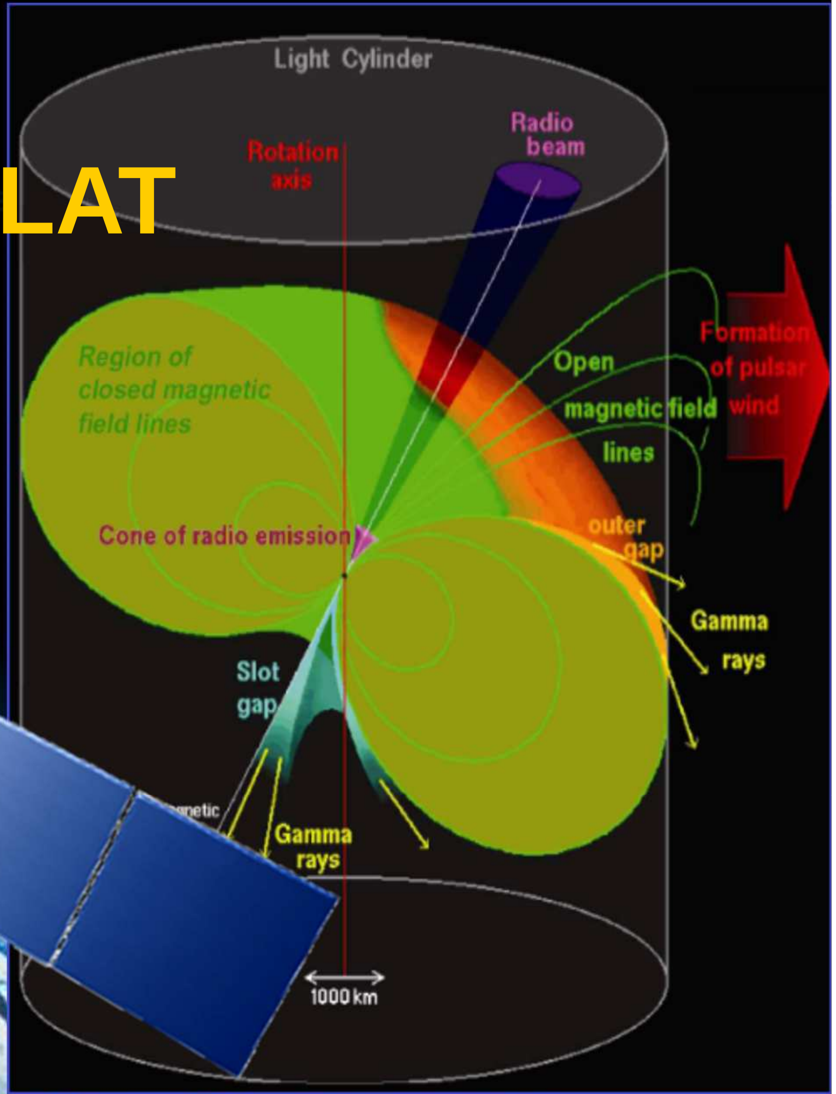
Pulsar Timing:

Experience from *Fermi* LAT



David A. Smith, for the *Fermi* LAT collaboration and pulsar consortia
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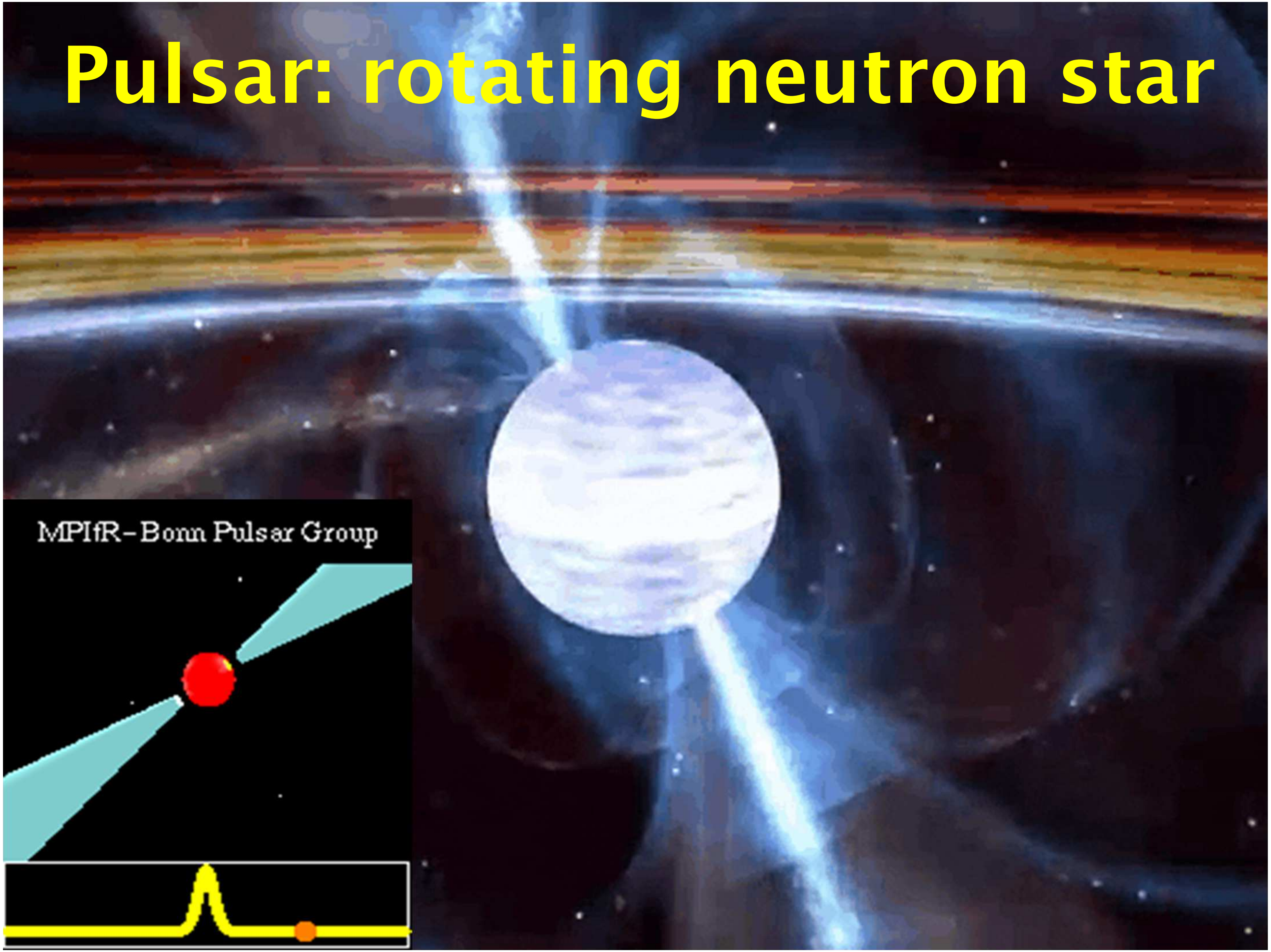
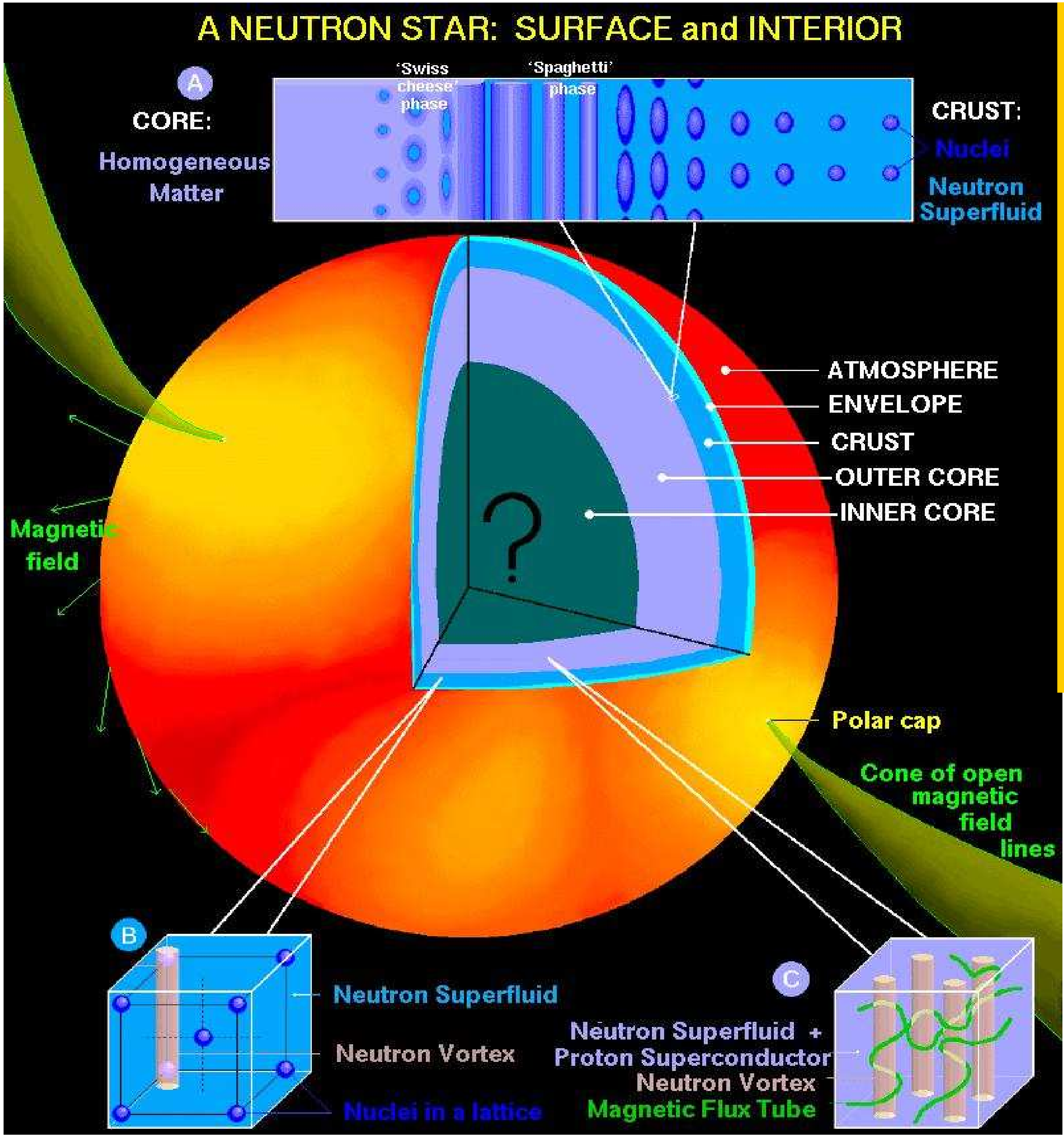
CTA Webinar
Cyberspace, 26 May 2022

This talk:

- Pulsars – a brief overview.
- A personal history of gamma-ray pulsars.
- *To search for gamma-ray pulsations, you only need:*
    - Good timestamps ; rotation ephemerides ; code
- LAT's needs (Large Area Telescope on *Fermi*, formerly GLAST)
- CTA's needs
- Friendly advice

Pulsar: rotating neutron star





~13 km radius.

< 1.4 to >2.5 solar masses. Superfluid core, hundreds of millions of tons per cm^3.

Iron crust.

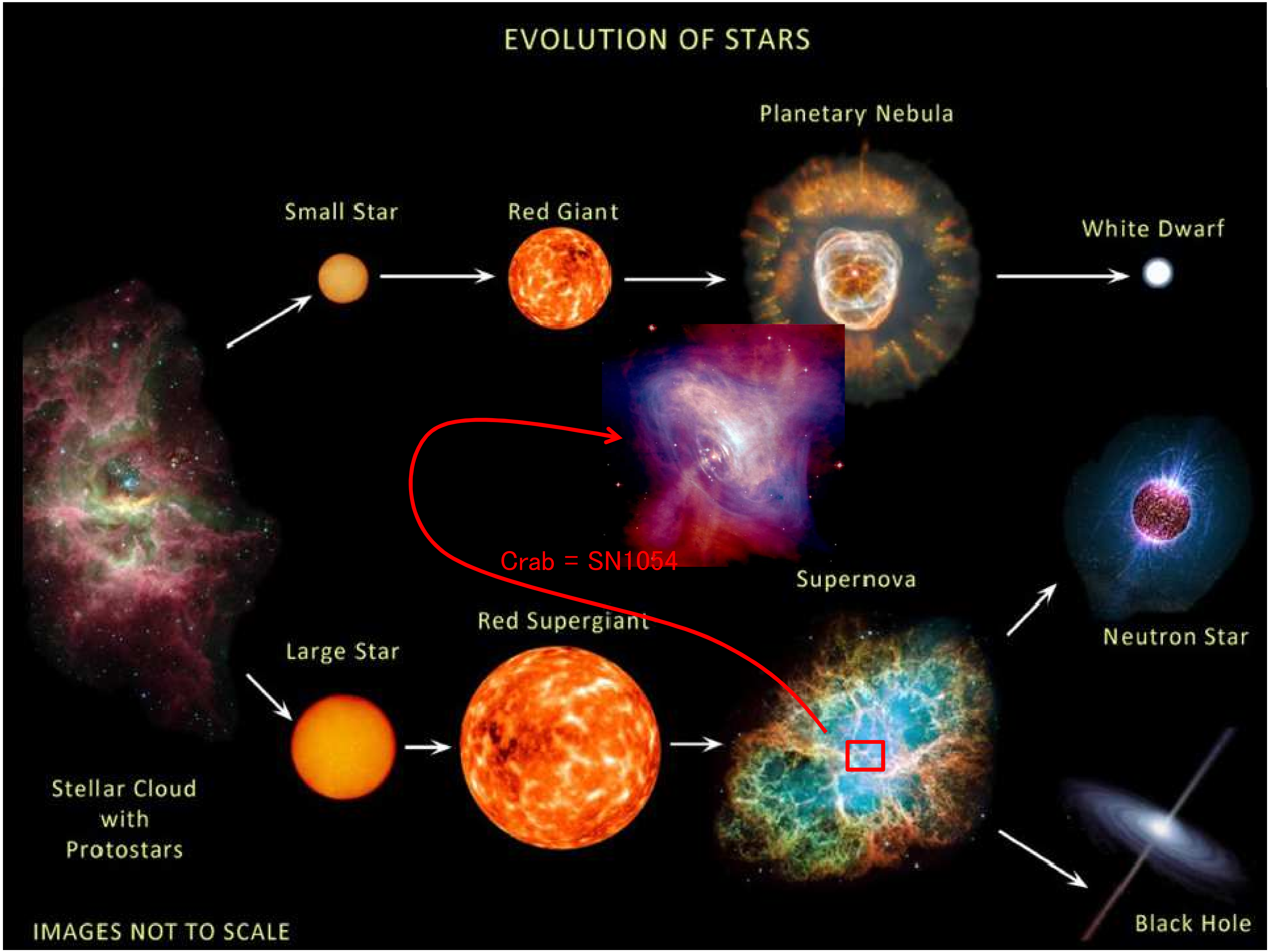
Whopping magnetic field.

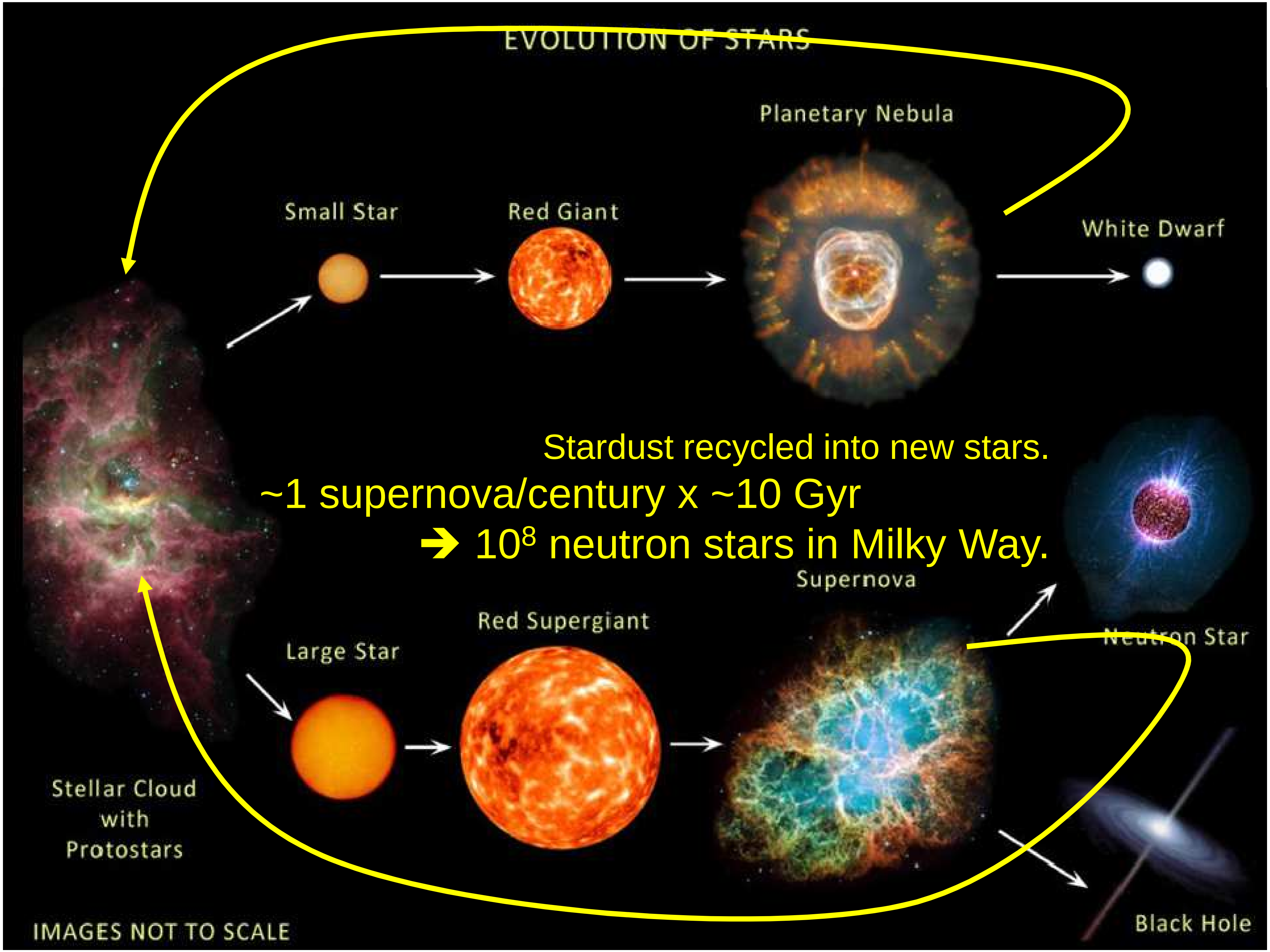
Nearby spacetime highly deformed.

Some spin faster than a blender!

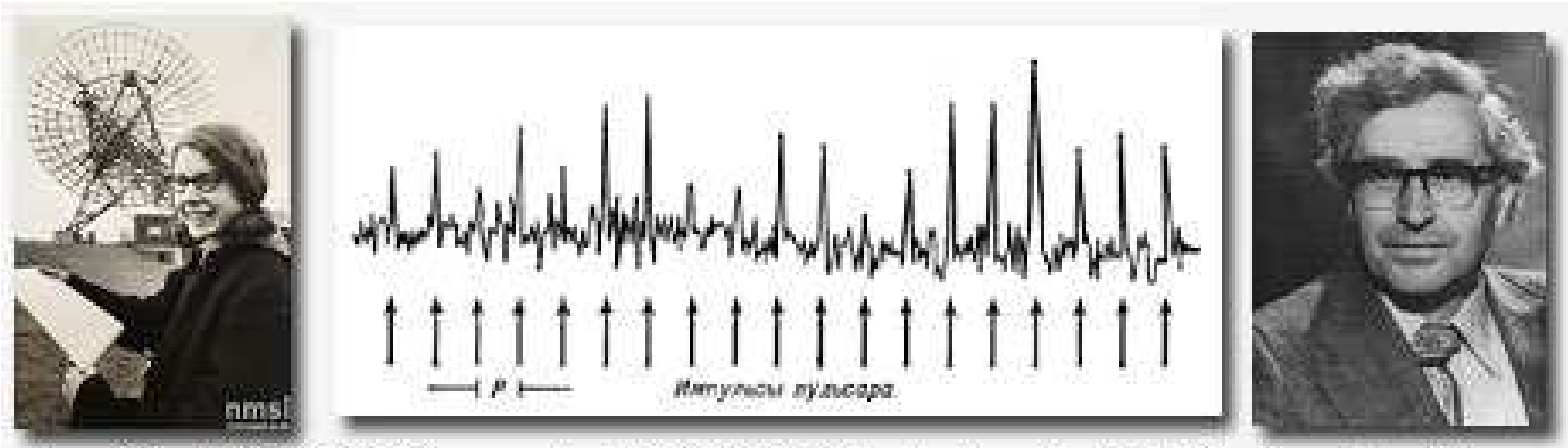
Maximum spin:
~ 45k rpm

(1.7 ms spin period)

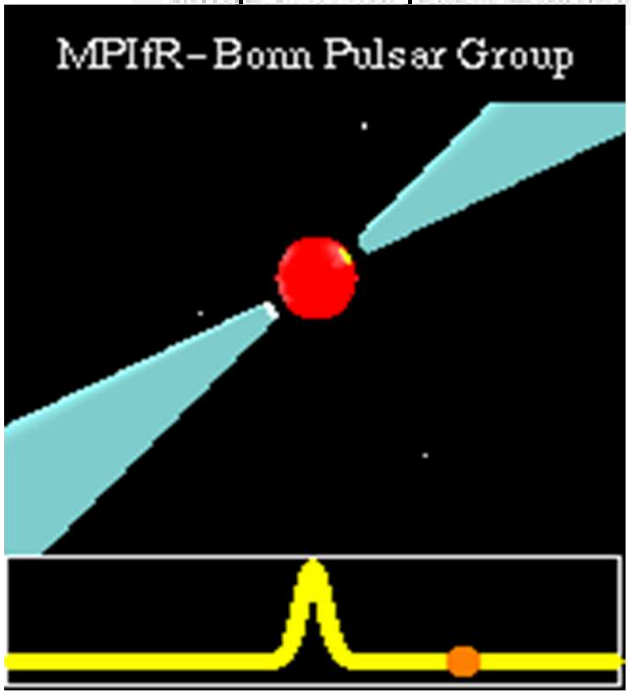

EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Crab = SN1054
Supernova
Neutron Star
Red Supergiant
Large Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Stardust recycled into new stars.
~1 supernova/century x ~10 Gyr
➔ 10^8 neutron stars in Milky Way.
Supernova
Red Supergiant
Neutron Star
Large Star
Stellar Cloud
with
Protostars
IMAGES NOT TO SCALE
Black Hole

The discovery of radio pulsars: 1967



La période 1,33730113 seconde de PSR 1919+21 entre Jocelyn Bell et Anthony Hewish

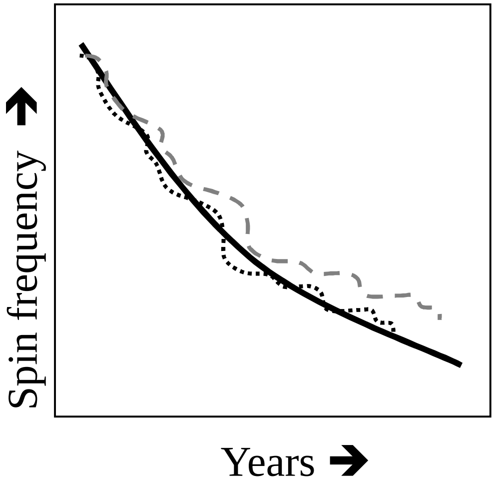


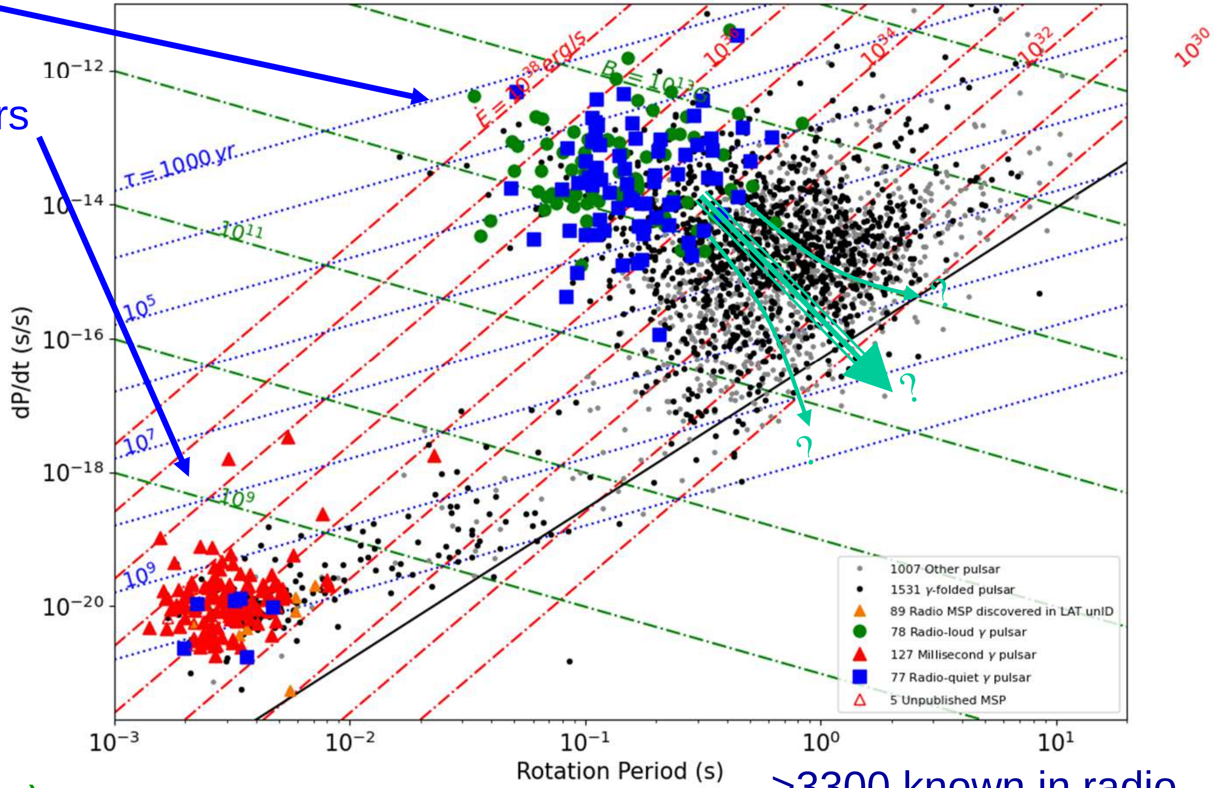
To discover new quasars via interstellar scintillation, they used faster electronics.

• A big surprise --they hadn't thought about Baade & Zwicky's 1935 prediction of neutron stars, nor that Pacini (1967) had deduced that the spinning magnet would act like a lighthouse.

Young & middle-aged pulsars

"*millisecond*" or "recycled" pulsars





The slow-down $\dot{P}$ slows down ($\dot{P}$dot) .

Perfect dipole : parabola.

Real life: <u>*not*</u> parabola. Also "timing noise"

(starquakes? Wind changes?)

>3300 known in radio

<10 pulse in optical

>60 in X-rays

~300 in gamma rays

Radio graveyard <giga-years.

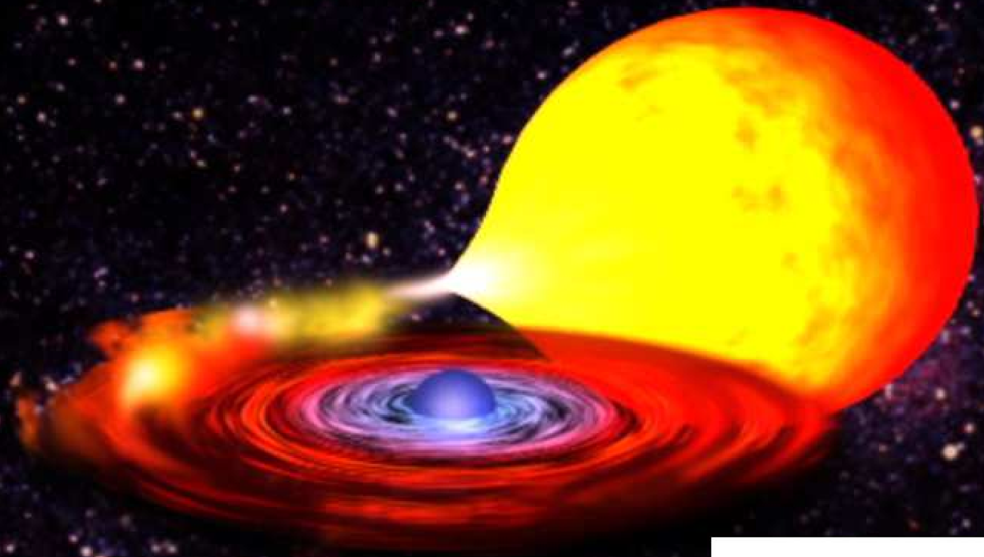
Gamma deathline $\dot{E} = -4\pi^2 I F0*F1 = 4\pi^2 I Pdot/P^3 \sim 10^{33}$ erg/s.

~1 million gamma pulsars in Galaxy?

$I \equiv 10^{45}$ gm-cm² is the moment of inertia for a neutron star with R=10 km and 1.4 $M_\odot$.

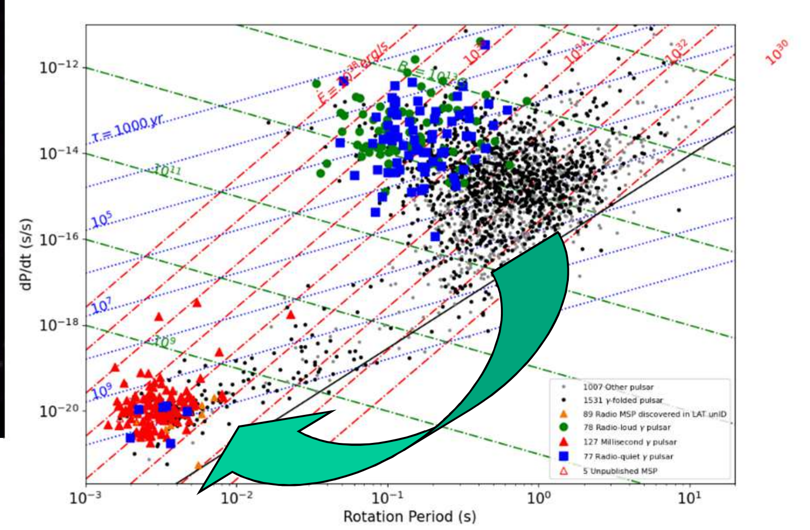
“recycled” = millisecond pulsars = MSPs *(life after death!)*

Fermi-led discoveries of many “*spiders*” (companion star ablated by pulsar wind)
Spiders test binary evolution theory.



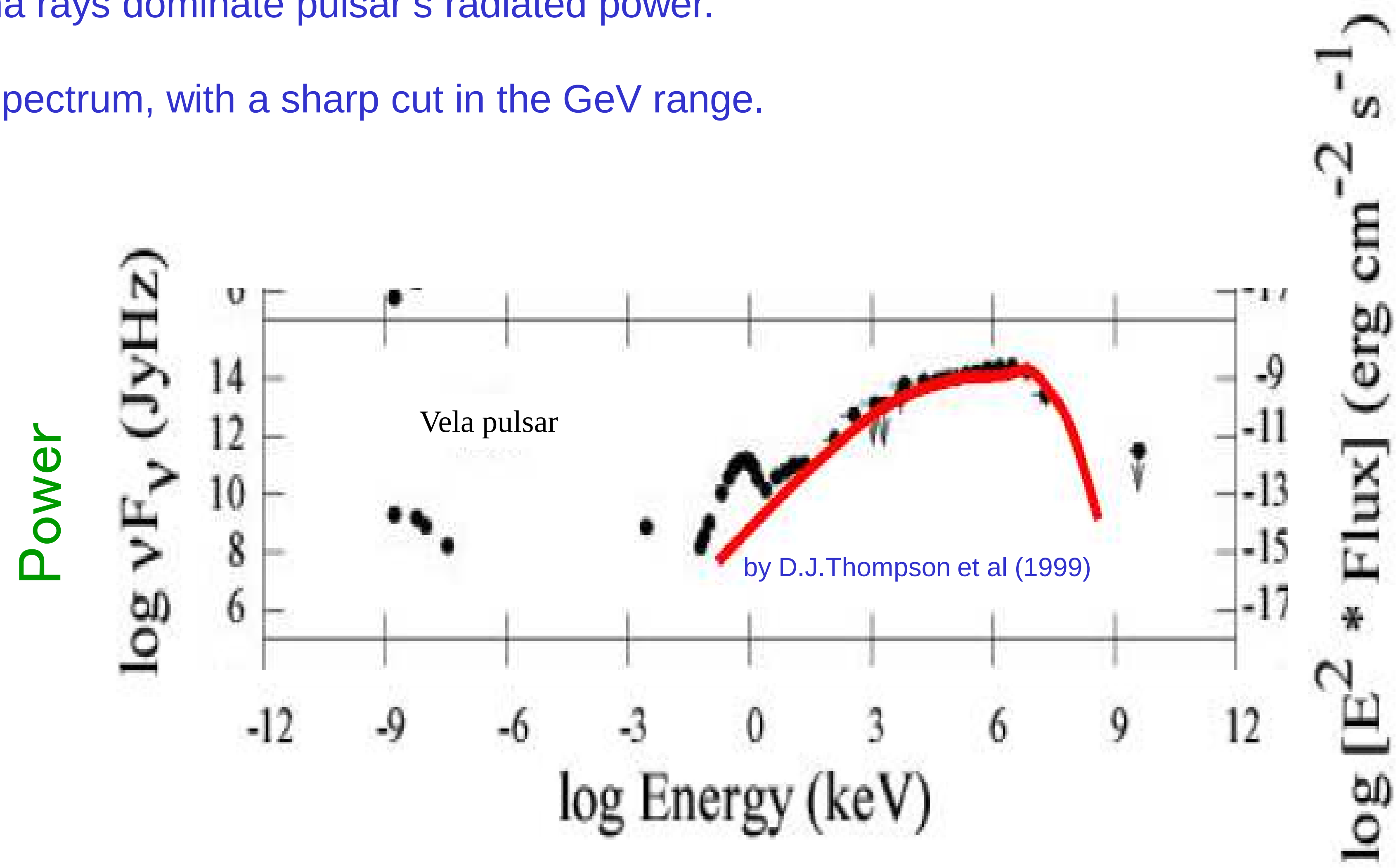
Before Fermi:
Expected few (no?) *gamma* MSPs.

Nearly half of the gamma pulsars!



Gamma rays dominate pulsar's radiated power.

Hard spectrum, with a sharp cut in the GeV range.

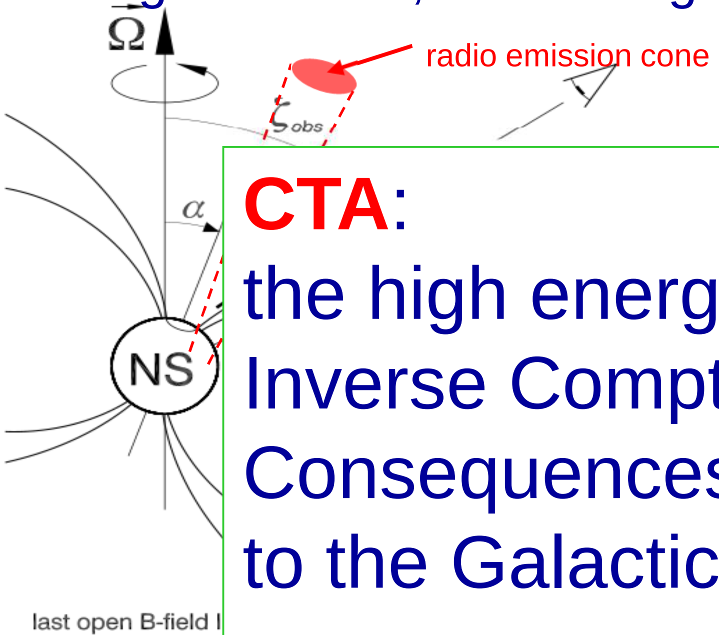


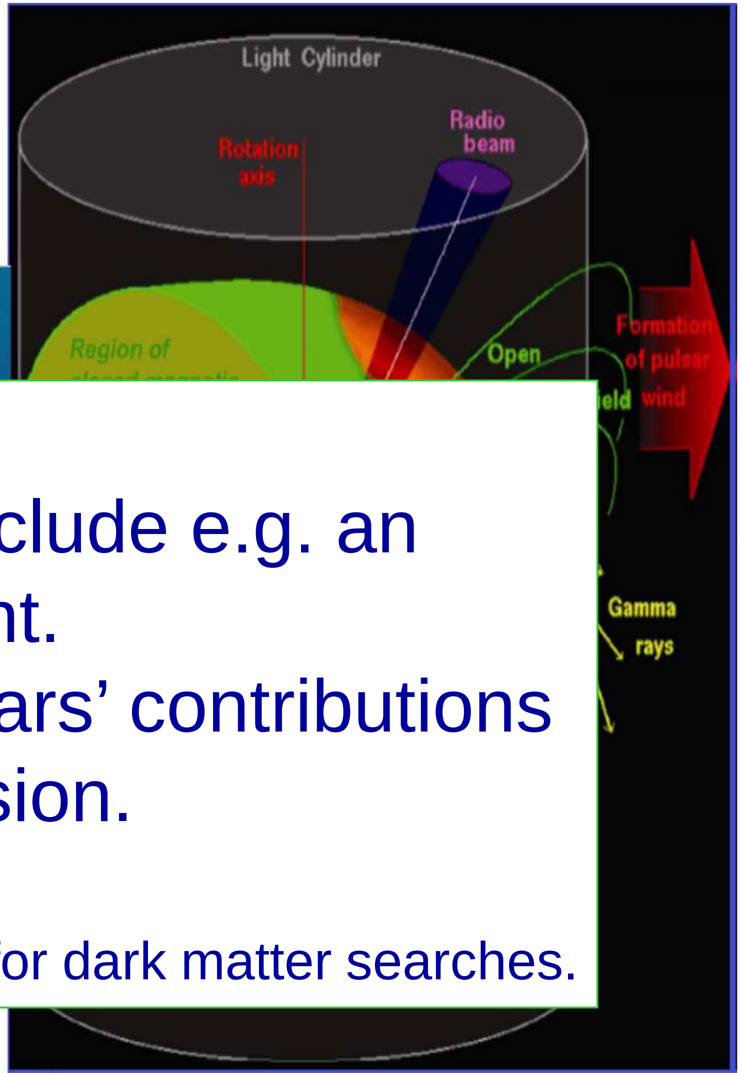
1^{e}-9 erg/cm²/s = 1^{e}-12 watt/m²

Gamma-ray beam:

Curvature radiation in ‘*gaps*’.

Long in latitude, thin in longitude (*caustics*).

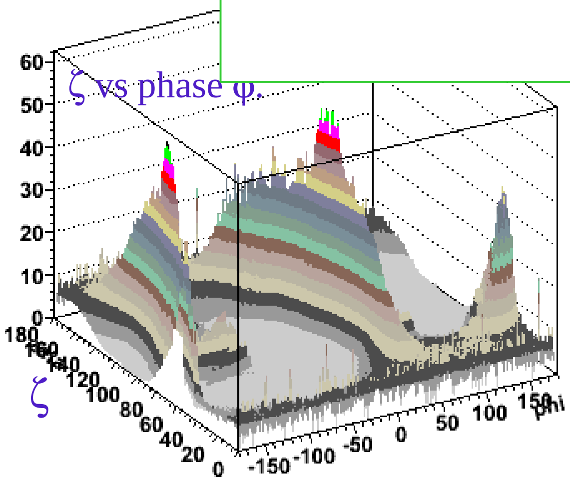


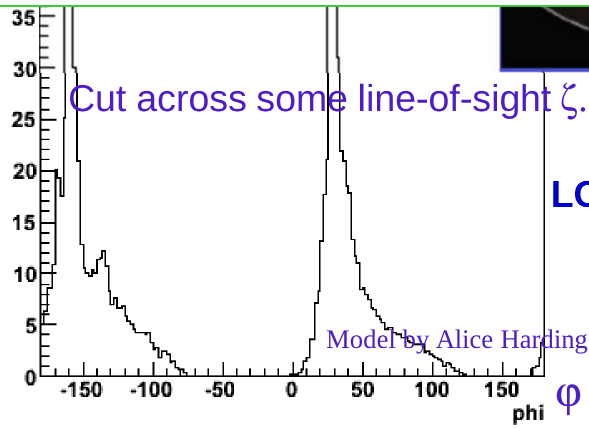


CTA:

the high energy tail could include e.g. an Inverse Compton component.
Consequences for e.g. pulsars’ contributions to the Galactic diffuse emission.

And, background for dark matter searches.



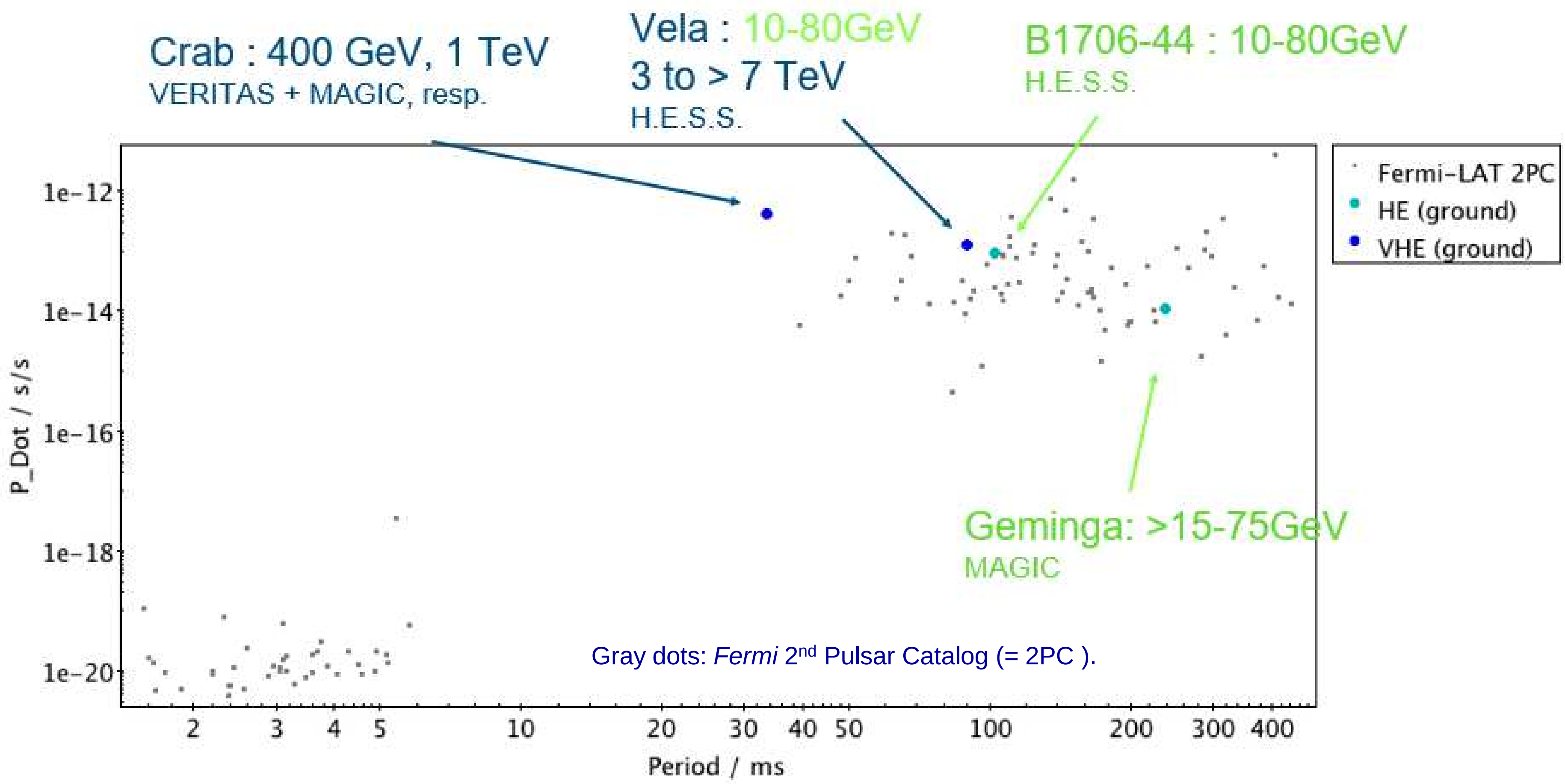


LOBs = Luminous Orbiting Bananas

Four pulsars detected from ground

Courtesy of Arache Djannati-Ataï

All four seen with EGRET on the Compton GRO satellite.



A. Djannati-Ataï, A. Burtovoi et al examine LAT pulsars best suited for CTA in their "CTA GPS Paper Call" slides, 11 December 2019.

Of 39 pulsars, they rate 12 "green" and **24 "yellow"**.

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~1991: CLUE, on La Palma, was my 1st Cherenkov telescope.

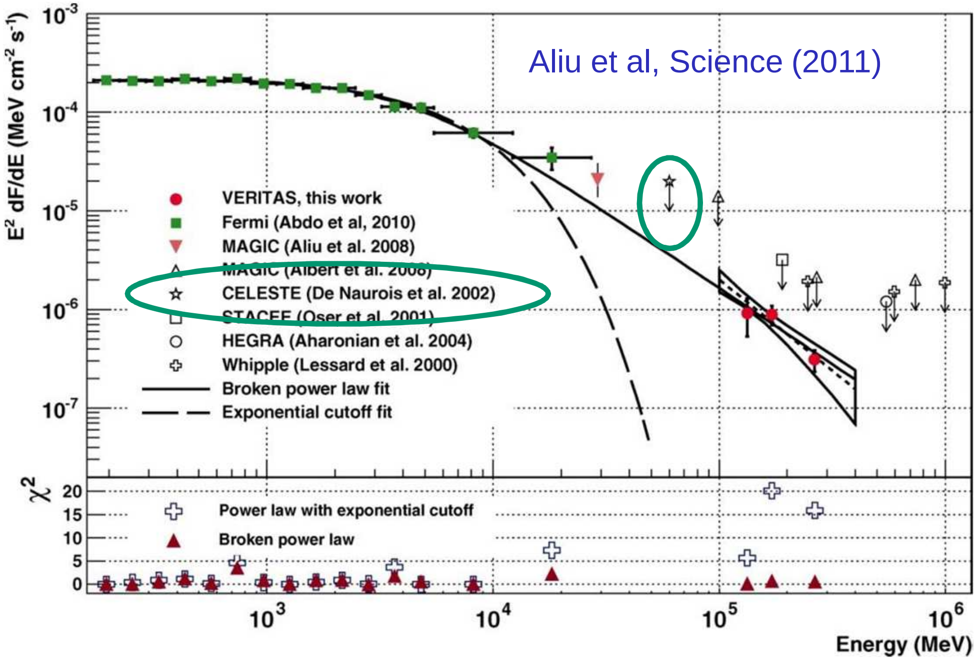
Learned the EGRET catalog. Includes 6 hi $\dot{E}$ pulsars. (<11 for CGRO).

1994 to 2004: CAT & CELESTE at Thémis (Pyrénées).

CELESTE had a 3σ pulsed Crab detection (Durand thesis, 2003).

Published an upper limit at 60 GeV (De Naurois, Holder et al, 2002).

Denis Dumora and I detected the optical Crab, to test our acquisition & analysis chain -- *I've been hooked on pulsars ever since*.



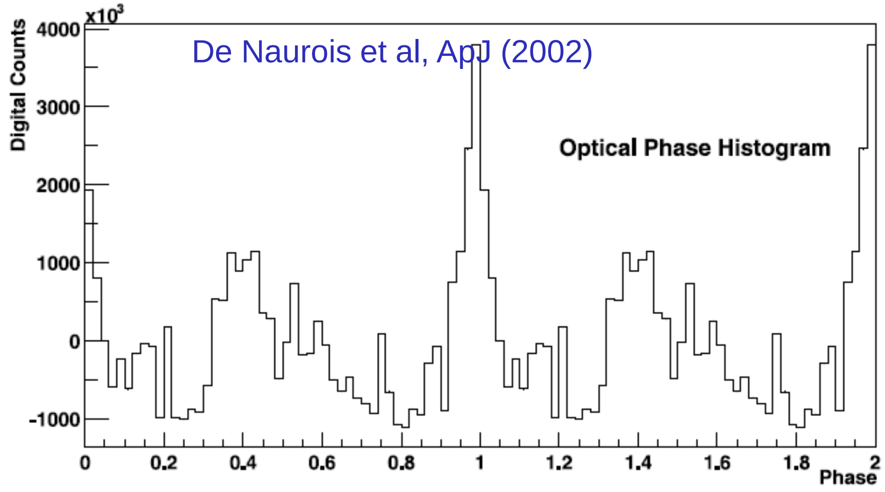


FIG. 16.—Phase histogram for the optical Crab data

2005: A year at Stanford, watching muons go through LAT calorimeter ('CAL') modules.

I learned that the LAT would be a wonderful pulsar machine, <u>but the topic was an orphan</u>.

2006: I organized a "*Pulsar timing for Glast*" splinter session at Prague IAU. Many radio pulsar experts attended.

This led to Smith, Guillemot et al A&A (2008),

and to the PTC (Pulsar Timing Consortium) MoU.

We motivated our intent to time 240 Edot>1e34 erg/s pulsars in ATNF psrcat at the time (441 today).

Grad student Guillemot showed the reliability of tempo2, and problems with GLAST Science tools (since abandoned).

Lucas G wrote the fermi tempo2 plugin before launch.

Pulsar Timing for the *Fermi* Gamma-ray Space Telescope

D. A. Smith[1,2], L. Guillemot[1,2], F. Camilo[3], I. Cognard[4,5], D. Dumora[1,2], C. Espinoza[6], P. C. C. Freire[7], E. V. Gotthelf[3], A. K. Harding[8], G. B. Hobbs[9], S. Johnston[9], V. M. Kaspi[10], M. Kramer[6], M. A. Livingstone[10], A. G. Lyne[6], R. N. Manchester[9], F. E. Marshall[8], M. A. McLaughlin[9], A. Noutsos[6], S. M. Ransom[10], M. S. E. Roberts[13], R. W. Romani[14], B. W. Stappers[6], G. Theureau[4,5], D. J. Thompson[8], S. E. Thorsett[15], N. Wang[16], and P. Weltevrede[9]

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Preprint online version: September 4, 2008

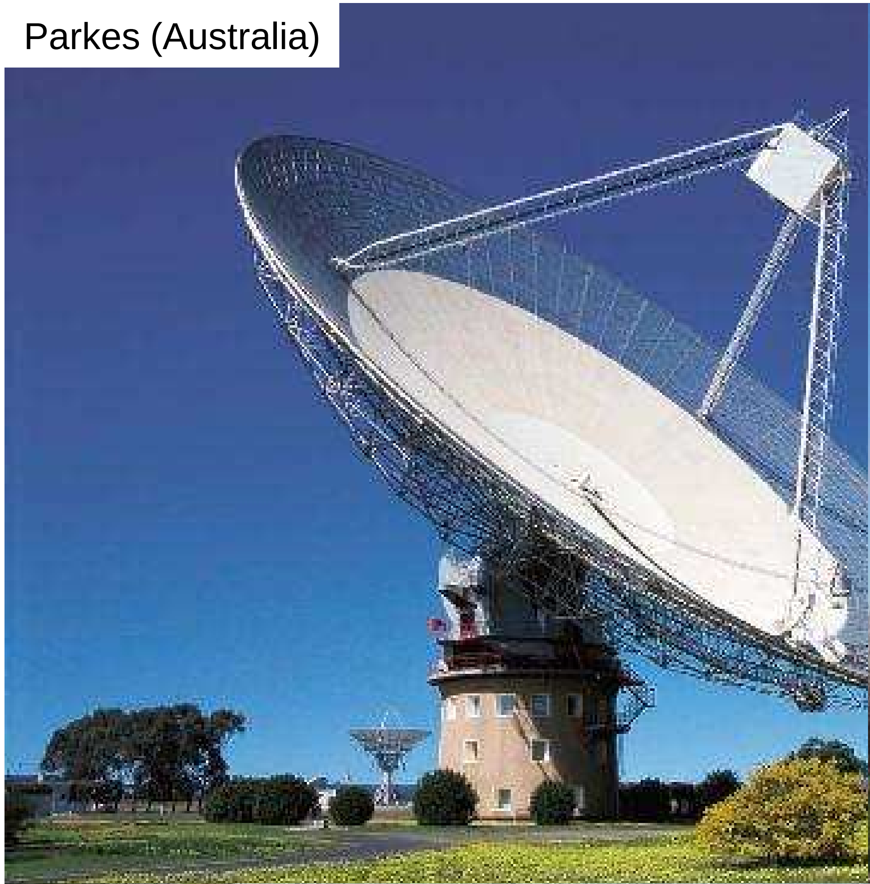
Here: $\dot{E}$ > 1E34 erg/s
Extra 800 with lower spindown.

ABSTRACT

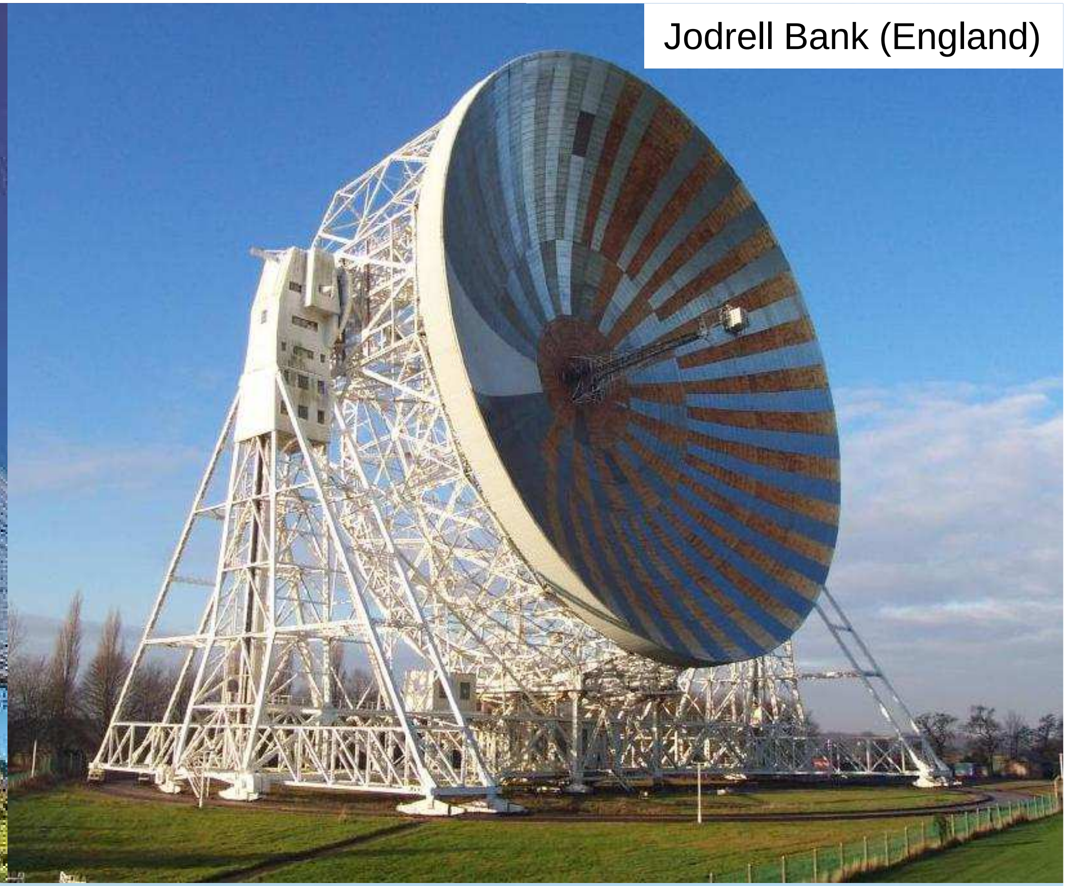
We describe a comprehensive pulsar monitoring campaign for the Large Area Telescope (LAT) on the *Fermi Gamma-ray Space Telescope* (formerly GLAST). The detection and study of pulsars in gamma rays give insights into the populations of neutron stars and supernova rates in the Galaxy, into particle acceleration mechanisms in neutron star magnetospheres, and into the "engines" driving pulsar wind nebulae. LAT's unprecedented sensitivity between 20 MeV and 300 GeV together with its 2.4 sr field-of-view makes detection of many gamma-ray pulsars likely, justifying the monitoring of over two hundred pulsars with large spin-down powers. To search for gamma-ray pulsations from most of these pulsars requires a set of phase-connected timing solutions spanning a year or more to properly align the sparse photon arrival times. We describe the choice of pulsars and the instruments involved in the campaign. Attention is paid to verifications of the LAT pulsar software, using for example giant radio pulses from the Crab and from PSR B1937+21 recorded at Nançay, and using X-ray data on PSR J0218+4232 from XMM-Newton. We demonstrate accuracy of the pulsar phase calculations at the microsecond level.

Key words. pulsars:general – Gamma-rays:observations – Ephemerides

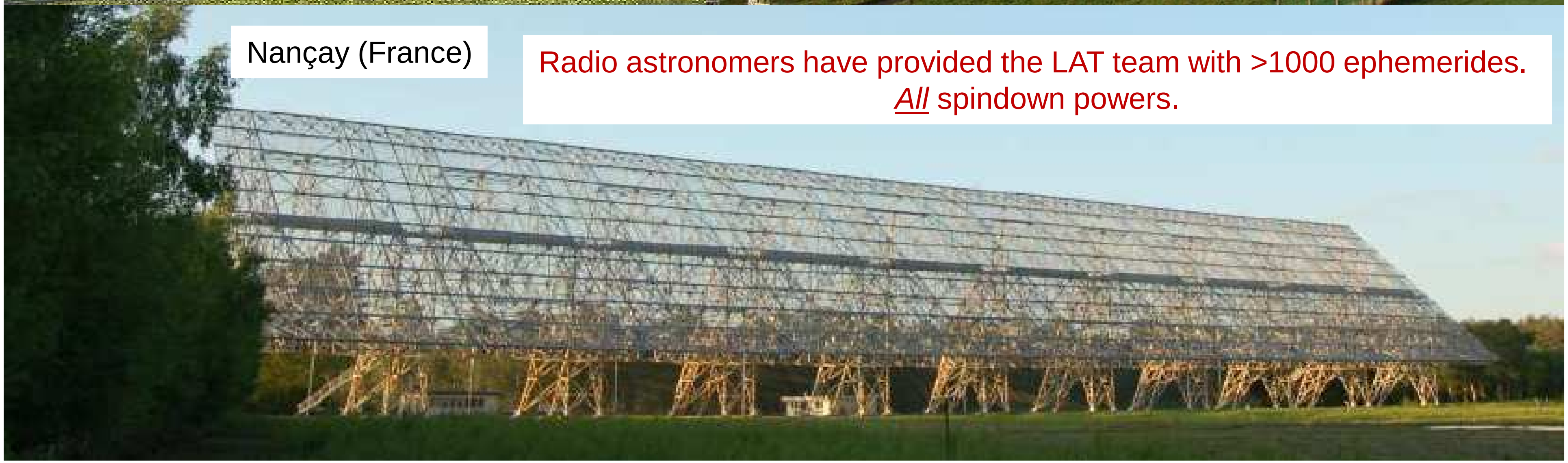
Astronomy & Astrophysics 492 (2008) 293



Parkes (Australia)



Jodrell Bank (England)



Nançay (France)

Radio astronomers have provided the LAT team with >1000 ephemerides.
All spindown powers.

LAT-TD-09047-01 LAT Pulsar Timing Consortium Page 1 of 7

PULSAR TIMING CONSORTIUM	Document # **LAT-MD-09047-01**	Date 21 March 2008
	Author(s) D.A. Smith, D.J. Thompson	Supersedes
	Subsystem/Office Multi-wavelength coordination	
Document Title **Memo of Understanding for a Pulsar Timing Consortium**		

Gamma-ray Large Area Space Telescope (GLAST)

Large Area Telescope (LAT)

Memo of Understanding for a

Pulsar Timing Consortium

Key points:

- Coordinate observations
  - ➢ Avoid duplicate efforts.
  - ➢ Avoid orphan pulsars.
- Share times-of-arrival (!!)
- Share effort of ephemeris building.
- Publication & authorship rules.

Things went *really* well – the MoU expired, but cooperation continues.

PTC inspired a highly successful PSC = Search Consortium: radio searches of LAT UnId sources.

2006: While at Stanford, I learned

a) LAT timestamps are complicated,

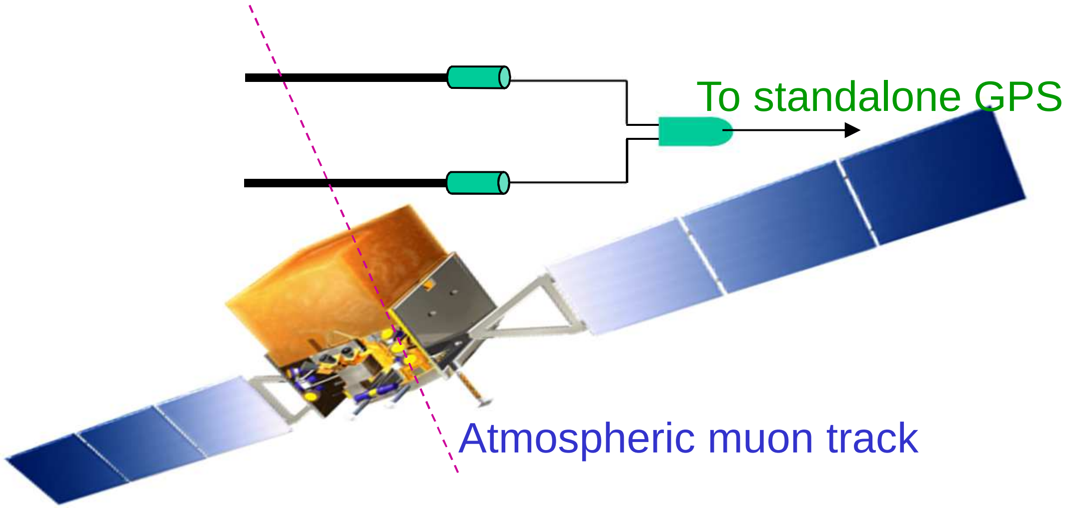
b) *<u>All</u>* (!) previous space missions had clock goofs (*),

c) There was no real plan to test the GLAST & LAT timing.

I proposed and executed LAT GPS clock tests, using atmospheric muons, with my NRL CAL friends.

A fatal bug was found & fixed! Accidents <u>REALLY DO</u> happen.

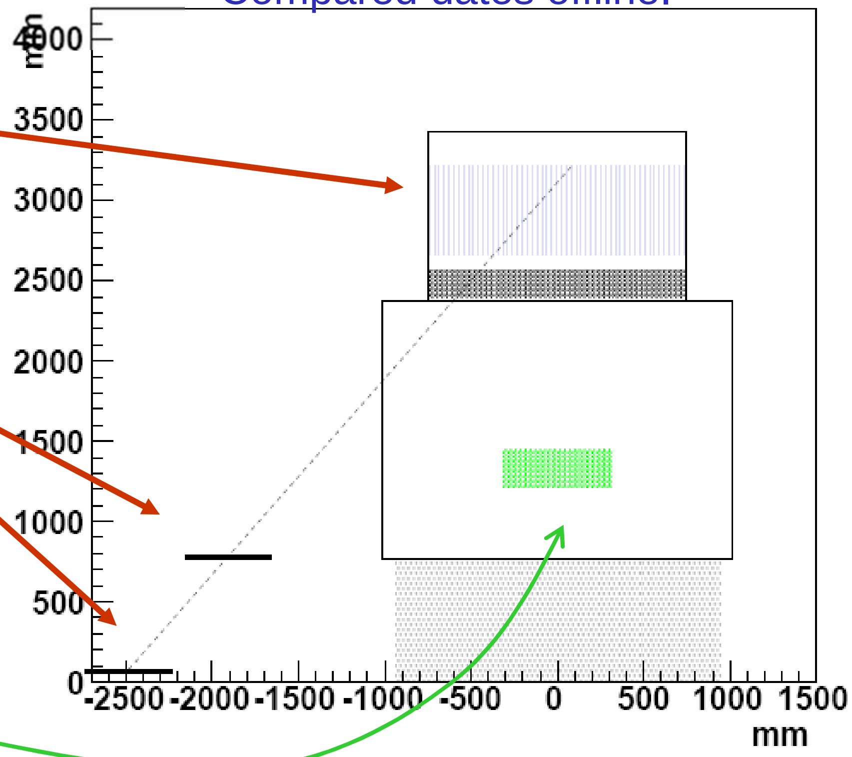
(*) Backup slides, if someone asks.



- Went to Arizona.
- Put scintillators next to GLAST.
- CAT & CELESTE triggerable GPS module interrupted a VME readout.
- Muons hit LAT and us within ns's.
- Compared dates offline.

LAT on spacecraft.

Two scintillator paddles.



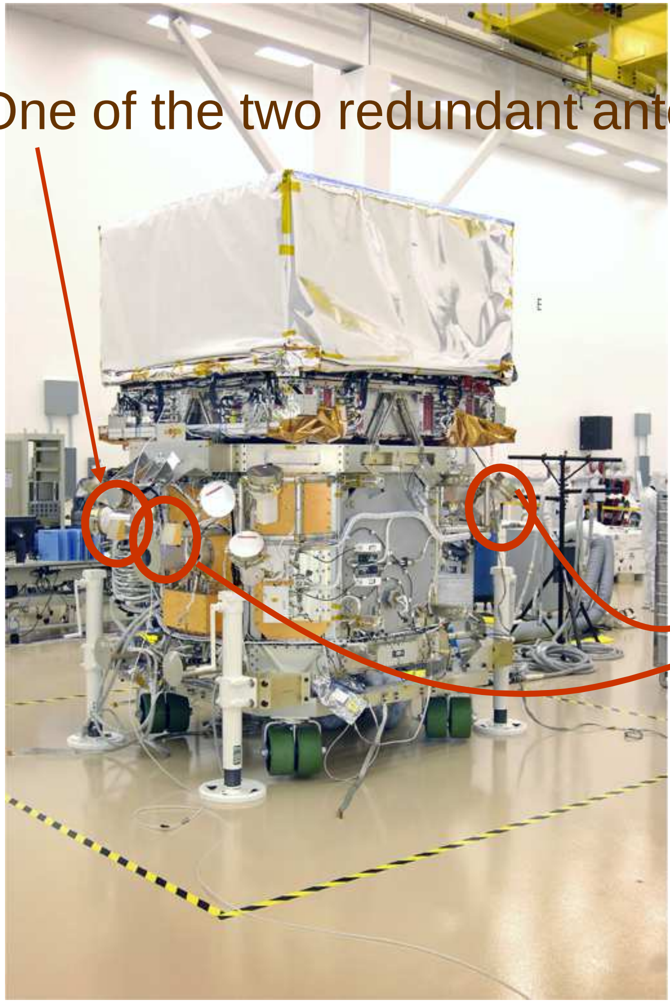
We also tested the GBM dates.

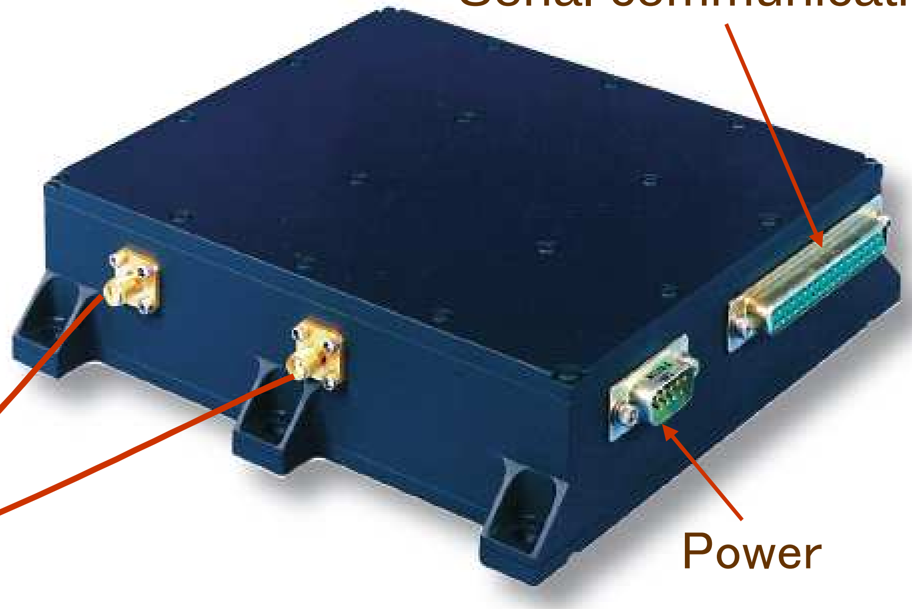
Viceroy™ GPS Spaceborne Receiver

(Two GPS units on spacecraft, here at GD's "*Factory of the Future*" in Arizona.)

standard positioning service in space

One of the two redundant antennae.





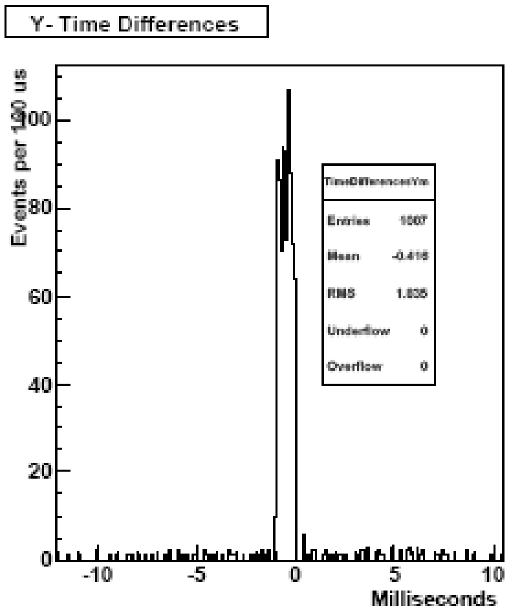
Serial communications

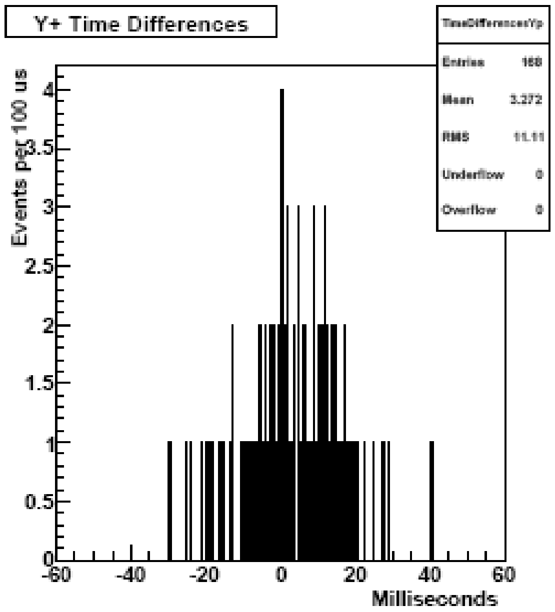
Power

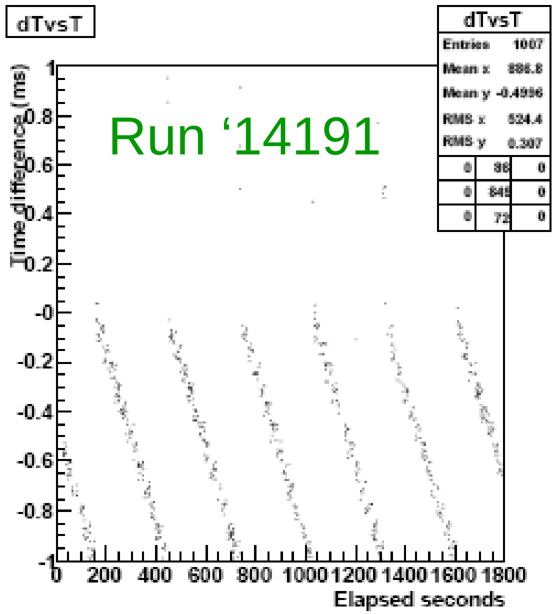
One antenna on each side of spacecraft, to see as many GPS satellites as possible.

Something was wrong…

- 8 half-hour muon runs: combinations of side A vs B, GPS locked/unlocked, etc.
- 0>dT>-1 ms sawtooth with ~290 s period during GPS lock runs.
- Bug diagnosed quickly. Fix took months (NASA procedures…).
- Undetected, LAT would have discovered few MSPs. Profiles would have resembled X-ray sinusoids instead of gamma-ray spikes.







Fermi LAT timing precision

- NASA requirement: δt_i <10 µs absolute time accuracy per event.
- LAT collaboration goal: < 2 µs.
- We achieved <1 µs (~300 ns).
- Position localization accuracy: Simply $c\delta t_i$ *(but in 3-D)*.

Example: 3e8 * 1e-6 = 300 m.

Documenting Glast/Fermi/LAT's clocks :

L. Guillemot thesis, pages 77-78.

http://adsabs.harvard.edu/abs/2009arXiv0910.4707G

The on-orbit calibration of the Fermi Large Area Telescope
http://adsabs.harvard.edu/abs/2009APh....32..193A (p.212)

Section 6.2 – On-orbit pulsar data confirms 300 ns seen in ground test.

Fermi Large Area Telescope Performance after 10 Years of Operation

https://ui.adsabs.harvard.edu/abs/2021ApJS..256...12A

Friendly advice for CTA

- Have a procedure to verify the accuracy of CTA's entire hardware through analysis chain.
- CTA north – a single pixel can see the optical Crab pulsar. Do it!

- CTA south – Crab magnitude 17, next brightest pulsars mag > 23.

(Might a small pixel, fast electronics, and a huge mirror allow you to see an optical pulsar 1000x fainter than the Crab? Do the calculation. Success would turn heads.)

- Else: inject a PPS into your DAQ chain. It won’t test barycentering but it will test much else. Or… simulate pulsed arrival times and inject them into your trigger.

2008 June 11: Launch.

Everything worked right away.

2009: 3 pulsar articles in Science.

Lots more since.

Currently:

A Gamma-ray Pulsar Timing Array Constrains the Nanohertz Gravitational Wave Background

We never dreamt our timing would be *that* good!

Science, 376, 521 https://arxiv.org/abs/2204.05226

2019: PTC lives on. We sample all spindown powers, $\dot{E}$.

Here: Six trials for each pulsar search –

(Ephemeris validity versus all data) X (three weighting parameter values)

➔ 4σ detections (H_{max}>25) are reliable.

Searching a Thousand Radio Pulsars for Gamma-Ray Emission

The Astrophysical Journal, 871:78 (13pp), 2019 January 20 Smith et al.

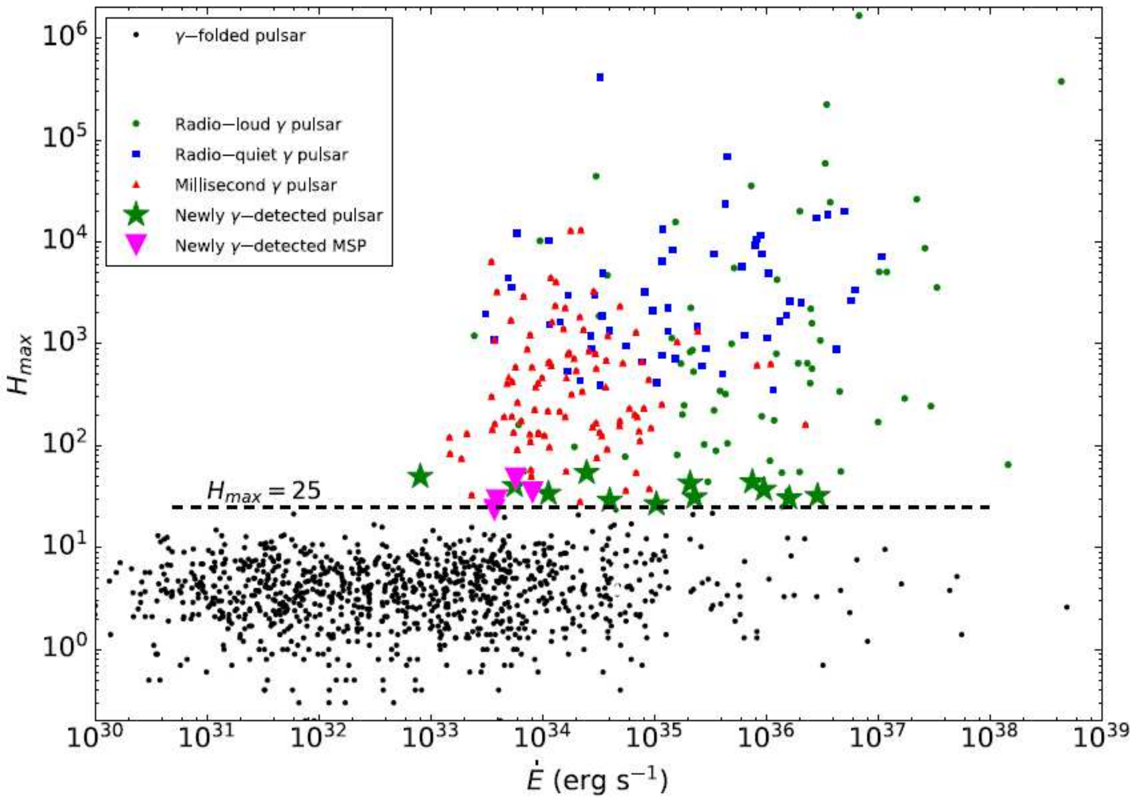


Figure 1. H_{max} (see Section 3) vs. the spindown power $\dot{E}$ for 1269 pulsars, for 9.6 yr of LAT data. Colored symbols indicate those known to pulse in LAT gamma-rays. Small black dots show pulsars that were gamma-ray phase-folded, for which pulsations are not detected. The Shklovskii $\dot{E}$ correction for proper motion has not been applied here. The 16 gamma-ray pulsars discovered in the course of this work are highlighted.

-- Warning –

ATNF psrcat provides ephemerides:

Use their web GUI* or their command line:

psrcat -e J2208+4056

to obtain a simple .par file.

Maybe good enough to recover a *radio* signal, with a modest scan around the nominal parameter values…

but I have never succeeded at seeing gamma pulsations using one.

- generally not detailed enough
- "scan" ➔ trials ➔ significant false positives

* https://www.atnf.csiro.au/research/pulsar/psrcat/expert.html

2022: 3rd Pulsar Catalog (3PC), in preparation.

In addition to 283 pulsed detections, we have ~40 PSC radio MSPs and spider candidates (optical and/or X-ray binaries) quite likely to become γ pulsars.

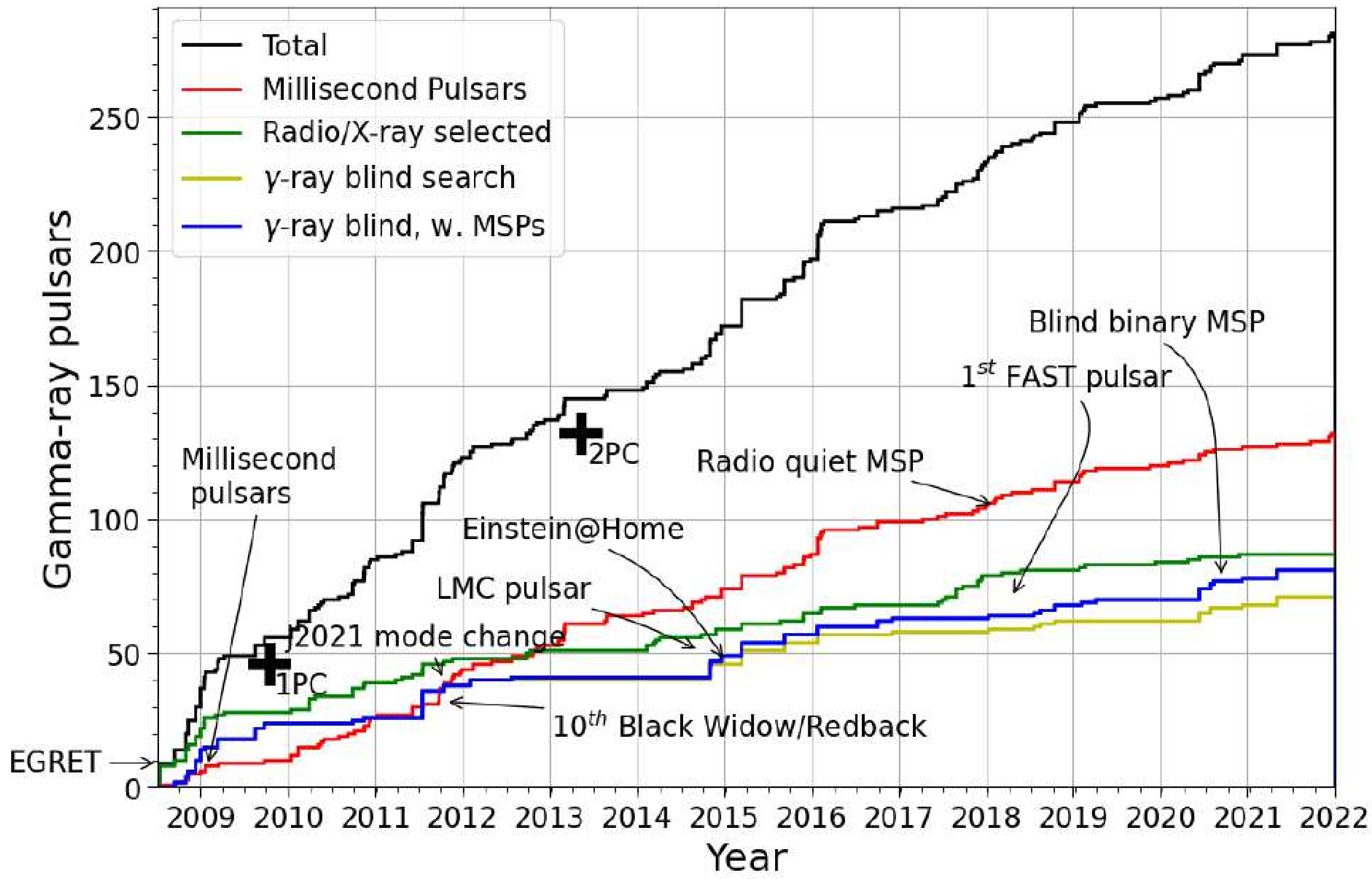


Figure 1. Cumulated number of known gamma-ray pulsars, beginning with the launch

This talk:

- Pulsars – a brief overview.
- A personal history of gamma-ray pulsars.
- LAT's vs CTA's needs ☐
- *To search for gamma-ray pulsations, you only need:*
  - Good timestamps ☑
  - Good rotation ephemerides ☐
  - Code to calculate neutron star rotational phases ☐
- Friendly advice

LAT's needs, CTA's needs.

- *Fermi* LAT scans the whole sky 8x per day.

  During this seminar, LAT continues to accumulate data from *all* pulsars.

- EGRET results made us expect to see young pulsars with $\dot{E} > 10^{34}$ erg/s.
- Zero observational cost, low analysis cost, to try to see all different types.

- But LAT is *small* (0.8 m^2). ~10 photons/year for the faintest pulsars.
- LAT requires coherent rotation ephemerides valid for years & years.

- We had to convince the radio astronomers to engage in long-term monitoring.
- The community had to learn to "industrialize" toa* ➔ .par creation.

"They said it couldn't be done, but we dood it anyway"

(Actually: they said it had never been done, and it would be hard.)

LAT needs hundreds of multi-year (=complex) **radio ephemerides**

* toa = time-of-arrival (more on this later)

LAT's needs, **CTA's needs.**

- All CTA pulsars are presumably also bright LAT pulsars.
  A dozen good candidates? Distributed in R.A. (season) and declination (north/south).

- Huge Cherenkov collection surface: many photons per hour.
- CTA "observation epoch" – many nights over a few (several) months.

CTA needs few, simple ephemerides.

- Can be made from LAT data by not-very-experts*.
- Phase-align results from different epochs over many years.

- *Fermi* LAT should fly for many years to come.

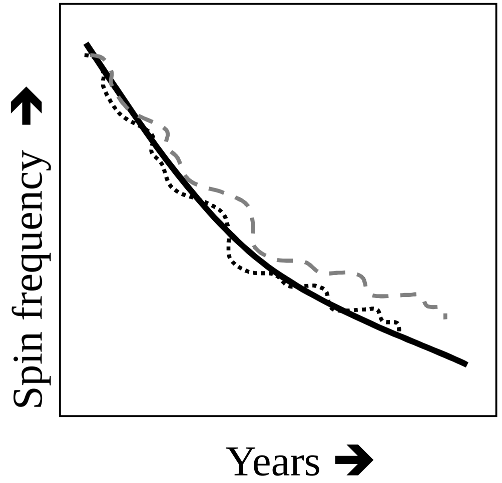
But… if LAT dies… CTA should make a plan "B" with radio astronomers.

For a given target list, we can point you to the right people/instruments.

* *Fantastic* grad student task – for several, has led to interesting careers.

Rotation ephemerides

a.k.a. `spindown' or 'timing' model,   or `.par file'



Case 1: Simple -- little timing noise.

$F(t) = F0 + F1*T + \frac{1}{2} F2*T^2 + \ldots$

where t is barycentered clock time, T = (t-T0).

The reference time T0 is called PEPOCH in .par files.

$F1 = dF/dt$, $F2 = d^2F/dt^2$, et cetera.

From T0 until t, the neutron star has turned $N = \int_{T0}^{t} F(t)dt$ times.

The *phase* is the integer remainder of N, $0 \leq \Phi(t) < 1$.

Phase $\Phi \equiv 0$ when t = TZRMJD (at TZRSITE and TZRFRQ).

Important for absolute phase alignment between different instruments,

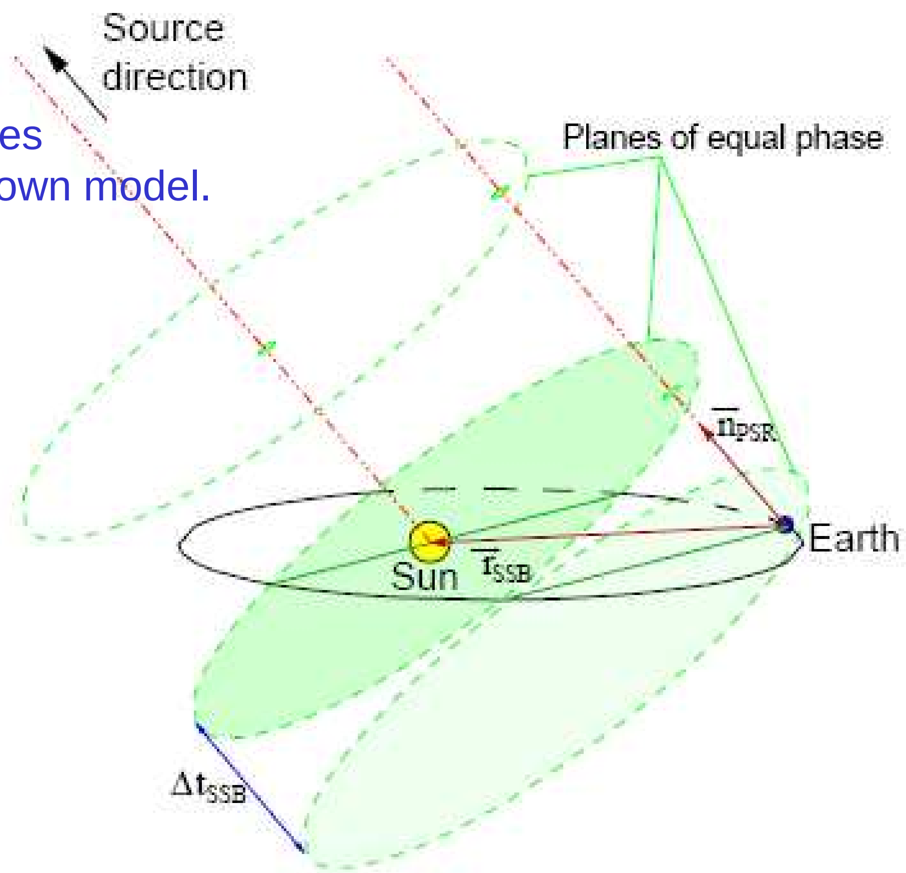
or when using .par files valid at different epochs (as for CTA).

“Barycentering”

Observatories move relative to the pulsar, so pulses arrive before or after times predicted by the spindown model.

e.g. *tempo2** shifts measured times to SSB
= solar system barycenter.

.par files have observatory location TZRSITE and name of planetary ephemeris, EPHEM.



(Jupiter etc cause SSB to move.

High accuracy absolute timing -- gravitational waves, general relativity -- requires latest & greatest planetary ephemeris.

Noisy gamma pulsars? No, washed out by the whitening…)

**tempo2* = widely used software. Will mention PINT later.

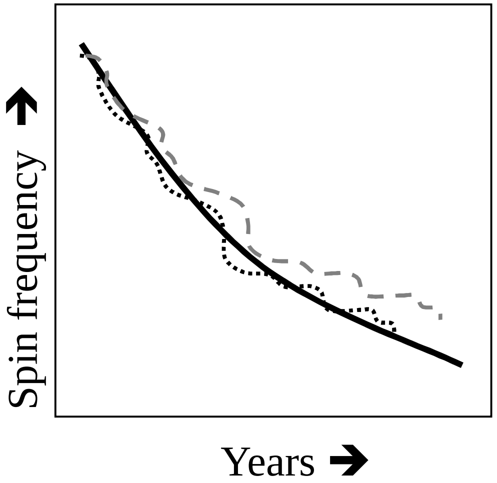
Rotation ephemerides

Simple Case 1, continued.

F2 is small (hard to measure).

Most often,

F2 reflects (and smoothes or “whitens”) timing noise.



F(t) ≈ straight line for low noise, short validity. (F0, F1 only)

$n = F0*F2/F1^2$ is called the *braking index*.

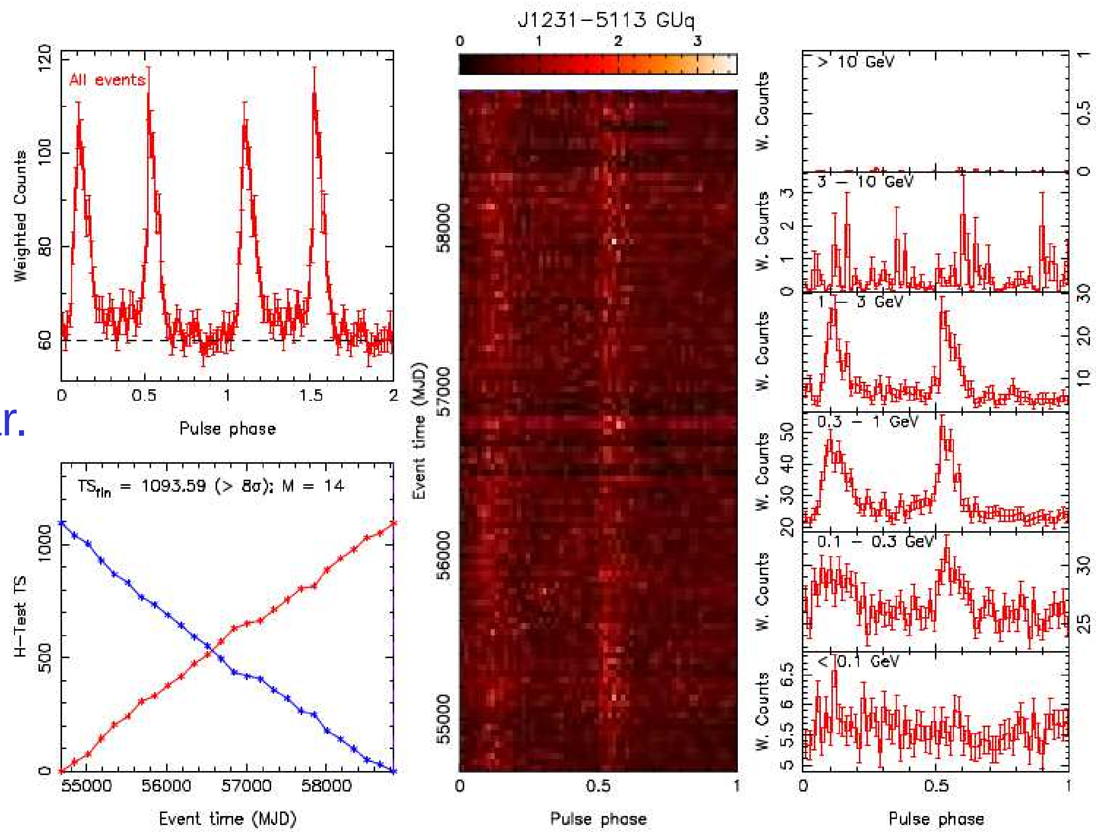
Curvature of the parabola. Interesting. Not for today’s talk.

Rotation ephemerides

Simple Case 1, continued.

```
$ more J1231-5113_LAT.par

PSRJ              J1231-5113
RAJ               12:31:35.653432705952213    1      1.85593194733329e-06
DECJ             -51:13:35.363892771028986    1      1.431375195644e-06
F0                4.84402084506679            1      1.66972241515502e-11
F1               -2.74322319361871e-15        1      3.98304500617431e-19
PEPOCH            56757
START             54681.0
FINISH            58833.0
TZRSITE           @
TZRFRQ            0
TZRMJD            56757
EPHVER            5
CLK               TT(TAI)
UNITS             TDB
EPHEM             DE421
CORRECT_TROPOSPHERE      N
```



Radio quiet, γ-ray blind search pulsar.
Stable rotation (little noise).

Simplest possible ephemeris*.

MJD vs phase plot *very* useful test.

** This one made by Colin Clark.*

Rotation ephemerides

Simple Case 1, continued.

```
$ more J1231-5113_LAT.par

PSRJ            J1231-5113
RAJ             12:31:35.653432705952213    1      1.85593194733329e-06
DECJ           -51:13:35.363892771028986    1      1.431375195644e-06
F0              4.84402084506679            1      1.66972241515502e-11
F1             -2.74322319361871e-15        1      3.98304500617431e-19
PEPOCH          56757
START           54681.0
FINISH          58833.0
TZRSITE         @
TZRFRQ          0
TZRMJD          56757
EPHVER          5
CLK             TT(TAI)
UNITS           TDB
EPHEM           DE421
CORRECT_TROPOSPHERE     N
```

START, FINISH: ephemeris validity.

(Simple case: good phases before & after.)

TZRSITE, FRQ, MJD: imposes phase≡0.

Typically radio telescope code (location) & frequency.

Here, solar system barycenter and “infinite” frequency.

Essential for absolute phase alignment between different instruments.

EPHVER (2) 5: (TEMPO) tempo2 conventions

TDB vs TCB time definitions

TZRFRQ: radio signals delayed (phase shifted) by interstellar electrons, as inverse radio frequency squared.

DM (Dispersion Measure) is the measured electron column density along the line of sight. (Unknown for this radio-quiet pulsar.)

Rotation ephemerides

Case 2: Mostly quiet pulsars, with *glitches*.
.par file GL* parameters, to get past occasional "bumps in the road".

Case 3: *Binary* pulsars (most, but not all, are MSPs).

- "Good timers" – a few more lines in the .par file, for orbital motion.
- "Spiders" – noisy as heck, whiten both the spindown and the orbit.

Case 4: Noisy pulsars and/or *looooong* epochs (as for the LAT).

To create an ephemeris:

fit F(t) to many radio, LAT (or radio or X-ray) times-of-arrival (toa's), from START to FINISH.

Then you can interpolate $\Phi(t_{CTA})$ for CTA event times t_{CTA}. *(and perhaps extrapolate…)*

The polynomial F(t) = F0 + F1*T + ½ F2*T^2 can be extended to F13 and beyond.

Better than a polynomial? WAVES… IFUNC… and other approaches.

For 3PC, we have cases with 50 WAVES (sinusoidal harmonics) and N glitches,
or >100 IFUNC lines (kind of like a spline…).

Some last words about **Rotation ephemerides**

For simple ephemerides and barycentered times, you can calculate phases with a few lines of code.

For a monster .par provided by a radio or gamma guru, *forget it*.

========================

Multi-year coherent timing of 100's of noisy pulsars wasn't a thing before *Fermi*.

Sub-microsecond multi-year MSP ephemerides for gravitational wave searches also drives developments (PTA = Pulsar Timing Arrays).

PTA MSPs have way more stable spindown than Vela et cetera,
but need way better precision.

Do It Yourself

Some words on software tools and what they do.

Personally, I use *tempo2*.

To build an ephemeris:

tempo2 -gr plk -f J1853+1303_NRT.par all.tim -nofit

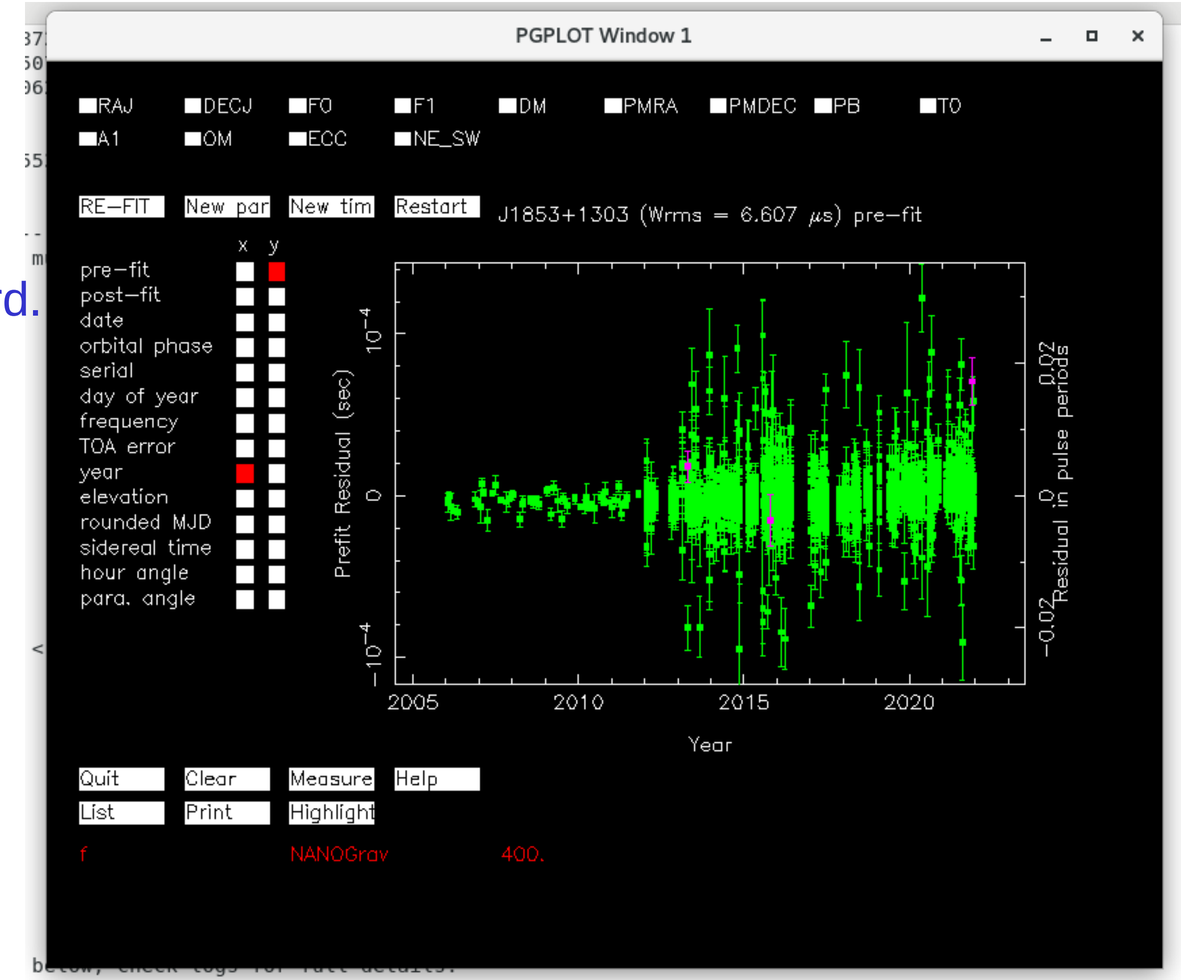
This 4.1 ms MSP is 5.3° off the plane, with $\dot{E}$=5e33 erg/s.

Nançay toa's, courtesy of Lucas Guillemot & Ismaël Cognard.

Also works with LAT toa's.

Better if someone can help you get started…

Our rule-of-thumb:
±20 mP residuals work nicely.

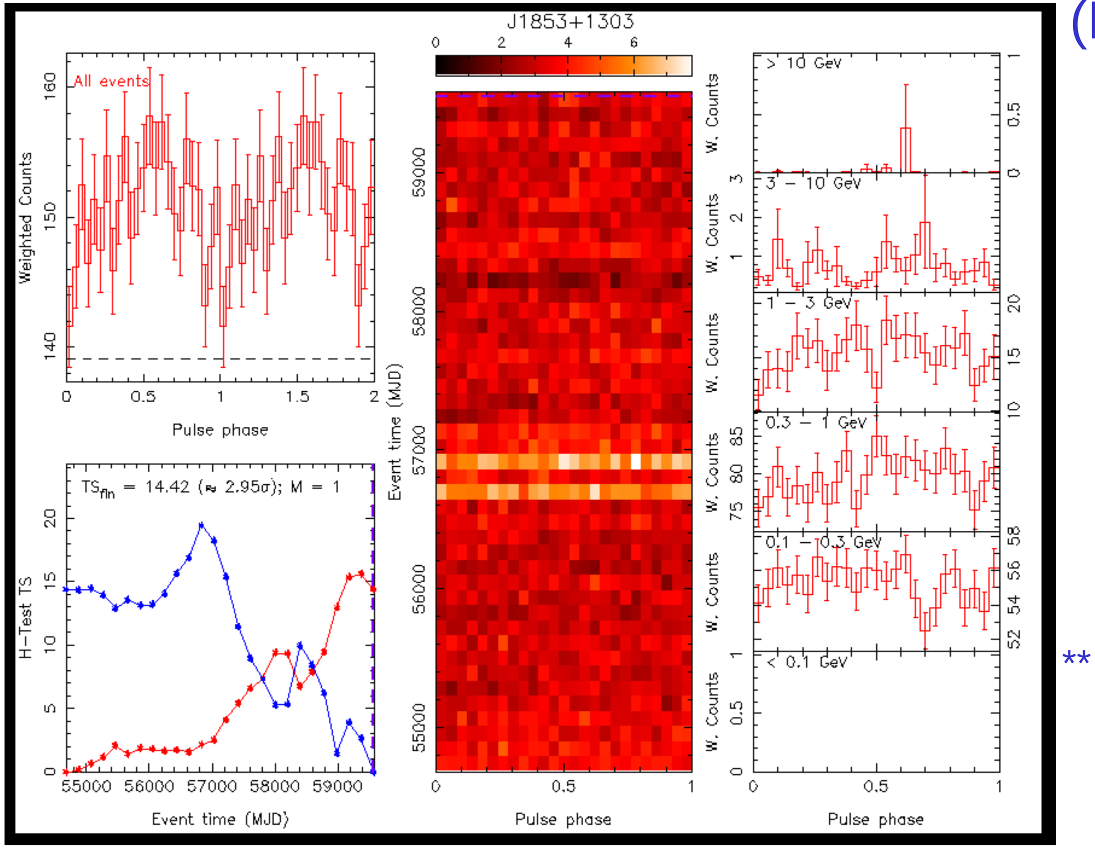


Do It Yourself

To phase-fold LAT gamma rays:
I have all LAT photons on my laptop (weekly FT1 files, 32 Gb).
*gtselect** to get >100 MeV photons within 2° of the position in the .par file.

tempo2 -gr fermi -ft1 J1853+1303.fits -ft2 lat_spacecraft_merged.fits -f J1853+1303_NRT.par -phase -graph 0 -cacheft2

Adds a PULSE_PHASE column to the FT1 file.
*Plot_phaso*** makes this nice plot -- NO gamma pulsations.
(No 4FGL-DR3 counterpart, either.)



Weighted Htest 14 after 5000 days.
m=1 (sinusoidal peak) is also a bad sign.

* Science tools at https://fermi.gsfc.nasa.gov/ssc/
** by Lucas Guillemot when he was a grad student.

Ray, Kerr, Parent et al * :

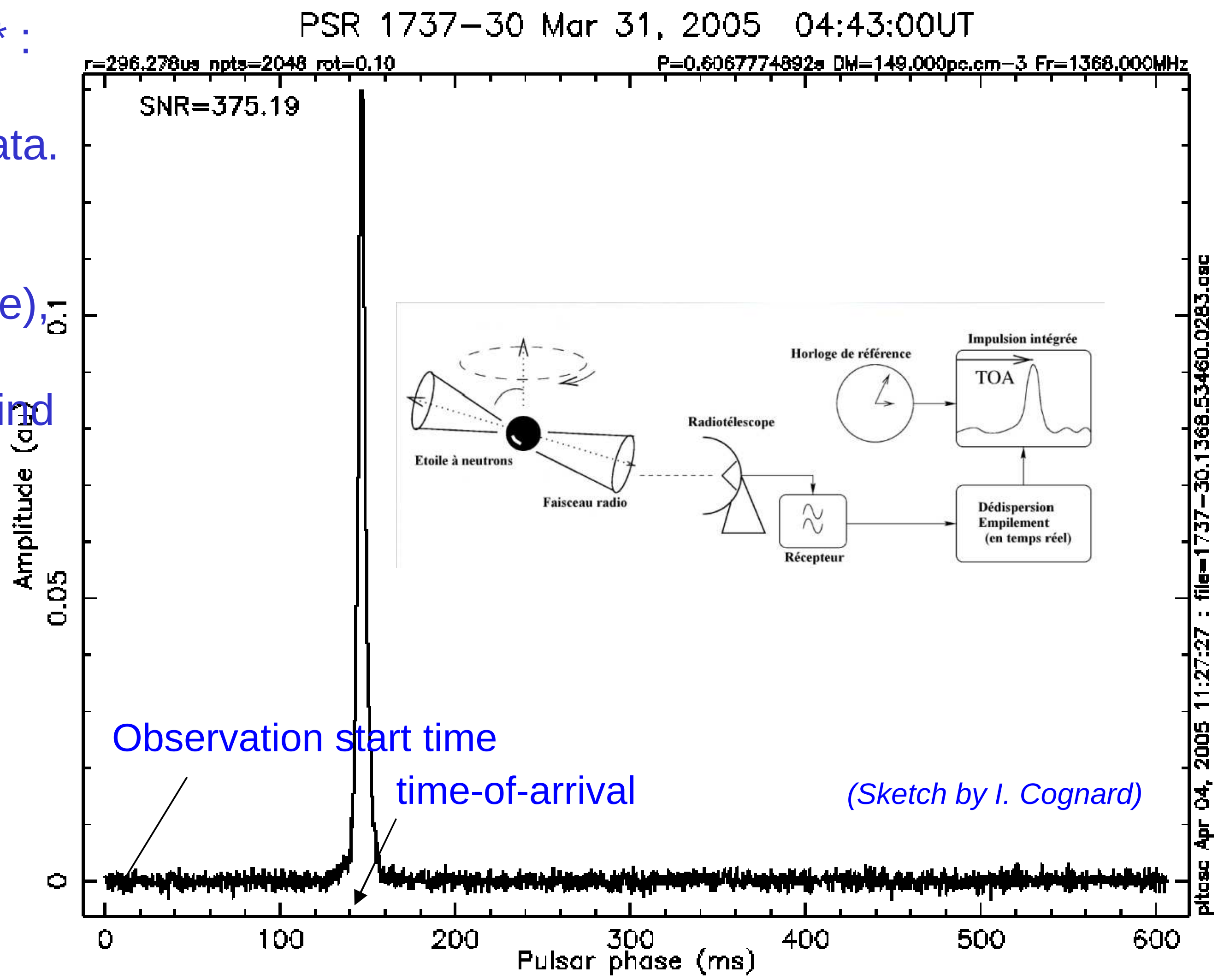
Make toa's from LAT data.

Basic idea:
as for radio (shown here), extract peaks for short stretches of data, and find offset from a reference template.

I use their
itemplate.py
and
upolyfold.py
available in GeoTOA.

Nota bene:
run gtbary first, to shift times to center-of-Earth.

Works great!



* https://ui.adsabs.harvard.edu/abs/2011ApJS..194...17R

https://fermi.gsfc.nasa.gov/ssc/data/analysis/user/ | 120 % | tempo2 tzrsite barycenter

ay ... Detected Gamma-Ray ... Fermi LAT Publications The ATNF Pulsar Data... Créer Home - GLAST LAT Sci... SAO/NASA ADS Custo... SIMBAD Astronomical...

National Aeronautics and Space Administration
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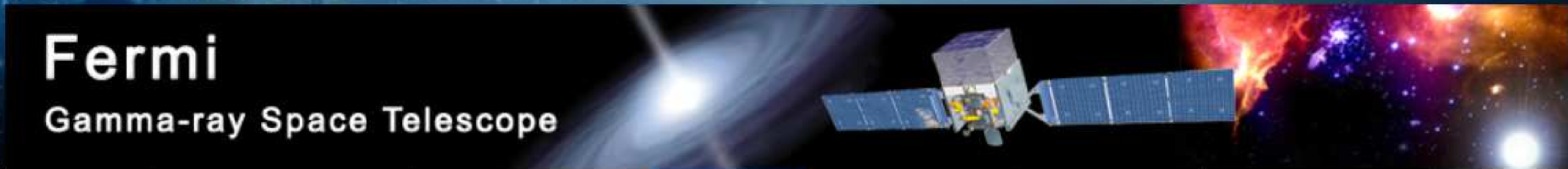

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Data

- Data Policy
- Data Access
- **Data Analysis**
  - + System Overview
  - + Software Download
  - + Documentation
  - + Cicerone
  - + Analysis Threads

User Contributions

The FSSC welcomes contributions to the Fermi Science Tools from the scientific community. If you have developed an extension to the science tools or any other tool useful for Fermi data analysis, please let us know and we will post it on this website. While the FSSC will work with the developer to resolve any issues with the software the contribution is provided "as is" and may not work after a software or data upgrade (e.g. to pass 8 data), updating the tool or script remains the responsibility of the developer. For the moment, please direct any communication to the Help Desk.

Program	Purpose	Read Me	Last Update	Author
GeoTOA-2.0.tgz	This python tool computes the pulse times of arrival (TOAs) at an observatory (or spacecraft) from unbinned Fermi LAT data using the maximum likelihood methods described in Ray et al. (2011, ApJS, 194, 17).	README	Jan 11, 2022	M. Kerr, P. Ray
add_weights.tar Weighting works wonderfully!!	Simple method to calculate photon weights (Bruel ~~2018~~), without a full spatial and spectral model, useful for pulsar phase-folding.	ReadMe	October 1, 2018	D.A. Smith, P.S. Ray, L. Guillemot

https://ui.adsabs.harvard.edu/abs/2019A&A...622A.108B

Beginners may prefer *fermipy* to the Science tools,

and PINT instead of *tempo2*.

David Smith Today at 11:48 AM

QUESTION -- is it true that to make toa's and phase connect them, PINT is a good tool?

2 replies

Paul Ray 1 hour ago

PINT is definitely a good alternative to `tempo2 -gr plk` (using `pintk`) and `tempo2 -gr fermi` (using `fermiphase`). PINT itself does not provide a way to compute TOAs, however. I use `photon_toa.py` from the NICERsoft package of contributed tools on github. That uses PINT for the calculations. In principle, it could be added to the PINT package too.

Paul adds:
photonphase is PINT code for ground-based TeV data.

Easy to add new sites to PINT.

Matthew Kerr 1 hour ago

I use PINT as a "library" in my pulsar timing pipeline to handle the phase computation. The likelihood part (which I use to estimate the timing model parameters) I do myself.

Conclusions

- CTA will precisely measure spectral shapes beyond pulsar cutoff energies, to clarify the emission mechanisms.

- CTA doesn't need a major radio timing campaign like LAT's.*
Rather, CTA can build rotation ephemerides from LAT data.

- Take care to make sure CTA absolute phases are accurate.

** As long as LAT keeps running…*

Backup slides

What, me worry?

The Astrophysical Journal, 708:1254–1267, 2010 January 10

FERMI-LAT OBSERVATIONS OF THE CRAB PULSAR AND NEBULA

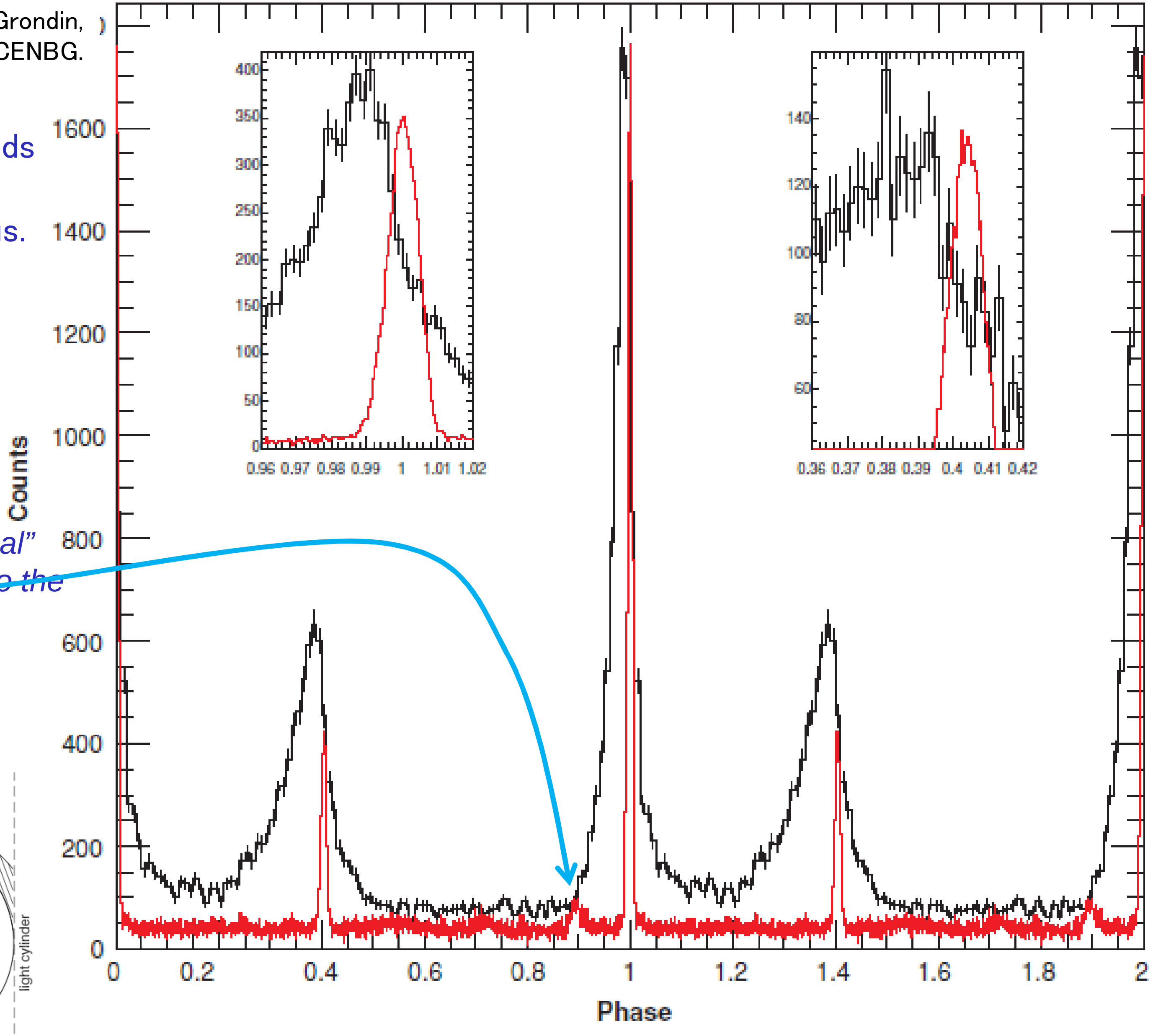
M. Lemoine–Goumard, M–H Grondin, CENBG.

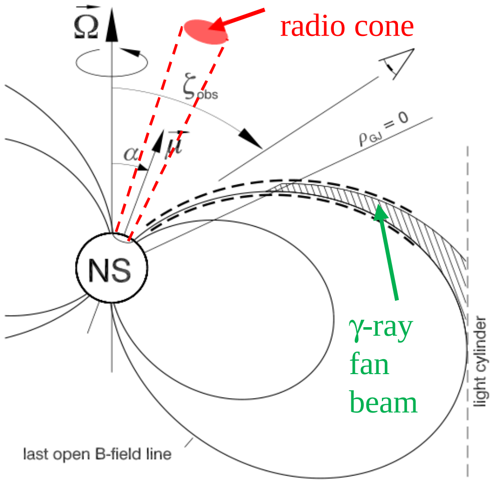
The main gamma peak leads the main radio pulse by δ = ~~280~~ 138* ± 12 ± 12 μs.

δ/P0 = 0.138 ms/33 ms
= 0.0044 in phase.

0.1 < δ < 0.3 for most young pulsars.

(The little blip is the "classical" radio peak, corresponding to the magnetic axis.)





* Erratum posted at http://fermi.gsfc.nasa.gov/ssc/data/access/lat/ephems/

THE ASTROPHYSICAL JOURNAL, 744:33 (13pp), 2012 January 1 L. Guillemot, ex-CENBG, now Nançay.

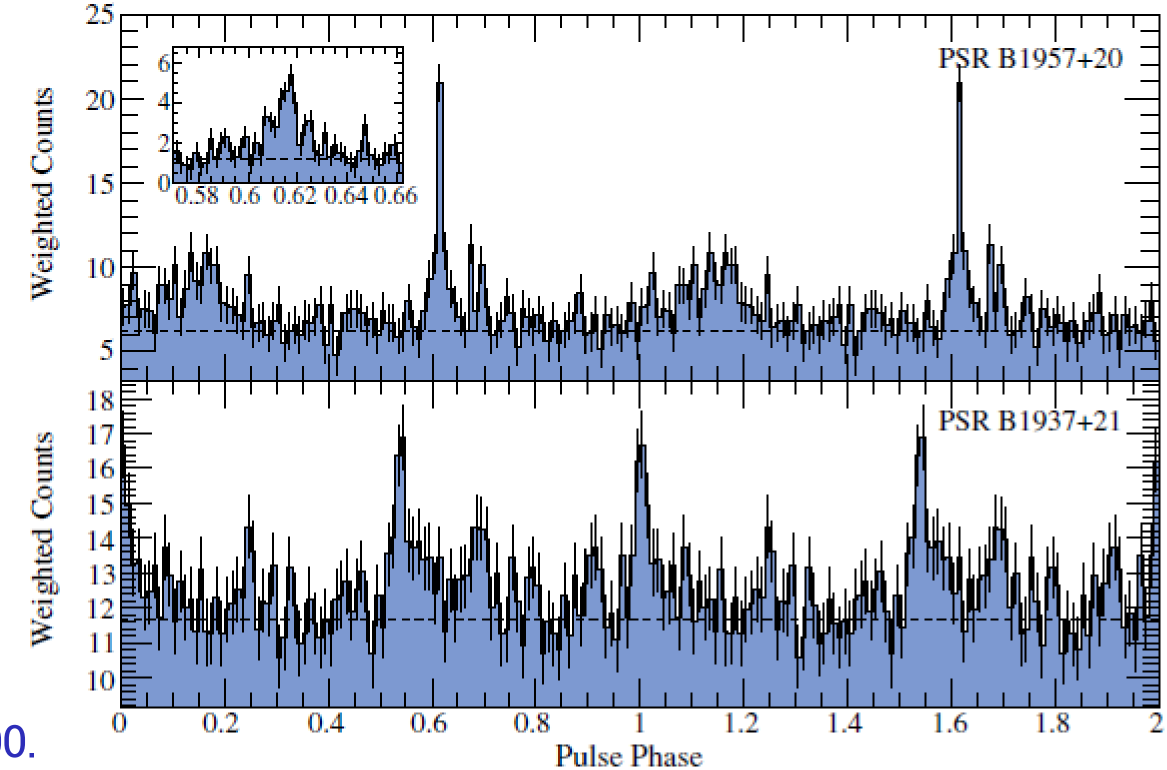
B1957 (= J1959+2048):
First known "black widow" MSP.

B1937 (= J1939+2134) :
First MSP discovered.

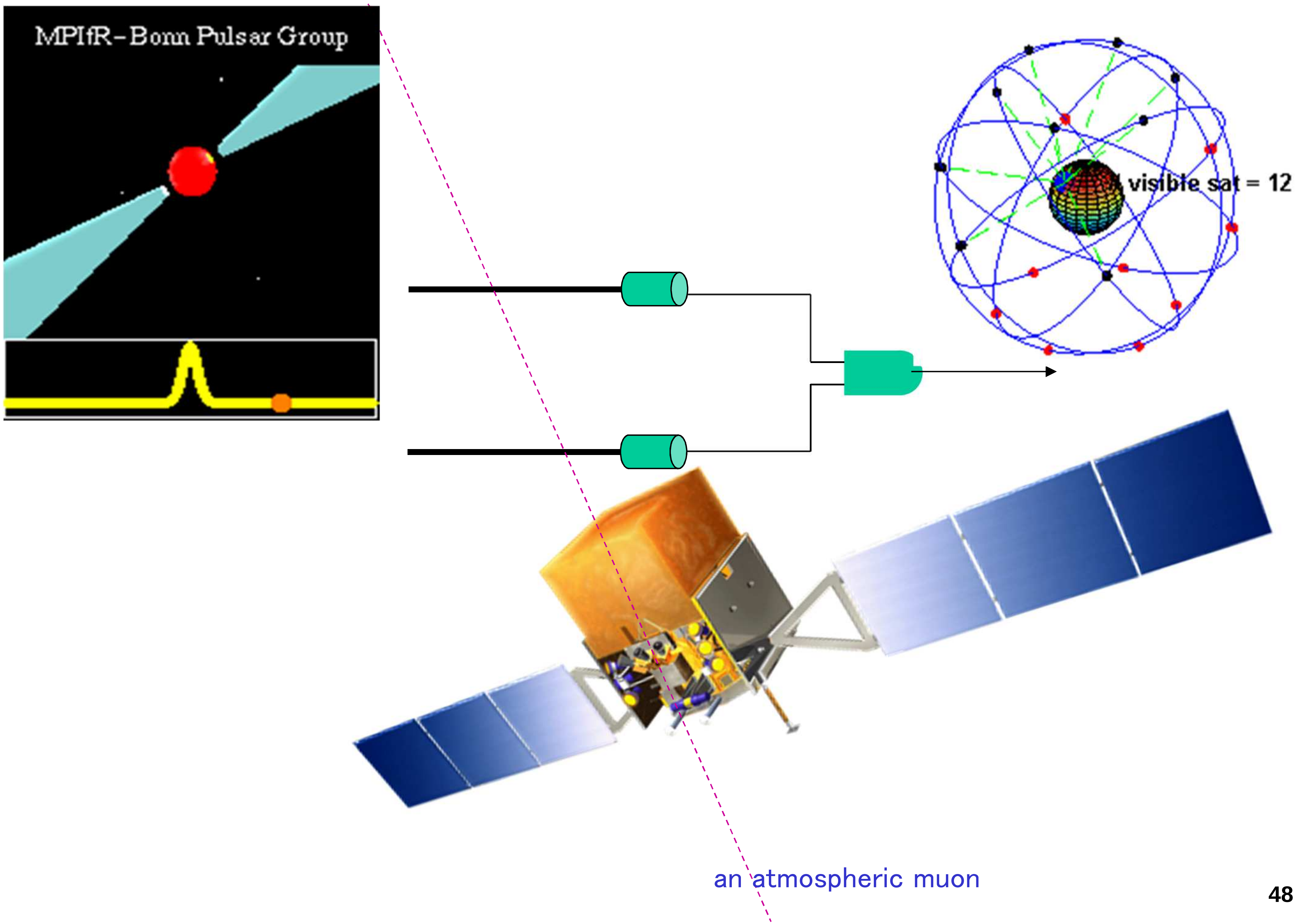
Both remain among the fastest:
P0 ≈1.6 ms.

0.014 ∗ 1.6 ms = 22 μs peak width.

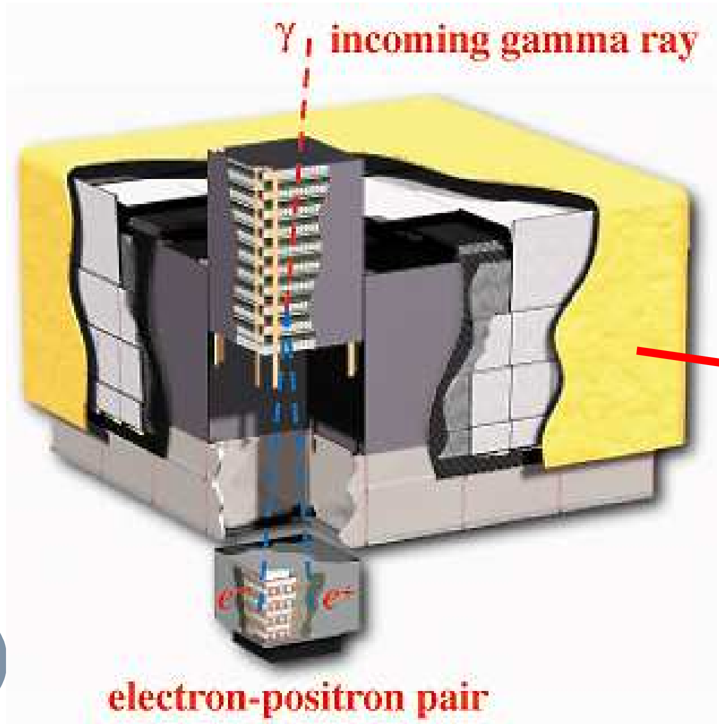
Photon fluxes >100 MeV ≈ Crab/200.

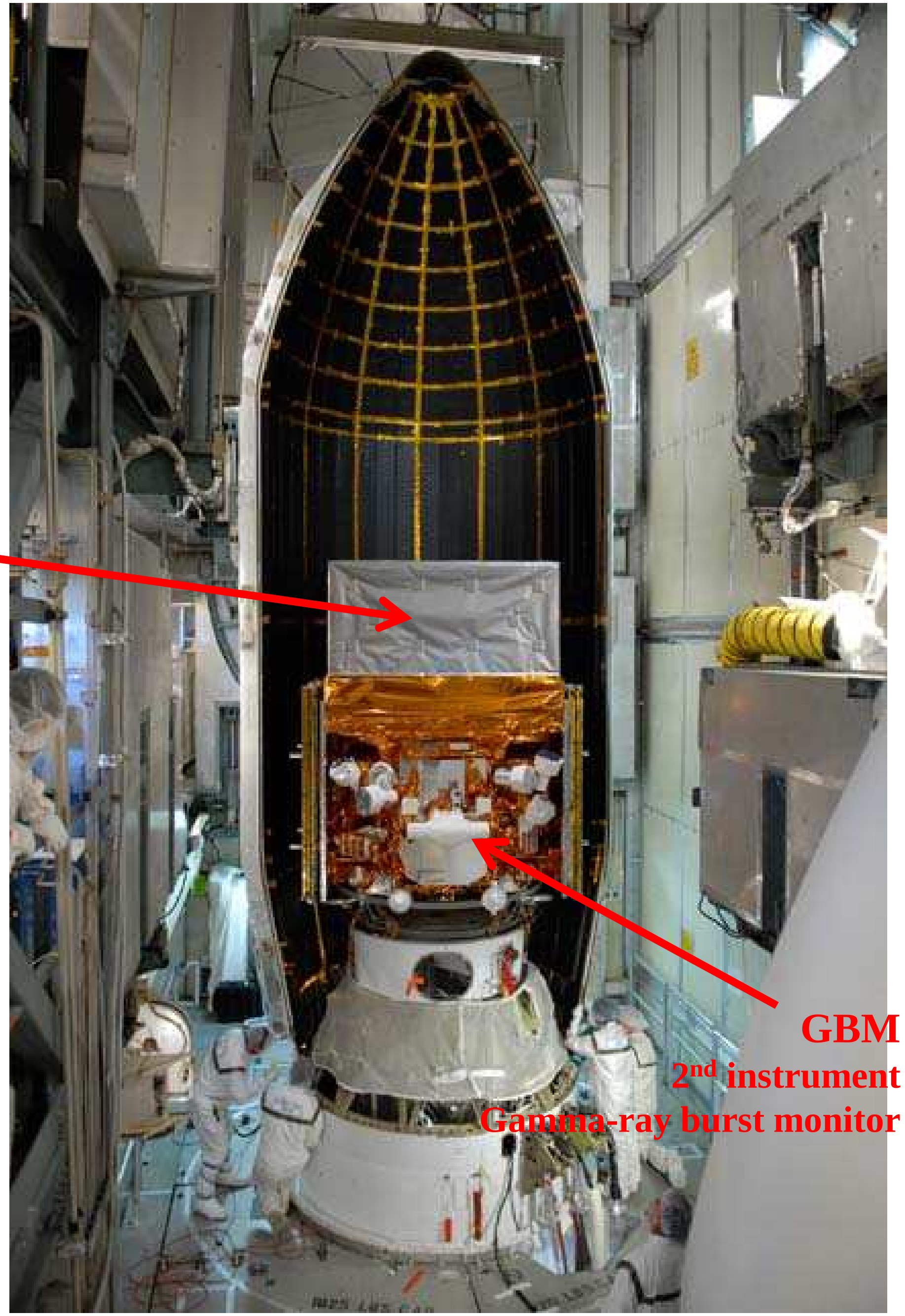


Parameter	PSR B1937+21	PSR B1957+20
First peak position, Φ_1	0.004 ± 0.009	0.146 ± 0.026
First peak full width at half-maximum, $FWHM_1$	0.030 ± 0.029	0.137 ± 0.074
First peak radio-to-gamma-ray lag, δ_1	-0.010 ± 0.009	-0.016 ± 0.026
Second peak position, Φ_2	0.543 ± 0.013	0.616 ± 0.002
Second peak full width at half-maximum, $FWHM_2$	0.041 ± 0.041	0.014 ± 0.007
Second peak radio-to-gamma-ray lag, δ_2	0.006 ± 0.013	0.012 ± 0.002


MPIfR-Bonn Pulsar Group
visible sat = 12
an atmospheric muon

Large Area Telescope
30 MeV to 300 GeV





The whole sky, 8 times per day:

- Known and unknown sources.
- Good localization.

Pulsar Braking Indices

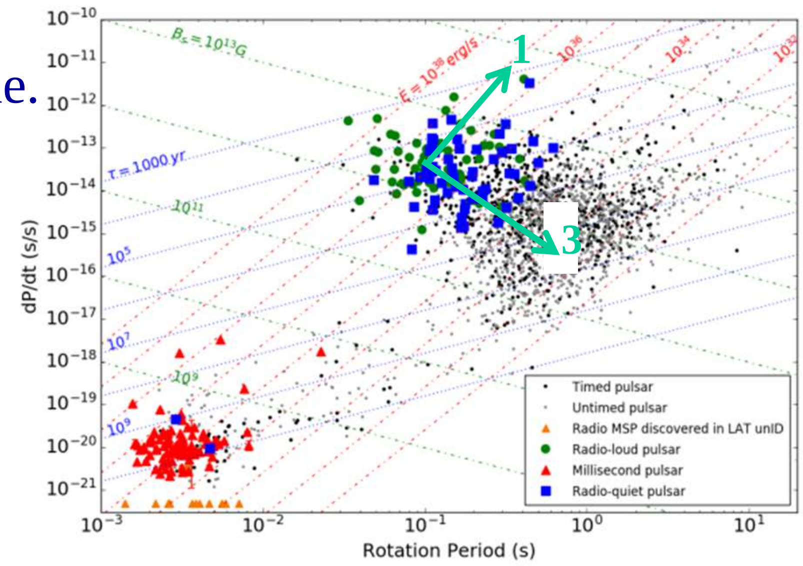
Torque $\tau = I\,\dot{\Omega} = k\Omega^n$ ➔ $n = F2F0/F1^2$.

Mechanism	n
Gravitational quadropole	5
Magnetic dipole	3
Wind	1
Infall disk propeller	0
Infall disk magnetic torque	-1

Linear combinations to obtain observed non-integer n<3 values.
Or… slowly changing B, α, I (Blandford & Romani 1988) (Lyne et al 2015)

(2-n) slope is evolution direction in the P$\dot{P}$ plane.

n<3 means characteristic age decreases, B increases.
(See Espinoza et al 2011)



Timing failures on 6 missions (1 of 2)

USA (X-rays): The GPS often froze on orbit and had to be reset a few times a day. The satellite would go through GPS µwave beams intense enough to confuse the receivers. Also, the speed of the satellite relative to GPS's was far from the design-regime for ground-based GPS's.

XMM: Two years elapsed before absolute phases were reliable, after a series of 5 different kinds of electronics problems. Proc. SPIE 5165, 85-95 (2004).

INTEGRAL: Orbital inaccuracies due to ground software caused 300 us problems.

CHANDRA: For the HRC, the time stamp of a given event was that of the previous event. On-board filters remove events, so obtaining the right date for a given event was impossible. The solution is to trigger only on the central CCD chip, to reduce the event rate, to allow sending all events to the ground ("timing mode").

S. Murray et al, ApJ 568:226-231 (2002) and references therein.

Timing failures on 6 missions (2 of 2)

Compton GRO: In the days before GPS. Events were assembled into packets on board, and the packets were grouped into a "major packet", to which a time stamp was afixed. These packets were sent to the ground. But the time stamp was from the preceding packet! And the time was off by over a second.

ROSAT: Excerpt from http://www.mporzio.astro.it/~gianluca/phdthesis/node28.html :
"A problem was…found…timing individual events, due to…software (Briel *et al.* 1994). The origin…was the spacecraft clock reset which followed the spacecraft tumbling incident of 1991 Jan. 25. All PSPC data after that time are affected. The problem leads to relative shift of 1s between adjacent PSPC events."

Never quite the same problem twice…
GPS issues seem *easily avoidable today, not the others…*
The above problems were either large (100's and 1000's of µs) or fatal.

Timing improvement on 1 mission

NUSTAR:
Timing Calibration of the NuSTAR X-Ray Telescope
https://ui.adsabs.harvard.edu/abs/2021ApJ...908..184B/abstract Matteo Bachetti, Craig Markwardt, Brian Greffenstette et al

Tight budget – no GPS. Mission requirement of 100 ms timestamp accuracy was achieved using a 21 MHz TCXO = Temperature Controlled Crystal Oscillator, and timing was good at the 2 or 3 ms level. These authors studied the residual temperature-dependent oscillator drift and implemented corrections into the analysis software. Accuracy is now about 65 µs.

Bachetti pointed us to the International Astronomical Consortium for High-Energy Calibration (https://iachec.org/) which has a Timing Working Group (https://iachec.org/timing/).

Incomplete Information

I was told that *the ARGOS satellite GPS system was only tested with GPS repeater antennas or GPS signal simulators, not in open air, so the amplitude was never as it would be in real operation.* Consequently, on orbit, the GPS receivers had issues like those of USA's (see above). (?) (I don't know if this is correct.)

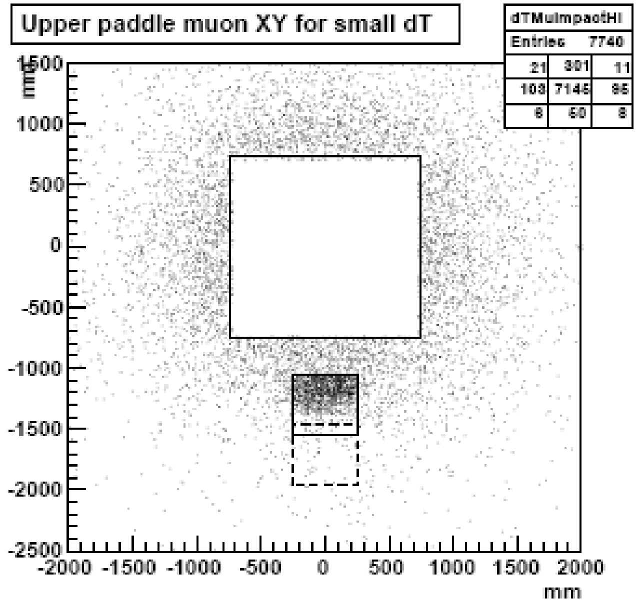
I didn't find any detailed information… here are some links anyway:

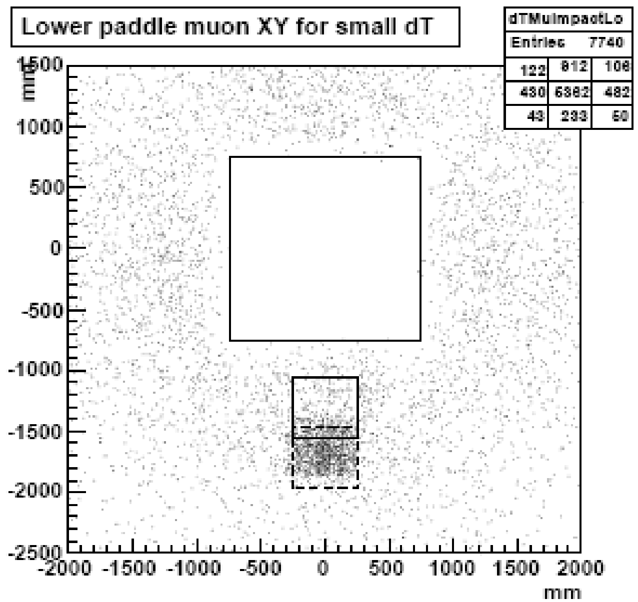
https://argo.ucsd.edu/data/data-faq/

https://artes.esa.int/projects/argo

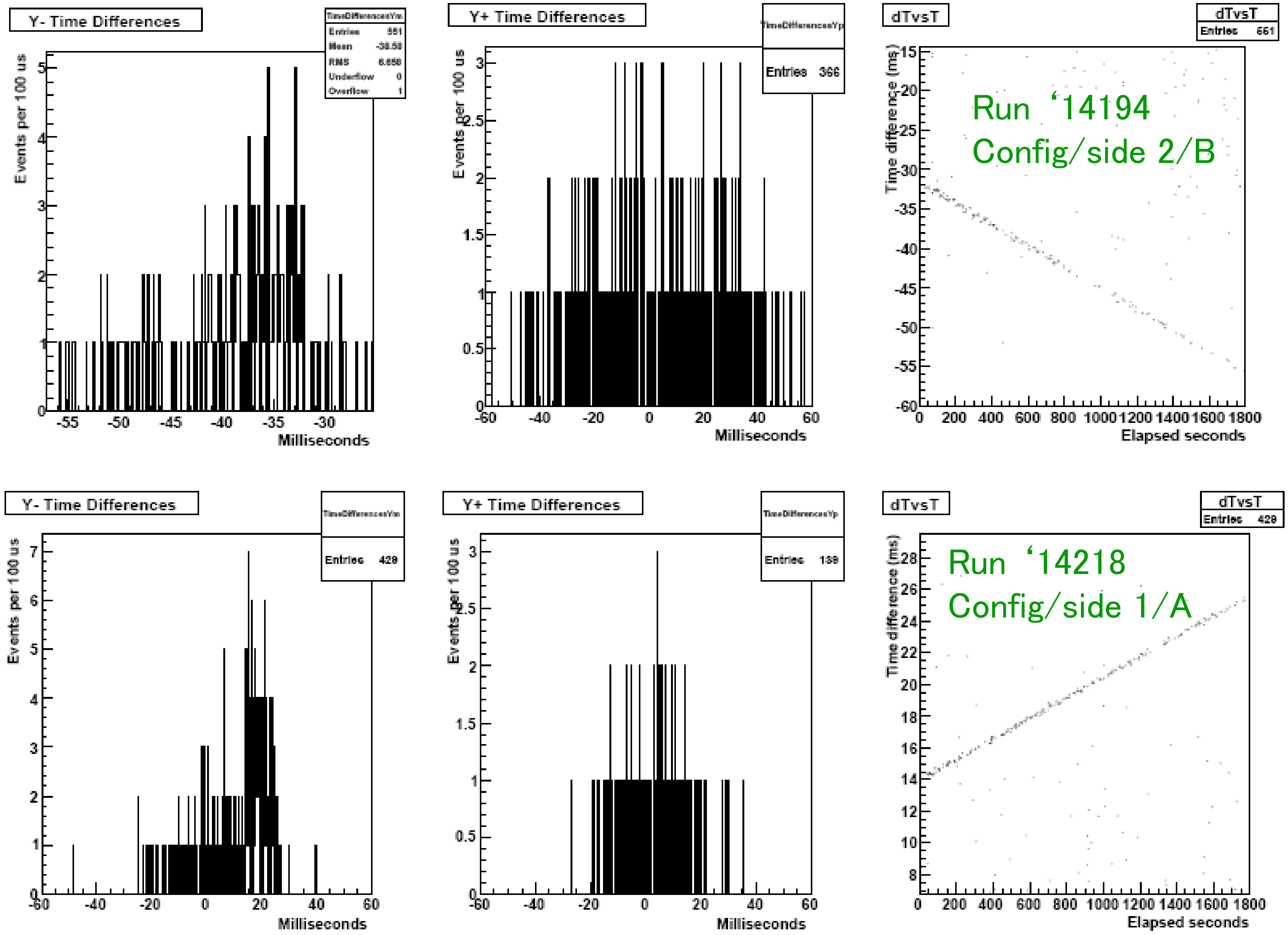
https://www.argos-system.org/support-and-help/faq-localisation-argos/

- Aerial view of LAT and μ telescope.
- Extrapolate TKR tracks to scintillator heights.
- For small GPS vs LAT time differences, the paddles appear.





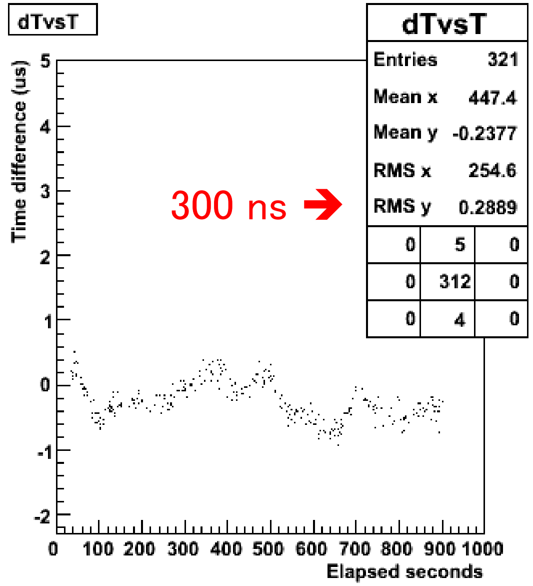
GPS unlock runs : no wrap-around



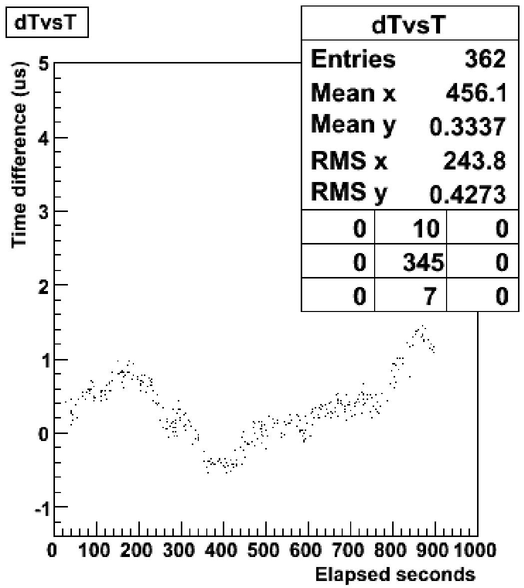
Eric Grove report to Collaboration, 7 months before launch.

Verification of Absolute Time Accuracy

- **SC PPS meets spec with and without GPS sync**
  - **July/Aug and Oct 07 retest demonstrate that SC FSW bug is fixed**
    - **With GPS sync, SC PPS is in phase with GPS PPS**
      - **See upper panel**
    - **Without GPS sync, SC PPS drift rate ~10x better than spec**
      - **See lower panel**



- **Getting the integer seconds right…**
  - **Our tests amply demonstrate that SC PPS will have correct subseconds**
  - **Integer seconds are set by procedure at SC power-up**
    - **Recall that SC time is seconds since reference epoch**
    - **LAT, GD, and GPO are working together on power-up procedure**



sparkfun START SOMETHING

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DISTRIBUTORS SUPPORT

SparkFun GPS Module - Copernicus II DIP (12 Channel)

GPS-11858 ROHS✔

★★★☆☆ 3

$74.95

1	quantity
◉	37 in stock
$74.95	1+ units
$71.20	10+ units
$67.46	25+ units
$63.71	100+ units

Eric G now flies gamma detectors in U2 “spy” planes to study thunderstorms.

He says this unit works well.

(U2’s have antennas on roof, and connectors inside.)

Trimble is a historical leader in the field…

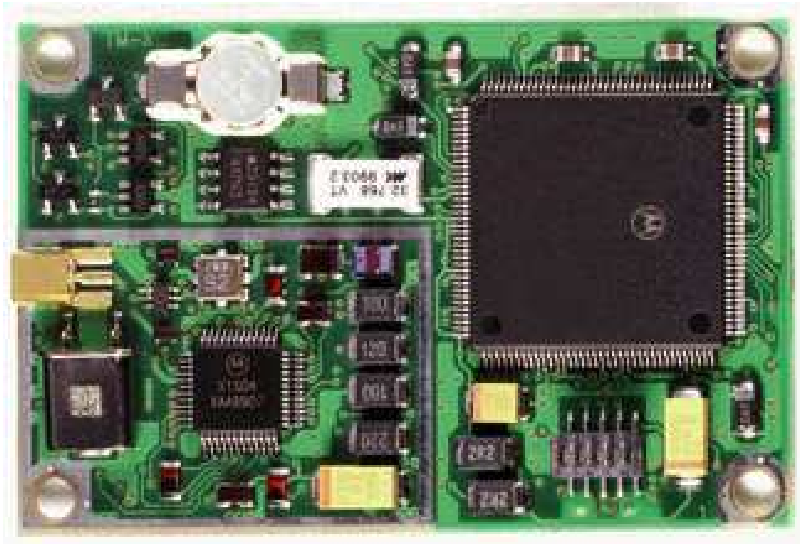
Works above 40,000 feet.

Not triggerable, but we don’t care.

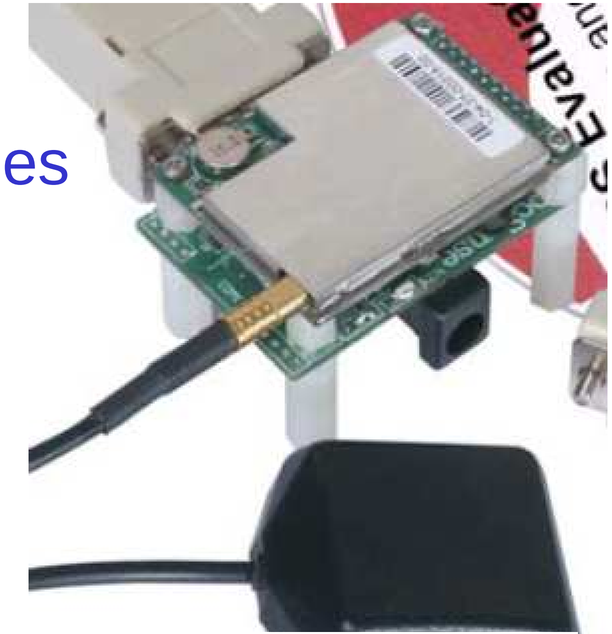
“The GPS for the first flight of EUSO-Balloon is the Motorola Oncore M12. For EUSO-SPB we are using differential GPS.” *–Simon Bacholle.*

Nota bene: some GPS’s disabled above ~40,000 feet.

Oncore M12 ↓ Old! Circa 1999.



an example of why to trust Bordeaux times



- RF solutions LS−40EVALR1, 168 euros.
- Use PPS output to trigger VME GPS “time capture”
- 50ks run (overnight)
- ± 0.5 μs dispersion.
- 500 ns offset due to cable run of one antenna.
- Lost satellite fix during 4% of the run.

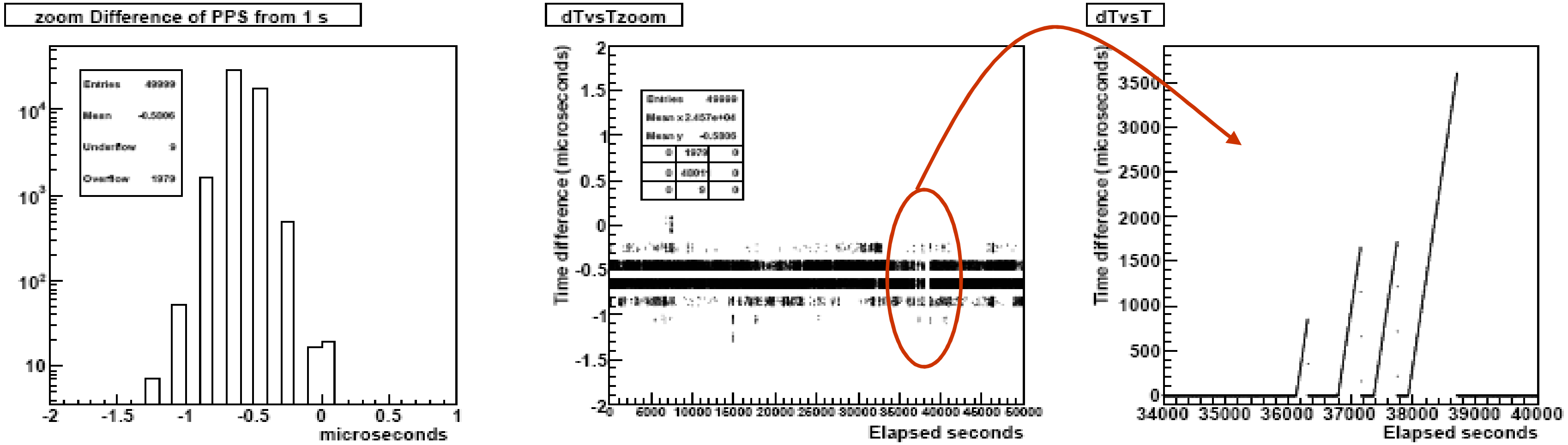


Figure 17: The deviation of the Symmetricom VME GPS times from an integer number of seconds, when the VME “time capture” is triggered by the PPS output of the *RF Solutions* GPS. Left: Histogram of values. The mean of -580 ns is roughly consistent with the cable run of the Trimble antenna used for the Symmetricom. The dispersion is better than the $\pm 1\,\mu s$ claimed by *RF Solutions*. Middle: Values versus elapsed time. It appears that satellite lock was lost briefly after 12k seconds, and again between 36k and 39k seconds. Right: Zoom on the long GPS-unlock period.