KBFI
Tallinn

Università degli Studi di Padova

INFN
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Phase transitions

Ville Vaskonen

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Electroweak phase transition in the SM

$$V = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

$$\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$$

$$\mathrm{U(1)_{EM}}$$

Cross-over transition.

Classically conformal $U(1)_{B-L}$ extension of the SM

$$\mathrm{SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}} \Rightarrow \mathrm{SU(2)_L \otimes U(1)_Y} \Rightarrow \mathrm{U(1)_{EM}}$$

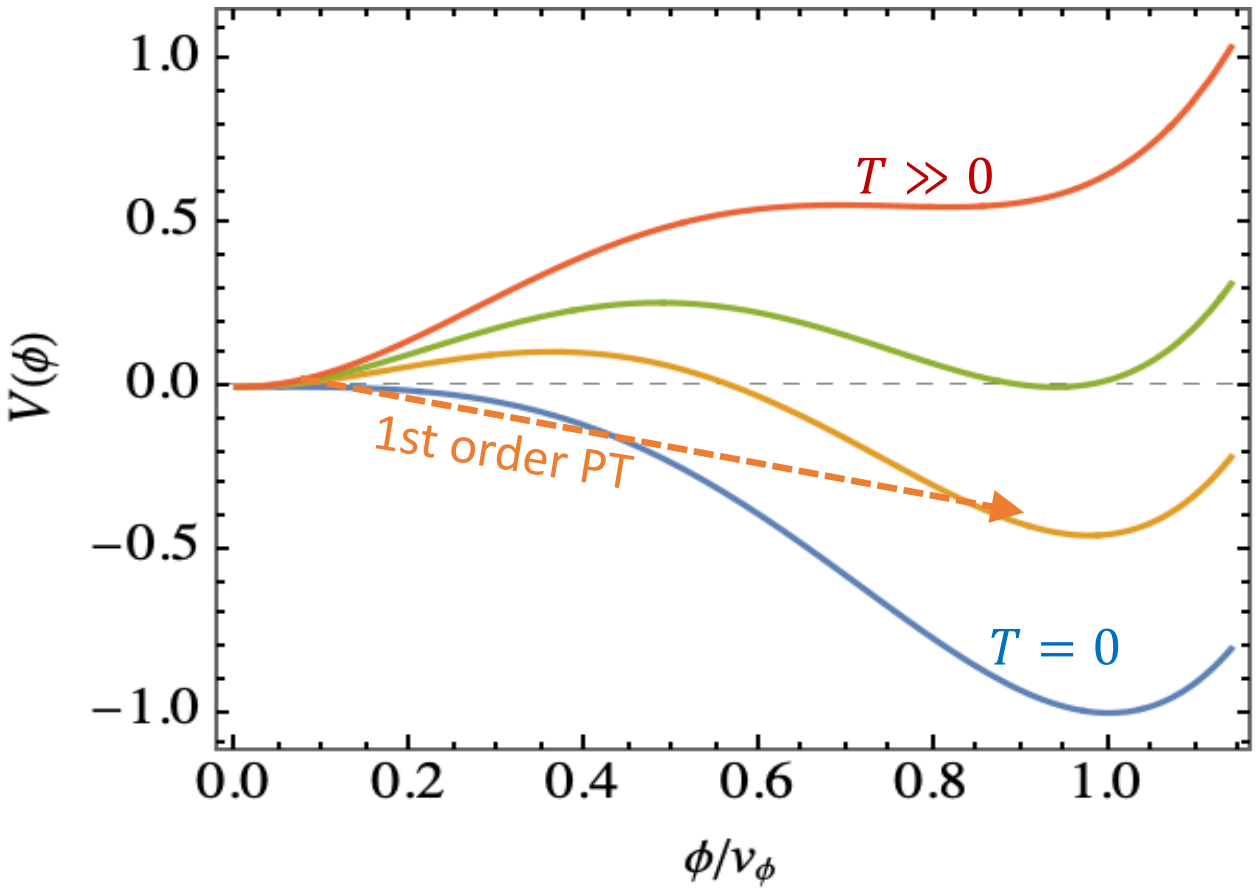
- new gauge boson Z' and a new scalar ϕ
- only dimensionless parameters:

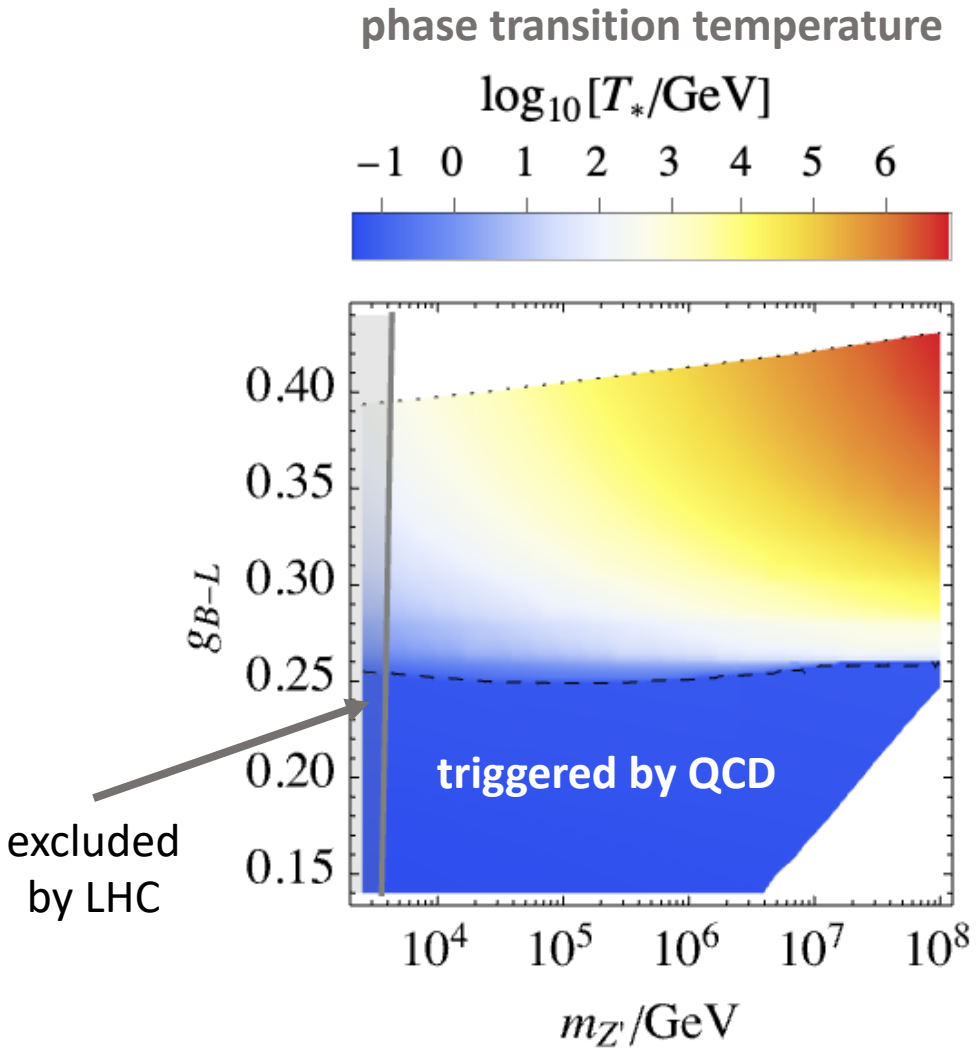
$$V = \lambda_H (H^\dagger H)^2 + \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_p (\phi^\dagger \phi)(H^\dagger H)$$

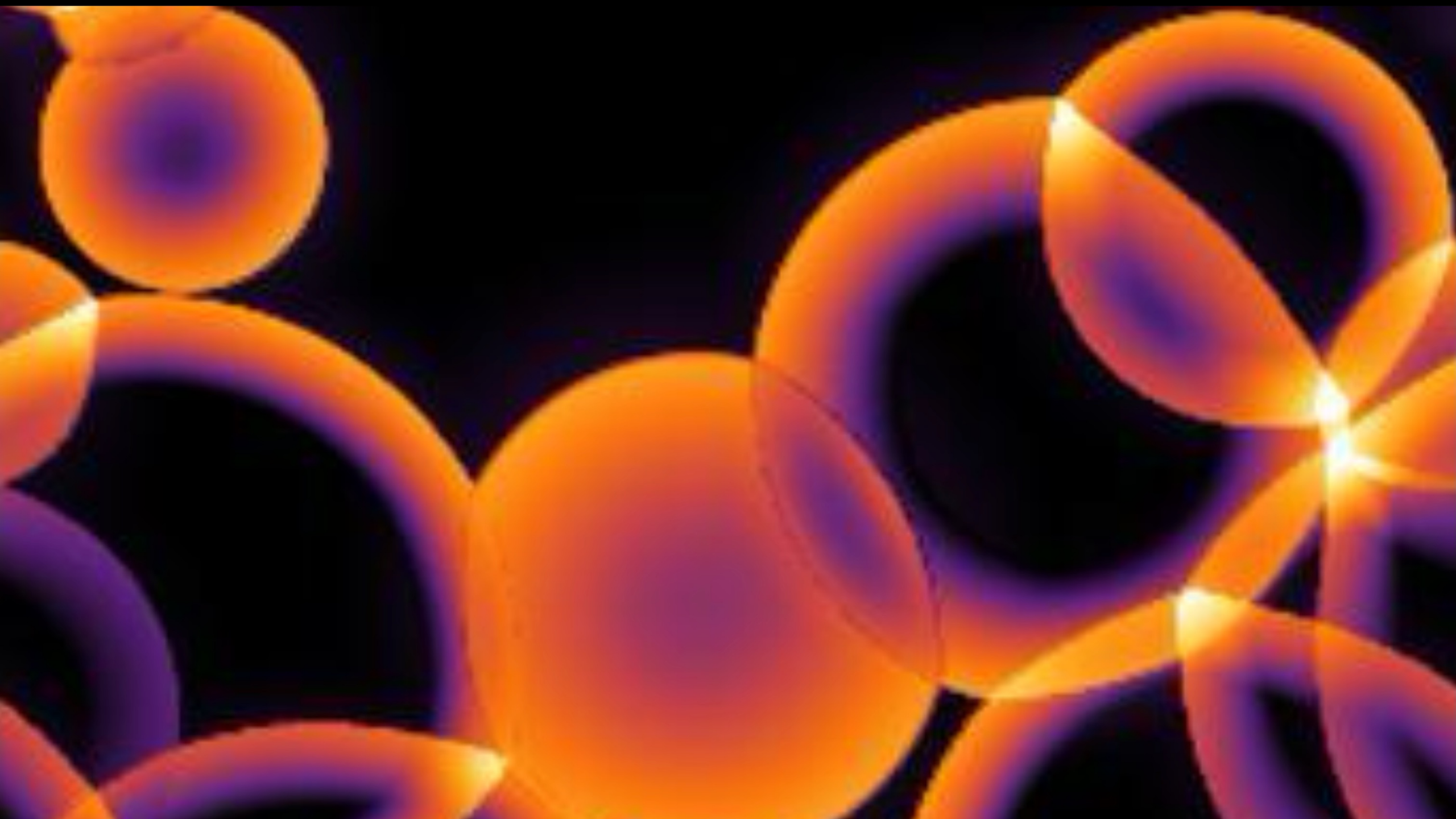
- radiative corrections break the conformal symmetry:

$$V \approx \underbrace{\frac{3g^4}{4\pi^2}|\phi|^4 \left[\log \frac{|\phi|^2}{w^2} - \frac{1}{2}\right]}_{\text{CW potential}} + \underbrace{g^2 T^2 |\phi|^2}_{\text{thermal correction}}$$

$U(1)_{B-L}$ breaking phase transition

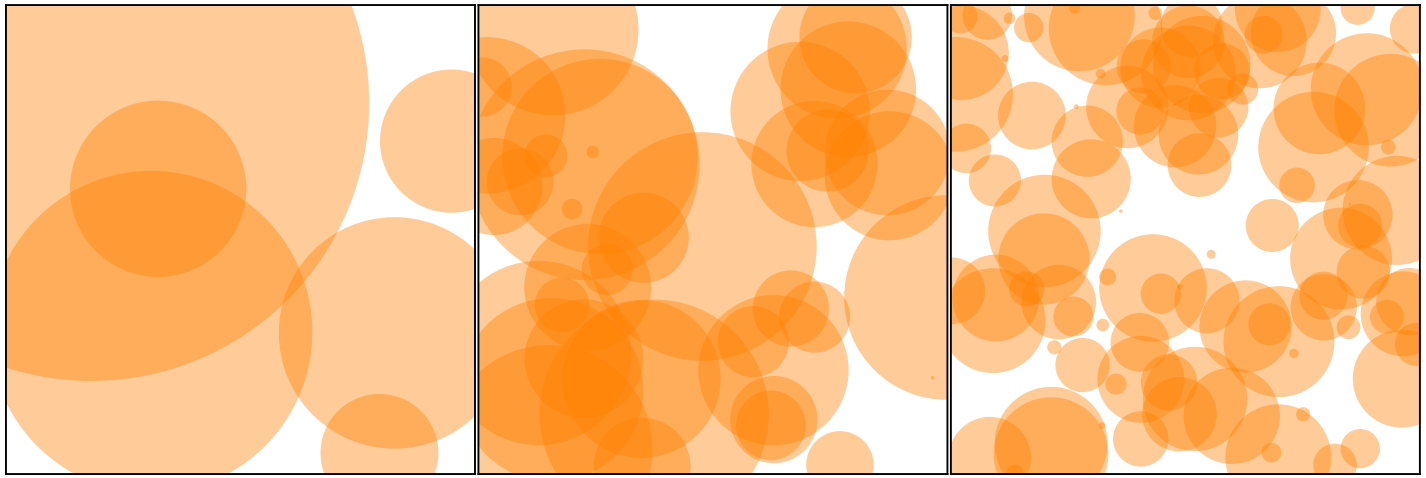






$U(1)_{B-L}$ breaking phase transition

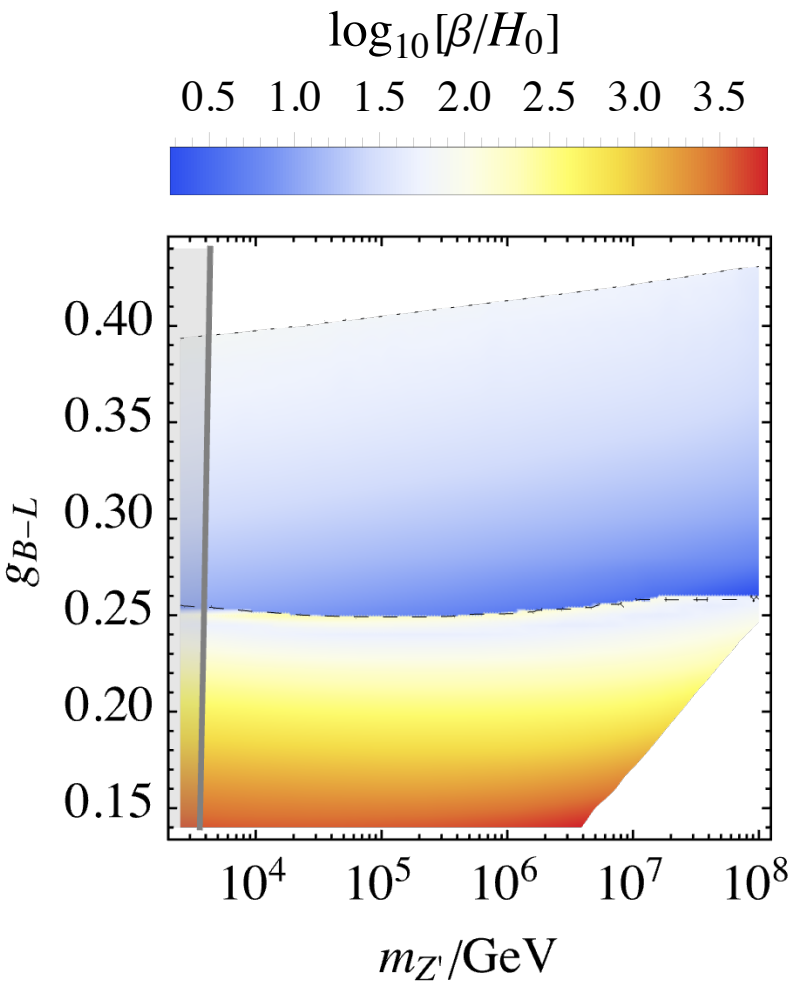
Bubble nucleation rate: $\Gamma = H_0^4 e^{\beta(t-t_n)}$



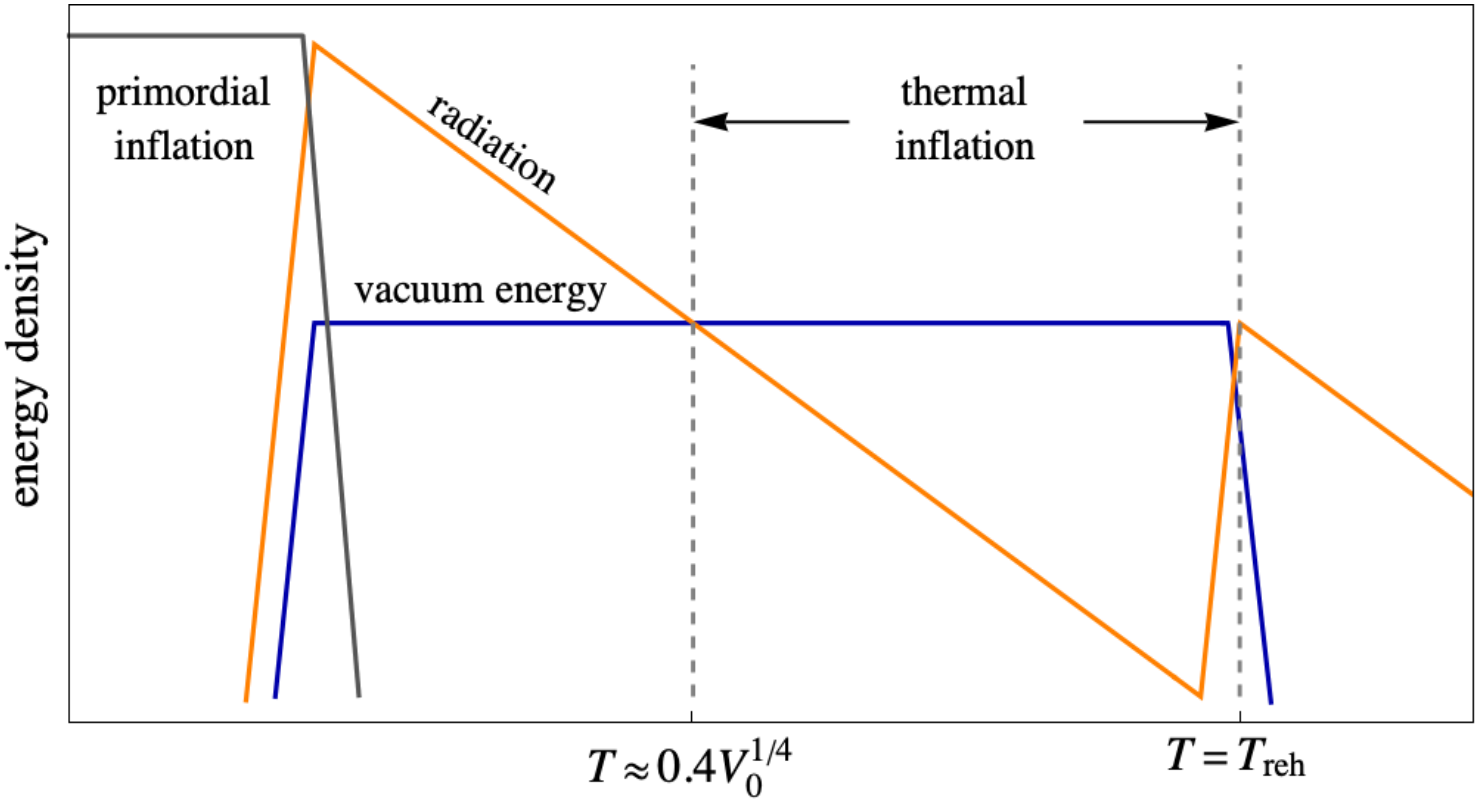
slow:
a few large bubbles,
small β/H

fast:
many small bubbles,
large β/H

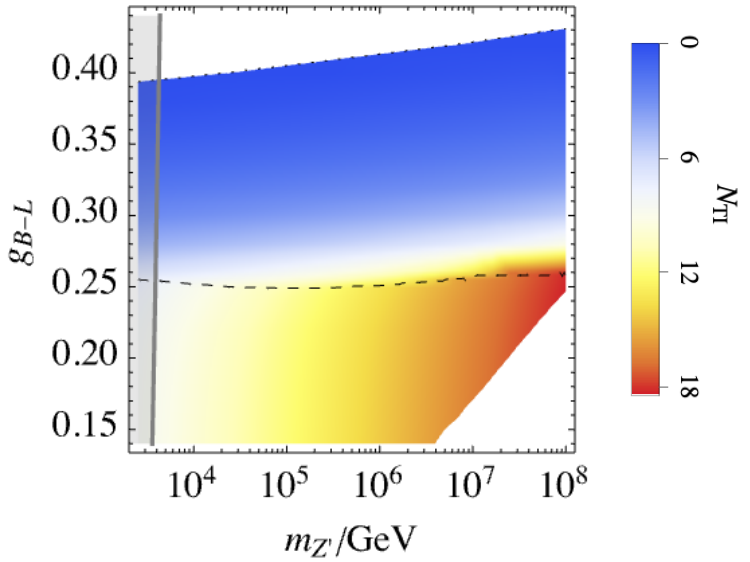
inverse duration of the transition



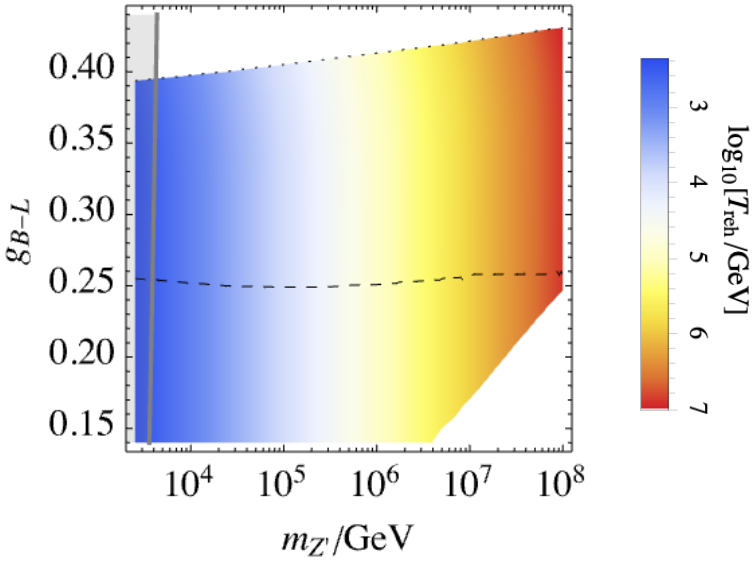
$U(1)_{B-L}$ breaking phase transition



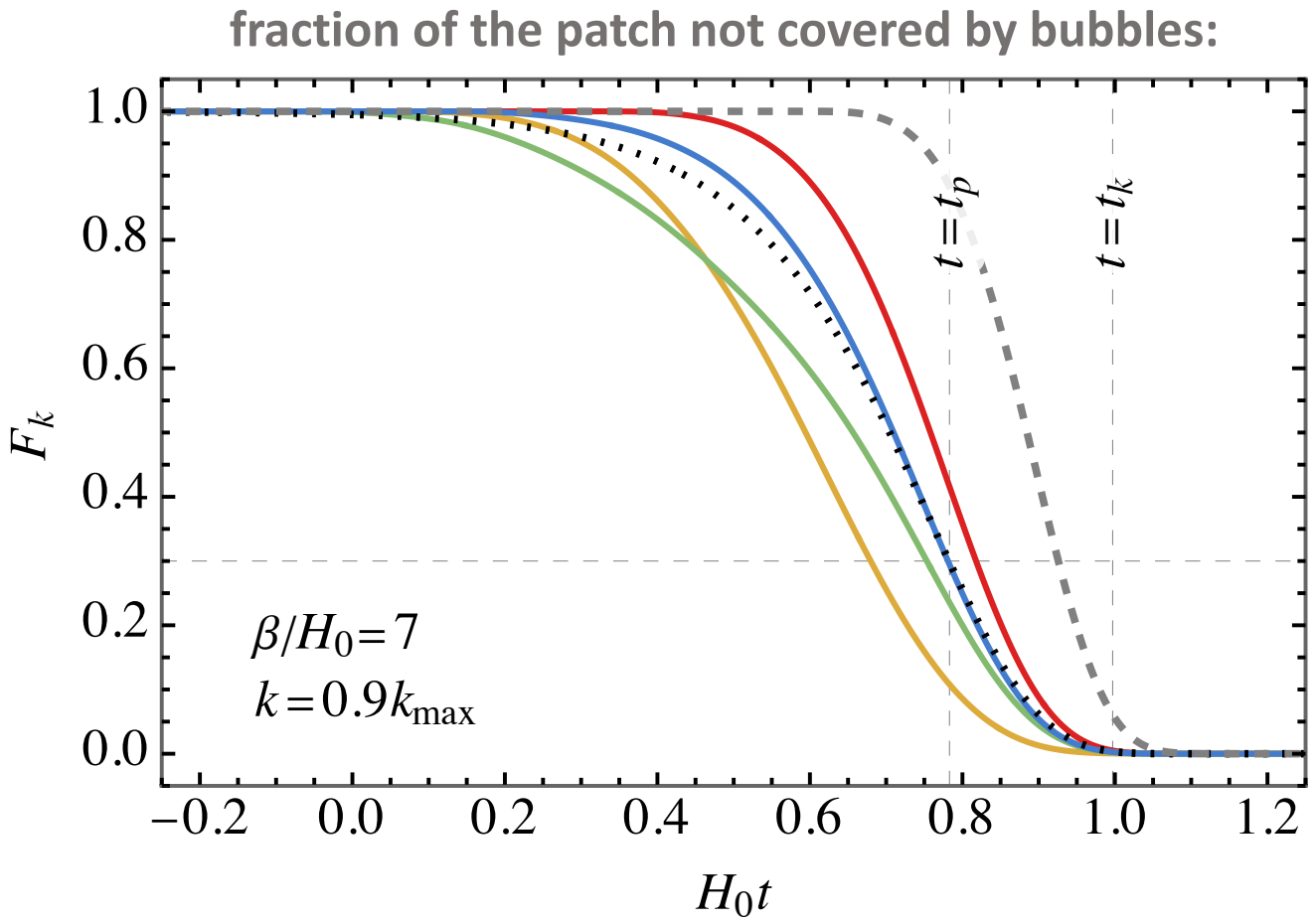
e-folds of thermal inflation

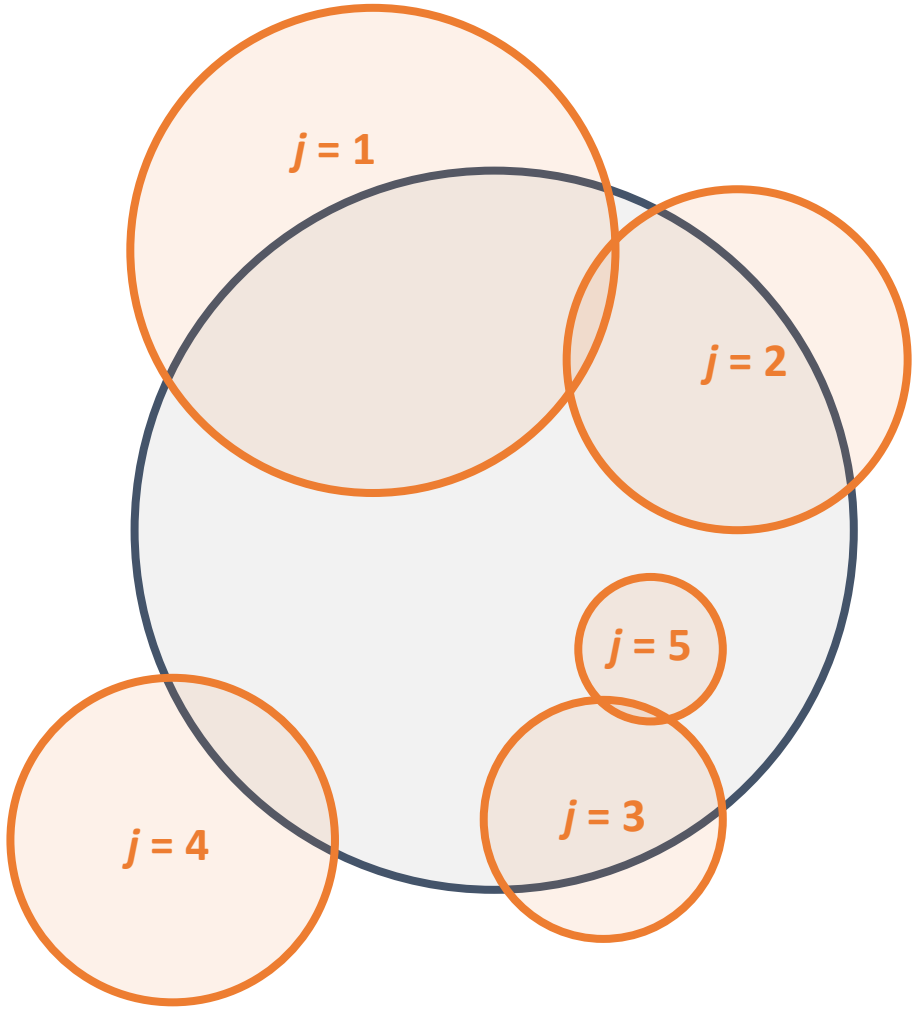


temperature <u>after</u> the transition

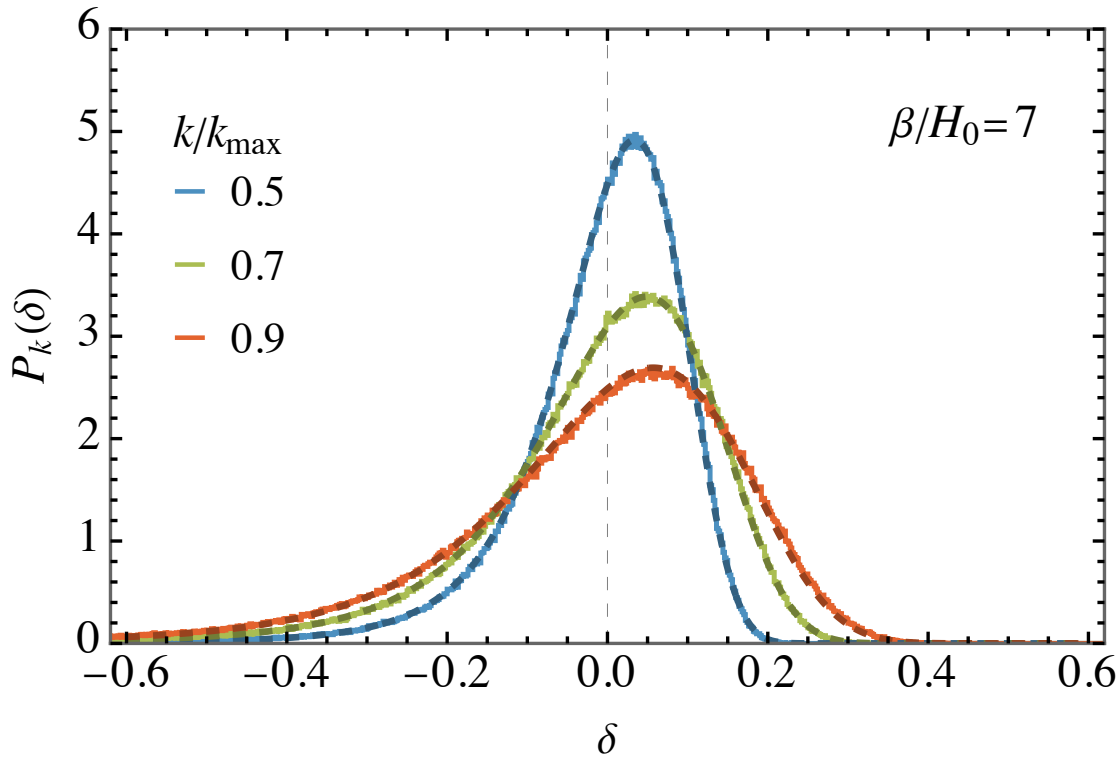


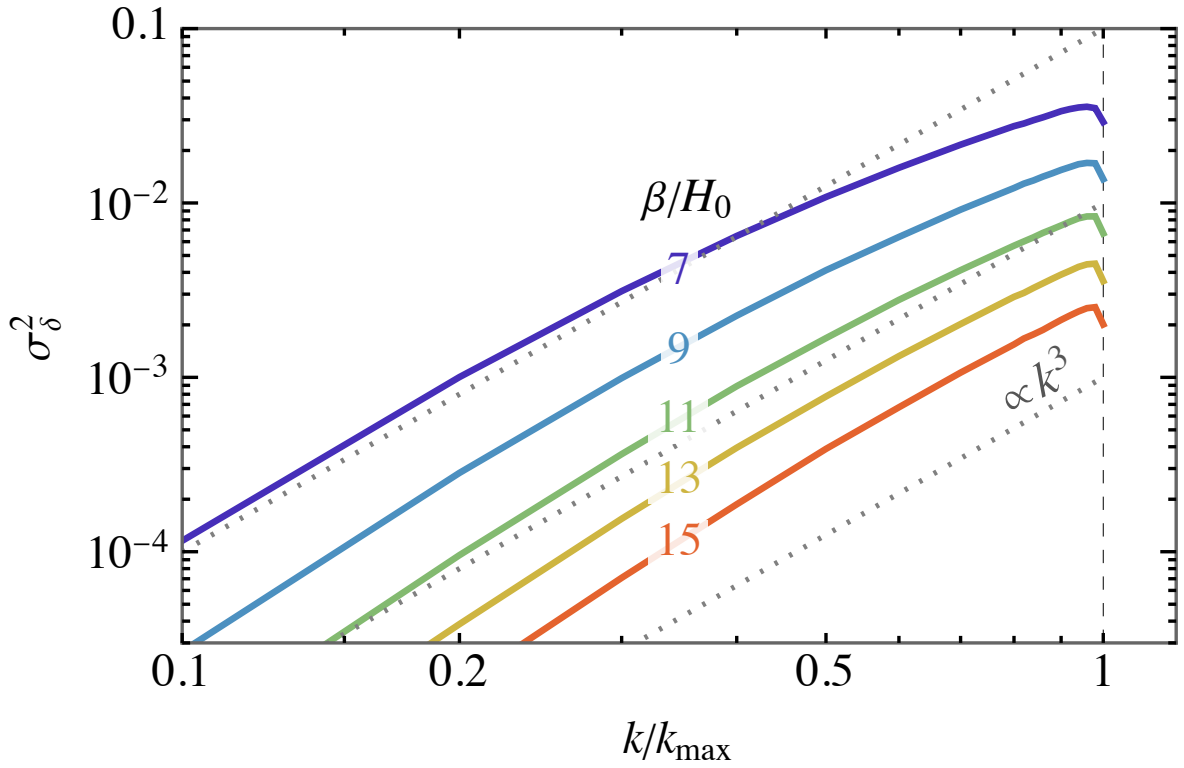
Evolution of finite patches





Distribution of density constrast

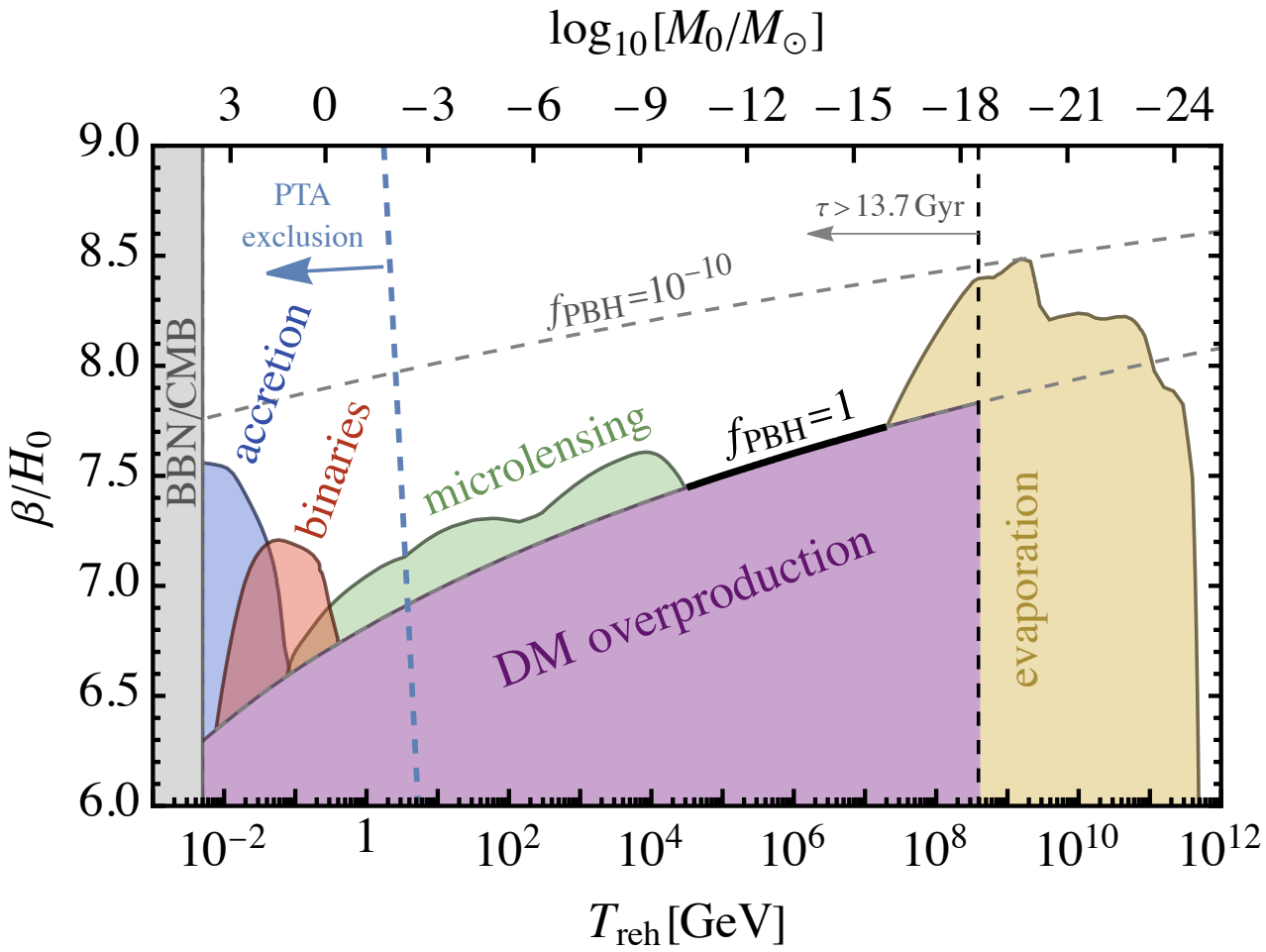




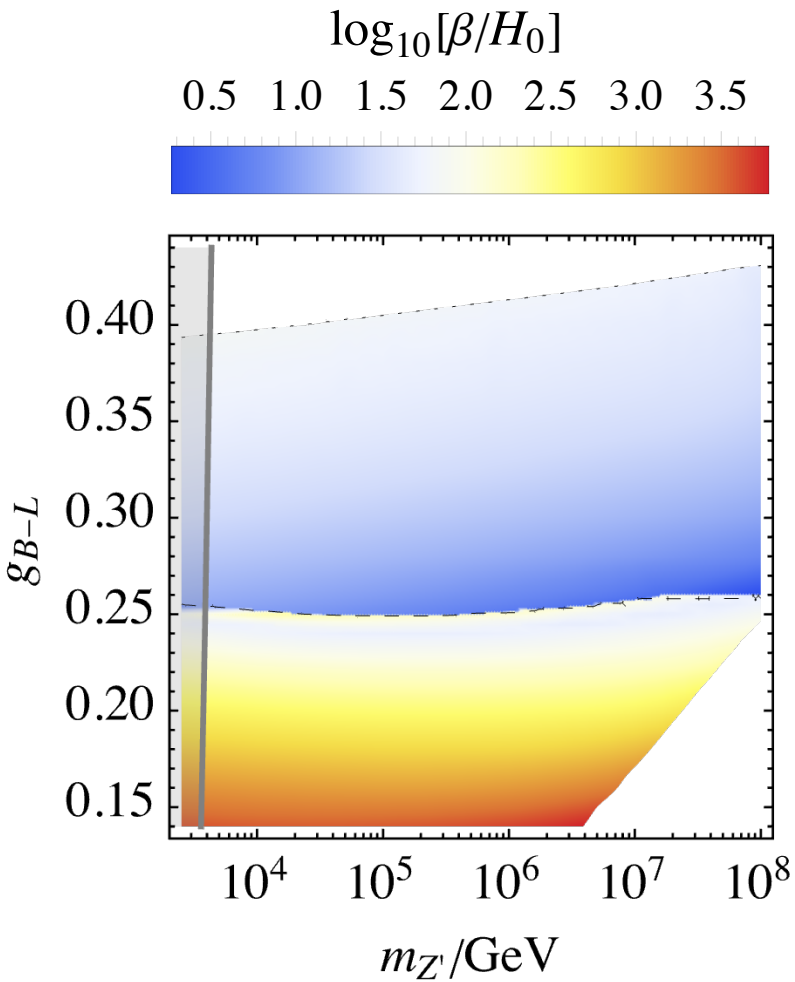
small β/H_0 $\Longrightarrow$ slow transition $\Longrightarrow$ large variance of δ

Primordial black holes

$$f_{\rm PBH} \sim \int {\rm d}\ln k \int_{\delta_c} {\rm d}\delta P_k(\delta) \ldots$$



$U(1)_{B-L}$ model



GW spectrum

Lewicki, Toczek, Vaskonen, arXiv:2402.04158

1. **Primary** GWs from bubble collisions:

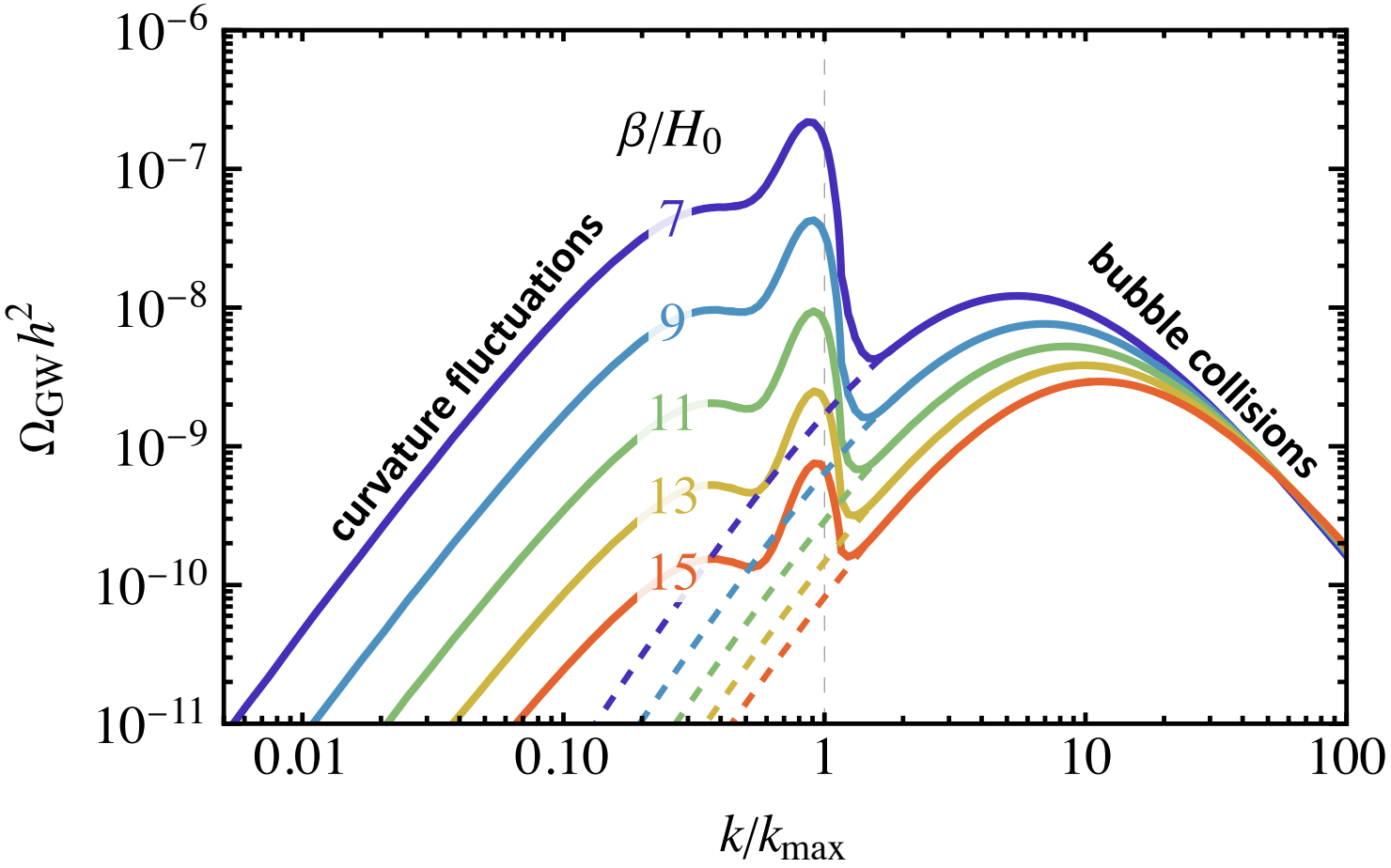
$$k_{\rm peak} \approx k_{\rm max}\, \beta/H_0$$

$$\Omega_{\rm PGW} h^2 \propto \left(\frac{\beta}{H_0}\right)^{-2}$$

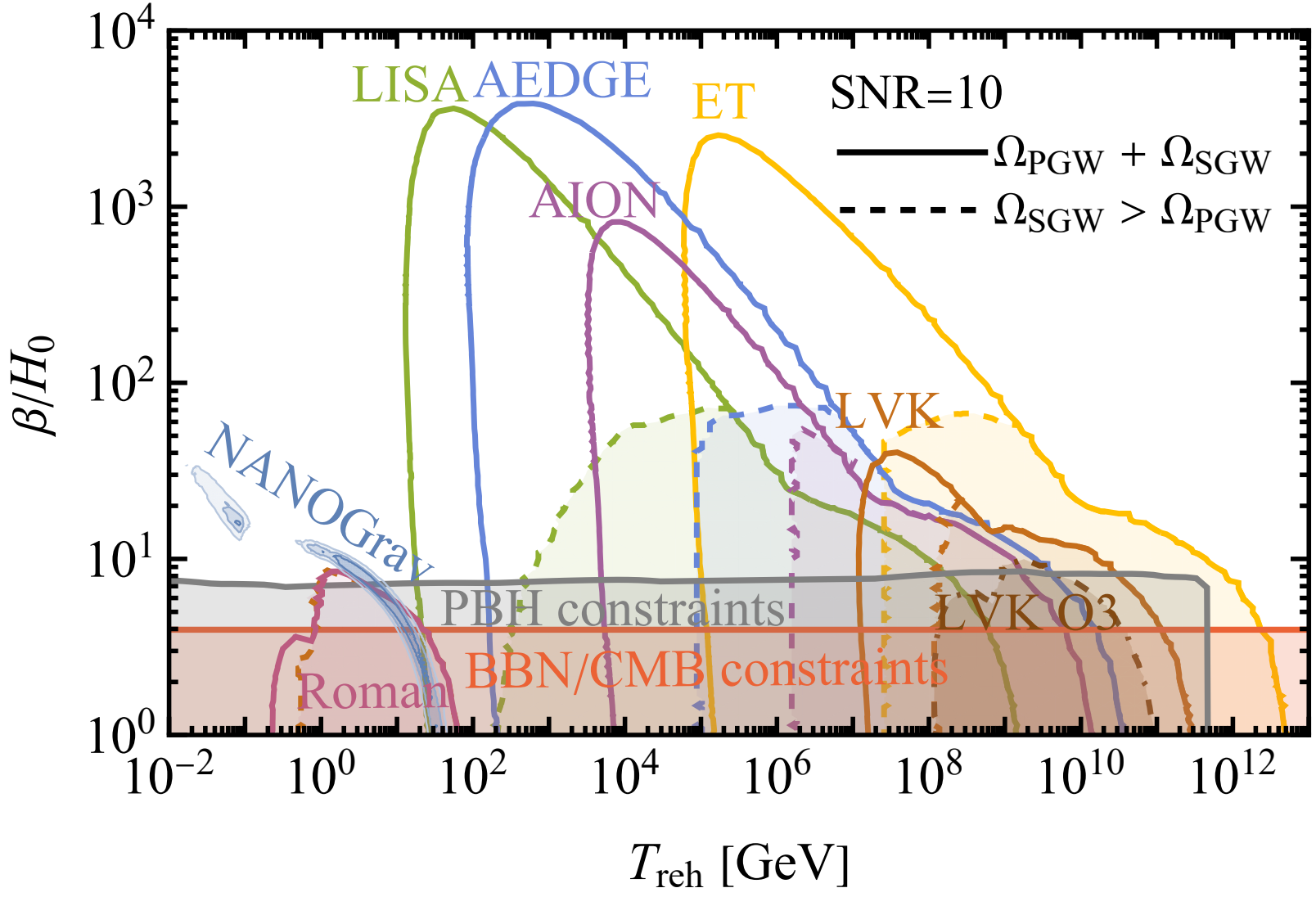
2. **Secondary** GWs induced by curvature fluctuations:

$$k_{\rm peak} \approx k_{\rm max}$$

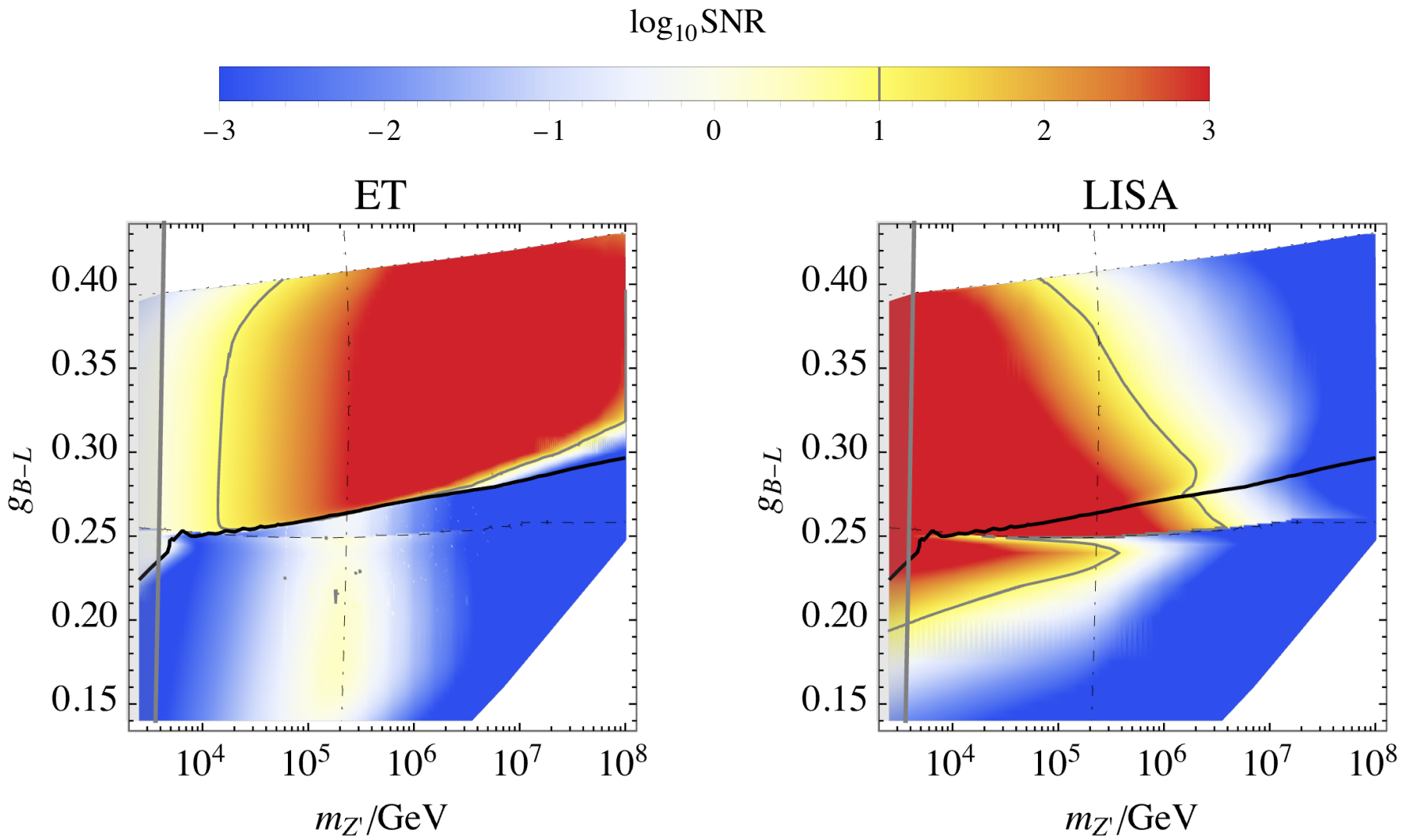
$$\Omega_{\rm SGW} h^2 \propto e^{-\beta/H_0}$$



GW prospects



GW signal in the $U(1)_{B-L}$ model



Summary

- Extensions of the SM can include first-order phase transitions.
- delayed transition $\Longrightarrow$ thermal inflation caused by the vacuum energy
- slow bubble nucleation $\Longrightarrow$ large density fluctuations $\Longrightarrow$ PBHs
- GWs from bubble collisions/fluid motions and from large curvature fluctuations
- GW experiments can probe parameter space not accessible by colliders.