TIMING THE FUTURE

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INTRODUCTION

PHASE & GAMMA-RAYS

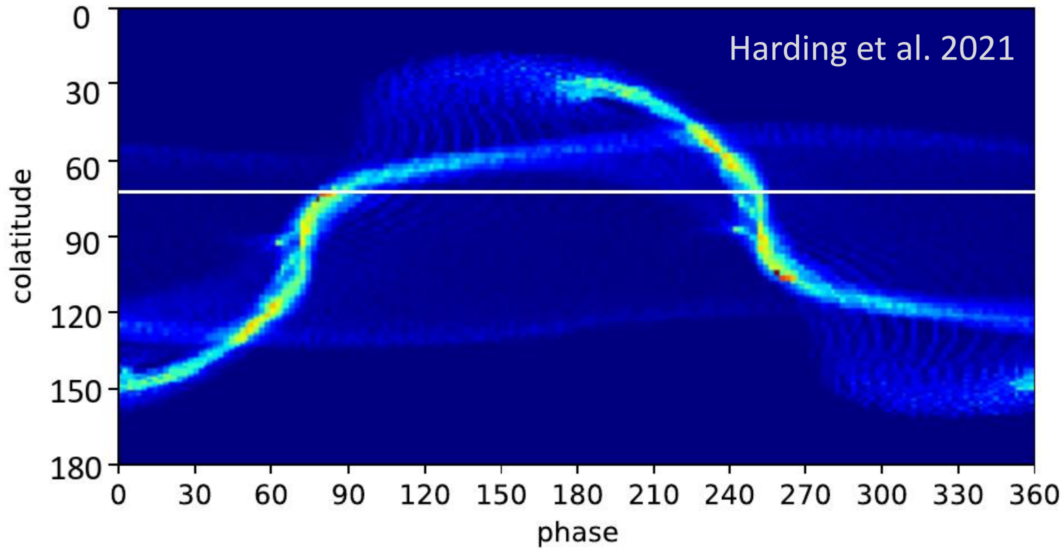
The interest in pulsar **rotational phase** has multiple causes.

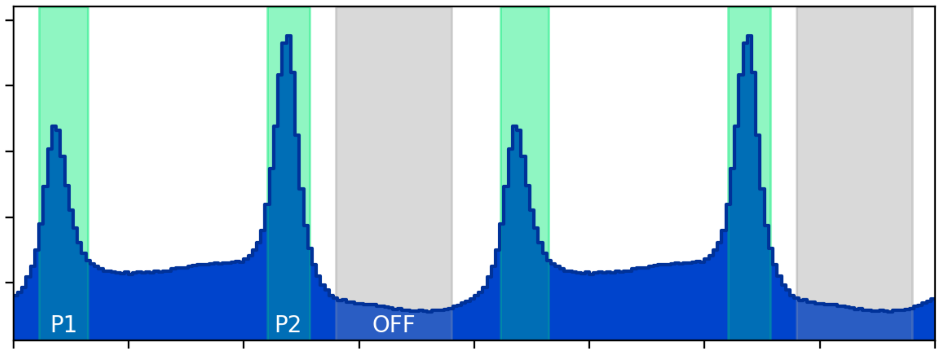
Scientific: it conveys **information on the emission region**, and can be used to constrain models.

Operative:

- it allows to select **regions of interest** in **time-domain**, greatly boosting the **sensitivity** for emission search.
- it allows to **selectively gate** the pulsar (or its PWN) to **separate** the objects.

Phase attribution and analysis require a pulsar **rotation ephemeris**.





RADIO EPHEMERIDES

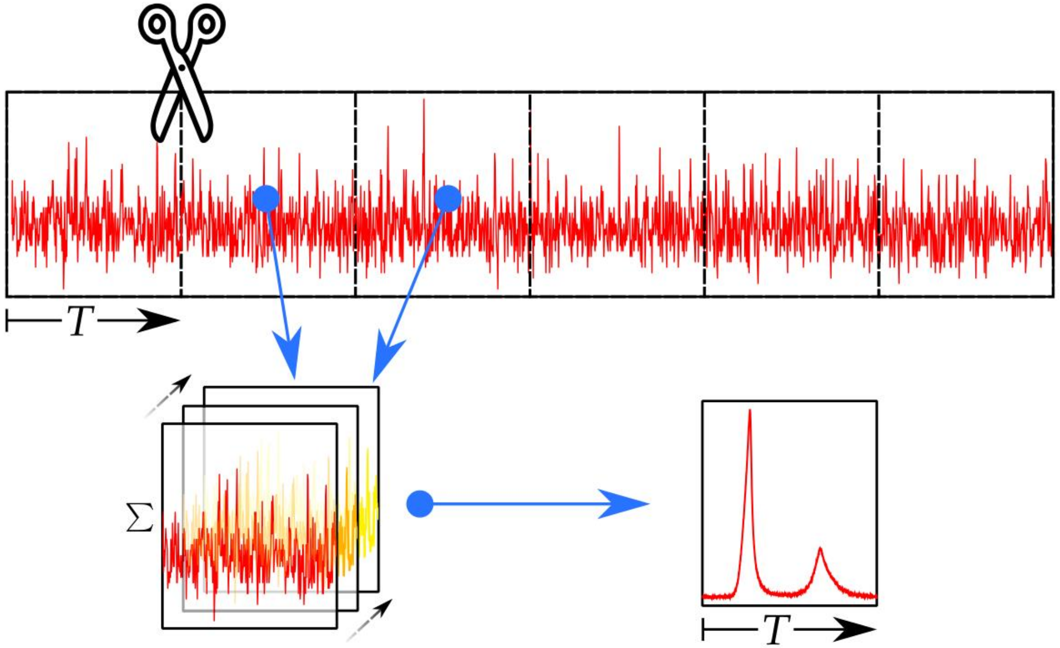
Folding of a **radio observation** yields a single **time of arrival** for the reference feature at the **observatory site** (**SAT**).

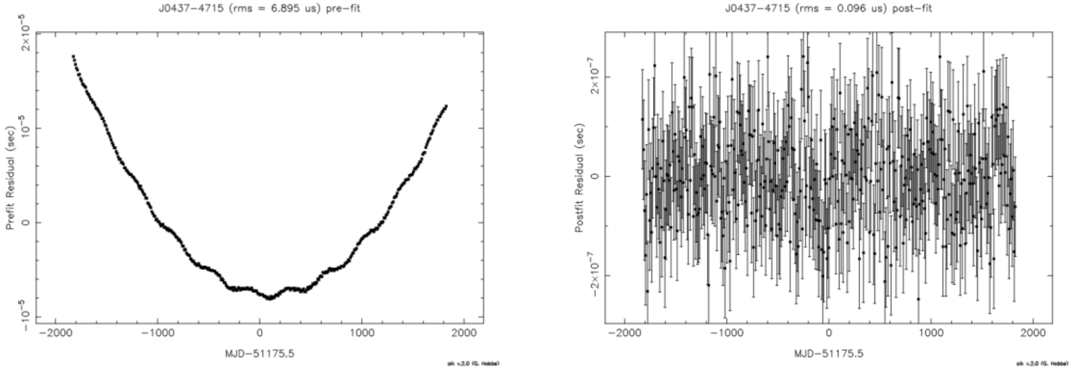
Clock corrections applied to obtain a **barycenter** arrival time (**BAT**).

BATs + pre-existing **ephemeris**: **pre-fit residuals**;

Model fitting:

- **Model parameters** (astrometry, rotation, binary, dispersion measure, GW background,…)
- **Post-fit residuals** (should be white).





GAMMA EPHEMERIDES

ISSUES

Low fluxes force **longer exposure times**, with a sensible **variation of the pulsar parameters** within the integration window.

Single event time-series (and possibly large background, e.g. in the **VHE** regime).

Need to correct **each event's SAT to a BAT before** even producing the phase diagram.

THE GOOD REASONS

Radio-quiet pulsars exist and are **interesting targets** (e.g. Geminga): **25% of LAT pulsars**.

Obtaining **radio data** typically requires **dedicated observation time**:

- Only the **Crab pulsar** has regularly updated publicly available ephemerides (JBO).

Gamma-rays are **unaffected** by the **dispersion measure**.

OBTAINING UPDATED EPHEMERIDES IS HARD!

(e.g. in Fermi-LAT's latest 3PC)

PSR J0248+6021 valid to MJD 54877 (15/02/2009) — — — — — — — — PSR J1857+0943 valid to MJD 59931 (18/12/2022)

GAMMA EPHEMERIDES

Working with an **outdated ephemeris** is generally **impossible**:

$$\varphi(t, \boldsymbol{\nu}_0, \boldsymbol{\mu}) = \varphi_0 + \nu_0(t - t_0) + {}^1\!/_2\,\dot{\nu}_0\,(t - t_0)^2 + \cdots + f(t, \boldsymbol{\mu})$$

$$\psi(t, \boldsymbol{\nu}_0, \boldsymbol{\mu}) = \varphi(t, \boldsymbol{\nu}_0 + \boldsymbol{\delta\nu}, \boldsymbol{\mu}) - \varphi(t, \boldsymbol{\nu}_0, \boldsymbol{\mu})$$

$$= \delta\nu\,(t - t_0) + {}^1\!/_2\,\delta\dot{\nu}(t - t_0)^2 + \cdots$$

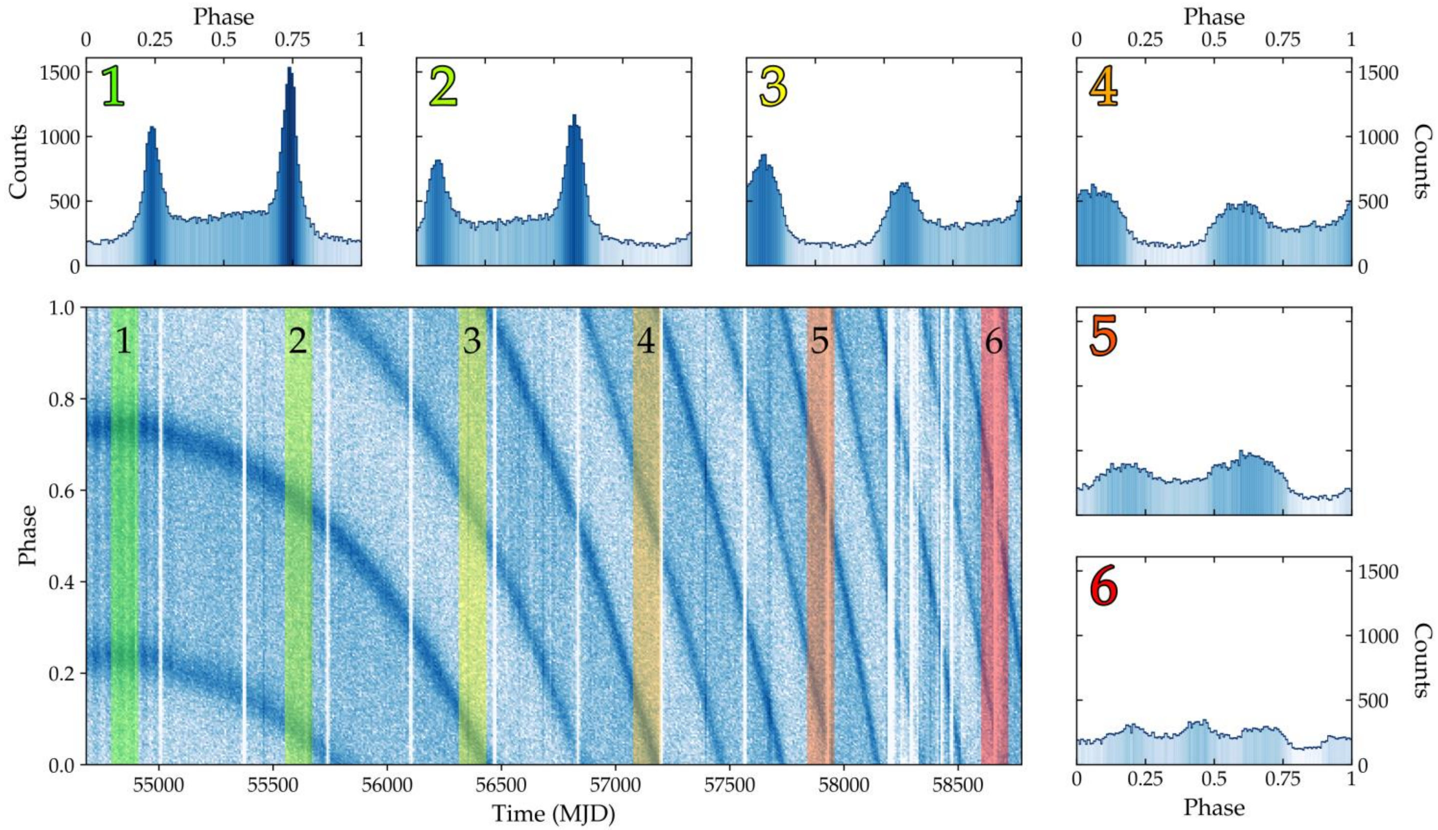
$$(\partial\psi/\partial t) \quad = \delta\nu + \delta\dot{\nu}(t - t_0) + {}^1\!/_2\,\delta\ddot{\nu}(t - t_0)^2 + \cdots$$

The "**rollover time**" τ (how much the model takes to go out of phase by a full cycle) is **proportional to** $|\boldsymbol{\partial t/\partial\psi}|$. If a term of order n is dominant in the expansion:

$$\tau_n = \frac{n!}{\delta\nu^{(n)}}(t - t_0)^{-n}$$

The rollover time **drops** roughly as a power law in time with n as exponent. If the ephemeris is validated only up to a certain date, after that date its **consistence will diverge** quickly.

GAMMA EPHEMERIDES



TECHNIQUES

DRIFT TRACKING

Tracking the **phase drift** allows to determine the $\Delta\boldsymbol{\nu}$ **vector** and to correct for it.

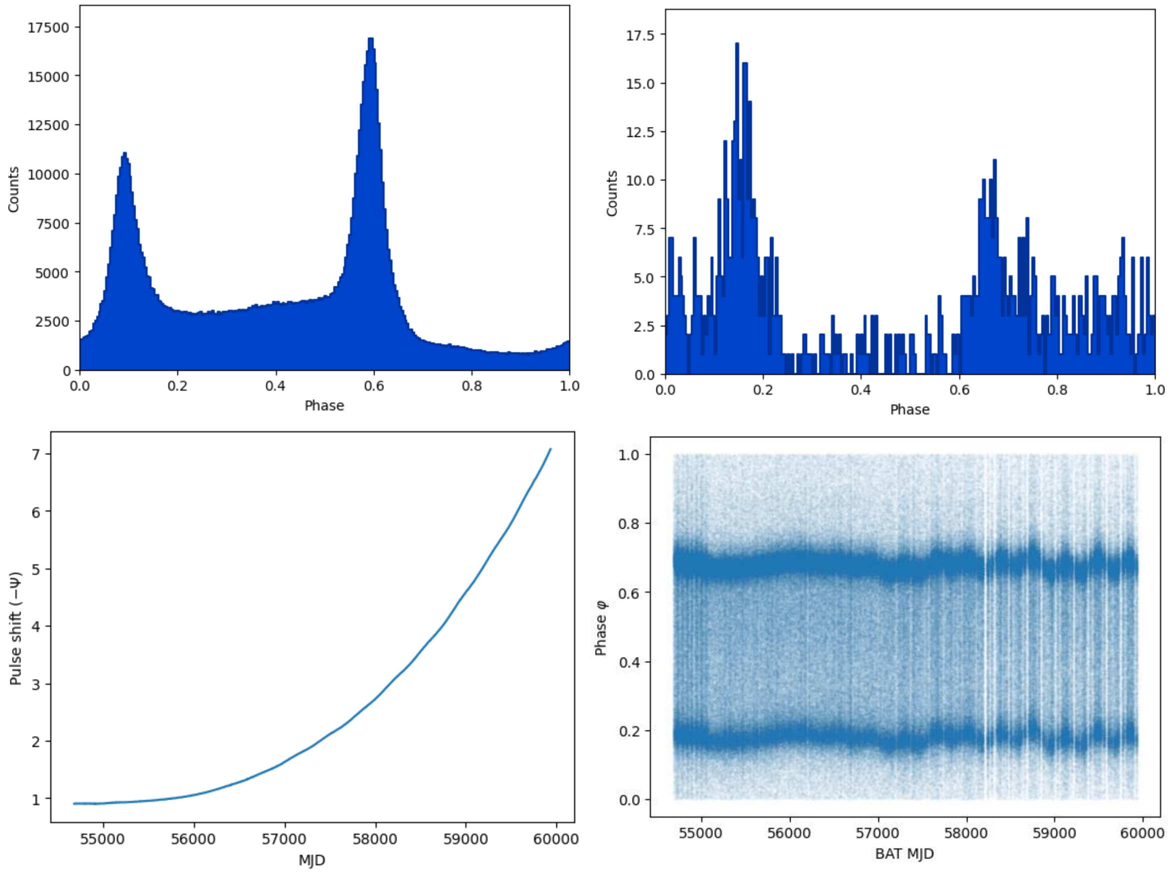
Divide the data-set in **time bins** of sufficient span, calculate **phase diagrams** $p(\varphi)$ and their Fourier transform $P(k)$.

Need a pulse profile **template** or a fiducial phase diagram $r(\varphi)$ to **cross-correlate** to:

- Cross correlation: $X(\psi) = \mathcal{F}^{-1}[R(k)P(k)]$
- Maximum of $X(\psi)$ equals to the mean drift in that time bin.

Weld together **phase wraps** at 1 and fit for the Taylor expansion.

Limited by the **statistics of the data** (flux of the pulsar) and extent of **the "rollover time".**



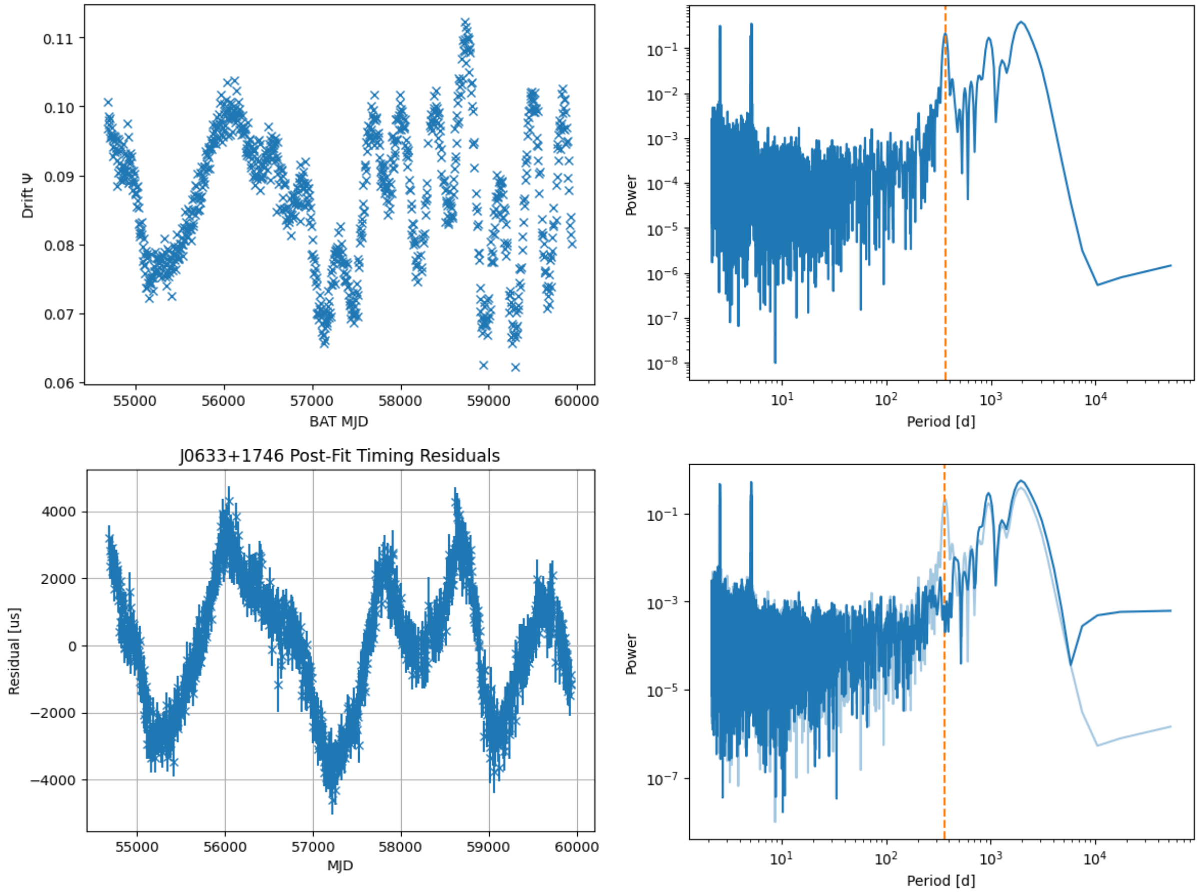
MODEL FITTING

Timing is affected by much **more** than the simple **Taylor expansion** for the **rotation**: position and proper motion, binary orbit, etc.

PINT or **TEMPO2** are the de-facto standards for pulsar timing, and can be employed to fit the residuals (pulse drift).

The fitted **phase drift** needs to be converted back to a **TOA** list (usually geocentric).

For the **uncertainties** on the derived parameters to be **meaningful**, the uncertainties of the SATs need to be **estimated carefully**.



UNBINNED LIKELIHOOD

Producing **TOAs** for **very dim pulsars** could be **challenging** or impossible.

Another approach is to directly work with the **unbinned time series** of events and maximize the **likelihood** of them resulting from a known **pulse template**.

$$\log \mathcal{L}(\boldsymbol{\nu}_0, \boldsymbol{\mu}) = \sum \log\left[w_i P\left(\varphi(t_i, \boldsymbol{\nu}_0, \boldsymbol{\mu})\right) + (1 - w_i)\right]$$

Here $P(\cdots)$ is the a pulse template and t_i , w_i are time of arrivals of **each photon**, and weights that it belongs to the pulsar emission (background fraction).

Viable alternative for dimmer pulsar, but computationally intensive.

Already proven to work well with **Fermi-LAT** data. E.g. several tens of MPS in *Fermi-LAT Collaboration (2002): doi:10.1126/science.abm3231*

OVERCOMING GLITCHES

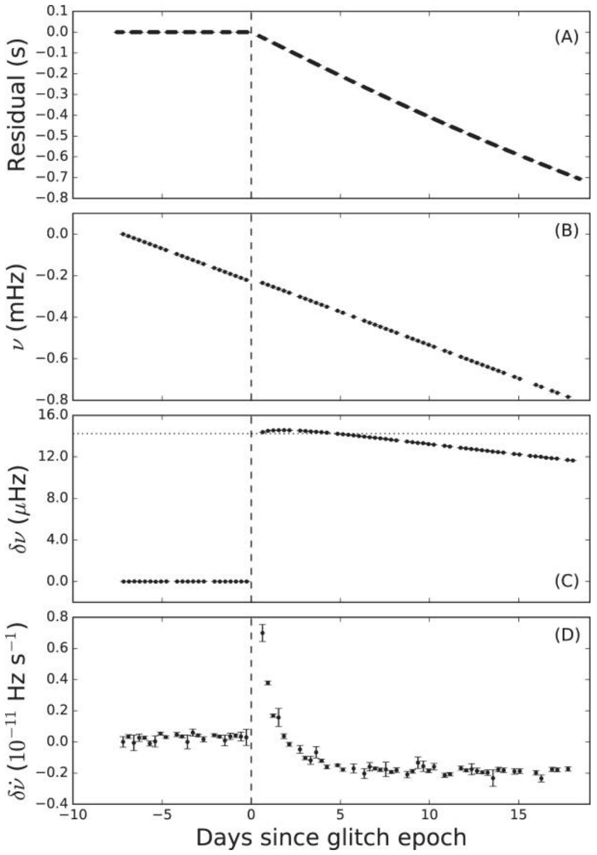
Sudden **increase** in the **rotation frequency** and **spindown** rate followed by exponential decay.

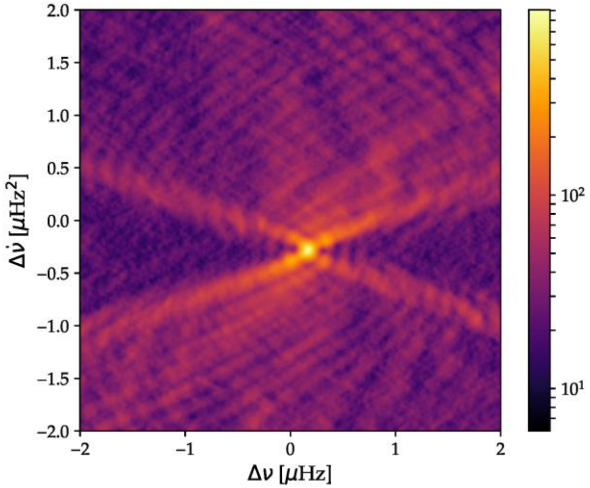
Modeled as **frequency jumps** at a certain epoch in TEMPO2/PINT.

If $\Delta\nu$ and $\Delta\dot{\nu}$ are roughly known (e.g. from radio) a tentative solution for the **post-glitch rotation parameters** can be derived.

If not, the problem is essentially equivalent to the techniques employed in **blind pulsar search** (e.g. using PRESTO):

- Joint scans in $\boldsymbol{\Delta\nu, \Delta\dot{\nu}}$ maximizing the test-statistics.
- **Computationally** intensive.





RESIDUAL NOISE

Residual spin noise: intrinsic property of the pulsar. Especially important for **young**, spin powered ones.

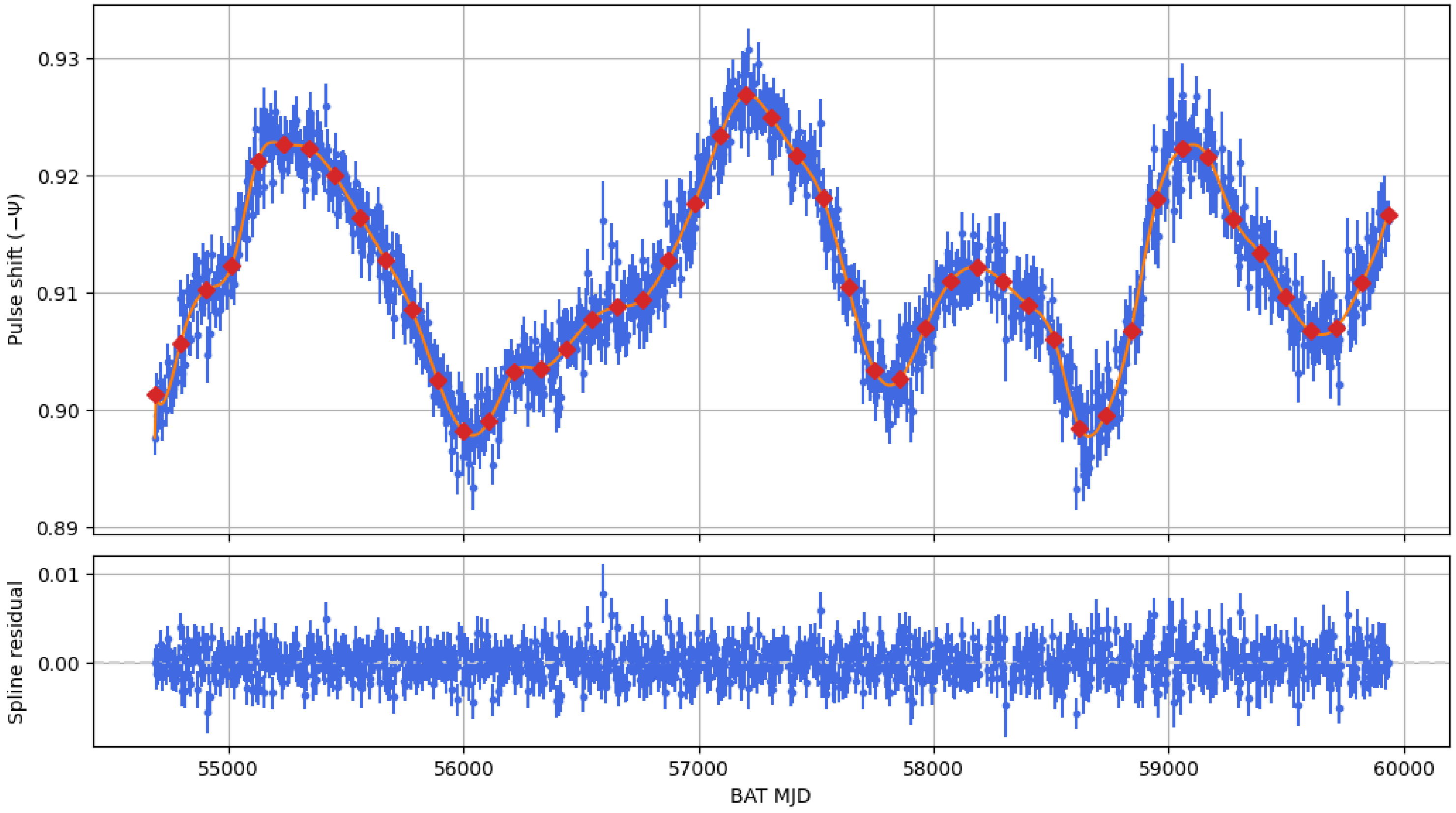
Typically the **subject of investigation** of pulsar timing**. Careful separation** of the **sources** of the noise is needed:

- Avoid **systematics** in the **physical parameters** and extends validity.
- Fitter should take **correlation of residuals** into account (e.g. Cholesky decomposition).

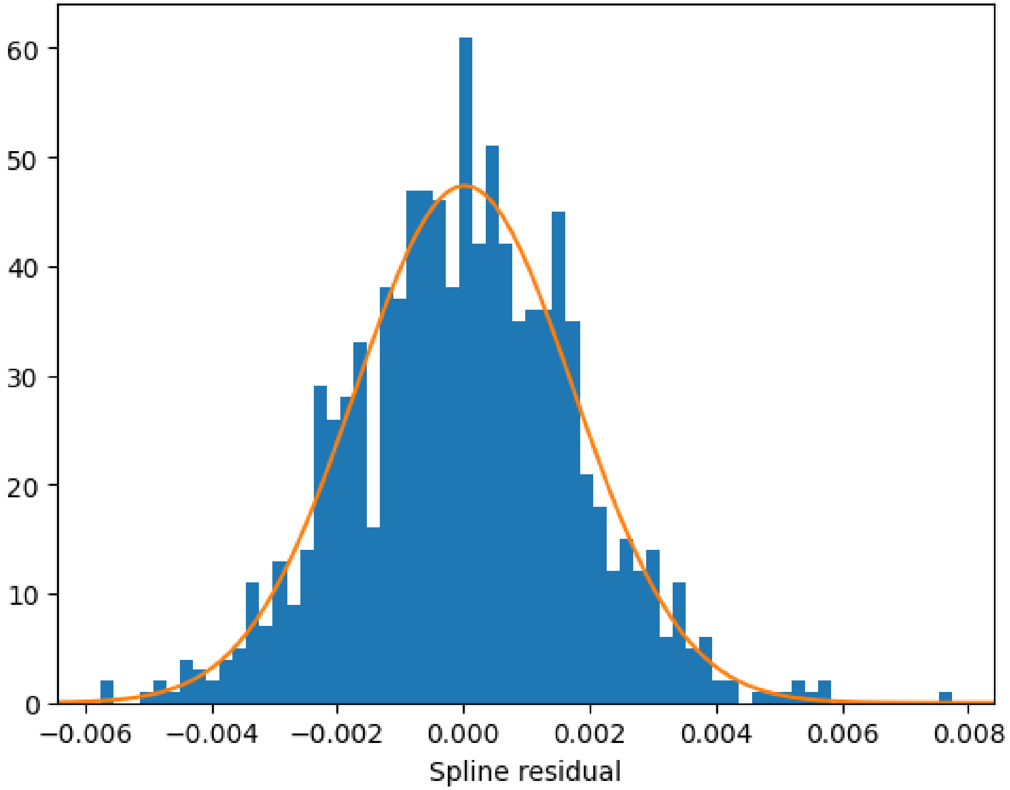
For the purpose of keeping the **pulse position fixed** for gamma-ray observations, various **interpolate on** methods.

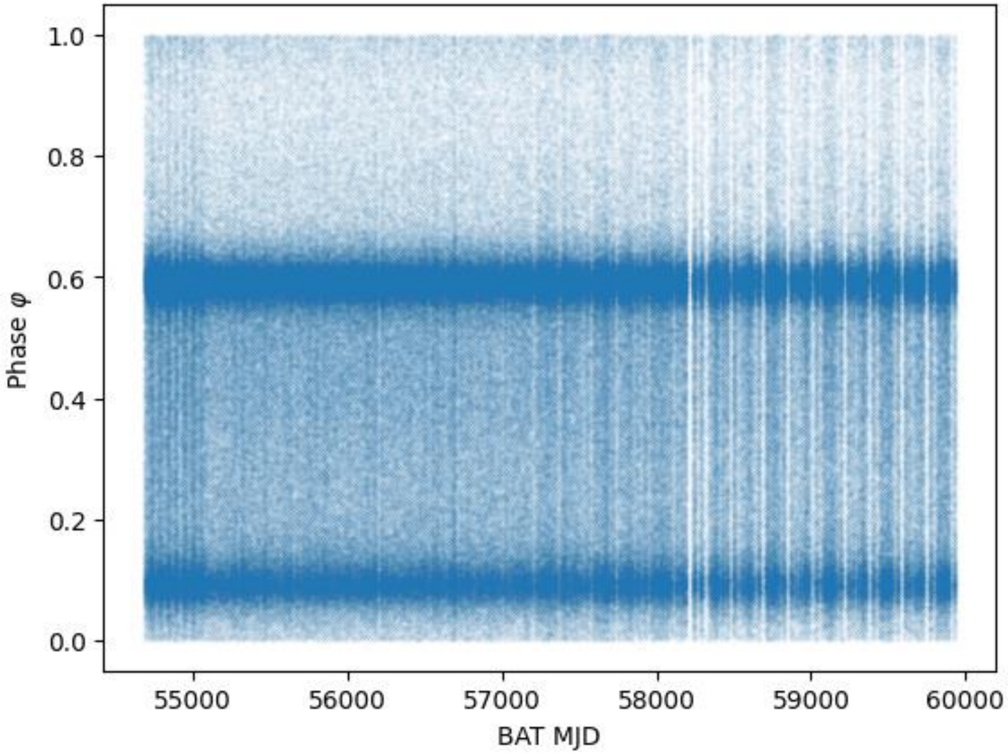
- **Linear**: IFUNC parameters;
- **Cubic**: short-term ephemerides, piecewise ephemeris with ancillary glitches (e.g. Crab JBO);
- **Sinusoidal**: WAVE parameters (e.g. some in 3PC);
- **Higher orders**: nowadays completely deprecated;

RESIDUAL NOISE



RESIDUAL NOISE





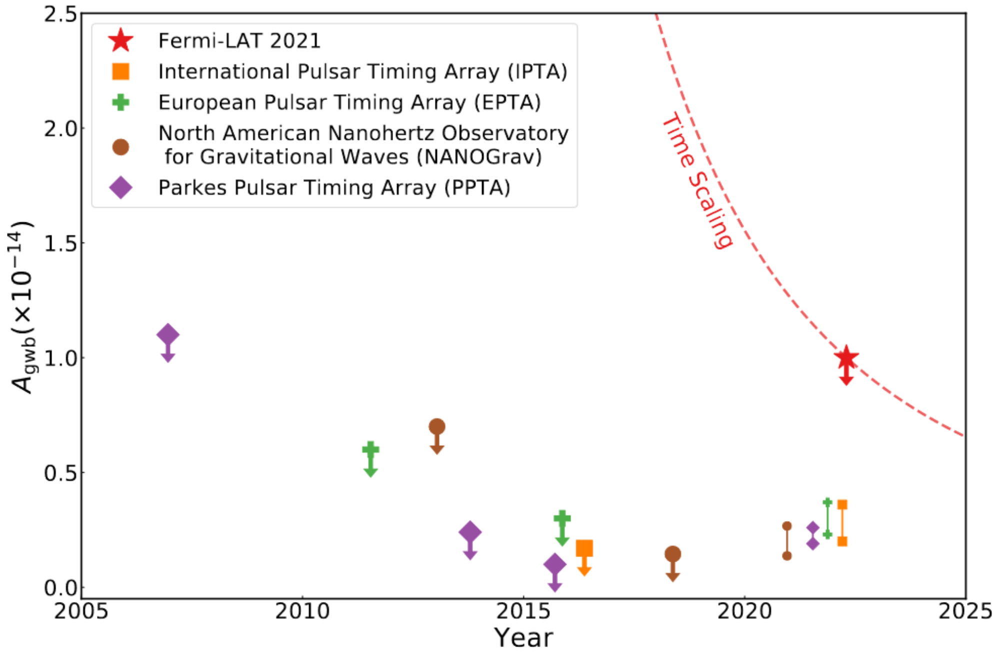
NOT ONLY A WORKTOOL

Pulsar timing is **not only a companion** tool to study the phase-dependency of pulsar emission.

Gamma-ray timing yields scientific results as well.

E.g. 2022 Fermi-LAT work on a **gamma-ray PTA** using several MPS, delivering limits on the **GW background** at f~nHz.

While challenging because of the low photon statistics, yields **independent** result from radio PTA, and **unaffected** by **dispersion measure**.

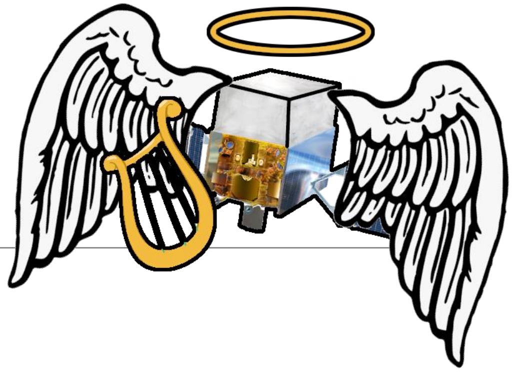


Fermi-LAT Collaboration, 2022

PERSPECTIVES

…AND PERPLEXITIES

FERMI-LAT ADDICTION



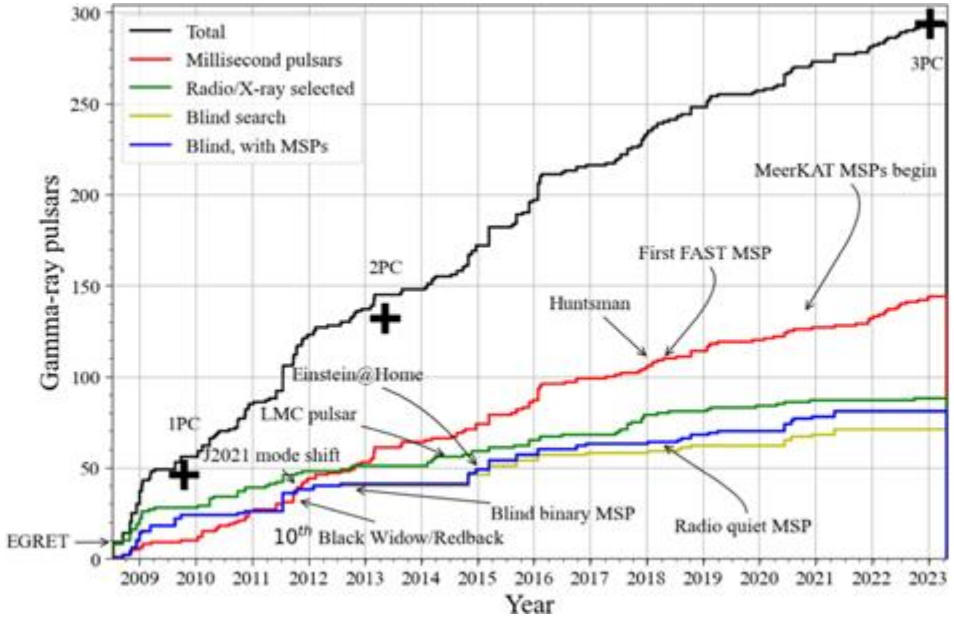
Fermi satellite launched in **2008** with a planned lifetime of **10 years**.

Solar panel issue on **2018** put an end to constant uniform exposure in every part of the sky.

Over the past **16 years**, the field of high- and very-high-energy astronomy has become **heavily dependent on Fermi-LAT**.

What if **Fermi-LAT** were to **suddenly terminate** operations?

- Not only losing the **further accumulation** of **data** between 10s MeV and 10s GeV…
- … losing also **timing information** for several pulsars!



Fermi-LAT Collaboration, 3PC, 2023

UPCOMING SATELLITES

COSI (Compton Spectrometer and Imager):

- Launch date: 2027
- Energy range: 0.2-5 MeV
- Effective area: 0.1-0.5 m^2
- Timing: 0.1-10 µs

AMEGO-X (All-sky Medium Energy Gamma-ray Observatory eXplorer):

- Launch date: >2035?
- Energy range: 100 keV - 1 GeV
- Effective area (pair-conversion): 0.05 m^2
- Timing: 0.1 µs

CONCLUSIONS

Ephemeris preparation is an essential part of the **observational techniques** of high-energy pulsar studies, yet often overlooked.

Timing solutions derived from **radio data** are ubiquitous, however they are not often **updated**, require external collaborations and **dedicated observations**, and may simply be **impossible.**

- **Radio quiet pulsars** make up **25%** of all **LAT** pulsars and up to ∼**50%** of **young spin-powered** ones.

Timing with **gamma-ray** data of **Femi-LAT** has proven a viable alternative, at least for brighter pulsars:

- **Drift tracking** and **glitch** detection/modeling available for slowly evolving, brighter pulsars;
- **Maximum-likelihood** analysis available even for dimmer pulsars;
- **Timing noise** interesting per-se and as a tool to establish a gamma-ray PTA.

We **depend on Fermi-LAT** in several aspects of our discipline. What challenges would we face, if it were to terminate?