Pulsar Timing & Data Combination

Deborah Good
June 13, 2023

Hi, I’m Deborah!

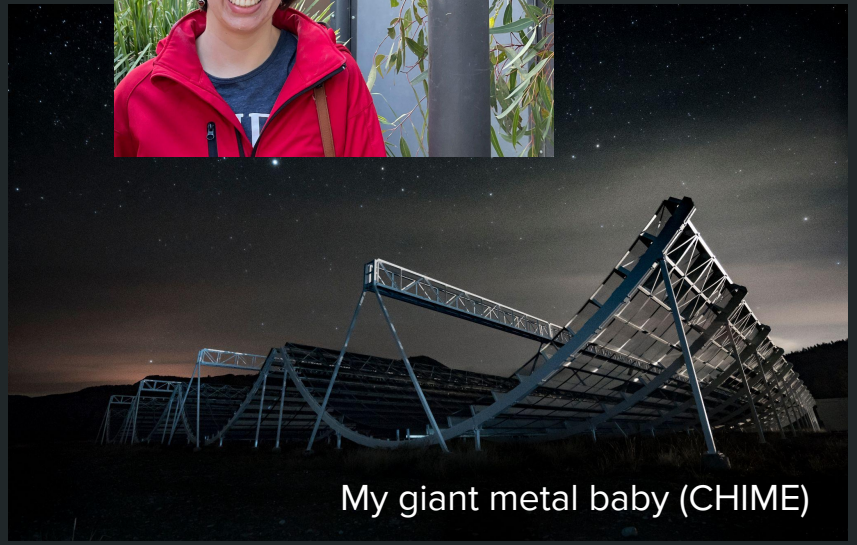
From the US (Michigan, Iowa, Colorado)

B.S. Colorado School of Mines
Ph.D. University of British Columbia (Canada)
Postdoc @ UConn(ecticut) and Flatiron Institute (NYC)

This is my first time in Australia!

Talk to me about: sewing/crafts, old movies, baseball (or tell me about your favorite sports)

Me with a koala



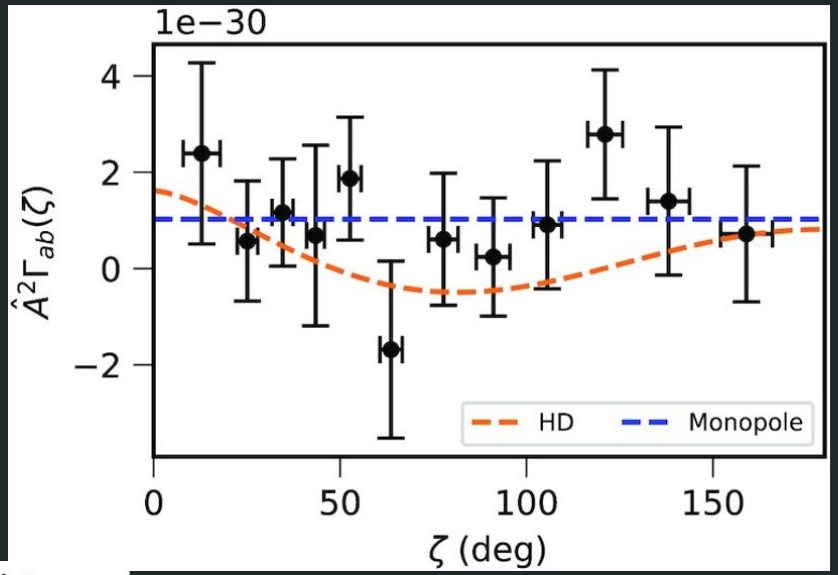
My giant metal baby (CHIME)

What is data combination?

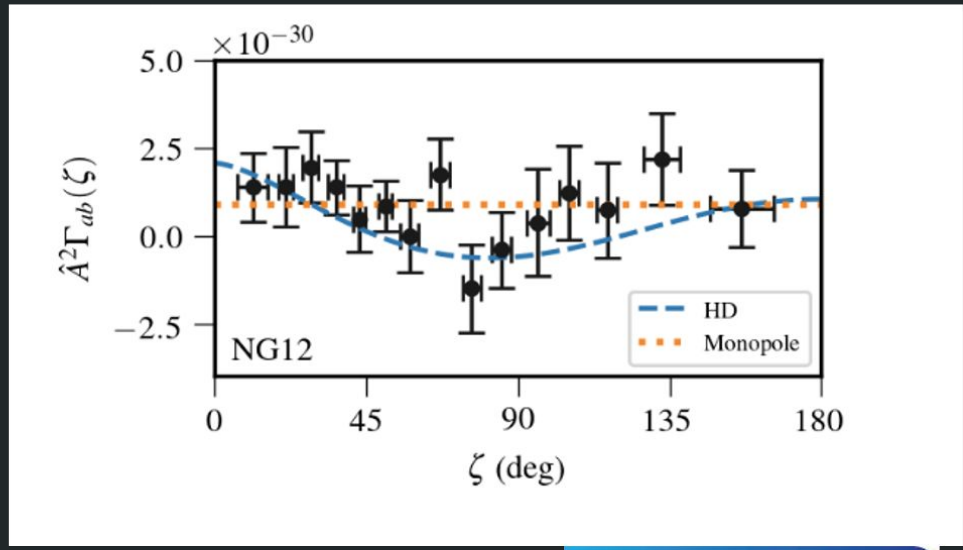
Exactly what it sounds like.


Lovell
Nançay
WSRT
SRT
Effelsberg
EPTa
GBT
Arecibo
VLA
CHIME
NANOGrav
FAST
CPTa
Parkes
MOST
PPTa
MeerKAT
MPTa
GMRT
Ooty
InPTa

Why do data combination?



(Antoniadis et al. 2021)



(Arzoumanian et al. 2020)

But data combination is hard.

But data combination is hard.

Why is data combination hard?

- Multiple PTAs, multiple timing philosophies
  - Timing software: PINT vs. tempo vs. tempo2
  - Different ways of classifying data (flagging)
  - Channelized vs. scrunched
  - DM modeling: DMX vs. Gaussian Process modelling
  - Different noise modeling approaches
- Lots and lots of data
- Our pulsar timing data & strategies are changing

How does pulsar timing change when we have more than one telescope?

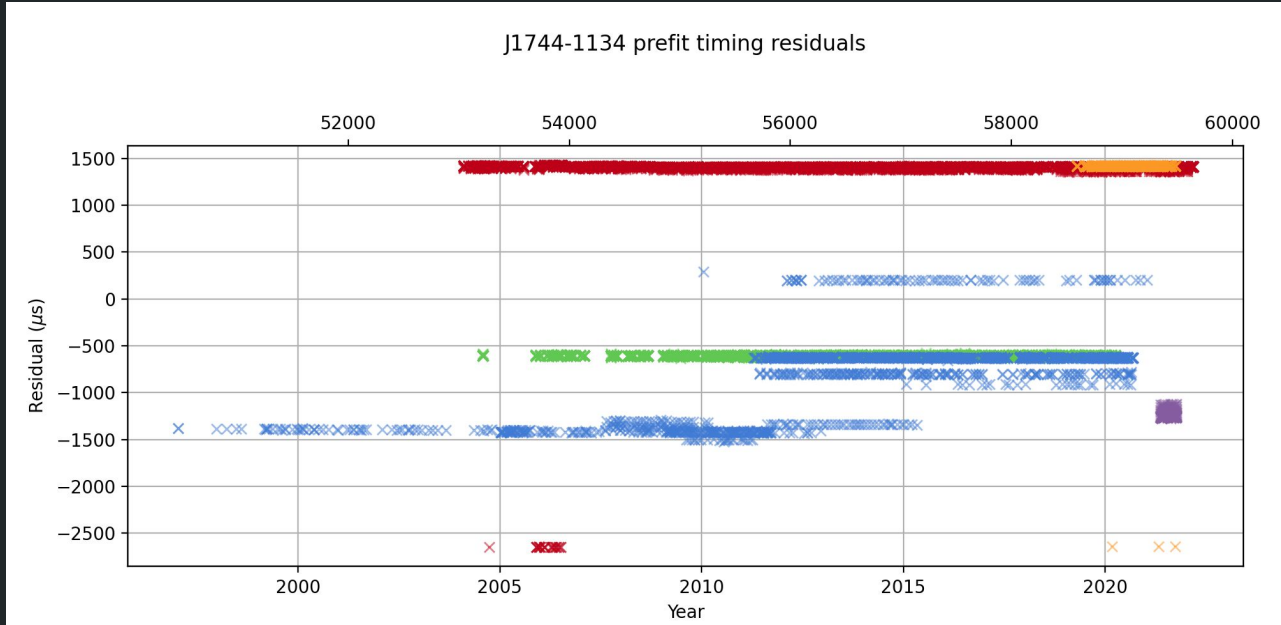
Jumps

Absolute phase offsets occur when you add a new system.

- Any time you have a new telescope.

But also:

- New receivers
- New processing systems (backends)

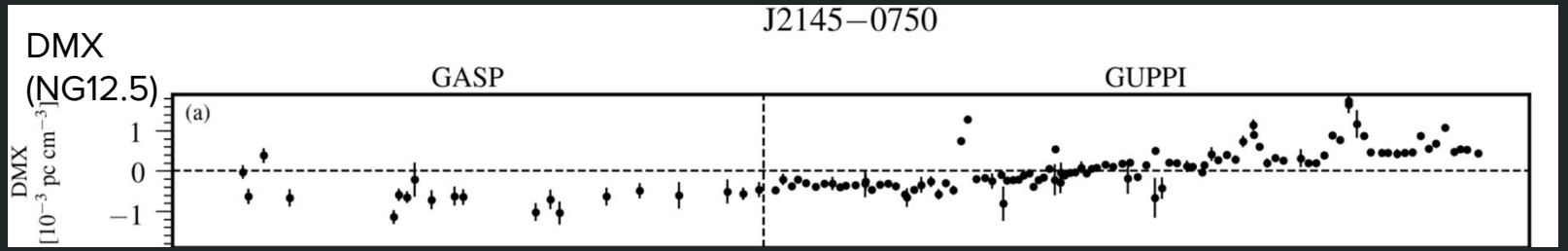


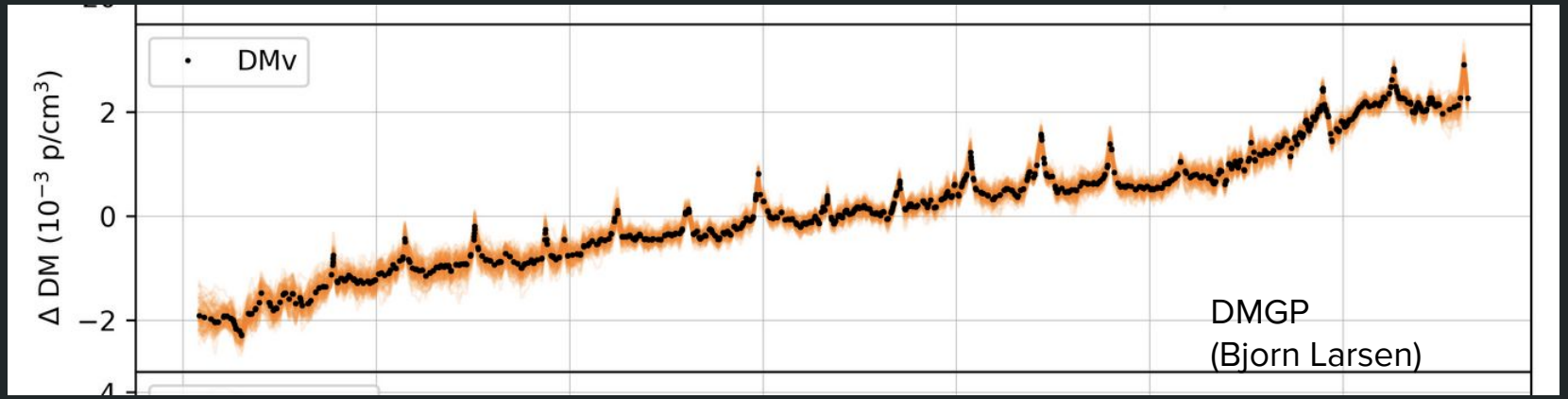
DM Modeling (when you have a lot of different approaches)

- Some options:
  - Ignore it entirely! (This is a very bad option).
  - Create a piecewise constant fit for DM variation at each observation (DMX).
  - Taylor series expansion.
  - Model as a red noise process (a power law with frequency squared dependence).
- Current approach:
  - Fit DM1 & DM2 (time derivatives of DM) during timing process
  - Create Gaussian Process red noise model for DM during noise modeling.

DM Modeling

DMX
(NG12.5)





DMGP
(Bjorn Larsen)

Other pitfalls

- Clock corrections
- Flags that don’t match or have different meanings (-f vs. -group vs. -sys)
- When should noise modeling be done and what should it look like?

Let’s look at some actual TOAs

c036364.align.pazr.30min 1353.499 55036.9312847556429 0.696 g -sys EFF.EBPP.1360 -pta EPTA -padd 0.0850671 -group EFF.EBPP.1360

/scratch2/kap033/PPTA_DR3/J1744-1134/subbands.Tpf4//sbG2/uwl_220306_001217_b4.rf.sbG2.Tpf4 2546.13300000 59644.026012077469928 84 1.20600 pks -fe UWL -be Medusa -f UWL_Medusa -pta PPTA -bw 832 -tobs 3026.1 -tmplt J1744-1134.std.sbG2 -gof 0.929 -nbin 1024 -nch 32 -snr 58.951 -gof 0.928678 -chan 3 -group UWL_sbG -B uwl_10CM -medusa_59200_jump 1 -group UWL_sbG -medusa_58925_jump 1 -pn 140014470388

guppi_57922_J1744-1134_0024.12y.x.ff 781.716980 57922.230378357651359 0.497 1 -fe Rcvr_800 -be GUPPI -f Rcvr_800_GUPPI -bw 3.125 -tobs 1599.9 -tmplt J1744-1134.Rcvr_800.GUPPI.9y.x.sum.sm -gof 1.08 -nbin 2048 -nch 2 -chan 44 -subint 0 -snr 164.81 -wt 0.77197 -flux 11.1862 -fluxe 0.068 -proc 12y -pta NANOGrav -ver 20170425

The Reality of DR3


Lovell
Nançay
WSRT
SRT
Effelsberg
EPTa
GBT
Arecibo
VLA
CHIME
NANOGrav
FAST
CPTa
Parkes
MOST
PPTa
MeerKAT
MPTa
GMRT
Ooty
InPTa

DR3 is going to be great...and huge

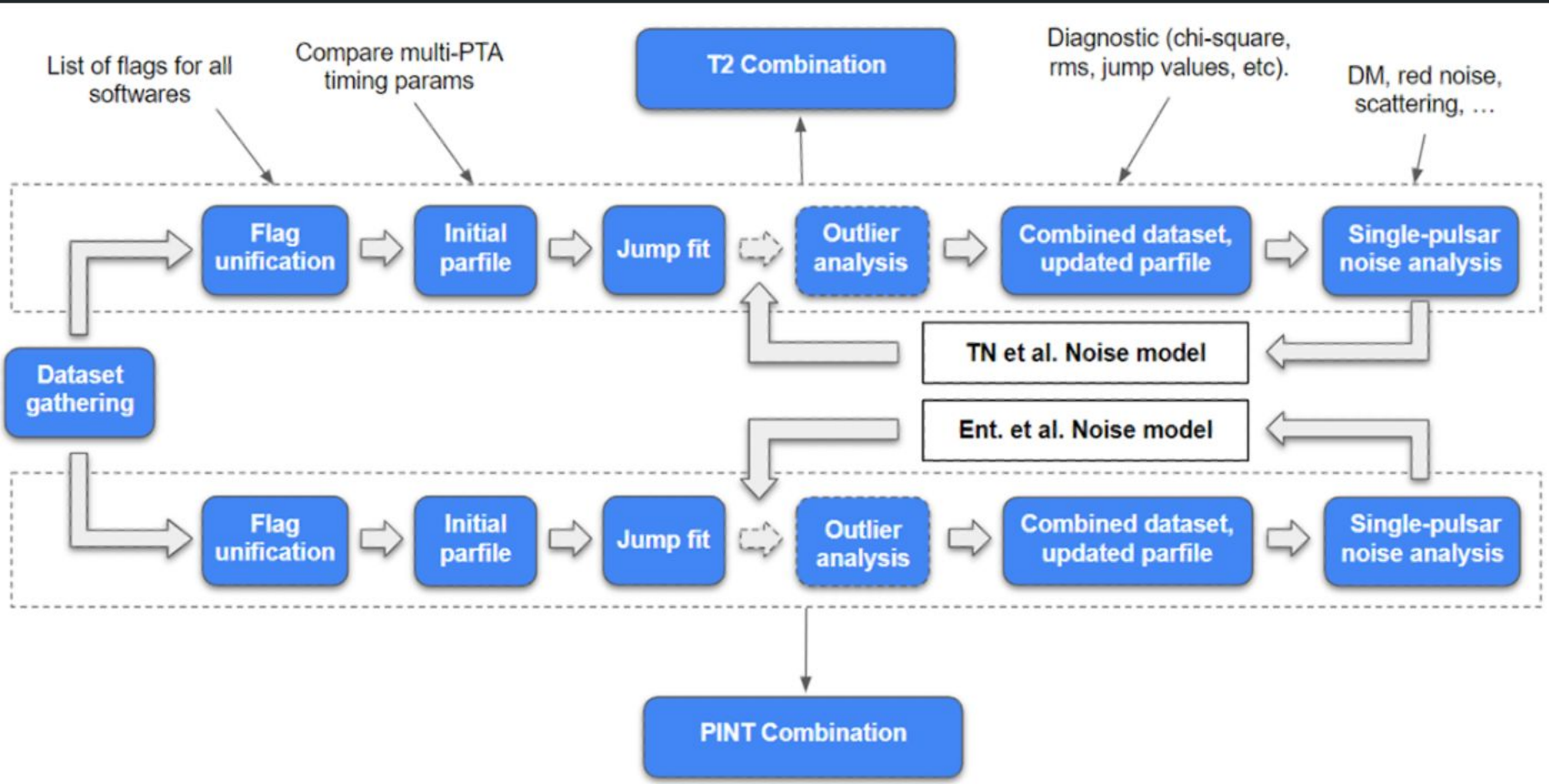
5 PTAs: EPTA, InPTA, MPTA, NANOGrav, PPTA

115 pulsars: 25 EPTA, 14 InPTA, 77 MPTA, 68 NANOGrav, 31 PPTA

15+ years of data for core datasets, up to 30 with legacy data.

How are we approaching the challenge of DR3?

- Building a team of people
- Intentionally redundant pipelines
  - PINT + ENTERPRISE
  - TEMPO2 + TEMPONEST
- Gradual build-up
  - Early DR3: start with 20 pulsars.
- Keeping an eye on the future
  - Documentation
  - Training
  - Clean code


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
TN et al. Noise model
Dataset gathering
Ent. et al. Noise model
Flag unification
Initial parfile
Jump fit
Outlier analysis
Combined dataset, updated parfile
Single-pulsar noise analysis
PINT Combination

How do we actually do a PINT combination?

1) Load in a model and TOAs

```
config = "sample.dr3.yaml"  # fill in actual path
par_directory = None   # default location
tim_directory = None   # default location
tc = TimingConfiguration(config, par_directory=par_directory, tim_directory=tim_directory)

# To combine TOAs, assumption is that cuts have already been applied properly
mo,to = tc.get_model_and_toas(apply_initial_cuts=False,usepickle=False)

# Uncomment this line to manually excise TOAs.
#tc.manual_cuts(to)

# Computing pulse numbers ensures param changes in the model will not break phase connection
to.compute_pulse_numbers(mo)

# Set non-binary epochs to the center of the data span
lu.center_epochs(mo,to)

# Summarize TOAs present
to.print_summary()
```

```
source: J1744-1134
par-directory: pars/
tim-directory: tims/J1744-1134/
timing-model: J1744-1134_PINT_20230317_prenoise.nb.par
compare-model:
toas:
- EFF.EBPP.1360.tim # Effelsberg
- EFF.EBPP.1410.tim
- EFF.EBPP.2639.tim
```

List your starting par file here.

List all your tim files here. (Note: currently need 2+ tims to run)

```
free-params:
            [PX, ELONG, ELAT, PMELONG, PMELAT, F0, F1, DM1, DM2, JUMP1, JUMP2, JUMP3,
            JUMP4, JUMP5, JUMP6, JUMP7, JUMP8, JUMP9, JUMP10, JUMP11,
            JUMP12, JUMP13, JUMP14, JUMP15, JUMP16, JUMP17, JUMP18, JUMP19, JUMP20, JUMP21,
            JUMP22,JUMP23, JUMP24, JUMP25, JUMP26, JUMP27, JUMP28, JUMP29, JUMP30, JUMP31,
            JUMP32, JUMP33, JUMP34, JUMP35, JUMP36, JUMP37, JUMP38, JUMP39, JUMP40,  JUMP41,
            JUMP42, JUMP43, JUMP44, JUMP45, JUMP46, JUMP47,JUMP48, JUMP49, JUMP50,  JUMP51,
            JUMP52, JUMP53]
free-dmx: Yes
toa-type: NB
fitter: DownhillGLSFitter
n-iterations: 20
ephem: DE440
bipm: BIPM2021
```

All parameters you want to fit need to be in free-params AND need a 1 in the par file. If either is missing it won't fit.

How do we actually do a PINT combination?

2) Define a “fitter” and plot an initial pre-fit solution.

```
# Define the fitter object and plot pre-fit residuals
fo = tc.construct_fitter(to,mo)
pu.plot_residuals_time(fo, colorby='pta',restype='prefit', legend=True)
if mo.is_binary:
    pu.plot_residuals_orb(fo, colorby='pta',restype='prefit', legend=True)
```

3) Do a fit

```
# Set free params based on list in the config file (want to update JUMP handling differently soon)
fo.model.free_params = tc.get_free_params(fo)

# Do the fit
try:
    fo.fit_toas(maxiter=tc.get_niter())
    fo.model.CHI2.value = fo.resids.chi2
except ConvergenceFailure:
    run_Ftest = False
    log.warning('Failed to converge; moving on with best result, but should address before final version.')
```

How do we actually do a PINT combination?

4) Look at your results & assess. Write out a new par.

```
# Plot post-fit residuals, print summary of results, write prenoise solution
pu.plot_residuals_time(fo, restype='postfit', legend=False)
if mo.is_binary:
    pu.plot_residuals_orb(fo, restype='postfit', legend=False)

fo.print_summary()
lu.check_convergence(fo)

lu.write_par(fo,toatype=tc.get_toa_type(),addext=ext)
```

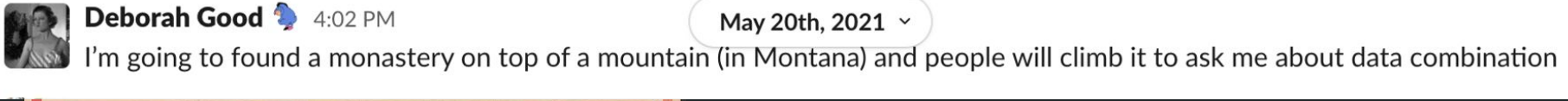
5) Do it again (repeatedly)

Note: you'll want to edit the par file line of your config to use your new par file.

6) Send it off for noise analysis. (Bjorn, wave to us.)

- Three co-chairs: Deborah Good (NANOGrav), Kuo Liu (EPTA), Golam Shaifullah (EPTA)
- Regular meetings
  - Every second Tuesday
  - Rotating between 8 UTC/15 UTC/20 UTC
- Slack channel: #data_combination
- Email list: ipta-dcwg@lists.pulsarastronomy.net
- Gitlab: https://gitlab.com/IPTA/DR3

- Three co-chairs: Deborah Good (NANOGrav), Kuo Liu (EPTA), Golam Shaifullah (EPTA)
- Regular meetings
  - Every second Tuesday
  - Rotating between 8 UTC/15 UTC/20 UTC
- Slack channel: #data_combination
- Email list: ipta-dcwg@lists.pulsarastronomy.net
- Gitlab: https://gitlab.com/IPTA/DR3



The “Choose your own adventure” session

I am new to pulsar timing.

Try “Timing_tutorial.ipynb”

The “Choose your own adventure” session

I am new to pulsar timing.

Try “Timing_tutorial.ipynb”

I feel confident with pulsar timing, but I don’t know much about PINT.

Try “PINT_Tutorial.ipynb”
Then move on to “process_ipta_v0.1_student_week.ipynb”

The “Choose your own adventure” session

I am new to pulsar timing.

Try “Timing_tutorial.ipynb”

I feel confident with pulsar timing, but I don’t know much about PINT.

Try “PINT_Tutorial.ipynb”
Then move on to “process_ipta_v0.1_student_week.ipynb”.

I know about pint & pulsar timing, but want to learn to combine data.

Start with “process_ipta_v0.1_student_week.ipynb”

The “Choose your own adventure” session

I am new to pulsar timing.

Try “Timing_tutorial.ipynb”

I feel confident with pulsar timing, but I don’t know much about PINT.

Try “PINT_Tutorial.ipynb”
Then move on to “process_ipta_v0.1_student_week.ipynb”.

I know about pint & pulsar timing, but want to learn to combine data (or combine data with PINT).

Start with “process_ipta_v0.1_student_week.ipynb”

I’m already familiar with all these things!

Review notebooks, work on your own data combination projects, help others.