Higgs Cosmology and dark matter

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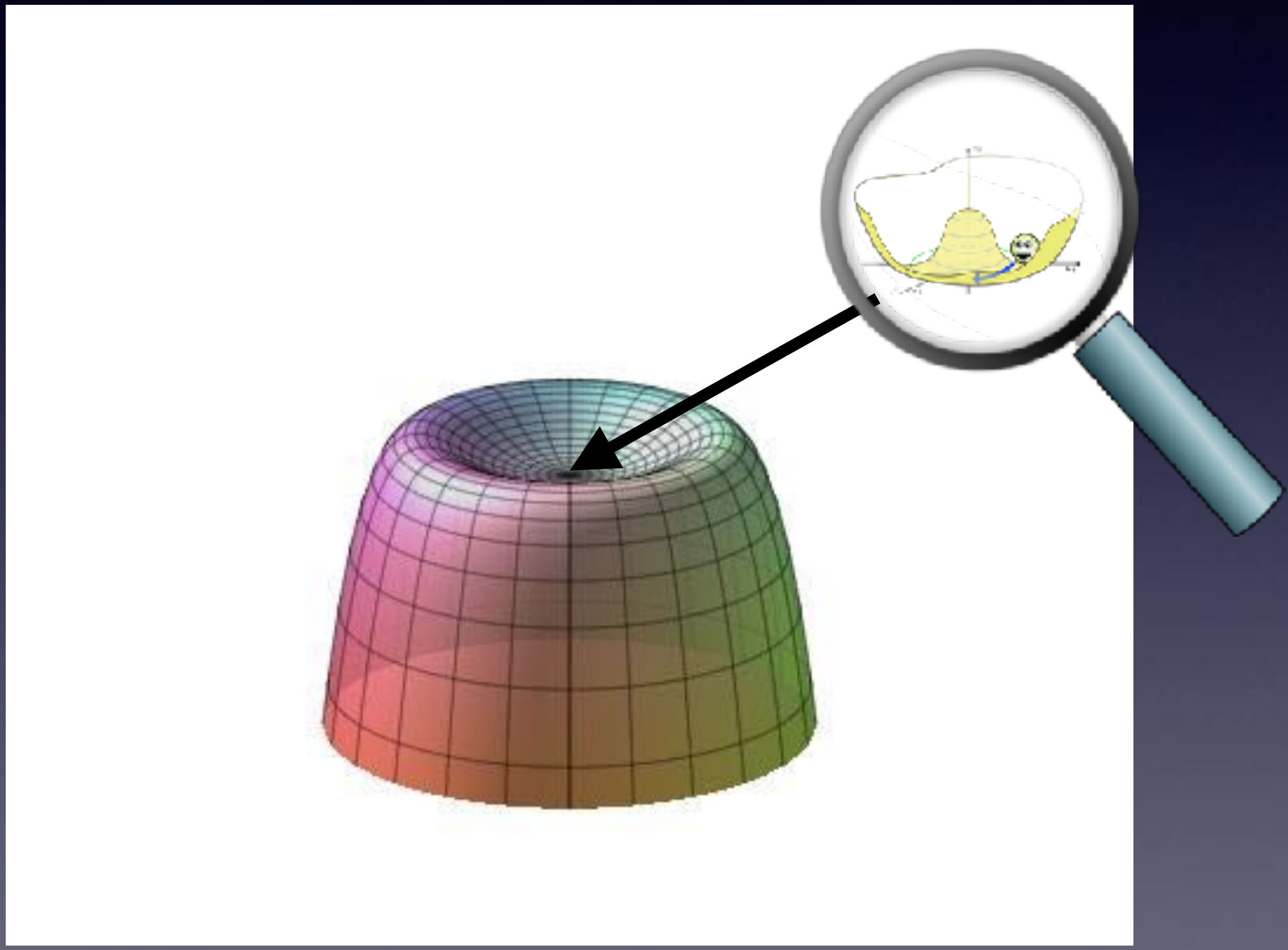
HIGGS AROUND 10^{10}-10^{19} GEV....



Higgs Instability

Your theory is crazy, the question is whether it's crazy enough to be true.

Bohr to Pauli

Contents

- Vacuum stability
- Present day Vacuum decay
- Early universe vacuum decay

Vacuum Stability

Quantum contribution to the Higgs potential

$$V_{\mathrm{vac}} = \sum_b \frac{1}{2}\hbar\omega_b - \sum_f \frac{1}{2}\hbar\omega_f$$

Frequencies depend on the particle mass

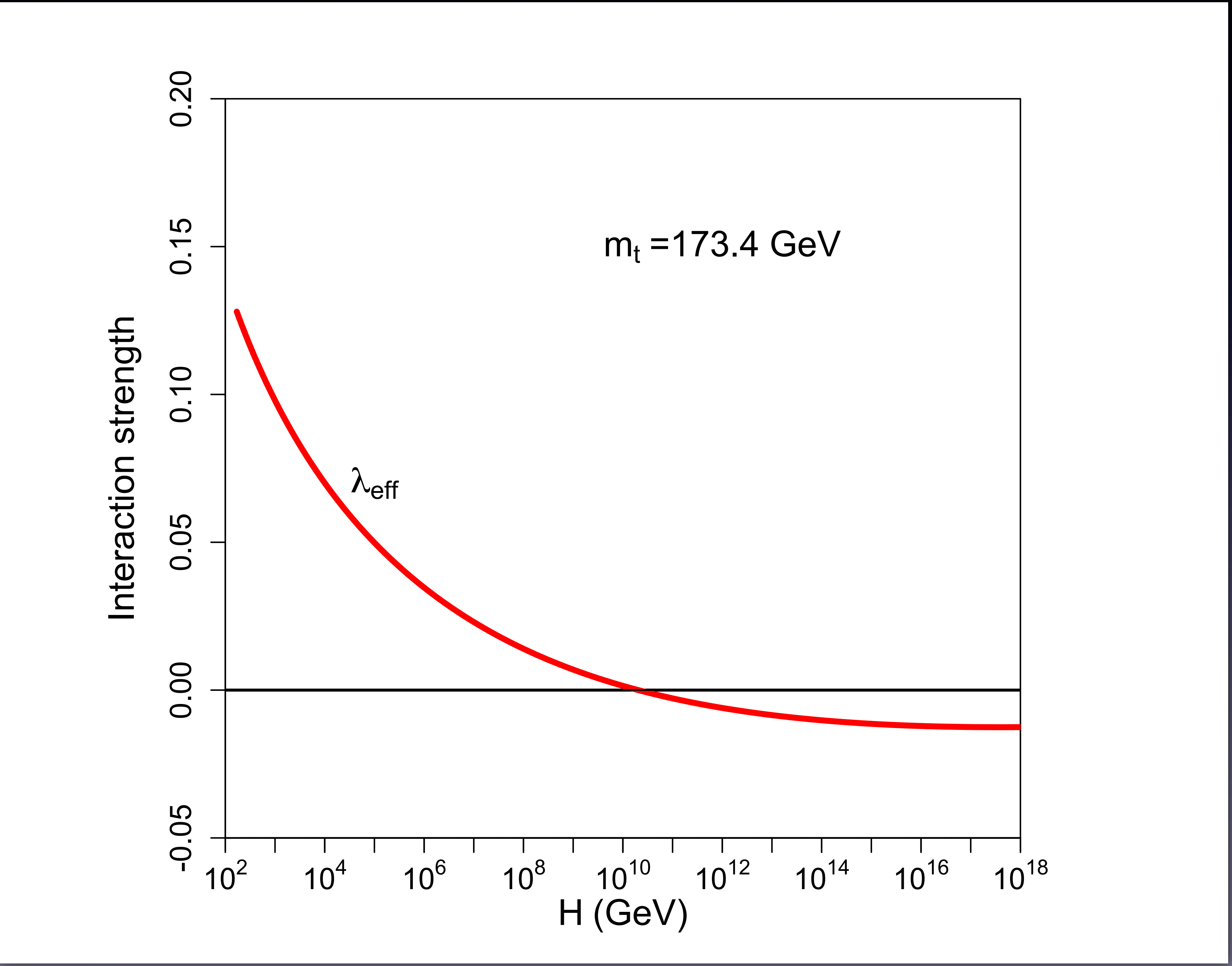
$$\omega = (k^2 + M^2\phi^2/v^2)^{1/2} \qquad v = 246\mathrm{GeV}$$

The effect on the Higgs potential can be summarised by an effective coupling.

Krive & Linde Nucl. Phys. B117 (1976) 265, old review by Sher.

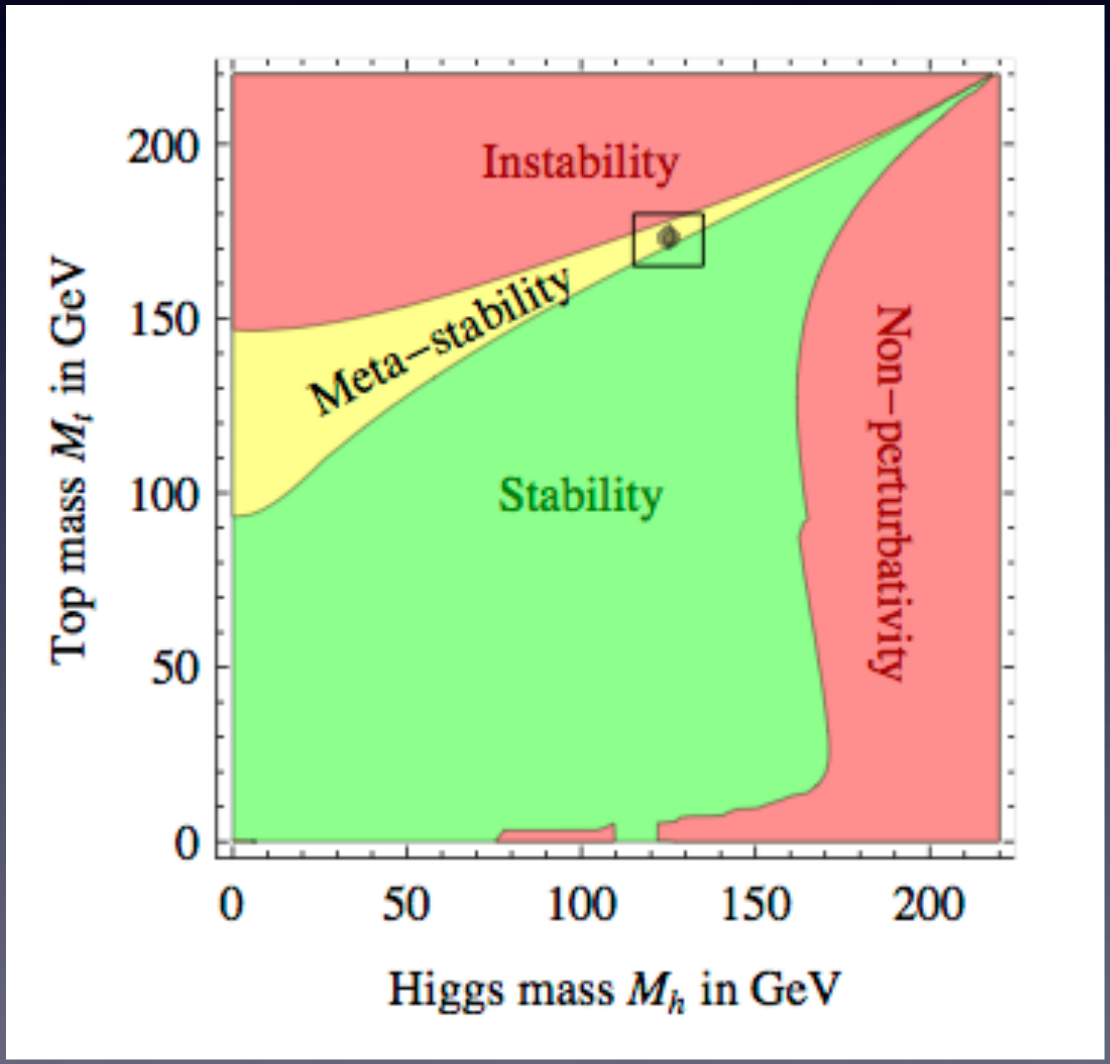
Higgs self-coupling

$$V_{\text{eff}} = \frac{1}{4}\lambda_{\text{eff}}(\phi)\phi^4$$



Stability regions*

$O(\hbar^2)$



The potential depends on the Higgs and Top mass

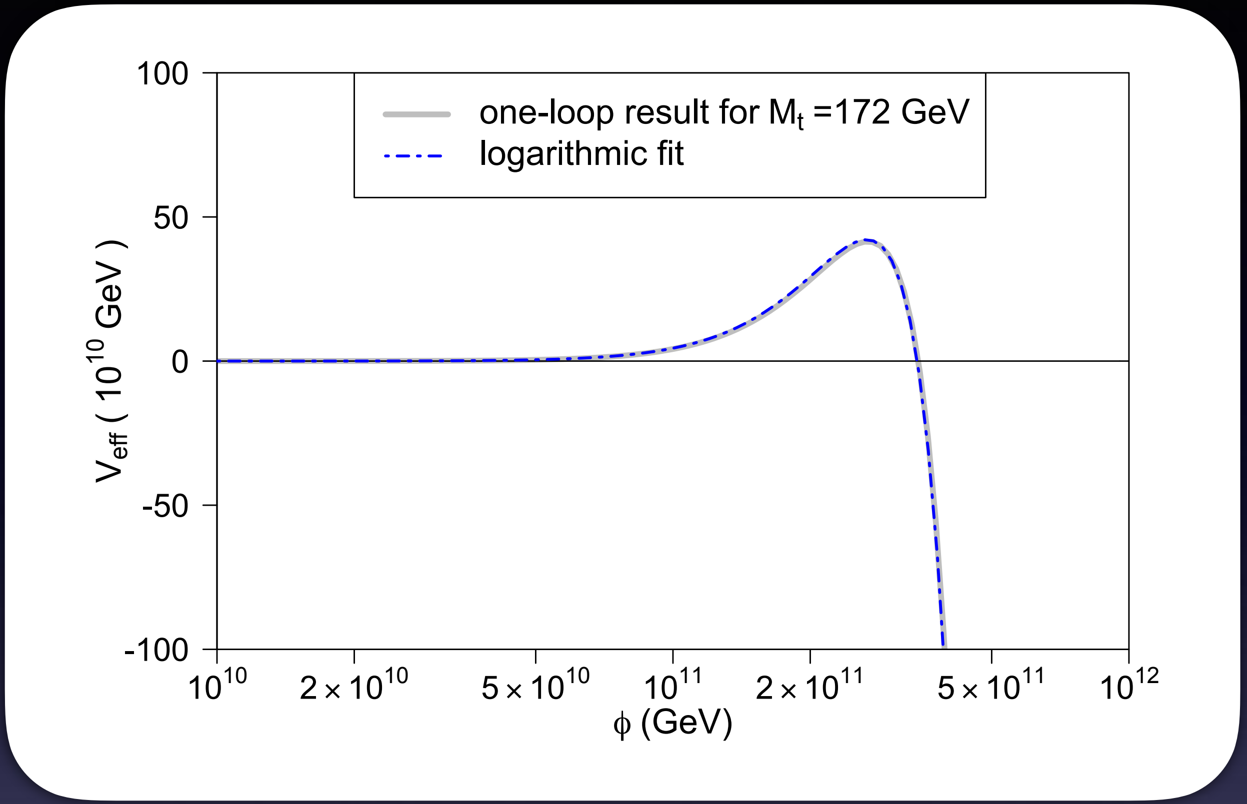
$$V_{\text{eff}} = \frac{1}{4}\lambda_{\text{eff}}(\phi)\phi^4$$

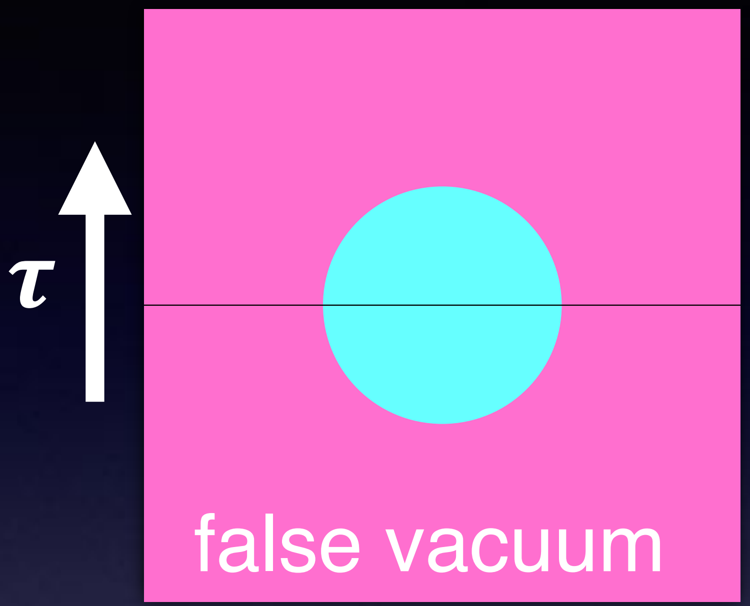
where

$$\frac{d\lambda_{\text{eff}}}{d\ln\phi} = \beta_\lambda - 4\gamma\lambda_{\text{eff}}$$

*Degrassi et al arXiv:1205.6497

The metastable state can only decay by tunnelling





O(4) symmetry

Vacuum decay proceeds by the nucleation of bubbles

Decay rate

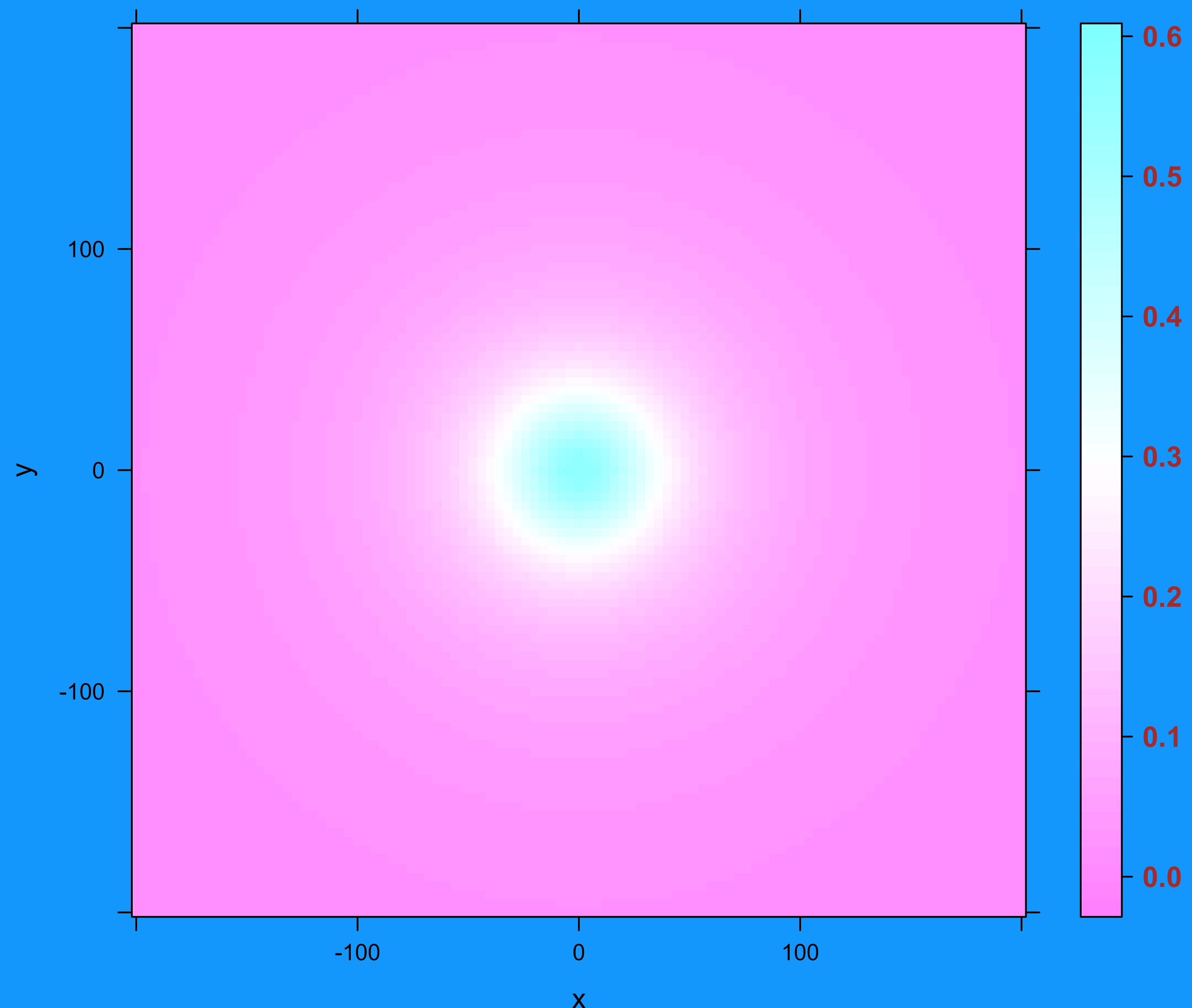
$$\Gamma = Ae^{-B}$$

$$B = S_E[\phi_b] - S_E[\phi_{\rm fv}]$$

$$A = \left| \frac{\det' S''_E[\phi_b]}{\det S''_E[\phi_{\rm fv}]} \right|^{-1/2} \frac{B^2}{4\pi^2}$$

Coleman, Phys Rev D15 2929 1977

Bubble solution



$\phi(\mathrm{M_p})$

$$\Delta I = 1363$$

Seeded nucleation

Most supercooled phase transitions are nucleated by impurities and imperfections.

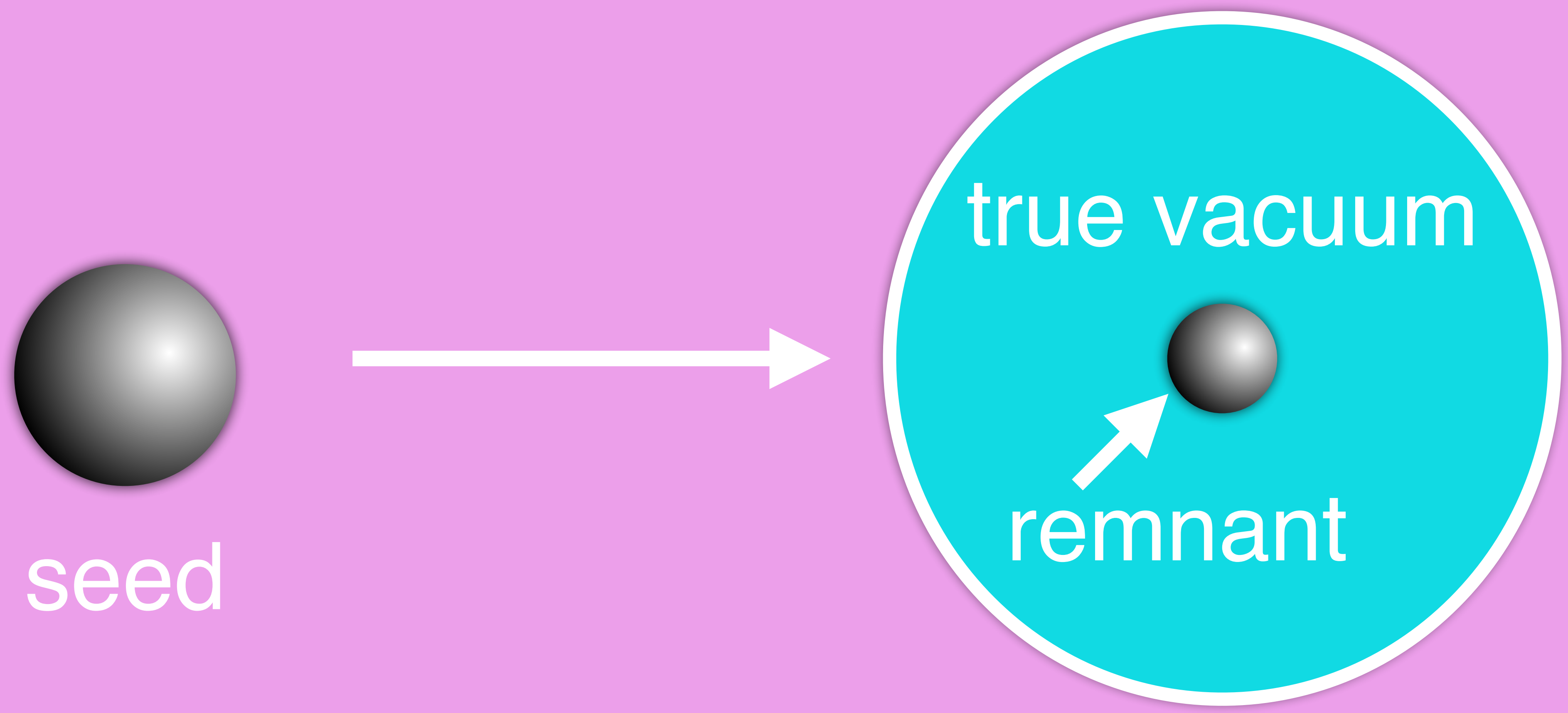
Hiscock, Phys Rev D35 1161 1987; Burda, Gregory, Moss, 1501.04937, 1503.07331

Black hole seeds

Primordial microscopic black holes:

produced in the early universe?

small ones evaporate, lose mass and eventually explode;



Philipp Burda, Ruth Gregory, IGM, 1501.04937, 1503.07331, 1601.02152
Ongoing work with Kate Marshal and Leo Cuspinera 1803.02871

Static bubbles dominate.

ΔI is now the difference in action between the bubble and the false vacuum black hole.

Amazingly simple result:

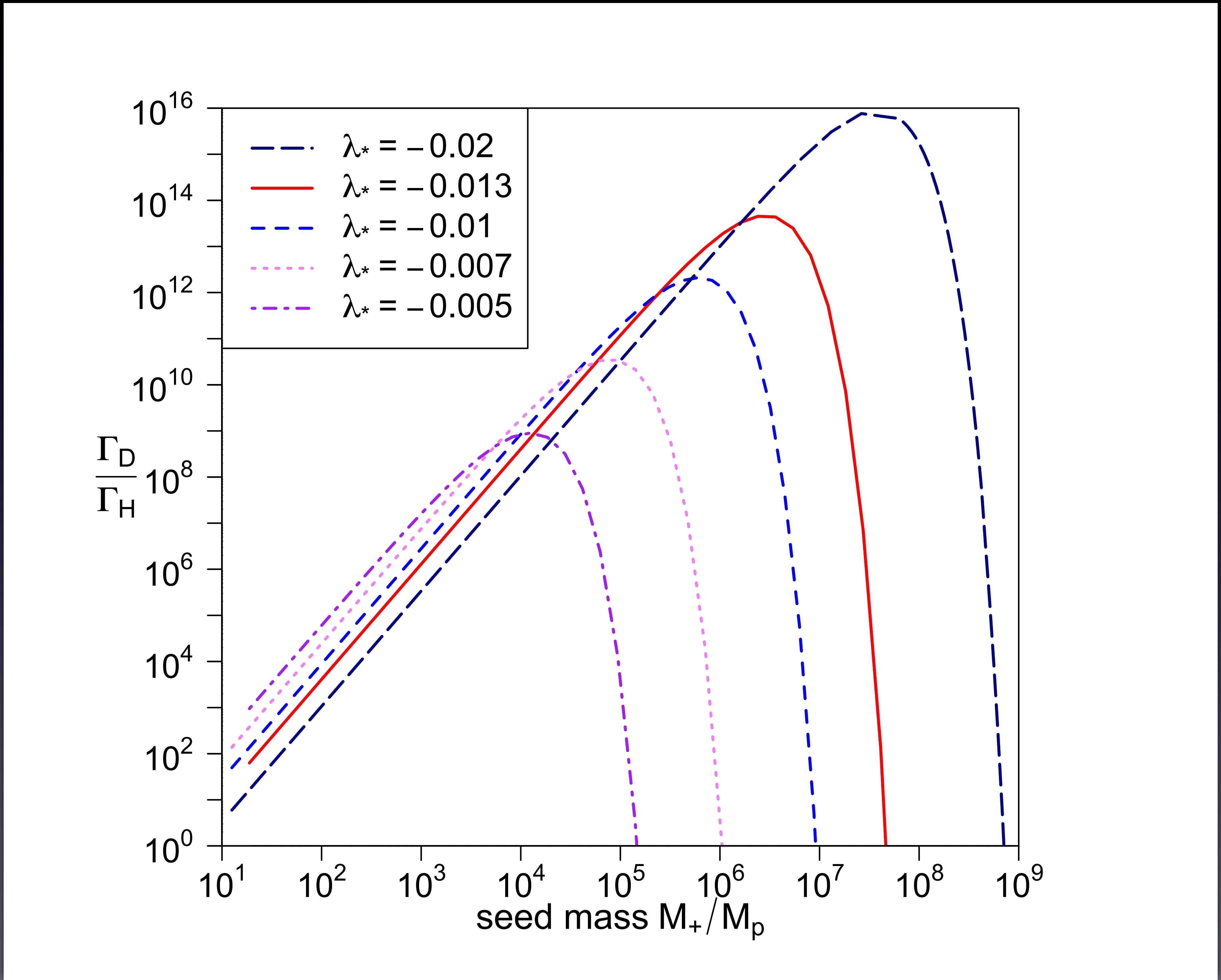
$$\Delta I = \frac{1}{4G}\mathcal{A}_{\rm seed} - \frac{1}{4G}\mathcal{A}_{\rm remnant} \equiv -\Delta S$$

where $\mathcal{A} = 16\pi M^2$ is the area of the event horizon.

Tunnelling rate given by Einsteins formula

$$e^{\Delta S}$$

Comparison of vacuum decay rates and evaporation rates



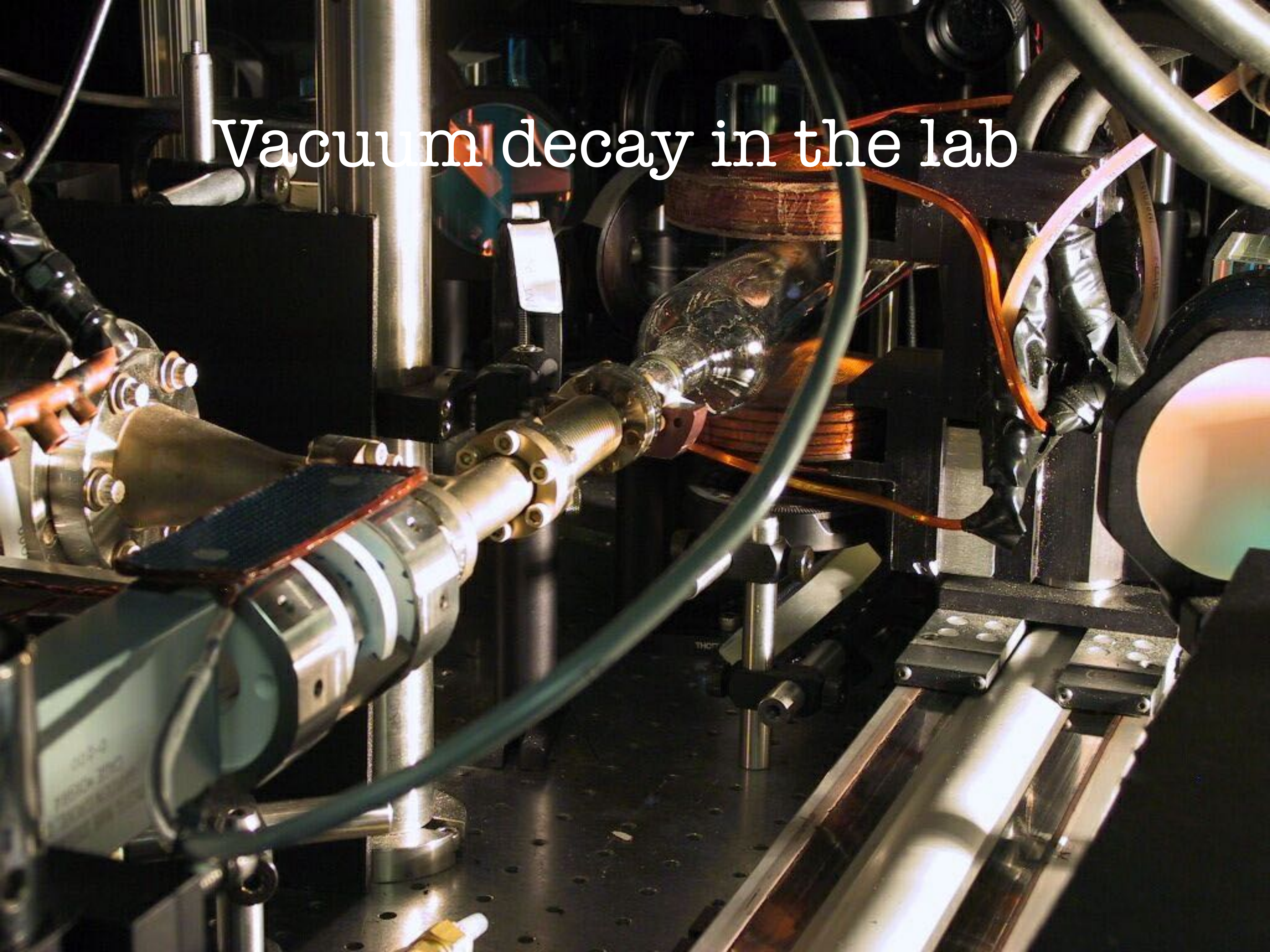
Seeded nucleation with $V(\phi) = \frac{1}{4}\{\lambda_* + b(\ln(\phi/\phi_*)^2\}\phi^4$

There is observational evidence that the false vacuum has not decayed by seeded nucleation.

Standard model + microscopic black holes that can decay in the lifetime of the universe ruled out

Even a single black hole of mass 10^{15} g is not allowed.

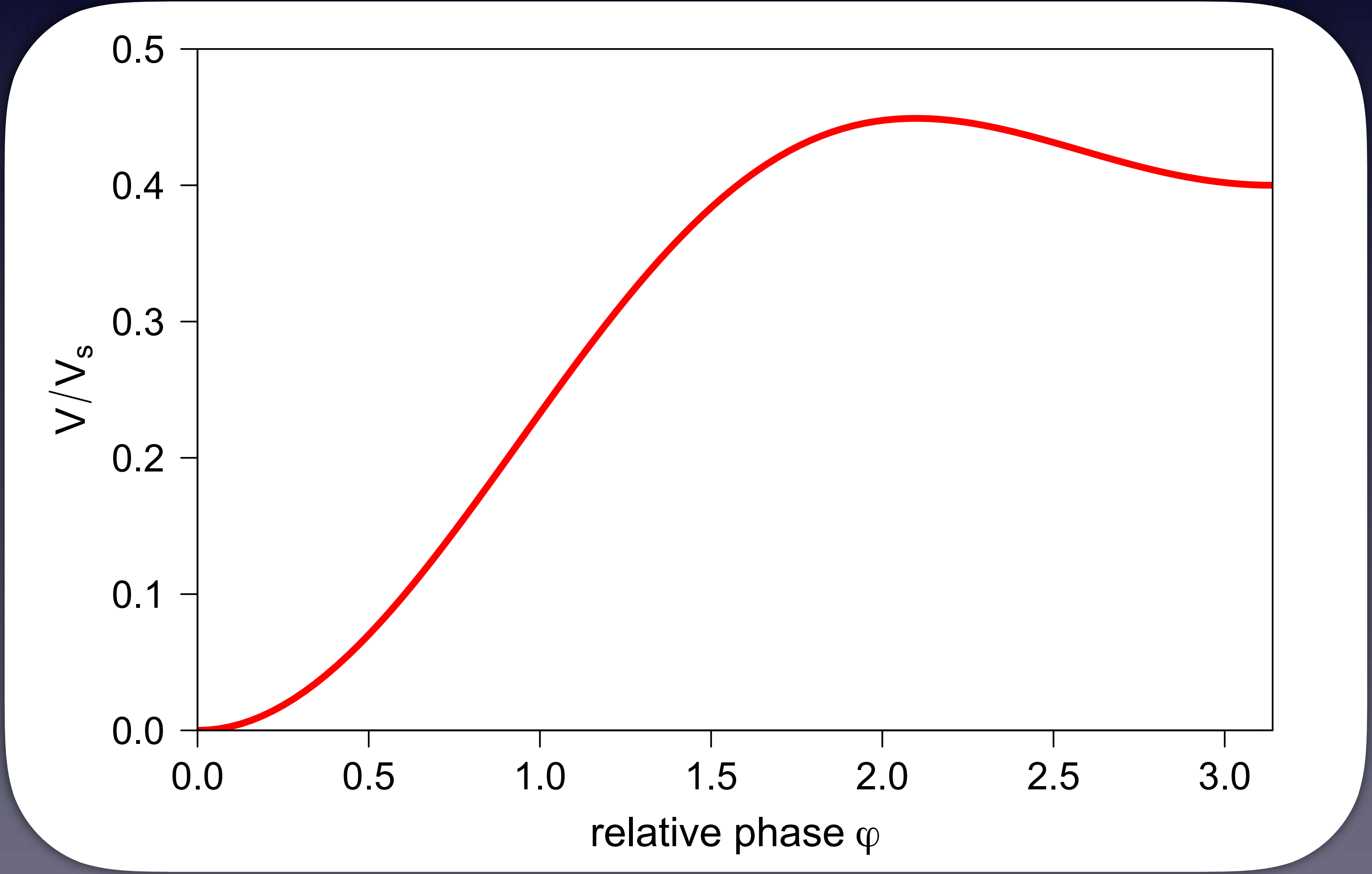
Vacuum decay in the lab



Vacuum decay in the lab

BEC, two atomic levels 1&2 with wave functions

$$\psi_1 = \rho(1 + \frac{\epsilon}{2}\delta\rho_-)e^{i\varphi/2} \qquad \psi_2 = \rho(1 - \frac{\epsilon}{2}\delta\rho_-)e^{-i\varphi/2}$$

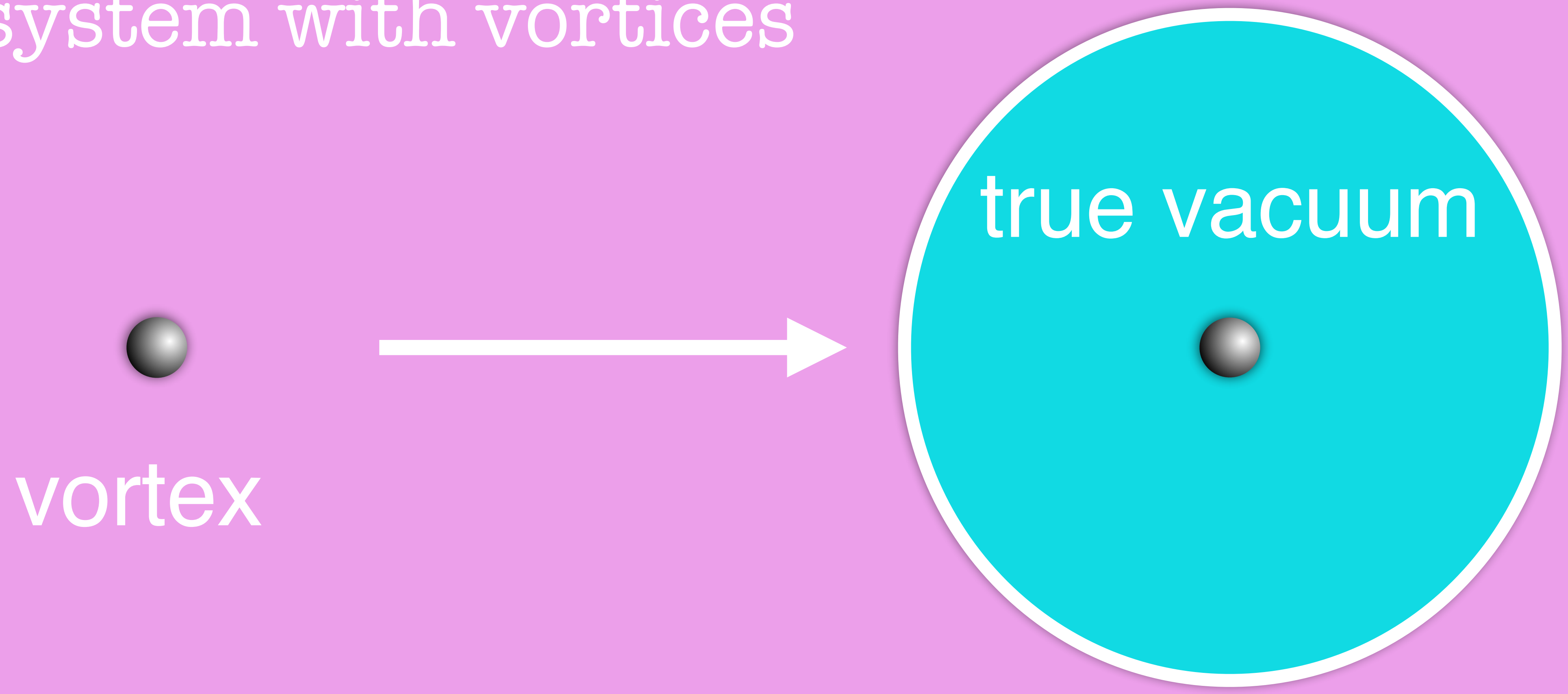


Still just a proposal

Fialko et al. , 1408.1163, 1607.01460. Braden et al. 1712.02356

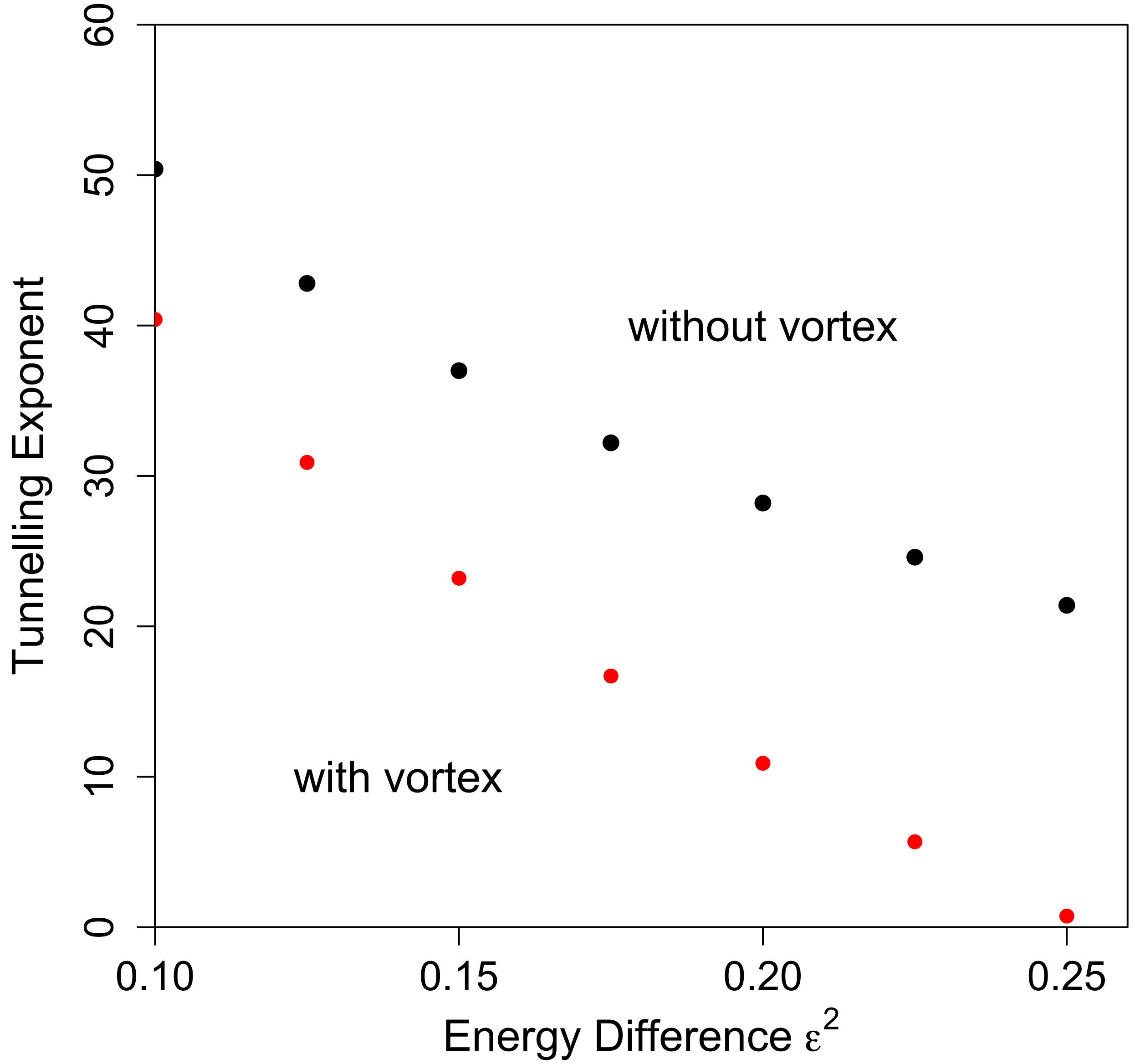
Seeded vacuum decay in the lab

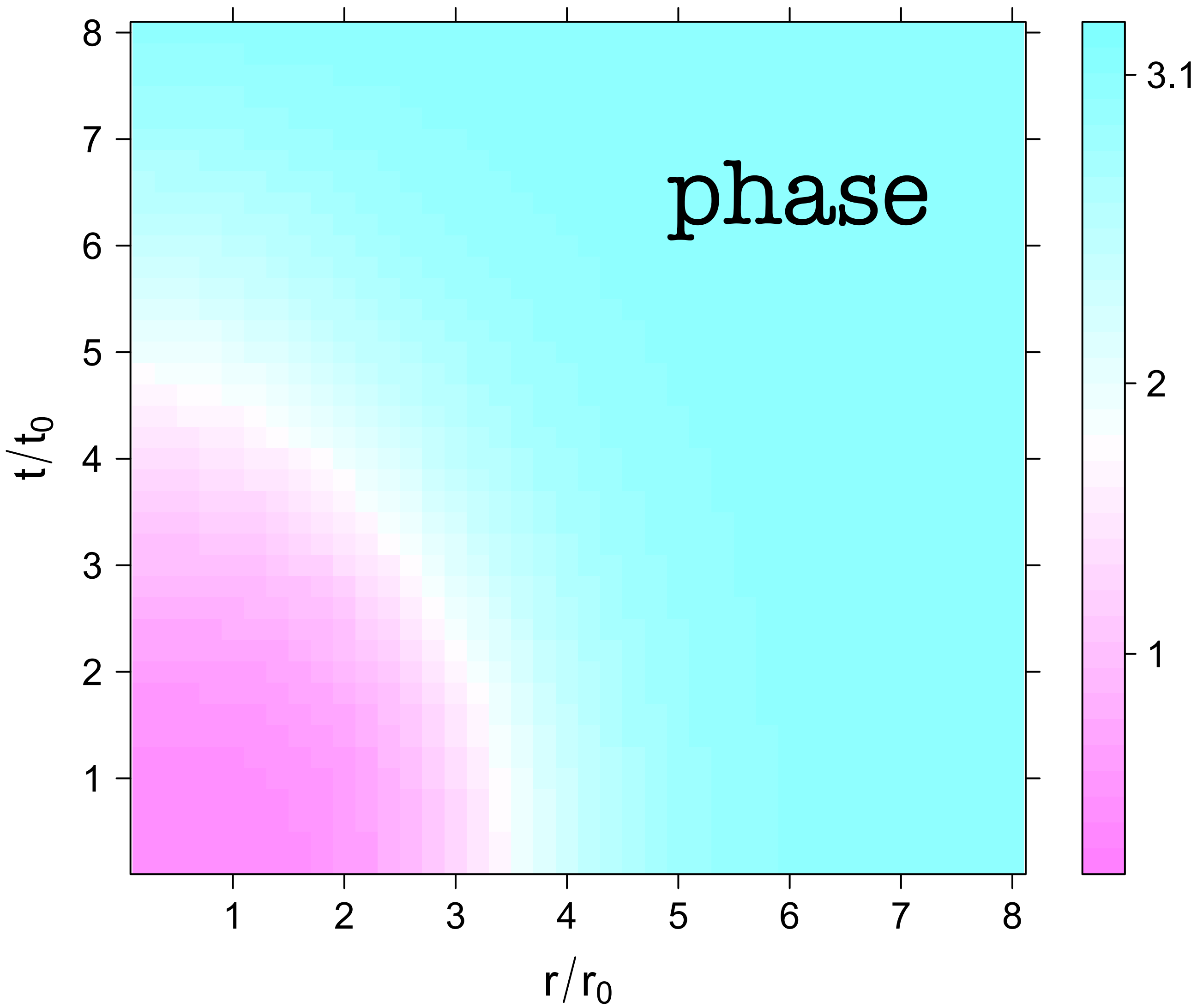
2D system with vortices



Tom Billam, Florent Michel, Ruth Gregory & IGM

Seeded vacuum decay in the lab





Vacuum decay in the early universe

Standard Model

General Relativity

Inflaton

Higgs stability during inflation

when the Higgs and the inflaton are distinct

$$\mathcal{L} = \frac{1}{2}M_p^2 R - \frac{1}{2}\xi R\phi^2 - \frac{1}{2}(\nabla\phi)^2 - V(\Phi,\phi)$$

1. De Sitter vacuum fluctuations can destabilise the Higgs $\delta\phi \sim H$
2. The curvature coupling can stabilise/ destabilise the Higgs during inflation.
3. The Higgs can seed large fluctuations

Higgs potential

Curvature and inflation couplings:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}\lambda_{\text{eff}}(\phi)\phi^4 - \frac{1}{2}\xi_{\text{eff}}(\phi)R\phi^2 - \frac{1}{2}g_{\text{eff}}(\phi)\phi^2\Phi^2 + \ldots$$

R is related to the expansion rate during inflation H

Stability depends on $\quad \xi_{\text{eff}}(\phi), \quad g_{\text{eff}}(\phi), \quad H$

Espinosa et al. 1112.3022, Herranen et al. 1407.3141,
Bounakis & IGM 1710.02987

What exactly is the metric?

Make a field redefinition to the Einstein frame

$$g_E = \left(1 - \xi\phi^2/M_p^2\right) g$$

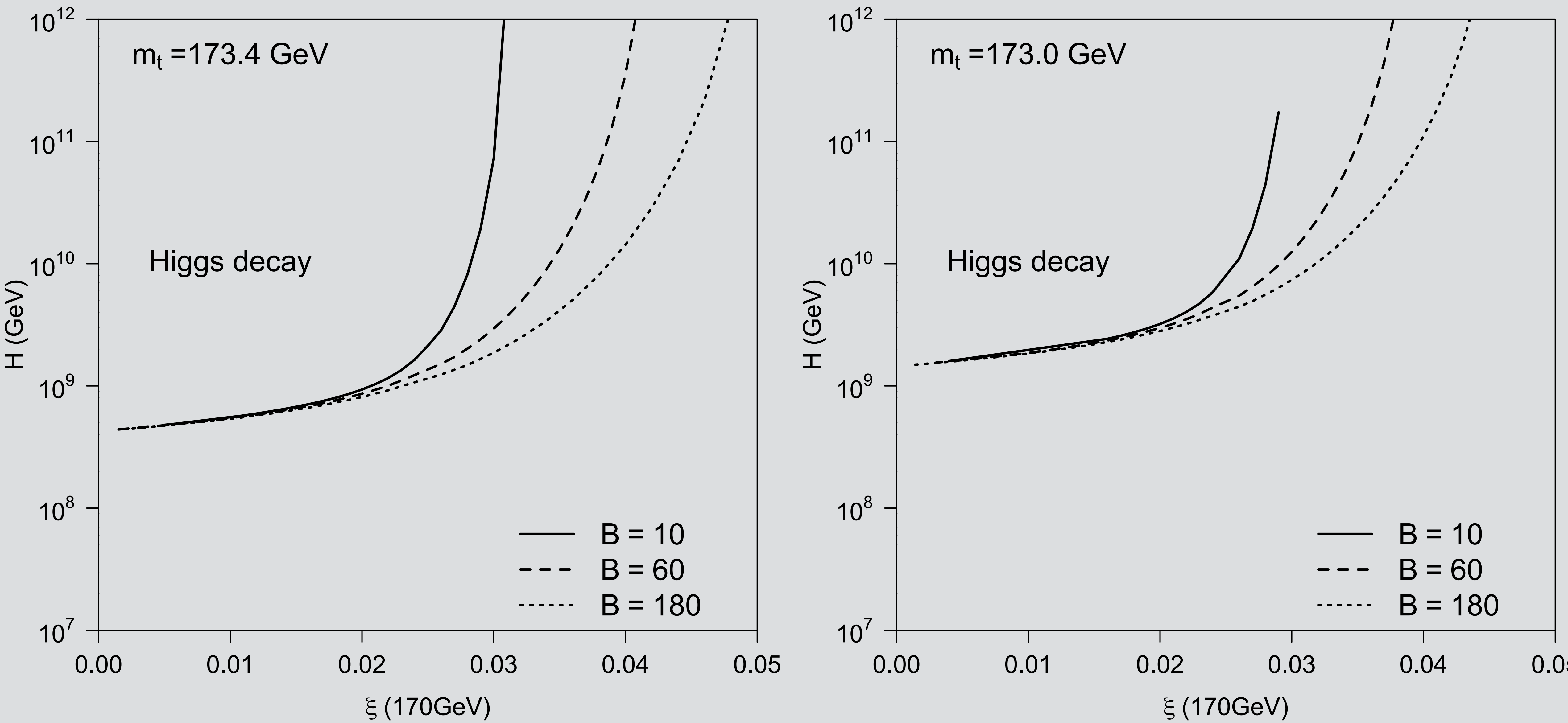
$$V_E(\phi) = \frac{V(\phi)}{(1 - \xi\phi^2/M_p^2)^2}$$

This mixes up $\xi_{\text{eff}}(\phi), \quad g_{\text{eff}}(\phi)$

The physics should be covariant under such field redefinitions

Bounakis & IGM 1710.02987

Effects on vacuum decay $\Gamma = Ae^{-B}$



Higgs fluctuations

Light field in de Sitter: can treat the quantum evolution through the barrier stochastically

Subsequent evolution of the Higgs gives fluctuations

$$\zeta_h \sim \frac{H^2}{\dot{\phi}(t_k)} \gg \zeta_\Phi \sim \frac{H^2}{\dot{\Phi}(t_k)}$$

These can form primordial black holes with mass $\lessapprox 10^{19}\,\mathrm{g}$ (dark matter candidates).

Rather fine tuned

Espinosa et al. 1710.11196, 1804.07731, 1804.07732.
Rigopoulos & IGM 1611.07589

Summary

- Microscopic black holes seed very rapid vacuum decay in a metastable theory.
- Vacuum decay may be testable in the lab
- The Higgs may be an active spectator during inflation

Philipp Burda and Ruth Gregory, 1501.04937, 1503.07331, 1601.02152

Ongoing work with Kate Marshal, Leo Cuspinera and Michel Florent

with Marios Bounakis 1710.02987

The End