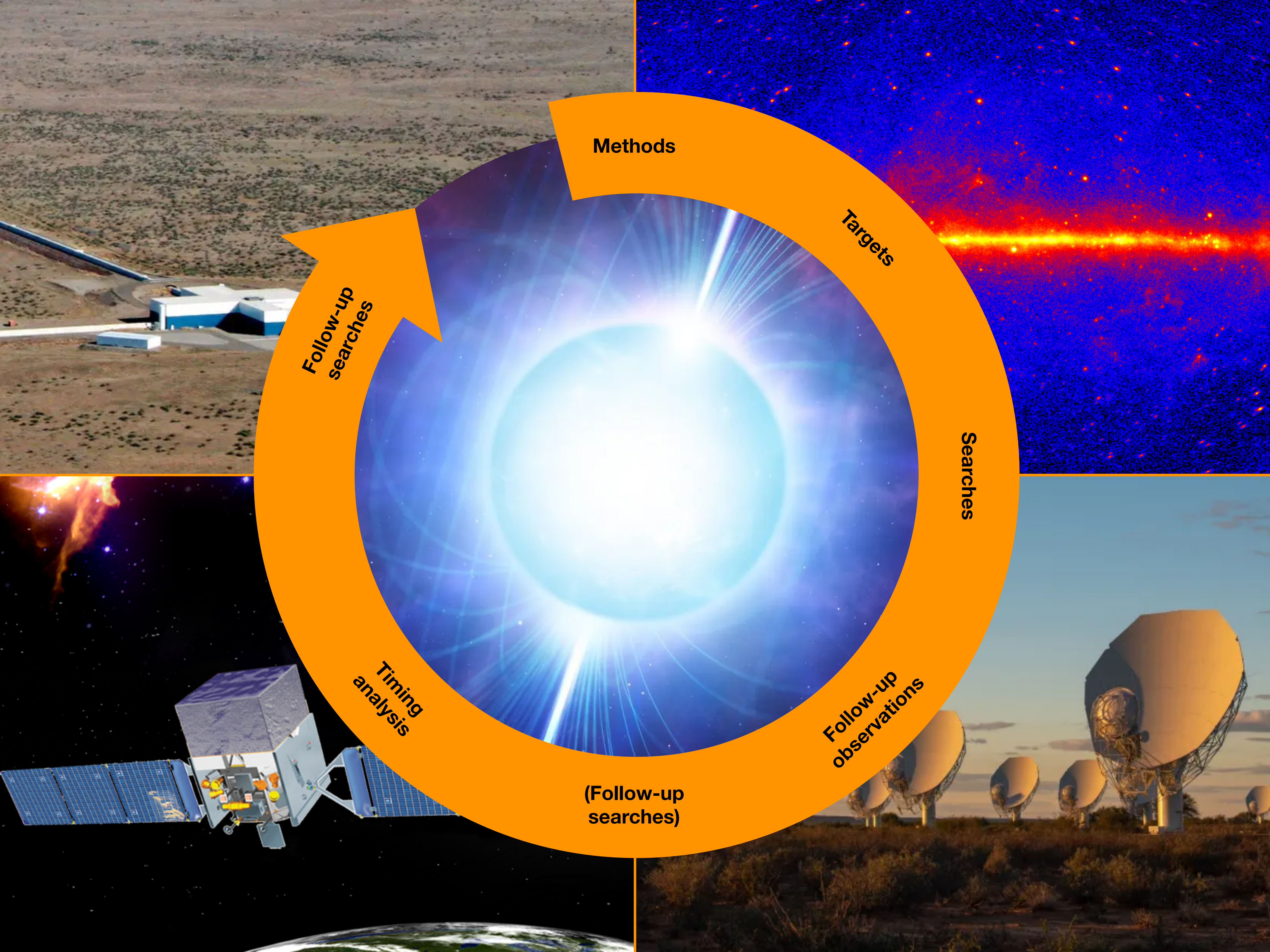
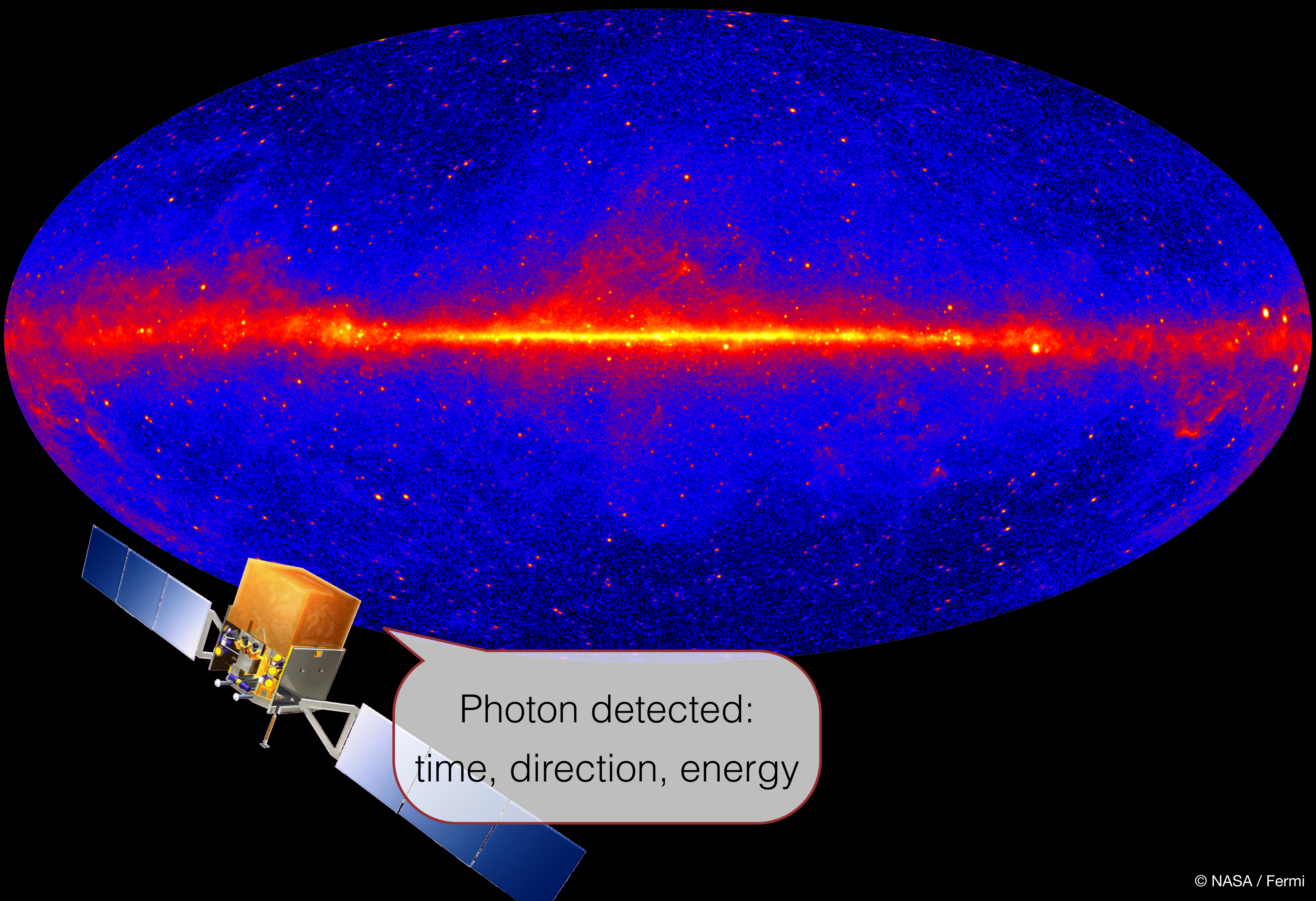
Long-term pulsar timing solutions with joint radio and gamma-ray analyses support searches for gravitational waves

Lars Nieder
Collaborators: M. Burgay, C. Clark, P. Freire
18. June 2024

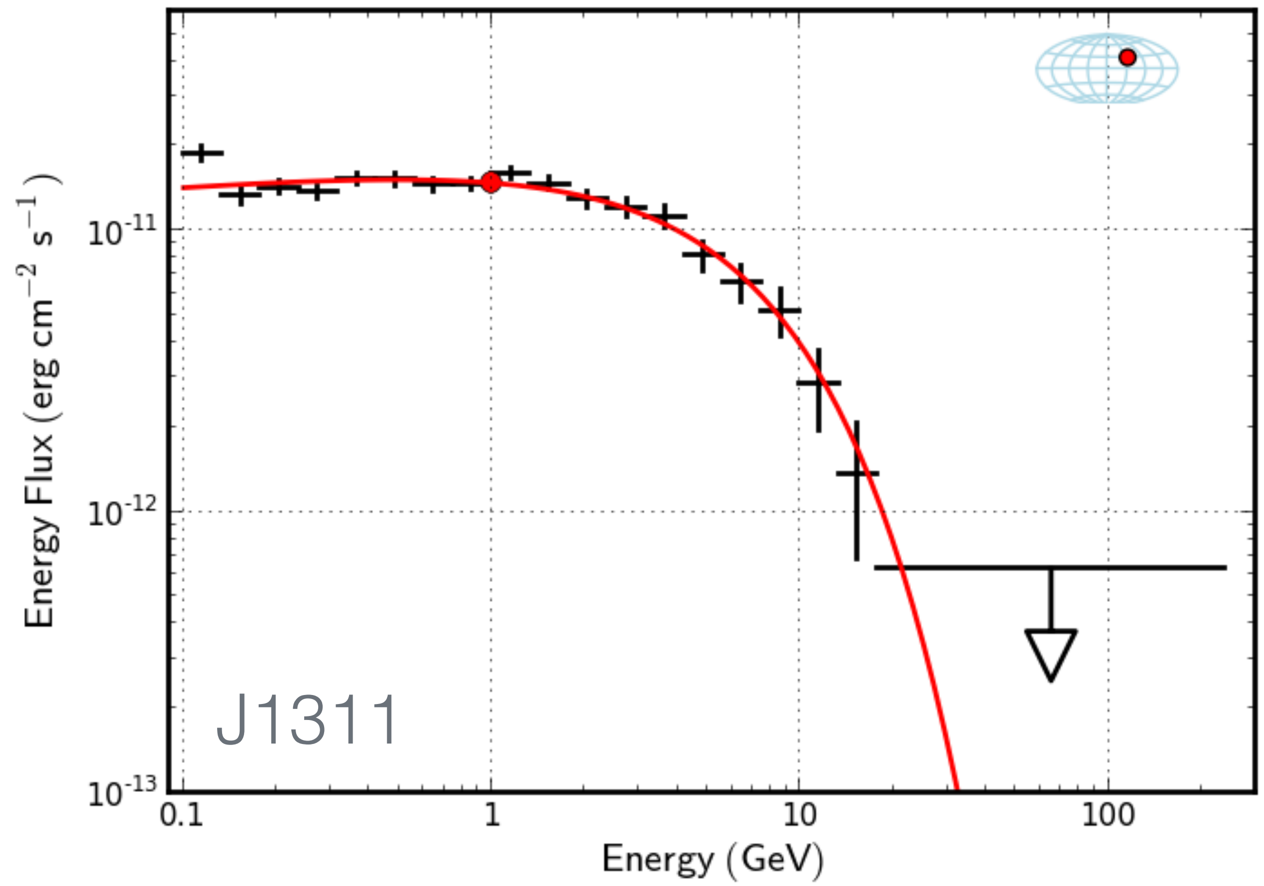
MAX-PLANCK-GESELLSCHAFT
Max Planck Institute for Gravitational Physics (Albert Einstein Institute)
Leibniz Universität Hannover
Fermi Gamma-ray Space Telescope

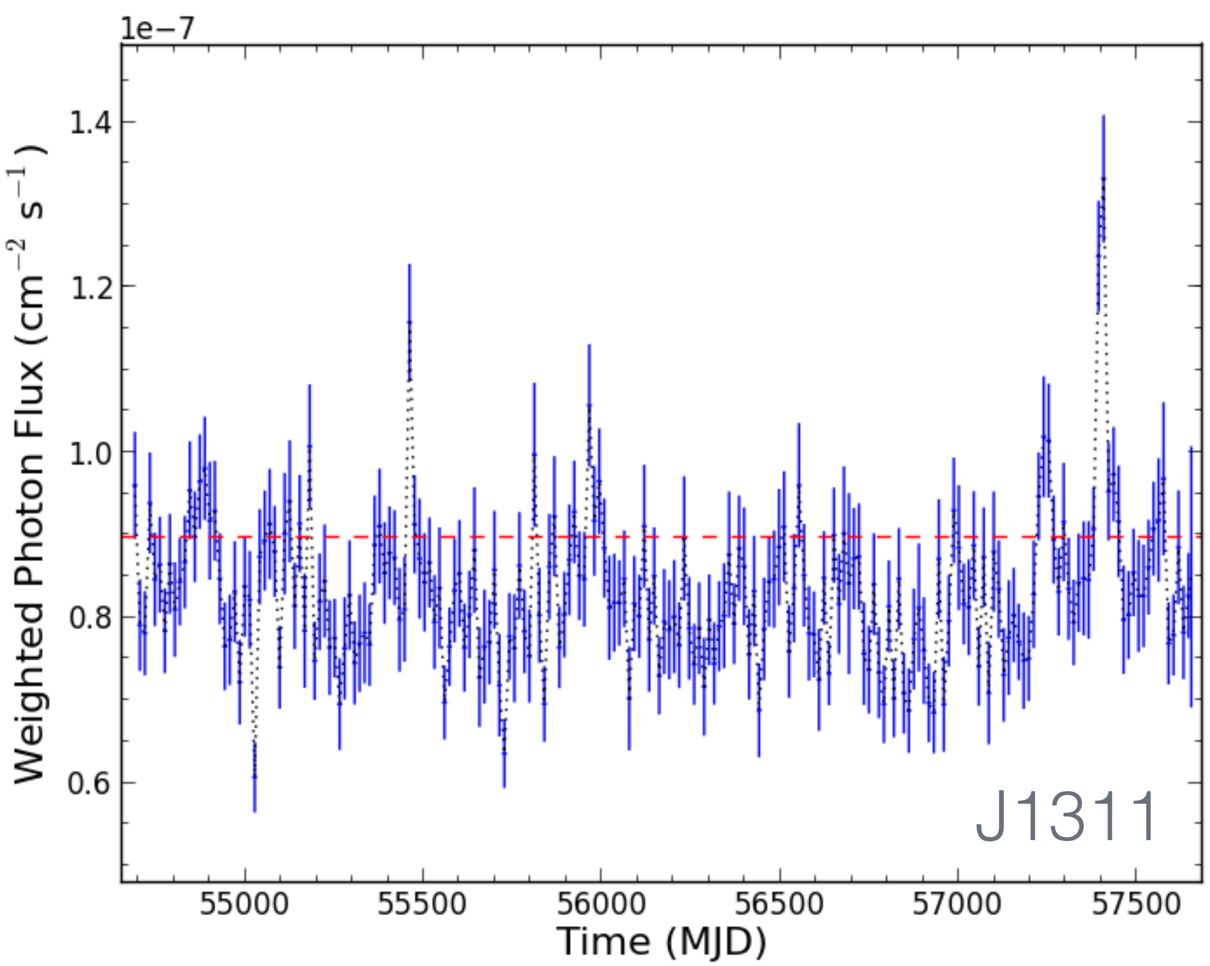

Methods
Targets
Searches
Follow-up observations
(Follow-up searches)
Timing analysis
Follow-up searches


Photon detected:
time, direction, energy
© NASA / Fermi

Typical Gamma-ray Pulsar Properties

Highly curved spectrum





Low time variability

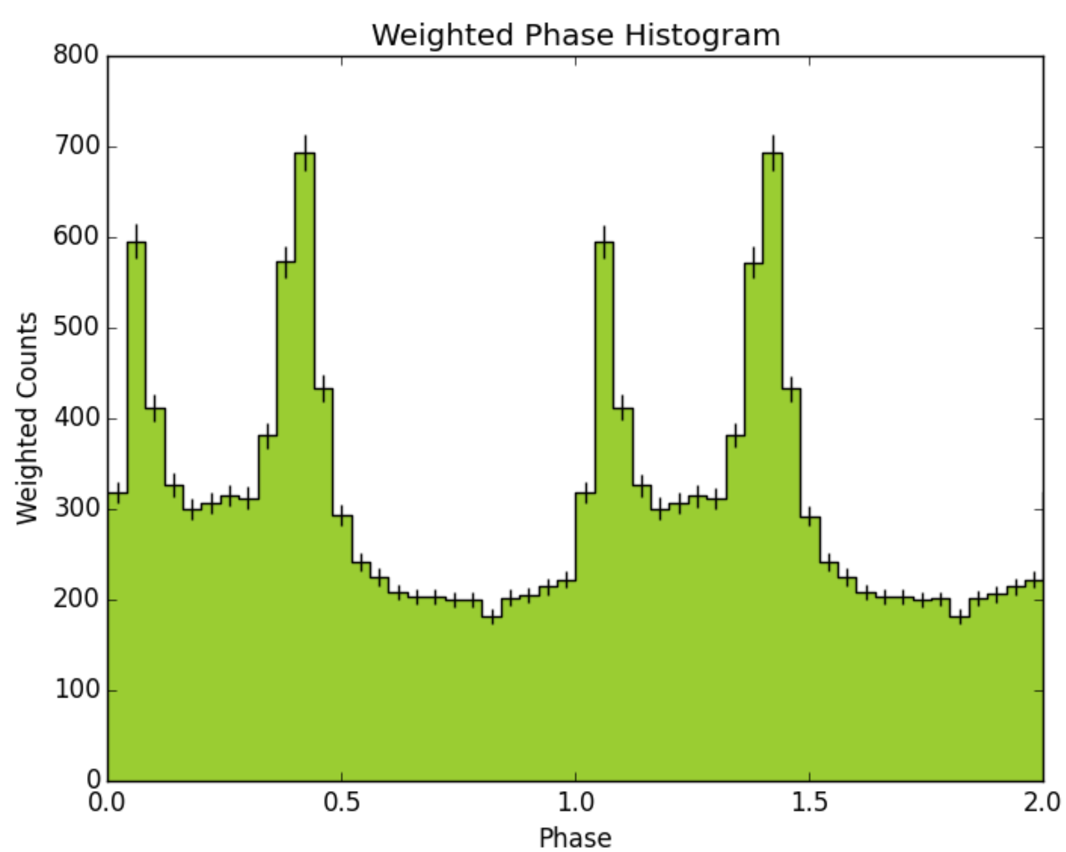
Credit: J. Wu

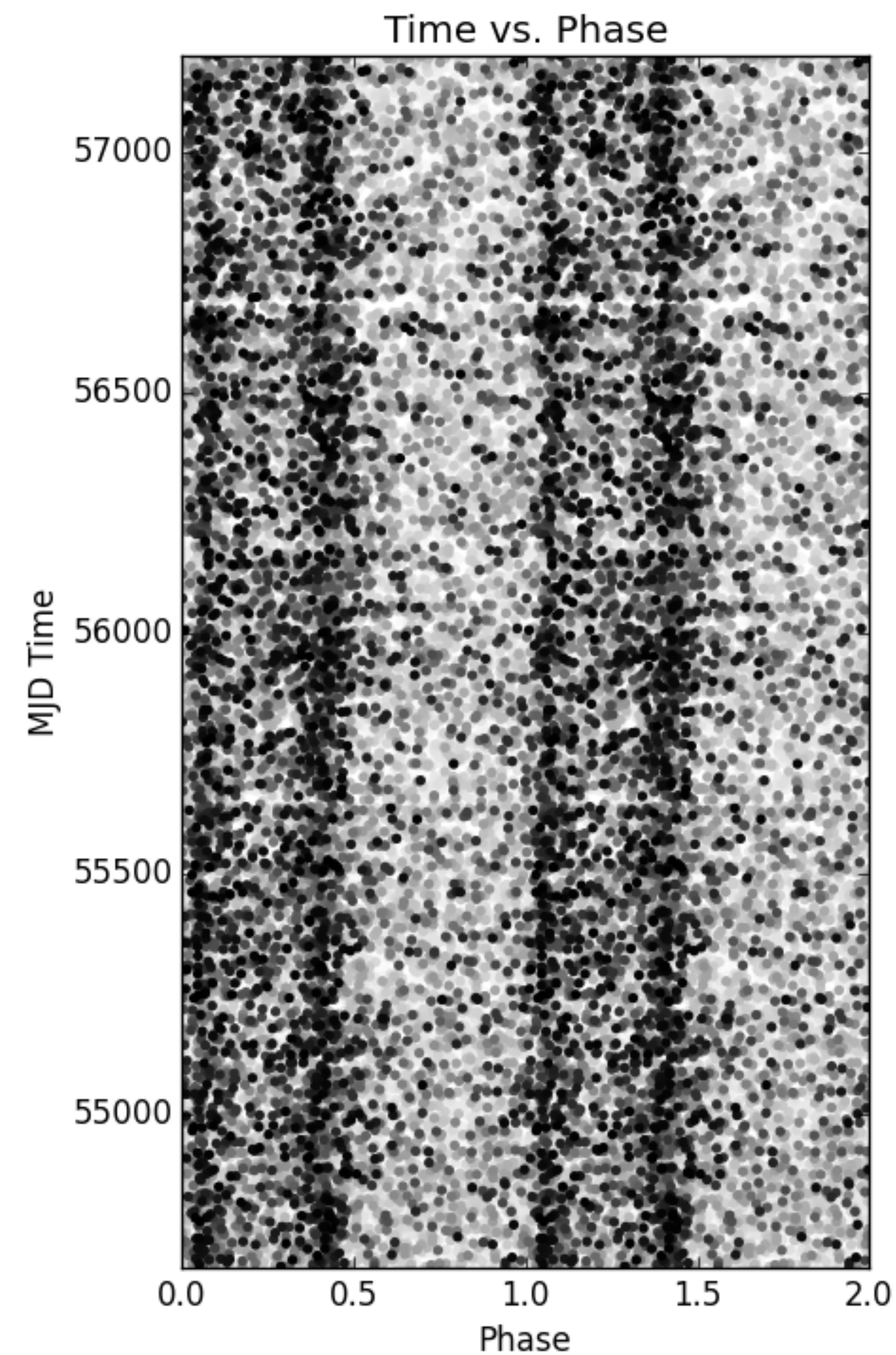
Folding Gamma-ray Data

- Phase model (counted in rotations):

$$\Phi = f t_{\rm psr} + \frac{1}{2}\dot{f} t_{\rm psr}^2$$

- Assign every photon with the pulsar's rotational phase at emission
- Need to account for Doppler shift

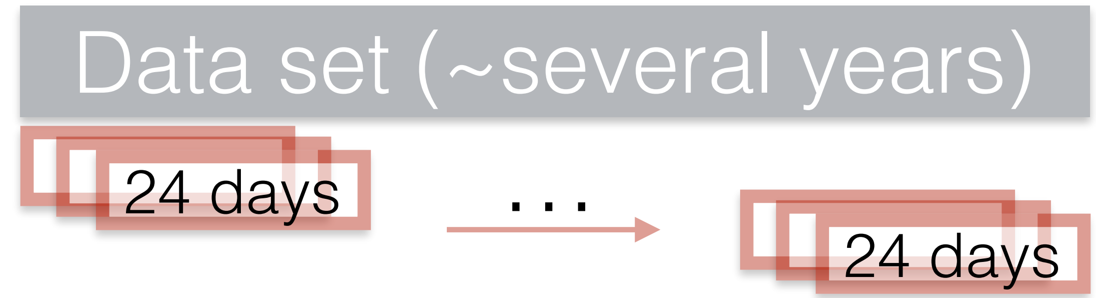




Credit: Pletsch+ (2012)

Search tools

Pletsch, H. J., & Clark, C. J. 2014, ApJ, 795, 75



Zooming in

Hierarchical multi-stage search:

- Semi-coherent stages

  Efficiently scan large parameter spaces

- Fully coherent follow-up in finer grid
- Include power in higher harmonics

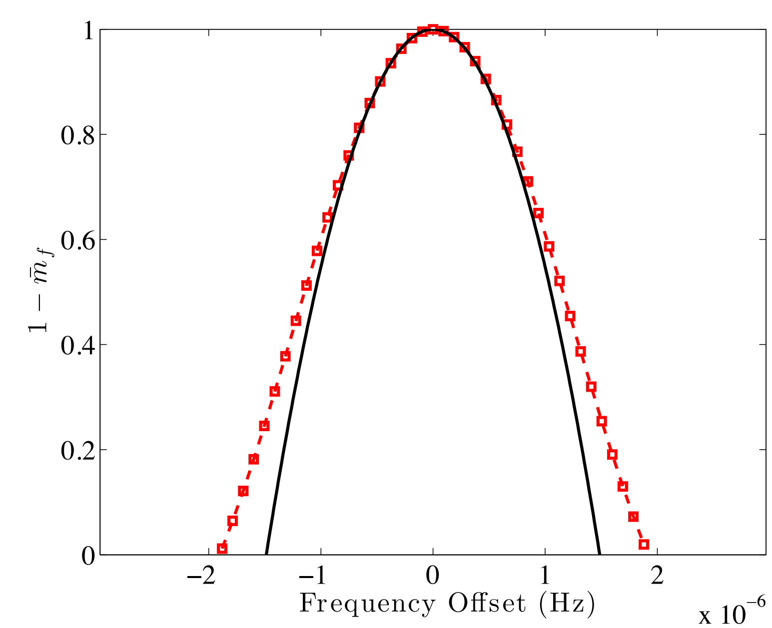
Computing resources:

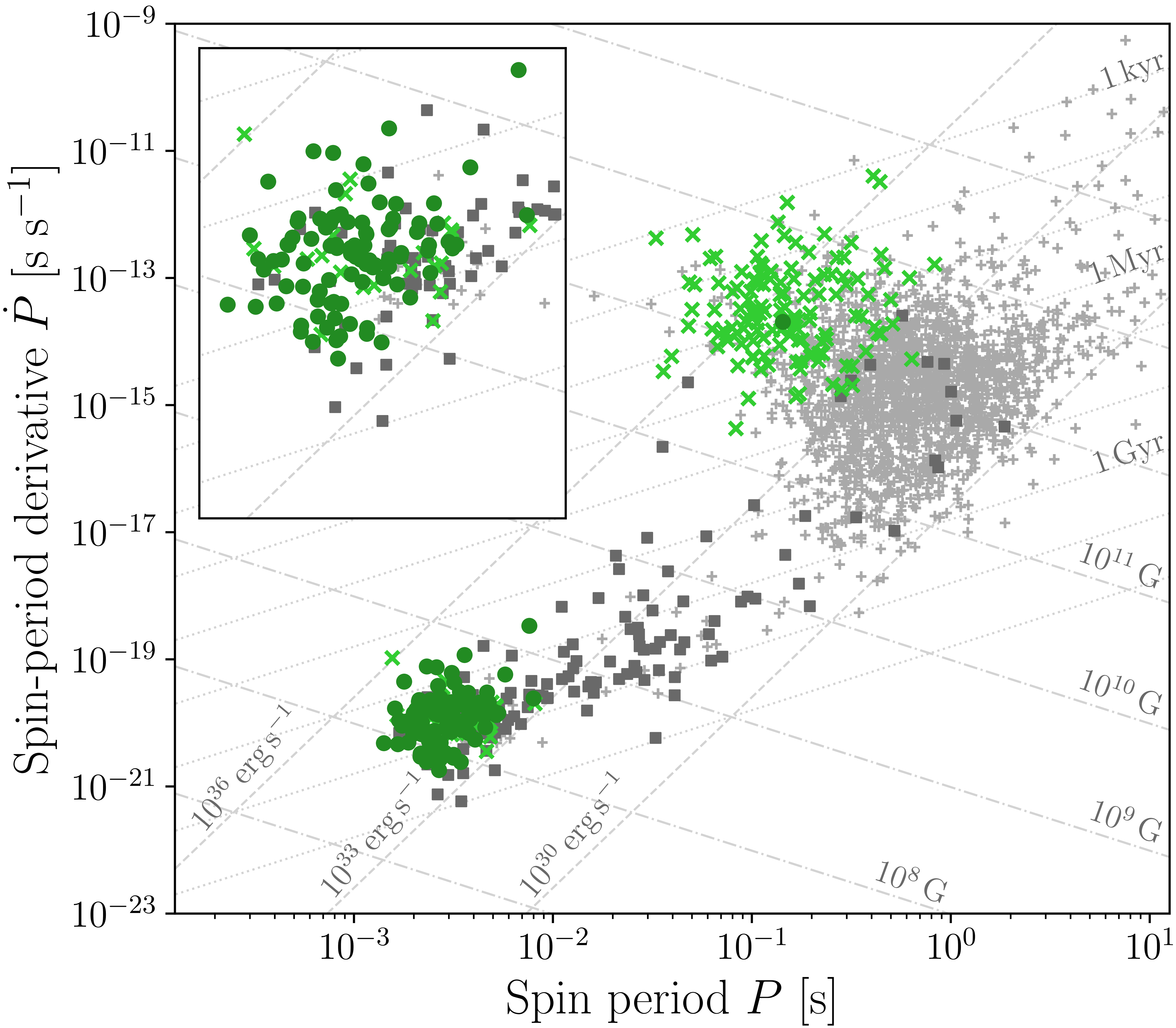
- ATLAS computing cluster at AEI
- Einstein@Home project using volunteer computer's idle time

Generation of efficient grid:

- Utilization of distance metric

  Second order approximation
  of expected signal-to-noise loss





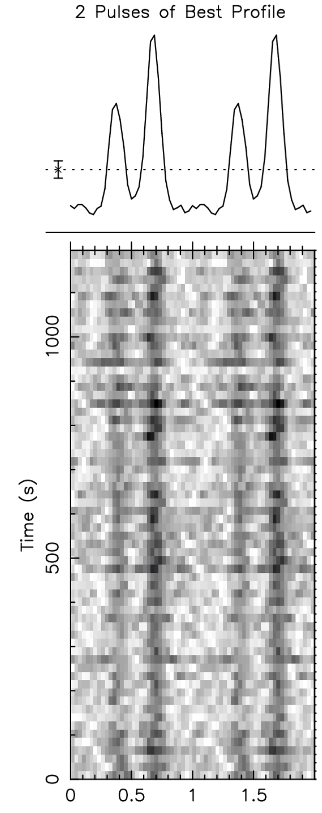
Spin-period derivative $\dot{P}$ [s s^{-1}]
Spin period P [s]
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
1 kyr
1 Myr
1 Gyr
10^{11} G
10^{10} G
10^{9} G
10^{8} G
10^{36} erg s^{-1}
10^{33} erg s^{-1}
10^{30} erg s^{-1}

CW follow-ups

PSR J0952−0607

- follow-up search
- black widow pulsar
- extremely fast spinning (707Hz)
- CW follow-up in O1data

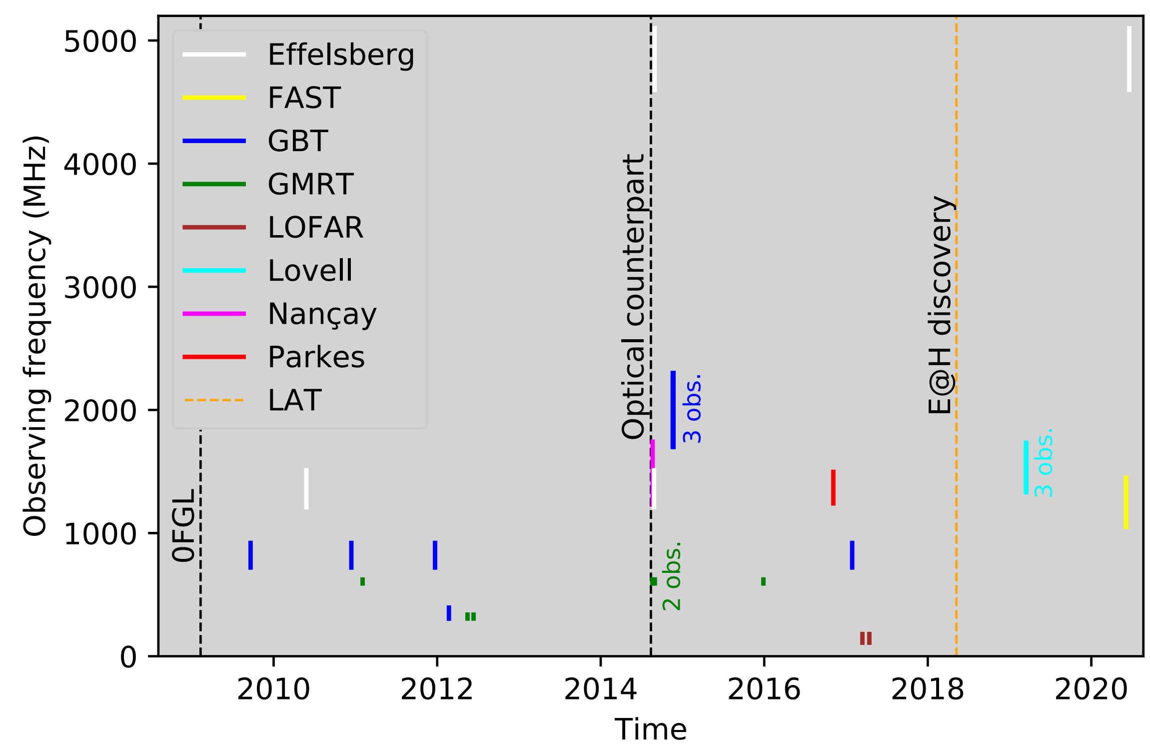
LOFAR core



Credit: Bassa+2017,Nieder+2019

PSR J1653−0158

- partially-informed search
- black widow pulsar
- tight orbit (75min, 0.01lts)
- CW follow-up in O1 & O2 data



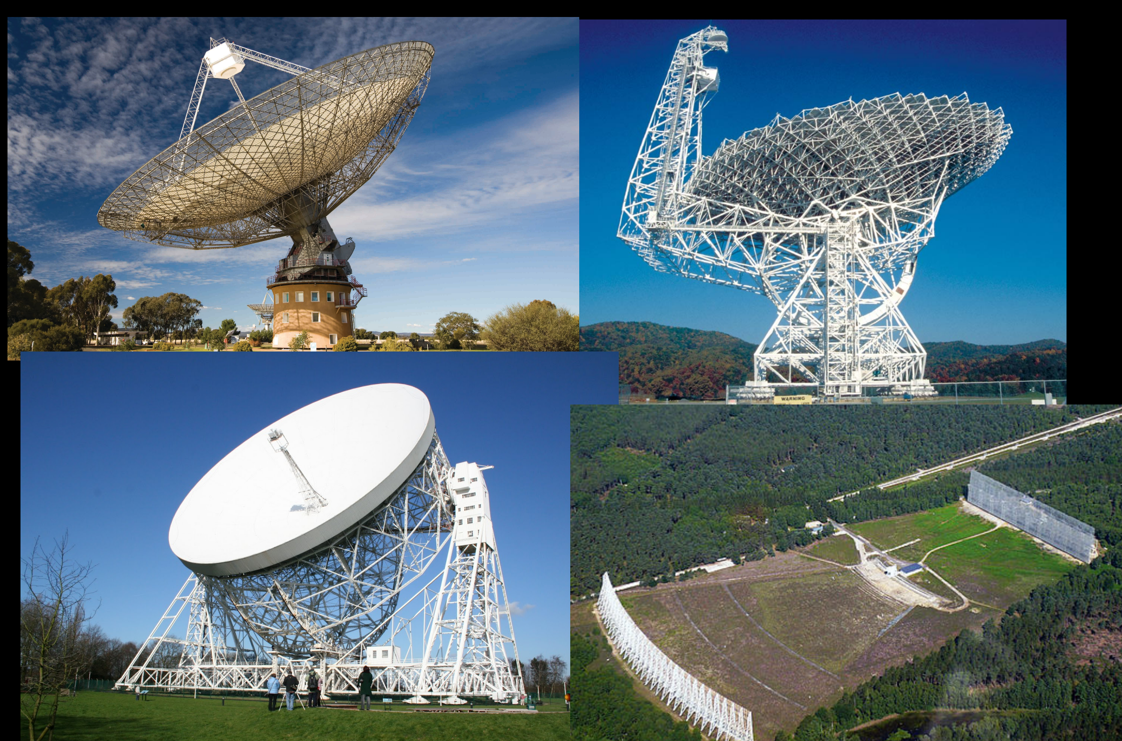
Credit: Nieder+2020

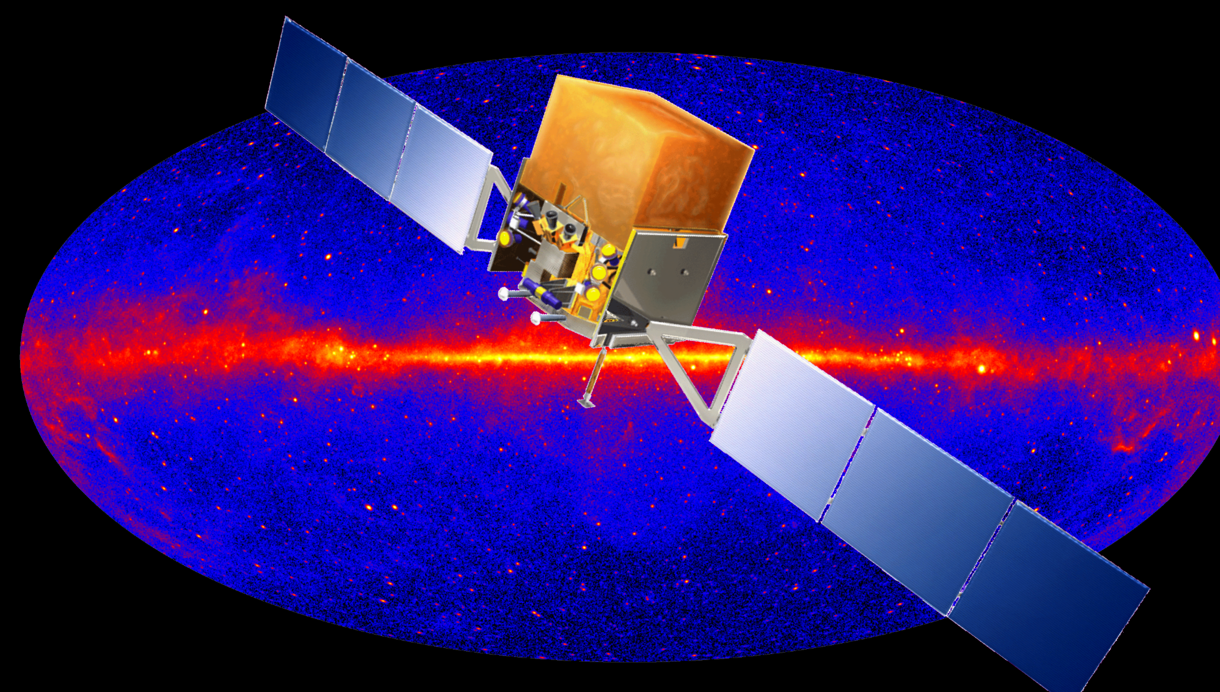
radio vs gamma

- targeting source
- gaps between observations
- high signal-to-noise ratio
- precise TOA
- (usual) time span: detection - last observation
- TS: chi2

- continuous, all-sky data
- unaffected by material
- sparse
- photons
- time span: 2008 - today

- TS: H-test & logL





TRAPUM

Transients and Pulsars with MeerKAT

MeerKAT:

- 64 x 13.5m radio interferometer in South Africa
- ~5x more sensitive than Parkes

TRAPUM:

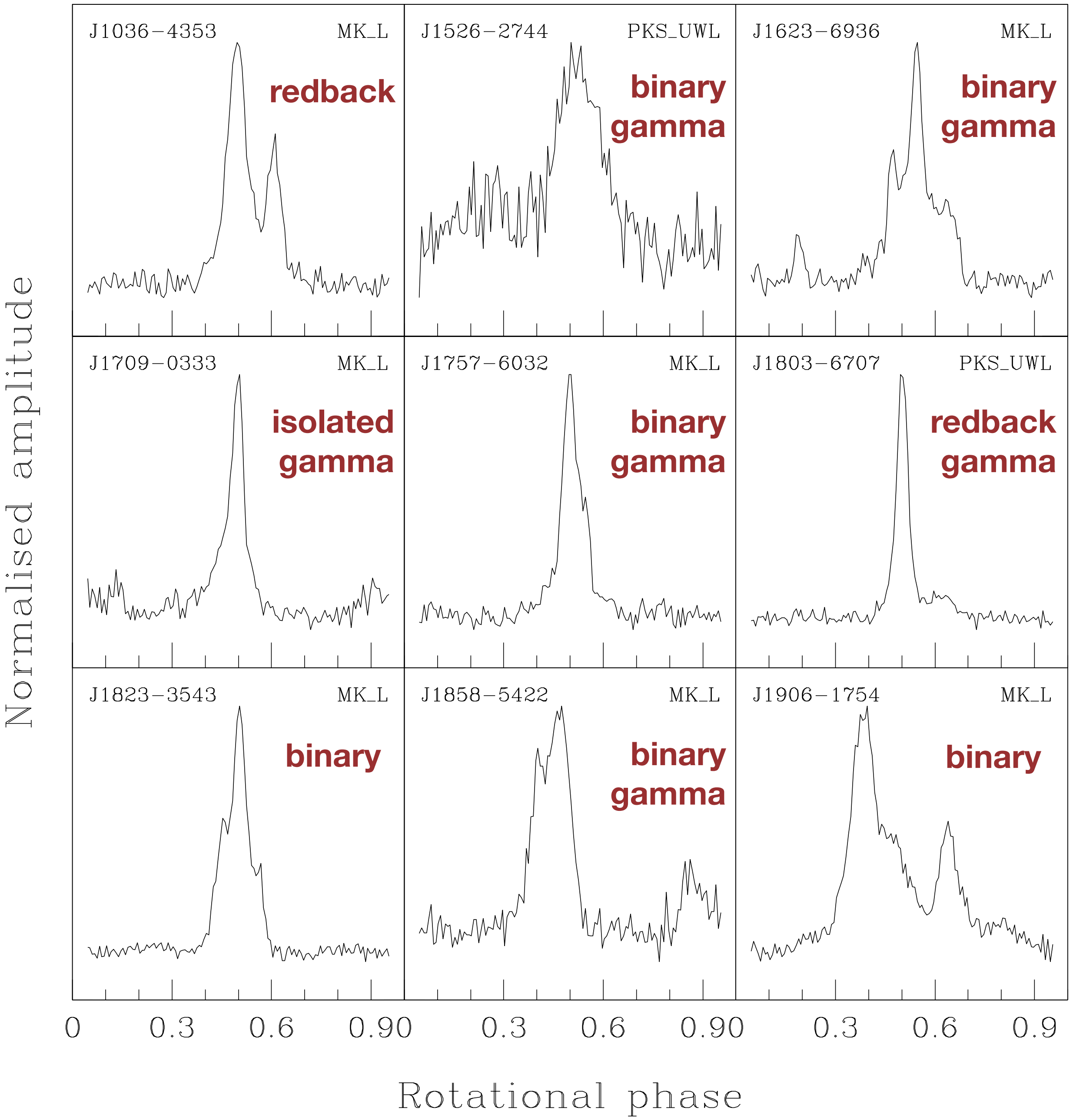
- Large Survey Project using MeerKAT
- Search for new pulsars in globular clusters, SNRs/PWNe/TeV sources, nearby galaxies and Fermi UNIDs

Image credit: South African Radio Astronomy Observatory (SARAO)

TRAPUM discoveries

- L-band survey in Fermi sources
  - Clark et al. 2023, MNRAS, 519, 5590
- 79 sources observed
- Nine new MSPs
  - one isolated
  - two redbacks
  - six other binary pulsars
- Six discovered in gamma-ray follow-up folding or searching

radio profiles

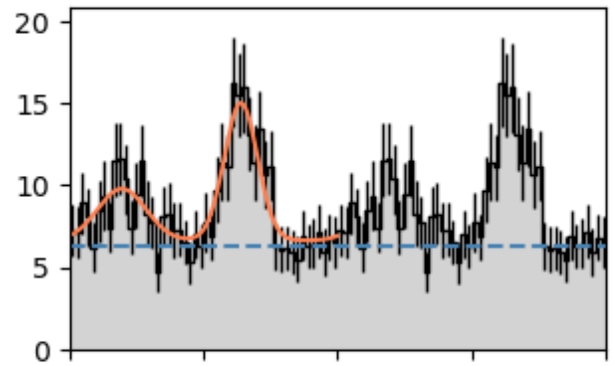


Gamma-ray pulsars

J1526-2744

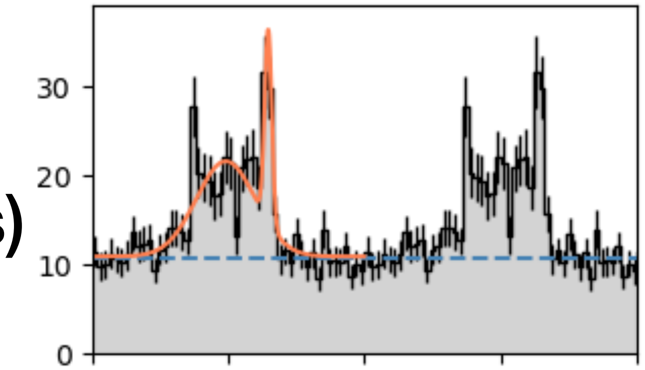
- follow-up search
- 401.7 Hz
- binary (0.2 days)
- CW follow-up

See: Ashok+2024



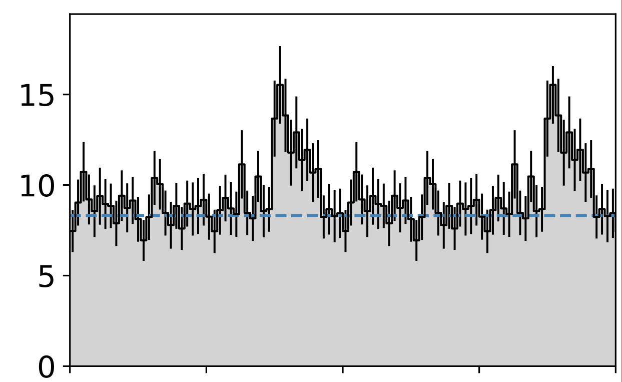
J1623-6936

- folding
- 415.0 Hz
- binary (11.0 days)



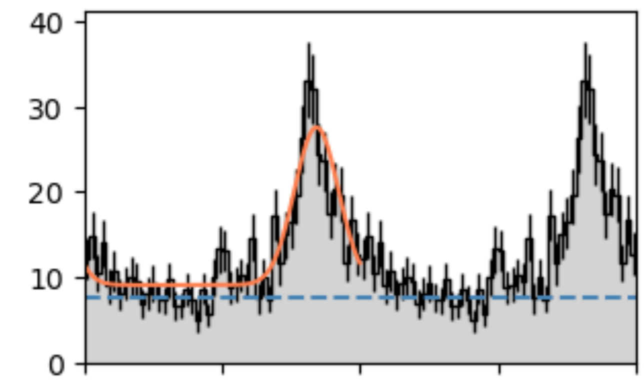
J1709-0333

- folding
- 283.8 Hz
- isolated
- faint



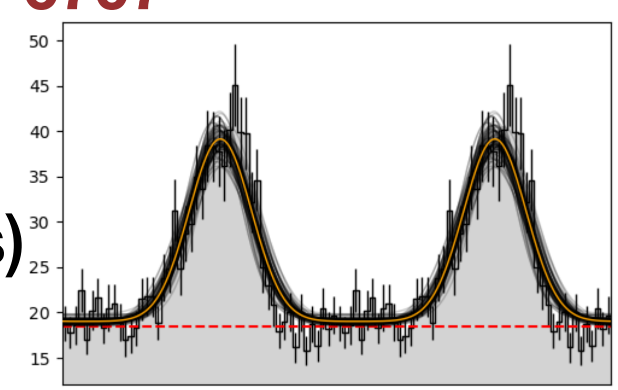
J1757-6032

- folding
- 343.3 Hz
- binary (6.3 days)



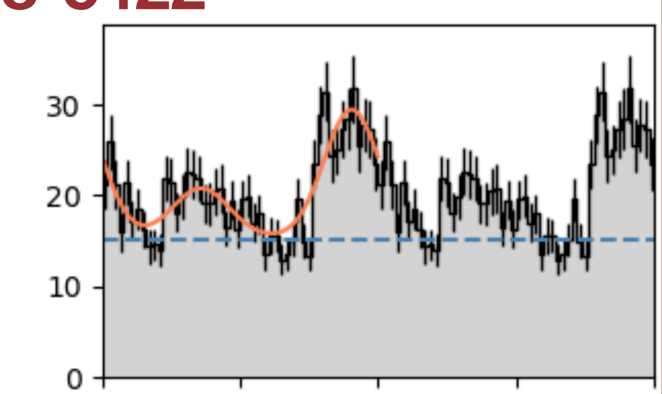
J1803-6707

- folding
- 468.5 Hz
- redback (0.4 days)
- strong OPV

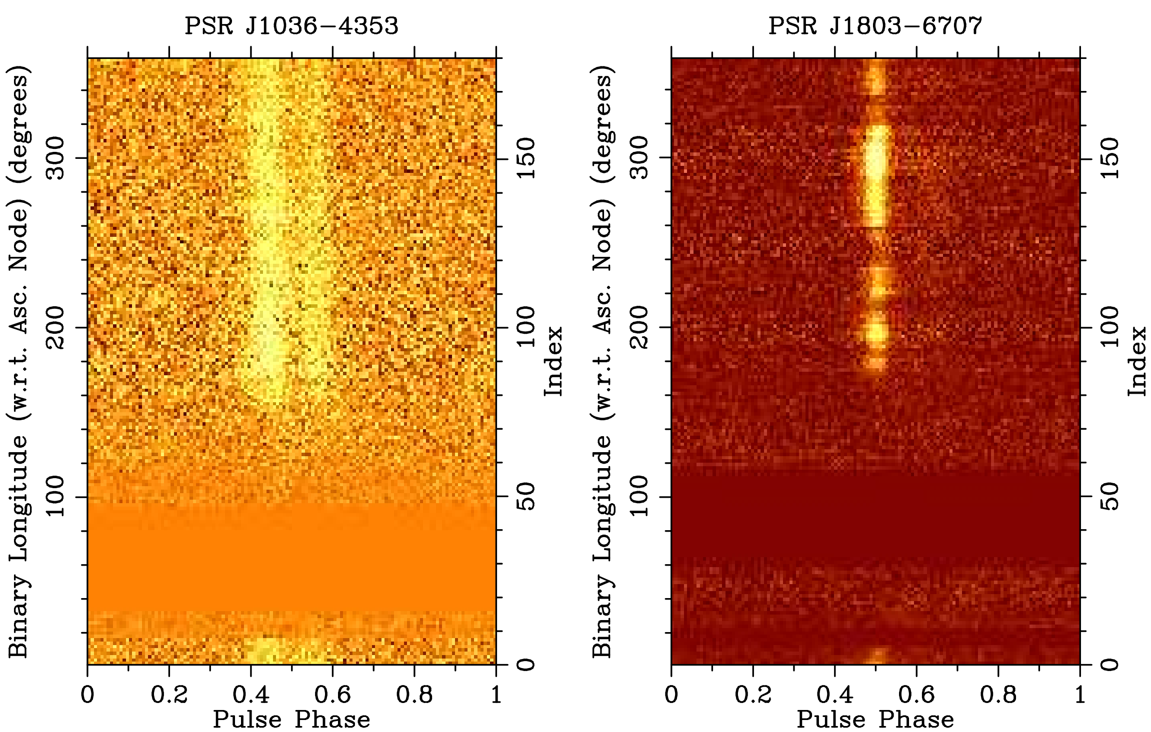


J1858-5422

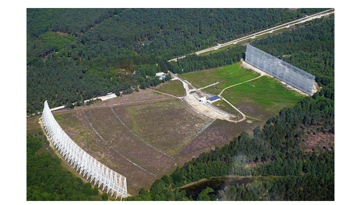
- folding
- 424.5 Hz
- binary (2.6 days)



Timing campaign



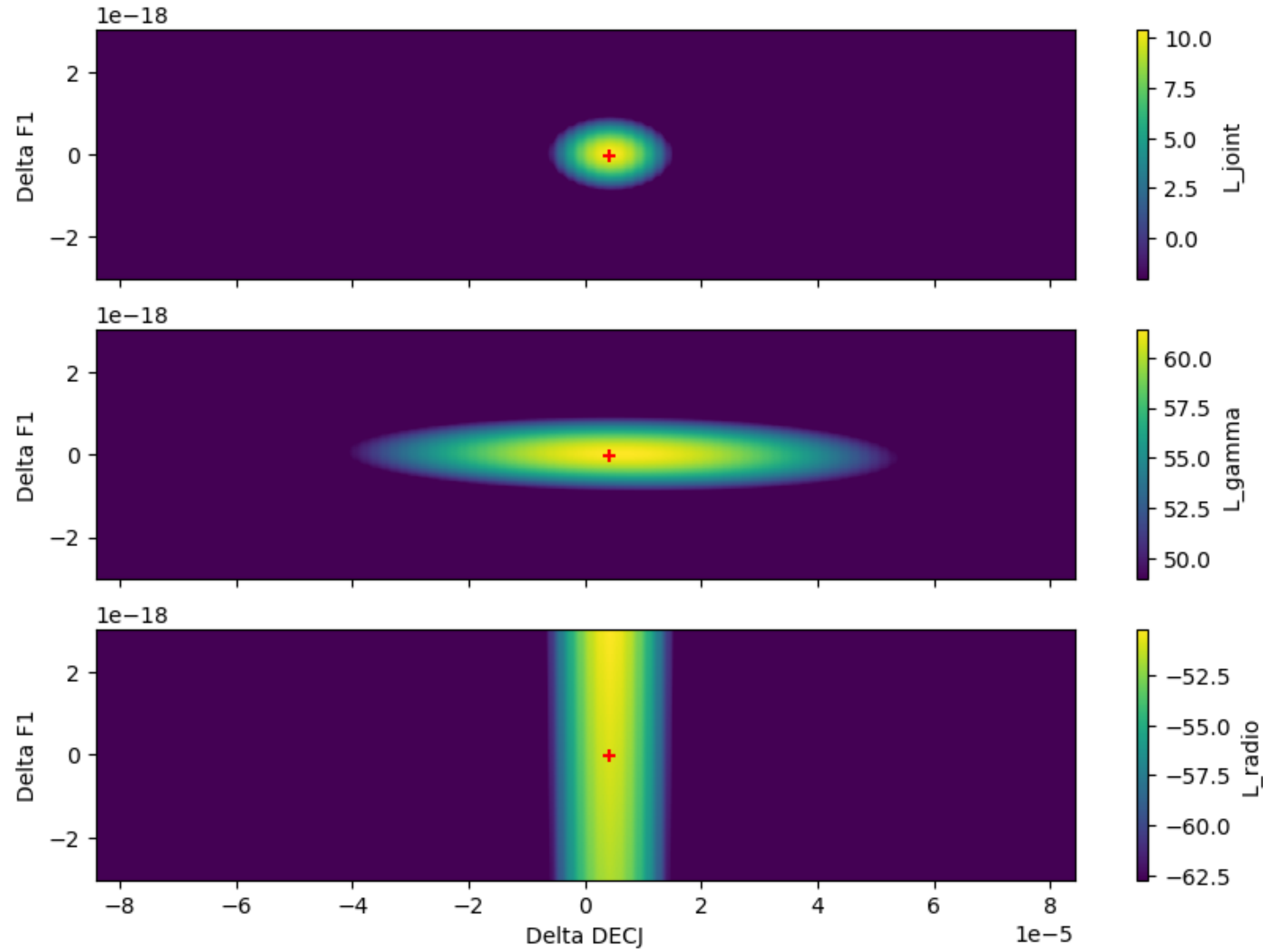
- Using MeerKAT, Parkes, Effelsberg, Nançay
- Pseudo-log cadence
- SeeKAT for position
- Avoiding eclipses for RBs



PSR	Data span (MJD)	MK obs#	PKS obs#	NCY obs#	EFF obs#	MK tobs	PKS tobs (h)	NCY tobs (h)	EFF tobs (h)	nToA
J1036-4353	59536 – 60015	20	15	–	–	1.7	29.8	–	–	180
J1526-2744	59304 – 59432	–	6	7	–	–	9.3	6.3	–	71
J1623-6936	59250 – 59683	23	14	–	–	2.2	14.6	–	–	178
J1709-0333	59304 – 60084	20	4	–	2	1.8	6.1	–	3.4	151
J1757-6032	59250 – 59725	29	12	–	–	4.1	13.9	–	–	310
J1803-6707	59197 – 59624	2	19	–	–	1.4	11.0	–	–	204
J1823-3544	59250 – 59684	19	9	10	–	1.8	9.7	7.4	–	259
J1858-5424	59250 – 59759	37	6	–	–	6.0	6.1	–	–	275
J1906-1754	59250 – 60148	43	5	–	20	4.0	6.1	–	48.9	285

Problems in timing analysis

- Usually iterative timing approach works fine
  - Keeping some parameters fixed for each data
  - Iterations until convergence
- Radio and gamma-ray data disagreed on sky position for some of the parameters
  - Could use posteriors from one timing run as prior for the next
  - Could do timing analysis jointly on both data



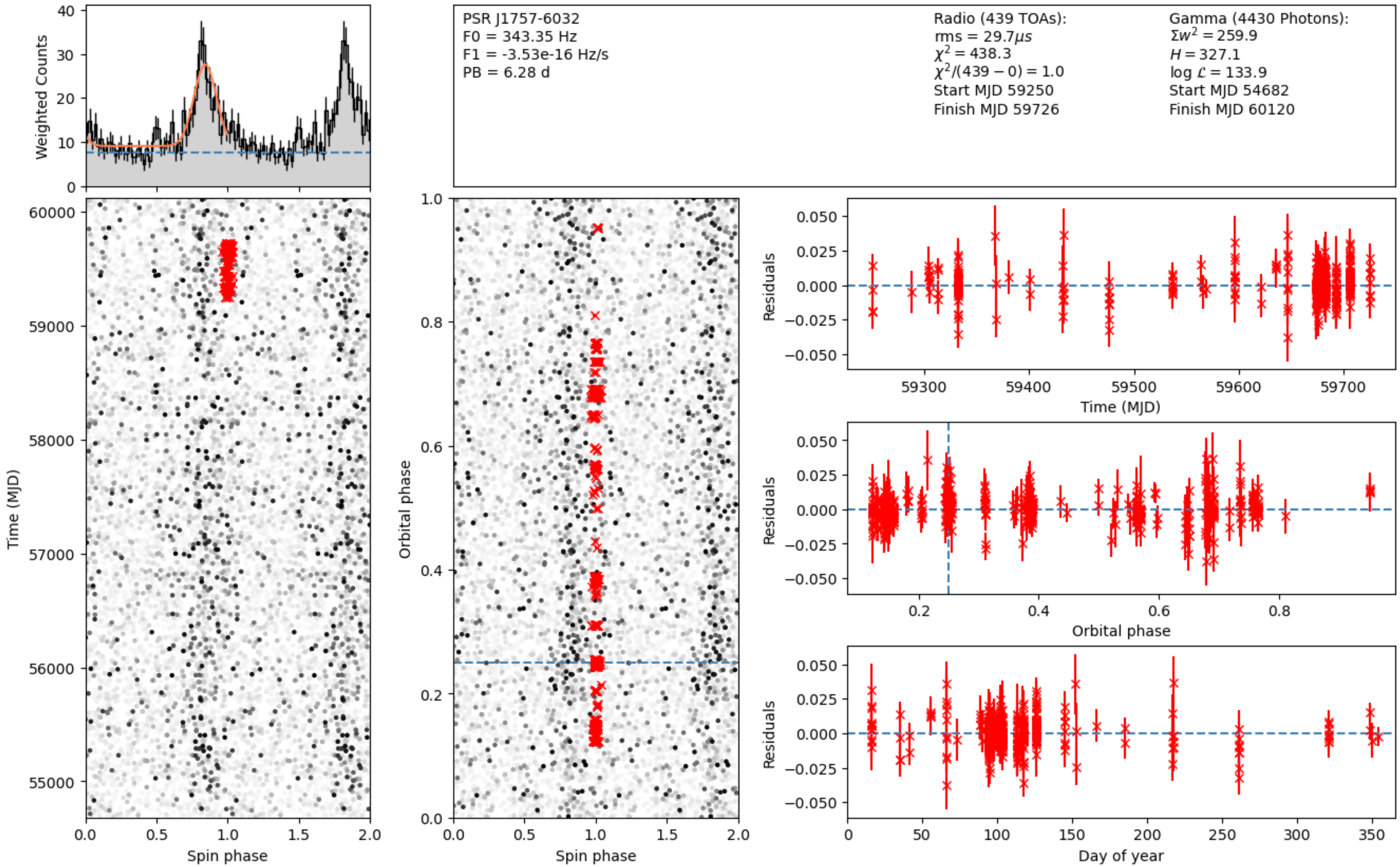
Joint timing — method

- Using MCMC to explore parameter space
  - maximise joint logL
  - using *emcee* & *PINT*
- Gamma likelihood
  - wrapped Gaussian peaks
  - joint marginalisation of template and pulsar pars
- Radio “likelihood”
  - joint marginalisation of jumps and pulsar pars

$$\begin{aligned}\log \mathscr{L} &= \log \mathscr{L}_{\text{prior}} + \log \mathscr{L}_{\text{gamma}} + \log \mathscr{L}_{\text{radio}} \\ &= \log \mathscr{L}_{\text{prior}} + \log \mathscr{L}_{\text{gamma}} - 0.5 \times \chi^2_{\text{radio}}\end{aligned}$$

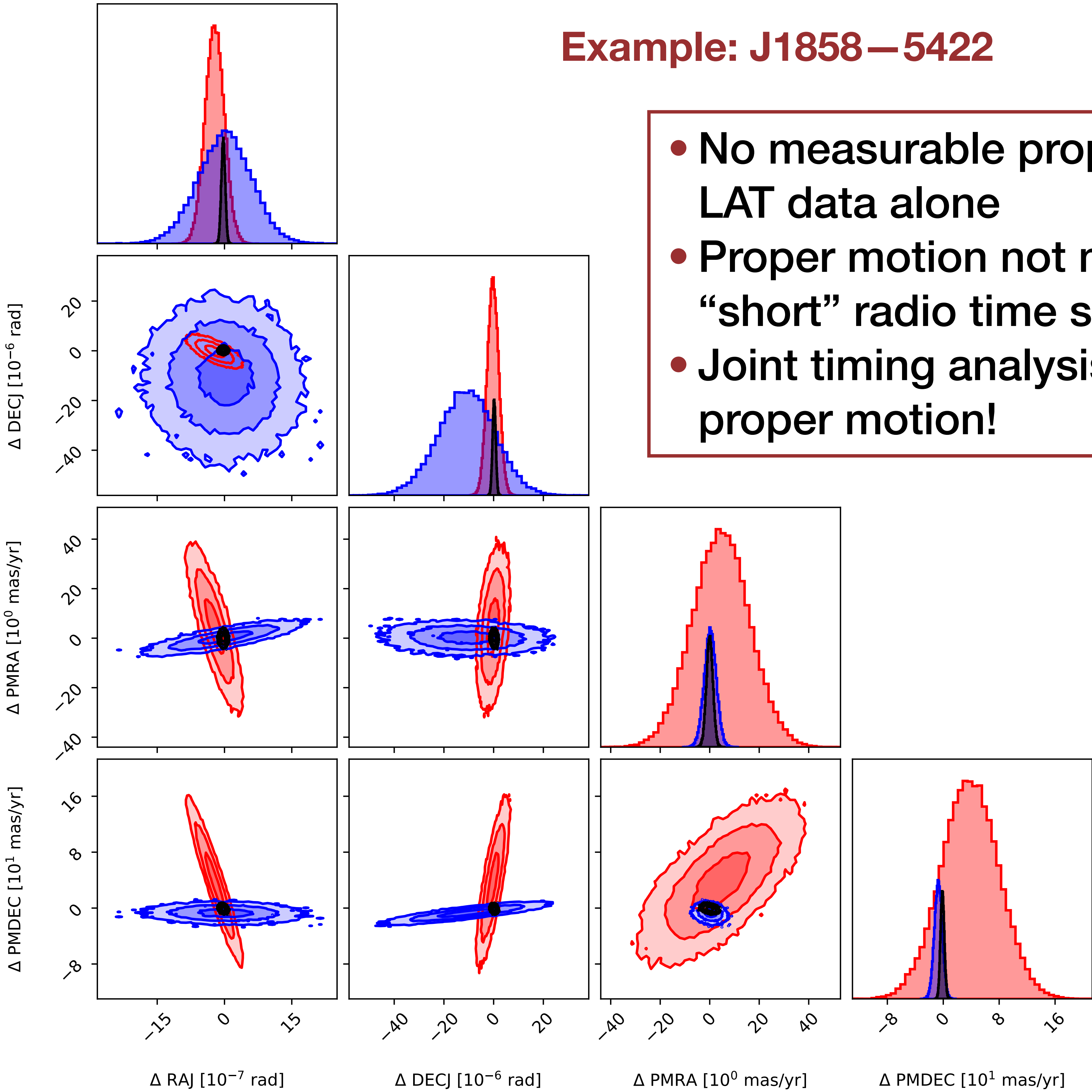
Joint timing — results (1)

Example: J1757−6032



Joint timing — results (2)

Example: J1858−5422

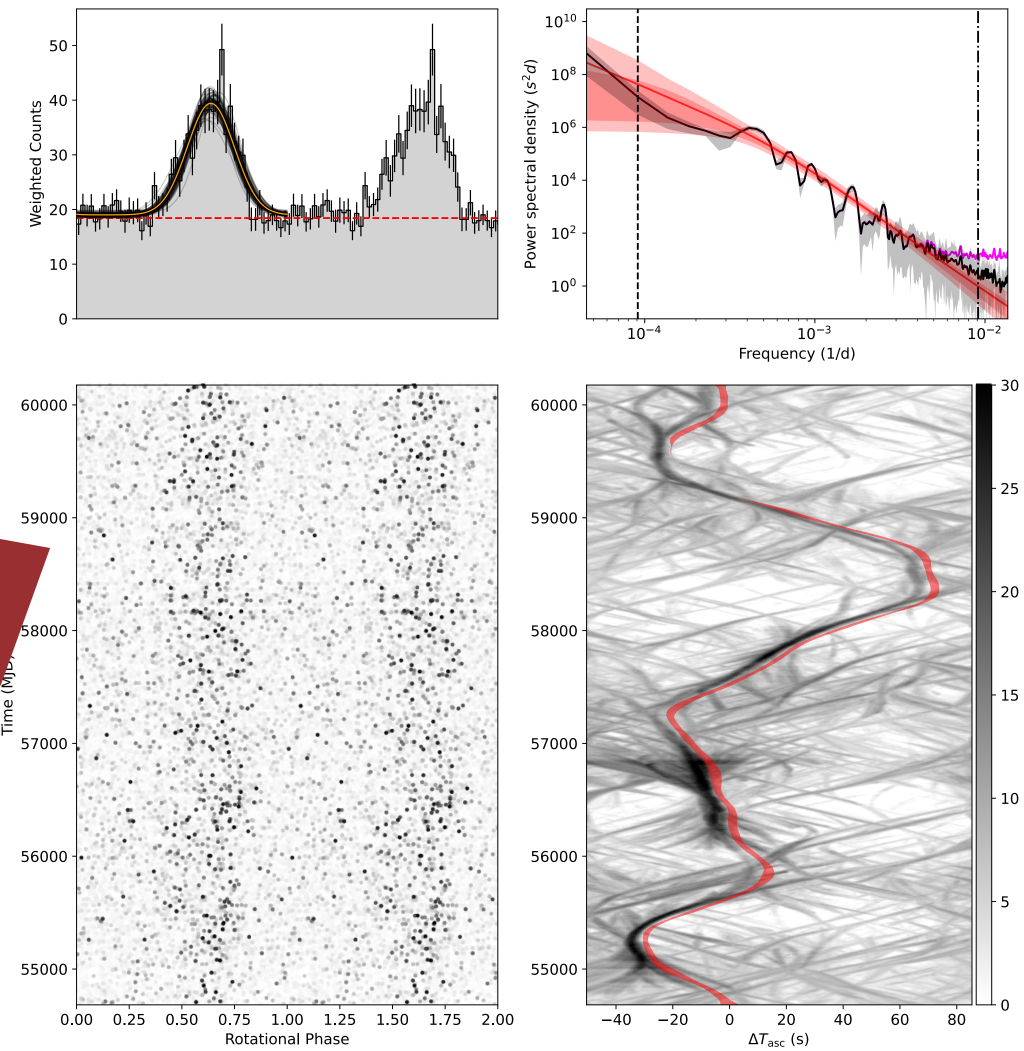


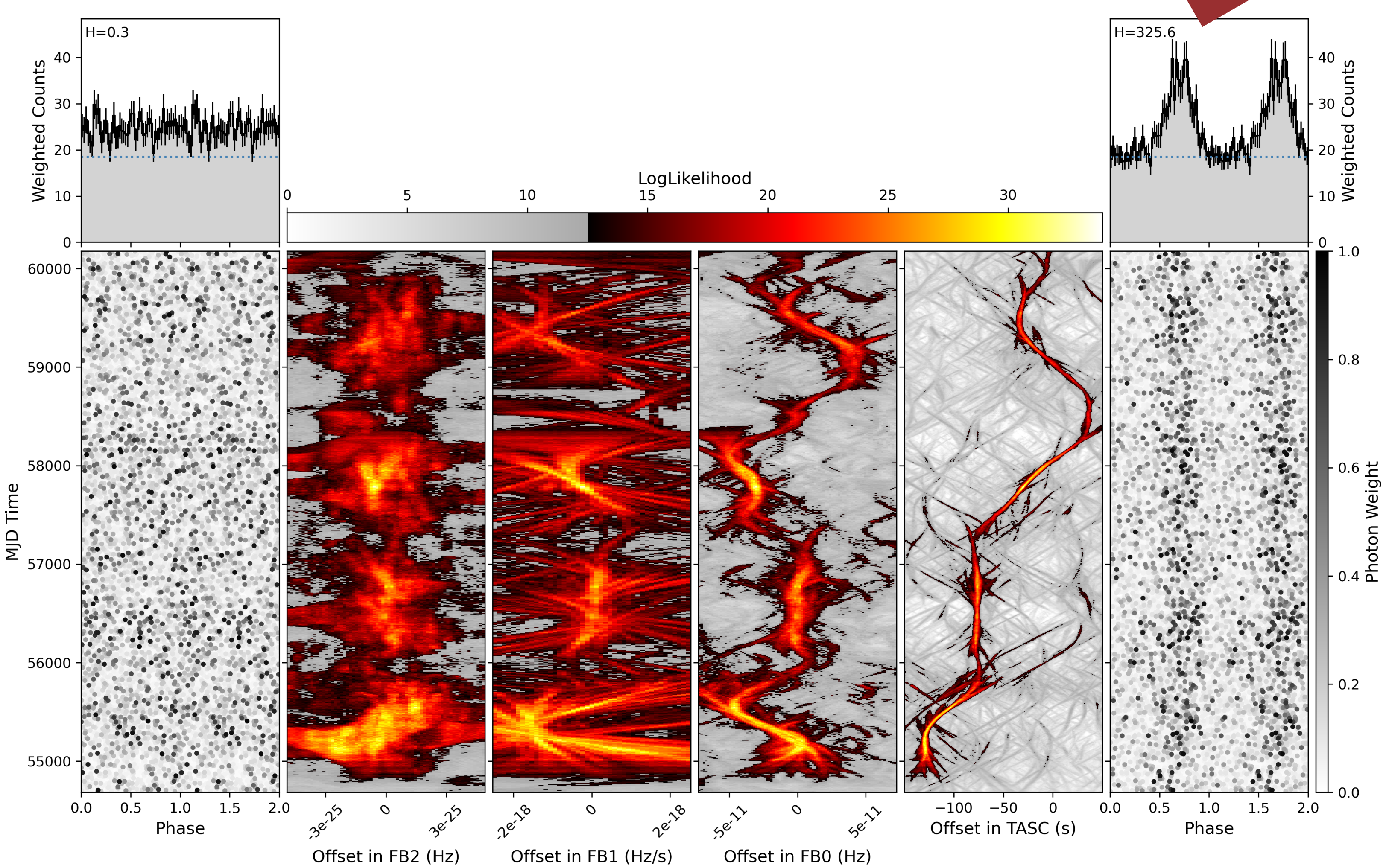
- No measurable proper motion in LAT data alone
- Proper motion not measurable in "short" radio time span
- Joint timing analysis reveals the proper motion!

Redback J1803−6707

J1803-6707

- 468.5 Hz
- redback (0.4 days)
- strong OPV
- new timing method

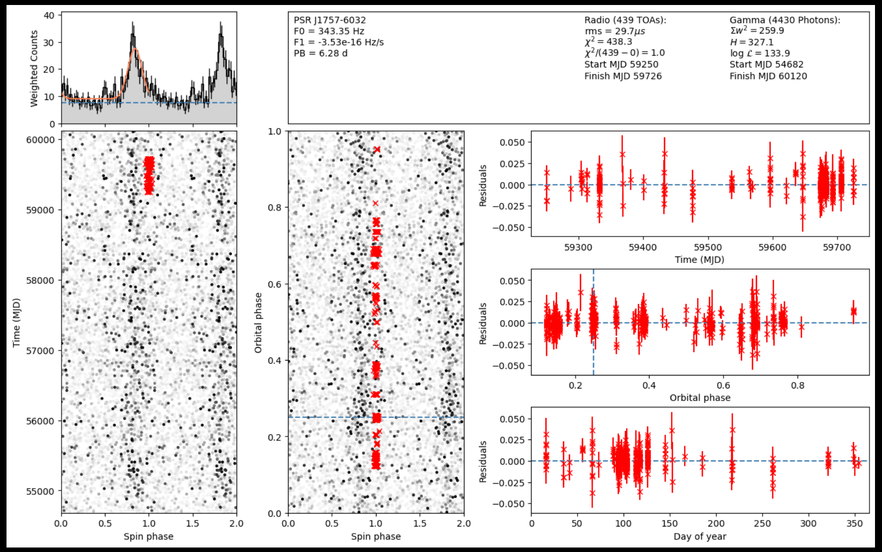




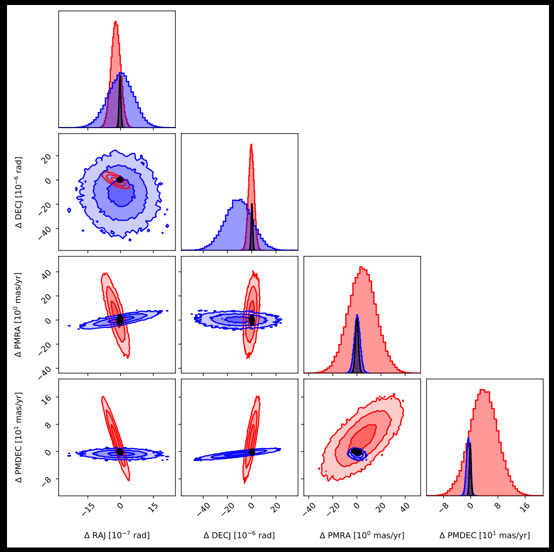
Fermi all-sky survey is uniquely suited to time orbital-period variations of redback pulsars!

Joint radio and gamma-ray analyses can support searches for continuous gravitational waves & in pulsar timing arrays

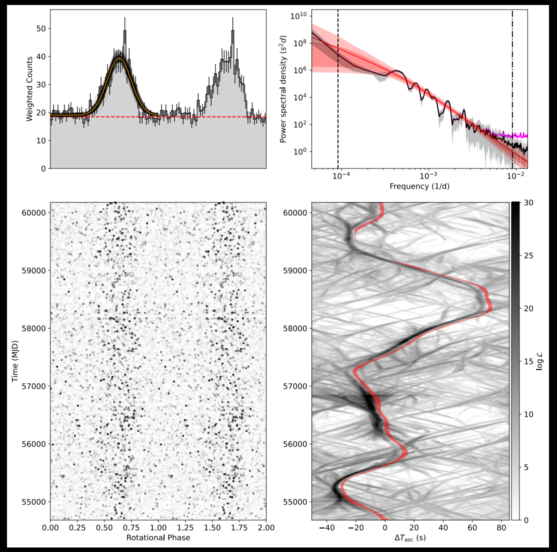
PSR 1757—6032



PSR 1858—5422



PSR 1803—6707



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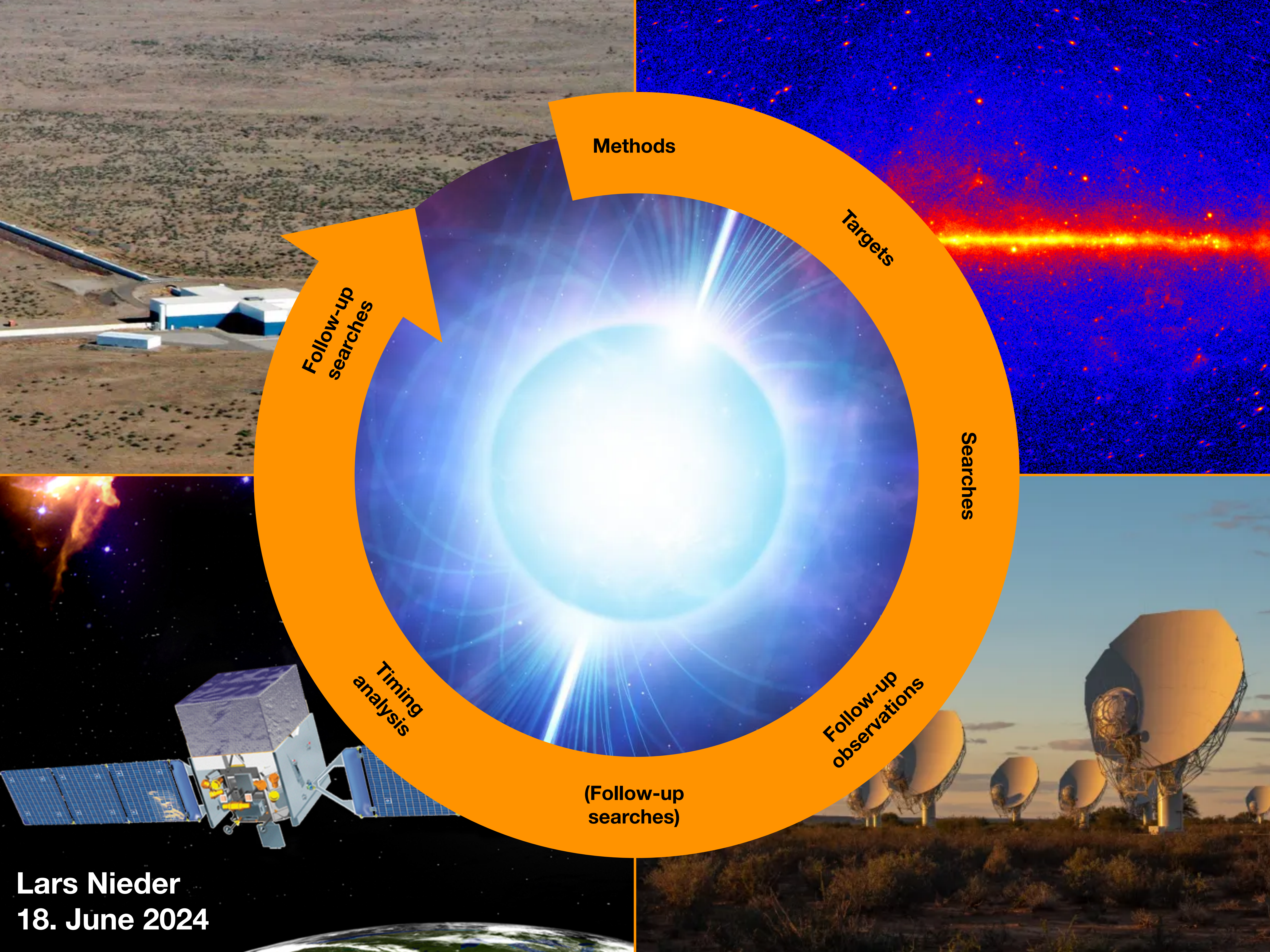
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