Title: Experimental Cosmology

Speakers: Matthew Johnson

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

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Experimental Cosmology

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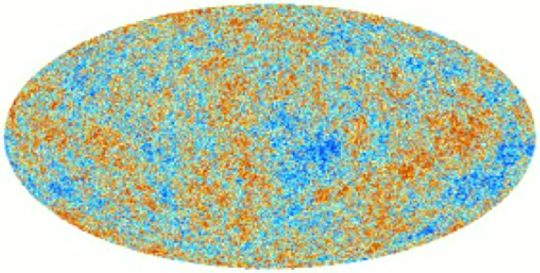
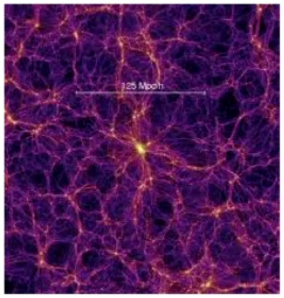
arXiv: 2204.11867, 2109.04496, 1904.07873, 1806.06069, 1712.02356

Cosmology

- Cosmology ~ archaeology. We get limited and imperfect records of the past, and have to reconstruct what happened.
- Luckily, cosmology is simple enough that we can build theories and calculate or simulate.



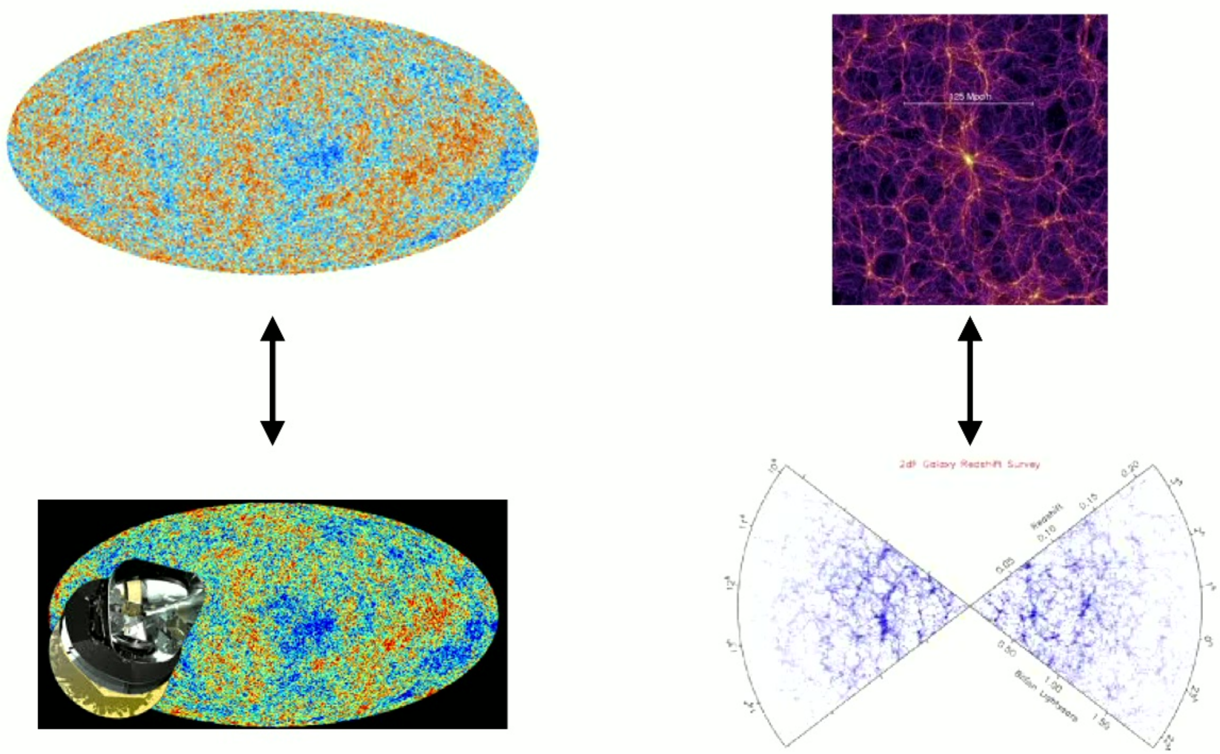
Linear theory



N-body

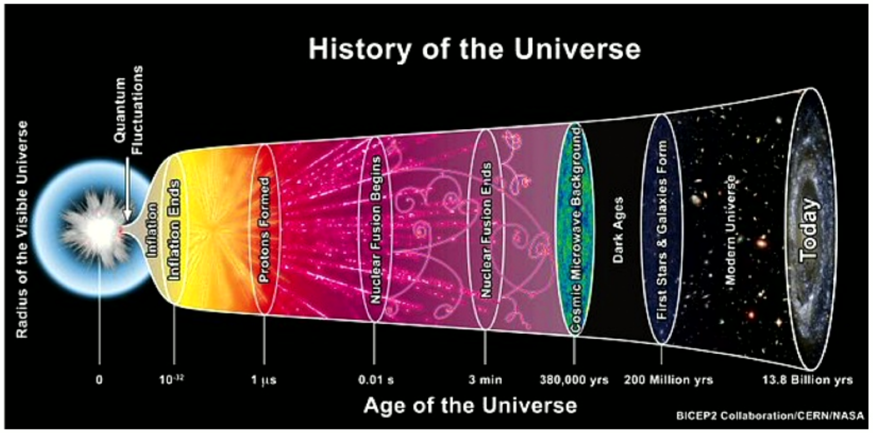
Cosmology

- Comparing with what we observe, we can iterate and learn more.



Cosmology

- Early Universe: little information left over, and unknown/new physics at play.



Cosmology

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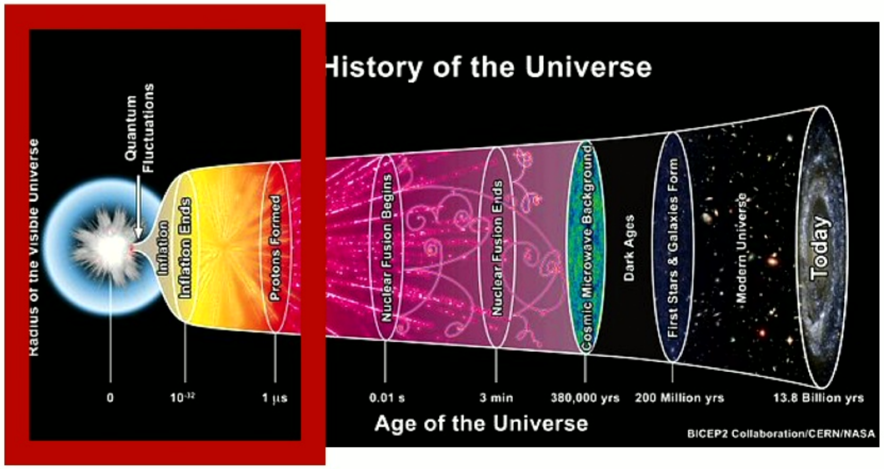
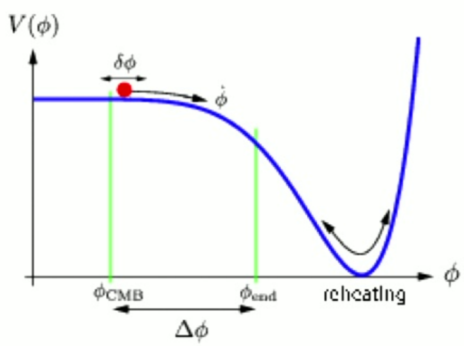
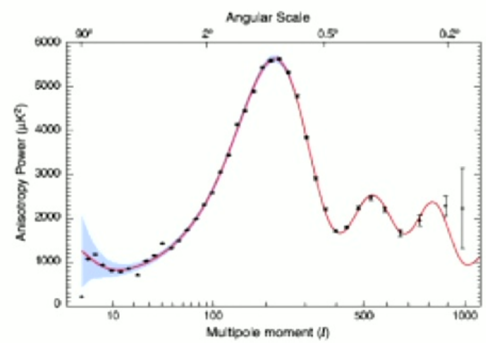


Quantum effects are important.

Quantum in Cosmology

- Easy quantum: inflationary fluctuations sourced by a field with almost no self-interactions. This is (almost) as easy as the harmonic oscillator problem in QM. Perturbation theory is a useful tool.





Quantum in Cosmology

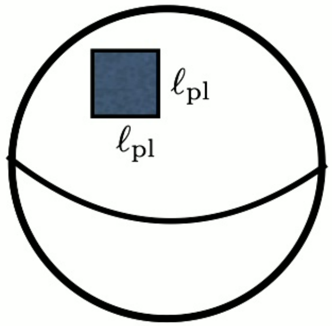
- Hard quantum: non-linear and non-perturbative phenomena, strong coupling, etc. — limited tools and limited understanding.

A few things from my corner of the Universe I'd like to understand better:

The 'theory' of de Sitter space.	Decay of metastable (false) vacua.
(I have little to say)	(I have lots to say)

de Sitter Holography

- Does the 'theory' of dS have a finite or infinite number of DOF?



$$S \sim \# \text{ of } \ell_p^2 \text{ pixels}$$
$$\sim \# \text{ of bits}$$
$$\sim 100 \text{ Tb}$$

(Inflation consistent with bound on r)

What's the Hamiltonian?

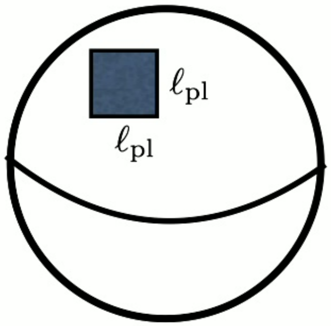
Thermodynamics of horizon -> density fluctuations?

Lots more DOF today. What about then?

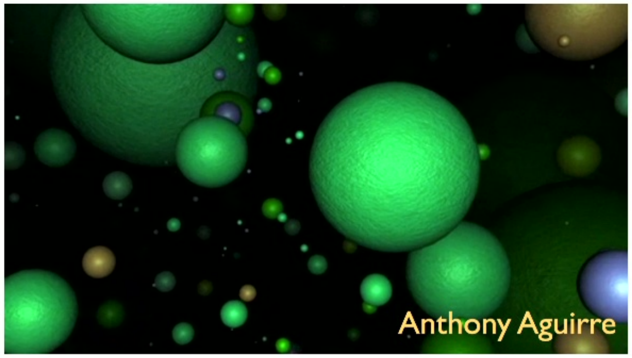
Complex mapping?

de Sitter Holography

- Does the 'theory' of dS have a finite or infinite number of DOF?



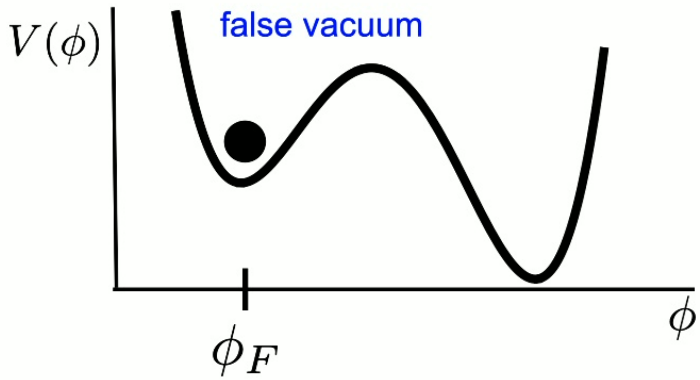
?OR?



∞ ?

Among the most important questions: can computation/simulation help?

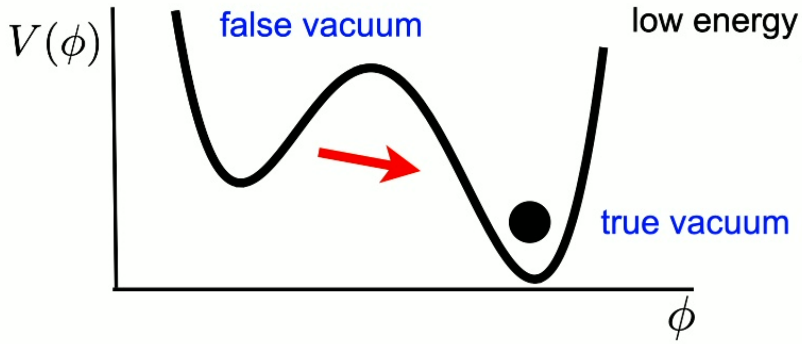
Metastable (false) vacuum decay

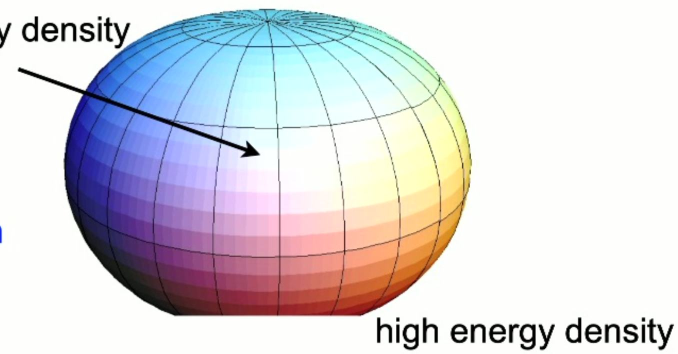


$$\mathcal{L} = (\partial\phi)^2 - V(\phi) + \mathcal{L}_{\text{other}}$$

Classically, if the field is everywhere in the false vacuum, it will remain there.

Metastable (false) vacuum decay

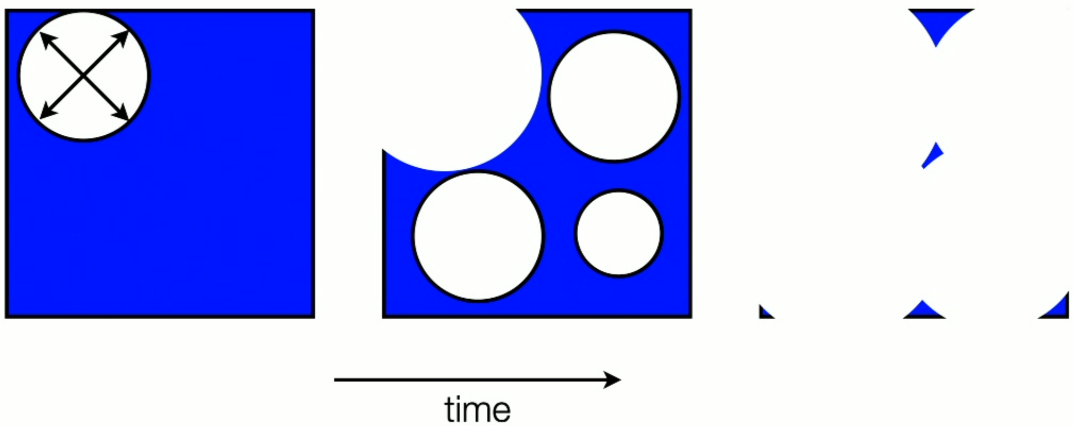




Quantum mechanically, the field can transition to the true vacuum!

Metastable (false) vacuum decay

- Many nucleation events eventually (in flat space) complete the phase transition.



Applications of vacuum decay

- Vacuum decay is ubiquitous in (B)SM physics and Early Universe Cosmology.
    - Higgs stability.
    - Electroweak phase transition.
    - Baryogensis.
    - Inflation/eternal Inflation.
    - SUSY/GUTs/string theory.
    - More…..

Fundamentals of vacuum decay

- Vacuum decay is a **non-perturbative** feature of **non-linear** quantum field theories.

We might learn something new!

- There are **approximate** techniques for calculating the rate of individual nucleation events, but still lots left to learn:
    - Real-time description.
    - Many-bubbles/fast decays.
    - Correlations between nucleation events.
    - Non-trivial initial states.
    - Time-dependent backgrounds.

Experimental cosmology

- Wouldn't it be nice if we could make a Universe in the lab to learn more about these and other questions?

Experimental cosmology

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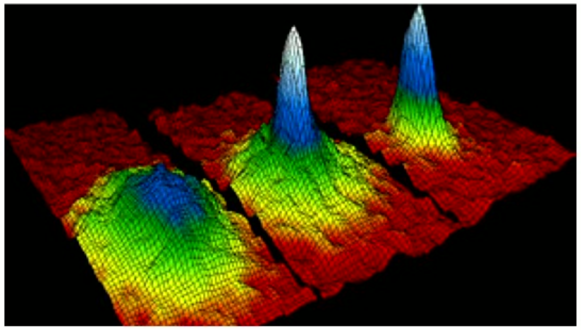
Quantum simulators



Lab systems like a BEC which can be used to simulate the early Universe.

Like an analog quantum computer - or actual quantum computer.

Experimental cosmology

40+ years after Unruh suggested black hole evaporation could be studied with sound horizons and 20 years after BECs were proposed as analogue systems for quantum fields in an expanding Universe…

- Viermann et. al. Nature (2022) - Massless scalar in AdS from phonons in a single-component trapped BEC.
- Eckel et. al. PRX (2018) - Scalar in 1+1 dS from phonons in expanding BEC ring.
- Wittemer et. al. PRL (2020) - Pair creation in expanding Universe from ion trap.
- Schmitt et. al. Nature (2023) - Schwinger pair production in graphene.

QSimFP

https://qsimfp.org

Consortium of theorists/ experimentalists in UK/Canada funded by UKRI to develop quantum simulators of fundamental physics in cosmology and black holes.

Quantum simulators of false vacuum decay

- Two-species Bose-Einstein Condensate systems can serve as quantum simulators of false vacuum decay:

GPEs:

$$i\hbar\dot{\psi}_1 = -\frac{\hbar^2\nabla^2}{2m}\psi_1 + g_s|\psi_1|^2\psi_1 + g_c|\psi_2|^2\psi_1 - \nu\psi_2$$

$$i\hbar\dot{\psi}_2 = -\frac{\hbar^2\nabla^2}{2m}\psi_2 + g_s|\psi_2|^2\psi_2 + g_c|\psi_1|^2\psi_2 - \nu\psi_1$$

scattering mixing/coupling

Son & Stephanov; Fialkov et. al.

- Change basis $\psi_i = \sqrt{\rho_i}e^{i\phi_i}$ and integrate out density and total phase:

$$\mathcal{L}_{\rm eff} = \frac{\dot{\varphi}^2}{2} - \frac{(\nabla\varphi)^2}{2} + \frac{4\nu\bar{n}(g_s - g_c)}{\hbar^2}\cos\varphi \qquad \varphi \equiv \phi_1 - \phi_2$$

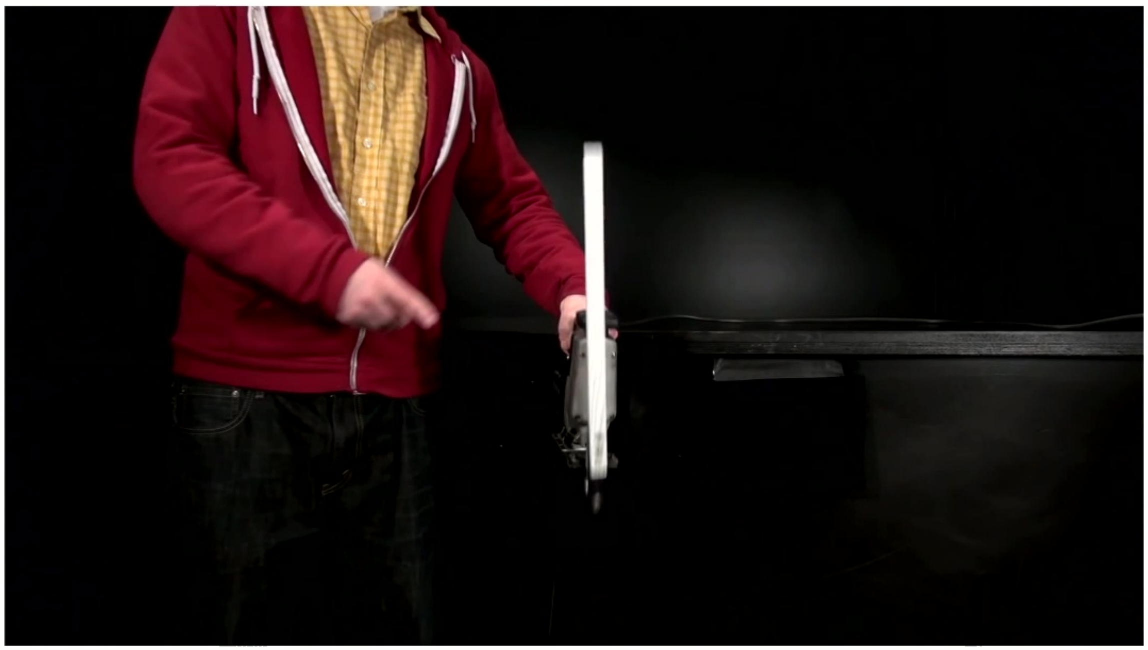
See 1712.02356 for details.

Quantum simulators of false vacuum decay

- We can create a false vacuum by introducing a time-dependent coupling:

$$\nu(t) = \nu_0 + \delta\hbar\omega\cos(\omega t)$$

Fialkov et. al.
Braden, MCJ, et. al.



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$$i\hbar\dot{\psi}_1 = -\frac{\hbar^2\nabla^2}{2m}\psi_1 + \underbrace{g_s\left|\psi_1\right|^2\psi_1 + g_c\left|\psi_2\right|^2\psi_1}_{\text{scattering}} - \underbrace{\nu\psi_2}_{\text{mixing/coupling}}$$

$$i\hbar\dot{\psi}_2 = -\frac{\hbar^2\nabla^2}{2m}\psi_2 + g_s\left|\psi_2\right|^2\psi_2 + g_c\left|\psi_1\right|^2\psi_2 - \nu\psi_1$$

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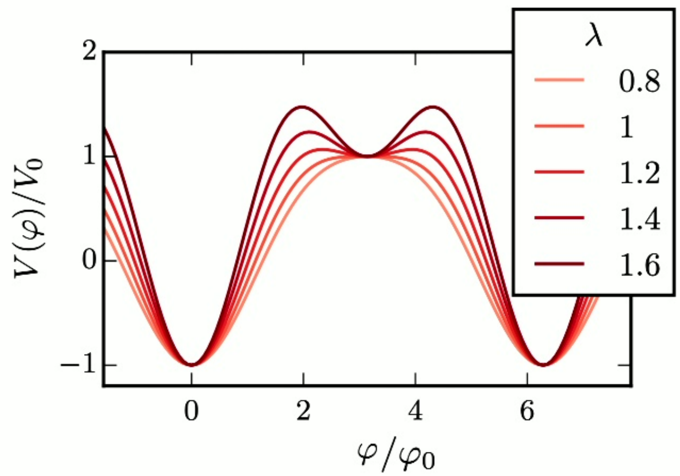
Quantum simulators of false vacuum decay

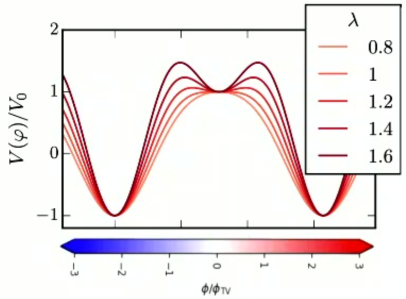
- Time-averaging, we obtain:

$$\mathcal{L}_{\text{eff}} = \frac{\dot{\varphi}^2}{2} - \frac{(\nabla\varphi)^2}{2} - V_0\left(-\cos\varphi + \frac{\lambda^2}{2}\sin^2\varphi\right)$$

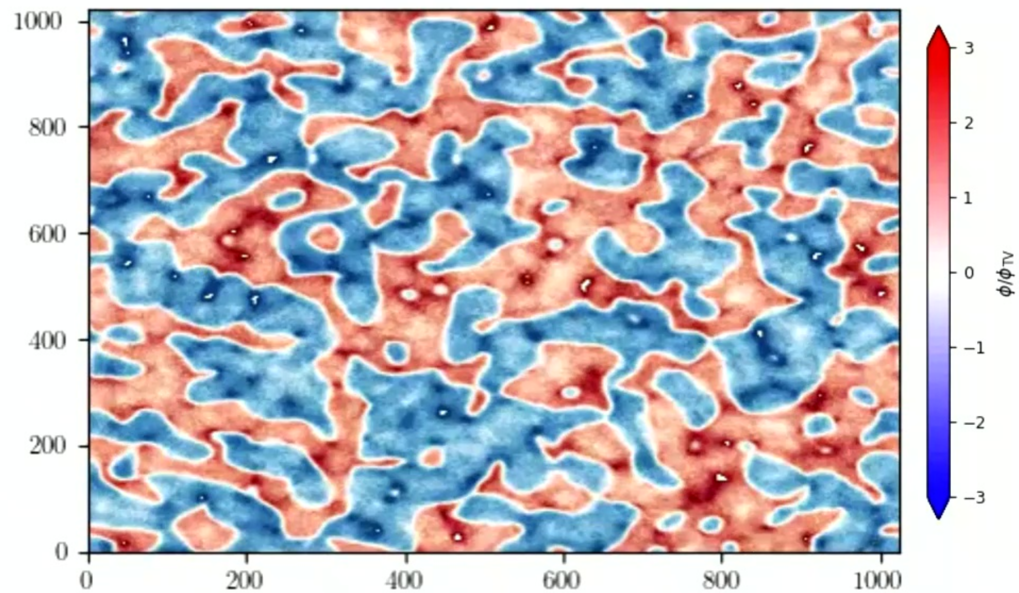
Tuneable potential: $\lambda^2 \propto \delta^2/\nu_0$



Quantum simulators of false vacuum decay

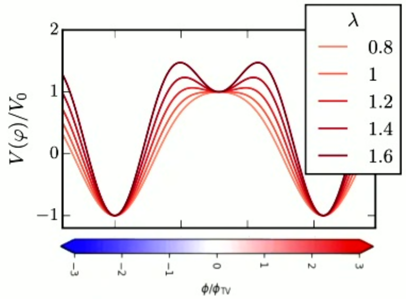


See 1904.07873 for details.



small λ

Quantum simulators of false vacuum decay



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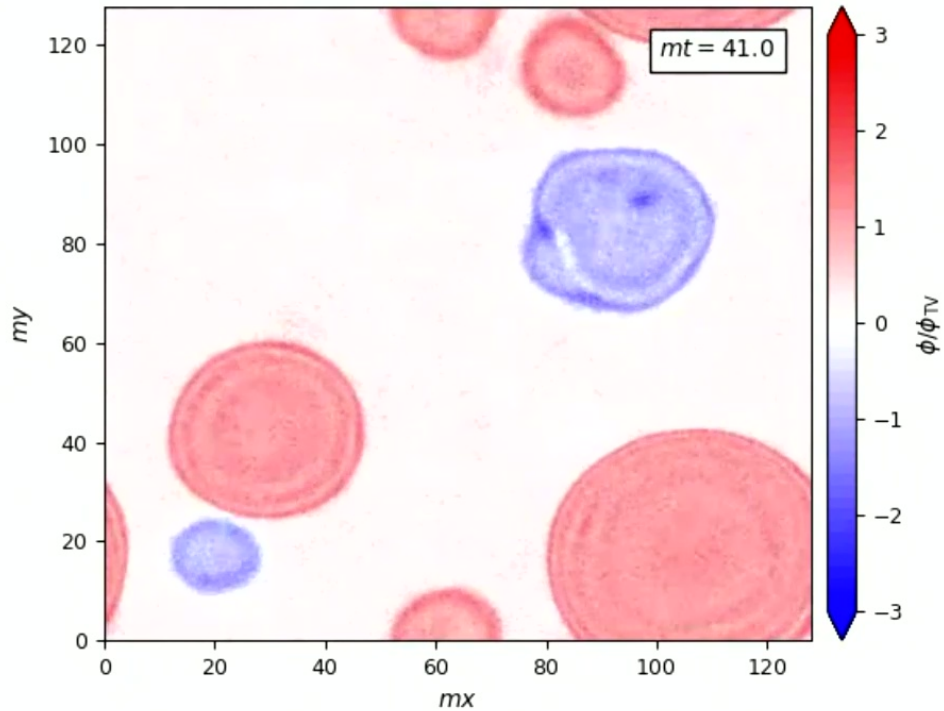
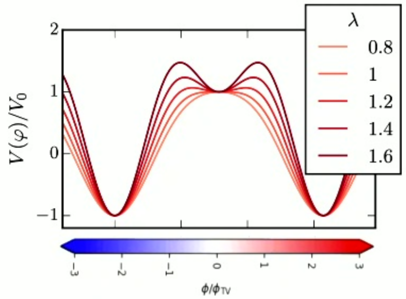


medium λ

Quantum simulators of false vacuum decay



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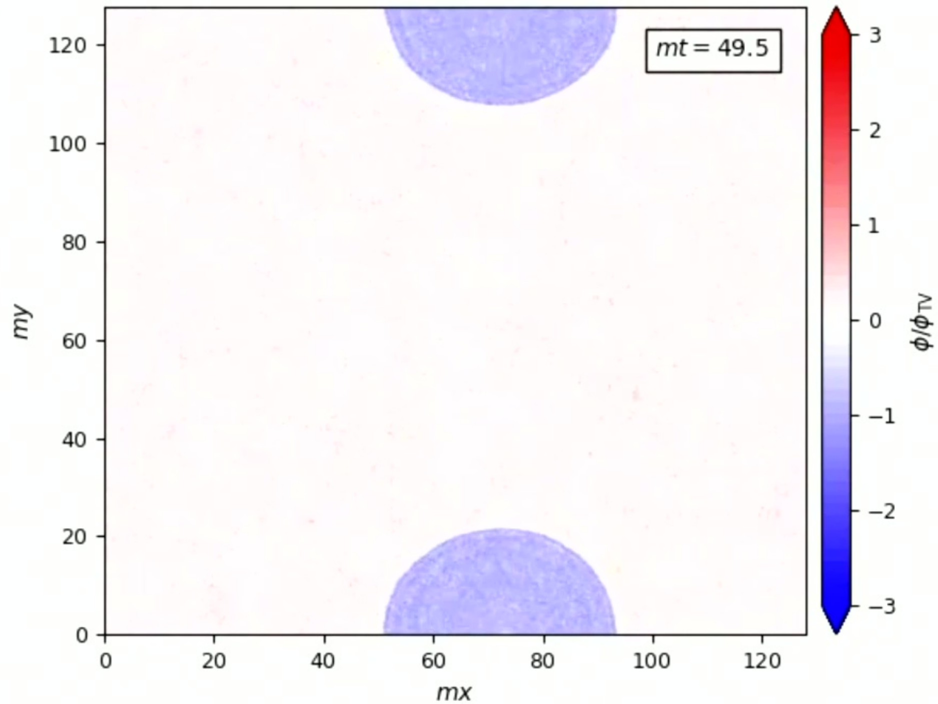
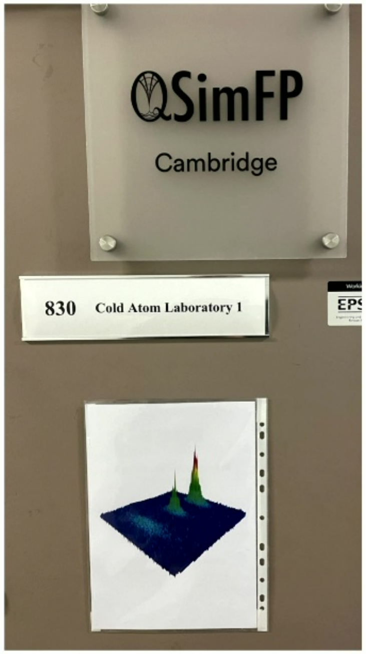


large λ

Can we do it?



Hadzibabic lab
Cambridge

- Many in-practice challenges (I'm a theorist :).
- In-principle challenges & questions:
    - Time-dependent couplings drive parametric resonance: do timescales work?
    - Expanding bubble walls length-contract: UV sensitivity (what happens sub-healing length?).
    - How faithful is the analogue?
    - What should we be measuring?
    - How can we compare to theory?
    - Quantum vs thermal?

A great re-think

- Even if the experiments are years off, already lots of new insights into vacuum decay:
  - New semi-classical real-time description of vacuum decay: 1806.06069
  - Bubble nucleation sites are correlated: 2109.04496
  - Bubbles and RG: 2204.11867
  - Bubble nucleation pre-cursors: Coming soon!
  - Bubbles don't nucleate at rest: Coming soon!

A real-time semi-classical approach

- From quantum mechanics:

$$V \propto x^2 \qquad \langle x(t) \rangle = x_{cl}(t), \quad \langle p(t) \rangle = p_{cl}(t)$$

- For non-linear potentials, this is approximately true as long as

$$(\Delta x)^2 \ll V'/V'''$$

- Can extend to statements about time evolution of a quantum state using the Wigner Function:

$$W(x,p) = \frac{1}{\pi\hbar} \int \langle x+y|\hat{\rho}|x-y\rangle e^{-2ipy/\hbar} dy$$

Quasi-probability distribution (e.g. not positive definite) on phase space.

A real-time semi-classical approach

- For a quadratic potential, the classical time-evolution of the Wigner function is equivalent to the Schrodinger equation:

$$\partial_t W = \{W, H\} \longleftrightarrow i\hbar\partial_t \psi = \hat{H}\psi$$

- A recipe for evolving the Wigner function:

  1. Create an ensemble of systems with initial conditions fairly drawn from Wigner function (works when positive definite: ground state).

  2. Time-evolve with the classical Hamiltonian.

  3. Re-calculate the distribution on phase space at a later time.

A real-time semi-classical approach

- Field theory: promote functions to functionals, and proceed as before:

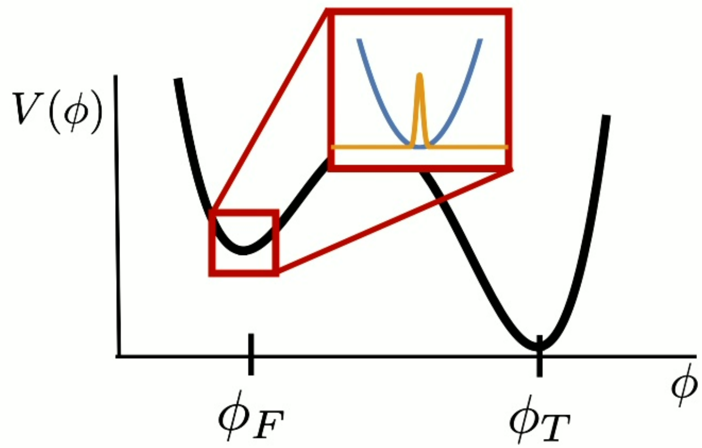
$$\left[\frac{\partial}{\partial t} + \int d^d x \left(\dot{\phi}\frac{\delta}{\delta\phi} + \dot{\Pi}\frac{\delta}{\delta\Pi}\right) + \mathcal{O}\left(\hbar^2\, V'''(\phi)\frac{\delta^3}{\delta\Pi^3}\right)\right] W\left[\phi(x), \Pi(x); t\right] = 0$$

classical evolution **quantum noise** **initial state**

- For a massive scalar, “quantum effects” enter only through the initial state.

- Interactions lead to additional effects, which can in principle be included perturbatively as stochastic contributions to classical evolution.

A real-time semi-classical approach



Sufficiently stable vacua can be approximated by a massive theory.

- Follow the recipe for evolving the Wigner Function(al) by performing ensembles of classical lattice simulations with different initial conditions.

A real-time semi-classical approach

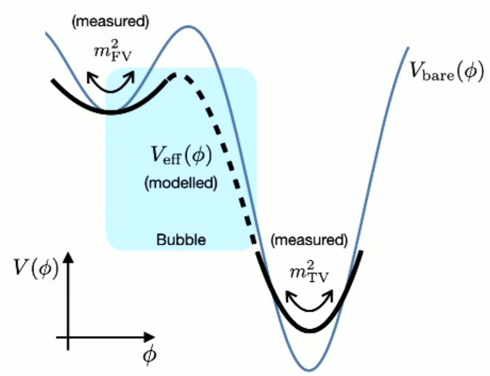
- Similar stochastic methods have been used to study preheating, sphalerons, cosmic strings, etc.
- This is leading order in hbar through the initial conditions, but no virtual particles - it is a semi-classical approximation.
- Bubbles, and their precursors, are many-particle states. A semi-classical description should be OK.

Comparing decay rates

- Coleman prediction for the decay rate:

$$\frac{\Gamma}{V} = Ae^{-B}$$ ← **Depends on the potential.**

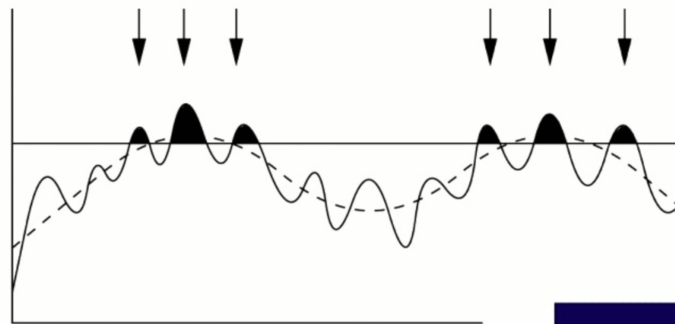
- The potential input to the simulations is not the one seen by the IR modes making up the bubble -> RG effects.
- Around minima, clear what to do. Over the barrier quite subtle….



See 2204.11867 for details.

Bubble bias

- Bubbles are biased tracers of the underlying quantum vacuum fluctuations.



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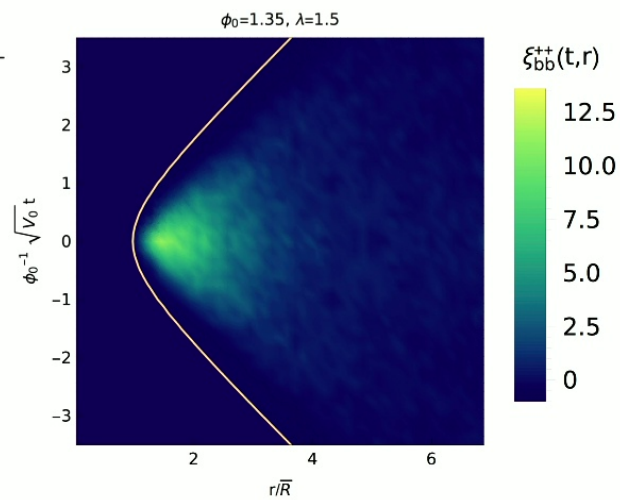


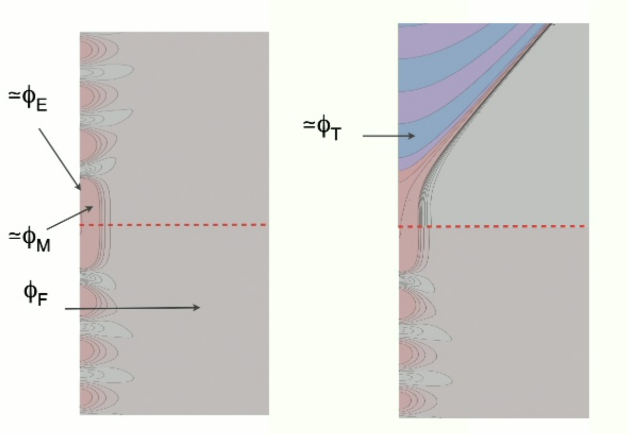
How do bubbles form?

- Q: What is the most likely time-evolution of large fluctuations away from thermal equilibrium?
- A: The CPT conjugate of the most likely way the system relaxes back to equilibrium.

See 1108.0417 for details.

- Thermal bubbles: a true vacuum bubble in unstable equilibrium between expansion and collapse.

Oscillon pre-cursor observed in sims.



Experimental Cosmology

- Can laboratory-based systems, quantum computers, etc. teach us something new about the early Universe?
- Cosmology is dynamics -> interface with quantum dynamics is fertile ground.
- Goal: connect back to observation! What are we not looking for?
- Goal: connect with big questions. Physics of accelerated expansion? Quantum Gravity? Non-perturbative effects in QFT?