X-ray study of **MeV pulsar**

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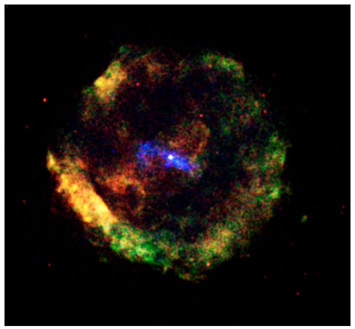
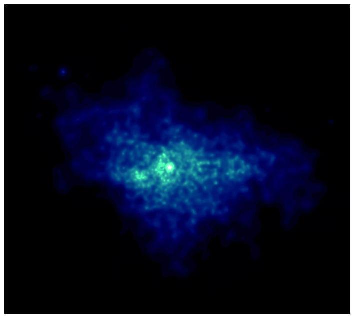
RCW 103/ PSR B1509-58

G11.2-0.3/PSR J1811-1925



G54.1+0.3/PSR J1930+1852



Outline

1. Introduction : MeV pulsar

2. Analysis of the X-ray emission

3. Model
   - Emission from polar cap cascade region

4. Summary

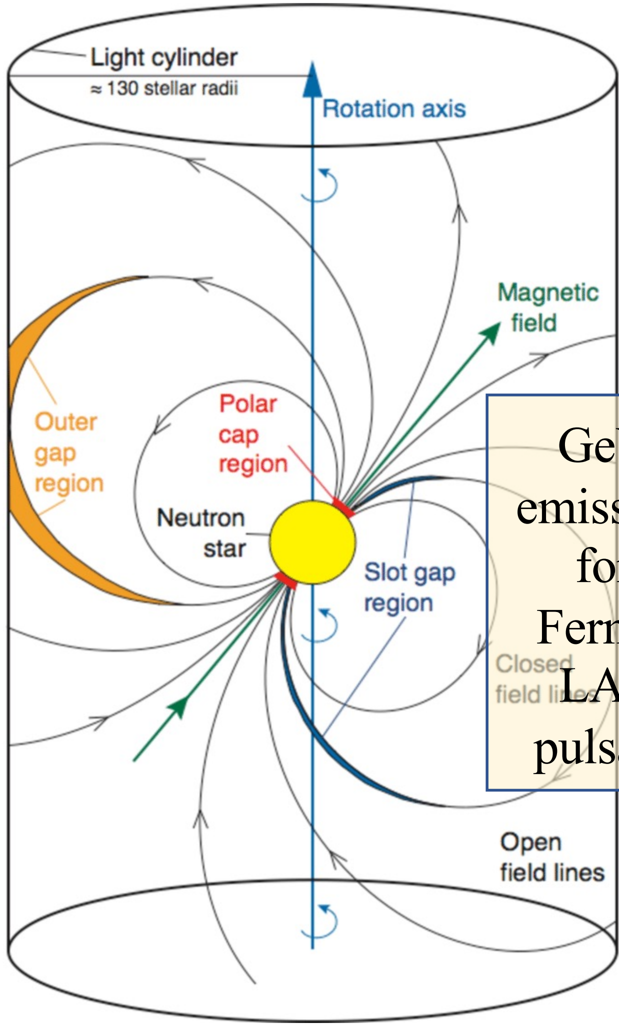
1 Introduction : Background

One of unresolved issue of pulsar emission :
Have we observed the high-energy emission from polar cap accelerator/cascade region?

- Polar cap pair-creation cascade is necessary for
  - radio emission
  - pulsar wind pairs
  - (magnetar, FRB)

- Primary GeV emission cannot escape from the polar cap cascade region.

- Is any signature of the cascade emission in <MeV observations of the pulsars?



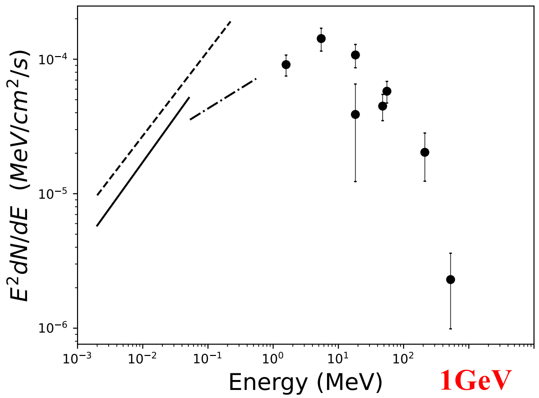
GeV emission for Fermi-LAT pulsars

1 Introduction : MeV pulsars

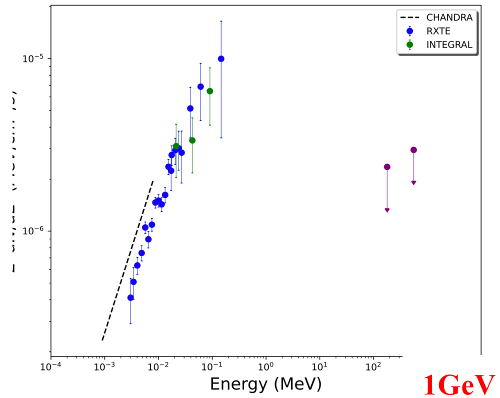
- GeV quiet
- Possible SED peak at around MeV

- 6 confirmed sources
  - **Radio loud**
    - B1509-58 (1.6×10^3yr)
    - J1617-5055 (8.1×10^3yr
    - J1930+1852(2.9×10^4y
  - **Radio quiet**
    - J1811-1925(1.2×10^4yr)
    - J1838-0655(2.2×10^4yr)
    - J1846-0258 (730yr)

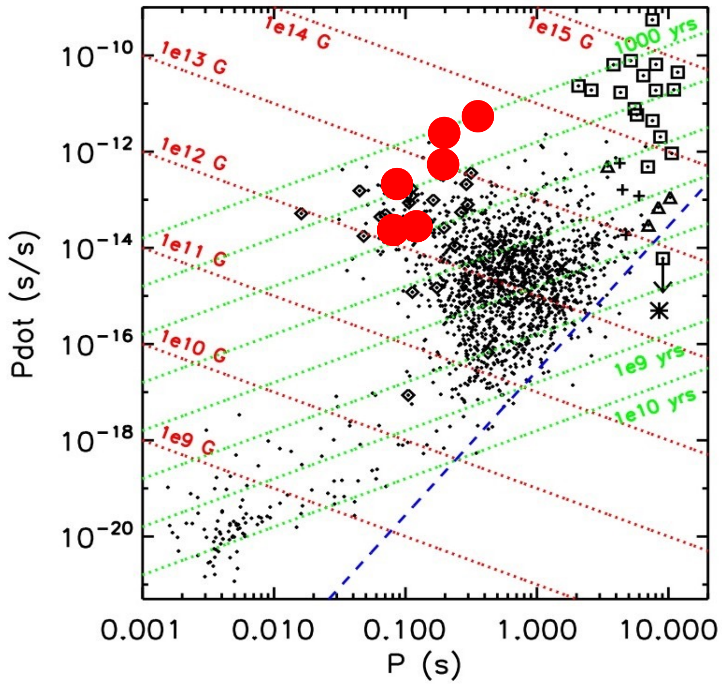
PSR B1509-58



PSR J1811-1925



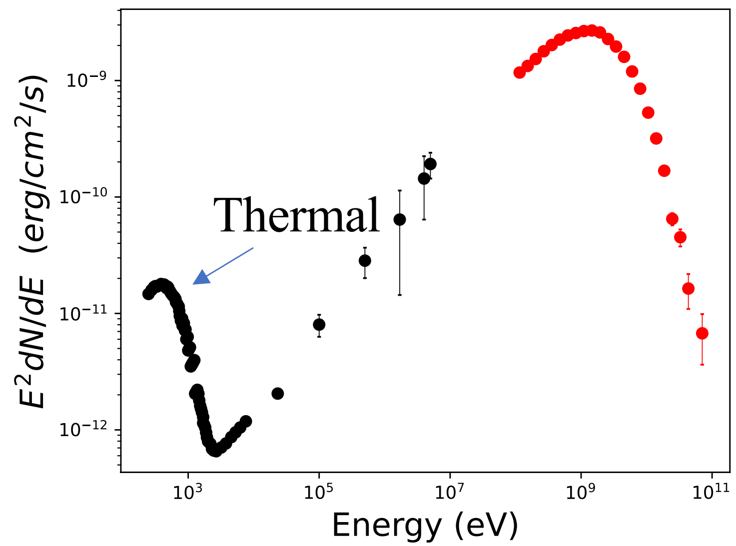
(Kuiper et al. 2015)



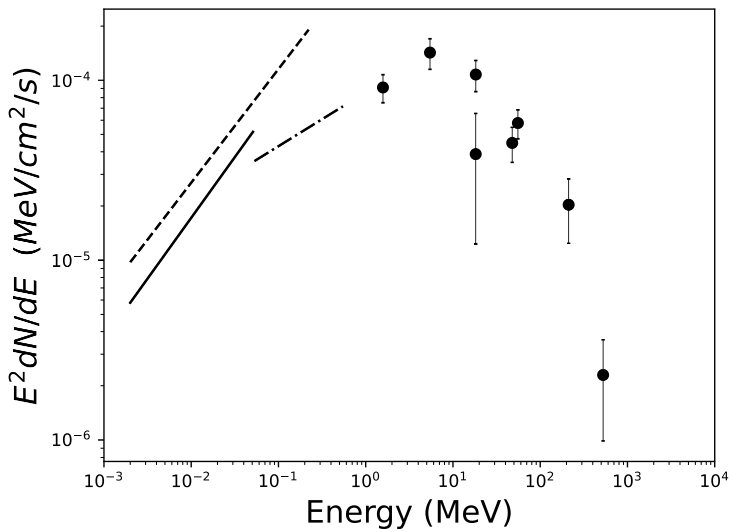
GeV pulsars vs. MeV pulsars

	GeV pulsars	MeV pulsars
Confirmed number	~300	6
SED peak	~GeV	~MeV
L_{GeV}/L_X	$\sim 10^3 >> 1$	<1
X-ray spectrum	Thermal + Non-thermal (e.g. Vela, Geminga)	Non-thermal

Vela (GeV pulsar)



B15090-58 (MeV pulsar)

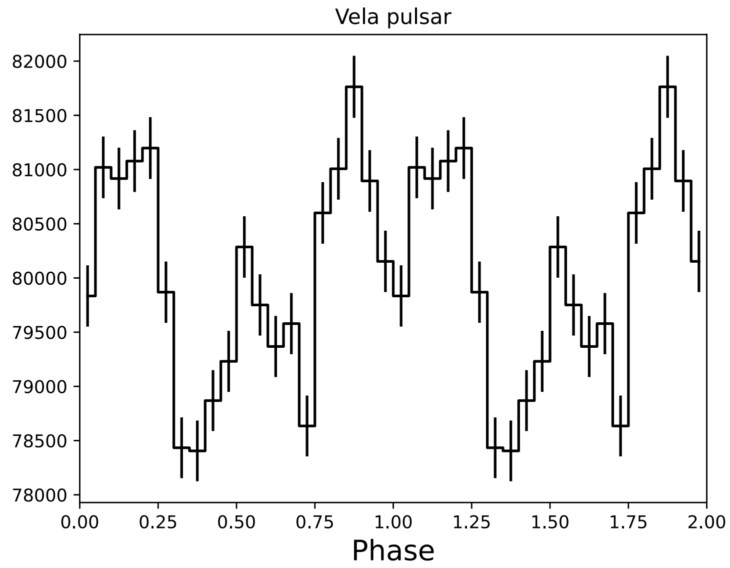


Kuiper et al. (2015)

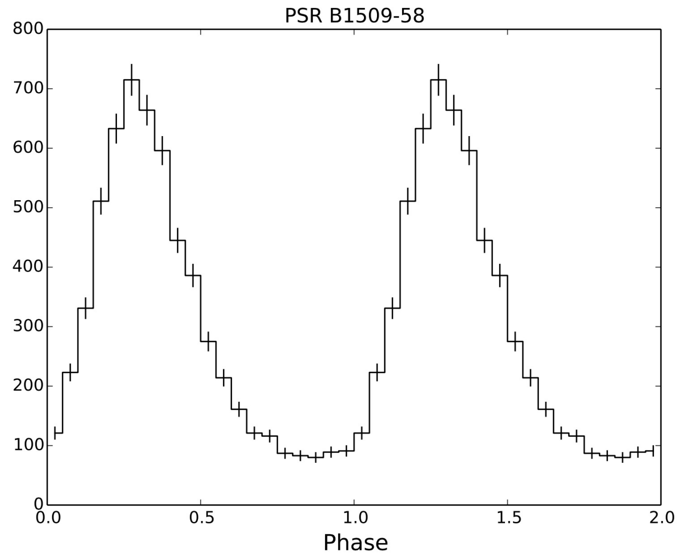
GeV pulsars vs. MeV pulsars

	GeV pulsars	MeV pulsar
Population	~300	6
SED peak	~GeV	~MeV
X-ray emission spectrum	Thermal + Non-thermal	Non-thermal
X-ray pulse profile	Multiple peaks	Single peak

Vela pulsar



B1509-58

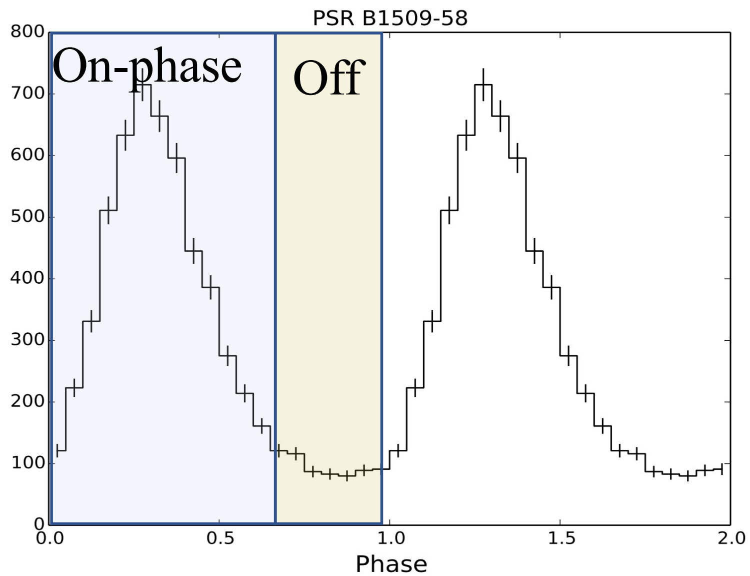


This study :

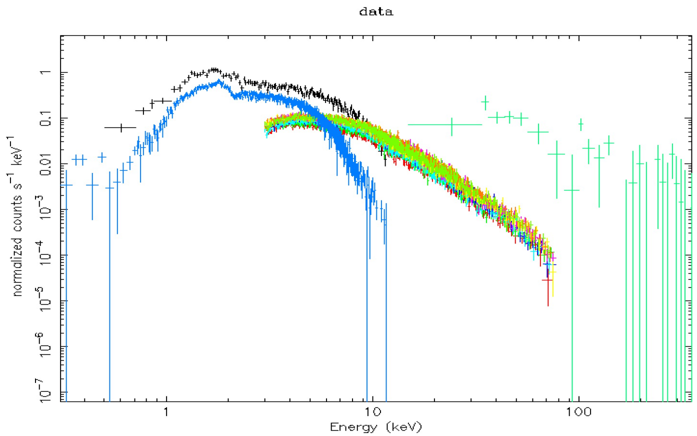
- Revisiting X-ray spectrum with accumulated data in the soft and hard X-ray bands.

- Investigating spectrum of the polar cap cascade emission.

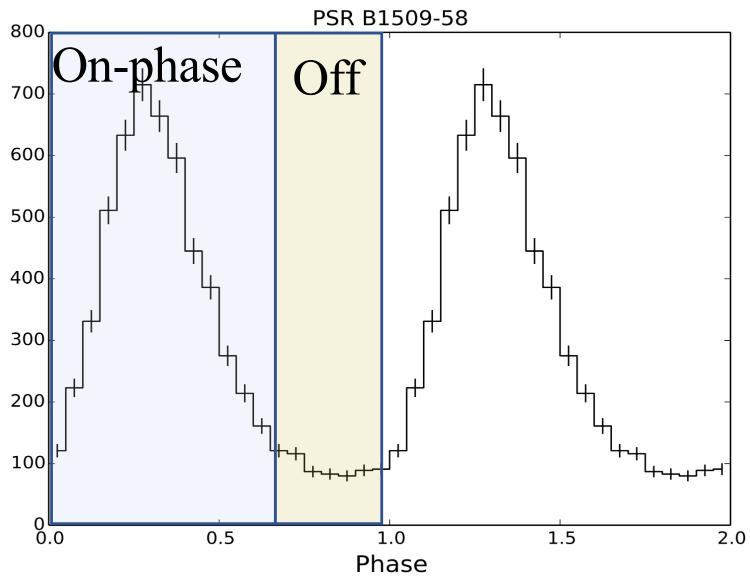
2. X-ray spectra of the *pulsed* emission



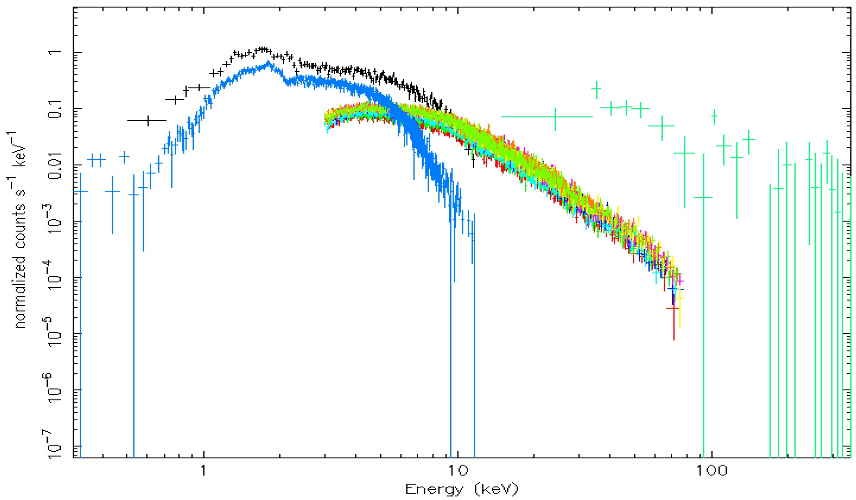
PSR B1509-58
(XMM, Chandra, NuSTAR, HXMT)

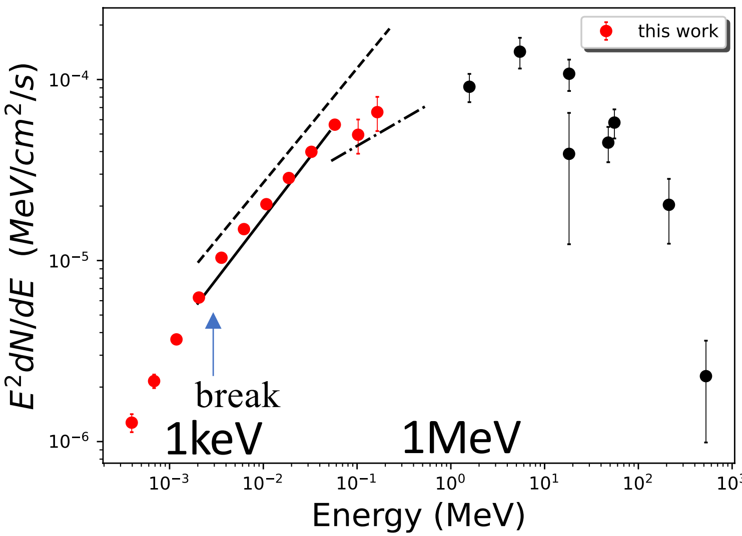


2. X-ray spectra of the *pulsed* emission



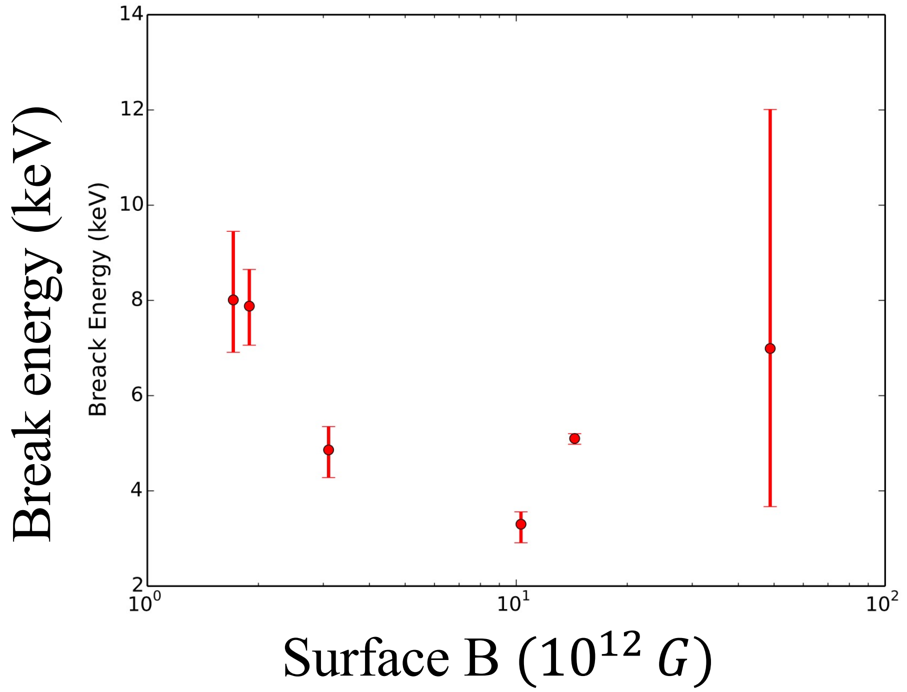
PSR B1509-58
(XMM, Chandra, NuSTAR, HXMT)





$$A(E) = \begin{cases} KE^{-\Gamma_1} & \text{if } E \leq E_{break} \\ KE_{break}^{\Gamma_2-\Gamma_1}(E/1keV)^{-\Gamma_2} & \text{if } E > E_{break} \end{cases}$$

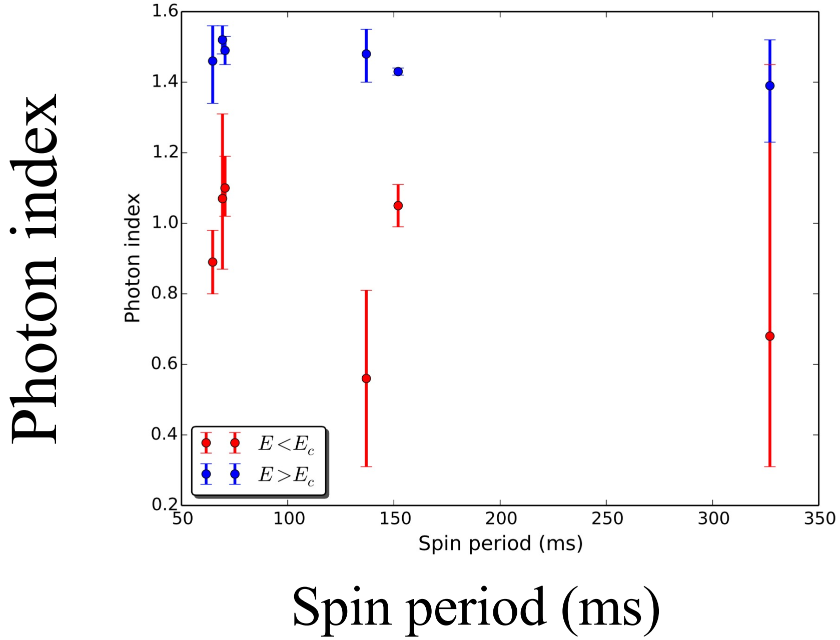
- **A broken power law model** **well describes in 0.3-100keV emission**



- Results of the spectral fitting.

(i) Break energy E_{break}~ 1-8keV,
 - higher than E_{break} <1keV for Fermi-LAT pulsars.

(ii) Photon index
 - For $E > E_{break}$, Γ_1~1.5.
 - For $E < E_{break}$, Γ_2~1.

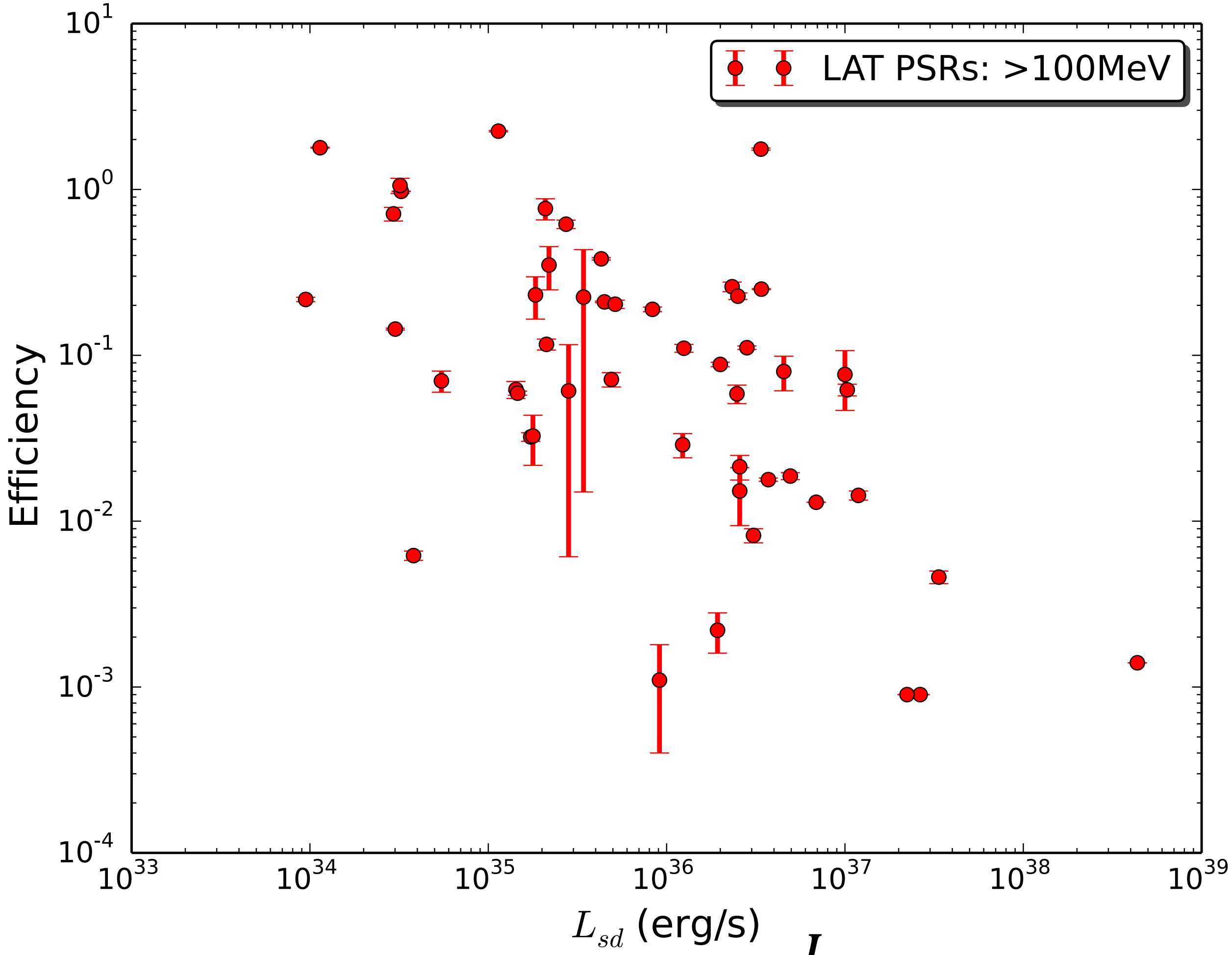


- Synchrotron emission
- Emission may come from region nearer stellar surface.

X-ray efficiency of MeV pulsars ~ GeV efficiency of Fermi-LAT pulsar

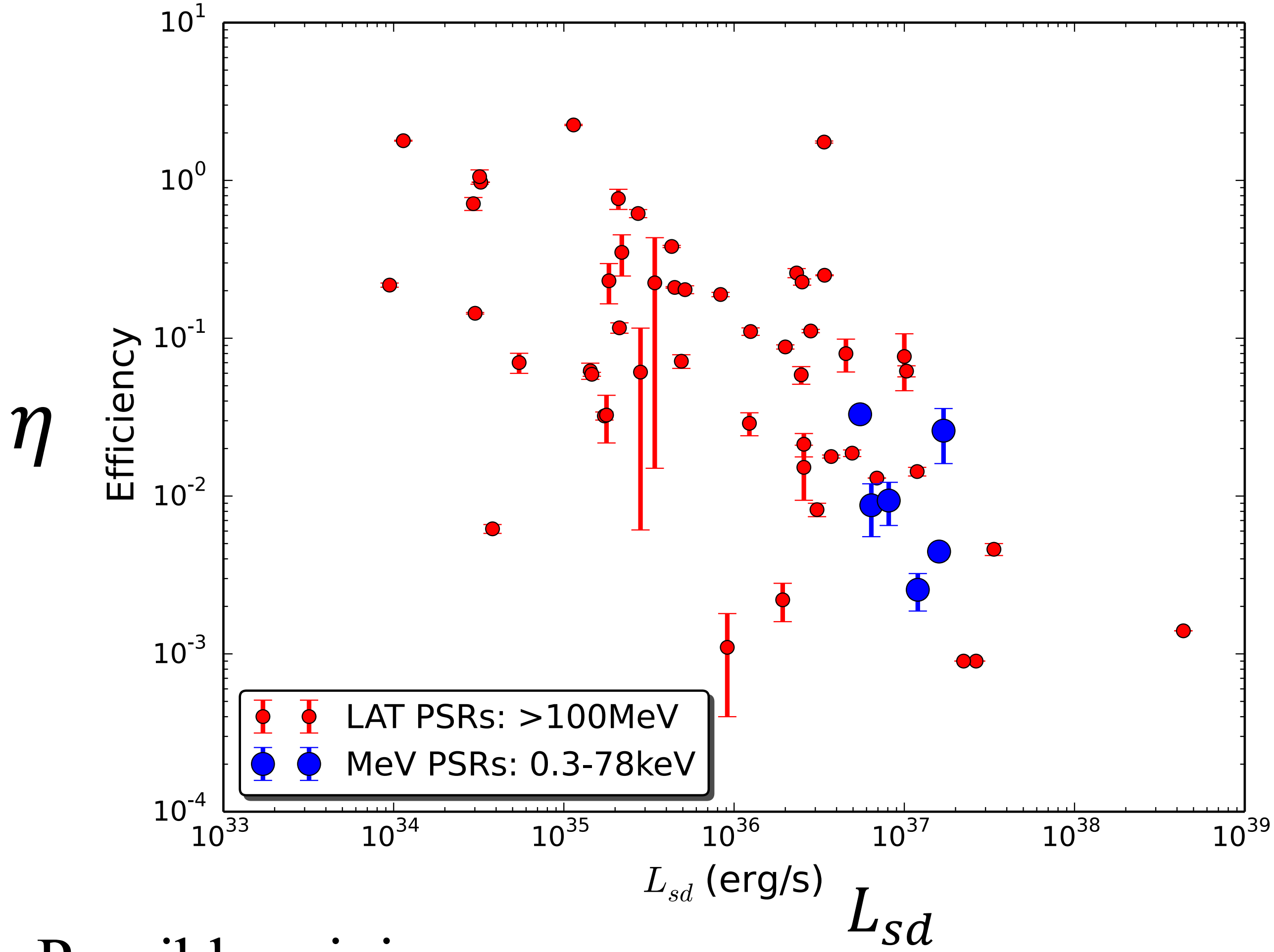
$$\eta \equiv \frac{L}{L_{sd}}$$

η



L_{sd}

X-ray efficiency of MeV pulsars ~ GeV efficiency of Fermi-LAT pulsar



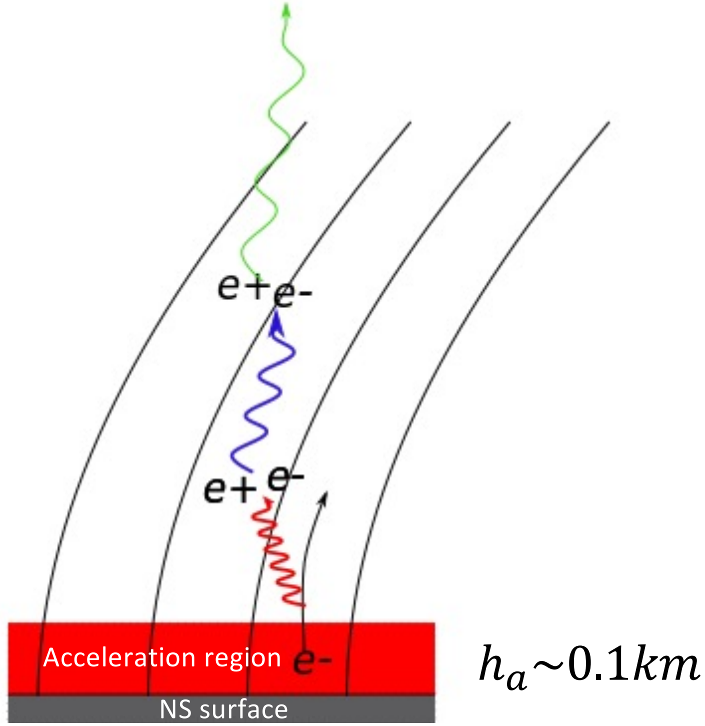
Possible origin :

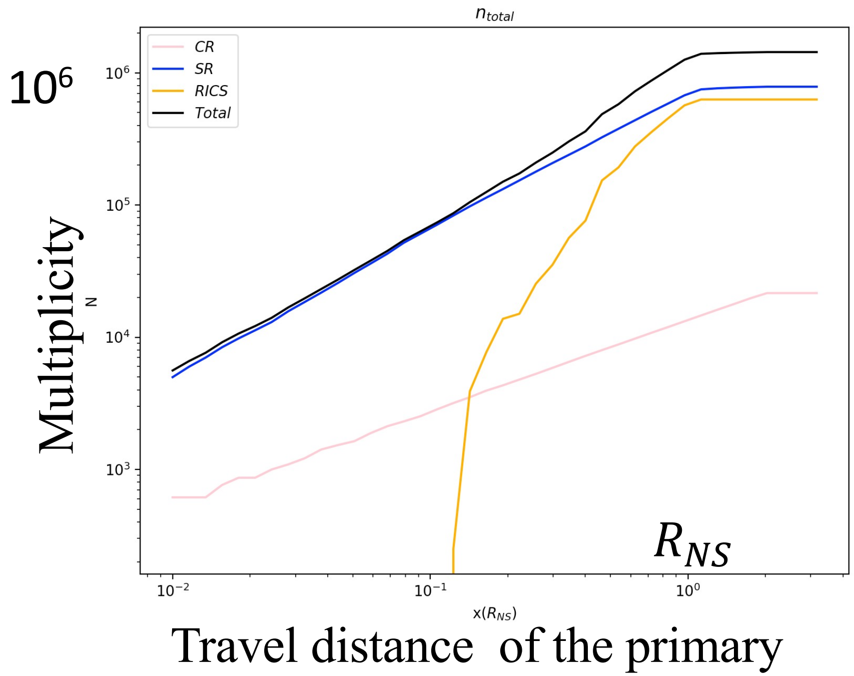
- Secondary emissions from the pairs, to which *most of the primary* emissions are converted.

3 Emission model

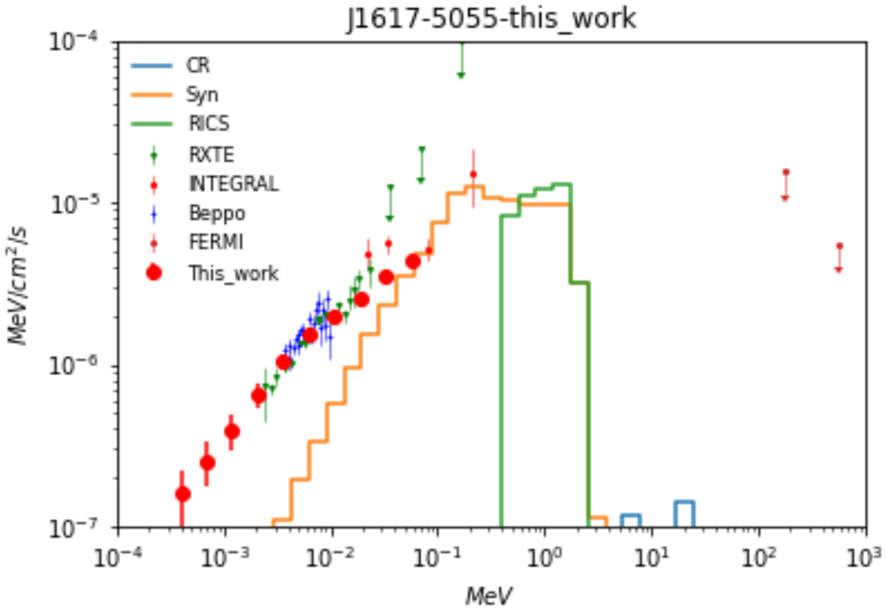
- 1-D model for the emission in the pair-creation cascade above the polar cap acceleration.
    - ✓ Curvature radiation of primary
    - ✓ Magnetic pair-creation
    - ✓ Synchrotron radiation
    - ✓ Resonant inverse-Compton scattering
- Multiplicity of the pairs

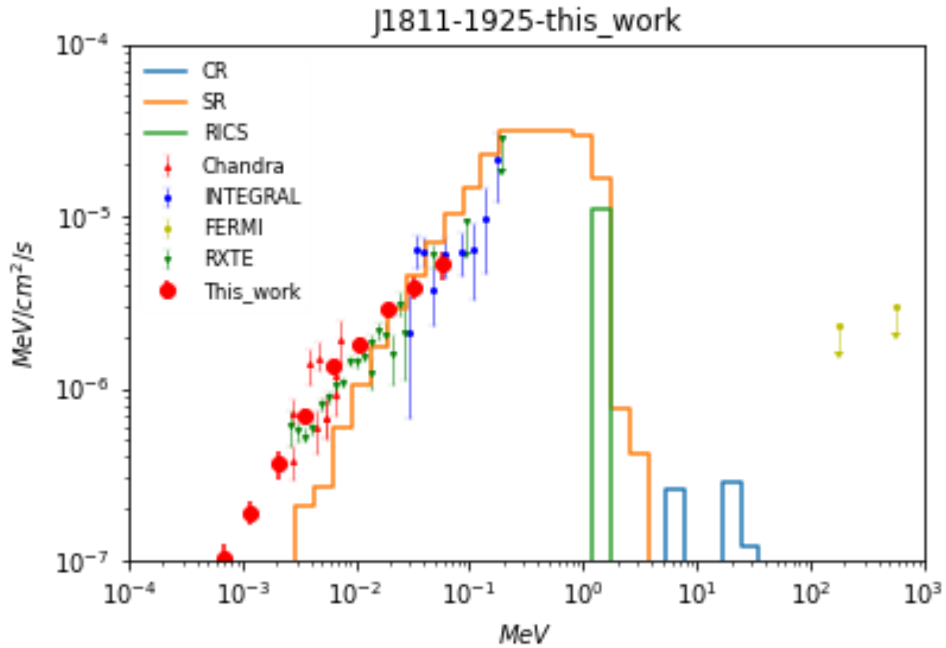
- **Spectrum**





Application to two MeV pulsars with $B_s < 10^{13}G$
-- Photon splitting process could be ignored.





- The total luminosity is consistent with the observations:
  -- Current model predicts a harder spectrum than the observation : PSR J1617-5055.

Future perspective

- What is the origin of the MeV pulsars?
- Where is the polar cap emission?

- Observations :

  -- MeV observation (population)

  -- Polarization in X-ray and in radio (Fermi-LAT pulsar vs MeV pulsar).

- Polar cap cascade model :

  -- Photon splitting process

  ✓ Magnetar

  ✓ FRB

Summary

I. Origin of the MeV pulsars are one of unresolve issue of the high-energy emission from pulsars.

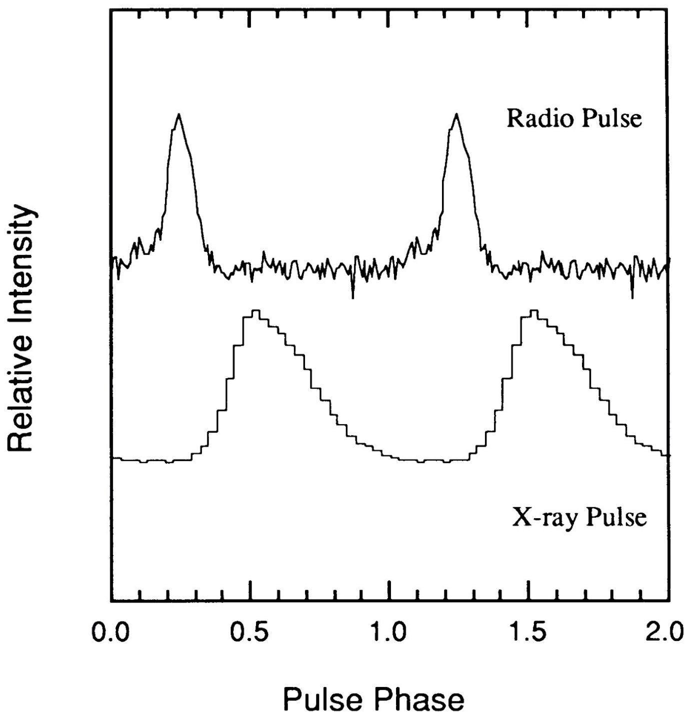
II. Its X-ray emission region is different from those of Fermi-LAT GeV pulsar.

- Magnetic field is probably stronger.

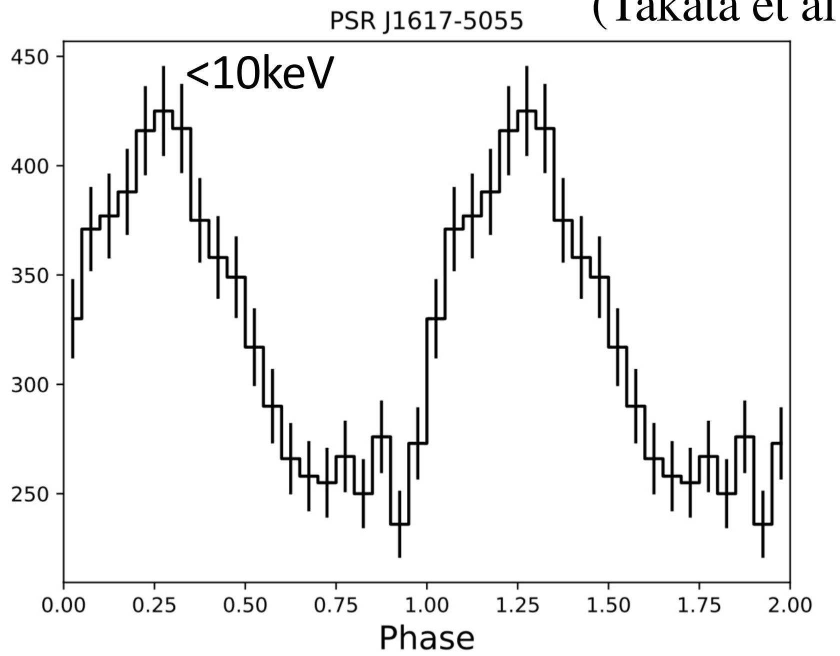
III. The polar cap cascade emission ?

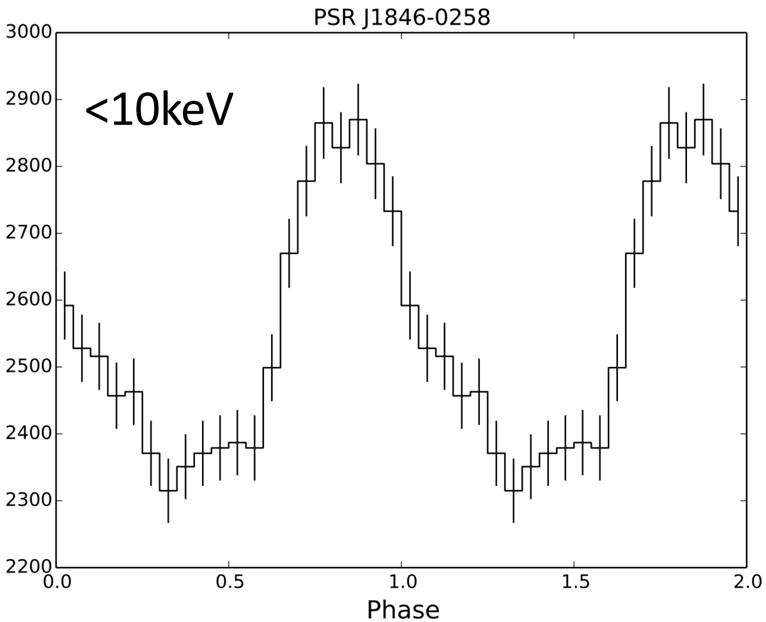
Thank you !!

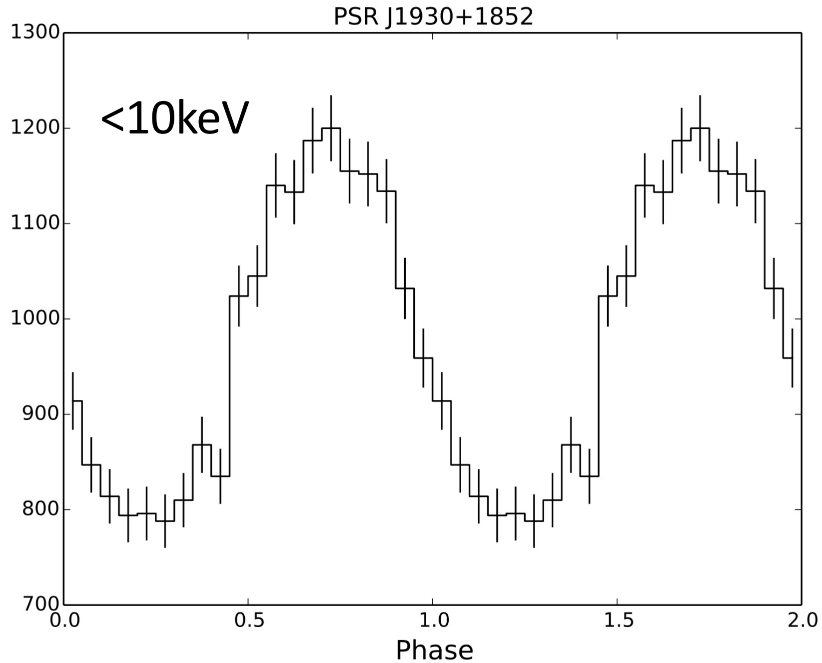
PSR B1509-58 (Kawai et al. 1991)



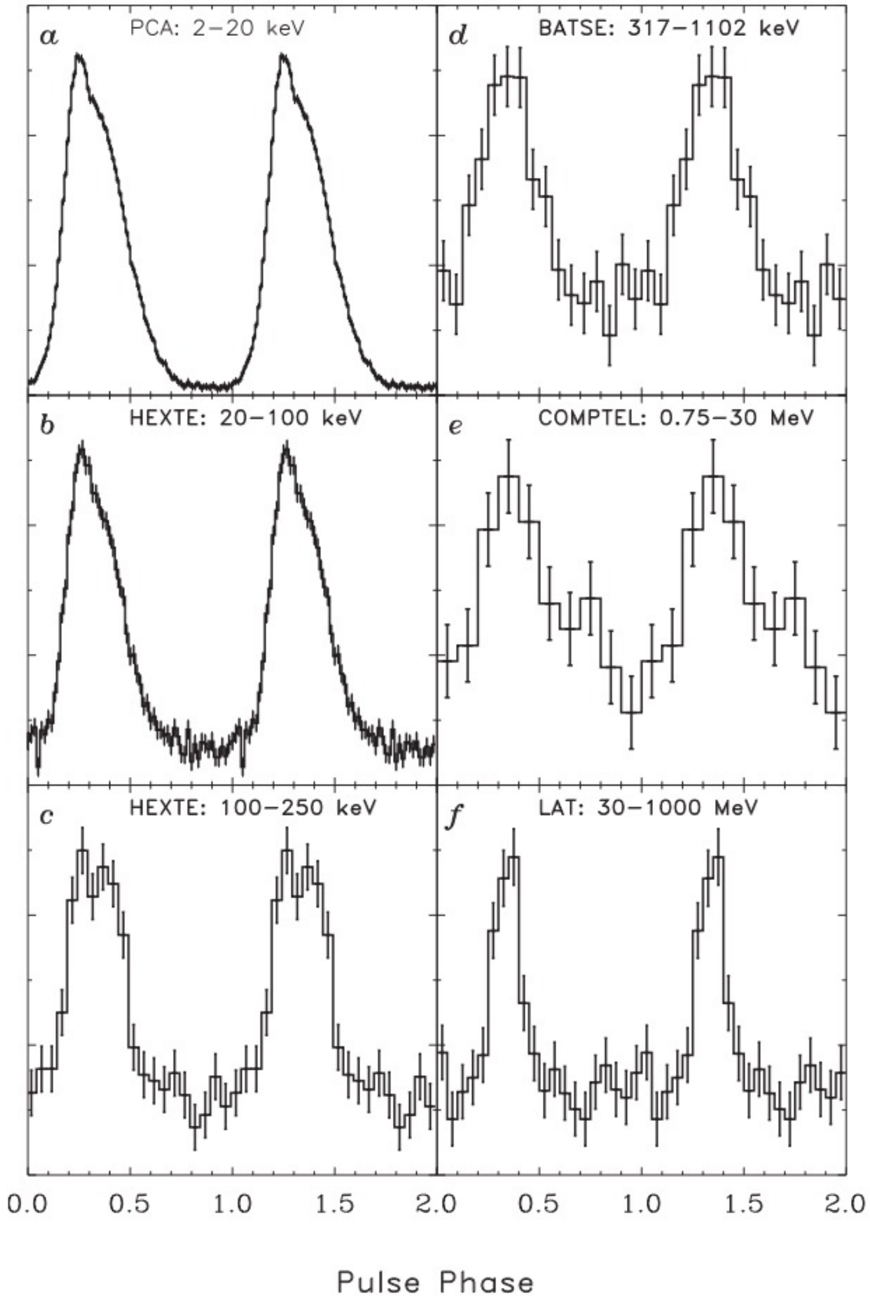
(Takata et al.)



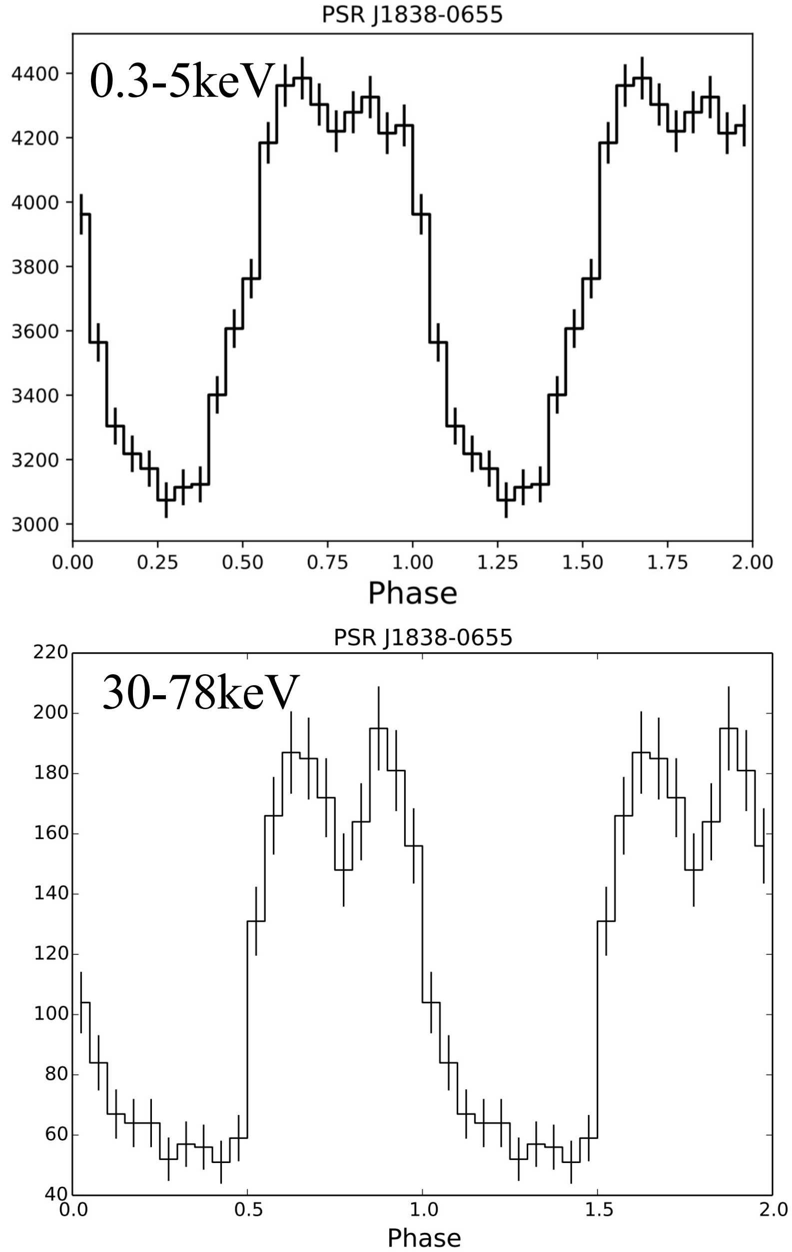




PSR B1509-58 (Kuiper & Hermsen (2015)



PSR J1838-0655 (Takata et al.)



- GeV dim/quiet
- X-ray emission

- high efficiency, hard spectrum, and single-broad (energy independent) pulse shape

→Emission mechanism/region may be probably different from the standard scenario.

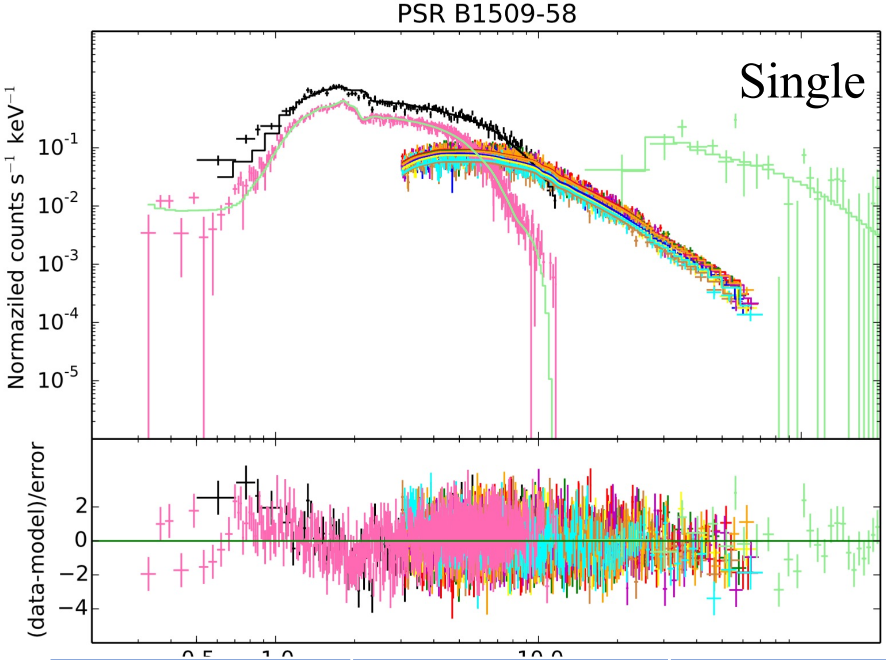
Q 1. What is the X-ray emission mechanism/region?

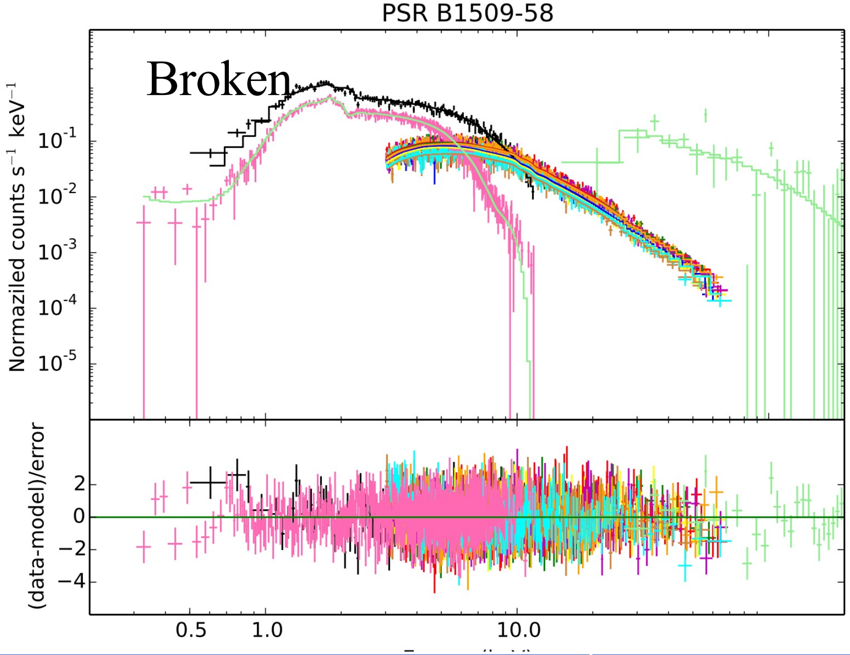
Q 2. Is this **primary emission** or **secondary emission**?

- **This study**

- Jointing spectral fitting of NuSTAR data with XMM/NICER/Chandra
- Efficiency in 0.3-78keV bands

Single power law or broken power law ?



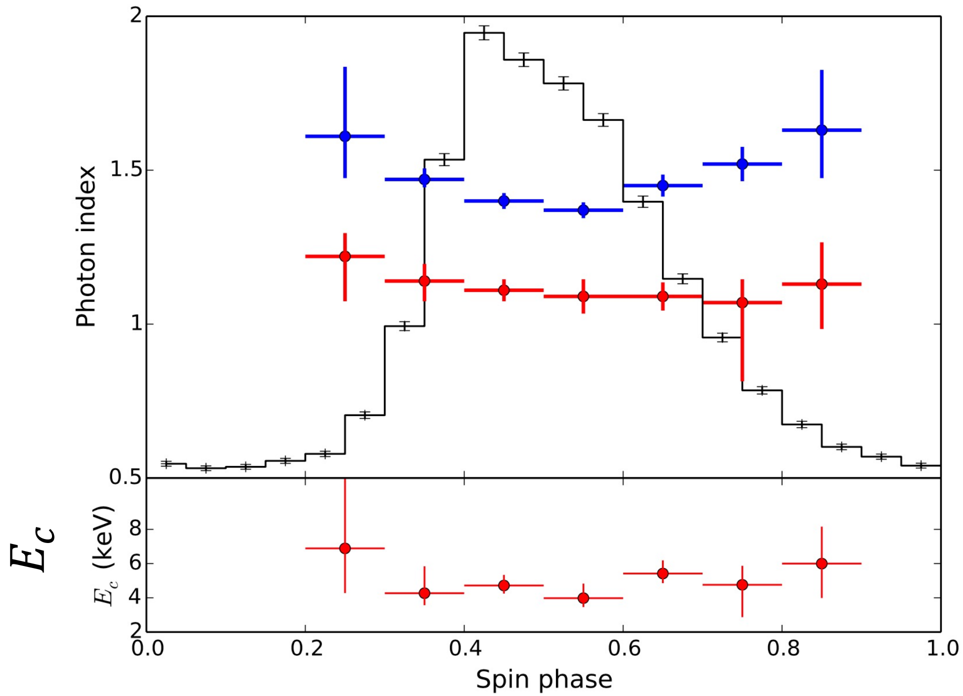


B1509-58						
	N_H $10^{22}/cm^2$	Γ	Γ_1	E_c (keV)	Γ_2	χ^2_ν
Single Power law	$1.30^{+0.02}_{-0.02}$	$1.40^{+0.01}_{-0.01}$	–			1.12(2721)
Broken power law	$1.05^{+0.04}_{-0.04}$	–	$1.05^{+0.06}_{-0.06}$	$5.1^{+0.12}_{-0.10}$	$1.43^{+0.01}_{-0.01}$	1.05(2719)

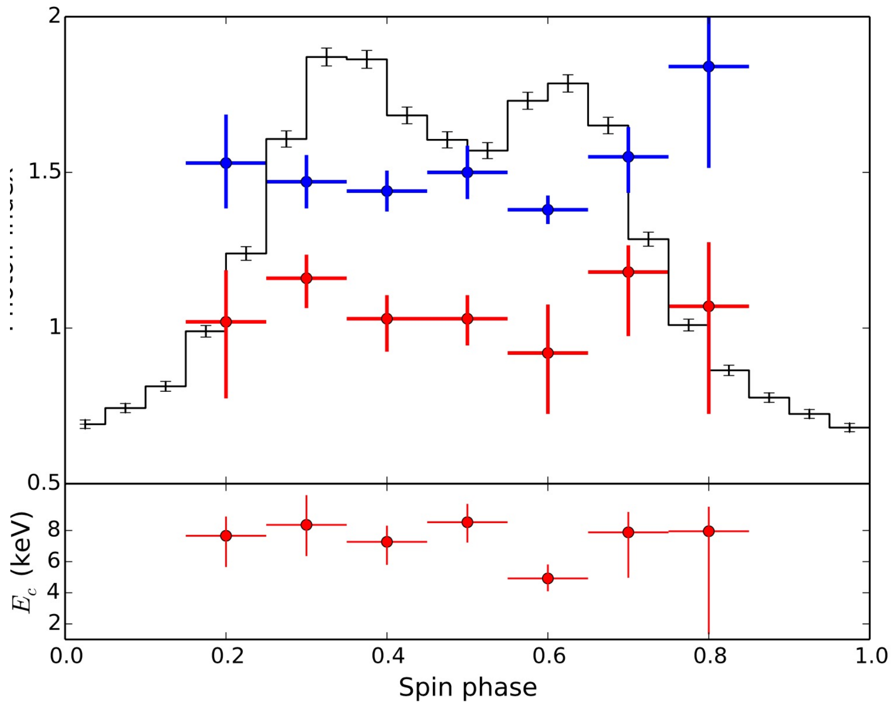
- **A significant spectral break, $\delta\Gamma \sim 0.4 - 0.5$, is expected.**
- PSR J1838-0655 also indicates a broken power law model.

Phase-resolved spectra

PSR B1509-58



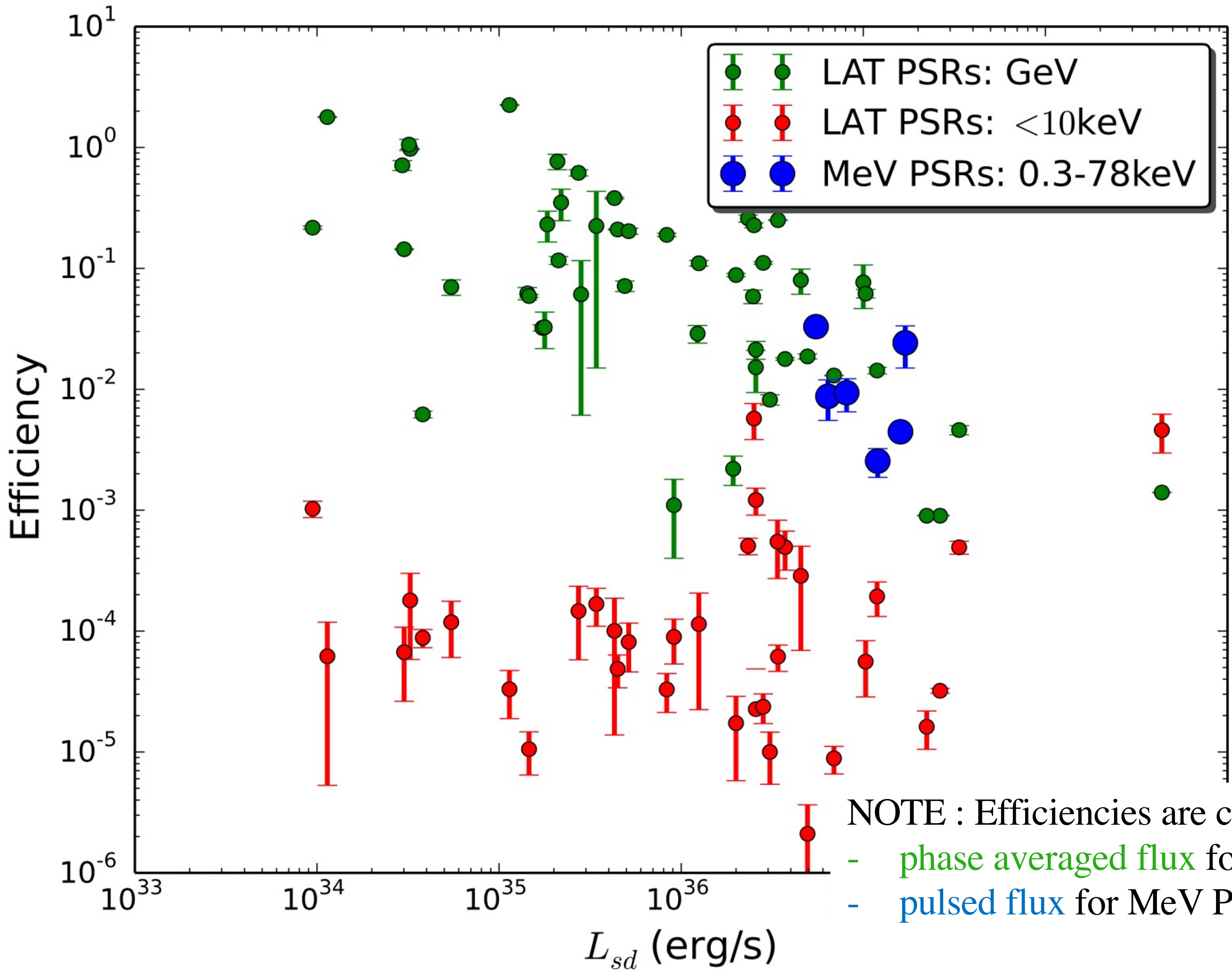
PSR J1838-0655



- Less evolution of a break energy

→ Emission is coming from compact region

Efficiency of MeV pulsar in 0.3-78keV bands



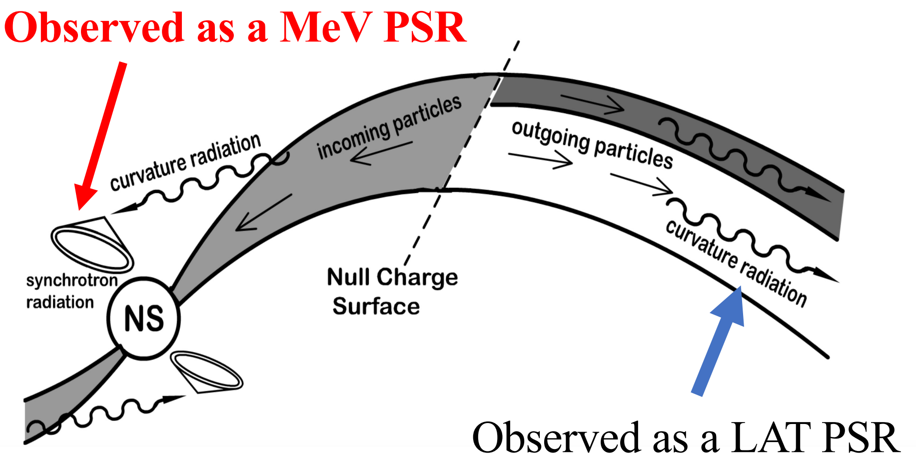
NOTE : Efficiencies are calculated from

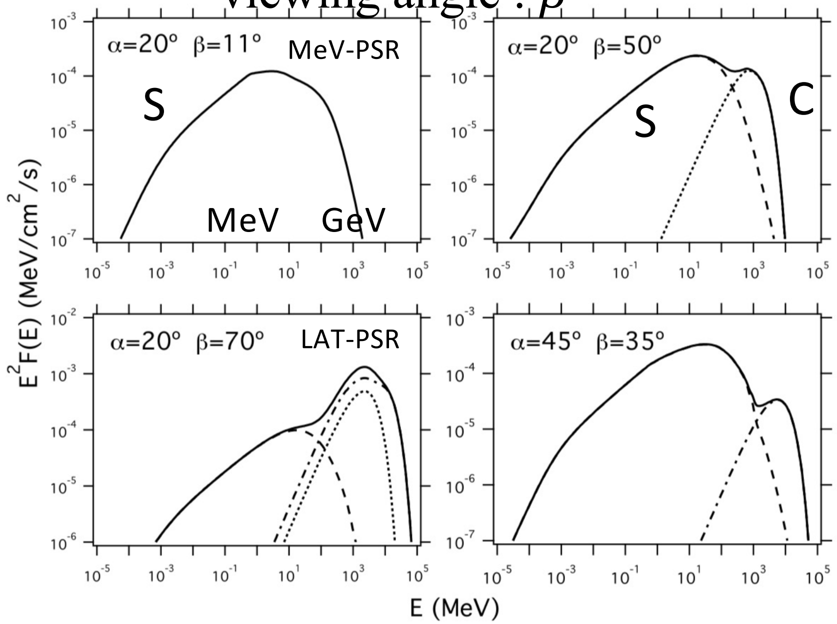
- phase averaged flux for LAT PSRs
- pulsed flux for MeV PSRs`

4. Constrain on emission region

- Geometrical effect ? (Wang et al. 2014; Harding et al. 2017)

magnetic inclination : α
viewing angle : β



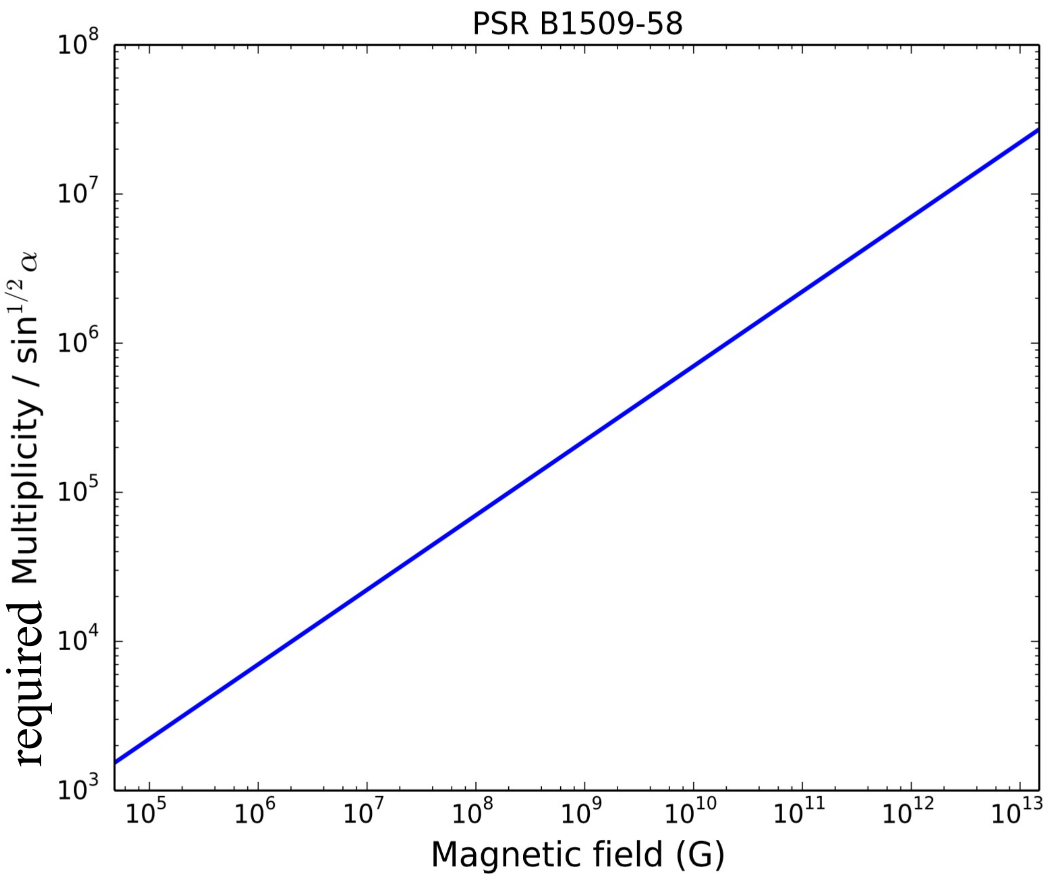


Wang et al. 2014

- Coming from the different primary/acceleration region ?

-- Polar cap?
-- Pulsar wind?
-- Multipole magnetic field region?

$$\text{Required multiplicity} = \frac{\text{Required Partcle Number Luminosity}}{\text{Goldreich} - \text{Julian Number luminosity}}$$



$r = R_{lc}$ $100R_{NS}$ $10R_{NS}$ R_{Ns}

- Synchrotron emission
- Efficiency =0.01
- Photon energy ~1MeV
- Magnetic field strength

Required particle number

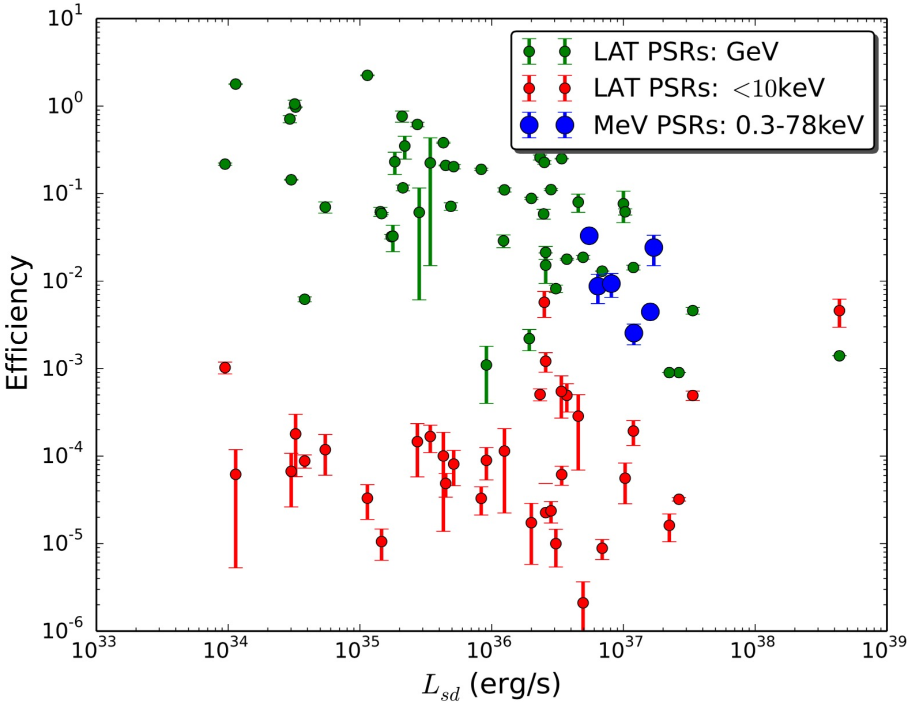
Multiplicity

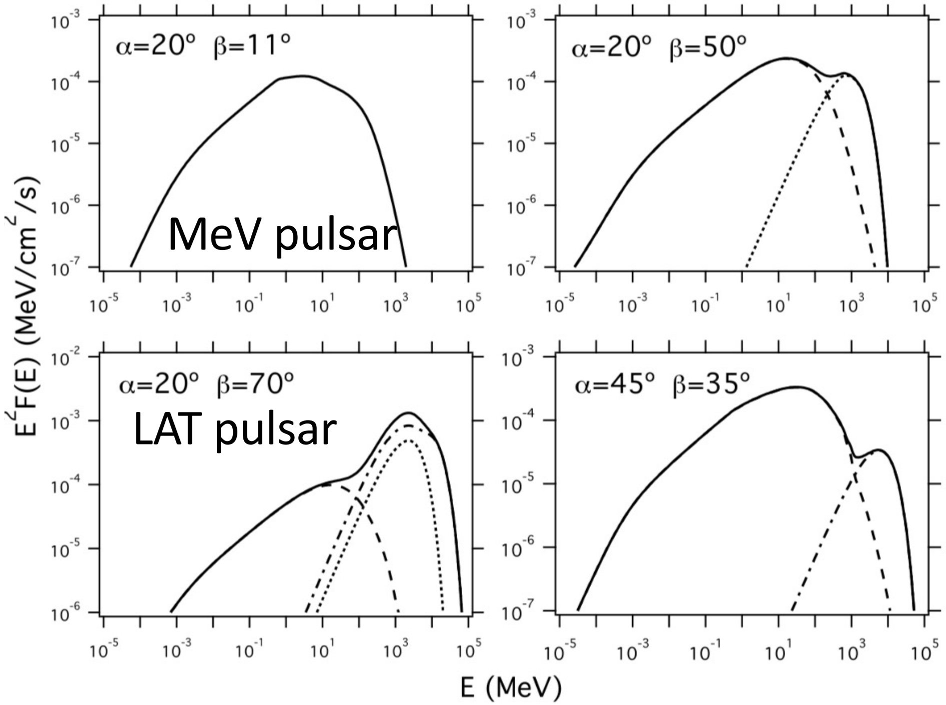
- Predicted maximum multiplicity at the polar cap region is $\sim 10^{5-6}$.
- It is very difficult to create a multiplicity $\sim 10^3$ at our magnetosphere.

The pairs streaming from the polar cap region main gain a perpendicular momentum at $> 10R_{NS}$ (?).

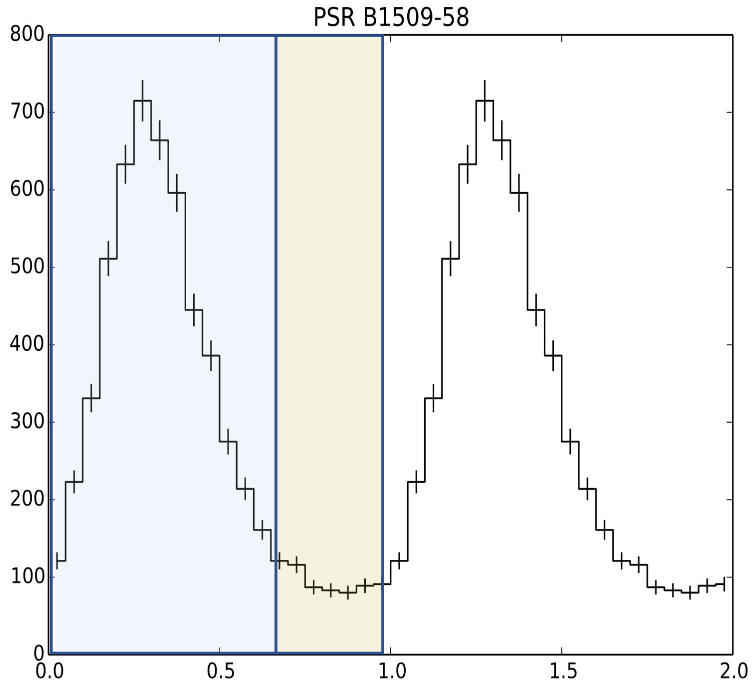
Future perspective

- Efficiency of >10keV bands for Fermi-LAT pulsars.
- New MeV pulsars.





FORCE observations for MeV pulsar



(B) 点源の場合(2HPD=30"の円領域)
基本的に(A)と同じですが、あらかじめ点源用 NXB を作成します。
 1) 点源用にNXBファイルを修正します。コピーして使ってください。

```
 UNIX> cp FORCE_NXB_10cm2_10Ms_c_20200108.fak FORCE_NXB_10cm2_10Ms_c_20200108_ForPointSrc.fak
 UNIX> fparkey 0.00237 FORCE_NXB_10cm2_10Ms_c_20200108_ForPointSrc.fak+1 BACKSCAL
```

 2) (A)の(1)~(3)を実行してください。ただし、NXBファイルは上記で作成したものを使います。
   また、モデルに const を加えてください。

例

```
----------------------------------------------
XSPEC12>model const*phabs*powerlaw
Input parameter value, delta, min, bot, top, and max values for ...
              1       0.01(      0.01)          0          0      1e+10      1e+10
1:constant:factor> 0.8
...
----------------------------------------------
```

FORCE_bestest_ALL_20200123.rsp

- **Simulation for Phase-resolved spectra**

On-phase - Off-phase =Pulsed component

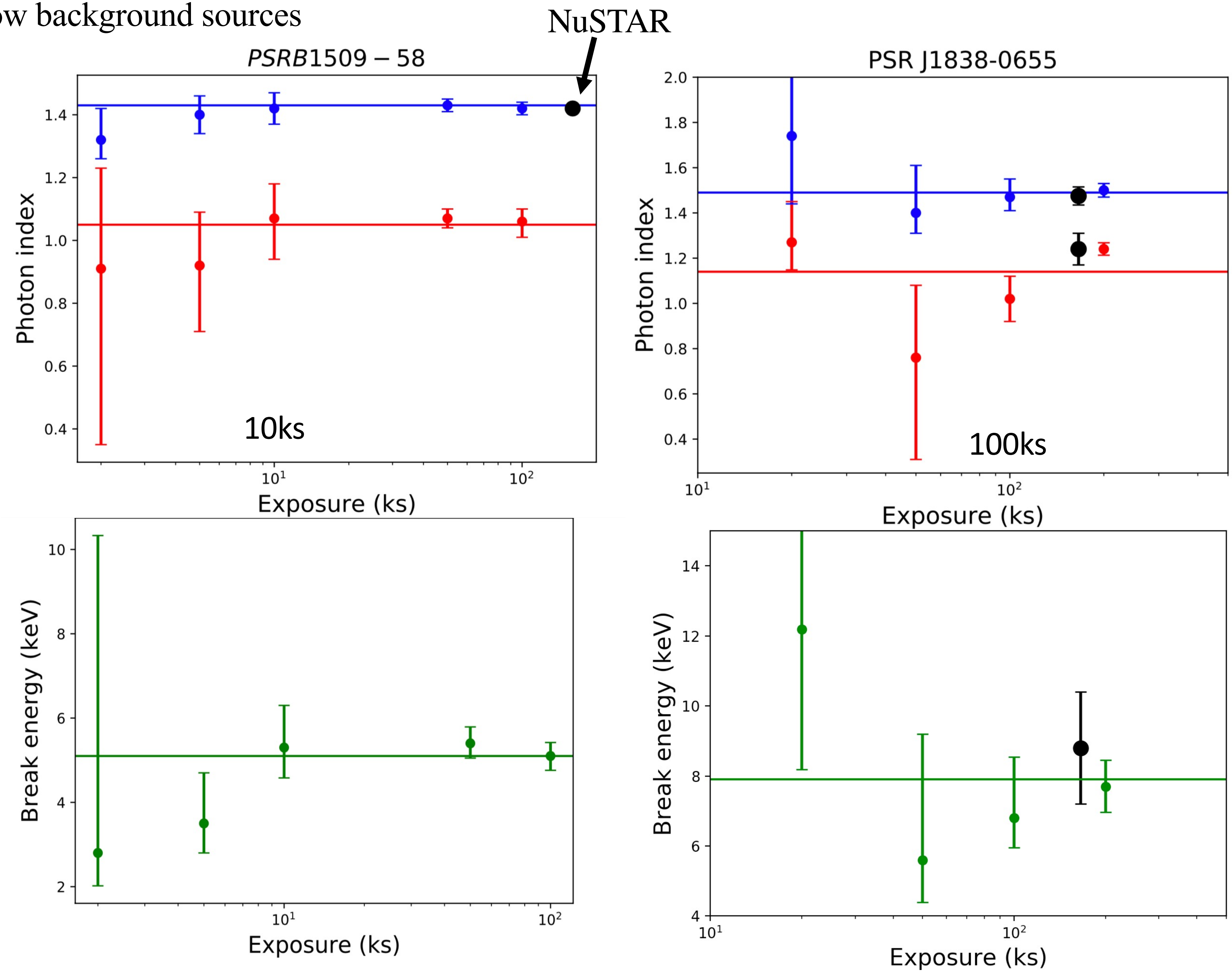
B1509-57	Broken Power law			Power Law
$N_H = 1.05\times10^{22}/cm^2$ (fixed)	Γ_1	E_c (keV)	α_2	α
Best fit for **off Phase** **(XMM/Nustar)**				1.70
Best fit for **Pulsed component**	1.05	5.1	1.43	

↓ Sum

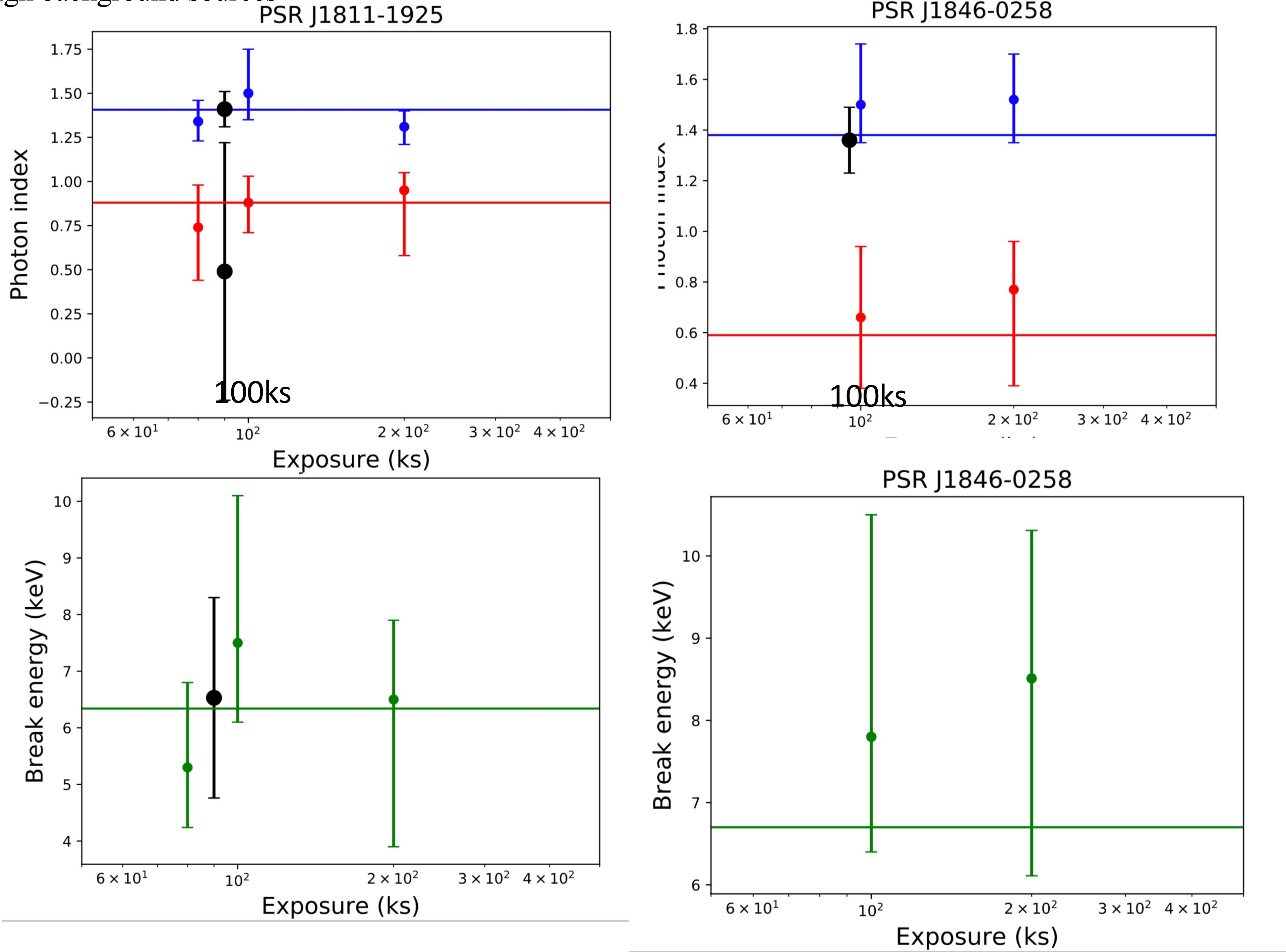
On Phase

- Required exposure to find a correct answer.

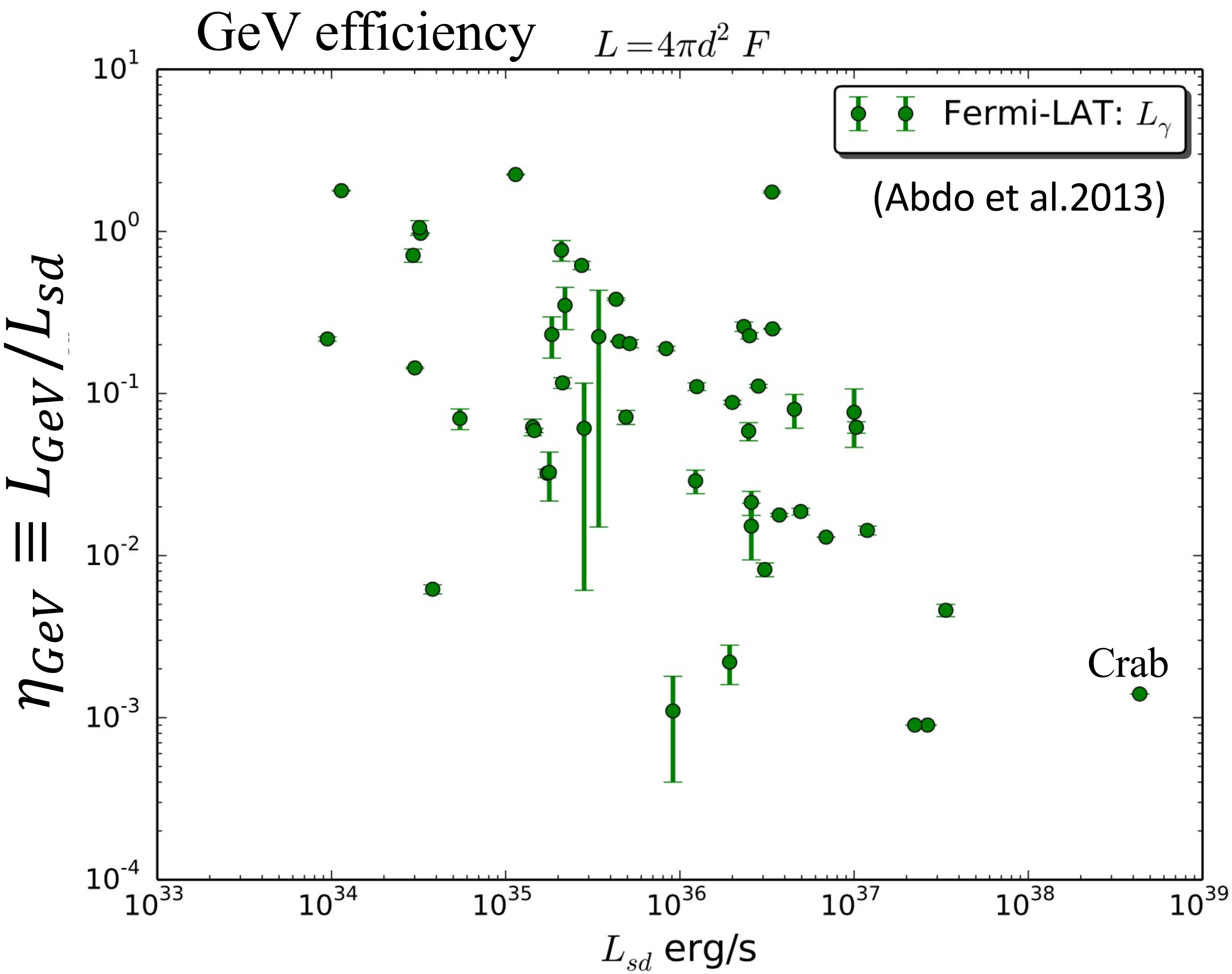
Low background sources



High background sources

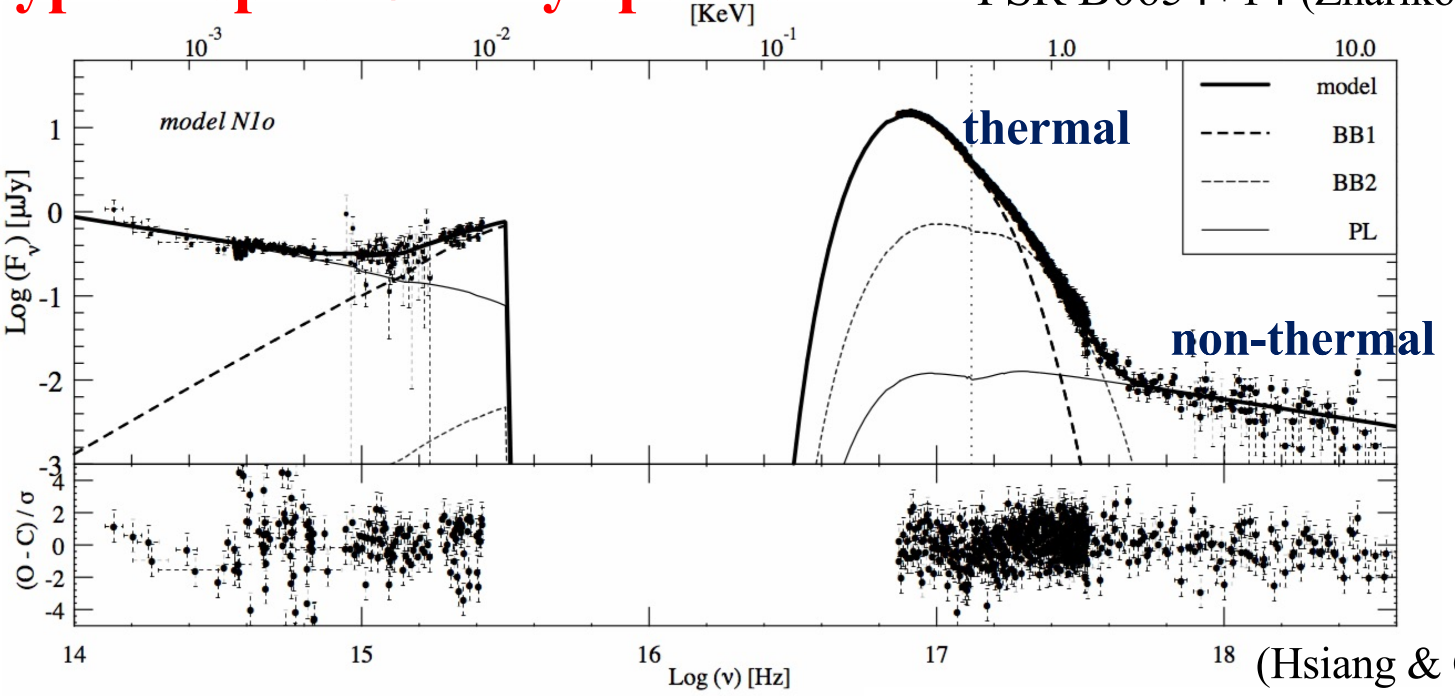


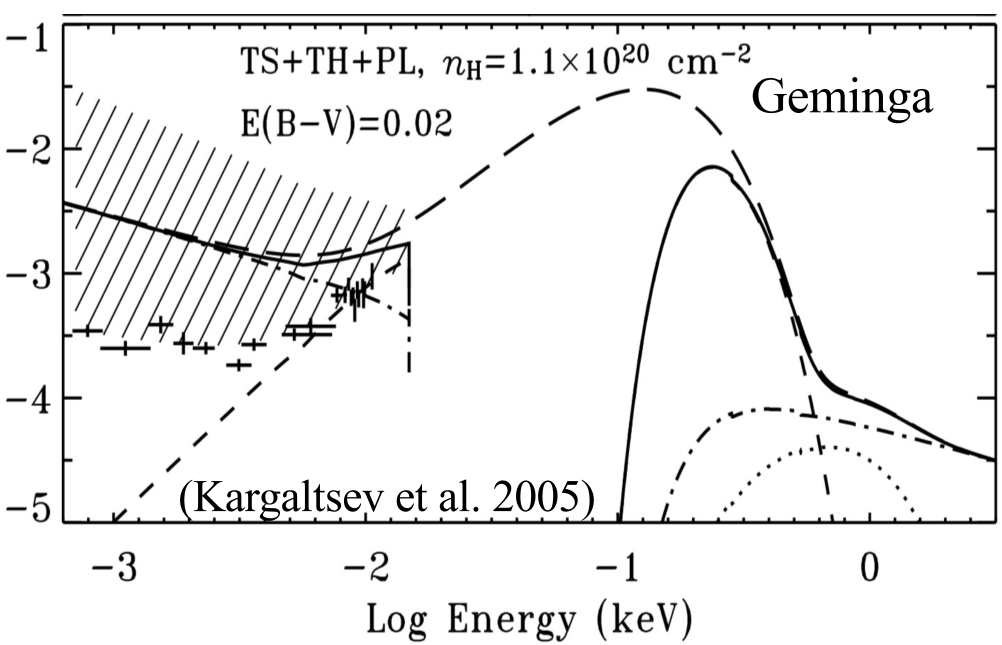
Efficiency = EM luminosity / Spin down power



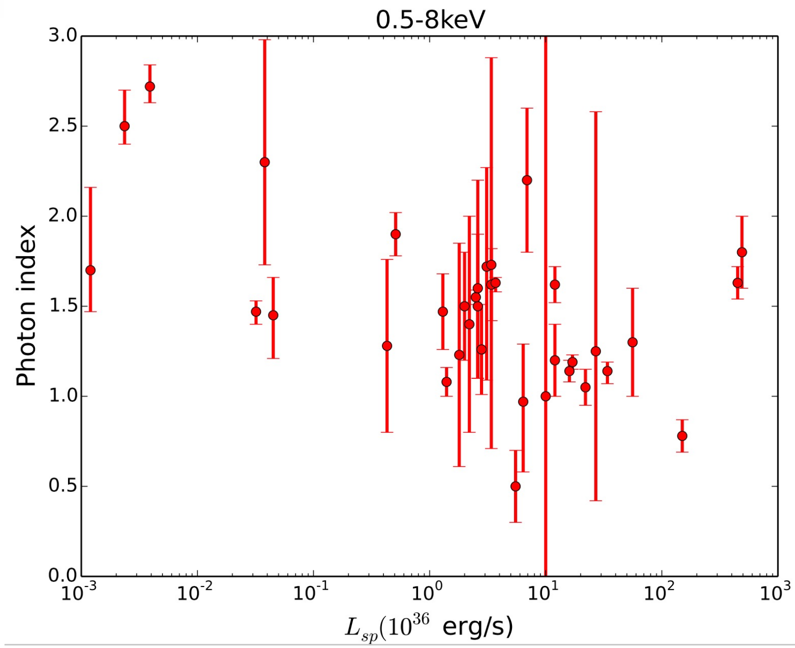
Typical optical/X-ray spectrum

PSR B0654+14 (Zharikov et al. 2021)



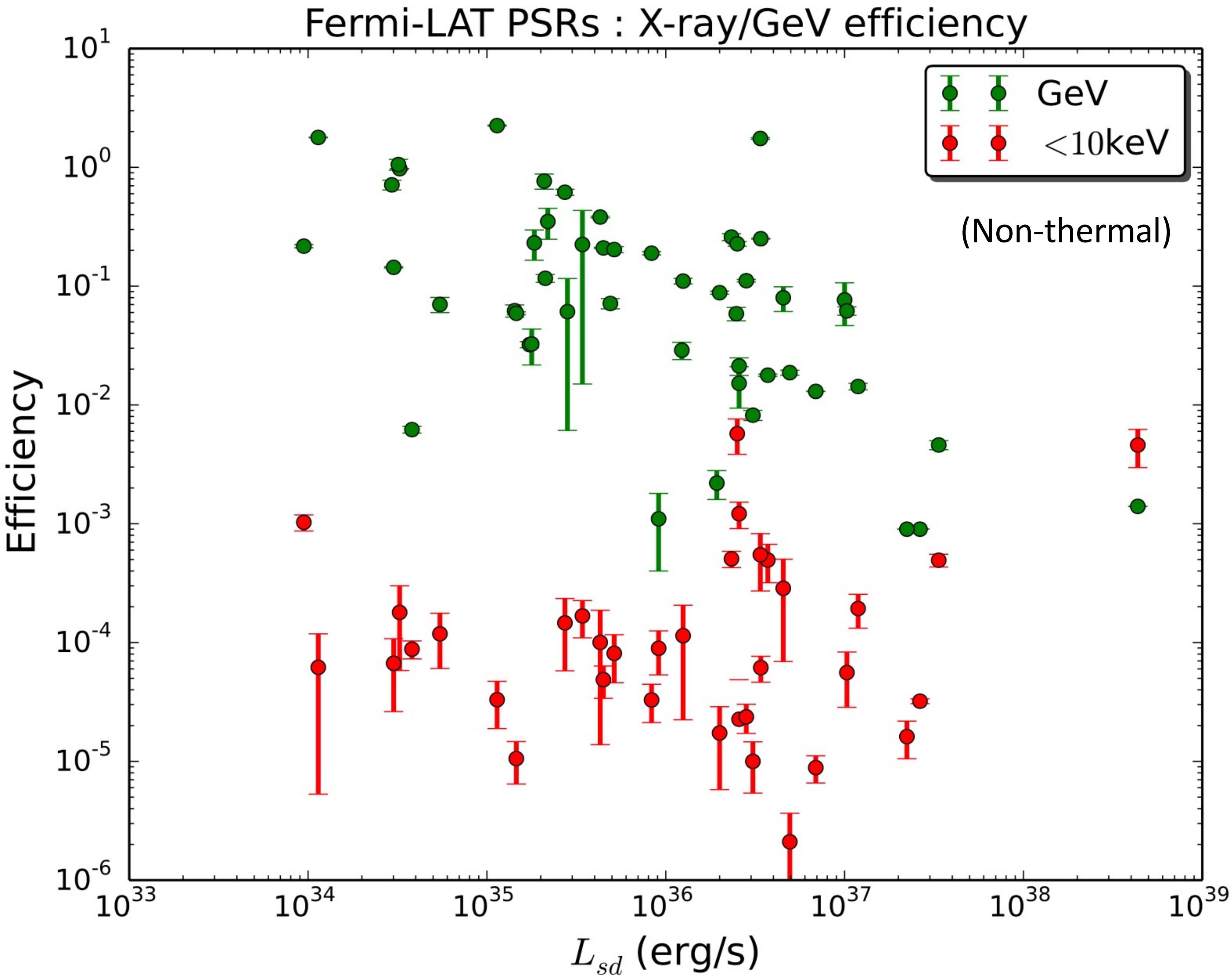


(Hsiang & Chang 2021)



(spin down power)

Data from Fermi-LAT pulsar catalogue



Standard scenario

- Primary emission at $r \sim R_{LC}$

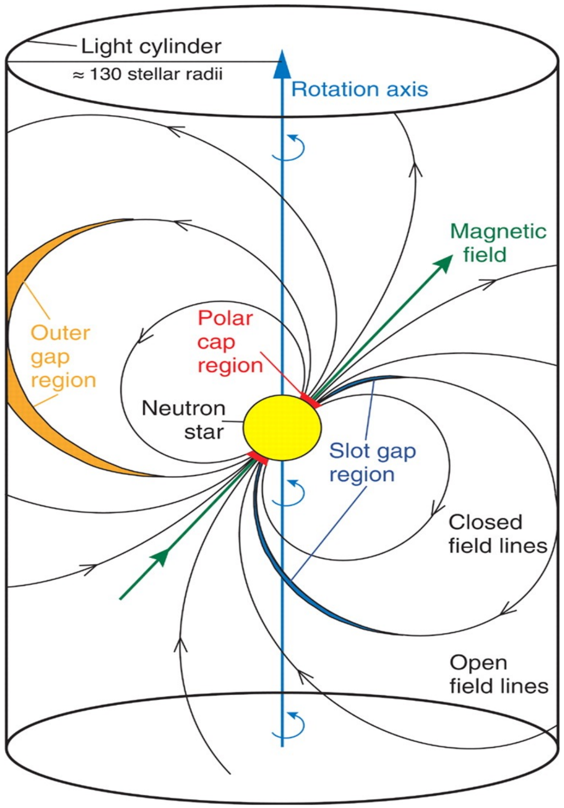
→ GeV: Curvature radiation

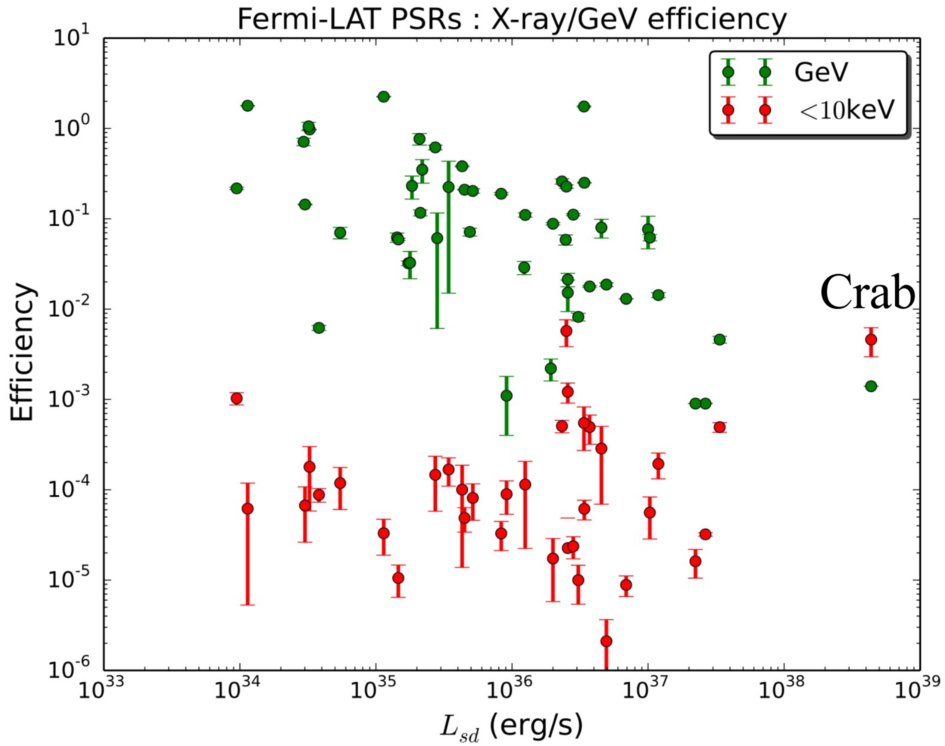
$L_{GeV} \sim total\ EM\ \ luminosity$

- Secondary emission $[X - ray\ (surface) + GeV\ \rightarrow e^{+} + e^{-}]$

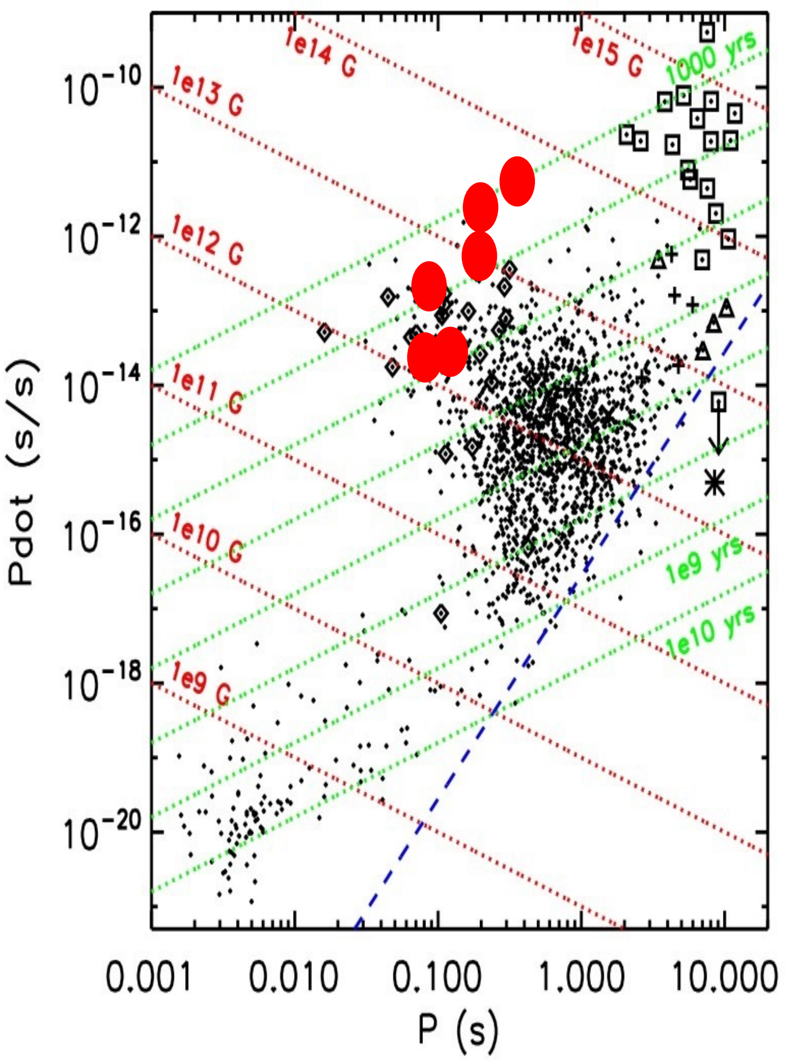
→ X-ray : Synchrotron radiation

$\eta_X \sim \tau_{X\gamma}\eta_{GeV}$ [$\tau_{X\gamma}$: Optical depth of pair-creation]





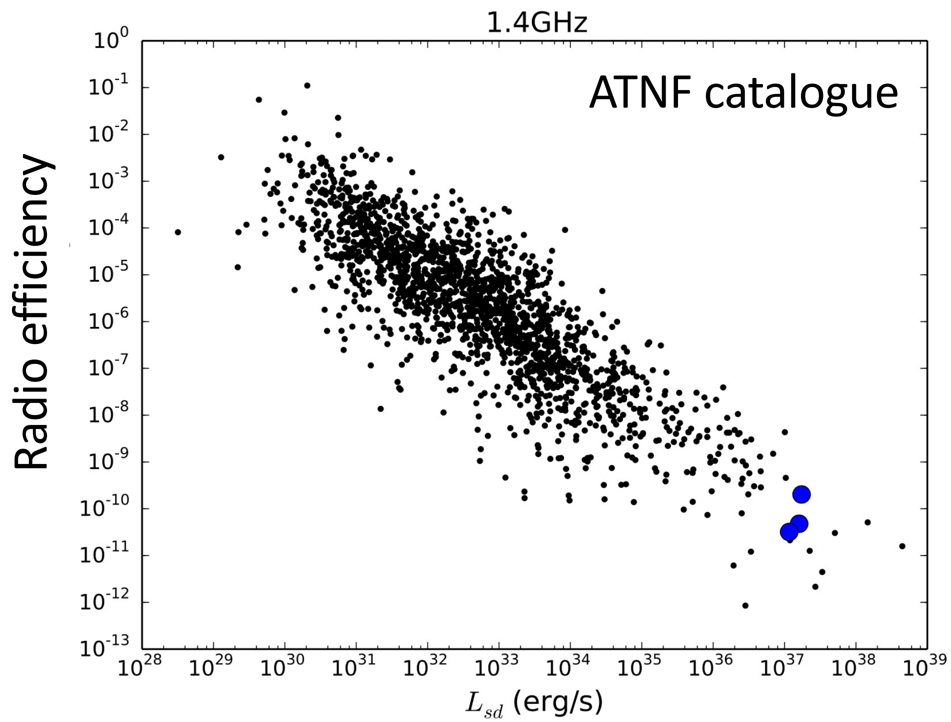
$\ll 1$ Optical depth ~ 1



(i) GeV quiet
(ii) Higher X-ray efficiency
(iii) Harder X-ray spectrum

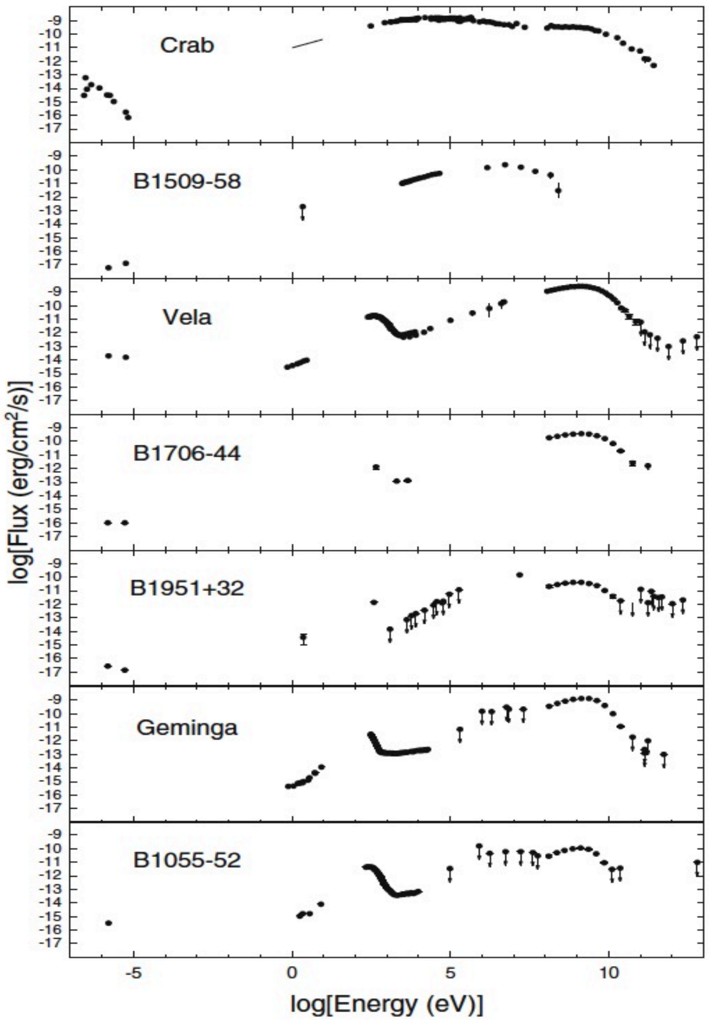
6 pulsars

- B1509-58 (1.6×10^3yr)
- J1617-5055 (8.1×10^3yr)
- J1811-1925(1.2×10^4yr) radio quiet
- J1838-0655(2.2×10^4yr) radio quiet
- J1846-0258(730yr) radio quiet/X-ray burst
- J1930+1852(2.9×10^4yr)



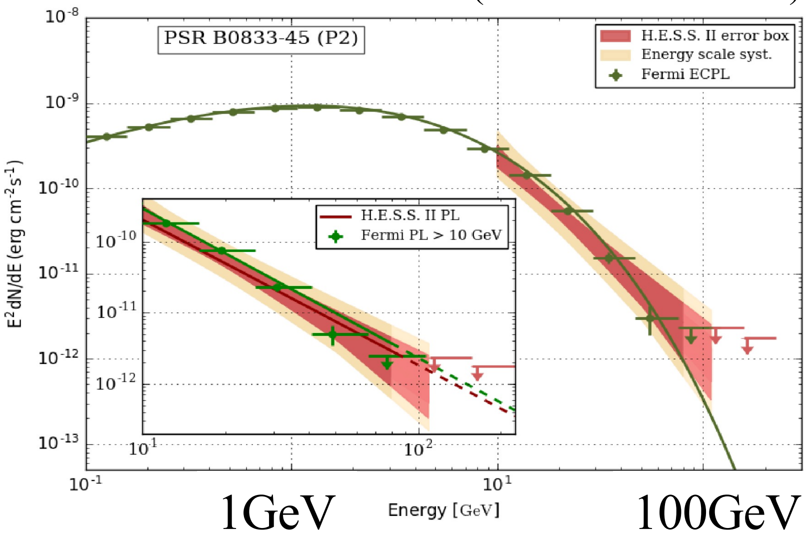
1. Fermi-LAT GeV pulsars (>250)

7 EGRET pulsar in Fermi-era

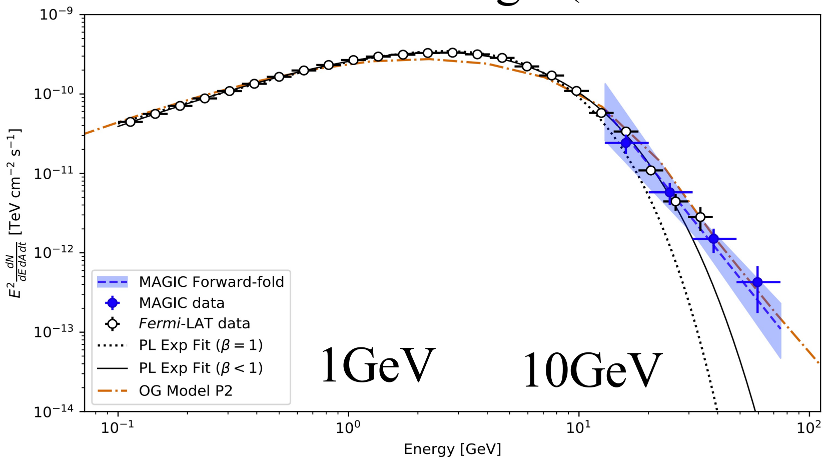


$$E^2 \frac{dN}{dE}$$

Vela (Abdallia et al. 2018)



Geminga (Acciari et al. 2020)



For LAT pulsars, EM output is dominated by GeV emission :

$$L_\gamma \sim total\ EM\ \ luminosity$$

Summary

- MeV pulsar is GeV-quiet but X-ray bright pulsar.

- The efficiency in 0.3-78keV bands is consistent with GeV efficiency of the Fermi-LAT pulsars.

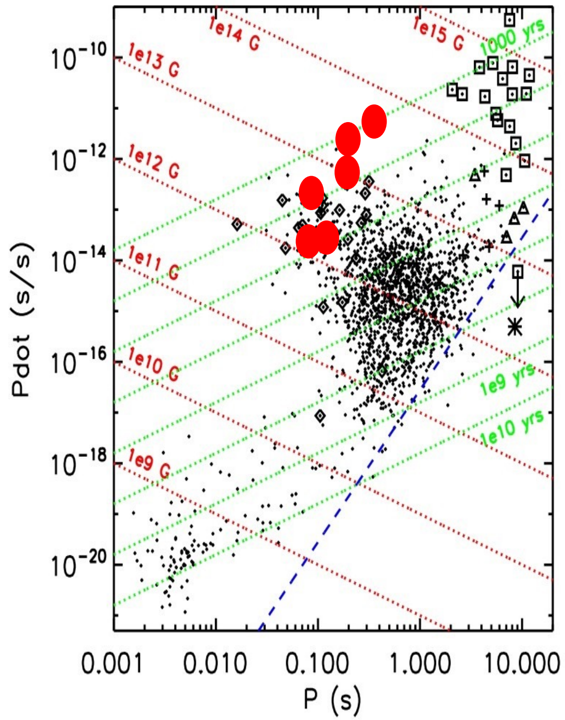
- Origin of the emission is still unknown.

- The efficiency >10keV of the Fermi-LAT pulsars is crucial to investigate the connection between MeV and LAT pulsars.

- 6 MeV pulsars

  - Radio loud
  - B1509-58 (1.6×10^3yr)
  - J1617-5055 (8.1×10^3yr)
  - J1930+1852(2.9×10^4yr)

  - Radio quiet
  - J1811-1925(1.2×10^4yr)
  - J1838-0655(2.2×10^4yr)
  - J1846-0258 (730yr)



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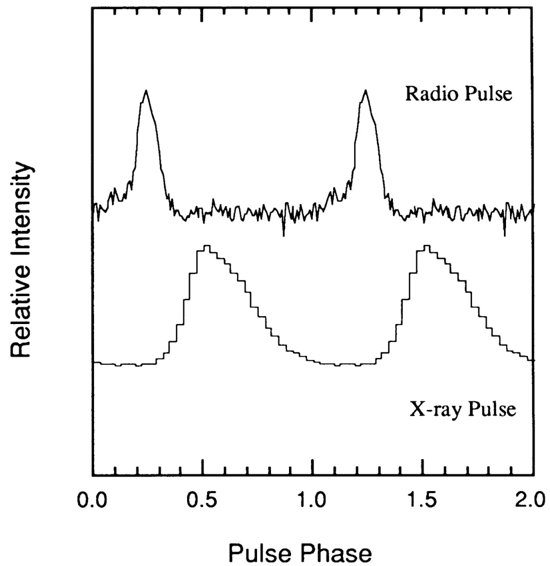
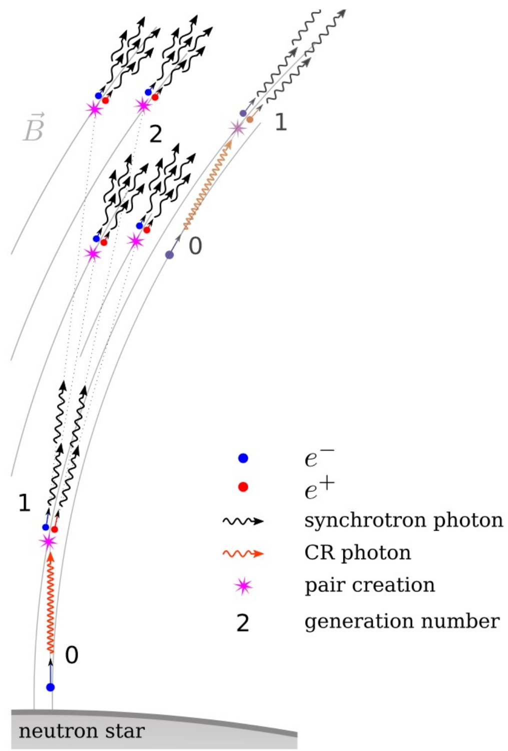
GeV pulsar vs. MeV pulsars

- Peculiar X-ray emission propert

-- Single broad peak

-- Non-thermal emission





$\vec{B}$
2
1
0
1
0
e^-
e^+
synchrotron photon
CR photon
pair creation
2
generation number
neutron star