Gravitational wave science of LISA

CQUeST

Dec 21st, 2022

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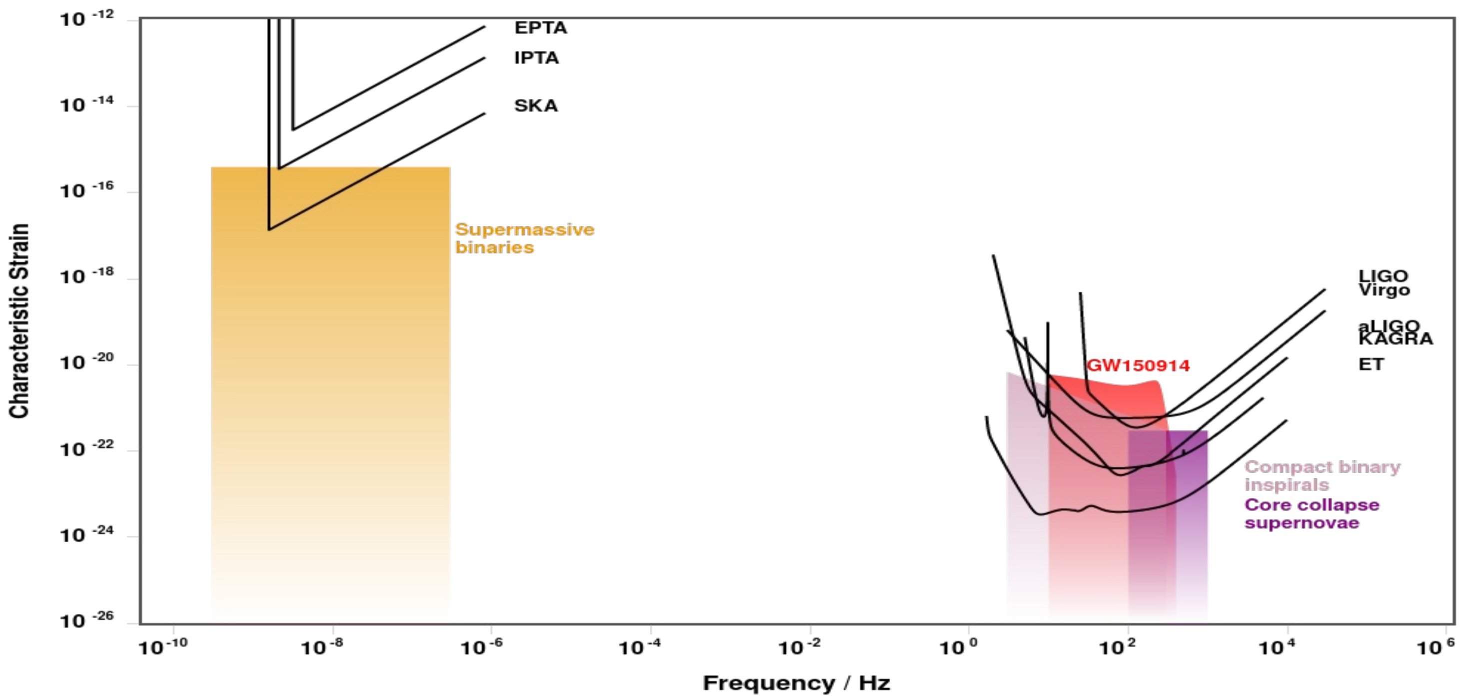
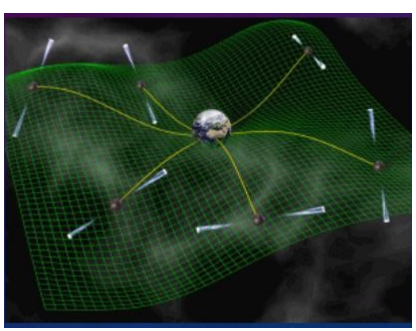
LISA CONSORTIUM

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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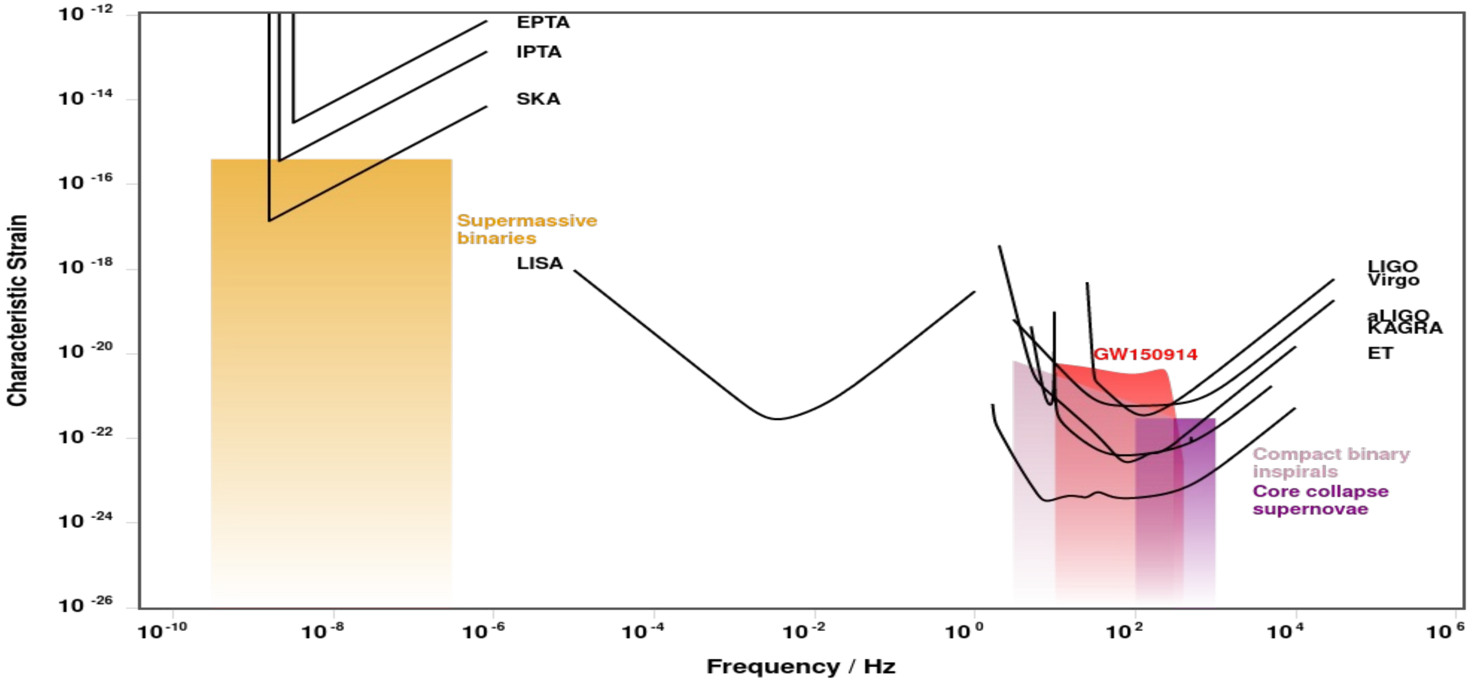
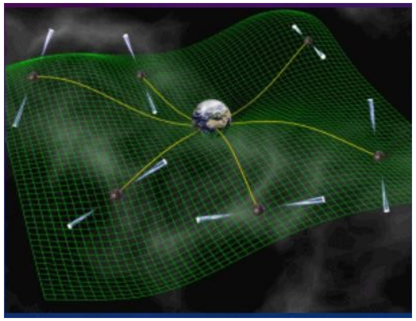
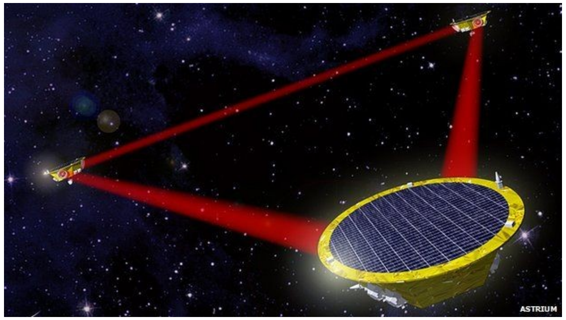
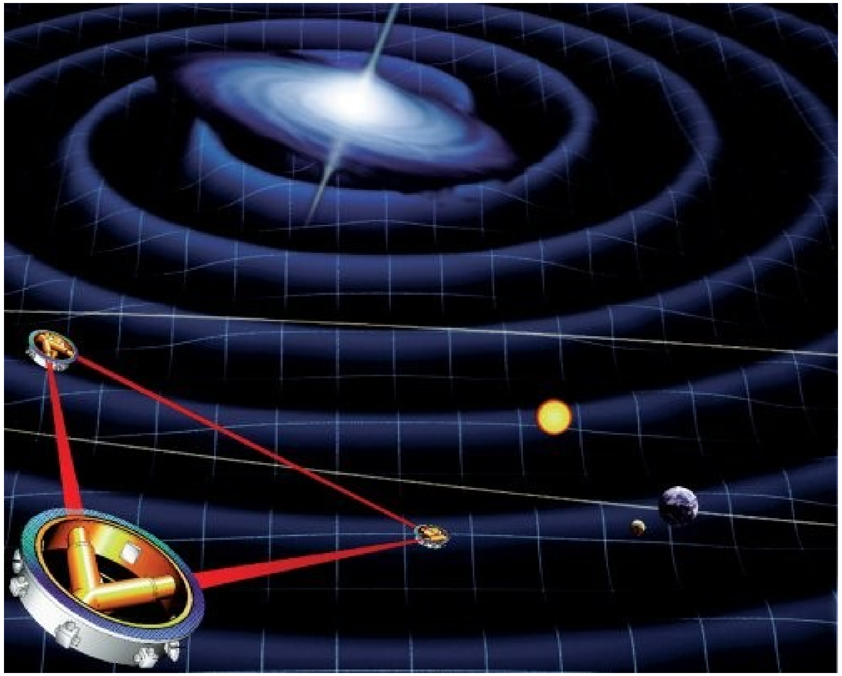
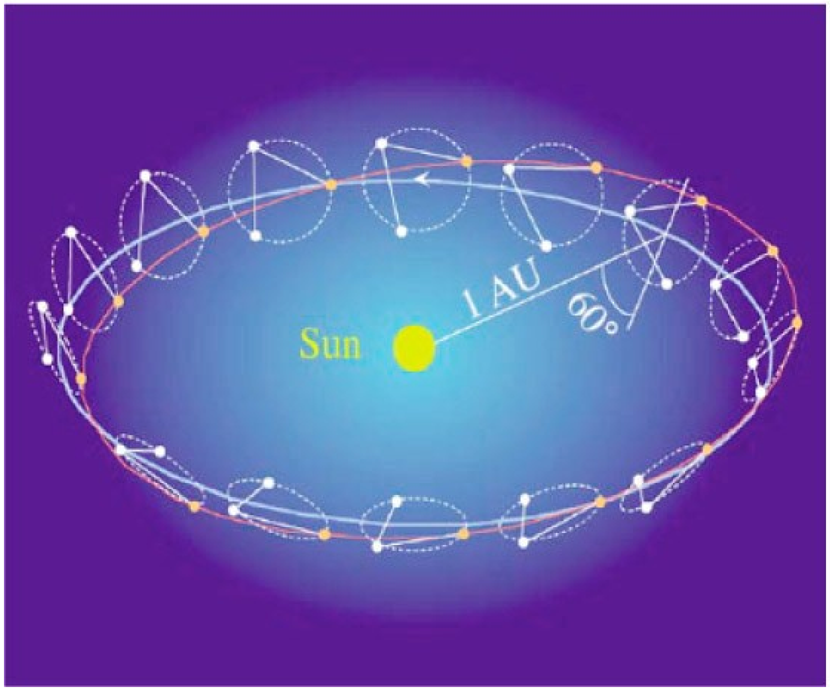






Laser Interferometer Space Antenna (LISA)

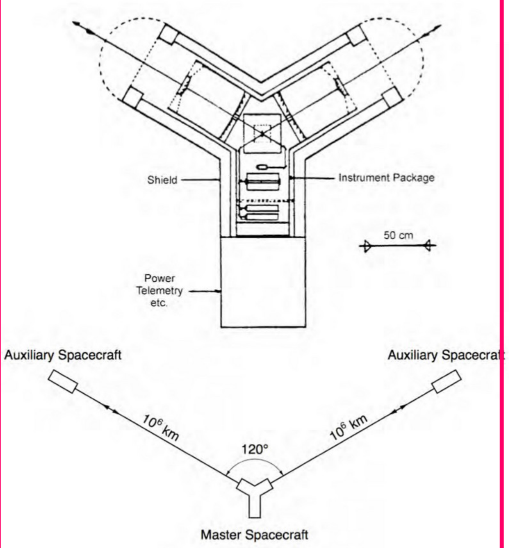




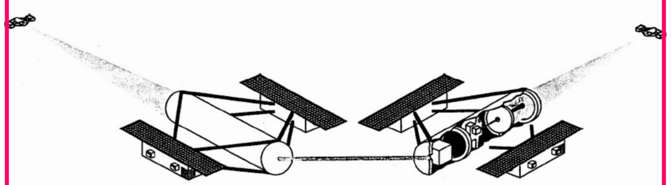
- LISA is kind of a scaled-up version of two LIGO detectors
- Three arms that are 2.5 million km long, with free-falling masses at their extrema
- The relative displacements of free-fall masses at L1 are measured by means of laser interferometry
- A GW passing through LISA displaces the free-fall masses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

LISA: a long story of ideas and efforts

1981: LAGOS

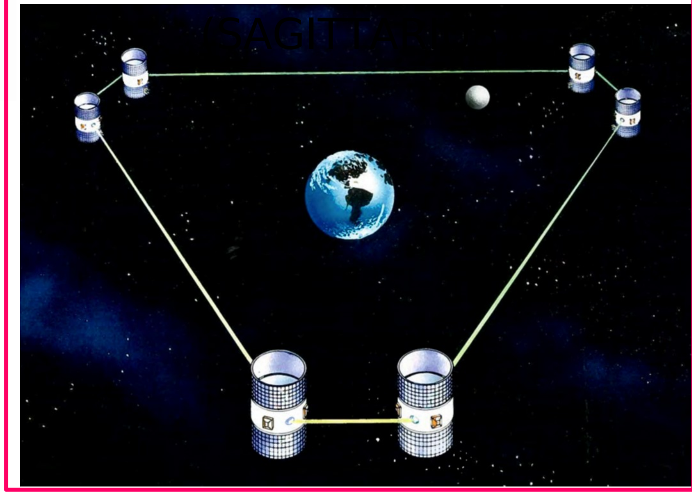


1983: LISA

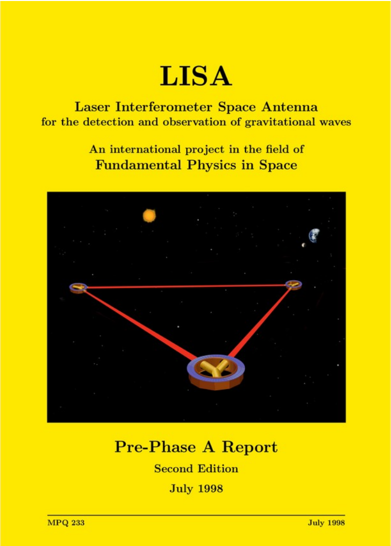


1993: SAGITTARIUS

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



1998: LISA



LISA

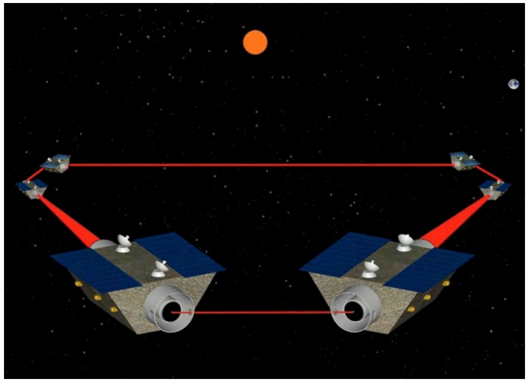
Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

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

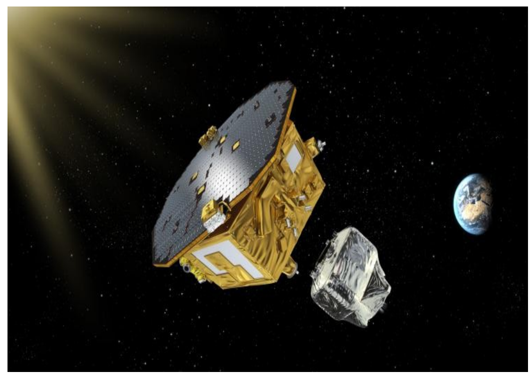
2016

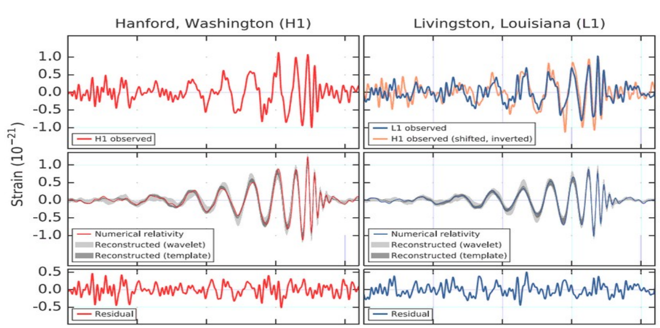
Results from LISA PathFinder

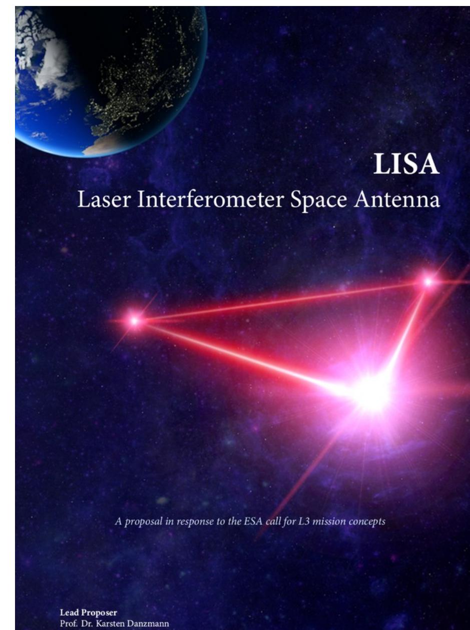
& GW150914 announcement

ESA L3 call

2017

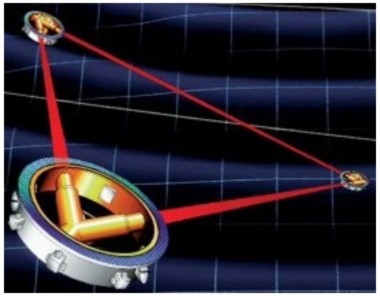






Audley, GN et al '17

LISA PathFinder: feasibility study of LISA technology



Ideal LISA: 1) put masses in free fall

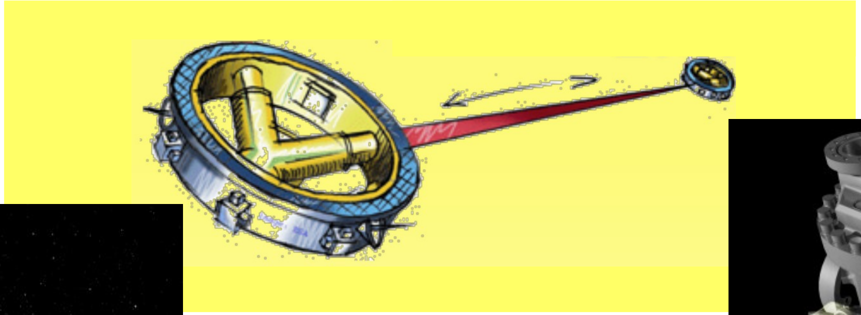
2) perfect interfer. measurement of relative displacement

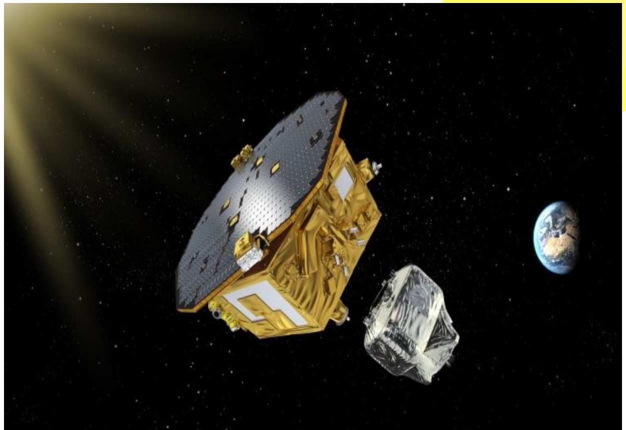
3) perfectly removal of the measurement disturbance

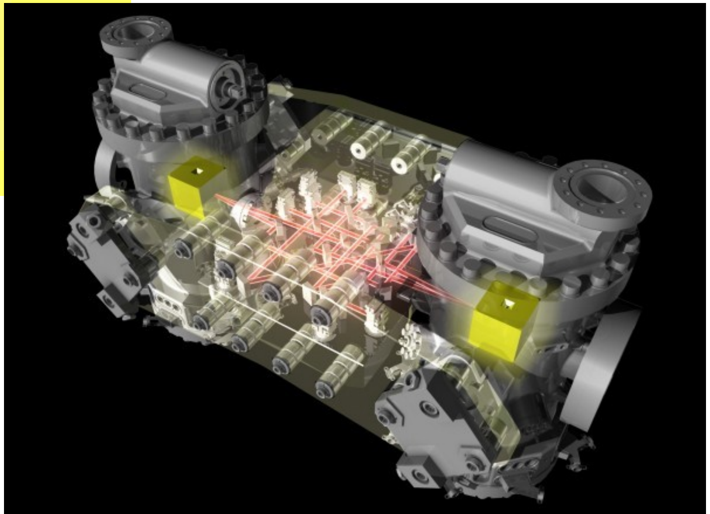
PathFinder: 1) squeeze a LISA arm into a spacecraft

2) put a mass in free fall at our best (and a mass fixed to the aircraft)

3) measure their relative displacement via interferometry at our best, with subtraction of the measurement disturbances (shot noise, etc...)



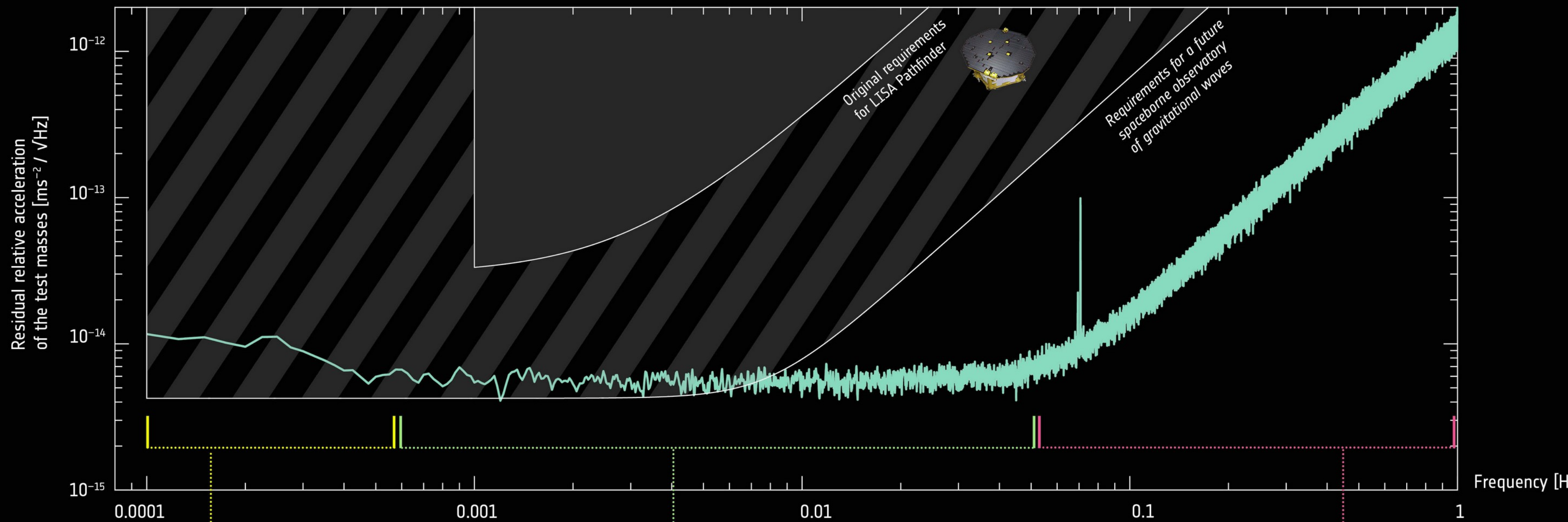




LISA PathFinder (2016 result)

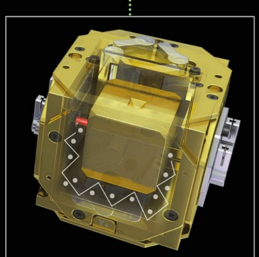
...and 2017 data even better
M.Armano et al., PRL 120 (2018)

➔ LISA PATHFINDER EXCEEDS EXPECTATIONS



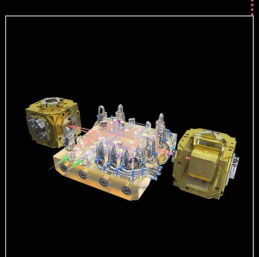
Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.



Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.



Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

www.esa.int

Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

European Space Agency

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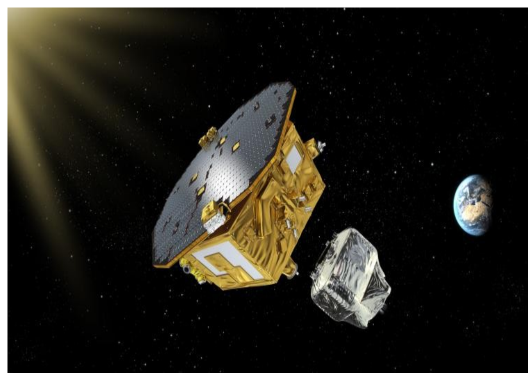
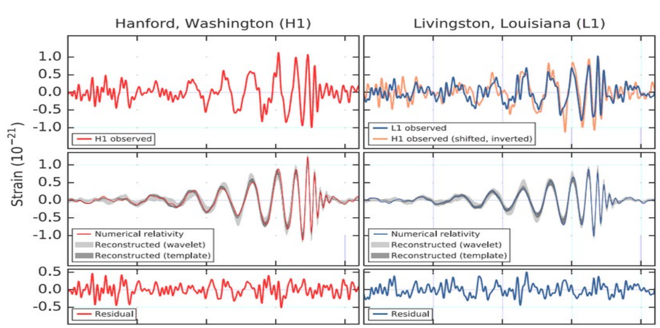
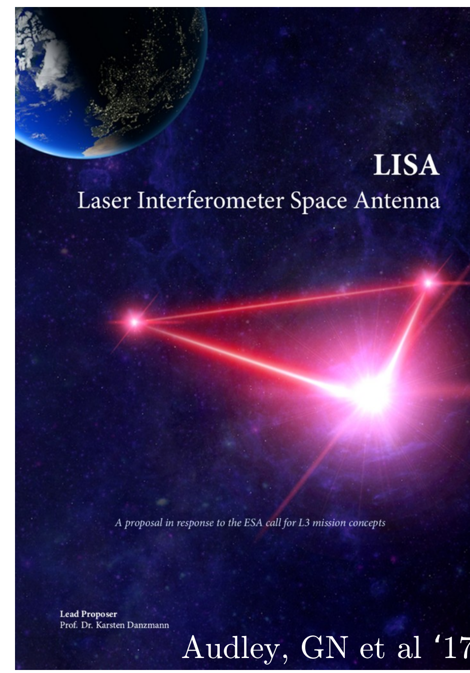
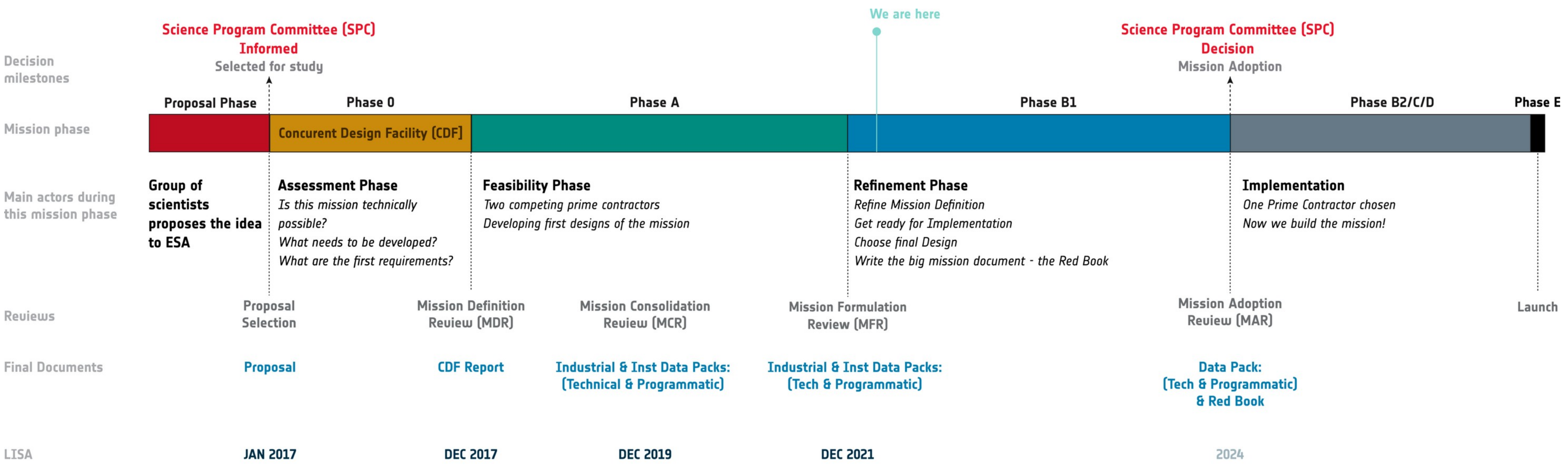






Audley, GN et al ‘17

LISA: present



Configuration:
3 arms (not 2)

Mission duration:
4 years / duty cycle

P.Amaone, GN et al. '21

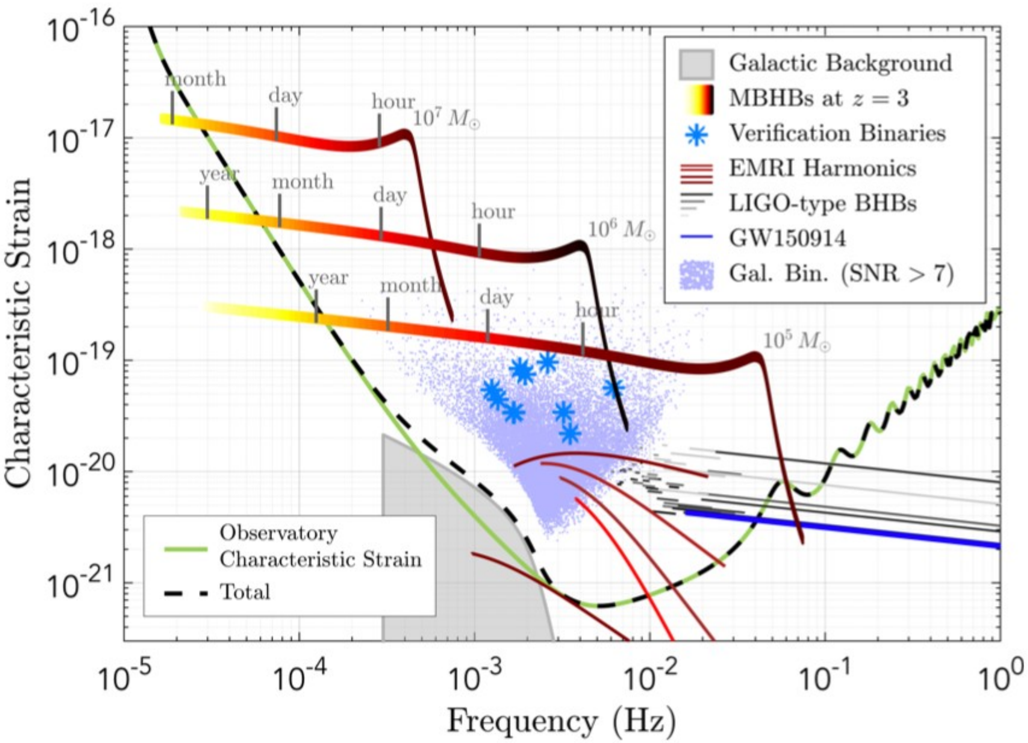
Low-freq. sensitivity:
No strong requirement at $f < 0.1$ mHz

P.Amaone, GN et al., to appear

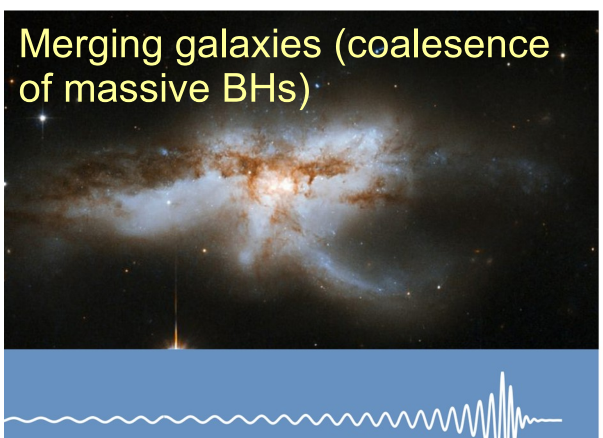
Red Book:
Science objectives defined as mission requirements (Figures of Merit)

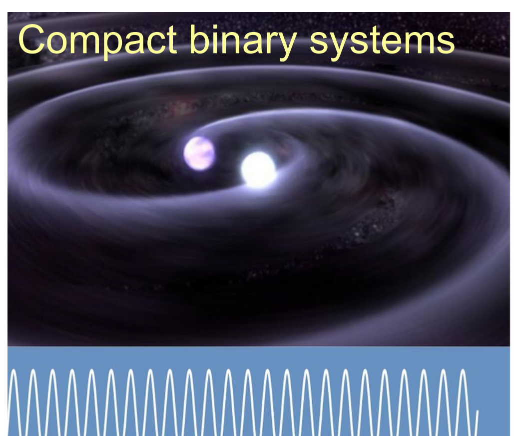
ESA - countries multilateral agreements

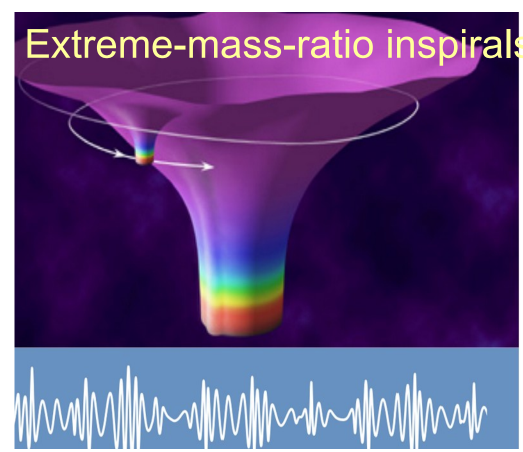
Astrophysical sources in LISA



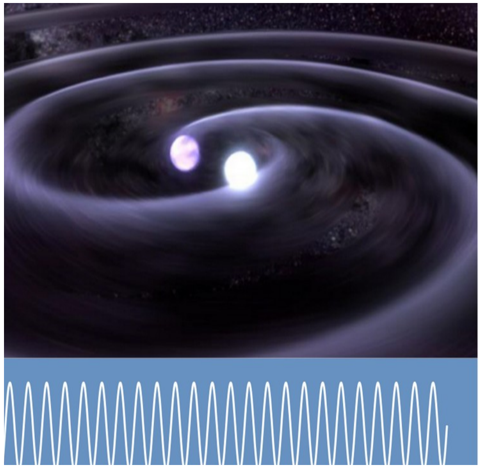
- O(10^4) resolv. galac. binaries
- Extragal. BBHs of 10^0–10^2 $M_\odot$
- Extreme mass-ratio inspirals
- Merging BBHs of 10^4–10^8 $M_\odot$

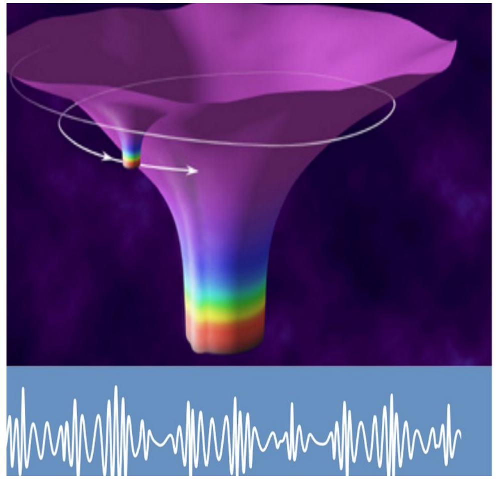


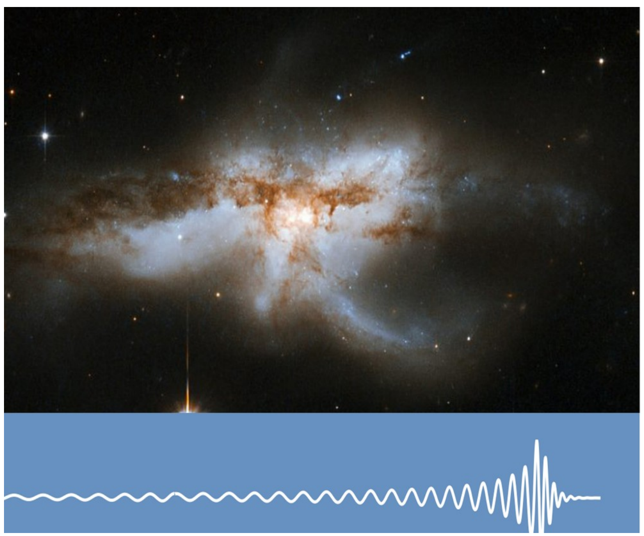




Science objectives







- 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:

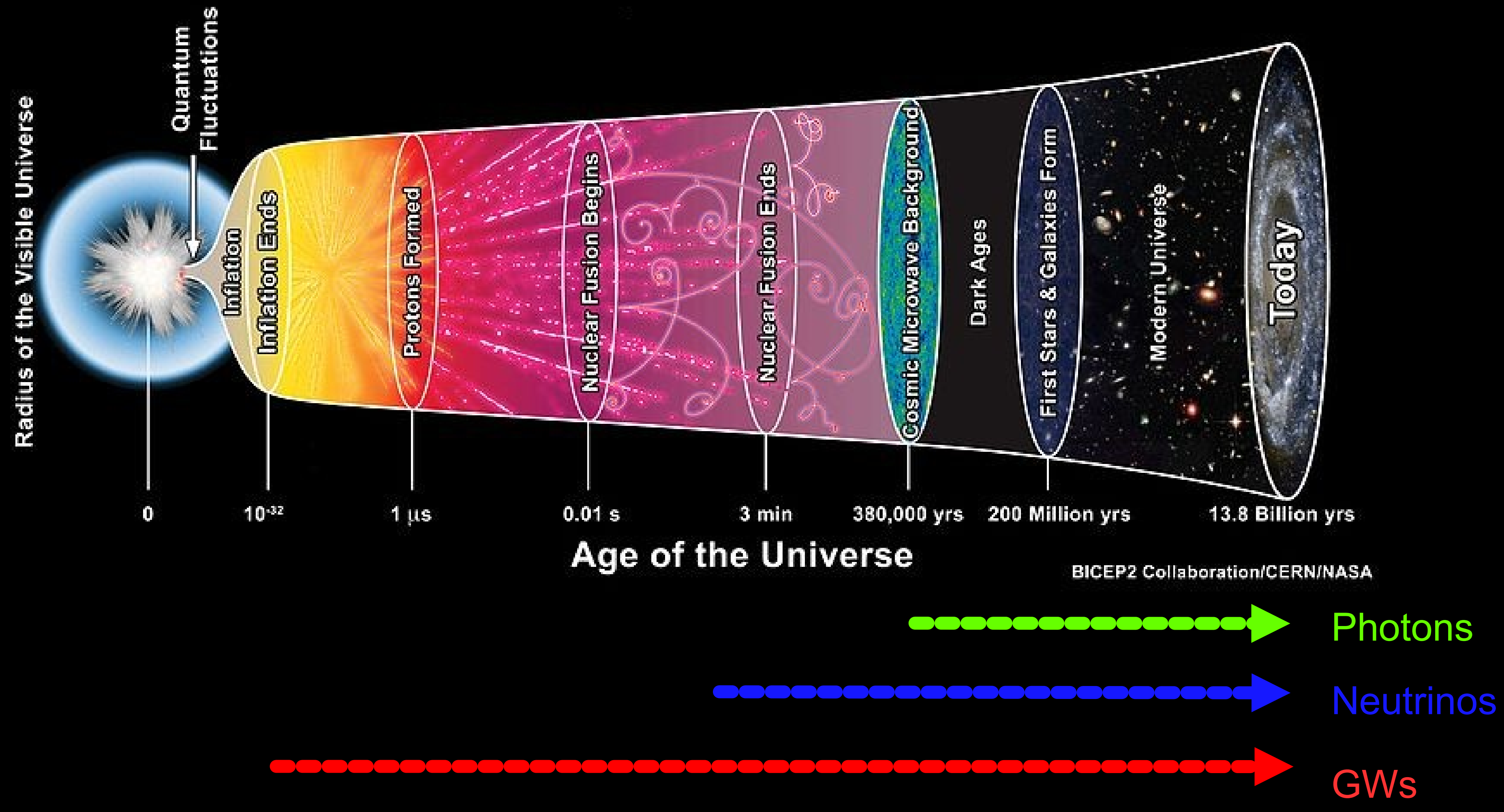
$$\frac{\rho_{GW}}{\rho_c} = \frac{c^2}{32\pi G} \langle \dot{h}_{ij} \dot{h}^{ij} \rangle = \frac{\pi c^2}{2G\rho_c} \int_{-\infty}^{+\infty} d(\log f) f^3 S_h(f) = \int_{-\infty}^{+\infty} d(\log f) \frac{d\rho_{GW}}{\rho_c d(\log f)}$$

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

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

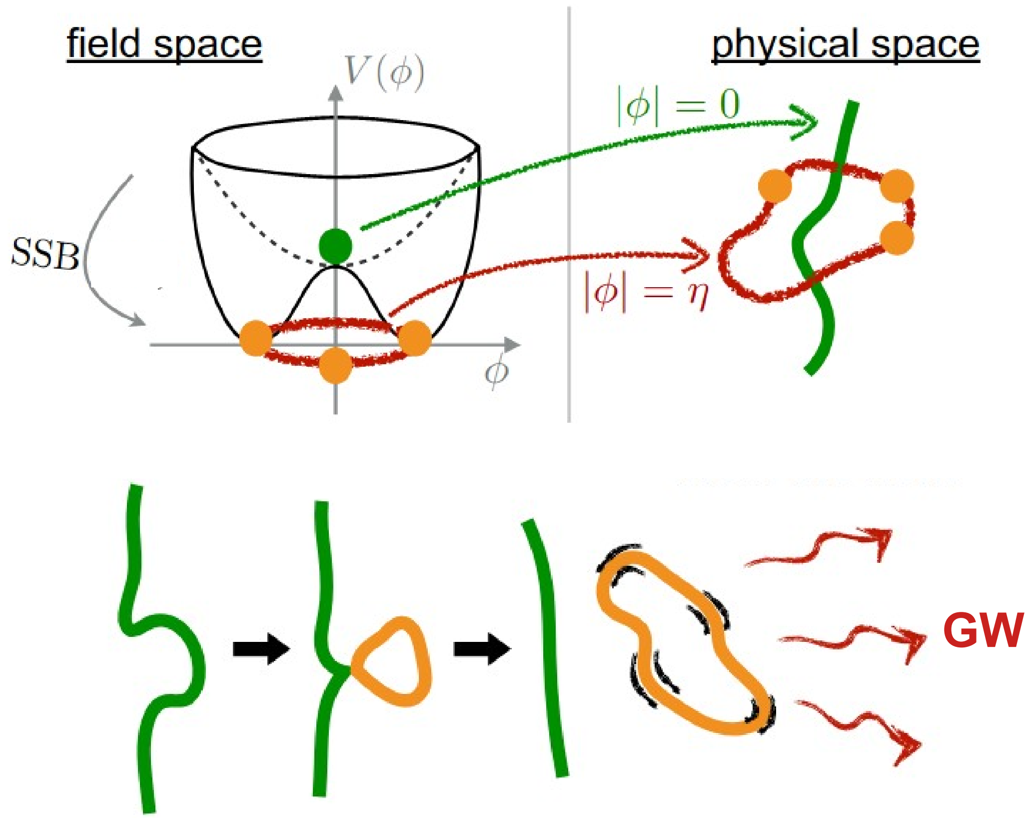
Characteristic strain

Why is a primordial SGWB detection exciting?

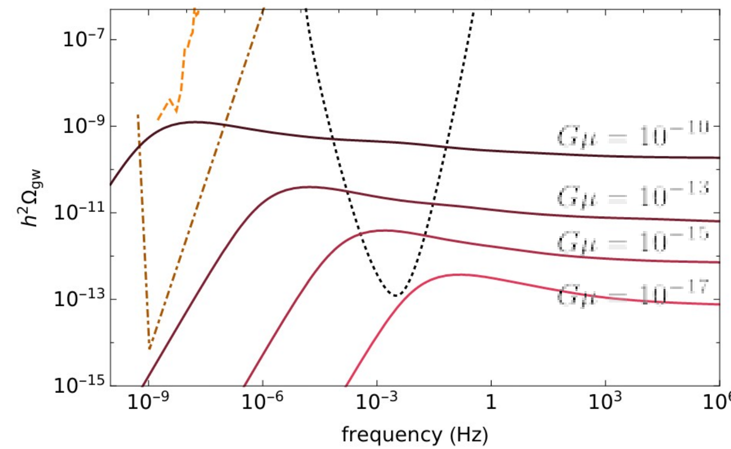


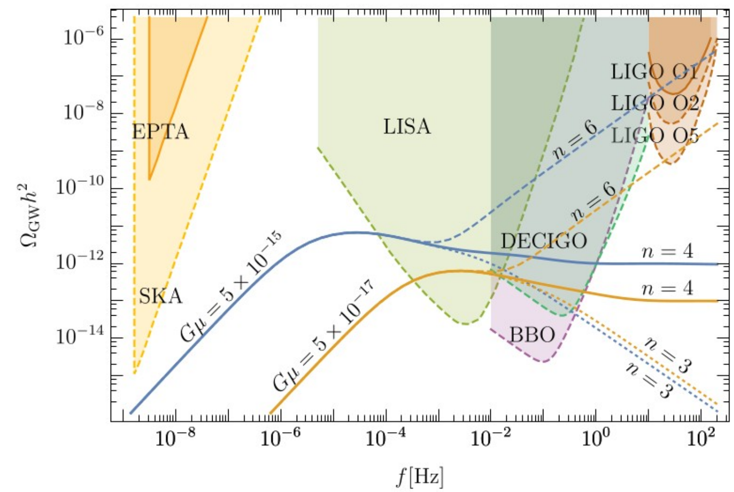
SGWB from cosmic strings

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



[credits: P. Simakachorn]



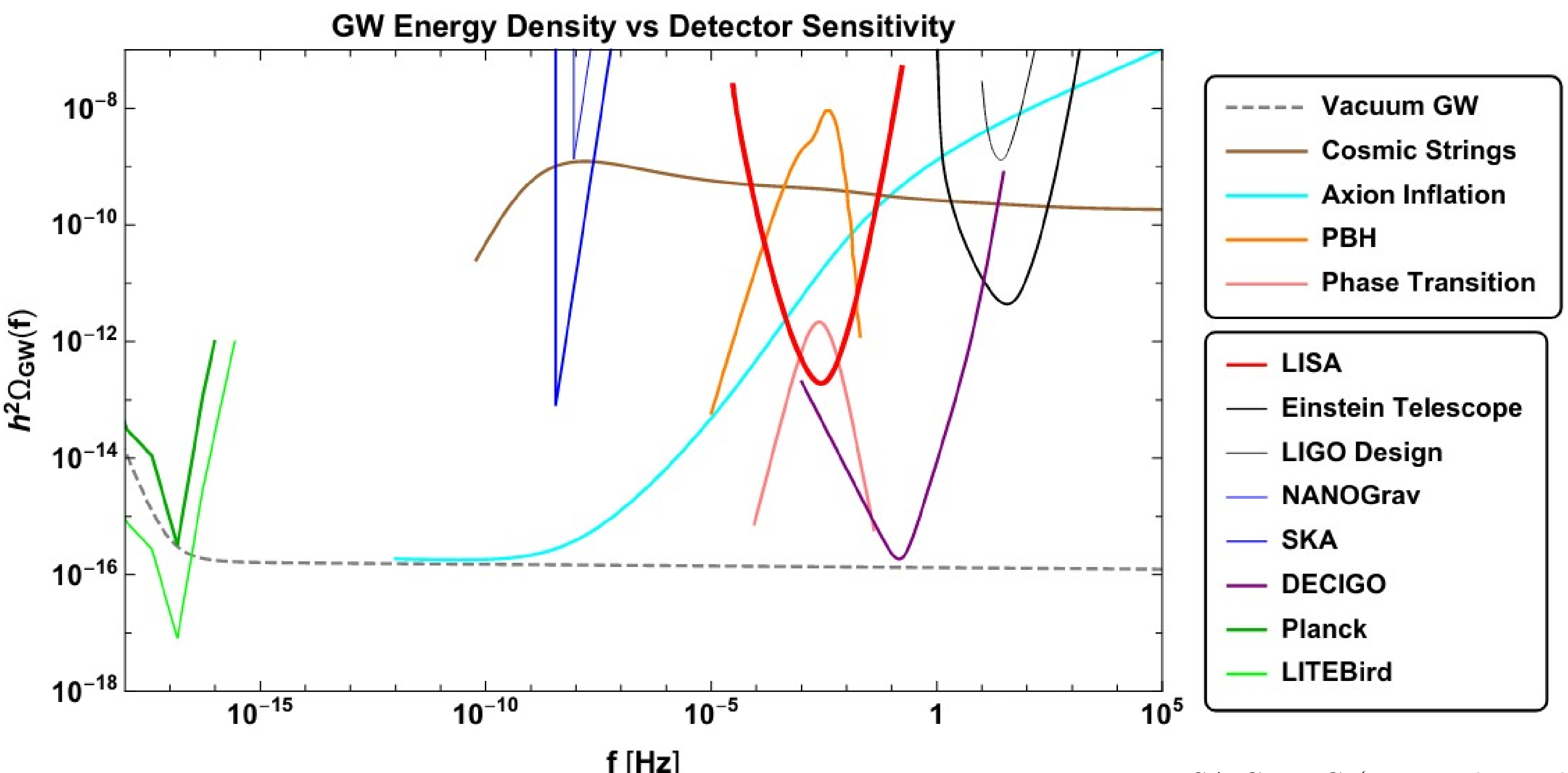


LISA CosWG (P.Auclair et al.) ‘19

LISA CosWG (P.Auclair et al.) ‘22

SGWB from the inflationary epoch

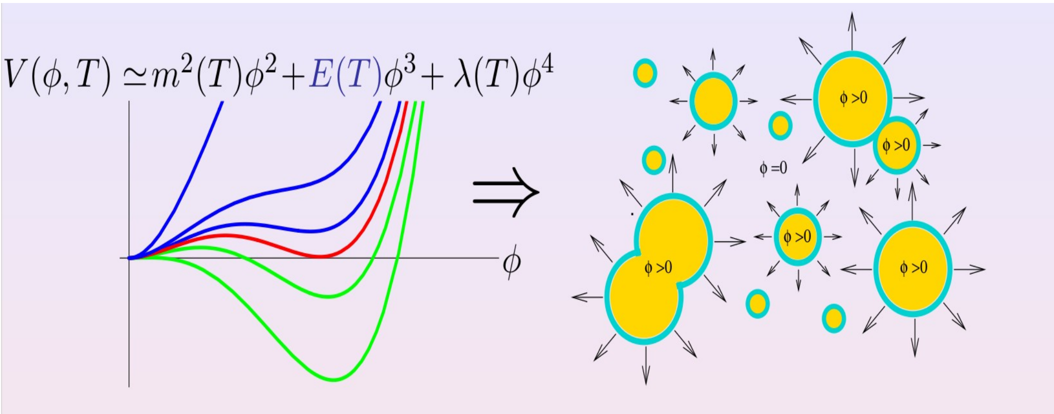
- **Inflation**: standard single-field slow-roll, inflation with spectators, preheating, … very model dependent!
  - Signal from vanilla scenario is very small

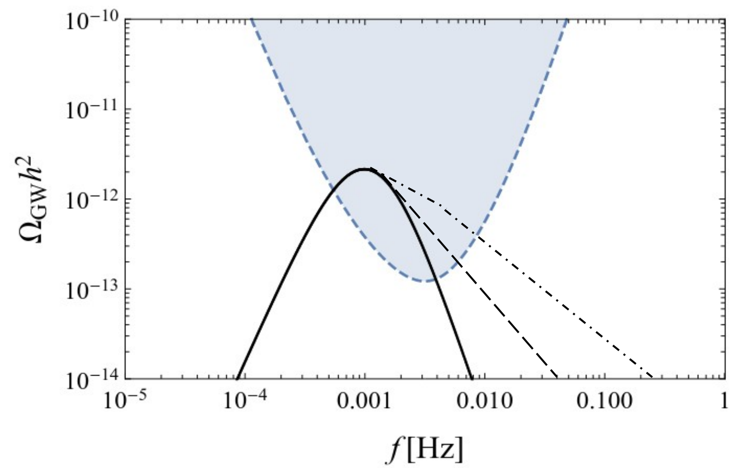


LISA CosWG (N.Bartolo et al.) '18
LISA CosWG (C. Contaldi et al.) '20
LISA CosWG (P.Auclair et al.) '22

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

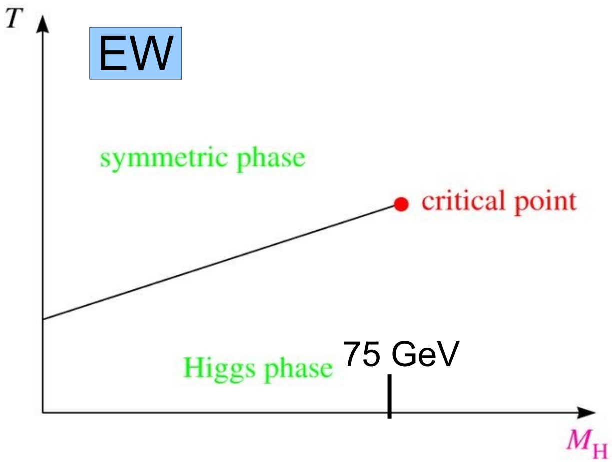
T_* : universe temperature when bubbles collide

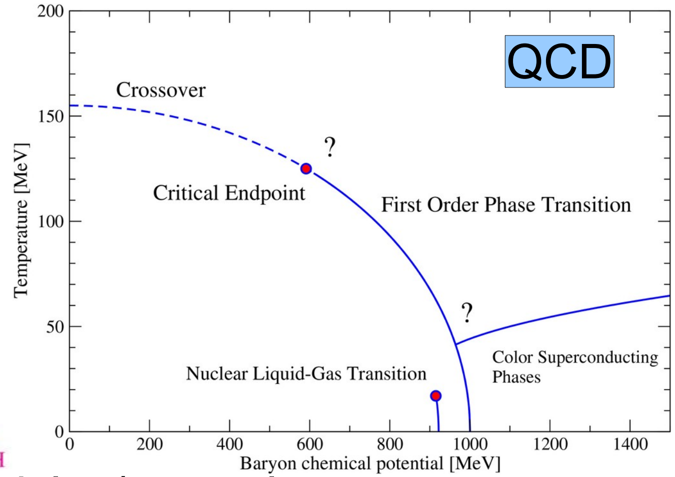
v_w : bubble wall velocity

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

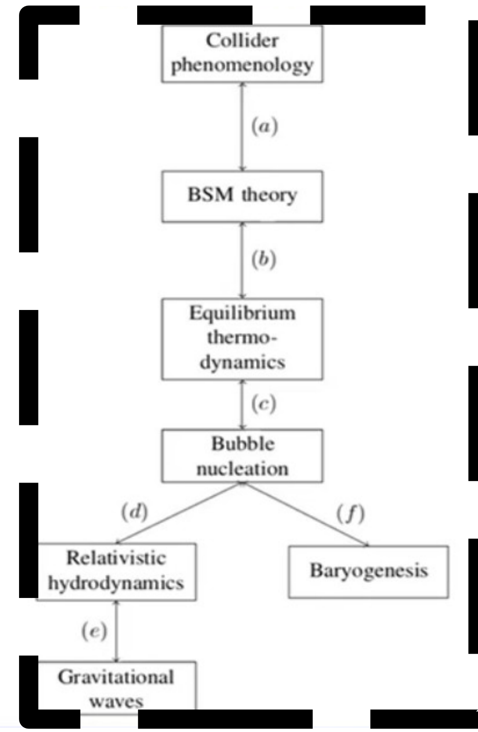




Kajantie et al. '96
Karsh,Neuhaus,Patkos '96
Csikor,Fodor,Hietger '98

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

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

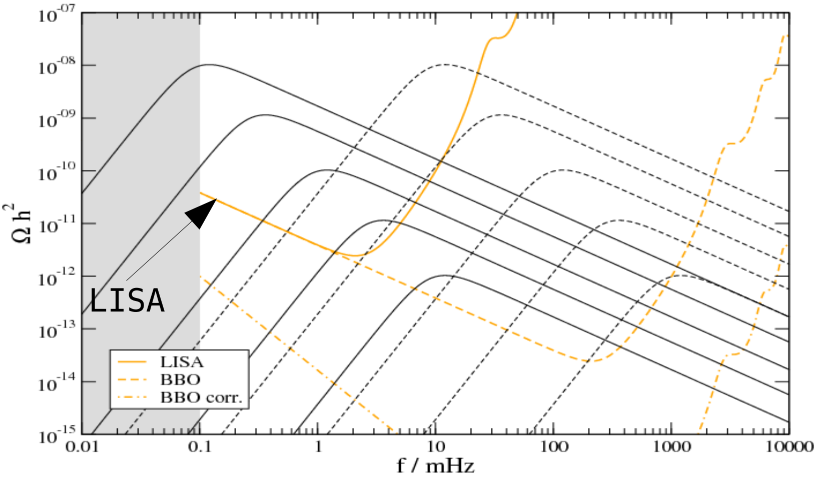


Some rationales:

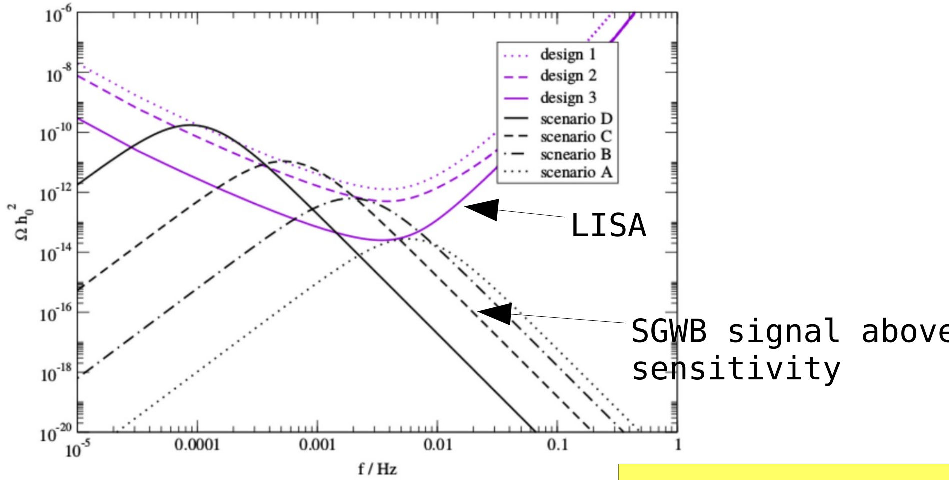
- New color fields → Large T effects but also Higgs gluon fusion changes
- New dynamical scalar fields → Mixing → Higgs signal strengths
- New fermions → no large T-effects (read: no barrier → no 1st order)
- Very heavy fields → Boltzmann suppressed and small low-energy effects

Some scenarios with EW first-order transitions

First order in Randall Sundrum

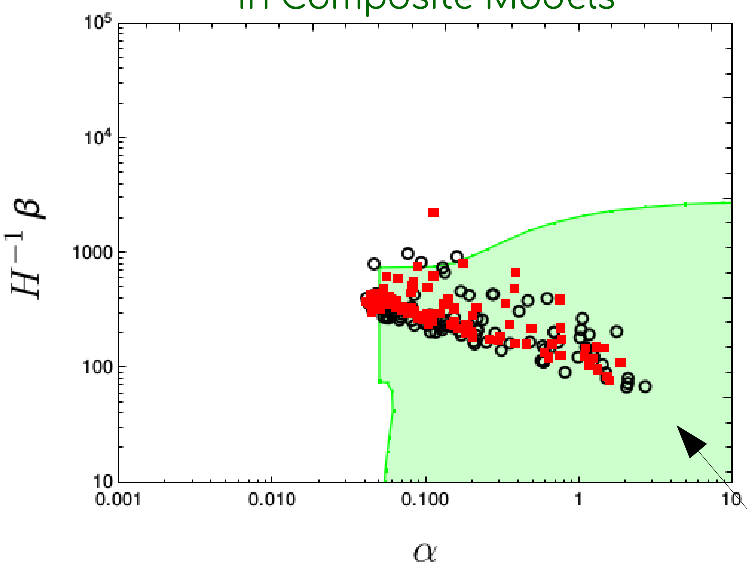


First order in SUSY

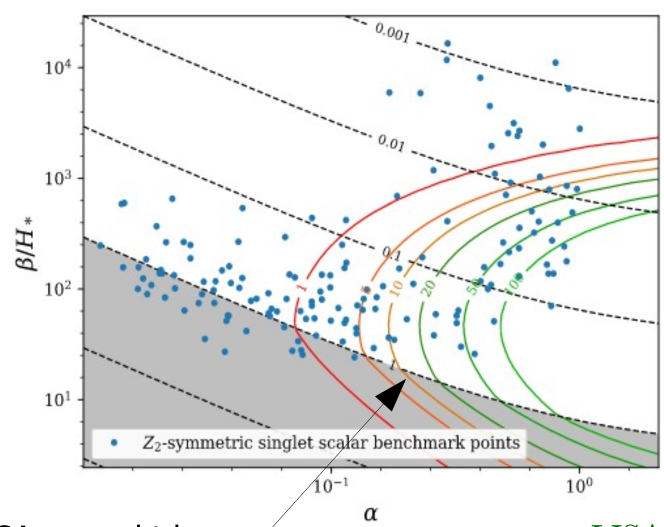


Complementarity with LHC, FCC, ...

First order
in Composite Models



First order in Z2 singlet

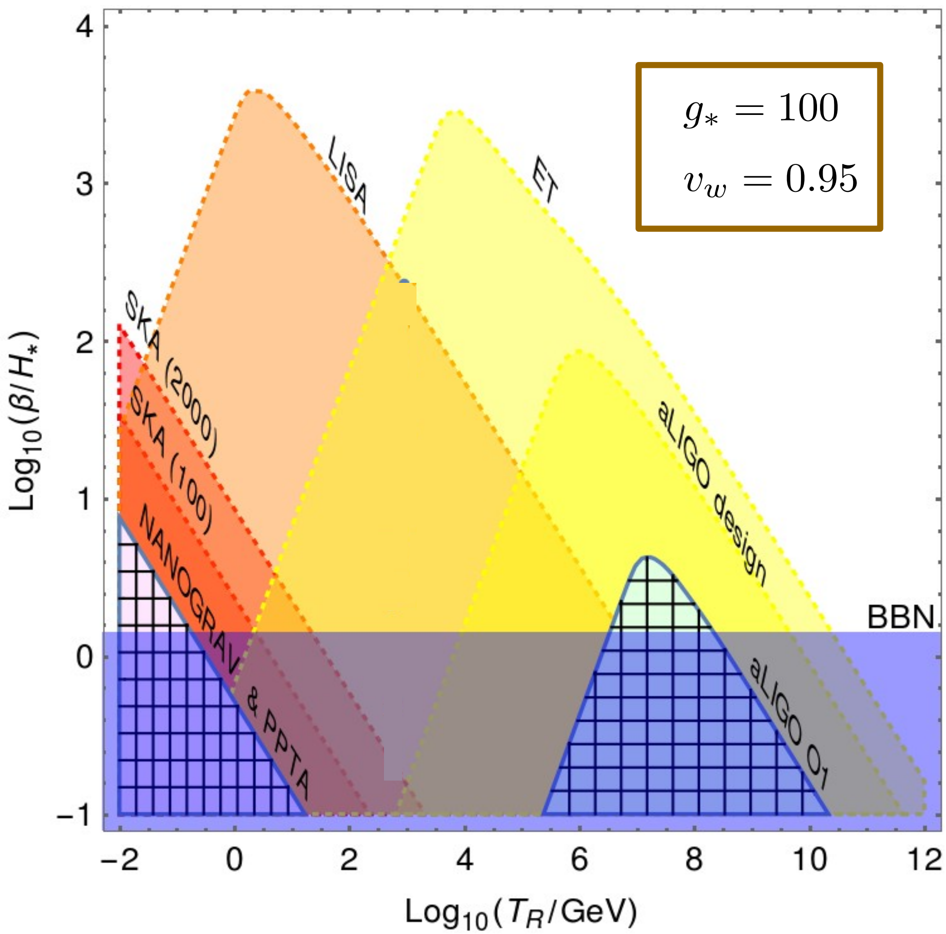


LISA sensitivy
region

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

Parameters:

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T_R : universe temperature when bubbles collide
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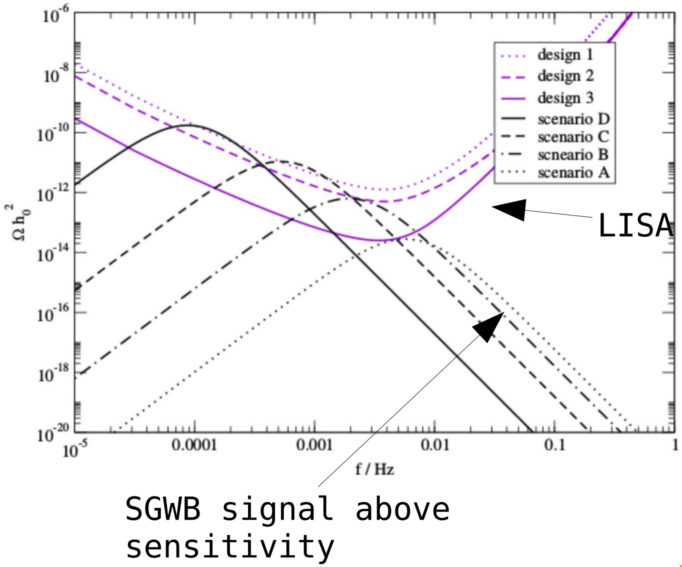
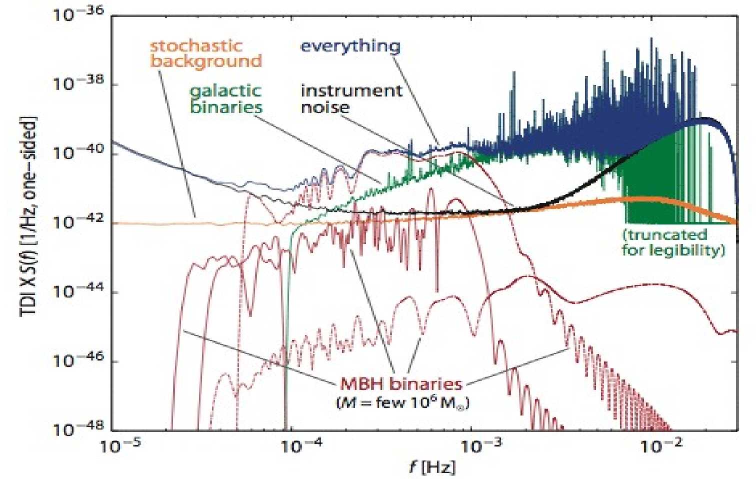
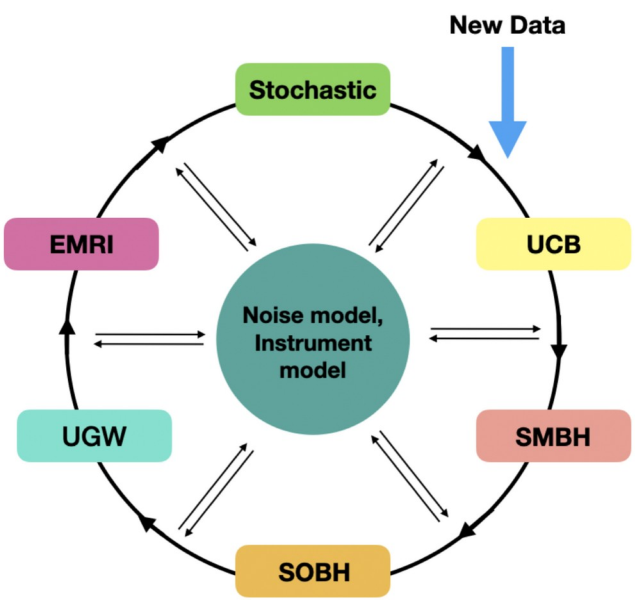
Primordial SGWB signal within sensitivity $\overset{?}{=}$ discoverable

First order in SUSY



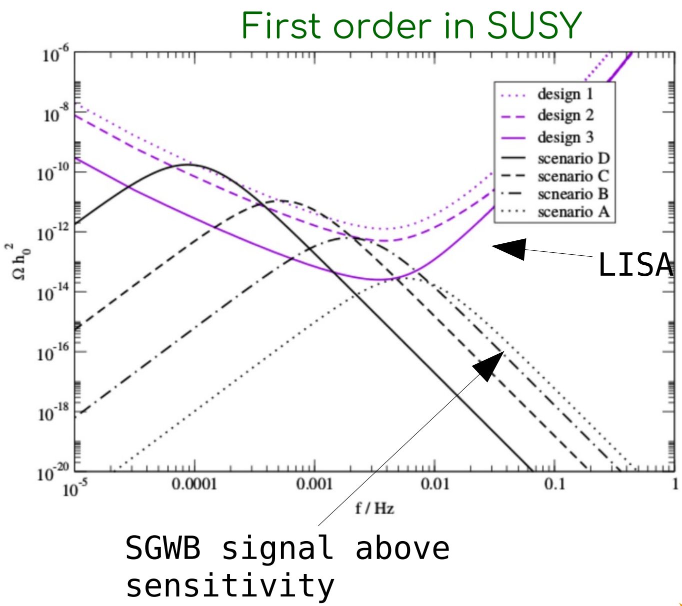
LISA is a signal-dominated experiment



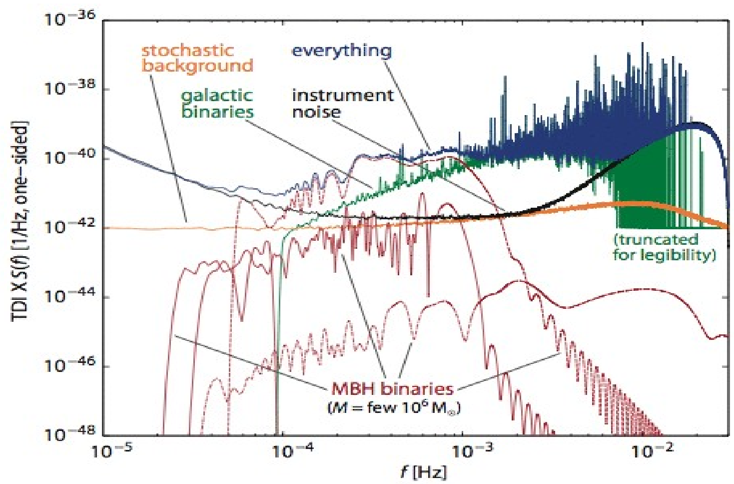


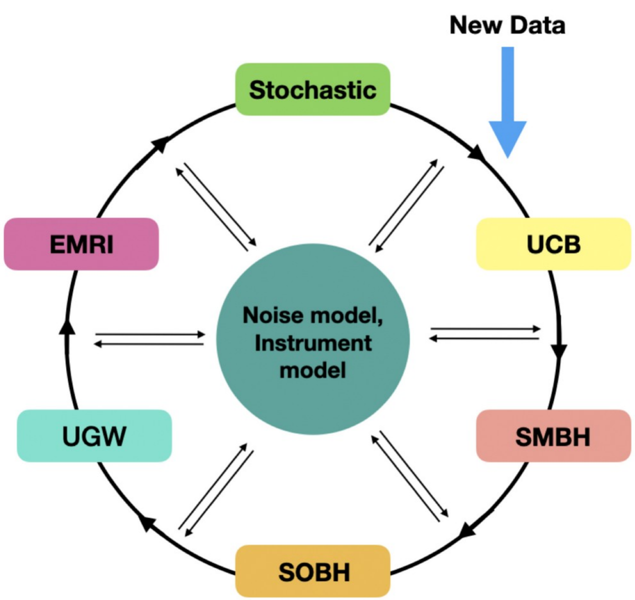
- A primordial SGWB is likely covered by astro. signals localized in time or frequency
- Reconstruct and subtract the astro. events with their waveforms. Only possible for the loudest events.
- The leftover contains:
  - The (faint) unresolved binaries
  - The instrumental noise
  - The primordial SGWB

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



LISA is a signal-dominated experiment



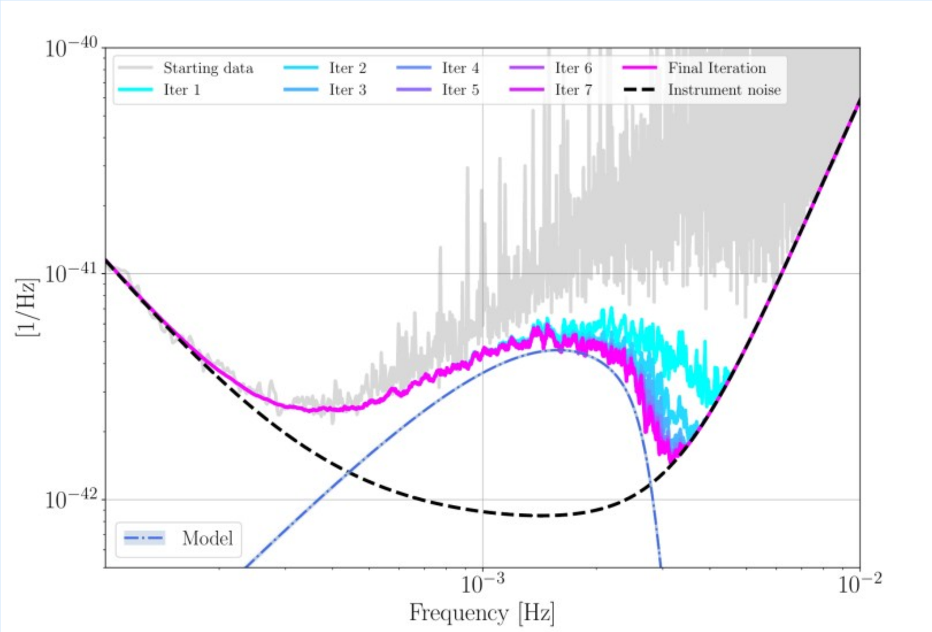


- A primordial SGWB is likely covered by astro. signals localized in time or frequency
- Reconstruct and subtract the astro. events with their waveforms. Only possible for the loudest events.
- The leftover contains:
  - The (faint) unresolved binaries **(next 4 slides)**
  - The instrumental noise **(mentioned in some minutes)**
  - The primordial SGWB **(just covered)**

“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 is above the detection threshold, remove the binary from the data

Iteration steps
+
Final residual from Gal. Binaries



N. Karnesis et al. ‘21

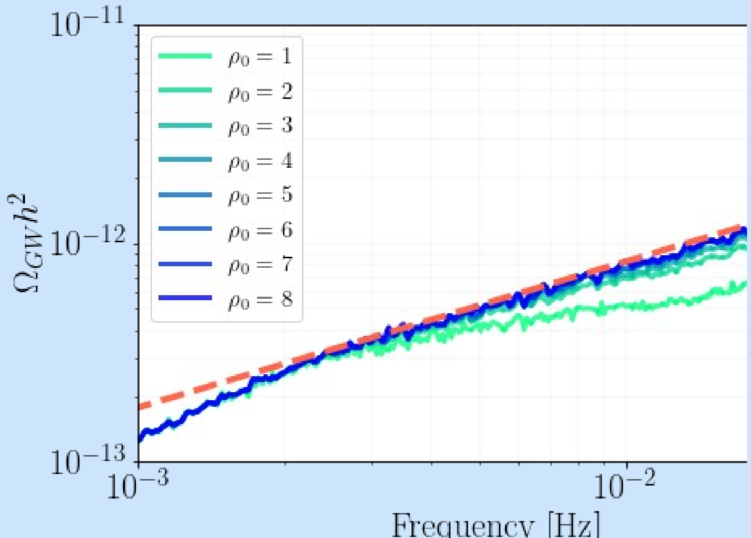
“faint unresolvable binaries” in stellar-origin BBHs

- From GWTC-3, LVKC constrains the SOBBH population up to z ~ 0.5. Astrophysics predicts the behavior at z > 1.

$$\frac{d^3N(z,\tau_c,\xi,\theta)}{d\xi dz d\tau_c^{(\mathrm{det})}} = R(z,\tau_c)\left[\frac{dV_c}{dz}(z)\right] p(\xi|\theta)\,\frac{1}{1+z}$$

$$R(z) = R_0 C \frac{(1+z)^{\kappa}}{1+\frac{\kappa}{r}\left(\frac{1+z}{1+z_{\mathrm{peak}}}\right)^{\kappa+r}}$$

- Make a realization of the population, …. , use SNR_{thr} as a proxy of the PE (SNR_{thr} = 8 standard, SNR_{thr} = 4 archival)).
- Iterations to subtract sources above SNR_{thr} w.r.t. the remaining overal signal



Final residual from SOBBHs with diff. SNR_{thr}

J. Torrado, GN et al. ‘23

“faint unresolvable binaries” in stellar-origin BBHs

- From GWTC-3, LVKC constrains the SOBBH population up to z ~ 0.5. Astrophysics predicts the behavior at z > 1.

$$\frac{d^3N(z,\tau_c,\xi,\theta)}{d\xi dz d\tau_c^{(\mathrm{det})}} = R(z,\tau_c)\left[\frac{dV_c}{dz}(z)\right] p(\xi|\theta)\,\frac{1}{1+z}$$

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- Make a realization of the population, …. , use $\mathrm{SNR_{thr}}$ as a proxy of the PE ($\mathrm{SNR_{thr}}$ = 8 standard, $\mathrm{SNR_{thr}}$ = 4 archival).
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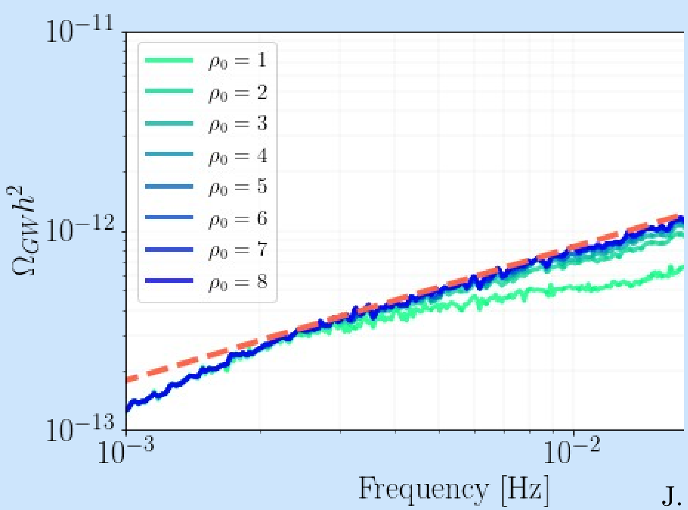
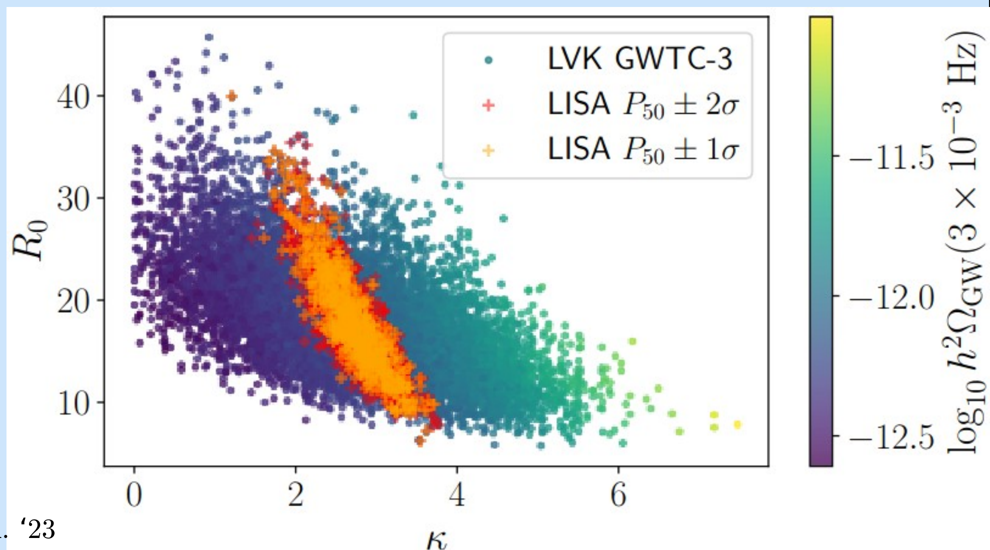
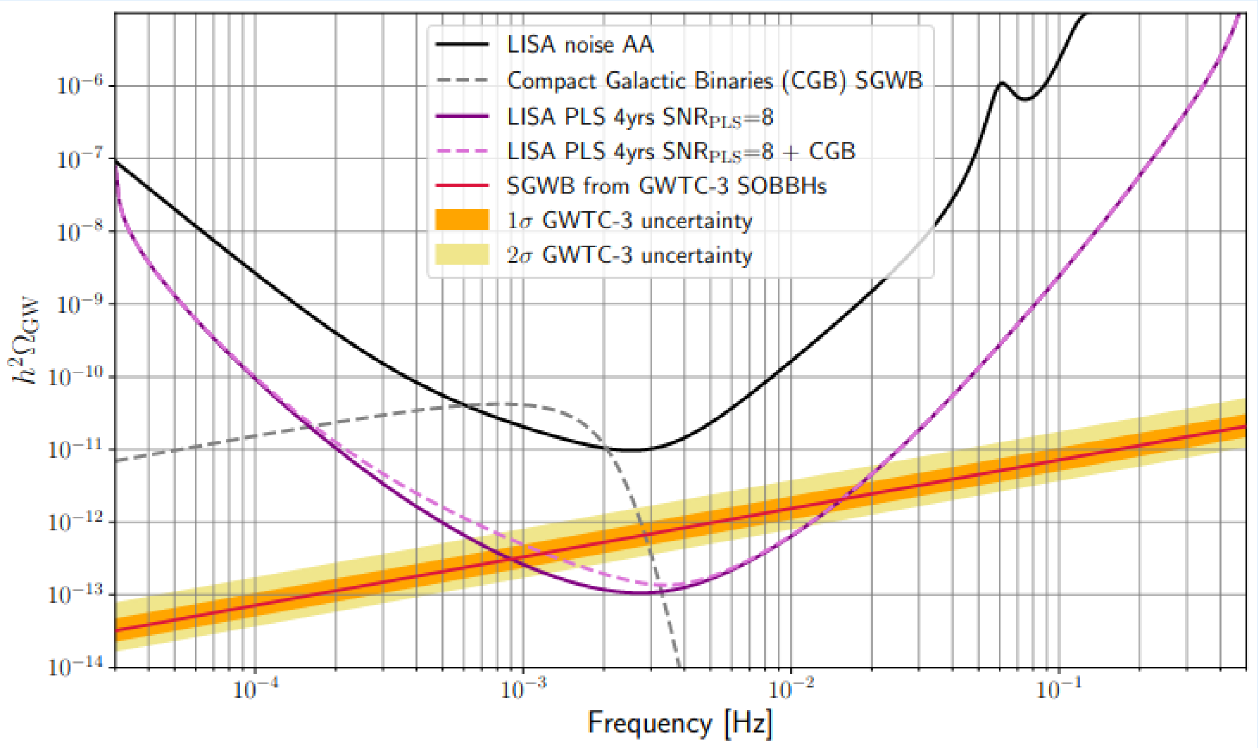


J. Torrado, GN et al. ‘23



Total “faint unresolvable binaries” (up to surprises and subtleties)



The sum of all unresolvable binaries tends to look a random, Gaussian signal.
Statistically, it is a SGWB

A region of the LISA sensitivity is covered by these foregrounds.

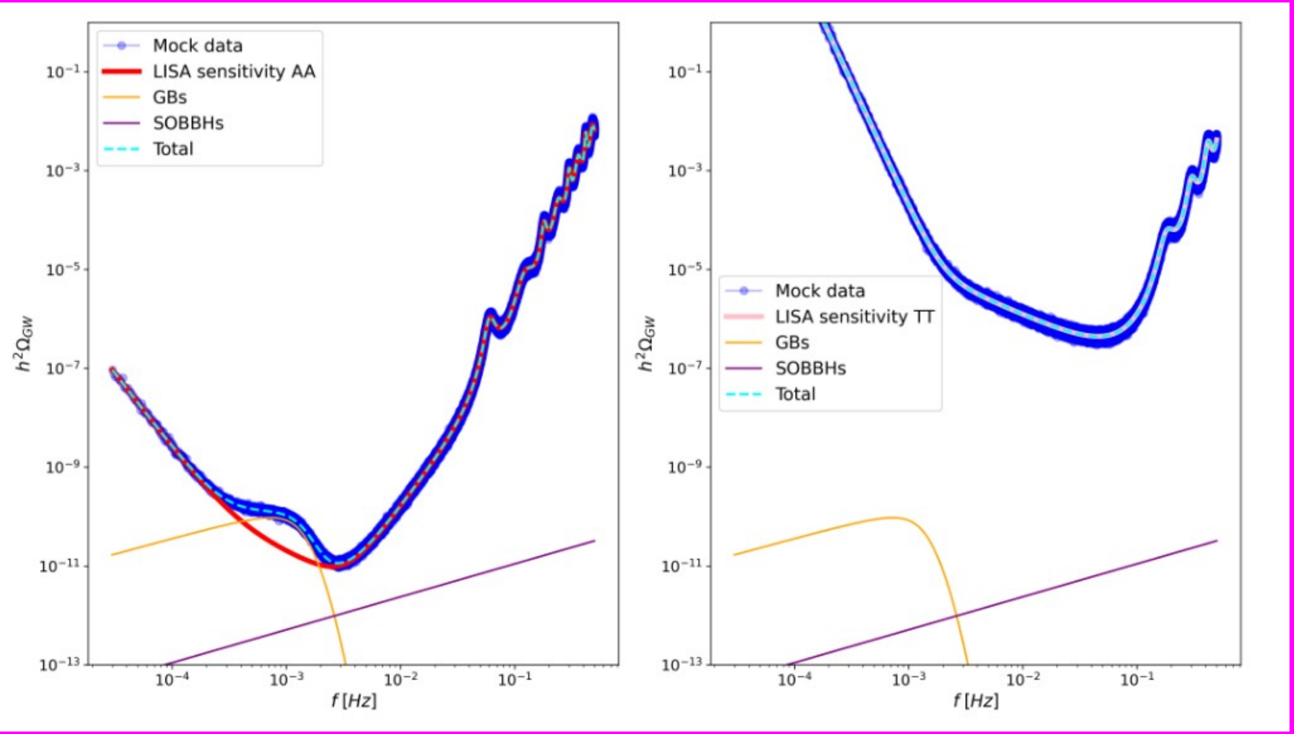
It is worth not completely loosing this region.

Key features of these signals to be exploited: these signals have clear predictions

The “instrumental noise” constitutes a SGWB too

- 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



Accurate noise modelling is important, otherwise risk of biases or sensitivity loss.

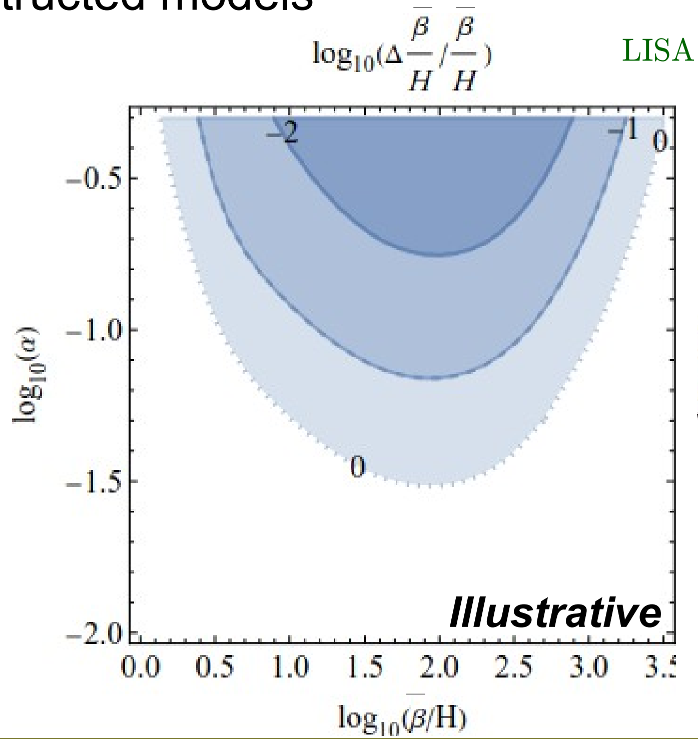
Different linear combinations of the LISA channels can be more or less to the signal/noise. Useful for noise calibration.

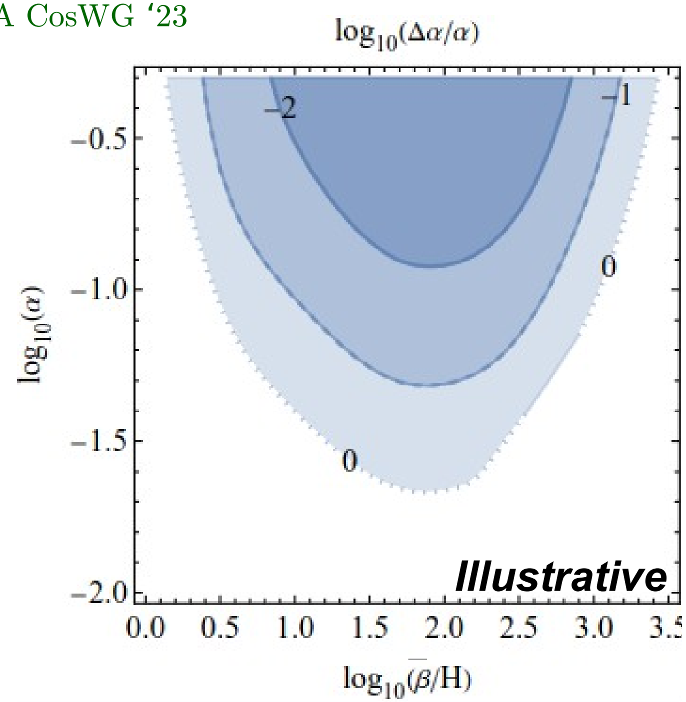
But the noise has also non-stationary, non-Gaussian component. Noise knowledege one of the main LISA challanges

LISA reconstruction forecast in the precise-template limit

Assumption: there will exist **precise templates** for the instrumental noise and the unresolved-binary signal, i.e. no sizeable mismatch between injected and reconstructed models

LISA CosWG '23





For reasonable first-order phase-transitions, the SGWB measurement is so precise that the source parameters can be reconstructed with O(1%) accuracy or better

See also:
Glowing et al. '22
Boileau et al. '22

Similar conclusions for cosmic strings and inflationary models

LISA CosWG '23

Conclusions

- A primordial SGWB detection will be a breakthrough in cosmology and particle physics
- No guarantee that the primordial SGWB is sufficiently strong for LISA or other forthcoming GW detectors. Nevertheless, detection or upper bound yields key information on cosmic strings, first-order phase transitions, inflation, …
- Accurate primordial SGWB reconstruction or bound requires accurate knowledge of:
  - the LISA foregrounds, aka “faint unresolvable binaries”
  - the LISA noise
- Several communities are working together to reach such an accurate knowledge
- If such an accurate knowledge will be achieved, LISA will be able to reconstruct the parameters of reasonably strong primordial SGWBs at O(1%) level or better
- But LISA has further science goals besides primordial SGWB. Mixed priorities.
- LISA flies in ~1 decade, but prioritization, science feasibility, and ground-segment design are in the next ~5 years. Industry contracts are now!