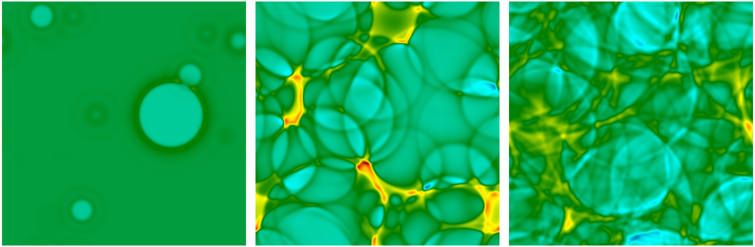
Particle physics and cosmology with gravitational waves

Kari Rummukainen
University of Helsinki and Helsinki Institute of Physics

Gravitational cosmology / computational field theory groups
Daniel Cutting, Jani Dahl, Mark Hindmarsh, Jaakko Hällfors, Venus Keus, Anna Kormu, Lauri Niemi, Jarno Rantaharju, Tobias Rindlisbacher, Ahmed Salami, Rikka Seppä, Satumaaria Sukuvaara, Essi Vilhonen, David Weir



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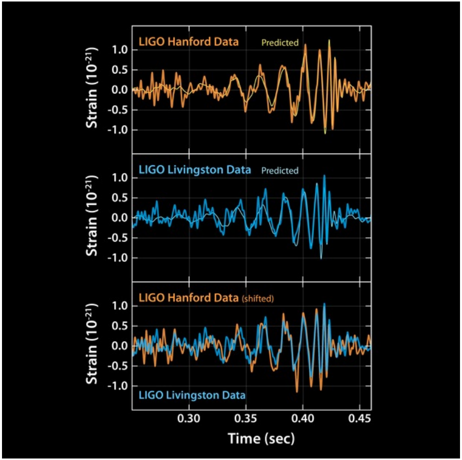
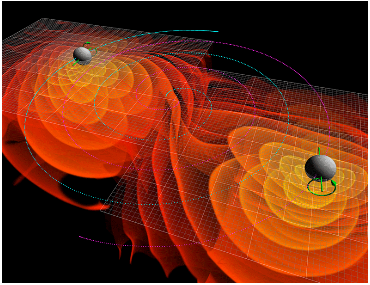
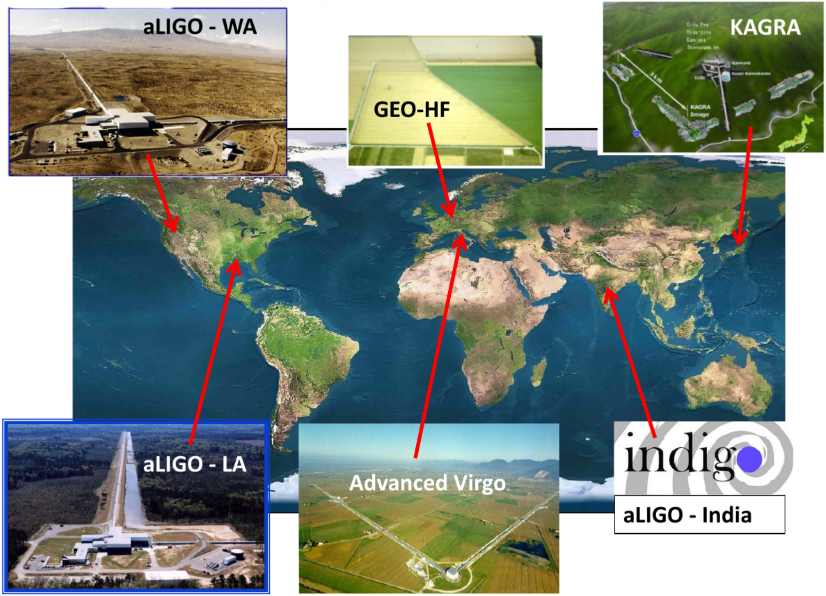
LIGO 2/2016: Gravitational waves observed!



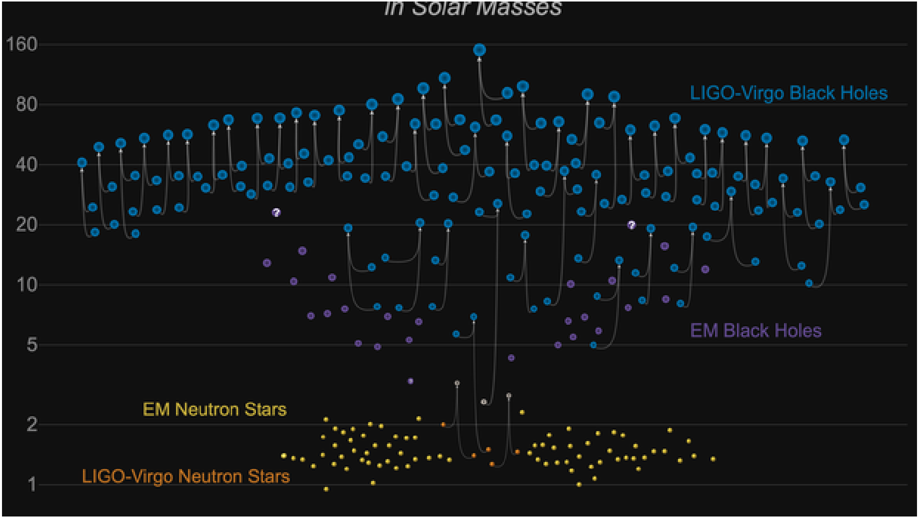
- 14.9.2015 at 12:50:45 Finnish time: the first observation of gravitational waves.
- A collision of 2 black holes, with 36 and 29 solar masses.
- **A new window to the universe!**



Gravitational wave window has opened!



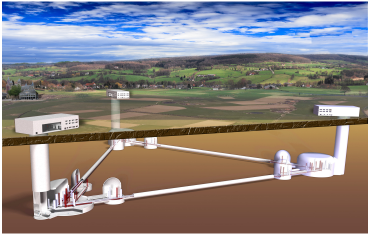
LIGO-Virgo observations now:



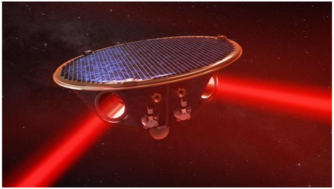
[LIGO-Virgo / Northwestern U / Frank Elavsky & Aaron Geller]

About 50 mergers

Future gravitational wave detectors



Laser interferometers on Earth: *Einstein Telescope*, 10km triangle (Europe)
Cosmic Explorer, 40km L-shape (USA)



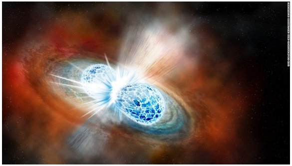
Laser interferometers in space:
LISA (2034, ESA/NASA)
TianQuin & Taiji (China); DECIGO (Japan)

Pulsar timing arrays:
EPTA, NANOgrav, IPTA (now)
Square Kilometer Array (SKA)

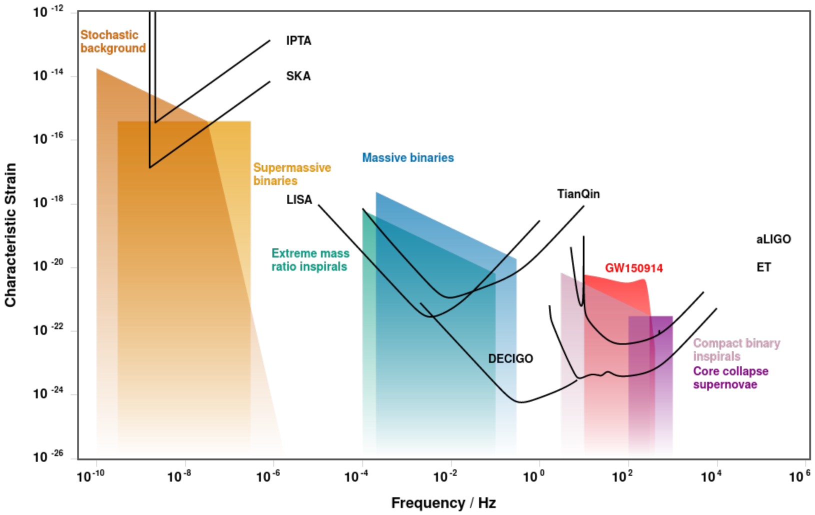
Sources of gravitational waves

- Astrophysics
  - Binary compact objects
    - ⋆ black holes
    - ⋆ neutron stars → Kurkela's talk ⟶
    - ⋆ binary dwarfs
  - Supernovae
- **Cosmological sources**
  - **Inflation, phase transitions, cosmic strings, primordial black holes** → 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 accelerator experiments

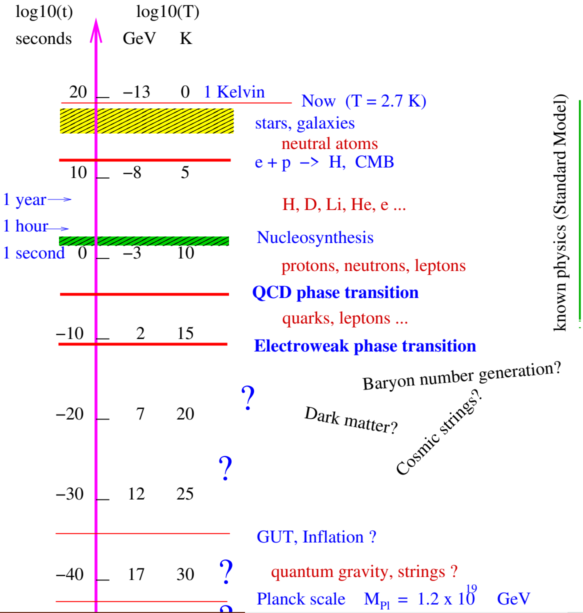


GW spectrum

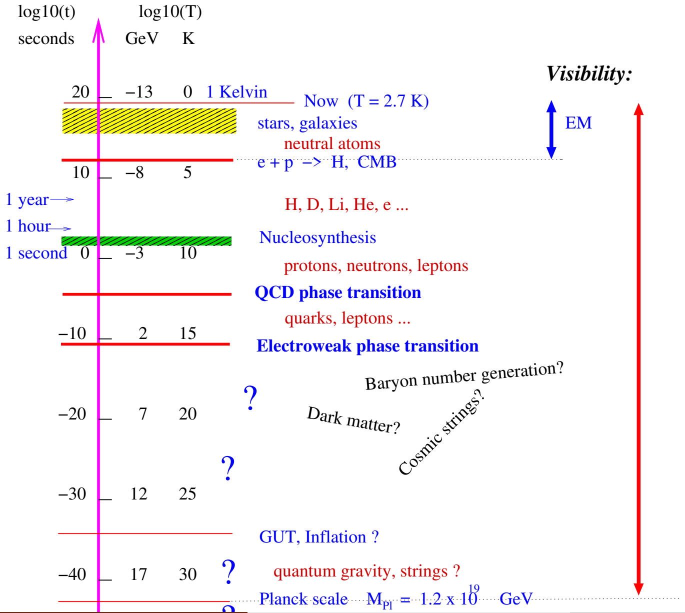


[Moore,Cole,Berry, gwplotter.com]

Peek into the early Universe

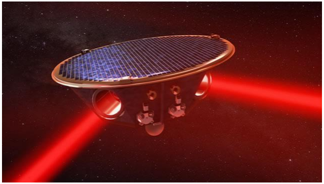


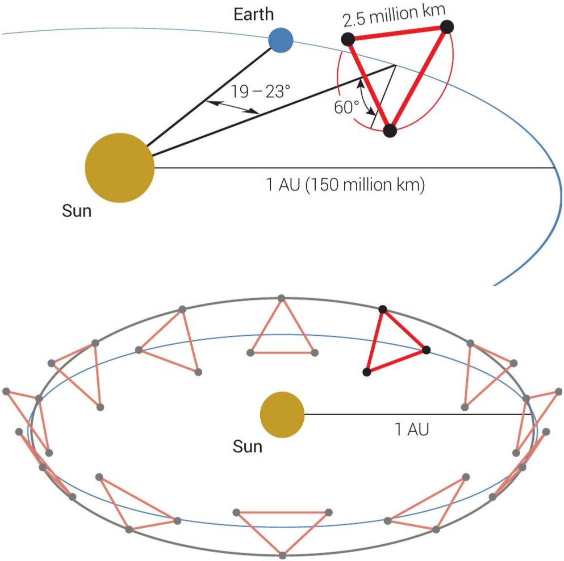
Peek into the early Universe



LISA gravitational wave mission

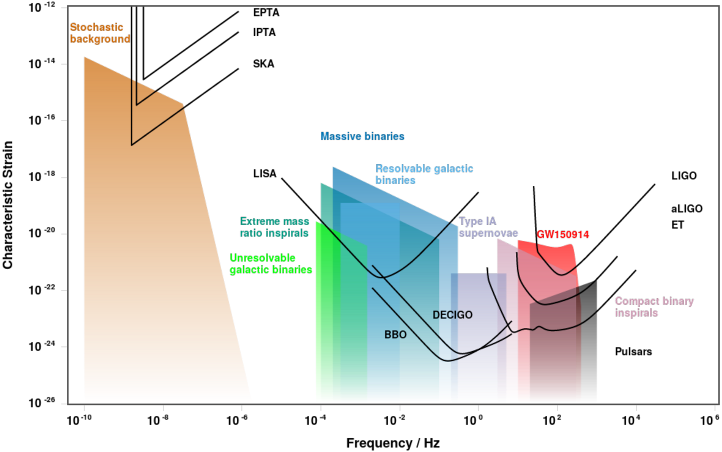
- "Free-flying" laser interferometer
- Strain sensitivity $\sim 10^{-21}$ @ 0.01 Hz ($\sim$ 1pm over 2.5 million km!)
- Launch 2034

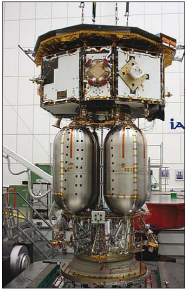




LISA

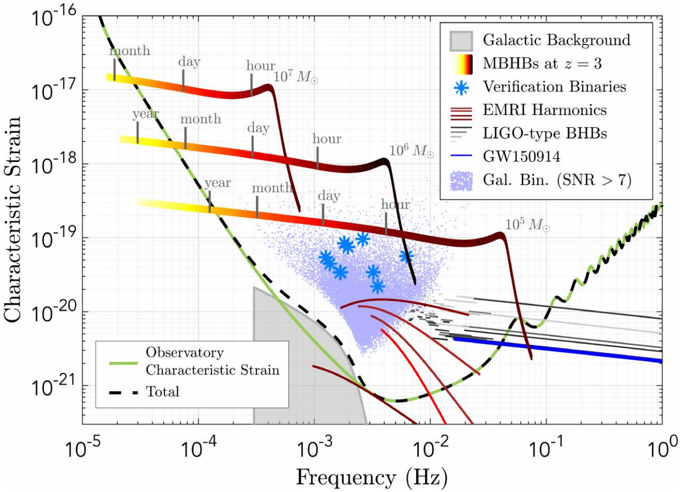
- Frequency window of LISA is right for gravitational waves from the electroweak and above -eras.
- LISA Cosmology Working Group – science case for cosmology
- LISA Pathfinder: technology demonstrator, launched Dec. 2015





[Moore,Cole,Berry, gwplotter.com]

Astrophysical objects seen by LISA

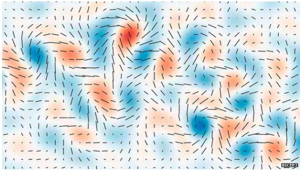


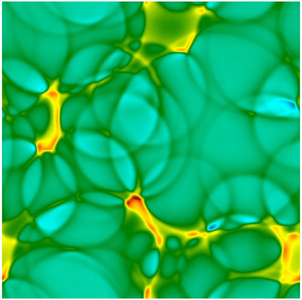
[Lisa mission proposal, 2017]

Cosmological signal *stochastic*: need to understand the "foreground"

Sources of gravitational waves in the early universe

- 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, dark sector . . .
- Cosmological GWs give a direct snapshot of the universe at the time they were generated!
- Stochastic signal, expected frequency $\sim$mHz



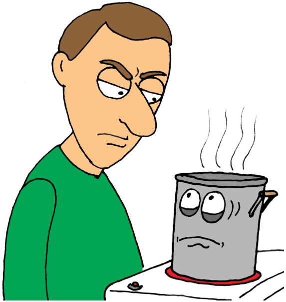


A watched pot never boils . . .

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

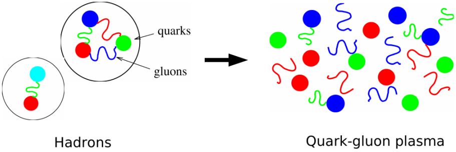
- Transition temperature 100° C.
- However, pure water can remain *metastable* up to 330° C! [Cho et al, PRL112 (2014)]
- At 110° C, metastability $\gtrsim$ age of the Universe!
- When superheated water finally boils, it is a violent process.

→ 1st order transitions can have dramatic consequences.

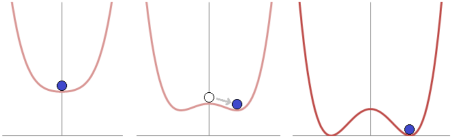


Almost-phase transitions in the Standard Model:

- 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!

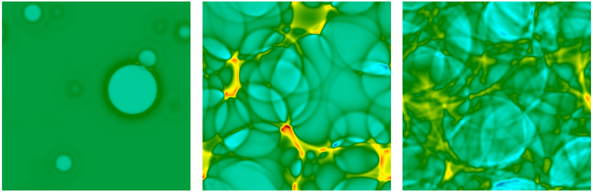


1st order phase transitions

A first order phase transition proceeds through

a) *supercooling*
b) *critical bubble nucleation*
c) *bubble growth and collision* → gravitational waves
d) *sound waves, shocks, turbulence* → *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, speed of sound**

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

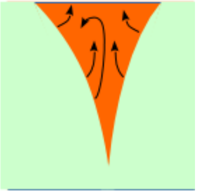
✓ Coupling to gravity: transverse-traceless part of $T^{\mu\nu}$

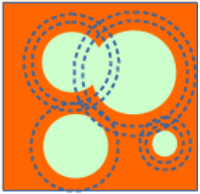
Generation of gravitational waves

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

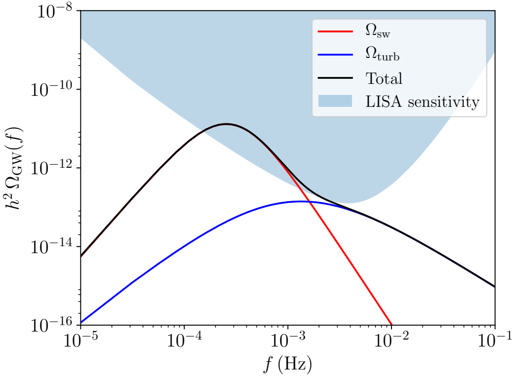




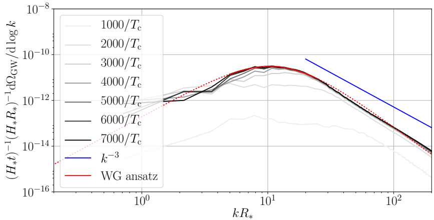
Some movies

Energy density slice [David Weir]
Transparent box
Strong transition ($\alpha = 0.5$, $v_{\rm wall} \approx 0.44$: Deflagration)
fluid velocity   vorticity   [Daniel Cutting]
See vimeo.com channel "Cosmic Defects" for more!

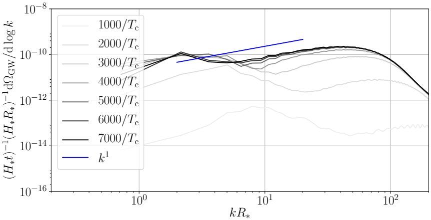
Results: LISA discovery potential



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/



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



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

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

Direct probe of BSM physics

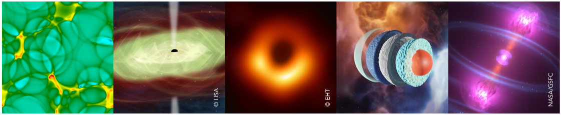
Breakthrough potential with gravitational waves

- Gravitational waves give us unique window to compact astrophysical objects and to the early universe: **potential for breakthrough discoveries**
  - **Probe of new physics:** complementarity with HL-LHC and dark matter searches
  - LISA has much higher "energy reach" than accelerators

Proposed Academy of Finland Centre of Excellence 2022-29:
Gravitational waves and Extreme Matter (GEM)

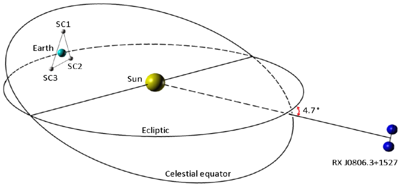
- Theory & observations: *cosmology, neutron stars, (supermassive) black holes, supernovae*
- Helsinki, Turku, Jyväskylä, Aalto, HIP, FINCA

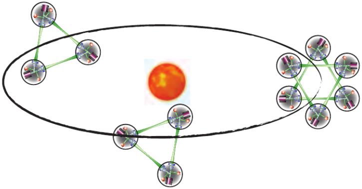
GEM

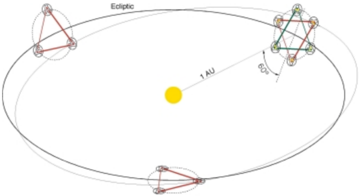


Centre of Excellence in
Gravitational waves
and Extreme Matter

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