Title: Bubble Baryogenesis

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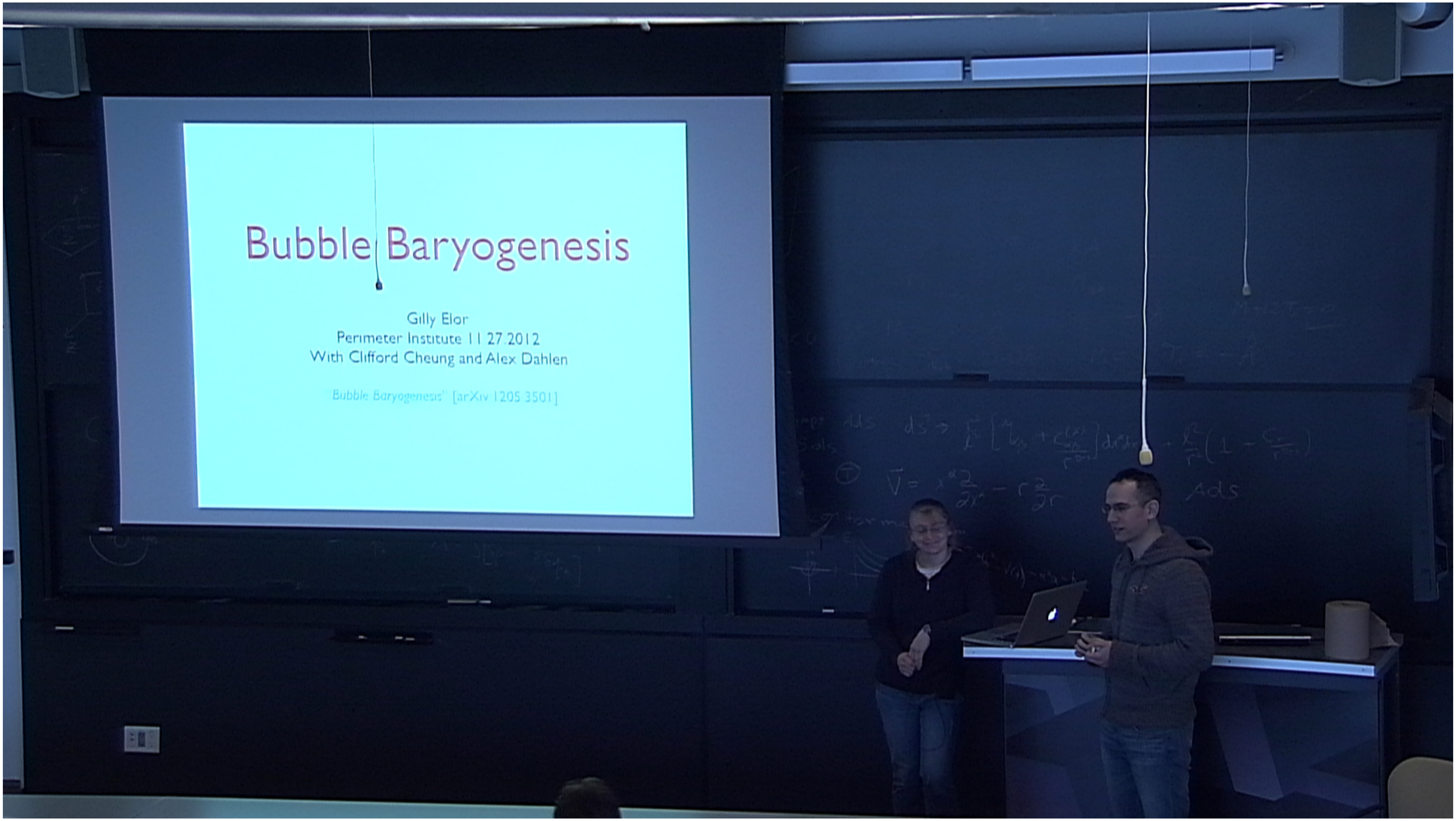
Abstract:


Bubble Baryogenesis
Gilly Elor
Perimeter Institute 11.27.2012
With Clifford Cheung and Alex Dahlen
"Bubble Baryogenesis" [arXiv:1205.3501]

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A need for new physics

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Our Proposal: A complex scalar field undergoes a percolating first order phase transition; tunneling across a B and CP violating barrier results in bubbles that carry an asymmetry in their walls. The walls collide, the asymmetry spreads, and can migrate to the standard model.

Outline of talk

1) Introduction to the mechanism: how to get baryons from bounces and bubbles.

2) Model independent: general requirements and statements about the asymmetry production, the effects of bubble collisions and washout.

3) Toy Model

4) Potential signals and Future Directions

Baryons from Scalar Fields

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Associated charge density is identified with baryon number density:

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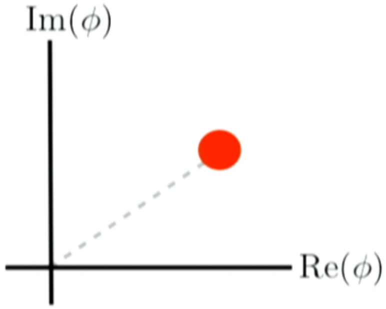
⇒ Must have "angular momentum" in field space to generate baryon number

Require:

- Displaced from the origin $r \neq 0$



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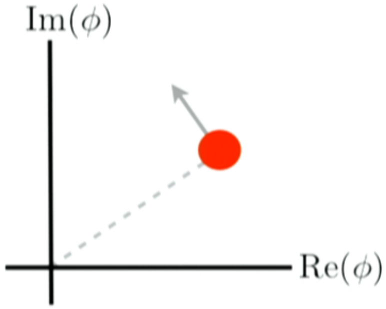

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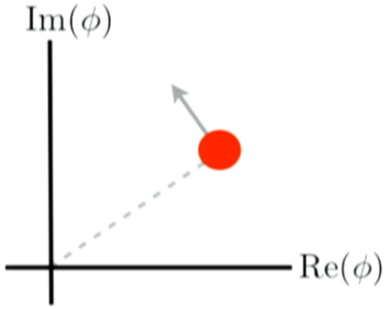
Can be achieved if the potential has B-violating terms $\frac{dV}{d\theta} \neq 0$



Baryons from Scalar Fields

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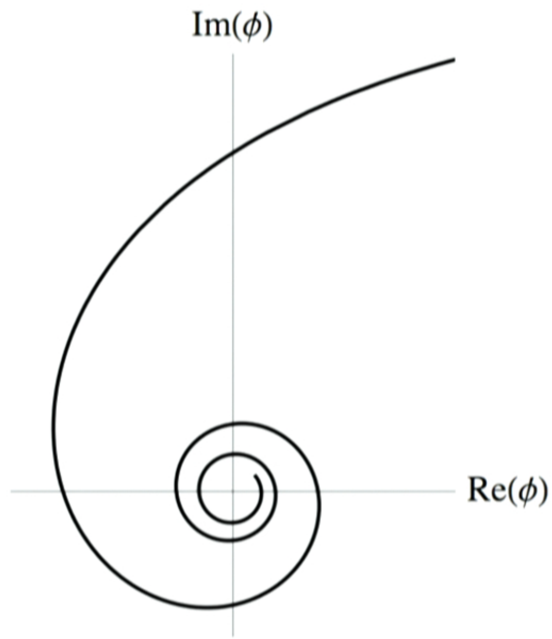

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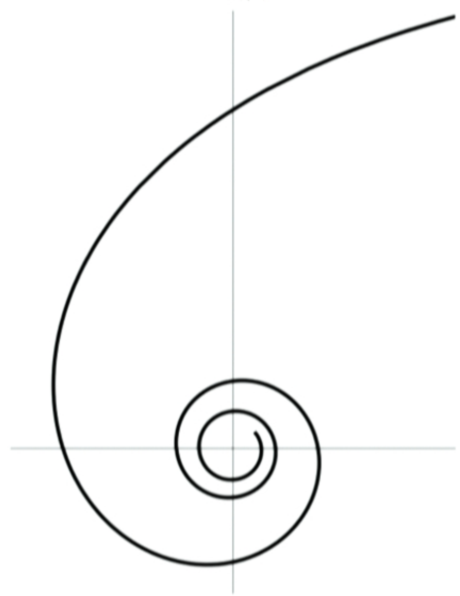


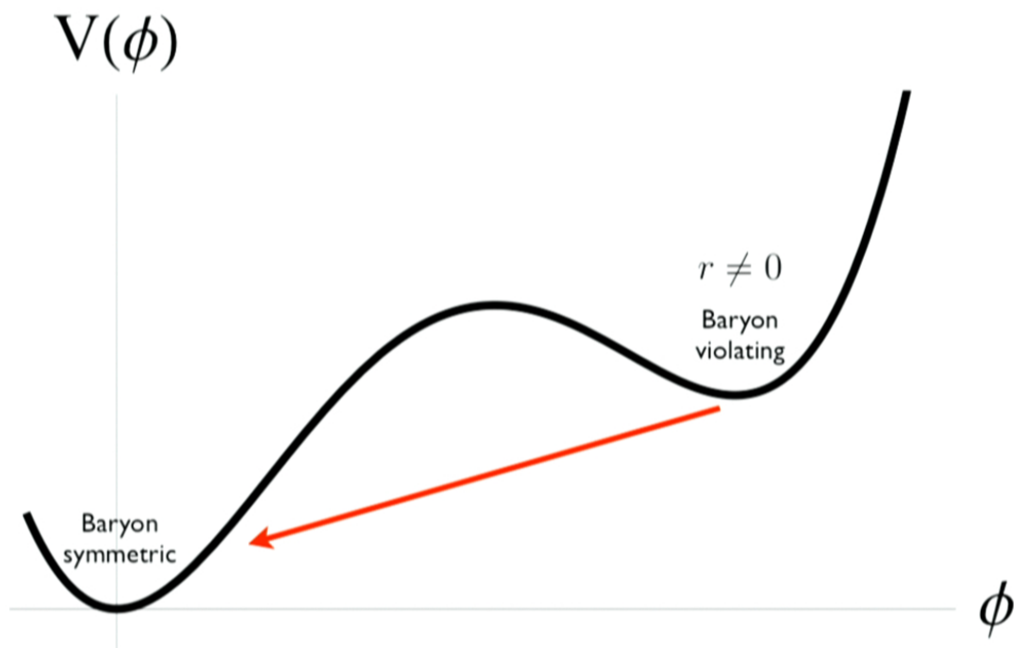
Greatly studied!

B violating terms result in a curved trajectory through field space $\dot{\theta} \neq 0$

Baryons from Scalar Fields

Our Proposal: consider the case of a potential without a classically allowed trajectory

Field tunnels to the symmetric vacua via bubble nucleation $\Gamma/V = Ke^{-\Delta S}$

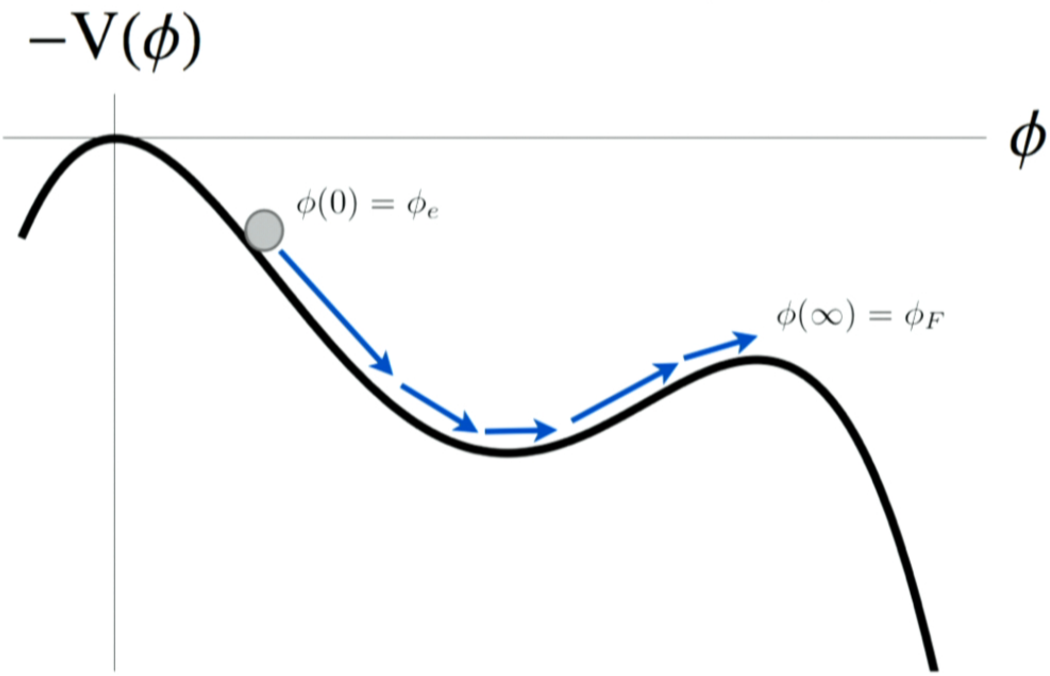


Coleman: The instanton solution gives the most likely bubble to nucleate and its decay rate.

Recall Coleman's overshoot/undershoot method for a *real* scalar field:

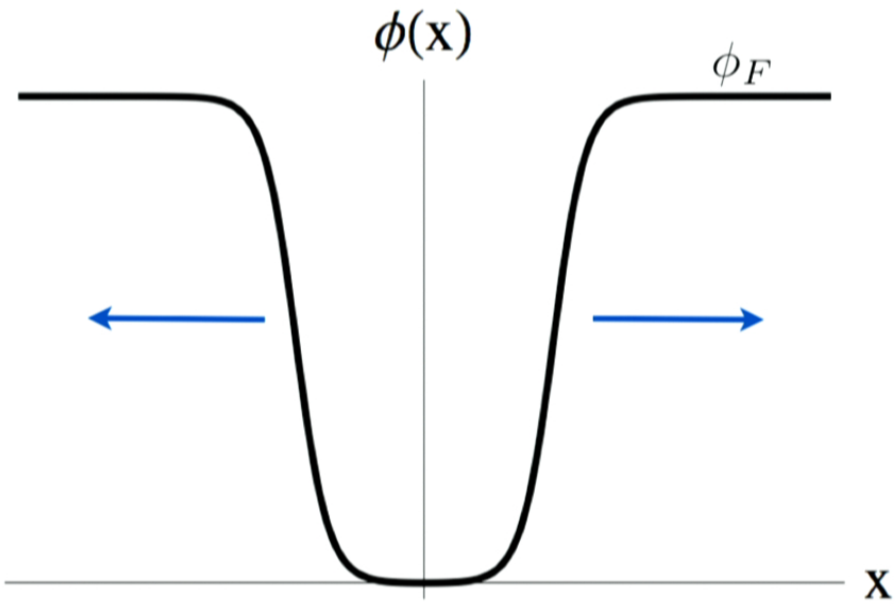
SO(4) symmetric bounce will have profile $\phi(\rho)$ where $\rho = \sqrt{x^2 - t^2}$

$$\Longrightarrow \quad \frac{d^2\phi}{d\rho^2} + \frac{3}{\rho}\frac{d\phi}{d\rho} = \frac{dV(\phi)}{d\phi}$$



Mechanical Analog - ball moving in negative potential

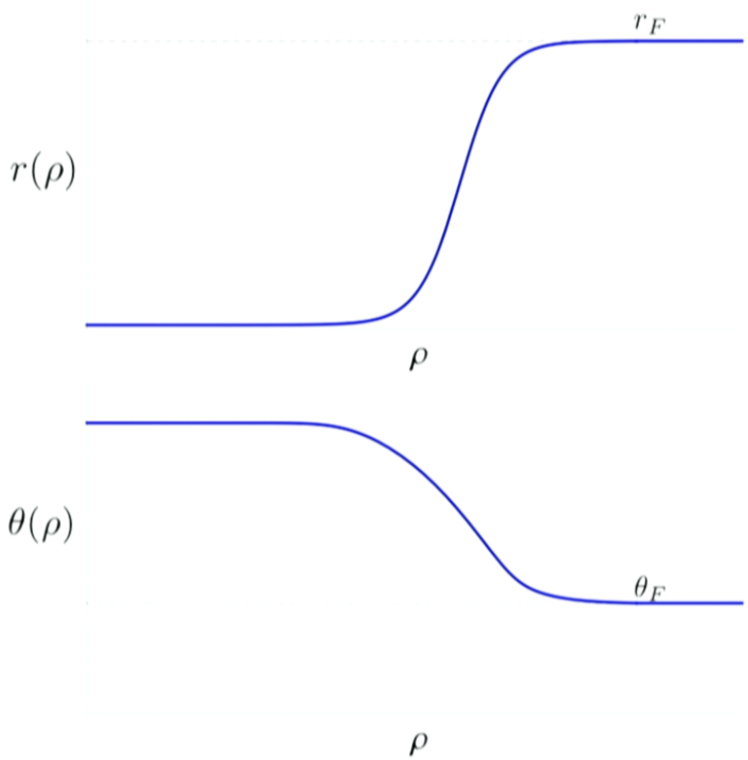
Resulting field profile:



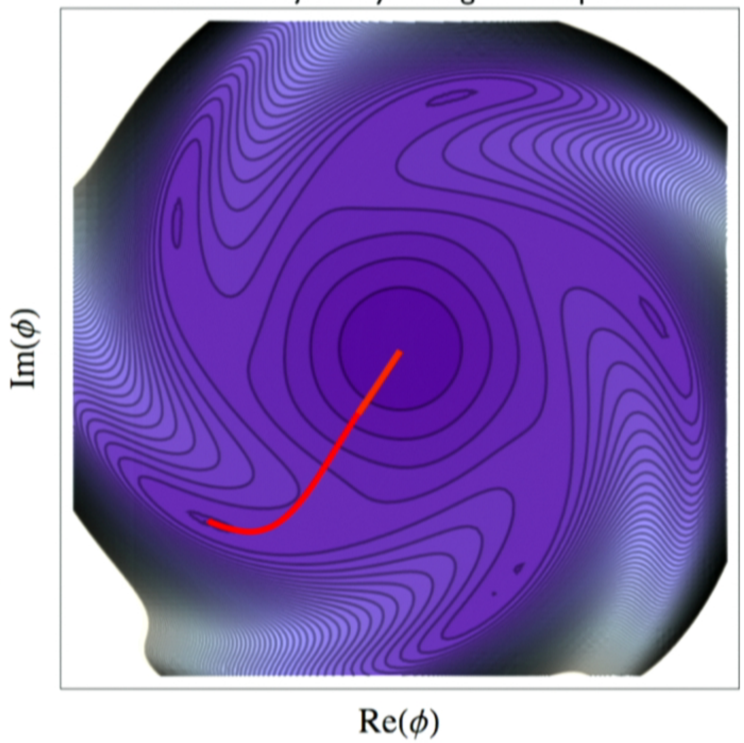
Spherical bubbles of true vacuum nucleate inside a false vacuum background and quickly expand.

Generalize to a complex scalar field $\phi(\rho) = r(\rho)e^{i\theta(\rho)}$

Sample numerical two field profile:

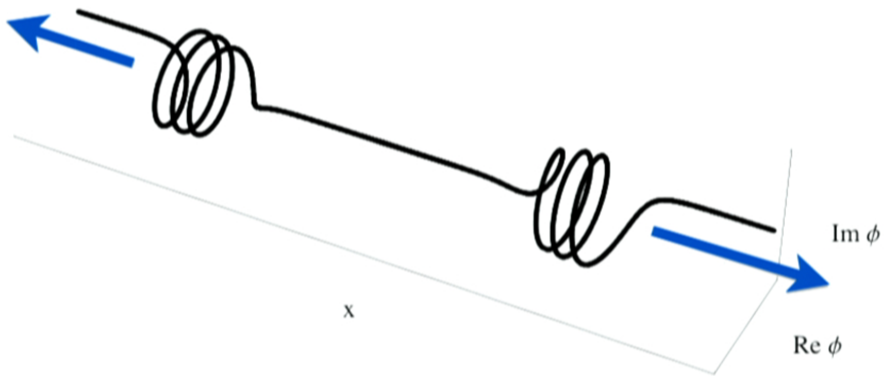


Tunneling in the angular direction results in a curved trajectory though field space



In analog to Affleck-Dine we expect baryon number to be generated when instanton arcs in field space.

Generalize to a complex scalar field $\phi(x,t) = r(x,t)e^{i\theta(x,t)}$



Specifically it is the bubble walls which take a curved trajectory through field space; walls accumulate baryon number as the bubble expands.

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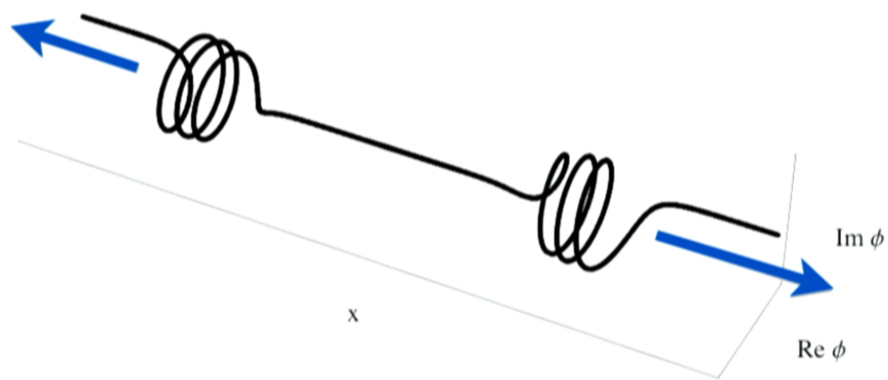

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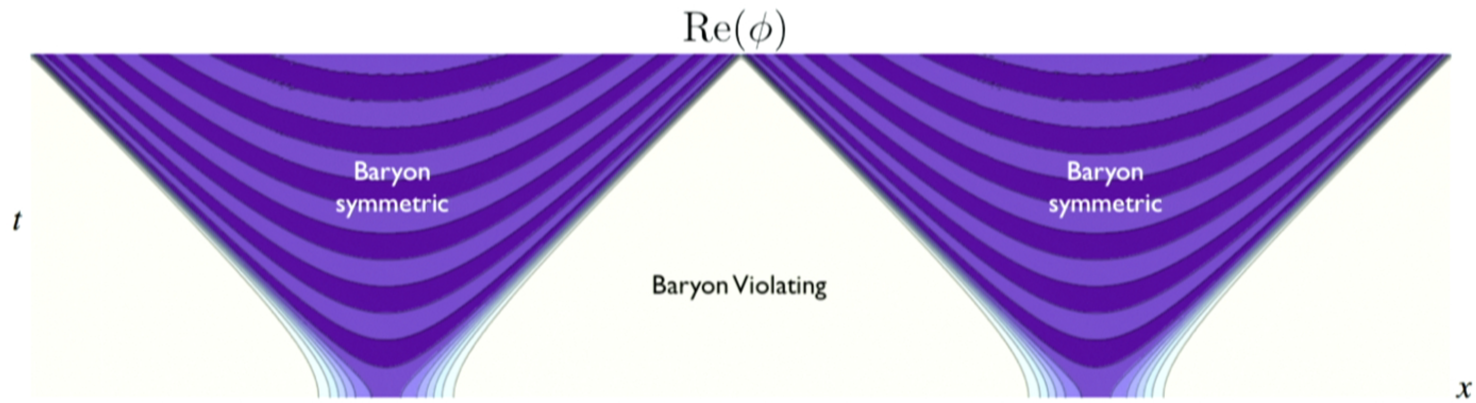
Multiple bubble nucleations result in a spatially inhomogeneously distributed asymmetry.

One bubble is not enough:



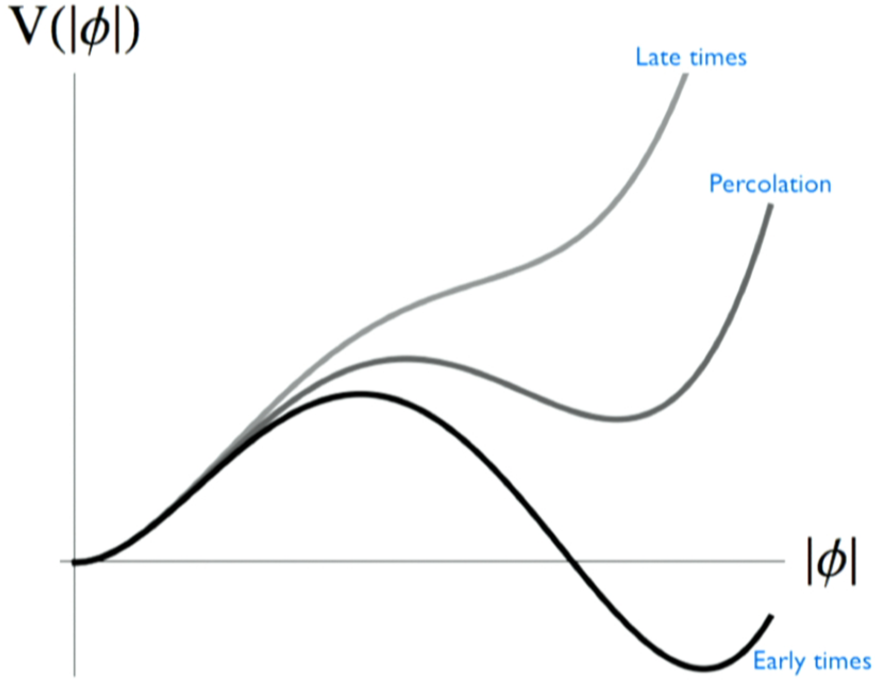
Need many bubbles to nucleate and eventually collide since the universe must completely transit from B-violating to B-symmetric phase and the asymmetry must not run off to infinity.

i.e. percolating first order phase transition

→ Motivates choice of effective potential

The Potential

B-symmetric vacua must be stable today; B-violating vacuum must disappear at late times so that no region of the universe is stuck there.



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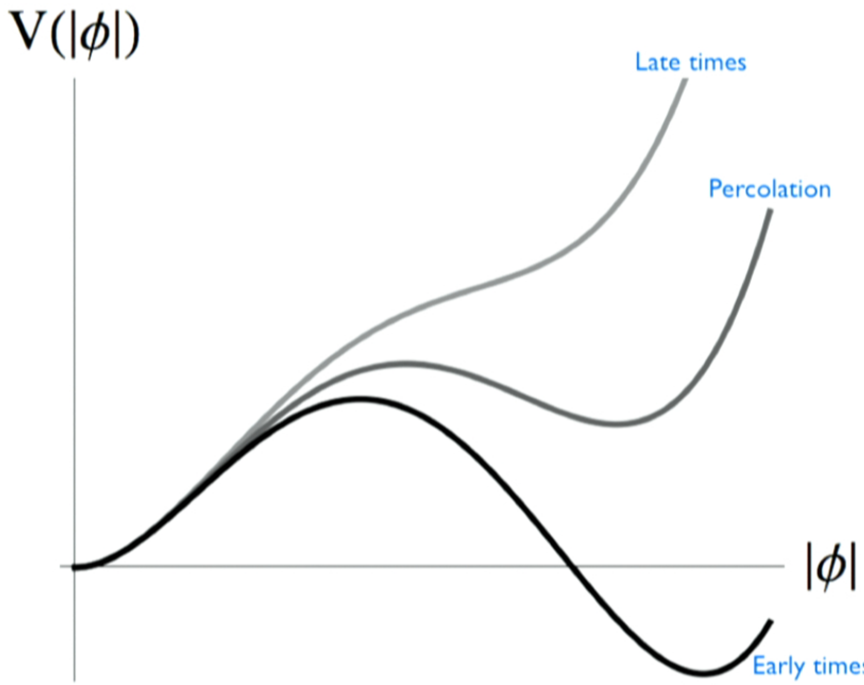


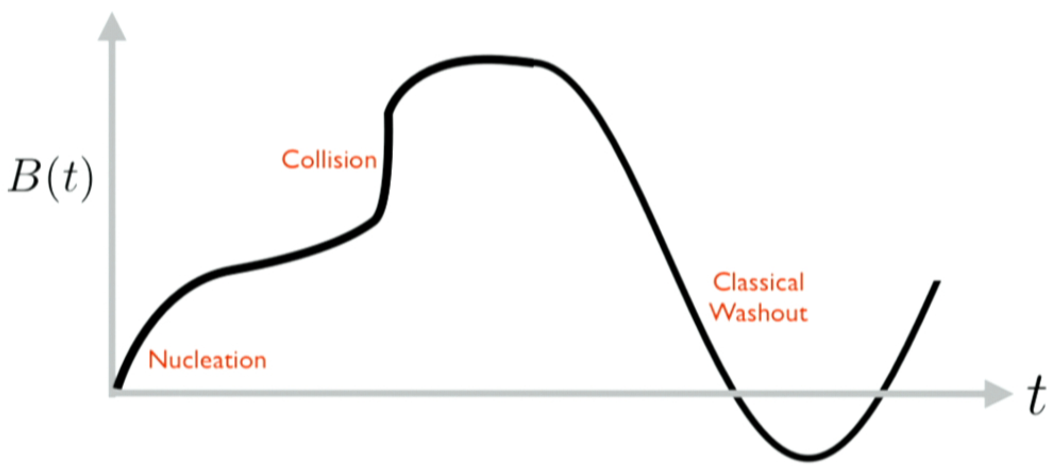
Two ways:

- Percolation after reheating: via couplings of the scalar to the big bang plasma.
- Percolation before reheating: via couplings of the scalar to the inflaton field.

M. Dine, L. Randall, S. Thomas [hep-ph/9507453]

Summary of requirements

- Asymmetry: B and CP violating terms in the potential must arc the instanton solution and accommodate the observed baryon asymmetry.
- Percolation: The potential must admit a percolating first order phase transition so that the universe today has been fully converted to the B-symmetric vacua.
- Washout: After percolation the asymmetry must persist; any washout effects must be under control.
- Decays: The generated asymmetry must migrate to the standard model sector.



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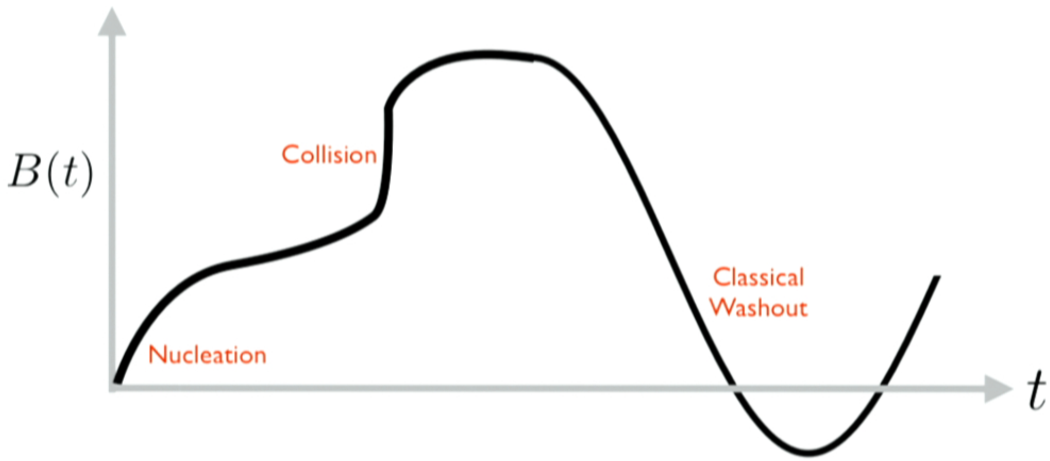
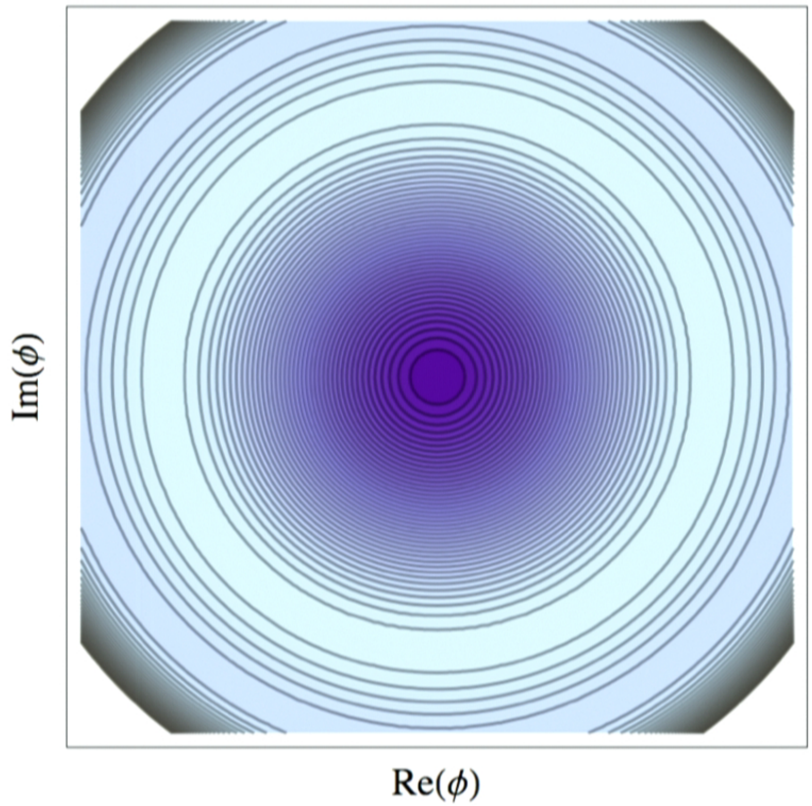


The Asymmetry

$U(1)_B$ symmetric and CP conserving potential:



$$\theta \xrightarrow{B} \theta + \text{const}$$

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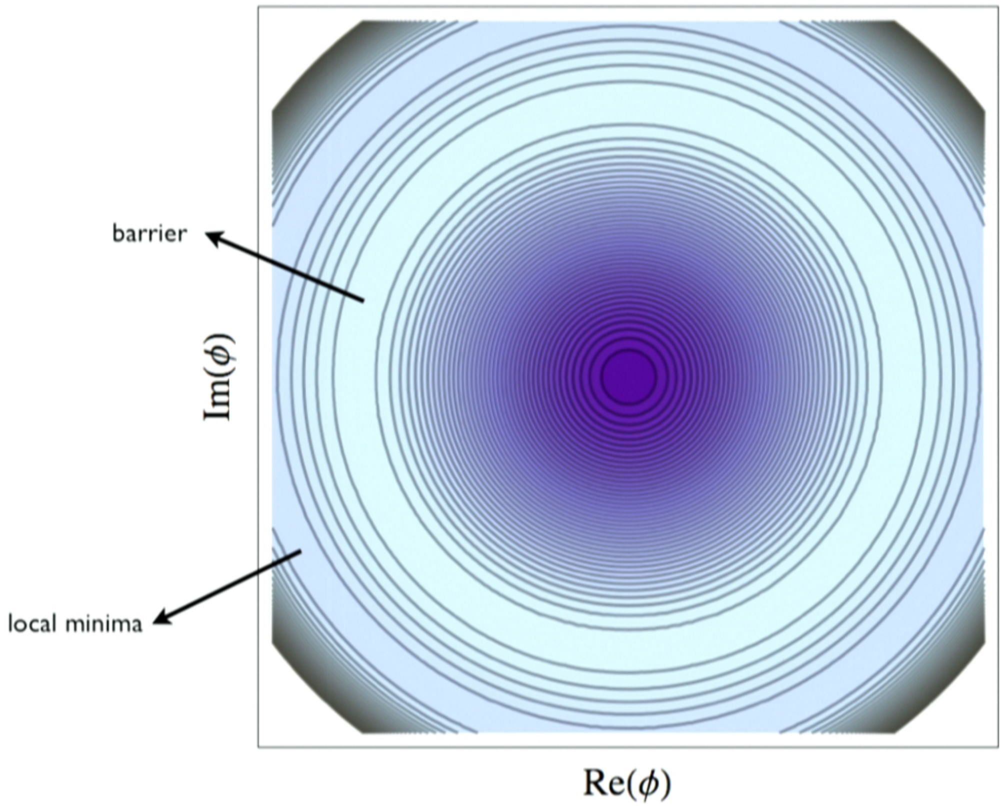

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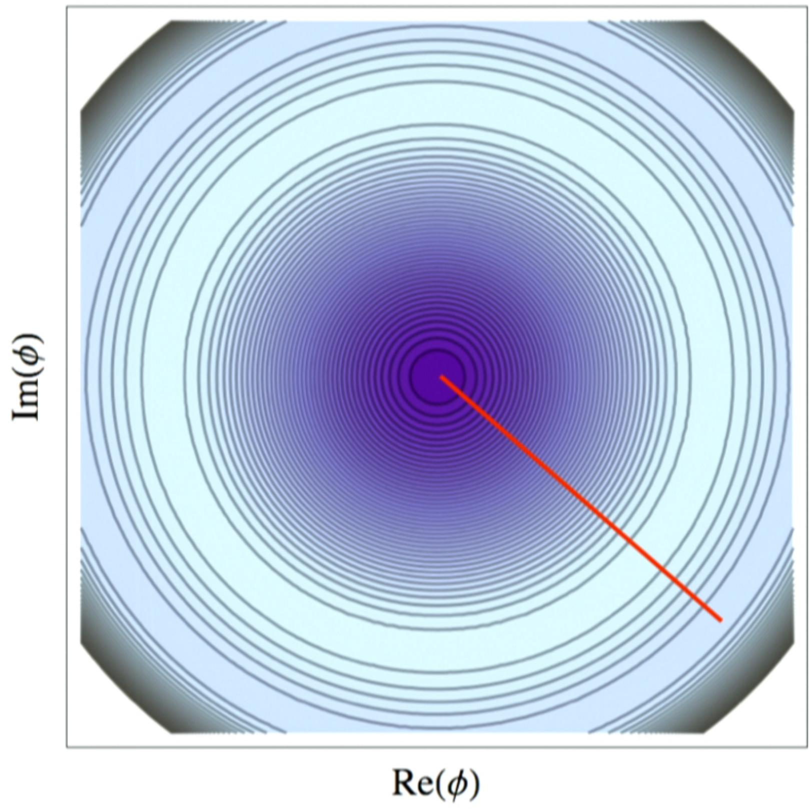

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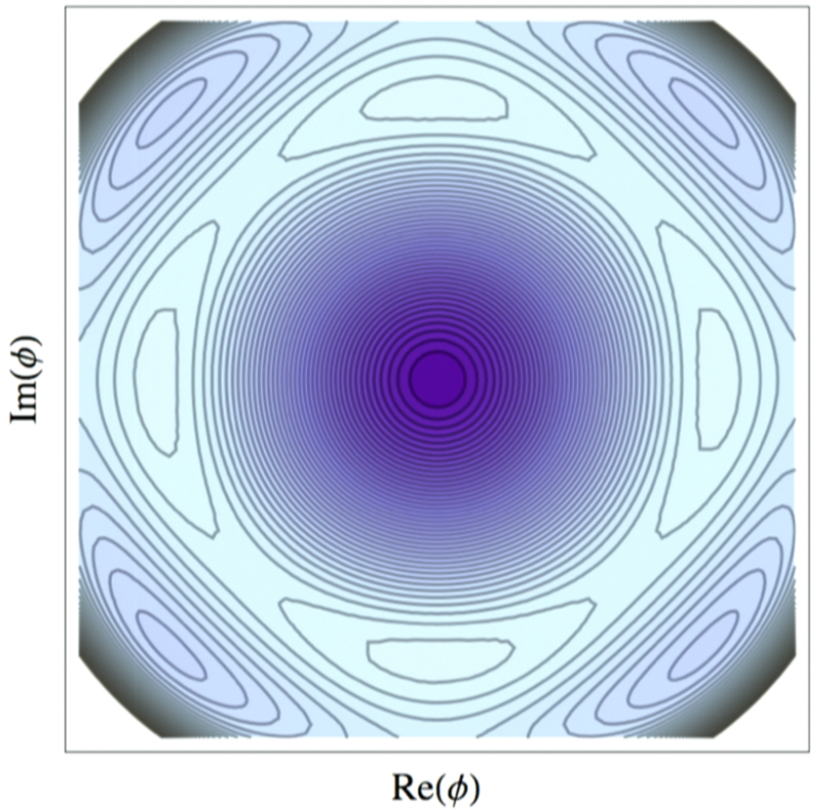
Radial bounce $r^2\dot{\theta} = 0$ ⟶ No baryons

How to get "curvey" bounces:

$U(1)_B$ violating and CP conserving: $\frac{dV}{d\theta} \neq 0$ e.g. $\phi^2 + \phi^4 + \mathrm{h.c.}$



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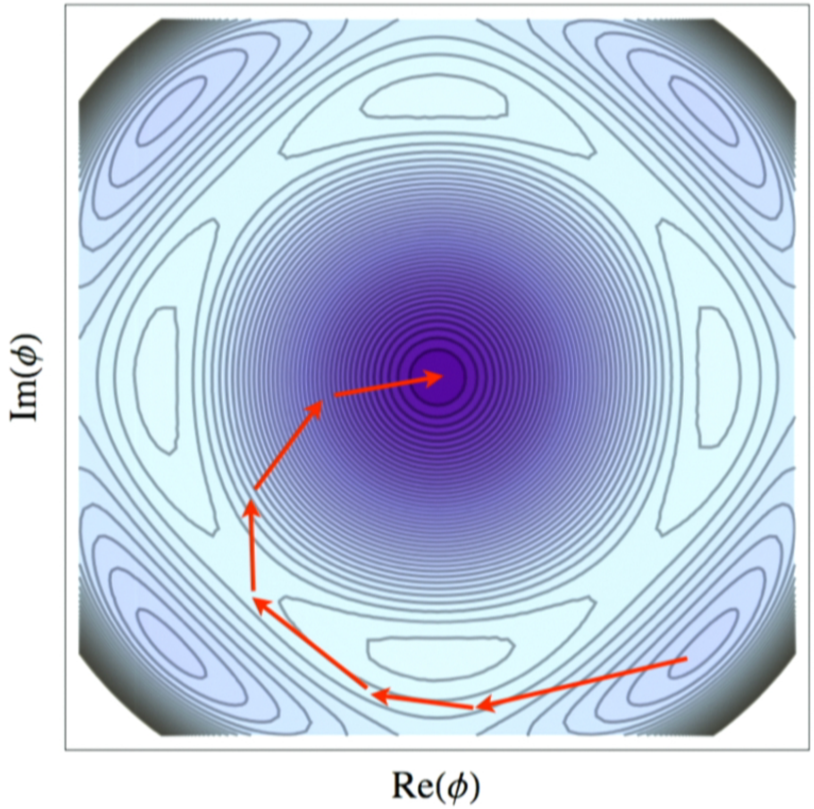

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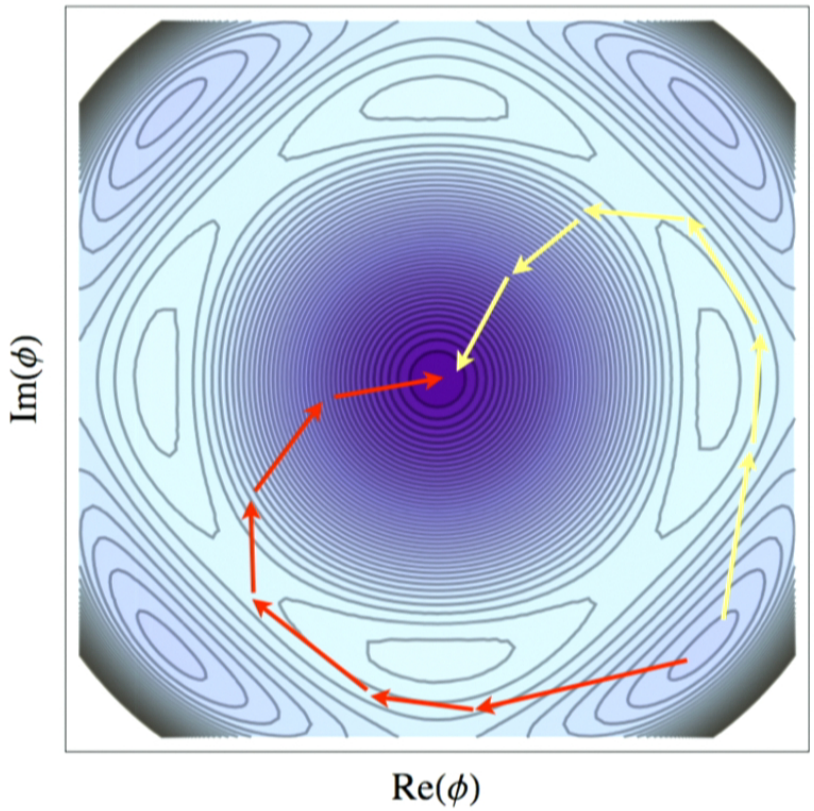

Curvey bounces possible... but will be cancel

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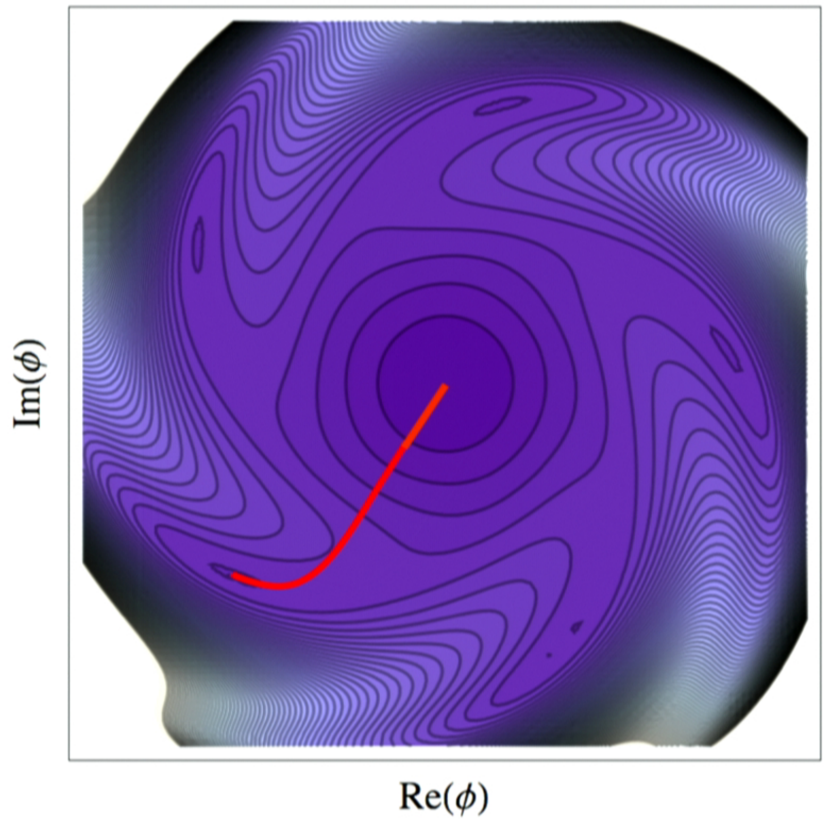

Asymmetry in the Bubble Walls

Total charge of the inhomogeneous scalar field is identified with baryon number

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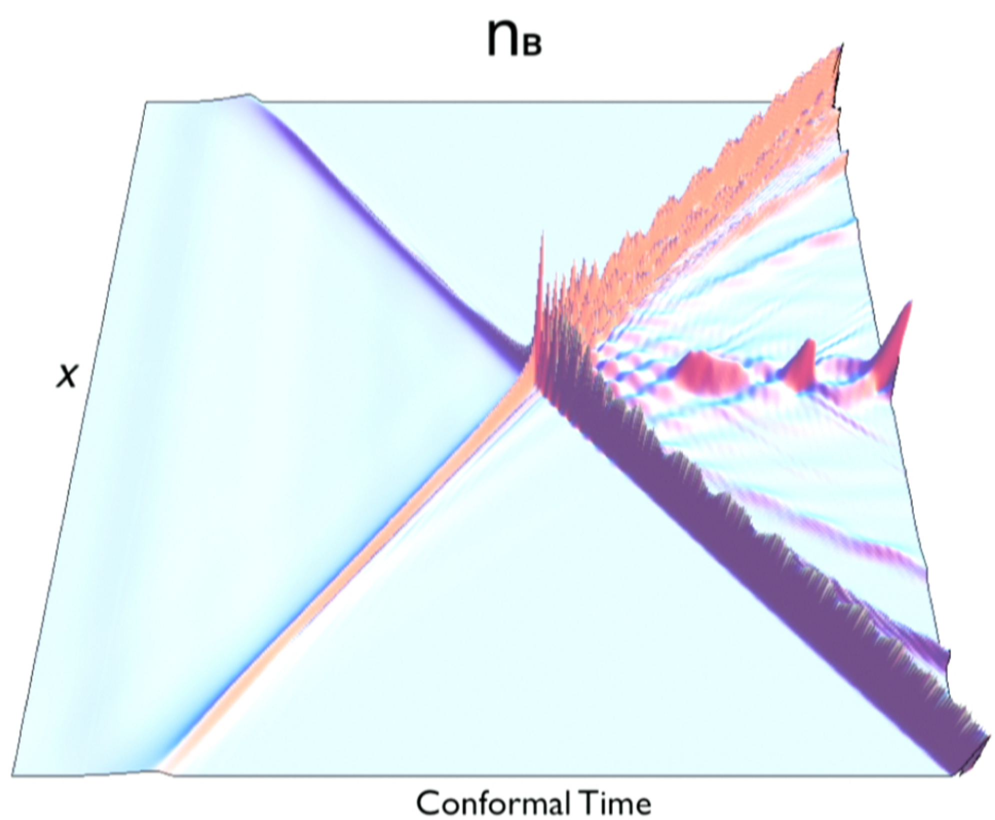
Note: no asymmetry is generated if only a single bubble nucleates

Baryon number density vanishes $L \to \infty$ Need many bubbles i.e. percolation

Simulated spacetime evolution of bubble walls:



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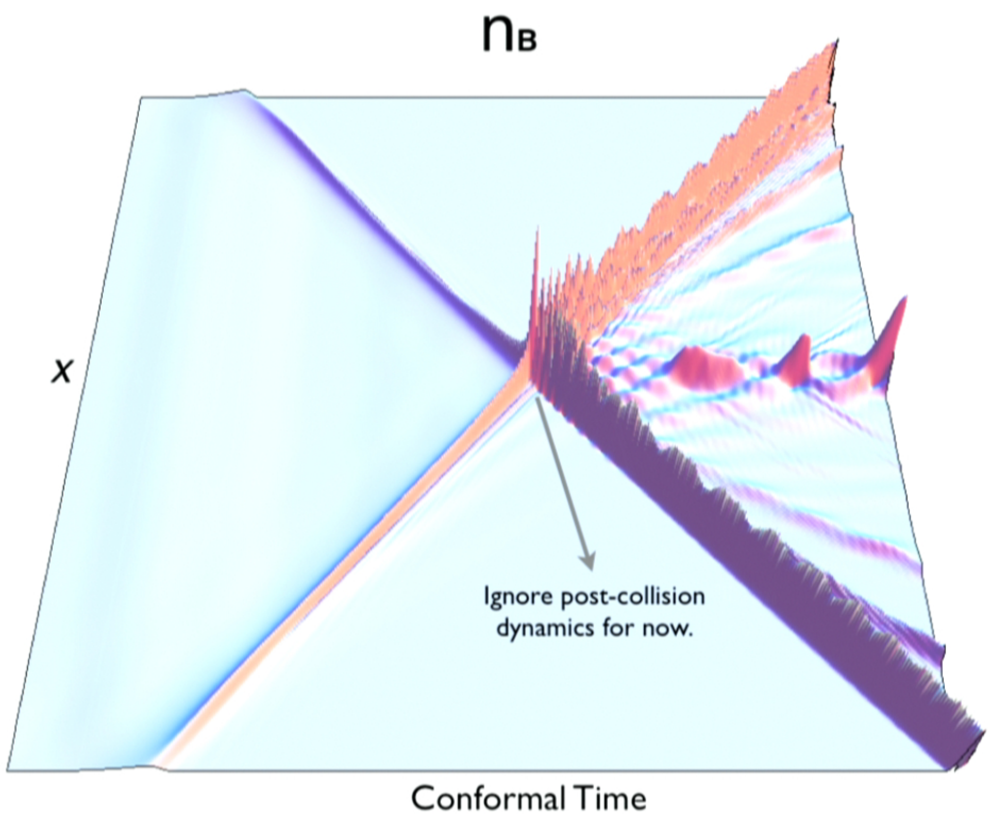

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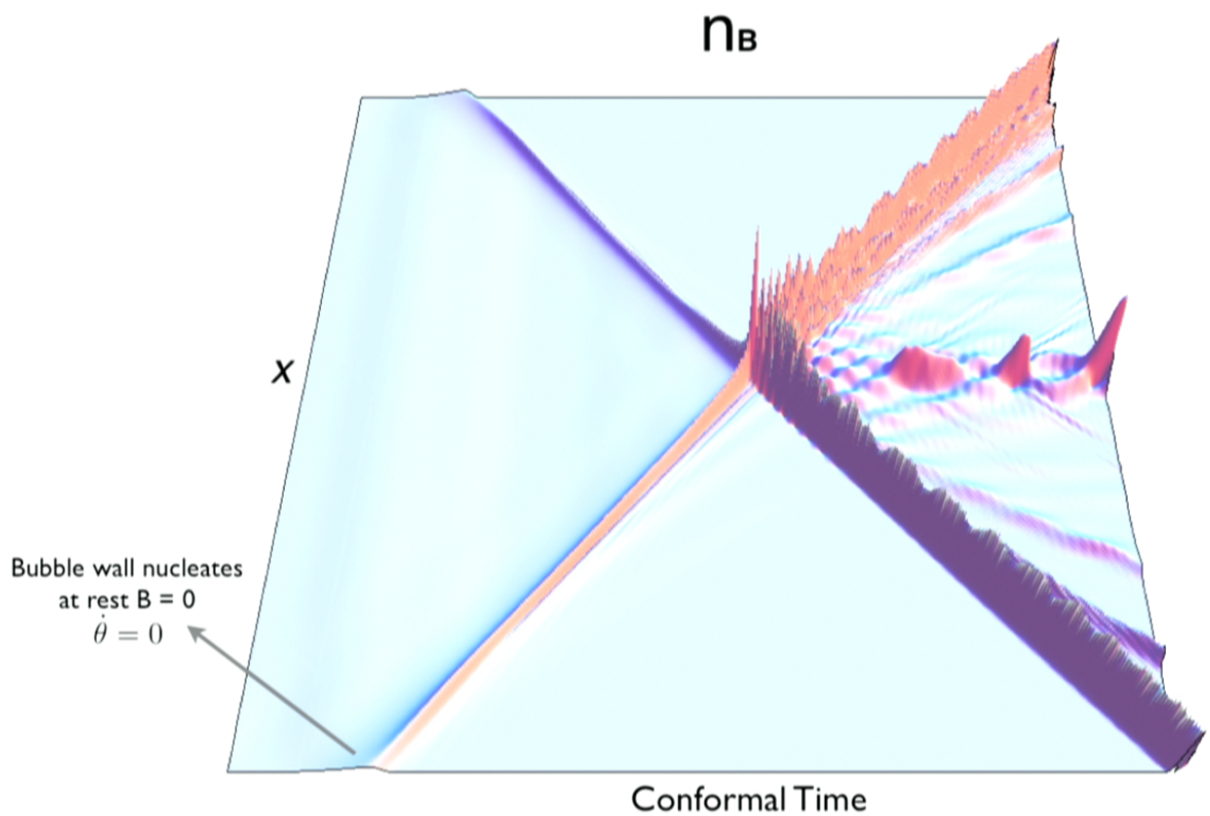
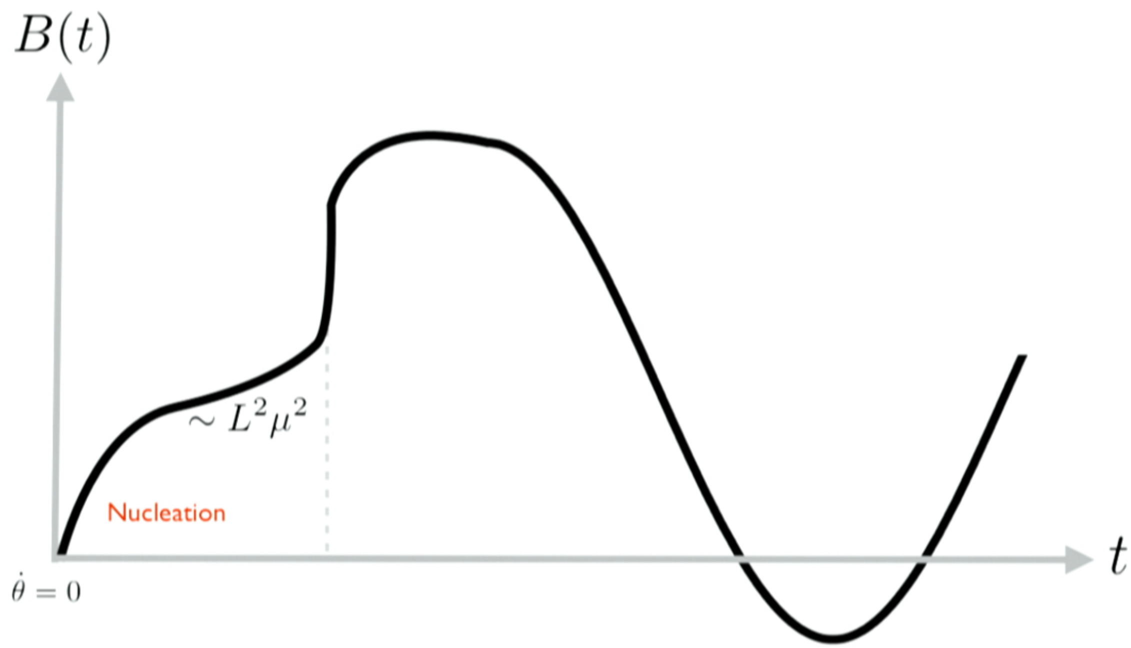
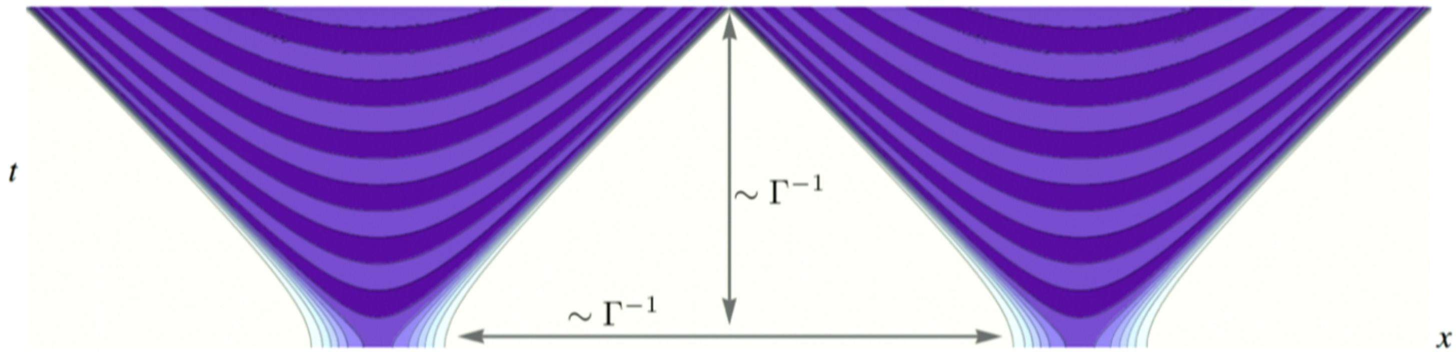



$B(t)$
$\sim L^2\mu^2$
Nucleation
t
$\dot{\theta} = 0$



Bubbles approximately expands to a volume ~ $1/\Gamma^3$ before colliding again:

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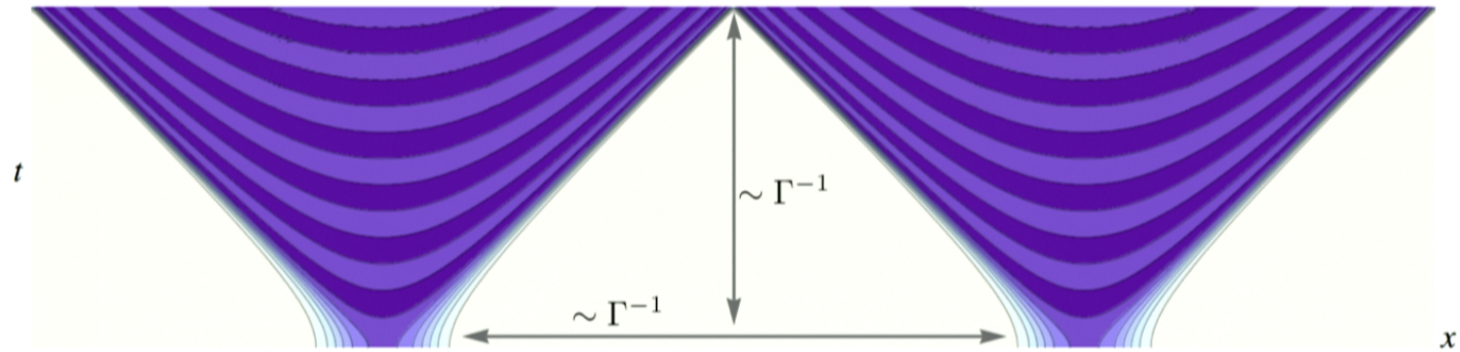

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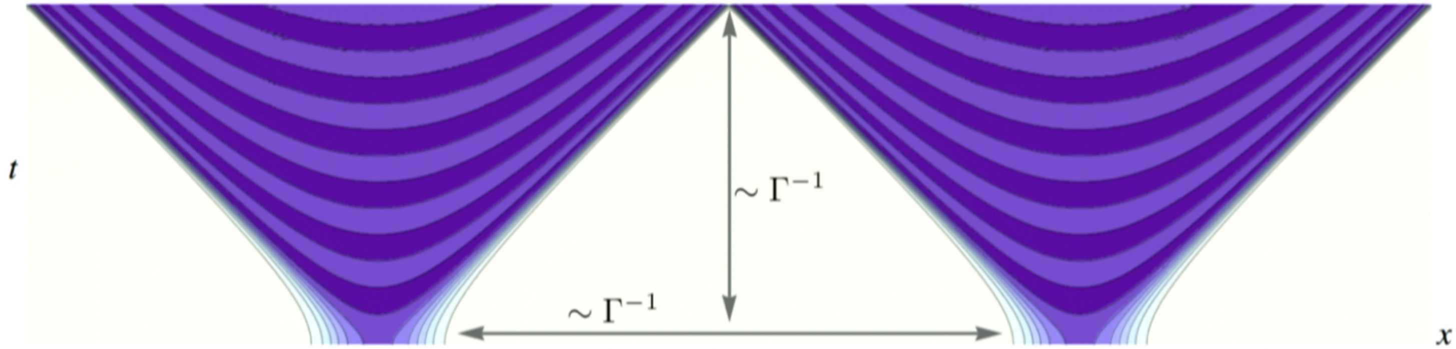

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At percolation there is on average one bubble wall stretched across each Hubble volume.

$$n_B \propto e^{-\Delta S} \sim H_\star$$

Percolation

Dynamics of the moment of collision:

Colliding walls are fast moving and very thin; they cross are very short time scales

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\phi''}{a(t)^2} = -V'(\phi)$$

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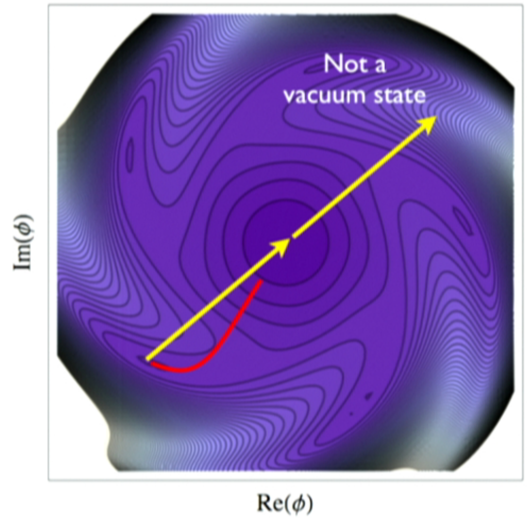
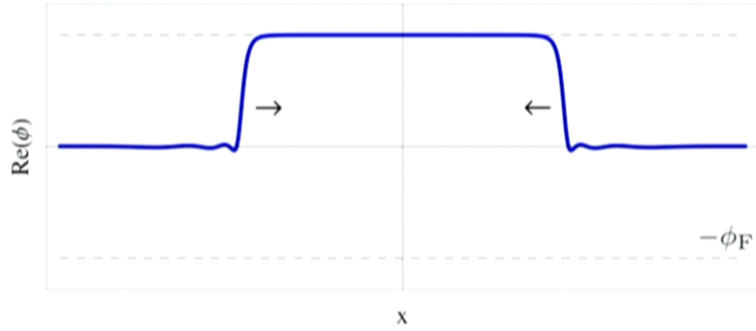


Profiles at a fixed time:

Pre collision: two walls accelerating towards each other



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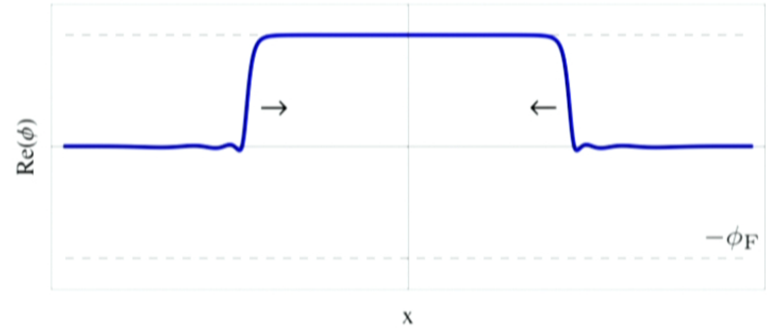
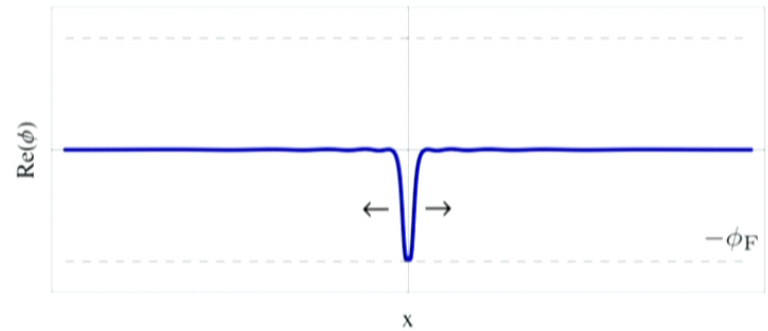


The moment of collision: field is thrown to other side of the potential.

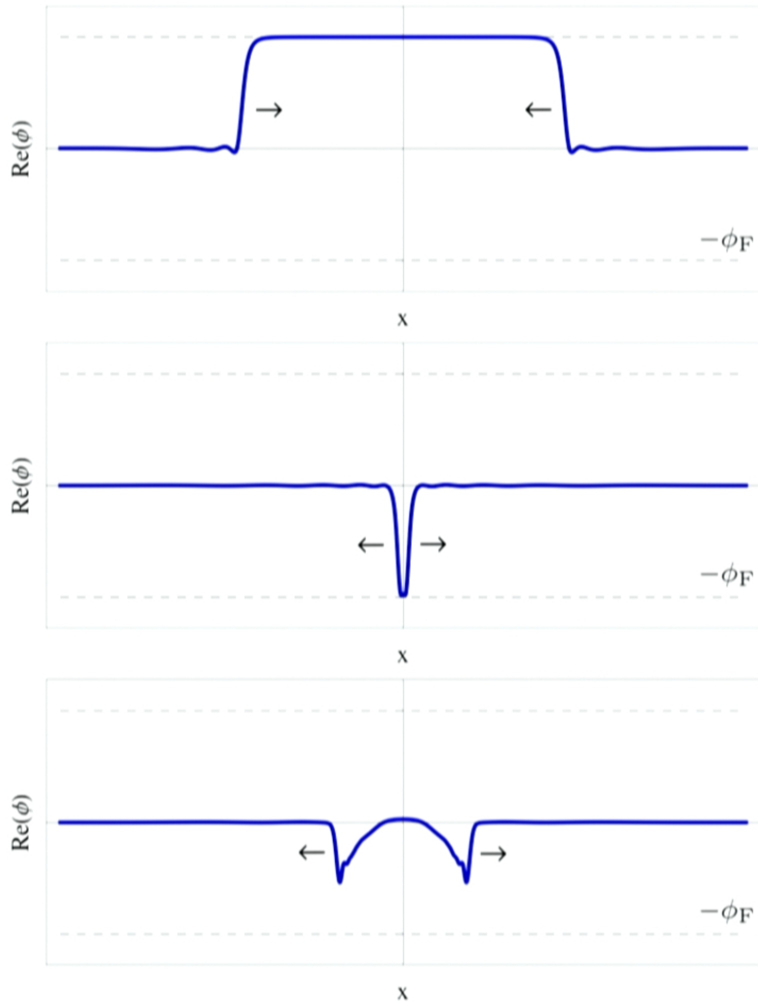


Profiles at a fixed time:

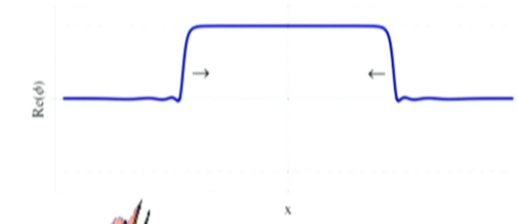
Pre collision: two walls accelerating towards each other

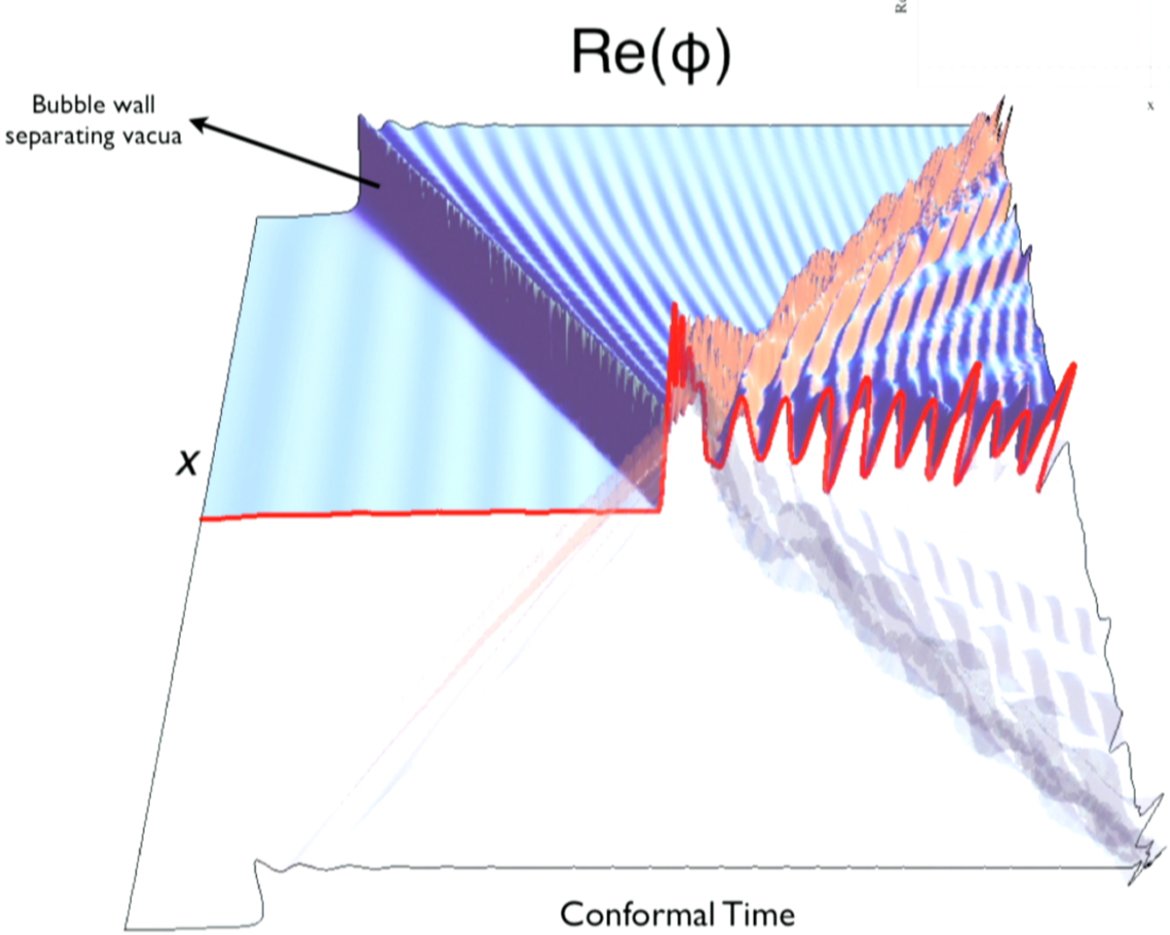
The moment of collision: field is thrown to other side of the potential.

Post collision: superposition no longer holds and field oscillation about the true minimum.



Simulated collision and subsequent field oscillations:





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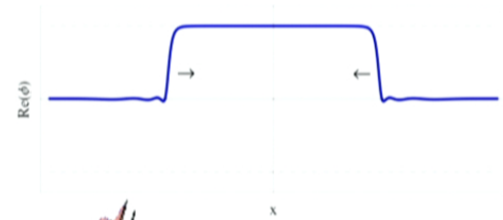

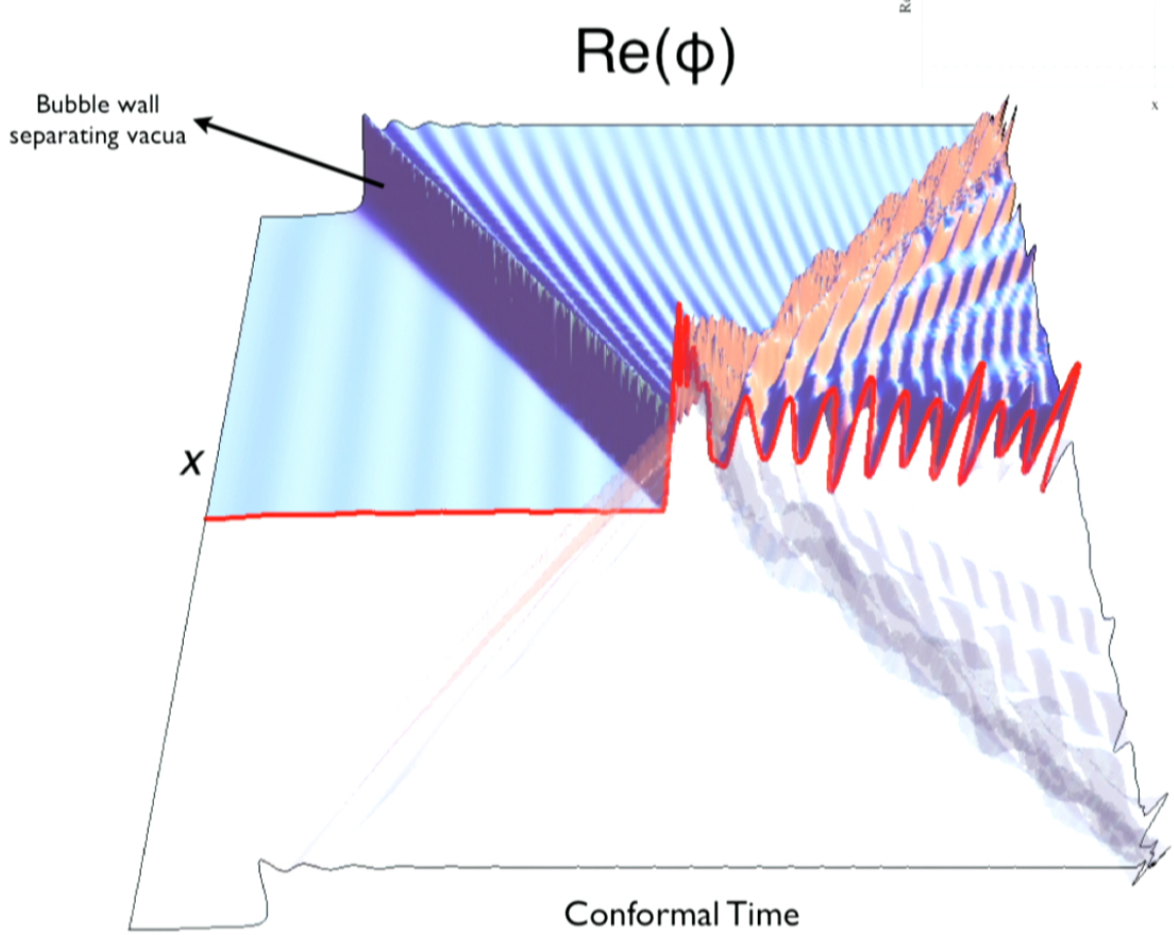

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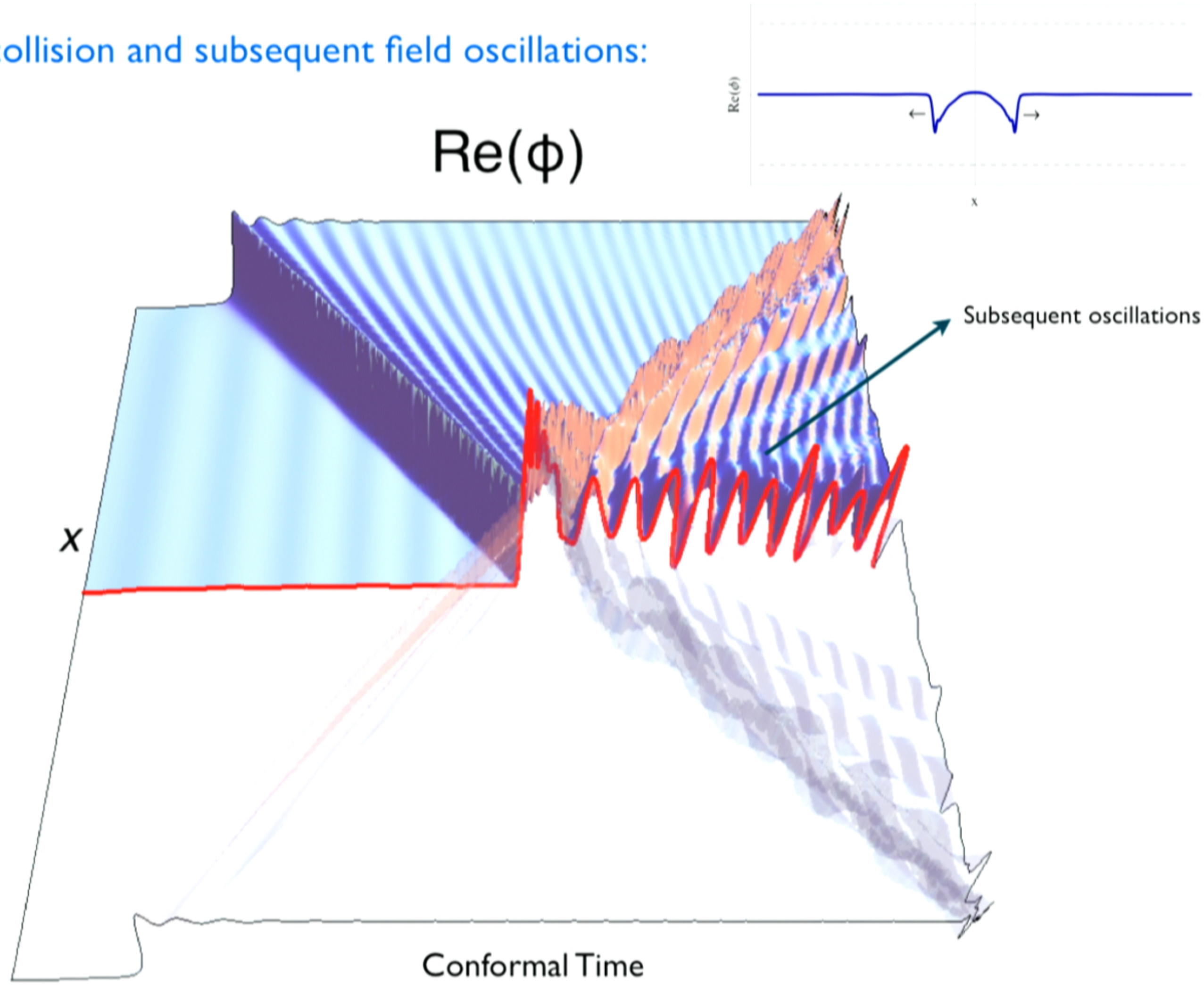
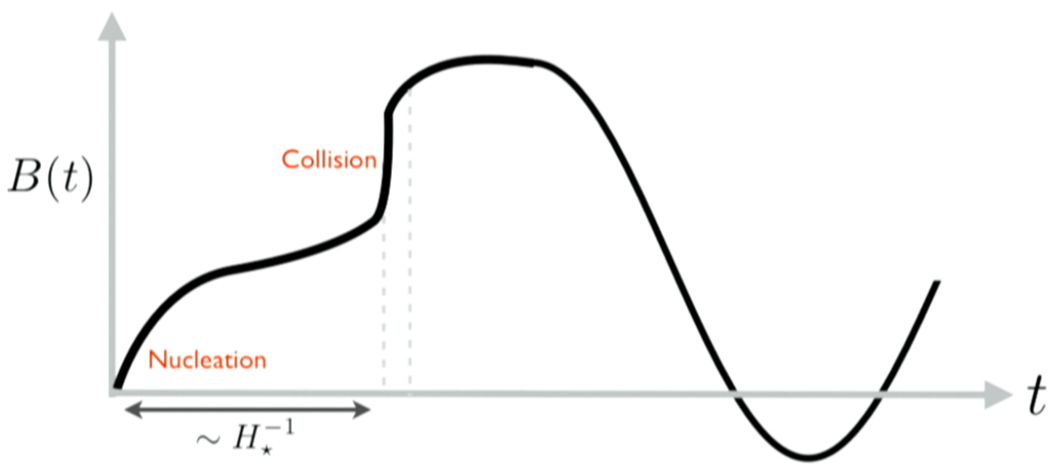


Field is back in a B-violating region - additional asymmetry generation via localized Affleck-Dine.

Baryon number generated by the collision:

Field at the collision site has been "thrown" back to a B-violating region of the potential resulting in a localized Affleck-Dine condensate forming and dissolving at the collision site.

Affleck-Dine mechanism: $n_B^{AD} = r^2\dot{\theta} \sim r_F^2 \epsilon m$



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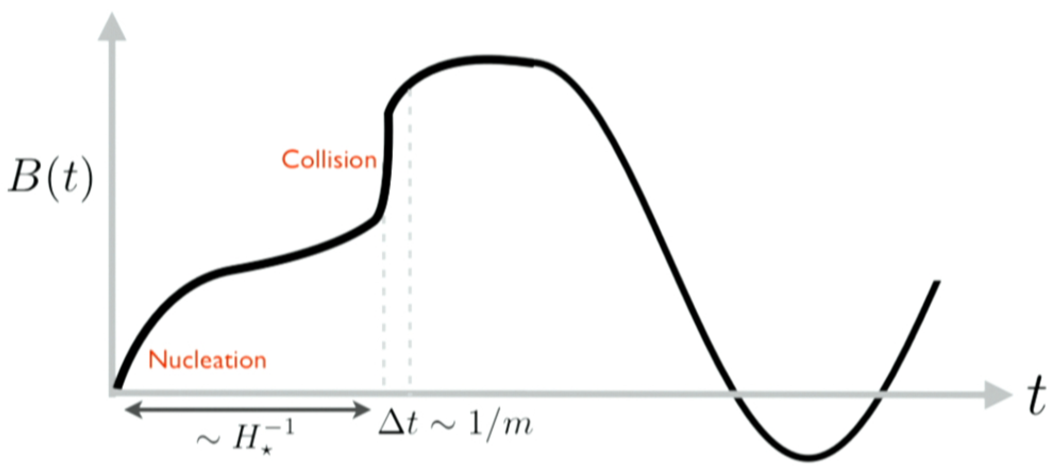
Time it takes the field to evolve from $-\phi_F$ to zero aka the spatial width of the condensate.

$$n_{B,\text{collision}} \sim n_B^{AD}\left(\frac{V^{\text{Mini AD}}}{V}\right) \sim \epsilon r_{\text{F}}^2 m \times \frac{\Delta t H_*^{-2}}{H_*^{-3}} \sim \epsilon r_{\text{F}}^2 H_*$$



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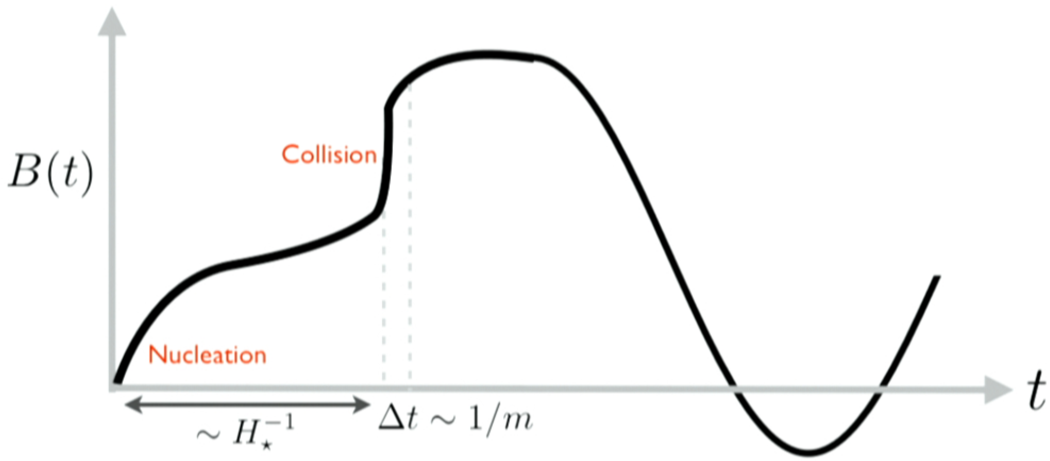
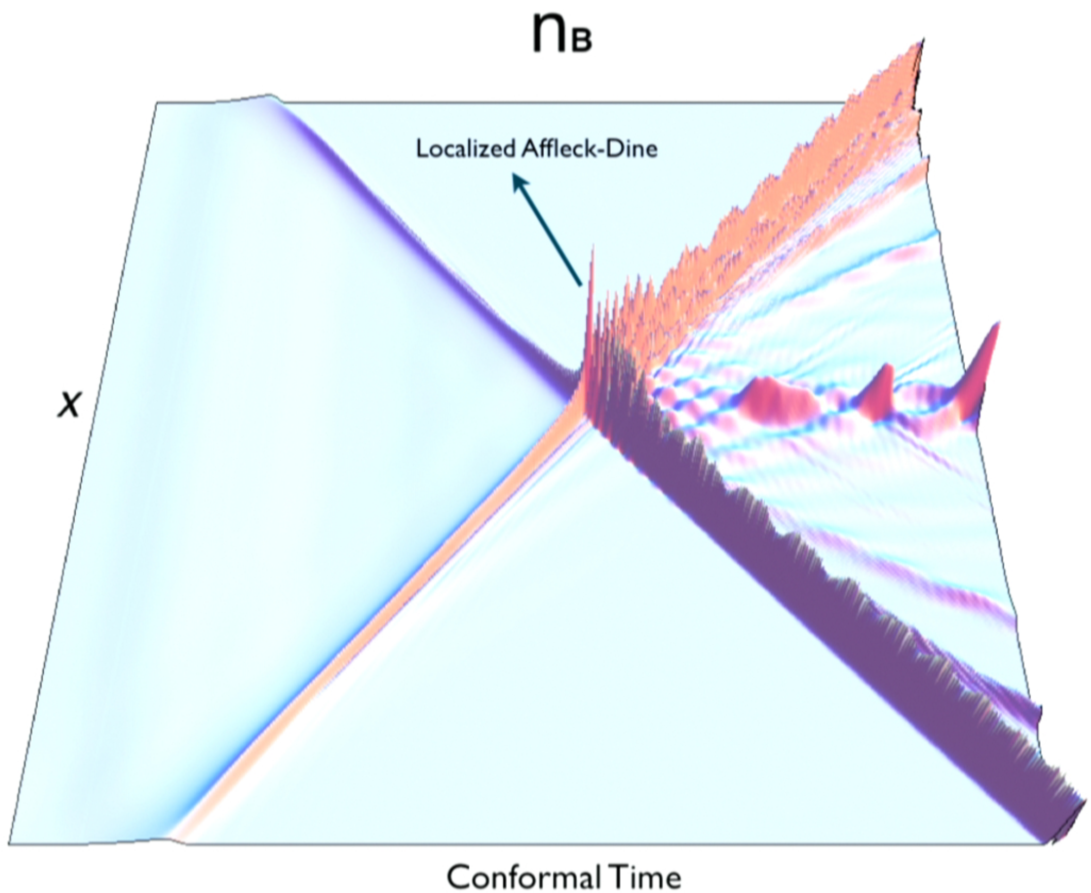
$$\Rightarrow \quad n_{B,\text{instanton}} \sim n_{B,\text{collision}} \sim \epsilon r_{\text{F}}^2 H_*$$



Corresponding baryon number density: $n_B = n_{B,\text{instanton}} + n_{B,\text{collision}}$



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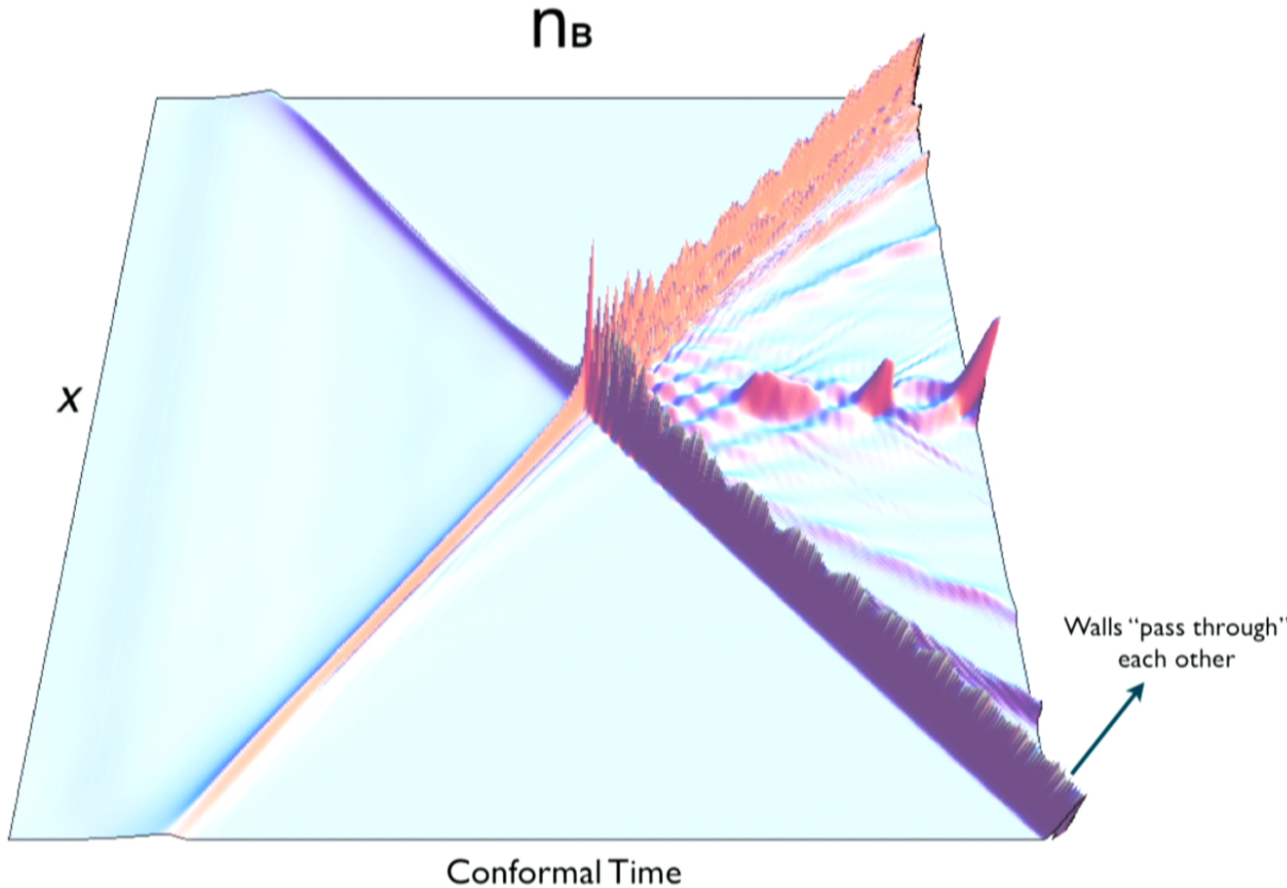

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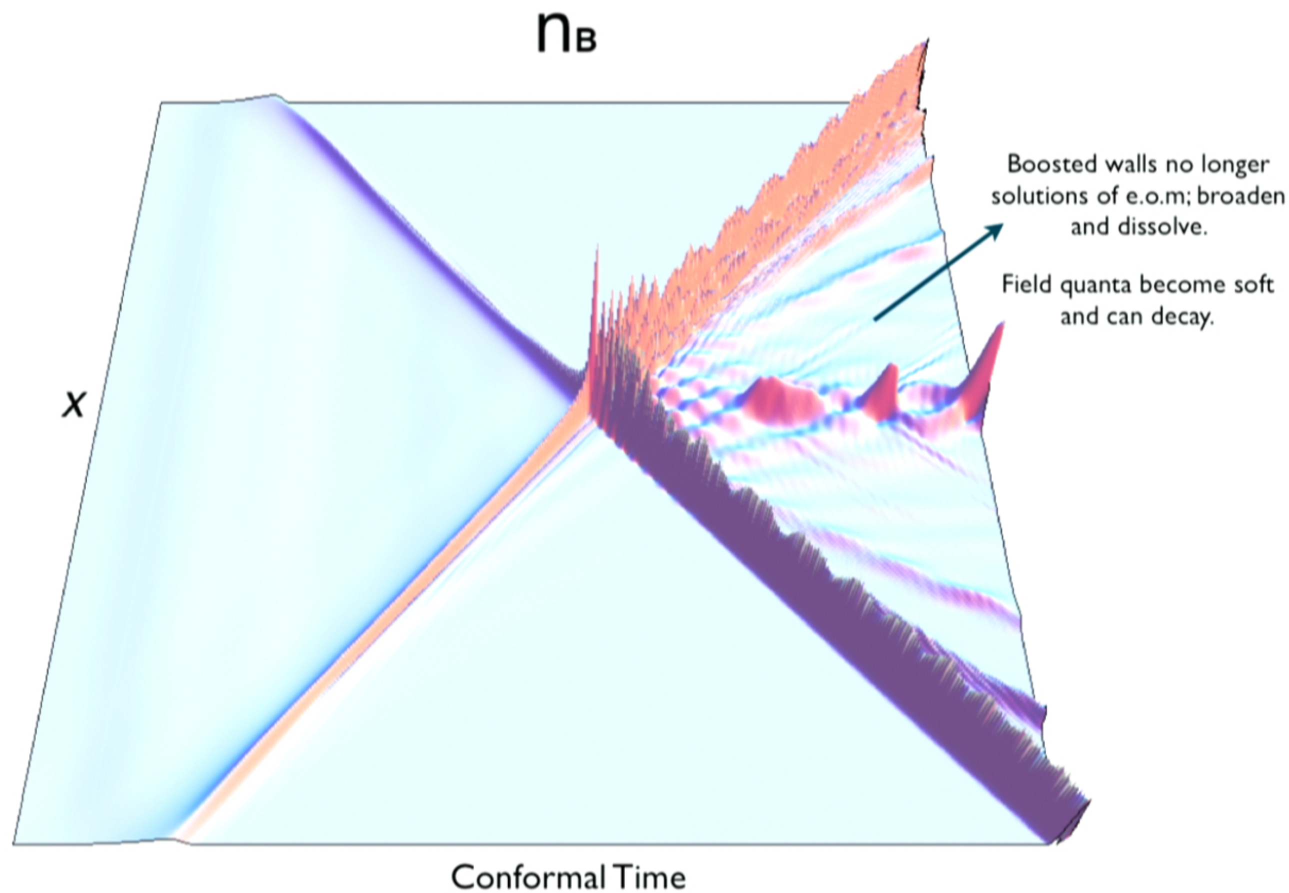


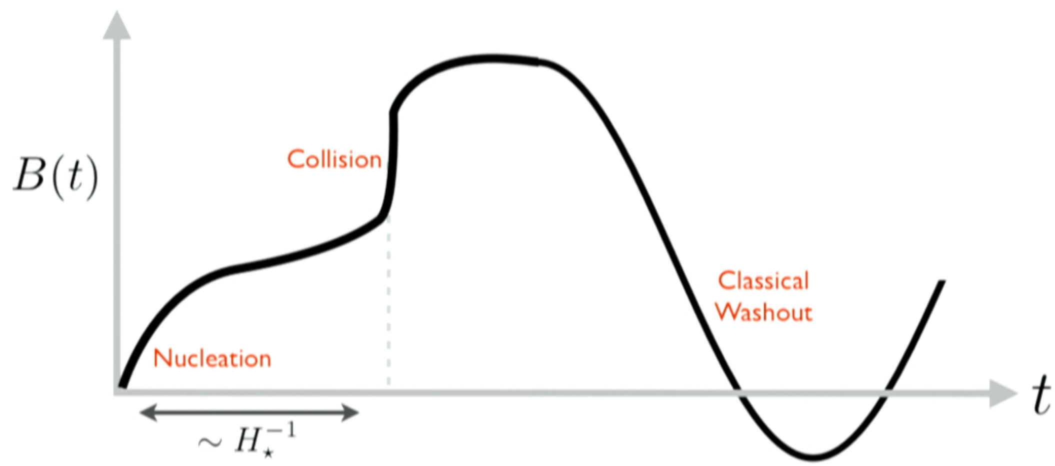
Washout and Decay

Model dependent classical washout effects can be avoided

$$V \subset m^2 \left(|\phi|^2 + \epsilon \phi^2 + \text{h.c.} \right)$$

(higher dimensional operators have even less of an effect)

Induces an "ellipticity" to the potential which splits the mass eigenstates causing the field to precess as it orbits the origin. Baryon asymmetry oscillates around its initial value.



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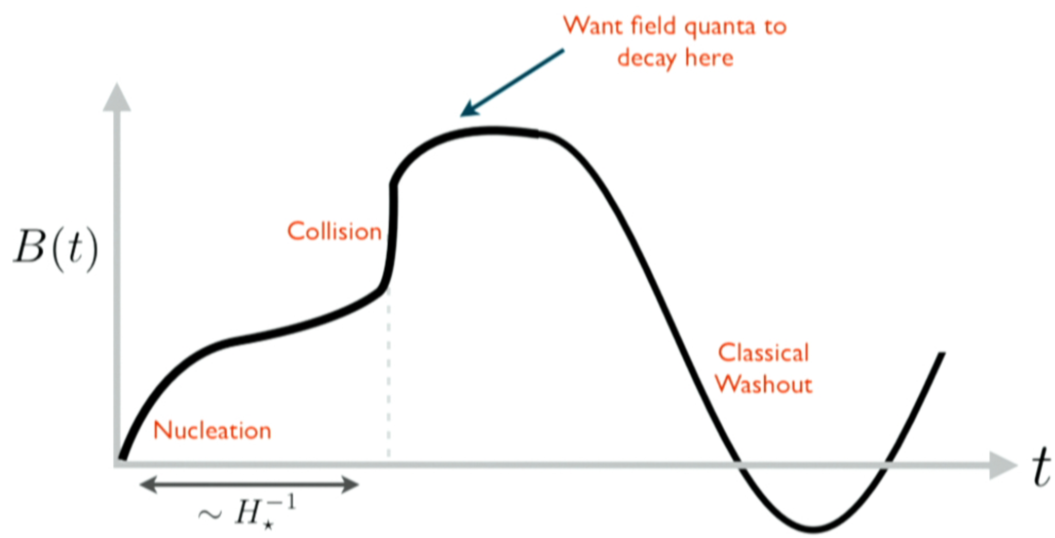

The Potential

Treat B and CP violation as small perturbation: $V(r,\theta) = V_0(r) + \epsilon V_1(r,\theta)$

B and CP symmetric: $$V_0 \;=\; m^2|\phi|^2 - A|\phi|^3 + \lambda|\phi|^4$$

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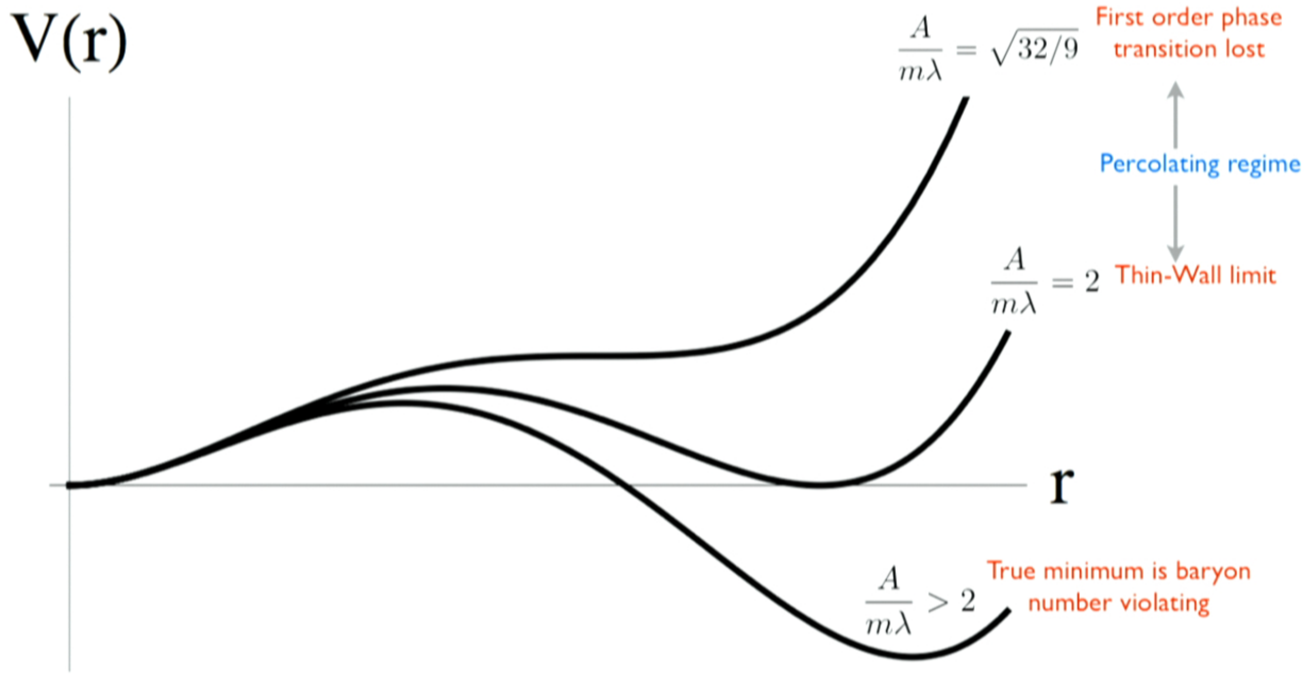
Couplings to the inflaton result in a time-varying potential (like Affleck-Dine)

e.g. susy $K \subset \frac{|\chi|^2|\phi|^2}{\Lambda^2}$ $\rho = |F_\chi|^2 = 3H^2 m_{Pl}^2$ Inflaton energy density

$$\Longrightarrow \quad m^2 = \tilde{m}^2 - \frac{3H^2 m_{Pl}^2}{\Lambda^2}$$

$U(1)_B$ is spontaneously broken at early times but restored in the present day: $\Lambda^2 > 0 \;\; \tilde{m}^2 > 0$

Cosmological History



B and CP violating terms

Numerical check: $n_B \sim \mu^2 H_\star \sim \epsilon r_F^2 H_\star$ with $\mu^2 = \int r^2(\rho) \frac{d\theta(\rho)}{d\rho} d\rho$

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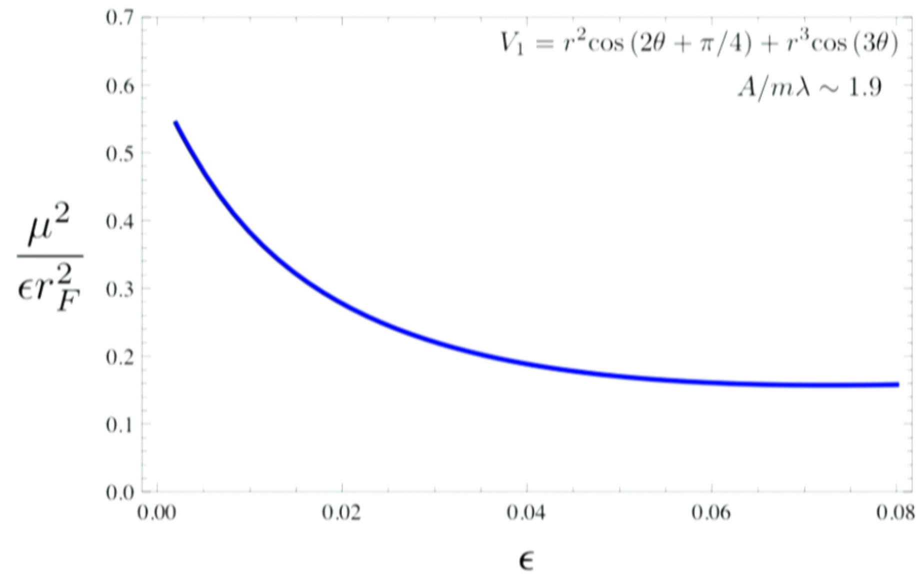

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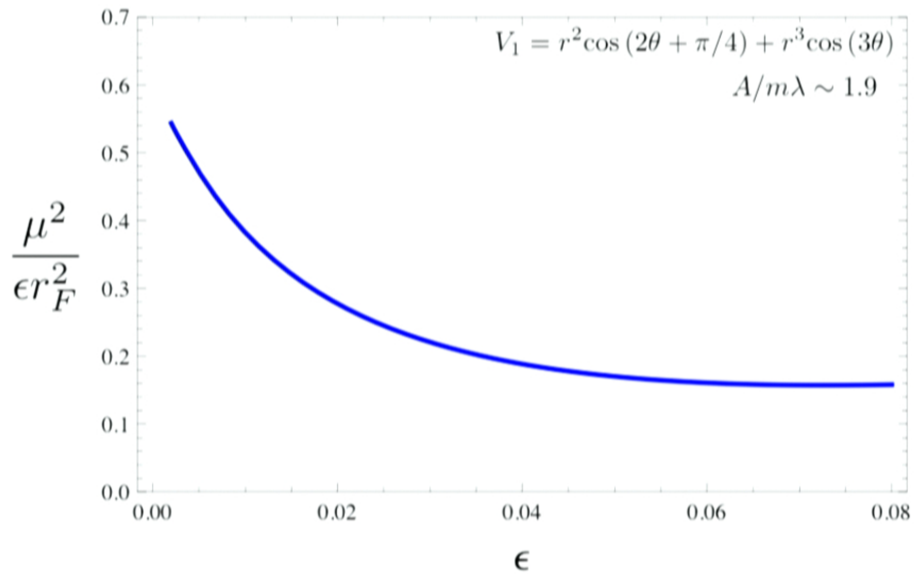

Assume:

- B violation is sourced by the inflaton alone; B violating operators shut off after the inflaton decays and thus thermal washout is evaded.
- At least two B breaking operators are required otherwise all CP phases can be removed by a field redefinition.

The Asymmetry

Compute the asymmetry: $n_{B,\mathrm{instanton}} \sim n_{B,\mathrm{collision}} \sim \epsilon r_{\mathrm{F}}^2 H_*$

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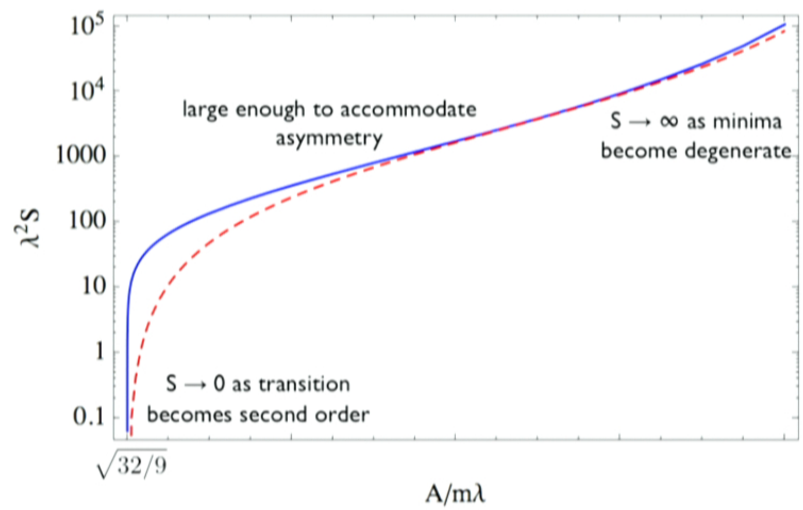

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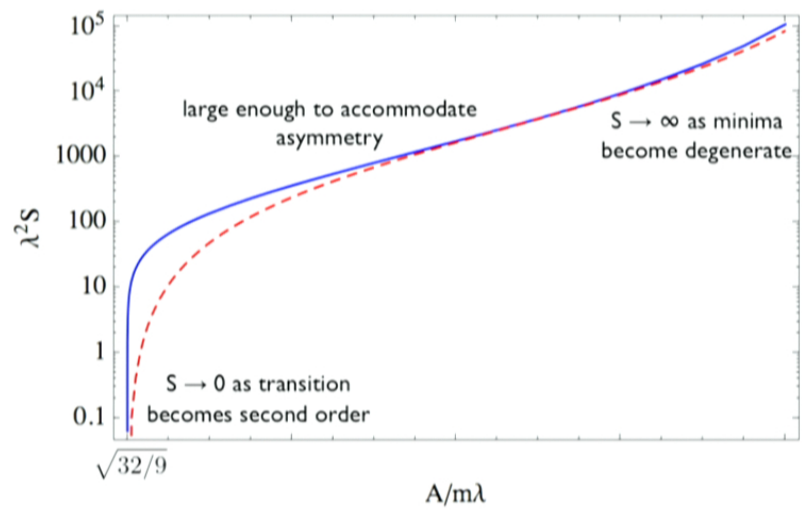
Numerically compute the symmetric Euclidean action from field profile at a given time in the cosmological evolution. Then solve for the value of the model parameters at percolation.

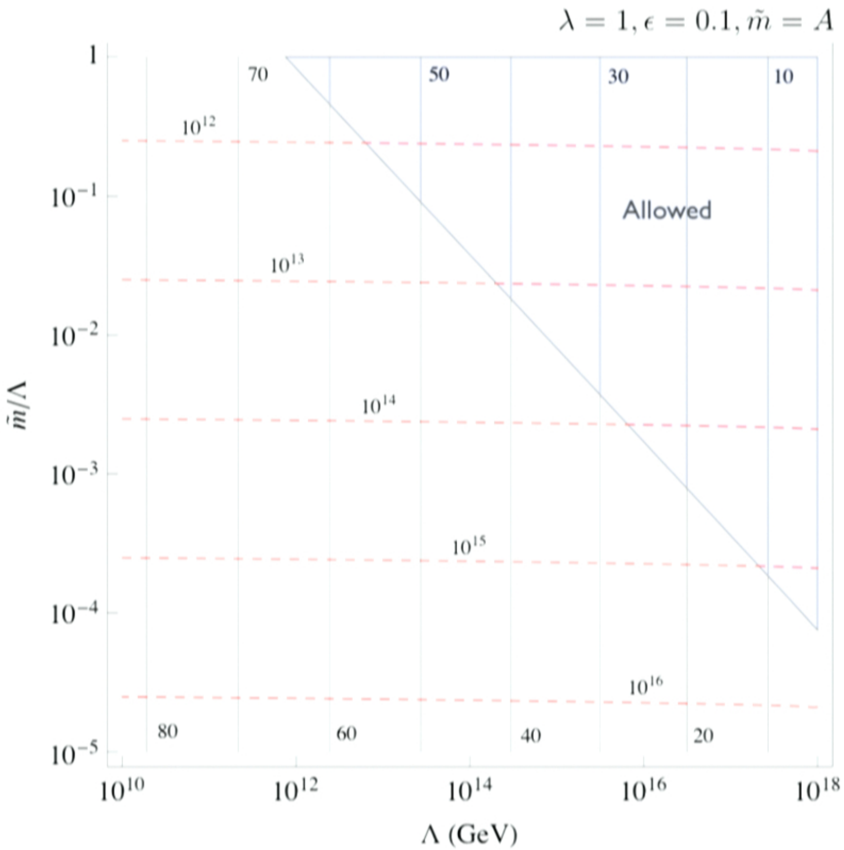
Reheating occurs after percolation; the asymmetric yield at the time of reheating is:

$$\eta_B \equiv \frac{n_B}{s_R} \frac{H_{\text{R}}^2}{H_*^2}$$
$$\propto \frac{\epsilon m_* T_{\text{R}}}{\lambda^2 m_{\text{Pl}} \Lambda \sqrt{\tilde{m}^2/m_*^2 - 1}}$$

For a given point in parameter space, requiring $\eta \sim 10^{-10}$ fixes the reheat temperature



Parameter Space



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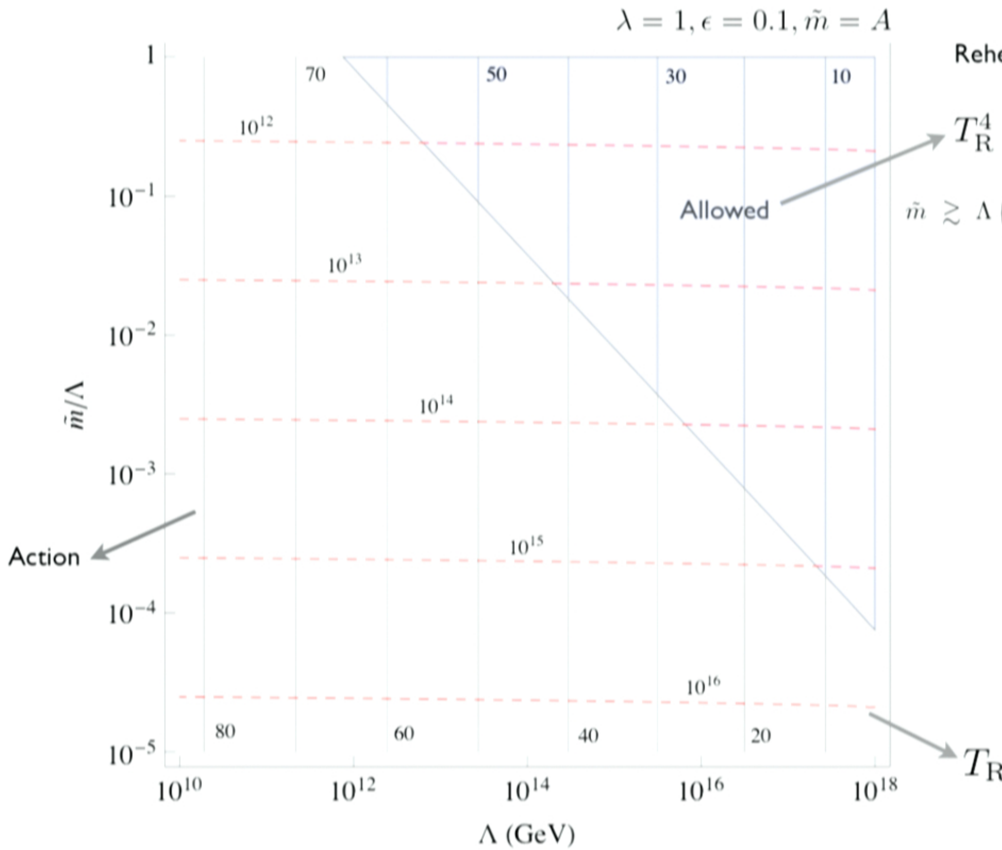

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$$T_{\rm R}^4 \sim \rho_{\rm R} \lesssim \rho_*$$

$$\tilde{m} \gtrsim \Lambda \left(\frac{10^{10}\ {\rm GeV} \times \lambda^2}{\epsilon \Lambda} \right)^{2/3}$$

Fast decays and washout

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New scale M is essentially a free parameter; at percolation decay rate can easily be much greater then Hubble.

→ The field within each nucleated bubble decays shorty after percolation thus minimizing classical washout.

Note: the asymmetry can of course be converted to a lepton number asymmetry:

$$\phi L H_u \quad \phi LLE \quad \phi QLD$$

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→ All the necessary ingredients for Bubble Baryogenesis

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Need to solve for multi-dimensional instanton profile. Defer to future work for now.

Observations and Signals

The presence of bubble collisions open up a variety of possible signals which may not exist in other mechanisms of baryogenesis

- Gravitational Waves produced by bubble collisions: Since colliding bubbles are roughly the same size, the spectrum will have a spike at $H_\star$ Still will be difficult to see since most of the energy density of the universe is from the inflaton.

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Future Directions

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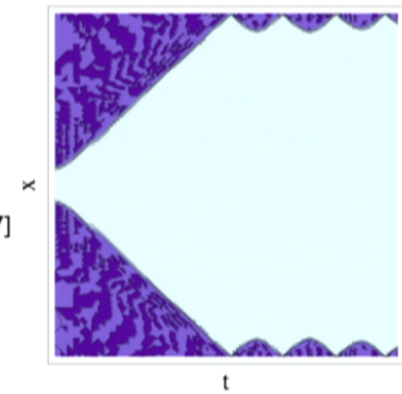

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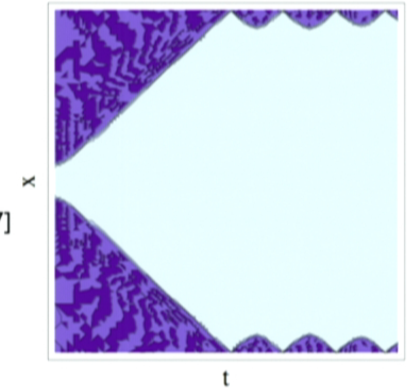

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Thank You