Gravitational Waves from first-order Phase Transitions in the Early Universe

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Seminar in particle physics and astrophysical sciences course

26.02.2025

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Introduction

- **Gravitational waves (GWs):** Ripples in space-time that propagate at the speed of light and were predicted by Albert Einstein in 1916.

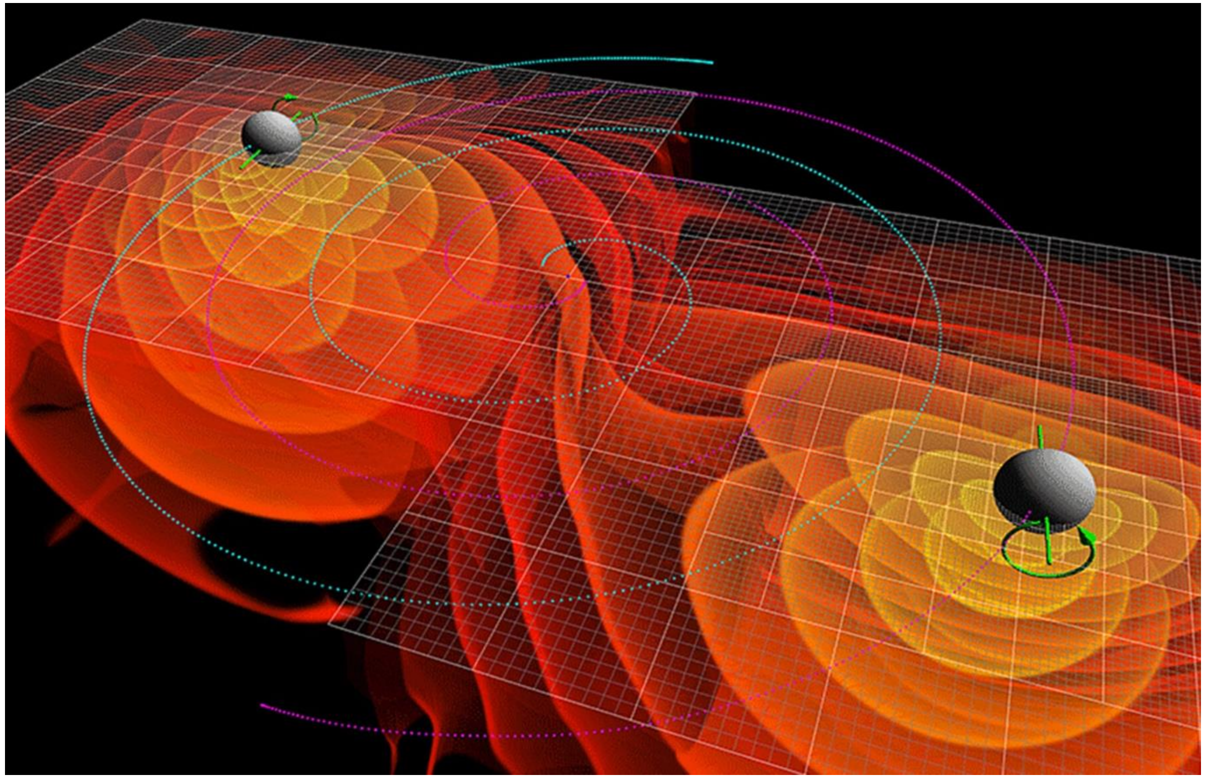

Image credit: Courtesy of C.Henze/ NASA Ames research center

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Why GWs Matter?

- **Cosmic Microwave Background (CMB):** The leftover glow of the first light that moved freely in the Universe, generated 380 000 years after the Big Bang.

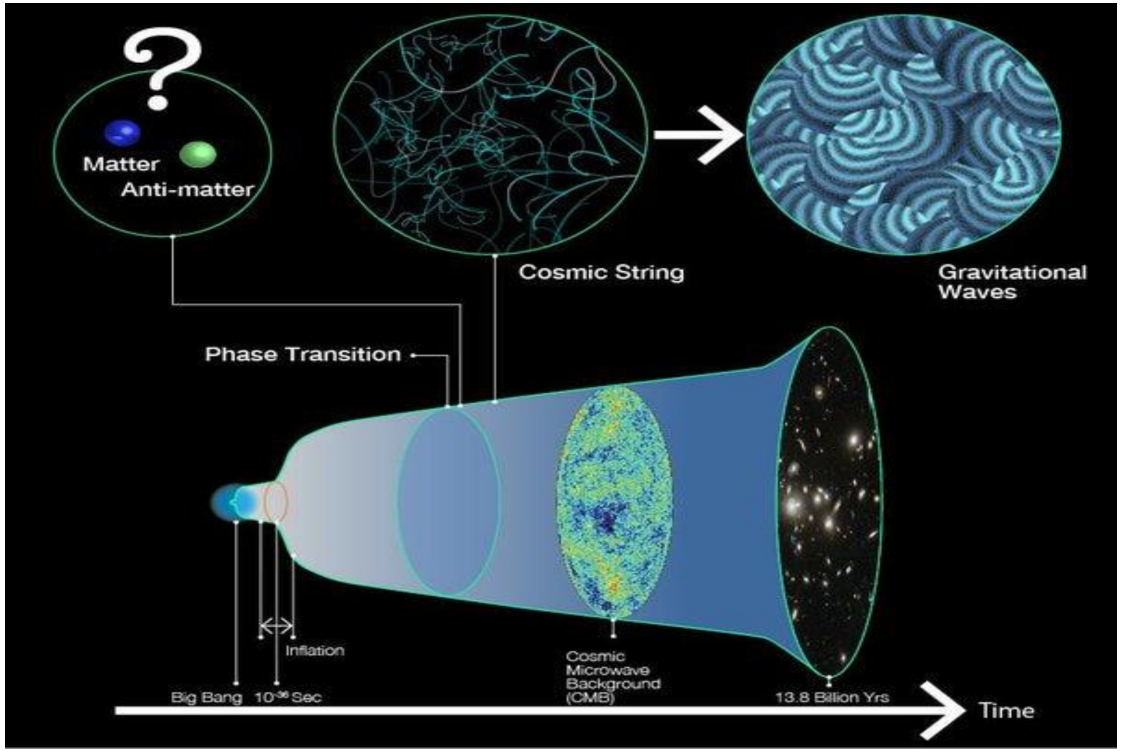

Image credit: R.Hurt/Caltech-JPL, NASA, and ESA

Phase transitions (PTs)

- **1st-order PTs:** A sudden, sharp change in a system's properties, with releasing or absorbing the latent heat and creation of bubbles.
- **2nd-order PTs:** A gradual and smooth change without a sudden jump in properties.

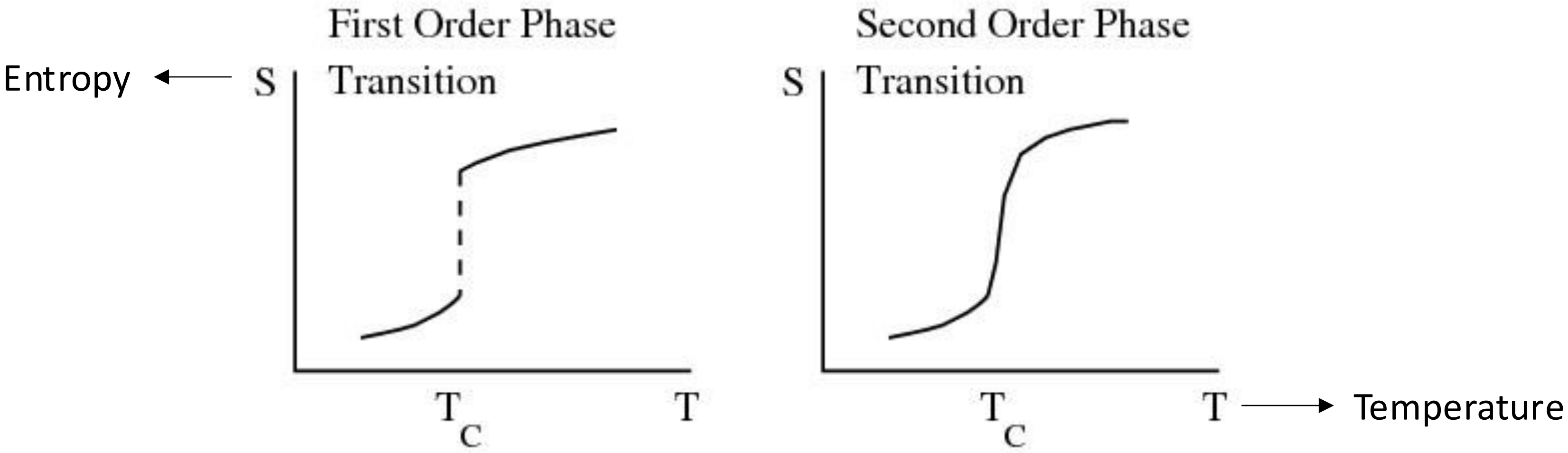

Image credit: UCI school of physical sciences

GW Generation Mechanisms

- **Bubble collisions:** Expanding bubbles of the new phase collide, releasing energy and producing GWs.

  The bubbles expand and collide until the universe has transitioned into the true vacuum phase (Enqvist et al. 1992).

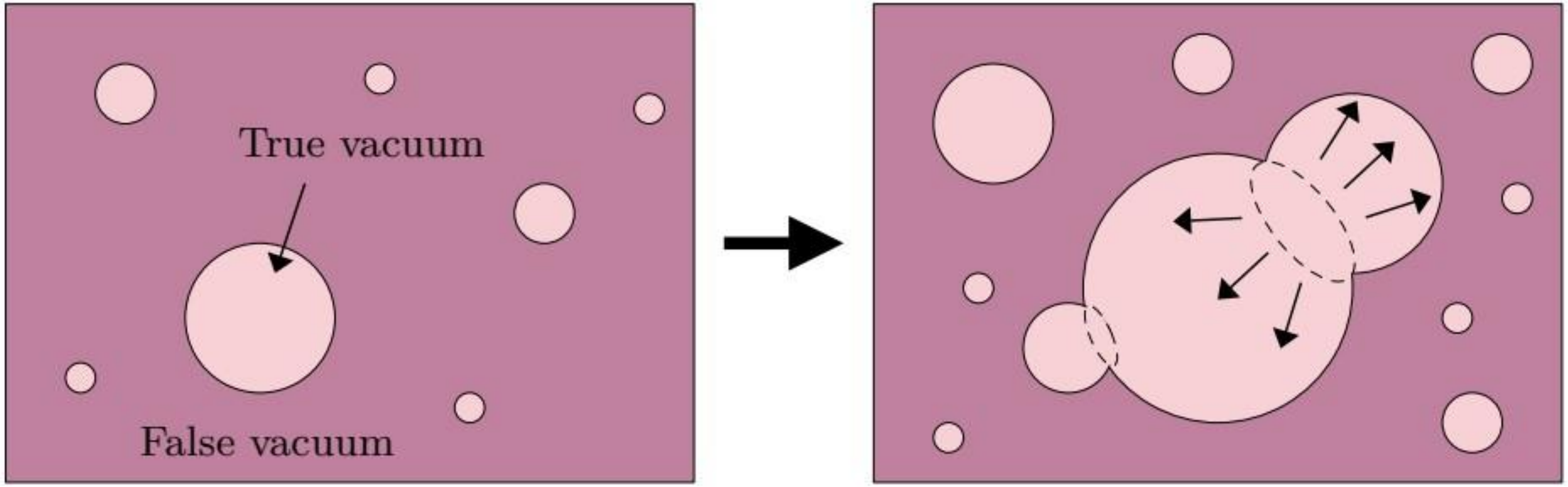

Image credit: (Enqvist et al. 1992)

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Generation mechanism

- **Sound waves:** The motion of the plasma after bubble collisions creates long-lasting sound waves, which become a dominant source of GWs (Fornal et al. 2020).
- **Turbulence:** The chaotic movement of plasma that stirs the cosmic fluid, generating additional GWs (Fornal et al. 2020).

Sound waves signal without the suppression factor

GW energy density spectrum

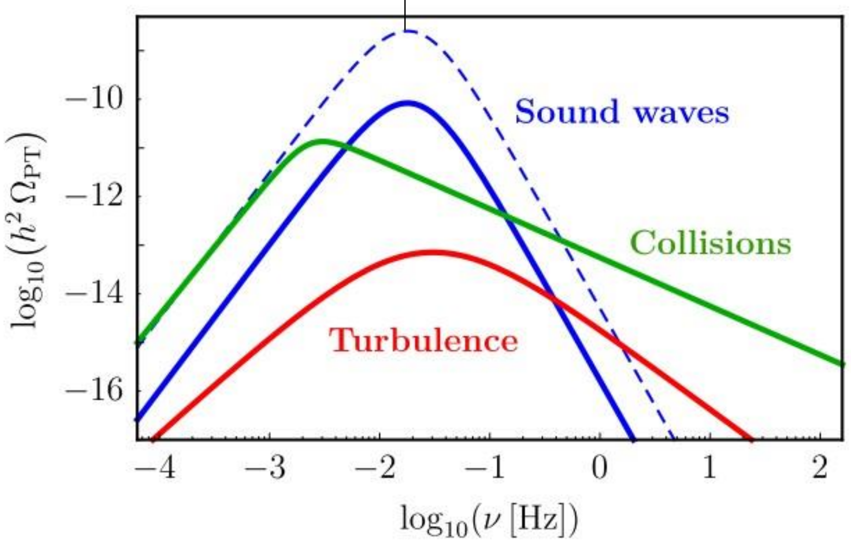

Image credit: (Fornal et al. 2020)

Theoretical model

- **Sound Shell Model (SSM):** Describes how sound waves from a 1^{st}-order PT in the early universe generate GWs (Croon et al. 2025).

- **Assumptions**
  1. Dominance of sound waves
  2. Efficient energy transfer
  3. Neglects early turbulence

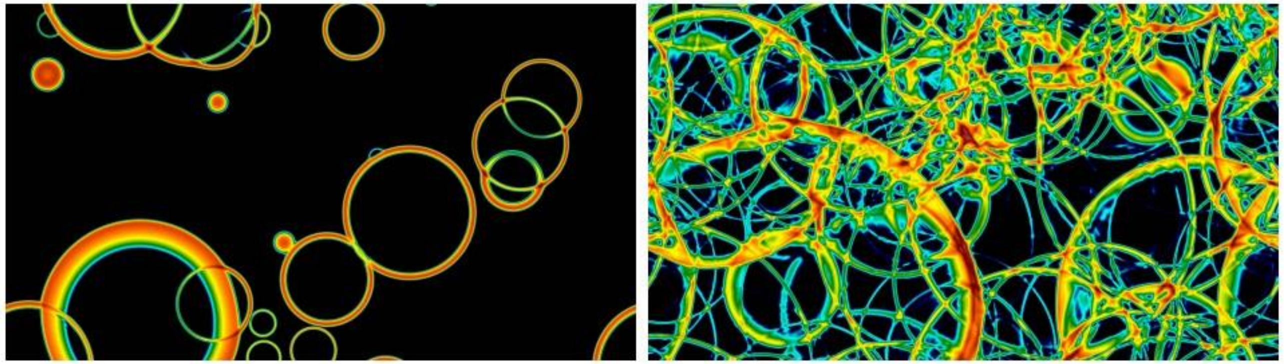

Image credit: Weir, 2018

Crucial parameters

- **Phase transition strength (α):** measures the ratio of the released energy to the energy of the plasma.

  Larger α (α >>1): More energy is available for bubble expansion, leading to stronger gravitational wave (GW) signals.

  Smaller α: Weaker phase transitions with a lower GW amplitude.

- **Wall velocity (v_w):** The speed at which the bubble walls expand during the phase transition (Hindmarsh et al. 2019).

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Different scenarios

- **Deflagration:** A type of bubble expansion where the bubble walls move slower than the speed of sound in the plasma ($v_w < c_s$).

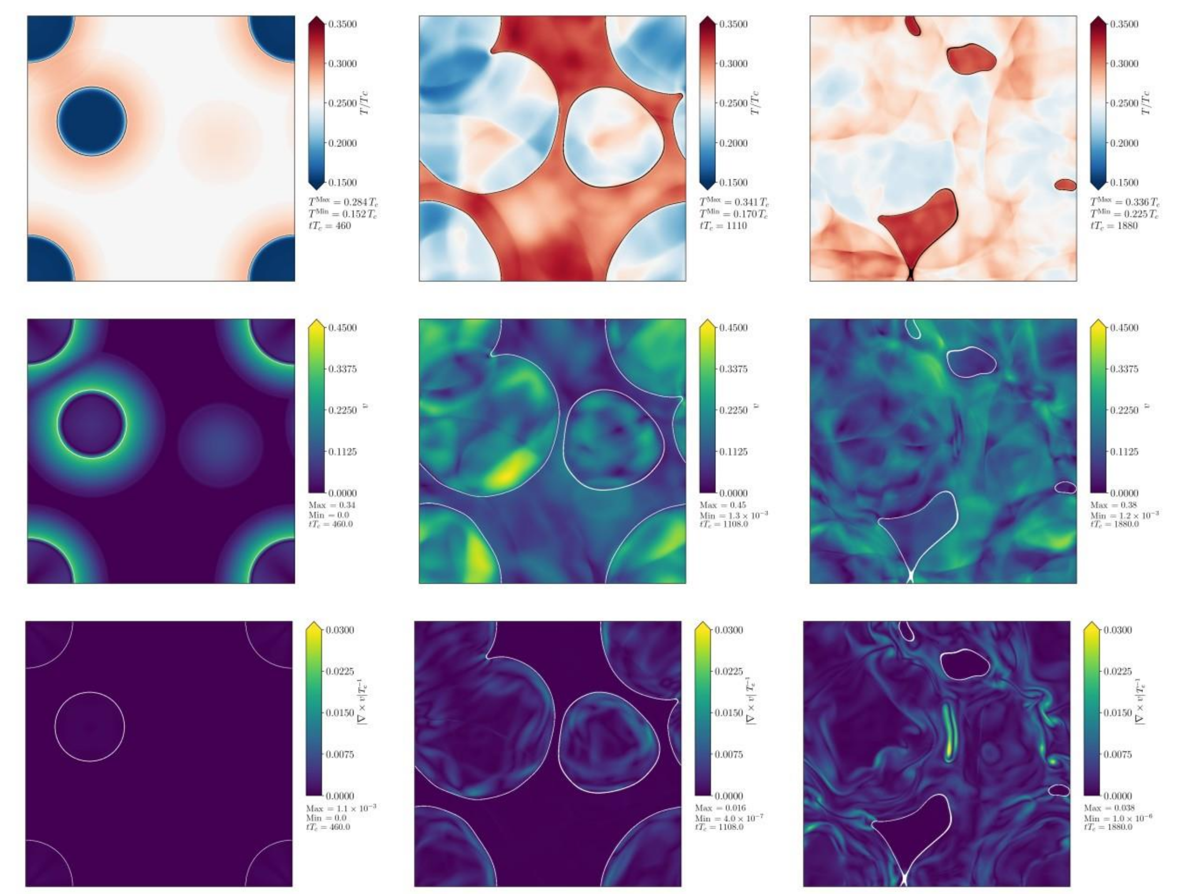

Image credit: Cutting et al. 2020

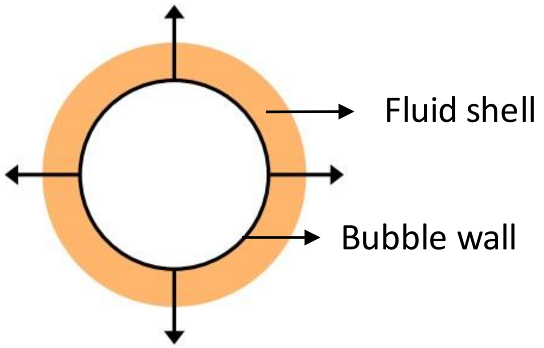

Image credit: Espinosa et al. 2010

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Different scenarios

- **Detonation:** A type of bubble expansion where the bubble walls move faster than the speed of sound in the plasma ($v_w > c_s$).

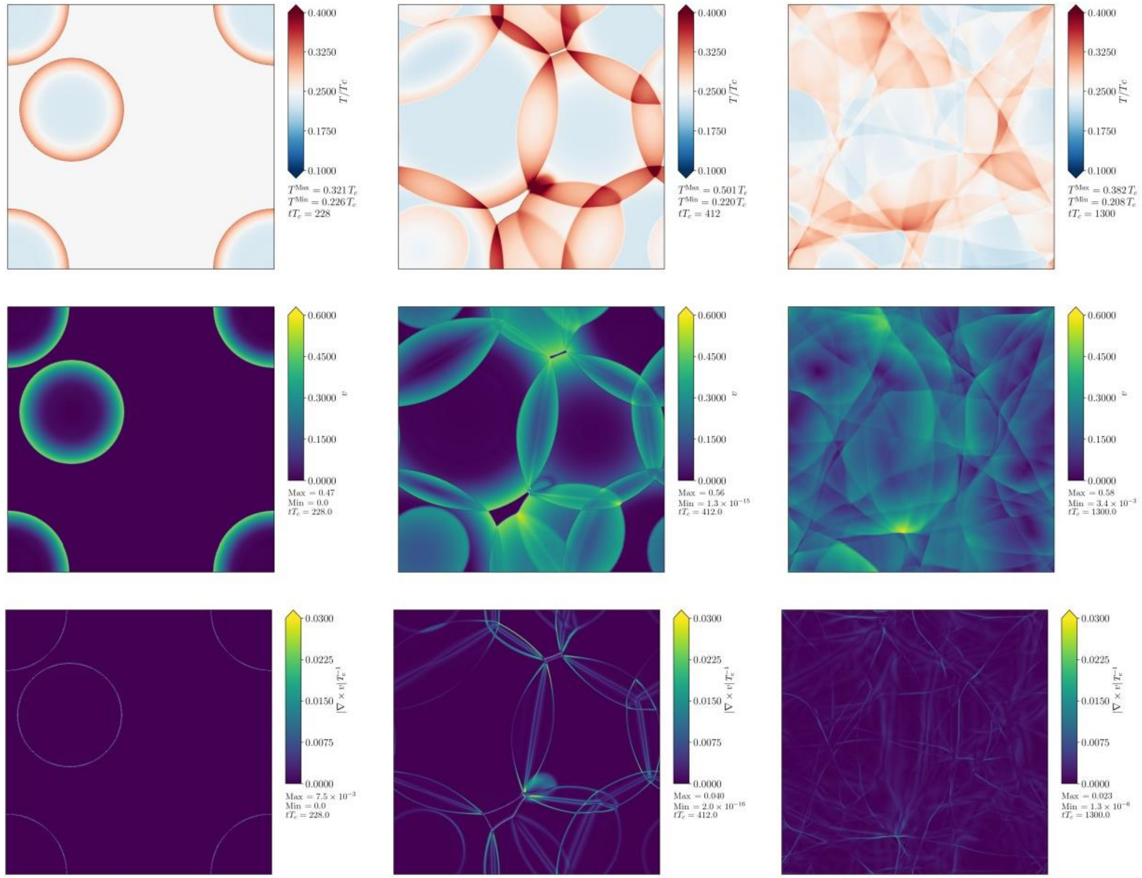

Image credit: Cutting et al. 2020

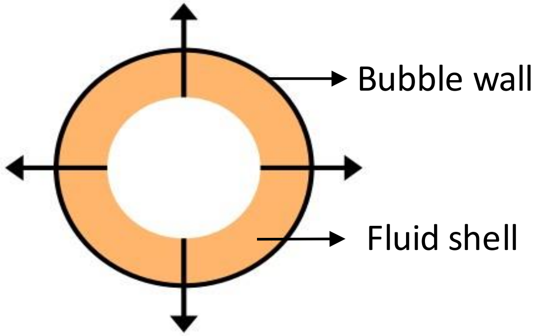

Image credit: Espinosa et al. 2010

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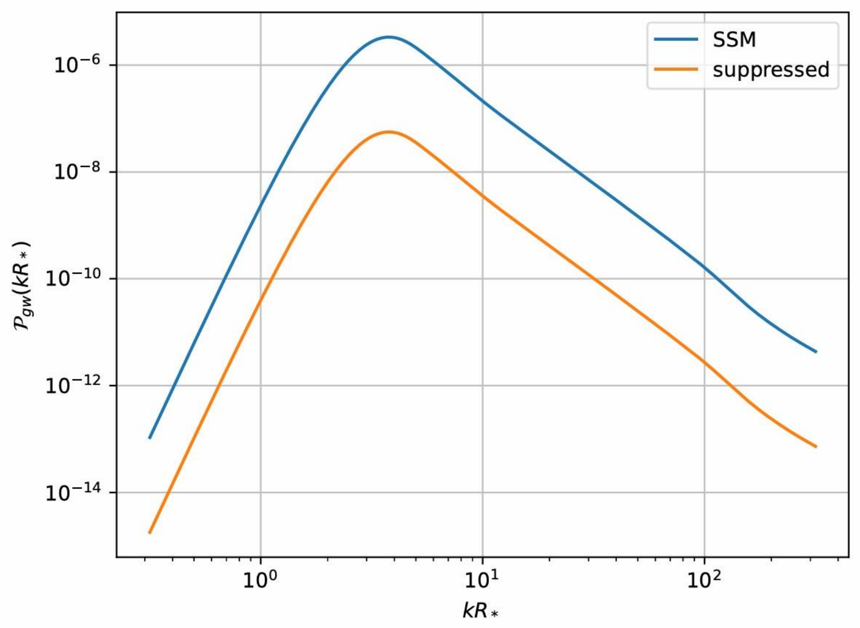
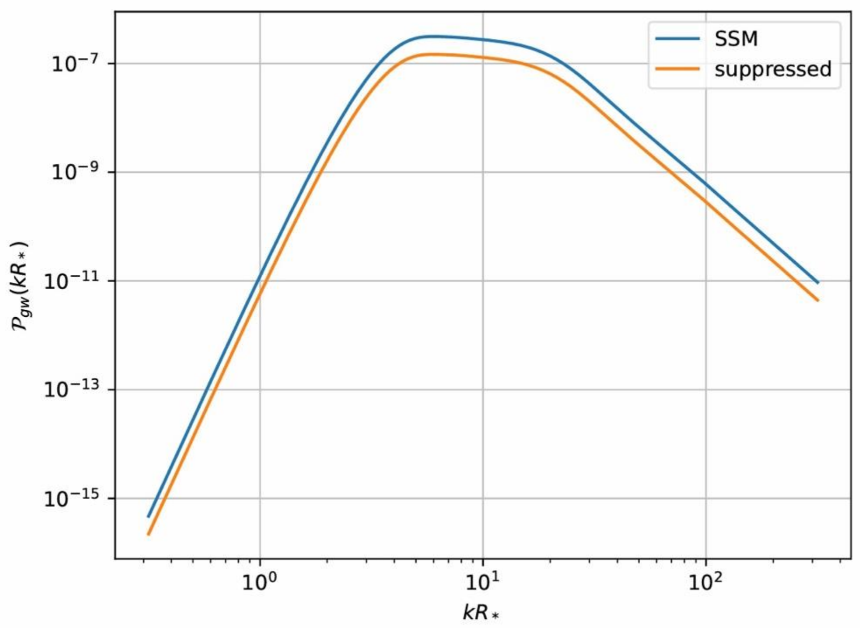
PTTools

- **SSM:** All kinetic energy from the phase transition is converted into sound waves, which then source gravitational waves.
- **Suppressed:** Adjusted version of the power spectrum, where additional physical effects are taken into account.



α = 0.005 , vw = 0.24



α = 0.005 , vw = 0.82

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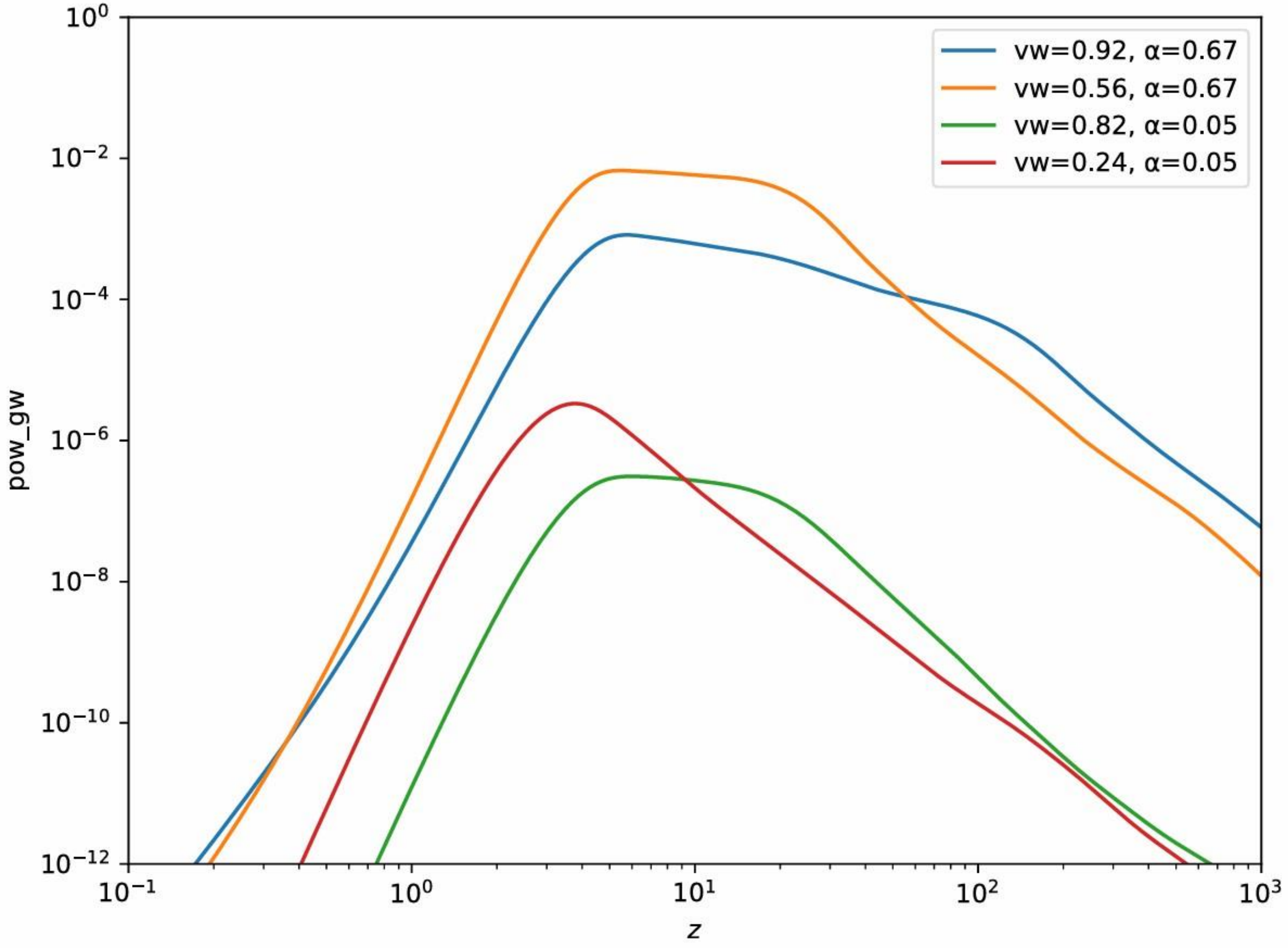
PTTools

How wall velocity (v_w) and phase transition strength (α) affect gravitational waves power spectrum:



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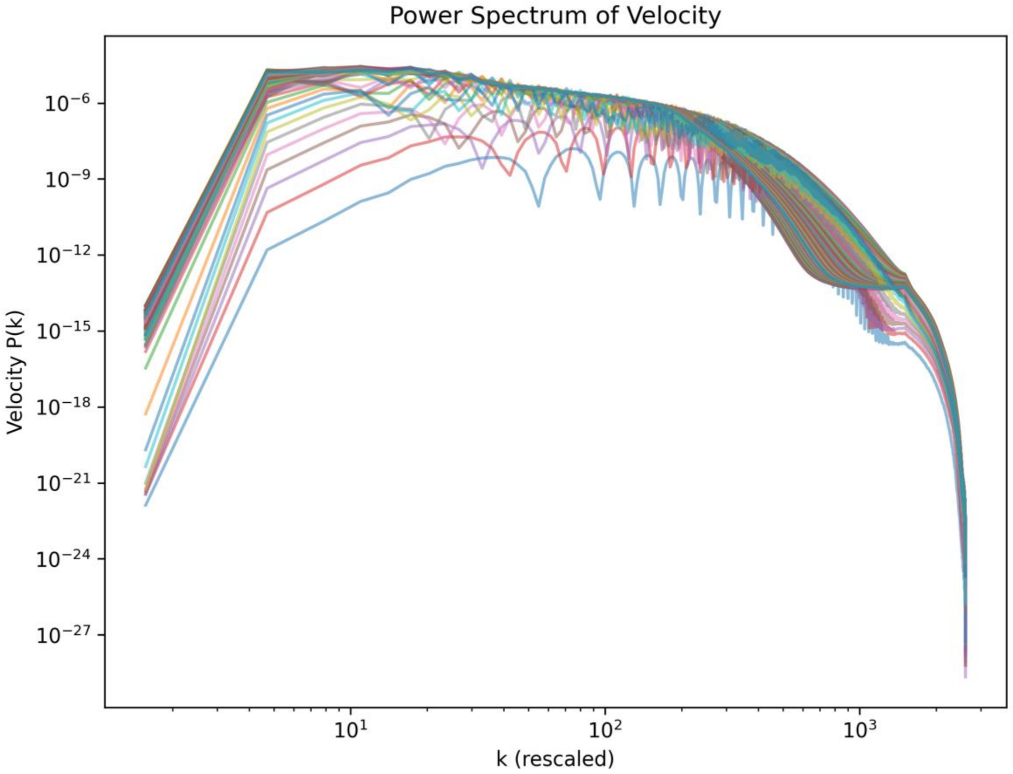
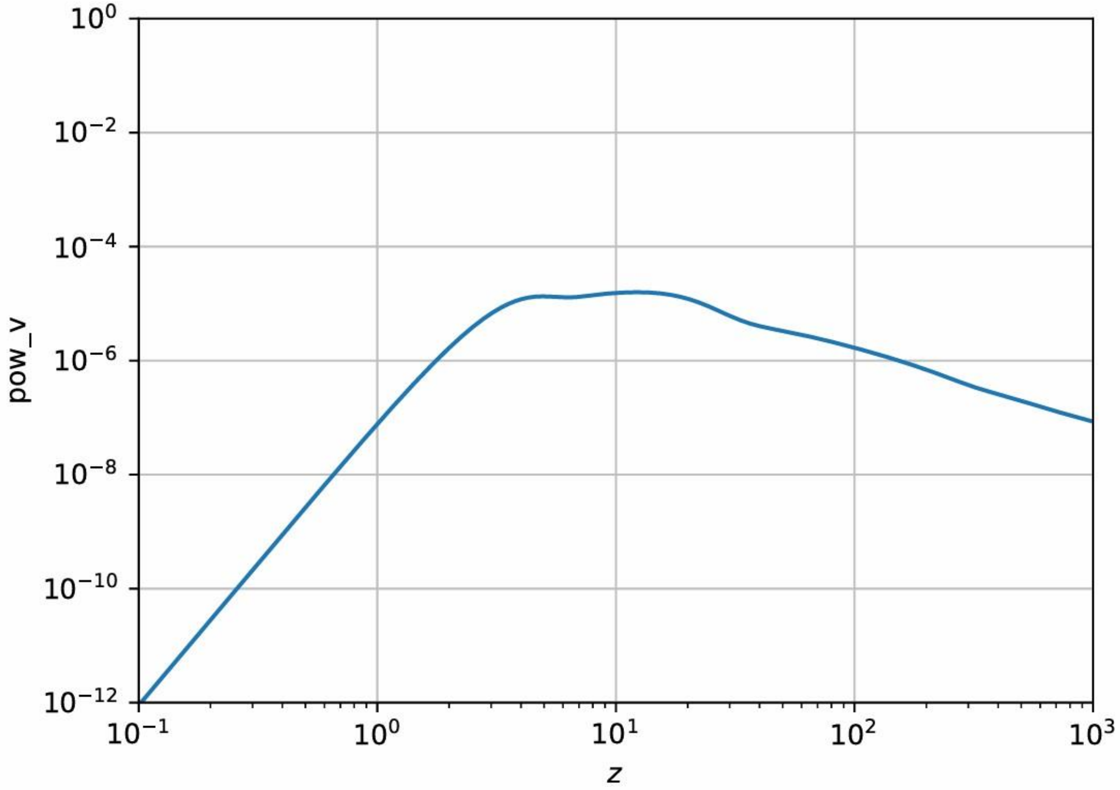
PTTools

Sound shell model (SSM) is a good framework for studying gravitational waves:





$\alpha = 0.005$, $vw = 0.82$

Future Prospects

- **LISA (Laser Interferometer Space Antenna):** The first space-based GW detector, designed to detect mHz-frequency waves, ideal for signals from early universe phase transitions (Caprini et al. 2020).

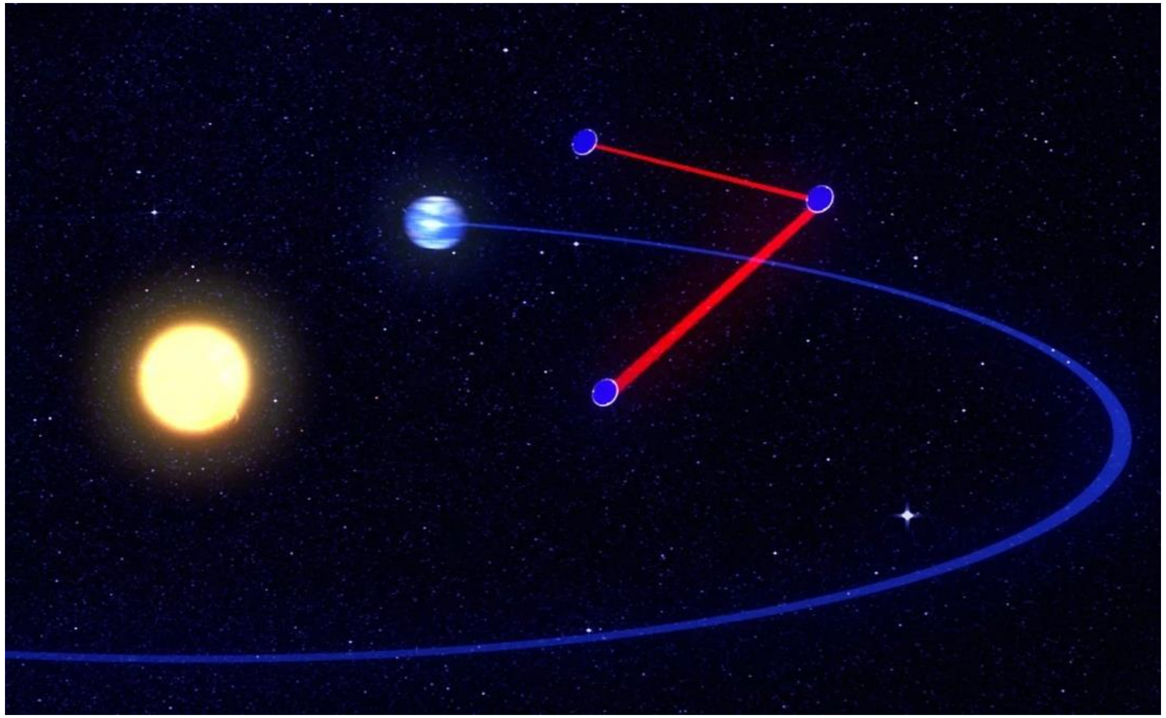


Image credit: Max Planck Institute for Gravitational Physics

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Take-home message

- Gravitational waves from first-order phase transitions offer a new way to study the early universe beyond the CMB.
- Understanding gravitational waves from phase transitions bridges cosmology and particle physics, revealing new physics beyond the Standard Model.
- The Sound Shell Model (SSM) shows that sound waves dominate GW production, influenced by phase transition strength (α) and wall velocity (v_w).
- Future detectors like LISA could detect these signals, unlocking new physics and revealing the universe's earliest moments.

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Thank you for your attention and engagement!