A Multi-Messenger Approach to High Energy Sources

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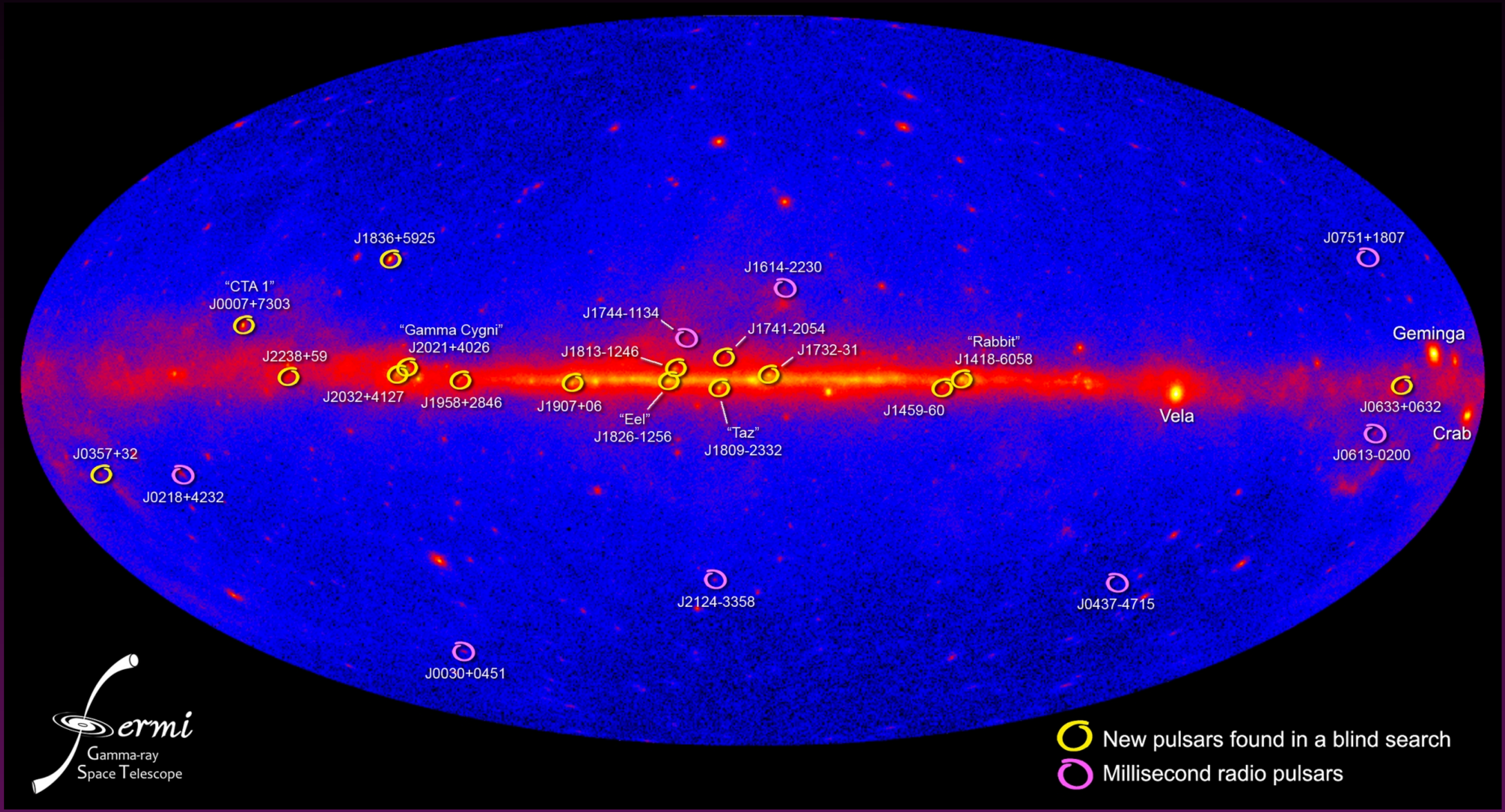
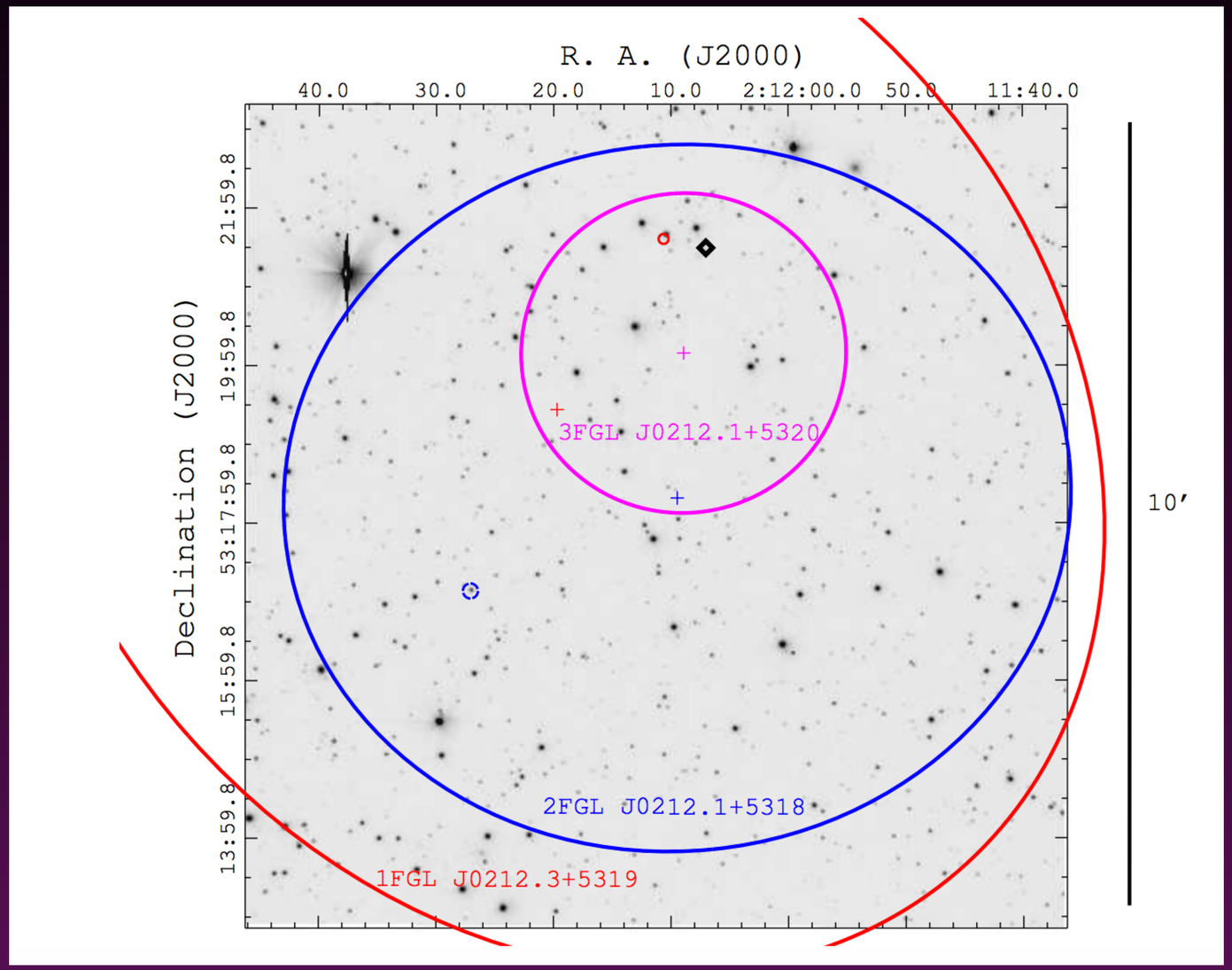
In astrophysics, localisation (hence the distance) is always the main problem

- Galaxies
- Quasars
- GRBs
- FRBs

Gamma-ray All Sky Map (>3000 sources)

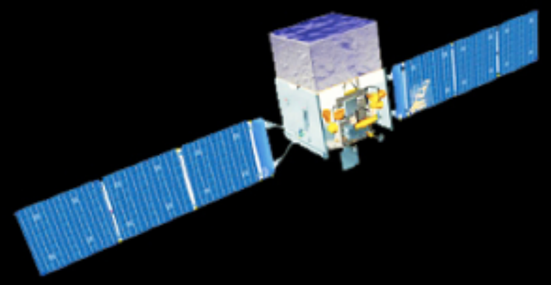


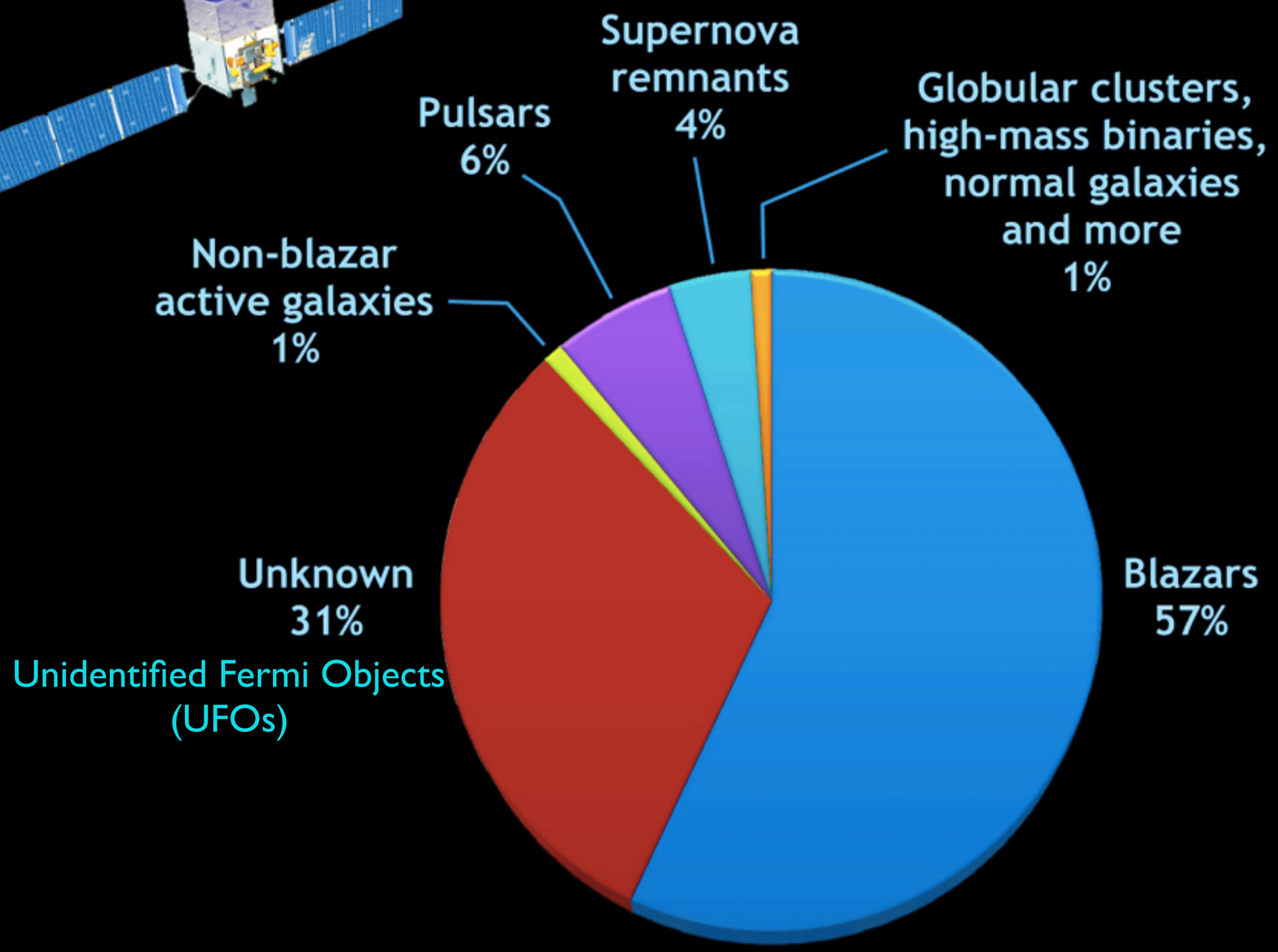
A Needle in a Haystack



Linares+ 2017

What has Fermi found: The LAT two-year catalog

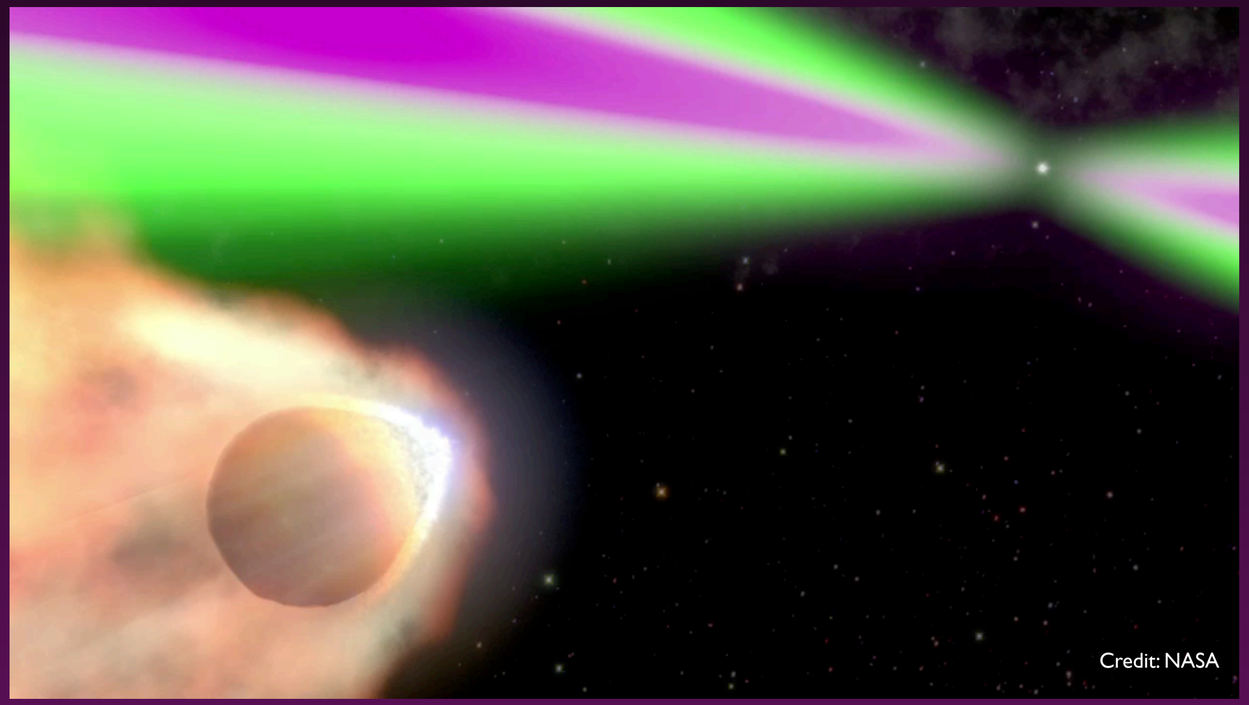




Credit: NASA/Goddard Space Flight Center

Black Widow MSPs

- PSR B1957+20 was first discovered in 1988 (Fruchter et al. 1988) as a radio eclipsed compact binary system
- Pulsar radiation can ablate the companion, leaving an isolated MSP at the end



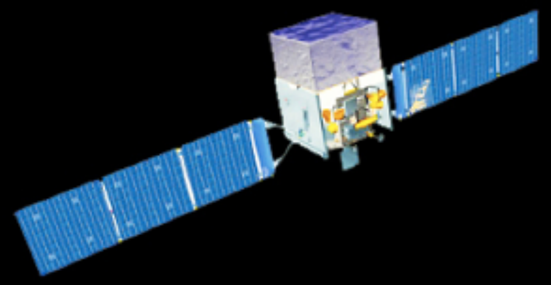
Black Widow MSPs

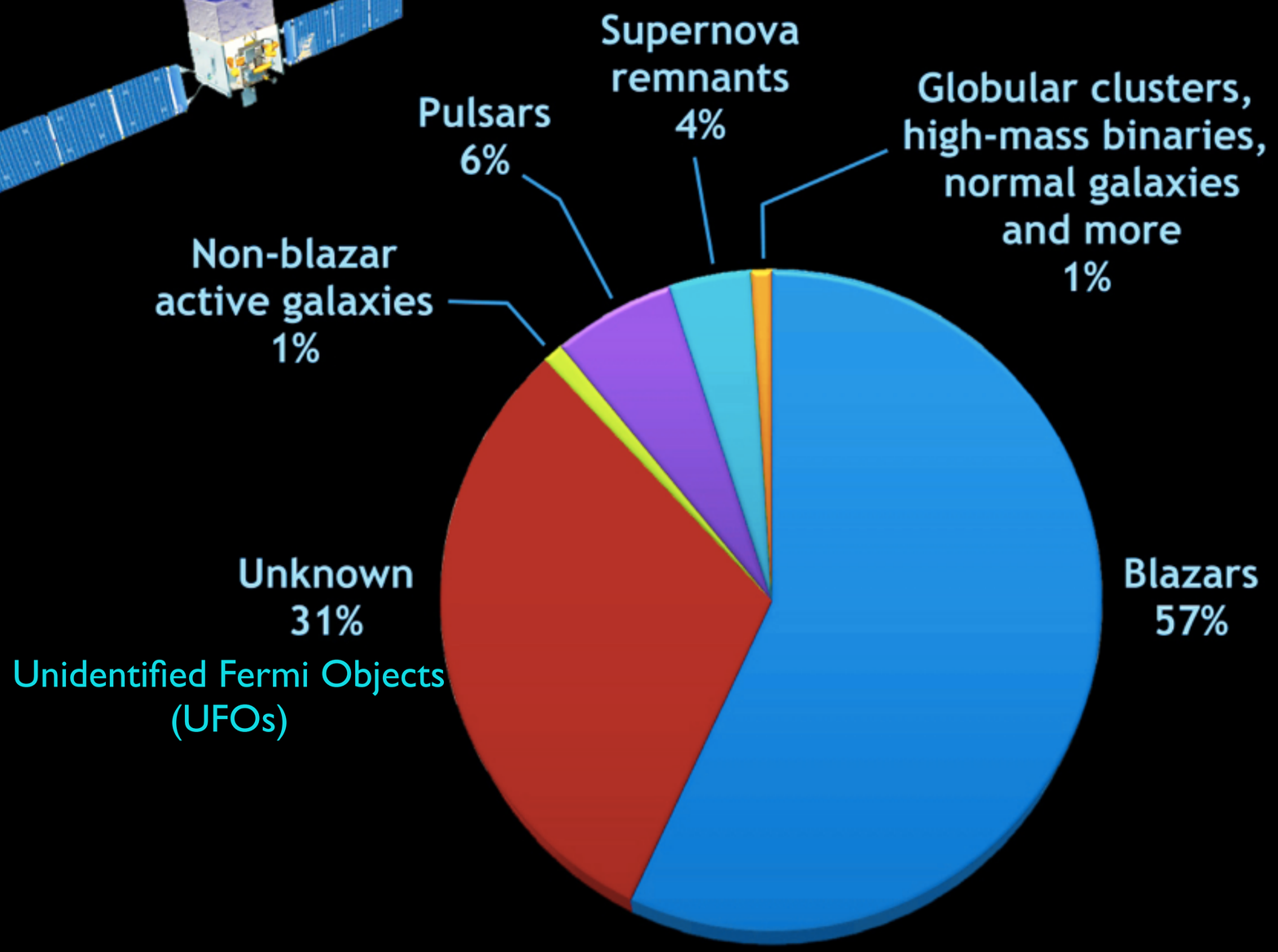
- Before the launch of Fermi in 2008, there are only 3 BW MSPs found out of > 100 MSPs.
- Traditionally, MSPs are found with radio timing.
- BW MSPs have orbital periods of < 1 day.
- Selection effects of radio biased the sample.
  - Timing in a compact system is difficult
  - Absorption and scattering in BWs is enormous
  - Radio plane survey
  - Usually discovered in globular clusters

Black Widow/Redback MSPs

- Fermi has changed the game
  - Radio/gamma-ray timing on Fermi sources
  - > 200 gamma-ray PSRs; many MSPs; > 20 MSP binaries with P_{orb} < 24 hr
- Companion can either be a less massive (< 0.1 $M_\odot$) degenerate object (black-widow) or a late-type-like > 0.1$M_\odot$ 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

What has Fermi found: The LAT two-year catalog

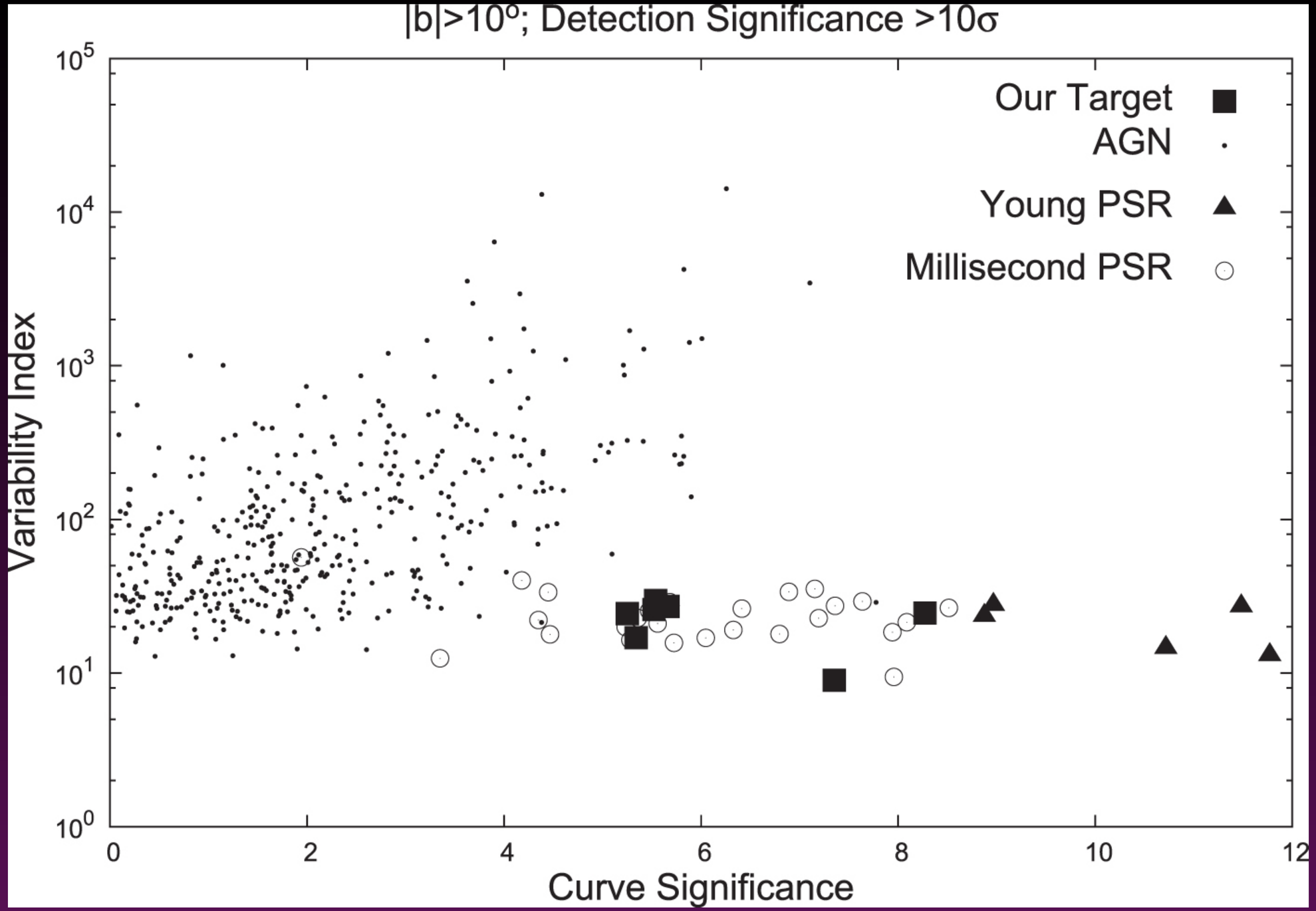




Credit: NASA/Goddard Space Flight Center

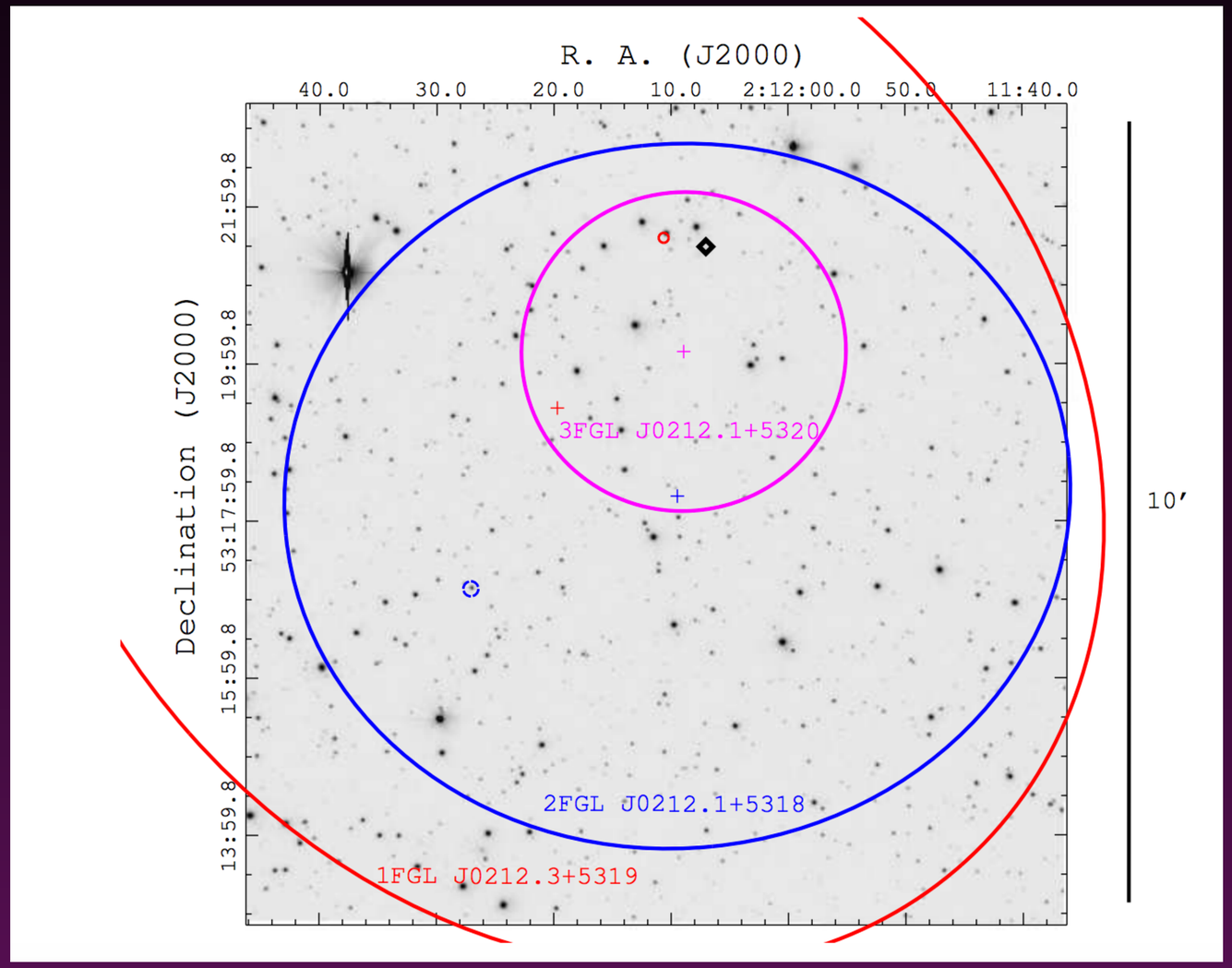
How can we search for BW/RB MSPs?

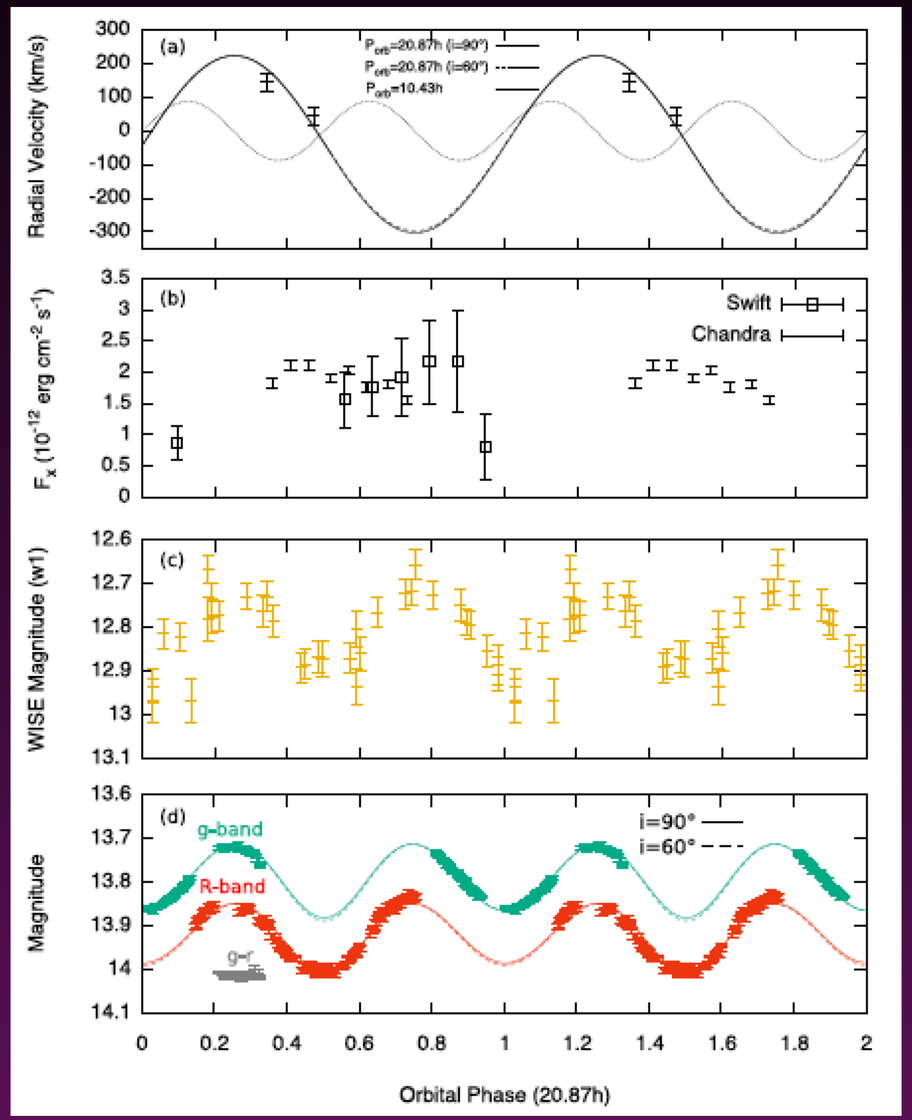
- Traditionally, MSPs are discovered via radio timing
- Radio timing at the Fermi's gamma-ray positions
- Blind search of gamma-ray pulsation is now possible with Fermi; it is however very hard for MSPs (Pletsch+ 2012, Science) and optical data are required
- MSPs can be ``radio-quiet''
- No radio => Need X-ray/gamma-ray data
- Too many X-ray sources and many different classes of sources
- Gamma-ray data are more ``simple''



Hui et al. 2015

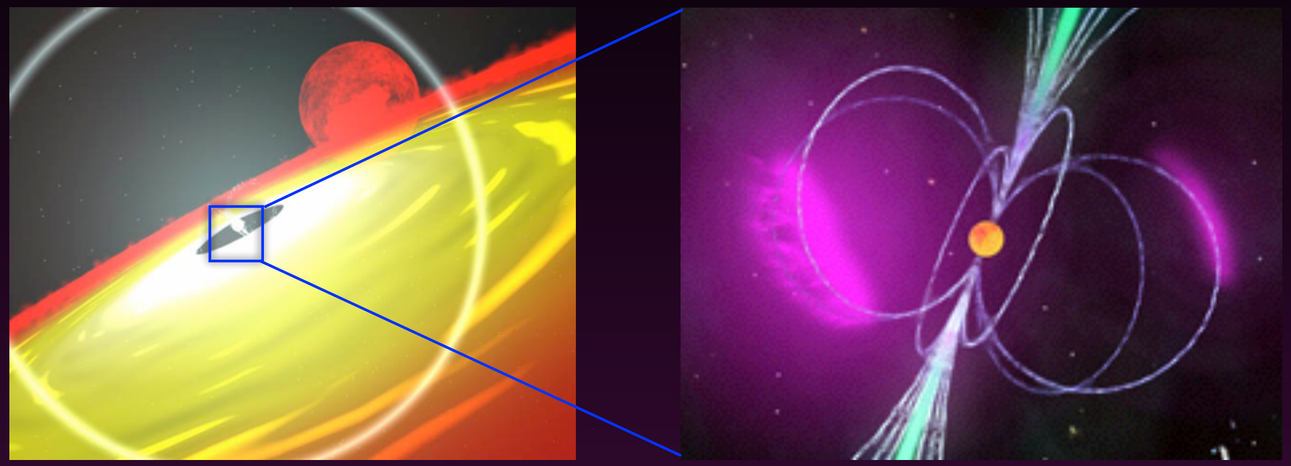
A Needle in a Haystack



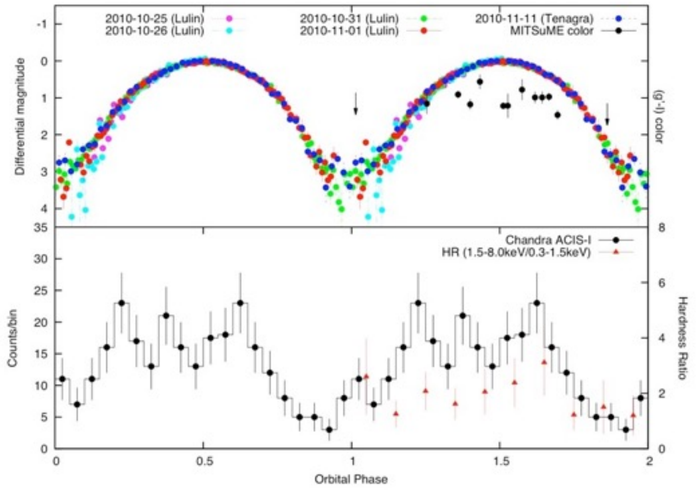


Li+ 2016; Linares+ 2017

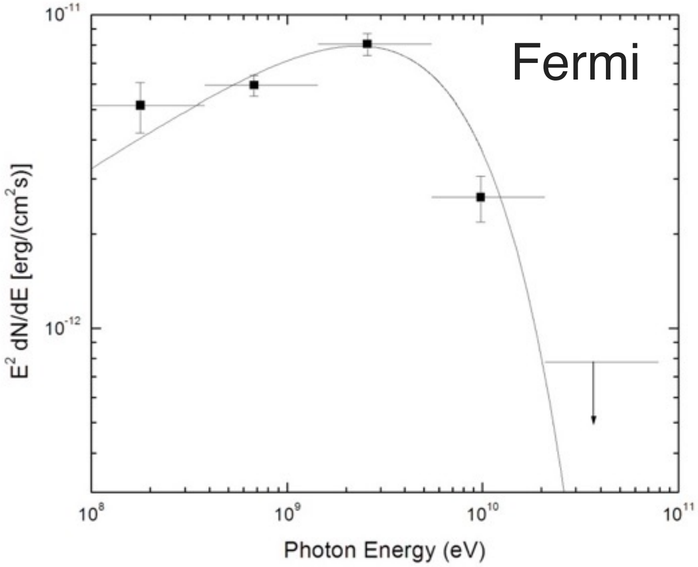
PSR J2339.7-0533: the first UFO as a redback



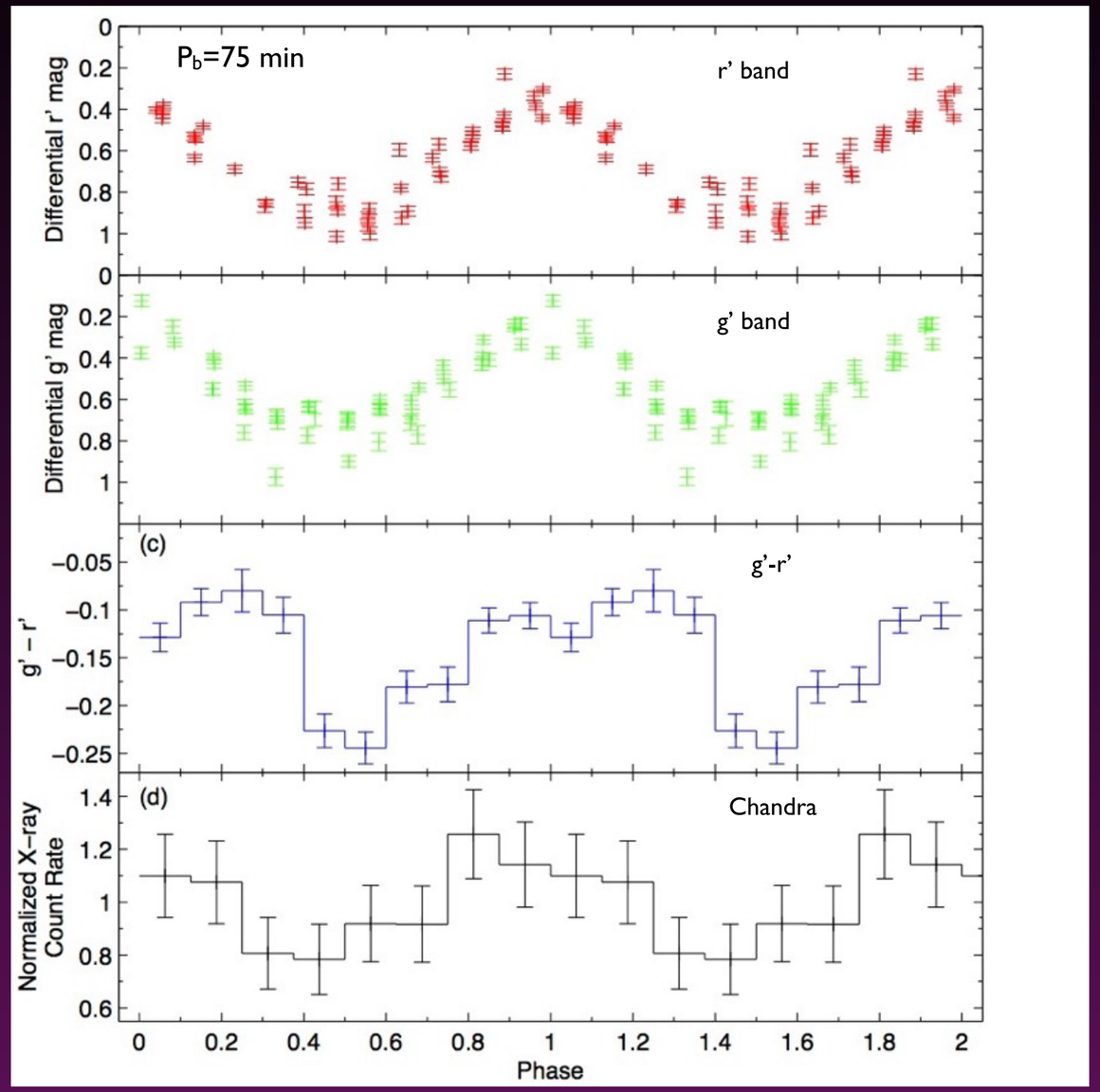
Optical/X-ray @4.6hr



Kong+ 2012



3FGL J1653.6-0158: a "radio-quiet" ultra-compact MSP?



Kong+ 2014

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
- 3FGL J1653.6-0158 could be the first example of an ultra-compact MSP

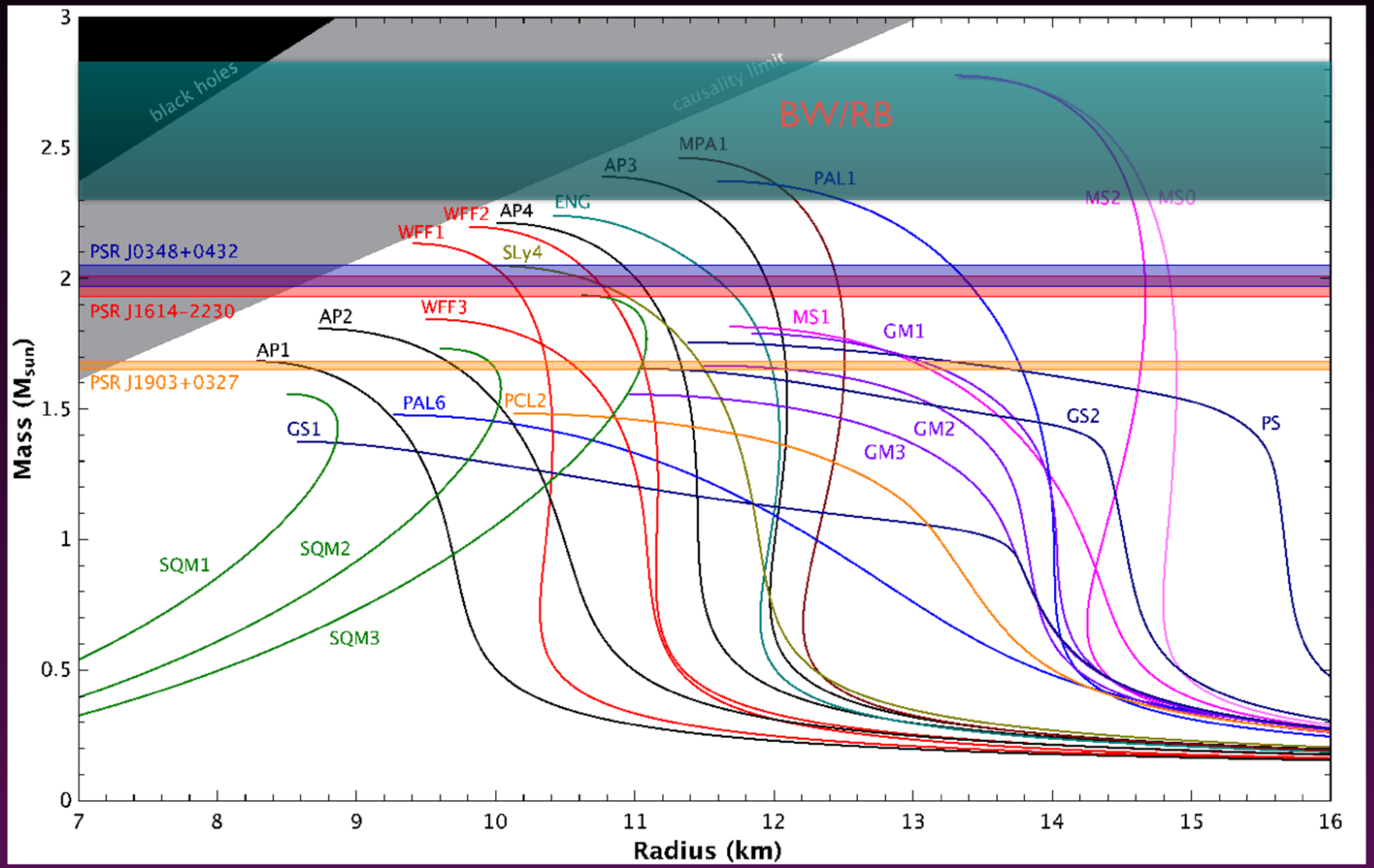
New BWs/RBs from UFOs

- 2FGL J1311.7-3429 = PSR J1311-3430 (Romani 2012)
- 1FGL J0523.5-2529 (Strader+ 2014)
- 2FGL J2039.6-5620 (Romani 2015; Salvetti+ 2015)
- 3FGL J1544-1125 (Bogdanov & Halpern 2015; tMSP candidate)
- 3FGL J1048.6+2338 = PSR J1048+2339 (Deneva+ 2016)
- 3FGL J0212.1+5320 (Li+ 2016)
- 3FGL J0838.8-2829 (Halpern+ 2017)
- See also Hui+ 2015 for other candidates

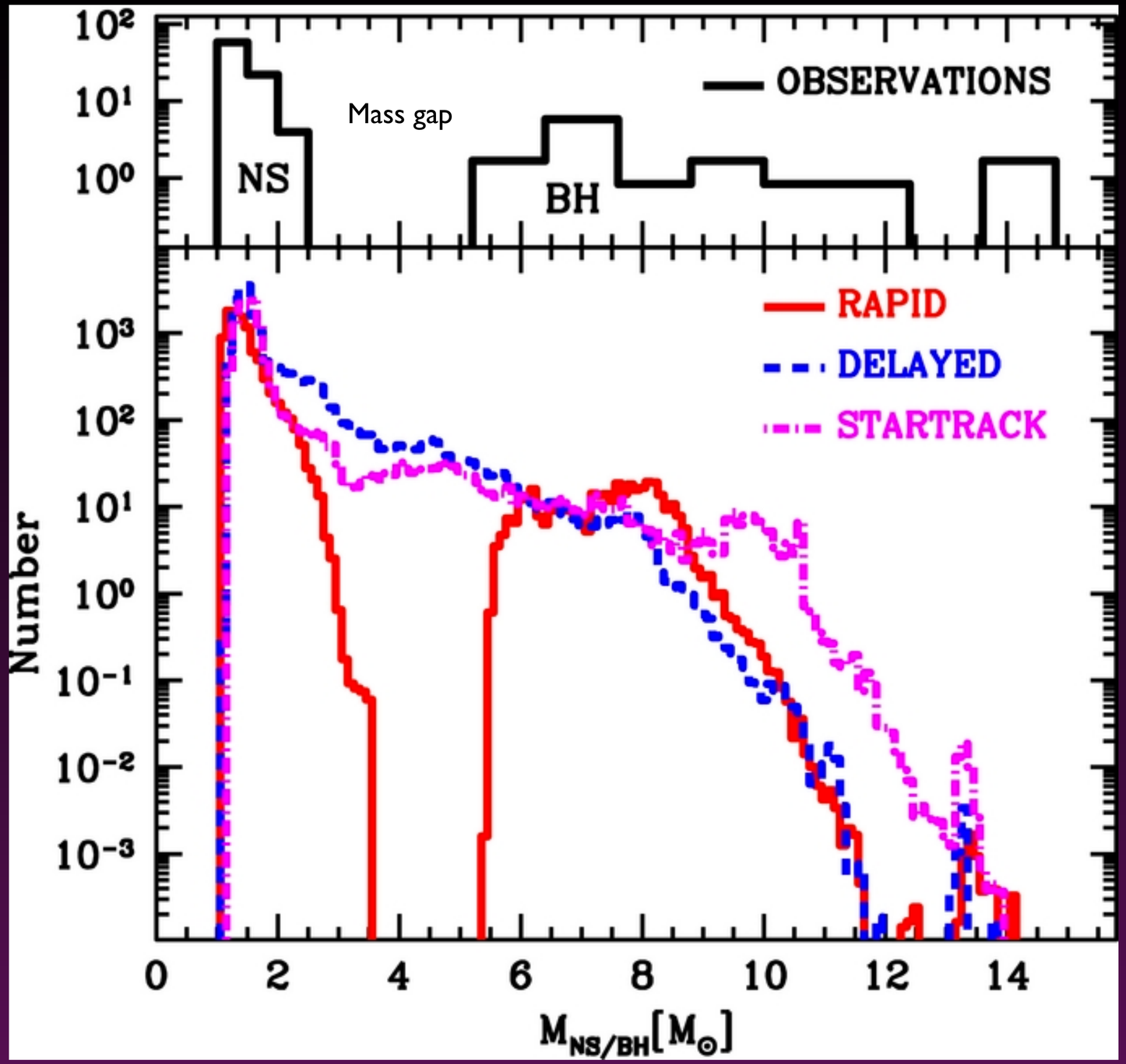
Constraining NS mass in BW/RB

- Classical pulsar timing involving relativistic effects cannot be used because of the winds and shocks
- We need optical light curves and spectra to constrain the mass ratio and inclination
- PSR J1959+2048: 2.40+/-0.12 solar (van Kerkwijk et al. 2011)
- PSR J2215+5135: 2.45(+0.22, -0.11) solar (Schroeder & Halpern 2014)
- PSR J1311-3430: 2.68+/-0.14 solar (Romani et al. 2014)

Equation of State



Kaspi 2016



GW150914
GW170104

Belczynski et al. 2012

Multi-wavelength Synergy

- Gamma-ray data with X-ray/optical identification play a key role in searching missing MSPs when radio pulsation search fails. There are still many UFOs. Radio-faint isolated MSPs? (see Clark+ 2018)
- The Fermi BWs/RBs have the shortest orbital periods and highest NS masses
- Optical/X-ray data are crucial in constraining the NS mass
  - Equation of State; mass gap of NS/BH
- Long-term all-sky gamma-ray/radio/optical survey will allow us to look for more “transformer” MSPs to understand the evolution of compact binaries

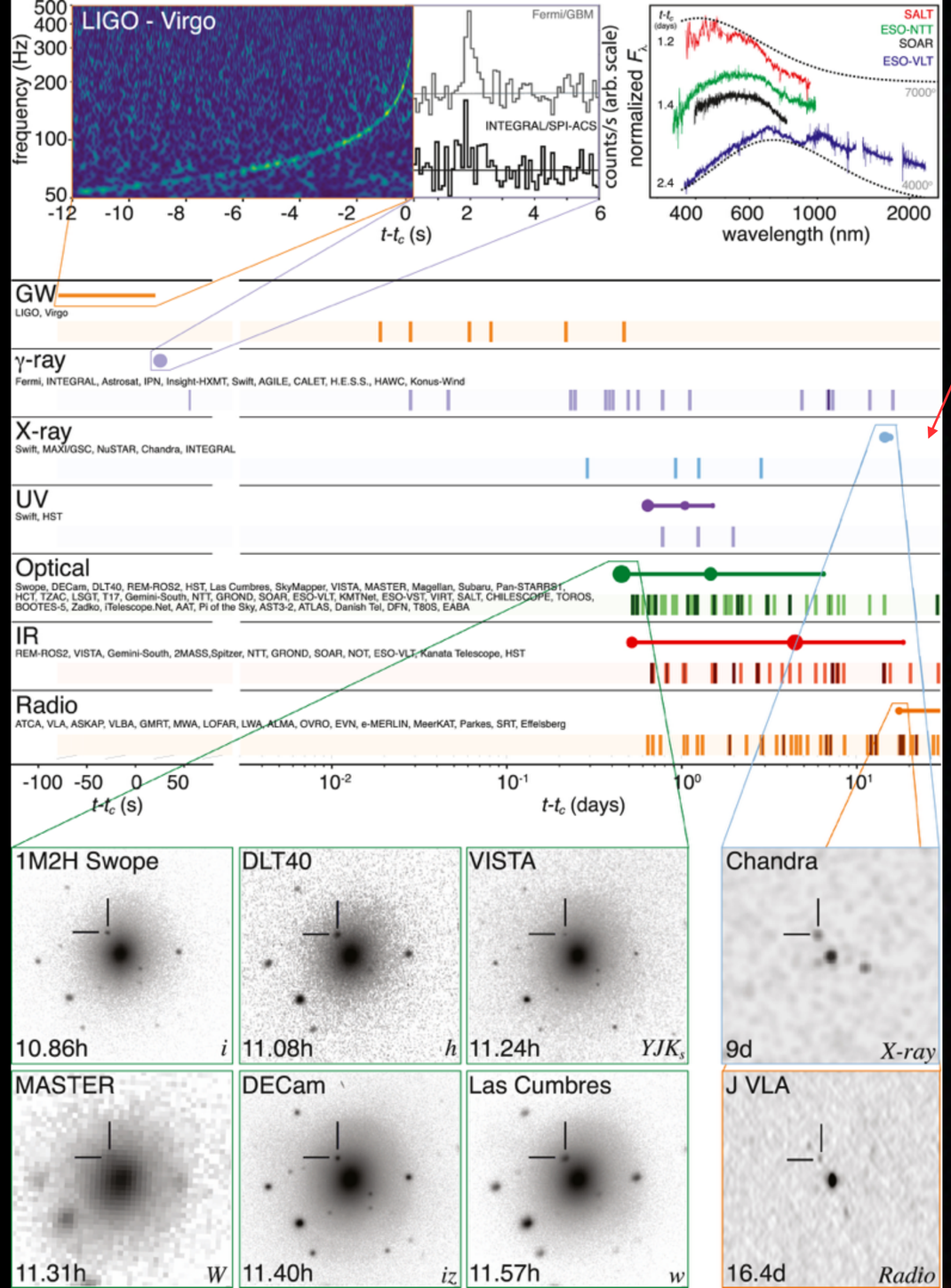
Why Multi-Wavelength and Multi-Messenger?

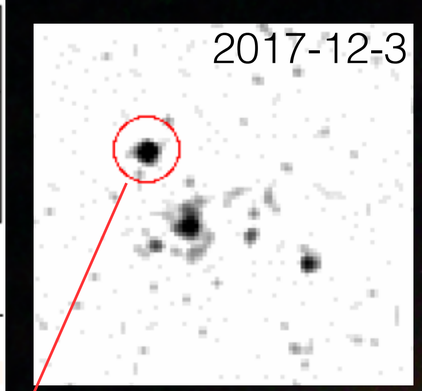
EM Wave

- Localisation
- Physical Origin
- Environment (stellar population, age, gas…)
- Host (if extragalactic)
- Distance
- Increase the confidence of a GW detection

GW

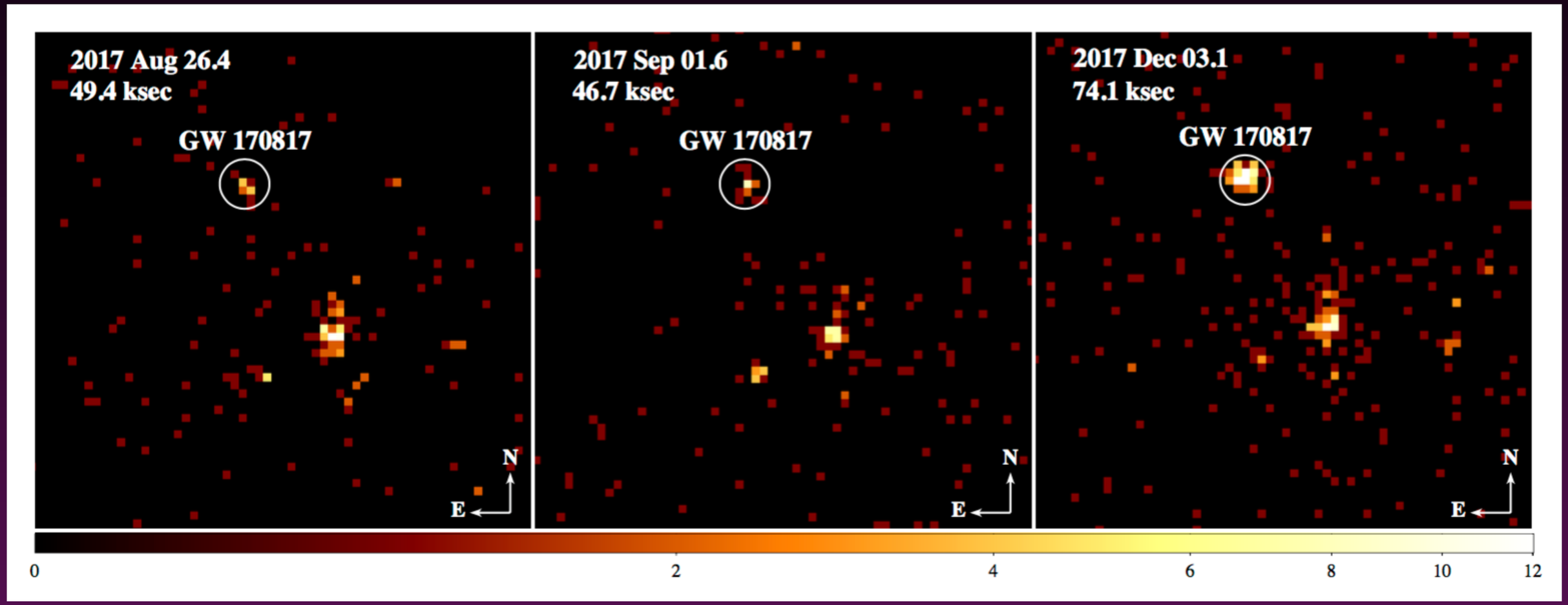
- Dynamics
- Progenitor mass and nature
- Distance
- Probe of central engine


LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized FλA
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-tc (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio

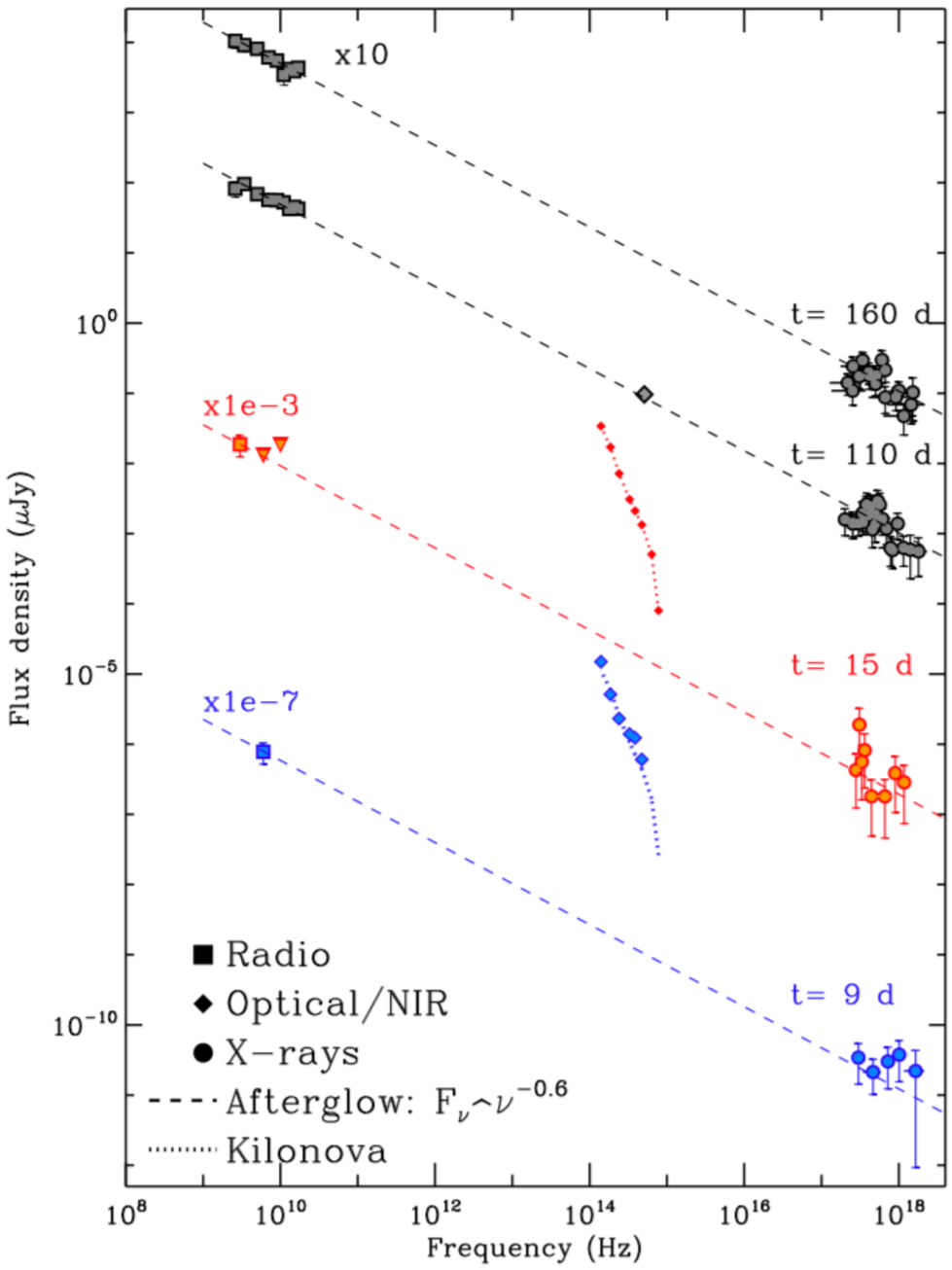

2017-12-3

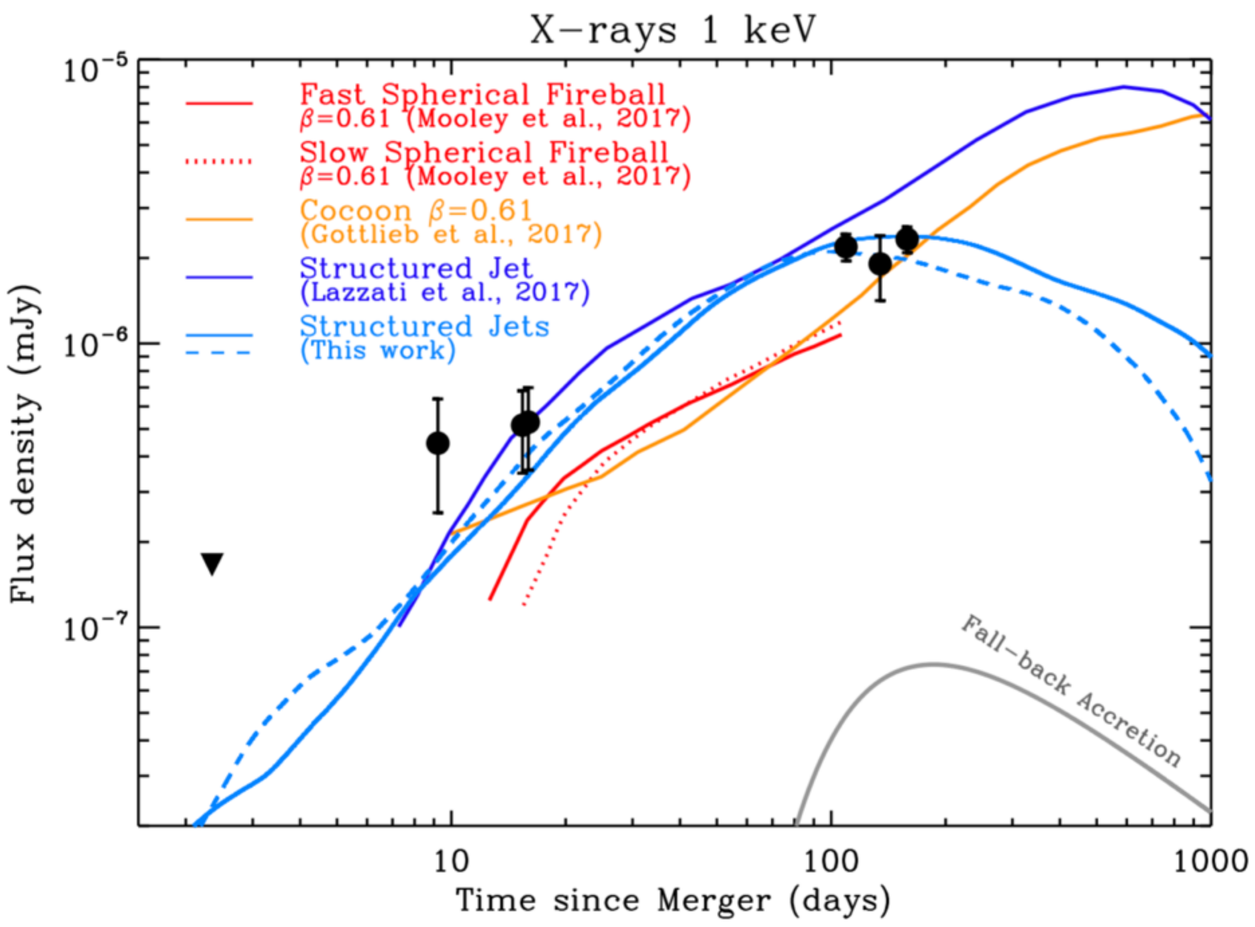

UV
IR
Radio

Chandra Follow-up



Pooley et al. 2018





Margutti et al. 2018

X-ray Brightening

- Day 108 is about 5 times brighter than that of Day 9
- Post-burst X-ray brightening rate is similar to radio and the SED can be described with a simple power-law
- X-ray and radio emission have a common origin (synchrotron emission)
- The emission is from an outflow afterglow models
  - A cocoon shocked by the jet, dynamical ejecta from the merger, or an off-axis structured jet
- Future X-ray follow-up may be able to distinguish different models
- Spectral change can imply a synchrotron cooling break at X-ray

X-ray Spectroscopy

- Current limitation is on the photon statistics
  - From ~20 counts to 100-200 X-ray photons
- Analysis based on chi2 minimisation provides no evidence of spectral evolution
- Spectra can be described with an absorbed power-law model with a photon index of ~1.6 (some errors are large: 0.8-3)

A Bayesian Approach

- Chi2 fitting requires Gaussian errors
  - It is common to bin the data so that each spectral bin has a Gaussian error (lost of information)
- For low photon counts, it is not the case
- Previous analyses involve background subtraction. The background subtracted data are not Poisson-distributed. Poisson-based statistic cannot be used
- The proper way to treat background data is to model them
- Chi2 fitting provides a less accurate estimate of the true values

A Bayesian Approach

- Because a Bayesian approach does not require Gaussian errors, we do not bin the energy spectra
- We include background using a background poisson process and we perform the fit simultaneously with the source data
- We allow the absorption as a free parameter
- Posterior distributions of spectral parameters were obtained by running 100,000 MCMC chains.

A Bayesian Approach

- With Bayesian analysis, we found that the X-ray spectra of GW170817 may change over the first 5 months after the burst
- The spectrum seems to be harder during the first observation
- The photon index is slightly steeper (photon index ~ 2.5) than previously obtained. The radio-X-ray SED may not be a simple power-law.
- This may have important implications for the models