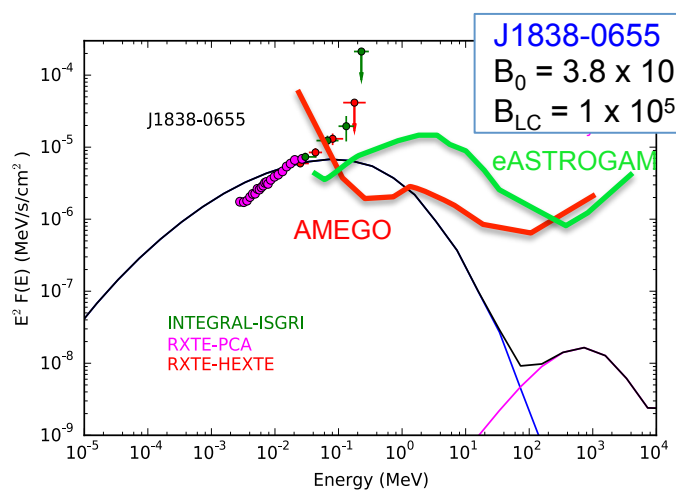
Pairs from outer gap,

$$E_{SR} \propto B_{LC}^{7/2}$$

Measurement of E_{SR} can locate source of pairs



J1846-0258
$B_0 = 9 \times 10^{13}$ G
$B_{LC} = 3 \times 10^4$ G



J1838-0655
$B_0 = 3.8 \times 10^{12}$ G
$B_{LC} = 1 \times 10^5$ G

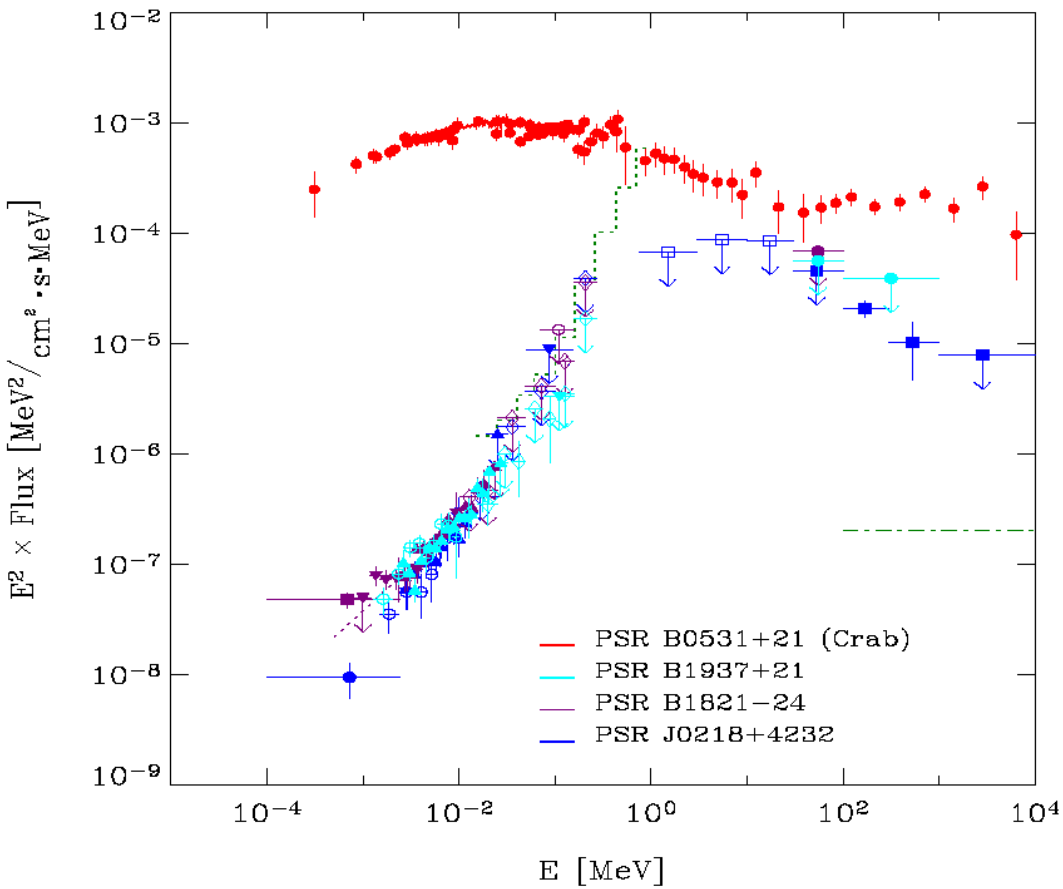
MeV pulsars – the tip of the iceberg?

name	period (ms)	age (kyr)	$^{10}\log(L_{sd})$	*Fermi* LAT/Pulsed	No radio
PSR J0205+6449 (3C58)	65.7	5.4	37.43	yes	
PSR J0534+2200/B0531+21 (Crab)	33.5	1.23	38.66	yes	
PSR J0537-6910 (N157B in LMC)	16.1	4.9	38.69	no	★
PSR J0540-6919/B0540-69 (N158A in LMC)	50.5	1.7	38.18	yes	
PSR J0835-4510/B0833-45 (Vela)	89	11	36.84	yes	
PSR J1400-6325 IGR J14003-6326	31.2	12.7	37.71	no	
PSR J1513-5908/B1509-58 (MSH 15-52)	150	1.6	37.26	yes	
PSR J1617-5055	69.0	8.0	37.20	no	
PSR J1640-4631 (G338.3-0.0)	206	3.4	36.64	no	★
PSR J1811-1925 (G11.2-0.3)	65.0	24.0	36.81	no	★
PSR J1813-1246	48.1	43.0	36.80	yes	★
PSR J1813-1749 (G12.82-0.02)	44.7	5.6	37.75	no	★
PSR J1838-0655 AX J1838.0-0655	70.5	23.0	36.75	no	★
PSR J1846-0258 (Kes 75)	324	0.72	36.91	no	
PSR J1849-0001 IGR J18490-0000	38.5	42.8	36.99	no	★
PSR J1930+1852 (G54.1+0.3)	136	2.9	37.08	no	
PSR J2022+3842 (G76.9+1.0)	48.6	8.9	37.47	no	
PSR J2229+6114 (G106.6+2.9)	51.6	10.5	37.34	yes	

$B_0 > 10^{13}$ G

Kuiper & Hermsen 2015

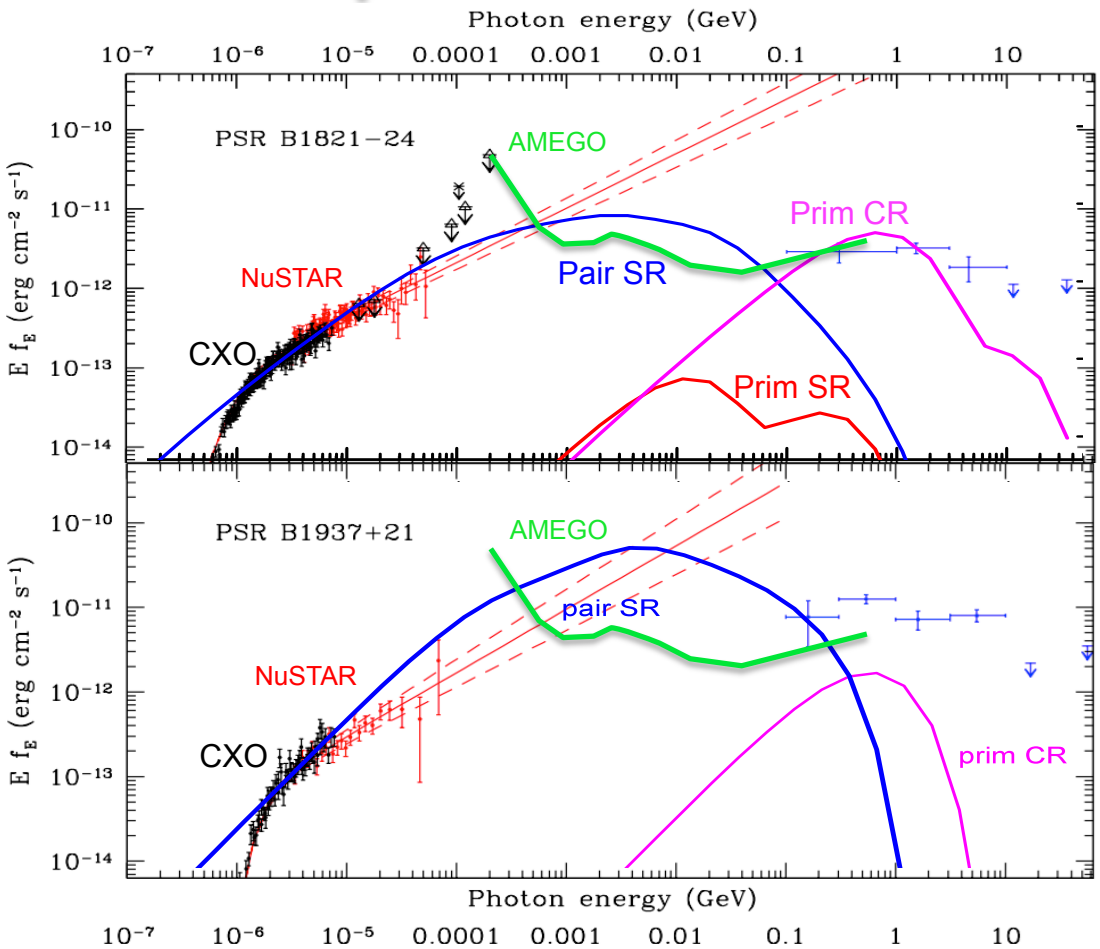
HE spectra of millisecond pulsars



Kuiper & Hermsen 2003

Energetic MSPs have hard, nonthermal X-ray spectra like MeV pulsars

Spectra of millisecond pulsars



Spectra continue to rise toward MeV band!

Gotthelf & Bogdanov 2017

Higher pair energies

Predicted SR spectra peak ~1-10 MeV

Harding & Kalapotharakos 2015

Polarization of pulsar emission

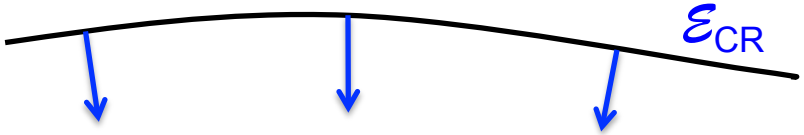
Synchrotron (SR) and curvature radiation (CR)

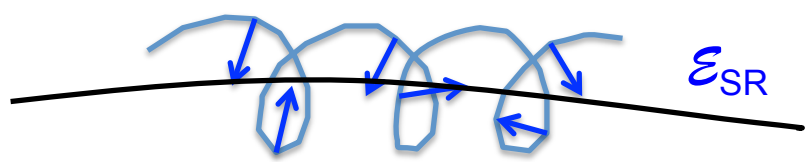
- Intrinsic polarization fraction

$$p(\varepsilon) = \frac{P_2(\varepsilon) - P_1(\varepsilon)}{P_2(\varepsilon) + P_1(\varepsilon)} = \frac{K_{2/3}(\varepsilon/\varepsilon_c)}{\int_{\varepsilon/\varepsilon_c}^{\infty} K_{5/3}(x)dx}, \qquad \begin{array}{l} \varepsilon << \varepsilon_c \Rightarrow 0.5 \\ \varepsilon = \varepsilon_c \Rightarrow 0.75 \\ \varepsilon >> \varepsilon_c \Rightarrow 1.0 \end{array}$$

- Position angle

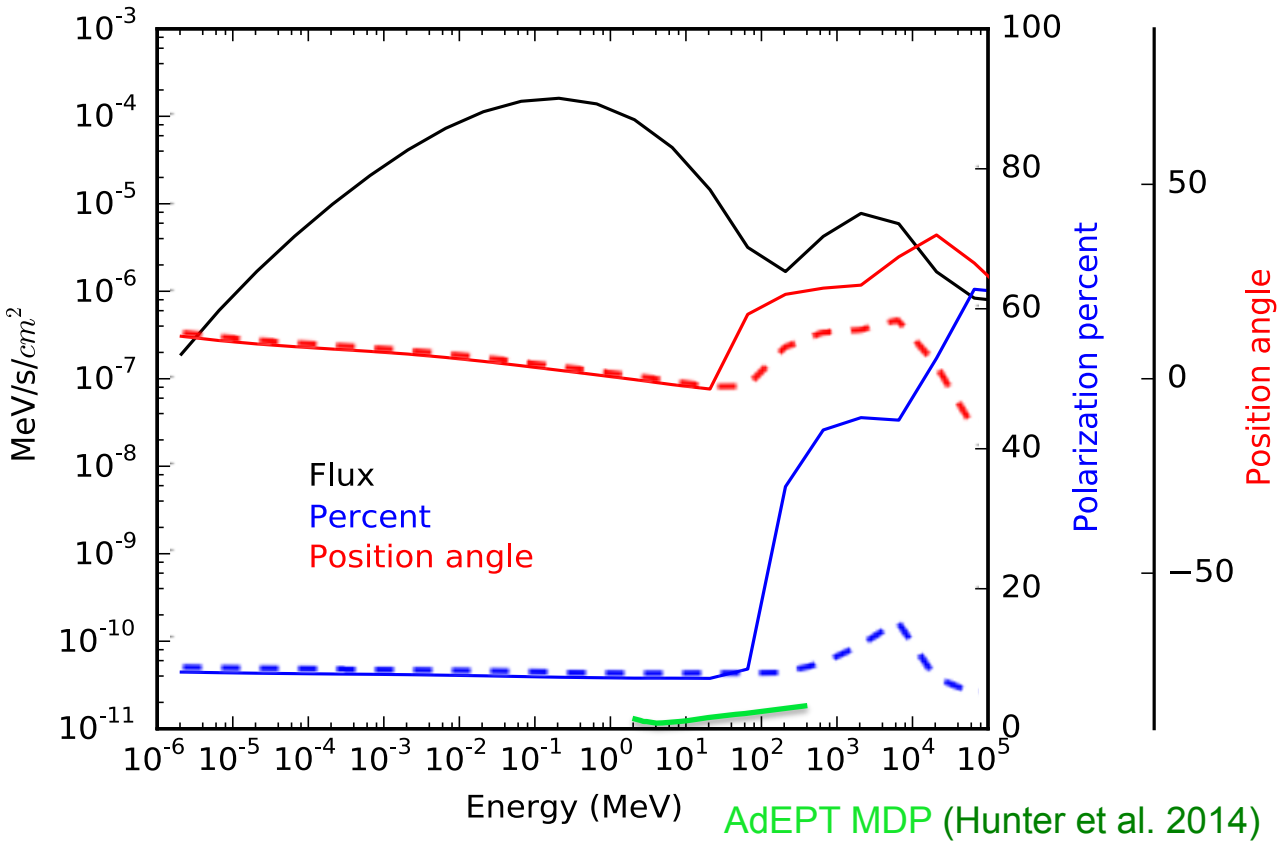
E vector || to electron acceleration vector





Phase-averaged polarization

Harding & Kalapotharakos 2017



- Transition between synchrotron and curvature radiation occurs at 10 – 100 MeV in Crab-like pulsars
- GeV CR: rise in polarization degree and change of PA at transition
- Determine mechanism of GeV emission!

GeV component is:

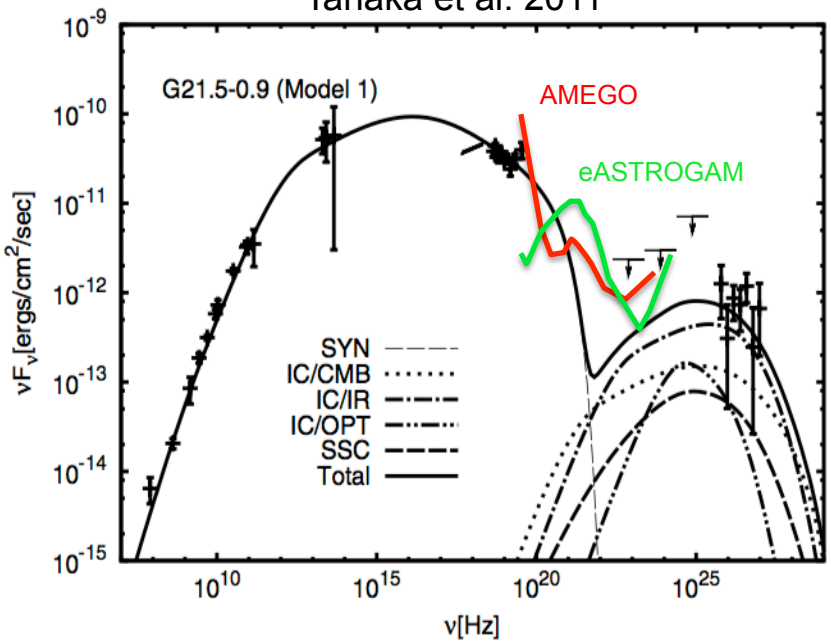
CR?
(Kalapotharakos et al. 2014)

SR?
(Cerutti et al. 2016)

IC?
(Lyutinkov 2012)

Spectral cutoffs in pulsar wind nebulae

Tanaka et al. 2011



SR-limited particle acceleration gives universal maximum SR photon energy - applies to Crab PWN

$$\tau_{SR} = \tau_{acc} \Rightarrow E_{\max} = 17\ TeV\ B_s^{-1/2}$$

$$\Rightarrow \varepsilon_{SR} \propto E_{\max}^2 B_s = 160\,MeV$$

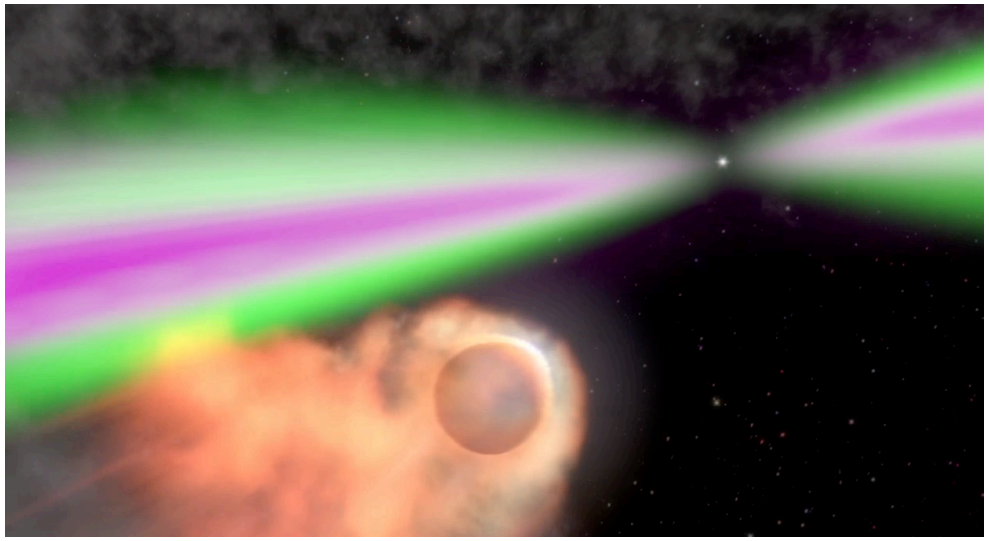
For most other PWNe, voltage across open field lines gives the particle energy upper limit, giving SR spectral cutoff in MeV range:

$$V_{open} = 6 \times 10^{12} eV\ B_{12} P^{-2} < E_{\max}$$

$$\Rightarrow \varepsilon_{SR} \propto V_{open}^2 B_s = 0.14\,MeV \left(\frac{L_{SD}}{10^{36} erg/s}\right)^{6/5} \left(\frac{\sigma}{1+\sigma}\right)^{1/2} \tau_{kyr}^{-3/10}$$

Constrain B_s and wind magnetization σ

Millisecond pulsar Binaries



- Black Widows MSPs with very low-mass binary companions
  - 10 – 80 Jupiter masses ($M_\odot$~.01)
- Pulsar wind ablates companion by exciting stellar winds

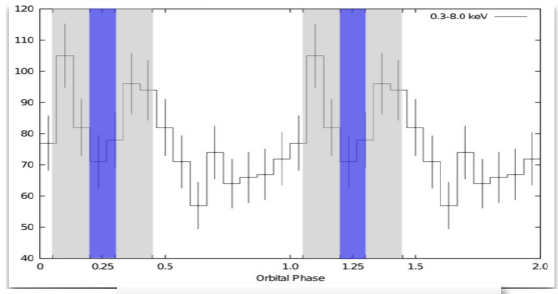
Redbacks (cousins)

~0.1 $M_\odot$ companions

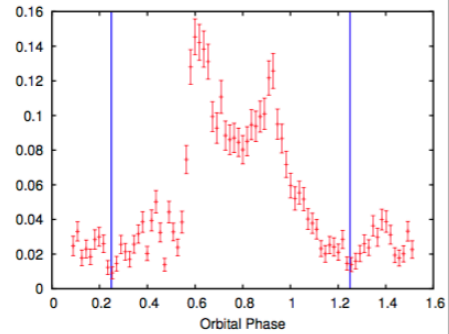
Before Fermi launch: 3 Black Widows, 1 Redback
Now: 19 Black Widows, 9 Redbacks – Total of 28!

Double-peaked soft X-ray light curves

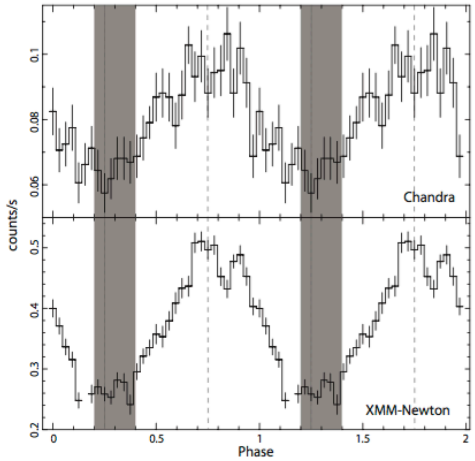
- Flux minimum around superior (BWs) or inferior (RBs) conjunction
- Spectral indices $\Gamma \sim 1 - 1.5$
- Synchrotron, modulated by Doppler boosting?



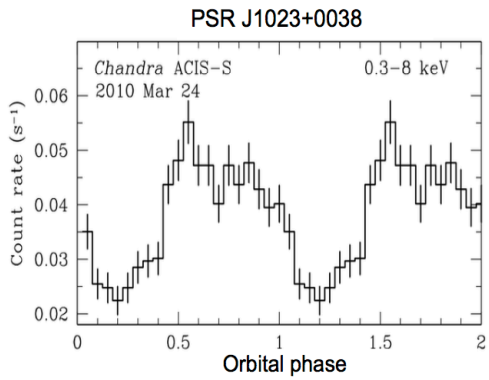
B1957+20 Huang et al. 2012



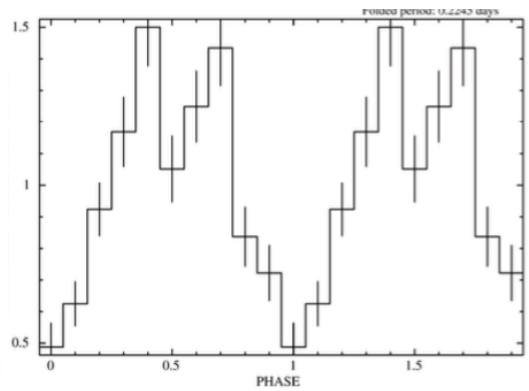
J2129-0429, Roberts et al. 2015



J1723-2837, Hui et al. 2014



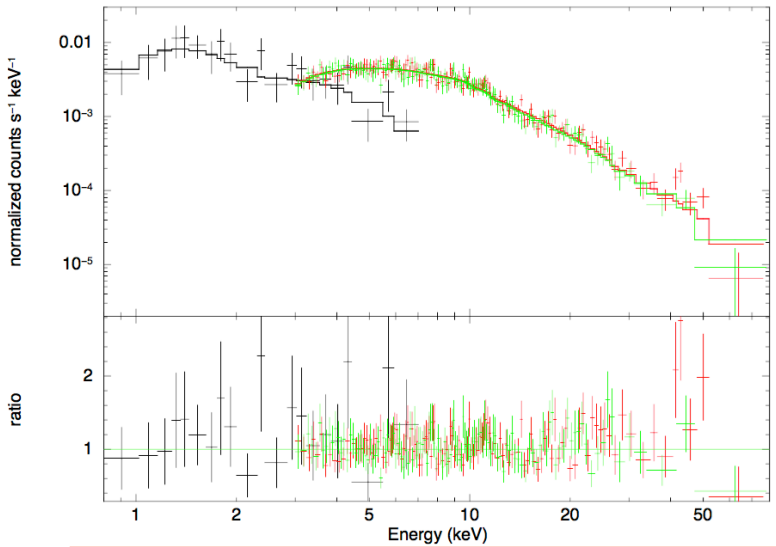
J1023+0038, Archibald et al. 2010



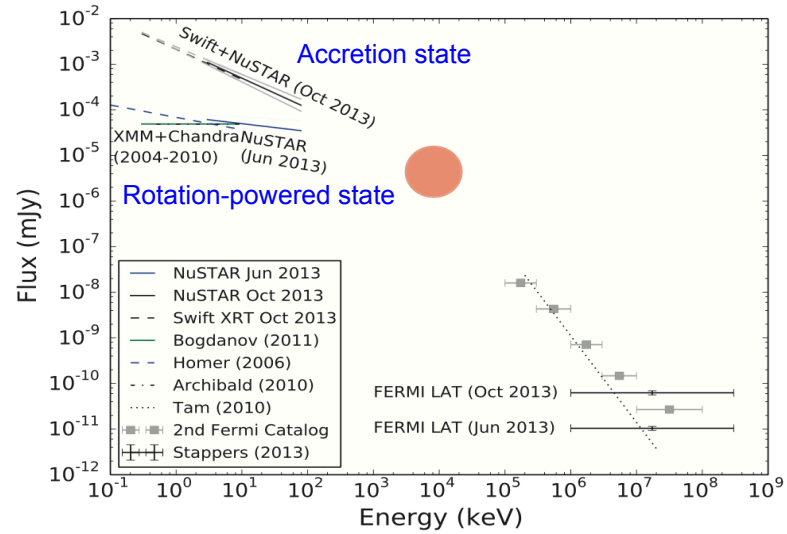
J2039-5618, Salvetti et al. 2015

Shock-acceleration maximum energy

PSR J1723-2837 with NuSTAR (Kong et al. 2017)
Emission observed up to 50 keV



J1023+0038 with NuSTAR (Tendulkar et al. 2017)
Emission up to 79 keV



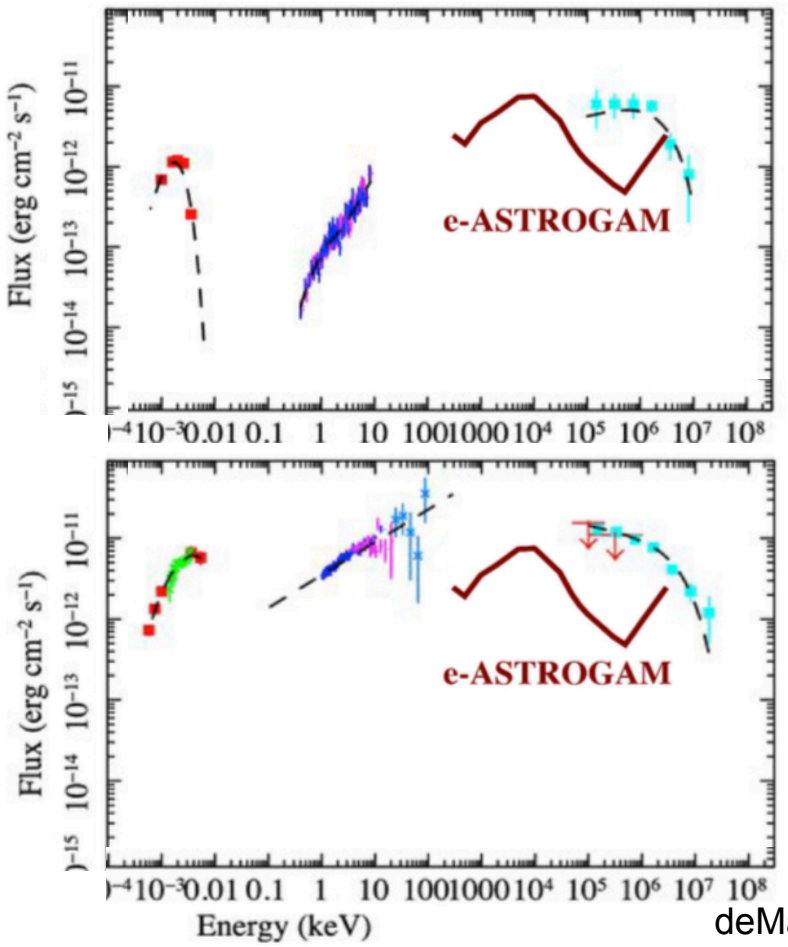
- Magnetic field at shock

$$B_S \approx \left(\frac{3\dot{E}_{SD}}{2c}\right)^{1/2} = 22\left(\frac{\dot{E}_{SD}}{10^{35}\mathrm{ergs}^{-1}}\right)^{1/2}\left(\frac{10^{11}\mathrm{cm}}{r_S}\right)^{2} G$$

- If E_{max} ~ 1 TeV, critical energy (Peak of SED) ~ 1 – 10 MeV

Wadiasingh et al. 2017

Transitional MSPs



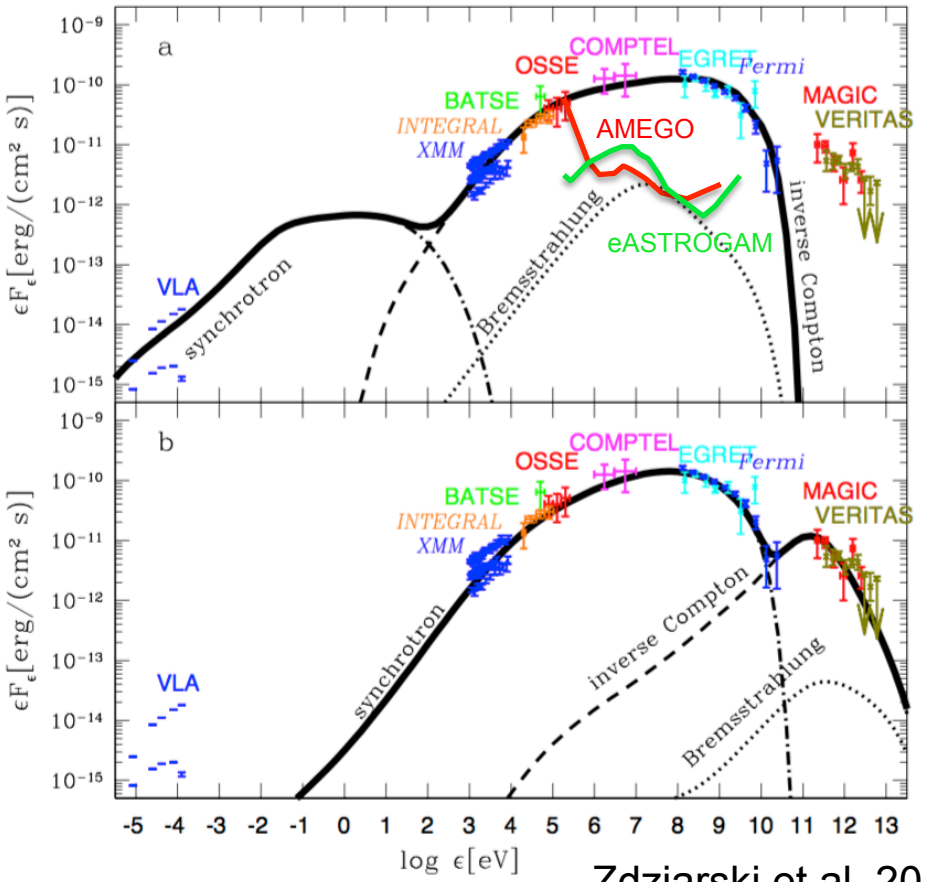
Rotation-powered state

Accretion-powered state

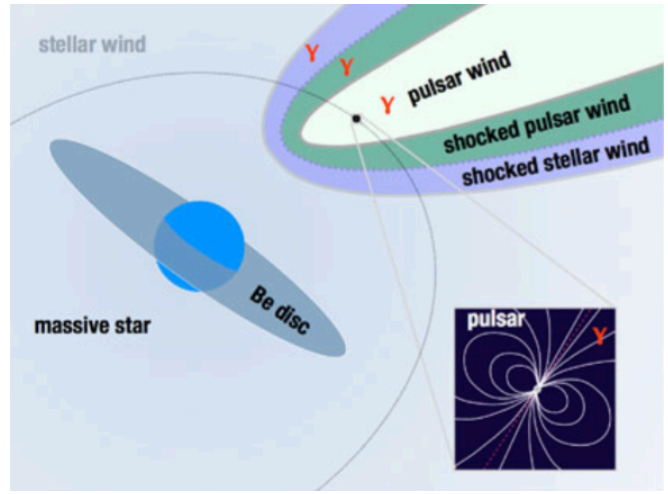
deMartino et al. 2015

- 3 tMSPs are known – all redbacks
- In LMXB state,
  - does disk penetrate pulsar magnetosphere to quench pulsar emission? Propeller SSC
  - or not - IC off disk photons
  - Is there a jet?
- In pulsar state,
  - HE spectra cutoff constrains shock acceleration

Gamma-ray binaries



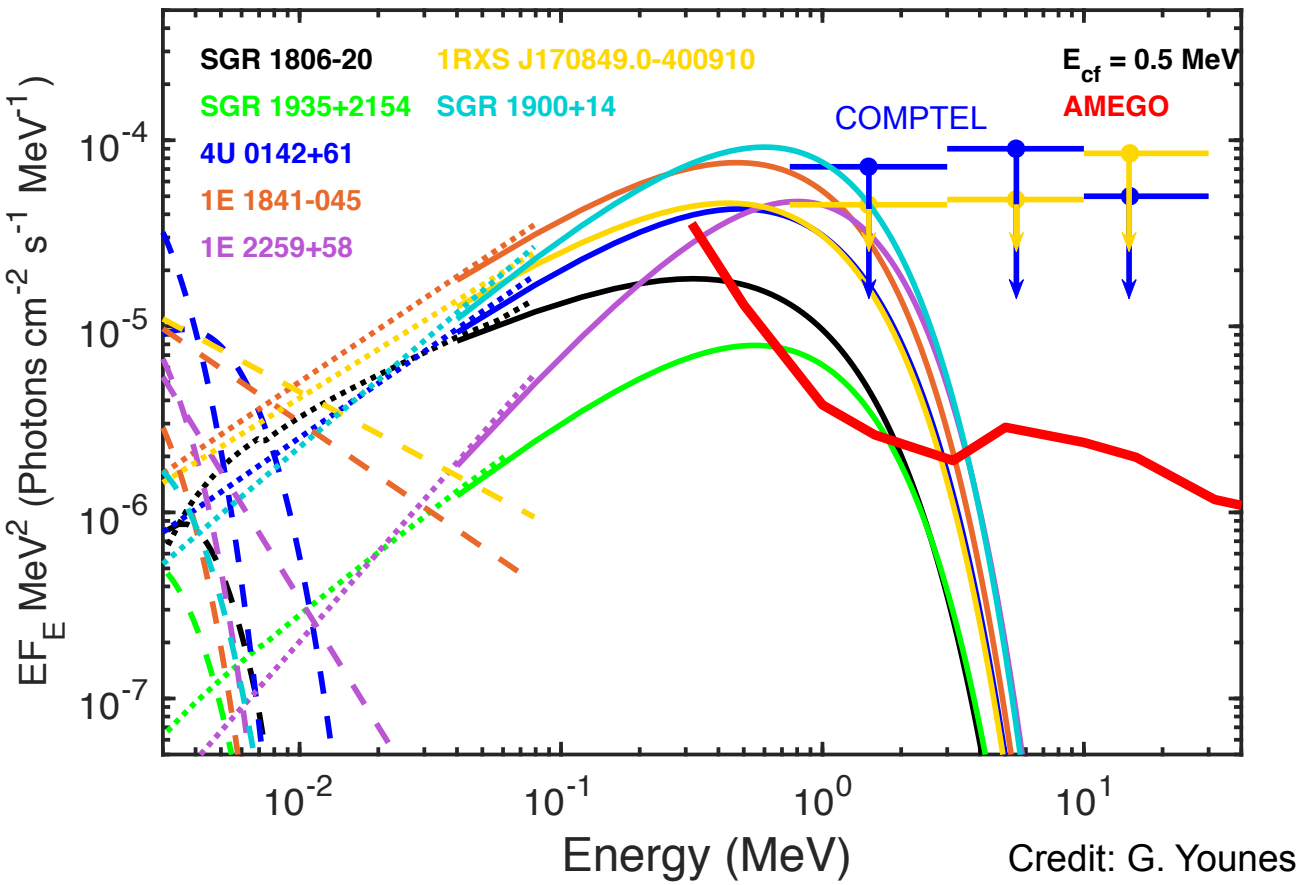
Zdziarski et al. 2010



Dubus 2013

- Six known gamma-ray binaries
- Main emission component either inverse Compton or synchrotron
- Better MeV telescope could decide
- If SR, HE cutoff constrains particle acceleration at shock
- If IC, can probe geometry of binary

Magnetar quiescent emission



Credit: G. Younes

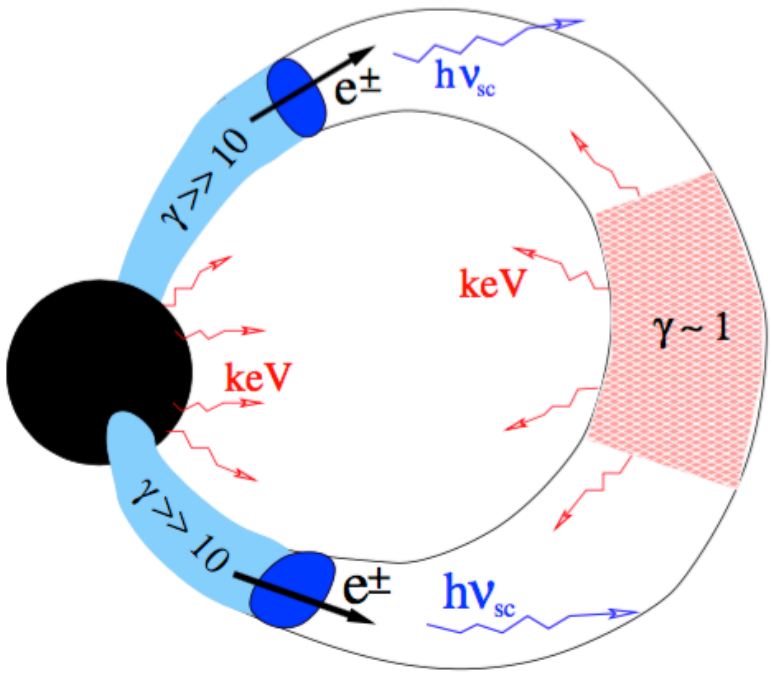
Low-energy thermal plus hard high-energy components up to 200 keV

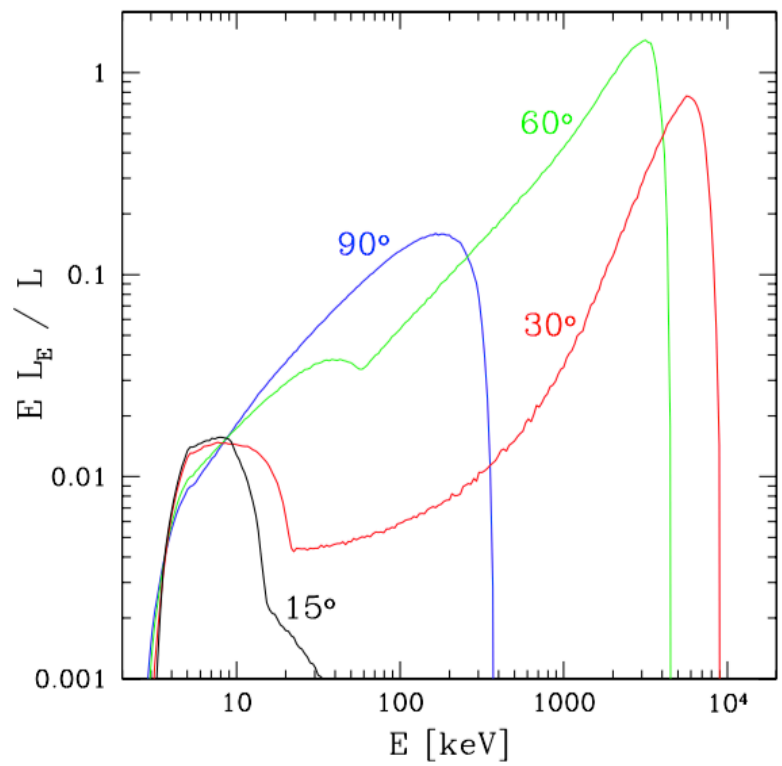
Data from:
INTEGRAL, NuSTAR and Suzaku

Enoto et al. 2017,
Kuiper et al. 2006,
Den Hartog, et al. 2008,
Tendulkar et al. 2015,
Younes et al. 2017

Magnetar quiescent emission theory

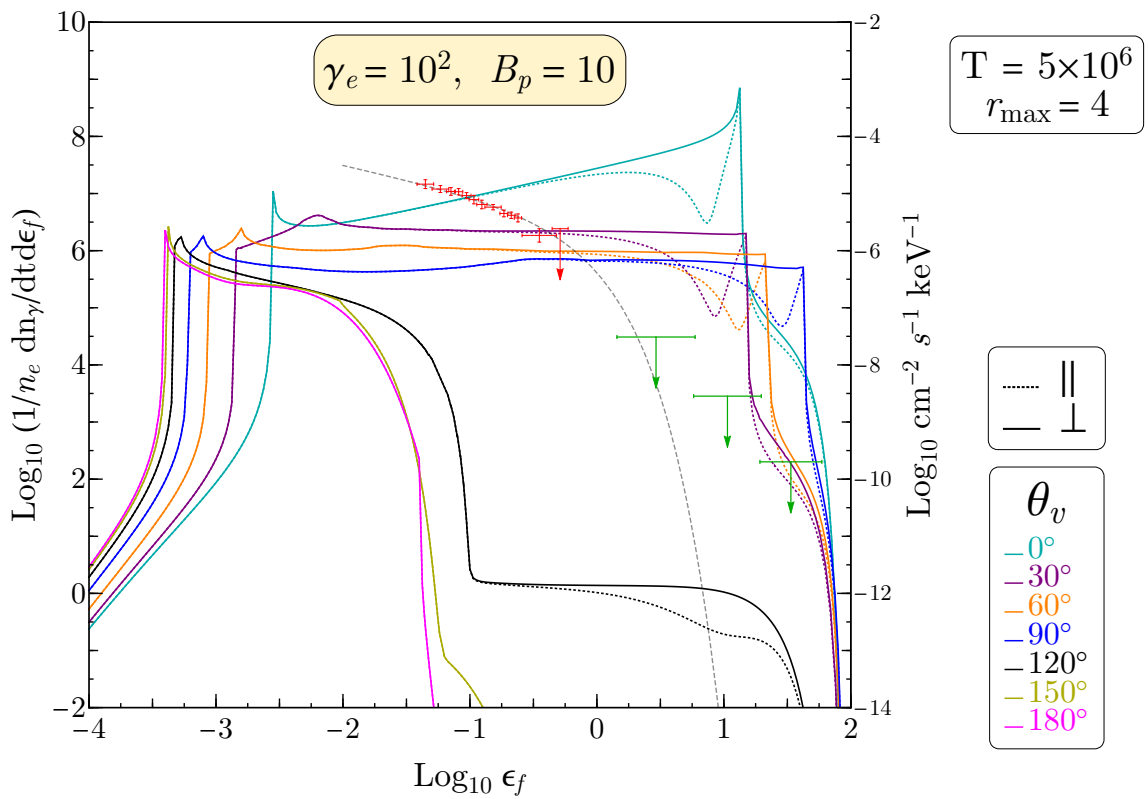
Cyclotron resonant upscattering and pair/splitting cascade
Measuring phase-resolved spectra can constrain magnetic field configuration
Baring & Harding (2004), Beloborodov (2013)





Polarization of resonant Compton upscattering

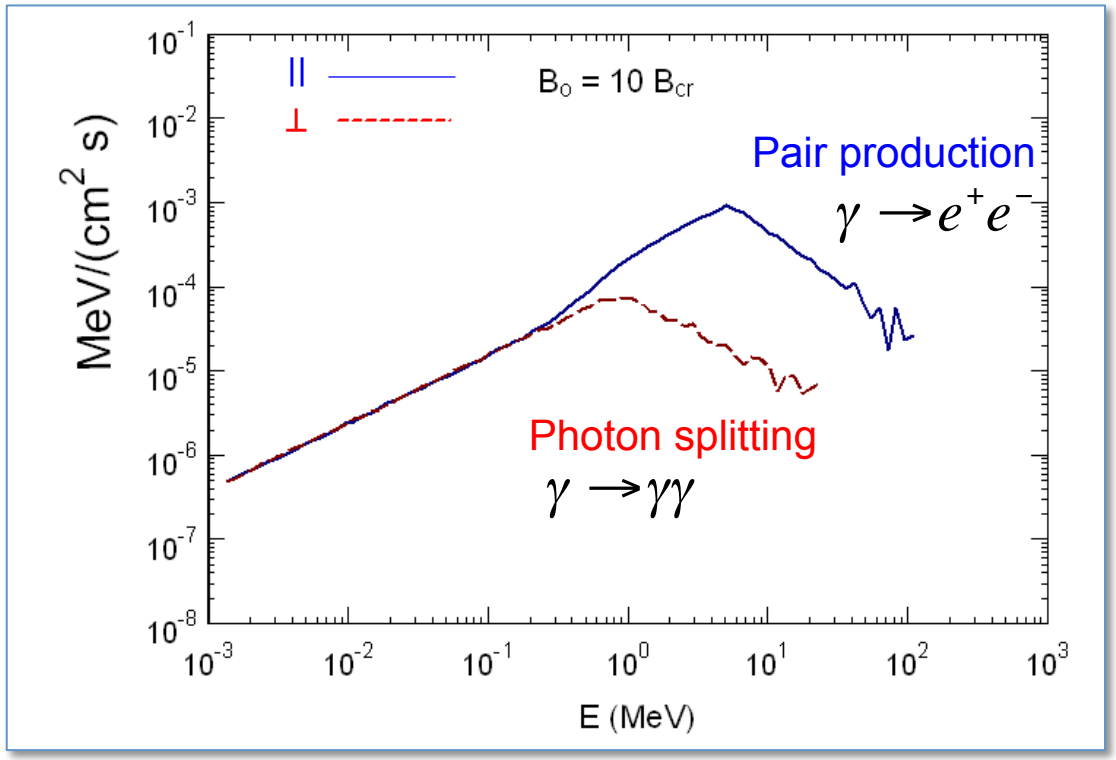
Spectrum is strongly polarized near upper limit (Wadiasingh et al. 2017)



Expect $\perp$ mode to dominate If maximum particle energy causes cutoff

Magnetars – signature of photon splitting?

Photon splitting cutoff at lower energy than pair production cutoff



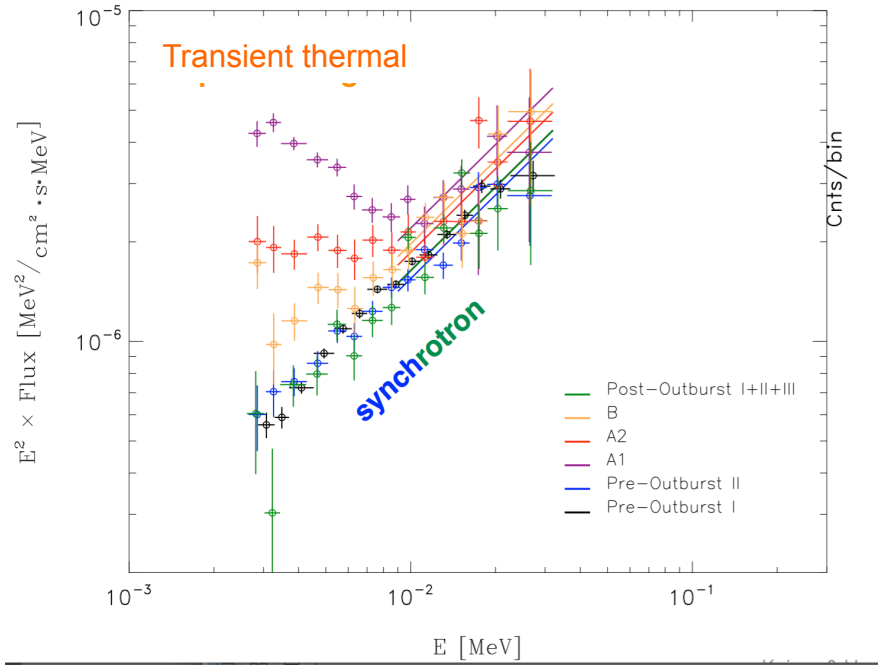
Look for 100% parallel polarization near the cutoff

Pulsar/magnetar connection

- Magnetar-like outbursts from rotation-powered pulsars
- Measure evolution of high-energy component – relaxation of toroidal magnetic field?

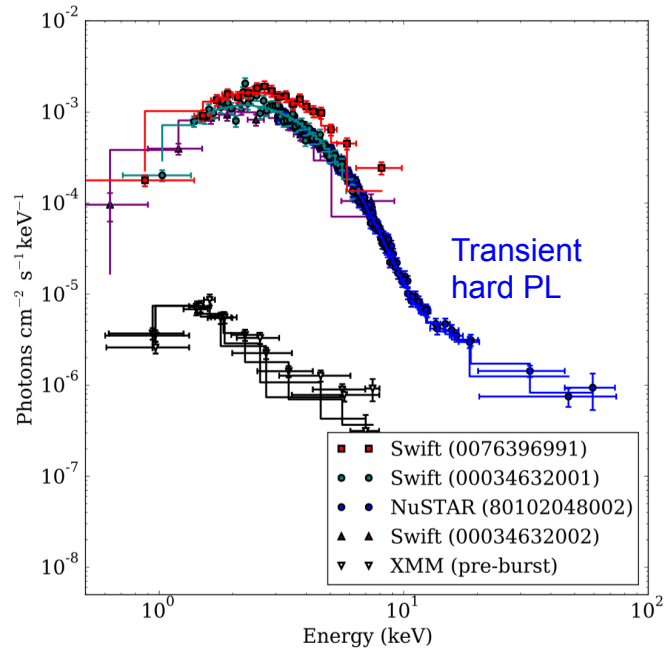
J1846-0258 2006 burst

Kuiper & Hermsen 2009



J1119-6127 2016 burst

Archibald et al. 2016



Summary

- Rotation-powered pulsars
  - Young ‘MeV’ and millisecond pulsars
  - Polarization – mechanism of GeV emission
- Magnetars
  - Phase-resolved cutoff in quiescent hard component
  - High polarization at cutoff: photon splitting ||; max γ, $\perp$
- Magnetar-like pulsars
  - Evolution of hard spectral cutoff after outburst
- Pulsar wind nebulae, MSP binaries
  - Spectral high-energy cutoff → maximum shock acceleration energy
    understanding pulsar wind

AMEGO at the 231st AAS

http://asd.gsfc.nasa.gov/amego

Monday

Gamma-SIG at 11:00 am (MD Ballroom 3)

Tuesday

Poster Session at 5:30 pm

MeV Emission from Local Seyfert Active Galaxies (E. Mullin)

Wednesday

Talk at 10:00 am (Maryland B)

Polarization Observations of Fermi Blazars (B. Rani)

Wednesday

Splinter at 1:00 pm (National Harbor 8)
https://asd.gsfc.nasa.gov/conferences/aas2018/

Astrophysical Extremes and Life Cycles of the Elements (A. Harding, D. Hartmann, J. Racusin, A. Fabian, R. Woolf, & T. Linden)

Poster Session at 5:30 pm

Fermi-LAT VIP AGN (D. Thompson)

GRBs and GW Counterparts with AMEGO (J. Racusin)

Neutrino Astrophysics in the MeV Band (R. Ojha)

Thursday

iPoster Session at 9:00 am

Development and Testing of the Tracker (S. Griffin)

Poster Session at 5:30 pm

Exploring Dark Matter (R. Caputo)

CsI Calorimeter Development for AMEGO (J. E. Grove)

Friday

Talk at 2:10 pm (Potomac C)

Advancing the MeV Frontier with AMEGO (D. Hartmann)