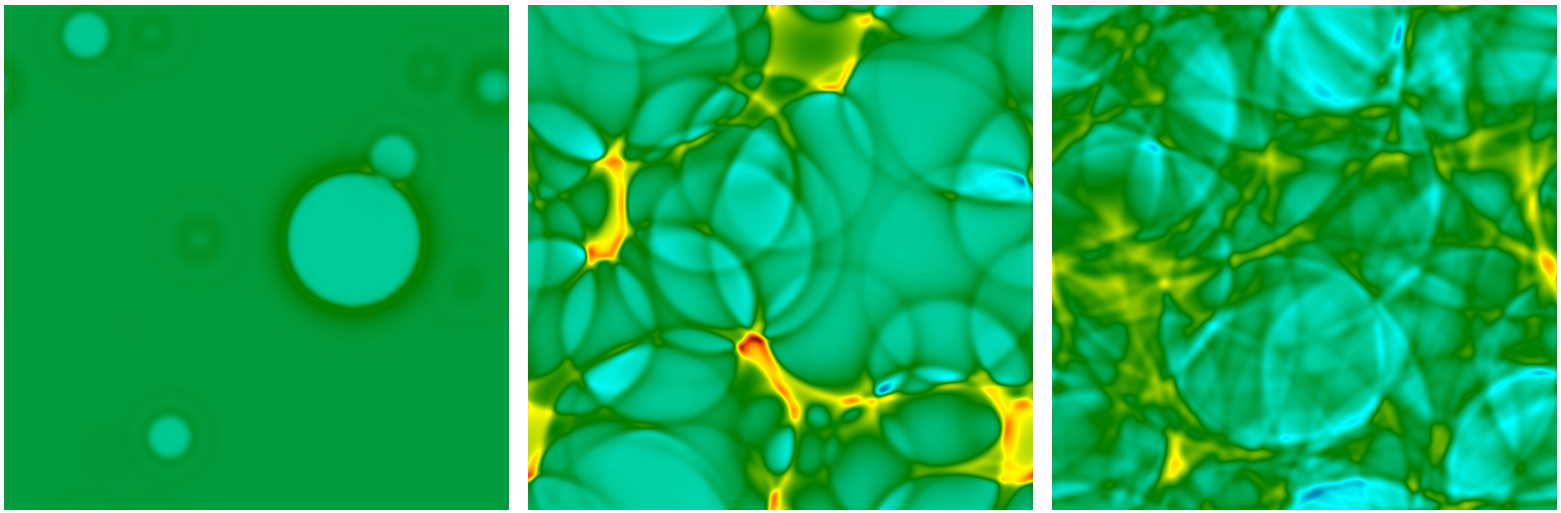
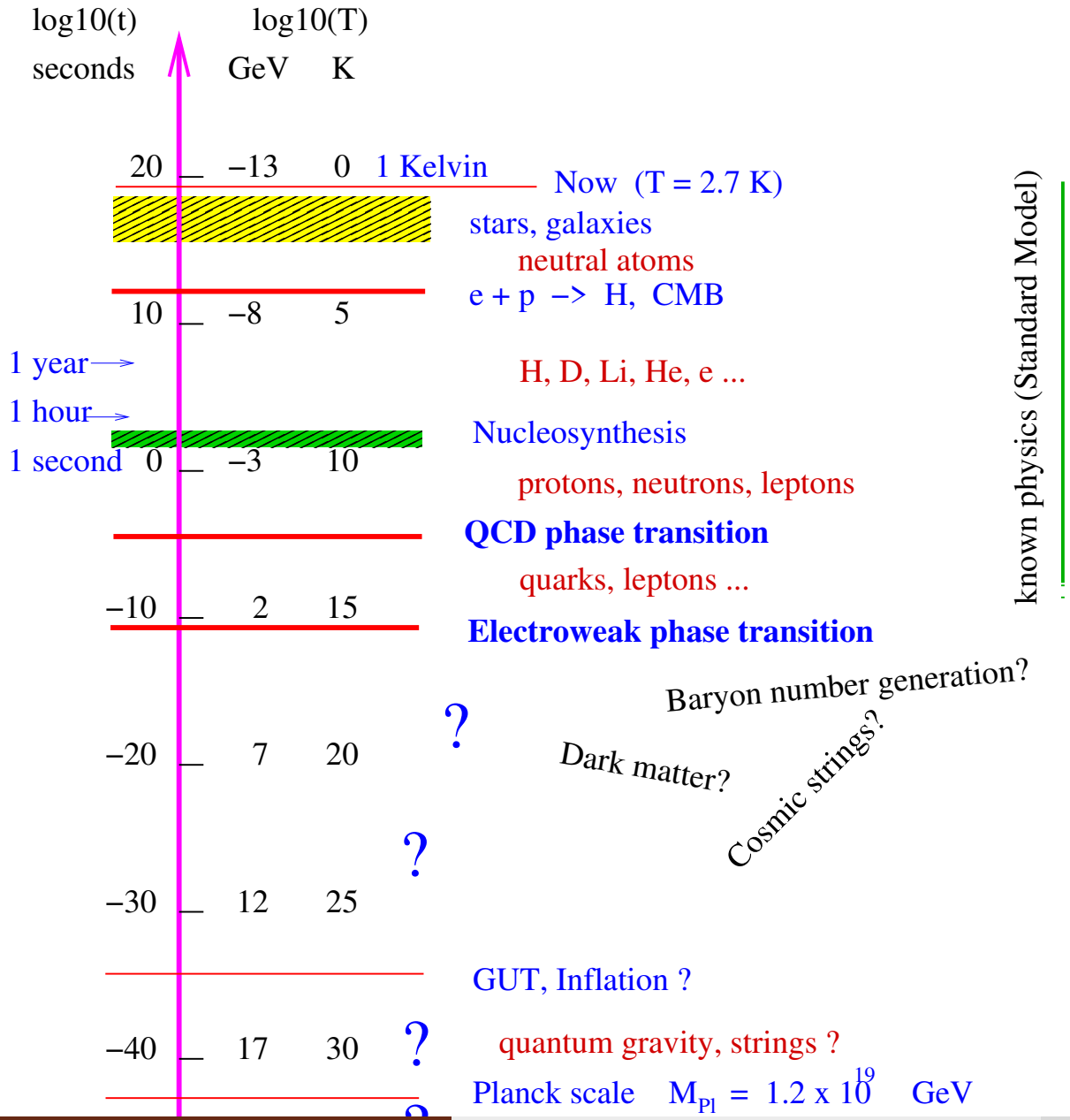
Gravitational waves from phase transitions in the Early Universe

Kari Rummukainen
University of Helsinki and Helsinki Institute of Physics

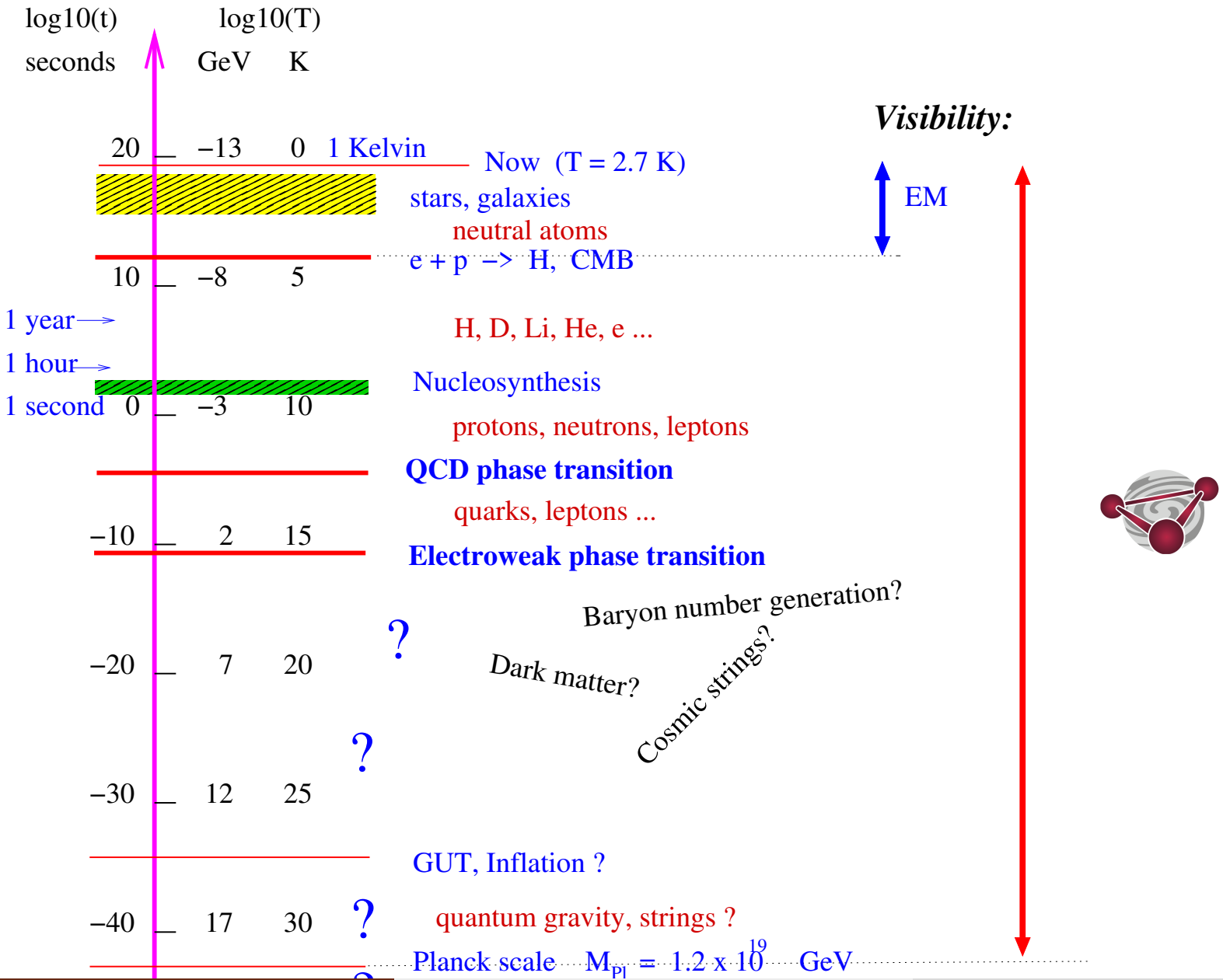
Lisa cosmology working group



Peek into the early Universe



Peek into the early Universe



A watched pot never boils . . .

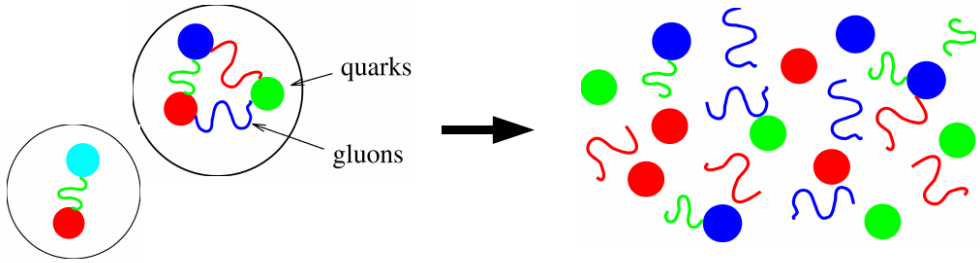
Water has a strong 1st order liquid-vapour transition at 1 ATM pressure:

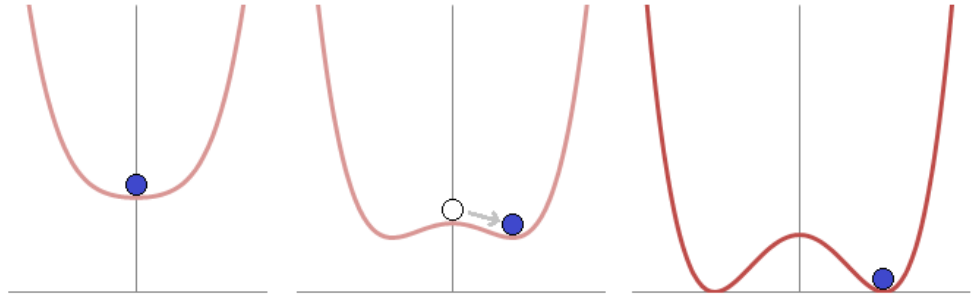
- Transition temperature 100° C.
- However, pure water can remain *metastable* up to 330° C! [Cho et al, PRL112 (2014)]
- At 110° C, metastability $\gtrsim$ age of the Universe!
- When superheated water finally boils, it is a violent process.

$\rightarrow$ 1st order transitions can have dramatic consequences.

We now know what happens in the Standard Model:

- QCD phase transition at $T \sim 170\,\text{MeV}$
  - hadrons $\leftrightarrow$ quark-gluon plasma
  - **Smooth cross-over**
  - Lattice QCD simulations necessary
- Standard Model electroweak phase transition at $T = T_c \approx 160\,\text{GeV}$
  - Perturbative & lattice simulations
  - Higgs expectation value v becomes non-zero
  - **Smooth cross-over**
  - At $T > T_c$, baryon number is not conserved!





First order electroweak phase transition?

- In some beyond the Standard Model extensions (BSM) the electroweak phase transition (or a new transition above the EW scale) can be of first order $\rightarrow$ bubble nucleation, growth and merger:

$\Rightarrow$ Primordial gravitational waves?

- If bubble separation $\sim$ Hubble scale, now frequency $\sim$ mHz $\rightarrow$ LISA
- No sign of BSM physics in experiments yet
- LHC has killed off many models, but many remain ...

1st order phase transitions

A first order phase transition proceeds through

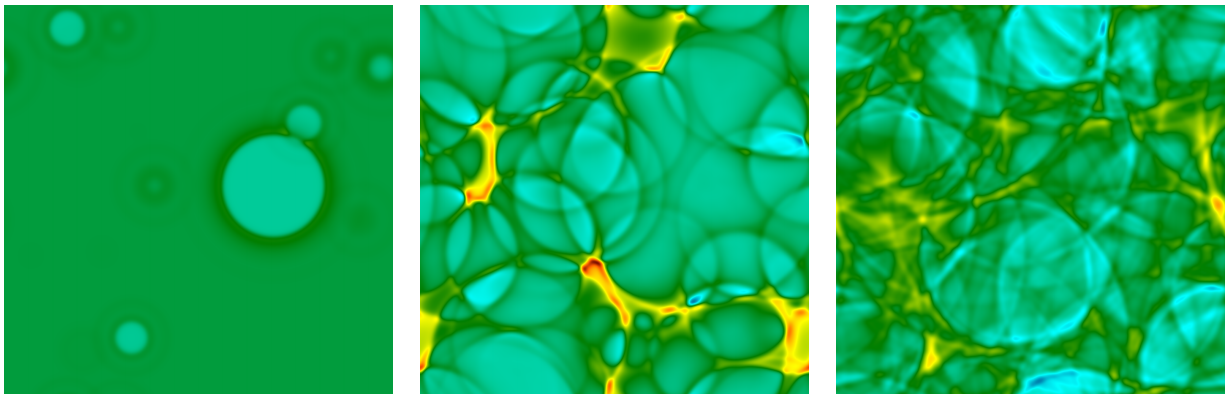
a) *supercooling*

b) *critical bubble nucleation*

c) *bubble growth and collision* $\rightarrow$

d) *generation of sound, shocks, turbulence* $\rightarrow$ *gravitational waves*

If the latent heat of the transition and supercooling are large, the process is violent (cf. superheated water)



[Hindmarsh et al.]

Goal: take a set of Beyond-the-Standard-Model candidates (MSSM, 2HDM, ...) and calculate the gravitational wave spectrum observed @ LISA
Conversely: how to use LISA to constrain BSM models?

Calculating the gravitational wave production

We need to know, for a theory candidate:

i) Thermodynamics (✓)
   - equation of state, **latent heat**

ii) Critical bubble **nucleation rate** (✓)
   - Determines degree of supercooling, *characteristic length scale*

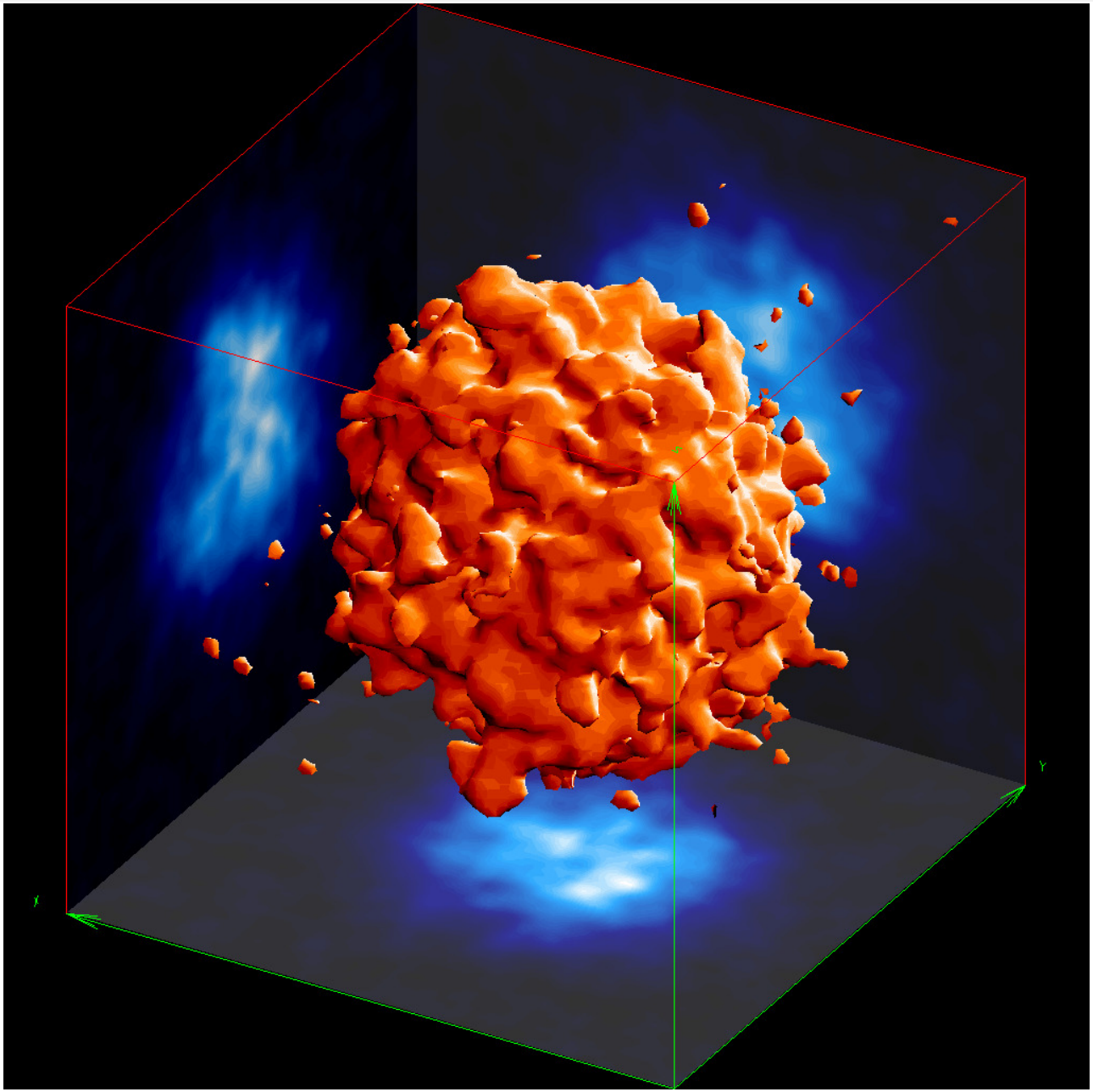
iii) Bubble wall - fluid interaction (?)
   - **bubble wall velocity**

} Microscopic QFT computation (analytical, numerical lattice)

iv) **Growth & collision of the bubbles, sound, shocks, turbulence** (✓?)
   - Numerical simulations of effective models

✓ Coupling to gravity: transverse-traceless part of $T^{\mu\nu}$

Critical bubble

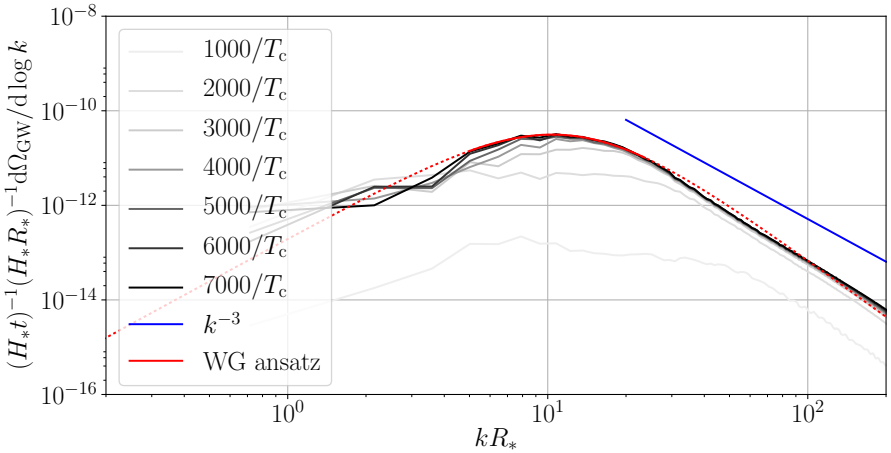


[Moore, Rummukainen, Tranberg 2001]

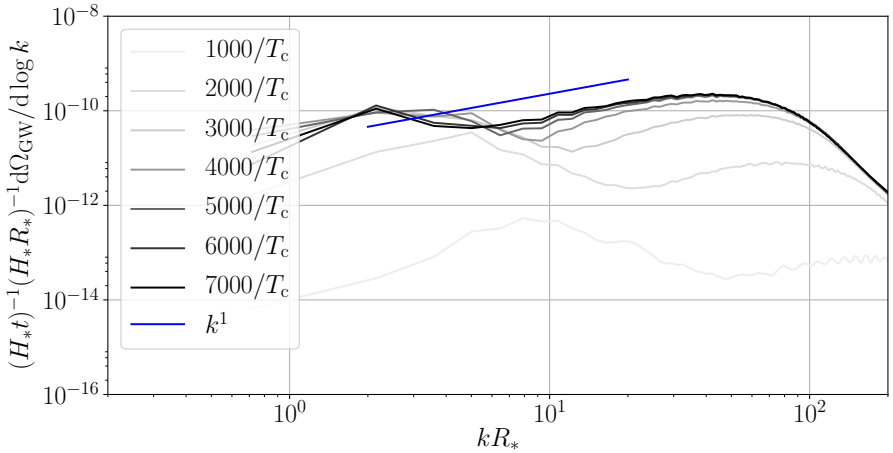
Some movies

Energy density slice [David Weir]
Transparent box
"Runaway transition" [Daniel Cutting]
See vimeo.com channel "Cosmic Defects" for some more

Results: power spectra



$v_{\mathrm{wall}} = 0.8$



$v_{\mathrm{wall}} = 0.56$

[arXiv:1704.05871]

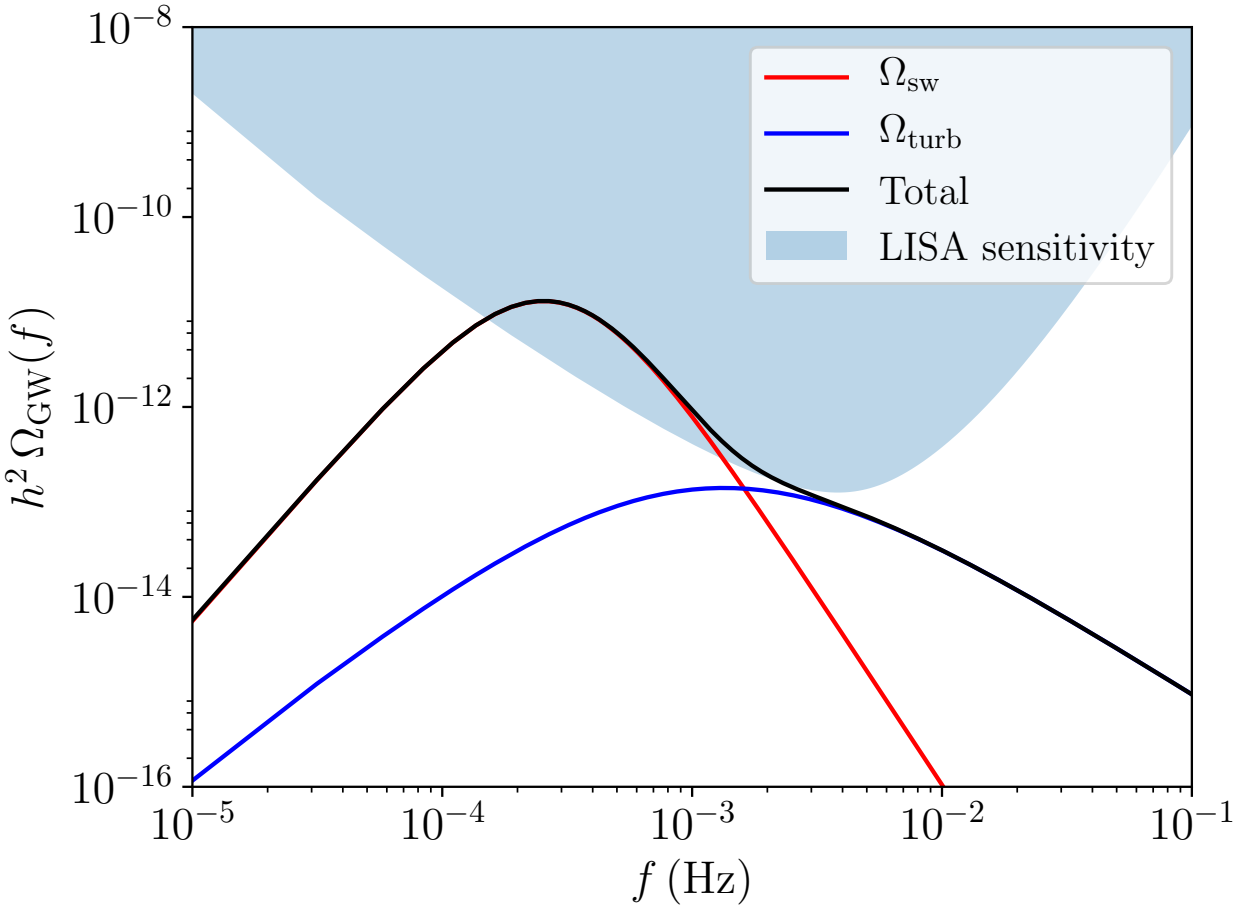
Typical power spectrum: broken power law
When $v_{\mathrm{wall}} \approx v_{\mathrm{sound}}$, (Jouguet) possibly more structure
Shape of the GW power spectrum $\rightarrow$ thermodynamic parameters of the theory!

Phase transitions in the LISA CosWG

Under preparation: an update of arXiv:1512.06239

- updated LISA sensitivity curve
- Updated catalog of BSM models and their GW signals
  - 2HDM, extra singlet, extra triplet, extra ...
- Nifty PTPlot web tool to calculate model GW spectra and SNR (David Weir) http://www.ptplot.org/ptplot/

Results: LISA discovery potential



Acoustic generation dominates on a wide range of parameters (caveat: origin of turbulence not well captured in simulations)

Breakthrough potential

- Gravitational waves give us unique window to the early Universe
- New physics: complementarity with HL-LHC and dark matter searches
- LISA has much higher "energy reach" than accelerators
- Theoretical understanding of 1st order PTs increasing