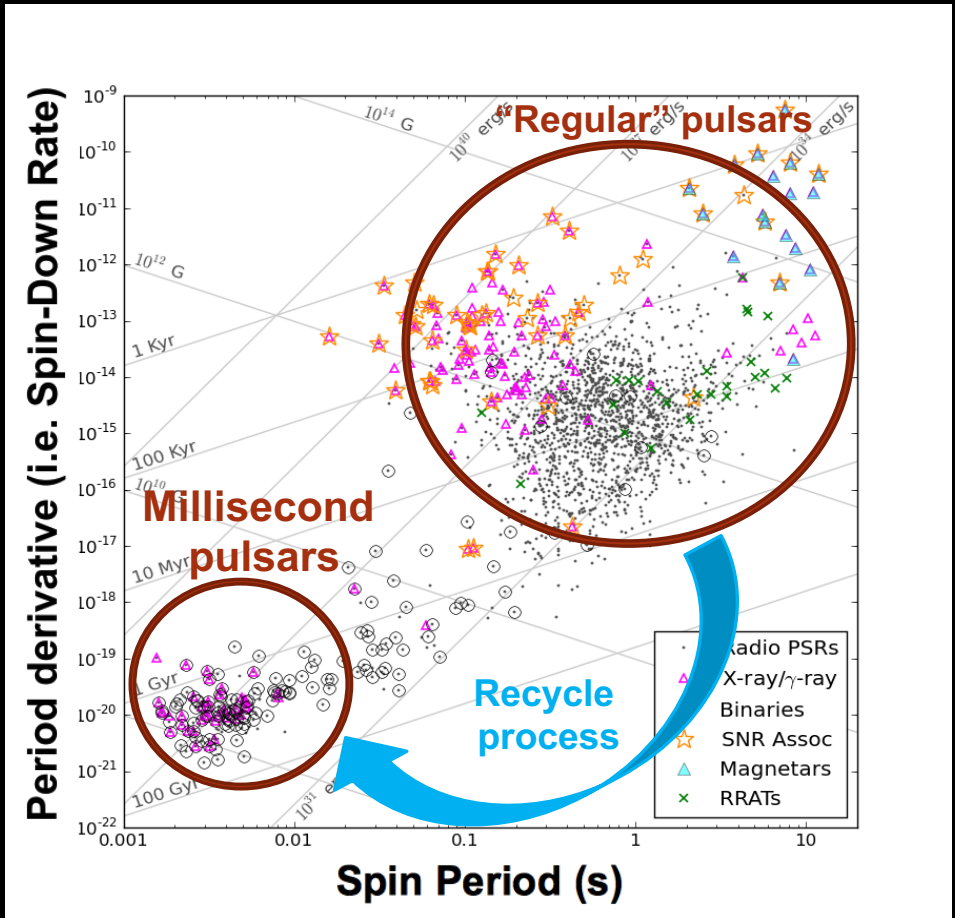
Discoveries of 16 Millisecond Pulsars (MSPs) in *Fermi* Unassociated Sources with the Green Bank Telescope (GBT)

SIRAPRAPA SANPA-ARSA (TUCK)
NATIONAL ASTRONOMICAL RESEARCH INSTITUTE OF THAILAND (NARIT)

S. M. RANSOM, F. CAMILO, P. S. RAY, T. JOHNSON, E. C. FERRARA, L. GUILLEMOT, M. S. E. ROBERTS, M. DECESAR, M. KERR, J. HALPERNS

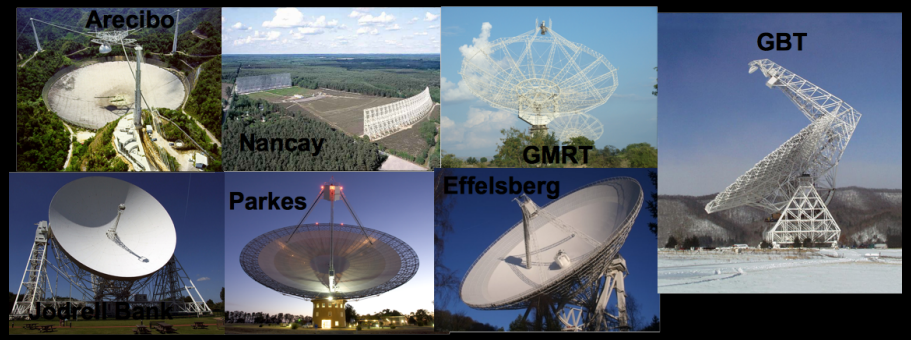
Why MSPs?



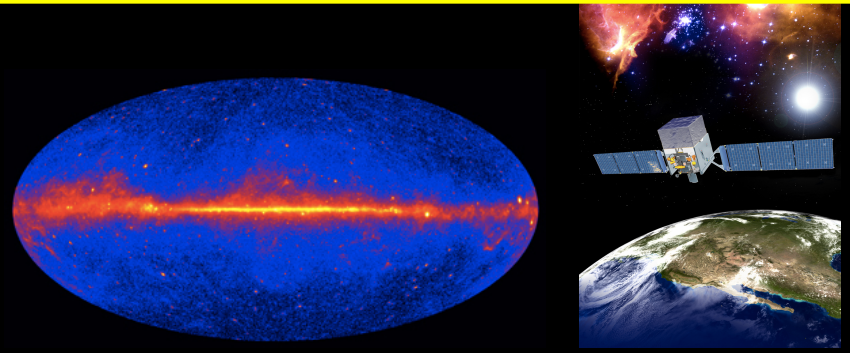
Pulsar is a highly magnetized, rotating neutron star that emits a beam of electromagnetic radiation. **"Physicists' playground"**

- **Millisecond pulsars (MSPs)**
- Recycle process : A pulsar has been spun up by accreting mass and angular momentum from a companion (Alpar et al. 1982)
- The spin down rate is much slower than for normal pulsars (visible for billions of years)
- **Great for pulsar timing**
- Tests of general relativity
- Constrains ultra-dense matter
- Binary and stellar evolution
- Direct detection of gravitational waves via Pulsar Timing Array (PTA)

Targeted Pulsar Search (for MSPs)

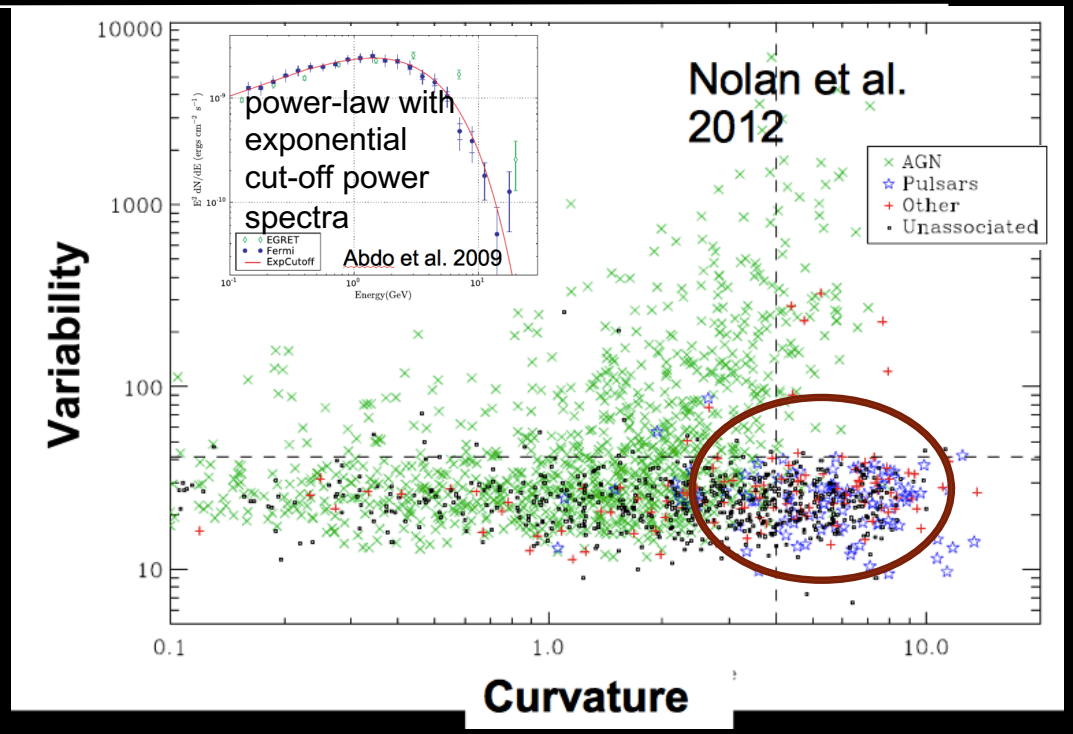


Pulsar is a radio source. The most efficient way to search for new pulsar is to use **single-dish radio telescopes**



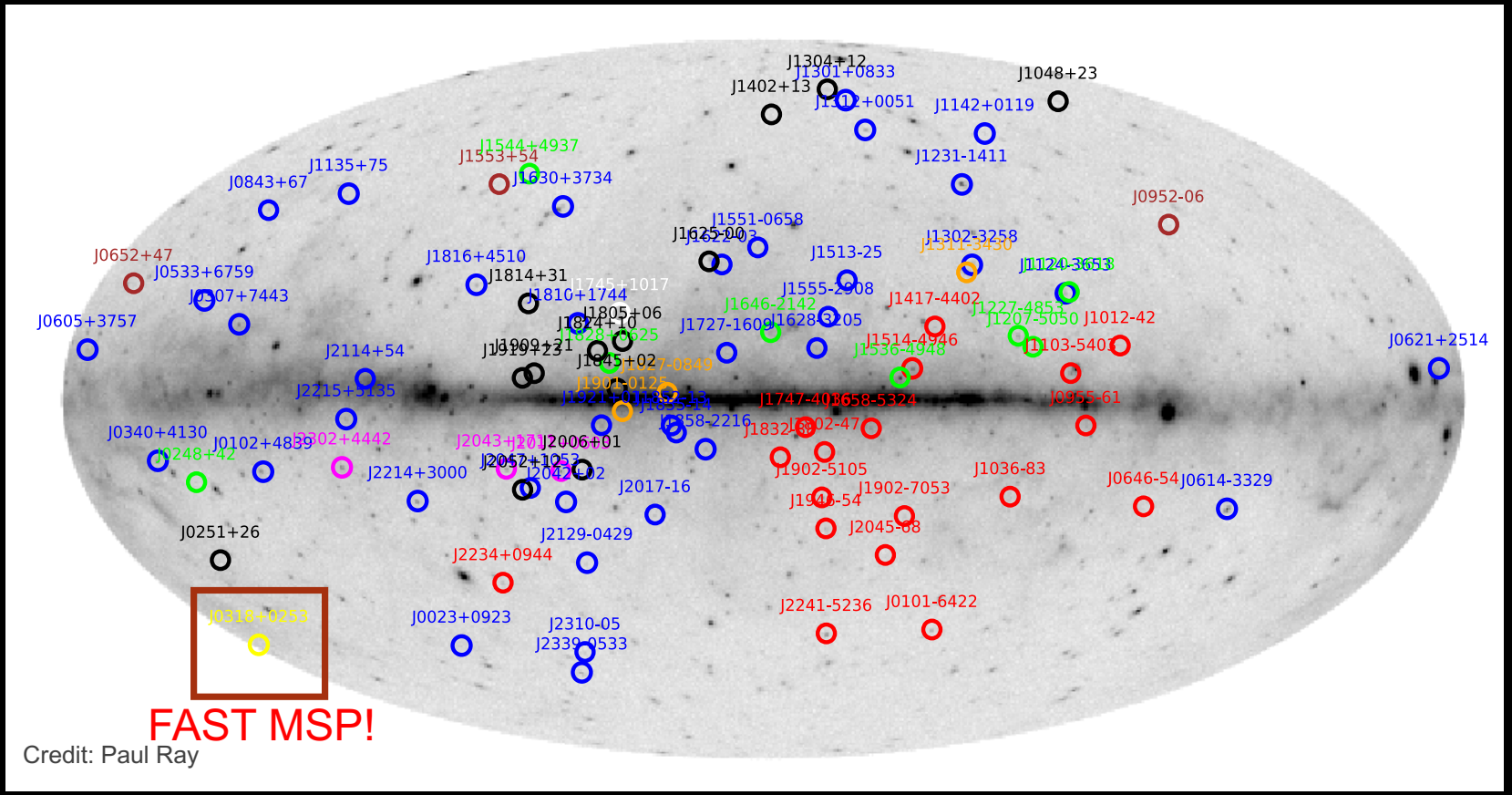
Credit: NASA/DOE/Fermi LAT Collaboration

Millisecond pulsars (MSPs) emit gamma-ray. *Fermi* is the most sensitive gamma-ray telescope; hence, ***Fermi* sources are the best MSPs sources**



- **What are pulsar-like sources?**
  - Known pulsars are likely to have power-law with exponential cut-off power spectra
  - High curvature (likelihood of having cut-off power spectra)
  - Low variability

Targeted Pulsar Search (for MSPs)



Credit: Paul Ray

- The Pulsar Search Consortium (PSC) led by Paul Ray, is an international collaboration of radio astronomers and telescopes, whose goal is to conduct the search and follow-up observations on the *Fermi* LAT pulsar-like unassociated sources and pulsars
- **With thousands hours of telescope time, 88 (++) Galactic MSPs were discovered (40 with the GBT) in the past 8 years**
- Prior to *Fermi*, it takes 25 years to find 75 MSPs

GBT 12 “normal” MSPs + 4 “Spiders”

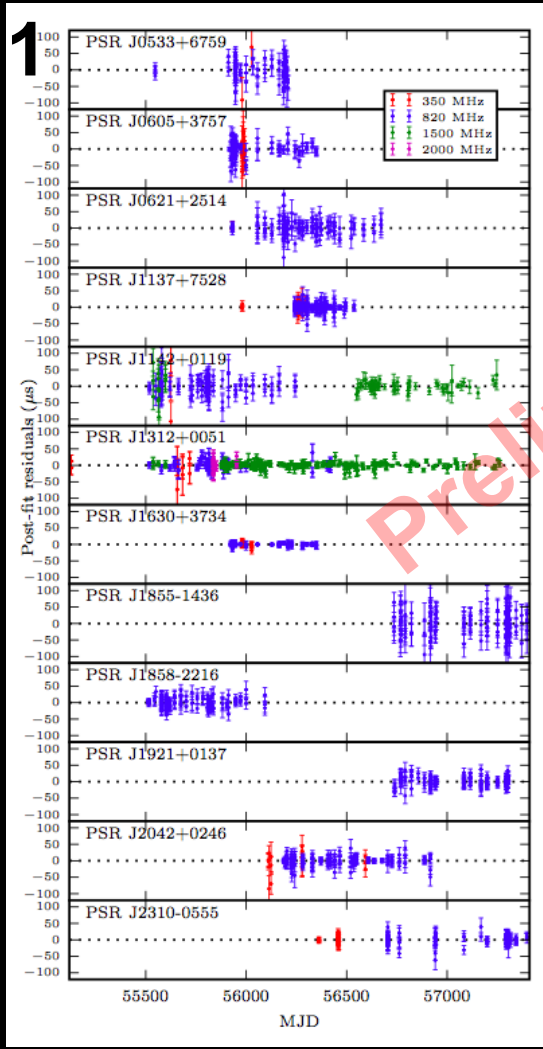
(Galactic)

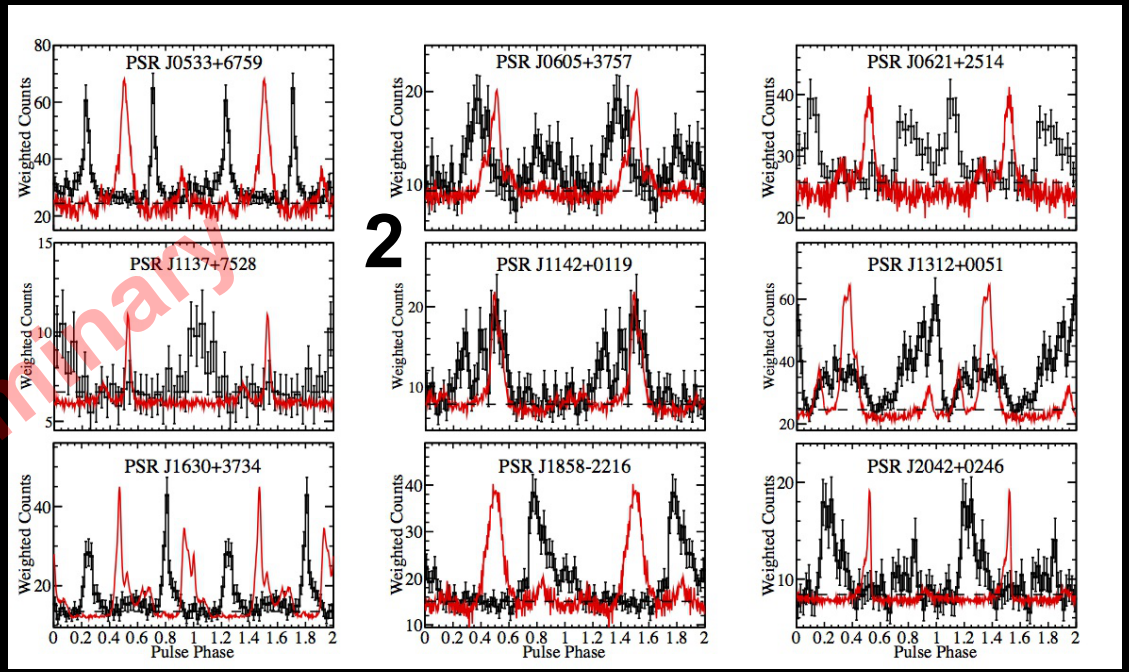
12 New "Normal" MSPs

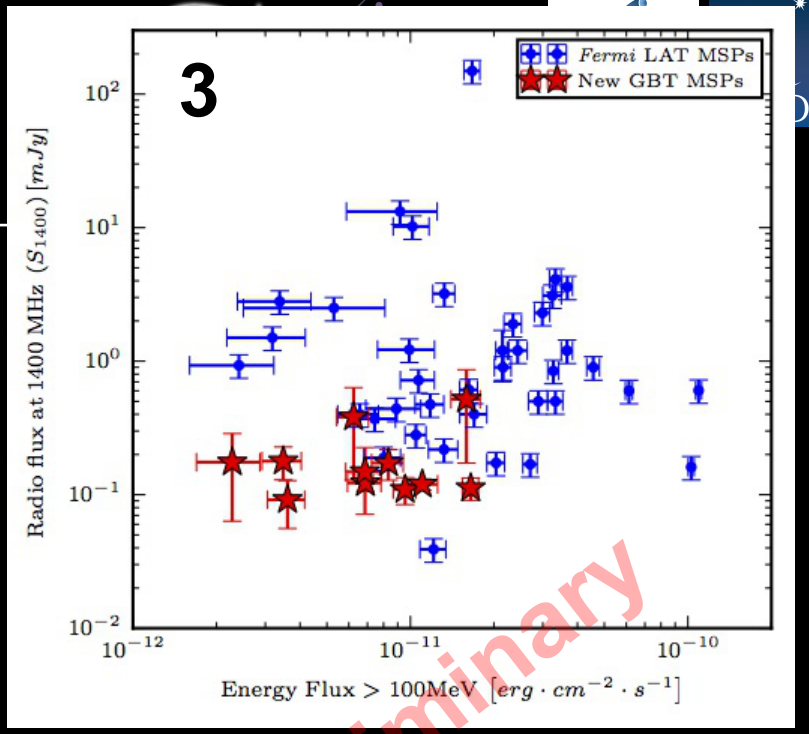
- **"Normal" MSPs = MSPs with He-WD companion**
- We searched 198 pulsar-like sources
  - Visible at the GBT (Dec > -40°)
  - GUPPI in search mode at
    - 350 MHz (FWHM 36'): $|b| > 5^\circ$, err. box > 13'
    - 820 MHz (FWHM 16'): $2^\circ < |b| < 5^\circ$, err. box < 13'
    - 2 GHz (FWHM 6.2'): $|b| < 2^\circ$, err. box < 6.2'
- 12 new MSPs were found. All of them now have phase-connected timing solutions.
  - 1 isolated system (PSR J0533+6759)
  - 11 MSPs with He-WD companion ("normal")
  - P: 2.38 - 5.06 ms. DM: 9.3 - 109.2 pc/cm^3

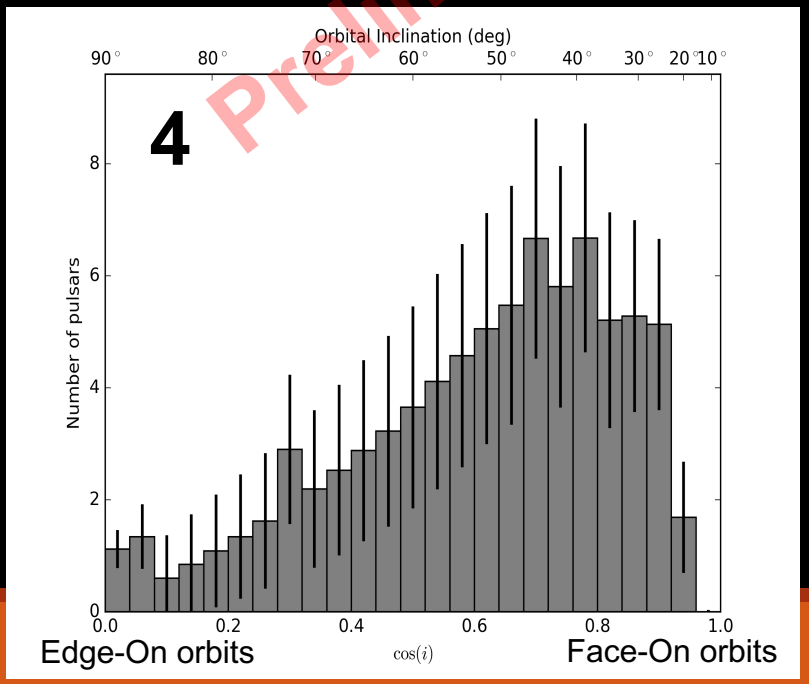
Sanpa-arsa et al. in prep

12 New "Normal" MSPs



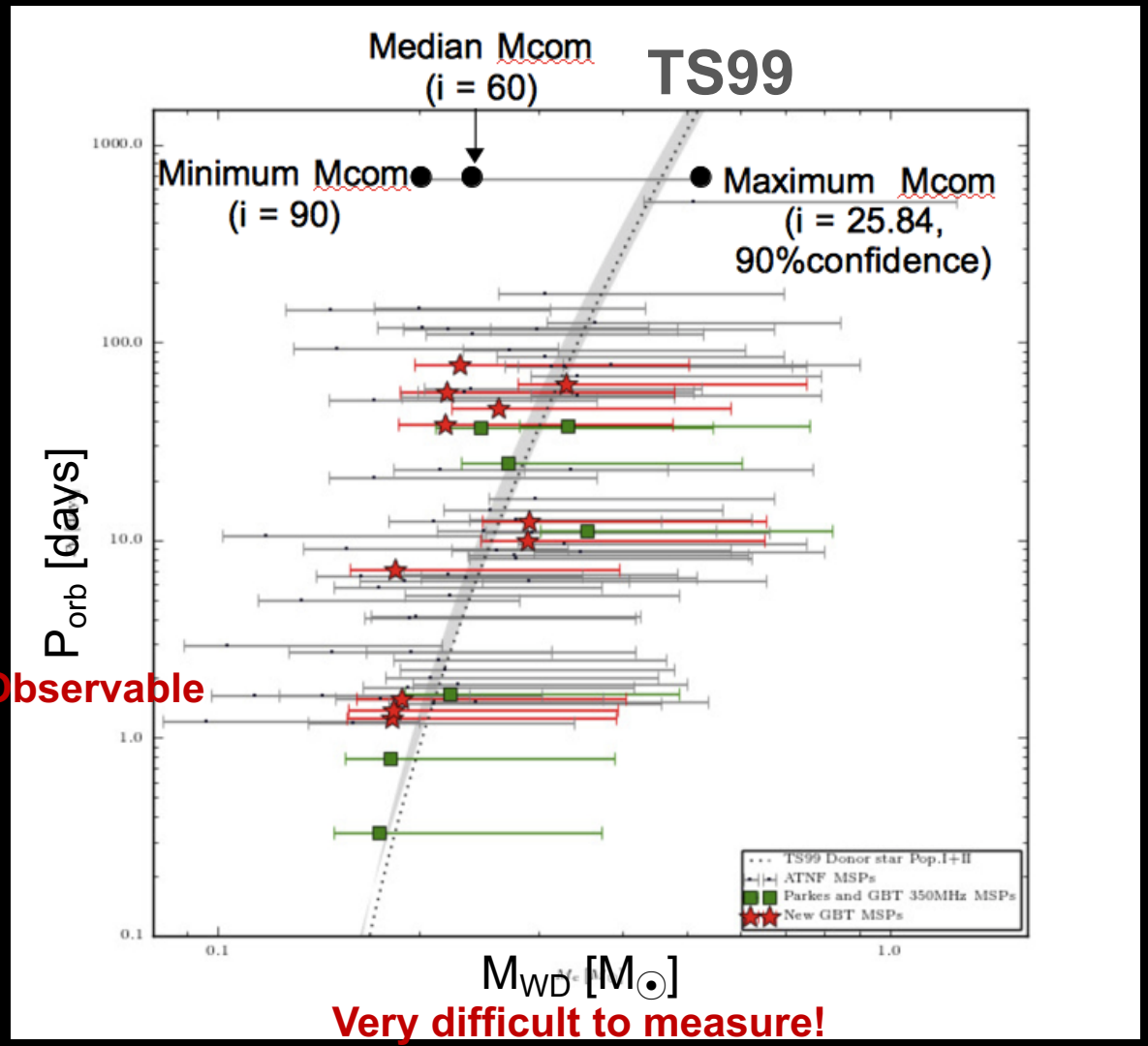






1. Timing solutions for all 12 MSPs
2. Every MSPs show gamma-ray pulsations
3. No correlation between radio and gamma-ray flux densities
4. Distribution of cos(i) is not flat => <u>we are more likely to observe MSPs with face-on orbit</u>

Orbital Period – Companion Mass Relation

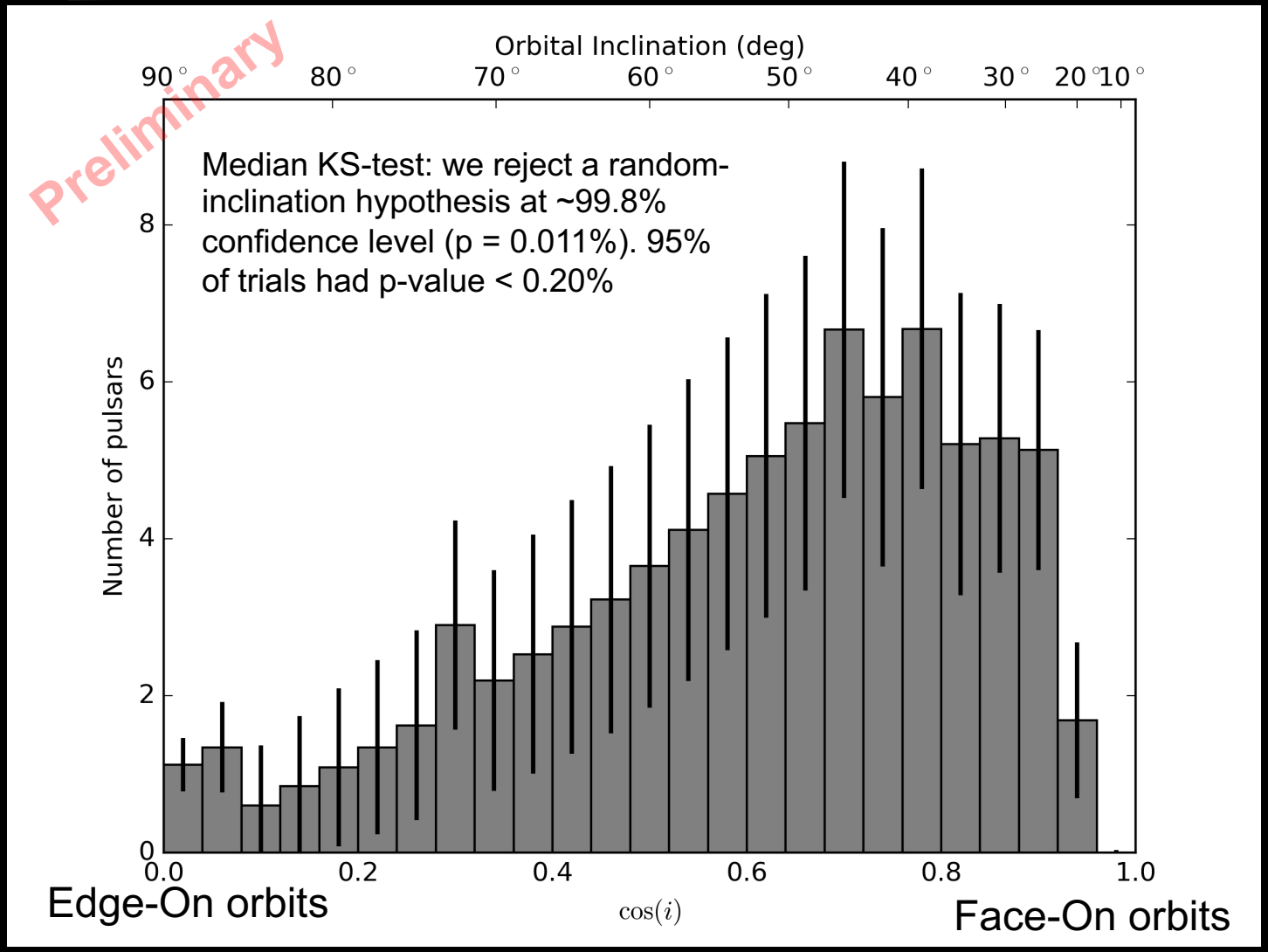


- Assumptions: TS99 (Tauris & Savonije, 1999) gives correct M_{WD}
- Test on TS99: we performed a simple MC analysis using **81** pulsars with He-WD companion in wide orbit (including the 11 new MSPs)
- We ran 10,000 iterations where we randomly selected each pulsar mass from **1.46+/-0.21 $M_\odot$** (Ozel et al. 2012) and **chose the inclination such that every MSP systems become consistent with** the **TS99**. For pulsars with known inclinations and masses use them

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a \sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

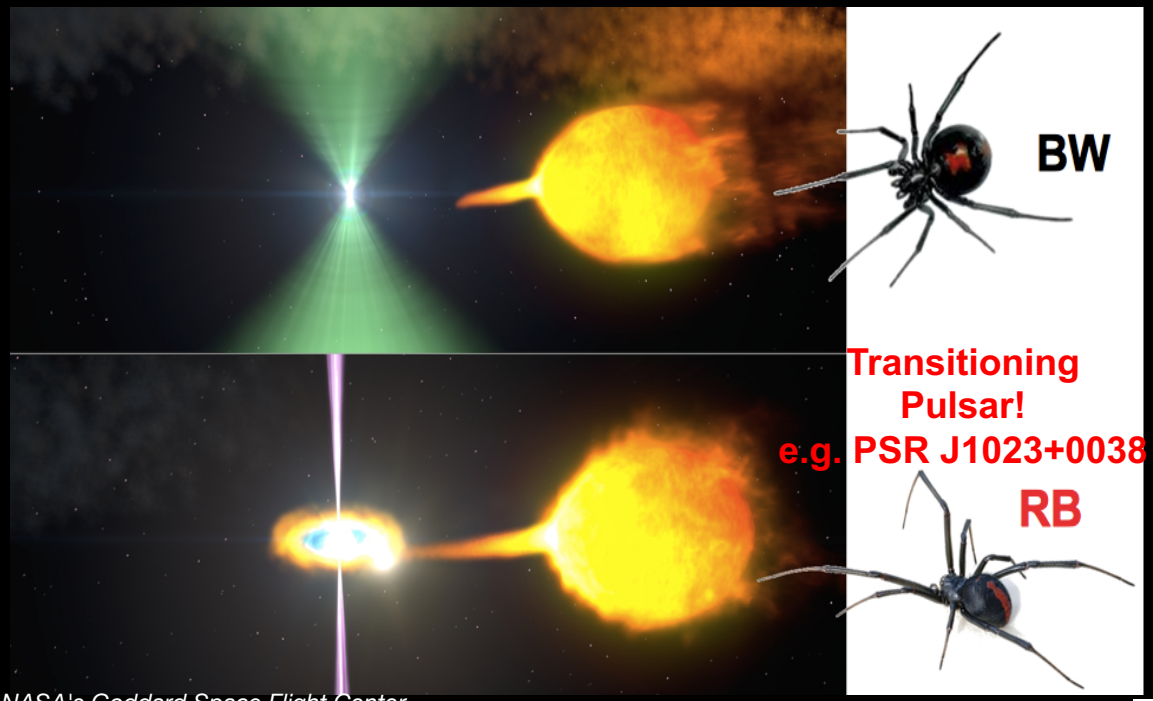
Observable

Orbital Period – Companion Mass Relation

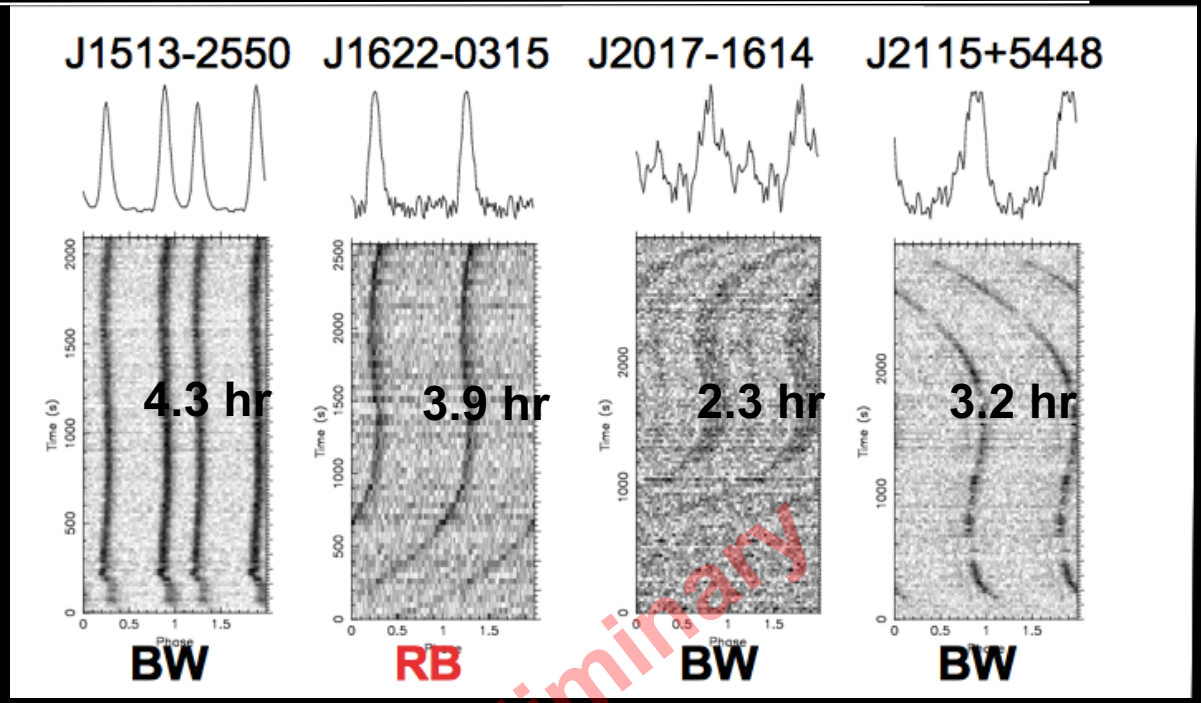


- If our analysis is correct and TS99 is valid, **we are more likely to observe MSPs with face-on orbits**
- MSP radio emission may be more concentrated near the spin axes of the pulsars (i.e. nearly aligned rotators) which we expect to be aligned with the orbital angular momentum due to accretion during the recycling process
- Future emission studies, perhaps using radio polarization information and gamma-ray emission modeling, may be able to investigate this aligned-emission hypothesis

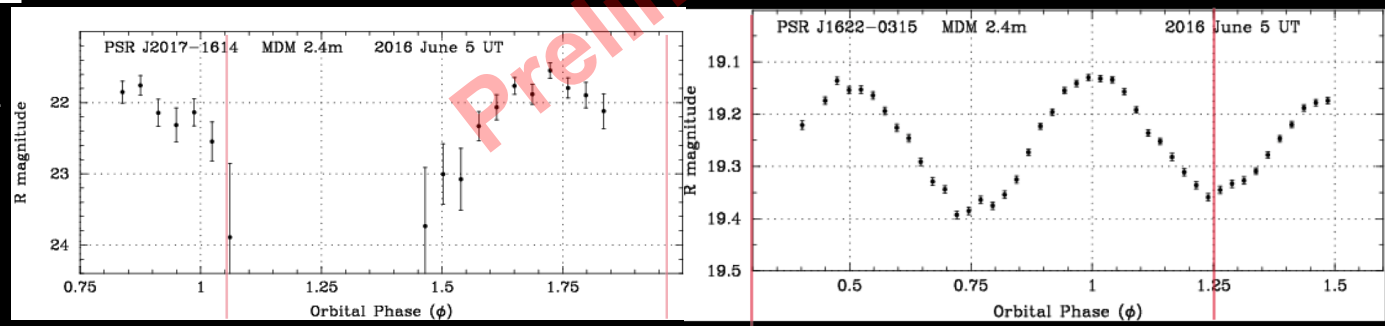
4 New "Spiders"



NASA's Goddard Space Flight Center

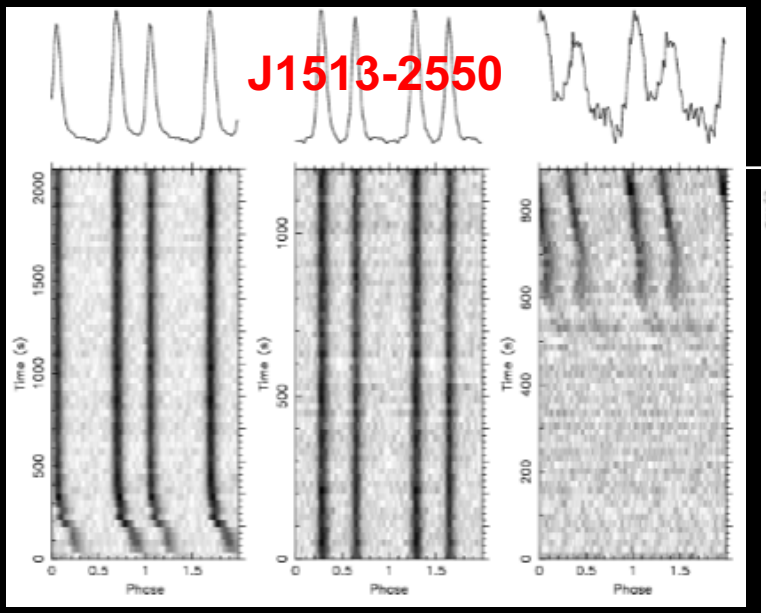


- **Spider: A MSP in a compact orbit (<u>orbital period < 1 day</u>).**
- Black Widow (BW): Extremely small companion mass (~0.01 $M_\odot$). Ablating away the companion.
- Redback (RB): Non-degenerated companion. Accreting mass from the companion.

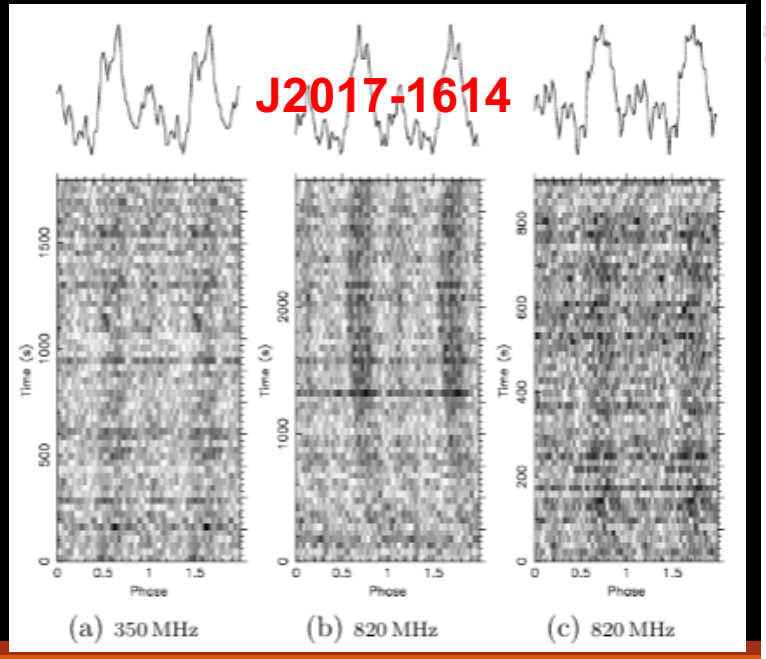


Optical counterparts with the Hiltner 2.4m Telescope (Jules Halpern)

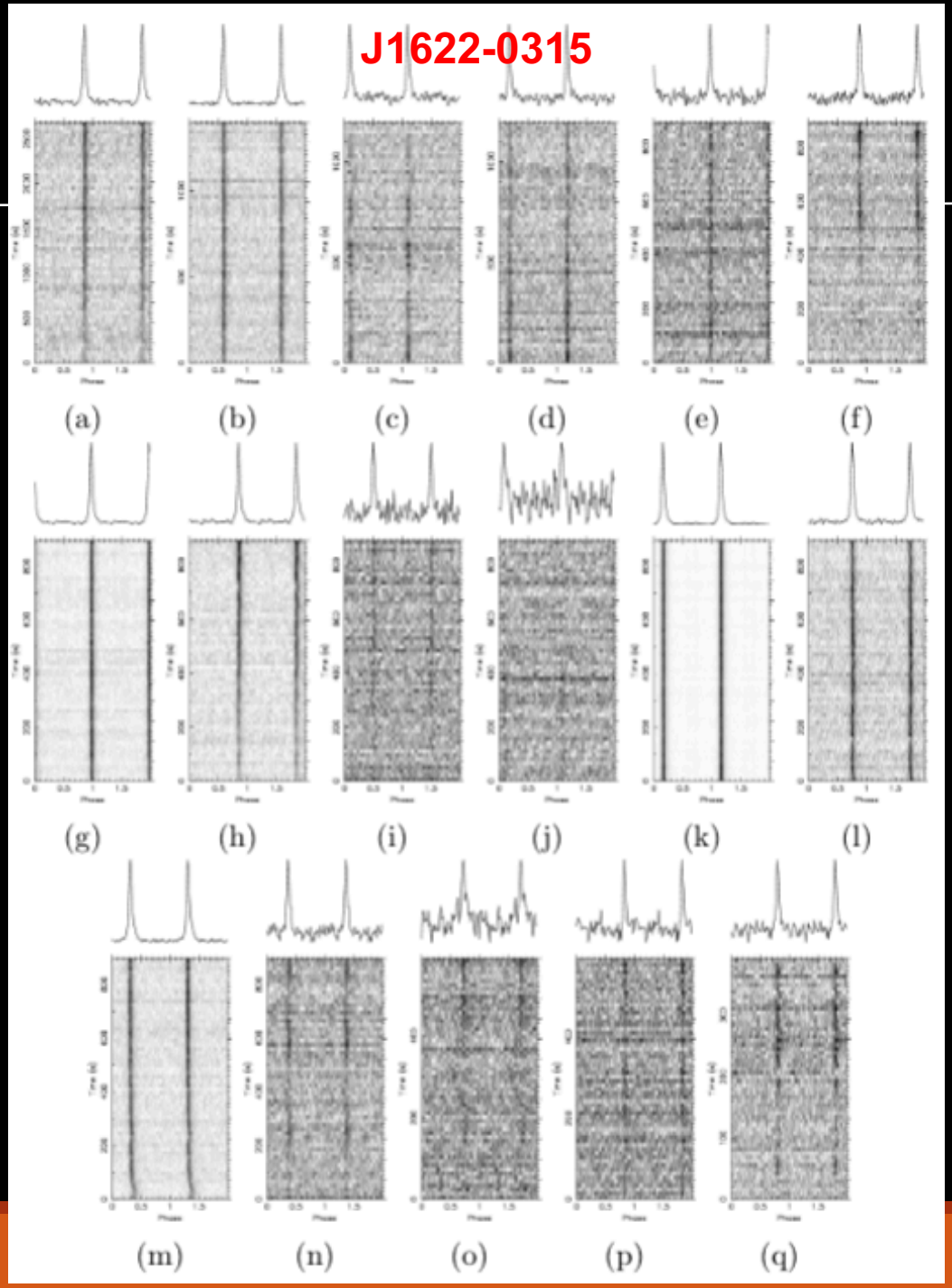
J1513-2550



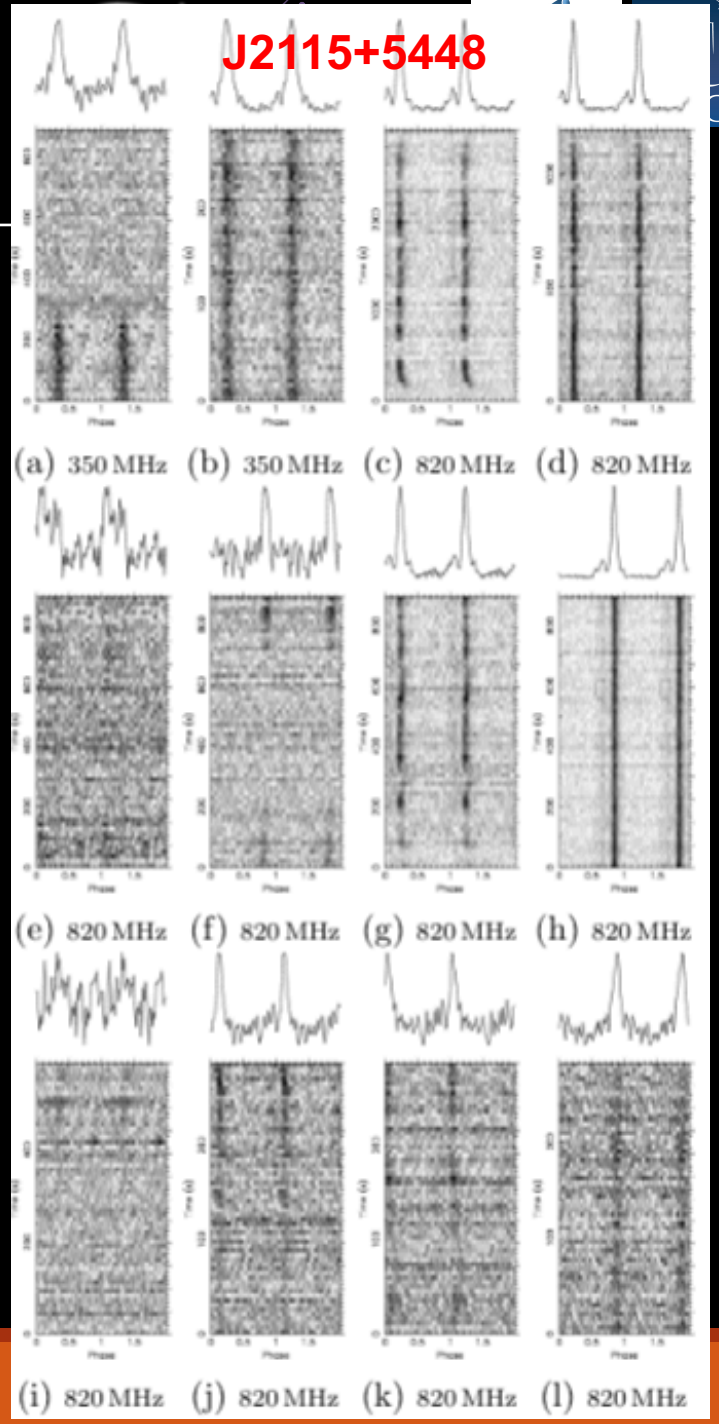
J2017-1614

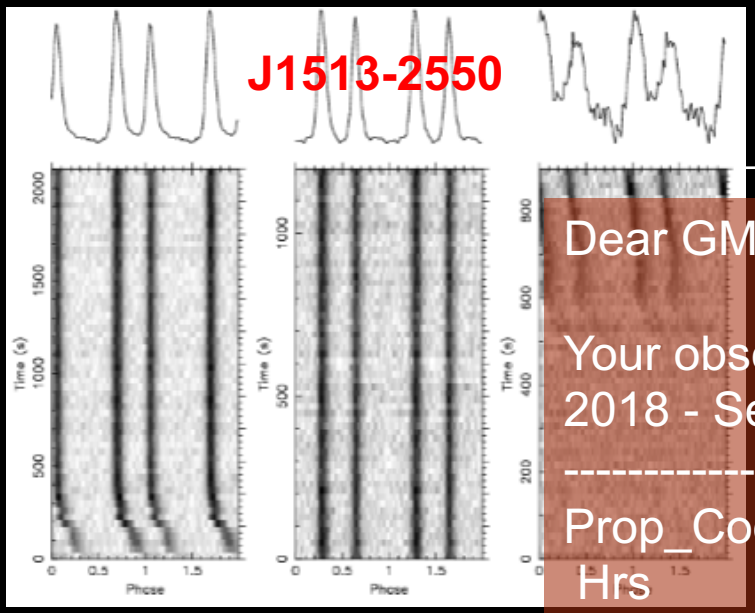


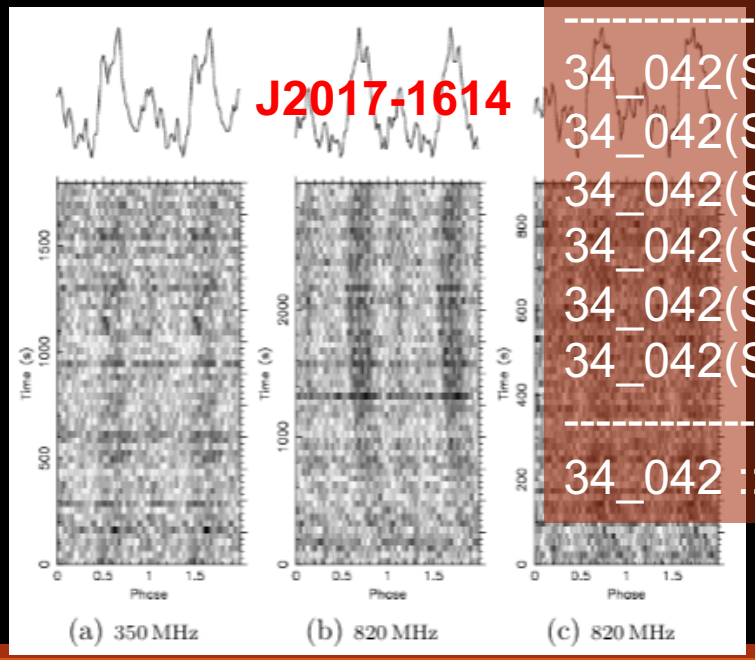
J1622-0315

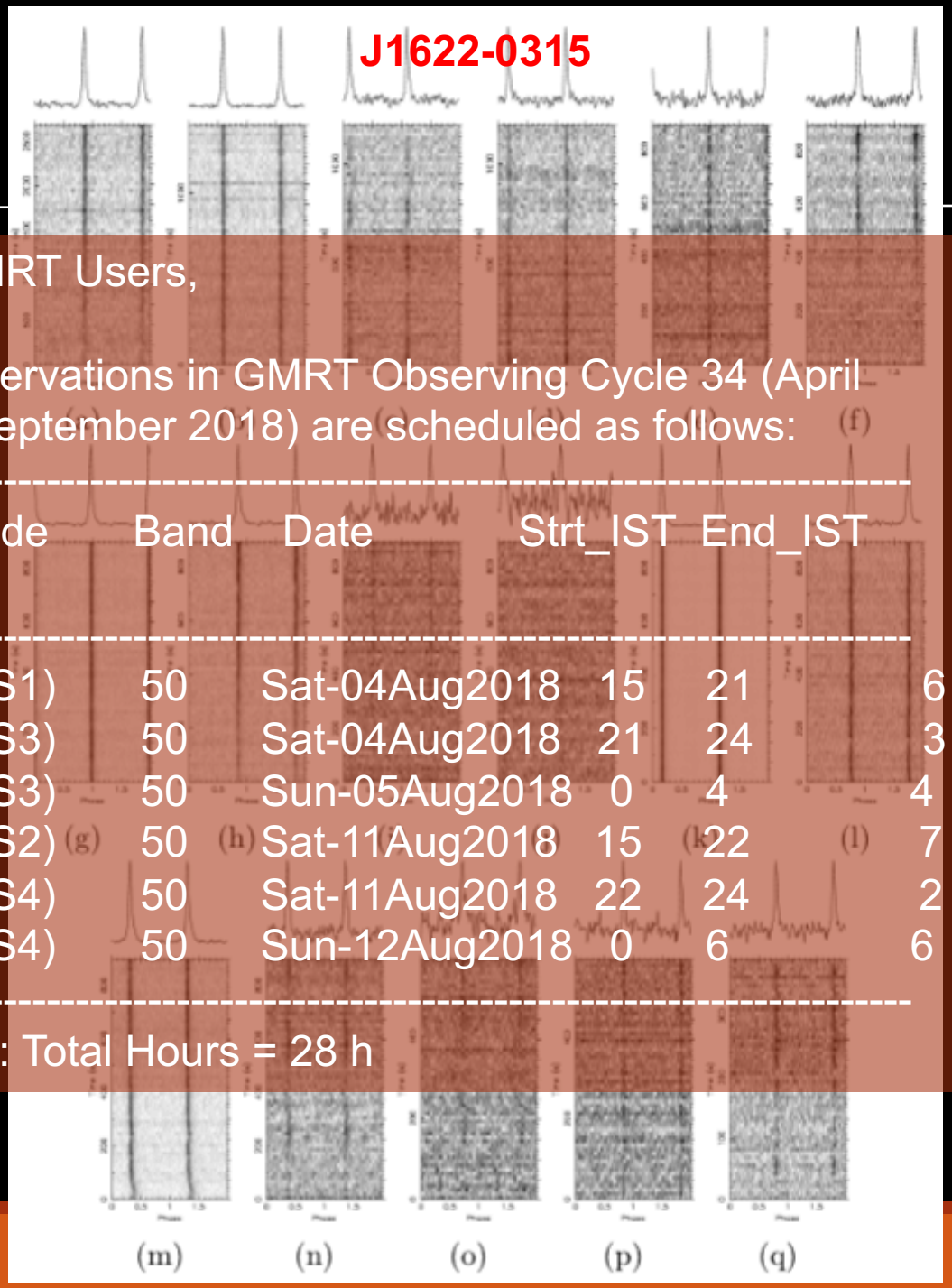


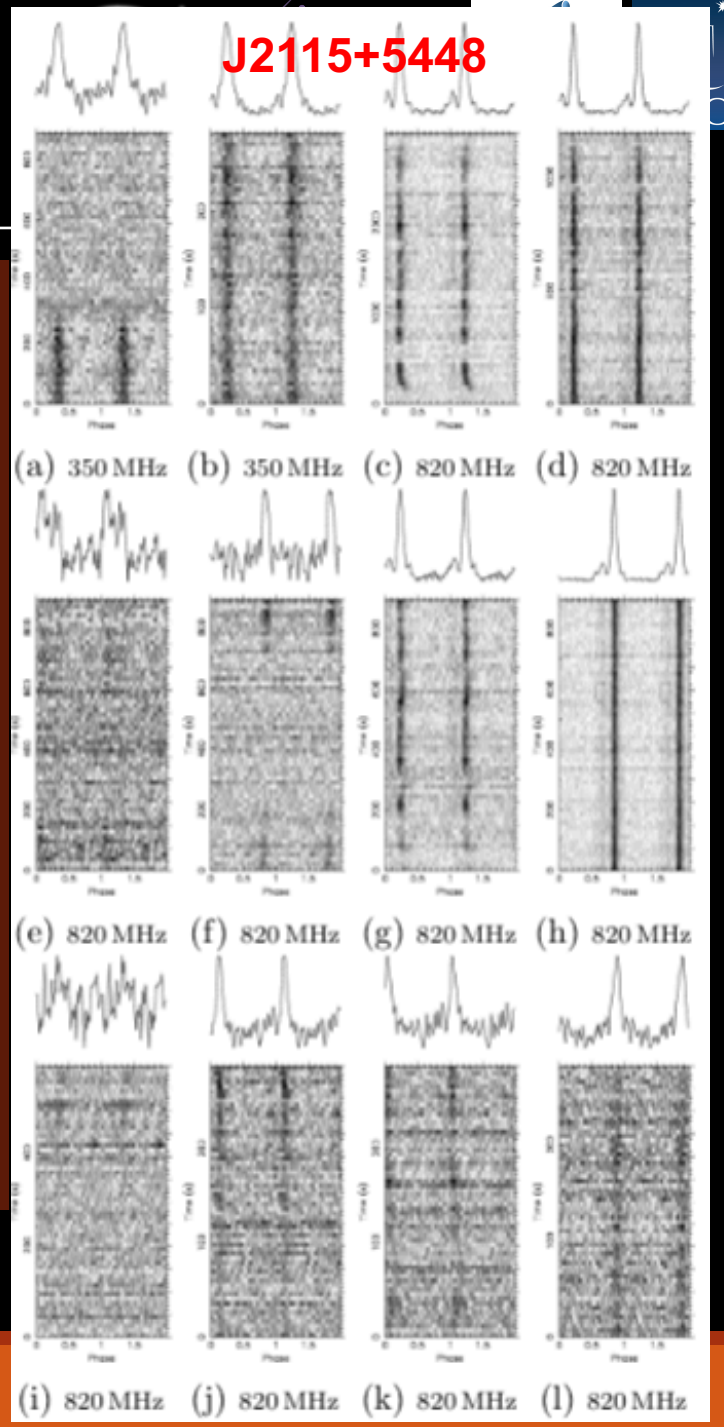
J2115+5448











Dear GMRT Users,

Your observations in GMRT Observing Cycle 34 (April 2018 - September 2018) are scheduled as follows:

Prop_Code	Band	Date	Strt_IST	End_IST	Hrs
34_042(S1)	50	Sat-04Aug2018	15	21	6
34_042(S3)	50	Sat-04Aug2018	21	24	3
34_042(S3)	50	Sun-05Aug2018	0	4	4
34_042(S2)	50	Sat-11Aug2018	15	22	7
34_042(S4)	50	Sat-11Aug2018	22	24	2
34_042(S4)	50	Sun-12Aug2018	0	6	6

34_042 :: Total Hours = 28 h

Summary

- 88 (++) Galactic MSPs were discovered (40 with the GBT) in *Fermi* unassociated sources by PSC [> 20 are spiders]
- *Fermi* unassociated sources are still great sources to search for MSPs (no correlation in gamma-ray and radio fluxes)
- TS99 analysis: from 81 pulsars with He-WD companion in wide orbit (including the 11 new *Fermi* MSPs), we found that the cos(i) distribution from the simulation is not uniform (flat) but favors larger cos(i) (face-on orbit)
- 4 new *Fermi* “spiders”: 1 RB + 3 BW.
- We can study eclipse mechanisms of the 4 spiders with simultaneous multi-frequency observations which is unique to the uGMRT.