Gravitational wave signature of a supercooled phase transition

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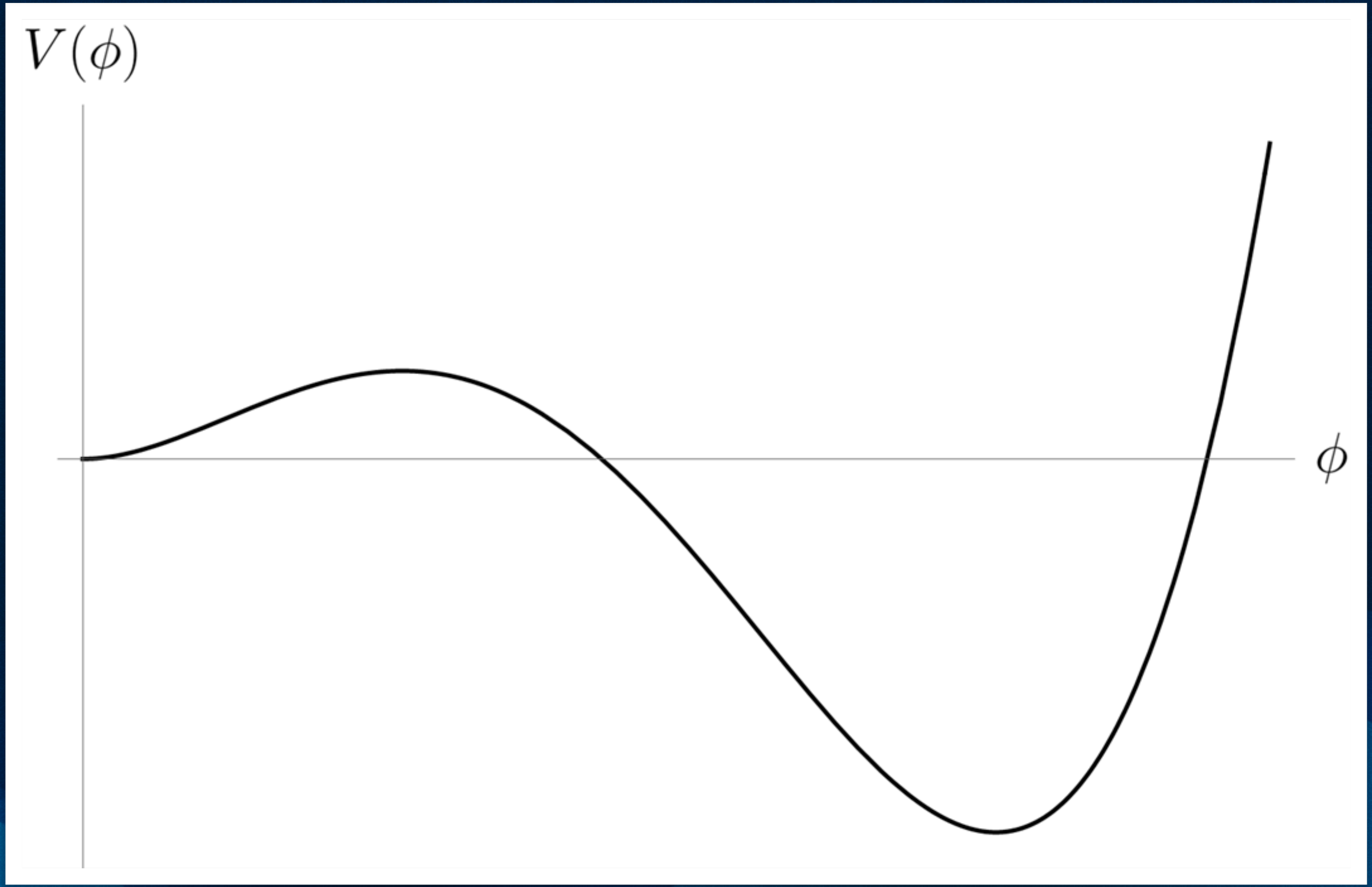
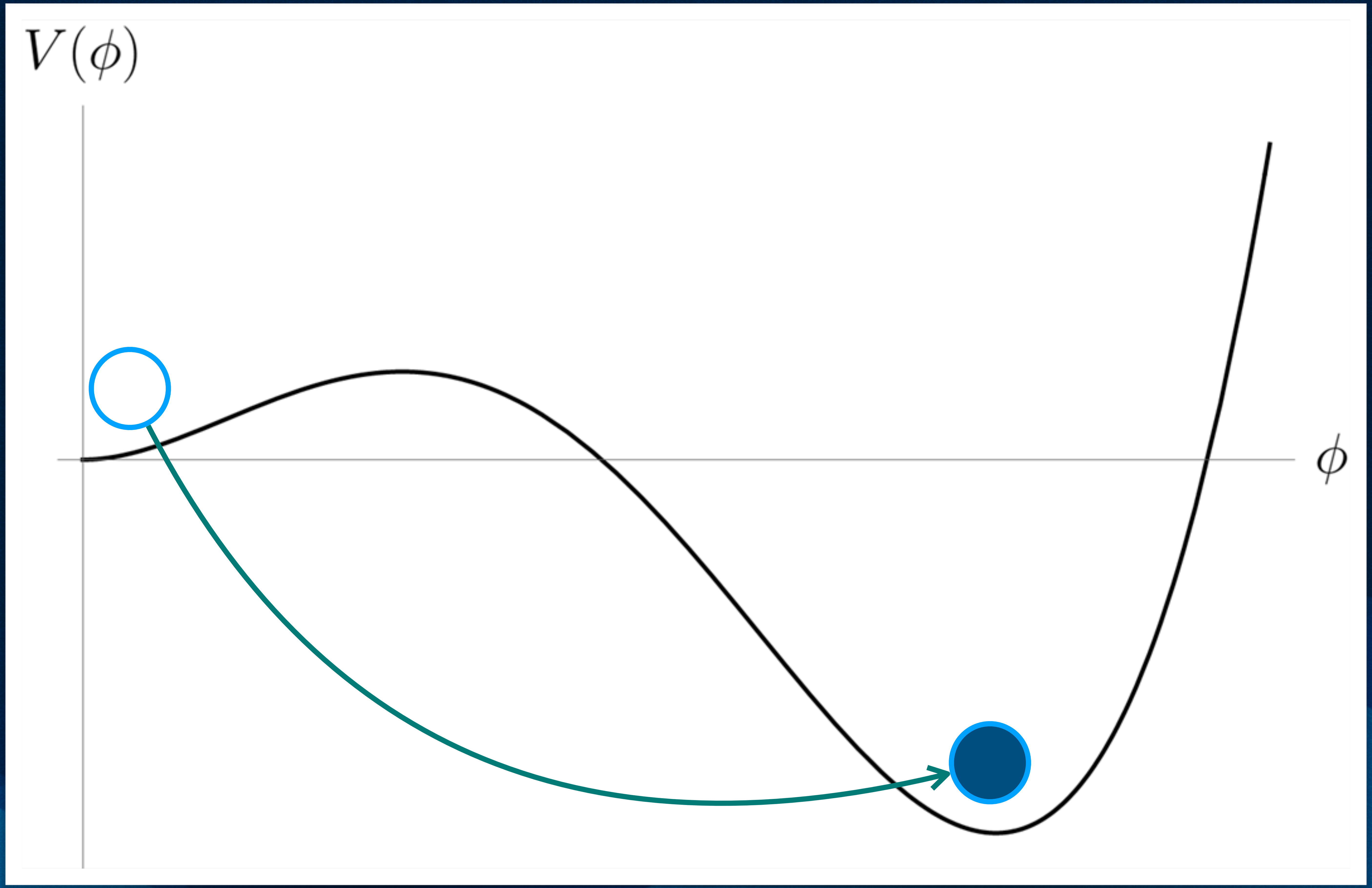
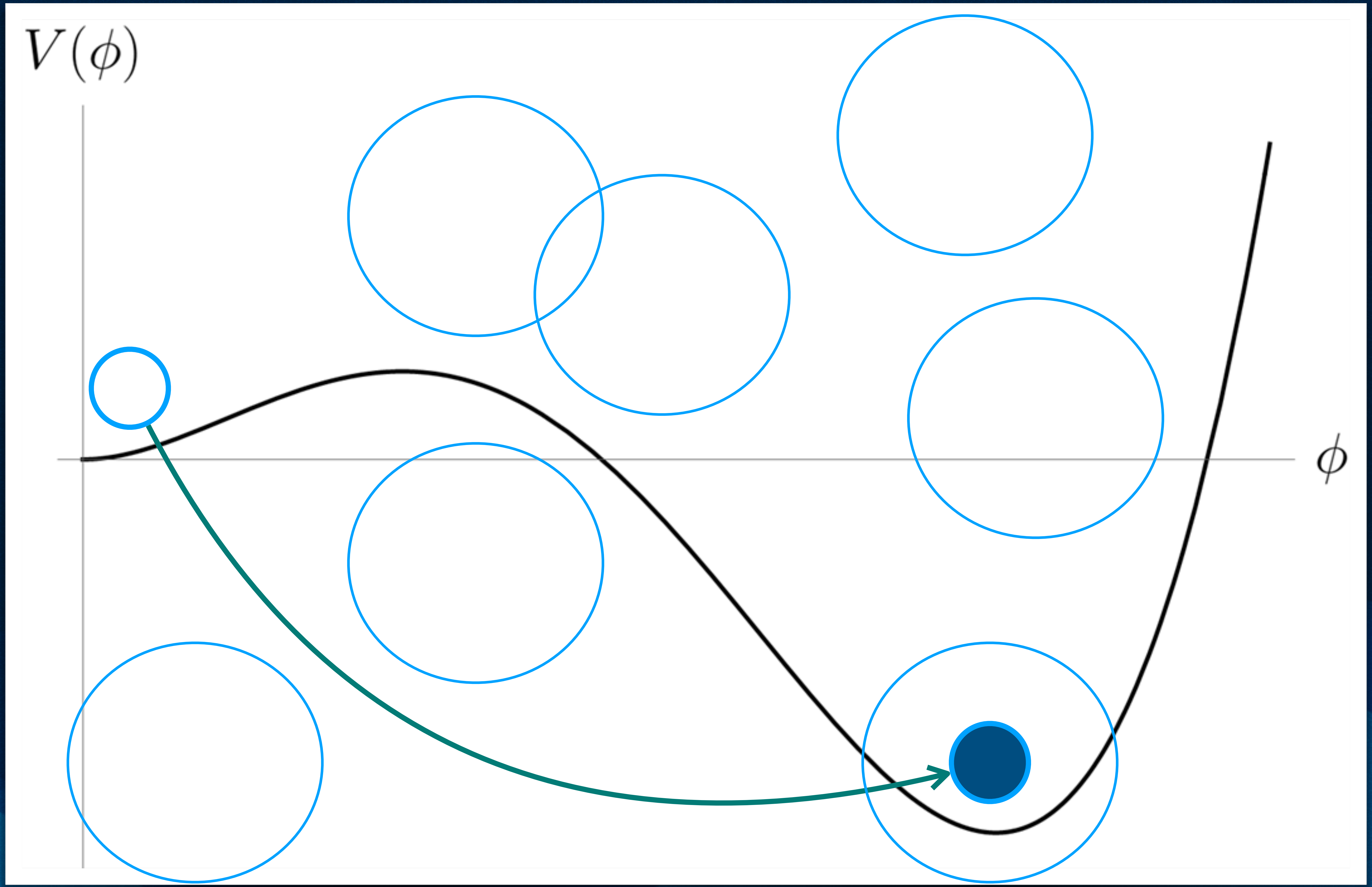
in collaboration
with Alexandros Karam, Bogumiła Świeżewska

Based on
arXiv:2210.07075



$V(\phi)$
ϕ

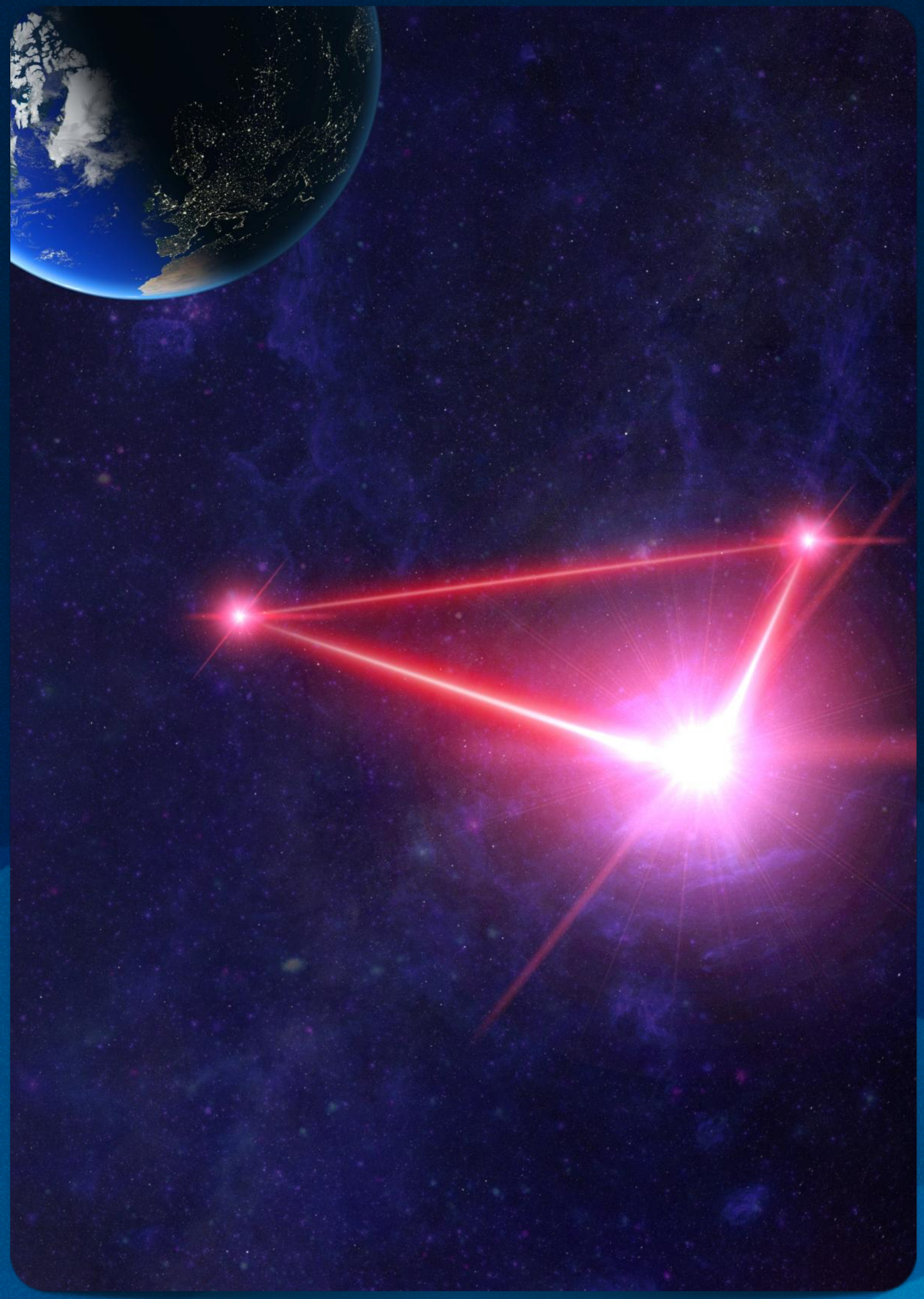

$V(\phi)$
ϕ

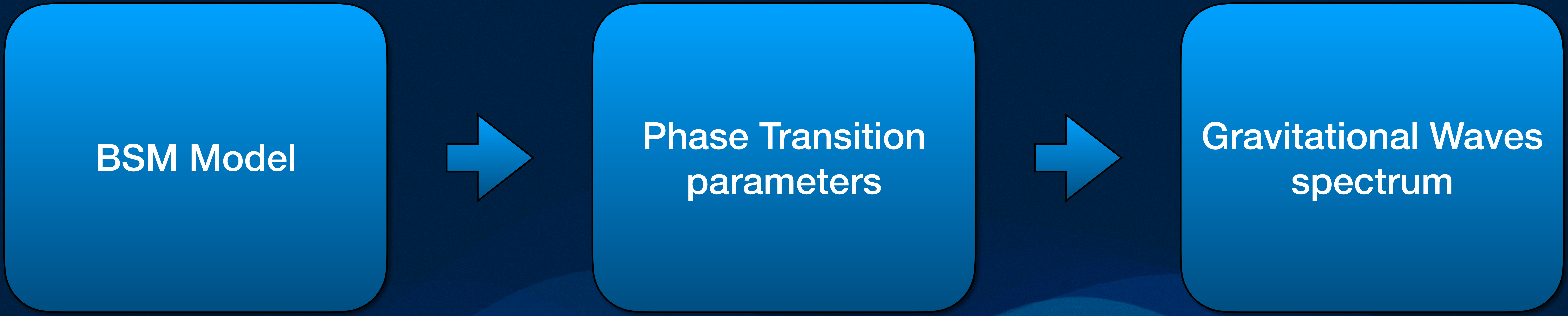


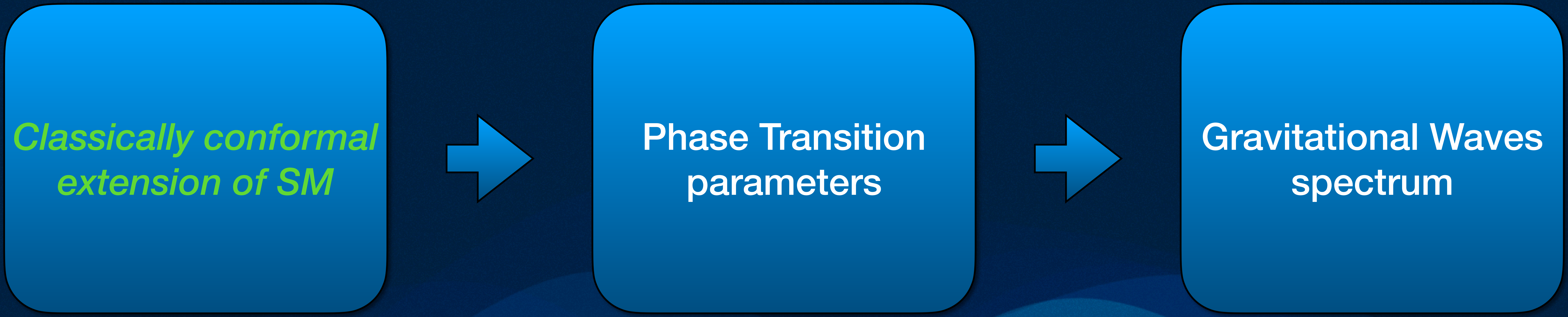
$V(\phi)$
ϕ

Motivation

- LISA detector will start collecting data in late 2030's
- LISA will be sensitive to the frequencies coming from the electroweak transition
- Detection of such signal is a "smoking gun" for new physics!
- There could be associated phenomena e.g. dark matter production, baryogenesis




BSM Model
Phase Transition parameters
Gravitational Waves spectrum


Classically conformal extension of SM
Phase Transition parameters
Gravitational Waves spectrum

Why classical conformal symmetry?

Dynamical generation of all mass scales

Predictivity - few free parameters

Generically strong GW signal testable with LISA

$$V_{\text{tree}} = \frac{1}{4}\left(\lambda_1 h^4 + \lambda_2 h^2 \phi^2 + \lambda_3 \phi^4\right)$$

See also: C. D. Carone et al, 1307.8428, T. Hambye et al, 1306.2329, D. Marfatia et al, 2006.07313, I. Baldes et al, 1809.01198

DM candidates are the stable X bosons

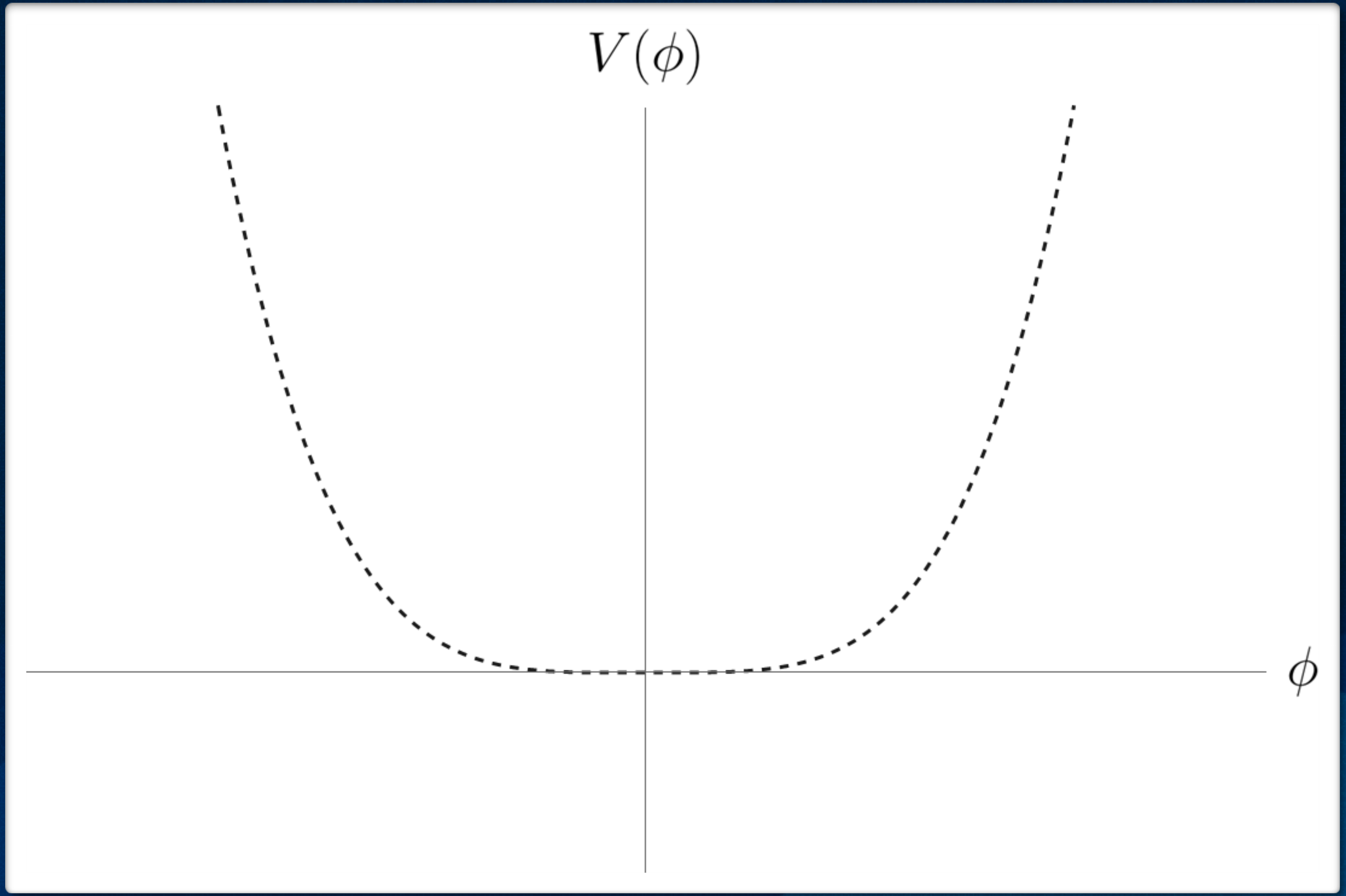
$\longrightarrow \mathbb{Z}_2 \times \mathbb{Z}_2'$

$$V_{\text{tree}} = \frac{1}{4}\left(\lambda_1 h^4 + \lambda_2 h^2 \phi^2 + \lambda_3 \phi^4\right)$$

See also: C. D. Carone et al, 1307.8428, T. Hambye et al, 1306.2329, D. Marfatia et al, 2006.07313, I. Baldes et al, 1809.01198

Radiative symmetry breaking

Example:
Massless Scalar Electrodynamics.

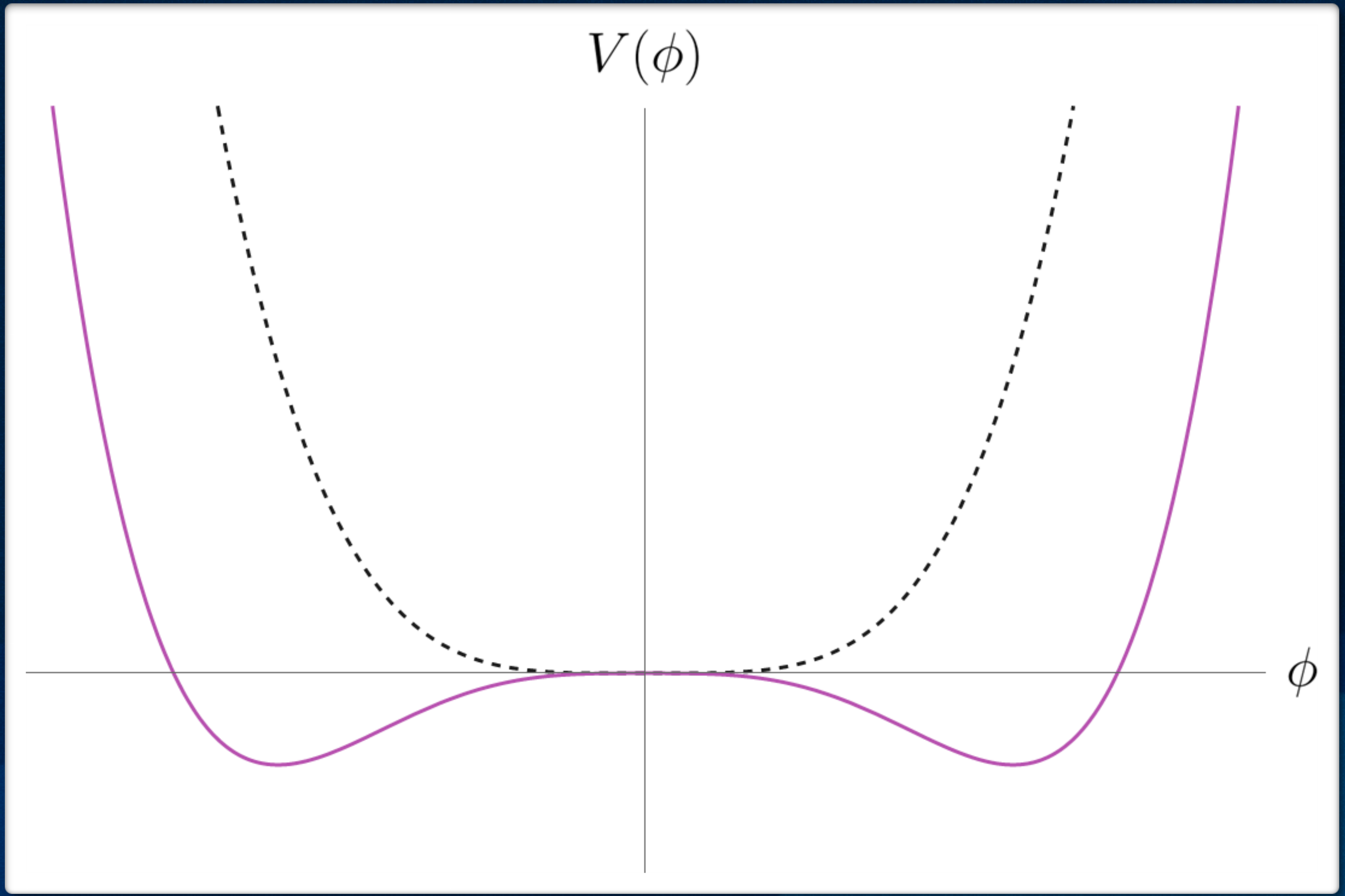


$$V_{CW} = \underbrace{\frac{\lambda}{4!}\phi^4}_{V_{\text{tree}}}$$

S. R. Coleman, E. J. Weinberg, Phys.Rev. D7 (1973) 1888

Radiative symmetry breaking

Example:
Massless Scalar Electrodynamics.



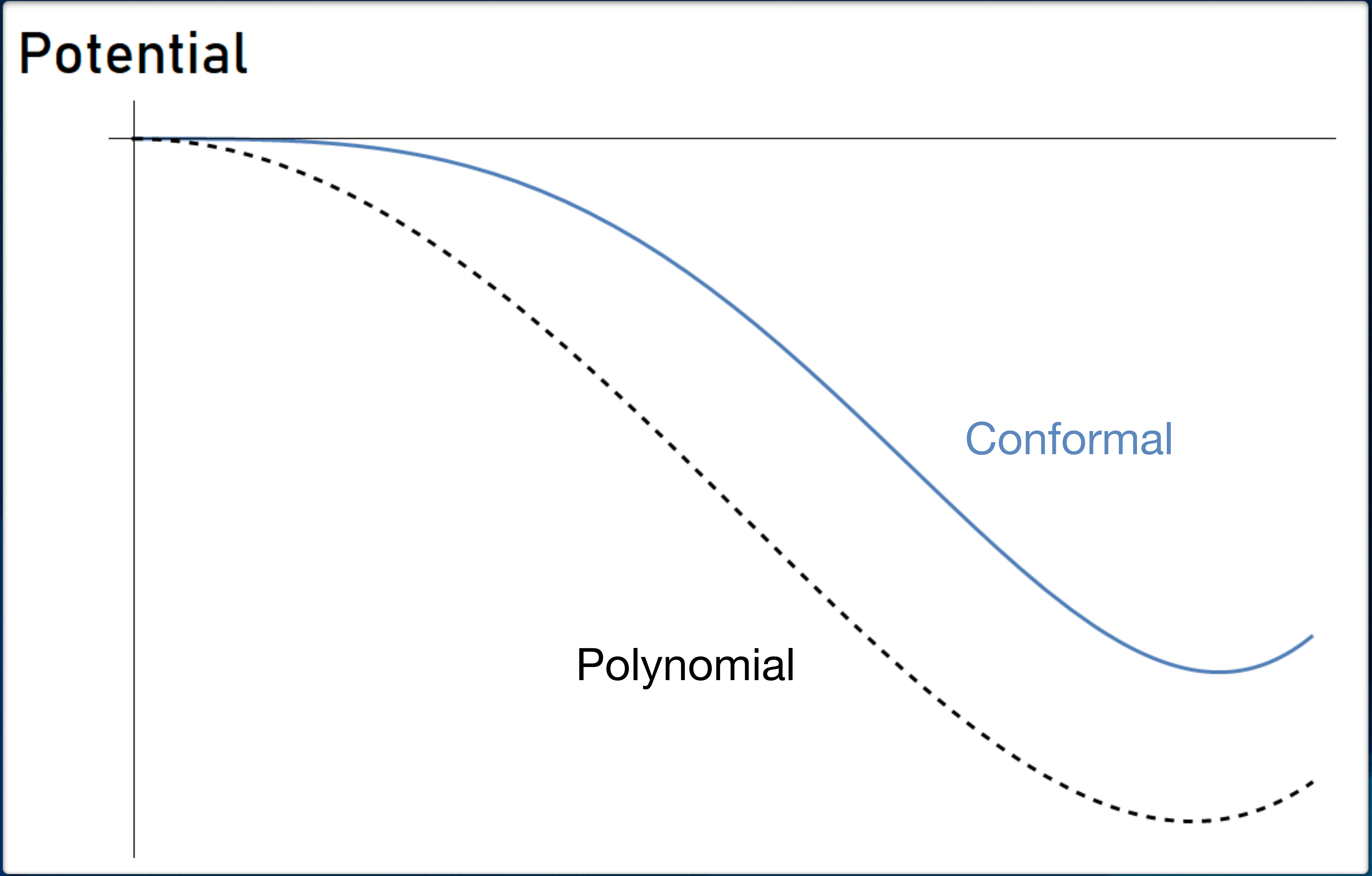
$$V_{CW} = \underbrace{\frac{\lambda}{4!}\phi^4}_{V_{\text{tree}}} + \underbrace{\frac{3e^4}{64\pi^2}\phi_c^4\left(\ln\frac{\phi_c^2}{\mu^2} - \frac{5}{6}\right)}_{\text{boson correction}}$$

S. R. Coleman, E. J. Weinberg, Phys.Rev. D7 (1973) 1888

Introducing: *supercooling*

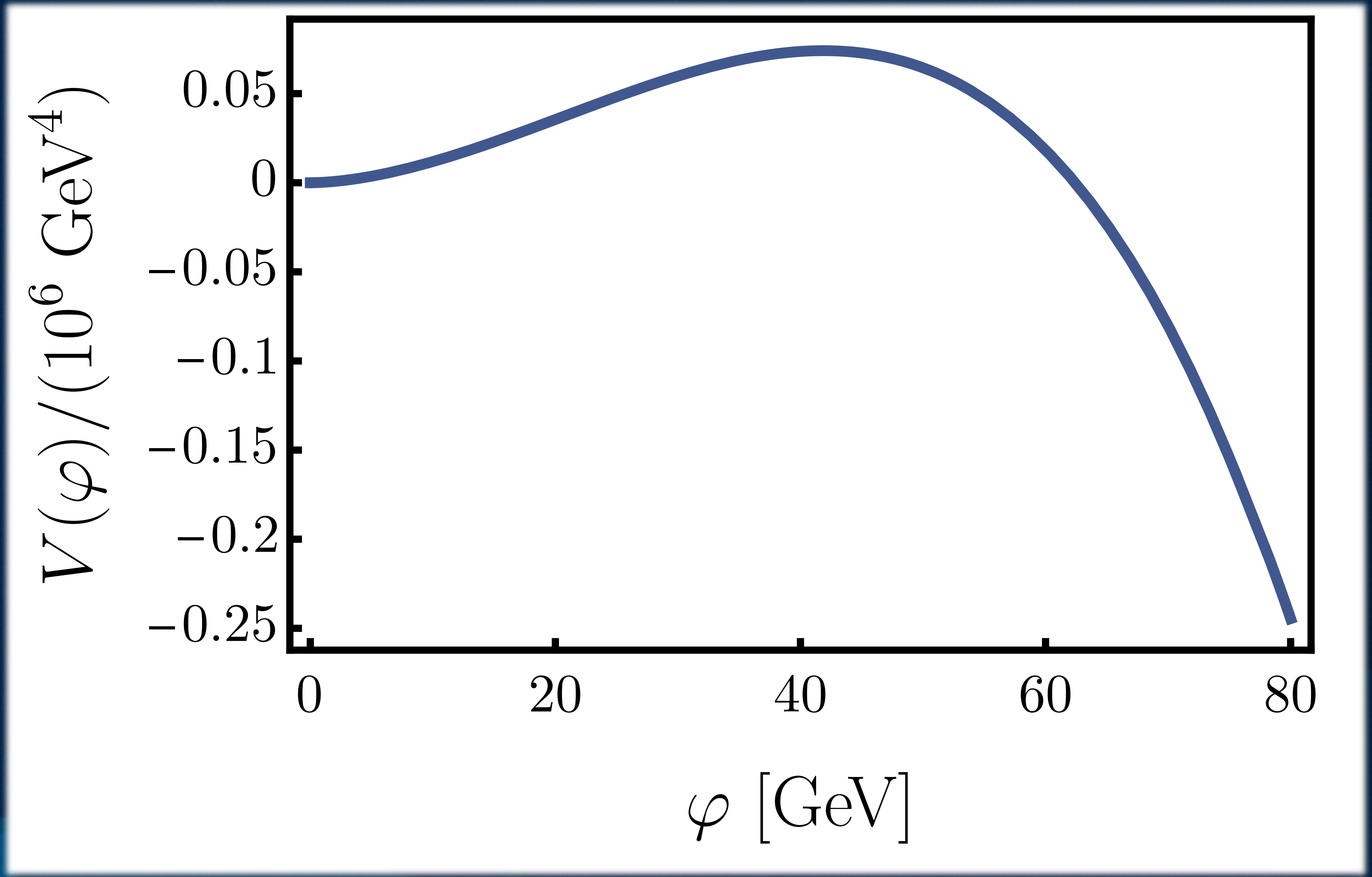
Features:

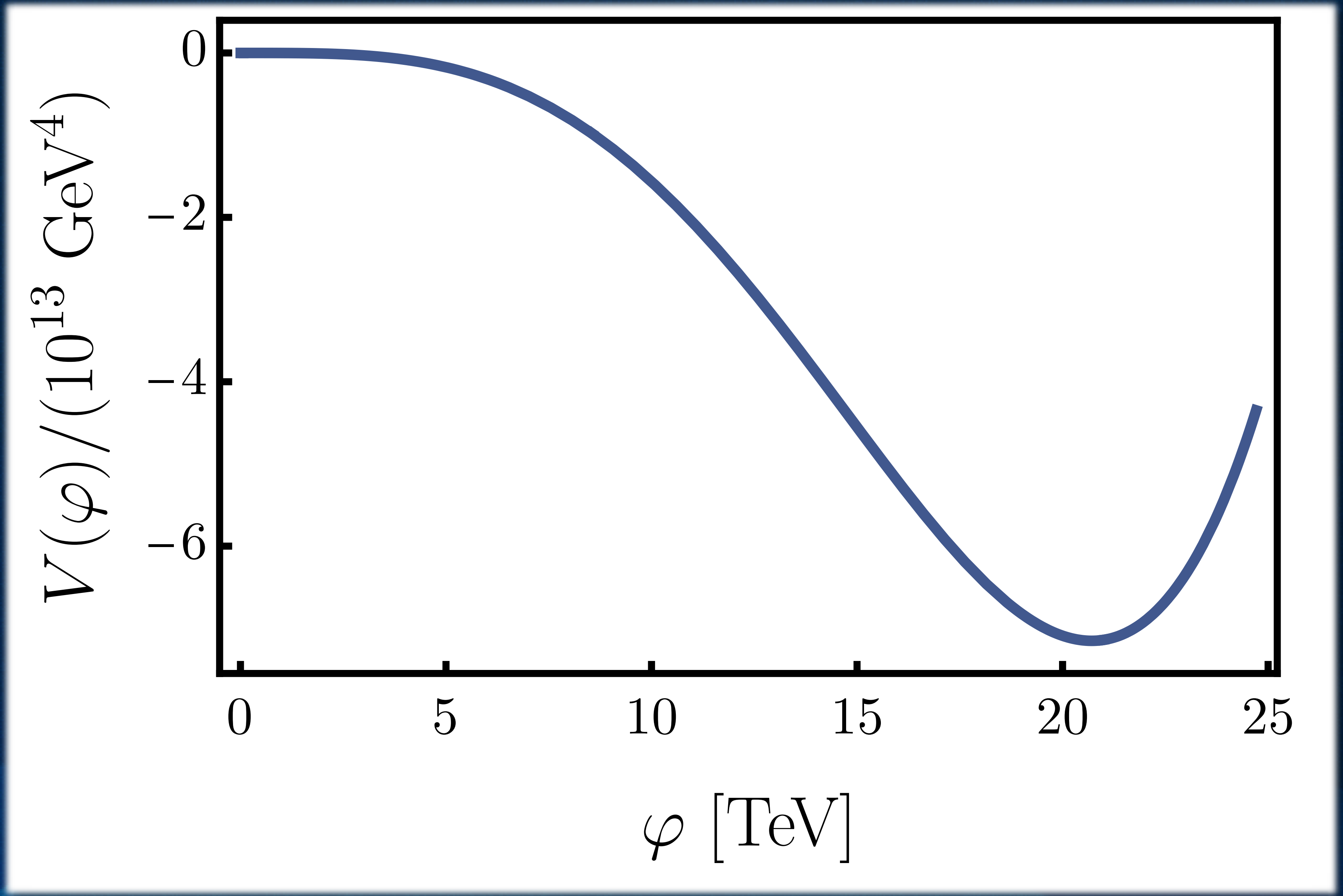
- Phase transition happens at temperatures significantly below EW scale
- Thermally produced barrier lasts till $T = 0$
- Induces a strong Gravitational Wave signal.



Problem: many scales present

$g_X = 0.9,\, M_X = 10^4$ GeV





Around the barrier, where the tunnelling takes place (left panel), and around the minimum (right panel).

See also: D. Croon et al, 2009.10080, P. Athron et al, 2208.01319.

Renormalisation Group improvement

$$\begin{aligned} g &\longrightarrow g(t) \\ \varphi &\longrightarrow Z(t)\varphi \end{aligned}, \text{ where } \; t = \ln\left(\frac{\mu}{\mu_0}\right)$$

See also: L. Chataignier et al, 1805.09292

Renormalisation Group improvement

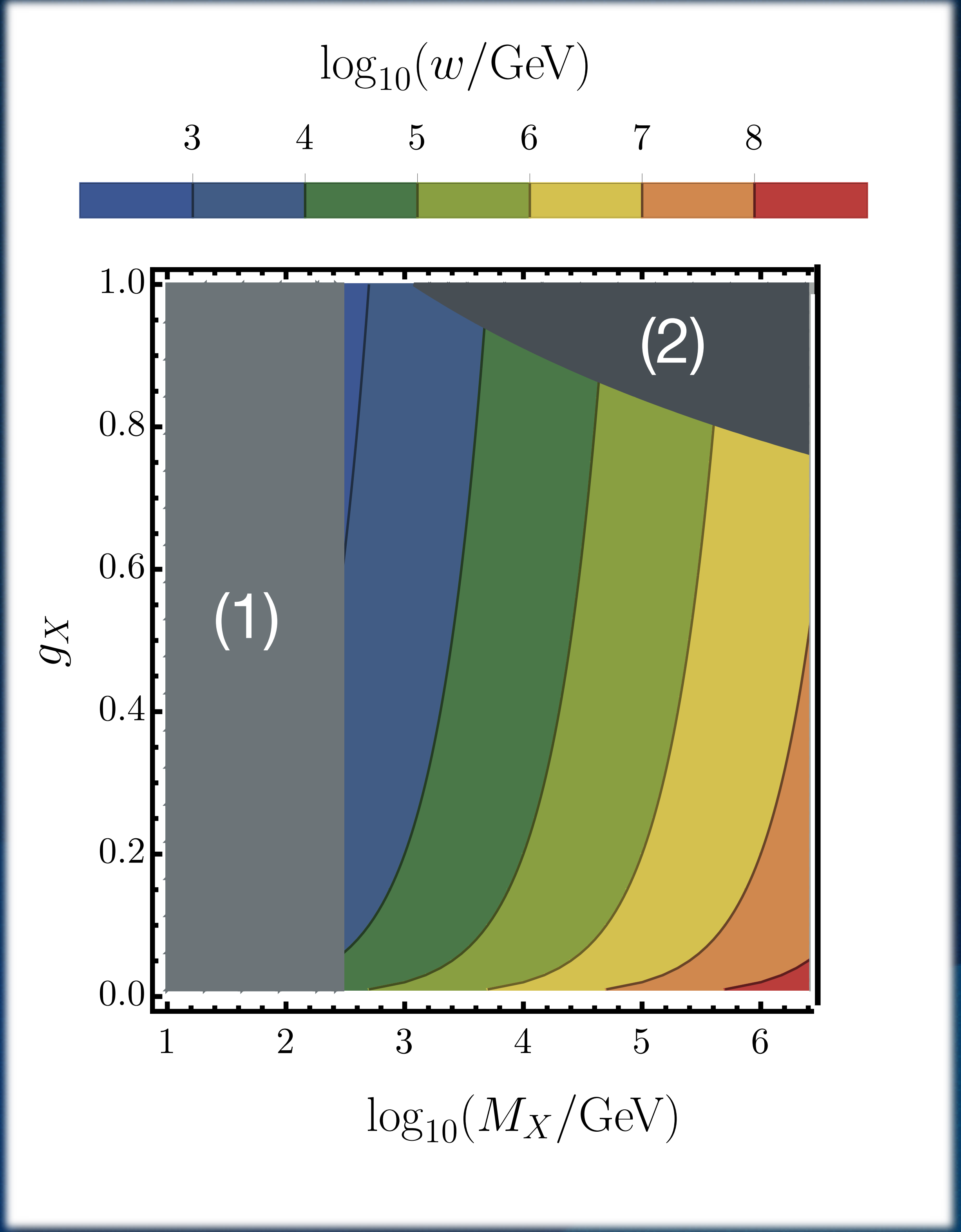
$$\begin{aligned} g &\longrightarrow g(t) \\ \varphi &\longrightarrow Z(t)\varphi \end{aligned}, \quad \text{where} \quad t = \ln\left(\frac{\mu}{\mu_0}\right)$$

$$\mu = \max\left(M_X(\varphi),\ 0.1\mathrm{GeV}\right), \quad \mu_0 = M_Z$$

See also: L. Chataignier et al, 1805.09292

Parameter space

- The SU(2)cSM lagrangian contains 4 parameters apart from the SM ones: $\lambda_1,\ \lambda_2,\ \lambda_3,$ and g_X
- Using the measured values of the Higgs VEV and Higgs mass we can eliminate two of them and be left with two free parameters.



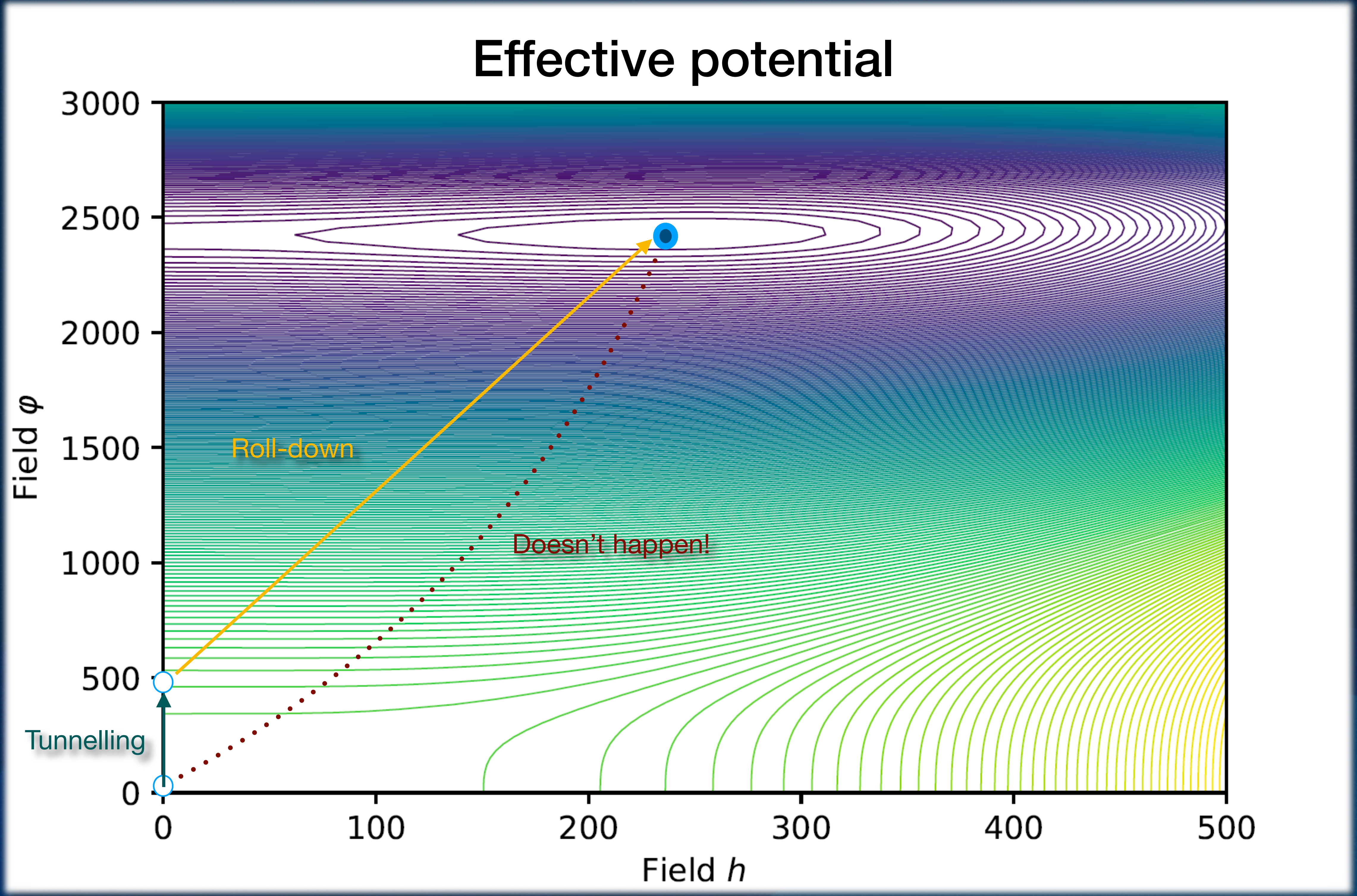
- (1) No EW minimum is reproduced
- (2) Perturbativity condition: $g_X@\mu = M_Z \leq 1.15$

RG Improved

$$V_{\rm eff}(\varphi, T=0) = \frac{1}{4}\lambda_3(t) Z_\varphi(t)^2 \varphi^4 + \frac{9M_X(\varphi,t)^4}{64\pi^2}\left(\log\frac{M_X(\varphi,t)^2}{\mu^2} - \frac{5}{6}\right)$$

See also: C. D. Carone et al, 1307.8428, T. Hambye et al, 1306.2329, D. Marfatia et al, 2006.07313, I. Baldes et al, 1809.01198

Tunneling scenario in SU(2)cSM



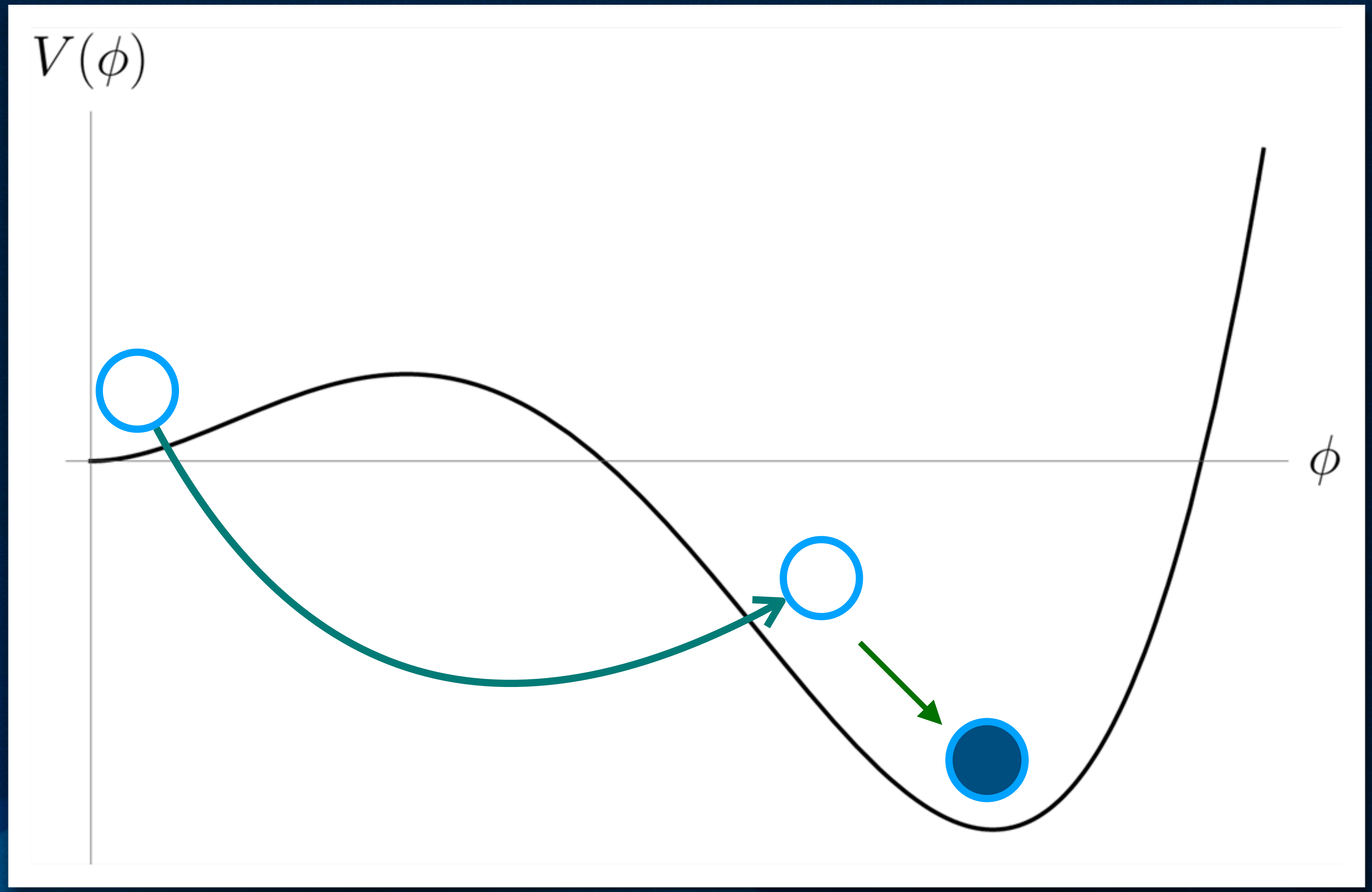
Thermal tunnelling

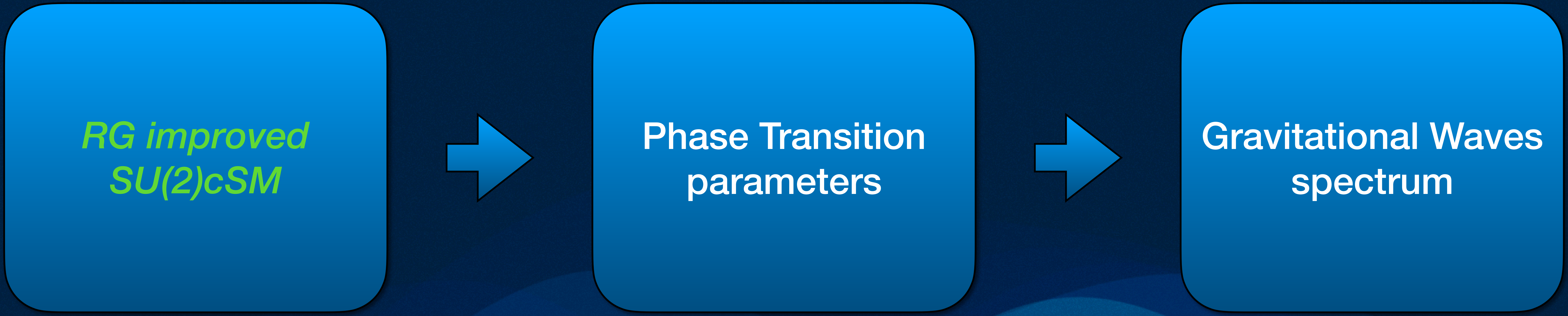
- Decay rate is given by:

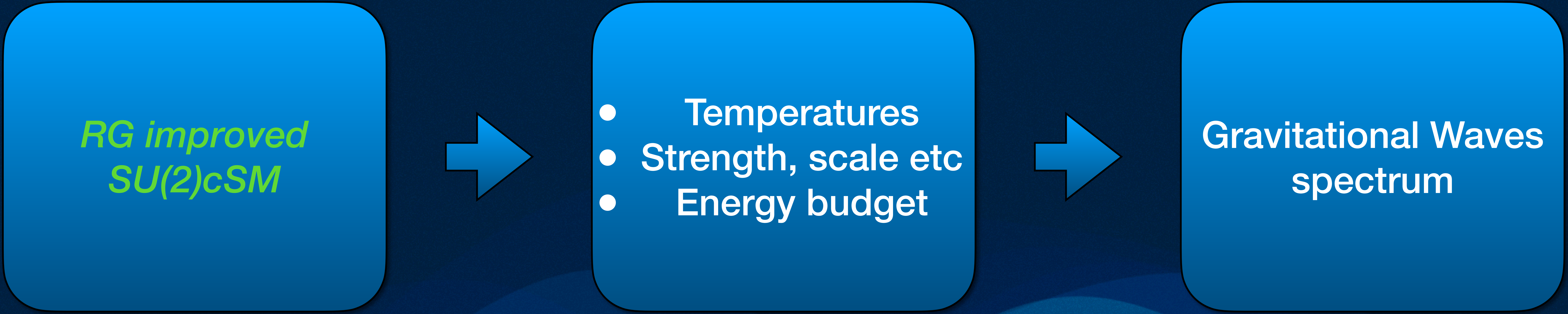
$$\Gamma \simeq e^{-\frac{S_3}{T}},$$

- Euclidean action along the bounce solution:

$$S_3 = 4\pi \int \mathrm{dr}\ \mathrm{r}^2 \left[\left(\frac{1}{2} \frac{\mathrm{d}\phi}{\mathrm{dr}} \right)^2 + \mathrm{V_{eff}}(\phi, \mathrm{T}) \right]$$

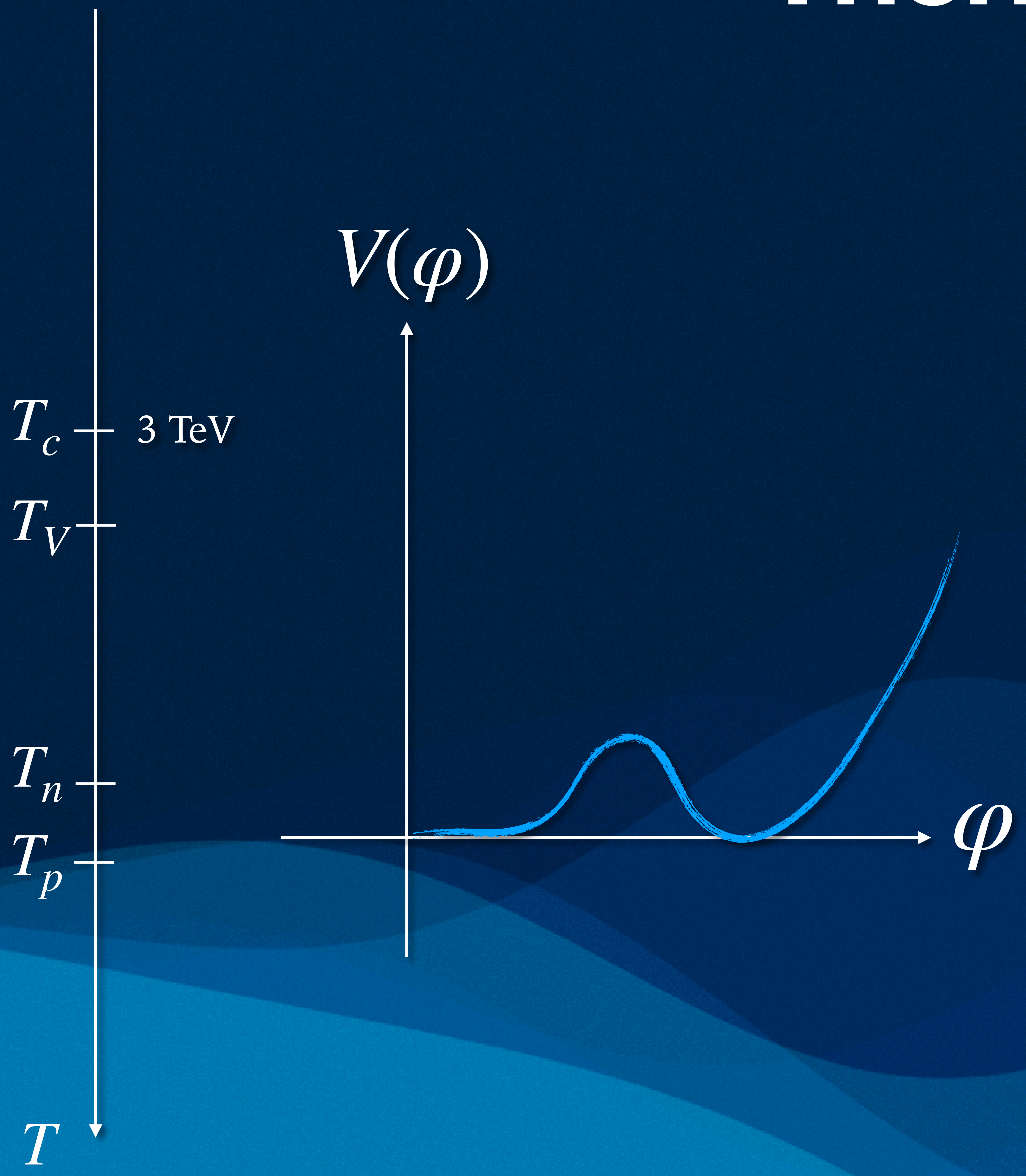



RG improved SU(2)cSM
Phase Transition parameters
Gravitational Waves spectrum


RG improved SU(2)cSM
Temperatures
Strength, scale etc
Energy budget
Gravitational Waves spectrum

$M_X = 9$ TeV, $g_X = 0.9$

Thermal evolution

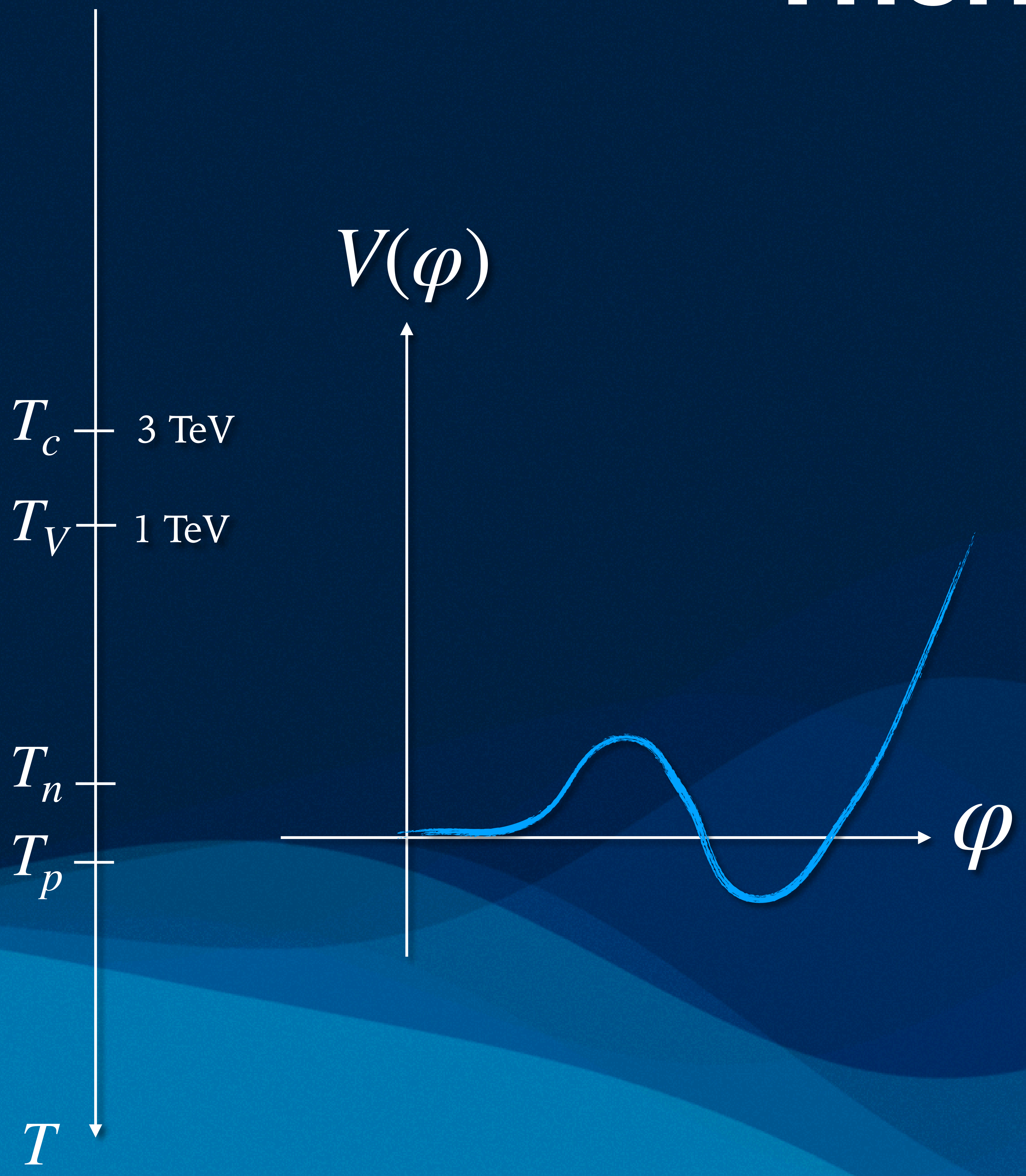


Critical temperature: two degenerate minima

Plots courtesy of B. Swiezewska (talk at Workshop on Multi-Higgs Models, 31.08.2022)

Thermal evolution

$M_X = 9$ TeV, $g_X = 0.9$



Vacuum domination begins

Hubble parameter is given as:

$$H^2 = \frac{1}{3M_{\rm pl}^2}\left(\rho_{\rm R} + \rho_{\rm V}\right) = \frac{1}{3M_{\rm pl}^2}\left(\frac{T^4}{\xi_g^2} + \Delta V\right)$$

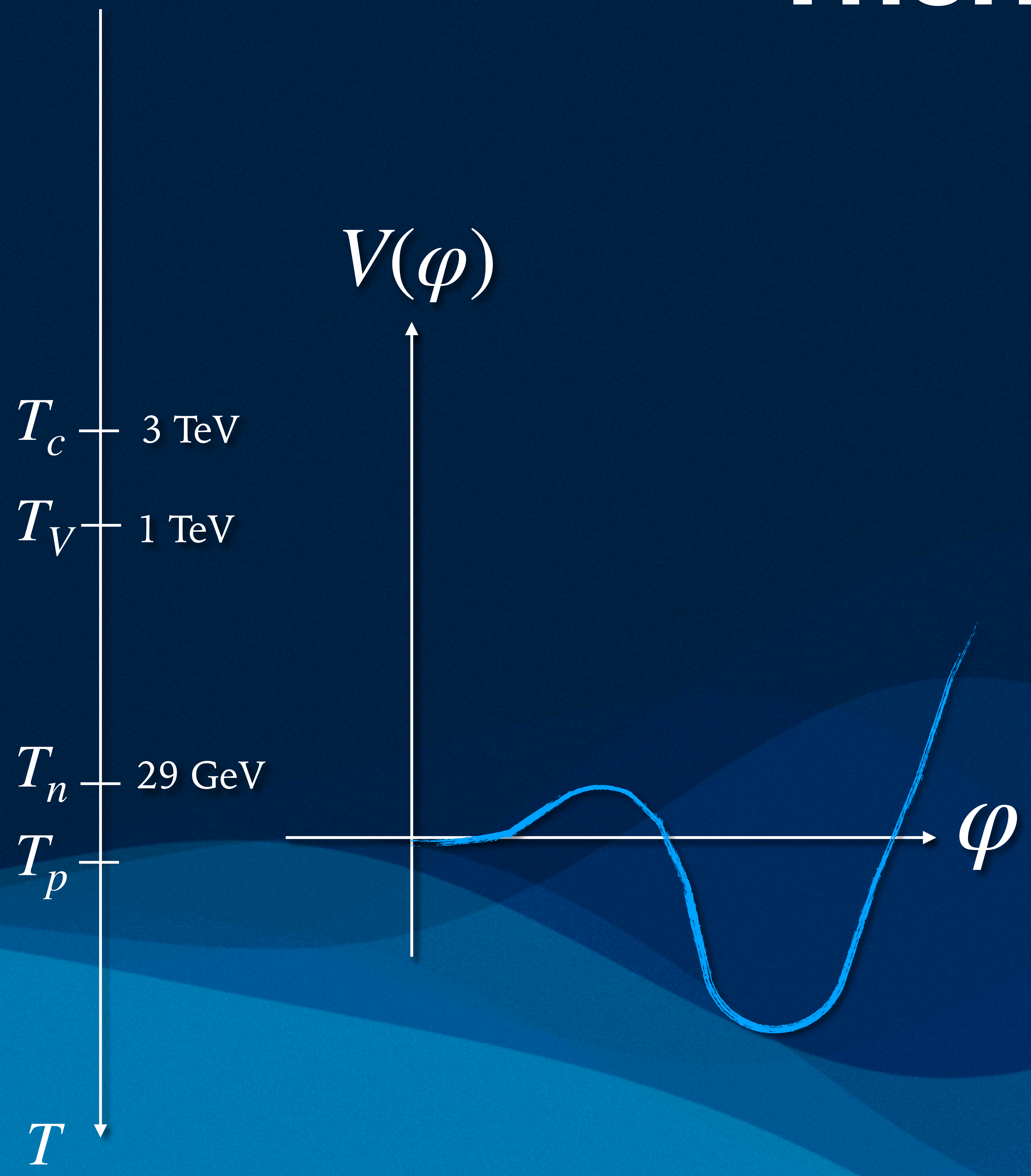
We enter into the vacuum domination at the temperature

$$T_V = \sqrt[4]{\Delta V \xi_g^2}$$

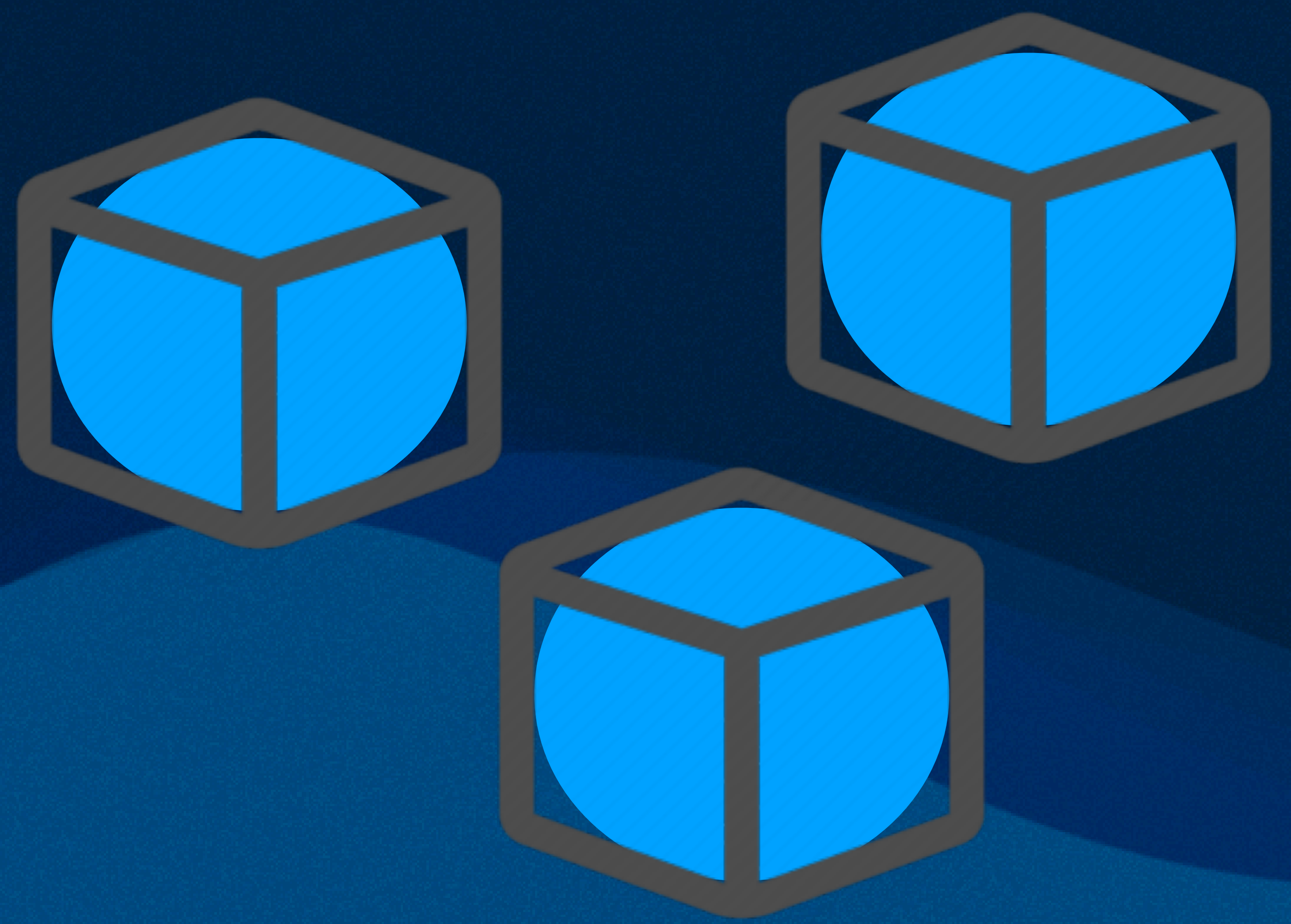
See also: T. Hambye et al, 1805.01473, J. Ellis et al, 1809.08242

$M_X = 9$ TeV, $g_X = 0.9$

Thermal evolution

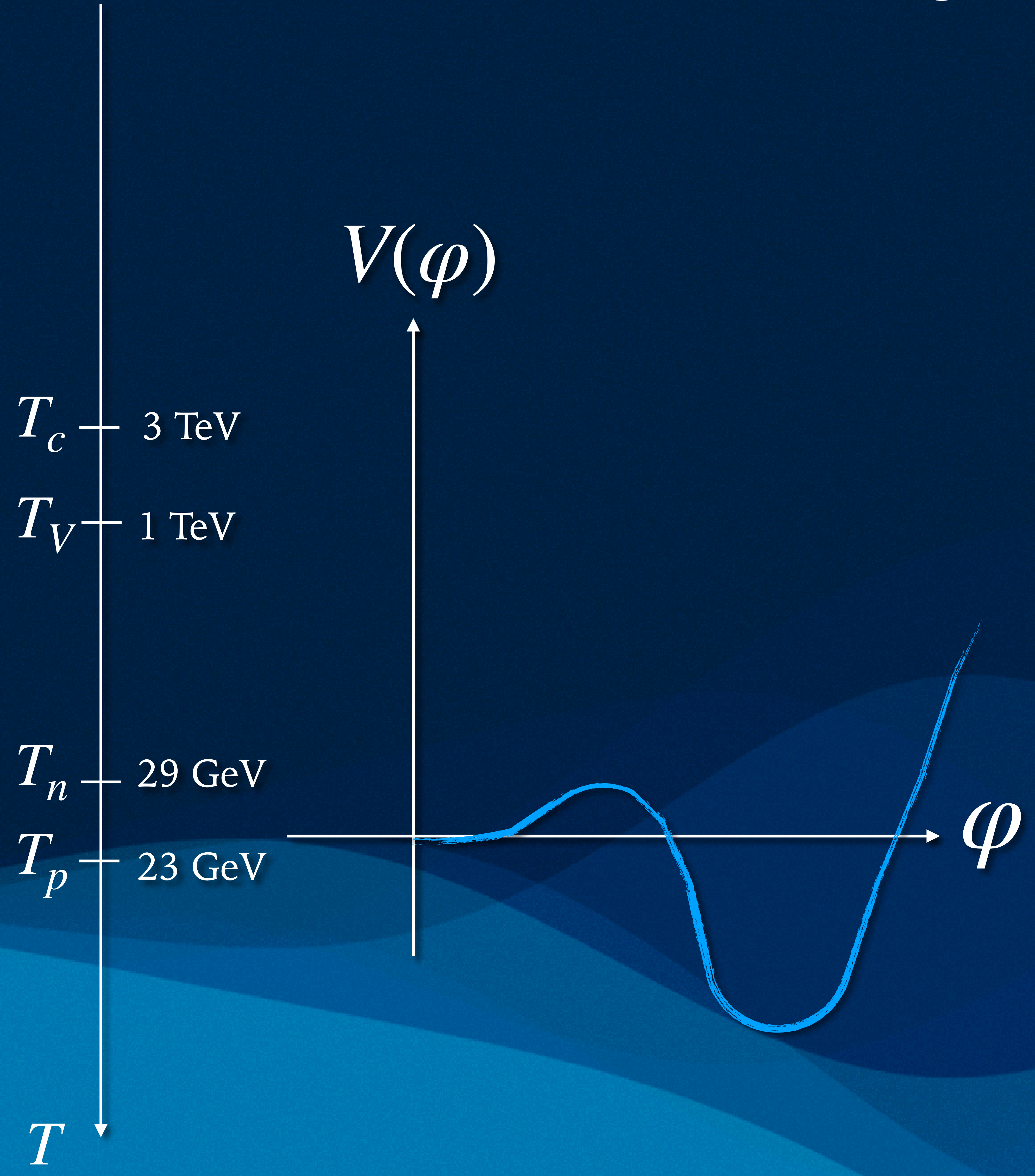


Nucleation:
one bubble nucleates per Hubble volume

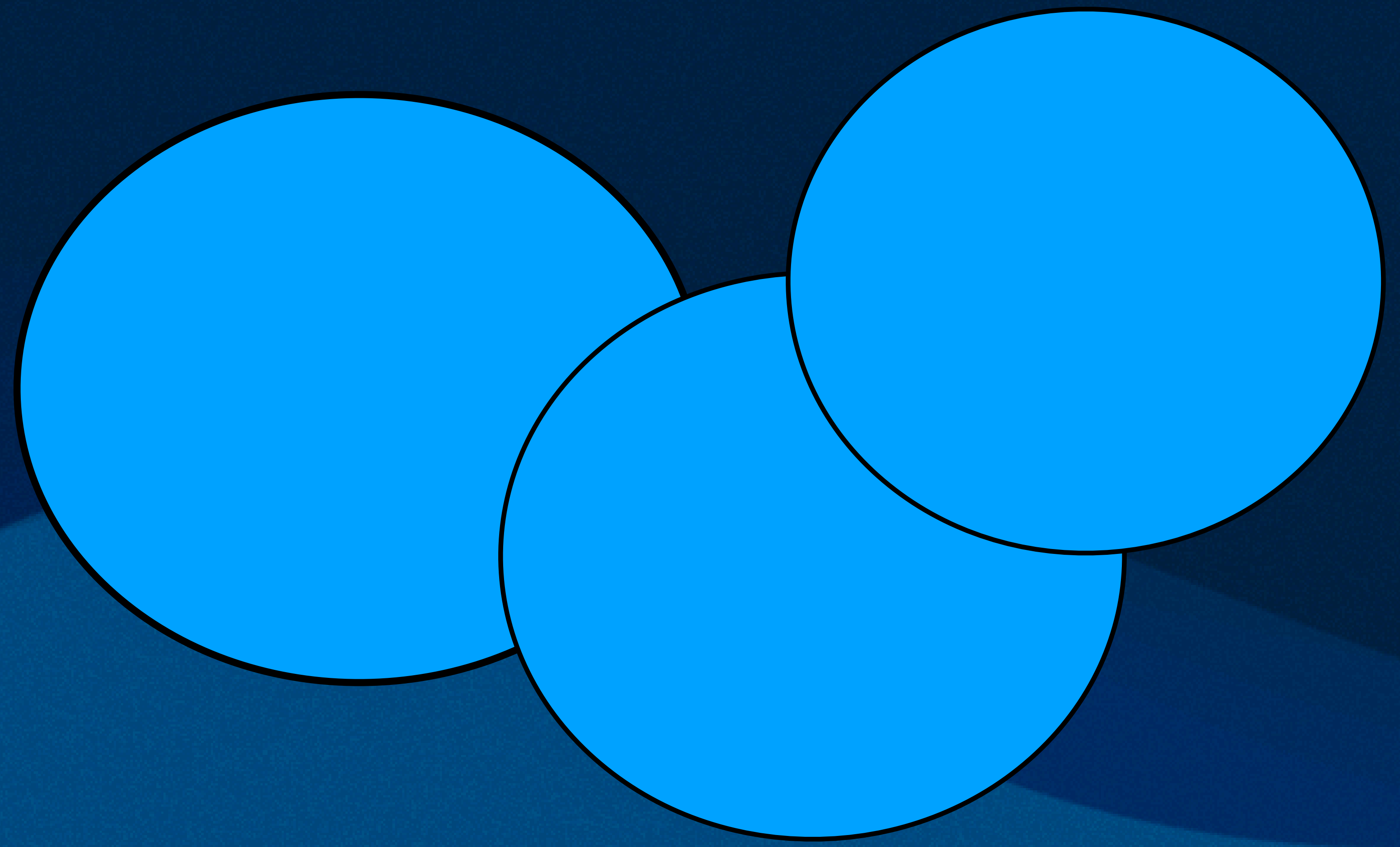


$M_X = 9$ TeV, $g_X = 0.9$

Thermal evolution



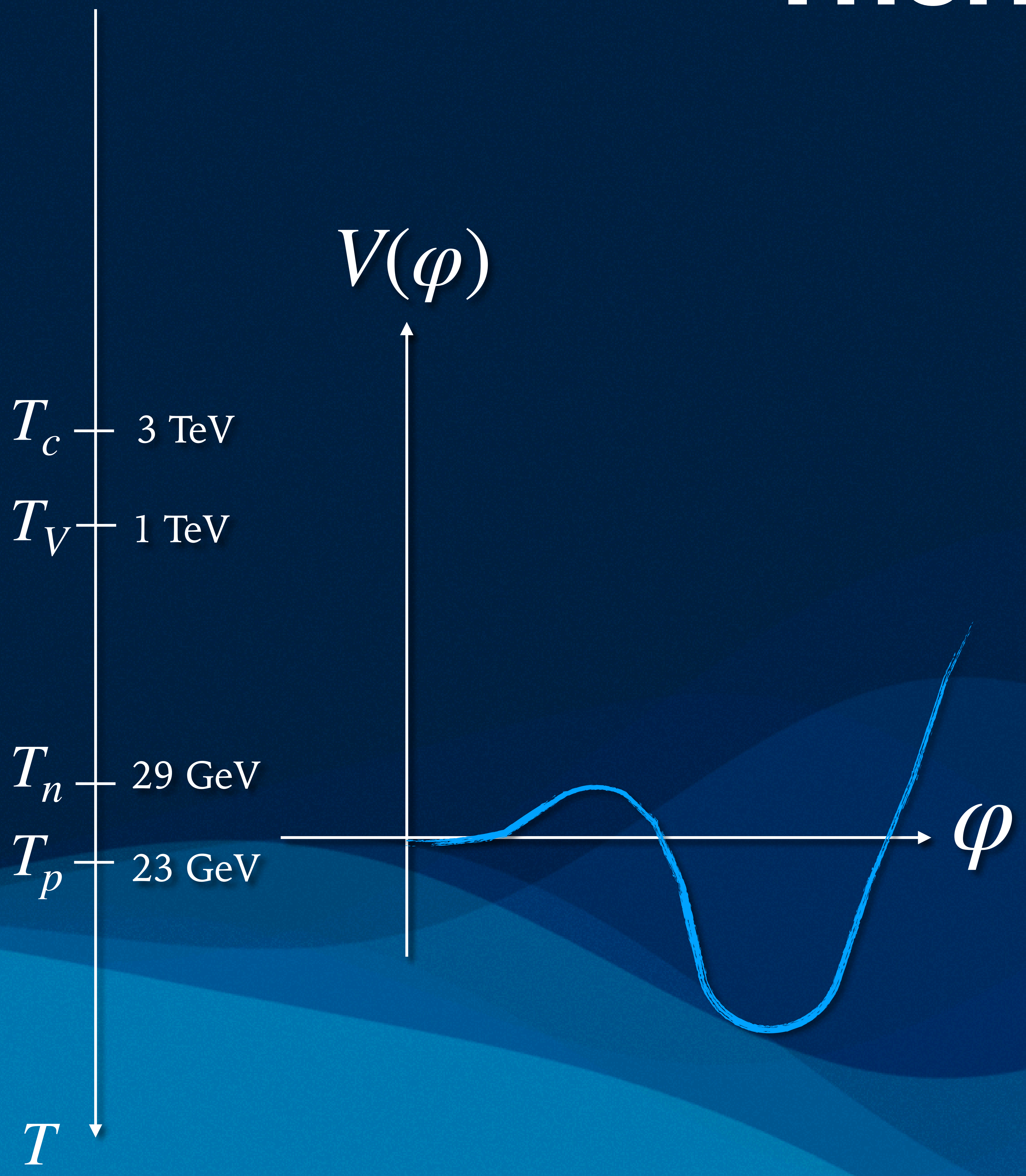
Percolation:
Phase transition completes!



See also: A. H. Guth et al, Phys. Rev. D 23 (1981), V. K. Shante et al, doi.org/10.1080/00018737100101261

$M_X = 9$ TeV, $g_X = 0.9$

Thermal evolution



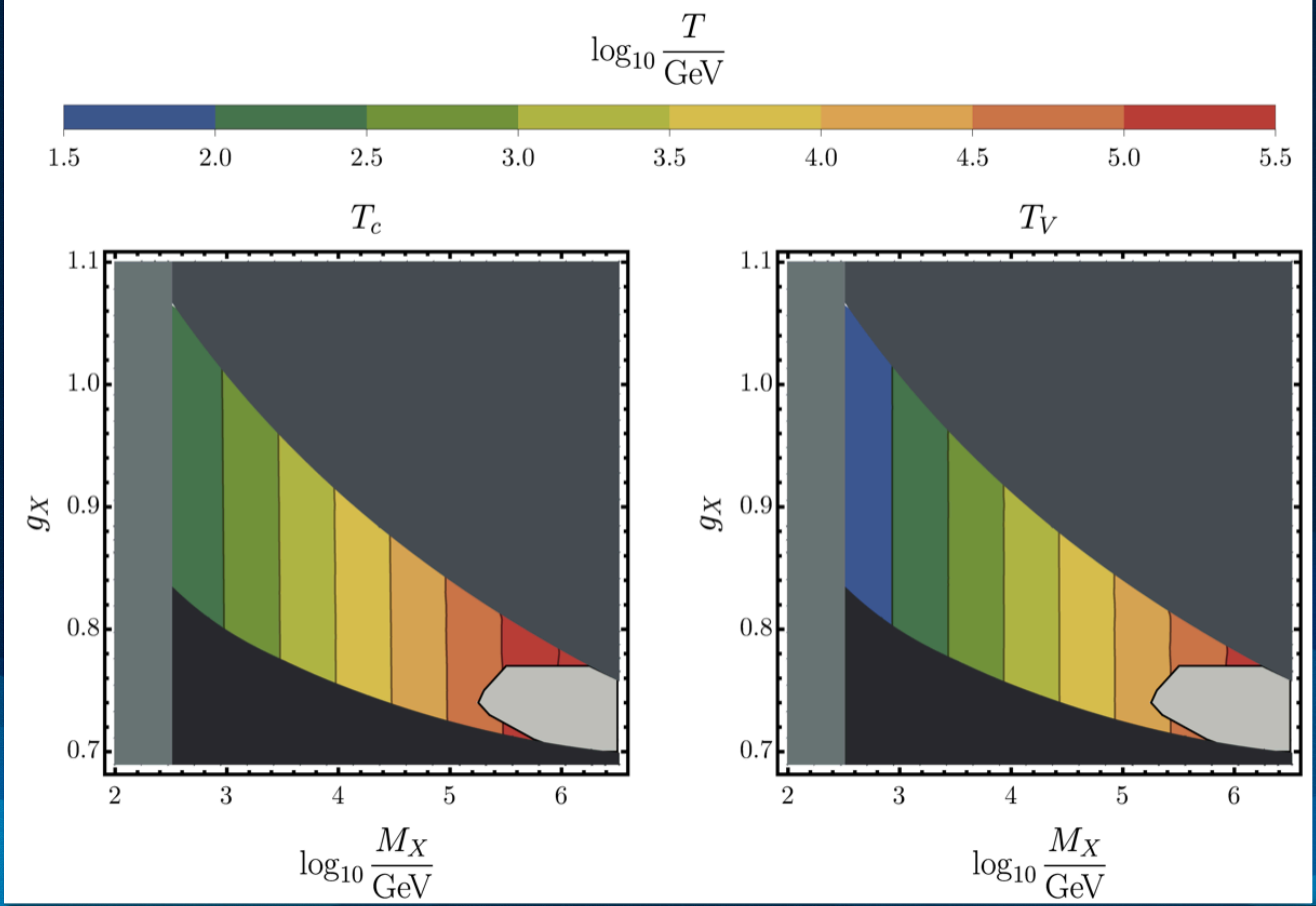
Reheating

$$\rho_{\text{vac}} \longrightarrow \rho_{\text{rad}}$$

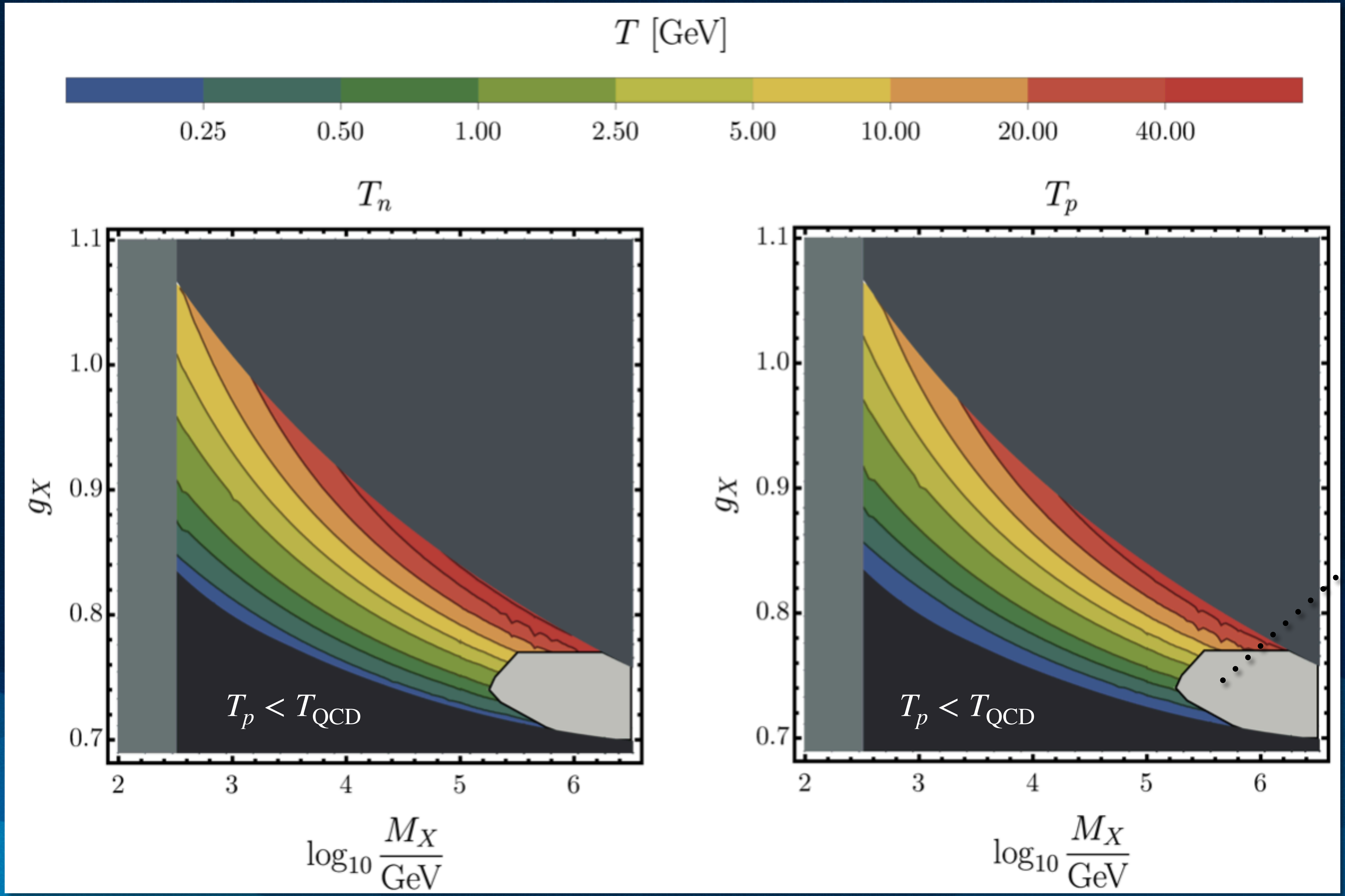
$$T_{\text{reh}} = T_V$$

See also: A. H. Guth et al, Phys. Rev. D 23 (1981), V. K. Shante et al, doi.org/10.1080/00018737100101261

Temperatures: critical vs vacuum domination

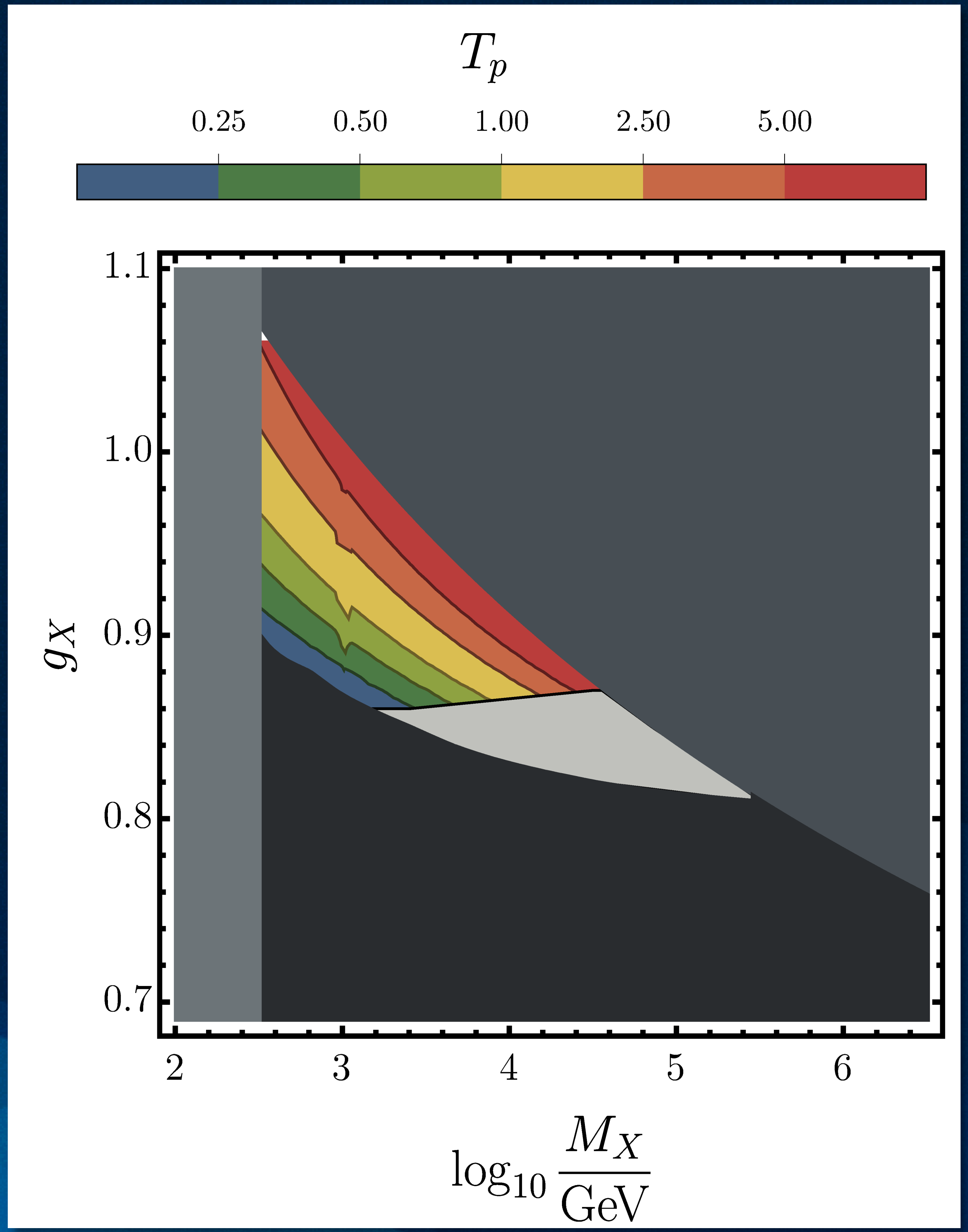


Temperatures: nucleation vs percolation

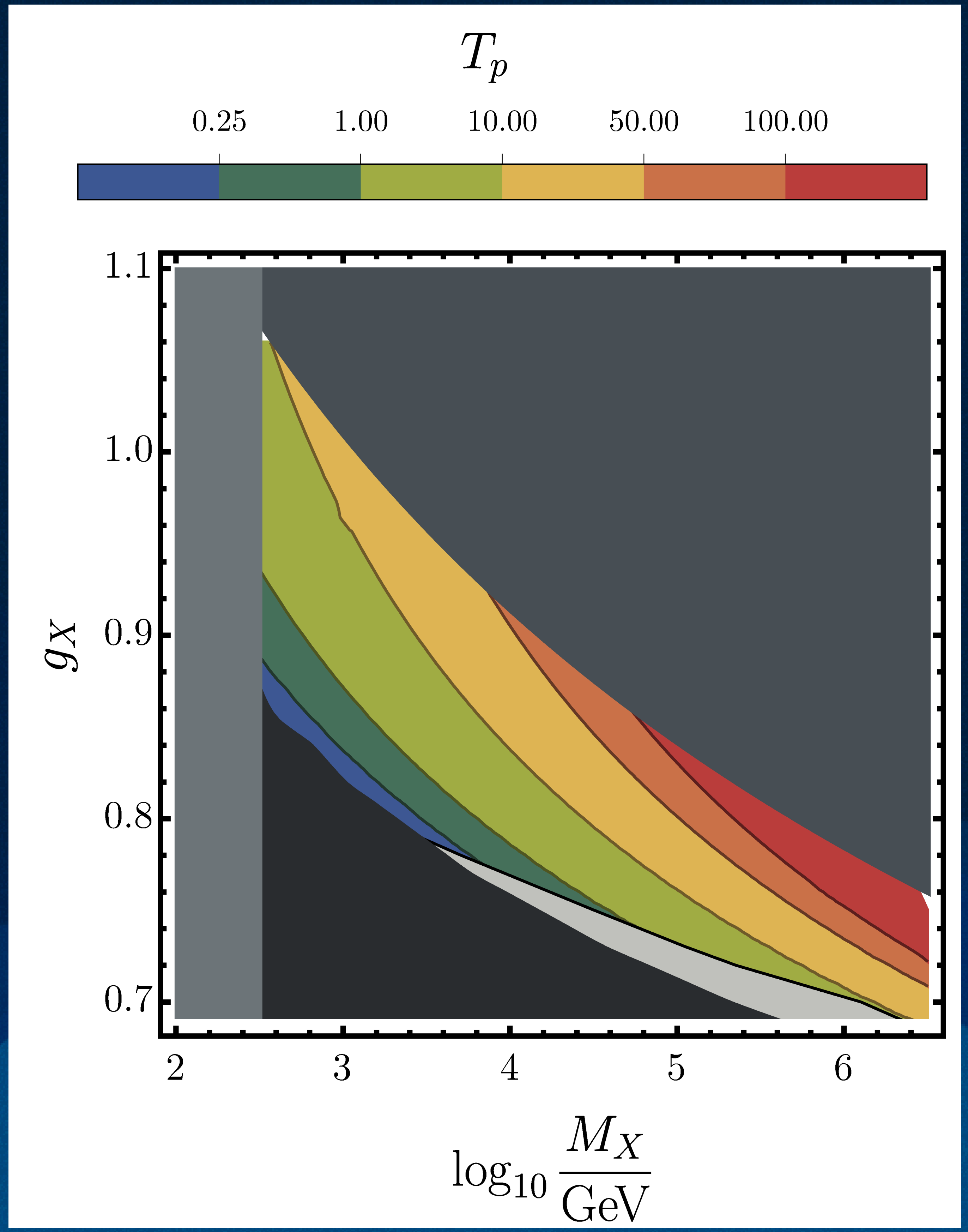


False vacuum doesn't shrink

Scale dependence of T_p



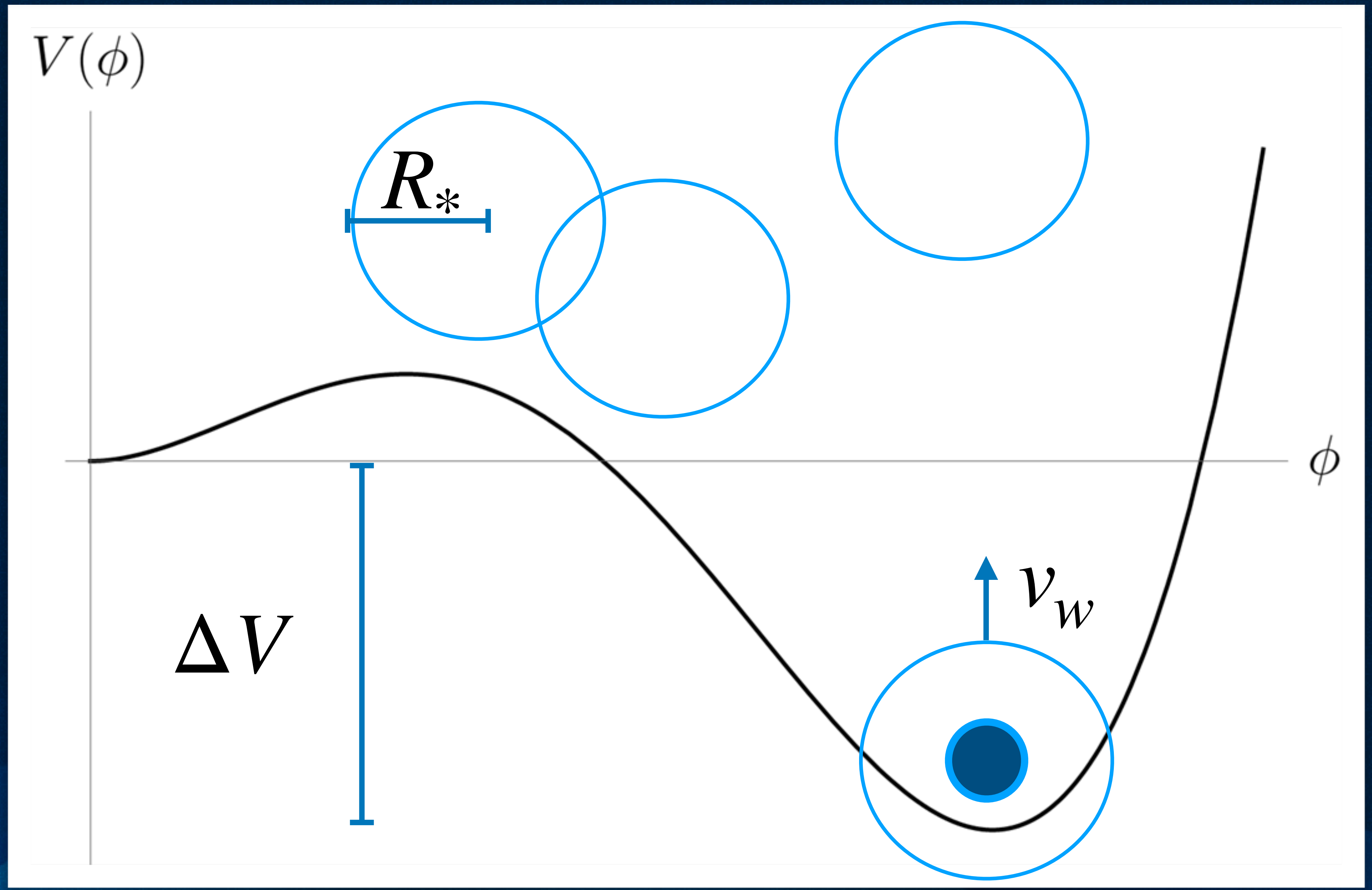
$@M_X$



$@M_Z$

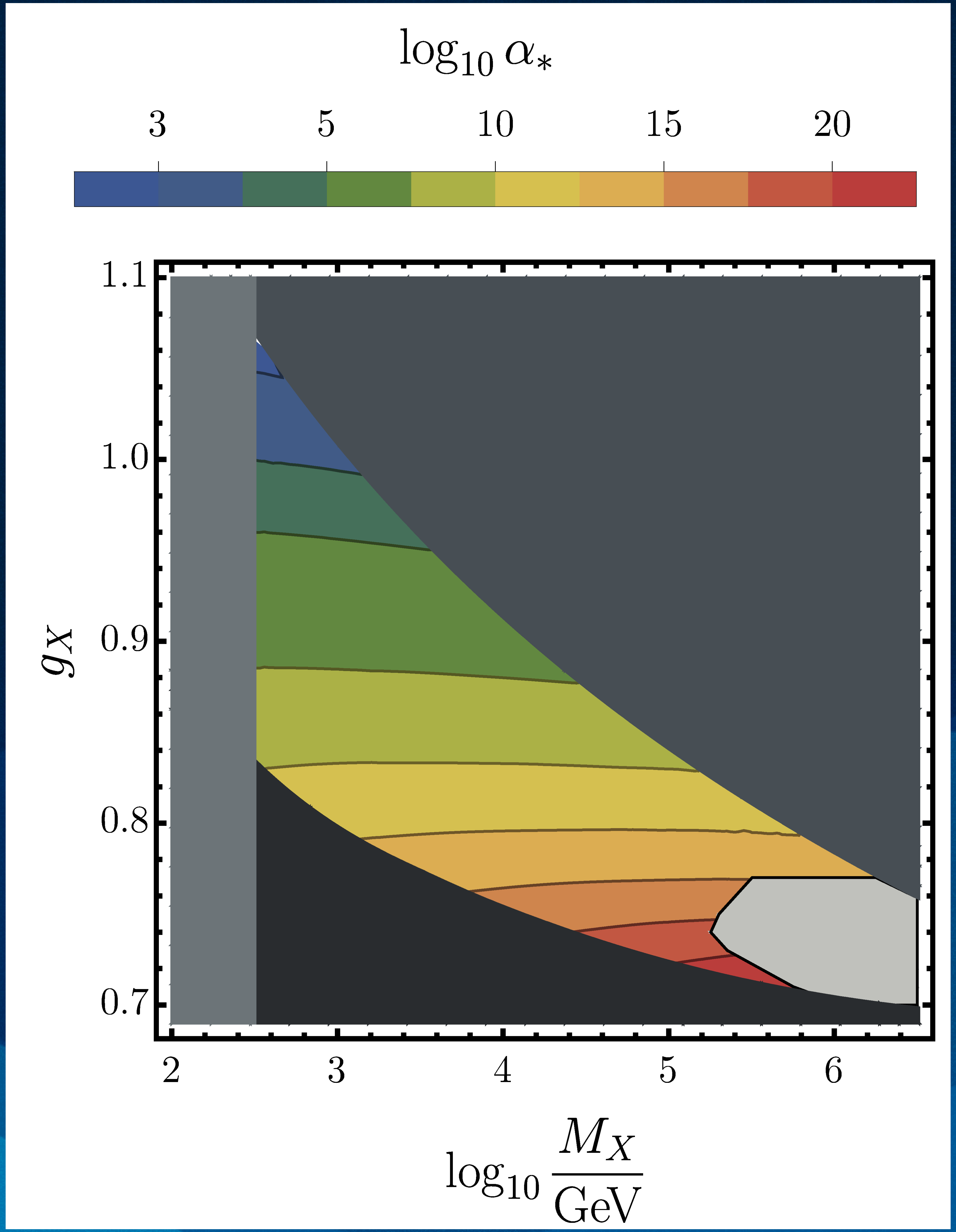
Strength, duration, wall velocity

- Transition strength $\alpha = \dfrac{\Delta V}{\rho_{\rm rad}}$
- Inverse time duration $\beta \simeq \dfrac{d}{dt} \ln \Gamma(T)$
- … or average bubble radius R_*
- Bubble wall velocity $v_w \simeq 1$

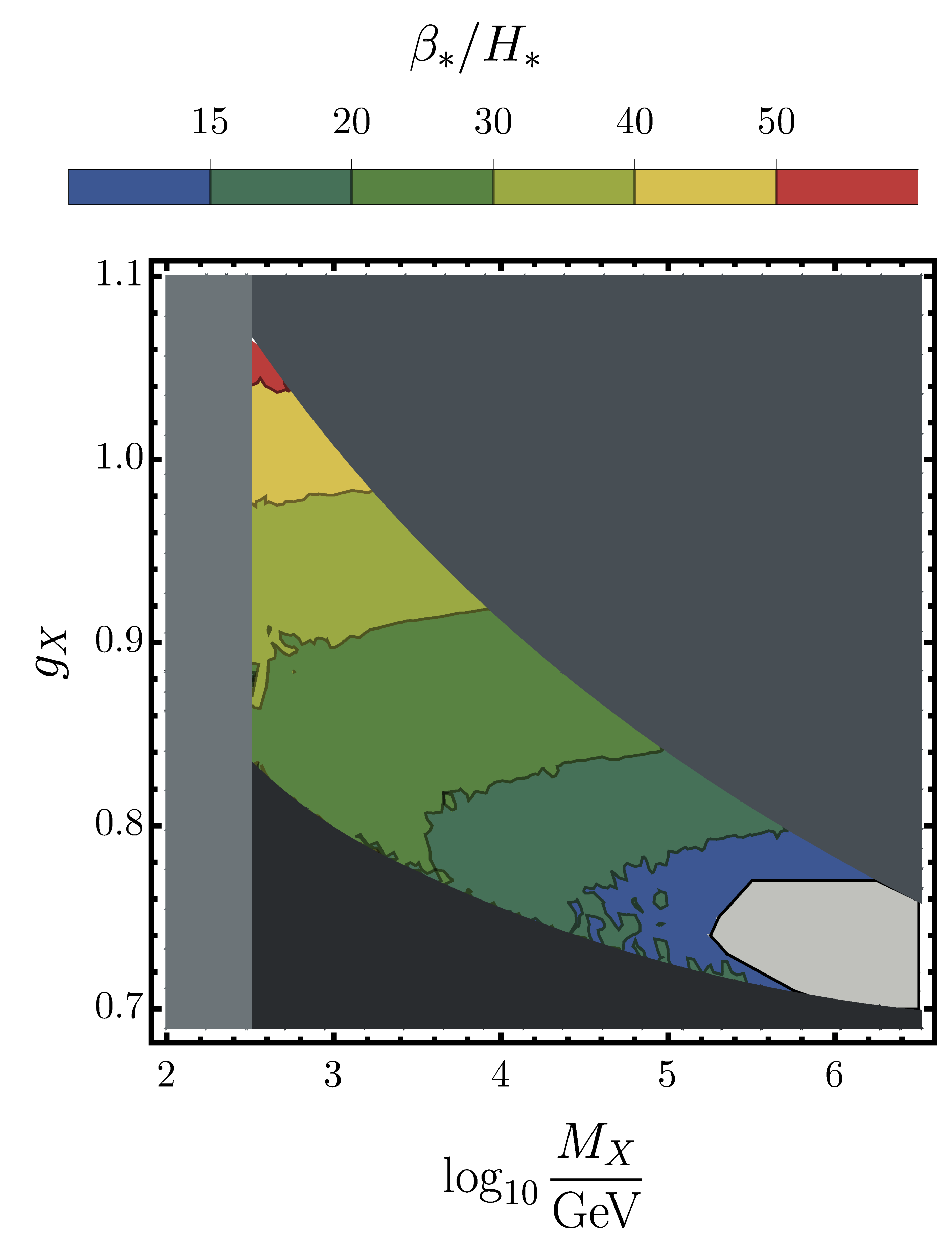


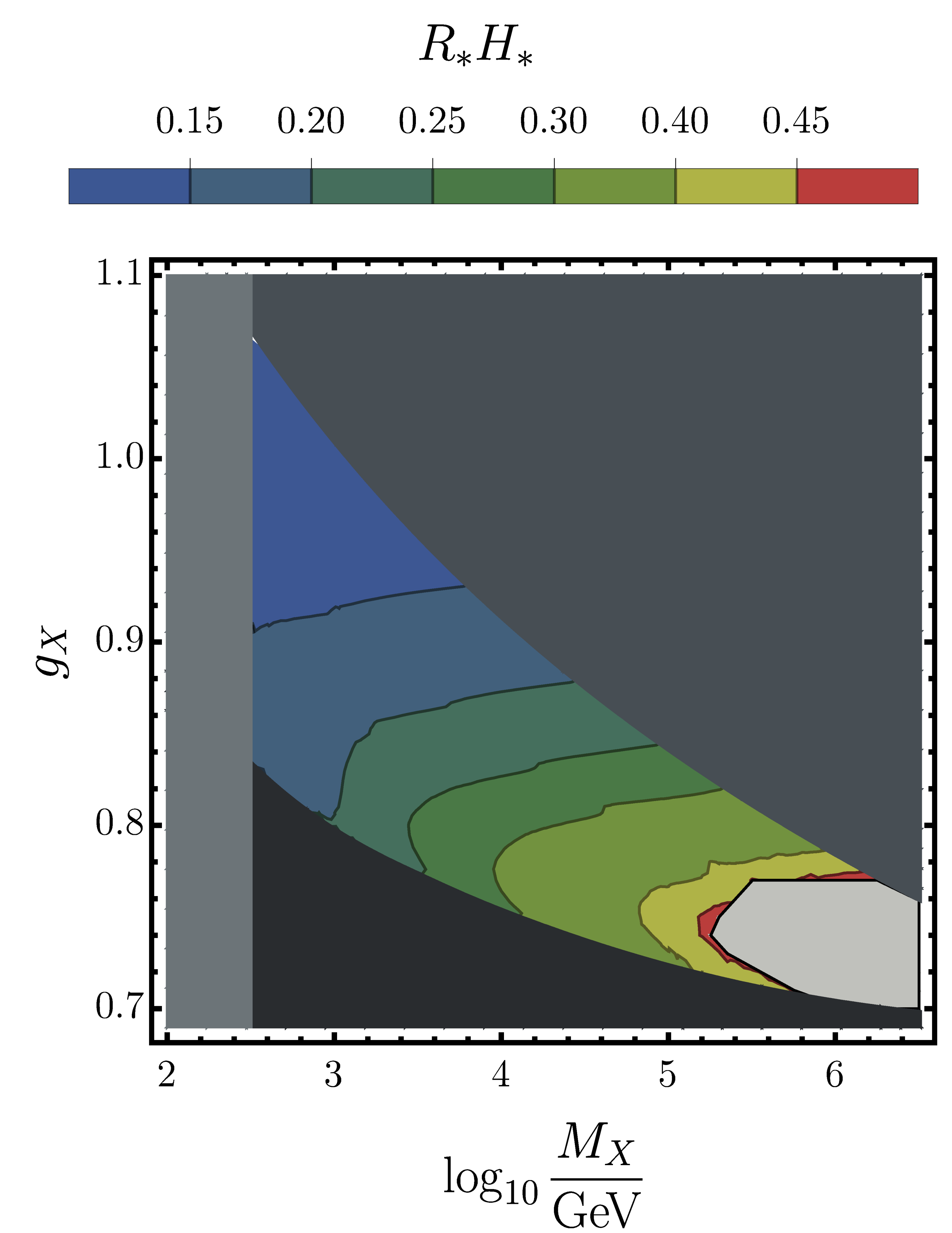
$$T = T_* = T_p$$

Transition strength

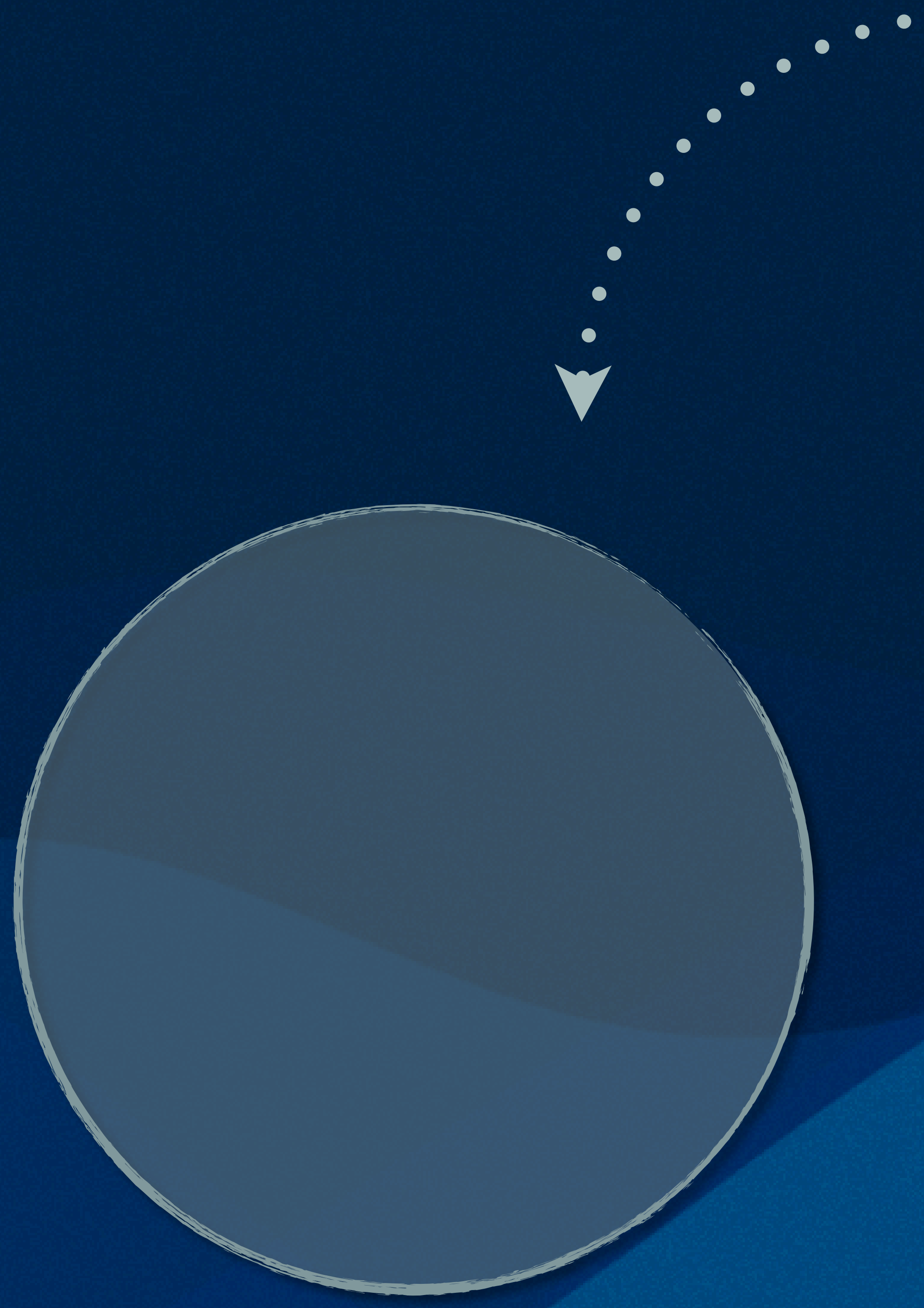


“Length scale” of the transition





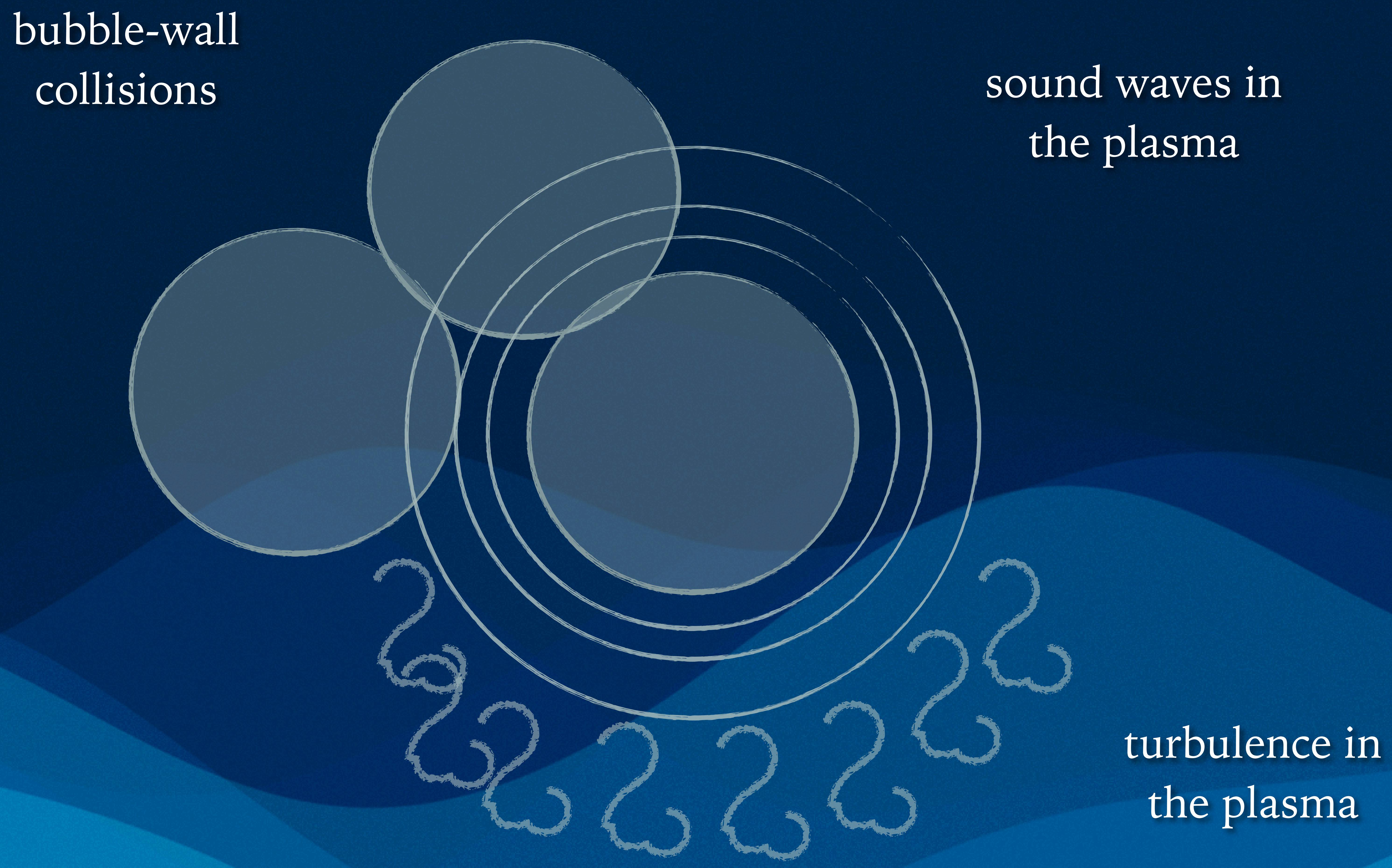
Sources of gravitational waves



lots of energy in the bubble

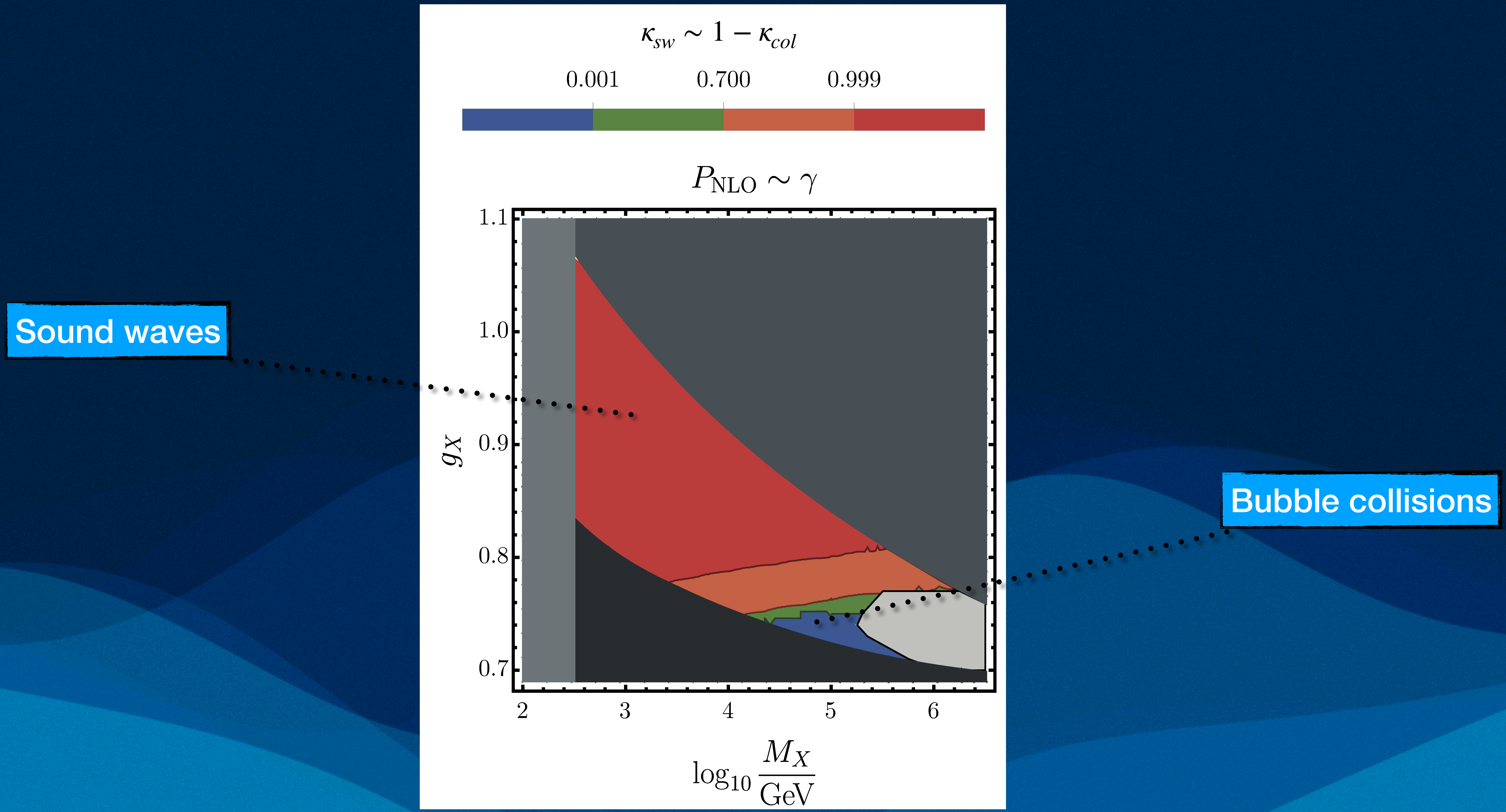
Figures courtesy of B. Swiezewska (talk at Workshop on Multi-Higgs Models, 31.08.2022)

Sources of gravitational waves



Figures courtesy of B. Swiezewska (talk at Workshop on Multi-Higgs Models, 31.08.2022)

PT parameters - energy budget



RG improved effective potential in SU(2)cSM

→

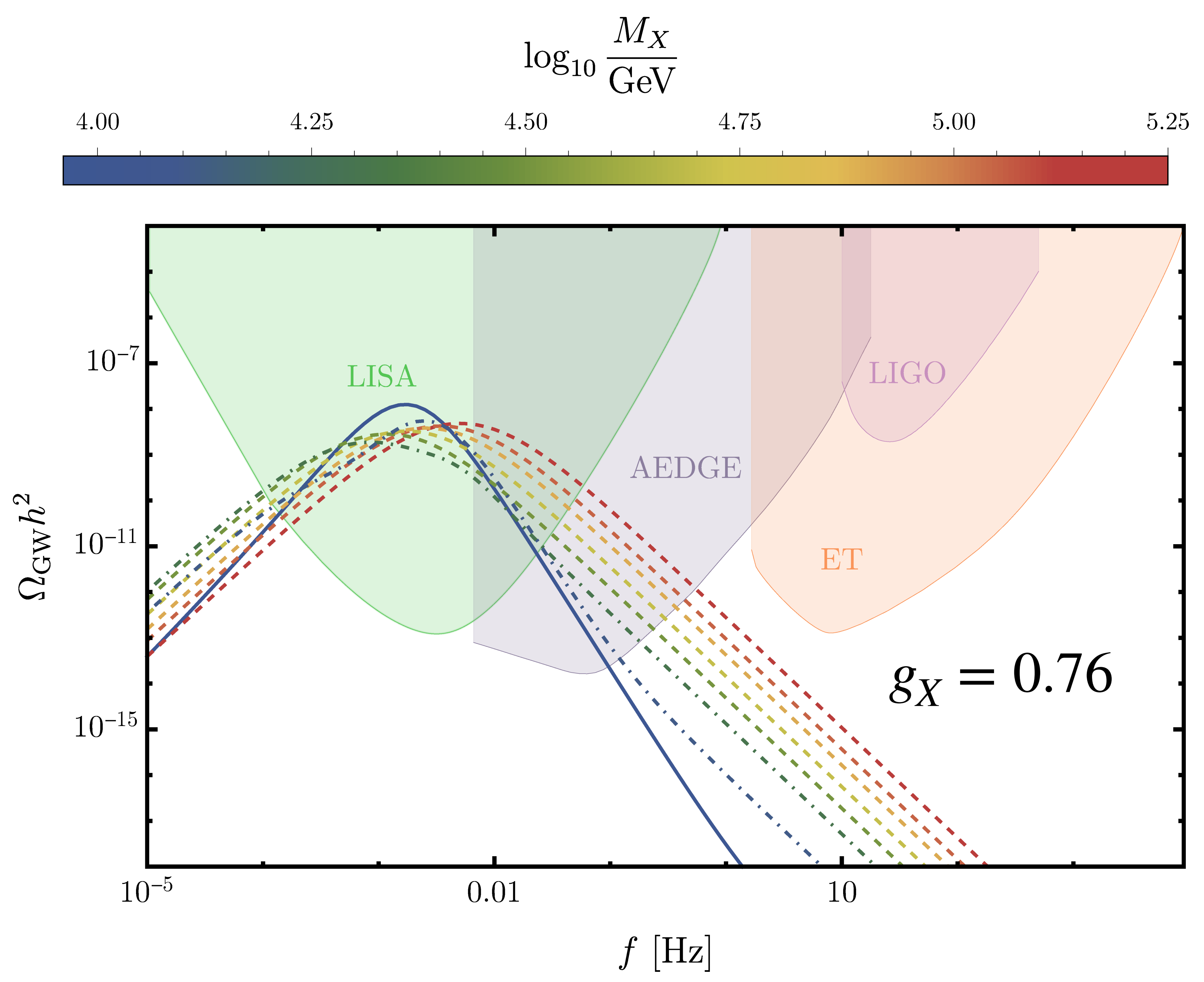
- $T_V,\ T_n,\ T_p$
- $\alpha_*,\ R_*H_*$
- $\kappa_{sw},\ \kappa_{col}$

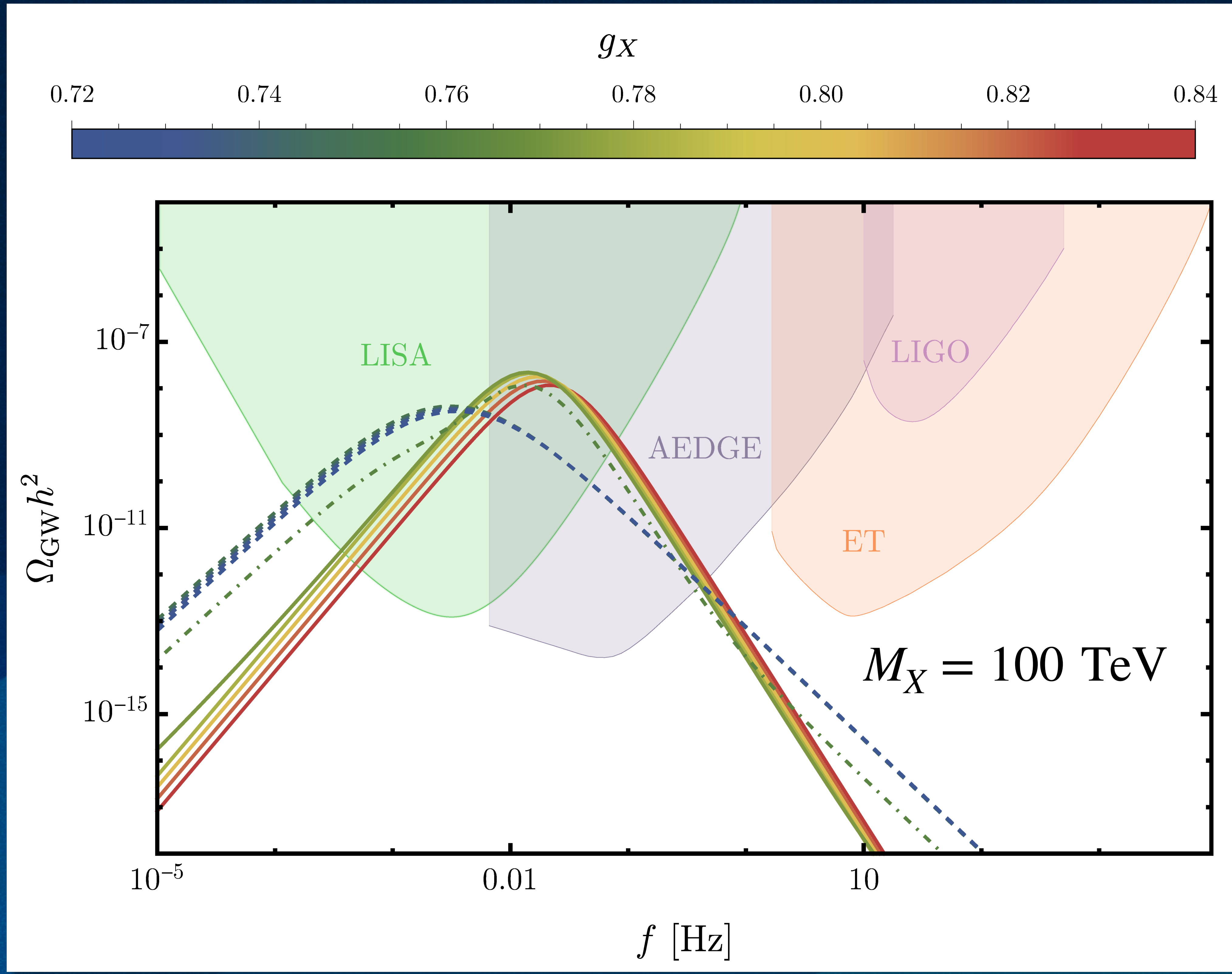
→

Gravitational Waves spectrum

GW spectra today

$$\Omega_{GW}h^2 \sim 1.67 \cdot 10^{-5} \times (R_* H_*)^c \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 S_{\rm fit}\left(\frac{f}{f_{\rm peak}}\right)$$

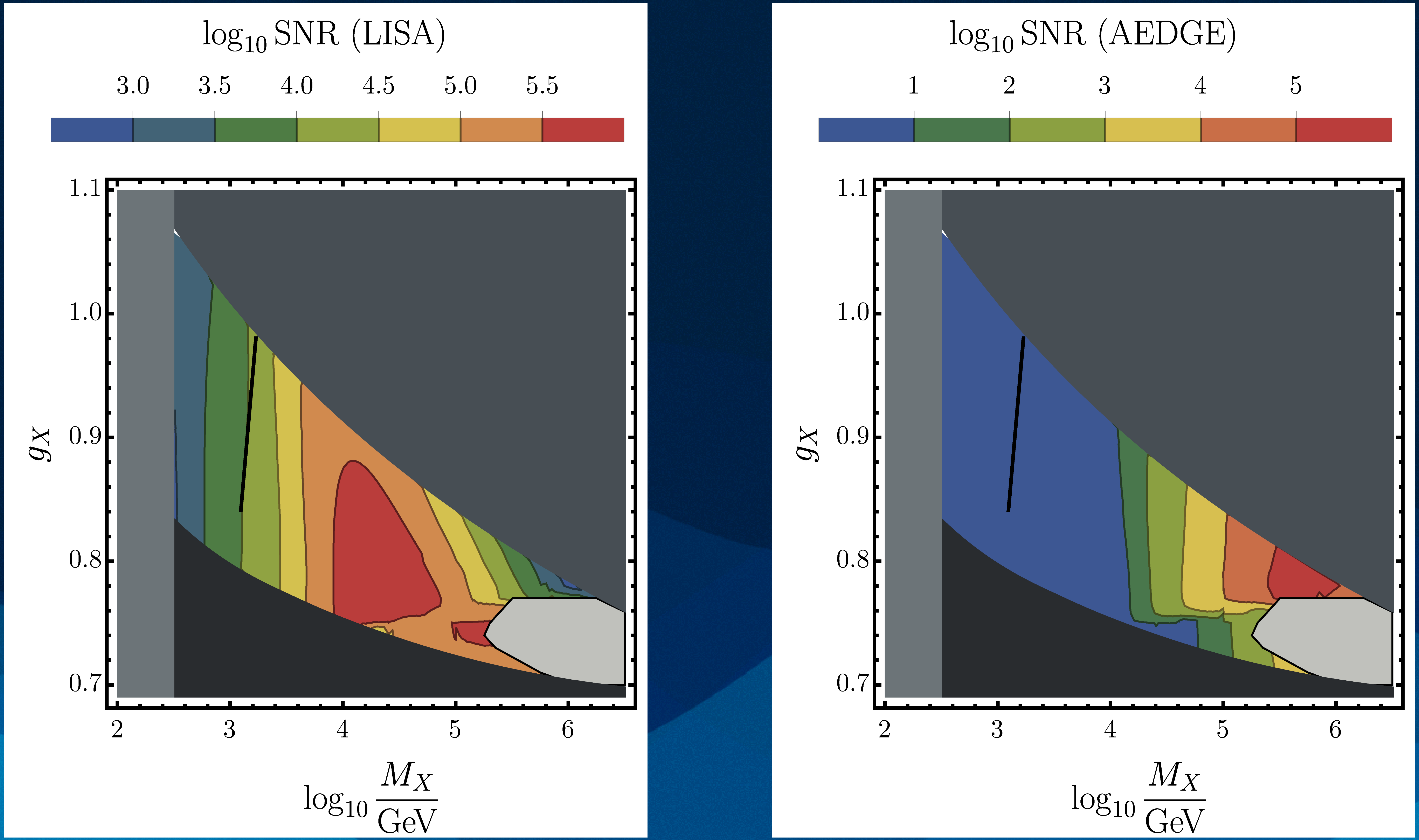




See also: M. Lewicki and V. Vaskonen, 2012.0782, 2208.11697, C. Caprini et al, 1512.06239

[sensitivity curves courtesy M. Lewicki]

GW Signal-to-noise ratio



RG improved effective potential in SU(2)cSM

→

$T_V,\ T_n,\ T_p$

$\alpha_*,\ R_* H_*$

$\kappa_{sw},\ \kappa_{col}$

→

$\Omega_{\rm GW} h^2$ + SNR

RG improved effective potential in SU(2)cSM

→

$T_V,\ T_n,\ T_p$

$\alpha_*,\ R_*H_*$

$\kappa_{sw},\ \kappa_{col}$

→

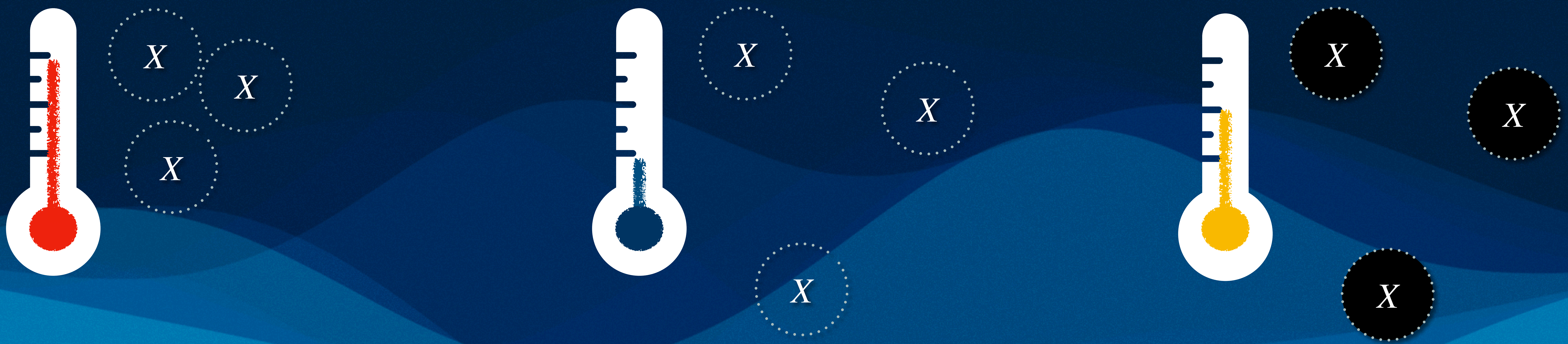
$\Omega_{\mathrm{GW}}h^2$ + SNR

Extra chapter

Dark Matter

(Supercool) Dark matter

Our DM candidates are the three vector bosons X^a_μ (where $a = 1,2,3$) of the hidden sector gauge group $\mathrm{SU}(2)$.



See also: T.Hambye, A.Strumia, PRD88 (2013) 055022, C.Carone, R.Ramos, PRD88 (2013) 055020, V.V.Khoze, C.McCabe, G.Ro, JHEP 08 (2014) 026, T. Hambye, A.Strumia, D.Teresi, JHEP 1808 (2018) 188, I.Baldes, C. Garcia-Cely, JHEP 05 (2019) 190, T.Prokopec, J.Rezacek, BS, JCAP02(2019)009, D. Marfaria, P. Tseng, JHEP 02 (2021) 022

Now if…

$T_{\text{dec}} > T_{\text{reh}}$

Supercooled Dark Matter

$T_{\text{dec}} < T_{\text{reh}}$

Standard freezeout

Now if...

$T_{dec} > T_{reh}$

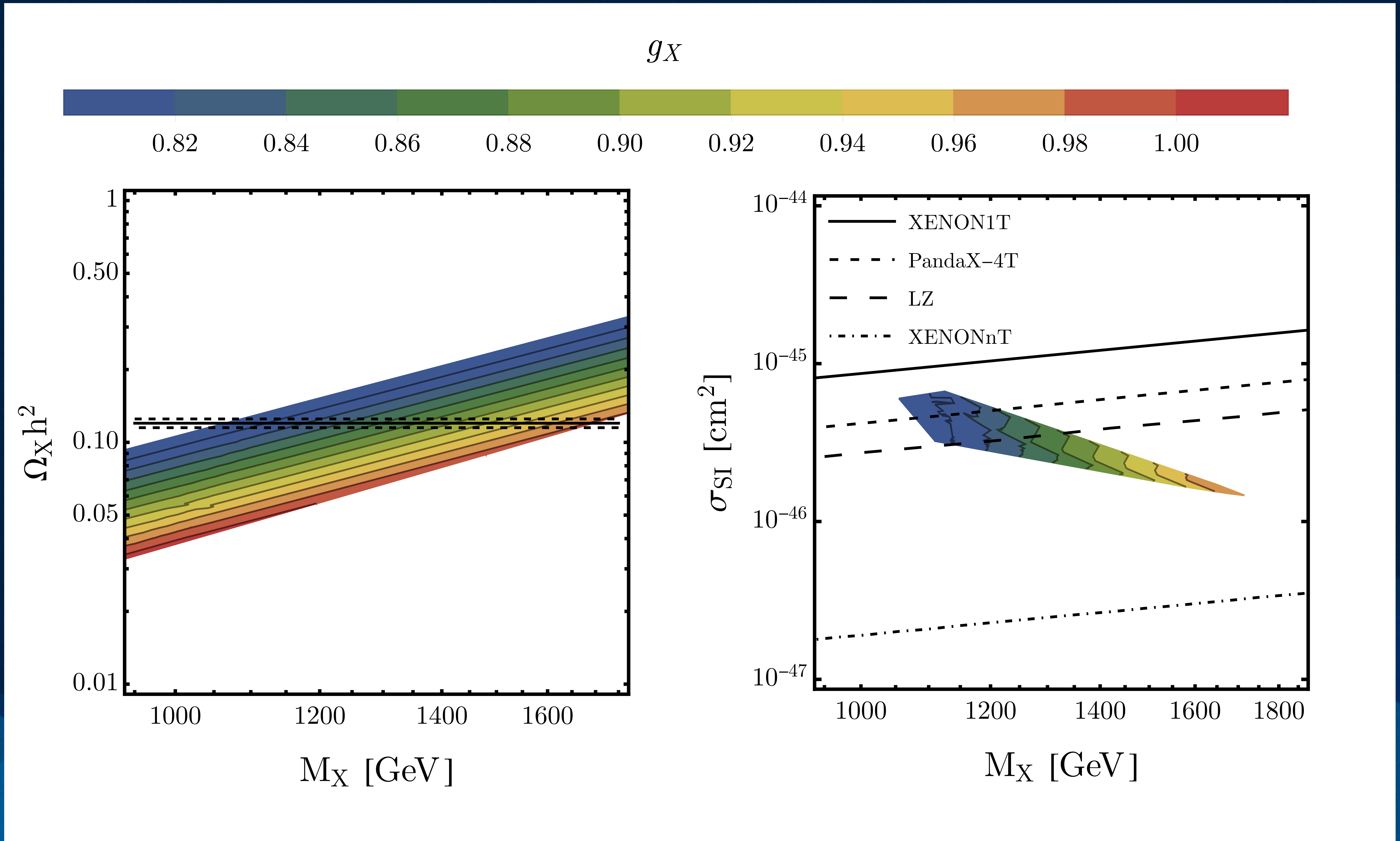
~~Supercooled Dark Matter~~

$T_{dec} < T_{reh}$

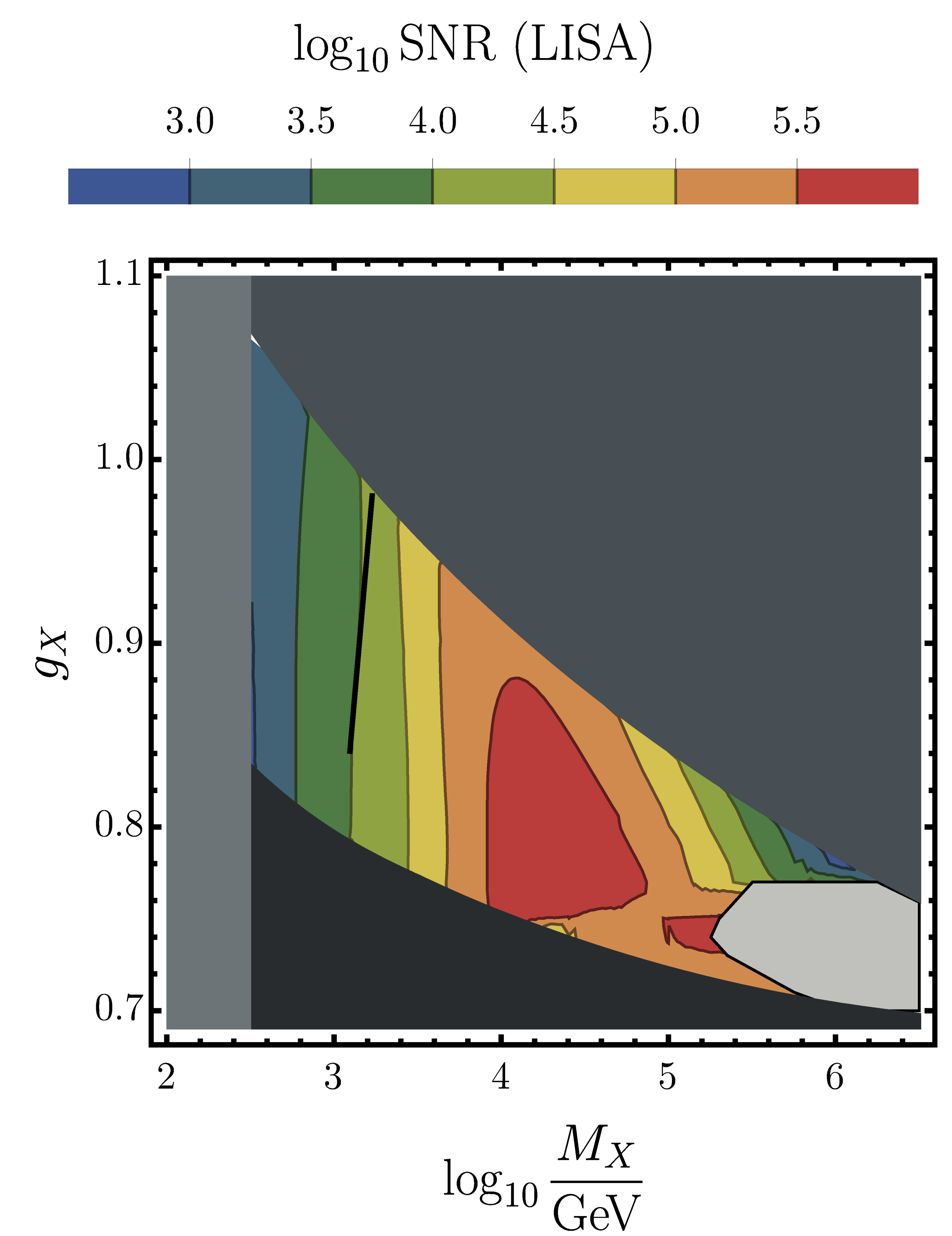
Standard freezeout

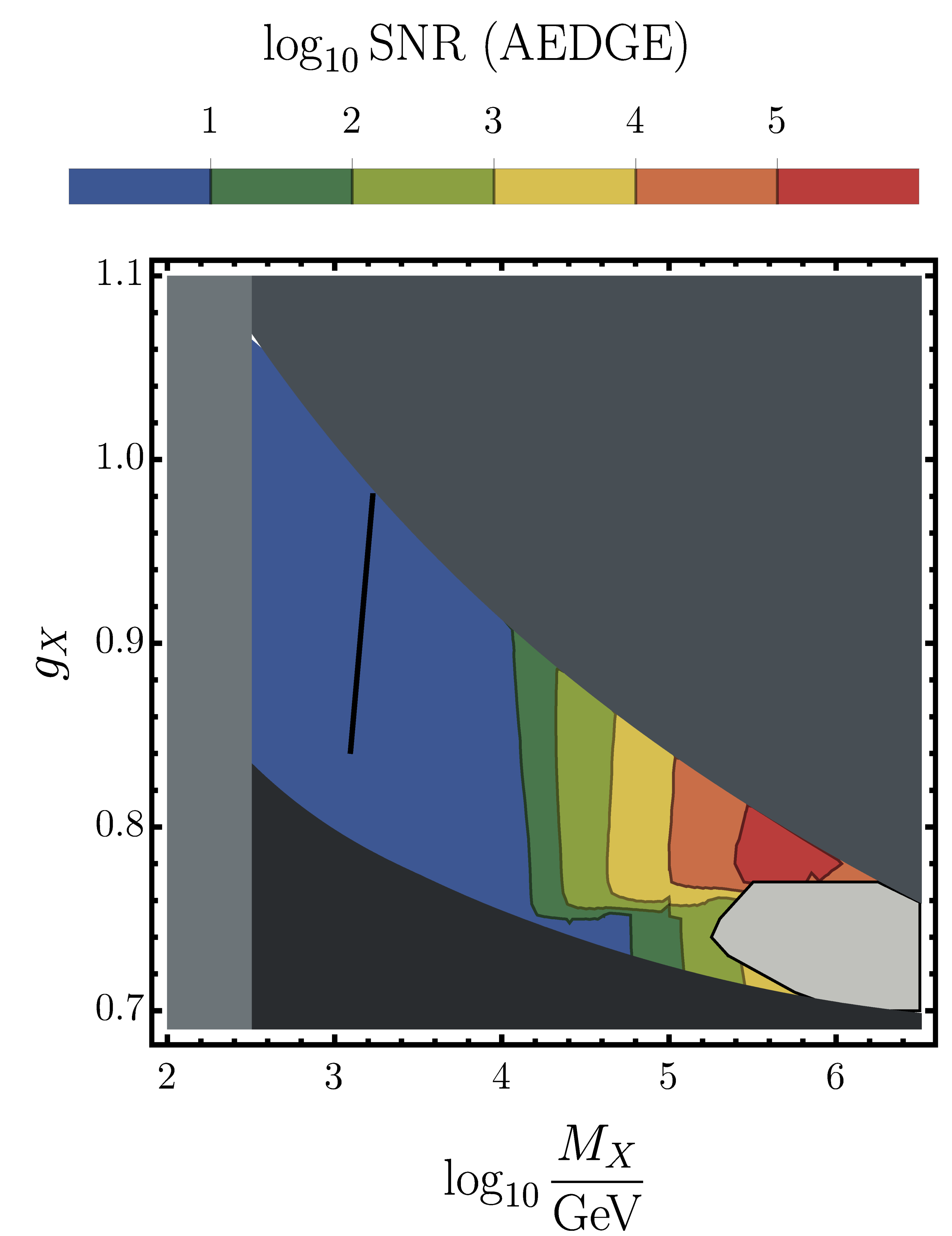
For whole of our parameter space

DM abundance and direct detection



GW Signal-to-noise ratio and DM





Summary

Conformal models
=
Generically strong GW signal

Scale dependence is a serious issue

(DM) parameter space is highly constrained from percolation criterion

Thank you!

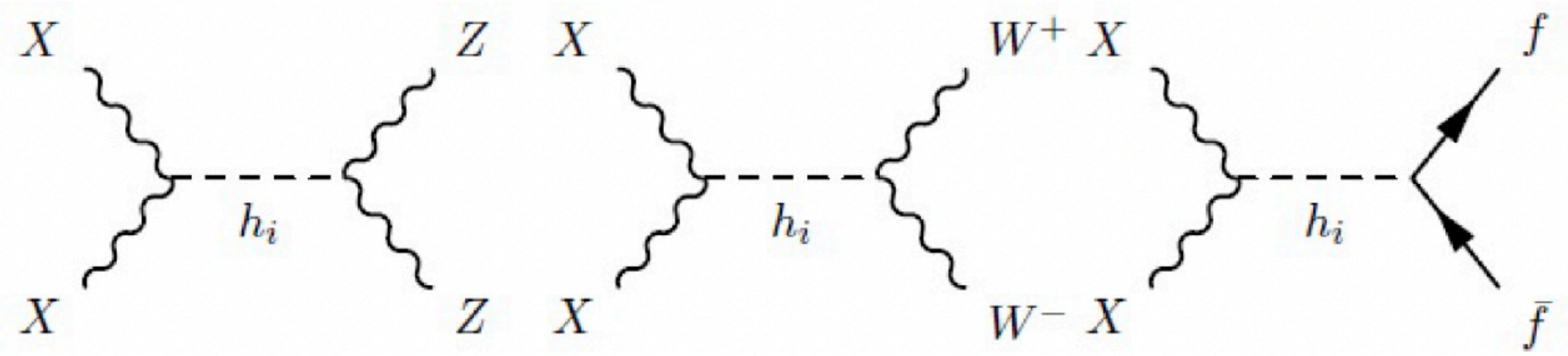


Figure 13: Feynman diagrams for DM annihilation to SM gauge bosons and fermions.

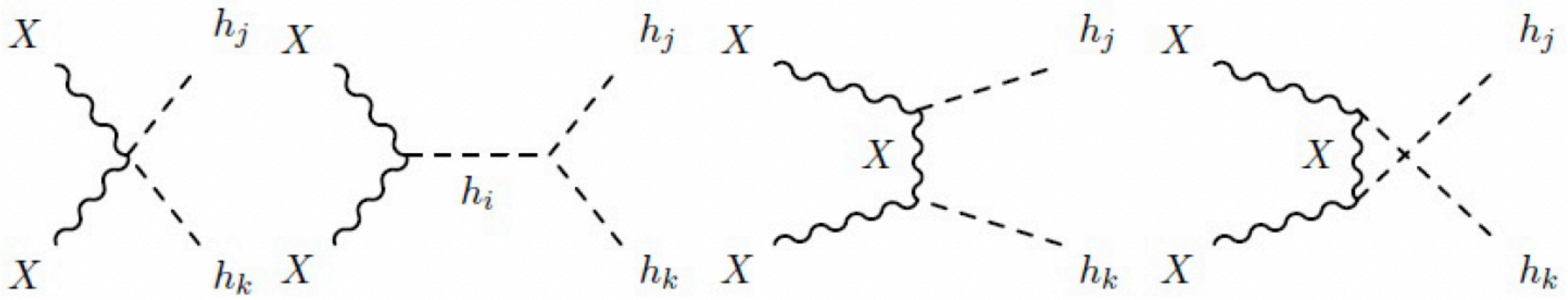


Figure 14: Feynman diagrams for DM annihilation to scalars.

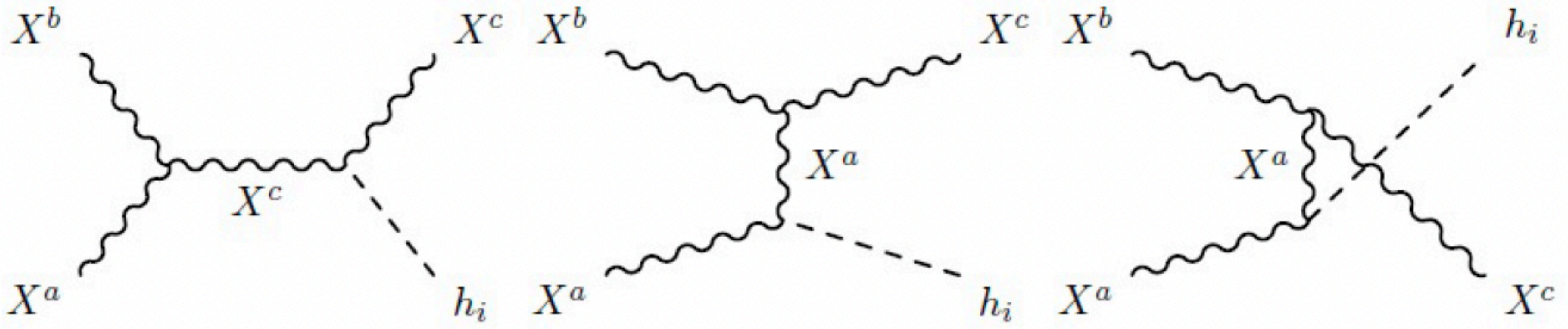


Figure 15: Feynman diagrams for DM semi-annihilation.

PT parameters - energy budget

$$\Delta P = \Delta V - P_{\rm LO} - P_{\rm NLO}$$