Pulsars and Pulsar Timing

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NSERC CRSNG

NASA Hubble Fellowship Program

GREEN BANK OBSERVATORY

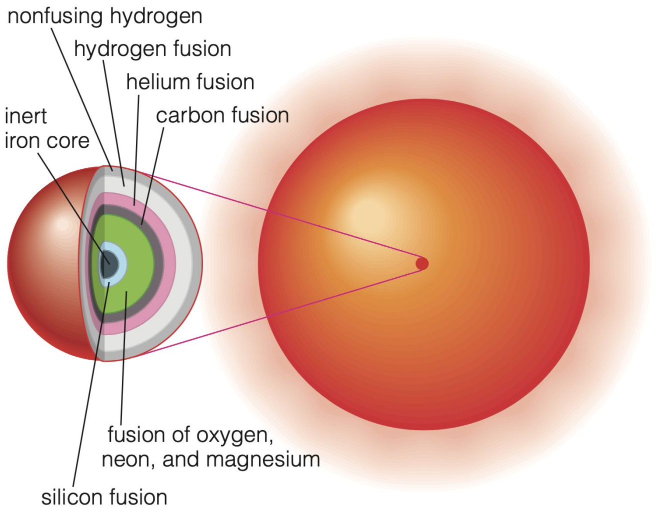
North American Nanohertz Observatory for Gravitational Waves
A National Science Foundation Physics Frontiers Center

Outline

- Neutron Stars
- Millisecond Pulsars
- The ISM
- Millisecond Pulsar Timing
- PTA Data Sets
- The Noise Budget
- NANOGrav’s Timing Pipeline

Neutron Stars

- The fate of stars depends on their mass
  - High mass stars go through the process of fusing H → He → heavier elements
  - Binding energy per nucleon highest for Iron
  - Core collapse when gravity wins
- <u>< 8 solar masses</u>: white dwarfs (1.4 $M_\odot$)
- <u>> 8 solar masses</u>: neutron stars (up to ~3 $M_\odot$)
- <u>> 10 - 30 solar masses</u>: black holes (> 3 $M_\odot$)

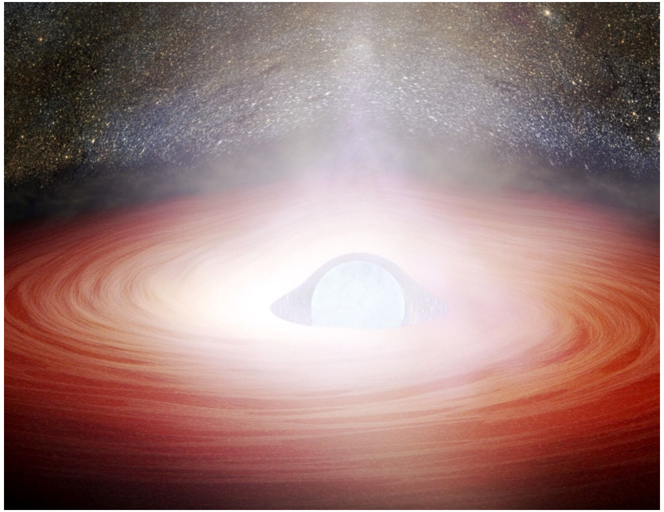


The Cosmic Perspective

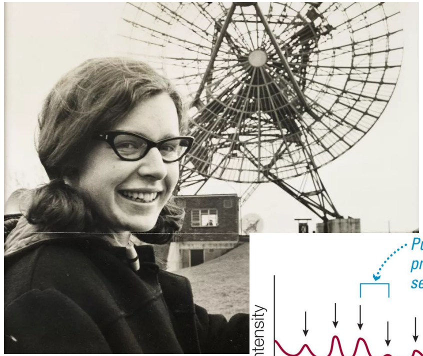
Neutron Stars

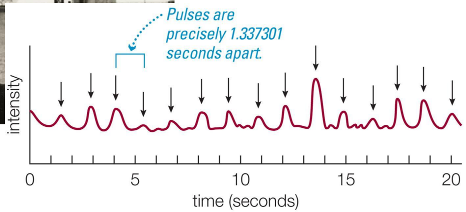
Massive stars can undergo supernovae and leave behind neutron stars:

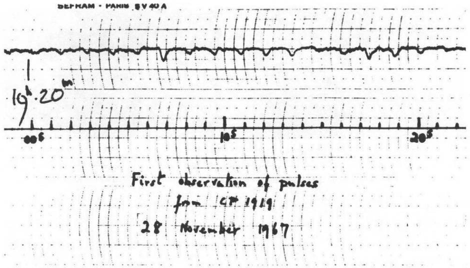
- Balls of neutrons supported by neutron degeneracy pressure
- Density: a paperclip with a neutron star's density would weigh as much as Mount Everest
- Typical NS: 1.4 $M_\odot$, $r \approx 10$ km



The Discovery of Neutron Stars (Pulsars)







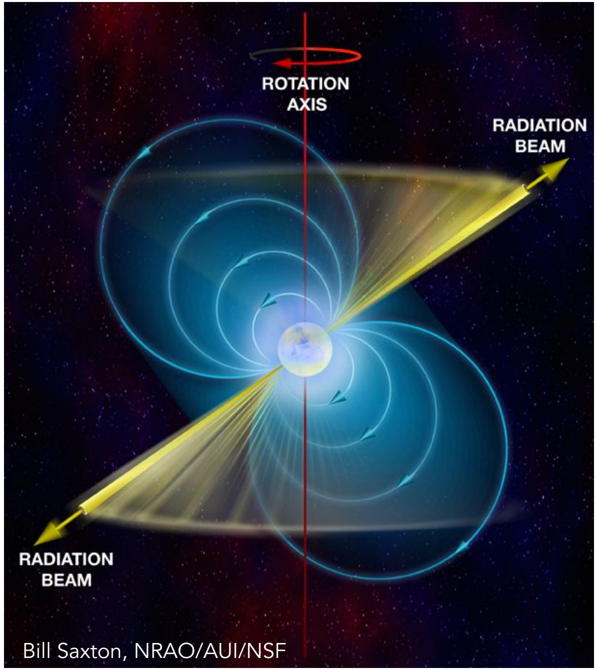
- Using a radio telescope in 1967, grad student Jocelyn Bell-Burnell noticed very regular pulses of radio emission coming from a single part of the sky
- Called “LGM” initially
- The pulses came from a spinning neutron star — a pulsar
- Process of iterating over theory and observations → notable: crab pulsar period increasing
- Bell-Burnell was snubbed by the Nobel committee in favor of her advisor and department head
  - Read her own account: http://www.bigear.org/vol1no1/burnell.htm

What are Pulsars?

- Don't pulse (lighthouses)
- Stable pulse periods (some more than others)
- Initial info can be learned by imposing requirement that centrifugal acceleration at the equator doesn't exceed gravitational acceleration:
    - Angular velocity $\Omega \equiv 2\pi/P$

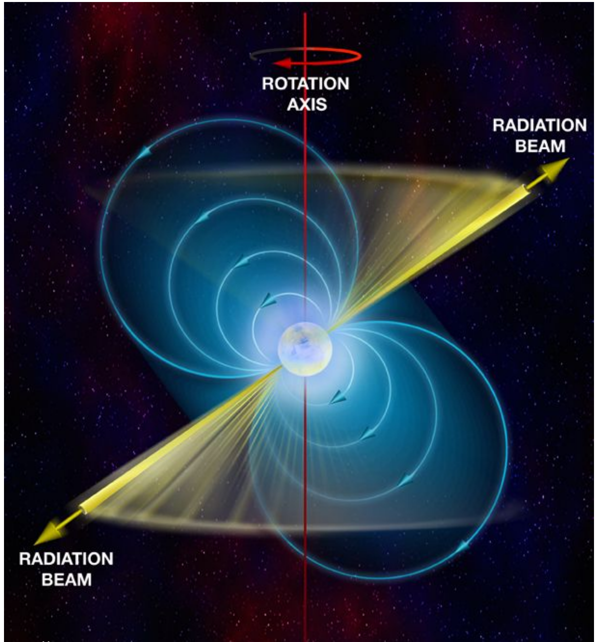
$$\Omega^2 R < \frac{GM}{R^2} \longrightarrow \rho > \frac{3\pi}{GP^2}$$

- Fastest < 1.4 ms → density > 10^{14} g cm^{-3} = atomic nuclei



What are Pulsars?

- Stars → approx. dipolar B fields
- Magnetic flux is conserved during collapse, so pulsars have B fields up to 10^{15} G (usually more like 10^{12}; Earth = 0.5 G)
- Rotating magnetic dipole model
    - Misaligned rotation and magnetic axis = dipole radiation; extracts energy; slows down over time
    - Example: Crab pulsar's dipole radiation heats up its nebula, then re-radiates in wide spectrum
    - It's more complicated than this!



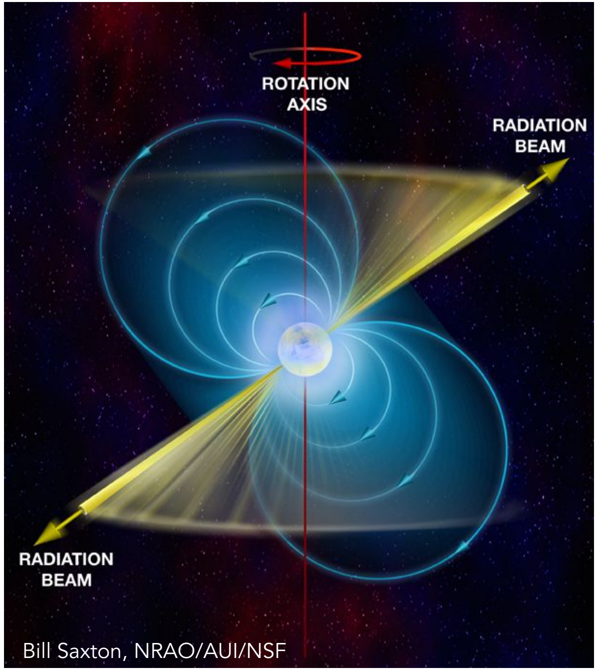
Bill Saxton, NRAO/AUI/NSF

What are Pulsars?

- Assuming dipole + measurement of spin-down, can calculate spin-down luminosity, B field strength, characteristic age

$$\tau \equiv \frac{P}{2\dot{P}}$$

- Most pulsars 10^5 < age < 10^{10} yr (Galaxy)

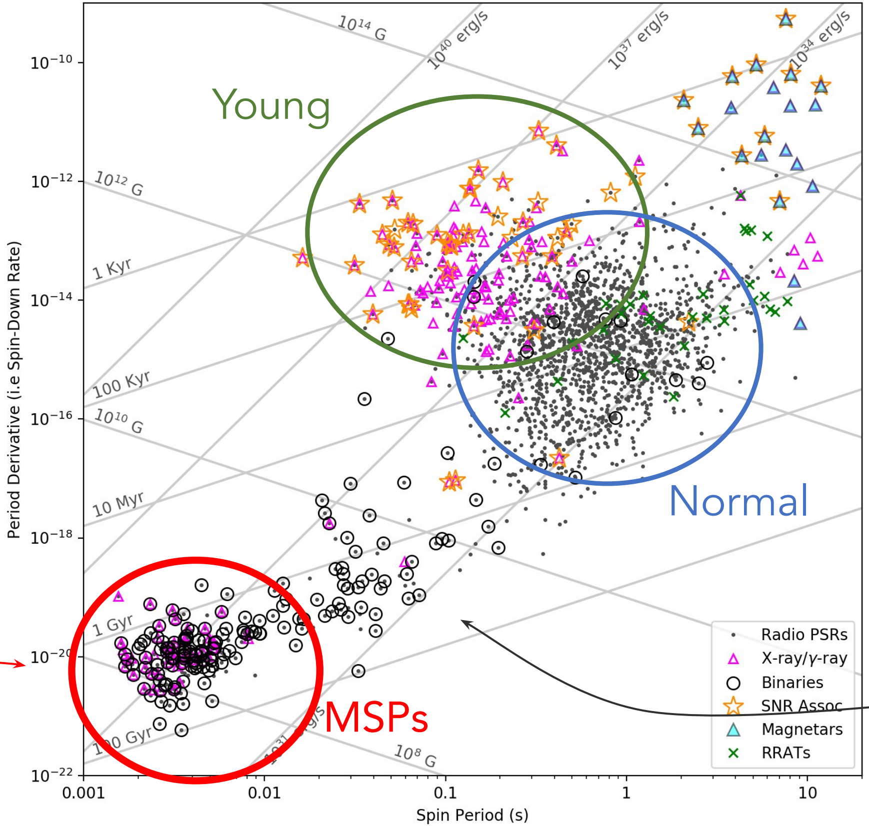


What are Pulsars?

MSPs:
fully recycled,
low-e orbits,
stable, fast!

Low B

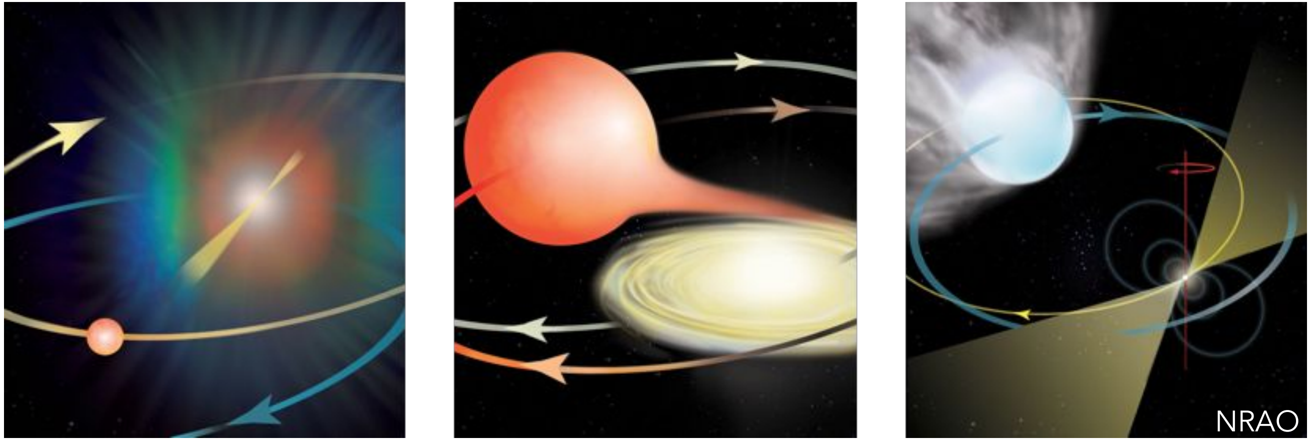
Essential Radio Astronomy



High B

Double NS:
~17; mildly
recycled, high-e
orbits, good GR
tests

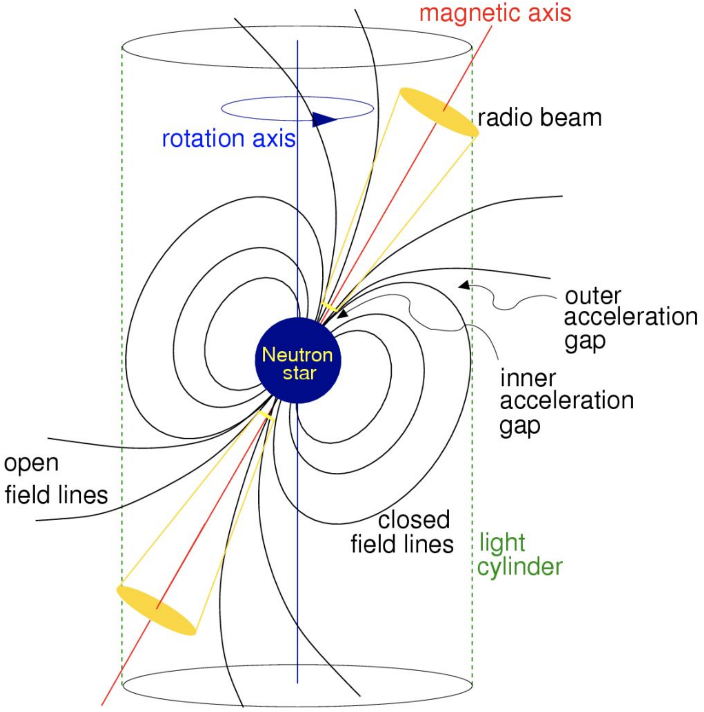
Millisecond Pulsar Recycling



- Low B-fields ($<10^{11}$ G); plasma shielding during accretion
- Spun up by stellar companion (almost always binaries) → recycling
- Not eccentric, very stable rotators

Pulsar Emission

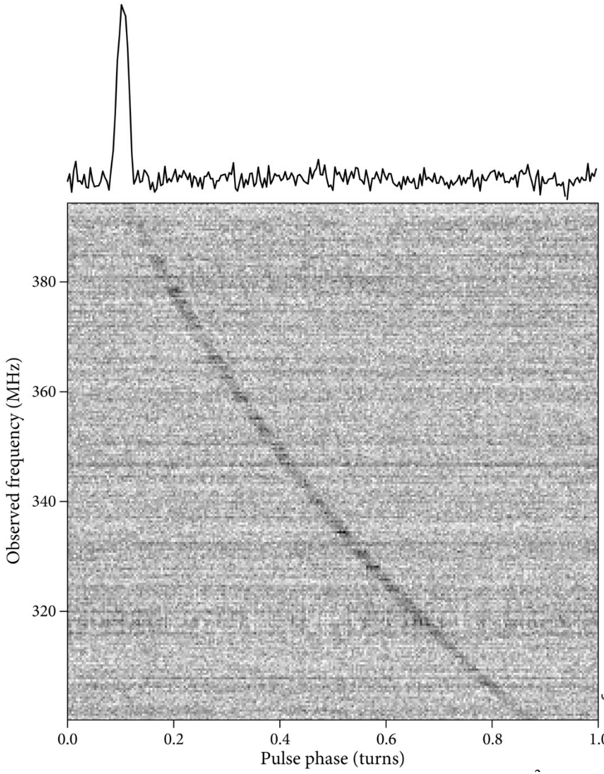
- B field → E field pulls charge from surface = magnetosphere
  - Co-rotates with pulsar
  - Light cylinder where plasma velocity approaches c
    - B field lines don't reconnect here
    - e- emit curvature radiation as they travel along the open field lines
    - Photons produced in the process trigger electron/positron cascade, pairs produce more photons = radio emission



Lorimer & Kramer (2004)

The Interstellar Medium

- Cold, ionized ISM causes interesting and complicated delays
  - Inhomogeneous and turbulent
- Dispersion measure (DM; next slide)
- Diffractive and refractive scintillation = flux density changes
- Scattering → pulse broadening
  - Multi-path propagation; some rays take longer paths
  - Usually proportional to $\sim\nu^{-4}$



Essential Radio Astronomy

Dispersion Measure

$$\mu = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}$$

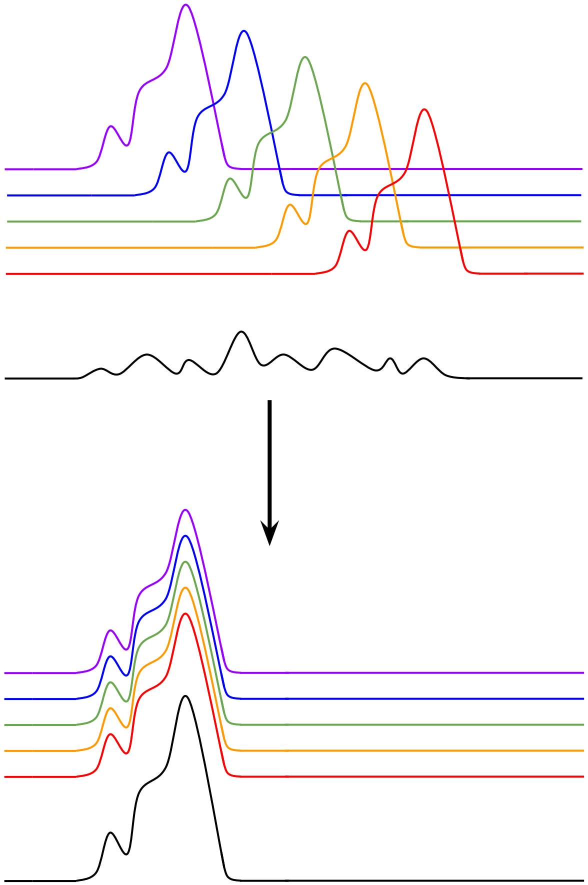
$$v_g \approx c\left(1 - \frac{\nu_p^2}{2\nu^2}\right)$$

$$t = \int_0^d v_g^{-1} dl - \frac{d}{c} = \frac{e^2}{2\pi m_e c} \frac{\int_0^d n_e dl}{\nu^2}$$

$$DM = \int_0^d n_e dl$$

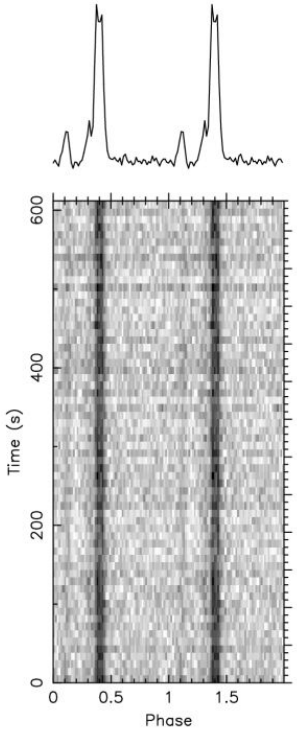
$$t \propto DM\, \nu^{-2}$$

Dispersion measure → estimate distance



How do we Study Pulsars?

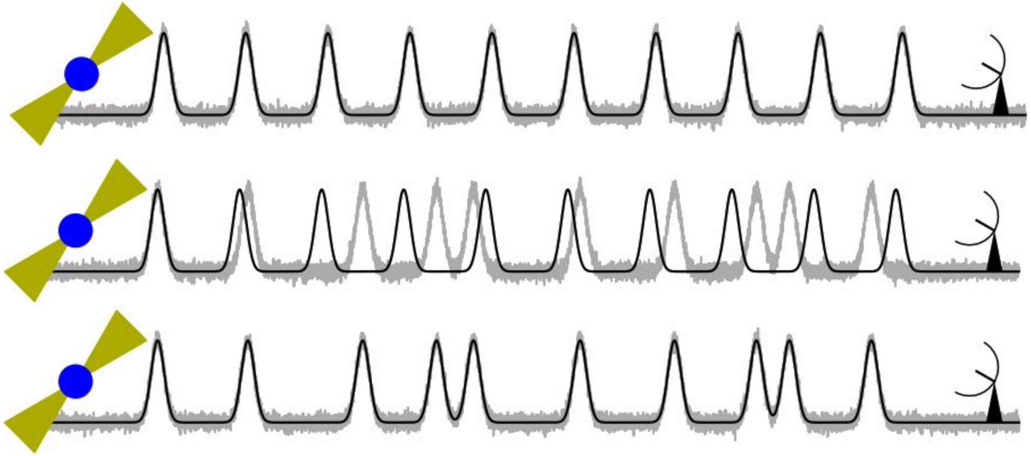
- Pretty weak! Need sensitivity
- They emit most at low frequencies (long wavelengths; they have steep spectra)
- Radio telescopes like the Green Bank telescope and the Arecibo telescope (plus FAST, CHIME, etc.)
- Usually observe from < 1 GHz → ~few GHz
- High-frequencies, too (NICER, *Fermi*-LAT)
- Dr. Bell-Burnell's pulsar isn't typical; need to fold the data modulo the pulse period to bring out the signal



OK, but what are they good for?

- They're space clocks!
- Some of the most accurate measurements ever (comparable to atomic clocks)
- PSR J1737+0747: Period = 4.570136528819804 +/- 0.000000000000001 ms
- How? Pulsar timing!

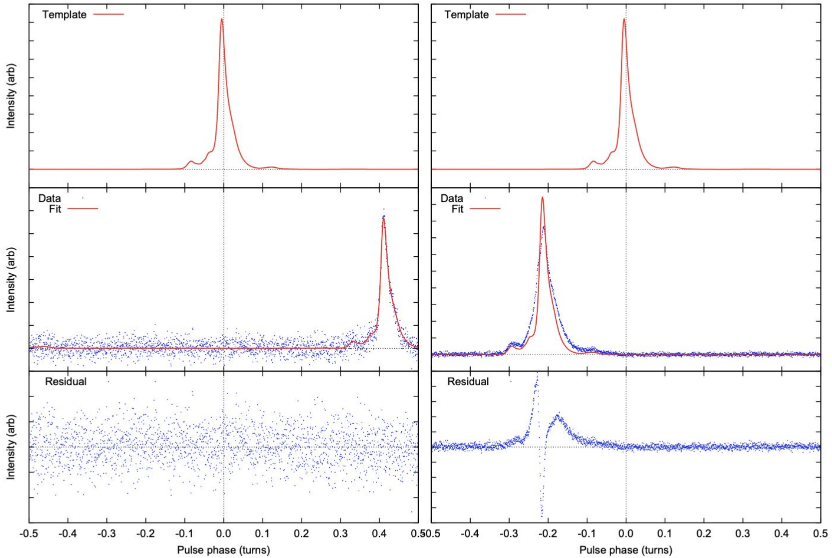
Pulsar Timing = modeling every rotation



- Two steps:
    - Extracting times of arrival (TOAs)
    - Fitting a timing model to the TOAs

Extracting TOAs

- Fold data from many pulses modulo the pulse period P
- Determine shift in rotational phase between the profile and a reference profile (template, usually many observations)
- Cross correlate template and data, usually in the Fourier domain, to find maximum
- The phase shift where correlation is maximized = difference between observed and model predicted pulse phases, averaged over the whole observation



Lommen & Demorest

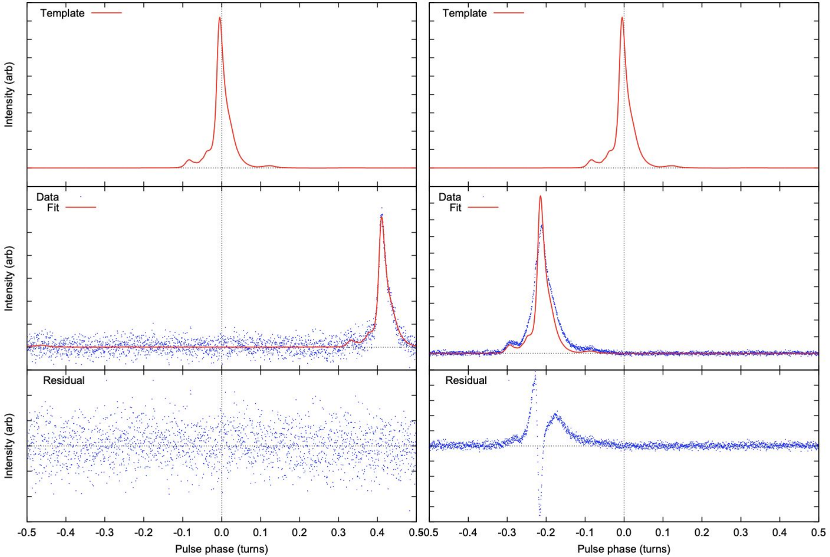
Left: profile from 1600 MHz GBT, Right: profile from 750 MHz GBT

Extracting TOAs

- Turn this into a TOA: subtract model-predicted phase at observation midpoint from measured phase shift, multiply by model predicted pulse period and add it to the reference time
- Time dependent phase of pulsar approximated with Taylor expansion (can measure frequency and frequency derivative):

$$\phi(t) = \phi_0 + f(t - t_0) + \frac{1}{2}\dot{f}(t - t_0)^2 + \cdots$$

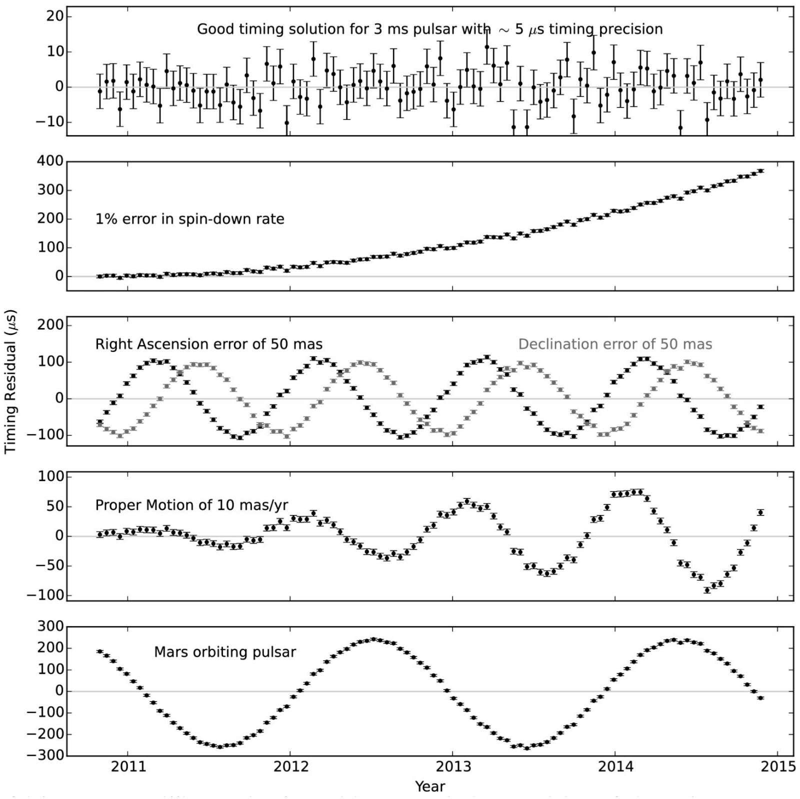
- Pulsar timing works because the rotational phase difference between each TOA must contain an integer number of rotations
- How well we can measure TOAs depends on S/N, sharpness of peak, etc.



Lommen & Demorest

Left: profile from 1600 MHz GBT, Right: profile from 750 MHz GBT

Fitting Timing Models

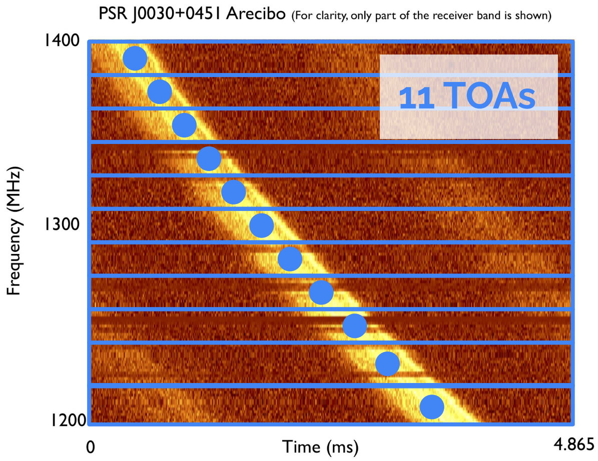


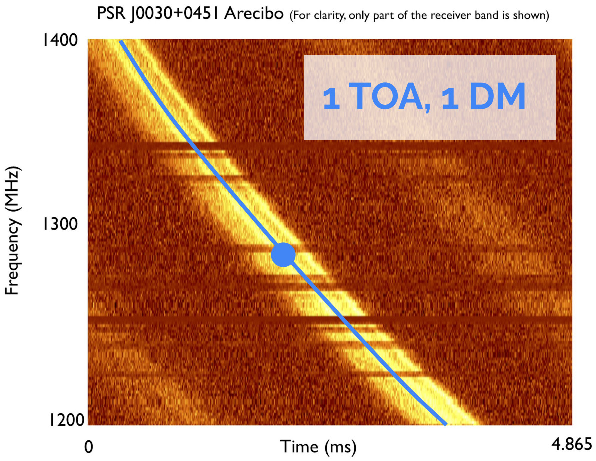
Essential Radio Astronomy

- Many factors dictate pulse arrival times
    - Most basic are pulse period, period derivative, pulsar position on sky (and Keplerian parameters if it's a binary)
    - DM, GR effects, etc. add more terms to the timing delays
- Difference between measured TOA and model = timing residual

More Timing Details

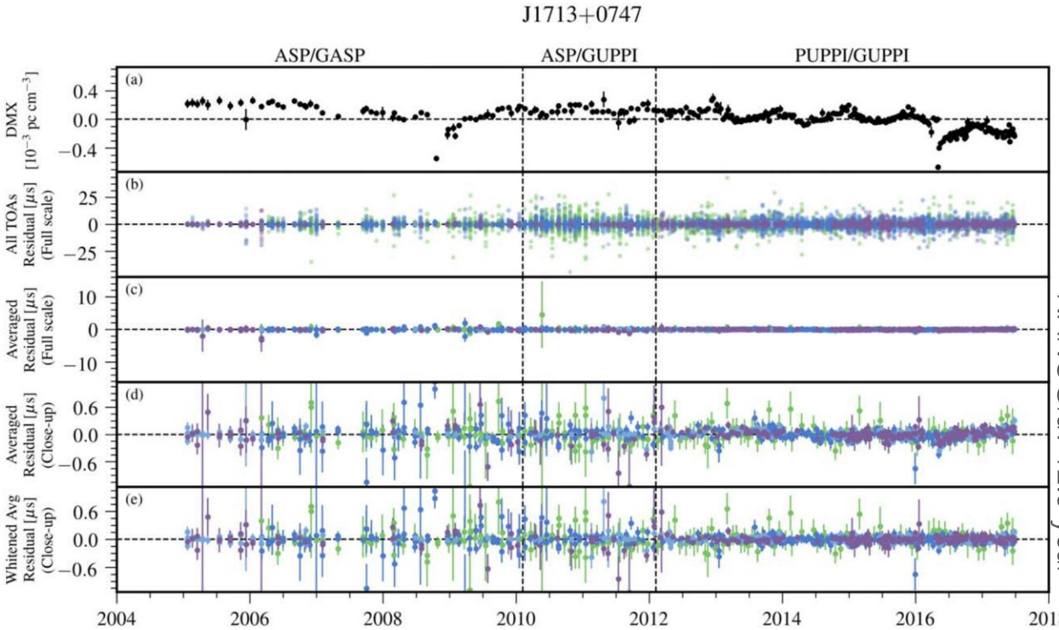
- Timing models are often fit using chi-square minimization, but other techniques can be used (MCMC)
- Many timing models have hundreds of parameters (there are lots of different ways to describe DM, for example)
- There are multiple ways to extract TOAs: “narrowband” and “wideband” pulsar timing





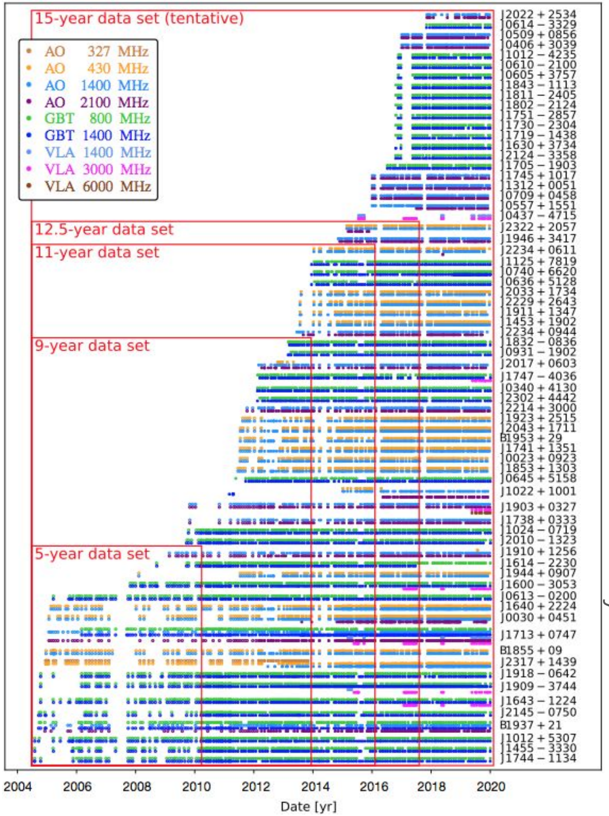
What is a PTA data set?

- Typical things to include:
  - *.par (parameter) files, i.e. best-fit values
  - *.tim (TOA) files
  - DM time series
  - For NG, wideband and narrowband par/tim
  - Versions compatible with different timing software



NANOGrav 12.5-year

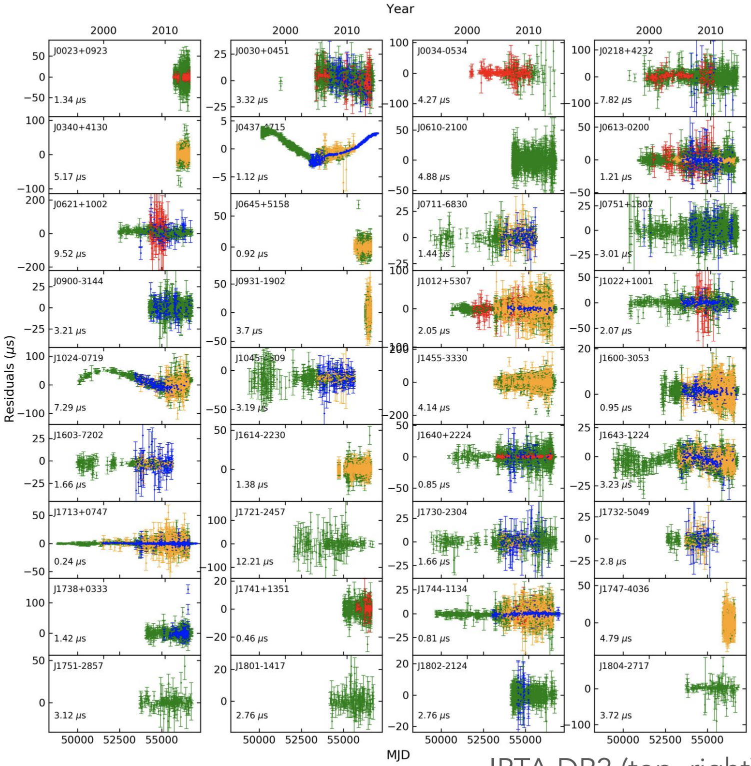
NANOGrav Data Sets



Courtesy David Nice

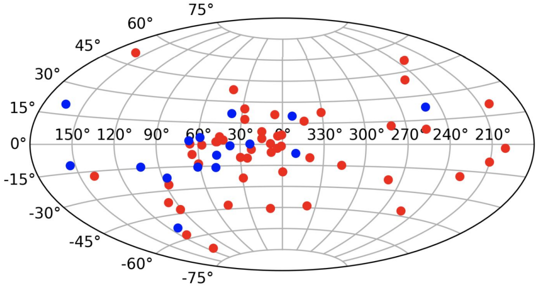
- 12.5-year data set (Alam et al. 2021 a, b)
  - First wideband data set
- 15-year data set (in progress)
  - 47 → 68 MSPs
  - VLA data, including J0437-4715
  - Completely overhauled timing pipeline
  - `PINT` (*"PINT is not TEMPO3"*)
    - Luo et al. 2021
  - Still releasing `TEMPO2` + `PINT` results, NB and WB data sets

IPTA Data Sets



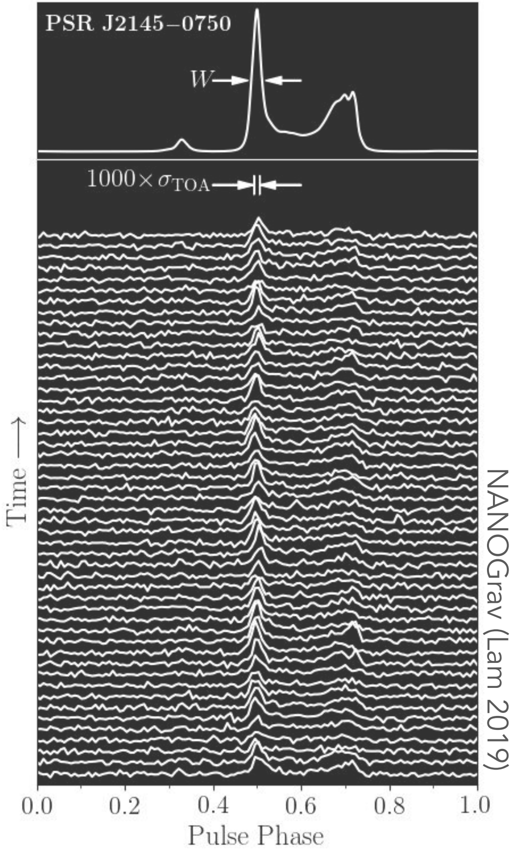
IPTA DR2 (top, right)

- IPTA = International Pulsar Timing Array
- Other PTAs (EPTA, PPTA, InPTA, MeerTime, CPTA, etc.)
- Combined data set = more sensitivity (in theory, but it's hard)
- IPTA DR2: EPTA DR1 (42 MSPs), PPTA DR1 + extended (20 MSPs), NANOGrav 9-year (37 MSPs)
  - All have their own strengths and weaknesses
  - 65 MSPs total (some overlap)



The "Noise Budget"

- PTAs need *great* timing precision, <1us
- White noise (dominant on short timescales):
  - Radiometer noise
  - Pulse jitter (shape changes between pulses)
- Red noise (dominant over long periods):
  - Achromatic red noise = spin / timing noise
    - Due to irregularities in pulsar rotation
  - Chromatic red noise
    - DM variations
- Deal with these with white and red noise parameters



NANOGrav (Lam 2019)

The `timing_analysis` pipeline

- **`toagen`**: raw data → calibration, subbanding, excision → template fitting → TOAs
- **`timing_analysis`**:
  - **`YAML`** configuration files make it easy to adjust parameters, track outlier excision and DMX issues, and log changes!
  - Jupyter notebook framework for easy use and auto-runs
    - Let's see the PDF output...

```yaml
source: J1022+1001
par-directory: results/
tim-directory: /nanograv/timing/releases/15y/toagen/releases/2021.08.25-9d8d617/
timing-model: J1022+1001_PINT_20220121.nb.par
compare-model: archive/J1022+1001_PINT_20220113.nb.par
toas:
- J1022+1001.430.PUPPI.15y.x.nb.tim
- J1022+1001.L-wide.PUPPI.15y.x.nb.tim

free-params: [ELONG, ELAT, PMELONG, PMELAT, PX, F0, F1, A1, PB, T0, E, OM, FD1, FD2,
free-dmx: Yes
toa-type: NB
fitter: DownhillGLSFitter
n-iterations: 20
ephem: DE440

  ...

ignore: # toa excision
  mjd-start:
  mjd-end: 59072.0
  snr-cut: 8
  bad-toa:
  bad-range:
  - [57984, 58447, PUPPI]
  bad-file:
  - [guppi_55625_J1022+1001_0003.15y.x.ff, isolated]
  - [guppi_55672_J1022+1001_0005.15y.x.ff, isolated]
  prob-outlier: 0.1

  ...

changelog:
- '2021-09-14 thankful.cromartie NOISE: switched to 20210914.Noise.nb.7d3eff0'
- '2021-09-14 thankful.cromartie REMOVE: A1DOT'
- '2021-09-15 thankful.cromartie NOISE: switched to 20210915.Noise.nb.3a02c6b'
- '2021-09-15 thankful.cromartie READY_FOR: v1.0'
- '2021-09-24 joe.swiggum NOTE: updated AO/GBO coords (pint v0.8.3) and refit'
- '2021-09-30 joe.swiggum NOTE: par file handed off to DWG for v1.0 is J1022+1001_PI
- '2021-12-10 joe.swiggum NOTE: we expect PMELAT to be poorly determined given ELAT
```

The `timing_analysis` pipeline

PSR J1713+0747 narrowband

Summary generated on 2022 Jan 27 (Thu) 20:06:11 GMT by Thankful Cromartie
Input par file: `results/J1713+0747_PINT_20220127.nb.par`
Input tim file directory: `/nanograv/share/15yr/timing/intermediate/20210908.Outlier.`
Input tim files:

- `J1713+0747.nb_excise.tim`

Span: 15.5 years (2005.1 – 2020.6)
Epochs (defined as observations within 6.5-day spans): 395
Wideband data: No
Fitter: DownhillGLSFitter

Timing model

This is the timing model as specified in the input par file, with no additional fitting.

```
# Created: 2022-01-27T20:06:29.234759
# PINT_version: 0.8.4
# User: jovyan
# Host: a5d33d8d9eff
# OS: Linux-3.10.0-862.14.4.el7.x86_64-x86_64-with-glibc2.31
PSR                           J1713+0747
EPHEM                              DE440
CLOCK                       TT(BIPM2019)
UNITS                                TDB
START              53393.5613838799041435
FINISH             59071.0046889241220602
CHI2                   59007.003379638016
ELONG               256.668699131799997 1 0.00000000198426318595
ELAT                 30.700358284037190 1 0.00000000346002920038
```

PDF output: quicker assessment of solutions, harder to miss problems, long-lived record of results and steps

Frozen parameters all zero?

Ignoring `START`, `FINISH`, `CHI2`, `POSEPOCH`, `PEPOCH`, `DM`, `DMEPOCH`, `DMX`, `TZRMJD`, `TZRFRQ`, `EFAC1`, `EQUAD1`, `EFAC2`, `EFAC3`, `EFAC4`, `EFAC5`, `EFAC6`, `EFAC7`, `EFAC8`, `EFAC9`, `EFAC10`, `EQUAD2`, `EQUAD3`, `EQUAD4`, `EQUAD5`, `EQUAD6`, `EQUAD7`, `EQUAD8`, `EQUAD9`, `EQUAD10`, `ECORR1`, `ECORR2`, `ECORR3`, `ECORR4`, `ECORR5`, `ECORR6`, `ECORR7`, `ECORR8`, `ECORR9`, `ECORR10`, `RNAMP`, `RNIDX`
Yes.

par file fully fit?

par file initial χ^2: 59007.00962619488
par file final χ^2: 59007.00962619488
Decrease: 0.0

Fitting produces no major change, all is probably fine.
Largest parameter change during fit was `JUMP5` by 0 sigma.

Reduced χ^2 close to 1.00?

Reduced χ^2 is 59007.009626/58976 = 1.000526 (false positive probability 0.463263)
False positive probability is believable

The `timing_analysis` pipeline

Excised TOAs by Frontend/Backend Combination

`Rcvr_800_GUPPI`: 8492 TOAs remain (371 cut; 8863 total).
`Rcvr1_2_GUPPI`: 22053 TOAs remain (1379 cut; 23432 total).
`3GHz_YUPPI`: 3470 TOAs remain (818 cut; 4288 total).
`L-wide_ASP`: 864 TOAs remain (670 cut; 1534 total).
`Rcvr1_2_GASP`: 1081 TOAs remain (548 cut; 1629 total).
`Rcvr_800_GASP`: 1012 TOAs remain (387 cut; 1399 total).
`S-wide_PUPPI`: 7440 TOAs remain (2643 cut; 10083 total).
`430_PUPPI`: 0 TOAs remain (45 cut; 45 total). **100.0% cut!**

Error parameters agree with chains?

Par file created: 2022-01-27T18:37:59.908153
Par file modified/checked out of git: 2022-01-27T19:30:41.127
Noise chains created: 2021-09-30T13:03:56.000

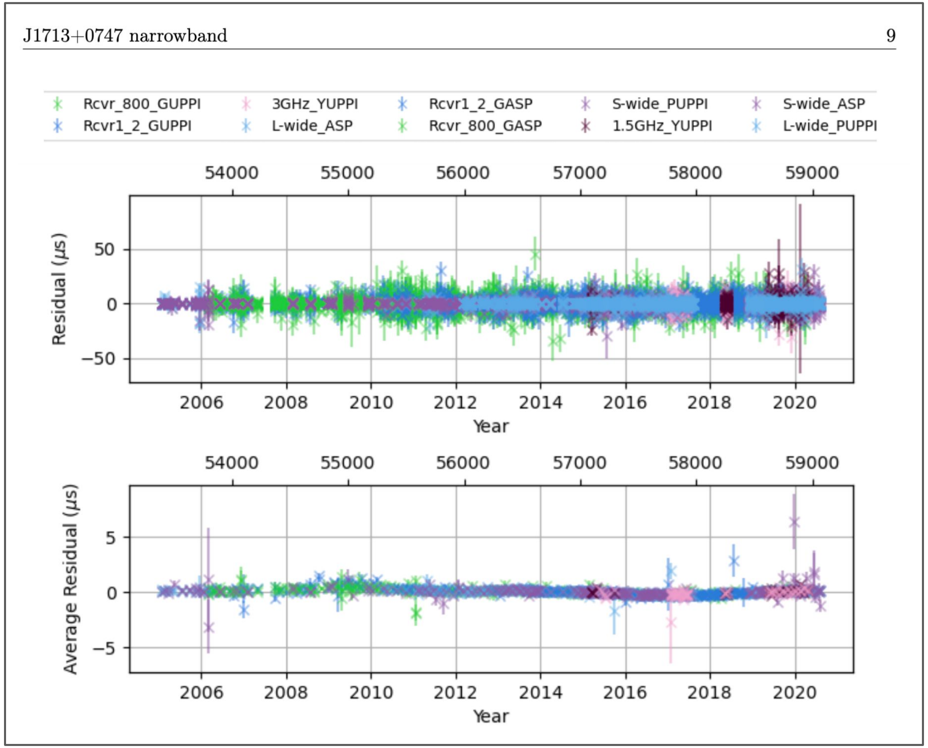
Software versions used in timing_analysis:

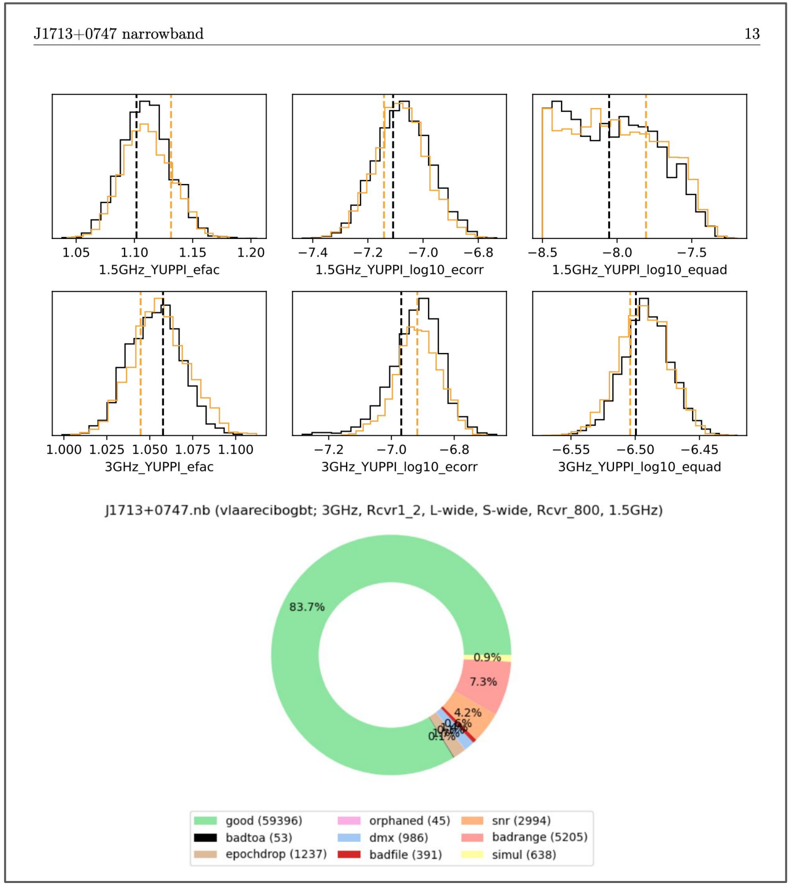
PINT: `0.8.4`
astropy: `4.3.1`
numpy: `1.21.0`
python: `3.9.5 | packaged by conda-forge | (default, Jun 19 2021, 00:32:32) [GCC 9.3.0]`
enterprise: 3.1.1.dev21+ga06d1f6

Hard to miss when things go wrong

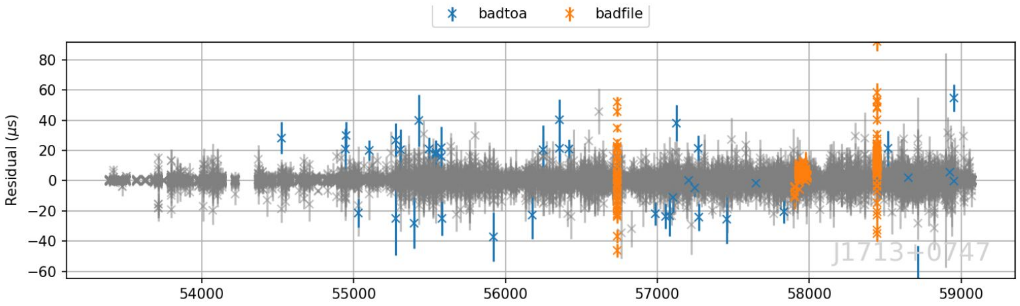
Permanent documentation of software / data release version

The `timing_analysis` pipeline

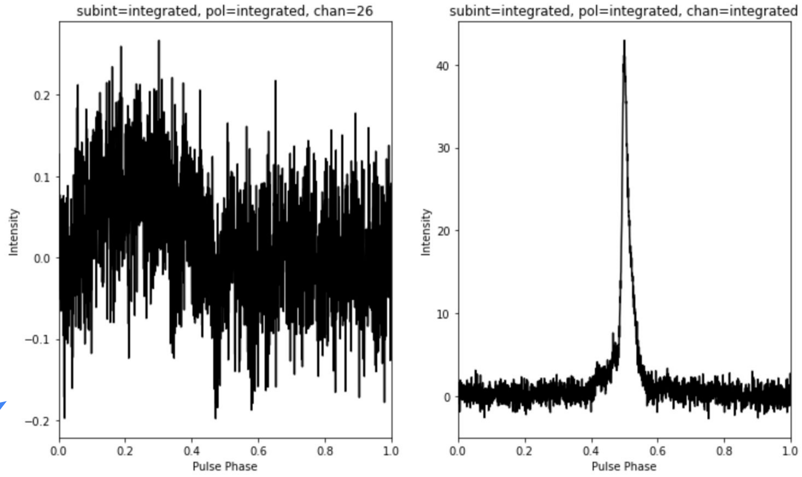




The `timing_analysis` pipeline




```
INFO: [Subband, subint] from bad-toa entry: [26,0] [timing_analysis.lite_utils]
Loading: /nanograv/timing/releases/15y/toagen/data/puppi/J1713+0747/puppi_57205_J1713+07
Load time: 0.22 s
```



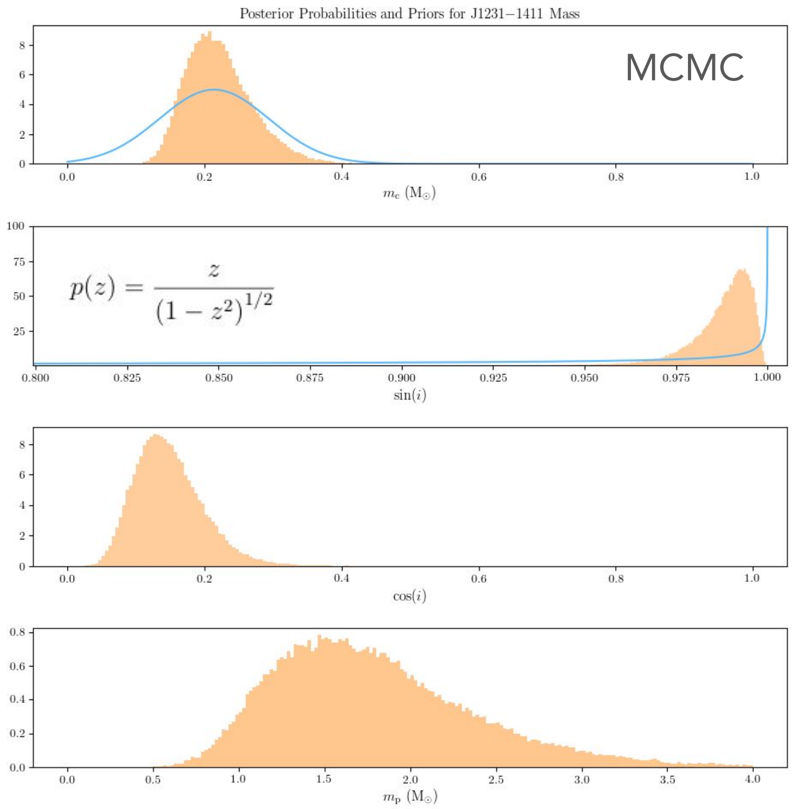
Bad-toas in YAML:

puppi_58950_J1713+0747_0080.15y.x | .ff | Profile (intensity vs. phase)

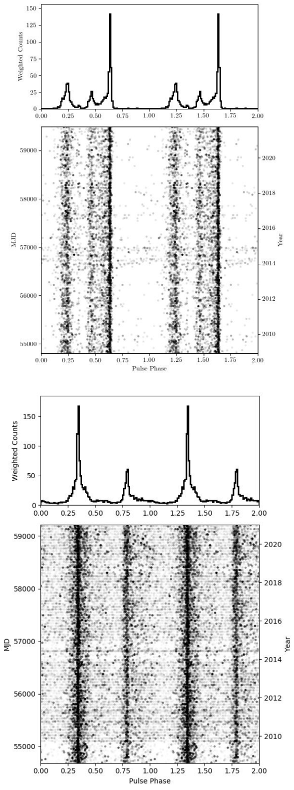
YAML is a record of manual excision (including reasons)

Advanced Timing Techniques

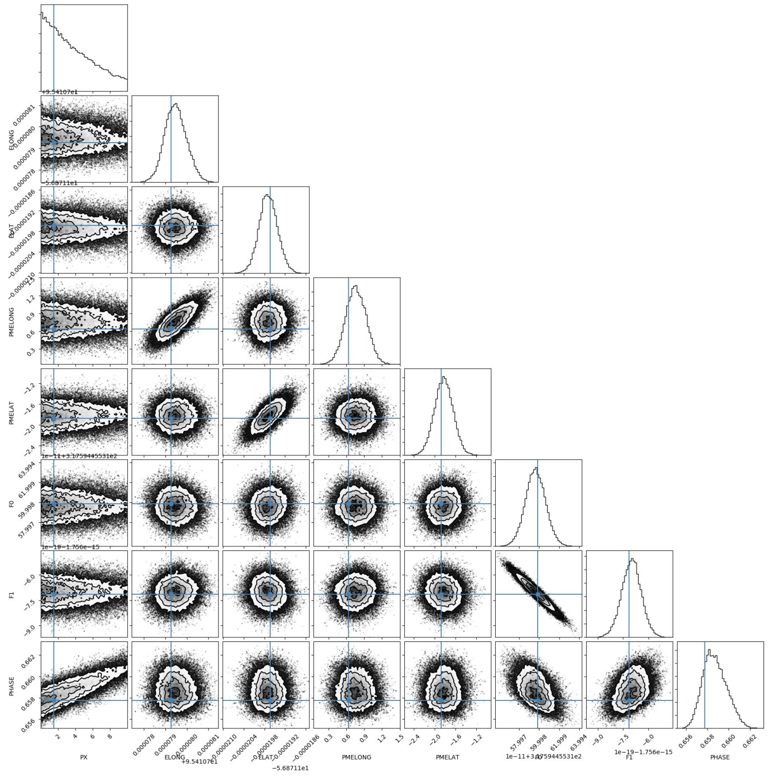
- Bayesian pulsar timing:
    - **Uncertainty:** parameters and correlations; model non-linear dependence
    - **Priors:** use physical information
    - **Model comparison:** compare models with different parameters
        - Nice summary in Vigeland & Vallisneri 2014
- Implemented in `PINT` as MCMCFitter
- For now, χ^2 gridding in `TEMPO(2)/PINT` helps; implementing in pipeline
- WB data set makes Bayesian timing feasible



High-Frequency Timing



- Detect as few as 1-2 photons per day
    - J1231: 4,627 photons over ~11 years ≈ 1.1 photon/day for brightest Gamma-ray MSP
- Single-photon timing: Bayesian technique yields timing solutions similar to those in radio
- `PINT event_optimize`
- This is helpful for NANOGrav
    - New paper in Science about Gamma-ray PTAs!



Conclusions

- Pulsar timing = accounting for each rotation of a pulsar
- Because MSPs can be timed to high precision, they're powerful tools for PTAs and other applications (neutron star masses, probing the ISM, and more)
- PTA data sets consist of best-fit parameters and time-of-arrival measurements
- Noise matters! Short term, long term, intrinsic and extrinsic
- NANOGrav has been building a long-lived pipeline for timing all our MSPs
- Other kinds of timing exist, including advanced fitting techniques and high-frequency (X and Gamma-ray)

Ezreal hopes you have a great time for the next two weeks!