Seeded Vacuum Decay

Ian Moss
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M. Caneletti, I Moss hep-th/2408.12229

Newcastle University

QSimFP

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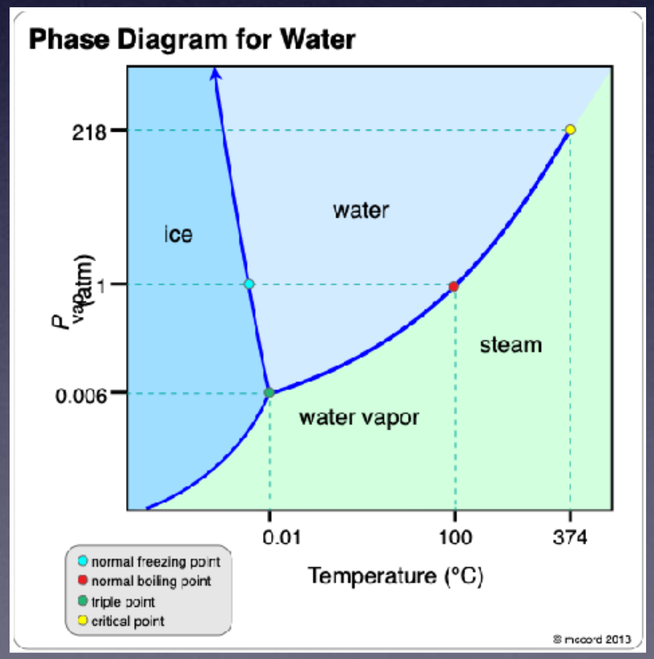
- Bubble nucleation
- Critical nucleation theory
- Seeded nucleation
- FVD in the laboratory

Bubble nucleation

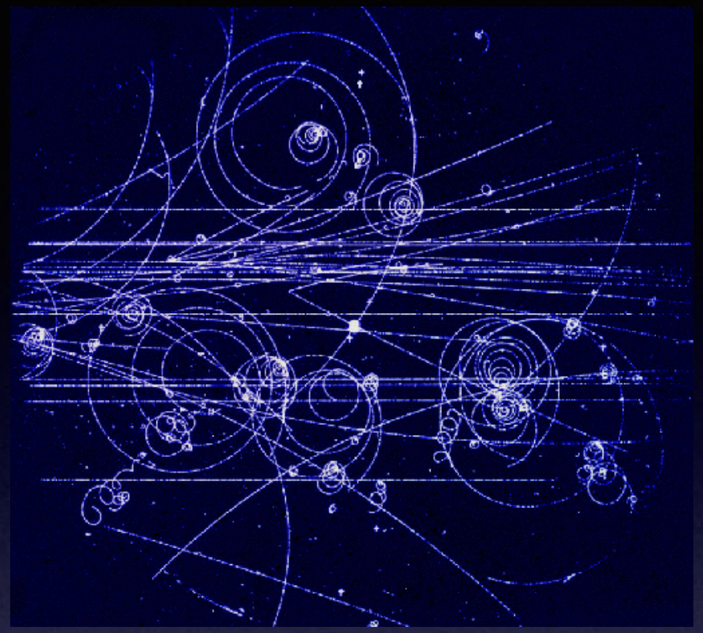
Cooling into a metastable state → Escape by bubble (or crystal) formation

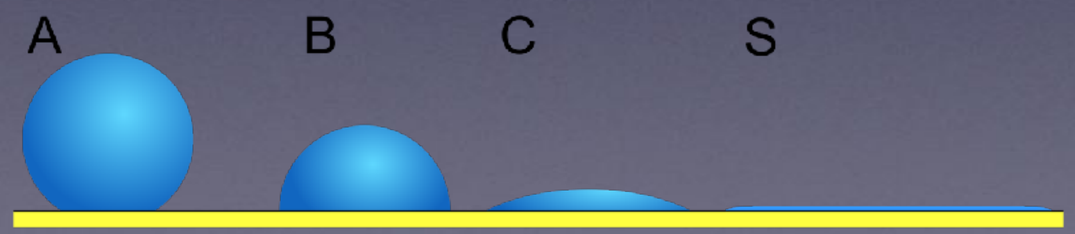


False vacuum decay

Cooling into a metastable vacuum → Escape by bubble formation

Nucleation seeds



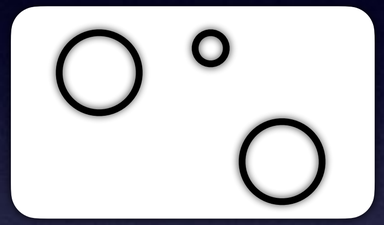


MesserWoland

TheBrockenInaGlory

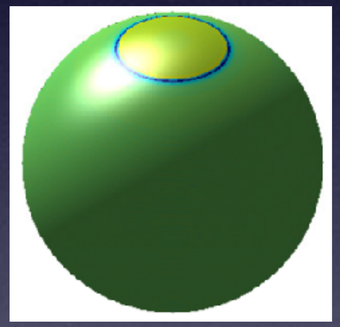
Bubble nucleation in cosmology

gravitational waves

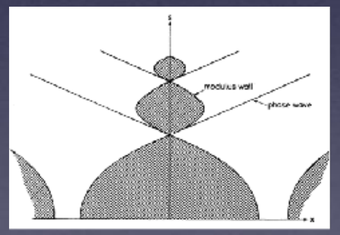


baryogenesis

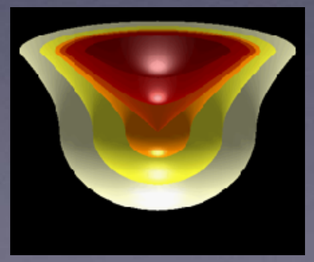
CMB distorsions



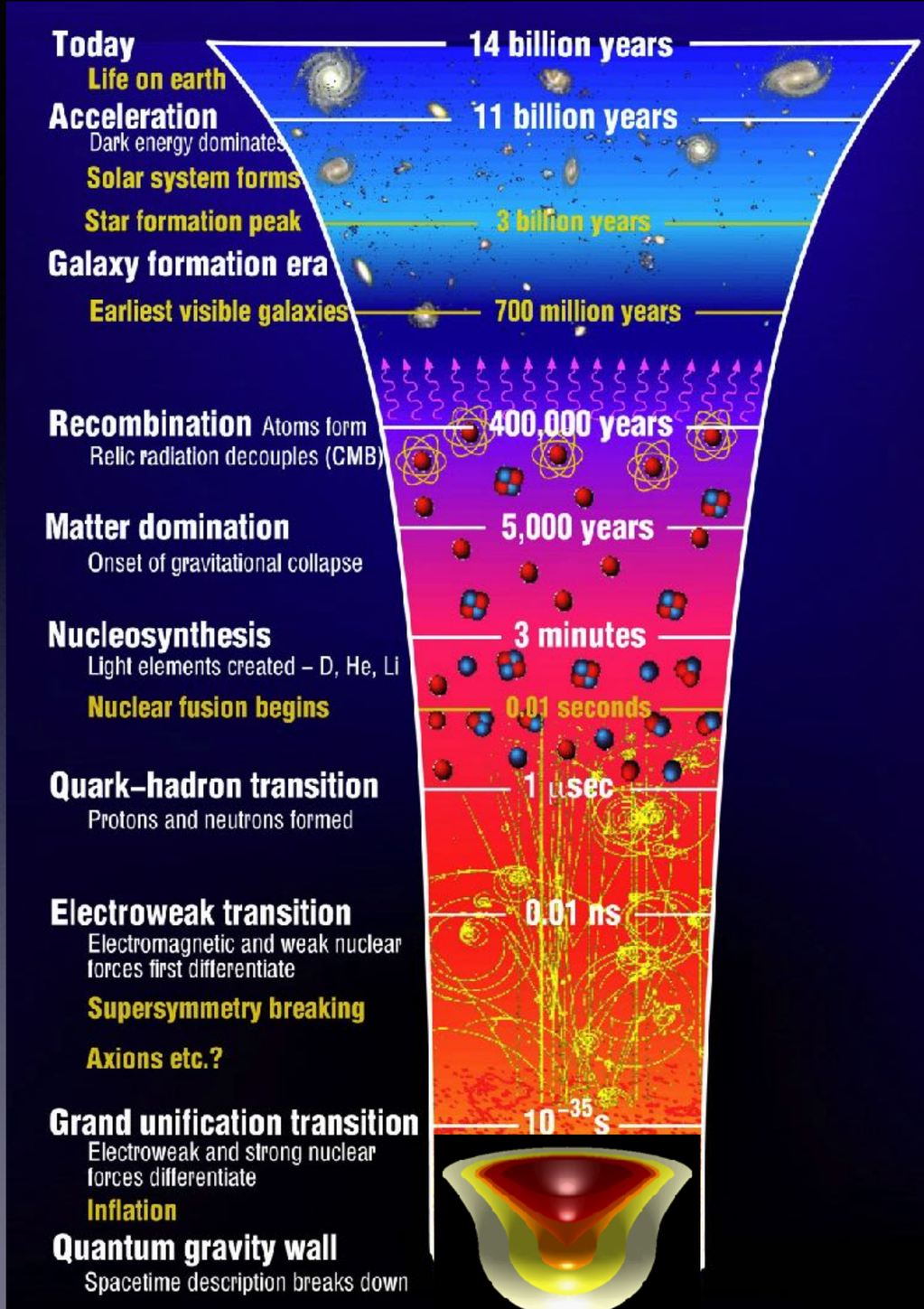
McEwen et al. 1202.2861



black holes

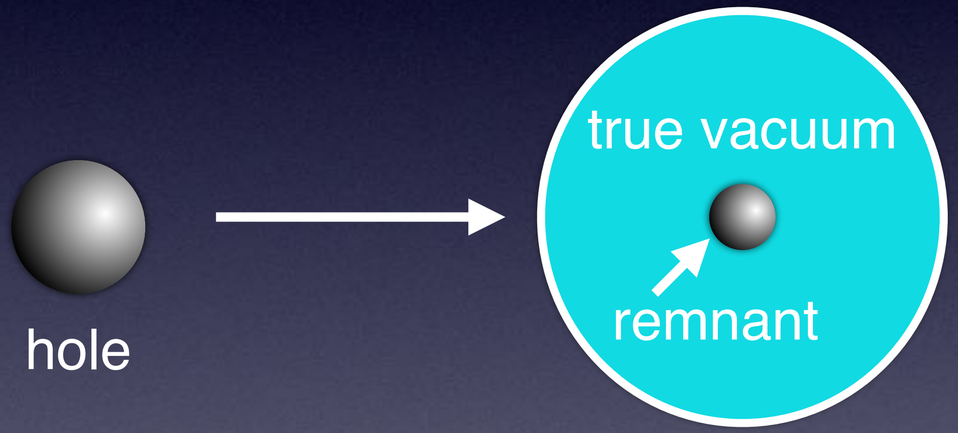


universe from nothing



Seeded vacuum decay

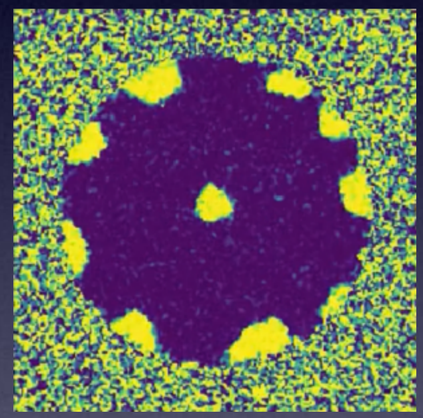
Black holes



Gregory, Moss, Withers 1401.0017

Vortices

BEC in a trap



Vortex in the centre

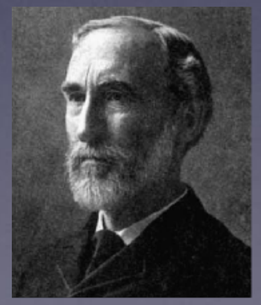
Billam, Michel, Moss, Gregory

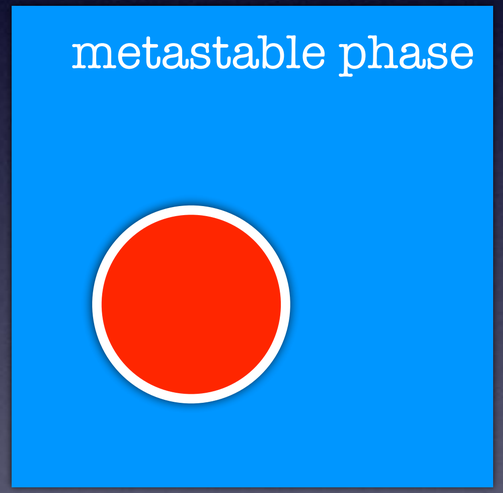
Critical Nucleation Theory

Critical bubbles in a thermal metastable state: Josiah Gibbs 1878!

Probability of a bubble fluctuation $\propto e^{\Delta S/k_B}$

Entropy changes by $\Delta S = -\frac{\Delta E}{T}$





J. W Gibbs, Equilibrium of heterogeneous substances, 1878, p416

Critical Nucleation Theory

$$\Delta E = 4\pi R^2 \sigma - \frac{4}{3}\pi R^3 \epsilon$$

σ surface tension

ϵ energy density lower

Critical case $\quad \dfrac{d\Delta E}{dR} = 0 \qquad R_c = \dfrac{2\sigma}{\epsilon}$

Nucleation rate $\quad \Gamma = \dfrac{N}{R_c^3}\dfrac{k_B T}{h}\left(\dfrac{\Delta E_c}{k_B T}\right)^{1/2} e^{-\Delta E_c / k_B T}$

$\Delta S / k_B$

Lifshitz and Pitaevski, Statistical Physics

Frenkel, Kinetic Theory of Liquids 1947

False vacuum decay

In quantum field theory, replace the bubble by a ‘bounce’ instanton, a solution to the field equations with **imaginary** time τ.

$$S_E = \int \left\{ \frac{1}{2} \nabla \varphi^2 + V(\varphi) \right\}$$

local potential minimum

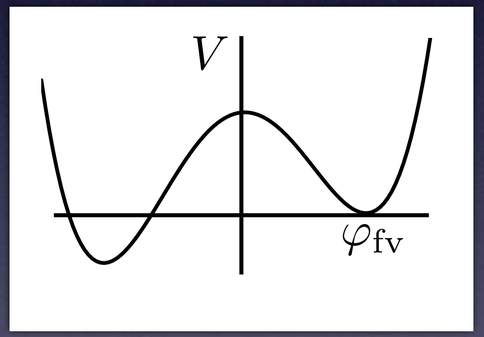
false vacuum decay

$\varphi = \varphi(\sqrt{\mathbf{x}^2 + \tau^2})$

false vacuum decay
at finite temperature

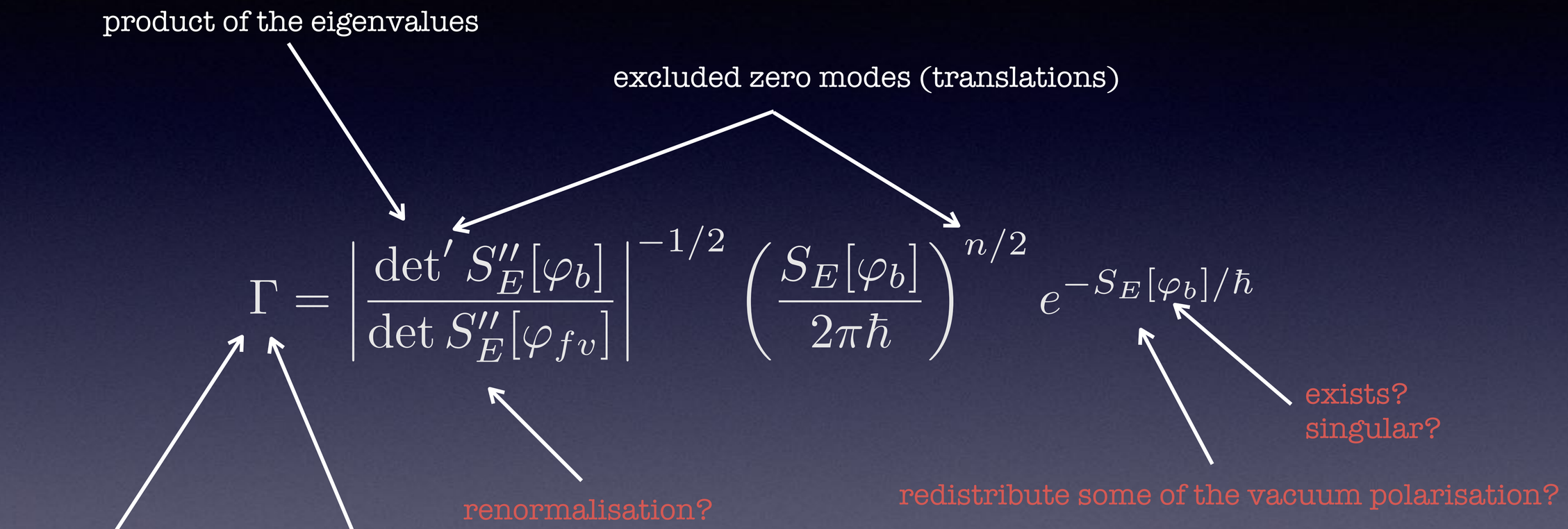
$\varphi = \varphi(x)$

$\beta = \hbar / k_B T$

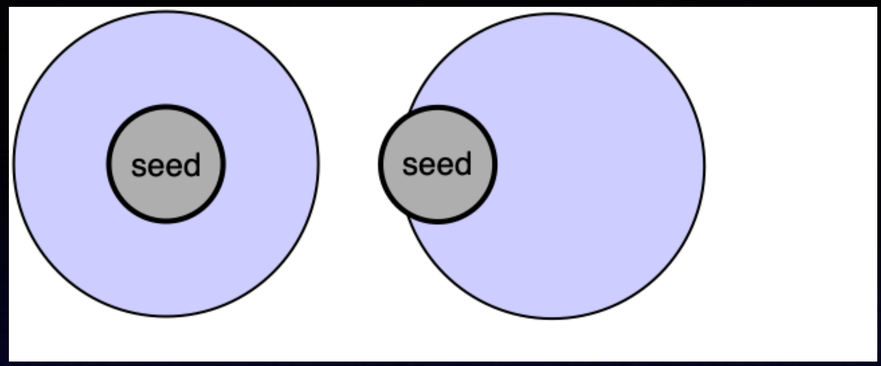


Coleman, Phys Rev D15 2929 1977

False vacuum decay rate

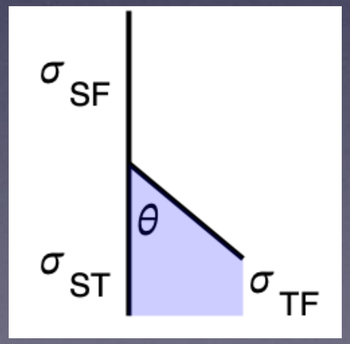


Seeded nucleation



Laplace's relation $\dfrac{1}{R_1} + \dfrac{1}{R_2} = \dfrac{\epsilon}{\sigma_{TF}}$

$$R = \frac{2R_1 R_2}{R_1 + R_2} = \frac{2\epsilon}{\sigma_{TF}}$$



Young's equation $\cos\theta = \dfrac{\sigma_{SF} - \sigma_{ST}}{\sigma_{FT}}$

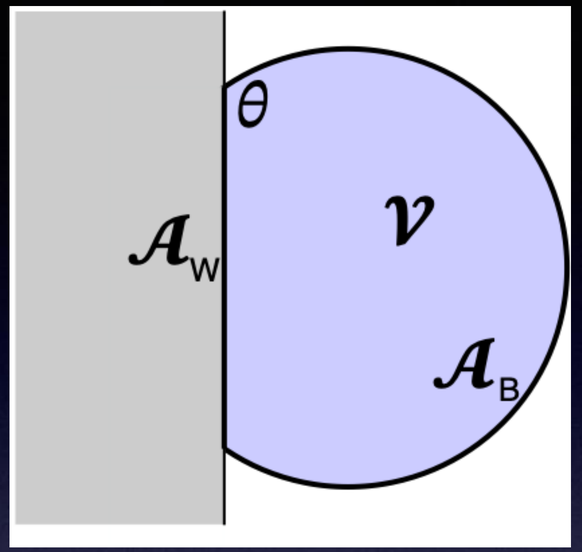
σ_{ST} between the seed and the true vacuum phase

σ_{SF} between the seed and the false vacuum phase

σ_{TF} between the true and the false vacuum phase

Seeded nucleation rates

$$\Gamma = \frac{N}{R_c^3}\frac{k_B T}{h}\left(\frac{\Delta E_c}{k_B T}\right)^{1/2} e^{-\Delta E_c / k_B T}$$



The energy difference between bubble and no bubble is

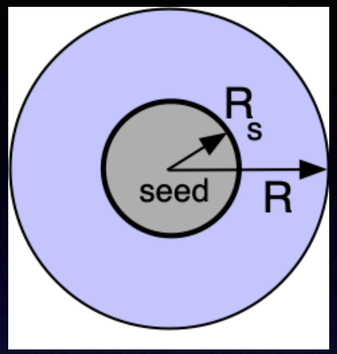
$$\Delta E = \mathcal{A}_W \sigma_{ST} + \mathcal{A}_B \sigma_{FT} - \mathcal{A}_W \sigma_{SF} - \epsilon \mathcal{V}.$$

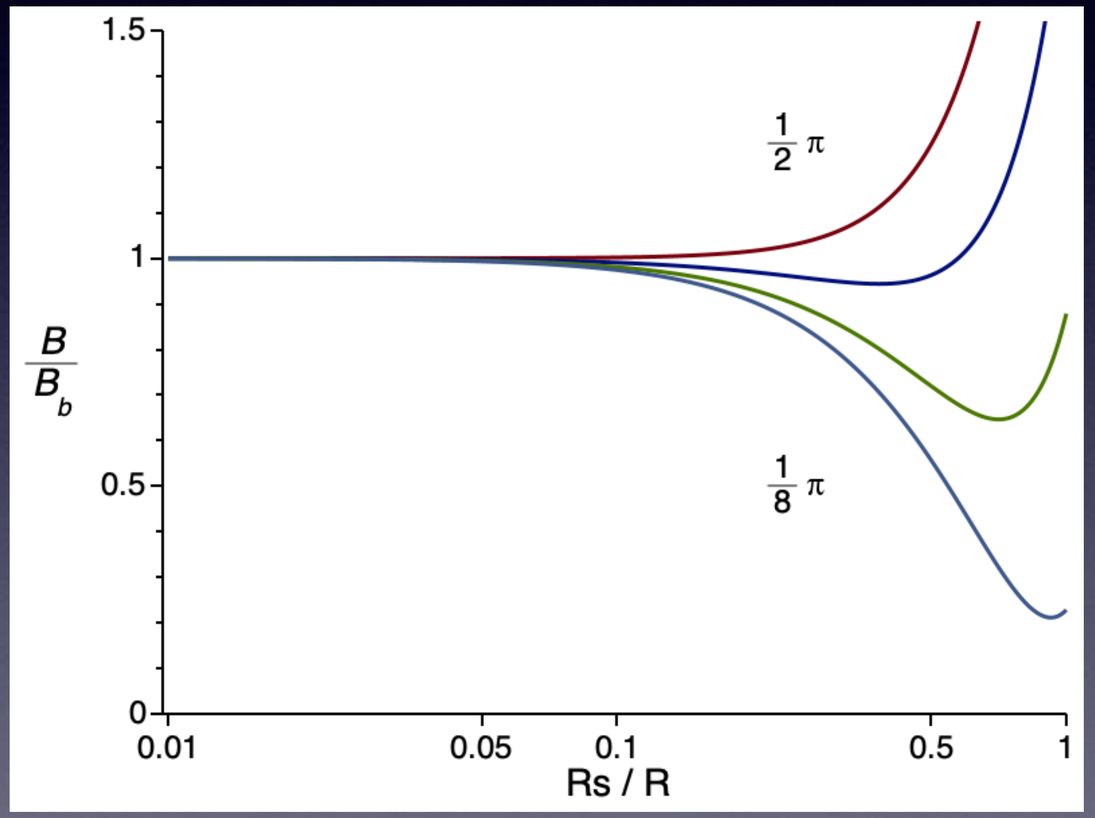
Young's relation implies

$$\Delta E = (\mathcal{A}_B - \mathcal{A}_W \cos\theta)\,\sigma_{FT} - \epsilon \mathcal{V}$$

$$\cos\theta = \frac{\sigma_{SF} - \sigma_{ST}}{\sigma_{FT}}$$

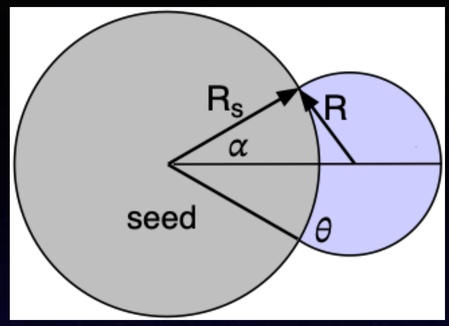
Seeded nucleation rates: interstitial

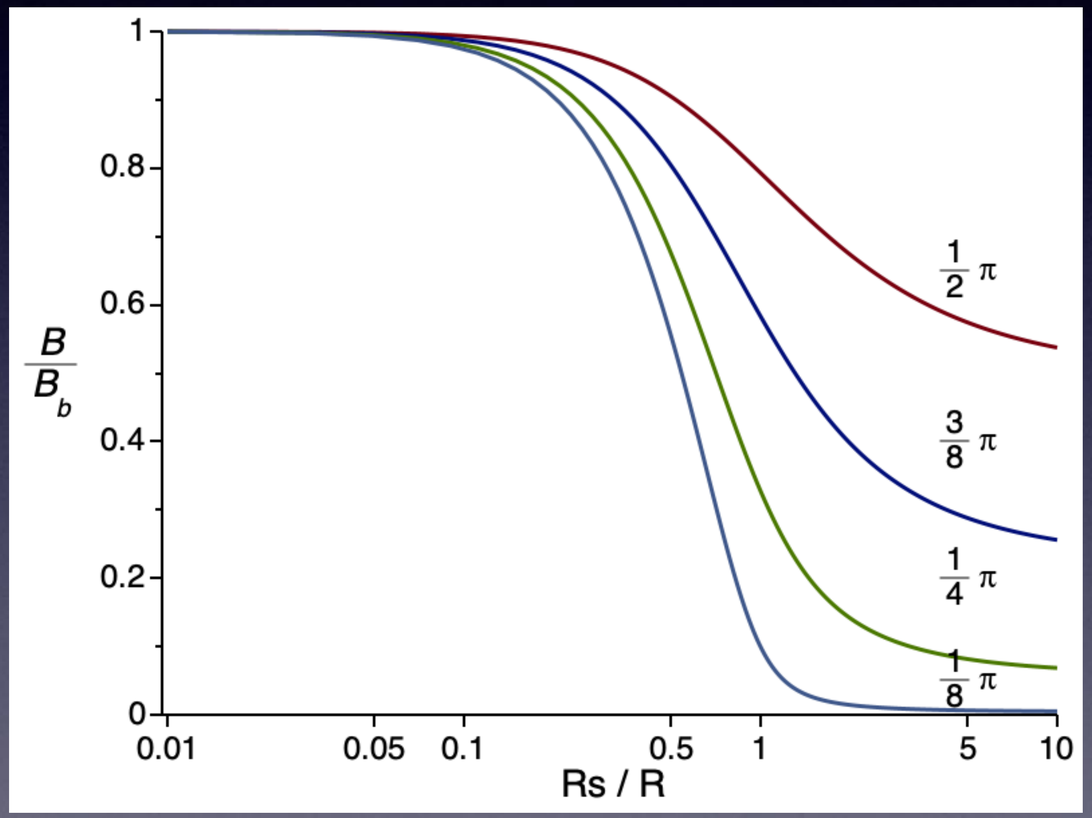




$$B = \Delta E / k_b T$$

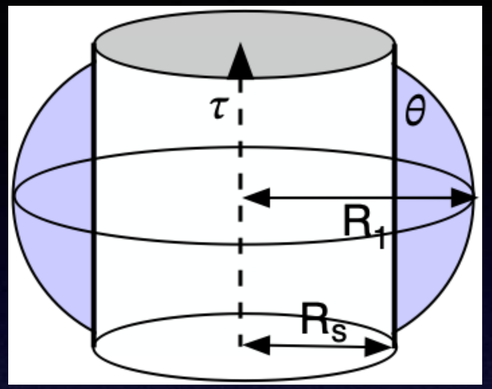
Seeded nucleation rates: edge

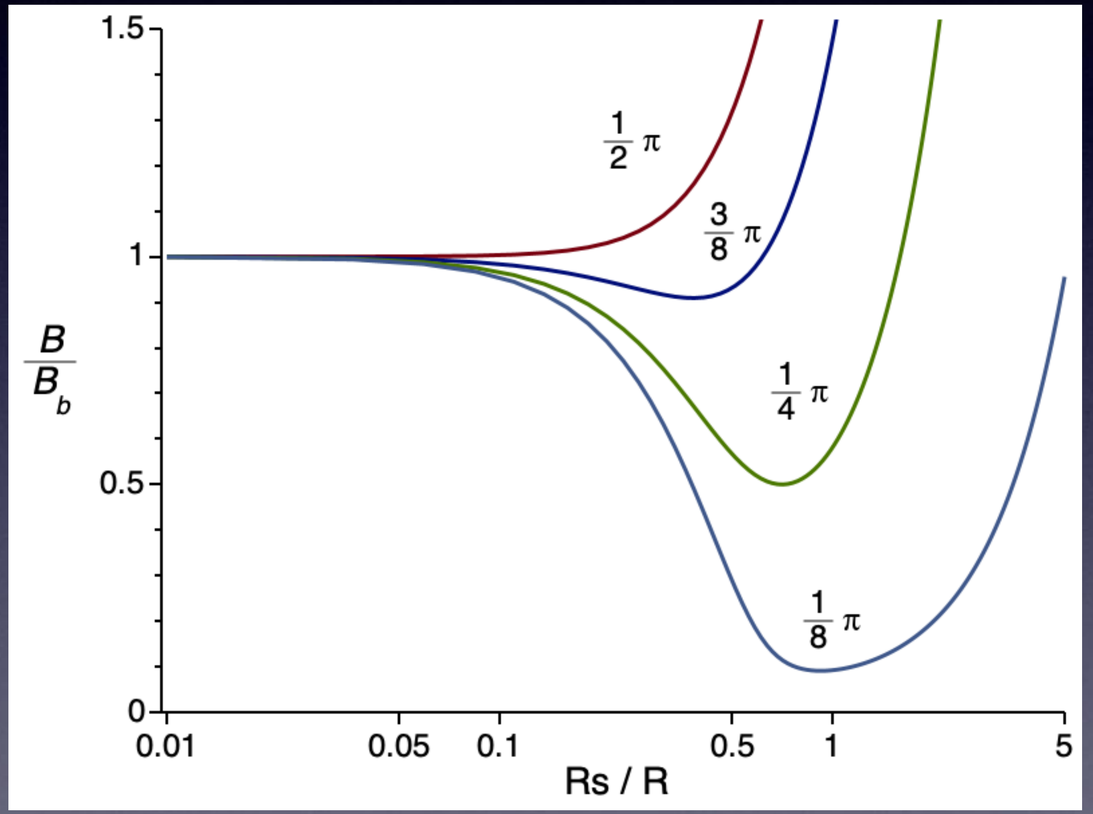




$$B = \Delta E / k_b T$$

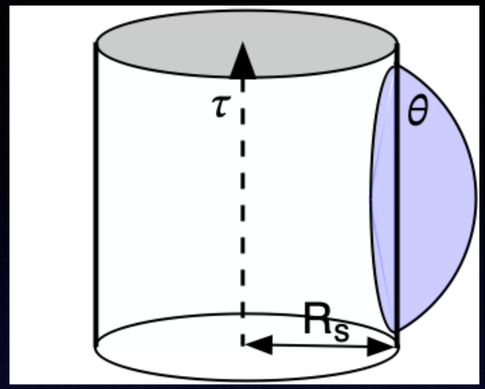
False vacuum decay: interstitial

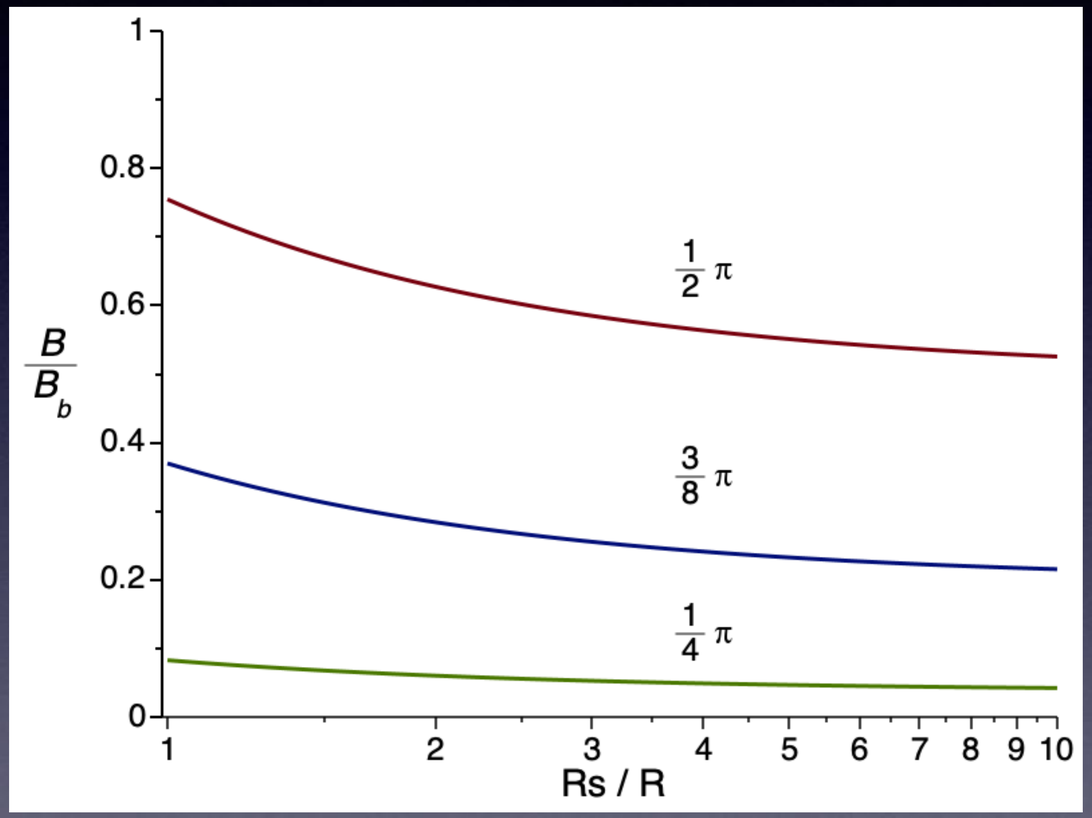




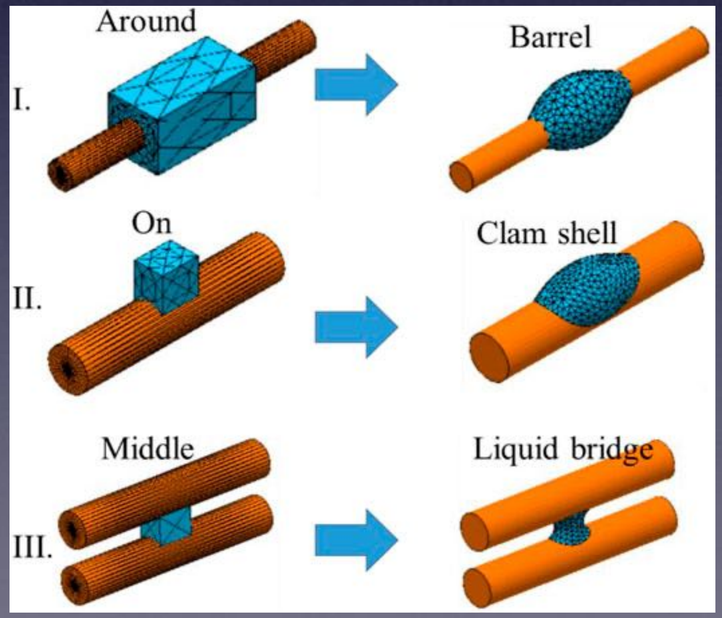
$$B = \Delta S_E/\hbar$$

False vacuum decay: edge





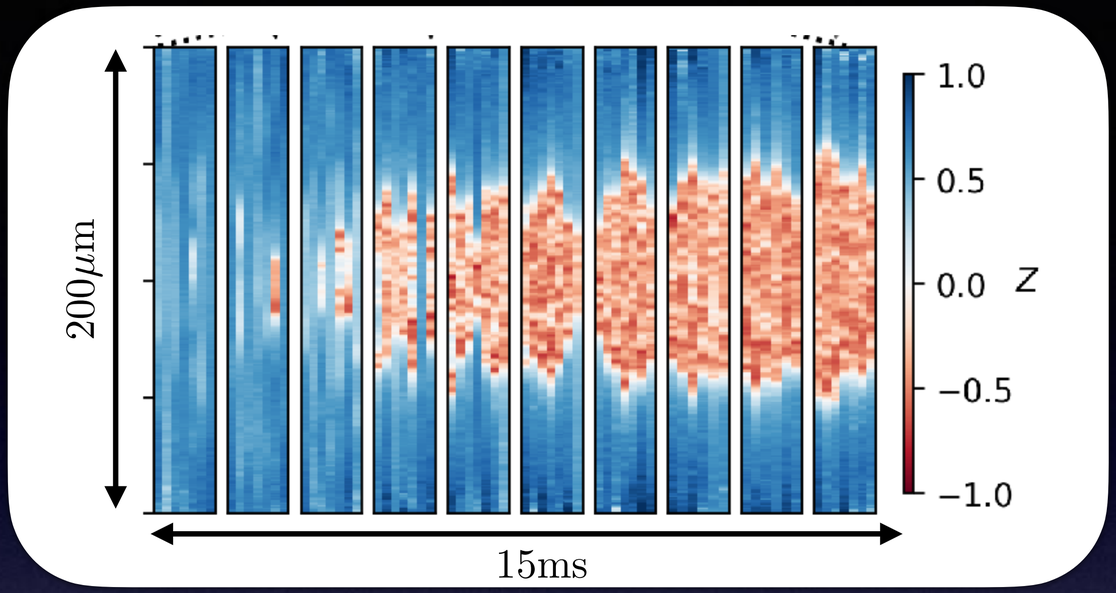
$$B = \Delta S_E/\hbar$$



Xu et al. Front Energy Res., 24 (2022)

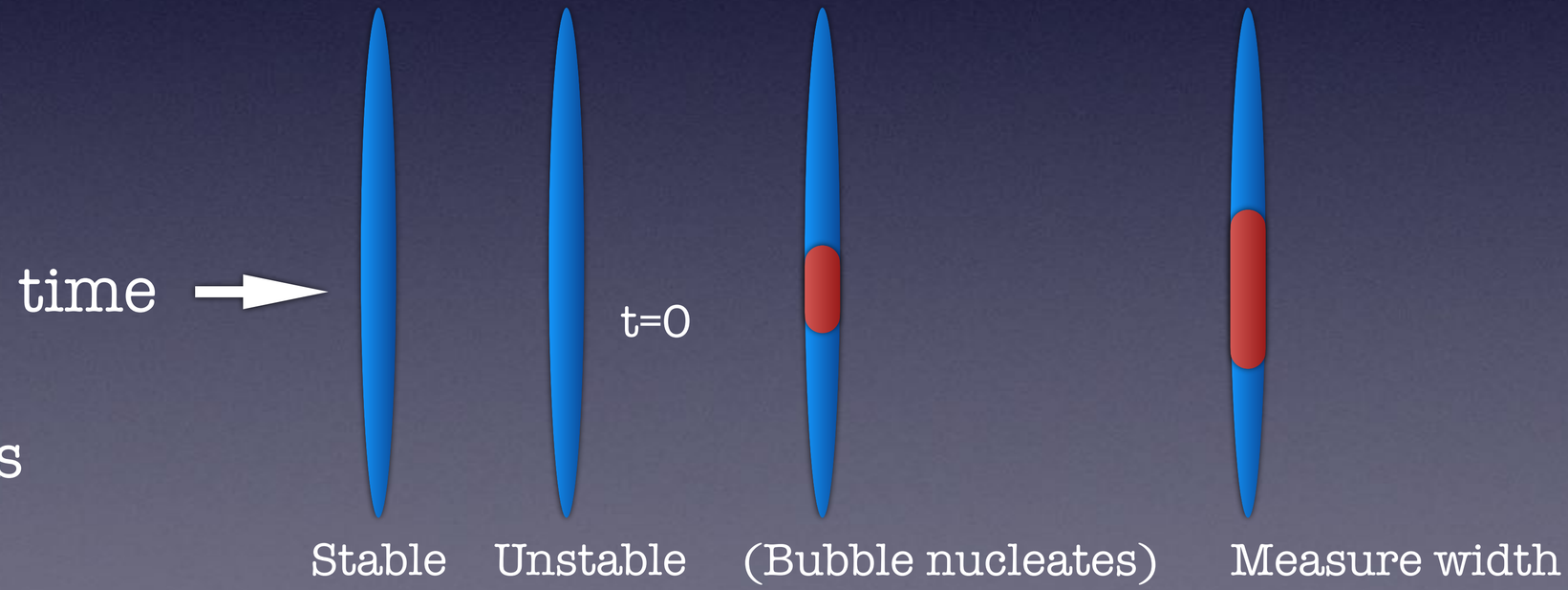
FalseVacuumDecay in the Lab (Trento)

A Zenesini, A Berti, R Cominotti, C Rogora, IG Moss, TP Billam, I Carusotto, G Lamporesi, A Recati, G Ferrari arXiv:2305.05225



Ferromagnetic bubbles in a two-component sodium BEC

Nucleation rate fits theory



FalseVacuum Decay in the Lab

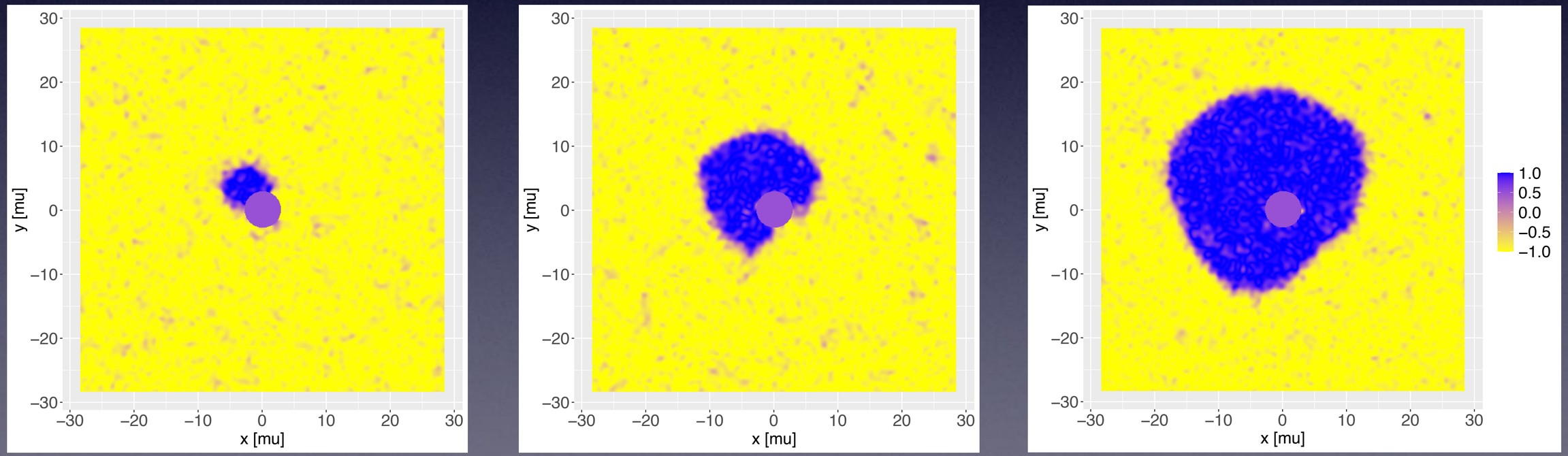
species	$\|F,m_F\rangle$ states	effective field	status
sodium 23	$\|1,-1\rangle$,$\|2,-2\rangle$	magnetisation	1D, finite T
potassium 39	$\|1,0\rangle$,$\|1,-1\rangle$	relative phase	2D under construction
rubidium 87	$\|1,1\rangle$,$\|1,0\rangle$,$\|1,-1\rangle$	relative phase	theory only

Seeded FalseVacuum Decay simulations: K39 in 2D

Real-time evolution uses the Stochastic Projected Gross Pitaevski equation

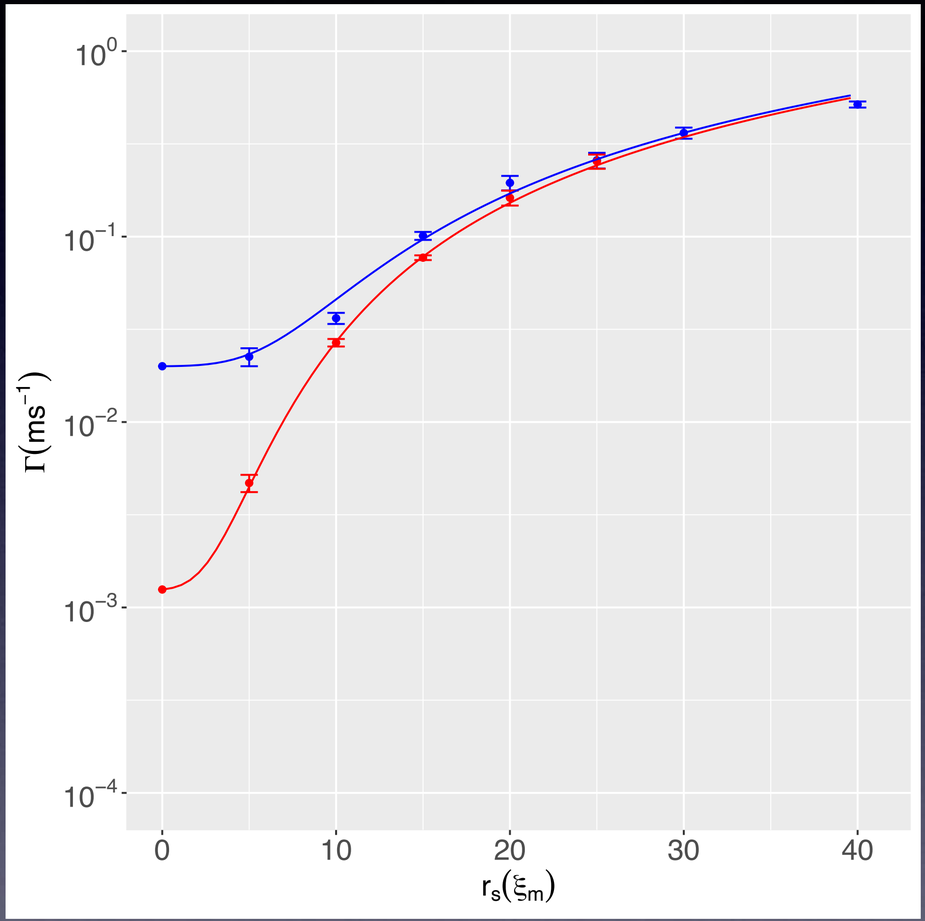
$$i\hbar\frac{\partial\psi_i}{\partial t} = \mathcal{P}\left\{(1+i\gamma)\frac{\partial H}{\partial\overline{\psi}_i} + \eta_i\right\}$$

The components represent two Zeeman levels of the BEC. The relative phase (plotted) undergoes false vacuum decay.



Simulated thermal bubble nucleation around a circular seed for a two dimensional BEC.

Seeded FalseVacuum Decay: comparison with theory



Bubble nucleation rate plotted as a function of the seed radius. The upper curve is for a periodic box of side L=400 and the lower curve L=200.

Seeded rate: $\Gamma_s = A_s R_s B_s^{1/2} e^{-B_s}$

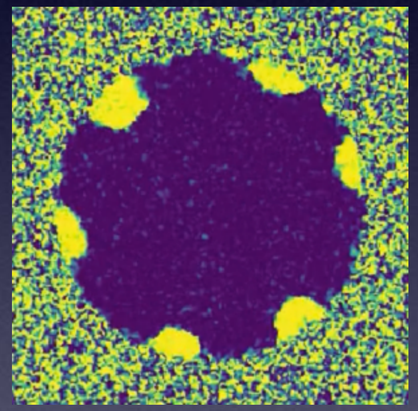
Where $B_s \equiv B_s(B_b, R_s, R, \theta)$

Unseeded rate: $\Gamma_b = A_b L^2 B_b e^{-B_b}$

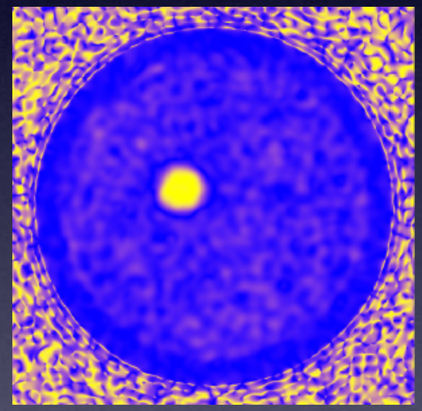
Total rate: $\Gamma = \Gamma_s + \Gamma_b$

The fit gives $R = 9.2\xi_m \quad (\xi_m \approx 0.2\mu\mathrm{m})$

FalseVacuum Decay in a trapping potential



hydrophobic coating

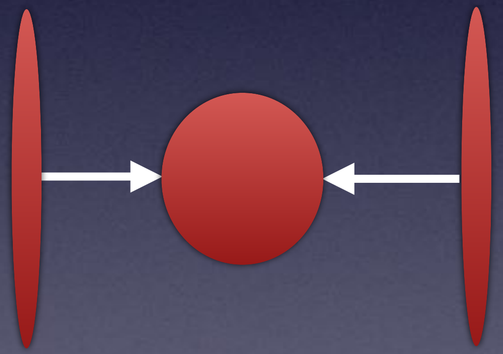


FalseVacuum Decay and particle collisions

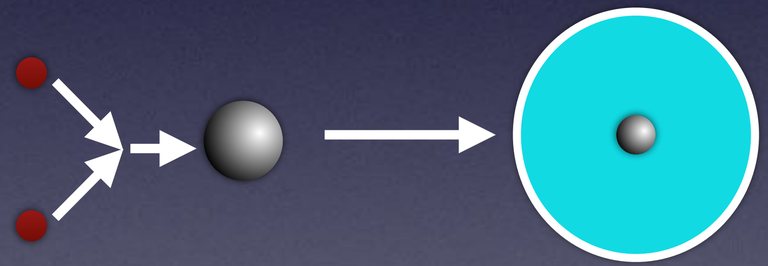
Could particle collisions cause vacuum decay today?

Most results have been 1+1 dimensions - but geometry is important

energy and size



heavy ion collisions



Cuspinera, Gregory, Marshall, Moss 1803.02871

From fantasy to reality?

We have seen the first experimental test of false vacuum decay at finite temperature in a BEC.

False vacuum decay is a non-perturbative quantum field theory phenomenon that may be important in understanding the origin of the universe.

Seeded nucleation may play a role in the early universe and future analogue vacuum decay experiments.

End