Scalar-Induced Gravitational Waves from Thermal Inflation in Supercool(ed) Phase Transitions

Tamara Caldas[1]
in collaboration with D. Schmitt & L. Sagunski

19 August 2026
SEWM 2026 @ Helsinki, Finland

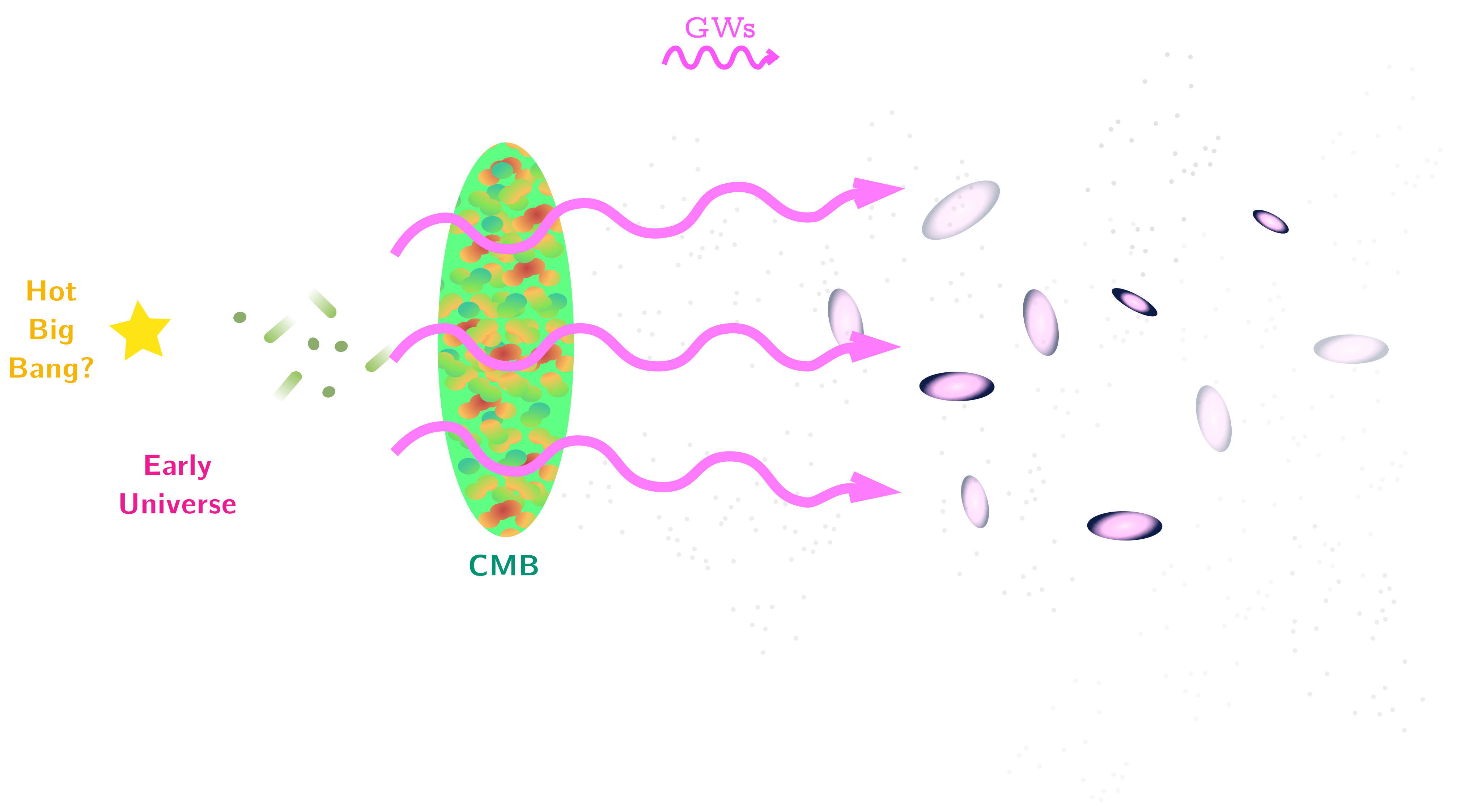
[1]caldas@itp.uni-frankfurt.de

Motivation

We are interested in:

GW probes of cosmological 1st order phase transitions

Require Beyond SM physics → smoking-gun signal!

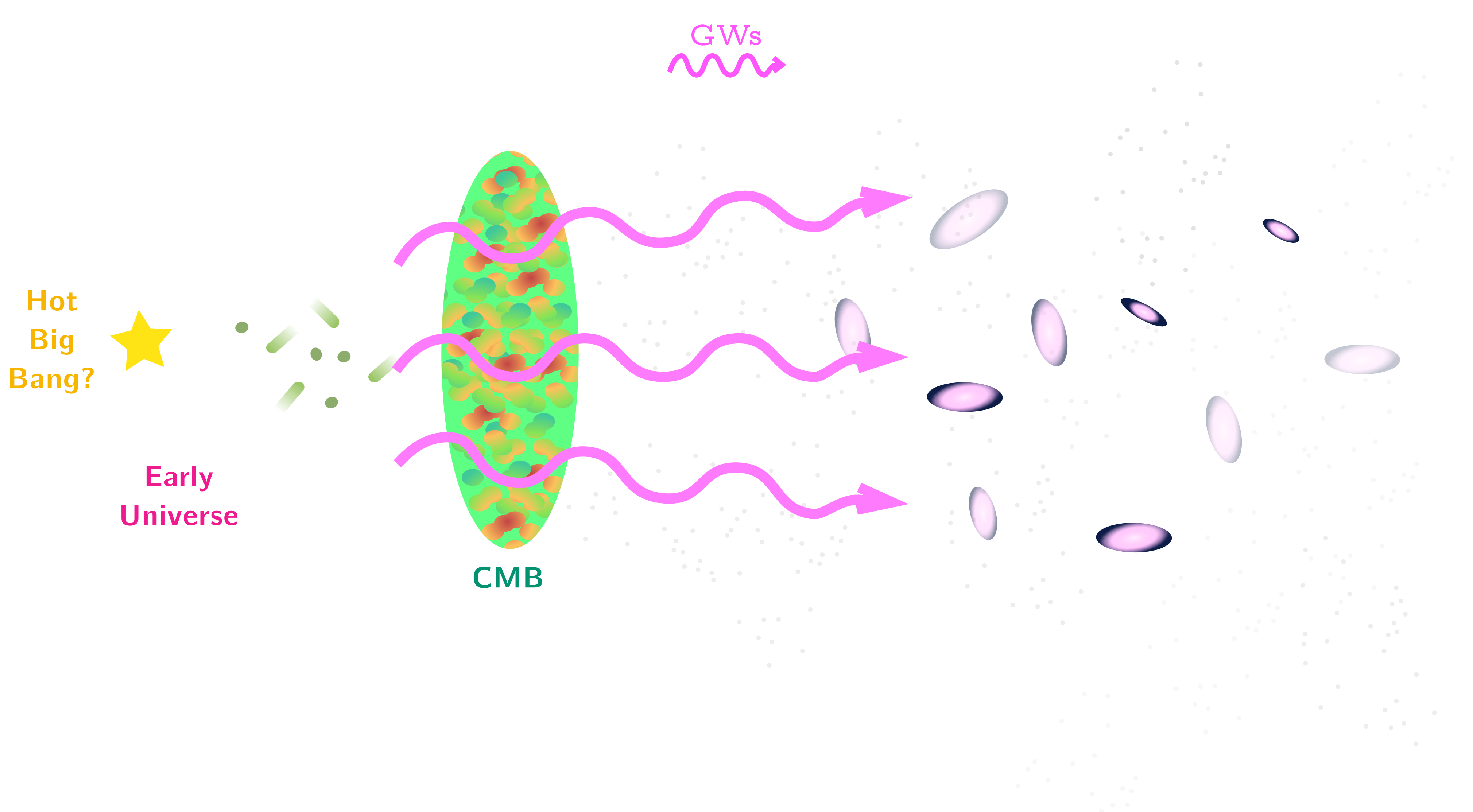


Motivation

We are interested in:

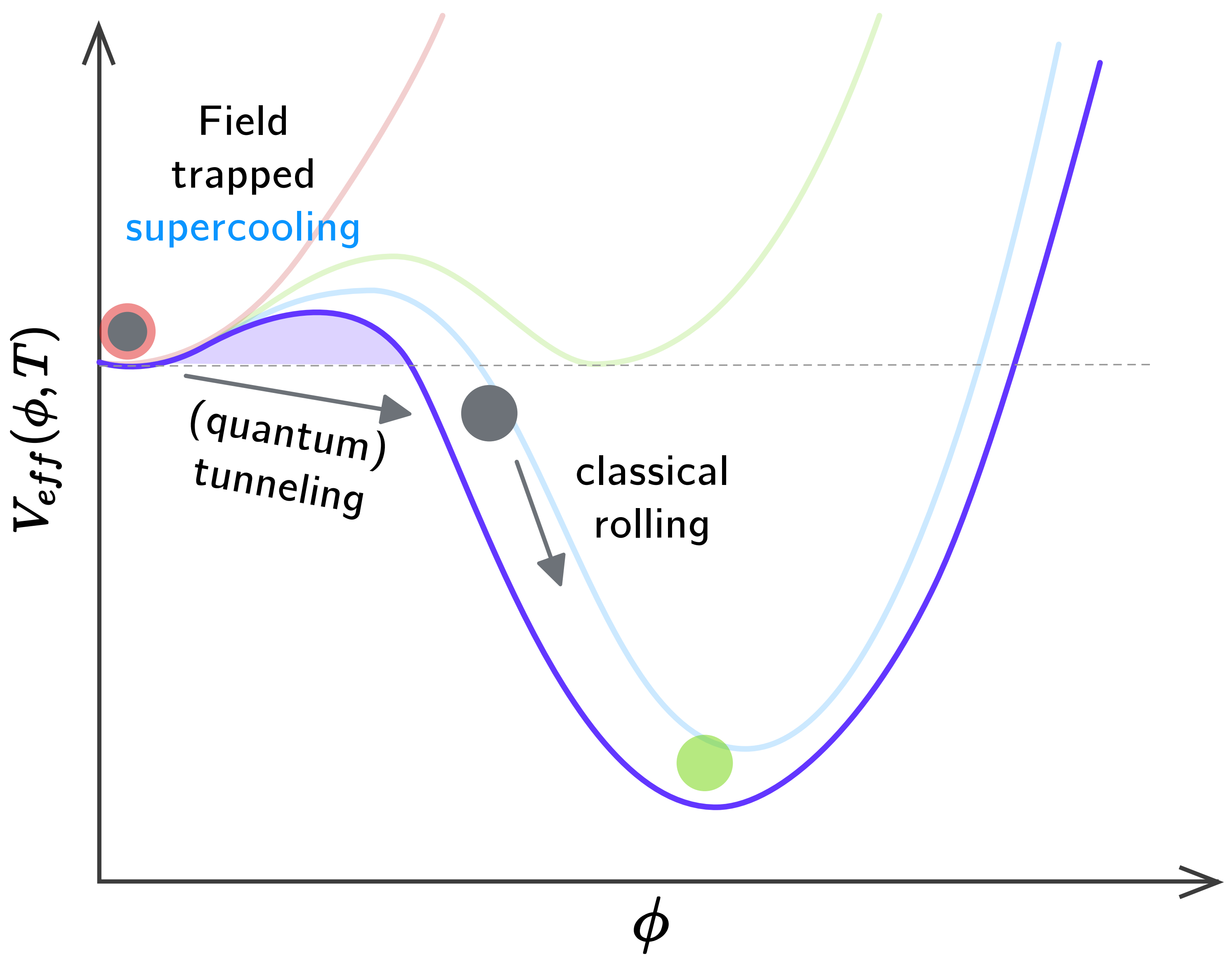
GW probes of cosmological 1st order phase transitions

Require Beyond SM physics → smoking-gun signal!

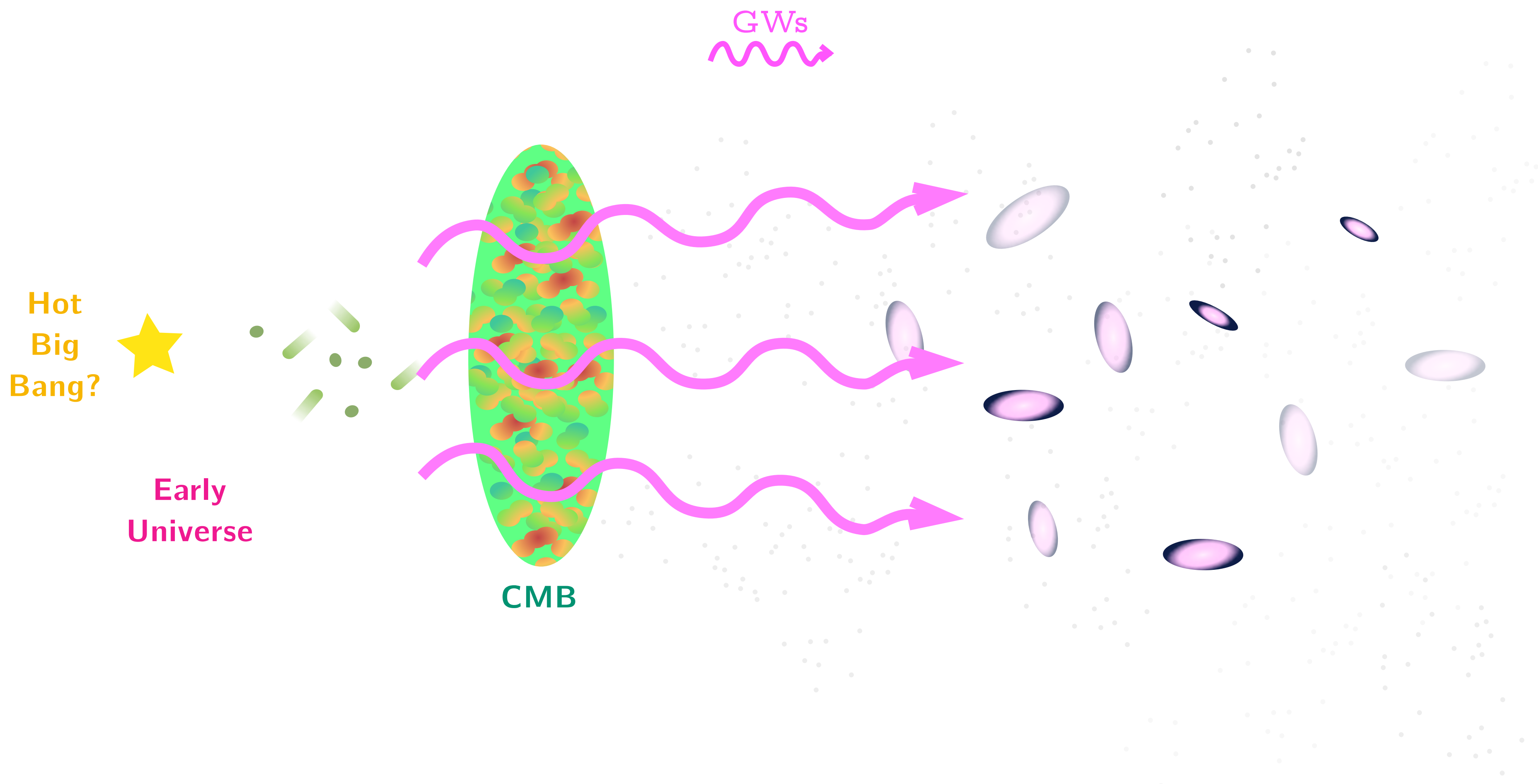


A common scenario:

Supercooled 1st order phase transition



Motivation



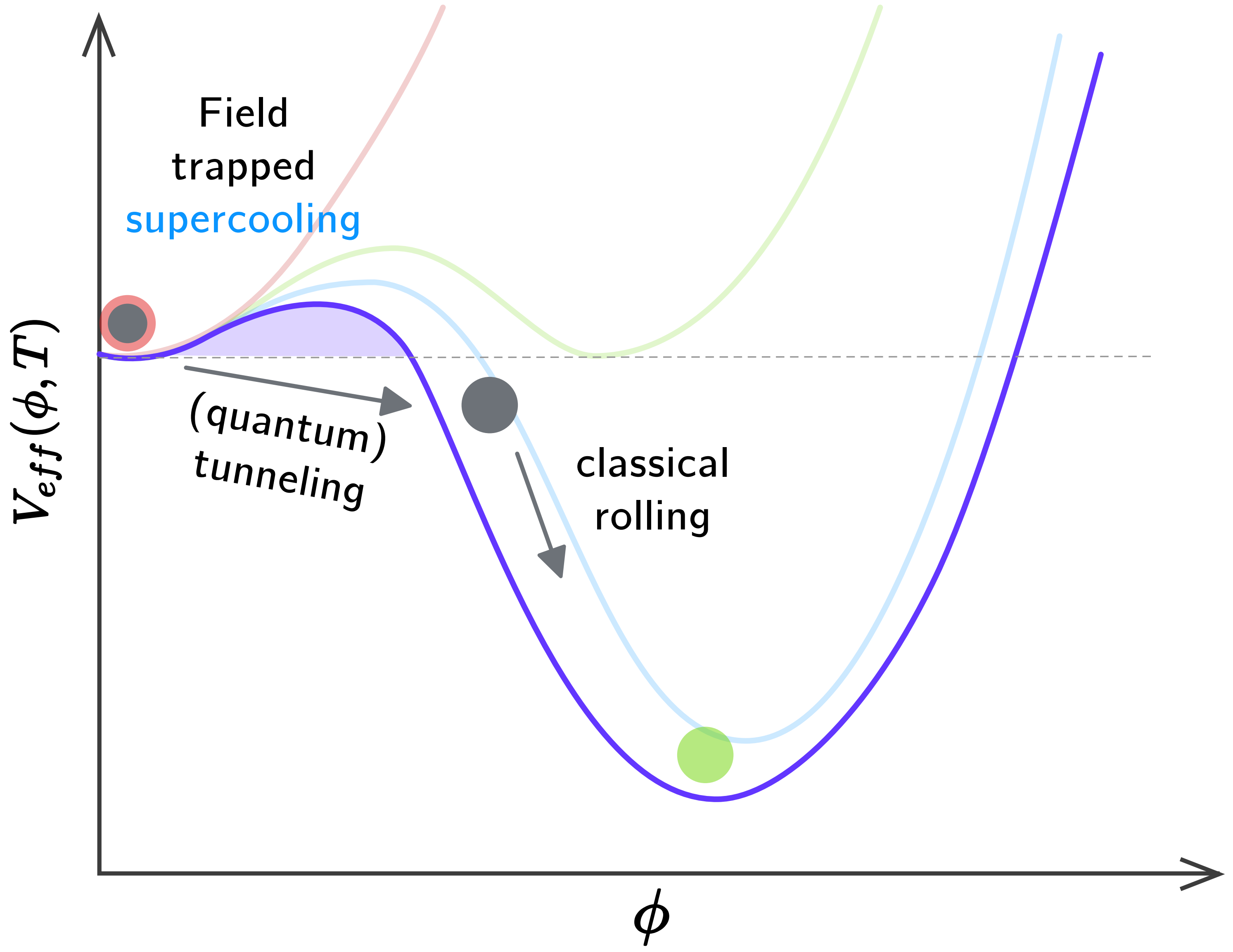
We are interested in:

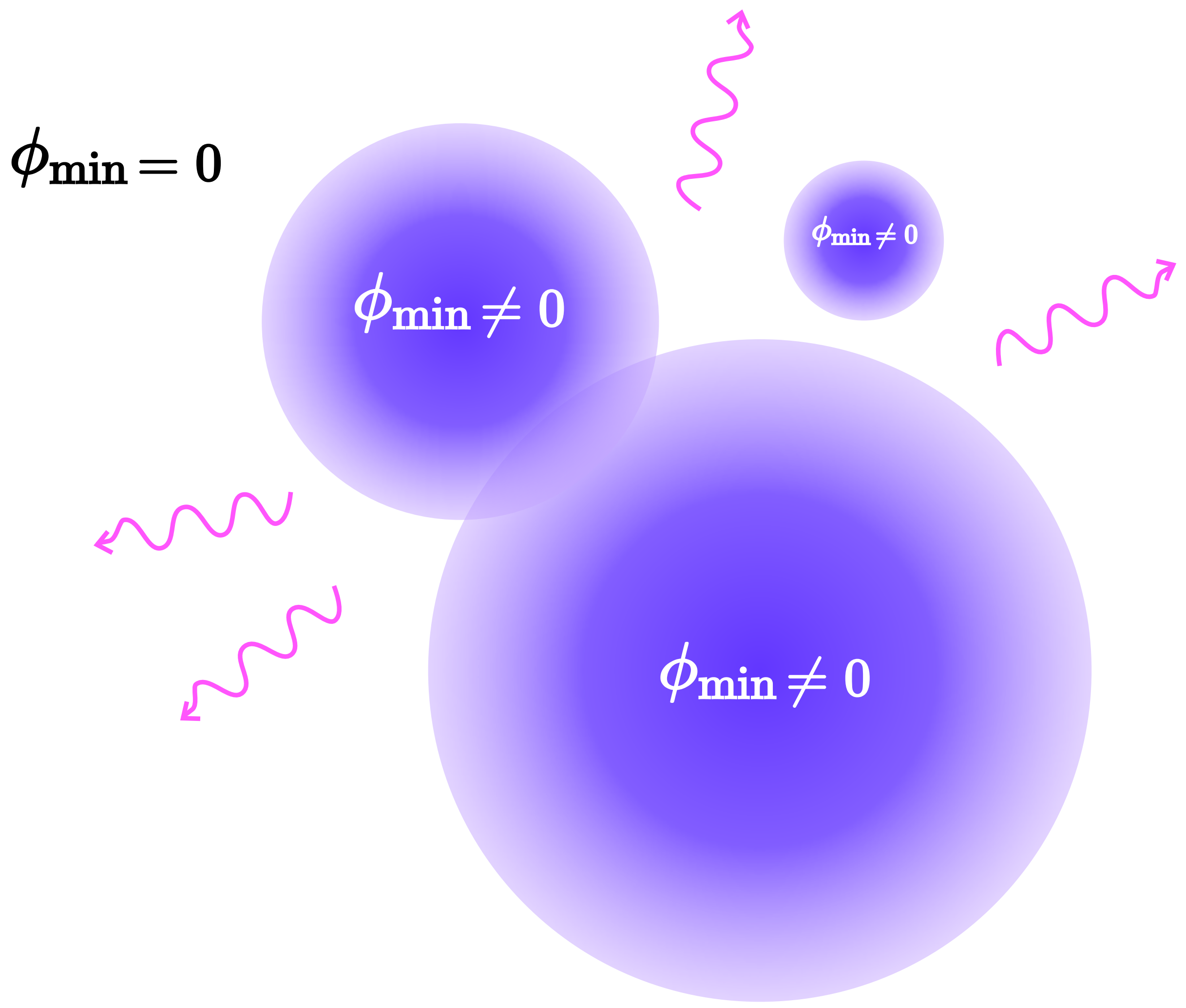
GW probes of cosmological 1st order phase transitions

Require Beyond SM physics → smoking-gun signal!

A common scenario:

Supercooled 1st order phase transition





Tunneling & bubble nucleation

Stochastic GW background

from vacuum bubble collisions & hydrodynamic aftermath

Motivation

We are interested in:

GW probes of cosmological 1st order phase transitions

Require Beyond SM physics → smoking-gun signal!

A common scenario:

Supercooled 1st order pha

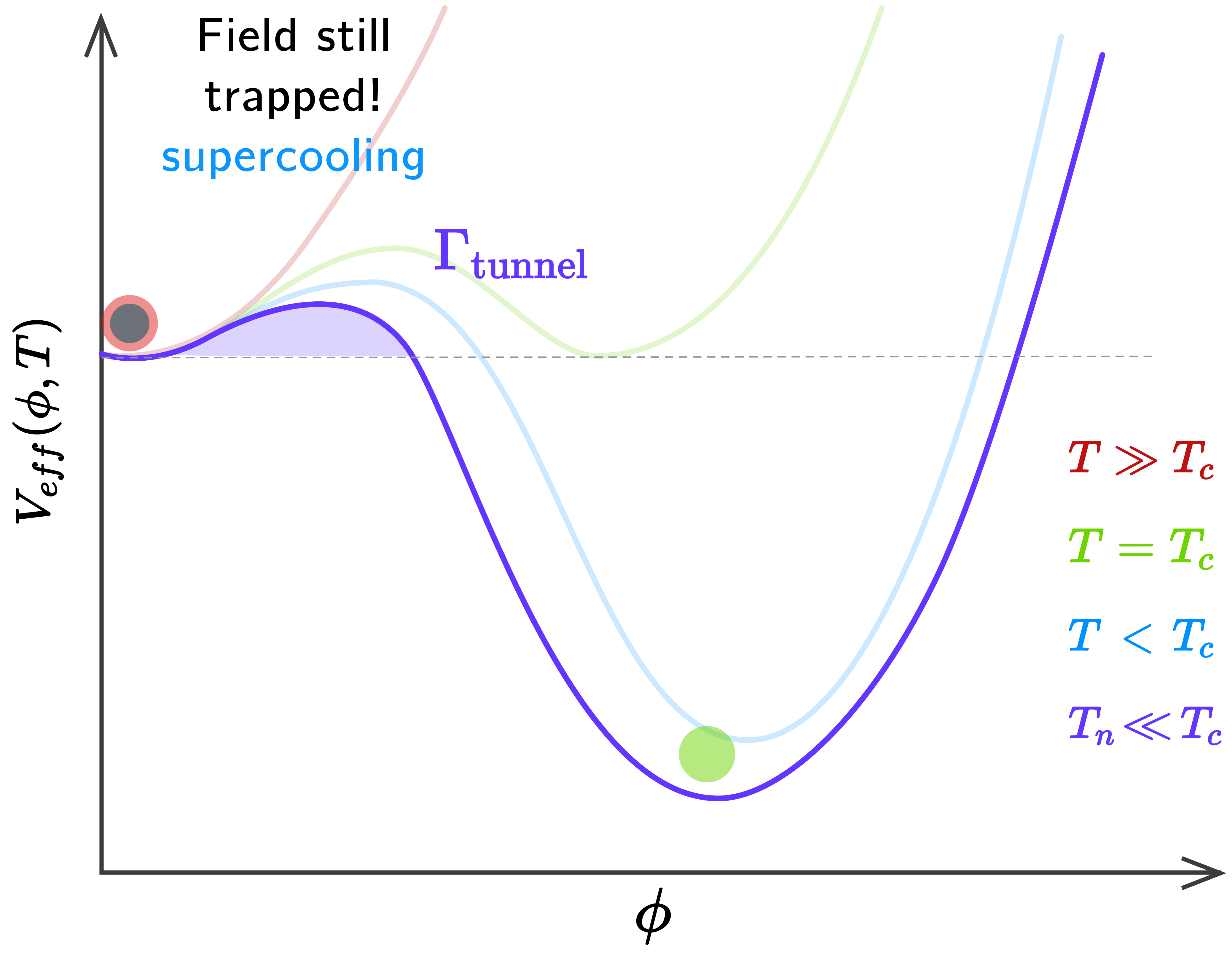
What if bubble nucleation is inefficient?

Tunneling & bubble nucleation

Stochastic GW background

from vacuum bubble collisions & hydrodynamic aftermath

Supercooled tachyonic phase transition

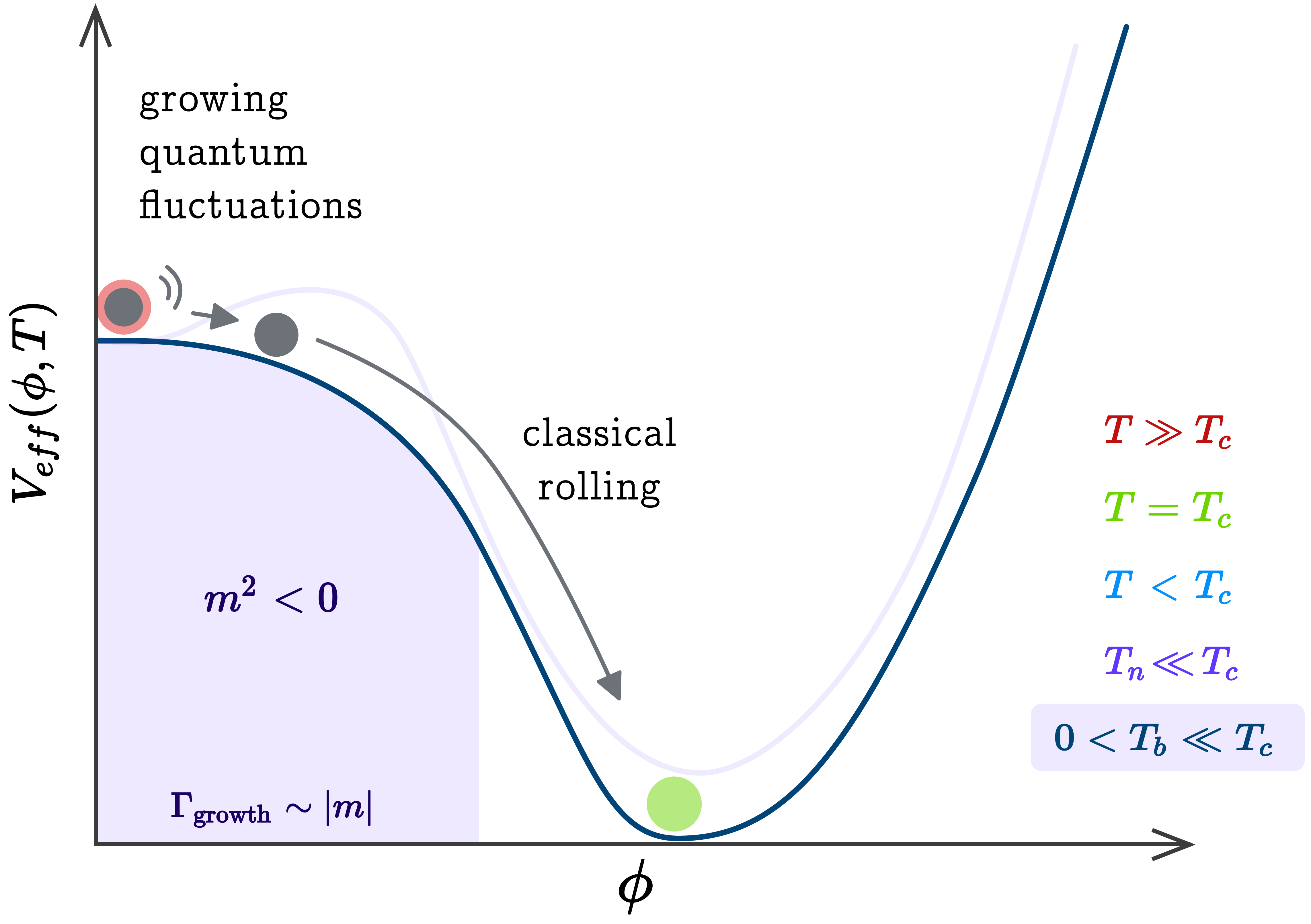


$\phi = \langle\Phi\rangle_J \quad \phi_{\text{min}} = \langle\Phi\rangle_{J=0}$

Supercooled tachyonic phase transition

→ Barrier melts before transition becomes efficient[1]

Tachyonic instability $m^2 < 0$
& super-horizon mode amplification
→ *spinodal decomposition*

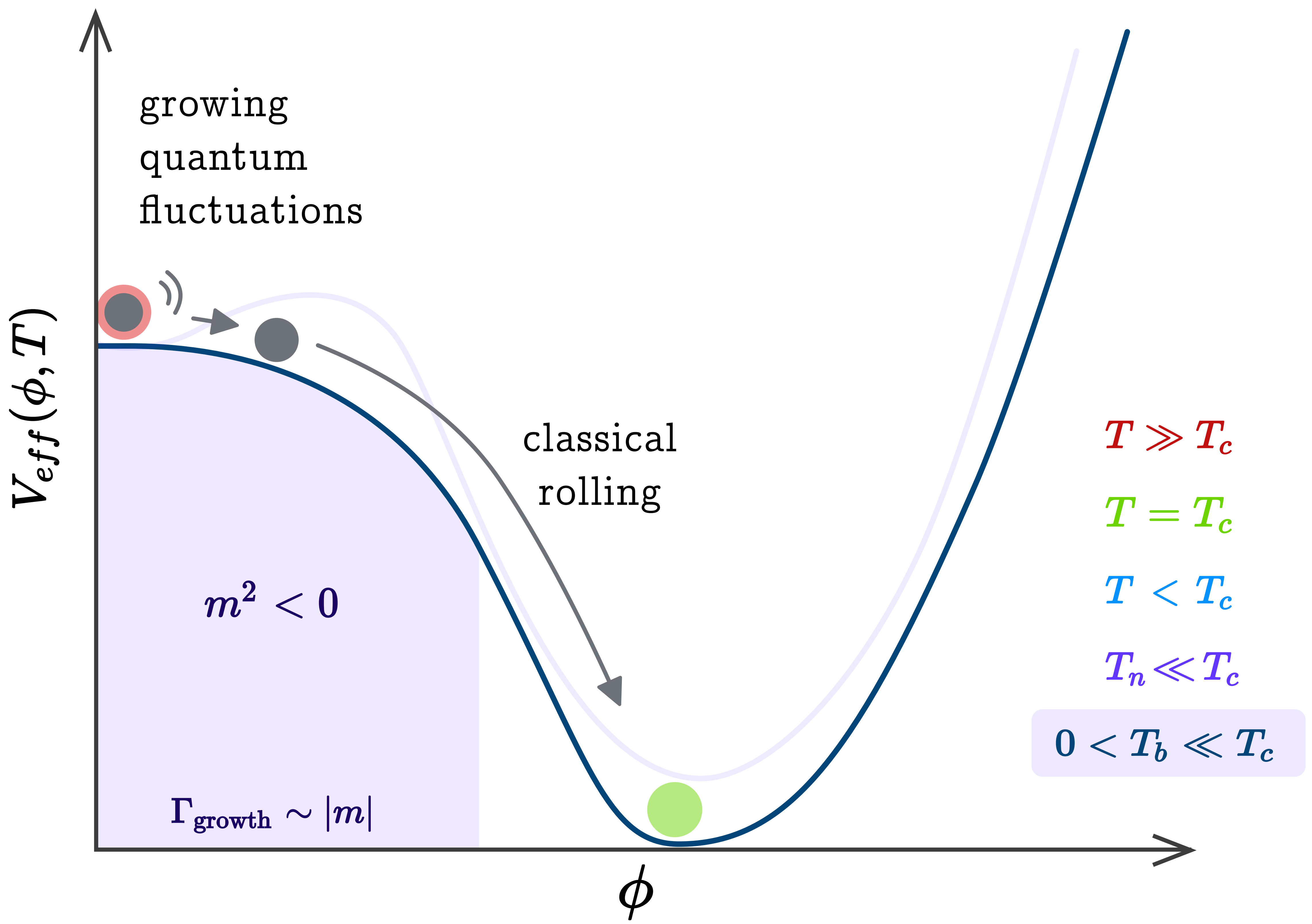


[1]D. Schmitt et al. (2024)

$\phi = \langle \Phi \rangle_J \quad \phi_{\text{min}} = \langle \Phi \rangle_{J=0}$

Supercooled tachyonic phase transition

→ Barrier melts before transition becomes efficient[1]



Tachyonic instability $m^2 < 0$
& super-horizon mode amplification
→ *spinodal decomposition*

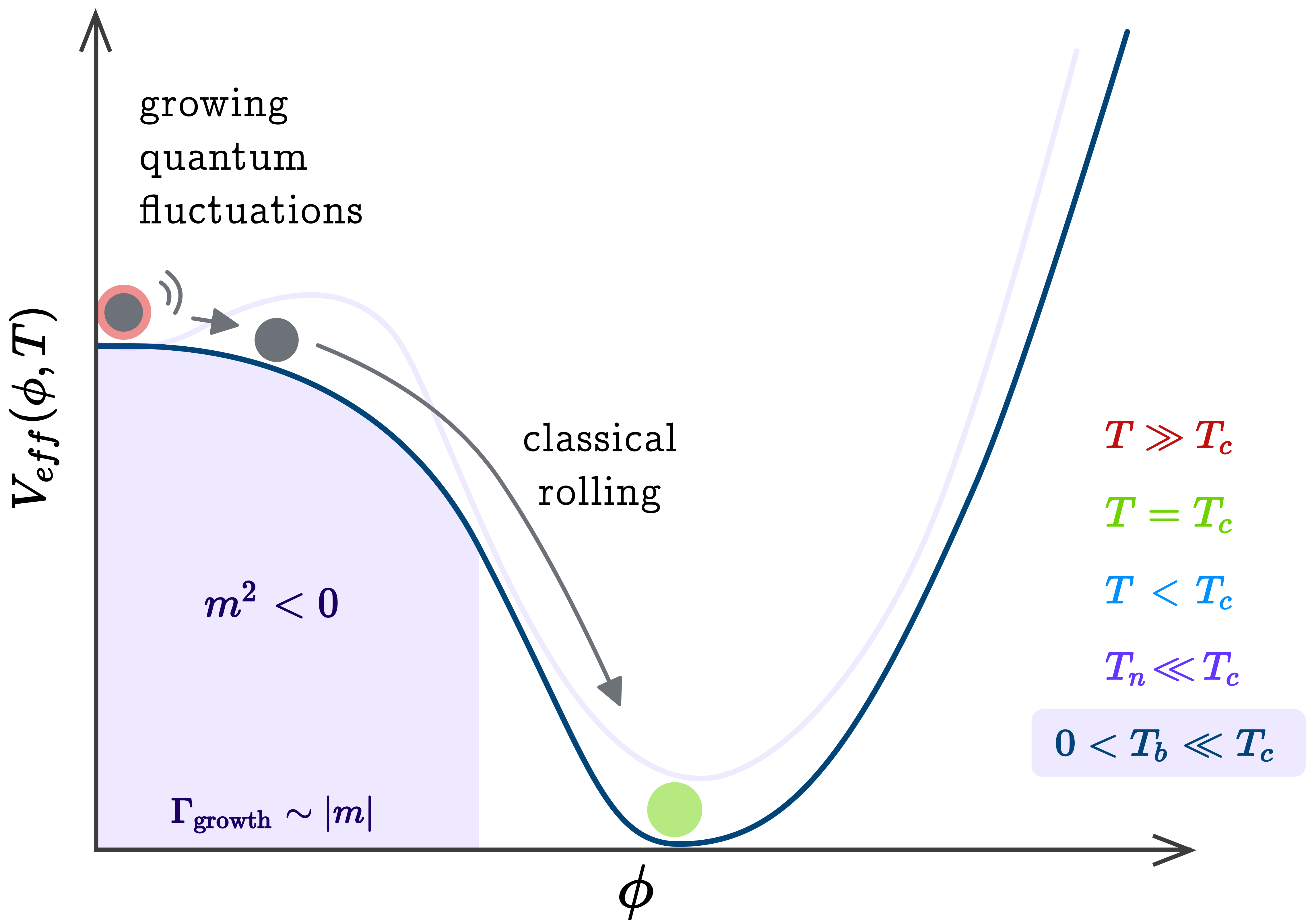
Scalar-induced
stochastic GW background
sourced by fluctuation amplification

$\phi = \langle\Phi\rangle_J \quad \phi_{\min} = \langle\Phi\rangle_{J=0}$

[1] D. Schmitt et al. (2024)

Supercooled tachyonic phase transition

→ Barrier melts before transition becomes efficient[1]



$\phi = \langle \Phi \rangle_J \quad \phi_{\min} = \langle \Phi \rangle_{J=0}$

Tachyonic instability $m^2 < 0$

& super-horizon mode amplification

→ *spinodal decomposition*

Scalar-induced
stochastic GW background

sourced by fluctuation amplification

Pipeline

from fluctuations to GWs[2]:

$$|u_k| \rightarrow \langle \Phi^2 \rangle \rightarrow \mathcal{P}_\zeta^{\text{SI}}(k) \rightarrow h^2 \Omega_{\text{GW}}^{SI}$$

[1] D. Schmitt et al. (2024)

[2] J. R. Espinosa et al. (2019); K. Kohri et al., (2018); M. Lewicki et al., (2021)

Beyond SM Physics

Classically Conformal B-L SM Extension[1]

Ingredients:

$$\{\Phi, Z', \nu\} \rightarrow V(\Phi, H) \supset \lambda_{\rm p}(\Phi^\dagger \Phi)(H^\dagger H)$$

Parameters: $\{m_{Z'}, g_{\rm BL}\}$

[1] S. Iso et al., (2009) & (2017)

Beyond SM Physics

Classically Conformal B-L SM Extension[1]

Ingredients:

$$\{\Phi, Z', \nu\} \rightarrow V(\Phi, H) \supset \lambda_{\mathrm{p}}(\Phi^\dagger \Phi)(H^\dagger H)$$

Parameters: $\{m_{Z'}, g_{\mathrm{BL}}\}$

QCD-induced B-L tachyonic phase transition

Supercooling to T_{QCD}
+ suppression of bubble nucleation rate

$$\hookrightarrow m^2(0, T \leq T_{\mathrm{QCD}}) = 2 g_{\mathrm{BL}}^2 T^2 - \frac{\lambda_{\mathrm{p}}}{2} v_{\mathrm{QCD}}^2$$

[1] S. Iso et al., (2009) & (2017)

Beyond SM Physics

Classically Conformal B-L SM Extension[1]

Ingredients:

$$\{\Phi, Z', \nu\} \rightarrow V(\Phi, H) \supset \lambda_p (\Phi^\dagger \Phi)(H^\dagger H)$$

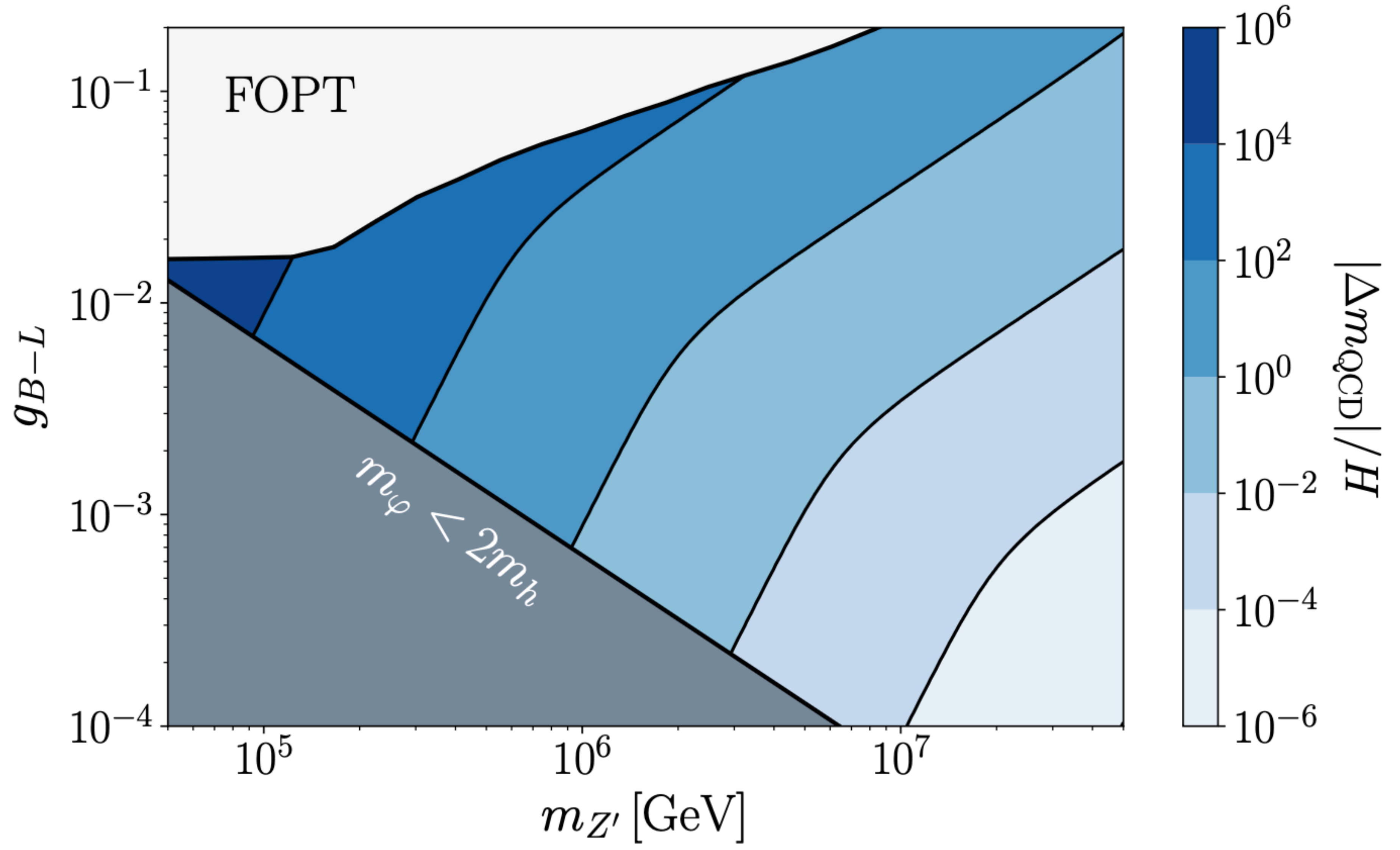
Parameters: $\{m_{Z'}, g_{BL}\}$

QCD-induced B-L tachyonic phase transition

Supercooling to T_{QCD}
+ suppression of bubble nucleation rate

$$m^2(0, T \leq T_{QCD}) = 2g_{BL}^2 T^2 - \frac{\lambda_p}{2} v_{QCD}^2$$

D. Schmitt et al., (2024)



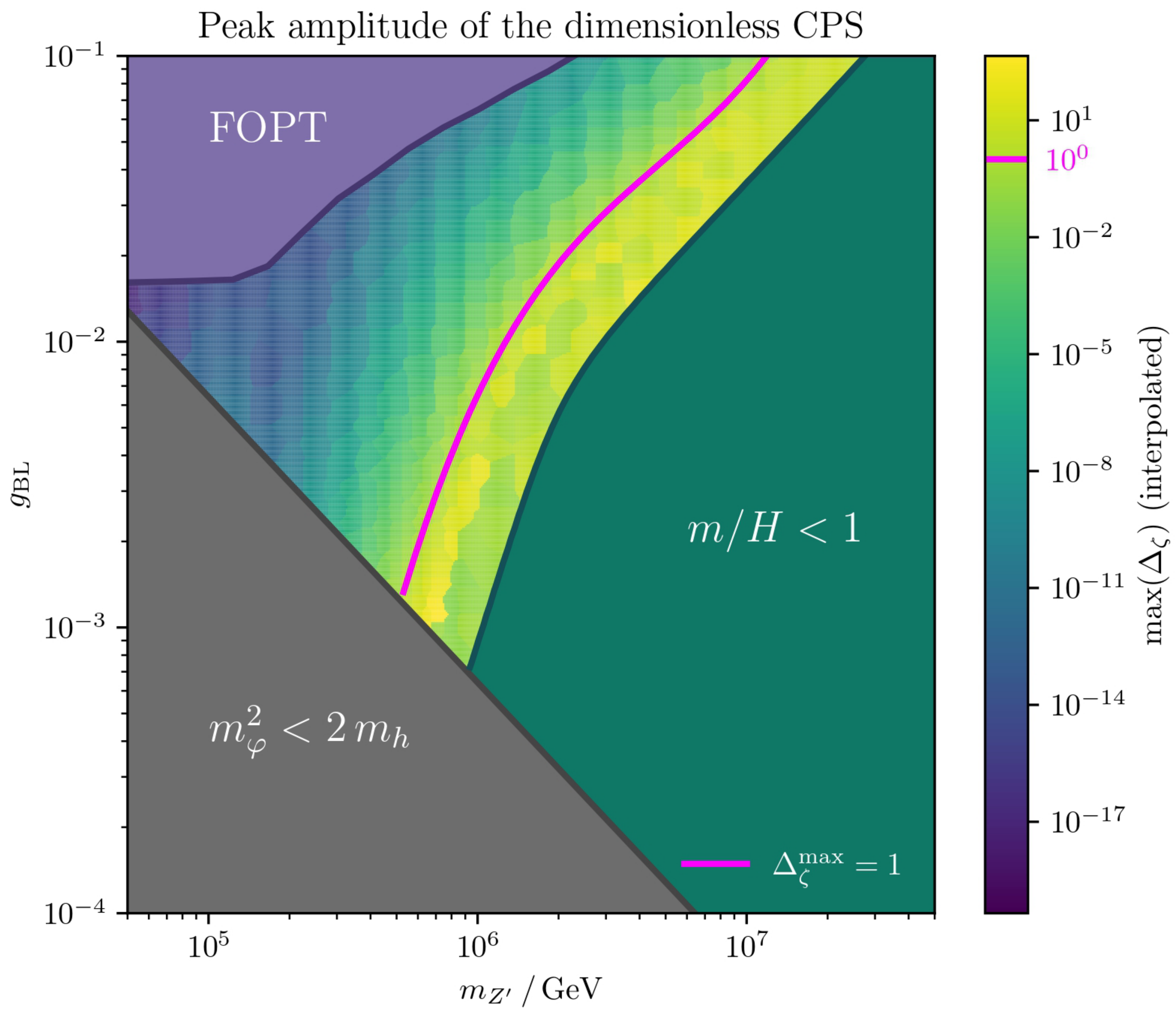
„Sweet spot" region: $|m|/H \gtrsim 1$

Moderate fluctuation growth rates, expect largest curvature perturbations

[1] S. Iso et al., (2009) & (2017)

Results I

Dimensionless curvature power spectrum

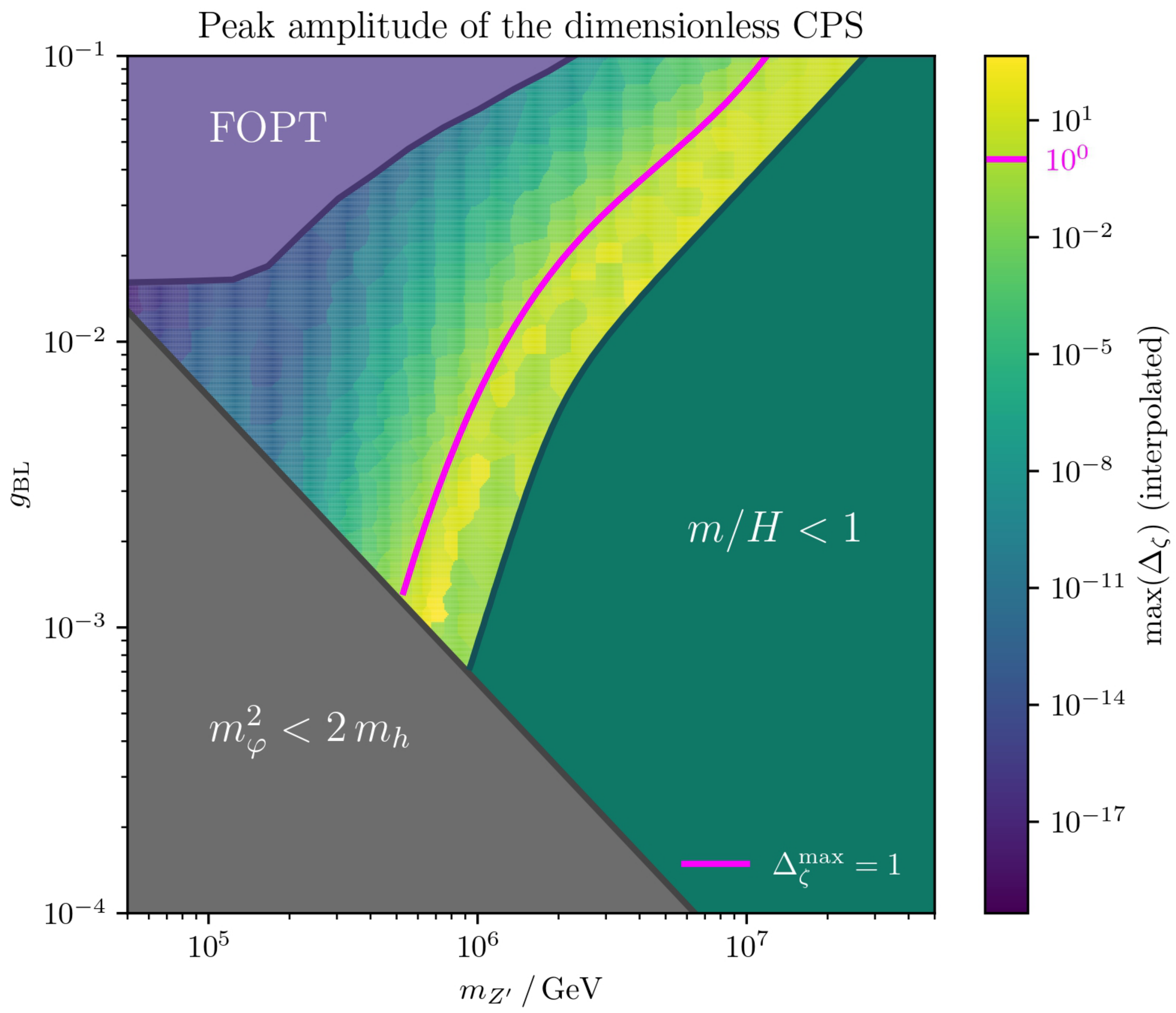


T. Caldas et al., (2026) (in preparation)

✓ Largest curvature perturbations & GWs to be found in the „sweet spot“ region

Results I

Dimensionless curvature power spectrum



T. Caldas et al., (2026) (in preparation)

✓ Largest curvature perturbations & GWs to be found in the „sweet spot" region

New feature:

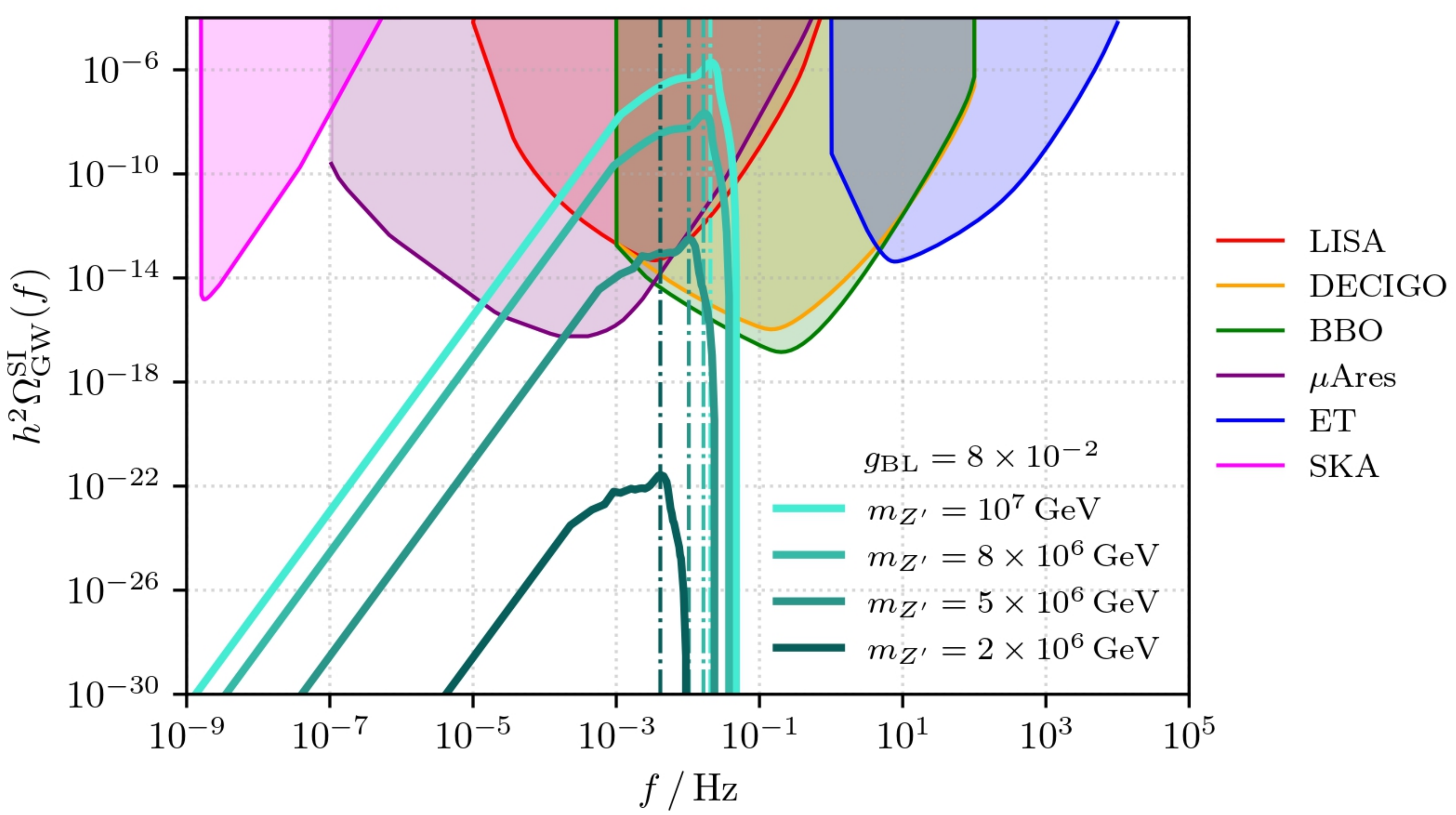
Additional constraint line for unphysically large curvature perturbations

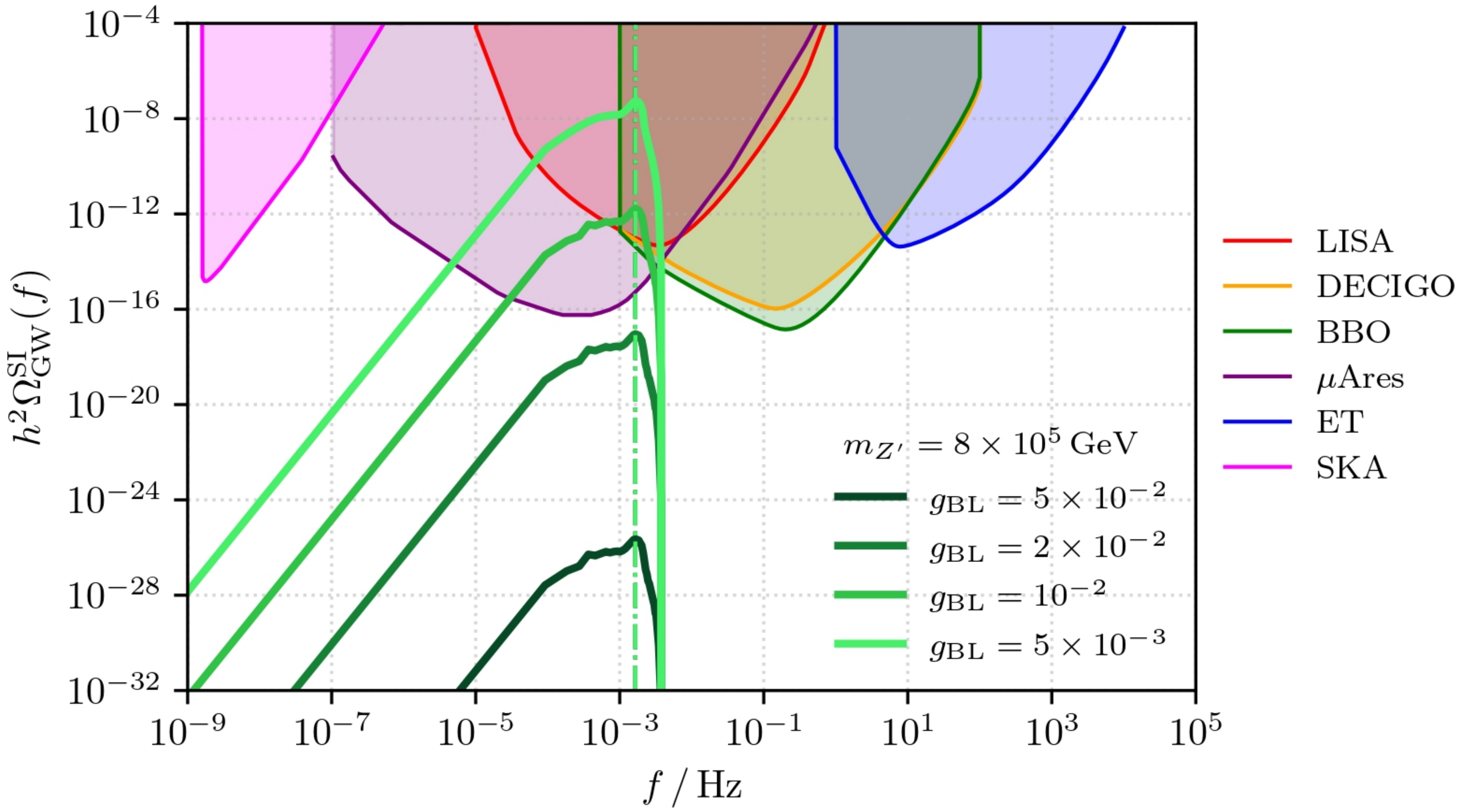
$$\max_k \left(\Delta_\zeta(k)\right) \geq 1$$

Results II

GW energy density spectra

T. Caldas et al., (2026) (in preparation)

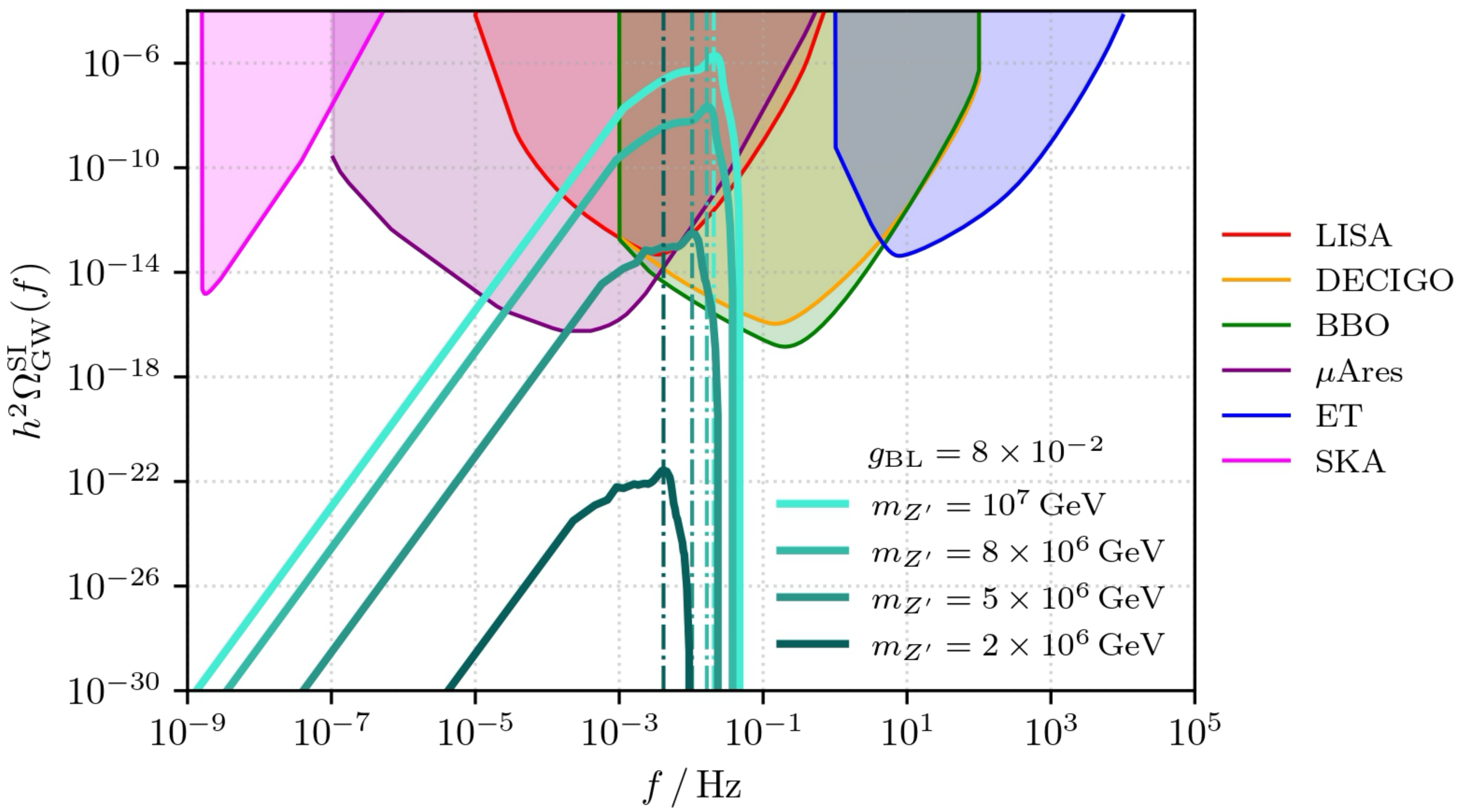


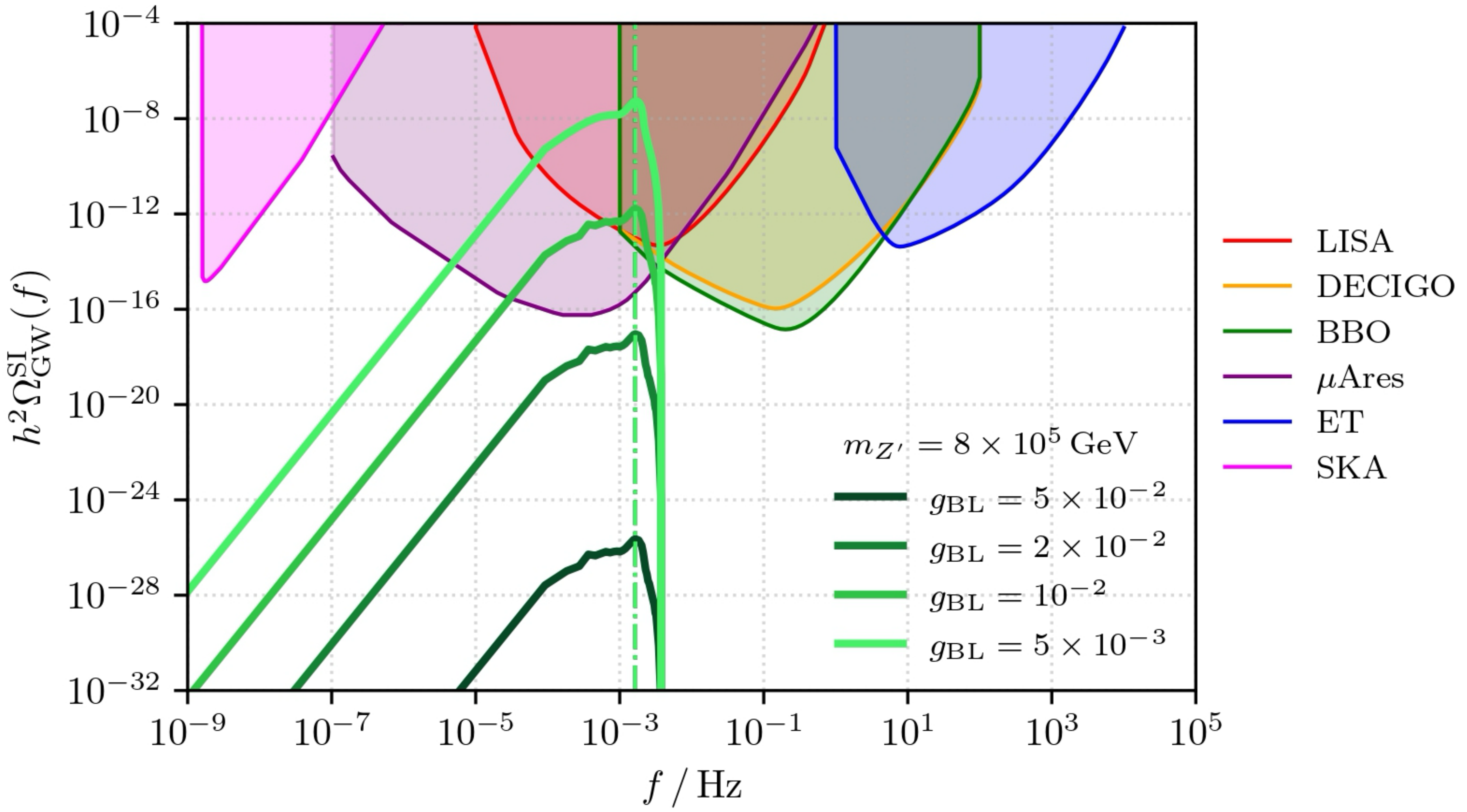


Results II

GW energy density spectra

T. Caldas et al., (2026) (in preparation)





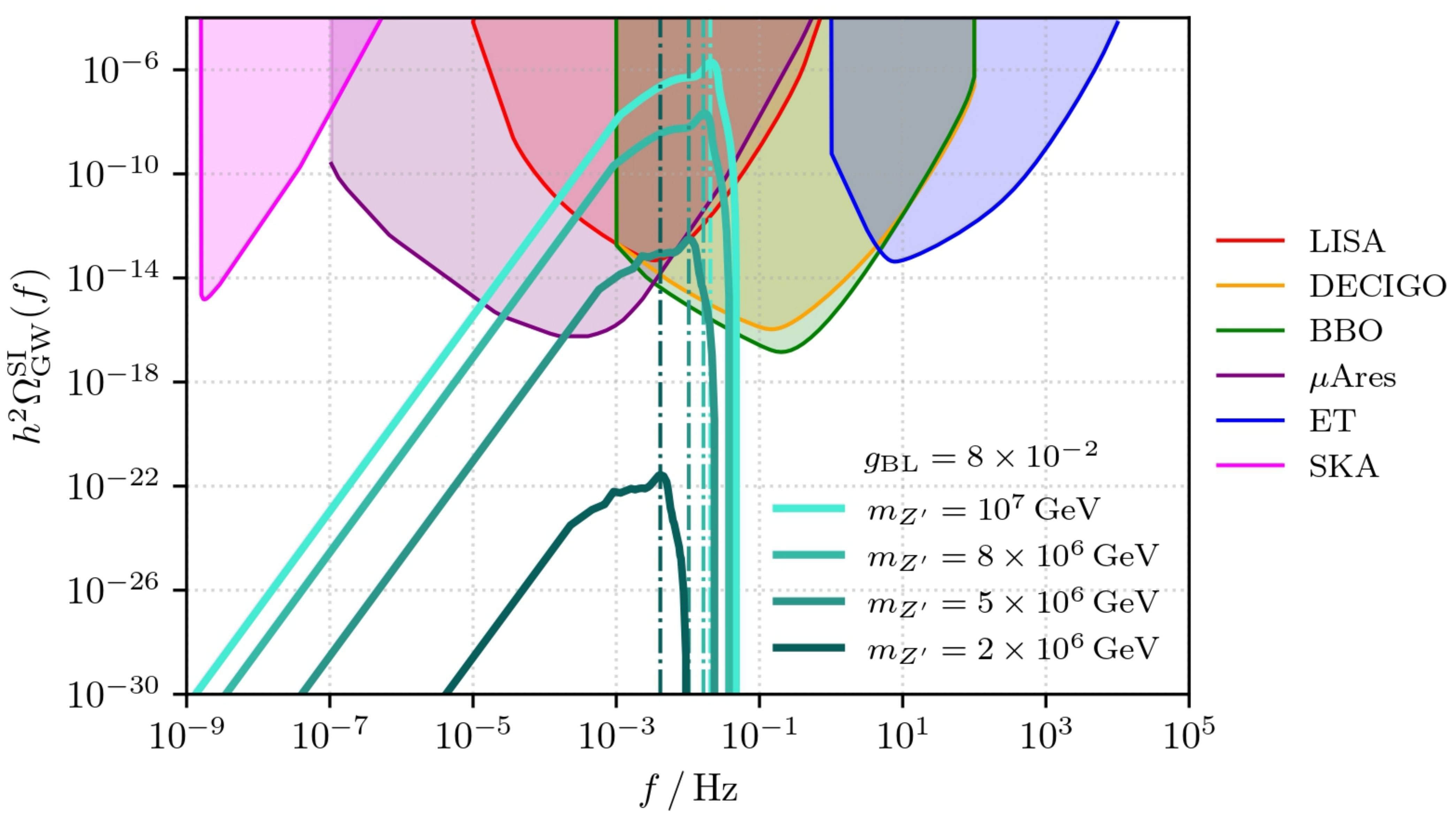
Main properties: $h^2\Omega_{\rm GW}^{\rm peak}(m_{\rm Z'}, g_{\rm BL})$ & $f_{\rm peak}(m_{\rm Z'})$

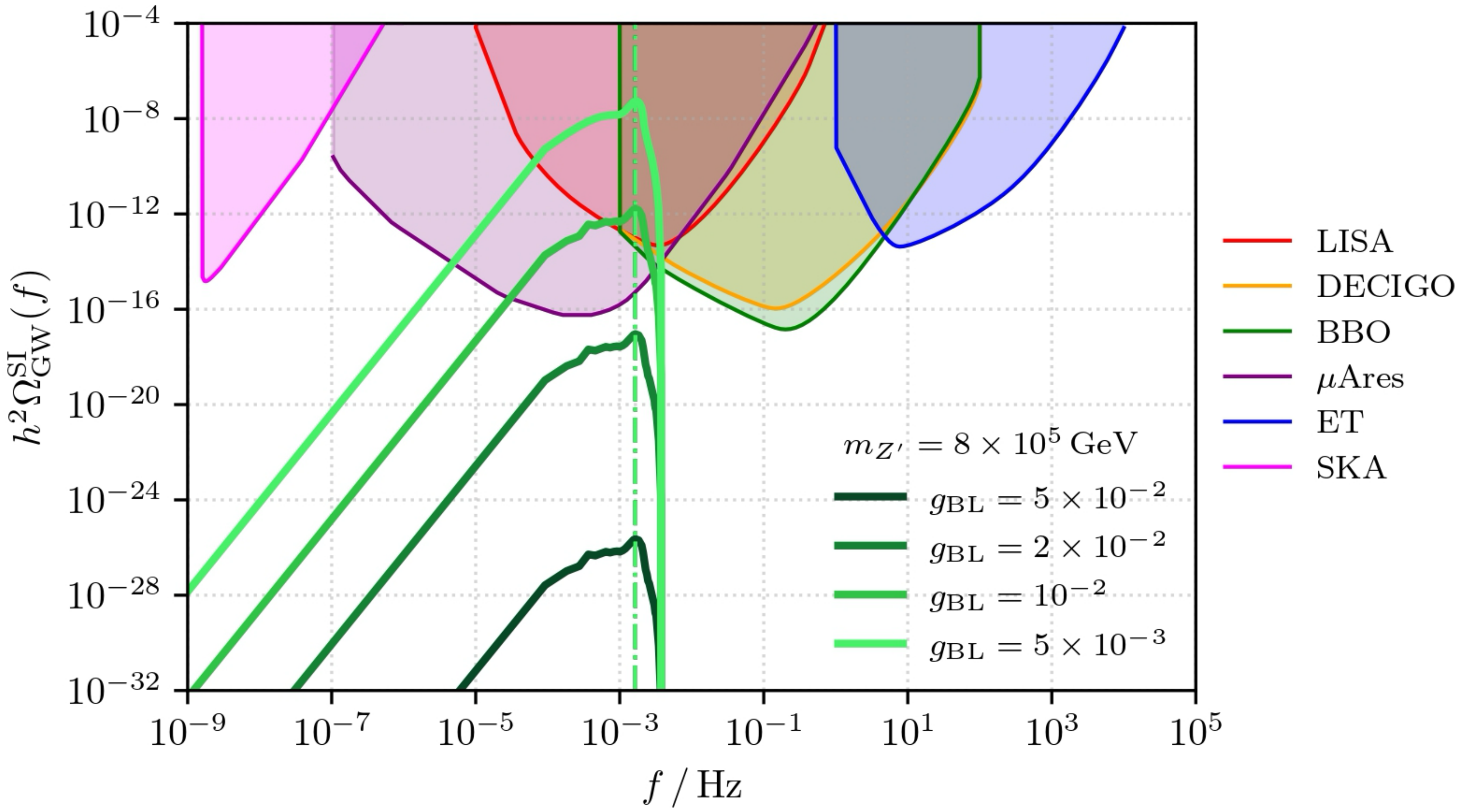
→ „Sweet spot“ in the reach of future GW detectors!

Results II

GW energy density spectra

T. Caldas et al., (2026) (in preparation)





Main properties: $h^2\Omega_{GW}^{peak}(m_{Z'}, g_{BL})$ & $f_{peak}(m_{Z'})$

→ „Sweet spot“ in the reach of future GW detectors!

Sweet spot region

$$f_{peak} \in [10^{-3}\ \text{Hz},\ 10^{-2}\ \text{Hz}]$$

$$h^2\Omega_{GW}^{peak} \in [10^{-15},\ 10^{-5}]$$

Take-away messages

New **tachyonic phase transition** scenario in BSM models featuring strong supercooling

→ QCD-induced tachyonic instability & super-horizon fluctuation amplification

↪ **NEW: Scalar-induced stochatic GW background** probable with future GW detectors

Take-away messages

New **tachyonic phase transition** scenario in BSM models featuring strong supercooling

→ QCD-induced tachyonic instability & super-horizon fluctuation amplification

↪ **NEW: Scalar-induced stochatic GW background** probable with future GW detectors

A look into the (near) future...

→ Updated GW predictions with two-loop dimensionally reduced effective potential

→ On the lattice: UV tail of GW spectrum due to non-linear sub-horizon fluctuation amplification[1]

[1] M. Will et al., (2026) (in preparation)

Thank you!

Any questions?

NEW

My thesis

Preceeding paper

Methodology: Scalar field evolution approximation

Approximate the scalar field (expectation value) evolution by the variance

$$\varphi(T) = \begin{cases} 0\,, & T > T_b \\ \sqrt{\langle \Phi^2 \rangle (T)}, & T \leq T_b \end{cases}$$

Field still trapped at false vacuum

Barrier gone: Field starts to move away from false vacuum due to growing fluctuations

T_b : Temperature at which thermal ppotential barrier in effective potential dissapears

This ansatz breaks down once the classical dynamics of the scalar field take over

→ Estimated by characteristic value $\varphi_{\rm cl}$

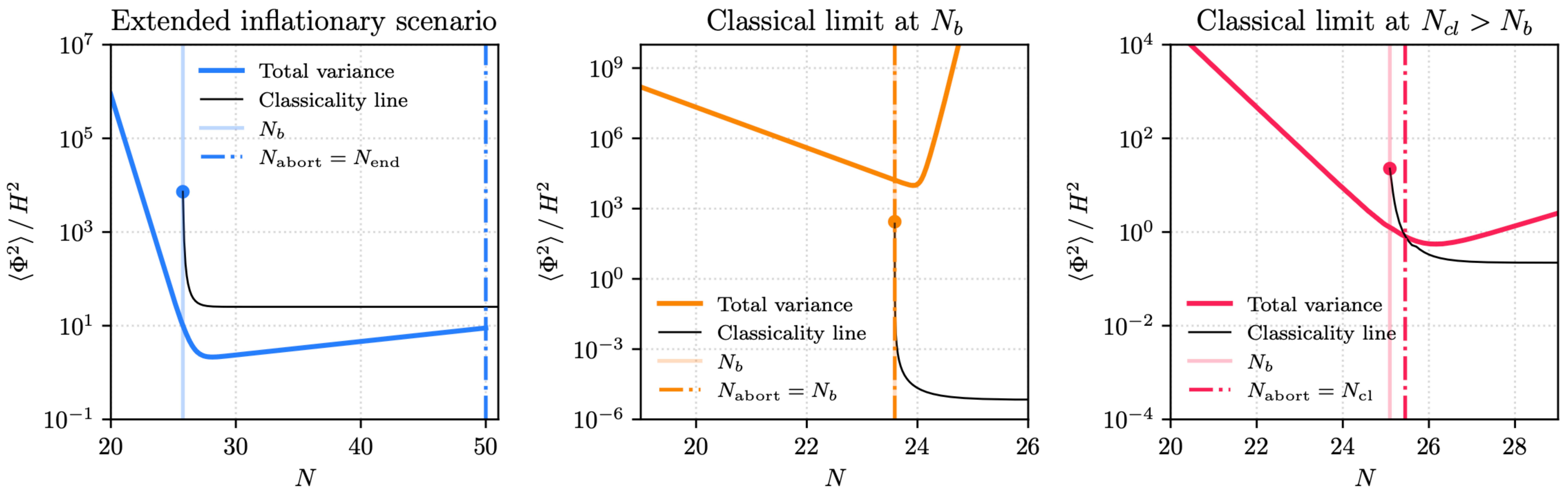
$$V'_{\rm eff}(\varphi_{\rm cl}, T)/3H = \dot\varphi \overset{!}{\geq} \dot\varphi_Q = H^2/2\pi$$

Dynamics: Variance evolution classes

$$\langle \Phi^2 \rangle (N_{\rm cl}) = \varphi_{\rm cl}(N_{\rm cl})$$

Approximate total scalar field's evolution with the help of its variance

→ Classify the scalar field's variance evolution by when the quantum regime ends



$N_{\rm b}$: Efold number at which thermal potential barrier melts and fluctuation modes become amplified