Gravitational wave science of LISA

DISCRETE 2022
October 9th, 2022

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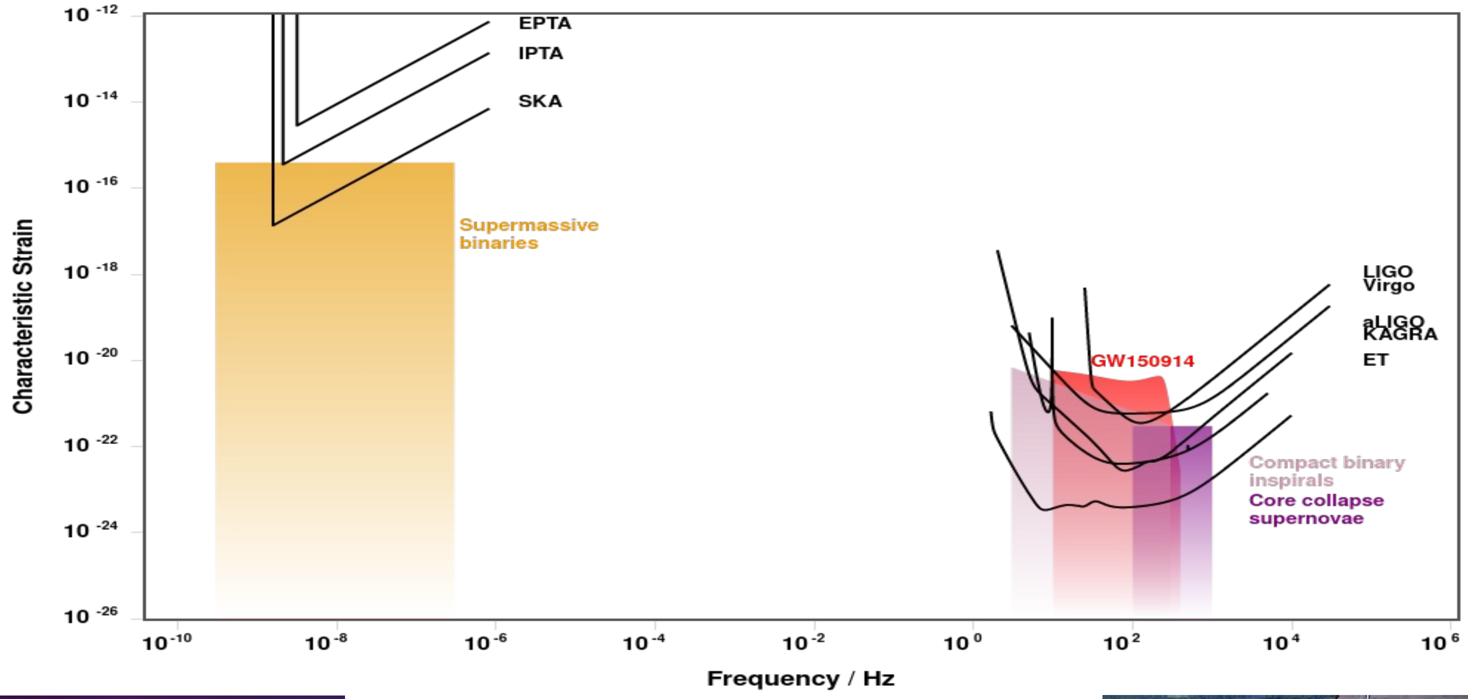
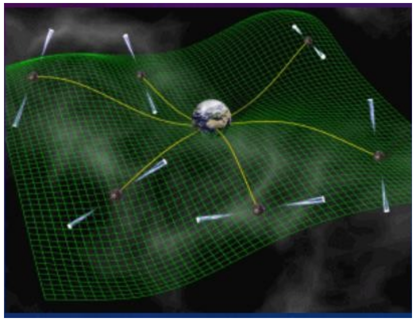
LISA CONSORTIUM

Existing Gravitational Waves Detectors

Pulsar timing arrays: GWs with 10^{-9}–10^{-6} Hz

Ground-based interferometers: GWs with 10^{0}–10^{4} Hz





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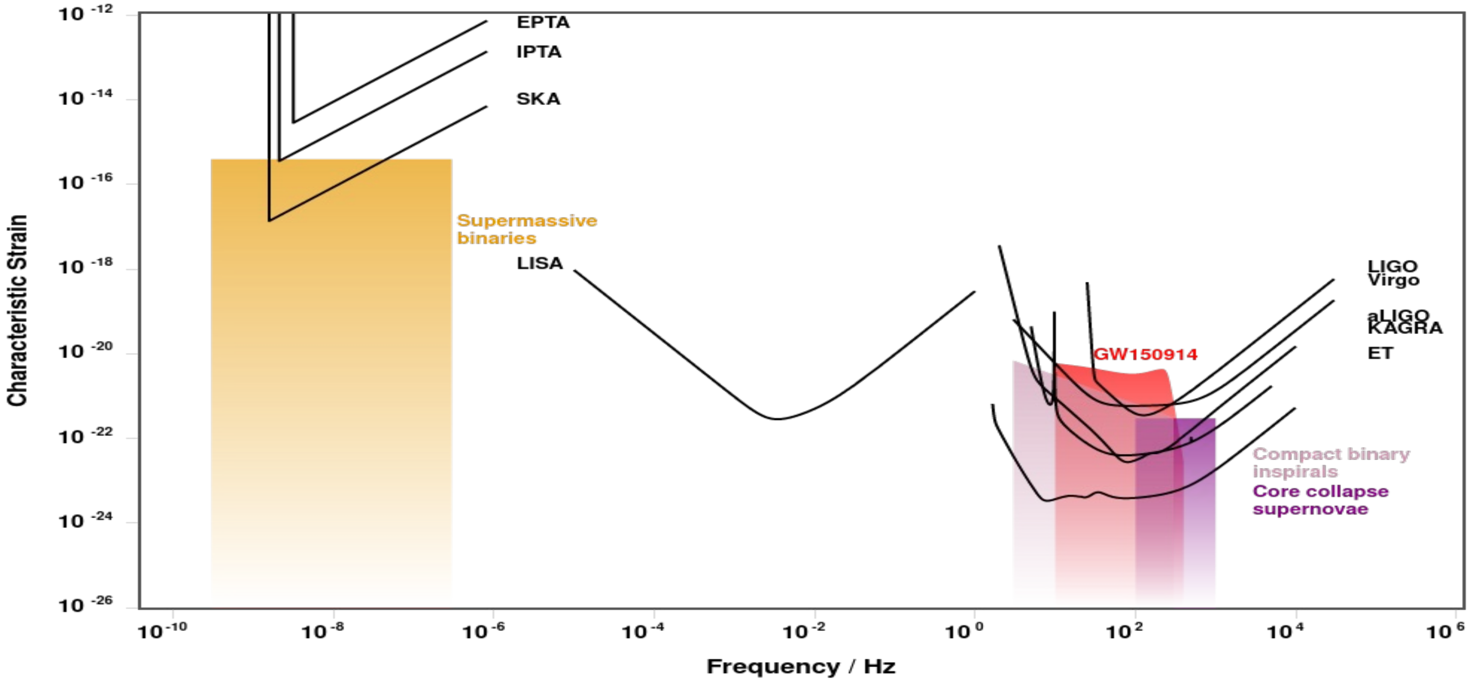
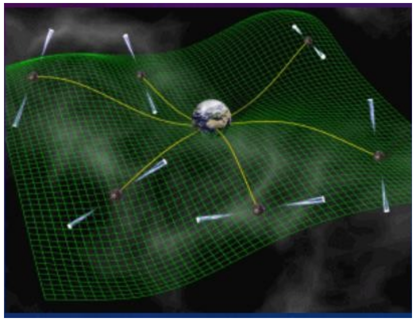
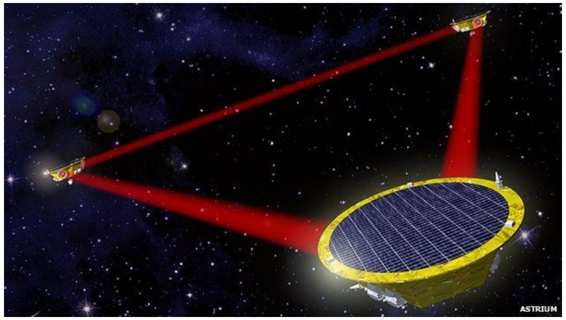
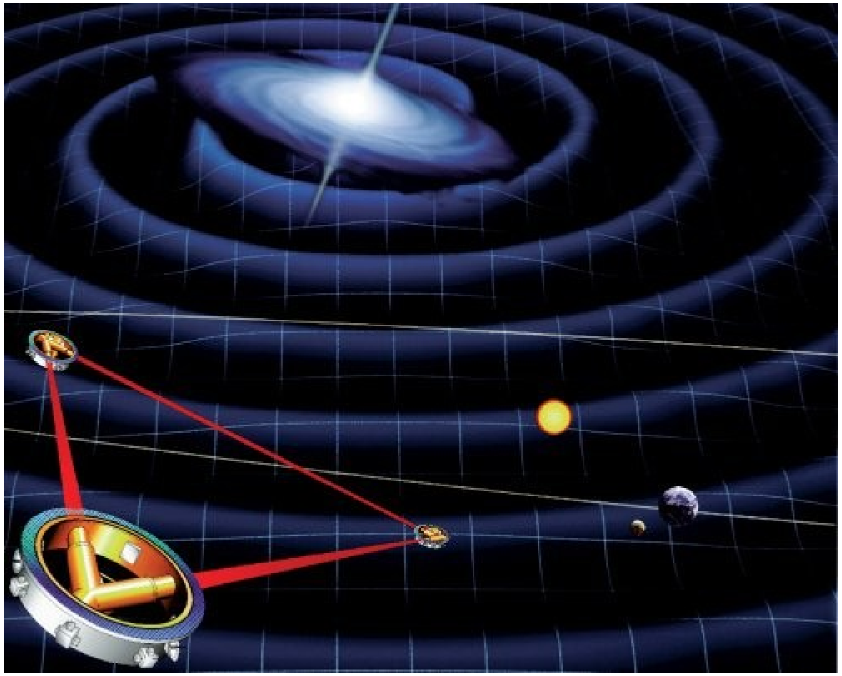
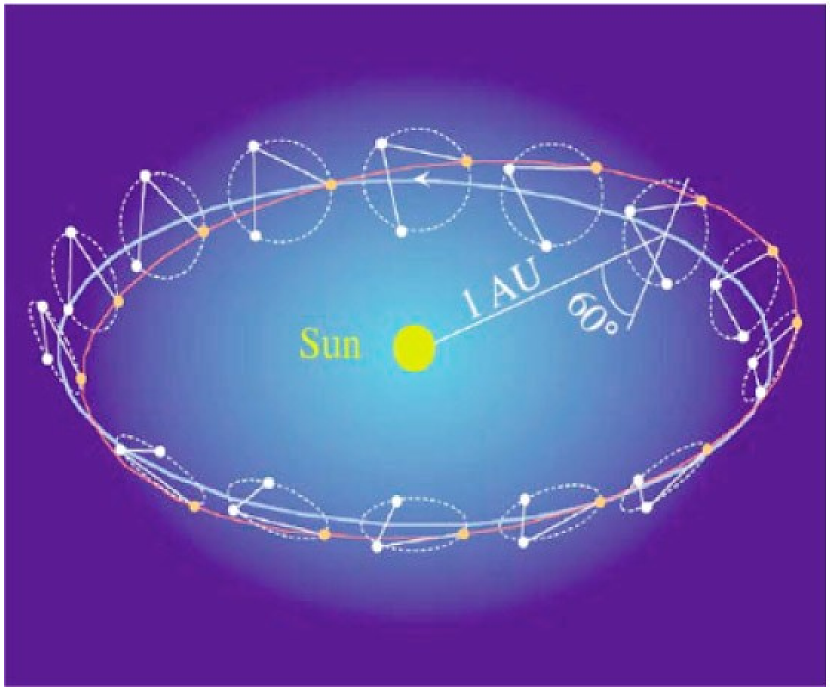






Laser Interferometer Space Antenna (LISA)

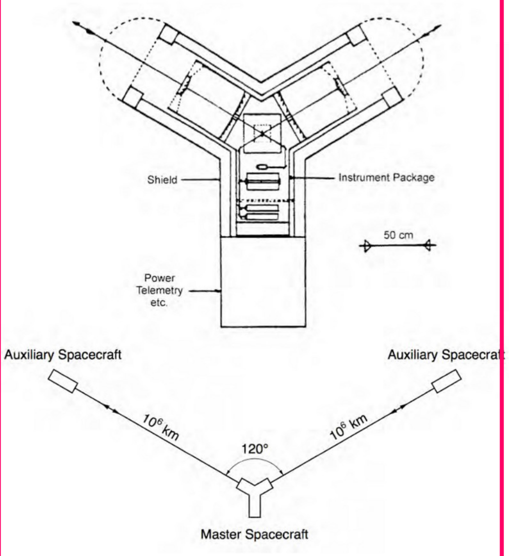




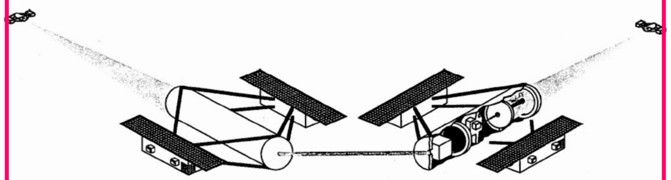
- LISA is kind of a scaled-up version of two LIGO detectors
- Three arms that are 2.5 million km long, with free-falling masses at their extrema
- The relative displacements of free-fall masses at L1 are measured by means of laser interferometry
- A GW passing through LISA displaces the free-fall masses
- Taking data for at least 4 (but expected ~10) years

LISA: a long story of ideas and efforts

1981: LAGOS

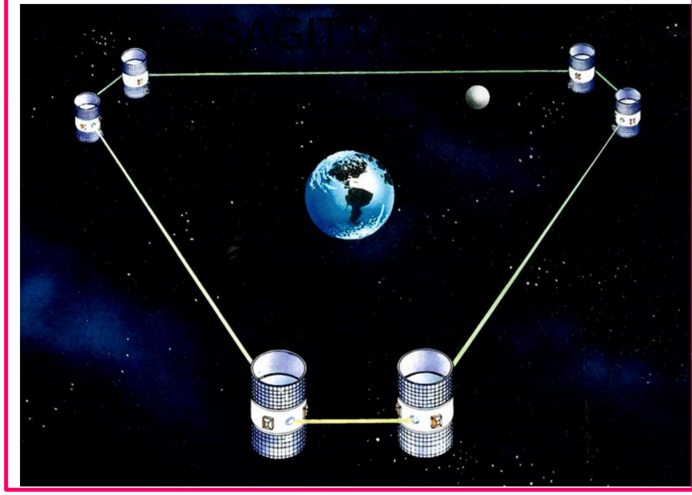


1983: LISA

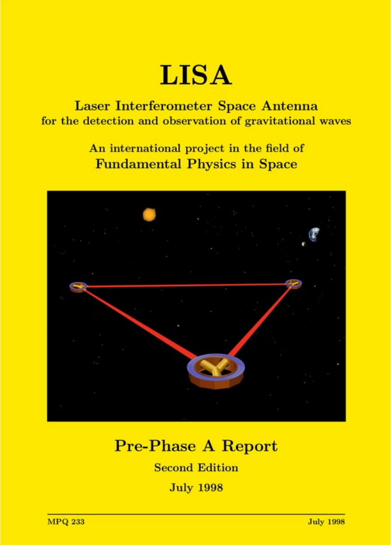


1993: SAGITTARIUS

Spaceborne Astronomical Gw Interferometer To Test Aspects of Relativity and Investigate Unknown Sources



1998: LISA


LISA

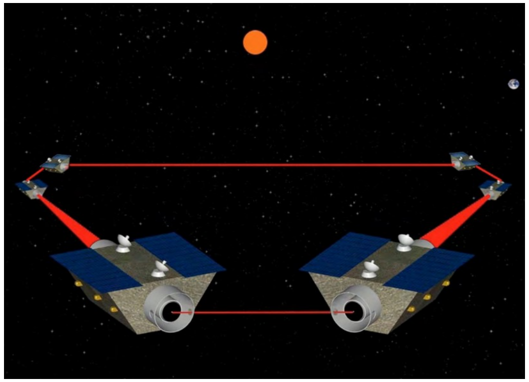
Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

An international project in the field of
Fundamental Physics in Space

Pre-Phase A Report
Second Edition
July 1998

MPQ 233 July 1998

1993: LISAG



- LIGO in space with Gm-long arms
- LIGO mirrors replaced by free falling masses
- Relative displacements of the masses measured by means of interferometry

LISA: recent past

Series of papers "Science with the space-based interferometer eLISA/LISA"

ESA selects L3 science theme:

"The Gravitational Universe"

2013

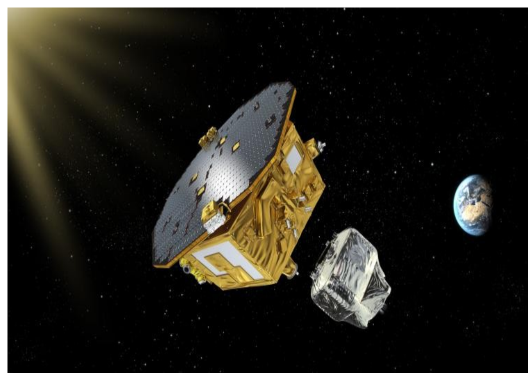
2016

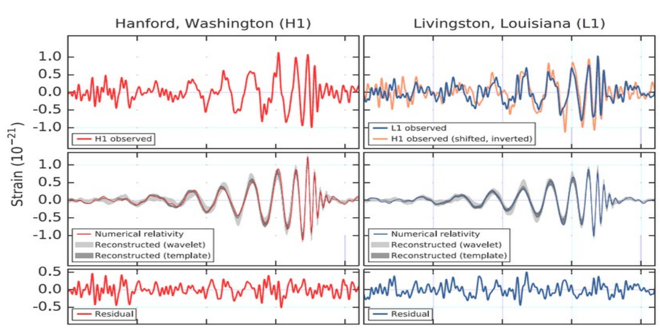
Results from LISA PathFinder

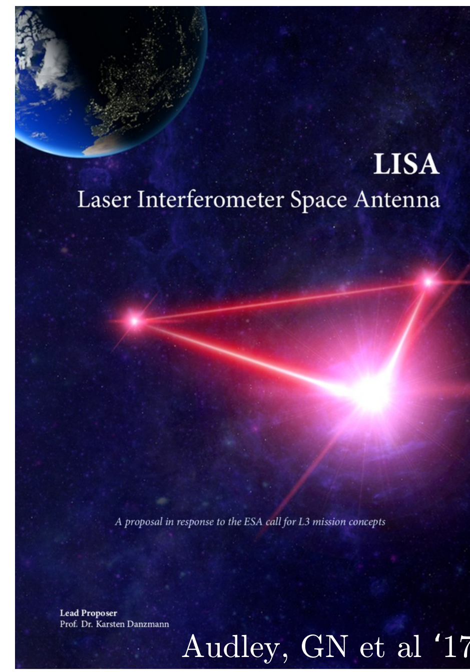
& GW150914 announcement

ESA L3 call

2017

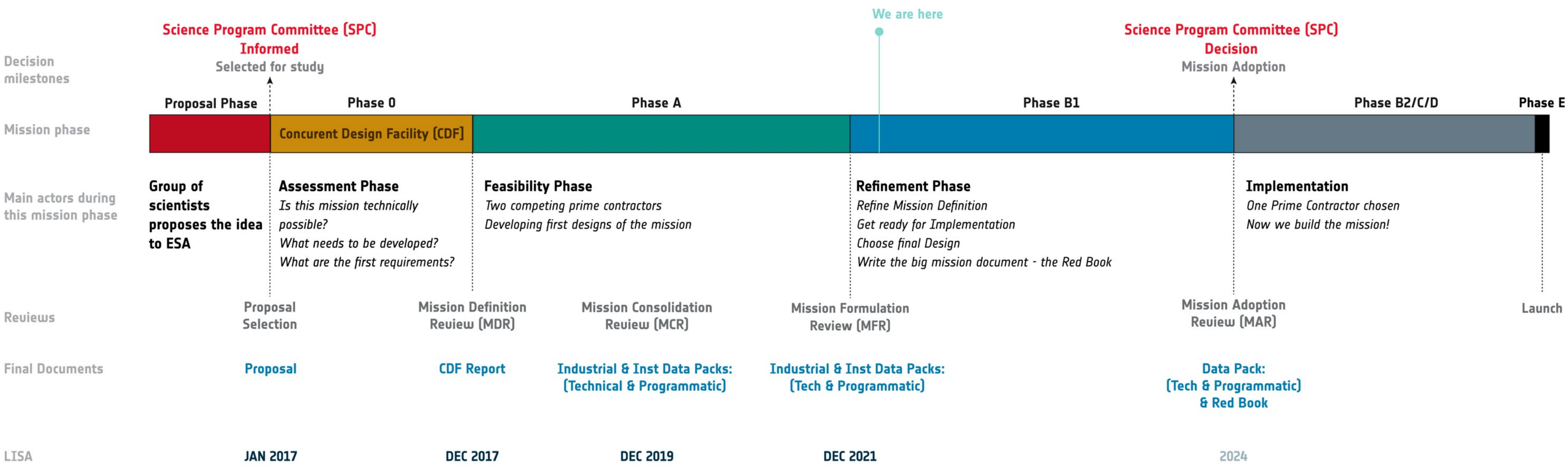






Audley, GN et al '17

LISA: present



Configuration:
3 arms (not 2)

Mission duration:
4 years / duty cycle

P.Amaone, GN et al. '21

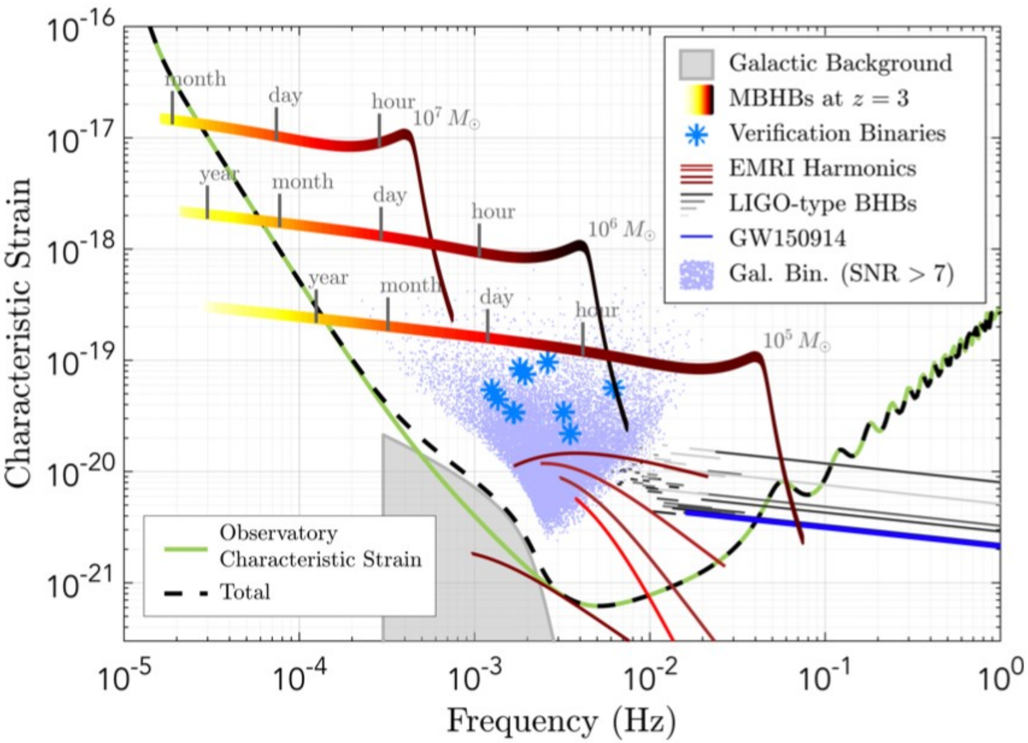
Red Book:
Science objectives defined as mission requirements (Figures of Merit)

Low-freq. sensitivity:
No strong requirement at f < 0.1 mHz

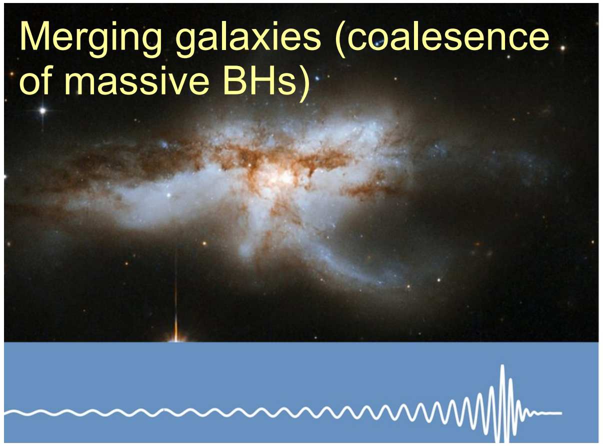
P.Amaone, GN et al., to appear

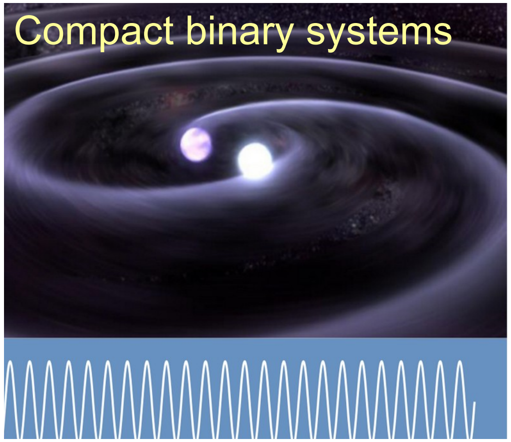
ESA - countries multilateral agreements

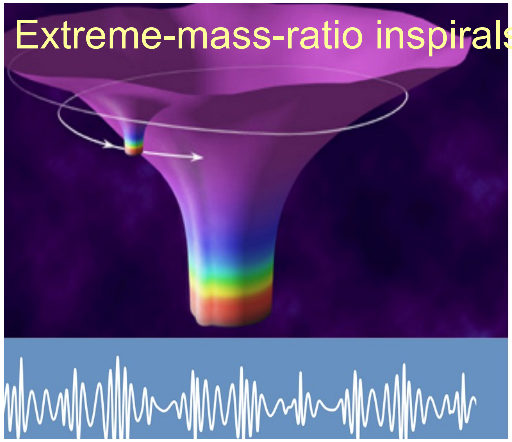
Astrophysical sources in LISA



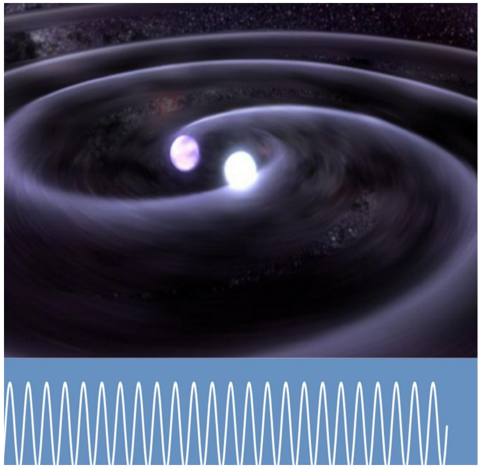
- O(10^4) resolv. galac. binaries
- Extragal. BBHs of 10^0–10^2 $M_\odot$
- Extreme mass-ratio inspirals
- Merging BBHs of 10^4–10^8 $M_\odot$

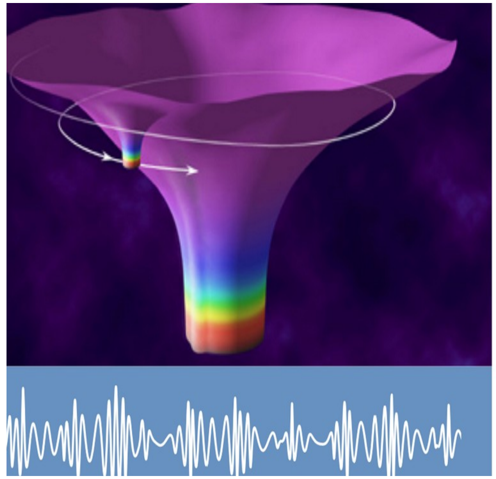


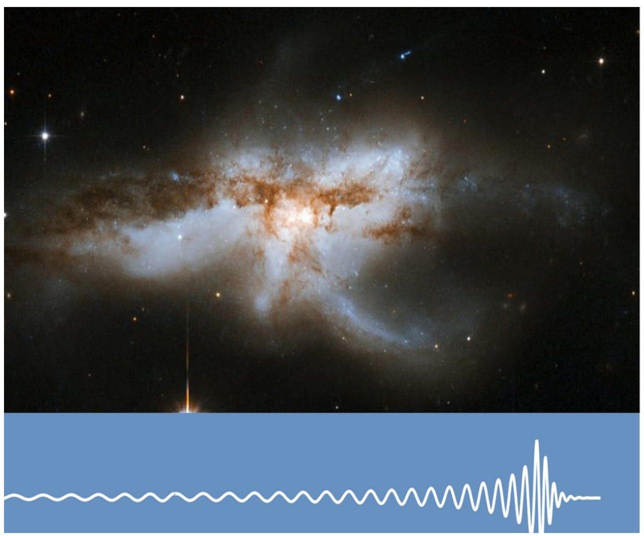




Science objectives







- Formation and evolution of the astro. population
- Primordial black holes ?
- BBH signatures of DM ?
- Tests of GR
- Measurement of cosmol. parameters
- Characterize the stochastic GW background (SGWB)

No science objective “surprises” but reasonably prepared to them

What is a SGWB signal ?

- GW plane expansion: $h_{ij}(\mathbf{x},t) = \sum_{A=+,\times} \int_{-\infty}^{+\infty} df \int d^2\mathbf{n}\, \tilde{h}_A(f,\mathbf{n}) e_{ij}^A(\mathbf{n}) e^{-2\pi i f(t-\mathbf{n}\cdot\mathbf{x}/c)}$

- For a SGWB:
  - $i,j = 1,2,3$ because from everywhere
  - $\tilde{h}_A(f,\mathbf{n})$ random variable

- Contrary to a point-like GW source:
  - $i,j = 1,2$ because orthogonal to $\mathbf{n}$
  - $\tilde{h}_A(f,\mathbf{n})$ waveform in fr. domain

- Primordial SGWB sources (typically !!!) lead to Gaussian, stationary, isotropic and unpolarized, i.e.:
  - $\tilde{h}_A(f,\mathbf{n})$ is a Gaussian random variable
  - $\langle \tilde{h}_A^*(f,\mathbf{n}) \tilde{h}_{A'}(f',\mathbf{n}') \rangle = \# \delta(f-f') \delta^2(\mathbf{n},\mathbf{n}') \delta_{AA'} S_h(f)$ ← *Strain PSD [1/Hz]*

- SGWB energy density spectrum:

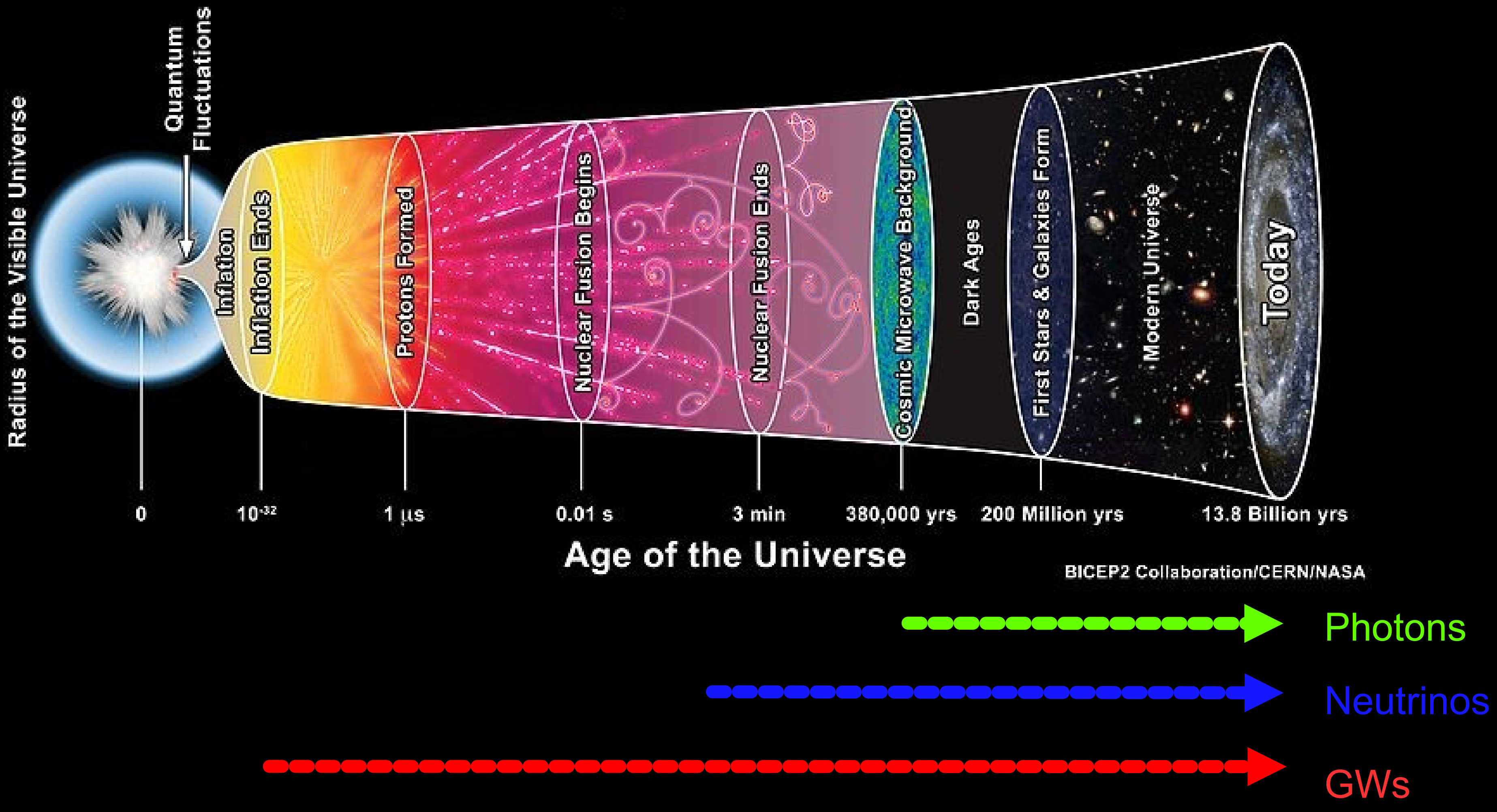
$$\frac{\rho_{GW}}{\rho_c} = \frac{c^2}{32\pi G} \langle \dot{h}_{ij} \dot{h}^{ij} \rangle = \frac{\pi c^2}{2G\rho_c} \int_{-\infty}^{+\infty} d(\log f) f^3 S_h(f) = \int_{-\infty}^{+\infty} d(\log f) \frac{d\rho_{GW}}{\rho_c d(\log f)}$$

$$\Omega_{GW}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{GW}}{\rho_c d(\log f)} = \frac{4\pi^2}{3H_0^2} f^3 S_h(f)$$

$$h_c(f) = \sqrt{f S_h(f)}$$

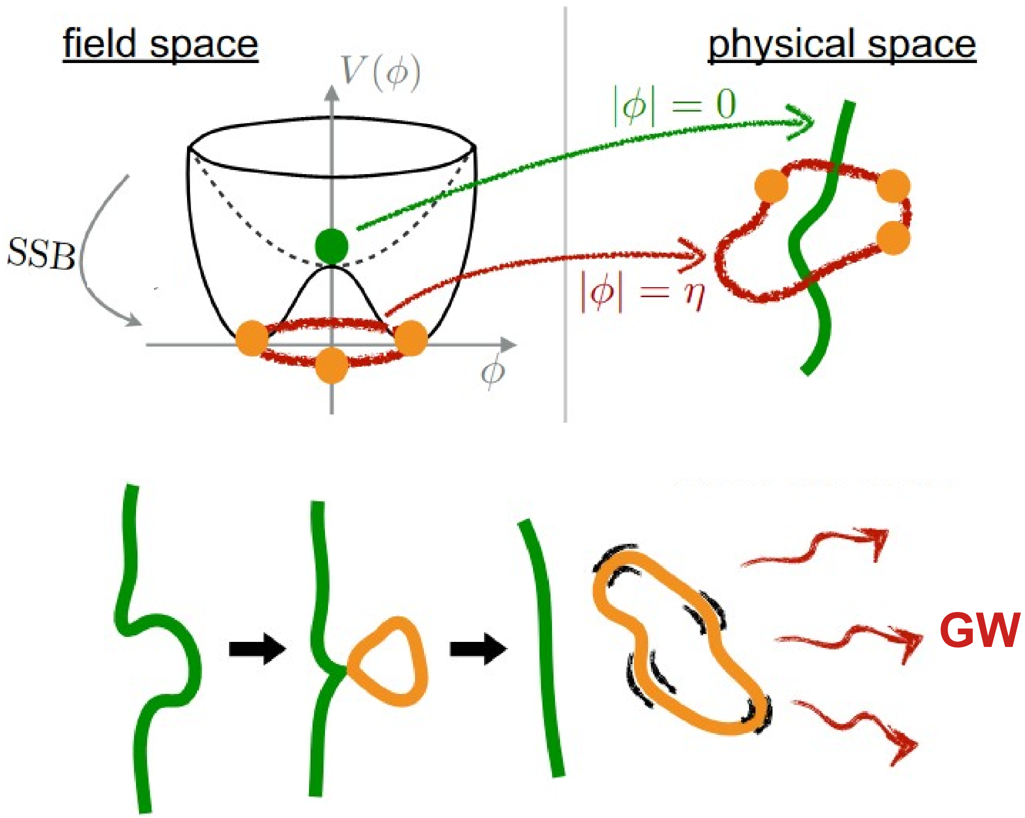
Characteristic strain

Why is a SGWB detection exciting?

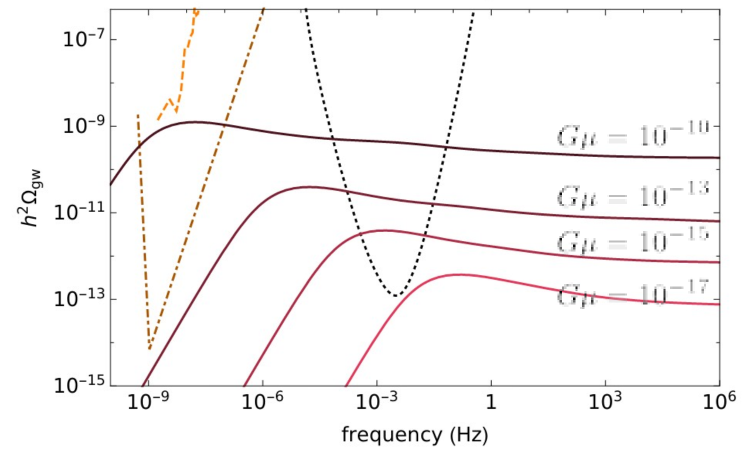


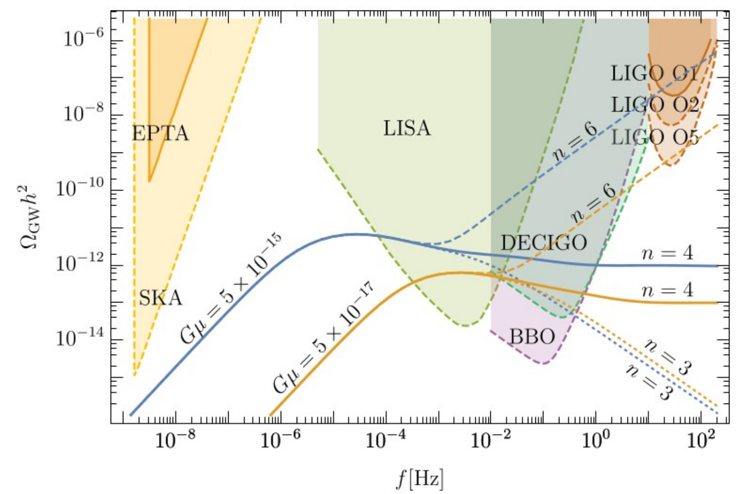
SGWB from cosmic strings

Cosmic strings: stable 1-dim. topological objects from (topologically non-trivial) spontaneous symmetry breakings



[credits: P. Simakachorn]

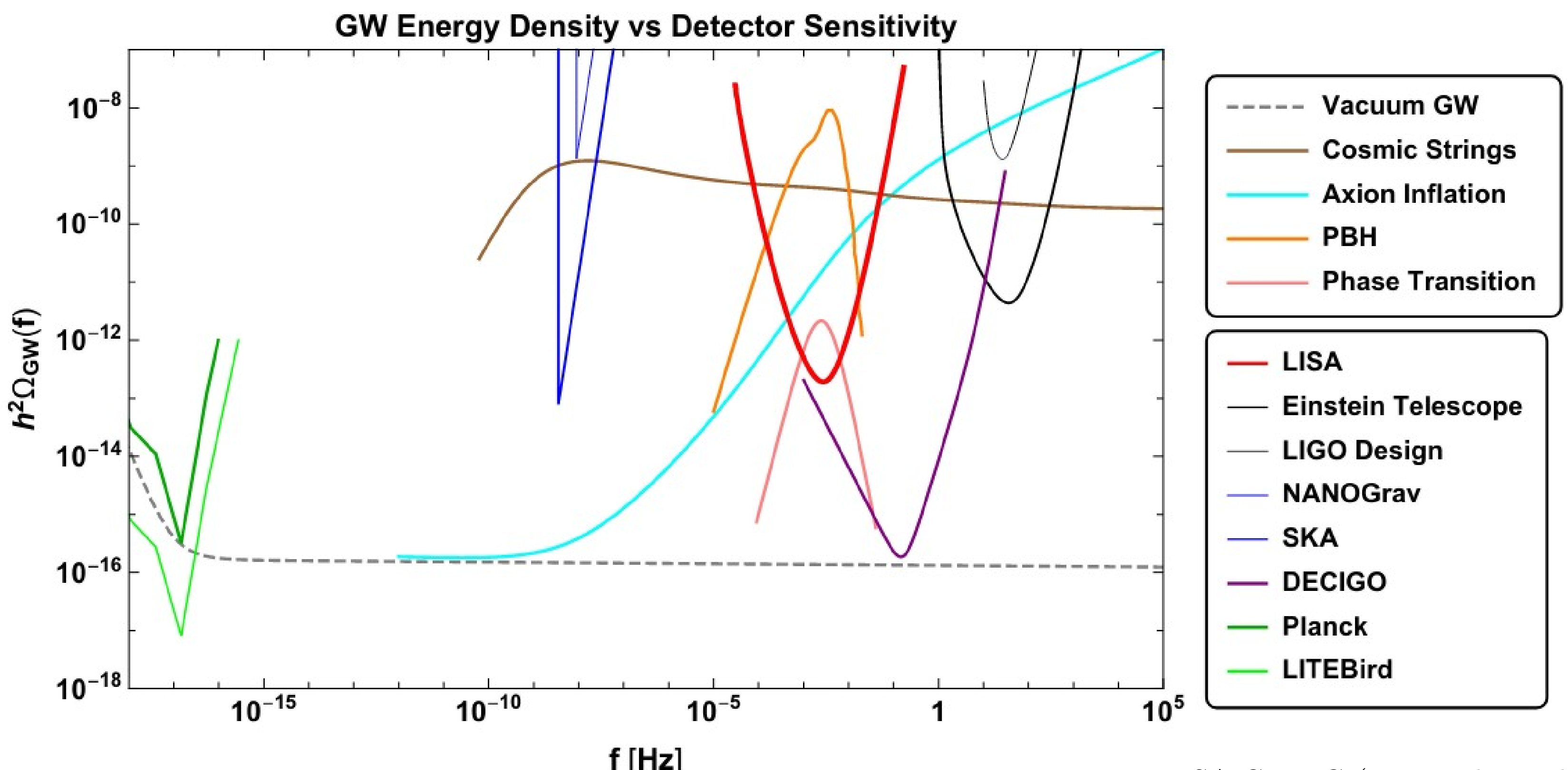




LISA CosWG (P.Auclair et al.) '19
LISA CosWG (P.Auclair et al.) '22

SGWB from the inflationary epoch

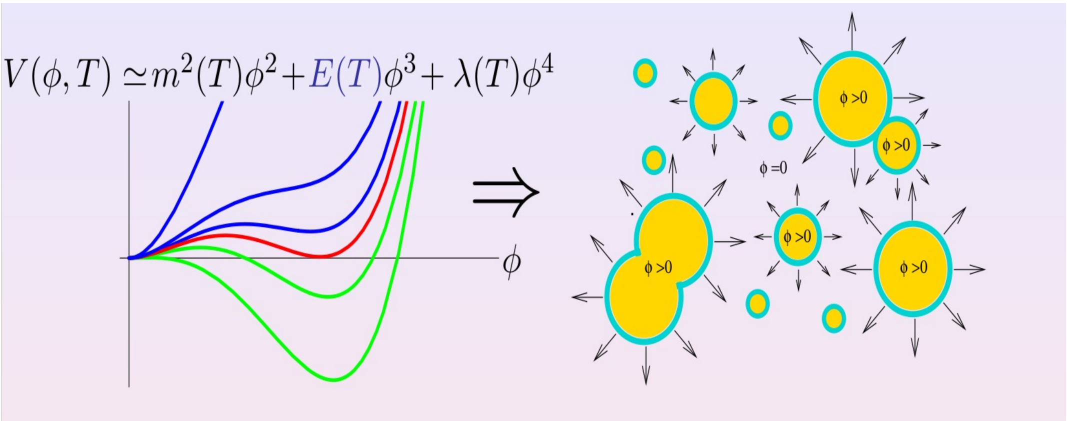
- **Inflation**: standard single-field slow-roll, inflation with spectators, preheating, … very model dependent!
  - Signal from vanilla scenario is very small

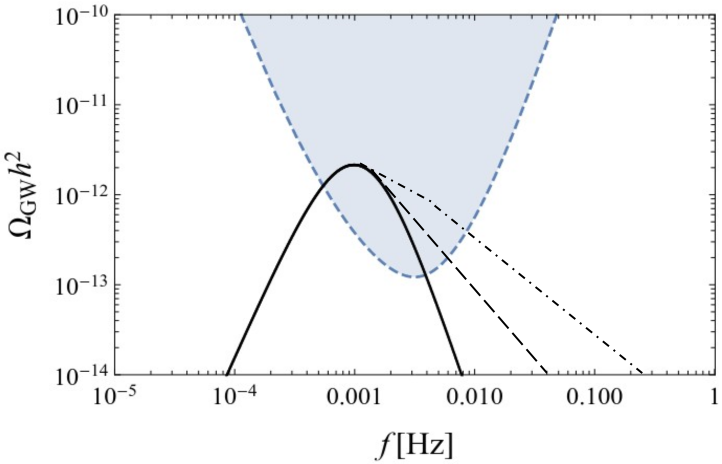


LISA CosWG (N.Bartolo et al.) '18
LISA CosWG (C. Contaldi et al.) '20
LISA CosWG (P.Auclair et al.) '22

First-order phase transition

First-order phase transitions: bubbles produced in spontaneous symmetry breakings via tunnelings or thermal jumps





<u>Parameters</u>:

α : approx. max. energy that can be converted in GW radiation

β/H : duration of the phase transition

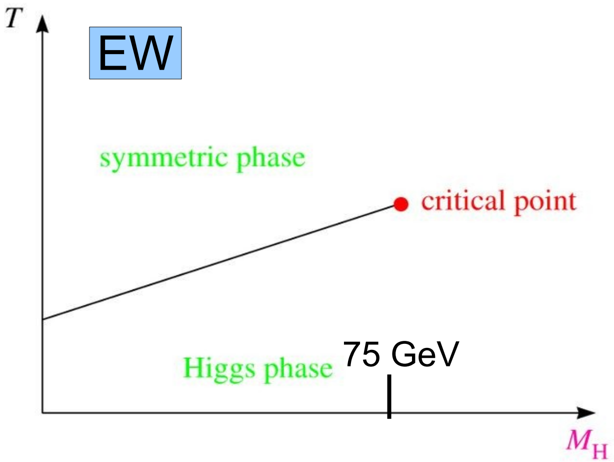
T_* : universe temperature when bubbles collide

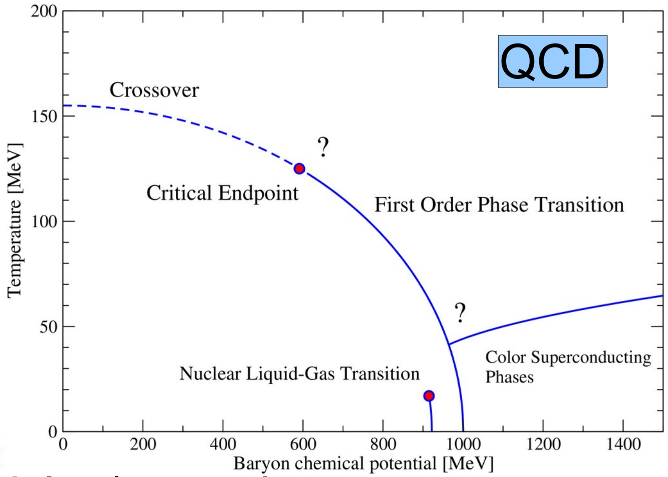
v_w : bubble wall velocity

κ_i : efficiency factor of each contribution (bubble wall, sound wave, turbulence)

LISA CosWG (C.Caprini et al.) '15
LISA CosWG (C. Caprini et al.) '19
LISA CosWG (P.Auclair et al.) '22

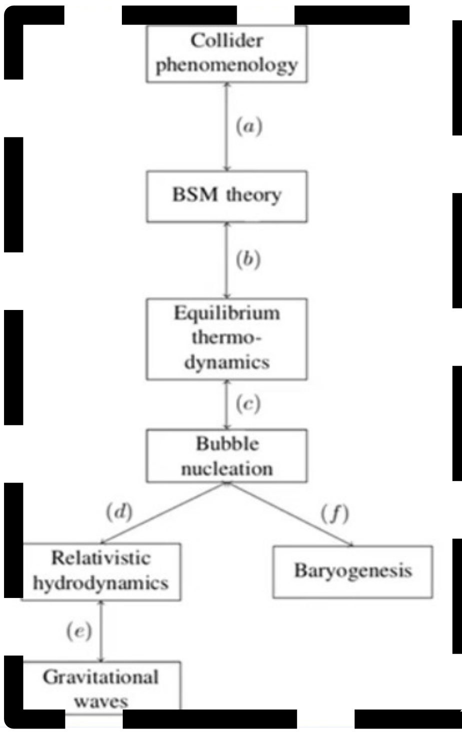
Model building for SGWB





Kajantie et al. '96
Karsh,Neuhaus,Patkos '96
Csikor,Fodor,Hietger '98

Gunkel et al. '21
Wigas, Oldengott + Bielefeld '18



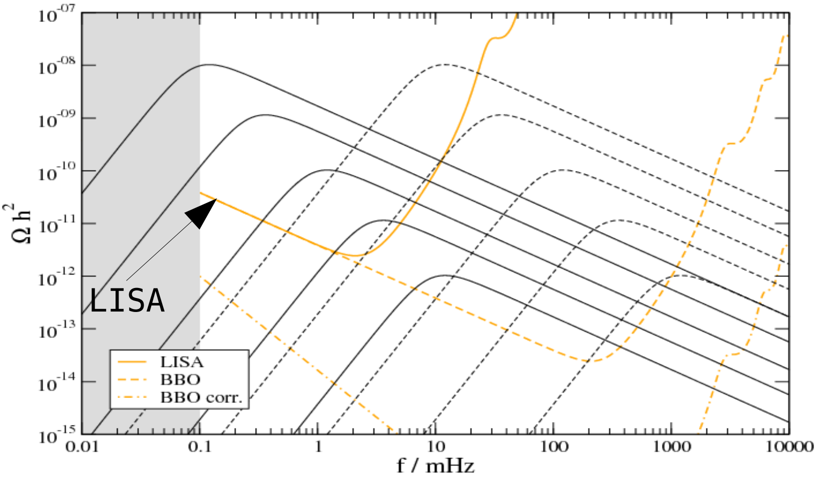
- No FOPT in the SM of particles/cosmology
- Conceivable in hidden sectors (see Biermann's talk), at high scales, or EW extensions (see Costa's talk)
- For EW extensions, need for a barrier via temp. radiative corrections or/and dynamical fields. New TeV-scale scalars

Some rationales:

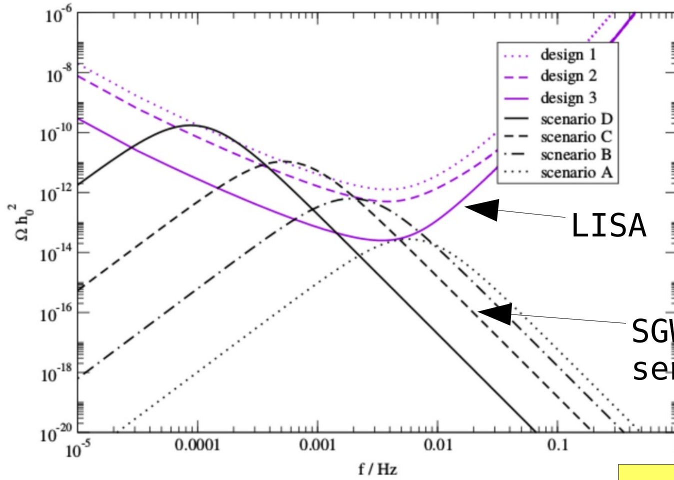
- New color fields → Large T effects but also Higgs gluon fusion changes
- New dynamical scalar fields → Mixing → Higgs signal strengths
- New fermions → no large T-effects (read: no barrier → no 1st order)
- Very heavy fields → Boltzmann suppressed and small low-energy effects

Some scenarios with EW first-order transitions

First order in Randall Sundrum

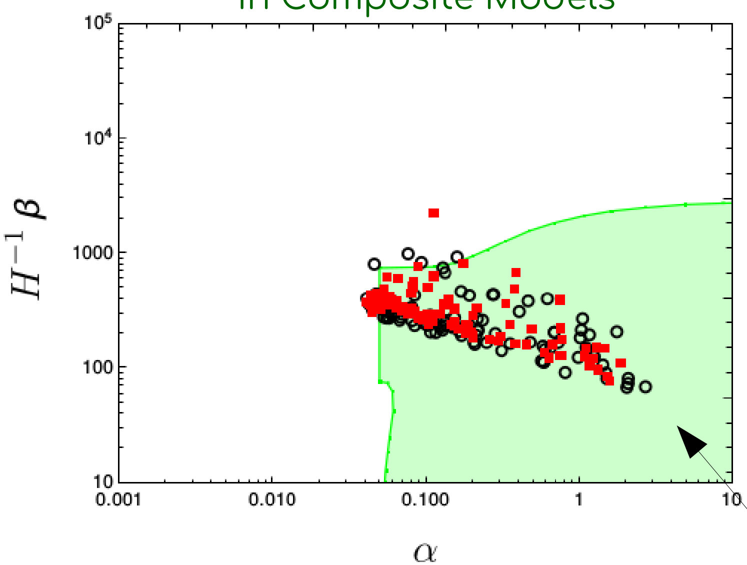


First order in SUSY

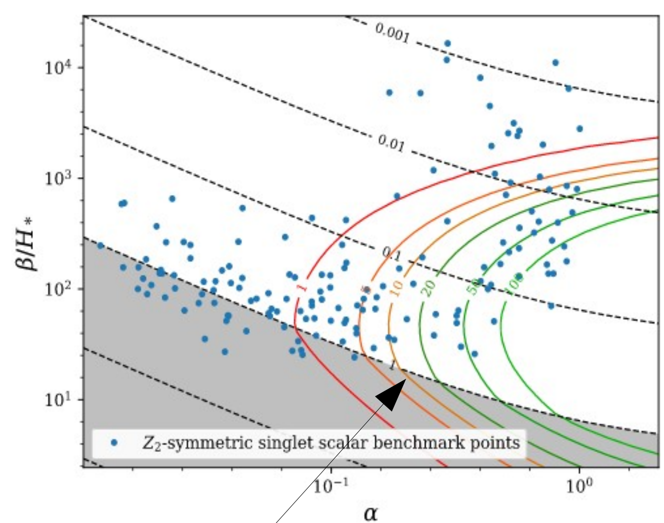


Complementarity with LHC, FCC, ...

First order in Composite Models



First order in Z2 singlet

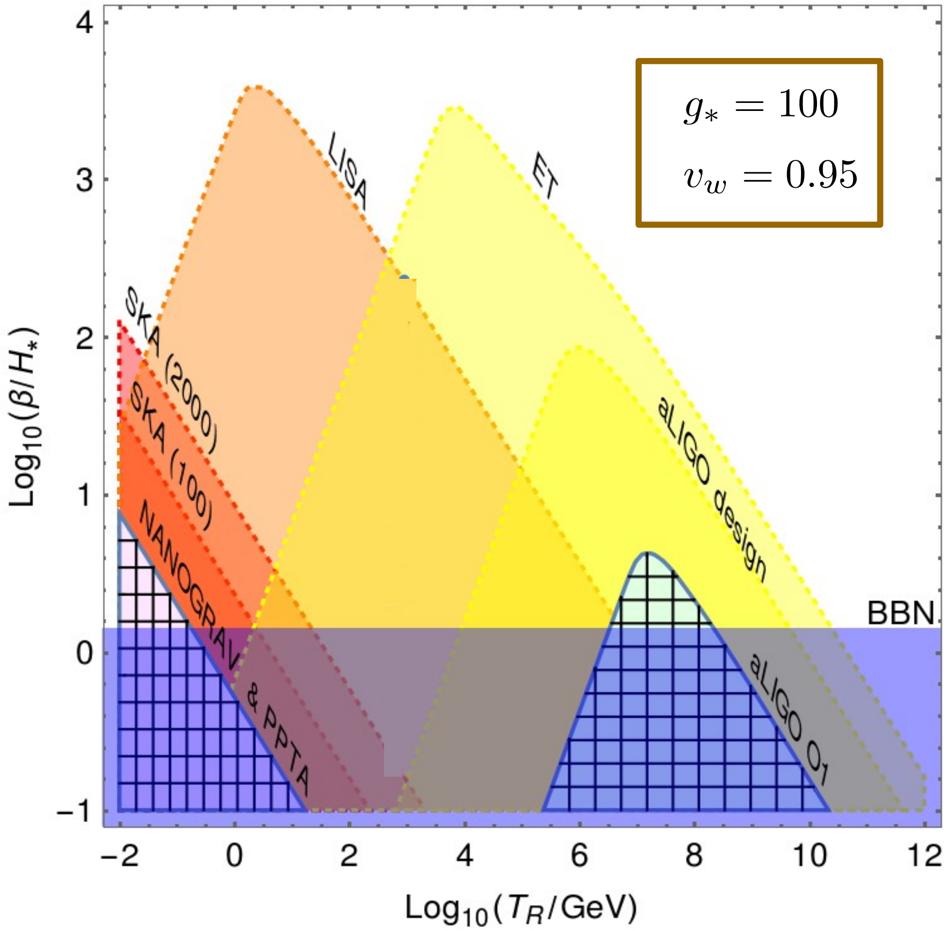


Besides Biermann Costa's talks!

Figs. from:
Konstandin, GN et al.'10
Huber, GN et al.'15
Chala, GN et al.'16

More examples in:
LISA CosWG (Caprini et al.)'16
LISA CosWG (Caprini et al.)'20

1st-Order-PT parameter space "within sensitivity"



E. Megias, GN, M. Quiros, '18
LISA CosWG (P. Auclair et al.) '22

Synergies among GW detectors

<u>Parameters</u>:

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β/H : duration of the phase transition

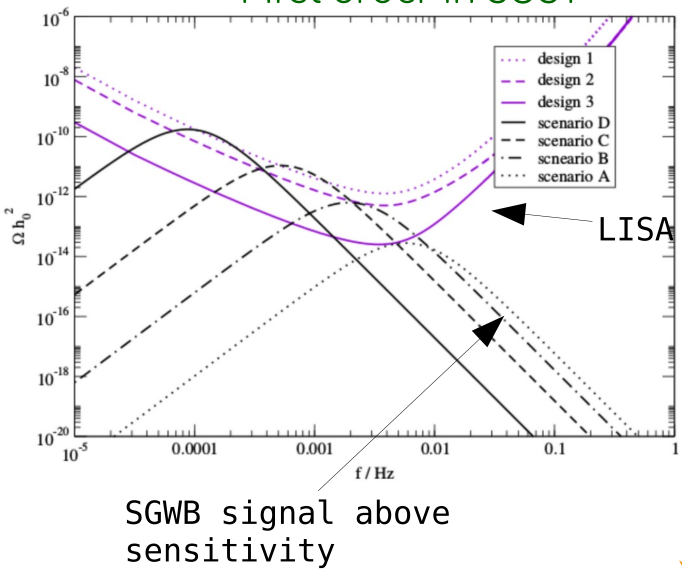
T_R : universe temperature when bubbles collide

v_w : bubble wall velocity

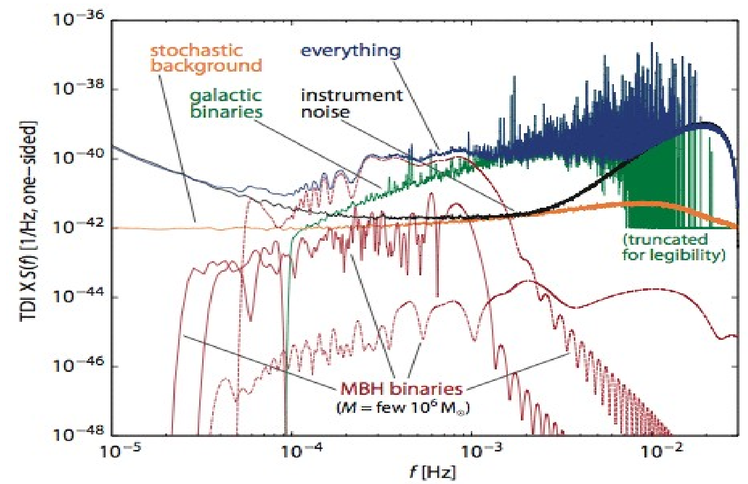
κ_i : efficiency factor of each contribution (**bubble wall**, sound wave, turbulence)

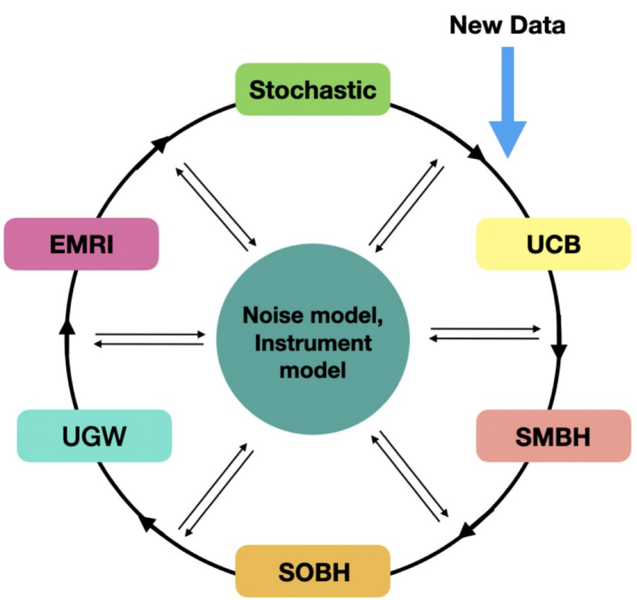
Primordial SGWB signal within sensitivity $\stackrel{?}{=}$ discoverable

First order in SUSY



LISA is a signal-dominated experiment



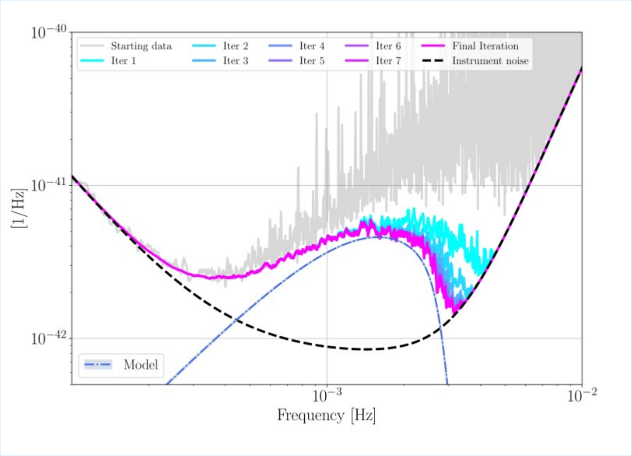


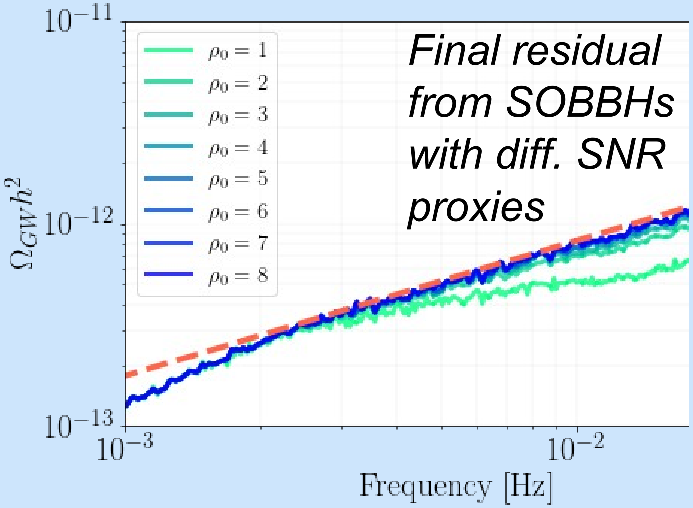
- A primordial SGWB is likely covered by astro. signals localized in time or frequency
- Reconstruct and subtract the astro. signals in the data with their waveforms
- The leftover contains:
  - The (faint) unresolved binaries
  - The instrumental noise
  - The primordial SGWB

“faint unresolvable binaries” constitutes a SGWB

- Use current theory and observations to predict a population
- Make a realization of the population, and obtain its mock data via LISA simulator
- Use SNR as a proxy of the param. reconstruction.
- Iteration of:
  1) Compute the SNR of the loudest binary w.r.t. the overall “signal + instr. noise”
  2) If the SNR above the detection threshold, remove the binary from the data

Iteration steps
+
Final residual from Gal. Binaries





The sum of all the unresolvable binaries looks a random, Gaussian, stationary signal.
Statistically, it is a SGWB

The “instrumental noise” also constitutes a SGWB

- Before launch, the LISA noise is known within some (large) margins

- The noise must be estimated after the instrument is switched on, i.e. from the data containing also the signals

The noise has a Gaussian, stationary component. This mimics a primordial SGWB

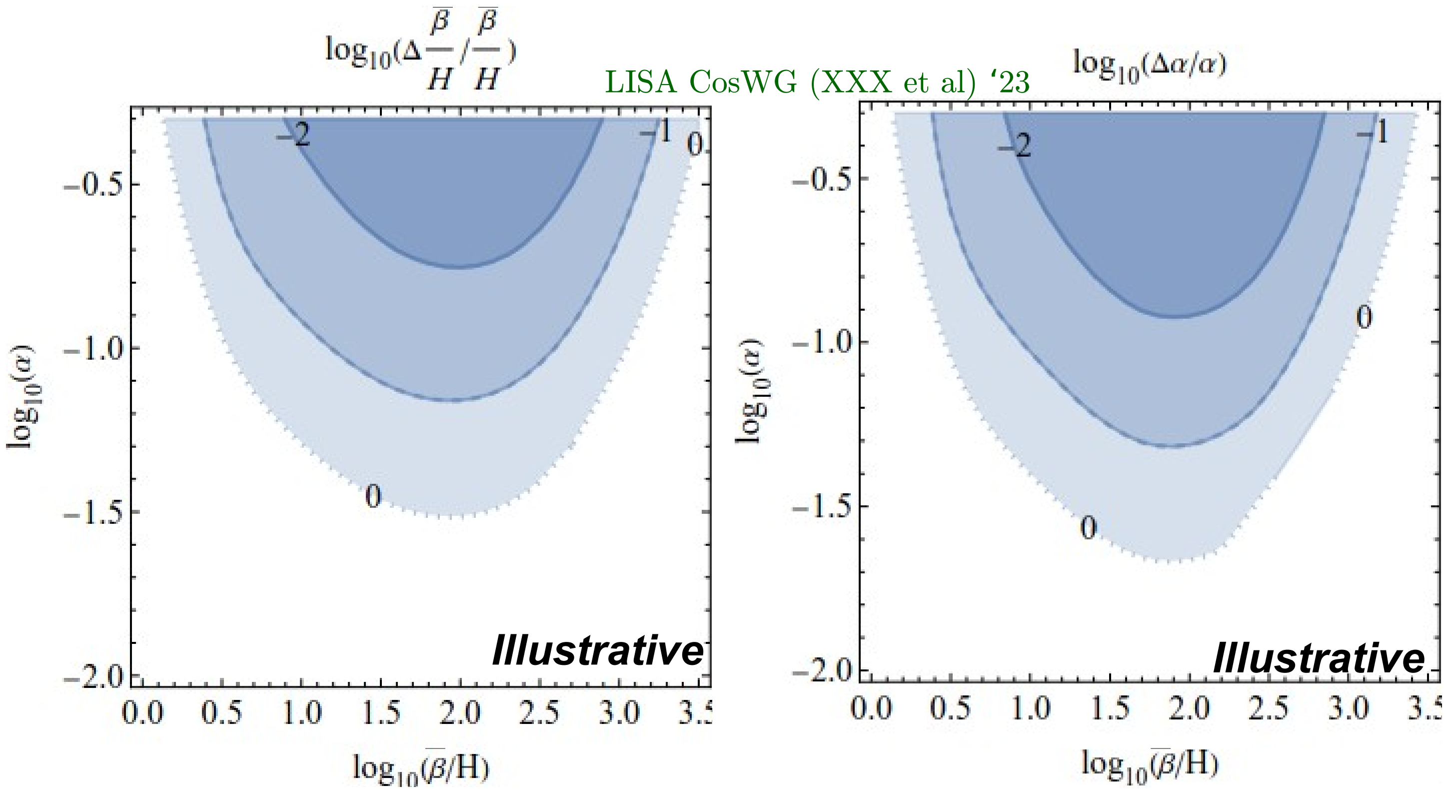
A precise separation of the unresolved-binaries signal, the noise and the primordial SGWB requires to know something else about them.

Identifying the optimal strategy and nailing down its uncertainties/systematics is one of the main scientific goals of the LISA mission

(Targeted) reconstruction forecast & conclusion

If we achieve **reliable templates** of the noise and of the unresolved-binary signal, then 4 years of LISA data may lead to historical breakthroughs:

LISA CosWG (XXX et al) '23



Reasonable phase-transitions lead to SGWBs that can be reconstructed with O(1%) accuracy or better

For other studies, see:
Glowing et al. '22
Boileau et al. '22

but several communities must work together to convert this potential into reality