Gravitational waves from the early Universe

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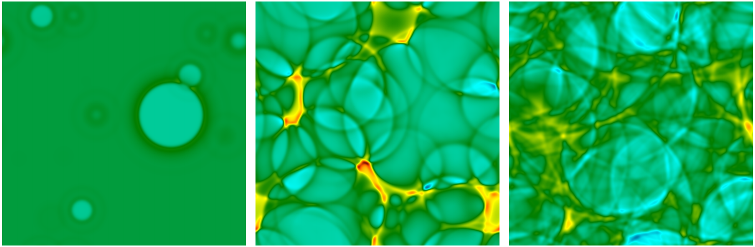
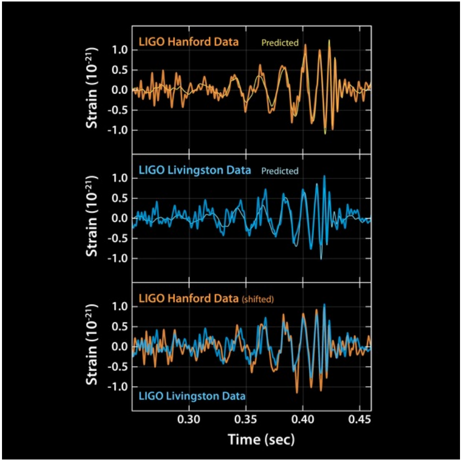
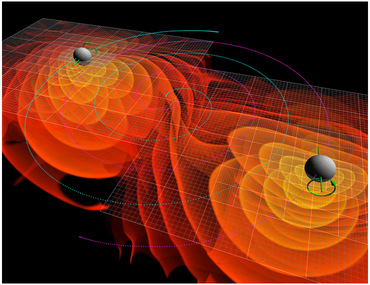


LIGO 2/2016: Gravitational waves observed!

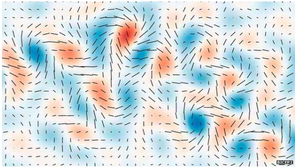


- 14.9.2015 at 12:50:45 Finnish time: the first observation of gravitational waves!
- A collision of 2 black holes, with 36 and 29 solar masses
- **A new window to the universe!**

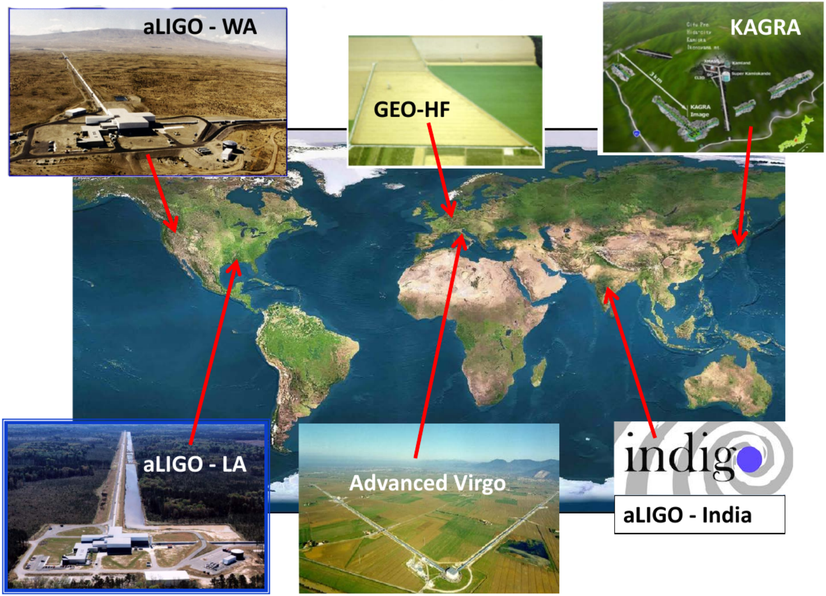


Sources of gravitational radiation

- Astrophysics
  - Binary compact object mergers
  - Supernovae
  - ...
- **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!

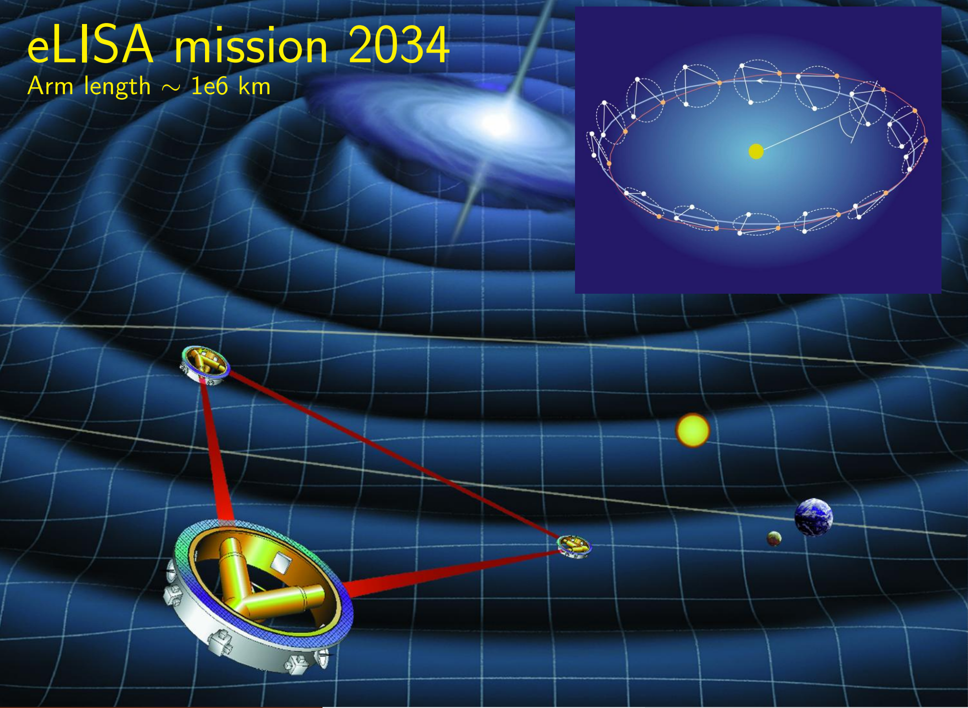


Gravitational wave window ~~is opening~~ has opened!



eLISA mission 2034

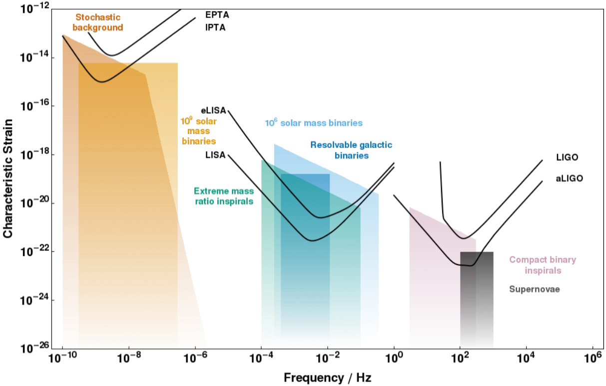
Arm length $\sim$ 1e6 km

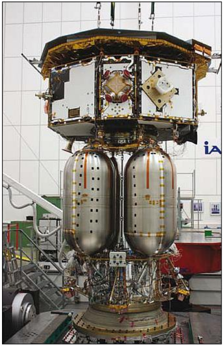


eLISA

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

[Moore,Cole,Berry 2014]





1st order phase transitions

1st order transition proceeds through supercooling, bubble nucleation & growth:

For GW production need to know:

- ✓ Equation of state
- ✓ Critical bubble nucleation rate

} Microscopic QFT computation

→ **Growth & collision of the bubbles, hydrodynamic flows**

- Requires numerical simulations → this work
- Relativistic fluid + scalar field, effective order parameter
  - Scalar: Higgs in SM-like models, χ-condensate in strong dynamics ...
- Large dynamical range, large volumes

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

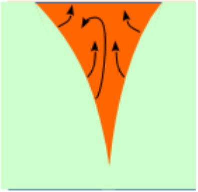
Sources of gravitational waves

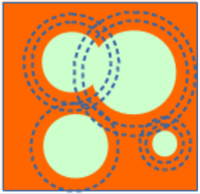
Single bubble does not radiate, need quadrupole moments

- Bubble collisions
  - *Envelope approximation* [Kosowski, Turner, Watson 92 + many].
    - ⋆ Only field, fluid ignored
    - ⋆ Semi-analytical, ∃ lots of quantitative results
- Turbulent flows
- 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]

Large-scale numerical simulations, up to 24 000 computer cores in one run





Ingredients for simulations:

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

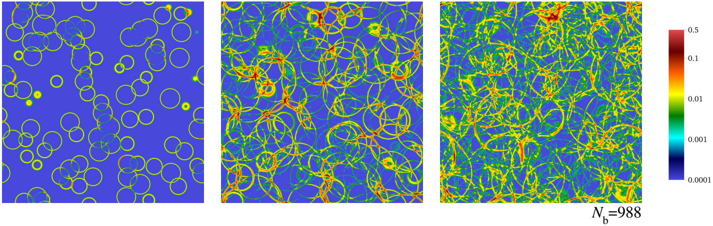
$$
\begin{aligned}
-\ddot{\phi} + \nabla^2\phi - \frac{\partial V}{\partial \phi} &= \eta W(\dot{\phi} + v^i \partial_i \phi) \\
\dot{E} + \partial_i(E v^i) + p[\dot{W} + \partial_i(W v^i)] - \frac{\partial V}{\partial \phi} W(\dot{\phi} + v^i \partial_i \phi) &= \eta W^2(\dot{\phi} + v^i \partial_i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

- 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:

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

Results: Fluid/sound dominates

Fluid kinetic energy density at $t = 500\,T_c^{-1}$, $1000\,T_c^{-1}$ and $1500\,T_c^{-1}$. 988 bubbles, $\eta = 0.15\,T_c$
(link to movie) (another link)



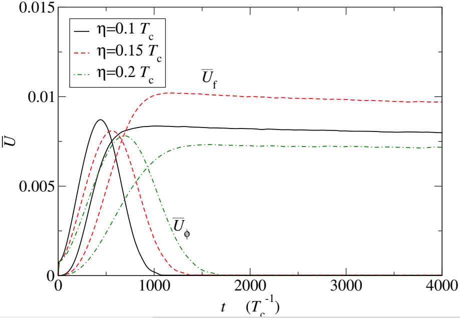
- GWs sourced by τ_{ij}
- Define RMS fluid velocity $\bar{U}_f$:

$$(\bar{\epsilon} + \bar{p})\bar{U}_f^2 = \frac{1}{V}\int dV \tau_{ii}^{\text{fluid}}$$

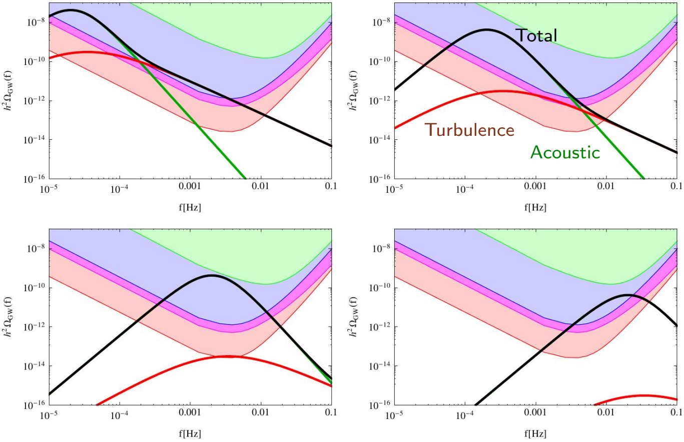
- Equivalent field quantity:

$$(\bar{\epsilon} + \bar{p})\bar{U}_\phi^2 = \frac{1}{V}\int dV \tau_{ii}^{\text{field}}$$

- Fluid remains active ∼ Hubble time after the transition!



Results: eLISA discovery potential

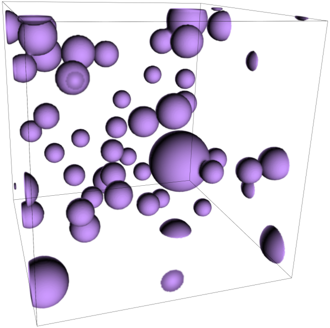


[eLISA GW working group]

Acoustic generation strongly dominates!

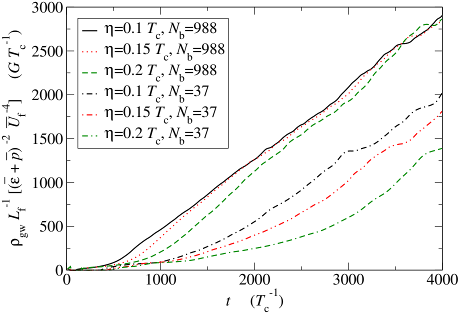
Conclusions

- Simulations very successful
- Dominant source for GWs: **sound waves**
- GW amplitude several orders of magnitude larger than in earlier estimates,
- Very good news for observation @ eLISA or other proposed detectors (DECIGO, BBO)



⋆ 750 GeV bump at LHC $\rightarrow$ new physics? Possibly with a strong transition?

Results: GW power growth



- New universal(?) relation for total GW power growth:

$$\rho_{\rm GW} = t[CGL_f(\bar{\epsilon}+\bar{p})^2\bar{U}_f^4], \quad \text{with } C = 0.8 \pm 0.2$$

- L_f: fluid flow characteristic length scale
- Total estimated GW power: approx. ~ 100 times larger than with envelope approximation