Searching for 100 TeV Long-Lived Particles with LISA

arXiv:1812.07577

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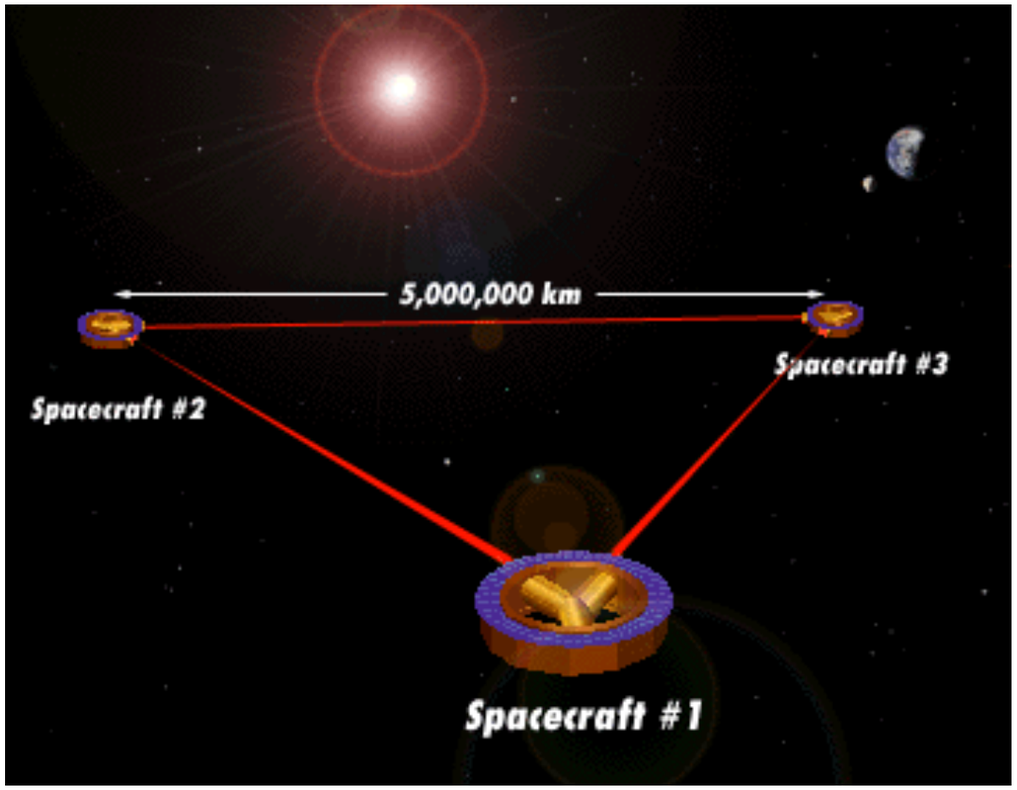
with R. Caldwell and T. Smith

Today: Discuss the "backlight effect" to search for long-lived particles* with LISA.

Direction: New Particle Physics Opportunities in Gravitational Wave Astronomy/Cosmology

*Probes second-order phase transitions as well. See arXiv:1812.07577!

What is LISA?
(Laser Interferometer Space Antenna)



*European Space Agency mission with NASA involvement.

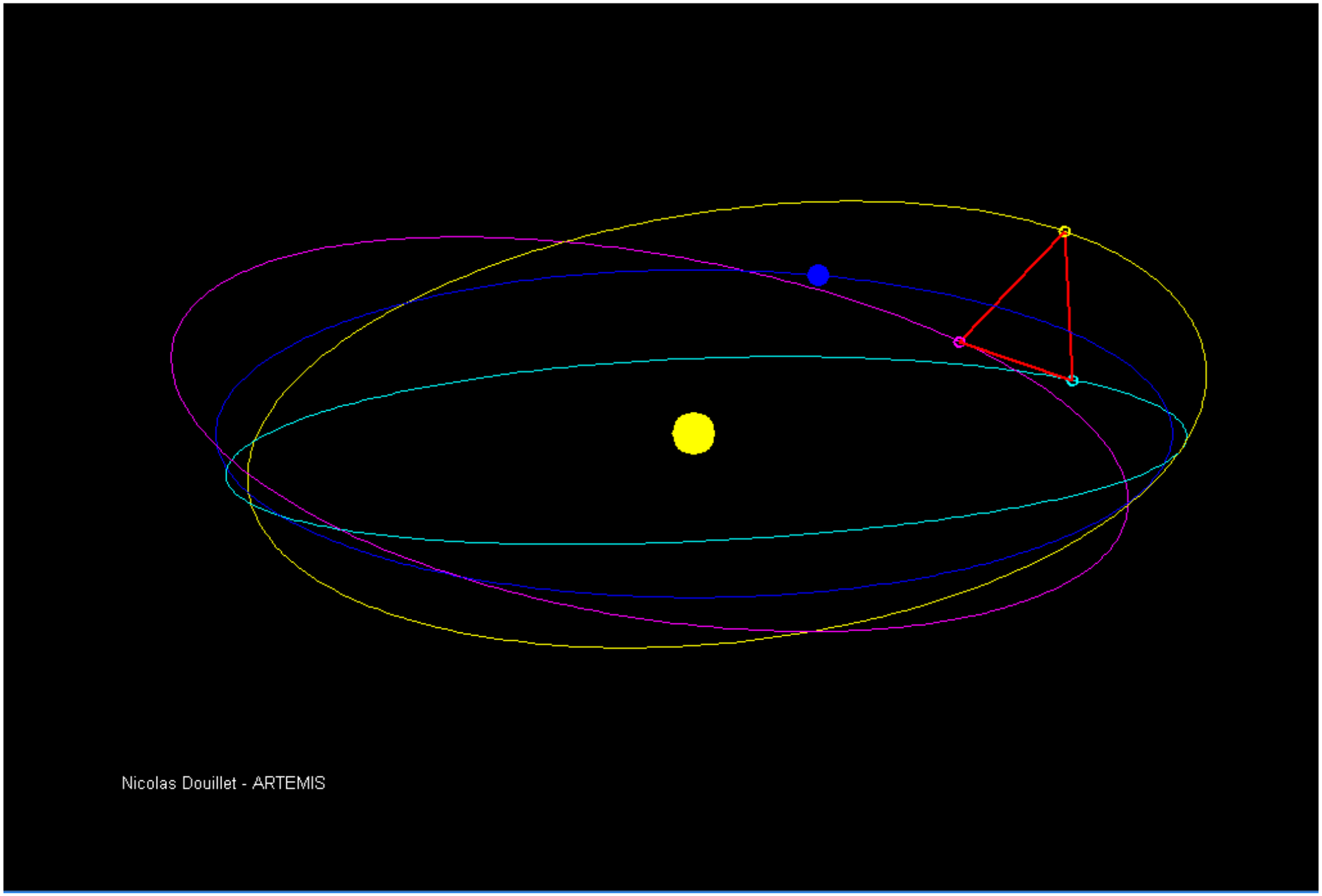
*Scheduled for 2030+.

*3 Spacecraft, 6 Test masses, 2.5 Million km interferometry

*4(10) year mission

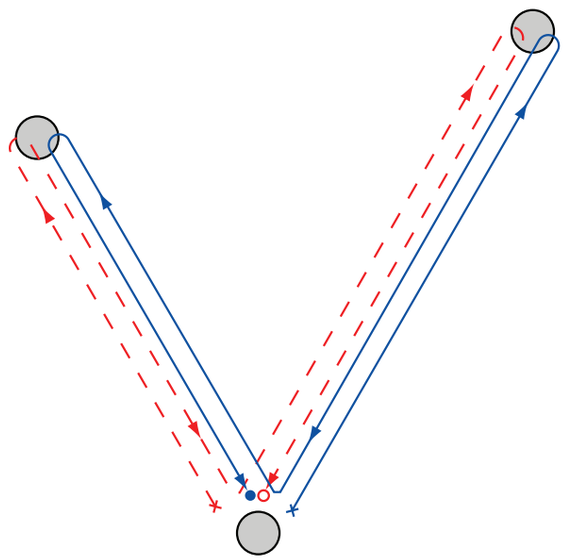
*Frequency range: f ~ 0.1 mHz - 0.1 Hz

Laser Interferometer Space Antenna



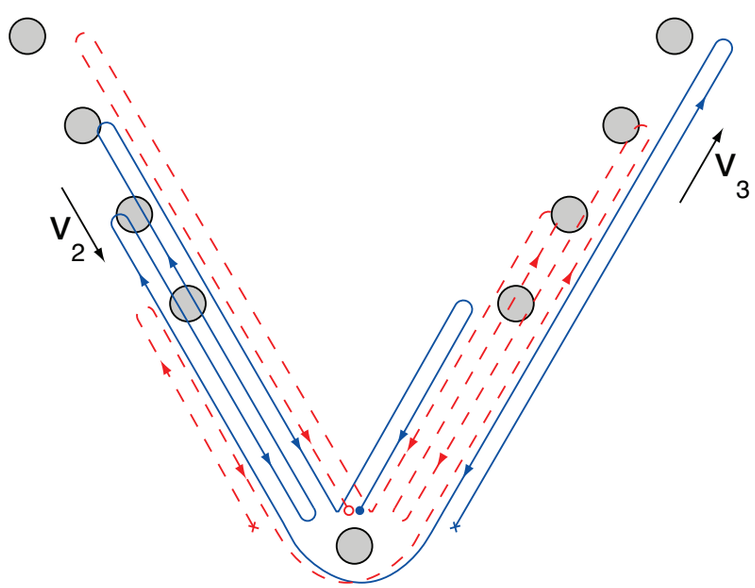
Planned LISA orbit at L1

How does LISA Work?



*Gravitational wave places strain, ΔL/L, on two free-falling test masses separated by length, L.

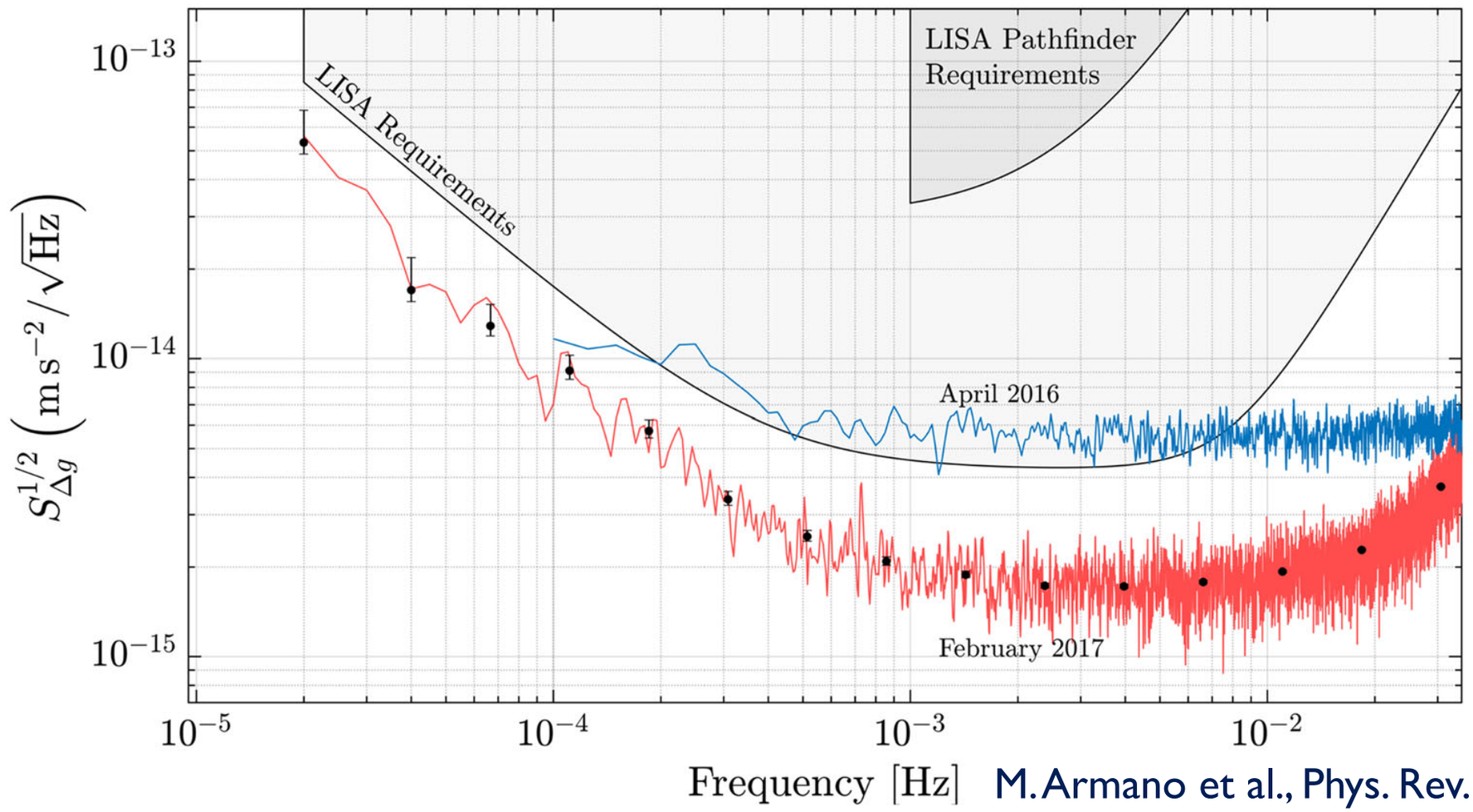
Wave stretches and compress the distance between the masses along the perpendicular directions by ΔL.



*LISA requires a sensitivity to displacement and acceleration of 1.5×10^{-11} m/root-Hz and 3×10^{-15} m/s^2/root-Hz, respectively.

arXiv:0909.0650

LISA Pathfinder



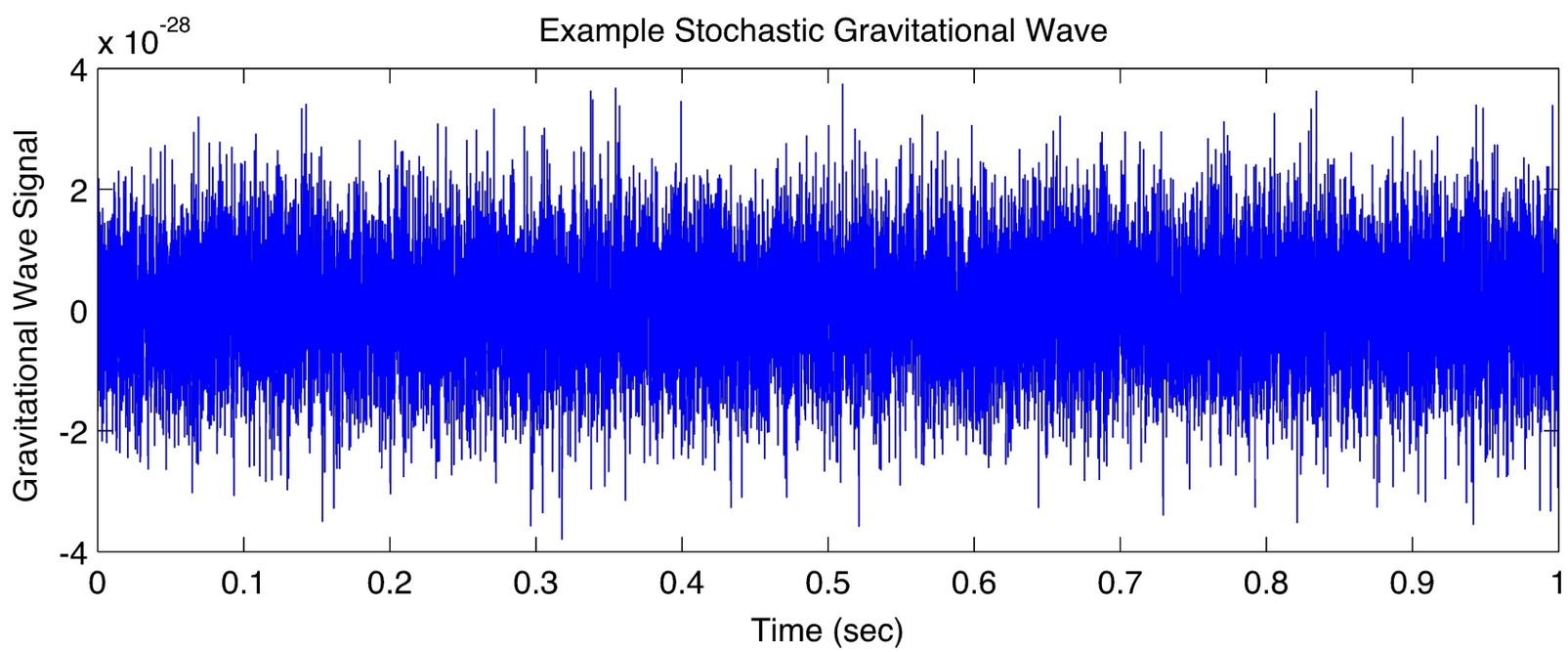
M. Armano et al., Phys. Rev. Lett. 120, 061101

- 2015 test of LISA conditions. Single spacecraft with interferometer arms shortened to 38 cm.
- The noise requirement levels met by a large margin!

Stochastic Gravitational Wave Backgrounds

- Stochastic Gravitational Wave Background is to gravity waves as the CMB is to photons.

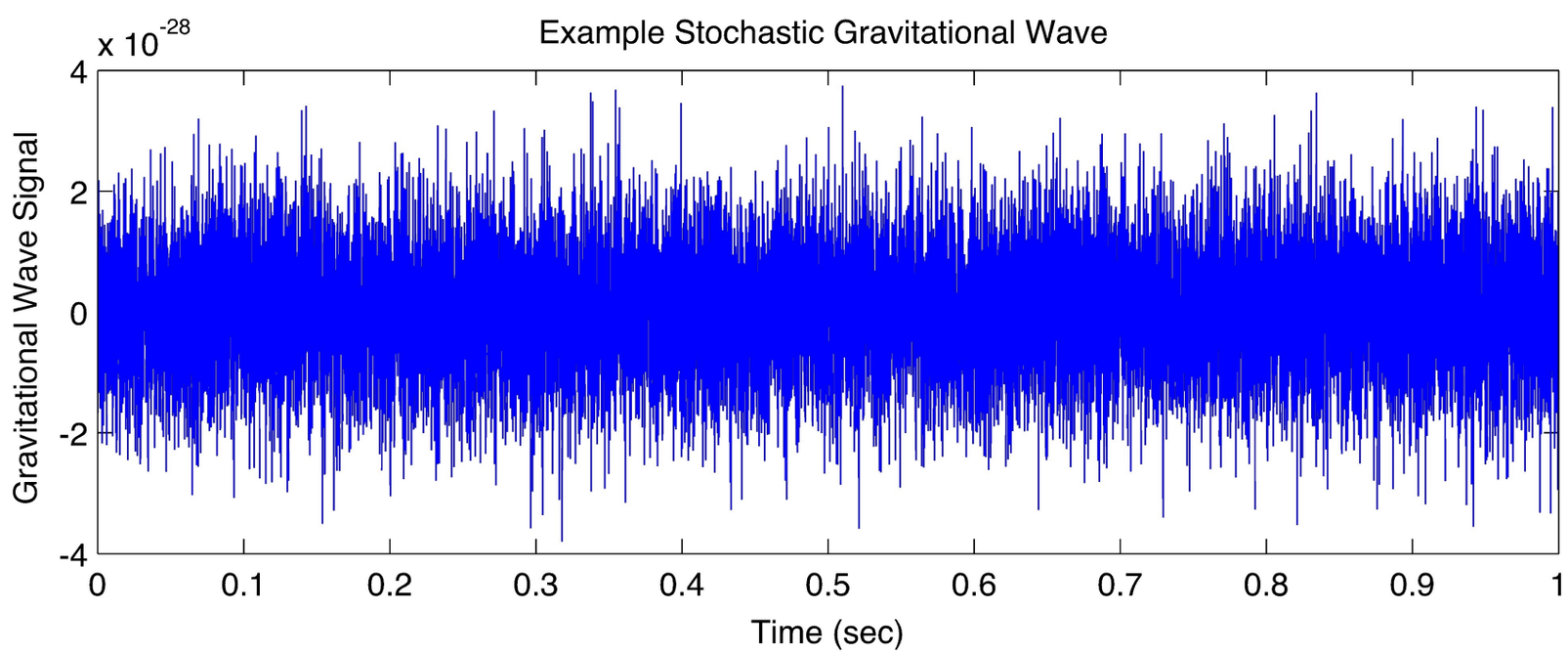
  (A large number of random, independent events combine to create the background.)



LIGO Collaboration

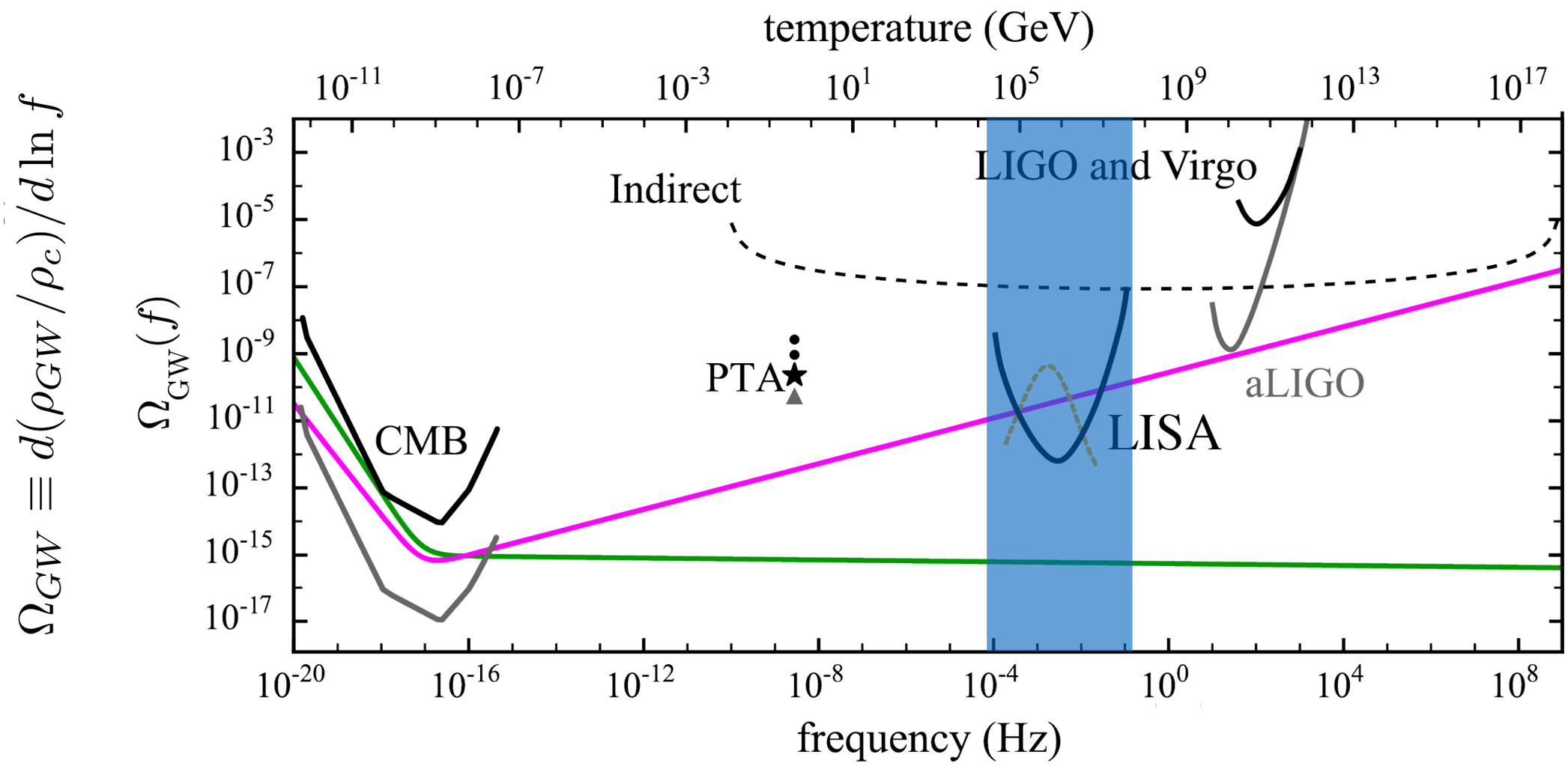
Stochastic Gravitational Wave Backgrounds

- Sources of Stochastic Gravitational Wave Background (SGWB) include inflation, strong first-order phase transitions and other exotic scenarios.
  - Can we exploit this to learn even more physics?



LIGO Collaboration

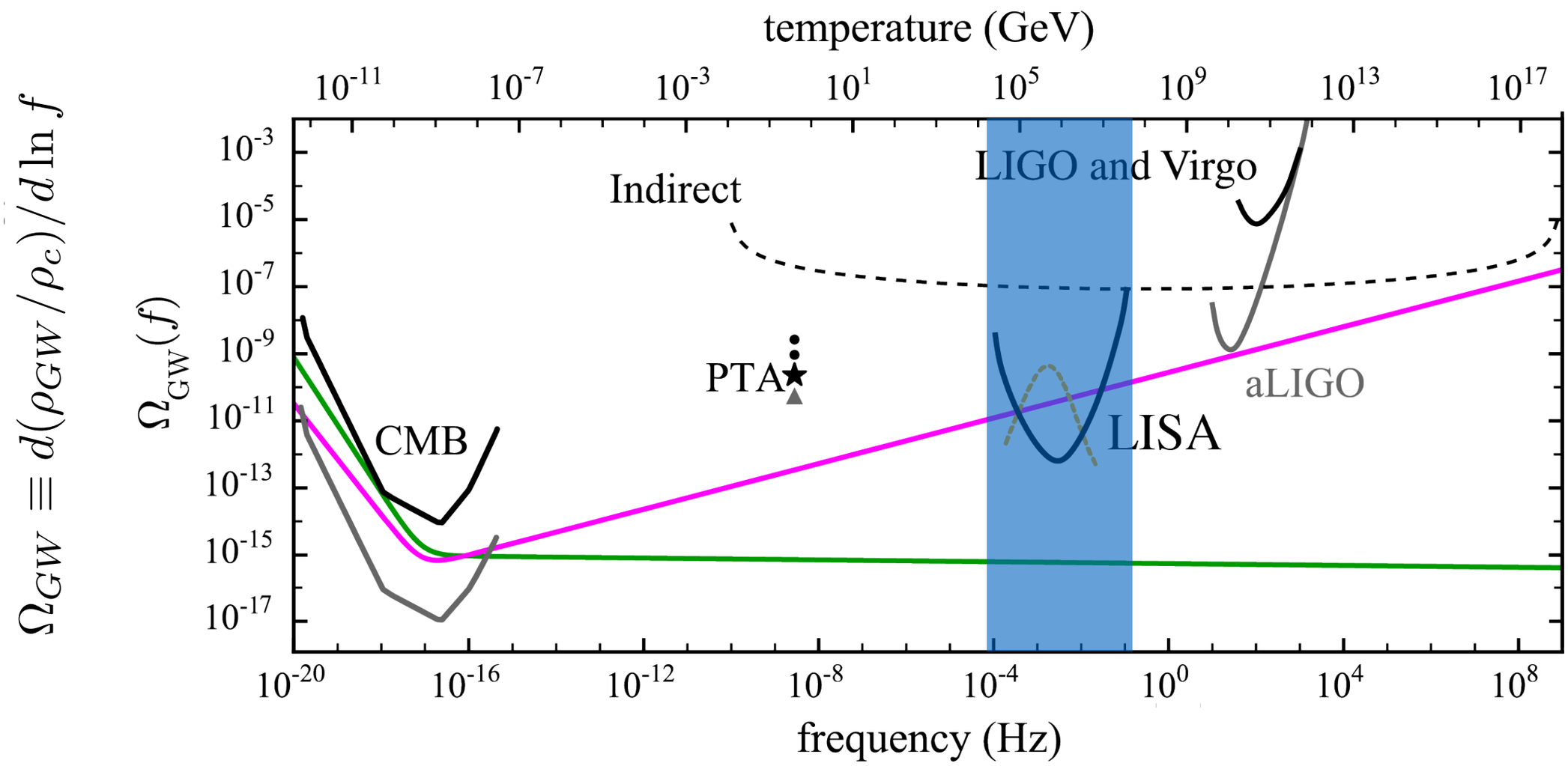
Stochastic Gravitational Wave Backgrounds



$$\rho_{GW} = \frac{1}{32\pi G a^2}\langle h'^{j}_{i}(\tau,\vec{x})h'^{i}_{j}(\tau,\vec{x})\rangle$$

$$\tilde{h}'' + 2\frac{a'}{a}\tilde{h}' + k^2\tilde{h} = 16\pi G a^2 \tilde{\Pi}$$

Stochastic Gravitational Wave Backgrounds



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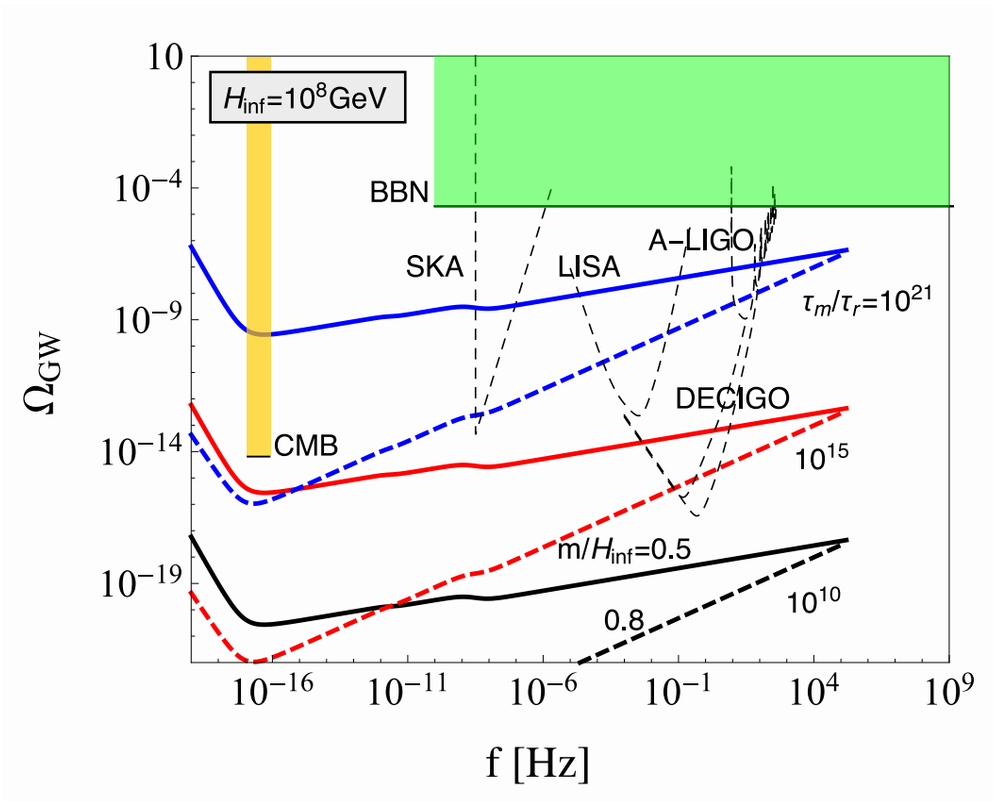
LISA probes 100 TeV physics.

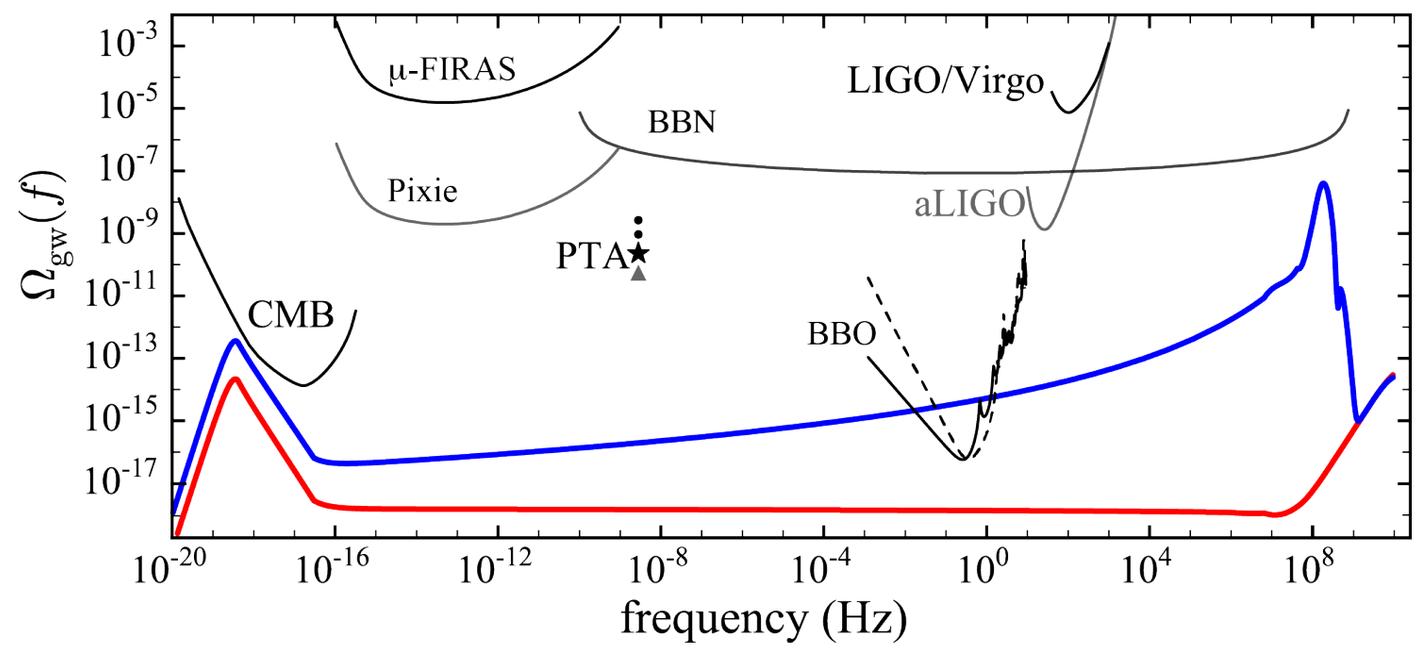
Example LISA Sensitive SGWB Models

Inflation with Massive Gravitons



Fujita, Kuroyanagi, Mizuno, and Mukohyama, Phys.Lett. B789 (2019)

Axion-Gauge Inflation



Caldwell and Devulder, Phys.Rev. D97 (2018)

Models which attempt natural inflationary potentials often have blue tilted SGWB spectrum.

What is the Backlight effect?

What is the Backlight effect?

Changes in the relativistic degrees of freedom in the early universe leave an imprint on a primordial spectrum of gravitational waves.

More Specifically…

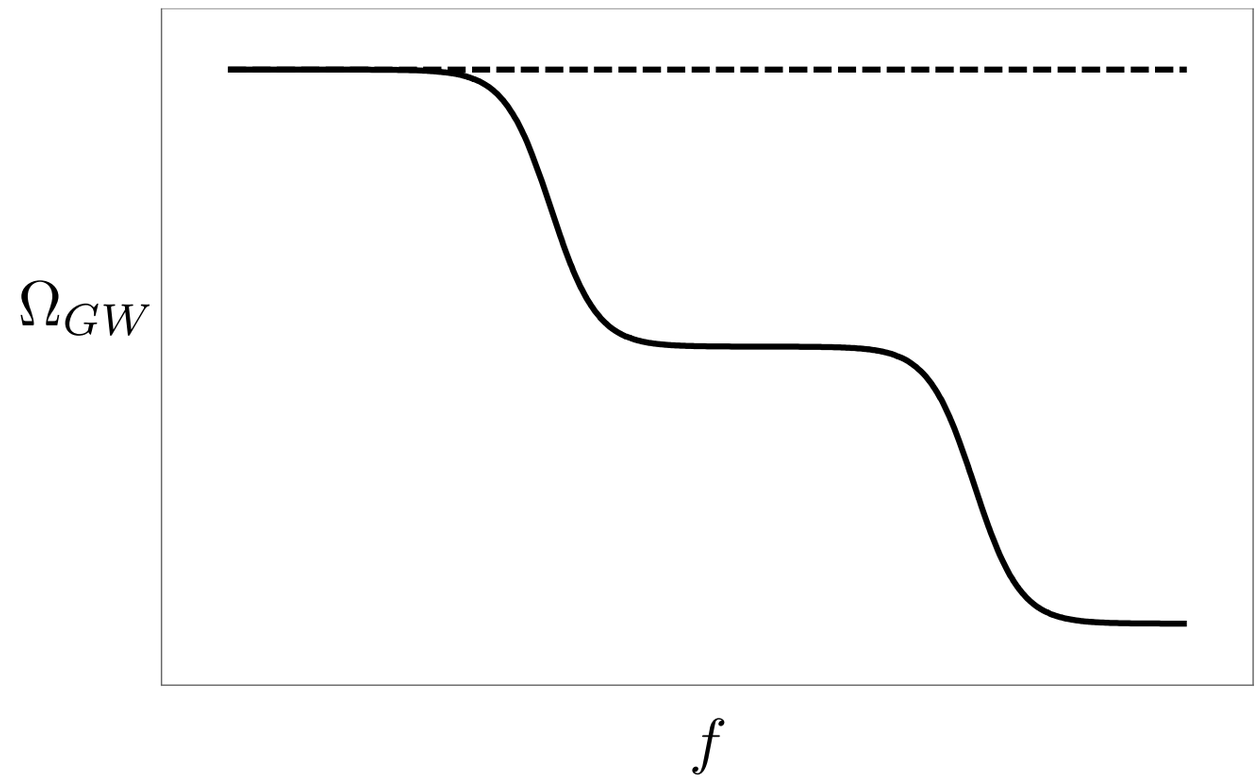
When the primordial fluid cools past a particle's rest mass, the expansion rate speeds up. All subhorizon gravitational radiation will be slightly diluted*.

Superhorizon waves are frozen.

*Bennett, Phys. Rev. D33, 872 (1986)

What is the Backlight effect?

Spectrum shows a series of steps, going from low to high frequency, corresponding to changes in the relativistic degrees of freedom*.



$$\Omega_{GW} \equiv d(\rho_{GW}/\rho_c)/d\ln f$$

*Y. Watanabe and E. Komatsu, Phys. Rev. D73, 123515 (2006)

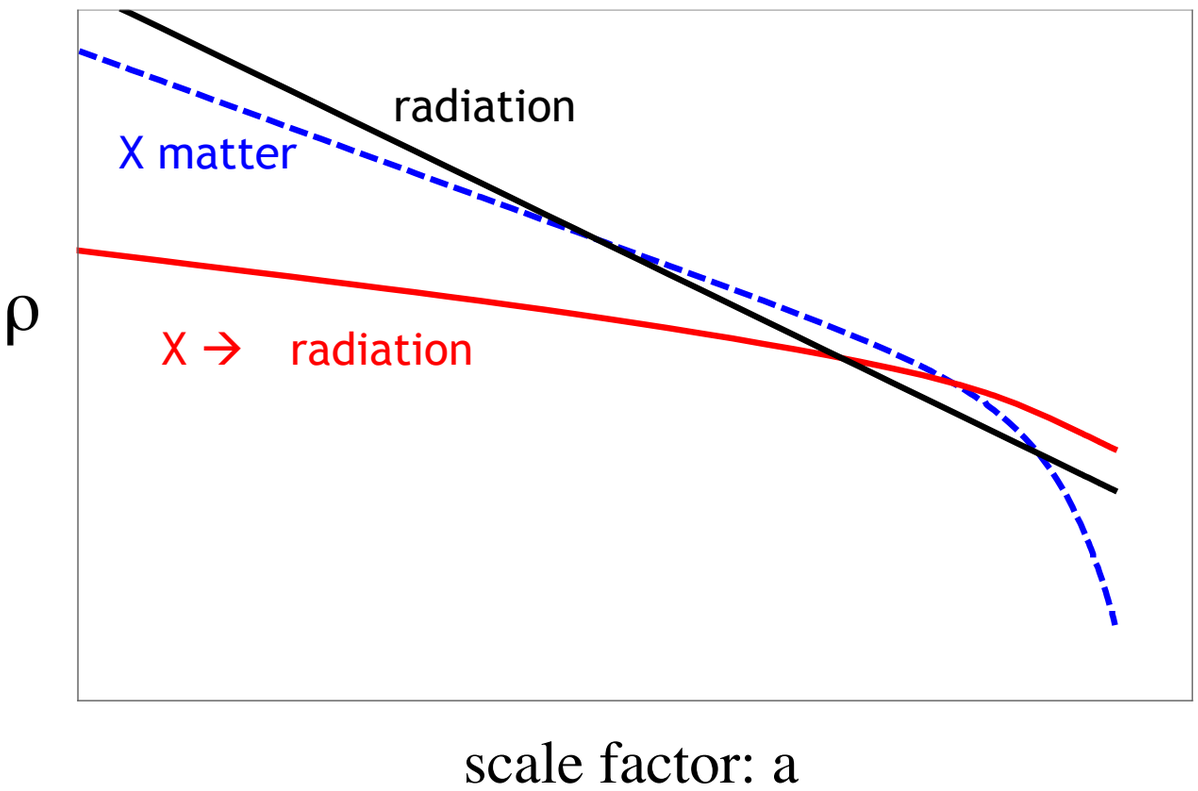
What is the Backlight effect?

Slight changes in the rate of cosmic expansion leave an imprint on all oscillatory modes of a SGWB.

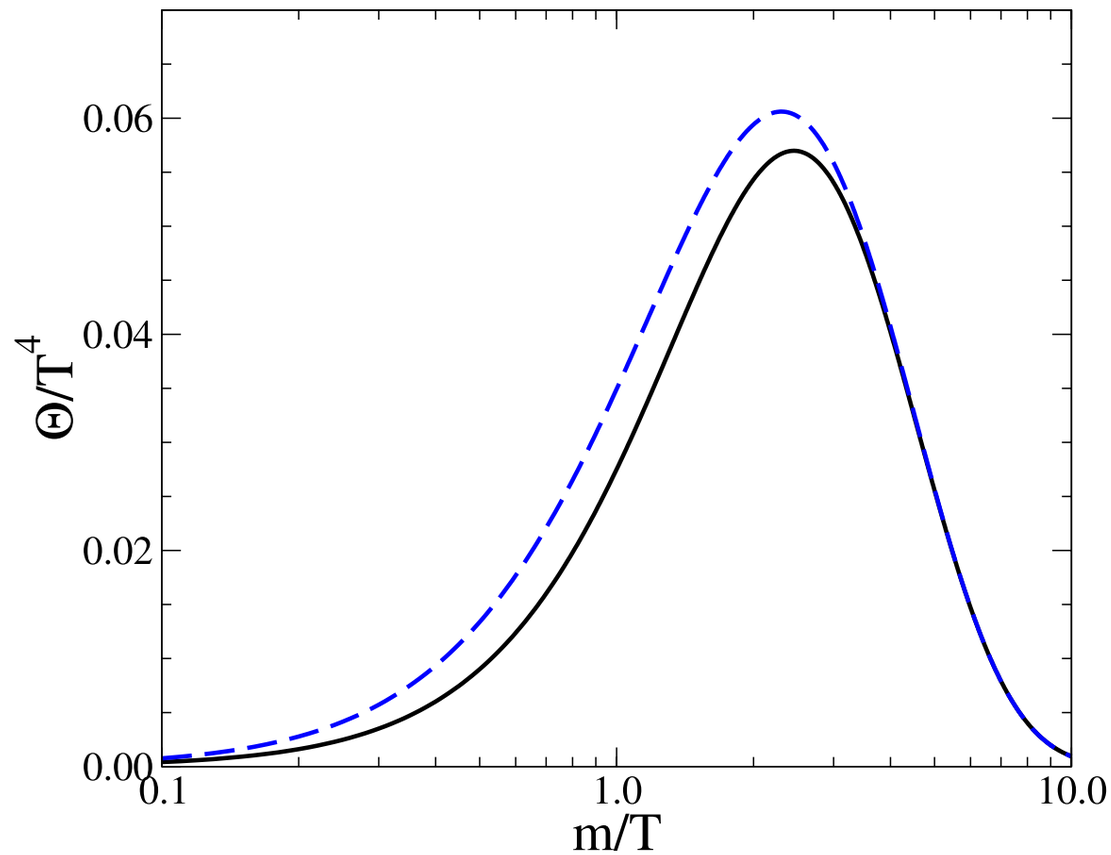
Such an imprint says "these modes were already oscillating." In this way, a SGWB is a "backlight" on the early expansion history of the Universe.

Goal: Quantify step size in the gravitational wave spectrum to show LLP may be within the reach of LISA.

Out-of-Equilibrium Decays



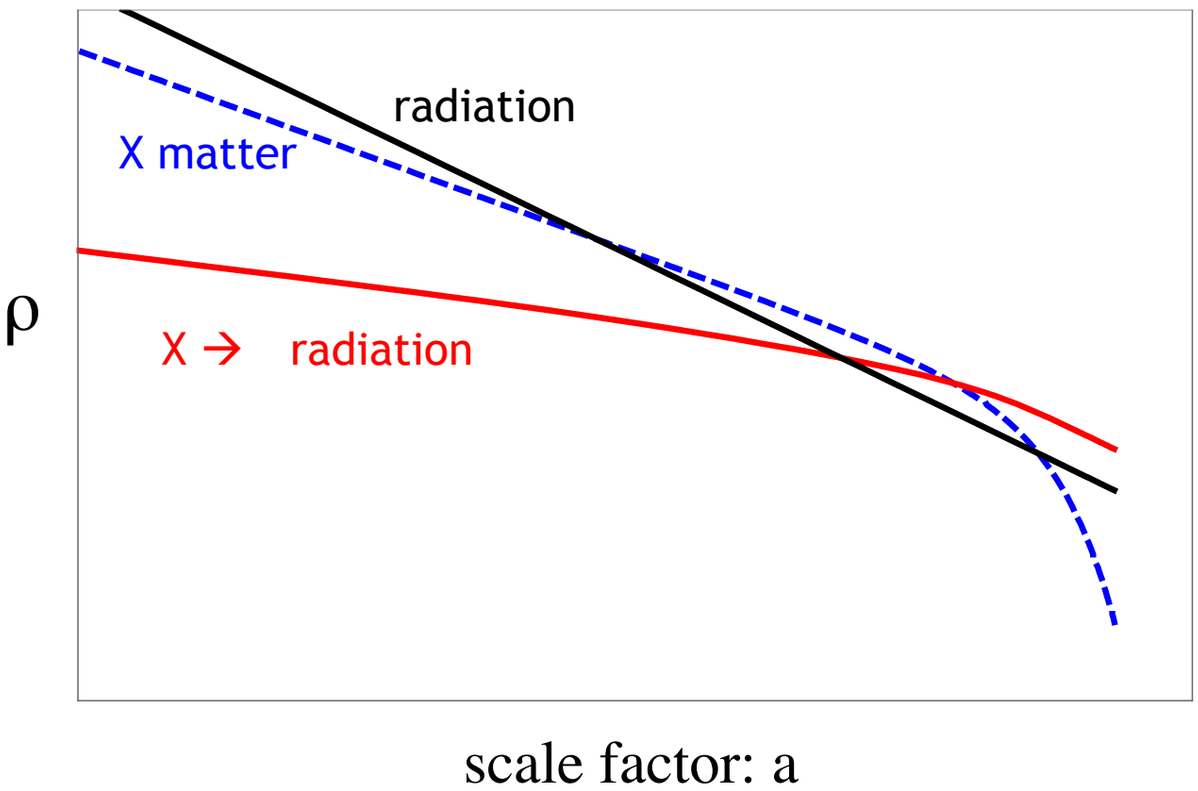
Out-of-equilibrium decays can effect the expansion.

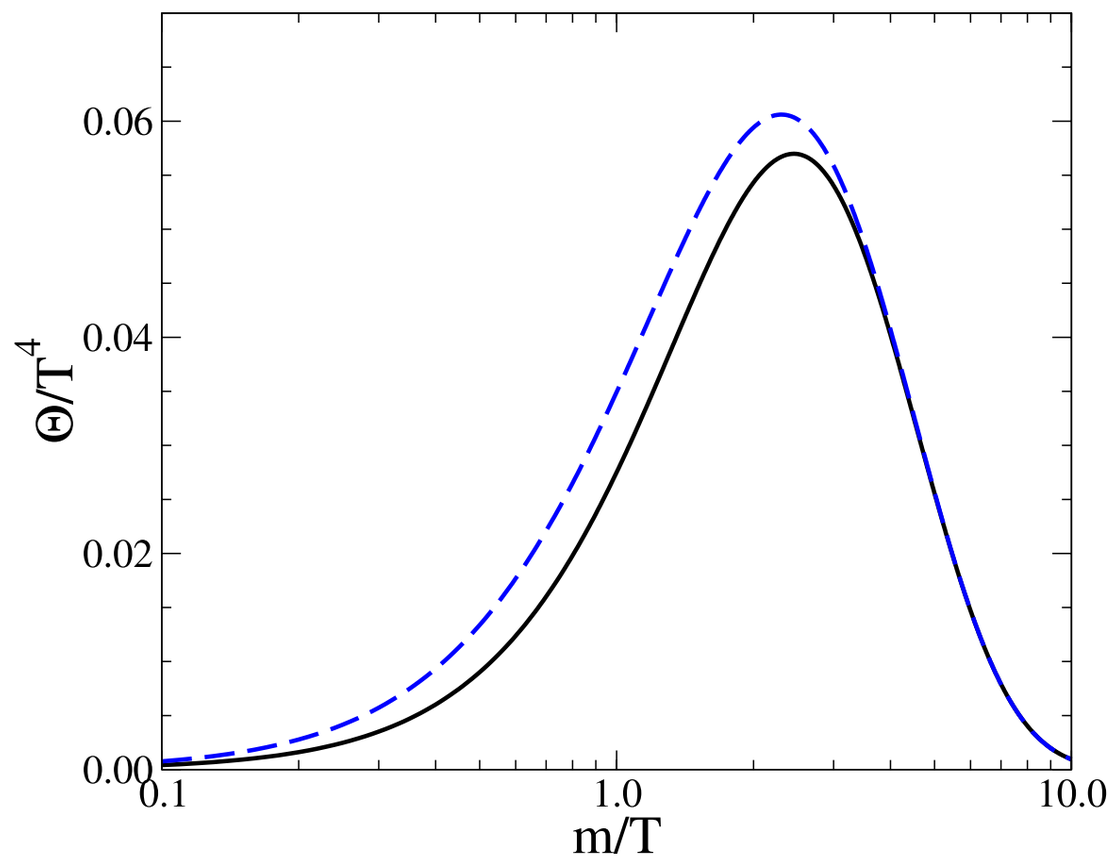


Change in the stress-energy tensor when a species becomes non-relativistic. The solid (dashed) line is for fermions (bosons).

Free-field treatment of radiation dominated epoch means the freeze out of each species results in a bump to the trace of the stress-energy tensor.

Out-of-Equilibrium Decays



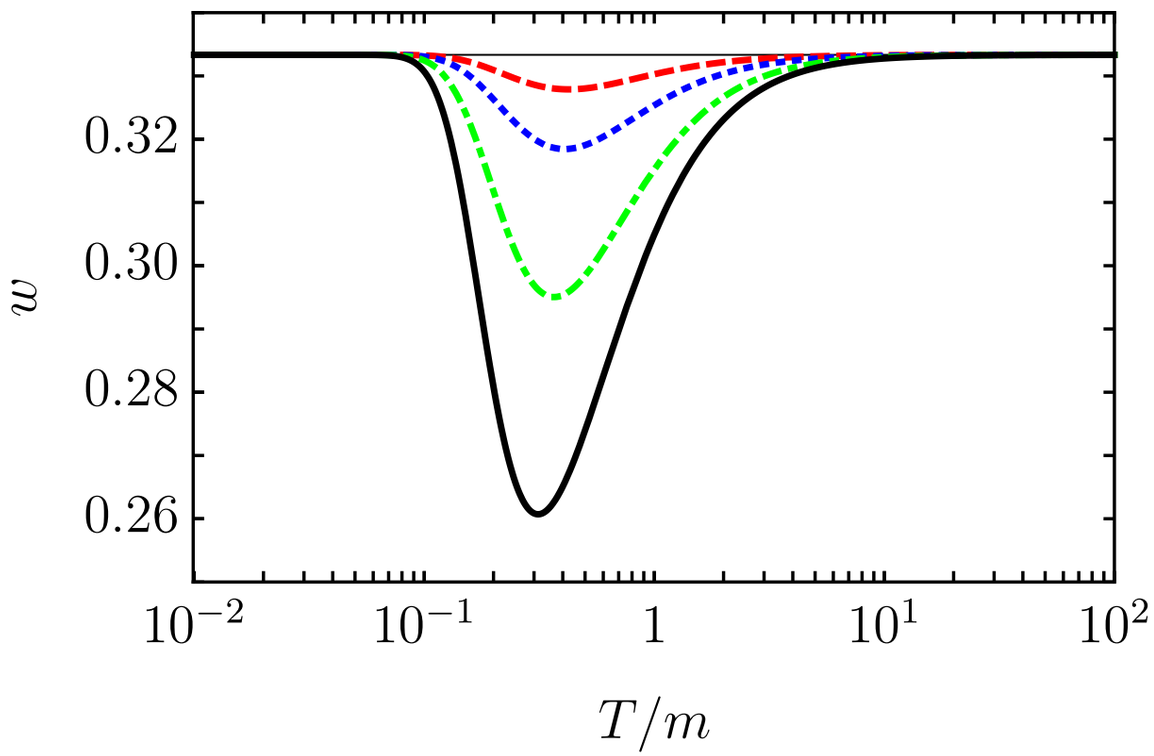


Thermal species become non-relativistic (m,g).

Crossover phase transition (m,g)

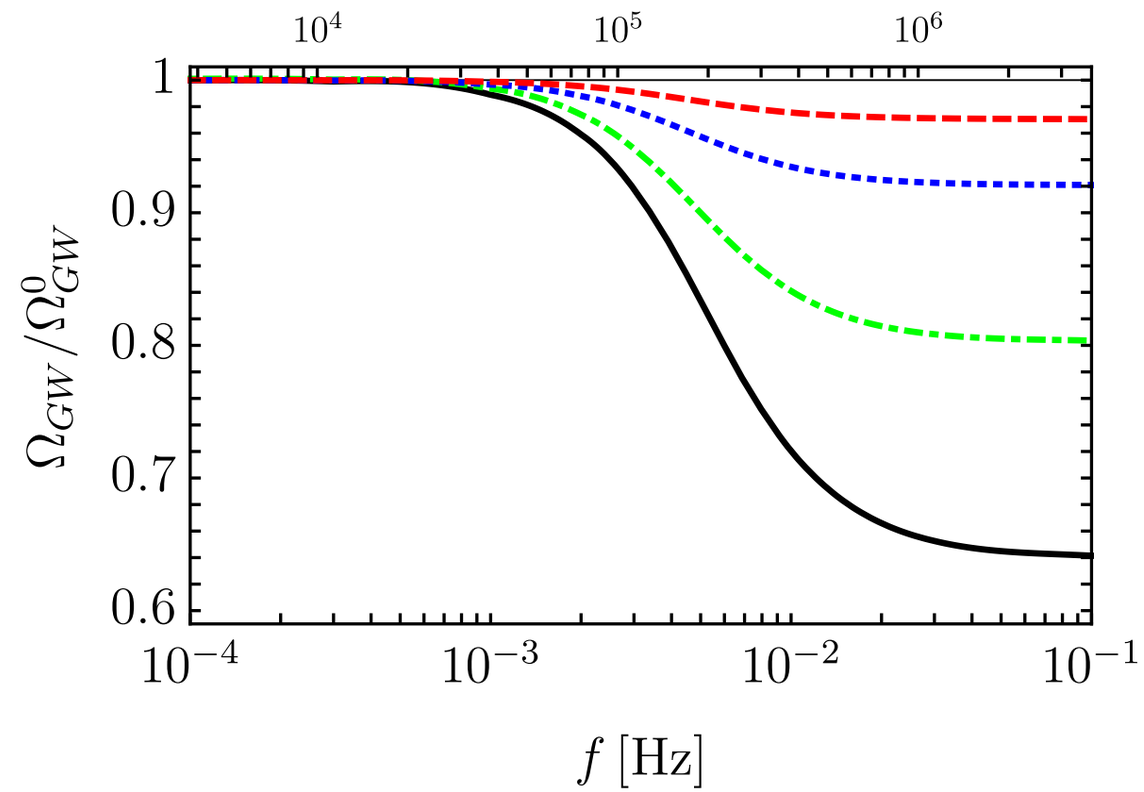
Dominance and decay of out-of-equilibrium species
($X \longrightarrow$ SM, translate $\Gamma, Y_X \longrightarrow$ m, g)

Results



Equation of state with 106.75 SM relativistic dof plus new physics dof.

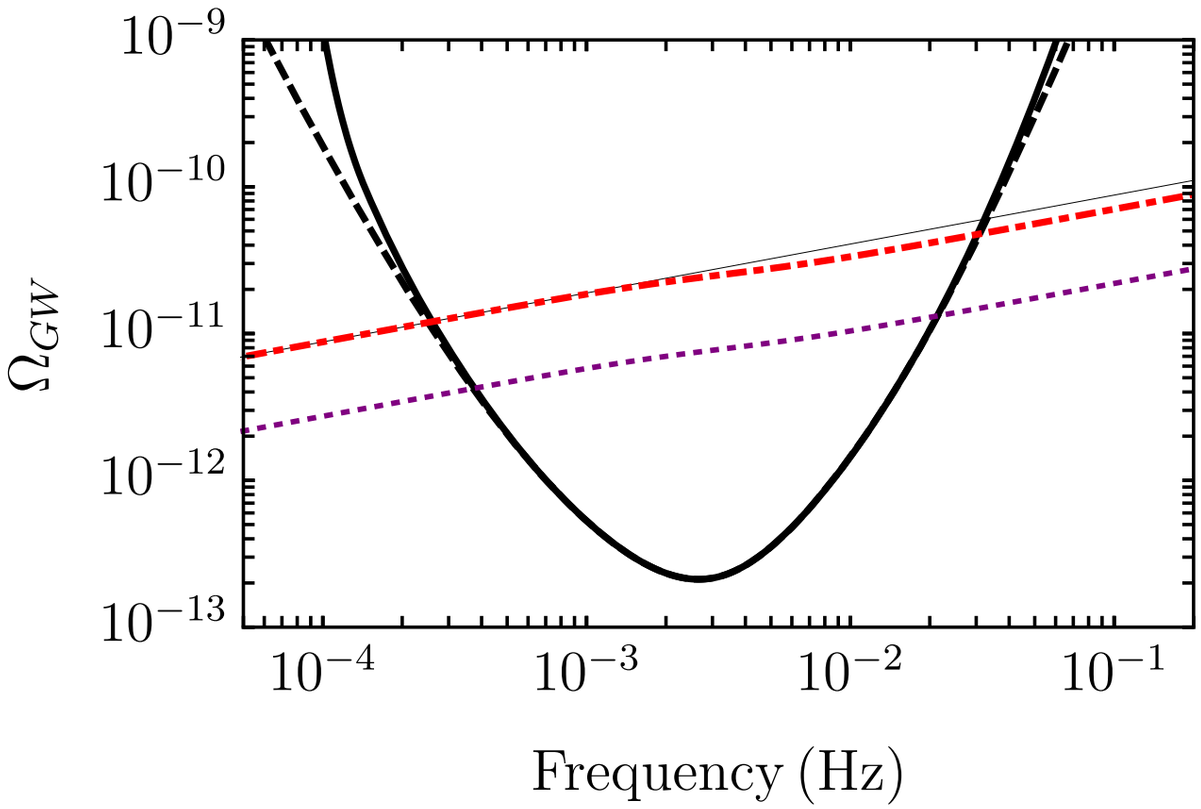
Above g_* = 0, 10, 30, 100, 300 degrees of freedom, descending for different lines and colors.

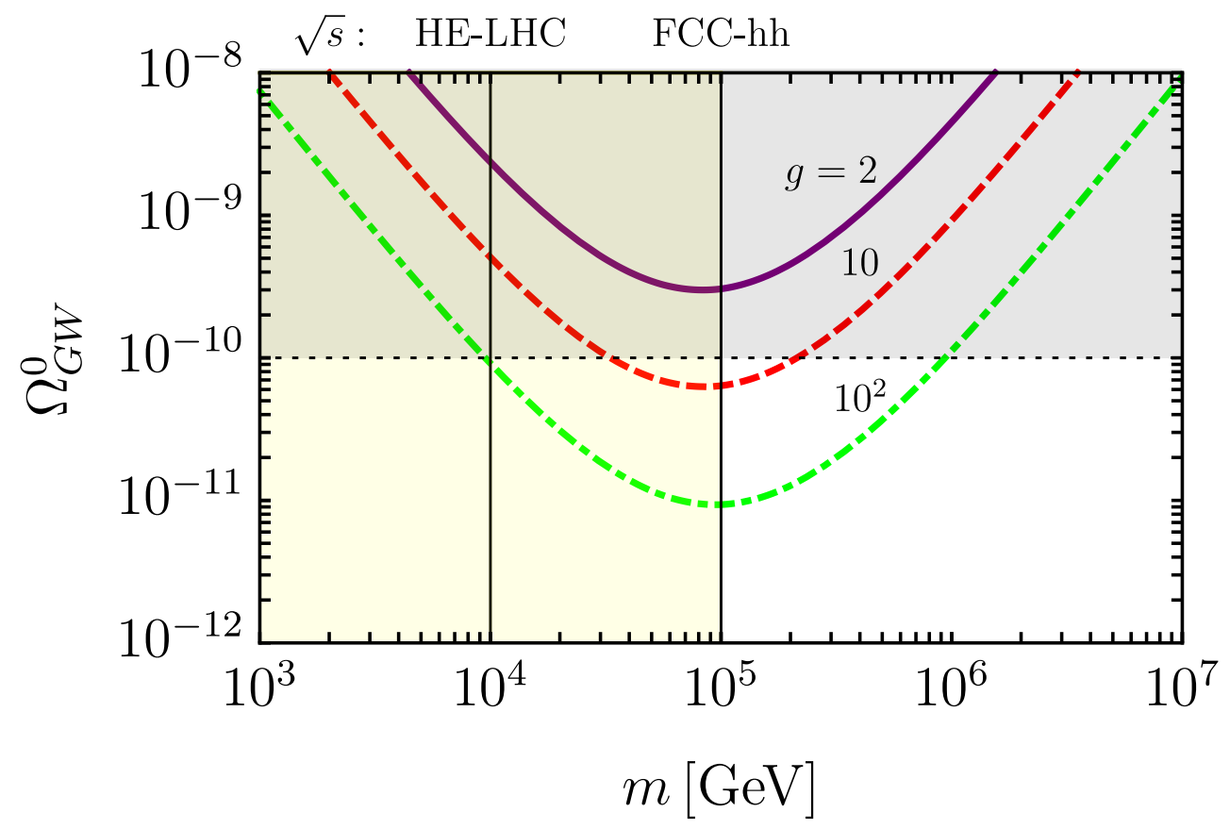


The step feature in a SGWB for g = 10, 30, 100, 300 degrees of freedom. Take a benchmark mass of m = 4 × 10^5 GeV. g_SM = 106.75 degrees of freedom.

For lower or higher masses, the curves shift left or right, respectively. The top axis gives the temperature of the cosmic fluid in GeV. (2π f = H_a/a_0).

Results





SGWBs consistent with current bounds that feature a step (g = 100, m = 100 TeV). Sensitivity curve for LISA is a black solid.

A SGWB without the step (dashed black line) is included for contrast.

The threshold Ω_{0GW} needed to identify the backlight effect for fixed degrees of freedom is shown as a function of the mass. The yellow shaded region shows the range of energies to be explored by proposed accelerators. The grey shaded region shows the level of SGWB excluded by current observations (in the absence of new physics at higher energies).

LISA Discovery Decision Tree for LLPs

Is there a SGWB? → No (Be happy with all the primary LISA science!)

→ Yes ***Is it a foreground?*** → Yes (Not a surprise. Keep looking)

→ No Congratulations!

Peaked SGWB? → Yes (1st order phase transition? Call CERN!)

B modes in CMB? → Yes (Confirm inflation?)

Featureless power law? → No (Are you sure it's not a foreground?)

→ Yes ***Is there a step?*** → No (A "late time" SGWB? Look for defects!)

→ Yes Congratulations! It is primordial!

Interpret in terms of m,g. Call CERN!

Conclusions

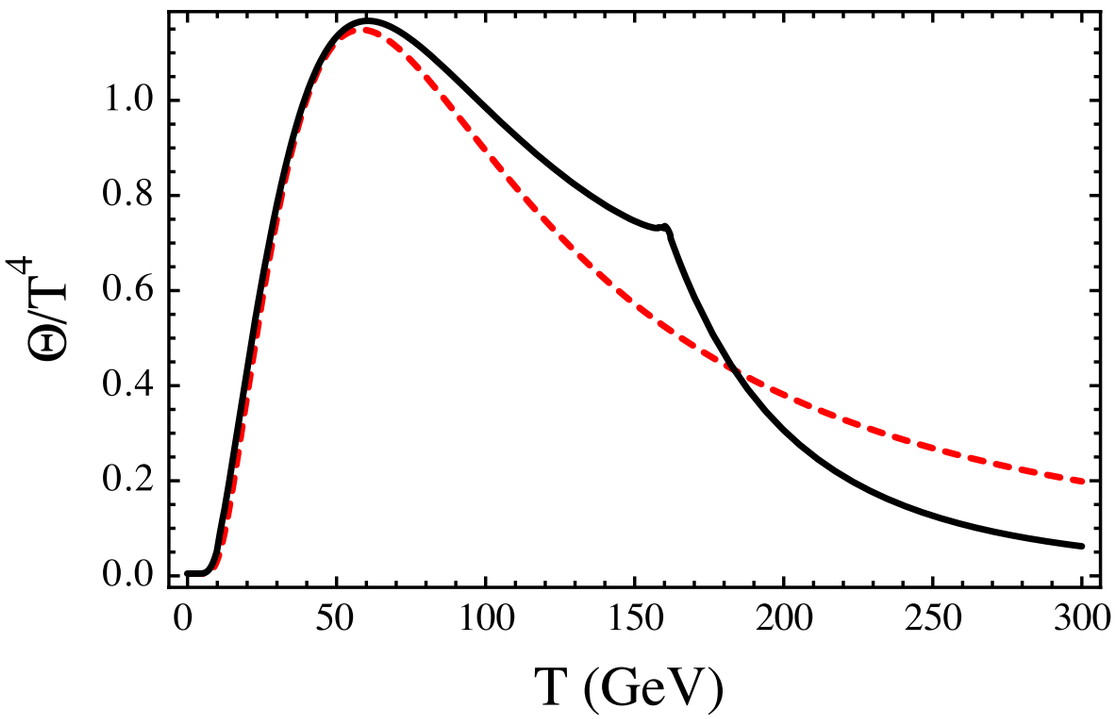
Detecting the SGWB at a wide range of frequencies provides crucial information about the physics that produces it.

Despite the many contributions to the SGWB, the backlight effect gives crucial information about of out-of-equilibrium effects and may help to illuminate 100 TeV decays of long-lived part.

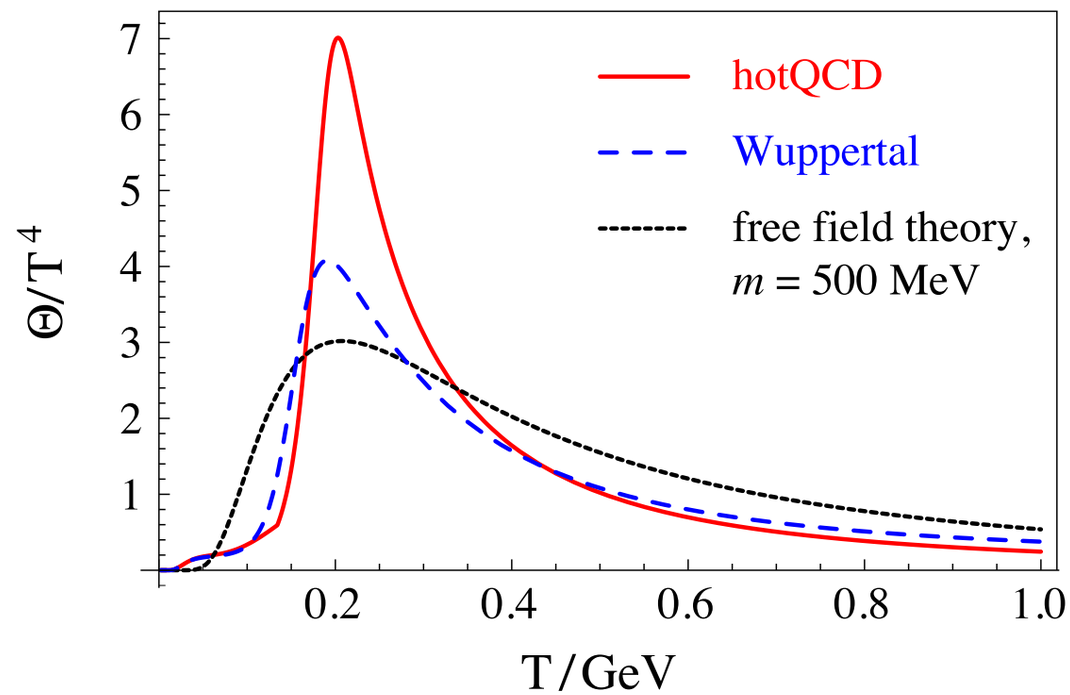
Thank you!

Additional Slides

Phase Transition Reminder



electroweak phase transition

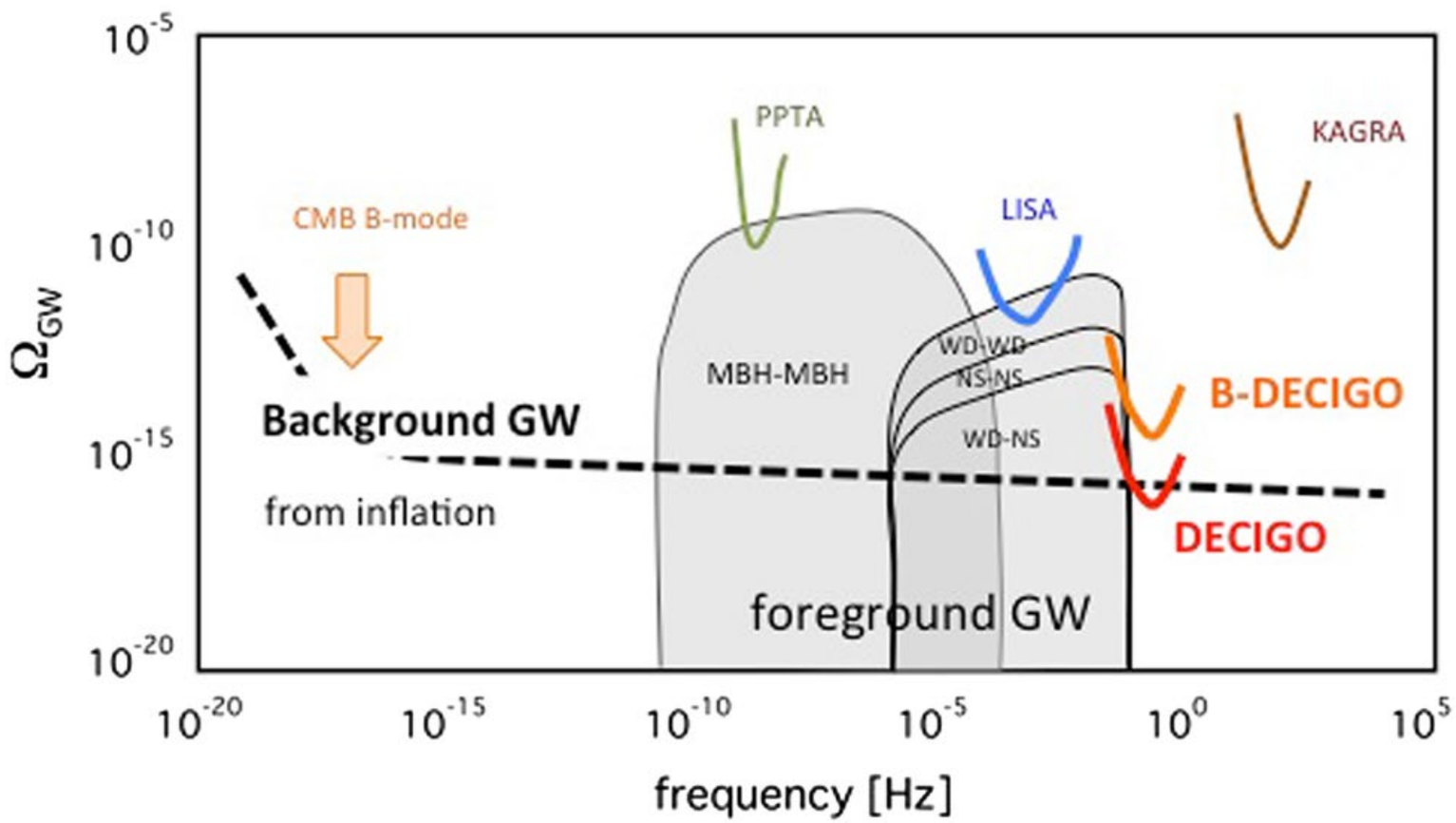


QCD phase transition

Ring-improved one-loop treatment of electroweak thermodynamics (solid black) with free field expectations (dashed red lines)

Peak for the electroweak phase and QCD phase transitions.

Another Proposed Experiment



DECIGO: Sensitive in the frequency band between 0.1 and 10 Hz. Designers hope to launch it in 2027 (funding pending).

*Kawamura; et al. (2008), J. Phys.: Conf. Ser. **122** (1).

Calculation of the sensitivity to the Step Feature

interferometer signal: Φ
response to GW: S
instrument noise: N

$$\langle \Phi_i(f)\Phi_j(f')\rangle = \frac{1}{2}(S_{ij}(f) + N_{ij}(f))\delta(f - f')$$

Standard SNR calculation

$$\mathrm{SNR}^2 = \sum_{a=AA,EE} T \int_0^\infty df \left(\frac{S_a}{N_a}\right)^2$$

Adapt: SNR due to step

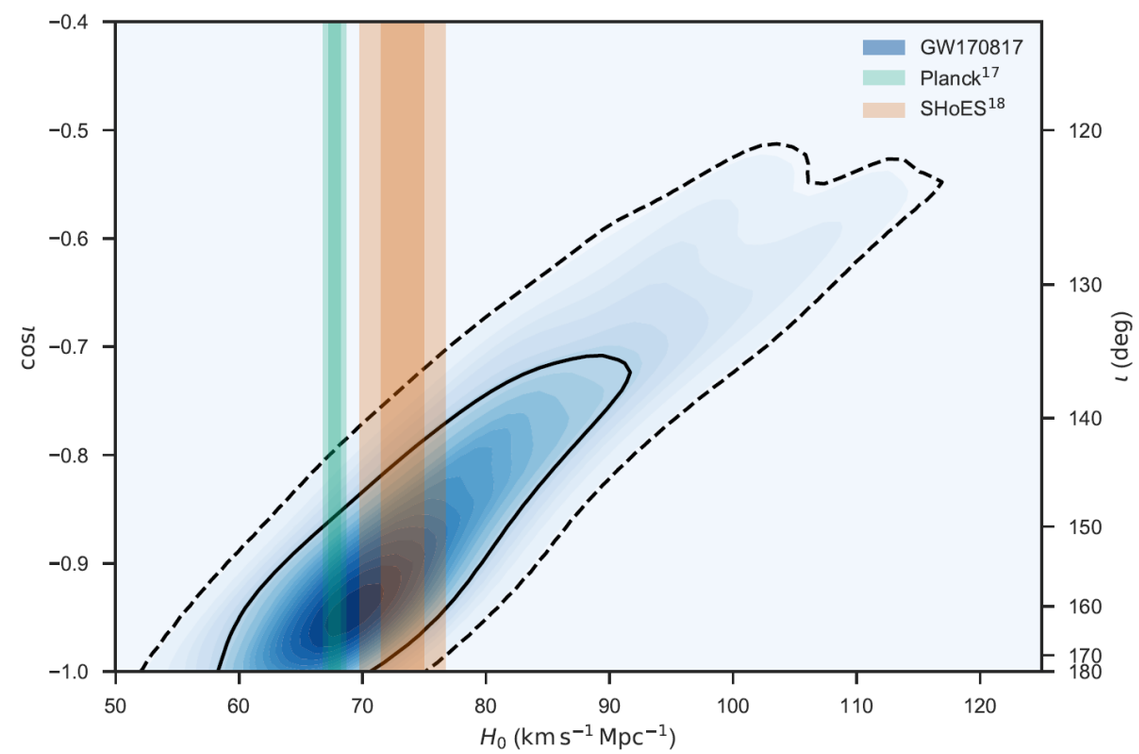
$$S_a \to S_a|_{\mathrm{w/step}} - S_a|_{\mathrm{w/o/step}}$$

Aside: More Information on Gravitational Wave Cosmology

- Standard Sirens* are analogous to standard candles for SNIa.

Black hole and neutron start binaries are the classic standard sirens. Generates chirp-like gravitational waveform as the binaries spiral together.

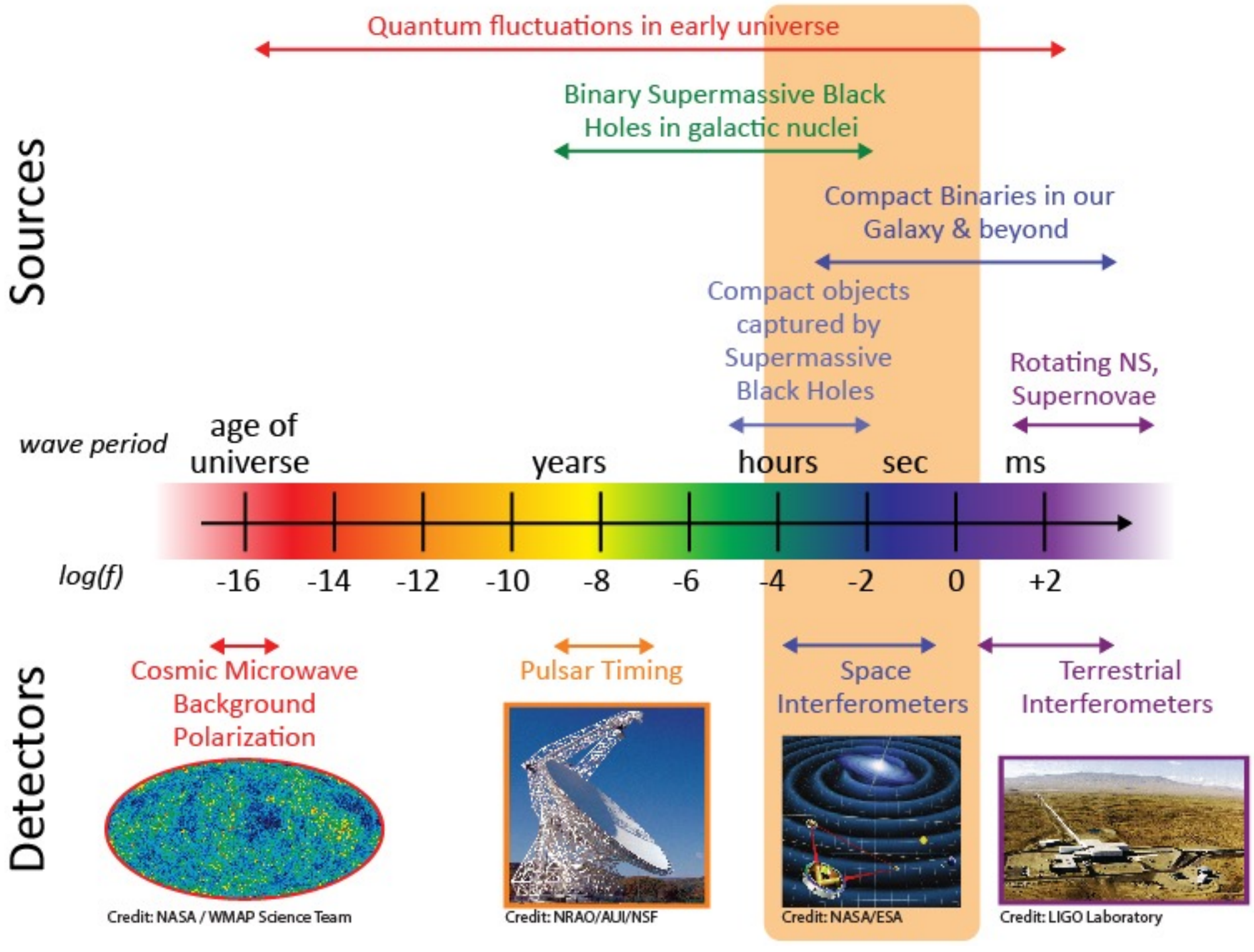
GW170817 used to estimate H_0.



LIGO, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE and MASTER Collaborations

*See, for example, Maggiore, M, *Gravitational Waves. Vol. 1: Theory and Experiments.*

The Gravitational Wave Spectrum



https://lisa.nasa.gov

LISA Science Goals

LISA Astrophysics:

Detect gravitational waves from massive black hole binaries, galactic white dwarf binaries, LIGO progenitors …

LISA Cosmology:

Standard sirens, stochastic backgrounds