Title: Gravitational waves from the sound of a first-order phase transition

Date: Mar 27, 2018 01:00 PM

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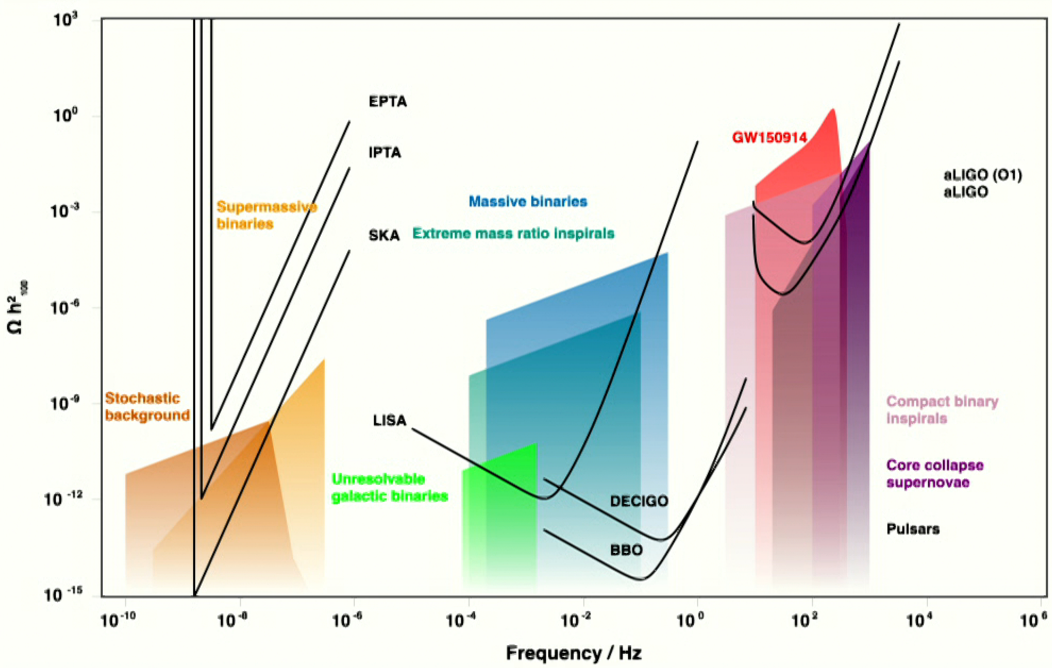
Abstract: <p>The space-based gravitational wave detector LISA may be able to detect gravitational waves from a first order phase transition at the electroweak scale. Acoustic waves produced during the transition are largely responsible for the resulting signal. I will present results from a large campaign of simulations studying such phase transitions, determining the spectral shape of the gravitational wave power spectrum with unparalleled accuracy. Measuring a cosmological stochastic background could place constraints on the phase transition parameters, such as the nucleation rate and temperature, and therefore provide important information about physics beyond the Standard Model. However, better understanding of the source, as well as the underlying theories of physics beyond the Standard Model, is required before the launch of LISA. I will outline how this understanding can be developed.</p>

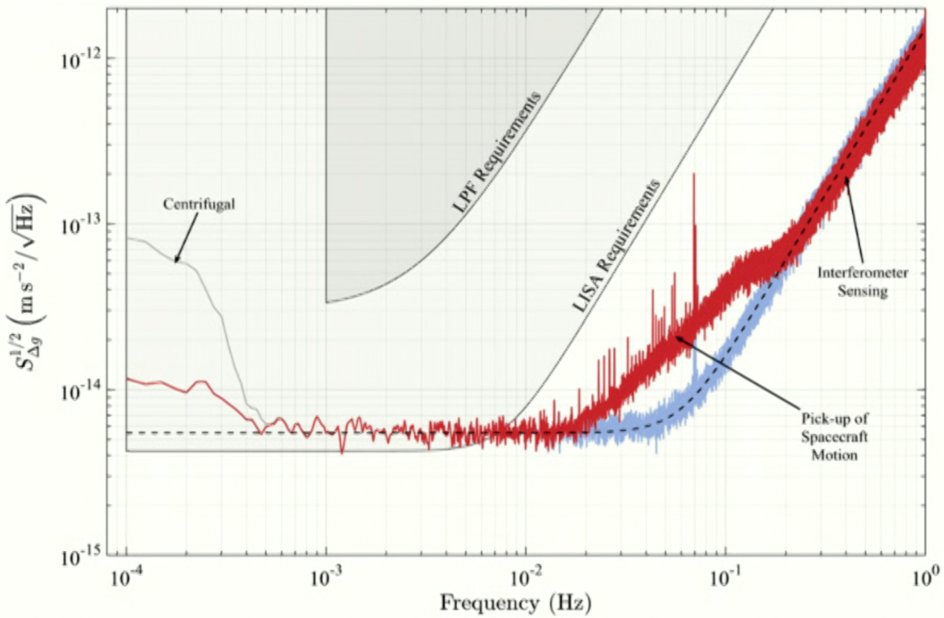
Lots of sources...



Source: GWplotter

LISA Pathfinder

PRL **116,** 231101 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

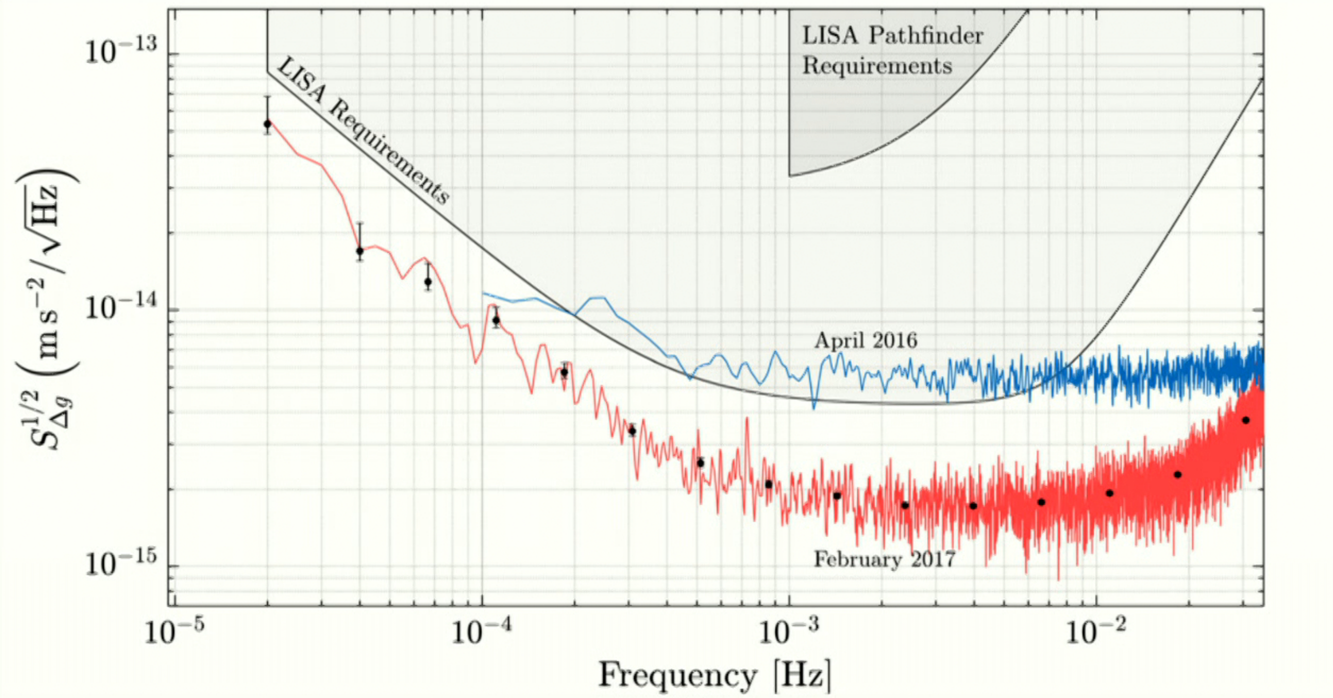


Exceeded design expectations by factor of five!

LISA Pathfinder

But that's not all...

PHYSICAL REVIEW LETTERS **120,** 061101 (2018)



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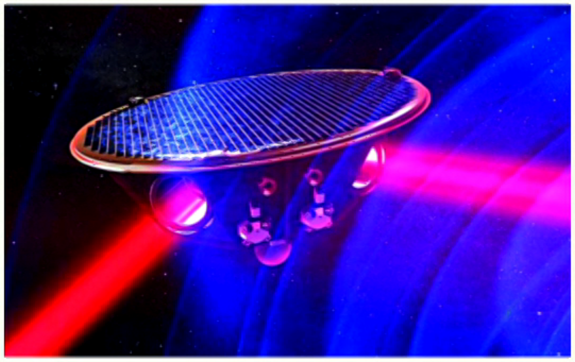
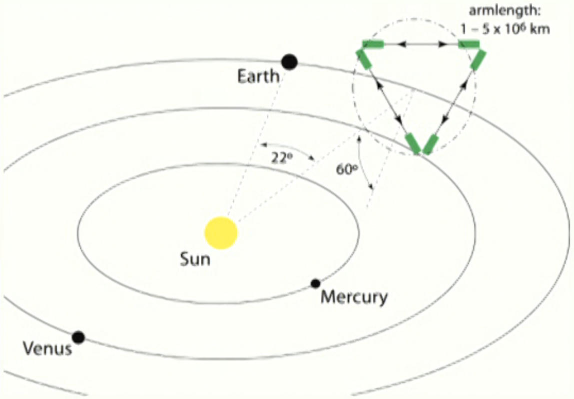
What's next: LISA





- LISA: three arms (six laser links), 2.5 M km separation
- Launch as ESA's third large-scale mission (L3) in (or before) 2034
- Proposal submitted a year ago 1702.00786
- Officially adopted on 20.6.2017

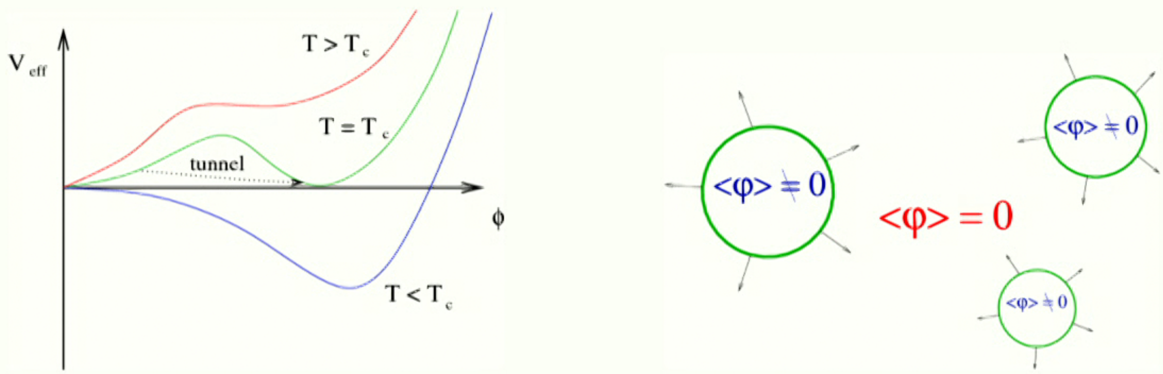
From the LISA proposal:

SI7.2 : Measure, or set upper limits on, the spectral shape of the cosmological stochastic GW background

OR7.2: Probe a broken power-law stochastic background from the early Universe as predicted, for example, by first order phase transitions [21] (other spectral shapes are expected, for example, for cosmic strings [22] and inflation [23]). Therefore, we need the ability to measure $\Omega = 1.3 \times 10^{-11} \left(f/10^{-4}\,\mathrm{Hz}\right)^{-1}$ in the frequency ranges $0.1\,\mathrm{mHz} < f < 2\,\mathrm{mHz}$ and $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$, and $\Omega = 4.5 \times 10^{-12} \left(f/10^{-2}\,\mathrm{Hz}\right)^{3}$ in the frequency ranges $2\,\mathrm{mHz} < f < 20\,\mathrm{mHz}$ and $0.02 < f < 0.2\,\mathrm{Hz}$.

Electroweak phase transition

- This is the process by which the Higgs 'turned on'
- In the minimal Standard Model it is gentle (crossover)
- It is possible (and theoretically attractive) in extensions that it would experience a first order phase transition



Source: Morrissey and Ramsey-Musolf

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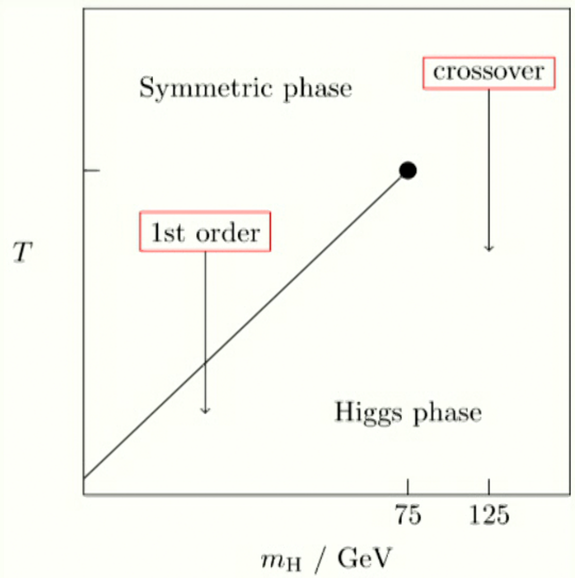
EW PT in the SM

Work in the 1990s found this phase diagram for the SM:



At $m_H = 125\,\text{GeV}$, SM is a crossover

Kajantie *et al.*; Gurtler *et al.*; Csikor *et al.*; ...

Dimensional reduction

- At high T, system looks 3D for long distance physics (with length scales $\Delta x \gg 1/T$)
- Decomposition of fields:

$$\phi(x,\tau) = \sum_{n=-\infty}^{\infty} \phi_n(x) e^{i\omega_n \tau}; \qquad \omega_n = 2\pi n T$$

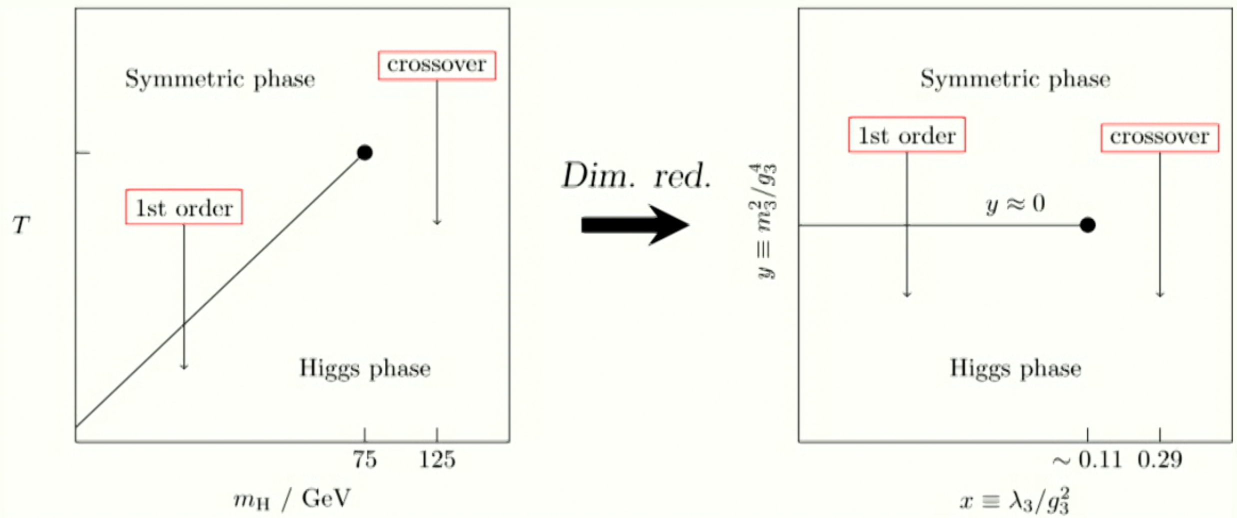
- Then integrate out $n \neq 0$ Matsubara modes due to the scale separation

$$Z = \int \mathcal{D}\phi_0 \mathcal{D}\phi_n \, e^{-S(\phi_0)-S(\phi_0,\phi_n)}$$
$$= \int \mathcal{D}\phi_0 \, e^{-S(\phi_0)-S_{\text{eff}}(\phi_0)}$$

- The 3D theory (with most fields integrated out) is easier to study, has fewer parameters!

Using the dimensional reduction

- Using the DR'ed 3D theory, can study nonperturbatively with lattice simulations.
- This was done very successfully in the 1990s for the Standard Model:



- [Q: Can we map any other theories to the same 3D model?]

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SM is a crossover: consequences

- No real departure from thermal equilibrium
  $\Rightarrow$ no significant GWs or baryogenesis
- Many alternative mechanisms for baryogenesis exist
  - Leptogenesis (add RH neutrinos, see-saw mechanism, additional leptons produced by RH neutrino decays)
  - Cold electroweak baryogenesis (non-equlibrium physics given by supercooled initial state)

  but let us instead consider additional fields which would yield a first order phase transition.

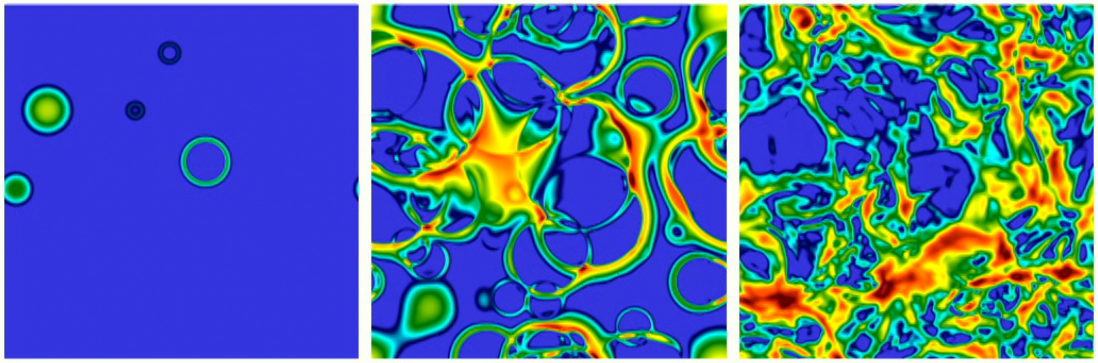
SM extensions with 1.PT

- Higgs singlet model - add extra real singlet field σ:
  quite difficult to rule out with colliders
- Two Higgs doublet model - add second complex doublet:
  many parameters, but already quite constrained
- Triplet models - add adjoint scalar field (triplet):
  few parameters, not yet widely studied, CDM candidate?

All these have unexcluded regions of parameter space for which the phase transition is first order

First order thermal phase transition:

1. Bubbles nucleate and grow
2. Expand in a plasma - create shock waves
3. Bubbles + shocks collide - violent process
4. Sound waves left behind in plasma
5. Turbulence; expansion



How the bubble wall moves

- Equation of motion is (schematically)

  Liu, McLerran and Turok; Prokopec and Moore; Konstandin, Nardini and Rues; ...

$$\partial_\mu \partial^\mu \phi + V'_{\rm eff}(\phi, T) + \sum_i \frac{dm_i^2}{d\phi} \int \frac{\mathrm{d}^3 k}{(2\pi)^3\, 2E_i} \delta f_i(\mathbf{k}, \mathbf{x}) = 0$$

  - $V'_{\rm eff}(\phi)$: gradient of finite-T effective potential
  - $\delta f_i(\mathbf{k}, \mathbf{x})$: deviation from equilibrium phase space density of ith species
  - m_i: effective mass of ith species:
    - Leptons: $m^2 = y^2 \phi^2/2$
    - Gauge bosons: $m^2 = g_w^2 \phi^2/4$
    - Also Higgs and pseudo-Goldstone modes

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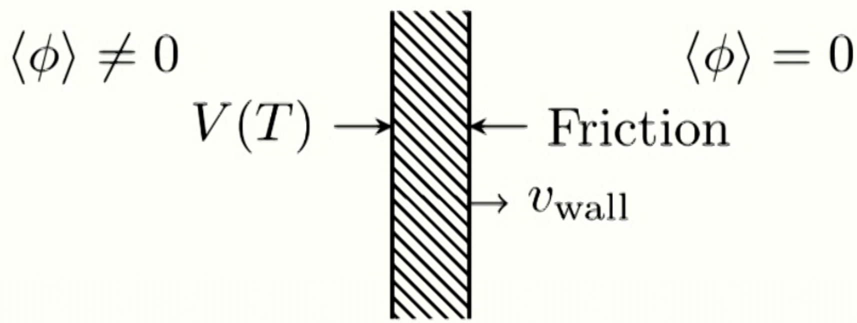
Put another way:

$$\overbrace{\partial_\mu T^{\mu\nu}}^{\text{Force on }\phi} - \overbrace{\int \frac{d^3k}{(2\pi)^3} f(\mathbf{k}) F^\nu}^{\text{Force on particles}} = 0$$

This equation is the realisation of this idea:



Yet another interpretation:

$$\overbrace{\partial_\mu T^{\mu\nu}}^{\text{Field part}} - \overbrace{\int \frac{d^3k}{(2\pi)^3} f(\mathbf{k}) F^\nu}^{\text{Fluid part}} = 0$$

i.e.:

$$\partial_\mu T^{\mu\nu}_\phi + \partial_\mu T^{\mu\nu}_{\text{fluid}} = 0$$

We will return to this later!

Gravitational waves from a thermal phase transition

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What the metric sees at a thermal phase transition

- Bubbles nucleate and expand, shocks form, then:
  1. $h^2\Omega_\phi$: Bubbles + shocks collide - 'envelope phase'
  2. $h^2\Omega_{\rm sw}$: Sound waves set up - 'acoustic phase'
  3. $h^2\Omega_{\rm turb}$: [MHD] turbulence - 'turbulent phase'

- Sources add together to give observed GW power:

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

Envelope approximation

Kosowsky, Turner and Watkins; Kamionkowski, Kosowsky and Turner

- Thin, hollow bubbles, no fluid
- Stress-energy tensor $\propto R^3$ on wall
- Solid angle: overlapping bubbles → GWs
- Simple power spectrum:
  - One length scale (average radius R_*)
  - Two power laws (ω^3, $\sim \omega^{-1}$)
  - Amplitude

  ⇒ 4 numbers define spectral form

NB: Used to be applied to shock waves (fluid KE), now only use for bubble wall (field gradient energy)

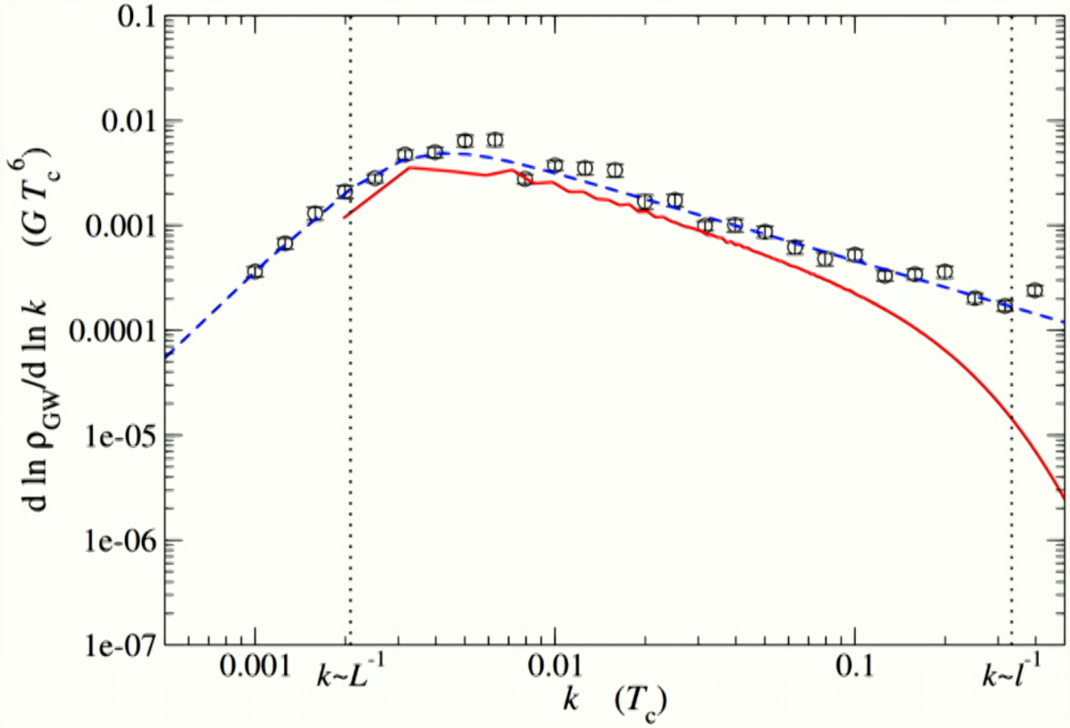
Envelope approximation

4-5 numbers parametrise the transition:

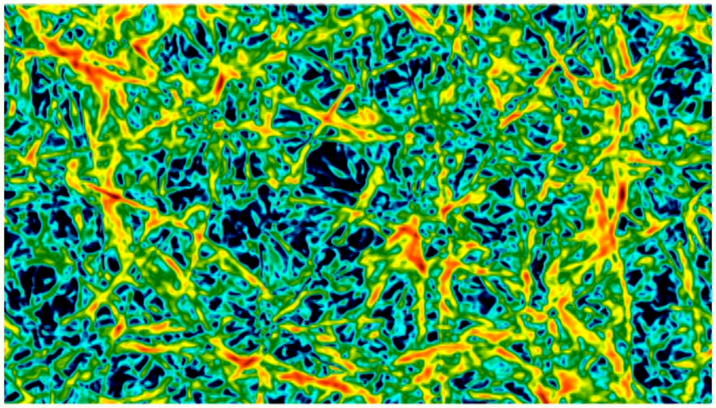
- α_{T_*}, vacuum energy fraction
- v_w, bubble wall speed
- κ_ϕ, conversion 'efficiency' into gradient energy $(\nabla\phi)^2$
- β/H_*:
  - β, inverse phase transition duration
  - H_*, Hubble rate at transition

→ ansatz for $h^2\Omega_\phi$

Envelope approximation



Step 2: Acoustic phase



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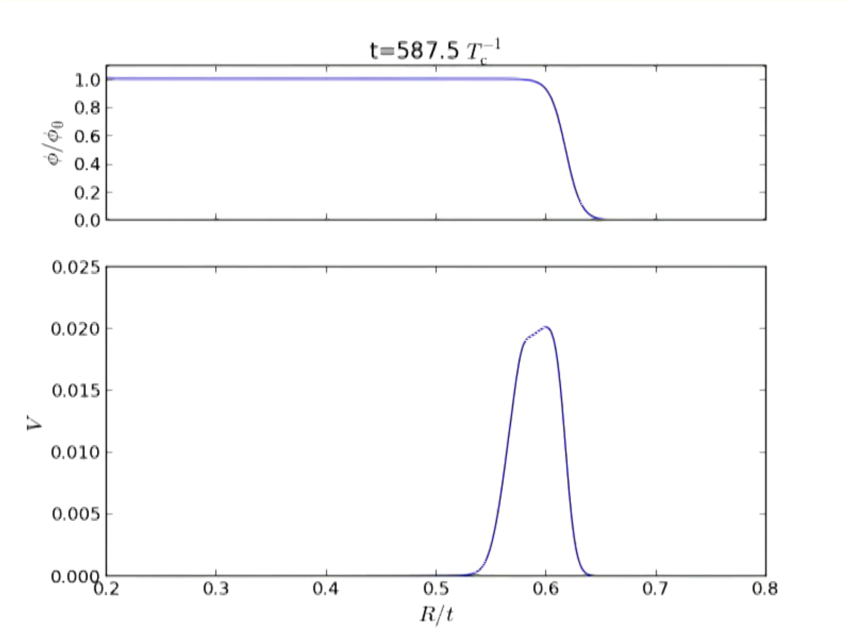
Coupled field and fluid system

Ignatius, Kajantie, Kurki-Suonio and Laine

- Scalar ϕ and ideal fluid u^μ:
  - Split stress-energy tensor $T^{\mu\nu}$ into field and fluid bits
$$\partial_\mu T^{\mu\nu} = \partial_\mu (T^{\mu\nu}_\phi + T^{\mu\nu}_{\text{fluid}}) = 0$$
  - Parameter η sets the scale of friction due to plasma
$$\partial_\mu T^{\mu\nu}_\phi = \tilde{\eta} \frac{\phi^2}{T} u^\mu \partial_\mu \phi \partial^\nu \phi \quad \partial_\mu T^{\mu\nu}_{\text{fluid}} = -\tilde{\eta} \frac{\phi^2}{T} u^\mu \partial_\mu \phi \partial^\nu \phi$$
  - $V(\phi, T)$ is a 'toy' potential tuned to give latent heat $\mathcal{L}$
  - $\beta \leftrightarrow$ number of bubbles; $\alpha_{T_*} \leftrightarrow \mathcal{L}$, $v_{\text{wall}} \leftrightarrow \tilde{\eta}$

What sort of solutions does this system have?

Velocity profile development: small $\tilde{\eta} \Rightarrow$ detonation (supersonic wall)



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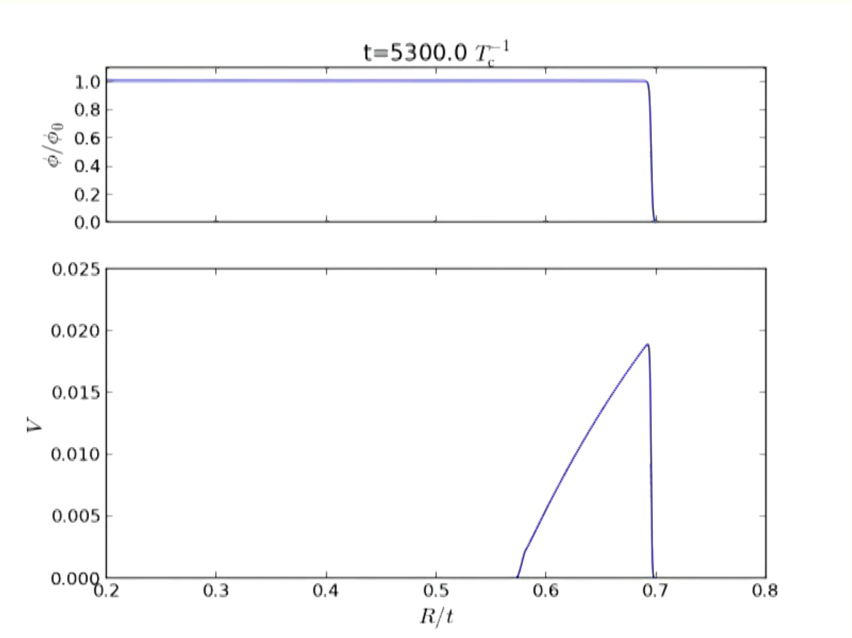
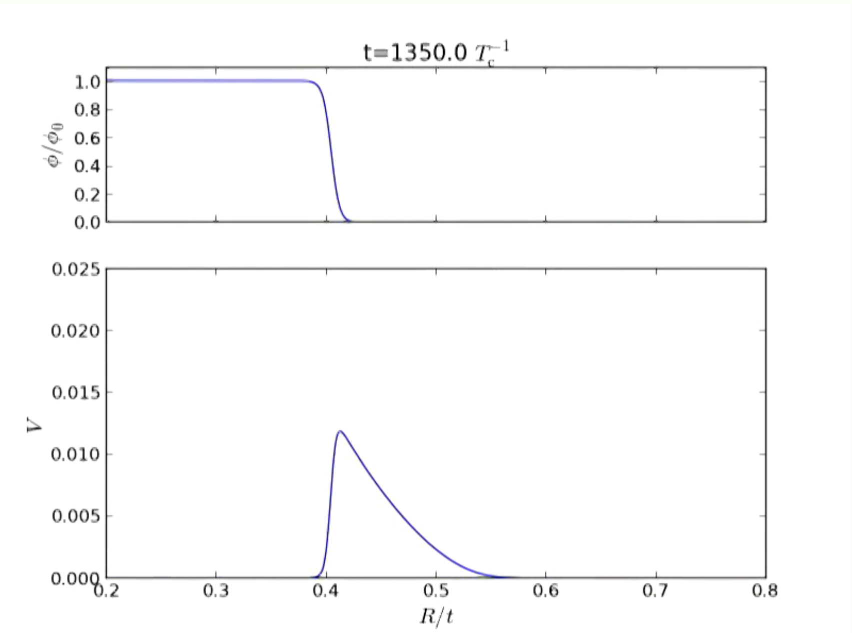
Velocity profile development: small $\tilde{\eta} \Rightarrow$ detonation (supersonic wall)



Velocity profile development: large $\tilde{\eta} \Rightarrow$ deflagration (subsonic wall)



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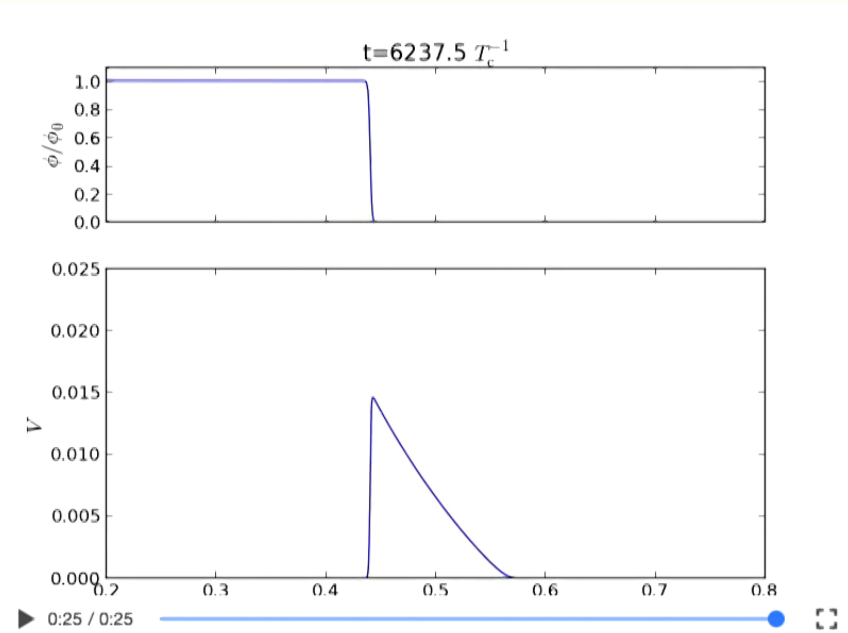
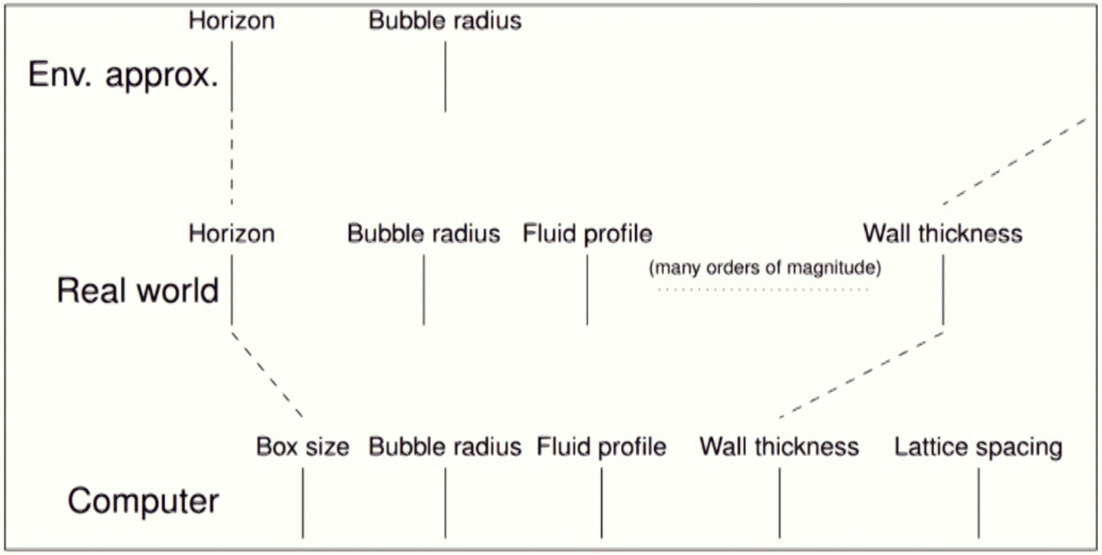


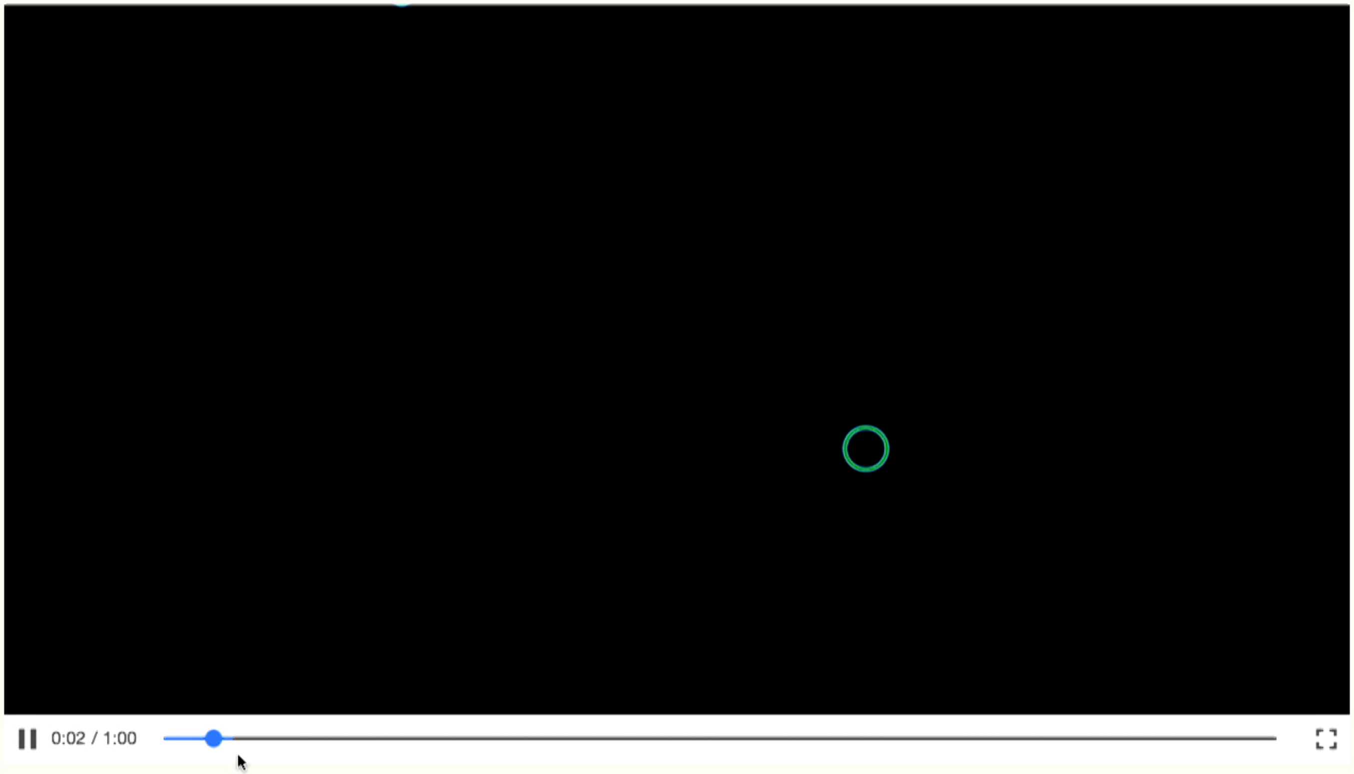
Dynamic range issues

- Early universe simulations usually handle one length scale
- Here, many length scales important

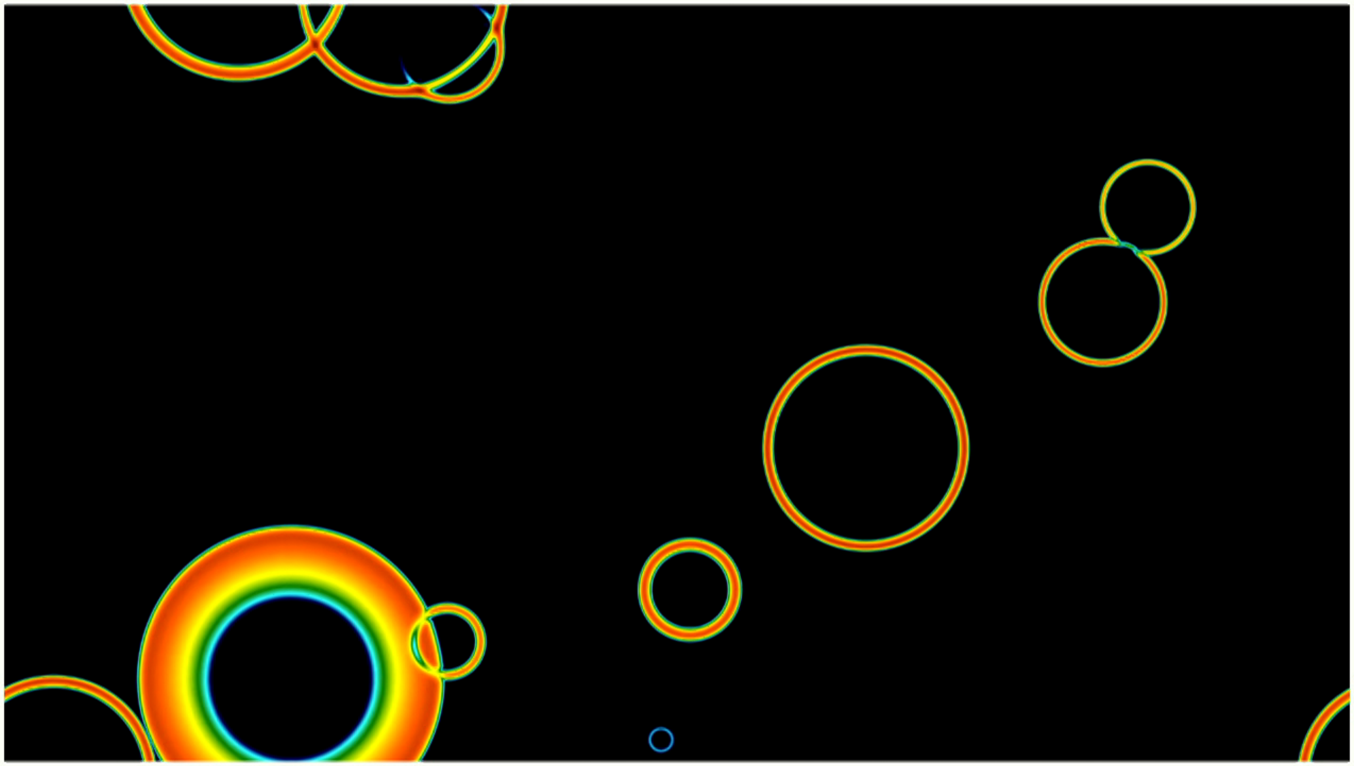


- Recently completed simulations with 4200^3 lattices, $\delta x = 2/T_c \rightarrow$ approx 1M CPU hours each (17.6M total)

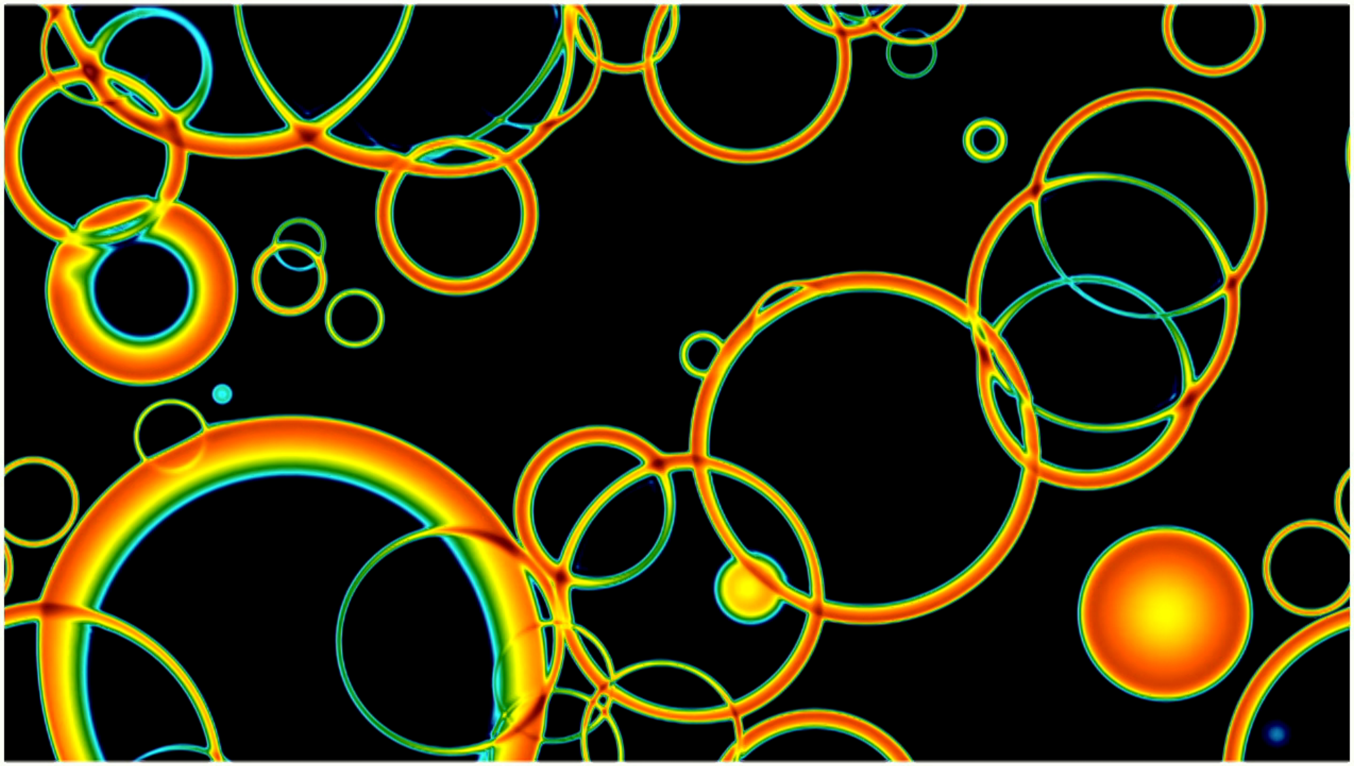
Simulation slice example



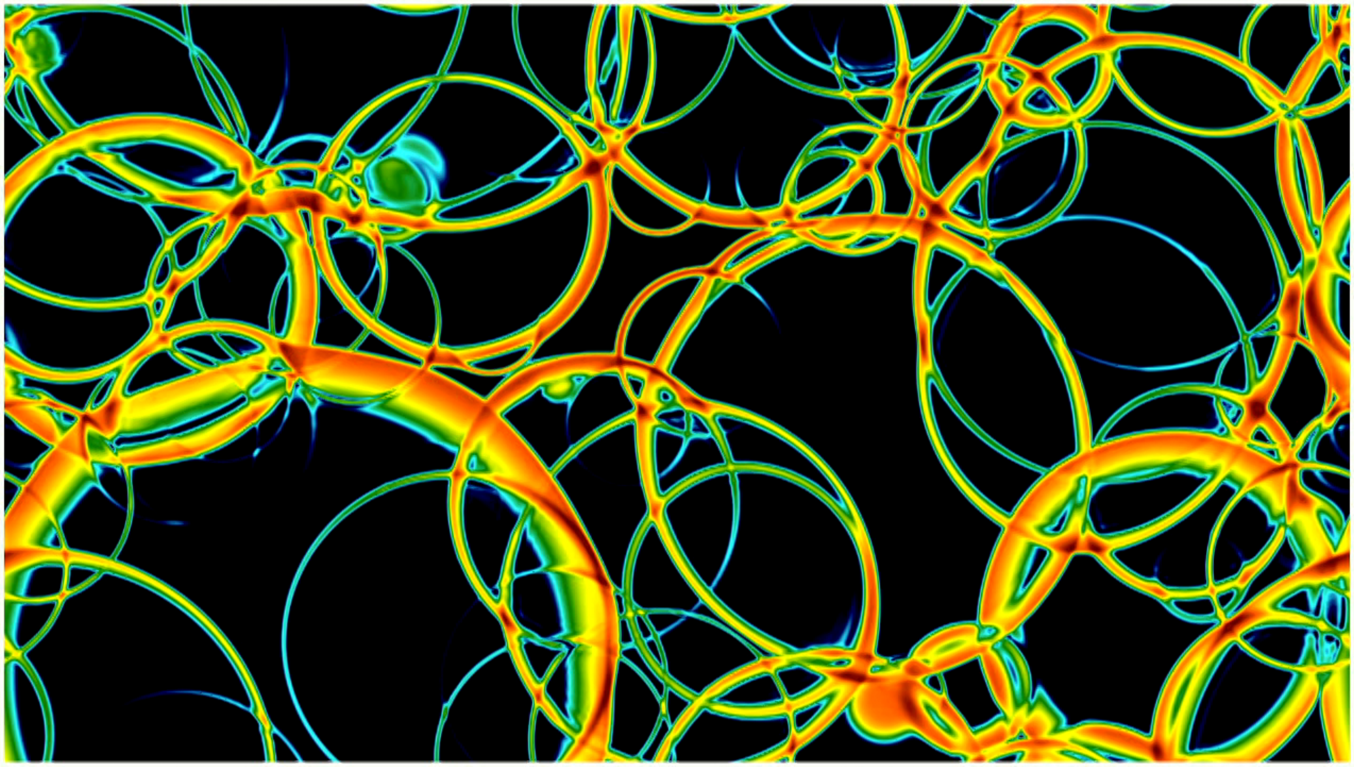
Simulation slice example



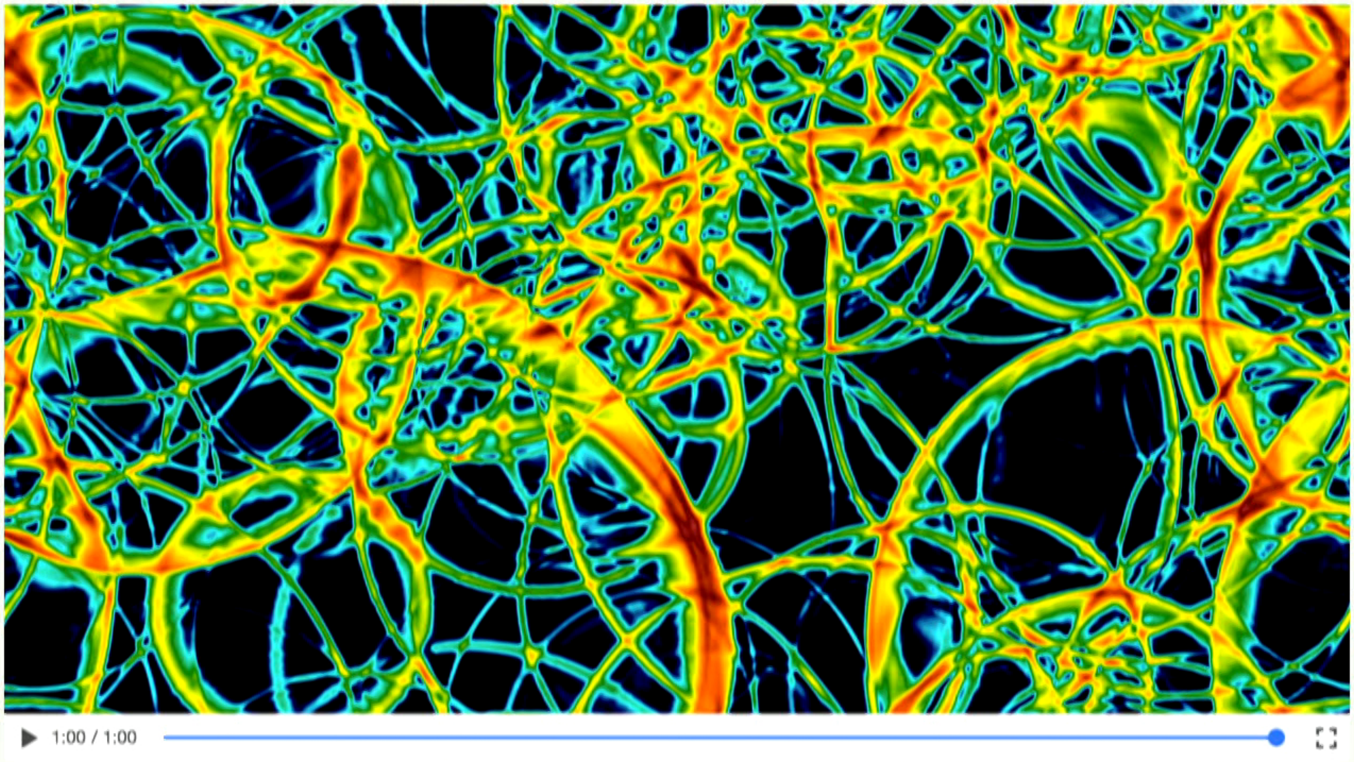
Simulation slice example



Simulation slice example

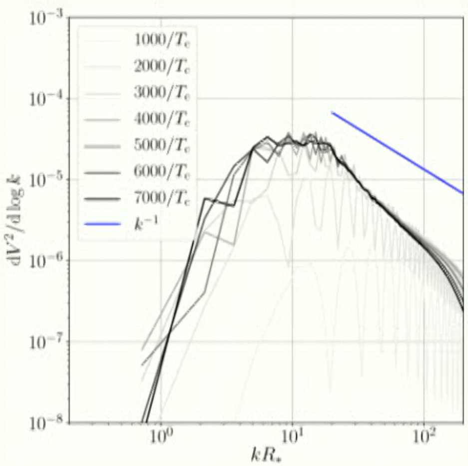


Simulation slice example

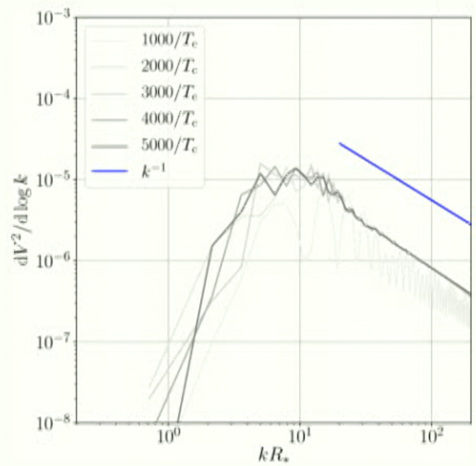


Velocity power spectra and power laws

Fast deflagration



Detonation



- Weak transition: $\alpha_{T_*} = 0.01$
- Power law behaviour above peak is between k^{-2} and k^{-1}
- "Ringing" due to simultaneous nucleation, unimportant

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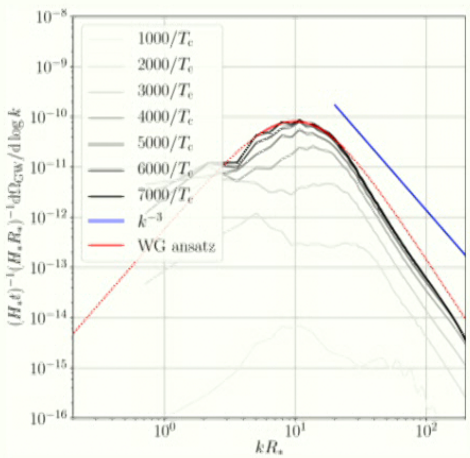
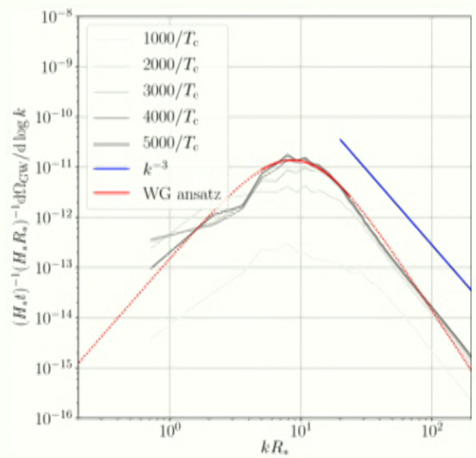
GW power spectra and power laws

Fast deflagration



Detonation



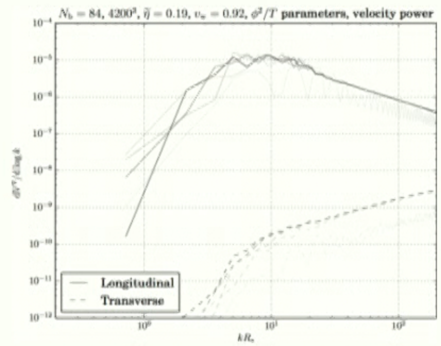
- Causal k^3 at low k, approximate k^{-3} or k^{-4} at high k
- Curves scaled by t: source until turbulence/expansion

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

Step 3: Turbulence

Source: Wikimedia Commons/Gary Settles (CC-BY-SA)

Transverse versus longitudinal modes – turbulence?



- Short simulation; weak transition (small α): linear; most power in longitudinal modes $\Rightarrow$ acoustic waves, turbulent
- Turbulence requires longer timescales $R_*/\overline{U}_\mathrm{f}$
- Plenty of theoretical results, use those instead

Kahniashvili et al.; Caprini, Durrer and Servant; Pen and Turok; ...

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

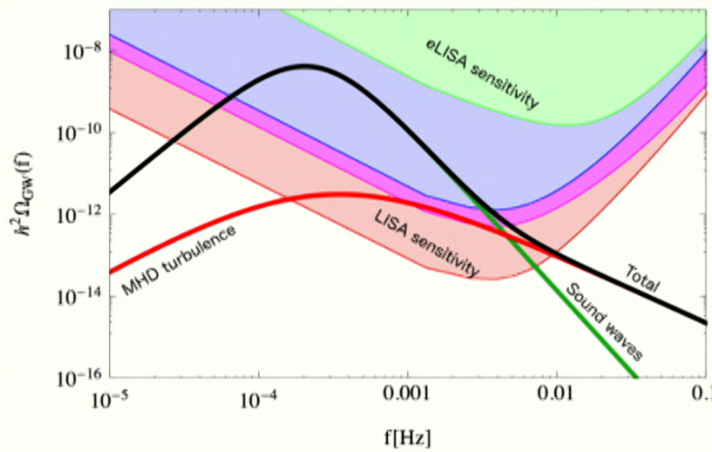
Putting it all together - $h^2\Omega_{\rm gw}$ 1512.06239

- Three sources, $\approx h^2\Omega_\phi,\, h^2\Omega_{\rm sw},\, h^2\Omega_{\rm turb}$
- Know their dependence on $T_*,\, \alpha_T,\, v_{\rm w},\, \beta$

Espinosa, Konstandin, No, Servant

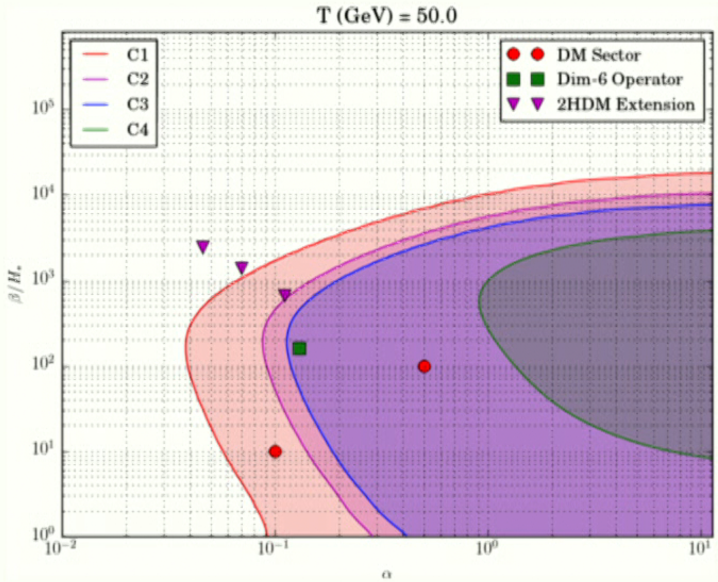
- Know these for any given model, predict the signal...

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



Putting it all together - physical models to GW power spectra

$$\text{Model} \longrightarrow (T_*, \alpha_{T_*}, v_w, \beta) \longrightarrow \text{this plot}$$



... which tells you if it is detectable by LISA (see 1512.06239)

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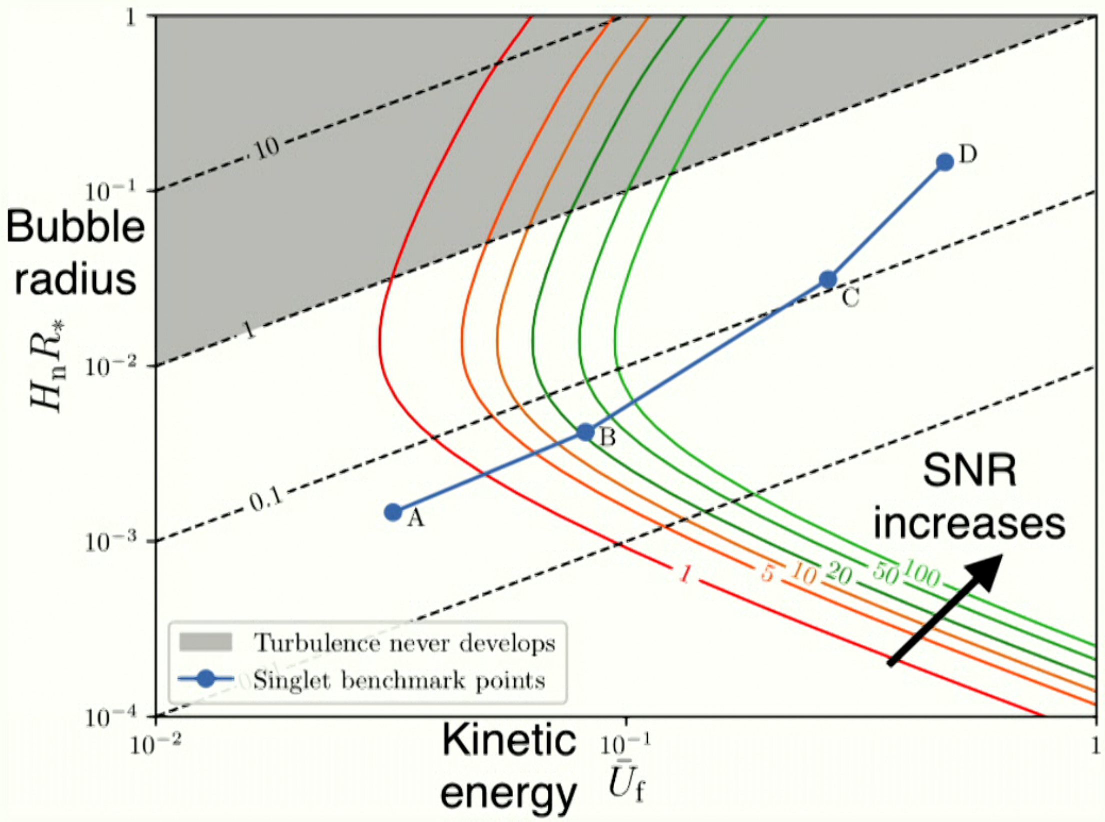
Detectability from acoustic waves alone



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The pipeline

1. Choose your model (e.g. SM, xSM, 2HDM, ...)
2. Dim. red. model Kajantie et al.
3. Phase diagram (α_{T_*}, T_*); lattice: Kajantie et al.
4. Nucleation rate (β); lattice: Moore and Rummukainen
5. Wall velocities (v_{wall}) Moore and Prokopec; Kozaczuk
6. GW power spectrum Ω_{gw}
7. Sphaleron rate

Very leaky, even for SM!

Next steps...

- Turbulence
  - MHD or no MHD?
  - Timescales $H_* R_* / \overline{U}_\mathrm{f} \sim 1$, sound waves and turbulence?
  - More simulations needed?

- Interaction with baryogenesis
  - Competing wall velocity dependence of BG and GWs?
  - Sphaleron rates in extended models?

- The best possible determinations for xSM, 2HDM, ΣSM, ...
  - What is the phase diagram?
  - Nonperturbative nucleation rates?