Title: Towards quantum simulation of vacuum decay

Speakers: Matthew Johnson

Collection/Series: Waterloo-Munich Joint Workshop

Subject: Quantum Information

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Abstract:

.Scalar quantum field theories can possess metastable vacuum states which decay through thermal and quantum fluctuations. In space, the decay of the metastable vacuum proceeds through the creation and subsequent expansion of bubbles containing a new phase, which coalesce and eventually complete the phase transition. Vacuum decay is a non-perturbative and non-linear dynamical problem, making it the perfect candidate for quantum simulators. Understanding this process has phenomenological implications for early Universe cosmology, including observables such as a stochastic gravitational wave background, meaning there may be novel ways to use quantum simulators to make predictions for observational cosmology. In this talk I will first describe theoretical work developing observables for vacuum decay, including nucleation site correlation functions and bubble nucleation pre-cursors. I will then describe experimental efforts within the Quantum Simulators for Fundamental Physics consortium to develop analog quantum simulators of vacuum decay with cold atomic gasses. Such experiments will allow us to empirically test early Universe physics in tabletop experiments.

Towards quantum simulation of vacuum decay

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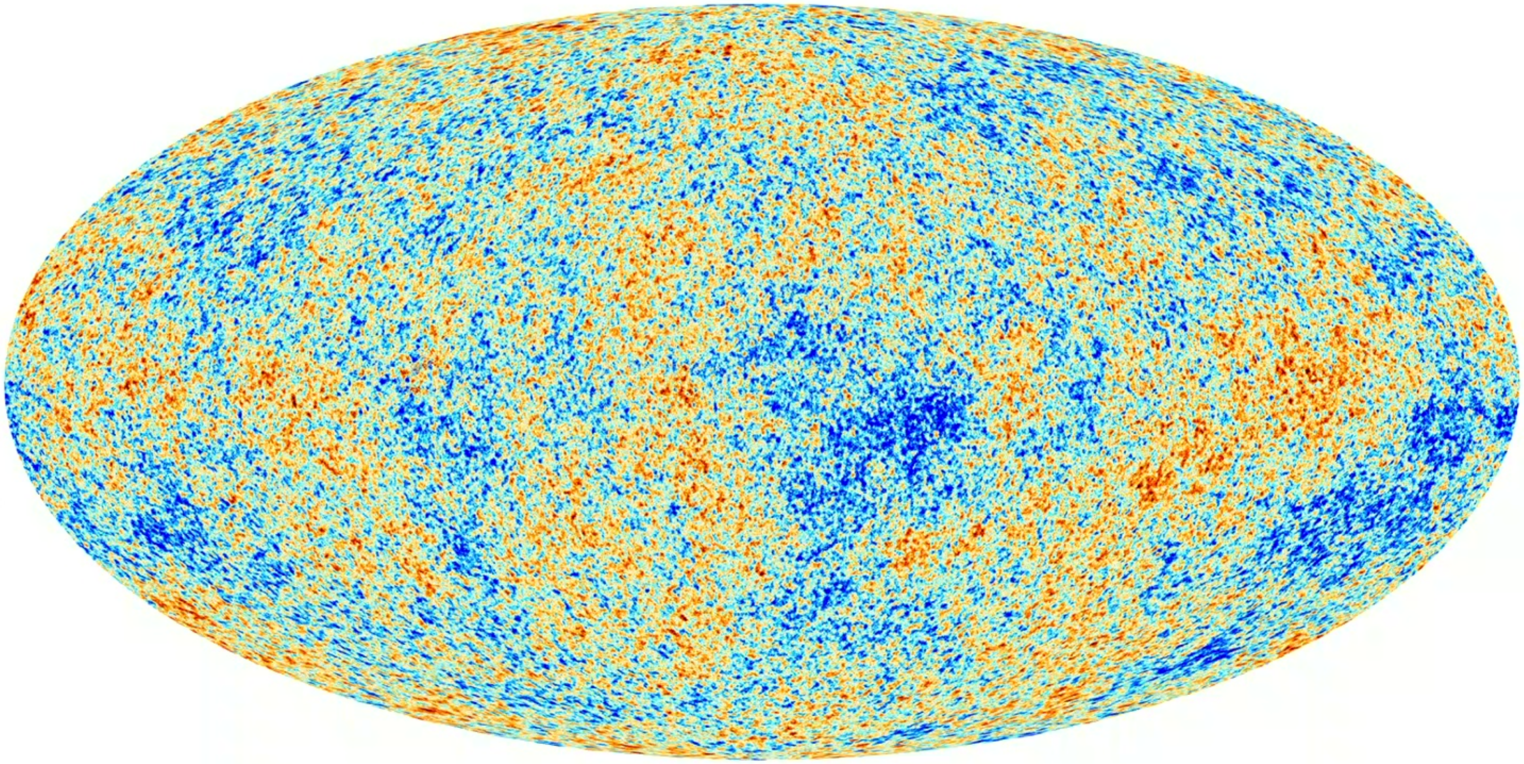
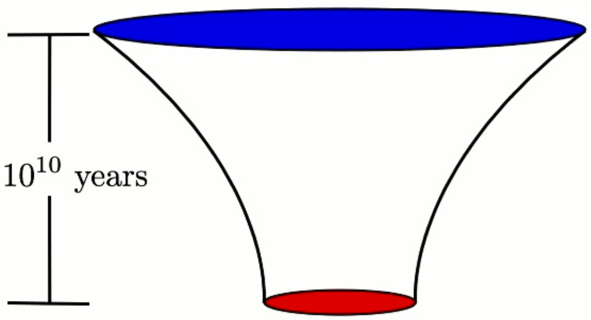
arXiv: 1904.07873, 2109.04496, **2307.02549, 2312.13364**

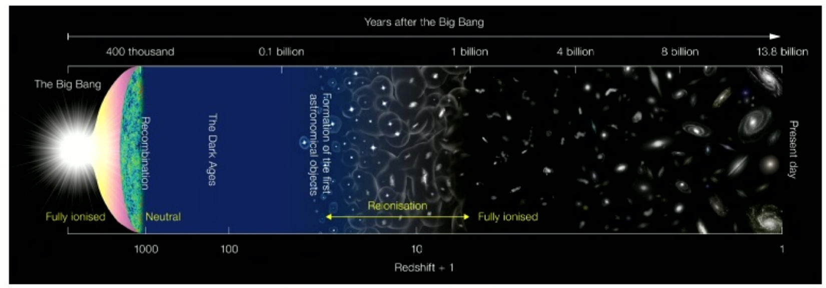
Cosmology



What Happened?

What does quantum have to do with it?

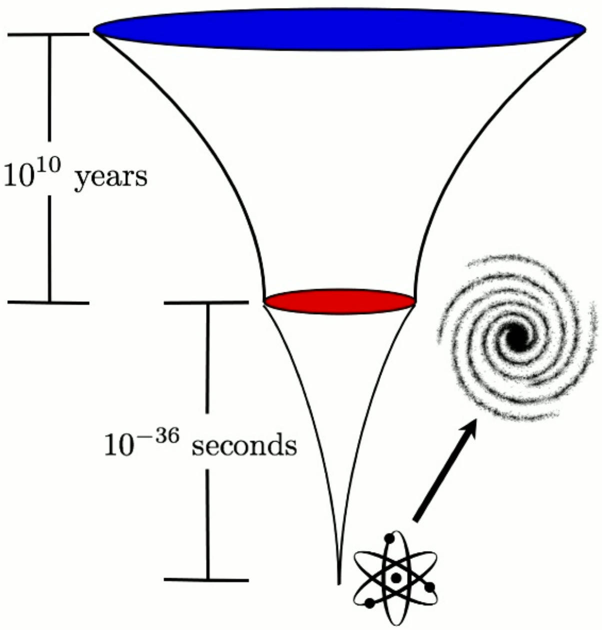




Extremely Simple Initial Conditions

Homogeneous	Adiabatic
Isotropic	Gaussian
Spatially flat	Scale invariant

What does quantum have to do with it?



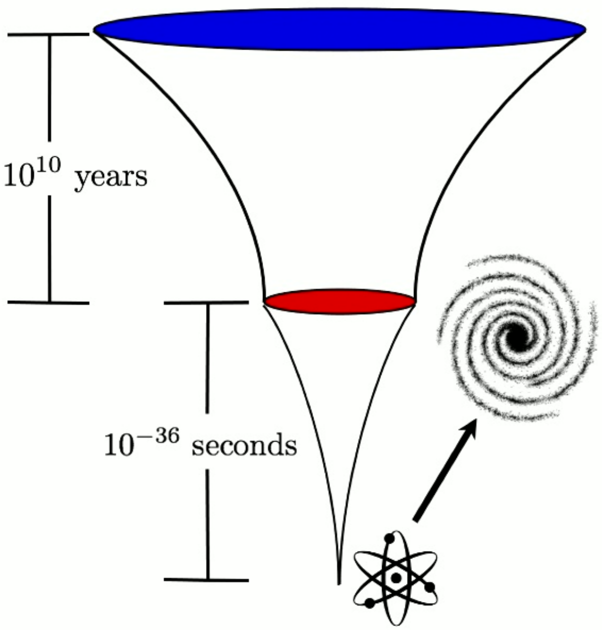
Inflation: exponential expansion.

Homogeneous

Isotropic

Spatially flat

What does quantum have to do with it?



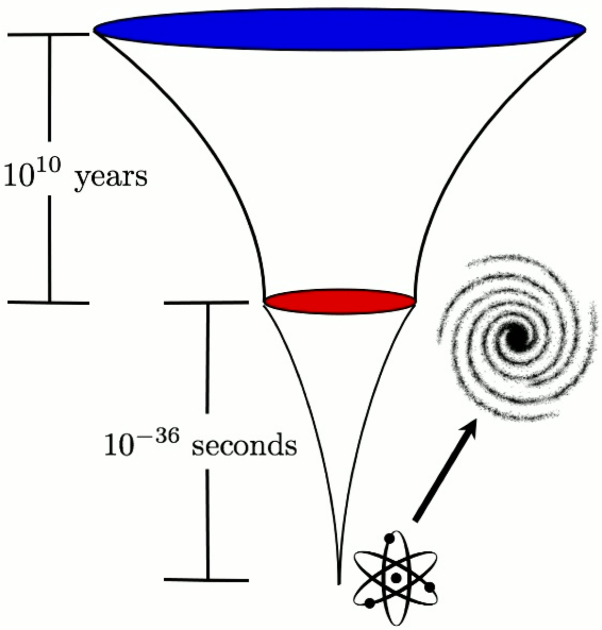
Inflation:

Prequel to the Universe.

The Inflaton:

A substance that does not dilute as the Universe expands.

What does quantum have to do with it?



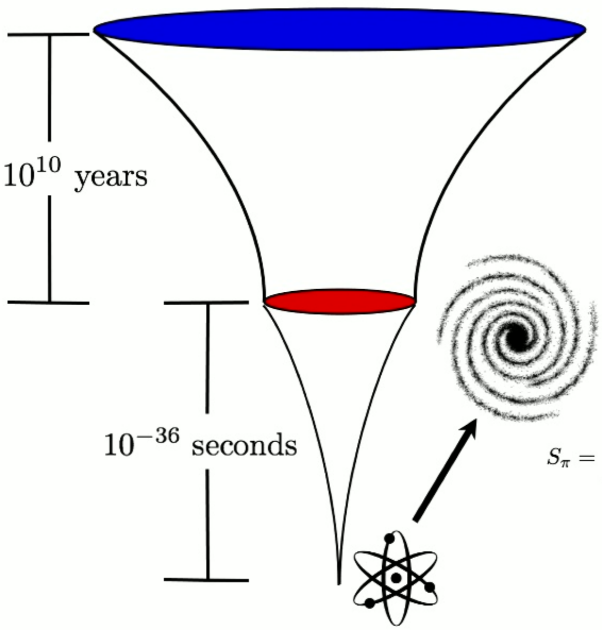
Inflation:

Prequel to the Universe.

The Inflaton:

Gravitating scalar field with a flat potential.

What does quantum have to do with it?



Inflation: weakly coupled scalar in expanding Universe.

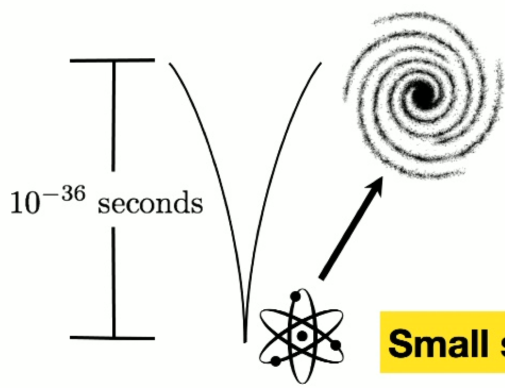
$$S_\pi = \int d^4x\,\sqrt{-g}\left[M_{\rm Pl}^2\dot{H}\,(\partial_\mu\pi)^2 + 2M_2^4\left(\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi}\frac{1}{a^2}(\partial_i\pi)^2\right) - \frac{4}{3}M_3^4\dot{\pi}^3 - \frac{\bar{M}^2}{2}\,\frac{1}{a^4}(\partial_i^2\pi)^2 + \dots\right]$$

Adiabatic

Gaussian

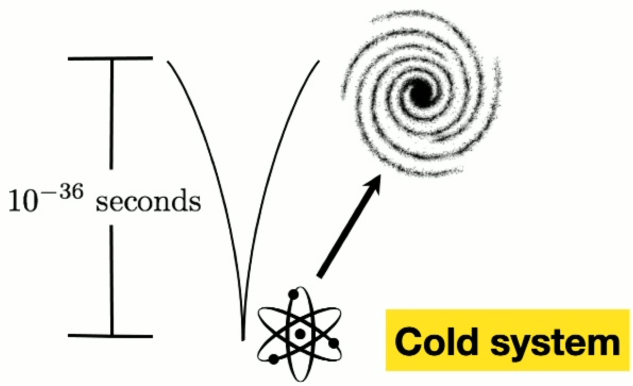
Scale invariant

What does quantum have to do with it?

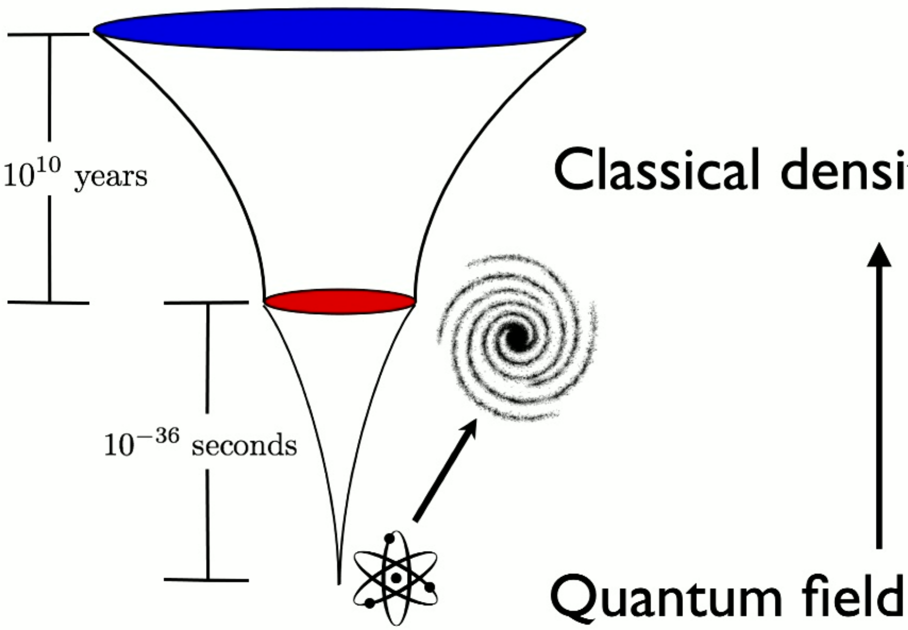


Small system $S \sim A \sim 10^{10}$

What does quantum have to do with it?



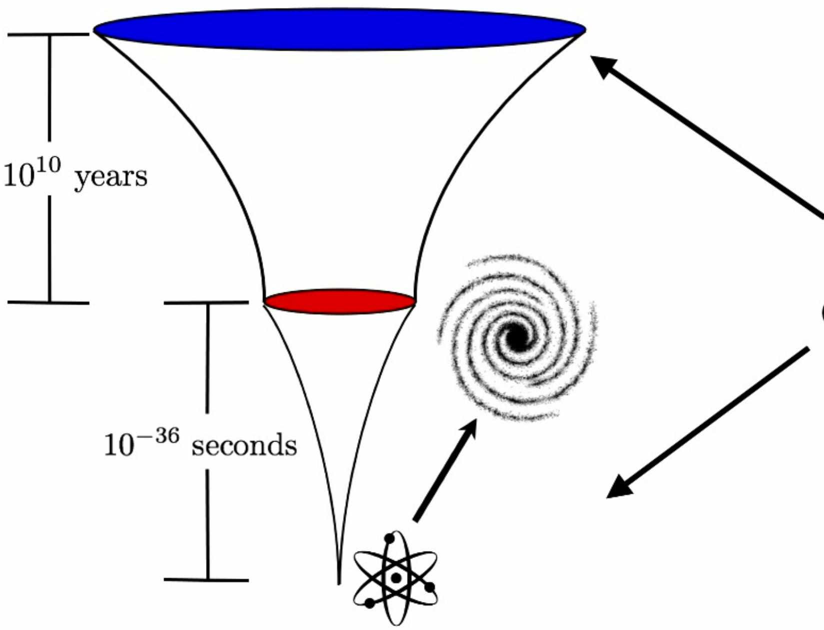
What does quantum have to do with it?



Classical density fluctuations

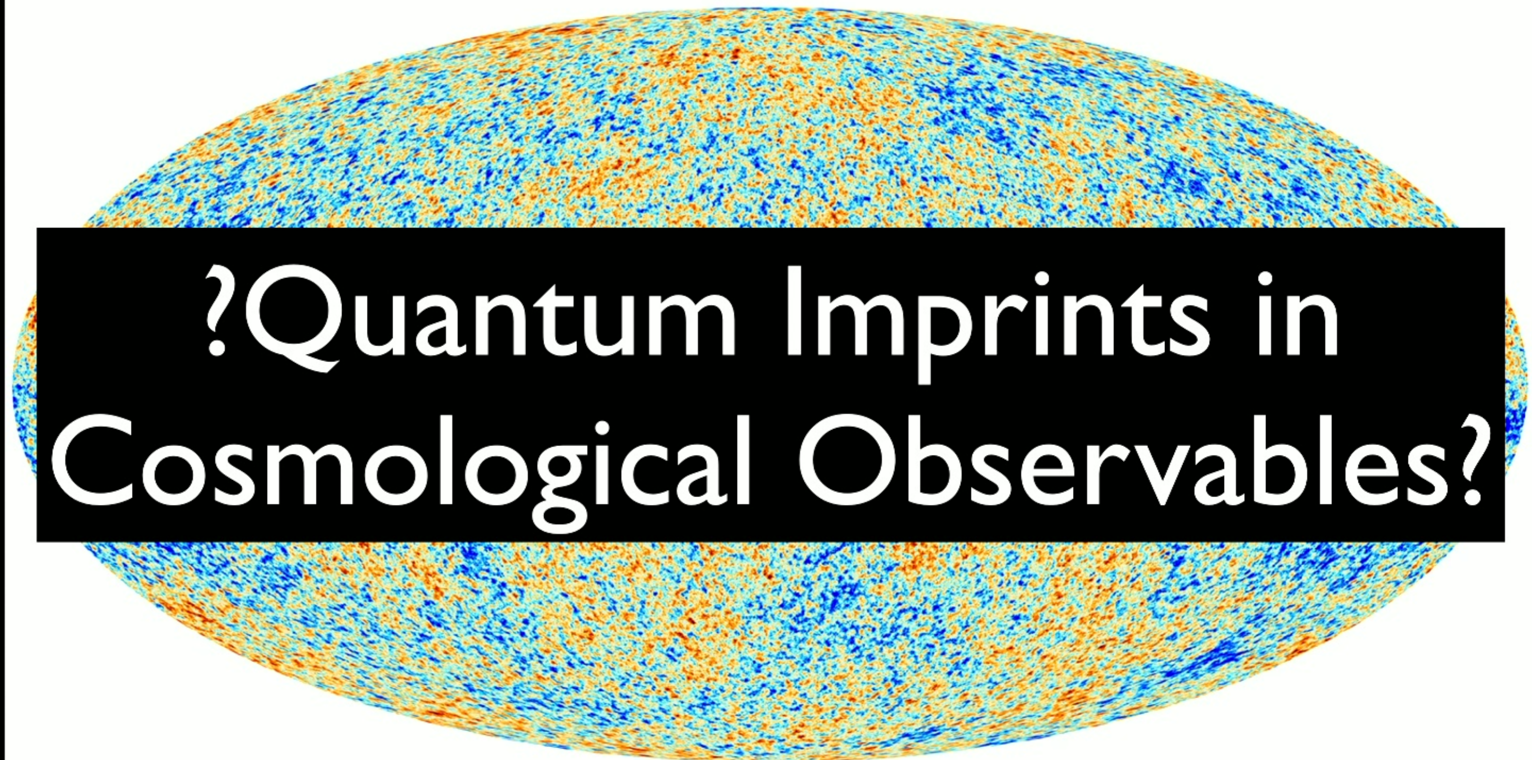
Quantum field fluctuations

What does quantum have to do with it?

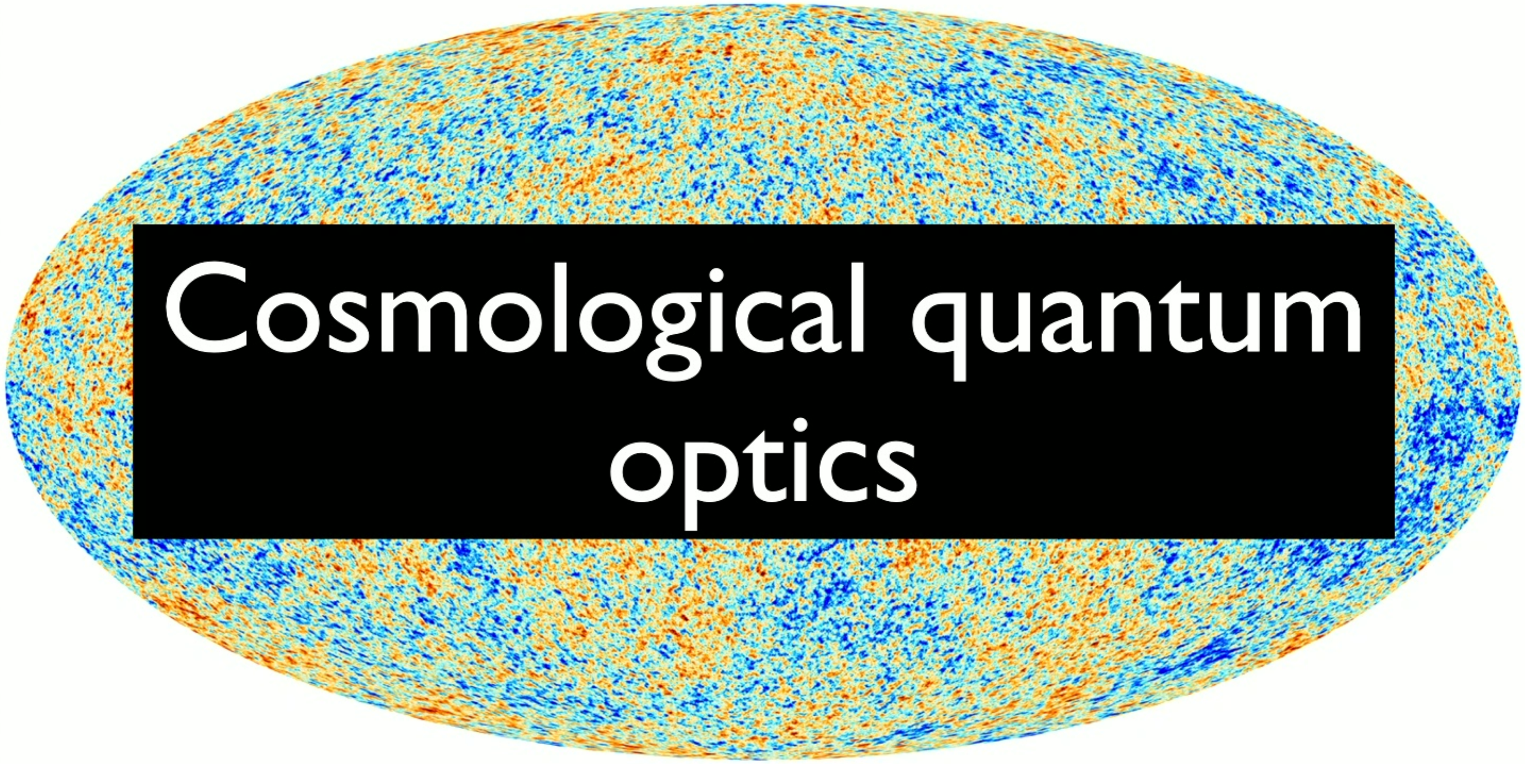


How does accelerated expansion begin and end?

Phase transitions


?Quantum Imprints in
Cosmological Observables?

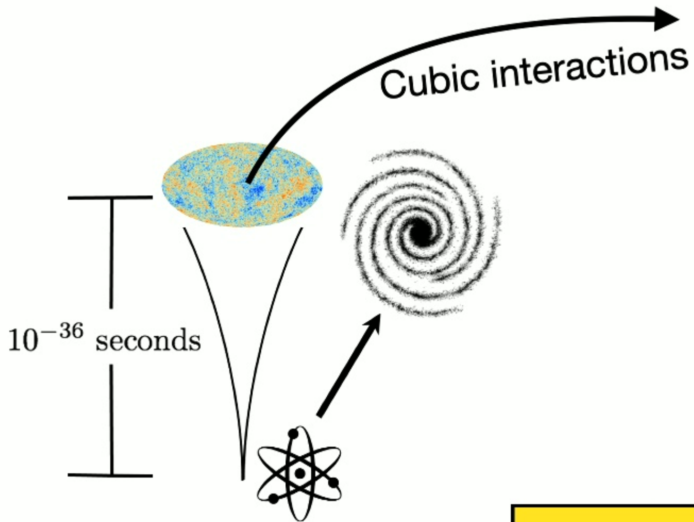
Cosmological quantum optics

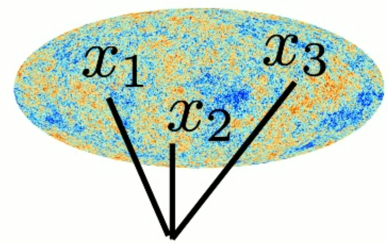


I see a random field: quantum or classical?

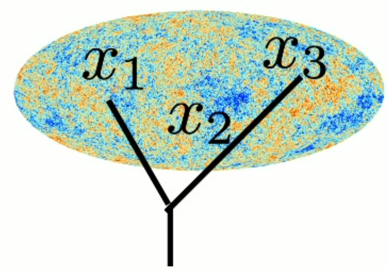
One way to look: three-point correlation functions

Green & Porto: 2001.09149





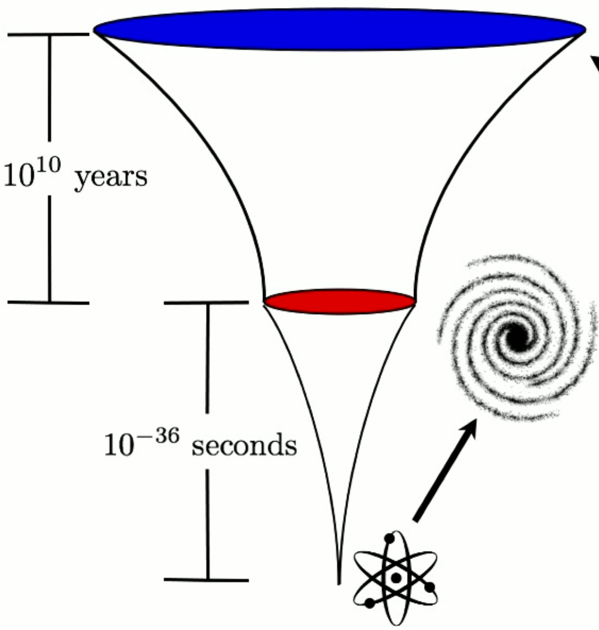
Quantum: virtual particles.



Classical: scattering particles in initial state.

$$\langle \pi(x_1)\pi(x_2)\pi(x_3)\rangle_{quant} \neq \langle \pi(x_1)\pi(x_2)\pi(x_3)\rangle_{class}$$

What does quantum have to do with it?

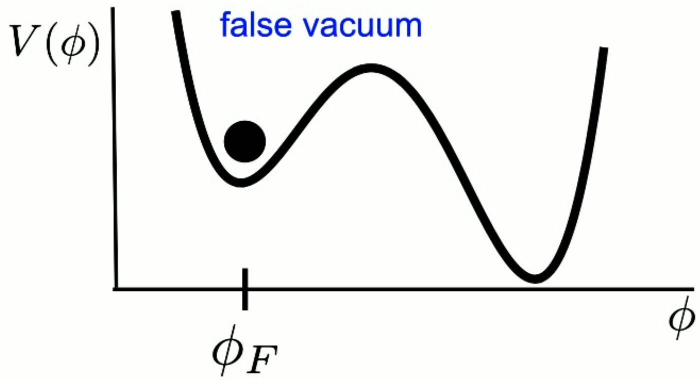


How does accelerated expansion begin and end?

Phase transitions

Beyond perturbation theory….

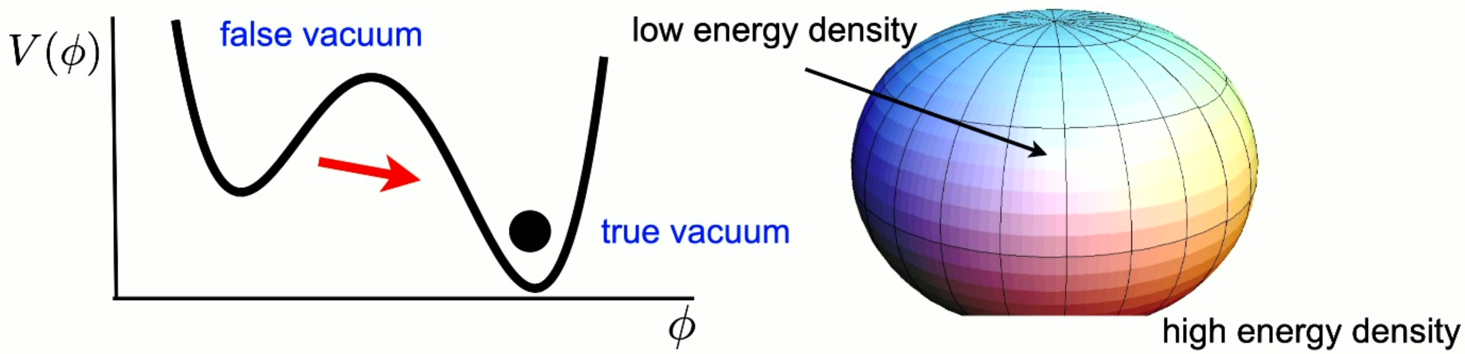
Metastable (false) vacuum decay



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

Classically, at zero temperature, if the field is everywhere in the false vacuum,
it will remain there forever.

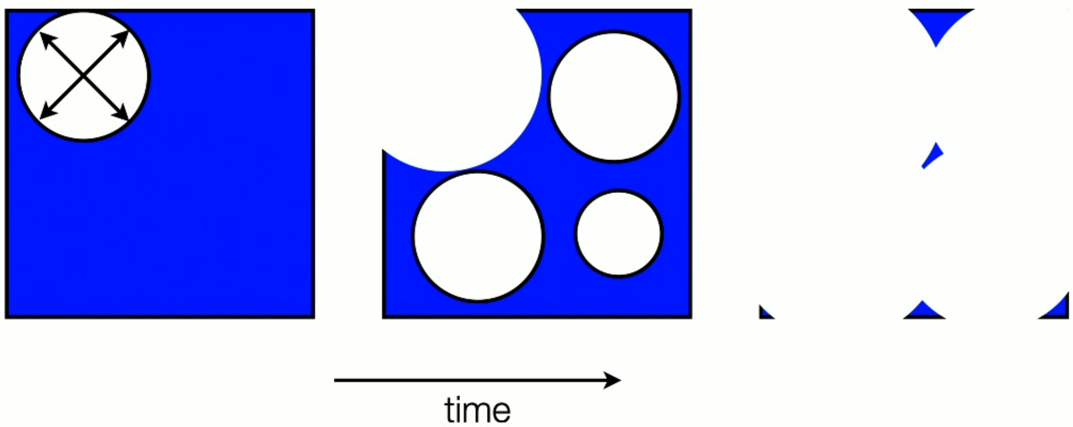
Metastable (false) vacuum decay



Through quantum tunnelling or thermal activation, 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 in ***non-equilibrium***.
- There are **approximate Euclidean** techniques for calculating the rate of individual nucleation events, but our understanding of vacuum decay is neither complete nor rigorous!

What are the observables?

Differences between thermal and quantum vacuum decay?

What does the approximate Euclidean picture miss?

Fundamentals of vacuum decay

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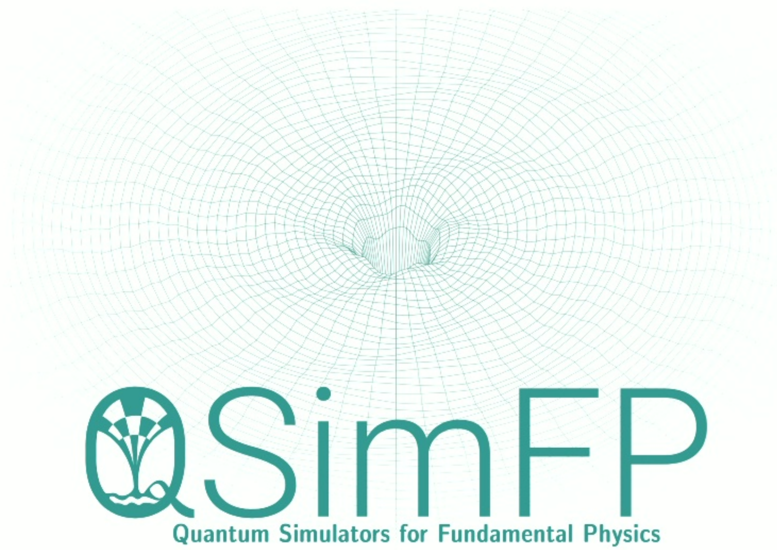
Quantum Simulation?

QSimFP



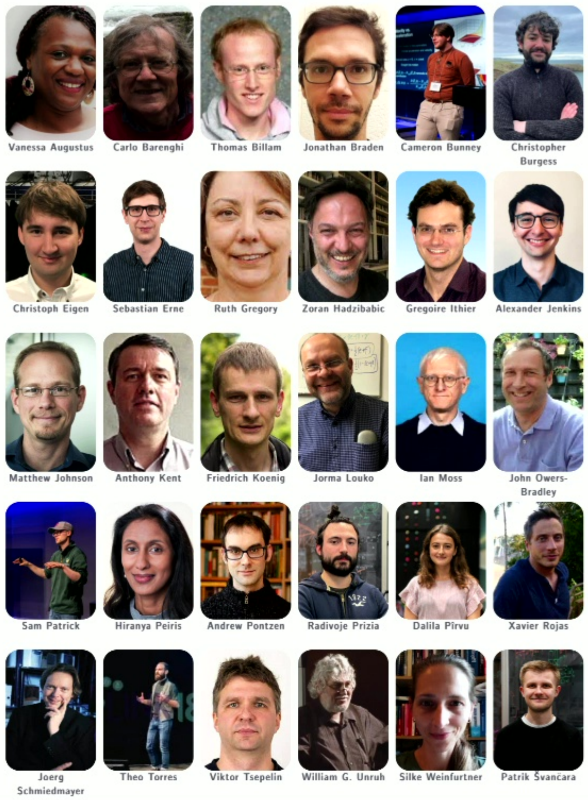
https://qsimfp.org

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

QSimFP

Team

World-leading researchers in the following STFC and EPSRC areas:



Quantum simulators of false vacuum decay

- Two-species Bose-Einstein Condensate systems (e.g. hyperfine states of Potassium 41) can serve as quantum simulators of false vacuum decay:

GPEs:

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

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

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:

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

See 1712.02356 for details.

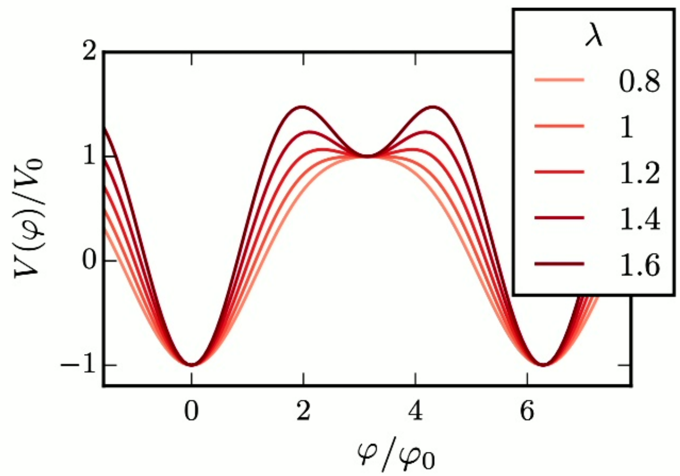
Quantum simulators of false vacuum decay

- Time-averaging, we obtain:

(Beware of parametric resonance: see 1712.02356 for details.)

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

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



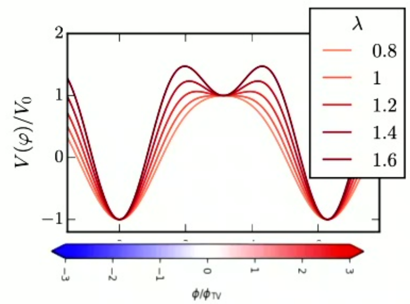
Quantum simulators of false vacuum decay

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

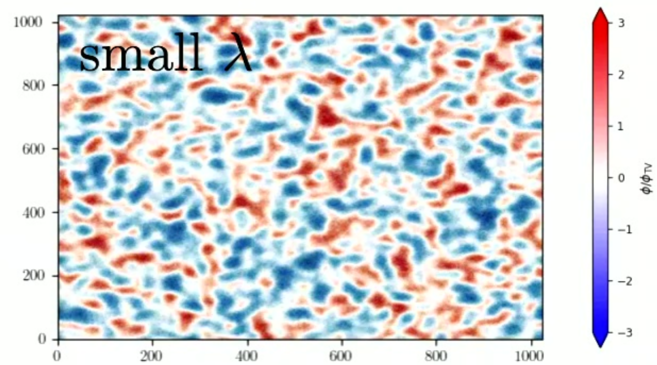
$$\nu(t) = \nu_0 + \delta\hbar\omega\cos(\omega t)$$

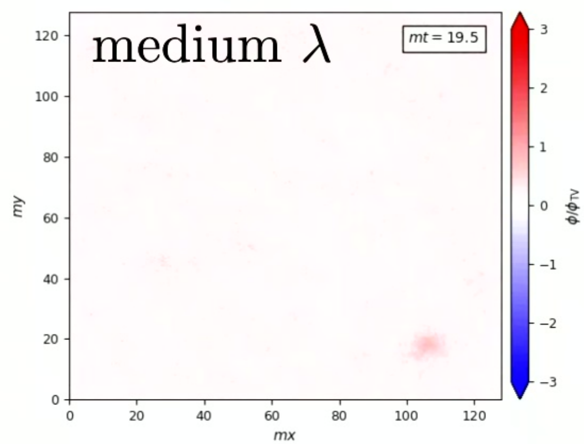
Fialkov et. al.
Braden, MCJ, et. al.

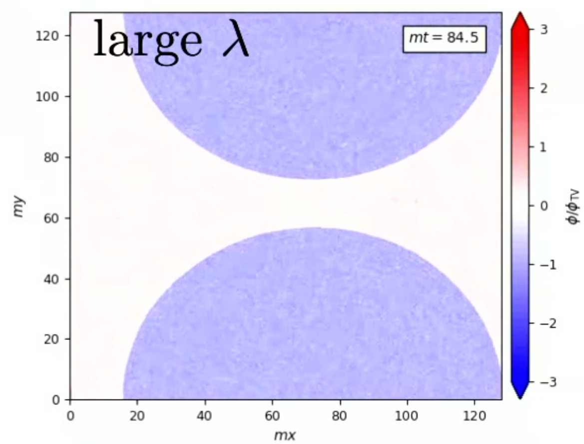
Quantum simulators of false vacuum decay



GPE/SPGPE in truncated Wigner;
see 1904.07873 for details.



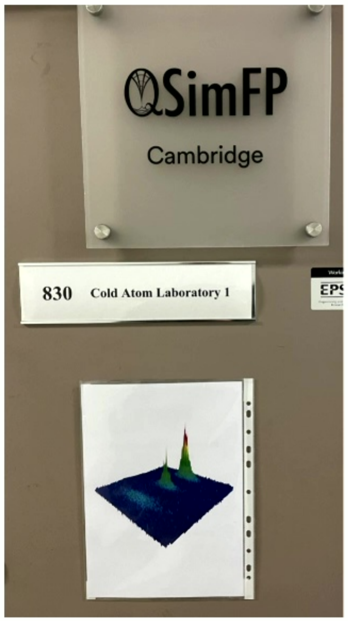


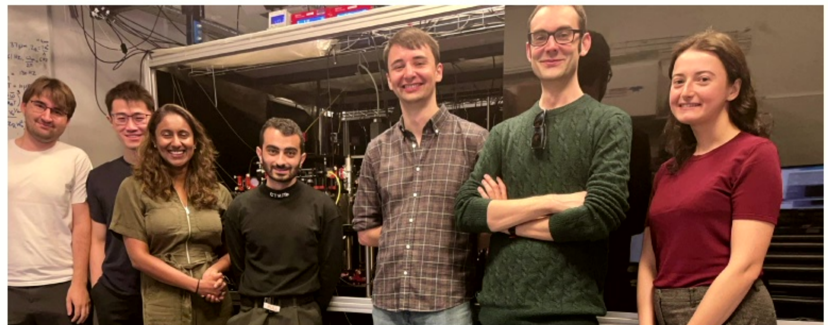


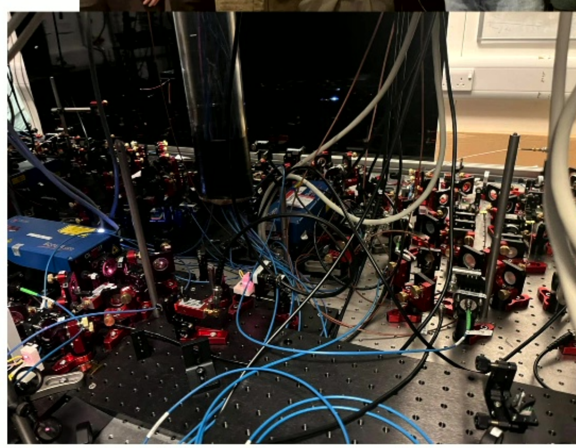
FVD Experiment

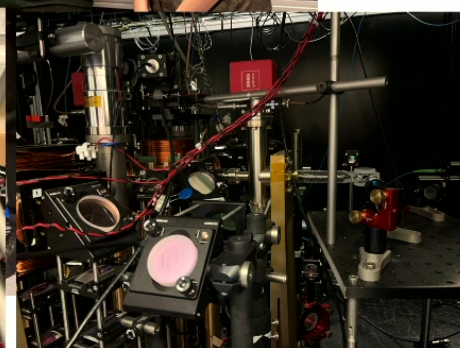
Hadzibabic lab

Cambridge









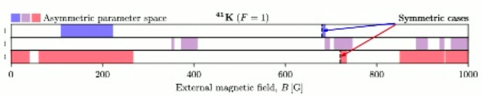
FVD Theory Modeling

(Jenkins et al 2311.02156)

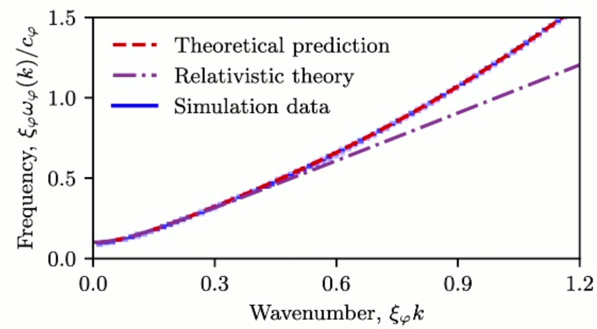
(Jenkins et al 2307.02549)

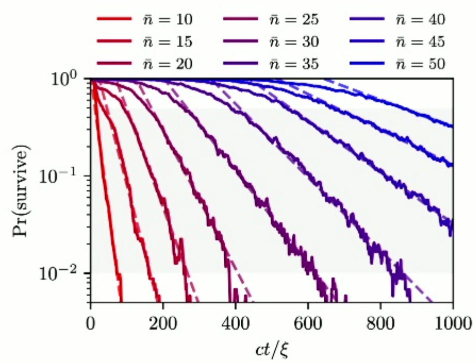
Exploring parameter space

Parameter	Value
Atomic isotope	^{41}K (potassium-41)
Atomic mass	$m = 40.96\,\mathrm{u} = 6.802 \times 10^{-26}\,\mathrm{kg}$
Hyperfine states	$\lvert F, m_F\rangle = \lvert 1,0\rangle, \lvert 1,+1\rangle$
Magnetic field	$B = 675.256\,\mathrm{G}$
Scattering length (3D)	$a = 60.24\,a_0 = 3.188\,\mathrm{nm}$
Healing length	$\xi = 80\,a = 0.2550\,\mu\mathrm{m}$
Box trap length	$L = 500\,\xi = 127.5\,\mu\mathrm{m}$
# atoms per species	$5000 \leq N \leq 25000$
Number density (1D)	$39.21\,\mu\mathrm{m}^{-1} \leq n \leq 196.1\,\mu\mathrm{m}^{-1}$
Dimensionless density	$10 \leq \bar{n} \leq 50$
Transverse trap frequency	$3.04\,\mathrm{kHz} \leq \omega_\perp/2\pi \leq 15.2\,\mathrm{kHz}$
Scattering strength (1D)	$0.08\,\mathrm{peV}\,\mu\mathrm{m} \leq g \leq 0.4\,\mathrm{peV}\,\mu\mathrm{m}$
Energy scale	$gn = 15.69\,\mathrm{peV}$
Temperature scale	$gn/k_\mathrm{B} = 182.1\,\mathrm{nK}$
Sound speed	$c = \sqrt{gn/m} = 6.079\,\mathrm{mm\,s^{-1}}$
Sound-crossing time	$L/c = 20.98\,\mathrm{ms}$
Mean rf field	$\nu_0 = 59.59\,\mathrm{Hz}$
Inter-species coupling	$\epsilon = \hbar\nu_0/gn = 2.5 \times 10^{-3}$
rf modulation amplitude	$\lambda = \sqrt{2}$
rf modulation frequency	$\omega \geq 680\,c/\xi = 2\pi \times 2.58\,\mathrm{MHz}$
False vacuum mass	$m_\mathrm{fv} = \sqrt{4\epsilon(\lambda^2 - 1)}\,m = 0.1\,m$



Exploring corrections (UV completion)

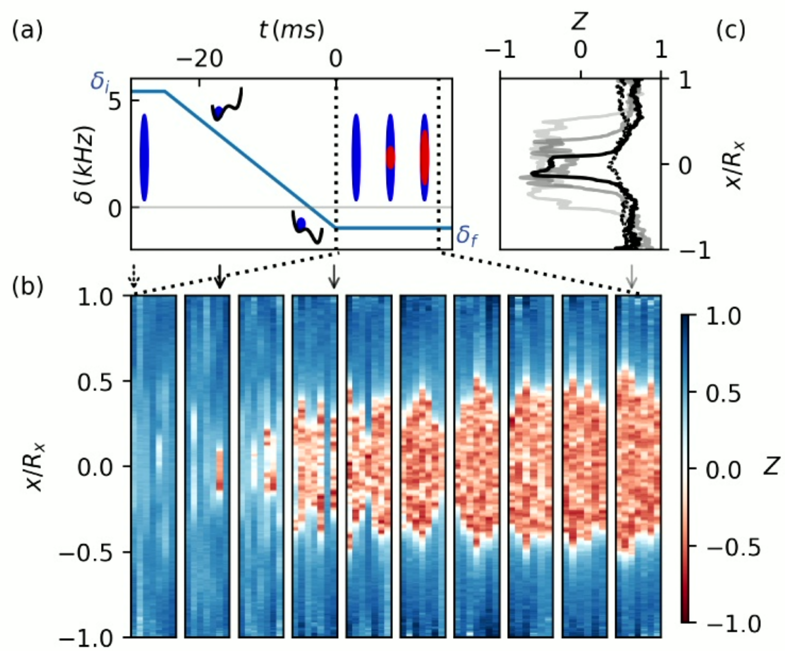




Predicting observables

Other examples

- Zenesini et al 2305.05225 - observed thermal vacuum decay in a 1-D superfluid analogue system



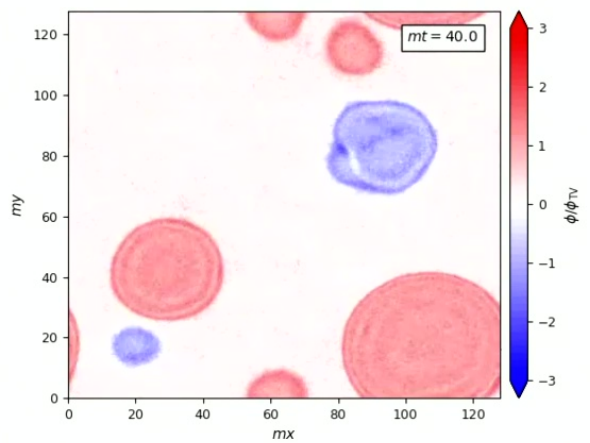
Observables in vacuum decay

(Brade, Pirvu + MCJ: 2109.04496)
(Pirvu, Sibiryakov + MCJ: 2312.13364)
(Pirvu, Shkerin, Sibiryakov: 2408.06411, 2407.06263)

- Given an ensemble of bubble nucleation events, how can we characterize them?
- Euclidean theory: decay rate.

↑

Ideal - only correct in some situations.

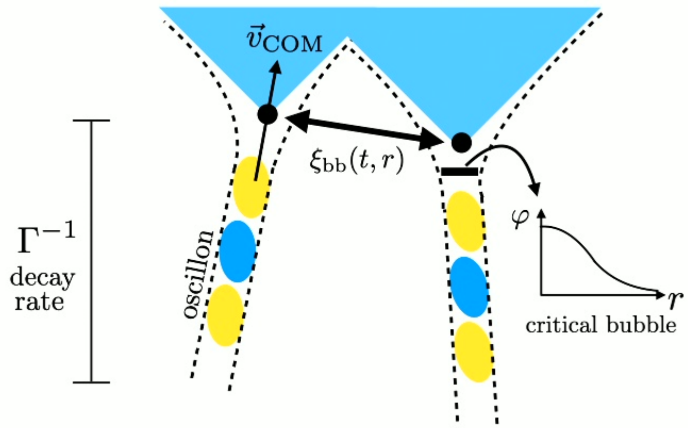


Misses rich (quantum) dynamics!!!!

Observables in vacuum decay

(Brade, Pirvu + MCJ: 2109.04496)
(Pirvu, Sibiryakov + MCJ: 2312.13364)
(Pirvu, Shkerin, Sibiryakov: 2408.06411, 2407.06263)

- Using finite temperature and semi-classical simulations in 1+1 dimensions, we have explored:



- Decay rate.
- Bubble-bubble correlation functions.
- Nucleation pre-cursors.
- Critical bubble configuration.
- Center of mass velocity distribution.

Generalization to zero temperature largely an open question!

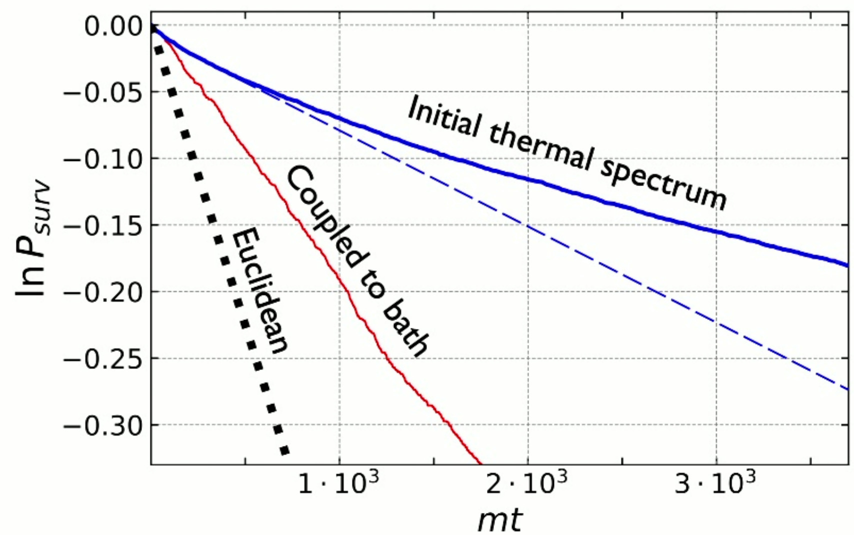
Decay rate (thermal)

(Pirvu, Sibiryakov + MCJ: 2312.13364)

(Pirvu, Shkerin, Sibiryakov: 2408.06411, 2407.06263)

- The decay rate is measured from the fraction of simulations remaining in the false vacuum:

$$\mathrm{Pr(survive)} = e^{-\Gamma L(t-t_0)}$$



'Classical Zeno Effect'

(From Pirvu, Shkerin, Sibiryakov: 2408.06411, 2407.06263)

Decay rate (thermal)

(Pirvu, Sibiryakov + MCJ: 2312.13364)

(Pirvu, Shkerin, Sibiryakov: 2408.06411, 2407.06263)

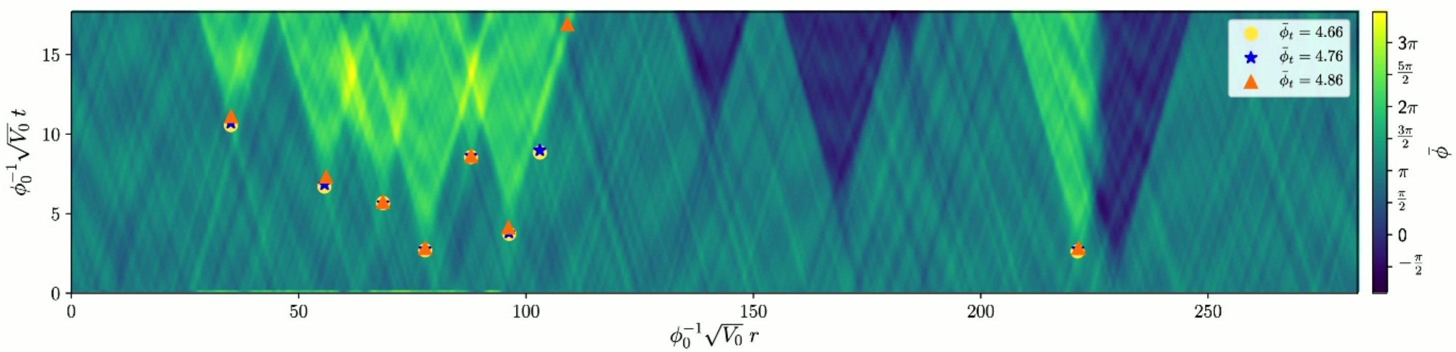
- Large difference between a closed system and one coupled to an external heat bath.
- For a single scalar, thermal equilibrium cannot be maintained during the nucleation process.
- Euclidean theory - idealized computation requiring equilibrium.

Bubble-bubble correlation functions

(Brade, Pirvu + MCJ: 2109.04496)

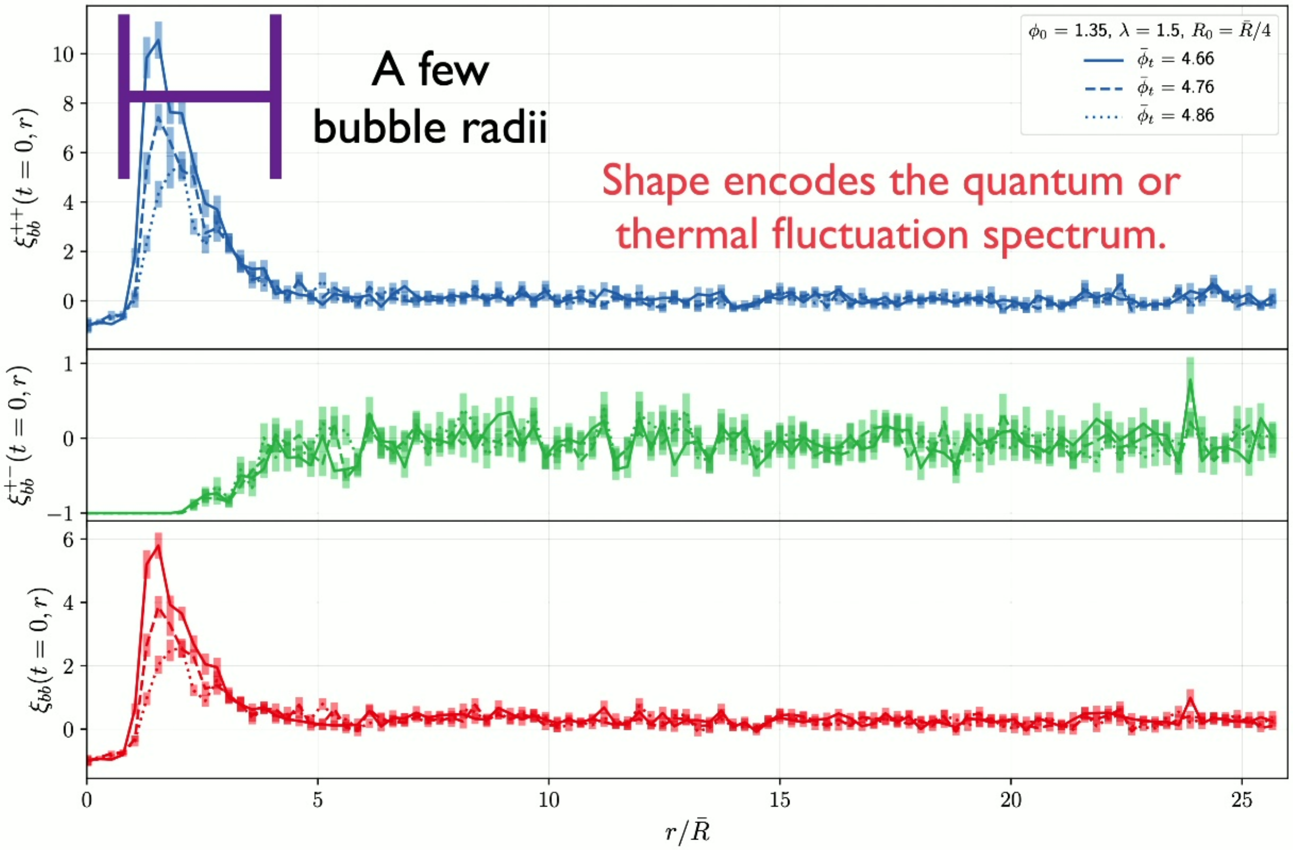
- Locating nucleation events in each simulation, we compute the bubble-bubble correlation function:

$$1 + \xi_{\rm bb}(t, x) \equiv \langle \frac{\#\text{ in shell about }\{\mathrm{t}, \mathrm{r}\}}{\text{expected }\#} \rangle$$



Spatial Correlation Function

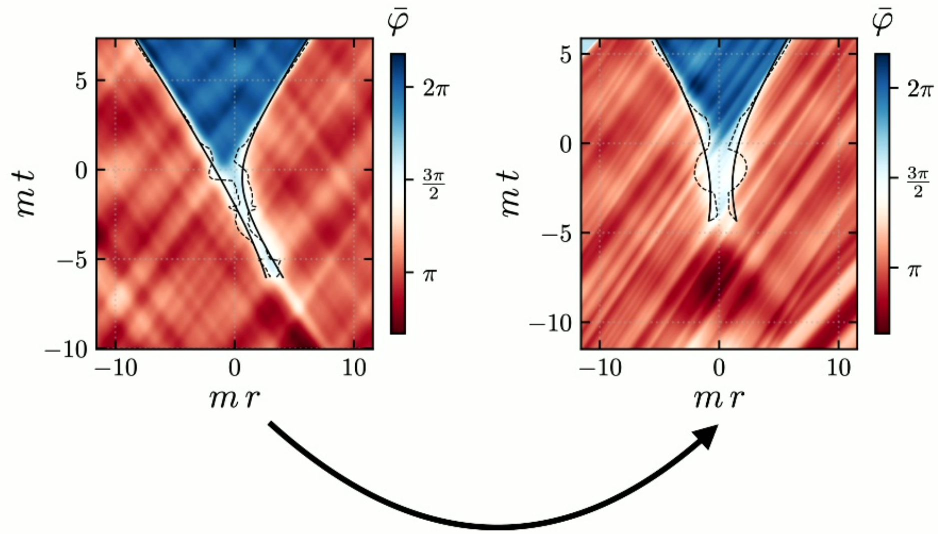
(Brade, Pirvu + MCJ: 2109.04496)



COM Velocity Distribution

(Brade, Pirvu + MCJ: 2109.04496)
(Pirvu, Sibiryakov + MCJ: 2312.13364)

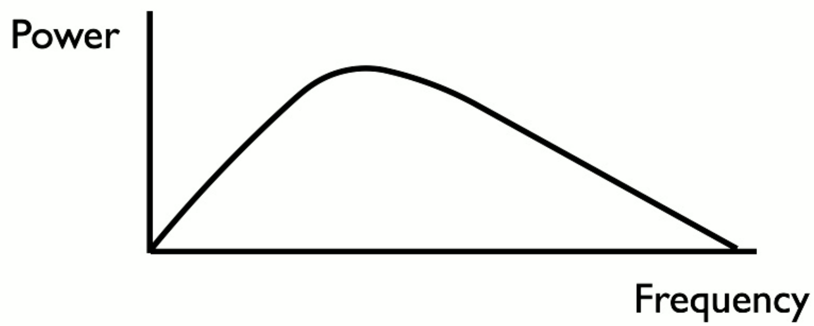
- Bubbles never form at rest!



Boost into the rest frame.

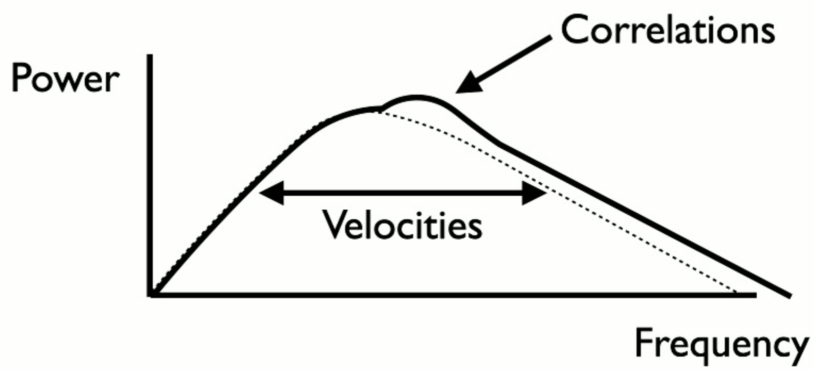
Phenomenology

- If a percolating phase transition happened in the early Universe, it creates a stochastic gravitational wave background.



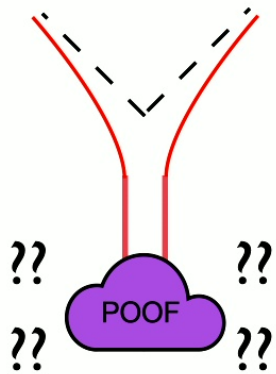
Phenomenology

- If a percolating phase transition happened in the early Universe, it creates a stochastic gravitational wave background.
- The bubble correlation function and velocities enter the prediction.



Bubble nucleation pre-cursors (Pirvu, Sibiryakov + MCJ: 2312.13364)

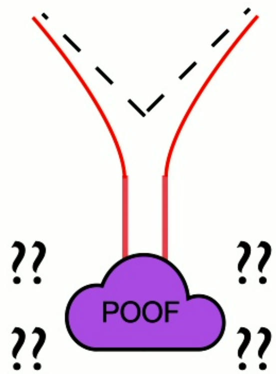
- What happens before a bubble nucleates?



Bubble nucleation pre-cursors

(Pirvu, Sibiryakov + MCJ: 2312.13364)

- What happens before a bubble nucleates?

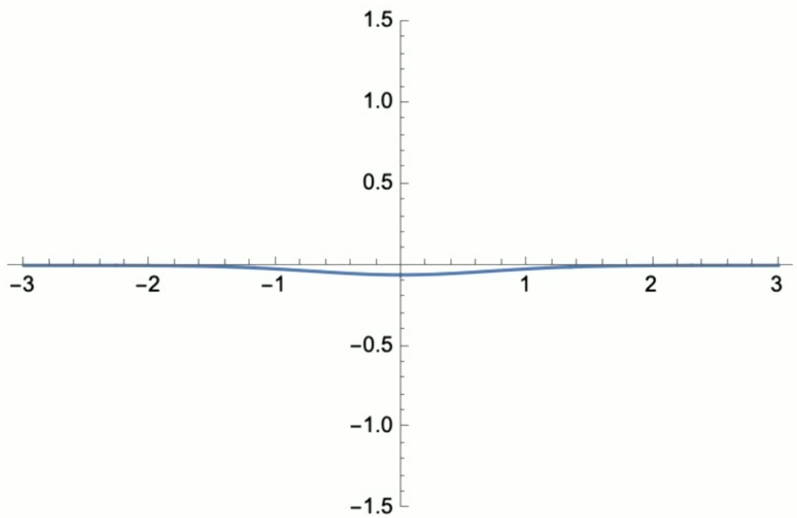


- A general argument (Aguirre, Carroll + MCJ: 1108.0417):

The most likely formation history of a rare fluctuation away from equilibrium is the time-reverse of decay back to equilibrium.

Bubble nucleation pre-cursors (Pirvu, Sibiryakov + MCJ: 2312.13364)

- Prediction from 1108.0417: Oscillon pre-cursor

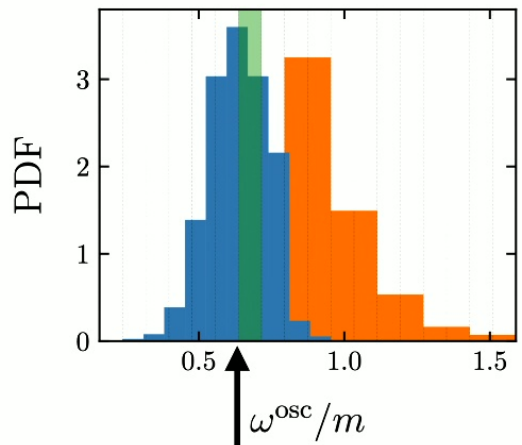


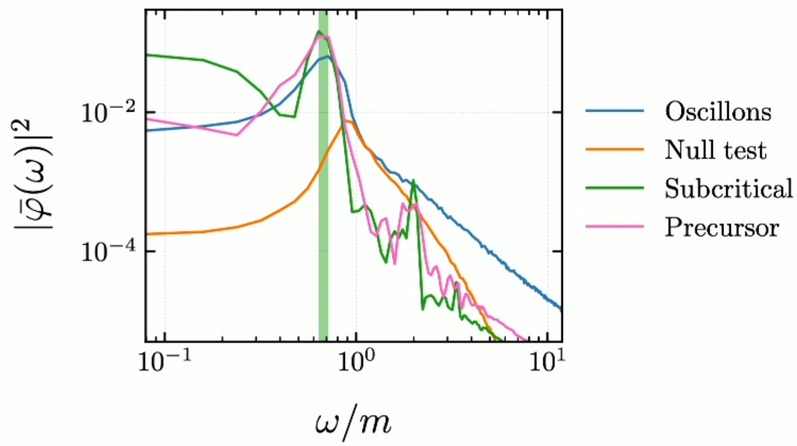
The genesis of oscillons (Gleiser 94)!

Bubble nucleation pre-cursors

(Pirvu, Sibiryakov + MCJ: 2312.13364)

- Spectral evidence for pre-nucleation bound state:





$\omega^{\rm osc} < m$ ⟶ **Bound state**

A fun thought experiment

- Can one build a 'Universe Decay Detector?'
- If I built one, could observation cause the Universe to decay (would it seed decay) or extend its lifetime (quantum Zeno)?

Conclusions

- Lots to learn about vacuum decay!
- What can we observe?
- Quantum vs thermal?
- Cosmology?
- Quantum simulation - results coming!
- Other quantum hardware?