COSMIC SUPERSTRINGS IN LARGE VOLUME COMPACTIFICATIONS

PTAs, LISA & time-varying tension

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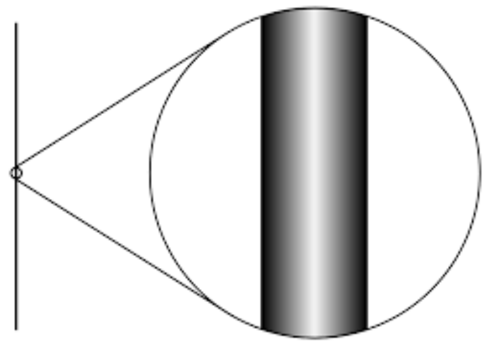
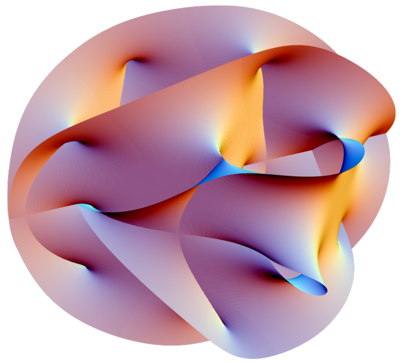
Based on 2411.04186 + 2504.20994 w/ (Anish Ghoshal), Gonzalo Villa

STRING THEORY FOR THE REAL WORLD

String Theory formulated in 10d: ***compactify*** *down to 4*



$\mathcal{M}_4 \times CY_3$



CY_3 *geometry* → *physics of* $\mathcal{M}_4$

Vast "String Landscape" - How can one ever make predictions?

Universal features:

- *New particles:* ***moduli, axions***
- *Extended objects:* ***strings***

Everything is dynamical

EXAMPLE 1 – NON STANDARD COSMOLOGY FROM STRINGS

*Exotic cosmological epochs arising from rolling **moduli and axions***

[Conlon,FR '22][Apers,Conlon,Copeland,Mosny,FR '24]

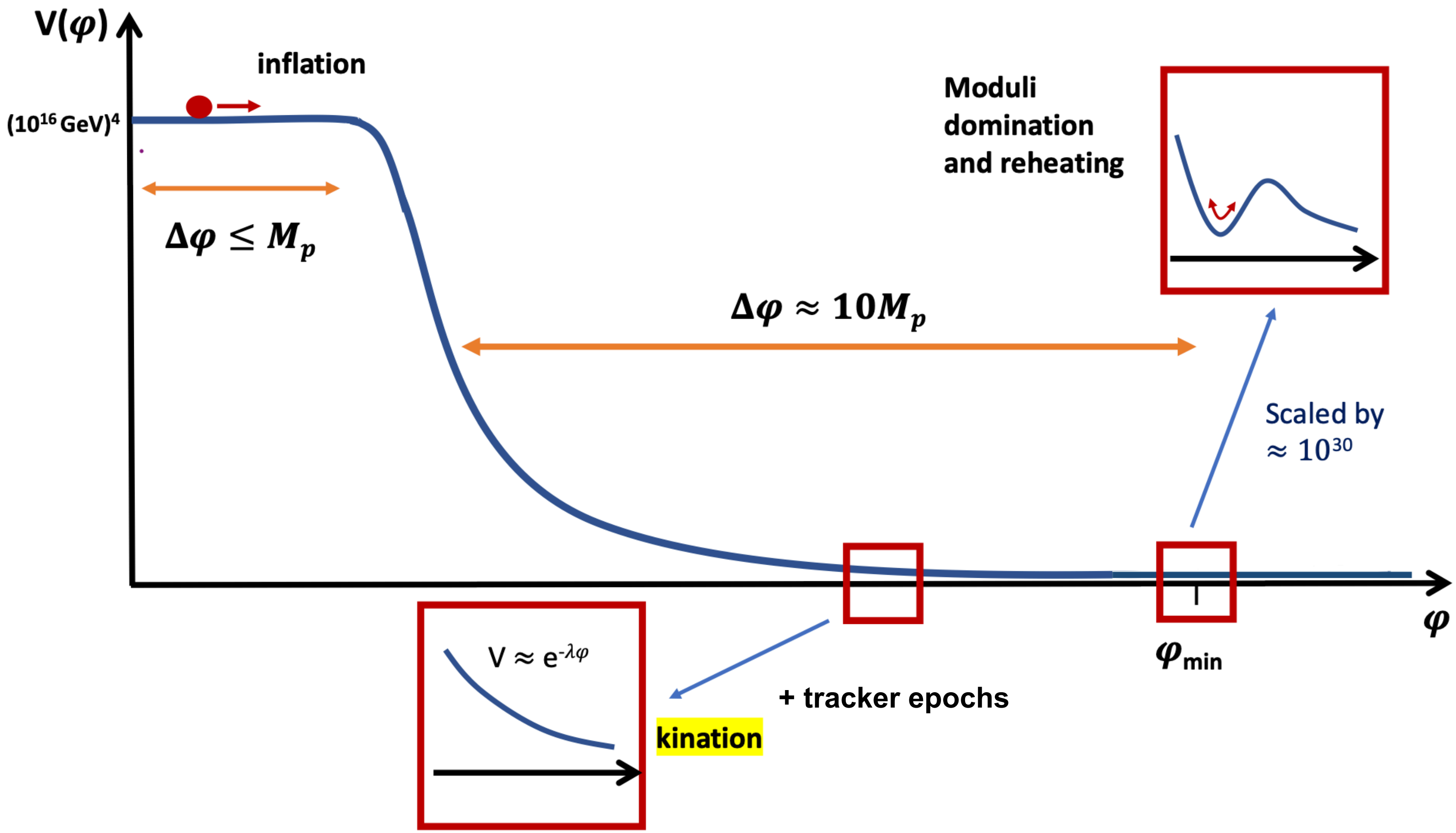


Figure from:

[Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23] [Apers,Conlon,Copeland,Mosny,FR '24]

EXAMPLE 2- COSMIC SUPERSTRINGS

Macroscopic F- or D- strings, produced in brane annihilation

[Witten '95][Polchisnki '88][Copeland,Myers,Polchinski '04]+...

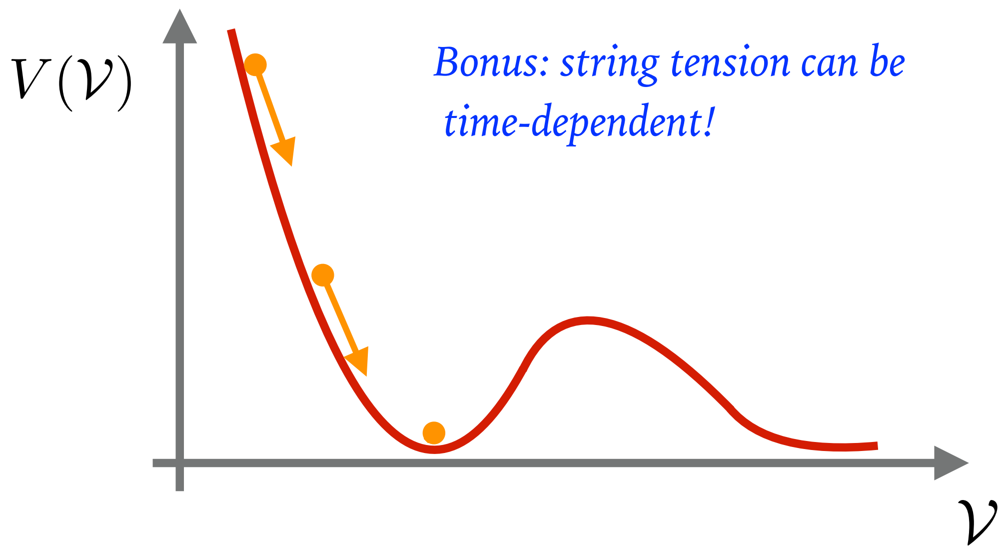
Puzzle: $$\sqrt{G\mu} = \frac{m_s}{M_P} \lesssim 10^{-6}$$

CMB, PTAs...

Very low string scale!

Two options: warping or <u>LARGE volume</u>

$$m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$$



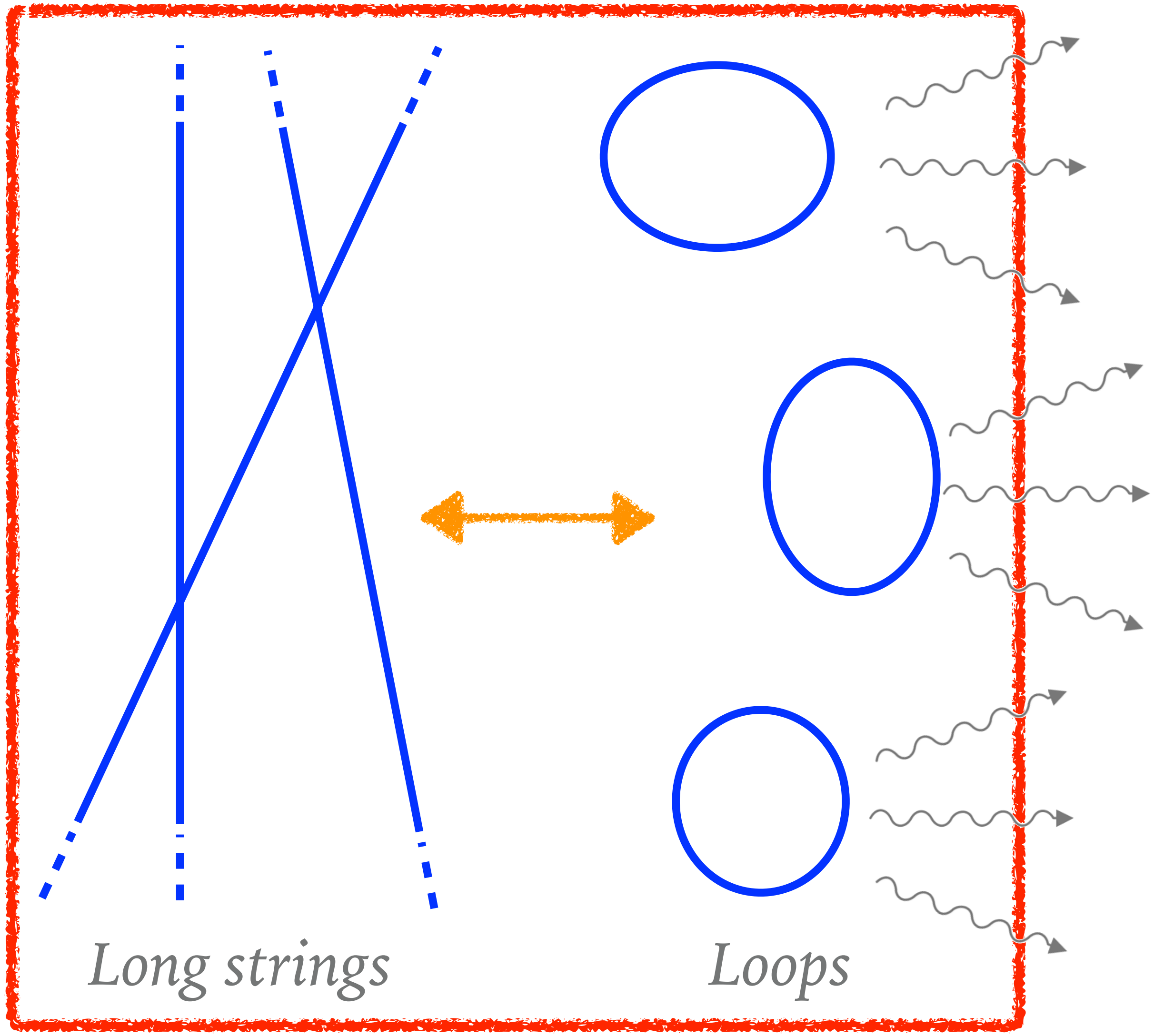
Bonus: string tension can be time-dependent!

<u>Natural incarnation:</u> ***LVS***

[Balasubramanian,Berglund,Conlon,Quevedo '05]
[Conlon,Quevedo,Suruliz '05]

GRAVITATIONAL WAVES FROM COSMIC (SUPER-)STRINGS I

"Scaling" equilibrium $\Omega_{\text{strings}} \sim \text{const}$



[Kibble '85][Bennet '86][Austin,Copeland,Kibble '93]
[Martins,Shellard '96][Martins,Shellard '02]+…

Gravitational waves

stochastic background

$\Omega_{GW} h^2$ *set by:*

$G\mu(\sim \mathcal{V}^{-1})$ *String tension*

$+$

$P(\sim g_s^2)$ *Intercomm. probability*

$+$

Cosmic history *Affected by moduli*

GRAVITATIONAL WAVES FROM COSMIC SUPERSTRINGS II

Long strings $\rho \sim \dfrac{\mu}{t^2}$

Loops decay to GWs $\dfrac{\mathrm{d}E}{\mathrm{d}t} = \Gamma G \mu^2$

energy in GWs

redshift

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\left|\frac{d\rho_{\rm GW}(f,t_0)}{df}\right| = \underbrace{\sum_k}_{\text{oscillator modes}} \frac{f}{\rho_c}\int_{t_F}^{t_0} d\tilde{t}\, \frac{dE_{\rm GW}}{d\tilde{t}}\, \underbrace{\frac{dn(\tilde{f},\tilde{t})}{d\tilde{f}}}_{\text{loop production}} \left(\frac{a(\tilde{t})}{a(t_0)}\right)^3$$

oscillator modes

loop production

I) GW emission extended in time — *signal extends to* ***low frequencies****

II) Information on cosmic history — *Background EOS affects slope*

Generalised framework for time-varying tension

[FR, Villa '24]
[Ghoshal, FR, Villa '25]

"STANDARD" LARGE VOLUME COMPACTIFICATION

*Depends **mostly** on* $\mathcal{V}, g_s$

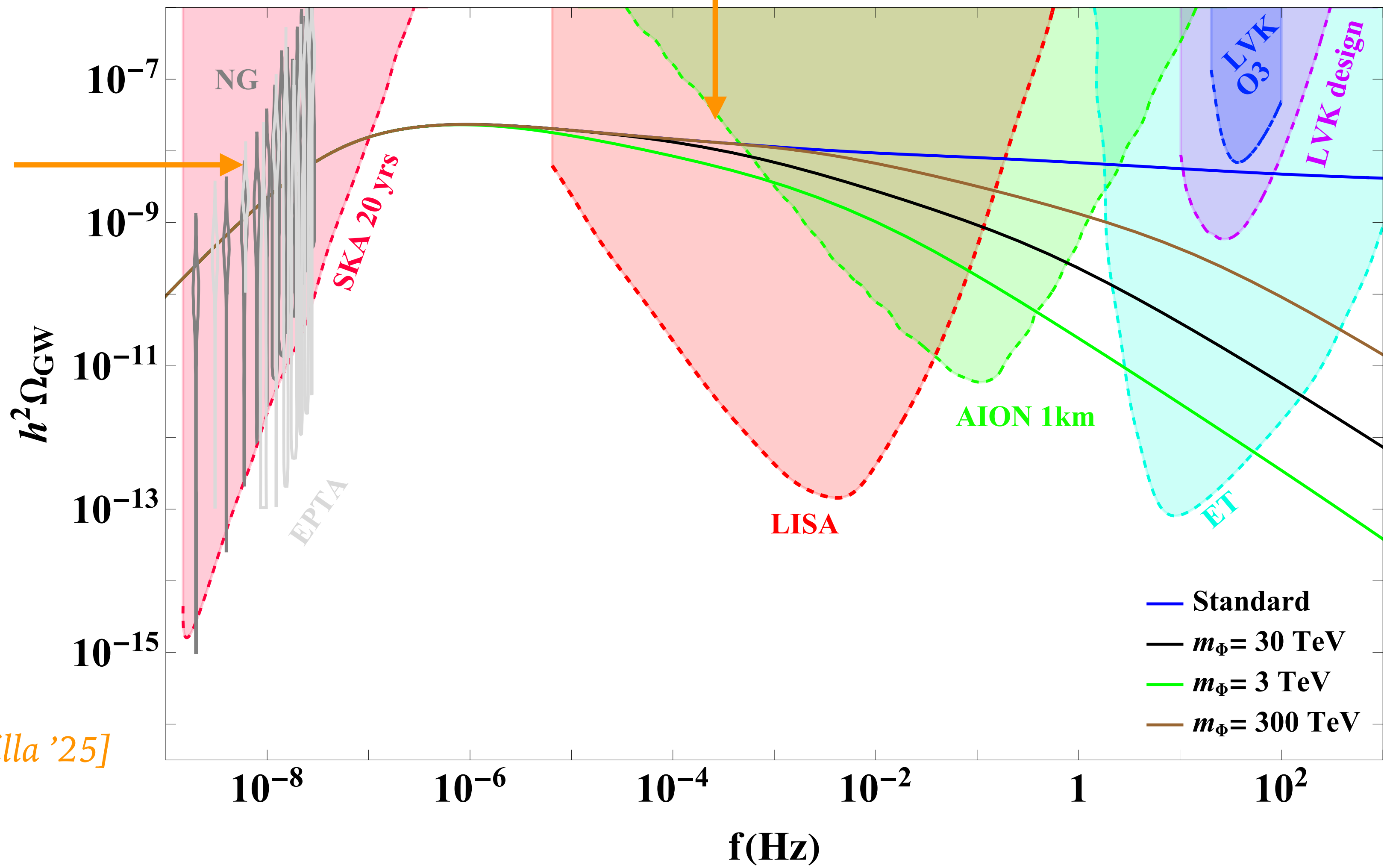
"stringy" parameters

Precisely right values in LVS ballpark!

Reheating from moduli decays

$$t_{\rm reh} \sim \frac{1}{\Gamma_\Phi} = \left(\frac{1}{4\pi}\frac{m_\Phi^3}{M_P^2}\right)^{-1}$$

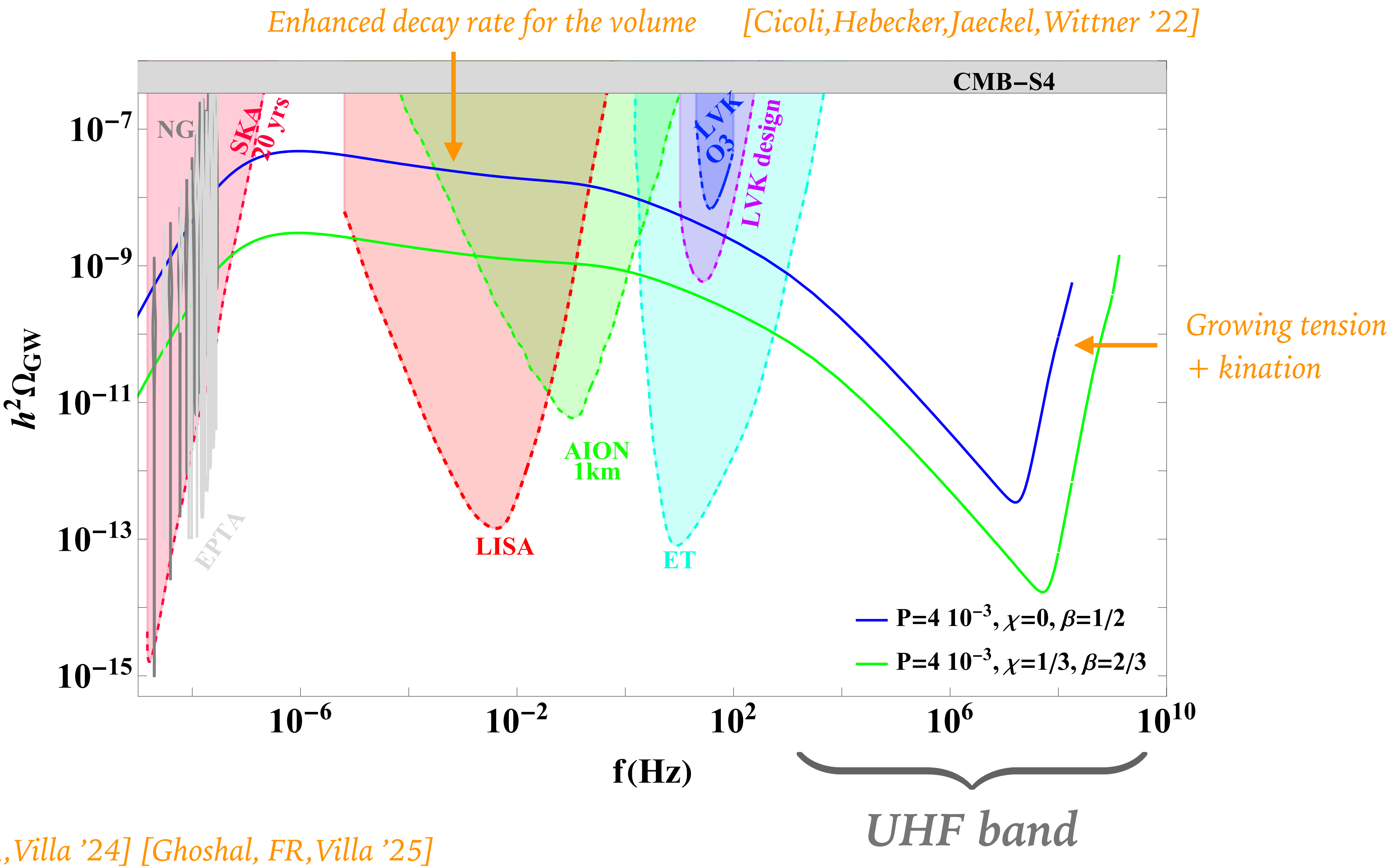
Amplitude fit to PTA data



[Ghoshal,FR,Villa '25]

EFFECT OF KINATION & VARYING TENSION

Fine tuned example: long kination, short matter domination



[FR,Villa '24] [Ghoshal, FR,Villa '25]

OUTLOOK

*Computed GW spectra for **cosmic superstrings** in various scenarios:*

Analytical + numerical	*Ballpark of realistic compactifications*	***time-dependent** tension*
Detailed understanding of turning points, slopes, etc	*Sharp predictions both in interferometer range and UHF*	*generic stringy prediction, also applicable for field theory strings*

Much more to explore:

other time-dep. moduli, wrapped branes, backreaction on cosmology

[Brunelli,Cicoli,Pedro '24-'25][Conlon,Copeland,Hardy,Sanchez-Gonzalez '24-'25][Brunelli,FR,Villa WIP]

***Long term** : cosmic(super)string "GW-verse"?*

THANK YOU FOR YOUR ATTENTION!

WHAT IS NEW ?

Explicit embedding into realistic string compactification:

i) Naturally predicts ***low string tension***

$$\mu = \frac{g_s^{1/2}}{2\mathcal{V}} M_P^2$$

ii) Signal shape fixed by few ***string theoretic*** *parameters*

E.g. intercommutation probability

$$P = 0.5 g_s^2 \left[\frac{6\pi}{\log\left(A\mathcal{V}\right)} \right]$$

iii) Stringy cosmology

E.g. reheating through moduli decays

$$m_\Phi = \mathcal{O}(1) \times \frac{M_P}{\mathcal{V}^{3/2} g_s^{1/4}}$$

$$\Gamma_\Phi = \mathcal{O}(1) \times \frac{1}{48\pi} \frac{m_\Phi^3}{M_P^2} \sim \frac{M_P}{\mathcal{V}^{9/2} g_s^{3/4}}$$

In LVS, length of matter domination epoch fixed by volume

STRINGS WITH VARYING TENSION

String EOMs

$$\overset{\bullet}{\begin{bmatrix} \textit{Energy density} \\ \textit{Momentum} \end{bmatrix}} + \overbrace{\left(2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu}\right)}^{H_{\text{eff}}} \begin{bmatrix} \textit{Energy density} \\ \textit{Momentum} \end{bmatrix} + \ldots = 0$$

[Emov, Ramazanov,Samanta '21][Conlon,Copeland,Hardy,Sanchez-Gonzalez '24-'25]

Modified network dynamics

[FR,Villa '24]

Relevant to <u>any</u> kind of string with varying tension: wrapped branes, axion or QFT strings

Enhanced GW emission

E.g. volume kination $\Omega_{\text{GW}} h^2 \sim f^4$

[Ghoshal,FR,Villa '24]

ANALYTICAL ESTIMATES

Transition between two regimes

t_Δ

$$\rho(t) \sim \begin{cases} a^{-m}, & t < t_\Delta \\ a^{-n}, & t \geq t_\Delta \end{cases}, \qquad G\mu(t) \sim \begin{cases} t^{-p}, & t < t_\Delta \\ t^{-q}, & t \geq t_\Delta \end{cases}$$

Loops can form $t < t_\Delta$ / $t \geq t_\Delta$ *and emit* $t < t_\Delta$ / $t \geq t_\Delta$

Need to understand which times dominate integrals

Kination to Tracker

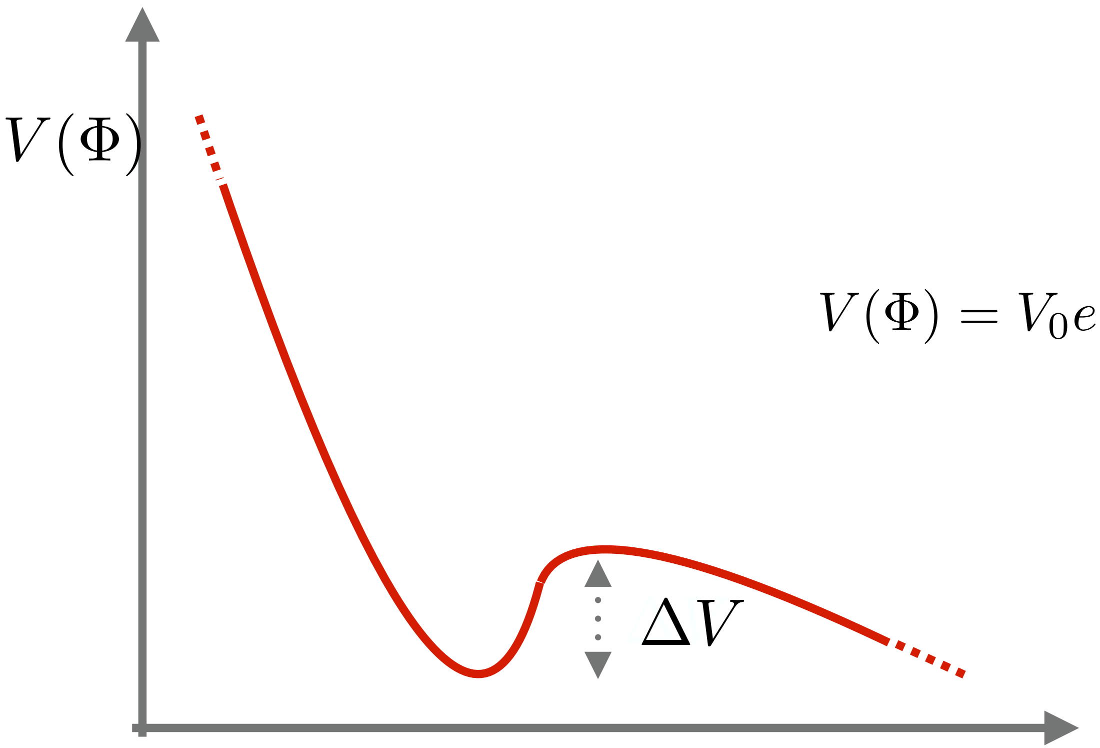
early times dominate

$$h^2\Omega_{\rm GW}^{(1)} \simeq A_\Delta \left(\frac{f}{f_\Delta}\right)^F, \quad F = \frac{2(m(p+1)-4)}{m-2}.$$

LARGE VOLUME SCENARIO (LVS)

Setting: Type IIB flux compactifications

Simple EFT for volume modulus Φ + *axion*



uplift to dS

$$V(\Phi) = V_0 e^{-\sqrt{\frac{27}{2}}\Phi}\left(1 - \alpha\Phi^{3/2}\right) + \varepsilon e^{-\sqrt{6}\Phi}$$

[Conlon, Quevedo, Suruliz '05]
[Balasubramanian, Berglund, Conlon, Quevedo '05]

$\mathcal{V}_{\text{min}} \sim e^{1/g_s}$ ⟶ *generates hierarchies*