Distinguishing Cosmic-String Modelings with LISA

with Androniki Dimitriou, Daniel G. Figueroa, Bryan Zaldivar [250Y.xxxxx]

(Y = 5?)

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The Dawn of Gravitational Wave Cosmology, Benasque

You want to search for
GW backgrounds (GWBs) from your favorite models
with **some GW detector.**

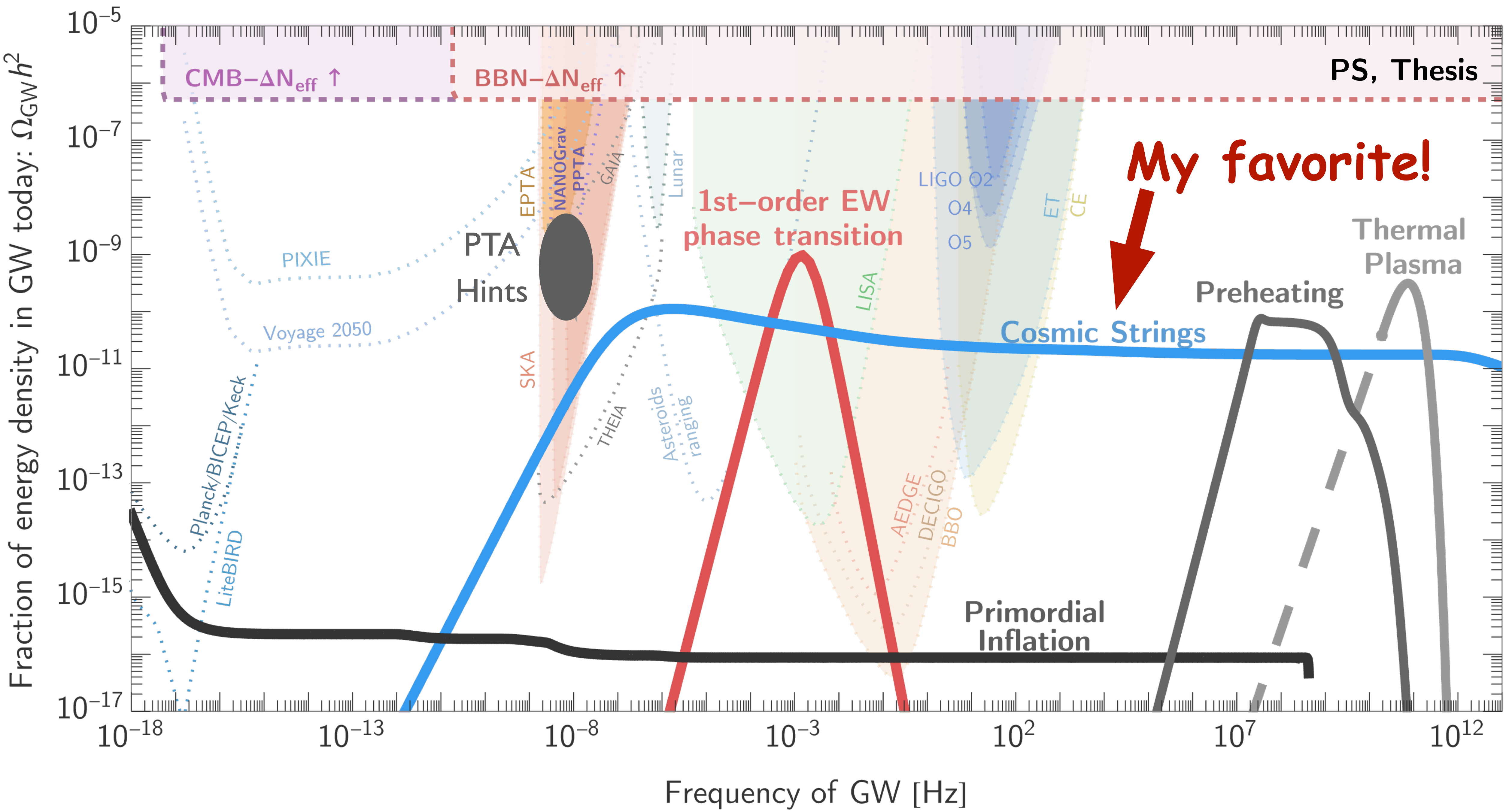
2 important questions are...

1. How well can the signal be detected?
i.e., how well can the underlying model's parameters be probed?

2. Can different models be distinguished?
whose GWB are very similar, but not overlap.
E.g., due to some theoretical uncertainties.

Gravitational Wave Backgrounds (GWBs) from cosmological origins.

Cosmic-string GWB can be loud and spans a broad frequency range.



GWB from Cosmic Strings

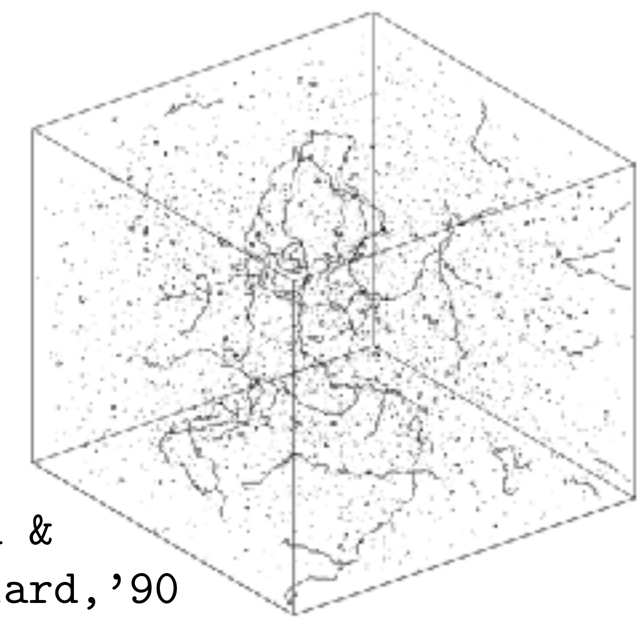
See also talks by Kai and Jose-Juan

A **cosmic string** = a line-like topological defect from a spontaneous symmetry breaking [e.g., U(1)], at energy scale η. [Kibble '76]

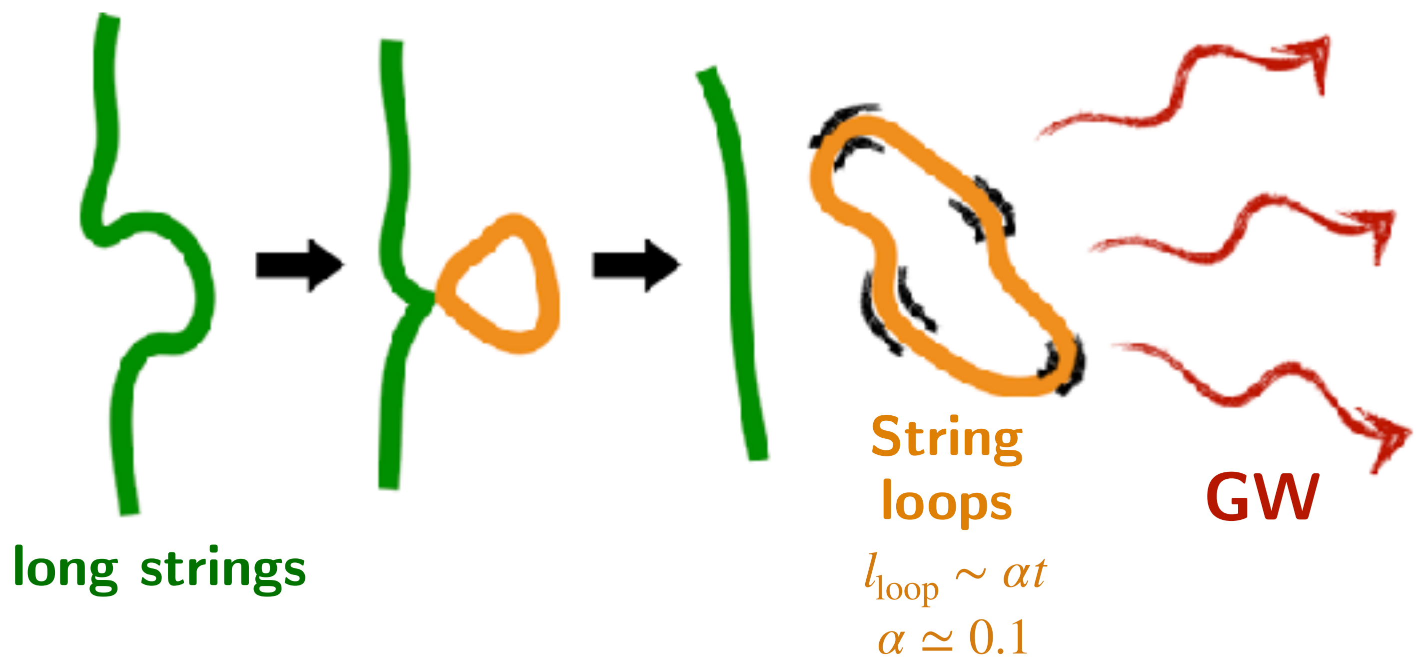
String tension [energy per length]

$$G\mu \simeq \left(\frac{\eta}{m_{\rm Pl}}\right)^2 \simeq 6.7\times 10^{-11}\left(\frac{\eta}{10^{14}\ {\rm GeV}}\right)^2$$

Network of cosmic



Allen & Shellard,'90



"The master formula"

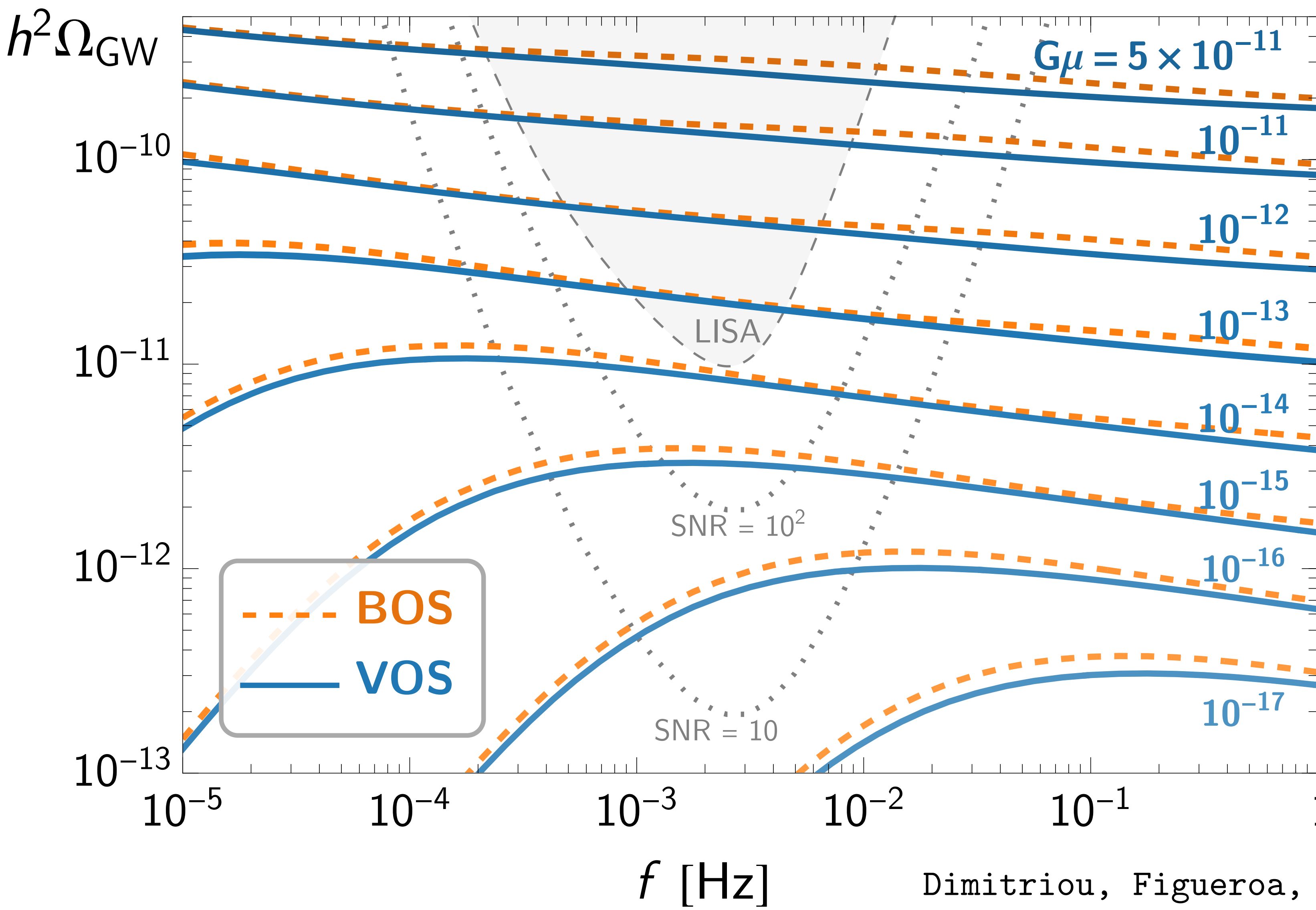
$$\Omega_{\rm GW}(f) = \frac{1}{3H_0^2 M_{\rm Pl}^2}\sum_{j=1}^{\infty}\underbrace{\frac{2j}{f}(G\mu^2 P_j)}_{\text{GW emission from single loops}}\int_{a_2}^{a_1} da\,\underbrace{\frac{1}{H(a)}\left(\frac{a}{a_0}\right)^4}_{\text{cosmic history}}\,\underbrace{\mathtt{n}\left[\frac{2j}{f}\cdot\frac{a}{a_0},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

Conventional templates

Nambu-Goto (NG) 1D strings: only GW emission

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

VOS	**NG analytics**	ΛCDM	**NG analytics**
BOS	**NG simulations**	ΛCDM	**NG simulations**



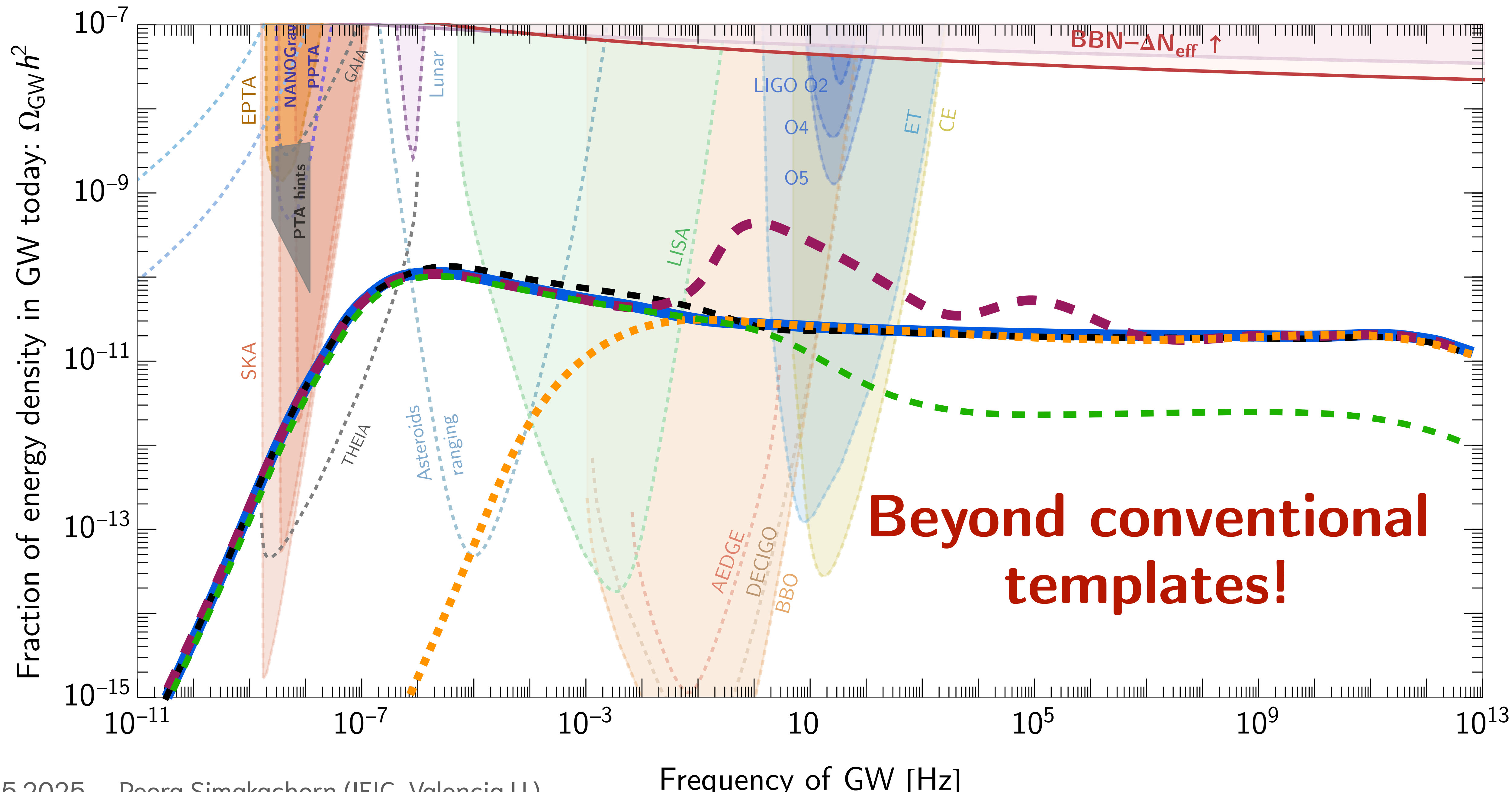
VOS: Velocity-dependent One-Scale model

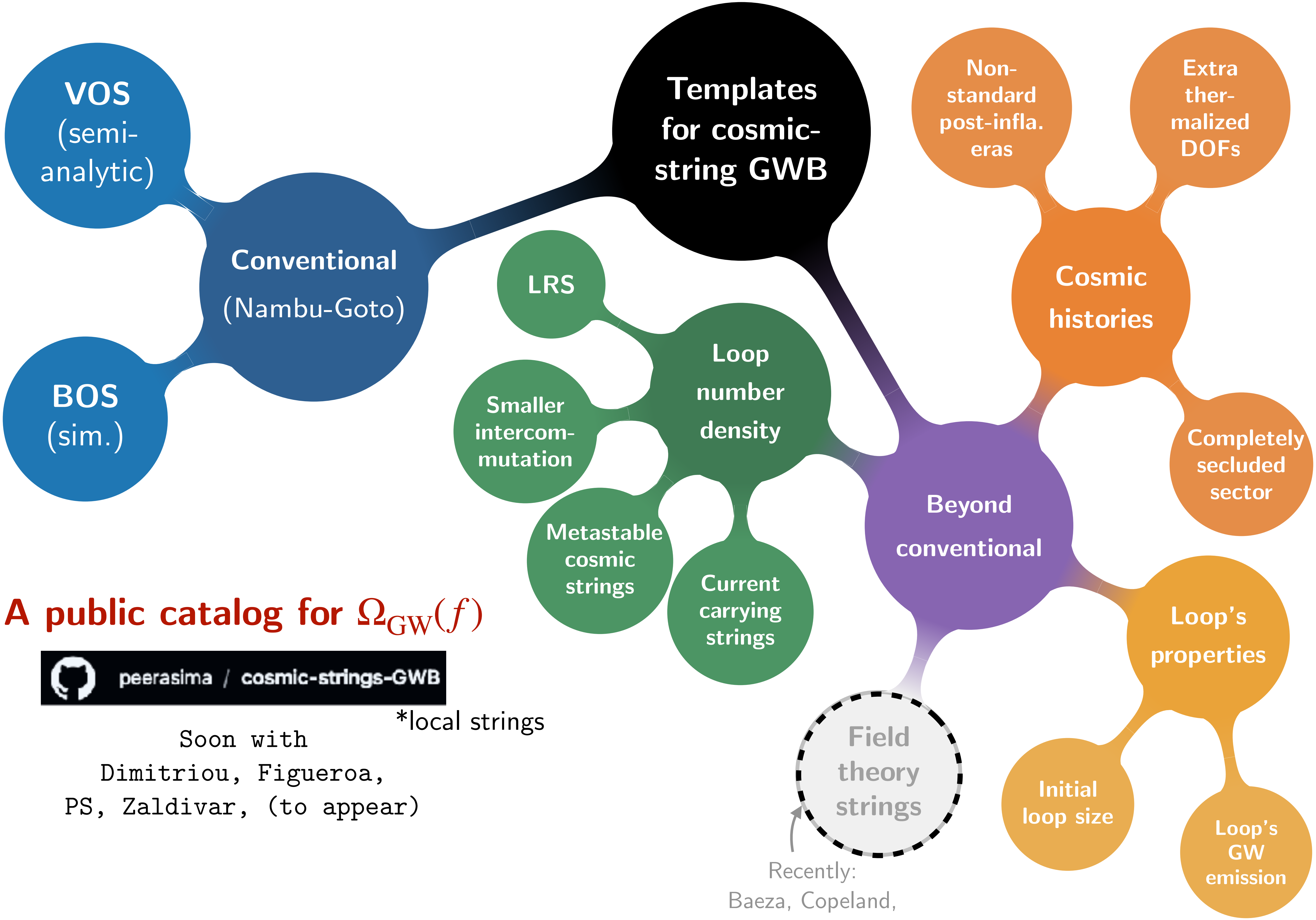
BOS: Blanco-Pillado, Olum, Shlaer, '13, '17

Dimitriou, Figueroa, PS, Zaldivar, (to appear)

Other BSM scenarios can modify these 3 ingredients.

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





*local strings

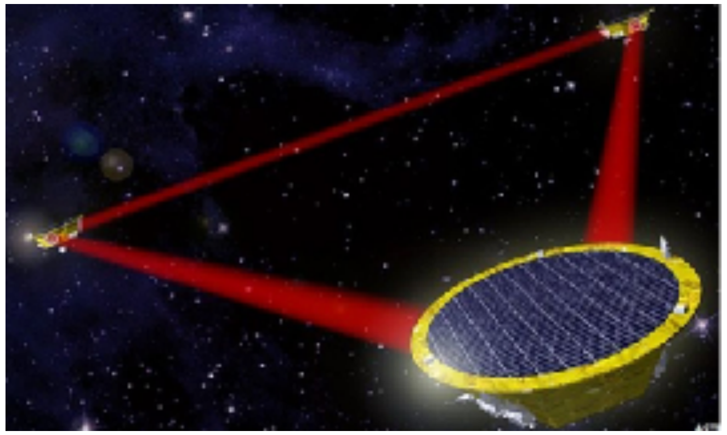
A public catalog for $\Omega_{\rm GW}(f)$

peerasima / cosmic-strings-GWB

Soon with
Dimitriou, Figueroa,
PS, Zaldivar, (to appear)

Searches for cosmic-string GWB

For example, **LISA**



We will see detector noises + stochastic signal.

1. How well can we detect the cosmic-string GWB?

and extract info about parameters: $G\mu$, other BSM parameters

(See also LISA CosWG '24)

2. Can LISA distinguish between cosmic string models?

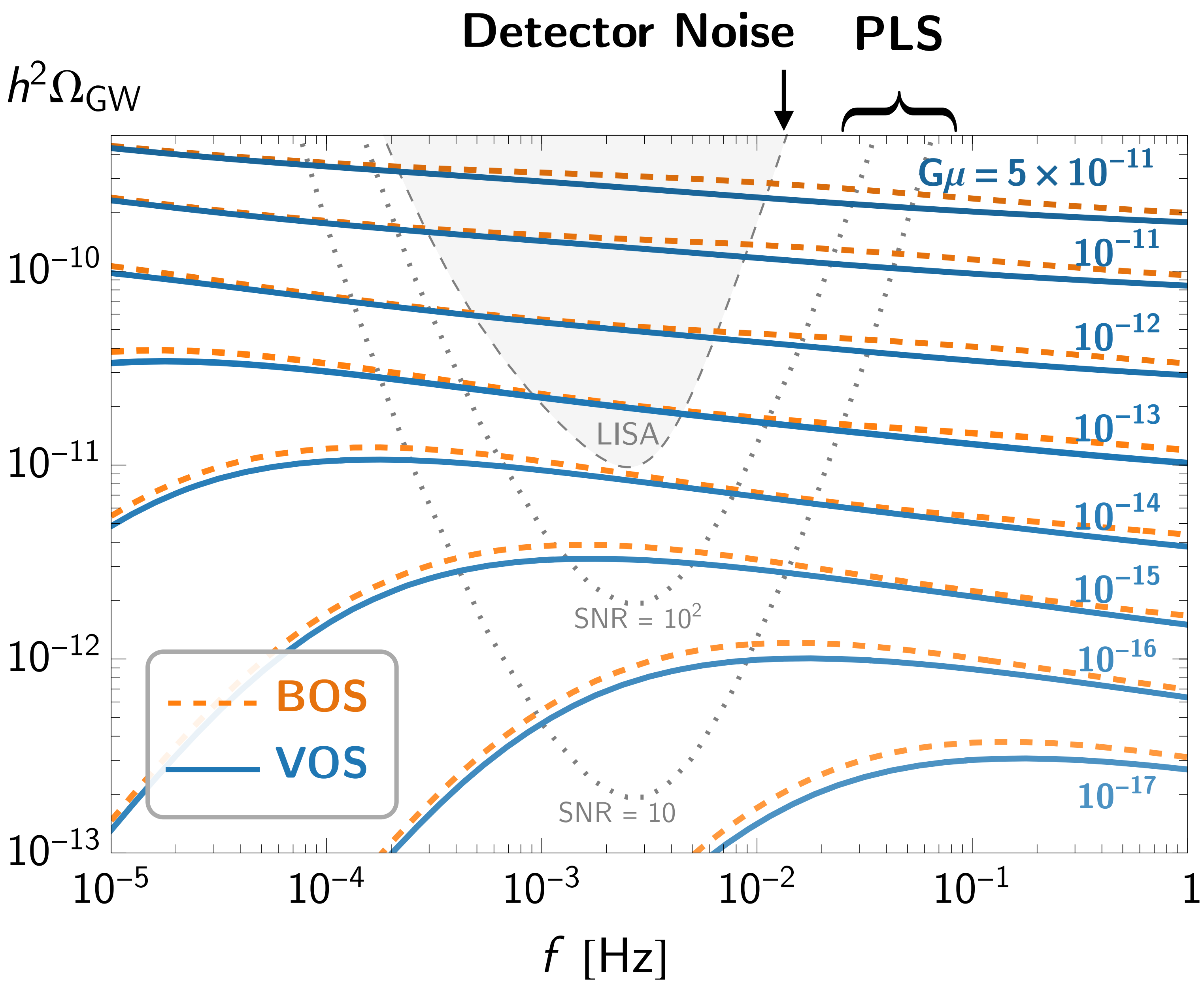
(because some of them are very similar, though they do not overlap.)

Previously… **Signal-to-Noise Ratio**

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

Or its graphical representation: **Power-law integrated sensitivity (PLS) curve**

[Thrane & Romano '13]



$T_{\mathrm{obs}} = 75\% \times 4$ yrs

"A signal with SNR = 10.
Our signal is detectable!"
(Peera in his PhD)

This is not realistic!

(e.g., the observation is noise.
How to get signal from observation?)

SNR is not enough!

What is the range of $G\mu$,
including uncertainty?
Is the signal VOS or BOS?

A better and more precise way…

Data analysis

when a (mock) data from detector is given.

Using the **simulation-based inference (SBI) technique**

(A machine-learning method)

with the “ **GWBackFinder** ” package

developed by Dimitriou, Figueroa, Zaldivar [2309.08430]

See Bryan Zaldivar's talk on Monday

SBI technique with “ GWBackFinder ”

See also Bryan Zaldivar’s talk on Monday

For a signal
from model M
with parameters $\vec{s}$
and a detector noise
$\Omega_{\rm noise}(\vec{n})$

*In A, E, T channels

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

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

Mock Data
$D(\vec{\theta})$

10^6 **samples**

(over all possible signals and noises), **neural networks are trained.**

Neural Posterior Estimation (NPE)

Probability **(Posterior)** distribution
of model’s parameters, given data
$\mathbb{P}(\vec{s}\,|\,D)$

Neural Likelihood Estimation (NLE)

Evidence given a parameter of some model
$\mathbb{P}(D\,|\,\vec{s}, M)$

SBI technique with “ GWBackFinder ”

Neural Posterior Estimation (NPE)

Probability **(Posterior)** distribution
of model's parameters, given data
$\mathbb{P}(\vec{s}\,|\,D)$

Q1: How well can the signal be detected?

A1: Parameter reconstruction !

Neural Likelihood Estimation (NLE)

Evidence given a parameter of some model
$\mathbb{P}(D\,|\,\vec{s}, M)$

Q2: How to distingush between models?

A2: Model comparison !

Once the network is trained (for hours/days),

SBI can obtain posterior/evidence instantly!

for each input = data D, model M and parameters $\vec{S}$.

* MCMC would take hours/days for each input.

See also Bryan Zaldivar's talk on Monday

I. ‘‘Parameter reconstruction’’ ability

$\Omega_{\rm signal} = \Omega^{M}_{\rm GW}(\vec{s}_{\rm inj})$ **from Model M.** (E.g., BOS with $G\mu_{\rm inj}$)

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

Mock Data
$D(\vec{\theta})$

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

NPE
for Model M

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

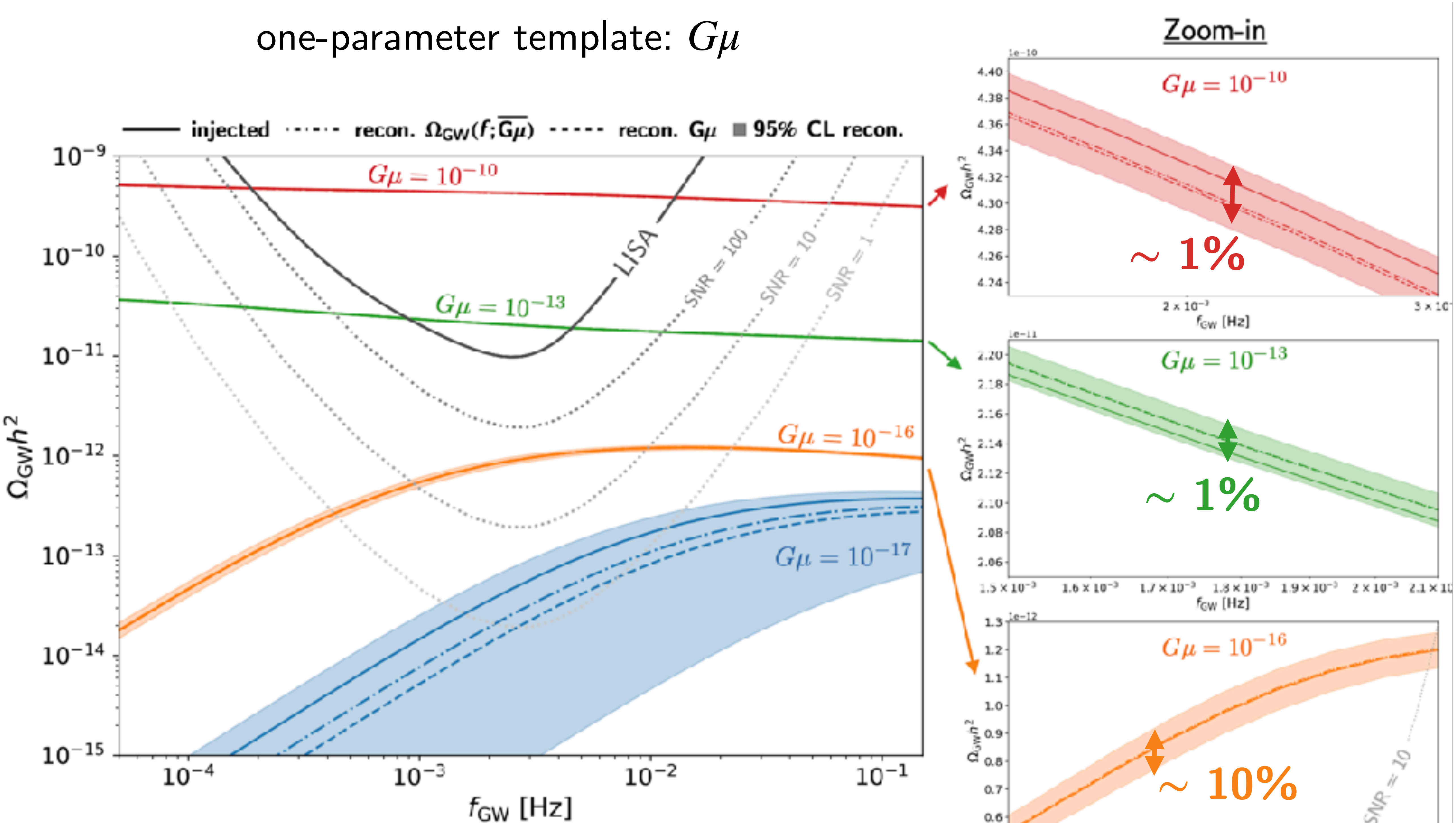
Instantly!

“ Uncertainty in detecting a signal of $\vec{S}_{\rm inj}$ with a GW detector.”

See also Bryan Zaldivar's talk on Monday

Example: Reconstructing $\Omega_{\rm GW}$ for BOS model

one-parameter template: $G\mu$

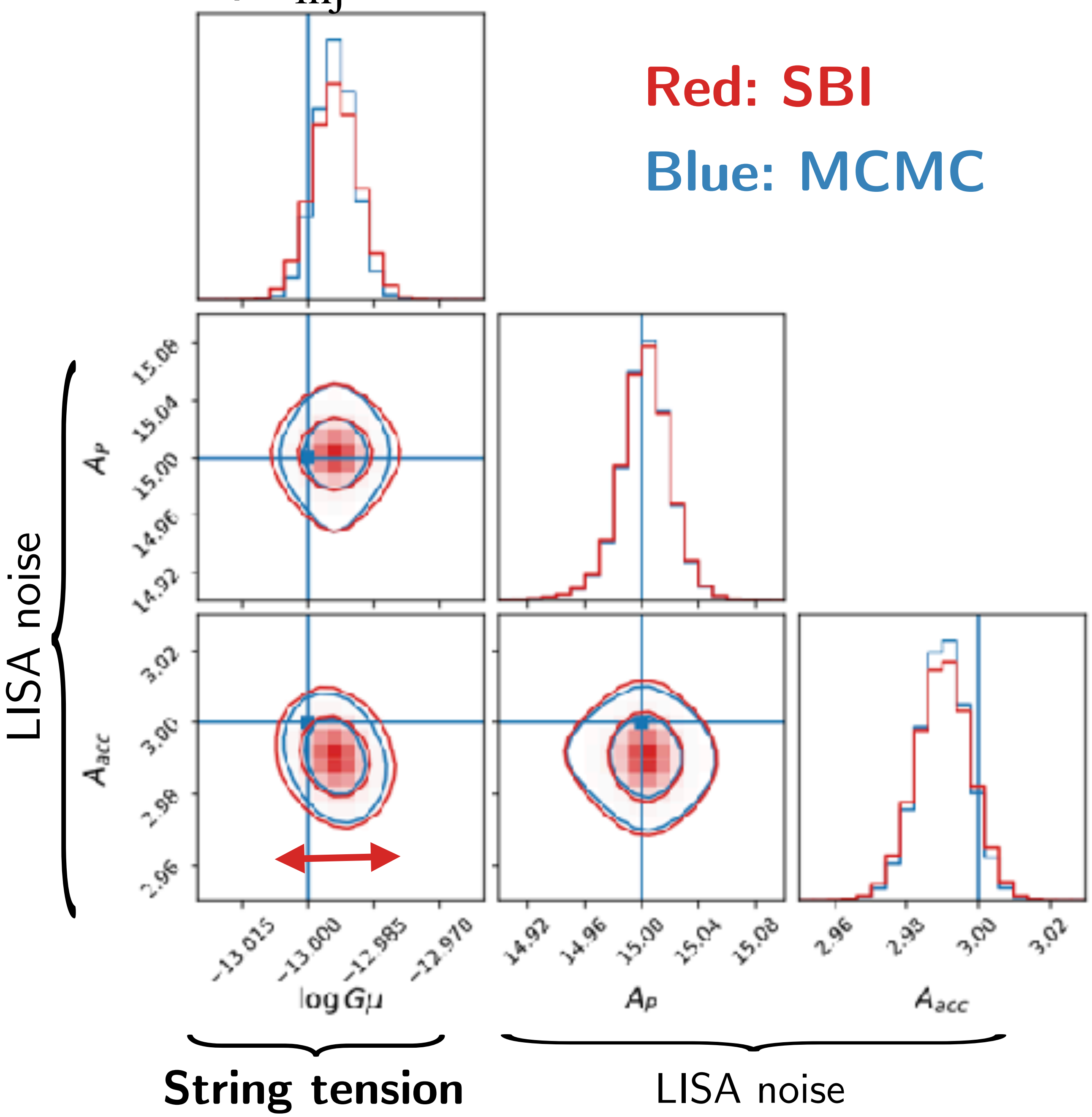


Band = 95% uncertainty range in $\Omega_{\rm GW}$

Dimitriou, Figueroa, PS, Zaldivar, (to appear)

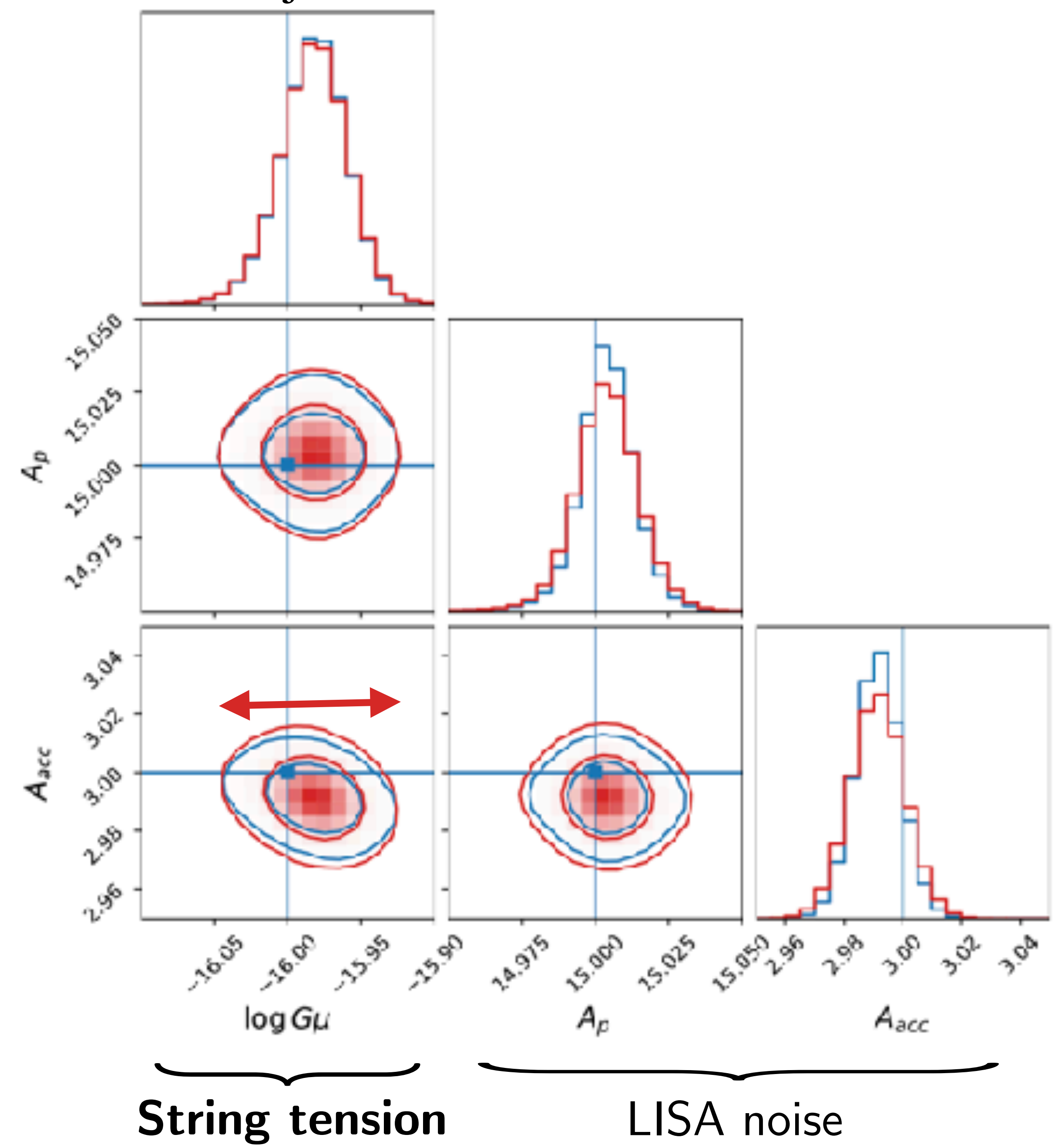
Example: Reconstructing $G\mu$ for BOS model

$(G\mu)_{\rm inj} = 10^{-13}$



Relative uncertainty in $\log G\mu$
$\sim$ 0.2% (95% CL)

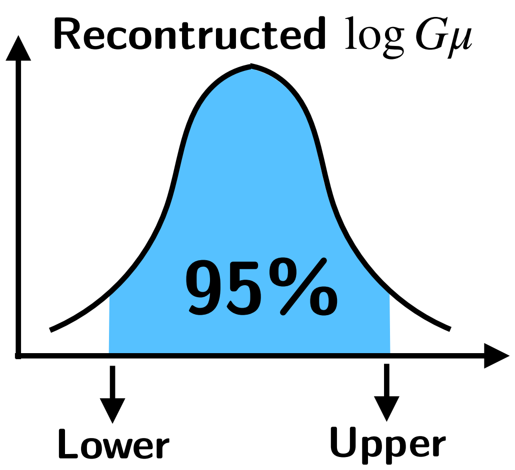
$(G\mu)_{\rm inj} = 10^{-16}$



Relative uncertainty in $\log G\mu$
$\sim$ 0.6% (95% CL)

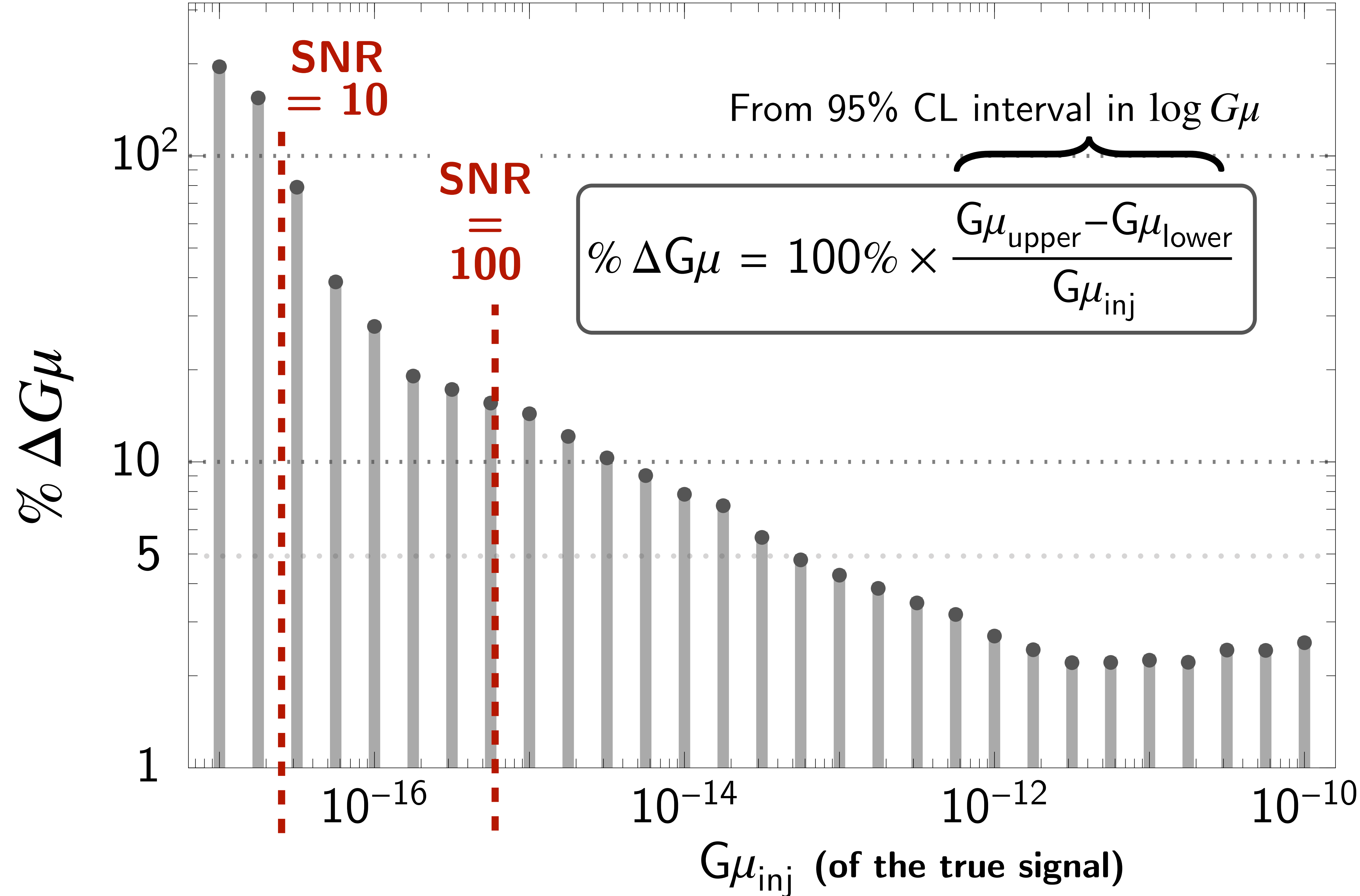
Dimitriou, Figueroa, PS, Zaldivar, (to appear)

Reconstruction uncertainty scanned over BOS model's parameter space

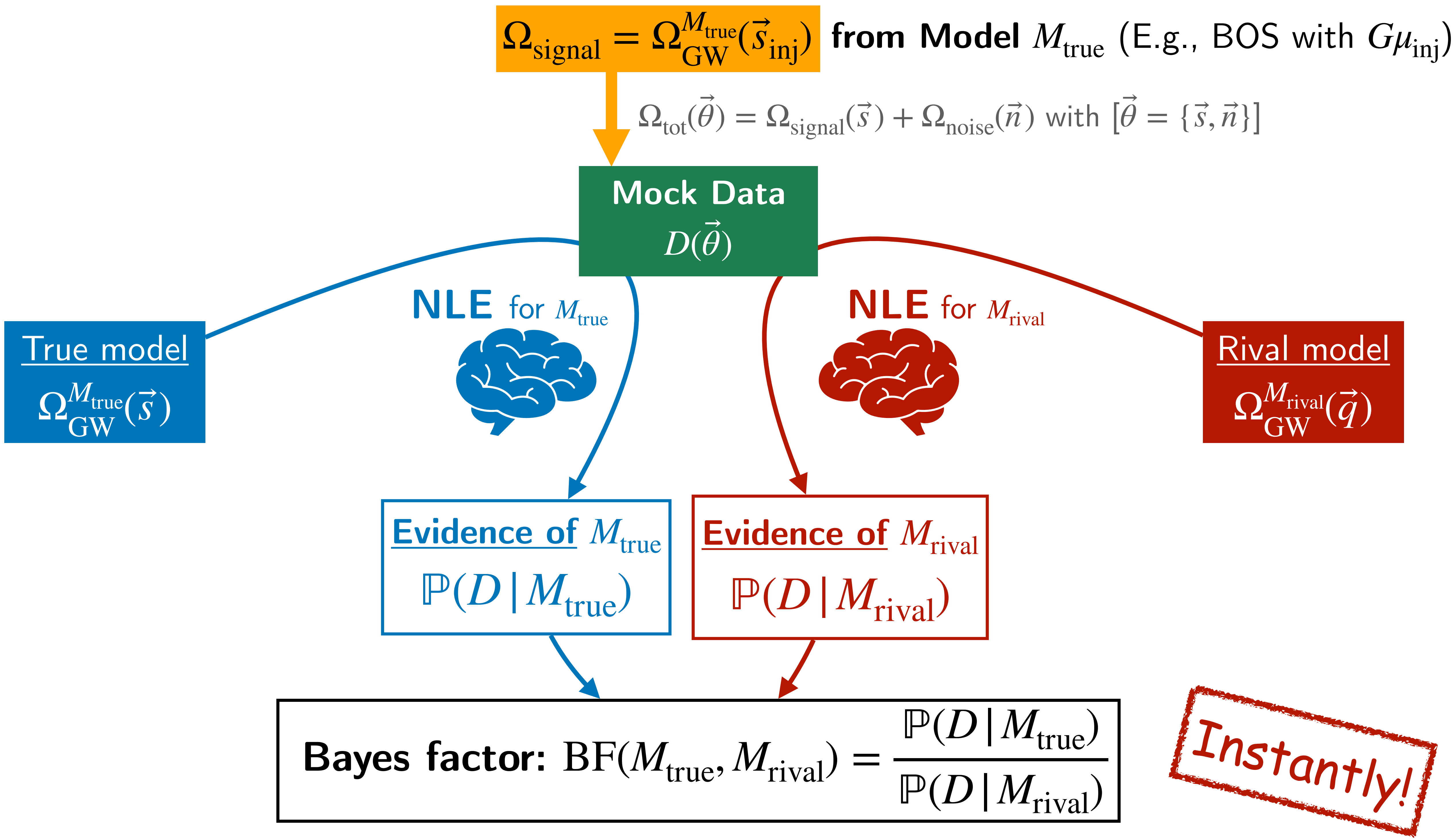


This is uncertainty in $G\mu$.

$\neq$ uncertainty in $\log G\mu$

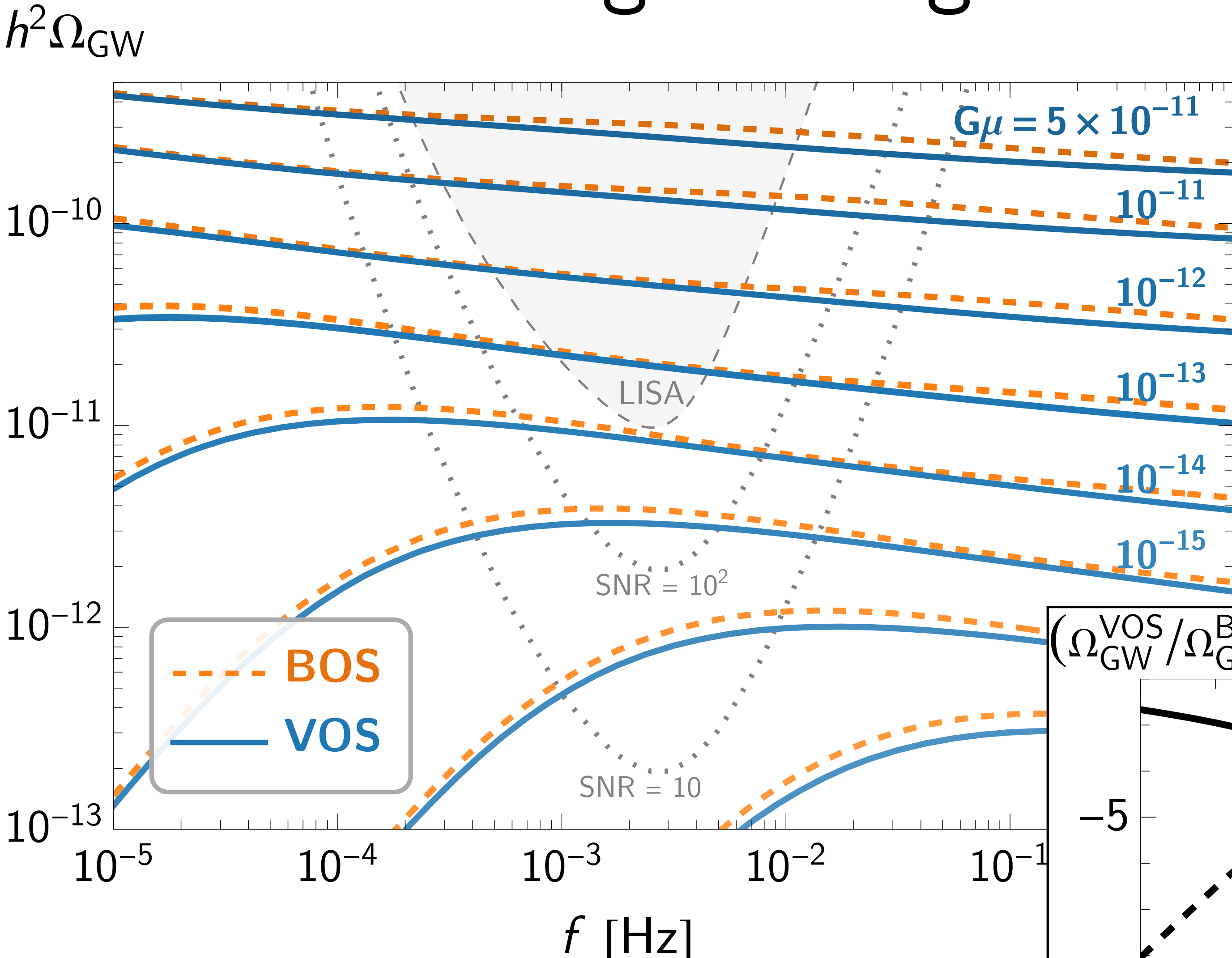


II. ‘‘Model comparison’’ ability



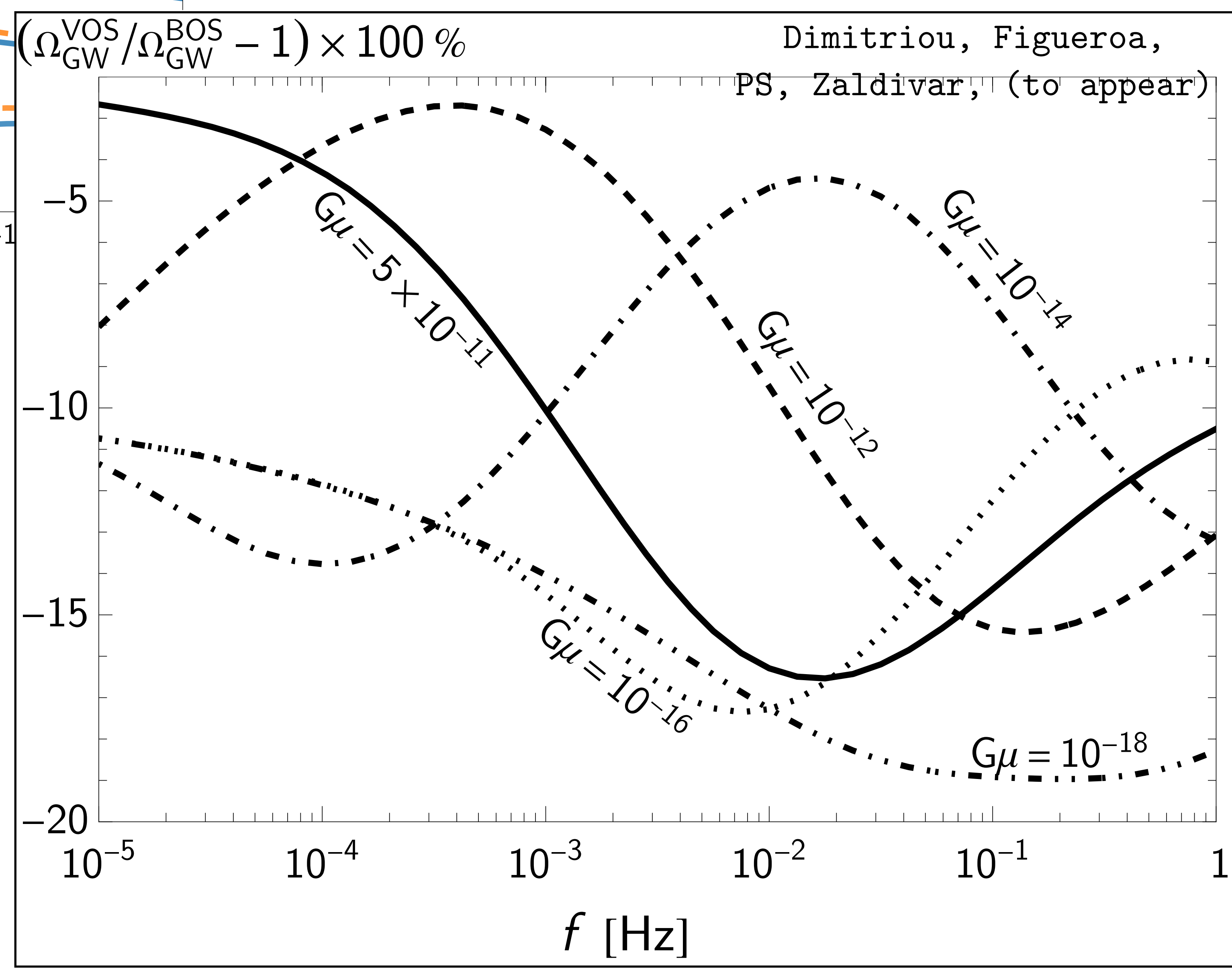
“ Ability to distinguish $M_{\rm true}$ from $M_{\rm rival}$
for a signal of $M_{\rm true}(\vec{S}_{\rm inj})$ with a GW detector.”

Distinguishing VOS and BOS with LISA?

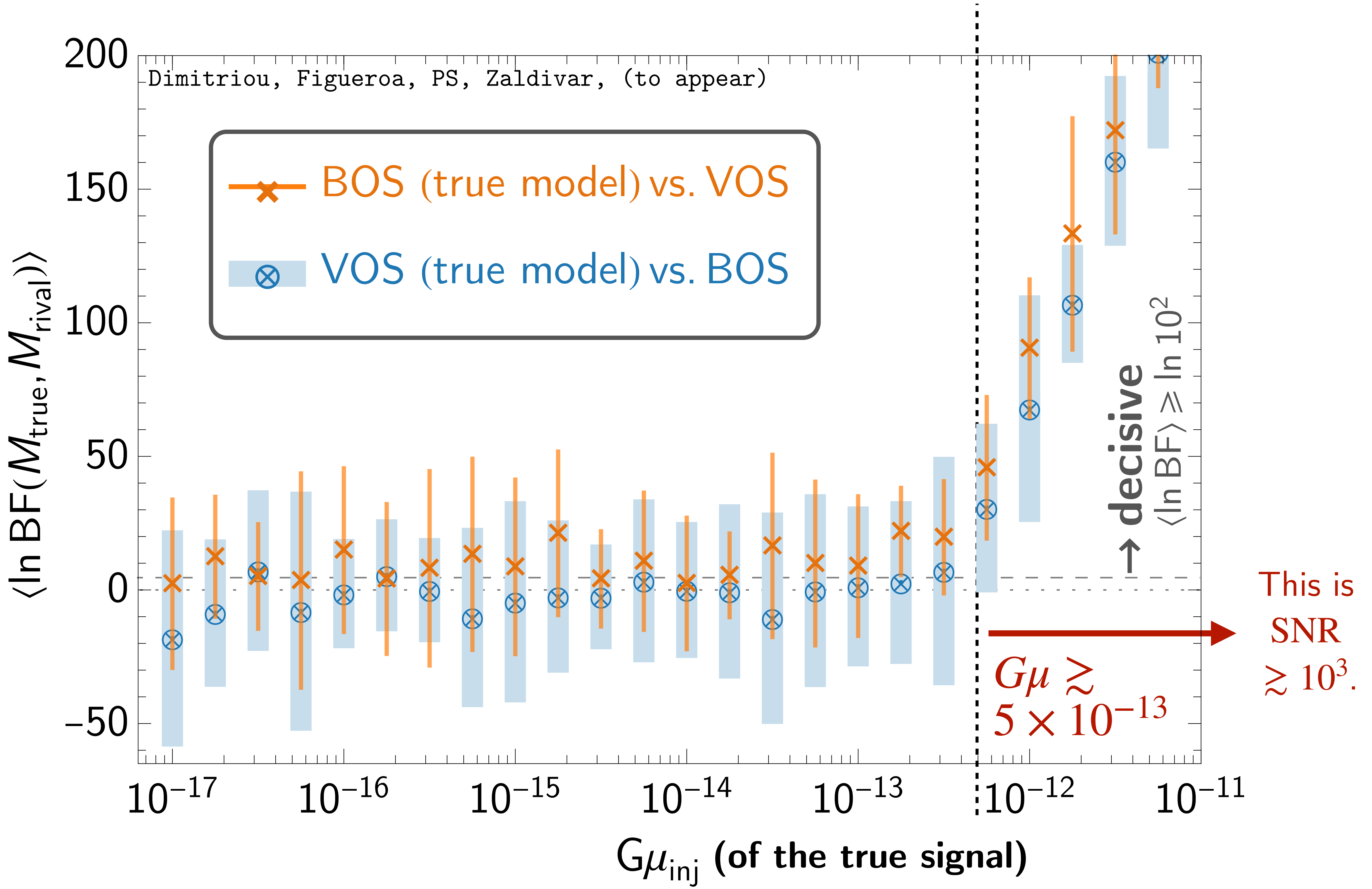


~ 10% relative difference in Ω_{GW}

If LISA can reconstruct
with much less uncertainty,
we can distinguish.



Distinguishing VOS and BOS with LISA?

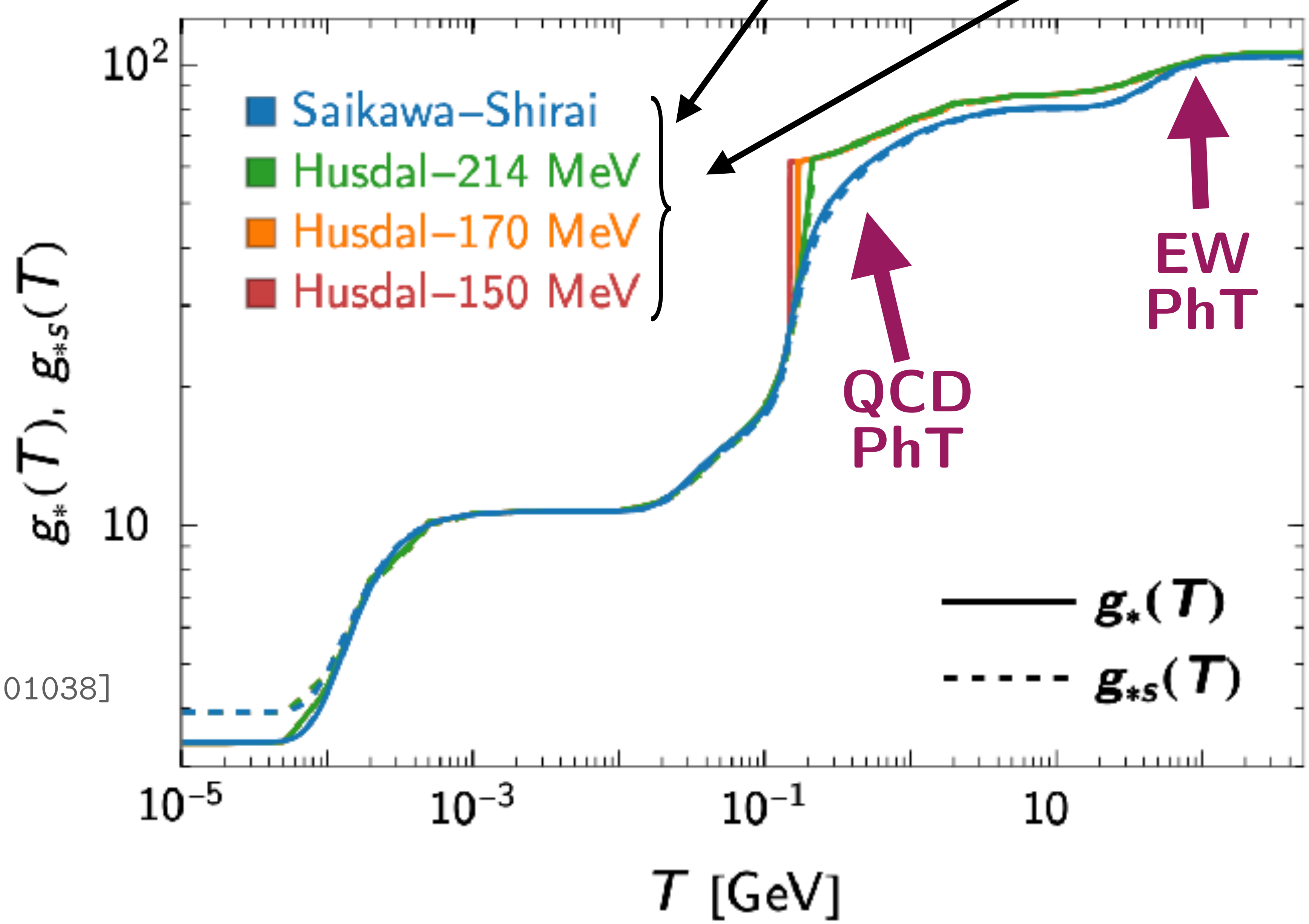


$\Omega_{\mathrm{GW}} \propto \sqrt{G\mu} \Rightarrow \Delta\Omega_{\mathrm{GW}} \sim \Delta G\mu/2$. For decisive comparison, it seems we need $\Delta\Omega_{\mathrm{GW}}^{\mathrm{recon}} \lesssim 0.1 \times$ diff. between spectra.

Other uncertainties for conventional templates: SM degrees of freedom (dofs) evolution

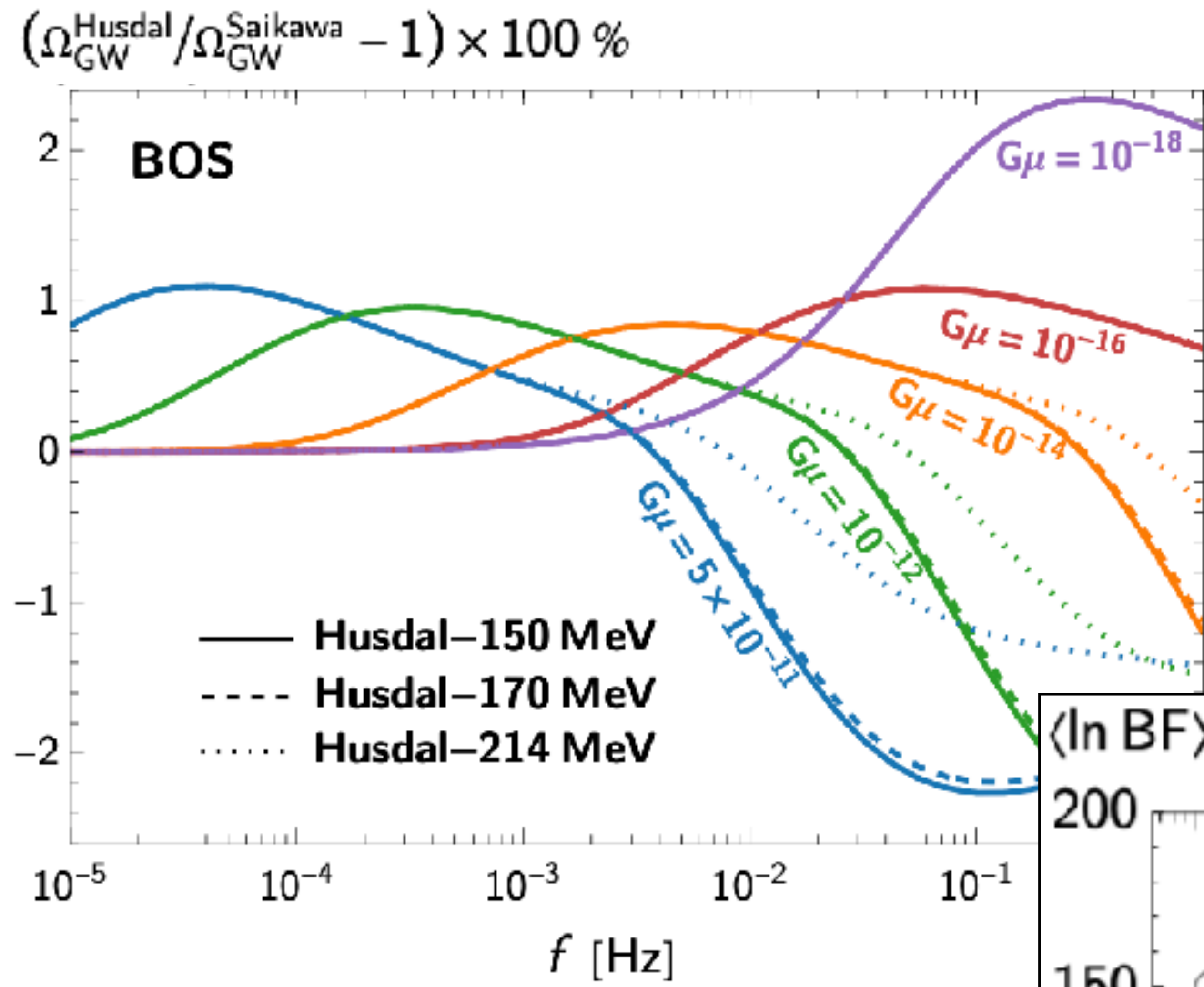
$$\Omega_{\mathrm{GW}}(f) = \frac{1}{3H_0^2 M_{\mathrm{Pl}}^2}\sum_{j=1}^{\infty} \underbrace{\frac{2j}{f}(G\mu^2 P_j)}_{\substack{\text{GW emission}\\ \text{from single loops}}} \int_{a_2}^{a_1} da \, \underbrace{\frac{1}{H(a)}\left(\frac{a}{a_0}\right)^4}_{\text{cosmic history}} \underbrace{\mathtt{n}\left[\frac{2j}{f}\cdot\frac{a}{a_0},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

SM relativistic dofs

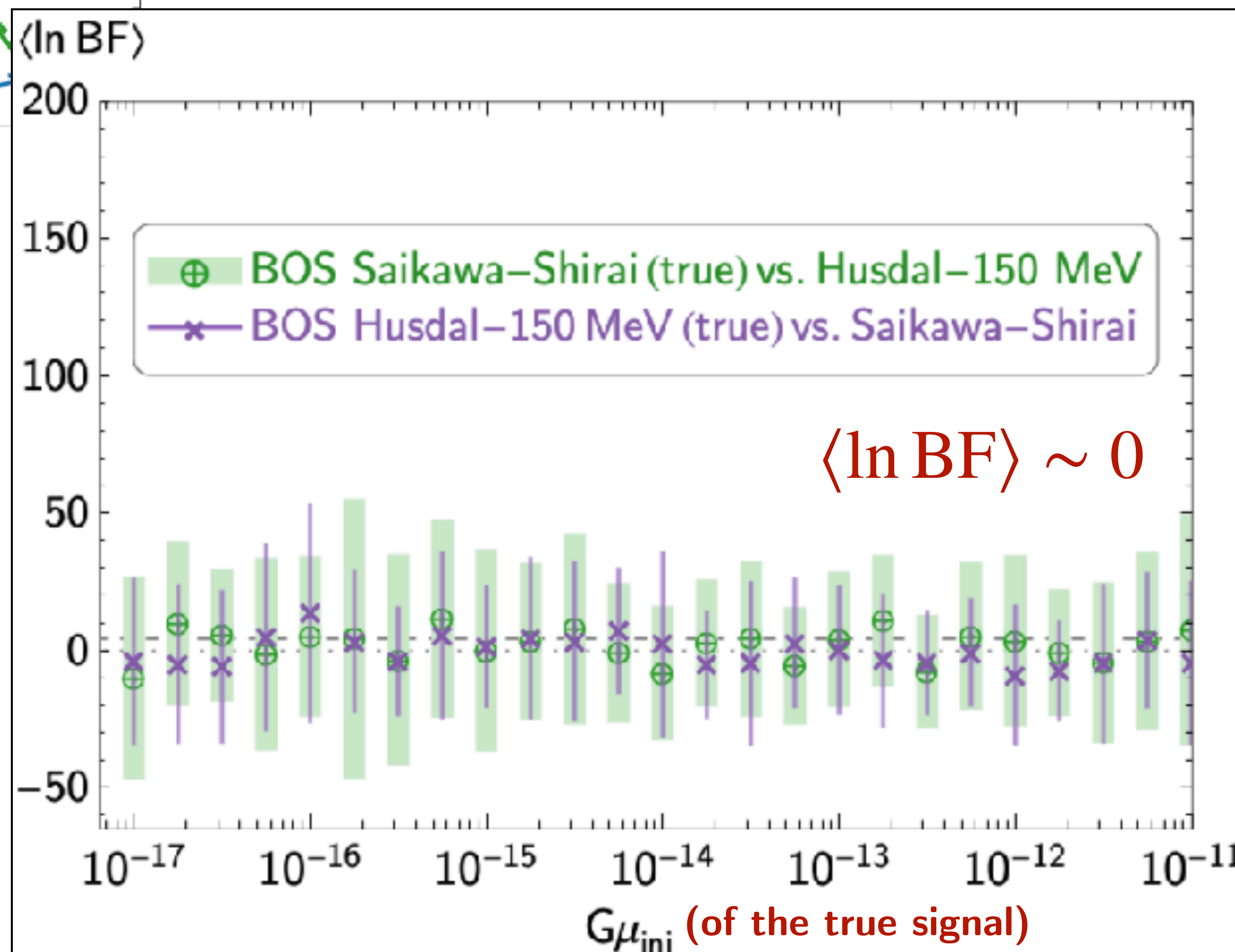


Saikawa-Shirai [1803.01038]
Husdal [1609.04979]

Distinguishing SM-dof evolutions with LISA?

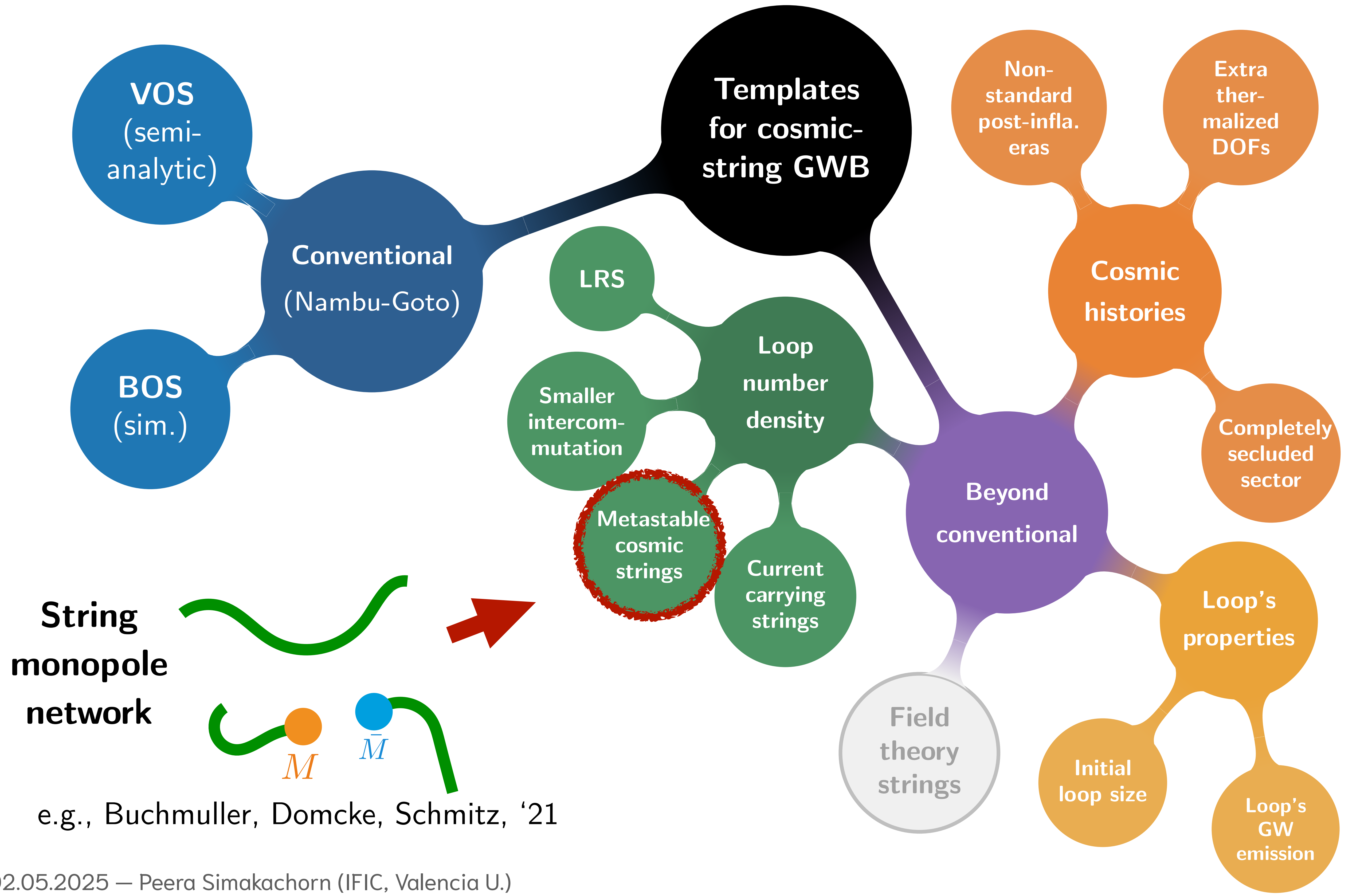


Require reconstruction with uncertainty $\lesssim 1-2\,\%$ in $\Omega_{\rm GW}$!



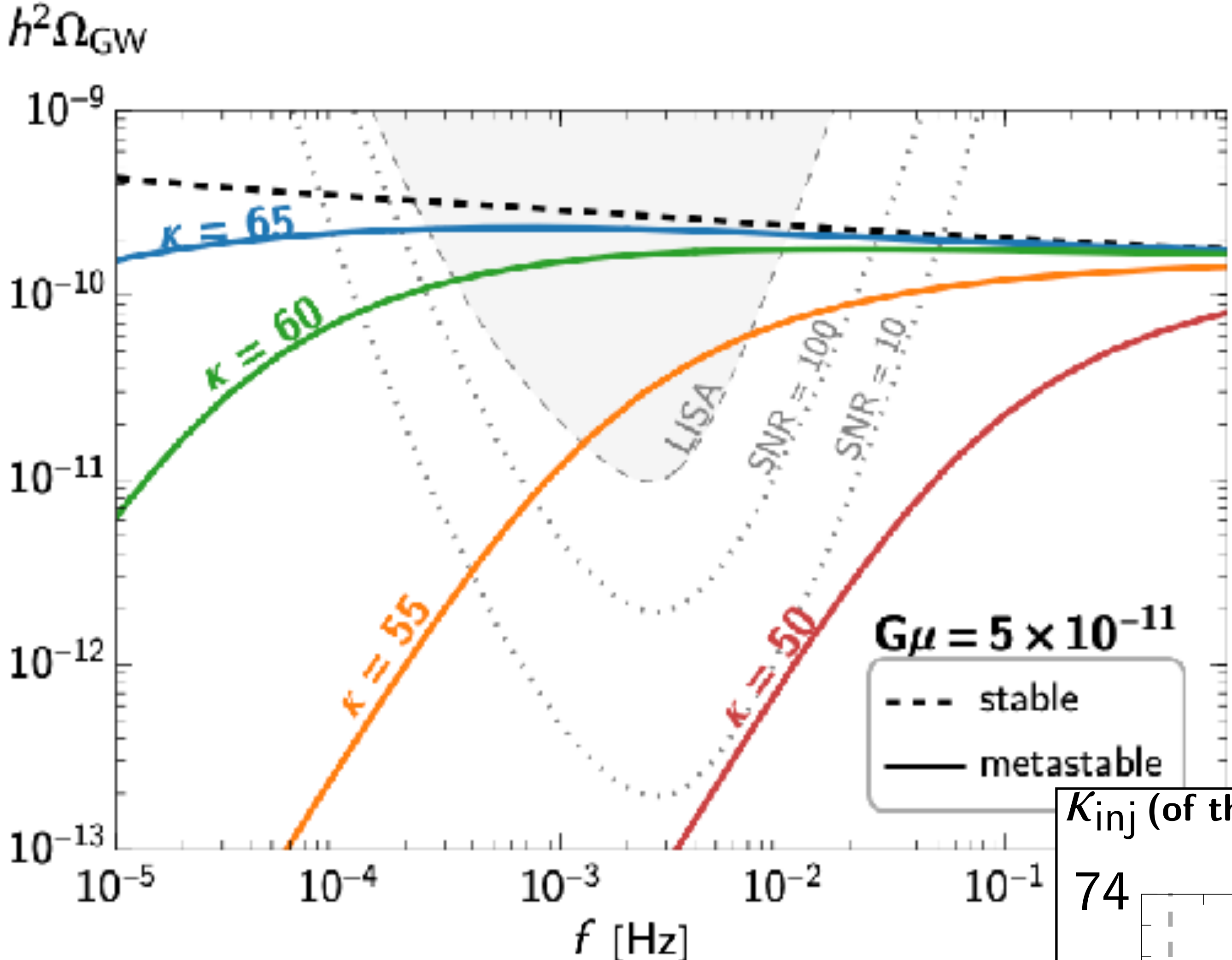
LISA cannot distinguish different SM-dof evolution from cosmic-string GWB, even for large SNR.

Distinguish other BSM scenarios from the conventional template?



e.g., Buchmuller, Domcke, Schmitz, '21

Metastable-string template

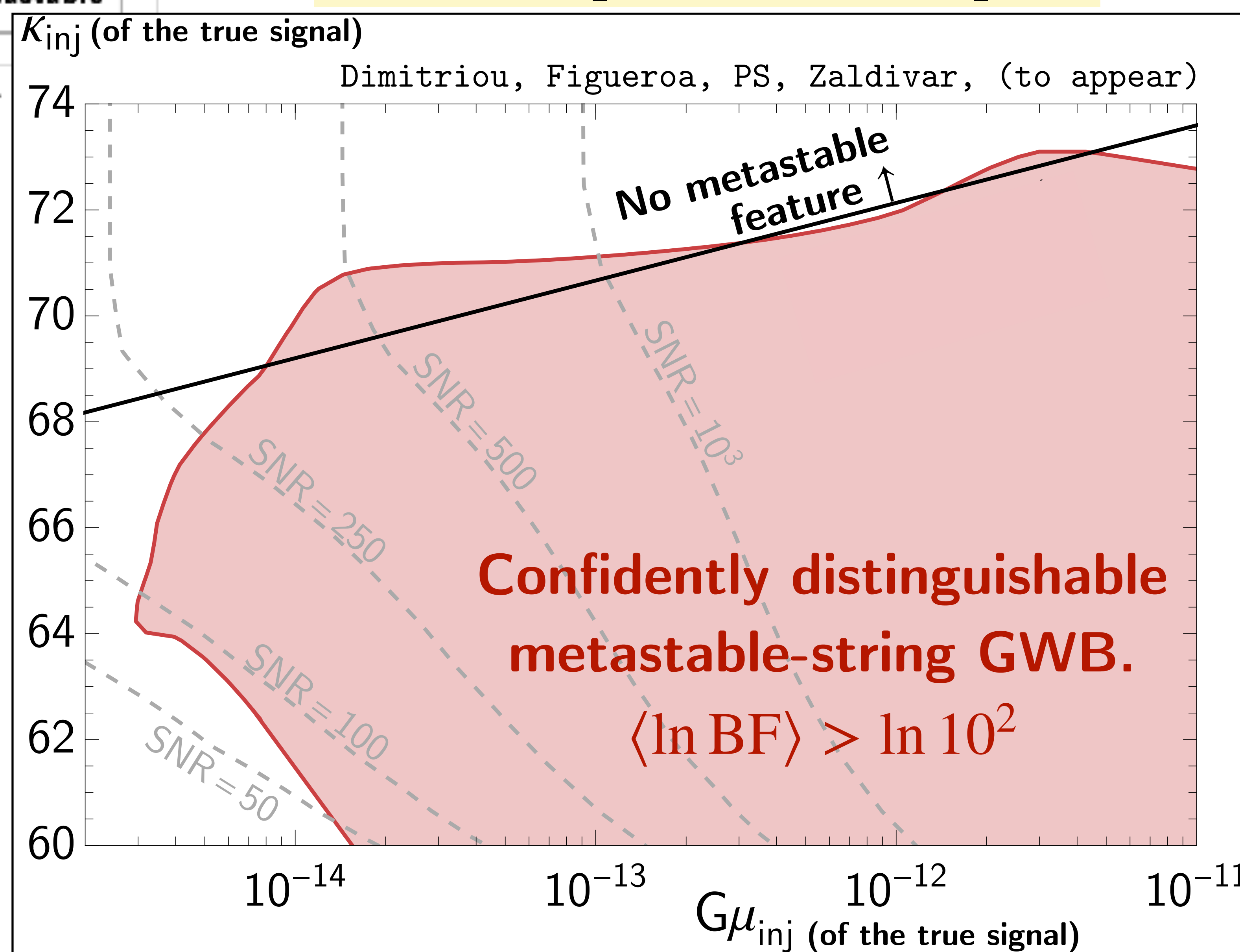


Low-frequency cutoff due to string network decay.

GWB spectrum depends on $G\mu = (\eta/m_{\rm Pl})^2$ and

$$\sqrt{\kappa} \equiv \frac{m_M}{\eta} \left[\frac{\text{monopole scale}}{\text{string scale}}\right] > 1$$

Comparing metastable strings (true model) vs. conventional (VOS) template



Take-home messages!

To search for
GWB from our favorite models
with **some GW detector.**

Important questions are

1. How well can the signal be detected?
i.e., how well the underlying model's parameters be probed?

2. Can different models be distinguished?
(whose GWB are very similar, but not overlap.)

The SNR is not enough!

Take-home messages!

We don't know yet the true signal of GWB.

— How well can we reconstruct?
— How well can we distinguish between different models?

} **Must scan over all possibilities across models' parameter spaces**

⇒ A characterization of LISA for (Nambu-Goto) **cosmic-string GWBs:**
parameter reconstruction and model-comparison abilities

Data analysis with SBI technique: Super fast $\mathcal{O}(\mathrm{secs} - \mathrm{mins})$!

What's next ?

A characterization of Detector X for GWB from Y.

Detector X	GWB from Y
LISA,	PhT, Inflation,
Einstein Telescope,	Scalar-induced,
Cosmic Explorer, etc...	Axion-kination, etc...

More realistic...including astro foregrounds, transients ⇒ " Global fit "

Still more works to be done!