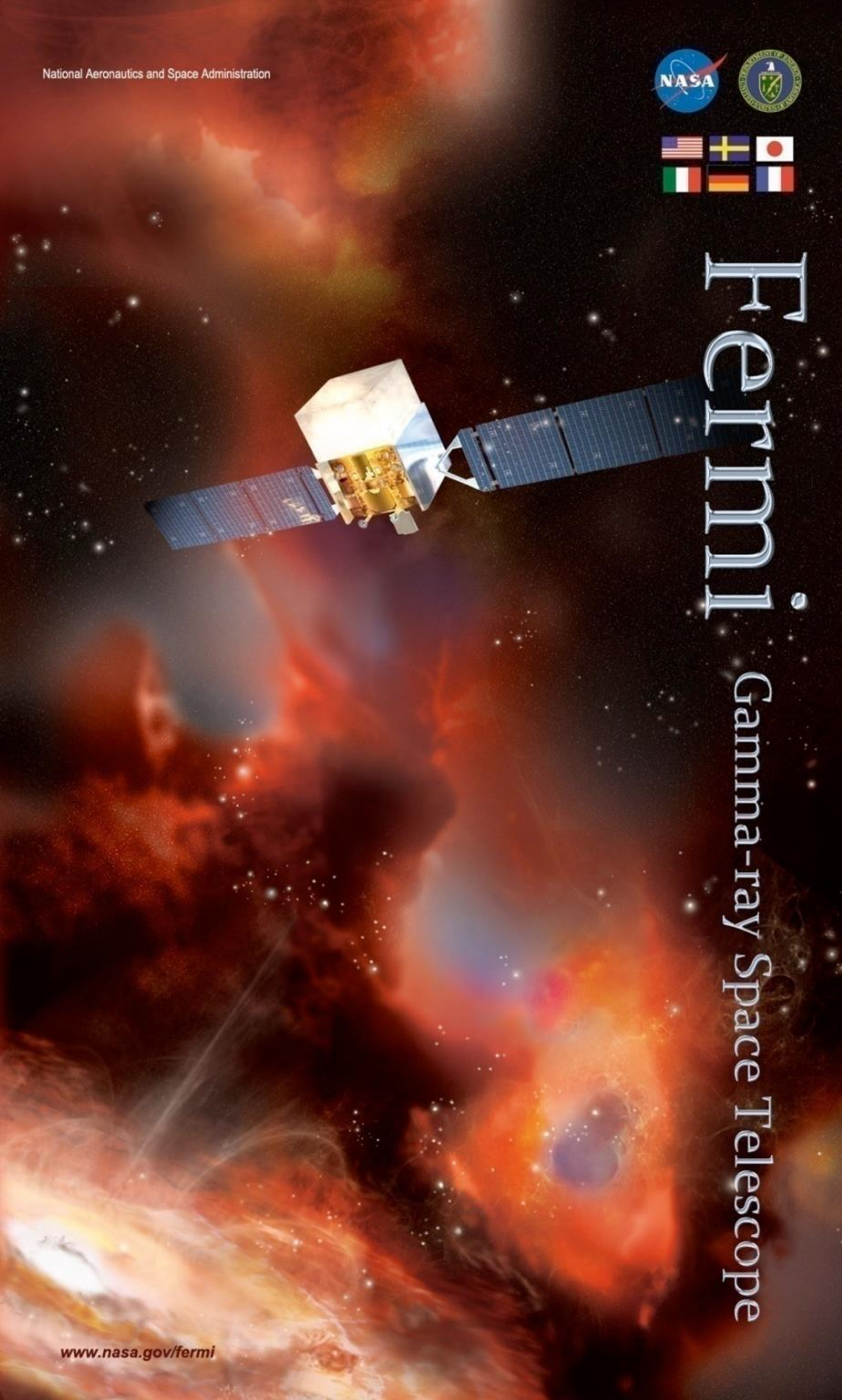


Pulsars and Pulsar Timing with the Fermi LAT

1. Pulsars are **GeV** sources
2. Pulsars are **good clocks**
3. Pulsars can be turned **OFF***

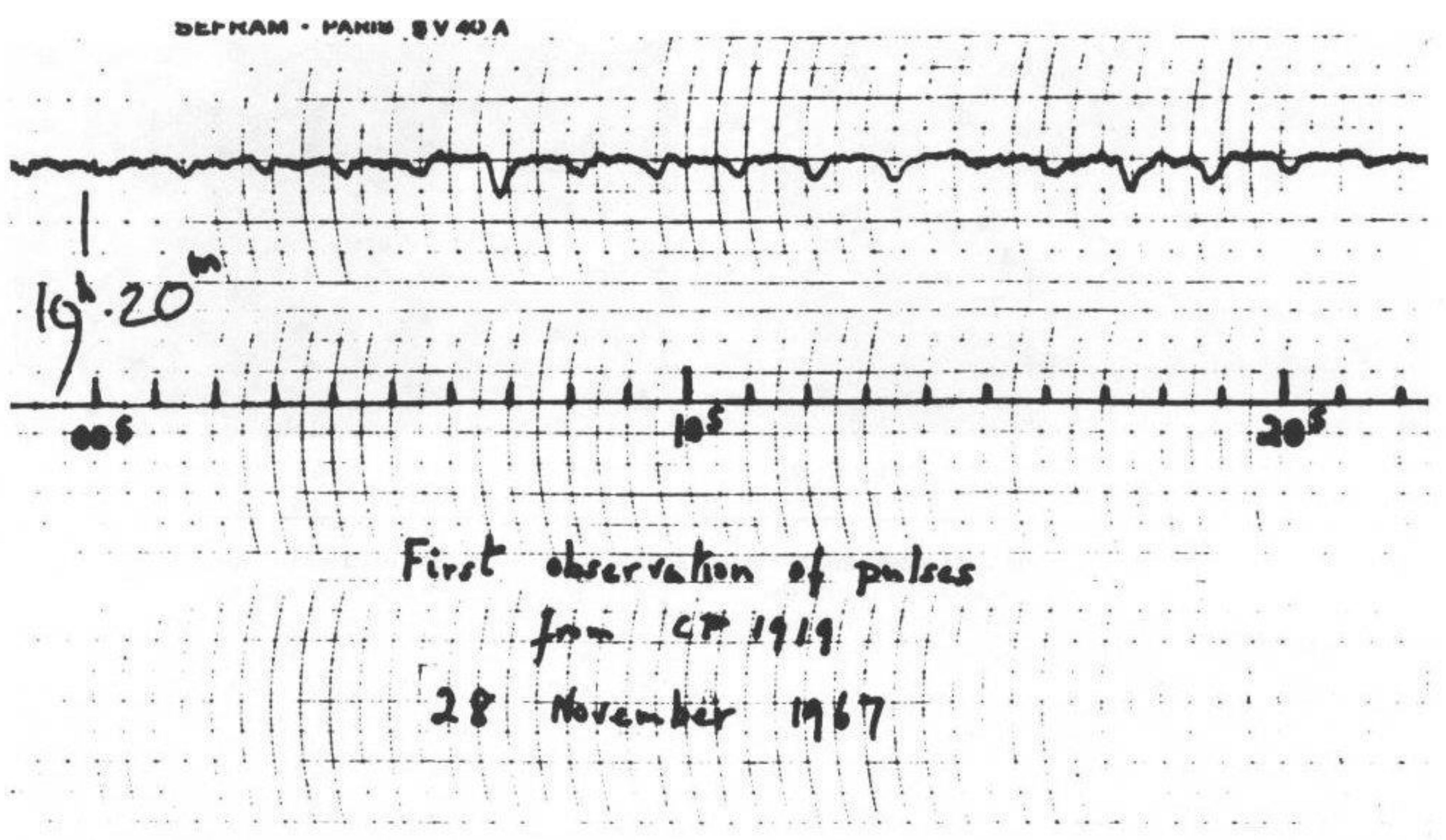
Matthew Kerr
matthew.kerr@gmail.com

Fermi-LAT Summer School
July 12,2012

*Kinda.

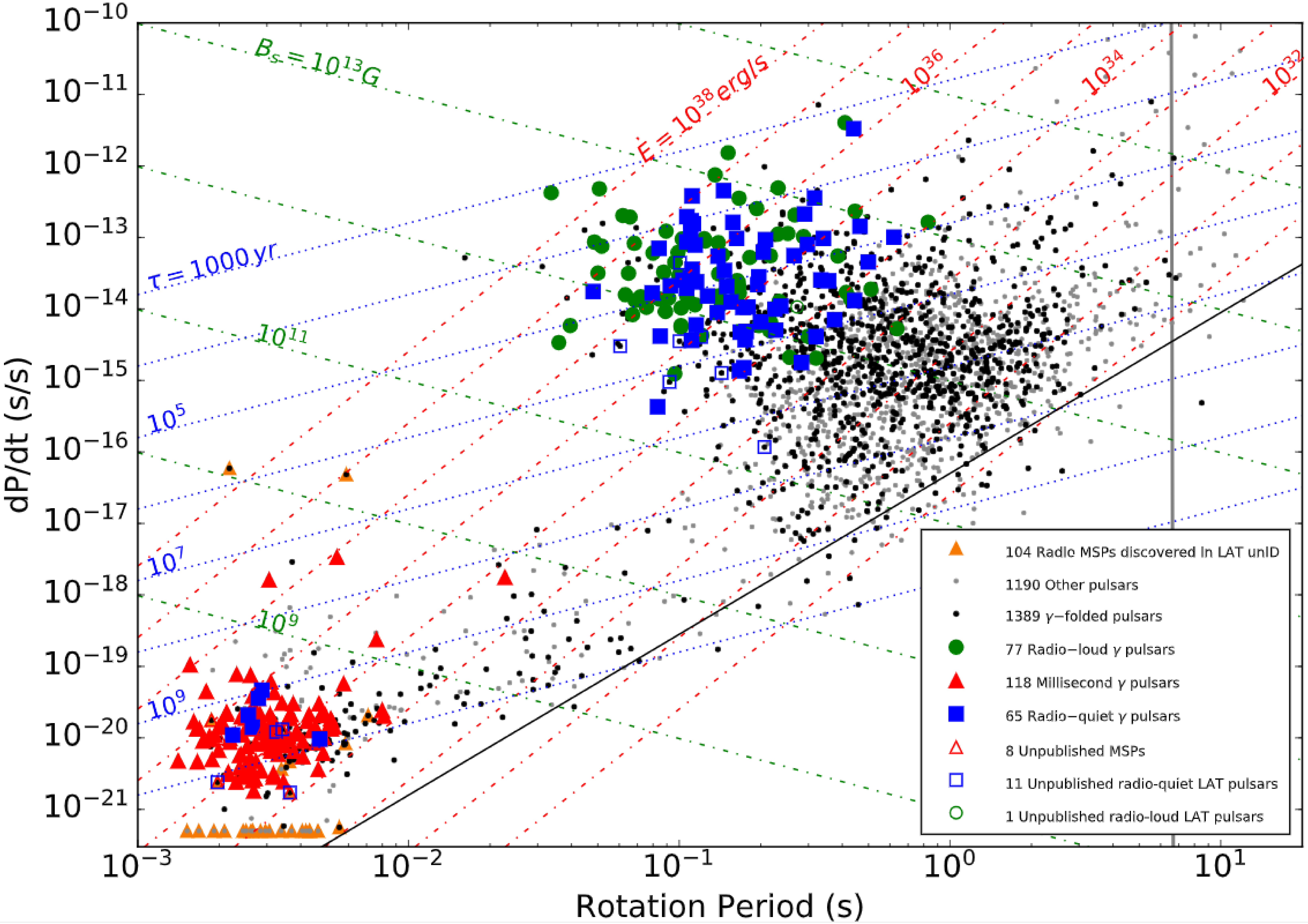
Pulsar Discovery

- **Pulsars discovered in 1967 using the moral equivalent of a field of coat hangers and a pen chart. If you read one single paper, read this one. (Hewish et al., 1968, *Nature*)**



Then and Now: The P-Pdot Diagram

- Neutron stars are basically the same, so once you know the period, you know the rotational energy.
- Once you know the period derivative, you know how rapidly the pulsar is losing that rotational energy: sets the energy budget, and tracks physical properties like age and the magnetic field.
- These two quantities thus tell you a lot about a particular pulsar and give a broad classification, along with some insights into pulsar emission mechanisms.

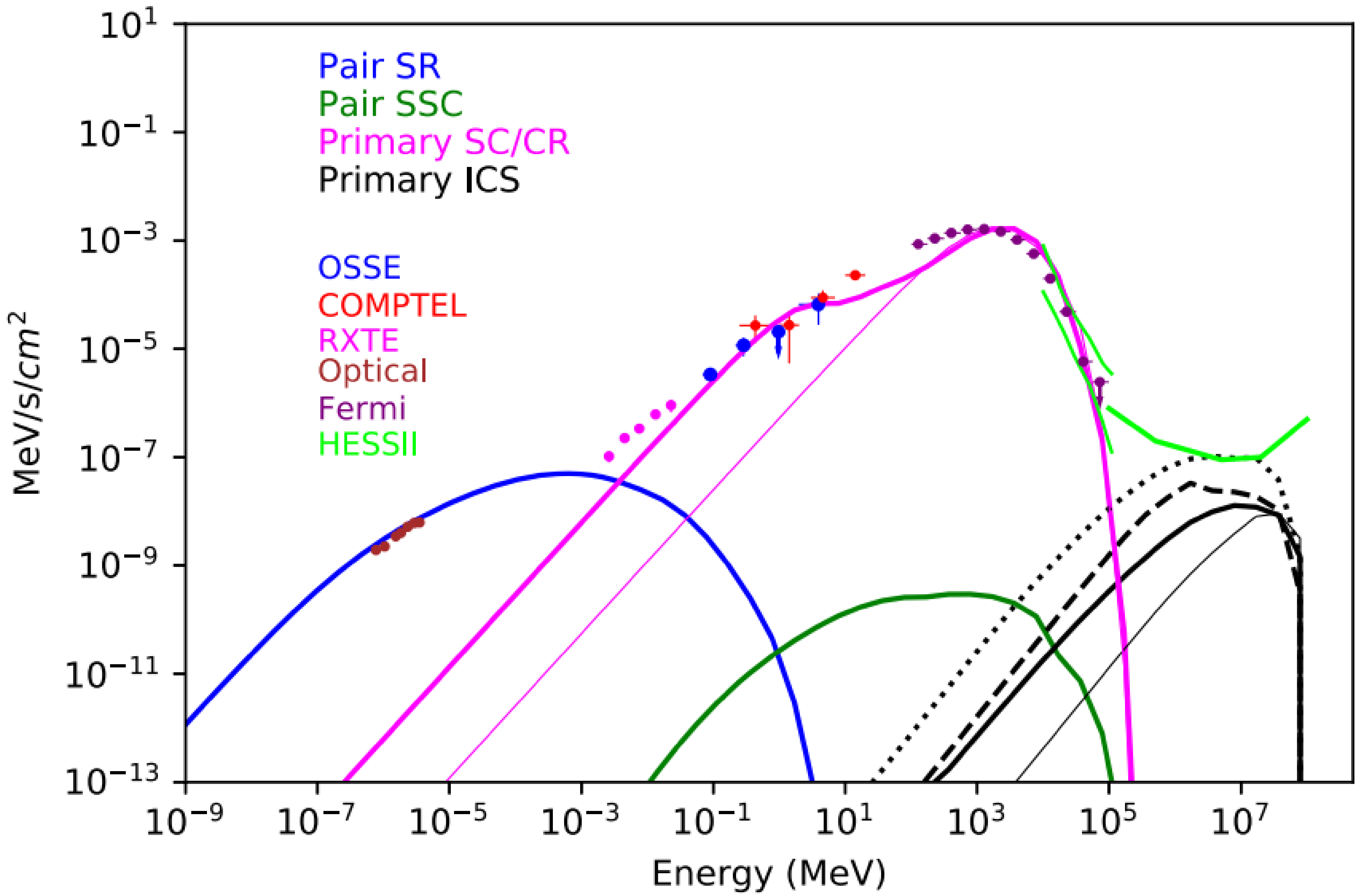


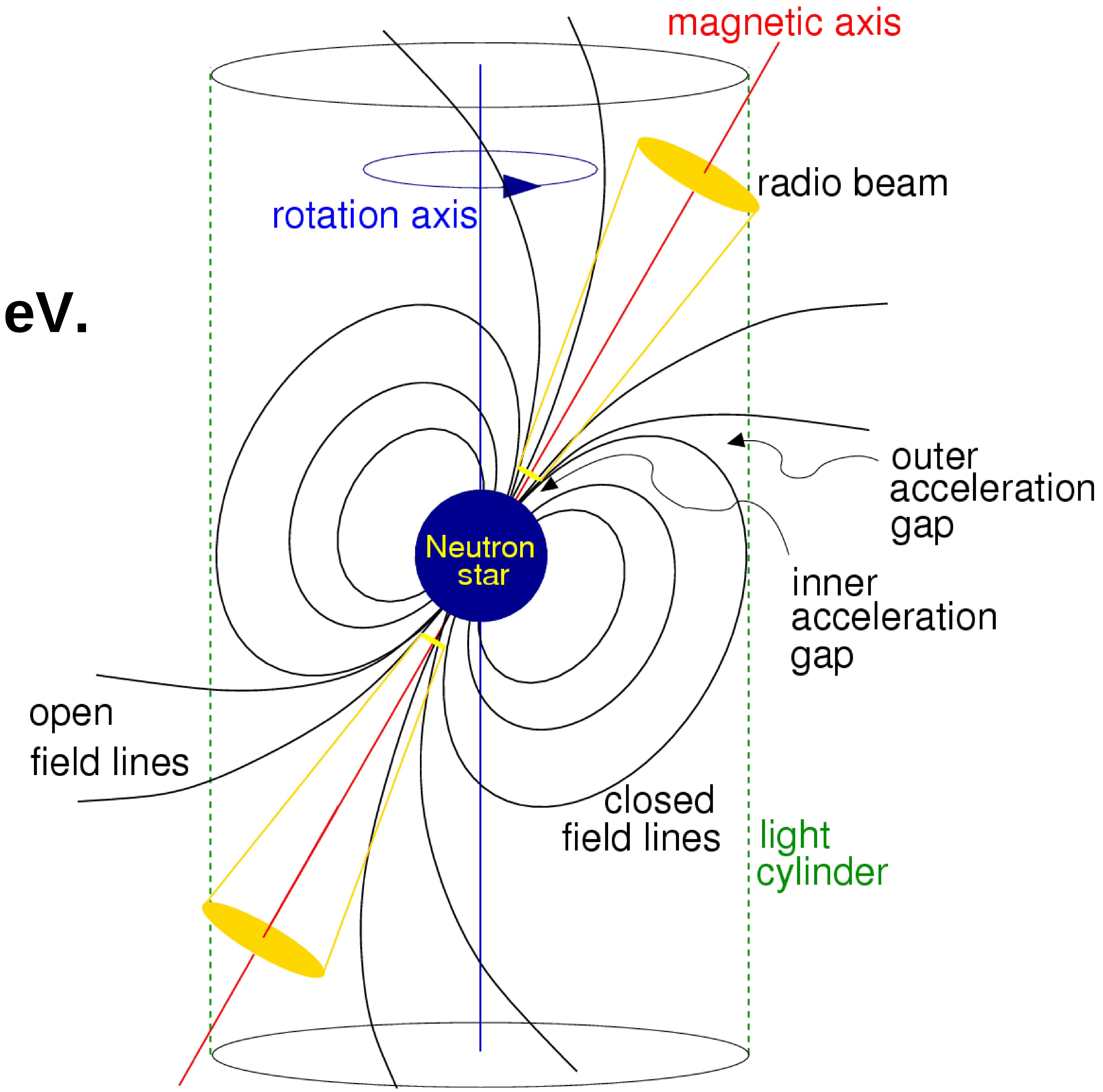
ATNF Catalog

- https://www.atnf.csiro.au/research/pulsar/psrcat/

Pulsars are GeV sources

- **Pulsar emission: geometry is key**
- **Rotating magnetic field (10^12 G) → 10^16V!**
- **Accelerates electrons to Lorentz factors ~10^7**
- **Particle cascades fill magnetosphere with plasma.**
- **Curvature radiation emitted with peak energy ~1 GeV.**
- **Consequences of emission from different places?**

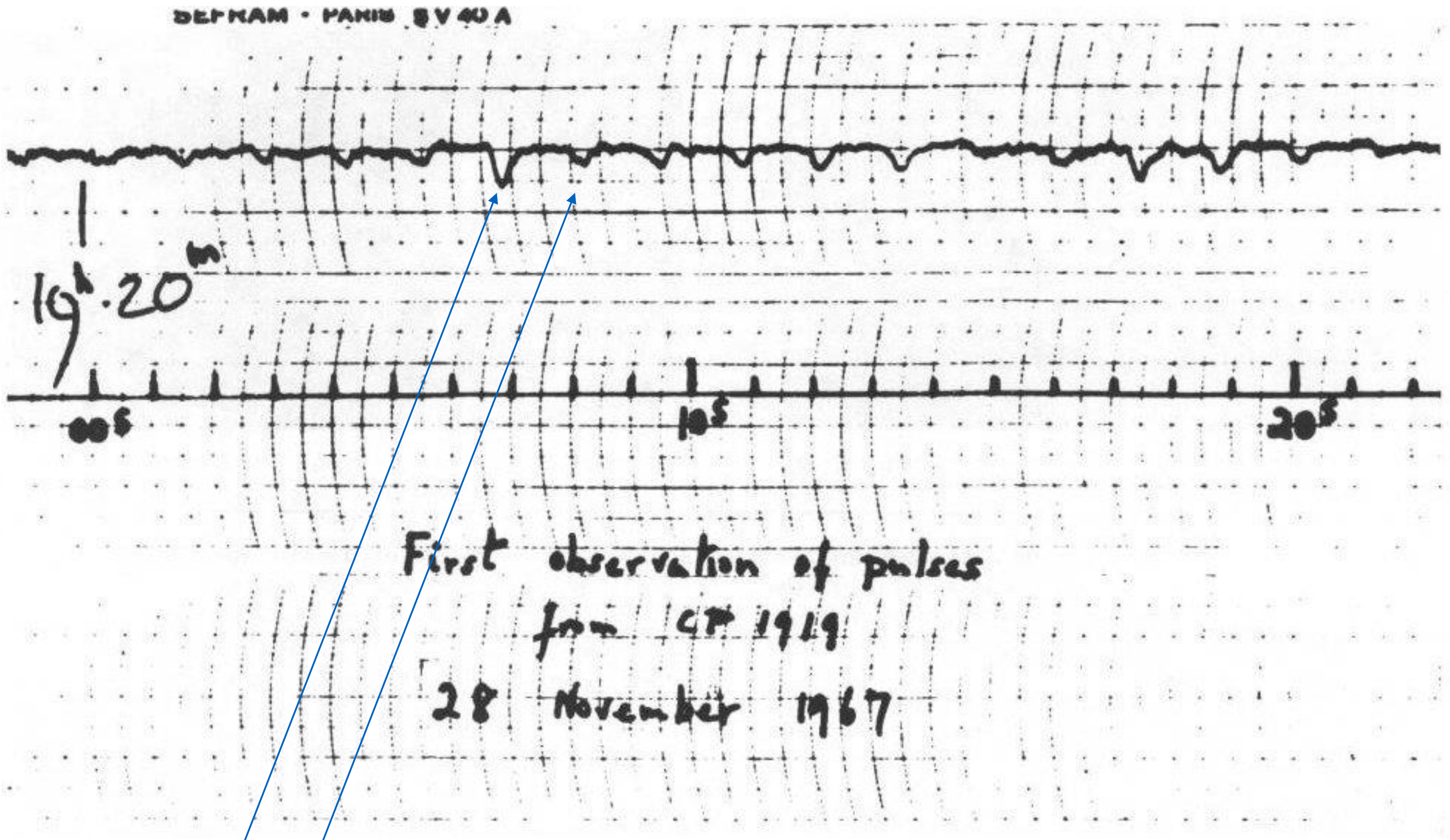




Pulsars are Good Clocks / Radio Pulsar Timing

https://compstar.uni-frankfurt.de/files/lectures_barcelona_2014/Hessels_Barcelona2014.pdf

Goal of *observational* pulsar timing is to measure the times at which pulses arrive with high precision.



Note that individual pulses vary in shape and are comparable to the noise in the system.

Conventions on pulsar spin phase:
A neutron star/pulsar rotation corresponds to a phase change of 1.

When we say "time at which pulse arrives", we mean "time at which the rotational phase is 0". This is again by convention. There is nothing special about any part of the pulse.

In most cases, almost always ignore the integer because timing models predict very close to true arrival time so residuals are small.

Pulsars are Good Clocks / Radio Pulsar Timing

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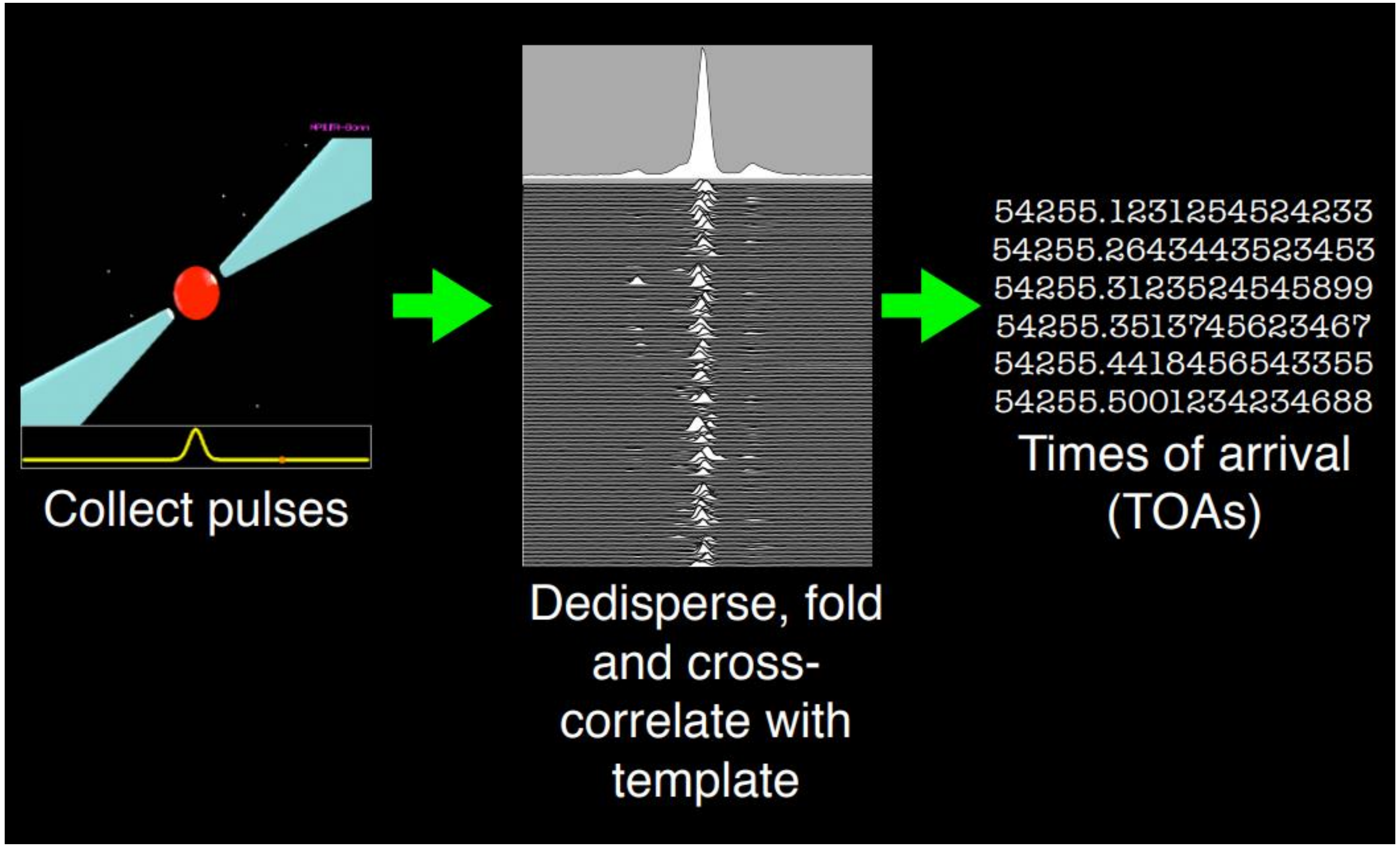
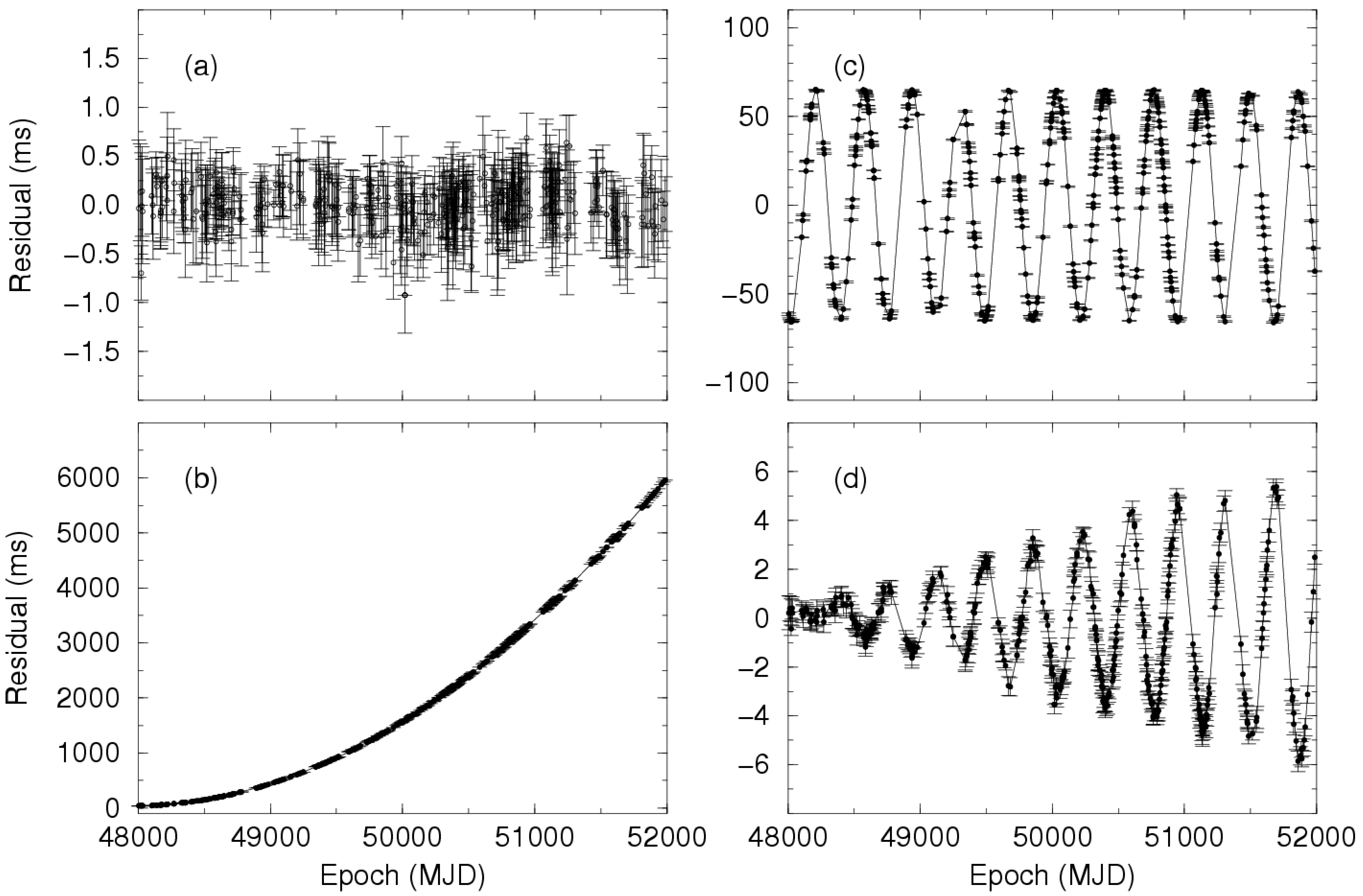
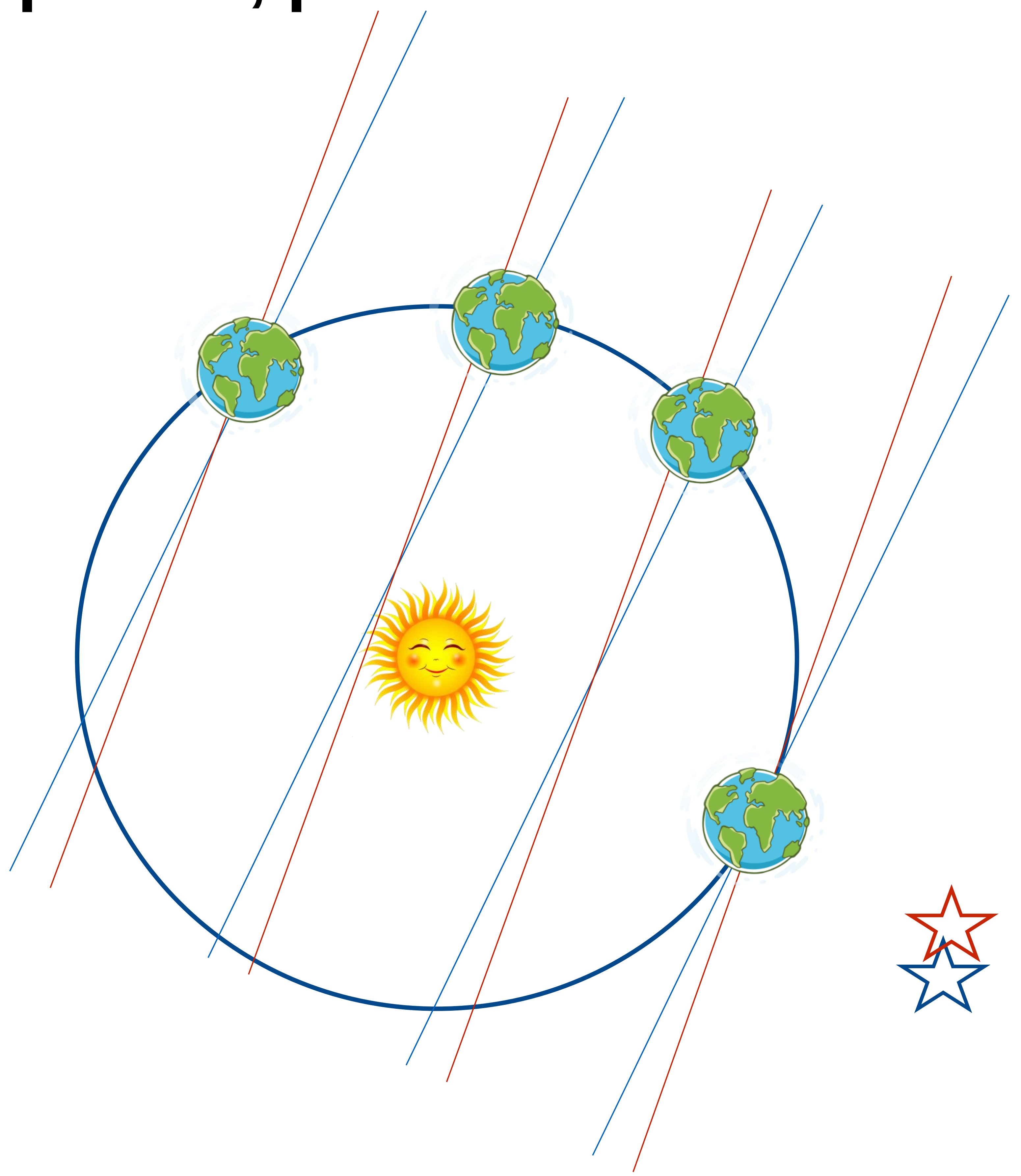


Excellent data reduction!
1 GHz b/w * 1hr *8-bit =
14.4TB → ~12 bytes

What affects TOAs?

- **Position, proper motion, spindown-rate, parallax, binary properties, post-Newtonian effects…**

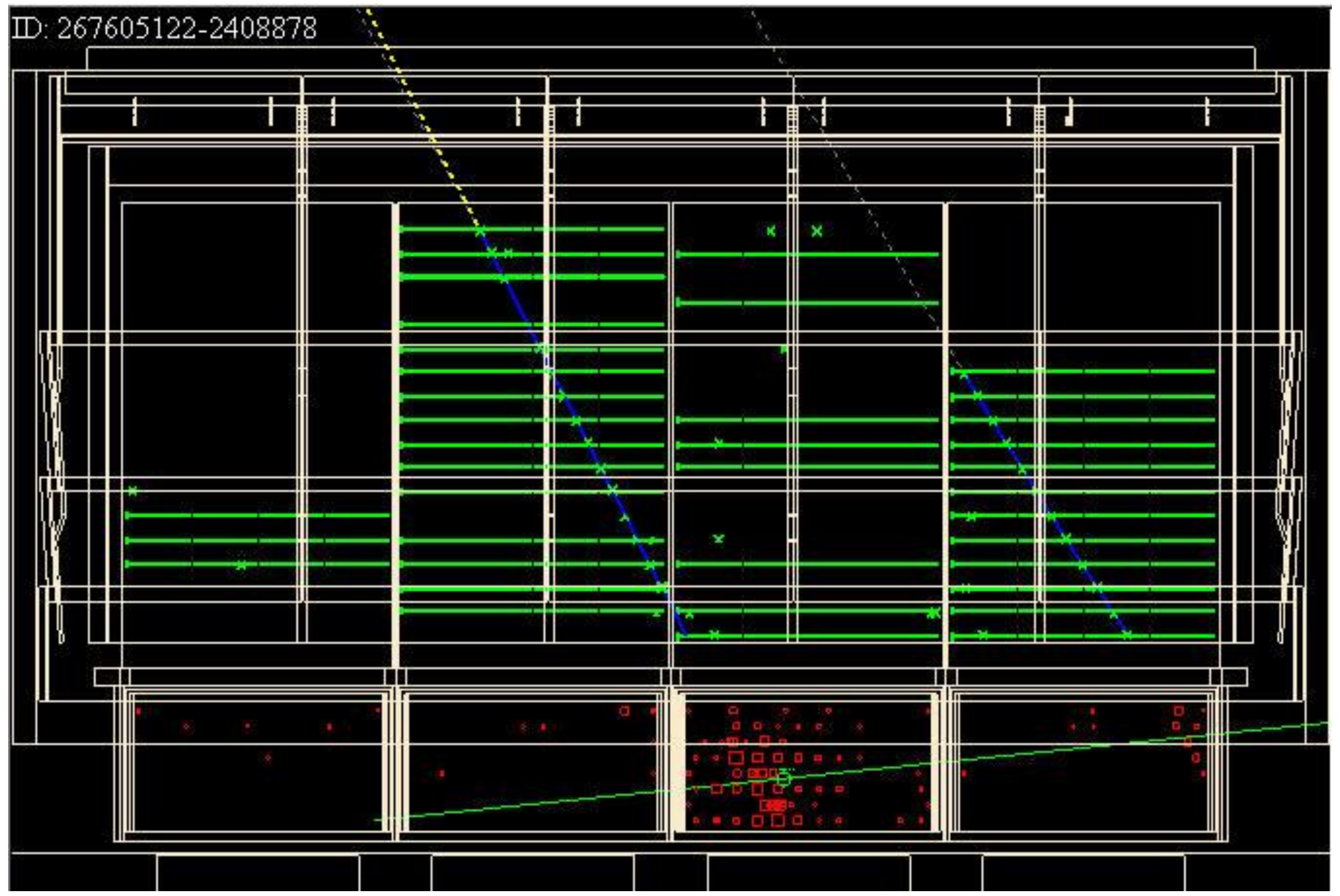


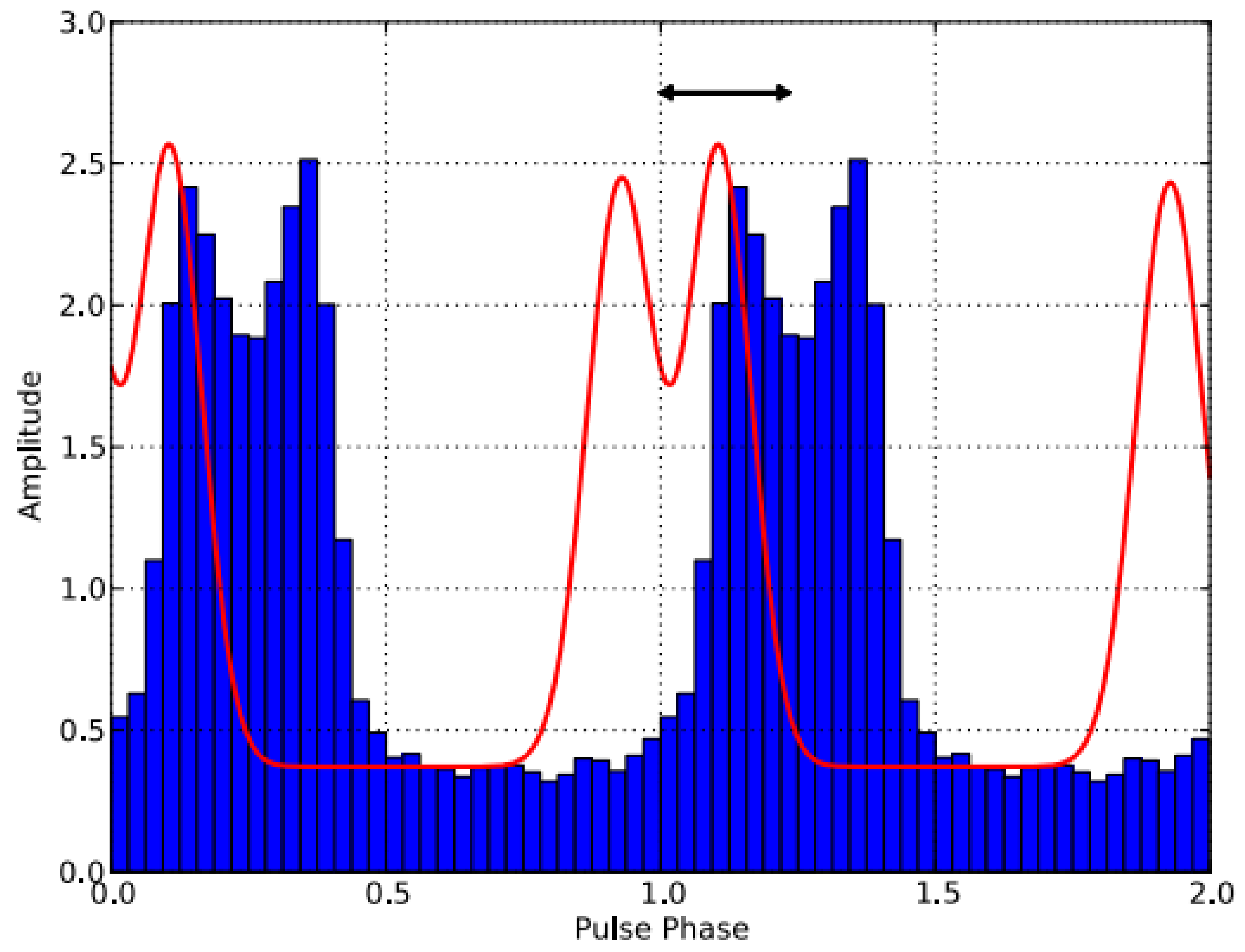


Positions measured using a 1AU baseline! Pulse times shifted by ~480s*err(rad)*cos(t/yr).

Pulsar Timing With Photons

- **Here's what a "TOA" looks like to Fermi!**
- **Impossible to associate a single photon with a pulse. Even the mighty Vela has <1e-4 chance of contributing 2 detected photons in a single pulse, which is surely the bare minimum you need to characterize a shape!**
  - **(1e-5 ph/cm2/s; P=89ms)**
- **Instead, use maximum likelihood (as you always should):**
  - **Preliminary version of timing solution → fold data over a period of time to estimate pulse shape.**
  - **Use that to make a TOA. Very similar to radio method, actually, but with much longer timescale.**
  - **Method presented in Ray et al. 2011, used to time 17 pulsars.**
  - **NB: histogram at right is binned in phase for clarity, but we used unbinned likelihood in the computation. (The binning is in time.)**

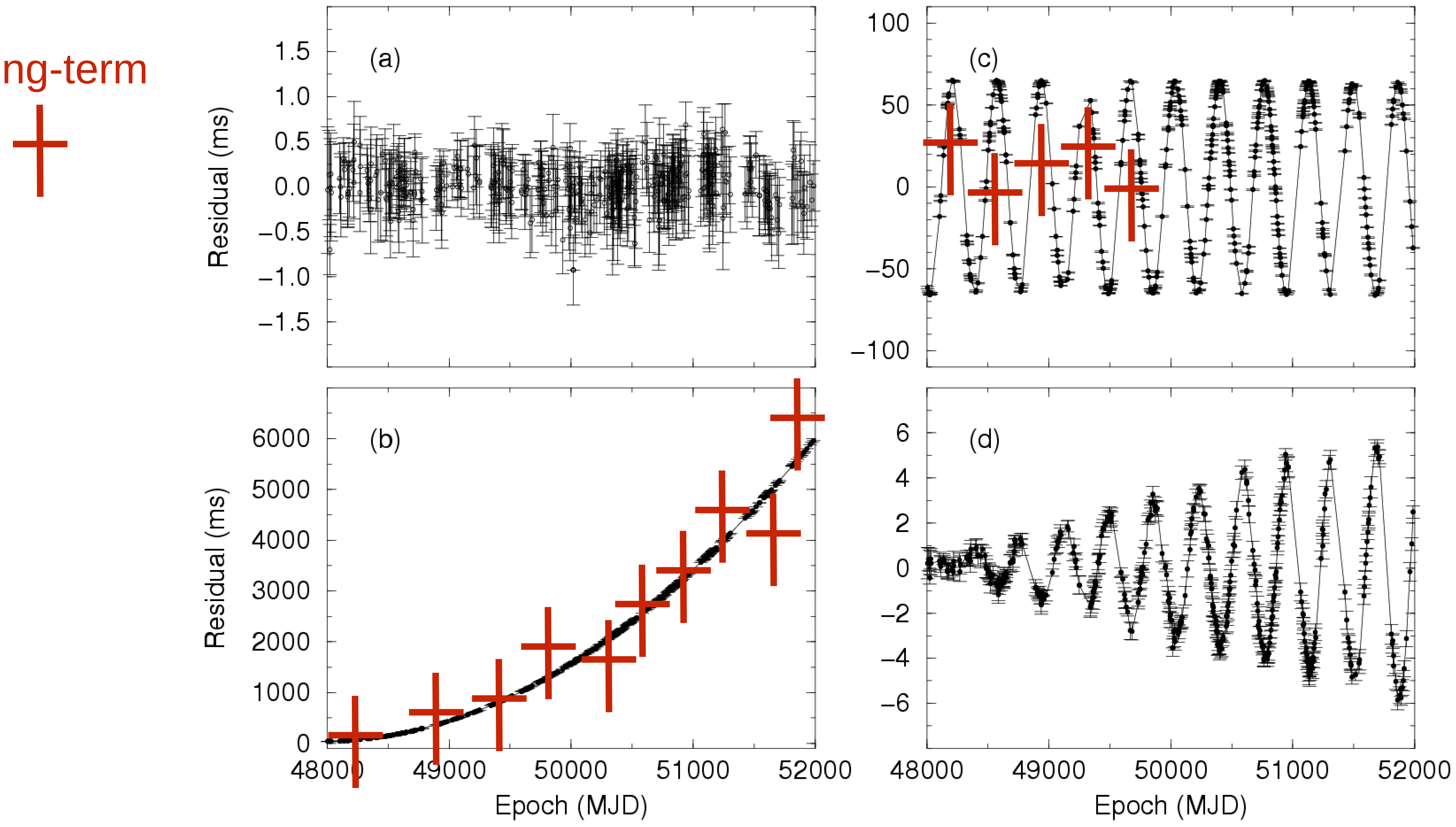




Timing with Fermi TOAs: be careful!

- **Source must be bright enough to resolve the features you're looking for. Otherwise you need independent constraints (radio timing e.g.) or to use an unbinned method.**

Simulated long-term Fermi TOAs



The brightest pulsars can get TOAs on <1 week timescales. Anything up to 1 month is fine for fitting a position.

But some will take months. Consider what you're needing to fit for: binary period? Could be less than 1 day!

I Don't Want Care About Pulsar Timing! I Just Want a Light Curve

- Suppose you're interested in a studying pulsars. You want to compare light curve shapes to model predictions, or search for pulsations in a known source, or…
- Just like needing to integrate enough photons to get a TOA, you're going to need a timing solution that spans much or all of the mission. How are you going to get it?
- Is the pulsar radio loud?
  - Yes!
    - Option 1: Ask a radio astronomer for a timing solution. Might not meet your requirements (duration, residual noise, …)
    - Option 2: Ask (or be ☺) a radio astronomer for TOAs and produce a timing solution using TEMPO2 or PINT.
    - Option 3: Ignore the radio and time in gamma rays (if possible).
  - No!
    - Option 1: Use a TOA-based method (software on FSSC: Ray+ 2011, Kerr+ 2015)
    - Option 2: Use an unbinned method (not packaged, yet)
  - I don't care! Ask David Smith or Matthew Kerr for help!

Tempo2 Demo

- **Hope the internet here is up for it.**

Plotting a Pulsar Light Curve

1. **Make a weighted FT1 file.** You need:

    -- 100%, really, use photon weights. These make a huge difference.

    -- a spectral model (XML file) – 4FGL DR2 is fine.

    -- an FT1 file: for a pulsar light curve, it doesn't need to be big. 3 deg radius is fine. Otherwise, the usual selections on quality, event type, energy, zenith angle, …

    -- run gtdiffrsp on the FT1 file (takes a long time; you can also get slightly stale versions with the diffuse "columns" already added from the FSSC)

    -- run gtsrcprob; only give it the (4FGL) name of of the pulsar you are interested in; will make a column with that name

2. Add pulsar phase: you can use the Tempo2 "fermi" plugin or the PINT script "fermiphase".

3. Make a weighted histogram with matplotlib. Play around with the number of bins. If you want a prescription for the error bars on the bins, consult the 2^{nd} Fermi Pulsar Catalog.

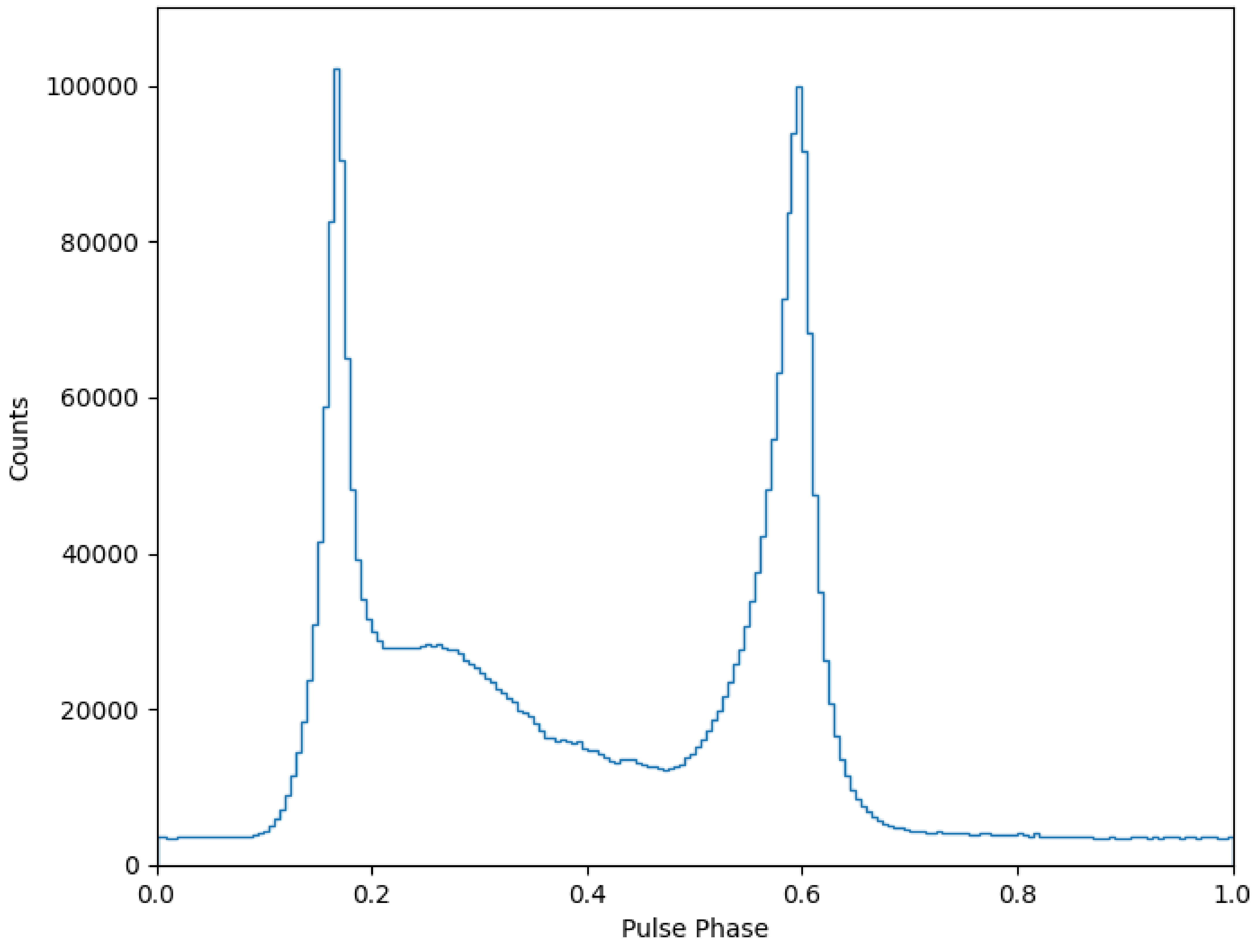
4. Make a 2-d histogram to check that your entire data set is folded OK.

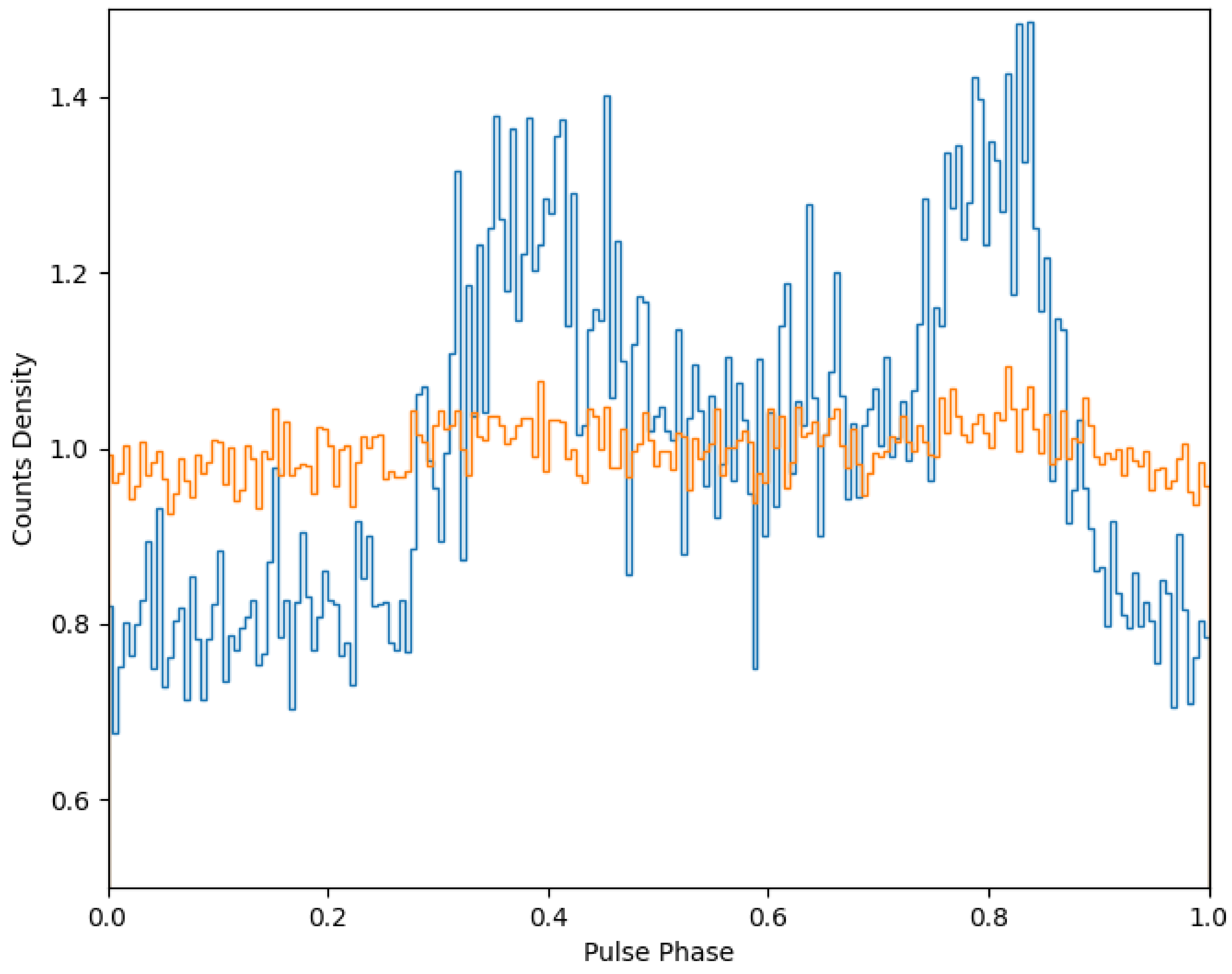
Fermi Light Curves: Use Weights!

Vela: brightest pulsar in the sky. Doesn't need weights!

(Curiously, Vela is the brightest radio pulsar too.)

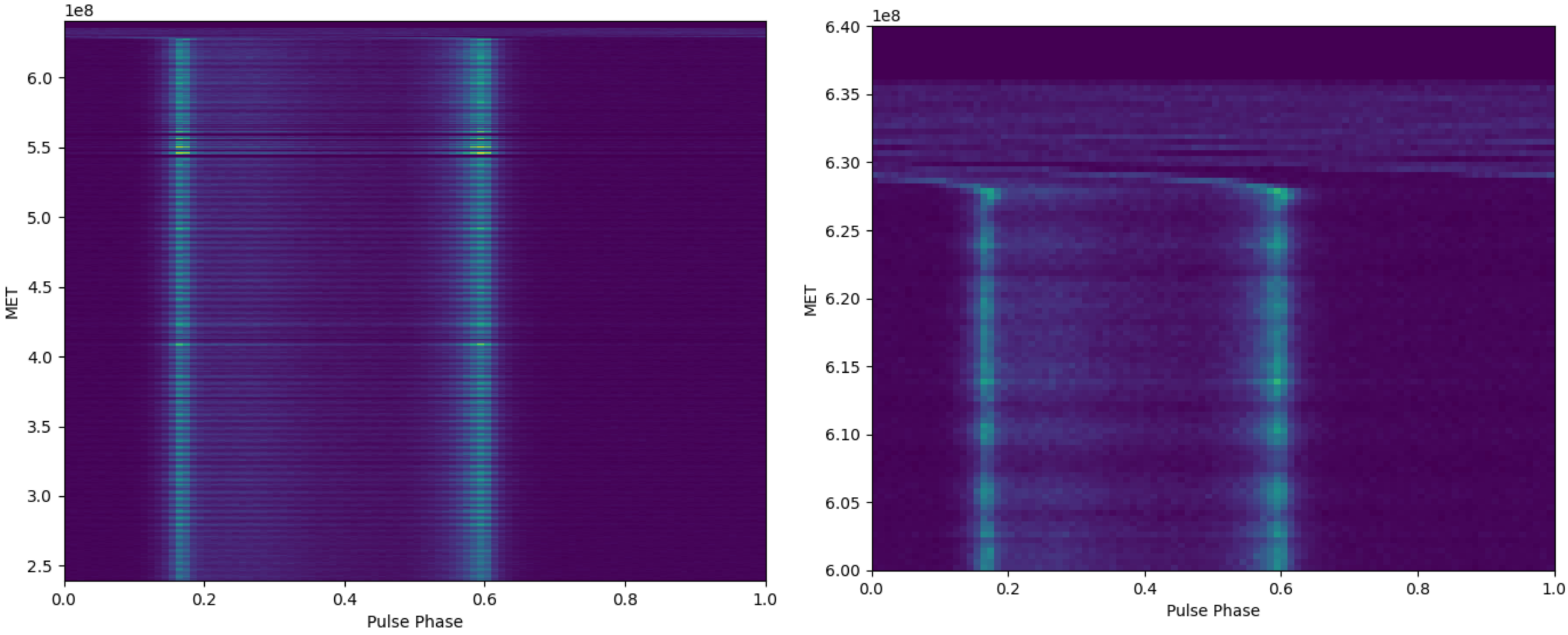
PSR J2215+5135: not the brightest pulsar in the sky.
Orange: unweighted histogram
Blue: weighted histogram.





Fermi Light Curves: Check ephemeris validity!

- **Vela Ephemeris validity ends ~ Mission Elapsed Time 628,000,000.**

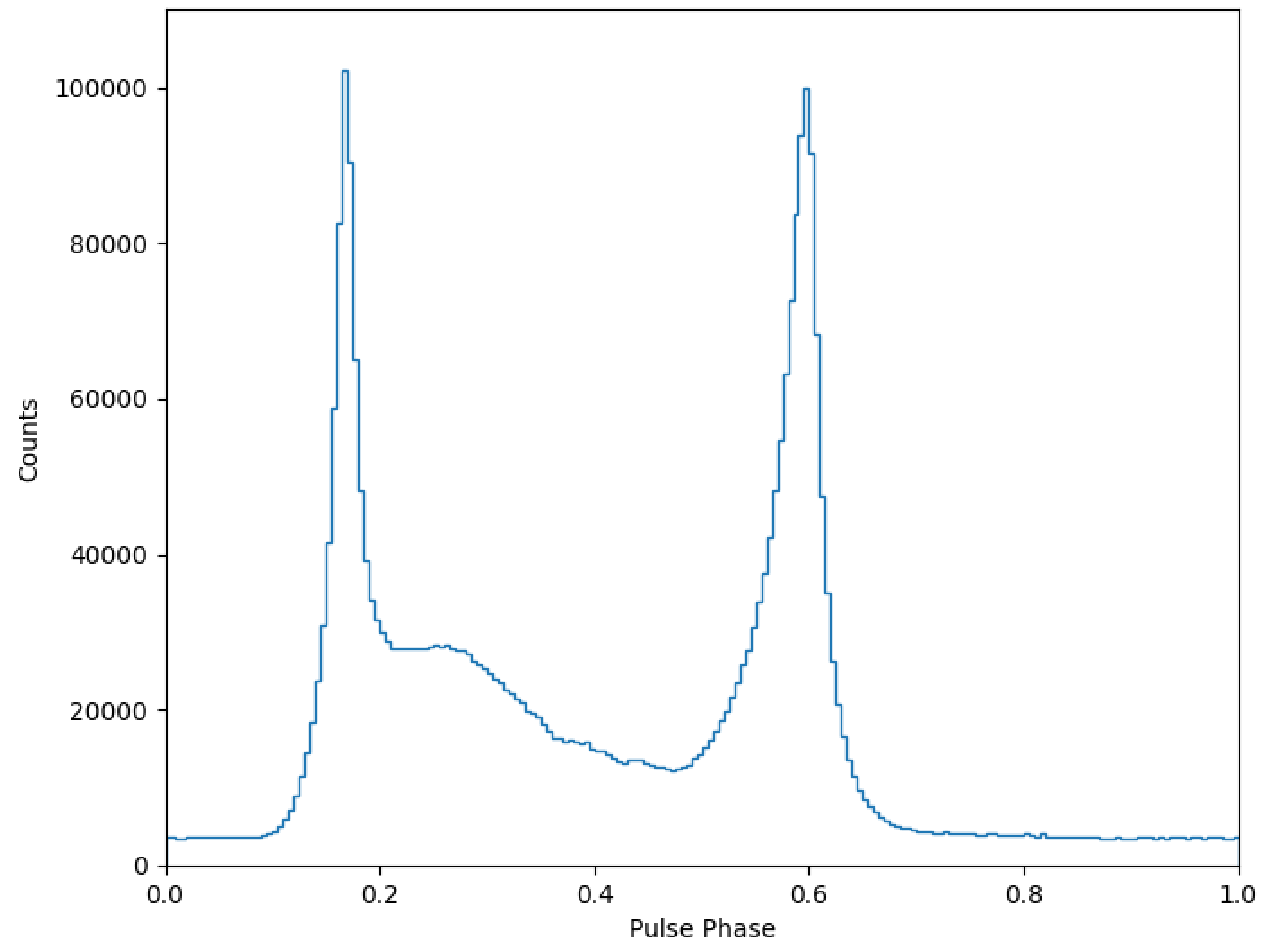


Concerns about your light curve

- You need to match the care with which you fold the data to your science case.
- It is (in)famously difficult to align pulses between different observatories and observing wavebands. Many of us have decades of experience and still get it wrong All. The. Time.
  - Seriously. I cannot overemphasize this.
- Are you looking for narrow features in the light curve, like a “giant pulse”? You need to be sure that your ephemeris tracks phase sufficiently well that sharp features aren’t washed out.
  - Particularly a problem with young pulsars with “timing noise”.
  - Also possible to “over whiten” a timing solution and produce features that don’t really exist!
- Pulsar timing solutions are generally only good for a limited period of time. If you extrapolate, *check* that you aren’t getting nonsense.
- Just things to be aware of. Feel free to ask me for more details if you’re working on something in this area.

Pulsars turn OFF

- The LAT background is complicated: particle background from detector, astrophysical background from earth, from sun, from diffuse emission in the galaxy, from unresolved sources…
  – Very difficult to model, and *most* photons are from the background. Dominant systematic.
- Pulsars offer a unique opportunity to check the LAT instrument response function because you can simply subtract the off-pulse signal from the on-pulse signal and obtain a pure, point source pattern.



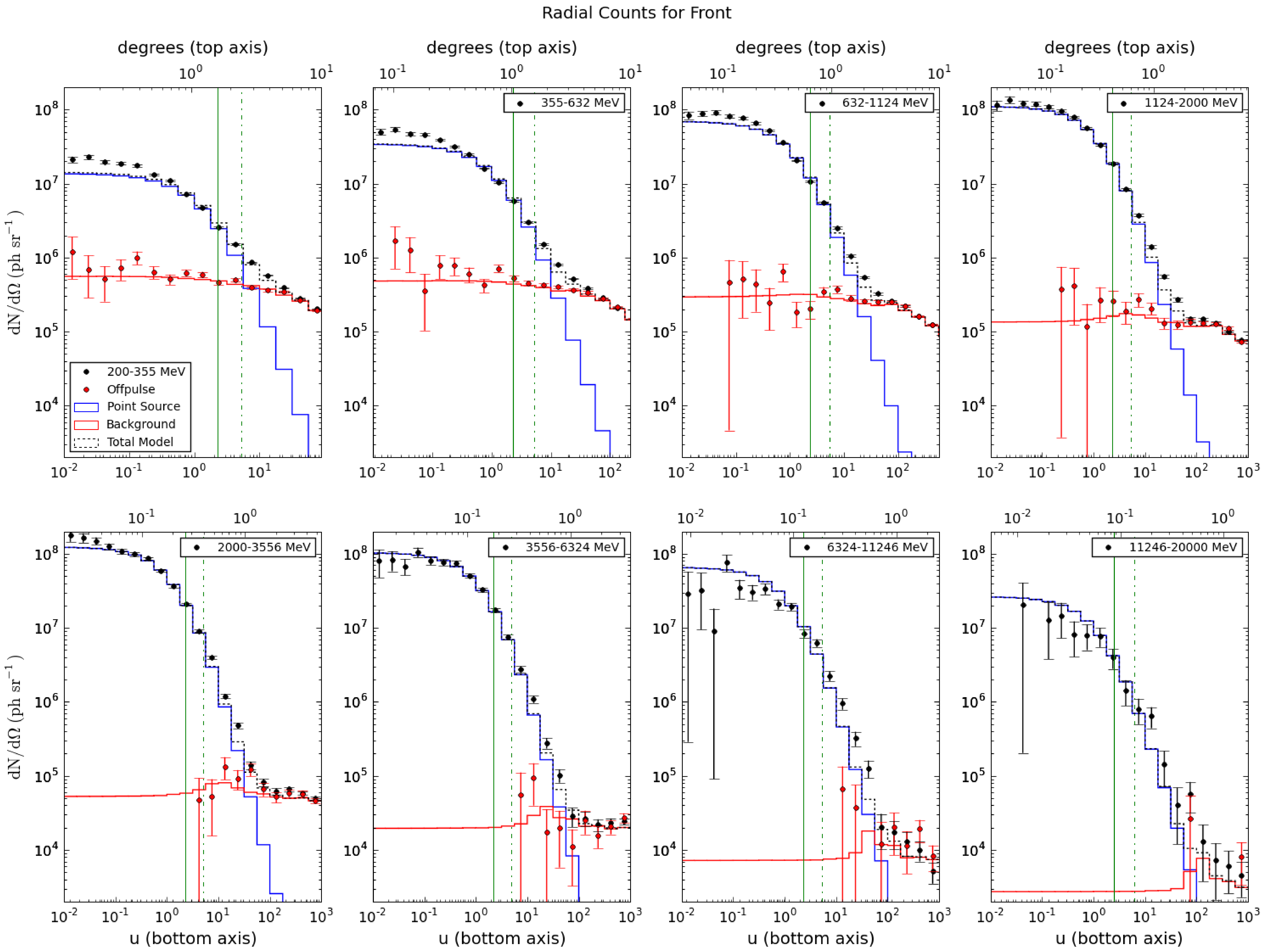
Pulsars turn OFF

An analysis I did way back in 2009 as a grad student!

Use the brightest pulsar (Vela) and simply estimate the background by counting photons in the off pulse.

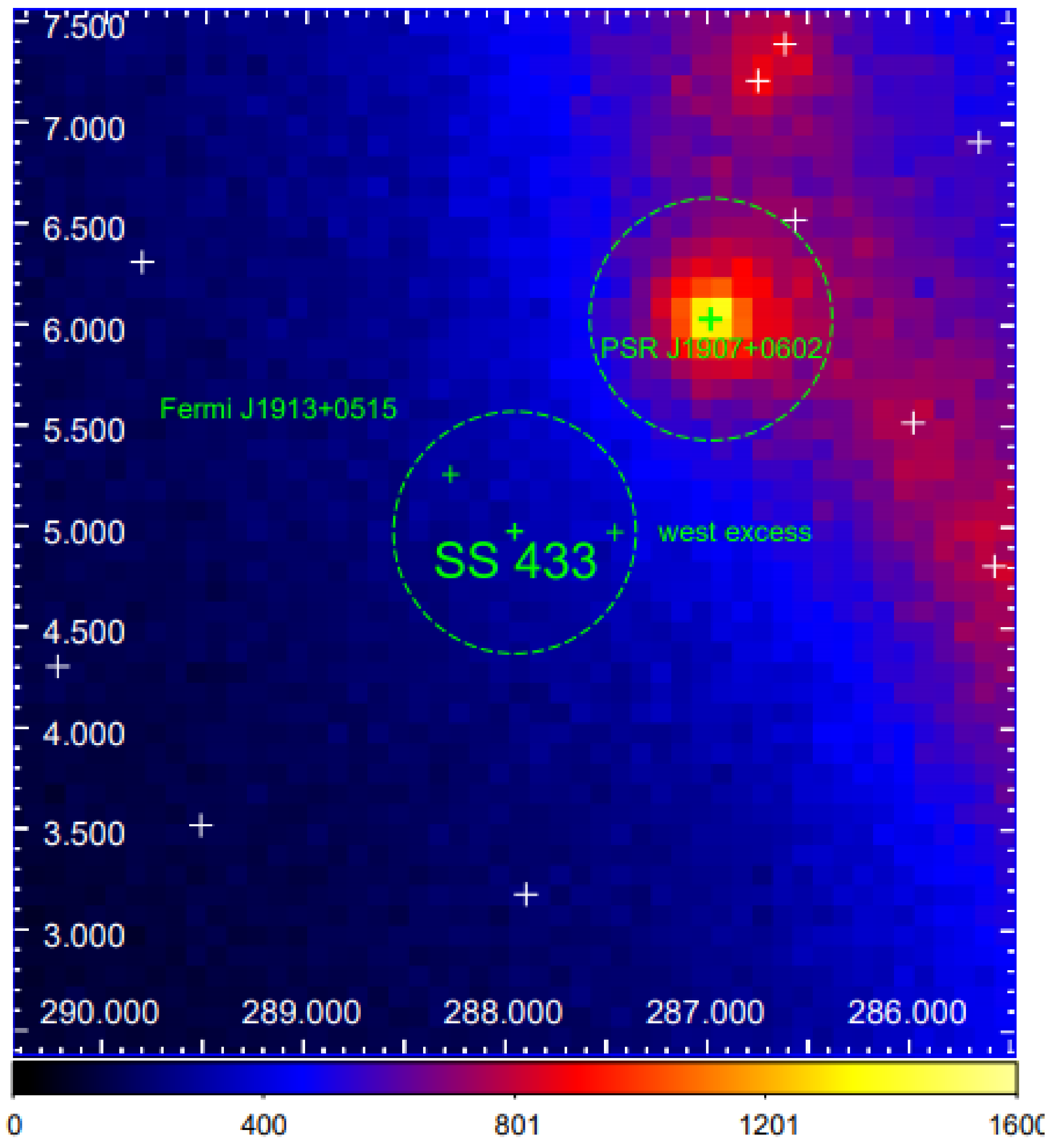
On-pulse analysis revealed inaccuracies in the PSF, which we could measure and correct.

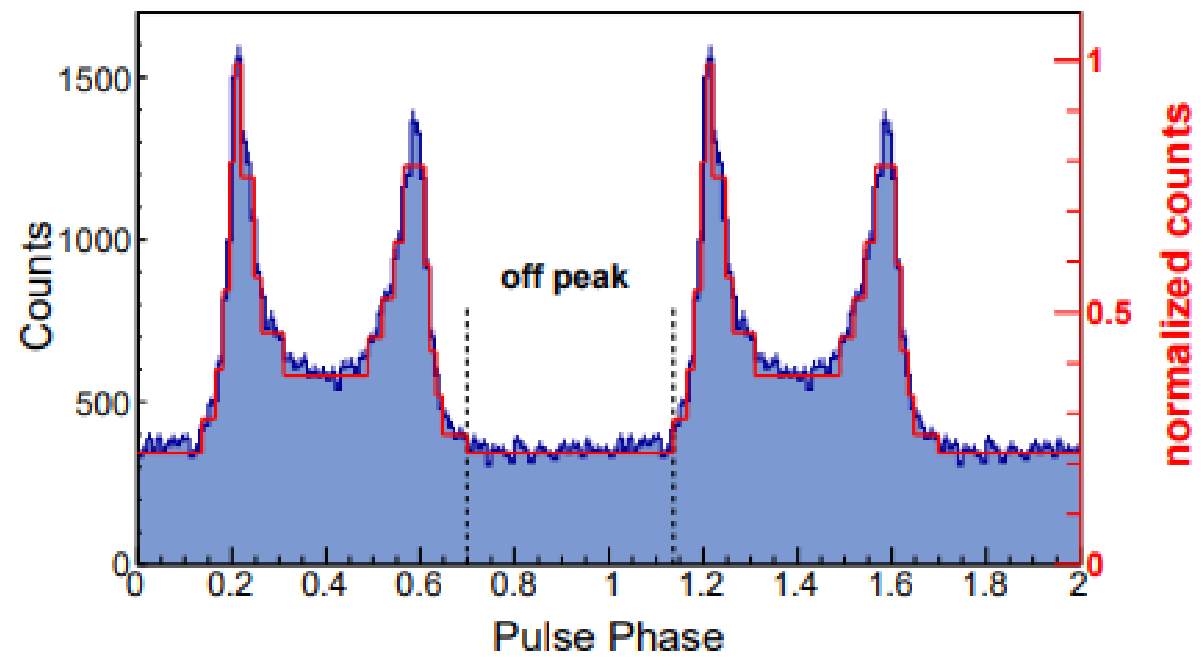
Much of this resolved with Pass8 and otherwise fixed by “in-flight” IRFs, measured using pulsars and AGNs.

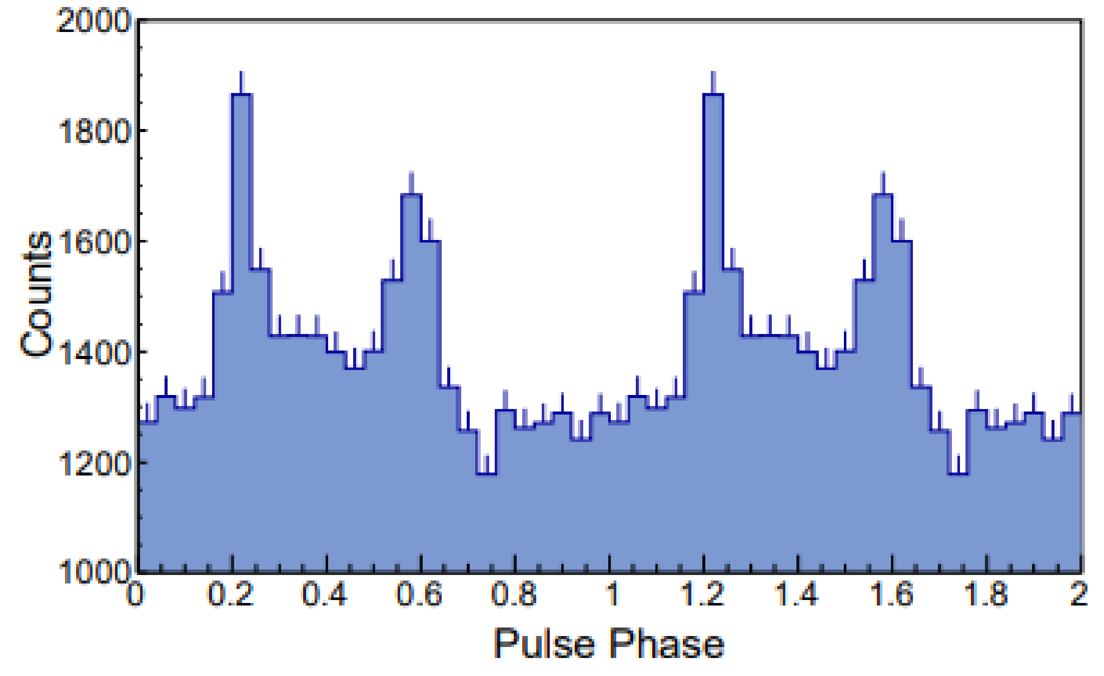


Pulsars turn OFF

- Faint source analysis: remove most pulsar emission by selecting the offpulse.
  - Lose some photons: optimize carefully!
- Most common use: analyzing faint, extended sources in the Galactic plane. SNRs tend to be found near pulsars, as do pulsar wind nebulae!
- Because GeV pulsars are so bright, almost all of the pulsars outshine the GeV emission from these other sources.
- Science questions to consider:
  - What is the spectrum of the source you are after like?
  - How bright is it?
  - What would the ratio of fluxes be?
  - How sharp is the pulse profile?
  - How might you trade residual contamination vs. extra data?

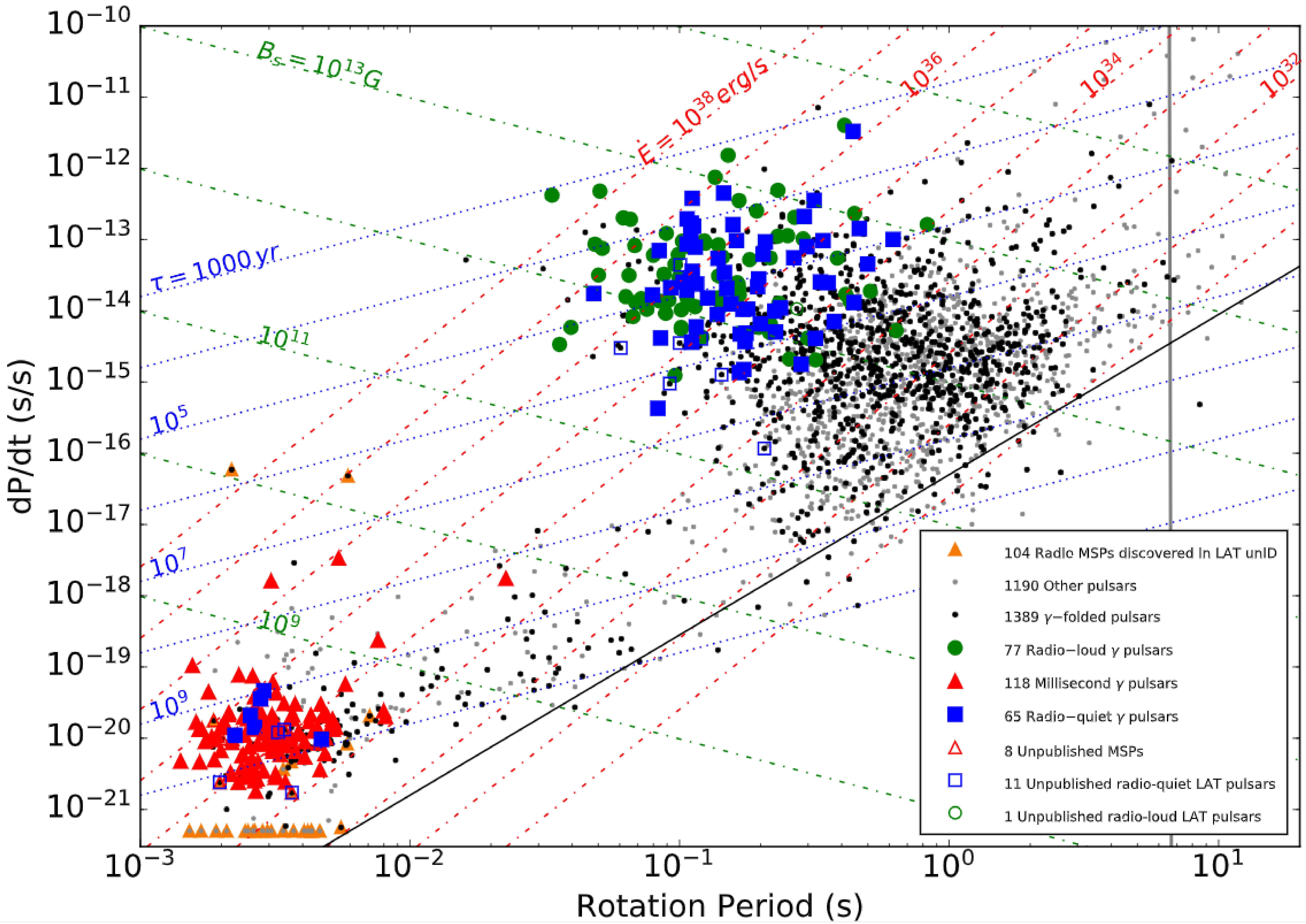






Back to pulsars as clocks: pulsar search!

- **Many of the pulsars we're detecting now are RADIO-QUIET.**



Back to pulsars as clocks: pulsar search!

- Many of the pulsars we're detecting now are RADIO-QUIET.
- How do we do this? "Blind search", i.e. search for a periodic signal in LAT data.
- This is bread and butter radio pulsar science, but it's a different problem because, just like timing, radio data are collected over ~1 hr, not 1 years!
- Huge parameter space to search.
- Just how huge?
- Rule of thumb: need to know timing parameters well enough to predict phase to about 0.1 (10% of a rotation).
- Phi = F0*(t-t0) + 0.5*F1*(t-t0)^2.
- If we center t0 in the data, then the largest value timespan for Fermi (in seconds) is about 2e8s.
- Thus, if we don't want to be off by more than 0.1, we need steps of
  - dF0 = 0.1/2e8 = 5e-10
  - dF1 = 0.1/(0.5*2.8e8**2) = 5e18
- What are the ranges of parameters?

Back to pulsars as clocks: pulsar search!

- Young pulsars: F0 < 40 Hz (give or take)
- Millisecond pulsars: F0 < 1000 Hz (give or take)
  - F0 trials: 1000/5e-10 = 2e12 trials! That's two trillion!
  - And that's not counting F1… or position, or binary parameters, or…
- What does a trial entail?
  - "Fold" photons using the trial value of F0/F1/…
  - Compute a "test statistic" for pulsation.
  - In other words, each trial involves many floating point computations!
- Use photon weights to cut as many photons as possible.
- Optimize the heck out of the code, use big computers, and GPUs.

- Bottom line here: if you want to search for pulsations, you can do it with a radio ephemeris, but if you need to do a blind search, you'll probably want to collaborate!
  - Colin Clark, Lars Nieder, Pablo Saz Parkinson

Breakout Topic 1: Turning a pulsar OFF

- When might you want to consider trying to remove pulsed emission from your data set?
  - What fraction of the background does the pulsar contribute? How does it vary with energy? How sharp is the pulse phase? (How much could you cut, and how much data would you lose?)
  - Hint: consider a Poisson signal-to-noise ratio, S / sqrt(S+B), with "S" the source counts and "B" the background counts. In the on pulse, "B" contains all the background, including the pulsar. In the offpulse. Consider a case where you lose half the data but can eliminate 90% of the pulsed signal. How big does it have to be, compared to B, to win?
    - Hint: set the two S/Ns equal to each other and assume S << any background term.
    - You should find you'll "win" if the pulsar contributes 75% of the total background.
  - You can answer this more exactly using the Fermi tools. What tool might be useful for comparing the ratio of the pulsar flux to the flux of the source you are interested in?
- What about energy spectra? Might you consider doing something different at high energies vs. low energies? (Remember, pulsars are GeV sources.)

- Interesting paper to consult: https://ui.adsabs.harvard.edu/abs/2020NatAs...4.1177L/abstract

Breakout Topic 2: How big of a computer do I need? (1)

- We looked at F0 trials factors. How many F1 trials factors might we need?
  - Hint: what is a typical range of F1 for young pulsars? MSPs? We have a plot of P and Pdot… can you use the chain rule? Or maybe consult the ATNF database and look up a few values of F1 for young pulsars (J0835-4510?) and MSPs (J0030+0451?).

- Do we need an accurate position for young pulsars? What about for millisecond pulsars? Consult the expression in the previous slide on pulsar timing!
  - How much could something like a Chandra position help?

- Given a typical LAT position error (0.1 deg), how many trials would be needed to search for position for a “typical” MSP with F0=400 Hz? Is it feasible?
  - Is proper motion important?

Breakout Topic 2: How big of a computer do I need? (2)

- (Stretch goal) Many MSPs are in binary systems. If you assume the binary is circular, what is the effect on pulse TOAs? Is it similar to other parameters you've seen?
  - Use the ATNF Pulsar catalog to plot "A1" vs "PB", the orbital semi-major axis (in light seconds) vs. the binary period (in days).
  - What affects the amplitude of the sine wave? Its period?
  - How many trials would you need to find a "black widow" MSP with PB < 1 day? Assume F0 = 400 Hz. (Look at the range of A1s for these periods. Note you see Kepler's Third Law here!)
- Which parameters become the most difficult with longer data sets?
- For finding pulsars, is the Fermi all-sky survey the best approach?

A Problem: Timing Noise

- **Non-MSP gamma-ray pulsars are young and energetic. This means they aren't actually such good clocks and show strong timing noise.**
  - **A seemingly random (though not always!) wander in observed from predicted phase.**
  - **Empirically seems like a stochastic process, possibly a stationary one.**
  - **MSPs have timing noise too, but typically below the measurement threshold for LAT.**

- **Because it's not been a big factor in radio timing, it had somewhat been ignored in the literature until pulsar timing arrays came on the scene.**
  - **From 2010 onwards, a number of papers deal with fitting pulsar data with stationary processes, in time domain and Fourier domain.**
  - **Time domain: use a non-diagonal covariance matrix (generalized least squares). Typical choice: Matern kernel maps to power law process.**
  - **Fourier domain: include Fourier coefficients of timing noise process in fit, constrained by a prior on their amplitudes (e.g. power law)**