Progress of Pulsar Astronomy in the Last Decade

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ICRR, University of Tokyo

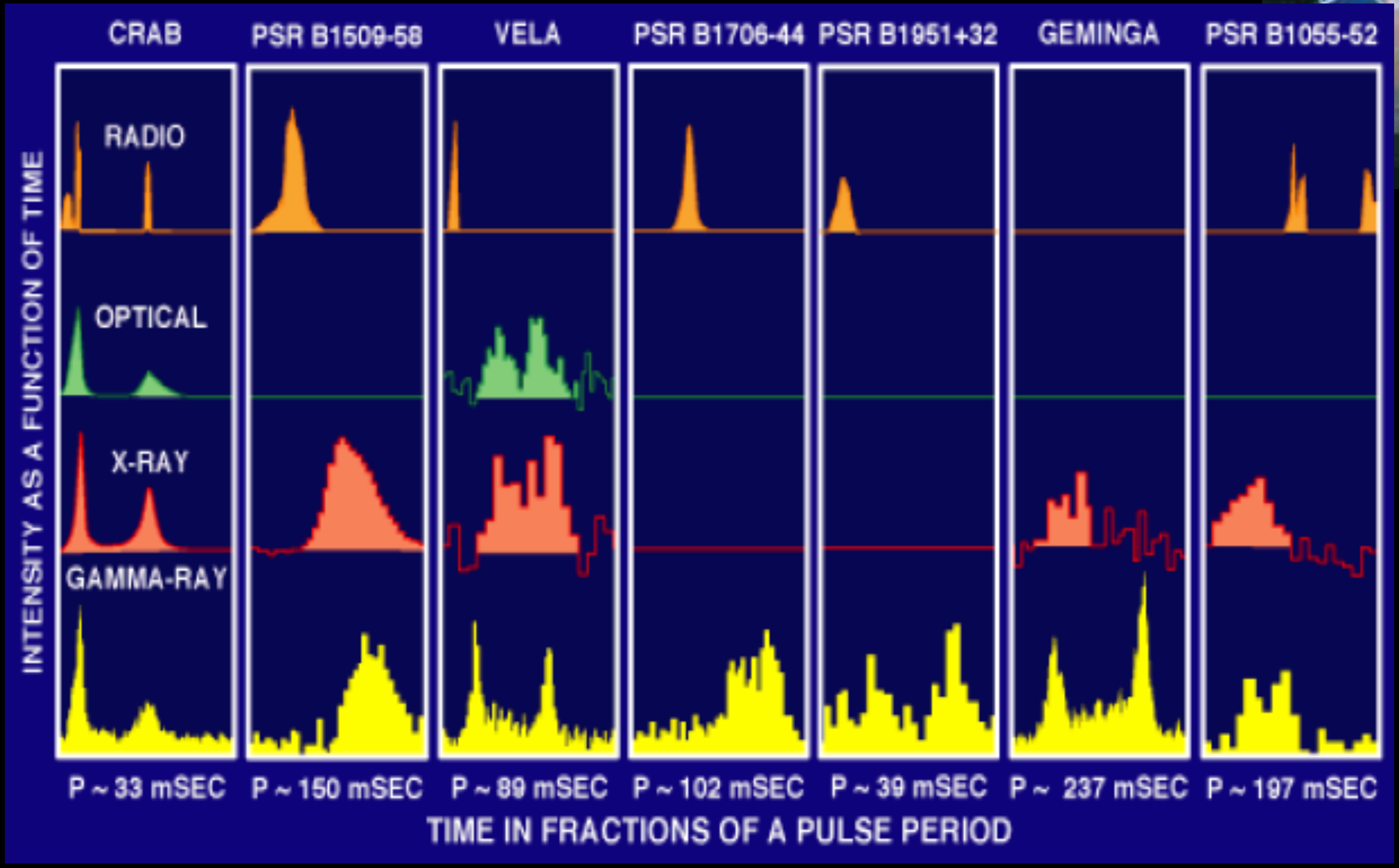
CTA-Japan Meeting 2017 Dec 18/19 2017

- Our understandings of pulsars in the last ten years have been advanced by *Fermi* and the coordinated MWL follow-ups since 2008.

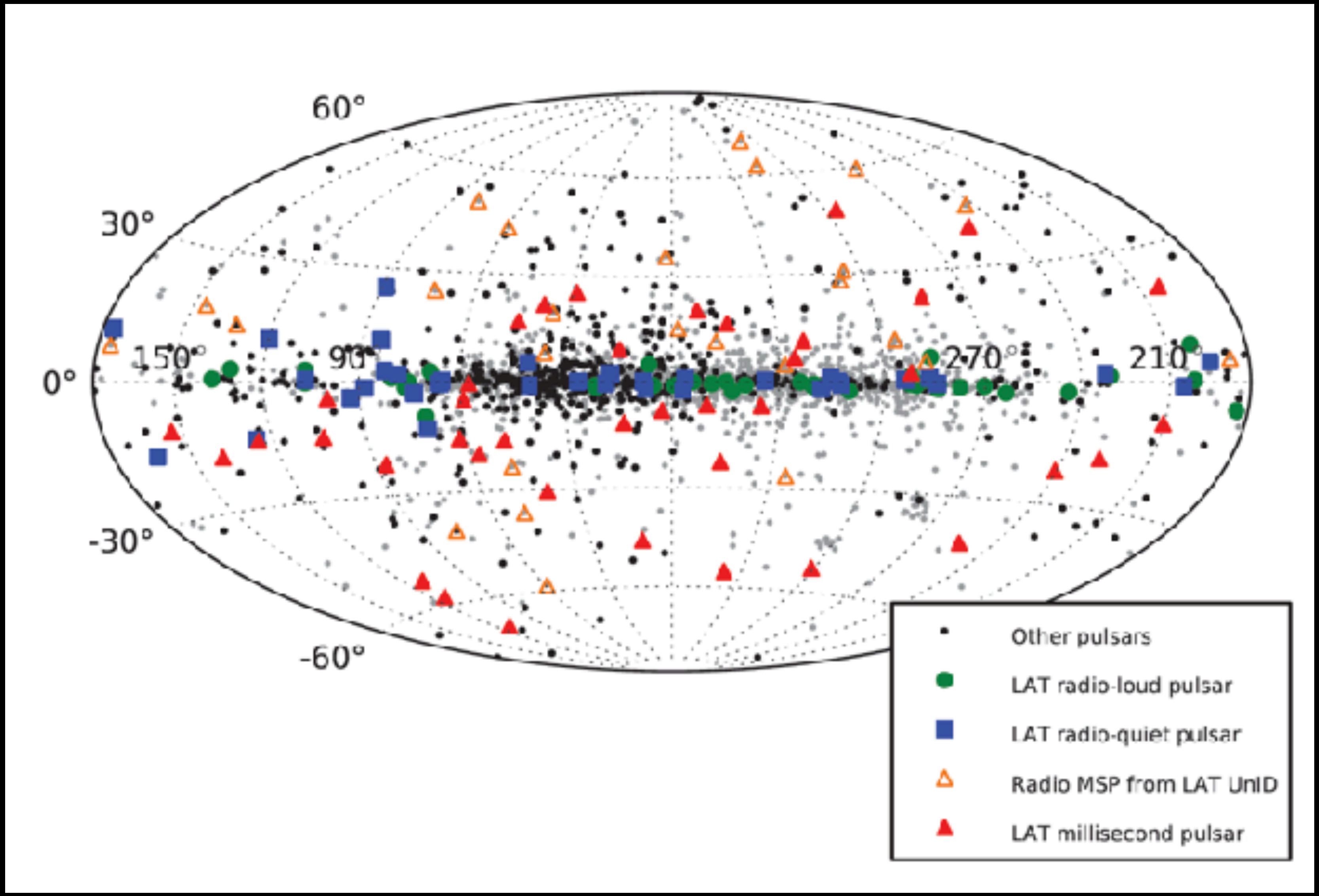
- Review a few major achievements in pulsar science.

- Prospects of CTA in the light of these achievements.

Magnificent 7 in EGRET Era



A New Era of Pulsar Astronomy



Abdo et al. (2013)

By now, there are 205 gamma-ray selected pulsars.

What's New?

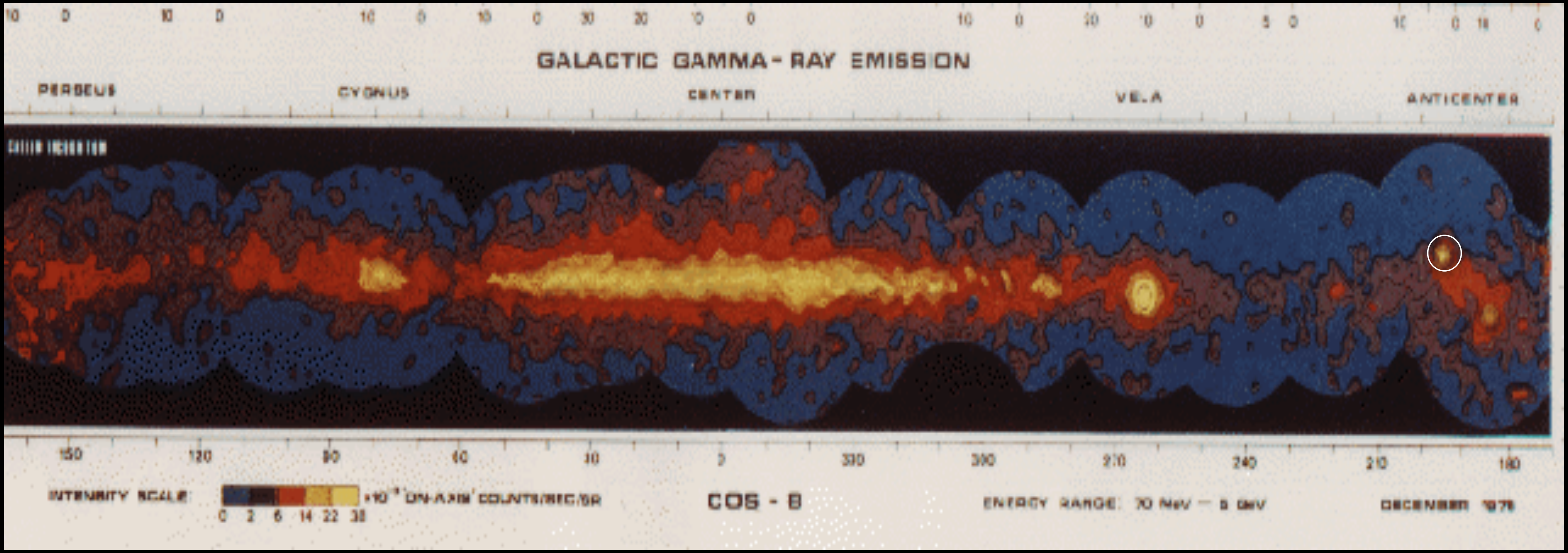
- **Radio-quiet gamma-ray pulsars**
- **Variable pulsar wind nebula**
- **Millisecond pulsars (MSPs)**
- **Globular clusters**
- **Variable gamma-ray pulsar (PSR J2021+4026)**
- **Gamma-ray binaries**

Importance of Synergy among X-ray, Gamma-ray & Radio

- Different wavelengths reflects different astrophysical processes / emission regions.
- Theoretically, properties in one energy band can help to constrain the properties in the others.
- Observationally, the limitations of observations in a particular wavelength can be complemented by the other bands.

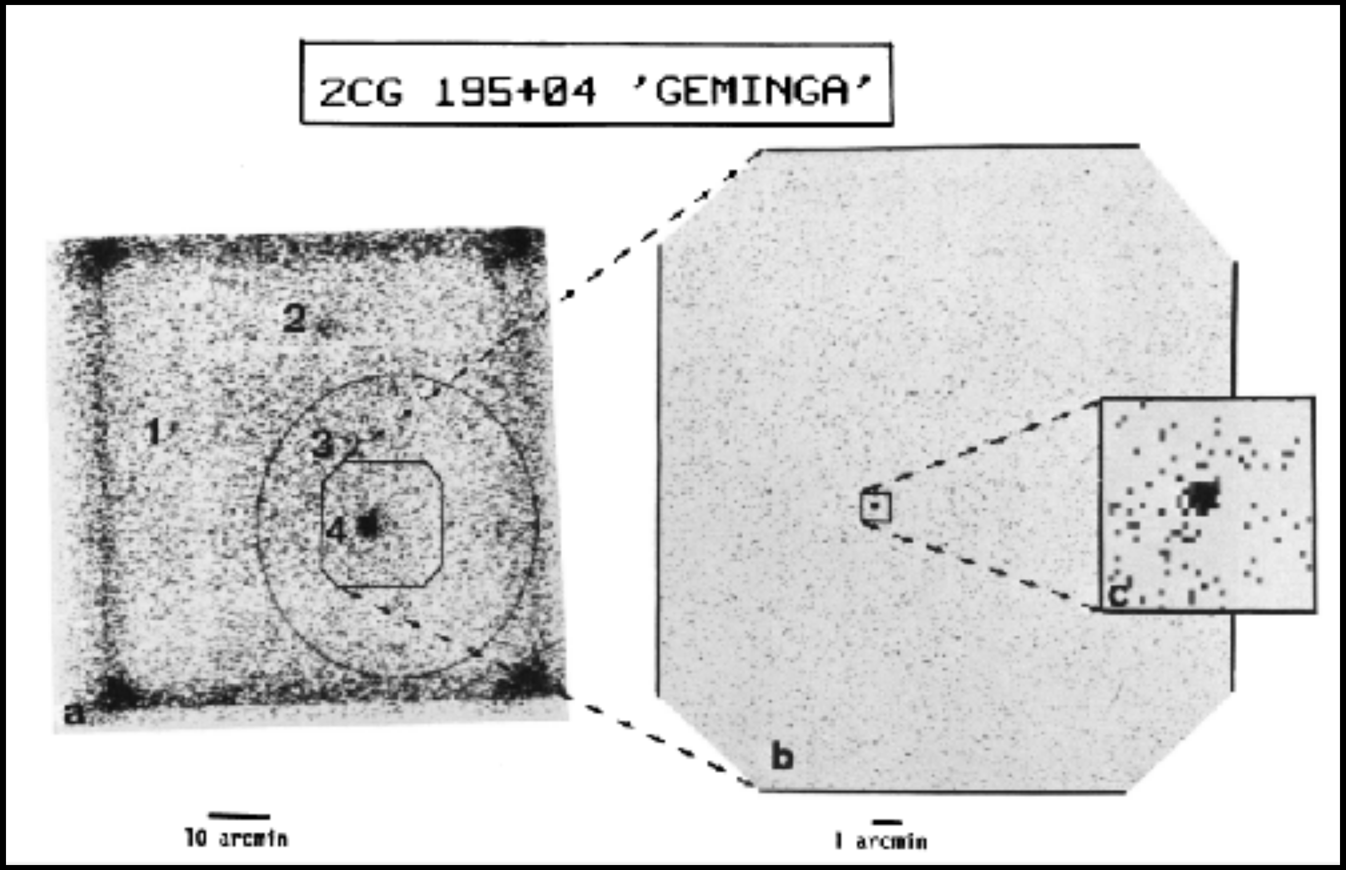
Geminga

- The 1st RQ-PSR - **Geminga**
- Its gamma-ray emission was detected by the experiments in the early-days - SAS-2, COS-B.



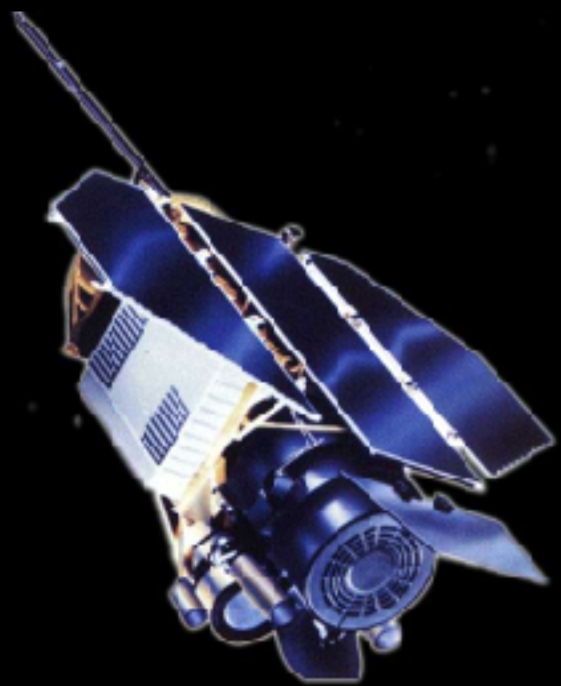
Geminga

Detection of a possible X-ray counterpart in *COS-B* error box with *Einstein* (Bignami et al. 1983)



Geminga

- Discovery of 0.237s period in X-ray by *ROSAT. (You have more photons in X-ray)*



letters to nature

Nature 357, 222 - 224 (21 May 1992); doi:10.1038/357222a0

Discovery of soft X-ray pulsations from the γ-ray source Geminga

J. P. HALPERN[*] & S. S. HOLT[†]

[*]Columbia Astrophysics Laboratory, Columbia University, 538 West 120th Street, New York, New York 10027, USA

[†]Director of Space Sciences, Code 600, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

- The X-ray ephemeris enabled the gamma-ray pulsation to be uncovered.

letters to nature

Nature 357, 306 - 307 (28 May 1992); doi:10.1038/357306a0

Pulsed high-energy γ-radiation from Geminga (1E0630+178)

D. L. BERTSCH[*], K. T. S. BRAZIER[†], C. E. FICHTEL[*], R. C. HARTMAN[*], S. D. HUNTER[*], G. KANBACH[†], D. A. KNIFFEN[‡], P. W. KWOK[*], Y. C. LIN[§], J. R. MATTOX[¶], H. A. MAYER-HASSELWANDER[†], C. V. MONTIGNY[†], P. F. MICHELSON[§], P. L. NOLAN[§], K. PINKAU[†], H. ROTHERMEL[†], E. J. SCHNEID[‖], M. SOMMER[†], P. SREEKUMAR[*] & D. J. THOMPSON[*]

[*][illegible]

[†]Max-Planck-Institut für Physik und Astrophysik, Institut für Extraterrestrische Physik, D-8046 Garching, Germany

[‡]Department of Physics, Hampden-Sydney College, Hampden-Sydney, Virginia 23943, USA

[§][illegible]

[‖][illegible]

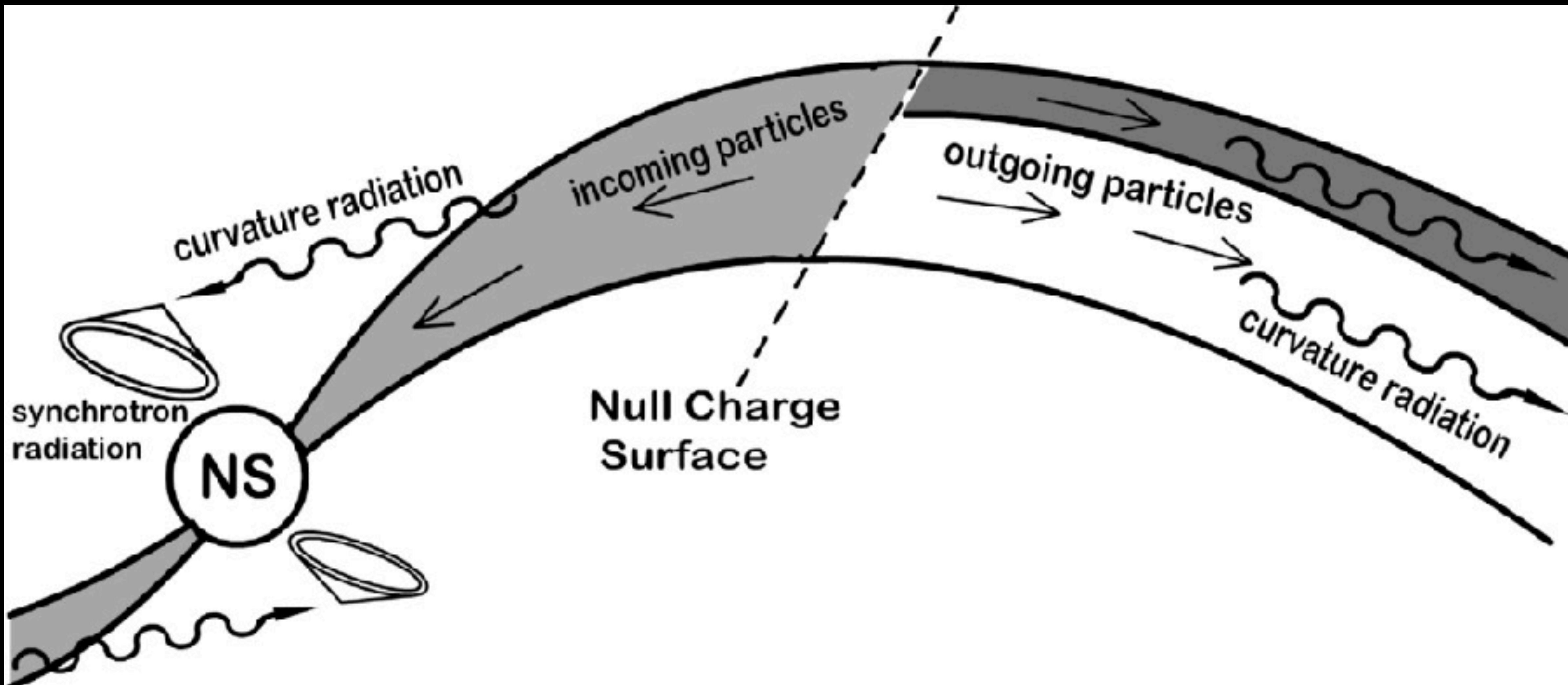
[¶][illegible]

HALPERN and Holt[1] have recently reported the detection of coherent pulsations with a period of 237 ms from the soft X-ray source 1E0630+178, which lies in the error box of the γ-ray source known as Geminga (2GC195+04). This observation provides compelling evidence that Geminga, an object whose nature has hitherto been mysterious, is an X-ray pulsar. Prompted by this discovery, we have searched the data from EGRET, the Energetic Gamma Ray Experiment Telescope on the Compton Gamma Ray Observatory, for a comparable signal in the γ-radiation from this part of the sky. We now report the detection of pulsed γ-rays, with energy >50MeV, from 1E0630+178, confirming the identification of Geminga with this X-ray source. The period derivative, $(11.4 \pm 1.7) \times 10^{-15} s s^{-1}$, suggests that Geminga is a nearby, isolated, rotating neutron star with a magnetic field of 1.6×10^{12} gauss, a characteristic age of 3×10^5 yr and a spin-down energy loss rate of 3.5×10^{34} erg s^{-1}.

RQ as a Matter of Geometry

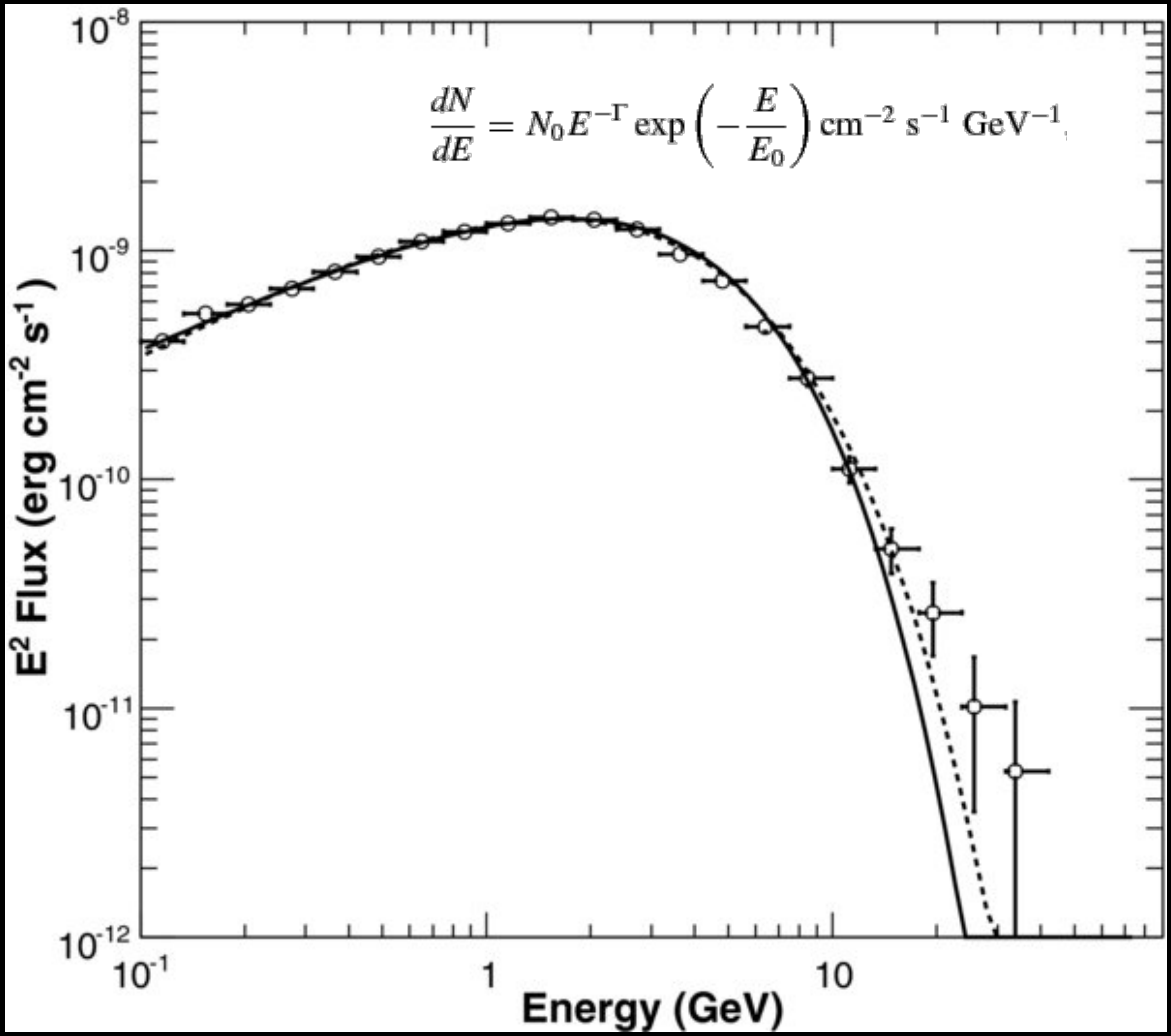
Animation courtesy: FSSC

High Energy Pulsar Magnetospheric Radiation



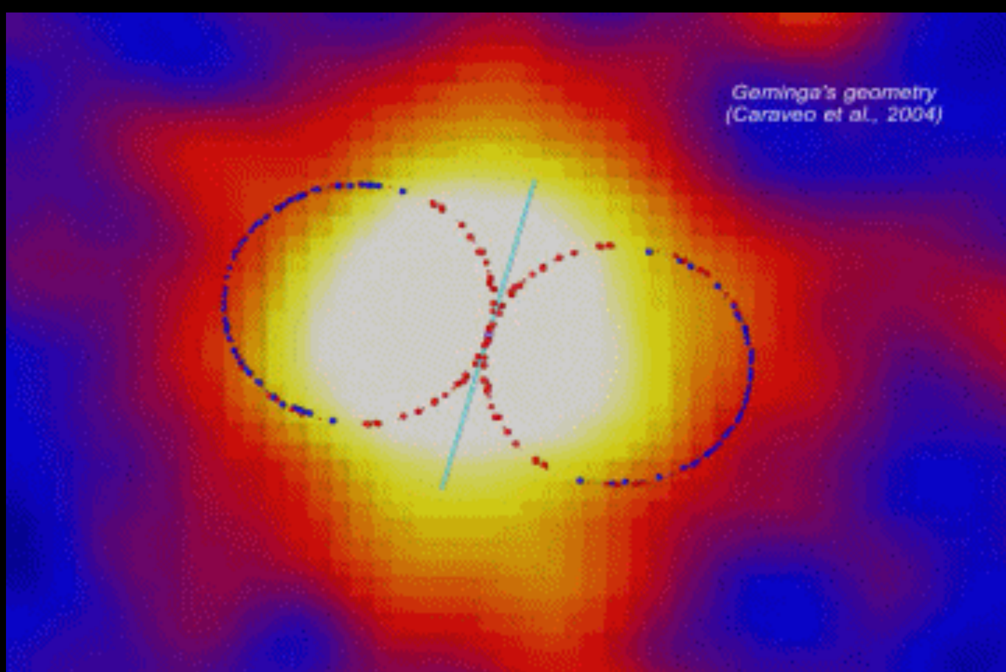
Wang et al. (2014)

Gamma-ray emission from Geminga

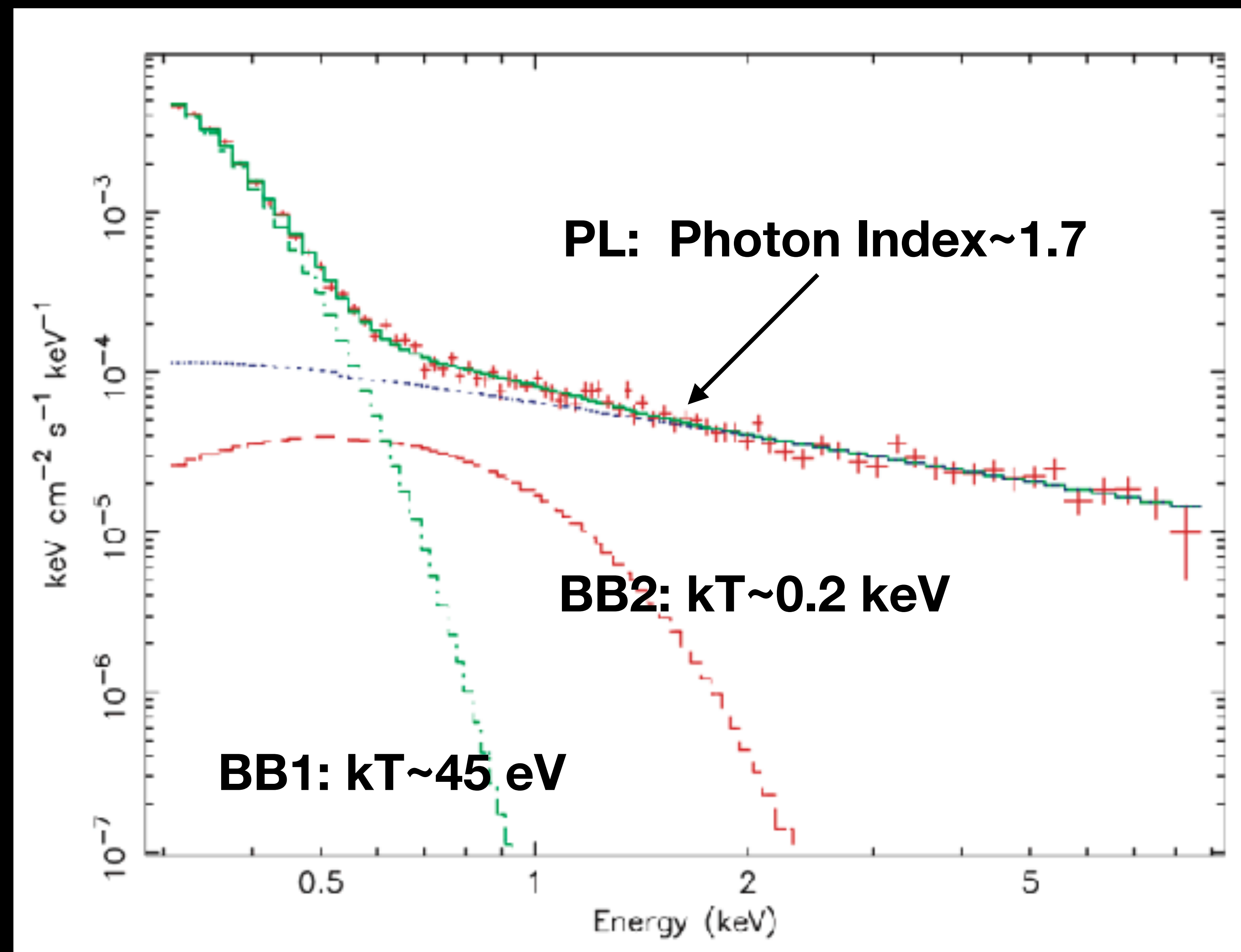


Abdo et al. (2010)

X-ray emission from Geminga



Animation courtesy: ESA



Caraveo et al. (2004)

Emission beyond the Magnetosphere

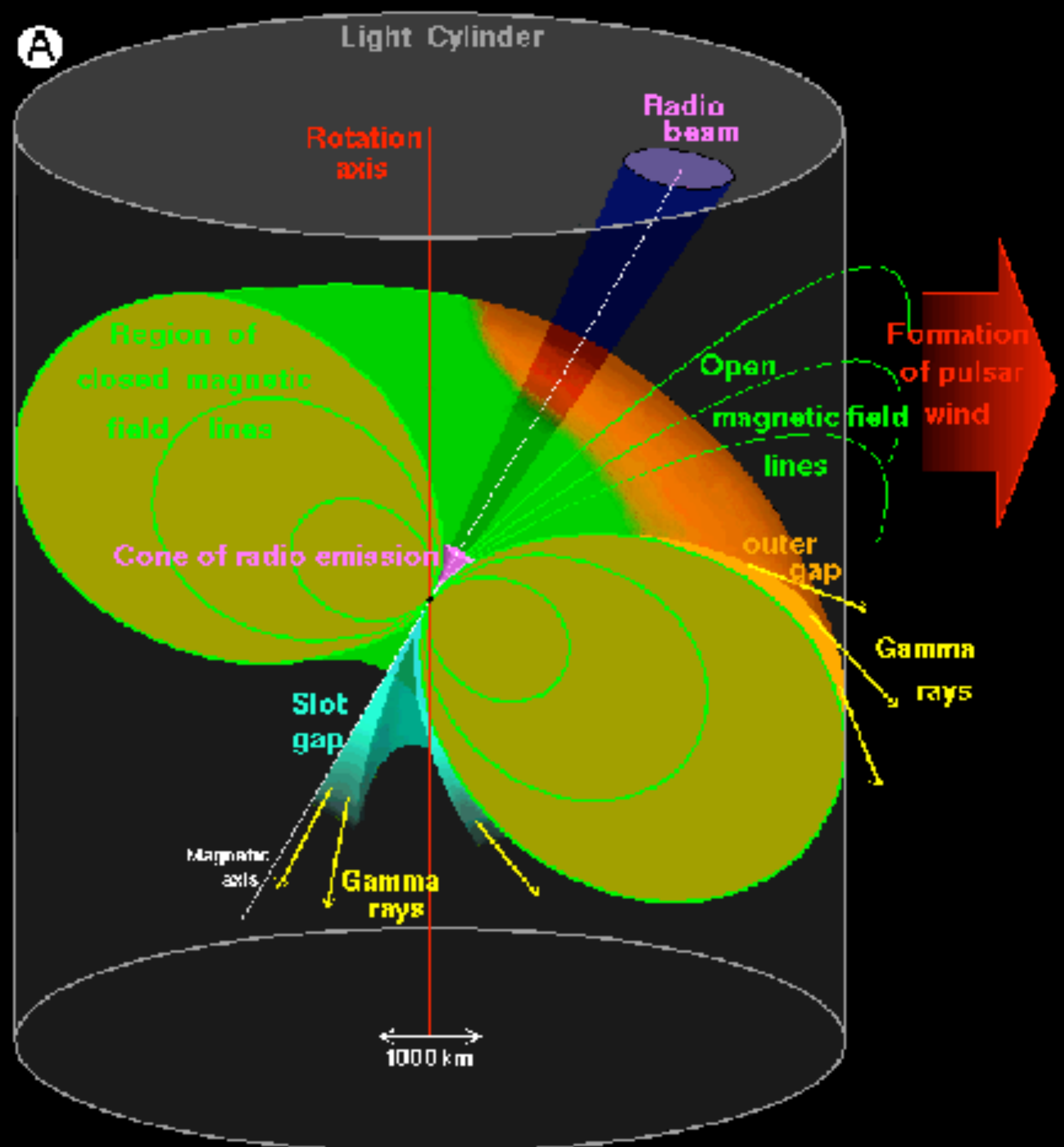
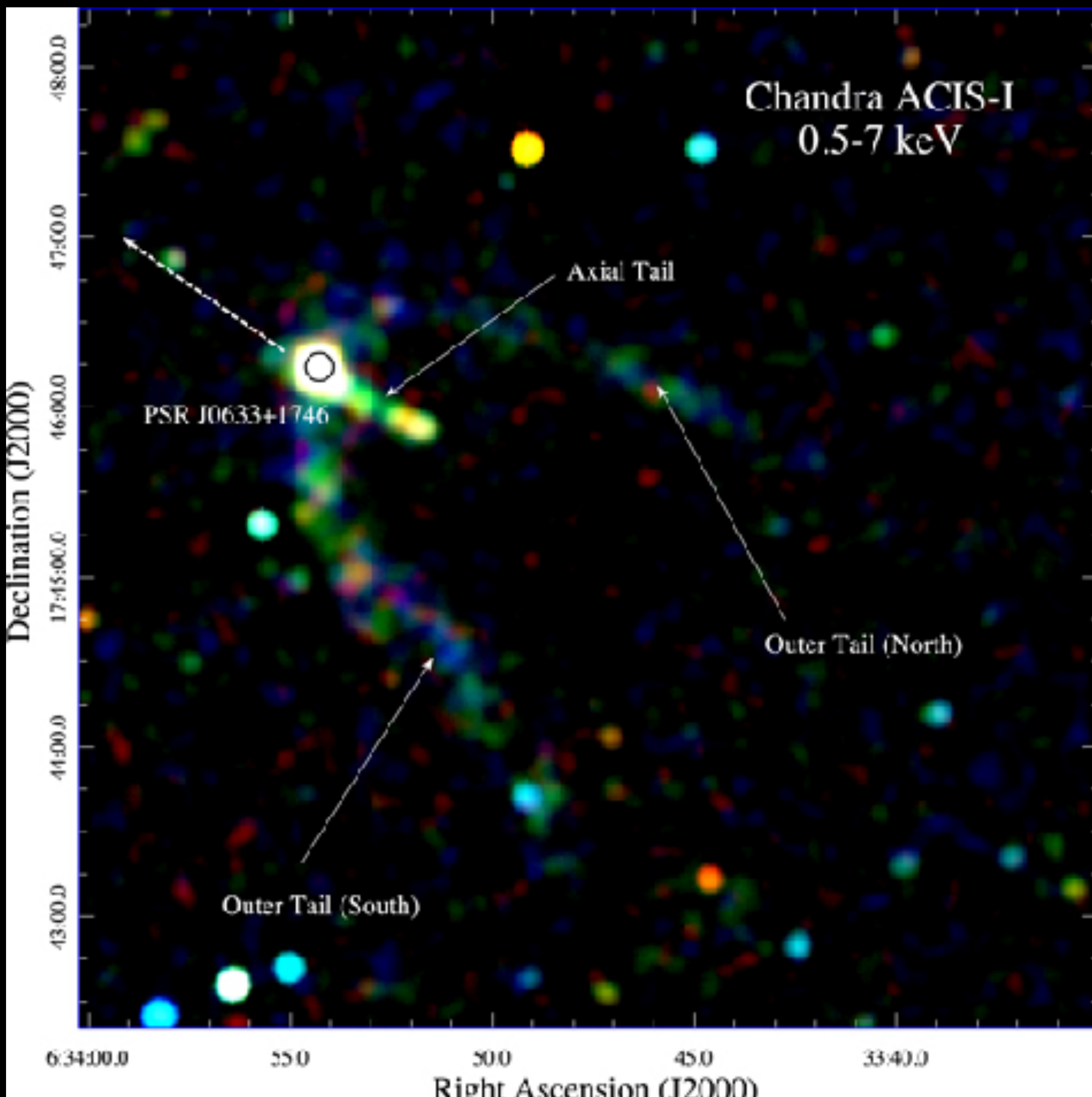
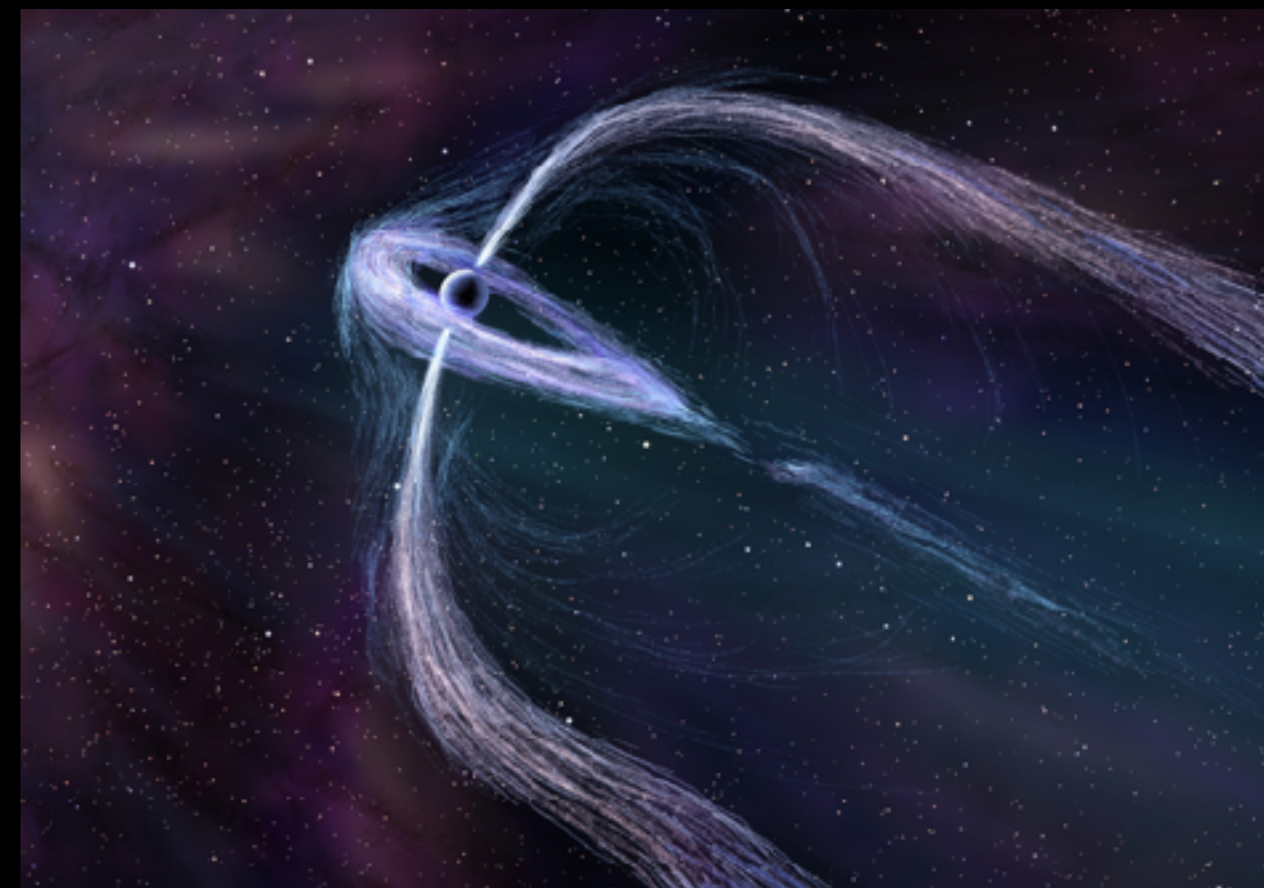


Illustration courtesy: Dany Page

- Most of the rotational energy are lost through the relativistic pulsar wind outflow.
- Typical speed of pulsar ~ 250 km/s
- Producing bow-shock

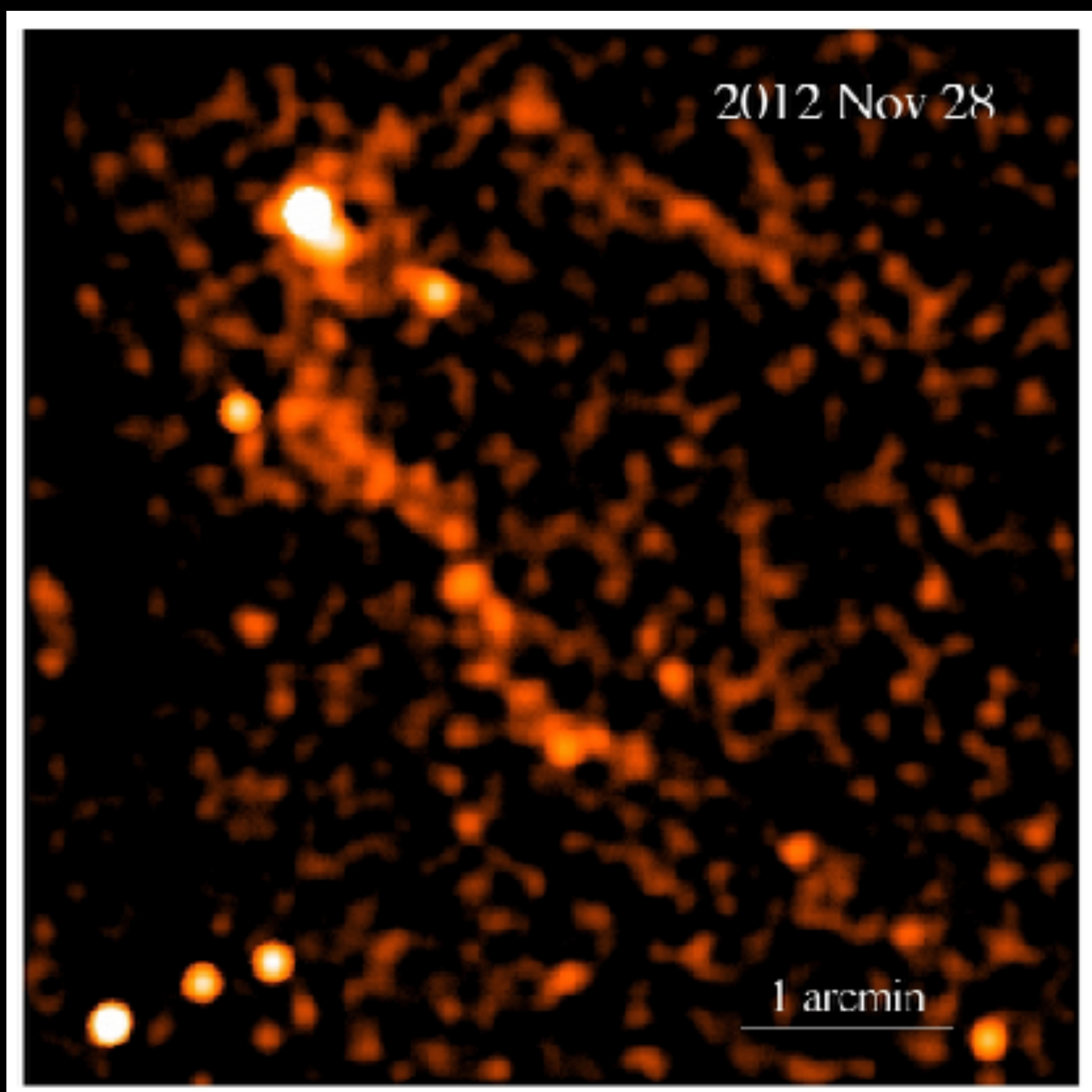
Extended X-rays from Geminga

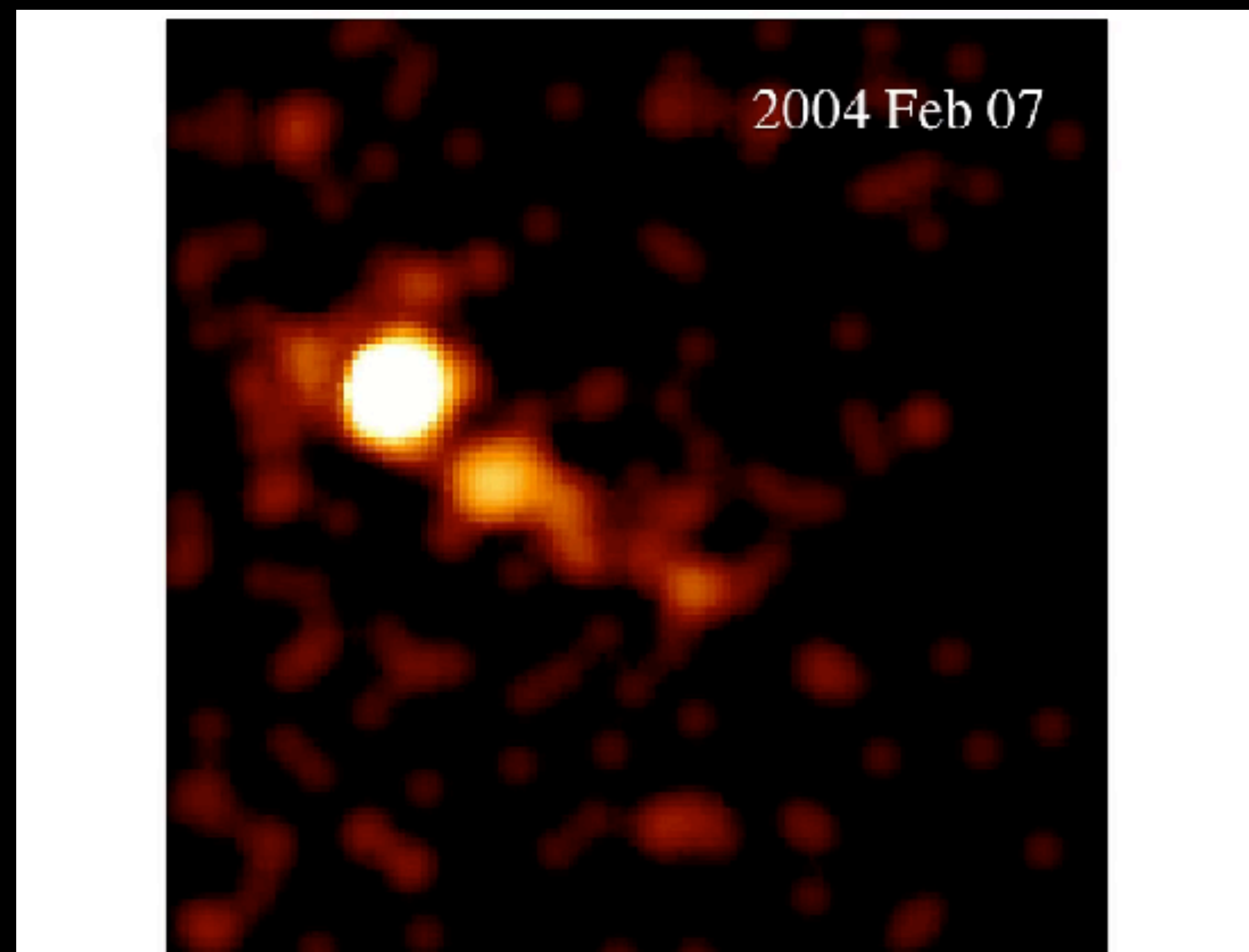




Hui et al. (2017a)

Fast X-ray variabilities of Geminga PWN

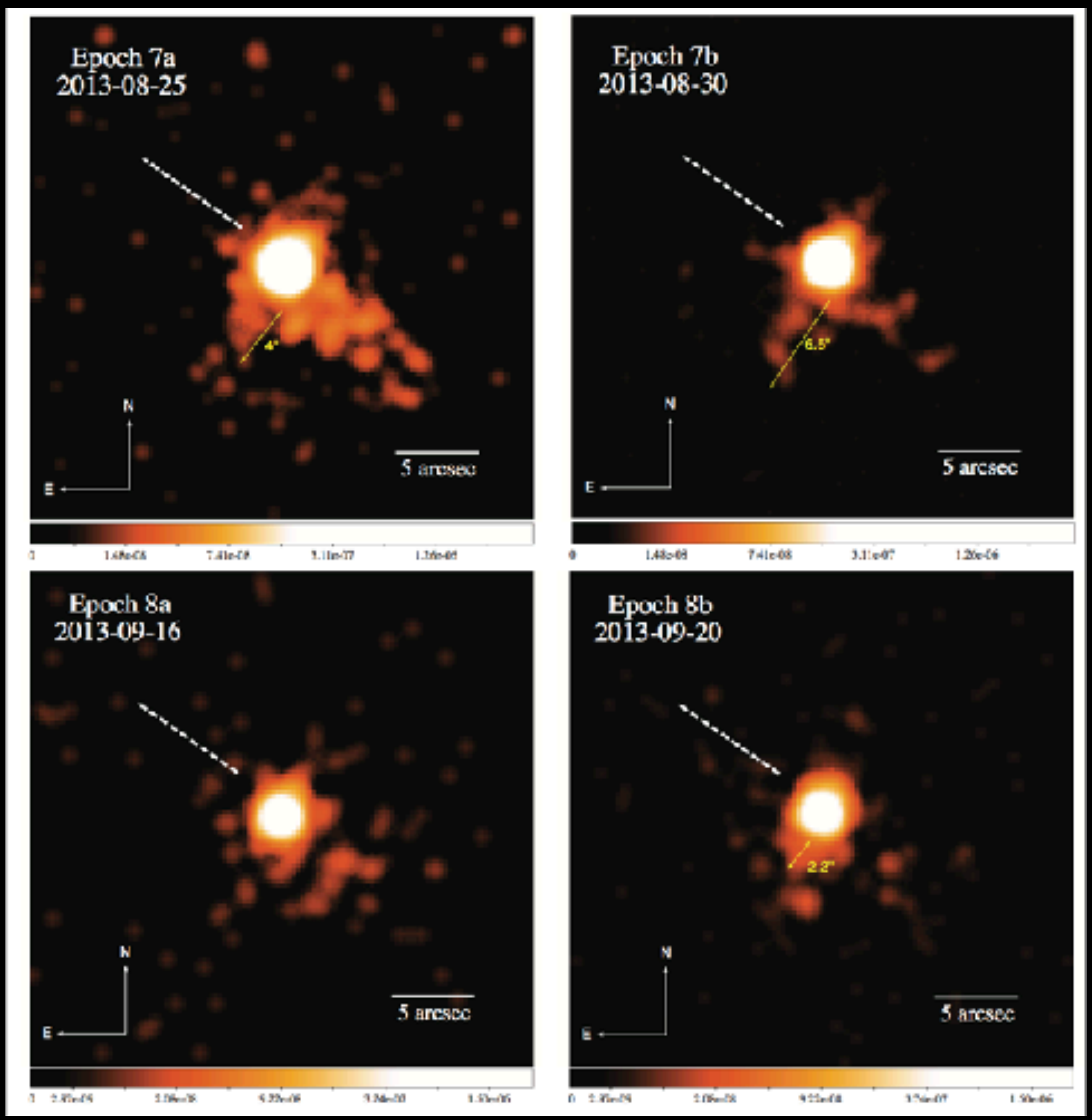


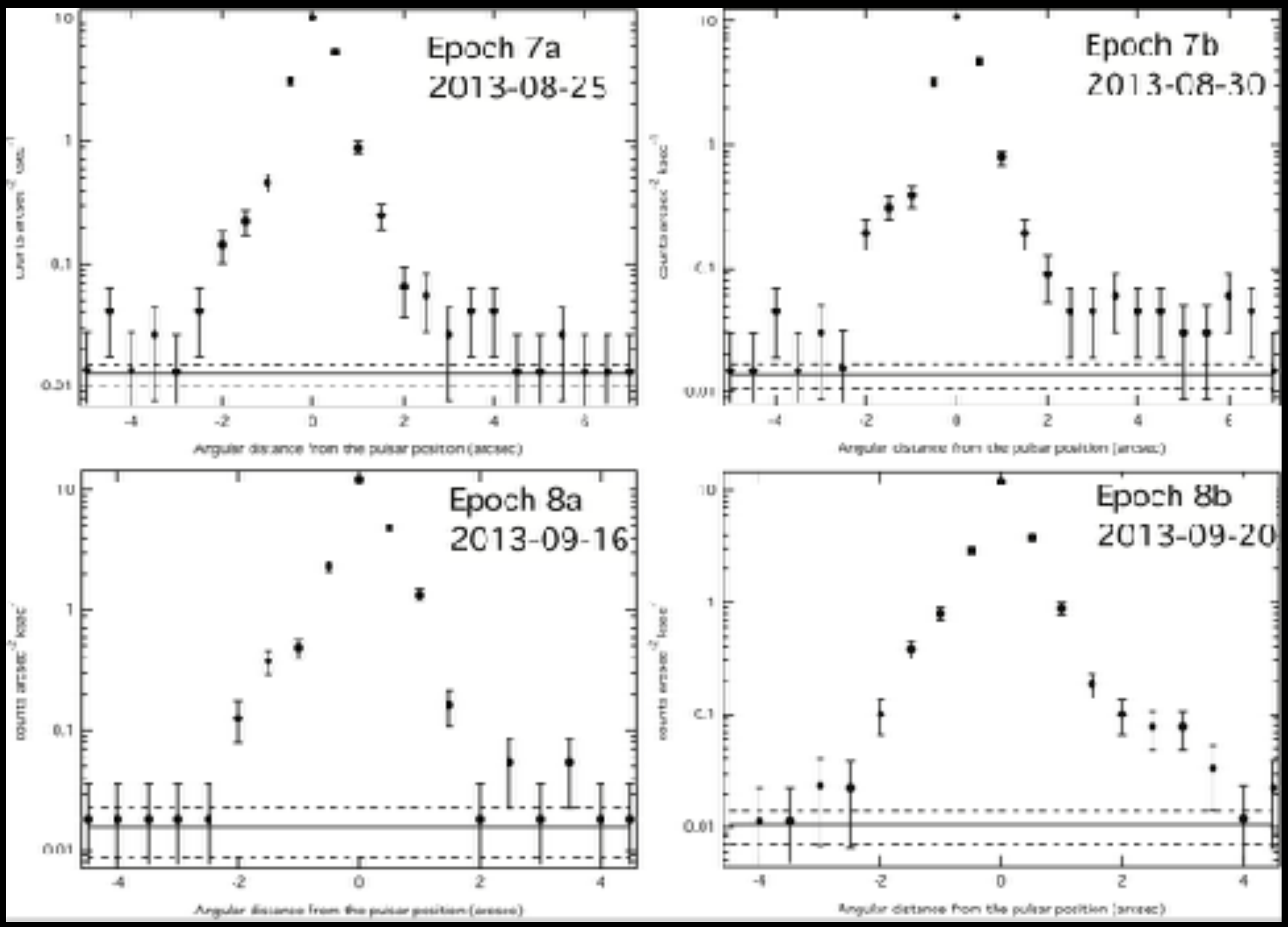


Hui et al. (2017a)

Fast X-ray variabilities of Geminga PWN

Hui et al. (2017a)

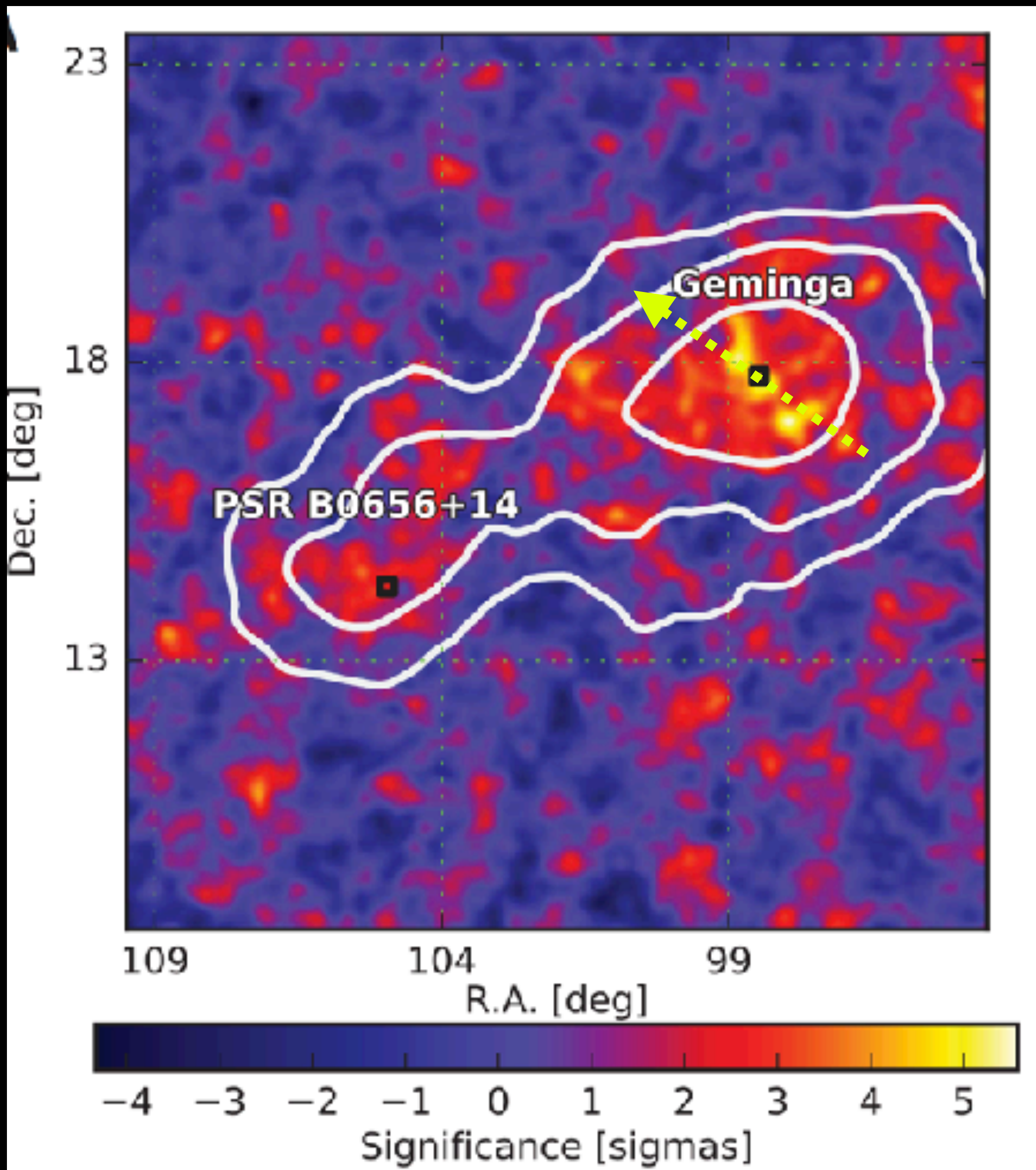




Variability occurred at ~0.8c.

The fastest X-ray variation in PWN observed!

TeV Emission from Geminga PWN



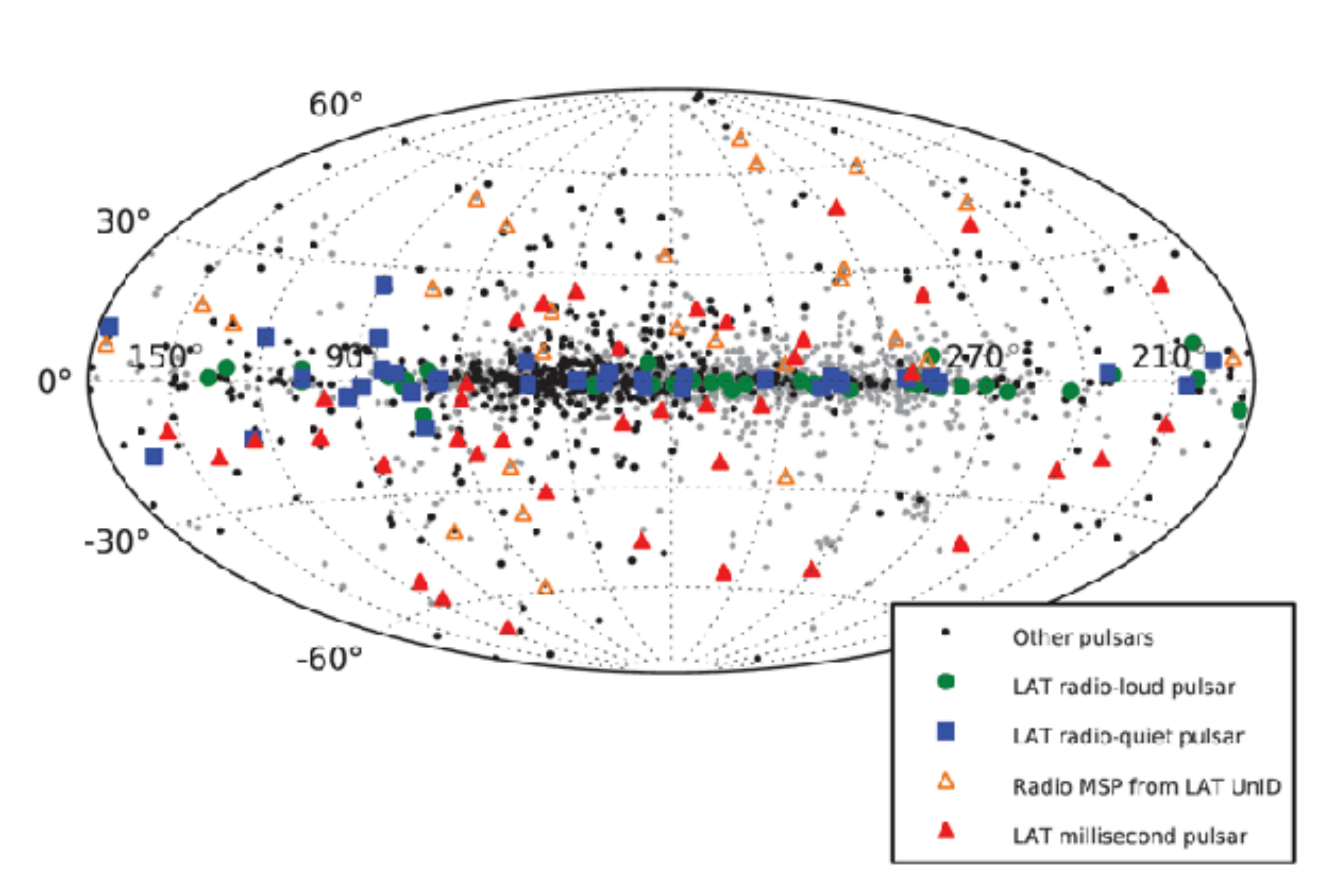
Abeysekara et al. (2017)

- **Extended TeV emission is detected by HAWC and Milagro.**
- **13 sigma in 1-50 TeV by HAWC.**
- **Spatial extent of ~few tens of pc.**

Questions for follow-up

- Align with proper motion?
- Counterpart in GeV?
- Variability?

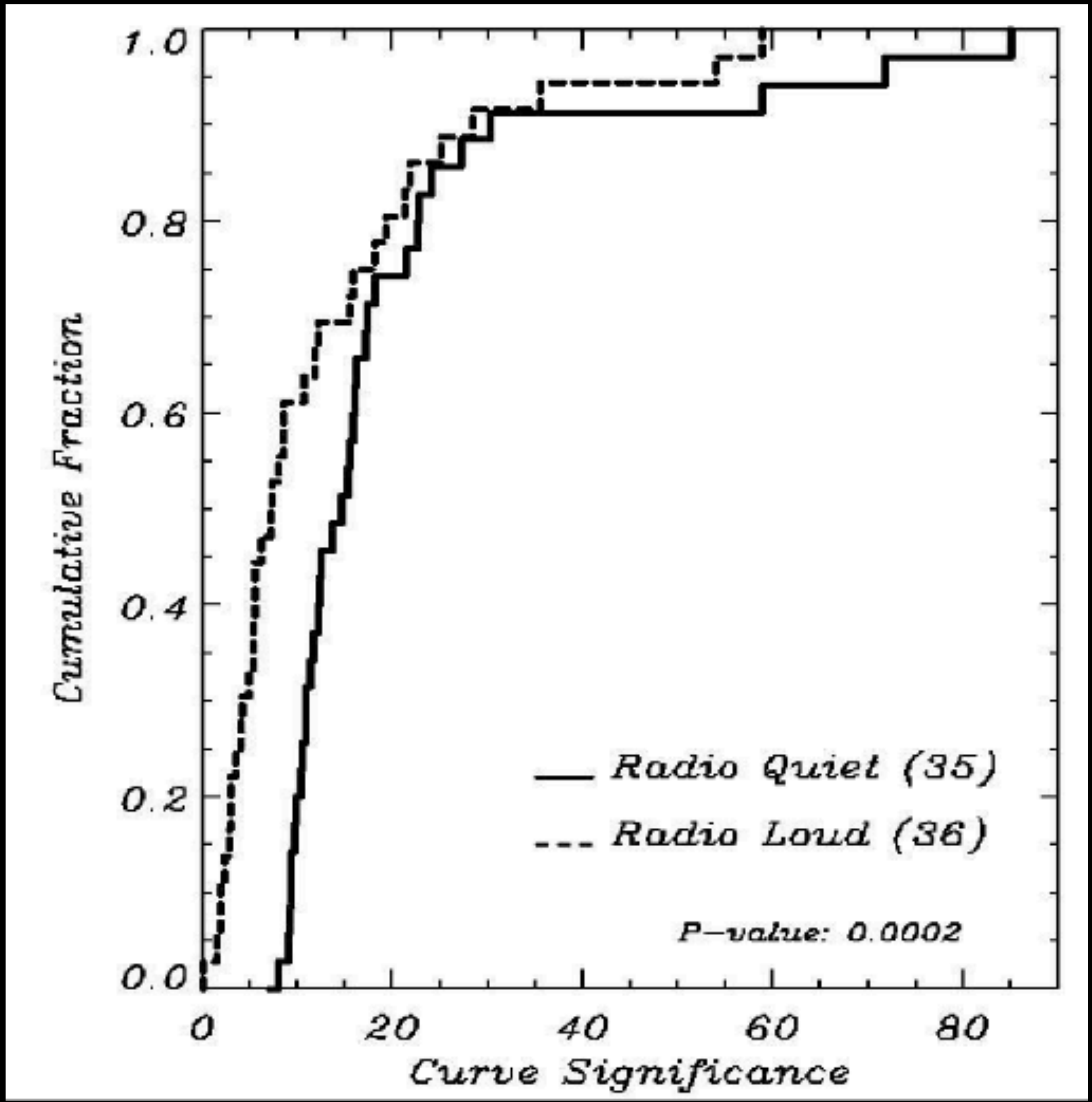
Differences between RQ and RL gamma-ray Pulsars



- In 2PC, there are 35 RQ PSRs and 42 non-recycled RL PSRs.
- Allow a meaningful statistical analysis.

Abdo et al. (2013)

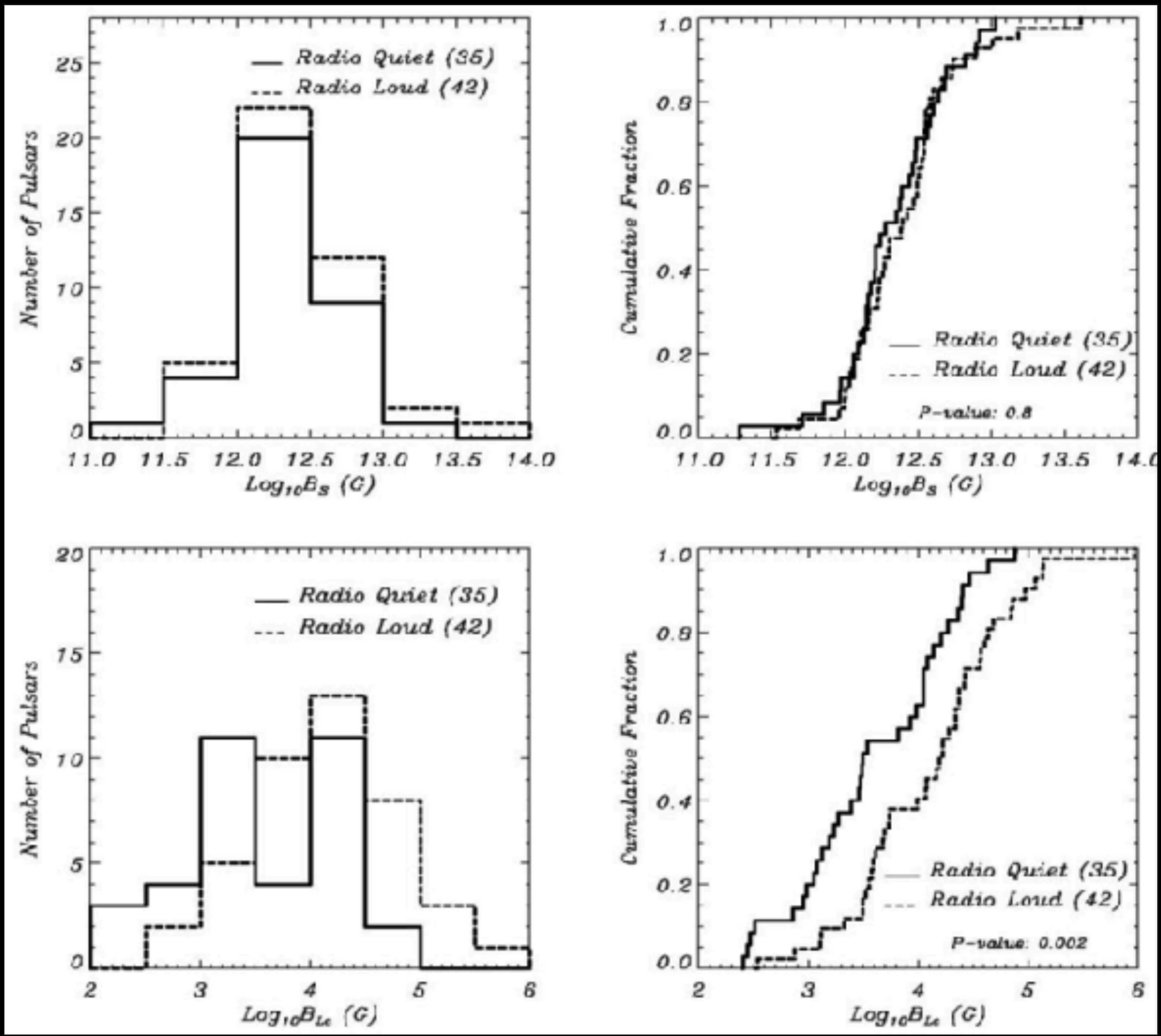
Differences between RQ and RL gamma-ray Pulsars



Hui et al. (2017b)

- **Spectral shape of RQ and RL gamma-ray PSRs are apparently different.**

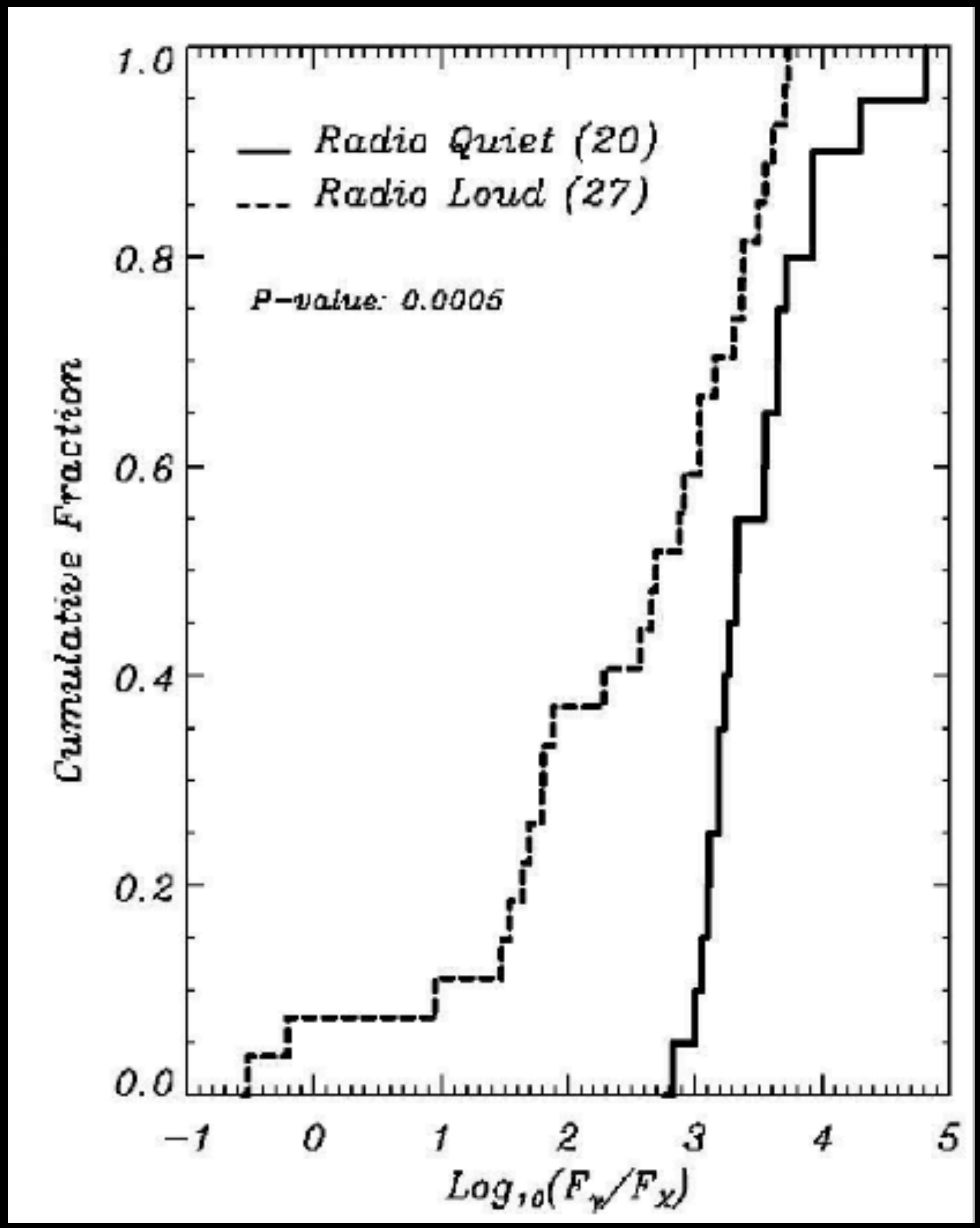
Differences between RQ and RL gamma-ray Pulsars



Hui et al. (2017b)

- **While the B-field at the stellar surfaces of RL and RQ PSRs are comparable,**
- **B-field at the light cylinder of these two populations are significant different.**

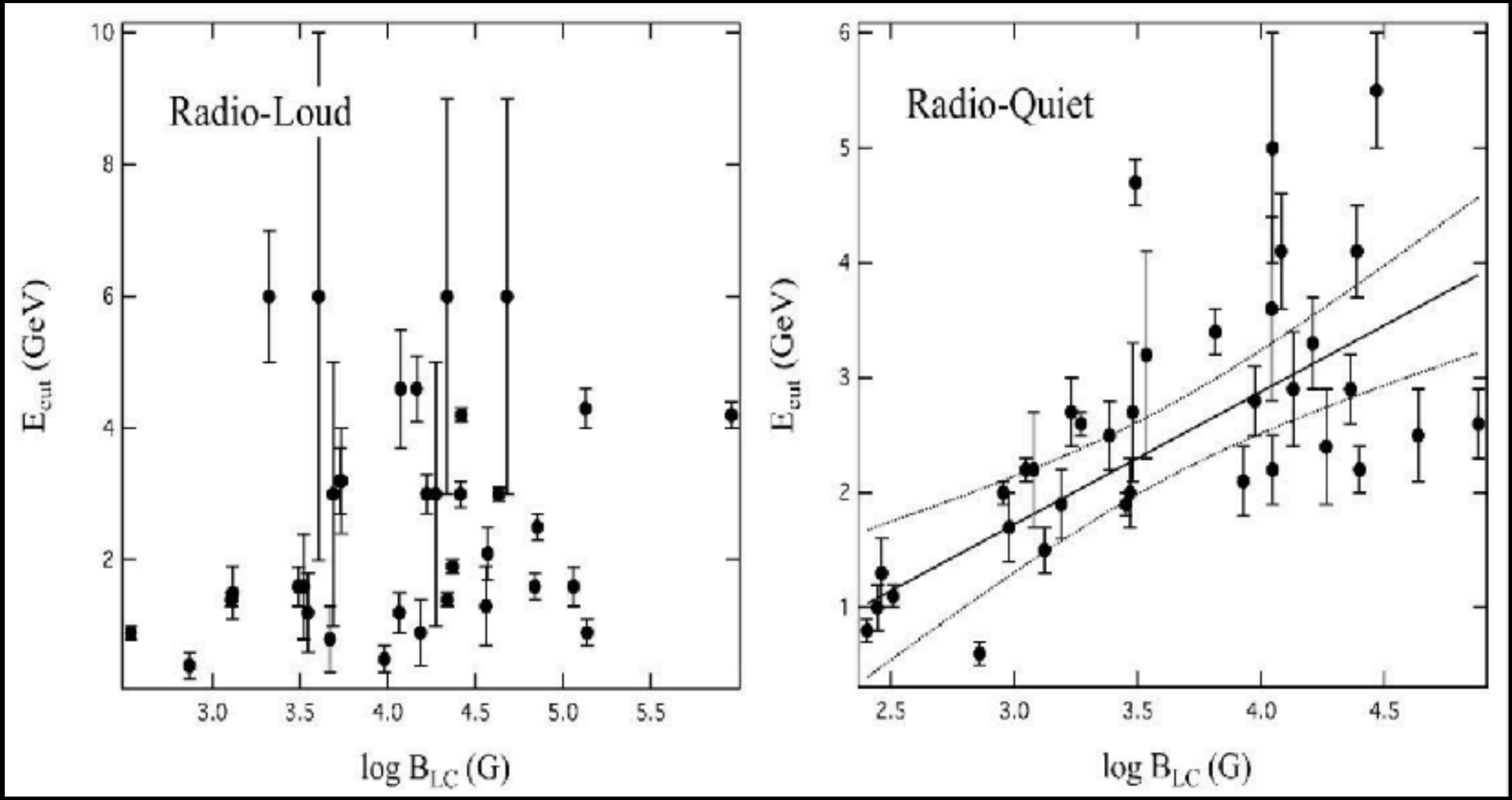
Differences between RQ and RL gamma-ray Pulsars



- **Gamma-ray to X-ray flux ratios of RQ gamma-ray PSRs are apparently higher.**

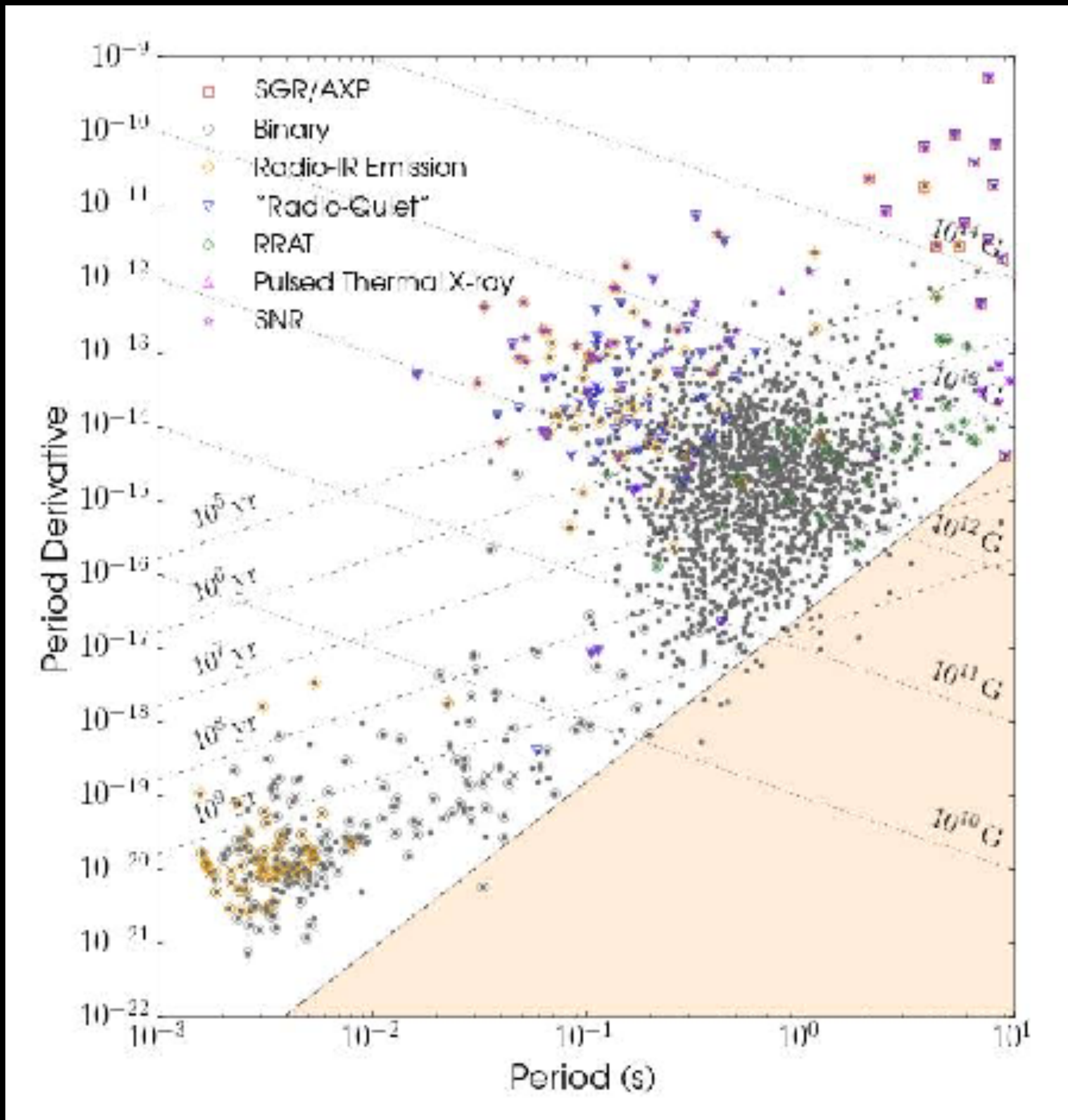
Hui et al. (2017b)

Differences between RQ and RL gamma-ray Pulsars

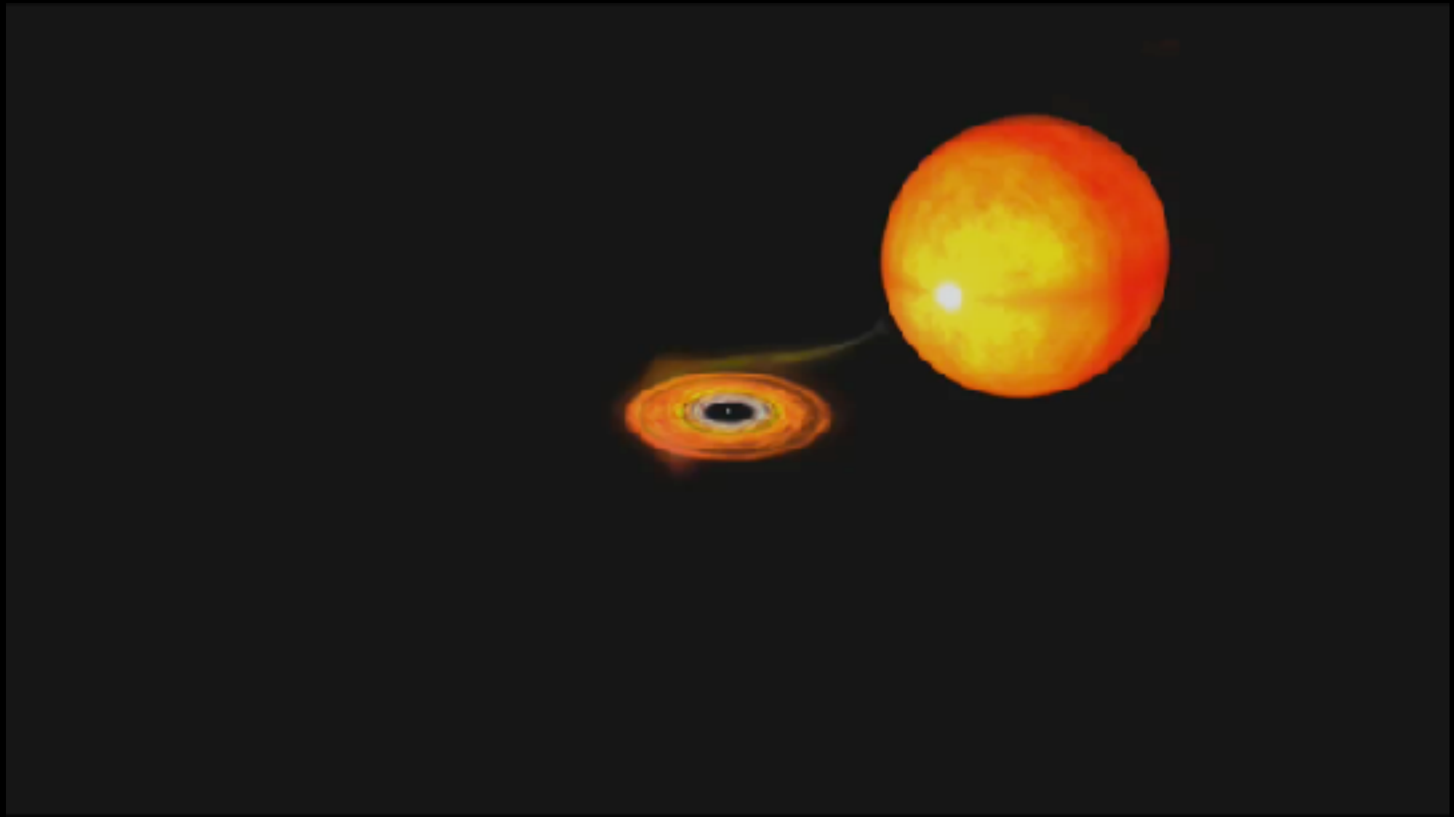


Hui et al. (2017b)

Millisecond Pulsars (MSPs)



Source: ATNF Pulsar Catalog



Animation courtesy: CXC

Zoo of MSPs

- **Black Widows** ($P<20$ hrs, $M_c < 0.05\ M_{sun}$)
- **Redbacks** ($P<20$ hrs, $M_c \sim 0.2\text{-}0.4\ M_{sun}$)
- **Isolated MSPs**
- **Wide-Orbit MSP/WD binaries**
- **MSP-Planet binary**

Black Widows

Animation courtesy: FSSC

letters to nature

Nature **333**, 237 - 239 (19 May 1988); doi:10.1038/333237a0

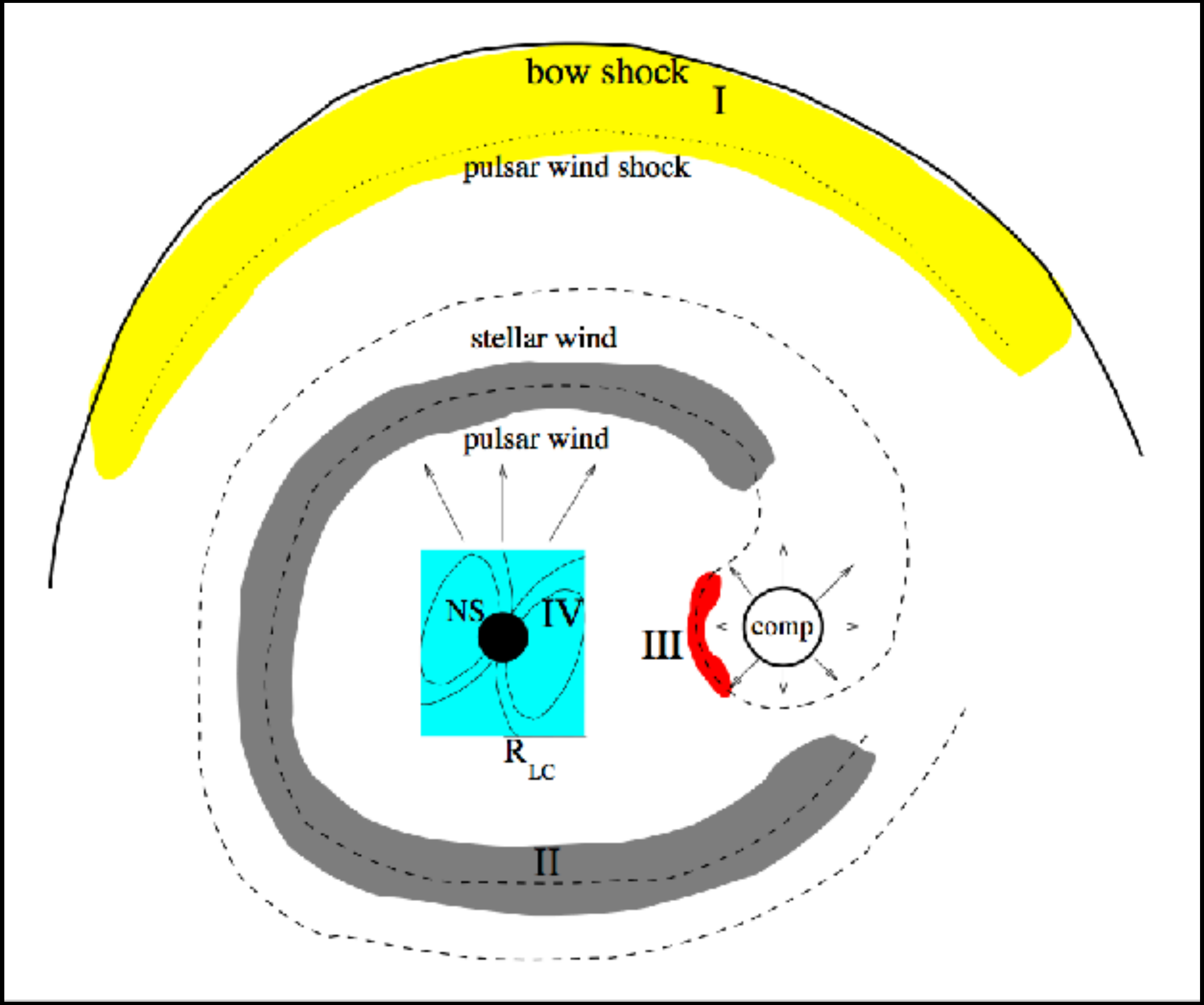
A millisecond pulsar in an eclipsing binary

A. S. FRUCHTER, D. R. STINEBRING & J. H. TAYLOR

Joseph Henry Laboratories and Physics Department, Princeton University, Princeton, New Jersey 08544, USA

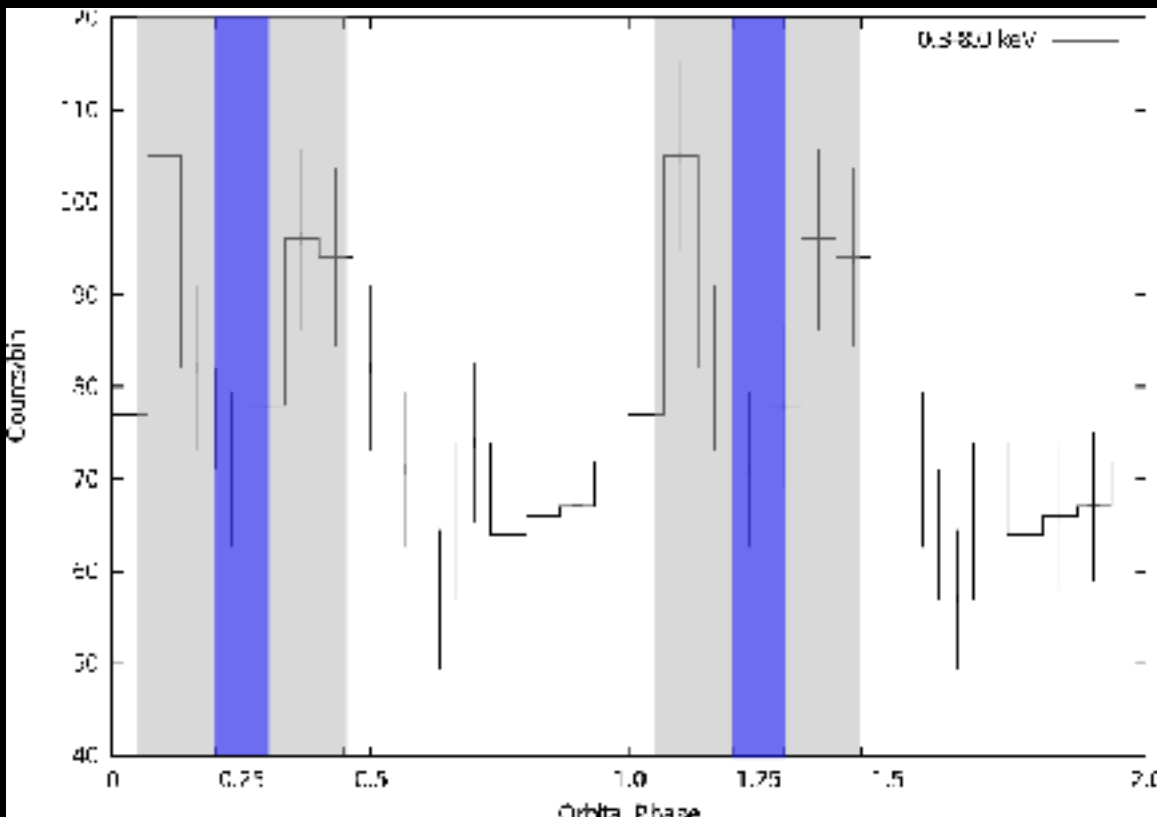
We have discovered a remarkable pulsar with period 1.6 ms, moving in a nearly circular 9.17-h orbit around a low-mass companion star. At an observing frequency of 430 MHz, the pulsar, PSR1957 + 20, is eclipsed once each orbit for about 50 minutes. For a few minutes before an eclipse becomes complete, and for more than 20 minutes after the signal reappears, the pulses are delayed by as much as several hundred microseconds—presumably as a result of propagation through plasma surrounding the companion. The pulsar's orbit about the system barycentre has a radius of 0.089 light seconds projected on to the line of sight. The observed orbital period and size, together with the fact that eclipses occur, imply a surprisingly low companion mass, only a few per cent of the mass of the Sun.

Black Widows

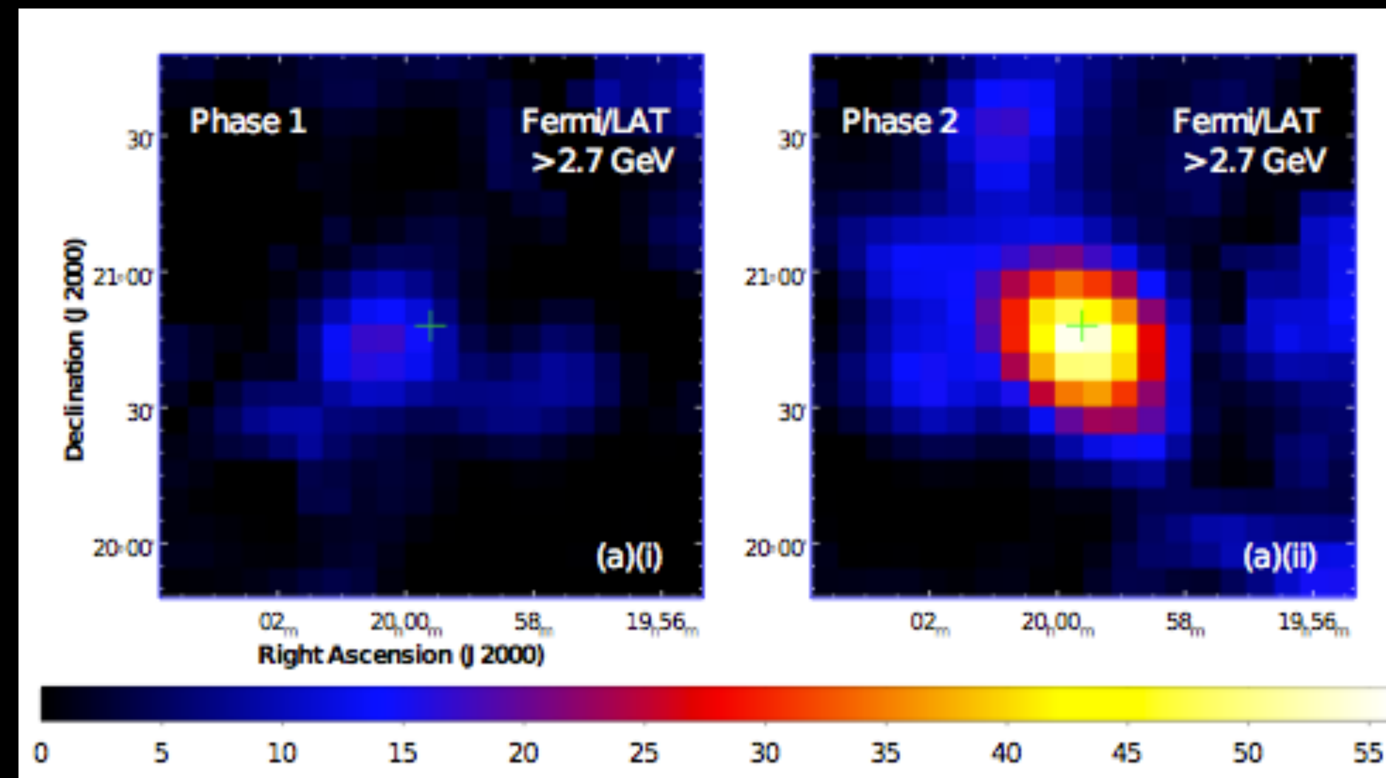


Ahnen et al. (2017)

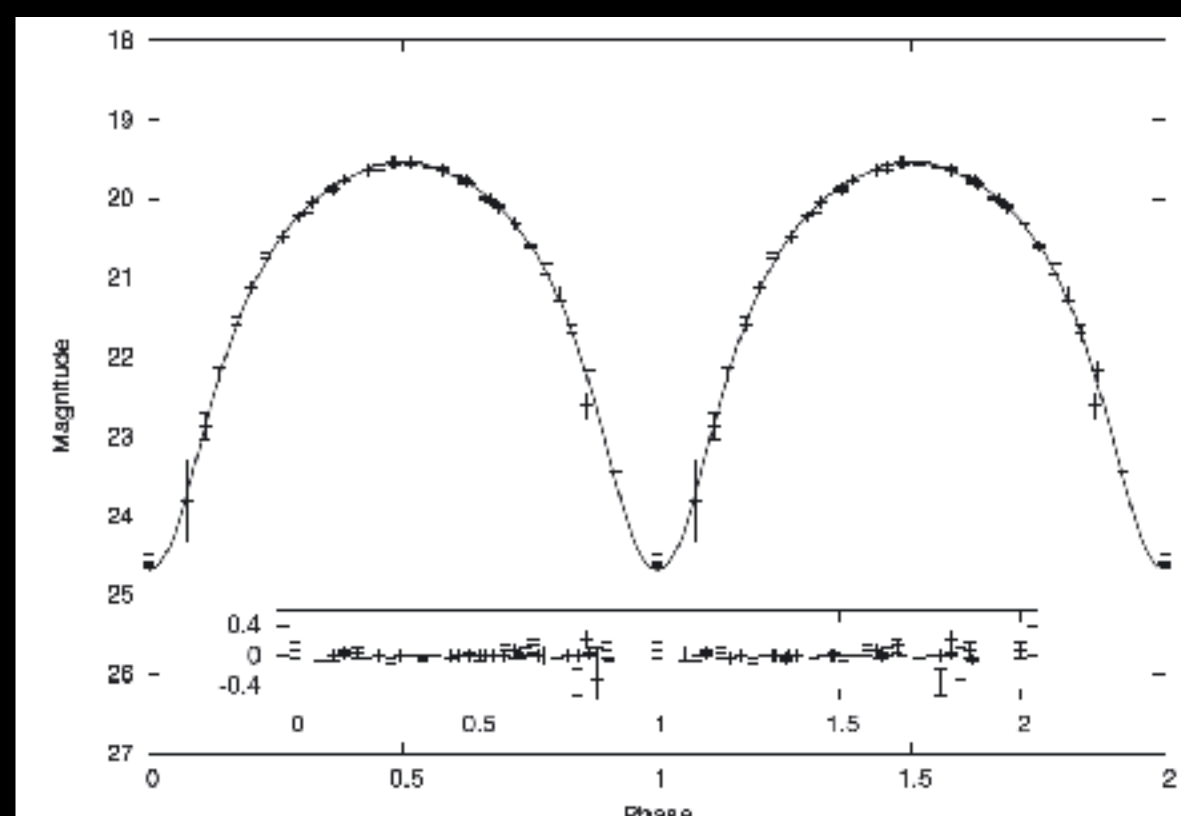
Intrabinary Shock of Black Widow



Huang et al. (2012)

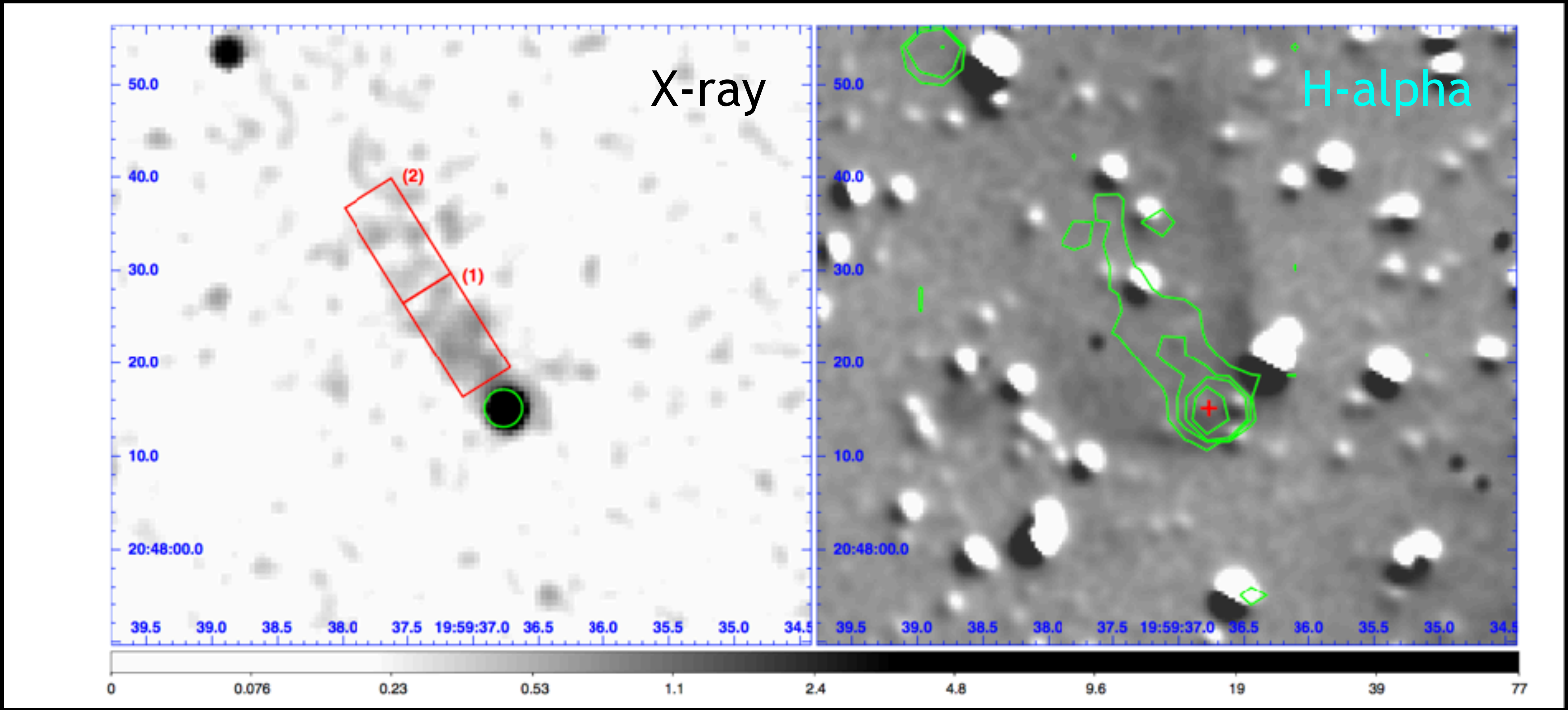


Wu et al. (2012)



Reynold et al. (2007)

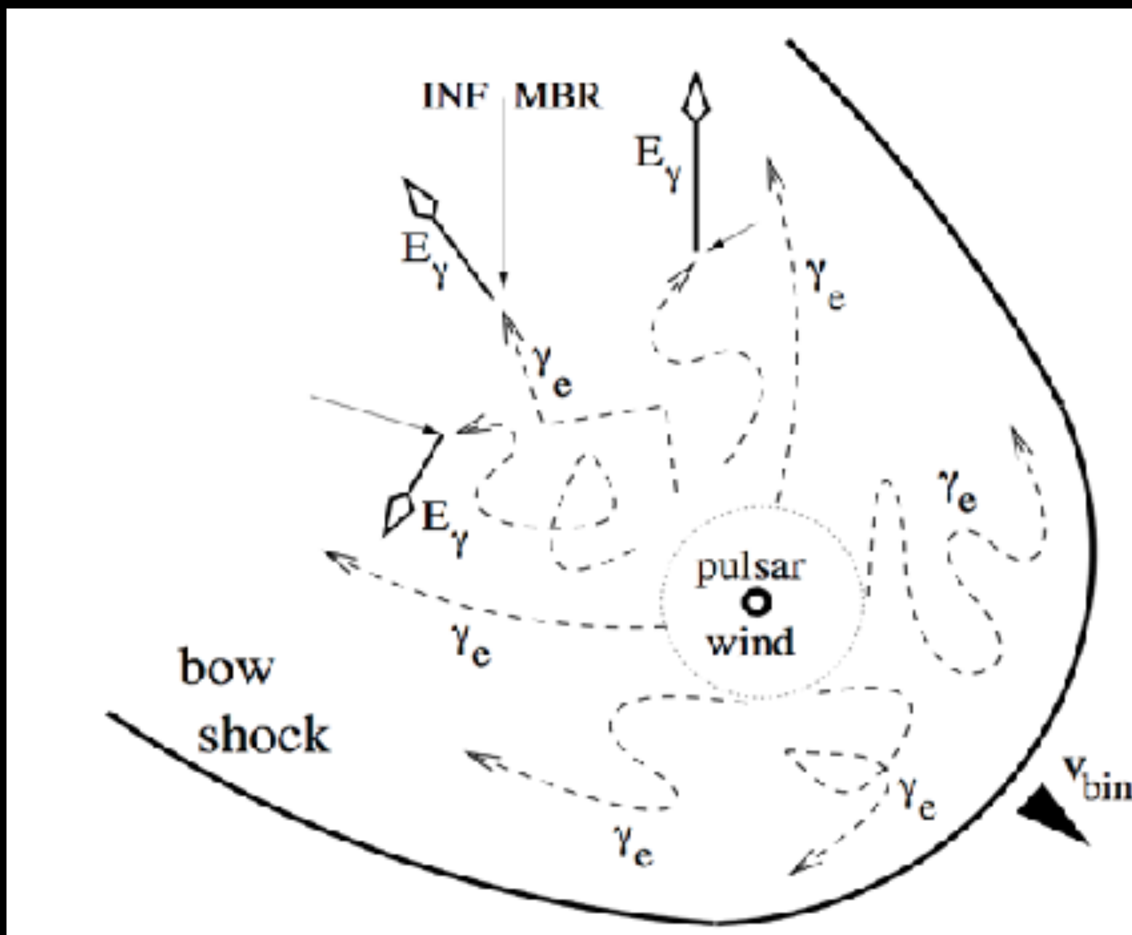
Bow Shock of Black Widow

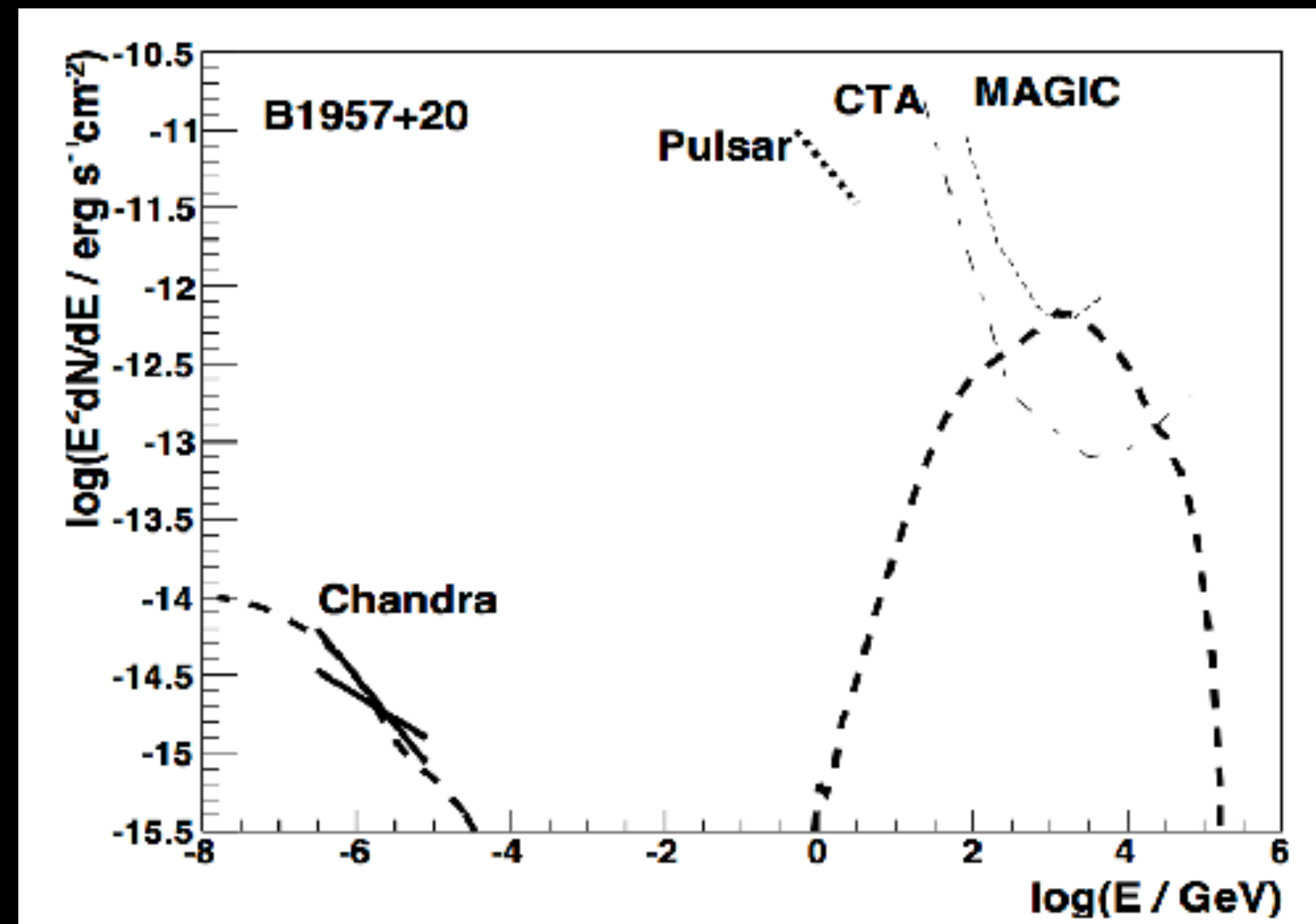


Huang et al. (2012)

VHE Emission from Black Widow Bowshock?

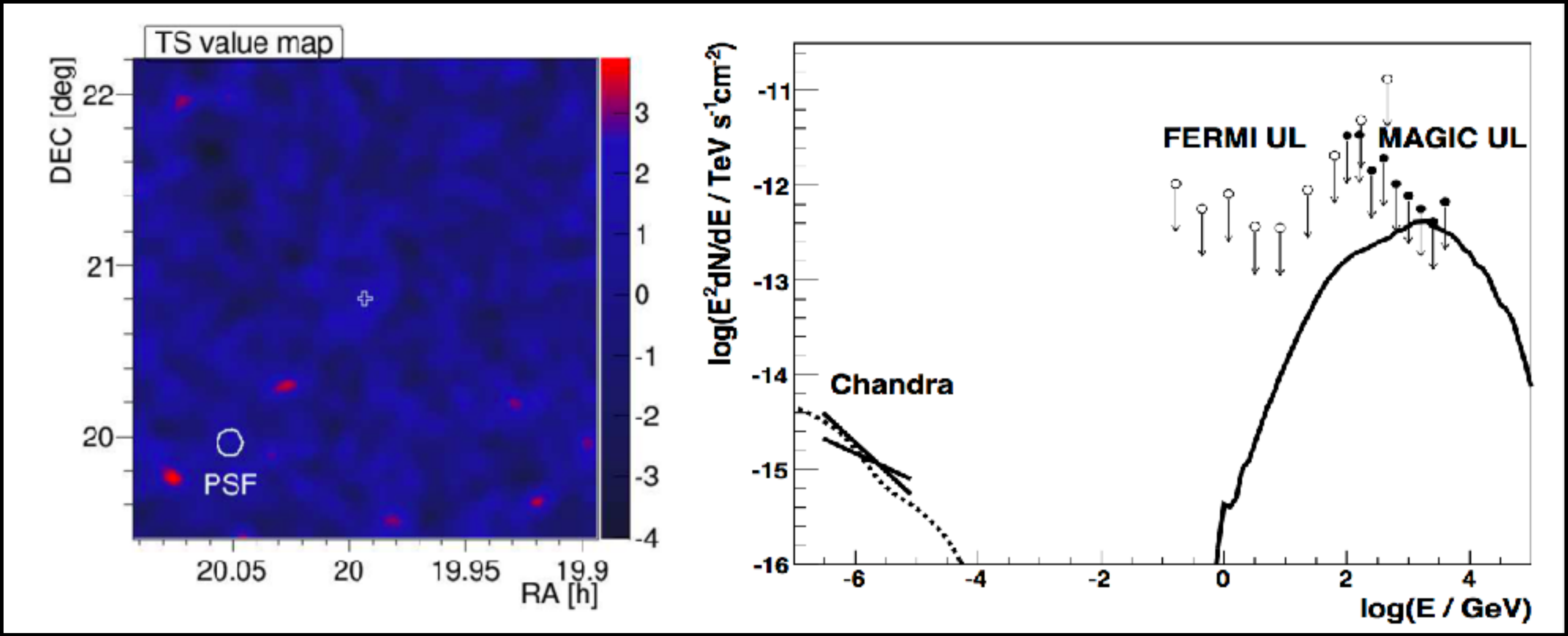
X-ray observations put strong constraints on the IC model





Bednarek & Sitarek (2013)

VHE Emission from Black Widow Bowshock?



Ahnen et al. (2017)

Redback

Animation courtesy: FSSC

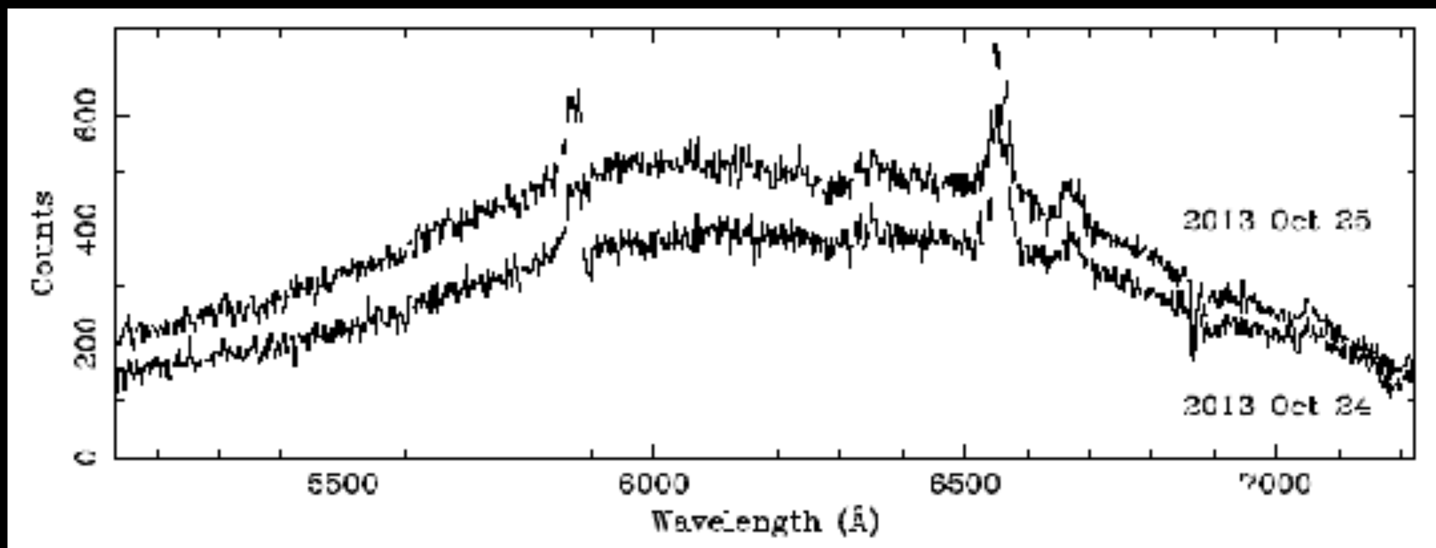
State-change in the "transition" binary millisecond pulsar J1023+0038

ATel #5513; *B. W. Stappers (University of Manchester), A. Archibald (ASTRON), C. Bassa (ASTRON), J. Hessels (ASTRON), G. Janssen (ASTRON), V. Kasp Lyne (University of Manchester), A. Patruno (University of Leidei Linear Accelerator Lab).*
on 25 Oct 2013; 18:32 UT
Distributed as an Instant Email Notice Transie
Credential Certification: Ben Stappers (ben.stappers@mai

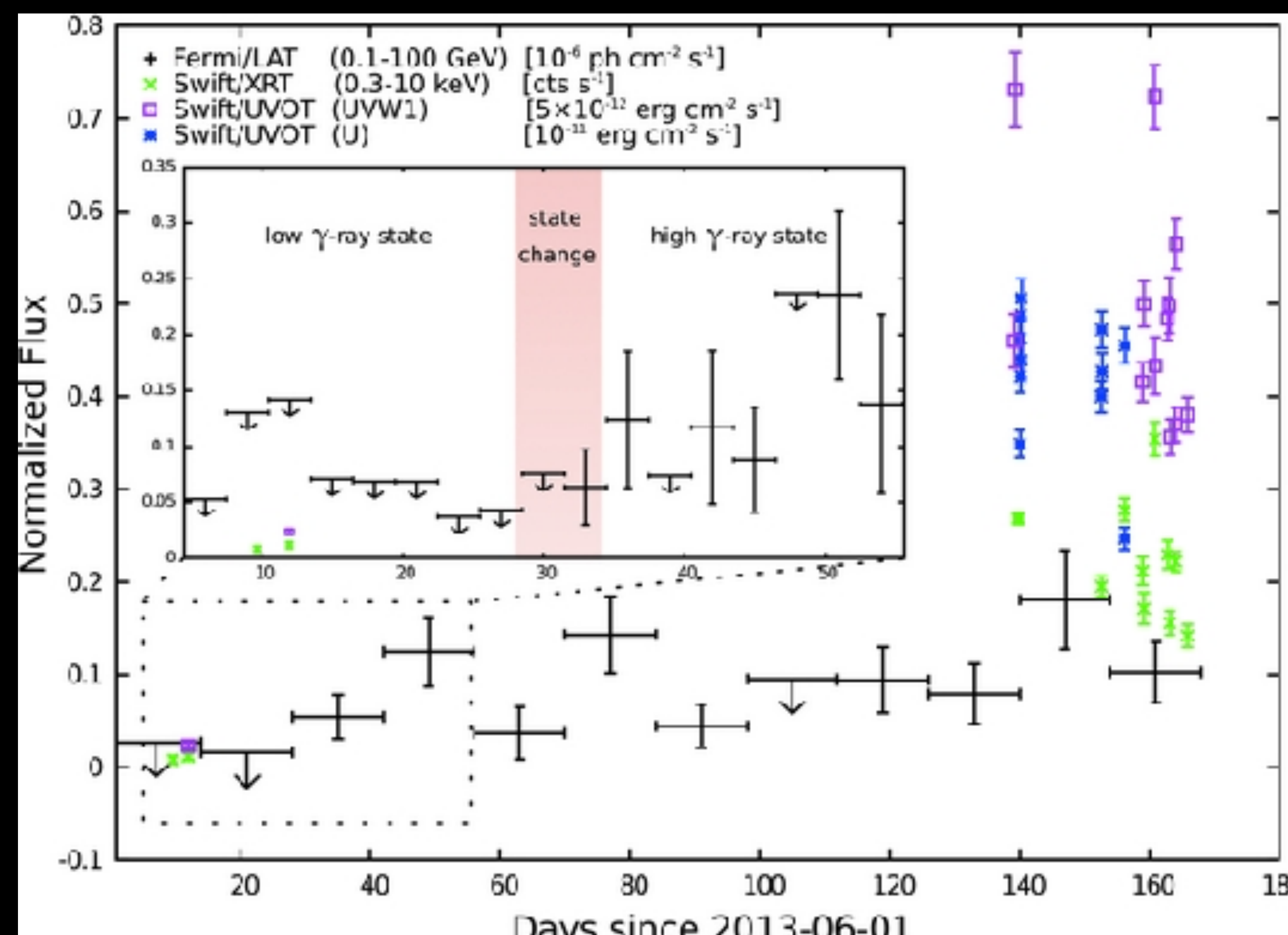
Optical Observations of the Binary MSP J1023+0038 in a New Accreting State

ATel #5514; *J. P. Halpern (Columbia U.), E. Gaidos (U. Hawaii Manoa), A. Sheffield, A. M. Price-Whelan, S. Bogdanov (Columbia U.)*
on 25 Oct 2013; 19:10 UT
Credential Certification: Jules Halpern (jules@astro.columbia.edu)

Redback



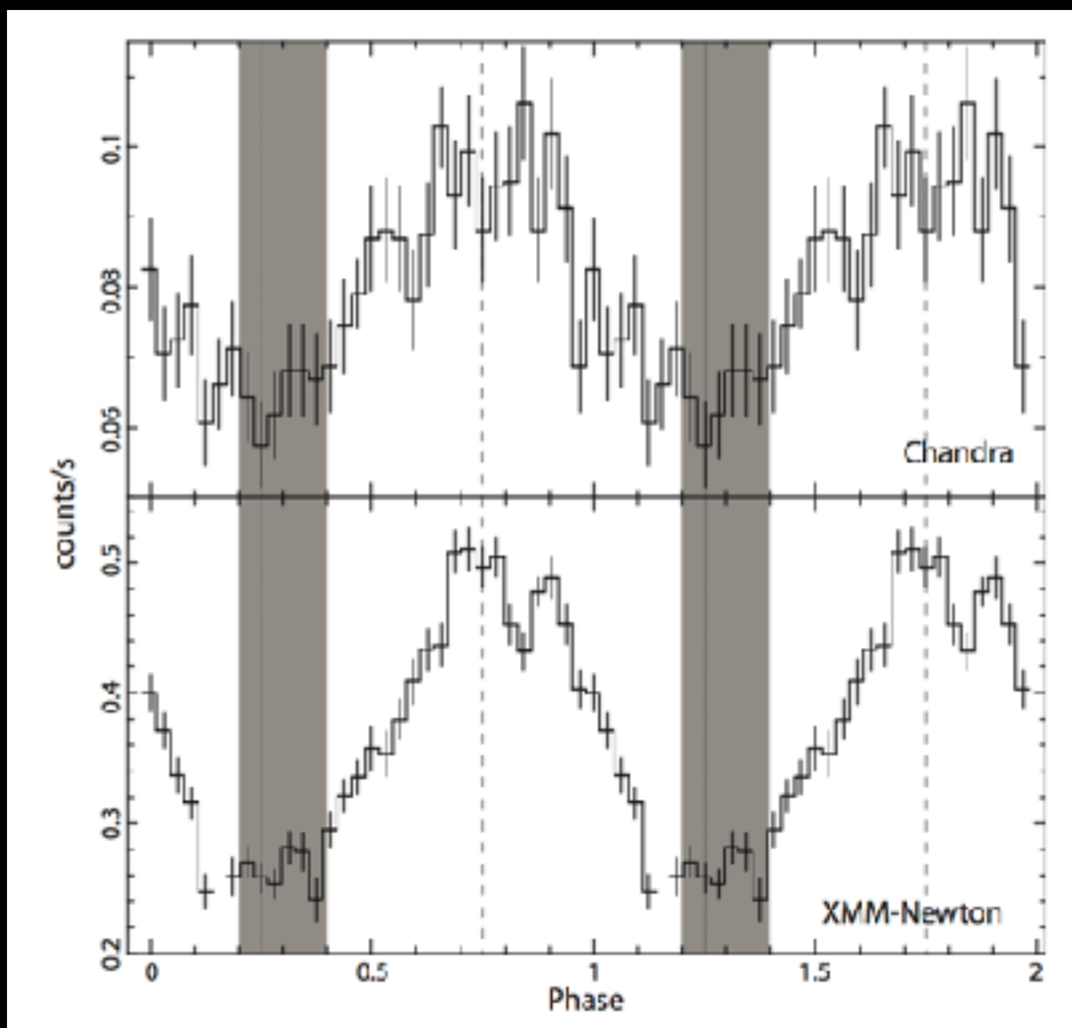
Halpern et al. (2013)



Takata et al. (2014)

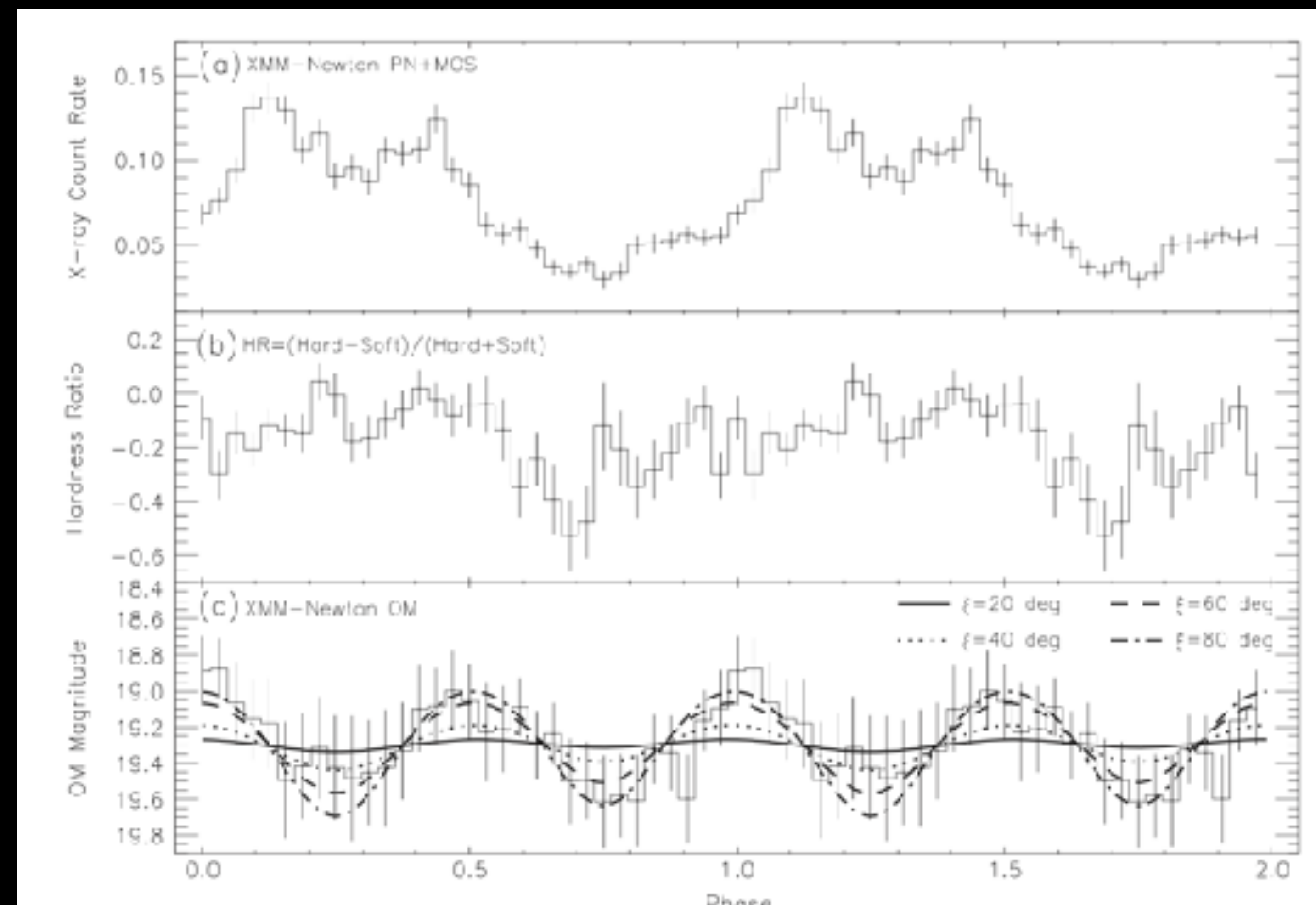
Intrabinary Shock from Redbacks

PSR J1723−2837



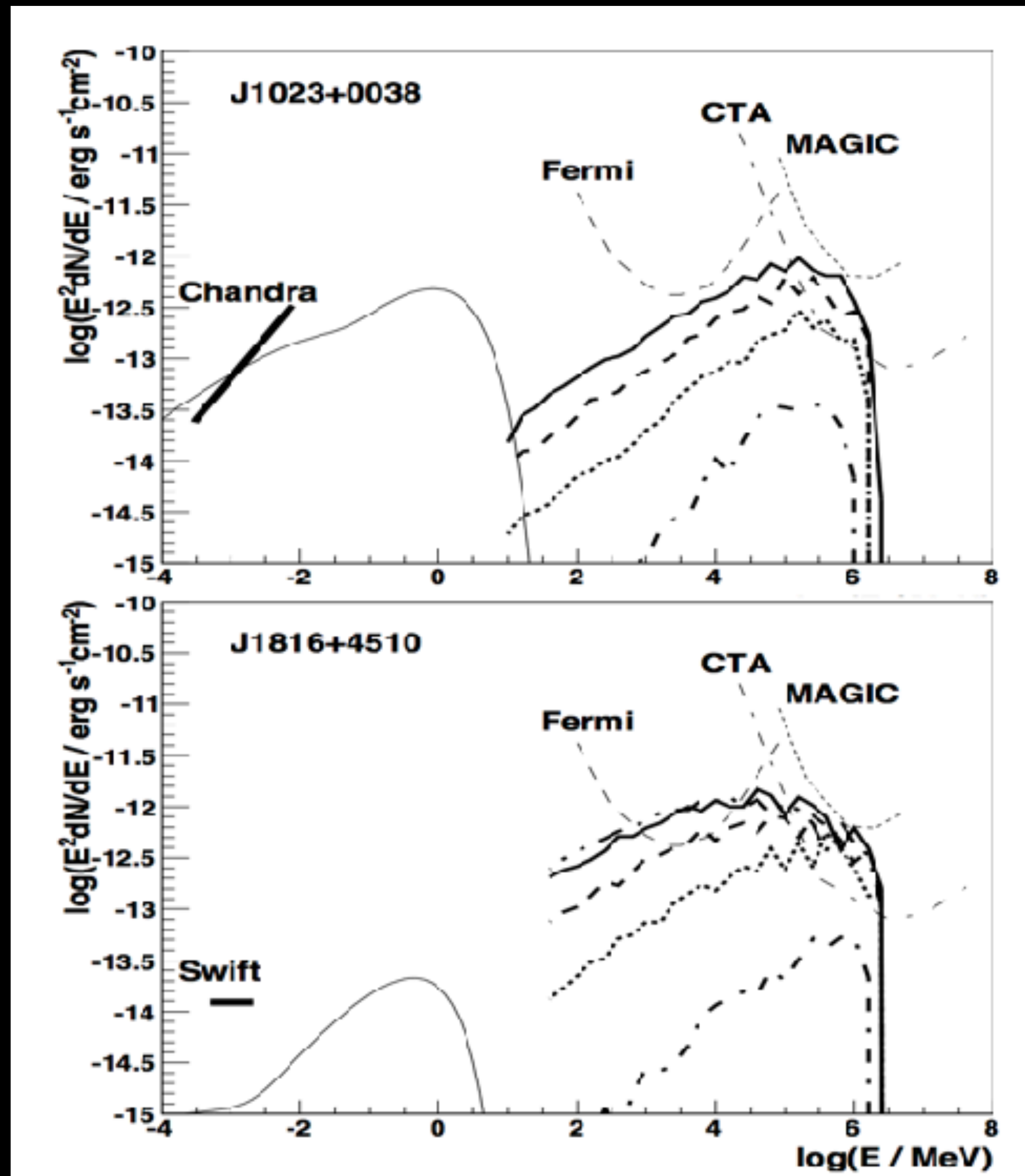
Hui et al. (2014)

PSR J2129-0429



Hui et al. (2015a)

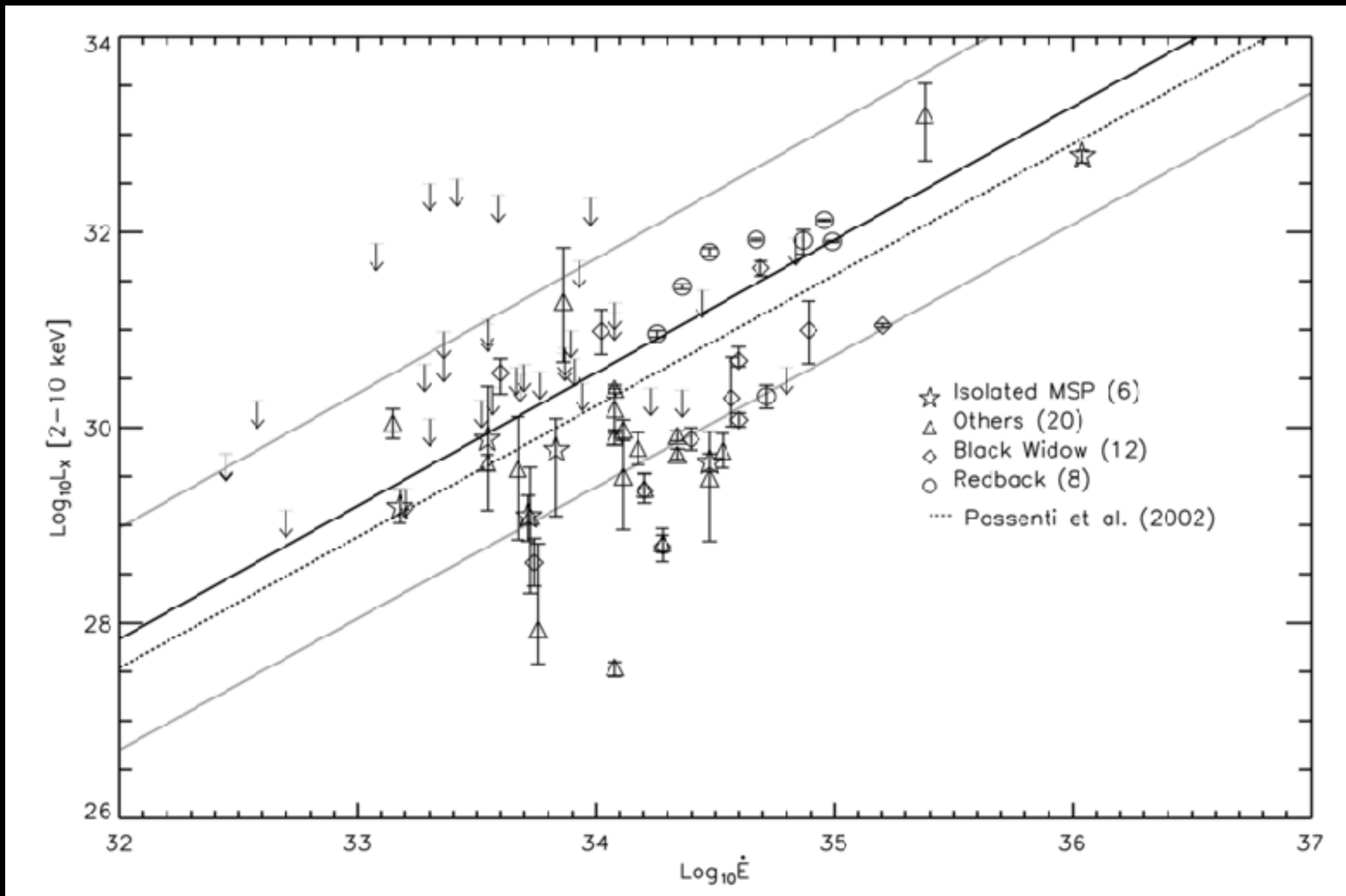
VHE Emission from Redback PW?



Bednarek (2014)

X-ray Luminosities of MSPs

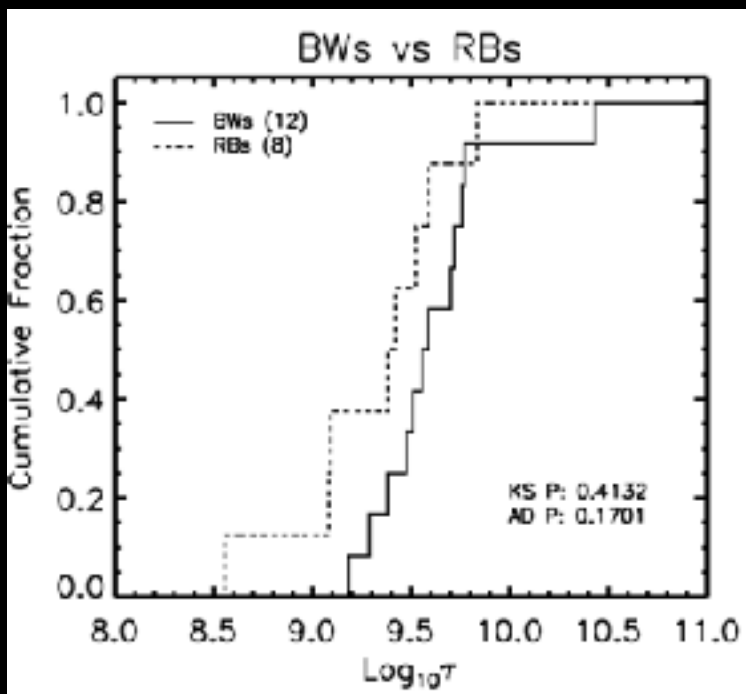
X-ray conversion efficiencies of MSP are comparable with non-recycled PSRs

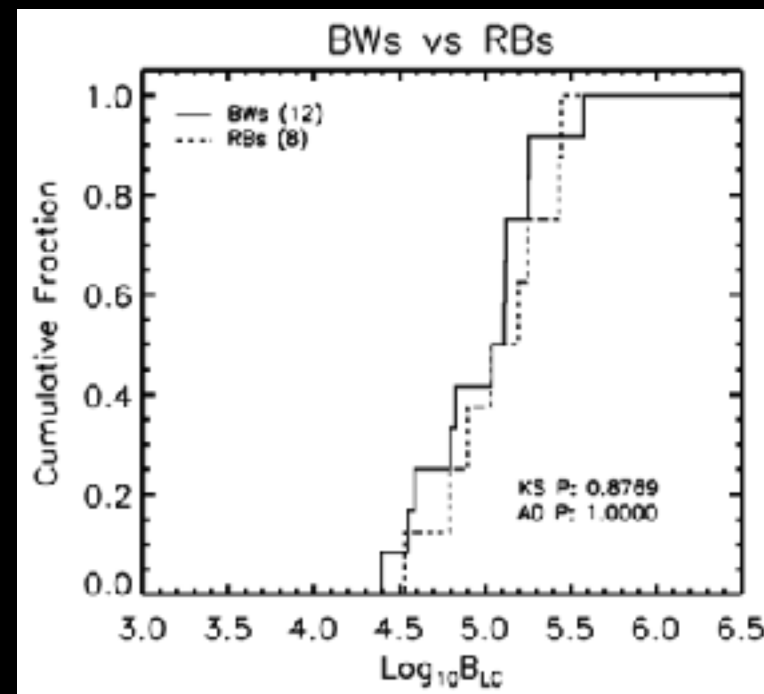


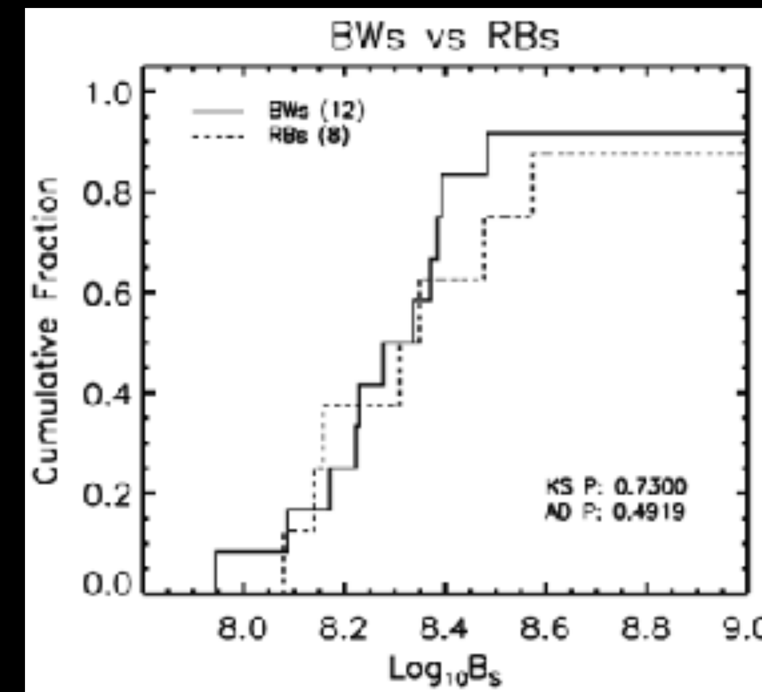
Lee et al. submitted

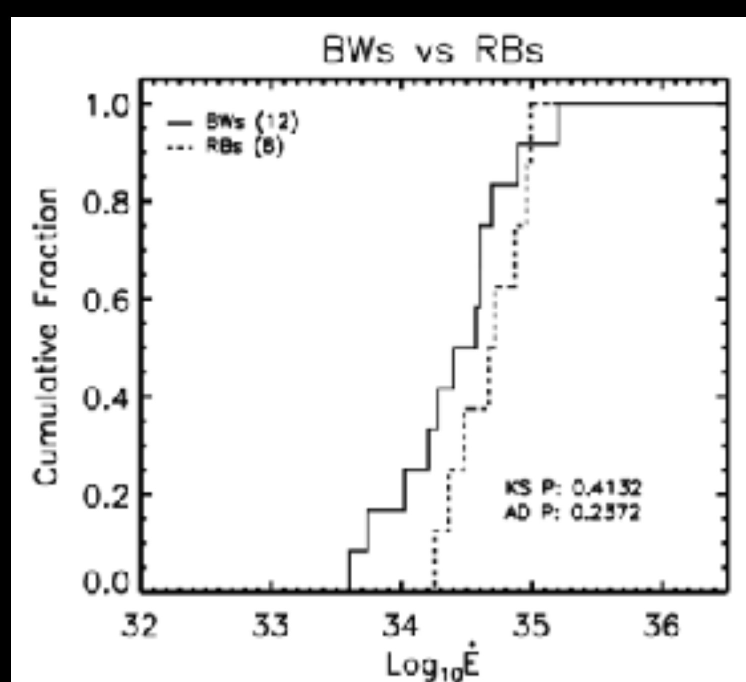
Redbacks vs Black Widows

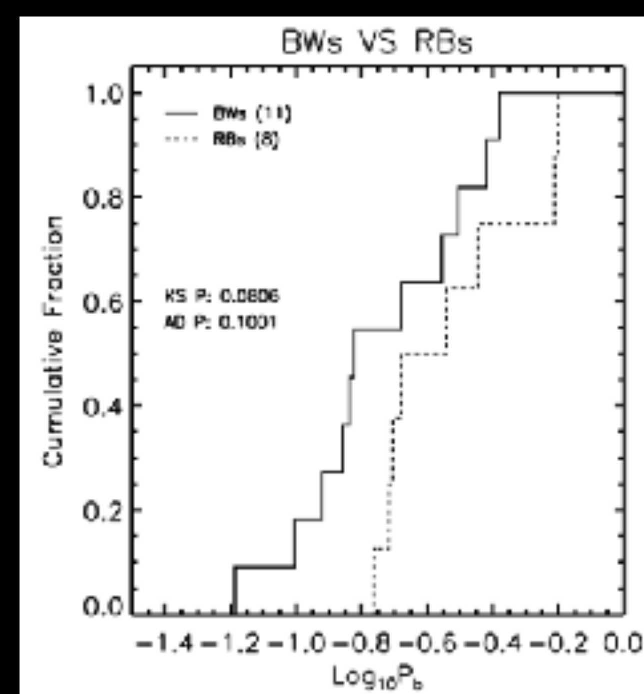
Rotational and orbital parameters of RBs and BWs are comparable.







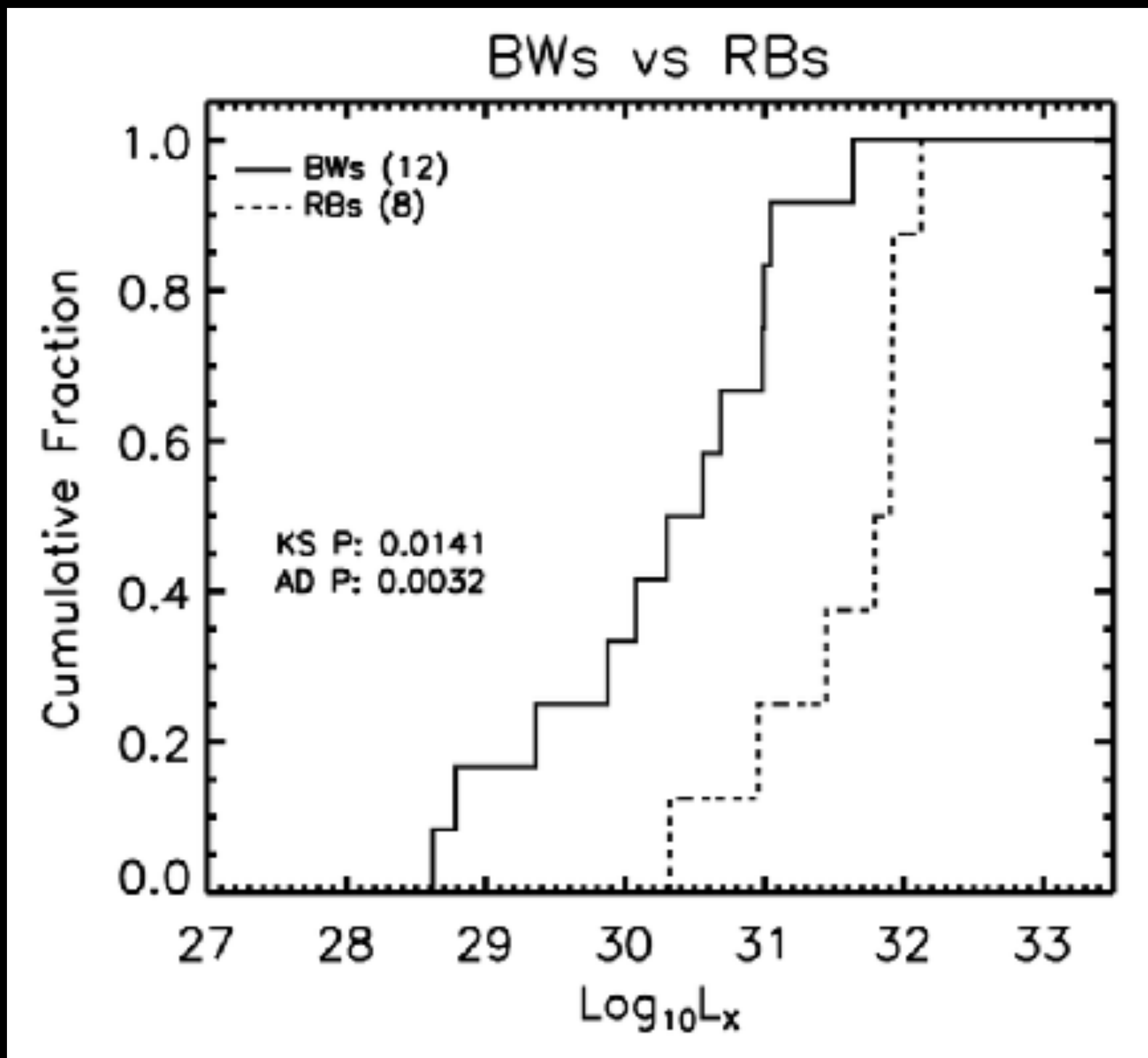


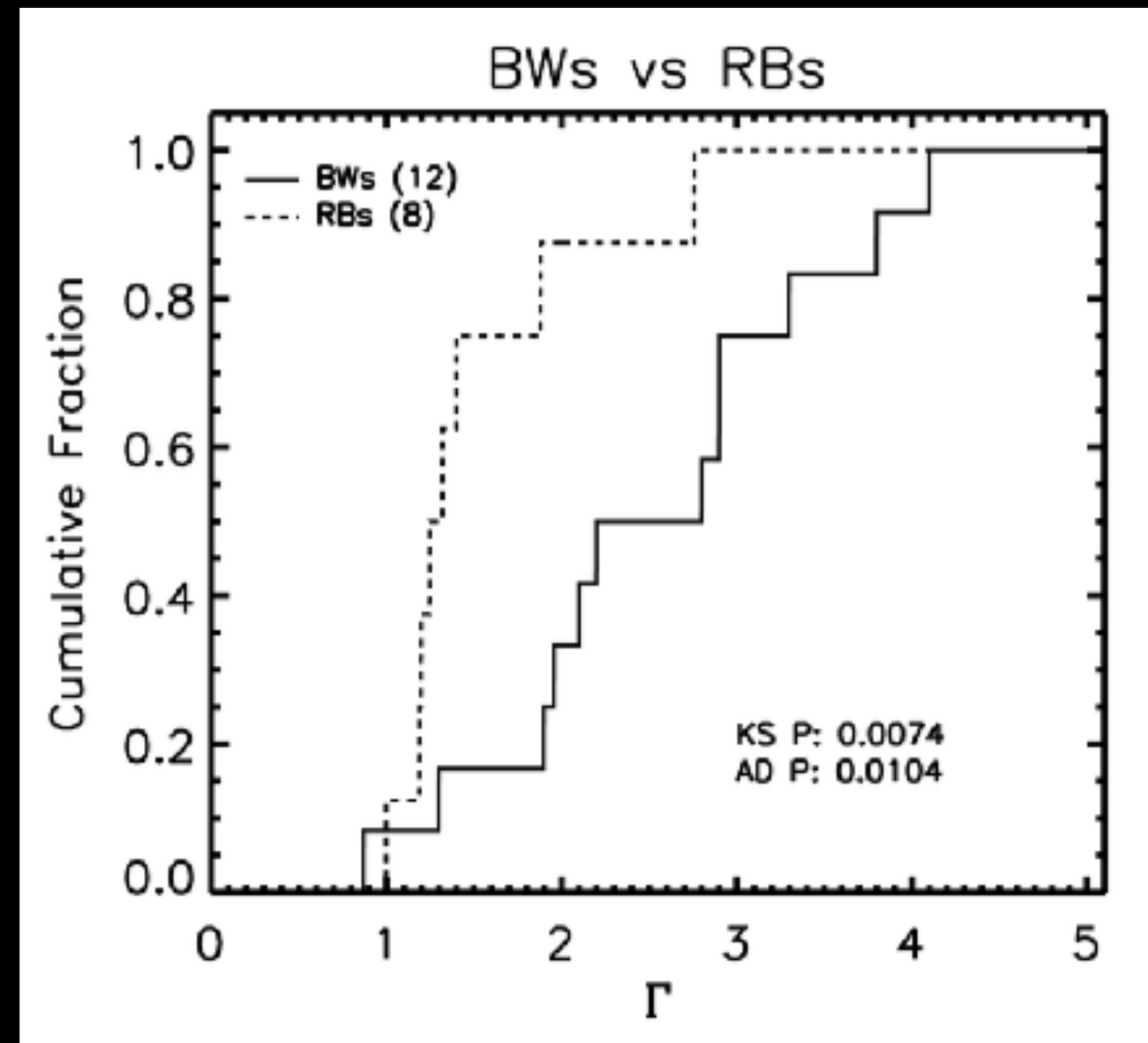


Lee et al. submitted

Redback vs Black Widows

X-ray emission of RBs are stronger and harder than BWs.





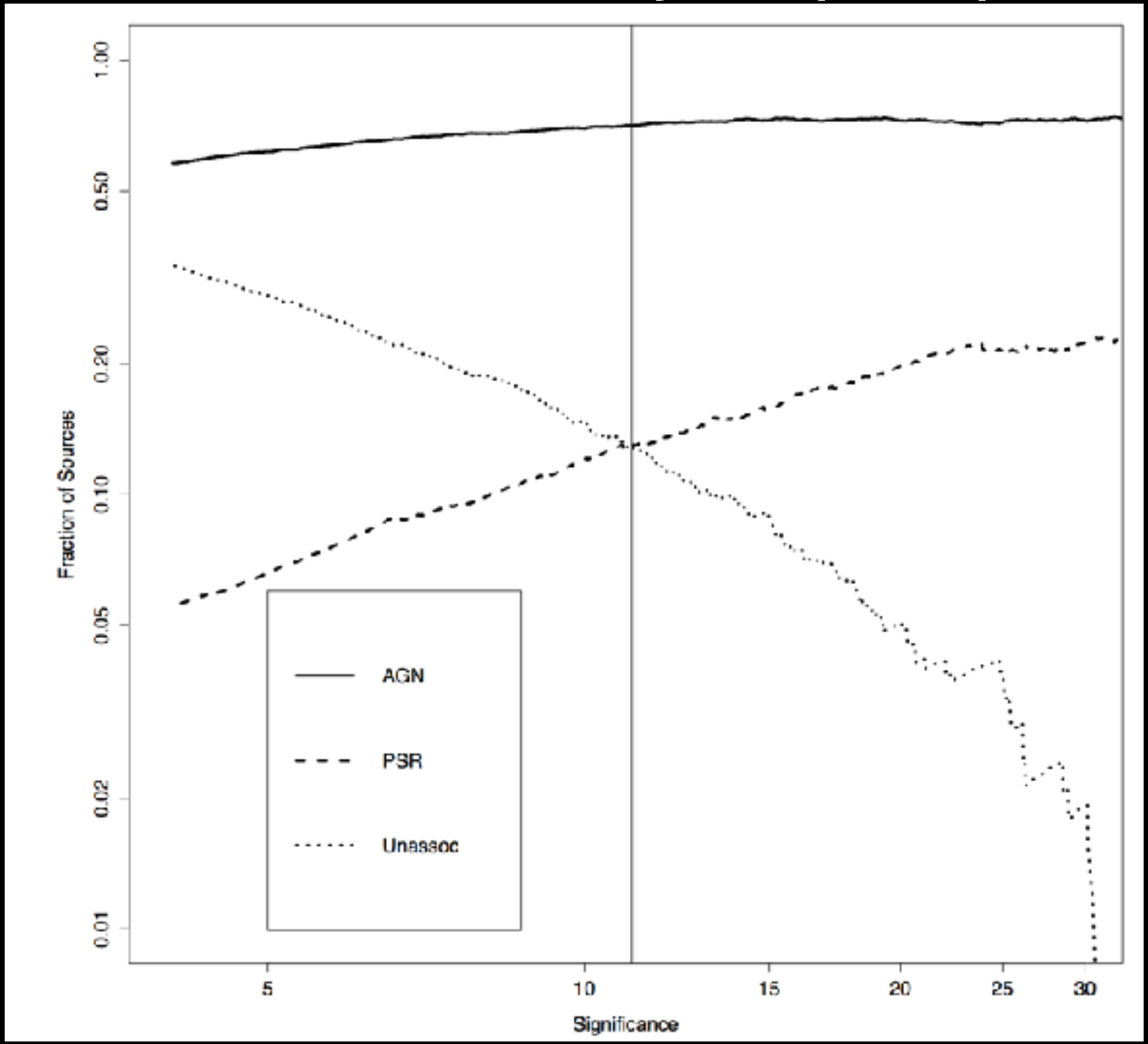
Lee et al. submitted

With these updated X-ray results, we can refine the feasibility of observing RB/BW with CTA.

Why the population of MSPs expands considerably?

Treasure Hunting in UFOs

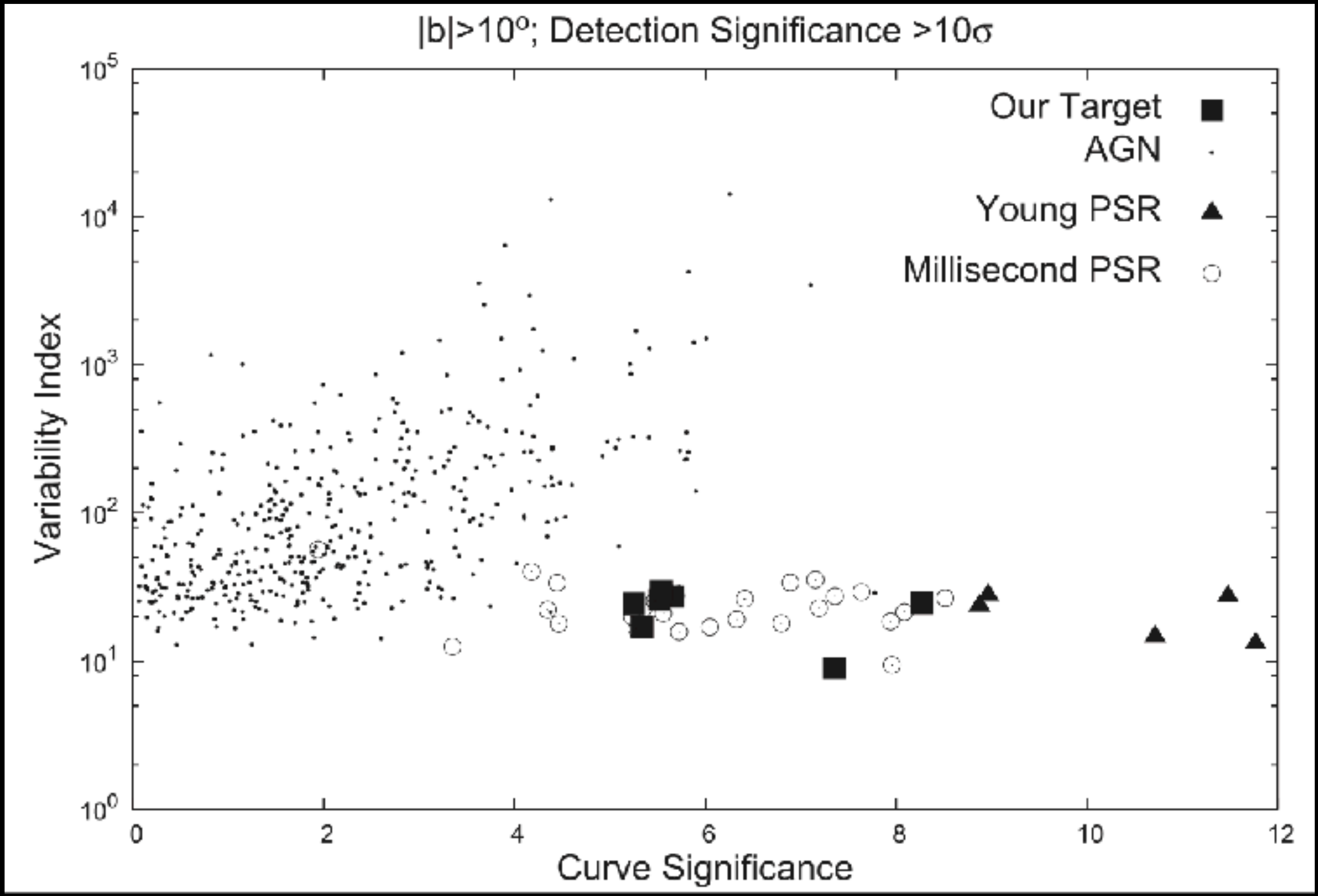
There is plenty of discovery space in the unidentified Fermi Objects (UFOs)



Saz Parkinson et al. (2016)

Treasure Hunting in UFOs

Hui et al. (2015b)



Coupling Classification with Automatic Feature Selection

1. Conventional classifications require some knowledge of the gamma-ray properties of different classes of objects which can be far from complete in view of the relatively short history of gamma-ray astronomy.

2. Instead of relying on a prior knowledge, automatic classification let the data "speak for themselves" and generate the classification model.

3. In the previous attempts of classifying gamma-ray sources with machine learning techniques (e.g. Saz Parkinson et al. 2016 ApJ 820 8), the power of automatic feature selection has not be fully exploited.

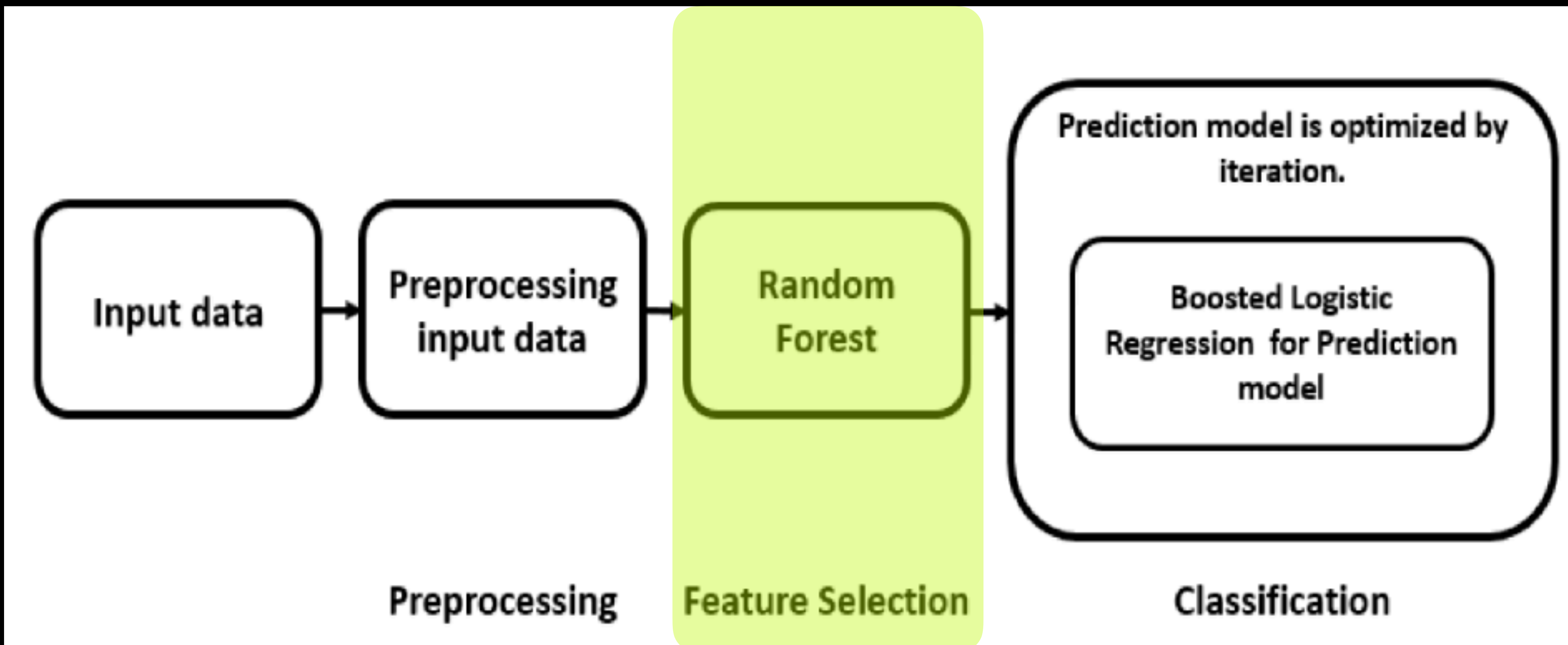
4. By coupling the classifiers with automatic feature selection algorithms, we aim to

   i) Improving the prediction accuracy

   ii) Provide a more cost-effective prediction model

   iii) Enhancing the discovery power in data mining

Coupling Classification with Automatic Feature Selection



Leung et al. in prep

Coupling Classification with Automatic Feature Selection

Importance Rank	PSR/AGN	YNG/MSP
1	Variability_Index	Unc_Energy_Flux100
2	Signif_Curve	GLAT
3	Spectral_Index	Flux_Density
4	hr45	Signif_Curve
5	Unc_Flux1000	hr34
6	SED1000_3000	hr23
7	Flux1000_3000	Spectral_Index
8	hr23	hr45
9	Unc_Energy_Flux100	-

Leung et al. in prep

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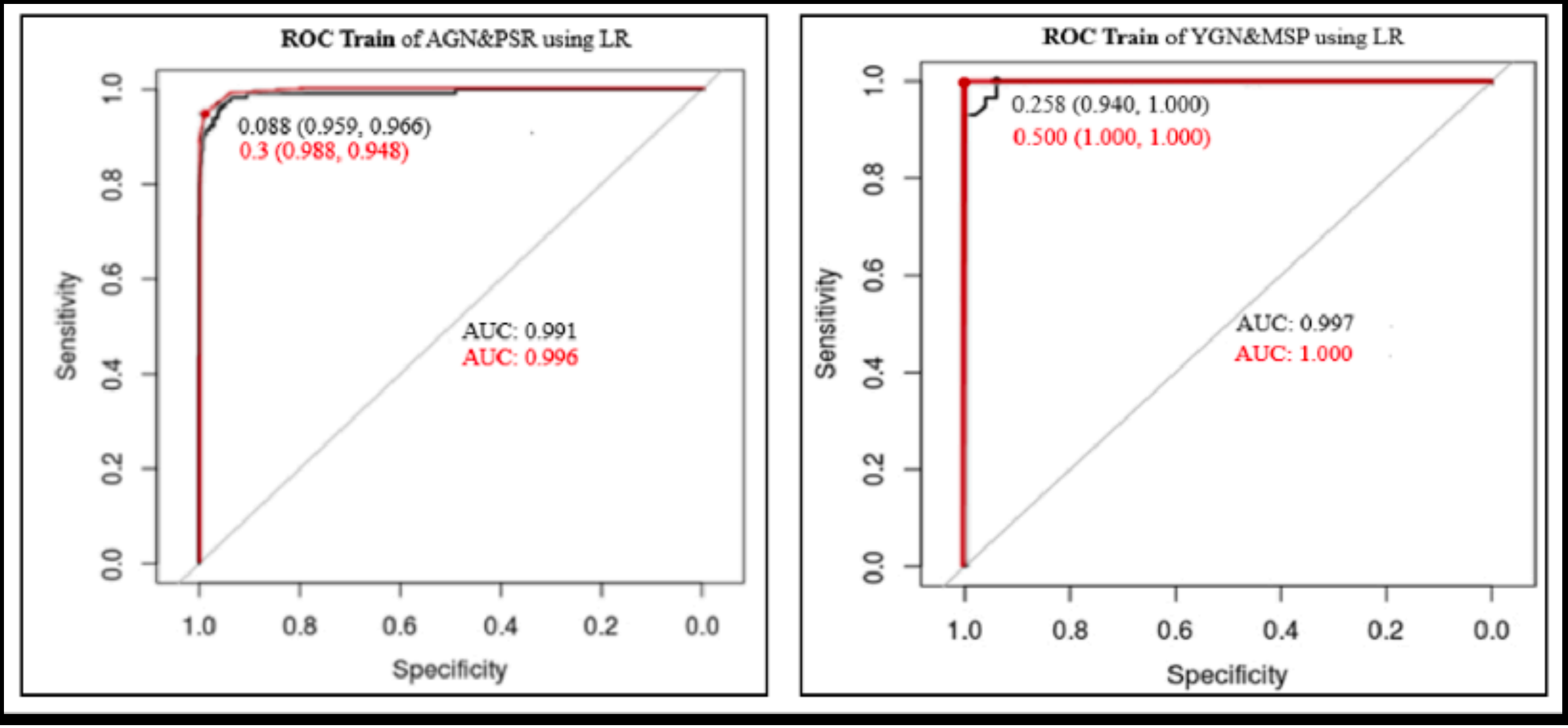
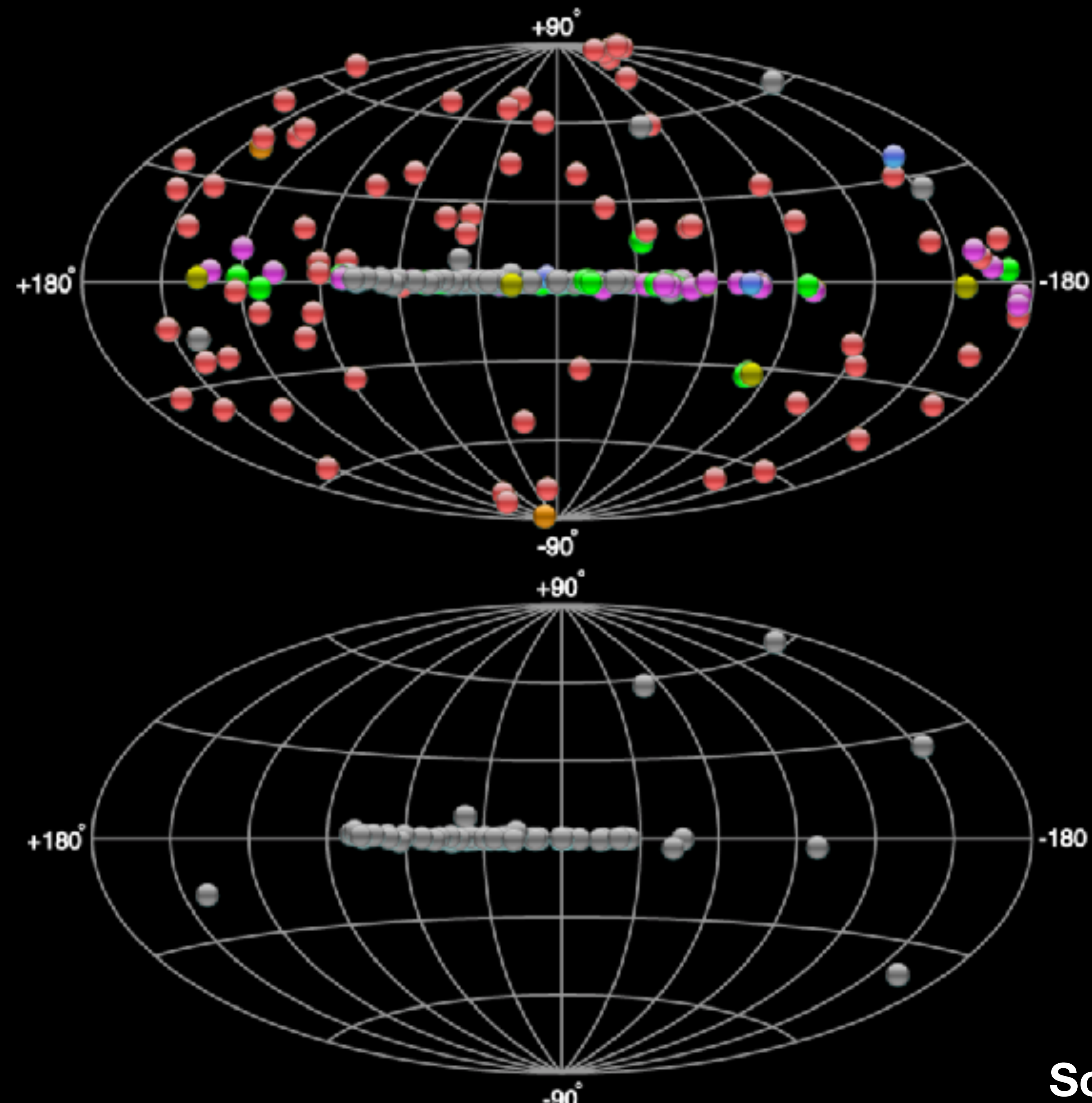


	Accuracy	
Prediction Model	PSR/AGN classification	YNG/MSP classification
Our method	98.2%	95.7%
Saz Parkinson et al. (2016) [1]	94.9%	90.7%

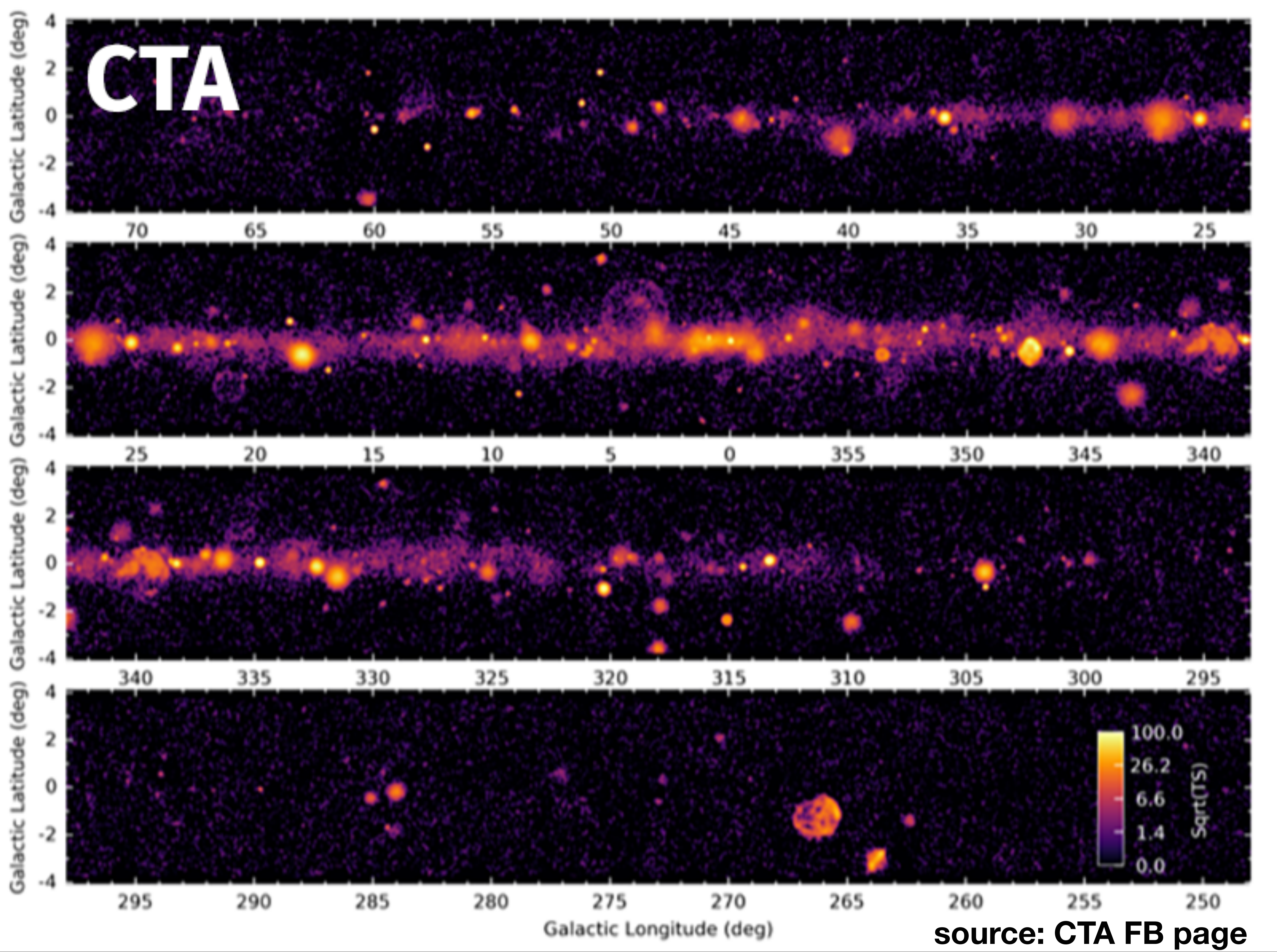
Leung et al. in prep

Unidentified TeV sources

~30% of currently detected TeV sources are unidentified.



Source: TeVCat


CTA
Galactic Latitude (deg)
Galactic Longitude (deg)
Sqrt(TS)
100.0
26.2
6.6
1.4
0.0
source: CTA FB page

Impacts of Automatic Feature Selection in CTA era

- **Improving the performance of classification.**
- **Instructing us in how to construct a cost-effective catalog so as to minimize the redundancy.**
- **Identifying features that we don't expect and advancing our understanding of emission nature od a specific class.**

Hope we can do even better in the next golden era of gamma-ray astronomy!