Gravitational waves from early universe first order phase transitions

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Based on arxiv:2107.05657

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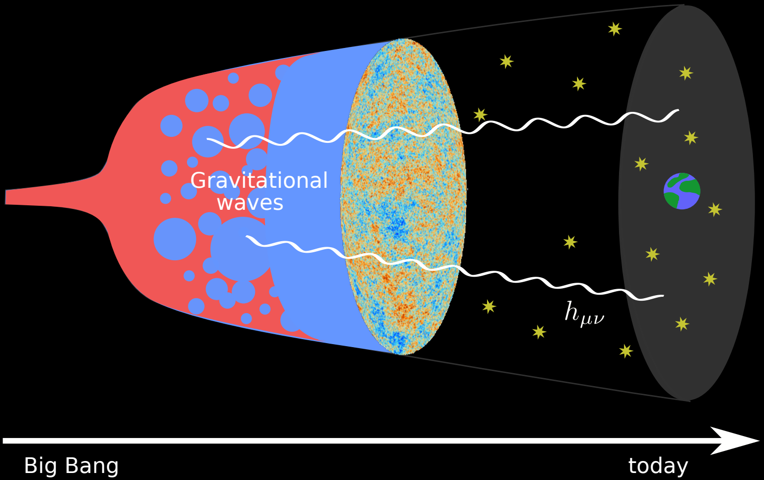


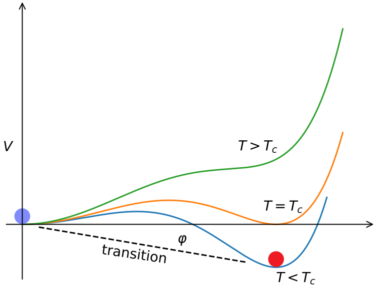
Picture: Oliver Gould

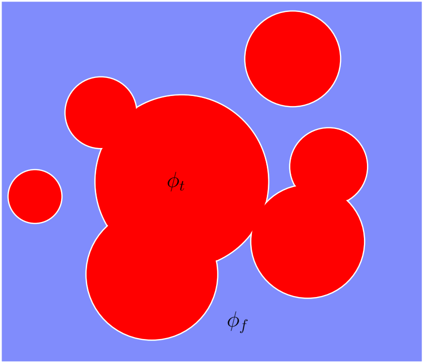
Early universe phase transitions

- Symmetry breaking transformations in the early universe
  - GUT, electroweak, QCD, dark sectors, etc.
- Standard model is incomplete
  $\Rightarrow$ Beyond the SM
- Detectable (or constrained) by gravitational waves

1st order phase transition

- Universe cools down
- Phases separated by a potential barrier
- Nucleates bubbles
- Bubbles begin to expand and collide with each other



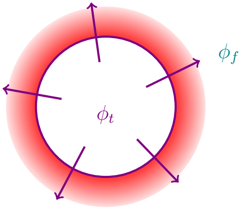


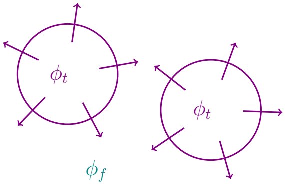
Nucleation and expansion

- Nucleation triggered by quantum or thermal fluctuations
  $\Rightarrow$ Critical bubble

- Bubbles in plasma
- Friction from fluid slows the expansion
- Terminal wall velocity

- Vacuum bubbles
- Field doesn't couple to plasma or effect negligible
- Bubble wall accelerates until collision.





Gravitational waves

- Produced by first order phase transitions
  - Gradient energy of scalar field
  - Sound waves in fluid plasma
  - Turbulence
- Possibly observable with future interferometers

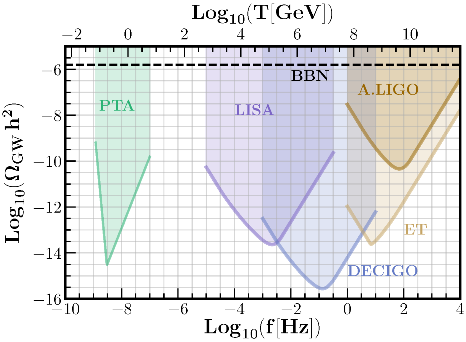
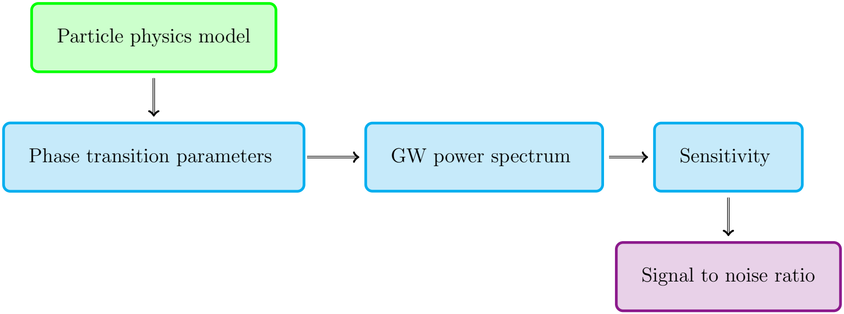


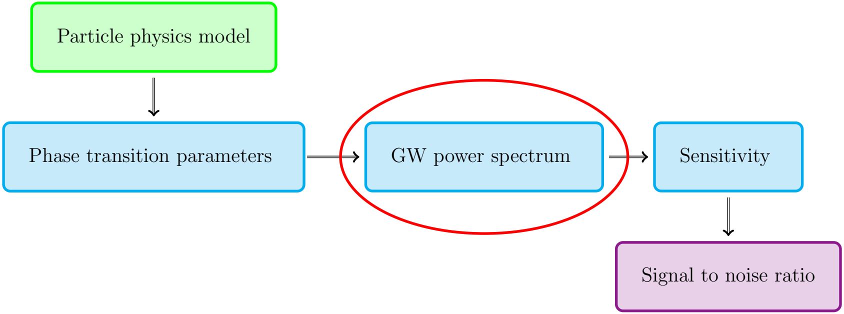
Figure: [arxiv:2109.01398]

Phase transitions to measurements



Modified from arxiv:1910.13125

Phase transitions to measurements



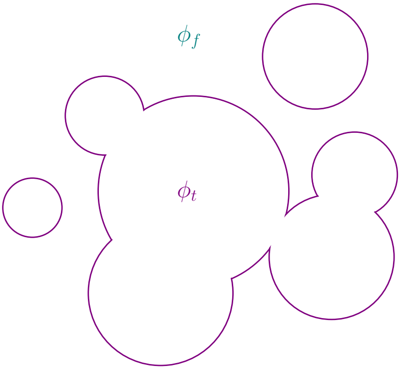
Modified from arxiv:1910.13125

- Numerically simulating vacuum bubbles

The gravitational wave spectrum

- Large 3+1 dimensional simulations are very expensive
- Envelope approximation

  Kosowsky & Turner, 1992
  - Stress-energy tensor in infinitesimally thin bubble wall
  - Ignore regions where bubbles overlap



Vacuum bubble dynamics

- Collisions are highly energetic
- When bubbles collide, the collision area can behave nonlinearly
- Specific features of bubble collisions depend on the potential parameters

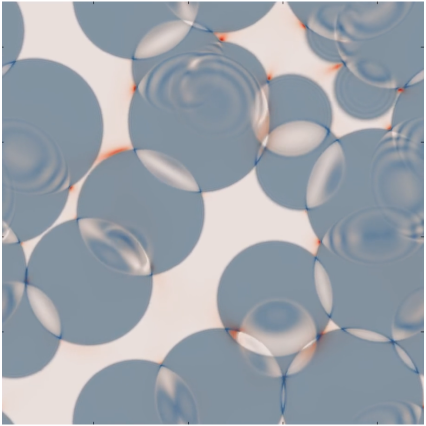


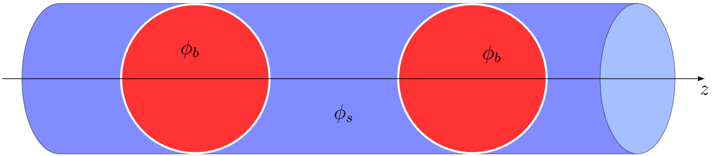
Figure: [Cutting]

Two bubbles

- Simplest scenario that produces gravitational waves

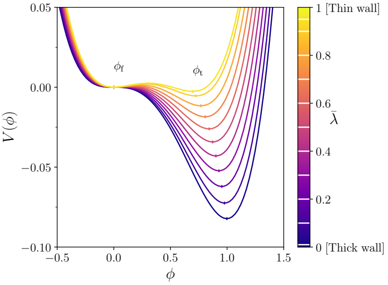
Hawking, Moss & Stewart, 1982

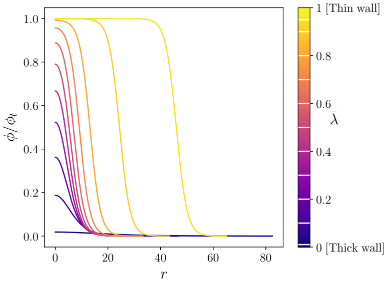
- What happens in a single collision
    - More precise information on the field behaviour in the collision area
- Symmetries $\Rightarrow$ dimension reduction
    - Hyperbolical coordinates, simulation in 1+1 D



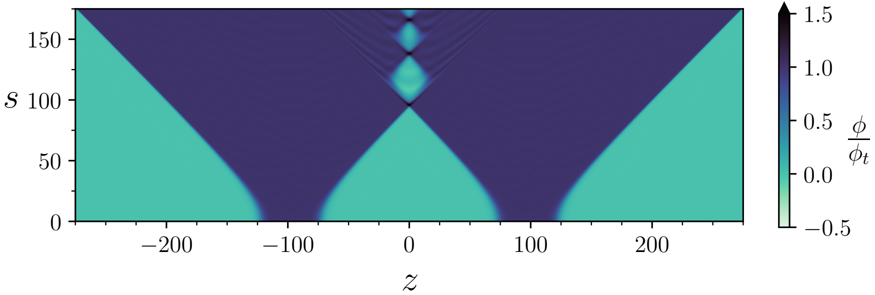
Thin and thick wall bubbles

- Two main categories: thin and thick walled bubbles
- Depends on the potential parameters
- Different behaviour while expanding and colliding

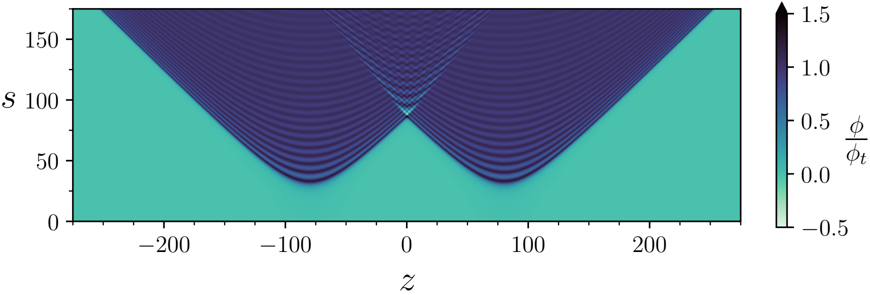




Thin wall bubbles

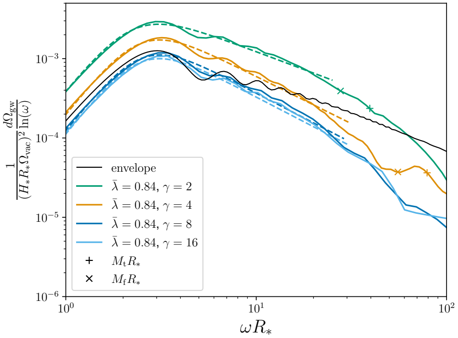


Thick wall bubbles

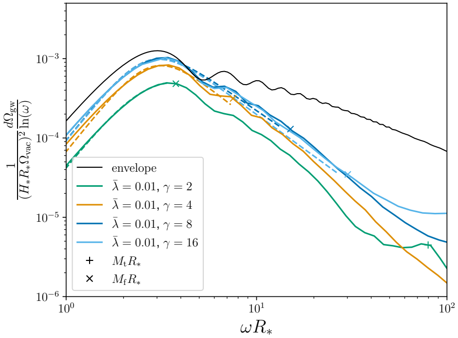


Gravitational wave spectrum

Thin wall



Thick wall

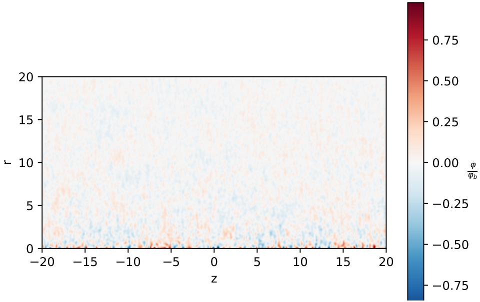


- Steeper high-frequency power law produced by thick wall bubble collisions

Including thermal fluctuations

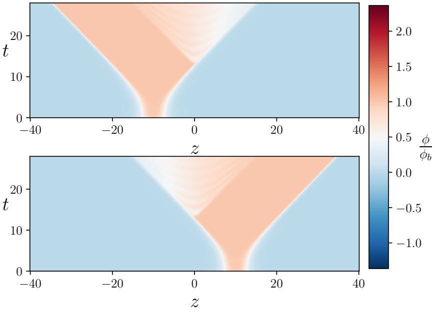
work with Oliver Gould,
Paul Saffin & David Weir

- Thermal fluctuations around the false minimum
- Hyperbolic symmetry broken $\Rightarrow$ Cylindrical coordinates
- Angular dependence ignored
- Working in O(N) field theory

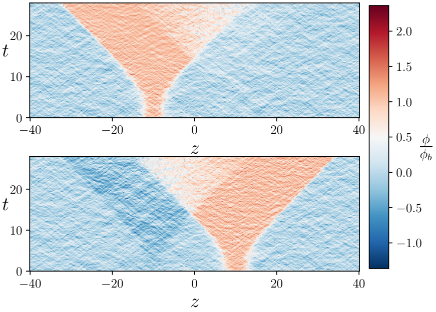


Field evolution

O(2) without fluctuations

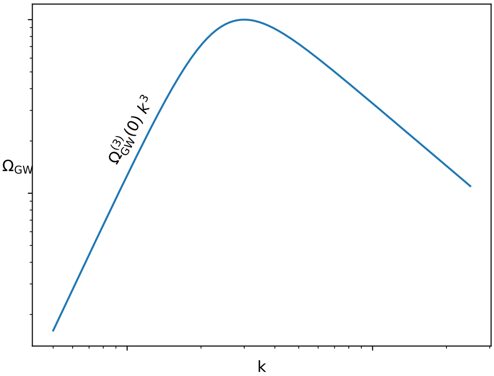


O(2) with fluctuations

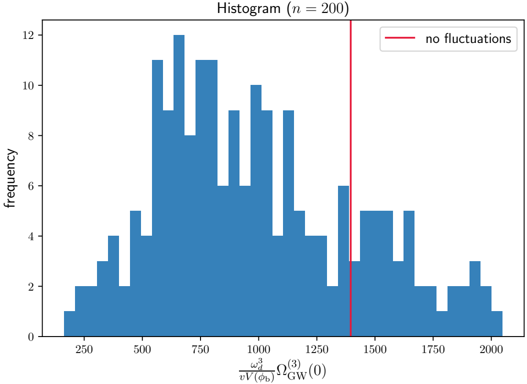


Gravitational wave proxy

- Proxy measure $\Omega_{\mathrm{GW}}^{(3)}(\omega = 0)$ for the gravitational waves
- Information without doing the tedious gravitational wave spectrum calculation

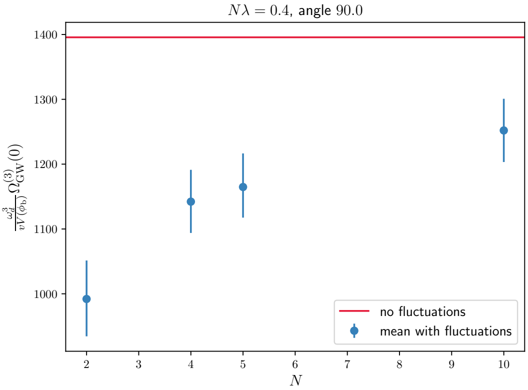


Effect of fluctuations



- On average a smaller gravitational wave proxy when simulation includes fluctuations

Preliminary results of O(N) dependence



- Dependence on N seems to exist

Summary

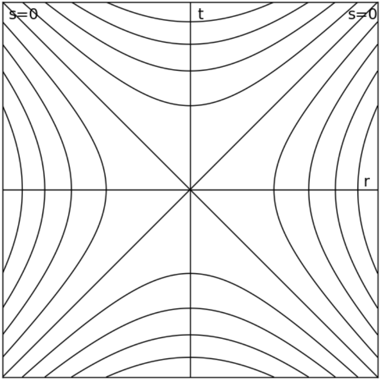
- First order phase transitions may have occurred in the early universe
- Future gravitational wave observations can detect traces of early universe events
- Simulations are necessary for finding the characteristics of a specific kind of phase transition

Thank you!

Backup: Hyperbolical coordinates

- $z = z$
- $s = |r^2 - t^2|$, $r^2 = x^2 + y^2$

- Dimension reduction
  - Takes into account all four dimensions
  - Code in 1+1 dimensions
- When $x = y = 0$, hyperbolic time $s = t$
- The equation of motion has the form: $\frac{\partial^2 \varphi}{\partial s^2} + \frac{2}{s}\frac{\partial \varphi}{\partial s} - \frac{\partial^2 \varphi}{\partial z^2} = -\frac{\partial V}{\partial \varphi}$



Backup: O(N) scalar field theory

- Field is a vector that consists of N components
- Due to symmetries, we can set bubbles so that the first bubble is in component 1 of the O(N) field, second bubble in components one and two at some angle relative to the first bubble
  - If only two bubbles O(N)=O(2)

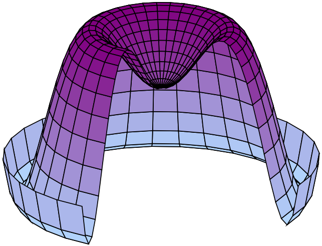


Figure: Potential in O(2).

Backup: Fluctuating field

- Random complex mode coefficients from a temperature dependent Gaussian distribution
- Cutoff in energy
- Find real field via a cylindrical Klein-Gordon transformation
    - a sum of Fourier and complex conjugate in the z direction
    - Hankel transformation in the cylindrical radial direction.