# Cosmic Strings

## Survey and Detection Prospects at LISA

Some parts from Dimitriou, Figueroa, PS, Zaldivar [in progress]

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Towards a realistic forecast detection of
Primordial Gravitational Wave Backgrounds

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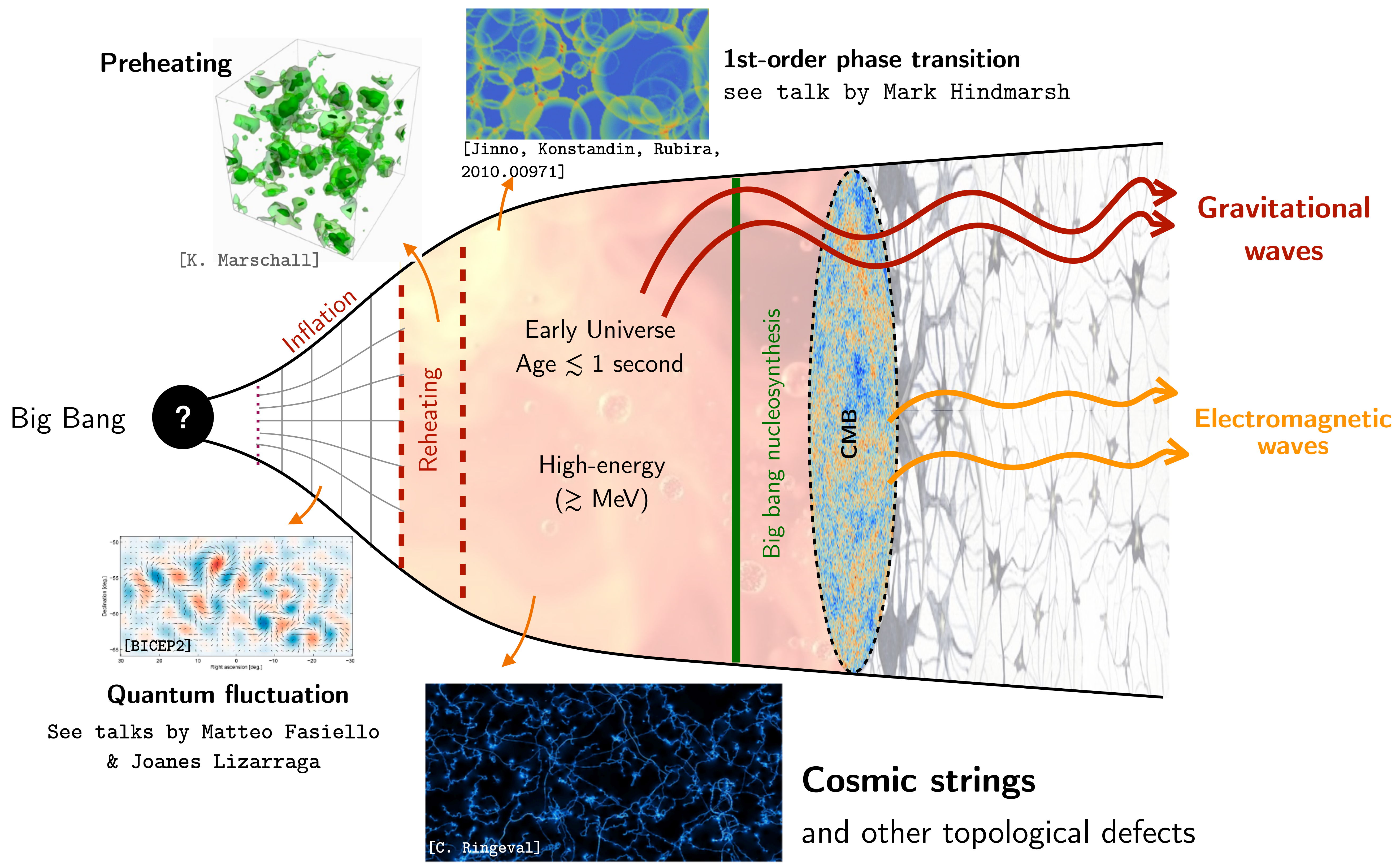
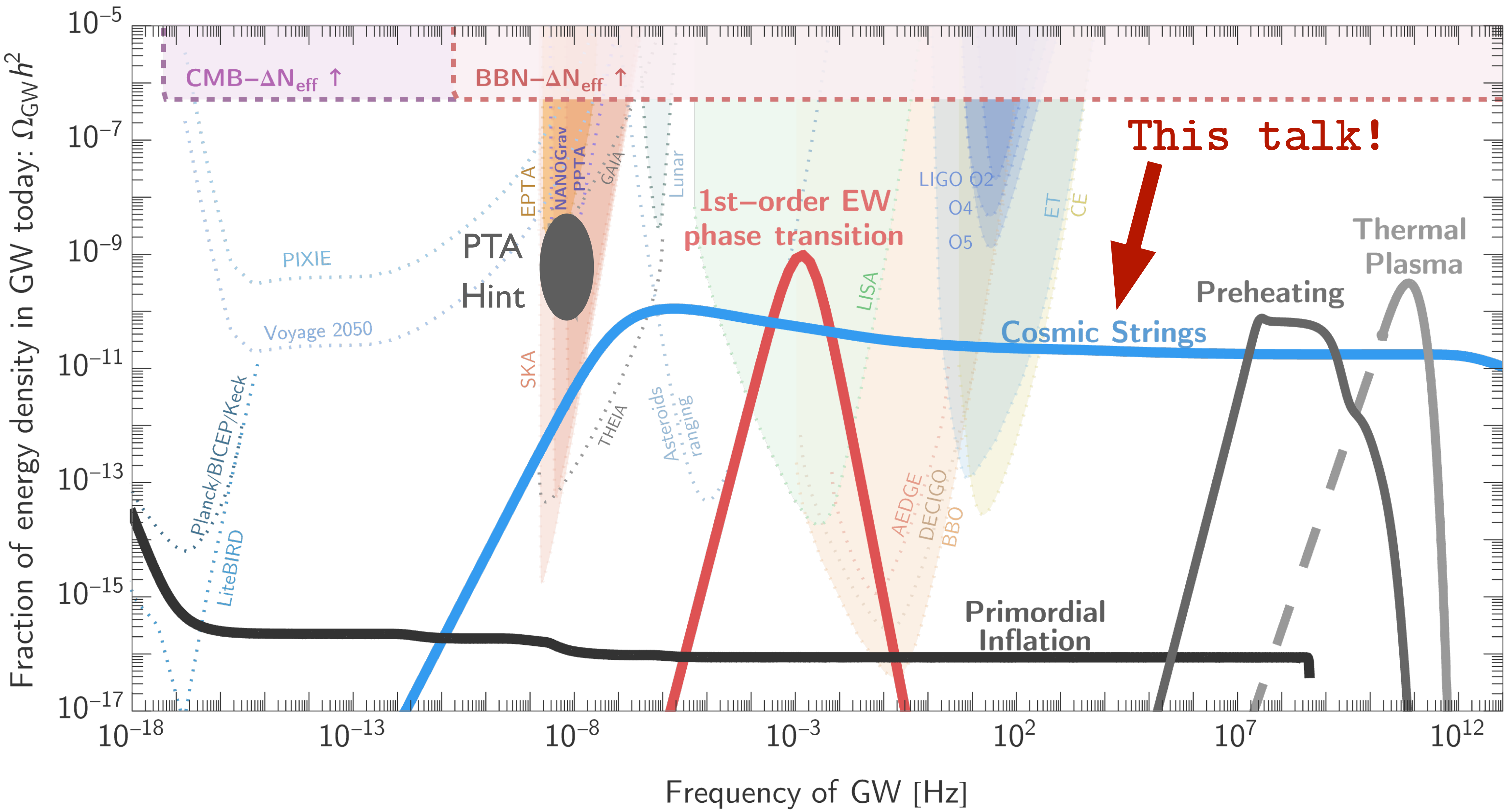
# GW as probes of the early Universe.



# The landscape of Primordial GWBs

Many GW observatories will search for GWB in many frequency windows in the near future.

Cosmic-string GWB can have a detectable signal that spans a broad frequency range.



# For today

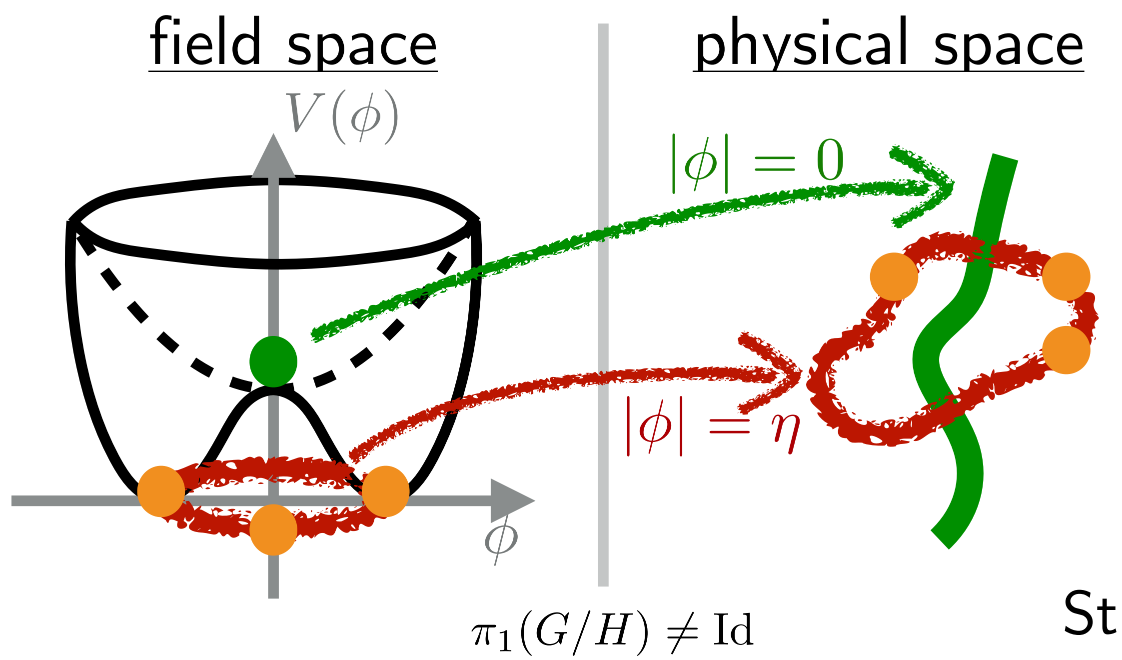
I. GWB from cosmic strings: a simple story

II. A survey of templates

- Conventional Nambu-Goto templates
- Beyond conventional (related to other BSM)
  - Part I : Loop number density
  - Part II : Modified loop shape and initial size
  - Part III : Non-standard cosmic history

III. What do we learn from a precise reconstruction e.g., with LISA

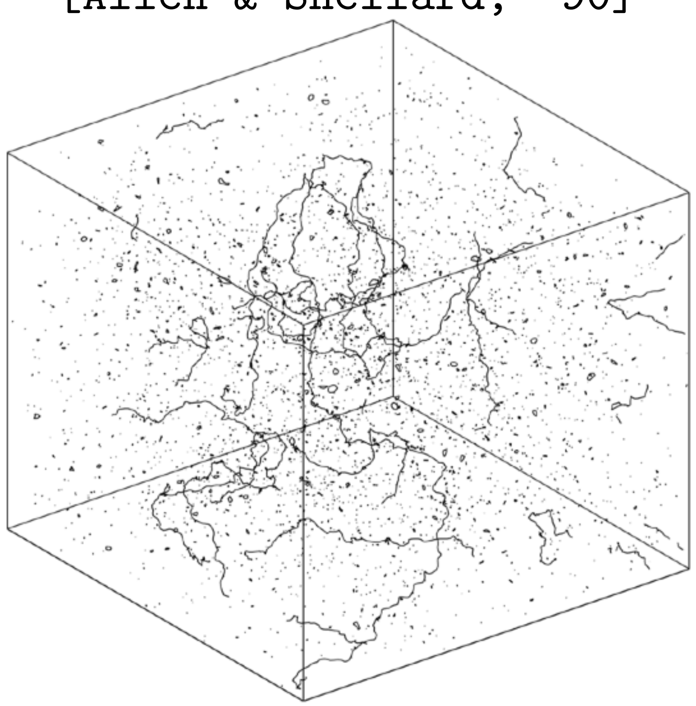
# Cosmic strings in the early Universe




A **cosmic string** is a line-like topological defect from the spontaneous symmetry breaking [e.g., $U(1)$] at some energy scale $\eta$ in the early Universe.
[Kibble '76]

String's core $\eta^{-1} \ll$ horizon size $\Rightarrow$ 1D classical object (**Nambu-Goto** string)

**Network of cosmic strings**
[Allen & Shellard, '90]



described by **the string tension [energy per length]**

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

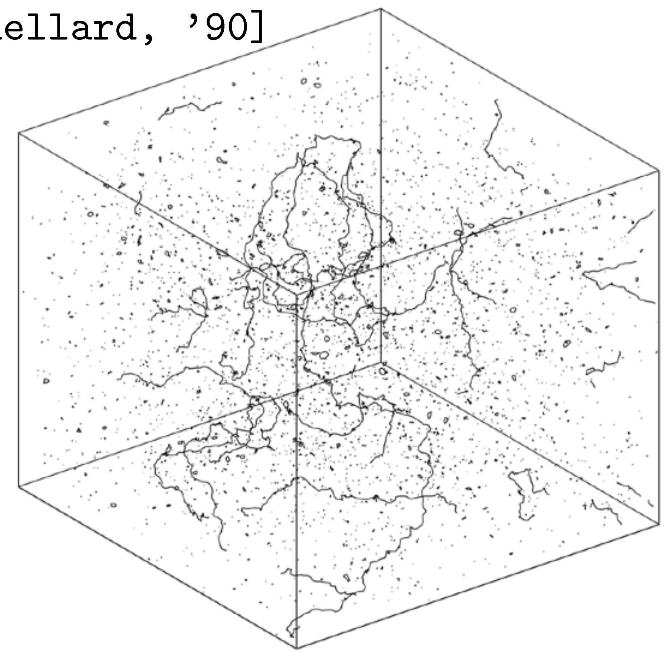
Local (global) symmetry breaking leads to local (global strings).
**We will focus on local strings for today!**

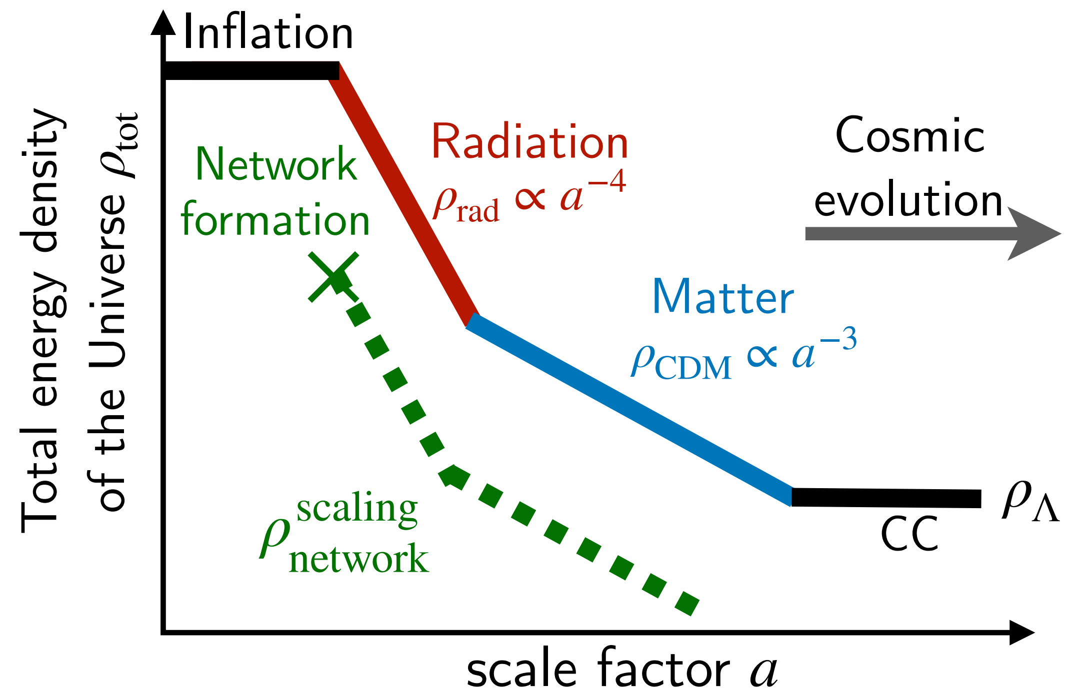
Reviews e.g., [Hindmarsh, Kibble '94], [Caprini, Figueroa, '18]
[LISA Cosmo, 1909.00819], [Servant, Gouttenoire, PS, 1912.02569] [Caprini+, 2406.02359]

# Cosmic strings in the early Universe

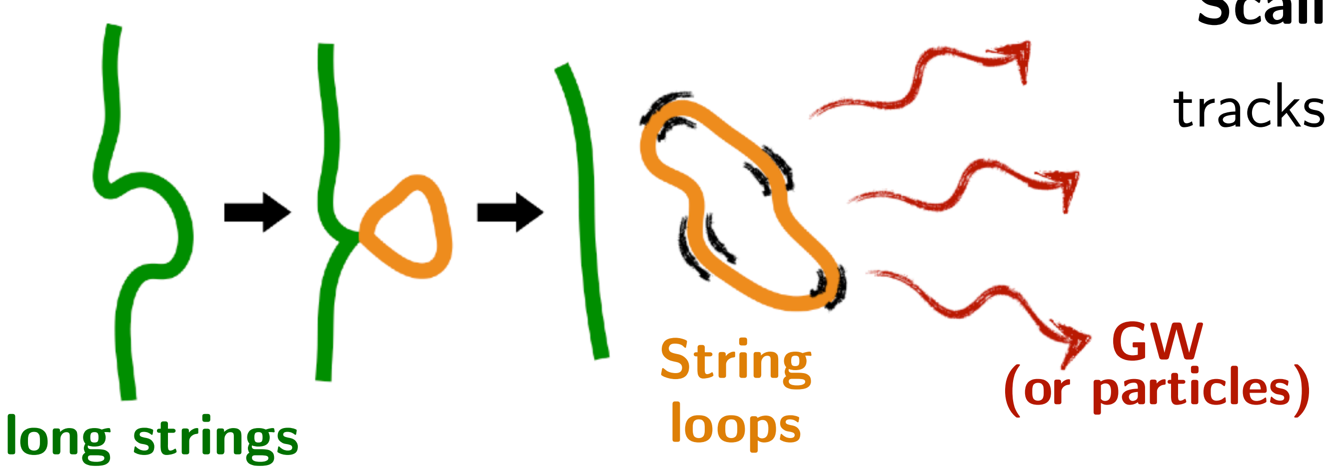
**Network of cosmic strings**

[Allen & Shellard, '90]






$$\dot{\rho}_{\rm network} + 2H\rho_{\rm network} = -\mathcal{P}_{\rm loss}$$




**"Scaling" regime:** the string network's energy density tracks the Universe's total energy density.

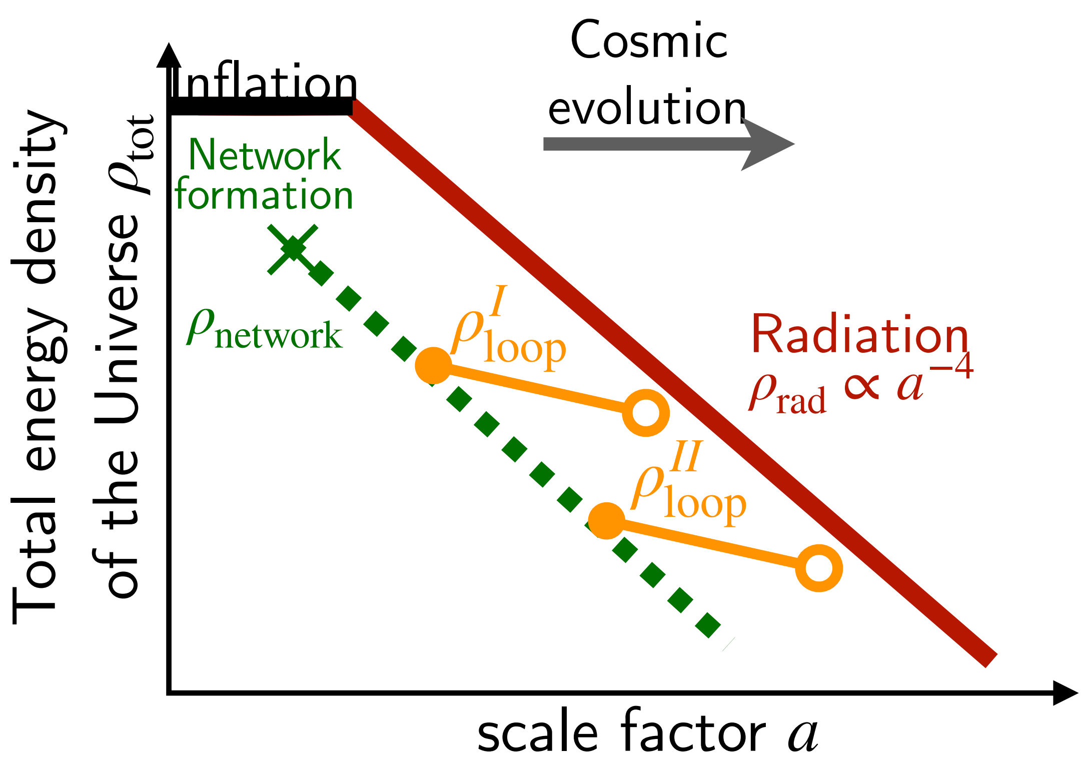
$$\boxed{\rho^{\rm scaling}_{\rm network} \simeq \mu/t^2 \sim G\mu\rho_{\rm tot}}$$

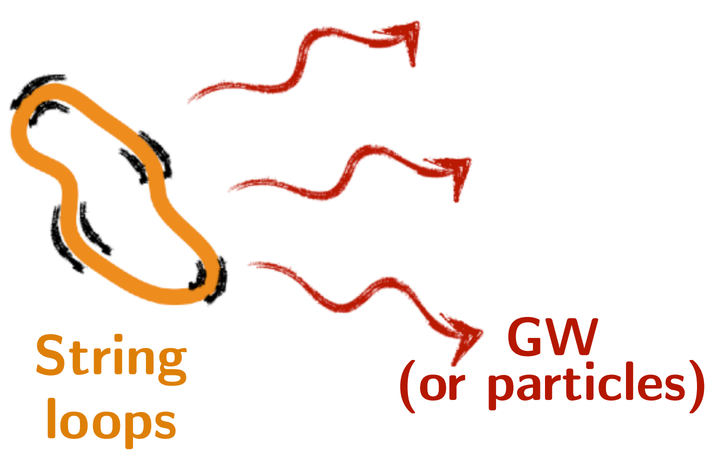
To conserve energy, at a given time,
the network spits out a population of loops with energy density,

$$\boxed{\rho_{\rm loop} \sim \mathcal{P}_{\rm loss} H \sim \rho^{\rm scaling}_{\rm network}}$$

(assuming no particles produced from long strings.)

# GW from cosmic strings




A gas of many loops as non-relativistic matter, so loop number density and energy density redshift,

$$\boxed{n_{\rm loop}(a) \propto \rho_{\rm loop}(a) \propto a^{-3}}$$

**Each loop** is produced with size: $l_i \simeq \alpha t_i$

with $\alpha \simeq 0.1$ [Blanco-Pillado+ '13]

**Assume:** continuously lose energy only into GW very slowly with power,

$$\frac{dE}{dt} = \mu \frac{dl}{dt} = -\Gamma G \mu^2 \Rightarrow \boxed{l(t) = l_i - \Gamma G\mu(t - t_i)}$$

($\Gamma \simeq 50$ [Blanco-Pillado+ '17])

$$\boxed{\textbf{Loops lifetime: } \tau \sim \frac{\alpha}{\Gamma G\mu} t_i}$$

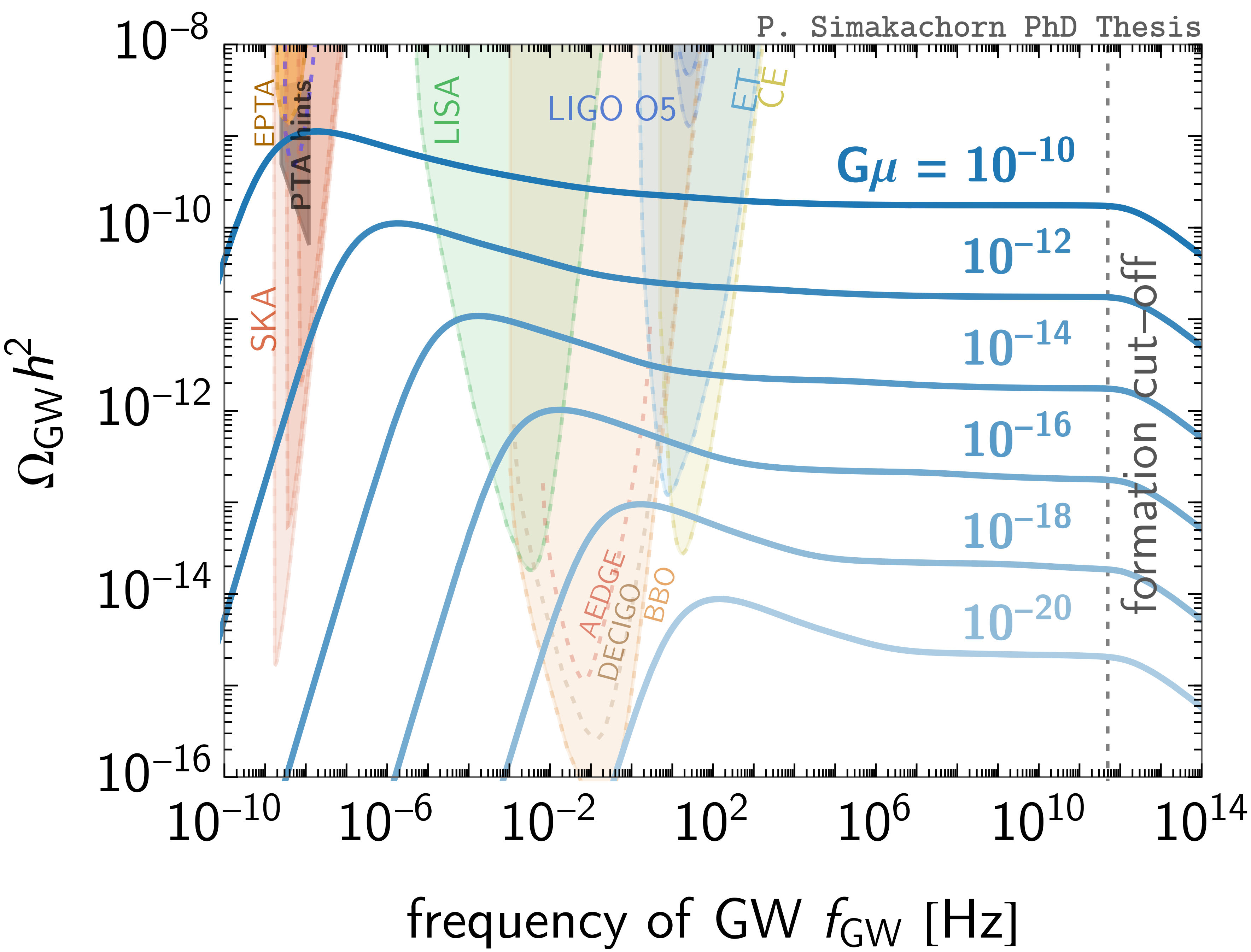
"Loops emitting only GW can live for a long time."

*if efficiently produce particles...loops die very fast.
Baeza-Ballesteros, Copeland, Figueroa, Lizarraga [2408.02364]

# GWB from cosmic strings

string network ⇒ many loops produced at many times ⇒ GW from all loops

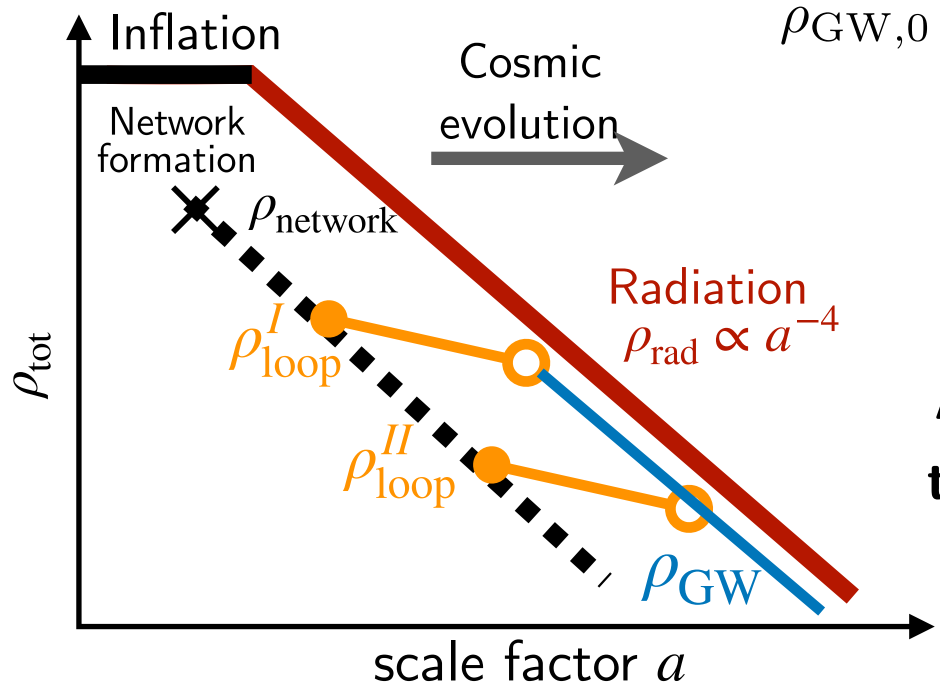
**Why broadband? Why this (scale-invariant) shape?**



# GWB from cosmic strings (simplified)

Each population of loops, produced at time $t_i$, emits GW with energy density today

$$\rho_{\mathrm{GW},0} = \rho^e_{\mathrm{GW}} \left(\frac{a_e}{a_0}\right)^4 \propto n_{\mathrm{loop}}(a_e) \left(\frac{a_e}{a_0}\right)^4 \propto G\mu\rho_{\mathrm{tot}}(a_i) \left(\frac{a_i}{a_0}\right)^4 \left(\frac{a_e}{a_i}\right)$$




$$\Rightarrow \boxed{\rho_{\mathrm{GW},0} \propto \rho_{\mathrm{tot}}(a_i) \left(\frac{a_i}{a_0}\right)^4}$$

$\boxed{n_{\mathrm{loop}}(a) \propto \rho_{\mathrm{loop}}(a) \propto a^{-3}}$

$\boxed{\rho^{\mathrm{prod}}_{\mathrm{loop}} \sim \rho^{\mathrm{scaling}}_{\mathrm{network}}}$

$\boxed{\rho^{\mathrm{scaling}}_{\mathrm{network}} \sim G\mu\rho_{\mathrm{tot}}}$

**Amplitude of cosmic-string GWB tracks the total energy density of the Universe.**

**Strongest GW from the latest loops**, i.e., $t_e \sim \tau \sim \dfrac{\alpha}{\Gamma G\mu} t_i$ is the loop life time.

(Rough estimate) All loops at $t_e \sim \tau$ generate max contribution to GW, i.e., $\rho^e_{\mathrm{GW}} \sim \rho_{\mathrm{loop}}(a_e)$.

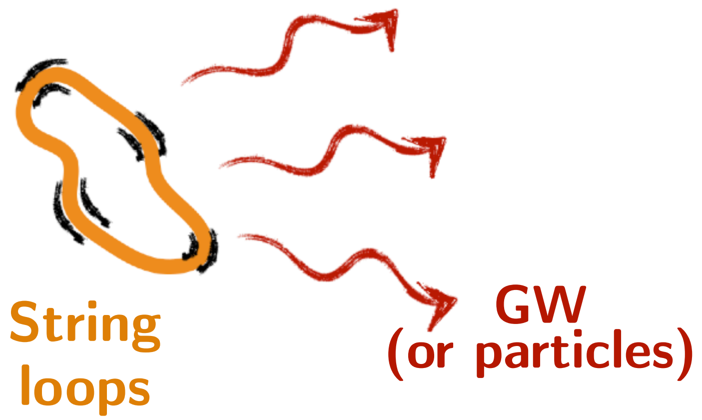
In radiation era $a \sim t^{1/2}$

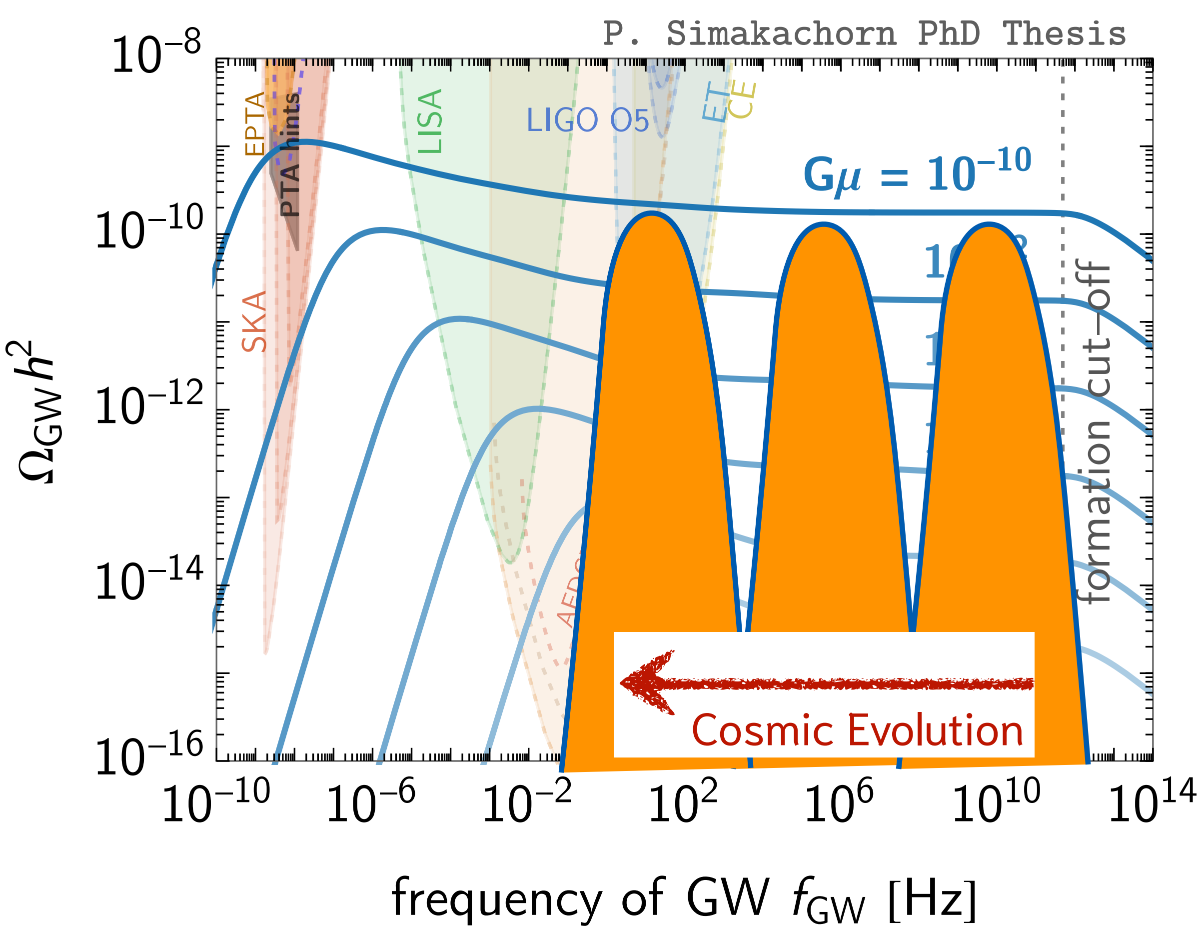
$$\Rightarrow \rho_{\mathrm{GW},0} \sim G\mu\rho_{r,0}(t_e/t_i)^{1/2} \Rightarrow \boxed{\Omega_{\mathrm{GW},0} \sim \mathcal{O}(10^{-10}) \left(\frac{G\mu}{10^{-10}}\right)^{1/2}}$$

Any loop population produced at any time $t_i$ and emitted GW **during the radiation era has the same $\Omega_{\mathrm{GW}}$.**

# GWB from cosmic strings (simplified)

$$\boxed{\Omega_{\mathrm{GW},0} \sim \mathcal{O}(10^{-10}) \left(\frac{G\mu}{10^{-10}}\right)^{1/2}}$$




Any loop population produced and emitted GW during the radiation era has **the same $\Omega_{\mathrm{GW}}$.**

**But not the same frequency.**

At GW emission

$$f^e_{\mathrm{GW}} \sim l^{-1}(t) \sim l_i^{-1} \sim H_i/\alpha$$

(since the energy loss is small.)

GW from loops formed in the Universe at temperature $T_i$ has **frequency today**

$$\boxed{\begin{aligned} f_{\mathrm{GW}} &= f^e_{\mathrm{GW}}(a_e/a_0) \\ &\simeq (6\ \mathrm{mHz}) \left[\frac{T_i}{0.1\ \mathrm{GeV}}\right]\left[\frac{10^{-10}}{G\mu}\right]^{1/2} \end{aligned}}$$

Earlier loops $\Rightarrow$ **higher GW frequency.**

# Basic shape of cosmic-string GWB spectrum

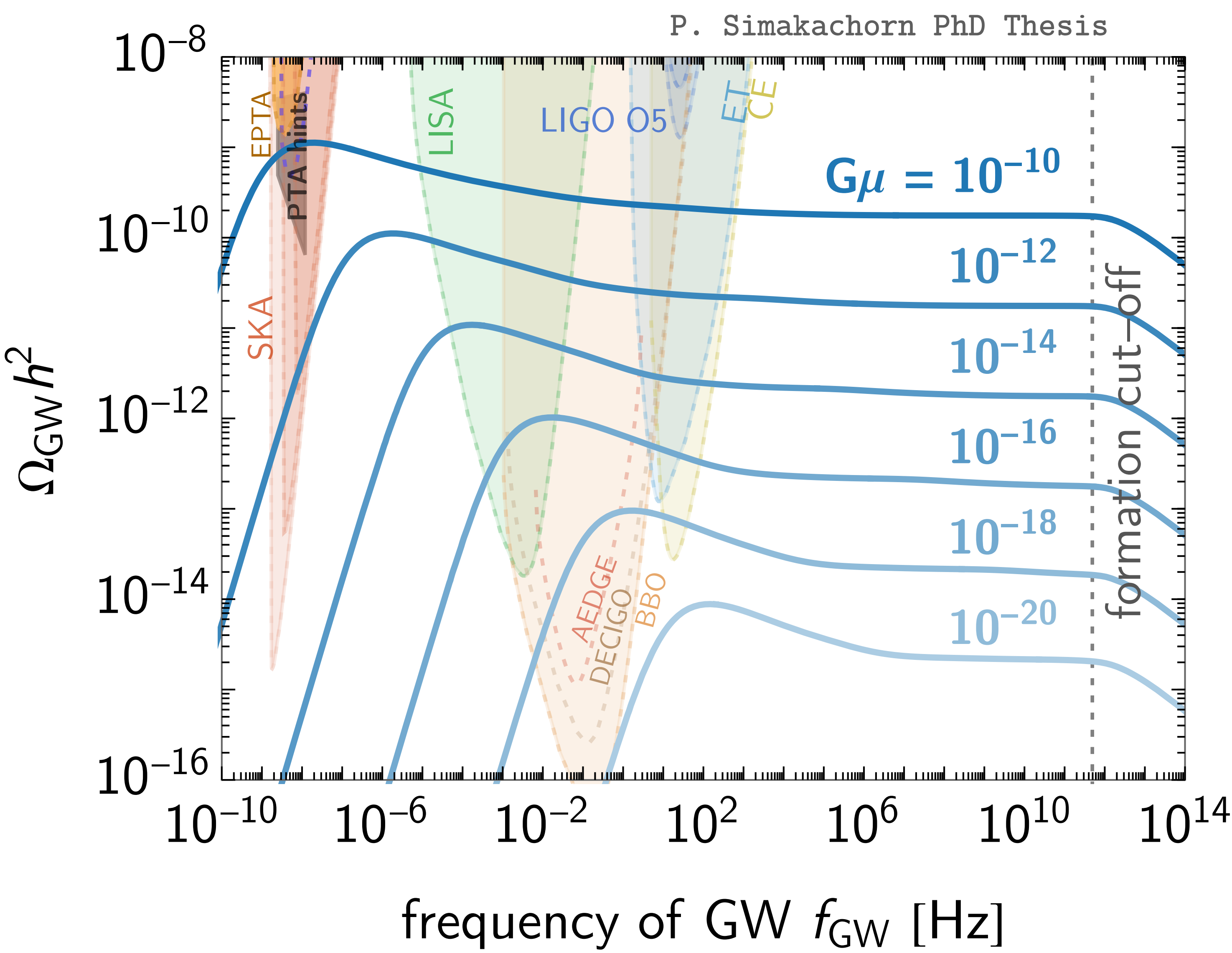
**Smoking gun signature:**
**Flat (scale-invariant) ⇔ radiation era**

**Cosmic-string GWB is**
**a " logbook " of our Universe.**
i.e., Early → late times
High → low frequencies

**Cosmic-string GWB as**
**a probe of the early Universe,**
**LISA** probes **QCD** scale physics;
**ET** probes **EW** scale physics.

$$\boxed{f_{\rm GW} \simeq (6~{\rm mHz}) \left[\frac{T_i}{0.1~{\rm GeV}}\right] \left[\frac{10^{-10}}{G\mu}\right]^{1/2}}$$

" Unlike GWB from phase transtions. (LISA ⇔ EW) "




**So far...**
**everything is derived naively.**

# Master formula for GWB from Nambu-Goto strings

In practice, we calculate the GWB spectrum from cosmic strings more carefully.
But the same story...

Integrating contribution from all loops

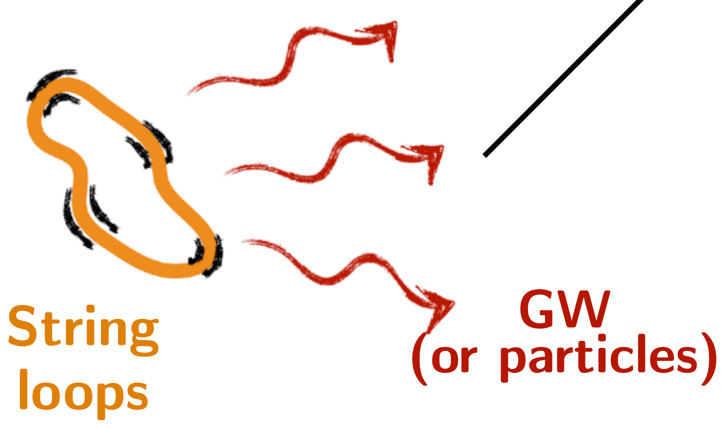
Redshift of GW $\sim a^{-4}$

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

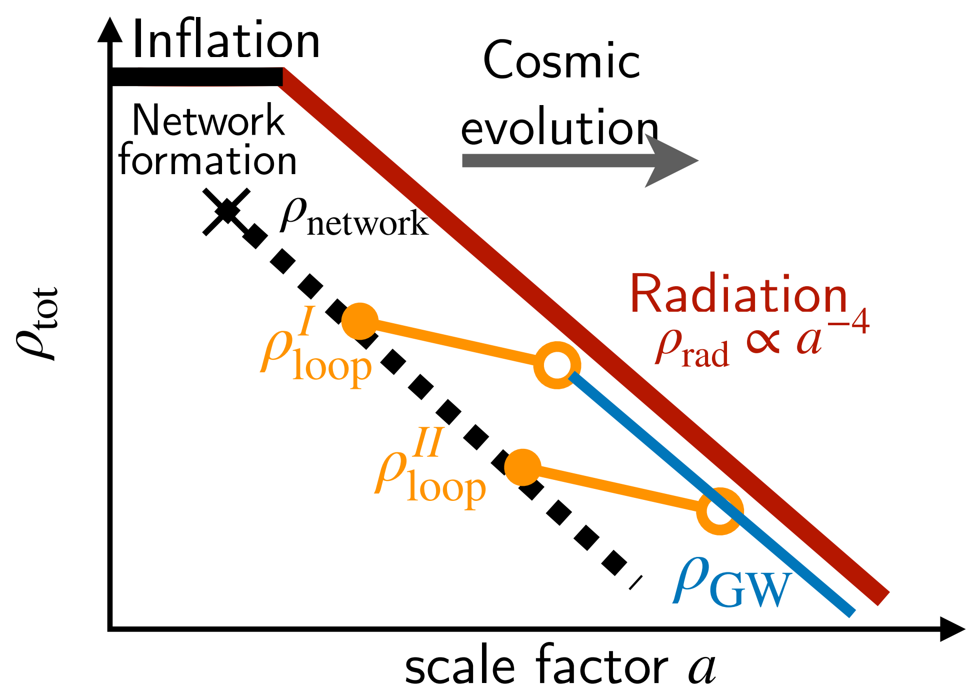
$$\#_{\rm loop}(t) = \mathtt{n}(l,t)dl = \int_{t_{\rm min}}^{t} \mathtt{f}[l_i(l), t_i] \left[\frac{a(t_i)}{a(t)}\right]^3 dt_i dl$$

Loop number density [per length] @ production

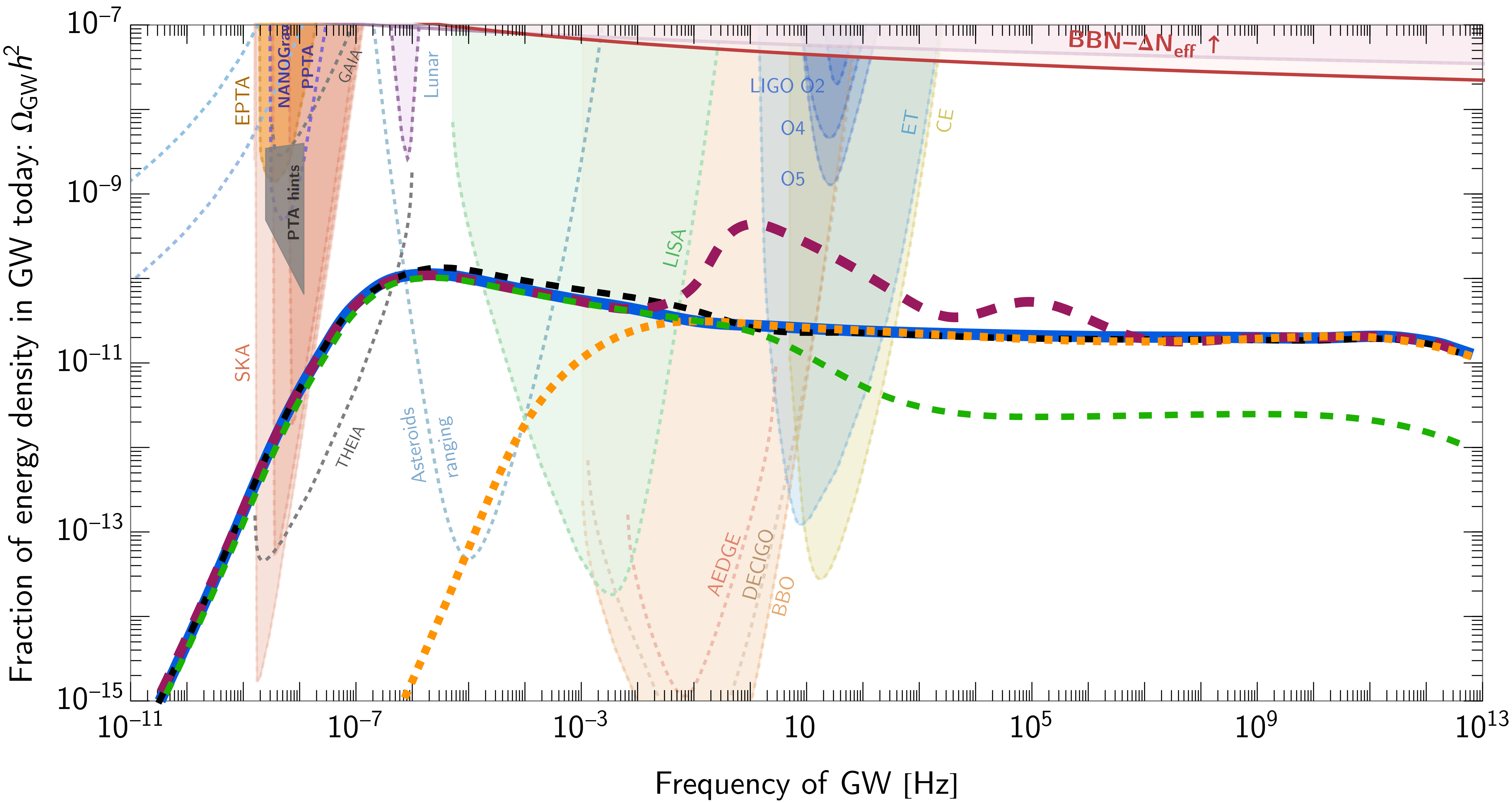
Redshift of loop number density $\sim a^{-3}$




Consider also the higher harmonics $j^{\rm th}$ of loop oscillation.



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



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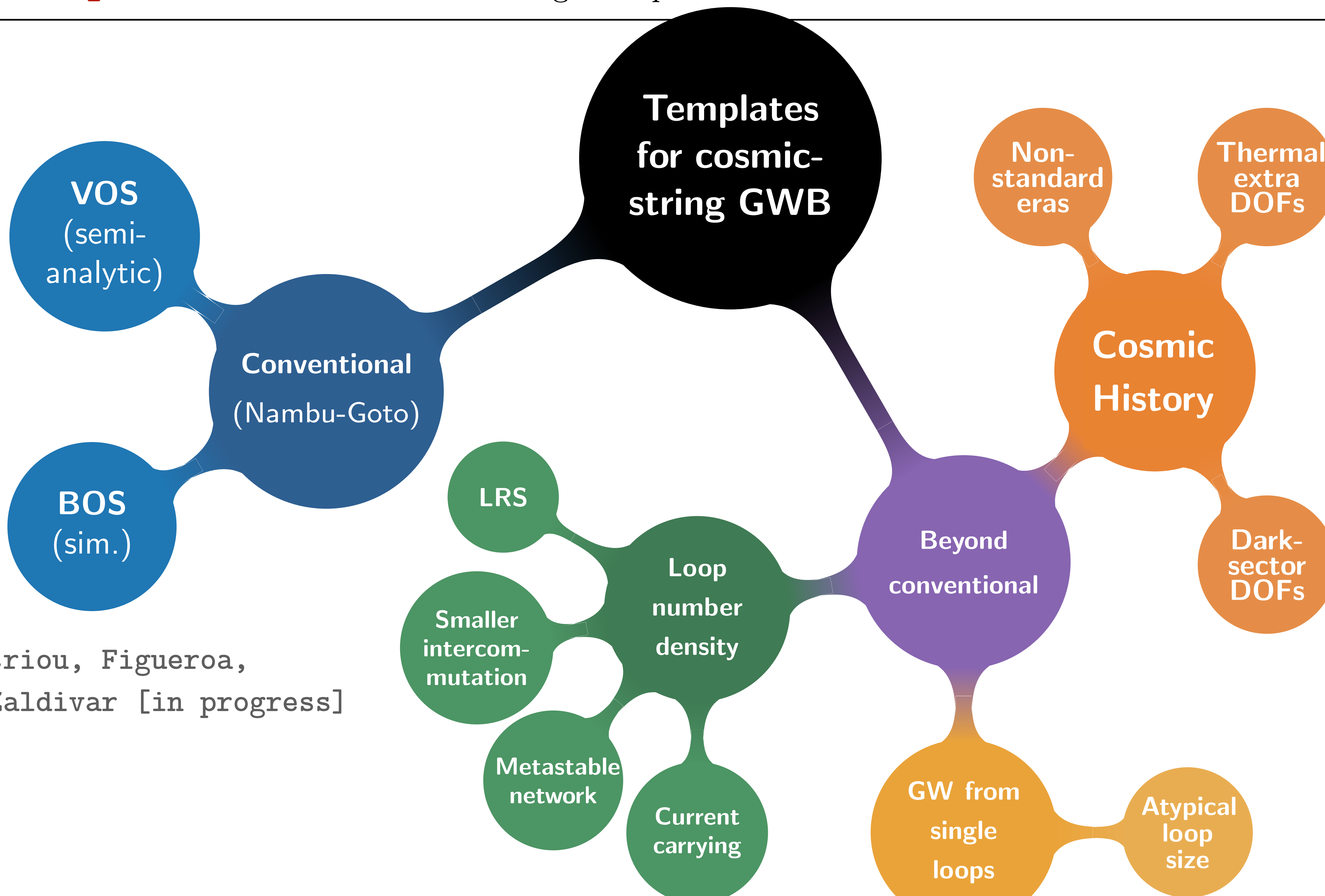
**3 dependencies:**




Dimitriou, Figueroa,
PS, Zaldivar [in progress]

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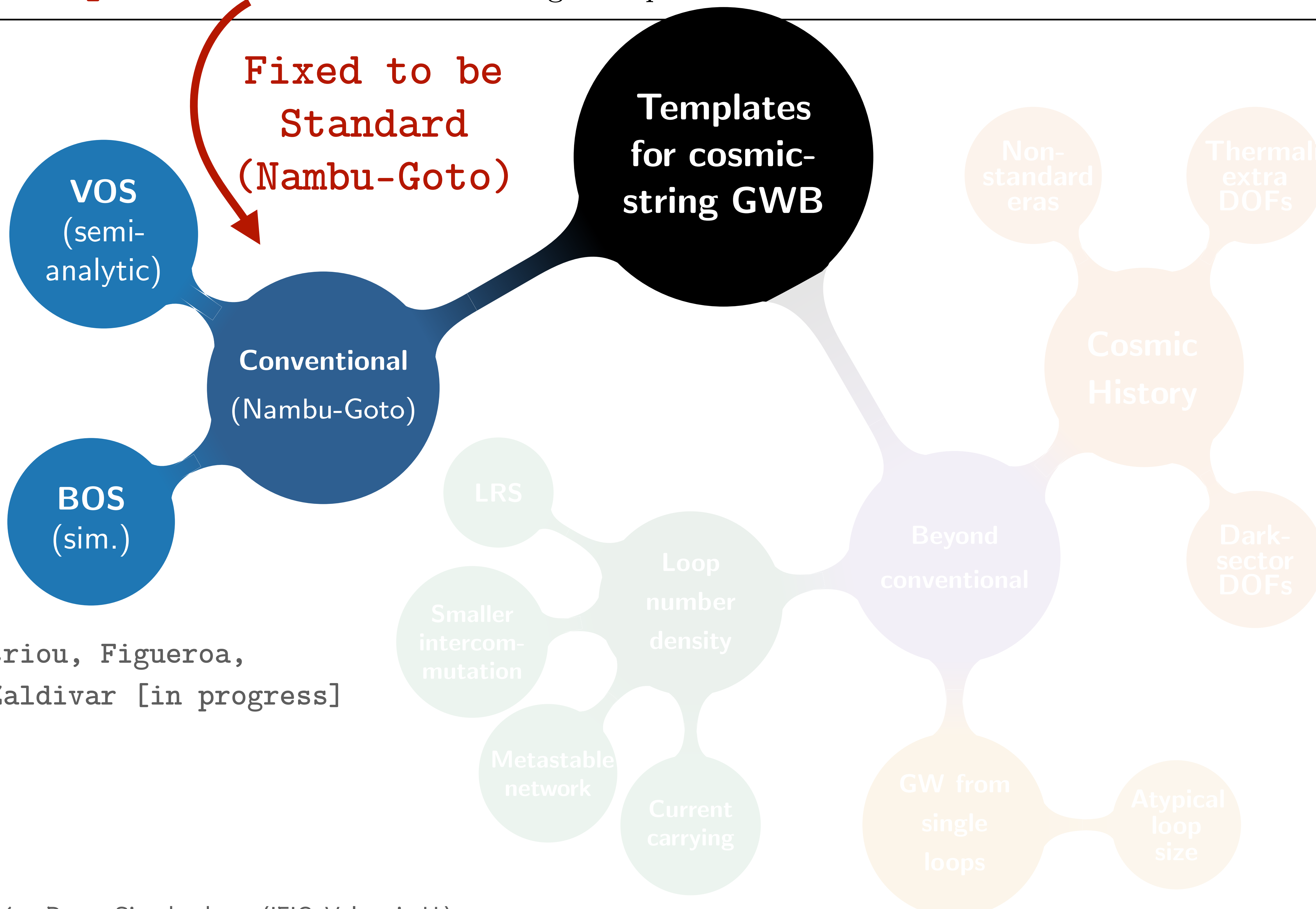
**3 dependencies:**




Dimitriou, Figueroa,
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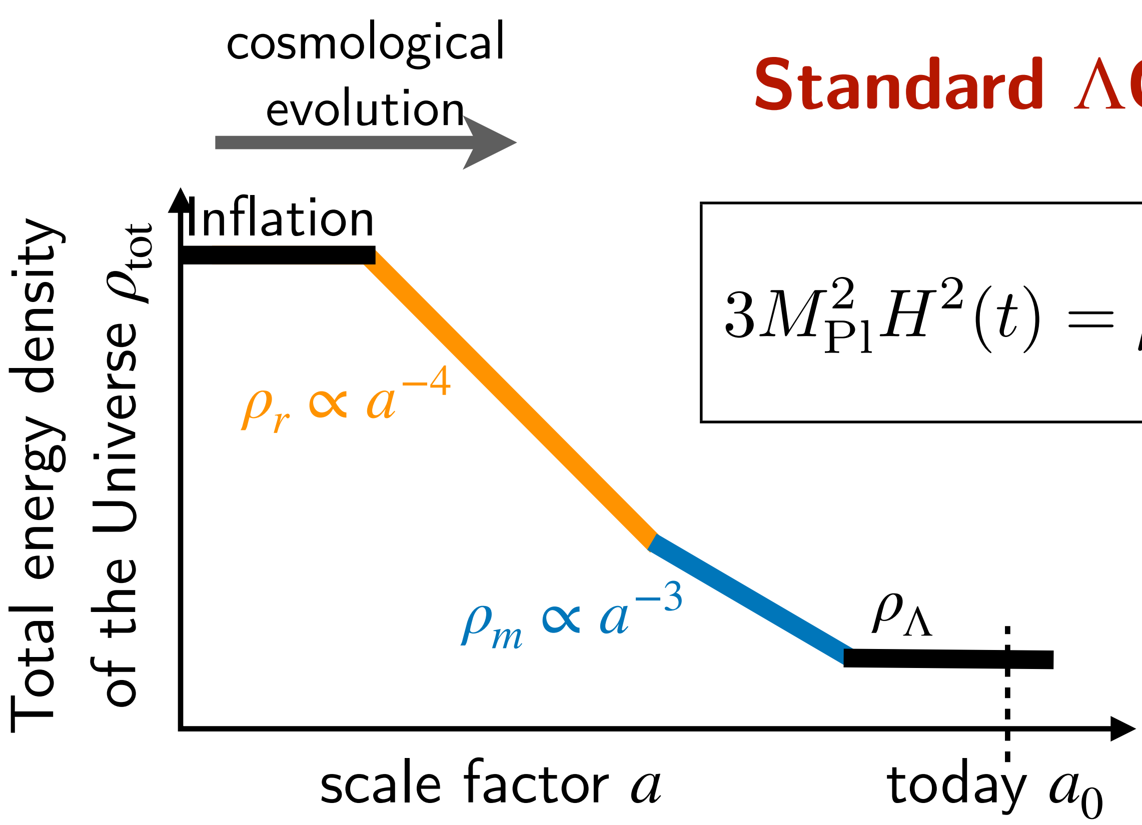
# Conventional Nambu-Goto Templates



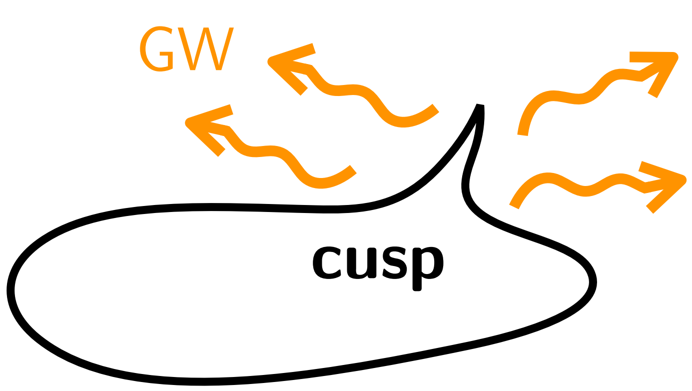

## Standard $\Lambda$CDM cosmic history

$$3M_{\rm Pl}^2 H^2(t) = \rho_{\rm tot}(t) = \rho_{r,0}\mathcal{G}[T(t)] \left[\frac{a_0}{a(t)}\right]^4 + \rho_{m,0}\left[\frac{a_0}{a(t)}\right]^3 + \rho_\Lambda$$

$$\mathcal{G}(T) \equiv \frac{g_*(T)}{g_*(T_0)}\left[\frac{g_{*s}(T_0)}{g_{*s}(T)}\right]^{4/3}$$

**Change of rela. DOFs in the Standard Model**

## GW emission from single Nambu-Goto string loops




Average GW emission: $P_{\rm GW} = \sum_j P_j G\mu^2 = \Gamma G\mu^2$

with $\Gamma = 50$ [Nambu-Goto sims.]

GW emission per harmonic $j^{\rm th}$ depends on shape: $P_j \propto j^{-q}$.

**A cusp is generic and can develop naturally on a loop. We take $\Rightarrow q = 4/3$.**

# Conventional Nambu-Goto Templates

**Loop number density of Nambu-Goto string network**

$$\boxed{\mathtt{n}(l,t) = \int_{t_{\min}}^{t} \mathtt{f}[l_i(l), t_i] \left[\frac{a(t_i)}{a(t)}\right]^3 dt_i}$$

## Numerical simulations by Blanco-Pillado, Olum, Shlaer (BOS) [1309.6637]

The loop number density is extracted directly from Nambu-Goto string sims.

Also used for calibrating semi-analytic models, e.g., 10% of loops contribute to GWB, the initial loop size $l_i/t_i = \alpha \simeq 0.1$.

Assume either $a \propto t^{1/2}$ for radiation era, $a \propto t^{2/3}$ for matter era.

**Capturing (Nambu-Goto) details of long strings and loops.**

## Semi-analytic Velocity-dependent One-Scale (VOS) model

[Kibble, Martins & Shellard, many others]

The loop number density is extracted from the energy conservation of the string network, described by
i) the correlation length (strings' separation)
ii) the mean velocity

Details of loop production is matched with simulations, e.g., production efficiency, fraction of large loops

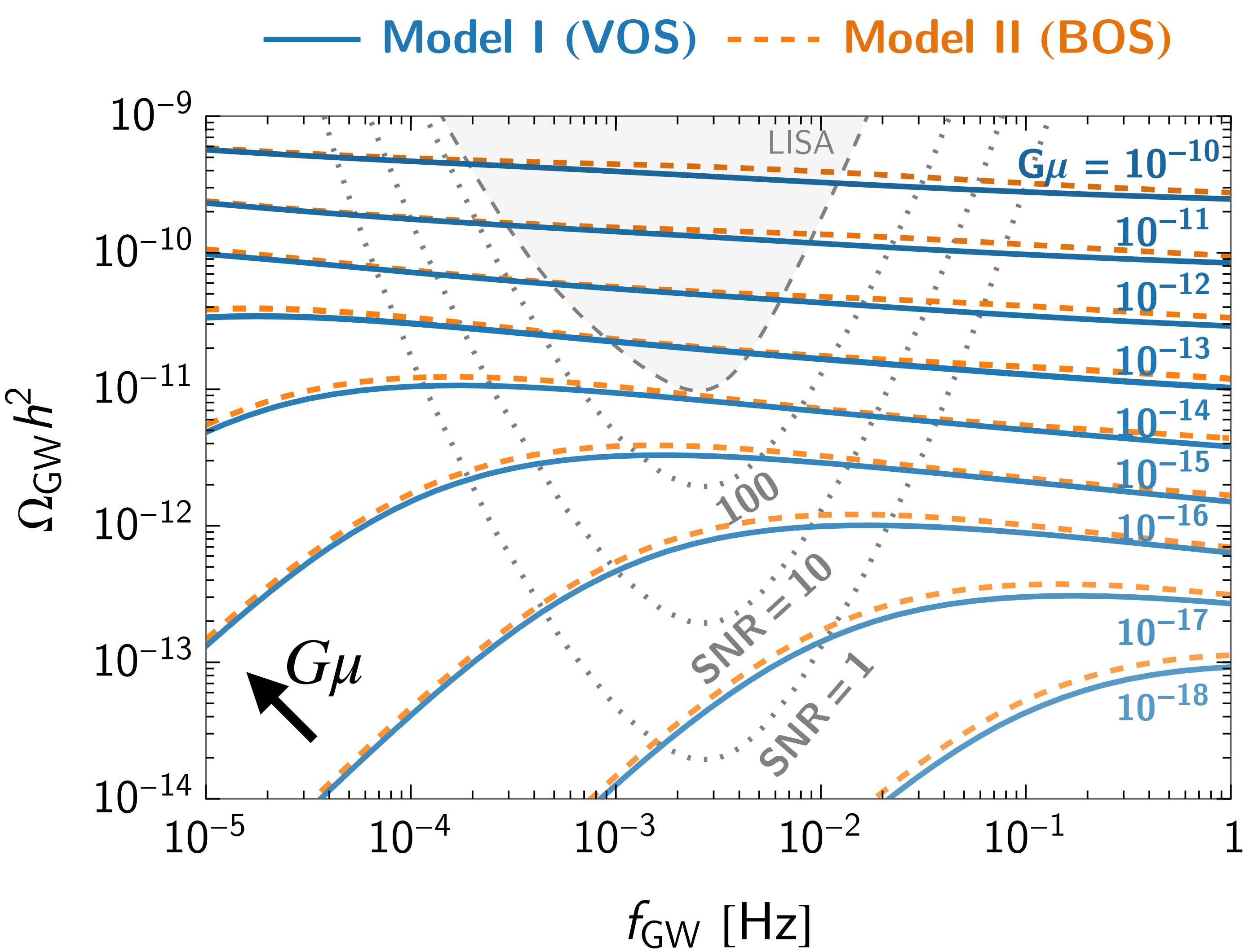
**Adaptable to any cosmic history and can be solved from the initial condition to the scaling regime.**

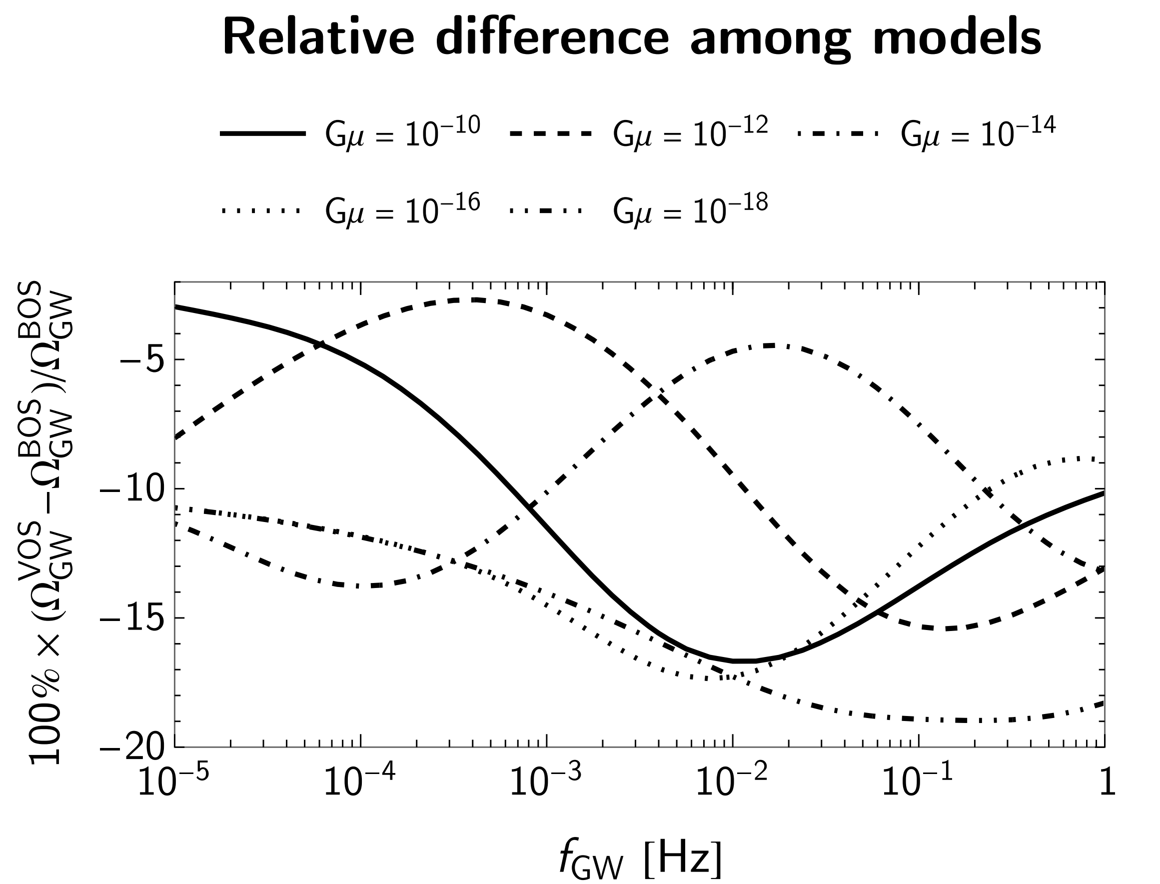
# Conventional Nambu-Goto Templates

**GWB depends on $G\mu$, i.e., the energy scale of the symmetry breaking.**

Current GW constraints: **LIGO** $G\mu \lesssim 10^{-7}$, **PTA** $G\mu \lesssim 10^{-10}$ [NANOGrav, EPTA, etc.]

With **LISA**, $G\mu \gtrsim 10^{-17} \Rightarrow$ symm.breaking @ energy scale $\eta \gtrsim 10^{10}$ GeV

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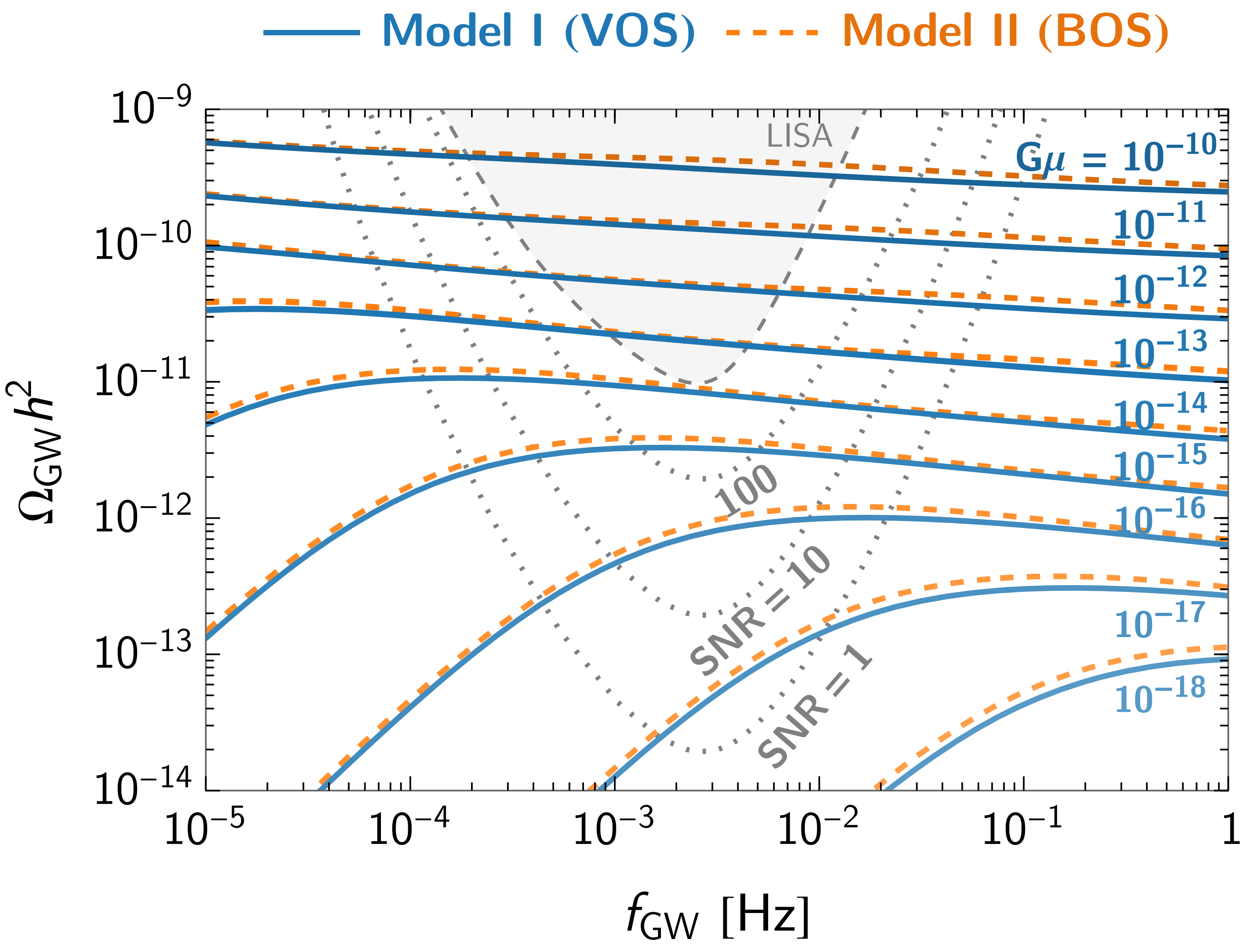
**To distinguish model, milestone for reconstruction:** $\left|\text{error in } \Omega_{\rm GW}\right| \lesssim \mathcal{O}(10\%)$

# Signatures of Standard Model particles



# Signatures of Standard Model particles

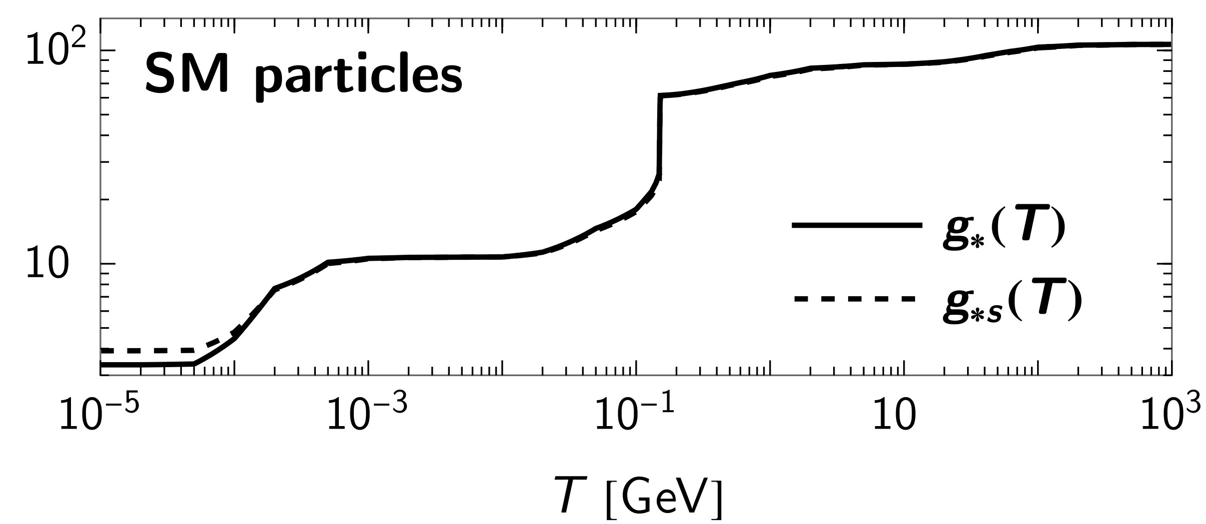
$$3M_{\rm Pl}^2 H^2(t) = \rho_{\rm tot}(t) = \rho_{r,0}\mathcal{G}[T(t)]\left[\frac{a_0}{a(t)}\right]^4 + \rho_{m,0}\left[\frac{a_0}{a(t)}\right]^3 + \rho_\Lambda$$

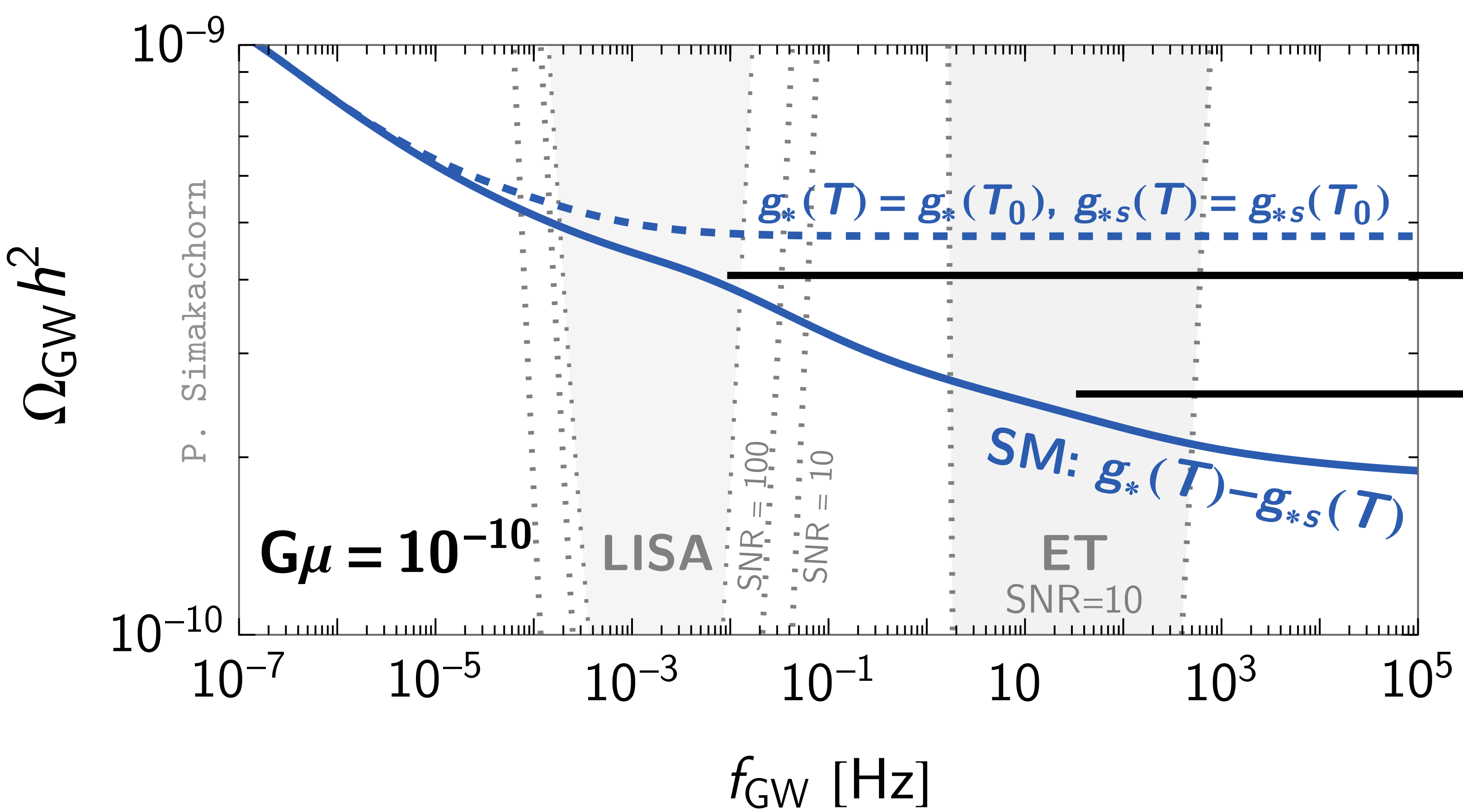
$$\mathcal{G}(T) \equiv \frac{g_*(T)}{g_*(T_0)}\left[\frac{g_{*s}(T_0)}{g_{*s}(T)}\right]^{4/3}$$

From the simple estimate:

$$\Omega_{\rm GW}^{\rm cs} \propto \rho_{\rm tot}(a/a_0)^4 \propto \mathcal{G}(T) \propto [g_*(T)]^{-1/3}$$

during the radiation era at high-$T$ ($g_* \simeq g_{*s}$)



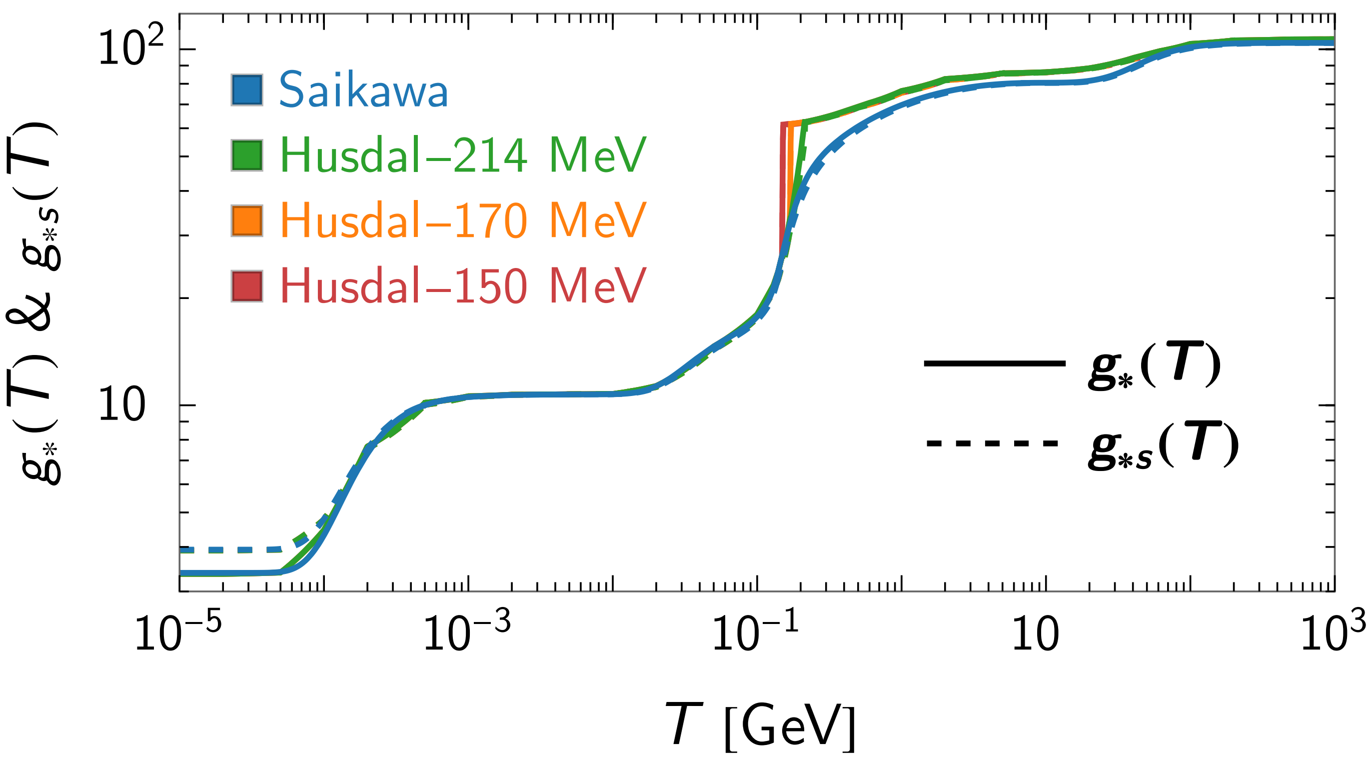

$$f_{\rm GW} \simeq (6\ {\rm mHz})\left[\frac{T_i}{0.1\ {\rm GeV}}\right]\left[\frac{10^{-10}}{G\mu}\right]^{1/2}$$

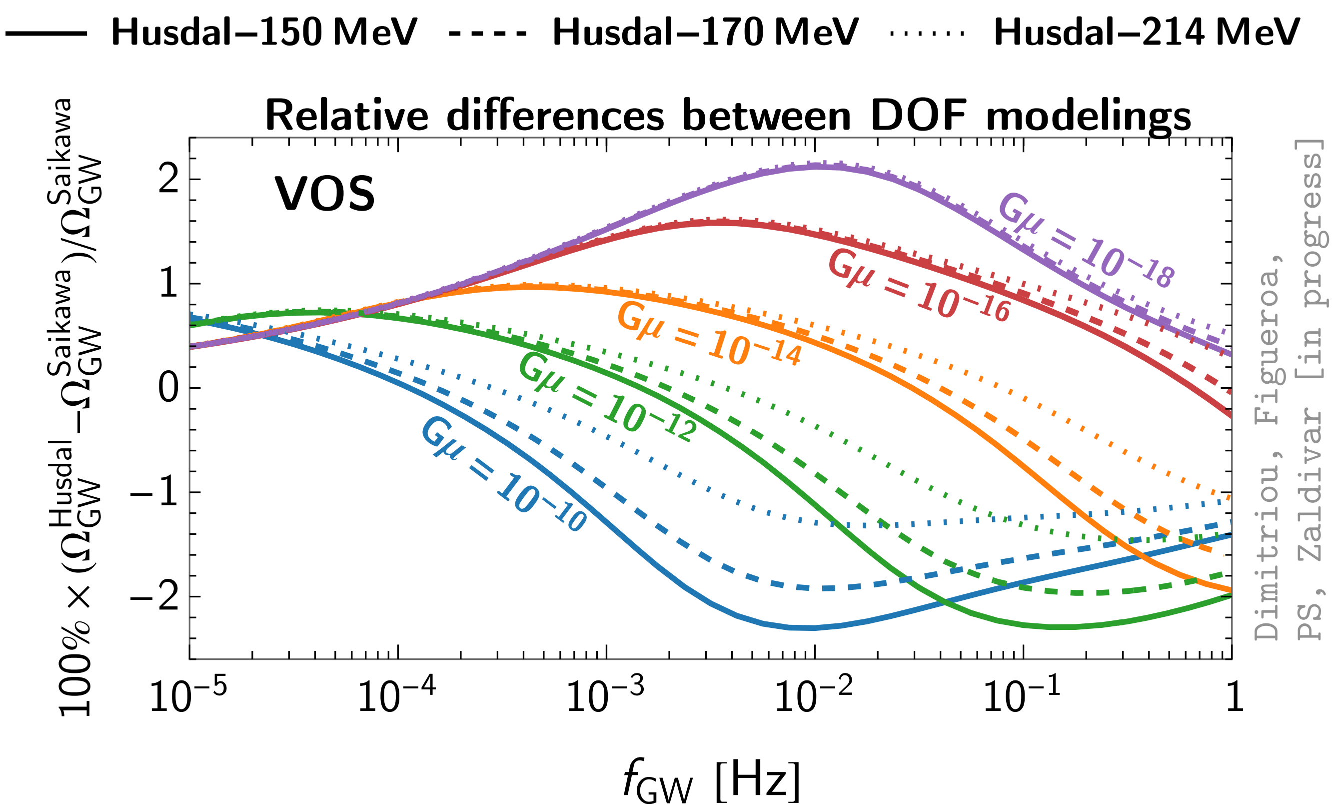
# Uncertainty due to Standard Model particles

**A change of rela. DOFs in the Standard Model has uncertainties.**

$\lesssim 3\,\%$ Reconstruction's precision and accuracy in $\Omega_{\rm GW}$
**LISA $\Rightarrow$ cosmic-string GWB is a unique probe of QCD phase transition.**

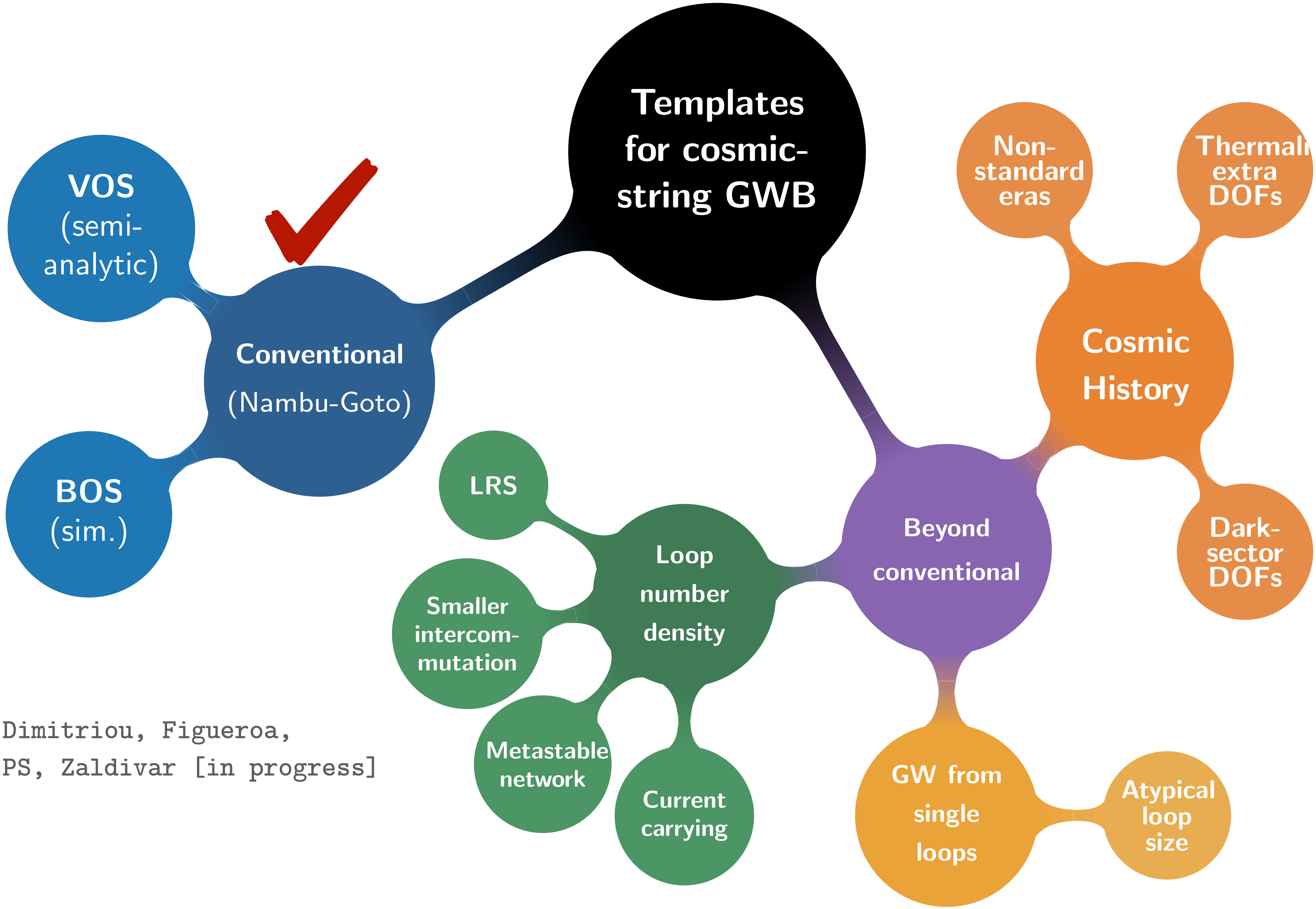
(Similarly, ET probes the EW scales.)




Saikawa-Shirai [1803.01038]
Husdal [1609.04979]

*Similarly for BOS model

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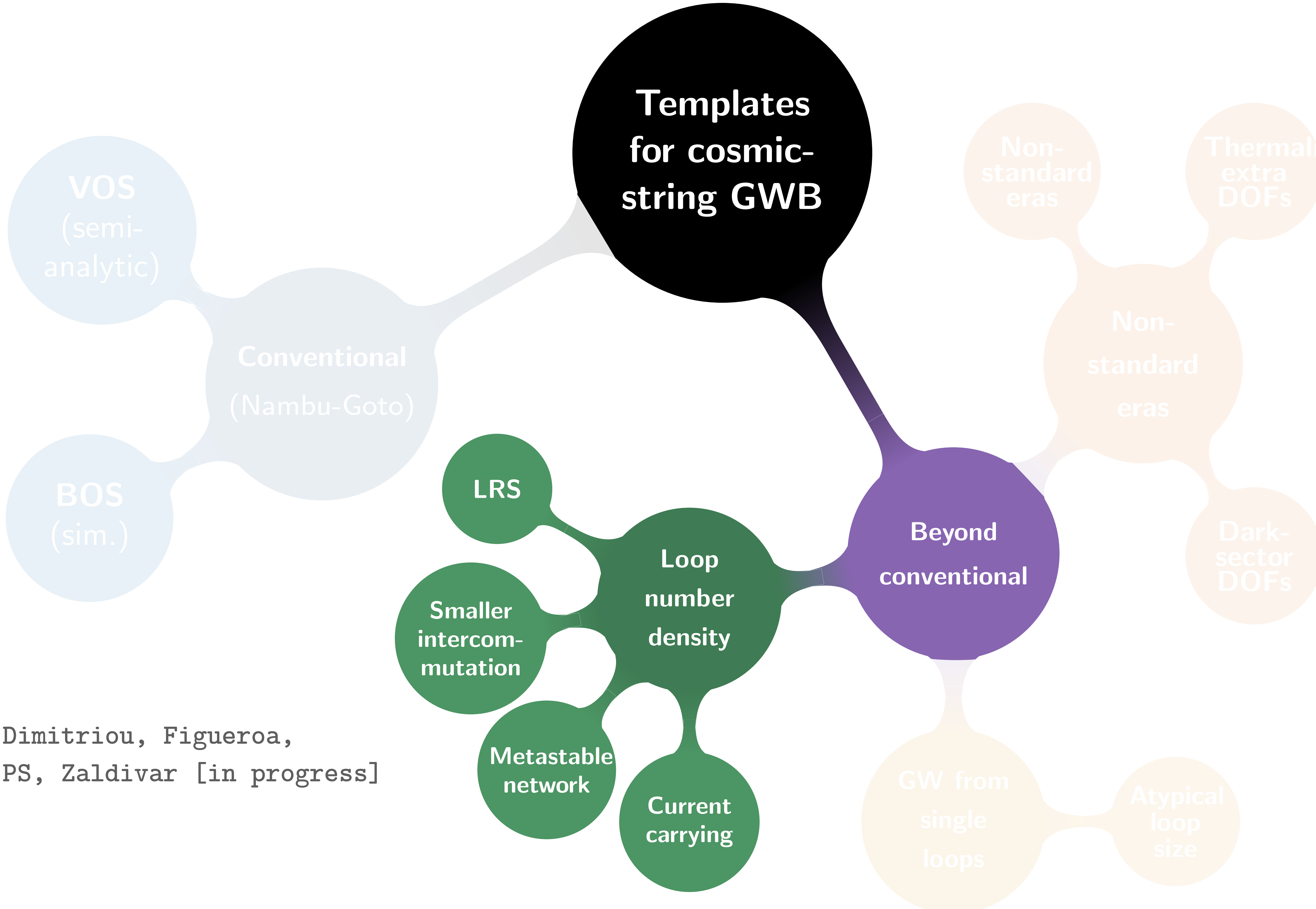



Dimitriou, Figueroa,
PS, Zaldivar [in progress]

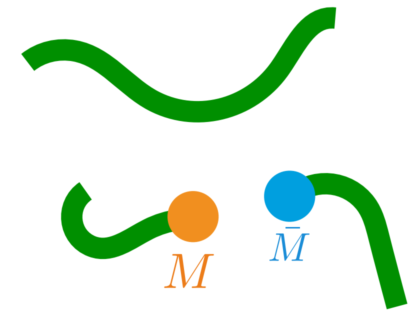
# Beyond Conventional Part I: " Loop number density "

**Metastable strings** Theories with multistep phase transition ⇒ hybrid defects network.

E.g., Pair production of monopoles on strings
at rate per unit length

$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa}$$

Vilenkin '82, Preskill&Vilenkin '93 Monin+ '08
Buchmüller, Domcke, Schmitz '19 '21 '23
Chitose+ 2312.15662




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

When $\Gamma_d l(t_{\rm brk}) = H_{\rm brk}$, strings get cut efficiently

$$\mathrm{n}_{\rm brk} = \mathrm{n}_{\rm stable}\Theta(t_{\rm brk} - t_{\rm prod})e^{-\Gamma_d[l(t-t_{\rm brk})\cdots]}$$

Shut off loops production

Depleting loop number density




**No more loops at late times.**
**⇒ an infrared cutoff in the GWB spectrum.**

**GWB depends on $G\mu$ and the monopole-to-string scale $\kappa = (m_M/\eta)^2$.**

# Beyond Conventional Part I: “ Loop number density ”

## Less-frequent intercommutation

e.g., in string theories, in pure Yang-Mills theory

Avgoustidis & Shellard ‘04, Yamada & Yonekura ’22

A smaller intercom. prob. $p < 1$
leads to a much denser network,
although loop production events is less frequent.

$$\boxed{\mathrm{n}_{(p<1)} = p^{-1} n_{(p=1)}}$$

## Field-theory strings

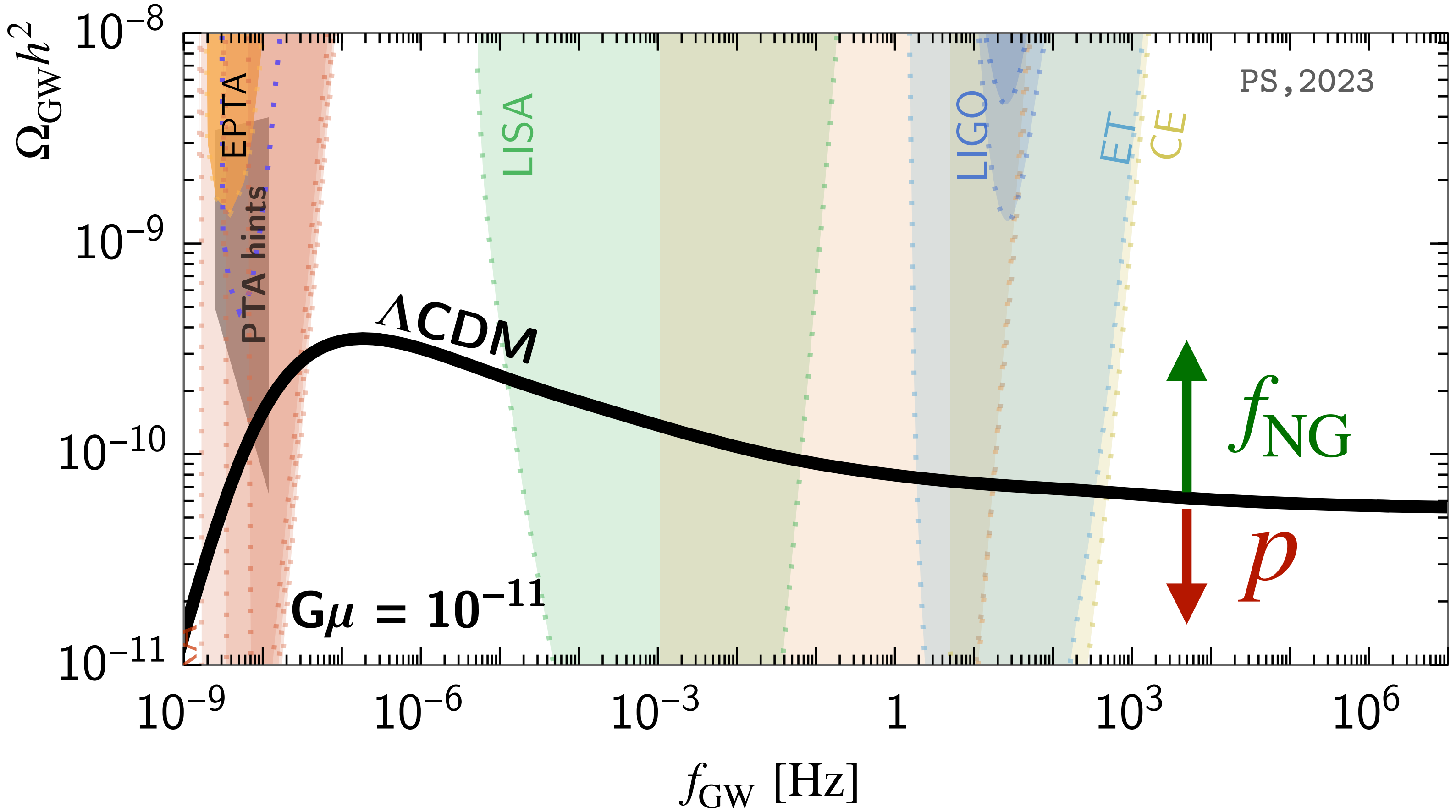
e.g., Hindmarsh, Lizarraga, Urio, Urrestilla [2103.16248]

Loops behaving as Nambu-Goto stings and emitting GW is

$$\boxed{\mathrm{n}_{(f_{\rm NG}<1)} = f_{\rm NG}\, n_{(f_{\rm NG}=1)}}$$

while other loops decay mainly into particles.

$f_{\rm NG} \lesssim 0.1$ [2103.16248]



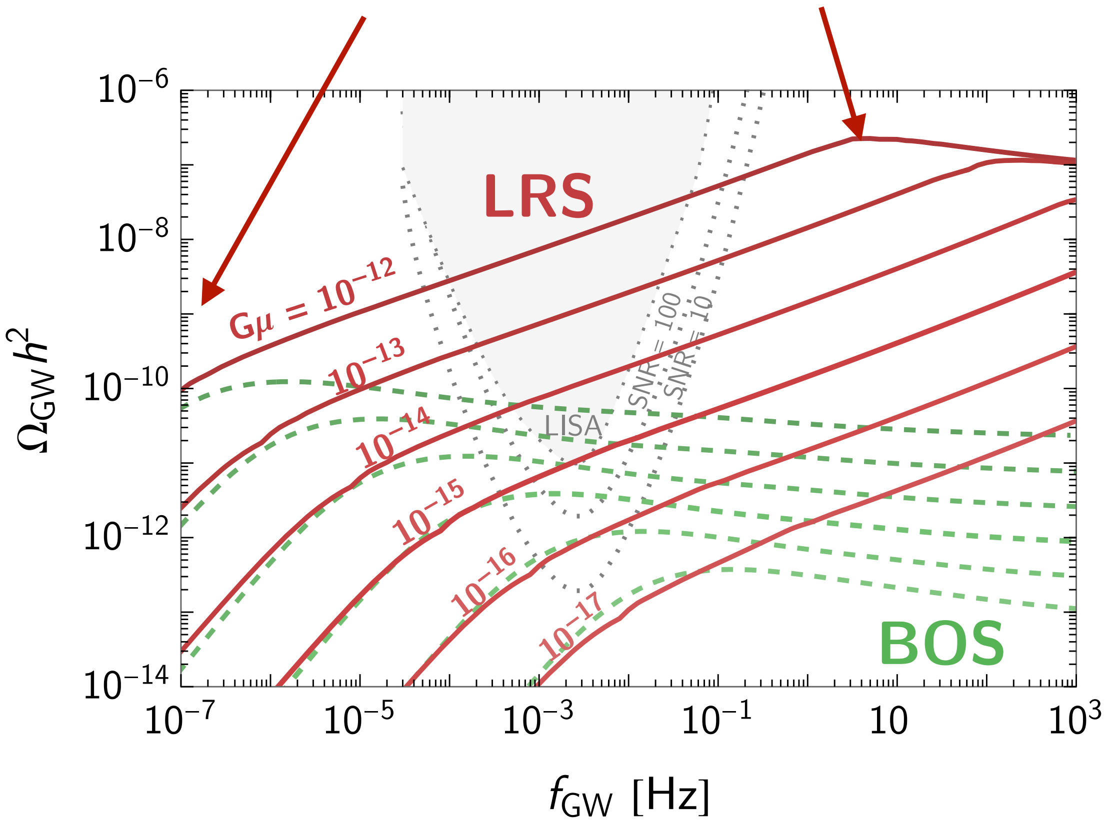

GWB depends on $G\mu$, $p$ (or $f_{\rm NG}$).

# Beyond Conventional Part I: “ Loop number density ”

## Smaller loop population
## Lorenz-Ringeval-Sakallariadou (LRS)

Lorenz, Ringeval and Sakellariadou ‘10

Loop population =
Large loops + small loops




Conventional templates (BOS & VOS) only have large loops.

`GWB depends on` $G\mu$.

## Current carrying strings

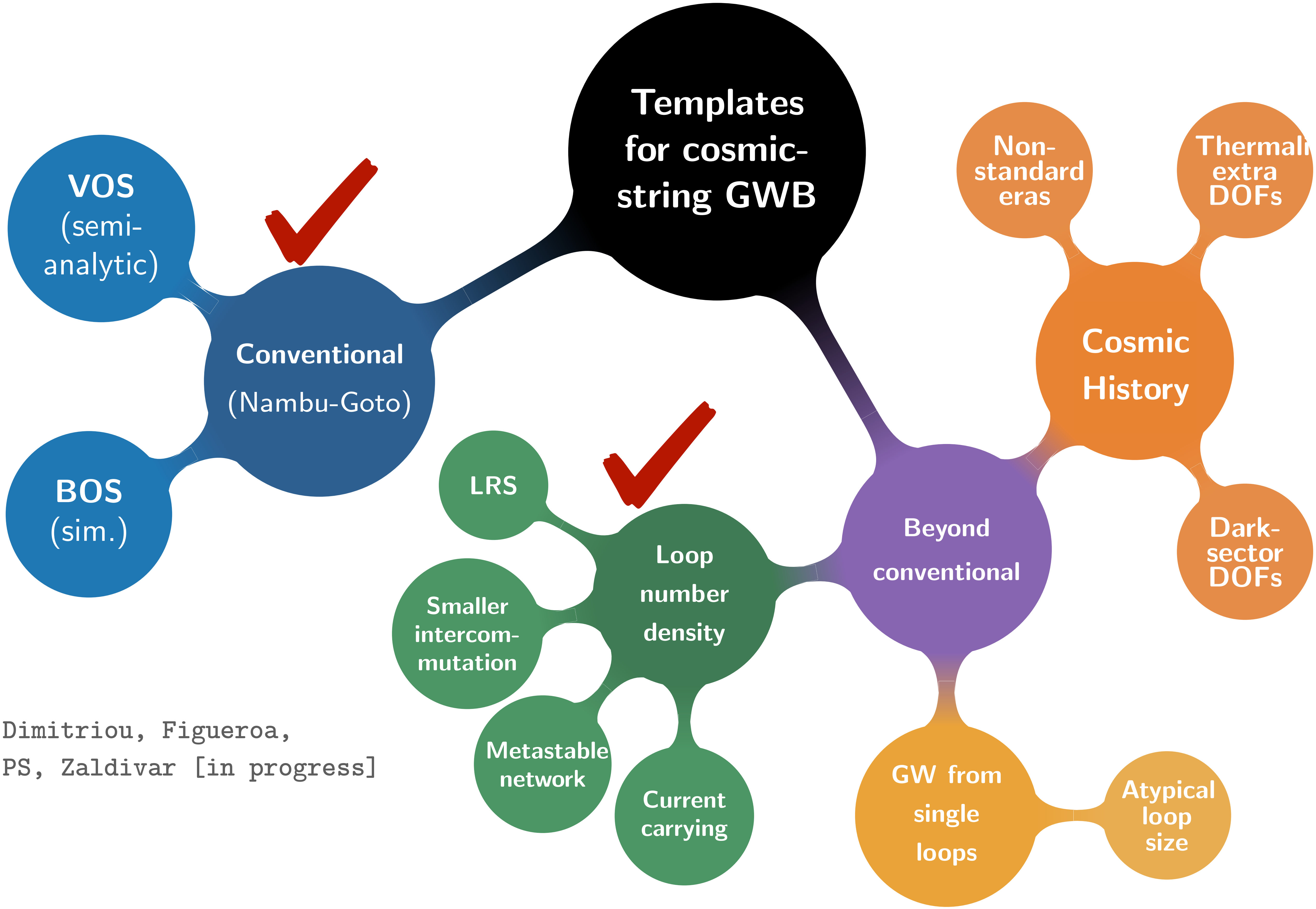
The current inside strings lead the network to a new scaling regime, where it is denser. More loops.

Assume a current from $T_{\rm on}$ to $T_{\rm off}$

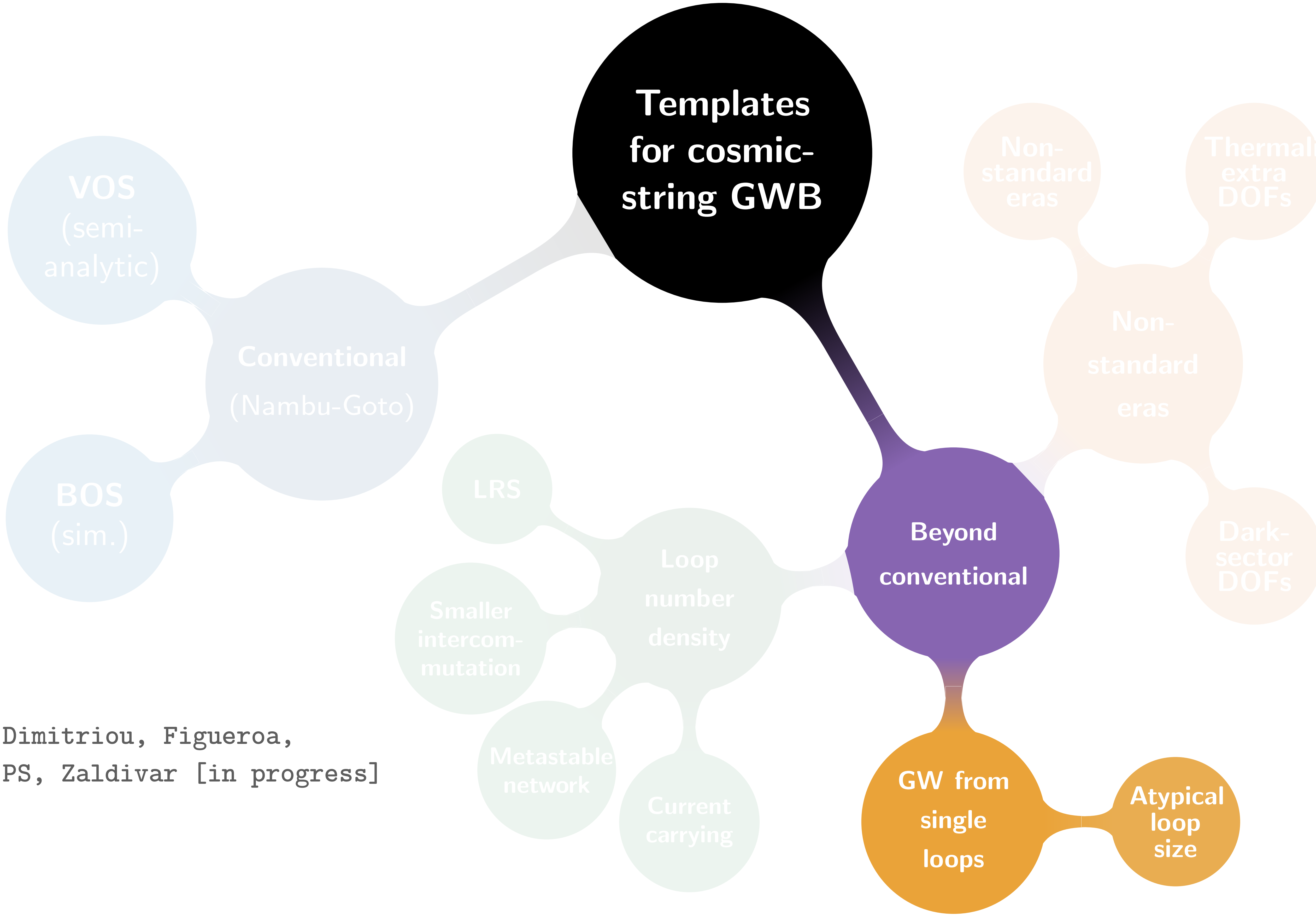
Auclair, Blasi, Brdar, Schmitz ‘22




`GWB depends on` $G\mu$,
`the current quenching time` $T_{\rm off}$,
`the duration with current` $r_Y = T_{\rm on}/T_{\rm off}$



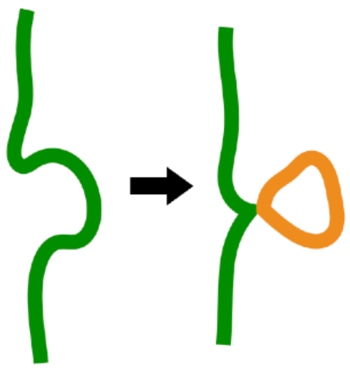

Dimitriou, Figueroa,
PS, Zaldivar [in progress]




Dimitriou, Figueroa,
PS, Zaldivar [in progress]

# Beyond Conventional Part II: “ GW emission from single loops ”

GWB depends on $G\mu, \alpha, q$.



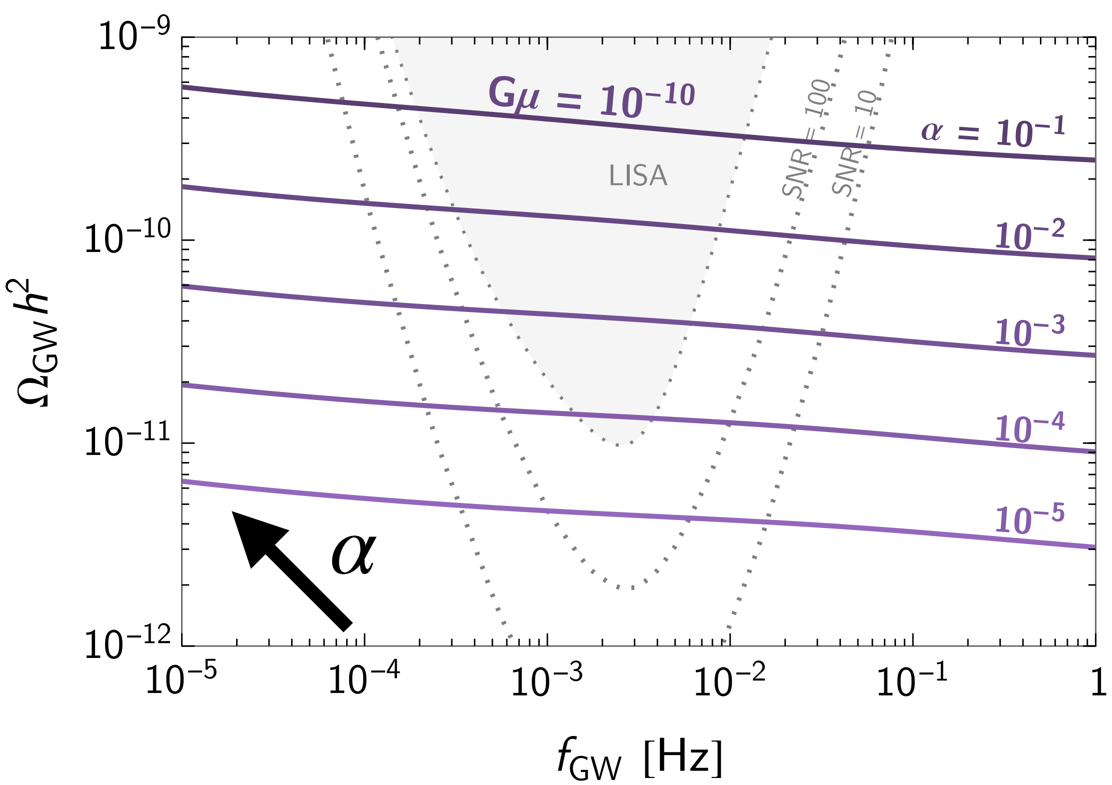
**Initial loop size**

$$l_i = \alpha t_i$$

Nambu-Goto simulations $\Rightarrow \alpha = 0.1$
other models can have $\alpha \neq 0.1$.

With smaller $\alpha$, loops decay faster $\tau \propto \alpha$, and GW signals get produced earlier and redshifted more.

$$\Omega_{\rm GW} \propto \sqrt{\alpha},\ f_{\rm GW} \propto \sqrt{\alpha}$$

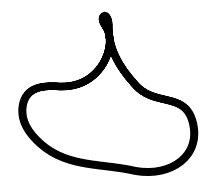



**Other loop shapes**

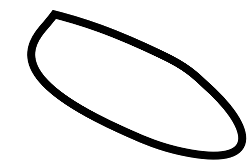
GW emission of oscillation mode $j^{\rm th}$ depends on shape: $\propto j^{-q}$.

GW emission per mode is $\Gamma G\mu^2 j^{-q}/\zeta(q)$.

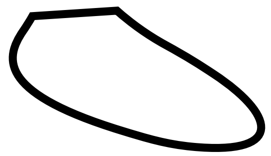
**Cusp**
$q = 4/3$

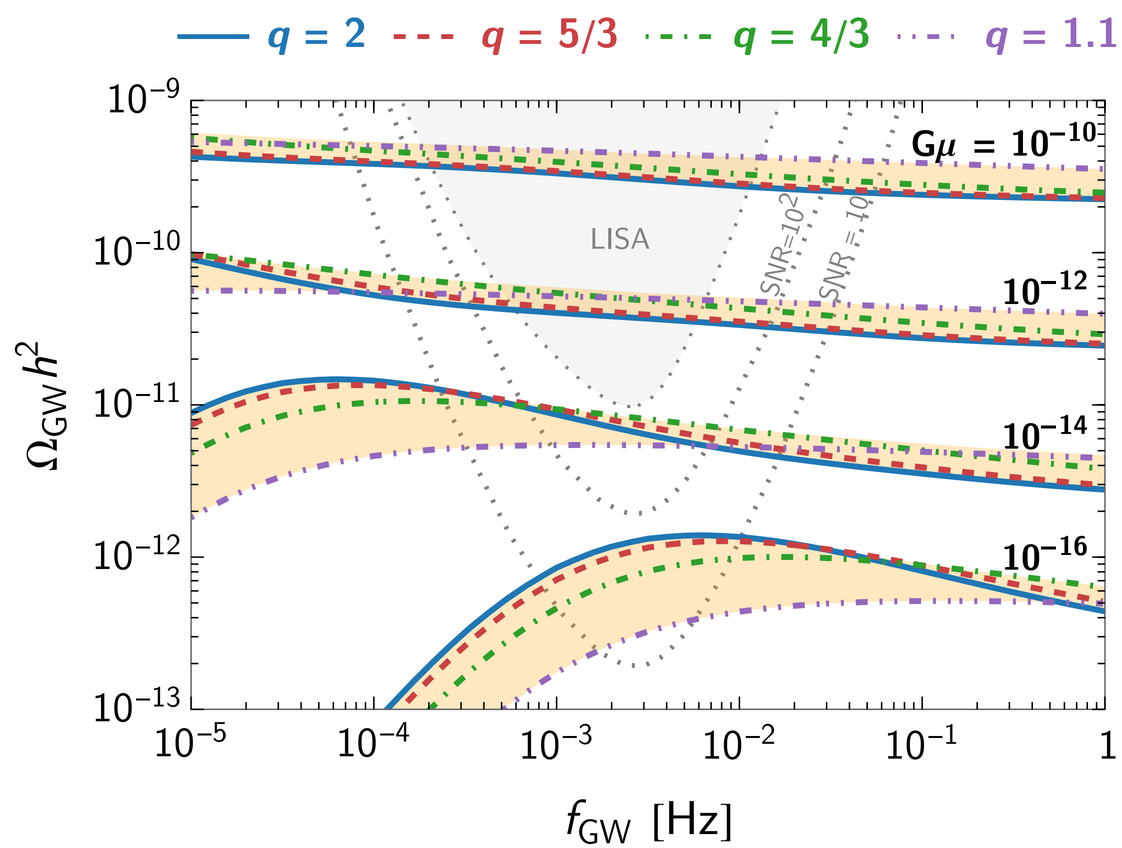


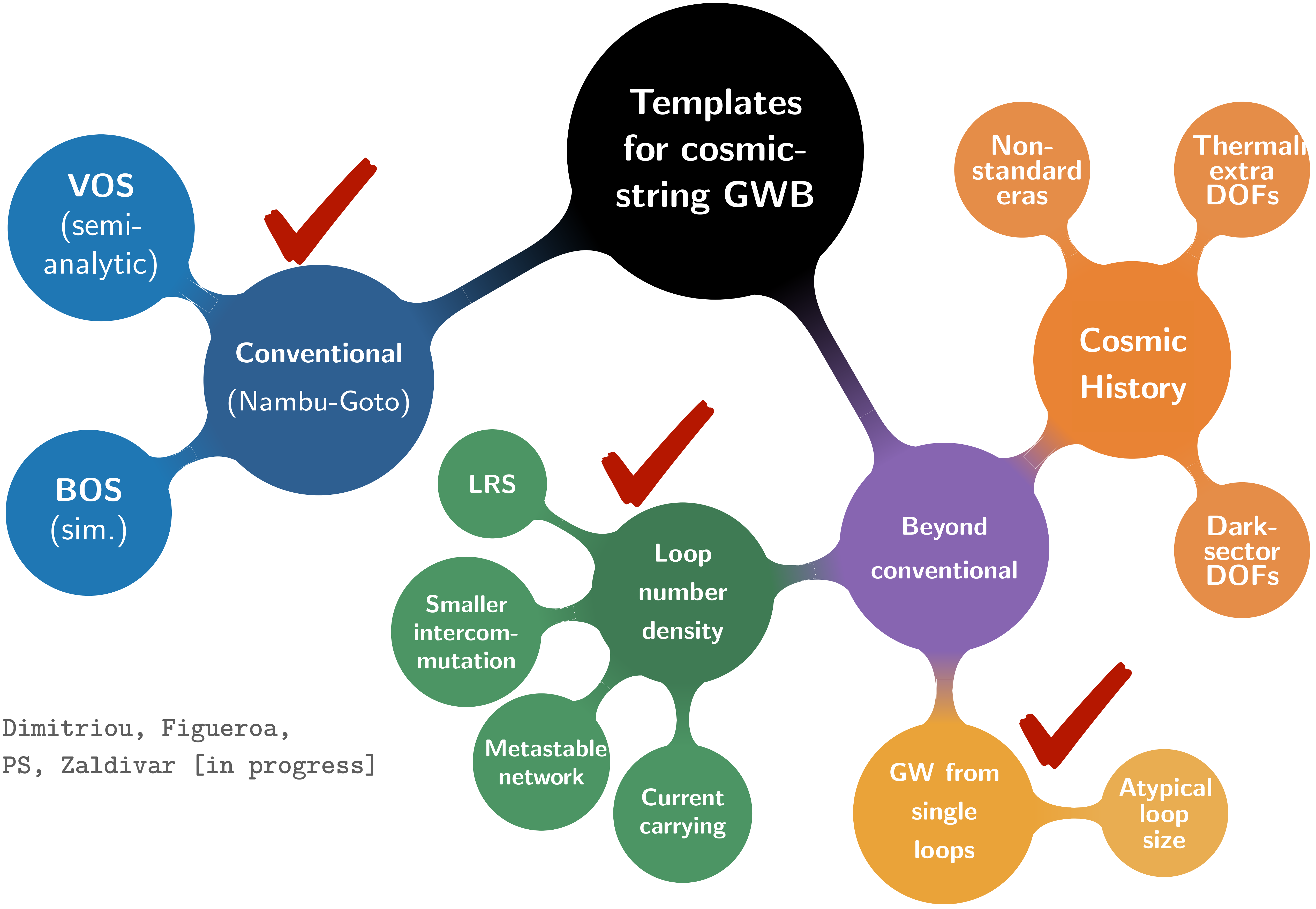
**Kink**
$q = 5/3$



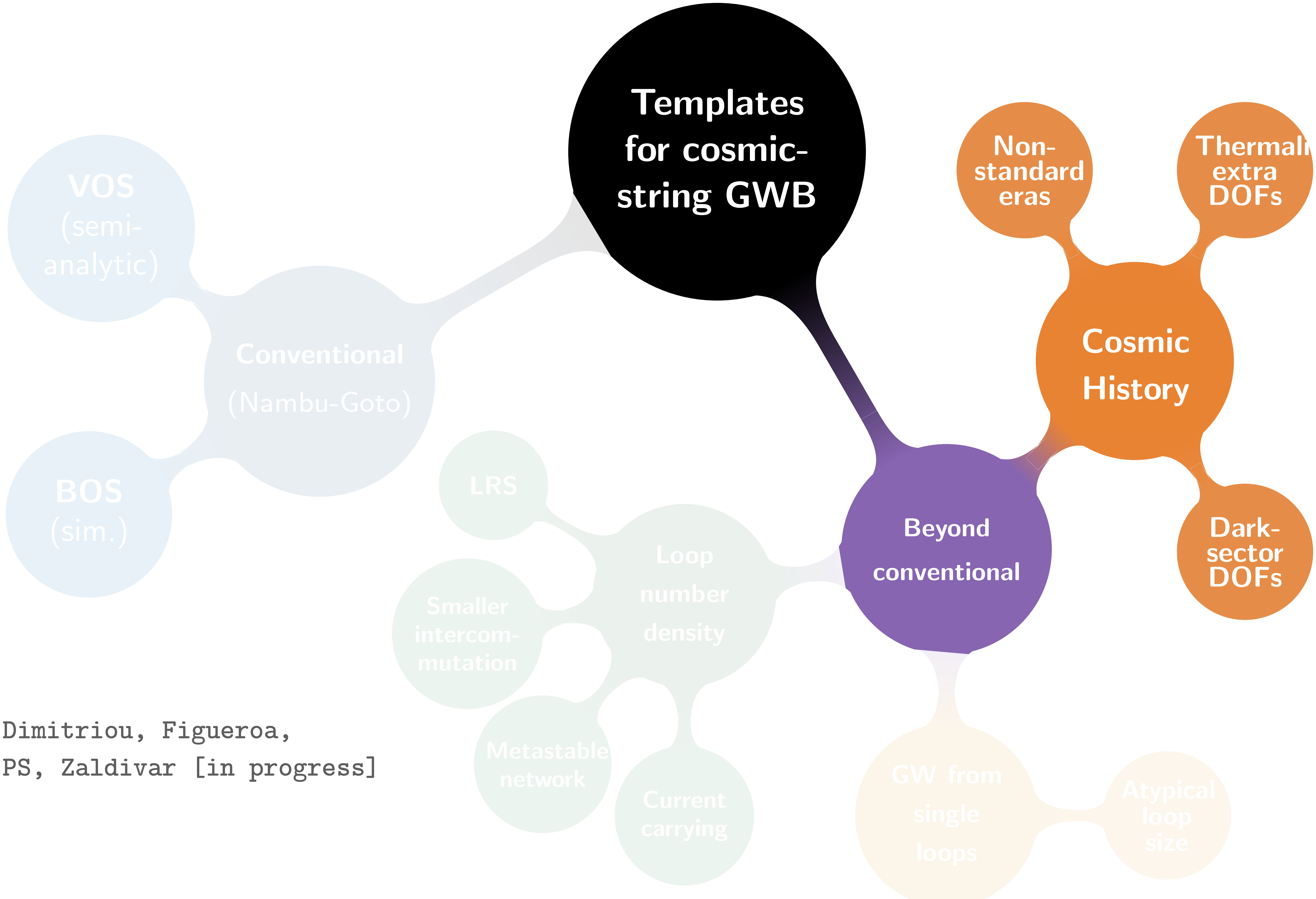
**Kink-kink**
$q = 2$





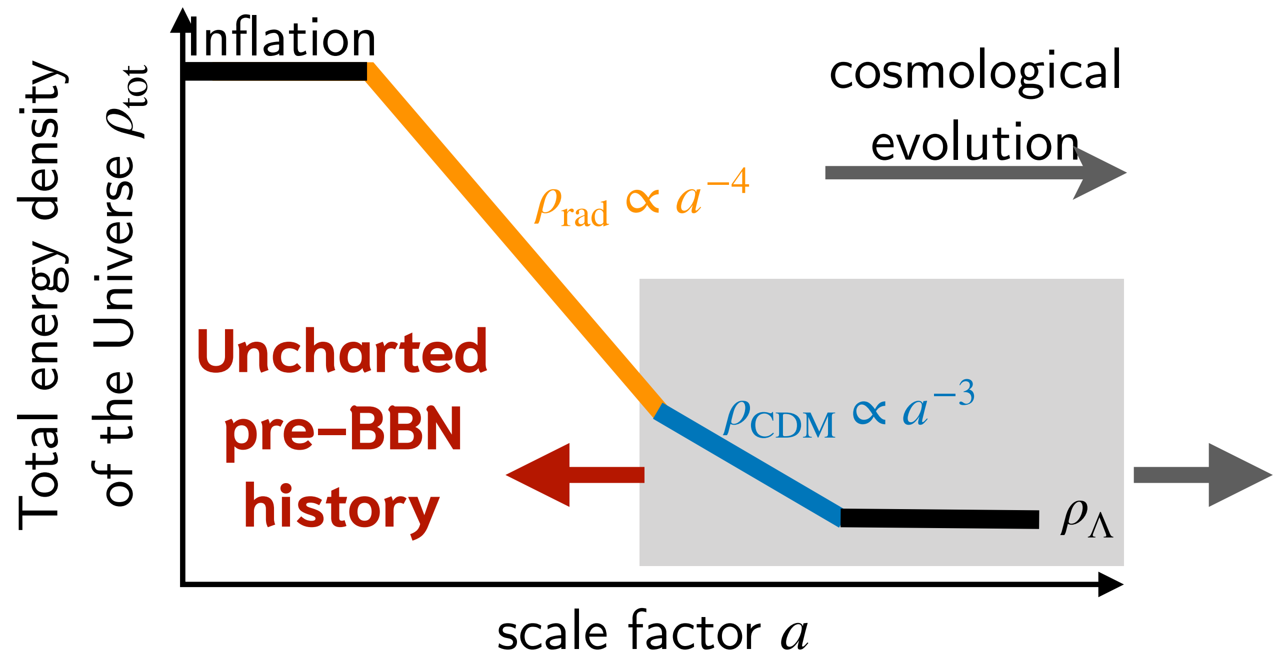



Dimitriou, Figueroa,
PS, Zaldivar [in progress]




Dimitriou, Figueroa,
PS, Zaldivar [in progress]

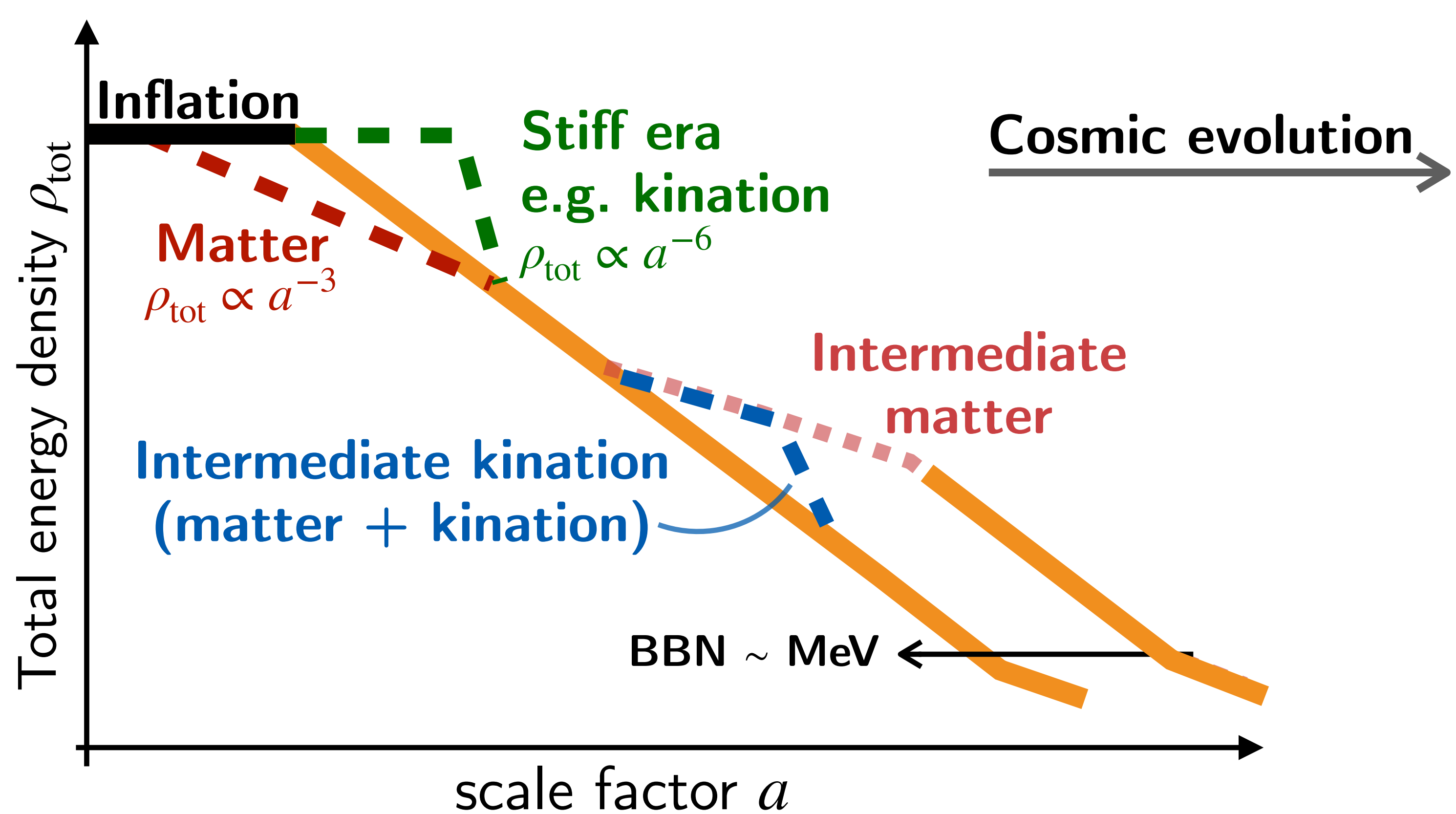
The Standard $\Lambda$CDM universe




Post-BBN history is well constrained. ($T \lesssim$ MeV, $t \gtrsim 1$ s)

**Cosmic histories beyond the standard ($\Lambda$CDM) picture.**

$$\rho_{\rm tot}(t) = \rho_{r,0}\mathcal{G}[T(t)]\left[\frac{a_0}{a(t)}\right]^4 + \rho_{m,0}\left[\frac{a_0}{a(t)}\right]^3 + \rho_\Lambda + \rho_{\rm BSM}(t)$$



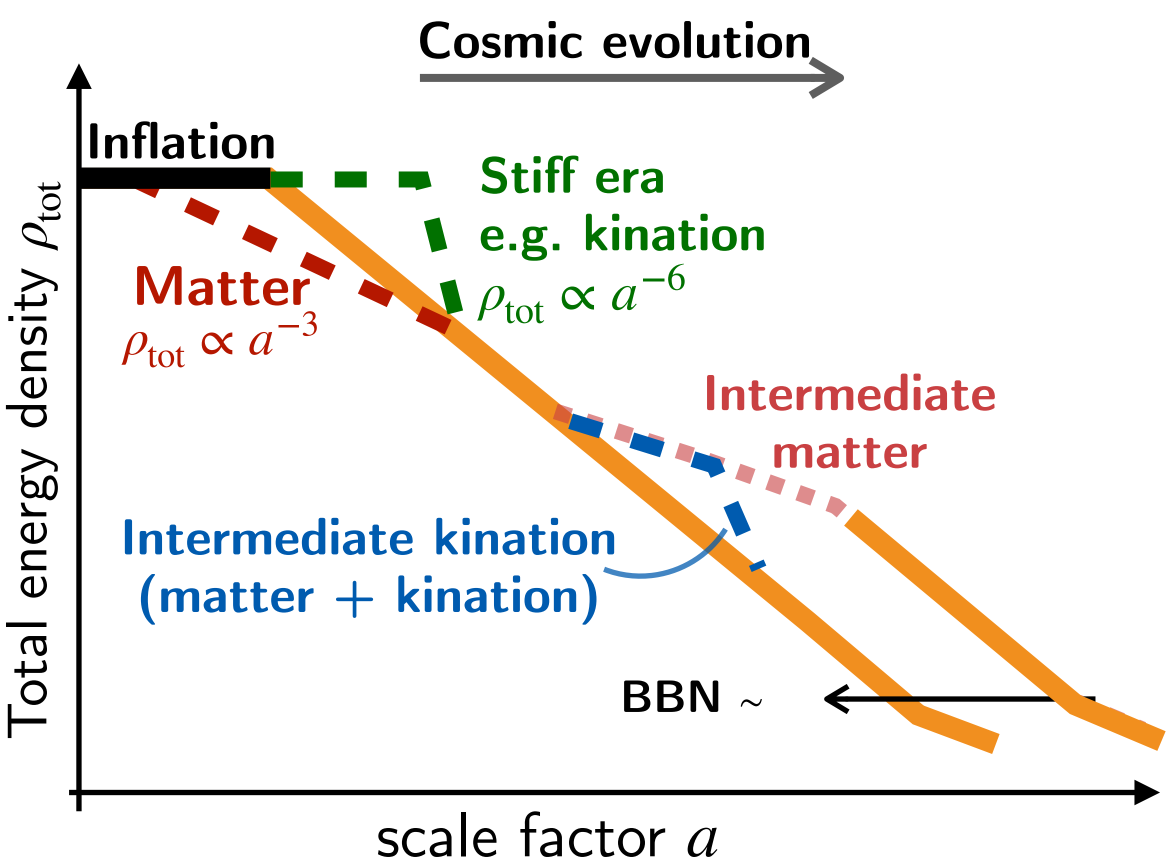
# Charting cosmic history with cosmic-string GWB

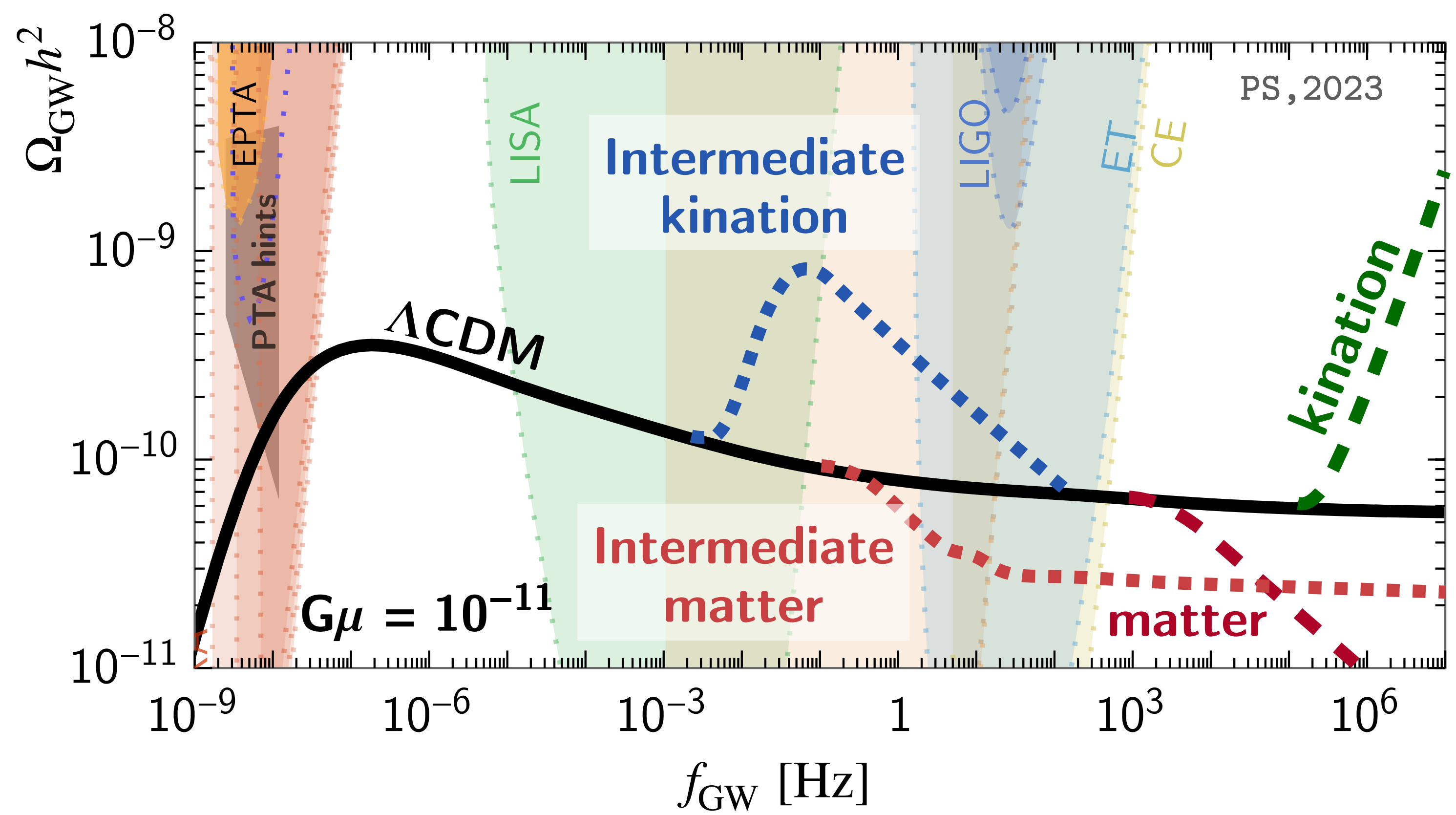
From the simple estimate: $\boxed{\Omega^{\rm cs}_{\rm GW} \propto \rho_{\rm tot}(a/a_0)^4}$

Cosmic history beyond the SM radiation ($\rho_{\rm tot}$ does not scale as $a^{-4}$),
GWB differs from standard prediction ⇒ smoking-gun signatures.

**GWB depends on $G\mu$,**

**the energy scale and duration of the nonstandard era.**




This behavior is present in GWB from long-lasting sources,
e.g., cosmic strings and inflation.

# Cosmic Archeology with cosmic-string GWB!


## I. Matter/Stiff

e.g., reheating after inflation

⇒ **Suppressed/Enhanced**

Cui, Lewicki, Wells, [1711.03104, 1808.08968]
Servant, Gouttenoire, PS [1912.02569]

## II. Intermediate Kination

e.g., "Rotating Axion"

Co, Dunsky, Harigaya, et al. 2108.09299
Servant, Gouttenoire, PS 2108.10328, 2111.01150

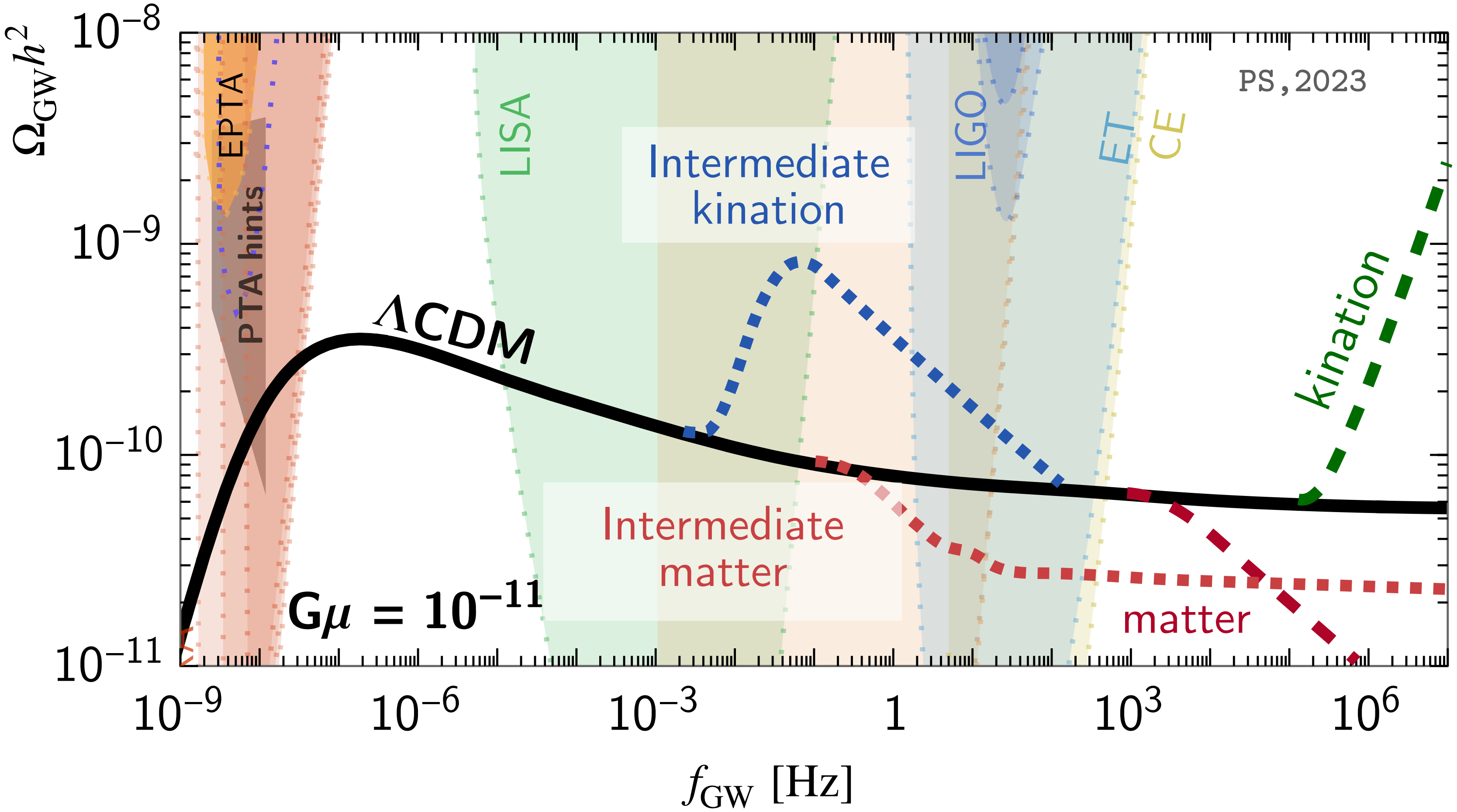
⇒ **"Peak" Signature**

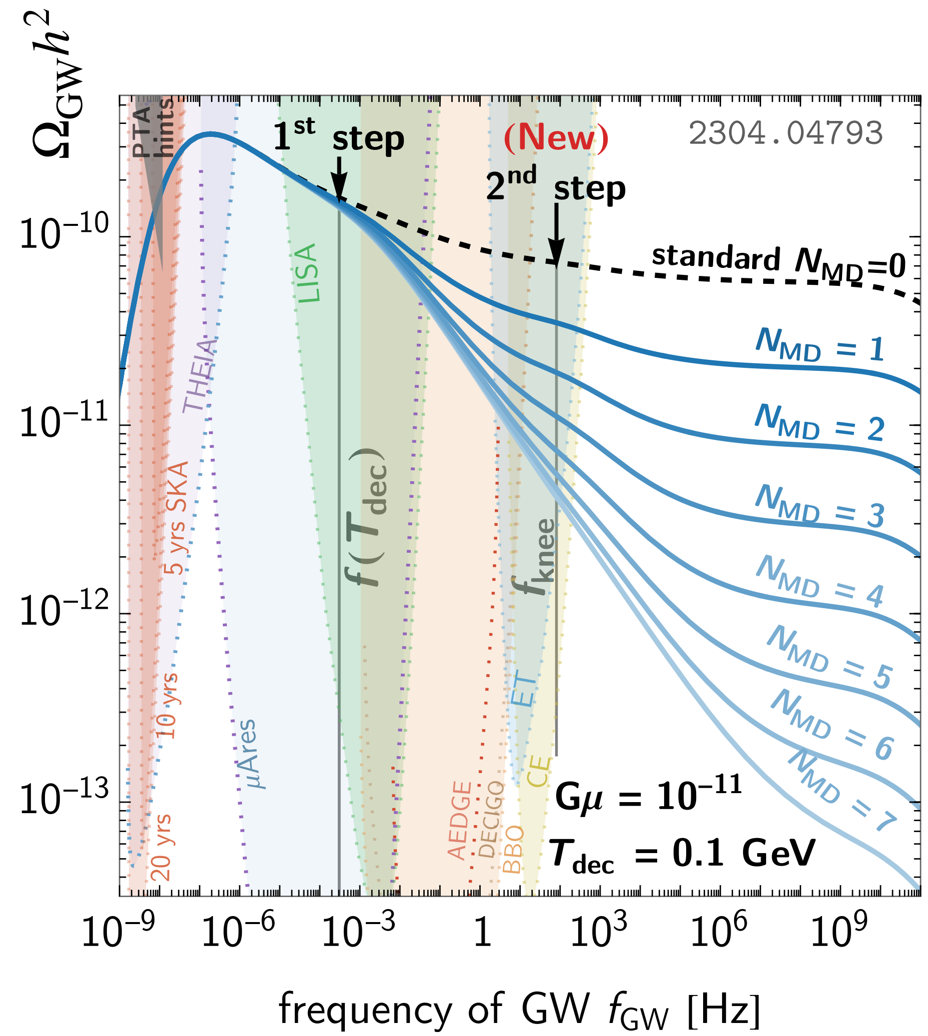
## III. Intermediate Matter

e.g., oscillating moduli, dark photons, primordial black holes,

Servant, Gouttenoire, PS 1912.03245
Blasi, Brdar, Schmitz, 2004.02889
Ghoshal, Gouttenoire, Heurtier, PS, 2304.04793

⇒ **(multi)-step signature**



# Relativistic BSM particles

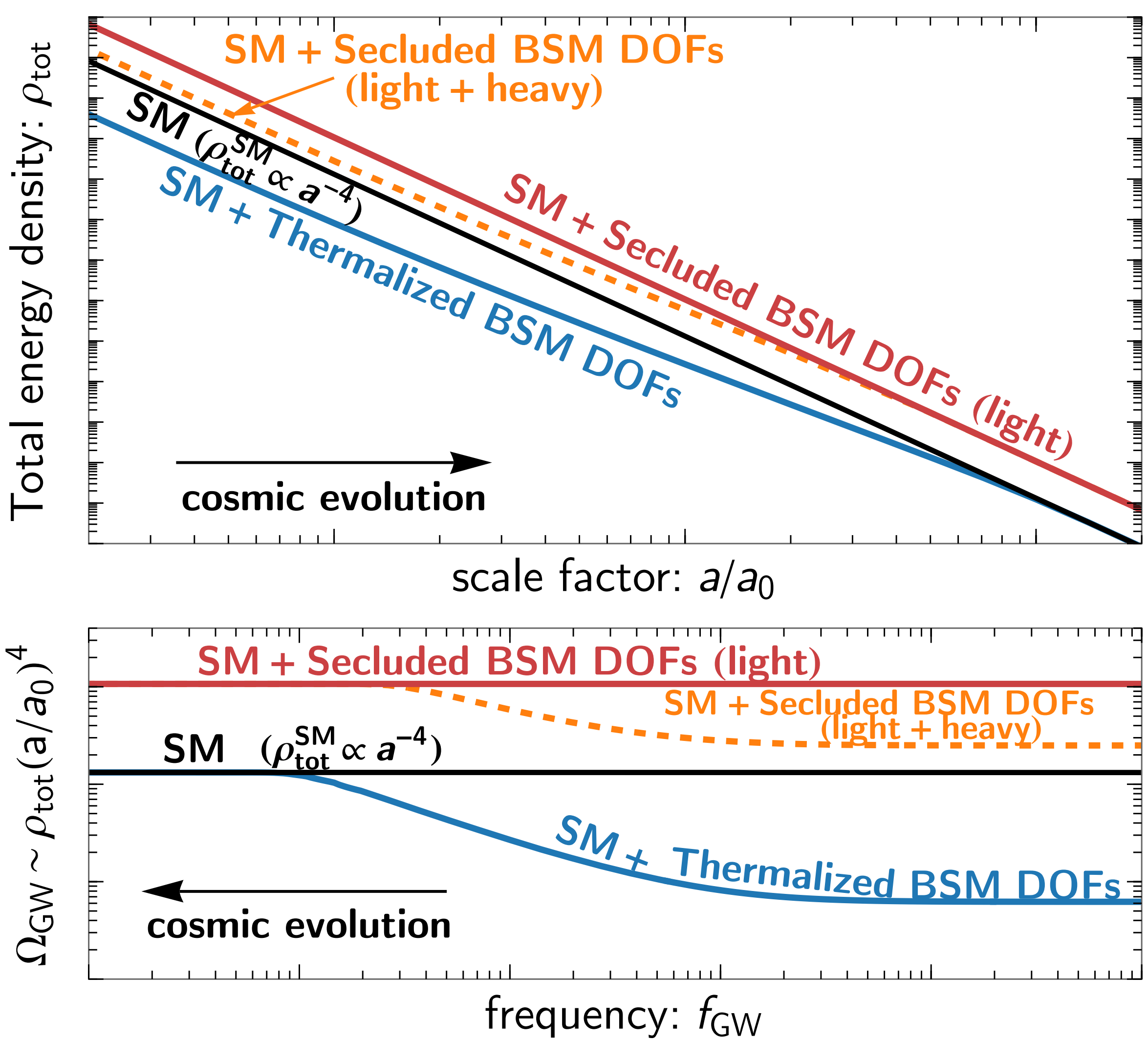
e.g., supersymmetric particles, extra-dimension theories, $N$Naturalness

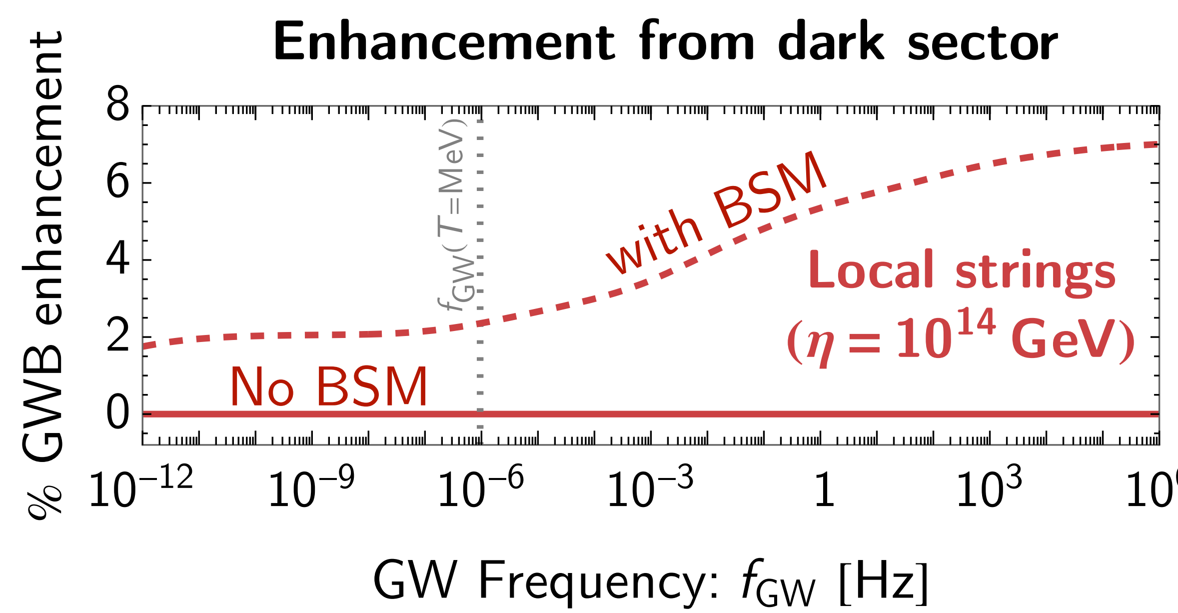
Géraldine Servant, PS, [To appear]

$$\Omega^{\rm cs}_{\rm GW} \sim \rho_{\rm rad,0} \times \begin{cases} [g_*^{\rm SM}(T) + g_*^{\rm BSM}(T)]^{-1/3} \\ \frac{1}{g_{*s}^{\rm SM}(T)^{\frac{4}{3}}} \left[g_*^{\rm SM}(T) + g_*^{\rm BSM}(T_D)\left(\frac{T_D}{T}\right)^4\right] \end{cases}$$

**Thermalized with SM:**
GWB suppressed with more BSM DOFs

**Completely-secluded:**
GWB enhanced with more BSM DOFs



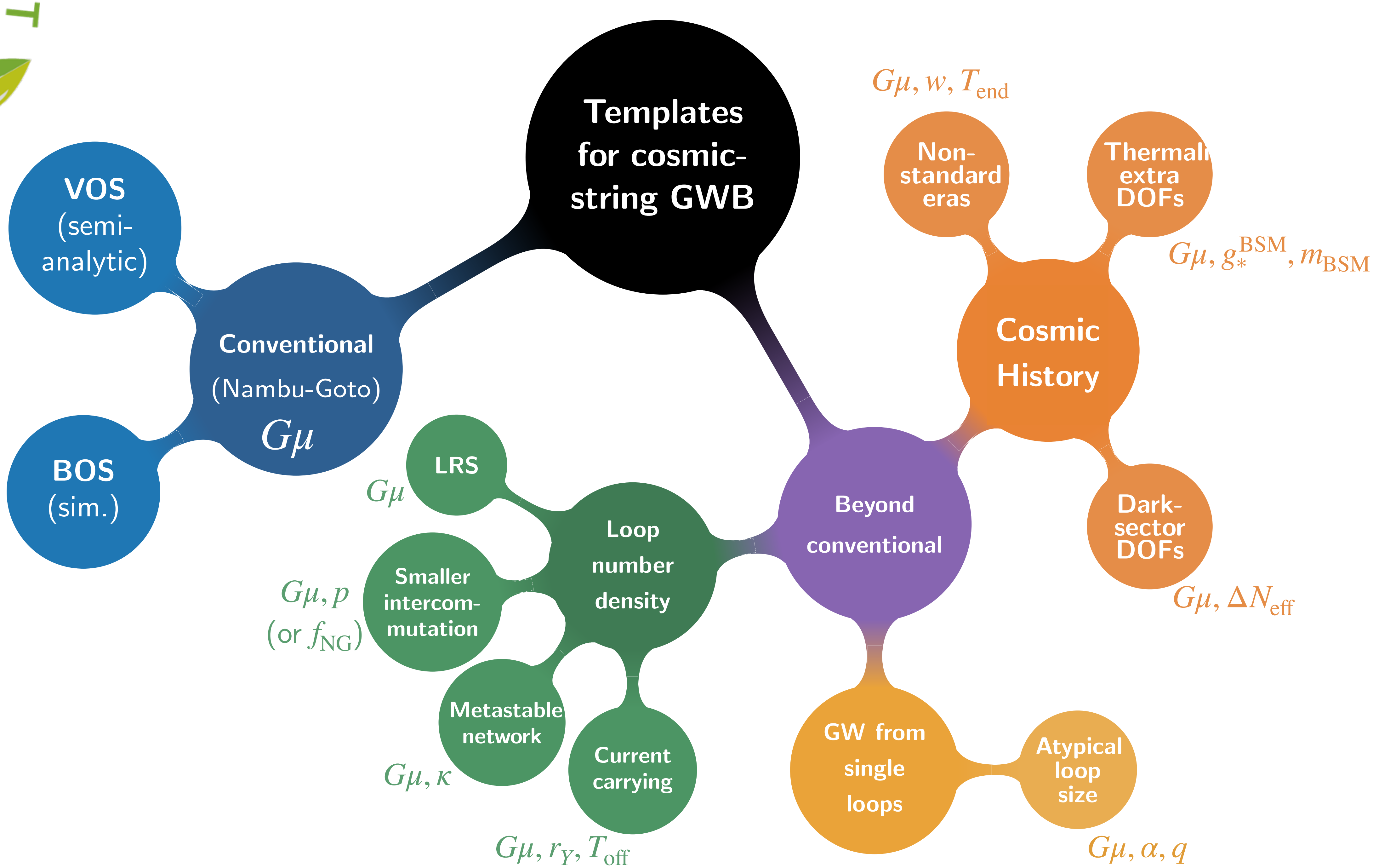

Max dark sector allowed by $\Delta N_{\rm eff} \lesssim 0.2$.

**The maximum enhancement is at $\sim 7\,\%$.**

# (shameless) Advertisement

A publicly-available catalog peerasima / cosmic-strings-GWB

Out soon with [Dimitriou, Figueroa, PS, Zaldivar, (in progress)]



How about detection prospects ?

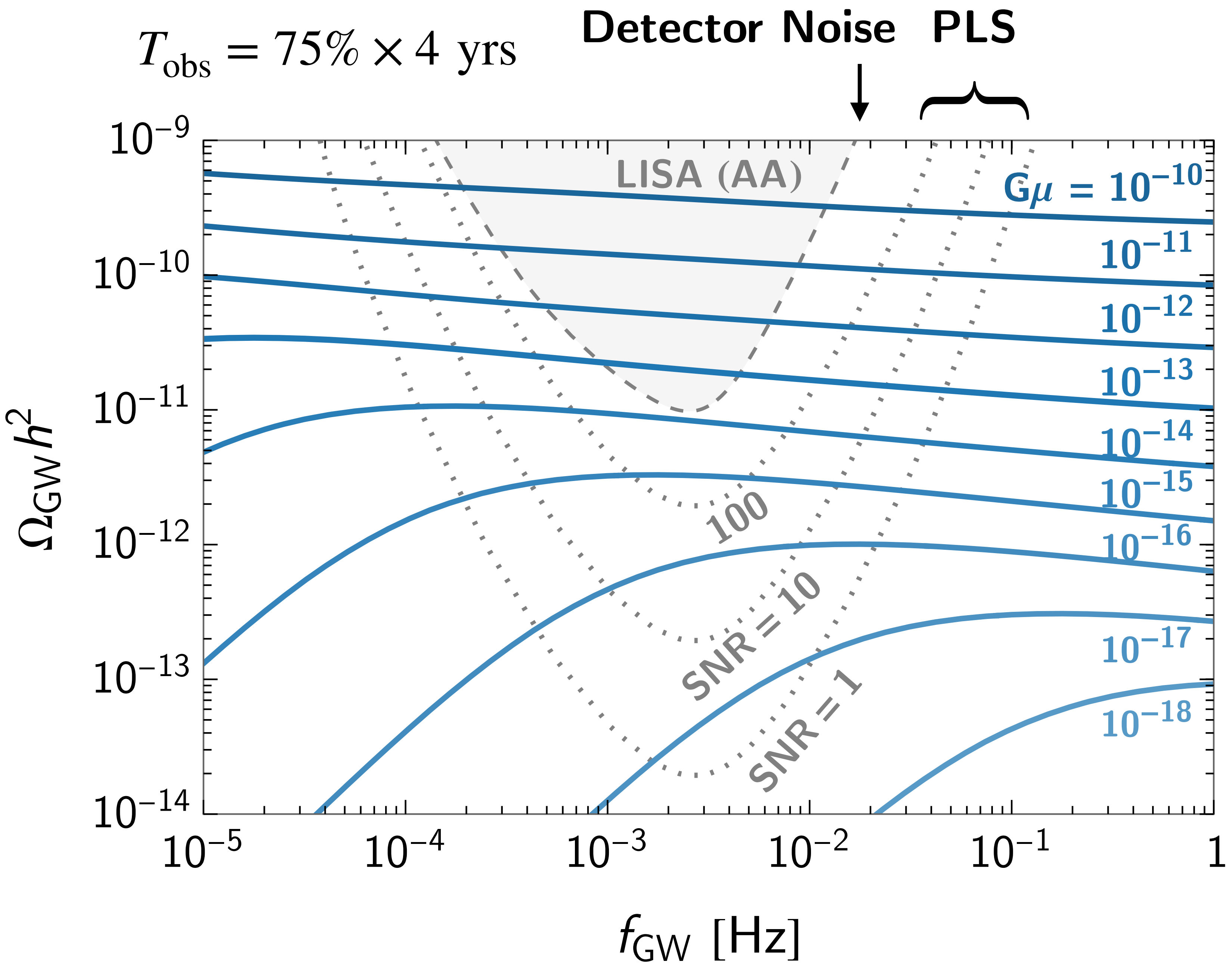
# Detection prospects . . .

**Power-law integrated sensitivity (PLS) curve:** a threshold for detecting a signal with a given SNR at a certain detector after some observation time.

[Thrane & Romano '13]

**LISA with**

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




**For PLS people,**

e.g., Peera during his PhD

"A signal passes the PLS of SNR, says 10. Our signal is detectable. Good!"

**Actually, not very satisfied!**

# Precise reconstruction of cosmic-string GWB with LISA

**Dimitriou, Figueroa, PS, Zaldivar [in progress]**

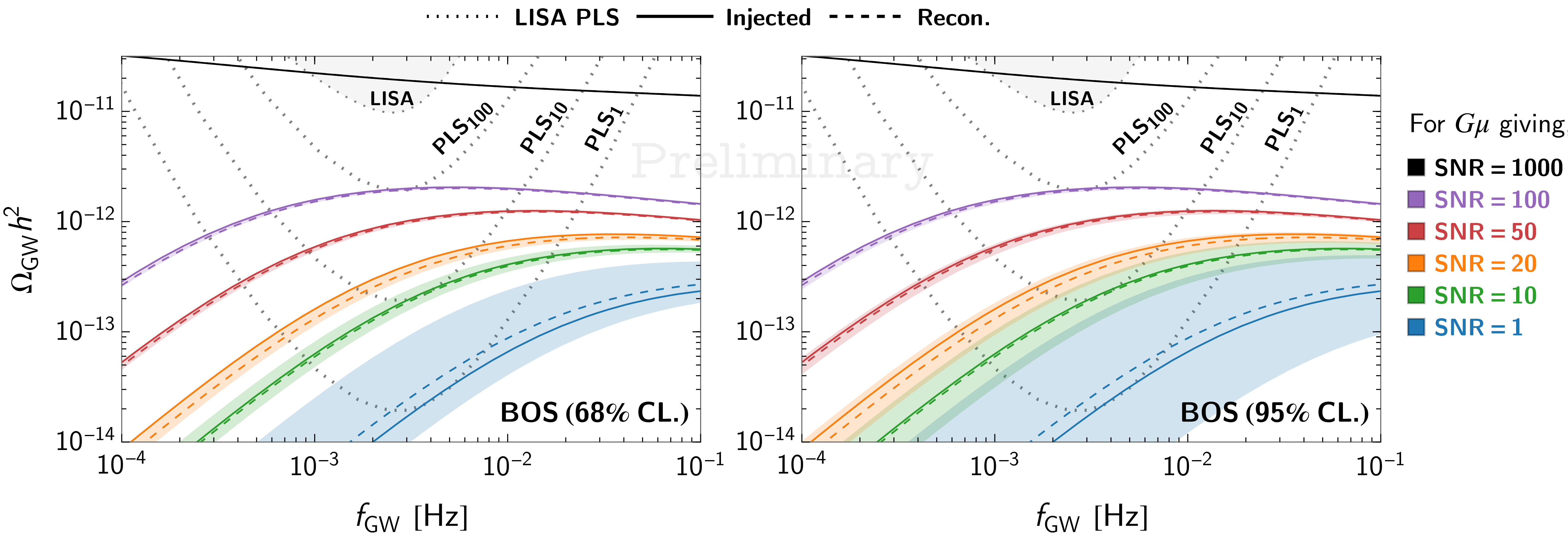
Using the simulation-based inference (SBI) technique
with the " **GWBackFinder** " package
developed by Dimitriou, Figueroa, Zaldivar [2309.08430]

**see talk by Bryan Zaldivar**

# Reconstructing conventional Nambu-Goto templates with LISA

Dimitriou, Figueroa, PS, Zaldivar [in progress]

Color bands = Uncertainty in reconstructing the signal




*Assuming the astrophysical foreground can be subtracted.
We will also consider the astrophysical foreground in the work.
See also the work of the LISA cosmology working group.

**Marginalized over LISA noises.

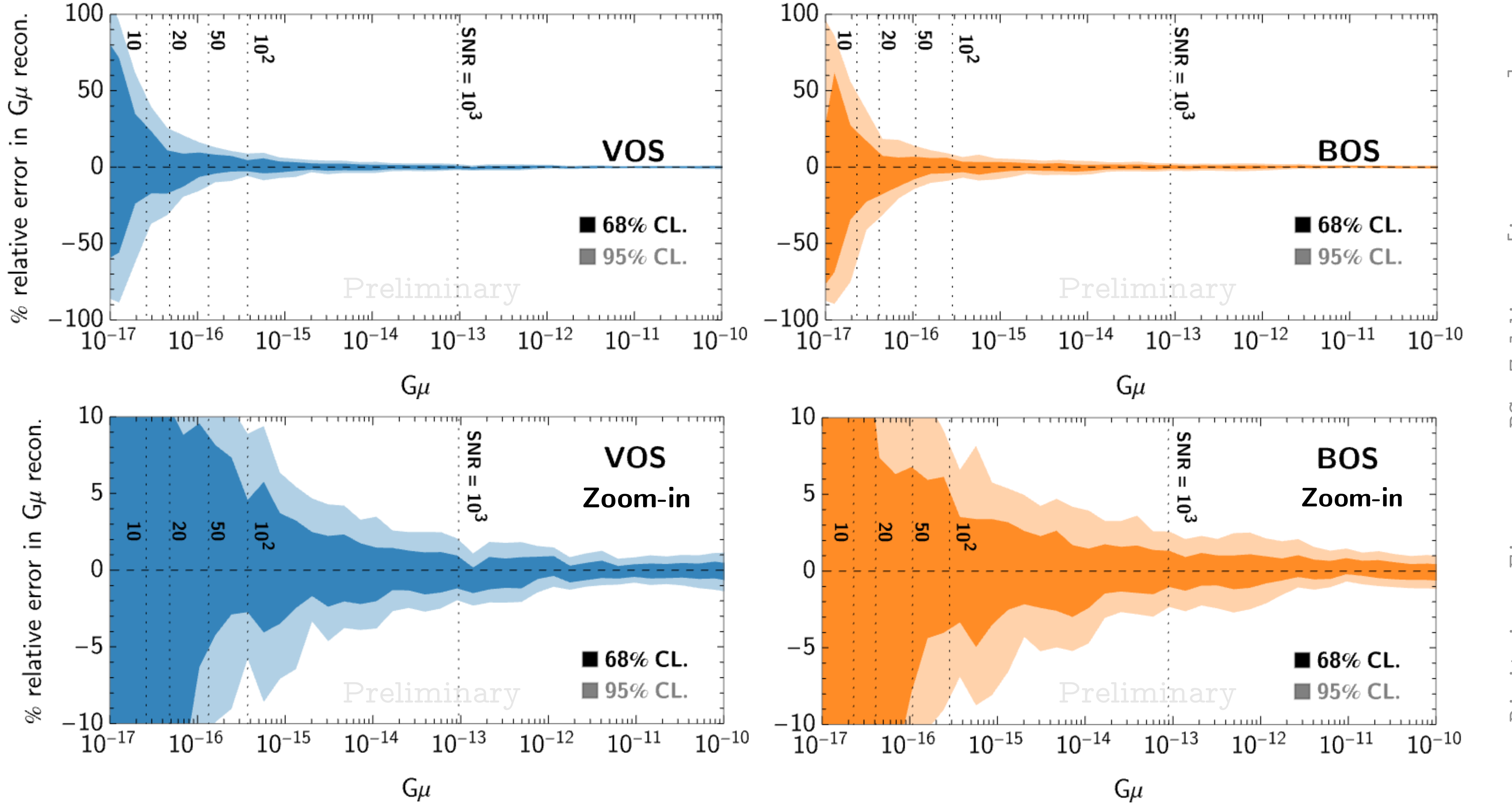
# Reconstructing conventional Nambu-Goto templates with LISA

$$\%\text{ relative error in G}\mu = 100\% \times \left(\frac{G\mu_{\text{recon}} - G\mu_{\text{inj}}}{G\mu_{\text{inj}}}\right)$$

Typical value used by PLS people

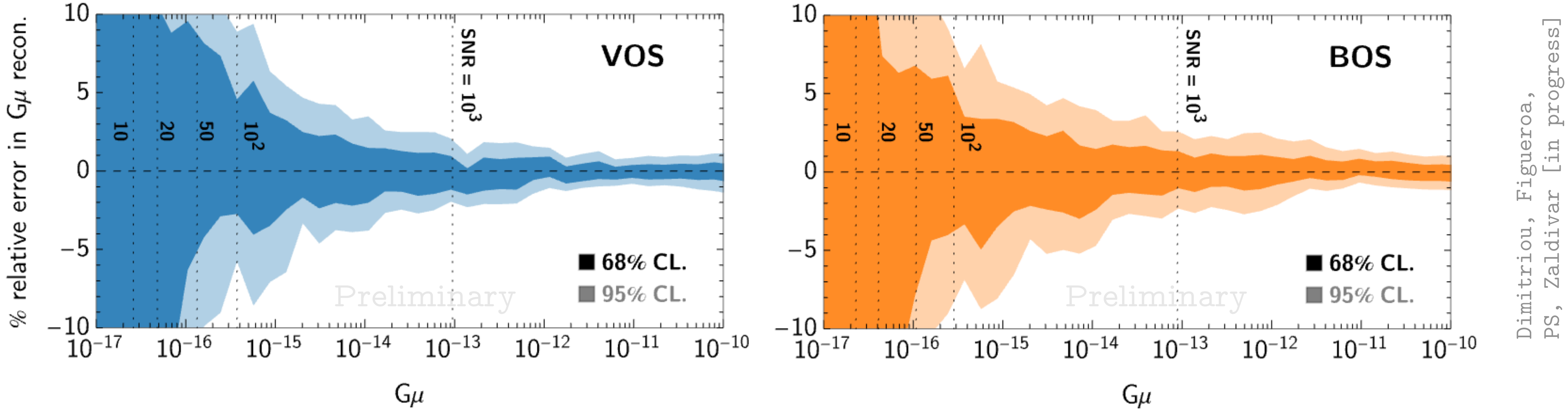
$$\text{SNR} \gtrsim 10 \Rightarrow \%\text{ error} \lesssim 50\,\%$$

$$\text{SNR} \gtrsim 10^2 \Rightarrow \%\text{ error} \lesssim 10\,\%$$




Dimitriou, Figueroa, PS, Zaldivar [in progress]

# Reconstructing conventional Nambu-Goto templates with LISA




$$\Omega_{\rm GW} \propto \sqrt{G\mu} \Rightarrow \frac{\Delta\Omega_{\rm GW}}{\Omega_{\rm GW}} = \frac{\Delta G\mu}{2G\mu} \Rightarrow \%\ \text{error in}\ \Omega_{\rm GW} = \frac{\%\ \text{error in G}\mu}{2}$$

Distinguishing VOS and BOS requires within $5-10\,\%$ in $\Omega_{\rm GW}$.

Distinguishing DOF $(g_* - g_{*_s})$ modelings requires less than $3\,\%$ in $\Omega_{\rm GW}$.

For beyond-conventional templates, the deviation from the conventional prediction is larger.
$\Rightarrow$ **Exploring large spaces of all templates' parameters quickly with SBI techniques**

**For $G\mu \gtrsim 10^{-16}$ or $\eta \gtrsim 10^{11}$ GeV,**
**the discrimination among cosmic-string models looks promising with LISA!**

# Summary and outlook

GWB from cosmic strings can have a large amplitude and span a wide frequency range.

The detection of the cosmic-string GWB will not only tell us about
the energy scale of symmetry breaking in the early Universe,
But we will be able to extract information about the **3 ingredients:**

$$\left.\begin{array}{l}\textbf{Loop number density}\\ \textbf{GW emission from loops}\end{array}\right\}\ \text{BSM underlying cosmic strings}$$

$$\textbf{Cosmic history} \longrightarrow \text{Other BSM}$$

We obtained templates for many models based on **Nambu-Goto** assumptions.

**LISA is possible for precise reconstructions and model discrimination.**
(Methods can be straightforwardly applied to other observatories.)

**Still, more works on the theory side:**
**Recent local-string results from field-theory sims.: much more efficient particle production,**
e.g., Baeza-Ballesteros, Copeland, Figueroa, Lizarraga [2408.02364]
**Global (axionic) strings**

The future looks promising!

# More stuffs . . .

# The scale–invariant local–string GWB during radiation–domination (simple argument)

**Fraction of energy density in GW today**

$$\Omega_{\mathrm{GW},0} = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4 = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot,prod}}}\right)\left(\frac{\rho_{\mathrm{tot,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4$$

constant

**Long-lasting** **Inflationary GW**

(scale-invariant) tensor perturbation: $\Delta_h^2 \simeq (H/M_{\mathrm{Pl}})^2$

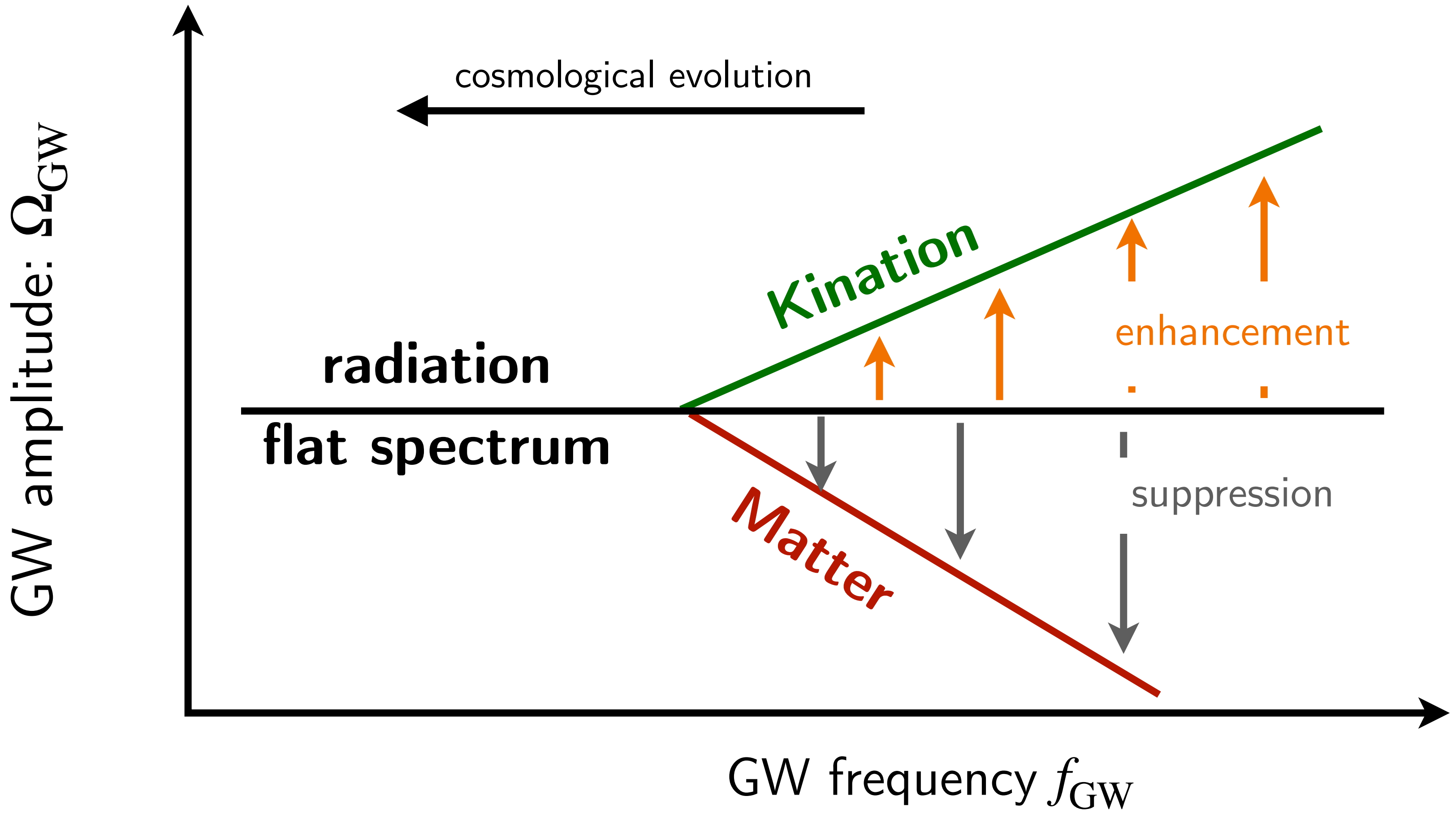
$(\rho_{\mathrm{GW}}/\rho_{\mathrm{tot}})_{\mathrm{prod}} = \text{constant}$

**Cosmic-string GW:**

$\rho_{\mathrm{GW}} \propto \rho_{\mathrm{string-network}} \propto \rho_{\mathrm{tot}}$

in the so-called "scaling regime"

**Gouttenoire, Servant, Simakachorn, 2111.01150**

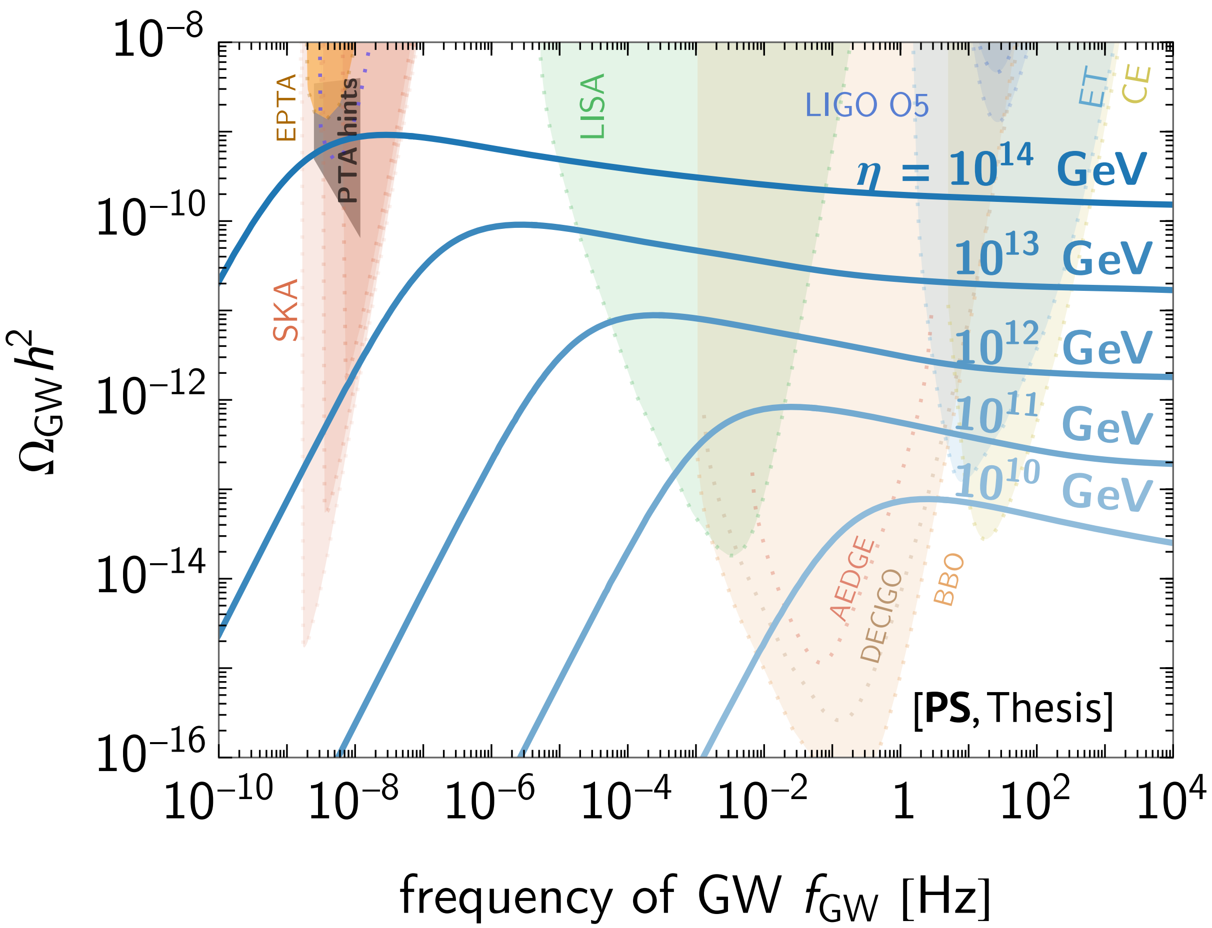



$$\rho_{\mathrm{tot}} \propto \begin{cases} a^{-3} & \text{for matter era,} \\ a^{-4} & \text{for radiation era,} \\ a^{-6} & \text{for kination era} \end{cases}$$

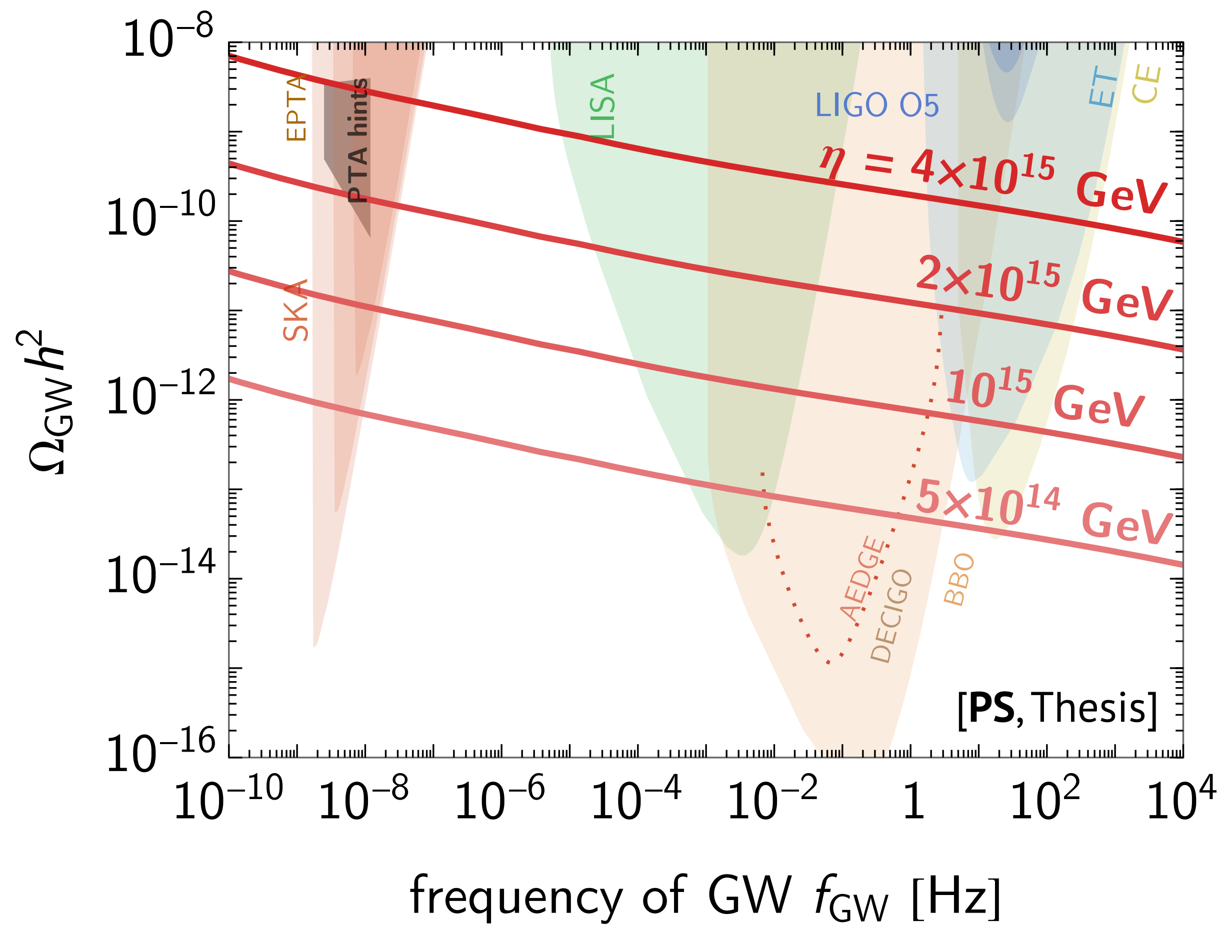
# GW from cosmic strings

generated from spontaneous symmetry breaking at an energy scale $\eta$

Local cosmic strings




Global cosmic strings




$$\Omega_{\rm GW}^{\rm local} \propto \sqrt{G\mu} \propto \eta \qquad\qquad \Omega_{\rm GW}^{\rm global} \propto \eta^4$$

$$f_{\rm GW}(T) \simeq \begin{cases} (2\times 10^{-3}\ \text{Hz}) \left(\frac{0.1\times 50\times 10^{-11}}{\alpha\times\Gamma G\mu}\right)^{1/2} \left(\frac{T}{\rm GeV}\right) \left[\frac{g_*(T)}{g_*(T_0)}\right]^{\frac{1}{4}} & \text{(local strings)}, \\ (4.7\times 10^{-6}\ \text{Hz}) \left(\frac{0.1}{\alpha}\right) \left(\frac{T}{\rm GeV}\right) \left[\frac{g_*(T)}{g_*(T_0)}\right]^{\frac{1}{4}} & \text{(global strings)}, \end{cases}$$

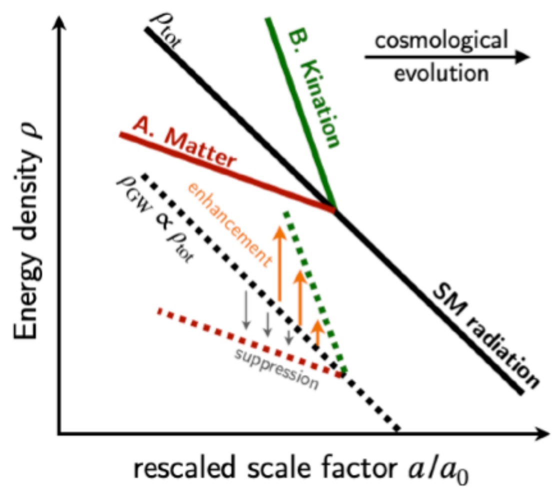
Temperature of the Universe

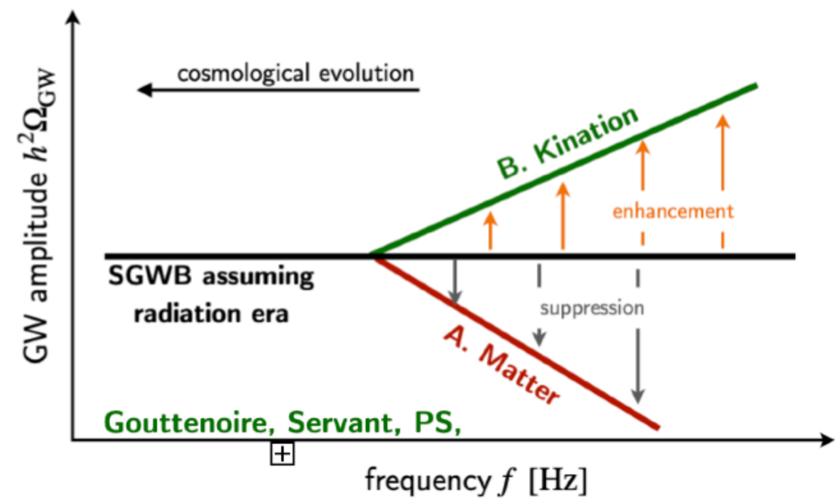
Peera Simakachorn (Uni. Hamburg) 28.10.2022

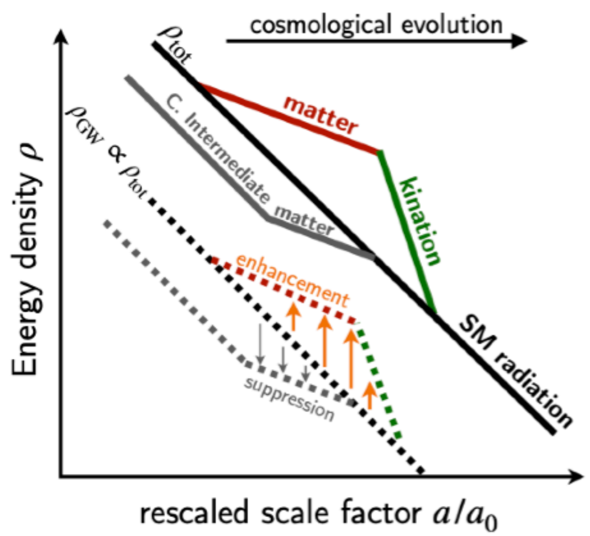
**Fraction of energy density in GW today**

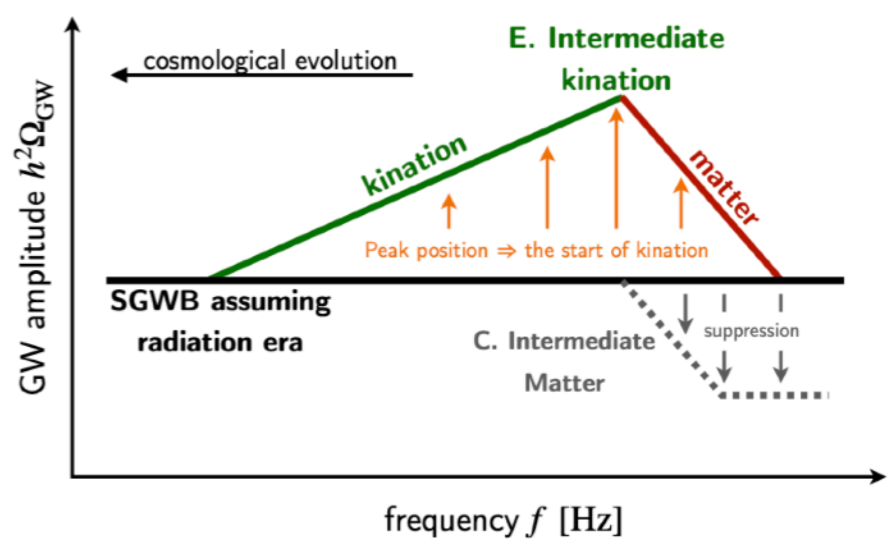
$$\Omega_{\mathrm{GW},0} = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4 = \left(\frac{\rho_{\mathrm{GW,prod}}}{\rho_{\mathrm{tot,prod}}}\right)\left(\frac{\rho_{\mathrm{tot,prod}}}{\rho_{\mathrm{tot},0}}\right)\left(\frac{a_{\mathrm{prod}}}{a_0}\right)^4$$

**Smaller/larger $\rho_{\mathrm{tot}}$ during matter/kination ⇒ suppression/**




**Inflation GW created during $\rho \propto a^{-n}$**

$$\Omega^{\mathrm{inf}}_{\mathrm{GW}}(f_*) = \Omega^{\Delta}_{\mathrm{st}}\left(\frac{f_*}{f_\Delta}\right)^{\beta} \quad \text{with} \quad \beta \equiv 2\left(\frac{n-4}{n-2}\right)$$

RD $n = 4$: $\beta = 0$ (flat)
MD $n = 3$: $\beta = -2$
KD $n = 6$: $\beta = 1$

**Local cosmic-string GW whose loops are formed during $\rho \propto a^{-n}$ and decay into GW during $\rho \propto a^{-m}$**

$$\Omega^{\mathrm{cs}}_{\mathrm{GW}}(f_*) = \Omega^{\Delta}_{\mathrm{st}}\left(\frac{f_*}{f_\Delta}\right)^{\beta} \quad \text{with} \quad \beta \equiv 2\left[\frac{3m - nm + n}{n(2-m)}\right]$$

Note: the lowest slope is fixed due to the mode summation. Cusp loops $\beta_{\mathrm{min}} = -1/3$.