Cosmic Superstrings in Large Volume Compactifications

Gonzalo Villa

2411.04186 [hep-ph], 2504.20994 [astro-ph.co]

With F. Revello (x2), A. Ghoshal

09/09/2025 – CA21106 3rd General Meeting, Sofia

Main points

- Cosmic (super)strings are detectable remnants of UV physics (+ window for pre-BBN physics!)

- VERY related to WISPs: axion DM, GWs, dark sector…

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Today

-Dependence on scalar field dynamics (dynamics & signatures).

-A prediction for LISA.

Results

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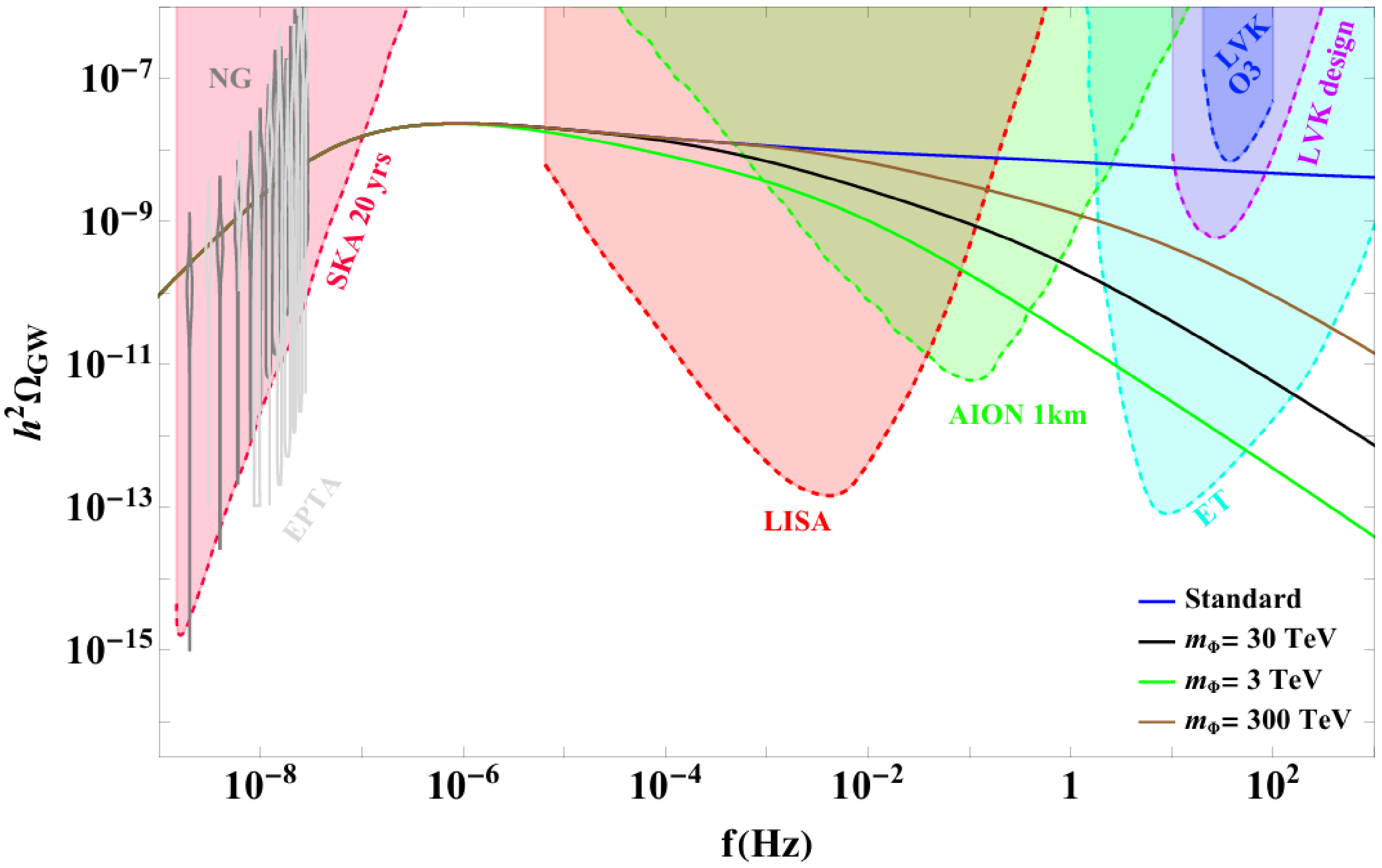

<u>Scenario 1</u>

LVS + PTA = LISA

Results

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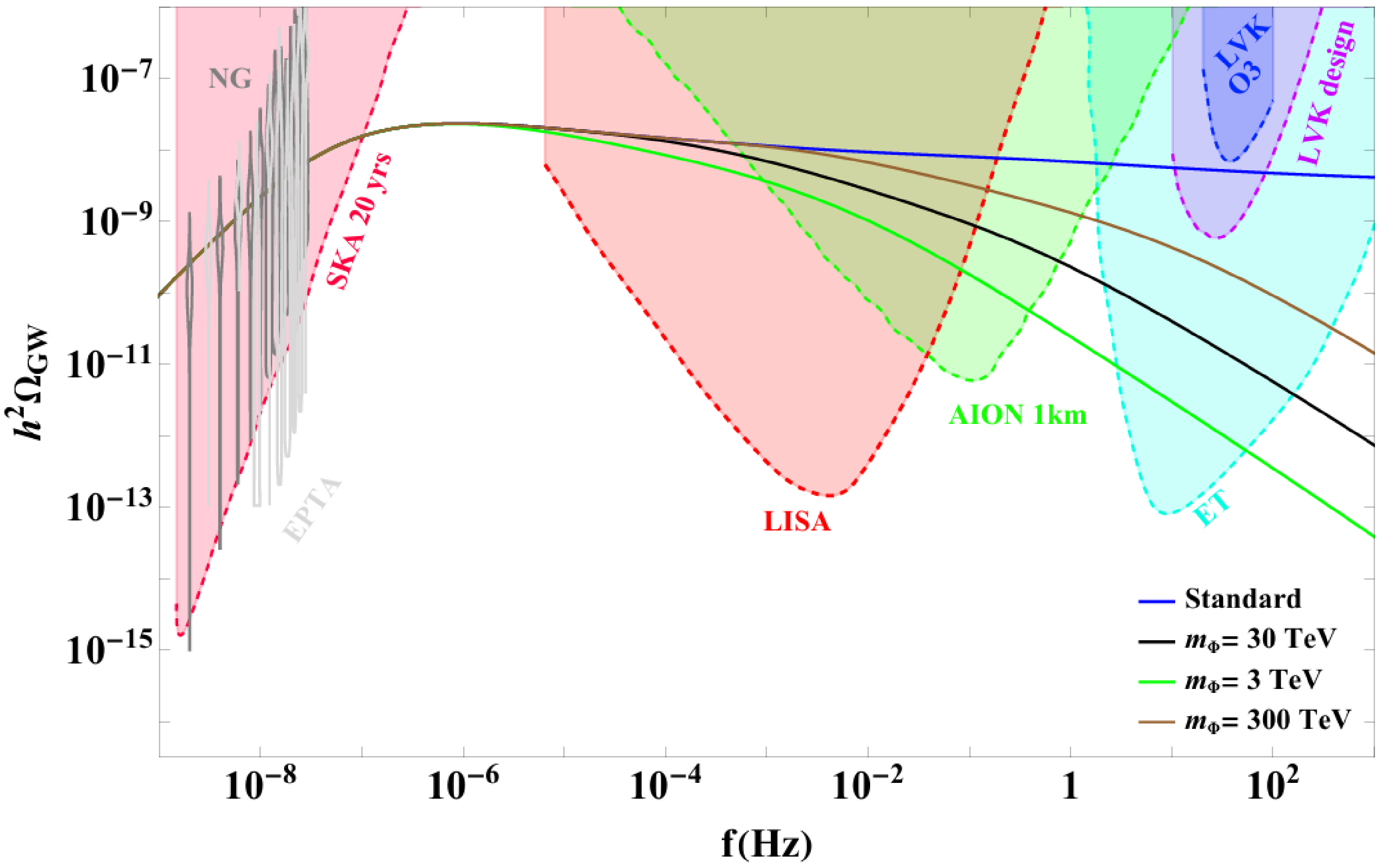

Scenario 1

LVS + PTA = LISA

- PTA fixes properties of the strings.
- LVS relates them to microphysics.
- Together, one free parameter sets the mass of a WISP.

Results

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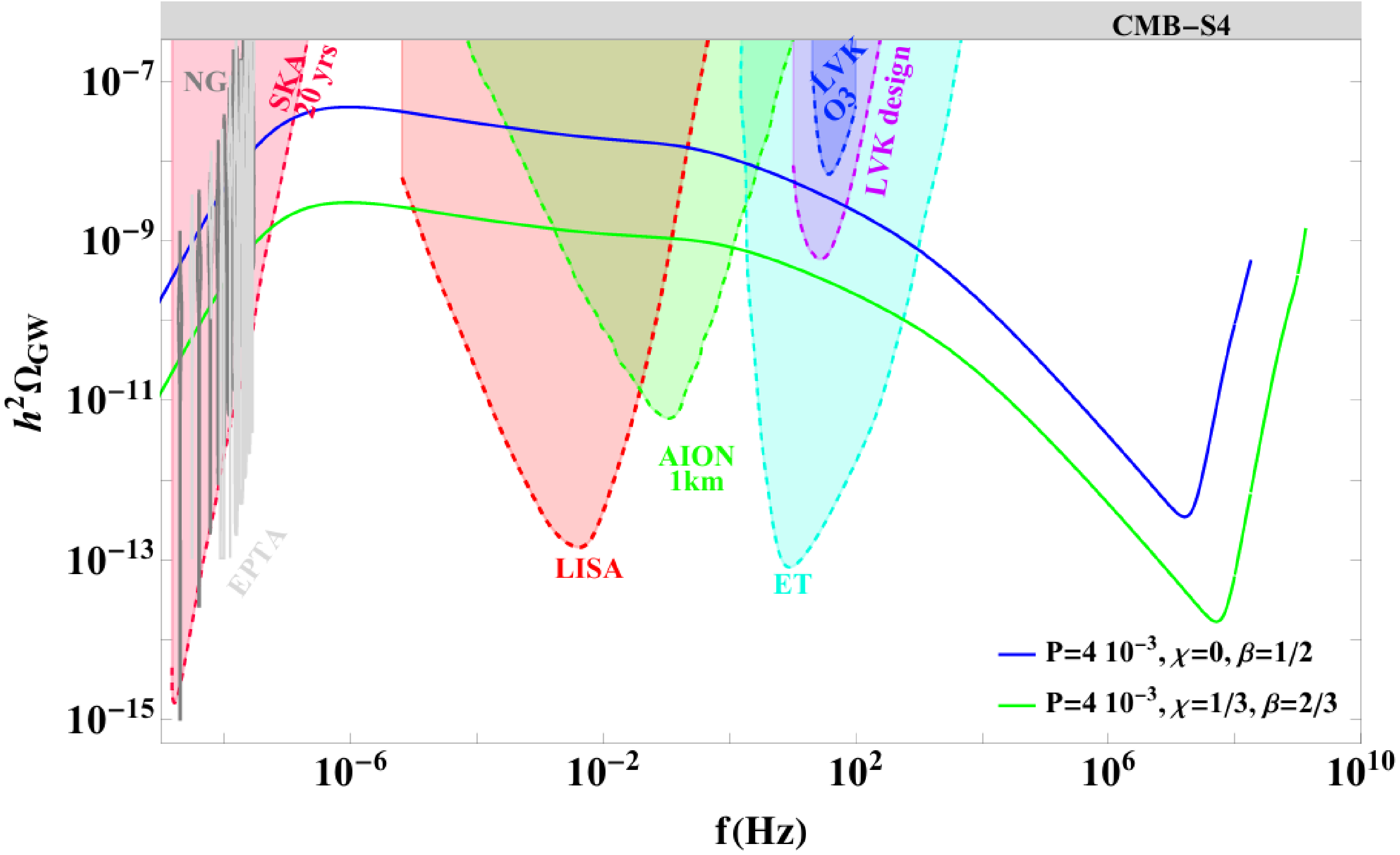

Scenario 2

Varying tension → HF boost

Results

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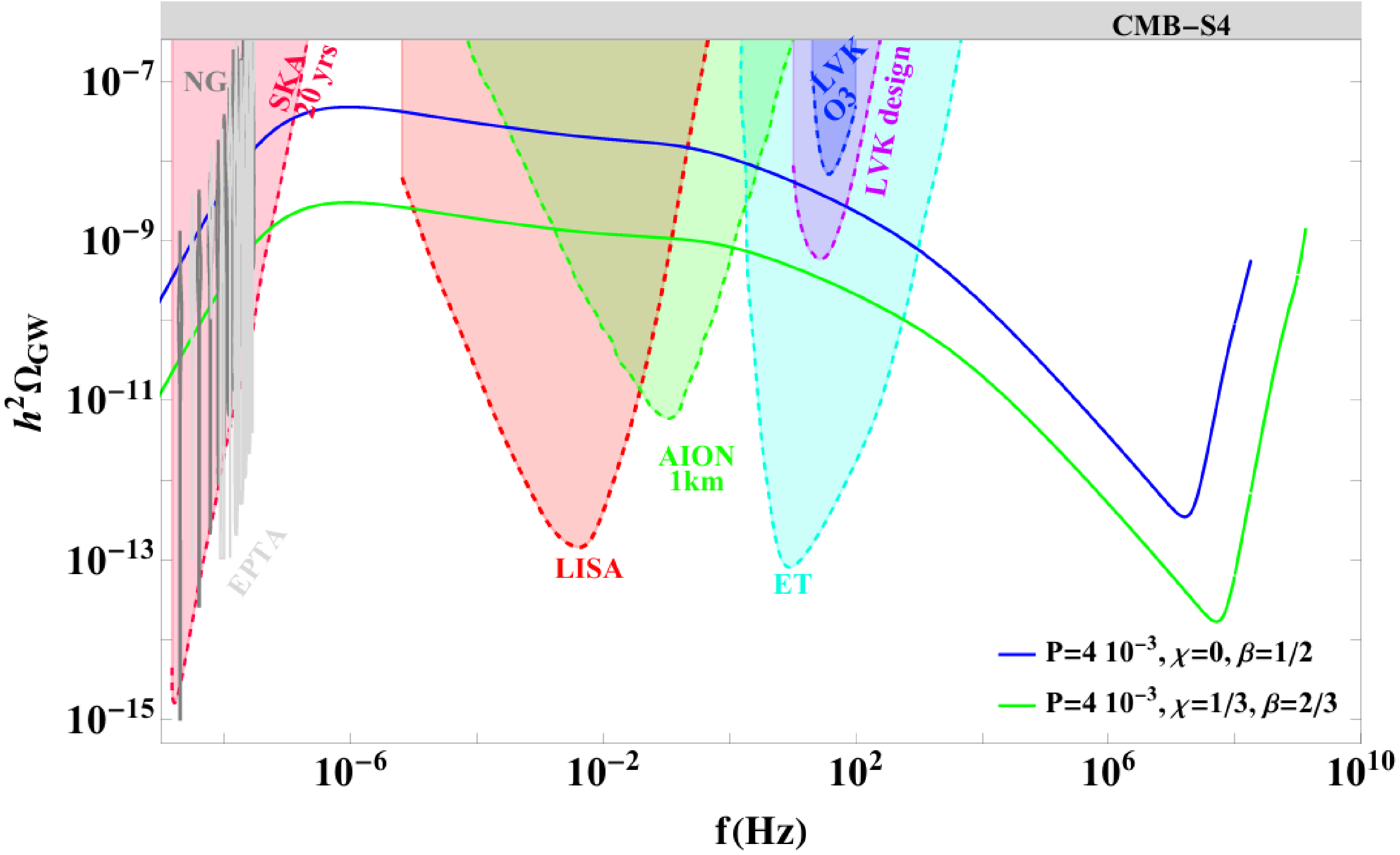

Scenario 2

Varying tension → HF boost

- Tension set by scalar VEV, dynamical in early Universe.

More tension implies:

- Larger relative fraction of strings.
- More GWs sourced.

Results

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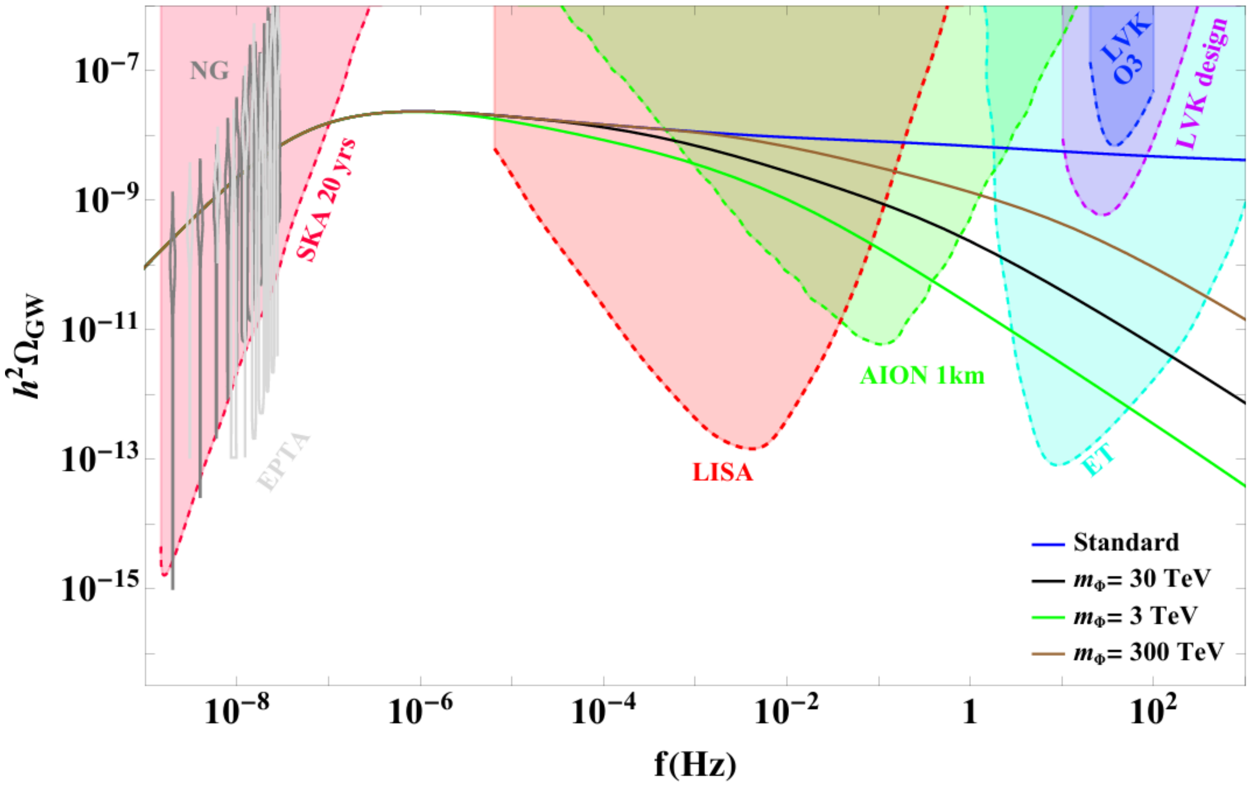
Scenario 1

LVS + PTA = LISA



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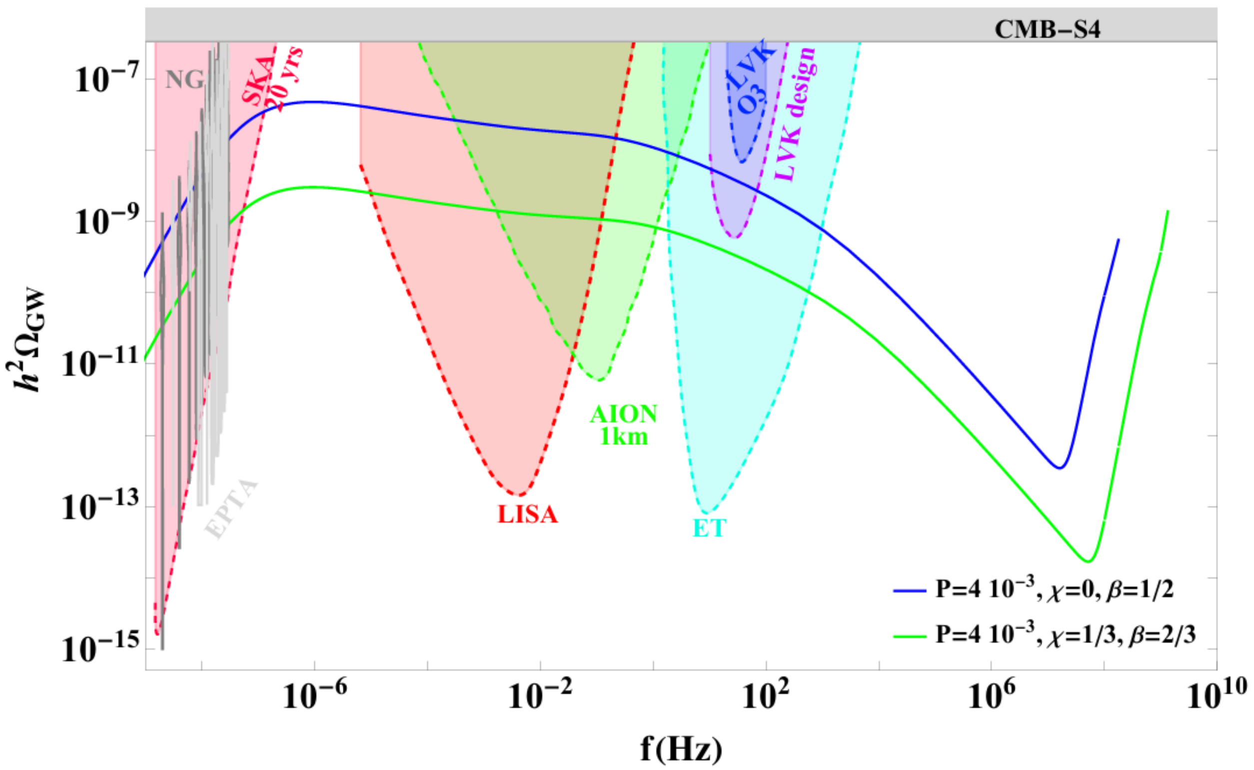

Moduli dynamics

aKa setting fundamental constants

aKa how WISPs appear in string theory

Dimensional reduction 101

- In 5D gravity, the equations of motion admit vacuum solutions of the form $\mathbb{R}^{3,1} \times S^1$ with the circle size unfixed. Write:

$$G_{\mu\nu} = \left(\frac{\sigma_0}{\sigma}\right)^{1/3} \left(g_{\mu\nu} - \kappa^2 A_\mu A_\nu\right) \,, \qquad G_{\mu 5} = -\kappa \sigma^{2/3} A_\mu \left(\frac{\sqrt{\alpha'}}{R}\right)^2 \,, \qquad G_{55} = \sigma^{2/3} \left(\frac{\sqrt{\alpha'}}{R}\right)^2$$

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- Then, at low energies:

$$S_{EH} = \frac{2\pi\sqrt{\alpha'}\sigma_0^{1/3}\, M_{p,5}^3}{2} \int d^4x \sqrt{-g} \left(R_{(4)} - \frac{1}{4}\sigma F_{\mu\nu}F^{\mu\nu} - \frac{1}{6}\frac{\partial_\mu \sigma\, \partial^\mu \sigma}{\sigma^2}\right) + \dots$$

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- The expectation value of σ determines the 4D Planck scale!

$$M_p^2 = 2\pi\sqrt{\alpha'}\sigma_0^{1/3} M_{p,5}^3$$

Dimensional reduction: takeaways

- Degeneracies to higher-dimensional equations manifest themselves at low energies as massless fields (*moduli*).

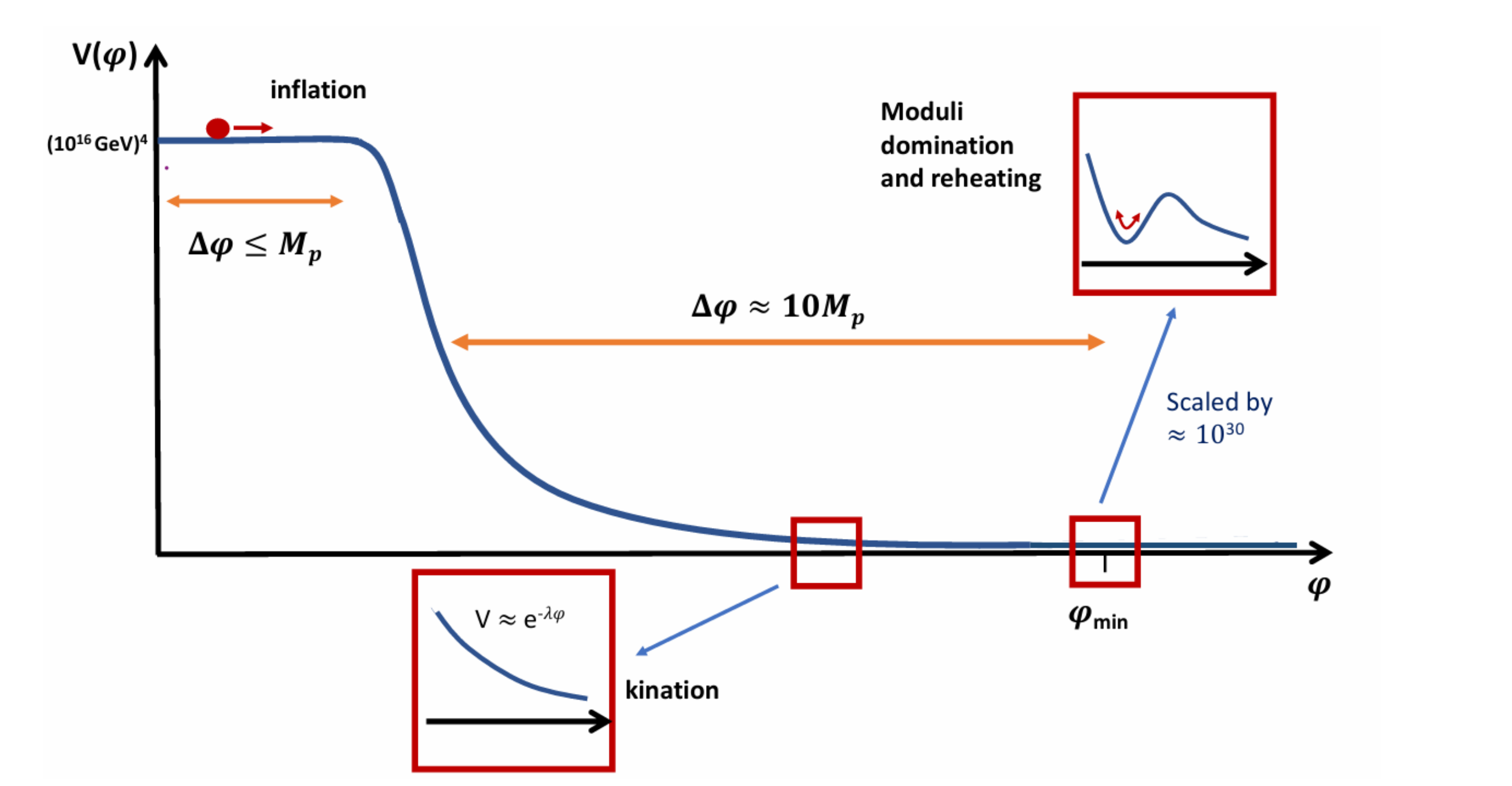
- The VEV of the moduli parametrize fundamental constants (here, the Planck scale).

- Quantum corrections provide small masses -> active in the early Universe?.

String theory & the first half of the Universe

Conlon et al'24, ...

String cosmology review: Cicoli et al'23



- Inflation $\rho \sim \text{const.}$
- Kination $\rho \sim a^{-6}$
- Tracker $\rho \sim a^{-4}$
- Moduli domination $\rho \sim a^{-3}$
- Standard cosmology

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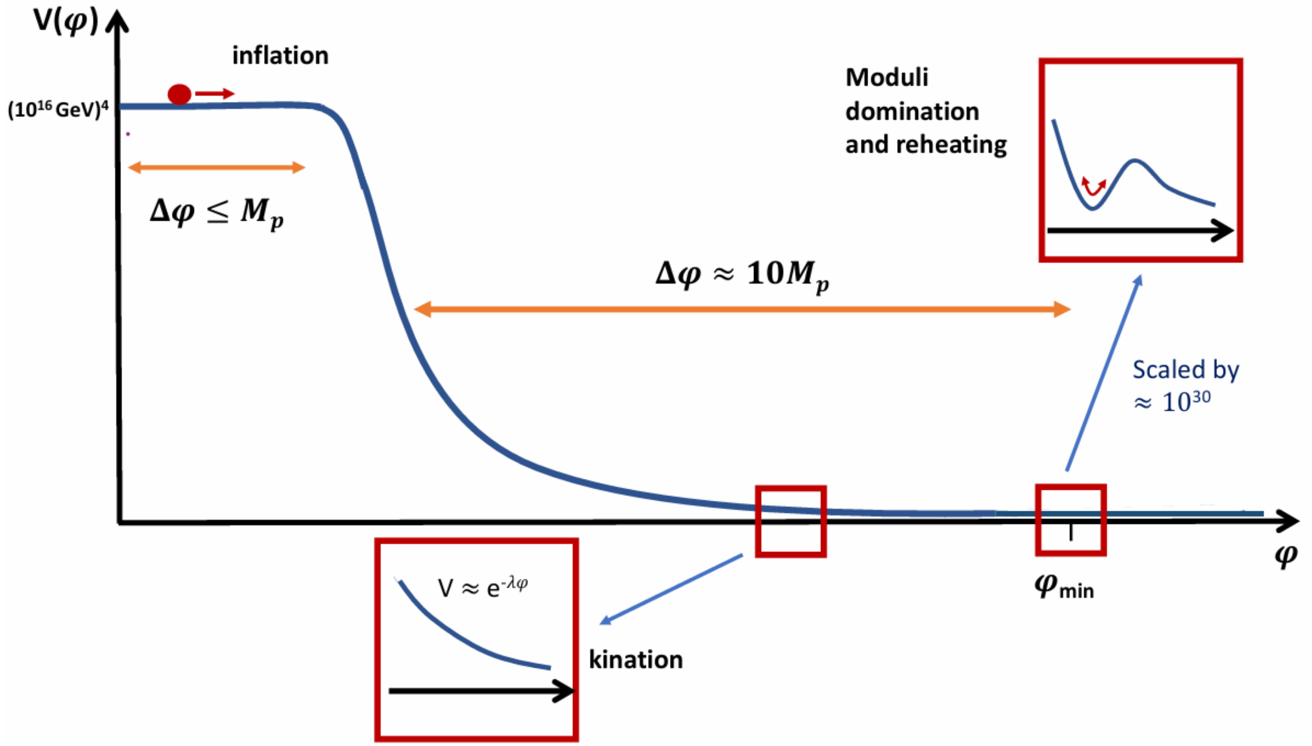

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Variation of fundamental constants??

Dimensional reduction: takeaways

- Moduli are generic in string vacua.

- Their dynamics is expected to alter the early universe:
    - Variation of fundamental constants.
    - Exotic fluids dominating the energy density.

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- Moduli are generic in string vacua.

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  - Exotic fluids dominating the energy density.

- This talk: explore how varying tension affects the GW signal from cosmic strings.

Cosmic strings & superstrings:

Dynamics with varying tension

Cosmic strings & superstrings

- Field theory: topological defects from symmetry breaking in the early Universe.

Kibble'76

- String theory: highly excited strings/D1 branes/wrapped higher dimensional branes. Formed after brane-antibrane inflation?

See Luca's talk!

Sarangi-Tye'02

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Sarangi-Tye'02

- For current purposes, networks described by $\boxed{G\mu\,,\ P}$

Moduli-dependent!

Worldsheet dynamics

- At low energies, described by the Nambu-Goto action:

$$S = -\int d^2\zeta \, \mu \sqrt{-\gamma}.$$

$$\gamma_{ab} = \frac{\partial X^\mu(\zeta)}{\partial \zeta^a} \frac{\partial X^\nu(\zeta)}{\partial \zeta^b} a(\tau)^2 \eta_{\mu\nu}$$

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- (One of the) equations of motion reads:

$$\dot{\varepsilon} + \left(2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu}\right)\varepsilon \dot{x}^2 = 0, \qquad \varepsilon \equiv \sqrt{\frac{x'^2}{1-\dot{x}^2}}\,.$$

Proper length

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Proper length

- So e.g. in volume modulus kination, the strings grow.

Conlon et al '24
See Luca's talk!

Cosmic strings & scaling

Cosmic strings track the energy density of the background:

- Slower dillution $\sim 1/a(t)^2$
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Averaged dynamics usually described by VOS model: scaling solutions are attractors of the averaged dynamics.

Martins-Shellard'96

Same is true if the tension varies.

Revello-GV'24

Loops: distribution and decay

Martins-Shellard'02

- Simulations suggest that:
  - Energy density to loops: $$\frac{d\rho}{dt} = \tilde{c}\bar{v}\frac{\rho}{L}\,,\ \tilde{c} \simeq 0.23\,,\ L = \xi t$$
  - Typical initial size: $$l(t_i) = \alpha t_i\,, \alpha \simeq 0.1$$
  - Decay via gravitational radiation: $$\frac{dE}{dt} = -\Gamma G\mu^2$$

Uncertainties!

- Dynamics governed by: $$\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\frac{\ell}{2\mu}\frac{d\mu}{dt} - \Gamma G\mu,$$

Loops: distribution and decay

Martins-Shellard'02

Sousa-Avelino'16

- Simulations suggest that:
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P- dependent!

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The Gravitational Wave spectrum

$$\Omega_{GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{GW,0}}{d\log f} = \frac{f}{\rho_c}\int_{t_0}^{t_i} d\tilde{t}\left(\frac{a(\tilde{t})}{a_0}\right)^4 \frac{dE_{GW}}{d\tilde{t}}\left(\frac{a(t_i)}{a(\tilde{t})}\right)^3 \frac{dl(\tilde{t})}{df}\frac{dt_i}{dl(\tilde{t})}\frac{dn}{dt_i}\,.$$

Initial loop distribution

The Gravitational Wave spectrum

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Loop distribution
at emission time

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Energy (today) sourced into GWs at emission time, per frequency interval

The Gravitational Wave spectrum

GW emission (mu)

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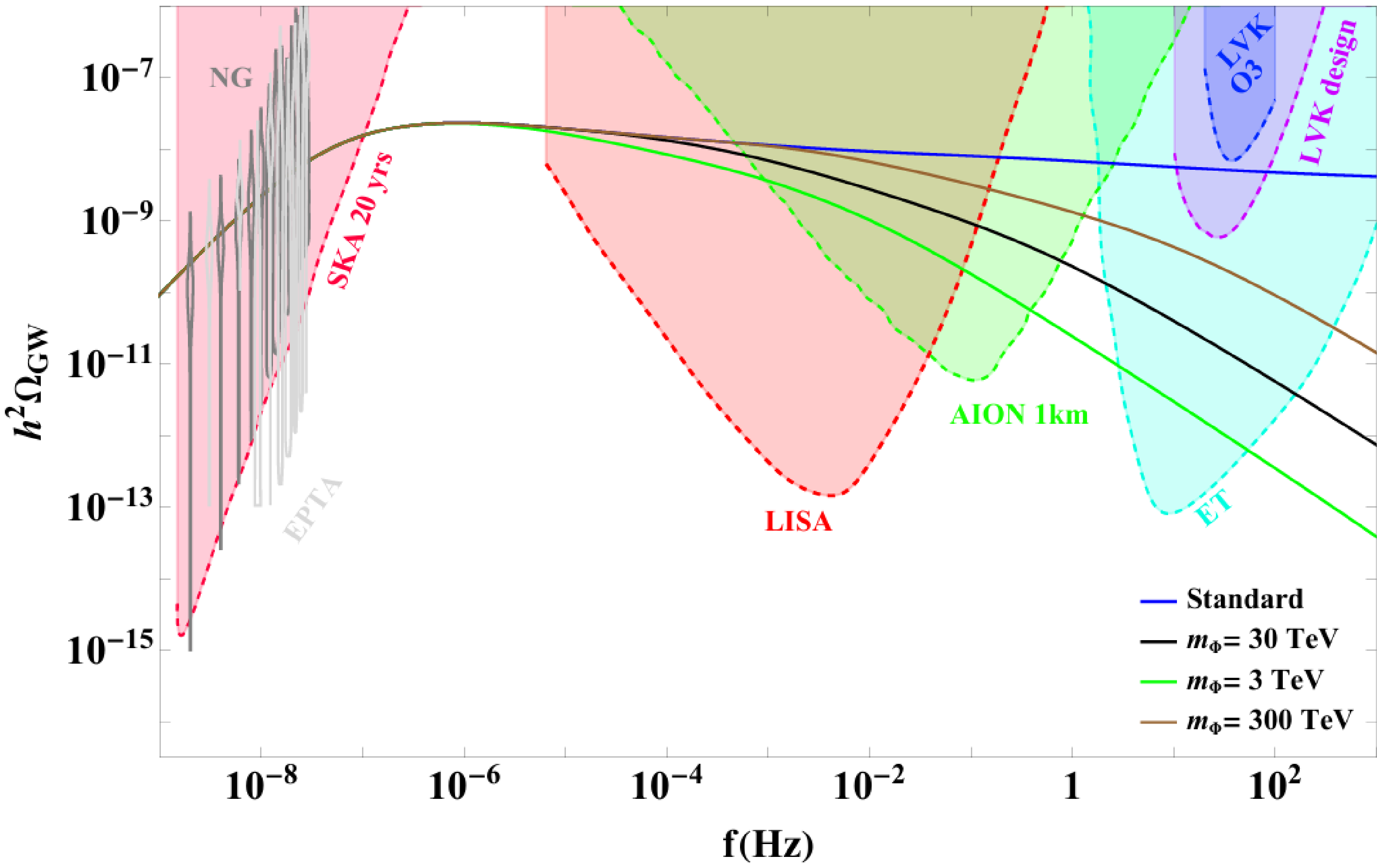
Loop dynamics
(P, mu)

Pre-BBN physics with cosmic strings



The GW spectrum is sensitive to the equation of state of the background

(Here: Matter domination + gravitational decay)

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Key takeaways

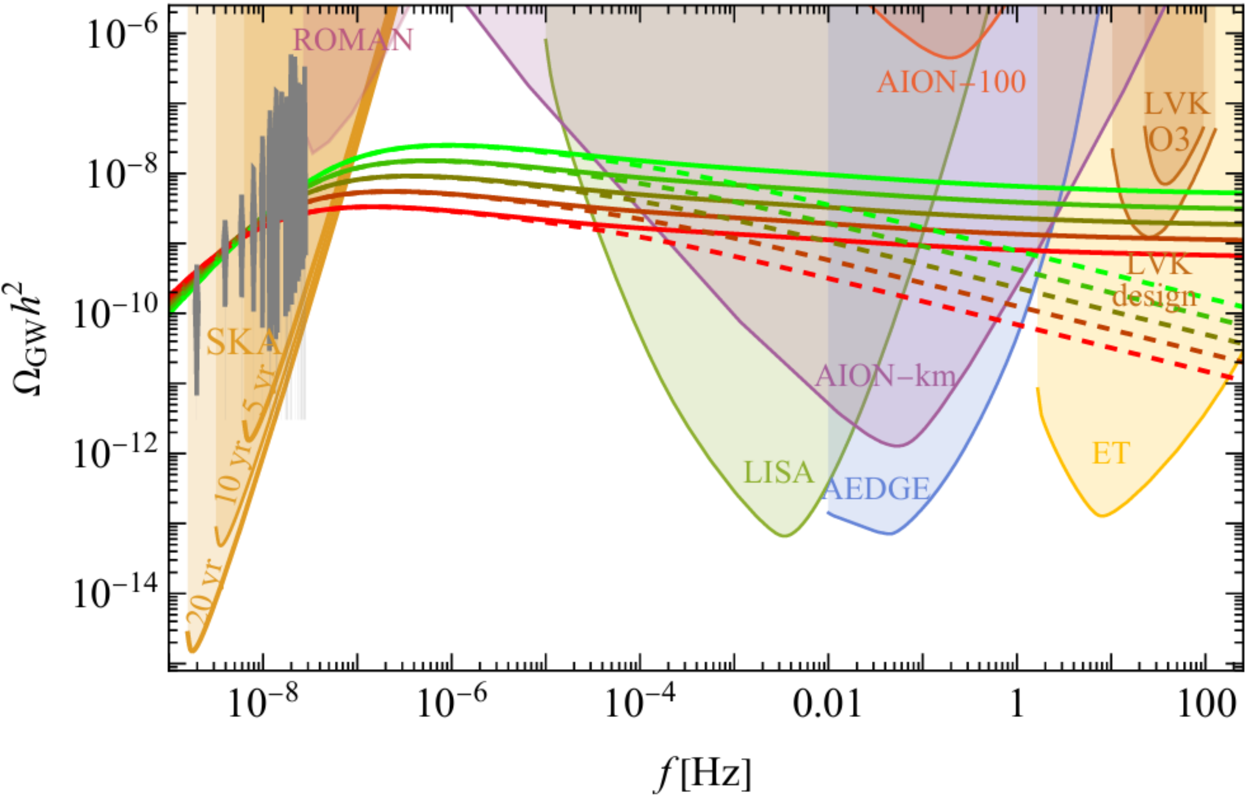
- The scaling regime ensures that at every time a meaningful fraction of GWs is released.
- One-to-one map between frequencies and times.
- Sensitive to equation of state of the background & variations in tension → window into pre-BBN physics

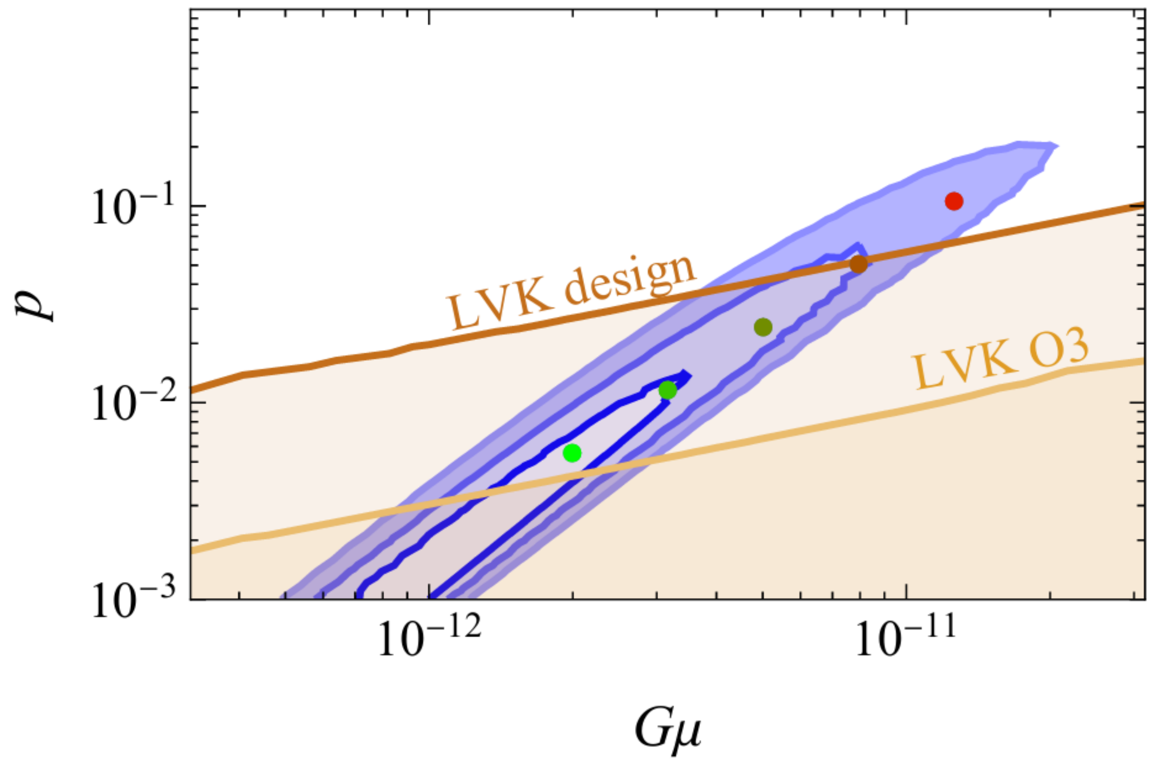
Plots from 2306.17147

PTAs!

Agazie et al'23...
Ellis et al'23

PTA experiments have strong evidence for a GW background at low frequencies, possibly explained by cosmic superstrings.





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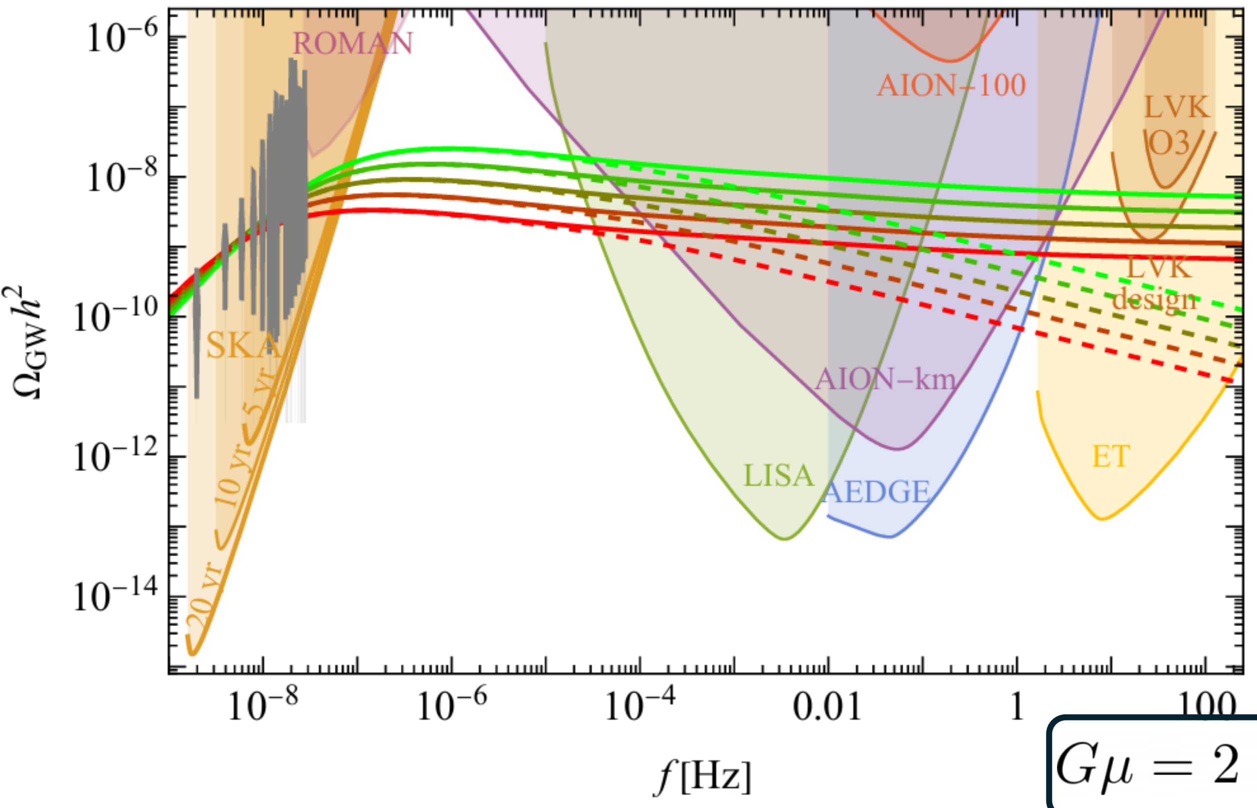

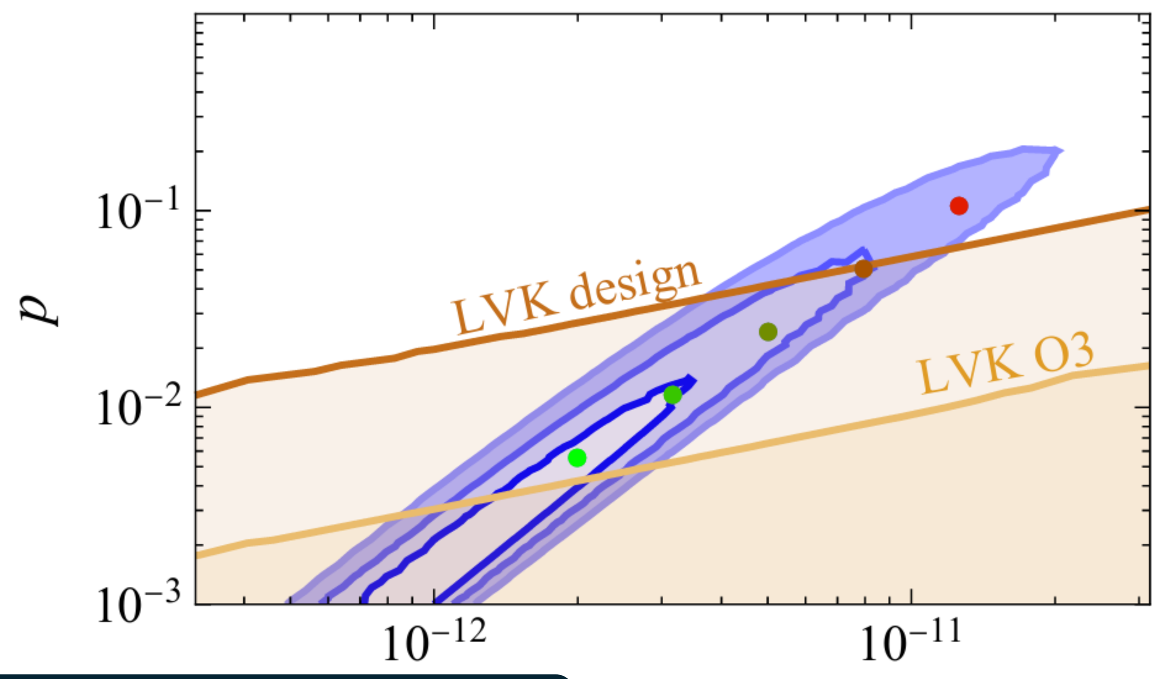

$$G\mu = 2 \cdot 10^{-12}\,, \qquad P = 4 \cdot 10^{-3}$$

UV completions: LVS

- In the LARGE volume scenario, three parameters:
  - Volume modulus. $\mathcal{V}$
  - Flux superpotential. W0
  - String coupling. g_s
- Fix string scale, intercommutation probability, modulus mass.

Balasubramanian et al'05

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  - Volume modulus. $\mathcal{V}$
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- Fix string scale, intercommutation probability, modulus mass.
- Assuming cosmic superstrings explain PTA signal:

$$\mathcal{V} = 3.3 \cdot 10^9 \,, \; g_s = 0.11$$

- 1 free parameter!

Balasubramanian et al'05

In the JJP box: Jackson et al'04
Other cases in e.g. O' Callaghan et al'10

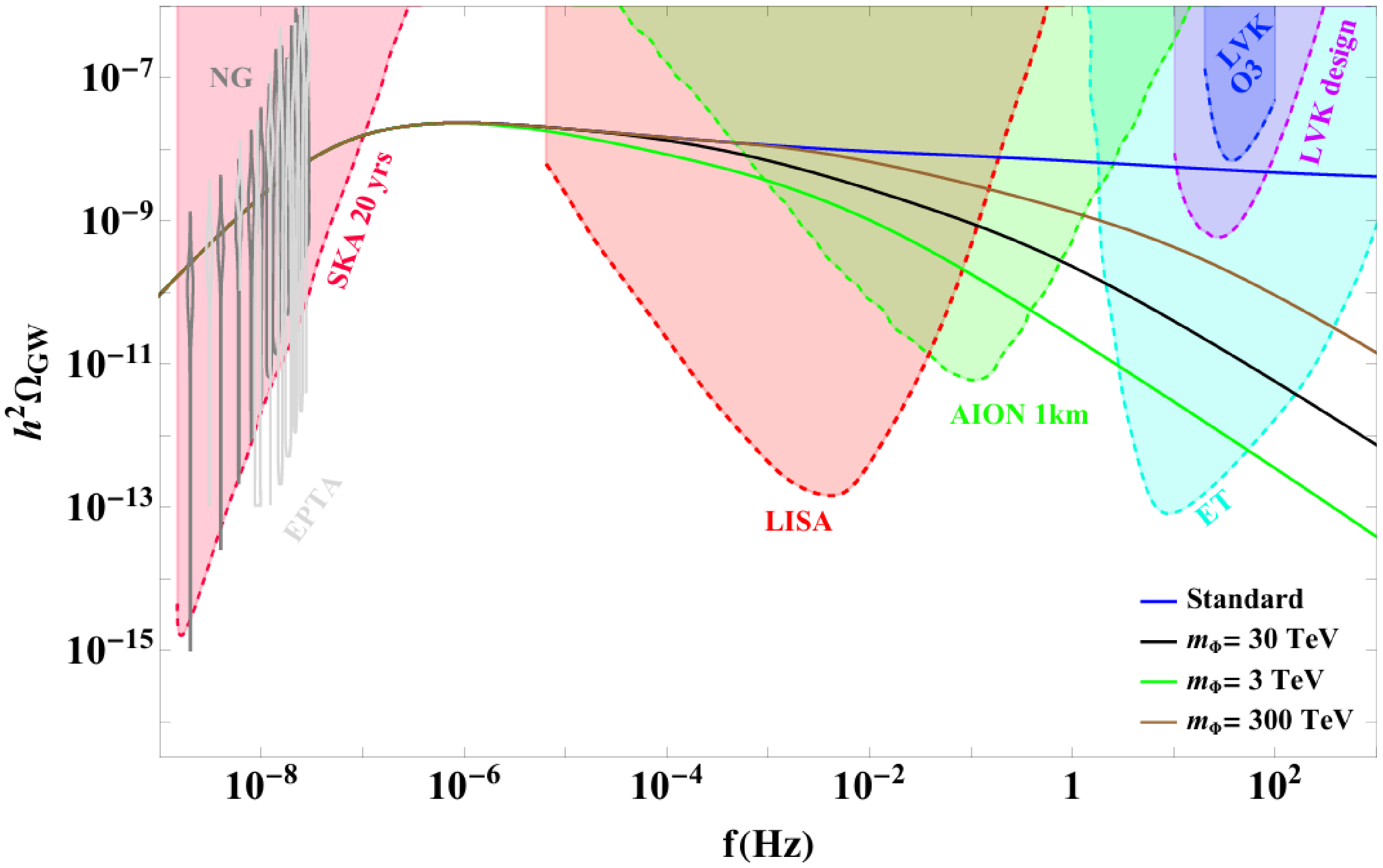
LVS + PTA = LISA

- In vanilla LVS, the volume modulus dominates the energy density and decays gravitationally:

$$f_{\mathrm{T}} = 8.6 \times 10^{-4}\ \mathrm{Hz} \quad \times \left(\frac{0.1}{\alpha P \chi} \times \frac{2 \times 10^{-12}}{G\mu} \times \frac{c_i}{48\pi} \right)^{1/2} \times \left(\frac{m_\Phi}{30\ \mathrm{TeV}} \right)^{3/2}$$

- The spectrum has a slope (matter domination) at a frequency fixed uniquely by W0!

Pre-BBN physics with cosmic strings



Vanilla LVS predicts a feature in the LISA band!

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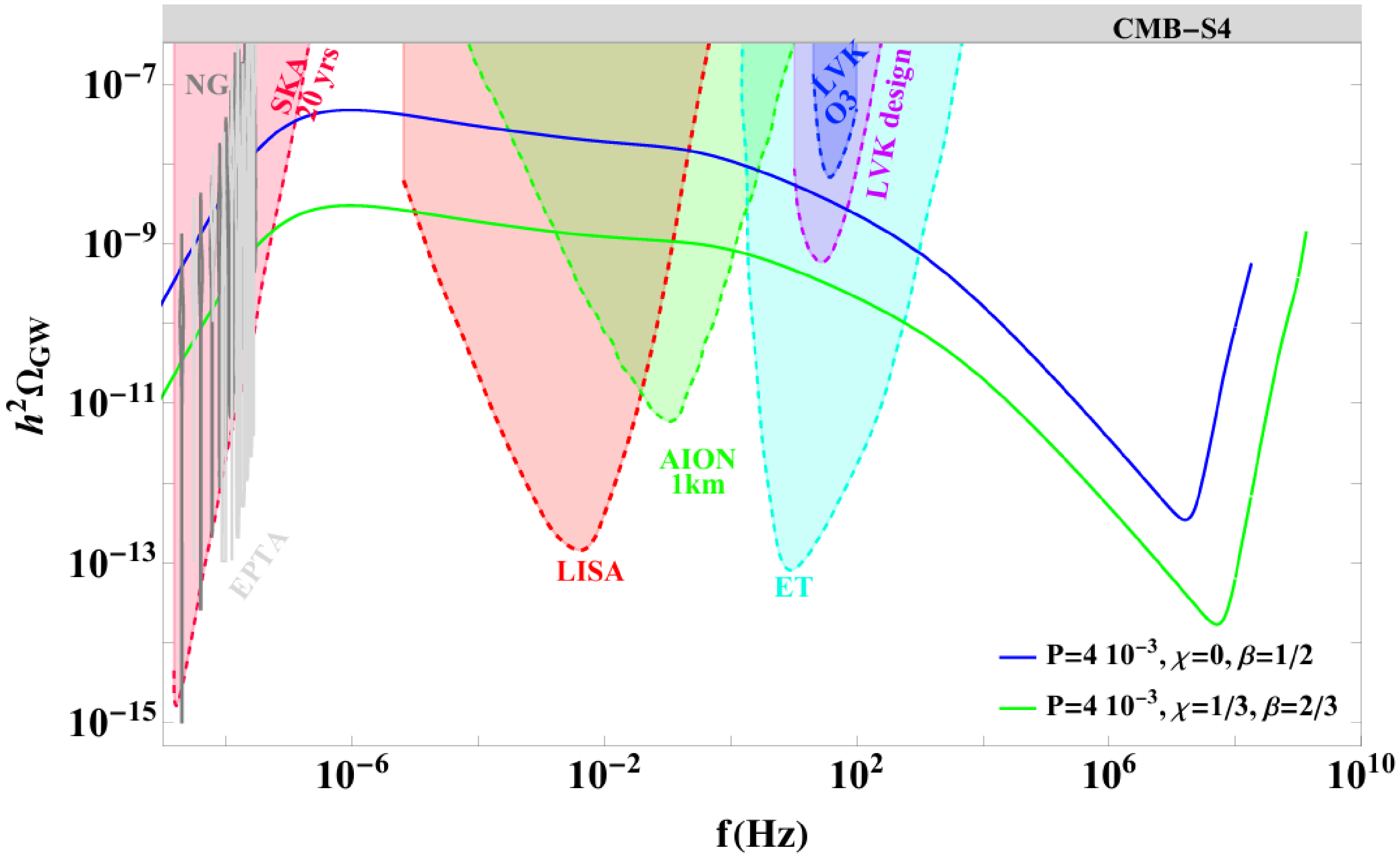
Varying tension

Constant tension:	Varying tension:
• Constant tension -> constant decay rate. • Loops shrink. • Maximum emission at half life.	• Decreasing tension -> more GWs at early times • Loops grow. • Maximum emission at formation.

More tension: more GWs



Two effects:

- Larger relative fraction of CS
- Larger tension: more GWs/efold
- Spectral indices not achievable with constant tension!

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Conclusions

- Cosmic (super)strings will be tested in the upcoming years.
- They provide a window into early Universe physics.
- UV complete scenarios make concrete predictions.
  - Eg: LVS has one (!) free parameter.
- In the hard-to-test case at low frequencies of very small tension, opportunities at high frequencies for high scale inflation!

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Thank you!

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