GRAVITATIONAL WAVES FROM VACUUM FIRST-ORDER PHASE TRANSITIONS

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INTRODUCTION

- First order phase transitions proceed through bubble nucleation and merger.
- Collision of bubble walls can source gravitational waves.
- In a vacuum transition bubble walls accelerate until collision.
  - i.e Fluid effects on wall minimal, behaves as if in a vacuum.
- Previous studies mostly use envelope approximation:
  - Stress-energy concentrated in infinitesimally thin shell at bubble wall.
  - Neglect overlap regions once bubbles have collided.

[Kosowsky et al, 1992] [Huber and Konstandin, 2008][Weir, 2016] [Konstandin, 2017]

MOTIVATION

- LISA will be sensitive to gravitational waves from a first-order transition around the electroweak scale.
- Extensions to the Standard Model can generate a first order phase transition around the electroweak scale.
- Can probe BSM physics if we can characterise the GW signal.

TOY MODEL

- Single real scalar field $\phi(x,t)$ with potential as follows:

$$V(\phi) = \frac{1}{2}M^2\phi^2 + \frac{1}{3}\delta\phi^3 + \frac{1}{4}\lambda\phi^4 \,.$$

- Vary parameters $M^2, \delta, \lambda \rightarrow$ critical bubble radius R_c, and wall width l_0.
- The scalar field evolves according to:

$$\Box\phi - V'(\phi) = 0 \,.$$

- Then the energy momentum tensor is given by:

$$T_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - \eta_{\mu\nu}\left(\frac{1}{2}(\partial\phi)^2 + V(\phi)\right).$$

GRAVITATIONAL WAVES

- Transverse traceless metric perturbation evolves as

$$\Box h_{ij}^{TT} = 16\pi G T_{ij}^{TT}.$$

- $P_{\dot{h}}(\boldsymbol{k}, t)$ is the spectral density of the time derivative of h_{ij}^{TT}:

$$\langle \dot{h}_{ij}^{TT}(\mathbf{k}, t)\dot{h}_{ij}^{TT}(\mathbf{k}', t)\rangle = P_{\dot{h}}(\mathbf{k}, t)(2\pi)^3\delta(\mathbf{k} + \mathbf{k}').$$

- Then the gravitational wave density parameter power spectrum is

$$\frac{d\Omega_{GW}}{d\ln(k)} = \frac{d\rho_{GW}}{d\ln(k)}\frac{1}{\rho_c} = \frac{1}{32\pi G\rho_c}\frac{k^3}{2\pi^2}P_{\dot{h}}(\mathbf{k}, t).$$

INITIAL CONDITIONS

- Different nucleation scenarios:
  - simultaneous
  - constant nucleation rate

$$p(t) = p_{\mathrm{c}}$$

  - exponential nucleation rate

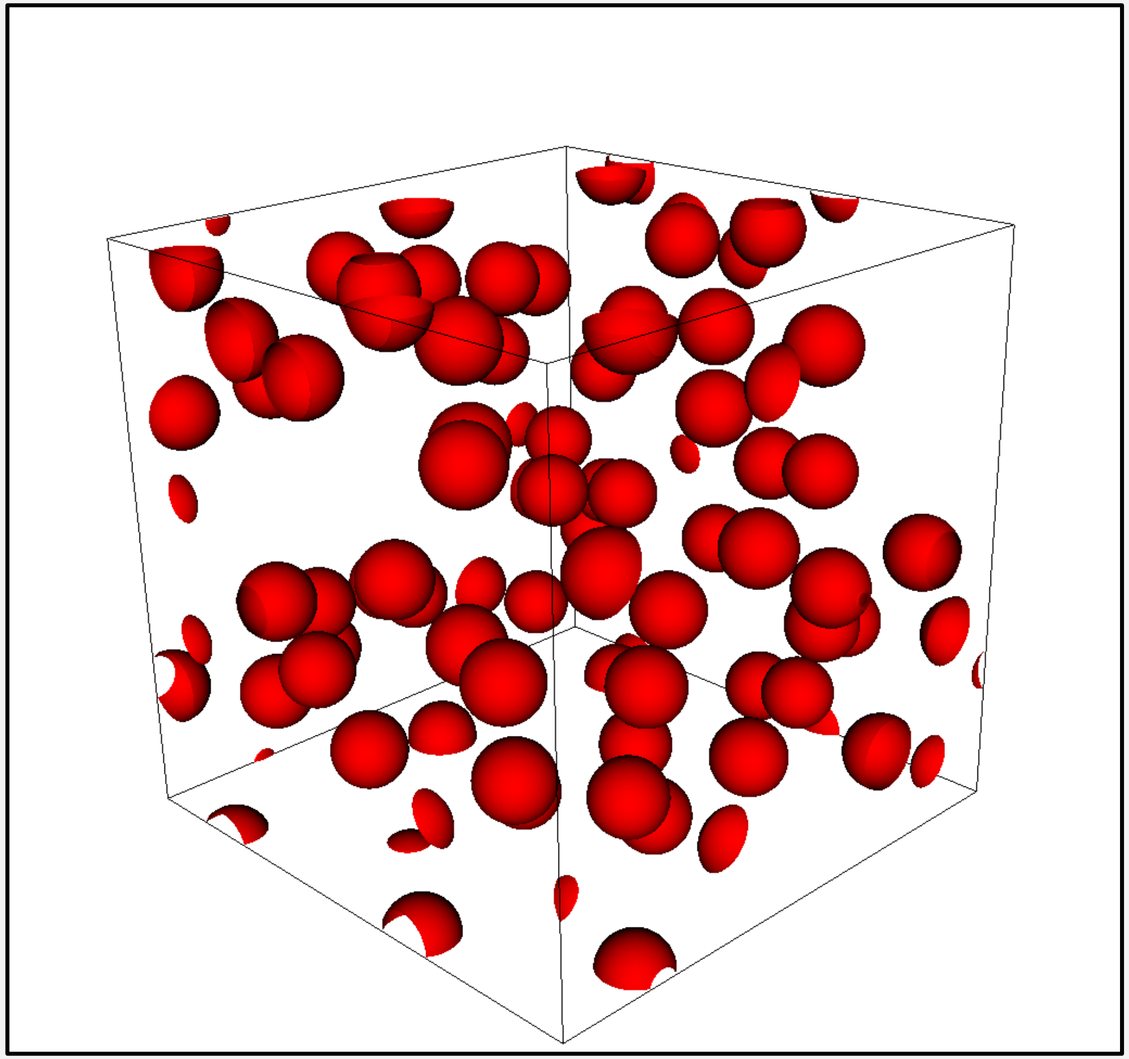
$$p(t) = p_0 \exp(\beta t)$$

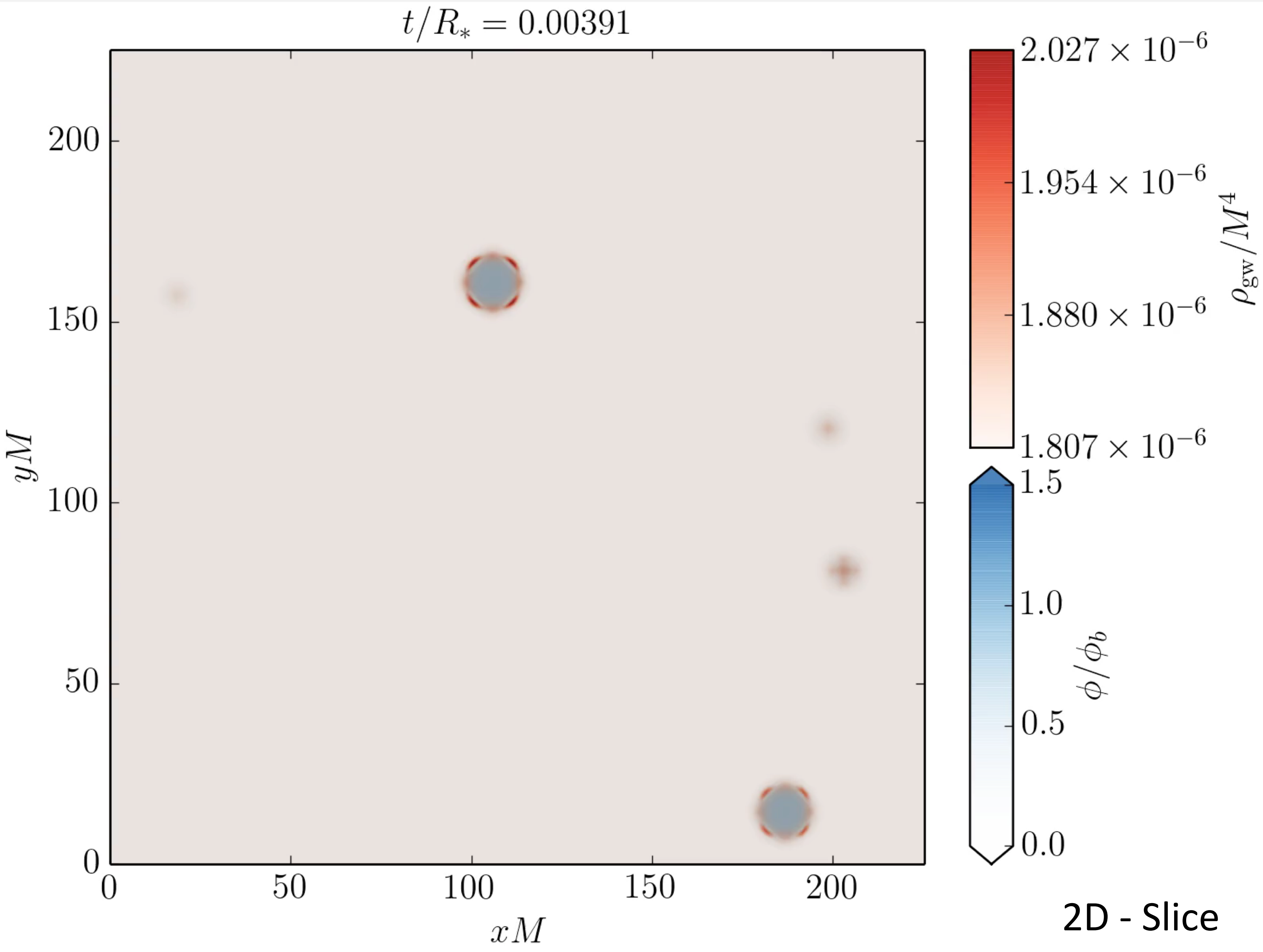
- Mean bubble separation:

$$R_* = \left(\frac{V}{N_b}\right)^{1/3}$$

- Lorentz factor of bubble wall at collision given by

$$\gamma_* = \frac{1}{2}\frac{R_*}{R_c}\,.$$





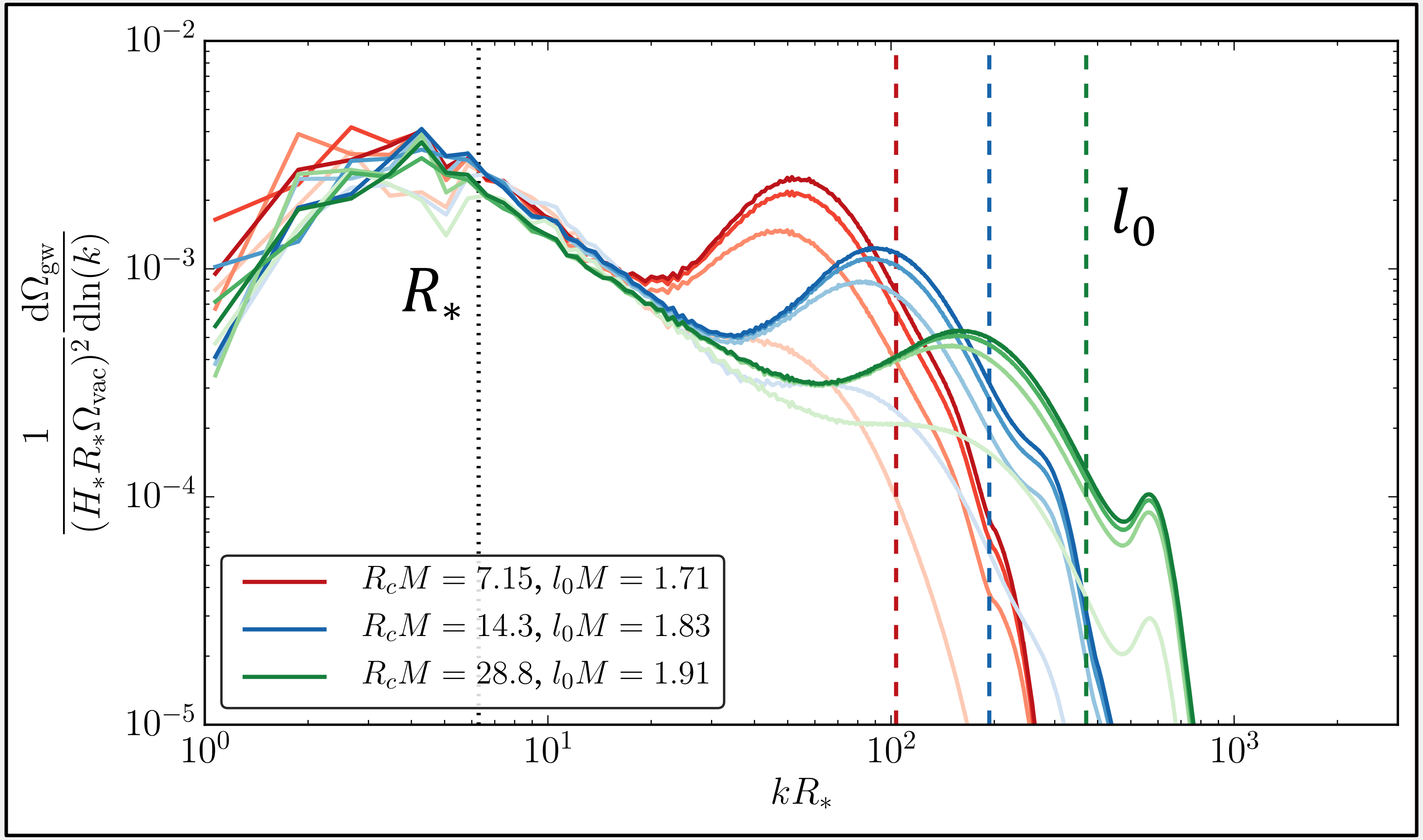
$t/R_* = 0.00391$
yM
xM
0
50
100
150
200
2.027×10^{-6}
1.954×10^{-6}
1.880×10^{-6}
1.807×10^{-6}
$\rho_{\rm gw}/M^4$
1.5
1.0
0.5
0.0
ϕ/ϕ_b

2D - Slice

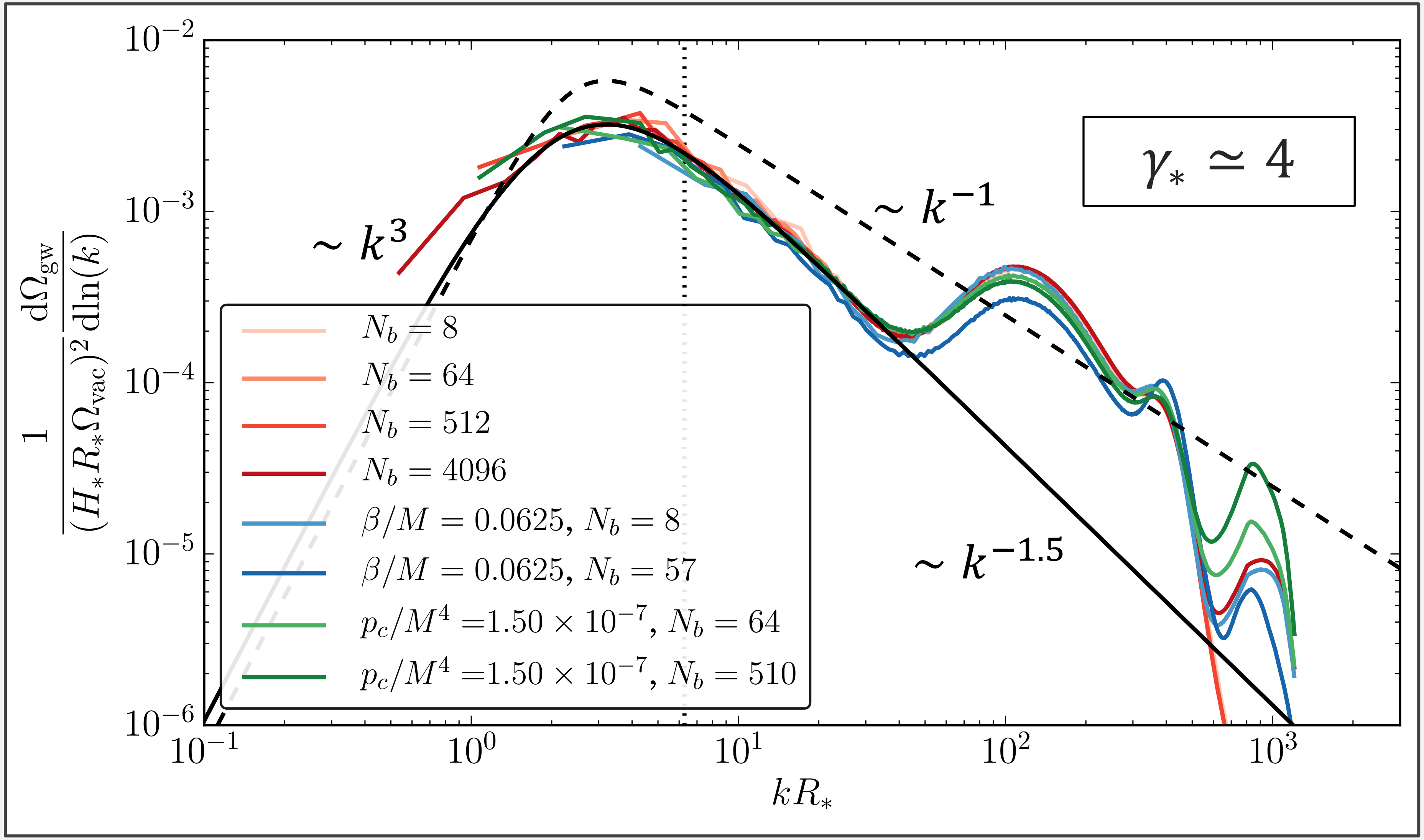
PEAKS IN THE SPECTRUM

$\gamma_* \simeq 2\,, N_b = 512$

- Dual peak structure.
- IR peak scales with bubble radius (dotted line).
- UV peak scale set by wall width (coloured dashed lines).
- Most models have $R_* \gg l_0$ and so UV peak suppressed.



IR PEAK



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
kR_*
$\frac{1}{(H_* R_* \Omega_{\rm vac})^2} \frac{d\Omega_{\rm gw}}{d\ln(k)}$
$\gamma_* \simeq 4$
$\sim k^3$
$\sim k^{-1}$
$\sim k^{-1.5}$
$N_b = 8$
$N_b = 64$
$N_b = 512$
$N_b = 4096$
$\beta/M = 0.0625,\ N_b = 8$
$\beta/M = 0.0625,\ N_b = 57$
$p_c/M^4 = 1.50 \times 10^{-7},\ N_b = 64$
$p_c/M^4 = 1.50 \times 10^{-7},\ N_b = 510$

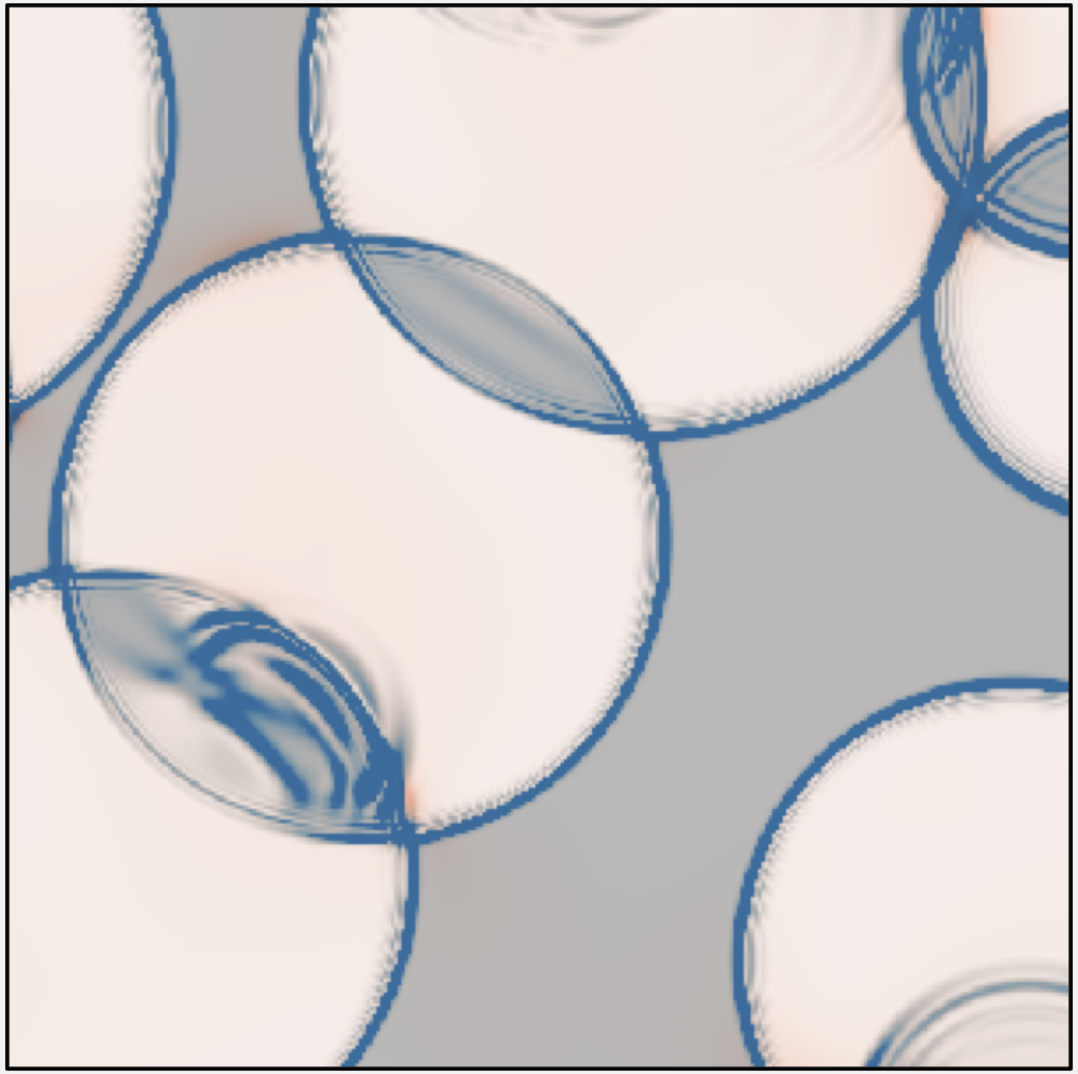
CONCLUSIONS

- Peak gravitational wave power has approximate agreement with envelope approximation fit.
- Peak frequency agrees well with the envelope approximation.
- Power law steeper than envelope for large γ_*, with $k^{-1.5}$ instead of k^{-1}.
- Second peak from scalar field oscillations found in UV.
- UV peak will have negligible contribution for most models.

ENVELOPE APPROXIMATION

- Assumptions:
  - Stress-energy concentrated in infinitesimal thin shell.
  - Neglect any region where bubbles overlap.
- Broken power law:
  - Rises as k^3 in IR.
  - Falls like k^{-1} towards UV.
  - Peak location and amplitude given by R_*.

[Huber and Konstandin, 2008] [Konstandin, 2017]



UV PEAK GROWTH

- Linear growth of UV peak contribution to spectrum Ω_{gw}^{osc},

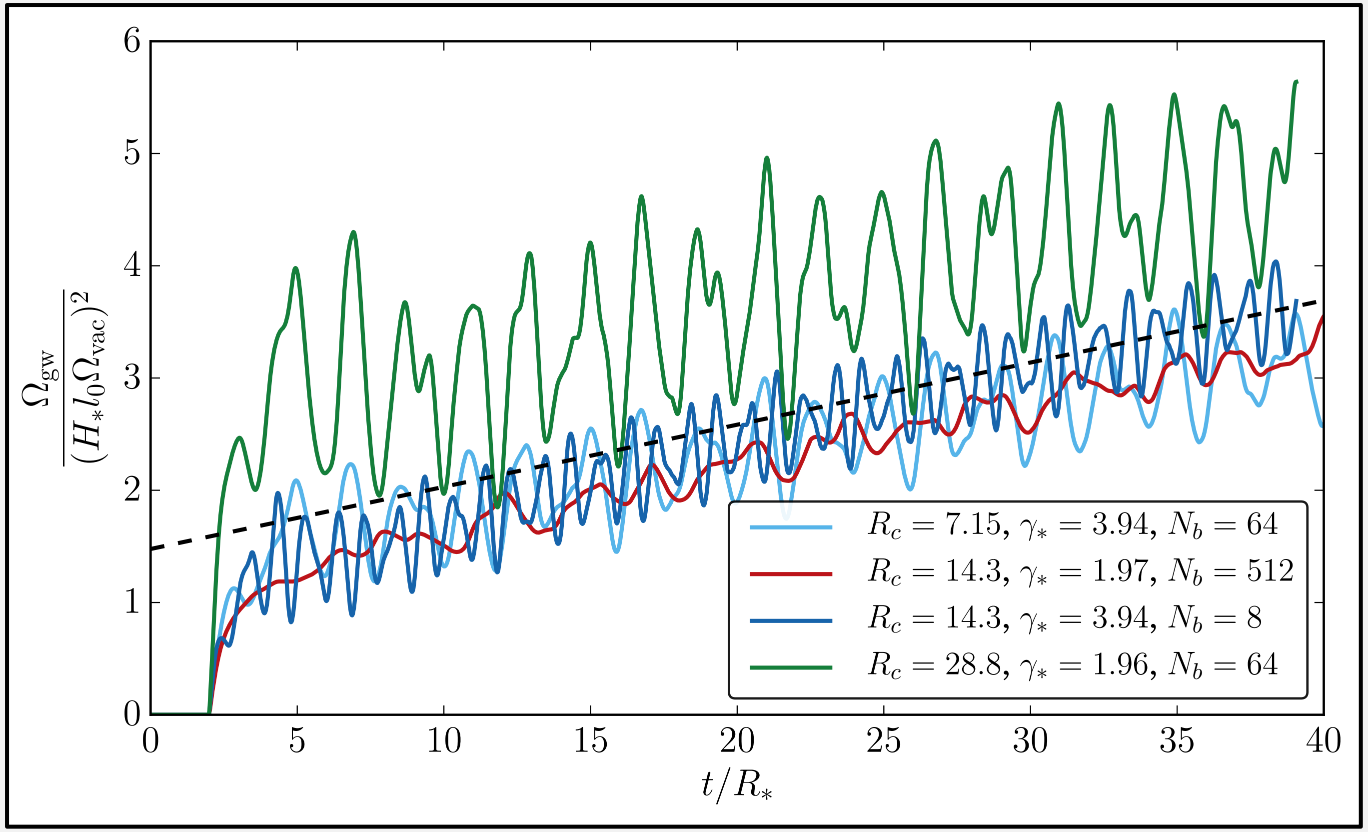
$$\frac{d\Omega_{\rm gw}^{\rm osc}}{dt} \sim 10^{-1}\frac{(H_* l_0 \Omega_{\rm vac})^2}{R_*}.$$

- Contribution from the bubble collisions is

$$\Omega_{gw}^{\rm coll} \sim 10^{-3}(H_* R_* \Omega_{\rm vac})^2.$$

- Ratio of contributions:

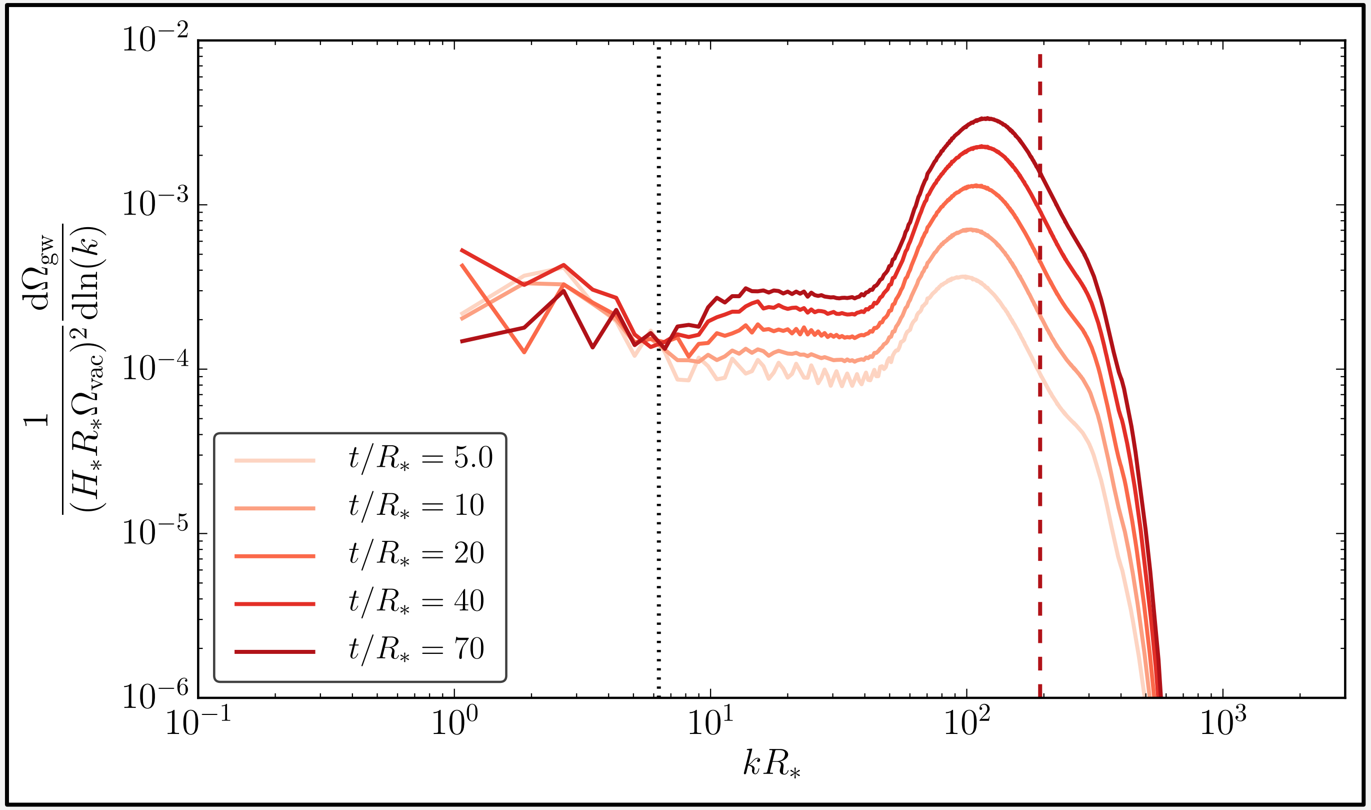
$$\frac{\Omega_{\rm gw}^{\rm osc}}{\Omega_{\rm gw}^{\rm coll}} \lesssim 10\frac{n_{\rm b}}{H_*^3}\left(\frac{M_{\rm b}}{m_{\rm Pl}}\right)^2.$$



UV PEAK

$\gamma_* \simeq 4, N_b = 512$

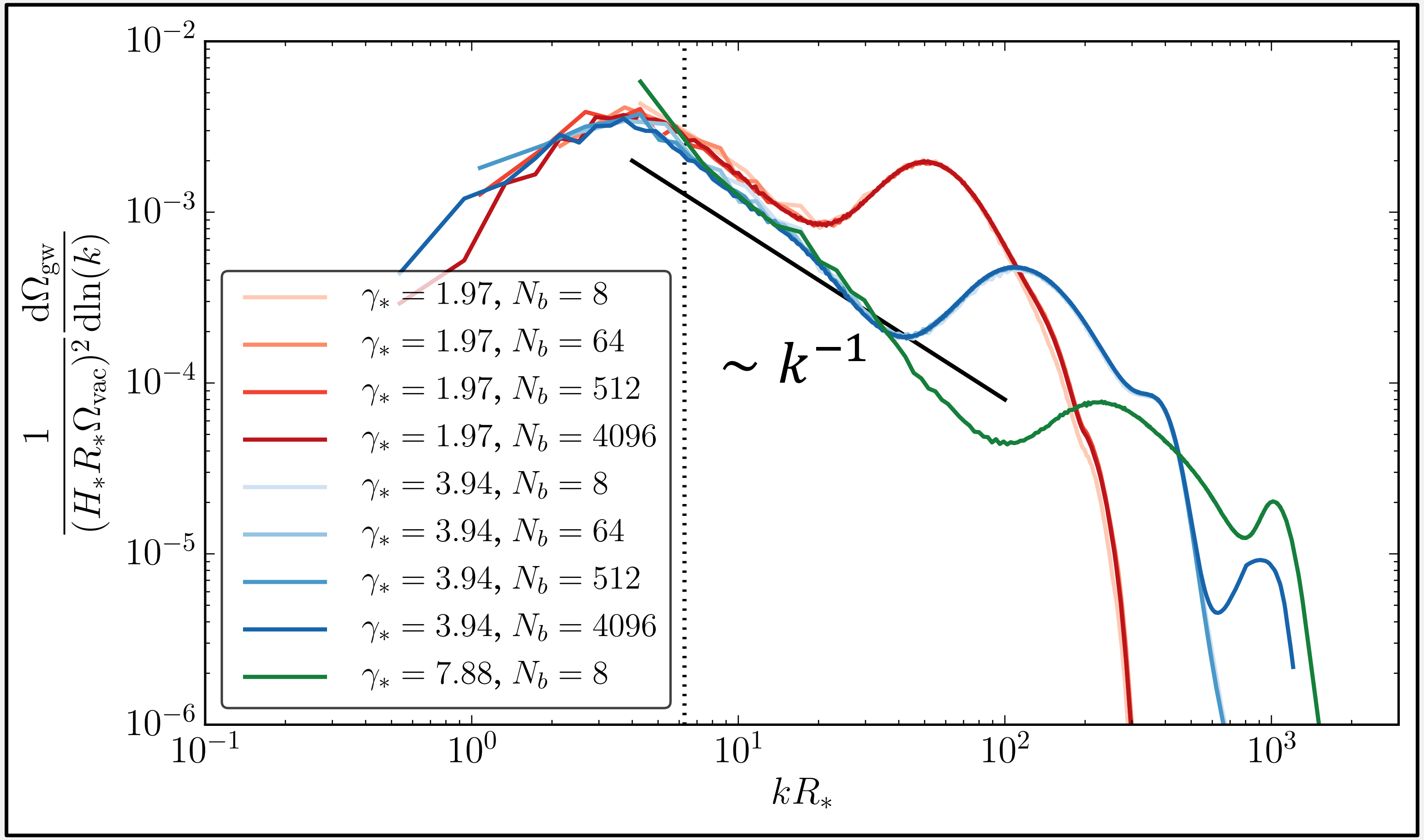
- Can turn off evolution of metric perturbations until bubbles finish colliding.
- Ringing in the IR for scales above R_*.
- UV peak continues to grow until late times.
- Growing plateau extending from R_* up until the UV peak.



GAMMA DEPENDENCE

- IR peak dependence on γ_* only via R_*
- Power law towards UV becomes steeper than k^{-1} for

$$\gamma_* \gtrsim 2.$$

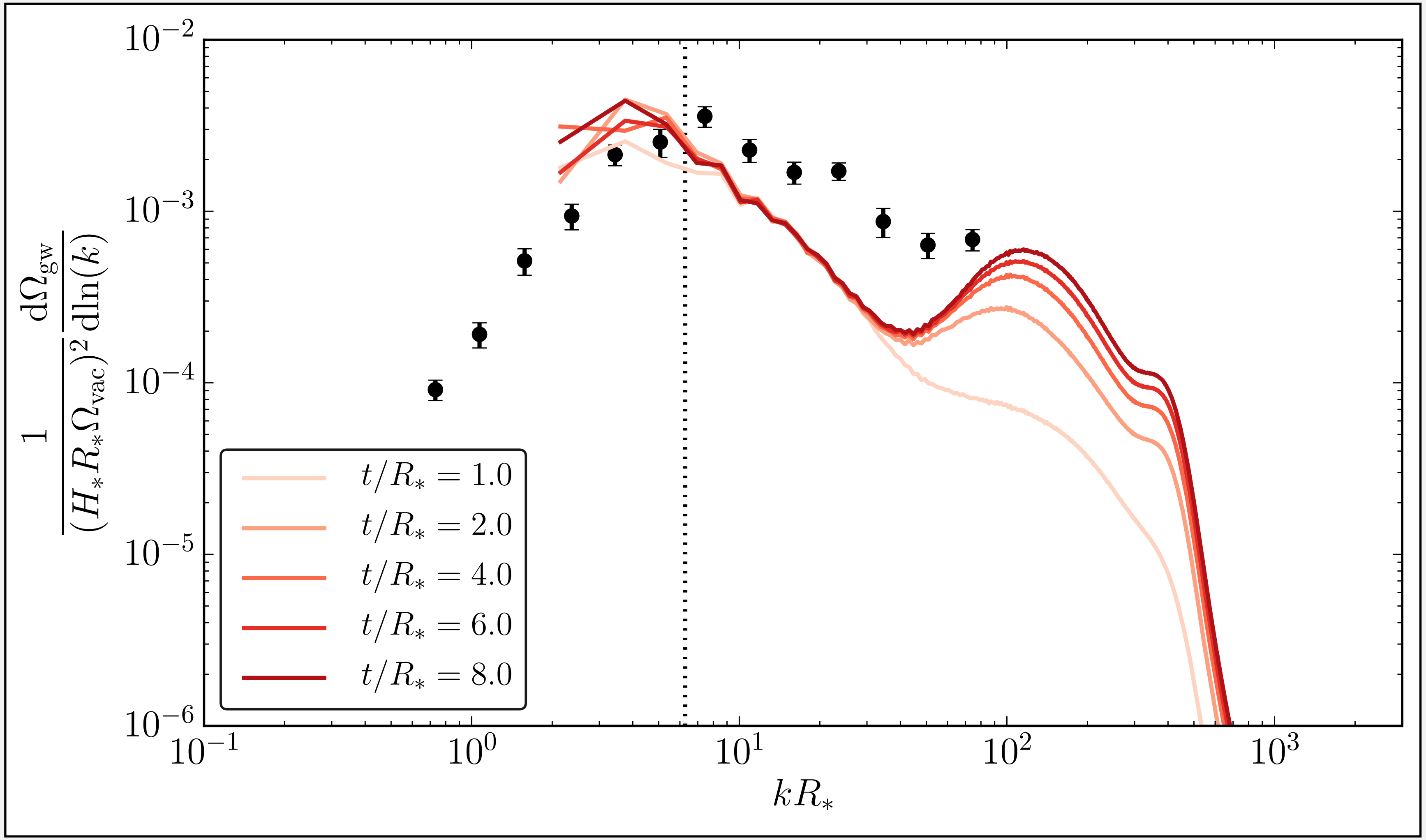


EVOLUTION OF GW SPECTRUM

$\gamma_* \simeq 4\,,\, N_b = 64$

Simultaneous nucleation

- Black dots gives spectrum from envelope simulation.
- Coloured lines show spectrum from lattice simulation.



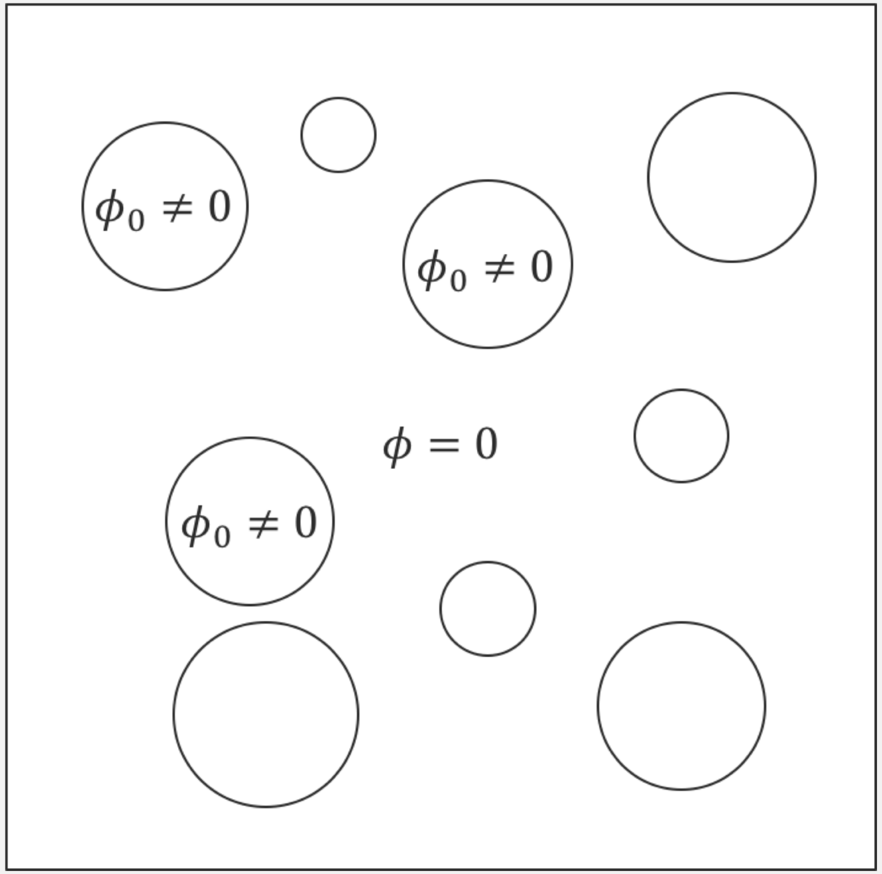
SIMULATION DETAILS

- 3+1 dimensional classical lattice simulation.
- Built using LATfield2, an open source massively parallel lattice code. *[Daverio, Hindmarsh and Bevis, 2015]*
- Periodic boundary conditions.
- The leapfrog algorithm to evolve fields.
- Resolve the bubble wall:

$$dx \ll l_* = l_0/\gamma_*$$

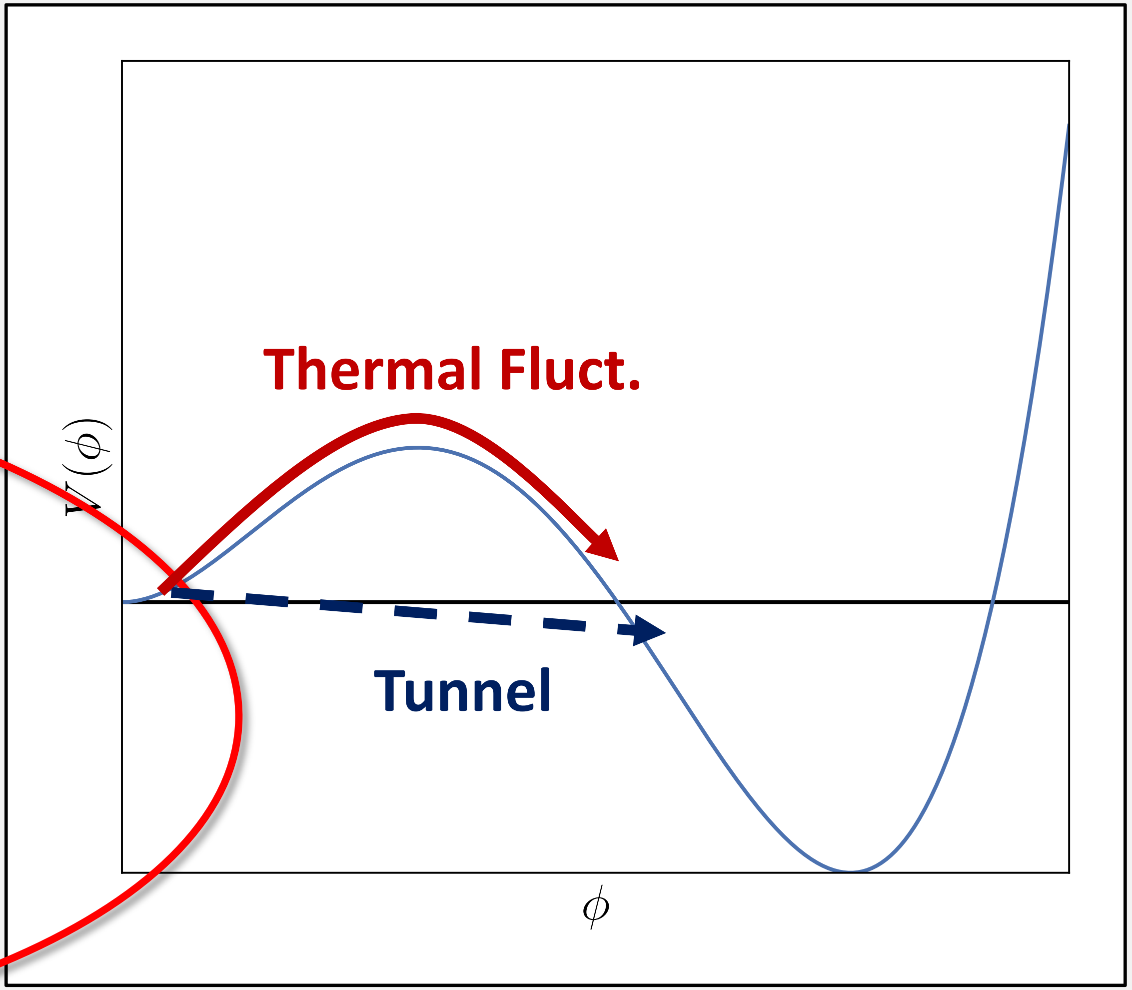
COSMOLOGICAL FIRST-ORDER PHASE TRANSITIONS

- In cosmological phase transitions (PTs) an (effective) scalar field transitions from false vacuum to true vacuum.
- In a first-order PT phases separated by potential barrier.
- Proceed through the nucleation and merger of bubbles.
- Extensions to the Standard Model can generate a first-order PT at the electroweak scale.



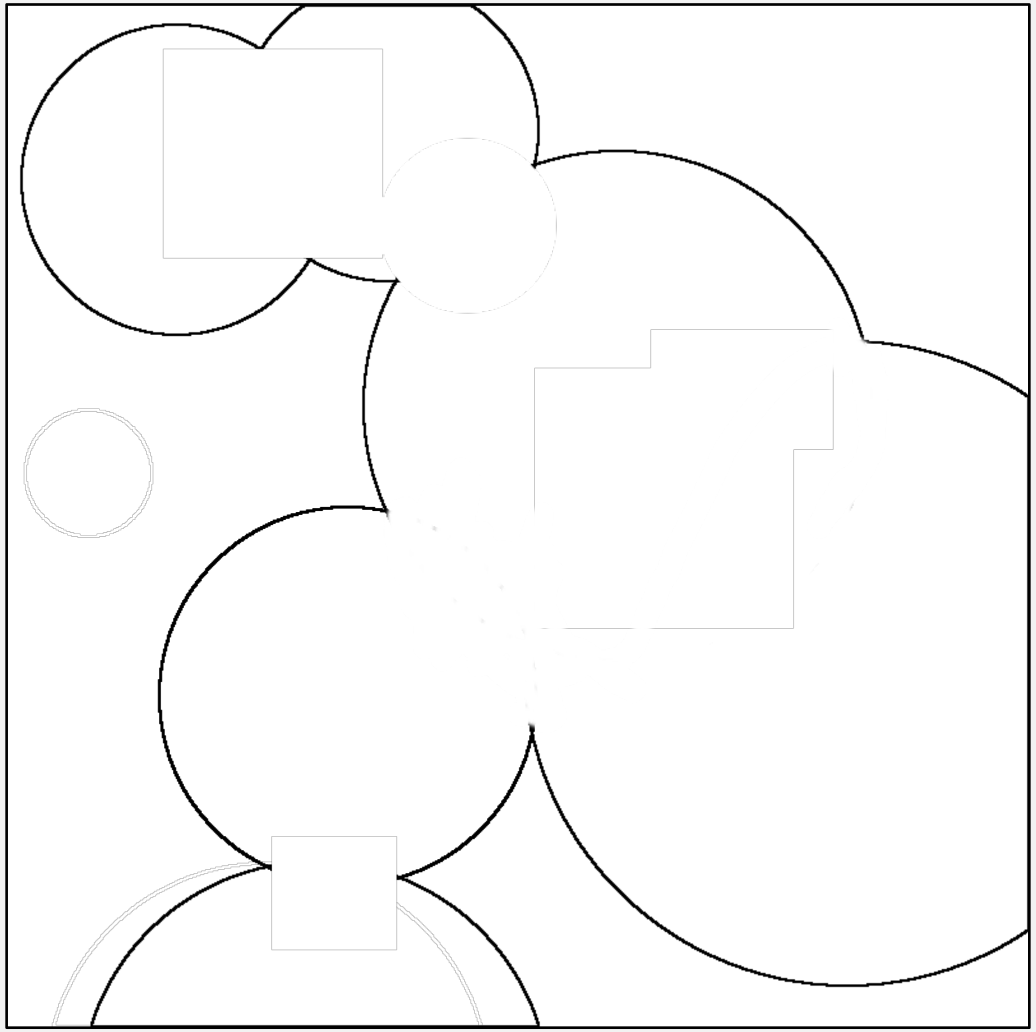
THERMAL VS VACUUM PHASE TRANSITIONS

- Thermal PTs:
  - Thermally fluctuate over barrier.
  - Fluid shell around bubble wall, exerts friction.
  - Terminal wall velocity.
  - Free energy difference mostly shared between bulk motion of fluid and thermal radiation.
- Vacuum PTs:
  - Quantum tunnel through barrier.
  - Fluid effects negligible.
  - Bubble wall accelerates until collision.
  - Free energy difference deposited into motion of the bubble wall.
  - Limit of highly super cooled PTs or a PT in a hidden sector.



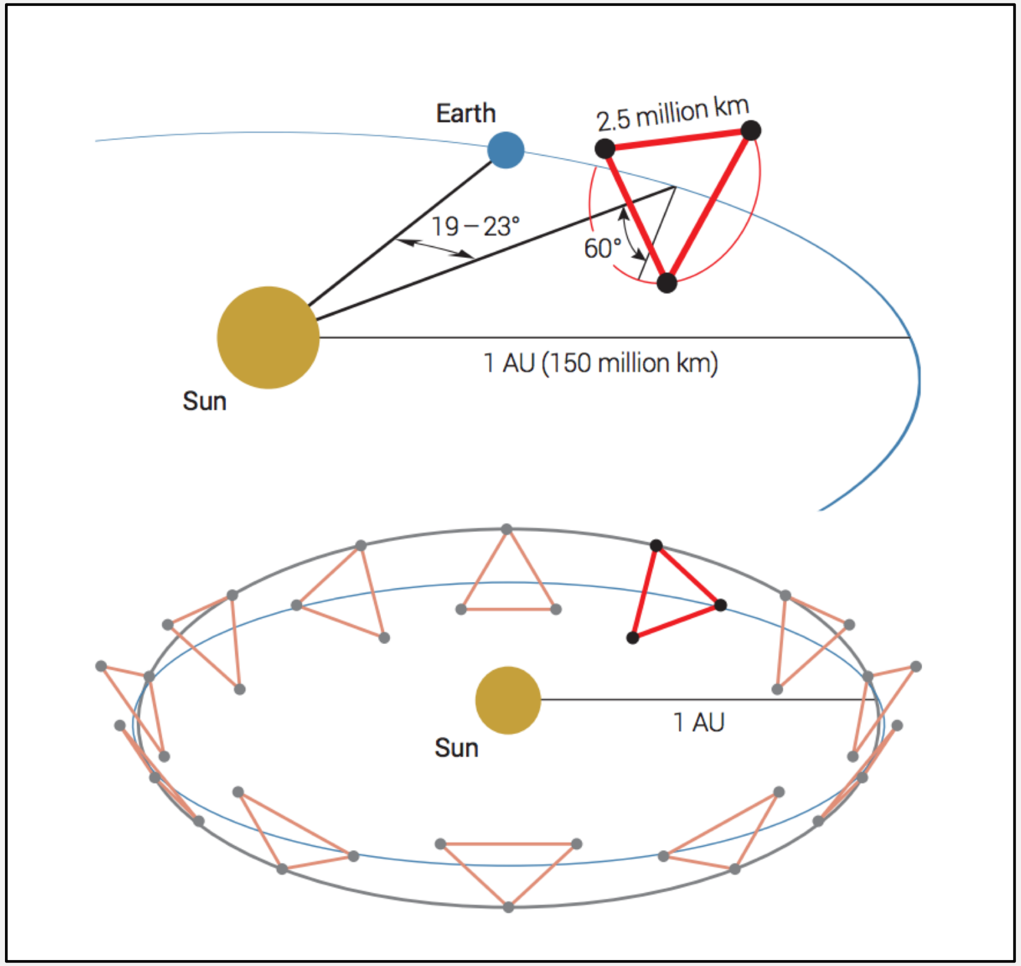
GRAVITATIONAL WAVES FROM COSMOLOGICAL PHASE TRANSITIONS

- Colliding bubbles break spherical symmetry → radiate gravitational waves (GWs).
- In thermal PTs the dominant GW signal is from acoustic oscillations in fluid.
  [Hindmarsh et al, 2014] [Hindmarsh, et al, 2015] [Hindmarsh et al, 2017]
- In vacuum PTs the GW signal expected to be from shear stress in scalar field at bubble wall.
- Scalar field contribution to GW signal previously studied using envelope approximation.
  E.g *[Kosowsky et al, 1992] [Huber and Konstandin, 2008] [Weir, 2016] [Konstandin, 2017]*

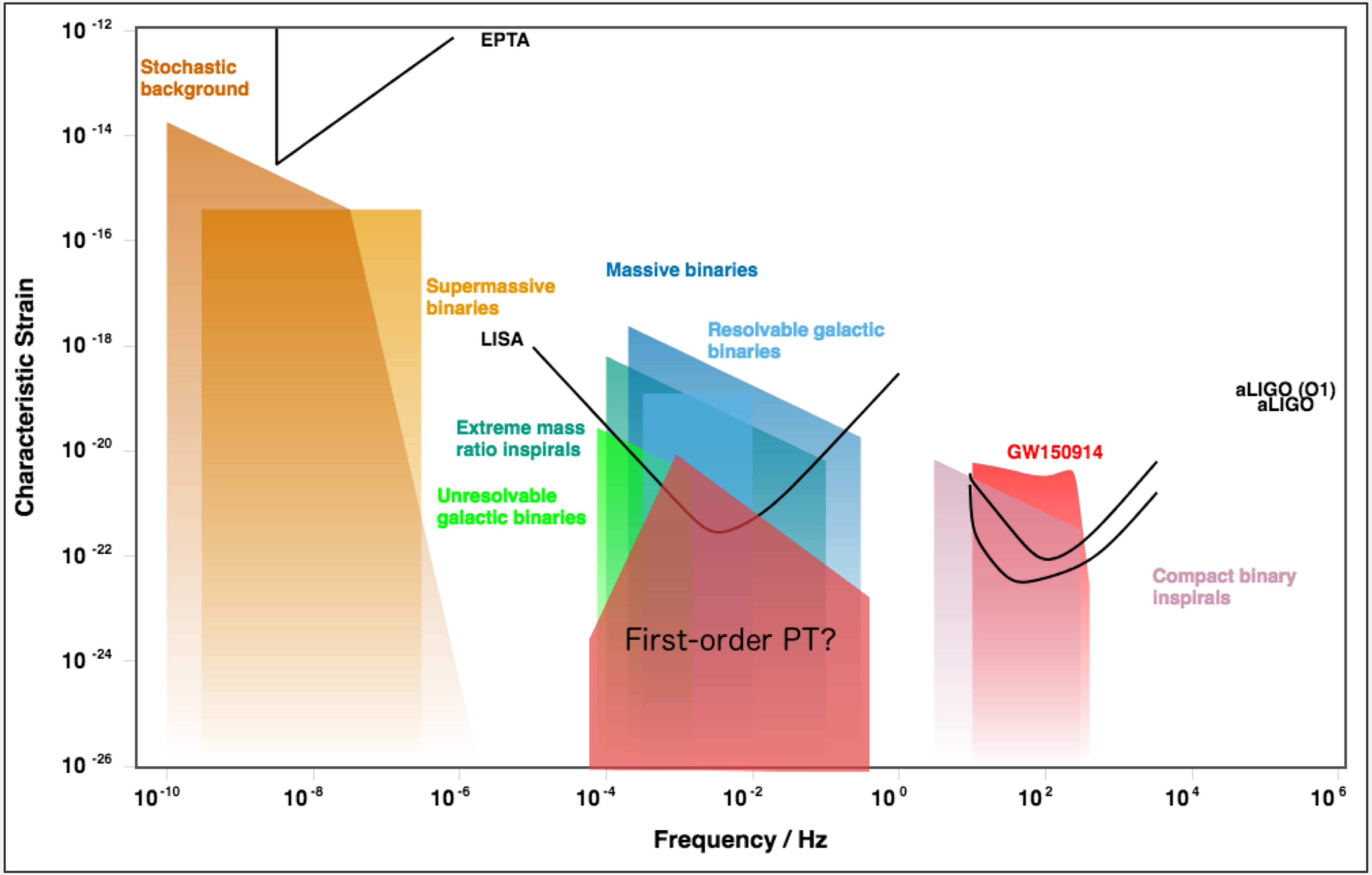


LASER INTERFEROMETER SPACE ANTENNA (LISA)

- Space based gravitational wave observatory using laser interferometry.
- Planned launch date of 2034.
- Three arms with length of 2.5 million km.
- Among goals is direct detection of a stochastic GW background of cosmological origin. *[arXiv:1702.00786]*
- Sensitive to GWs with frequencies of $10^{-4} Hz$ to $10^{-1} Hz$. [*arXiv:1702.00786]*
(Electroweak scale)

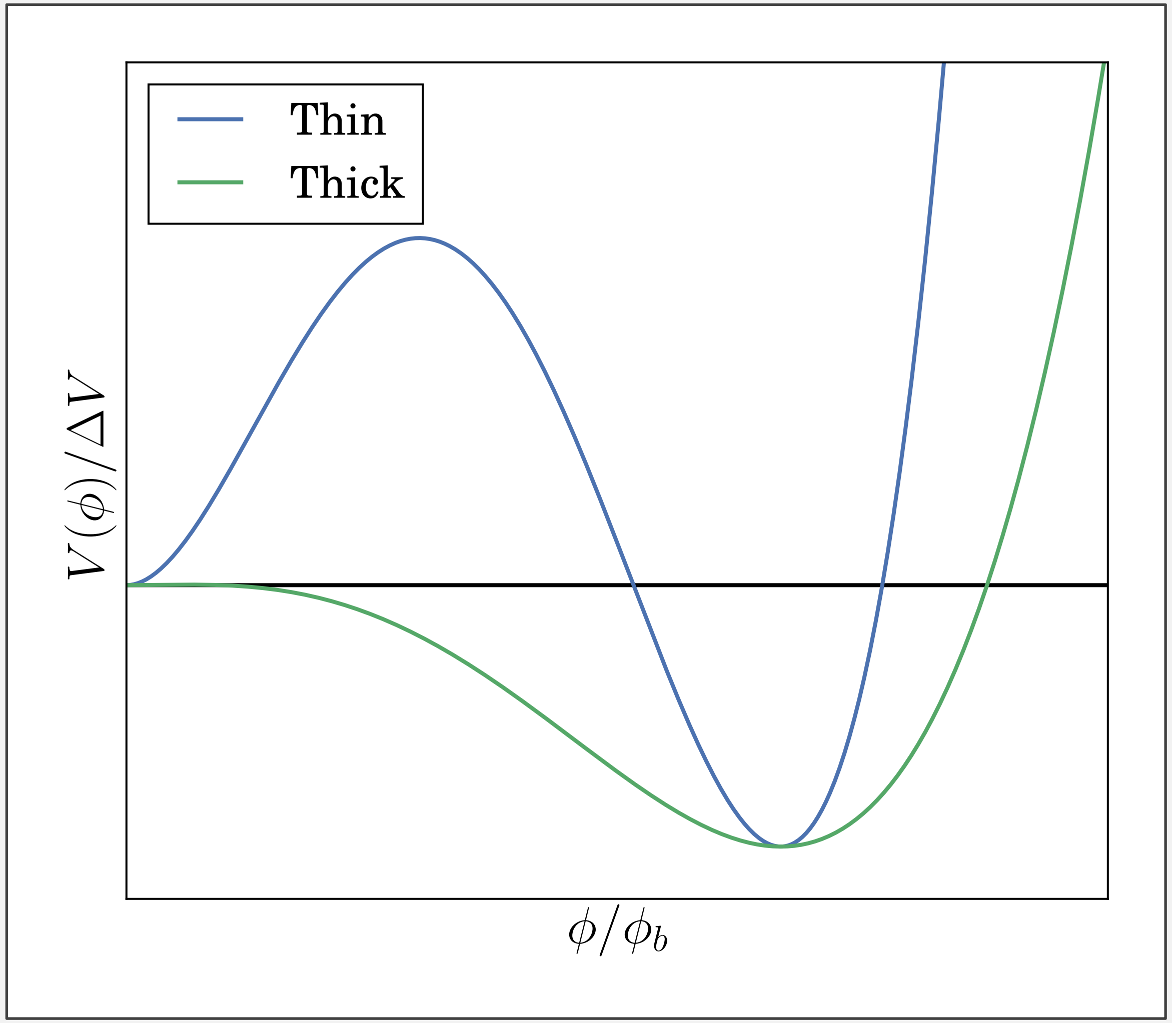


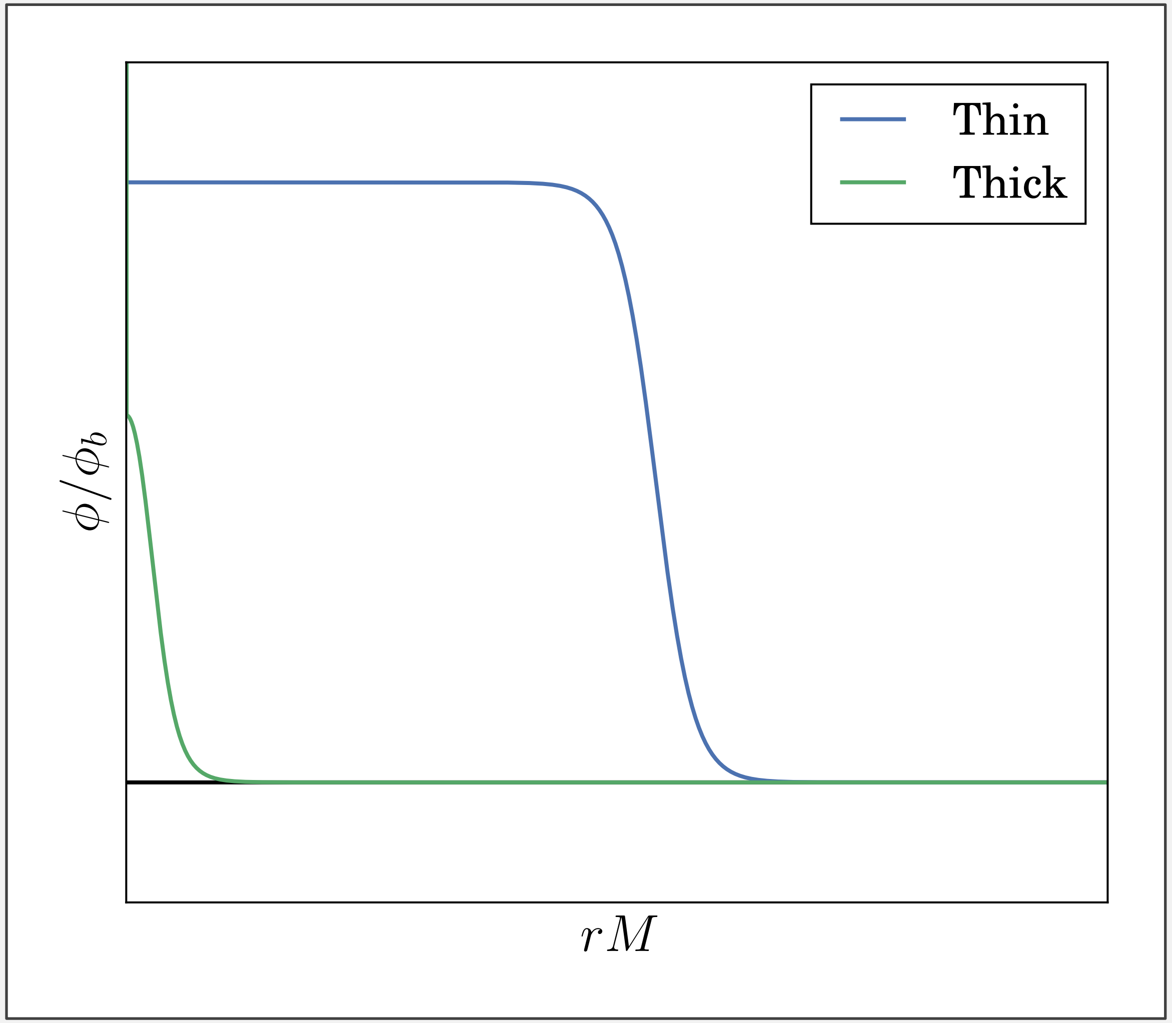
Taken from: arXiv:1702.00786



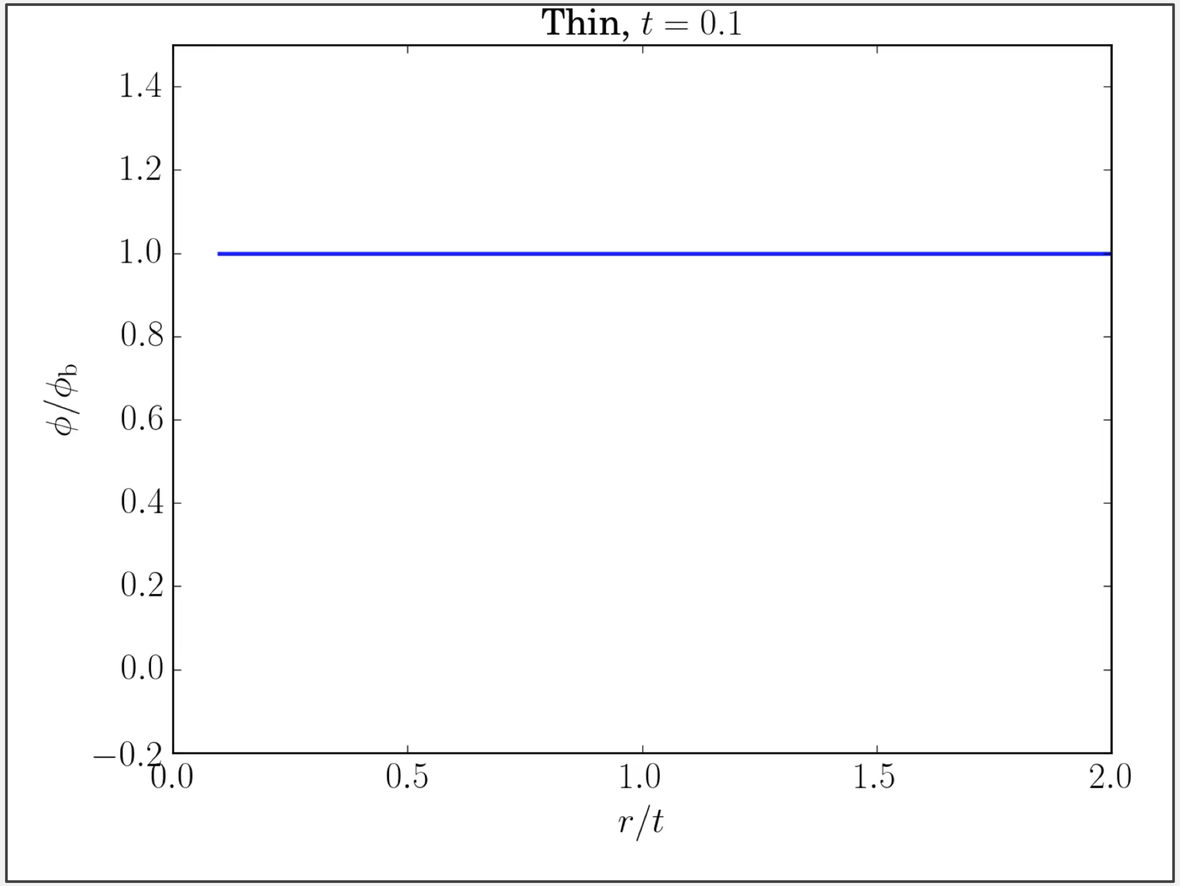
Source: GWplotter

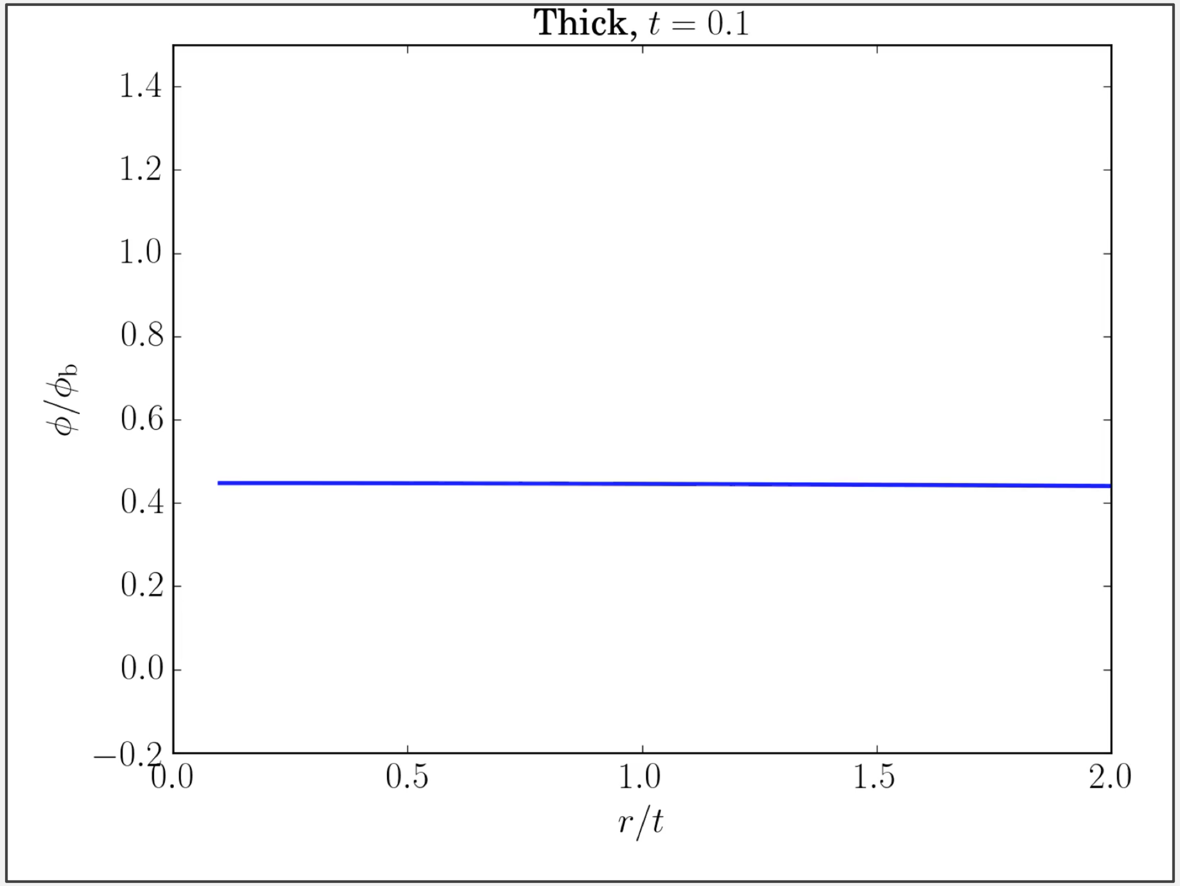
CRITICAL BUBBLE PROFILE





BUBBLE EXPANSION





Movie credit: Elva Granados Escartin