NORTH AMERICAN NANOHERTZ OBSERVATORY for GRAVITATIONAL WAVES

NANOGrav Physics Frontiers Center

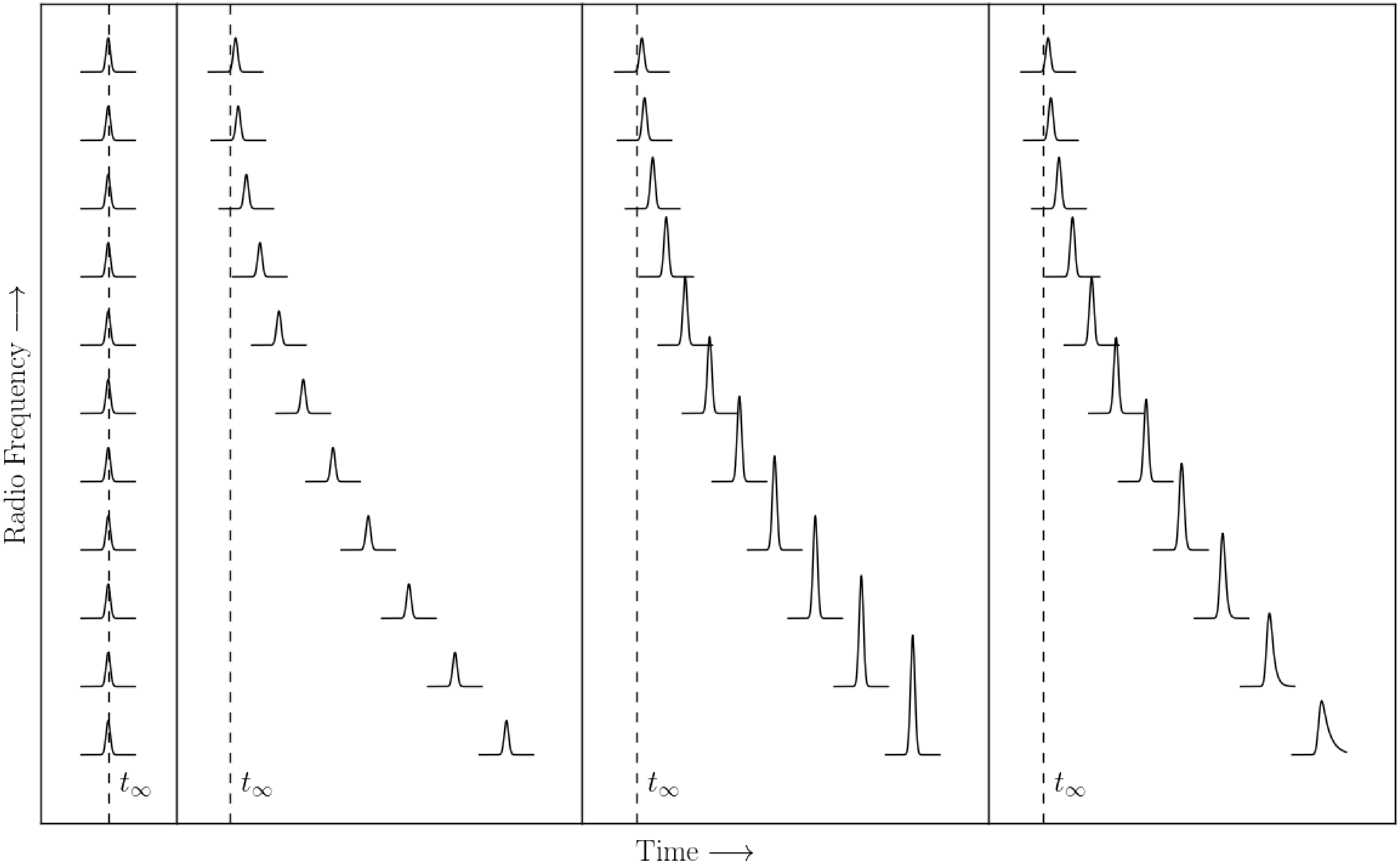
Optimal Frequency Ranges for Sub-Microsecond Precision Pulsar Timing

Michael T. Lam

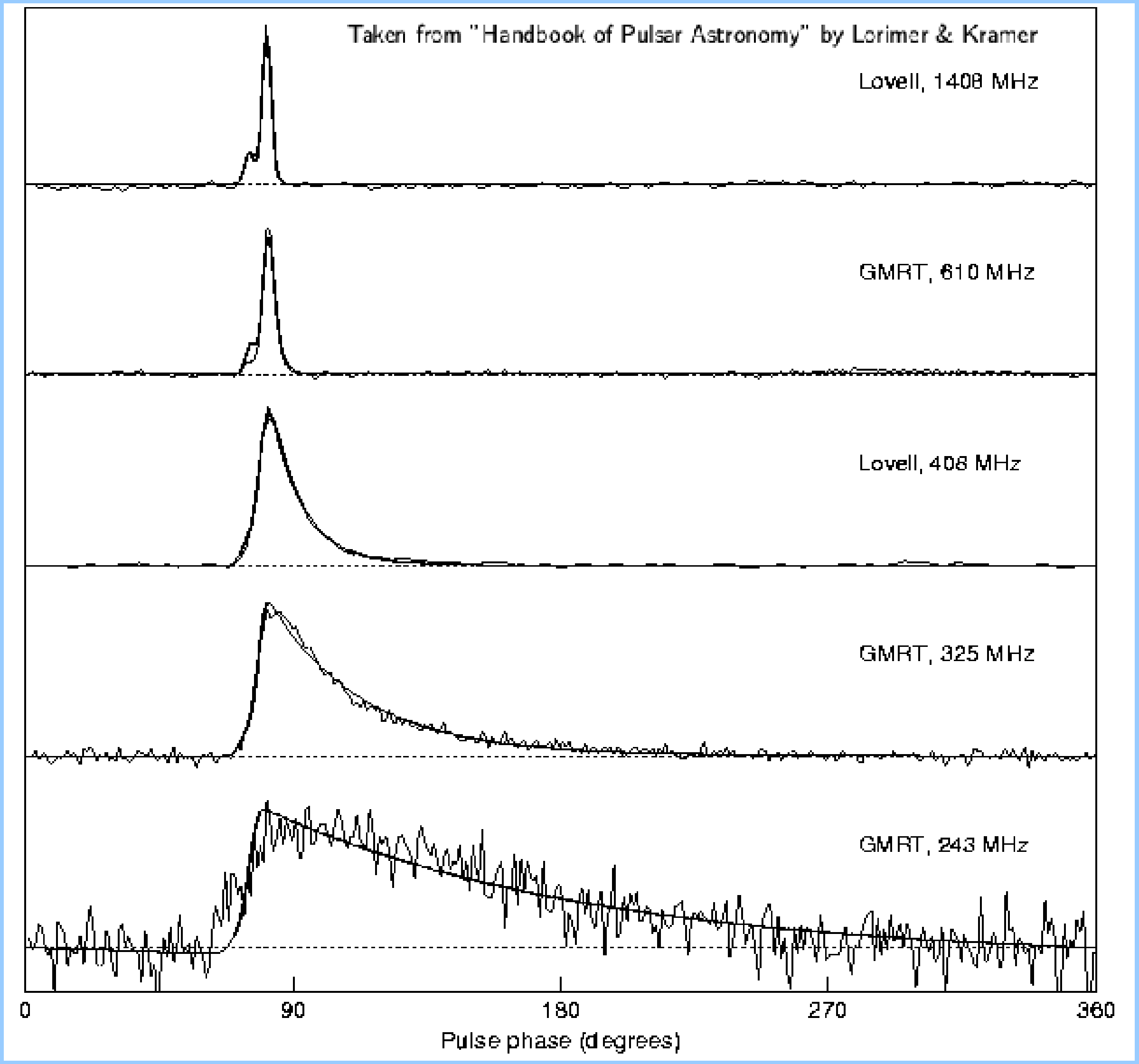
Transformative Science with GBO, 17 Oct 2017

GRAVITATIONAL WAVES AND COSMOLOGY

Frequency-Dependent Effects



Frequency-Dependent Effects



Lorimer & Kramer 2005

Frequency Optimization

Table 1
Selected Timing Effects

Term	Symbol	Dependence[a]	Section Discussed
Template-Fitting	$\sigma_{S/N}$	$\frac{W_{\rm eff}(\nu,\tau_{\rm d})}{S(\nu,\tau_{\rm d})\sqrt{N_\phi}} \propto \sqrt{BT}$	§2.2.1
Flux-Density Spectrum	I	$I_0\left(\frac{\nu}{\nu_0}\right)^{-\alpha}$	§2.2.1, Eq. 9
Profile Evolution	$U_{\rm int}$	Varies	§2.2.1, Eq. 8
Pulse Broadening	$h_{\rm PBF}$	$\tau_{\rm d,0}\left(\frac{\nu}{\nu_0}\right)^{-22/5}$	§2.2.1, Eq. 8
System Temperature	$T_{\rm sys}$	$\cdots$	§2.2.1, Eq. 11
Cosmic Microwave Background	$T_{\rm CMB}$	Constant	§2.2.1, Eq. 11
Receiver Bandpass	$T_{\rm rcvr}$	∼Constant	§2.2.1, Eq. 11
Galactic Background	$T_{\rm Gal}$	$T_{\rm Gal,0}\left(\frac{\nu}{\nu_0}\right)^{-\beta}$	§2.2.1, Eq. 11,12
Pulse Phase Jitter	$\sigma_{\rm J}$	∼Constant	§2.2.2
Diffractive Interstellar Scintillation[b]	$\sigma_{\rm DISS}$	$\approx \tau_{\rm d,0}\left(\frac{\nu}{\nu_0}\right)^{-8/5}\left(\frac{\Delta t_{\rm d,0}\Delta\nu_{\rm d,0}}{\eta_t\eta_\nu TB}\right)^{1/2}$	§2.2.3
DM Estimation	$\sigma_{\delta{\rm DM}}$	$\cdots$	§2.3.1, Eq. 24
from white-noise[c]	$\sigma_{\widehat{\rm DM}}$	$\simeq \frac{\epsilon_{\nu_1} - r^2\epsilon_{\nu_2}}{r^2-1}$	§2.3.1
from Systematic Chromatic Delays[c]	$\sigma_{\delta t_C}$	$\simeq \frac{t_{C,\nu_1} - r^2 t_{C,\nu_2}}{r^2-1}$	§2.3.1
from Frequency-Dependent DM	$\sigma_{{\rm DM}(\nu)}$	$\approx 9\ {\rm ns}\ k_{{\rm DM}(\nu)} E_{11/3}(r)\left(\frac{\nu}{\rm GHz}\right)^{-1}\left(\frac{\nu/\Delta\nu_{\rm d}}{100}\right)^{5/6}$	§2.3.1, Eq. 23
Telescope	$\sigma_{\rm tel}$	$\cdots$	§2.3.2
Polarization Calibration	$\sigma_{\rm pol}$	$\varepsilon\pi_{\rm V}W \sim \varepsilon\eta^{1/2}\pi_{\rm L}W$	§2.3.2, Eq. 25

[a] All variables are discussed in text.
[b] When the number of scintles $n_{\rm ISS}$ is large in both time and frequency.
[c] The form here shows the scaling for two individual narrowband frequencies.

Lam et al. 2017, submitted

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Term	Symbol	Dependence[a]
Template-Fitting	$\sigma_{S/N}$	$\dfrac{W_{\rm eff}(\nu,\tau_{\rm d})}{S(\nu,\tau_{\rm d})\sqrt{N_\phi}} \overset{\propto}{\approx} \sqrt{BT}$
Flux-Density Spectrum	I	$I_0\left(\dfrac{\nu}{\nu_0}\right)^{-\alpha}$
Profile Evolution	$U_{\rm int}$	Varies
Pulse Broadening	$h_{\rm PBF}$	$\tau_{\rm d,0}\left(\dfrac{\nu}{\nu_0}\right)^{-22/5}$
System Temperature	$T_{\rm sys}$	...
Cosmic Microwave Background	$T_{\rm CMB}$	Constant
Receiver Bandpass	$T_{\rm rcvr}$	$\sim$Constant
Galactic Background	$T_{\rm Gal}$	$T_{\rm Gal,0}\left(\dfrac{\nu}{\nu_0}\right)^{-\beta}$
Pulse Phase Jitter	$\sigma_{\rm J}$	$\sim$Constant
Diffractive Interstellar Scintillation[b]	$\sigma_{\rm DISS}$	$\approx \tau_{\rm d,0}\left(\dfrac{\nu}{\nu_0}\right)^{-8/5}\left(\dfrac{\Delta t_{\rm d,0}\Delta\nu_{\rm d,0}}{\eta_t\eta_\nu TB}\right)^{1/2}$
DM Estimation	$\sigma_{\delta{\rm DM}}$	...
from white-noise[c]	$\sigma_{\widehat{\rm DM}}$	$\simeq \dfrac{\epsilon_{\nu_1} - r^2\epsilon_{\nu_2}}{r^2-1}$
from Systematic Chromatic Delays[c]	$\sigma_{\delta t_C}$	$\simeq \dfrac{t_{C,\nu_1} - r^2 t_{C,\nu_2}}{r^2-1}$
from Frequency-Dependent DM	$\sigma_{{\rm DM}(\nu)}$	$\approx 9\ {\rm ns}\ k_{{\rm DM}(\nu)}E_{11/3}(r)\left(\dfrac{\nu}{\rm GHz}\right)^{-1}\left(\dfrac{\nu/\Delta\nu_{\rm d}}{100}\right)^{5/6}$
Telescope	$\sigma_{\rm tel}$	...
Polarization Calibration	$\sigma_{\rm pol}$	$\varepsilon\pi_{\rm V}W \sim \varepsilon\eta^{1/2}\pi_{\rm L}W$

[a] All variables are discussed in text.
[b] When the number of scintles $n_{\rm ISS}$ is large in both time and frequency.
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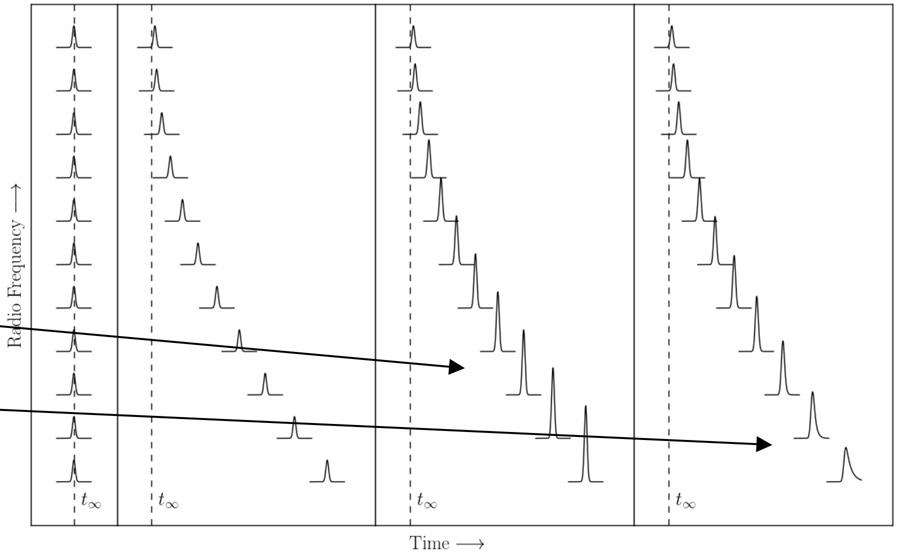

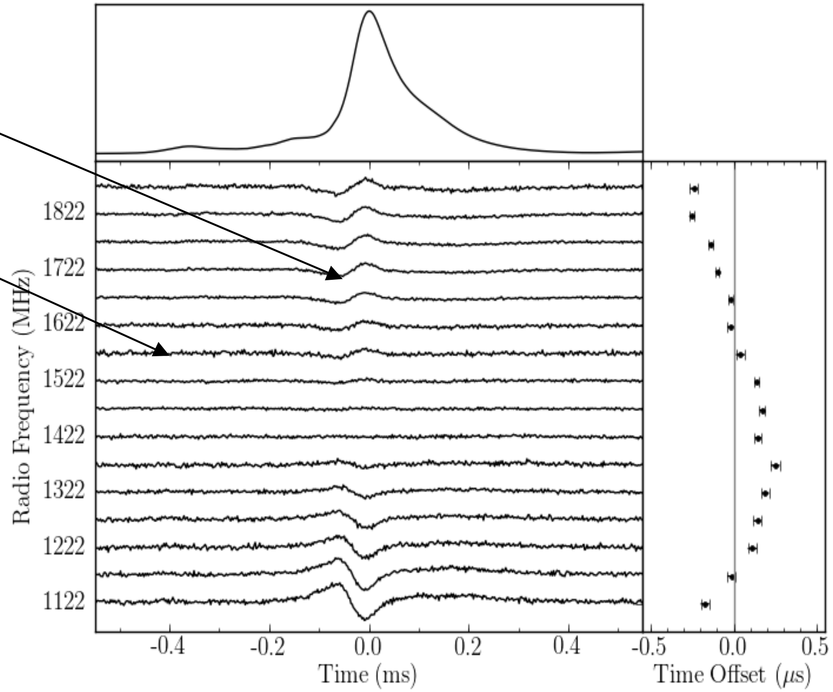

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Term	Symbol	Dependence[a]
Template-Fitting	$\sigma_{\rm S/N}$	$\frac{W_{\rm eff}(\nu,\tau_{\rm d})}{S(\nu,\tau_{\rm d})\sqrt{N_\phi}} \overset{\propto}{\approx} \sqrt{BT}$
Flux-Density Spectrum	I	$I_0\left(\frac{\nu}{\nu_0}\right)^{-\alpha}$
Profile Evolution	$U_{\rm int}$	Varies
Pulse Broadening	$h_{\rm PBF}$	$\tau_{\rm d,0}\left(\frac{\nu}{\nu_0}\right)^{-22/5}$
System Temperature	$T_{\rm sys}$	$\cdots$
Cosmic Microwave Background	$T_{\rm CMB}$	Constant
Receiver Bandpass	$T_{\rm rcvr}$	$\sim$Constant
Galactic Background	$T_{\rm Gal}$	$T_{\rm Gal,0}\left(\frac{\nu}{\nu_0}\right)^{-\beta}$
Pulse Phase Jitter	$\sigma_{\rm J}$	$\sim$Constant
Diffractive Interstellar Scintillation[b]	$\sigma_{\rm DISS}$	$\approx \tau_{\rm d,0}\left(\frac{\nu}{\nu_0}\right)^{-8/5}\left(\frac{\Delta t_{\rm d,0}\Delta\nu_{\rm d,0}}{\eta_t\eta_\nu TB}\right)^{1/2}$
DM Estimation	$\sigma_{\delta \rm DM}$	$\cdots$
from white-noise[c]	$\sigma_{\widehat{\rm DM}}$	$\simeq \frac{\epsilon_{\nu_1} - r^2\epsilon_{\nu_2}}{r^2-1}$
from Systematic Chromatic Delays[c]	$\sigma_{\delta t_C}$	$\simeq \frac{t_{C,\nu_1} - r^2 t_{C,\nu_2}}{r^2-1}$
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Telescope	$\sigma_{\rm tel}$	$\cdots$
Polarization Calibration	$\sigma_{\rm pol}$	$\varepsilon\pi_{\rm V}W \sim \varepsilon\eta^{1/2}\pi_{\rm L}W$

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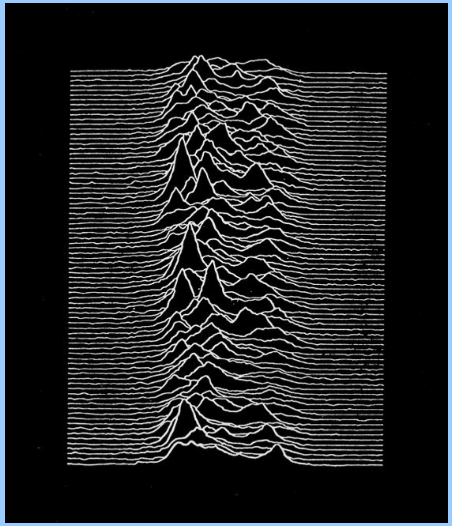
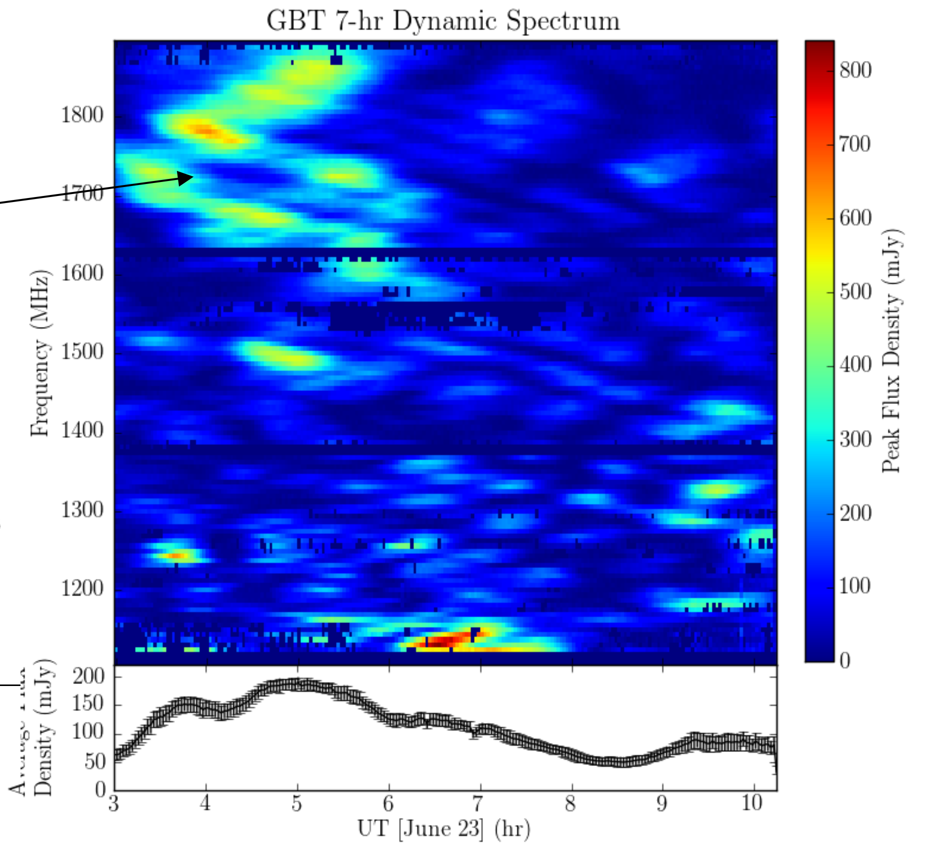


Time ⟶



BR: NANOGrav Data

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Selected Timing Effects

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Template-Fitting	$\sigma_{S/N}$	$\dfrac{W_{\rm eff}(\nu,\tau_{\rm d})}{S(\nu,\tau_{\rm d})\sqrt{N_\phi}} \propto \sqrt{BT}$
Flux-Density Spectrum	I	$I_0\left(\dfrac{\nu}{\nu_0}\right)^{-\alpha}$
Profile Evolution	$U_{\rm int}$	Varies
Pulse Broadening	$h_{\rm PBF}$	$\tau_{\rm d,0}\left(\dfrac{\nu}{\nu_0}\right)^{-22/5}$
System Temperature	$T_{\rm sys}$	...
Cosmic Microwave Background	$T_{\rm CMB}$	Constant
Receiver Bandpass	$T_{\rm rcvr}$	$\sim$Constant
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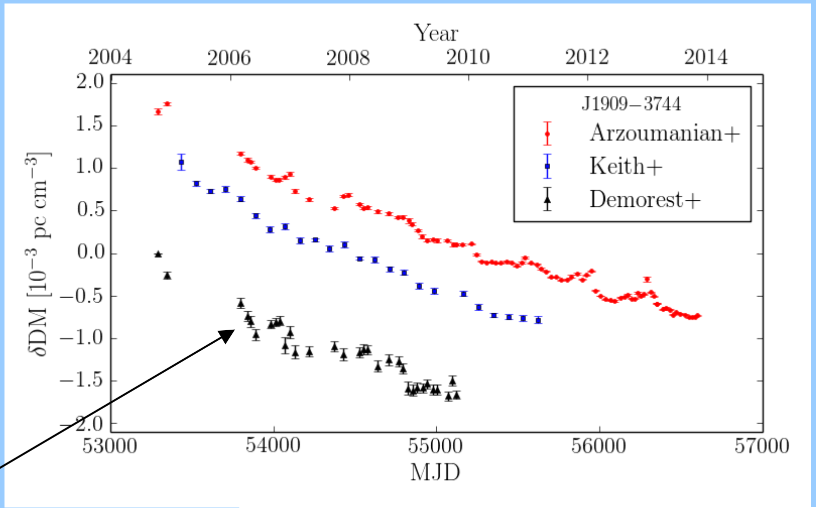

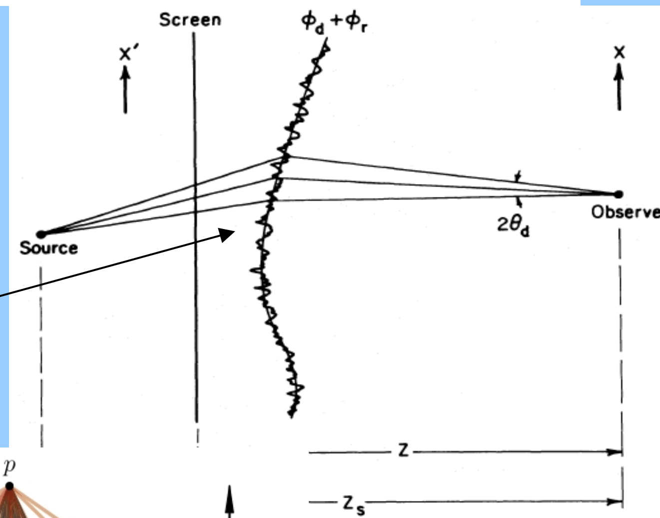

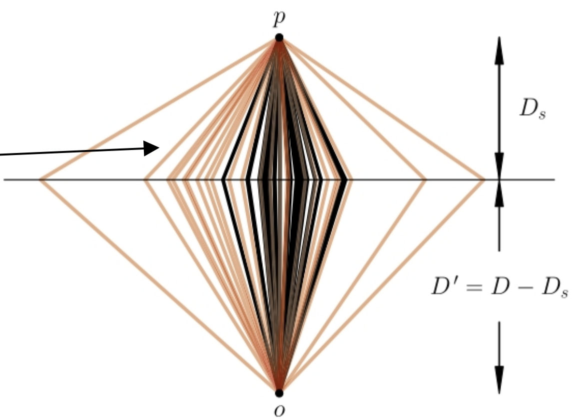

TR: Lam et al 2016b
MR: Cordes et al 1986
BR: Cordes et al 2016

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Selected Timing Effects

Term	Symbol	Dependence[a]
Template-Fitting	$\sigma_{S/N}$	$\frac{W_{eff}(\nu,\tau_d)}{S(\nu,\tau_d)\sqrt{N_\phi}} \overset{\propto}{\approx} \sqrt{BT}$
Flux-Density Spectrum	I	$I_0\left(\frac{\nu}{\nu_0}\right)^{-\alpha}$
Profile Evolution	U_{int}	Varies
Pulse Broadening	h_{PBF}	$\tau_{d,0}\left(\frac{\nu}{\nu_0}\right)^{-22/5}$
System Temperature	T_{sys}	$\cdots$
Cosmic Microwave Background	T_{CMB}	Constant
Receiver Bandpass	T_{rcvr}	~Constant
Galactic Background	T_{Gal}	$T_{Gal,0}\left(\frac{\nu}{\nu_0}\right)^{-\beta}$
Pulse Phase Jitter	σ_J	~Constant
Diffractive Interstellar Scintillation[b]	σ_{DISS}	$\approx \tau_{d,0}\left(\frac{\nu}{\nu_0}\right)^{-8/5}\left(\frac{\Delta t_{d,0}\Delta\nu_{d,0}}{\eta_t\eta_\nu TB}\right)^{1/2}$
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Telescope	σ_{tel}	$\cdots$
Polarization Calibration	σ_{pol}	$\varepsilon\pi_V W \sim \varepsilon\eta^{1/2}\pi_L W$

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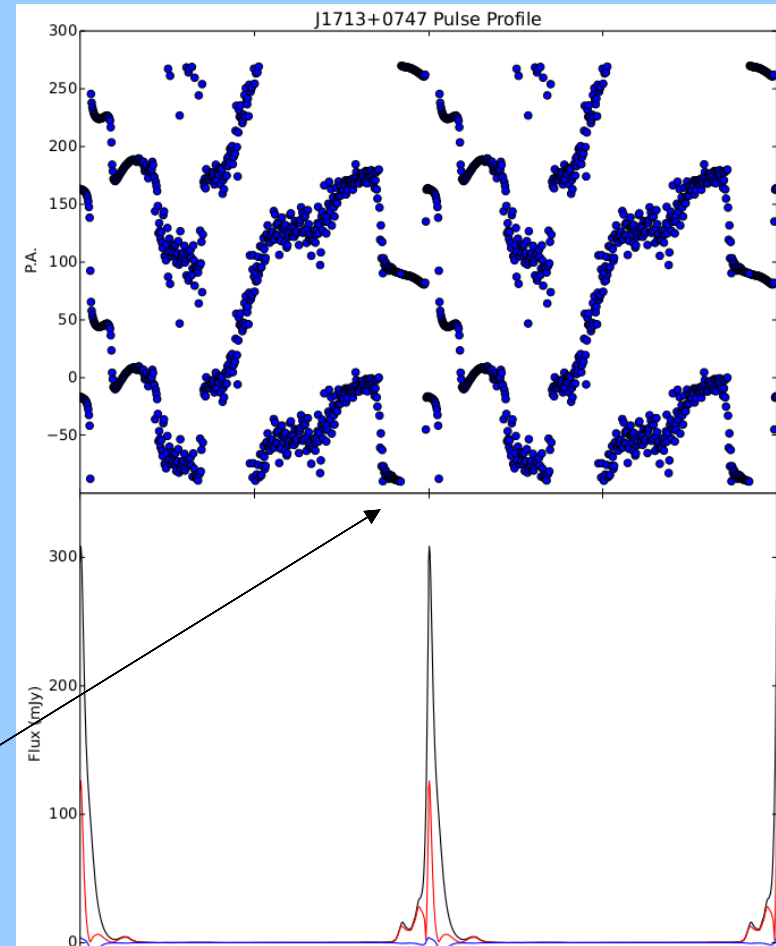
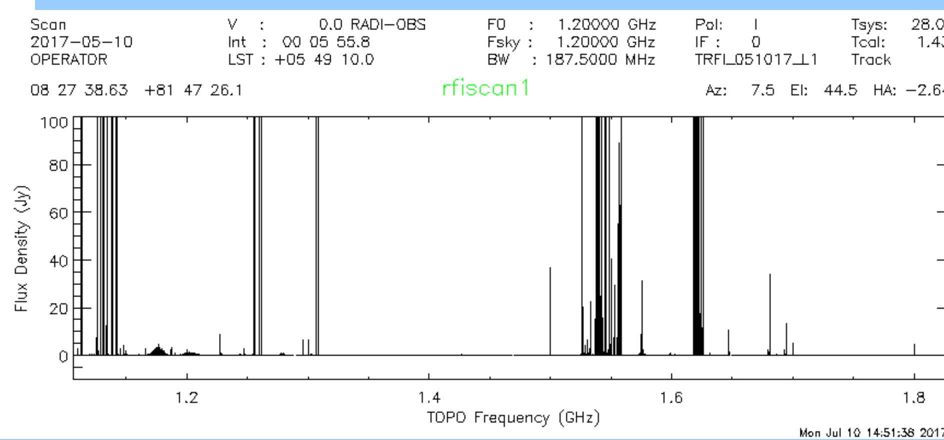
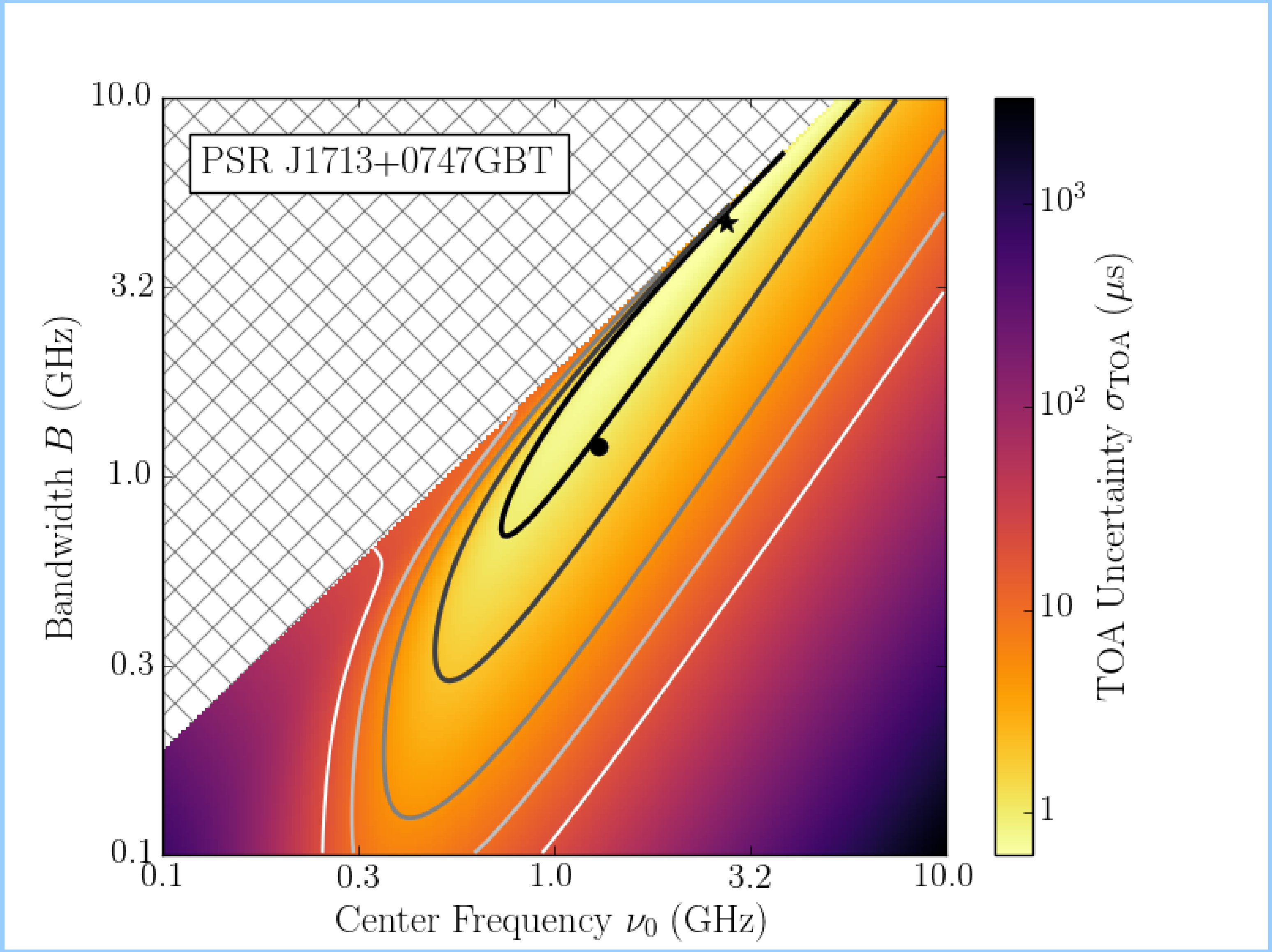




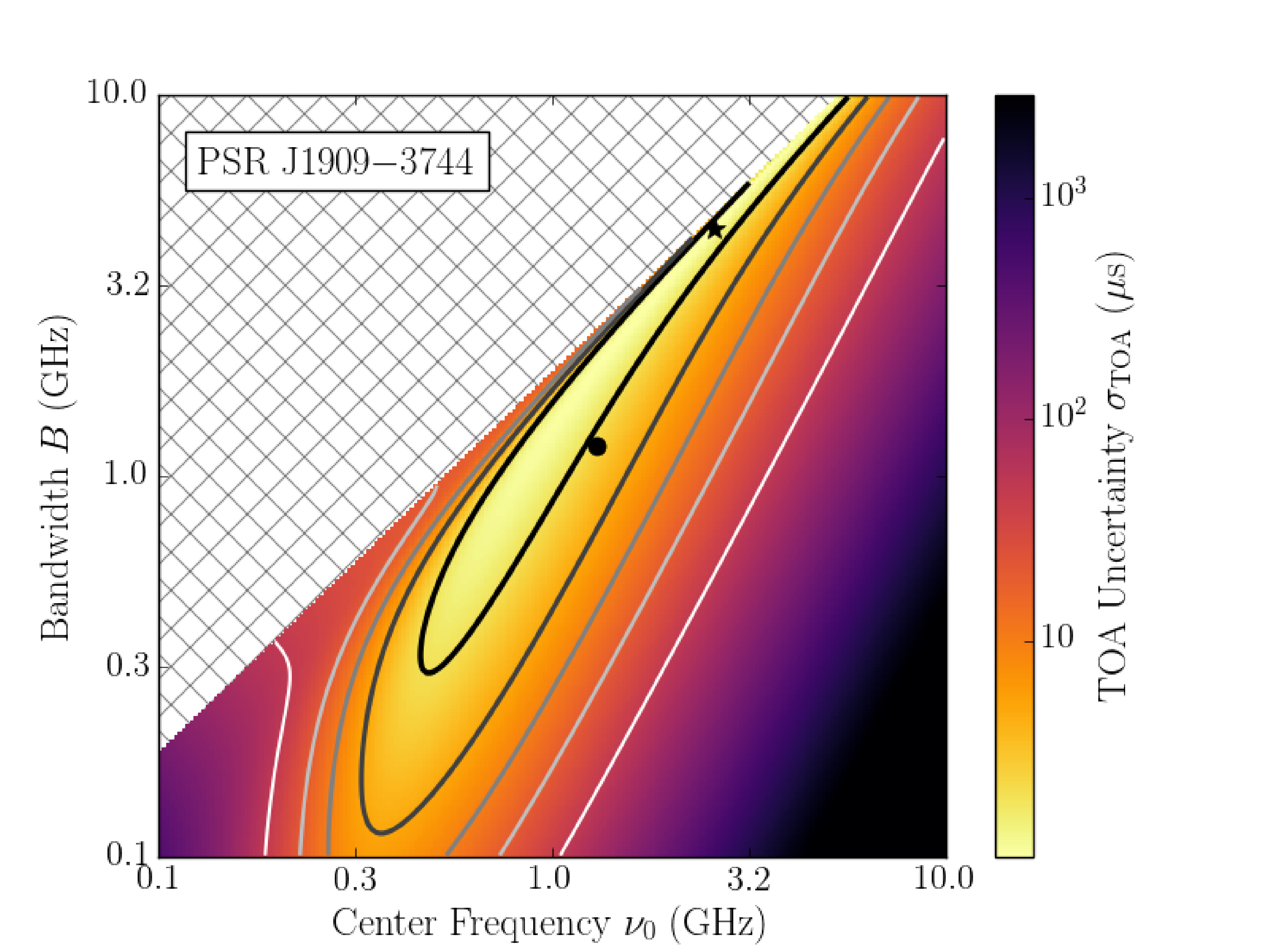
TR: Gentile et al in prep
BR: Green Bank RFI Scans

Frequency Optimization



Lam et al. 2017, submitted

Frequency Optimization



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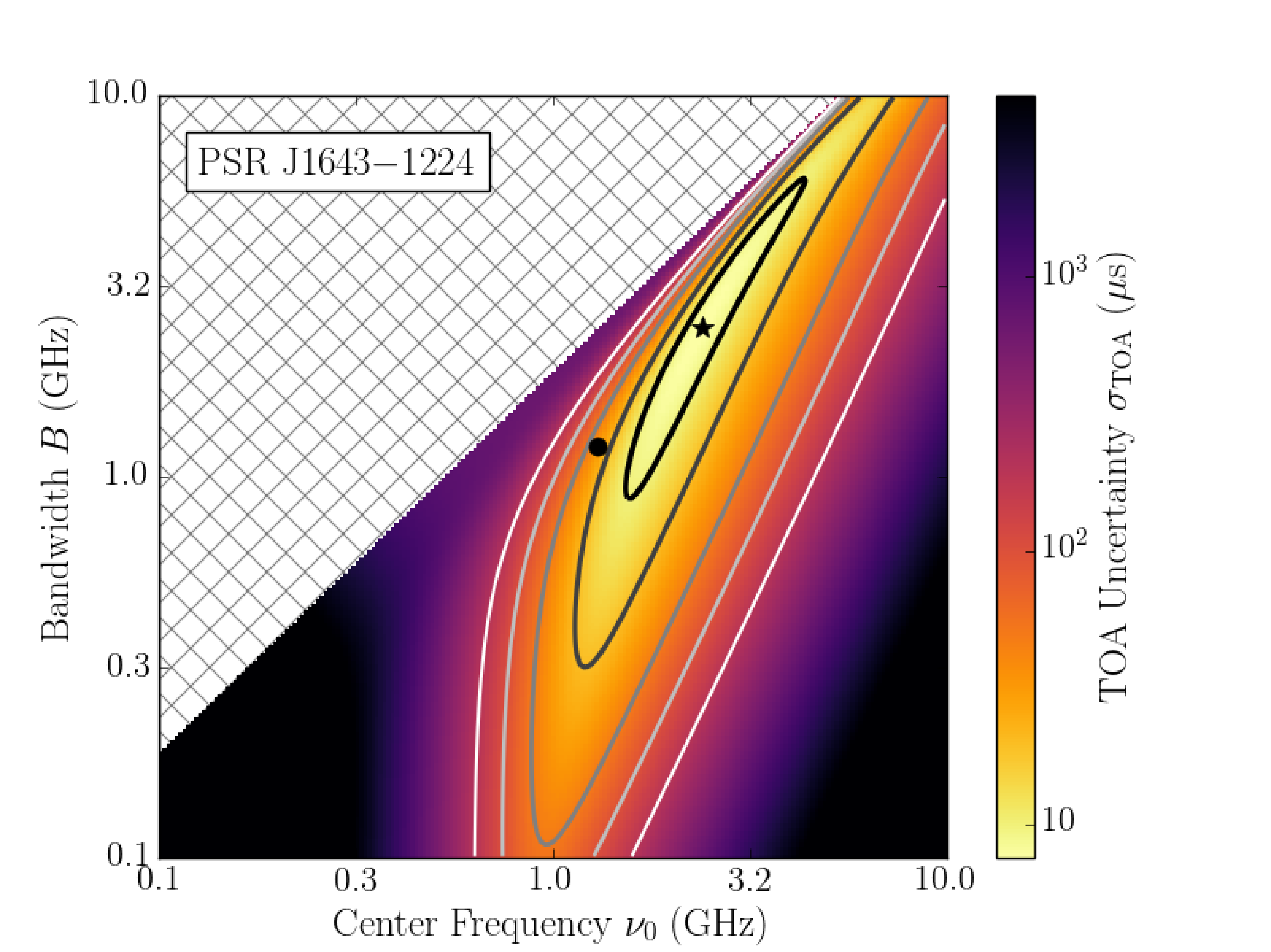

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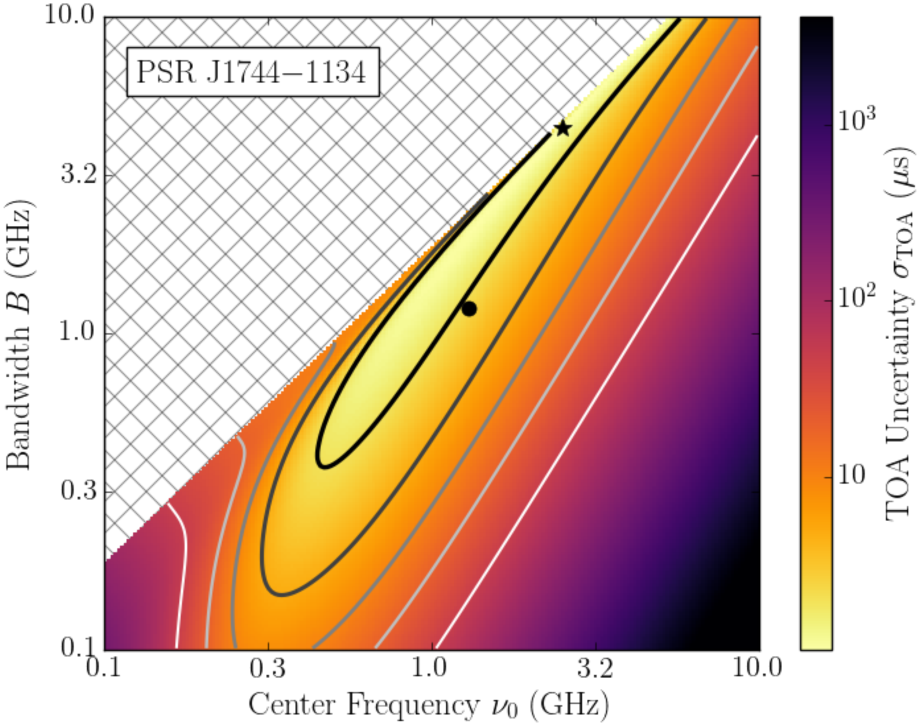

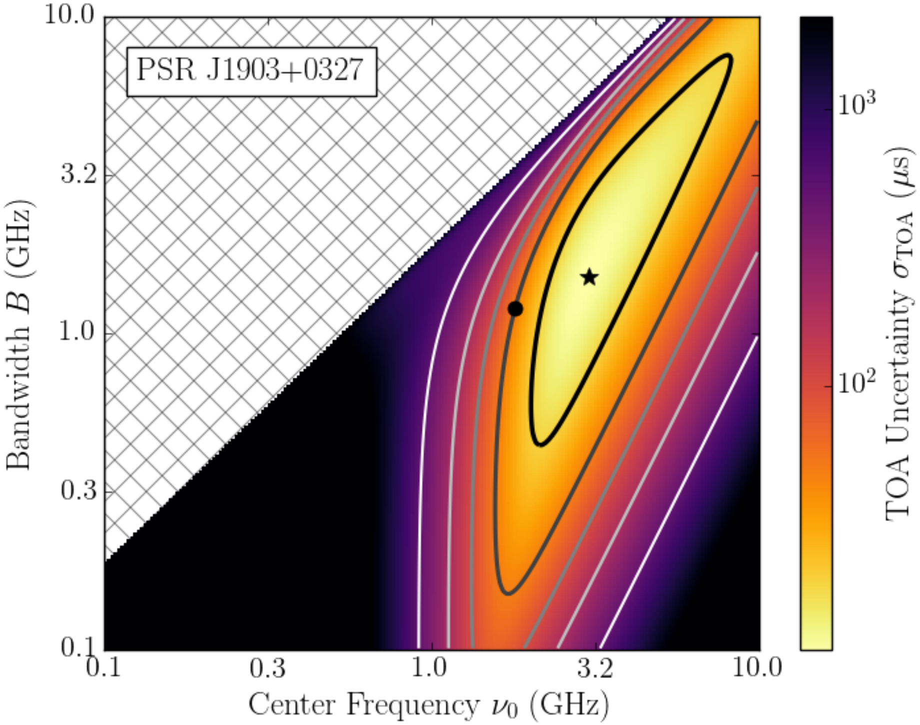

Lam et al. 2017, submitted

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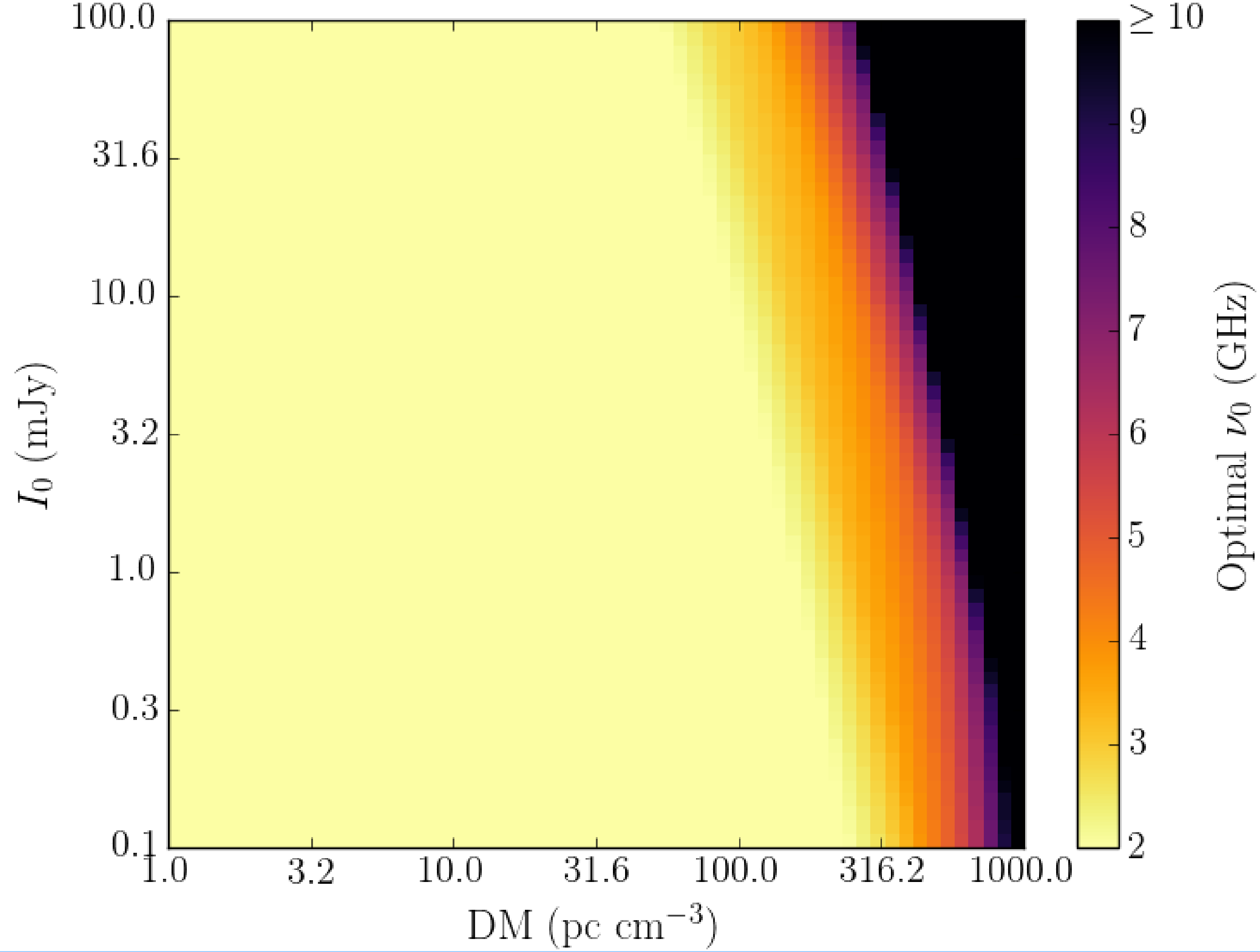
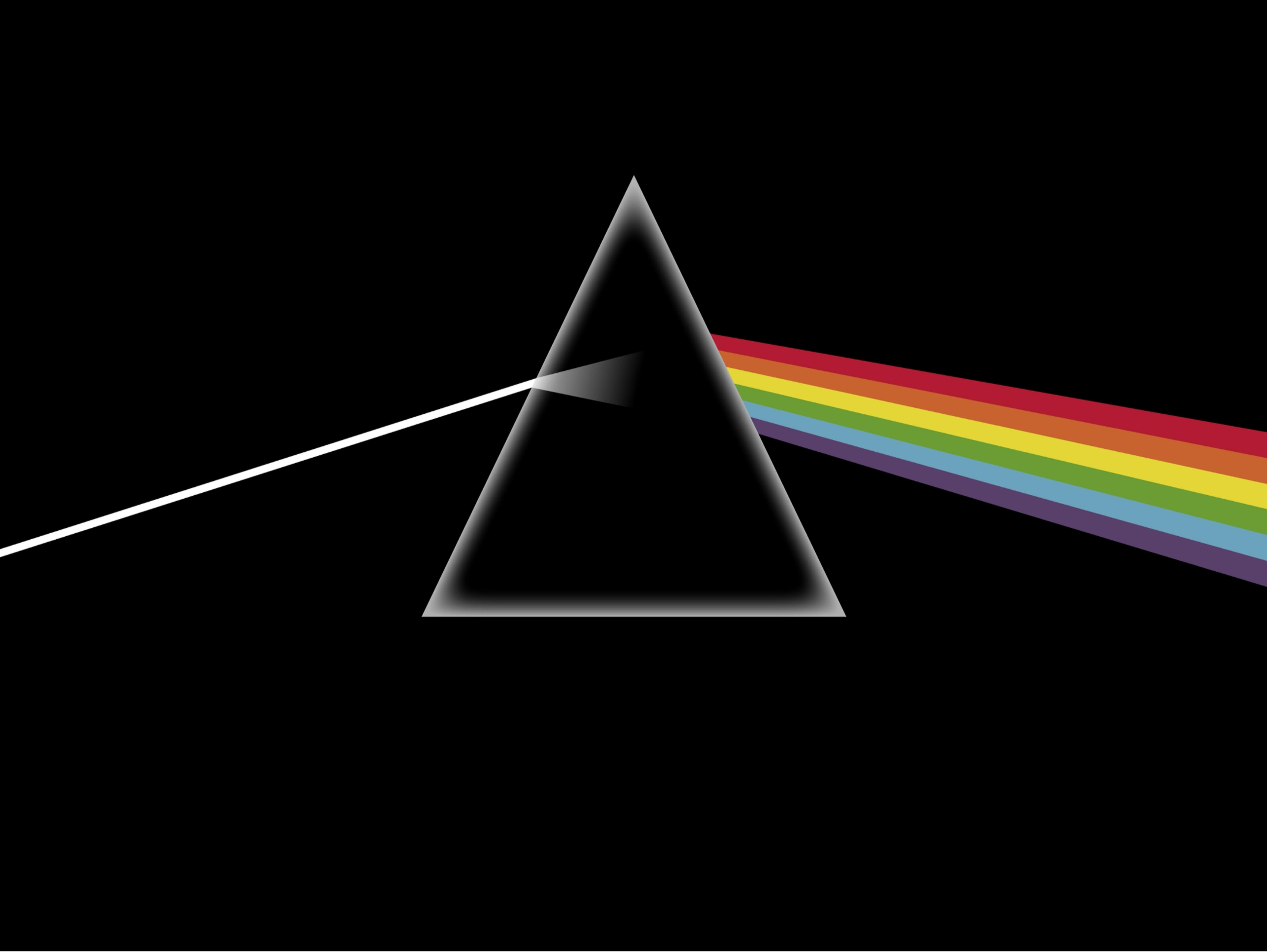


Lam et al. 2017, submitted

Points to Remember

- Wideband receiver ↑ > System Temperature ↑
- Multiple receivers can provide coverage
- Do NOT reduce bandwidth
- Timing RMS can be very different
- PTA optimization is an ongoing effort



Extra Slides