

From Domain Walls to Cosmic Strings: What Can LISA Actually Reconstruct?

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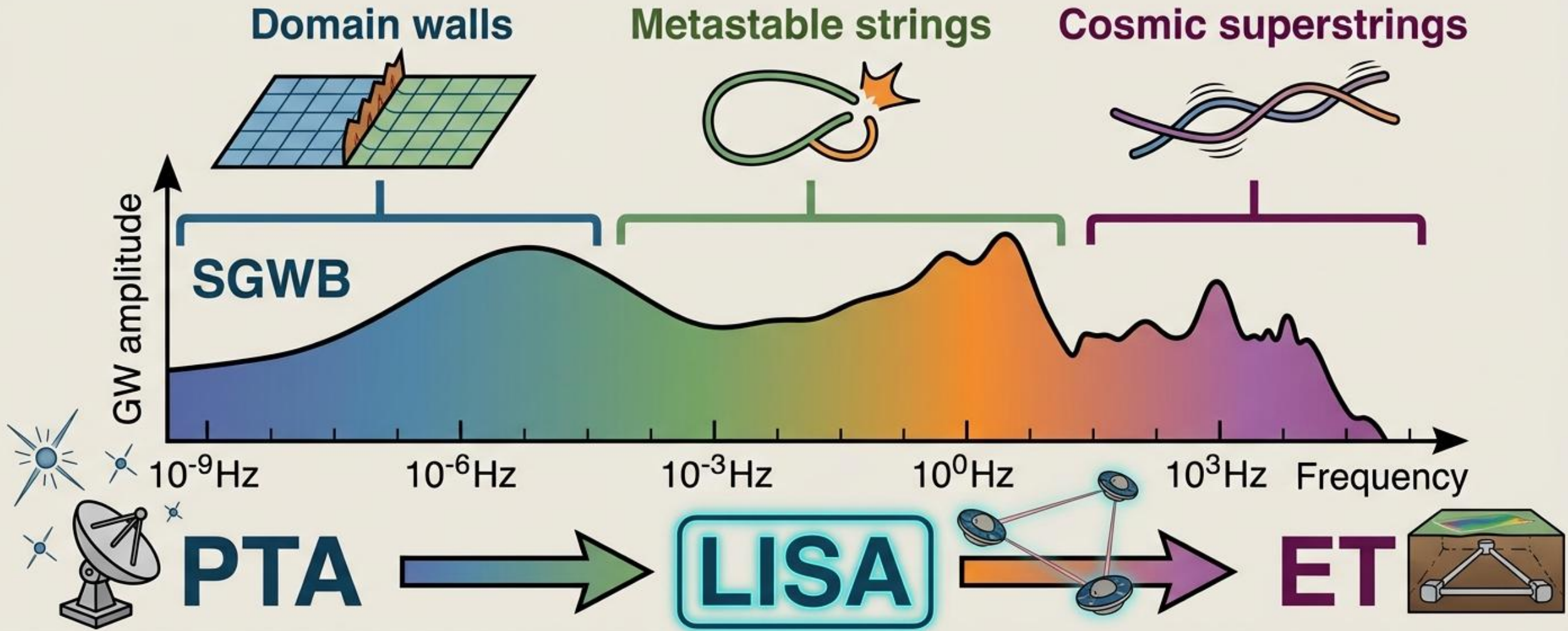
Nanjing Normal University

Based on: 2606.09713, 2606.15387, 2607.28592, 2608.19406

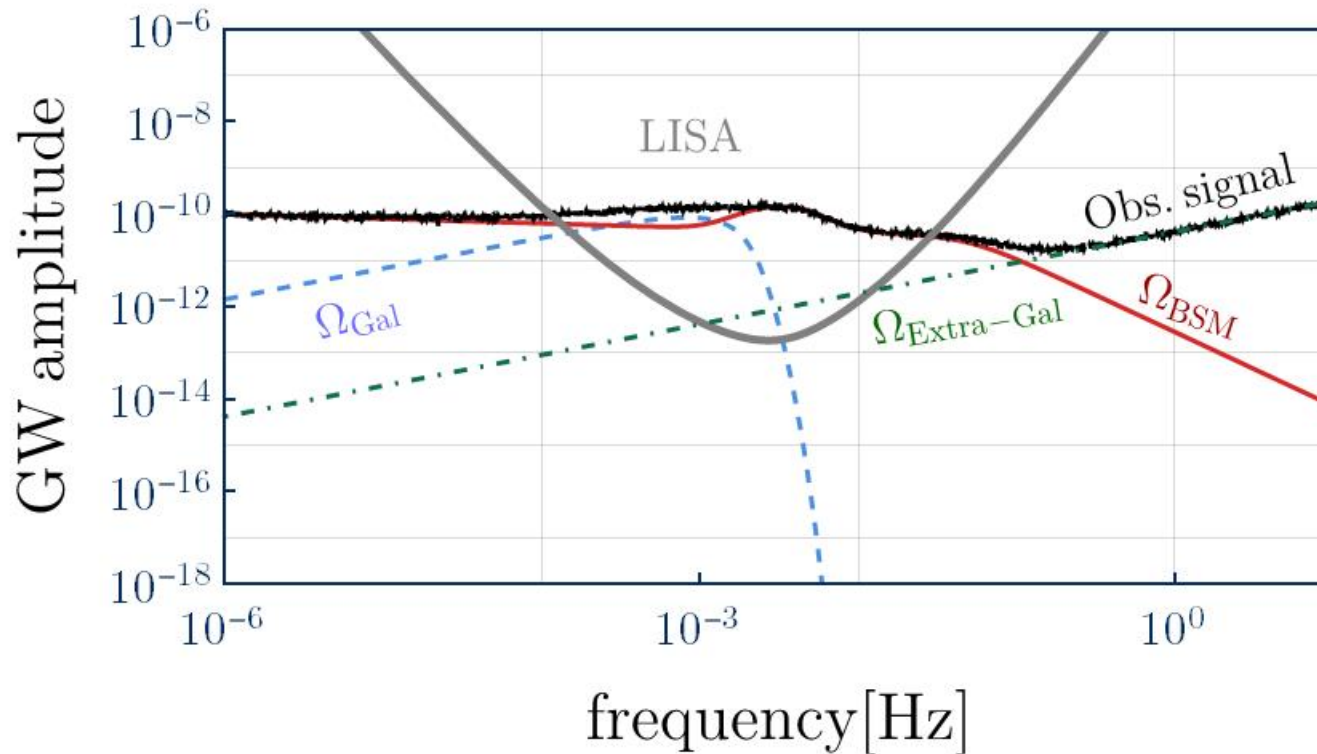
Collab: R. Samanta

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LISA does not see the cosmological signal alone.



Observed data $\neq$ BSM signal alone

Cosmological SGWB: Ω_{BSM}

Galactic DWD confusion: Ω_{Gal}

Extragalactic compact binaries: $\Omega_{\text{Extra-Gal}}$

Instrumental noise: N_{inst}

The source parameters must be inferred while accounting for the astrophysical and instrumental environment.

Joint Bayesian inference

10 parameters = 2 signal + 8 nuisance

From source physics to a posterior

$$\theta$$



$$\Omega_{\text{GW}}(f; \theta)$$



$$d(f)$$



$$p(\theta, \eta \mid d)$$

Source Physics

e.g. (α_*, T_*)
 $(G\mu, \kappa_{\text{CS}})$
 $(G\mu, P)$

Physical Spectrum

GW amplitude +
peak/turnover +
spectral shape

Realistic LISA data

signal + foregrounds +
instrumental noise :
A, E, T channels

Bayesian Posterior

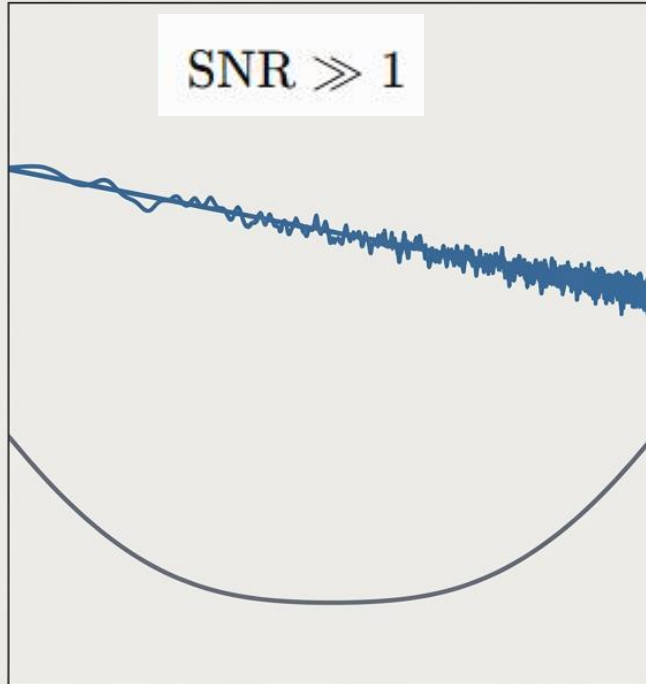
Reconstruction of
Source and nuisance
parameters

$$\Omega_{\text{GW}}(f) = \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \ln f}.$$

Physics $\rightarrow$ Spectrum $\rightarrow$ Observation $\rightarrow$ Inference

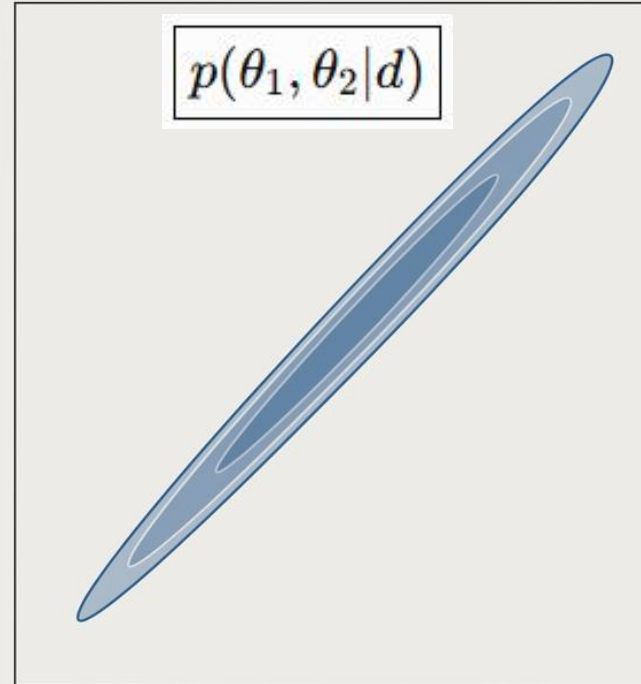
A loud signal can still hide its physics

Detection



Signal clearly detected

Reconstruction



But which parameters produced it?

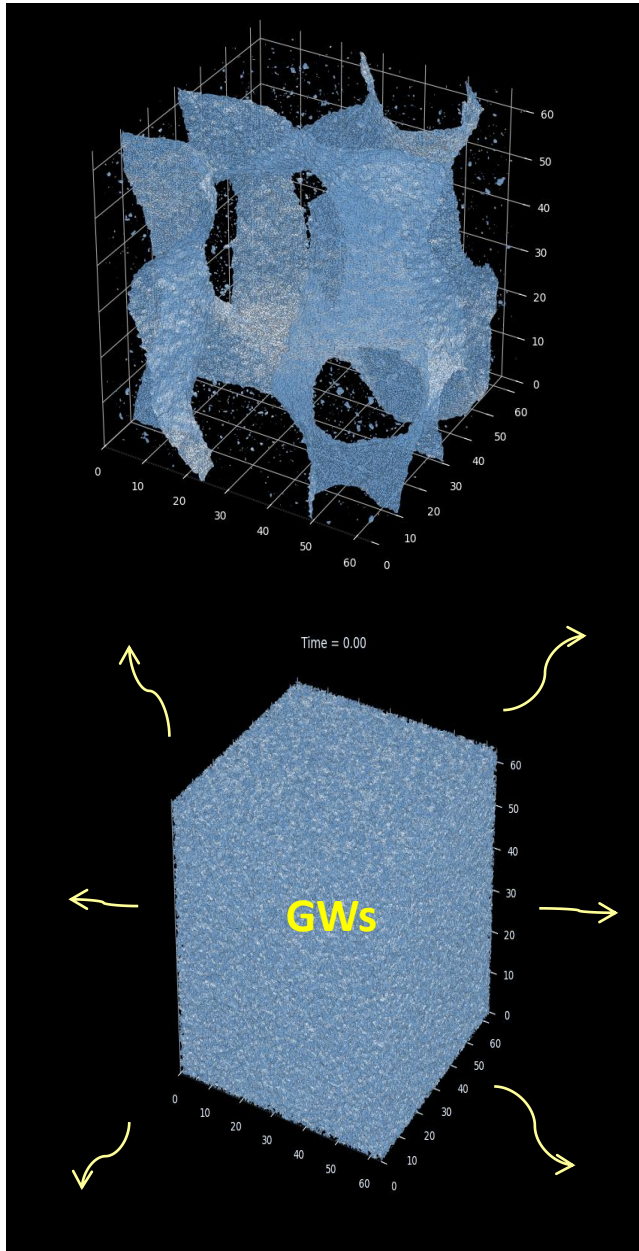
Detection $\neq$ Reconstruction

High SNR $\nRightarrow$ unique parameters

Amplitude + Frequency leverage + Spectral shape $\Rightarrow$ Physical information

Next: Domain walls — the cleanest example of this principle.

Domain walls: the spectrum carries the physics



$$\Omega_{\text{GW}} h^2 = \frac{3}{32\pi} \mathcal{D} \tilde{\epsilon} \alpha_*^2 \mathcal{S}\left(\frac{f}{f_p}\right)$$

α_* : wall energy fraction at annihilation

T_* : annihilation temperature

$$\mathcal{S}(x) = \frac{(a+b)^c}{(bx^{-a/c} + ax^{b/c})^c}, \quad x \equiv \frac{f}{f_p}$$

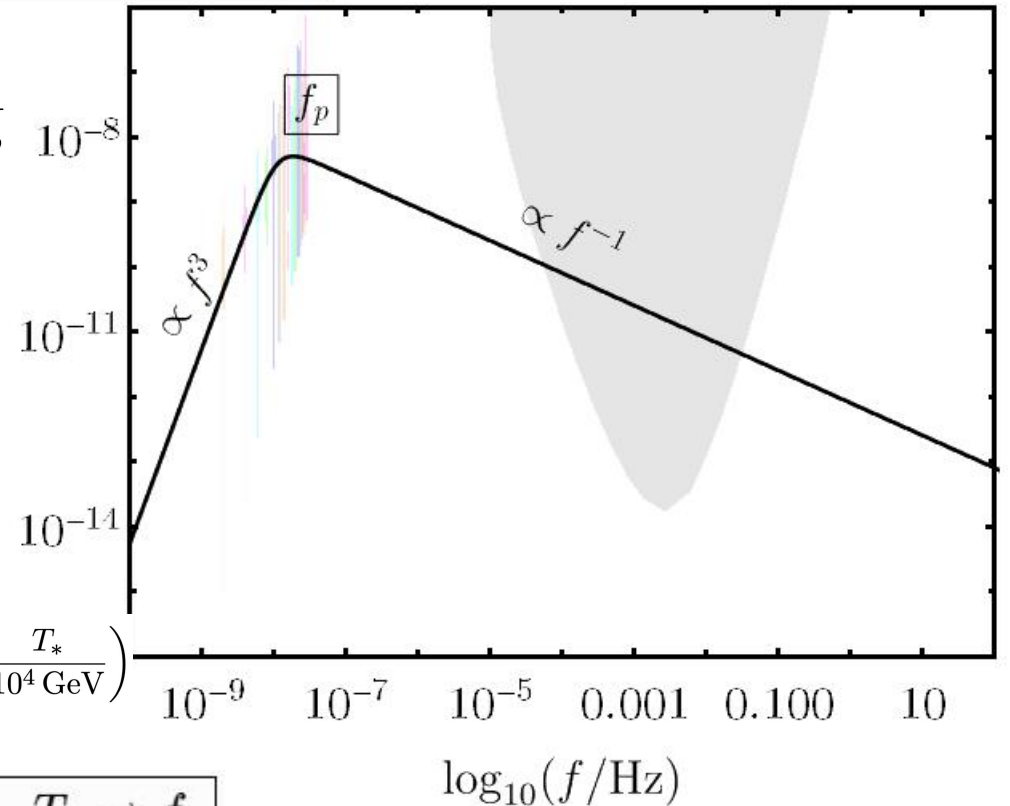
$$a = 3, \quad b = 1, \quad c = 1$$

$$\log_{10}(\Omega_{\text{GW}} h^2)$$

$$f_p = 1.14 \text{ mHz} \left(\frac{10.75}{g_{*,s}}\right)^{1/3} \left(\frac{g_*}{10.75}\right)^{1/2} \left(\frac{T_*}{10^4 \text{ GeV}}\right)$$

$$\alpha_* \rightarrow \text{amplitude}, \quad T_* \rightarrow f_p$$

α_* controls the scale; T_* sets where the spectrum appears.



When LISA sees only one side of the spectrum

$$\mathcal{S}(x) = \frac{(a+b)^c}{(b x^{-a/c} + a x^{b/c})^c}, \quad x \equiv \frac{f}{f_p}$$

$$\Omega_{\text{GW}} h^2 = \frac{3}{32\pi} \mathcal{D} \tilde{\epsilon} \alpha_*^2 \mathcal{S}(f/f_p)$$

$$\mathcal{S}(f/f_p) \simeq \frac{4}{3} \left(\frac{f}{f_p} \right)^{-1} \quad (f \gg f_p)$$

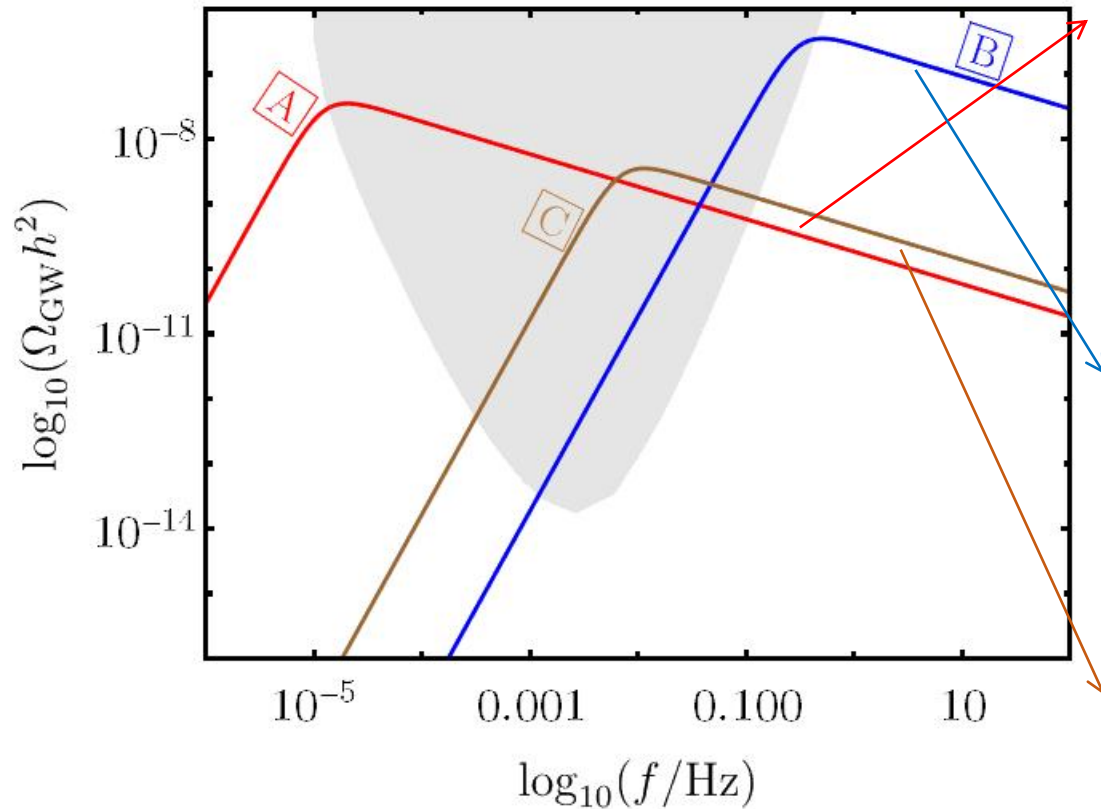
$$\Omega_{\text{GW}} h^2 \propto \alpha_*^2 f_p \propto \alpha_*^2 T_*$$

$$\alpha_*^2 T_* = \text{const.}$$

$$\mathcal{S}(f/f_p) \simeq 4 \left(\frac{f}{f_p} \right)^3 \quad (f \ll f_p)$$

$$\Omega_{\text{GW}} h^2 \propto \alpha_*^2 f_p^{-3} \propto \alpha_*^2 T_*^{-3}$$

$$\alpha_*^2 T_*^{-3} = \text{const.}$$



Case A: LISA samples UV side

Case B: LISA samples IR side

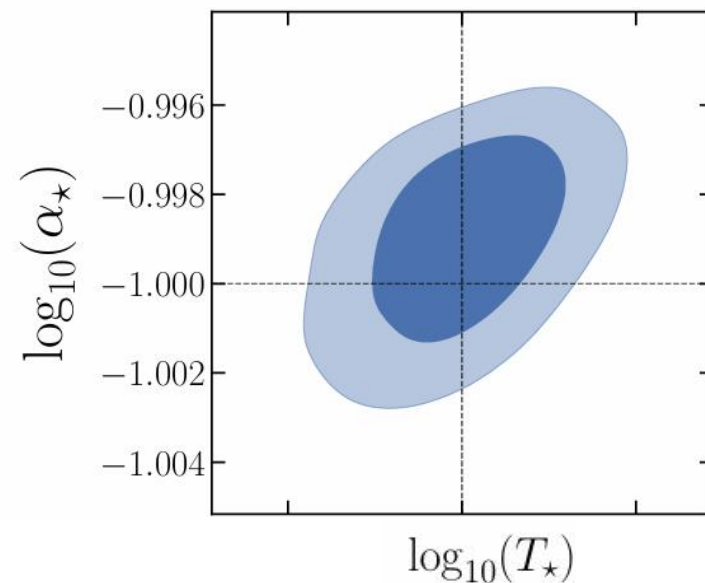
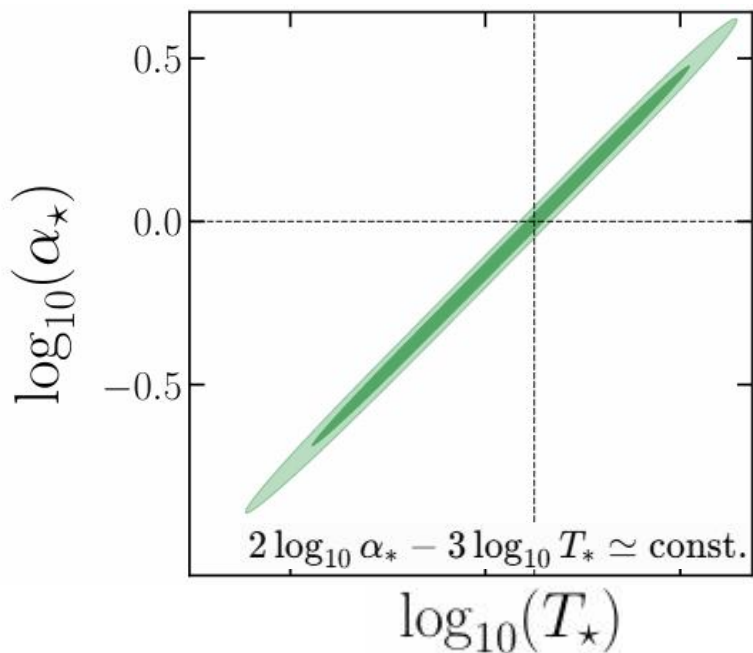
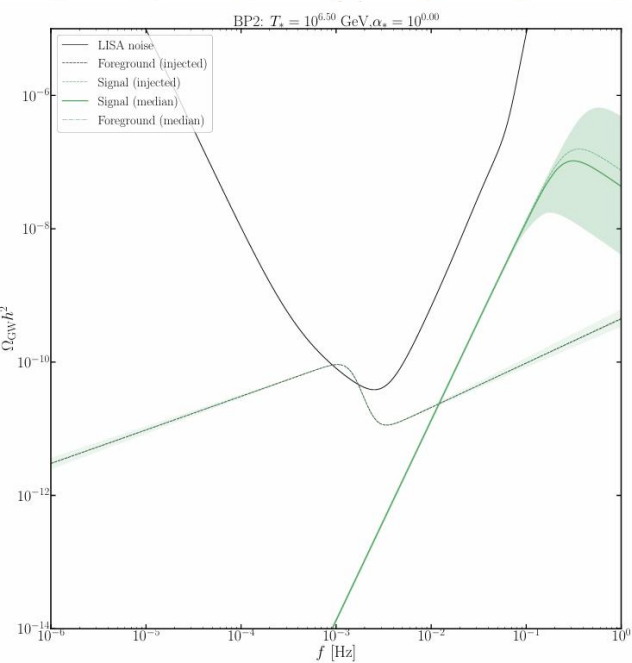
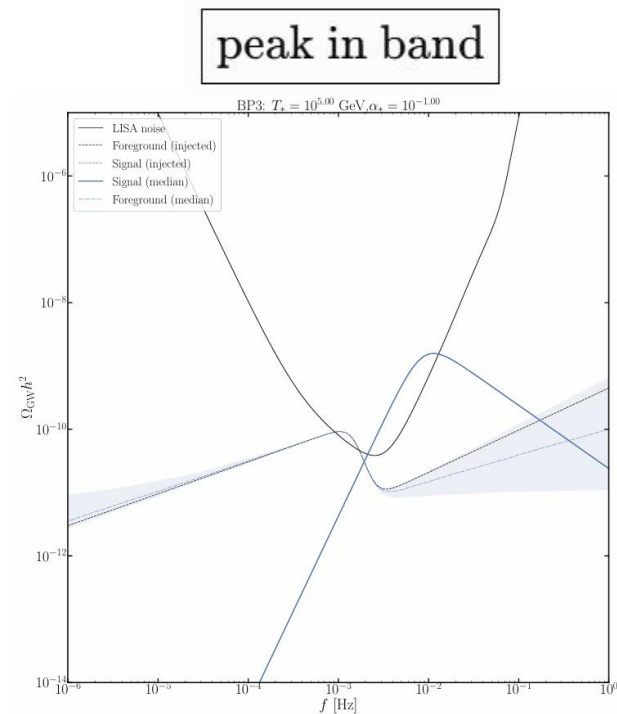
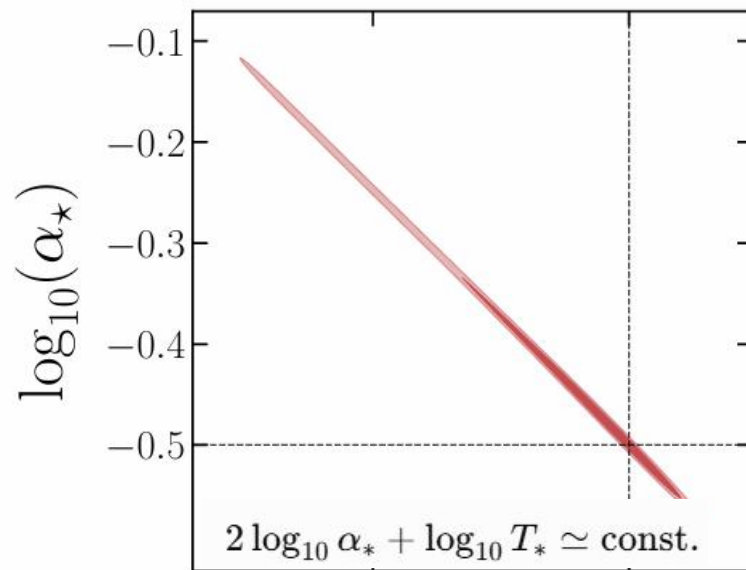
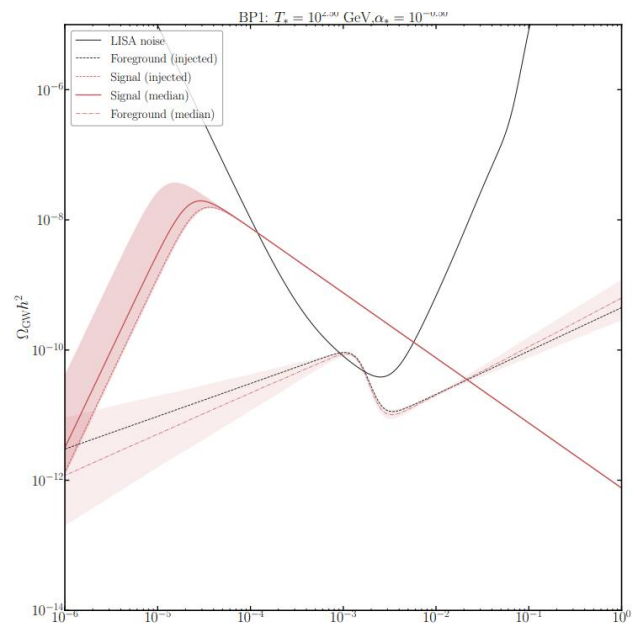
Case C: LISA samples peak/turnover

$$f_p \propto T_*$$

$$\Omega_{\text{GW}}^{\text{peak}} \propto \alpha_*^2$$

Tail-only observations contain only one effective combination of (α_*, T_*)

Tail physics → parameter degeneracy



A peak in the band is not enough

Turnover in band



Signal strong enough



Both parameters constrained

$$\Omega_{\text{GW}}^{\text{peak}} \propto \alpha_*^2$$

Lower α_*



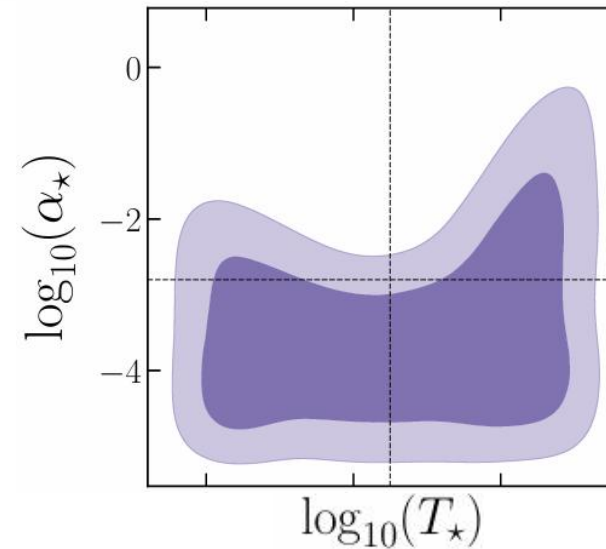
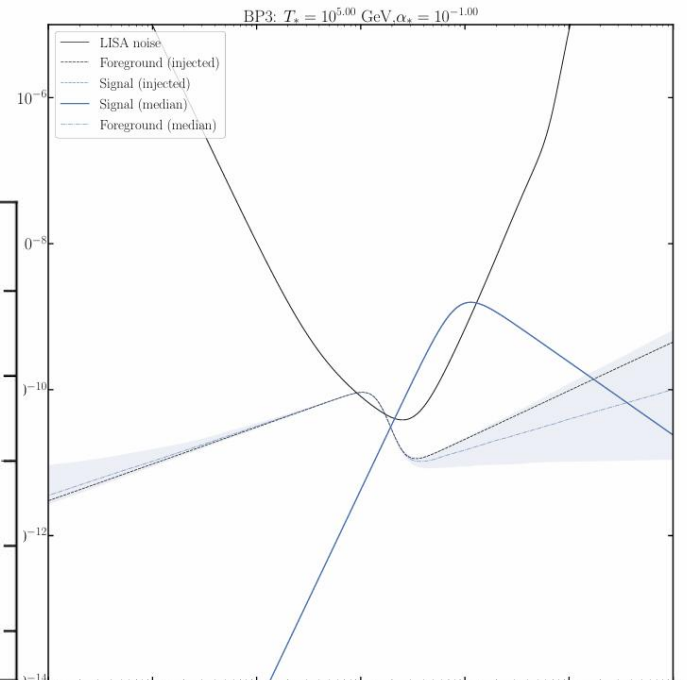
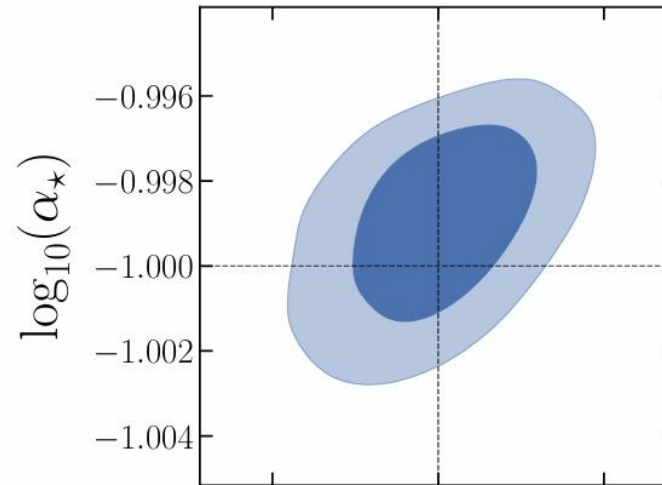
Weaker signal



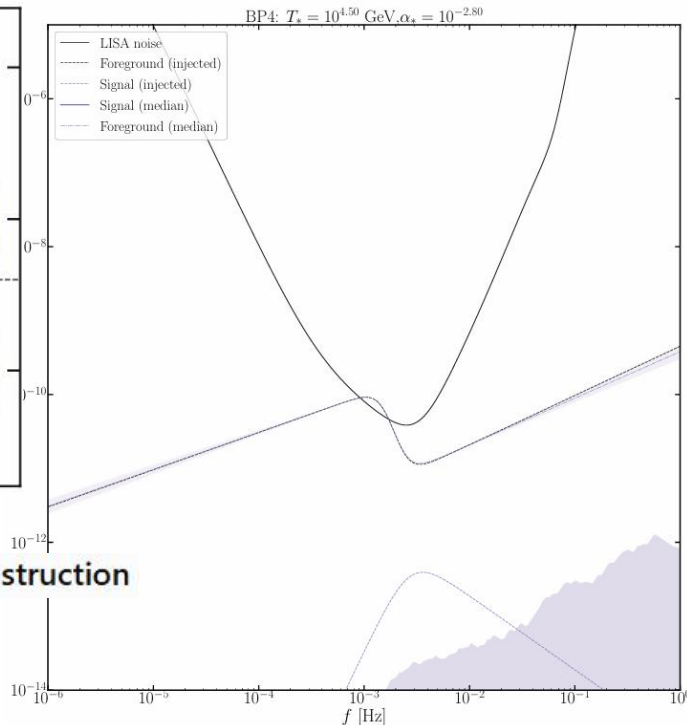
Less informative posterior

Good reconstruction = favorable spectral shape + sufficient signal strength

BP3 — good reconstruction



BP4 — weak signal / poor reconstruction



Posterior geometry: shape, size and information

$$\theta_1 = \log_{10} \alpha_*, \quad \theta_2 = \log_{10} T_*$$

$$C = \text{Cov}(\boldsymbol{\theta}) = \begin{pmatrix} \sigma_1^2 & \rho\sigma_1\sigma_2 \\ \rho\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix}$$

$$\lambda_{\pm} = \frac{1}{2} \left[\sigma_1^2 + \sigma_2^2 \pm \sqrt{(\sigma_1^2 - \sigma_2^2)^2 + 4\rho^2\sigma_1^2\sigma_2^2} \right]$$

$$\lambda_{\parallel} \equiv \lambda_+, \quad \lambda_{\perp} \equiv \lambda_-$$

posterior degeneracy

$$\kappa_{\text{deg}} = \frac{\lambda_{\parallel}}{\lambda_{\perp}}$$

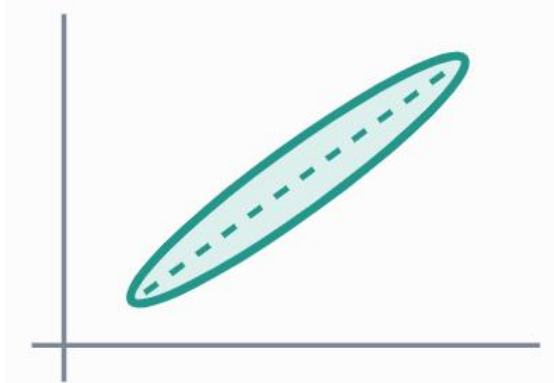
covariance area

$$A_{\text{cov}} = \sqrt{\det C} = \sqrt{\lambda_{\parallel} \lambda_{\perp}}.$$

marginalized widths

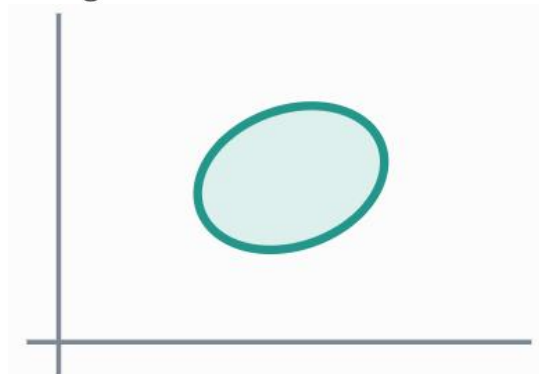
$$\sigma_{\log_{10} \alpha_*} = \sqrt{C_{11}}, \quad \sigma_{\log_{10} T_*} = \sqrt{C_{22}}.$$

$\kappa_{\text{deg}} \gg 1$ small A_{cov}



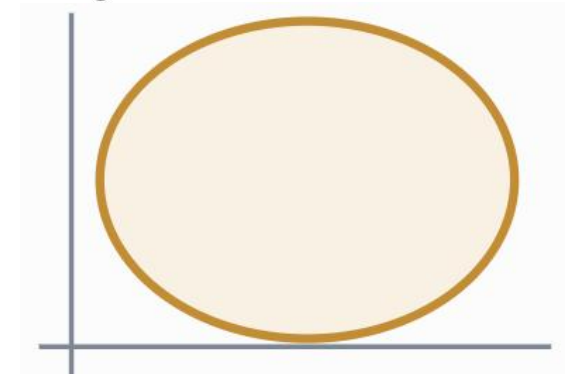
Strong correlation: one combination is constrained better than the other.

$\kappa_{\text{deg}} \sim 1$ small A_{cov}



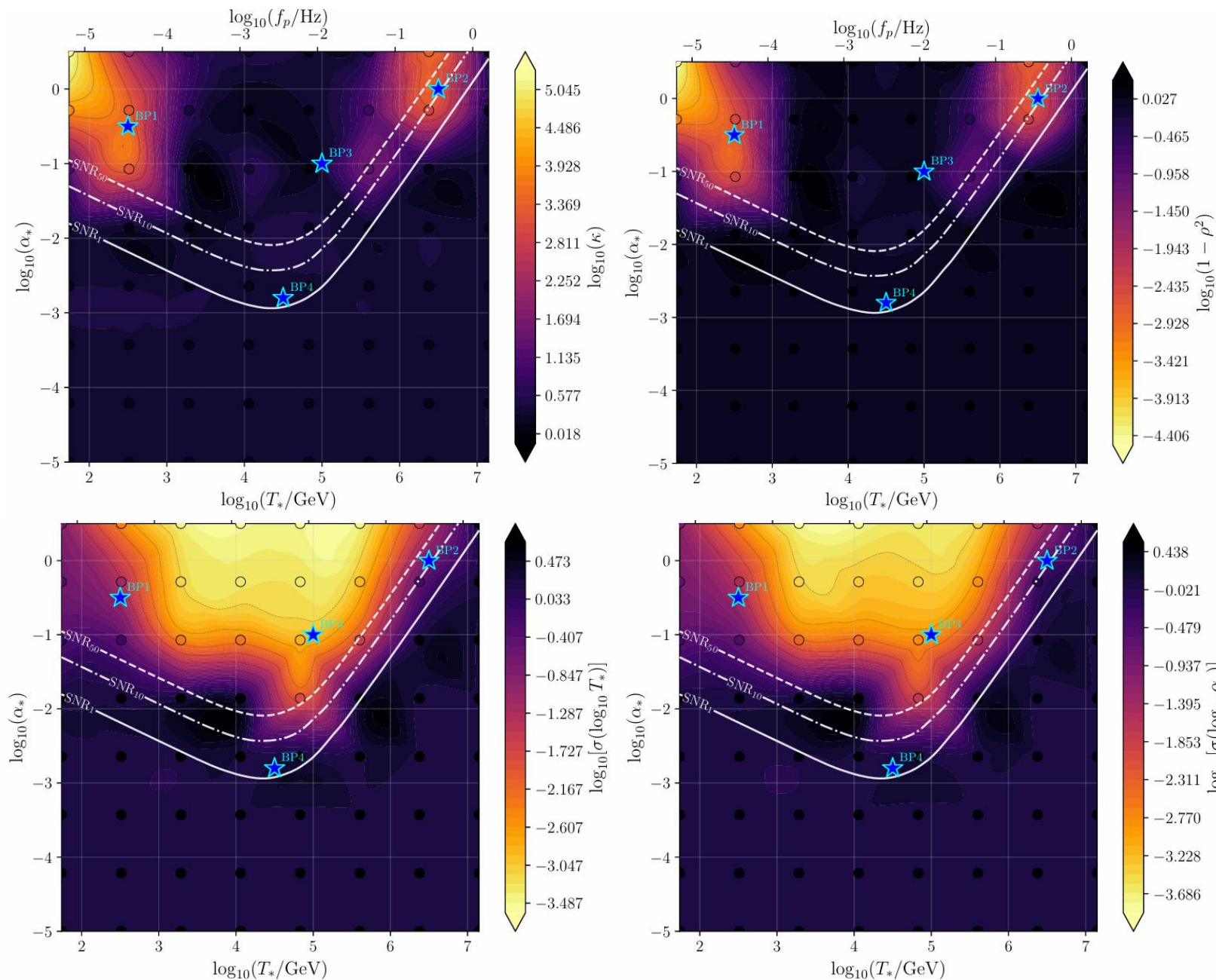
Small uncertainties: both parameters can be constrained well.

$\kappa_{\text{deg}} \sim 1$ large A_{cov}



Weak constraints: the data may not localize either parameter.

Where can LISA reconstruct both domain-wall parameters?



TAIL-DOMINATED REGIONS

$\kappa_{\text{deg}} \gg 1$ (Long, degenerate posteriors)

CENTRAL REGION

$\kappa_{\text{deg}} \sim 1$ (The two parameters are more distinguishable.)

A nearly round posterior is not enough if the signal is too weak

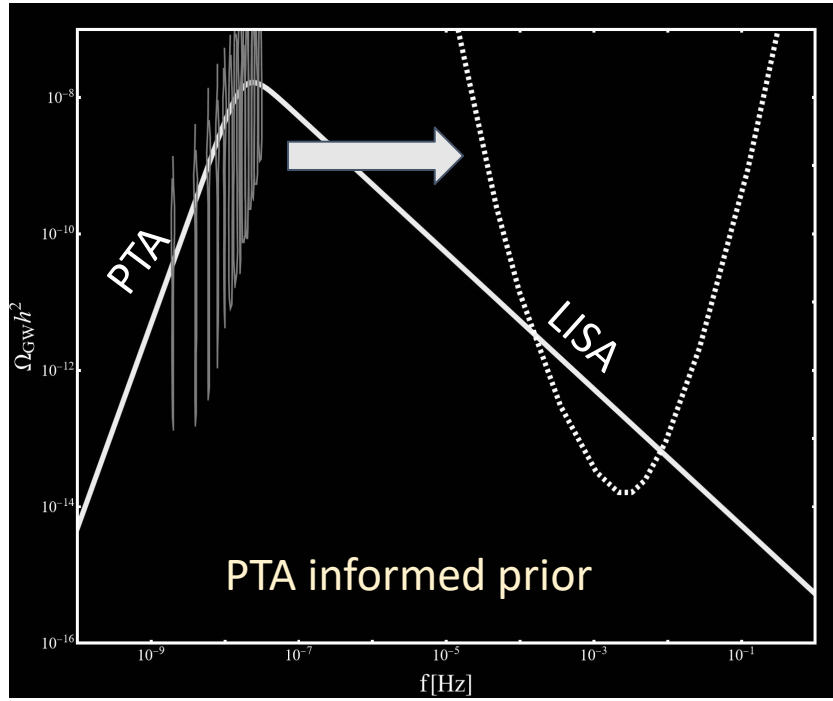
Check the SNR

$$T_* \sim 10^3 - 10^6 \text{ GeV}, \quad \text{SNR} \gtrsim 50$$

$\text{SNR} \sim 10$

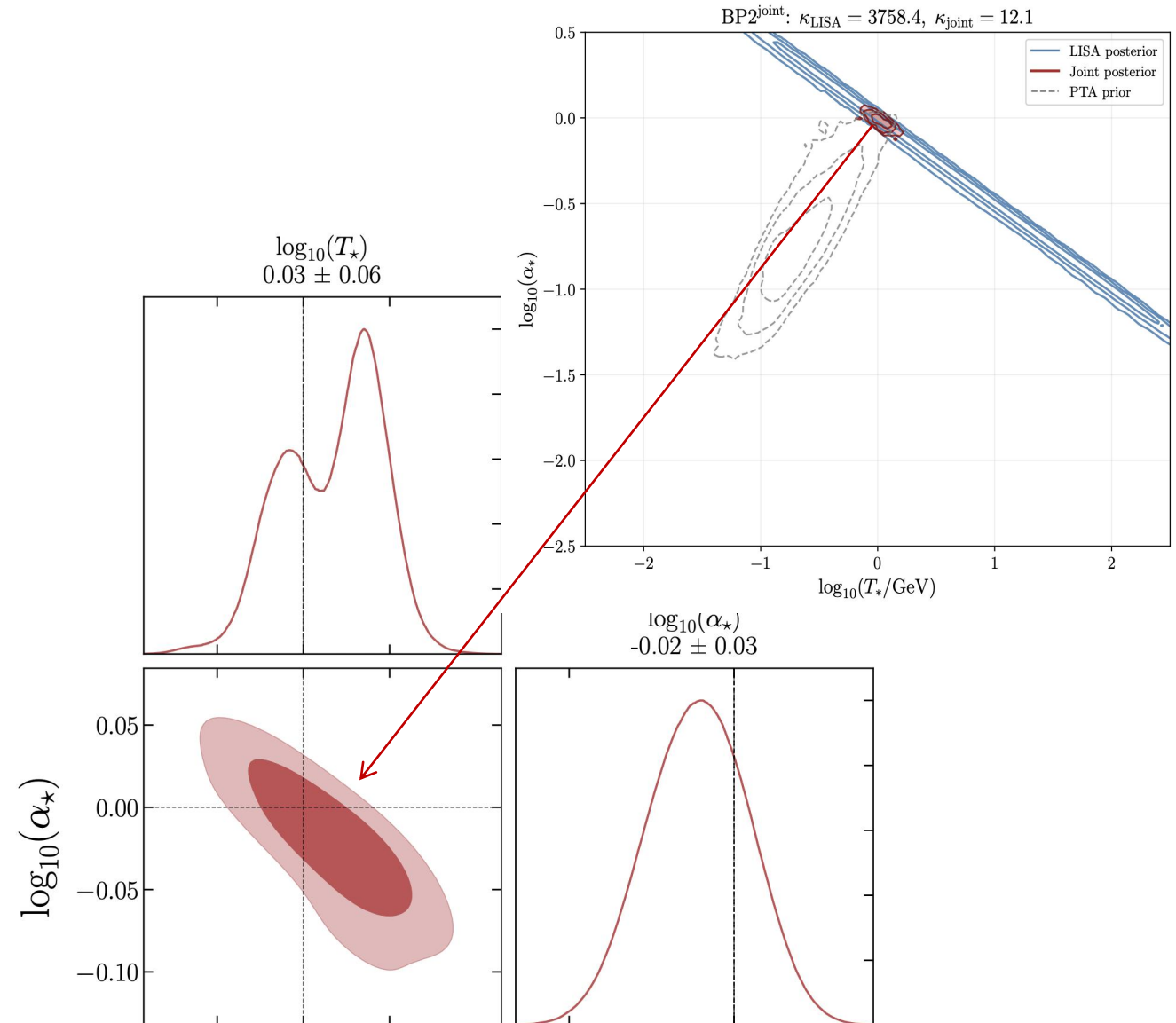
narrower region concentrated near $T_* \lesssim 10^5 \text{ GeV}$

PTA + LISA: different frequencies, complementary information



$$\kappa_{\text{LISA}} = 3758.4 \rightarrow \kappa_{\text{joint}} = 12.1 \quad (300 \times \text{less degenerate})$$

LISA adds information beyond PTA alone



Cosmic strings: from loops to gravitational waves

1D Strings

intercommute

loop

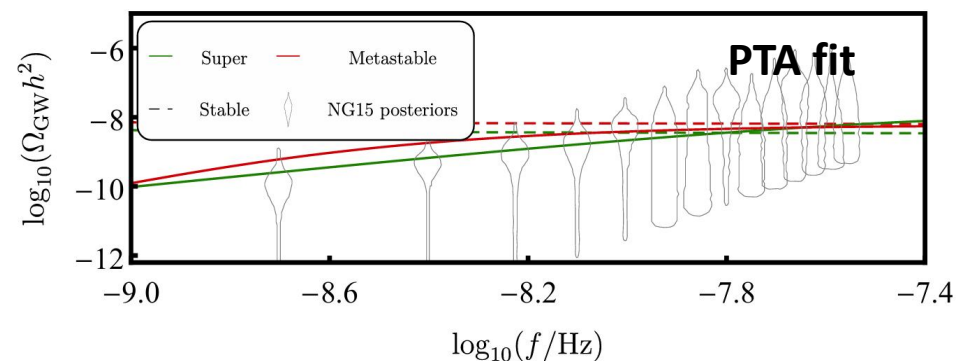
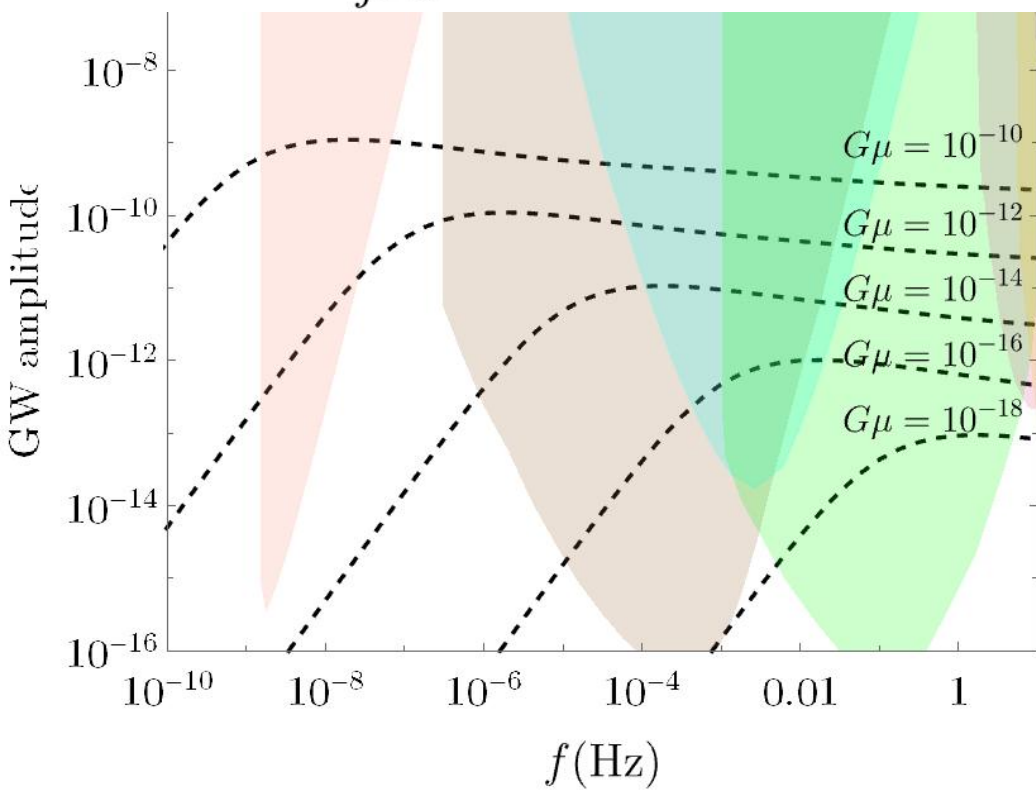
GWs

string tension $G\mu$

Plateau amplitude

$$\Omega_{\text{GW}}(f) = \sum_{j=1}^{j_{\text{max}}} \frac{2j G\mu^2 \Gamma_j}{f \rho_c} \int_{t_F}^{t_0} dt \left[\frac{a(t)}{a(t_0)} \right]^5 \frac{\mathcal{F}_\alpha A_\beta(t_i)}{t_i^4 \alpha(\alpha + \Gamma_{\text{GW}} G\mu)} \left[\frac{a(t_i)}{a(t)} \right]^3 \Theta(t_i - t_{\text{scl}}) \Theta\left(t_i - \frac{l_c}{\alpha}\right)$$

$$\Gamma_j = \frac{\Gamma k^{-\delta}}{\sum_{m=1}^{\infty} m^{-\delta}}, \quad \delta = \begin{cases} 4/3 & \text{cusps} \\ 5/3 & \text{kinks} \end{cases}$$



Strings with microscopic decay: **metastable strings**

Strings with suppressed intercommutation: **superstrings**

What if cosmic strings can break?

Multi-step GUT symmetry breaking, e.g.

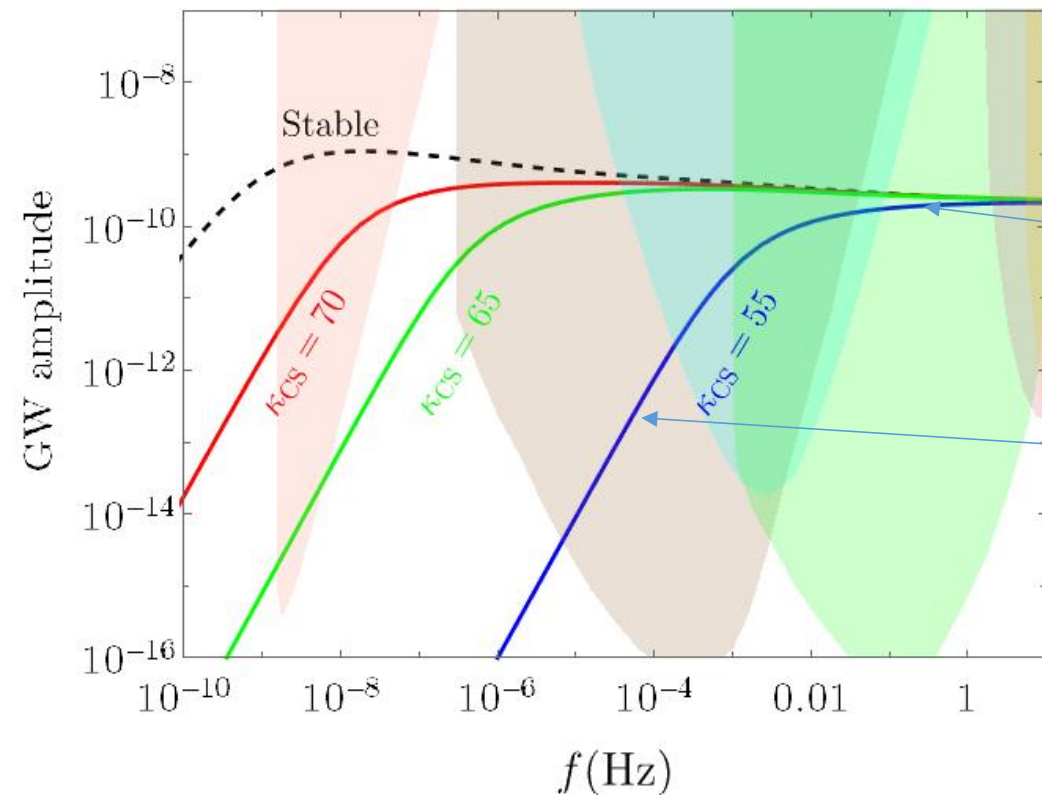
Earlier transition: **monopoles** → Later transition: **strings**

Monopole–antimonopole pair nucleation acts as microscopic string decay →

$$\kappa_{\text{CS}} \equiv \frac{m_M^2}{\mu}, \quad S_4 \sim \pi \kappa_{\text{CS}}$$

$$\Gamma_d \sim \frac{\mu}{2\pi} e^{-S_4}$$

Decay enters through → $n_{\text{meta}}(\ell, t) = n_{\text{stable}}(\ell, t) D(\ell, t)$



The loop-survival factor

$$D(l, t) = \exp \left[-\Gamma_d \left(l(t - t_i) + \frac{1}{2} \Gamma_{\text{GW}} G\mu (t - t_i)^2 \right) \right] \Theta(t_s - t_i)$$

Characteristic low-frequency scale

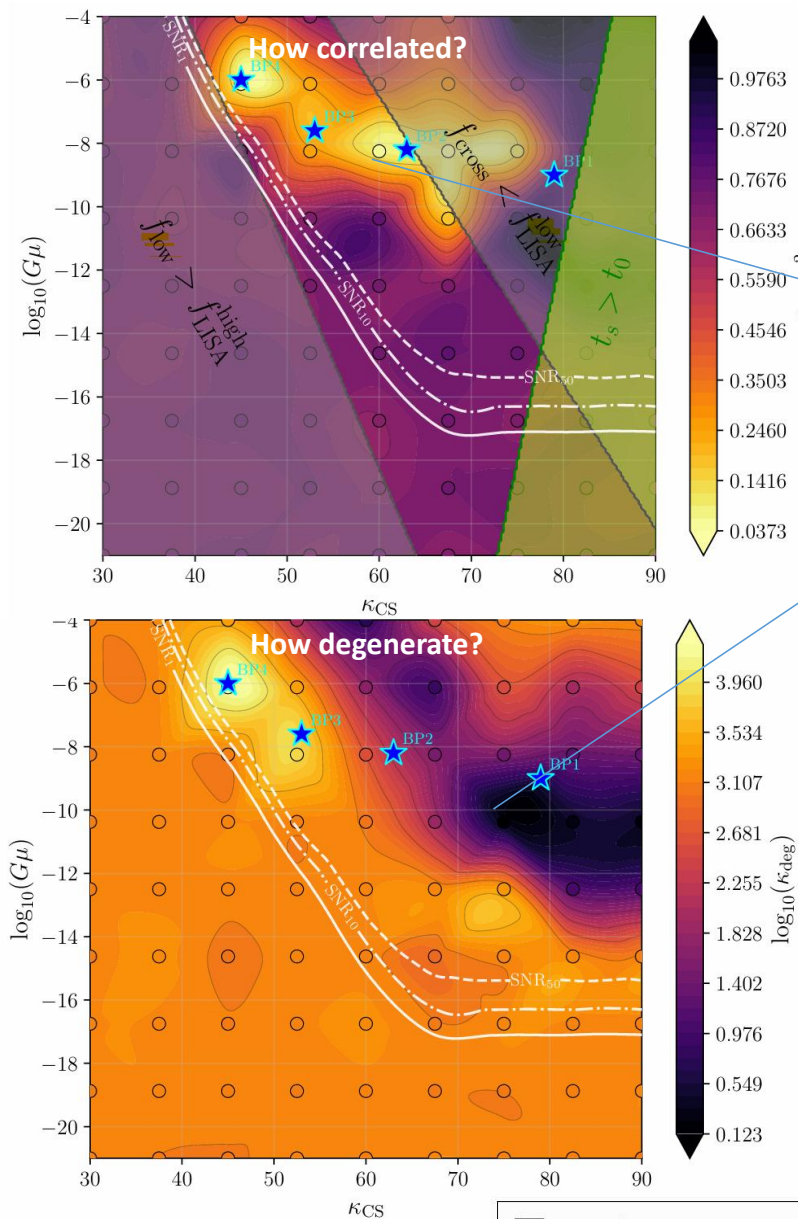
$$f_{\text{low}} \simeq 10^{-4} \text{ Hz} \left(\frac{10^{-15}}{G\mu} \right)^{1/2} \exp \left[-\frac{\pi}{4} (\kappa_{\text{CS}} - 64) \right]$$

Observable consequence →

$$f \ll f_{\text{low}}$$

$$\Omega_{\text{GW}}(f) \propto f^2$$

Can LISA reconstruct the string lifetime?



f_{cross} stable-like contribution begins to dominate over the decay-sensitive part

The most favorable reconstruction expected in

$$f_{\text{cross}} \sim f_{\text{LISA}}^{\text{low}} \quad \text{and} \quad f_{\text{low}} \sim f_{\text{LISA}}^{\text{high}}$$

f^2 tail $\rightarrow$ transition $\rightarrow$ plateau

High SNR can still resolve the decay term.

What limits the inference?

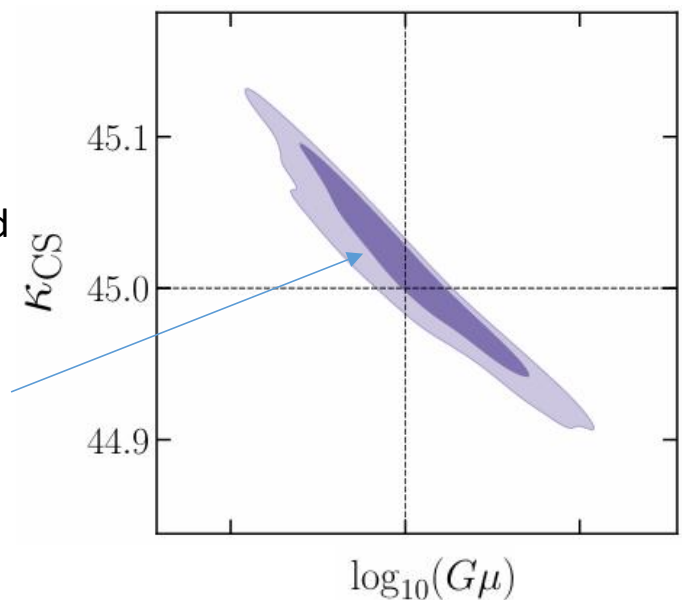
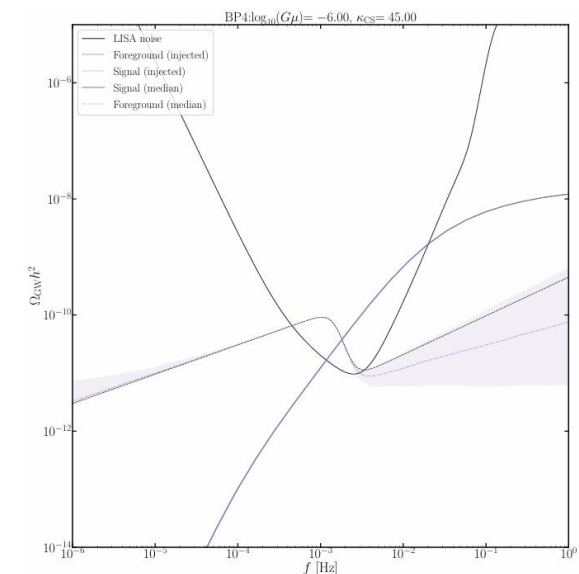
$$G\mu \uparrow \longleftrightarrow \kappa_{\text{CS}} \downarrow$$

An amplitude–lifetime trade-off can produce a correlated posterior

Compact but anti-correlated

but the allowed region is localized.

$$\log_{10}(G\mu) = -6, \quad \kappa_{\text{CS}} = 45$$



Tension controls the amplitude; lifetime controls the spectral evolution.

Cosmic superstrings: amplitude is not the whole story

String-inspired compactifications can produce cosmic superstrings with $P < 1$

Smaller $P \longrightarrow$ more loops $\longrightarrow$ enhanced GW amplitude

Model I (amplitude only)

$$\Omega_{\text{SS}}^{\text{I}}(f; G\mu, P) = P^{-\beta} \Omega_{\text{cusp}}(f; G\mu) \quad \beta = 1$$

$$\Omega_{\text{cusp}} \propto (G\mu)^q$$

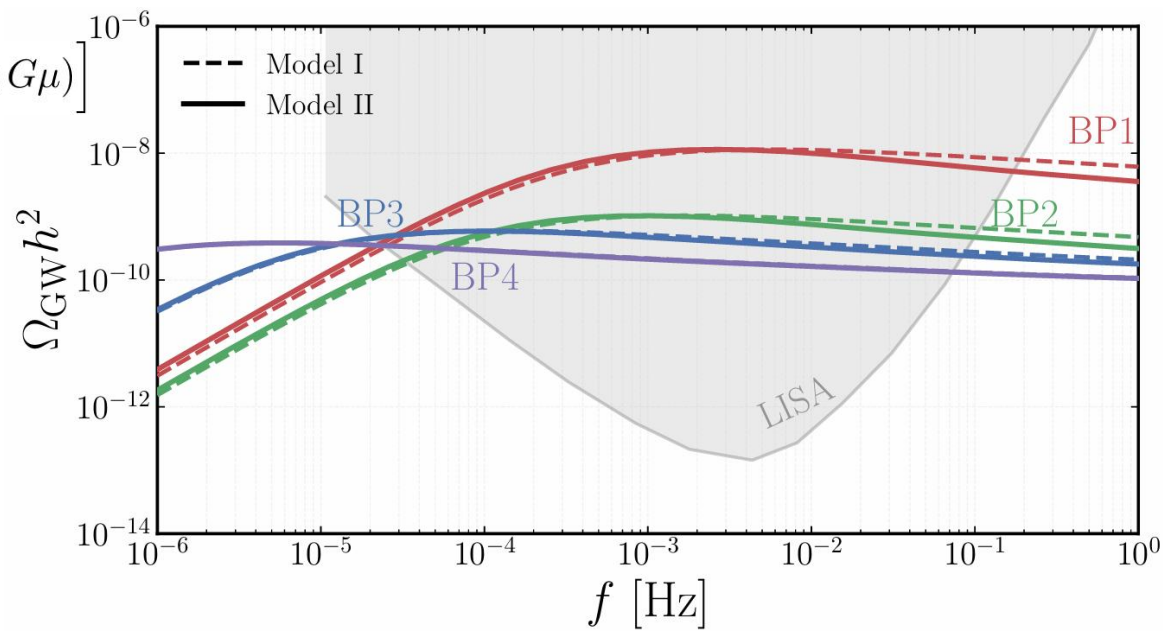
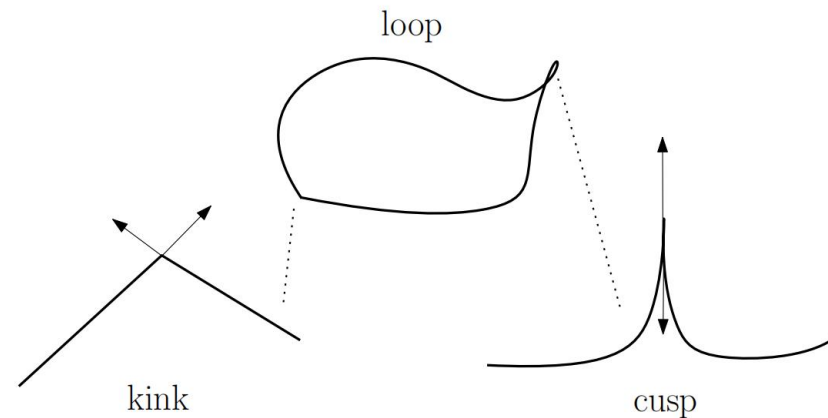
$$q \log_{10} G\mu - \beta \log_{10} P \simeq \text{const.}$$

Model II (amplitude + spectral shape)

$$\Omega_{\text{SS}}^{\text{II}}(f; G\mu, P) = P^{-\beta} \left[p_{\text{cusp}}(P) \Omega_{\text{cusp}}(f; G\mu) + (1 - p_{\text{cusp}}(P)) \Omega_{\text{kink}}(f; G\mu) \right]$$

$$p_{\text{cusp}}(P) = \frac{P^\eta}{P^\eta + P_0^\eta} \quad P_0 = 10^{-2}, \quad \eta = 1$$

P changes the cusp–kink mixture as well as the amplitude



Can LISA distinguish the superstring models?

Bayesian evidence: how well does each model explain the data overall?

$$Z_i = \int \mathcal{L}(d | \boldsymbol{\theta}_i, M_i) \pi(\boldsymbol{\theta}_i | M_i) d\boldsymbol{\theta}_i$$

Bayes factor

$$B_{1,2} = \frac{Z_1}{Z_2}$$

Data are generated from Model II; both models are fitted.

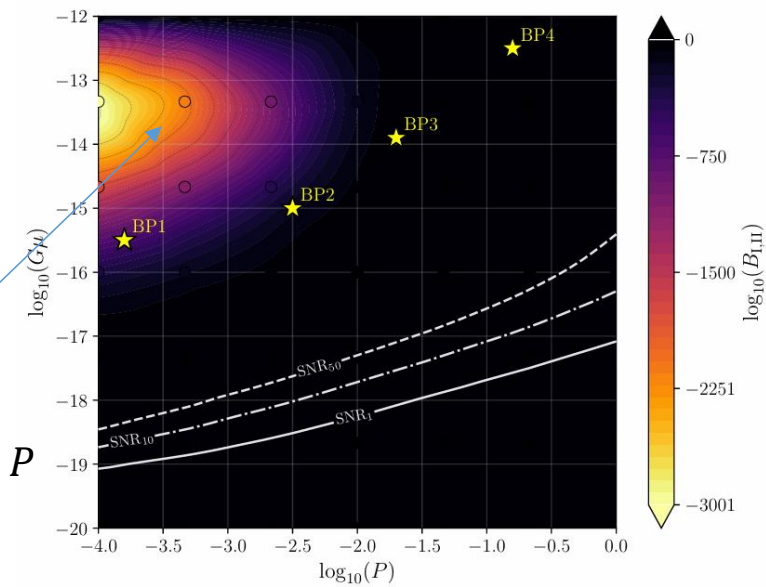
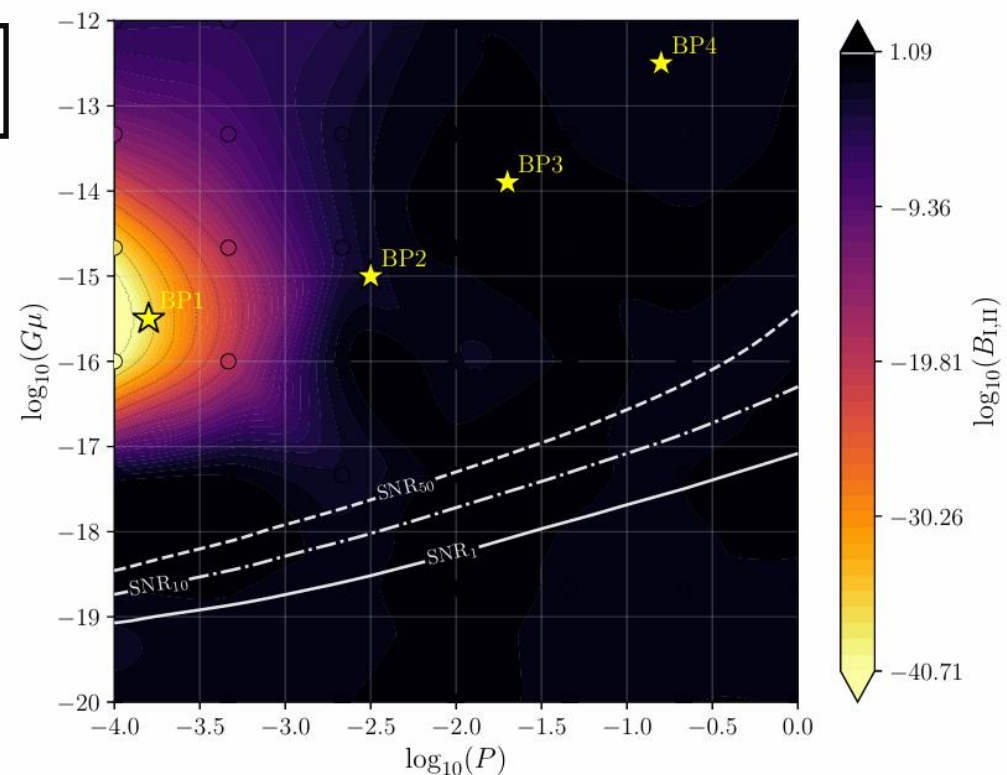
$\log_{10} B_{1,2} < 0 \Rightarrow$ Model II preferred

$\log_{10} B_{1,2} \simeq 0 \Rightarrow$ models indistinguishable

$\log_{10} B_{1,2} > 0 \Rightarrow$ Model I preferred

$P \gg P_0 : \text{ cusp dominated } \Rightarrow M_{\text{II}} \simeq M_{\text{I}}$

Better foreground knowledge (e.g. tanh template) $\rightarrow$ Model II is favoured at larger P



Conclusions: LISA needs a second lever

LISA measures one combination of parameters very well. The second one needs a lever.

SOURCE

Domain walls

Metastable strings

Superstrings

THE LEVER

Peak inside the LISA band
($T^* \sim 10^3\text{--}10^6$ GeV, $\text{SNR} \gtrsim 50$)

Bend between tail and plateau
inside the band

Cusp–kink shape visible,
signal loud

WITHOUT IT

Tail only: one combination,
a thin ridge

Plateau only: amplitude,
not lifetime

Large P: the two models
look the same

No lever → we detect the signal, but we cannot reconstruct the source.

Detection tells us something is there. Reconstruction tells us what it is.

Limits: simulated data, isotropic foregrounds, fixed templates.

Thank you for your attention!