Gravitational effects in First Order Phase Transitions

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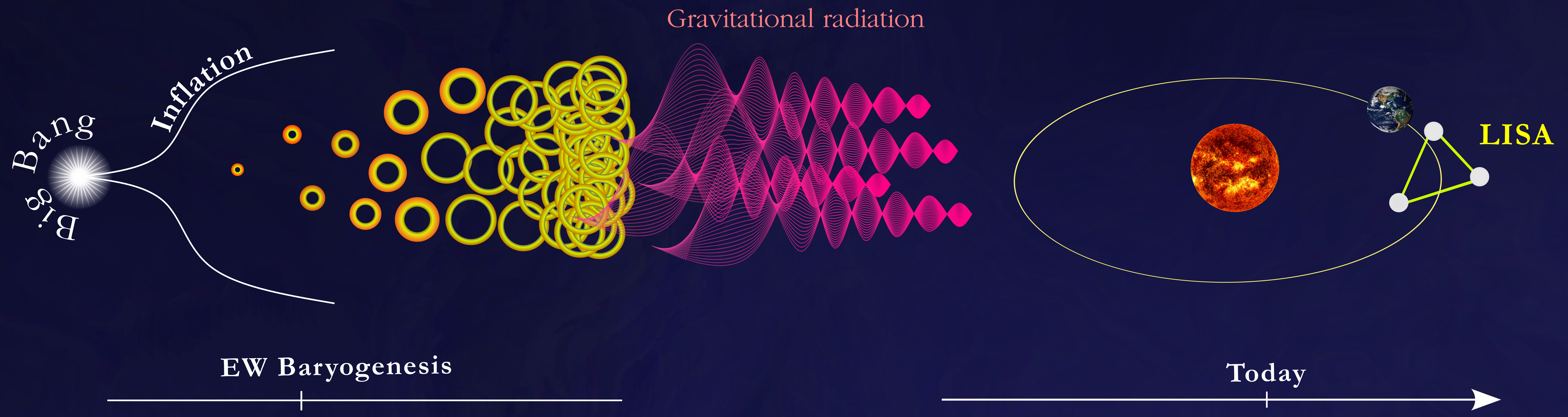
Sound waves from first order phase transitions

Cosmological first order phase transitions proceed with the formation, expansion and merging of bubbles comprising a low-temperature phase. During the expansion, the free energy difference between the two phases is converted into kinetic and thermal energy of the fluid. Shells of compression and rarefaction are formed around the bubbles and propagate in the plasma forming long-lasting sound waves. These become source of anisotropic stress and thus gravitational radiation [1,2]. Numerical simulations indicate that sound waves are the dominant contribution to the gravitational wave power spectrum [3-5]. Other sources, not considered in this project, are the collision between bubbles' interfaces and vortical turbulence.



The Large Bubbles regime: motivations

1) LISA (Laser Interferometer Space Antenna) frequency band 0.1 mHz - 10 Hz can test physics at the electroweak scale [6].

If the nucleation process is slow enough, bubbles can grow to sizes comparable with the causal Universe, where the effects of space-time curvature and self-gravity of the fluid become relevant. Moreover:

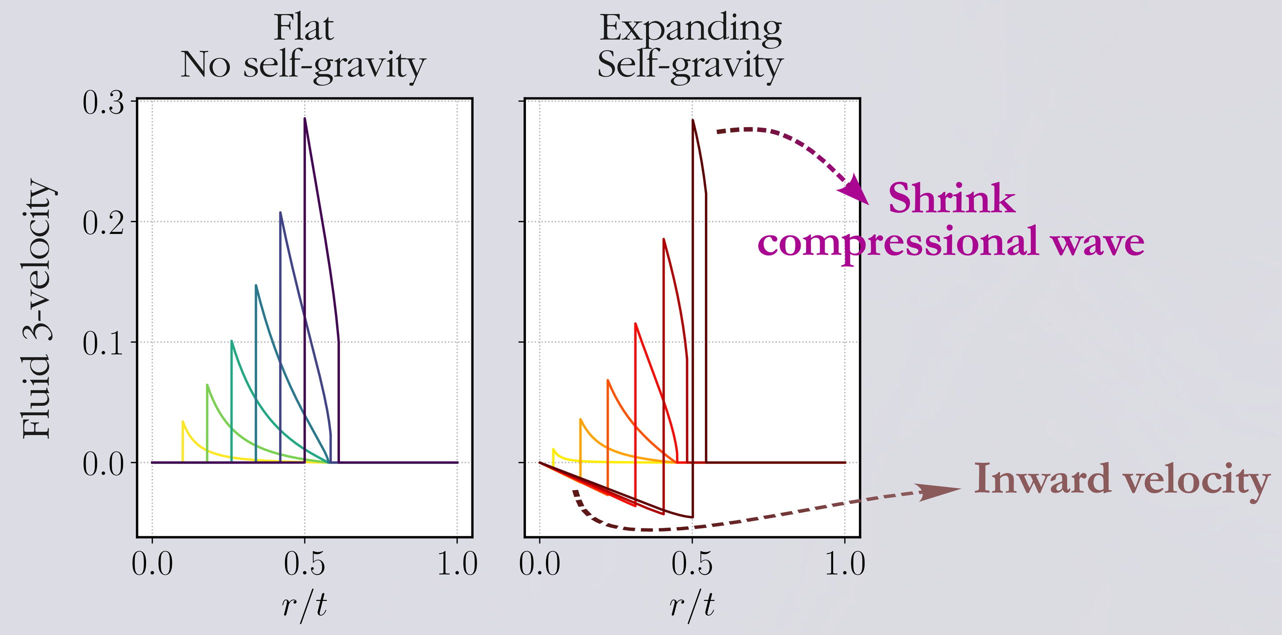
2) The amplitude of **primary gravitational waves** from sound waves increases with the bubble radius [6].

3) Secondary gravitational waves induced by curvature perturbations become relevant [7].

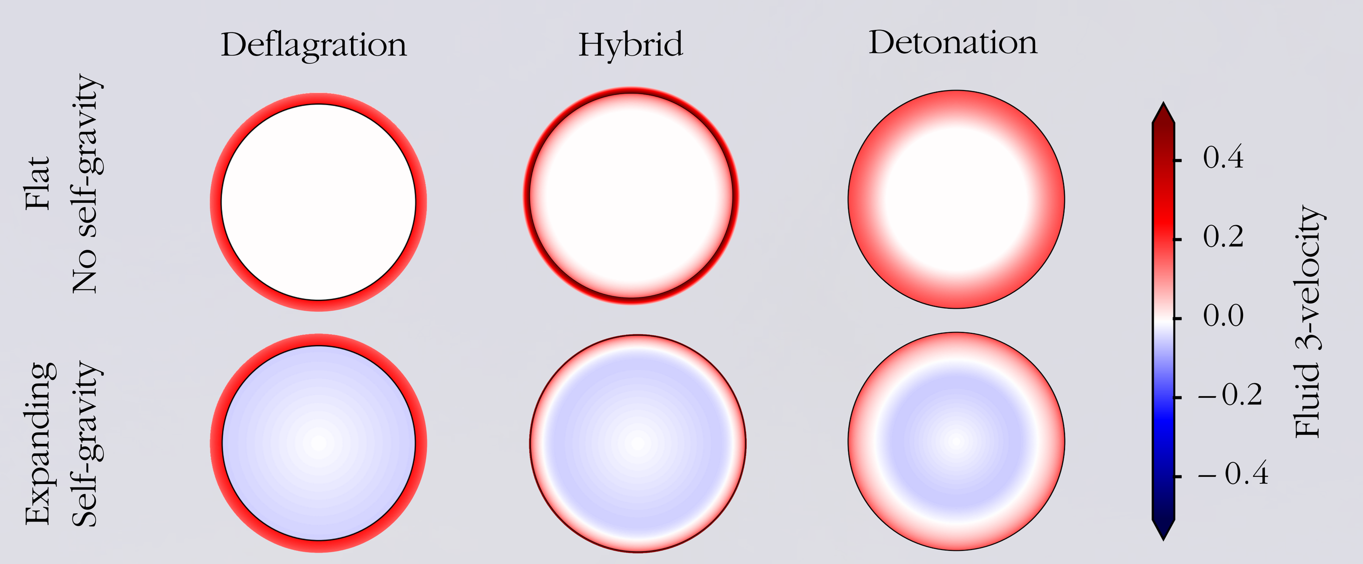
1. Expansion dynamics

Self-similar fluid profile of individual bubbles growing into an **expanding Universe** with full General Relativity. **Self-gravity** modifies the dynamics of the fluid, with direct implications on the production of primary gravitational waves that are yet to be explored.

Want to know more?

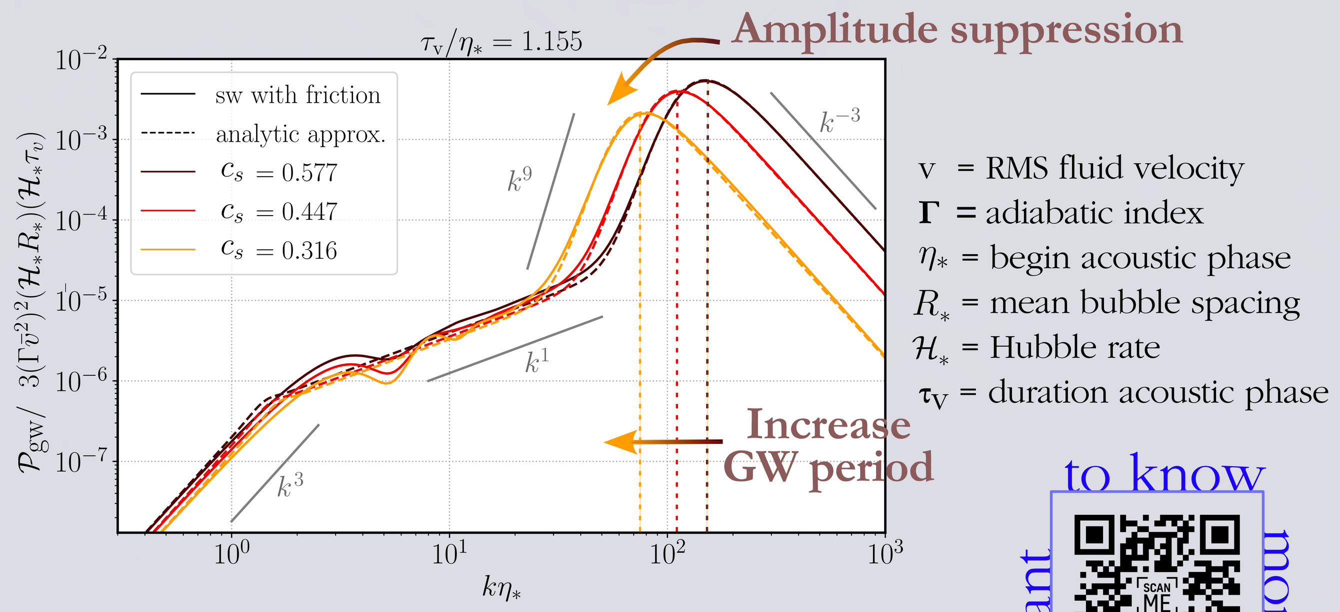


- **Inward velocity** behind the wall extends to the origin.
- **Shrinking** of the **compressional wave** in front of the wall.



2. Gravitational wave power spectrum: Speed of sound

The phase transition is accompanied by a change of equation of state from that of pure radiation. We carry out the analytic calculation of the gravitational wave power spectrum assuming that speed of sound c_s and fluid shear-stress remain stationary during the acoustic phase [8].



$\bar{v}$ = RMS fluid velocity
Γ = adiabatic index
η_* = begin acoustic phase
R_* = mean bubble spacing
$\mathcal{H}_*$ = Hubble rate
τ_v = duration acoustic phase

Want to know more?

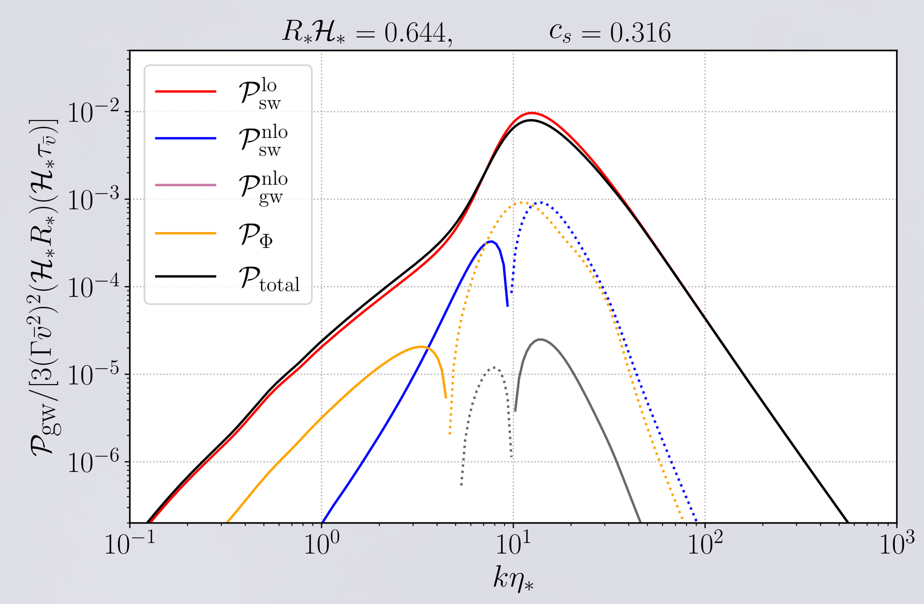
Signatures of the speed of sound:

- Increase gravitational wave period.
- Scale-independent suppression from (faster) Universe expansion rate. → **Gravitational wave energy dilution**
- Scale-independent suppression from Hubble friction in sound waves. → **Acoustic friction**

3. Gravitational wave power spectrum: Curvature perturbations

General relativistic contributions beyond the leading order in $R_*\mathcal{H}_*$ become important when the bubbles grow large $R_*\mathcal{H}_* \sim \mathcal{O}(1)$. These include:

- $\mathcal{P}^{\rm nlo}_{\rm sw}$: correction to the propagation of sound waves.
- $\mathcal{P}^{\rm nlo}_{\rm gw}$: correction to the propagation of gravitational waves.
- $\mathcal{P}_{\Phi}$: **secondary gravitational waves** from curvature perturbations.



References

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