Cosmic strings parameter reconstruction

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[arXiv:2405.03740]

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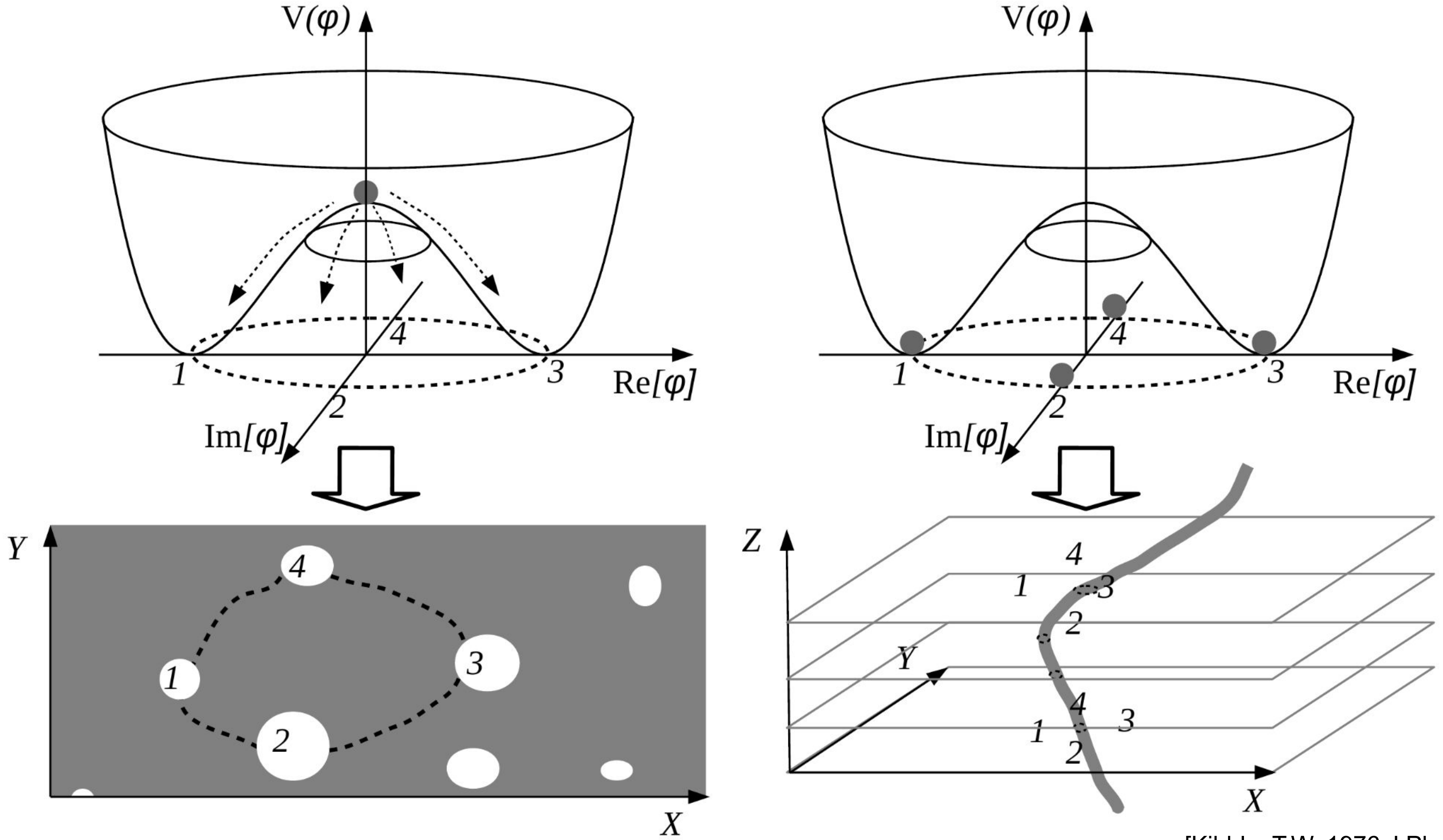
The goal:

To create a template databank of possible sources that can generate the stochastic gravitational wave background (SGWB, particularly from cosmic strings.

Content

- What are cosmic strings, and why do we care about them?
- Approach for understanding the cosmic string network evolution (Model Ⅰ, Model Ⅱ).
- SGWBinner pipeline with instrumental noise, (extra)galactic foreground.
- Results of the signal reconstruction.
- Non-standard cosmology.
- Further steps?

Cosmic strings (Kibble mechanism)



[Kibble, T.W.,1976.J.Phys.A,9(8),p1387]

Are cosmic strings common?

[TWB Kibble, J. Phys. A, 1976.]

Classification:

$\pi_0\,(G/K) \neq I$ - walls;

$\pi_1\,(G/K) \neq I$ - strings;

$\pi_2\,(G/K) \neq I$ - monopoles;

$\pi_3\,(G/K) \neq I$ - textures.

- The dynamical generation of right-handed-neutrino masses in the early Universe naturally entails the formation of cosmic strings.

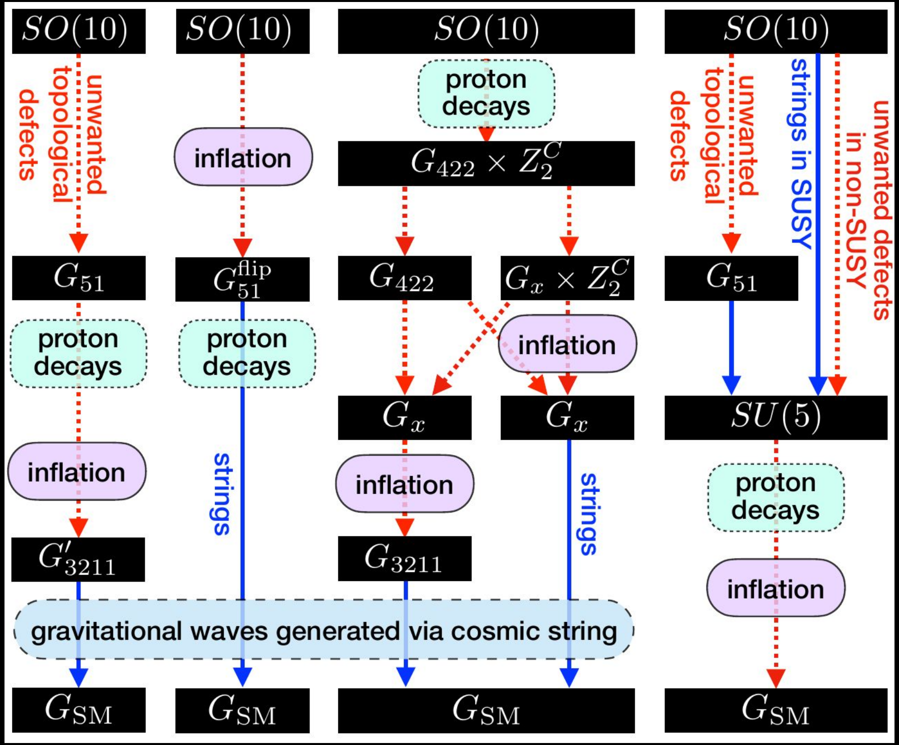
  [Blasi, Brdar, Schmitz, Phys.Rev.Research 2, 043321 (2020)]

- QCD color fluxes (deconfinement to confinement)

  [Yamada, Yonekura, PRD 106 (2022) 12]

- Complementarity to proton decay to probe viability of GUT SO(10)

  [King, Pascoli, Turner, Zhou, JHEP 10 (2021) 225]



[King, Pascoli, Turner, Zhou, PRL. 126, 021802 (2021)]

[Lazarides,vMaji, Shafi, PRD 104, 095004 (2021)]

… and many others

Cosmic string network

We assume that cosmic strings are described by Nambu-Goto (NG) action.

It represents Abelian Higgs strings with critical coupling, though see discussion

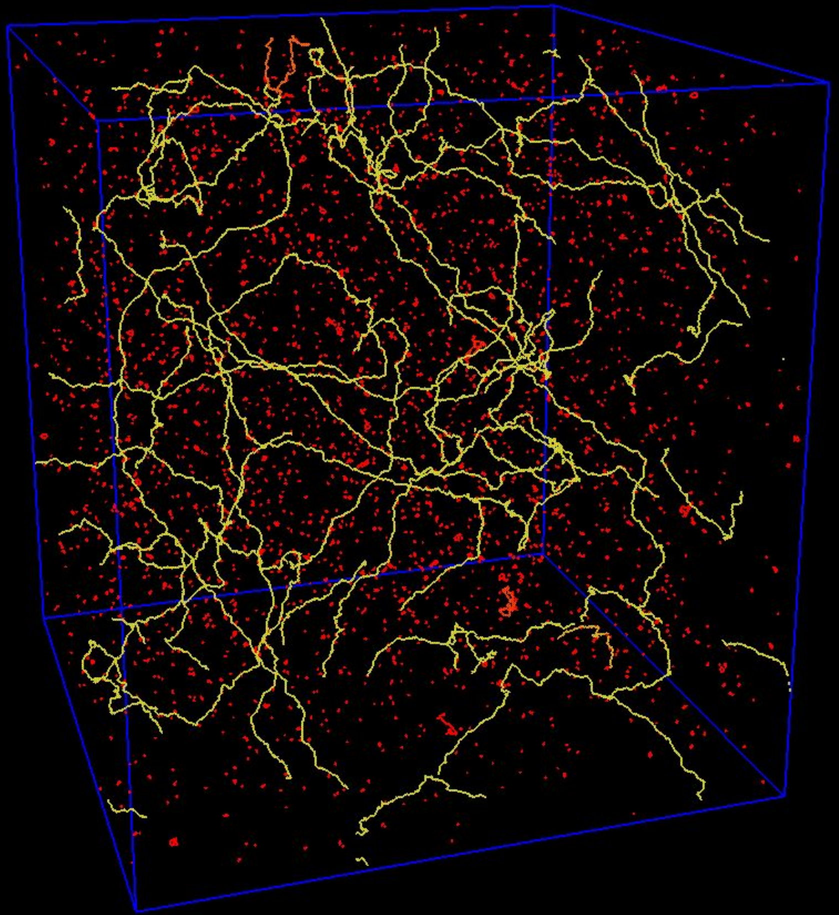
[Hindmarsh,Lizarraga,Urrestilla, Daverio,Kunz, PRD 96 (2017)]

Energy density: $\rho = \frac{\mu_0}{L^2}$ μ_0 - tension

Characteristic length: $L \sim t$

Root mean square velocity: v

NG simulations of networks:



https://www.ctc.cam.ac.uk/outreach/origins/cosmic_structures_four.php

[Allen, Shellard, Phys. Rev. Lett.1990,8;64(2):119] [Ringeval,Sakellariadou,Bouchet,JCAP 02 (2007) 023]

Model I (semi-analytical model)

Evolution according to the velocity-dependent one-scale (VOS) model

[Martins, Shellard PRD 54 (1996) 2535-2556, PRD 65 (2002) 043514]

$$\frac{d\bar{v}}{dt} = \left(1-\bar{v}^2\right)\left[\frac{k(\bar{v})}{L} - 2H\bar{v}\right]$$

$$\frac{dL}{dt} = \left(1+\bar{v}^2\right)HL + \frac{\tilde{c}}{2}\bar{v}\,,$$

$$k(\bar{v}) = \frac{2\sqrt{2}}{\pi}\left(1-\bar{v}^2\right)\left(1+2\sqrt{2}\bar{v}^3\right)\frac{1-8\bar{v}^6}{1+8\bar{v}^6}$$

loop chopping efficiency
(fixed from simulations)

If the scale factor $a \propto t^\beta$ <u>scaling solution:</u> $L = \xi_\beta t \quad \bar{v} = v_\beta$

[Caldwell, Battye, Shellard, PRD 54 (1996) 7146-7152,
Sousa, Avelino, PRD 88 (2013) 2, 023516]

Here we assume that the length of produced loops is a fraction of characteristic length:

$$\int_0^\infty x f(x)\; dx = \tilde{c}\frac{\bar{v}}{\xi^3} \qquad f(x) = \tilde{C}\delta(x-\alpha_L\xi)$$

Model I (semi-analytical model)

[Sousa, Avelino, Guedes, PRD 101 (2020) 10, 103508]

The stochastic gravitational wave background (SGWB) generated by cosmic strings as a density parameter for a frequency f

$$\Omega_{\rm gw}(f) = \frac{8\pi}{3}\left(\frac{G\mu}{H_0}\right)^2 f \sum_{j=1}^{\infty} P_j \Omega_{\rm gw}^j(f)$$

power spectrum: $P_j = \frac{\Gamma}{\zeta(q)} j^{-q}$

spectral index: $q = 4/3$ (cusps)

$q = 5/3$ (kinks)

$q = 2$ (kink-kink)

$$\Omega_{\rm gw}^j(f) = \frac{2j}{f^2}\int_{t_i}^{t_0} \mathbf{n}\left(\frac{2j}{f}\frac{a(t)}{a_0}, t\right)\left(\frac{a(t)}{a_0}\right)^5 dt$$

loop number density: $n(l,t) = \frac{A_\beta C_\beta(\alpha)}{t^{3\beta}\left(l + \Gamma G\mu t\right)^{4-3\beta}}$

where $A_\beta = \frac{\tilde{c}}{\sqrt{2}}\frac{v_\beta}{\xi_\beta^3}\mathcal{F}$

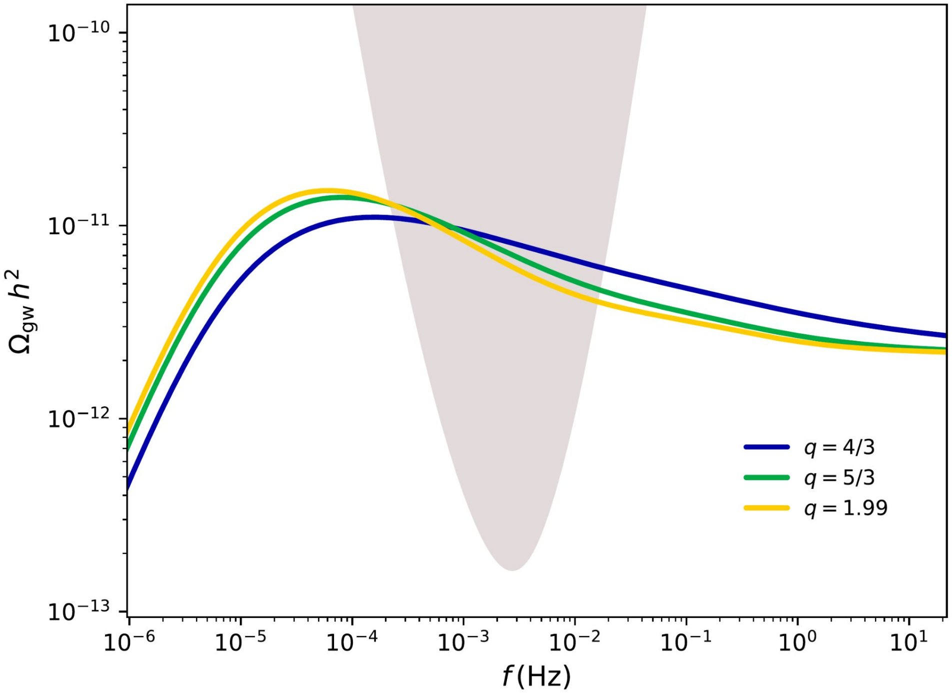
$$C_\beta(\alpha) = \frac{\left(\alpha\xi_\beta + \Gamma G\mu\right)^{3(\beta-1)}}{\alpha\xi_\beta}$$

We obtained an analytical approximation for $\Omega_{\rm gw}(f)$

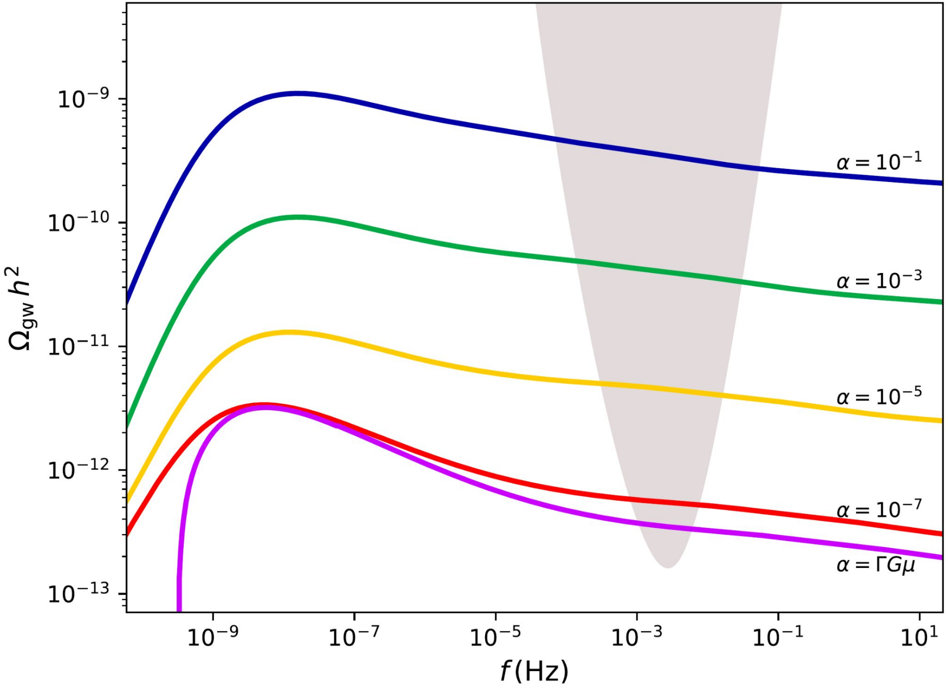
(assumptions: network at scaling, loops are produced of one size and at scaling, power law spectrum)

Model I (semi-analytical model)

Variation of the spectral index



Variation of the loop size



Model II (BOS model)

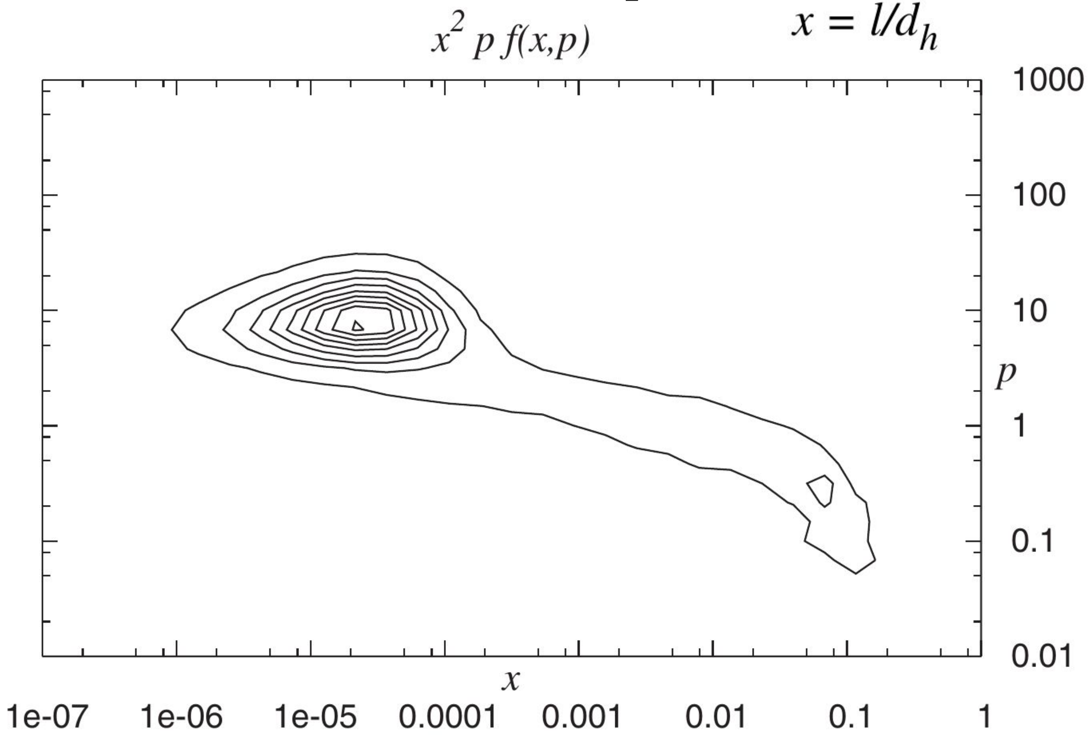
[Blanco-Pillado, Olum, Shlaer, PRD 83 (2011) 083514]

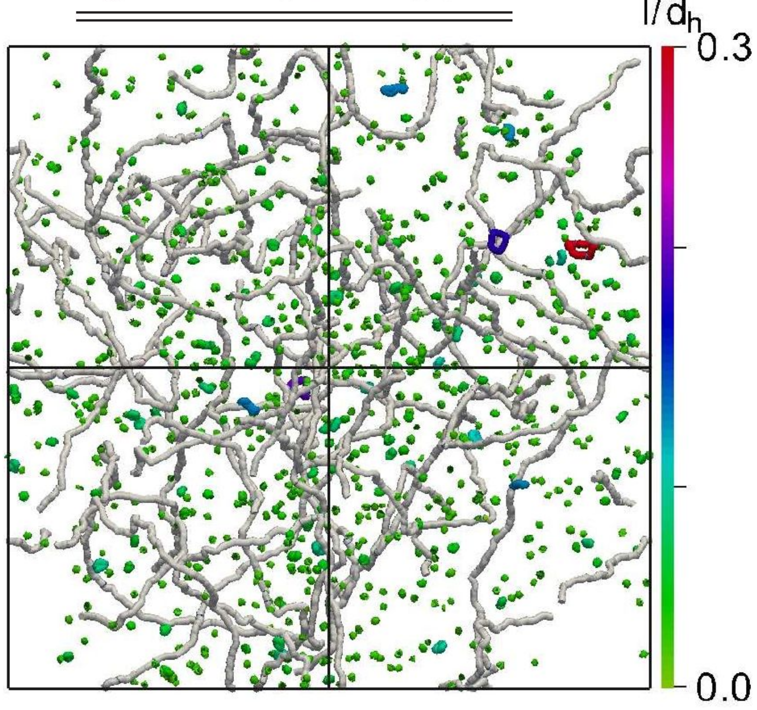
Nambu-Goto string network scaling at radiation and matter dominated epochs.

Distribution of loops power p (radiation)

	γ	$\langle v_\infty^2 \rangle$
Matter	0.17	0.35
Radiation	0.15	0.40
Flat	0.12	0.45

$x = l/d_h$





Model II (BOS model)

[Blanco-Pillado, Olum, Shlaer, PRD 83 (2011) 083514]

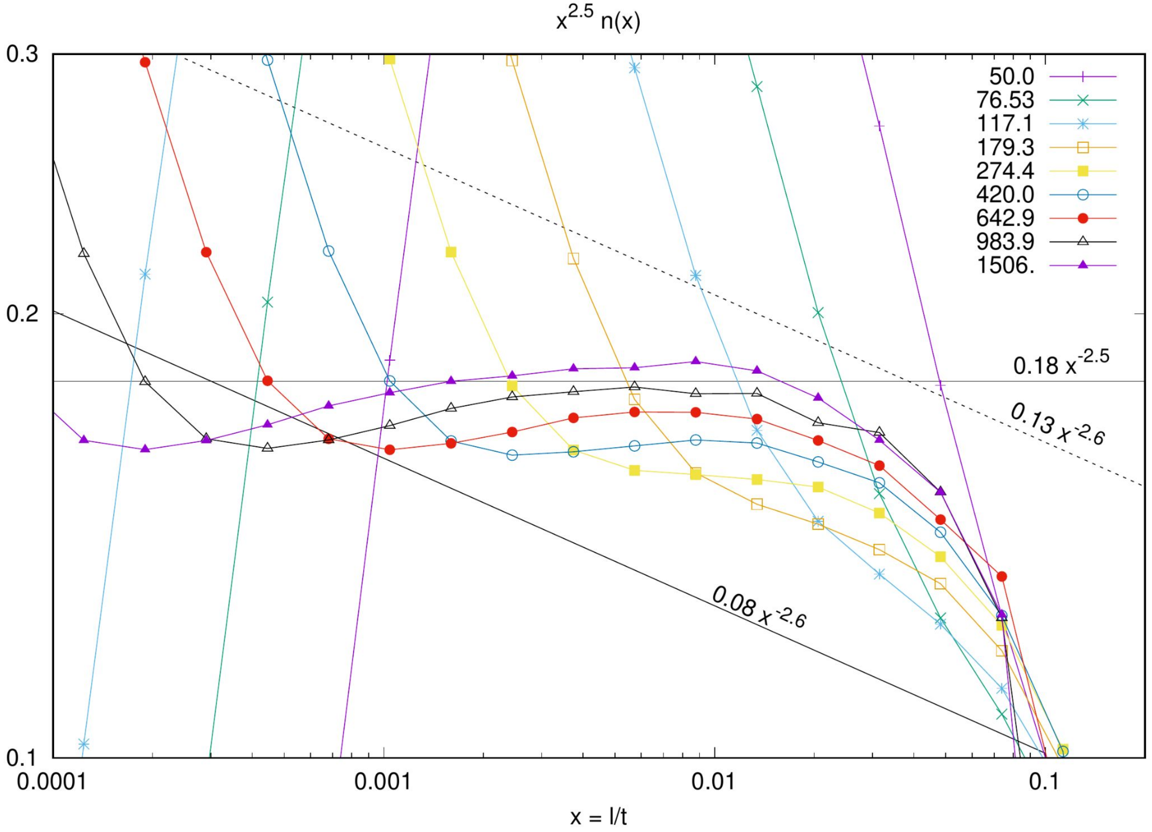
The loop number densities are obtained directly from a scaling population of non-self-intersecting loops

[Blanco-Pillado, Olum, Shlaer, PRD 89 (2014) 023512, PRD 92 (2015) 063528]

$$\mathbf{n}_r(l,t) = \frac{0.18}{t^{3/2}(l+\Gamma G\mu t)^{5/2}},$$

$$\mathbf{n}_{rm}(l,t) = \frac{0.18(2\sqrt{\Omega_r})^{3/2}}{(l+\Gamma G\mu t)^{5/2}}\left(\frac{a_0}{a}\right)^3,$$

$$\mathbf{n}_m(l,t) = \frac{0.27-0.45(l/t)^{0.31}}{t^2(l+\Gamma G\mu t)^2}.$$



[Blanco-Pillado, Olum, PRD 101 (2020) 103018]

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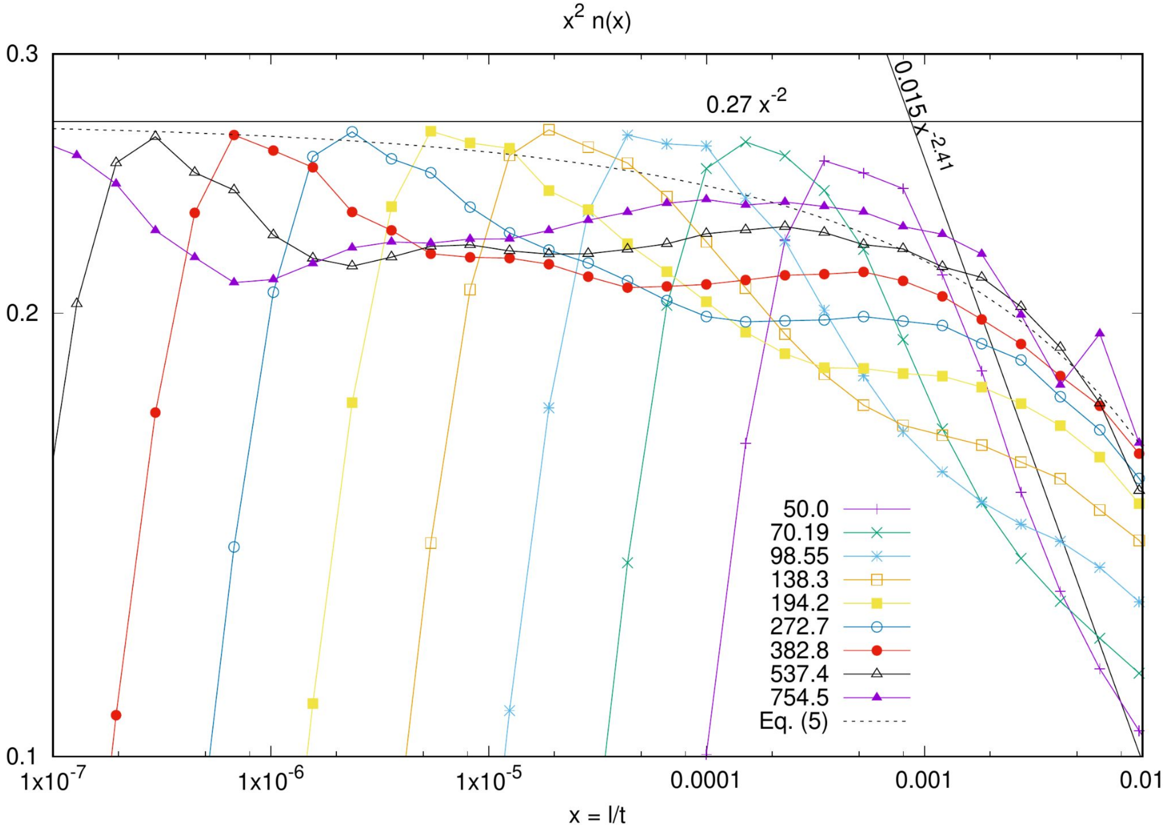


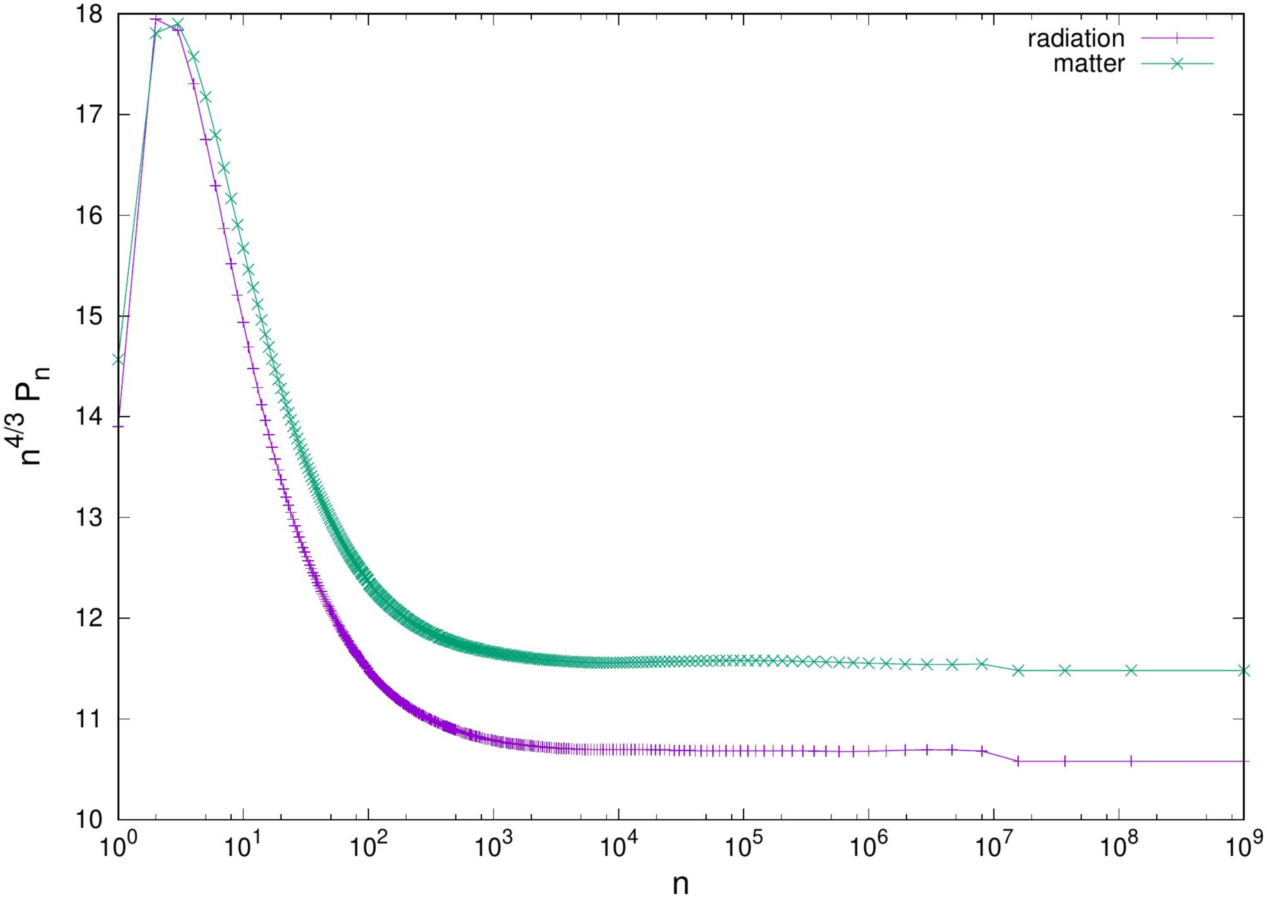
[Blanco-Pillado, Olum, PRD 101 (2020) 103018]

Model II (BOS model)

[Blanco-Pillado, Olum, Shlaer, PRD 83 (2011) 083514]

The spectrum is from around 1000 non-self-intersecting scaling loops and includes gravitational backreaction.

[Blanco-Pillado, D. Olum, PRD 96 (2017) 104046]



(see Jeremy's talk for updates)

Model I and Model II agree when we fix $\alpha = 0.1,\ q = 4/3,$ and $\mathcal{F} = 0.1$

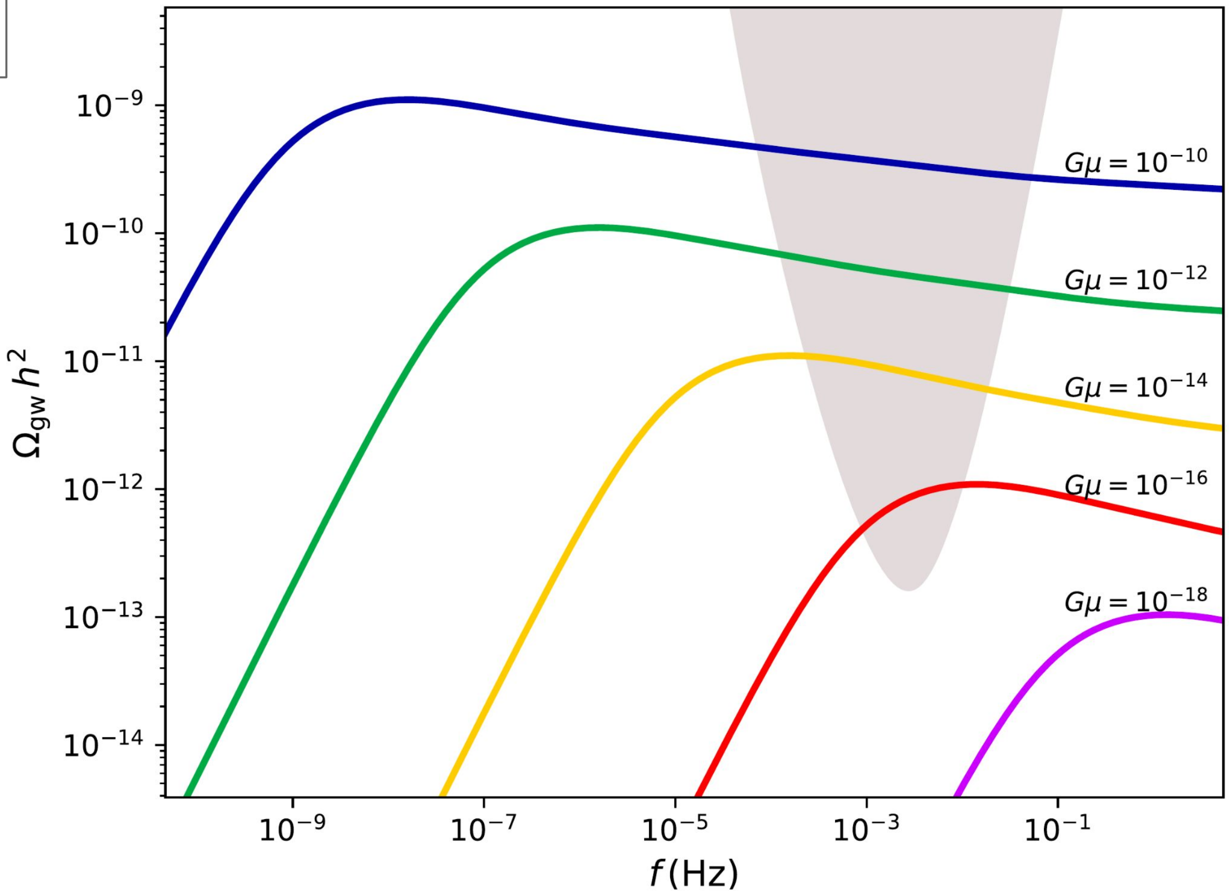
Variation of the string tension

The difference mostly appears in implementation of the Standard Model degrees of freedom (DOF).

[Bélanger, Boudjema, Pukhov, Semenov, Comput. Phys. Commun. 192 (2015) 322]

`micrOMEGAs 3.6.9.2`

(the Model I tries to take into account the “out of scaling” behavior)



We utilize the `SGWBinner` code to carry out reconstruction of the signal.

[Chiara Caprini et al JCAP11(2019)017]

Optical Measurement System (OMS) and Test Mass (TM) errors

$$S_{ii}^{\mathrm{OMS}}(f) = P^2 \left(1 + \left(\frac{2\times 10^{-3}\,\mathrm{Hz}}{f}\right)^4\right) \times \left(\frac{2\pi f}{c}\right)^2 \times \left(\frac{\mathrm{pm}^2}{\mathrm{Hz}}\right)$$

[M. Colpi et al., LISA Definition Study Report]

$$S_{ii}^{\mathrm{TM}}(f) = A^2 \left(1 + \left(\frac{0.4\,\mathrm{mHz}}{f}\right)^2\right)\left(1 + \left(\frac{f}{8\,\mathrm{mHz}}\right)^4\right)\left(\frac{1}{2\pi f c}\right)^2 \left(\frac{\mathrm{fm}^2}{\mathrm{s}^3}\right)$$

$P = 15 \text{ and } A = 3$

Extragalactic noise

[Babak, Caprini, Figueroa, Karnesis, Marcoccia, Nardini et al., JCAP 08 (2023) 034]

$$h^2\Omega_{\mathrm{gw}}^{\mathrm{Ext}} = (h^2\Omega_{\mathrm{Ext}})\left(\frac{f}{\mathrm{mHz}}\right)^{2/3}$$

Galactic noise

[Karnesis, Babak, Pieroni, Cornish, Littenberg, PRD 104 (2021) 043019]

$$h^2\Omega_{\mathrm{gw}}^{\mathrm{Gal}}(f) = h^2\Omega_{\mathrm{Gal}}\frac{f^3}{2}\left(\frac{f}{\mathrm{Hz}}\right)^{-\frac{7}{3}}\left[1+\tanh\left(\frac{f_{\mathrm{knee}}-f}{f_2}\right)\right]e^{-(f/f_1)^{\upsilon}}$$

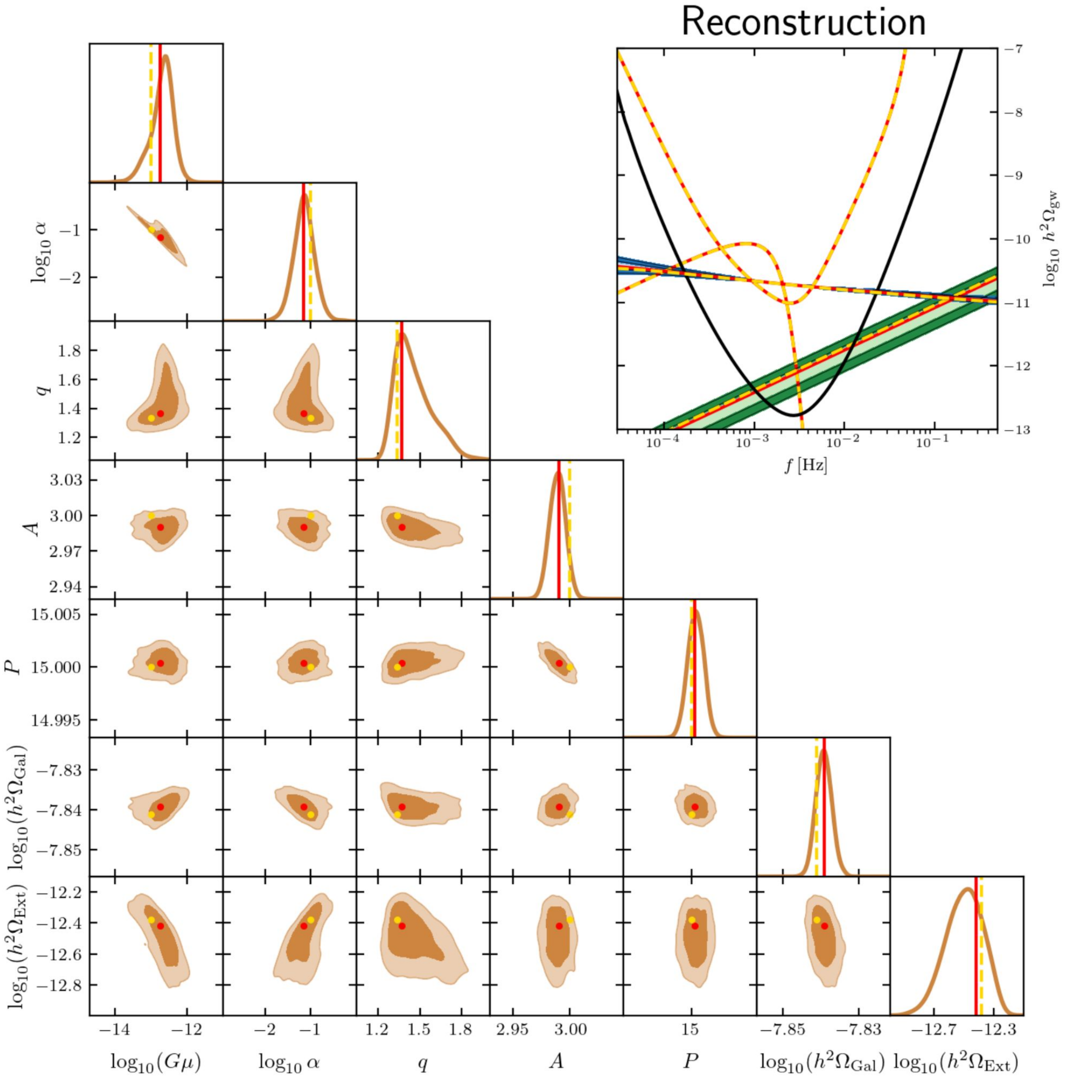
`SGWBinner` reconstruction for the Model I

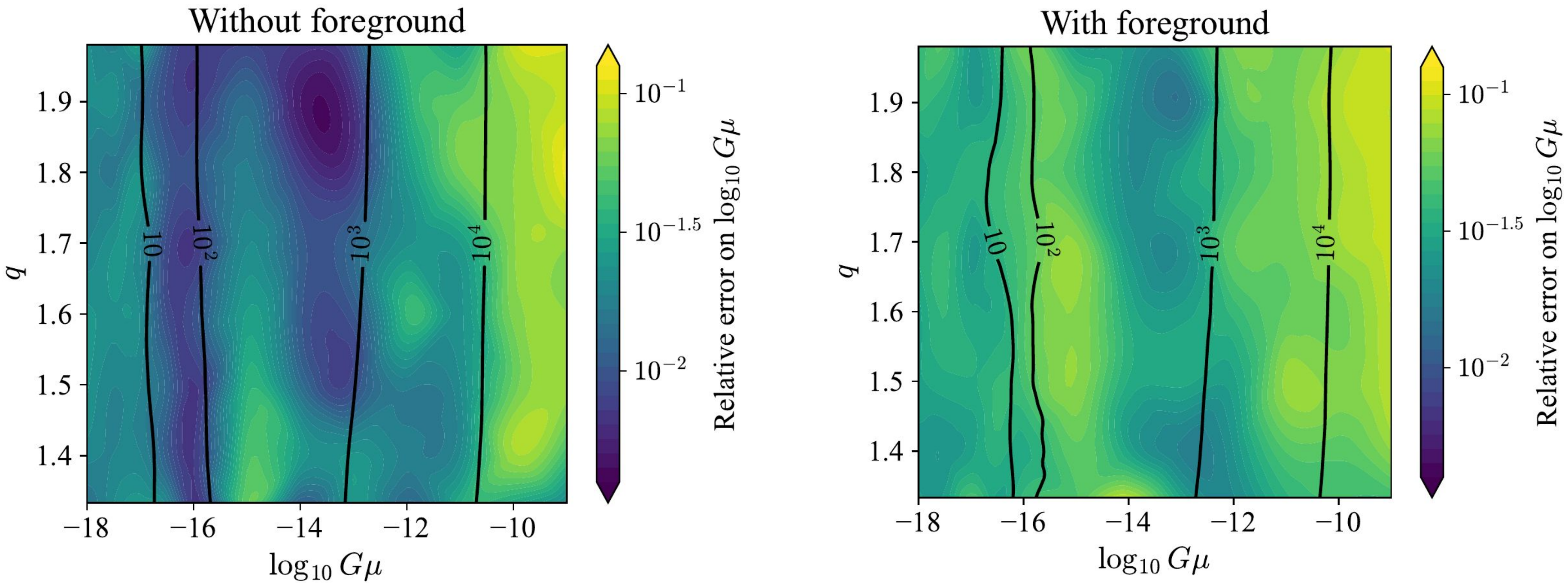
1σ and 2σ posterior distribution of parameters.

Fiducial parameters (yellow color):
$\log_{10}(G\mu) = -13.0,\ \log_{10}\alpha = -1.0,\ q = 4/3$
The recovered spectrum is depicted by red color.

String parameters: q - spectral index
α - loops size
Gμ - tension

Strong correlation between loops size α and string tension Gμ





Relative error in the reconstruction of parameters for the Model I with and without Extragalactic and Galactic foregrounds. The solid black line represents Signal-to-Noise Ratio (SNR).

Error is smallest at the intermediate values of the tension:

- for $G\mu<10^{-17}$ the error increases because the signal lower than LISA sensitivity;
- for $G\mu>10^{-13}$ the error increases due to degeneracy between parameters.

`SGWBinner` reconstruction for the Model II

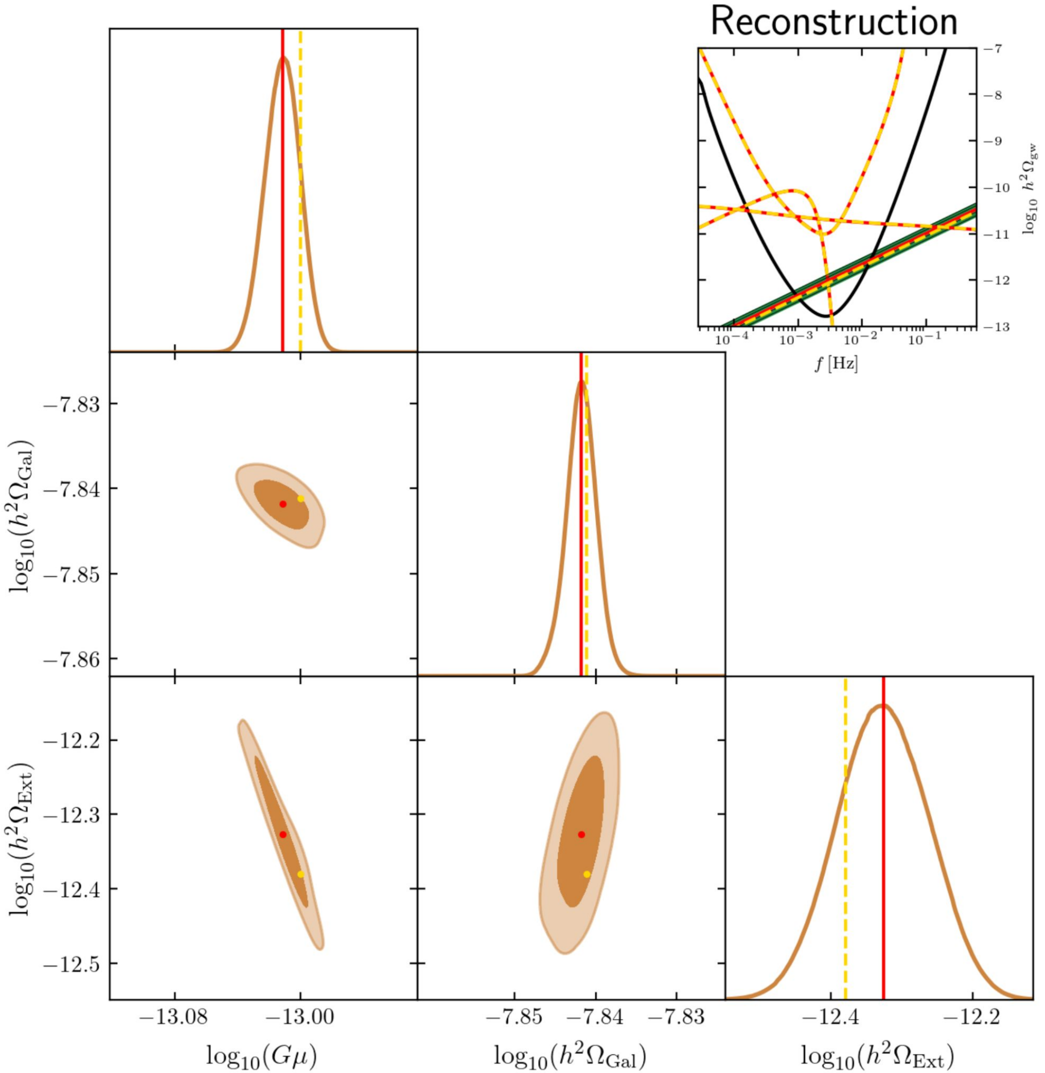
The template uses data table for interpolation in the range:

$\log_{10}(\Omega_{gw}h^2)$ values for
- $\log_{10}(f) \in [-5,0]$ with step 1/20
- $\log_{10}(G\mu) \in [-18.-9.5]$ with step 1/10

1σ and 2σ posterior distribution of parameters.

String parameter: Gμ - tension

Recovery of a string tension Gμ is better



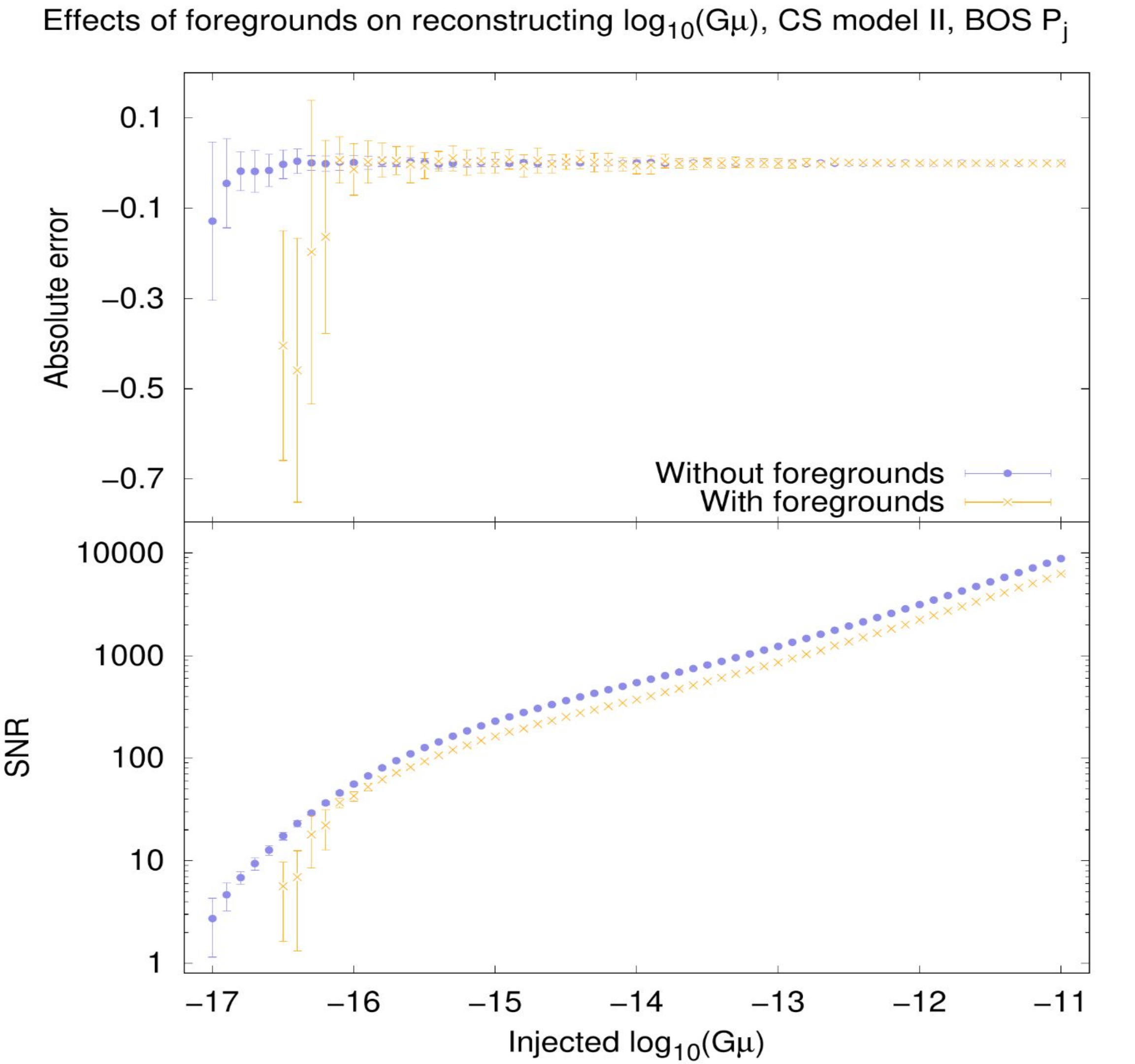
`SGWBinner` reconstruction for the Model II

Absolute error and SNR in the reconstruction of an injected Model II

-without foreground ($10^{-17} < G\mu < 10^{-11}$)

-with foregrounds ($10^{-16.5} < G\mu < 10^{-11}$)

30 trials performed at each tension value.

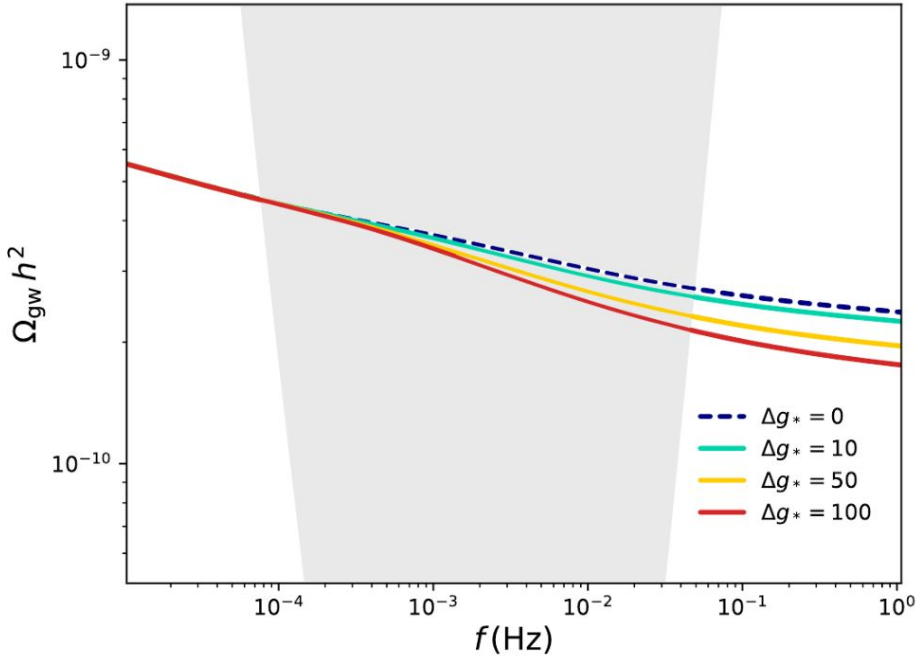


Non-standard cosmology (extra degrees of freedom)

Universe expansion is affected by change of DOF: $$H^2 = H_0^2 \left[\Delta_r(a)\,\Omega_r \left(\frac{a}{a_0}\right)^{-4} + \Omega_m \left(\frac{a}{a_0}\right)^{-3} + \Omega_\Lambda \right]$$

$$\Delta_r(a) = \frac{g_*(a)}{g_*(a_0)} \left(\frac{g_{*S}(a_0)}{g_{*S}(a)}\right)^{4/3}$$

Extra DOF brings changes in the spectrum.



Non-standard cosmology
(extra degrees of freedom)

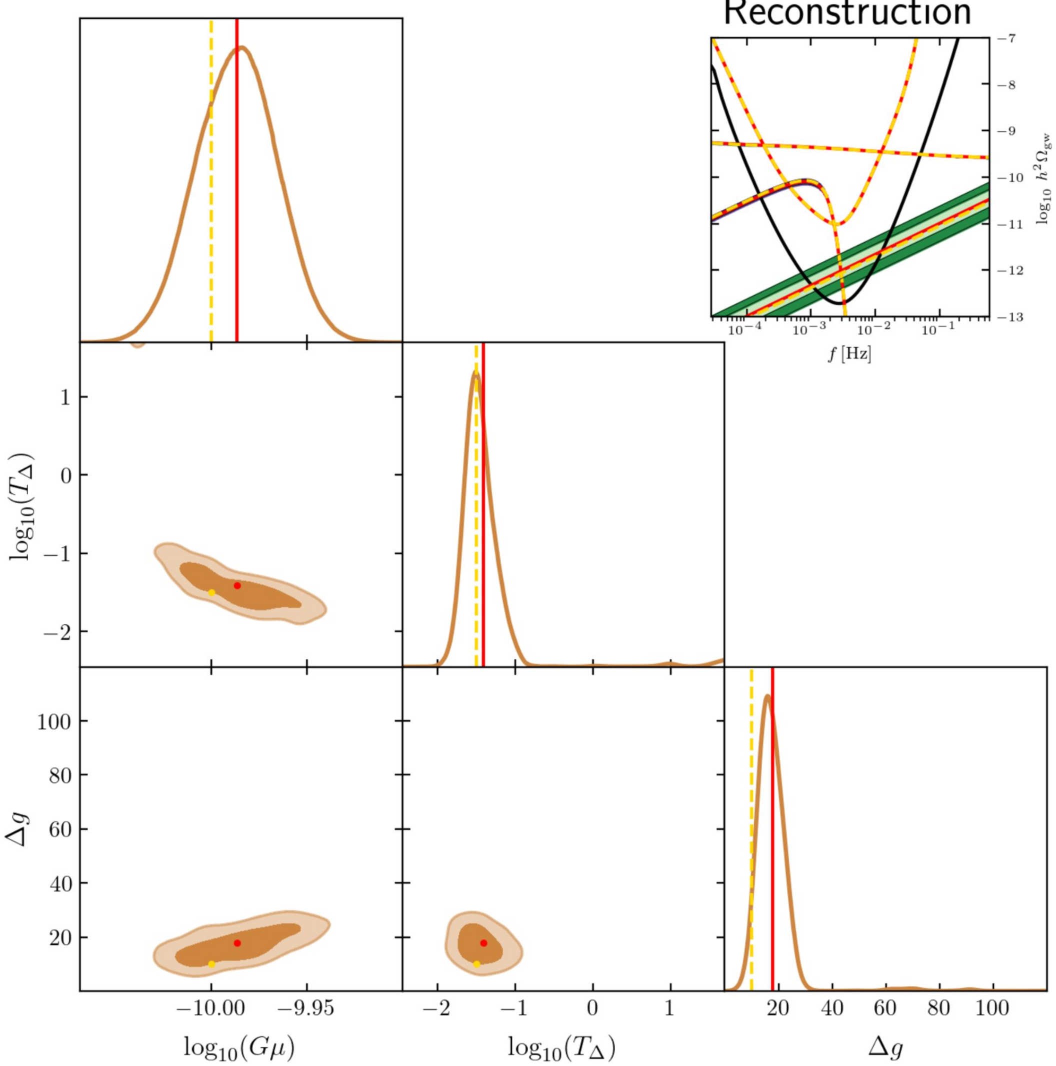
Reconstruction of an injected Model II signal with extra DOF.

10 extra DOF at

$T_\Delta = 10^{-1.5}$ GeV and

tension $G\mu = 10^{-10}$.

For tension $G\mu = 10^{-10}$, the Model II (with fixed by simulations parameters), can distinguish 10 extra DOF by LISA



Non-standard cosmology
(extra degrees of freedom)

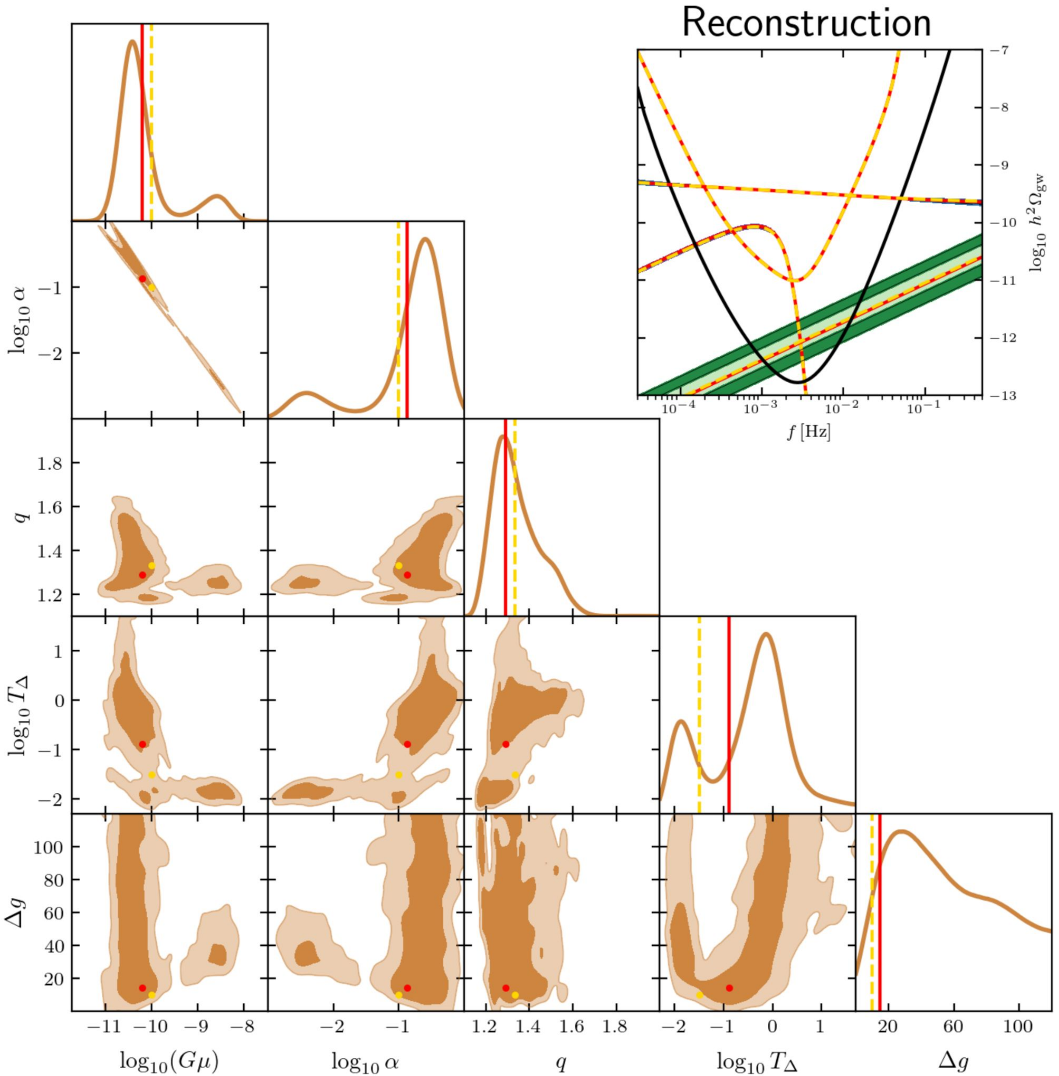
Reconstruction of an injected Model I signal with extra DOF.

10 extra DOF at

$T_\Delta = 10^{-1.5}$ GeV and

tension $G\mu = 10^{-10}$.

Due to generacy in parameters, Model I does not provide such sensitive test for extra DOF in comparison with Model II.



Non-standard cosmology
(extra degrees of freedom)

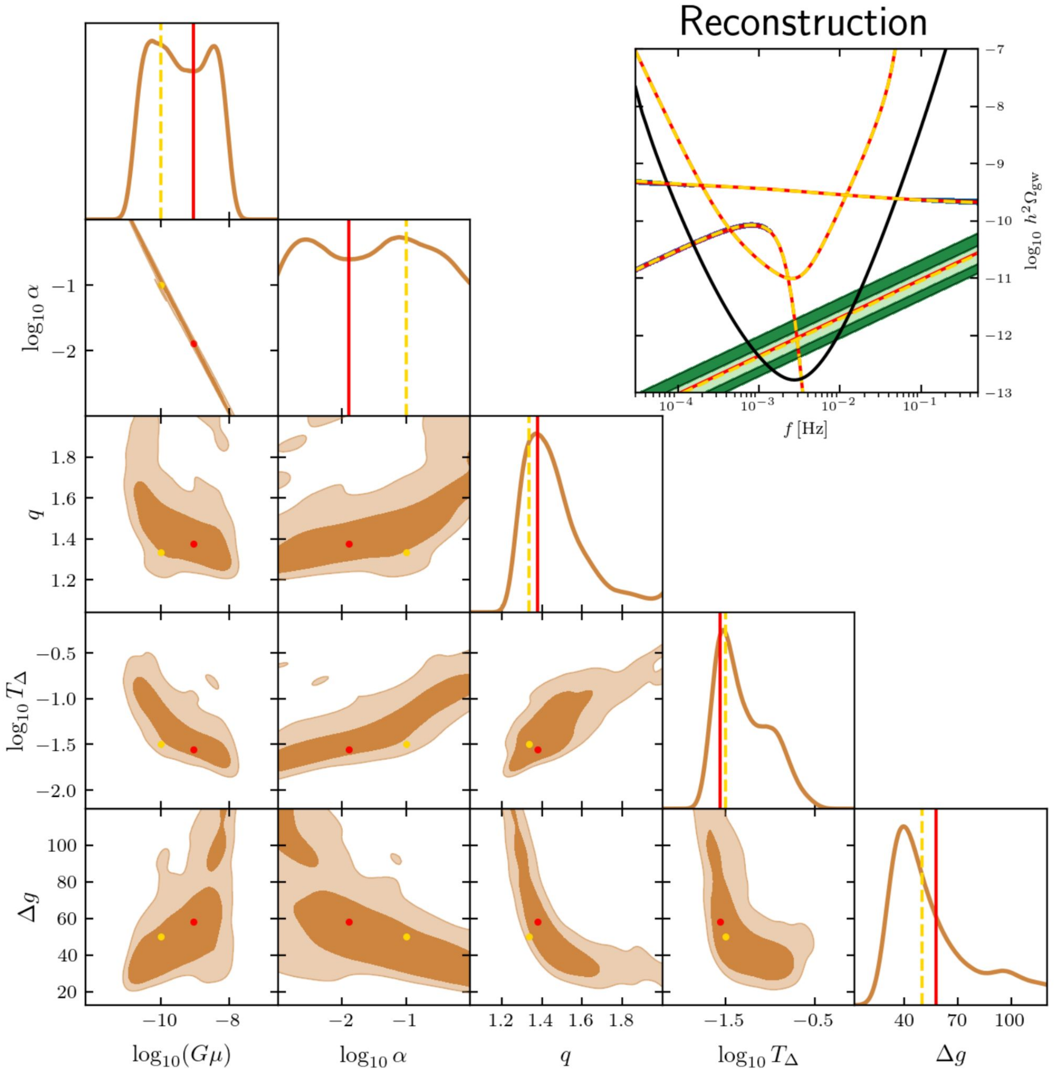
Reconstruction of an injected Model I signal with extra DOF.

50 extra DOF at

$T_{\Delta}=10^{-1.5}$ GeV and

tension $G\mu = 10^{-10}$.

Due to generacy in parameters, Model I does not provide such sensitive test for extra DOF in comparison with Model II.

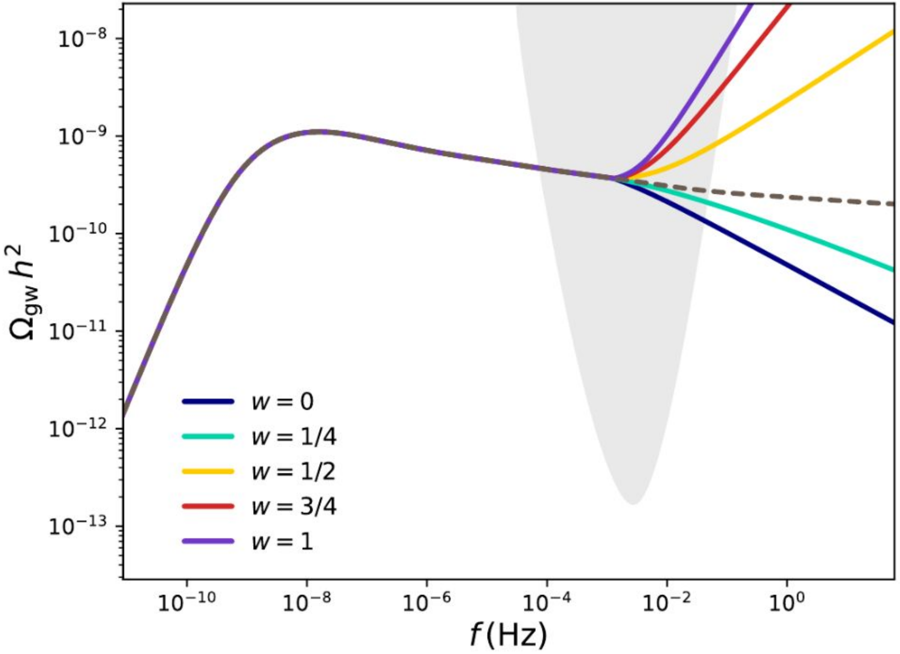


Non-standard cosmology (additional component of energy domination)

If we assume that the early universe is dominated by by the energy component: $\rho \propto a^{-3(1+w)}$ for temperature $T > T_{\rm rd}$. The slope has corresponding change:

$$\Omega^*_{\rm gw}(f \gg f_{\rm rd}, q, G\mu, \alpha, f_{\rm rd}, d) \propto \left(\frac{f_{\rm rd}}{f}\right)^{d_*}, \quad \text{with} \quad d_* = \begin{cases} d & , \; w > \frac{1}{3}\frac{3-q}{q+1} \\ q-1 & , \; w \leq \frac{1}{3}\frac{3-q}{q+1} \end{cases}.$$

Spectrum for any w<1/9 are the same and similar to the inflation influence.



Non-standard cosmology
(additional component of energy domination)

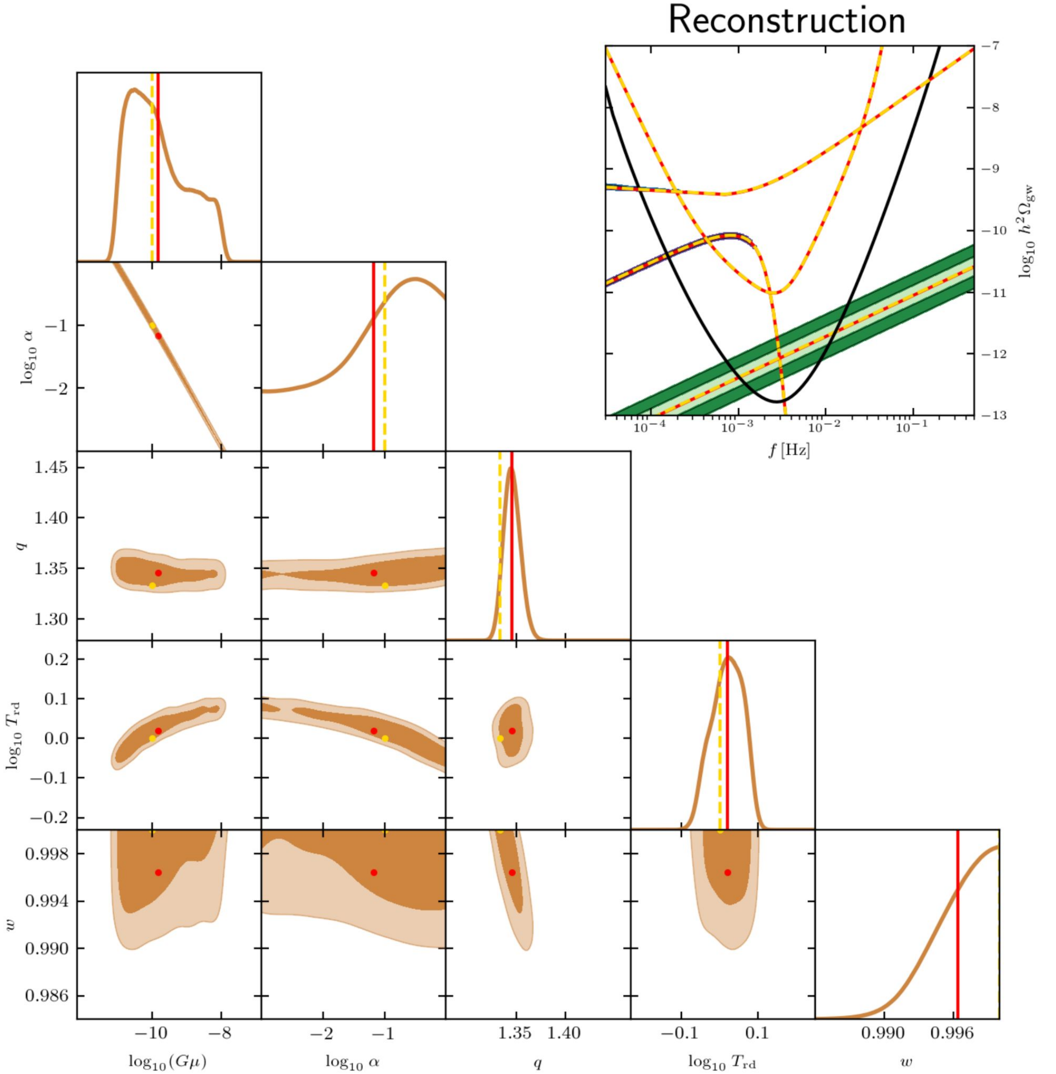
Reconstruction of an injected Model I signal with kination period in the early stage of the universe evolution.

w=1 until

$T_{rd}=10^{-1.5}$ GeV and

tension $G\mu = 10^{-10}$.

Reconstruction for w=1 successful, but won't work for w<1/3, because of negative slope.



Conclusions and further steps

- We created templates for SGWB generated by cosmic strings
- Using `SGWBinner` we reconstructed signal from cosmic strings with astrophysical and instrumental noise (up to $G\mu = 10^{-16}$-10^{-17}).
- In the optimistic case we can probe BSM up to T_Δ=0.05 GeV.
- Modelling:

  AH effects (type I, II), gravitational backreaction, Y-junctions, superconductivity, …
- Analyses:

  Can we distinguish cosmic strings from other possible sources of SGWB?

<u>Thank you for your attention!</u>

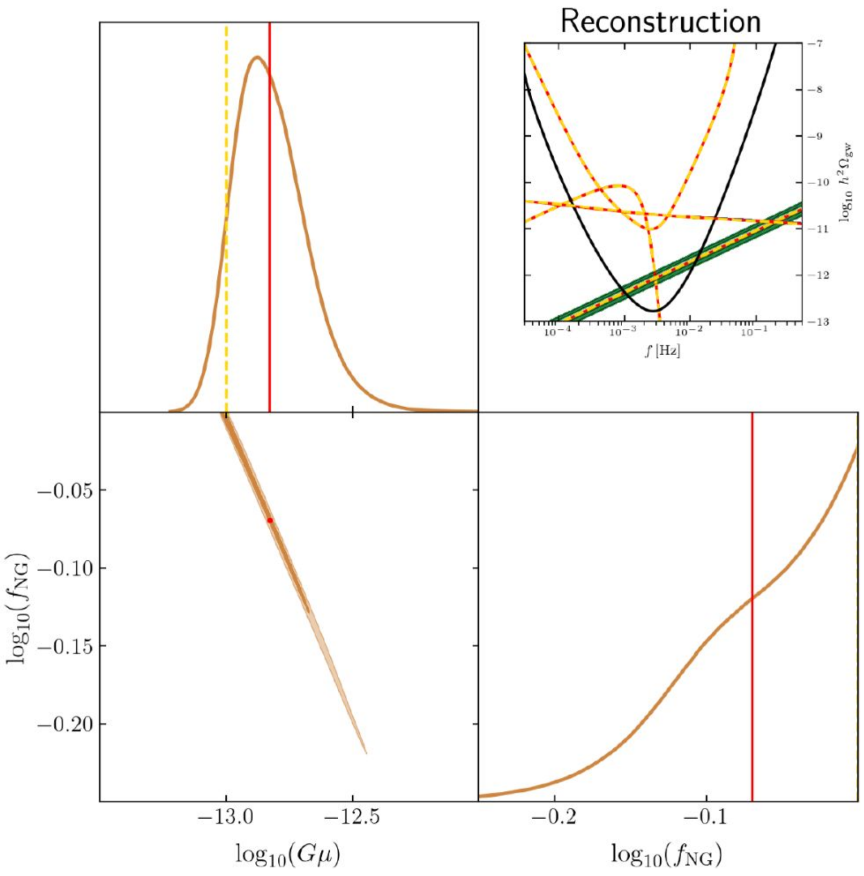
Backup slides

Parameter name	Parameter symbol	Range
String tension (Model I)	$\log_{10}(G\mu)$	$[-18.0, -7.0]$
String tension (Model II)	$\log_{10}(G\mu)$	$[-18.0, -9.5]$
Power spectral index	q	$[1.10, 1.99]$
Loop size	$\log_{10}(\alpha)$	$[-3, 0]$
New degrees of freedom (DoF)	Δg	$[0, 120]$
Temperature of new DoF decoupling	$\log_{10}(T_\Delta/1\,\mathrm{GeV})$	$[-2.3, 1.7]$
Equation-of-state	w	$[0, 1]$
Temperature of radiation domination	$\log_{10}(T_{rd}/1\,\mathrm{GeV})$	$[-2.3, 1.7]$

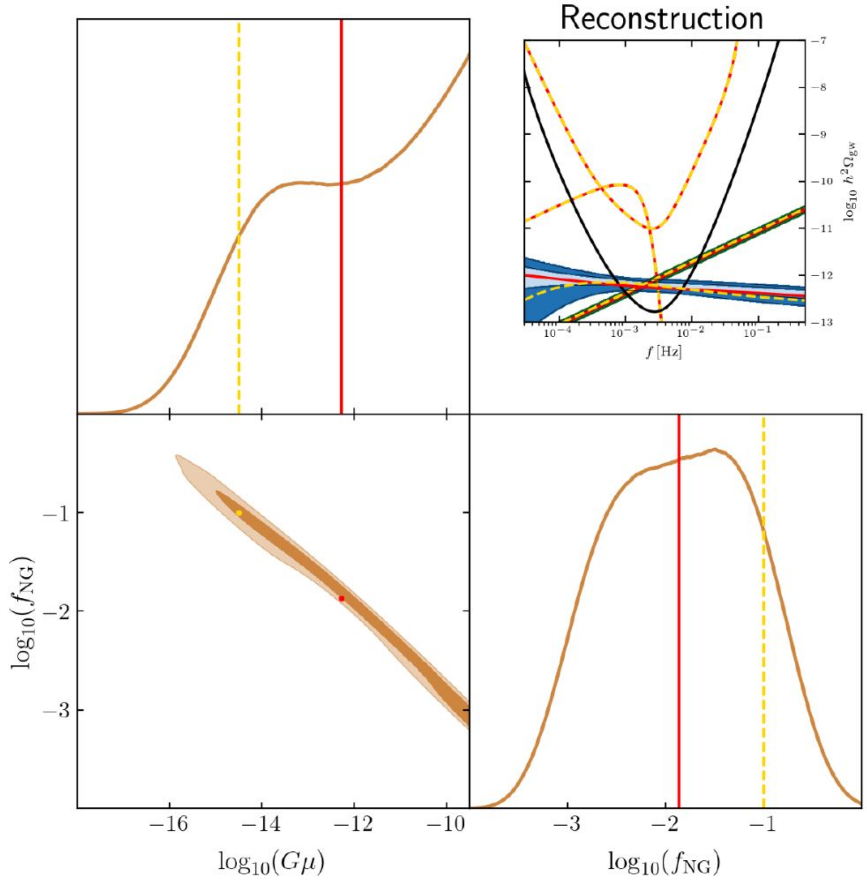
Parameters have flat priors during reconstruction.

Abelian Higgs

$$\Omega_{\rm gw}^{\rm (AH)} = f_{\rm NG}\Omega_{\rm gw}^{\rm (NG)}$$



Tension $G\mu = 10^{-13}$, $f_{NG}=1$



Tension $G\mu = 10^{-14.5}$,

Extragalactic noise:

[Babak, Caprini, Figueroa, Karnesis, Marcoccia, Nardini et al., JCAP 08 (2023) 034]

$$h^2\Omega_{\rm gw}^{\rm Ext} = (h^2\Omega_{\rm Ext})\left(\frac{f}{\rm mHz}\right)^{2/3}$$

$$h^2\Omega_{\rm Ext} = 10^{-12.38}$$

$$h^2\Omega_{\rm Gal} \;=\; 10^{-7.84}$$

Galactic noise:

[Karnesis, Babak, Pieroni, Cornish, Littenberg, PRD 104 (2021) 043019]

$$h^2\Omega_{\rm gw}^{\rm Gal}(f) = h^2\Omega_{\rm Gal}\frac{f^3}{2}\left(\frac{f}{\rm Hz}\right)^{-\frac{7}{3}}\left[1+\tanh\left(\frac{f_{\rm knee}-f}{f_2}\right)\right]e^{-(f/f_1)^{\upsilon}}$$

$$\log_{10}(f_1/{\rm Hz}) \;=\; a_1\log_{10}(T_{obs}/{\rm year})+b_1$$

$$\log_{10}(f_{\rm knee}/{\rm Hz}) \;=\; a_k\log_{10}(T_{obs}/{\rm year})+b_k$$

$$a_1 \;=\; -0.15,\;\; b_1 \;=\; -2.72,\;\; a_k \;=-0.37$$

$$b_k \;=\; -2.49,\;\; \upsilon \;=\; 1.56,\;\; f_2 \;=\; 6.7\times 10^{-4}\,{\rm Hz}$$