Gravitational waves from bubble collisions: simulations and approximations

PRL 112, 041301 (2014) [arXiv:1304.2433]

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SEWM, 18 July 2014

Why study first-order phase transitions?

- Baryogenesis!
- Strongly first-order EW phase transitions dump lots of energy into GWs
  - Need to make predictions for the observable power spectrum

    Talk by Hindmarsh
- What physics can we extract from GW power spectrum at EW scales?
- Extended models in which EW phase transition would be first order

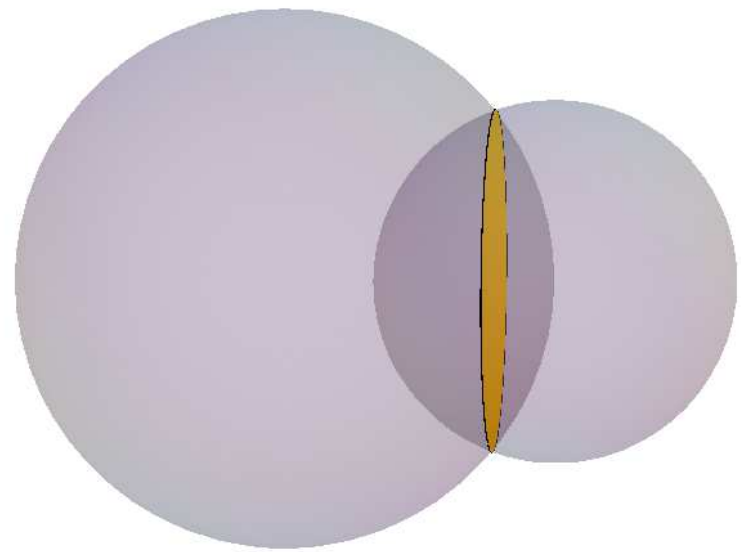
  Andersen, Laine *et al.*, Kozaczuk *et al.*, Kamada and Yamada, Carena *et al.*, Bödeker *et al.*. . .
  - 2HDM
  - MSSM (‘light stop’), nMSSM, NMSSM
  - Dimension 6 operators
  - If you feel lucky: technicolor
- Test envelope approximation

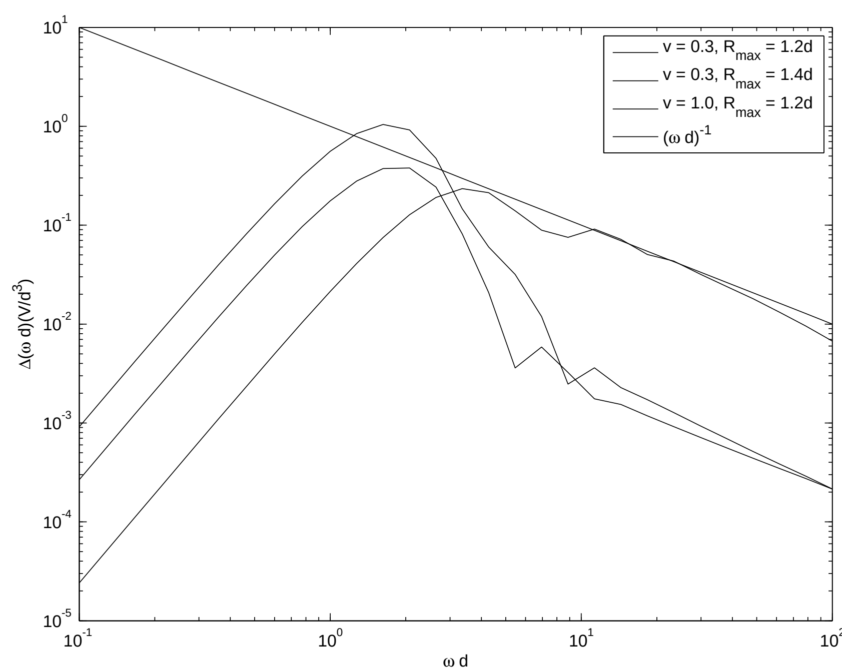
  Kosowsky, Turner and Watkins; Huber and Konstandin
- GUT-scale phase transitions also interesting

  Giblin and Mertens, Child and Giblin

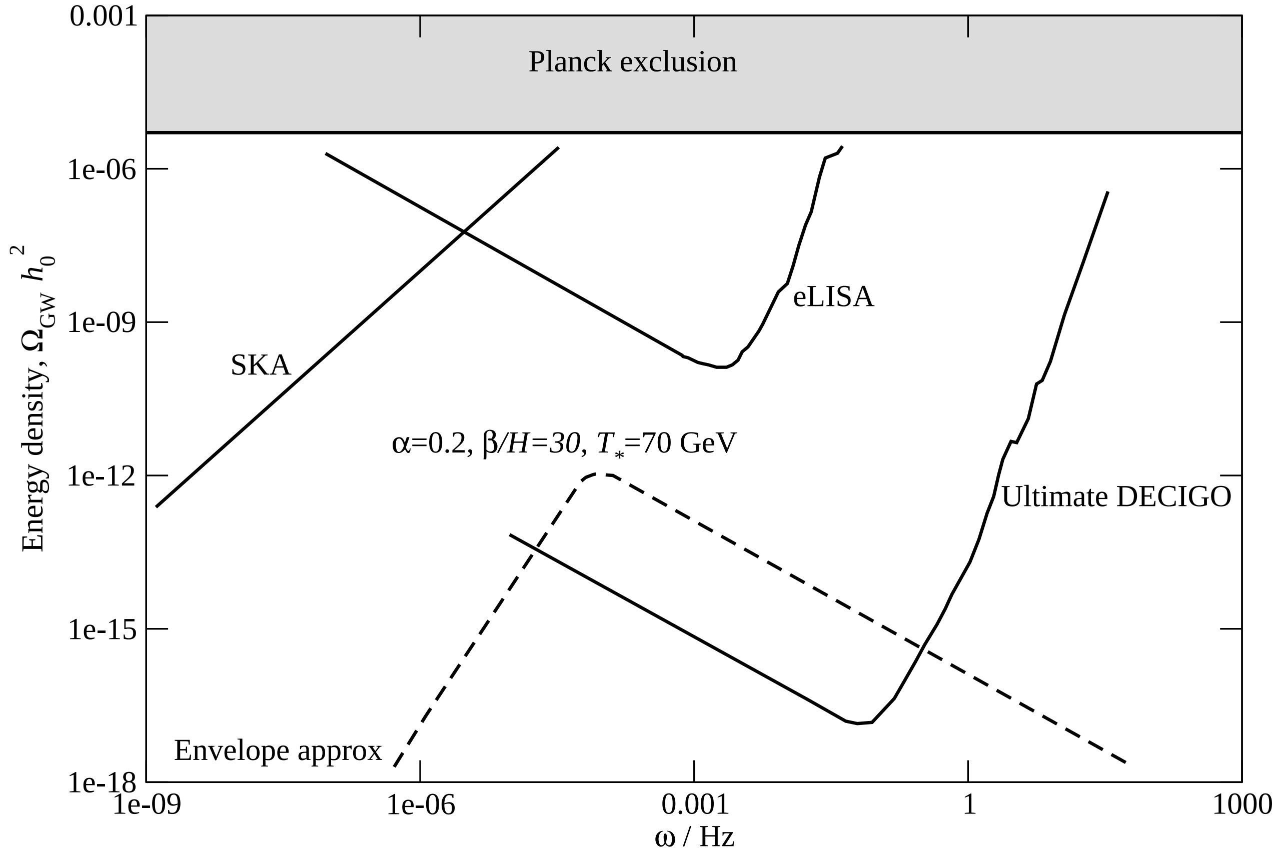
Envelope approximation Kosowsky, Turner and Watkins; Huber and Konstandin

- Thin-walled bubbles, no fluid
- Bubbles expand with velocity $v_{\rm w}$
- 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 (R_*)
  - Two power laws (k^3, k^{-1})



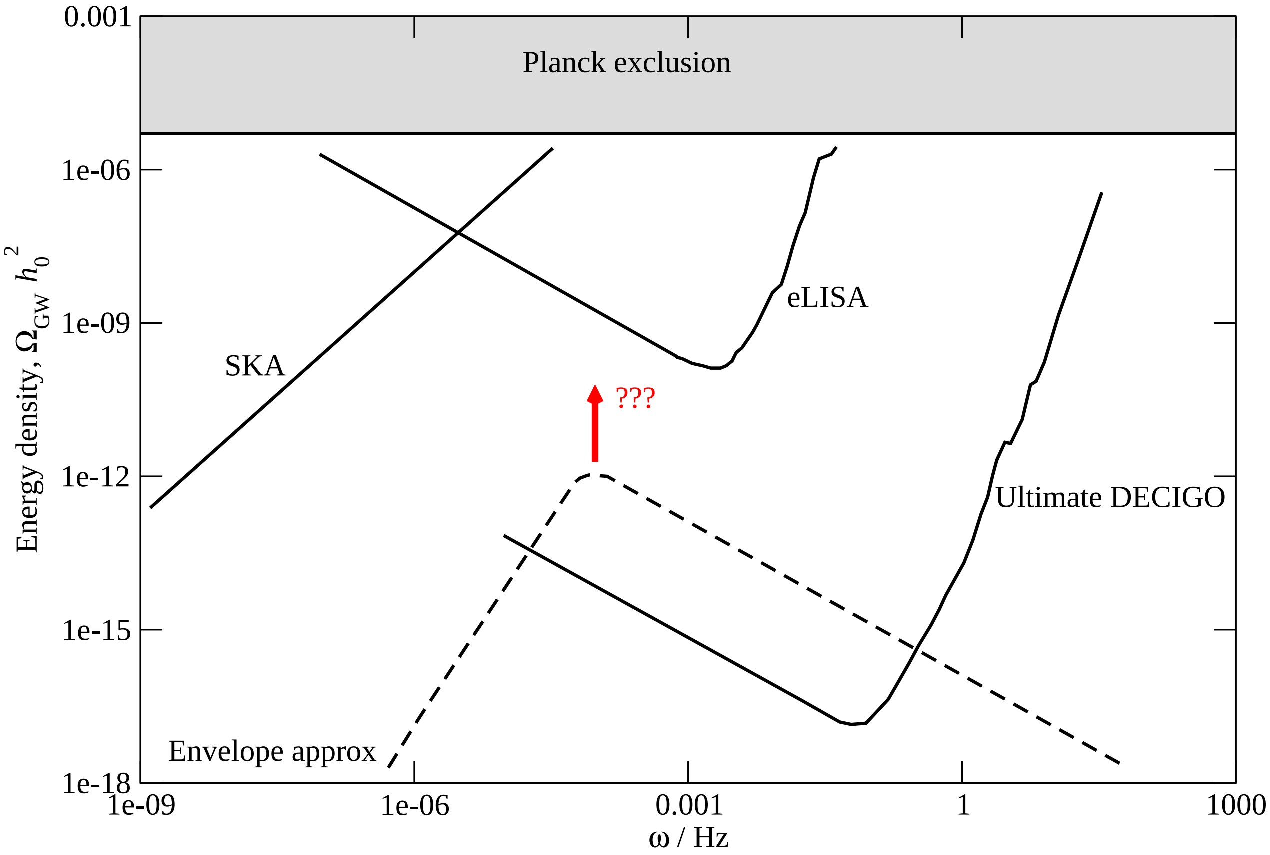


The envelope approximation makes predictions



Predict k^3 in IR, peak at R_*^{-1}, then k^{-1} in UV...

But are they too conservative? Where does the energy go?



The shock waves set up by the expanding higgs field are neglected.

Our approach

- Scalar field plus ideal relativistic fluid, usual relativistic hydro
  Wilson and Matthews
  - Split stress-energy tensor $T^{\mu\nu}$ into field and fluid bits
    Ignatius, Kajantie, Kurki-Suonio and Laine

$$\partial_\mu T^{\mu\nu} = \partial_\mu (T^{\mu\nu}_{\text{field}} + T^{\mu\nu}_{\text{fluid}}) = 0$$

  - The parameter η sets the scale of friction caused by the bubble moving through the plasma:

$$\partial_\mu T^{\mu\nu}_{\text{field}} = \eta u^\mu \partial_\mu \phi \partial^\nu \phi \qquad \partial_\mu T^{\mu\nu}_{\text{fluid}} = -\eta u^\mu \partial_\mu \phi \partial^\nu \phi$$

- $V(\phi, T)$ can be kept quite simple

$$V(\phi, T) = \tfrac{1}{2}\gamma(T^2 - T_0^2)\phi^2 - \tfrac{1}{3}\alpha T \phi^3 + \tfrac{1}{4}\lambda\phi^4$$

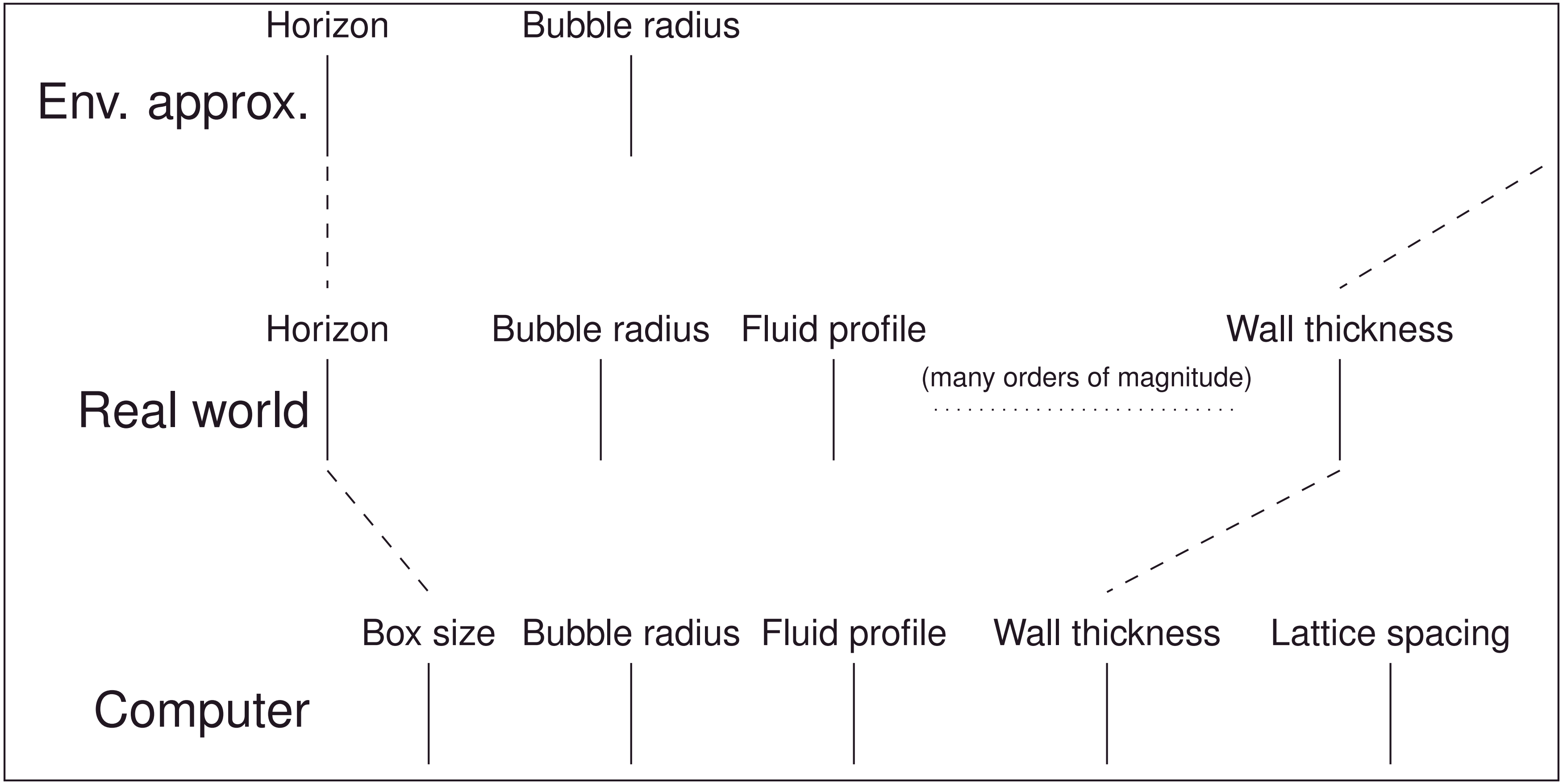
  - α, β, γ, T_0 chosen to match scenario of interest
- Assume friction η quite big (not runaway case)
  - Scalar field dynamics trivial: tracking field that gives us shocks

Velocity profile development - deflagration

The strongest deflagration we dare treat: $v_{\mathrm{f}}^{\mathsf{max}} \approx 0.12$

Dynamic range issues

- Most realtime lattice simulations in the early universe have a single [nontrivial] length scale
- Here, many length scales important



- Difficult to fit everything on a computer :(

Nucleation process

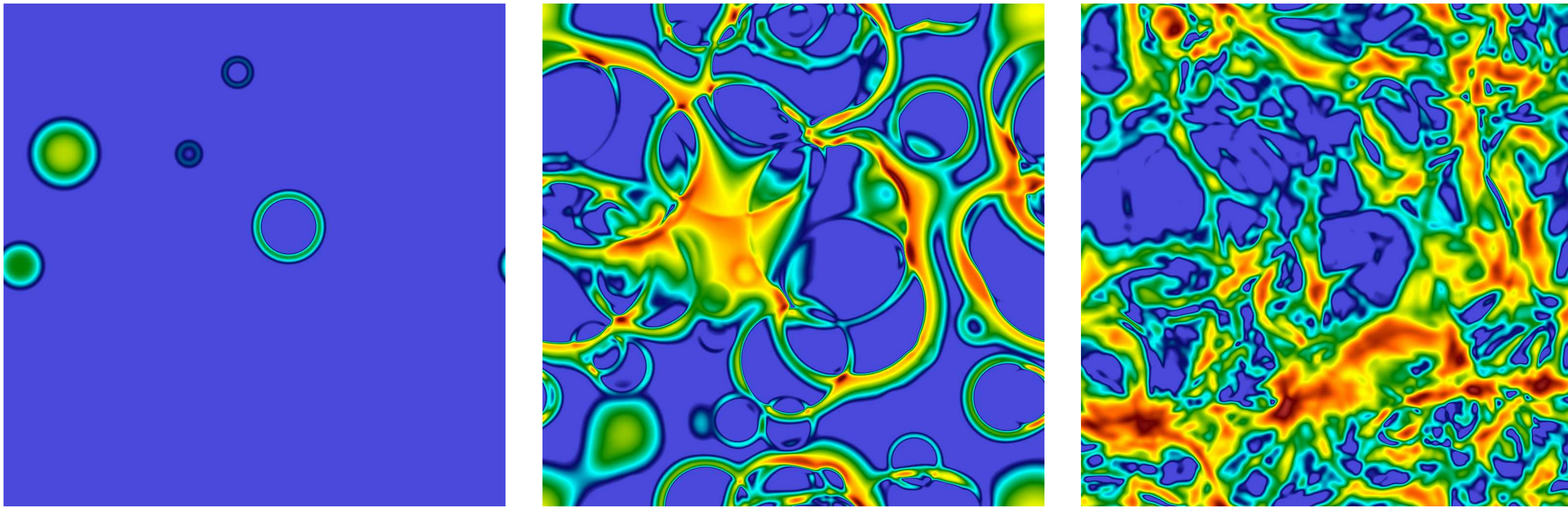
- No expansion (not relevant on transition timescales)
- Bubbles have to be macroscopic initially
- Start with slightly-larger-than-critical macroscopic bubble (alternative: insert scaling profile)
- Nucleate bubbles with an exponentially increasing rate per unit volume (neglecting the T-dependence)

$$P = P_0 \exp(\beta(t - t_0))$$

- Dwindling false vacuum turns this into a double exponential
- All the results in this talk are for a ‘somewhat’ strong transition ($\alpha_{\mathrm{N}} = 0.1$)
- Mostly study deflagrations; detonations seem quite similar (to us!)

Slices – acoustic waves

Simulations at 1024^3, deflagration, fluid kinetic energy density, ∼250 bubbles



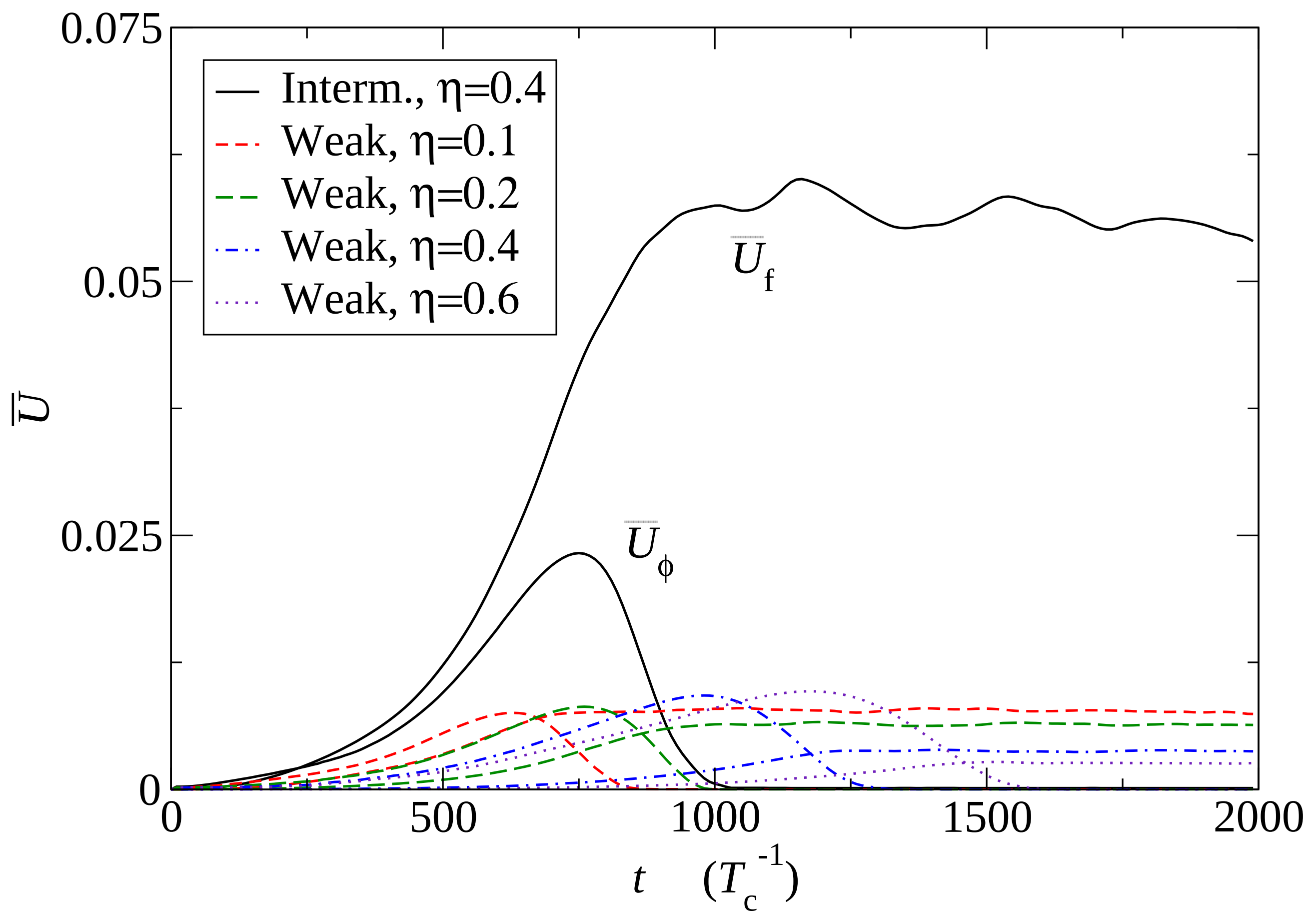
$t = 500\,T_c^{-1}$ $t = 750\,T_c^{-1}$ $t = 1000\,T_c^{-1}$

- After the scalar field dynamics have ceased, acoustic waves are visible.
- Distinct (not 'envelope'-like) GW source that remains on for a Hubble time.
- In true EW scenario, fluid source much longer lasting than scalar field.

Lots of latent heat = lots of fluid kinetic energy

Relative size of field and fluid stress-energy contributions

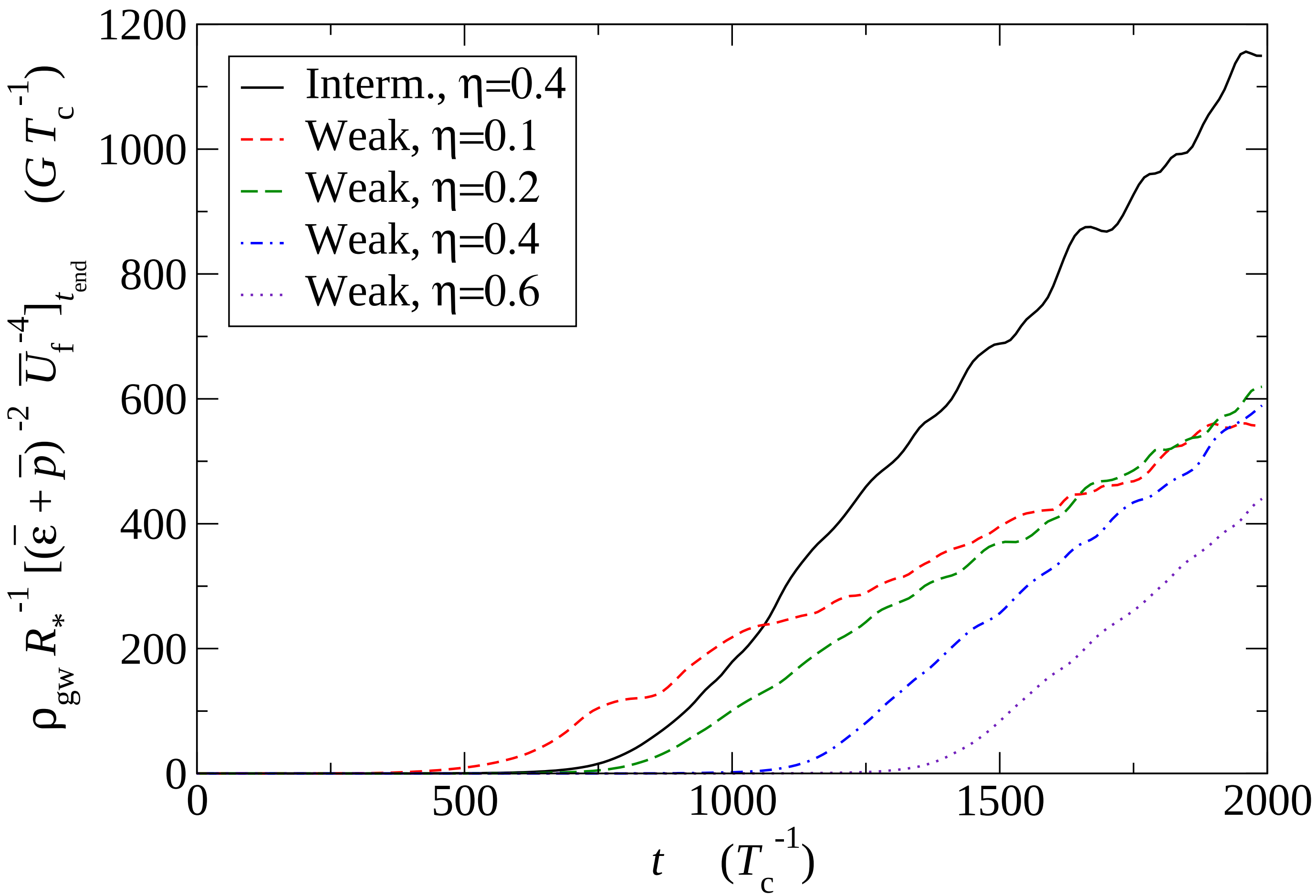
$$(\bar{\epsilon}+\bar{p})\overline{U}_\phi^2 = \frac{1}{V}\int d^3x(\partial_i\phi)^2 \qquad (\bar{\epsilon}+\bar{p})\overline{U}_f^2 = \frac{1}{V}\int d^3x\gamma^2(\epsilon+p).$$



Simulation slice example

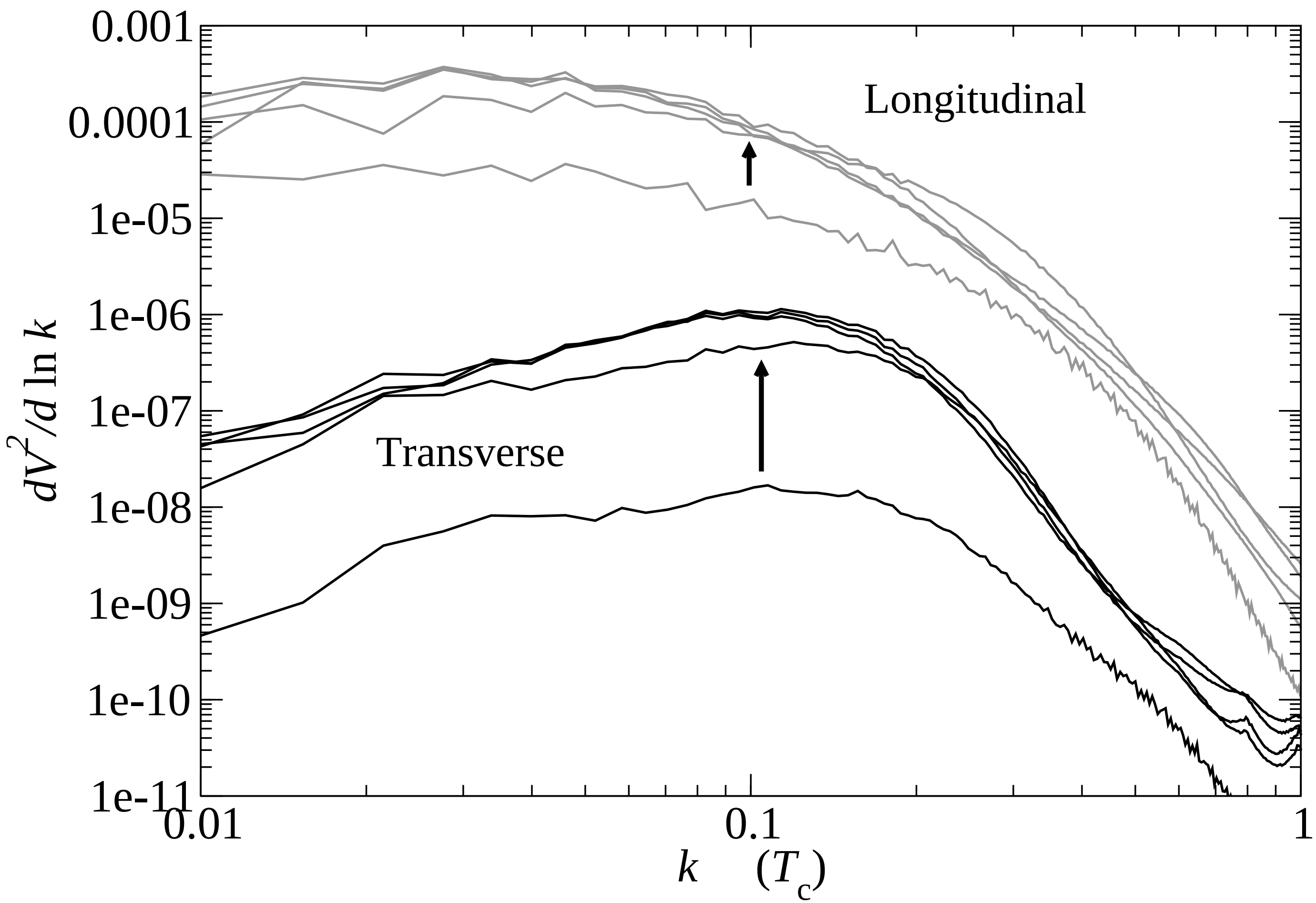
Acoustic waves source linear growth of gravitational waves

- Sourced by T^{fluid} only (T^{field} source is small constant shift)



- Source scales as $(\overline{\varepsilon} + \overline{p})^2 U^4$ (and R_* on dimensional grounds)
- Slopes match, up to $O(1)$ differences, despite huge differences in T^{fluid}

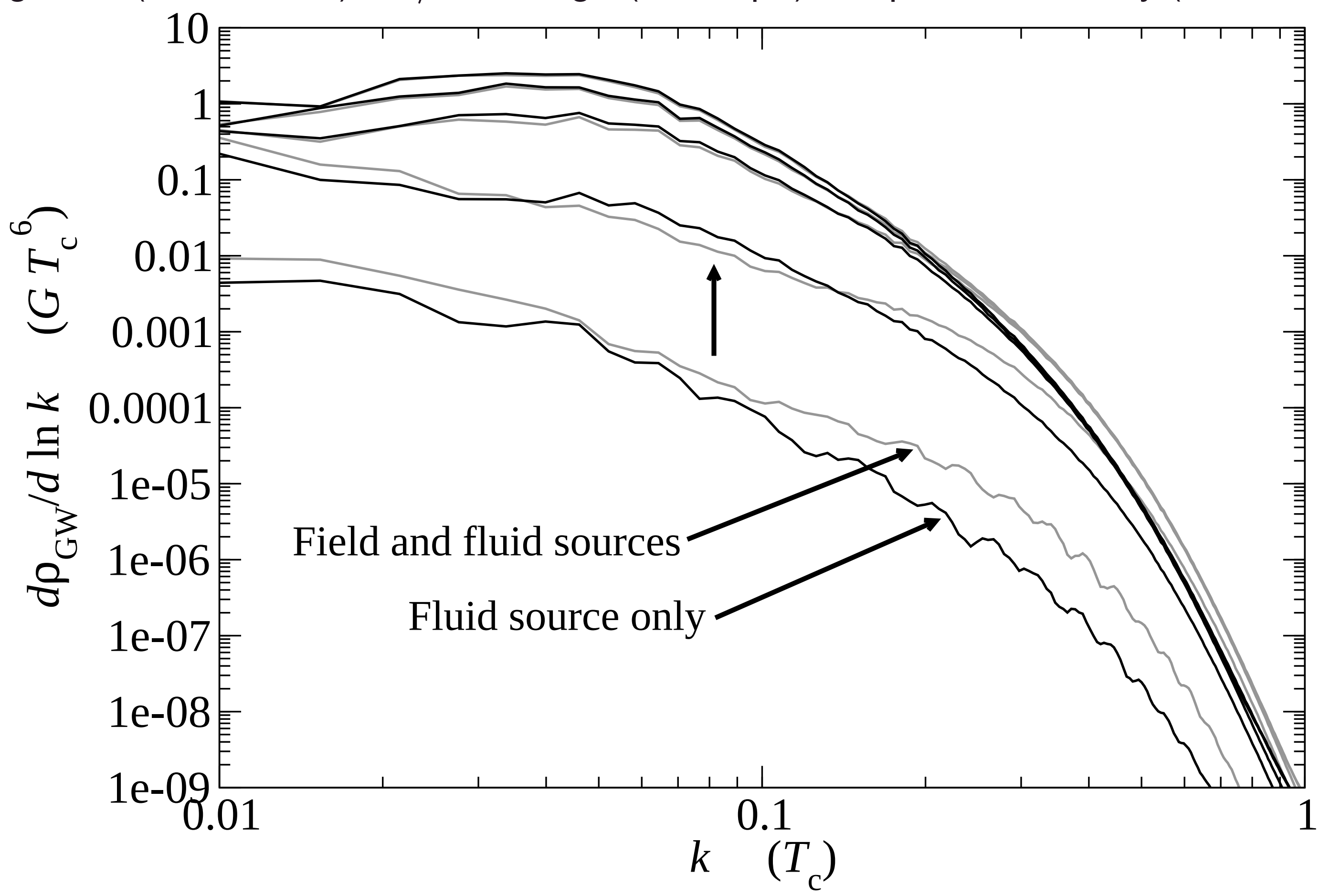
Velocity power spectra for a strong (ish) transition, $\alpha_{\mathrm{N}} = 0.1$



- Most power is in the longitudinal modes – acoustic waves, not turbulence
- System is quite linear. No power laws? Reynolds number is 100.
- If we know $\mathrm{d}V^2/\mathrm{d}\ln k$, can work out $\dot{\rho}_{\mathrm{GW}}/\mathrm{d}\ln k\ldots$?

GW power spectra

k^3 growth (white noise) – $1/k$ scaling? (envelope) – exponential decay (bubble wall)



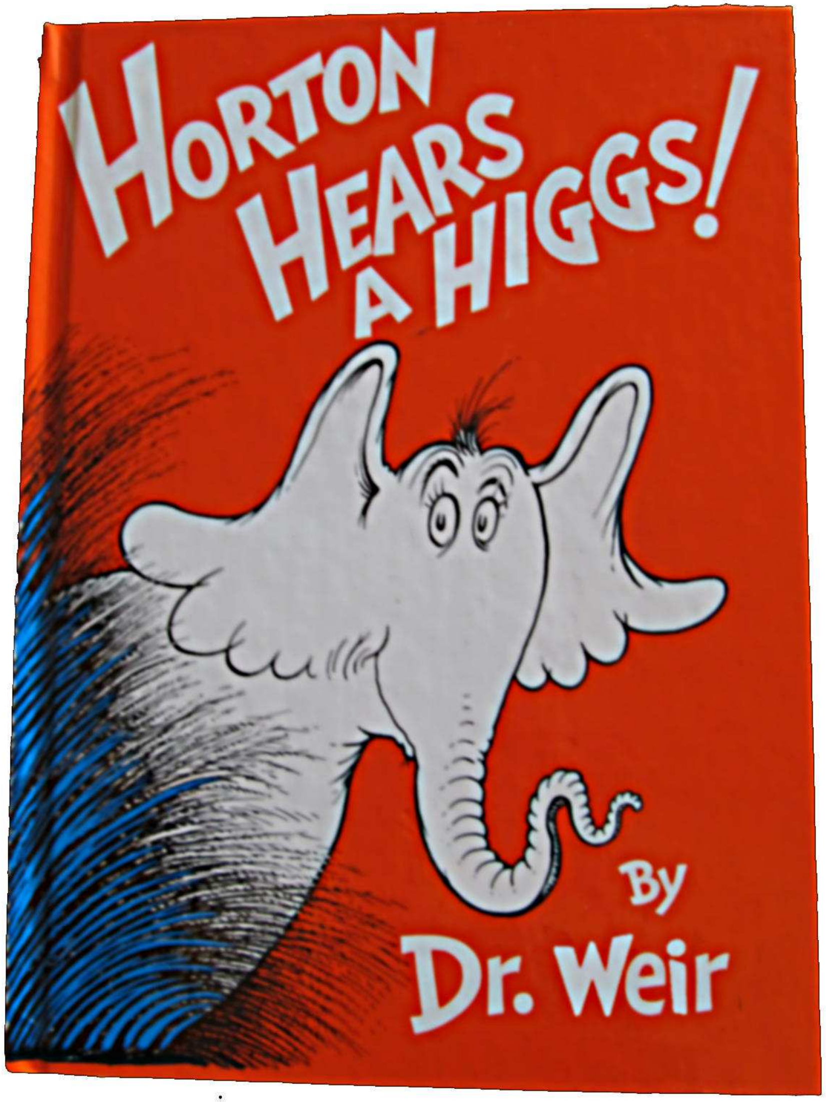
- By late times, fluid source dominates at all length scales
- Will only be stopped by expansion: [up to] $1000\times$ enhancement!

Conclusions

- Acoustic waves set up after bubble collisions are a significant source of gravitational wave power in first-order phase transitions
- A strongly first order phase transition at the electroweak scale would source far more gravitational waves than previously thought
- The ‘Envelope approximation’ (energy density carried on the surface of a bubble) does not correctly model the collisions of bubbles
- System is very linear: the fluid power spectrum is just a convolution away from the GW power spectrum
- Motivates an ‘acoustic approximation’: superimposed random fluid shells with different bubble radii frozen in
- For slow wall velocities, can then replace a highly nonlinear 2D source (envelope approx) with a linear 1D source (intersecting fluid shells)

Thanks!


STEREO
COLUMBIA
SIMON & GARFUNKEL
SOUNDS OF 2HDM


HORTON HEARS A HIGGS!
By
Dr. Weir