慧眼HXMT脉冲星研究进展

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内容

- 脉冲星简介
- 慧眼HXMT介绍
- 年轻脉冲星研究进展
- 磁星研究进展
- MeV脉冲星搜索
- 总结

脉冲星简介

脉冲星:旋转的强磁场中子星

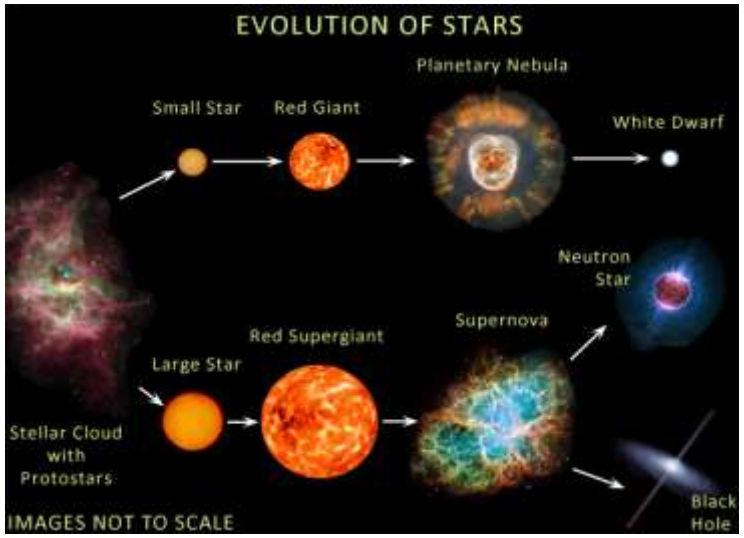
强磁场:$10^{8\text{-}14}$ G

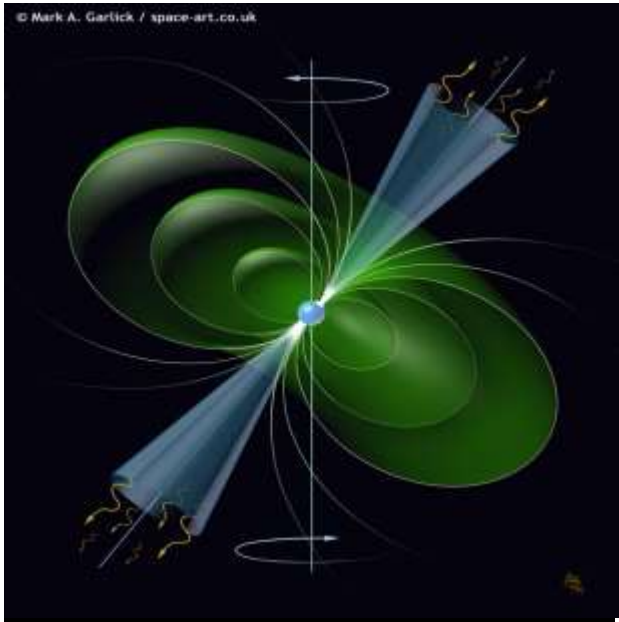
高密度:10^{14}g/cm^3

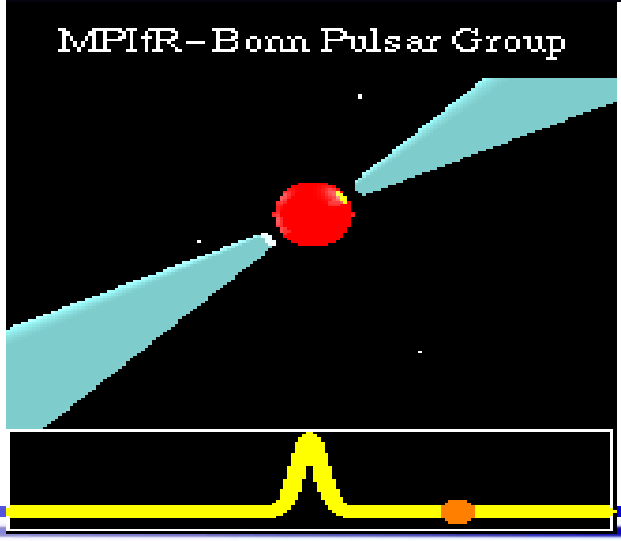
半径:约10km

$$L_{sd} = 4\pi^2 I \nu \dot{\nu}$$

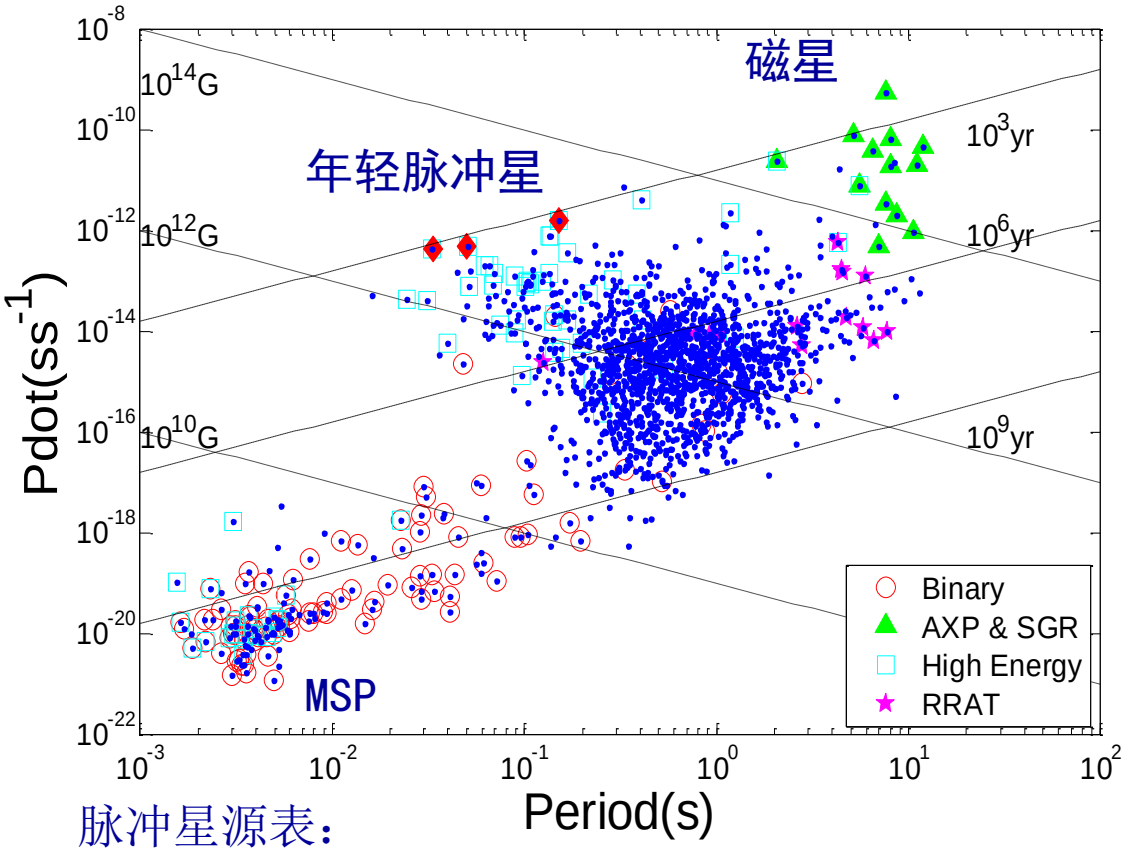
自转能
磁能
吸积能





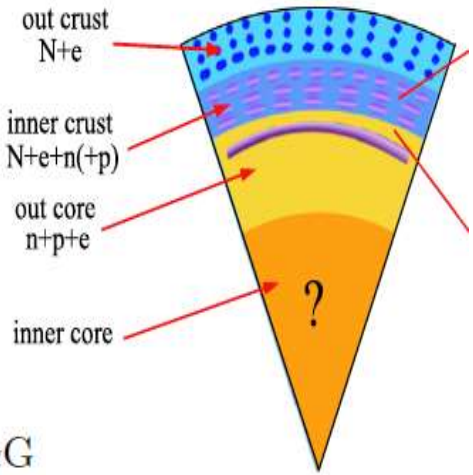


脉冲星简介



脉冲星源表：
https://www.atnf.csiro.au/people/pulsar/psrcat/

- 旋转的磁化中子星
- 辐射模型
  - Outer gap
  - Slot gap
  - Annular gap
  - …
- 中子星EOS



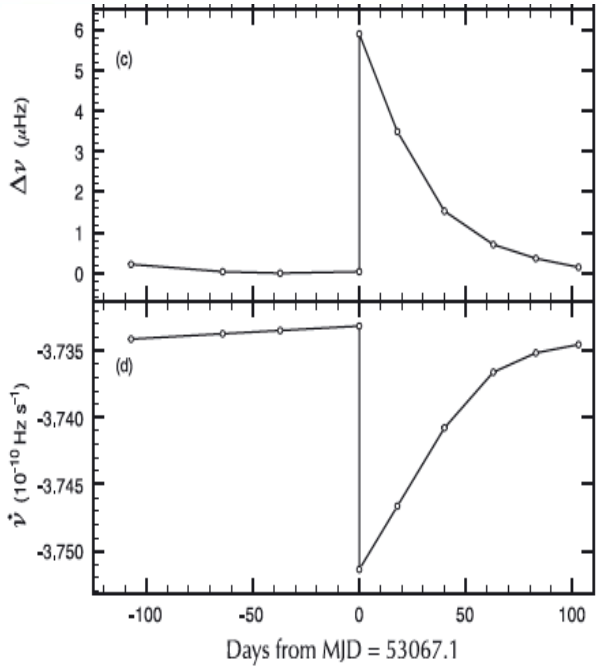
$$E = \tfrac{1}{2} I \Omega^2 \qquad B = \frac{1}{\sin\alpha}\sqrt{\frac{3IcP\dot{P}}{2\pi^2 R^6}} \approx 6.4\times 10^{19}\sqrt{P\dot{P}}\,/\sin\alpha \mathrm{G}$$

$$\dot{E} = \frac{dE}{dt} = I\Omega\dot{\Omega} \qquad n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2}$$

制动指数

周期跃变

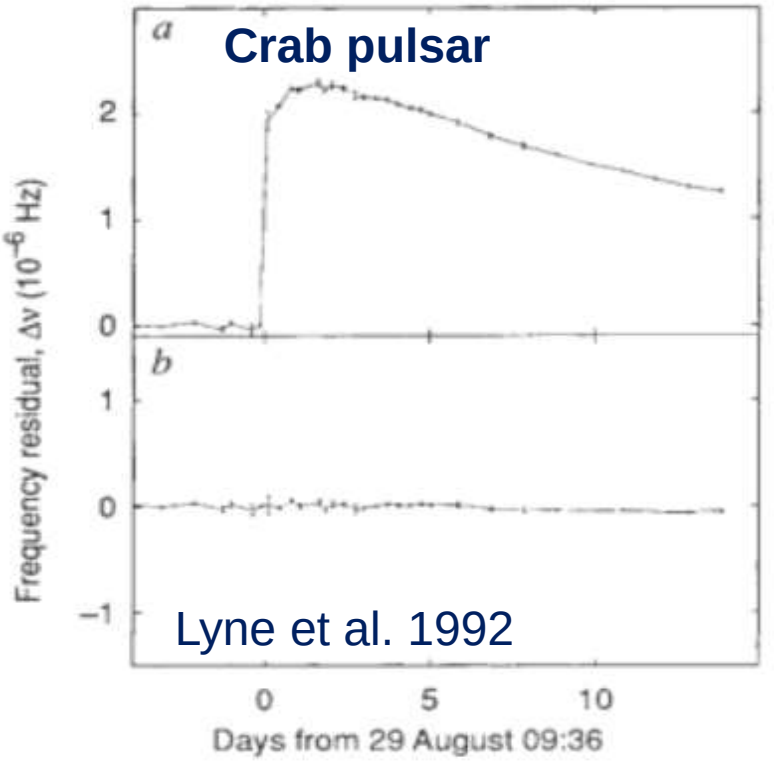
典型周期跃变

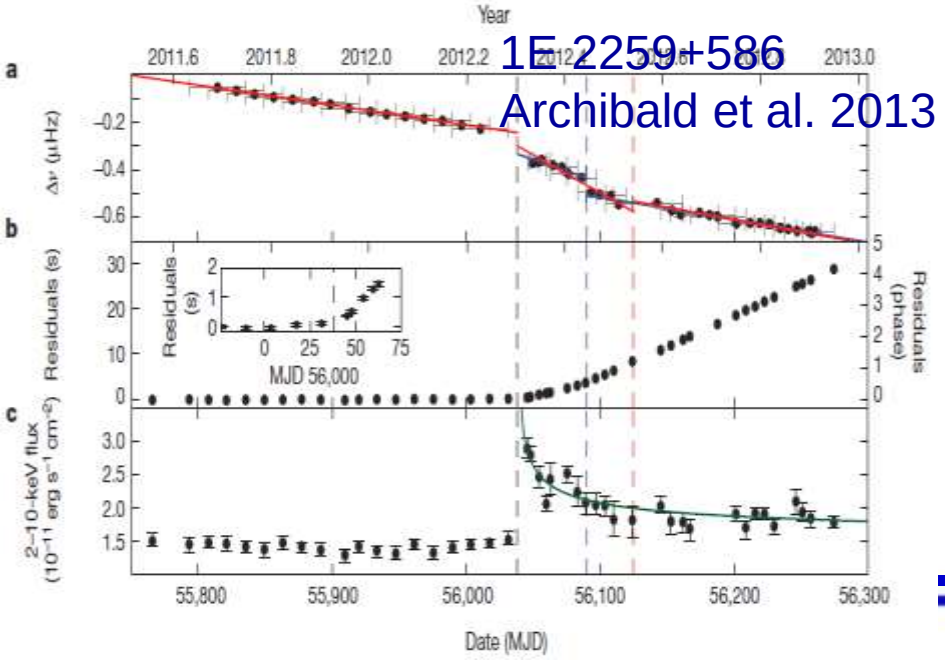


$$\Delta\nu = \Delta\nu_p + \Delta\dot{\nu}_p t + \frac{1}{2}\Delta\ddot{\nu}_p t^2 + \sum_n \Delta\nu_n e^{-t/\tau_n}$$

Vela脉冲星: 多个成分（4个）
Dodson et al. 2002,564,85

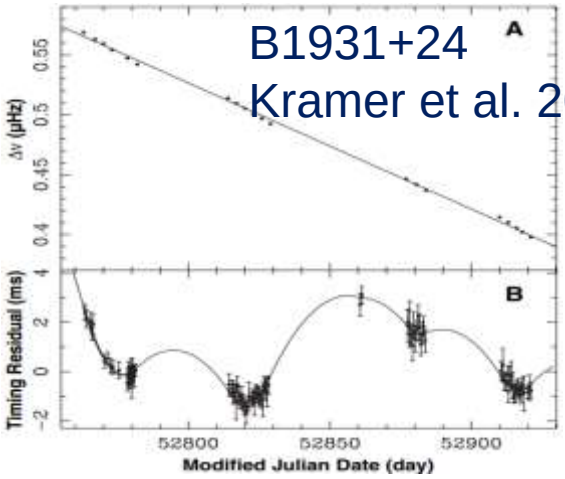
慢周期跃变
Anti-glitch



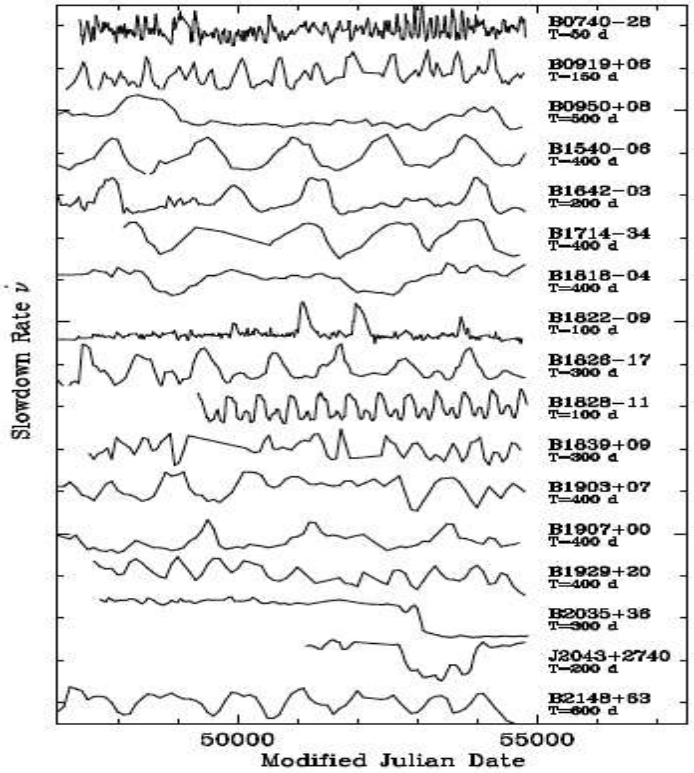


状态转换

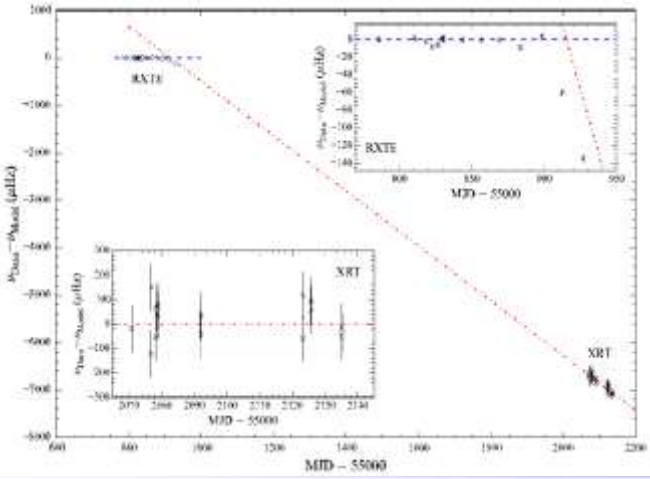
- 磁层变化



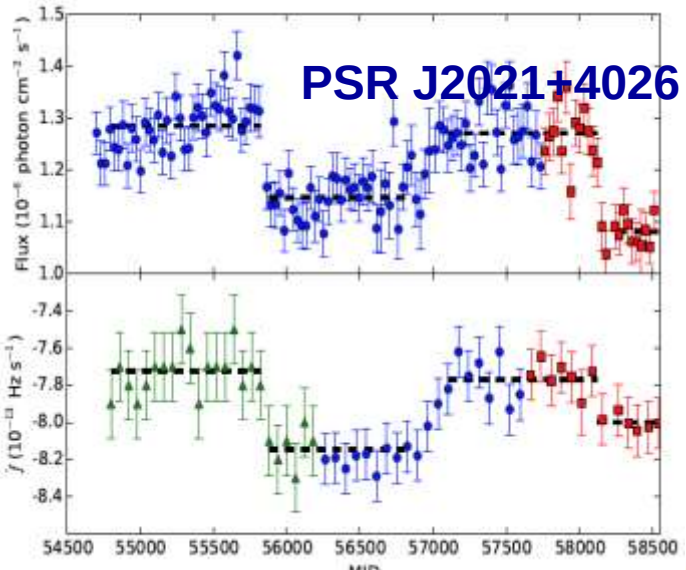
B1931+24
Kramer et al. 2006



Lyne et al. 2010. 特征年龄~百万年

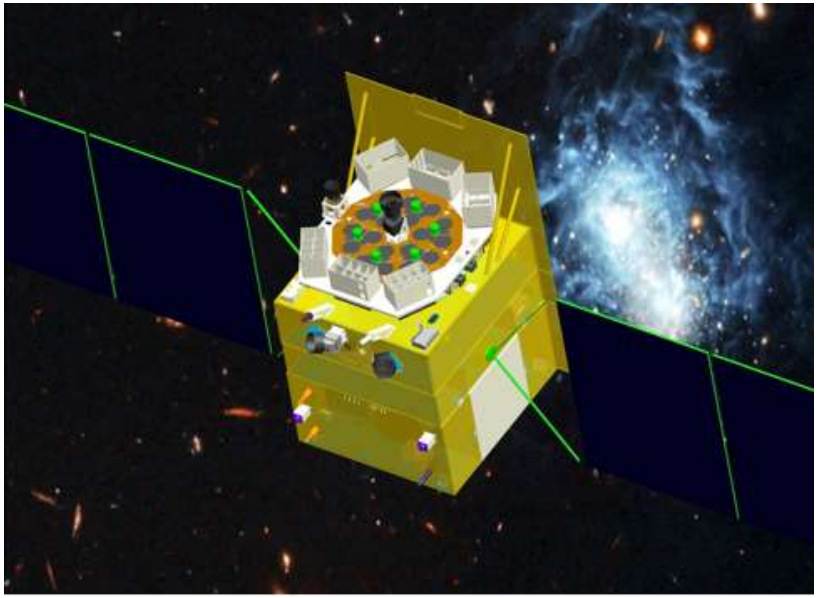


目前，2颗年轻脉冲星也存在类似行为



Takata et al. 2020

慧眼HXMT介绍

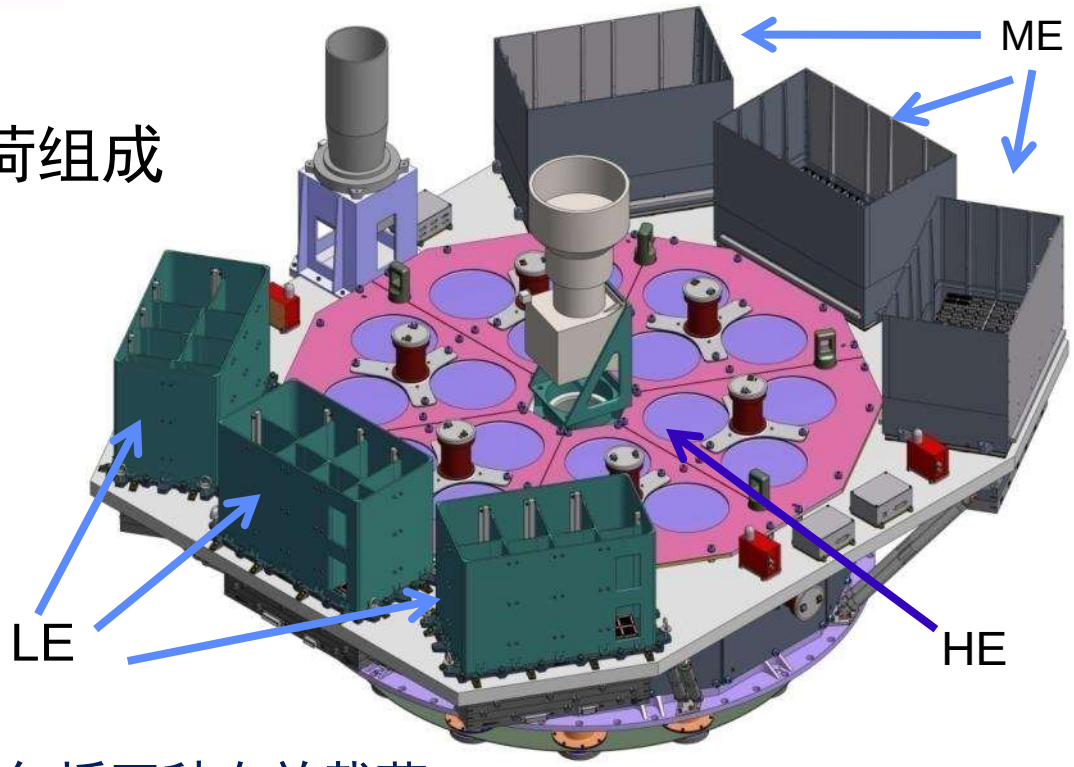


我国首颗X射线天文卫星—慧眼

2017年6月15日在酒泉卫星发射基地升空，2018年1月31日正式交付使用。已在轨稳定运行5年。

慧眼HXMT介绍

主载荷组成



单机：111台
信号：1881路
质量：~1000kg
功耗：350W

HXMT 包括四种有效载荷

高能X射线望远镜HE: NaI/CsI 5000 cm^2, 20-250 keV

中能X射线望远镜ME: Si-PIN,952 cm^2, 5-30 keV

低能X射线望远镜LE: SCD (Swept Charge Device), 384 cm^2, 1-15 keV

空间环境监测器SEM

慧眼HXMT介绍

探测器	LE: SCD, 384 cm^2; ME : Si-PIN, 952 cm^2 HE : NaI/CsI, 5000 cm^2
能区覆盖	LE: 1-15 keV;ME: 5-30 keV;HE: 20-250 keV LG mode：200-3000 keV
时间分辨率	HE: 12μs; ME: 200μs;LE: 1ms
能量分辨率	LE: 2.5% @ 6 keV ME: 15% @ 17.8 keV HE: 17% @ 60 keV
视场	LE: 6°×1.5°; 6°×4°; 60°×3°; blind; ME: 4°×1°; 4°×4°; blind; HE: 5.7°×1.1°; 5.7°×5.7°； blind

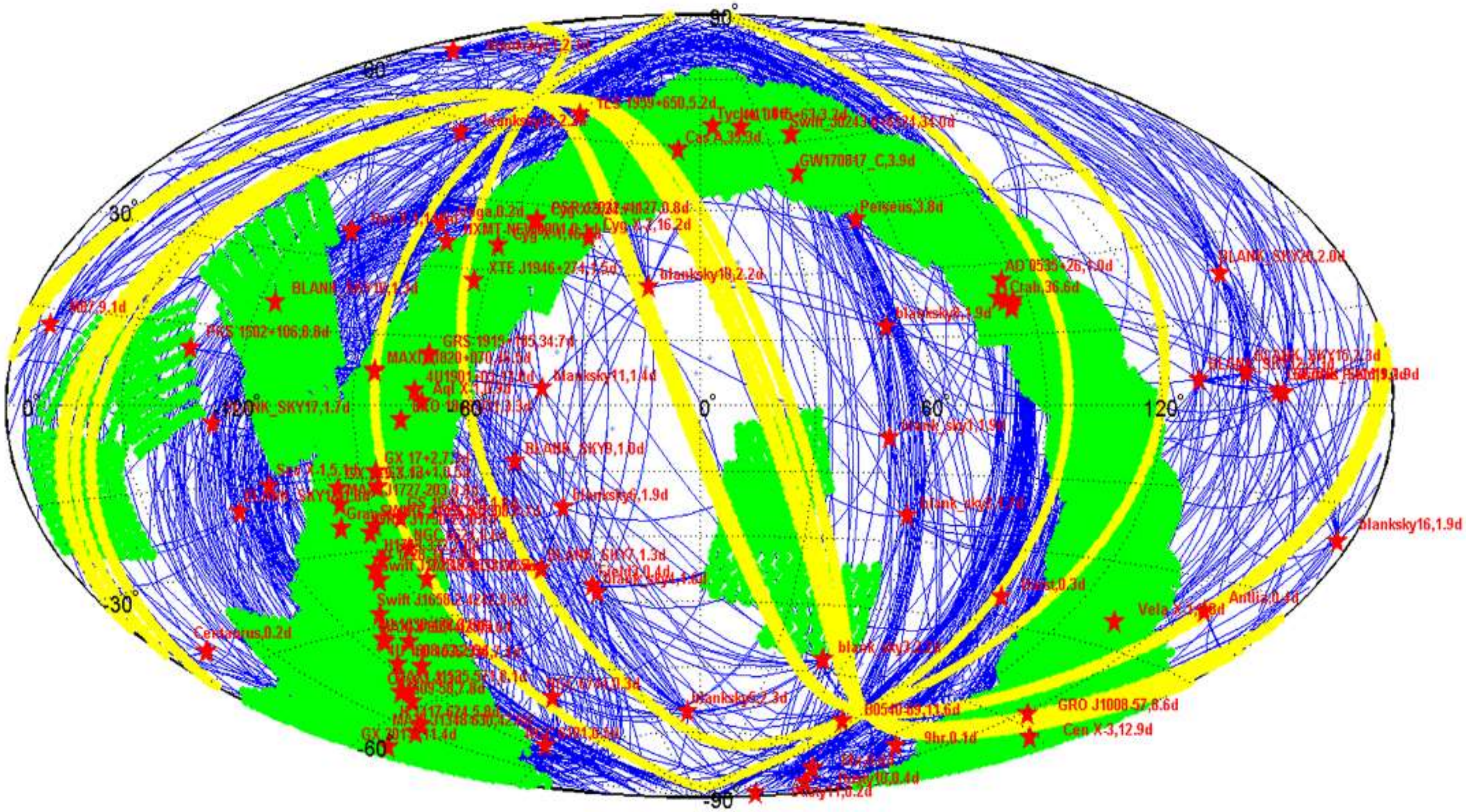
慧眼定点观测的主要优点：

覆盖能段宽、在高能X射线能段的有效面积最大、时间分辨率高、探测死时间很小、对强源观测没有光子堆积效应

➡ 具有独特的研究天体多波段快速光变的能力。

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Insight-HXMT exposure map



定点观测

Crab
PSR B1509-58
PSR B0540-69
PSR J2022+3842

双星:
PSR J2032+4127

磁陀星:
SGR J1935+2154
SGR 1830-0645
PSR J1846-0258

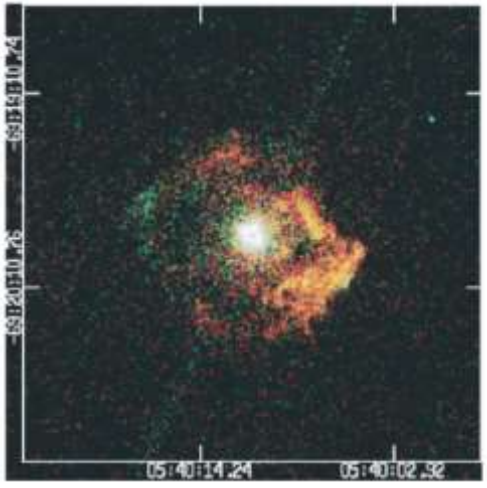
年轻脉冲星研究进展

PULSARS WITH APPARENT AGE OF LESS THAN 5 kyr

PSR	τ_c (kyr)	P (ms)	B ($\times 10^{12}$ G)	$\dot{E}$ ($\times 10^{36}$ ergs s^{-1})	SNR	d (kpc)	L_{1400} (mJy kpc^2)
J0537−6910	5.0	16	1	480	N157B	50 (LMC)	<150
B0531+21	1.3	33	4	440	Crab	2.0	40
B0540−69	1.7	50	5	150	0540−693	50 (LMC)	200
J0205+6449	5.4	65	4	27	3C 58	2.6	≲2
B1509−58	1.6	150	15	18	G320.4−1.2	5.2	35
J1124−5916	2.9	135	10	12	G292.0+1.8	~5	~2
J1846−0258	0.7	323	48	8	Kes 75	~19	≲50
J1811−1926	24	65	2	6	G11.2−0.3	5	< 2
J1119−6127	1.6	407	41	2	G292.2−0.5	~6	~30

Crab

B1509-58



B0540-69

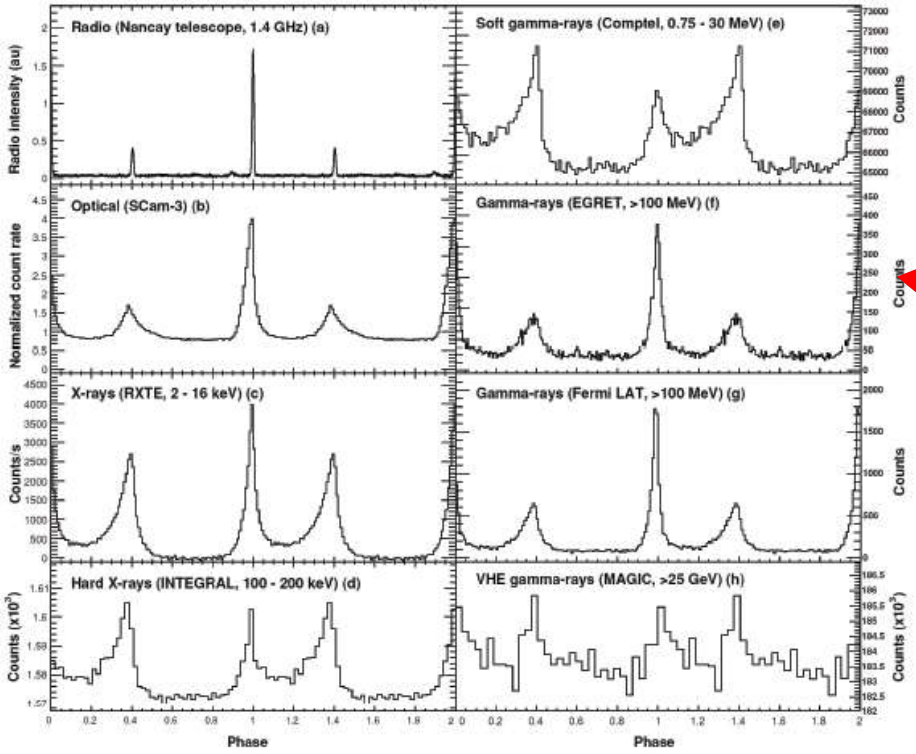
J1124-5916

Crab脉冲星

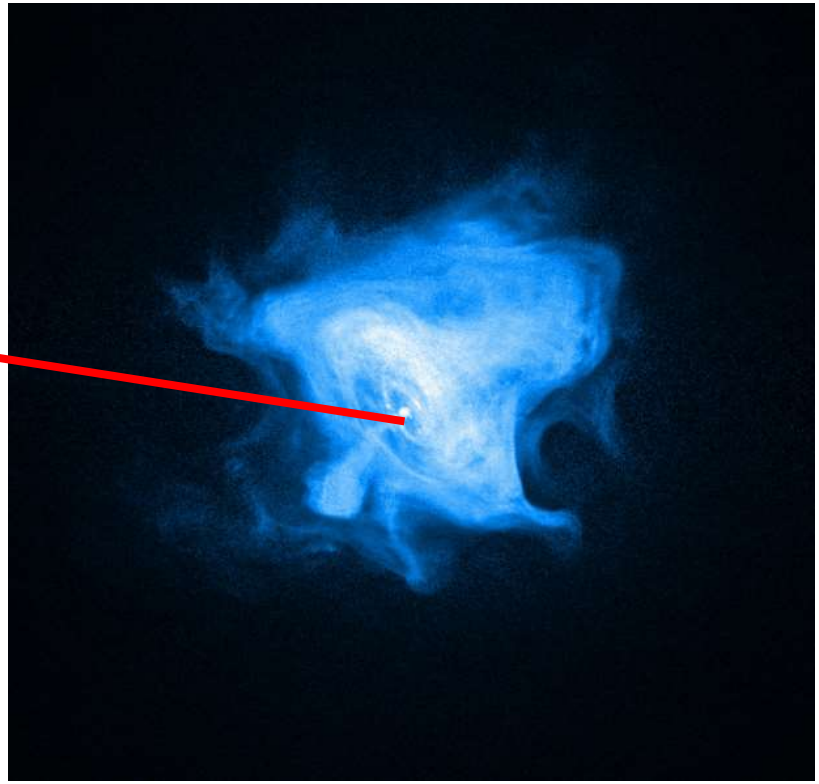
- SN1054

脉冲辐射典型的双峰结构，射电、红外、光学、紫外、X射线伽马射线

(Abdo et al.2010, Ge et al. 2012)



Chandra X射线观测图像

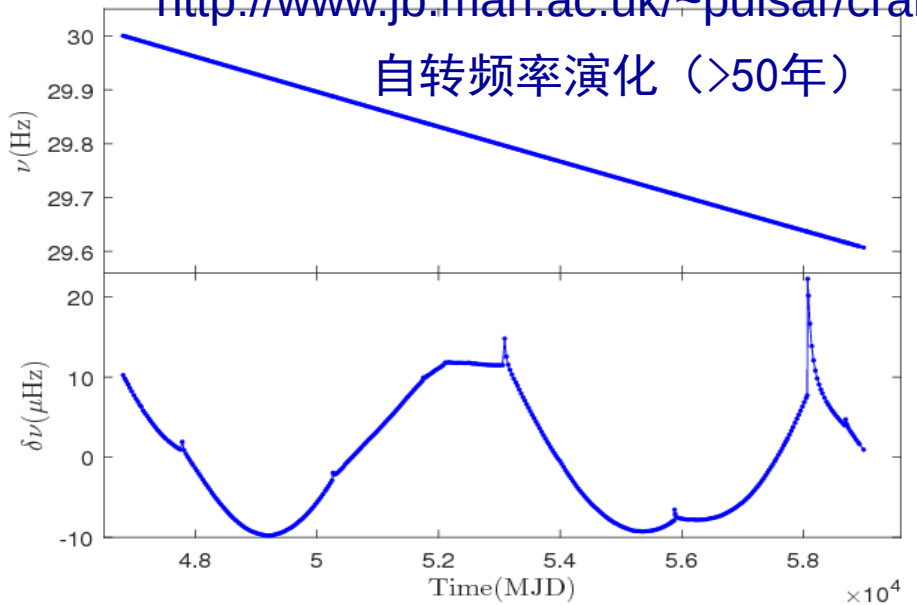


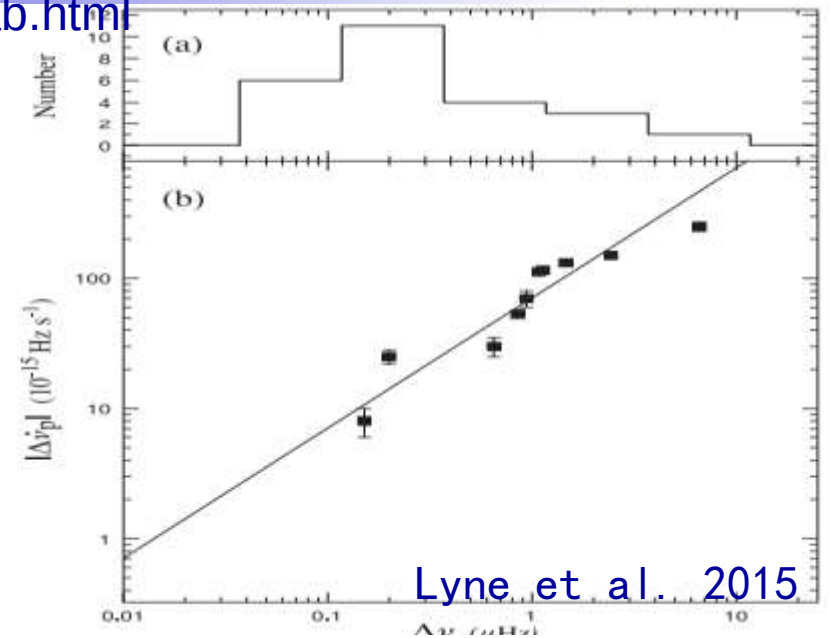
Abdo et al.(2010)

Crab脉冲星

http://www.jb.man.ac.uk/~pulsar/crab.html

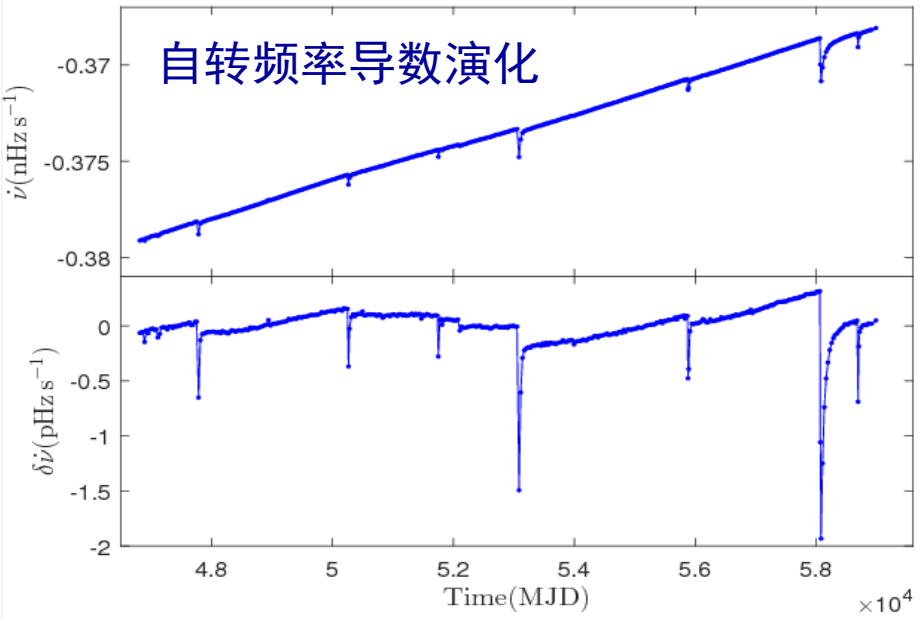
自转频率演化（>50年）

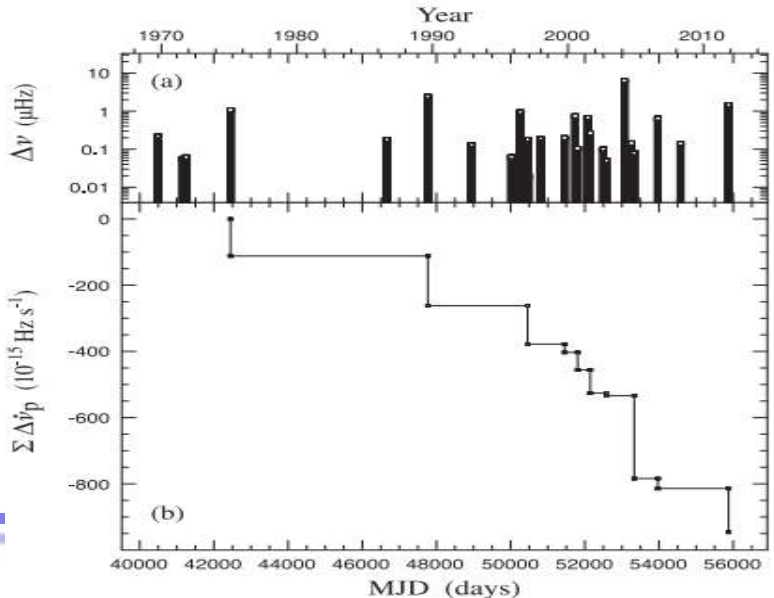




Lyne et al. 2015

自转频率导数演化



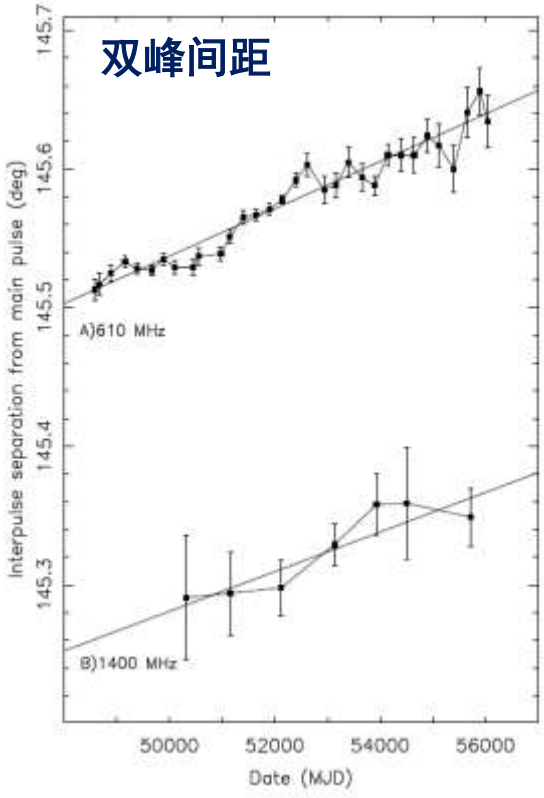


Crab脉冲星

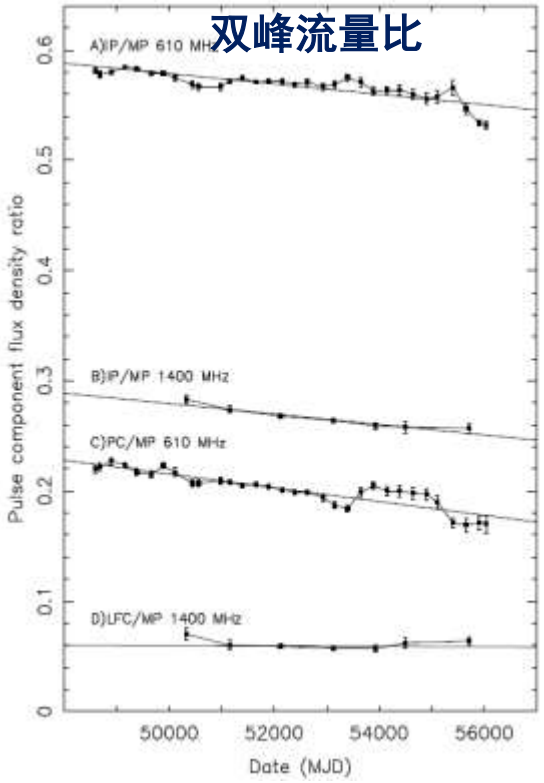
➢ 脉冲轮廓演化

磁倾角0 .6°/100yr (Lyne et al. 2013)

双峰间距

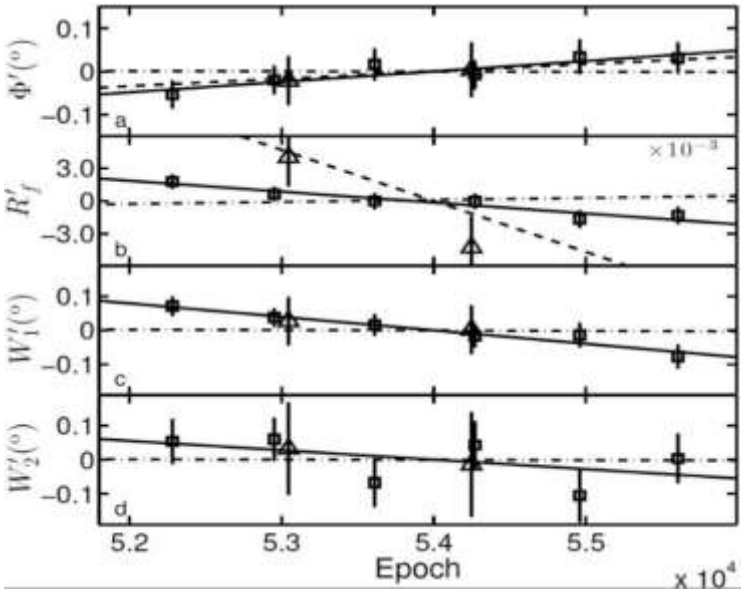


双峰流量比



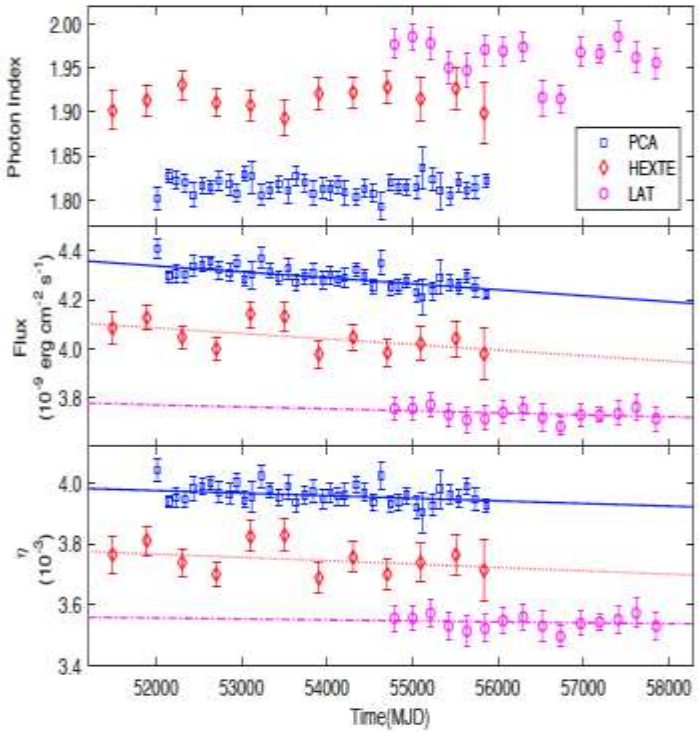
Lyne et al. (2013)

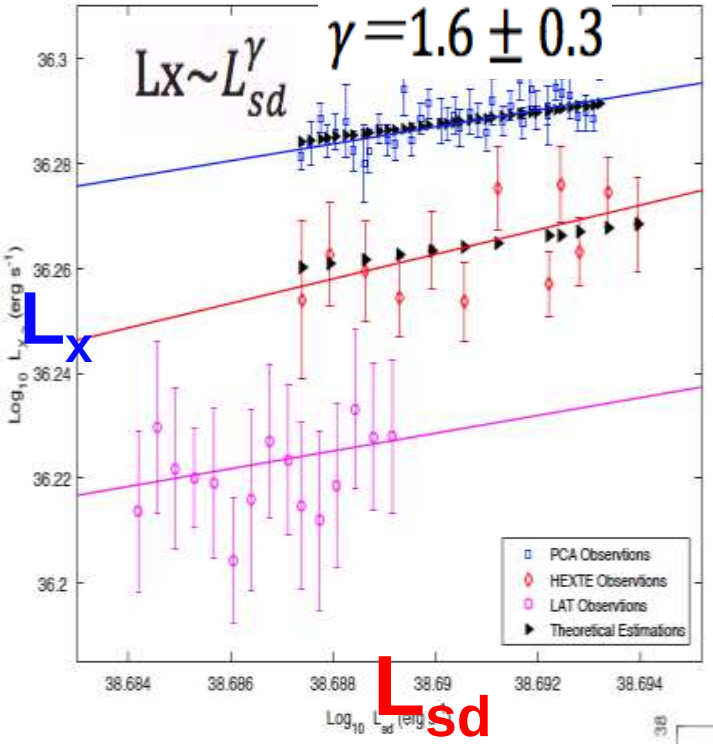
X射线脉冲轮廓



Ge et al.(2016)

Crab脉冲星

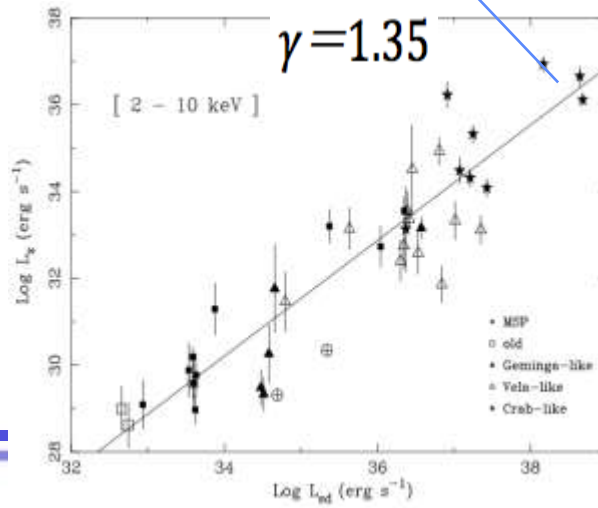




Lx

Lsd

更多脉冲星样本

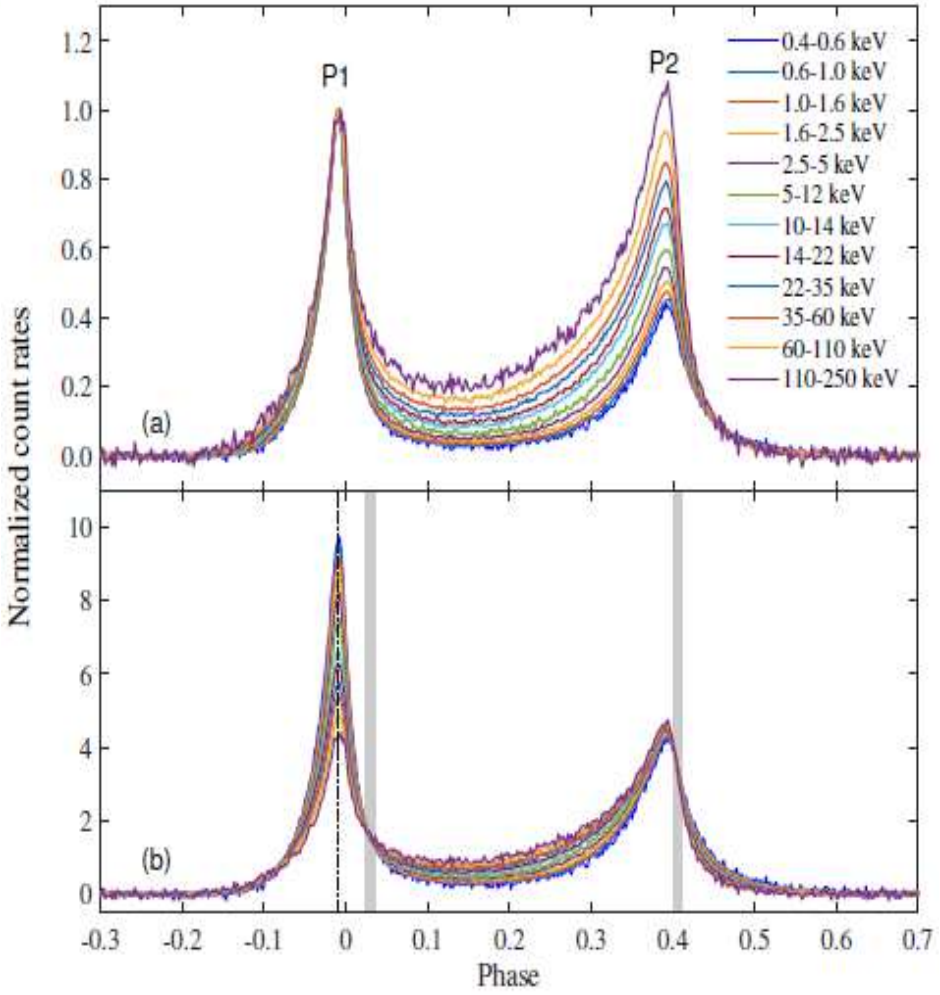


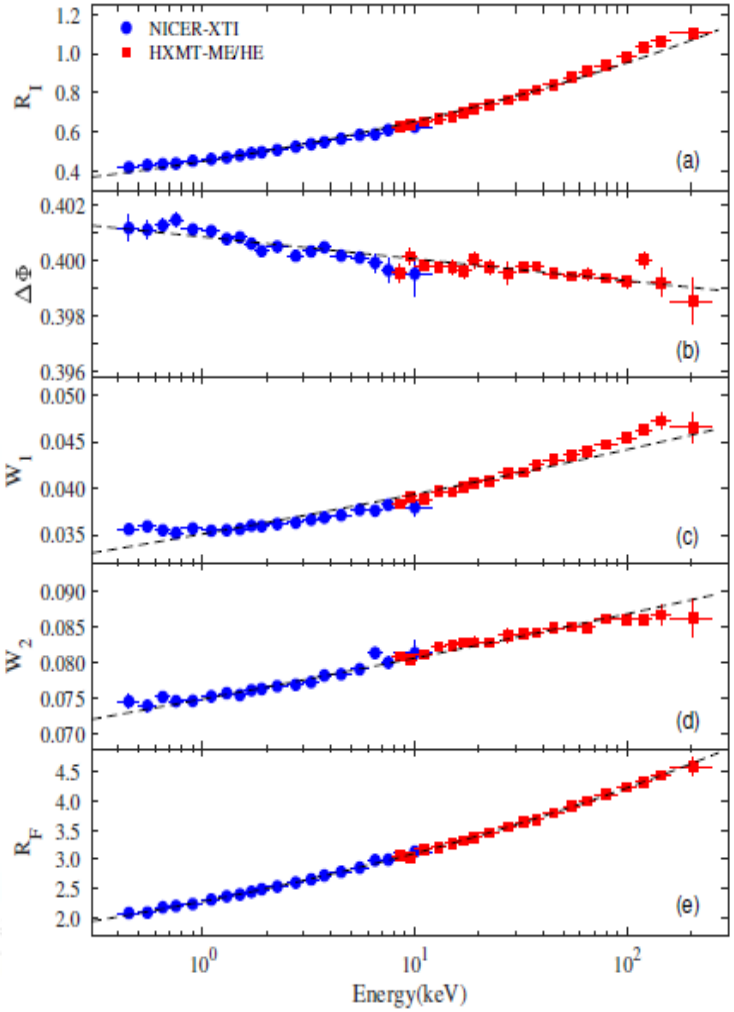
Crab脉冲星X射线脉冲光度逐渐降低

Yan et al. 2018

Possenti et al. 2002

Crab脉冲星





双峰峰值流量比

双峰相位差

P1宽度

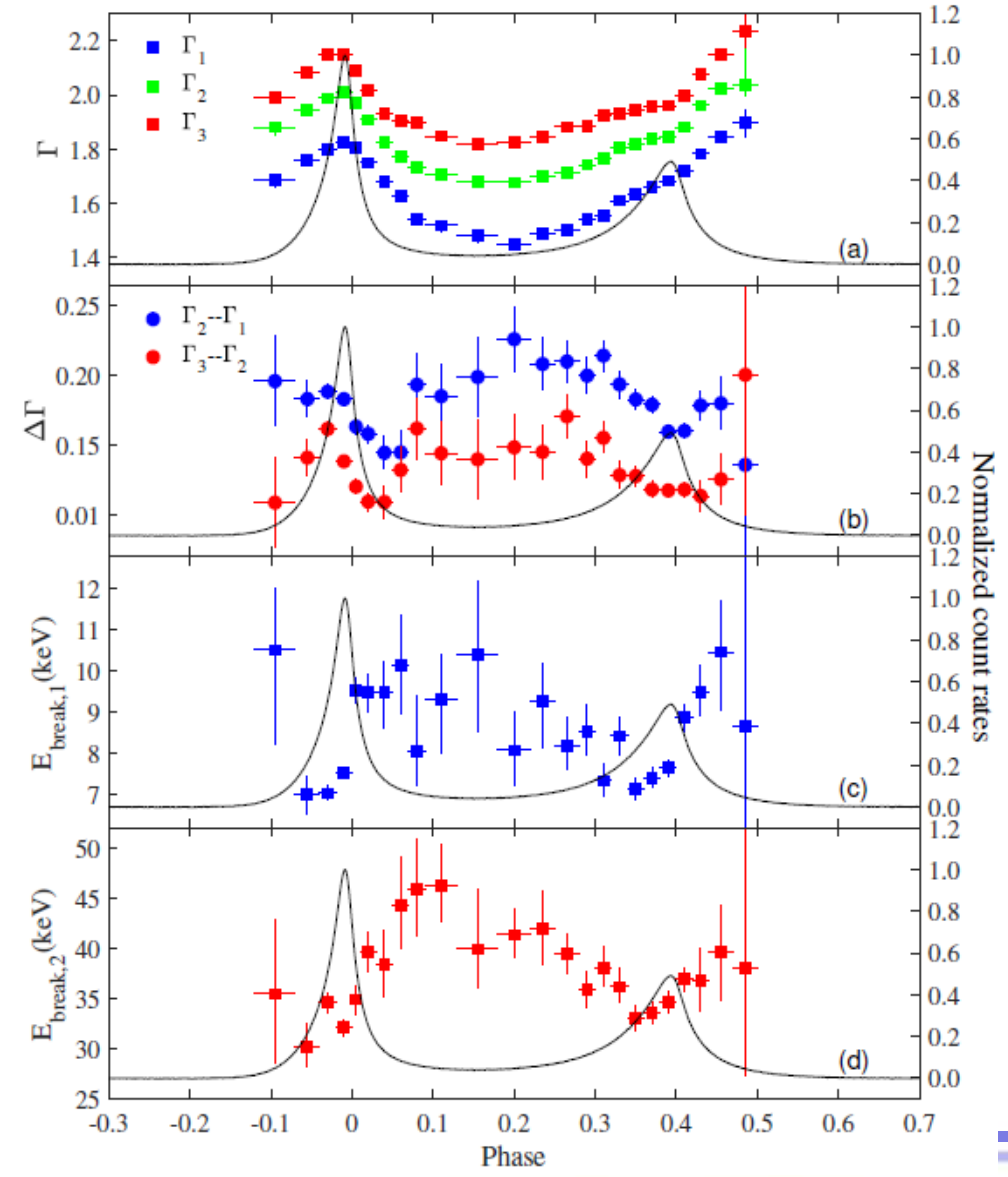
P2宽度

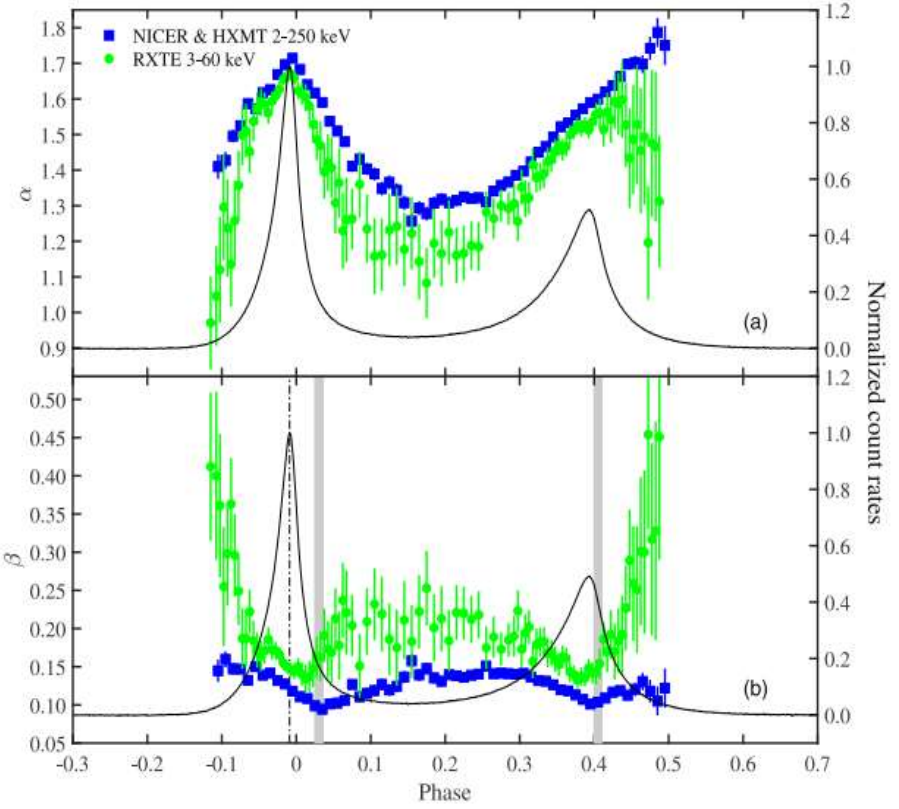
双峰流量比

脉冲轮廓随能量演化

Yan,L.L. 2022

Crab脉冲星

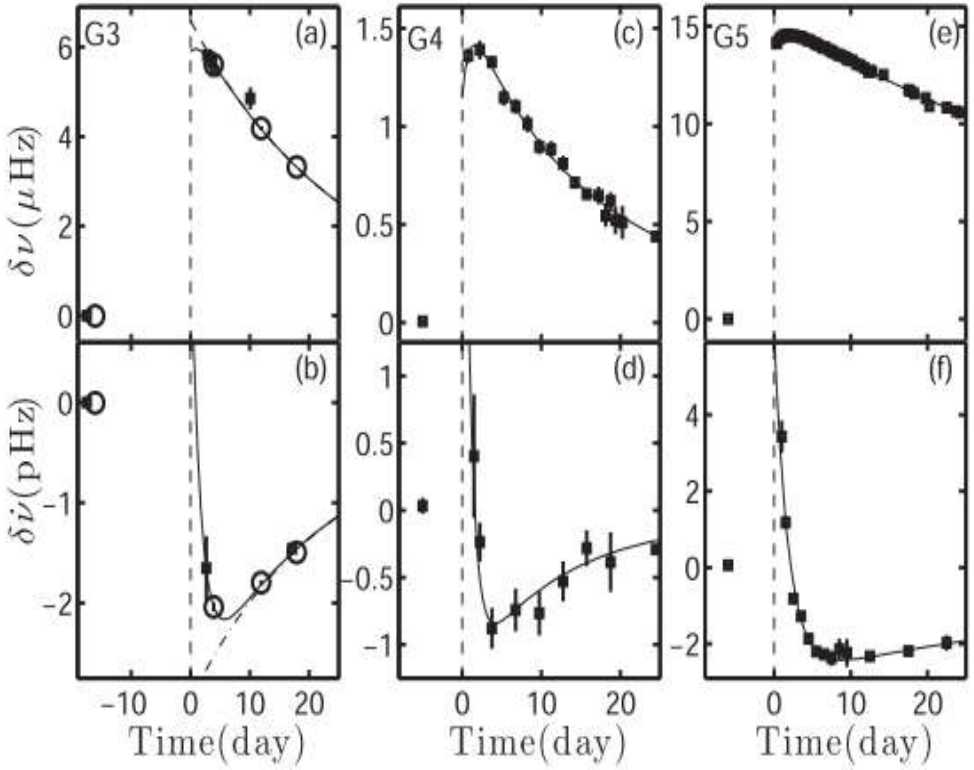


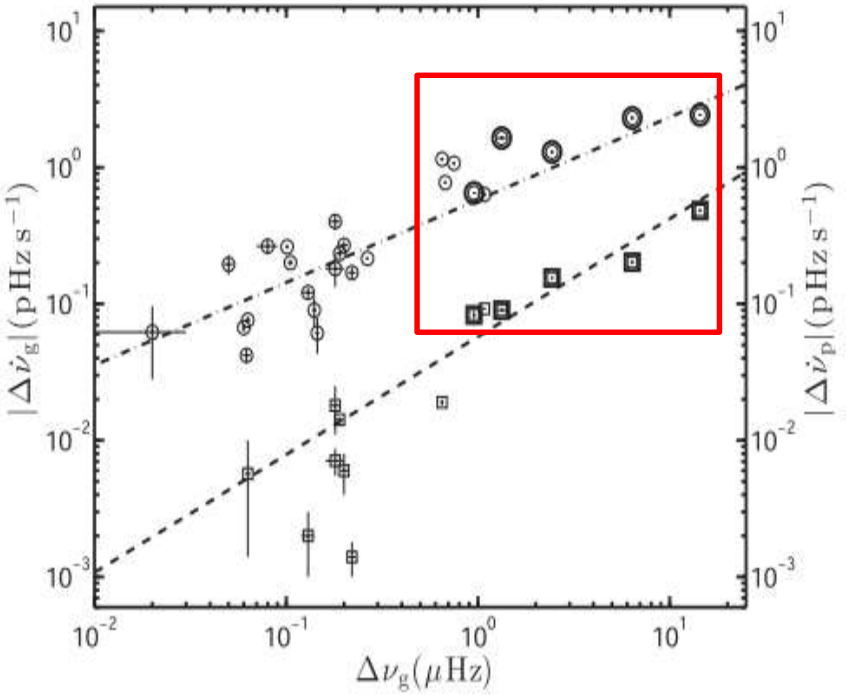


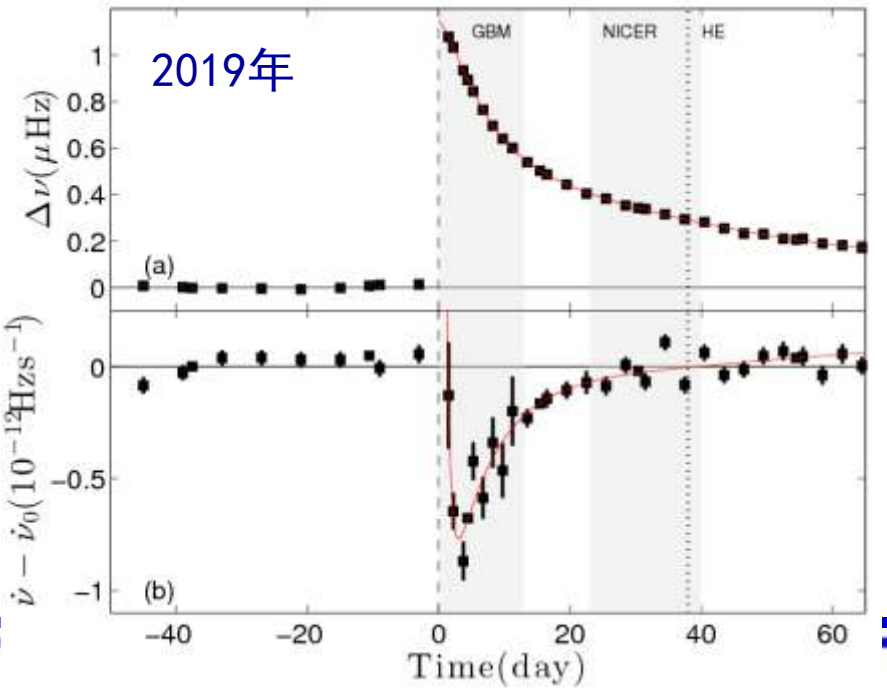
$$F(E) = K(E/E_0)^{-(\alpha+\beta\log(E/E_0))},$$

Yan,L.L. 2022

Crab脉冲星



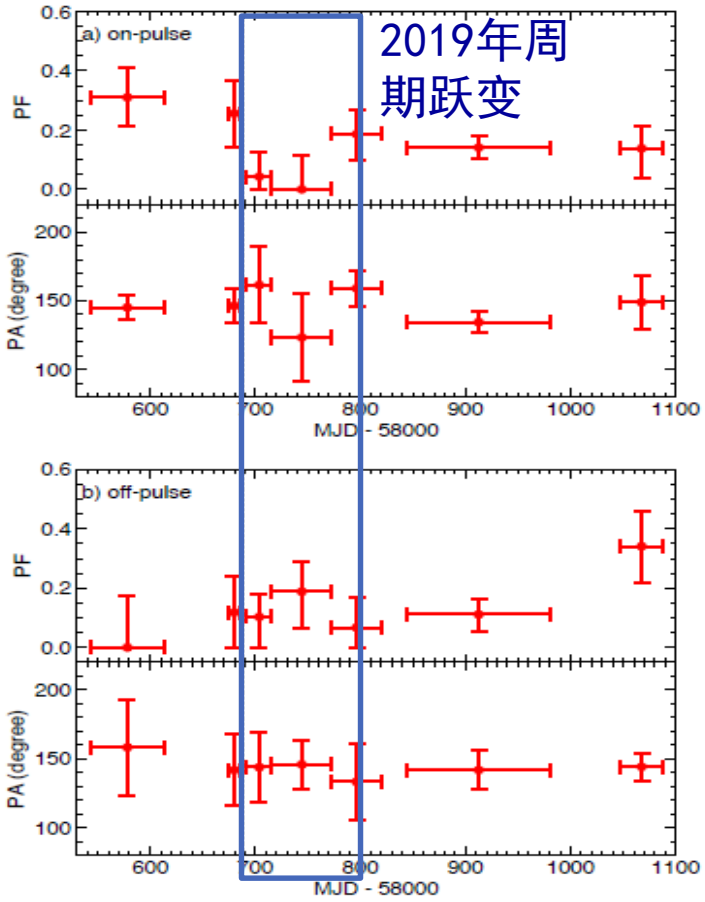




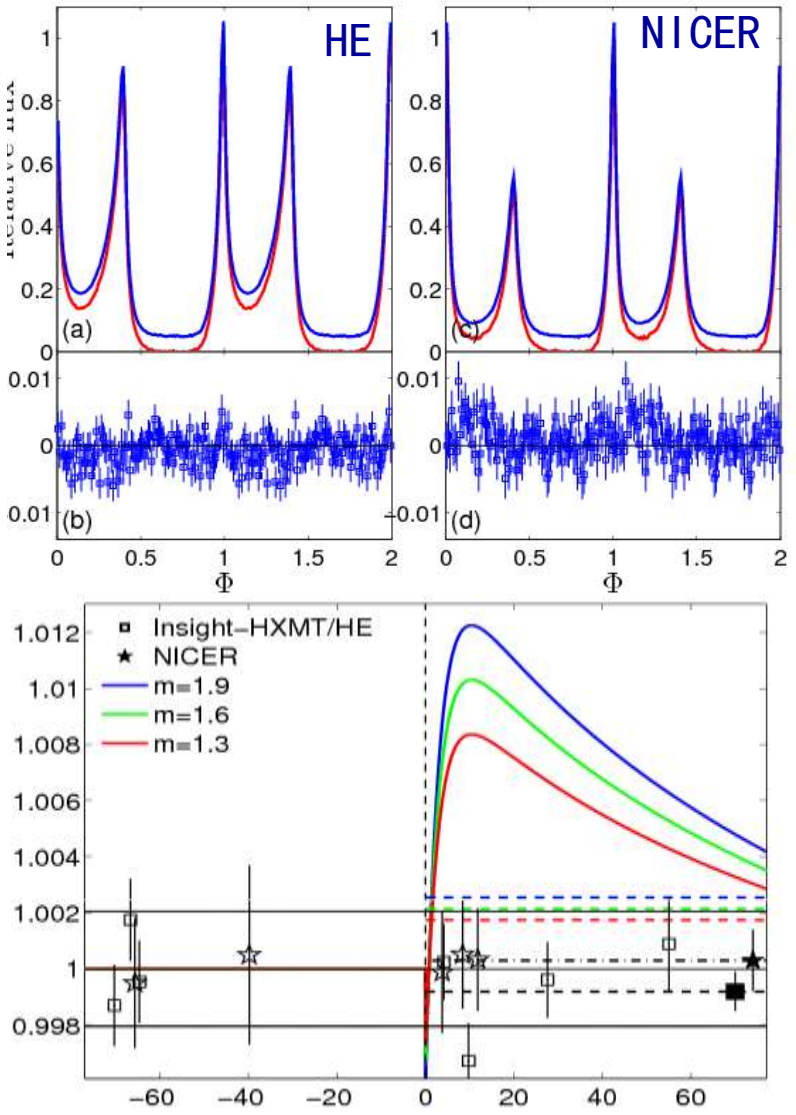
Crab pulsar
Delayed spin-up process

Lyne et al. 1992
Wong et al. 2001
Ge et al. 2020

Crab脉冲星



2019年周期跃变



针对2017 & 2019 两次周期跃变

X射线脉冲轮廓没有变化

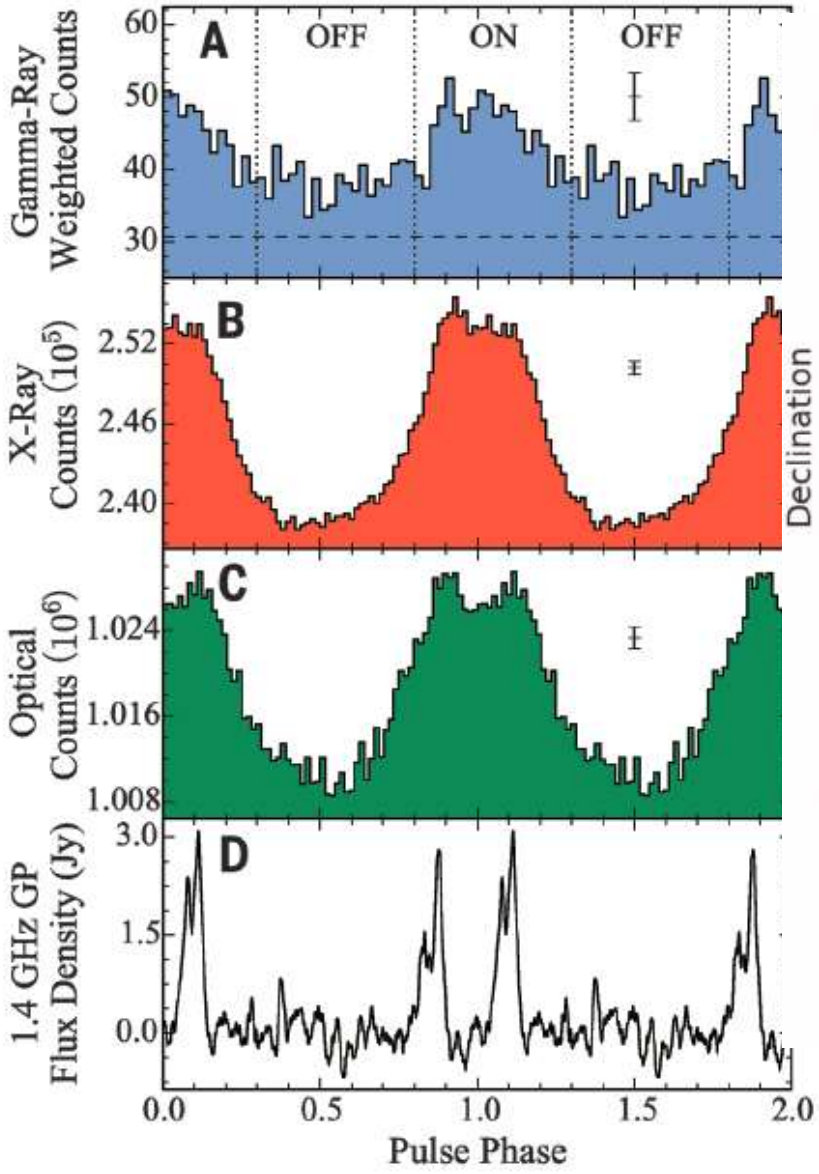
流量也没变化（2.8sigma）

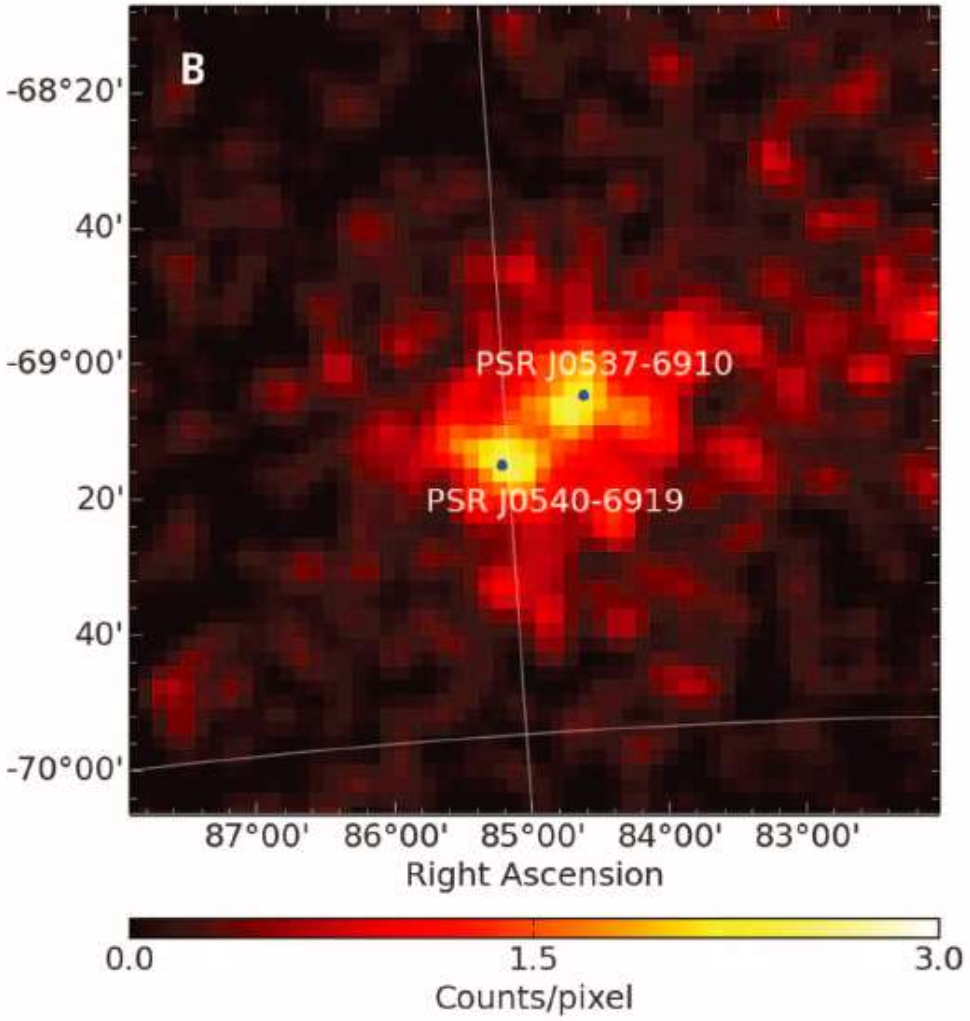
Zhang, Y. H. et al. 2022

周期跃变后偏振演化
Feng et al. 2020

$$R_{sd} = I\dot{\nu}/I_0\nu_0\dot{\nu}_0,$$

B0540-69

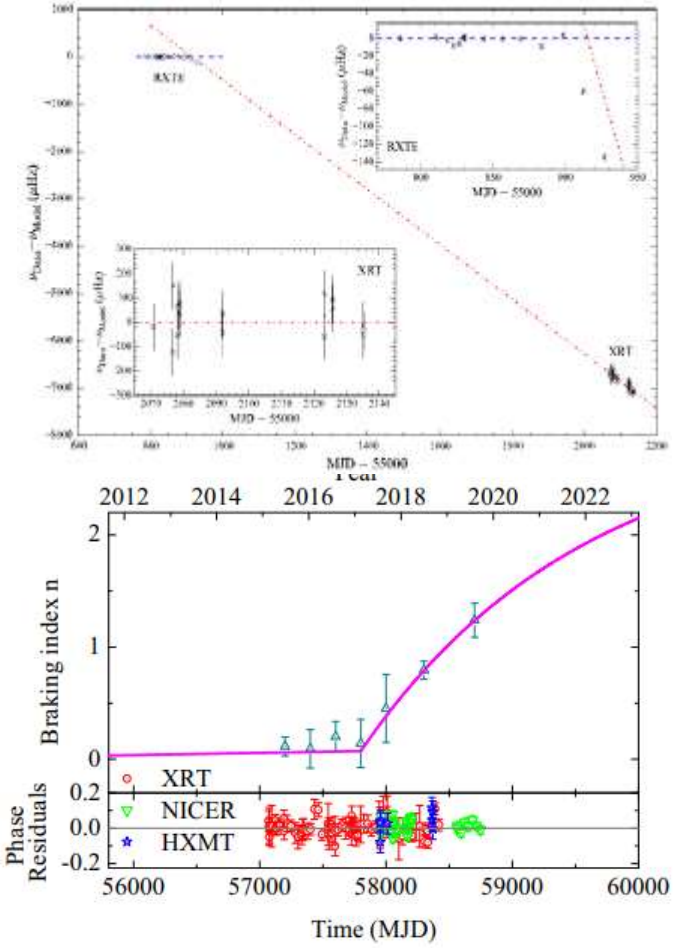




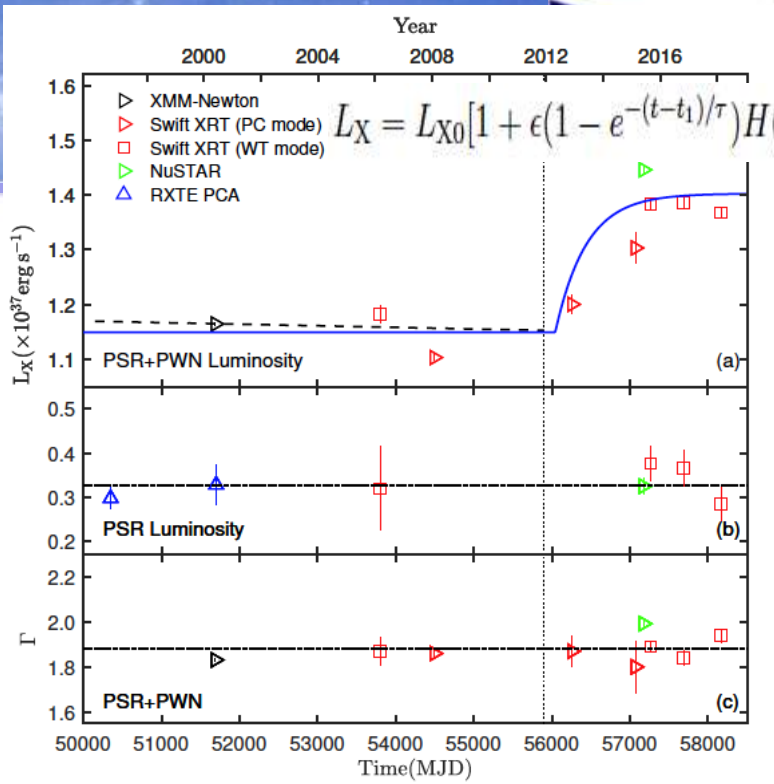
Fermi LAT Collaboration, 2015

B0540-69

Marshall et al. 2015



Spin-down rate transition（SRT）~36%

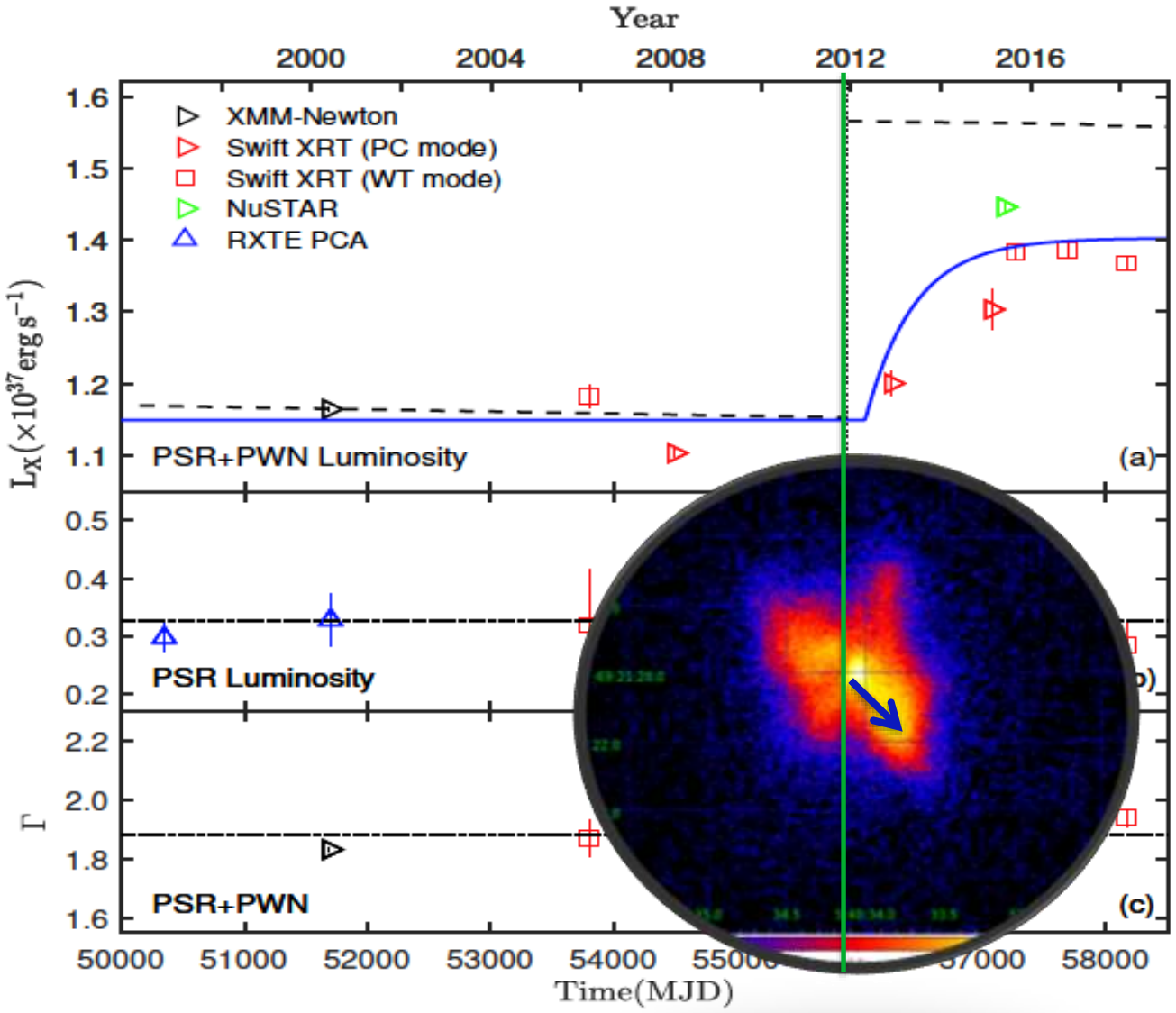


n = 2.5 n is 0.031 ± 0.013 (90% confidence)

- 脉冲星脉冲轮廓/光度不变
- 脉冲星风云增加32(8)%
- 上升时标400 day
- 脉冲星风云处磁场 $0.78^{+4.50}_{-0.28}$ mG
- 制动指数在快速恢复中

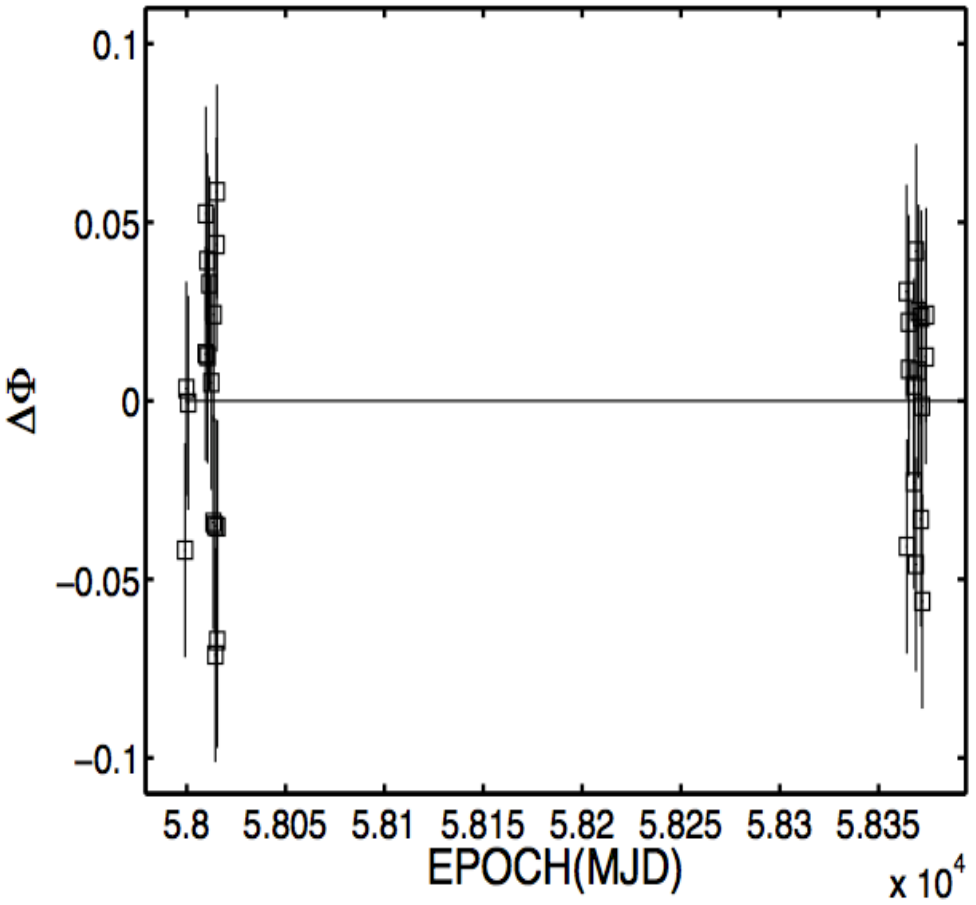
Ge et al. 2019
Wang et al. 2020

B0540-69

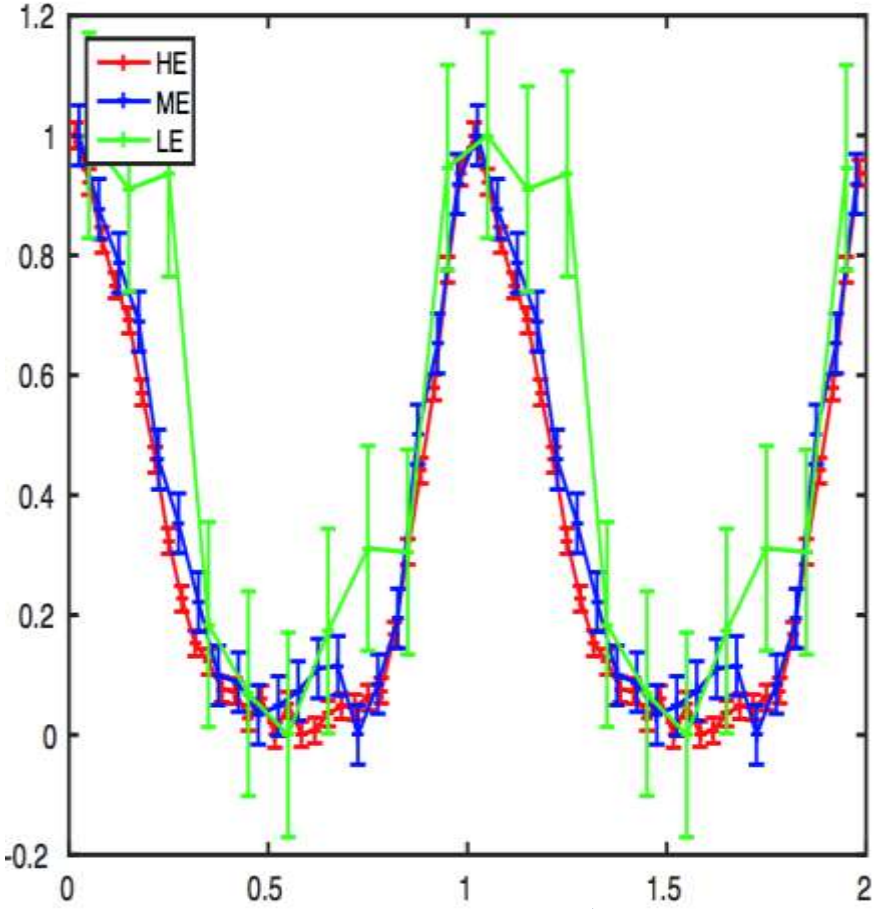


Ge et al. 2019

PSR B1509-58

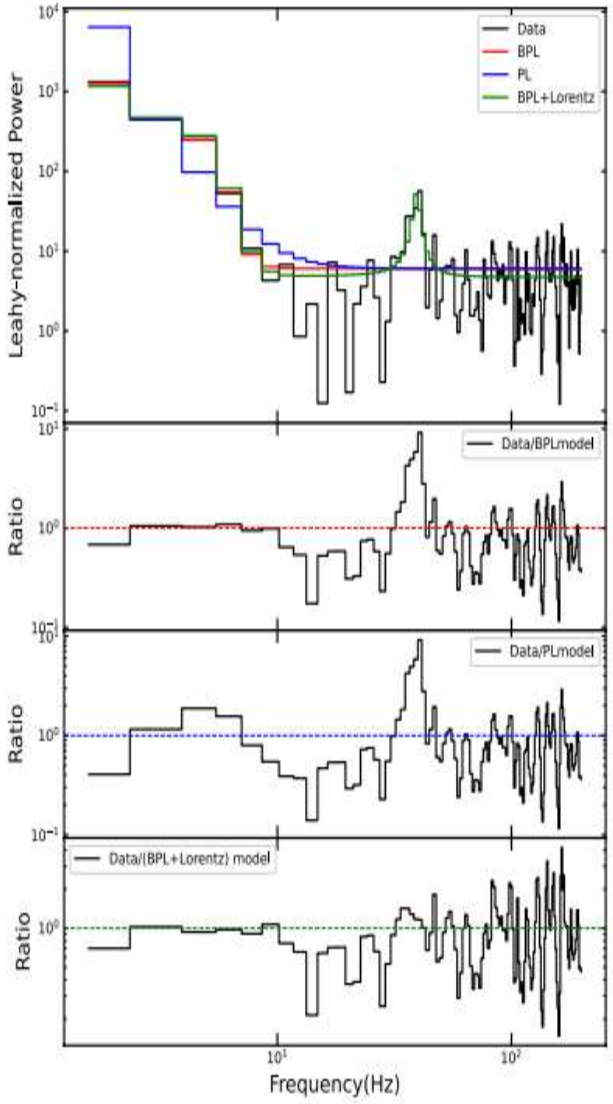


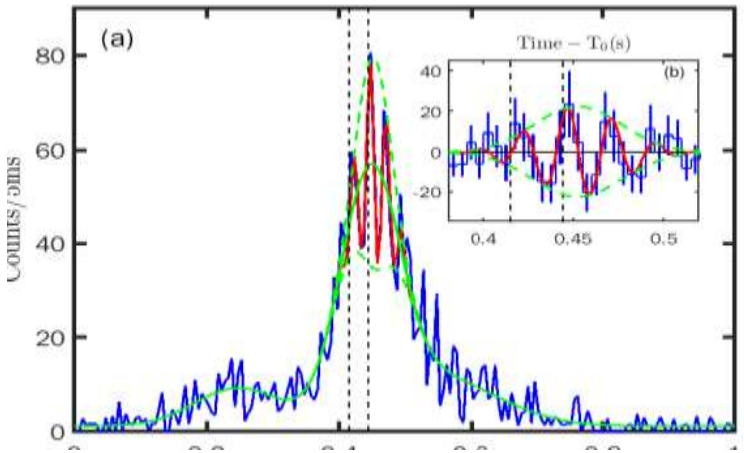
计时残差

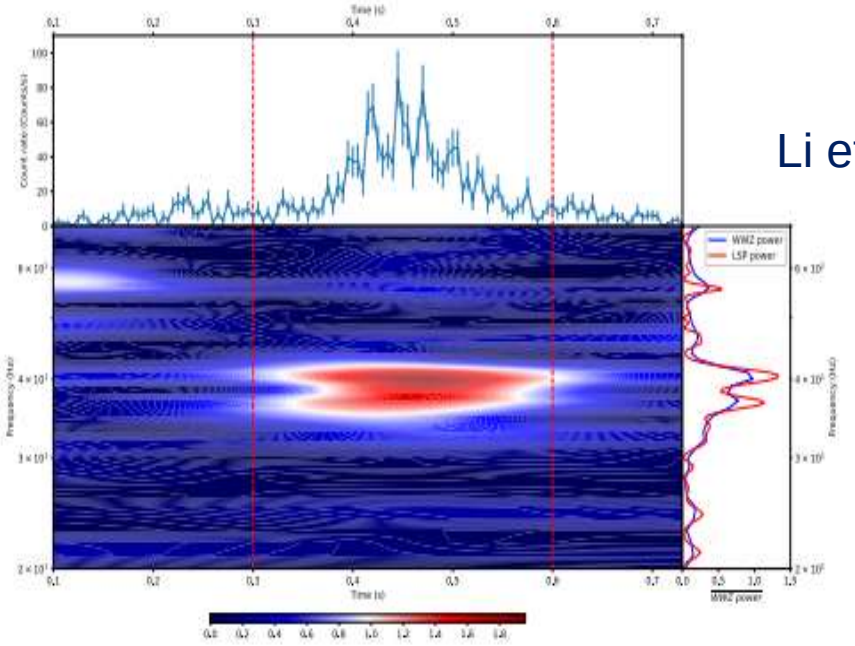


HE, ME和LE的脉冲轮廓

SGR J1935+2154







HXMT-ME/Konus-wind
40Hz
显著性：3.4 sigma

Li et al. 2022

MeV脉冲星搜索

J0357+3205	59.468641	32.090186
J0633+0632	98.43423294	6.543040311
J1048-5832	162.0508333	-58.53494444
J1057-5226	164.4951667	-52.44897222
J1732-3131	263.1397396	-31.5229928
J1809-2332	272.4596207	-23.55960258
J1836+5925	279.0570337	59.424989
J0007+7303	1.7565	73.05230556
J1028-5819	157.1164958	-58.31811806
J1418-6058	214.6779604	-60.963525
J1709-4429	257.4280333	-44.48562222
J1826-1256	276.5351709	-12.94271483
J1907+0602	286.9780992	6.03803425
J2021+3651	305.27275	36.85133333
J2229+6114	337.272	61.23591667
J0835.3-4510	128.83585	-45.17
J1952+3252	298.242525	32.8779191

J1413-6205	213.374703	-62.09398737
J1429-5911	217.4942905	-59.19349982
J1459-6053	224.8749513	-60.88908324
J1718-3825	259.5565208	-38.42168333
J1741-2054	265.4908333	-20.90333333
J1954+2836	298.5797938	28.60166424
J1958+2846	299.666957	28.76496081
J0659+1414	104.9507056	14.23916713
J1044-5737	161.1366557	-57.6220268
J1509-5850	227.3630417	-58.84891667
J1620-4927	245.173	-49.46030556
J1746-3239	266.7289458	-32.6655
J1846+0919	281.6081746	9.329524714
J1957+5033	299.4122549	50.55511881
J2028+3332	307.08275	33.53454444
J2030+3641	307.5010867	36.6908753
J2030+4415	307.7139583	44.26058333
J2055+2539	313.9539867	25.66689863
J2139+4716	324.983125	47.27027778
J0633+1746	98.47620417	17.77066111
J1813-1246	273.3490486	-12.76633743
J1833-1034	278.389875	-10.56875
J1803-2149	270.7901333	-21.82027778
J1124-5916	171.1629167	-59.27222222
J2111+4606	317.8505417	46.10869444
J2238+5903	339.6177816	59.06133751
J0106+4855	16.60441667	48.93105556

选取亮的伽马射线脉冲星，计时获取星历

折叠MeV波段的观测数据，是否存在MeV的脉冲辐射？

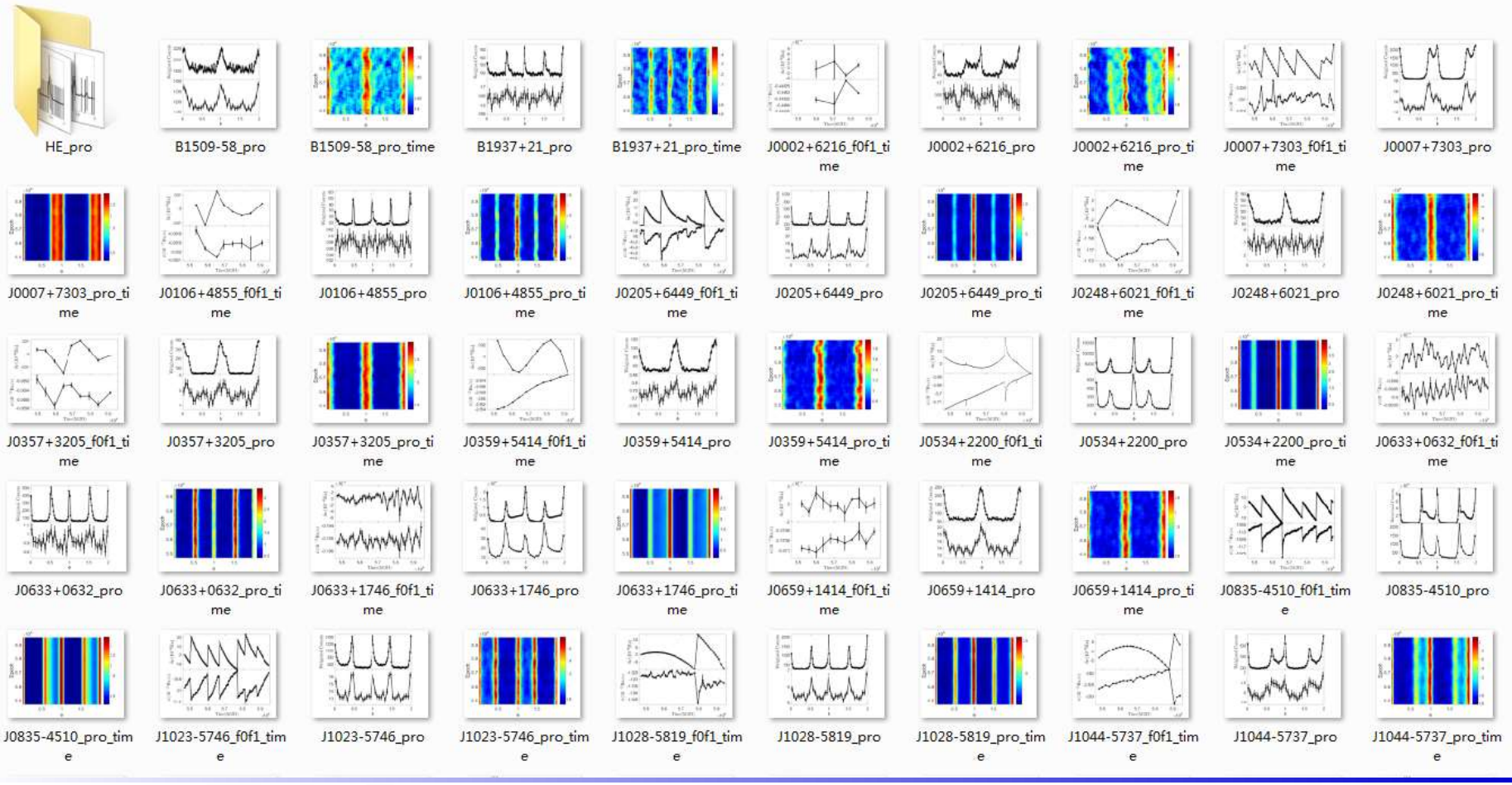
数据：
HXMT-HE/CsI
Fermi-GBM

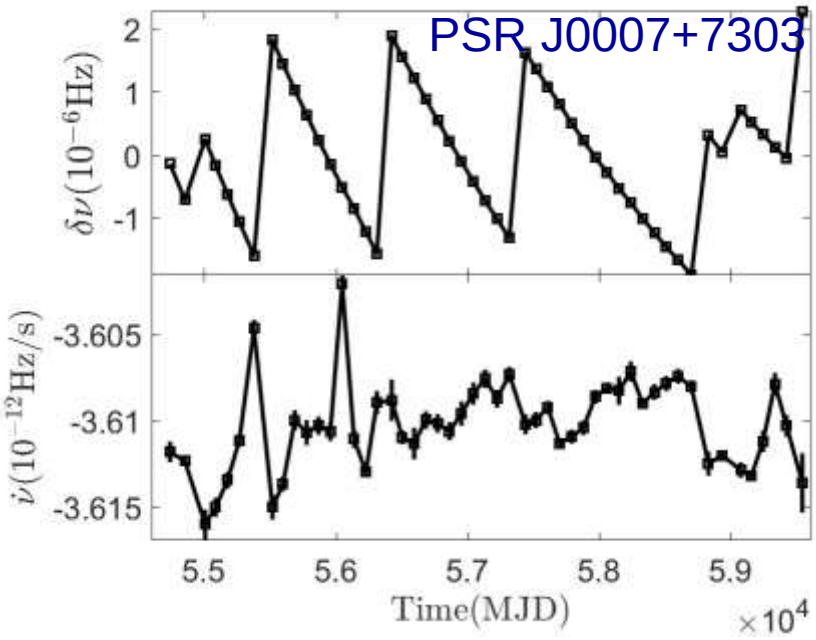
Astro-SAT的CZTI<380keV也在进行类似工作

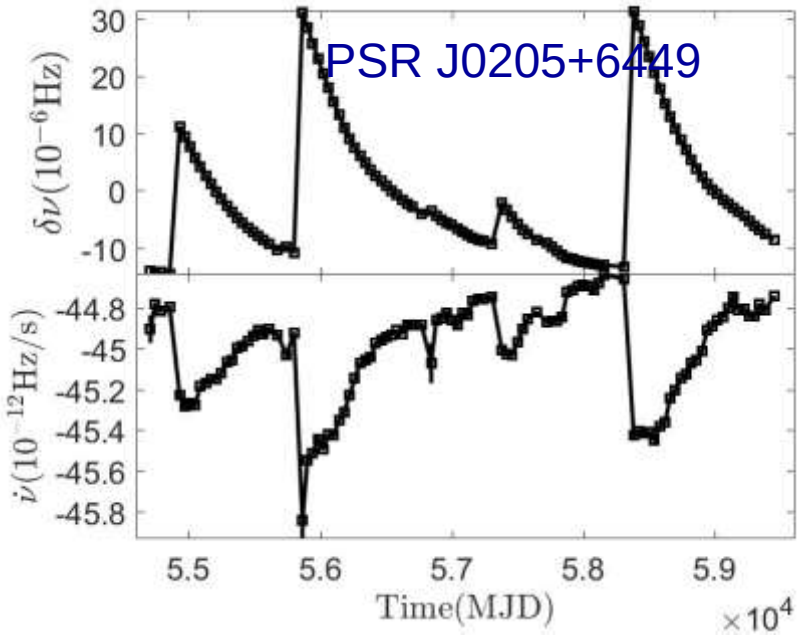
计时与脉冲轮廓

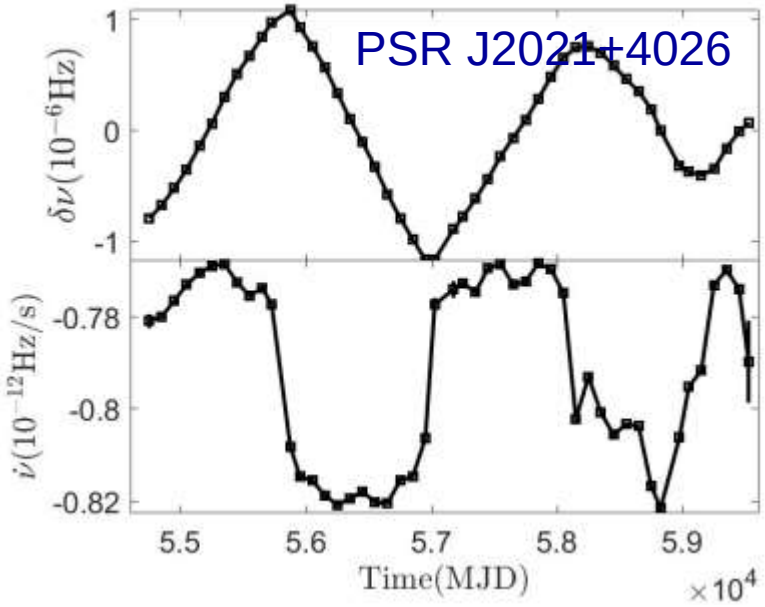
- 计时：~60个周期跃变
- 伽马脉冲轮廓：时间，能段

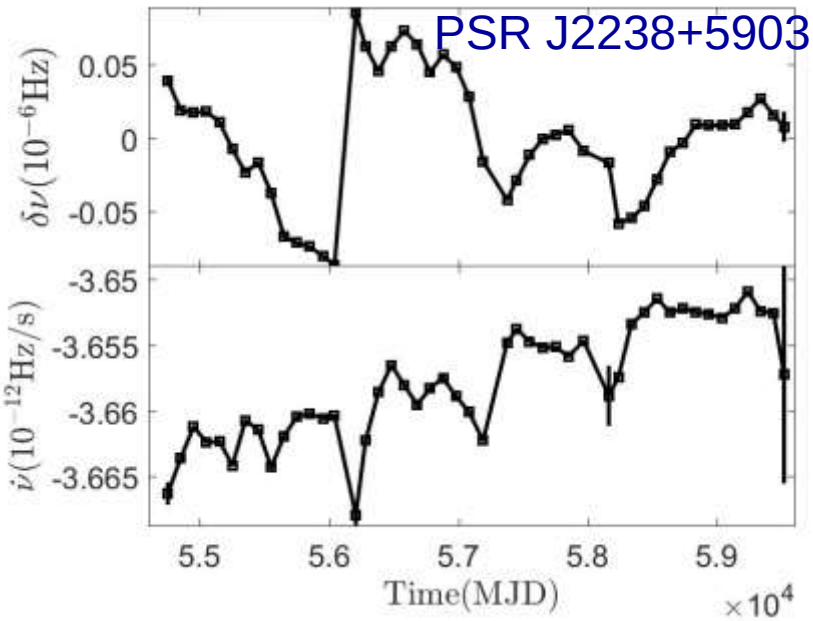
特殊源：
状态改变
周期跃变

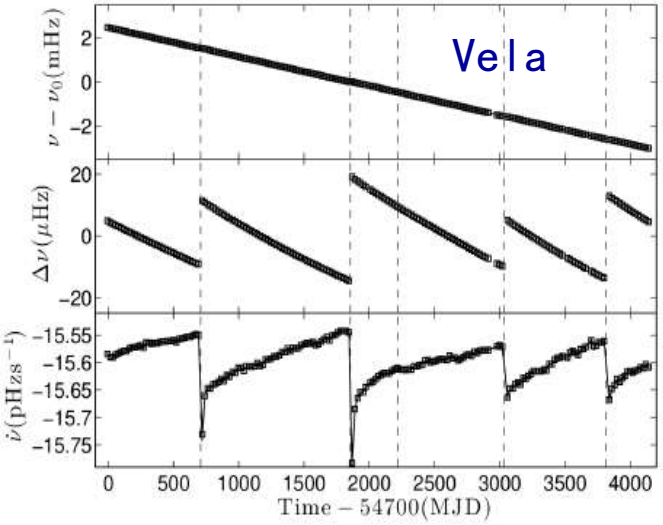


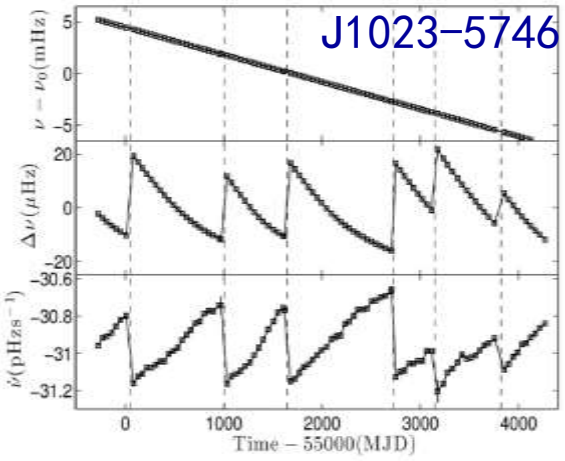

PSR J0007+7303
$\delta\nu(10^{-6}\mathrm{Hz})$
$\dot{\nu}(10^{-12}\mathrm{Hz/s})$
Time(MJD)
$\times 10^4$

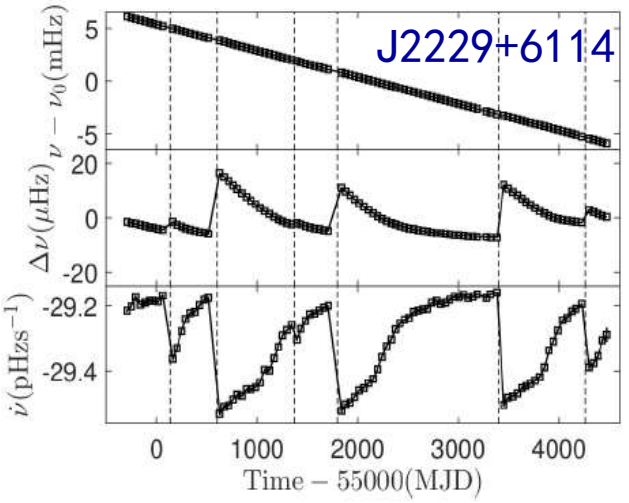

PSR J0205+6449
$\delta\nu(10^{-6}\mathrm{Hz})$
$\dot{\nu}(10^{-12}\mathrm{Hz/s})$
Time(MJD)
$\times 10^4$

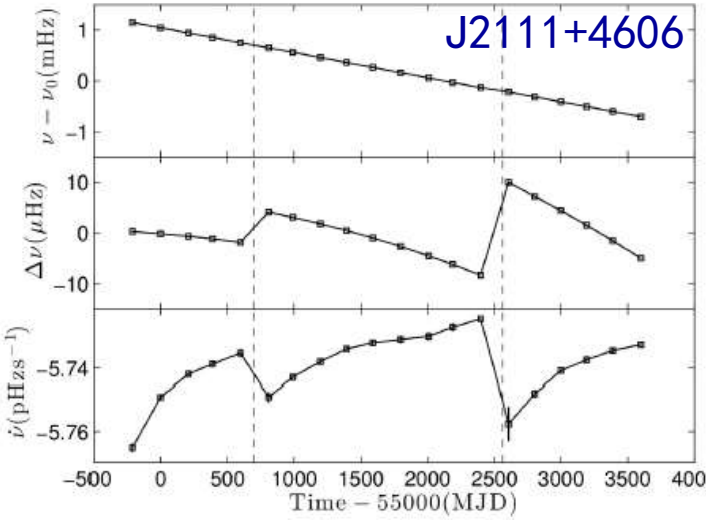

PSR J2021+4026
$\delta\nu(10^{-6}\mathrm{Hz})$
$\dot{\nu}(10^{-12}\mathrm{Hz/s})$
Time(MJD)
$\times 10^4$

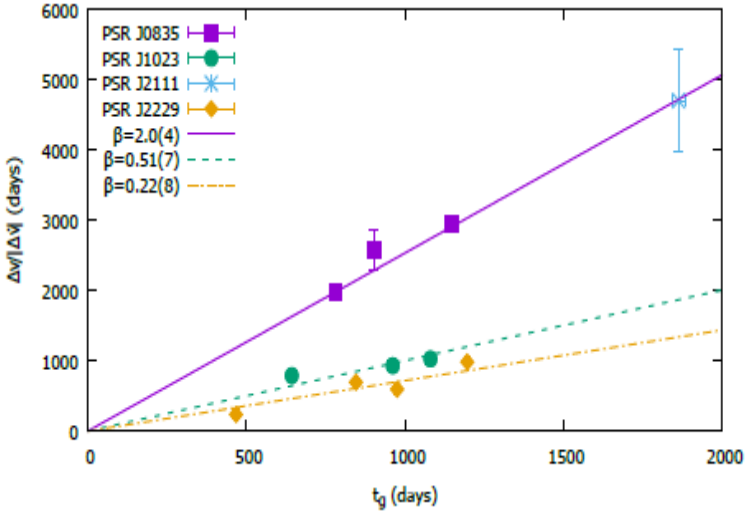

PSR J2238+5903
$\delta\nu(10^{-6}\mathrm{Hz})$
$\dot{\nu}(10^{-12}\mathrm{Hz/s})$
Time(MJD)
$\times 10^4$









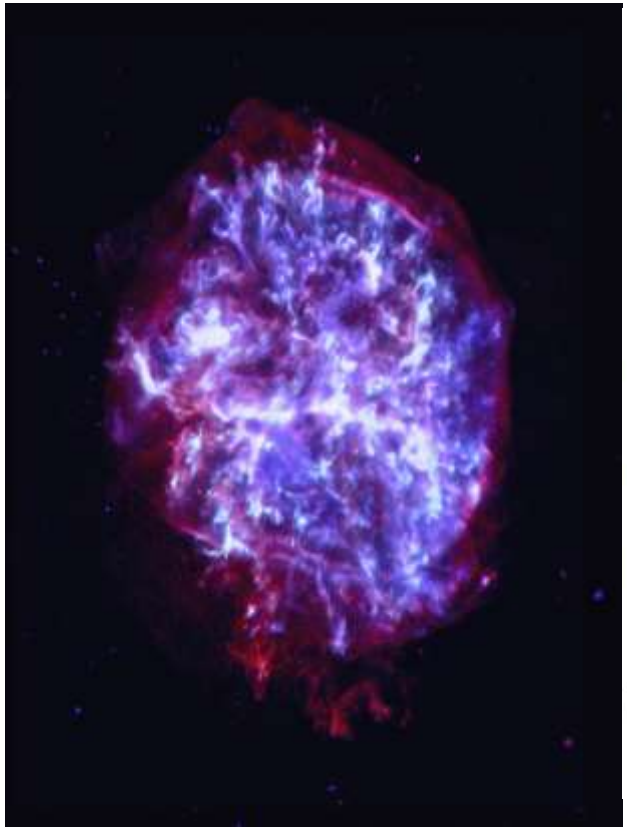


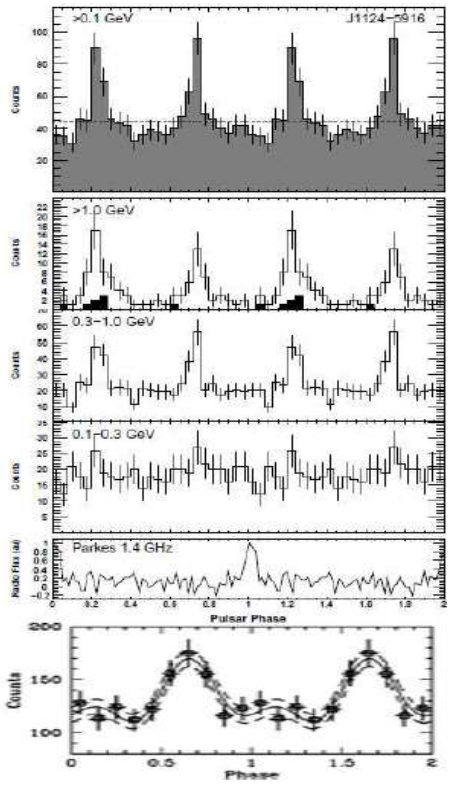
$$\frac{\Delta\nu}{|\Delta\dot{\nu}|}=\left(\frac{1}{2}+\beta\right)t_g.$$

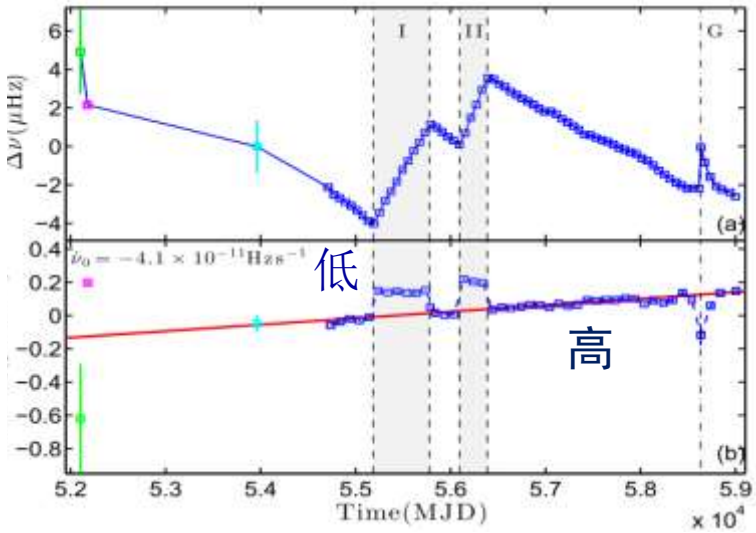
Erbil et al. 2021

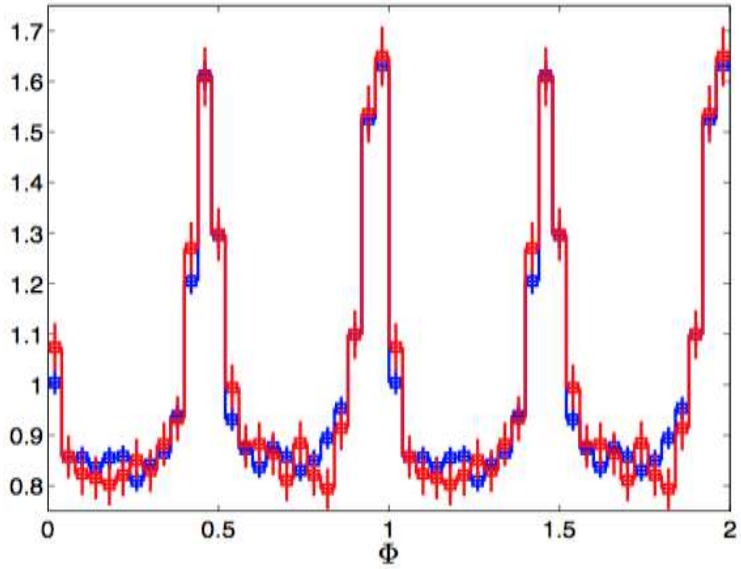
PSR J1124-5916

Ge et al. 2020







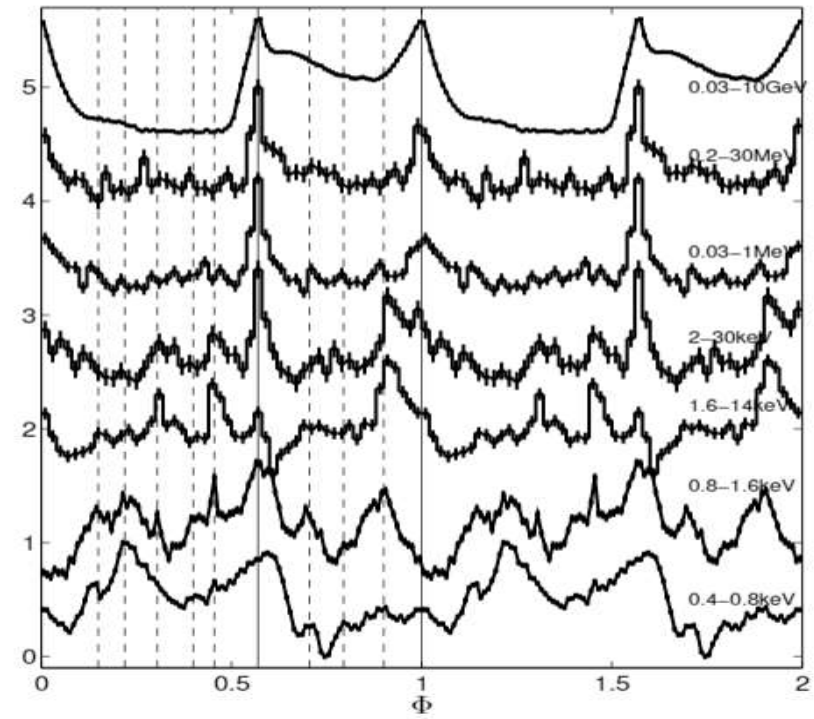


G292.0+1.8
2.9kyr,
F0=7.37Hz,
F1=-4.1E-11 Hzs^{-1}

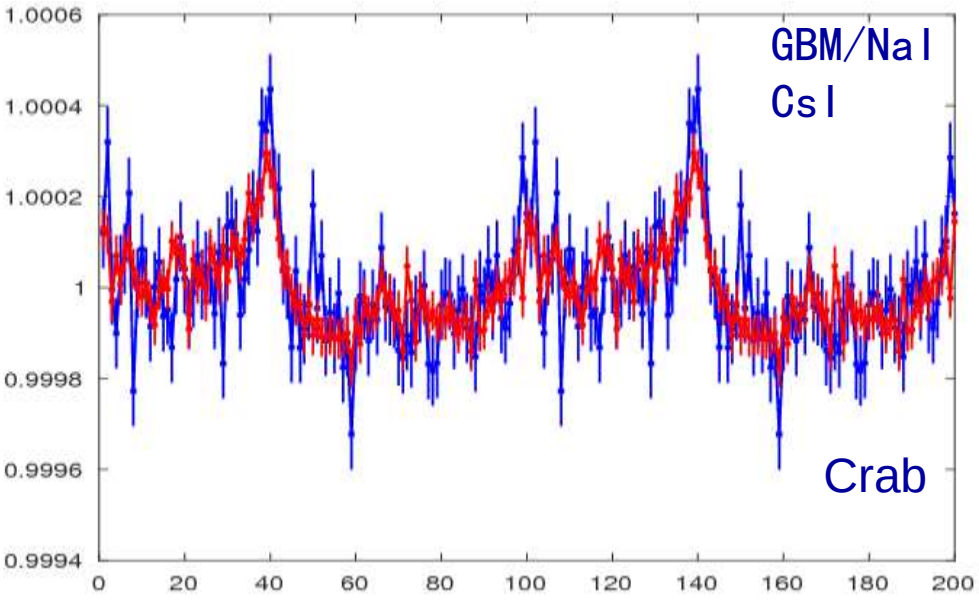
第二颗年轻脉冲星存在状态改变：0.4%
制动指数：~ 1.98
与B0540-69类似

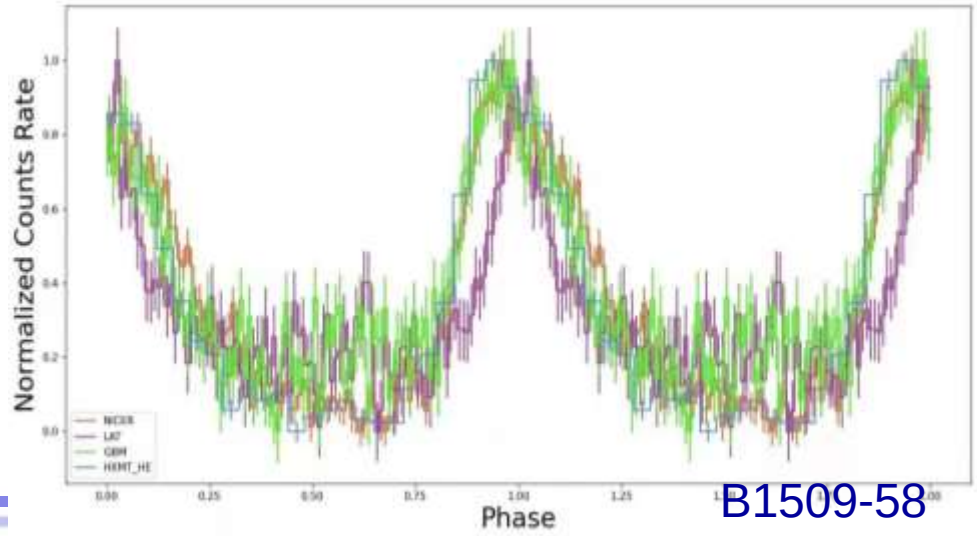
Fermi伽玛射线脉冲轮廓没有变化

MeV脉冲星搜索



Vela





B1509-58

慧眼HXMT-HE/CsI结果
Crab、Vela、B1509-58.

其他源没有观测到正信号。

总结

- 慧眼HXMT针对部分年轻脉冲星进行了详细观测，取得很多观测成果；Crab脉冲星周期跃变前后轮廓和流量没有变化。
- 慧眼HXMT 磁星观测，FRB 200428对应的X射线暴，在ME中存在QPO现象。
- MeV脉冲星脉冲信号： Crab、Vela、B1509-58。
- 年轻脉冲星存在状态改变，磁层发生变化。