Baryogenesis, gravitational waves and thermal phase transitions

PRL 112, 041301 (2014) [arXiv:1304.2433],
PRD 92, 123009 (2015) [arXiv:1504.03291],
JCAP 1604 (2016) 001 [arXiv:1512.06239],
and PRD 93, 124037 (2016) [arXiv:1604.08429].

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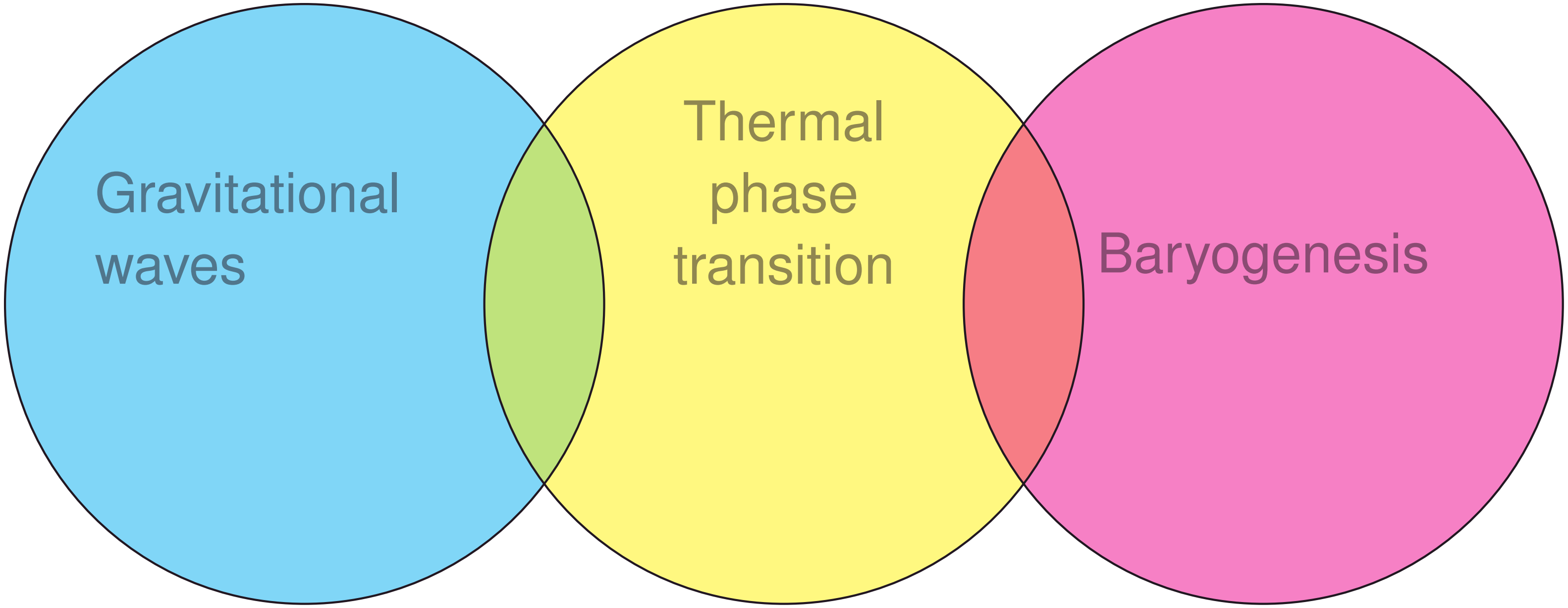
with Mark Hindmarsh, Stephan J. Huber and Kari Rummukainen

and the eLISA Cosmology Working Group

TeVPA 2016, 13 September 2016

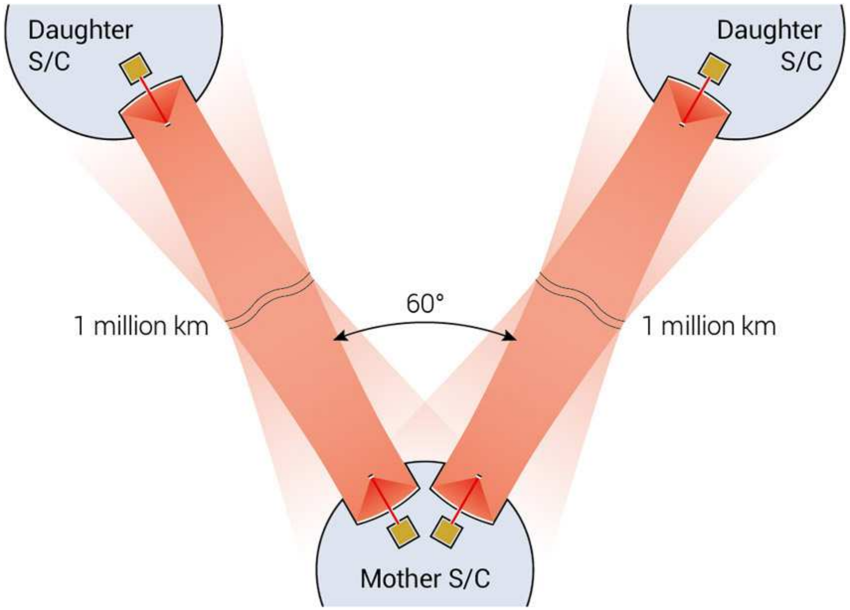
This talk

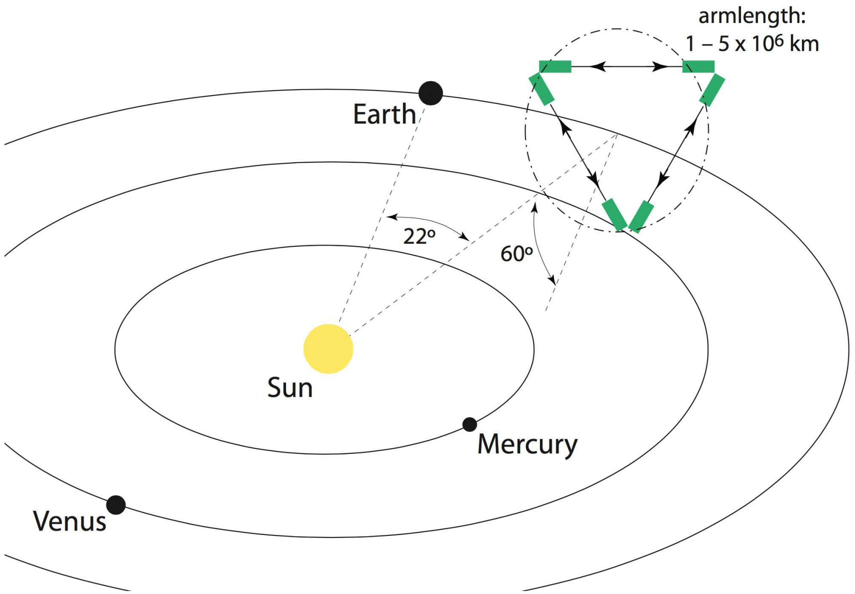


- First order EWPT can produce observable gravitational wave signatures
- Future projects including LISA can probe a range of extended EW models
- It's *possible* to believe that a phase transition that produces observable GWs also could explain baryogenesis Megevand; Joyce, Prokopec, Turok; Fromme, Huber, Seniuch; Caprini and No; . . .

What's "next": [e]LISA Talks by Scott Hughes and others

Peak sensitivity in mHz: well-placed to see background from EWPT





- eLISA would have two arms (four laser links), 1M km separation
- Launch as ESA's third large-scale mission (L3) in c.2034
- Cheaper version of LISA (2 arms, smaller, noisier, shorter duration)
- In light of events:
  - Restore missing arm?
  - Increase separation?
  - Extend mission duration?

Extended Standard Model with first-order PT.
Around temperature T_*,

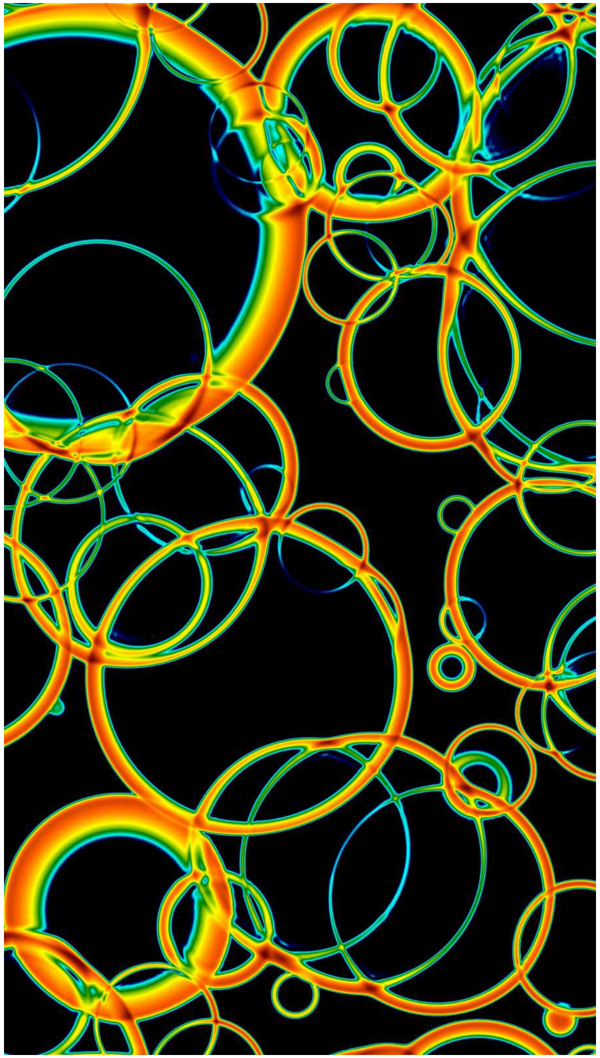
- Scalar field bubbles nucleate
  – with rate β
- Bubbles expand, liberate latent heat
  – characterised by α_{T_*}
- Bubbles interact with plasma
  – deposit kinetic energy with efficiency κ_{f}
- Friction from plasma acts on bubble walls
  – walls move with velocity v_{wall}
- Bubbles collide
  – producing gravitational waves

β, α_{T_*}, v_{wall} (and T_*):
3 (+1) parameters are all you need

Espinosa, Konstandin, No, Servant;

Kamionkowski, Kosowsky, Turner

(can get κ_{f} from α_{T_*} and v_{wall})



Electroweak baryogenesis

Standard lore:

1. Bubbles of the broken phase nucleate and expand
   – within the broken phase, the baryon number is frozen out
2. Particles in the plasma scatter off the bubble wall
   – generating $\mathcal{C}$ and $\mathcal{CP}$ asymmetries in front of the wall
3. Particles diffuse back into the symmetric phase
   – sphaleron transitions convert this into a baryon asymmetry
4. Baryon asymmetry remains when bubble wall 'catches up' – and in the broken phase a baryon asymmetry is produced

Need:

- A strongly first-order phase transition (to avoid washout within the bubble walls) – Good for GWs!
- Slow bubble wall velocity (must normally be subsonic, and slower the better for diffusion processes to work) – Bad for GWs!

Key question: how does the GW power spectrum depend on the wall velocity?

What the metric sees at a thermal phase transition

- Bubbles nucleate, most 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:

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

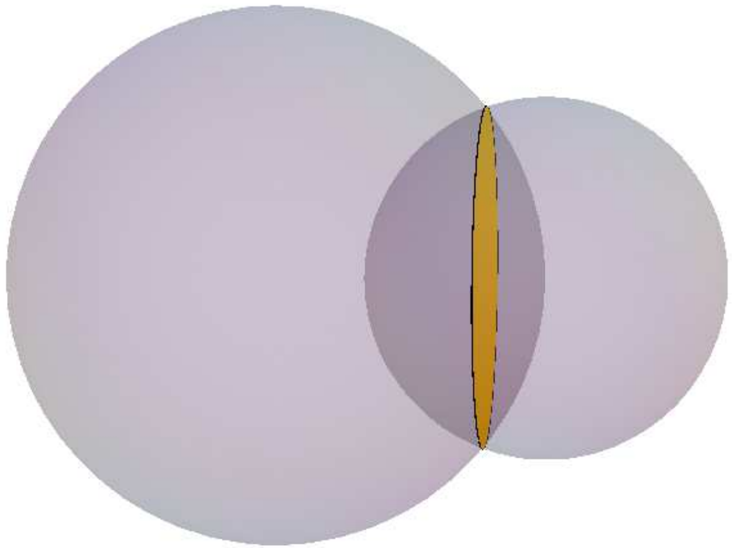
- Each phase's contribution depends on the nature of the phase transition.
- Now: explore steps 1-2 through two types of simulations:
  1. The 'envelope approximation' $\to h^2\Omega_\phi$
  2. Field ϕ ('Higgs') coupled by friction to fluid U^μ ('plasma') $\to h^2\Omega_{\text{sw}}$

1: Envelope approximation

Kosowsky, Turner and Watkins; Kamionkowski, Kamionkowsky and Turner

- Thin-walled 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 source gravitational waves
- Resulting power spectrum is simple
  - One scale (avg. bubble radius R_*)
  - Two power laws (ω^3, $\sim \omega^{-1}$)
  - Amplitude

$\Rightarrow$ 4 numbers define spectral form

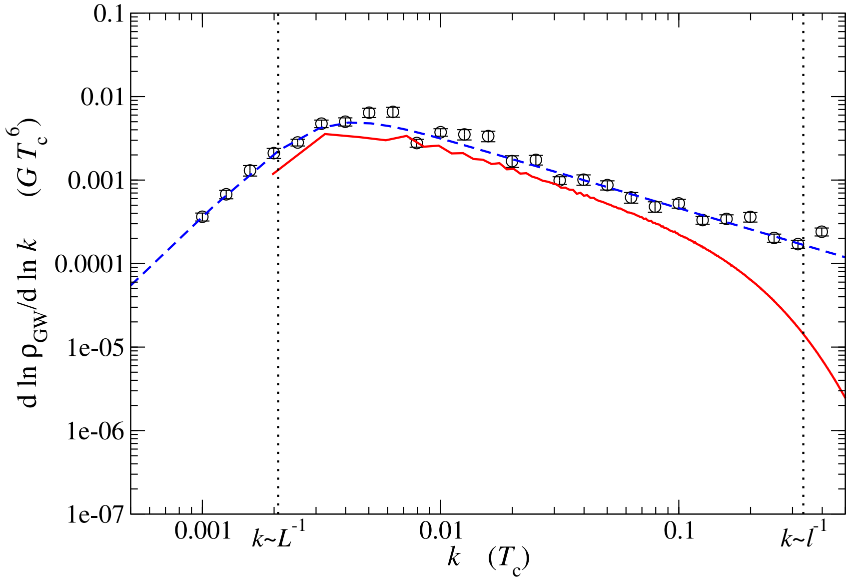


1: Making predictions with the envelope approximation

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' to $(\nabla\phi)^2$



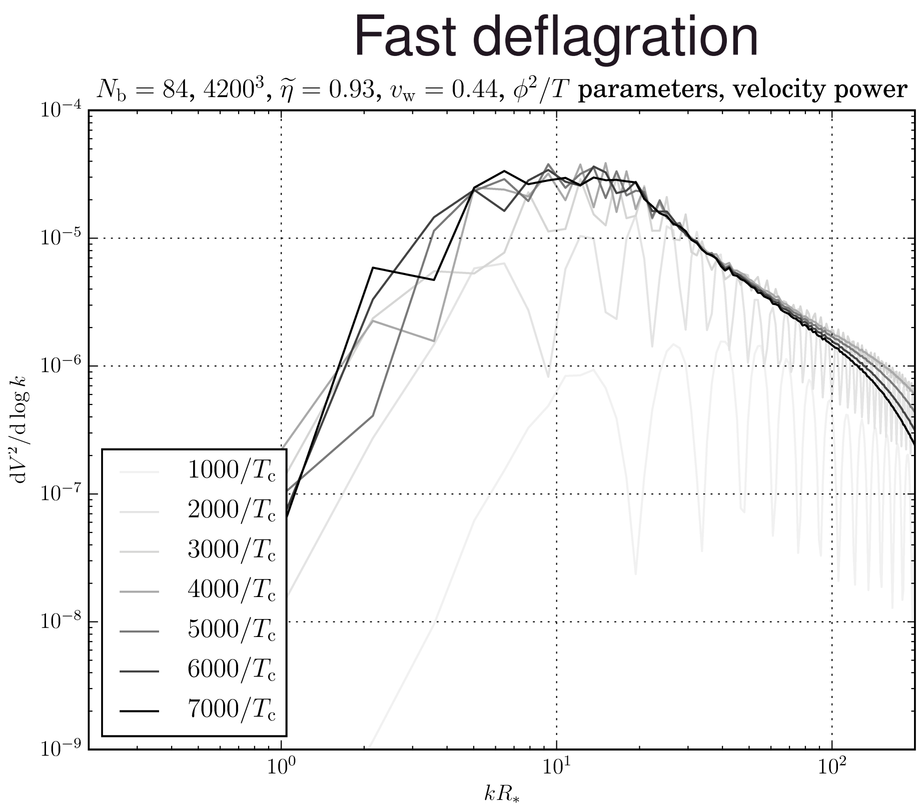
- Transition rate:
  - H_*, Hubble rate at transition
  - β, bubble nucleation rate

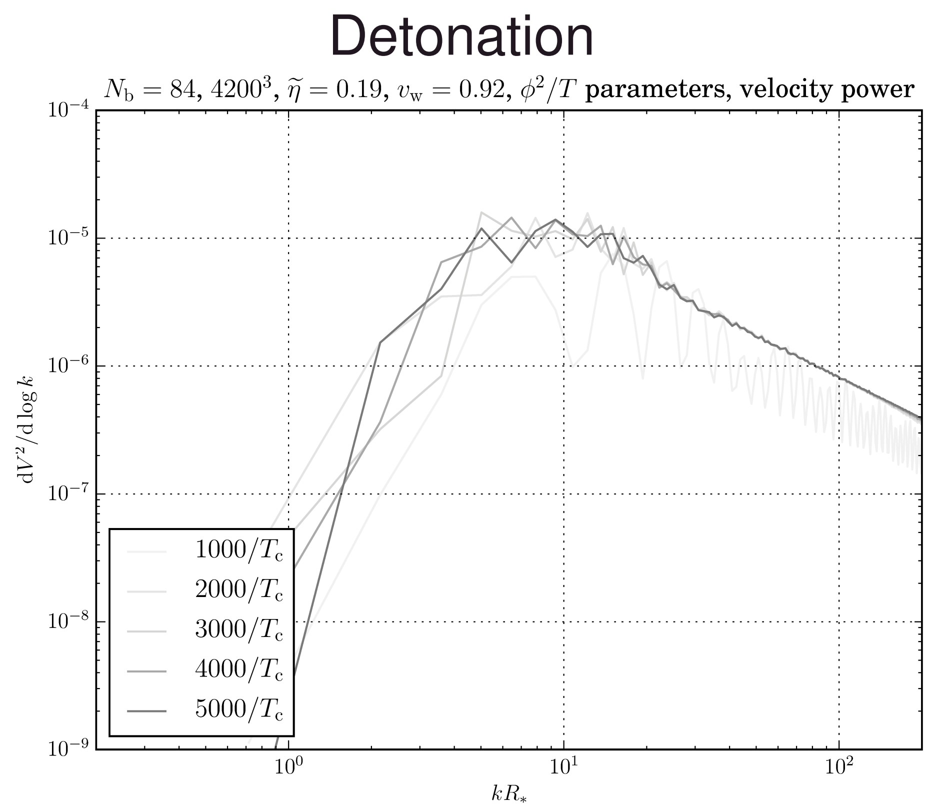
  $\rightarrow$ ansatz for $h^2\Omega_\phi$

NB: if applied to a *thermal* transition, energy in GWs would be

$$h^2\Omega_{\text{GW}} \propto \frac{0.11 v_{\mathrm{w}}^3}{0.42 + v_{\mathrm{w}}^2}\frac{\kappa_{\mathsf{f}}^2\alpha^2}{(\alpha+1)^2}\left(\frac{H_*}{\beta}\right)^2\left(\frac{100}{g_*}\right)^{1/3}$$

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



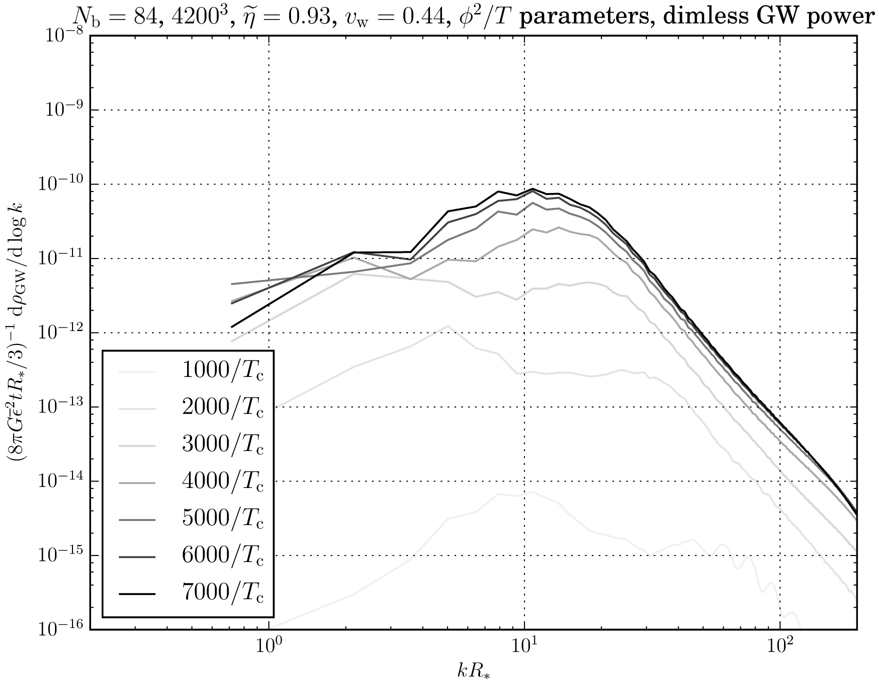


- Weak transition: $\alpha_{T_N} = 0.01$
- Power law behaviour above peak is between ω^{-2} and ω^{-1}
- “Ringing” due to simultaneous bubble nucleation, not physically important

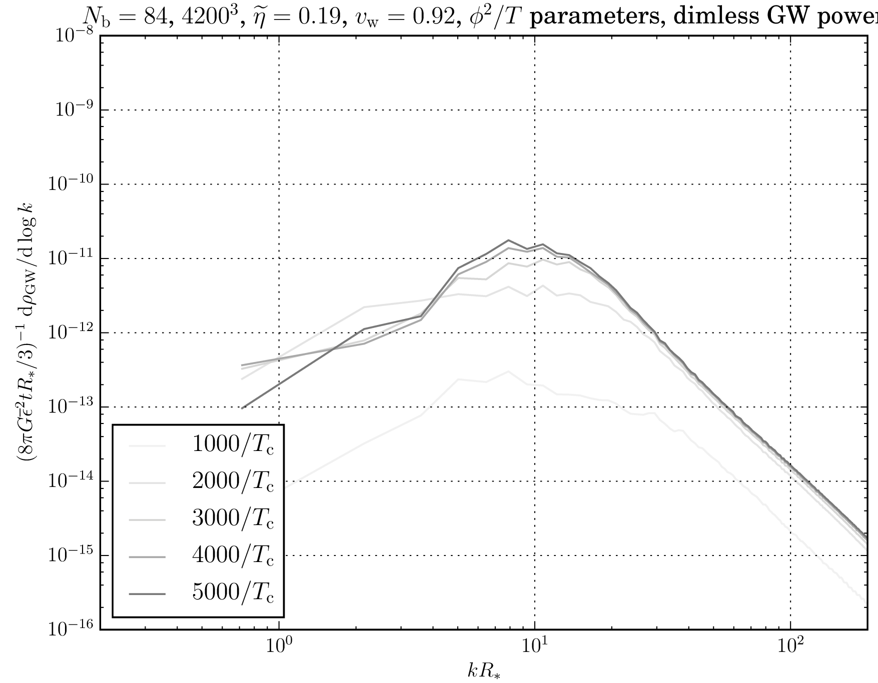
2: GW power spectra and power laws

- Sourced by T^{f}_{ij} only

Fast deflagration



Detonation

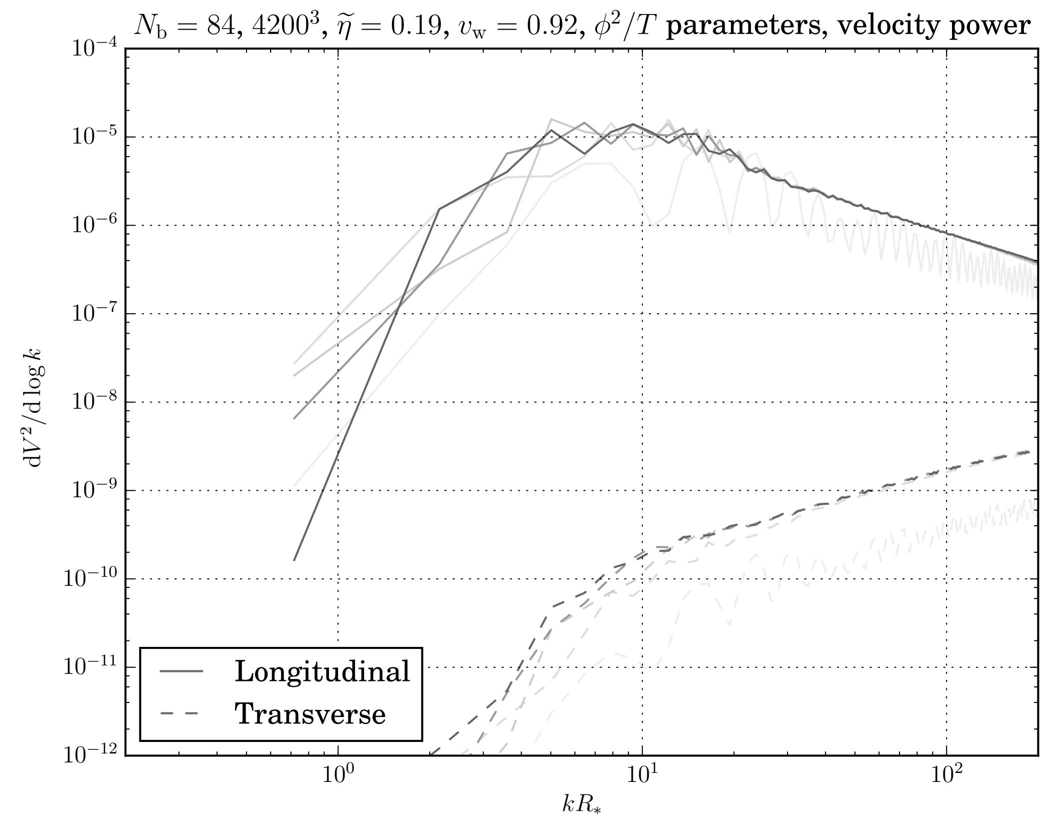


- Curves scaled by t: source ‘on’ continuously until turbulence/expansion

$$h^2\Omega_{\mathrm{sw}} \propto v_{\mathrm{w}} \frac{\kappa_{\mathrm{f}}^2 \alpha^2}{(\alpha+1)^2} \left(\frac{H_*}{\beta}\right) \left(\frac{100}{g_*}\right)^{1/3}$$

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

3: Transverse versus longitudinal modes – turbulence?

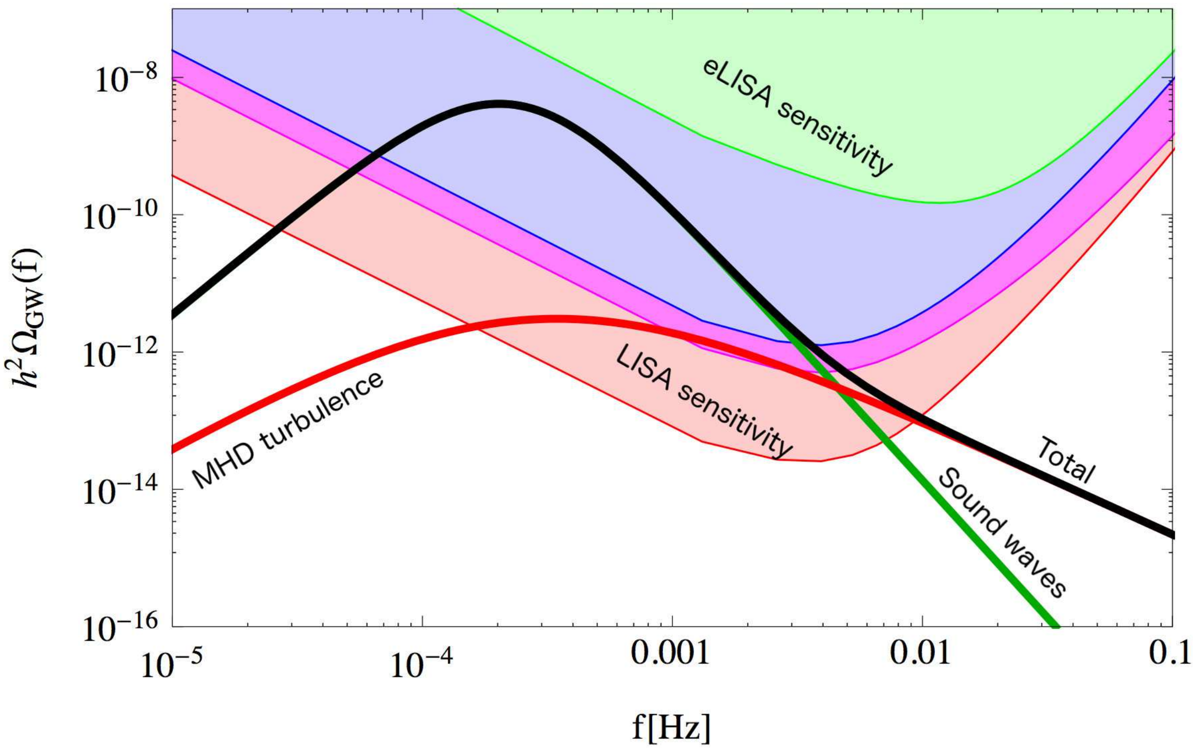


- Weak transition (small α): physics is linear; most power is in the longitudinal modes – acoustic waves, not turbulence
- Is turbulence is something that would happen later?
- Power spectrum would have causal ω^3 then $\omega^{-5/3}$ from Kolmogorov velocity power spectrum Caprini, Durrer and Servant

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

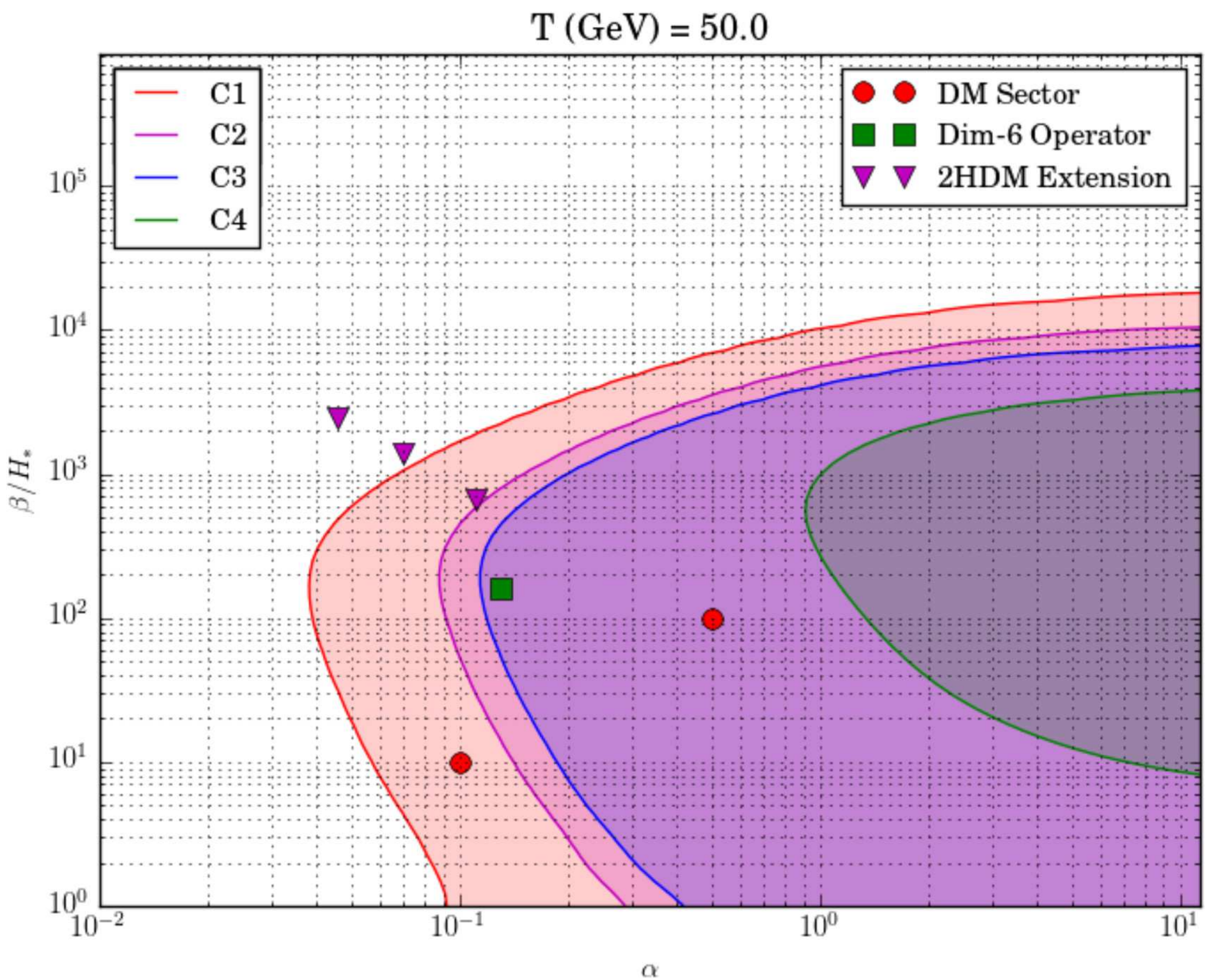
- We have three sources, $\approx h^2\Omega_\phi$, $h^2\Omega_{\text{sw}}$, $h^2\Omega_{\text{turb}}$
- We know how they vary as a function of T_*, α_T, v_{w}, β
- So we can (tentatively) say whether eLISA can detect the phase transition associated with a given model…

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



Putting it all together - physical models to GW power spectra

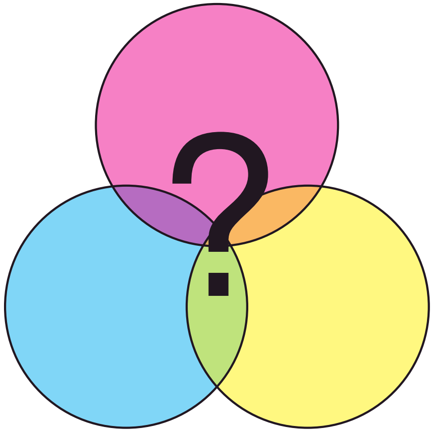
Map your favourite theory to $(T_*, \alpha_{T_*}, v_\mathrm{w}, \beta)$; we can put it on a plot like this



. . . and tell you if it is detectable by the different [e]LISA cases.

Summary and outlook

- Now:
  - Understand 'what happened during a first order PT'
  - Recent work shows source may be stronger than previously thought
  - Many models of first order EWPTs can produce observable gravitational waves, with lower wall velocities than expected – good for baryogenesis!



- Next:
  - Strong transitions, turbulence, instabilities still poorly understood
  - Connections with baryogenesis Katz and Riotto; Chala, Nardini, Sobolev; ...