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PRACE

Acoustic waves and detectability of first-order phase transitions

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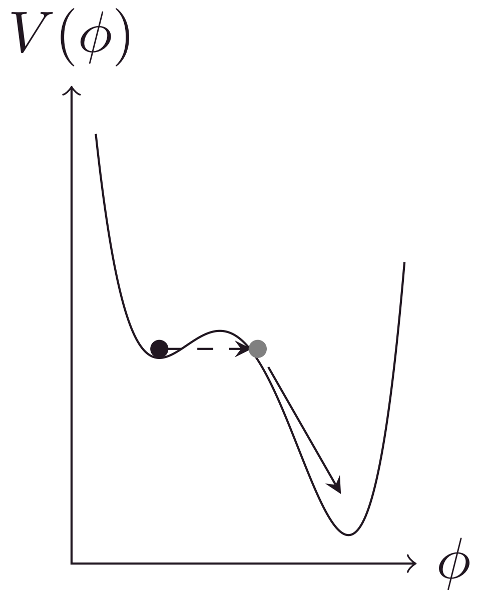
Motivation and context

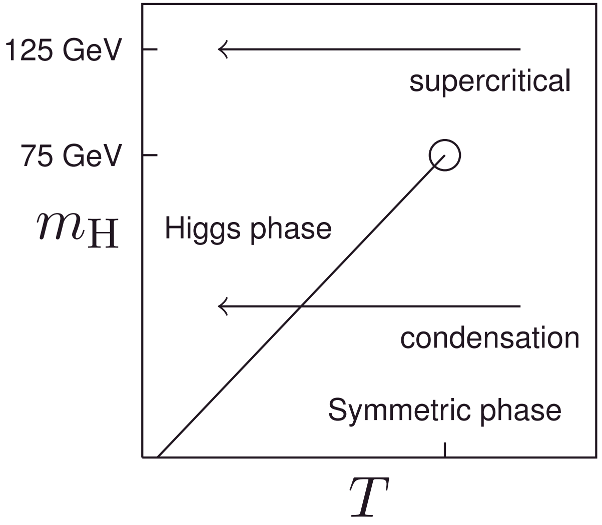
- In first order PTs bubbles nucleate, grow and collide; collisions produce gravitational waves



- Standard Model EW PT is a crossover, but first order generic in extensions (singlet, 2HDM, . . .)

  Andersen, Laine *et al.*, Kozaczuk *et al.*, Kamada and Yamada, Carena *et al.*, Bödeker *et al.*, Damgaard *et al.*

- First order PT around the EW scale *could* give right conditions for baryogenesis (but would then not give a good signal for GWs)



- Today: concentrate on simulations of thermal phase transitions at EW scale. What physics can we extract from the GW power spectrum?

What sources GWs at a thermal phase transition?

- Bubbles nucleate, bubble walls experience friction, energy goes into plasma, then:

1. $h^2\Omega_\phi$: Bubble walls and shocks collide – ‘envelope phase’
2. $h^2\Omega_{\text{sw}}$: Sound waves set up after bubbles have collided, before expansion dilutes KE – ‘acoustic phase’
3. $h^2\Omega_{\text{turb}}$: MHD turbulence – ‘turbulent phase’

- These sources then add together to give the observed GW power:

$$h^2\Omega_{\text{GW}} \approx h^2\Omega_\phi + h^2\Omega_{\text{sw}} + h^2\Omega_{\text{turb}}$$

- Each phase’s contribution depends on the nature of the phase transition.
- Now: explore steps 1-2 through two types of simulations:

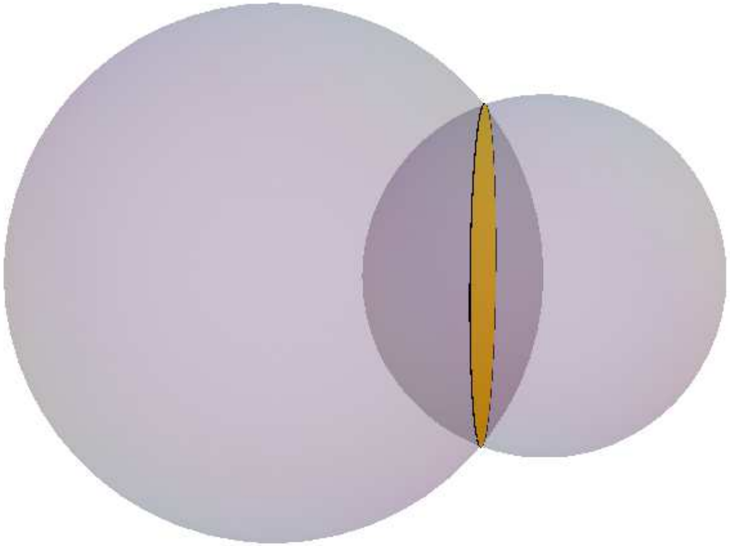
1. The ‘envelope approximation’ $\rightarrow h^2\Omega_\phi$
2. A field ϕ (‘Higgs’) coupled by friction to a fluid U^μ (‘plasma’) $\rightarrow h^2\Omega_{\text{sw}}$

1: Envelope [and thin wall] approximation

Kosowsky, Turner and Watkins; Kamionkowski, Kamionkowsky and Turner

- Thin, hollow bubbles, no fluid
- Bubbles expand with velocity v_{w}
- Stress-energy tensor $\propto R^3$ on wall
- Overlapping bubbles $\rightarrow$ GWs
- Keep track of solid angle
- Collided portions of bubbles disappear, sourcing gravitational waves
- Resulting power spectrum is simple
  - One length scale (average bubble radius R_*)
  - Two power laws (ω^3, $\sim \omega^{-1}$)
  - Amplitude

$\Rightarrow$ 4 numbers define spectral form



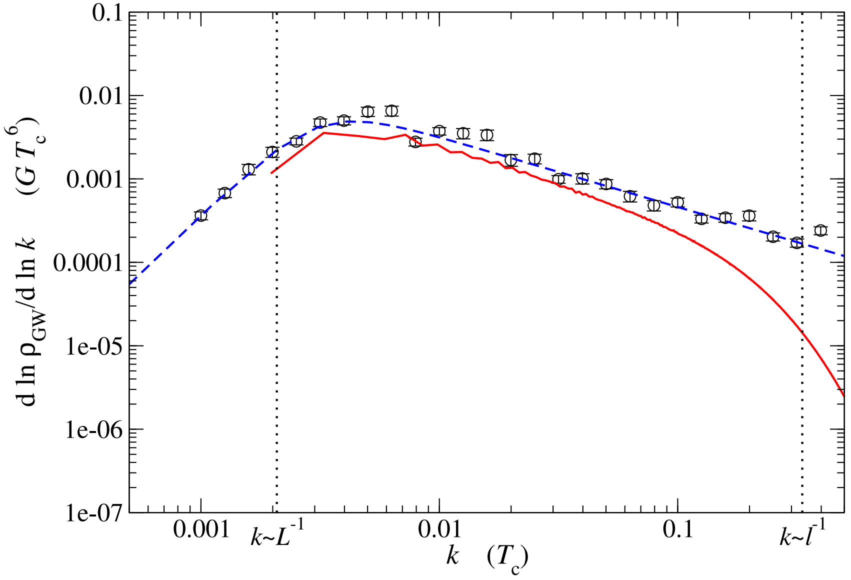
1: Making predictions with the envelope approximation

Espinosa, Konstandin, No and Servant; Huber and Konstandin

4-5 numbers parametrise the transition:

- α_{T_*}, vacuum energy fraction
- v_{w}, bubble wall speed
- κ_ϕ, conversion ‘efficiency’ into gradient energy $(\nabla\phi)^2$
- Transition rate:
  - H_*, Hubble rate at transition
  - β, bubble nucleation rate

→ ansatz for $h^2\Omega_\phi$



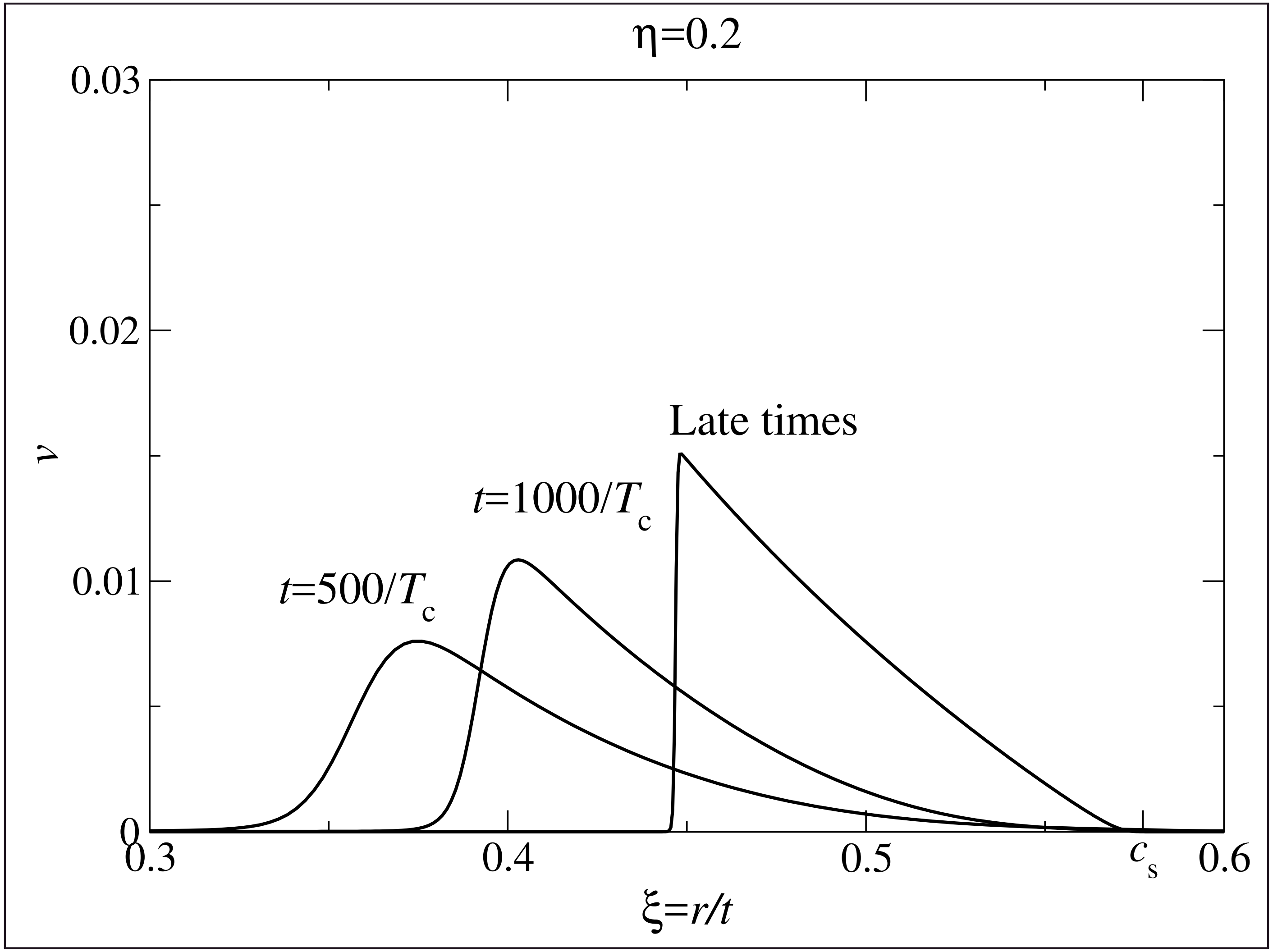
NB: applied to colliding shocks *instead of* walls ($\kappa = \kappa_{\mathrm{f}}$), energy in GWs is

$$\rho_{\mathrm{GW}} \propto \frac{0.11 v_{\mathrm{w}}^3}{0.42 + v_{\mathrm{w}}^2} \left(\frac{H_*}{\beta}\right)^2 \frac{\kappa_{\mathrm{f}}^2 \alpha^2}{(\alpha+1)^2}$$

assumes the shocks are **thin** and disappear after the bubbles collide: this is an underestimate; the dominant source from the fluid KE is sound waves…

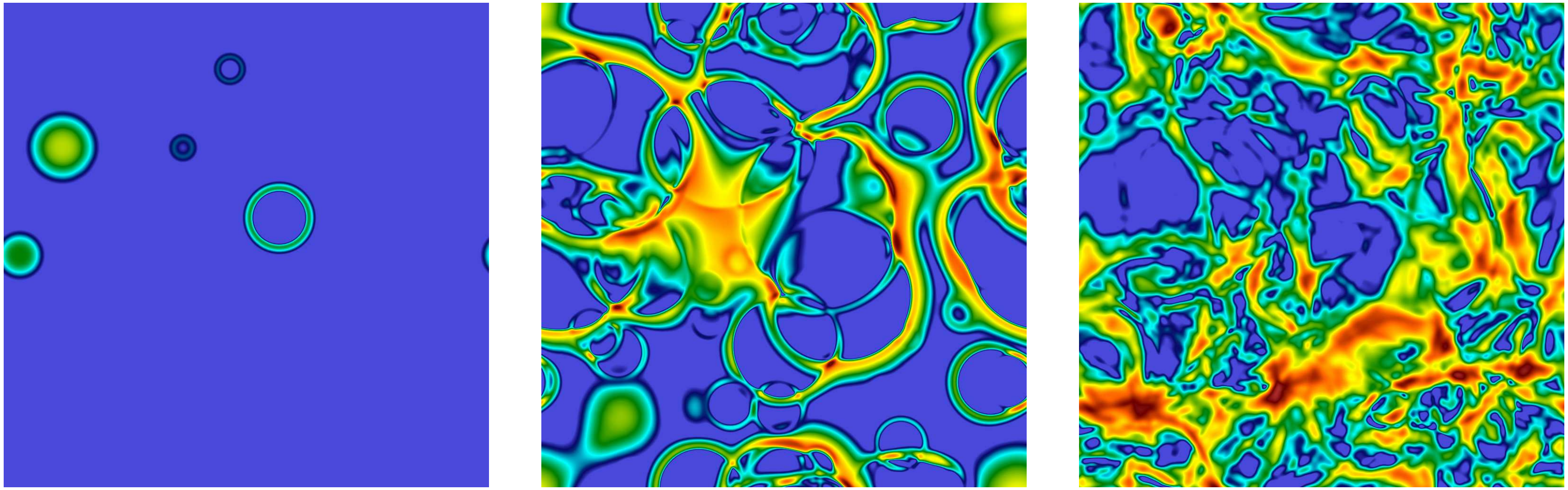
2: Velocity profile development - deflagration [optional movie]

Here, $\eta = 0.2$ (deflagration)



2: Simulation slice example [optional movie]

Simulations at 1024^3, deflagration, fluid kinetic energy density, $\sim$250 bubbles



$t = 500\ T_\mathrm{c}^{-1}$ $t = 750\ T_\mathrm{c}^{-1}$ $t = 1000\ T_\mathrm{c}^{-1}$

2: Lifetime of sound waves and increase in GW power

- Does the acoustic source matter?
  - Sound is damped by (bulk and) shear viscosity

    Arnold, Dogan and Moore; Arnold, Moore and Yaffe

$$\left(\frac{4}{3}\eta_{\mathrm{s}} + \zeta\right) \nabla^2 V^i_{\parallel} + \ldots \Rightarrow \tau_\eta(R) \sim \frac{R^2 \epsilon}{\eta_{\mathrm{s}}}$$

  - Compared to $\tau_{H_*} \sim H_*^{-1}$, on length scales

$$R^2 \gg \frac{1}{H_*} \frac{\eta_{\mathrm{s}}}{\epsilon} \sim 10^{-11} \frac{v_{\mathrm{w}}}{H_*} \left(\frac{T_{\mathrm{c}}}{100\,\mathrm{GeV}}\right)$$

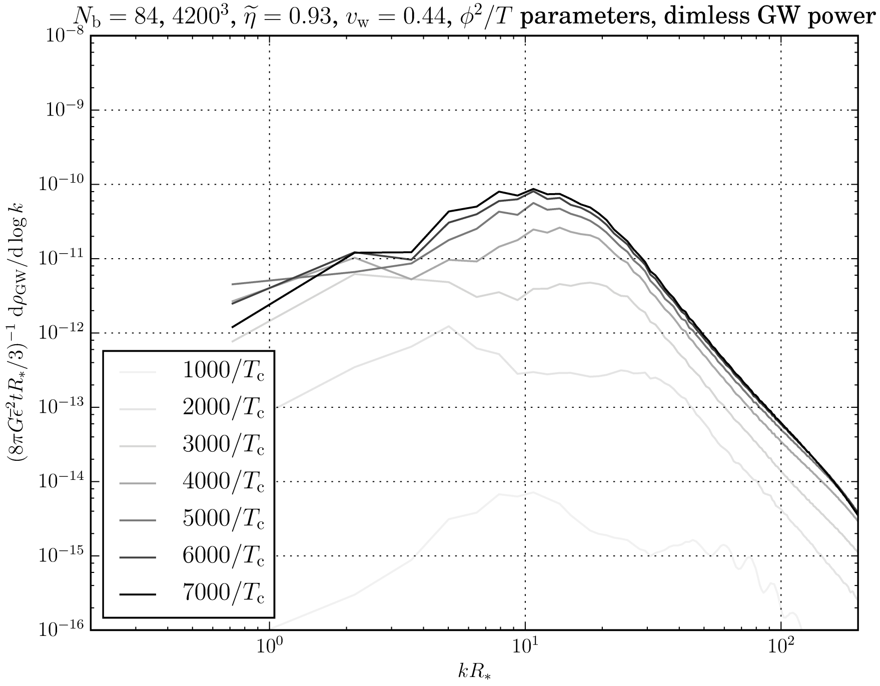
    the Hubble damping is faster than shear viscosity damping.

- Does the acoustic source enhance GWs?
  - Yes, we have

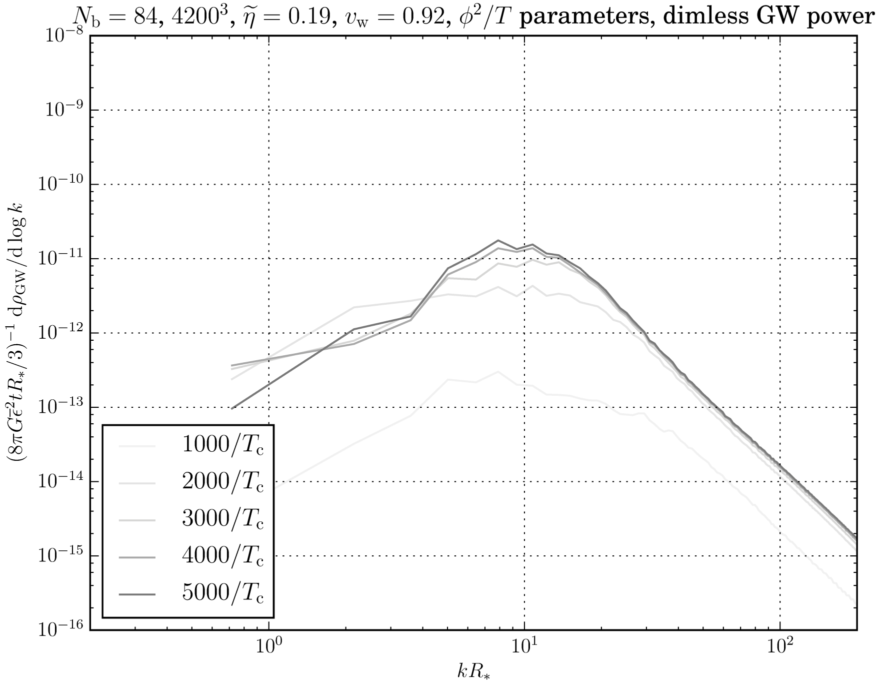
$$\Omega_{\mathrm{GW}} \approx \left(\frac{\kappa\alpha}{\alpha+1}\right)^2 (H_* \tau_{H_*})(H_* \xi_{\mathrm{f}}) \Rightarrow \frac{\Omega_{\mathrm{GW}}}{\Omega_{GW}^{\text{envelope}}} \gtrsim 60 \frac{\beta}{H_*}.$$

2: GW power spectra and power laws

- Latest simulation results (1M hours per run, 4200^3 simulation volume):



Fast deflagration

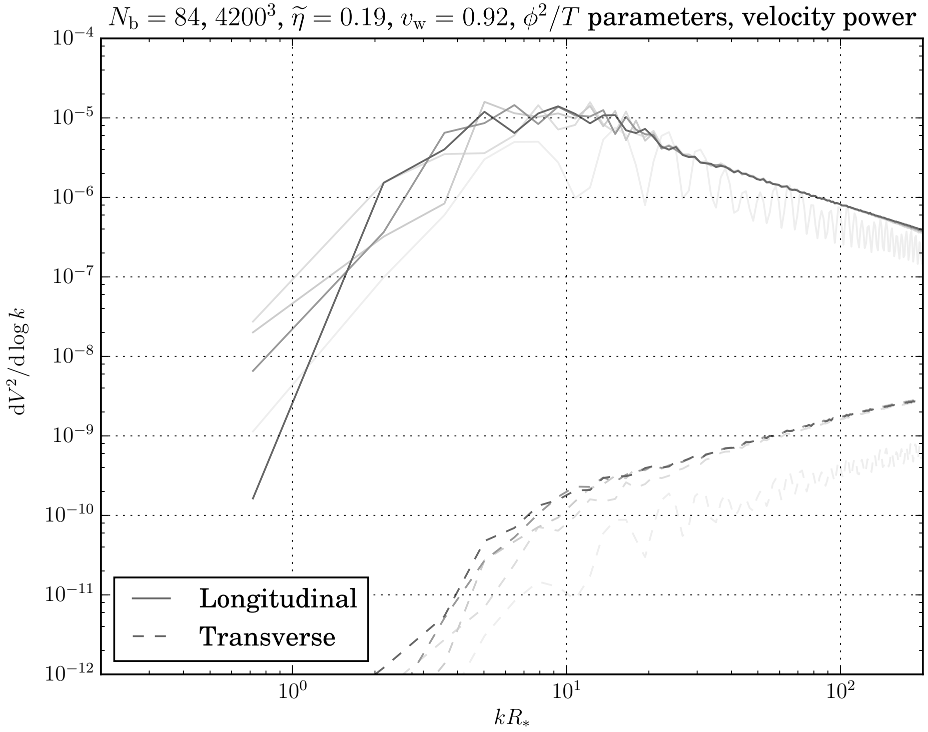


Detonation

- Approximate ω^{-3} to ω^{-4} power spectrum at high ω
- Expect causal ω^3 at low ω
- Curves scaled by t: source ‘on’ continuously until turbulence/expansion

$\rightarrow$ power law ansatz for $h^2\Omega_\mathrm{sw}$

3: Transverse versus longitudinal modes – turbulence?



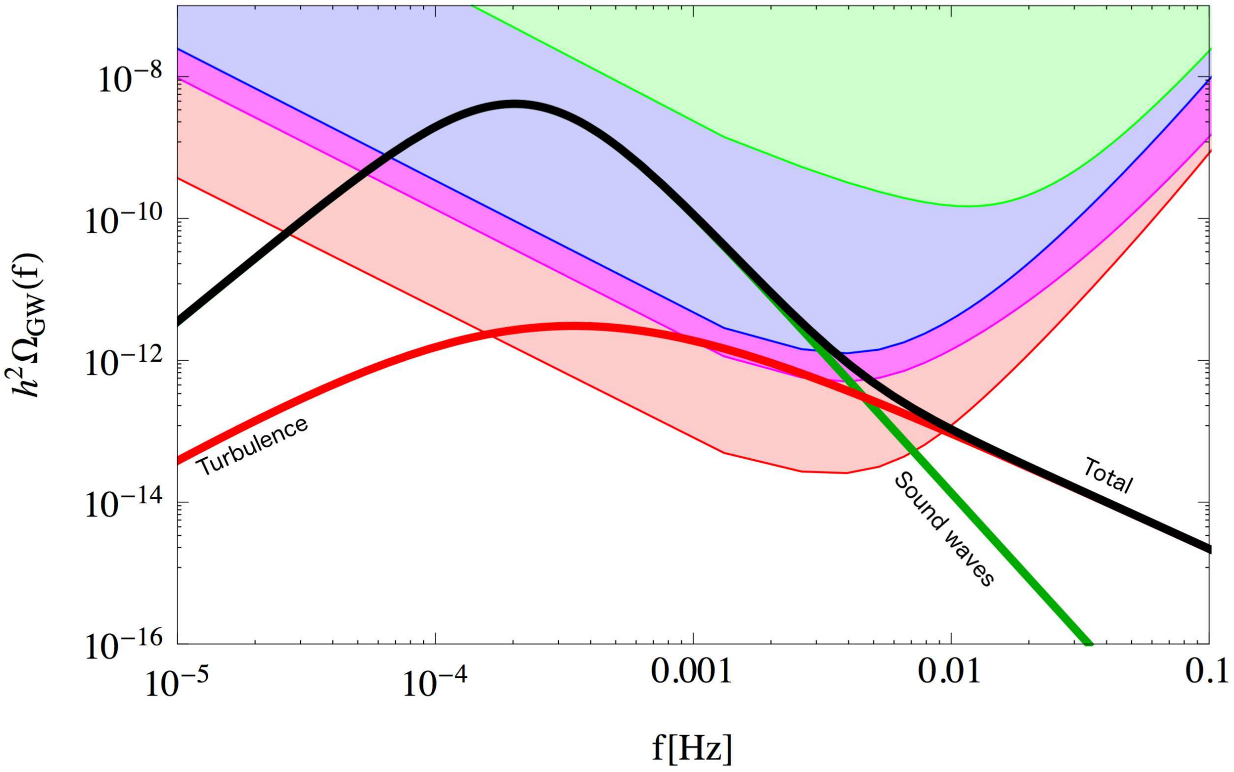
- Weak transition (small α): physics is linear; most power is in the longitudinal modes – acoustic waves, not turbulence
- Need stronger transitions or longer, larger simulations to model turbulence
- Use results from the literature Caprini, Durrer and Servant

→ power law ansatz for $h^2\Omega_\mathrm{turb}$

Putting it all together - $h^2\Omega_{\text{gw}}$

- We have three sources, $\approx h^2\Omega_\phi$, $h^2\Omega_{\text{sw}}$, $h^2\Omega_{\text{turb}}$
- We know how they vary as a function of T_*, α_T, v_{w}, β
- Predict whether LISA can detect PT given a certain model

(example with $T_* = 100\text{GeV}$, $\alpha_{T_*} = 0.5$, $v_{\text{w}} = 0.95$, $\beta/H_* = 10$)



Check out eLISA CosWG report: JCAP 1604 (2016) 001 [arXiv:1512.06239]

Summary and outlook

- Now:
  - Have a good understanding of what happened during a first order PT, and implications for GWs
  - Recent work shows source is stronger than previously thought
    – acoustic source gives large enhancement
  - Hence many models yielding first order EWPTs can produce observable gravitational waves

- More to do:
  - Strong transitions, turbulence, instabilities
  - Wall velocities; connections with baryogenesis