Cosmology with Gravitational Waves - Current Status and Future Prospects

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22 May 2024 - Virgo/ET Pisa

Latest Updates

In June 2021, the European Strategy Forum on Research Infrastructures (ESFRI) decided to include the Einstein Telescope (ET) in the update of its roadmap for 2021.

In June 2022 formal establishment of ET collaboration (today 1400 members)

In June 2023 Italian government present the Italian candidacy to host the Einstein Telescope,

On 25 January 2024 LISA has been adopted by ESA and construction will start in January 2025

On 25 March 2024 ASI presented the LISA mission to the scientific community

Where we are - LVK

The third observing run (B) from April 2019 to March 2020

Total number of gravitational waves observed to date (with probability of astrophysical origin > 0.5): ~ **90**

(mostly BBHs, 2 BNS and 2 NS-BH)

GWTC-3 catalogue: arXiv:2111.03606

The fourth run O4b has started with Virgo online

10 April

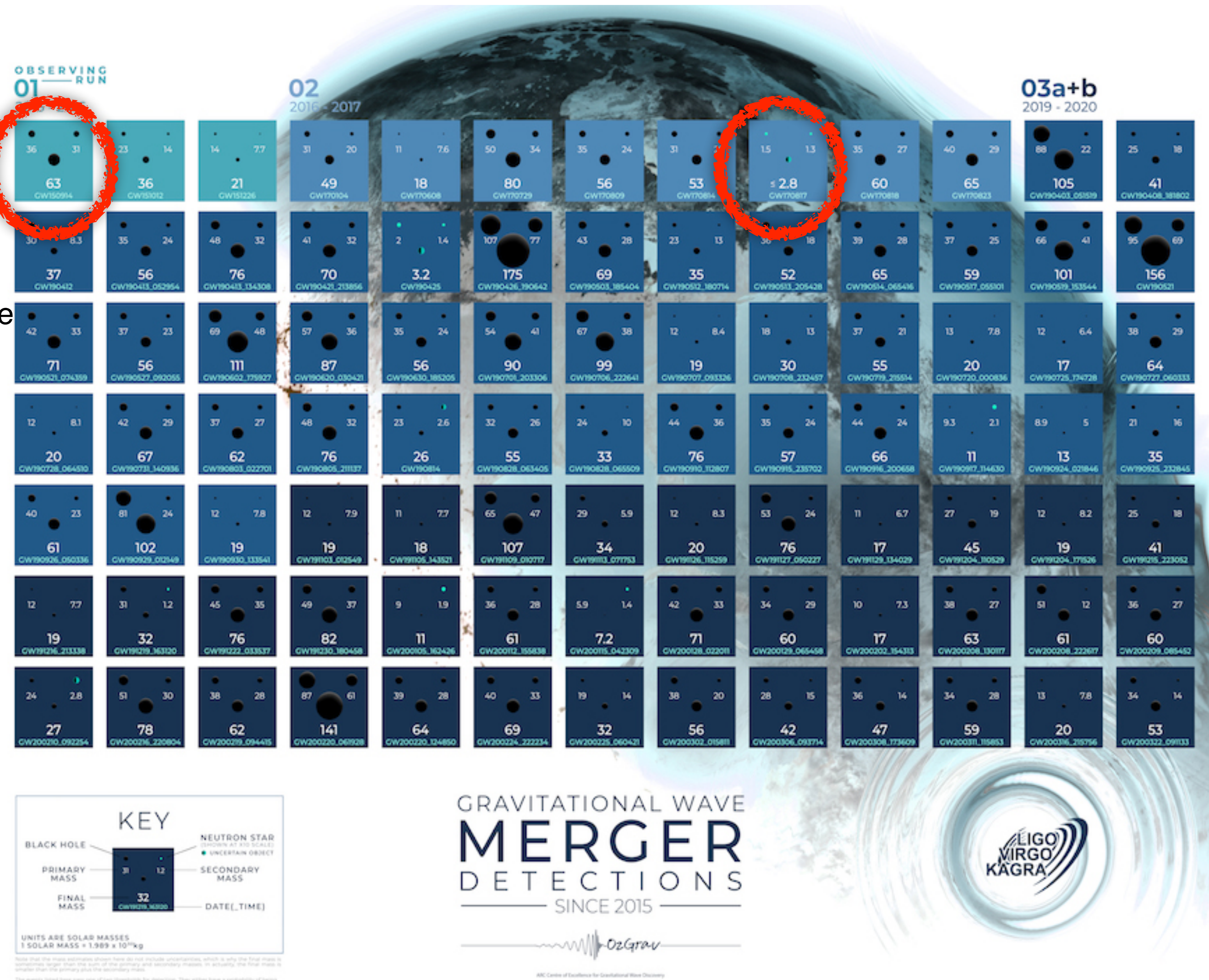
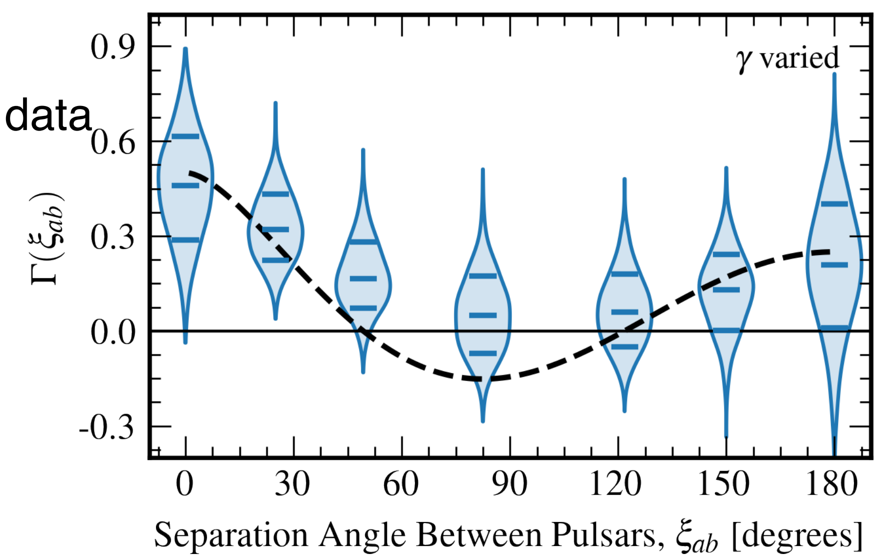


Image credit: LIGO / Virgo / KAGRA / C. Knox / H. Middleton

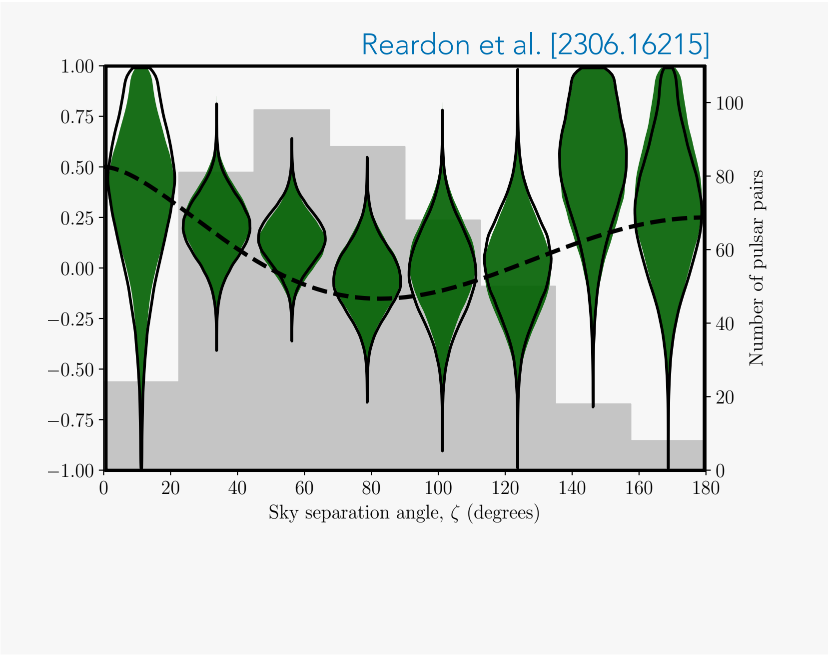
Where we are - PTA

NANOGRav:
68 pulsars, 16 yrs of data
$\sim 3-4\sigma$significance

Agazie et al. [2306.16213]



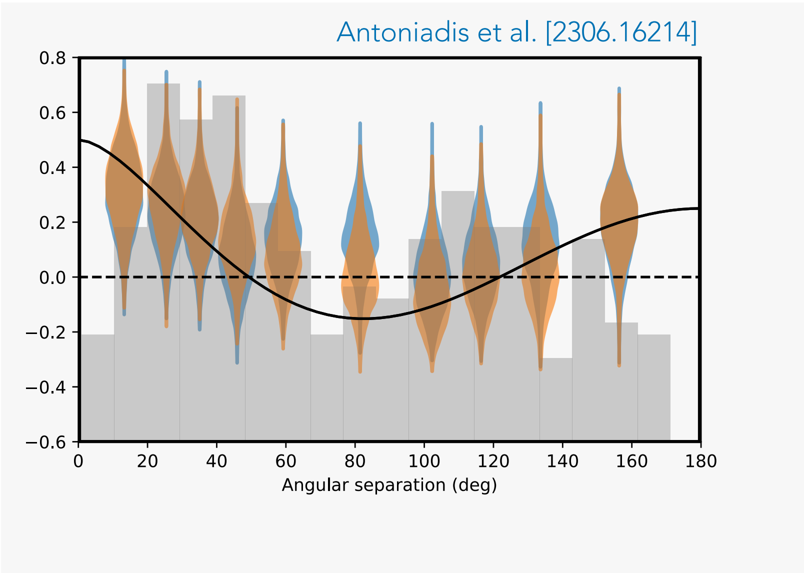
PPTA:
32 pulsars, 18 yrs of data
$\sim 2\sigma$ significance



First Detection of a SGWB

EPTA+InPTA:
25 pulsars, 24 yrs of data

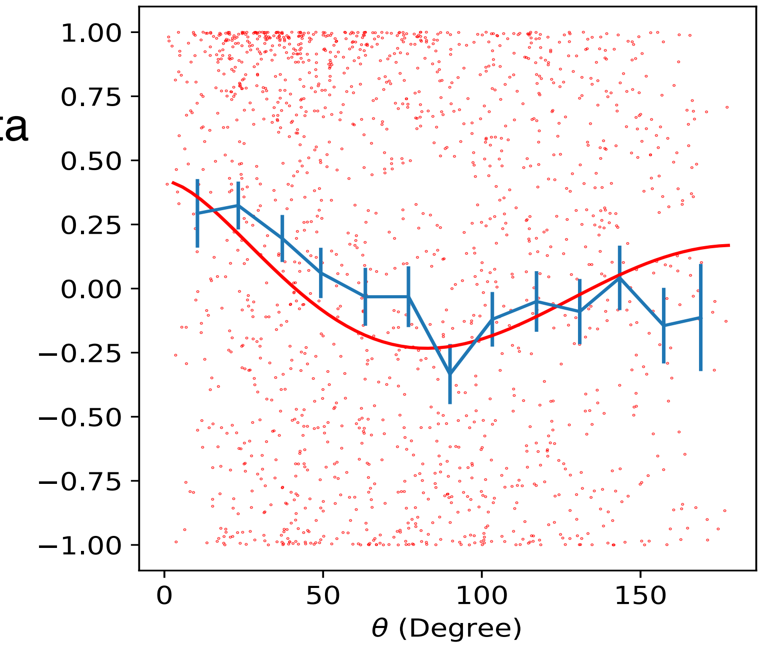
$\sim 3\sigma$ significance



CPTA:
57 pulsars, 3 yrs of data

$\sim 4.6\sigma$ significance

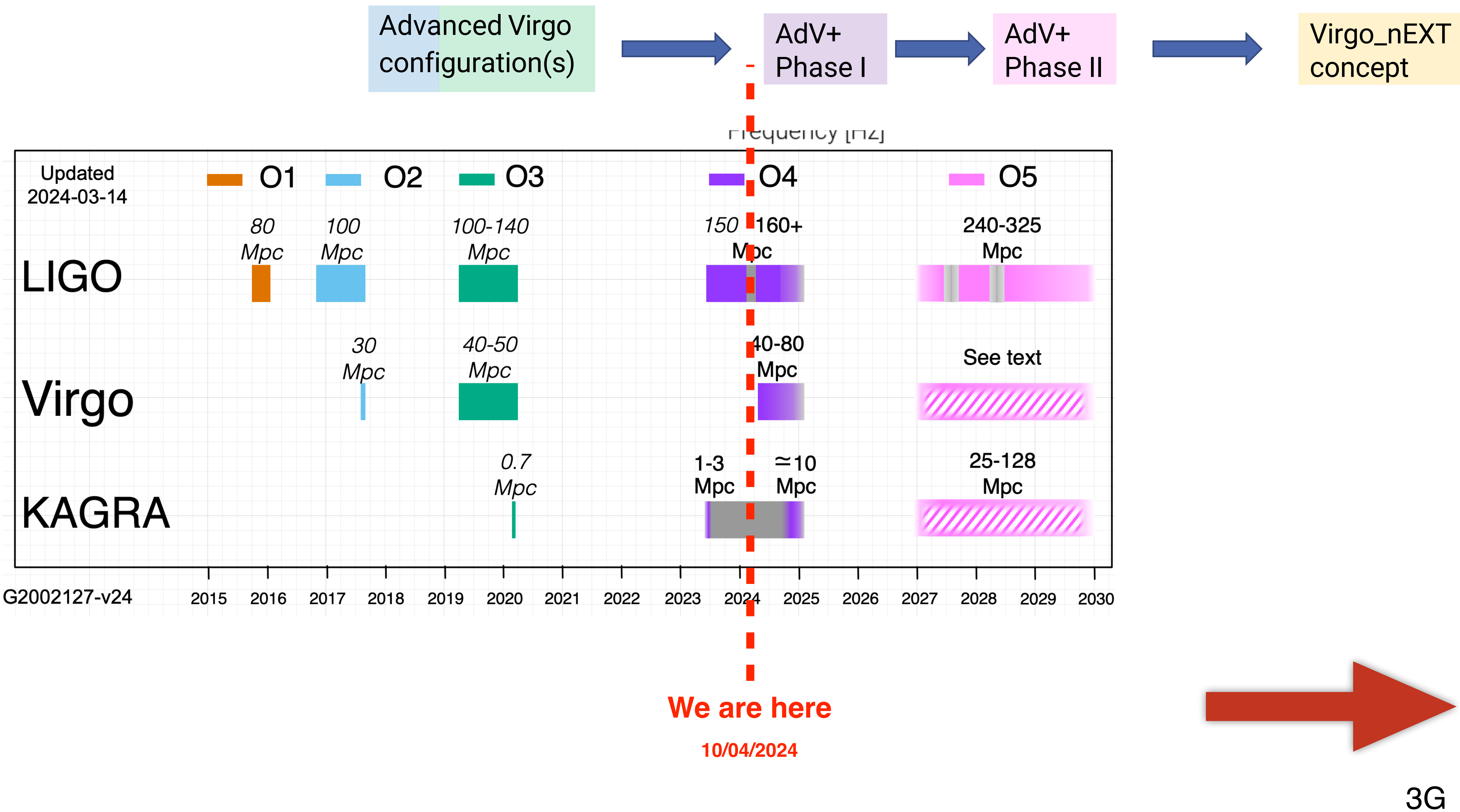
Xu et al. [2306.16216]



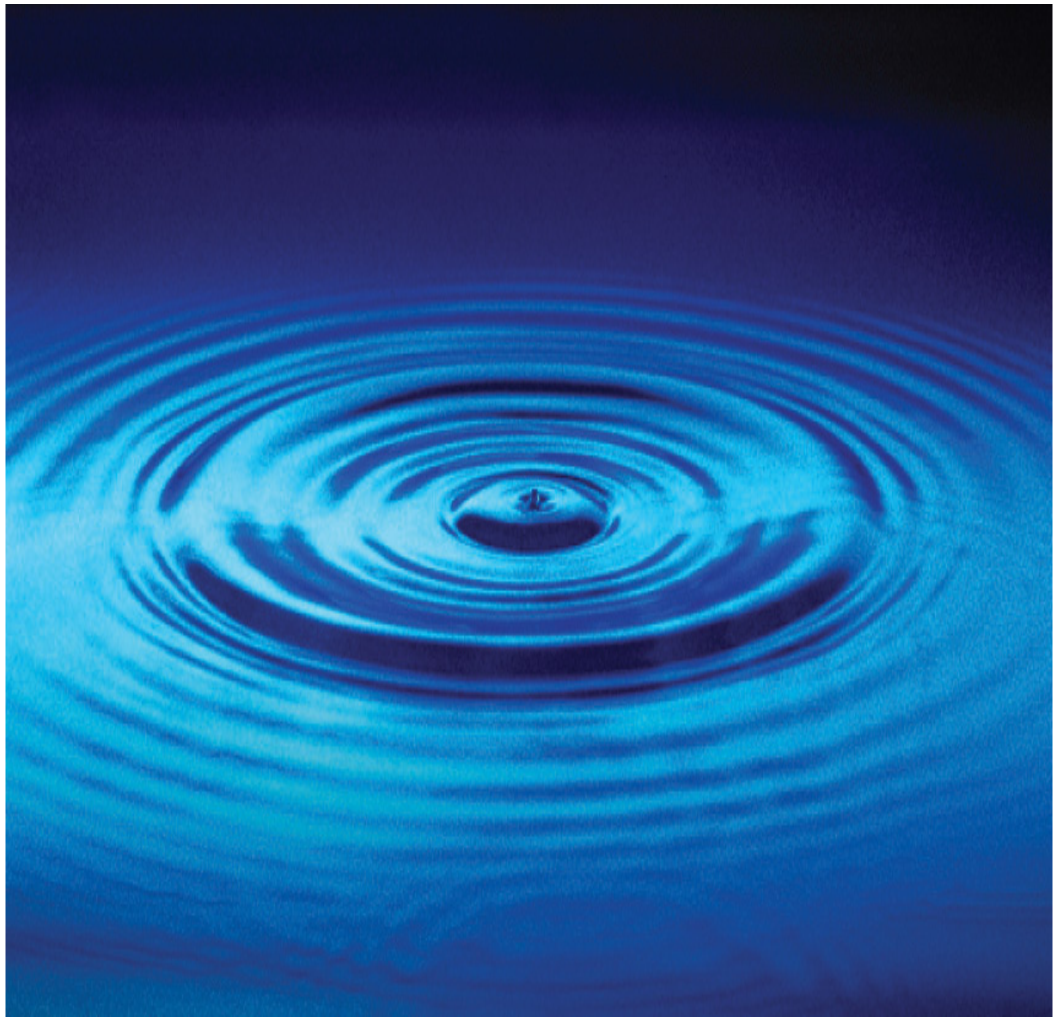
Bayesian reconstruction of normalized inter-pulsar correlations

Violins plot = marginal posterior densities (plus median and 68% credible values)

What are the plans for the LVK runs?

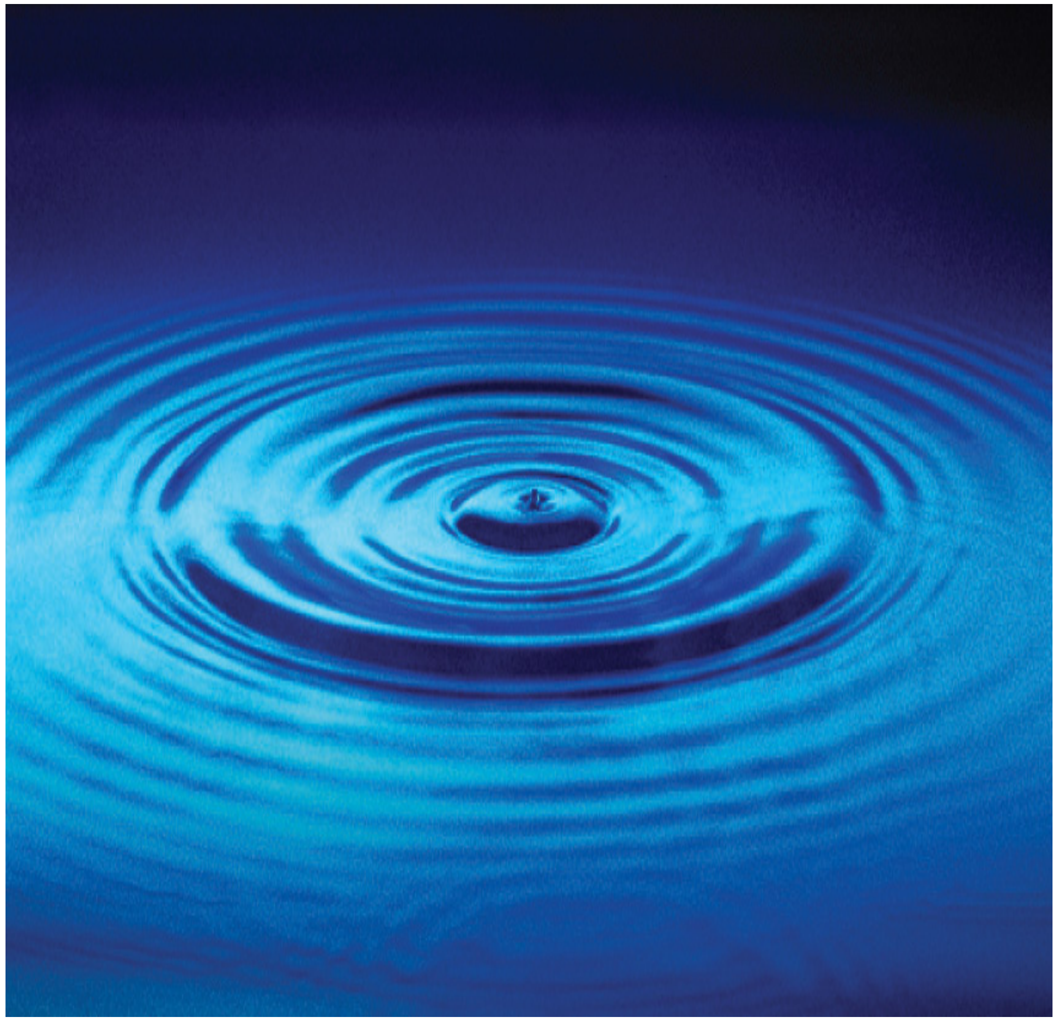


What are Gravitational Waves?



Rock in a pond

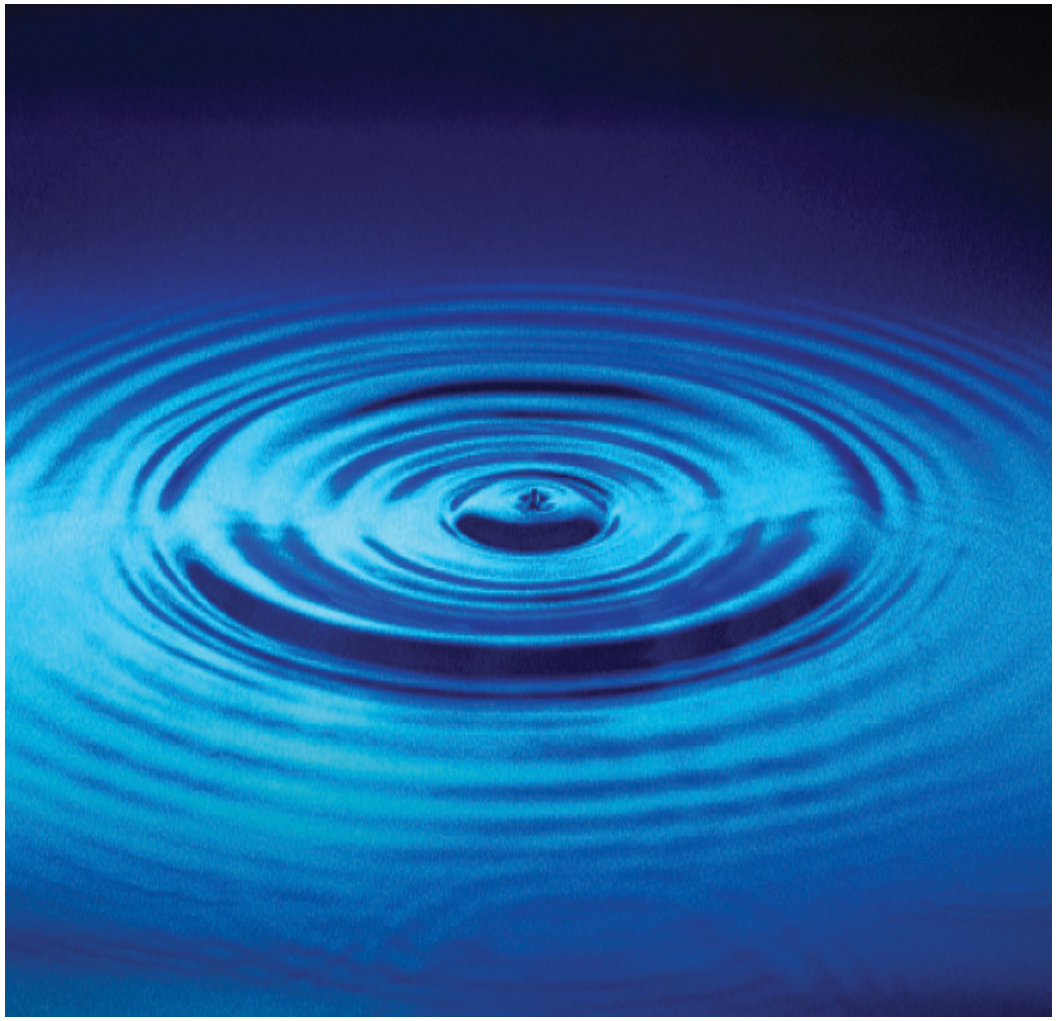
What are Gravitational Waves?



Rock in a pond

Merging COs in our universe

What are Gravitational Waves?



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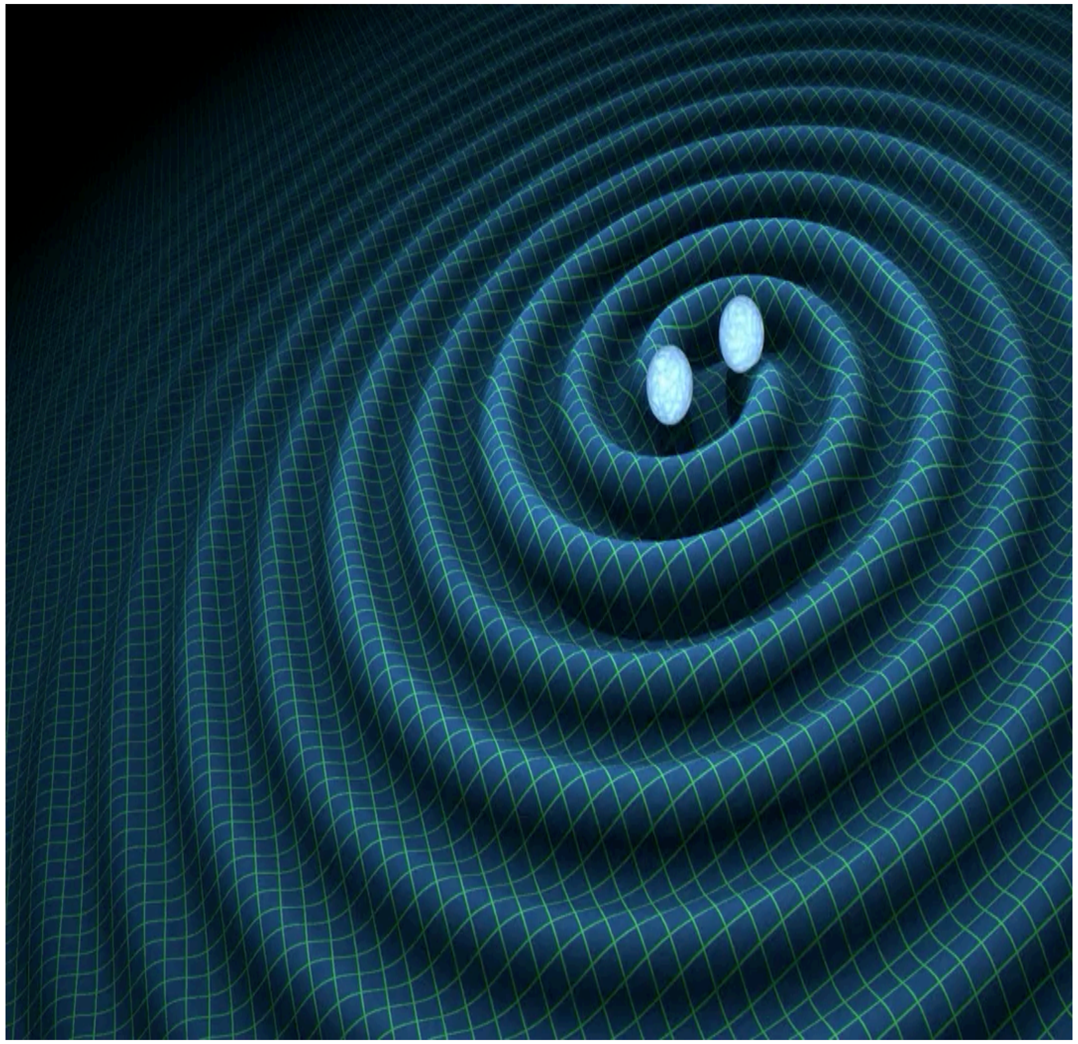
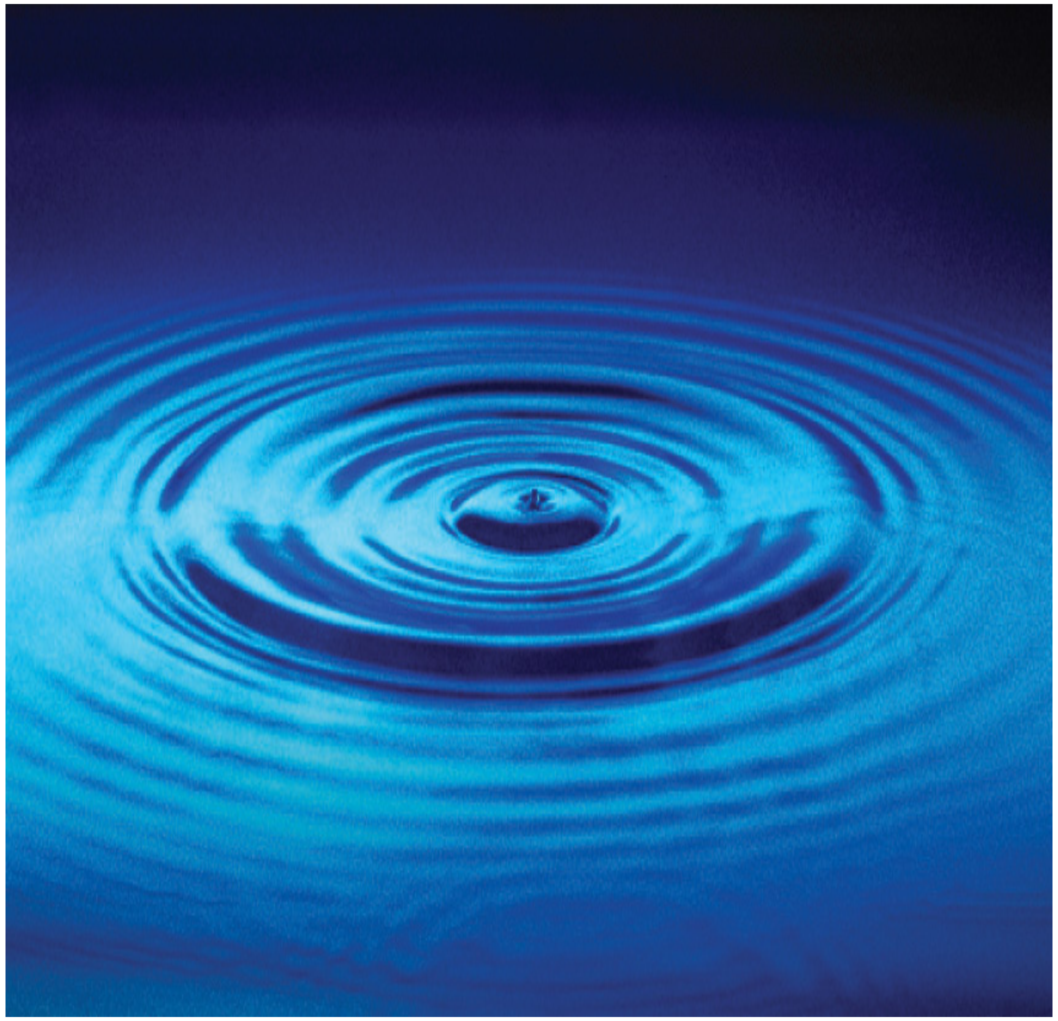


Merging COs in our universe

What are Gravitational Waves?



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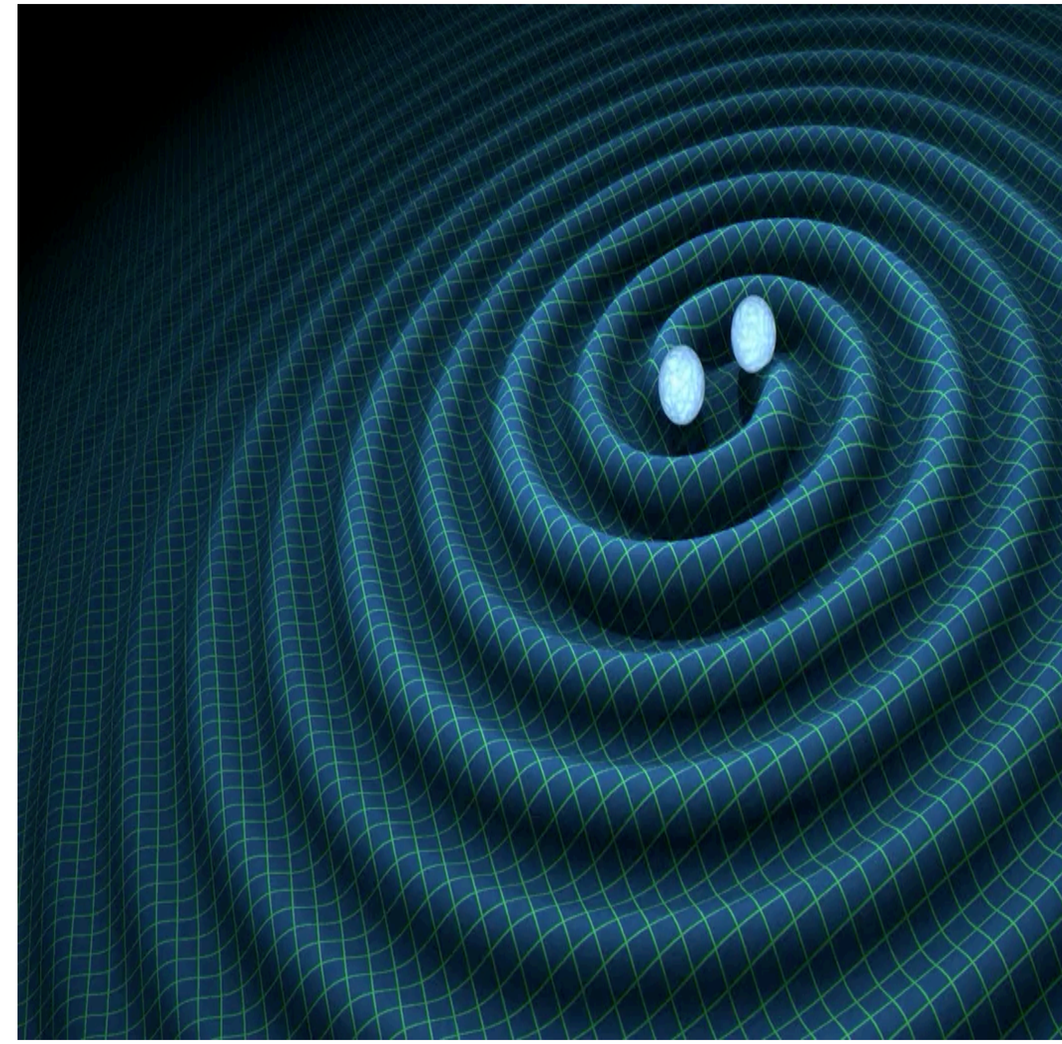


Merging COs in our universe

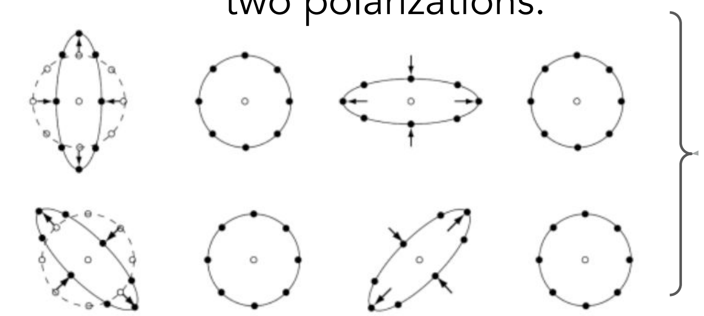
$$g_{\mu\nu} = \overbrace{\eta_{\mu\nu}}^{\text{flat}} + \overbrace{\boxed{h_{\mu\nu}}}^{\text{perturbation}}$$

linearized theory

$$\underbrace{\Box \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}}$$

wave equation for the perturbative metric term

two polarizations:



Gravitational Waves:
waves of space–time curvature
that accelerate free–falling particles

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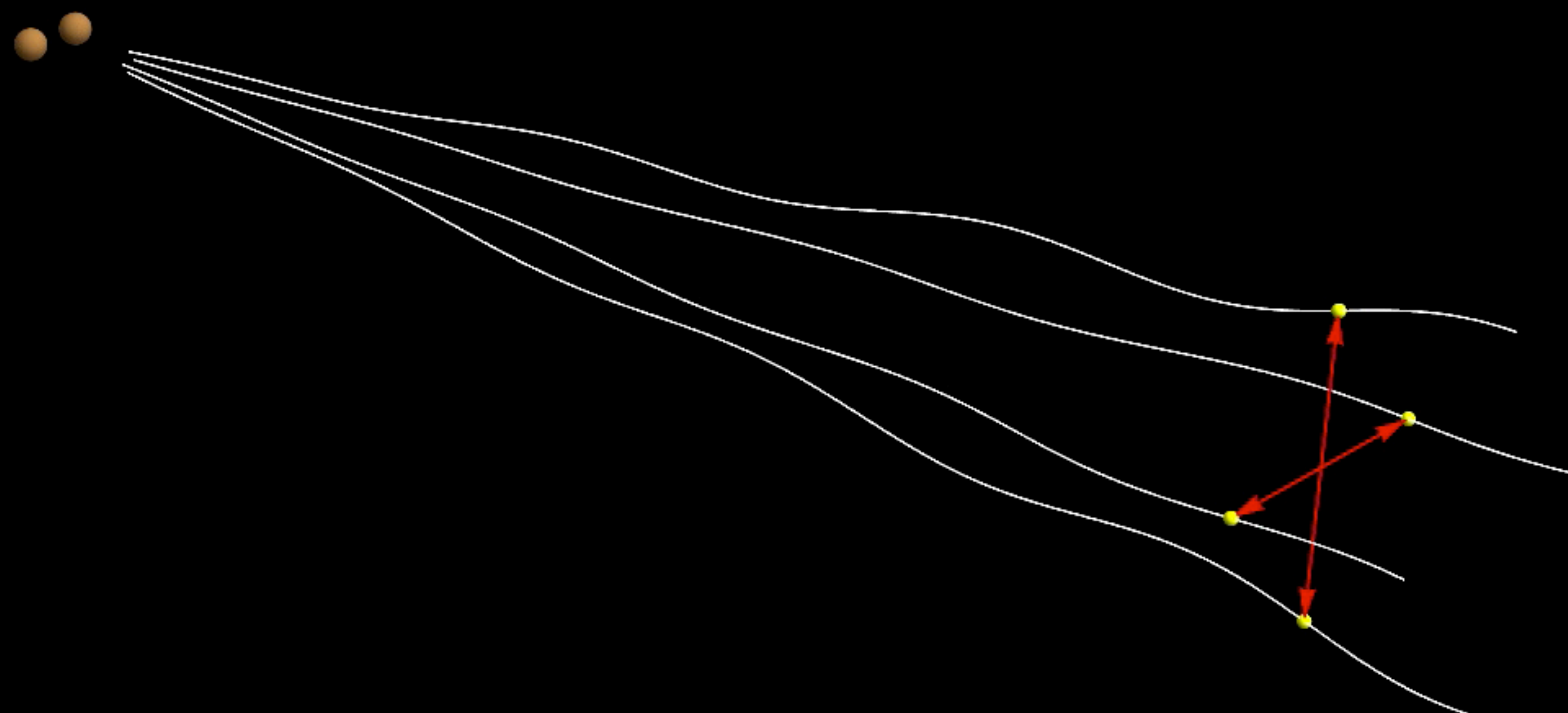
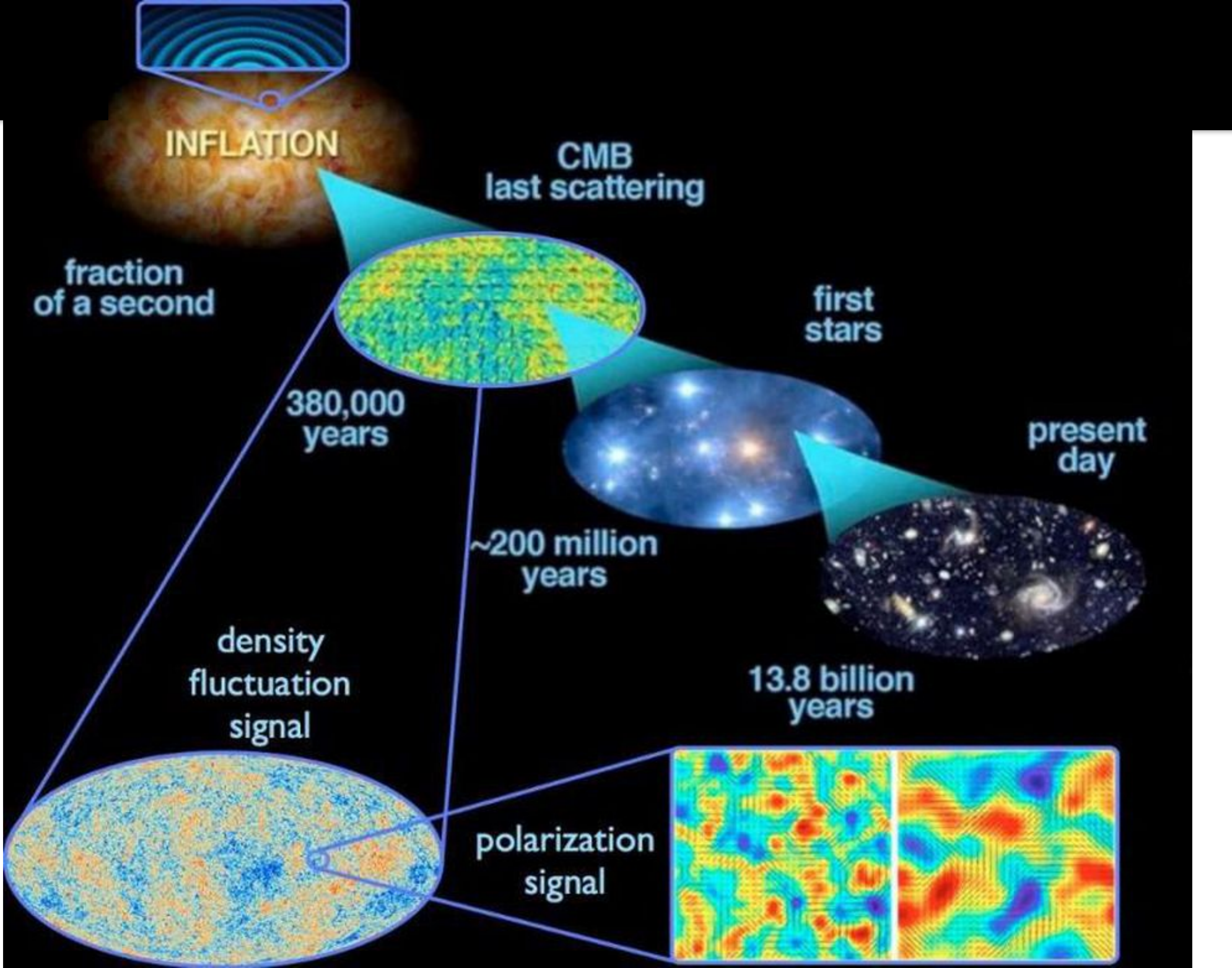


S. Vitale U.Trento/TIFPA


INFLATION
CMB
last scattering
fraction
of a second
first
stars
380,000
years
present
day
~200 million
years
density
fluctuation
signal
13.8 billion
years
polarization
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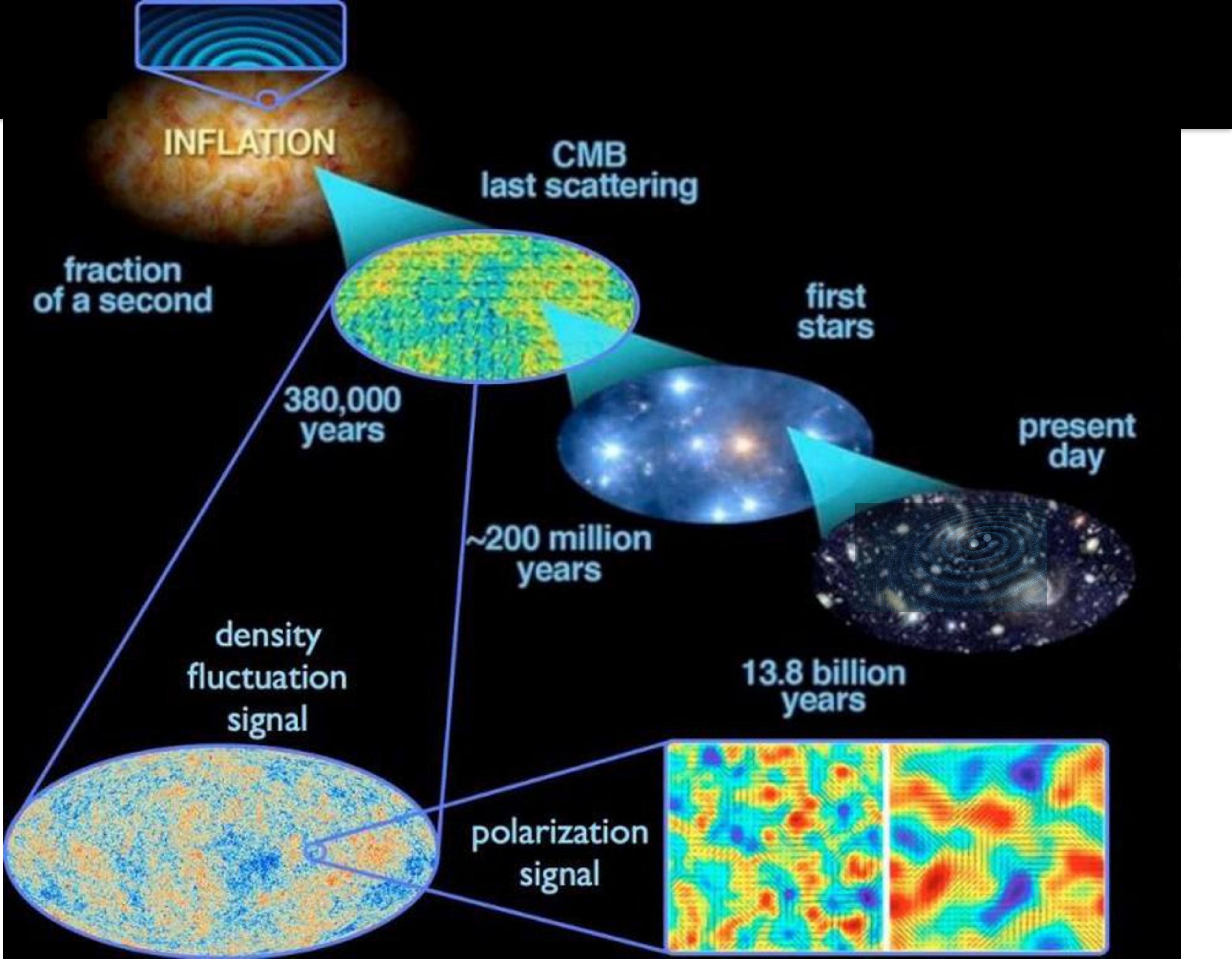

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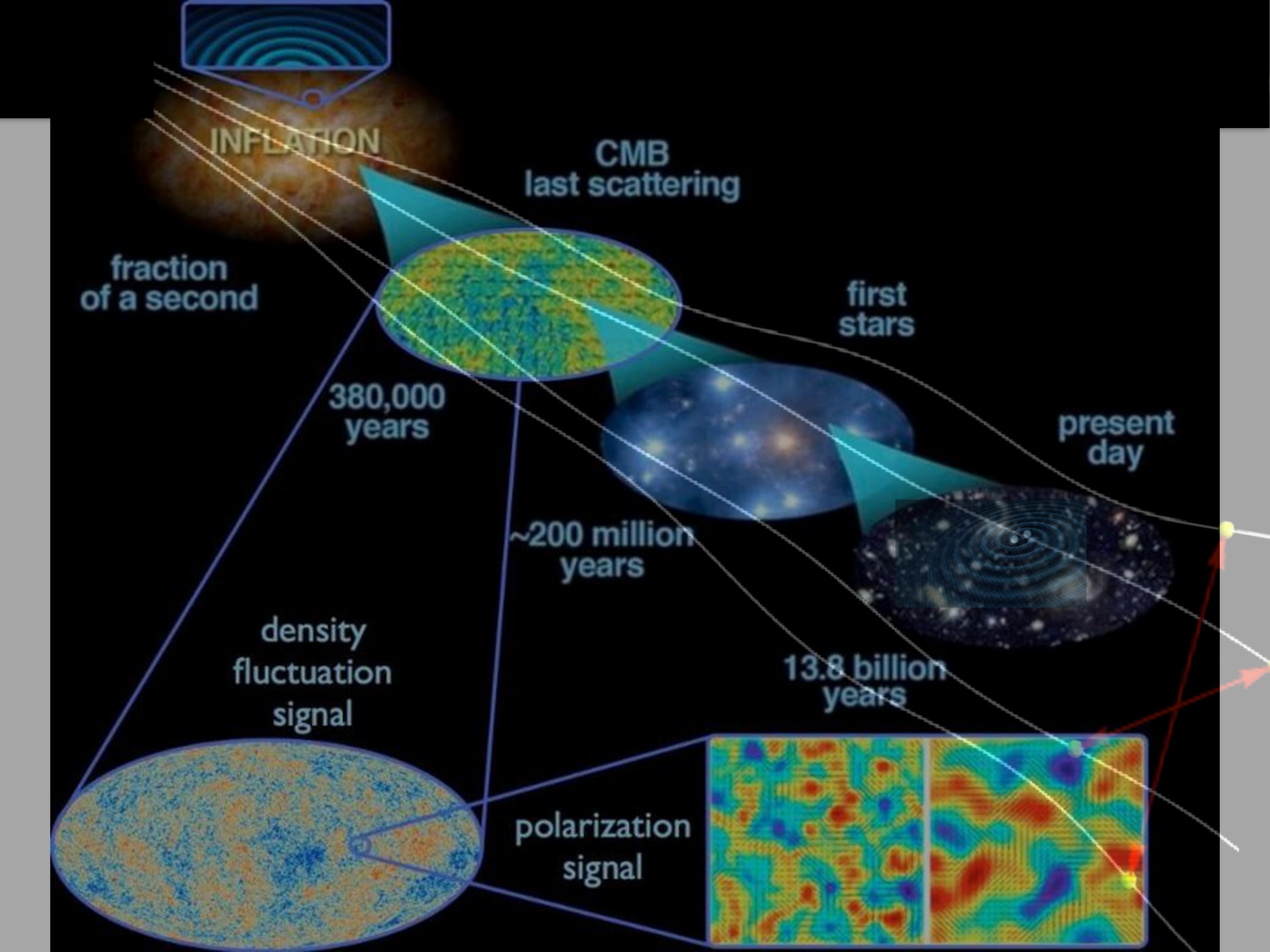
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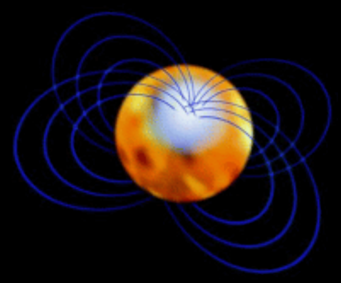
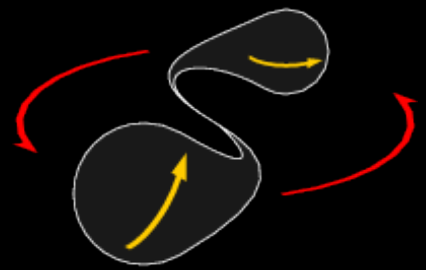
Sources of Gravitational Waves

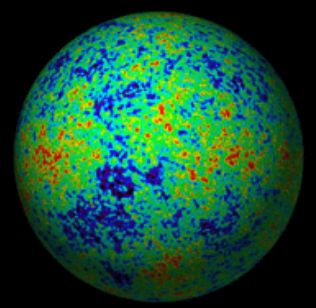
- **Supernova**: Explosion caused by the collapse of an old, burnt-out star
- Produces a burst of gravitational radiation, *if it is non-symmetric!*



- **Neutron star**: A city-sized atomic nucleus!
- Can spin at up to 600 cycles per second
- Emits continuous gravitational radiation (again, if it is non-symmetric)



- **Merging compact binary**: Collision of two stellar remnants (neutron stars or *black holes*)
- Produce a sweeping "chirp" as they spiral together



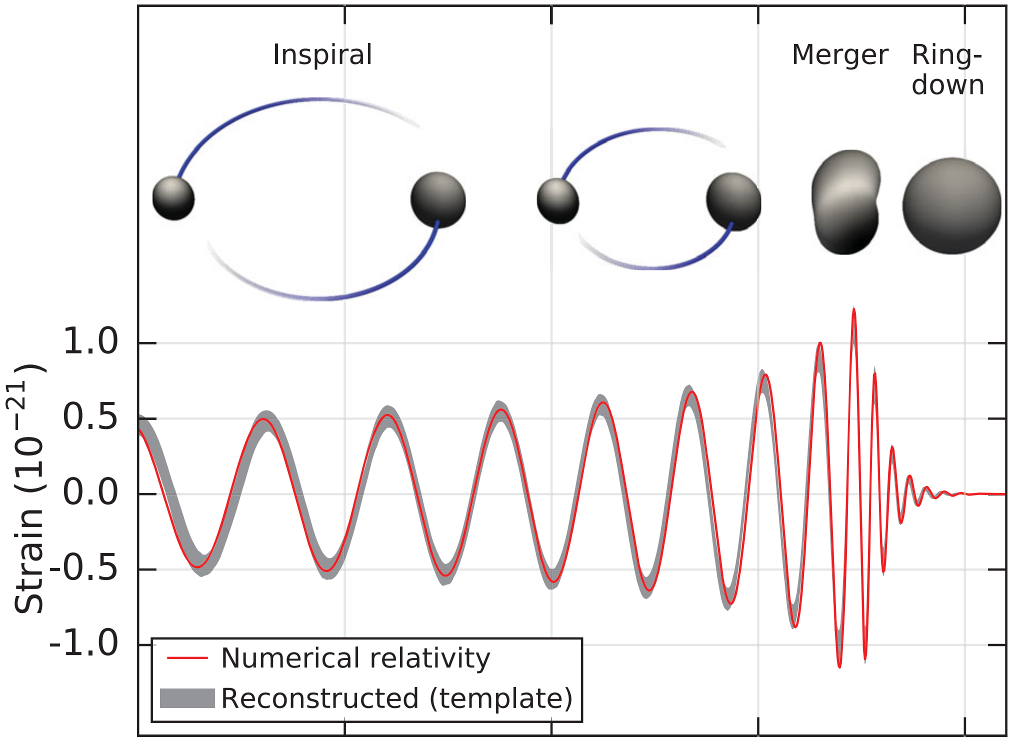
- **Primordial background**: Leftover radiation from the beginning of the Universe
- Tells us about the state of the Universe at *or before* the Big Bang!
- Sounds like "noise" with a characteristic spectrum

Other sources

Sources of Gravitational Waves

Resolved Sources:

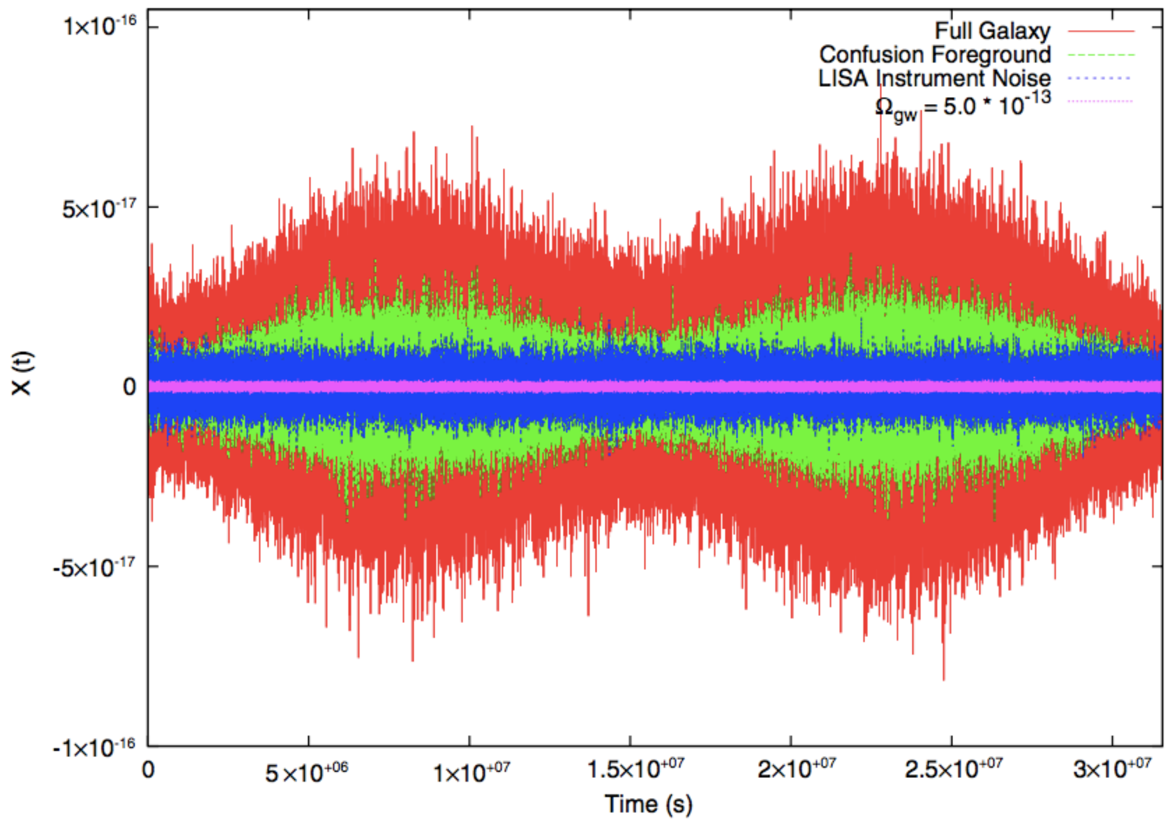
- Black Holes
- Neutron Stars
- White Dwarfs
- Supernovae
- …



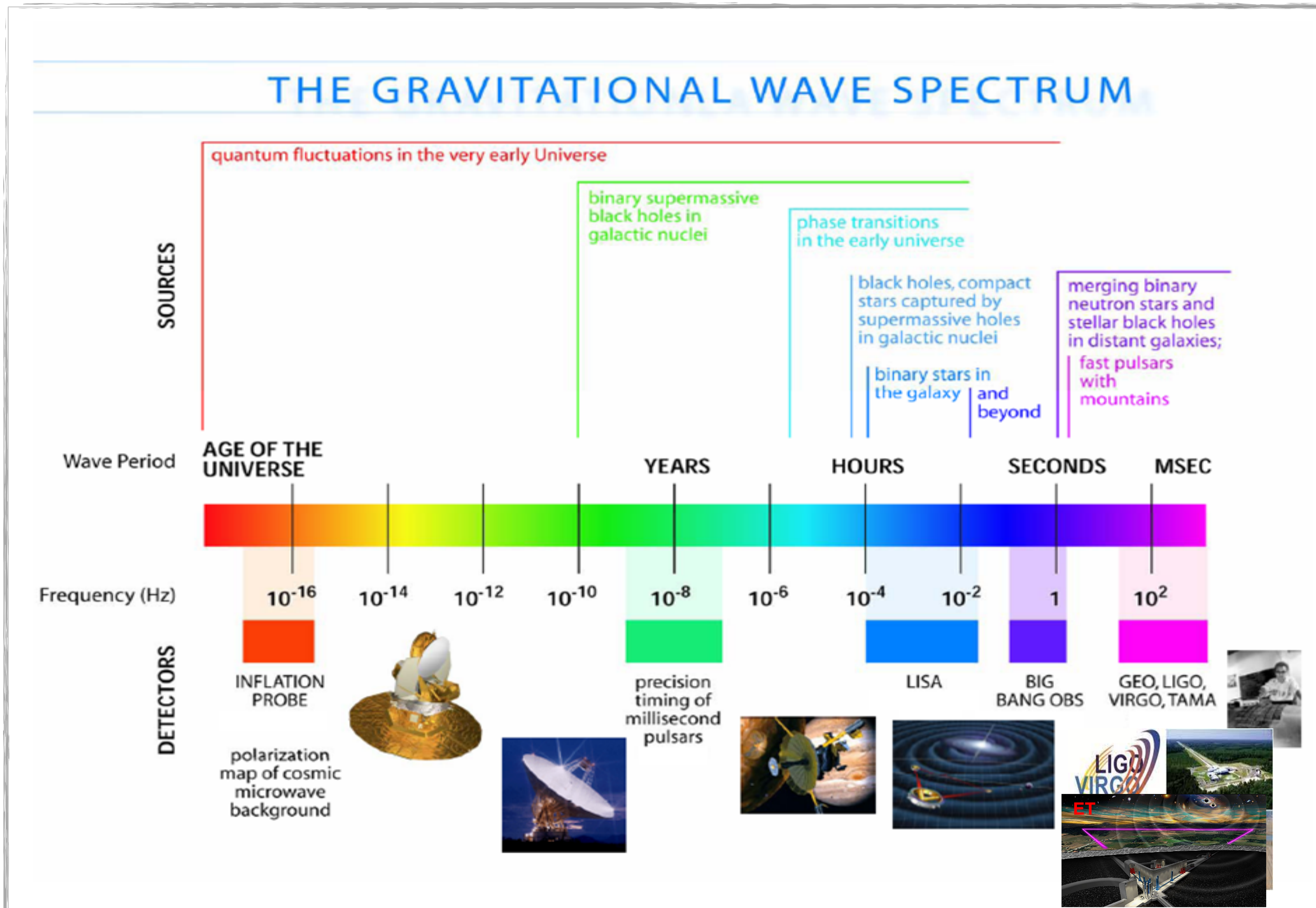
Unresolved Sources:

Stochastic Backgrounds

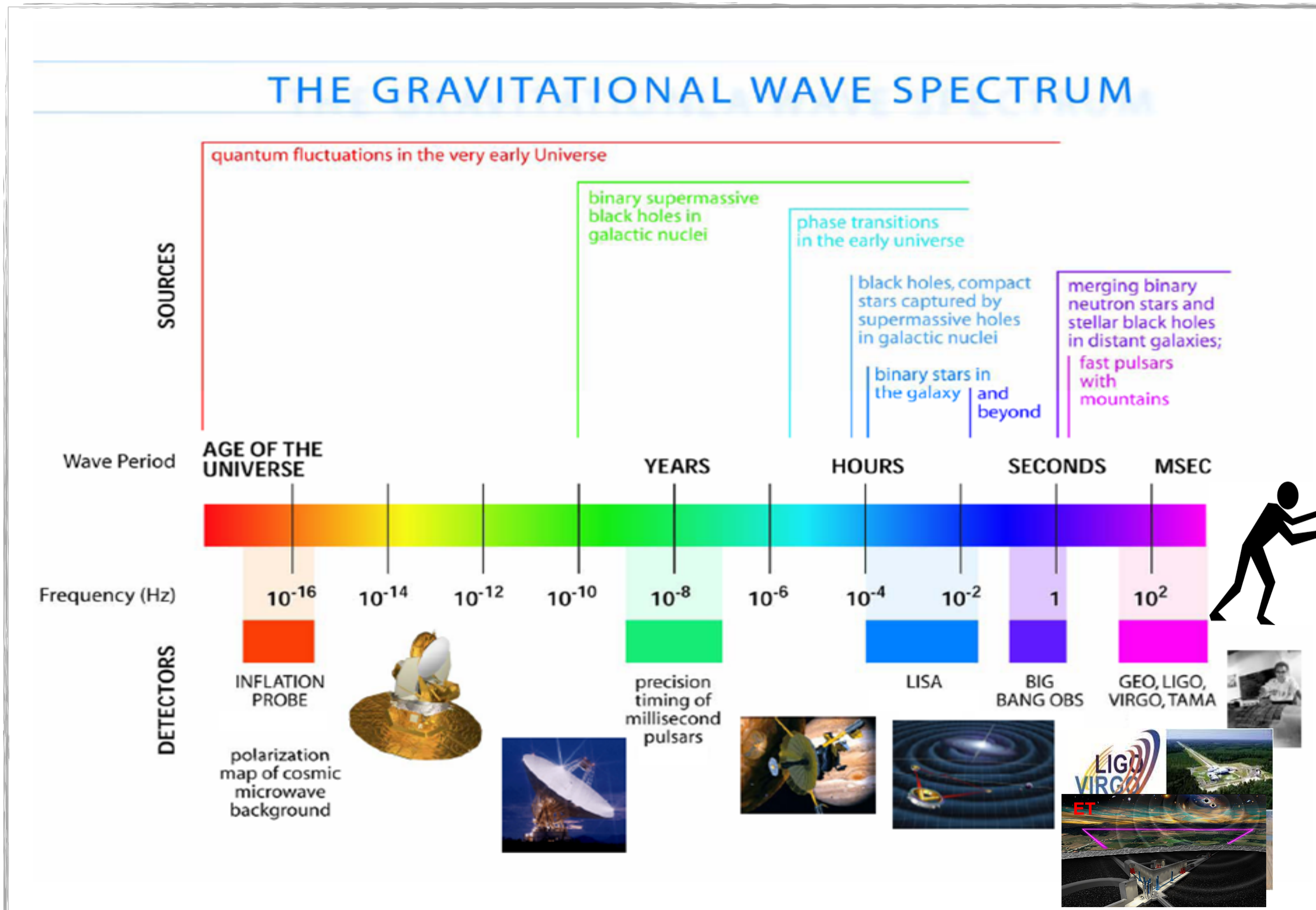
- **Astrophysical**
- **Cosmological**



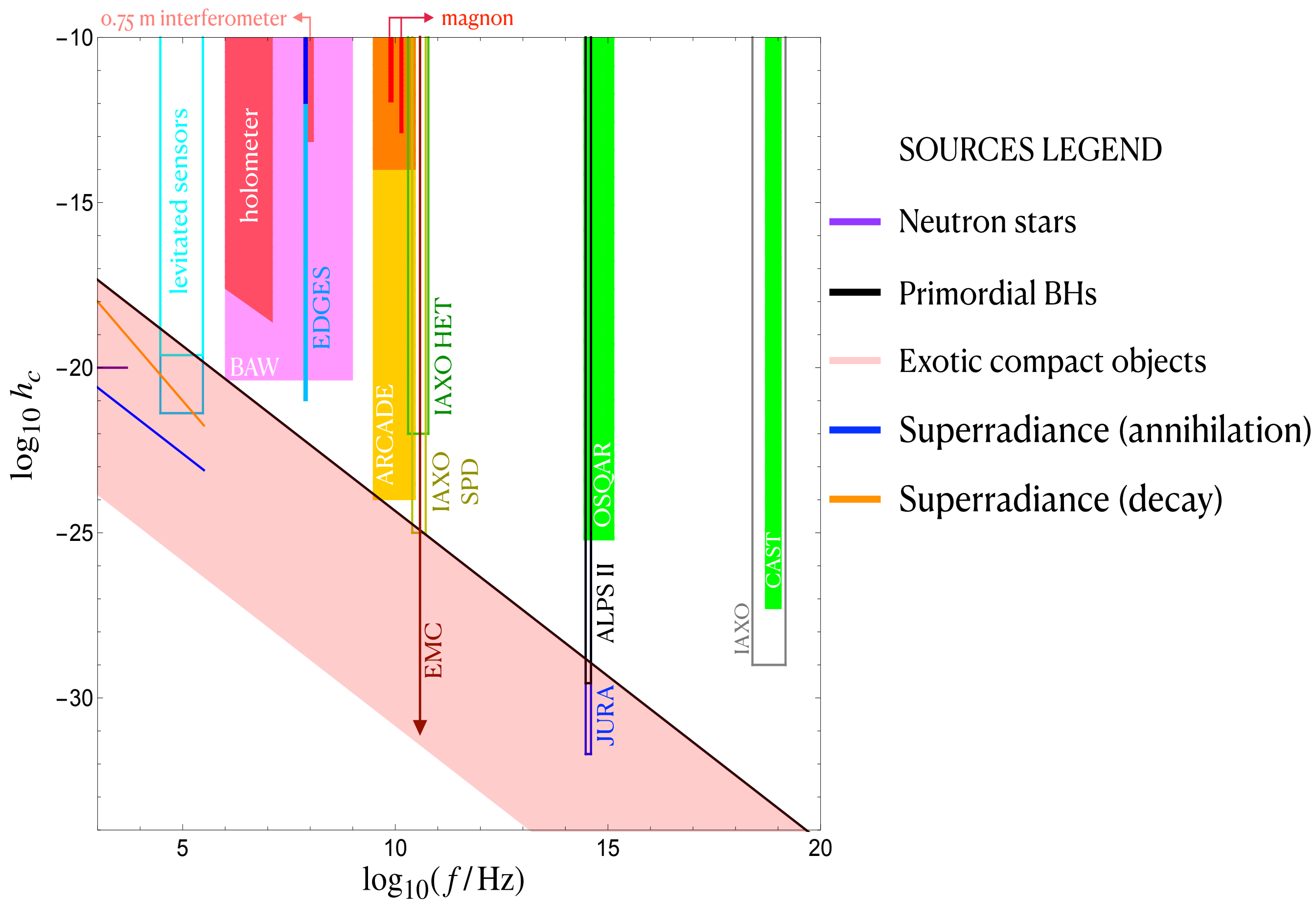
The Gravitational Wave Spectrum

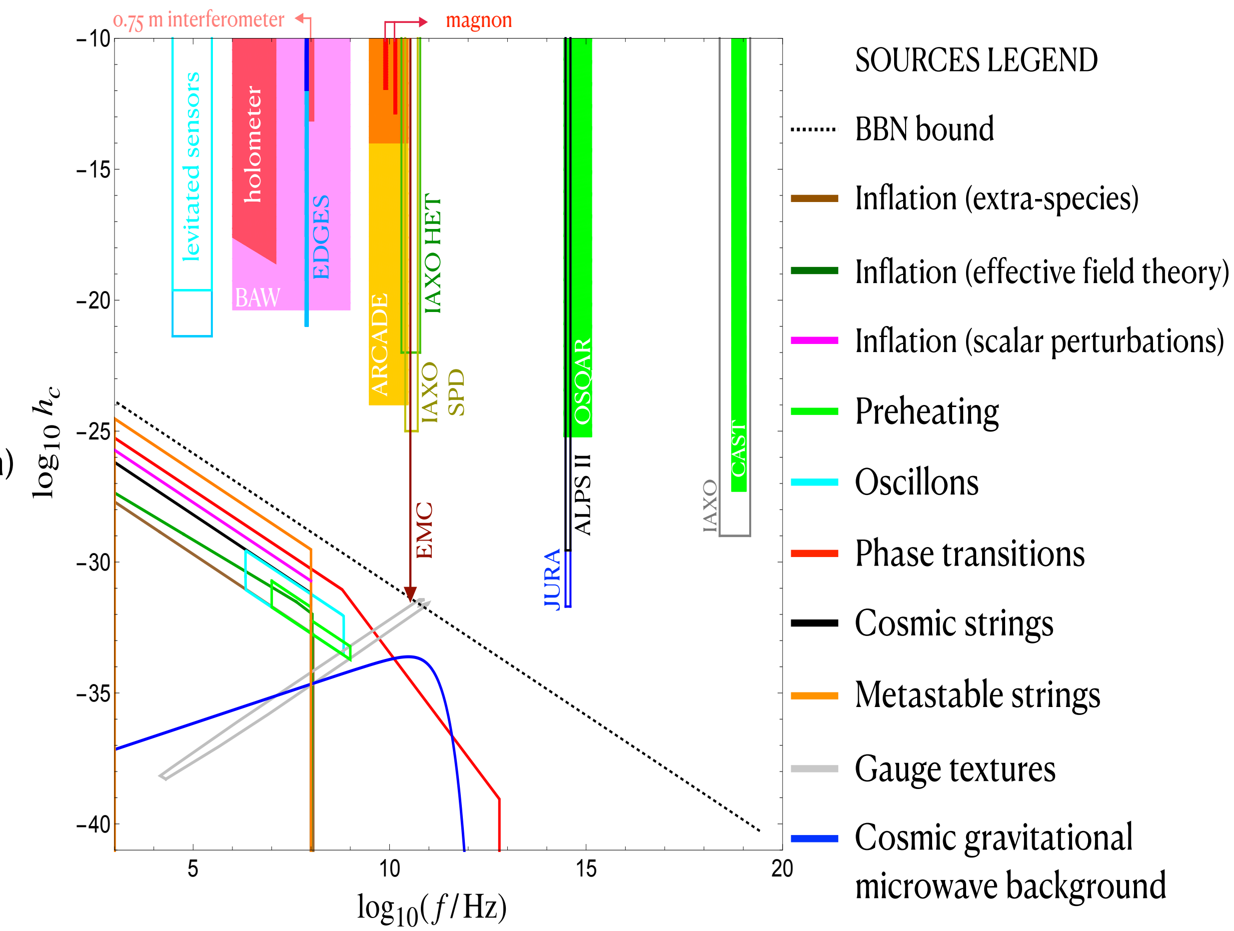


The Gravitational Wave Spectrum



High Frequency GWs

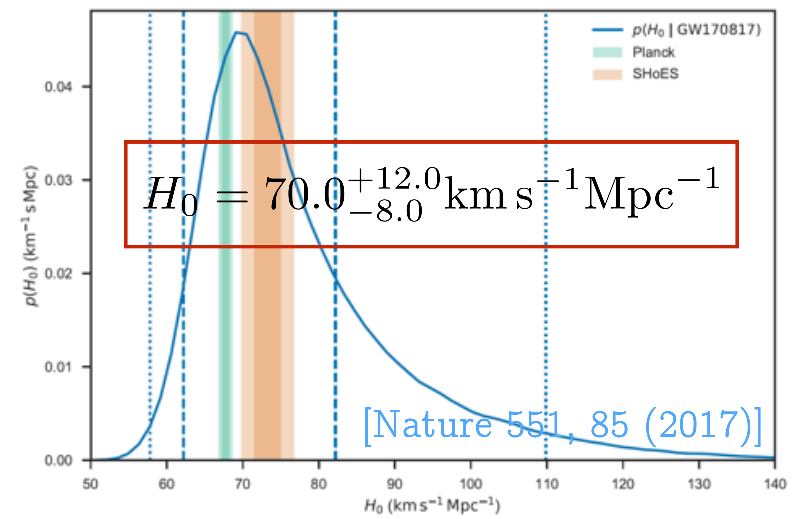




N. Aggarwal et al 2011.12414

What we have learned about Cosmology so far?

- We obtained the **first measurement of the Hubble constant using GWs**



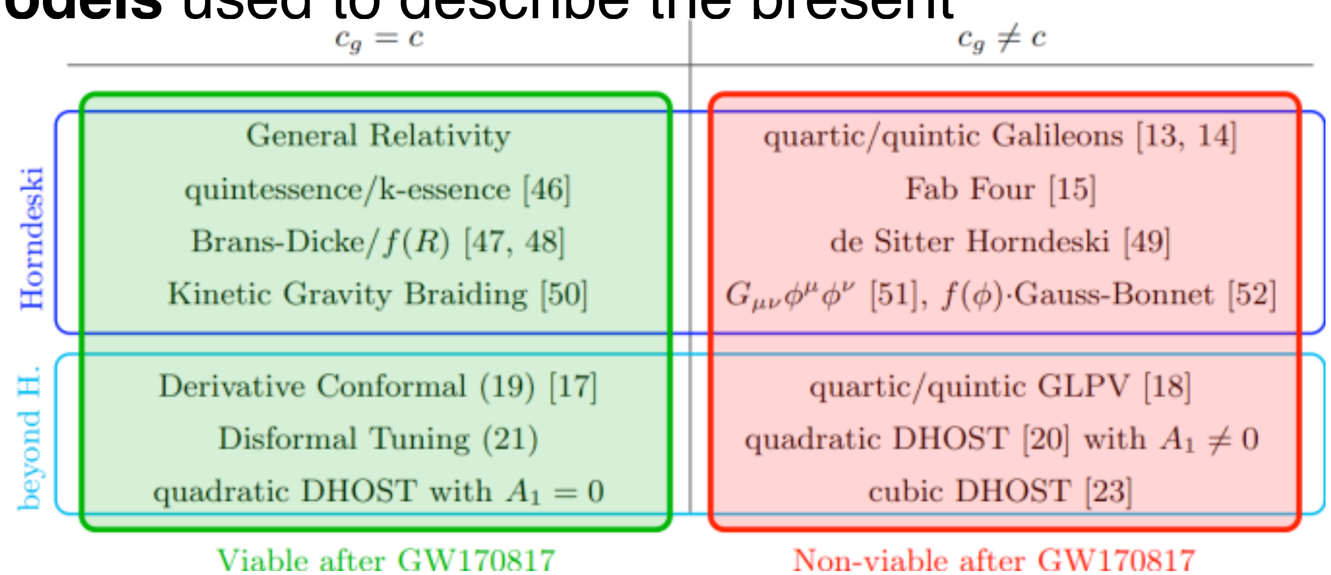
- **We have tested and bounded deviations from GR** (e.g., graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.)

$$m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV/c^2}$$

- **The speed of GWs is the same as the speed of light**

$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 6 \cdot 10^{-16}$$

- We have **ruled out many Modified Gravity models** used to describe the present acceleration of our Universe



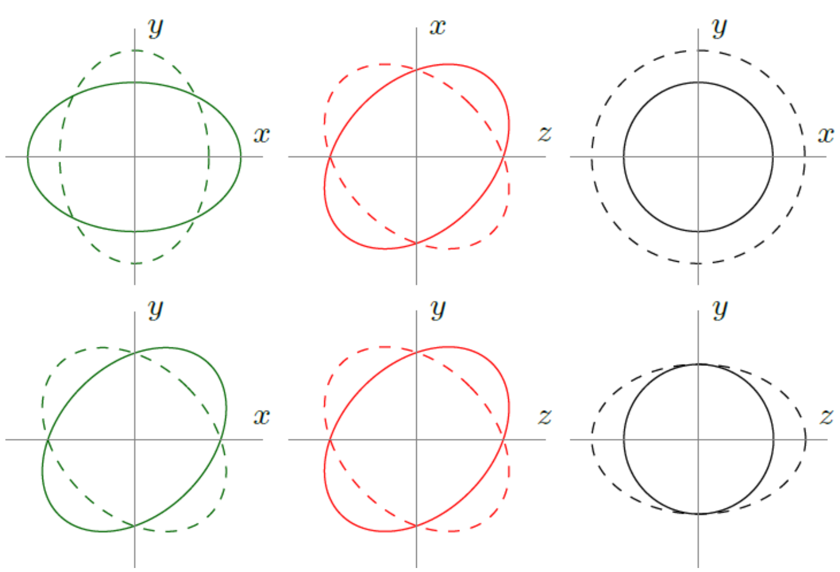
LVK arxiv:2112.06861

Fundamental physics: polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

General metric theories also know
vector (V) and scalar (S) polarizations

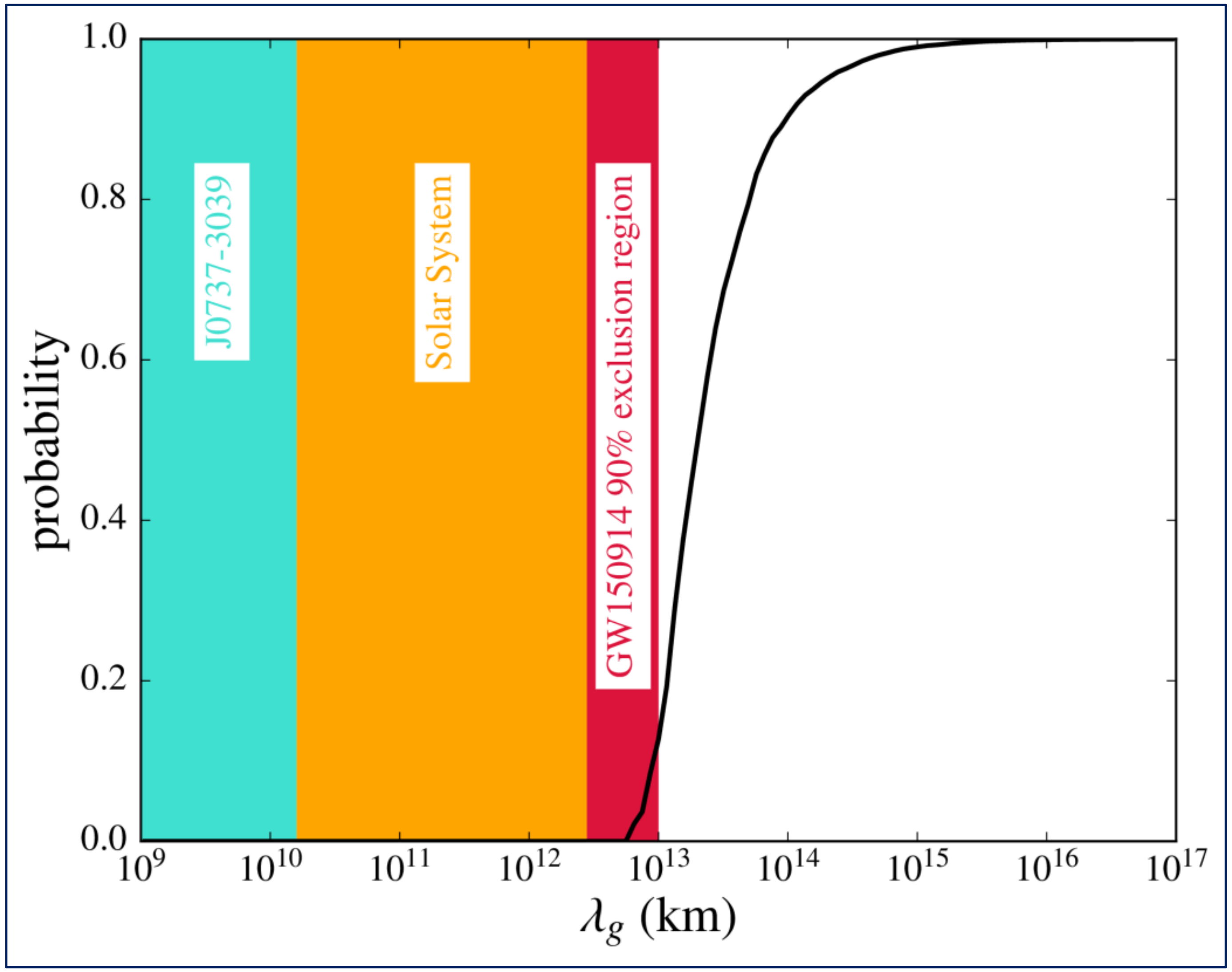


Theory	+	x	x	y	b	l
General Relativity	allowed	allowed	forbidden	forbidden	forbidden	forbidden
GR in noncompactified 4/6D Minkowski	allowed	allowed	allowed	allowed	allowed	allowed
Einstein-Æther	allowed	allowed	allowed	allowed	allowed	allowed
5D Kaluza-Klein	allowed	allowed	allowed	allowed	allowed	forbidden
Randall-Sundrum braneworld	allowed	allowed	forbidden	forbidden	forbidden	forbidden
Dvali-Gabadadze-Porrati braneworld	allowed	allowed	depends	depends	depends	depends
Brans-Dicke	allowed	allowed	forbidden	forbidden	allowed	allowed
f(R) gravity	allowed	allowed	forbidden	forbidden	allowed	allowed
Bimetric theory	allowed	allowed	allowed	allowed	allowed	allowed
Four-Vector Gravity	forbidden	forbidden	allowed	allowed	forbidden	forbidden

Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther]. allowed / depends / forbidden

Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2c^4$

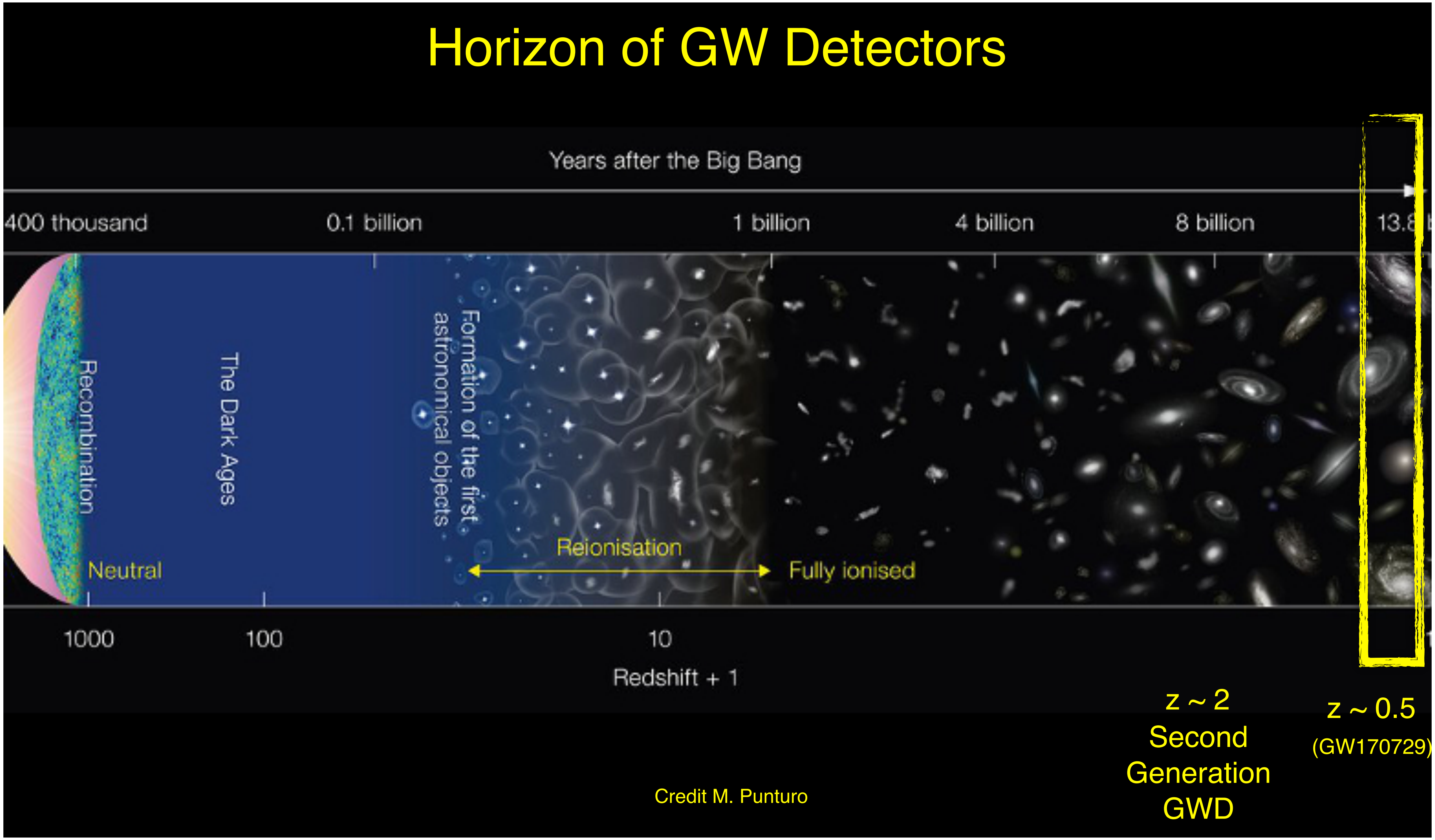
We have $\lambda_g = h/(m_g c)$

Thus frequency dependent speed
$\frac{v_g^2}{c^2} \equiv \frac{c^2p^2}{E^2} \cong 1 - h^2c^2/(\lambda_g^2 E^2)$

$\lambda_g > 10^{13}$ km
$m_g \leq 5 \times 10^{-23}\mathrm{eV}/c^2$

See "*Tests of general relativity with GW150914*"
http://arxiv.org/abs/1602.03841

Where is the horizon?

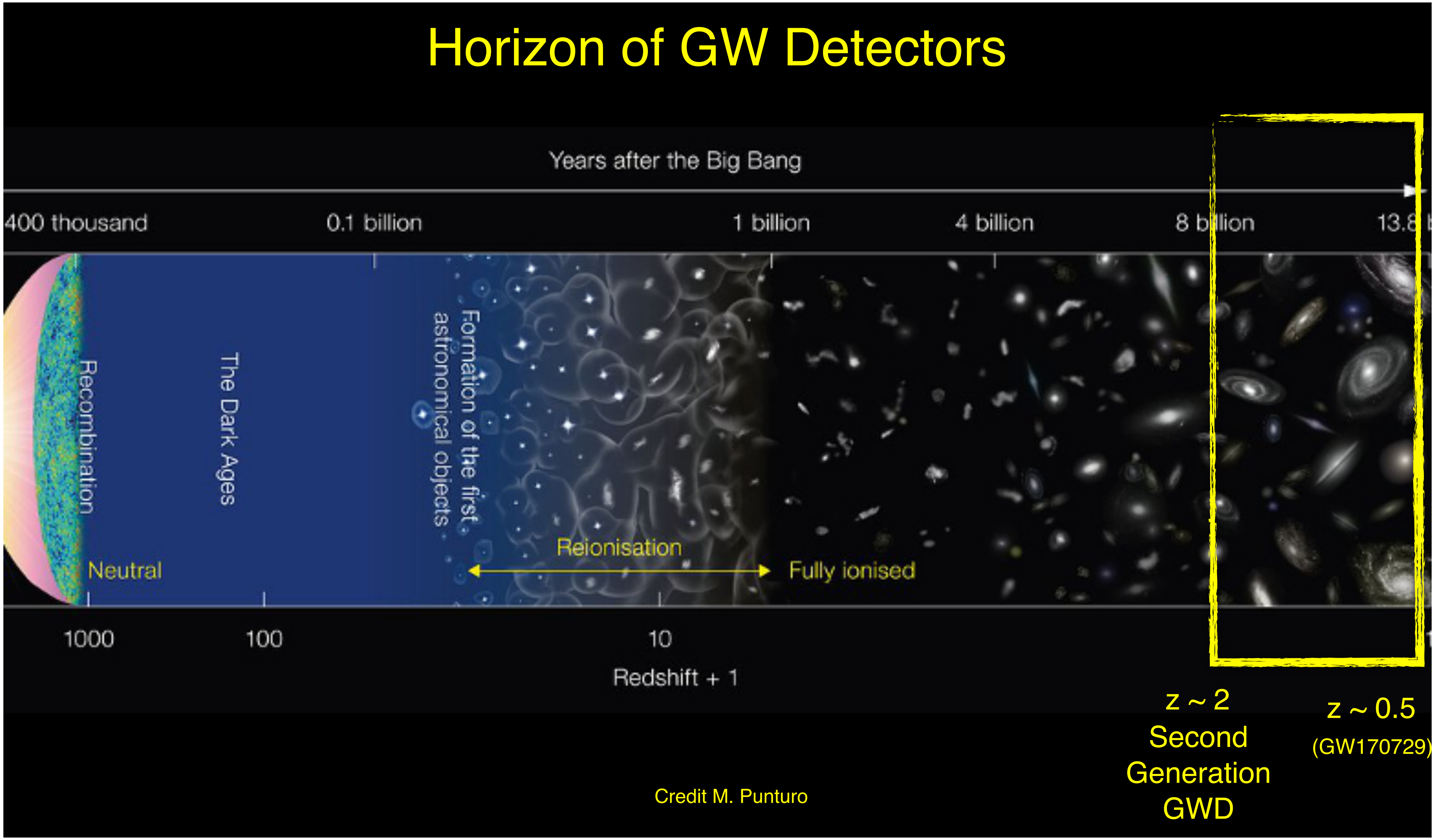


Adv LIGO - Virgo - KAGRA:

BBHs only up to $z \sim 2$

BNSs in the very local Universe

Where is the horizon?



Adv LIGO - Virgo - KAGRA:
- BBHs only up to $z \sim 2$
- BNSs in the very local Universe

Open questions in Cosmology

Early Universe

Primordial GWs

Cosmic Structure

Dark Matter

Primordial BHs?

Axion particles

Late Universe

Dark Energy

Modified Gravity?

Cosmic Tensions

H_0 measurements?

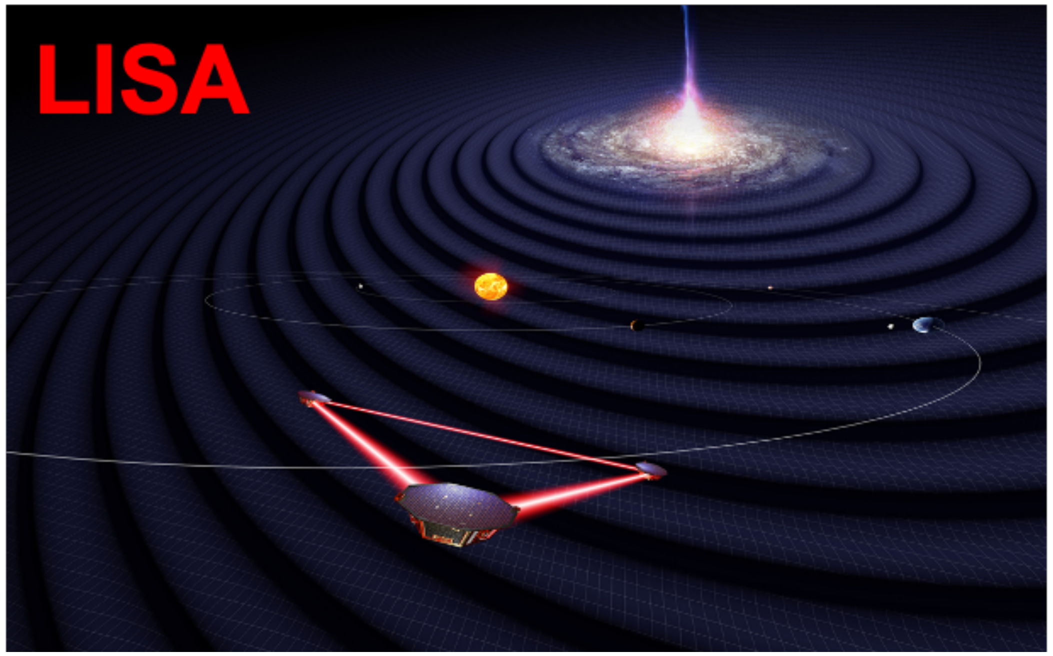
Isotropy

Testing Cosmological Principle

RESOLVED SOURCES

SGWB

Prospects for next Generation GW Interferometers

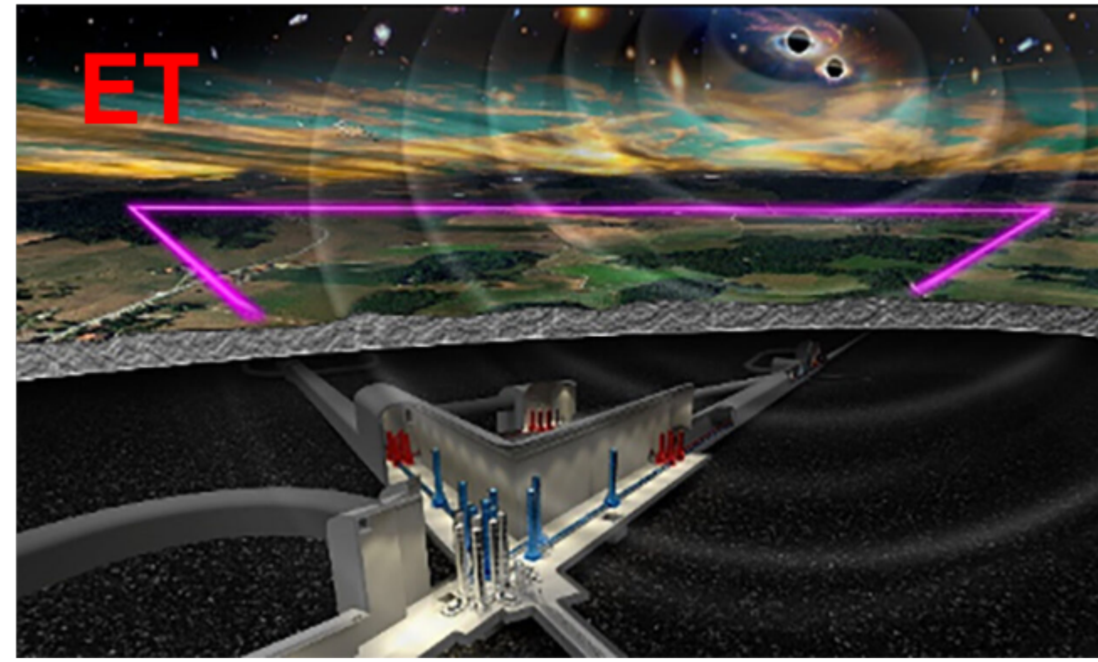


Geometry: **Constellation of 3 spacecraft in an equilateral configuration** (a giant interferometer)

Mission duration: **4 y science mission**
10 y nominal mission

Arm Length: **2.5 million km**

Expected Launch: 2034



Geometry: **Ground-based Triangular detector (HF+LF)**

Arm Length: **10 km**

Expected to be operative in: 2034

ET collaboration officially launched

+ CE, DECIGO, BBO, Taiji, TianQin, etc

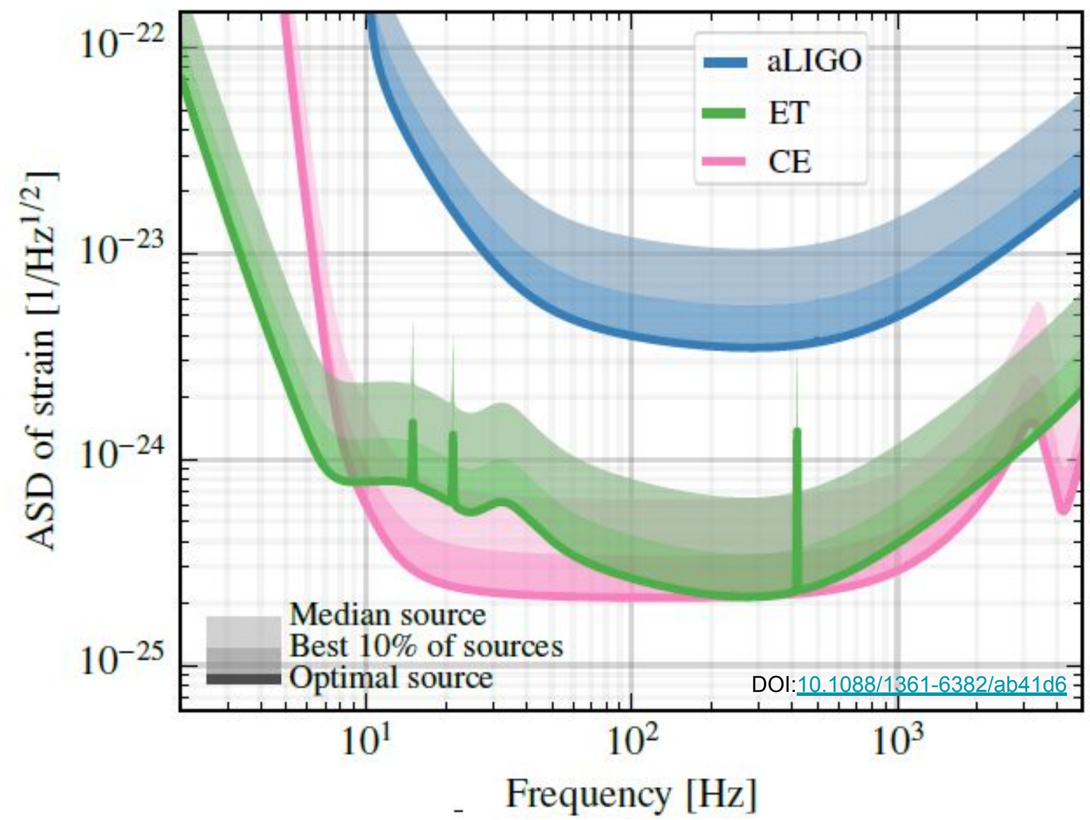
Without forgetting AdV -> Virgo-nEXT

Einstein Telescope

But current LVK detectors have limitations: need to jump to next generation detectors:

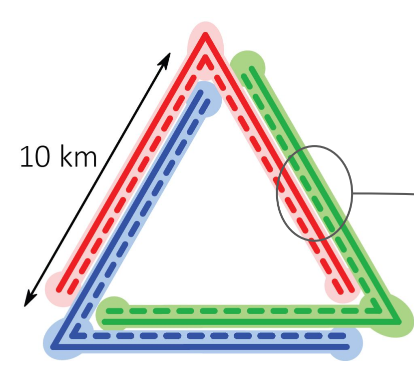
- **Einstein Telescope (ET)**:
  - EU proposal for 3G observatory
  - Design study (baseline) triangle with arms of 10km
- **Cosmic Explorer (CE)**:
  - US proposal for 3G observatory
  - L-shaped 40km interferometer

ET and CE will provide an improvement in sensitivity by one order of magnitude and a significant enlargement of the bandwidth



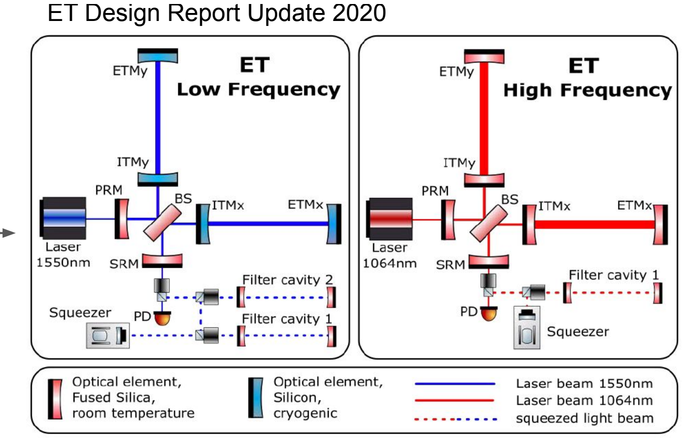
The current design of ET:

- **single site** located **200-300 meters underground** in order to significantly reduce seismic noise;
- **triangular shape**, consisting of three nested detectors
  - providing redundancy
  - resolving the GW polarizations and a null stream
- **'xylophone'** configuration: each detector consists of two interferometers
  - ○ one tuned toward **high frequencies (HF)**, and using high laser power
  - ○ one tuned toward **low-frequency (LF)**, working at cryogenic temperatures and low laser power



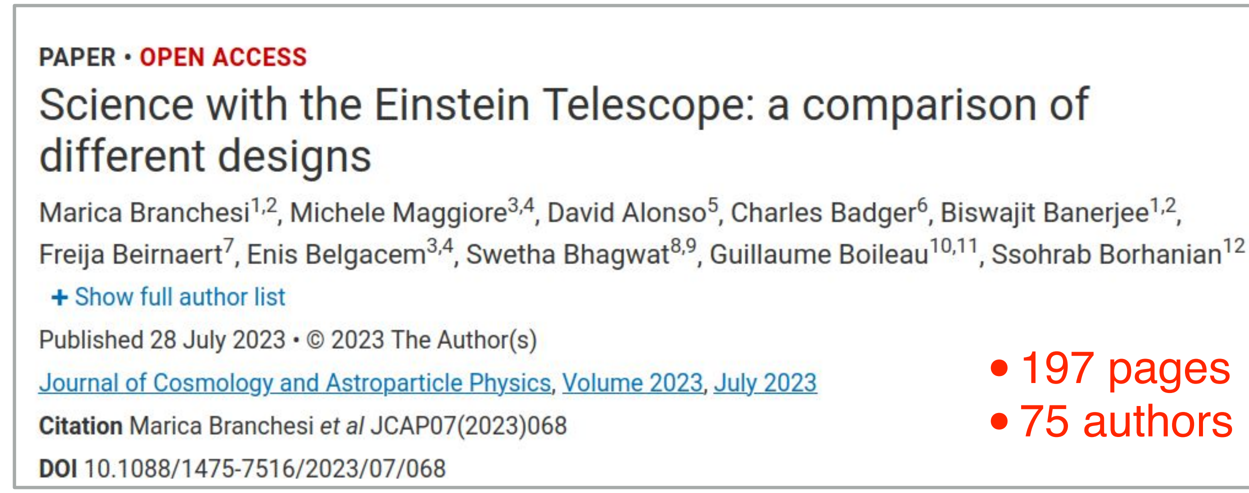
ET Design Report Update 2020

ET Design Report Update 2020



Einstein Telescope - possible designs

In the last years, proposals for **different designs** were made as they may bring **scientific advantages** with respect to the baseline design.


PAPER • OPEN ACCESS

Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi[1,2], Michele Maggiore[3,4], David Alonso[5], Charles Badger[6], Biswajit Banerjee[1,2], Freija Beirnaert[7], Enis Belgacem[3,4], Swetha Bhagwat[8,9], Guillaume Boileau[10,11], Ssohrab Borhanian[12]

+ Show full author list

Published 28 July 2023 • © 2023 The Author(s)

Journal of Cosmology and Astroparticle Physics, Volume 2023, July 2023

Citation Marica Branchesi *et al* JCAP07(2023)068

DOI 10.1088/1475-7516/2023/07/068

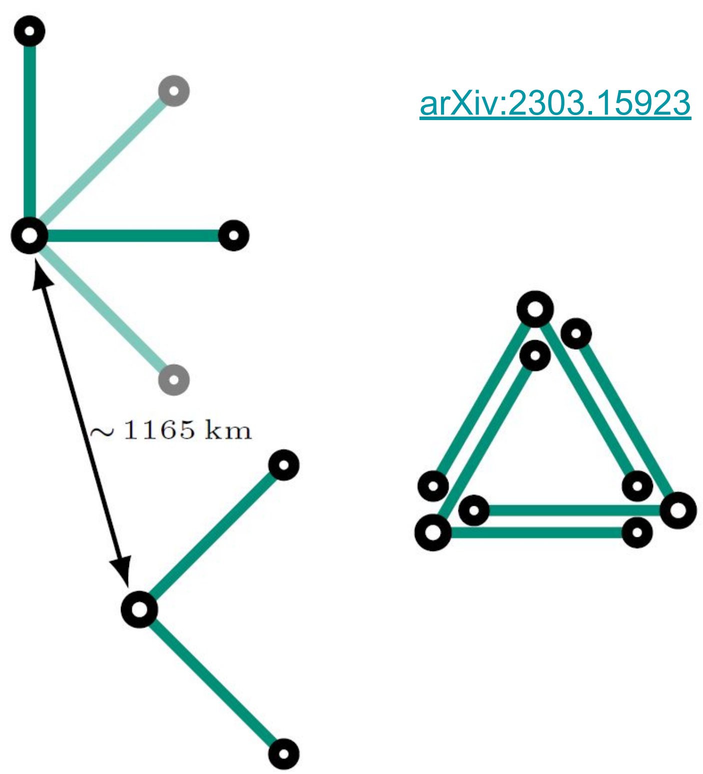
- 197 pages
- 75 authors

Different geometries are studied:

- **1 Triangular detector** vs **2 L-shaped detector**
- **different arm length** (10, 15, 20 km)
- Cryo LF may be challenging to achieve: **HF+LF** vs **HF only**

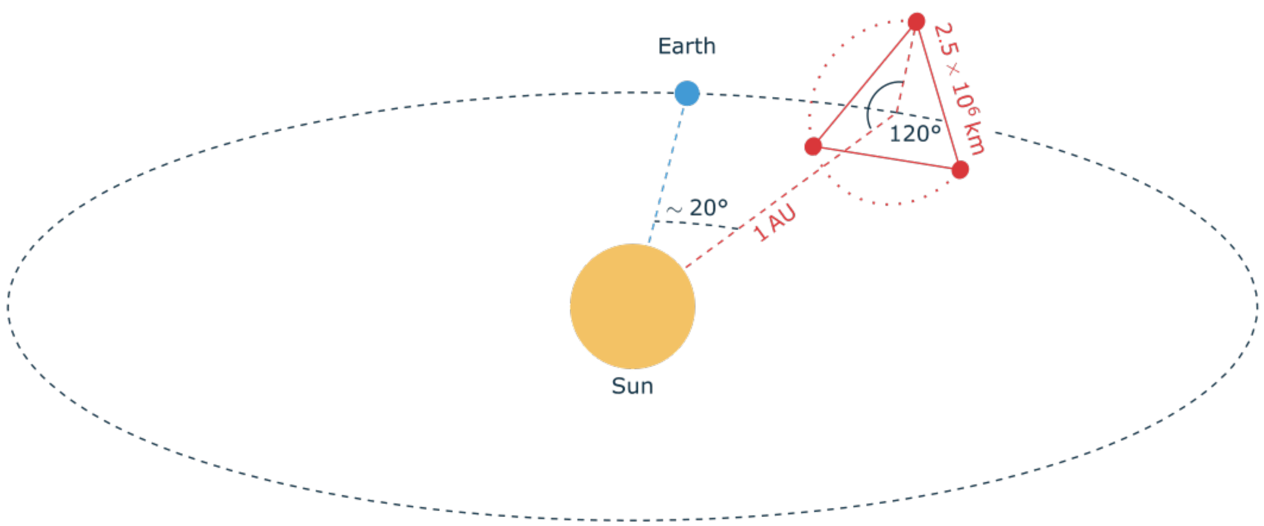
For **2L-shape** two different orientations are proposed:

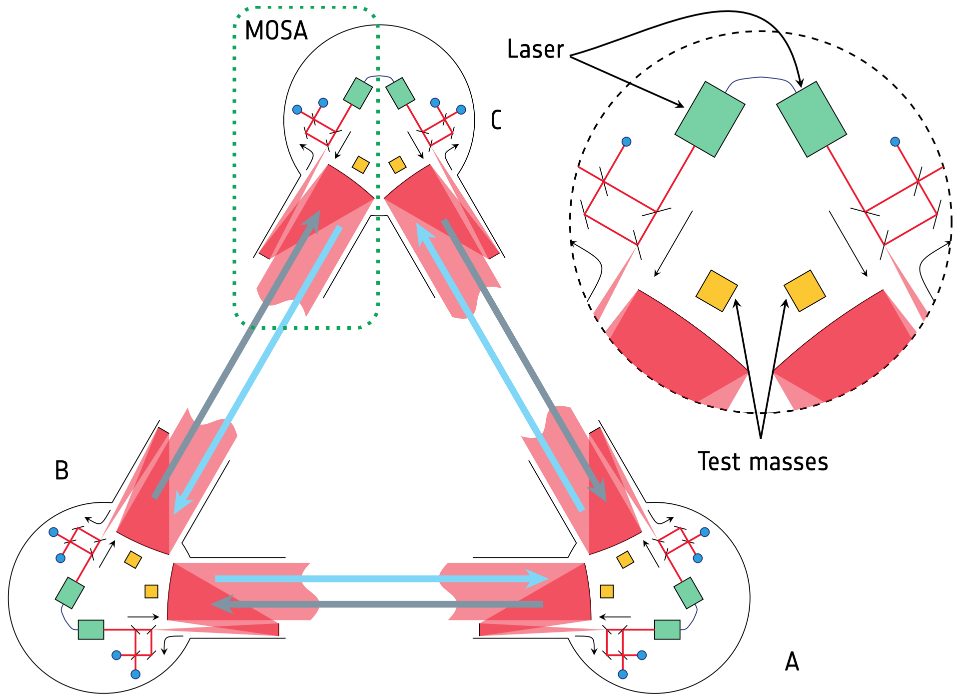
- parallel
- 45° angle



arXiv:2303.15923

LISA





Mission	
Duration	4.5 years science orbit • >82 % duty cycle • ~6.25 years including transfer and commissioning
Constellation	Three drag-free satellites forming an equilateral triangle • 2.5×10^6 km separation • trailing/leading Earth by ~20° • inclined by 60° with respect to the ecliptic
Orbits	Heliocentric orbits • semimajor axis ~1 AU • eccentricity $e \approx 0.0096$ • inclination $i \approx 0.96°$

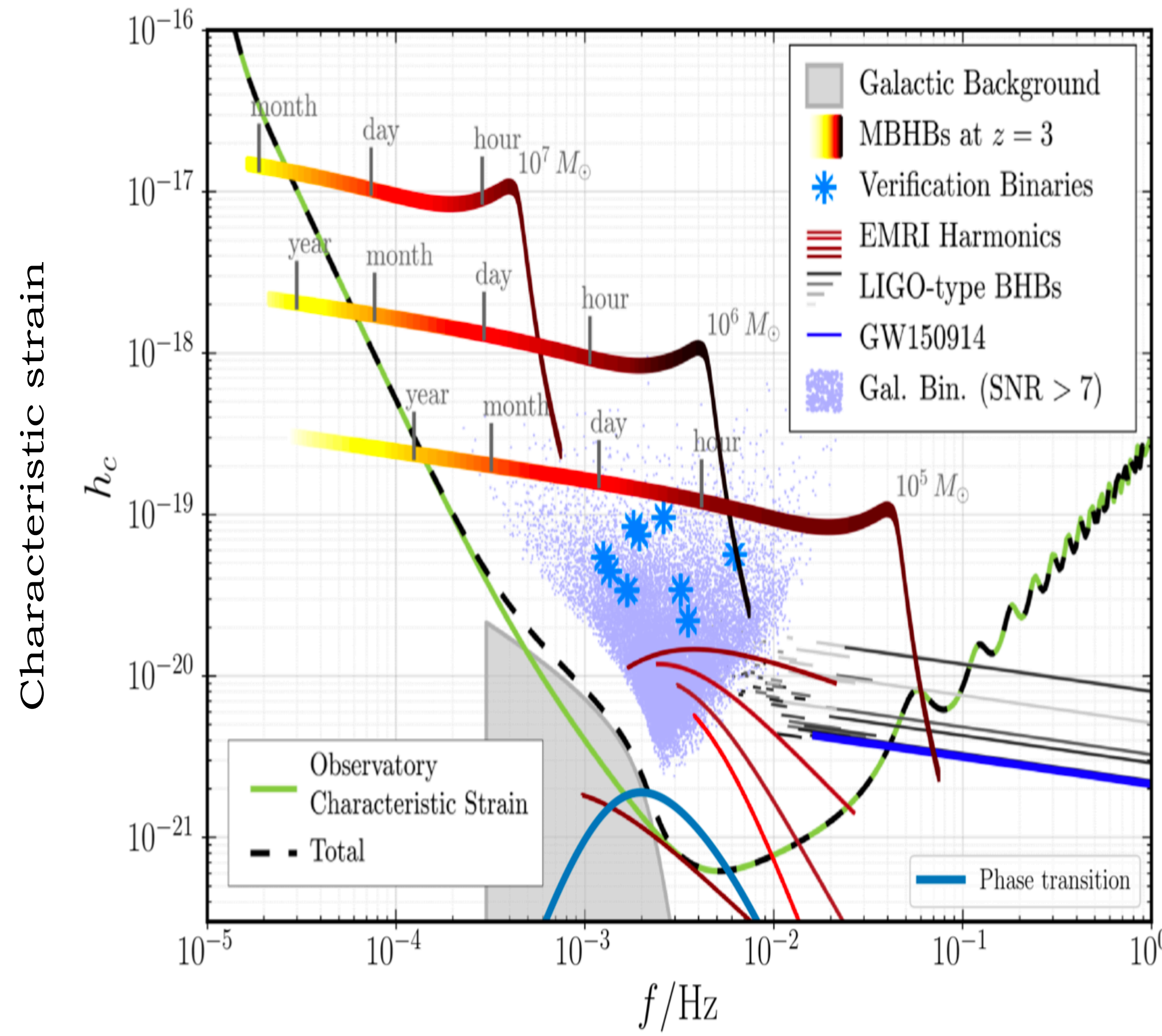
Payload	
Lasers	2 per spacecraft • 2 W output power • wavelength 1064 nm • frequency stability 300 Hz/$\sqrt{\text{Hz}}$
Optical Bench	2 per spacecraft • double-sided use • high thermal stability (Zerodur)
Interferometry	heterodyne interferometry • 15 pm/$\sqrt{\text{Hz}}$ precision • Inter-spacecraft ranging to ~1 m
Telescope	2 per spacecraft • 30 cm off-axis telescope • high thermal stability
Gravitational Reference System	2 per spacecraft • acceleration noise <3 fm/(s^2 $\sqrt{\text{Hz}}$) • 46 mm cubic AuPt test mass • Faraday cage housing • electrostatic actuation in 5 degree of freedom

LISA RED BOOK- ESA

LISA - Science Objectives

Science Objectives

- Study the formation and evolution of **compact binary stars** and the structure of the Milky Way Galaxy
- Trace the origins, growth and merger histories of **massive Black Holes** across cosmic epochs
- Probe the properties and immediate environments of Black Holes in the local Universe using **extreme mass-ratio inspirals** and **intermediate mass-ratio inspirals**
- Understand the astrophysics of **stellar-mass Black Holes**
- Explore the **fundamental nature of gravity** and Black Holes
- Probe the rate of **expansion of the Universe** with standard sirens
- Understand **stochastic gravitational wave backgrounds** and their implications for the early Universe and TeV-scale particle physics
- Search for gravitational wave bursts and **unforeseen sources**



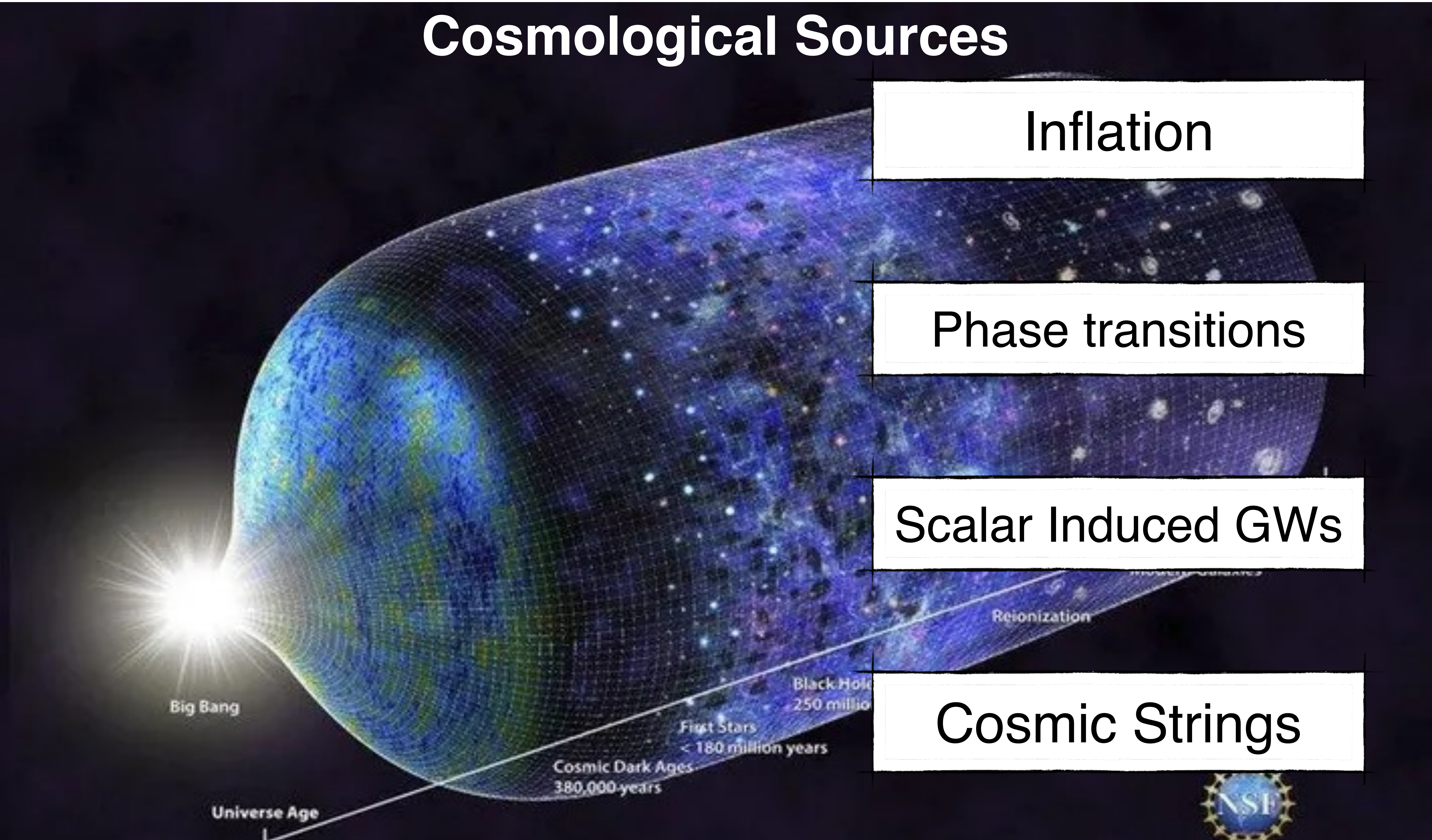
GW frequency today

LISA consortium arXiv:1702.00786

LISA RED BOOK- ESA

Probing the Early Universe

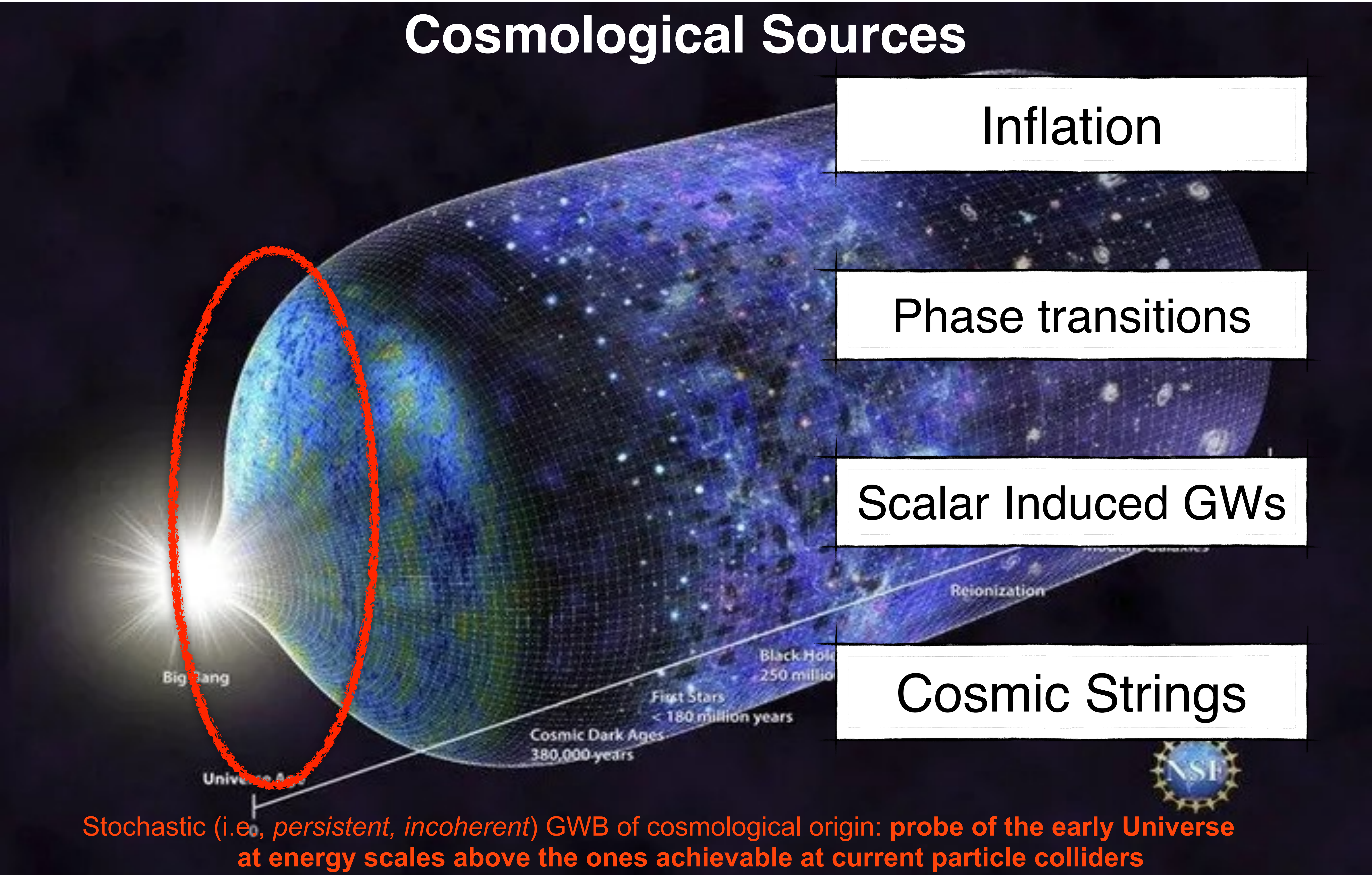
Cosmological Sources



- Inflation
- Phase transitions
- Scalar Induced GWs
- Cosmic Strings

Stochastic (i.e., *persistent, incoherent*) GWB of cosmological origin: **probe of the early Universe at energy scales above the ones achievable at current particle colliders**

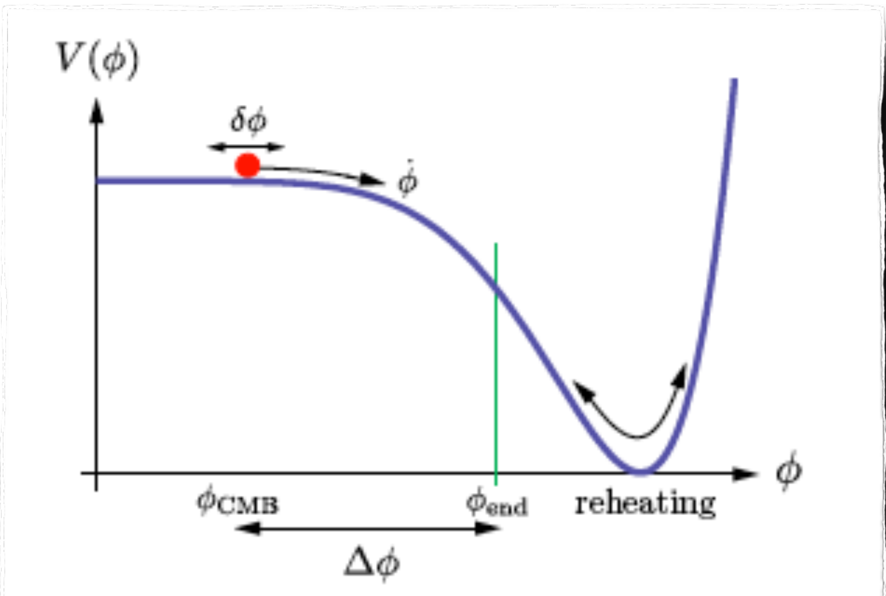
Cosmological Sources



- Inflation
- Phase transitions
- Scalar Induced GWs
- Cosmic Strings

Stochastic (i.e., *persistent, incoherent*) GWB of cosmological origin: **probe of the early Universe at energy scales above the ones achievable at current particle colliders**

Inflation and Primordial GWs



- Period of accelerated (exponential) expansion driven by a scalar field (inflaton) that rolls down on its flat potential

Solve Standard Big-Bang shortcomings

Generation of TENSOR and scalar perturbations

Stretches the microphysics scales to super-horizon sizes

GW are represented by tensor perturbation h_{ij} of the FLRW metric

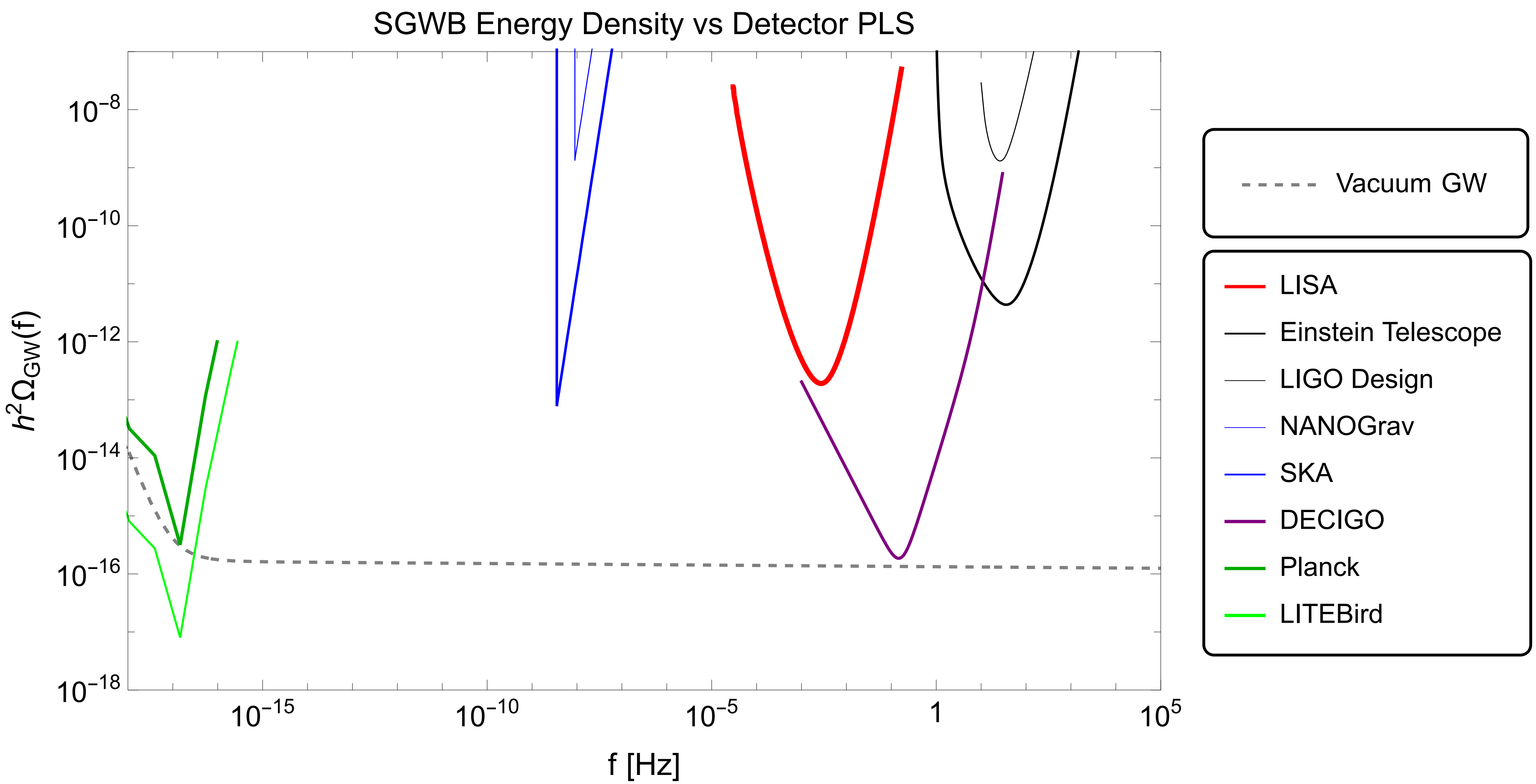
$$ds^2 = -dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j$$

Transverse and Traceless $\partial_i h^i_{\ j} = h_{ii} = 0$ → 2 D.O.F (2 polarizations)

Inflation and Primordial GWs

SGWB from the very early Universe

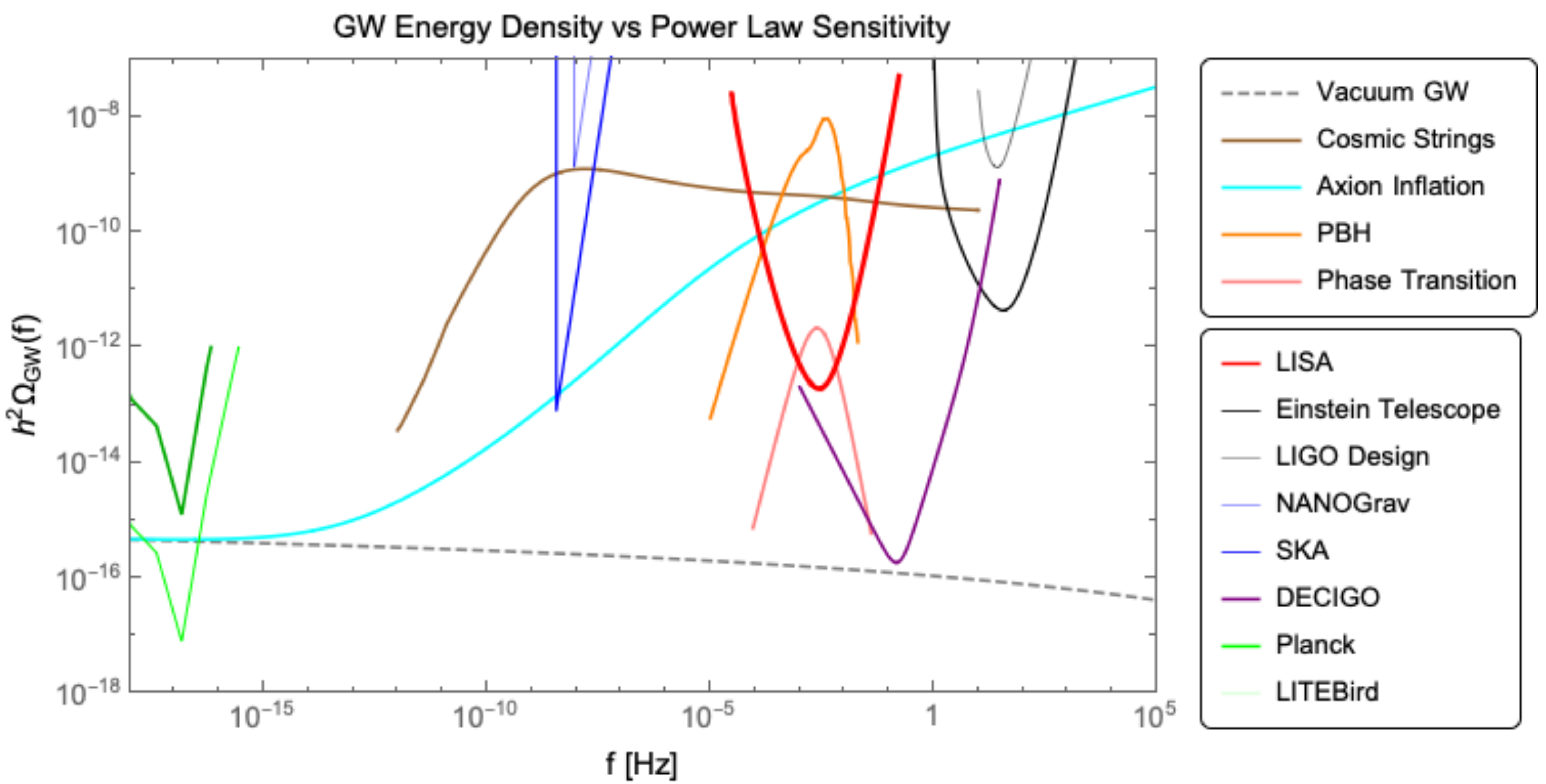
$$\ddot{h}_{ij} + 3H\dot{h}_{ij} + k^2 h_{ij} = 0$$



Inflation and Primordial GWs

If there is a process that give rise to a **non-zero** tensor **anisotropic stress** in the Early Universe can directly **source GW**

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} + k^2 h_{ij} = 16\pi G \Pi_{ij}^{TT}$$

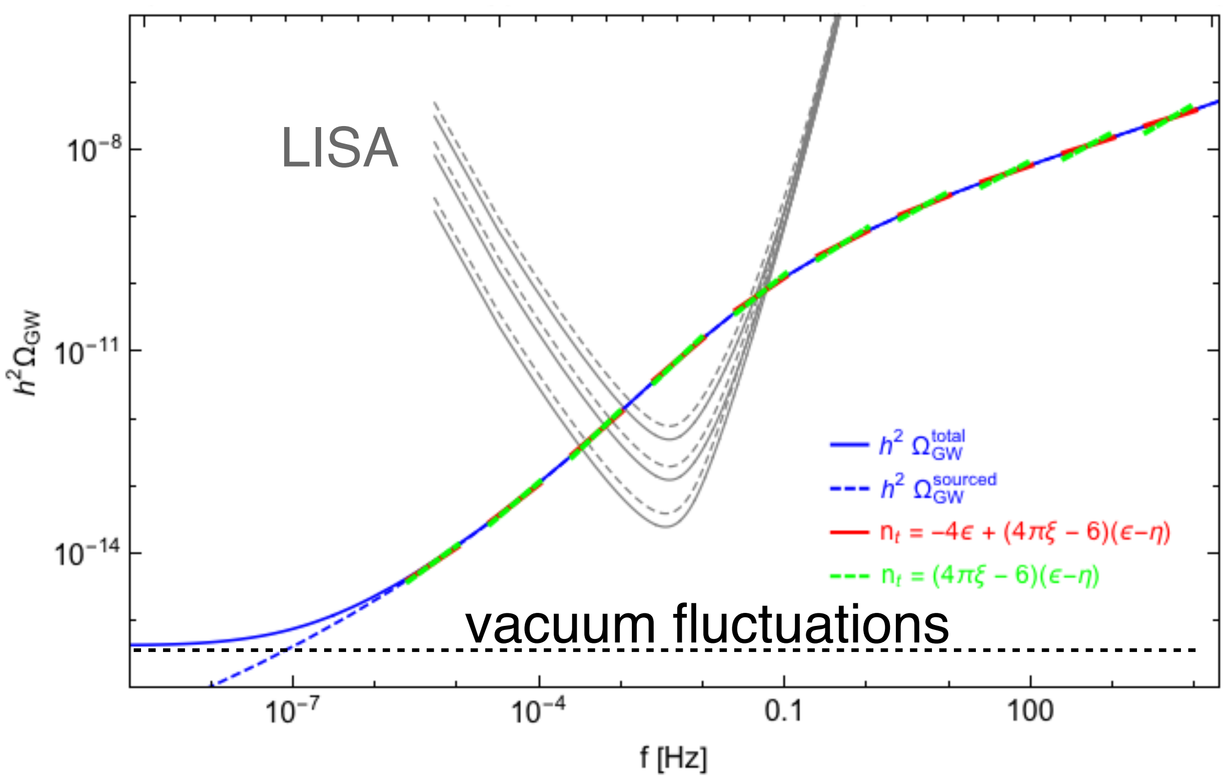


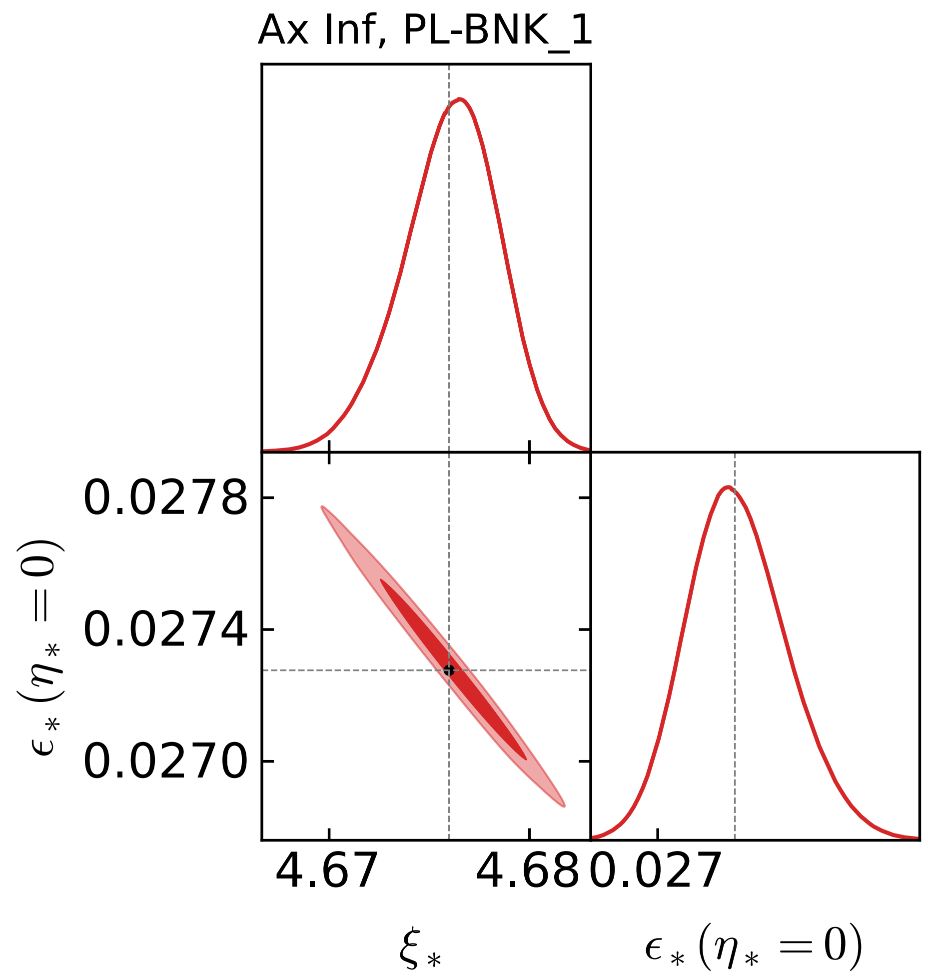
What we can learn

Axion-inflation

$$\mathcal{L} \supset -\frac{\varphi}{4f} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \xi \equiv \frac{\dot{\varphi}}{2fH}$$

GW energy spectrum today





$$\Omega_{\rm GW}^{\rm TOT}(f) = \Omega_{\rm GW,vacuum}(f) + \Omega_{\rm GW,sourced}(f)$$

Presence of other fields (e.g. axions) in the Early Universe

Testing fundamental physics (e.g. axion decay constant) - related to high energy physics

Testing peculiar features of the SGWB - parity violation

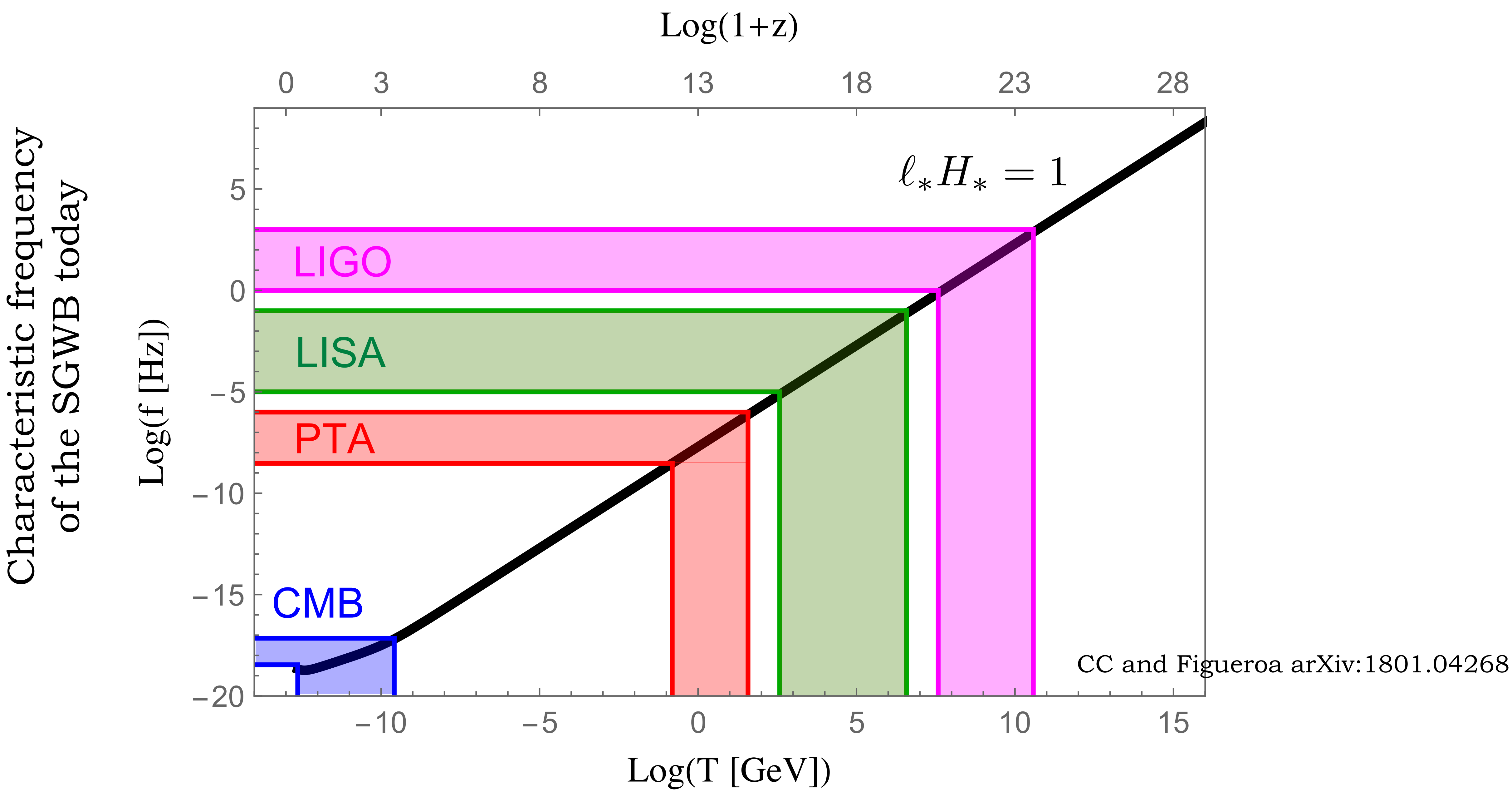
[Bartolo N., et al. '16 - LISA CosWG paper]

[Cook & Sorbo, '11]

Phase Transition in the Early Universe

For causal sources $f_* \sim \frac{1}{\ell_*} \geq H_*$

$$f = f_* \frac{a_*}{a_0} = \frac{1.65 \times 10^{-7}}{\ell_* H_*} \left(\frac{g(T_*)}{100}\right)^{1/6} \frac{T_*}{\text{GeV}}\,\text{Hz}$$



Energy scale (temperature) in the early universe

Phase Transition in the Early Universe

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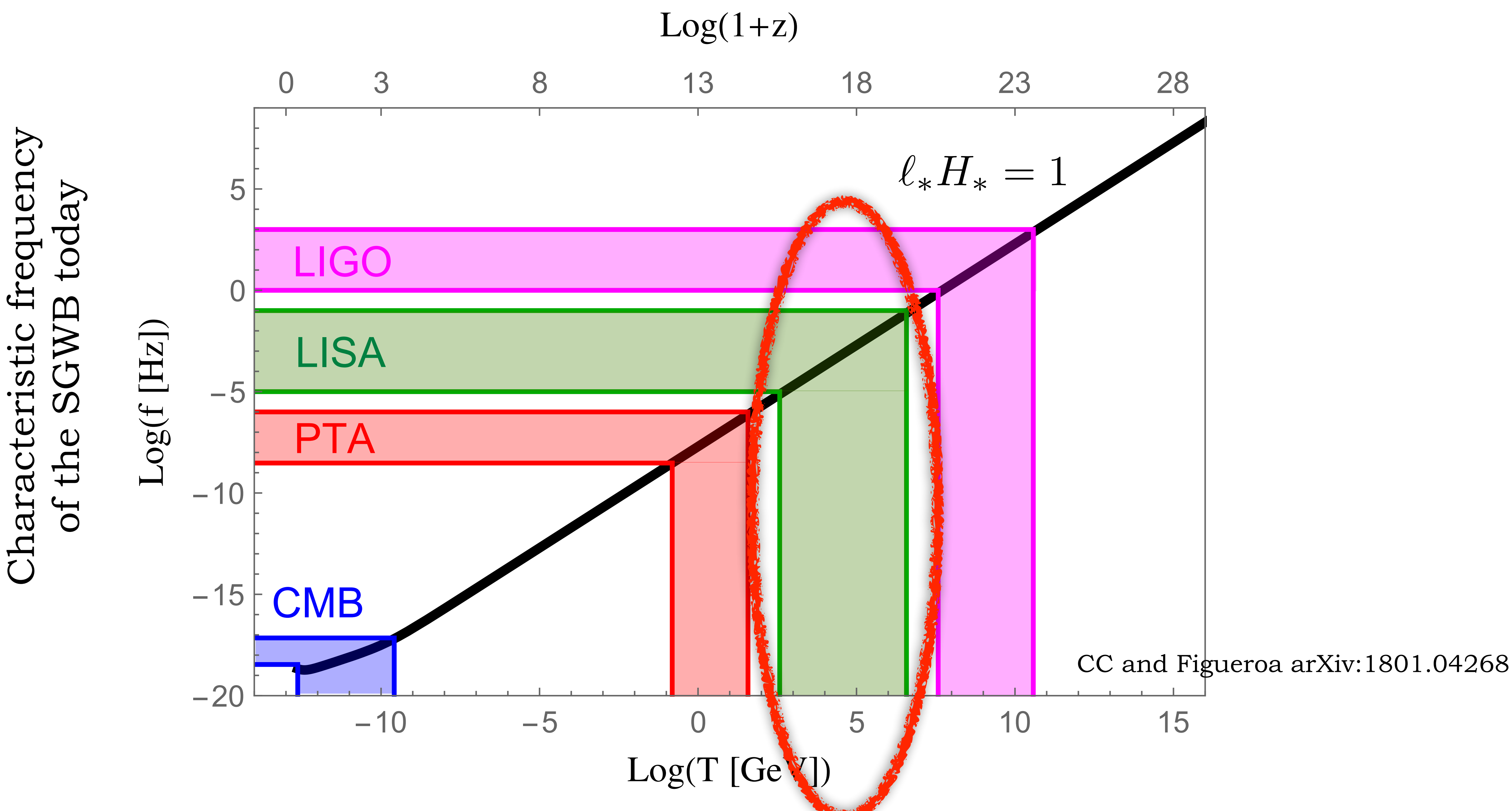
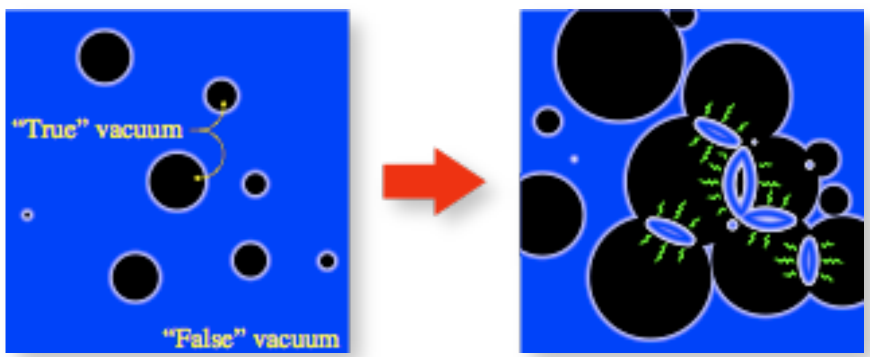


Energy scale (temperature) in the early universe

Phase Transition in the Early Universe

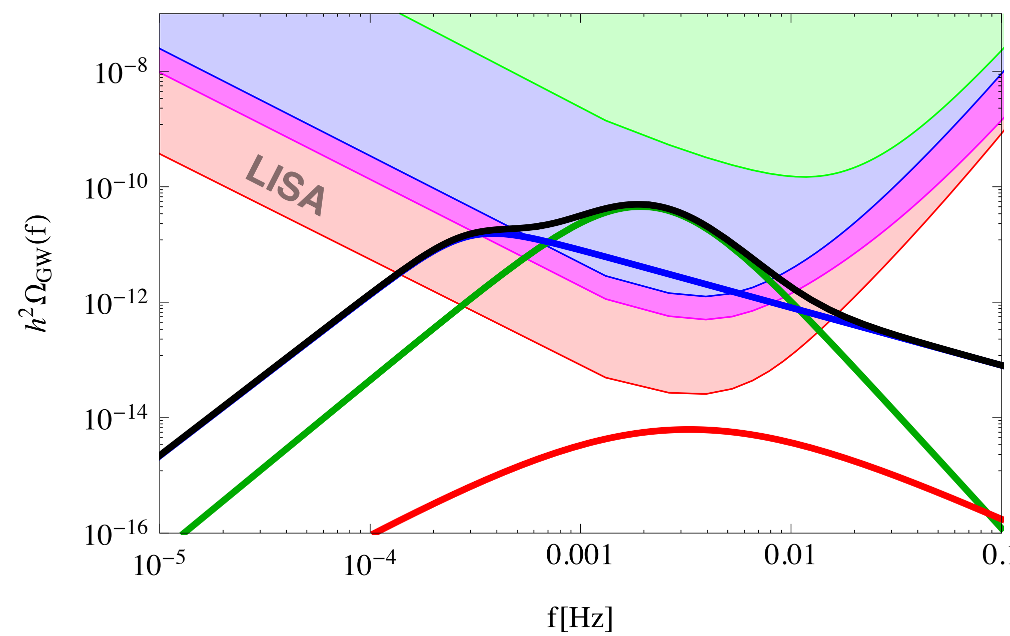
As the temperature in the very early universe decreases, there can be several **PTs: QCD, EW**....Beyond Standard Model?

If the PT is first order, the SGWB signal could be detectable by LISA



Processes

- Bubble collisions
- MHD Turbulence
- Sound Waves



- peaked spectrum with

$$f_{\rm peak} \sim 10^{-3}\ \mathrm{Hz}\ \frac{T}{100\ \mathrm{GeV}}$$

- LISA could act as a **probe of Beyond Standard Model physics, complementary to colliders**
- In some BSM scenarios possible **joint detection at LISA and LHC/FCC**

[Caprini C., et al '16, '19- LISA CosWG paper]

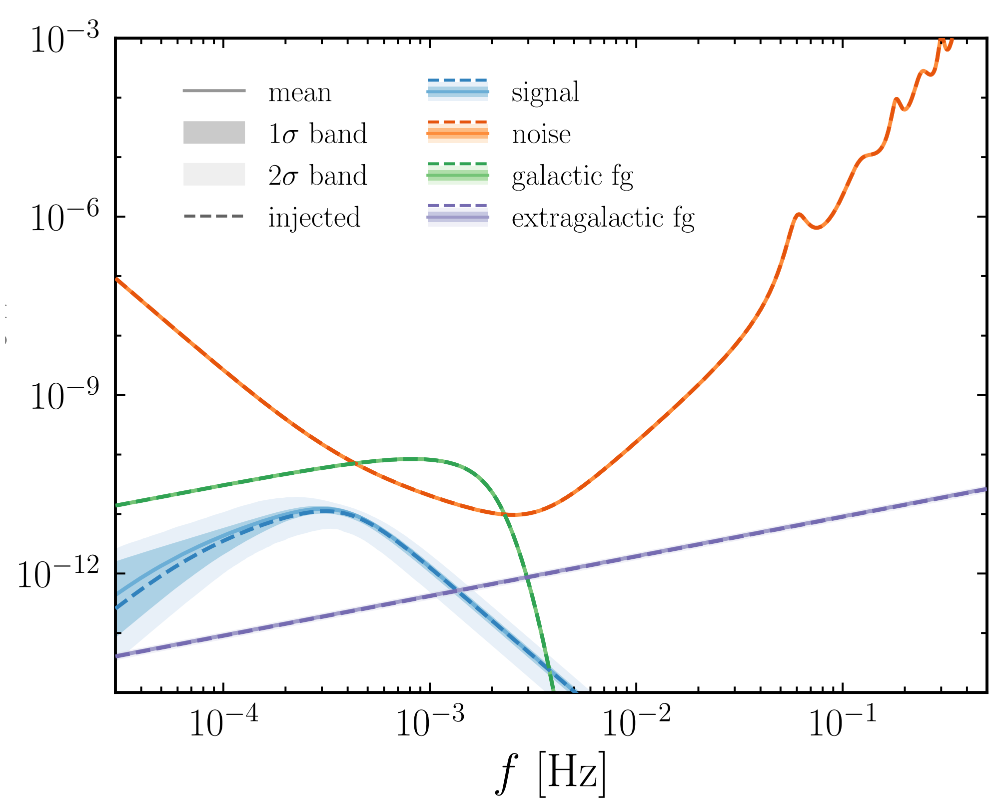
LISA Red Book

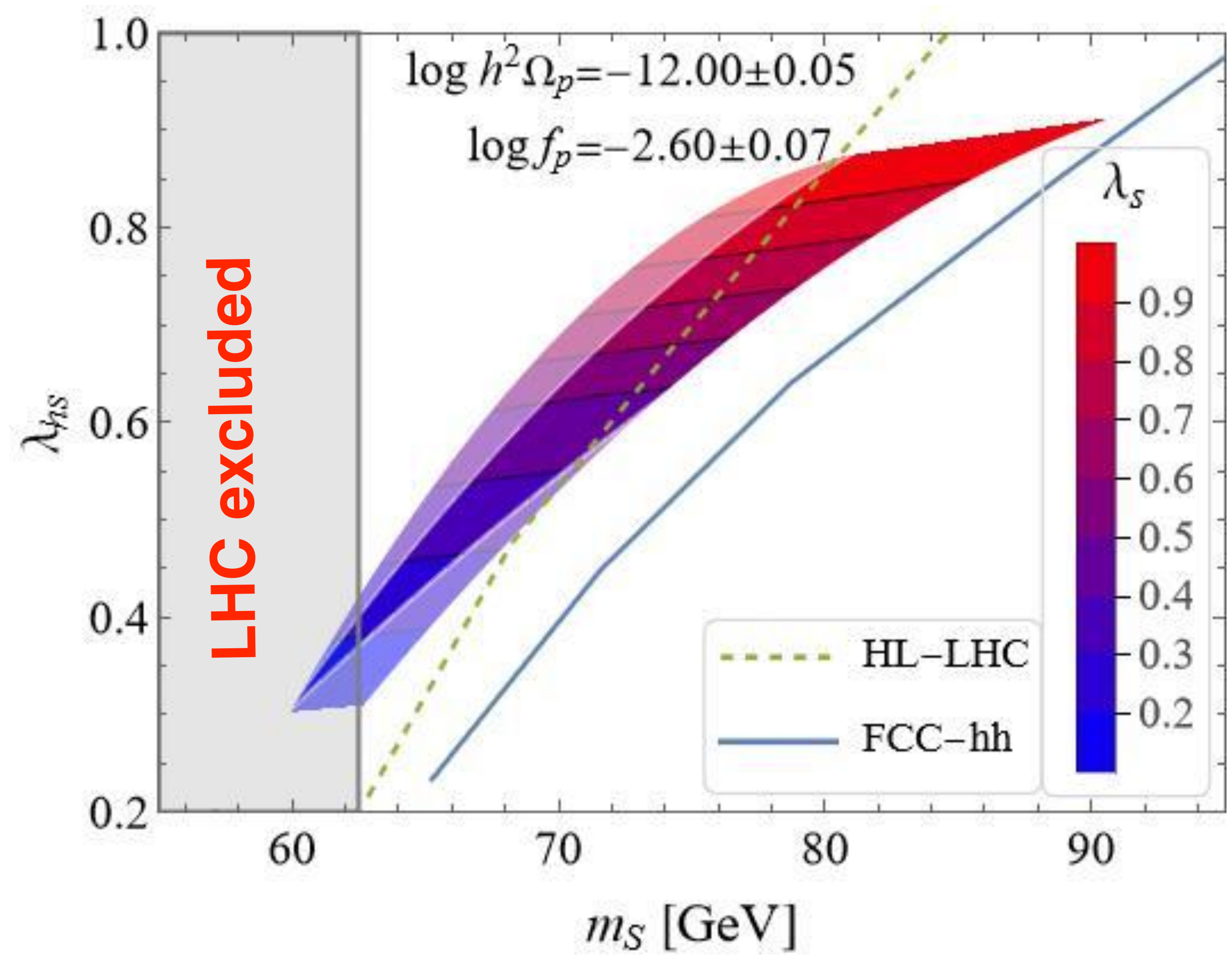
What we can learn from Phase Transition?

- LISA could act as a **probe of Beyond Standard Model physics, complementary to colliders**

Simplest extensions of the SM $$V_{\text{tree}}(\Phi, s) = -\mu_h^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2 + \mu_s^2 \frac{s^2}{2} + \frac{\lambda_s}{4} s^4 + \frac{\lambda_{hs}}{2} s^2 \Phi^\dagger \Phi,$$

Extra scalar singlet under the SM gauge group endowed with a Z_2 symmetry





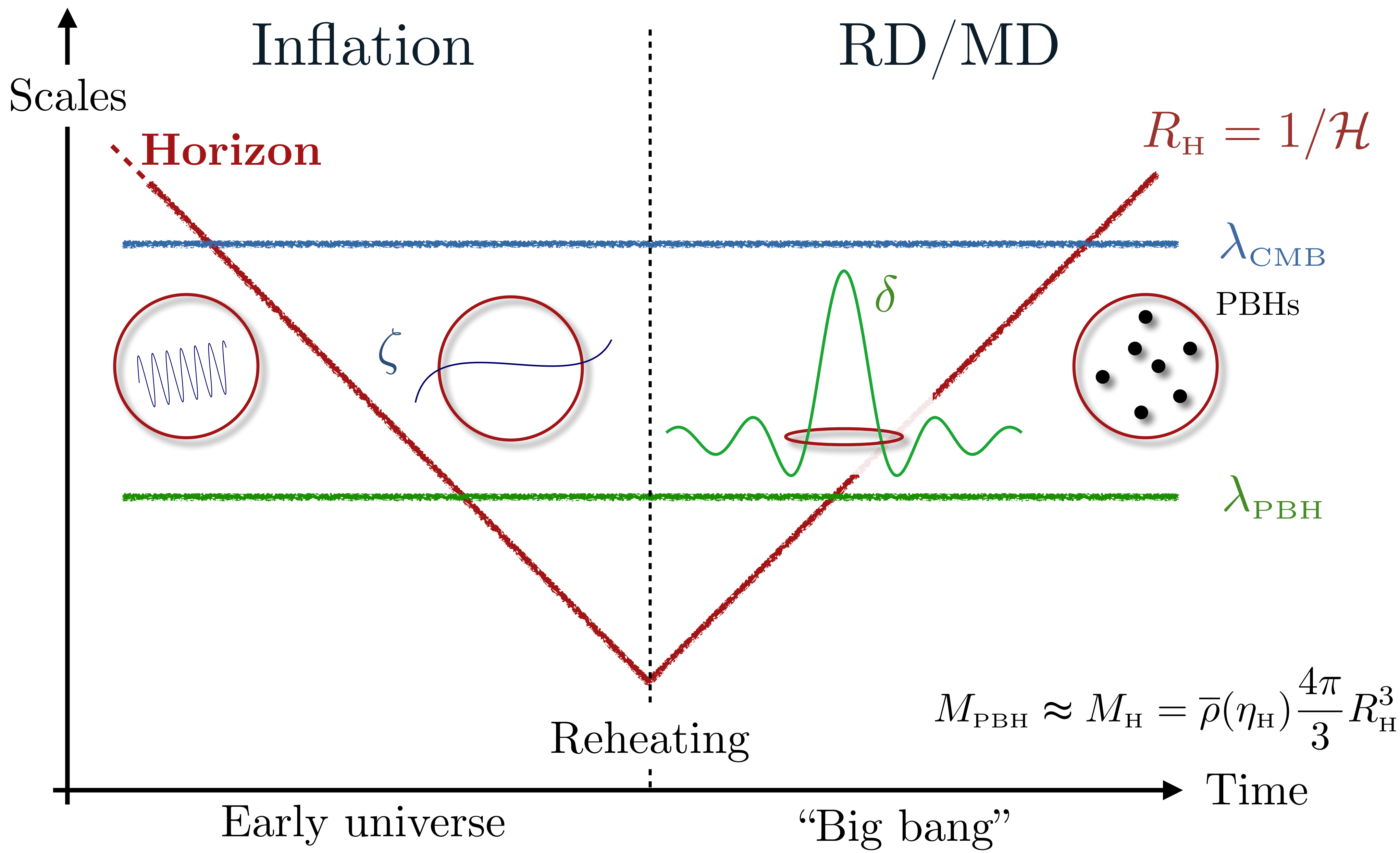
λ_{hs} Singlet coupling

m_s Singlet mass

- In some BSM scenarios possible **joint detection at LISA and LHC/FCC**

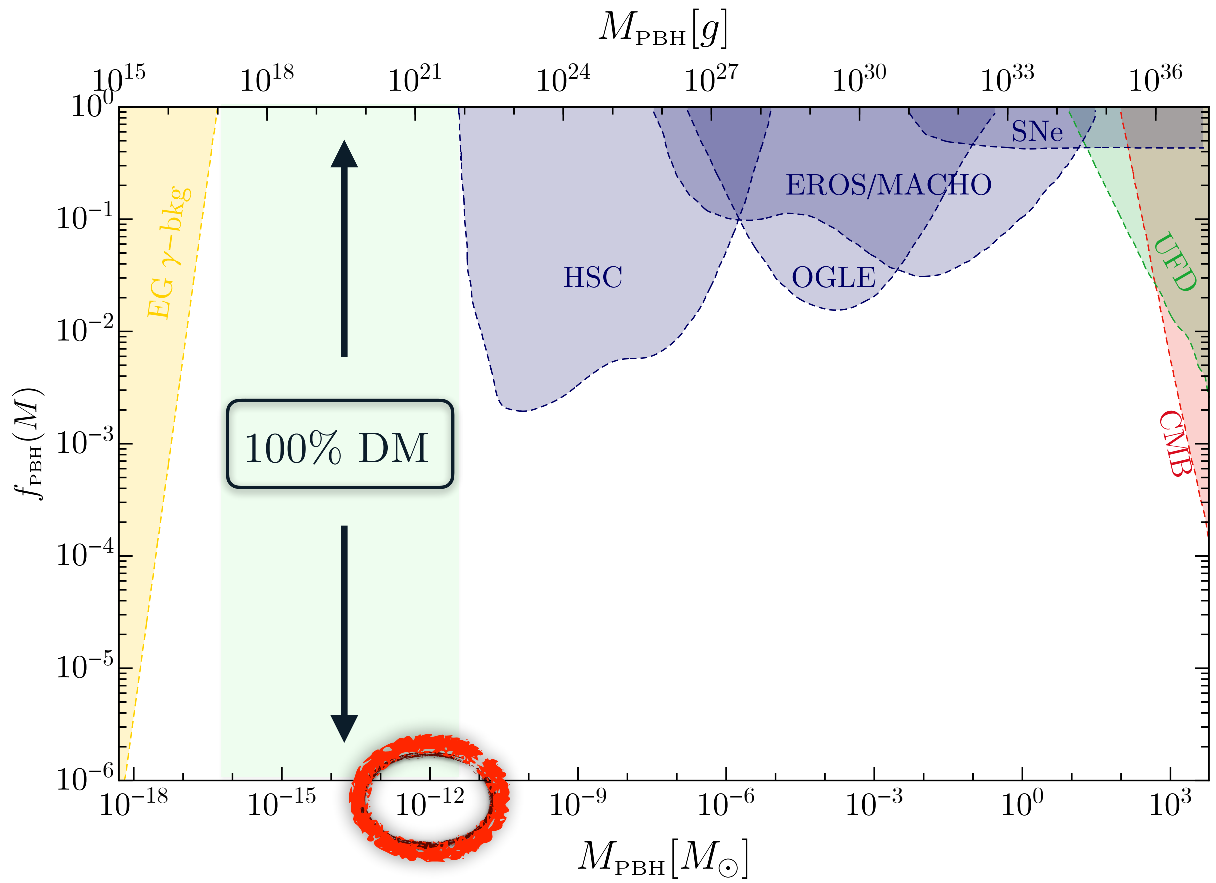
LISA Red Book

GWs - Primordial Black Holes and Dark Matter

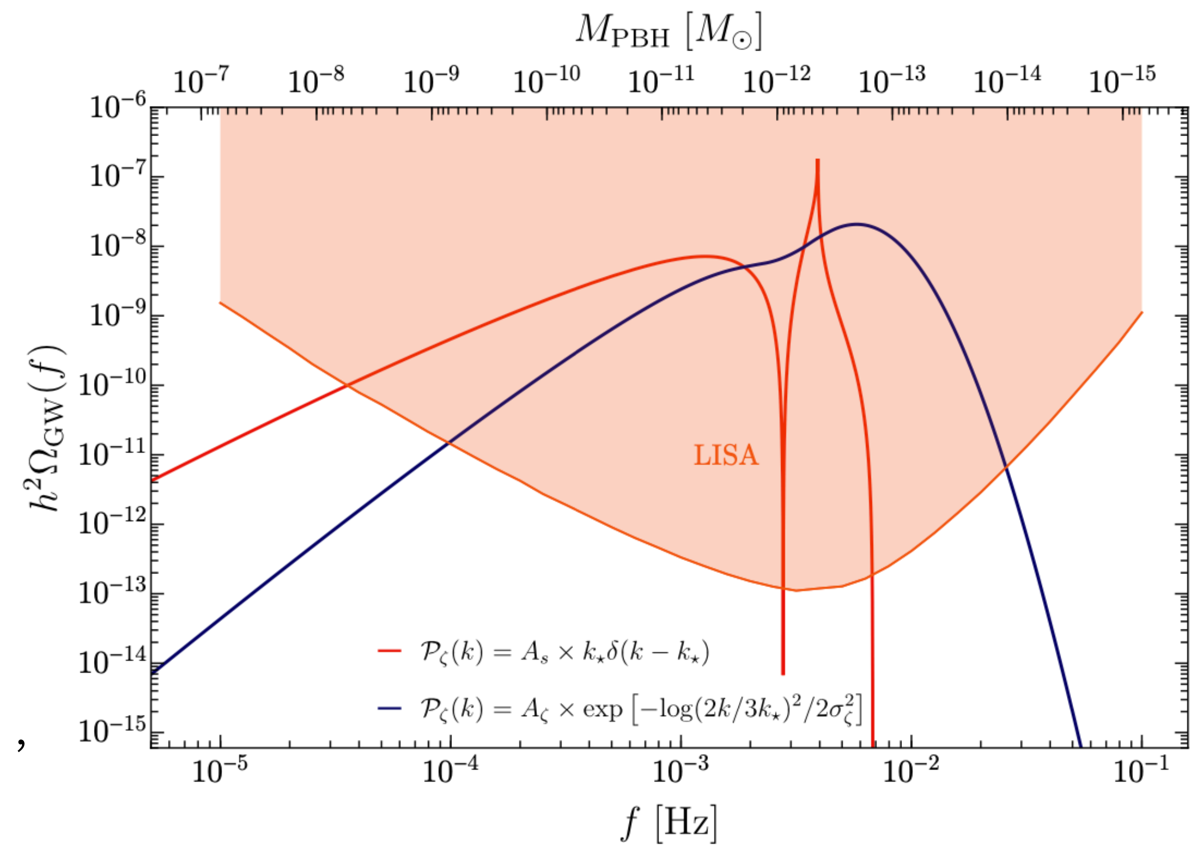


$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$

GWs - Primordial Black Holes and Dark Matter



,



$$f \simeq 3 \cdot 10^{-9}\,\text{Hz} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{M}{M_\odot}\right)^{-1/2}$$

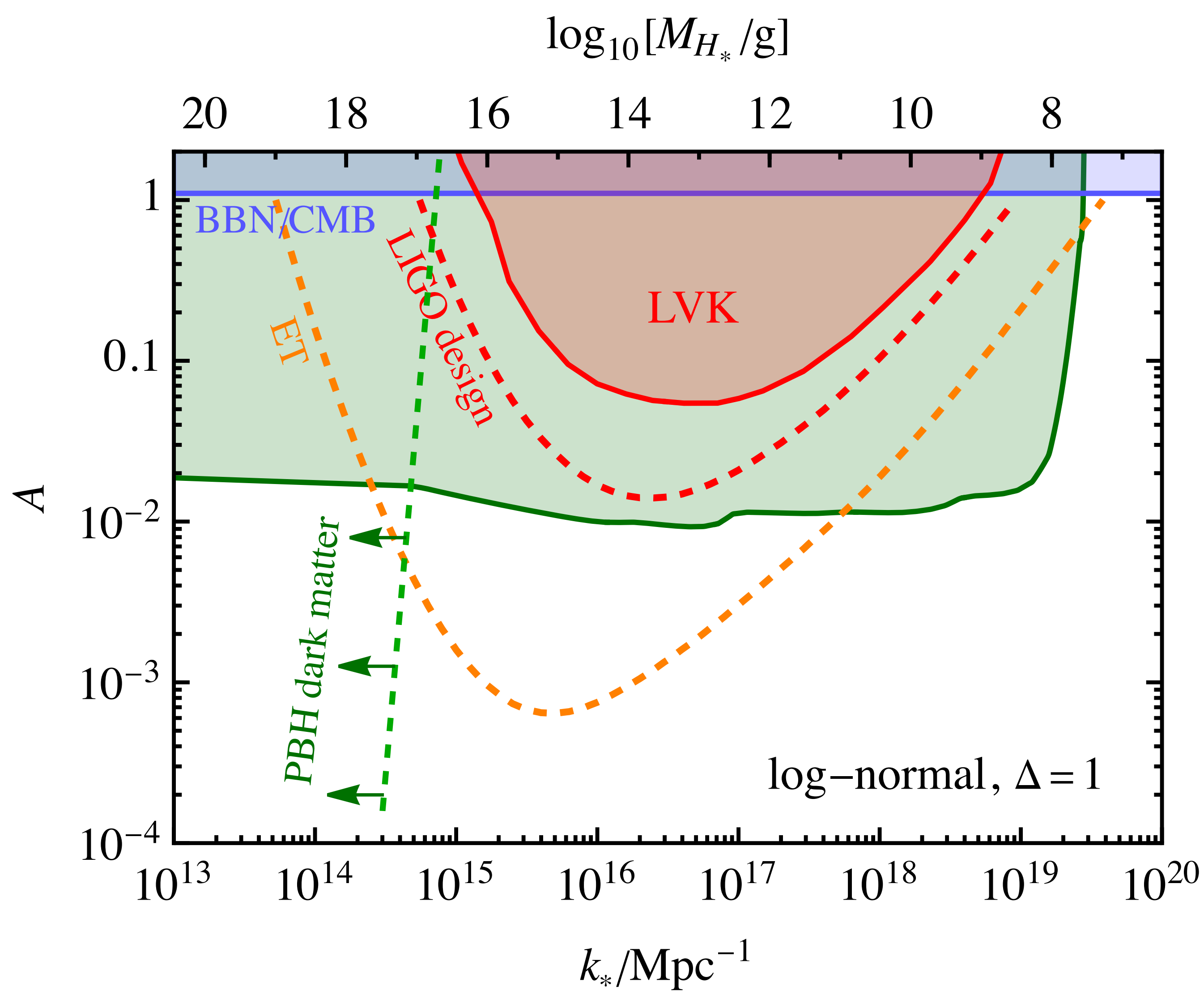
$$M \simeq 10^{-12} M_\odot \quad \longleftrightarrow \quad f \simeq 10^{-3}\text{Hz}$$

[Espinosa, et al., 2018]

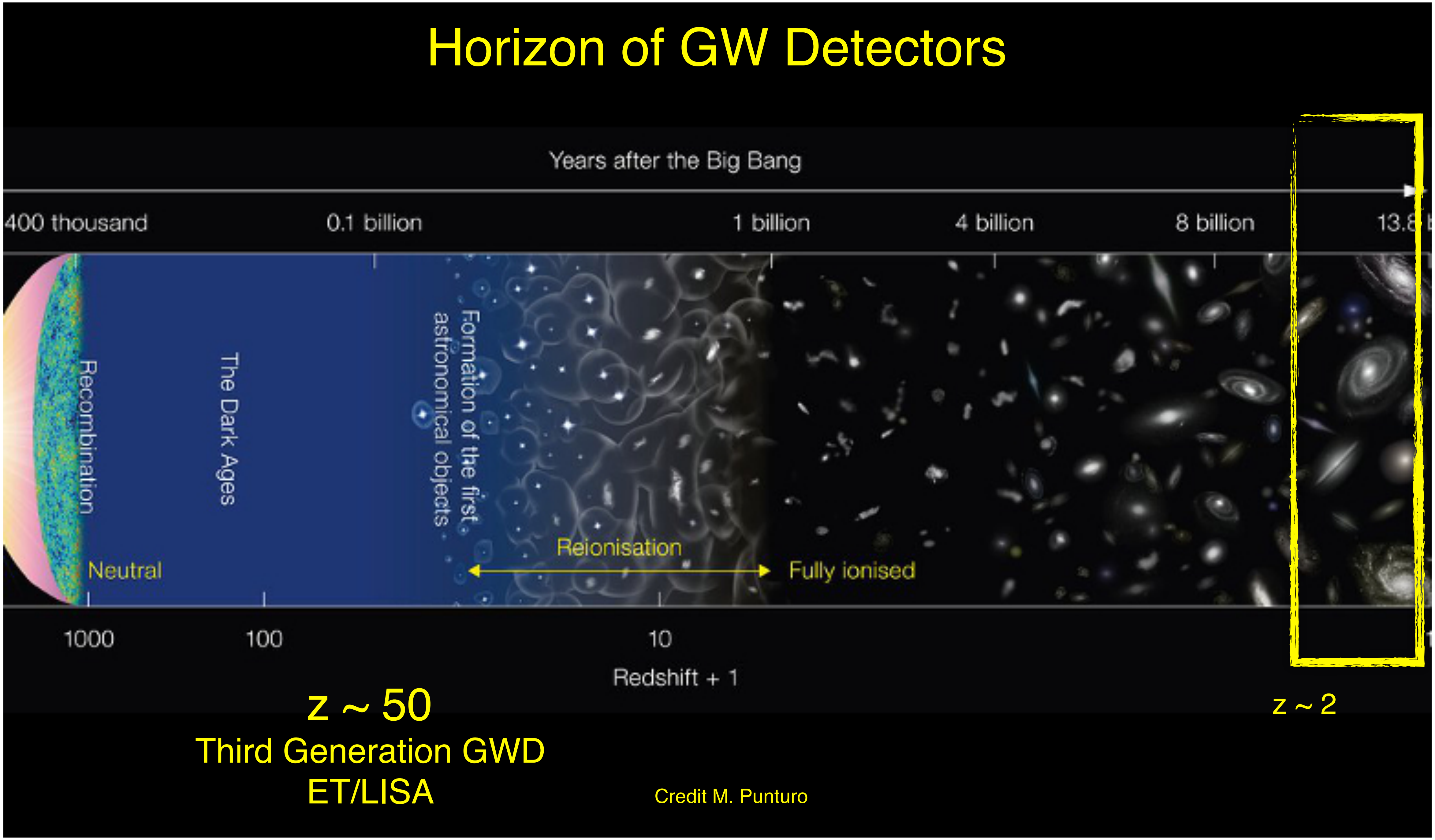
[Bartolo, N., et al., PRL 2019]

[De Luca, V., et al., PRL 2021]

Upper bound on the amplitude of the curvature power spectrum at small scales A



Where is the horizon for 3G detectors?

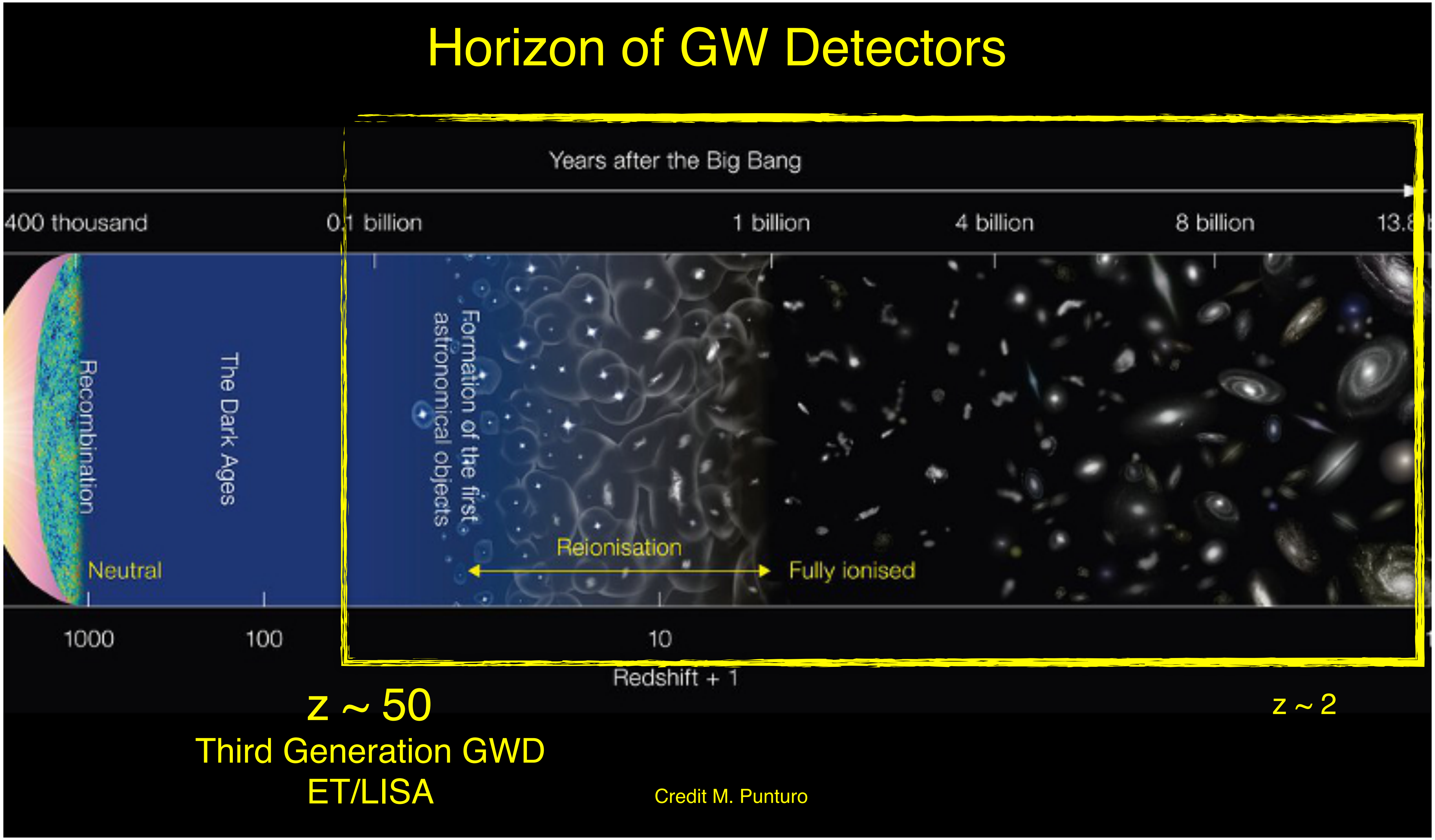


Einstein Telescope:

BBHs up to cosmic Dark Ages (z > 30)

BNSs up to cosmic Noon (z~2)

Where is the horizon for 3G detectors?



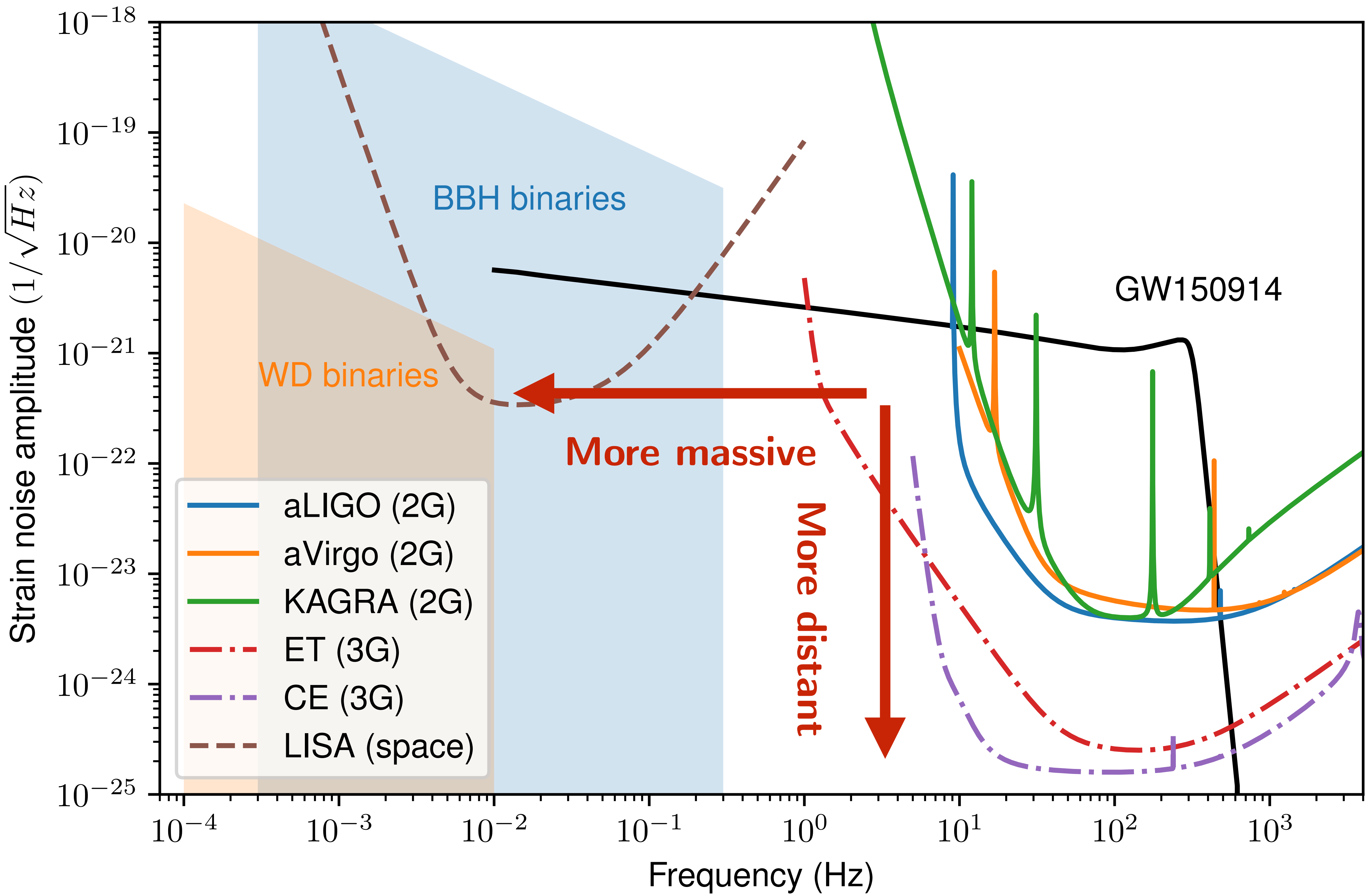
Einstein Telescope:

BBHs up to cosmic Dark Ages (z > 30)

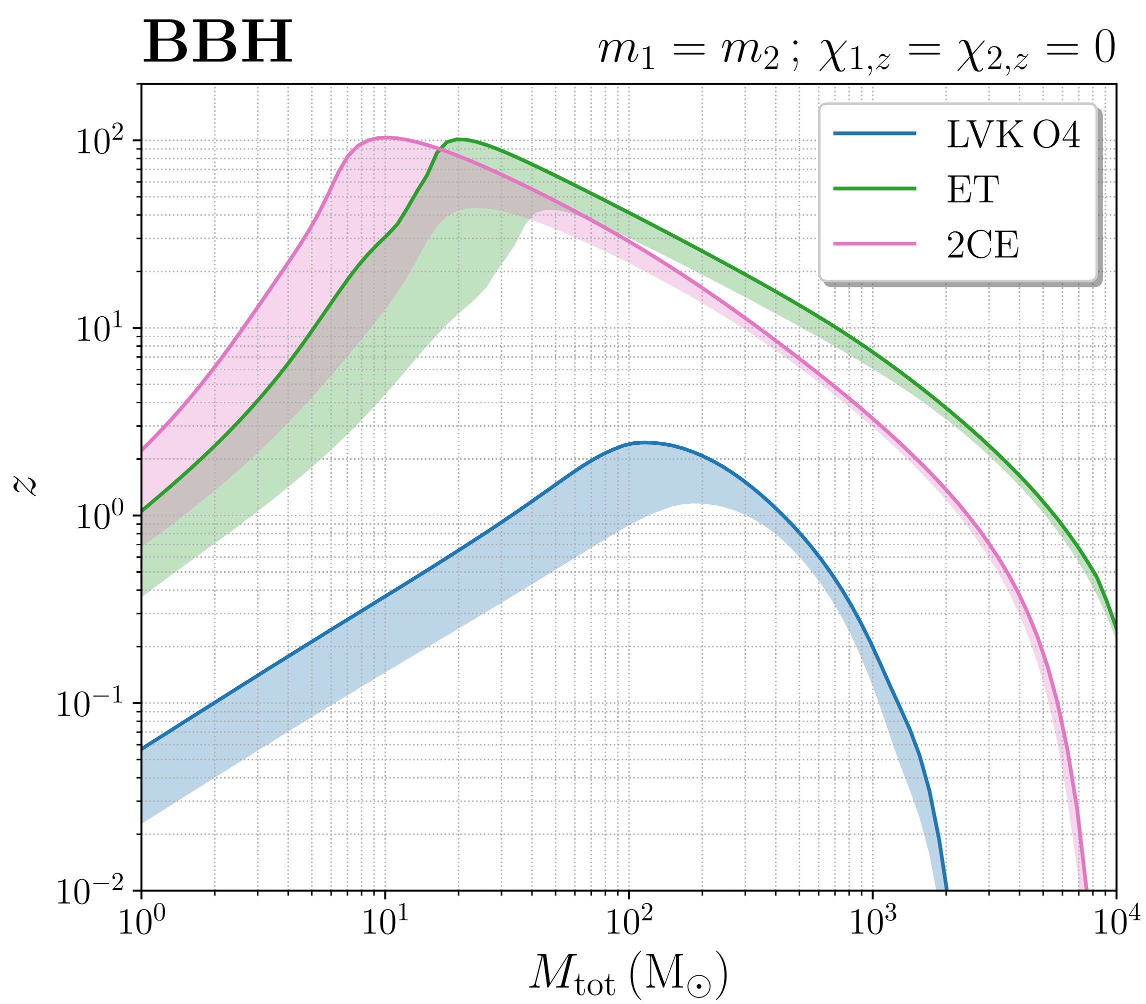
BNSs up to cosmic Noon (z~2)

From 2G to 3G detectors: ET and LISA

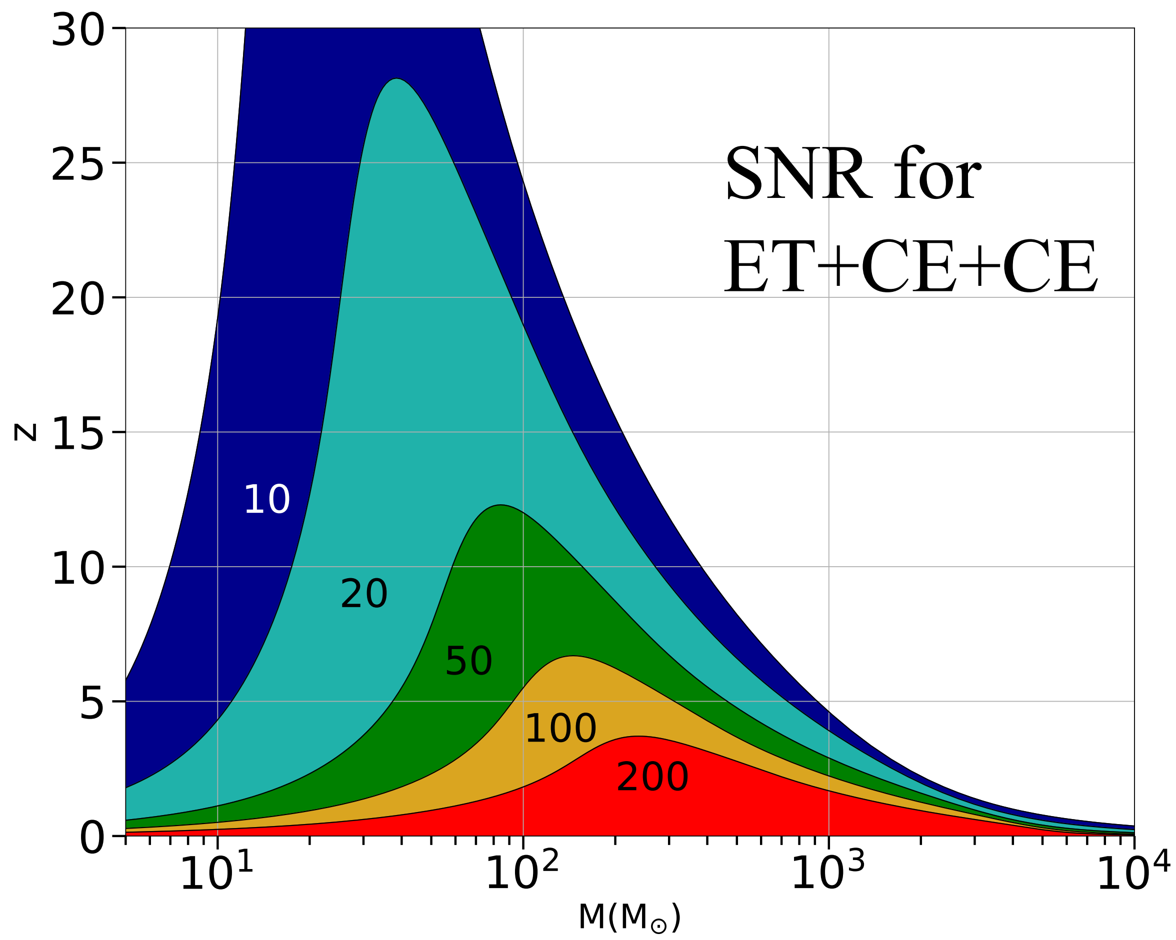
$$h_{\rm gw} \sim 1/d_L \qquad f_{\rm gw} \sim 1{\rm kHz}\left(\frac{10M_\odot}{M}\right)$$



Probing the Late Universe



Astrophysical redshift reach
for equal mass binaries



Astrophysical redshift reach

BBH up to $z \sim \mathcal{O}(20-100)$

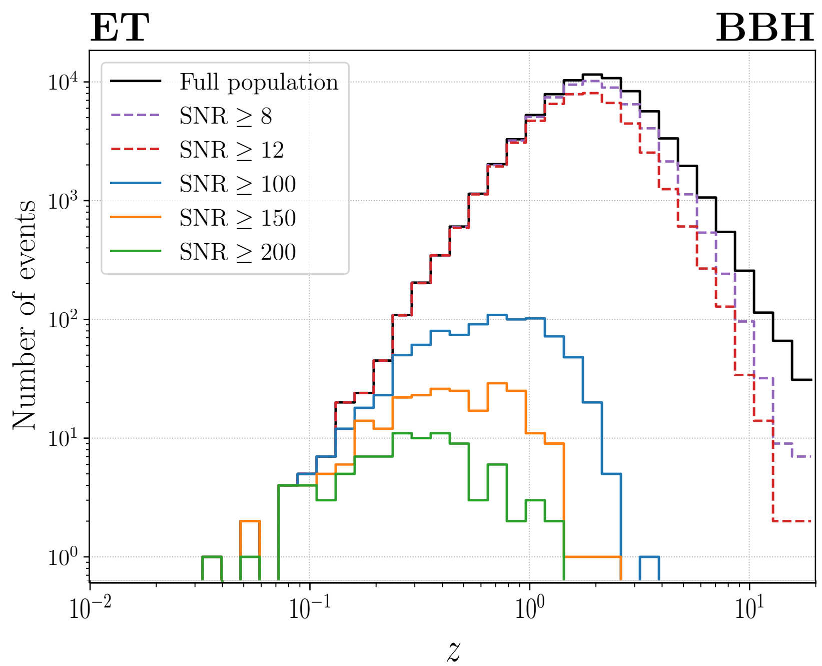
10^6 BBH/yr

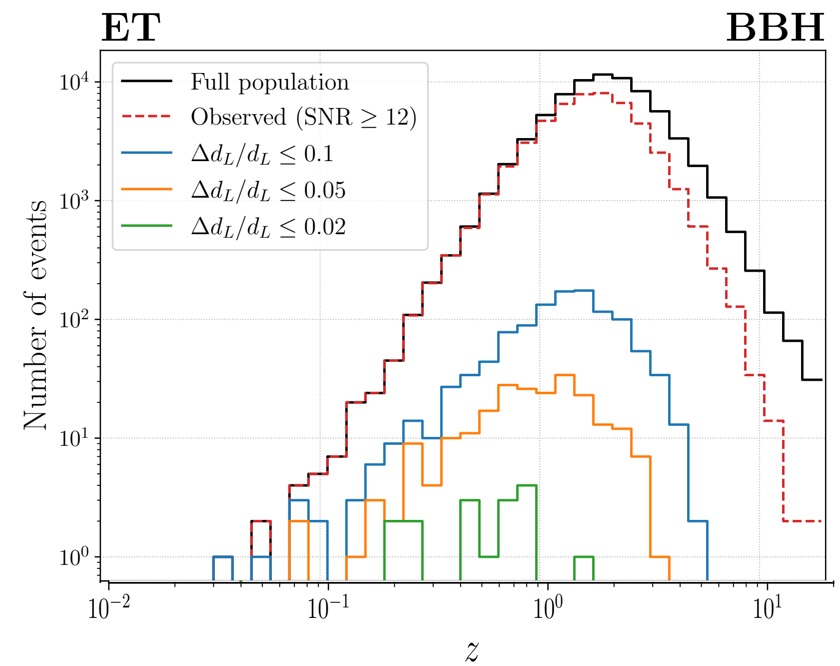
Masses up to $10^3 M_{sun}$

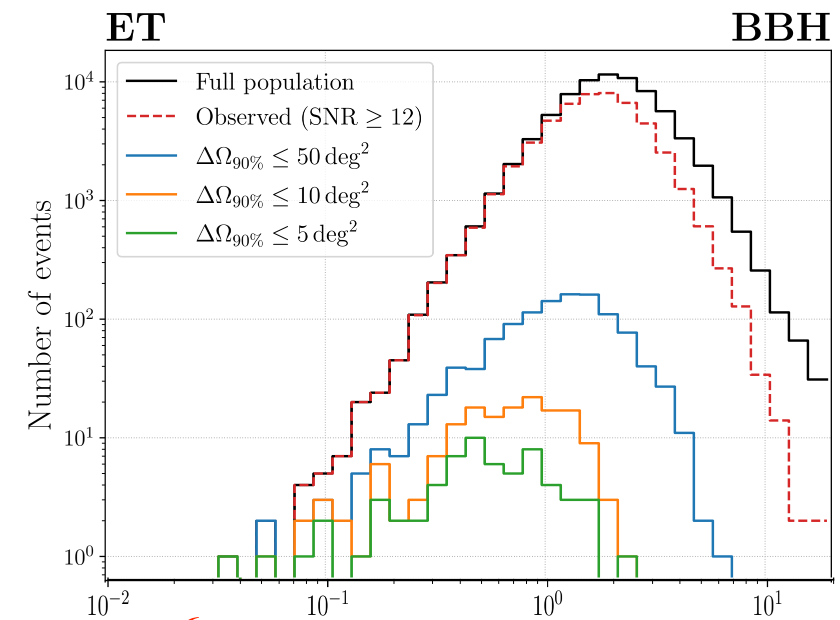
BNS up to $z \sim 2$

high SNR

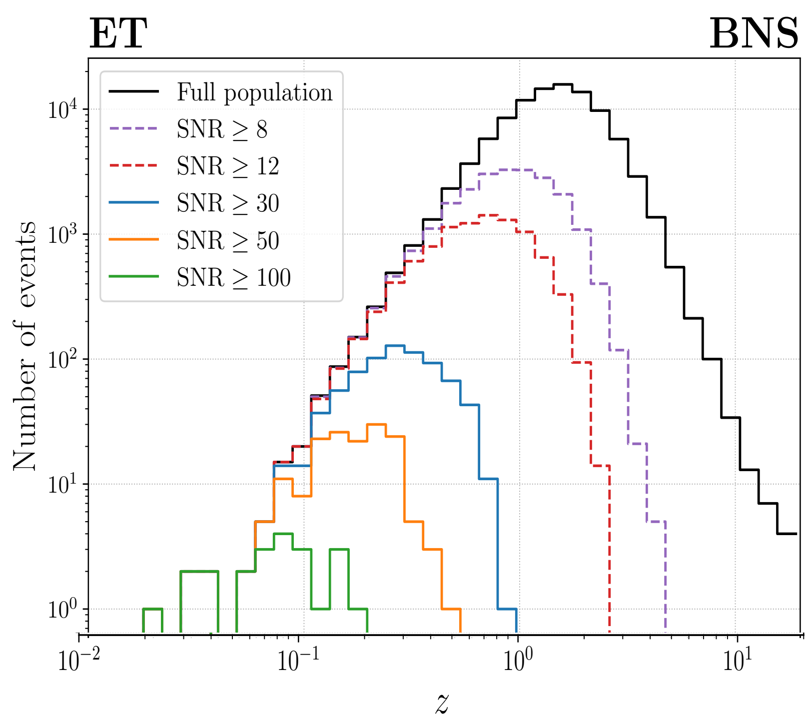
Probing the Late Universe with ET

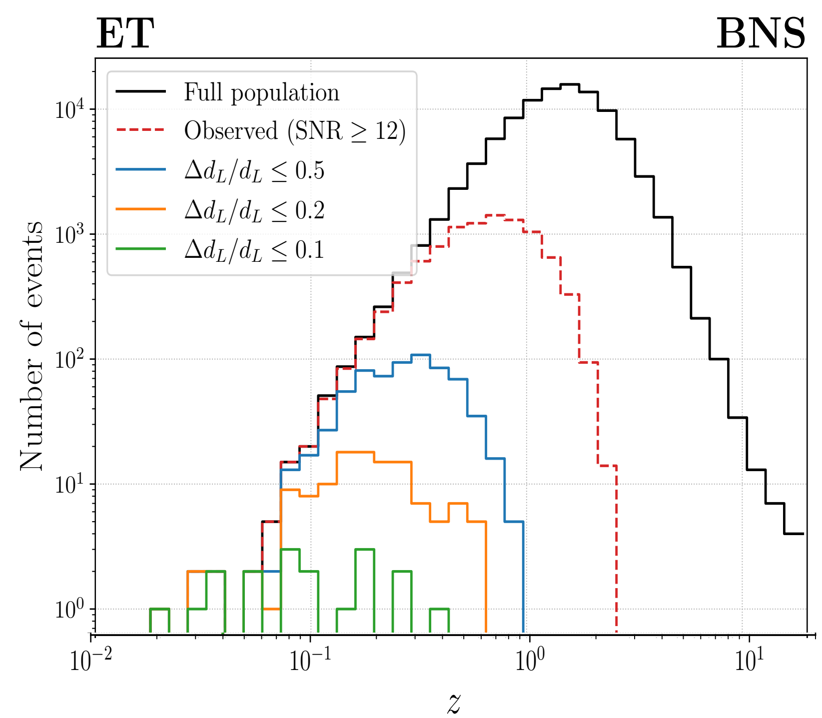


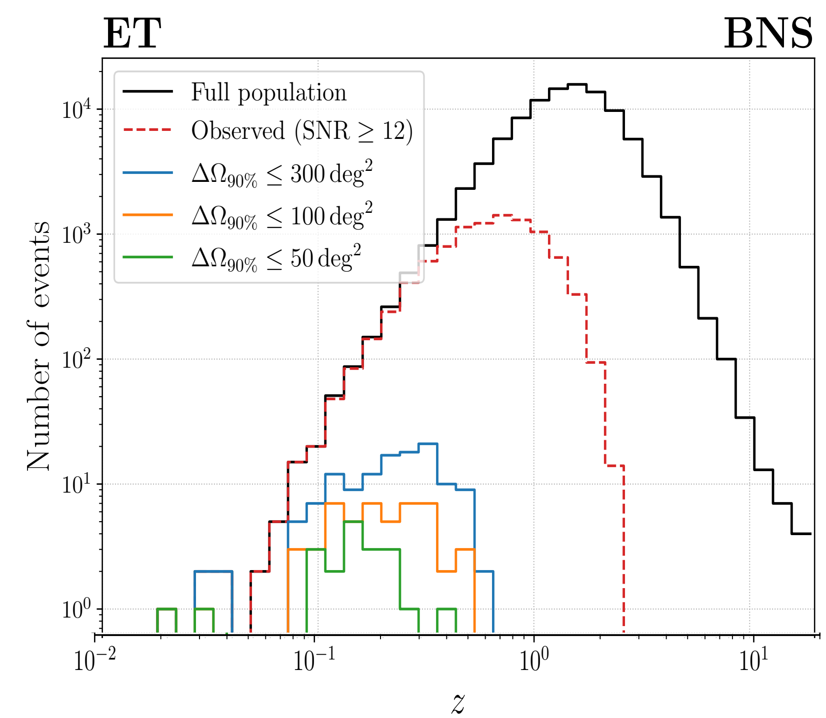




10^6 BBH mergers/yr up to z ~ 50





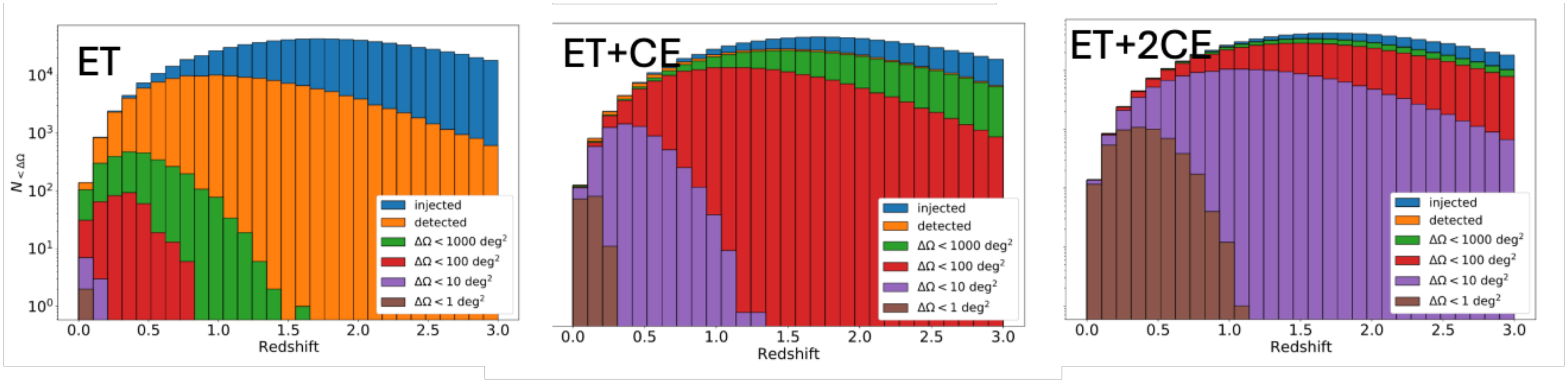


10^5 BNS mergers/yr up to z ~ 2

Many Golden Events

Large number of detected sources (also at high redshift) and resolution

Sky-localization



ET: $\mathcal{O}(100)$ **detection per year with sky localization < 100 sq.deg (90% CL)**

ET+CE: $\mathcal{O}(1000)$ **detection per year with sky localization < 10 sq.deg (90% CL)**

ET+2CE: $\mathcal{O}(1000)$ **detection per year with sky localization < 1 sq.deg (90% CL)**

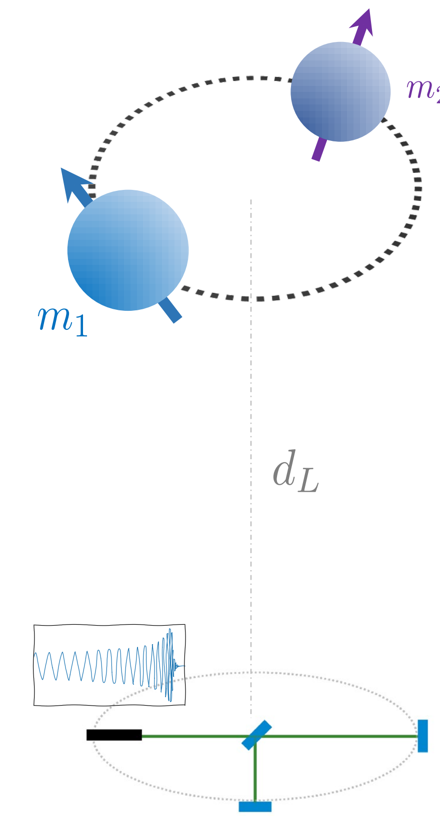
Branchesi, Maggiore et al 2023, JCAP
Ronchini et al A&A. 2022

Many Golden Events

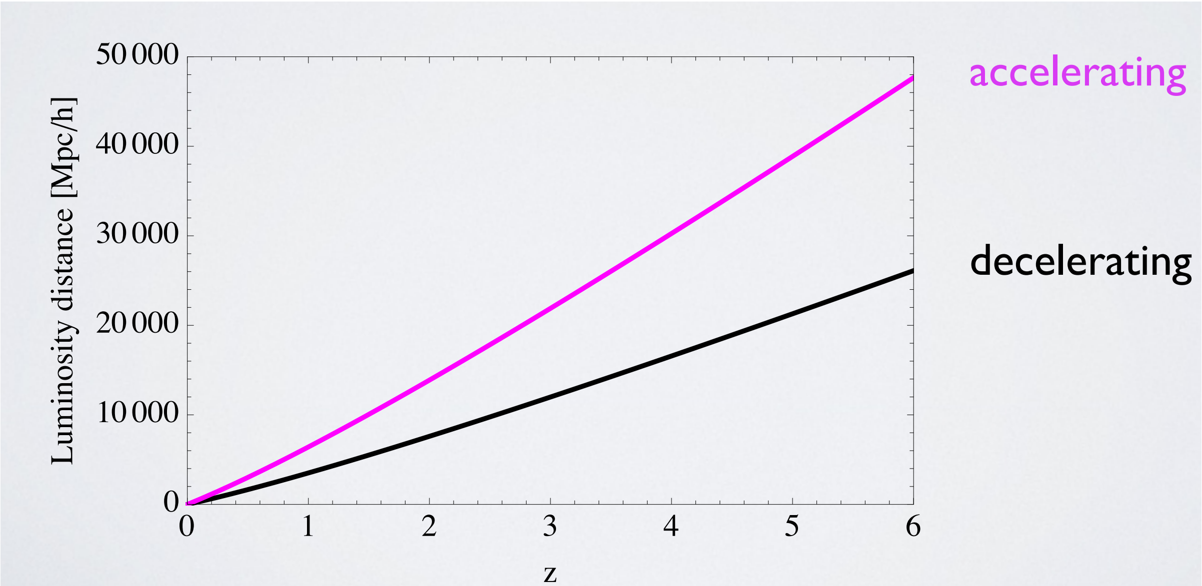
Using GWs as Standard Sirens

Gravitational waves from **individual sources at cosmological distances (e.g. binary black holes, binary neutron stars...) have the potential to give a <u>totally independent measurement of H0</u>**

[B.Schultz, Nature, 1986] standard sirens



- Detect GWs emitted by coalescing binaries
- From the waveform, measure directly the luminosity distance $d_L(z)$
- If, in addition, can determine the redshift z of the source, then have a point on curve $d_L(z)$



Direct probe of cosmology

$$D_{\rm L} = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\left[\Omega_{\rm M}(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}\right]^{1/2}}.$$

For $z \ll 1$, the relationship reduces simply to the Hubble law:

$$c\,z = H_0 \times d_L$$

redshift → z; Hubble constant → H_0; Luminosity distance → d_L

Using GWs as Standard Sirens

$$c\,z = H_0 \times d_L$$

redshift

Hubble constant

Luminosity distance

- three quantities: pick any two and infer the third.
- With standard sirens:

  d_L from GW measurements;

  z from, e.g. electromagnetic measurements (if have an optical counterpart, and know the host galaxy, can determine z).

=> independent measure of H_0

Cosmology via the distance-redshift relation
... but no redshift measurement with GW data alone
(Degeneracy with masses)

Using GWs as Standard Sirens

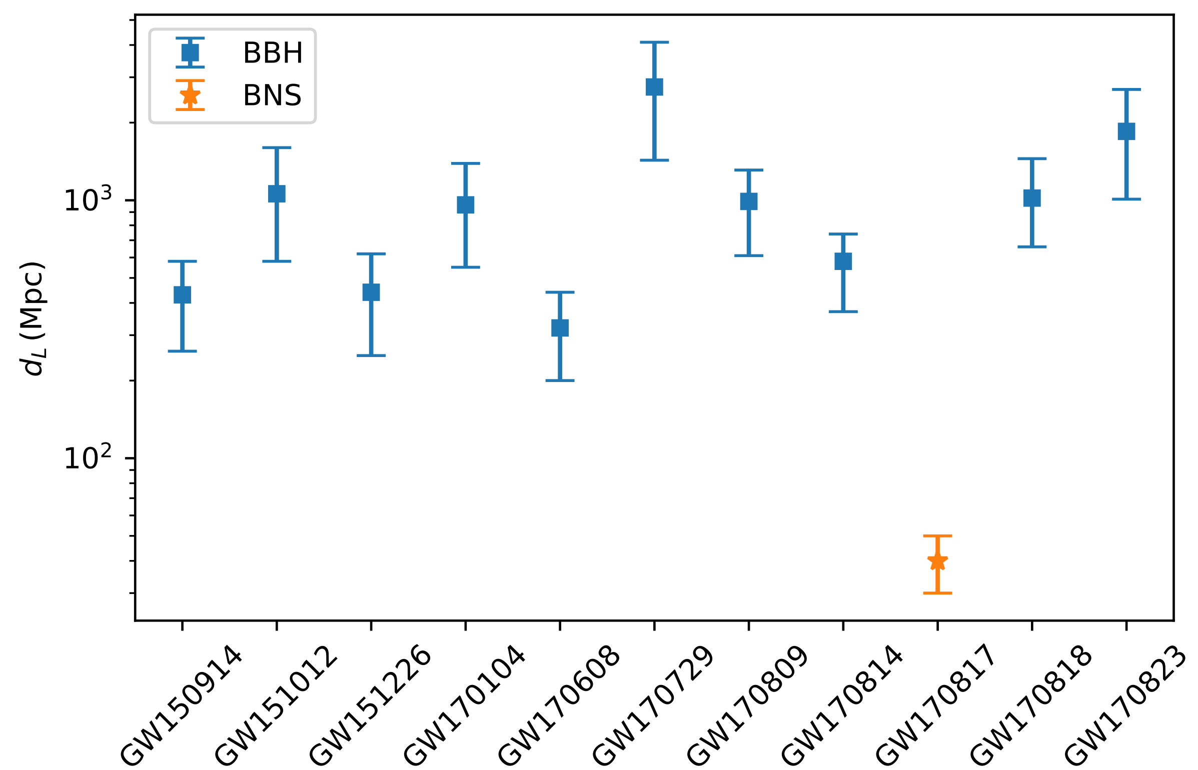
- Compact binaries at cosmological distances

$$h_c(t_{\rm obs}) \sim \frac{\mathcal{M}_z^{5/3} f_{\rm obs}^{2/3}}{d_{\rm L}^{\rm gw}}$$

$$d_L^{\rm GW}(z) = (1+z)\int_0^z \frac{{\rm d}z'}{H(z';\lambda_{\rm cosmo})} \qquad \{H_0, \Omega_{m0}, w_0, ...\}$$

$$f_{\rm gw} = (1+z) f_{\rm obs} \qquad \mathcal{M}_z = (1+z)\mathcal{M}_c$$

GW's amplitude scale with the inverse of luminosity distance!



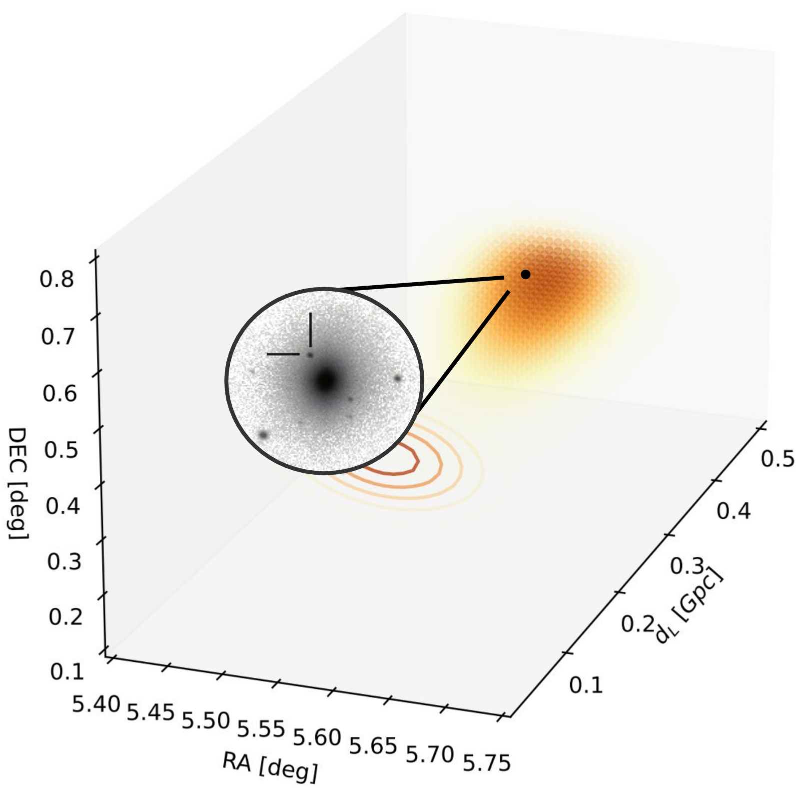
We need an independent redshift measurement to do cosmology

$$h\,(m_1, m_2, z=0) = h\left(\frac{m_1}{1+z}, \frac{m_2}{1+z}, z\right)$$

Using GWs as Standard Sirens - Redshift Information

Bright Sirens

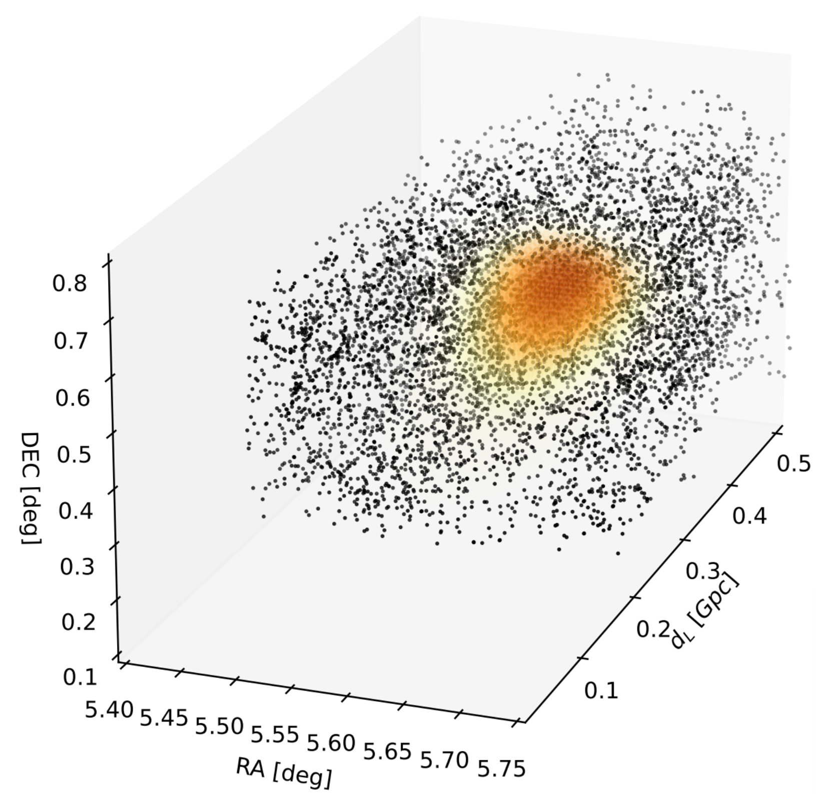
An **EM counterpart** is observed and used to obtain the host galaxy redshift.



(Holz & Hughes 2005)

Dark Sirens

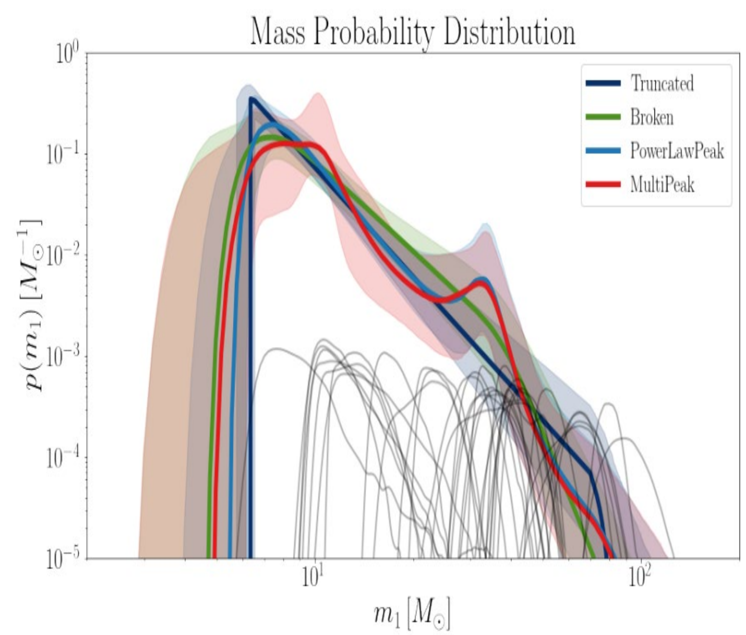
No EM counterpart observed. **Galaxy surveys** are used to provide redshift estimates for potential host galaxies.



(Schutz 1986, Del Pozzo 2012)

Spectral sirens

No EM counterpart or galaxy survey is used. Features in the **mass distribution** of the GW population break the mass-redshift degeneracy.

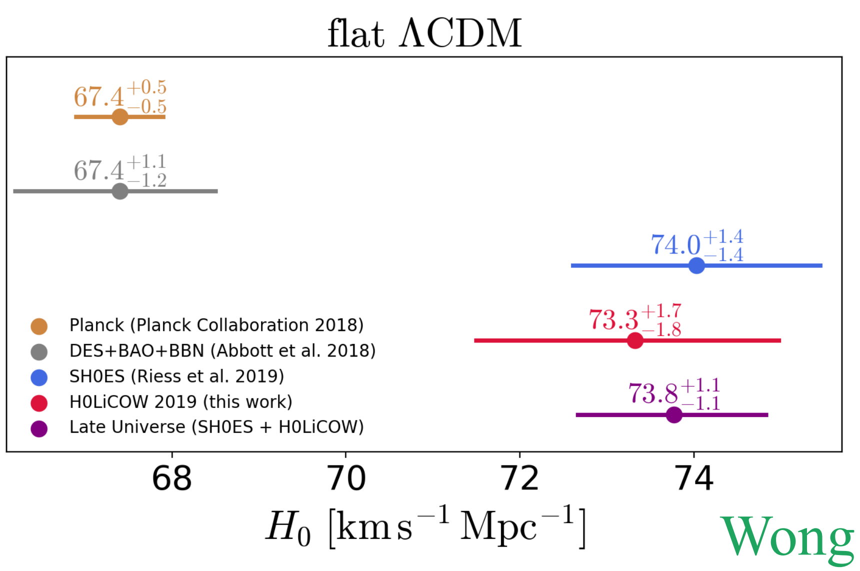


(Chernoff & Finn 1993)

H_0 - where we are

~ 5 \sigma tension between low and high redshift measurements of the Hubble parame

$$H_0 = 67.36 \pm 0.54 \mathrm{km\,s^{-1}\,Mpc^{-1}} \text{ (Early Universe)}^1$$
$$H_0 = 73.30 \pm 1.04 \mathrm{km\,s^{-1}\,Mpc^{-1}} \text{ (Late Universe)}^2$$



Wong et al., H0LiCOW 2019

[a] Abbott et al., 2017 [arXiv:1710.05835]
[b] Abbott et al., 2021 [arXiv:2111.03604]

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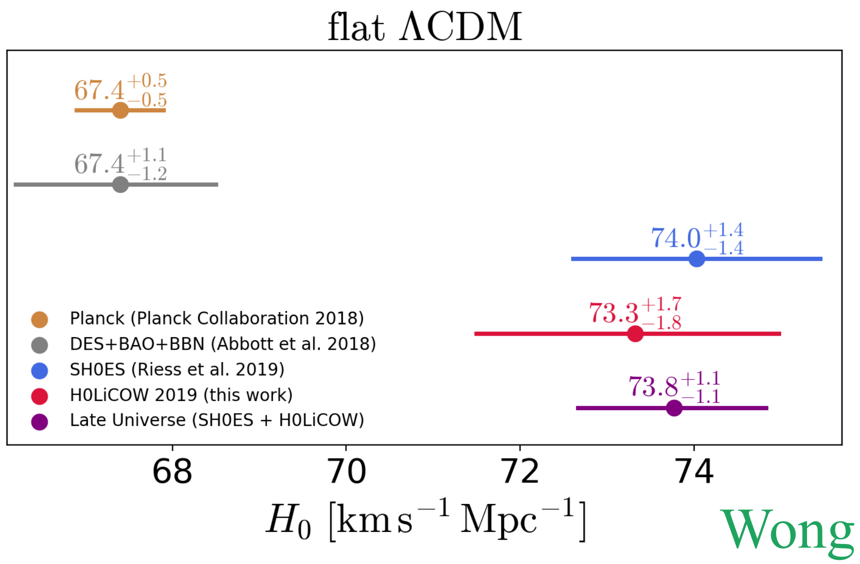
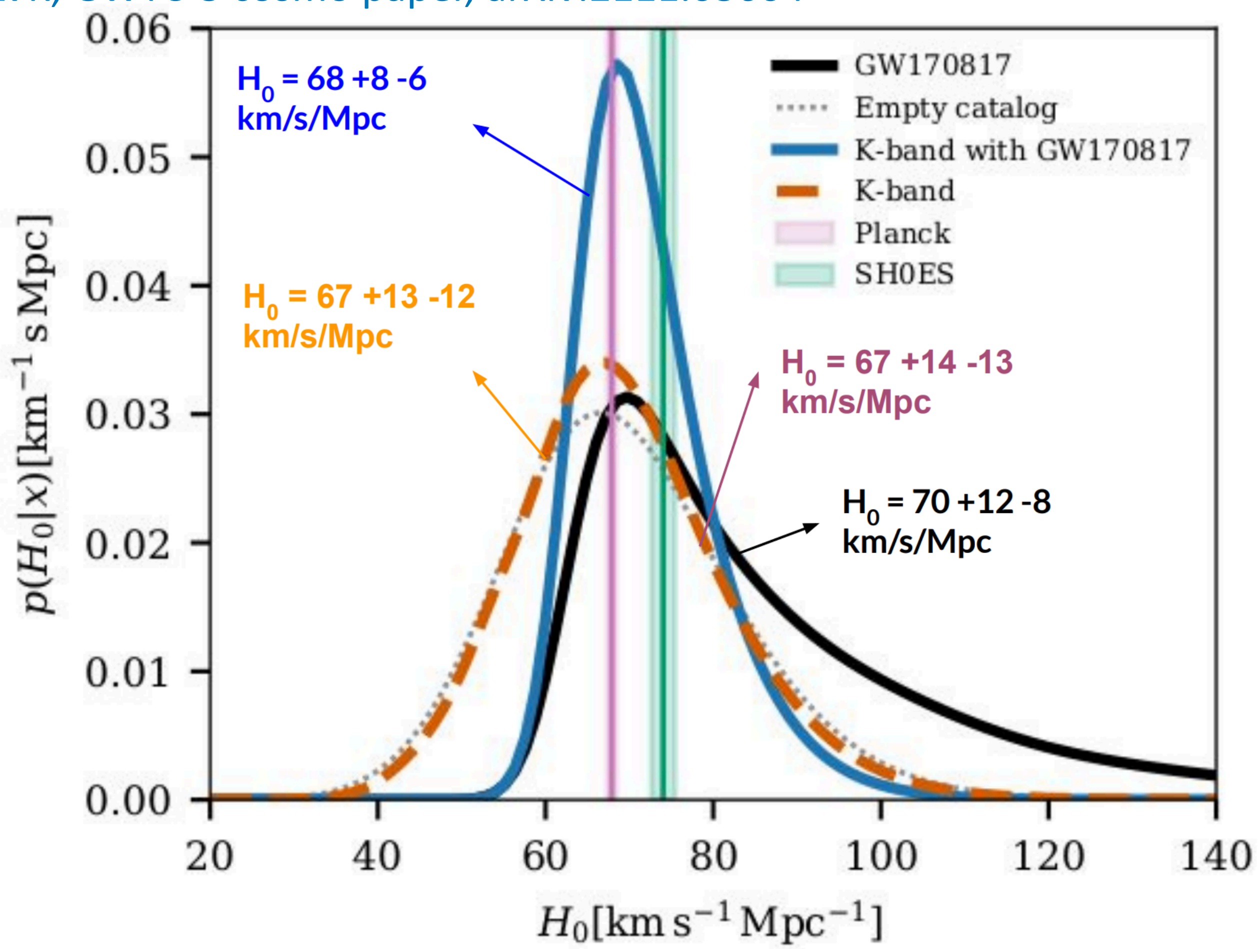


Wong et al., H0LiCOW 2019

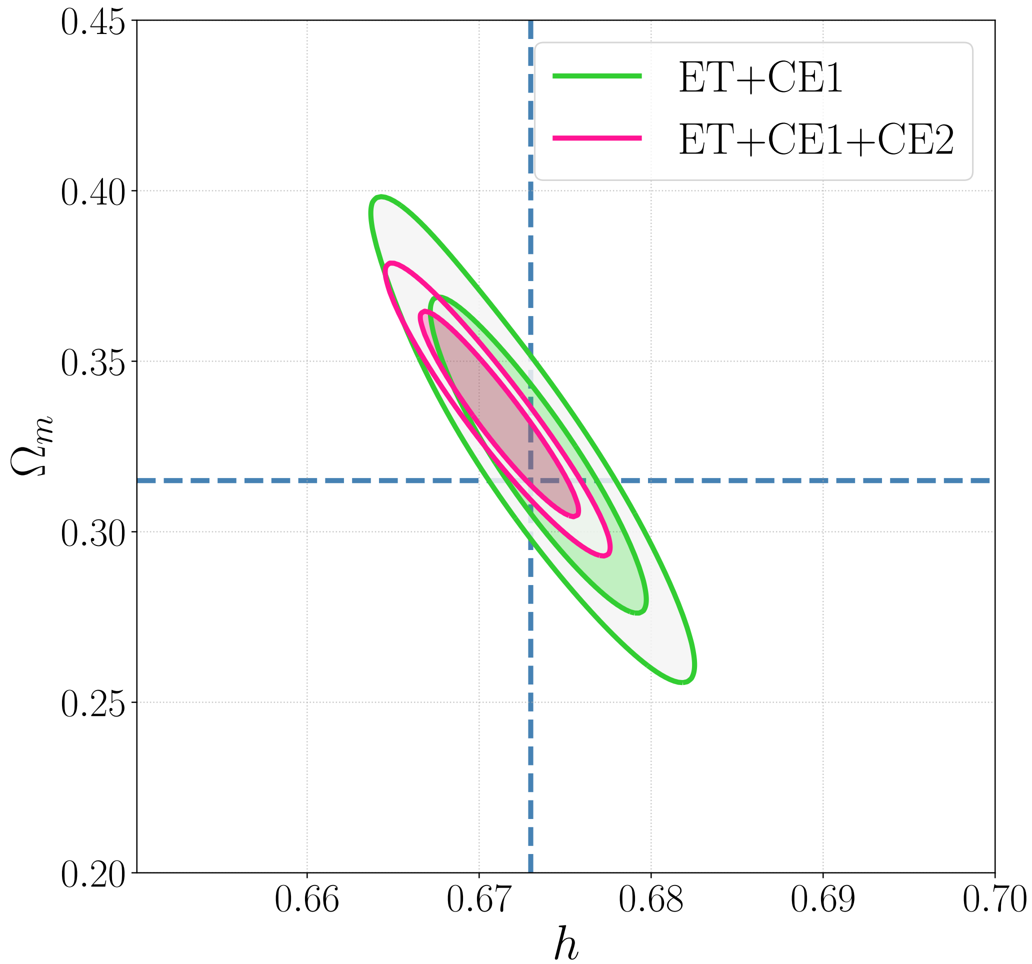
LVK, GWTC-3 cosmo paper, arXiv:2111.03604

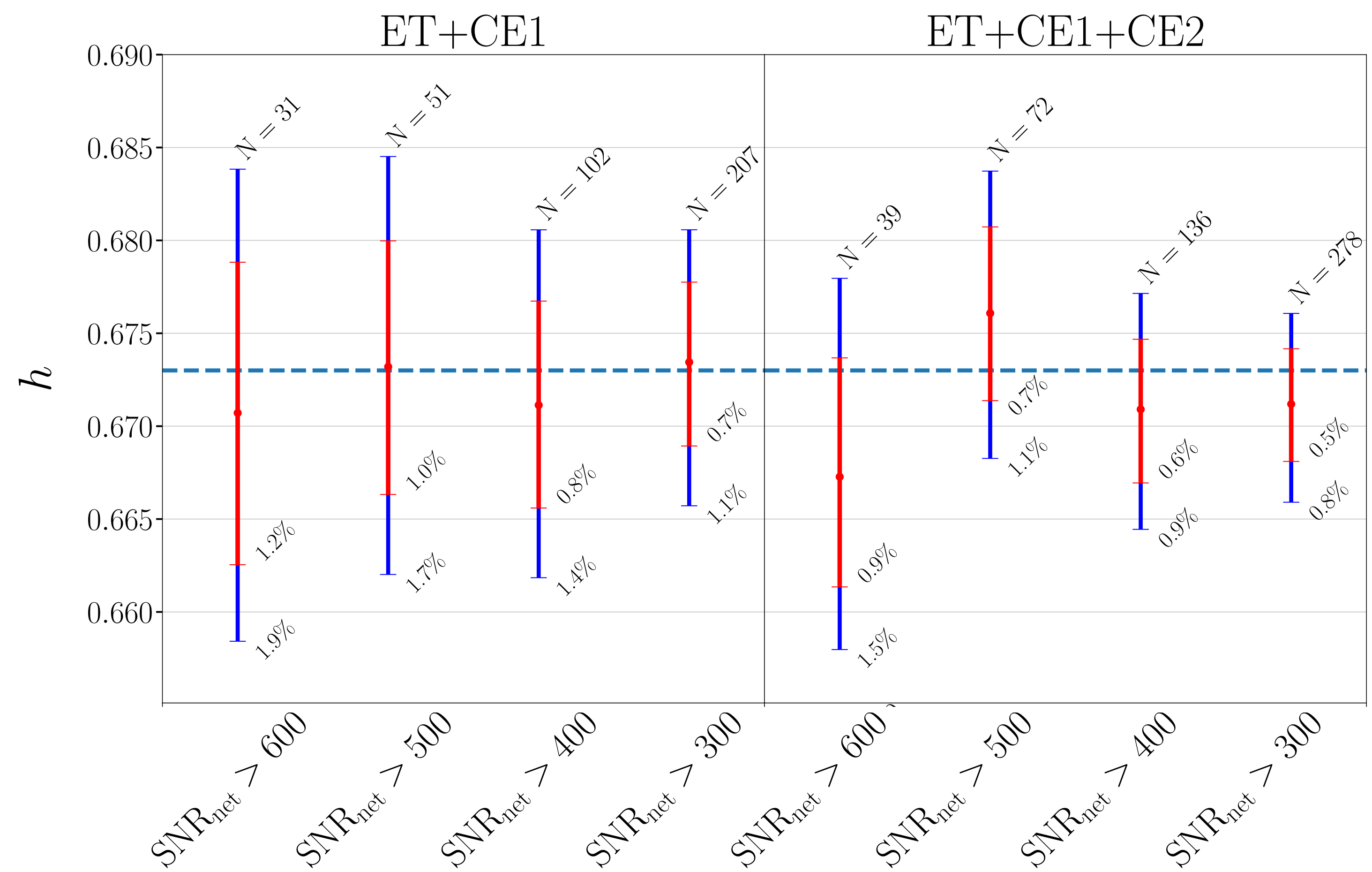


- $H_0 = 72.2^{+13.9}_{-7.5}$ km/s/Mpc
  [Finke et al., JCAP (2021) with GWTC-2 catalog]
- $H_0 = 72.8^{+11.0}_{-7.55}$ km/s/Mpc
  [Palmese et al., ApJ (2023) with GWTC-3 catalog]

[a] Abbott et al., 2017 [arXiv:1710.05835]
[b] Abbott et al., 2021 [arXiv:2111.03604]

H_0 - where we will be with ET? DARK SIRENS method





Fiducial scenario

1 year of observation

Complete galaxy catalogue

Full duty cycle

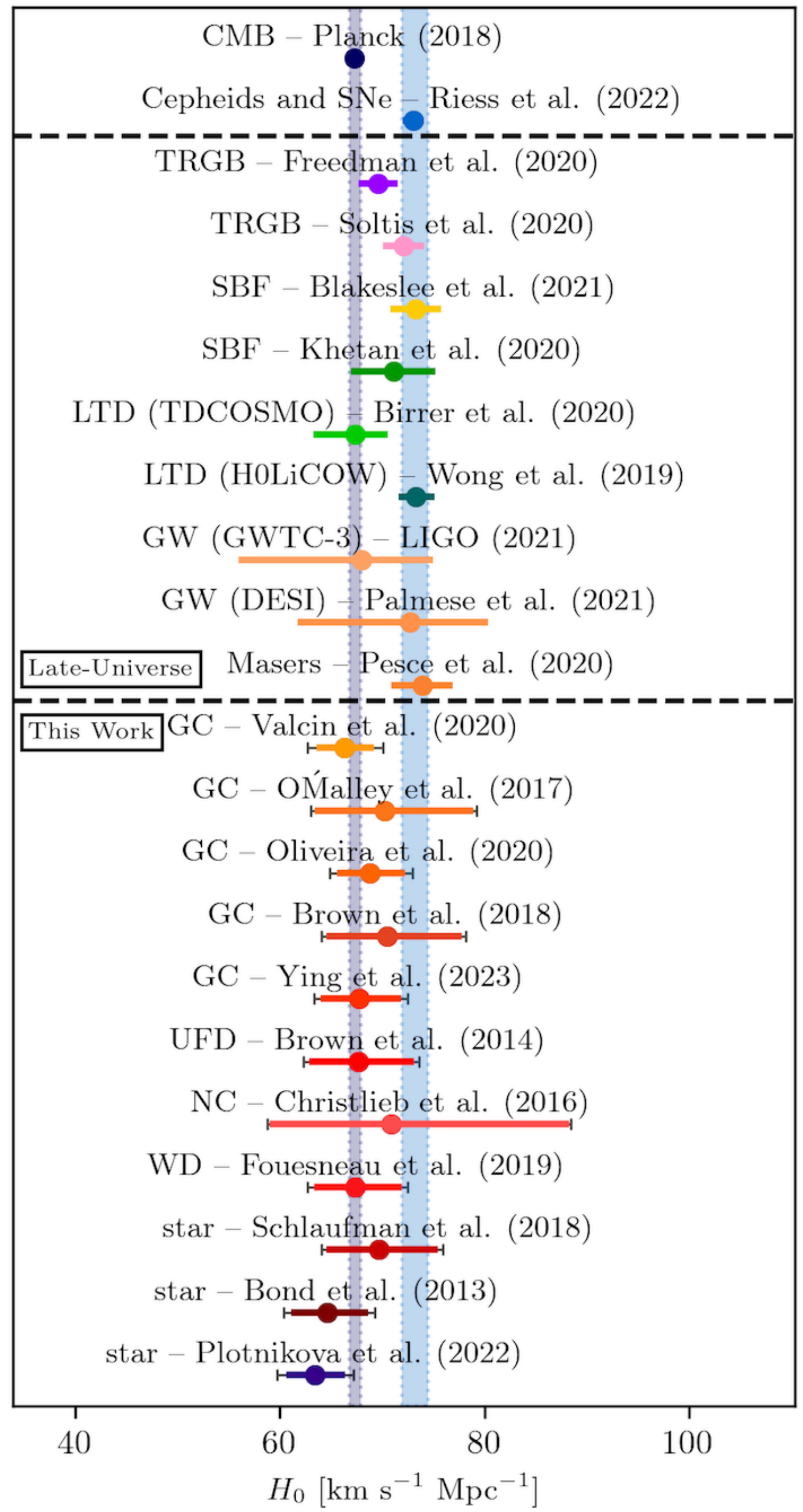
precision for the inference of h with dark sirens with a galaxy catalog complete up to z < 1

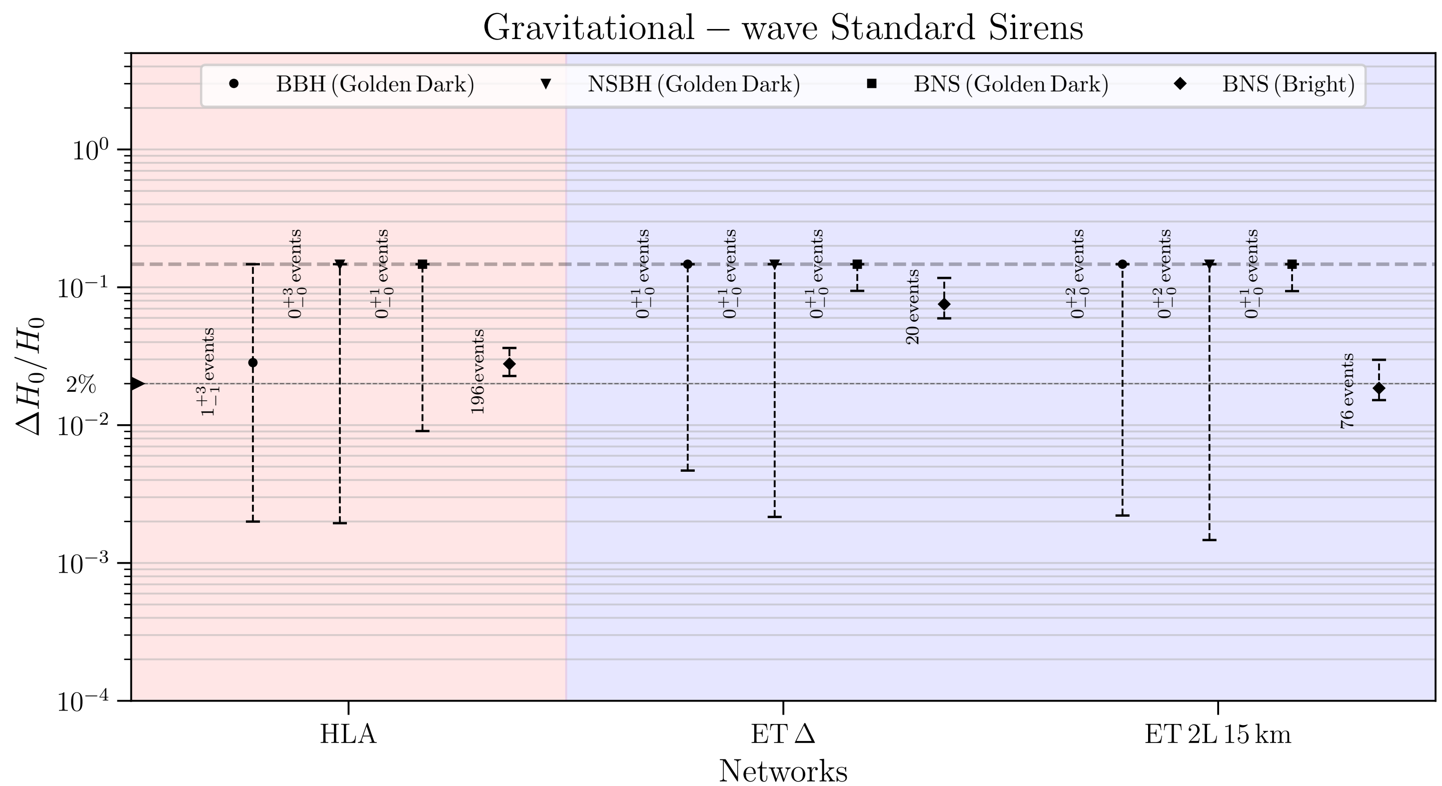
Network	N		$\Delta h/h$ (%)				$\Delta\Omega_m/\Omega_m$ (%)		
	$z<1$	$z<3$	$z<1$	$z<1$ fixed Ω_m	$z<1$ single-host	$z<3$	$z<1$	$z<1$ single-host	$z<3$
ET+CE1	207	248	0.6 (1.1)	0.2 (0.4)	3.3-7.1 (5.6-11.2)	0.7 (1.1)	8.8 (14.4)	-	8.8 (14.6)
ET+CE1+CE2	278	348	0.5 (0.8)	0.2 (0.3)	1.7-2.1 (2.7-3.3)	0.4 (0.7)	6.1 (10.0)	-	5.3 (8.7)

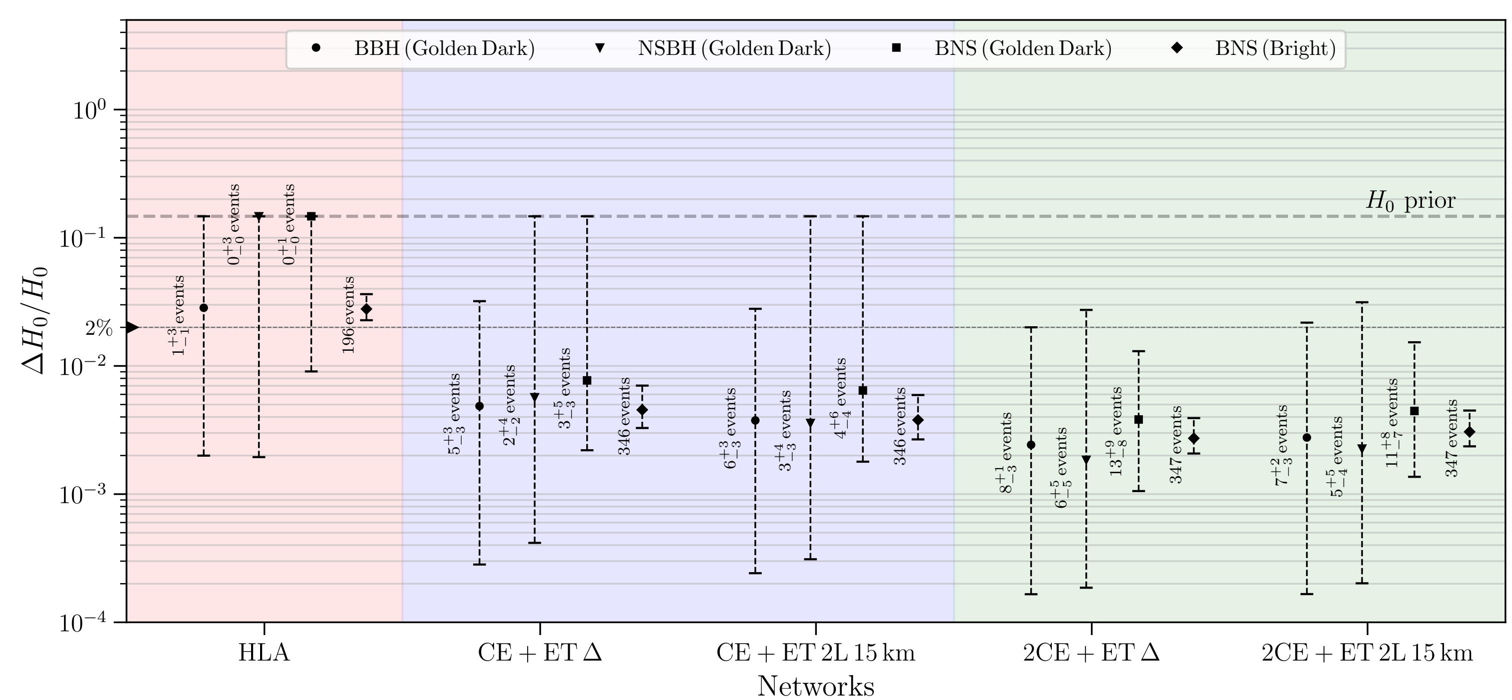
Expected cosmological constraints at the 68% (90%) CI for multiyear 3G observations estimated from the 1 year fiducial results

Nicolo Muttoni et al. 2023

H_0 - shedding light on the H_0 tension

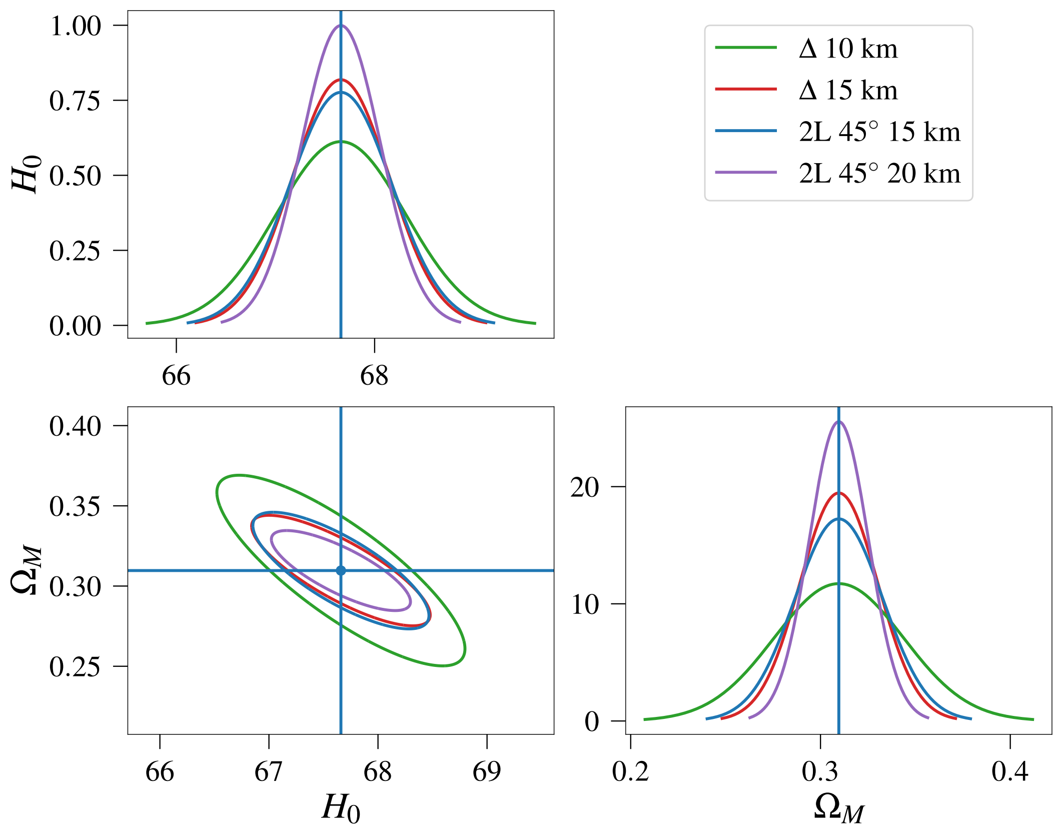


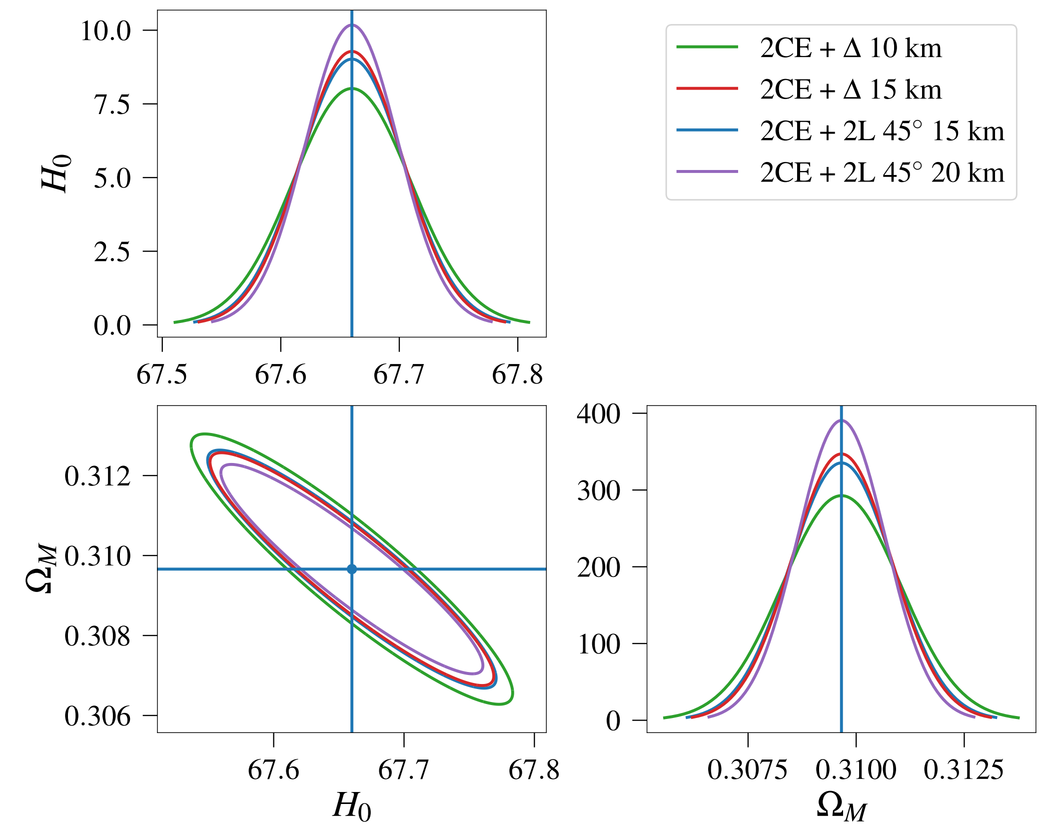




Work in progress

H_0 - where we will be with ET? EM counterpart (BNS)





Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	9.63×10^{-3}	1.10×10^{-1}
Δ-15km	7.20×10^{-3}	6.62×10^{-2}
2L-15km-45°	7.59×10^{-3}	7.47×10^{-2}
2L-20km-45°	5.90×10^{-3}	5.04×10^{-2}

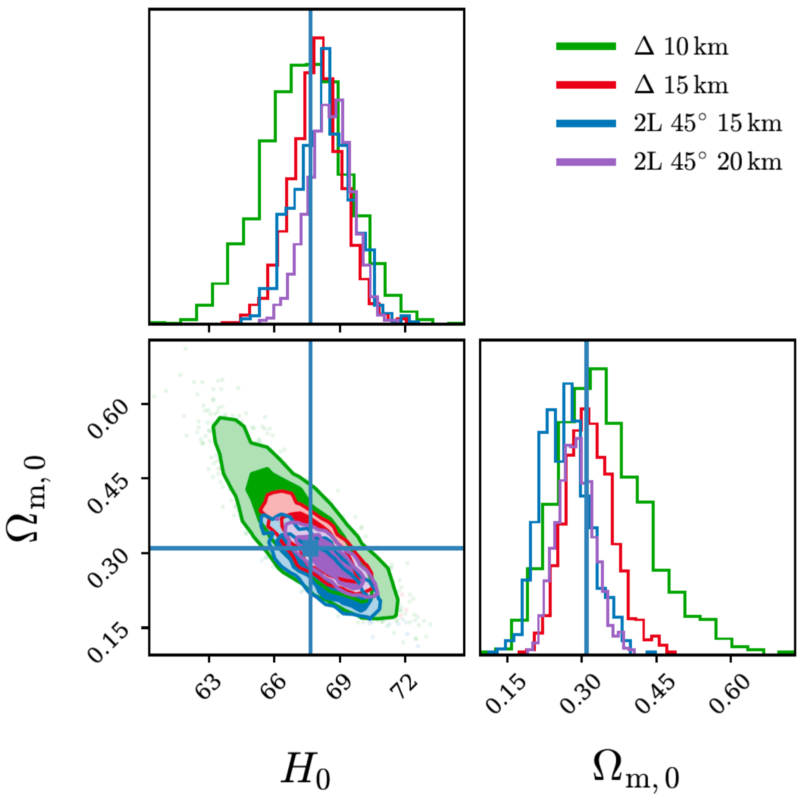
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km +2CE	7.35×10^{-4}	4.40×10^{-3}
Δ-15km +2CE	6.35×10^{-4}	3.71×10^{-3}
2L-15km-45° +2CE	6.54×10^{-4}	3.84×10^{-3}
2L-20km-45° +2CE	5.79×10^{-4}	3.30×10^{-3}

Constraints on the parameters H0 and ΩM in ΛCDM model using one year GW observations from BNS alone for different ET geometries.

ET CoBA document

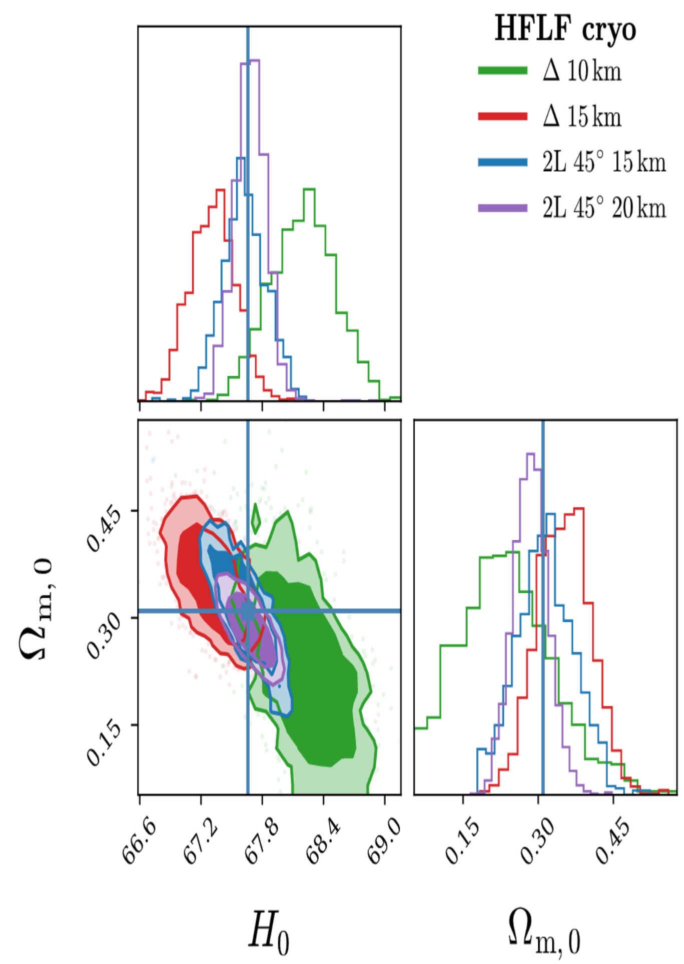
H_0 - where we will be with ET?

Joint GW-GRB detections, ET+THESEUS



Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.057	0.546
Δ-15km	0.035	0.290
2L-15km-45°	0.040	0.370
2L-20km-45°	0.029	0.276

Joint GW-kilonova detections, ET+VRO



HFLF cryogenic		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.009	0.832
Δ-15km	0.007	0.303
2L-15km-45°	0.006	0.370
2L-20km-45°	0.004	0.243

HF only		
Configuration	$\Delta H_0/H_0$	$\Delta\Omega_M/\Omega_M$
Δ-10km	0.065	1.23
Δ-15km	0.057	1.86
2L-15km-45°	0.066	1.31
2L-20km-45°	0.031	1.22

Note: the bounds becomes stronger using the Planck prior on Ω_M

ET CoBA paper, Branchesi et al 2023

Using GWs to Constrain Dark Energy

If the Dark Energy equation of states evolves in time $p_{\rm DE}(z) = w_{\rm DE}(z)\rho_{\rm DE}(z)$

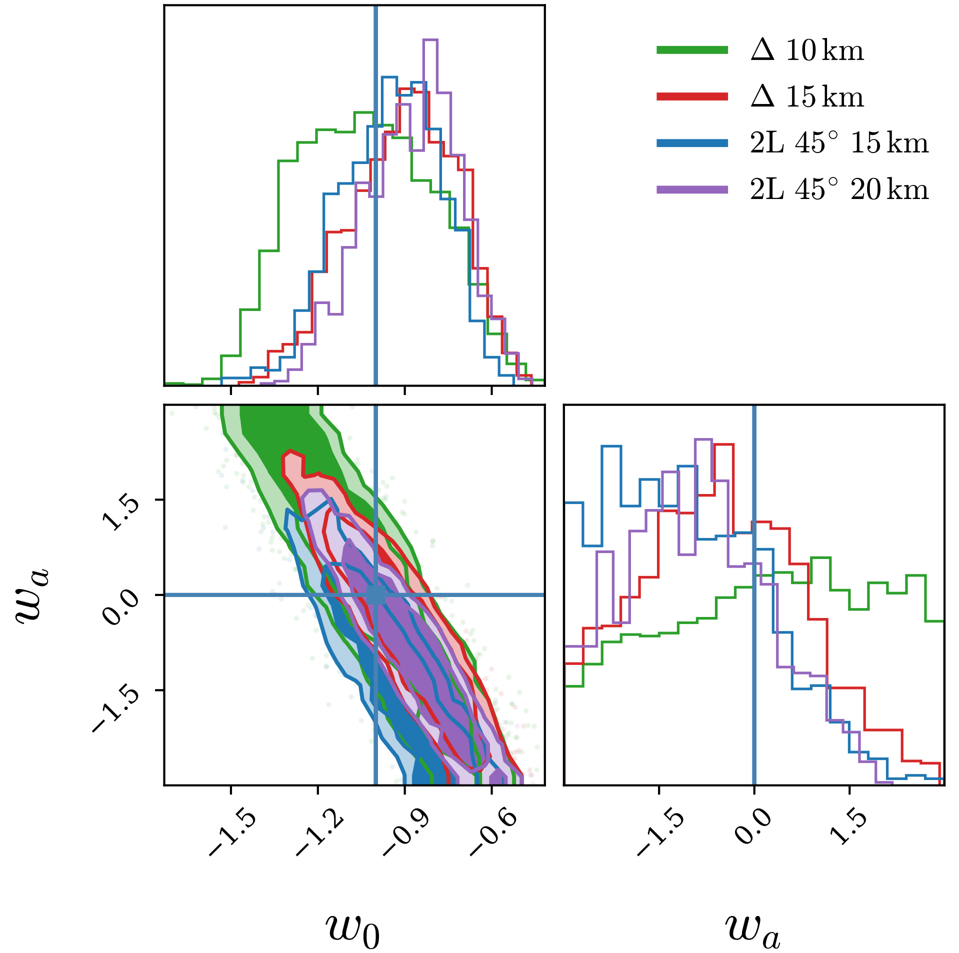
$$\frac{\rho_{\rm DE}(z)}{\rho_0} = \Omega_{\rm DE} \exp\left\{3\int_0^z \frac{d\tilde{z}}{1+\tilde{z}}\left[1+w_{\rm DE}(\tilde{z})\right]\right\}$$

Einstein Telescope with 10^3 standard sirens

$$w_{\rm DE}(z) = w_0 + \frac{z}{1+z} w_a$$

Configuration	Δw_0	Δw_a
Δ-10km	0.49	3.81
Δ-15km	0.40	2.65
2L-15km-45°	0.35	2.55
2L-20km-45°	0.34	2.40

joint GW+EM events obtained with ET+THESEUS, 5 yrs observation



ET CoBA document

Modified GW propagation

In GR $$h''_{ij} + 2\mathcal{H} h'_{ij} + k^2 h_{ij} = 0$$

In Modified Gravity $$h''_{ij} + 2(1+\nu(z))\mathcal{H} h'_{ij} + (c_T^2 k^2 + a^2 m_g^2) h_{ij} = 0$$

Modified `friction'
→ changes GW amplitude

Modified
propagation
speed

Graviton mass

This affects the propagation of GWs across cosmological distance

The net effect is that the quantity extracted from GW observations is a 'GW luminosity distance'

$$\tilde{h}_{+,\times}(f) \propto \frac{\mathcal{M}_z^2}{d_L} (\pi \mathcal{M}_z f)^{-\frac{7}{6}} \times \text{(polarisation angles)} \times \text{(inclination factor)}$$

$$\frac{d_L^{\mathrm{GW}}}{d_L} \neq 1$$

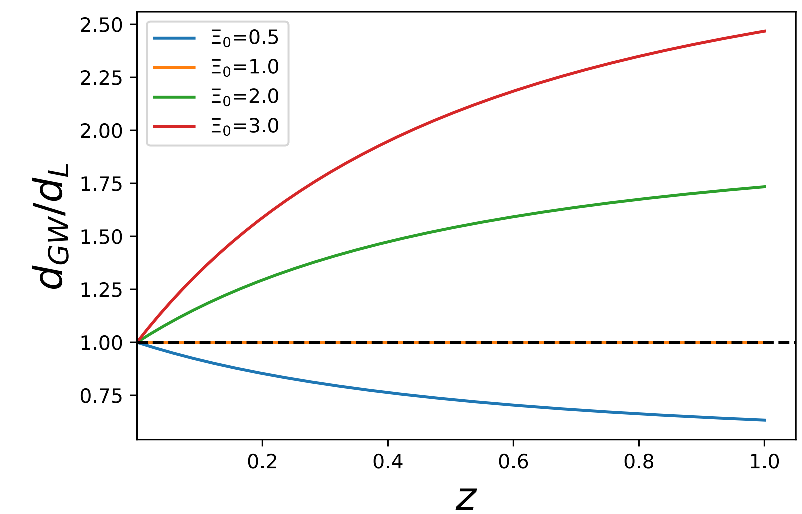
$$\frac{d_L^{\mathrm{GW}}}{d_L} = exp\left[\int_0^z \frac{\nu(\tilde{z})}{1+\tilde{z}} d\tilde{z}\right]$$

$$\frac{d_L^{\mathrm{gw}}(z)}{d_L^{\mathrm{em}}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n},$$

GW luminosity distance parametrization

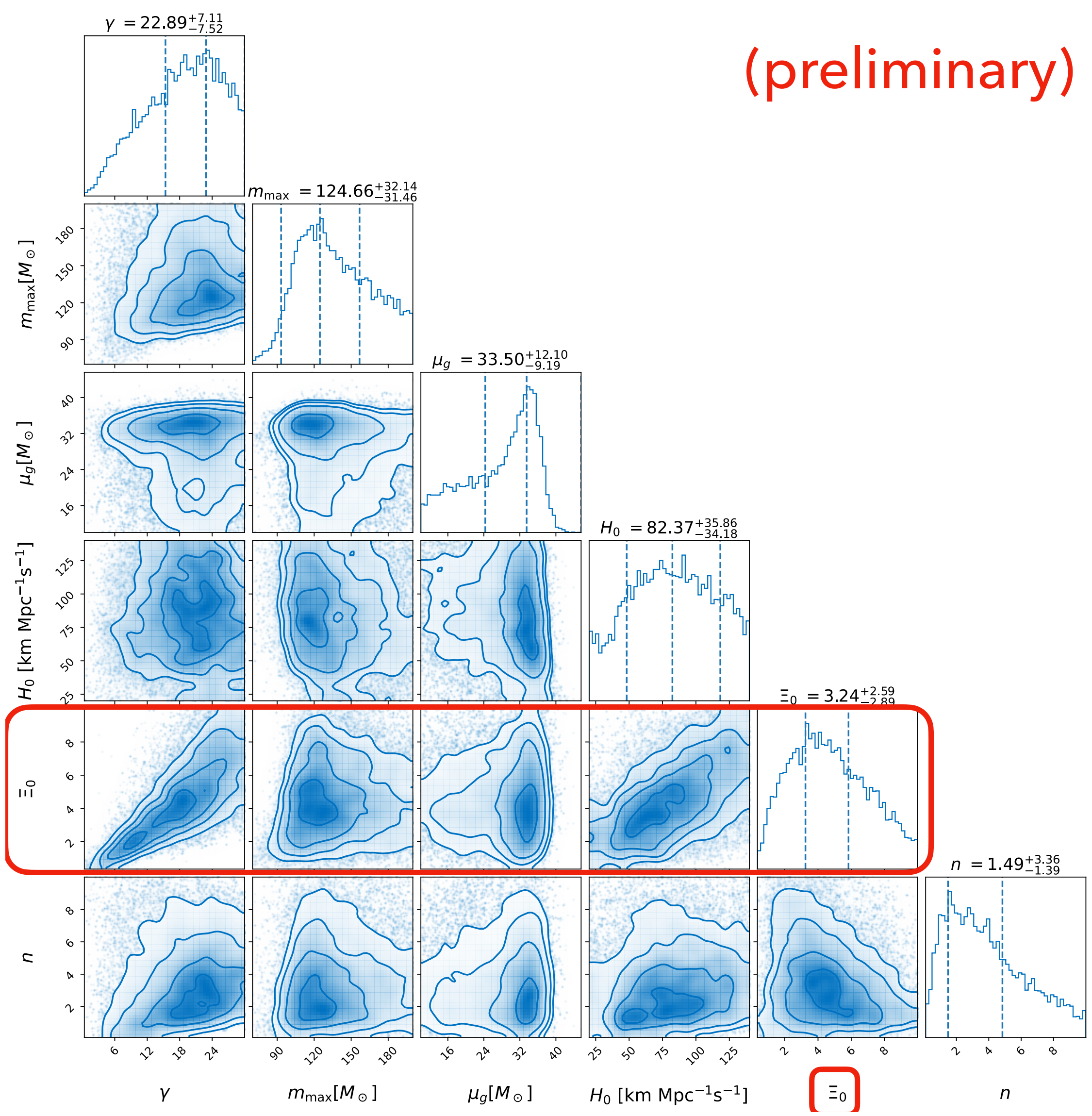
Modified GW propagation

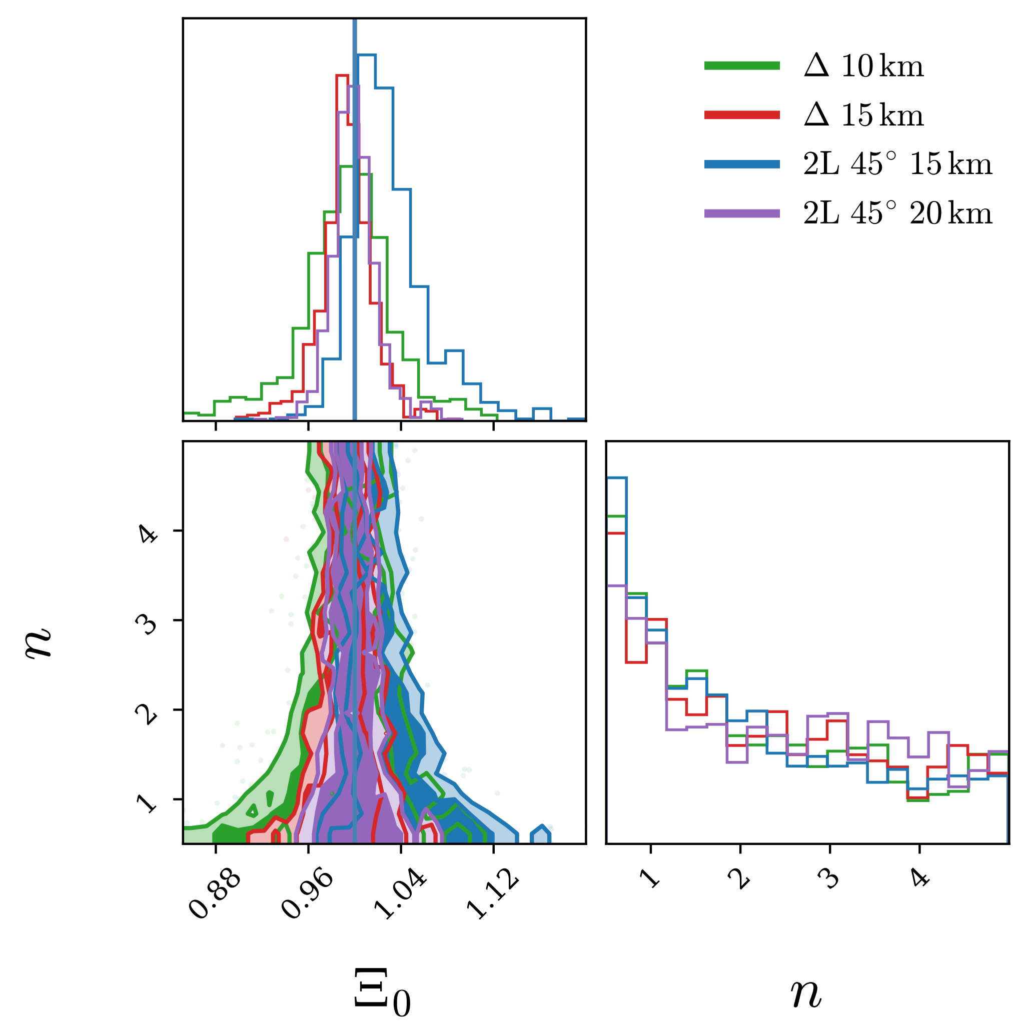
$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n} \, ,$$



Results with GWTC-3 BBHs

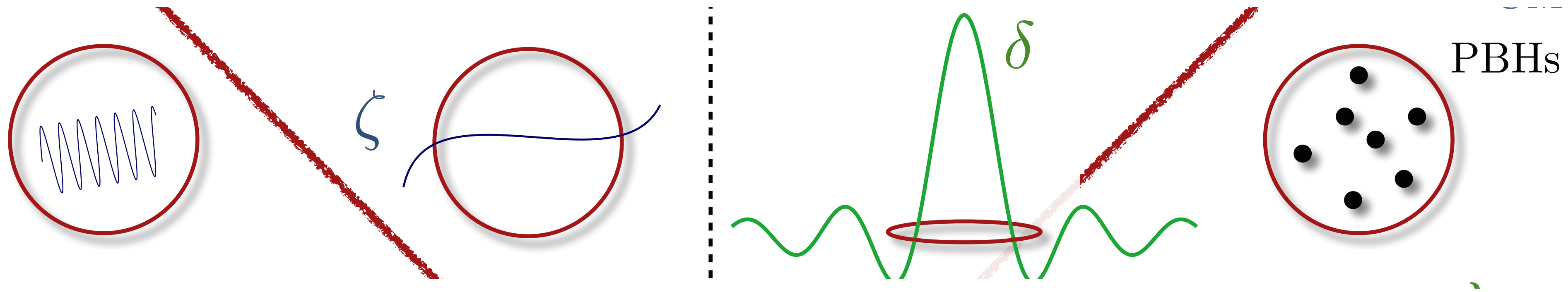
(preliminary)





Belgacem et al 18

Using GWs to Probe Dark Matter



Detections at z> 30 are a smoking-gun signature

Configuration	$N_{\rm det}(z>10)$ [1/yr]	$N_{\rm det}(z>30)$ [1/yr]	$f_{\rm PBH}^{\rm constrained}$ [$\times 10^{-5}$]
Δ-10km	**1140.01**	**76.81**	**2.61**
Δ-15km	1763.87	260.65	1.42
2L-15km-0°	1596.61	238.16	1.48
2L-15km-45°	1650.87	220.86	1.54
2L-20km-0°	1983.97	433.82	1.10
2L-20km-45°	2080.13	415.80	1.12

(based on a PBH population model fitted to GWTC-3)

LF crucial: N(z>30) =0 otherwise !

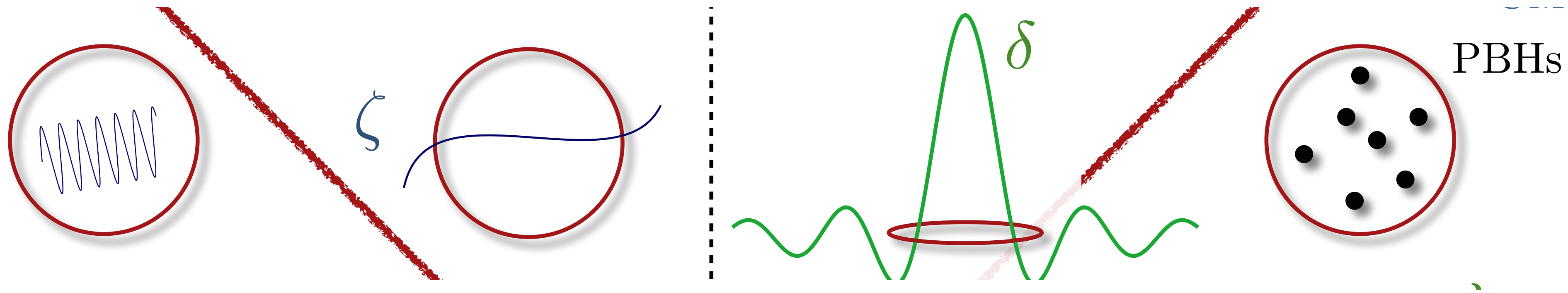
significant differences also in a network with 1CE

Configuration	$N_{\rm det}(z>10)$ [1/yr]	$N_{\rm det}(z>30)$ [1/yr]	$f_{\rm PBH}^{\rm constrained}$ [$\times 10^{-5}$]
CE40km	1373.48	47.07	3.34
Δ-10km + CE40km	1940.35	180.08	1.71
Δ-15km + CE40km	2275.96	372.14	1.19
2L-15km-45° + CE40km	2210.49	332.89	1.26
2L-20km-45° + CE40km	2476.43	522.32	1.00

ET CoBA paper, Branchesi et al 2023

A null observation for a primordial population with ET+CE can be translated into an upper bound on the PBH abundance

Using GWs to Probe Dark Matter



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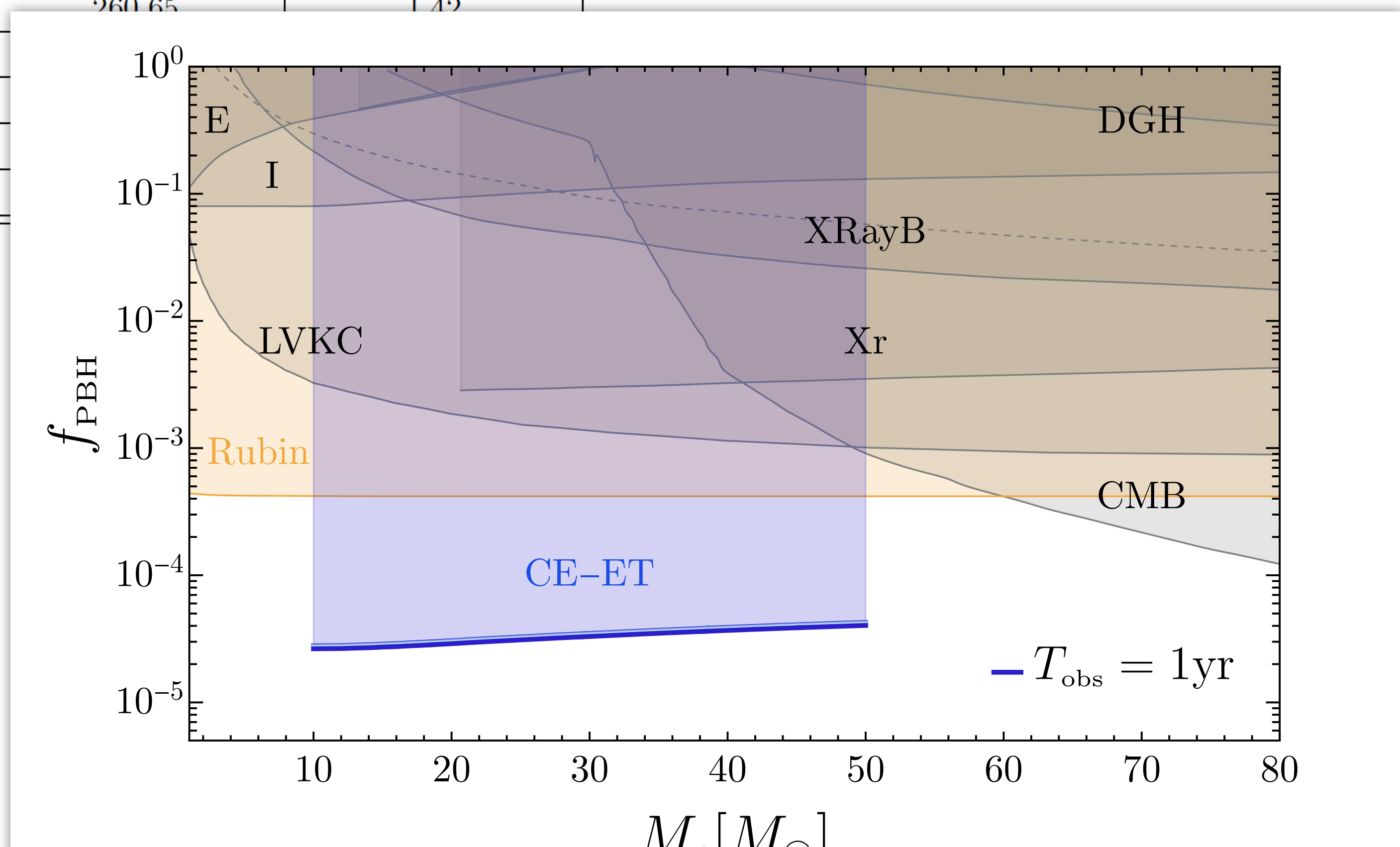
2L-20km-45°	2080.13		

(based on a PBH population model fitted to GWTC-3)

se !



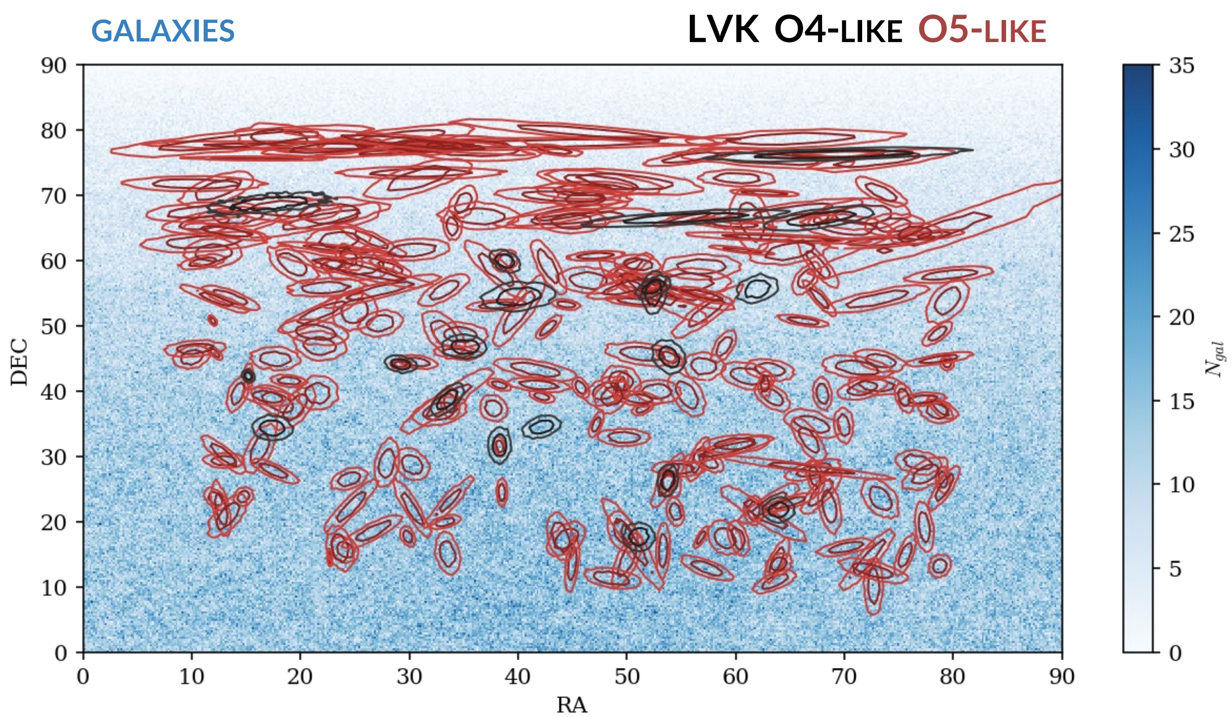
$N_{\rm det}(z>30)$ [1/yr]	$f_{\rm PBH}^{\rm constrained}$ [$\times 10^{-5}$]
47.07	3.34
180.08	1.71
372.14	1.19
332.89	1.26
522.32	1.00

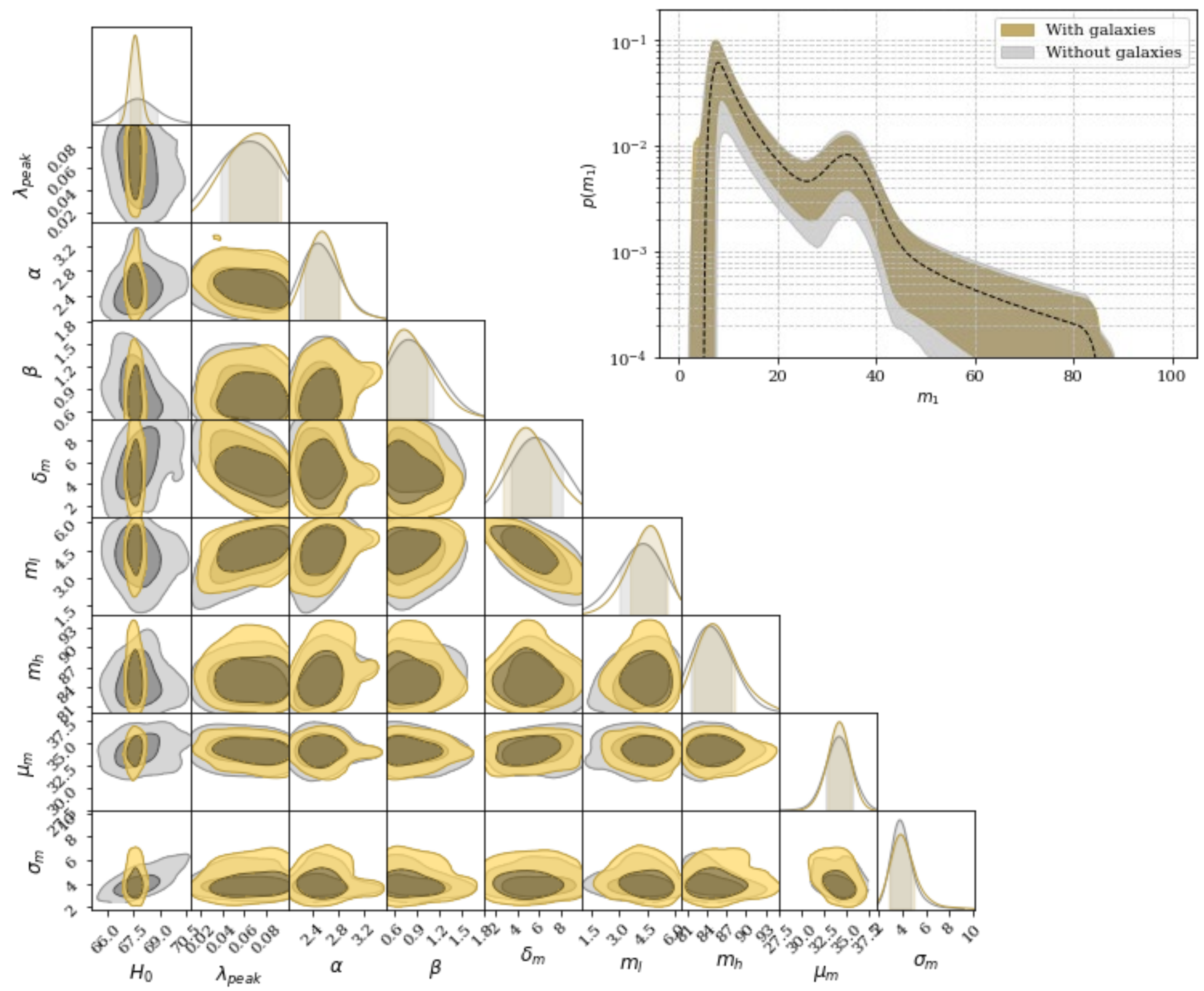
ET CoBA paper, Branchesi et al 2023

A null observation for a primordial population with ET+CE can be translated into an upper bound on the PBH abundance

Cross-correlation between GW and LSS

➢ Mock galaxy catalog (**MICEv2**, Crocce+2015) x simulated BBH events





- Analysis of well-localized events ($\Delta\Omega_{90\%}$ < 10 deg^2):

  ~ 15 events in LVK-O4

  ~ 100 events in LVK-O5

Forecasts for **O4 and O5 x DES-like survey**

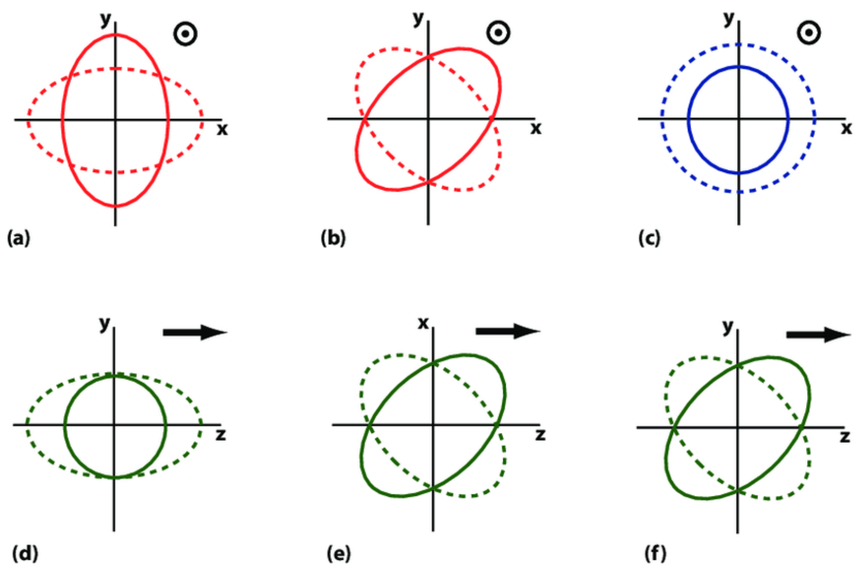
Forecasts for **ET x Euclid**

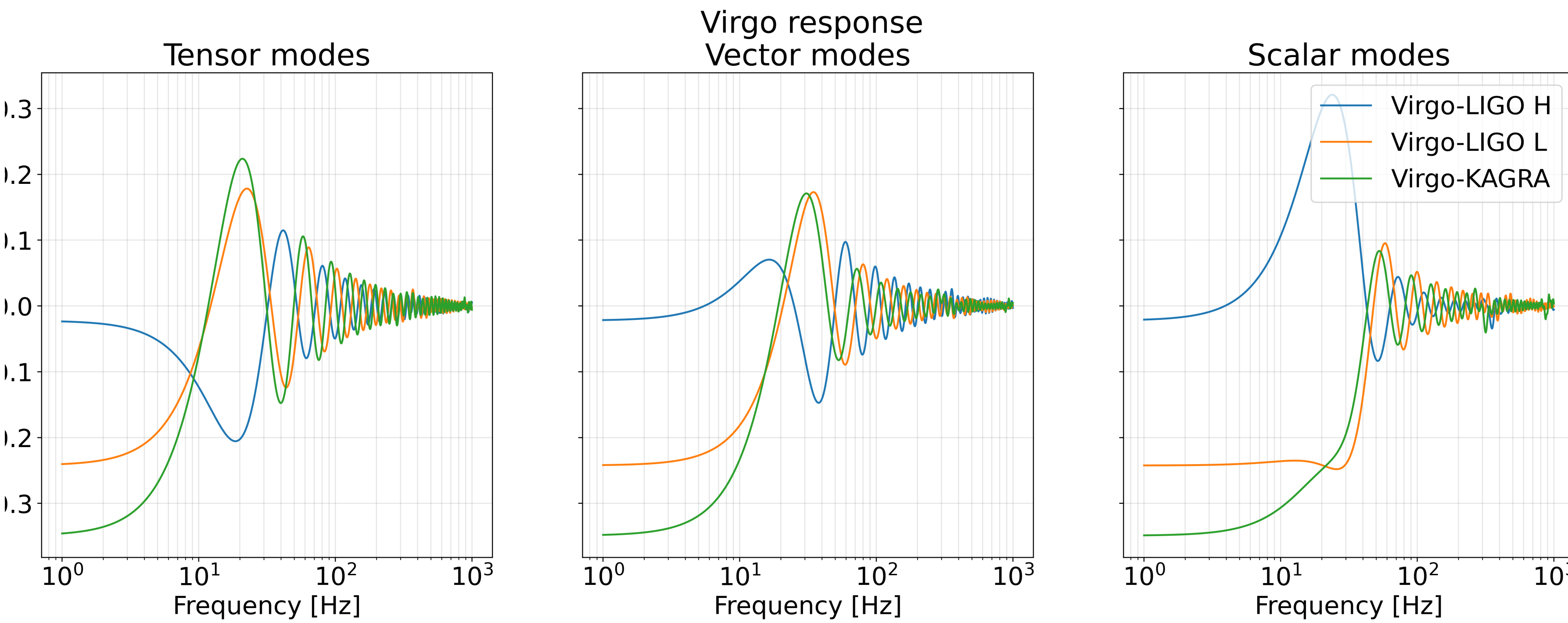
SkyFast pipeline - in preparation

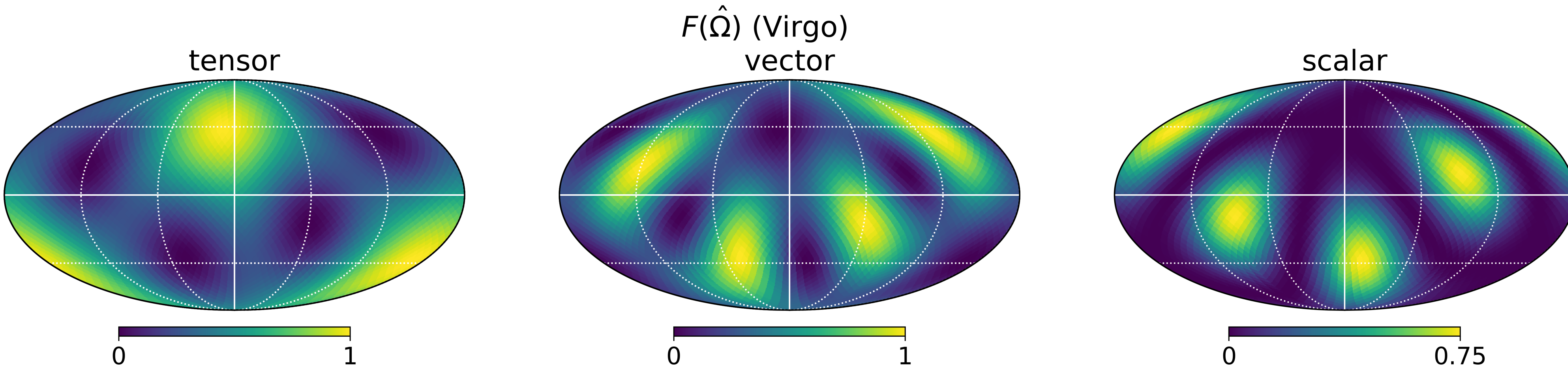
Courtesy: Nicola Borghi et al.

Ongoing (local) projects - GWdet

Public code to compute pattern function, overlap function, PLS, response of every detector network





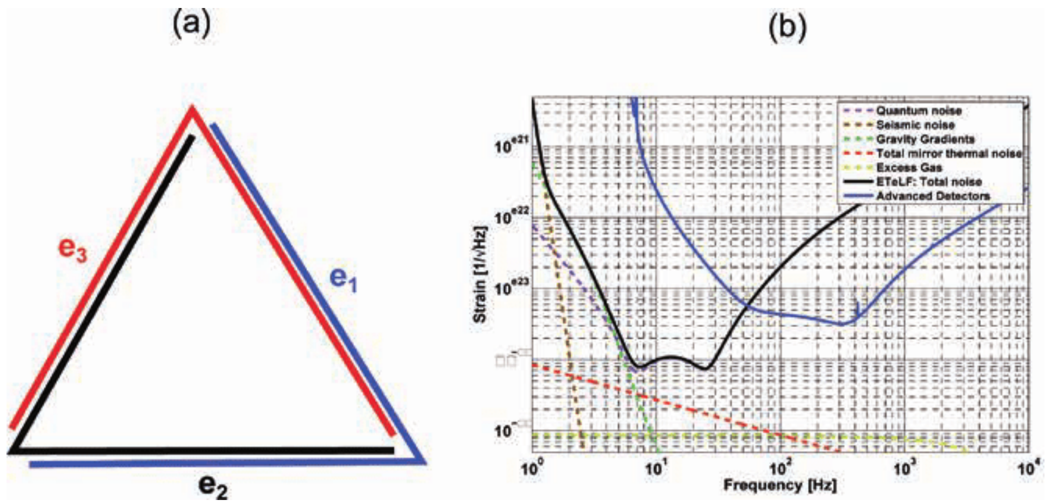


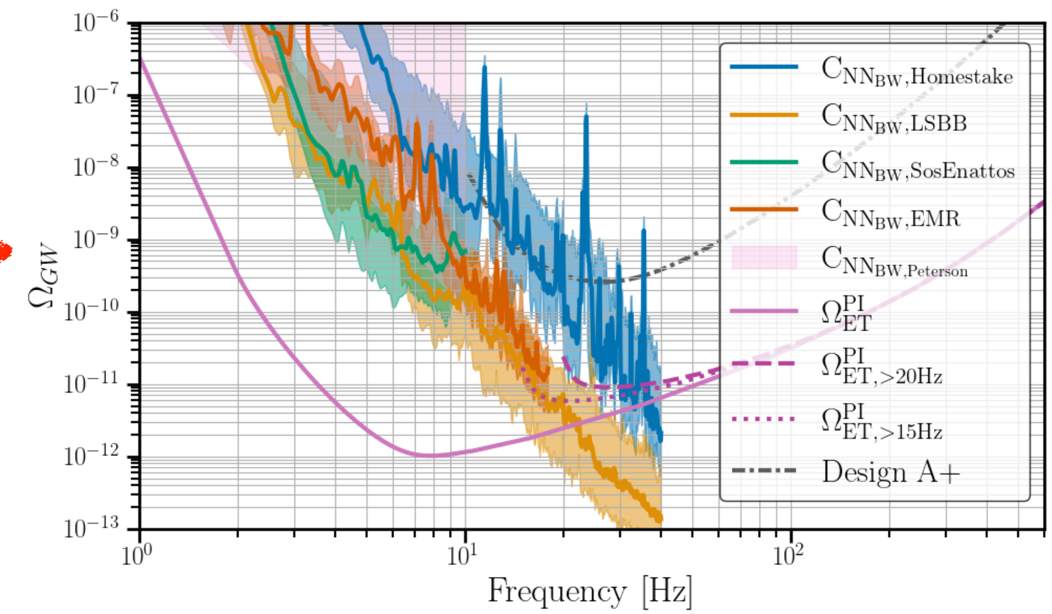
Preliminary

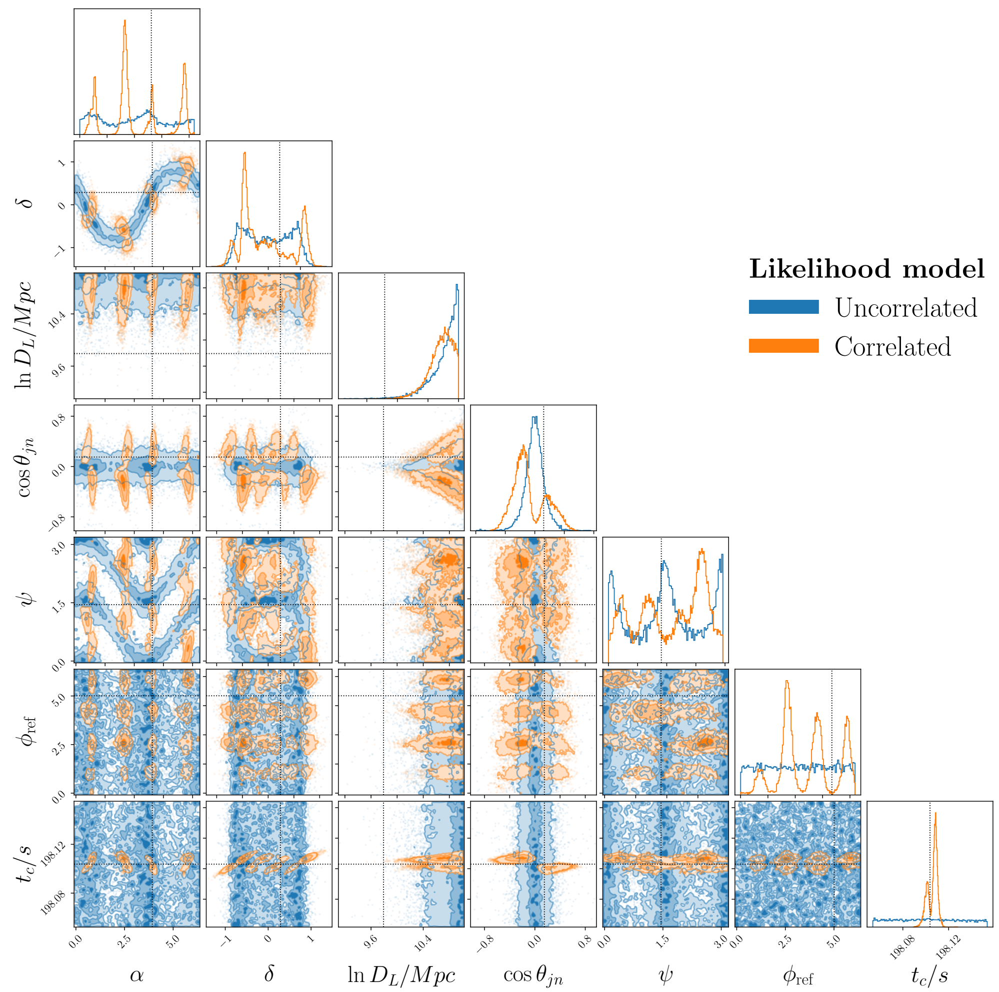
Virgo-Pisa

Ilaria Caporali

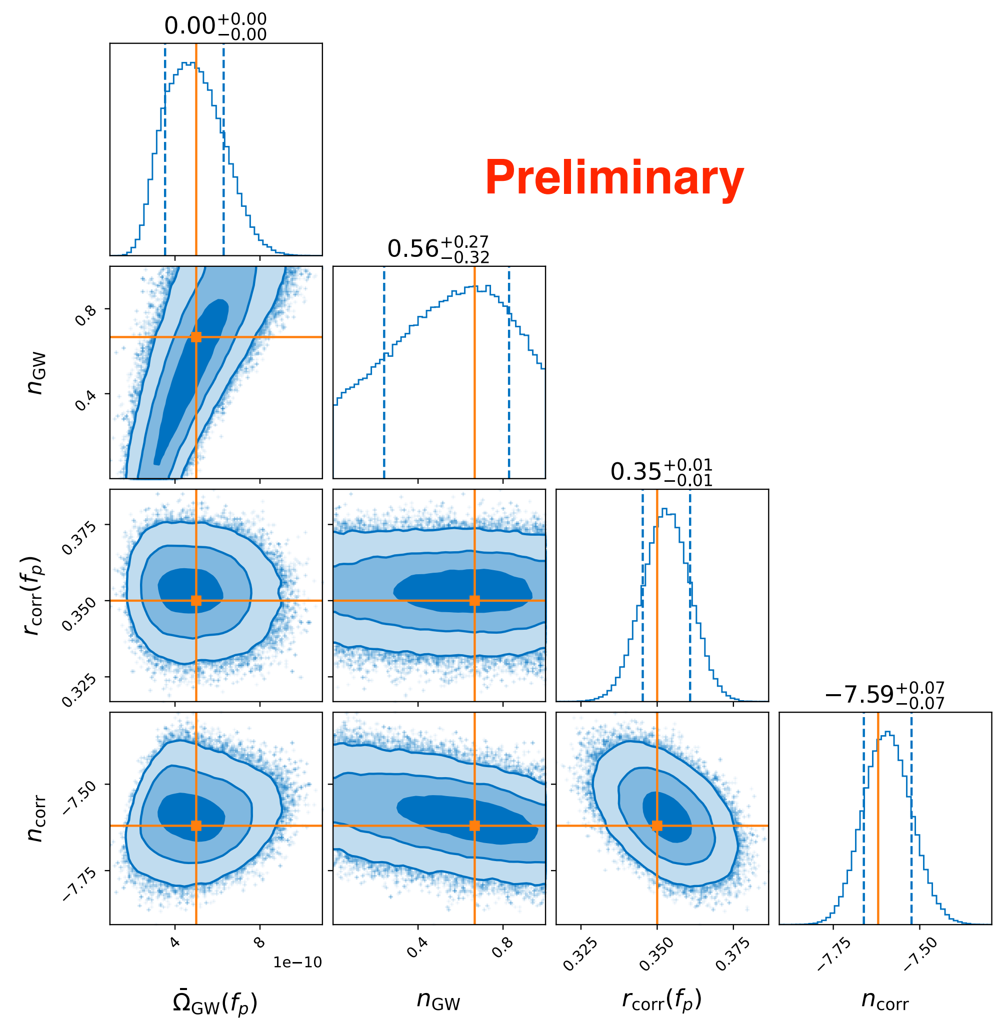
Ongoing (local) projects - Impact of ET correlated noise







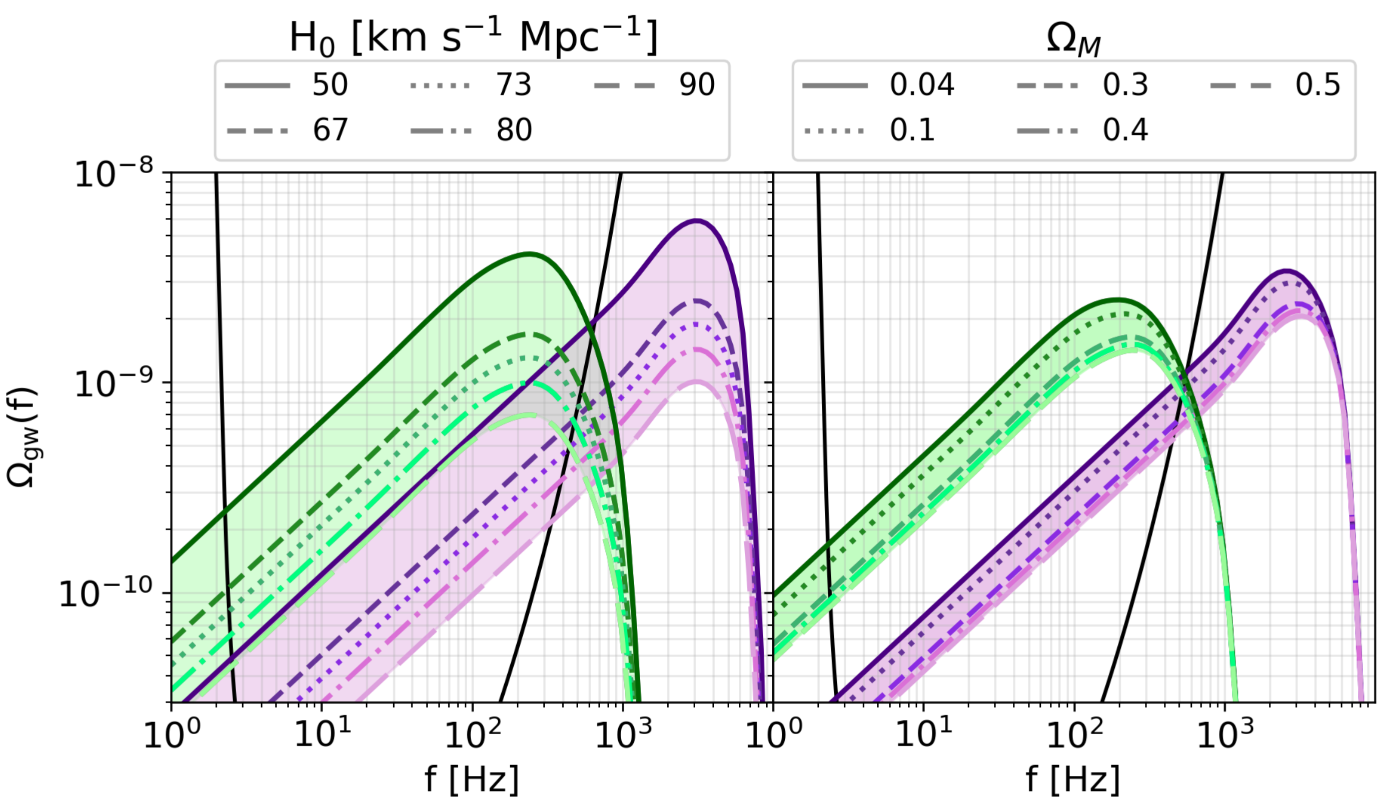
Impact on PE Resolved sources [Cireddu, Del Pozzo et. al]



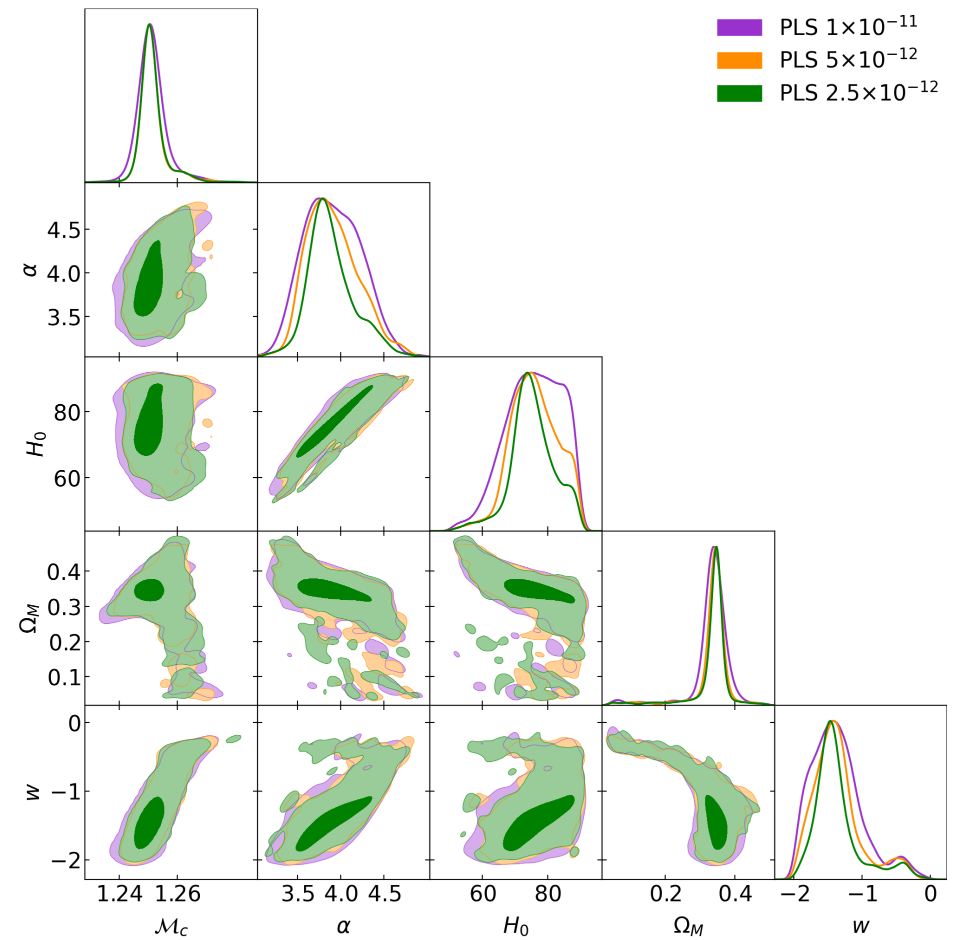
Impact on PE SGWB

The astrophysical background as a cosmological probe

$$\Omega_{\rm gw}(f) = \frac{8\pi G f}{3H_0^3 c^2}\int dz d\theta_a\, p(\theta_a)\,\frac{dE_{\rm gw}}{df_s}(f_s, z|\theta_a)\,\frac{R(z|\theta_a)}{(1+z)h(z|\theta_c)}.$$



Effect of varying the value of H0 and ΩM on the energy density of the GWB from BBHs (green) and BNSs (purple).



Astro+Cosmo Joint constraints

Giulia Capurri + master student(s)

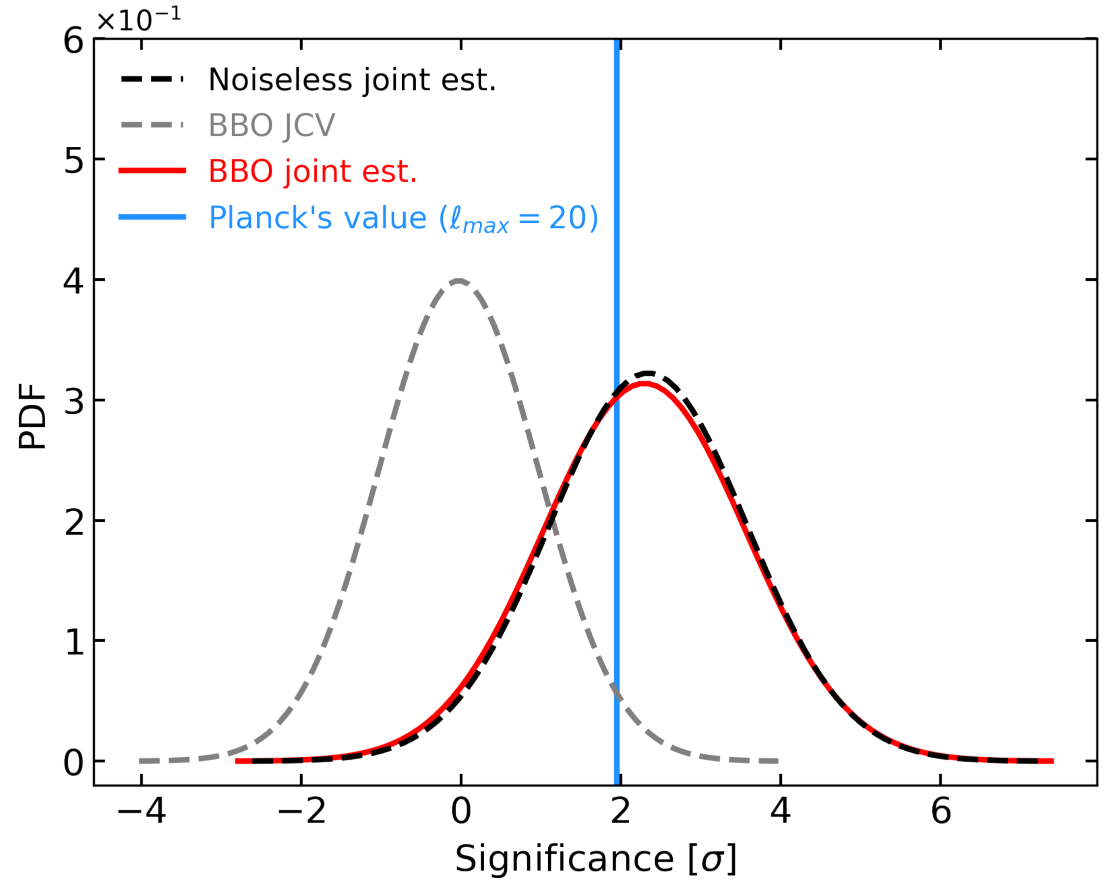
Is the SGWB frame the same as the CMB?

We focus on the **hemispherical power asymmetry** observed in CMB maps by WMAP and Planck

Study evolution of GW in presence of a modulating field:

$$\zeta(\vec{x}) = g(\vec{x})[1 + h(\vec{x})]$$

Using a minimal variance estimator (Hu & Dvorkin, 2008)



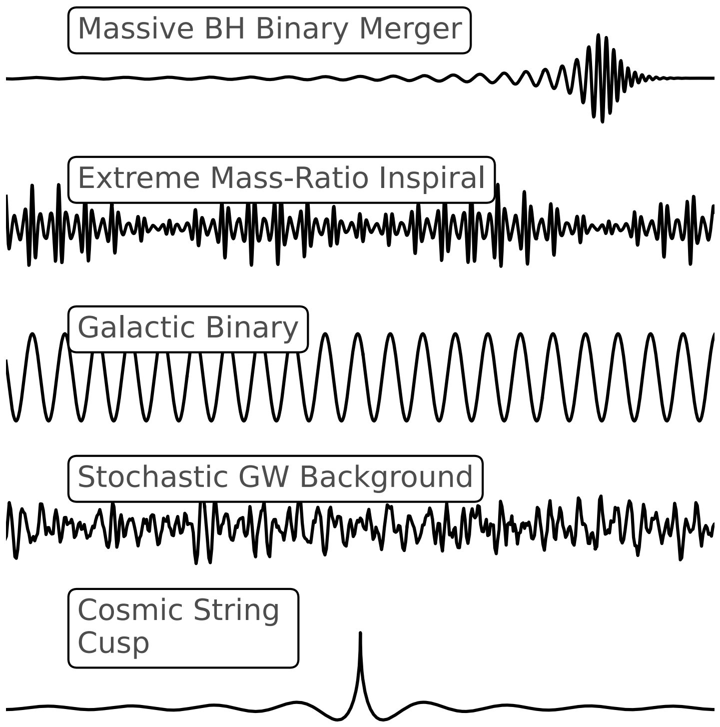
significance ≥ 3σ

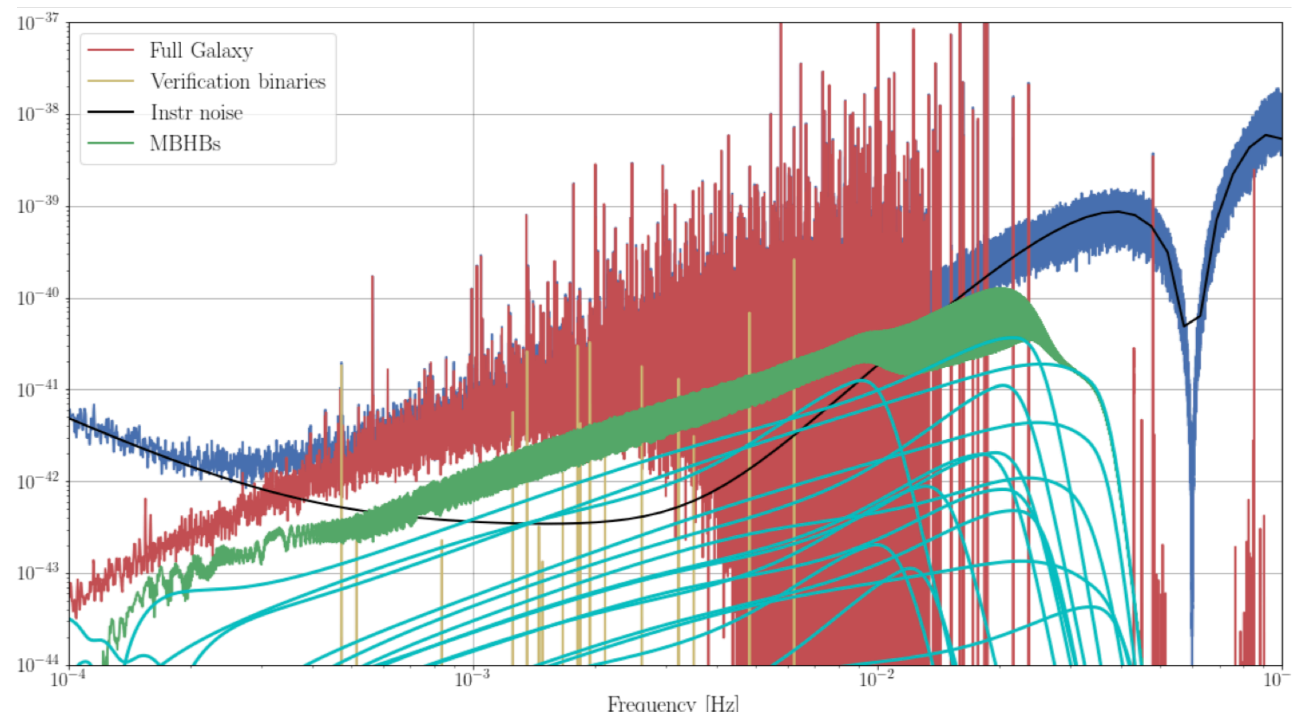
BBO have indeed the potential to shed light on the significance of the CMB power asymmetry

Galloni et al., 2022

Galloni et al., 2023 **Focused on the lack of correlation anomaly**

How to approach the data analysis





- Large number of overlapping sources
- Residuals from sources subtraction
- Confusion from unresolved sources
- One doesn't cross-correlate like LVK
- Prediction of the instrumental noise?
- Artefacts: gaps in the data, glitches...

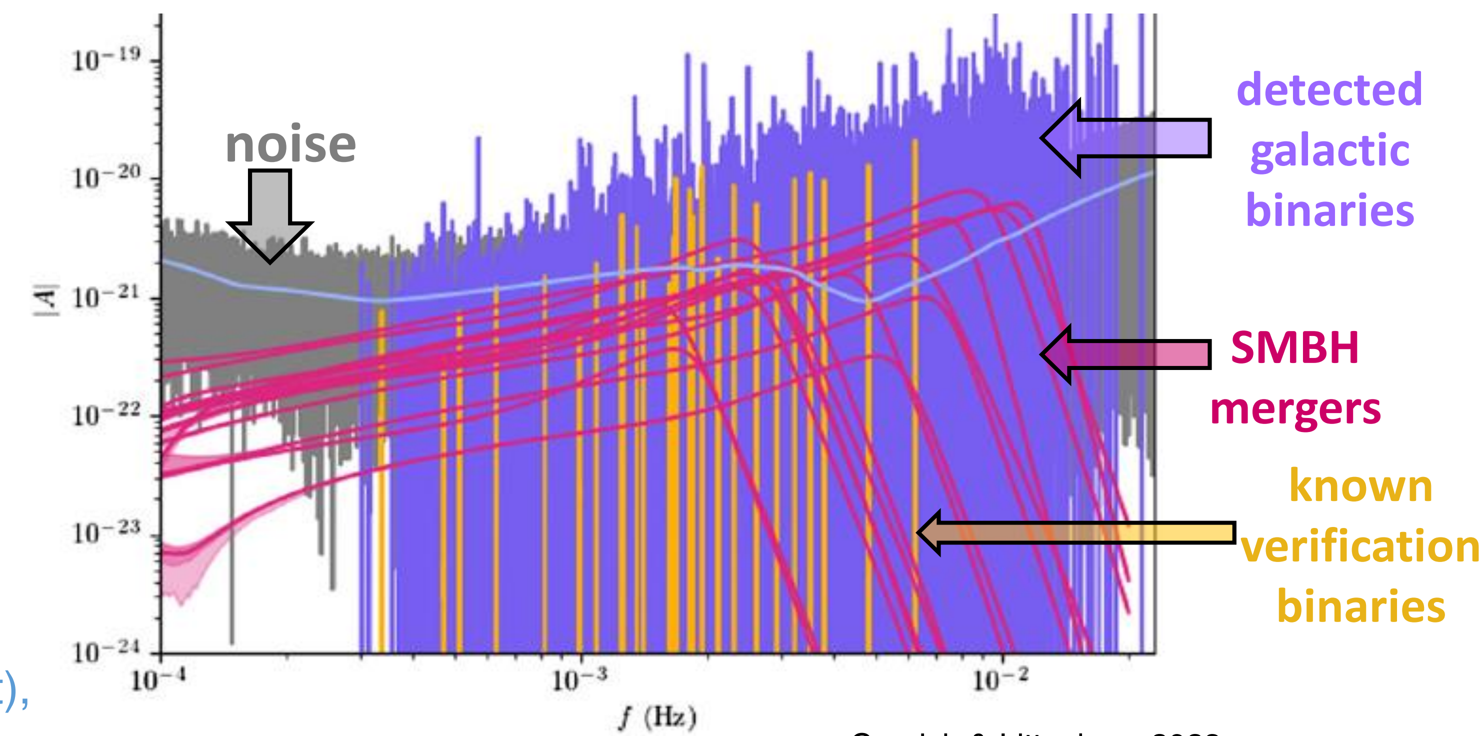
LISA Ground Segment - Italia

Develop a GLOBAL FIT pipeline for LISA

(Similar approach for ET)

(Initial) Nodes: Pisa, Trieste and Milano

ASI commitment to provide data center (HW + eng support), plus pipeline development



Cornish & Littenberg 2023

Conclusions

- All **GW interferometers** have been initially **conceived as GW astrophysics observatories**, they have **not been designed to do cosmology**

- **However**, they can provide new information on a variety of scales: from the Galaxy to Hubble scales, from the present time to the **very early universe** -> therefore they can be used as a **cosmological observatory** as well

- We can test the ***late-time universe*** through the observation of the GW emission from compact binaries, and **measure cosmological parameters.**

- We can test the ***gravitational interaction***, ***Dark Energy*** and constrain **modifications to General Relativity** in the cosmological context and **Dark Matter**

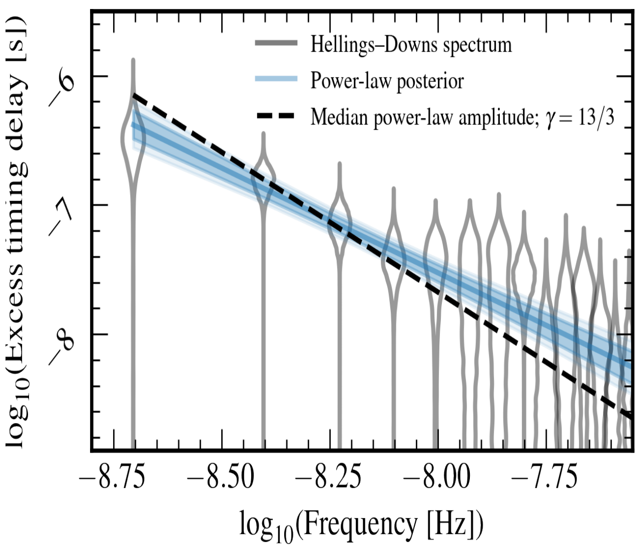
- **A lot of expertise here in PISA to push forward on these topics (astro+cosmo+fundamental physics+noise characterization)**

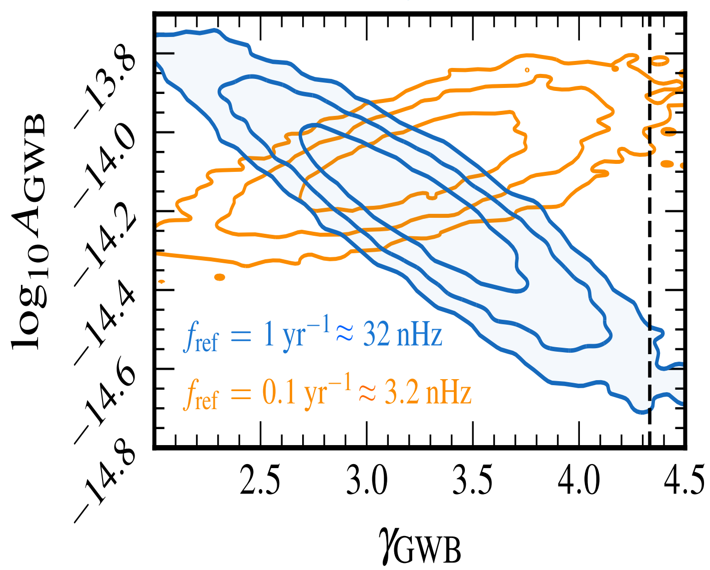
Thank you!

PTA Spectra

NANOGrav

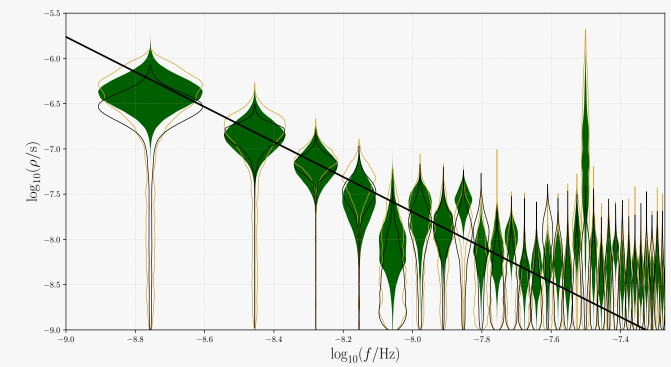
Agazie et al. [2306.16213]

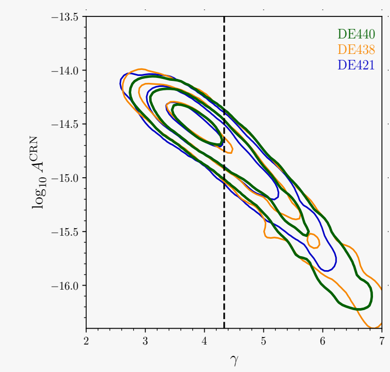




PPTA

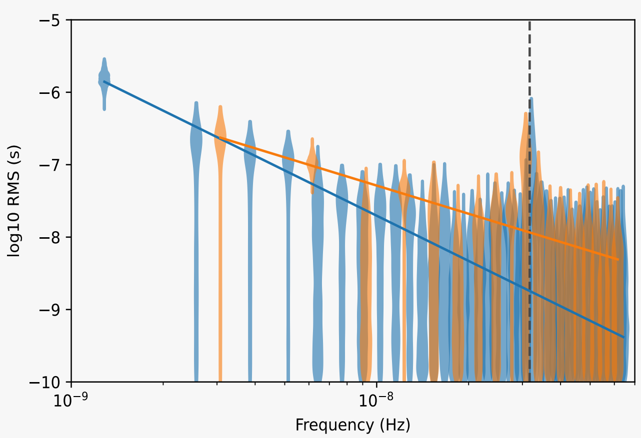
Reardon et al. [2306.16215]

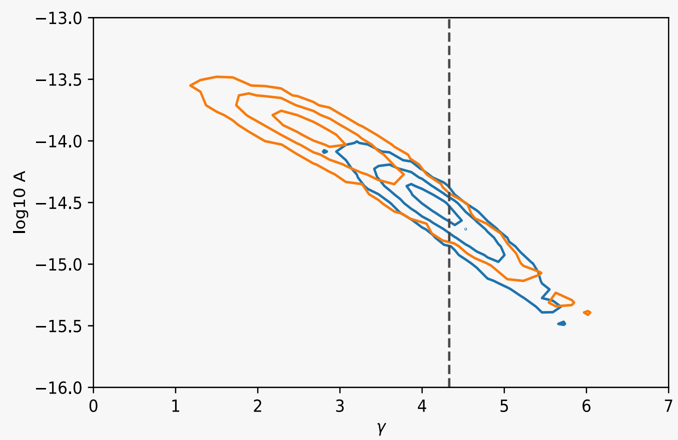


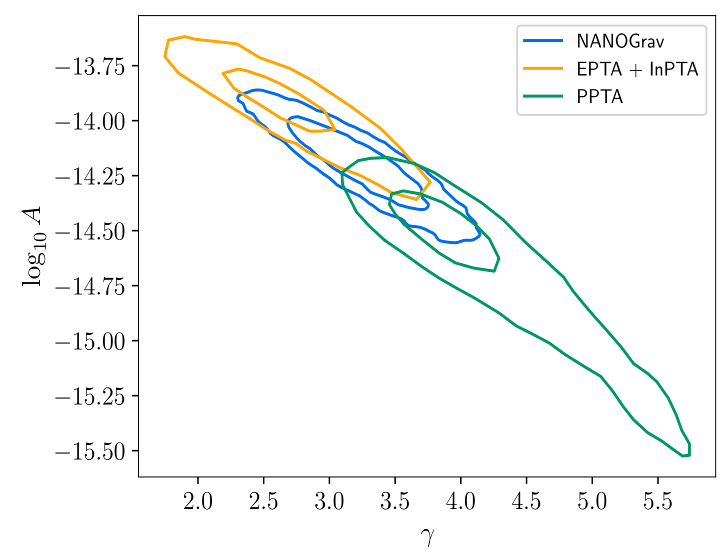


EPTA + InPTA

Antoniadis et al. [2306.16214]





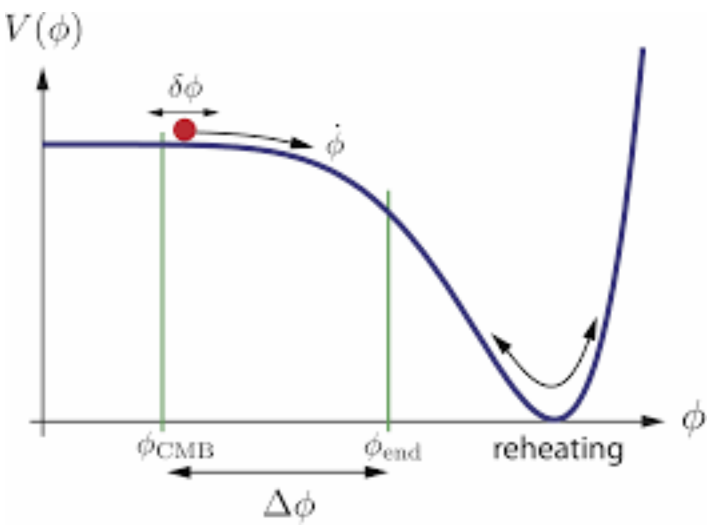


$$h_c(f) = A_{\rm yr} \cdot \left(f/{\rm yr}^{-1}\right)^{-\alpha}$$

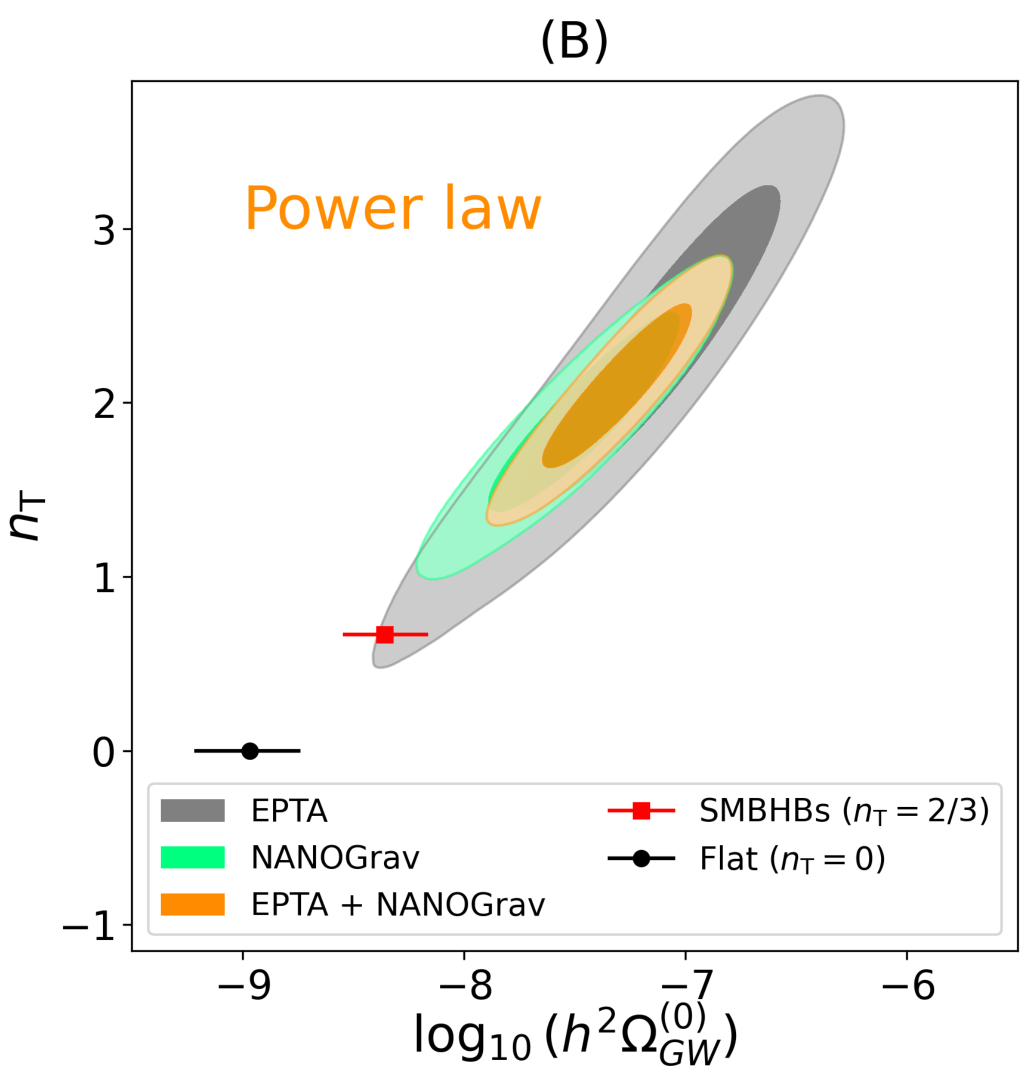
$$\Omega^{(0)}_{\rm GW}(f) = \frac{2\pi^2 f_{\rm yr}^2}{3H_0^2} A_{\rm CP}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$

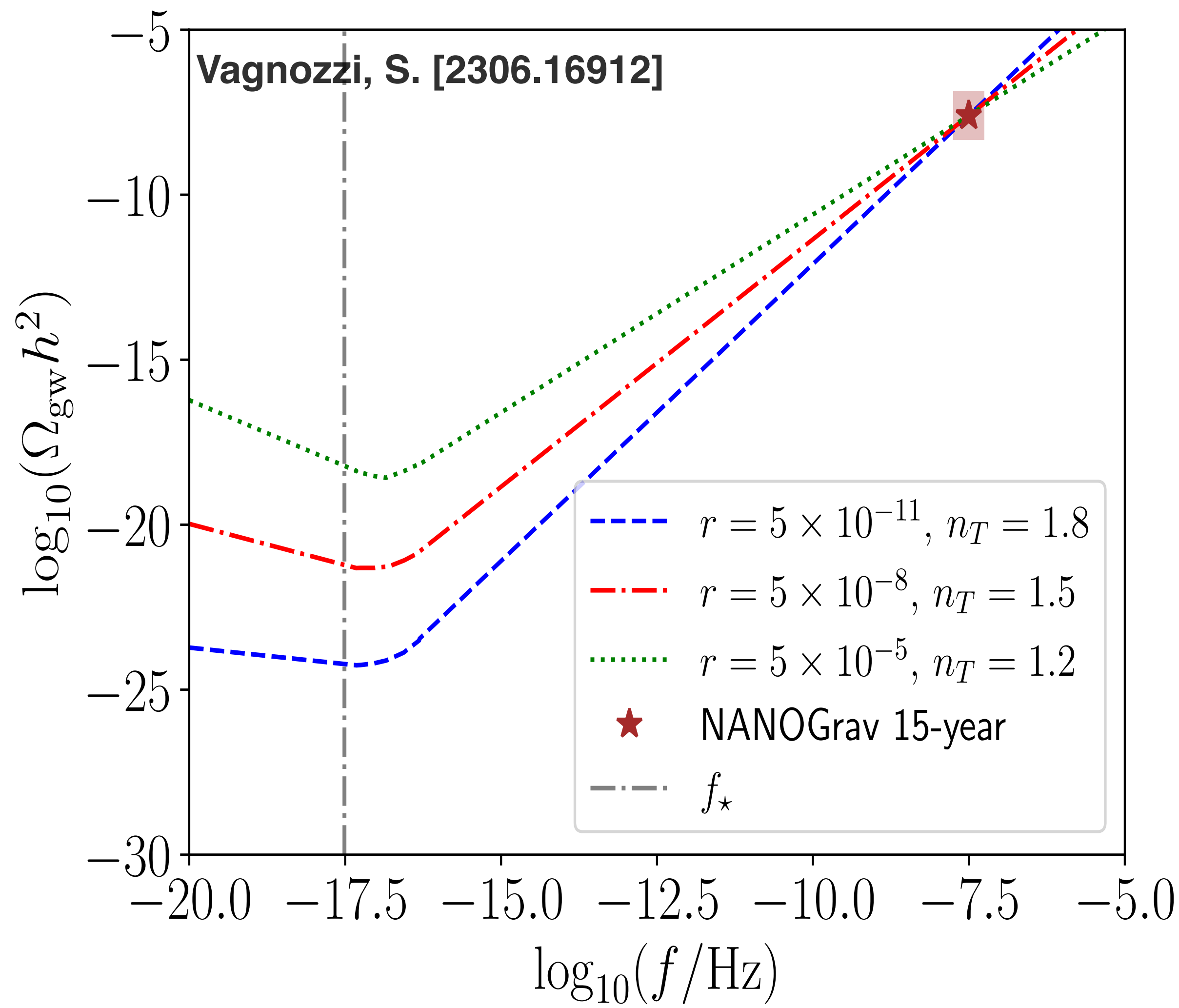
$$\gamma = \frac{13}{3} \text{ for SMBHB}$$

Inflation



$$\Omega_{\rm GW}^{(0)}(f) = \mathcal{A}_{\rm inf}^{(*)}\,(f/f_*)^{n_{\rm t}}$$



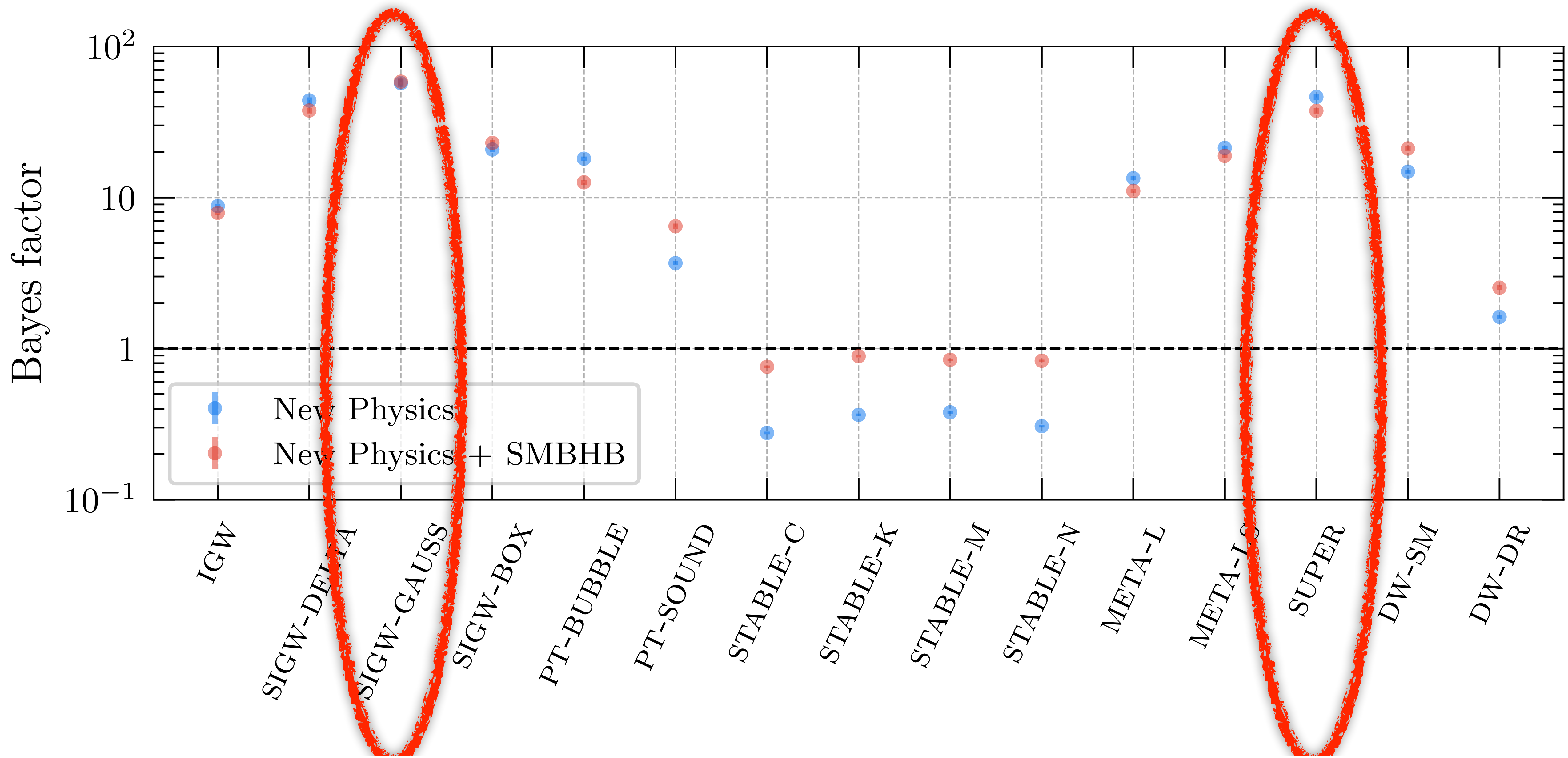


Figueroa, Pieroni, AR, Simakachorn, [2307.02399] likelihood function

prior distributior

$$B_i = \frac{\text{evidence}[\mathcal{H}_\text{i}]}{\text{evidence}[\mathcal{H}_\text{SMBHB}]}$$

$$\text{evidence} = \int \text{d}\Theta \text{P}(\mathcal{D}|\Theta, \mathcal{H}) \times \text{P}(\Theta|\mathcal{H})$$



How to explain the signal?

Super Massive Black Hole Binaries (SMBHB)

Astro Theoretical Modelling requires better understanding

Many assumptions in the search

- Isotropy
- Gaussianity
- Stationarity

Early Universe Sources

GWB spectrum model dependent

Degeneracies between different sources