“Wideband Timing” Overview

Tim Pennucci
Eötvös Loránd University
Budapest, Hungary

OzGrav – 14 May 2019

Some Literature

→ *Early ideas / TOA measurement:*

- Liu, K., et al. (2014)
- Pennucci, T. T., Demorest P. B., Ransom S. M. (2014)
- also see Pennucci PhDT (2015)

→ *New method for modeling profile evolution:*

- Pennucci T. T. (2019)

→ *Scattering:*

- Lentati, L. et al. (2017b)
- Pennucci T. T., et al. (in prep.)

→ *Related:*

- Lentati, L. et al. (2017a)

How to improve precision of timing measurements (σ_{TOA})

$$\sigma_{\mathrm{TOA}} \propto \frac{T_{\mathrm{sys}}}{A_{\mathrm{eff}}\sqrt{t_{\mathrm{obs}}\,\Delta f}} \times \frac{P\,\delta^{3/2}}{S_{\mathrm{mean}}}$$

a) Longer integration times (t_{obs})

b) Lower receiver temperature (T_{sys})

c) Wider instantaneous bandwidth (Δf)

d) Increase telescope area (A_{eff})

How to improve precision of timing measurements (σ_{TOA})

$$\sigma_{\rm TOA} \propto \frac{T_{\rm sys}}{A_{\rm eff}\sqrt{t_{\rm obs}\,\Delta f}} \times \frac{P\,\delta^{3/2}}{S_{\rm mean}}$$

a) Longer integration times (t_{obs})

→ Limited telescope time for increasing N pulsars

b) Lower receiver temperature (T_{sys})

→ Receivers near engineering limits

c) Wider instantaneous bandwidth (Δf)

→ New receivers now being developed/deployed

d) Increase telescope area (A_{eff})

→ New pulsar telescopes don't come around often

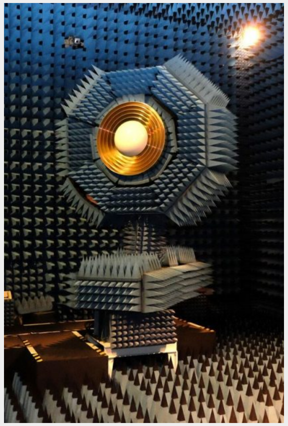
But: IPTA, CHIME, MeerKAT, FAST…

The Next Generation of Broadband (Pulsar) Telescopes:

'mid' frequency telescopes:

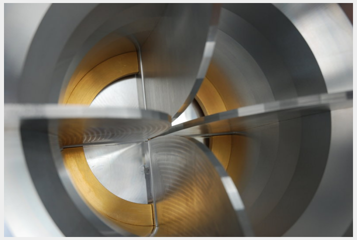
Parkes (PPTA)

[Australia]



Effelsberg (EPTA)

[Germany/Europe]



MeerKat (MeerTime)

[South Africa/Int'l]

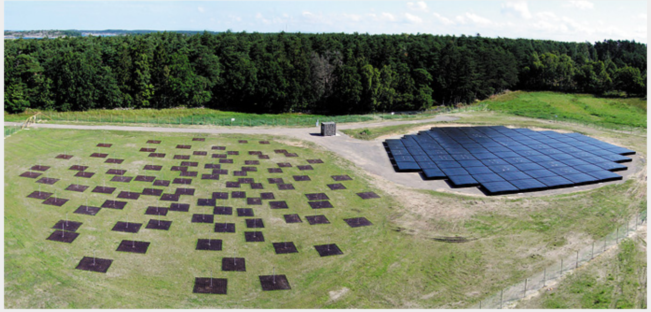
'low' frequency telescopes:

CHIME

[Canada]

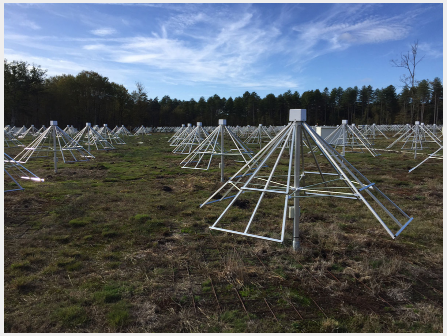
LOFAR

[Netherlands/Europe]



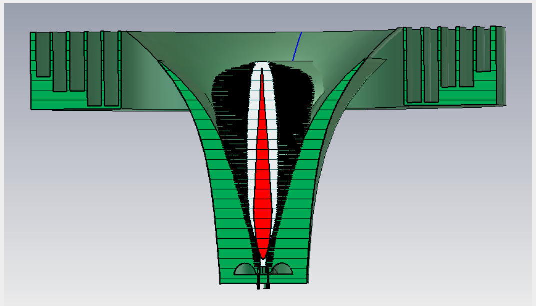
NenuFar

[France]



and more .. (e.g., GBT & AO(?) upgrades).

Finally, an ultra-wideband feed for NANOGrav!



→ Moore Foundation funded 0.7 – 4 GHz receiver for the GBT (~800k USD)

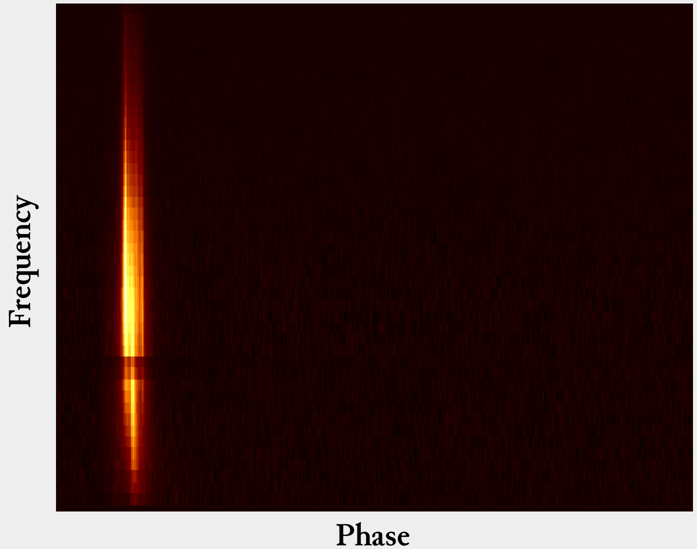
→ Parkes UWL design

→ Could see first light late 2020 / early 2021

→ Hopefully, a similar system a few years later for Arecibo…

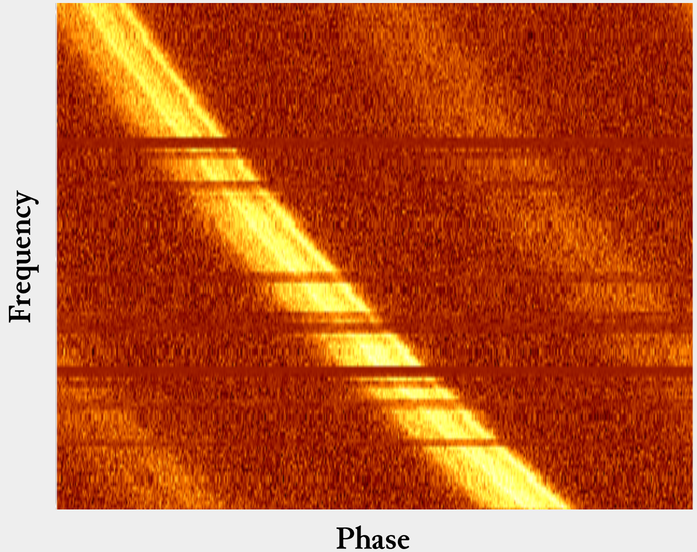
However, with great bandwidth comes great responsibility:

→ Across large fractional bandwidths, pulse profiles intrinsically evolve:



(may also evolve due to scatter broadening…)

→ Across large fractional bandwidths, you can measure dispersion (the DM) from epoch to epoch:



(scale exaggerated here; DM variation usually induces ~phase bin level difference)

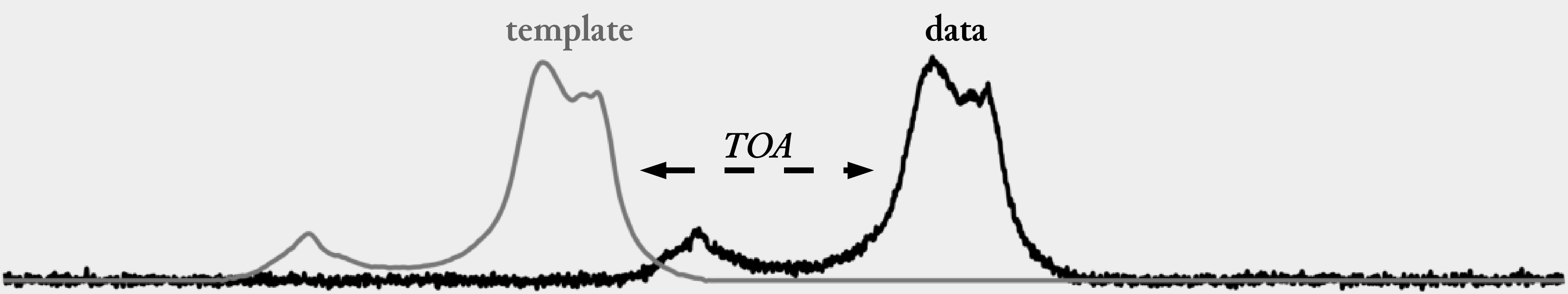
However, with great bandwidth comes great responsibility:

→ Pulse times-of-arrival (TOAs) are still the fundamental quantities for pulsar timing experiments

→ TOAs are related to time offsets measured in via template-matching

→ This was straightforward when it was acceptable to average over a narrow bandwidth, in which neither profile evolution nor DM(t) were discernible

e.g.,



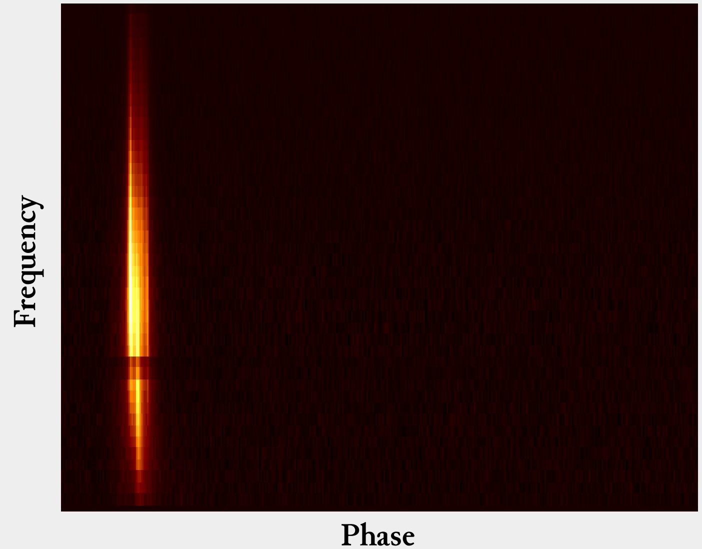
But! you sacrifice timing precision and can introduce bias by doing this!

However, with great bandwidth comes great responsibility:

"So how do I measure a TOA?"

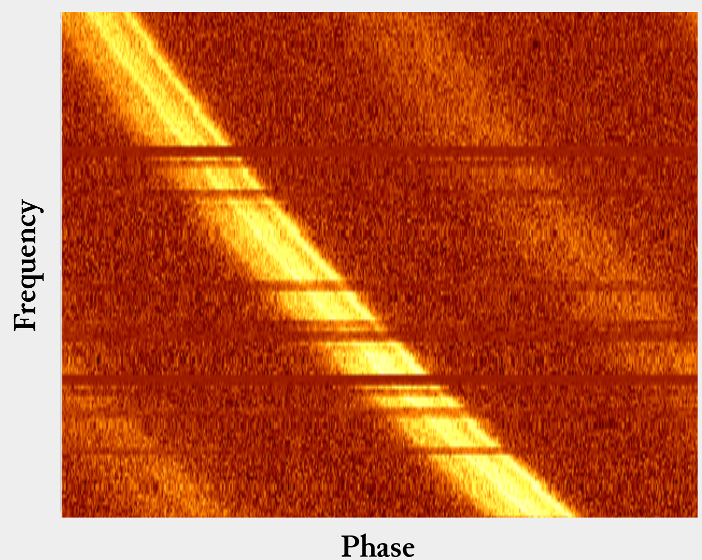
However, with great bandwidth comes great responsibility:

→ Across large fractional bandwidths, pulse profiles intrinsically evolve:



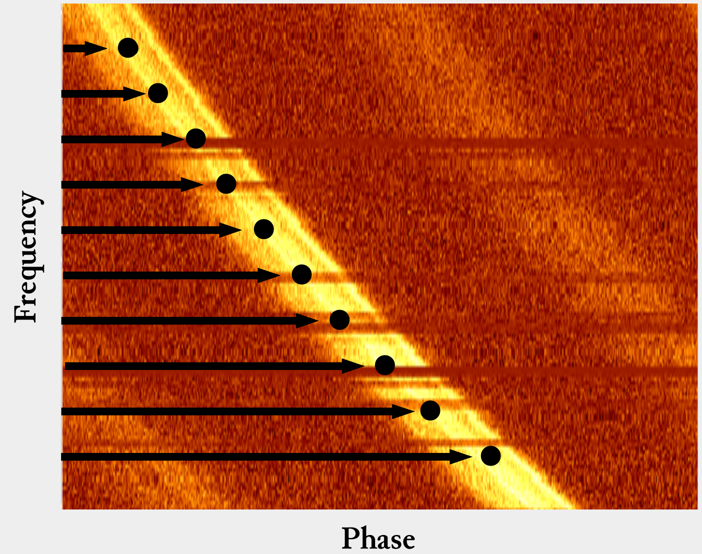
Always account for profile evolution!

→ Across large fractional bandwidths, you can measure dispersion (the DM) from epoch to epoch:



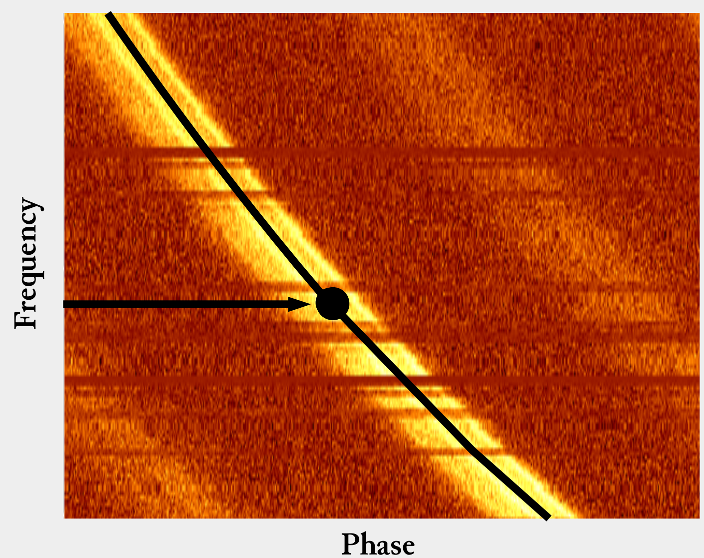
Always account for dispersion variation!

“Conventional” or “Channelized” = 1 TOA per subintegration *per frequency subband*



(many TOAs! the same profile template is used across the band, mismatched to the data!)

“Wideband” (WB) = 1 TOA & 1 DM per subintegration



(one set of measurements using a model of profile evolution!)

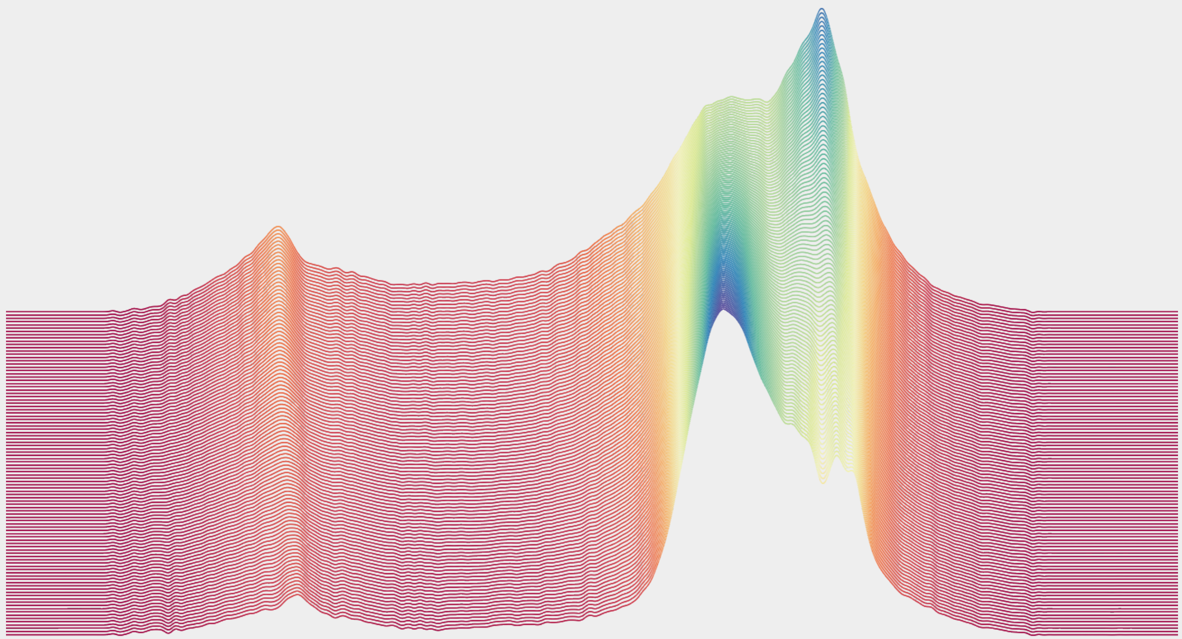
→ In this way, the wideband dataset is ~15-30x smaller

Wideband TOA ≠ Average of Subband TOAs

→ In summary: a fixed model of profile evolution substitutes for a single template profile & *ad hoc* timing model parameters

i.e., the wideband matched-template scheme uses something like this:

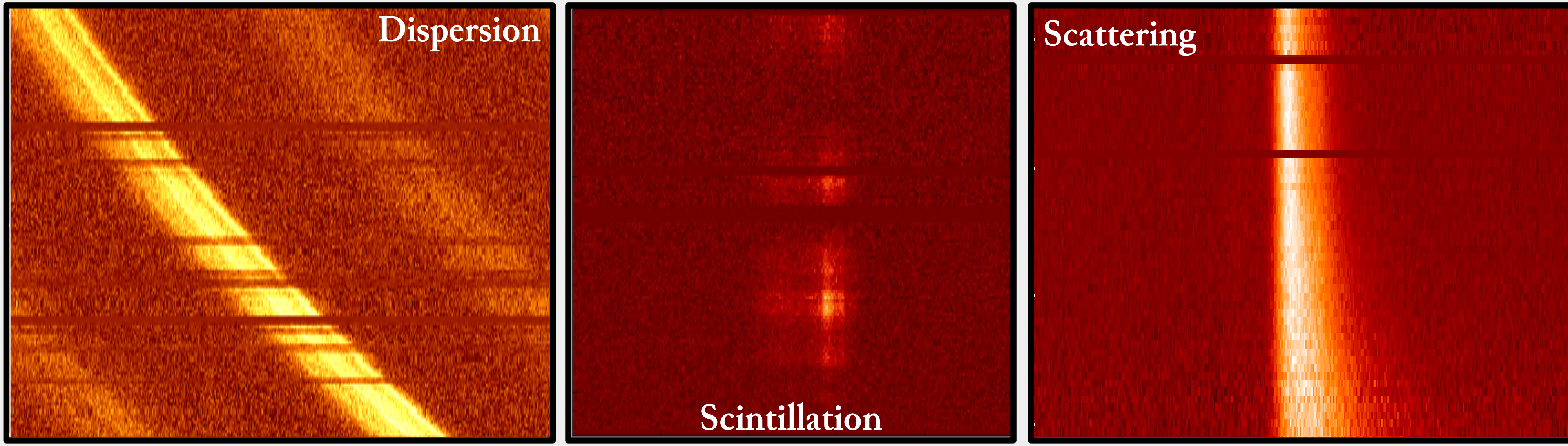
(a "portrait")



instead of this:

(a "profile")

Wideband method handles most common ISM effects:



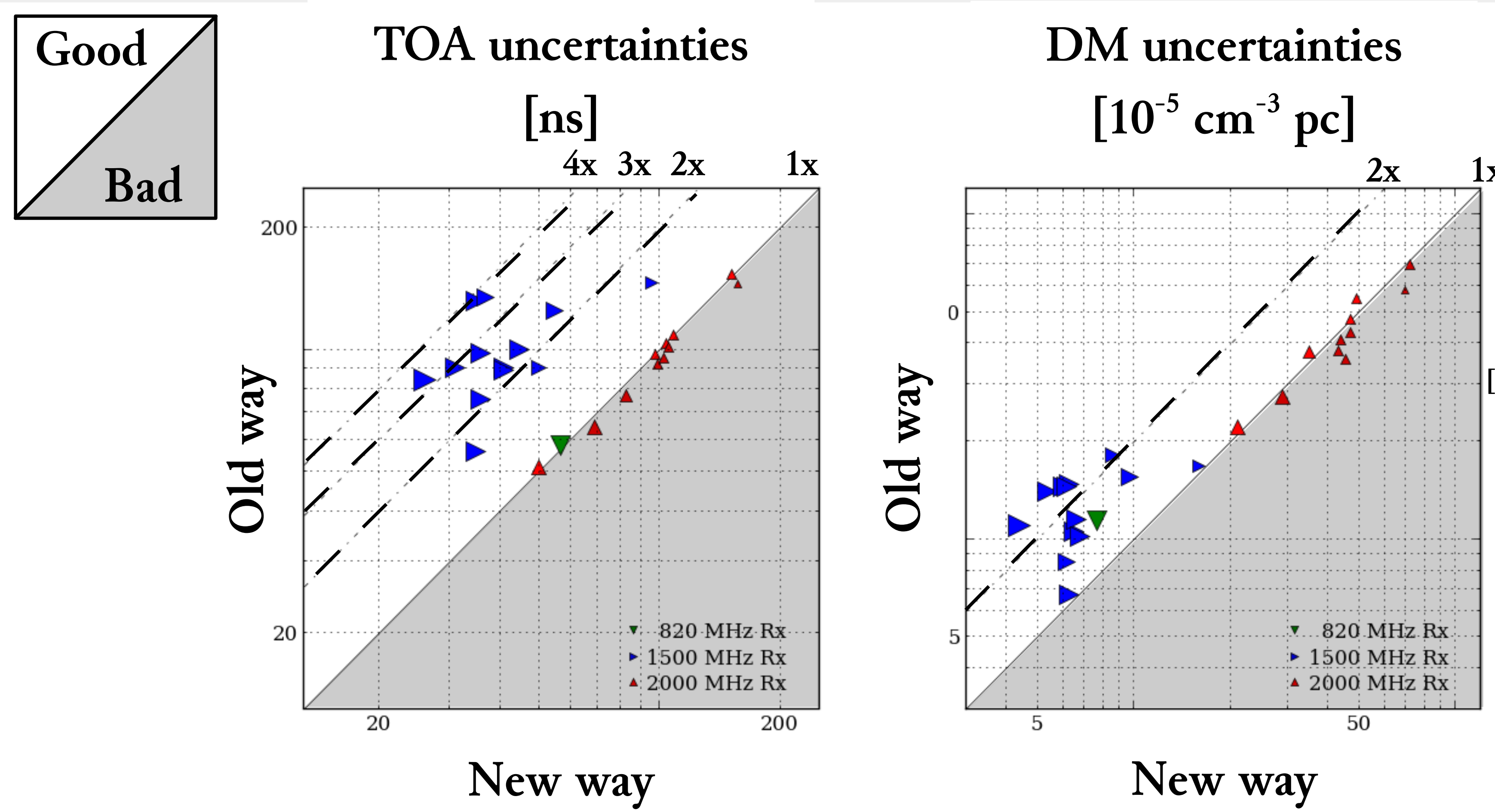
Dispersion Measure — Scintillation — Data — τ, α — Model — ϕ°_{ref}, DM

$$\chi^2(\phi^{\circ}_{ref}, \mathrm{DM}, \tau, \alpha, a_n) = \sum_{n,k} \frac{|d_{nk} - a_n b_{nk} p_{nk} e^{-2\pi i k \phi_n}|^2}{\sigma'^2_n}$$

TOA — Scattering — channel index — Fourier harmonic — Noise

→ The above is a form of template-matching performed in the Fourier domain

Reduced Measurement Uncertainties

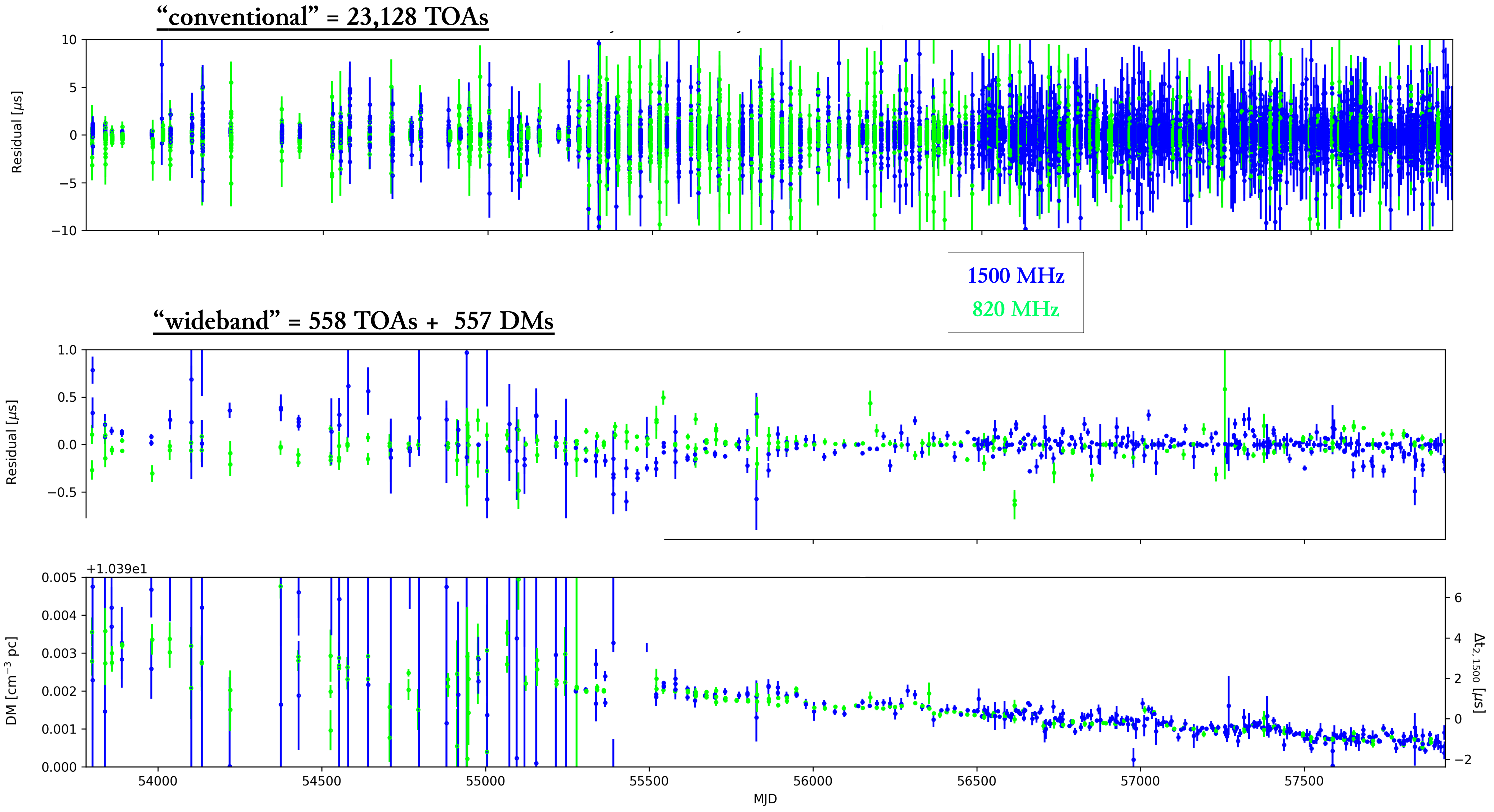


[Pennucci, Demorest, & Ransom (2014)]

→ By modeling pulse profile evolution, the uncertainties of the TOA and DM measurements are improved

→ These leads to better timing precision (= better GW sensitivity…)

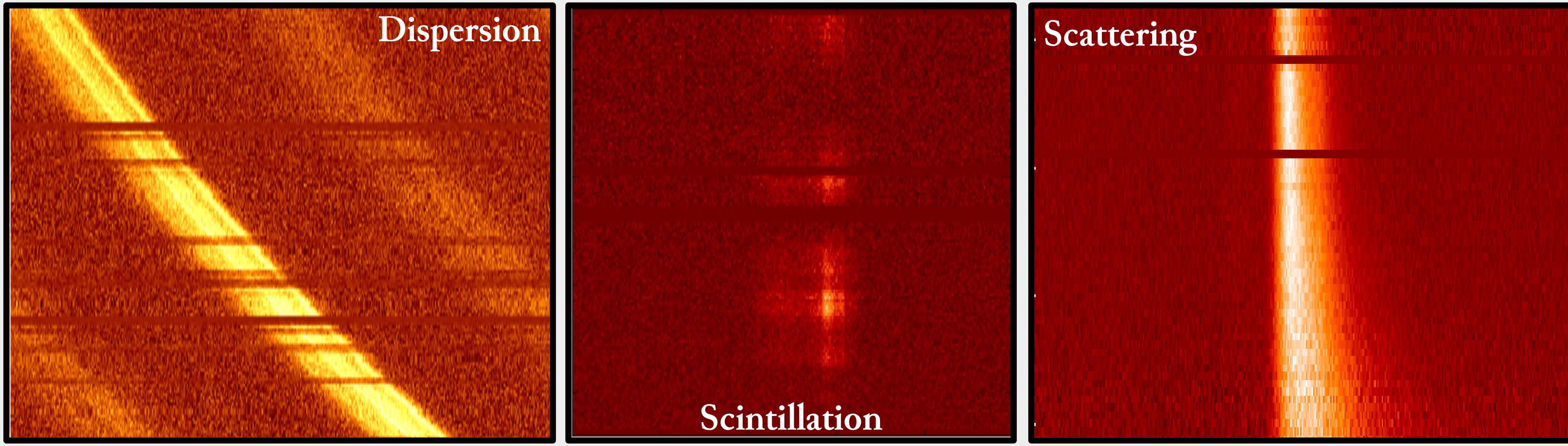
Example 12.5y data for J1909-3744 (GBT – GASP+GUPPI)



→ The task now is to modify the timing & GW analyses to incorporate these new DM measurements

→ GW+noise analyses run *much* faster with reduced data volume

Wideband method handles most common ISM effects:



$$\chi^2(\phi^\circ_{ref}, \mathrm{DM}, \tau, \alpha, a_n) = \sum_{n,k} \frac{|d_{nk} - a_n b_{nk} p_{nk} e^{-2\pi i k \phi_n}|^2}{\sigma_n'^2}$$

Dispersion Measure → DM
Scintillation → a_n
Data → d_{nk}
τ, α → b_{nk}
Model → p_{nk} ?
ϕ°_{ref}, DM → ϕ_n
TOA → ϕ°_{ref}
Scattering → τ, α
channel index → n
Fourier harmonic → k
Noise → $\sigma_n'^2$

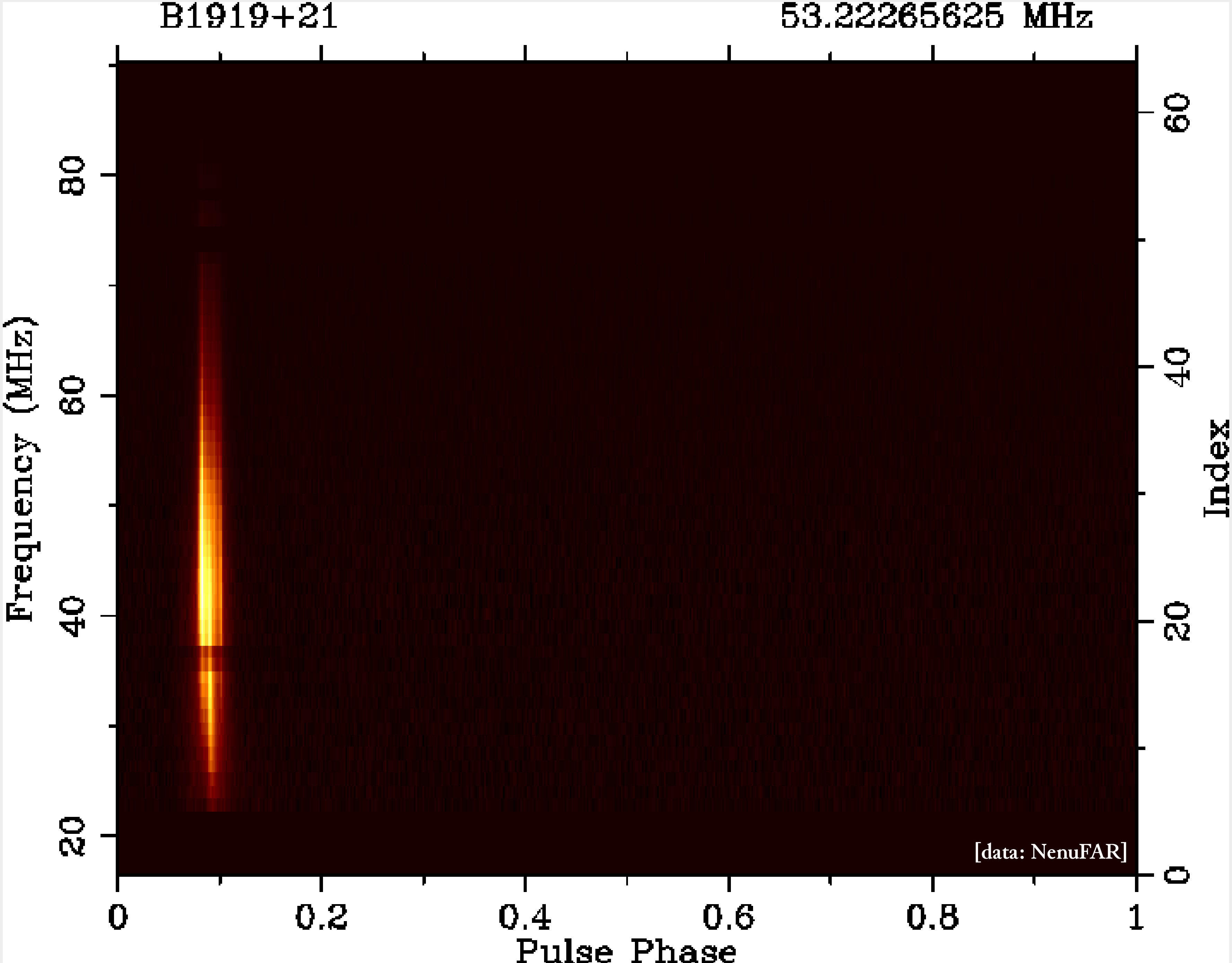
→ The above is a form of template-matching performed in the Fourier domain

However, with great bandwidth comes great responsibility:

"So how do I model profile evolution?"

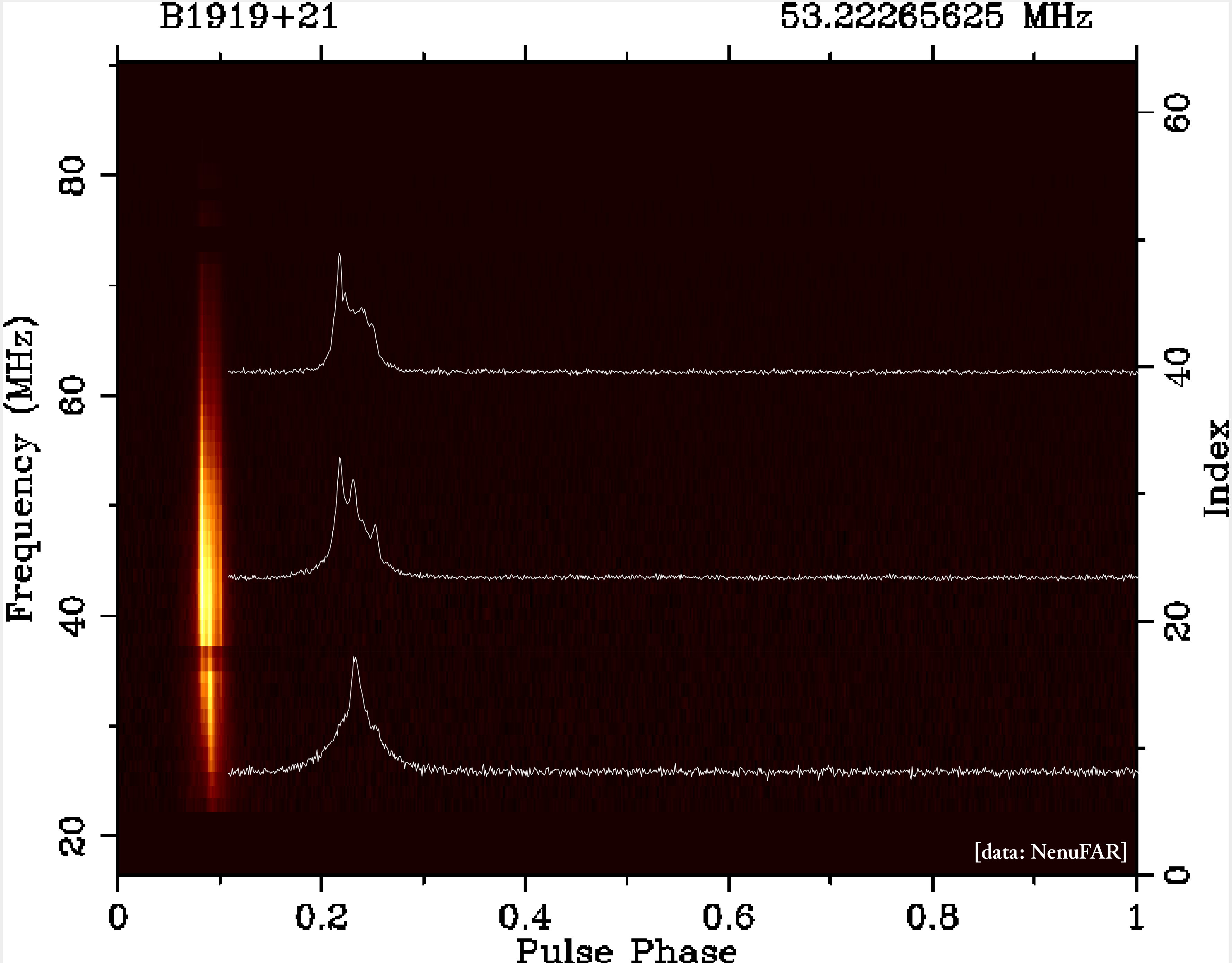
Bleeding-edge example:

→ B1919+21, the *original* pulsar (“LGM 1”) observed near its original detection frequency, from NenuFAR



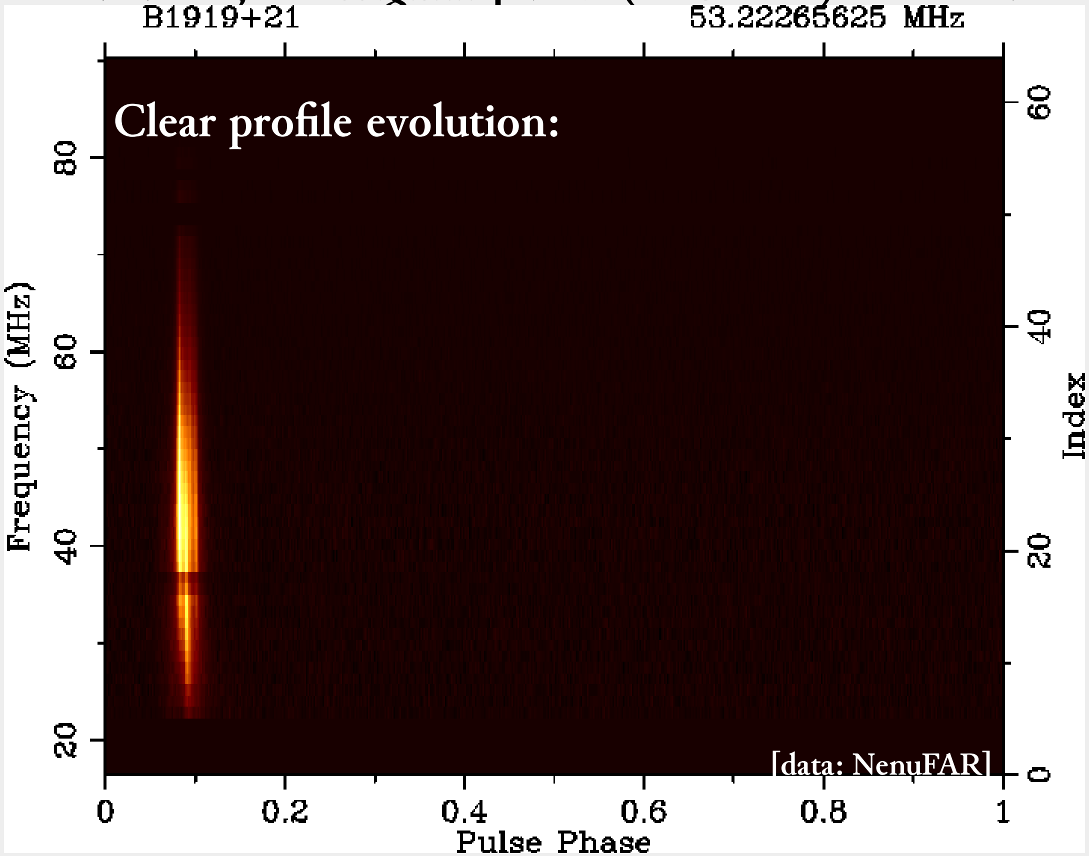
Bleeding-edge example:

→ B1919+21, the *original* pulsar ("LGM 1") observed near its original detection frequency, from NenuFAR

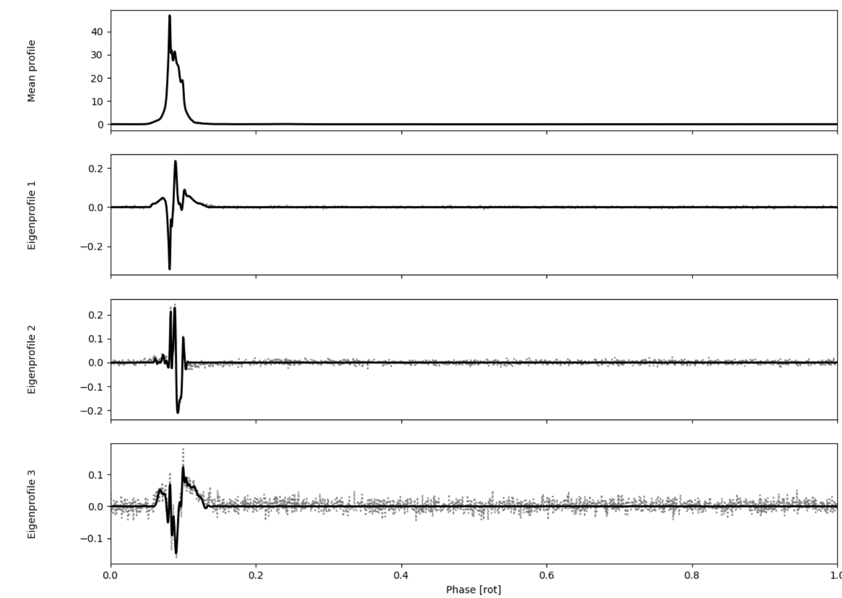


Bleeding-edge example:

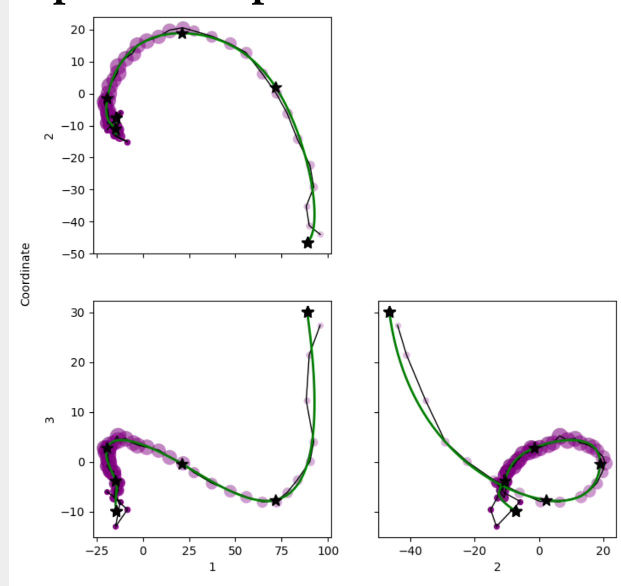
→ B1919+21, the *original* pulsar (“LGM 1”) observed near its original detection frequency, from NenuFAR



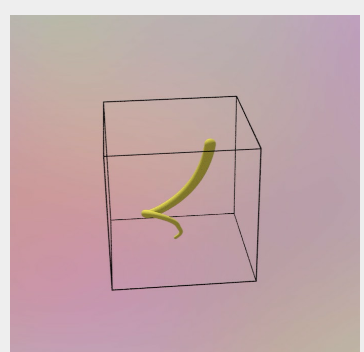
PCA decomposition:



Spline interpolation model:



Movie of model:



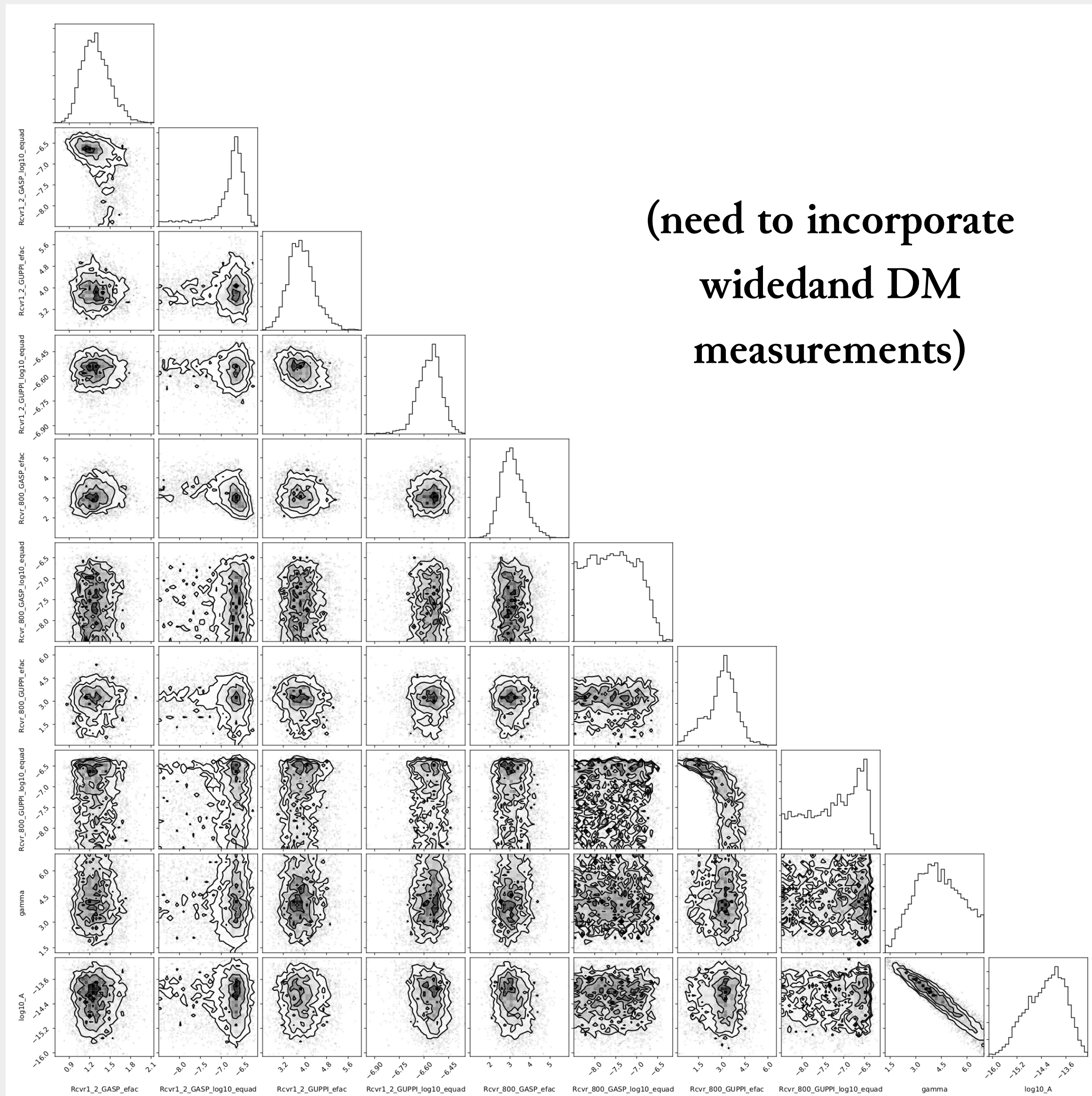
[movie: A. Bilous]

→ Method recently accepted for publication in *ApJ*, Pennucci (2019)

→ Bottom line: high-fidelity templates give better timing results

Future Developments:

→ Proper integration into noise & GW analyses (`enterprise`)

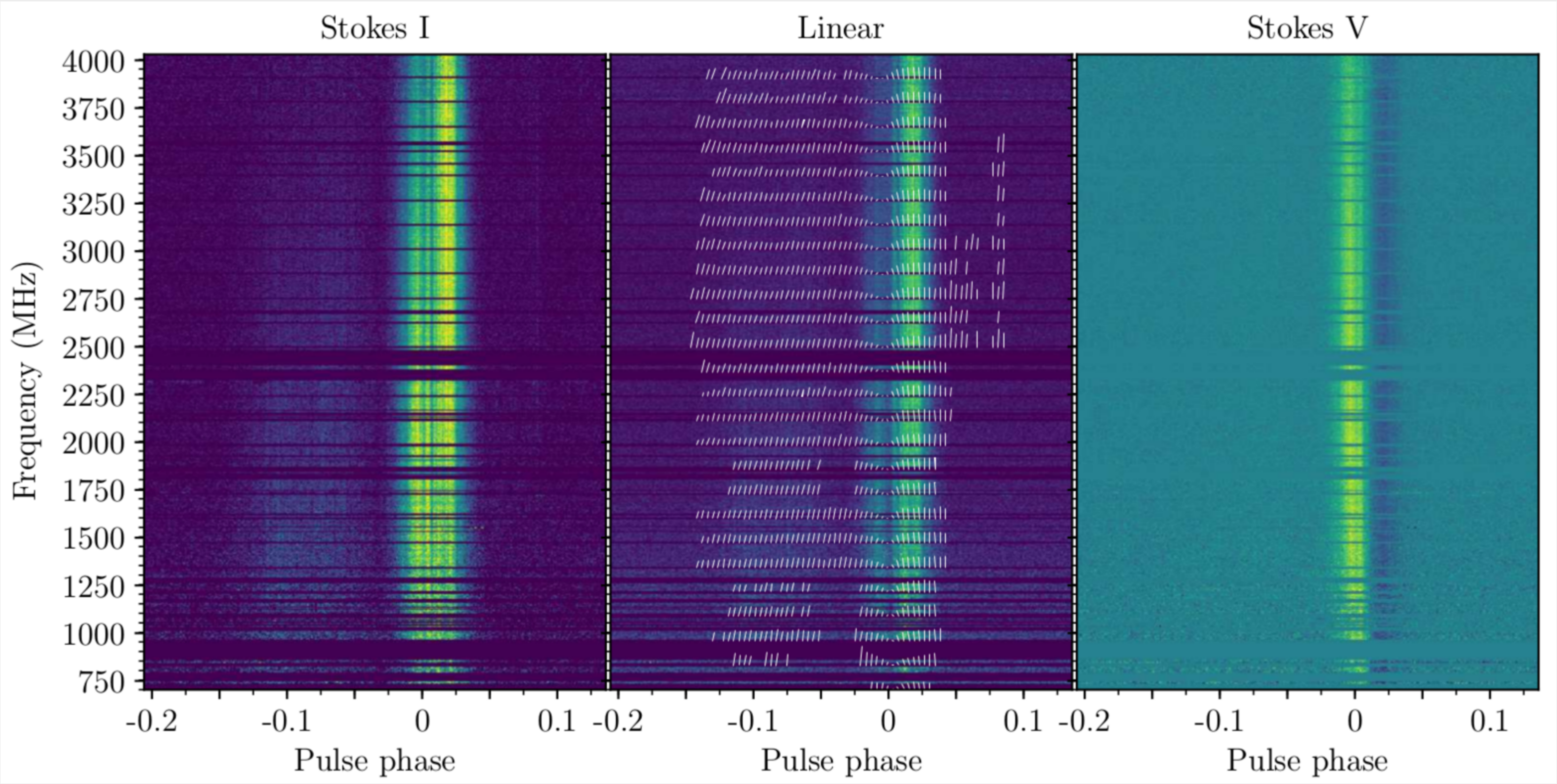


(need to incorporate widedand DM measurements)

Future Developments:

→ **Model/use polarization information in wideband timing**

(*a la* Matrix Template Matching; van Straten, W., (2006))



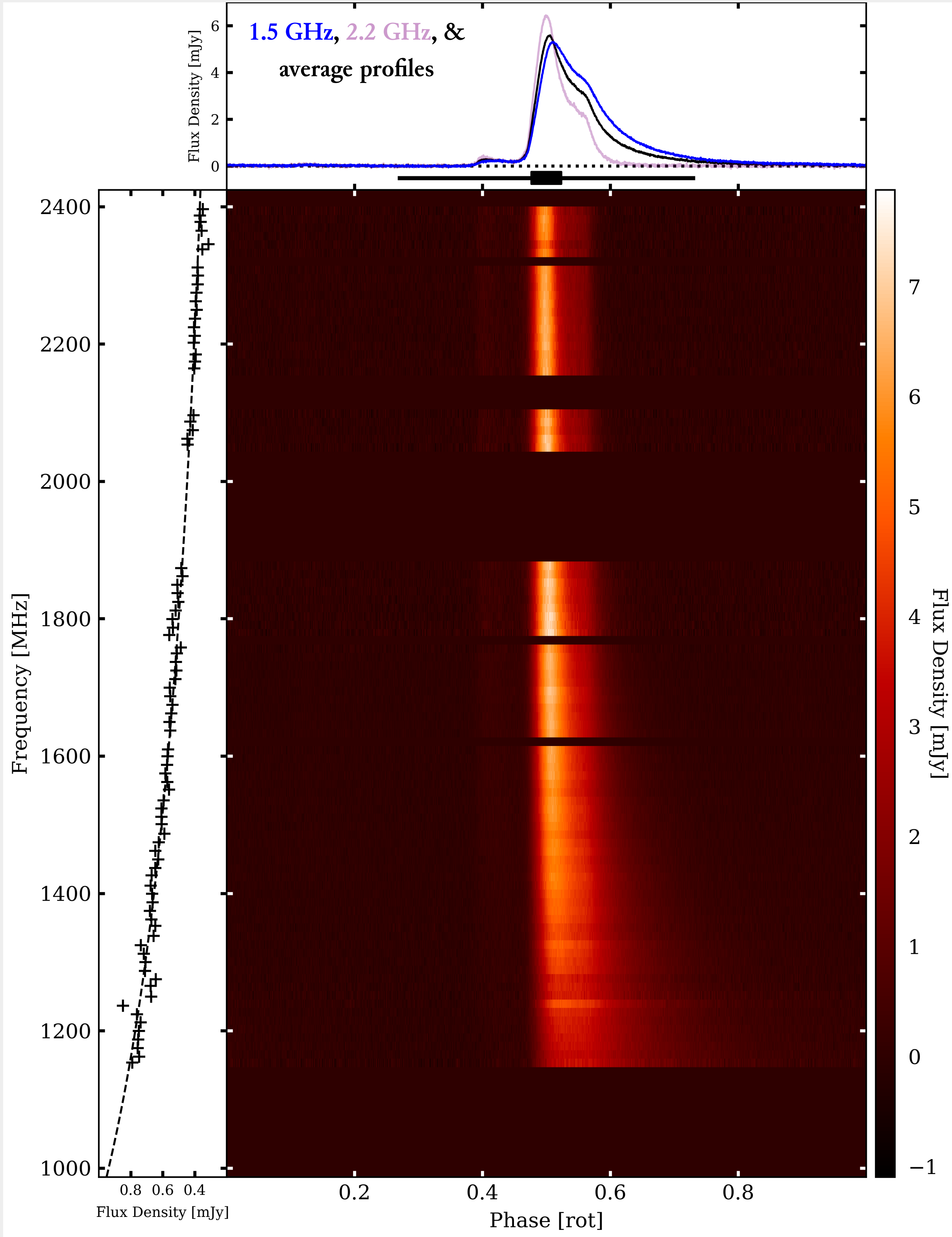
Dai, S., et al. (2019)

Future Developments:

→ RFI migation & bad data flagging using 2D templates
(e.g., `coastguard`; Lazarus, P., et al. (2016))

→ Extend to include time-variable profiles
(e.g., the double pulsar)

→ Investigate underlying magnetospheric modeling



12.5-year NANOGrav data for J1903+0327

→ Average of all data shown at left

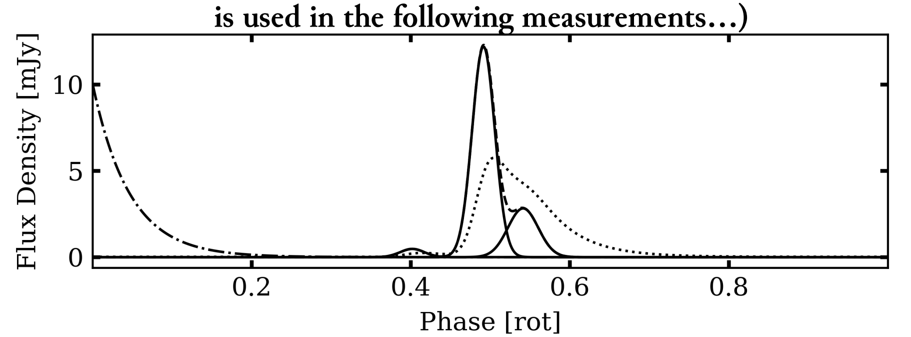
→ Data from the 1.5 and 2.2 GHz receiver bands have been concatenated

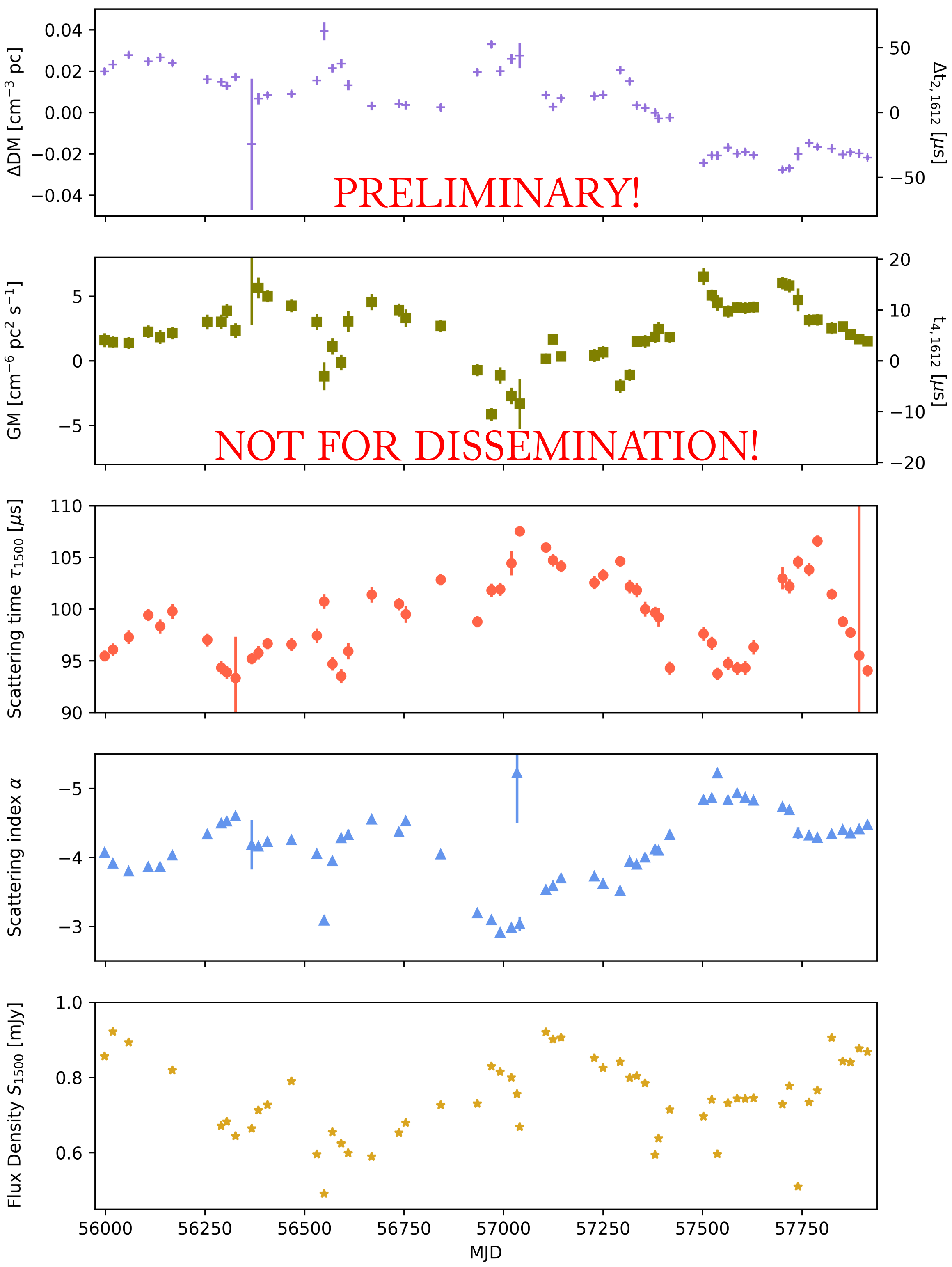
→ Scattering is obvious below ~1.8 GHz

→ Decomposed into three non-evolving Gaussian components to make profile model

→ Used new wideband methods to track ISM variations

(the below 3-component *unscattered* model is used in the following measurements…)





12.5-year NANOGrav data for J1903+0327

→ The TOA, DM, scattering amplitude & index, and frequency^{-4} delay are all measured together

→ Such simultaneous, high-cadence measurements of ISM parameters have not been previously published

→ Similar, broader studies with data from low-frequency telescopes will inform models of the turbulent, ionized interstellar medium

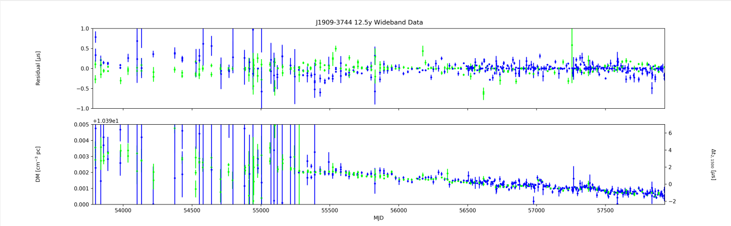
→ However, DM may vary with frequency

→ How the timing may improve is TBD

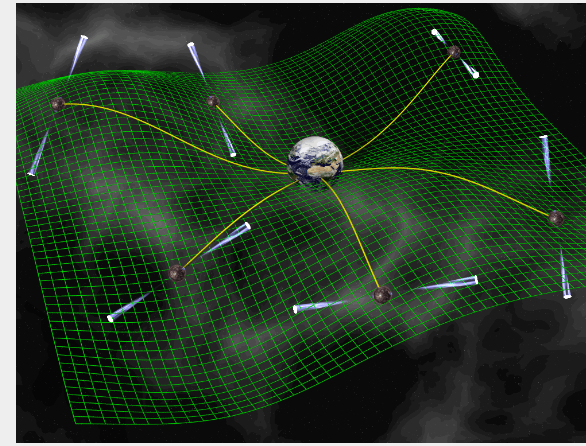
In Summary:

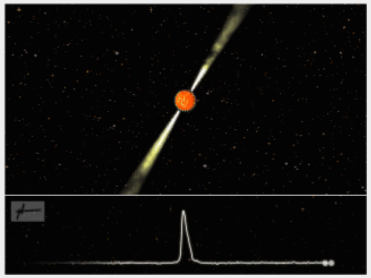
→ Pulsar observations with modern high fractional bandwidth systems (>0.5) will need to adopt new methods for timing to account for issues pertaining to profile evolution, the ISM, and data volume.

Thank you!

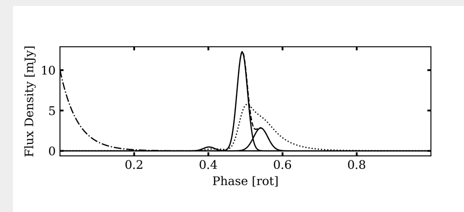


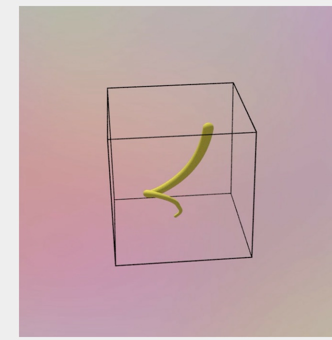
NANOGrav
Physics Frontiers Center

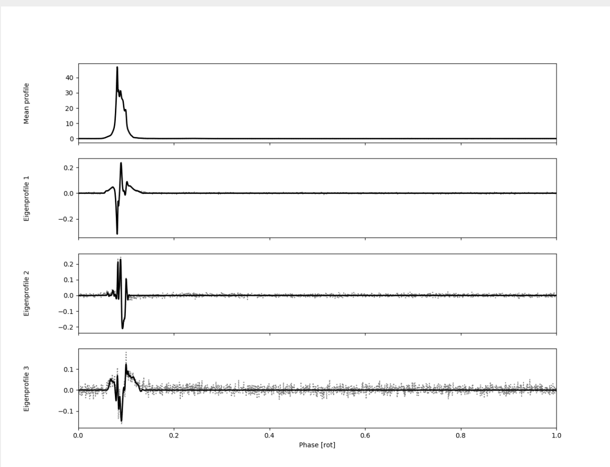


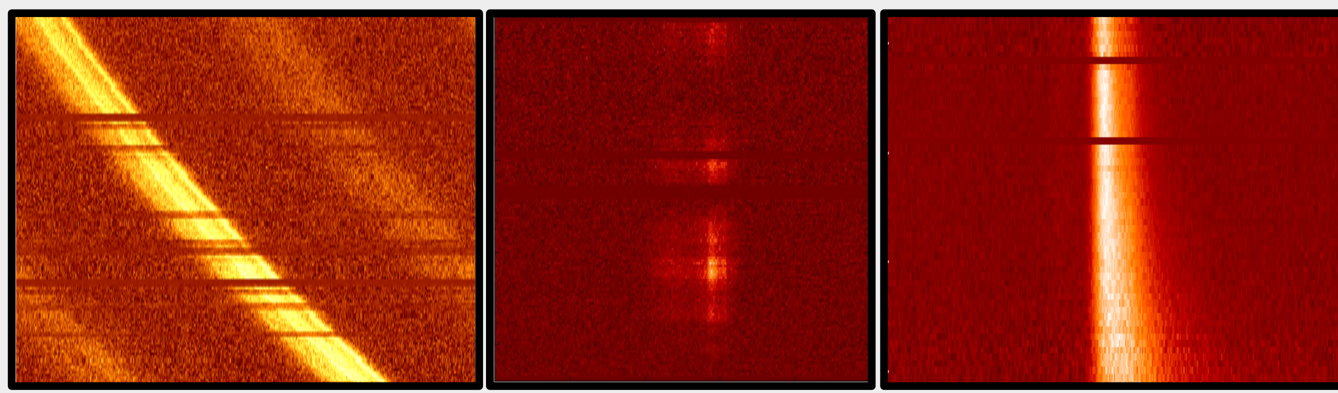


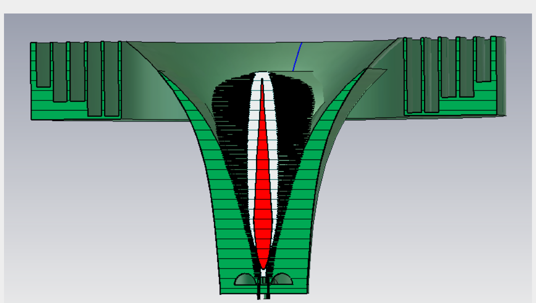
INTERNATIONAL PULSAR TIMING ARRAY
IPTA











UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA
1635

MAGYAR TUDOMÁNYOS AKADÉMIA
1825