



# Discovery of an Ultra-Compact Gamma-ray Millisecond Pulsar Binary Candidate

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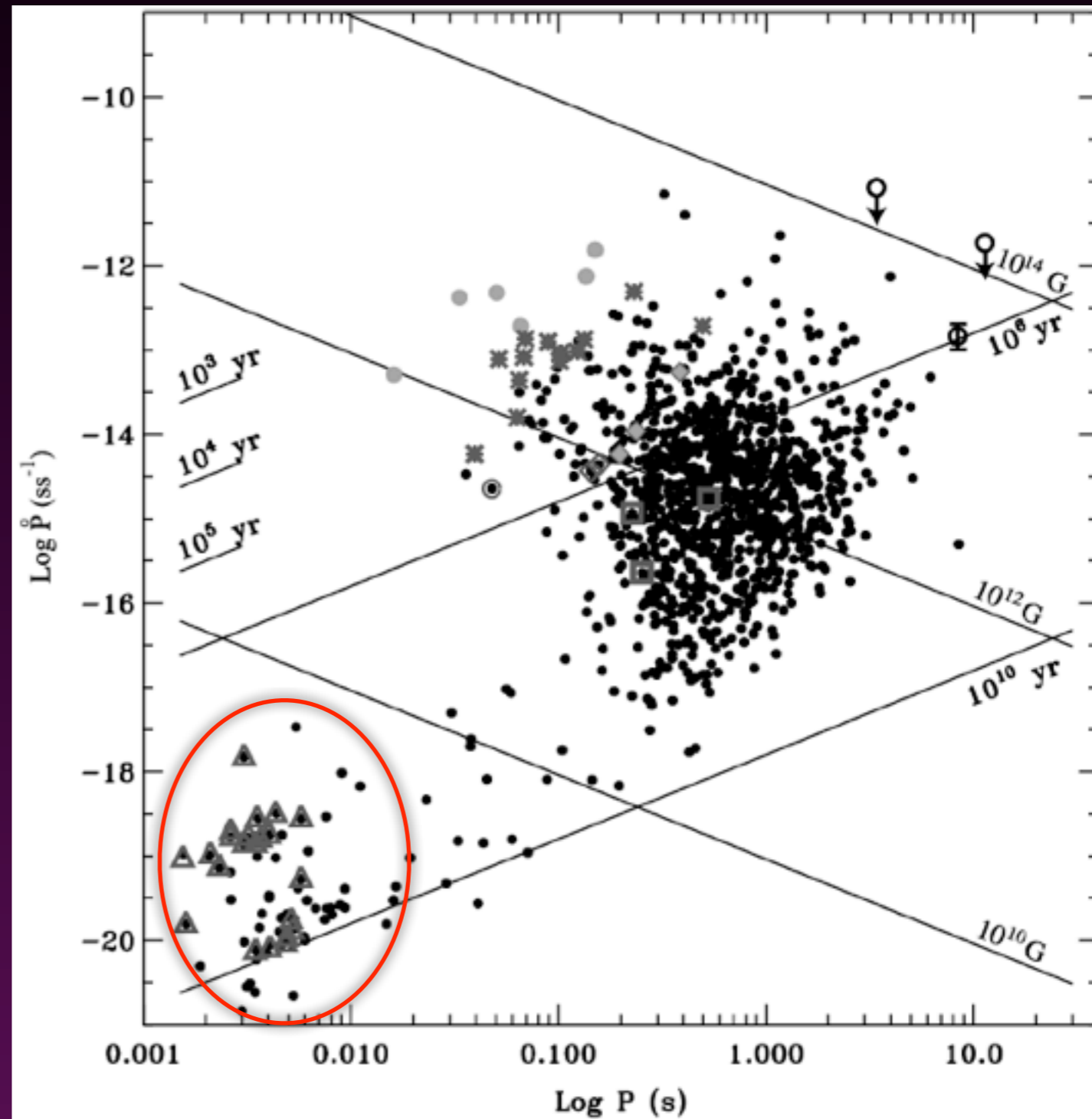
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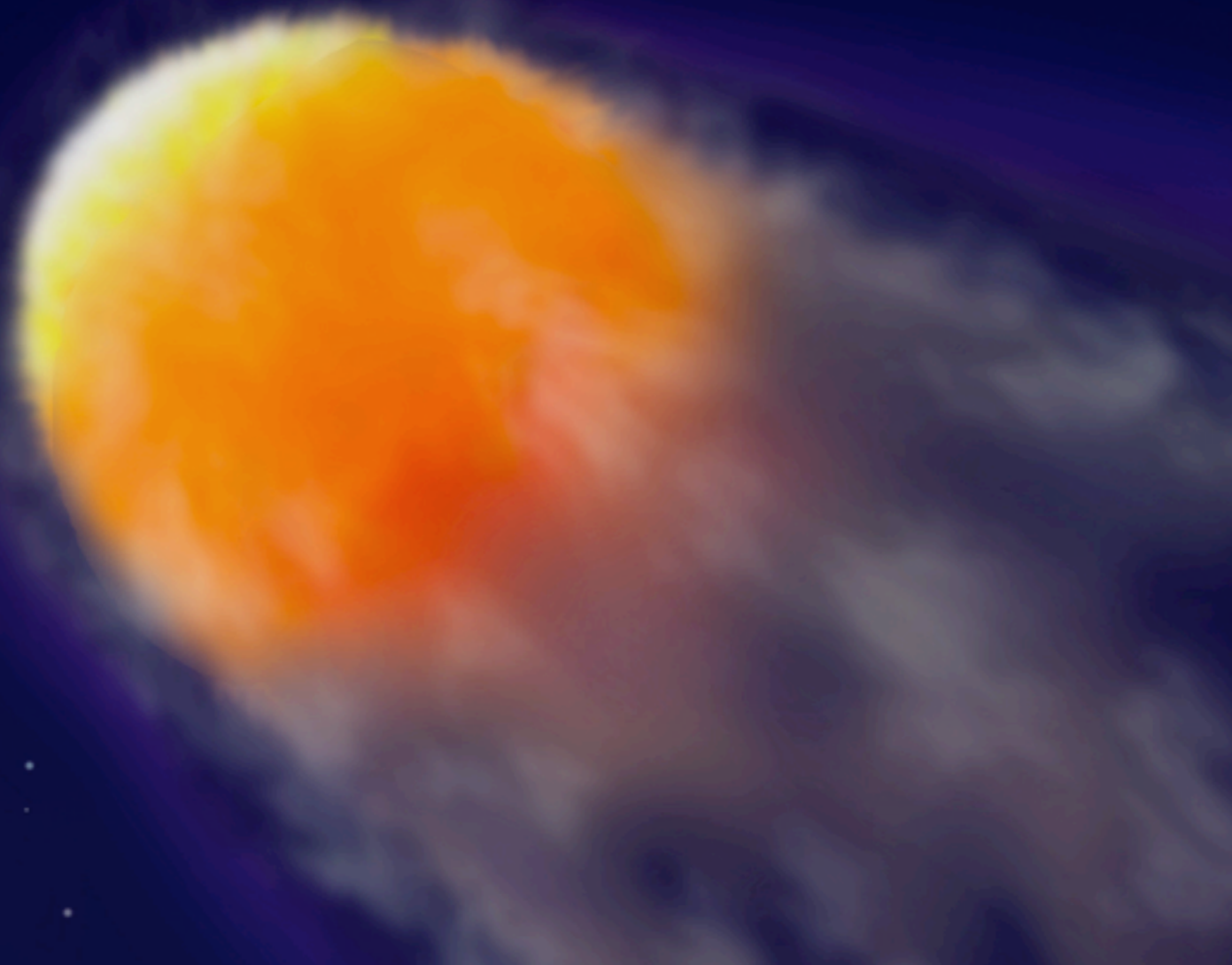
# Millisecond Pulsars (MSPs)

- Very rapid rotating neutron star
- Majority are in binaries
- Some are isolated systems
- MSPs are detected in the radio, X-ray, gamma-ray, and OIR
- MSP begins its life as a normal pulsar and is spun up via accretion from its companion



# Black Widow MSPs

- Some MSP binaries have an orbital period of  $< 1$  day
- Pulsar radiation can ablate the companion, leaving an isolated MSP at the end





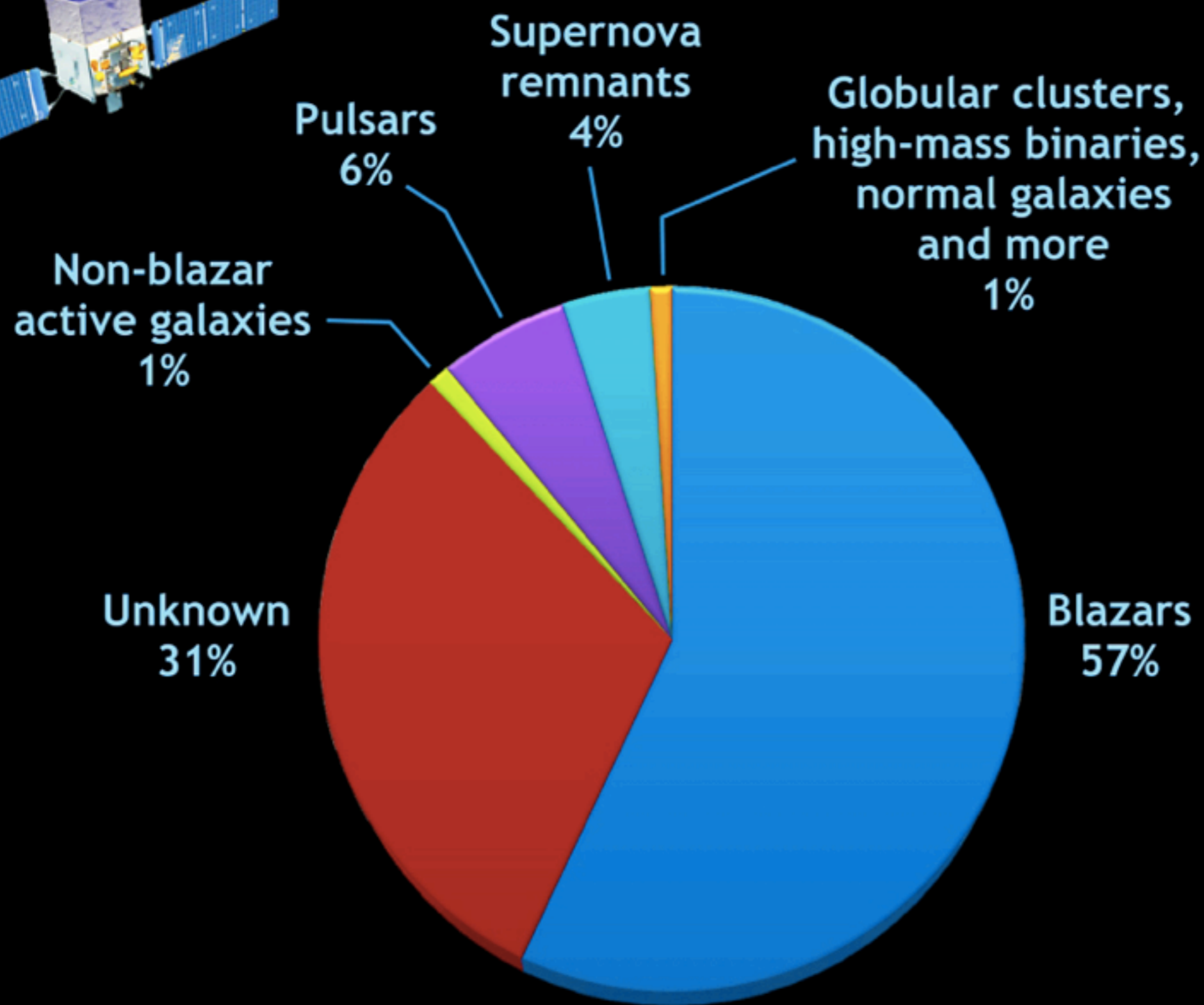
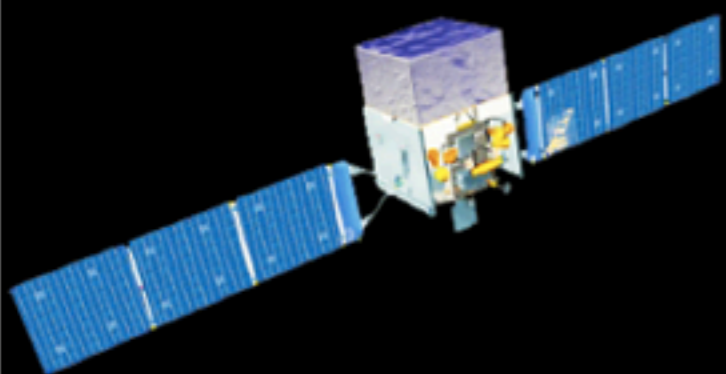
# Black Widow MSPs

- Companion can either be a less massive ( $< 0.05 M_{\odot}$ ) degenerate object (black-widow) or a late-type star (redback)
- BW/RB MSPs are the missing link between LMXBs and isolated MSPs
- Because of the pulsar's heating on the companion, the optical emission from the companion can be changed by more than 2 magnitudes in an orbital cycle

# How can we search for BW/RB MSPs?

- Traditionally, MSPs are discovered via radio timing
- Radio timing at the Fermi's gamma-ray positions
- Blind search of gamma-ray pulsation is now possible with Fermi; it is however very hard for MSPs (Pletsch+ 2012, Science) and optical data are required
- MSPs can be "radio-quiet" that have not been seen yet
- No radio => Need X-ray/gamma-ray data
- Too many X-ray sources and many different classes of sources
- Gamma-ray data are more "simple"

# What has Fermi found: The LAT two-year catalog



# Selecting MSP candidates in the Fermi catalog

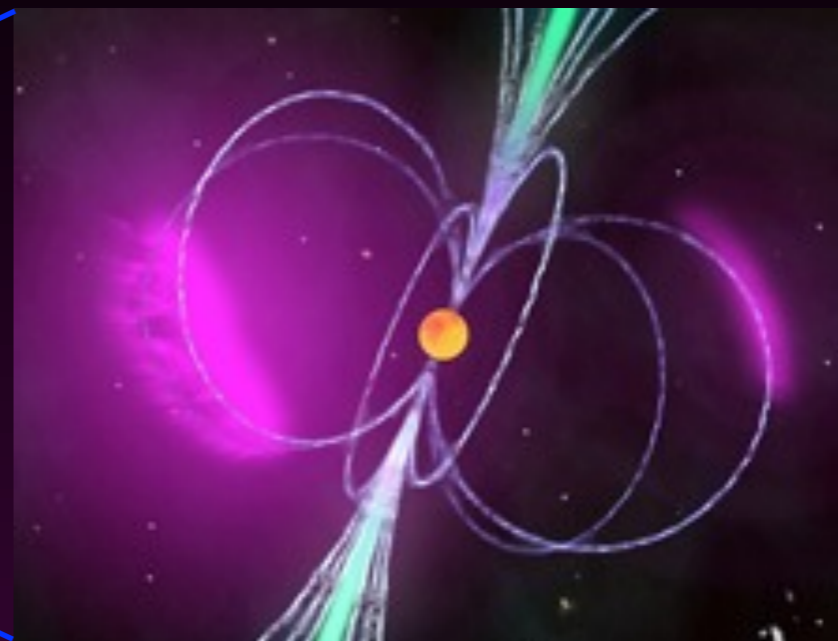
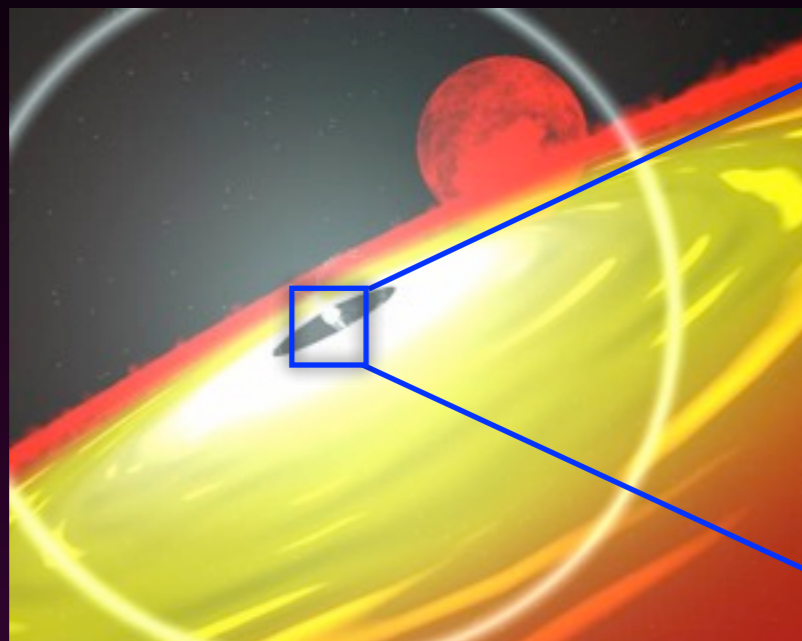
- Steady (variability index)
- Non power-law source (curvature index)
- High Galactic latitude
- No reported radio emission
- Archival X-ray imaging data (compare gamma-ray and X-ray, and hopefully multi-wavelength follow-up)

# Multi-wavelength campaign for searching “radio-quiet” MSPs

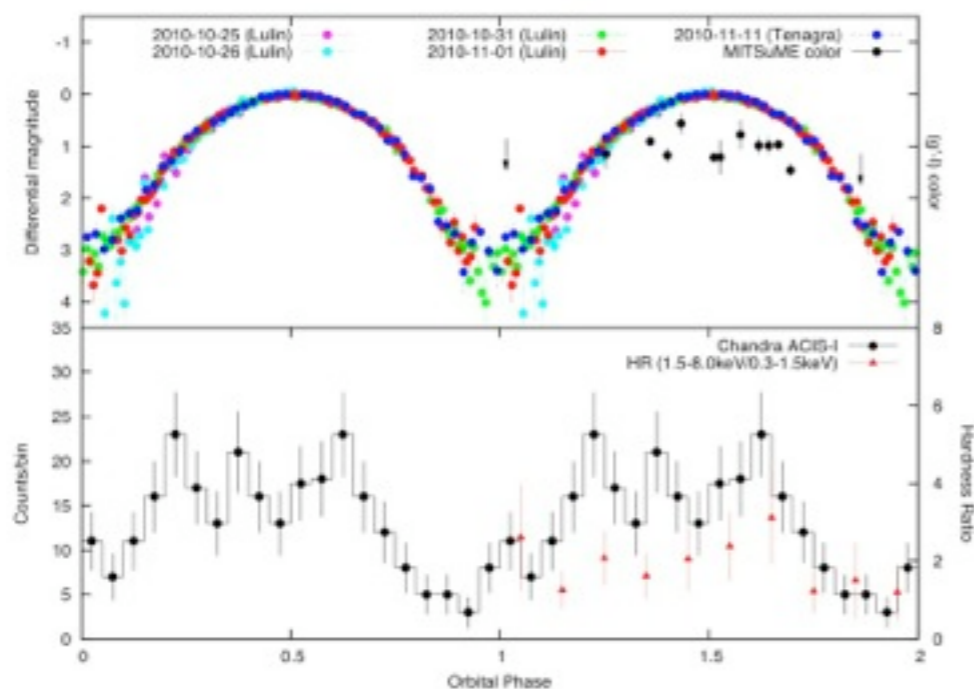
- Select suitable unidentified Fermi objects (UFOs) for follow-up X-ray and optical observations
- Swift/Chandra/XMM observations can identify possible counterparts; no radio counterparts
- Identify the optical counterpart and look for optical variability due to the orbital modulation



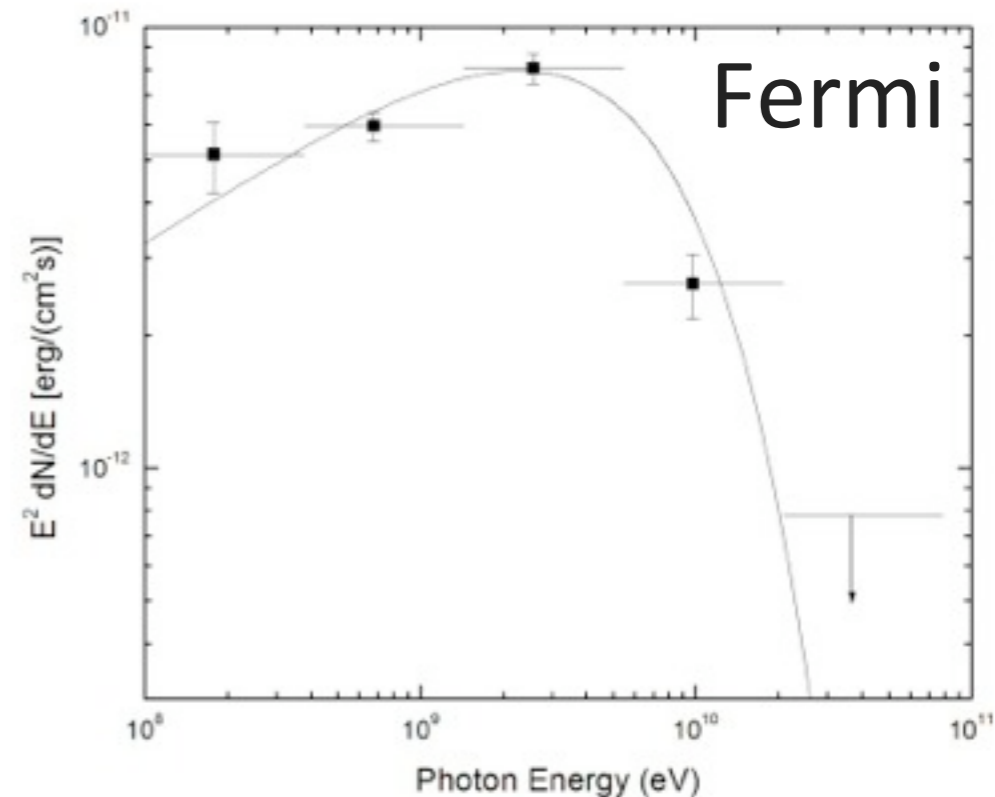
# UFO as a "radio-quiet" gamma-ray emitting MSP in a binary? 1FGL J2339.7-0531



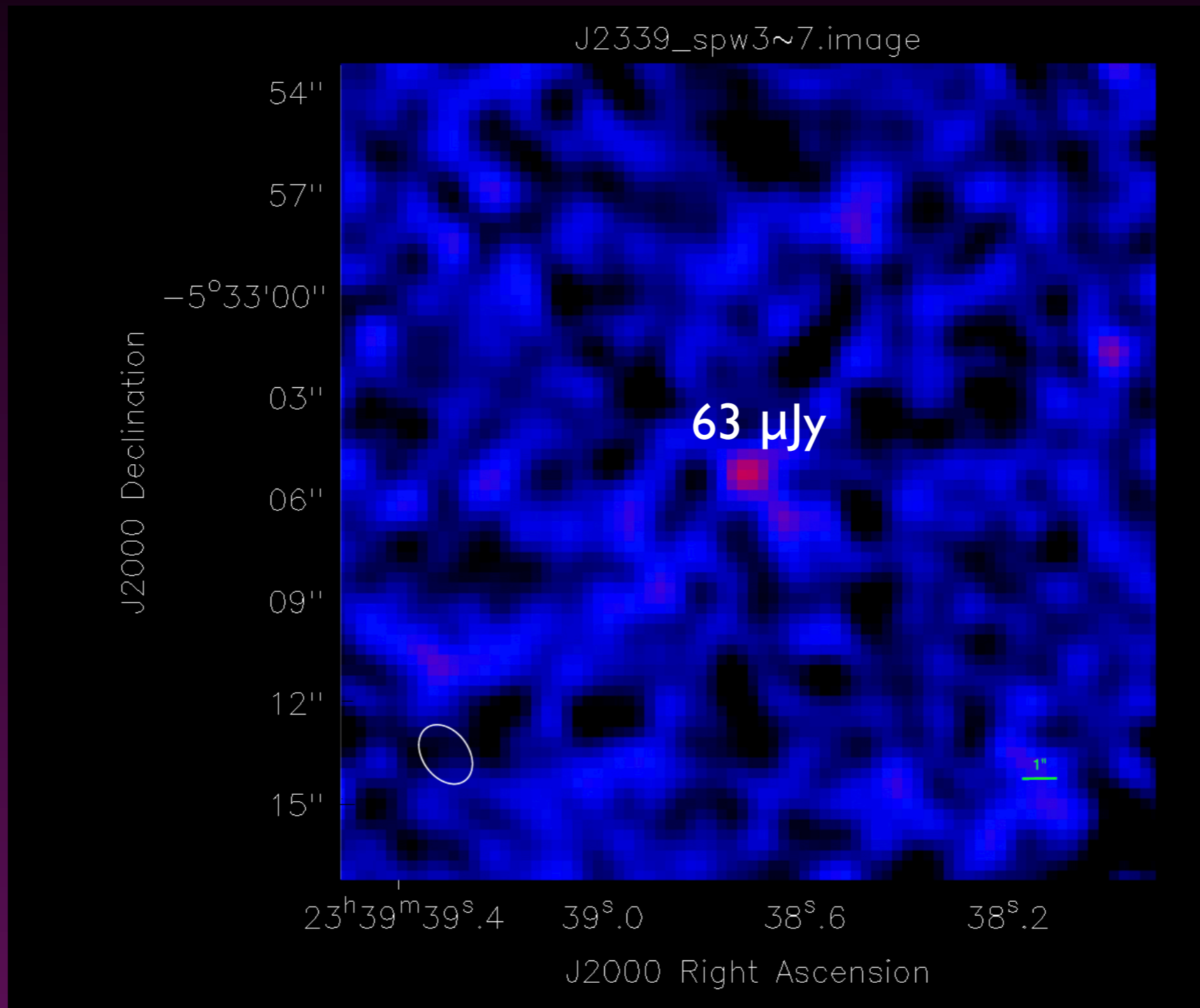
## Optical/X-ray @4.6hr



Kong+ 2012



# JVLA Continuum Observation of the RB MSP 1FGL J2339.7-0531



# 1FGL J1653.6-0158: a “radio-quiet” ultra-compact MSP?

- Steady gamma-ray source
- Exponential cutoff power-law spectrum
- X-ray/gamma-ray flux ratio:  $\sim 0.5\%$  (typical of MSPs)
- No pulsation from GBT (Ransom+ 2011) and Effelsberg (Barr+ 2013)
- The brightest X-ray source within the Fermi error circle has an optical counterpart ( $R \sim 20$ )

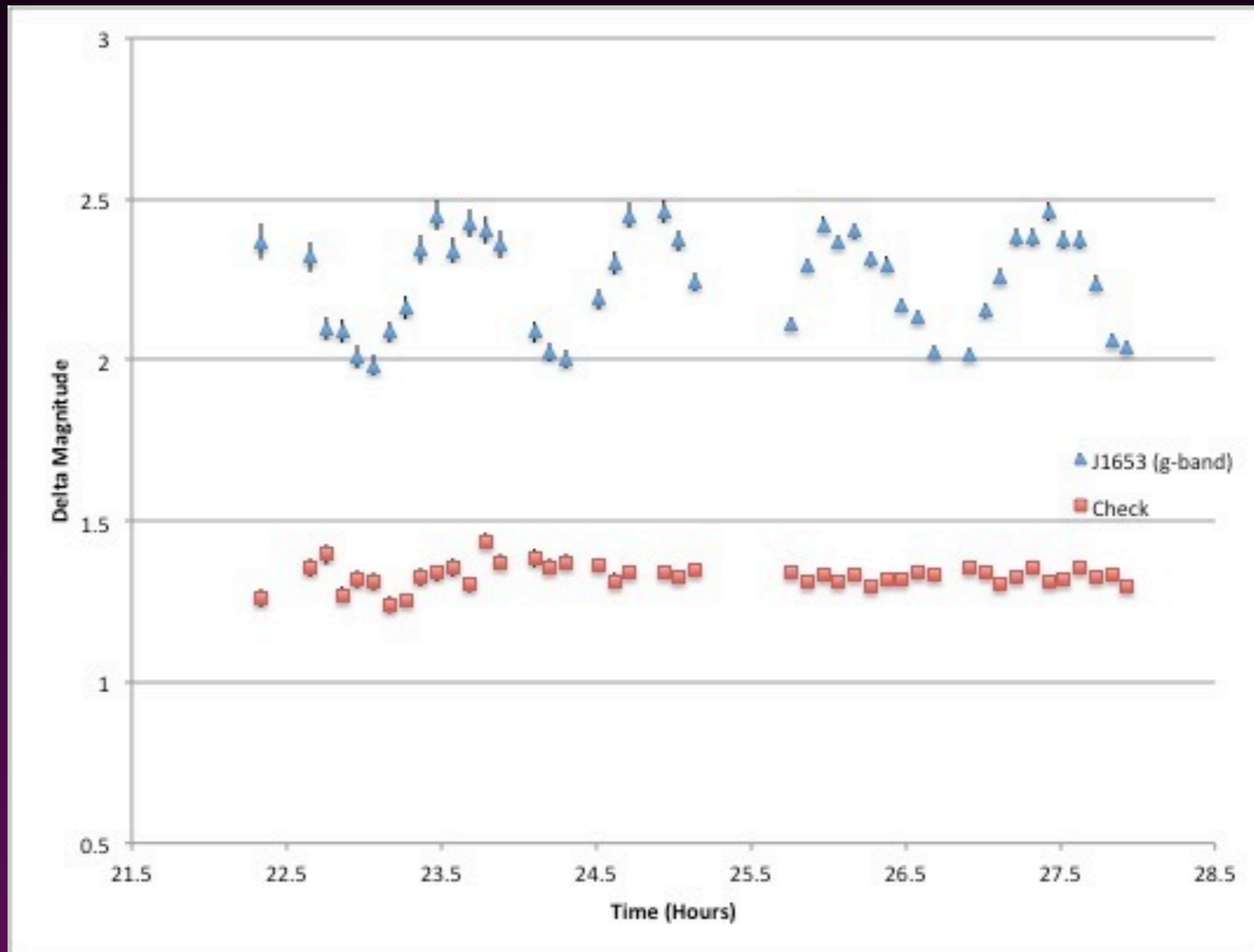
# IFGL J1653.6-0158: a “radio-quiet” ultra-compact MSP?

- Preliminary study was performed with the 1m telescope at Lulin Observatory in Taiwan
- Variability on timescale of 1 hour is seen
- We performed a time-series observation with the 2.5m INT at La Palma in 2014 June.

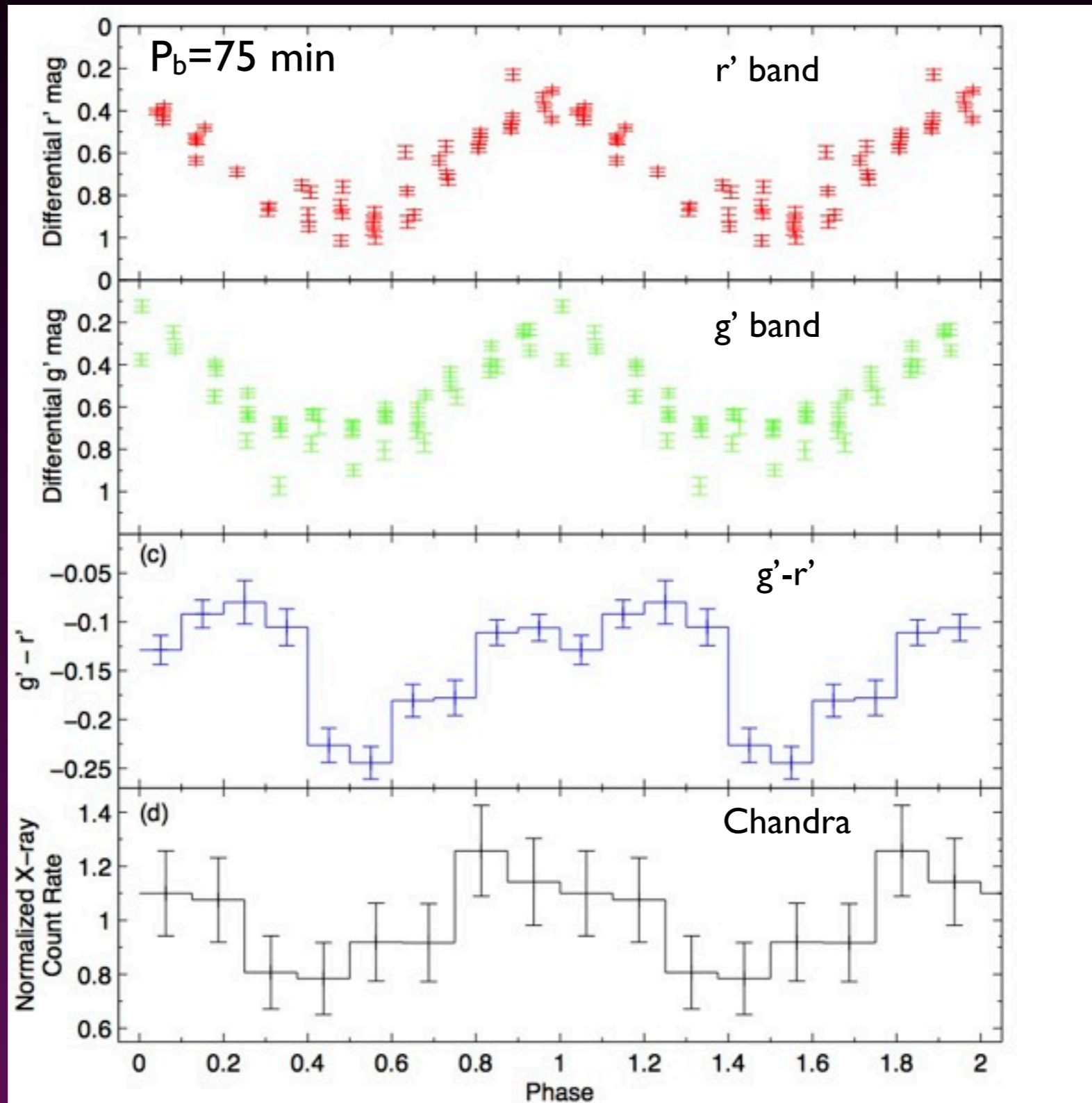




# IFGL J1653.6-0158: a “radio-quiet” ultra-compact MSP?



# 1FGL J1653.6-0158: a “radio-quiet” ultra-compact MSP?



# Ultra-compact MSP: A Missing Black Widow

- Accreting millisecond X-ray pulsars (AMXPs) have been found with ultra-compact ( $< 80$  min) binary periods
- An ultra-compact binary consists of a compact object and a degenerate or partially degenerate companion
- Ultra-compact binaries are important sources for gravitational waves
- It should be natural to have an ultra-compact rotation-powered MSP when the accretion of an ultra-compact AMXP stops
- IFGL J1653.6-0158 could be the first example of an ultra-compact MSP

# Ultra-compact MSP: A Missing Black Widow

- Optical spectroscopy shows that 1FGL J1653.6-0158 is hydrogen poor (Romani+ 2014) => more likely a black widow instead of a redback
- Pulsation search (radio, gamma-ray, and X-ray) will be the ultimate test
- An accurate optical orbital period will be crucial
- JVLA proposal was proposed to confirm if it is truly “radio-quiet”
- XMM and NuSTAR observations to obtain a better X-ray lightcurve and phase-resolved spectroscopy were proposed
- We are looking forward to the 3FGL catalog (>300 new UFOs)