Title: Cosmic-string gravitational wave backgrounds: detectability, signal reconstruction, and model comparison at LISA

Speakers: Dani Figueroa

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: April 10, 2025 - 1:00 PM

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Abstract:

Cosmic string networks are expected to generate a large gravitational wave background (GWB). We present a survey of GWB signal templates depending on the underlying hypothesis of the cosmic-string network. Following, we introduce a machine learning method based on SBI techniques, to determine the detectability of these signals by LISA, including signal spectral reconstruction and model comparison procedures.

The gravity of the cosmic-string case

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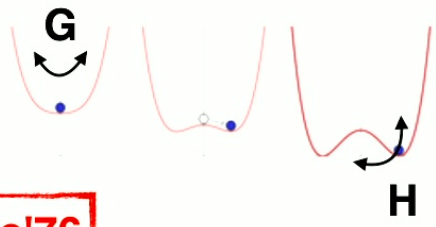
(**w/ A. Dimitriou, P. Simakachorn, B. Zaldivar**)

Perimeter Institute, Waterloo, Canada, Strong Gravity Seminar, April 10th 2025

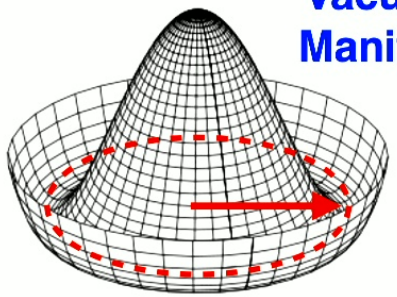
Cosmic Defects

Spontaneous Symm. Break.



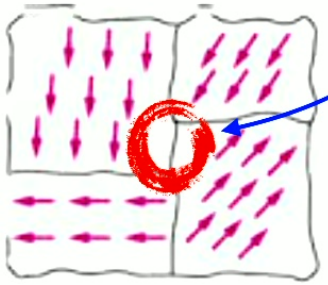
Kibble'76

Higgs fld Vacuum Manifold



M = G/H

Spatial Dist.



Topological Properties

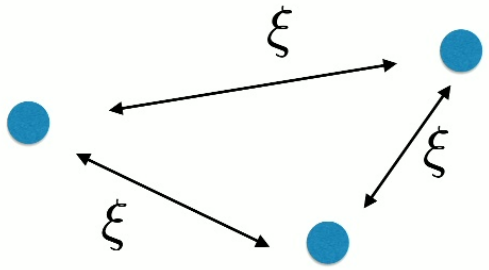
(Homotopy Groups $\Pi_n(M) \neq I$)

$\Pi_1(M) \neq I$ ⇨ **Strings**

Cosmic Defects

$$\text{DEFECTS: Aftermath of PhT} \rightarrow \begin{cases} \begin{cases} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{cases} \\ \text{Non} - \text{Topological} \end{cases}$$

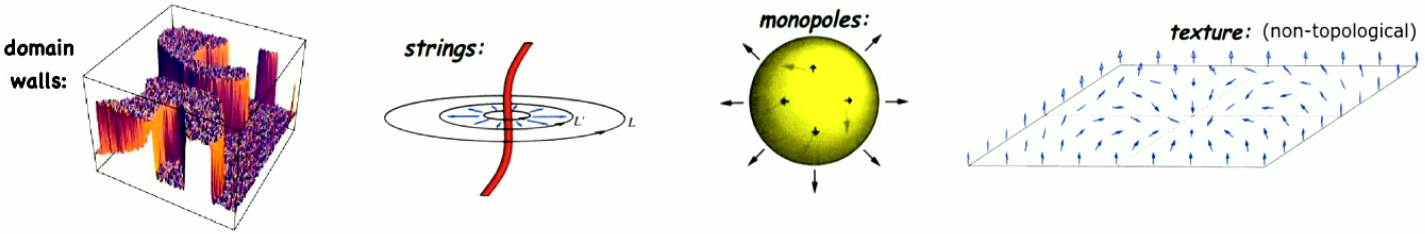
CAUSALITY & MICROPHYSICS $\Rightarrow$ Corr. Length: $\xi(t) = \lambda(t)\, H^{-1}(t)$



Defect Networks

Cosmic Defects

$$\text{DEFECTS: Aftermath of PhT} \rightarrow \begin{cases} \begin{cases} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{cases} \\ \text{Non} - \text{Topological} \end{cases}$$



MICRO-PHYSICS ⟹ COSMIC DEFECTS

(M = G/H)

Cosmic Defects

$$\text{DEFECTS: Aftermath of PhT} \rightarrow \begin{cases} \begin{cases} \text{Domain Walls} \\ \text{Cosmic Strings} \\ \text{Cosmic Monopoles} \end{cases} \\ \text{Non} - \text{Topological} \end{cases}$$

CAUSALITY & MICROPHYSICS $\Rightarrow$ Corr. Length: $\xi(t) = \lambda(t)\, H^{-1}(t)$

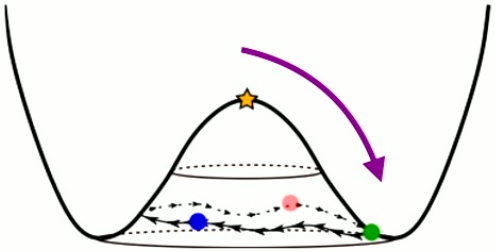
(Kibble' 76)

SCALING:* $\lambda(t) = \text{const.} \quad \rightarrow \quad \lambda \sim 1$

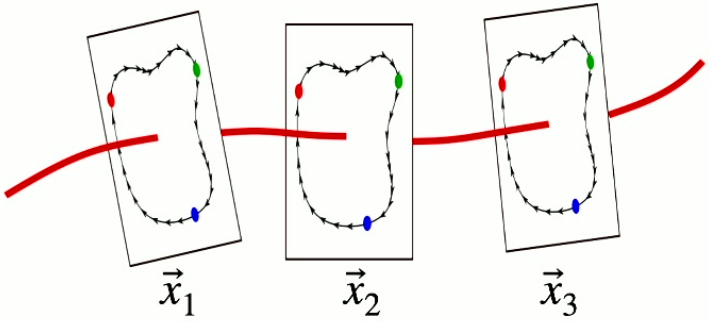
* Could be not exact in some cases

Cosmic Strings

One-dimensional topological detects $(\Pi_1(M) \neq I)$



Symm. Breaking Fld ('Higgs')

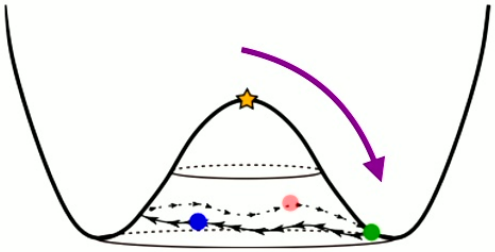


Different Vacua (at different locations)

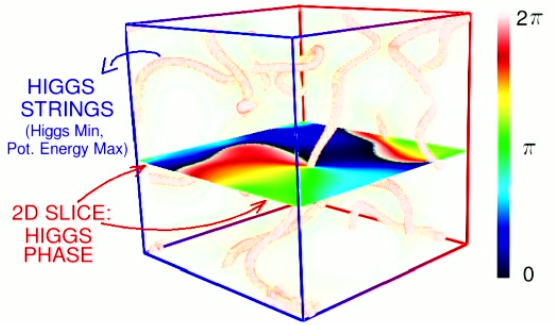
e.g. ~~U(1)~~

Cosmic Strings

One-dimensional topological detects $(\Pi_1(M) \neq I)$



Symm. Breaking Fld ('Higgs')



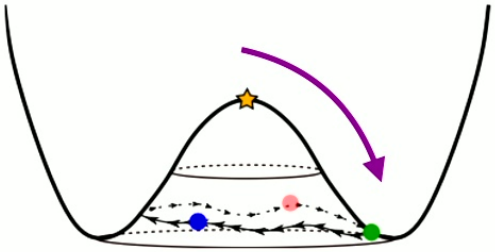
Different Vacua (at different locations)

e.g. ~~**U(1)**~~

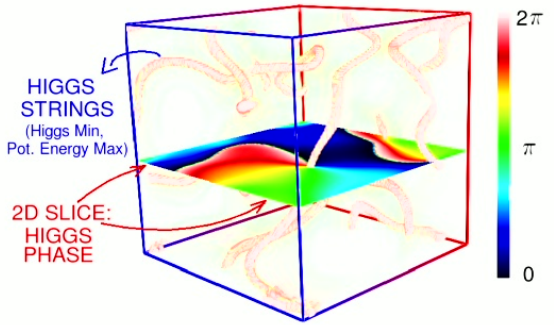
DGF, PhD Thesis 2010

Cosmic Strings

One-dimensional topological detects $(\Pi_1(M) \neq I)$



Symm. Breaking Fld ('Higgs')



Different Vacua (at different locations)

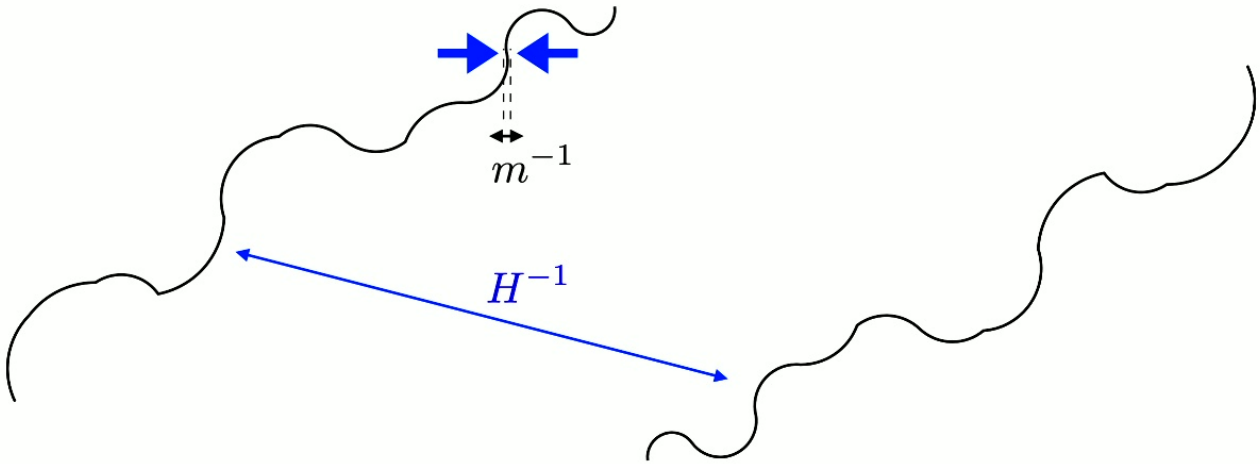
Global (ϕ)
* Long range int.
* $m_1 = 0, m_2 \neq 0$
* e.g. Axion DM

or

Local (ϕ, A_μ)
* Short range int.
* $m_1 \neq 0, m_2 \neq 0$
* e.g. GUT models

Cosmic String Networks

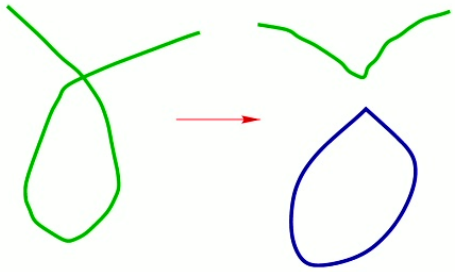
'Infinitely' thin: $H^{-1} \gg m^{-1}$

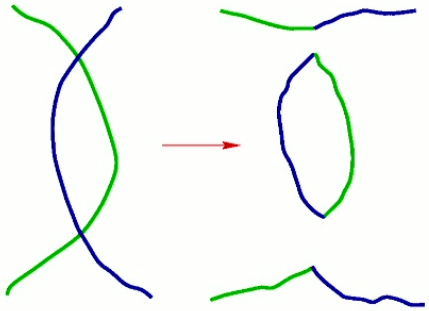


Nambu-Goto

Cosmic String Networks

Intercommutation





Loops !

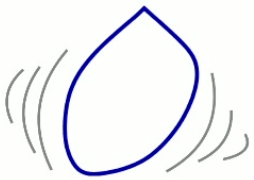
Loops !

Cosmic String Networks

Loops are formed !

$G\mu \equiv (\eta/M_p)^2$

Vibrate under their **tension** !



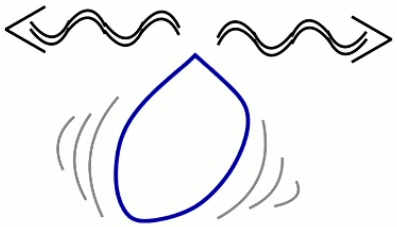
Periodic Oscillations

Cosmic String Networks

$G\mu \equiv (\eta/M_p)^2$

Loops are formed !

Vibrate under their **tension** !



Gravitational Waves (GW) are emitted !

$$L = l(t_e) \quad \Rightarrow \quad f_j = \frac{2}{L} \cdot j \;\; ; \;\; j = 1,2,3,...$$

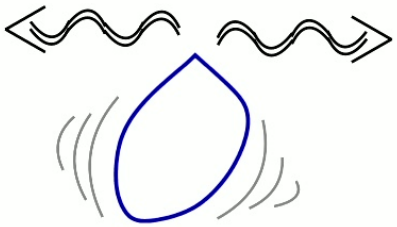
(Harmonic freq's)

Cosmic String Networks

$G\mu \equiv (\eta/M_p)^2$

Loops are formed !

Vibrate under their **tension** !



Gravitational Waves (GW) are emitted !

$$L = l(t_e)$$

$$f = \left[\frac{2j}{l(t_e)}\right] \cdot \left[\frac{a(t_e)}{a_0}\right]$$

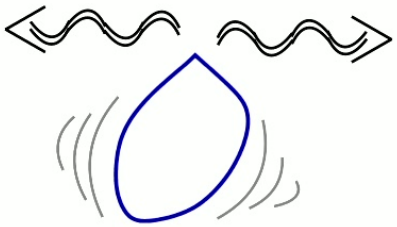
(Freq. Today)

Cosmic String Networks

$G\mu \equiv (\eta/M_p)^2$

Loops are formed !

Vibrate under their **tension** !

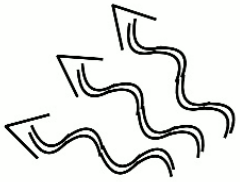


Gravitational Waves (GW) are emitted !

Superposition from many loop signals

=

Gravitational Wave Background

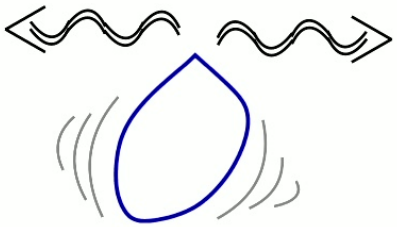


Cosmic String Networks

$G\mu \equiv (\eta/M_p)^2$

Loops are formed !

Vibrate under their **tension** !



Gravitational Waves (GW) are emitted !

Word of Caution !

Field-theory strings can also decay via **particle production**

Following … we assume GW emission dominates* !

(* We will review this at the end of the talk)

Grav. Wave Background

$$\frac{d\rho_{\rm GW}^{(0)}}{df} \equiv \int_{t_*}^{t_0} dt \left(\frac{a(t)}{a(t_0)}\right)^3 \int_0^{\alpha/H} dl\, n(l,t)\, P_{\rm GW}(f,l)$$

- $\left(\frac{a(t)}{a(t_0)}\right)^3$: expansion history
- l: length
- $n(l,t)$: Loop number density
- $P_{\rm GW}(f,l)$: GW power emission (Nambu-Goto calculation)

$$\propto 1/(fl)^q$$

GW power emission (NG)

$$\left(\frac{dE}{dt}\right)_{\rm tot} = \Gamma G\mu^2 = G\mu^2 \sum_j P_j$$

Γ: Just a number; $\sum_j$: Sum over harmonics

$$P_j \equiv \Gamma \frac{j^{-q}}{\zeta(q)}$$

Grav. Wave Background

$$\frac{d\rho_{\rm GW}^{(0)}}{df} \equiv \int_{t_*}^{t_0} dt \left(\frac{a(t)}{a(t_0)}\right)^3 \int_0^{\alpha/H} dl\; n(l,t)\; P_{\rm GW}(f,l)$$

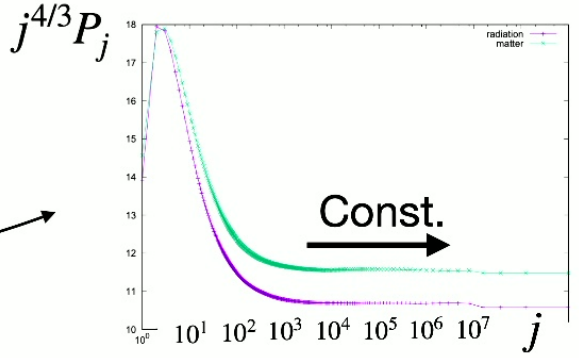
- $\left(\frac{a(t)}{a(t_0)}\right)^3$: **expansion history**
- l: **length**
- $n(l,t)$: **Loop number density**
- $P_{\rm GW}(f,l)$: **GW power emission** $\propto 1/(fl)^q$ (**Nambu-Goto calculation**)

GW power emission (NG)

$$P_j \equiv \Gamma \frac{j^{-q}}{\zeta(q)}$$

$q = \frac{4}{3}$ (cusps)

Reality…
(From NG sim's)



(Blanco-Pillado, Olum, 2017)

Grav. Wave Background

$$\Omega_{\rm GW}(f) = \frac{1}{3H_0^2 m_{\rm Pl}^2} \sum_{j=1}^{\infty} \underbrace{\frac{2j}{f}(G\mu^2 P_j)}_{\substack{\text{GW emission} \\ \text{from single loops}}} \int_{a_2}^{a_1} da \, \underbrace{\frac{1}{H(a)} \left(\frac{a}{a_0}\right)^4}_{\text{cosmic history}} \underbrace{\mathtt{n}\left[\frac{2j}{f} \cdot \frac{a}{a_0}, t(a)\right]}_{\text{loop number density}}$$

(C) NG analytics

(B) ΛCDM

(A) NG analytics

Conventional

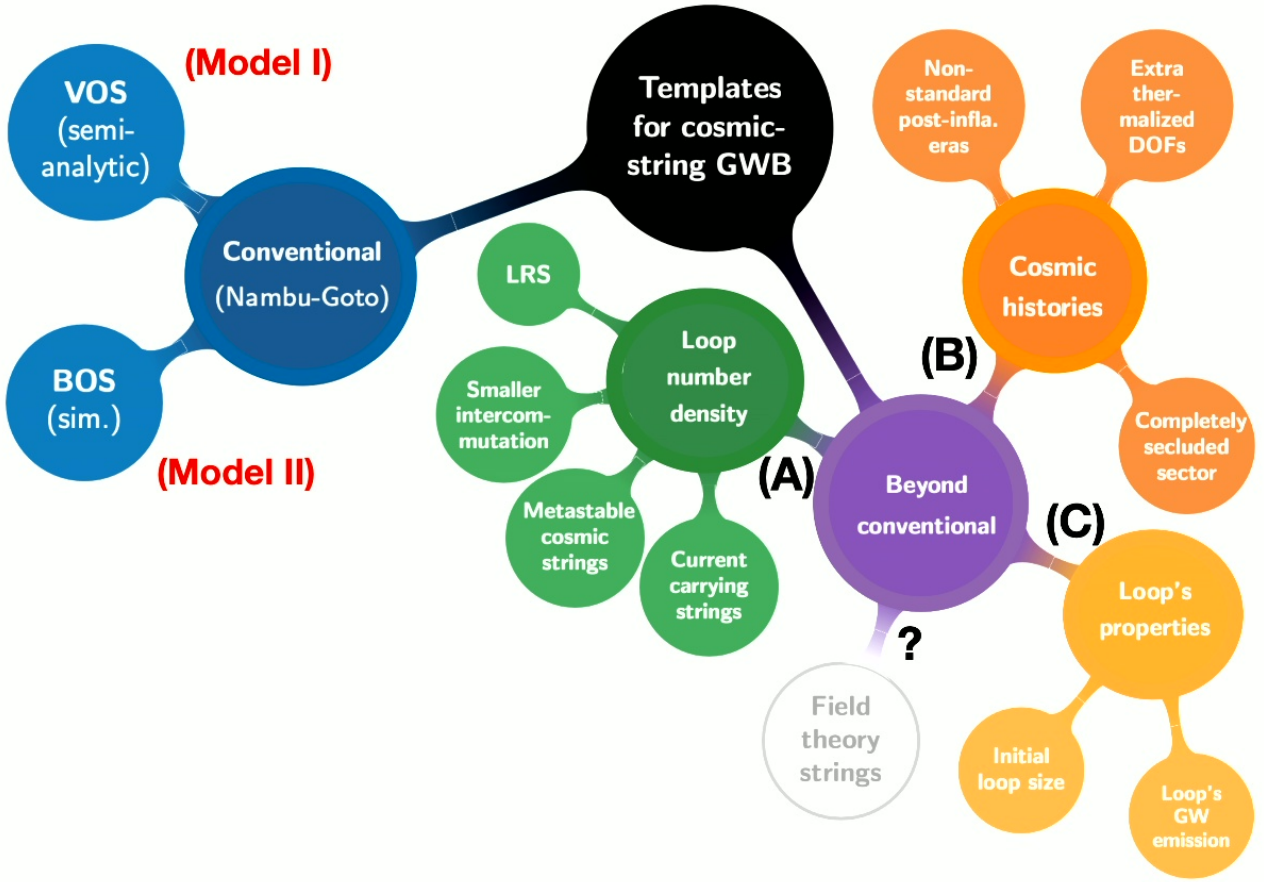
Beyond Conventional

Grav. Wave Background

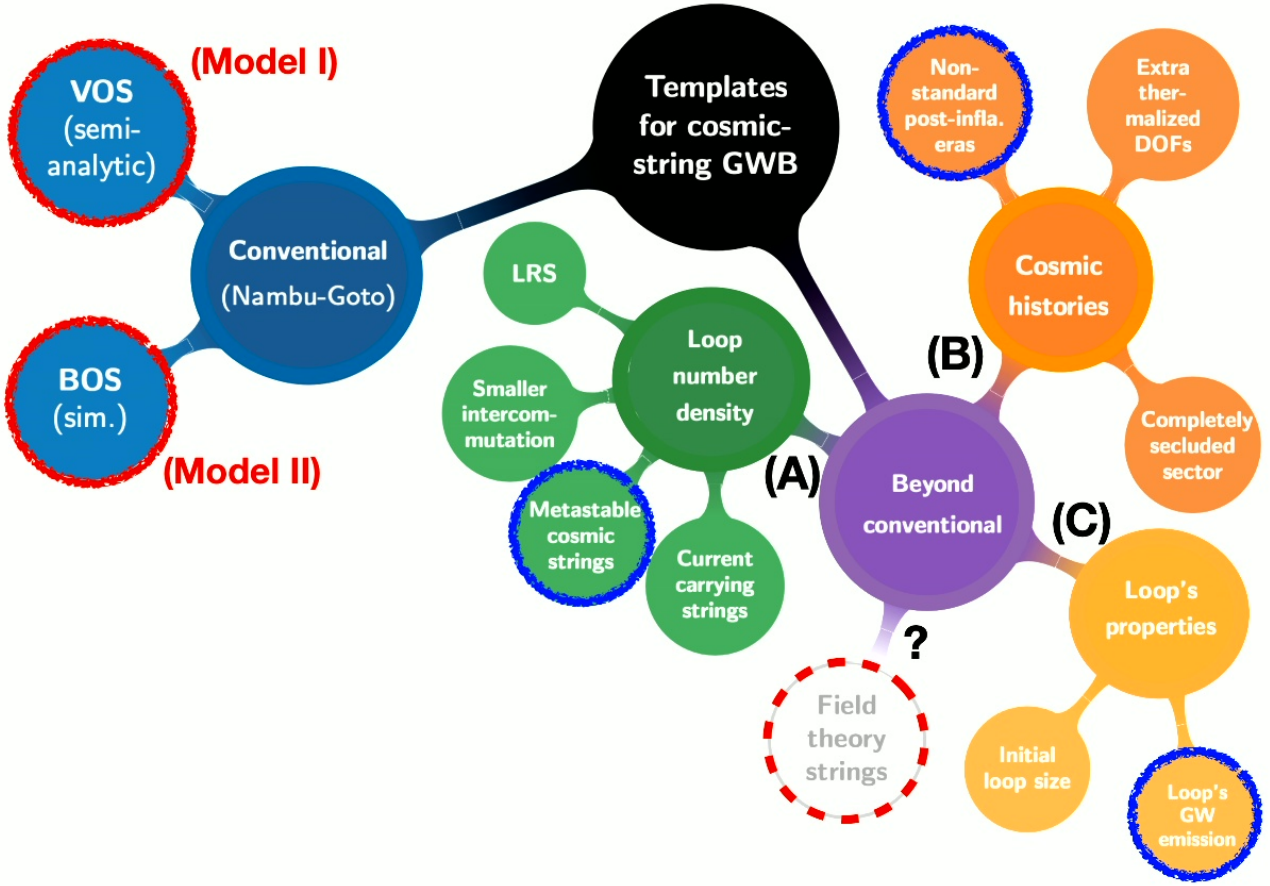
$$\Omega_{\rm GW}(f) = \frac{1}{3H_0^2 m_{\rm Pl}^2} \sum_{j=1}^{\infty} \underbrace{\frac{2j}{f}(G\mu^2 P_j)}_{\substack{\text{GW emission} \\ \text{from single loops}}} \int_{a_2}^{a_1} da \, \underbrace{\frac{1}{H(a)} \left(\frac{a}{a_0}\right)^4}_{\text{cosmic history}} \underbrace{\mathtt{n}\left[\frac{2j}{f} \cdot \frac{a}{a_0}, t(a)\right]}_{\text{loop number density}}$$

	(C)	(B)	(A)
Conventional	NG analytics NG sims	ΛCDM ΛCDM	NG analytics NG sims
Beyond Conventional	....	e.g. Kination	....
	q ≠ 4/3	....	....
	....	....	e.g. Metastable strings

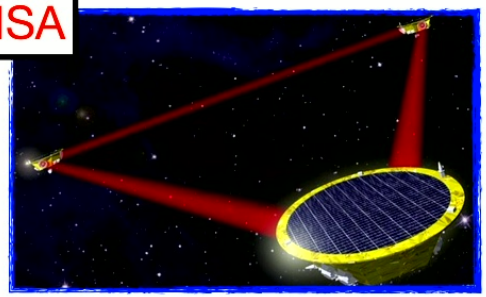
Grav. Wave Background(s)



Grav. Wave Background(s)



GW Background Signals: Detectability



3 interferometric channels

X, Y, Z $\longleftrightarrow$ A, E, T

$$\begin{pmatrix} XX & XY & XZ \\ YX & YY & YZ \\ ZX & ZY & ZZ \end{pmatrix} \qquad \begin{pmatrix} AA & 0 & 0 \\ 0 & EE & 0 \\ 0 & 0 & TT \end{pmatrix}$$

$$x_f \equiv \frac{2\pi f L}{c}$$

$$N_{\rm AA}(f; A_P, A_{\rm acc}) = N_{\rm EE}(f; A_P, A_{\rm acc})$$
$$= 8\sin^2 x_f \left[4(1+\cos x_f+\cos^2 x_f)P_{\rm acc}(f;A_{\rm acc}) + (2+\cos x_f)\, P_{\rm IMS}(f;A_P)\right]$$
$$N_{\rm TT}(f; A_P, A_{\rm acc}) = 16\sin^2 x_f \left[2(1-\cos x_f)^2 P_{\rm acc}(f;A_{\rm acc}) + (1-\cos x_f)P_{\rm IMS}(f;A_P)\right].$$

$$P_{\rm IMS} = 1.6\times 10^{-43} A_P^2 \left[1+(2\,{\rm mHz}/f)^4\right] x_f^2\ {\rm Hz}^{-1}, \quad \text{(Interferometry Metrology System, e.g. shot noise)}$$
$$P_{\rm acc} = 7.7374\times 10^{-46} A_{\rm acc}^2 \left[1+(0.4\,{\rm mHz}/f)^2\right]\left[1+(f/8\,{\rm mHz})^4\right] x_f^{-2}\ {\rm Hz}^{-1} \quad \text{(Mass acceleration)}$$

$A_{\rm acc} = 3 \pm 0.6$

$A_P = 15 \pm 3$

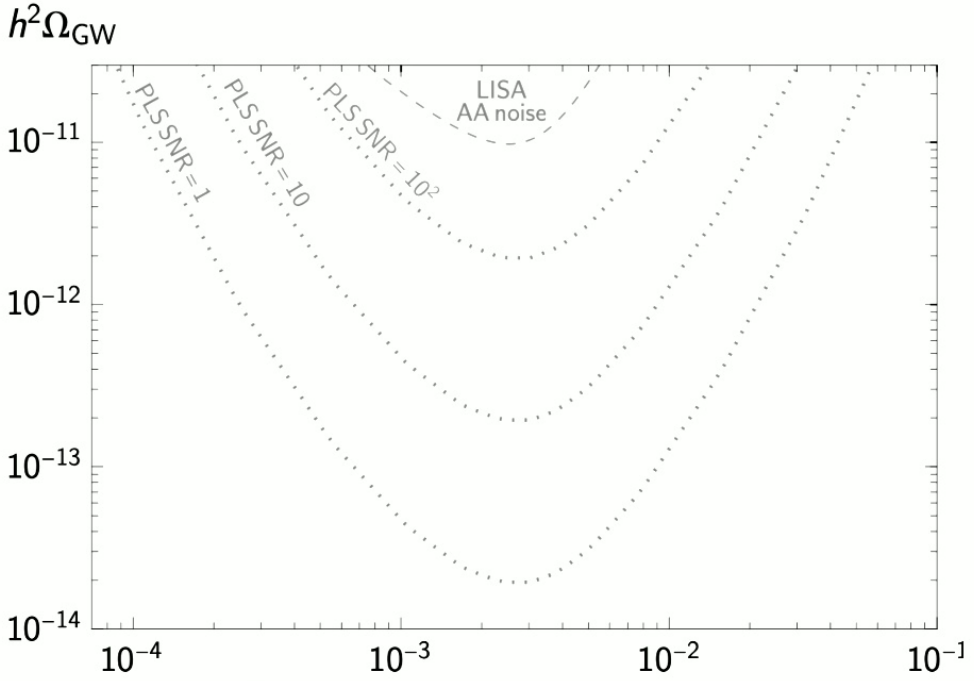
LISA Data Challenge Manual. Tech. Rep.
LISA-LCST-SGS-MAN-002. APC Paris, July 2020.

LISA Pathfinder (2016) PhysRevLett.116.231101

GW Background Signals: Detectability

$$\mathrm{SNR} = \sqrt{T_{\mathrm{obs}} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} df \left[\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{noise}}(f)} \right]^2}$$

Signal-to-Noise Ratio
(Naive Method ?)

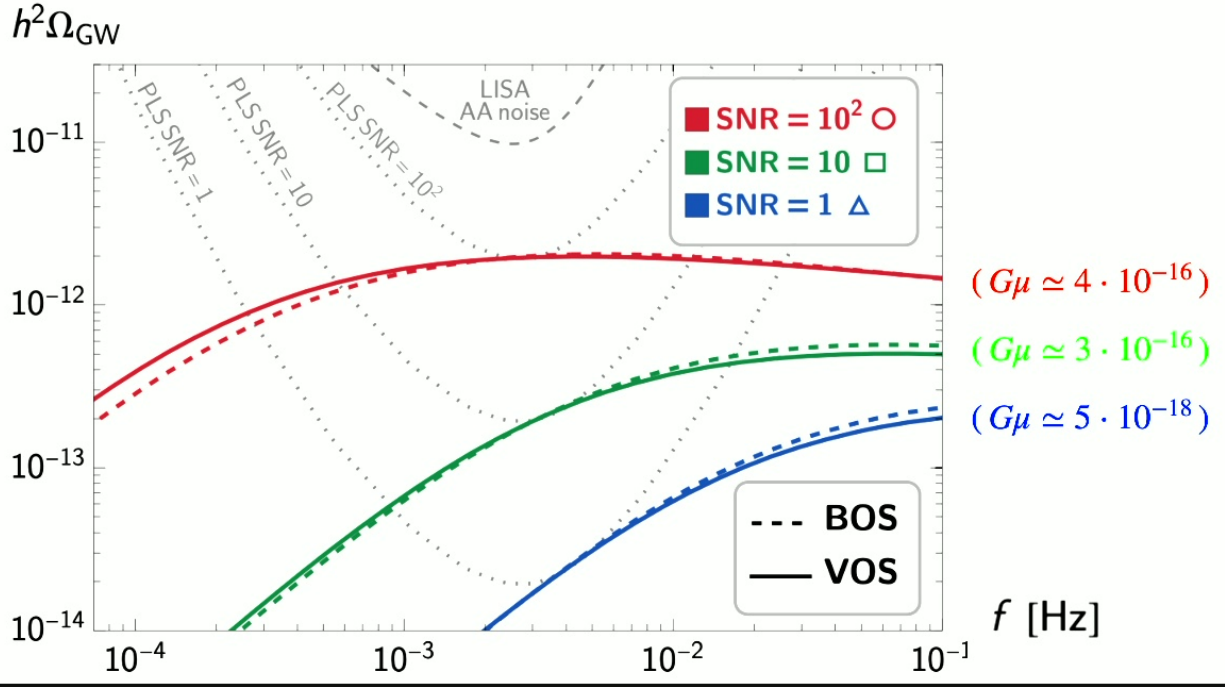


PLS (PowerLaw Sensitivity) Curves

GW Background Signals: Detectability

$$\mathrm{SNR} = \sqrt{T_{\mathrm{obs}} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} df \left[\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{noise}}(f)} \right]^2}$$

Signal-to-Noise Ratio
(Naive Method ?)



$(G\mu \simeq 4 \cdot 10^{-16})$

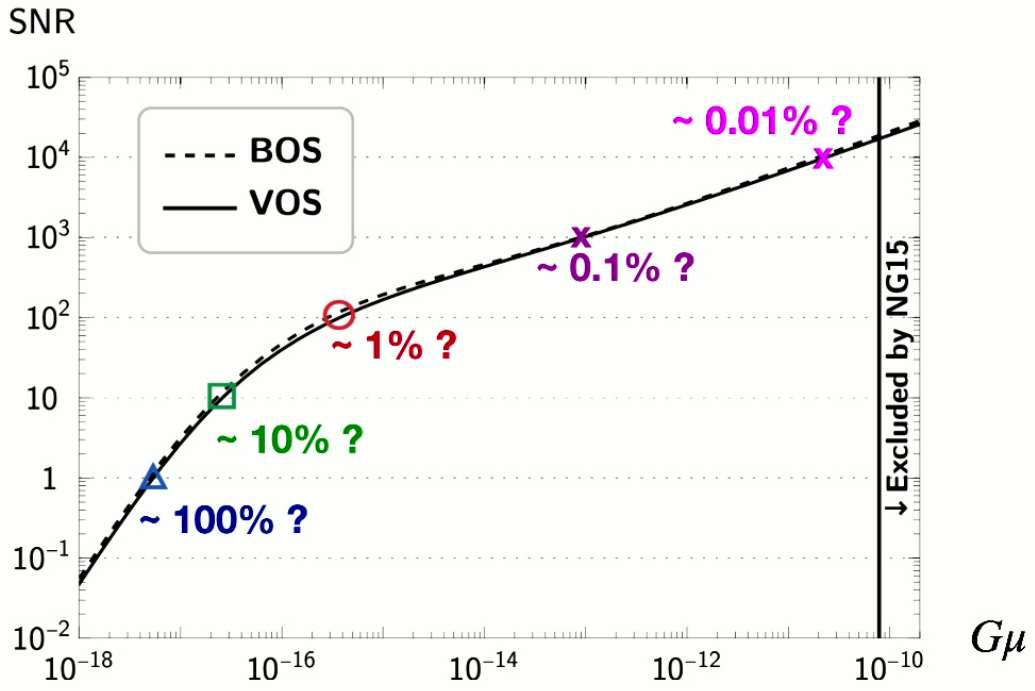
$(G\mu \simeq 3 \cdot 10^{-16})$

$(G\mu \simeq 5 \cdot 10^{-18})$

GW Background Signals: Detectability

$$\mathrm{SNR} = \sqrt{T_{\mathrm{obs}} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} df \left[\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_{\mathrm{noise}}(f)} \right]^2}$$

Signal-to-Noise Ratio
(Naive Method ?)



GW Background Signals: Detectability

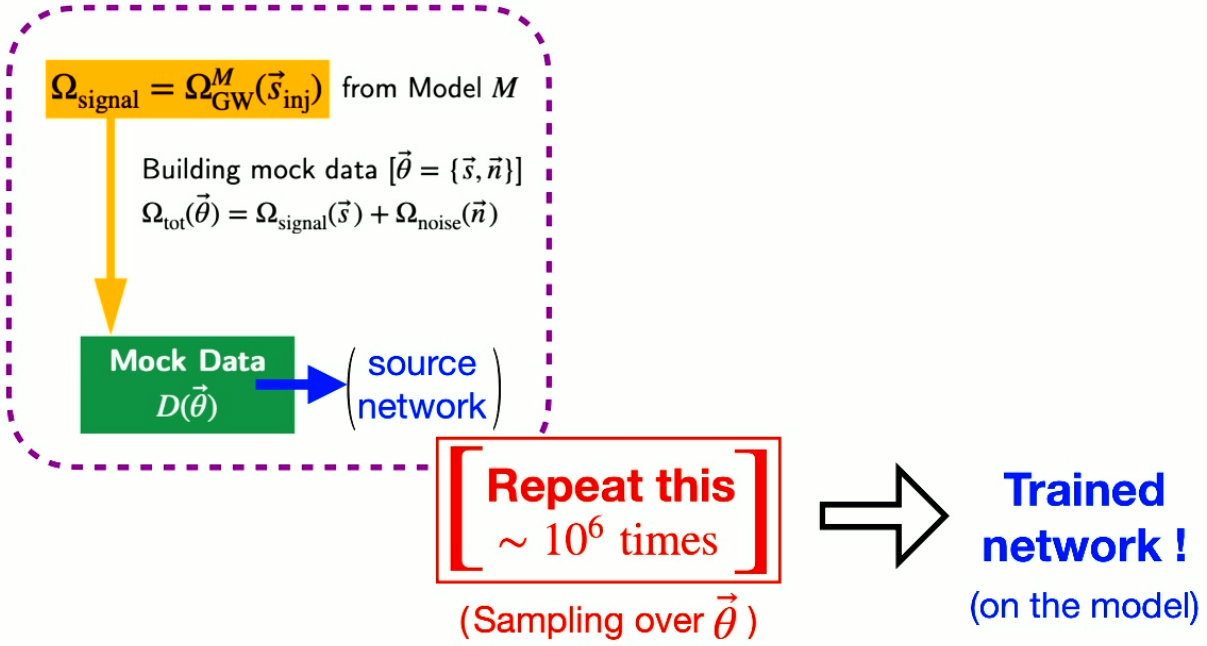
We want precision cosmology/HEP !

- Signal error reconstruction
- Proper Parameter Estimation

GW Background Signals: Detectability

Simulation-Based Inference (SBI)

(**Machine Learning method**)

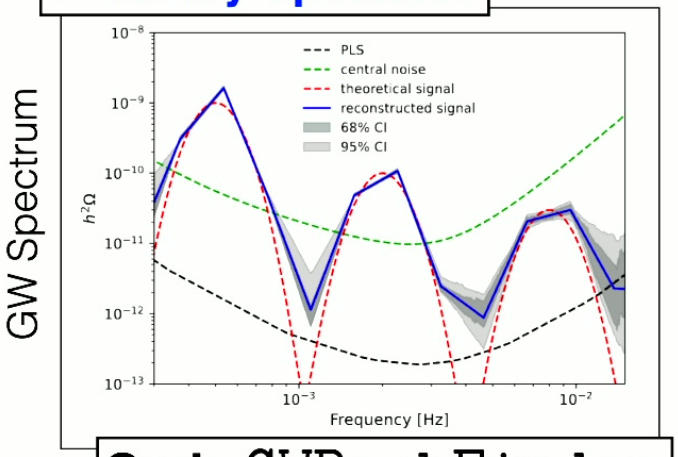


GW Background Signals: Detectability

Simulation-Based Inference (SBI)

Blind signal Reconstruction

Arbitrary Spectrum



Code `GWBackFinder`

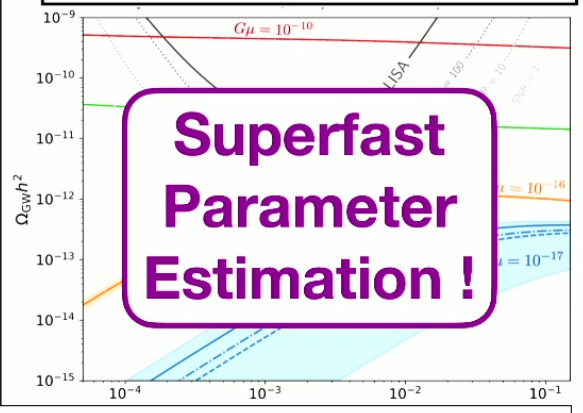
(Dimitriou et al **2309.08430**)

GW Background Signals: Detectability

Simulation-Based Inference (SBI)

Template signal reconstruction

Template ($\vec{\alpha}$) Spectrum



Superfast Parameter Estimation !

Applications to Cosmic Strings, Phase Transitions, Inflation, …

Dimitriou et al, **Work in progress**

GW Background Signals: Detectability

I. "Signal reconstruction" ability

$\Omega_{\rm signal} = \Omega^{M}_{\rm GW}(\vec{s}_{\rm inj})$ from Model M

Building mock data $[\vec{\theta} = \{\vec{s}, \vec{n}\}]$

$\Omega_{\rm tot}(\vec{\theta}) = \Omega_{\rm signal}(\vec{s}) + \Omega_{\rm noise}(\vec{n})$

Mock Data $D(\vec{\theta})$ **(1 sample)**

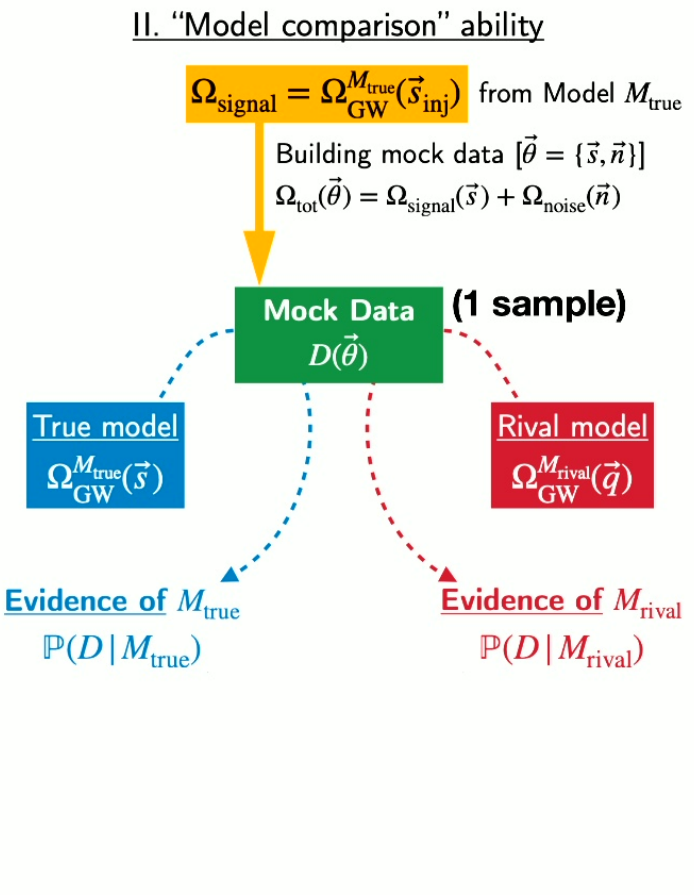
Model $\Omega^{M}_{\rm GW}(\vec{s})$

Posterior of $\vec{s}$

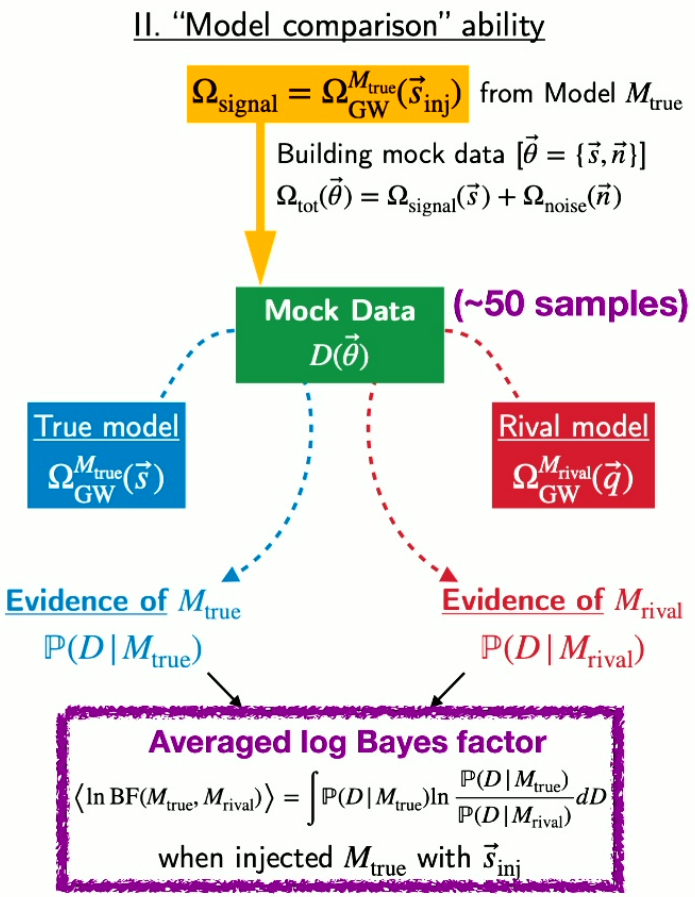
$\mathbb{P}(\vec{s}\,|\,D)$

for injected $\vec{s}_{\rm inj}$

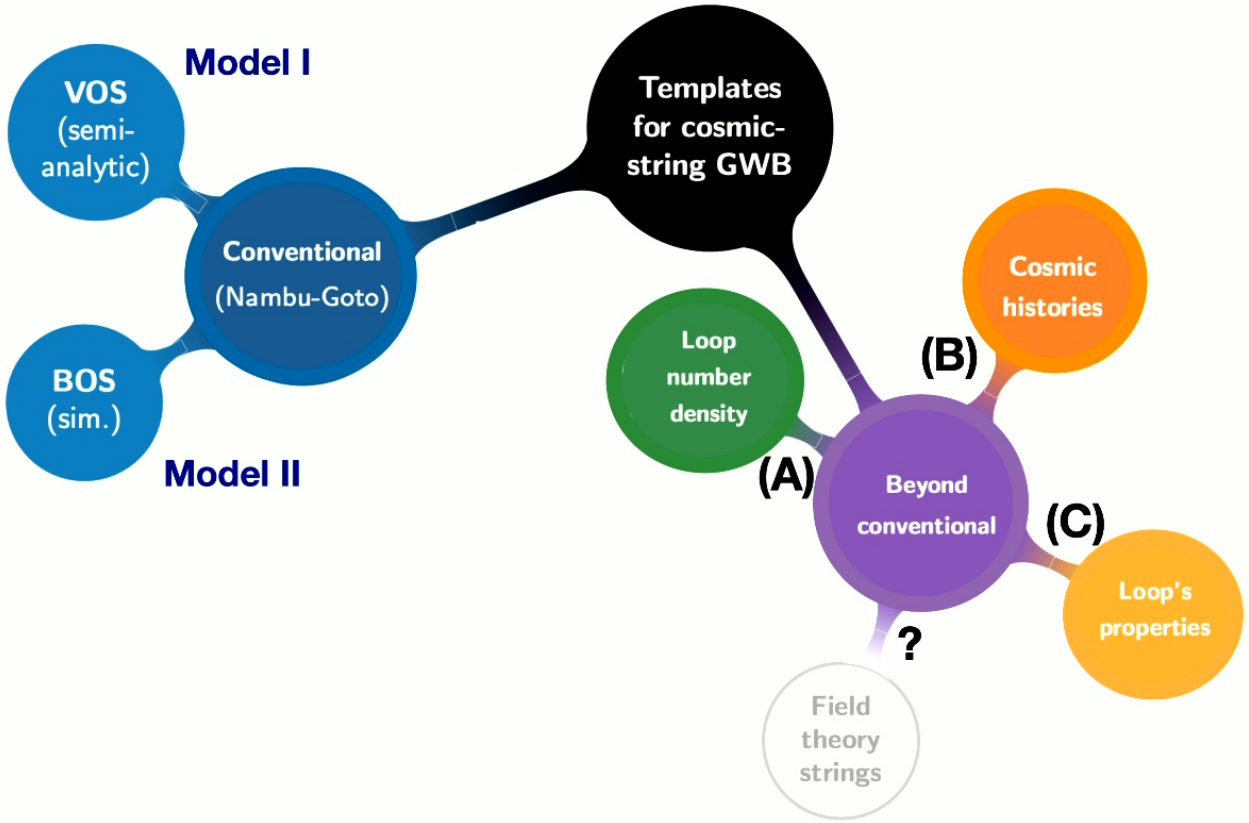
GW Background Signals: Detectability



GW Background Signals: Detectability



GW Background Signals: Detectability



Conventional Signals: VOS & BOS

(analytical) (simulation)

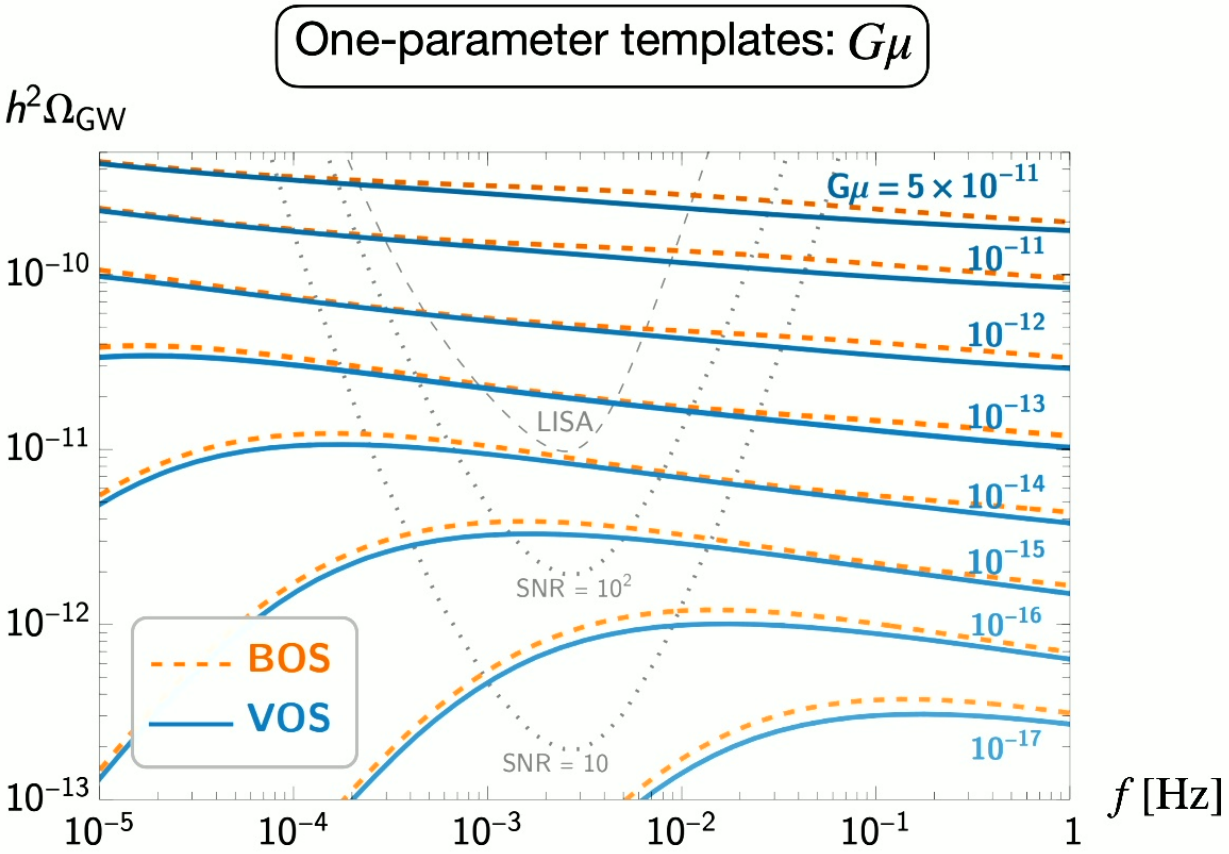
One-parameter templates: $G\mu$

(String tension $G\mu$: log–uniform $[10^{-18}, 10^{-9}]$)

$$\Omega_{\rm GW}(f) = \frac{1}{3H_0^2 m_{\rm Pl}^2} \sum_{j=1}^{\infty} \underbrace{\frac{2j}{f}(G\mu^2 P_j)}_{\substack{\text{GW emission} \\ \text{from single loops}}} \int_{a_2}^{a_1} da \, \underbrace{\frac{1}{H(a)} \left(\frac{a}{a_0}\right)^4}_{\text{cosmic history}} \underbrace{\mathbf{n}\left[\frac{2j}{f} \cdot \frac{a}{a_0}, t(a)\right]}_{\text{loop number density}}$$

Conventional Signals: VOS & BOS

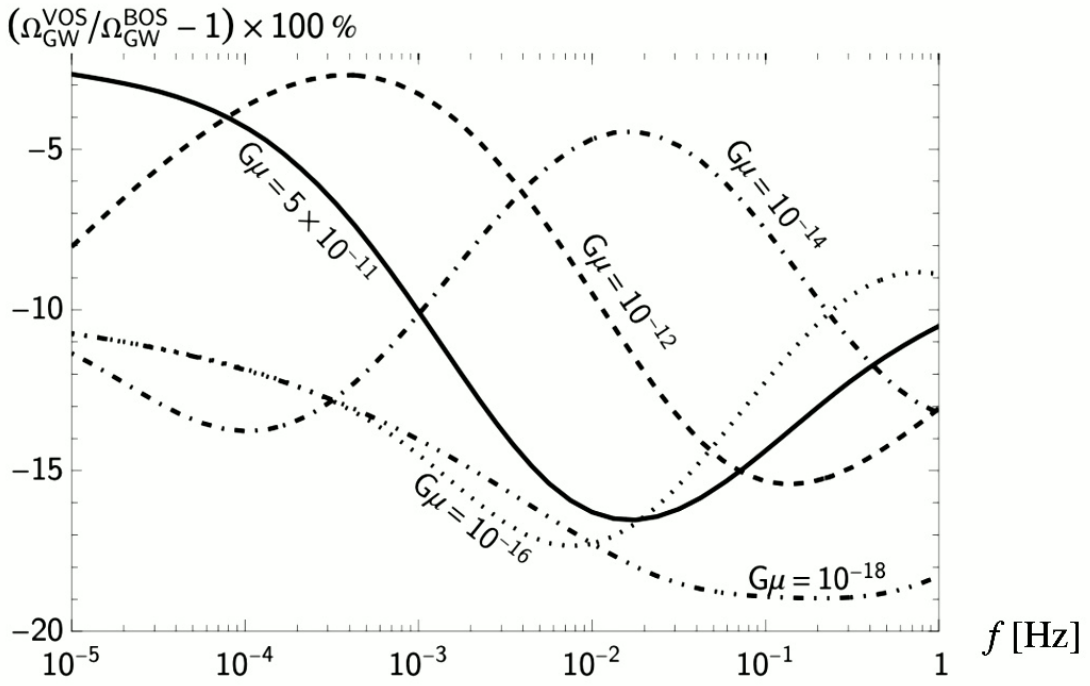
(analytical) (simulation)



Conventional Signals: VOS & BOS

(analytical) (simulation)

One-parameter templates: $G\mu$



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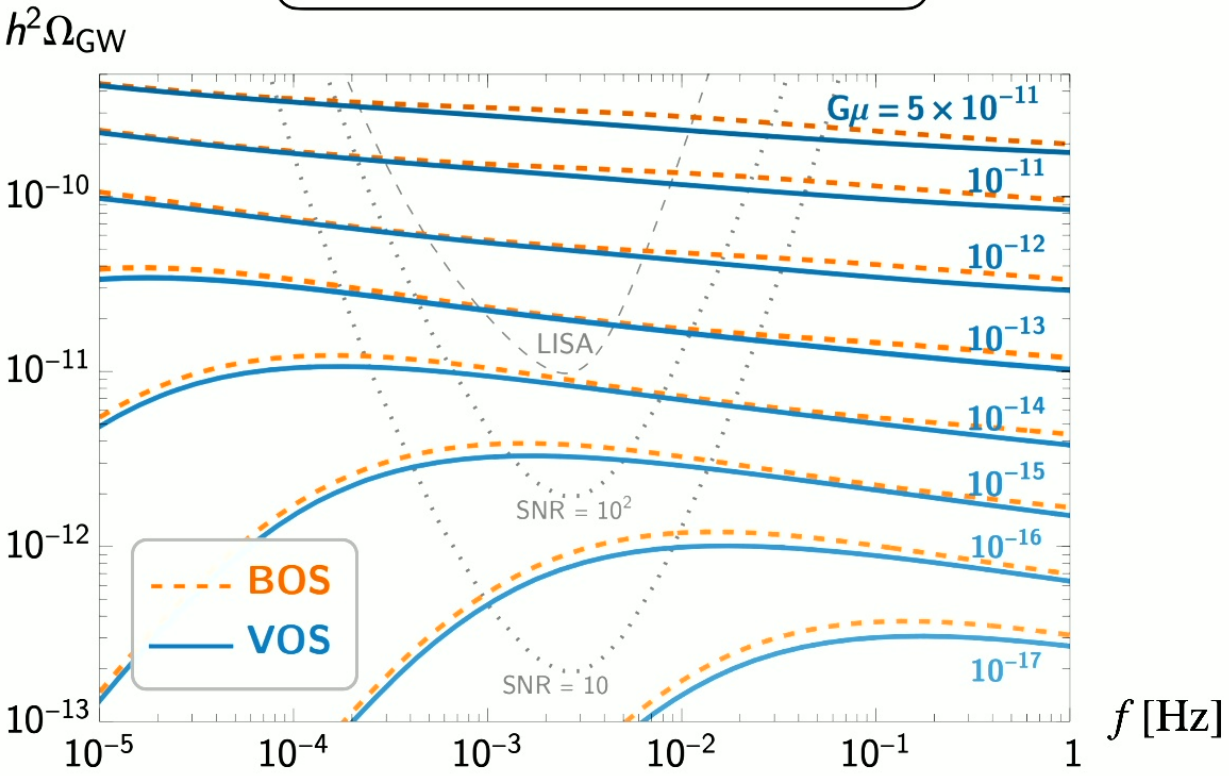
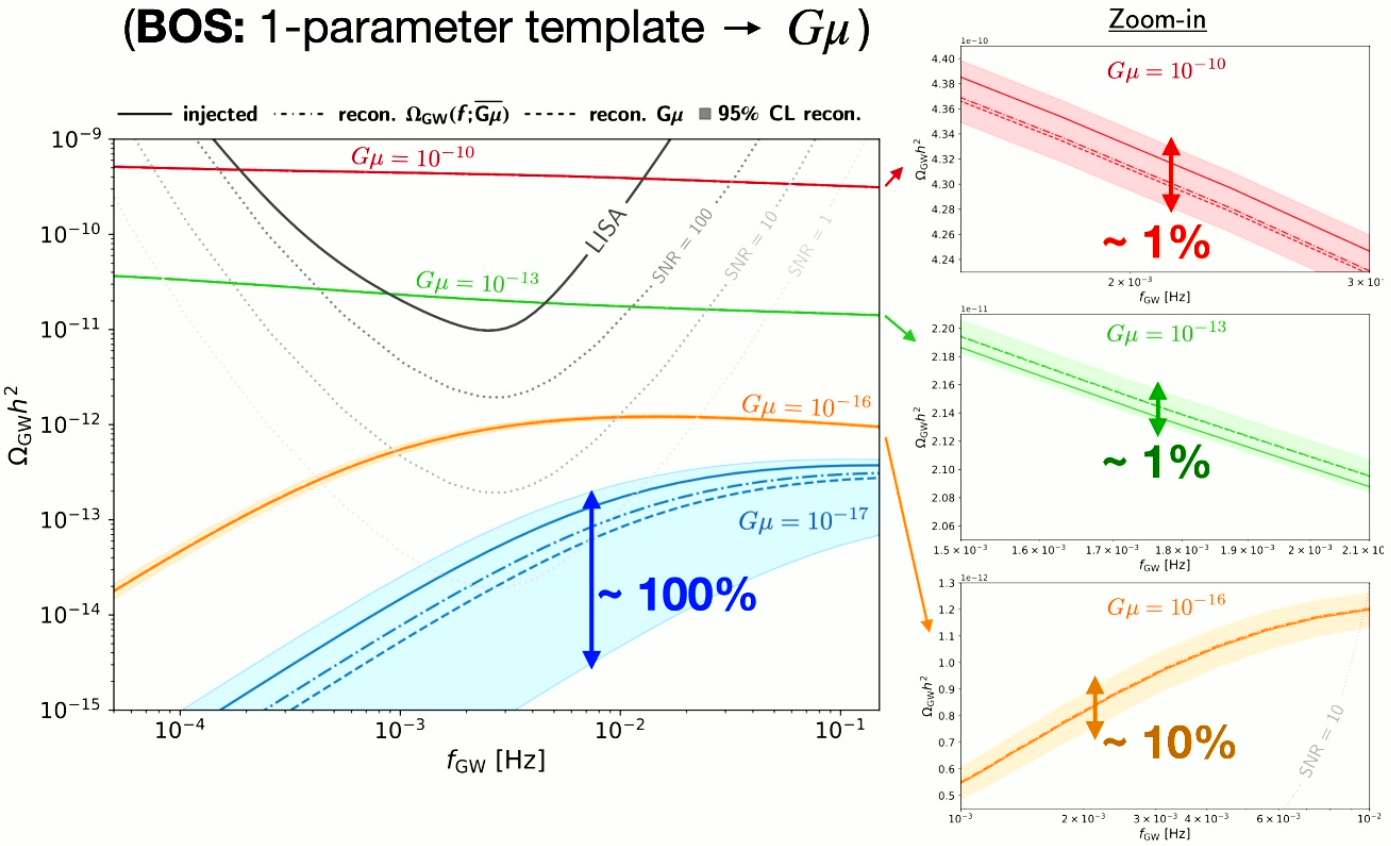


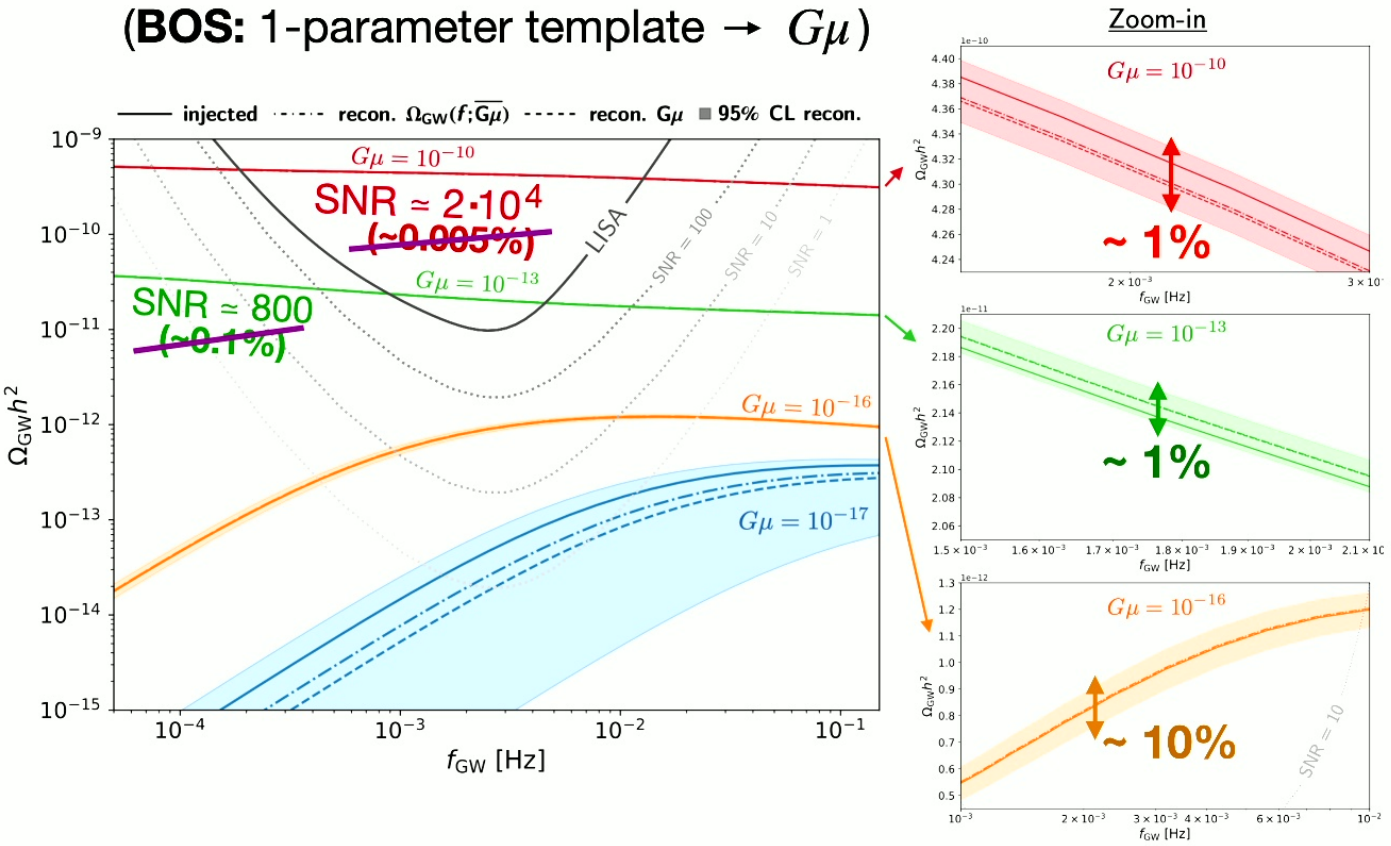
Conventional Signal Reconstruction

(**BOS:** 1-parameter template → $G\mu$)

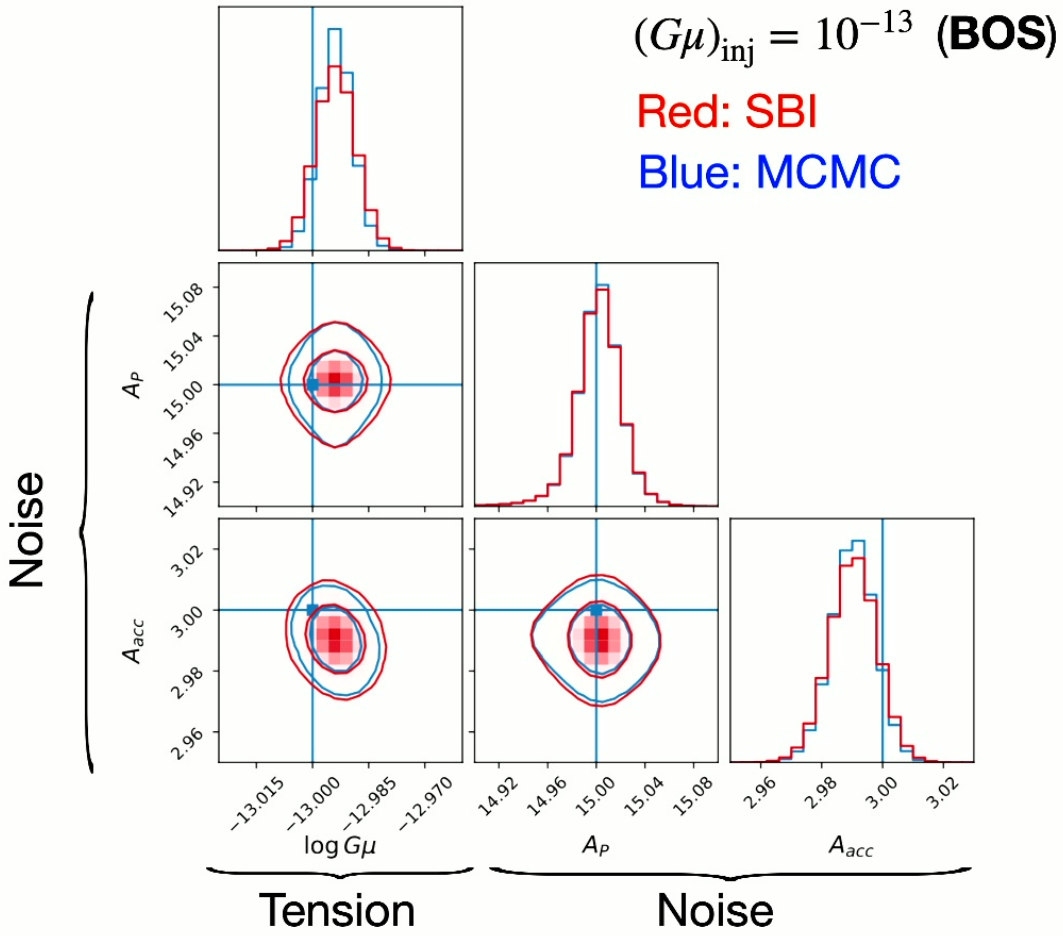


Conventional Signal Reconstruction

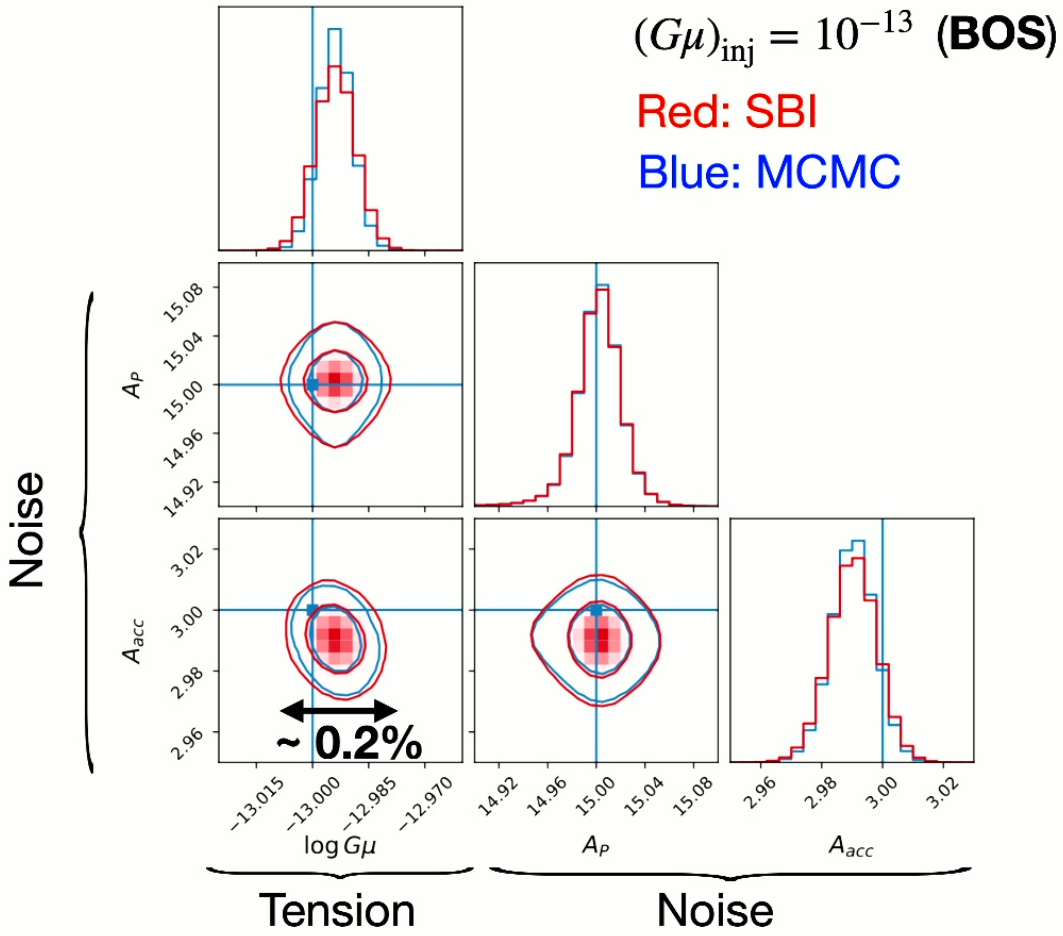
(**BOS:** 1-parameter template → $G\mu$)



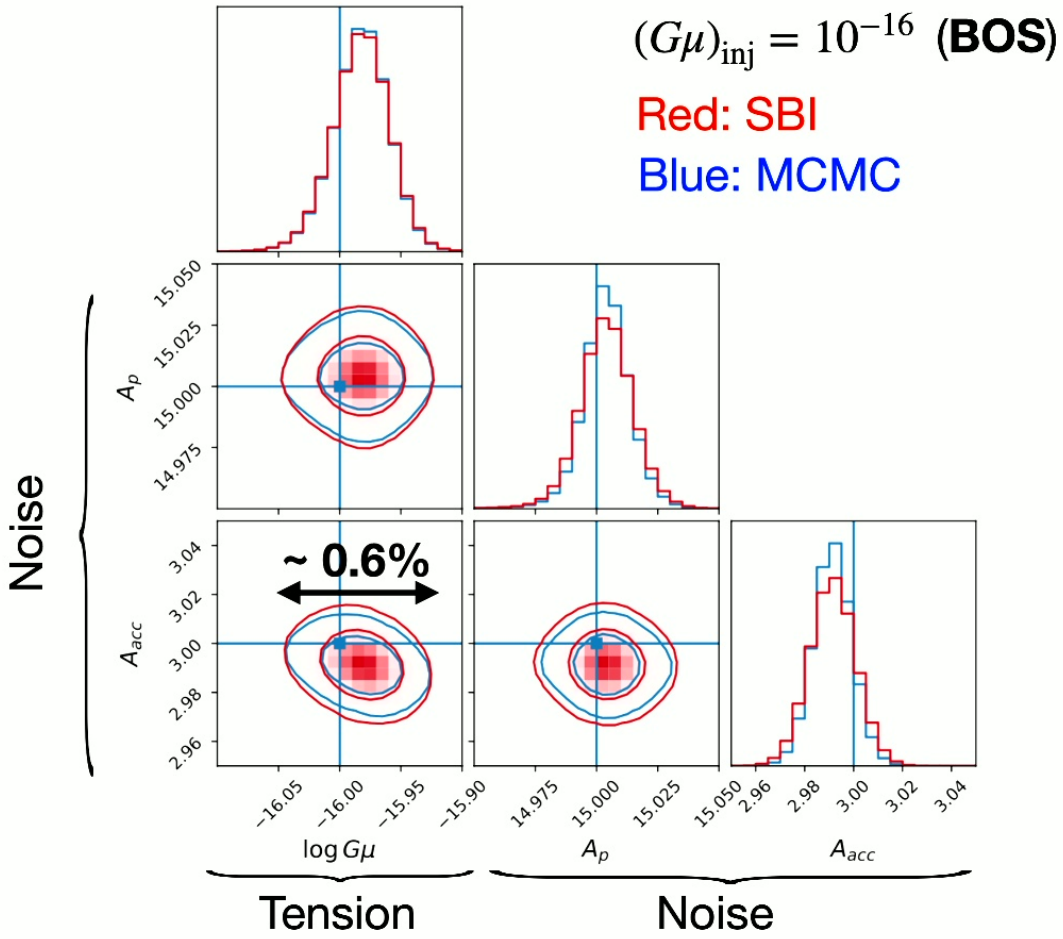
Conventional Signal Reconstruction



Conventional Signal Reconstruction

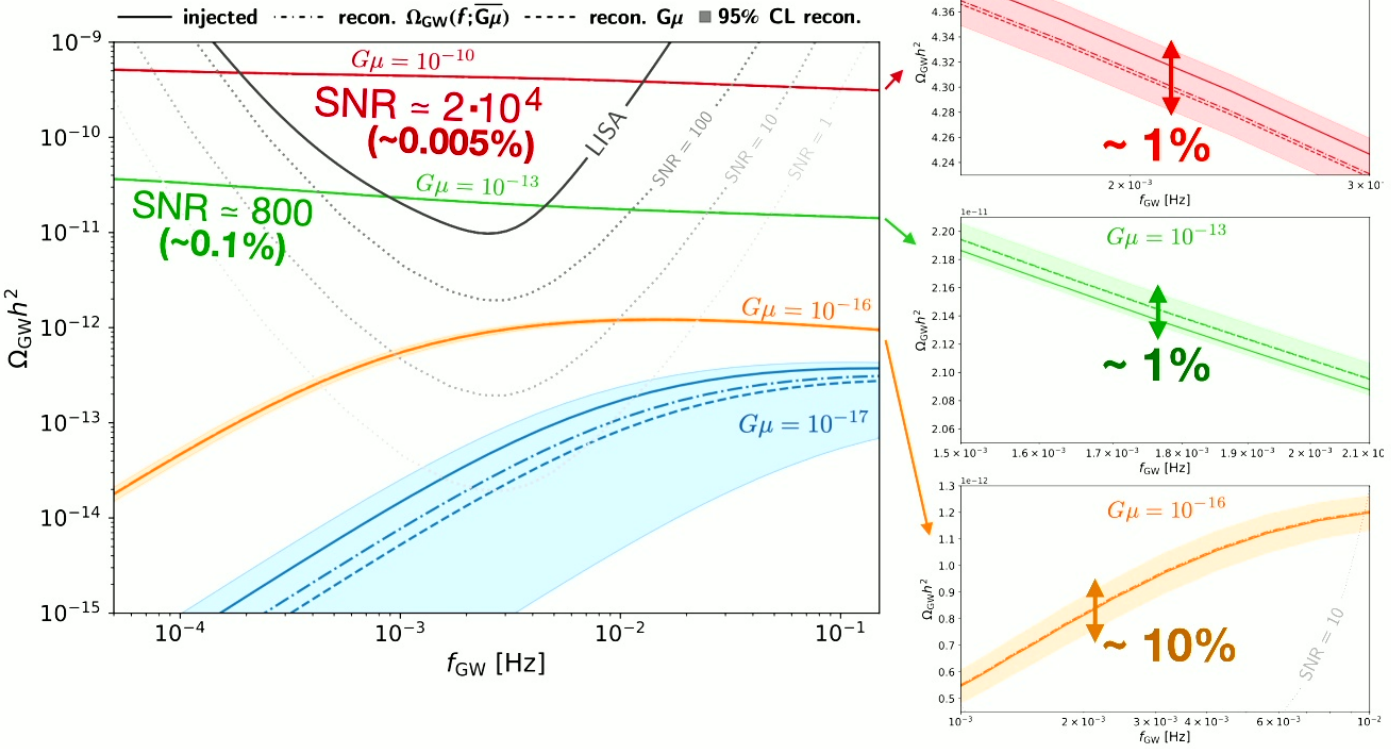


Conventional Signal Reconstruction

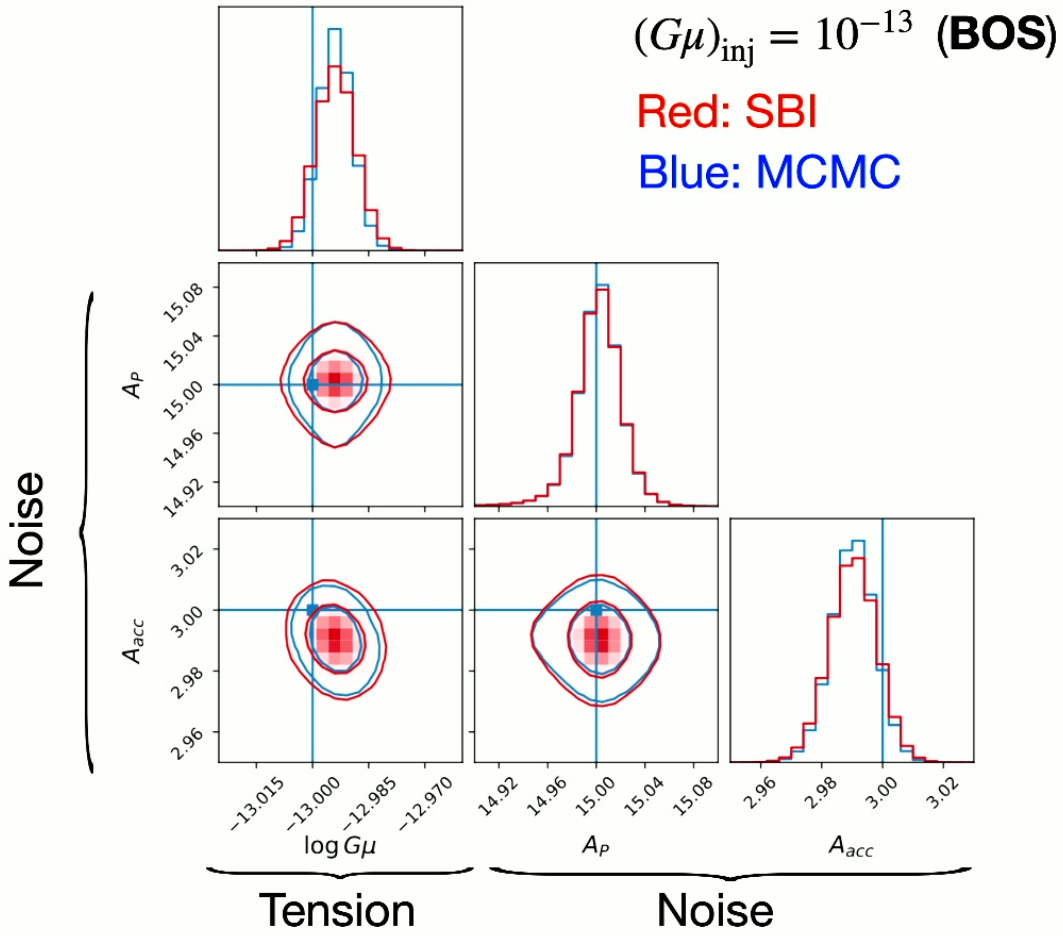


Conventional Signal Reconstruction

(**BOS:** 1-parameter template → $G\mu$)

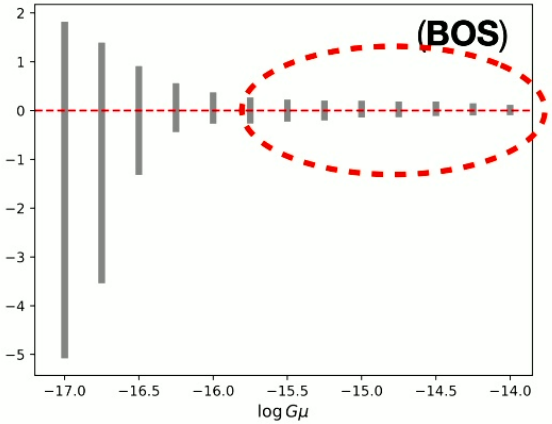


Conventional Signal Reconstruction



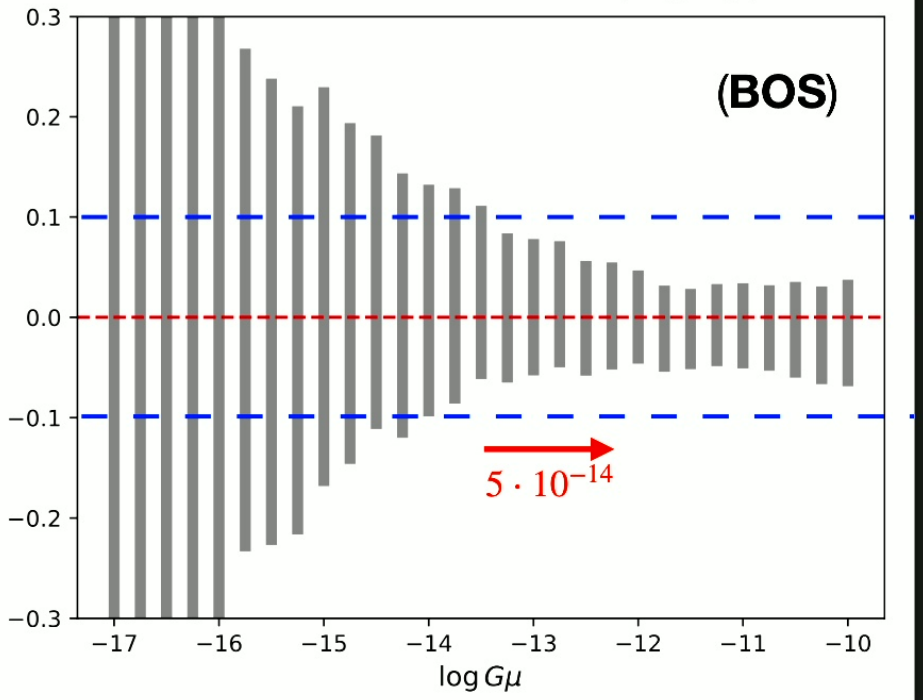
Conventional Signal Reconstruction

% Relative Error: $\Delta(\log G\mu)$

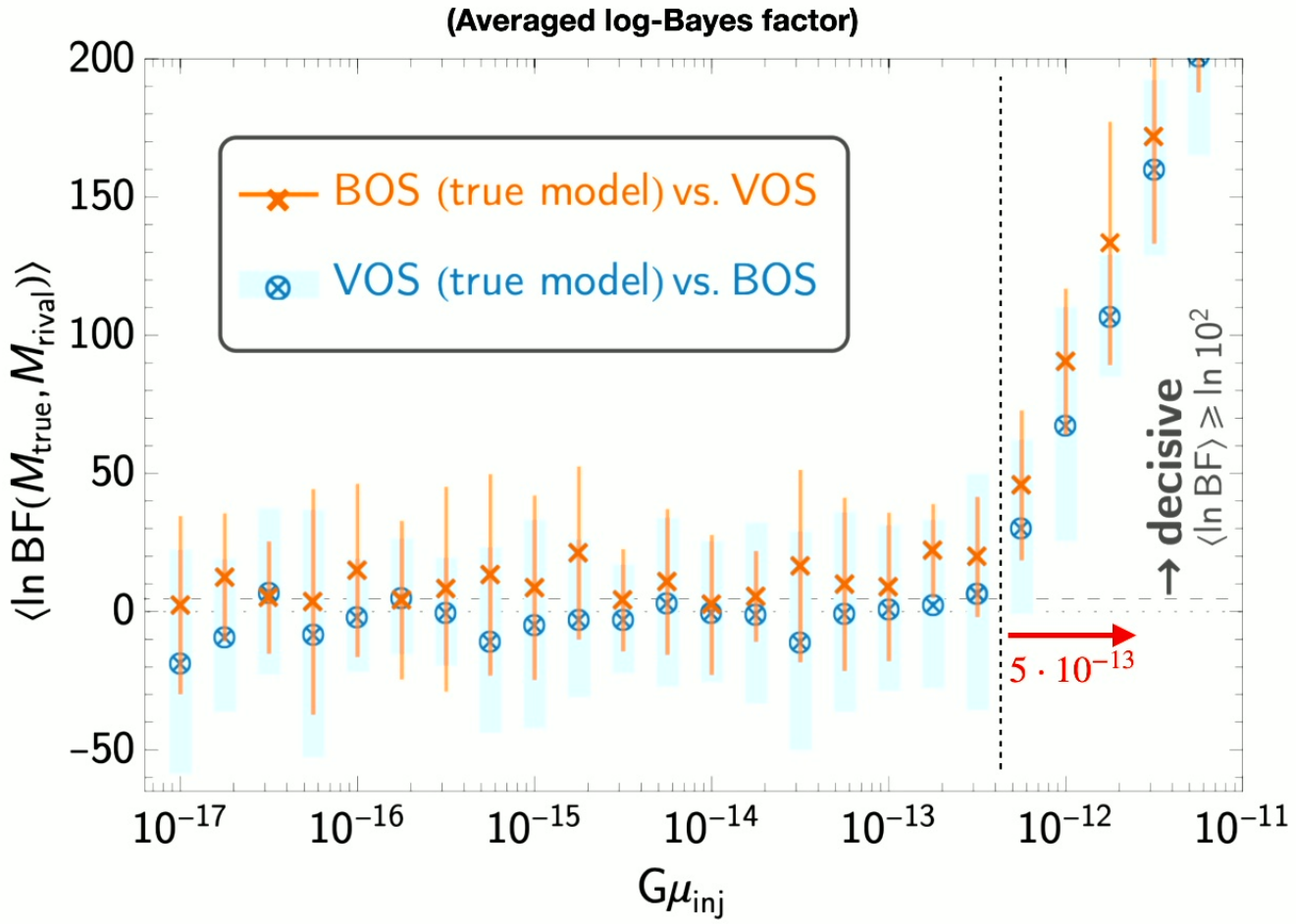


ZOOM-IN

% Relative Error: $\Delta(\log G\mu)$

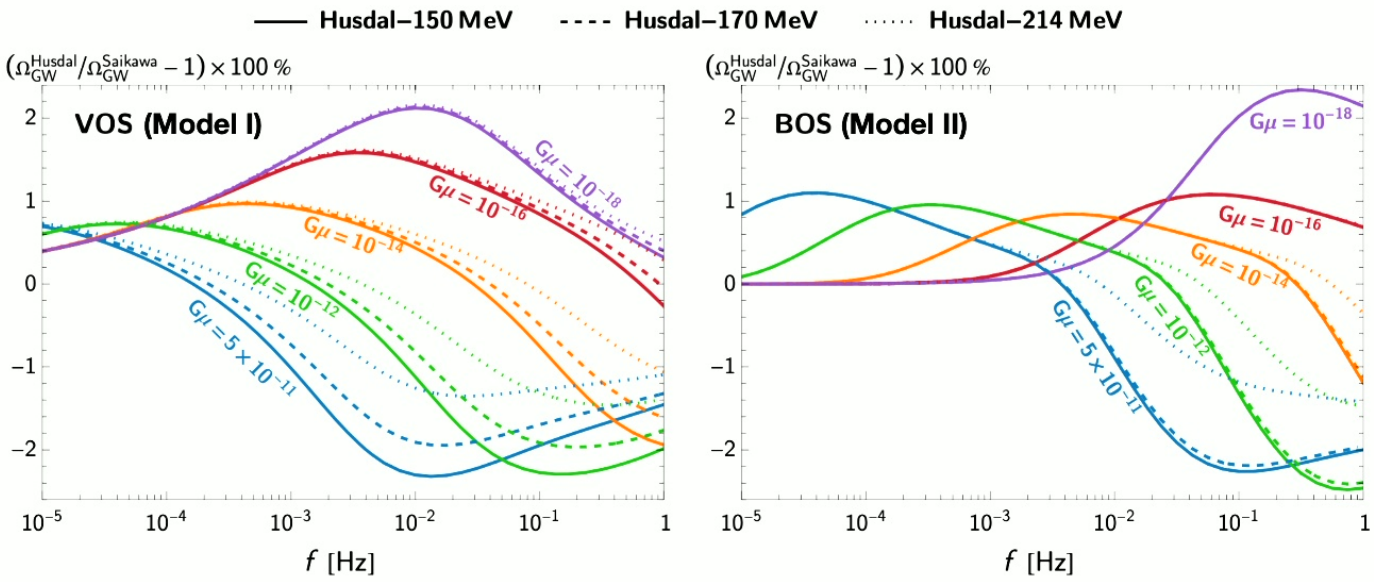


Model Comparison: BOS vs VOS



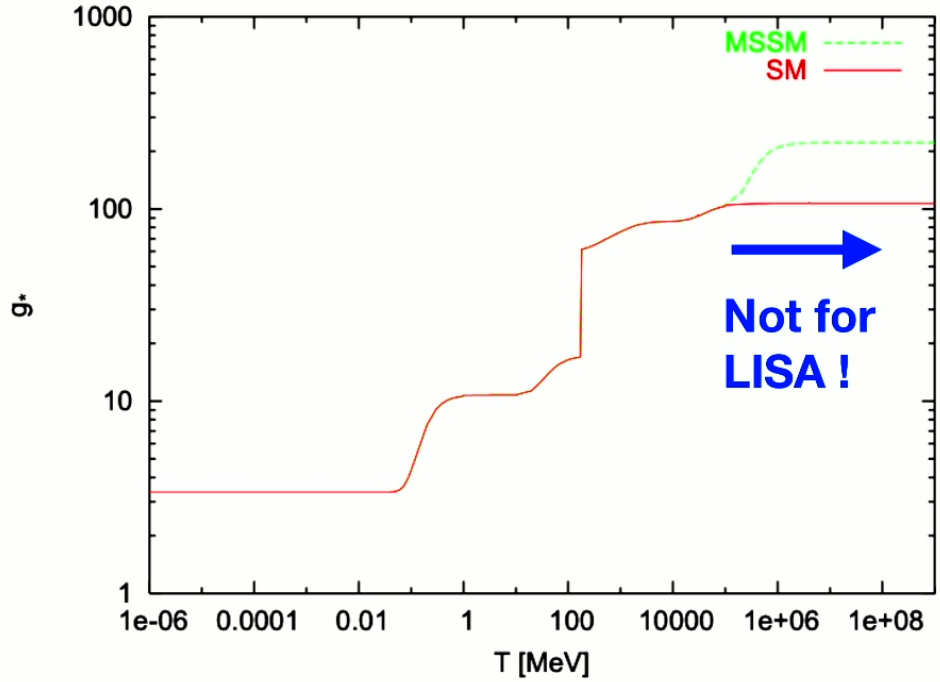
Model Comparison: *dof* evolution

$$\Omega_{\rm GW}(f) = \frac{1}{3H_0^2 m_{\rm Pl}^2} \sum_{j=1}^{\infty} \underbrace{\frac{2j}{f}(G\mu^2 P_j)}_{\substack{\text{GW emission} \\ \text{from single loops}}} \int_{a_2}^{a_1} da \, \underbrace{\frac{1}{H(a)}\left(\frac{a}{a_0}\right)^4}_{\text{cosmic history}} \underbrace{\mathtt{n}\left[\frac{2j}{f}\cdot\frac{a}{a_0}, t(a)\right]}_{\text{loop number density}}$$



Model Comparison: *dof* evolution

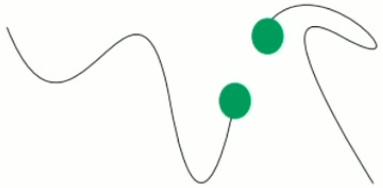
But opens  to BSM !



Beyond Conventional Signals: Detectability

(A) MetaStable Cosmic Strings

(Domcke et al 2020-2023)



Grand Unified Theories: Symm. Breaking @ multiple steps

(monopoles & strings)

Monopole-antimonopole pair nucleates → cuts loops → segments

Nucleation rate

$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa} \quad , \text{ with } \quad \kappa \equiv \left(\frac{m_M}{\eta}\right)^2 .$$

monopole formation scale

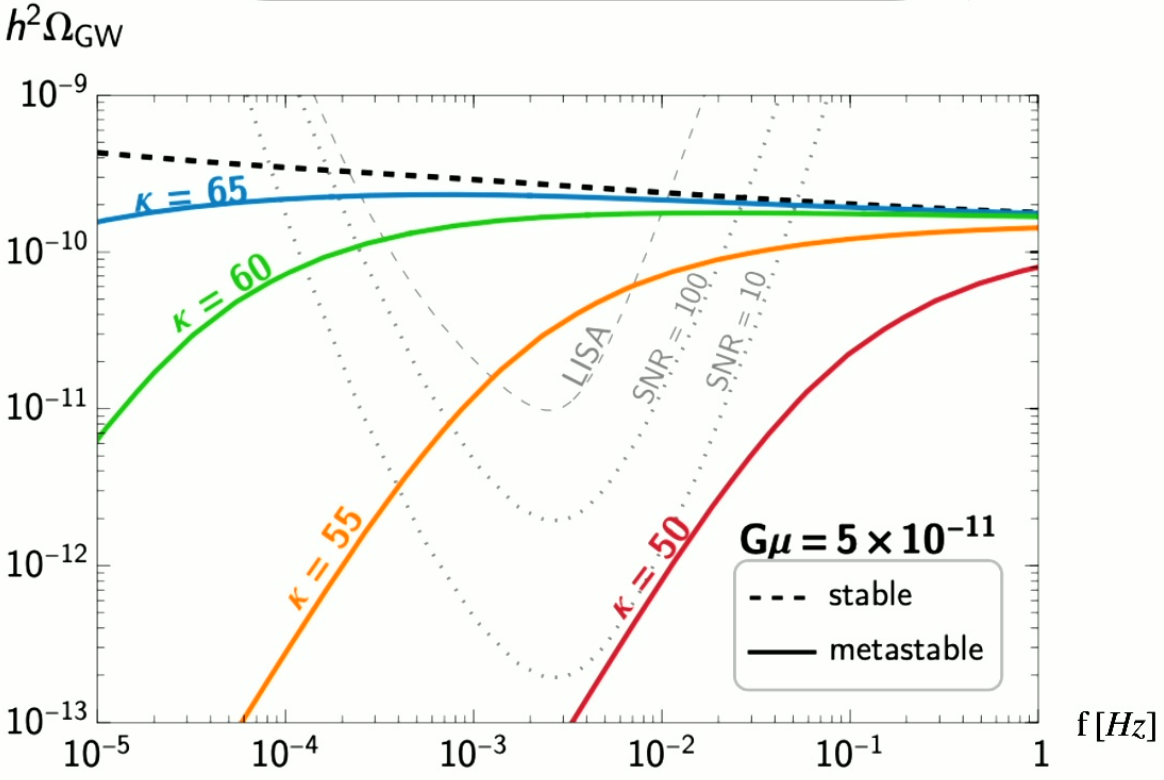
String formation scale

Beyond Conventional Signals: Detectability

(A) MetaStable Cosmic Strings

Two-parameter template: $G\mu, \kappa$

$\left(\begin{matrix} G\mu\text{: Log-uniform } [10^{-18},10^{-9}] \\ \kappa\text{: Uniform } [40,80] \end{matrix}\right)$



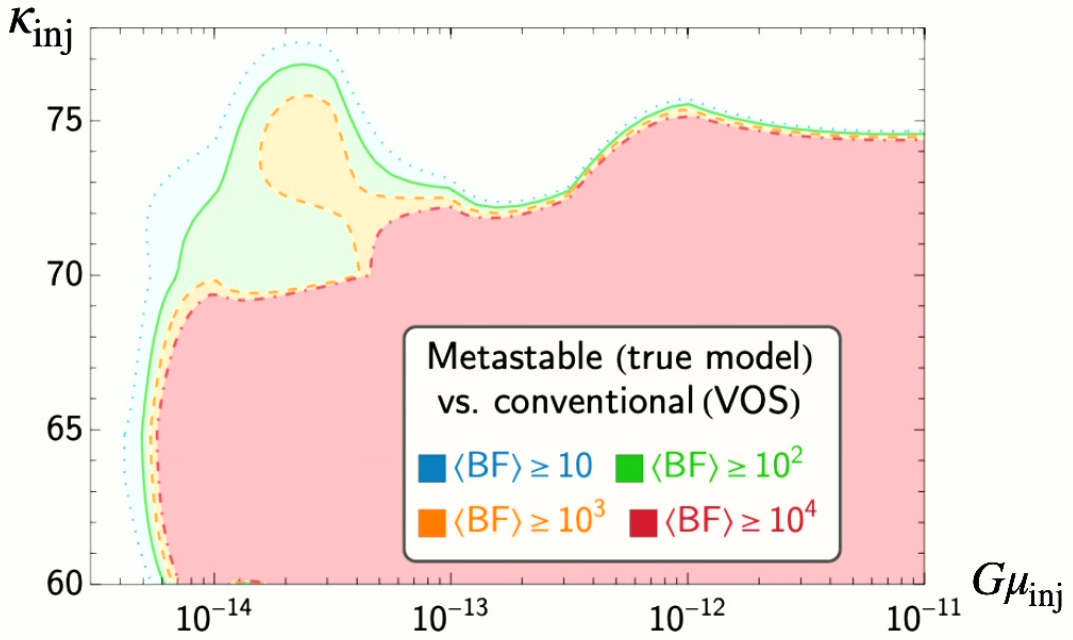
Beyond Conventional Signals: Detectability

(A) MetaStable Cosmic Strings

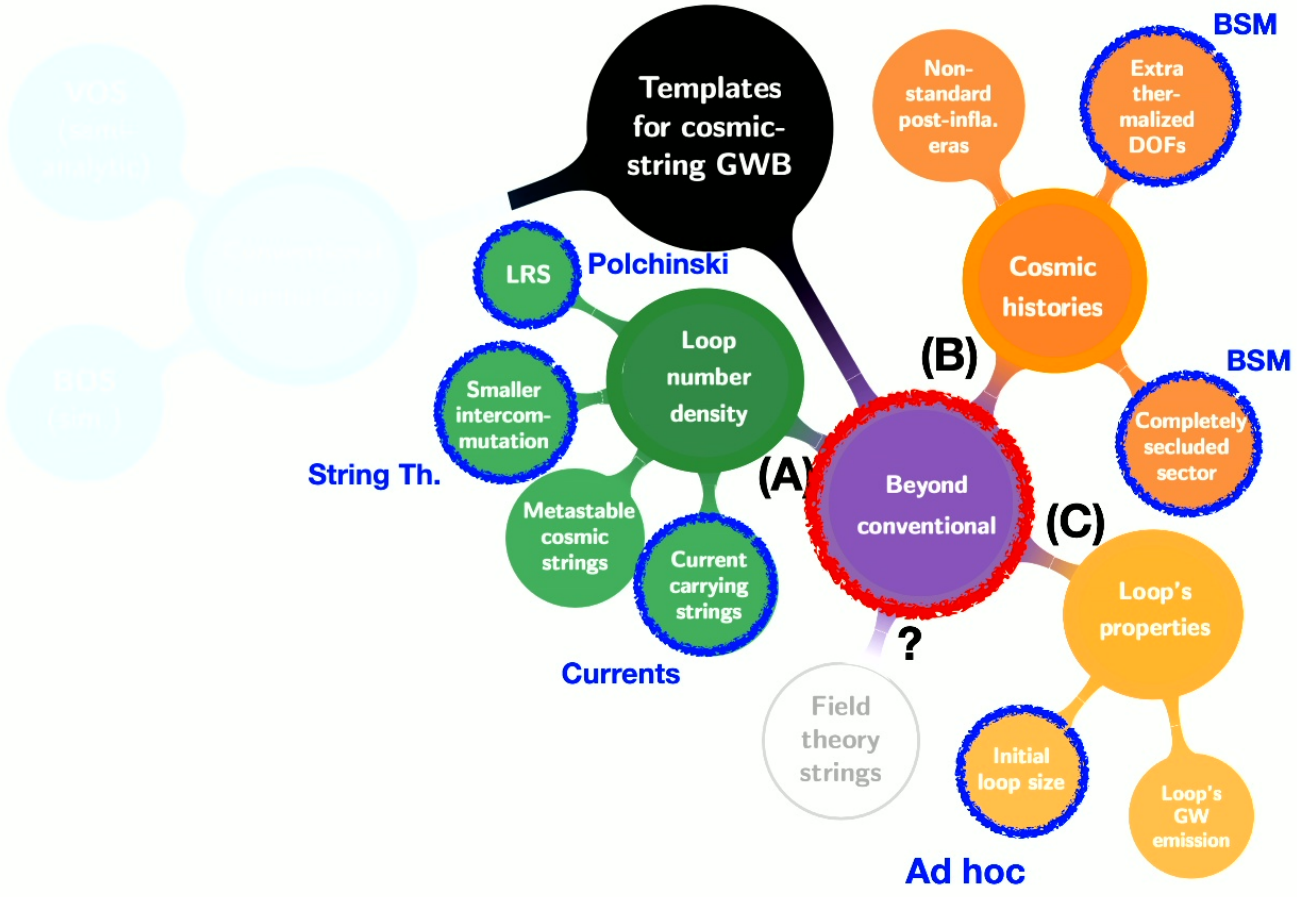
Two-parameter template: $G\mu, \kappa$

($G\mu$: Log-uniform $[10^{-18}, 10^{-9}]$; κ: Uniform $[40, 80]$)

Model comparison: conventional vs meta-stable



Beyond Conventional Signals: Detectability



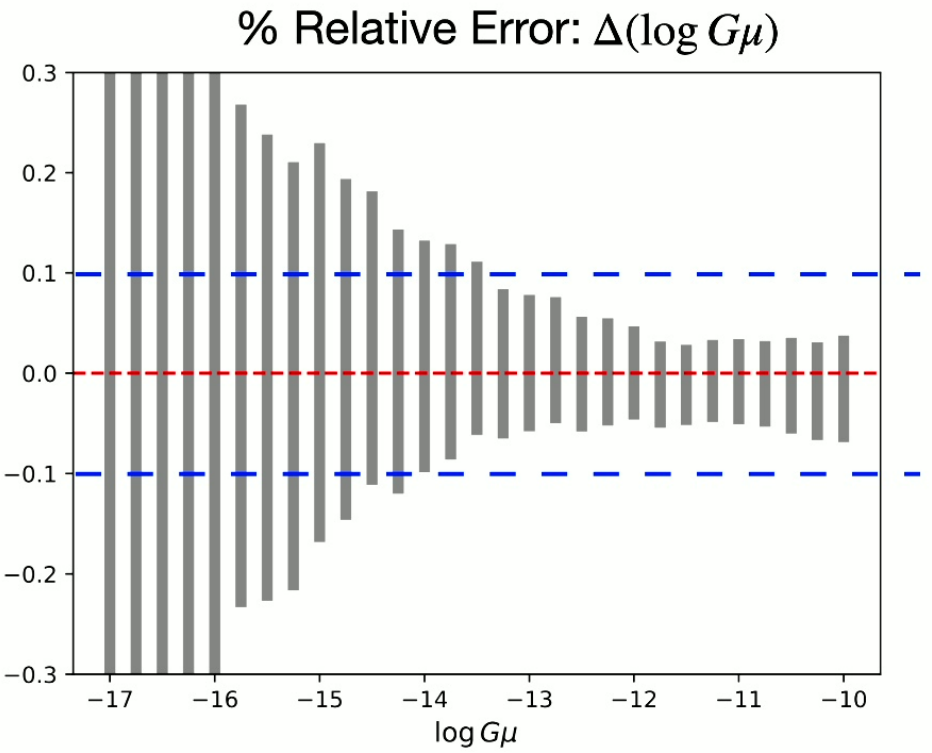
GW Background Signals: Detectability
(over foregrounds)

Which foregrounds ?

GW Background Signals: Detectability
(over foregrounds)

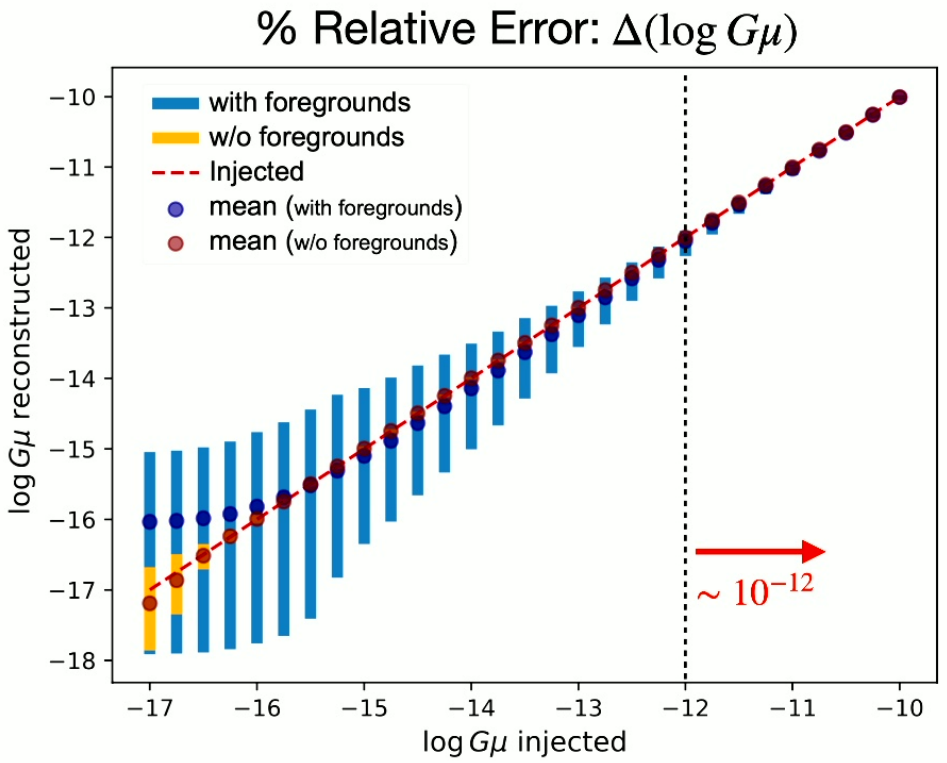
If you remember:

No foregrounds

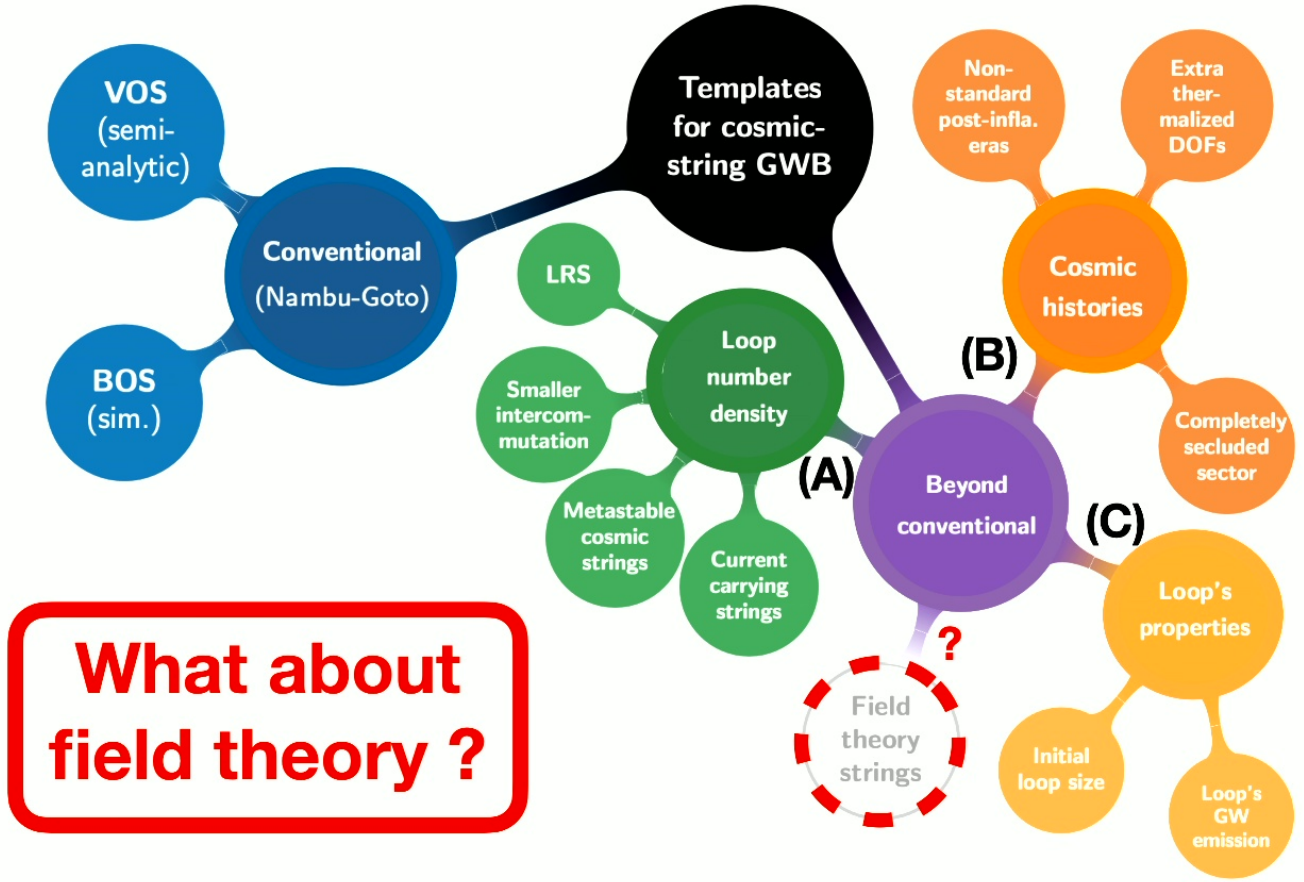


GW Background Signals: Detectability
(over foregrounds)

With/without foregrounds

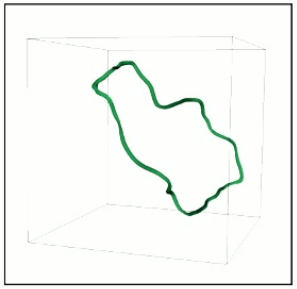


GW Background Signals: Detectability

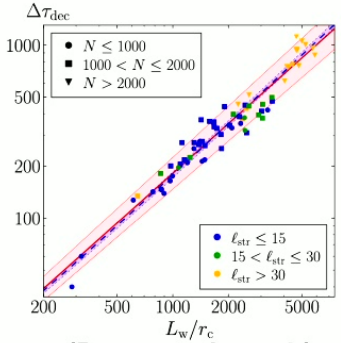


String Loop Dynamics + GW emission

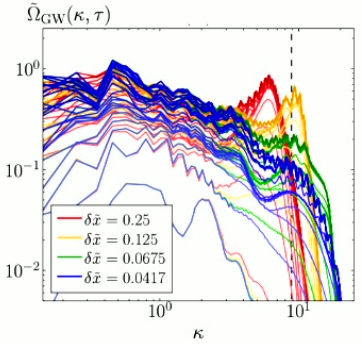
GWs & Particles Emitted



(Loops isolated)



(Decay vs Length)



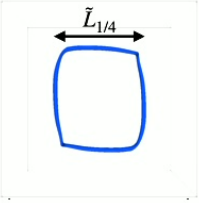
(GW emission)

Baeza-Ballesteros et al, 2024

(Local Strings)

$[\ L/w \simeq 200 - 6000\ ]$

If loops Artificial (w/ Kinks)



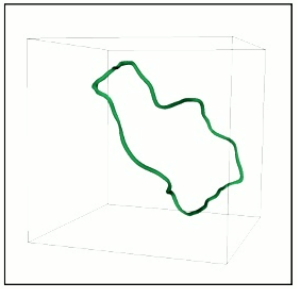
String Loop Dynamics + GW emission

GWs & Particles Emitted

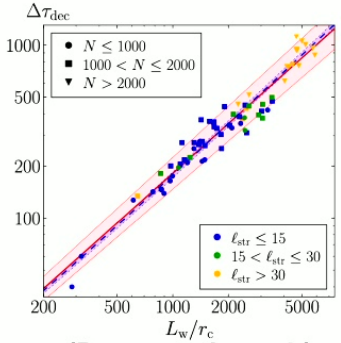
This will open PTA bounds to GUT scales !

String Loop Dynamics + GW emission

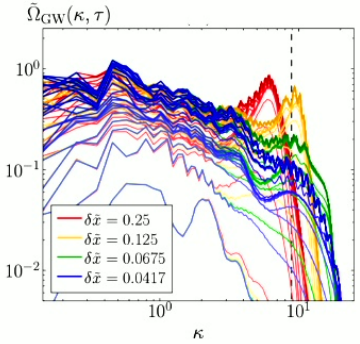
GWs & Particles Emitted



(Loops isolated)



(Decay vs Length)



(GW emission)

Baeza-Ballesteros et al, 2024

(Local Strings)

$[\ L/w \simeq 200 - 6000\ ]$

If loops Artificial (w/ Kinks)

Critical Length L_c

(Vachaspati et al 2019)

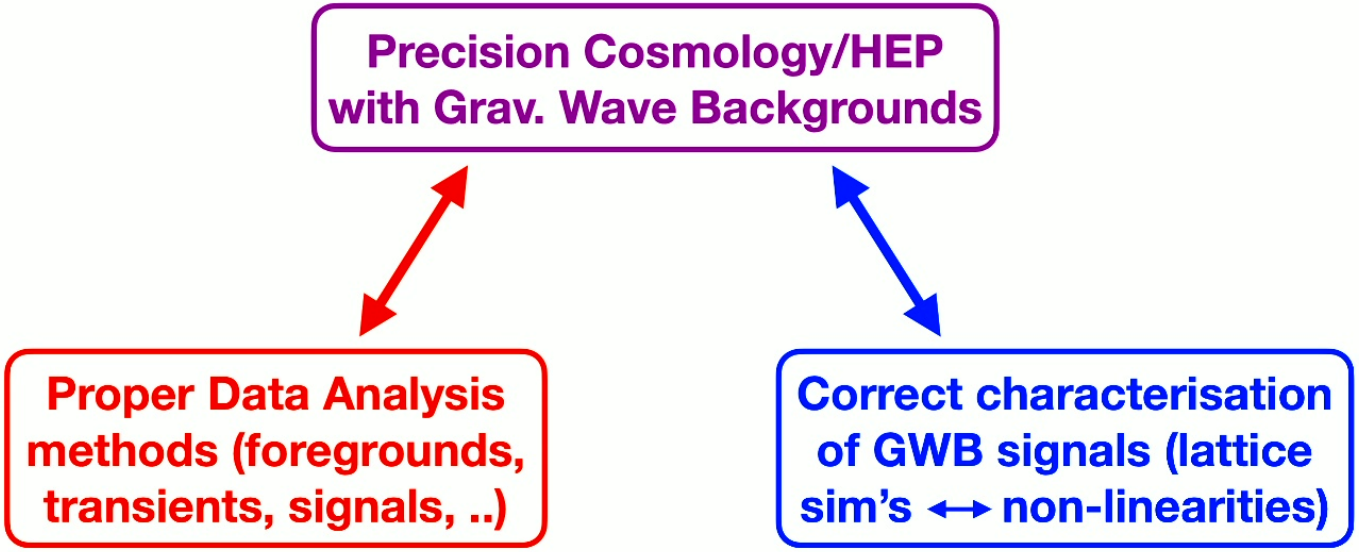
If $L \gg L_c : \dfrac{P_{\rm GW}}{P_\phi} \gg 1$

(In agreement with NG)

A message before we conclude …

Precision Cosmology/HEP with Grav. Wave Backgrounds

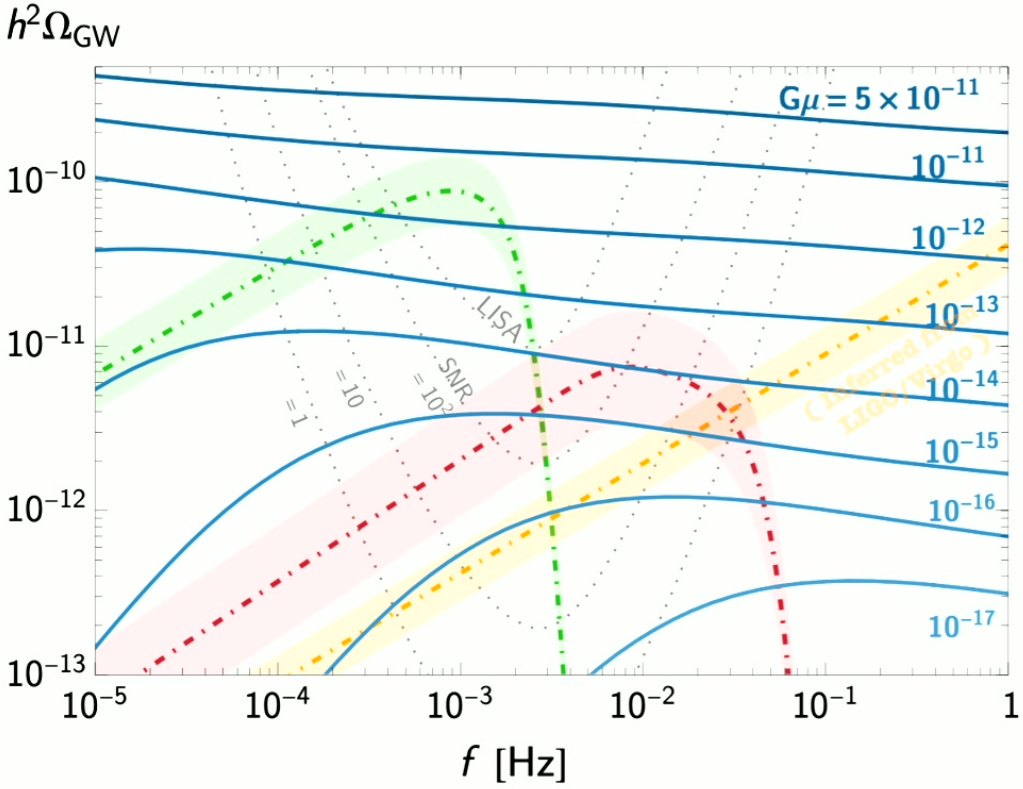
A message before we conclude …



Thanks for your attention

Merci pour votre attention

GW Background Signals: Detectability
(over foregrounds)



BOS ($G\mu$)

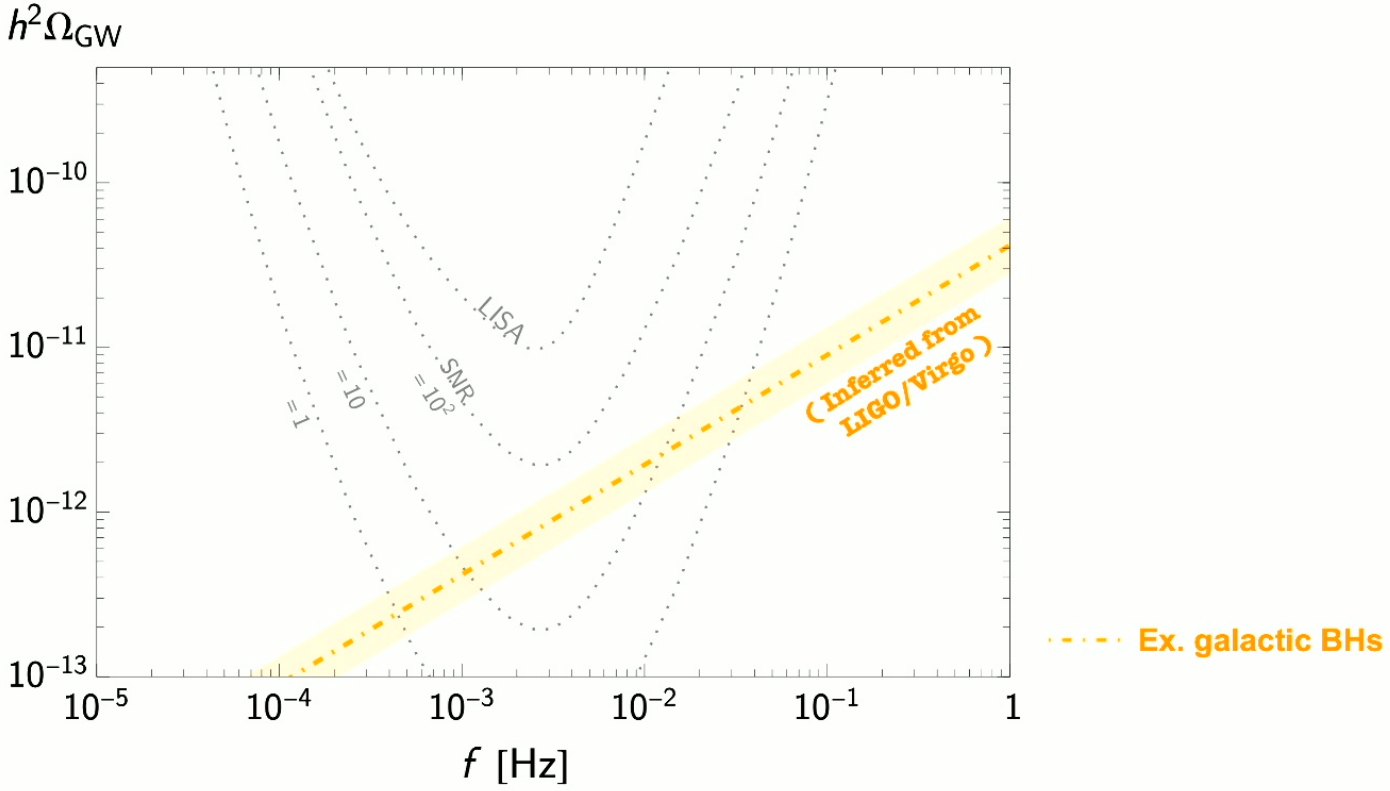
Galactic WDs

Ex. galactic WDs

Ex. galactic BHs

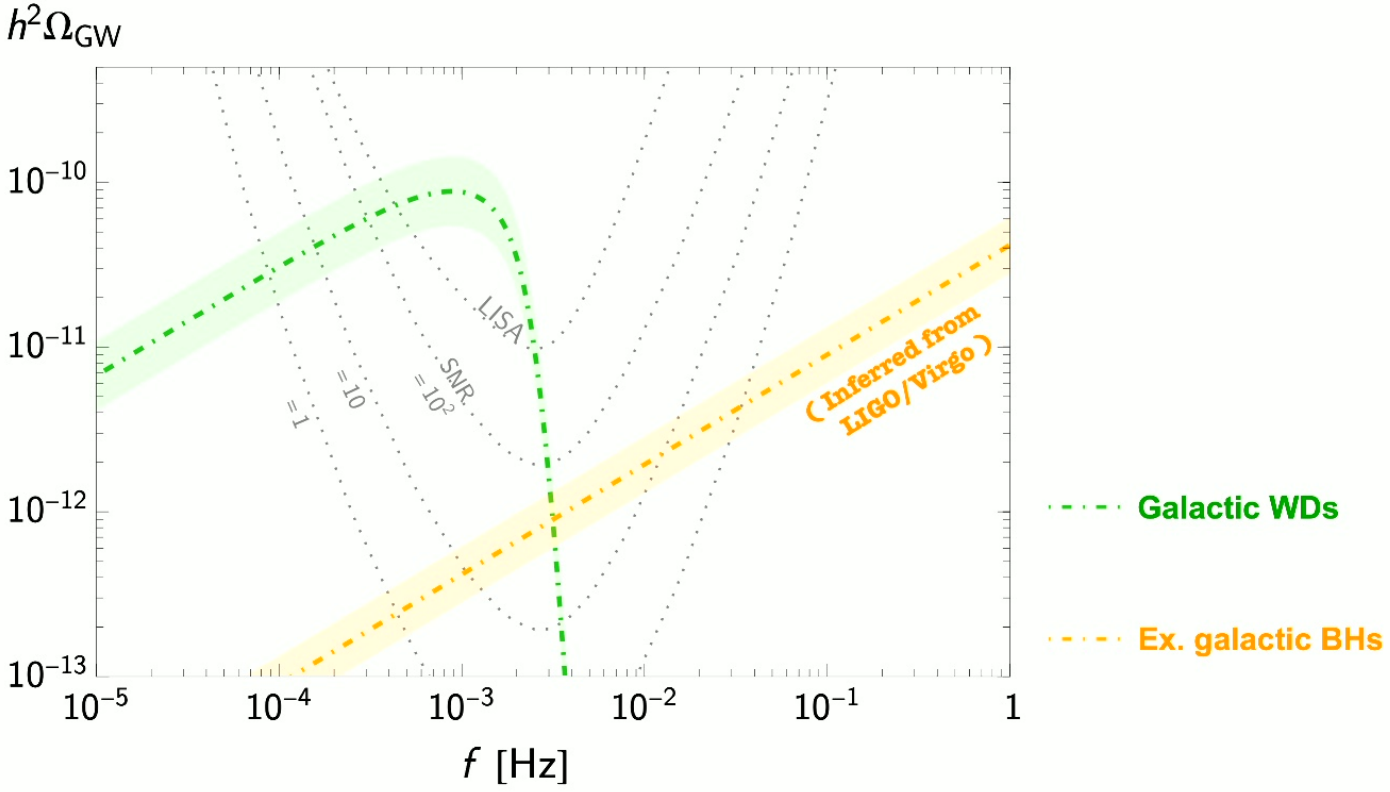
2407.10642
2304.06368
2304.06368

GW Background Signals: Detectability
(over foregrounds)



2304.06368

GW Background Signals: Detectability
(over foregrounds)



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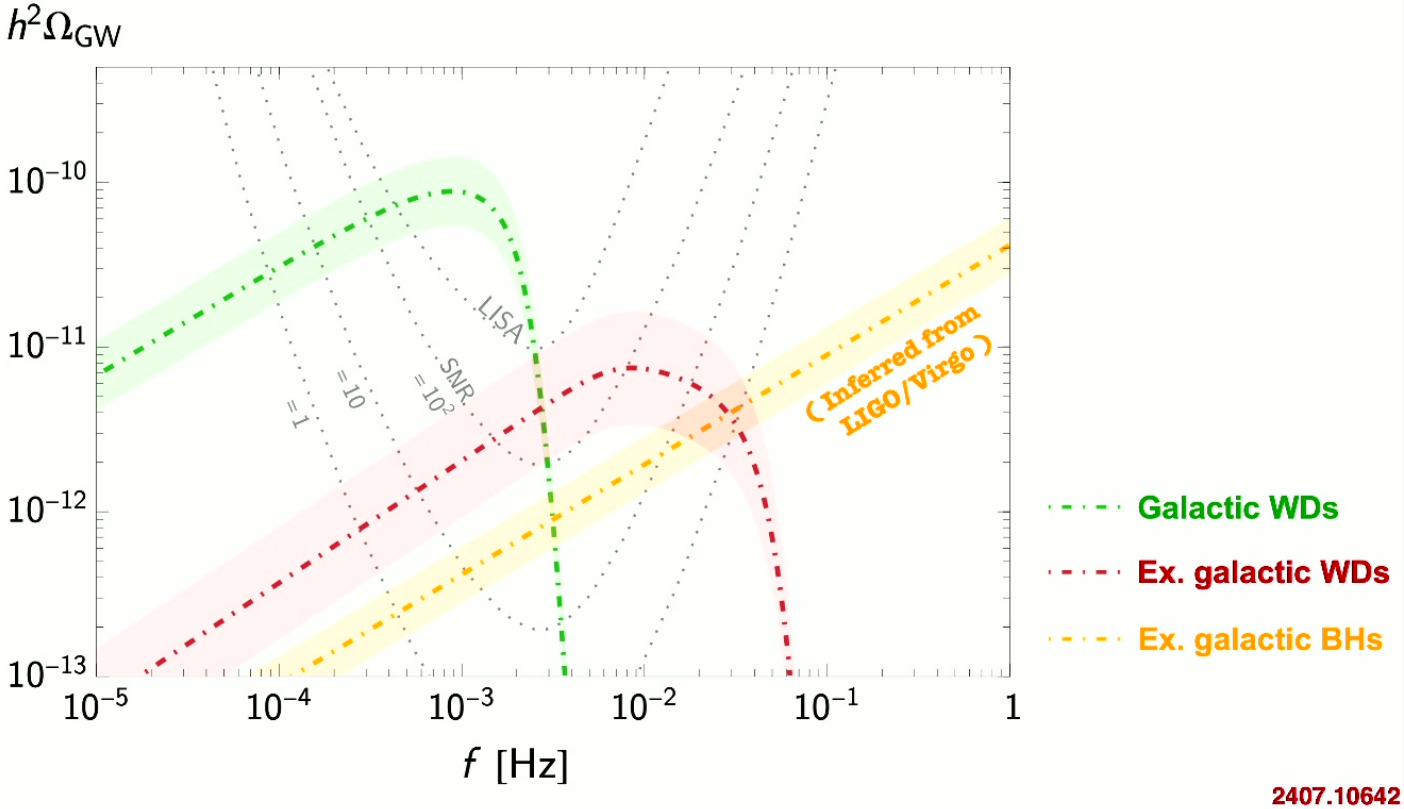

2407.10642
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