Pulsar Timing Arrays

GWADW2023 - Isola d'Elba

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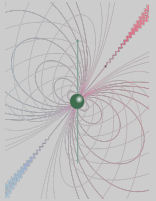
i do not know what it is about you that closes
and opens; only something in me understands
the voice of your eyes is deeper than all roses
-- E. E. Cummings

It’s not a bird, it’s not a plane, definitely not LGM

Pulsars are like giant flywheels in space, their compact masses give rise to **incredibly stable rotation.**

On each rotation, the pulsar beam produces a ***‘pulse’*** at Earth, and the photons in that pulse can be assigned a **time-of-arrival.**



... just supernovae leftovers and a hardworking astronomer

Models, models, models

TOAs can be predicted using a model with the following (sets of) parameters:

- **astrometric**,
- **pulsar rotation** and
- **binary** (when applicable).

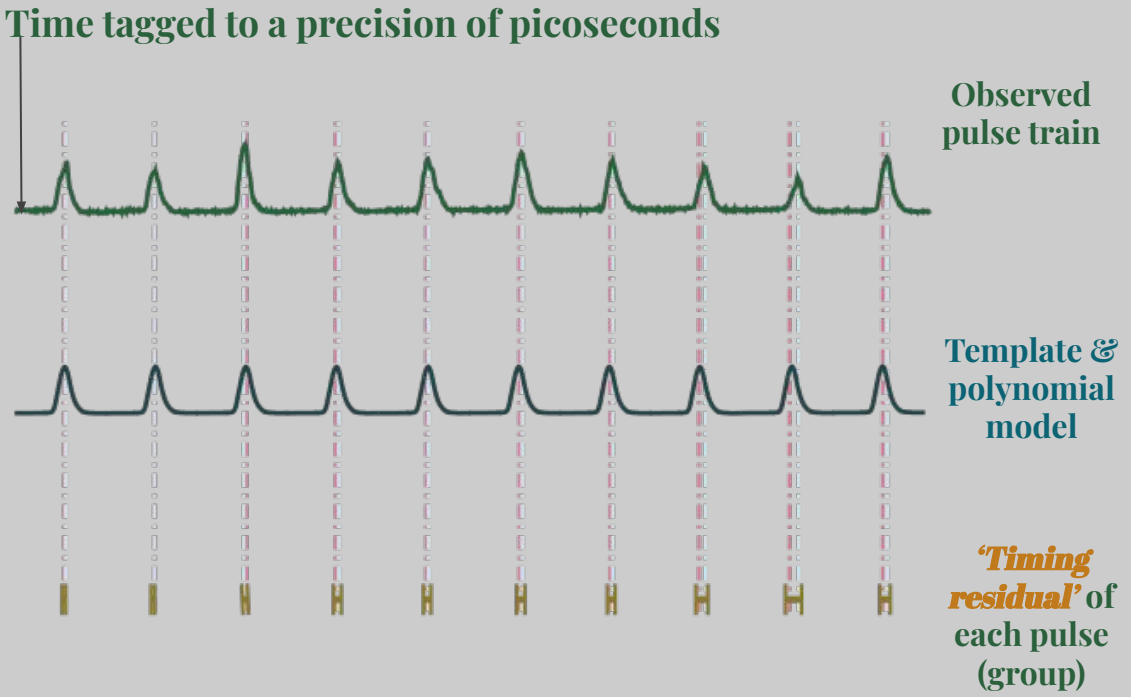
Apart from these each pulsar is affected by:

- **Dispersive delays due to the intervening plasma**
- **Red noise (low frequency) processes**
- **Pulsar jitter**

High precision pulsar timing

Once we have estimates of pulsar properties, we can predict *very precisely* when the next pulse will arrive. Or the one after 20 million rotations.

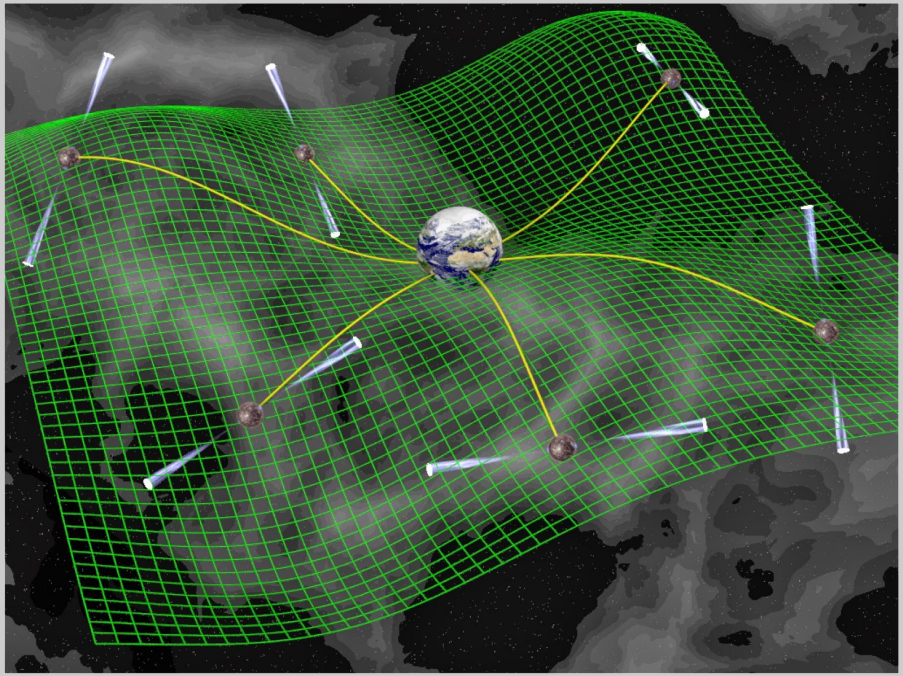
When pulses are averaged this precision quickly tends to tens of microseconds to **tens of nanoseconds.**



Pulsar timing arrays

- TOA stability scales with number of rotations averaged - use **millisecond pulsars (MSPs)!**

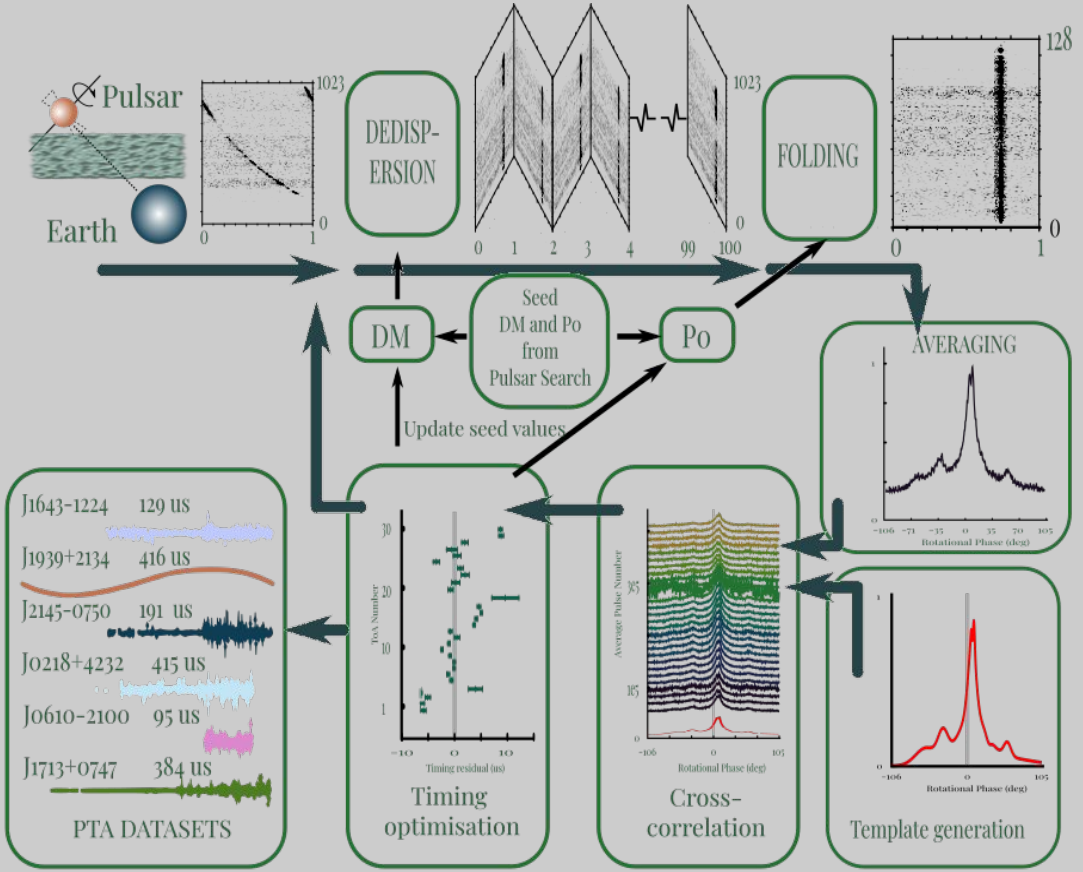
- Single pulsars are ‘jittery’ and affected by noise, use an **array of MSPs**



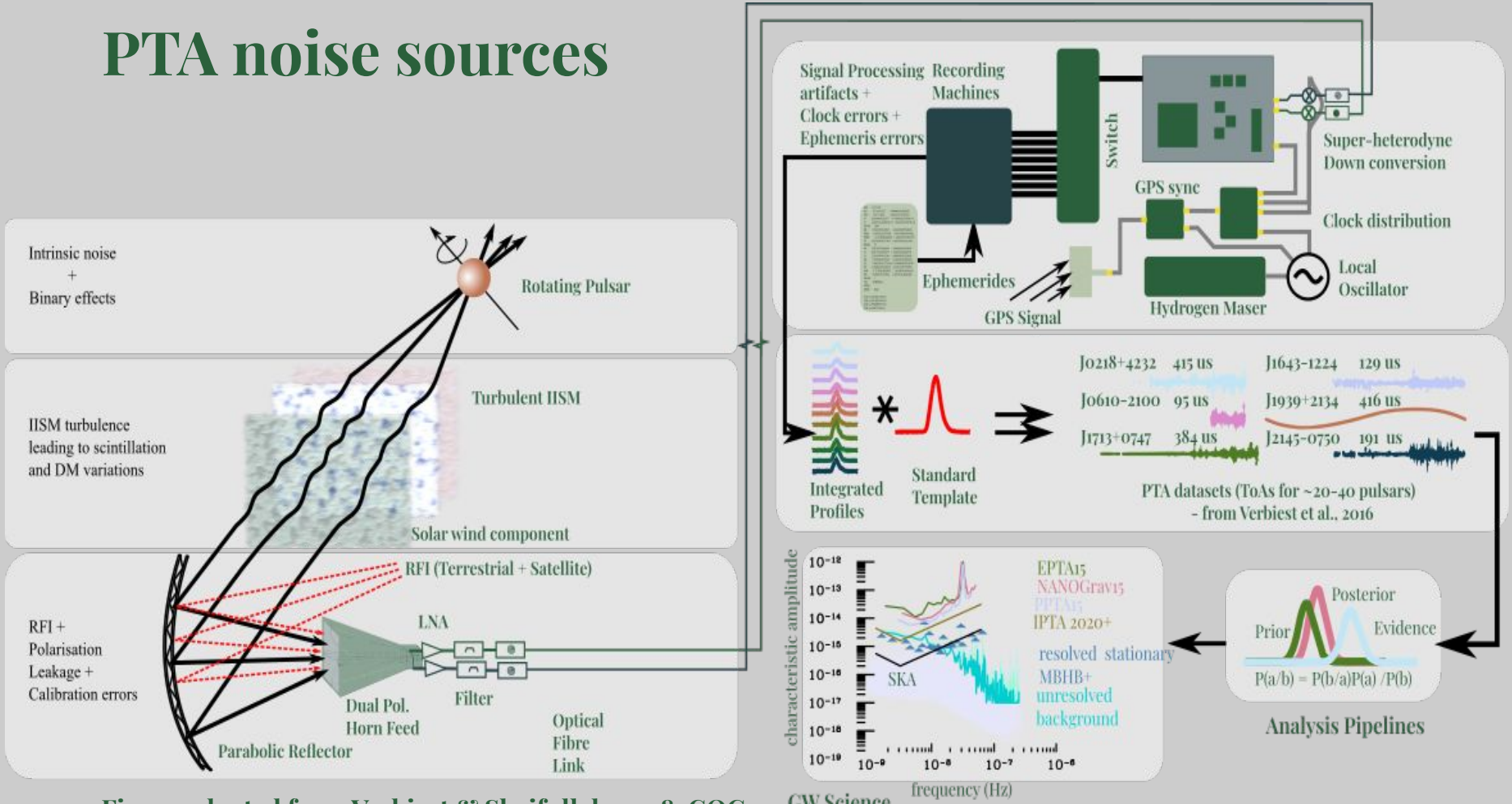
FreqBayes™ pulsar timing:

- Observe a pulsar
- De-disperse
- Stack
- Average
- Make a template
- Cross-correlate
- Line up your TOAs
- Repeat for another 20 - 100 sources
- Sprinkle post-docs for flavour
- Bake for ~30 years, turning it over once or twice a decade.

Figure from Verbiest & Shaifullah, 2018, CQG

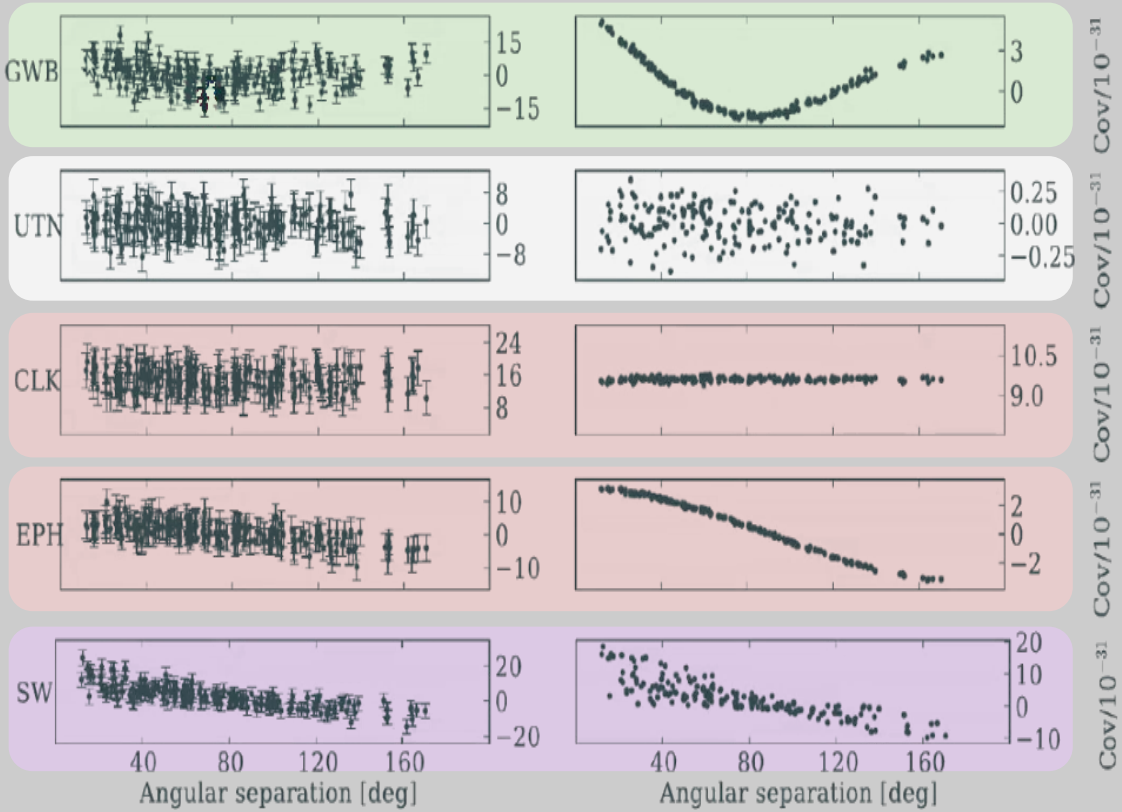


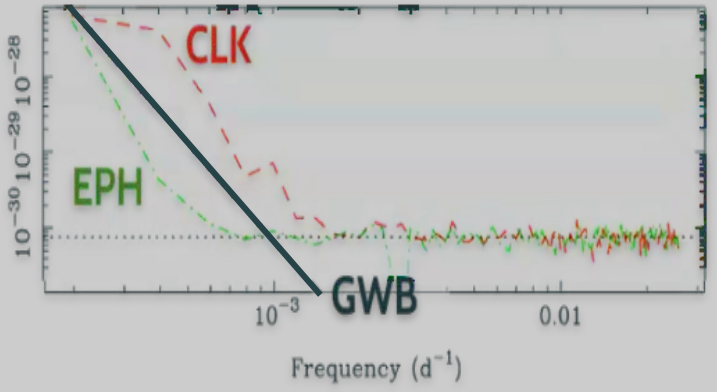
PTA noise sources



- Figure adapted from Verbiest & Shaifullah, 2018, CQG

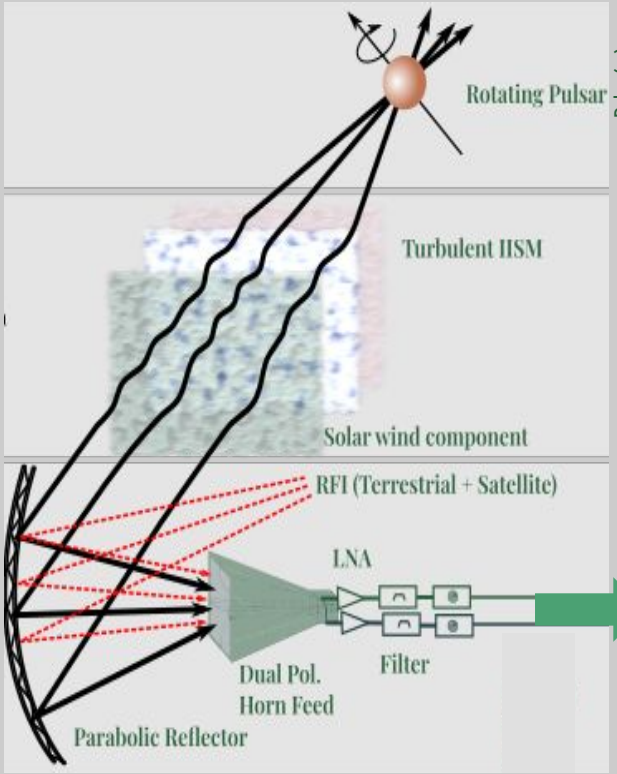
A whisper in the crowd

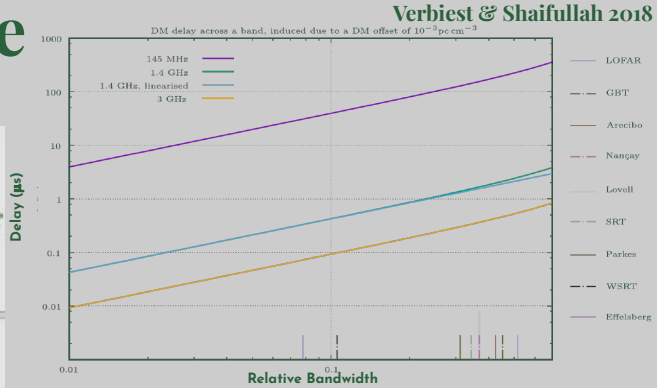


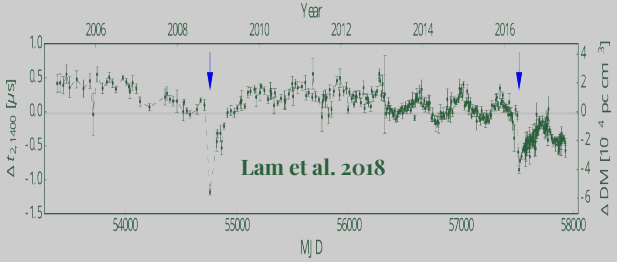


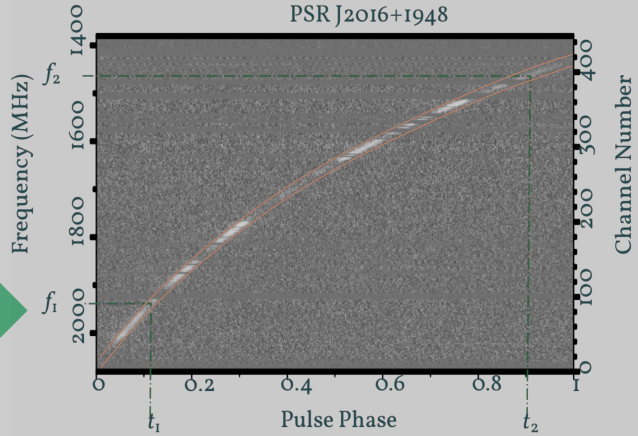
Tiburzi et al (MNRAS, 2016)

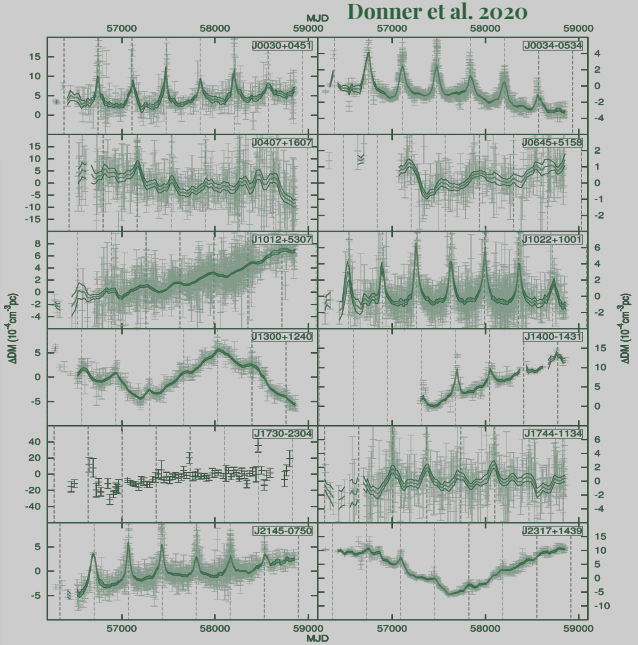
Dispersion Measure









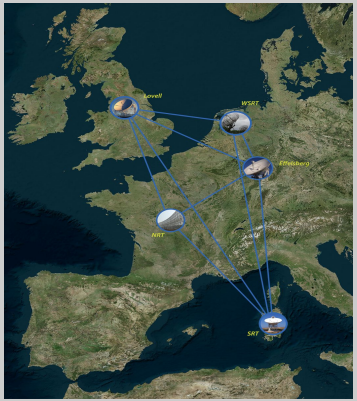


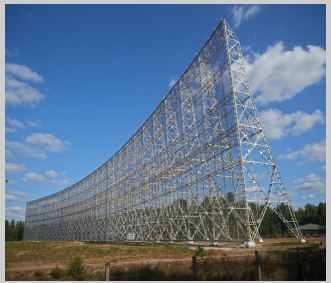
$$\mathrm{DM} \equiv \int_0^d n_e dz \ \mathrm{cm}^{-3}\ \mathrm{pc}$$

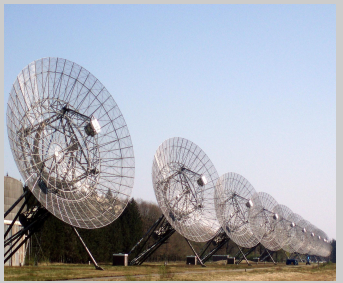
$$\Delta t \simeq 4.15 \times 10^6 \left(\frac{\mathrm{DM}}{\mathrm{cm}^{-3}\ \mathrm{pc}}\right)\left(\frac{f^{-2}}{\mathrm{MHz}}\right)\ \mathrm{ms}$$

EPTA data combination 2.0

- **5+1** telescopes.
- Augmented with the **EPTA-DR1** (Desvignes et al, 2016).
- New data spanning ~10 years (a total of 24.5)
- **Double the observing bandwidth**
- **Coherent dedispersion**
- Two to ten times **greater observing cadence**
- Significantly boost timing sensitivity
- Combine only **25+7** out of 42 sources



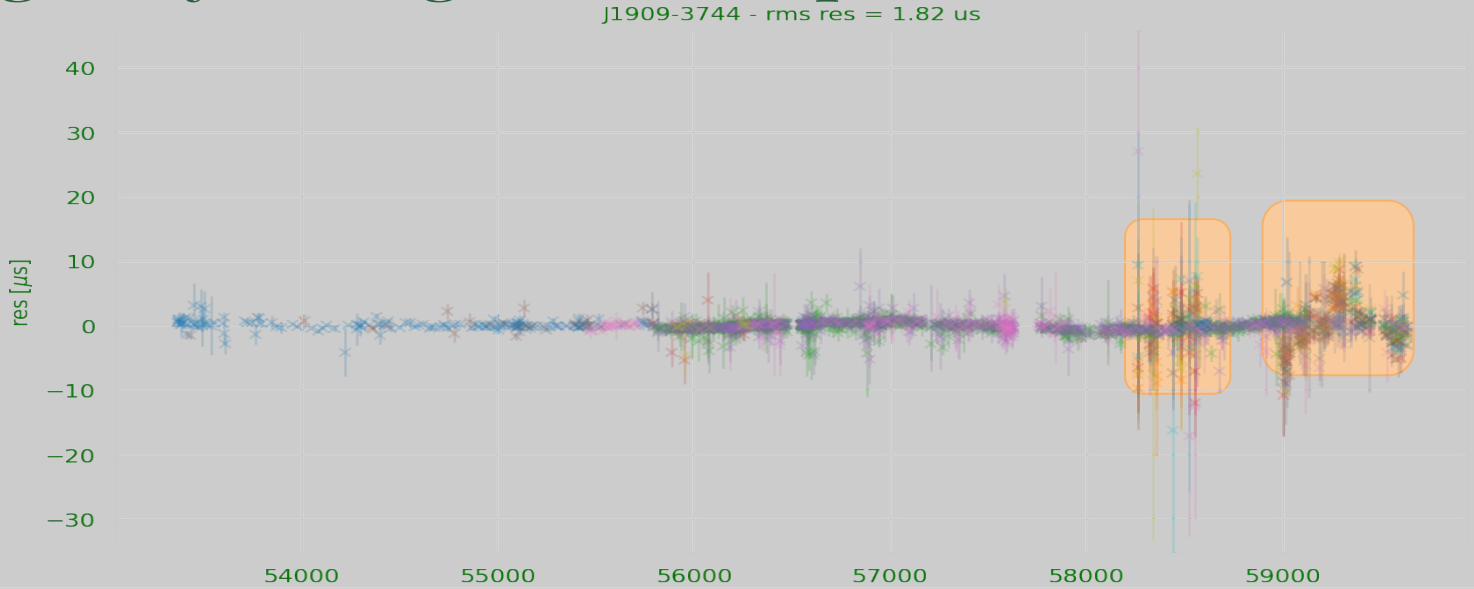




EPTA + InPTA

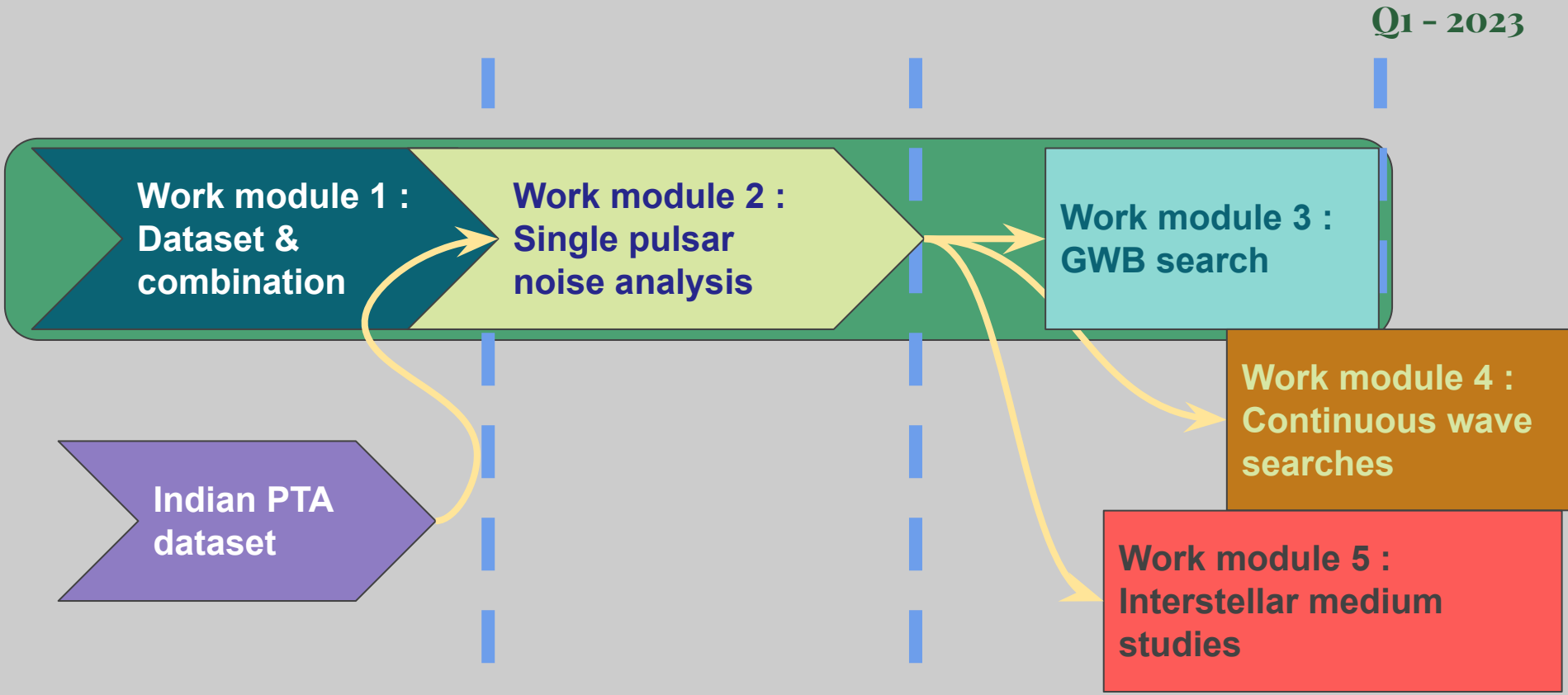
- New data spanning ~3 years
- Overlap of **10** sources
- Significantly improves DM sensitivity
- Simultaneous low and high frequency!

Obligatory timing residuals plot

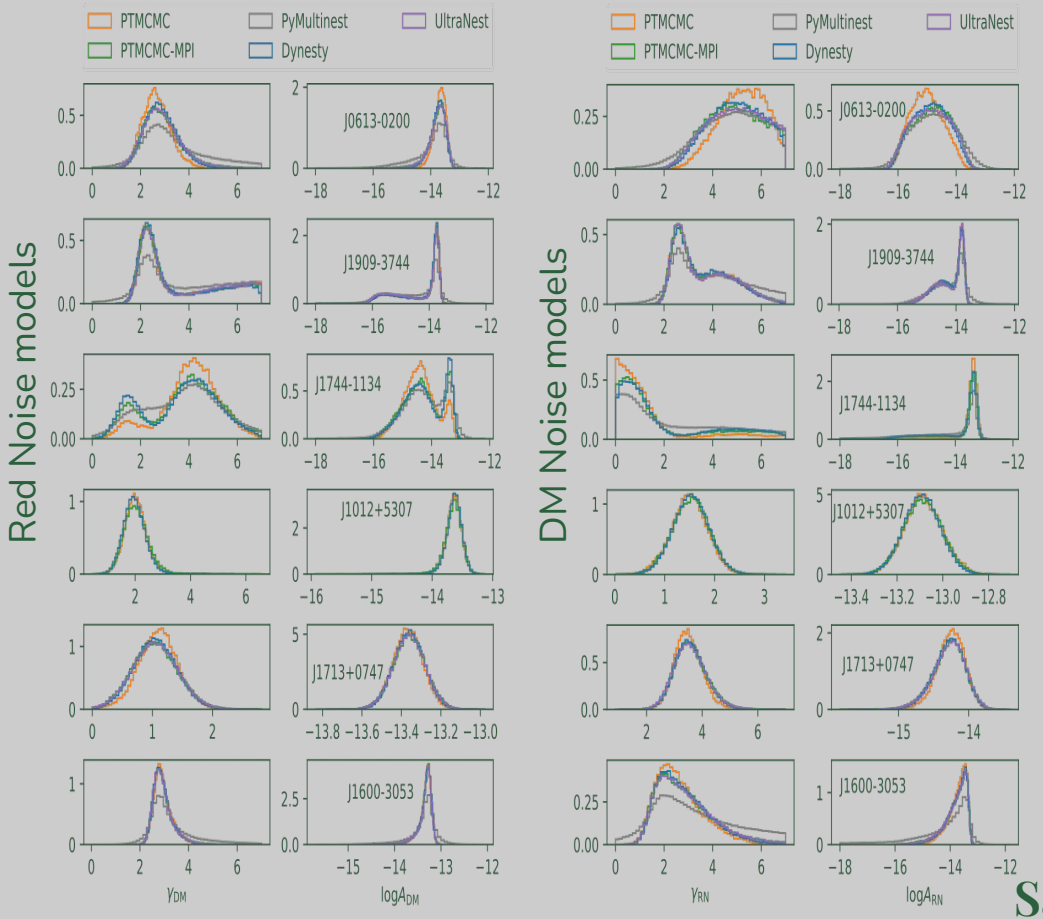


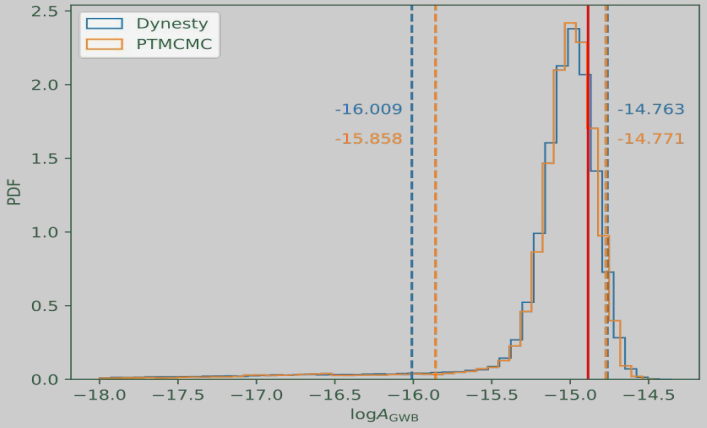
- NRT.BON.1400
- GM_GWB_500_200_b1.487
- NRT.NUPPI.1662
- GM_GWB_500_200_b1.362
- NRT.NUPPI.2346
- GM_GWB_500_200_b1.337
- NRT.NUPPI.2090
- GM_GWB_500_200_b1.361
- GM_GWB_500_100_b1.418
- GM_GWB_500_200_b1.386
- GM_GWB_1460_200_b0.1385
- GM_GWB_500_100_b1.468
- NRT.NUPPI.2046
- GM_GWB_1460_100_b1.1447
- GM_GWB_1460_100_b1.1397
- GM_GWB_500_200_b1.437
- GM_GWB_1460_100_b1.1372
- GM_GWB_1460_200_b0.1335
- GM_GWB_500_200_b1.312
- GM_GWB_500_200_b1.336
- GM_GWB_500_200_b1.461
- GM_GWB_500_100_b1.481
- NRT.NUPPI.1676
- NRT.NUPPI.2218
- NRT.NUPPI.2411
- NRT.BON.2000
- GM_GWB_1460_200_b0.1285
- GM_GWB_500_200_b1.387
- GM_GWB_1460_100_b1.1422
- GM_GWB_500_100_b1.406
- NRT.NUPPI.1790
- GM_GWB_500_100_b1.431
- GM_GWB_500_200_b1.436
- GM_GWB_500_200_b1.486
- NRT.NUPPI.1548
- GM_GWB_500_100_b1.443
- NRT.BON.1600
- GM_GWB_500_200_b1.462
- GM_GWB_500_200_b1.411
- GM_GWB_500_100_b1.493
- NRT.NUPPI.1918
- GM_GWB_500_200_b1.412
- NRT.NUPPI.1292
- GM_GWB_500_100_b1.456
- NRT.NUPPI.1420
- GM_GWB_500_200_b1.311
- NRT.NUPPI.2667
- GM_GWB_1460_200_b0.1435
- NRT.NUPPI.1962

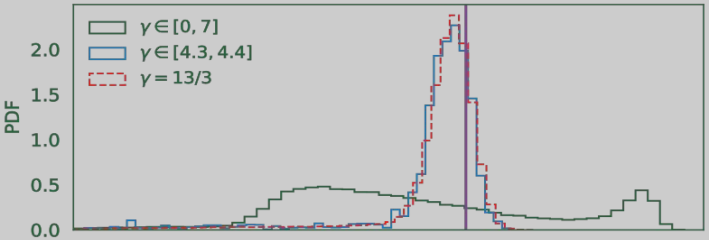
Divide, assemble, conquer, repeat.

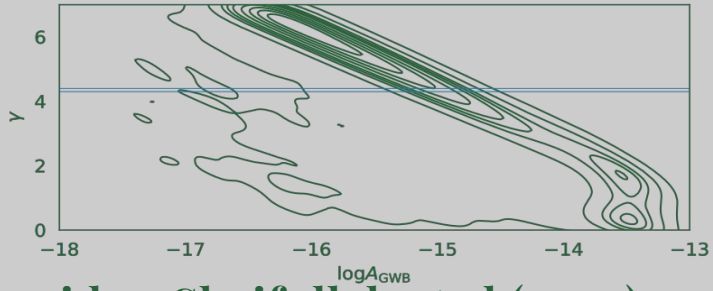


Testing our tools



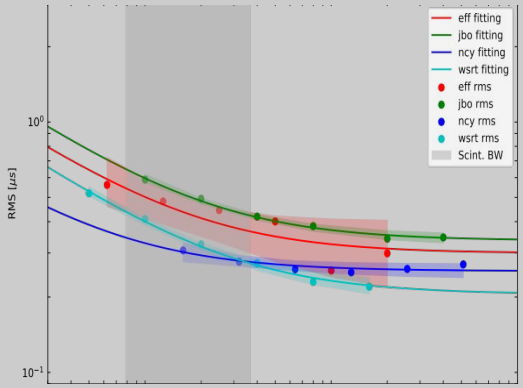


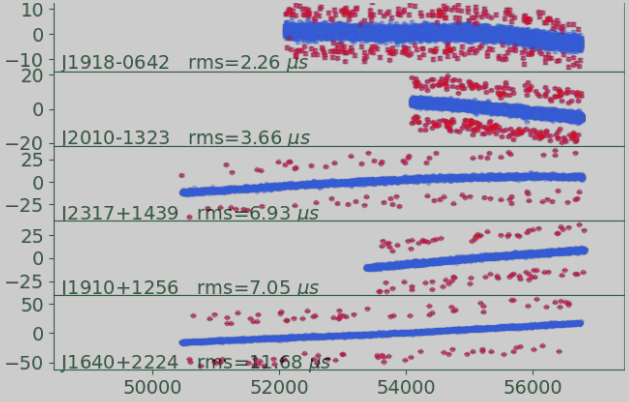


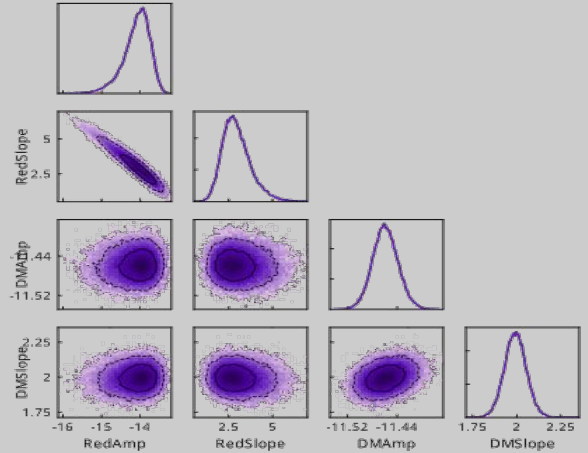


Samajdar, Shaifullah et al (2022),

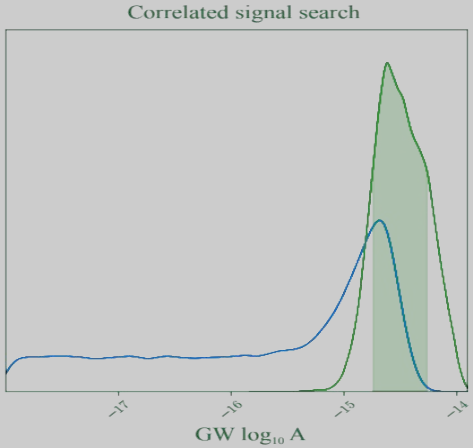
How can we get better?



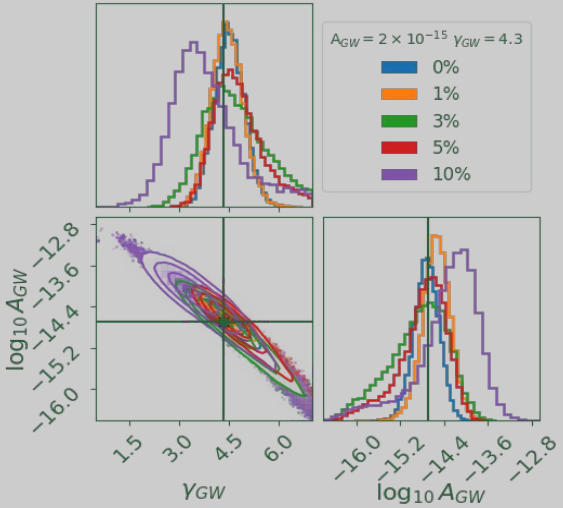


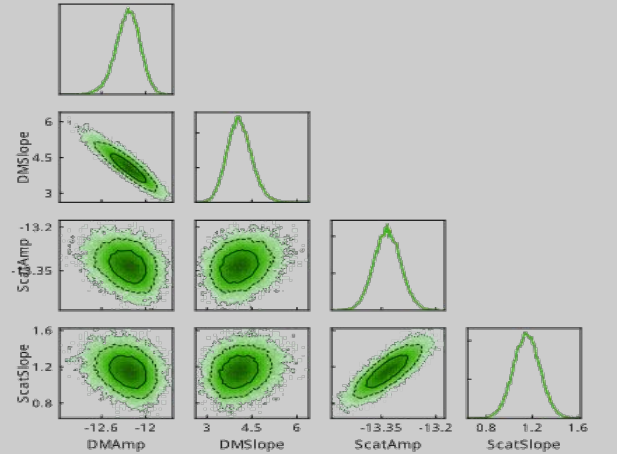


Shaifullah, Wang et al, (in prep)



Fumagalli, Shaifullah et al, (in prep)





The PTA world

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

EPTA

NANOGrav

PPTA

InPTA

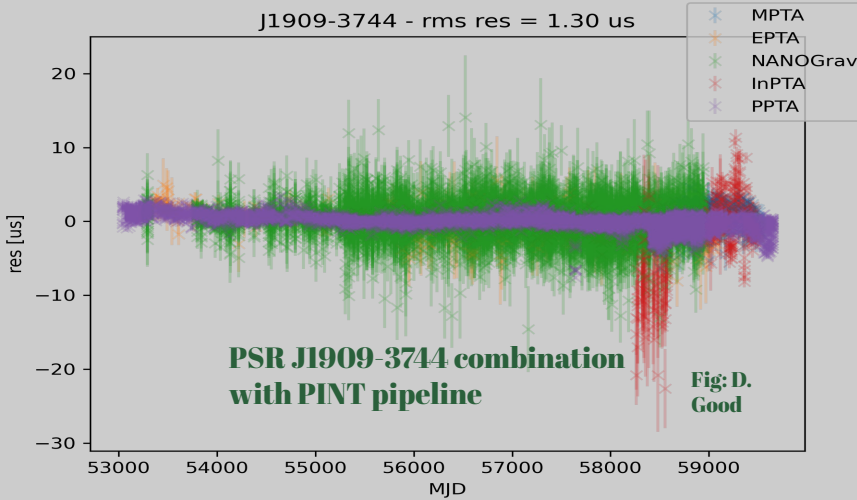
Indian Pulsar Timing Array

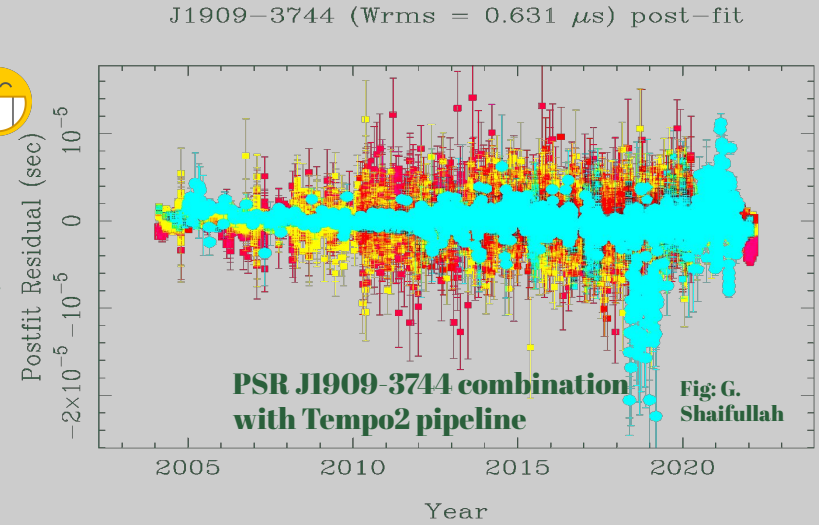
MPTA

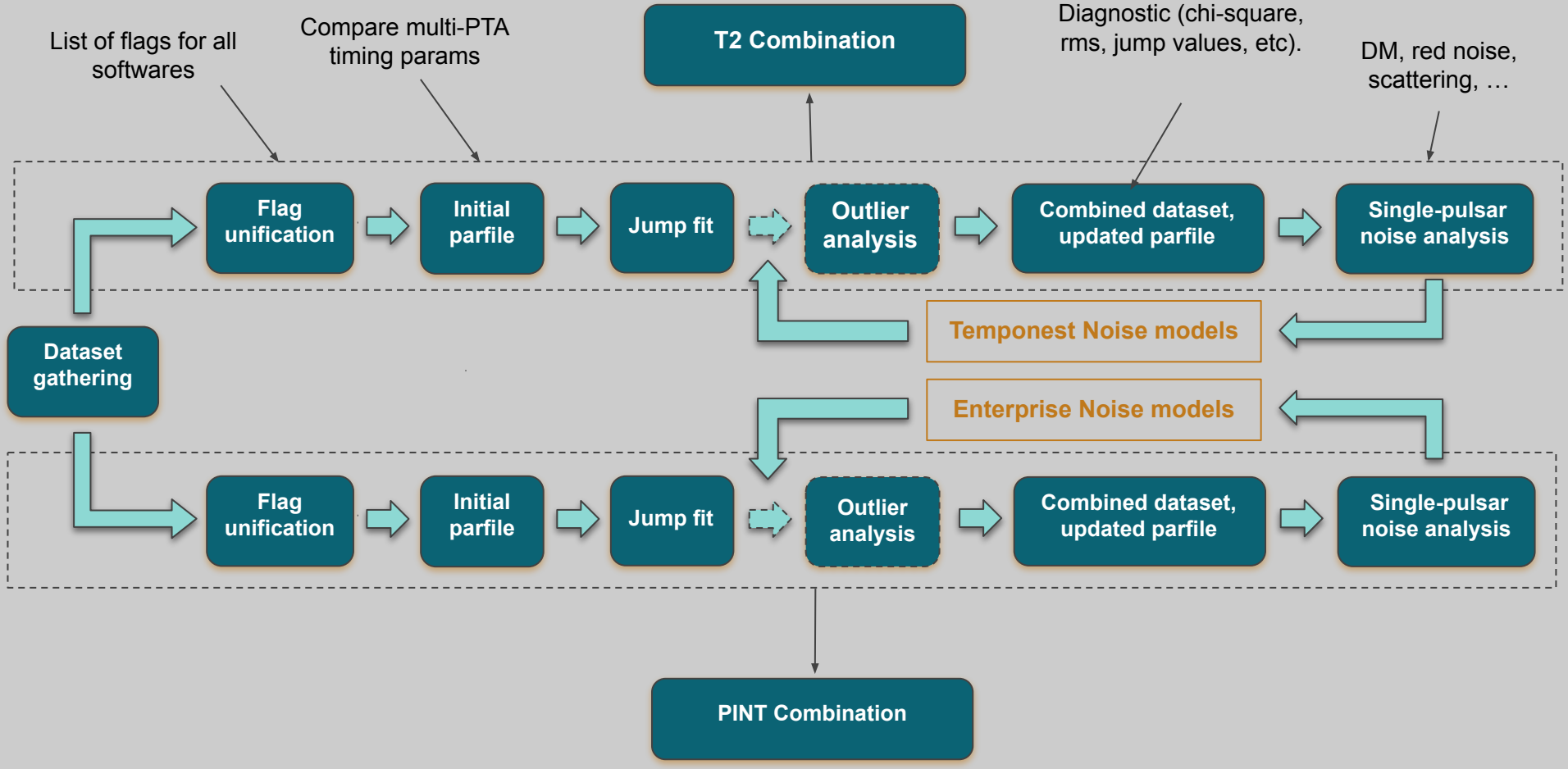
IPTA DR3

- Add data from 5 PTAs:
  - EPTA
  - NANOGrav
  - PPTA
  - InPTA
  - MPTA (MeerKAT)
- **Two independent data combination pipelines**
- **115 pulsars, down to <100 ns for a few pulsars (~5)**
- Greater sky coverage!
- More pulsar pairs for angular correlation searches.
- **Lots of TOAs**
- **Loads of compute**
- **Currently working on "Early Data Release" (eDR3), which includes the 20 best/longest-timed pulsars**

- Nearly all 20 pulsars have been preliminarily combined






List of flags for all softwares
Compare multi-PTA timing params
T2 Combination
Diagnostic (chi-square, rms, jump values, etc).
DM, red noise, scattering, …
Flag unification
Initial parfile
Jump fit
Outlier analysis
Combined dataset, updated parfile
Single-pulsar noise analysis
Temponest Noise models
Enterprise Noise models
Dataset gathering
Flag unification
Initial parfile
Jump fit
Outlier analysis
Combined dataset, updated parfile
Single-pulsar noise analysis
PINT Combination

- "All our papers are going through the review process and will be publicly released in few months, please bear with us for a bit longer."
- **All PTAs see a common, uncorrelated signal**
- ***Exciting times ahead!***
- IPTA "Early Data Release" (eDR3), which includes the 20 best/longest-timed pulsars is nearing completion.