GRAVITATIONAL WAVES FROM COSMIC STRINGS & WRAPPED BRANES

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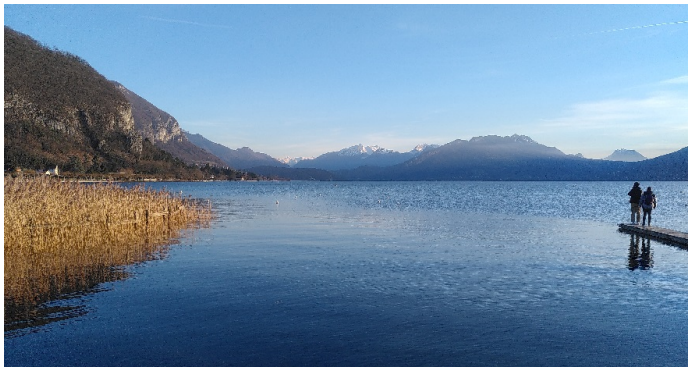
Strings and Cosmology meeting, Annecy

KU LEUVEN



Based on 2411.04186 , 2504.20994, 2512.xxxxx

with Luca Brunelli, Anish Ghoshal, Gonzalo Villa

FROM STRINGS TO THINGS

Vast String Landscape - how can one ever make predictions?

Universal features:

New particles: ***moduli, axions, dark photons***

Can affect background cosmology

Couplings are ***dynamical***

Recent discussion in [Sen' 25]

Extended objects: ***strings, branes***

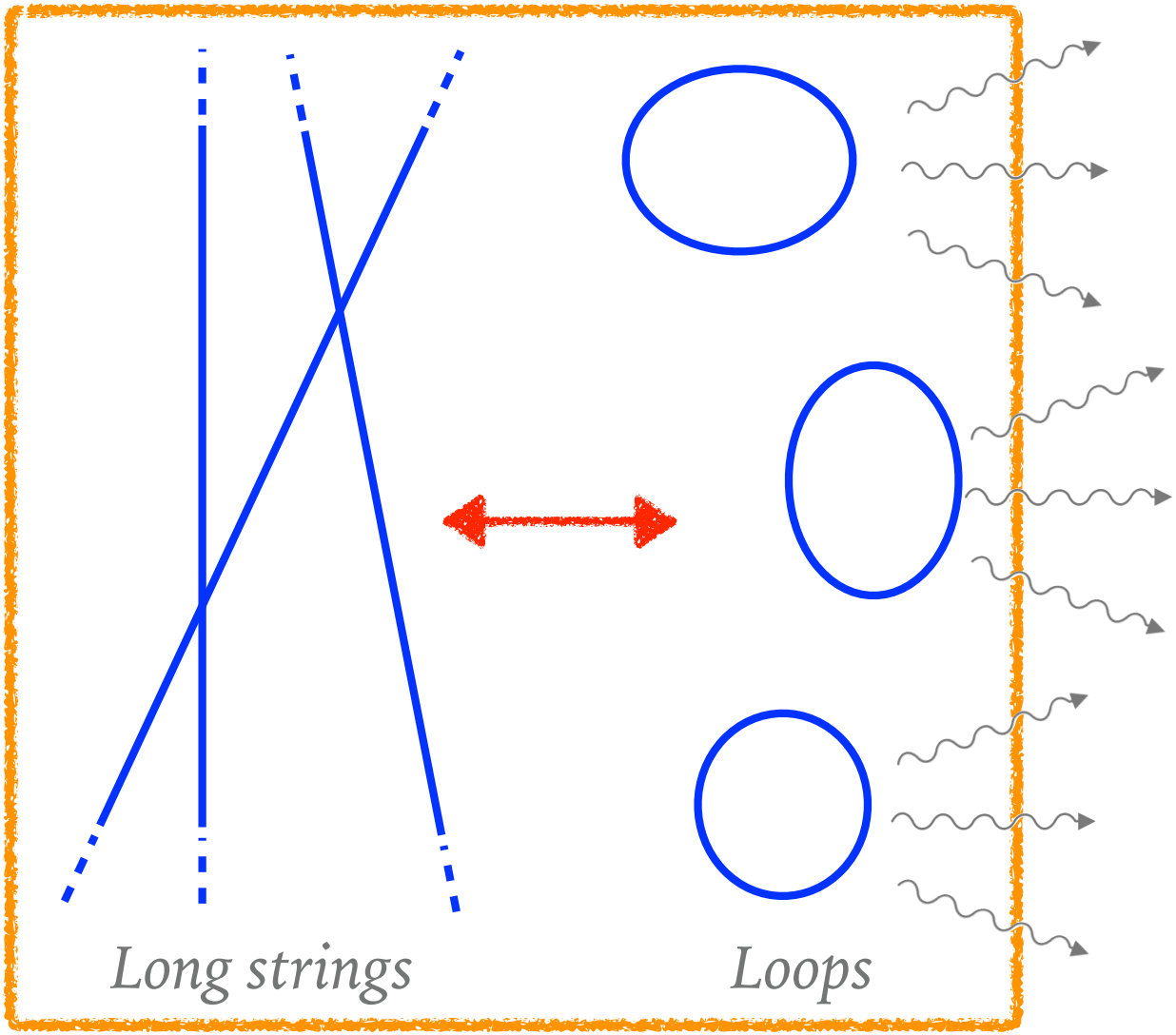
Can emit GWs

Connections between ***String Pheno, Swampland & Cosmology***

COSMOLOGY INGREDIENTS

COSMIC (SUPER-)STRING NETWORKS

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



Gravitational waves

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

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

$+$

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

$+$

Cosmic history *Affected by moduli*

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

GRAVITATIONAL WAVES FROM COSMIC STRINGS

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

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

energy in GWs

redshift

$$\Omega_{\mathrm{GW}}(f) \equiv \frac{f}{\rho_c}\left|\frac{d\rho_{\mathrm{GW}}(f,t_0)}{df}\right| = \sum_k \frac{f}{\rho_c}\int_{t_F}^{t_0} d\tilde{t}\,\frac{dE_{\mathrm{GW}}}{d\tilde{t}}\,\frac{dn(\tilde{f},\tilde{t})}{d\tilde{f}}\left(\frac{a(\tilde{t})}{a(t_0)}\right)^3$$

oscillator modes

loop production

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

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

STRING THEORY INGREDIENTS

LOW ENERGY IMPRINTS: MODULI & AXIONS

THE universal prediction: moduli and axions

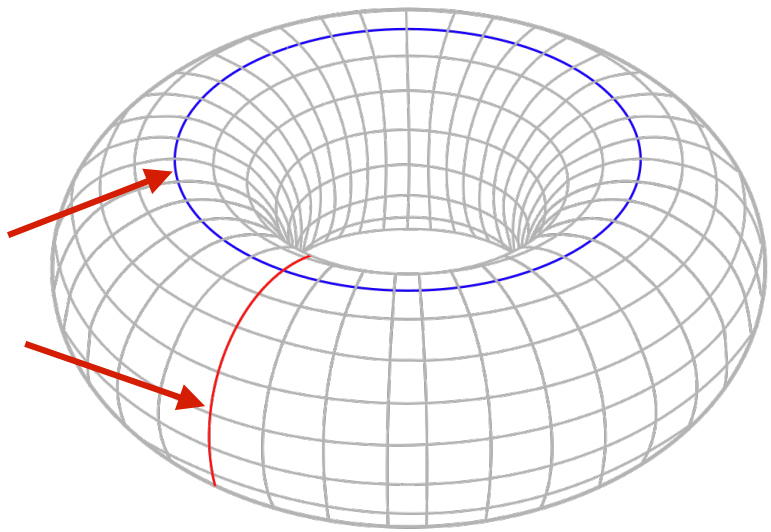
Zero modes of 10d fields ⟷ *Massless scalars in 4d*

$g_{\mu\nu}, B_{\mu\nu}, C_{\mu\nu}, C_{\mu\nu\rho\sigma}$

$\Phi_i = \varphi_i + i a_i$

metric — *higher forms* — *saxion* — *axion*

Examples:



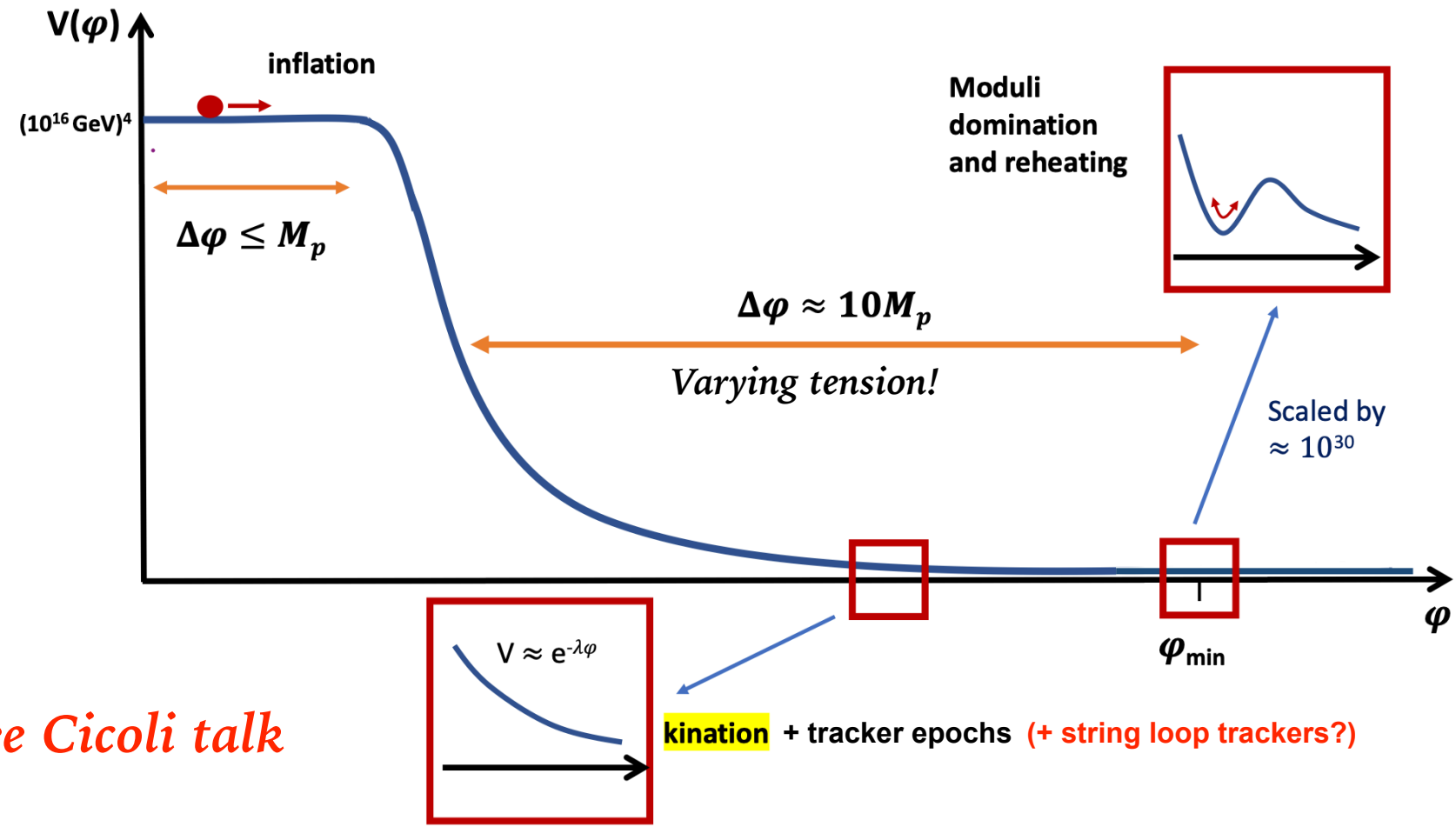
cycle volumes

overall volume

NON STANDARD COSMOLOGY FROM MODULI

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

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



See Cicoli talk

Figure adapted from [Cicoli,Conlon,Maharana,Quevedo,Parameswaran,Zavala '23]

STRINGS & WRAPPED BRANES

4d strings → *10d strings in non-compact dimensions*

4d strings → *10d p-brane wrapping (p-1)cycle* *[Brunelli,Cicoli,Pedro '25 x2]*

F-strings

$$\mu_{\mathrm{F1}} \equiv m_s^2 = \frac{{g_s}^{1/2} M_{P,4}^2}{4\pi \mathcal{V}}$$

Wrapped branes

$$\mu_{Dp} \sim \frac{m_s^2}{g_s} \mathcal{V}_\Sigma$$

Can change also at fixed overall volume

"Swampy" bounds

(Upper bound on) QG cutoff

$$\mu \gtrsim \Lambda_s^2$$

where

$$\left| \frac{1}{\Lambda_s} \frac{\mathrm{d}\Lambda_s}{\mathrm{d}t} \right| \leq H\sqrt{d-1}$$

[Martucci,Risso,Valenti,Vecchi '24]
[Grieco,Ruiz,Valenzuela '25]

[Brunelli,FR,Villa '25]

STRINGS WITH VARYING TENSION

$\mu \equiv \mu(\varphi_i(t))$ *time dependence from moduli*

Affects GW emission

$$\mu \sim t^{-q} \quad a(t) \sim t^{2/n}$$

$$\Omega_{\rm GW} = \Omega_{\rm GW,0} \left(\frac{f}{f_0}\right)^A, \quad A \equiv 2\left[1 + \frac{qn-2}{n-2}\right]$$

General bound

$$A \leq 2 + \frac{8}{n-2}$$

(Assumptions TBD)

$q = 1$ *for D3's, NS5's in type IIB compactifications*

A becomes independent of background!

[Brunelli, FR, Villa '25]

PUTTING EVERYTHING TOGETHER: “CONCRETE” SCENARIOS

COSMIC STRINGS IN THE REAL WORLD

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

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

Puzzle:

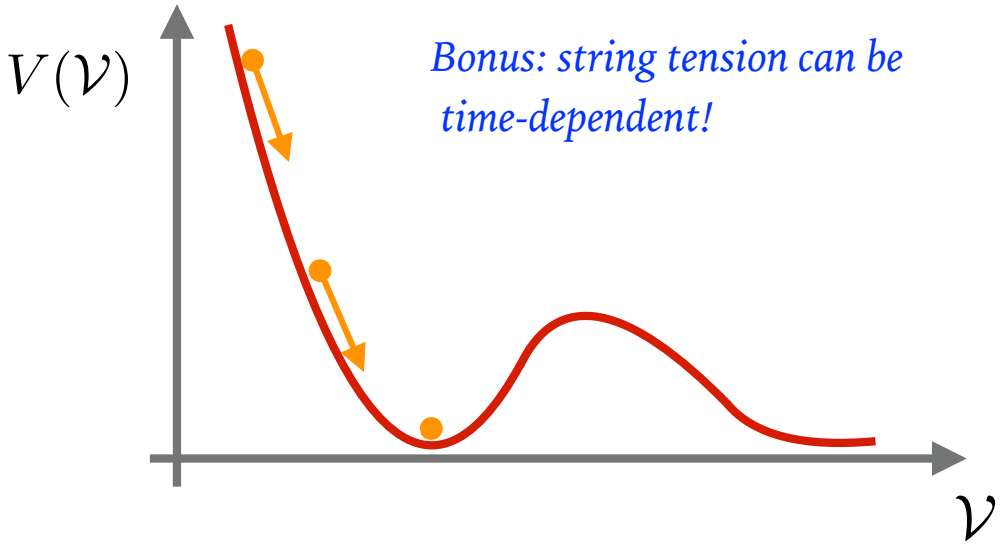
$$\sqrt{G\mu} = \frac{m_s}{M_P} \lesssim 10^{-6}$$

CMB, PTAs…

Very low string scale!

Two options: warping or LARGE volume

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



Bonus: string tension can be time-dependent!

Natural incarnation: ***LVS***

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

VANILLA LVS – CONSTANT TENSION

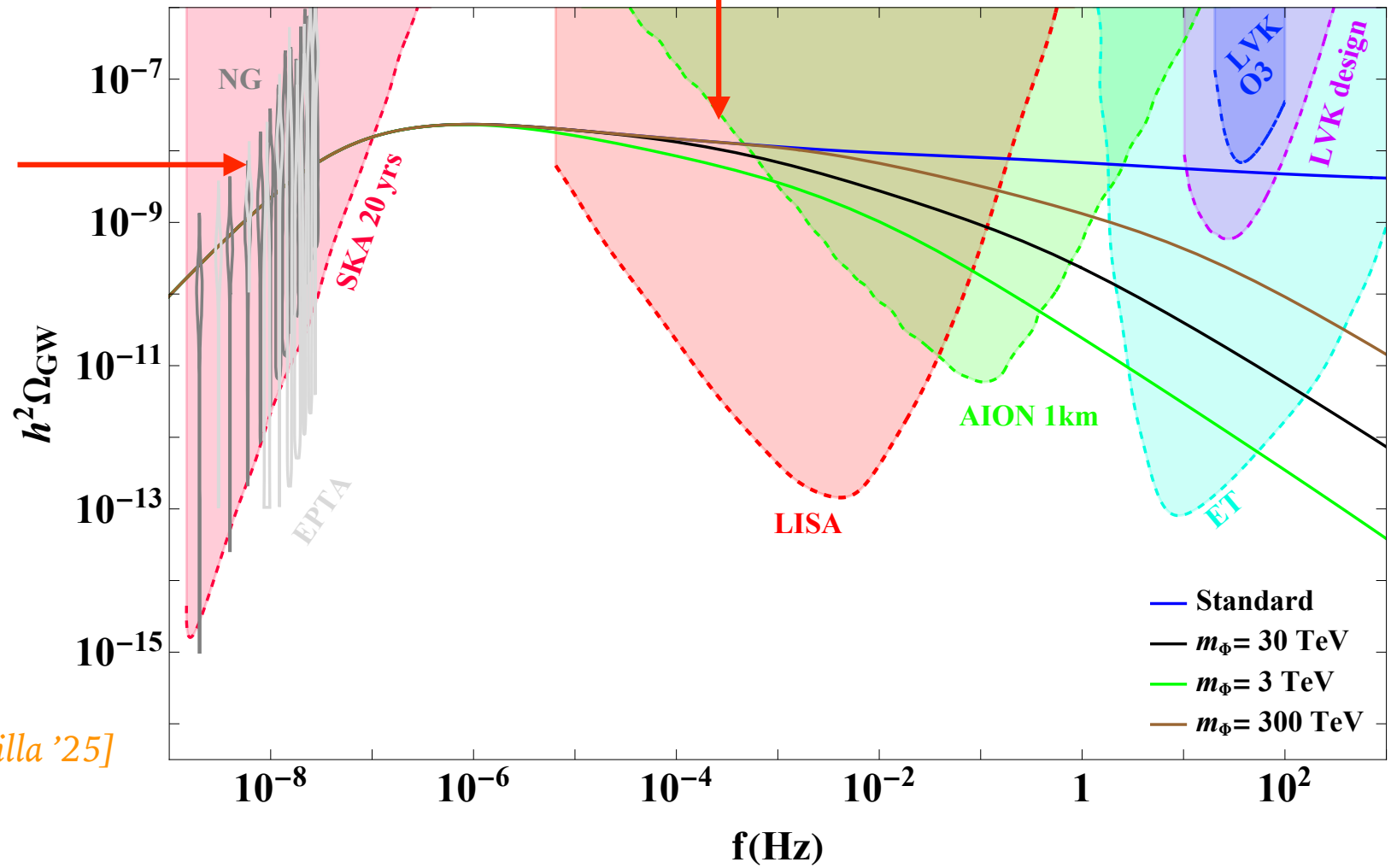
Depends only on $\mathcal{V}, g_s$

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

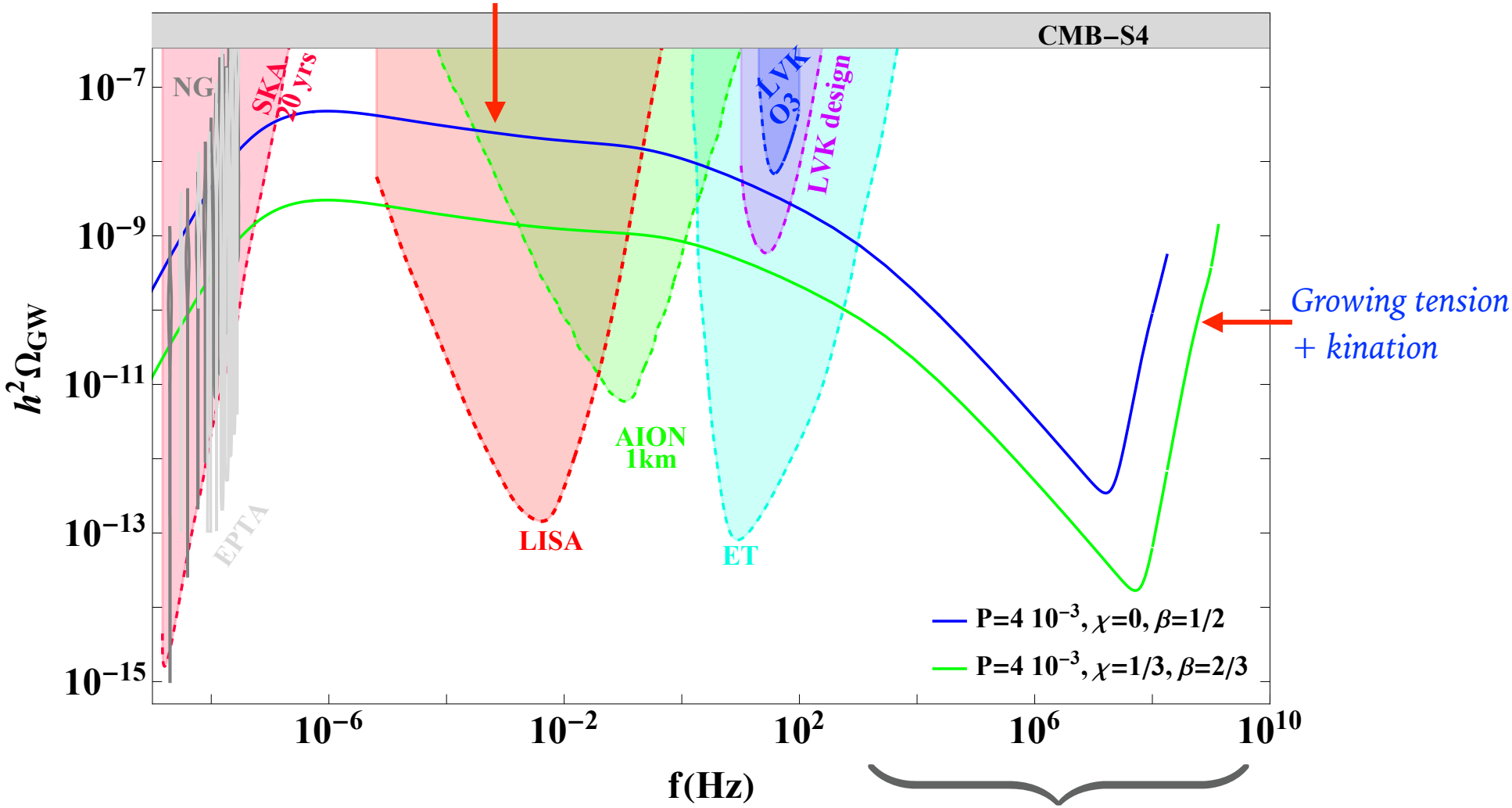


[Ghoshal,FR,Villa '25]

EFFECT OF VOLUME KINATION & VARYING TENSION

Fine tuned example: long kination, short matter domination

Enhanced decay rate for the volume *[Cicoli,Hebecker,Jaeckel,Wittner '22]*



Growing tension + kination

[Ghoshal,FR,Villa '25]

UHF band

OUTLOOK

- *Cosmic strings: promising bridge between strings/cosmology*

Qualitative new features: time-dependent tension, small P

F-strings *wrapped branes*

Percolation, Backreaction (loop trackers) *[Conlon,Copeland,Hardy,Sanchez-Gonzalez '24-'25 (x2)]*

- *Numbers in right ballpark to connect with experimental efforts*

In "vanilla" string compactification scenarios, e.g. LVS

- *Swampland conjectures give bounds on* $\frac{\dot{\mu}}{\mu}$ *and slope of* Ω_{GW}

connection to other observables?

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

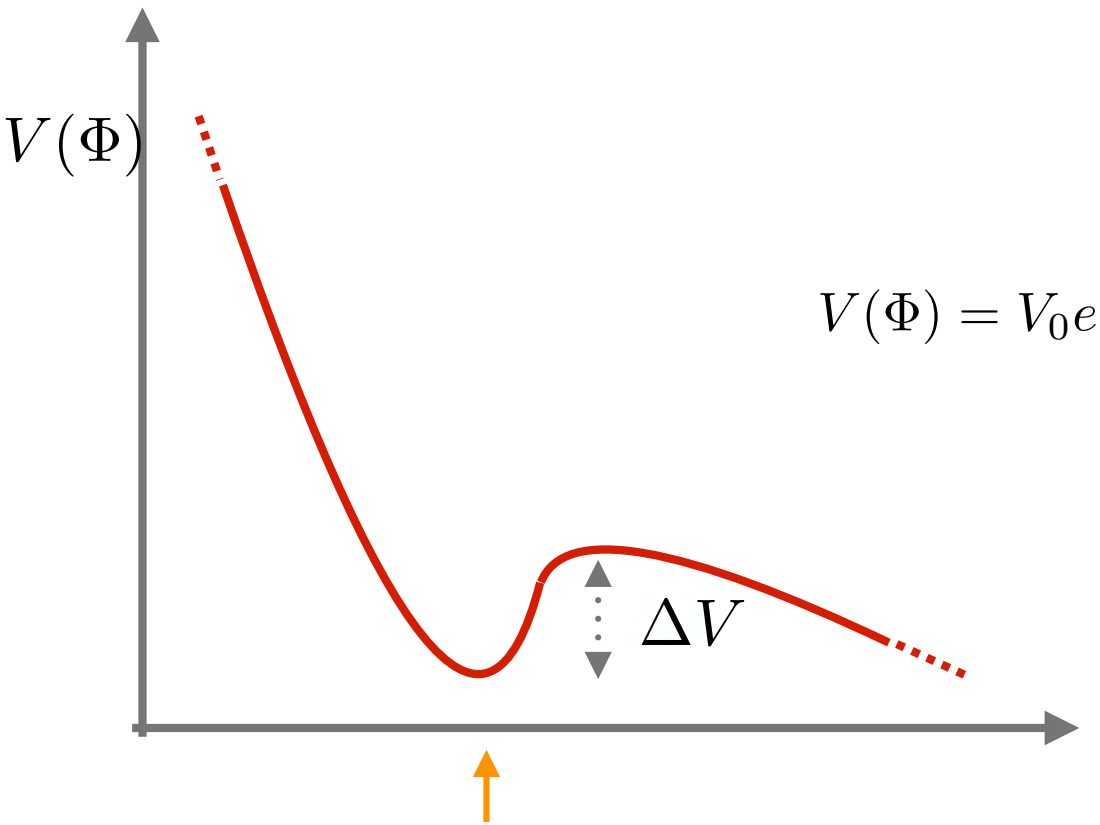
THANK YOU FOR YOUR ATTENTION!

BACK-UP SLIDES

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]

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

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

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

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

SHORTENING MATTER DOMINATION

Volume long lived as it is gravitationally coupled to axions

What about other fields?

$$m_H^2 \sim m_{3/2}^2 \left[\alpha_0 + \alpha_{\rm loop}\ \ln\left(\frac{m_{\rm KK}}{m_{3/2}}\right)\right] \simeq \left(\frac{W_0}{\mathcal{V}}\right)^2 \left[\alpha_0 + \alpha_{\rm loop}\ \ln\left(\frac{\mathcal{V}^{1/2}}{W_0}\right)\right] M_P^2$$

Fine tuning @TL gives enhanced coupling!

[Cicoli, Hebeecker, Jaeckel, Wittner '22]

$$\Gamma_{\Phi\to HH} \gg \Gamma_{\Phi\to aa}$$

Short Volume Lifetime (SVL)

Less GW suppression from matter domination → *Access high frequency/ earlier times*

STRINGS WITH VARYING TENSION

String EOMs

$$\dot{\begin{bmatrix} \text{Energy density} \\ \text{Momentum} \end{bmatrix}} + \Big(\underbrace{2\frac{\dot{a}}{a} + \frac{\dot{\mu}}{\mu}}_{H_{\rm eff}}\Big) \begin{bmatrix} \text{Energy density} \\ \text{Momentum} \end{bmatrix} + \ldots = 0$$

[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

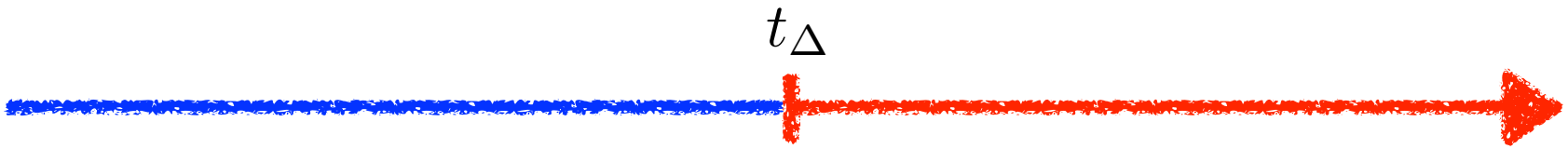
E.g. volume kination

$$\Omega_{\rm GW} h^2 \sim f^4$$

[Ghoshal, FR, Villa '24]

ANALYTICAL ESTIMATES

Transition between two regimes



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

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

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