MASTERING RANDOMNESS IN NS ROTATION
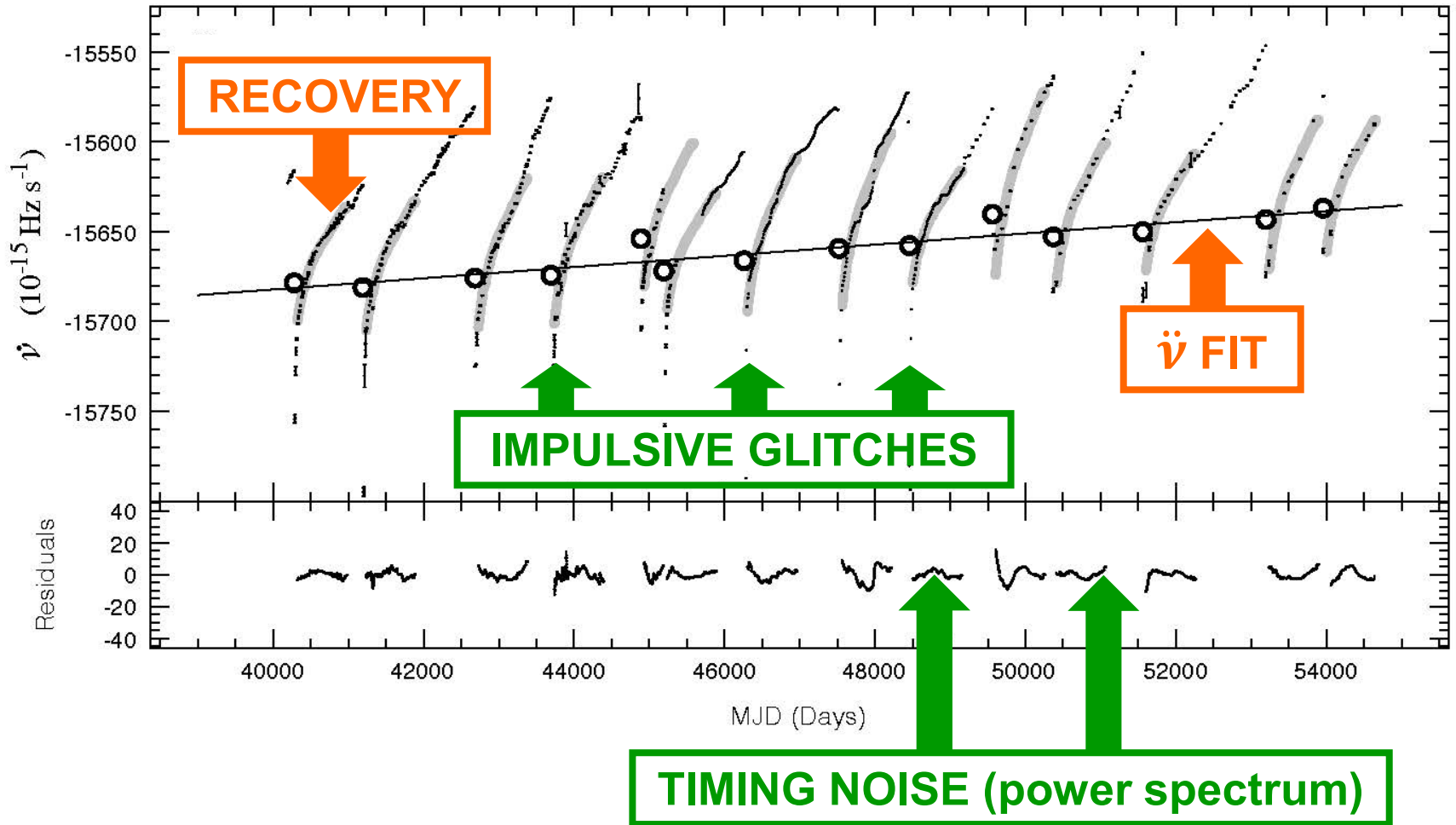
A. Melatos (U. Melbourne)

1. Timing noise ↔ Kalman filter

CRUST-SF COUPLING

2. Glitches ↔ hidden Markov model

3. Stress-relax dynamics

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ARC Centre of Excellence for Gravitational Wave Discovery

PSR J0835-4510
(Espinoza et al. 17)
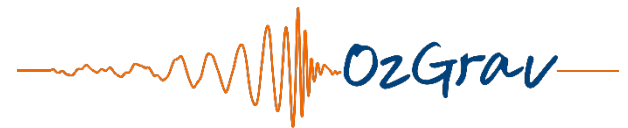
Subtracted "noise" is **informative…** dynamics!

$$\frac{d\Omega_c}{dt} = -\frac{\Omega_c - \Omega_s}{\tau_c} + \frac{N_c}{I_c} + \xi_c(t) + \Delta\Omega_g \delta(t - T_g)$$

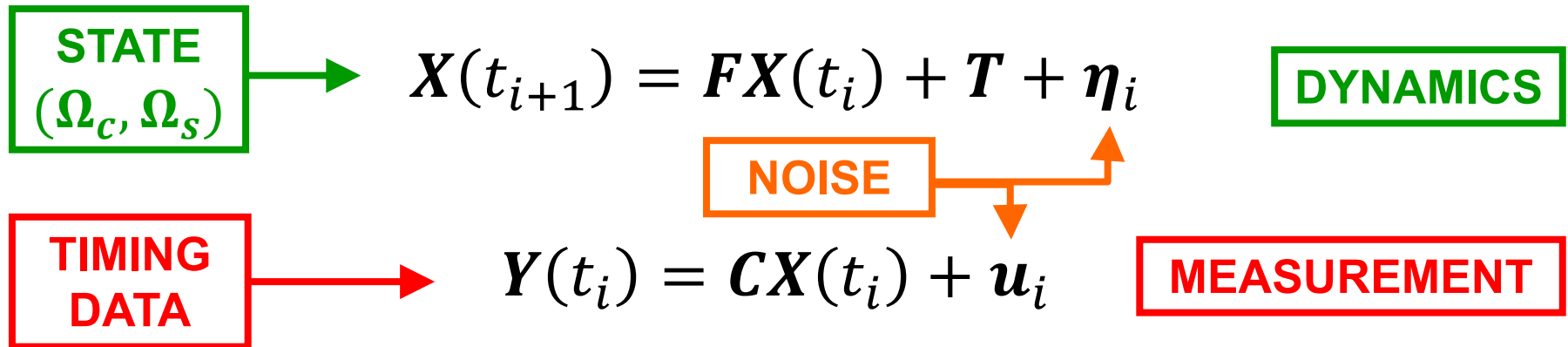$$\langle \xi_c(t)\xi_c(t') \rangle = \sigma_c^2 \delta(t - t')$$

- Two-component **glitch recovery** (Baym et al. 69)
- **Superfluid neutrons** Ω_s plus **rigid crust** Ω_c locked magnetically to protons and electrons

- Coupling time-scale τ_c and secular torque N_c
- Timing noise = **white noise** torque $\xi_c(t)$
- Glitch = **instantaneous** angular **impulse** $\Delta\Omega_g$

I. TIMING NOISE

Measuring crust-superfluid coupling
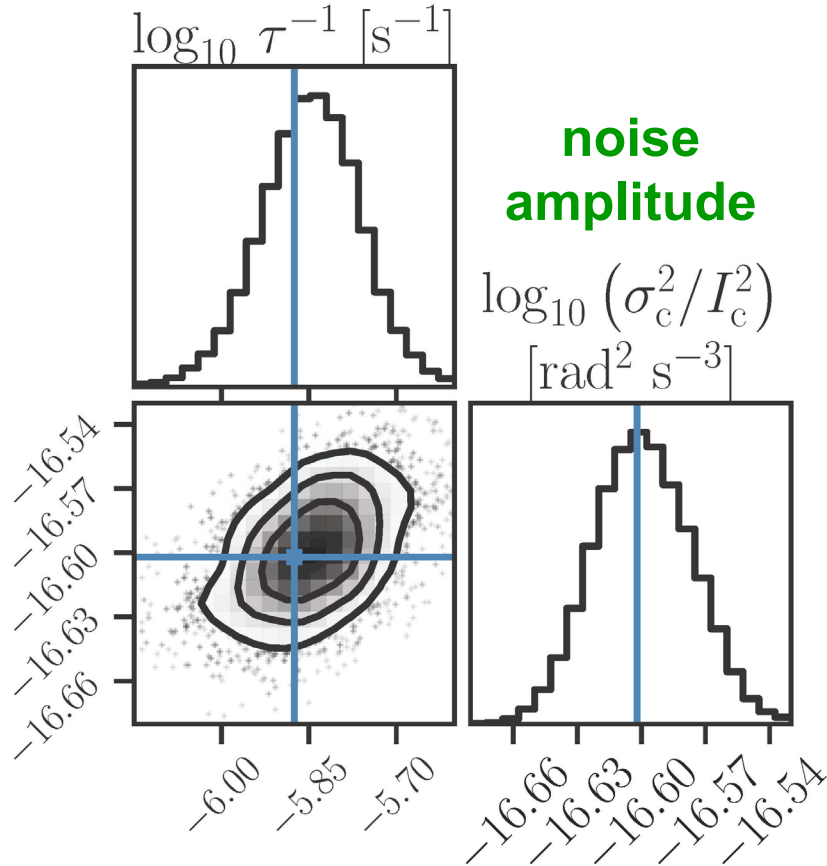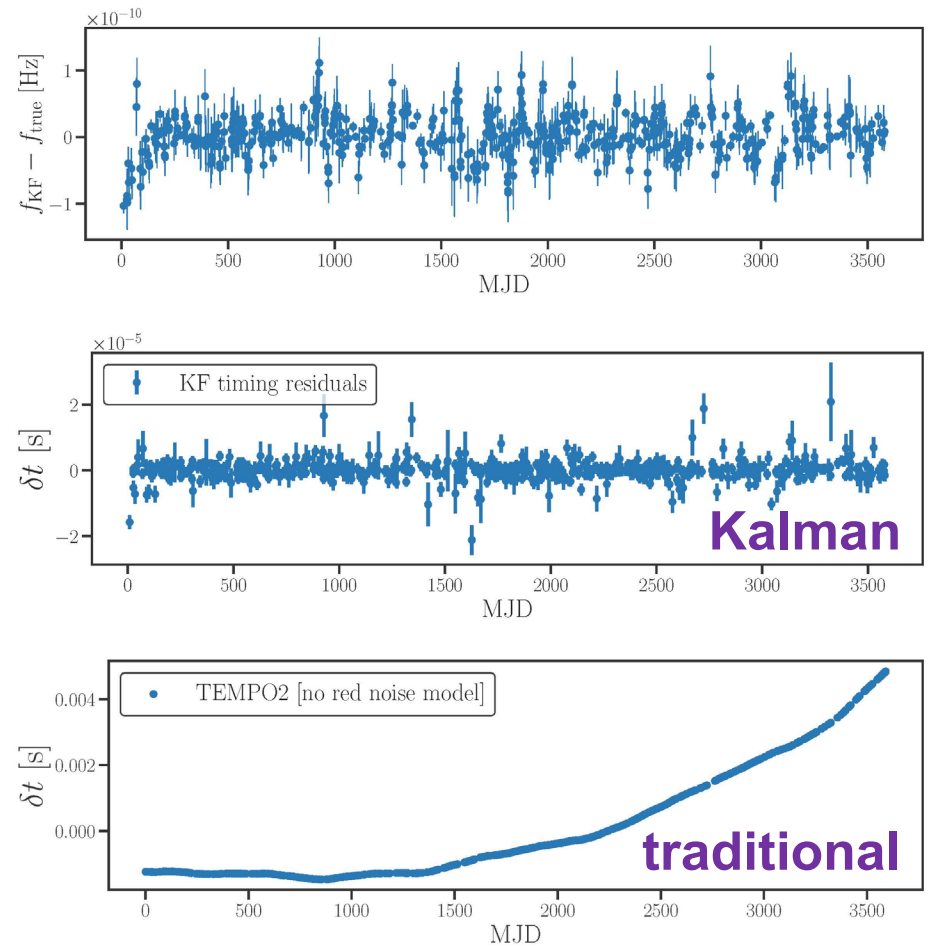with Kalman tracking

KALMAN FILTER

STATE (Ω_c, Ω_s)

$$X(t_{i+1}) = F X(t_i) + T + \eta_i$$

DYNAMICS

NOISE

TIMING DATA

$$Y(t_i) = C X(t_i) + u_i$$

MEASUREMENT

- Two-step state estimate (predict, update) $\widehat{X}(t_i)$ minimizing $|\widehat{X}(t_i) - X(t_i)|^2$ given data $Y(t_i)$

- Likelihood $p(\{Y(t_i)\} | \tau_{c,s}, \sigma_{c,s}, N_{c,s}, ...) \rightarrow$ MCMC

- Posteriors on **secular** $(F, T \rightarrow \tau_{c,s}, N_{c,s})$ and **stochastic** $(\langle \eta_i \eta_j \rangle \rightarrow \sigma_{c,s})$ parameters

coupling time
$$\tau = \tau_c \tau_s / (\tau_c + \tau_s)$$

noise amplitude

RESIDUALS

Kalman

traditional

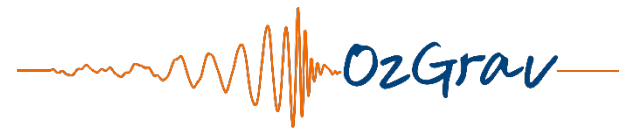Test with synthetic data (Meyers et al. 21)

FUTURE QUESTIONS

- Fast, accurate estimates of $\tau_{c,s}$ and $\sigma_{c,s}$ for specific random realization, cf. time-averaged noise spectrum (not stationary!)

- Bayesian model selection: **one or two stellar components preferred?**

- Distinguish glitch recovery from timing noise
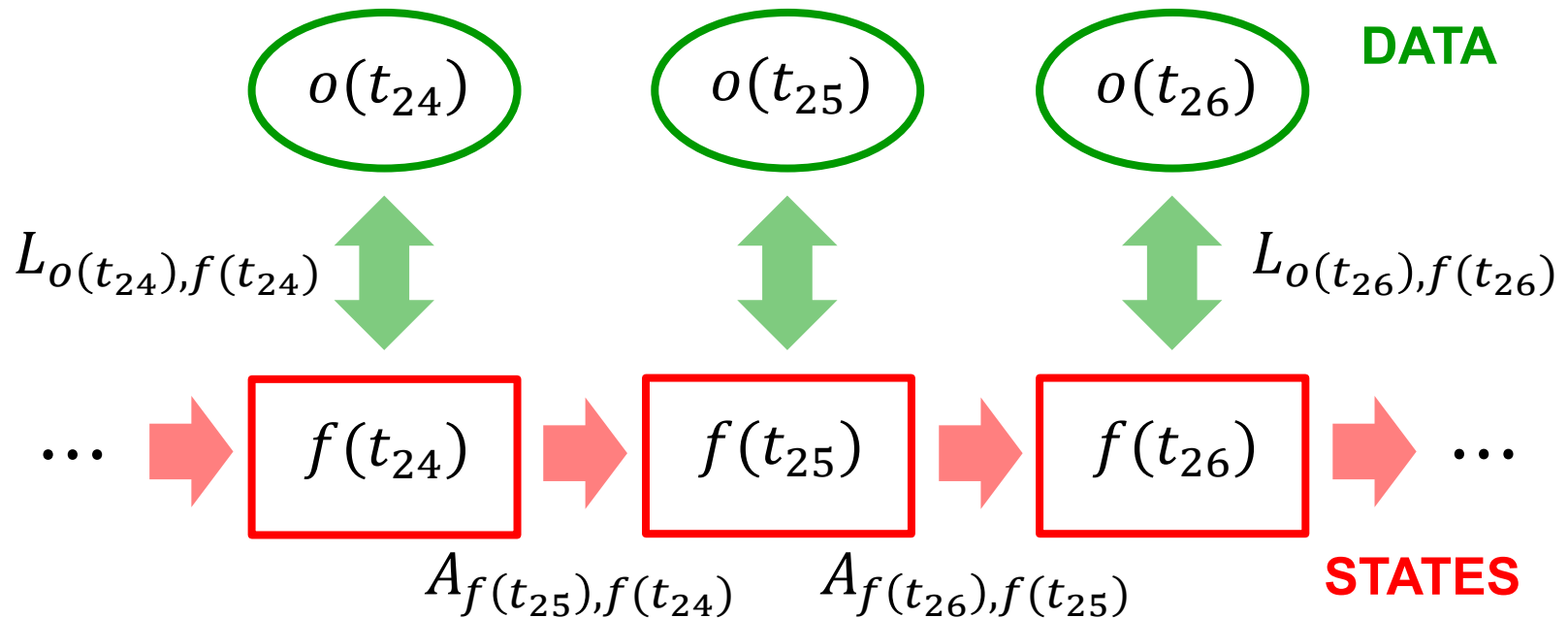
- Are large **braking indices** an artifact?

Talk by O'Neill #586, NS1, Wed 09:50

II. GLITCHES

Distinguishing timing noise and glitches
$\rightarrow$ complete glitch catalogue

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HIDDEN MARKOV MODEL

$o(t_{24})$ $o(t_{25})$ $o(t_{26})$ **DATA**

$L_{o(t_{24}),f(t_{24})}$ $L_{o(t_{26}),f(t_{26})}$

$\ldots$ $f(t_{24})$ $f(t_{25})$ $f(t_{26})$ $\ldots$
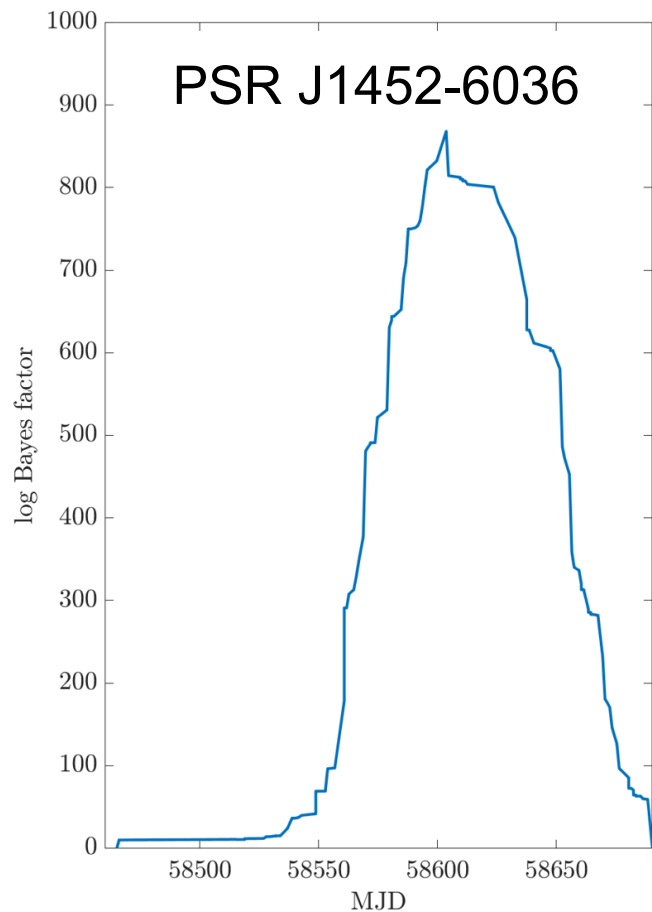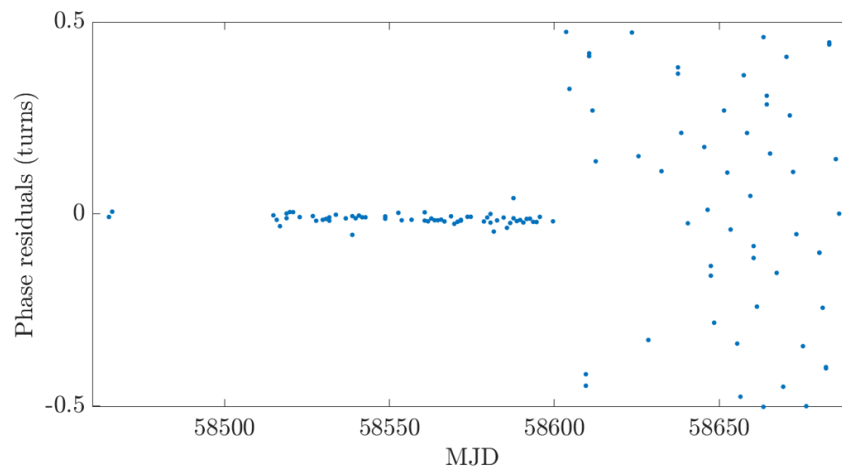
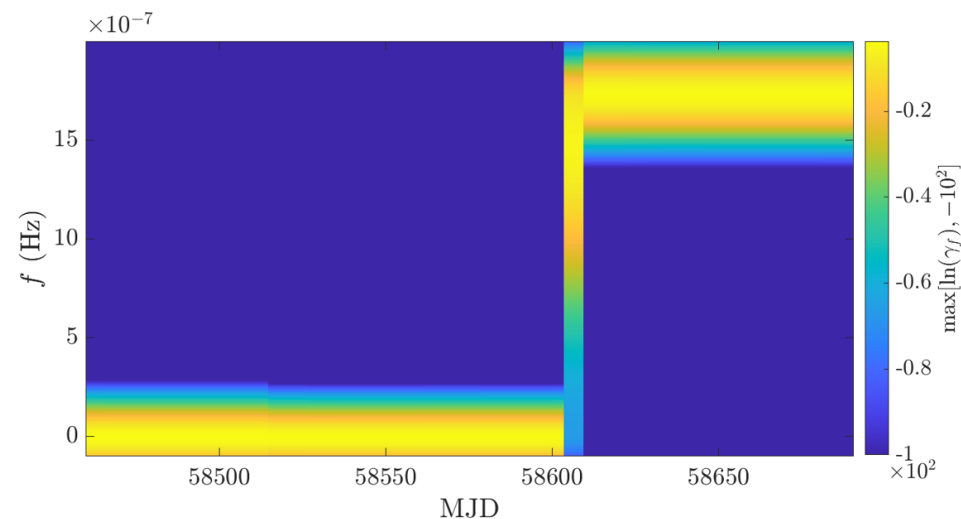$A_{f(t_{25}),f(t_{24})}$ $A_{f(t_{26}),f(t_{25})}$ **STATES**

- **Bayes factor:** glitch at time step t_k versus zero glitches (Melatos et al. 20)

- **Posterior** on frequency $f(t_k)$ and derivatives

TEMPO PHASE RESIDUALS

PSR J1452-6036

BAYES FACTOR

$f(t_k)$ POSTERIOR

$$P(O_{1:N_T}|M) = \sum_{F_{1:N_T}} \Pi_{f(t_1)} L_{o(t_1)f(t_1)} \prod_{n=2}^{N_T} A_{f(t_{n-1})f(t_n)} L_{o(t_n)f(t_n)}$$

FUTURE QUESTIONS

- Fast, systematic, unsupervised
- Real-time operation (UTMOST) (Dunn et al. 21)
- **False alarm** probability P_a? False dismissal?
- **Completeness:** smallest glitch detectable given P_a and timing noise amplitude?

- Most likely model for specific realization, cf. time-averaged noise spectrum (not stationary!)

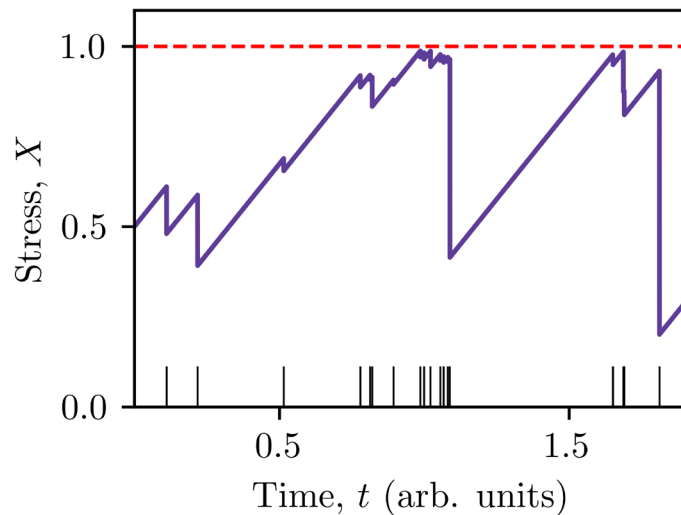**Talk by Dunn #637, NS3, Fri 08:35**

III. STRESS-RELAX DYNAMICS

Falsify meta-models of slow stress
accumulation and fast stress release,
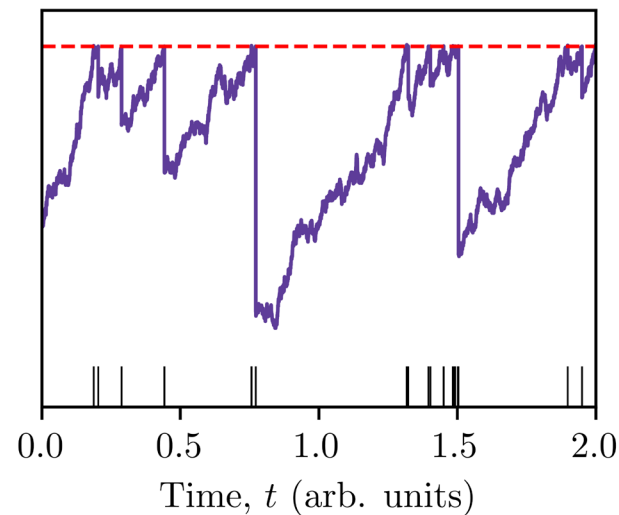e.g. starquakes, SF vortex avalanches

**LONG-TERM
GLITCH STATISTICS**

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STATE-DEPENDENT POISSON (SDP) — **BROWNIAN (BSA)**

- Globally uniform **"stress"** $X(t)$

- Between glitches: linear ramp, random walk

- **Trigger** (crust cracking, vortex unpinning…)
  - **SDP:** Poisson process whose rate $\lambda(t)$ increases as $X(t)$ approaches **threshold** X_{cr} (Fulgenzi et al. 17)
  - **BSA:** deterministic at $X(t) = X_{cr}$ (Carlin & Melatos 20)

PSR J0537 − 6910/Gaussian η
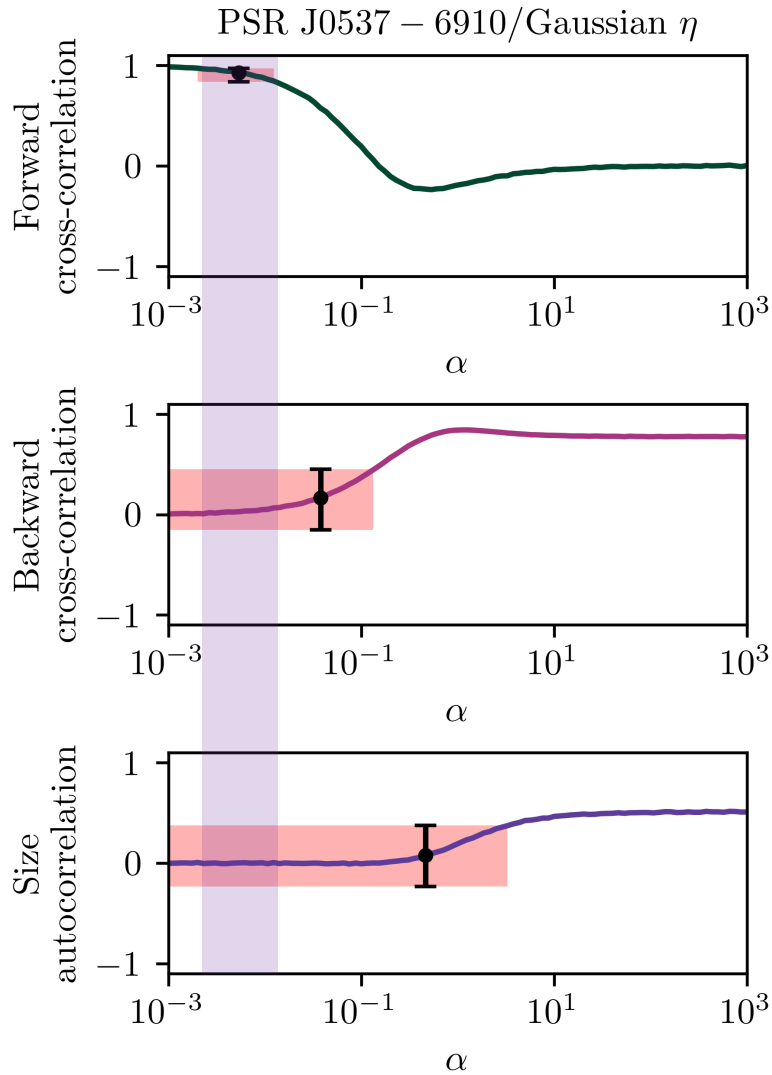
TORQUE

- Control parameter α ≈ reference trigger rate divided by torque

- **Size and waiting-time auto/cross-correlations**

- **Falsify** meta-model if red bands don't overlap in α! (Carlin & Melatos 19, 20, 21)

- Size and waiting-time PDFs (Fulgenzi et al. 17)

FUTURE QUESTIONS

- **Predict** what pulsars have strong **auto** and **cross-correlations** (Melatos et al. 18)

- Do existing data **falsify** SDP and/or BSA?

- When the torque doubles, do sizes double, waiting times halve, or a bit of both?

- Measure properties of **bulk nuclear superfluid,** e.g. vortex **pinning** forces

Talk by Carlin #585, NS3, Wed 12:00

SUMMARY

- Timing noise ↔ Kalman filter

- Measure crust-superfluid coupling

  O'NEILL #586

- Glitches ↔ hidden Markov model

- Complete glitch catalogue

  DUNN #637

- Stress-relax glitch dynamics

  CARLIN #585

- Falsify meta-models; measure nuclear pinning

Don't subtract randomness; track it!