Particle physics with gravitational waves

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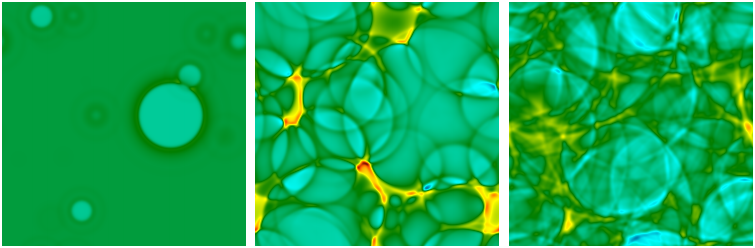

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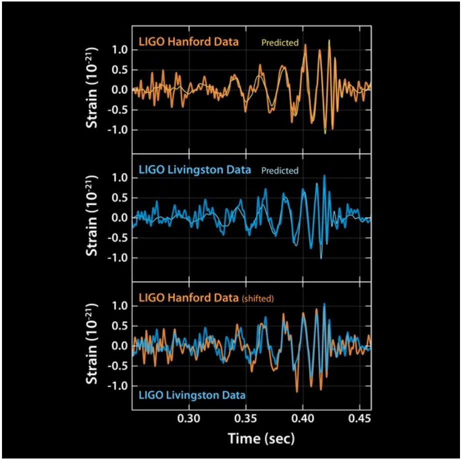
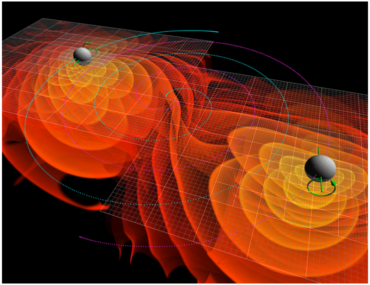
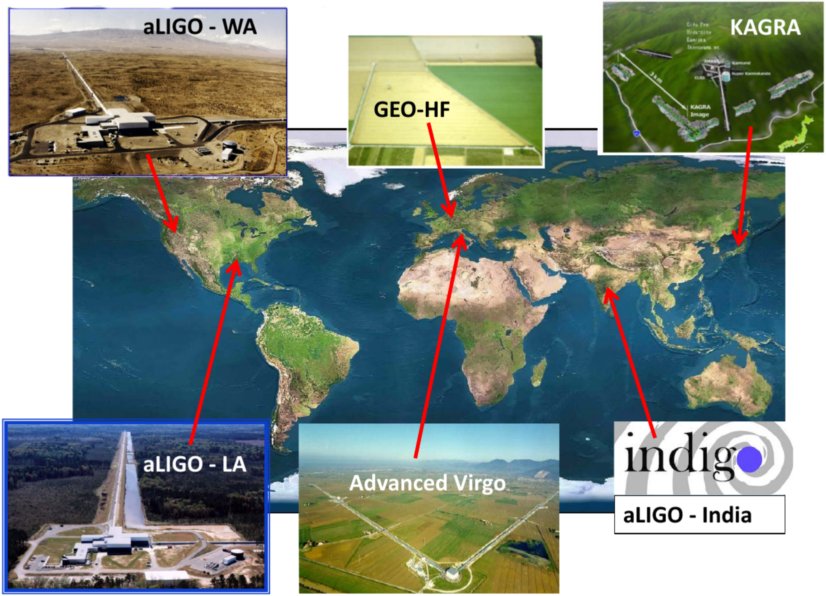
LIGO 2/2016: Gravitational waves observed!



- 14.9.2015 at 11:50:45 German time: the first observation of gravitational waves!
- A collision of 2 black holes, with 36 and 29 solar masses
- **A new window to the universe**



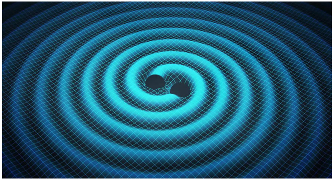
Gravitational wave window has opened!



Sources of gravitational waves

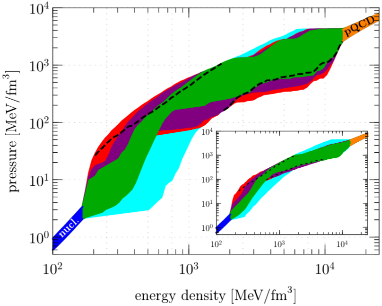
- Astrophysics
  - Binary compact object mergers
    - black holes (now several collisions)
    - neutron stars (1!)
  - Supernovae
- **Primordial gravitational waves**
  - Violent processes in the early Universe can produce gravitational waves
  - The Standard Model of particle physics – "known physics" – cannot produce gravitational waves

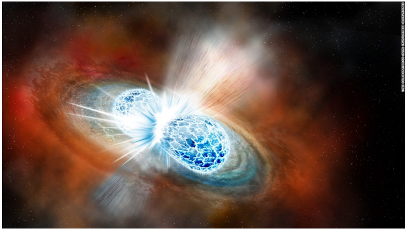
  ⇒ Observation of primordial gravitational waves: signal of "new physics", physics beyond the Standard Model
  - Complementary with the particle accelerators (LHC)

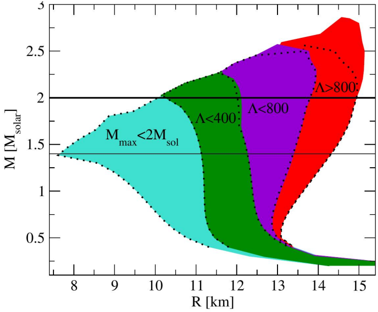


Gravitational waves and dense nuclear matter

- The single LIGO binary neutron star event already restricts neturon star mass - R -relation (red region)
- Dense nuclear matter equation of state, notoriously hard to study theoretically







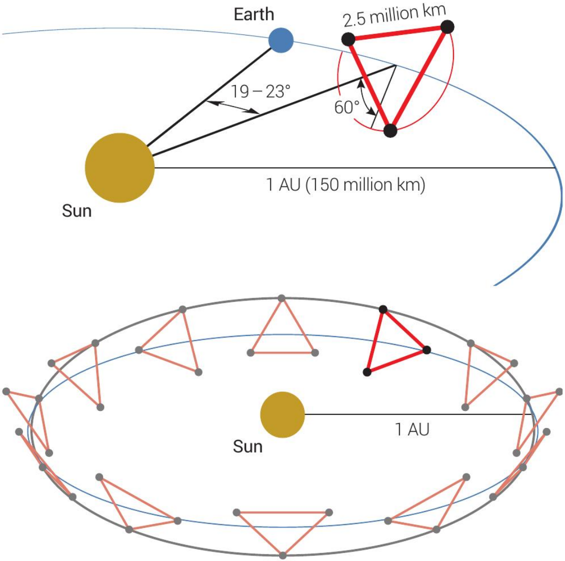
[Annala et al., 2017]

LISA mission 2034

Arm length $\sim$ 2.5e6 km

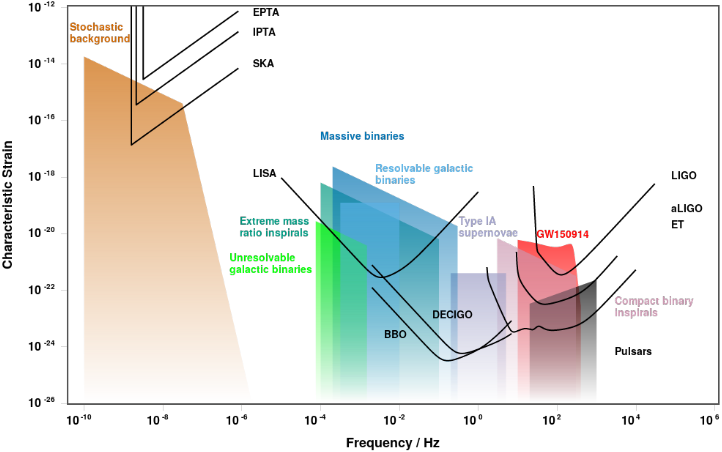
LISA orbit

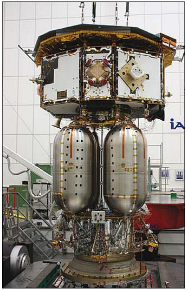
"Free-flying" laser interferometer
Strain sensitivity $\sim 10^{-21}$ 0.01 Hz ($\sim$ 1pm over 2.5 million km!)



LISA

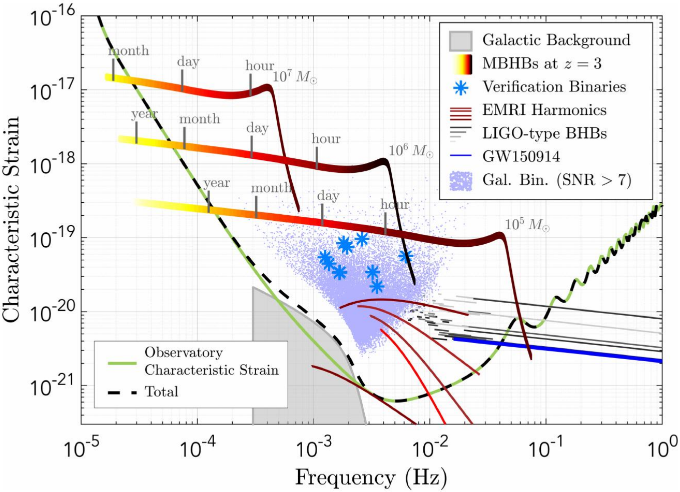
- Frequency window of LISA is right for gravitational waves from the electroweak and above -eras.
- LISA Cosmology Working Group – science case for cosmology
- LISA Pathfinder: technology demonstrator, launched Dec. 2015





[Moore,Cole,Berry, gwplotter.com]

Astrophysical objects seen by LISA

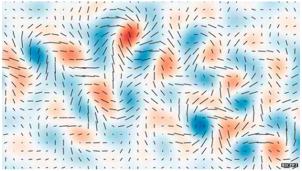


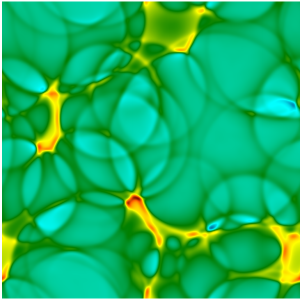
[Lisa mission proposal, 2017]

Cosmological signal *stochastic*: need to understand the “foreground”

Sources of primordial gravitational waves

- Inflation (Bicep. . .)
- Cosmic strings
- **1st order phase transitions**
  - Do not exist in the Standard Model (QCD or EW)
  - Strong phase transition is possible in many extensions of the SM: many Higgses, SUSY, compositeness . . .
- Primordial GWs give a direct snapshot of the universe at the time they were generated!
- Stochastic signal, expected frequency $\sim$mHz



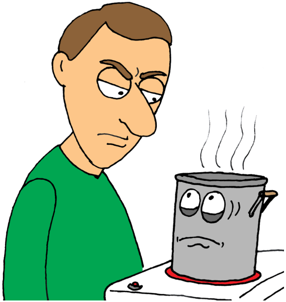


A watched pot never boils . . .

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

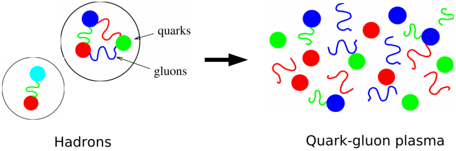
- Transition temperature 100° C.
- However, pure water can remain *metastable* up to 330° C! [Cho et al, PRL112 (2014)]
- At 110° C, metastability $\gtrsim$ age of the Universe!
- When superheated water finally boils, it is a violent process.

→ 1st order transitions can have dramatic consequences.

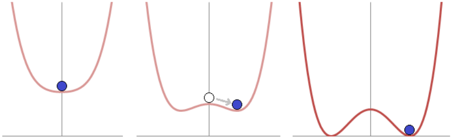


No true phase transitions in the Standard Model:

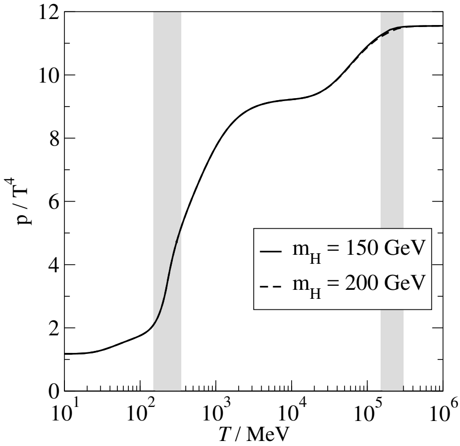
- QCD phase transition at $T \sim 170\,\mathrm{MeV}$
  - Age of the universe $t \sim 10\mu s$
  - Hadrons $\leftrightarrow$ quark-gluon plasma
  - Smooth cross-over $\rightarrow$ no GWs produced
  - Lattice QCD simulations necessary



- Electroweak phase transition at $T = T_c \approx 160\,\mathrm{GeV}$
  - $t \sim 10^{-11}\mathrm{s}$
  - Higgs expectation value v becomes non-zero
  - Smooth cross-over $\rightarrow$ no GWs
  - At $T > T_c$, baryon number is not conserved!



Standard Model pressure



[Laine, Schröder 2006]

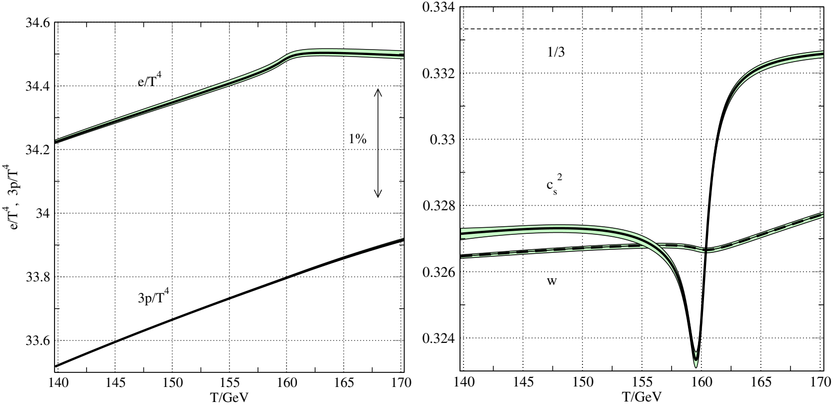
- Massless ideal gas:

$$\frac{p}{T^4} = g_* \frac{\pi^2}{90}$$

with $g_* = n_B + \frac{7}{8} n_F = 106.75$ for the SM

- Perturbation theory + Lattice QCD + hadron resonance gas
- Lattice QCD: lots of results
- EW transition here featureless

Zooming in on EW cross-over



[D'Onofrio, K.R. 2015]

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

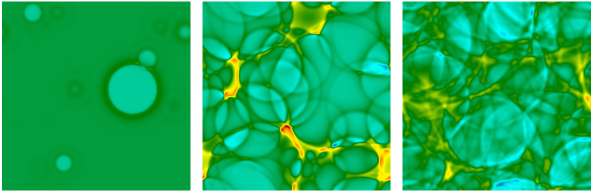
a) *supercooling*

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** (✓?)
   - Requires numerical simulations
   - Relativistic hydrodynamics + scalar field, effective order parameter
     - ⋆ Scalar: Higgs in SM-like models, χ-condensate in strong dynamics ...
   - Large dynamical range, large volumes
   - Only a few relevant parameters: T_c, strength of the transition α, duration of the transition β, bubble wall velocity v_W, # of dof's g

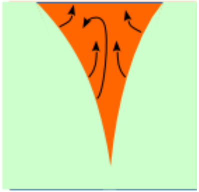
✓ Coupling to gravity: transverse-traceless part of $T^{\mu\nu}$

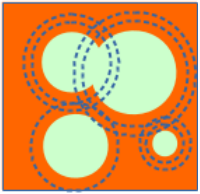
Generation of gravitational waves

Single bubble does not radiate, need quadrupole moments

- Bubble collisions
  - Subleading source, short duration
  - Can also be estimated by *envelope approximation* [Kosowski, Turner, Watson 92 + many].
    - ★ Only field, fluid ignored
    - ★ Semi-analytical, ∃ lots of quantitative results
- Turbulence
  - [Caprini et al., Kahniasvili et al.]
  - (Magnetic fields?)
- Sound [Hogan 86]
  - Bubbles push fluid, compression waves: **sound**
  - Sound remains active long after bubbles have vanished

  ⇒ Our discovery: sound is the *dominant source for GWs* [Hindmarsh, Huber, KR, Weir 2014–15]
  - Develops into turbulence at time $\propto \ell/v_{\rm fluid}$, where ℓ is the length scale





Ingredients for simulations:

- Scalar field ϕ (with potential $V(\phi, T)$) coupled to
- Relativistic fluid with energy density $\epsilon(T)$ and pressure $p(T)$

$$
\begin{aligned}
-\ddot{\phi} + \nabla^2\phi - \frac{\partial V}{\partial \phi} &= \eta W(\dot{\phi} + v^i \partial_i \phi) \\
\dot{E} + \partial_i(E v^i) + p[\dot{W} + \partial_i(W v^i)] - \frac{\partial V}{\partial \phi} W(\dot{\phi} + v^i \partial_i \phi) &= \eta W^2 (\dot{\phi} + v^i \partial_i \phi)^2 \\
\dot{Z}_i + \partial_j(Z_i v^j) + \partial_i p + \frac{\partial V}{\partial \phi} \partial_i \phi &= -\eta W(\dot{\phi} + v^j \partial_j \phi)\partial_i \phi.
\end{aligned}
$$

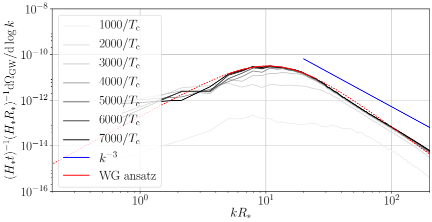
- W: relativistic γ-factor, v^i: fluid 3-velocity, $E = W\epsilon$ fluid energy density, $Z_i = W^2(\epsilon + p)v_i$ fluid momentum density
- η: field-fluid coupling (rhs of equations) [Ignatius et al 94; Kurki-Suonio and Laine 98]
- In addition, keep track of the metric perturbation:

$$\ddot{h}_{ij} - \nabla^2 h_{ij} = 16 G T_{ij}^{TT}$$

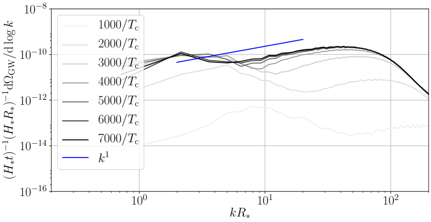
Some movies

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

Results: power spectra



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

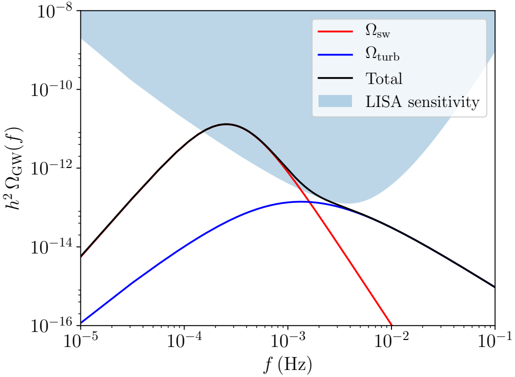


$v_{\mathrm{wall}} = 0.56$

Characteristic shape of the GW power spectrum $\rightarrow$ possibility for obtaining thermodynamic parameters of the theory!

Direct probe of BSM physics

Results: LISA discovery potential



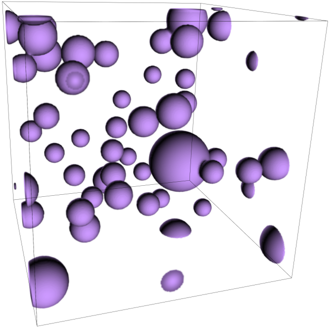
Acoustic generation dominates on a wide range of parameters [Hindmarsh et al.]
Plot done with the nifty PTPlot tool which includes our current best knowledge of GW spectra and SNR (David Weir)
http://www.ptplot.org/ptplot/

Status so far:

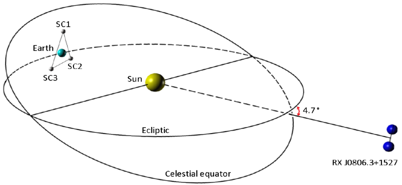
- We know how to obtain accurate results for
  - i) Thermodynamics
    - ⋆ Done for version of MSSM
  - ii) Bubble nucleation rate
    - ⋆ Done only for a "toy model"
- iii) Bubble wall friction calculation needs development (ongoing)
- Given parameters obtained from i) – iii), we can fix the parameters of the iv) bubble growth + collision code
- This chain is not yet completed for any microscopic model!
- Only weak and medium-strength transitions studied in iv) so far
  - Results very promising

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
- Simulations very successful
- Unanticipated source for GWs: **sound waves**
- GW amplitude can be orders of magnitude larger than in earlier estimates,
- Very good news for observation @ LISA or other proposed detectors (DECIGO (Japan), TianQuin (China), Taiji (China))

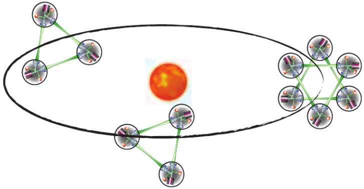


Beyond/besides LISA:



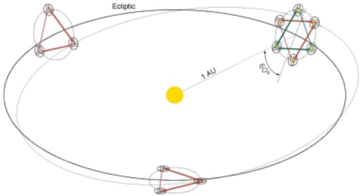
- TianQuin (China): Earth-centered triangle, $\sim 10^5$ km

  Before 2030?



- DECIGO (Japan): 4 interferometers, 12 satellites $\sim 10^4$ km

  in 2030's?



- Big Bang observer (ESA): 4 interferometers $\sim 10^5$ km