Overview WG4 Gravitational waves and cosmology

Workshop of the JENAS Initiative “Gravitational Wave Probes of Fundamental Physics”

February 9th, 2024
Sapienza University of Rome

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and

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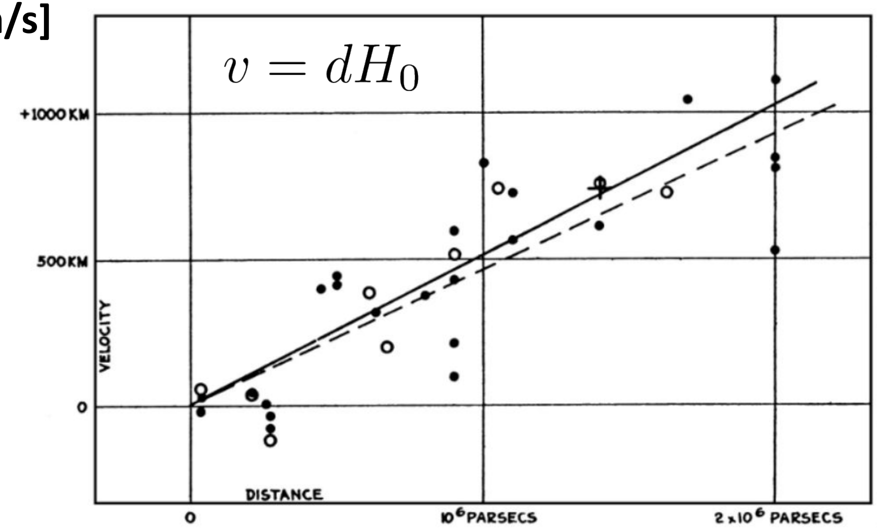
DESY Hamburg

The standard cosmological model?

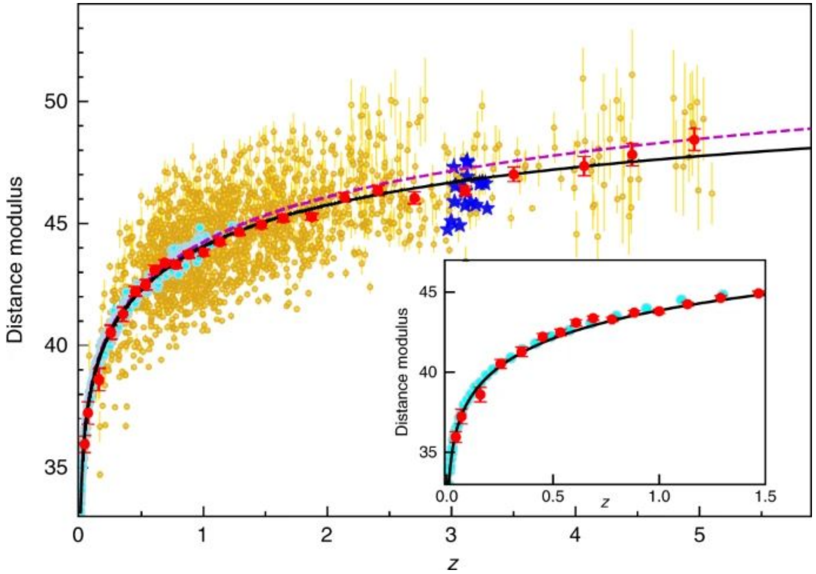
For almost 100 years, we have been measuring the expansion of the Universe

Velocity [km/s] *[E. Hubble 1929]*



Distance [Mpc]

[G. Risalti et al, Nature 2023]



The standard cosmological model?

According to General Relativity, and confirmed by many observations, the Universe is expanding with a rate described by

$$\frac{H(z)}{H_0} = \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4 + \Omega_k(1+z)^2}$$

Hubble constant — Dark matter — Dark energy — Radiation — Curvature

Critical density

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

Energy density

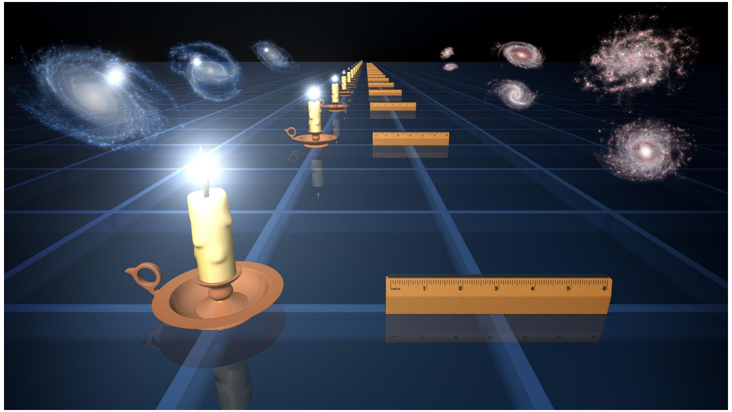
$$\Omega_X = \frac{\rho_X}{\rho_c}$$

The cosmic expansion offers us many potential discoveries:

- *What are the energy species living in our Universe?*
- *Is General Relativity valid on cosmological scales?*
- *What are the average and critical densities of the Universe?*

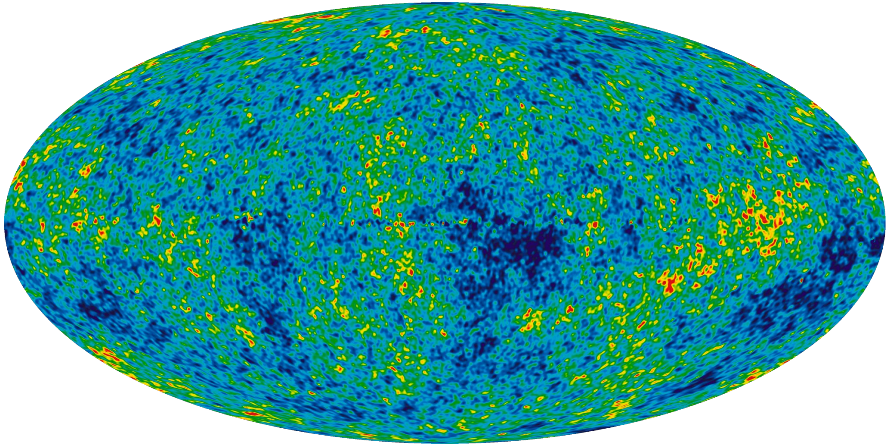
How have been measuring the Universe expansion so far?

Direct (Standard Candles)



- Cepheids, Supernovae Type IA, Active Galactic nuclei, Kilonovae (?) and short Gamma-ray Burst
- **Issues:** Requires complex astrophysical calibration

Indirect

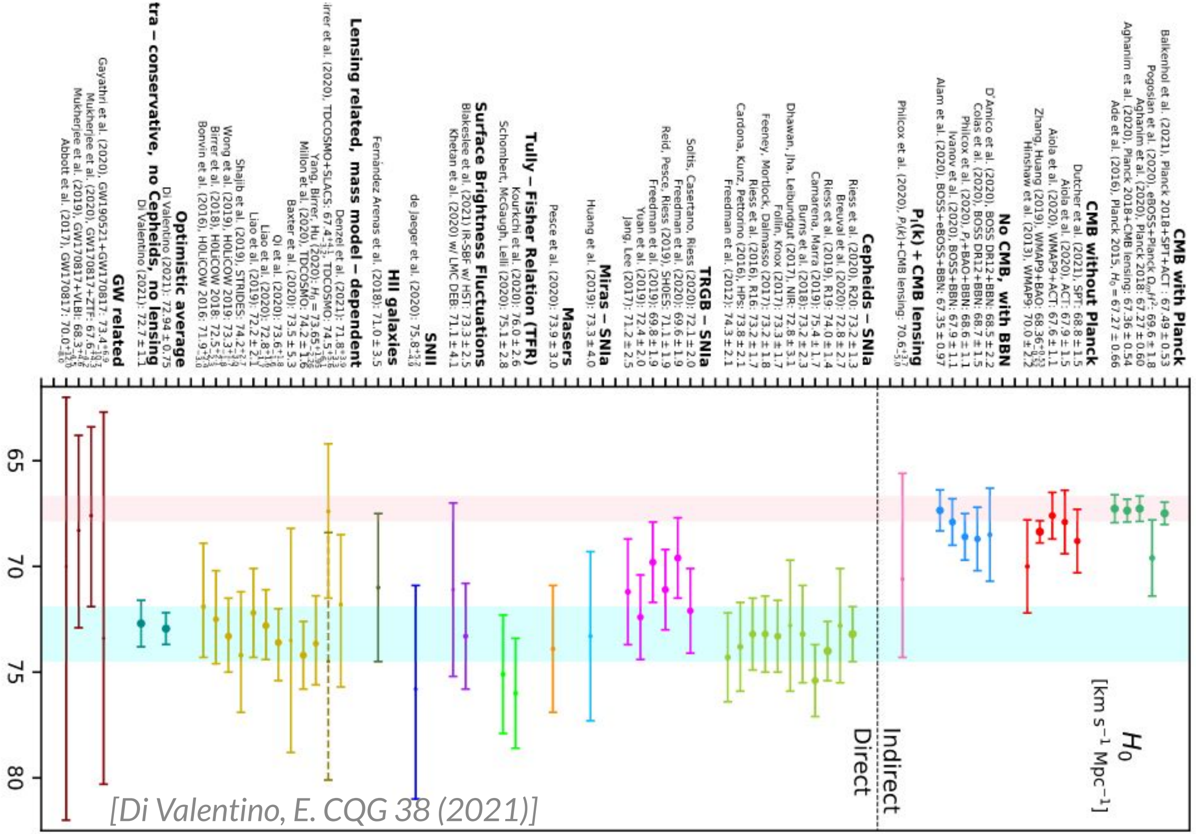


- Cosmic Microwave Background temperature fluctuations, Baryonic nucleosynthesis
- **Issues:** Cosmic variance (a single Universe)

Measurements of the Hubble constant

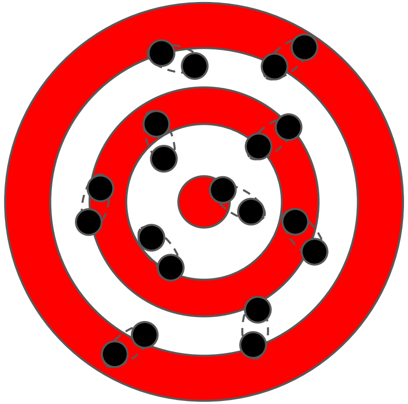
- There is a tension between direct and indirect measurements of the Hubble constant.
- Although in-depth studies for hidden systematics the tension has not been yet alleviated.
- We require to directly measure the Universe expansion in all the observable Universe.

See Nils' talk this morning



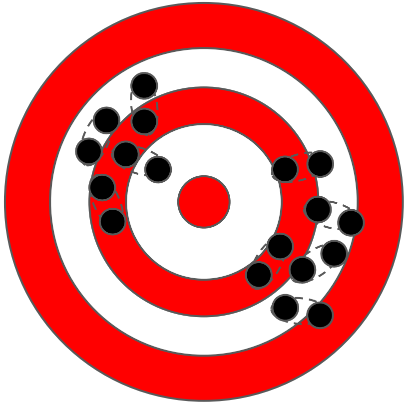
[Di Valentino, E. CQG 38 (2021)]

Precision



- Lensing cosmology
- HII galaxies

Accuracy



- Cosmology with Supernovae Type IA
- CMB cosmology

Where is GW cosmology?

Gravitational Wave sources at cosmological scales

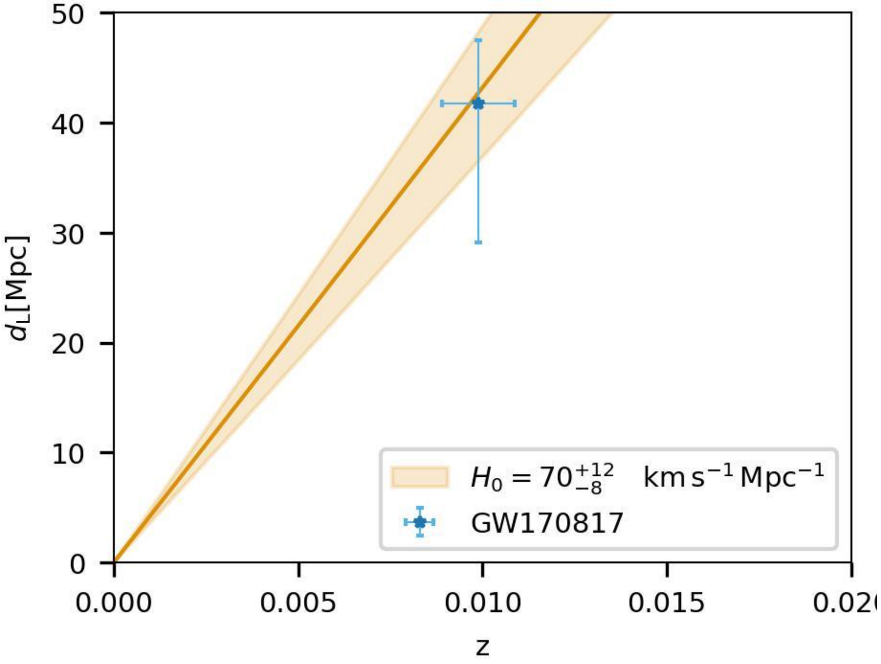
From GWs we can not measure the source redshift (escaping velocity)

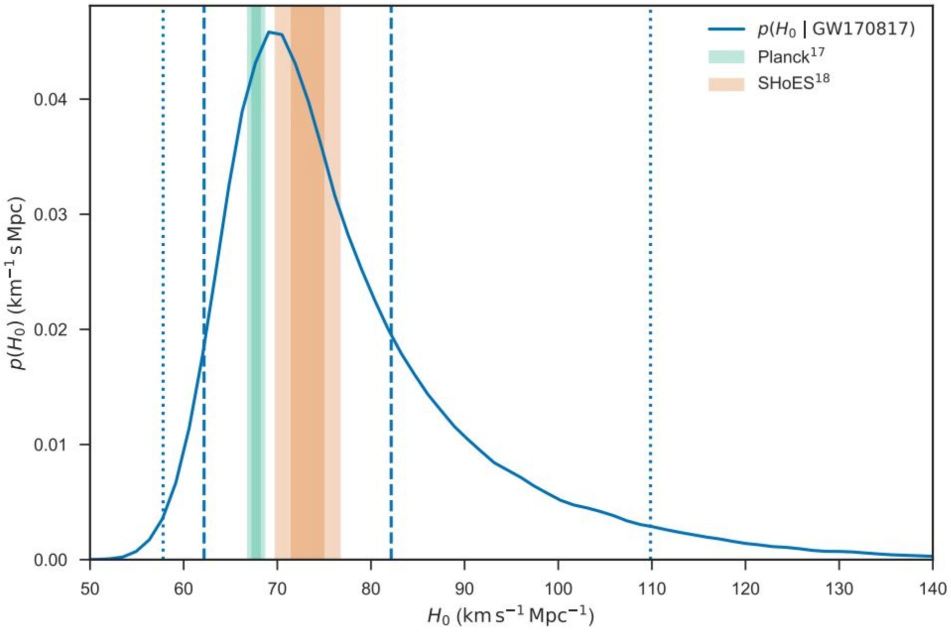
In recent years, we used several methods to assign a redshift to GW sources

- **Bright sirens:** An associated Electromagnetic (EM) counterpart (GRB, Kilonova etc...) can provide the identification of the host galaxy.
- **Dark sirens:** Galaxy surveys can be used to identify possible hosts in the GW localization volume.
- **Spectral sirens:** Knowledge of the source-frame mass distribution can be used to assign a redshift to GW sources.

See M. Moresco et al, LRR 2022 for a review on cosmology
See S. Mastrogiovanni el al, ANDP 2022 for a review focused on current GW cosmology
See H. Chen et al 2024 for a recent review on GW cosmology with next gen GW detectors.

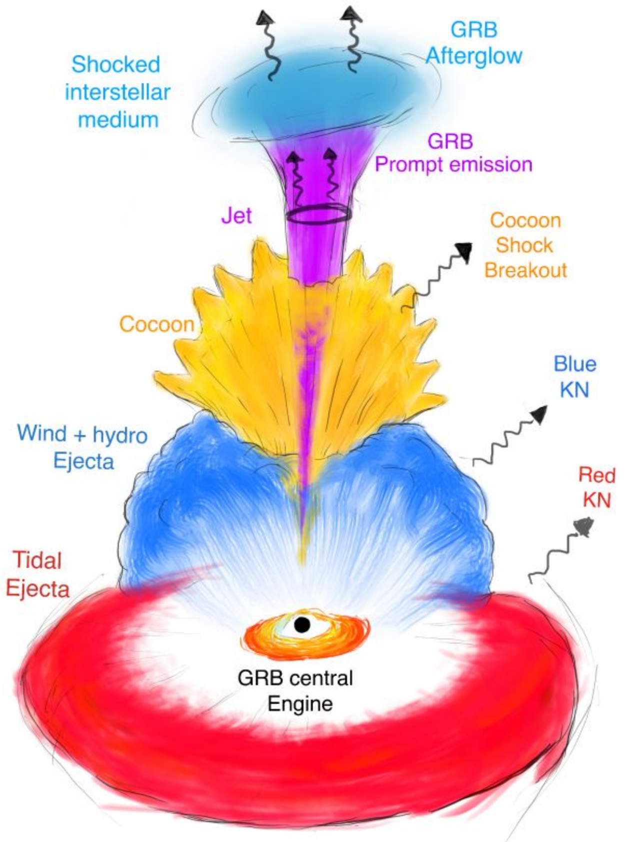
Bright sirens: Cosmology with GW170817

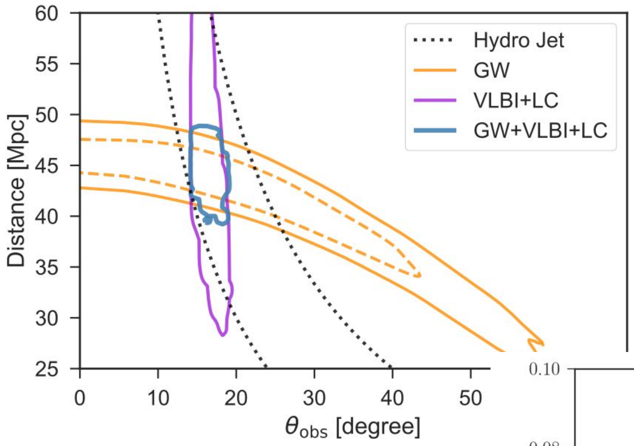




[LVC+, Nature (2017)]

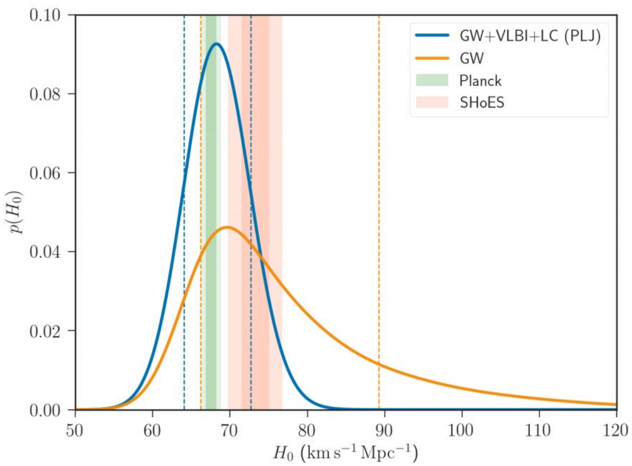
Bright sirens: Cosmology with GW170817





[K. Hotokezaka, Nature Astronomy, 3(2019)]

Afterglow informed cosmology



- ***Open questions:***

  Can we standardize the GRB and KN emissions from BNS mergers?

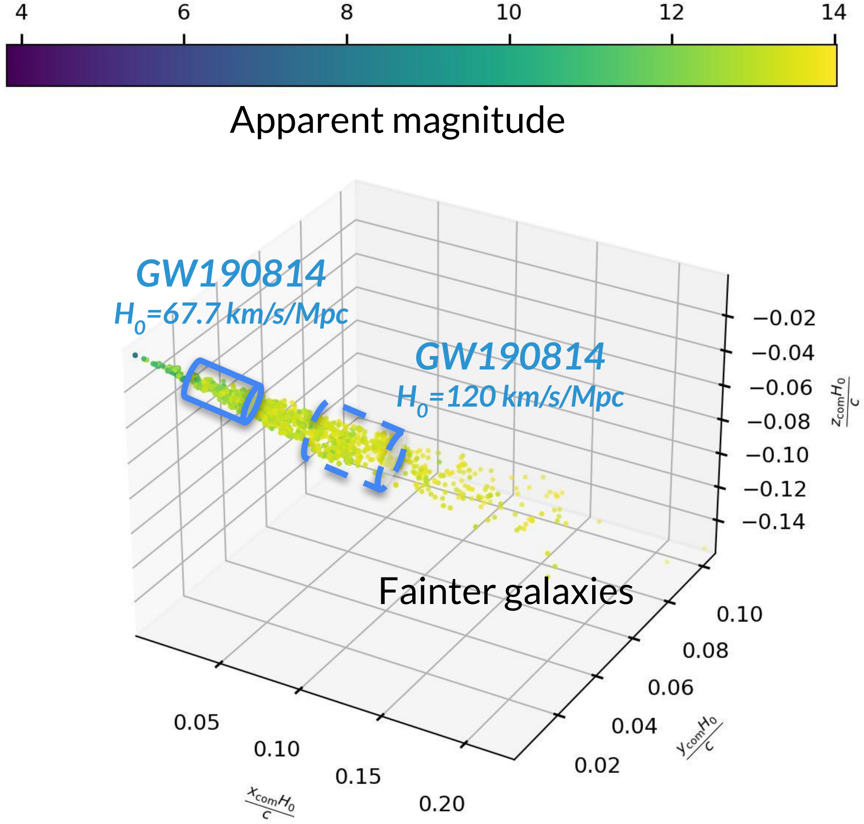
  Do we really understand GRB physics? E. g. GRB211211A
  Mei et al Nature, Volume 612 (2022)

Dark sirens: Cosmology aided by galaxy surveys

- A cosmological model has statistical support when the GW localization matched an *overdensity* of galaxies.

- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections in order to now bias our analyses *[R. Gray+, PRD (2019)].*

- ***Open question:*** *How does galaxy properties correlate with CBC hosting?*
    - *Two main actors: Star Formation rate and total stellar mass* [M. Artale +, MNRAS (2021)]
    - *How does Large Scale Structure tracers correlate with GWs?*



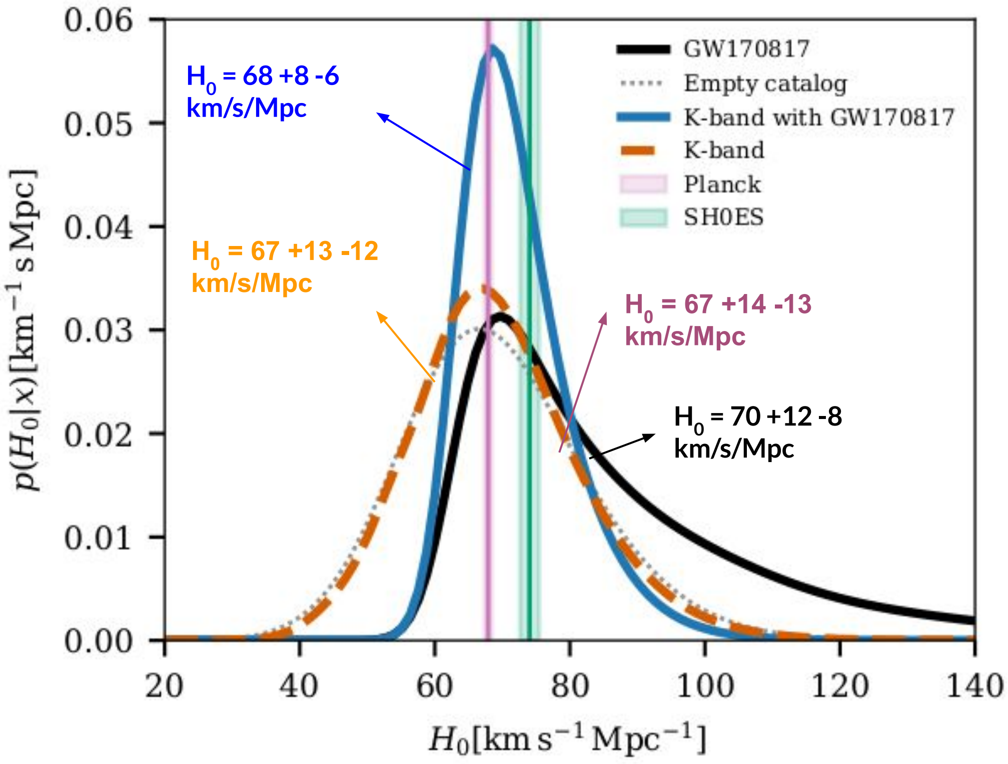
GW cosmology after GWTC-3: Dark sirens

Main result of the paper showing various H0 posteriors.

We select the K-band for the luminosities of galaxies and the preferred mass model (powerlaw+Gaussian peak)

GW cosmology is entering in the systematics era

[LVK+, ApJ 949 76 (2023)]



Spectral sirens: GW-only cosmology

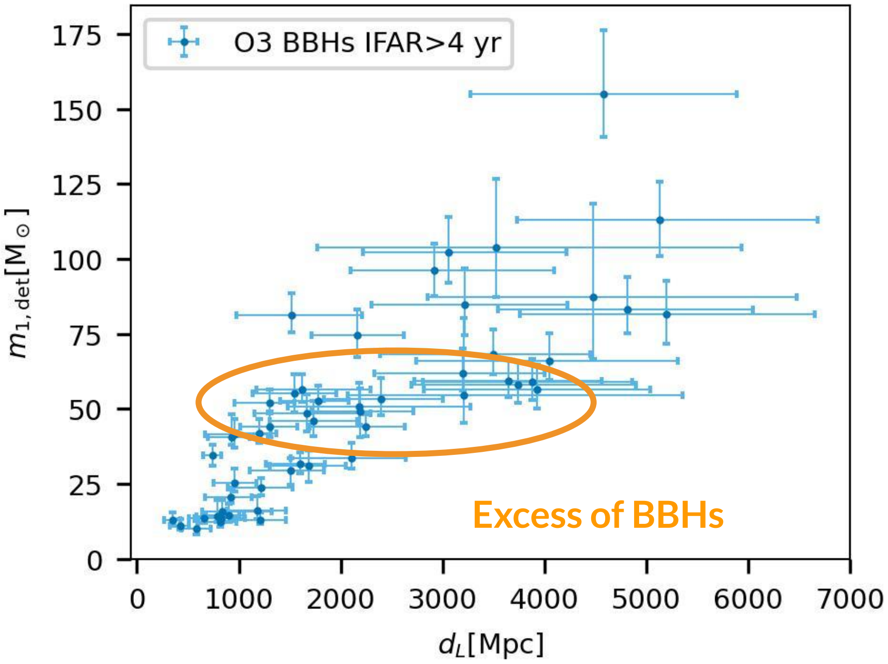
- Many GW are detected with large sky localizations and are very far (galaxy catalogs highly incomplete).

- If BBHs are *preferentially* produced at a given mass, we can exploit the mass-redshift relation to assign a redshift to the GW source *[SM+, PRD 104 (2021)]*.

$$m_{1,\mathrm{det}} = m_{1,\mathrm{s}}(1+z)$$

How and when Binary black holes are produced in our Universe?

[See M. Mapelli (2021), *HBGWA for a nice review*]

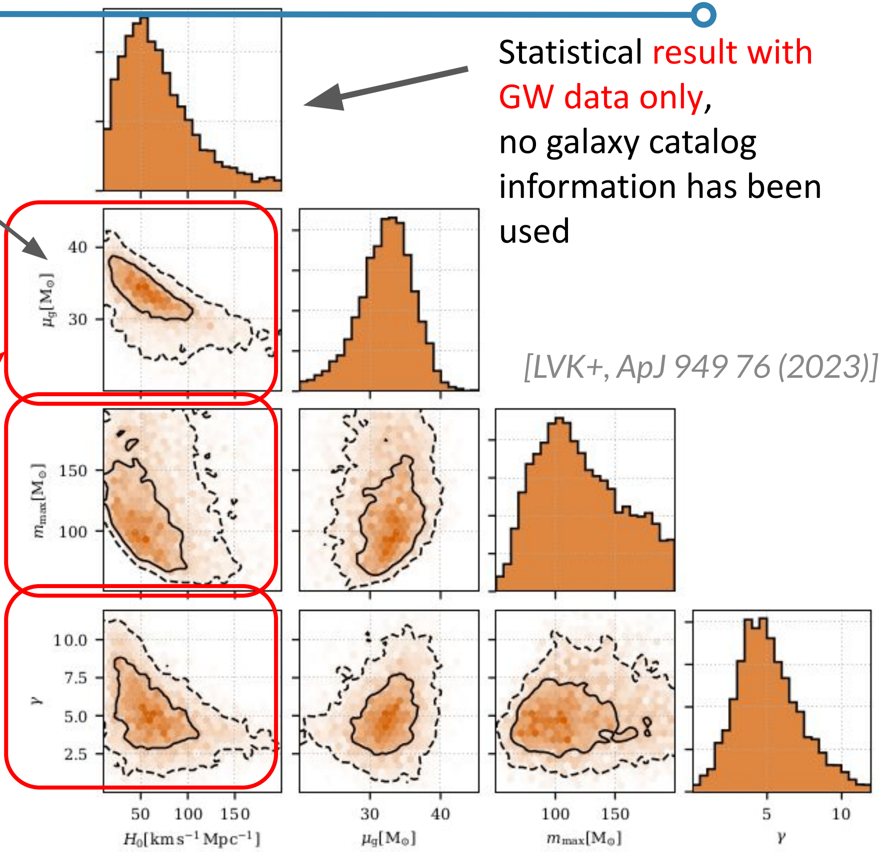


GW cosmology after GWTC-3: Spectral sirens

The excess of BBHs around 35 solar masses sets a scale for the redshift and provides constraints on H0.

Population parameters that correlate with H0

Posteriors of H_0, mu of the Gaussian peak, maximum mass of the BH and the merger rate evolution.



Statistical result with GW data only, no galaxy catalog information has been used

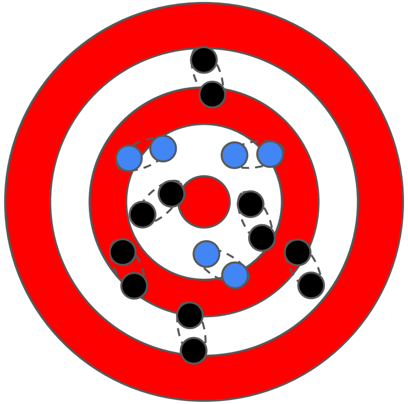
[LVK+, ApJ 949 76 (2023)]

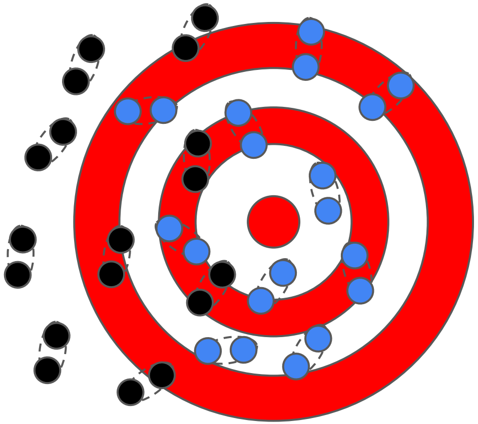
GW

GW + GRB+ model

Pop model 1

Pop model 2



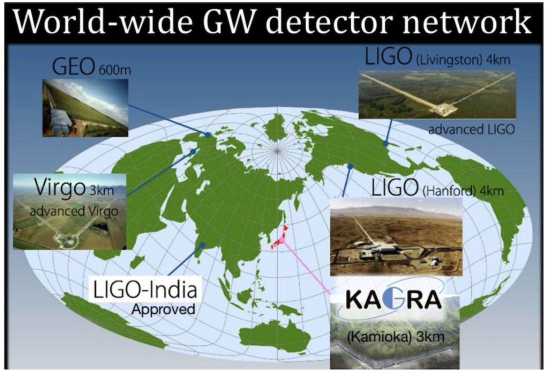


GW Bight sirens cosmology

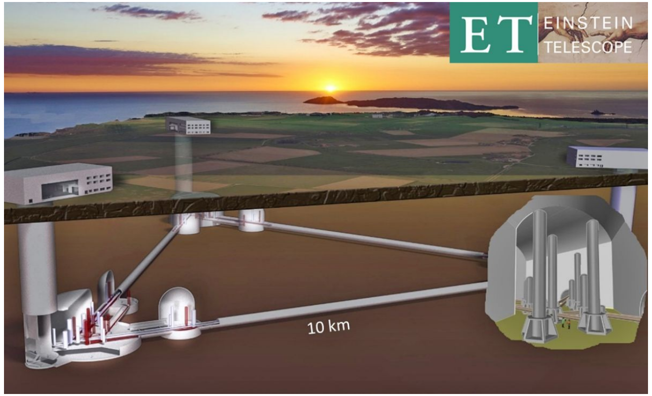
GW Dark sirens cosmology

What is next for GW cosmology?

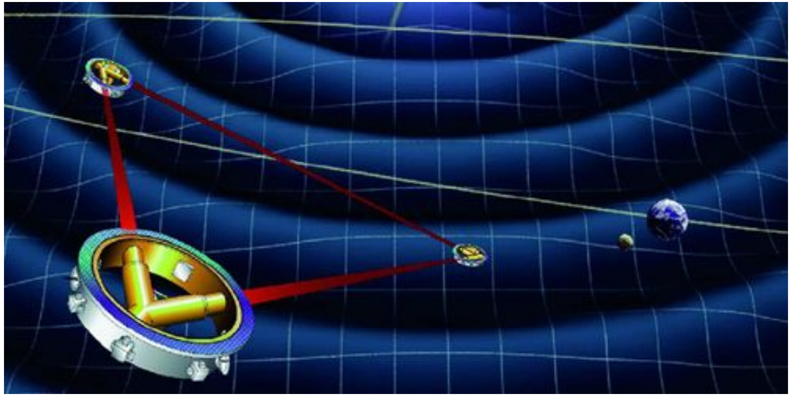
Improving the current detector network < 2035



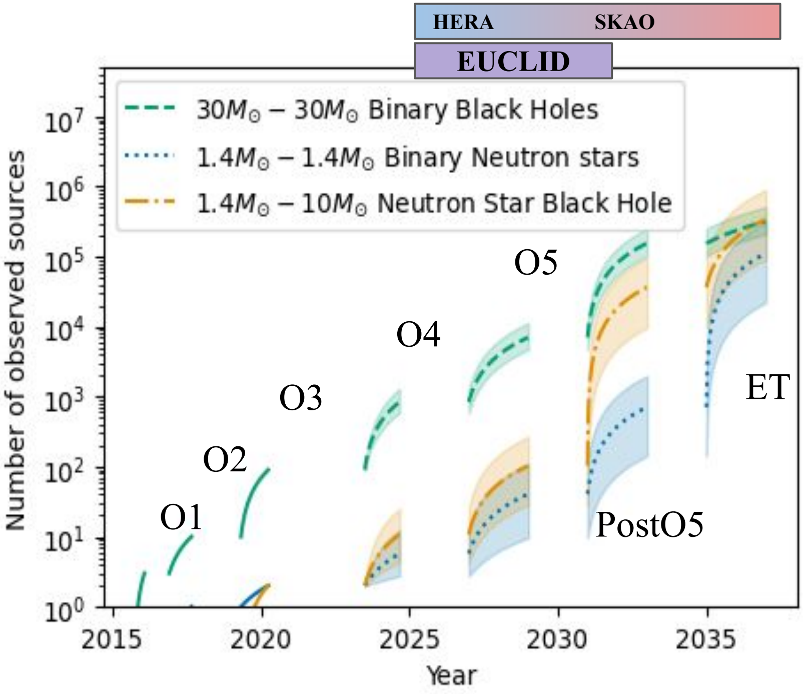
Einstein Telescope 2035+



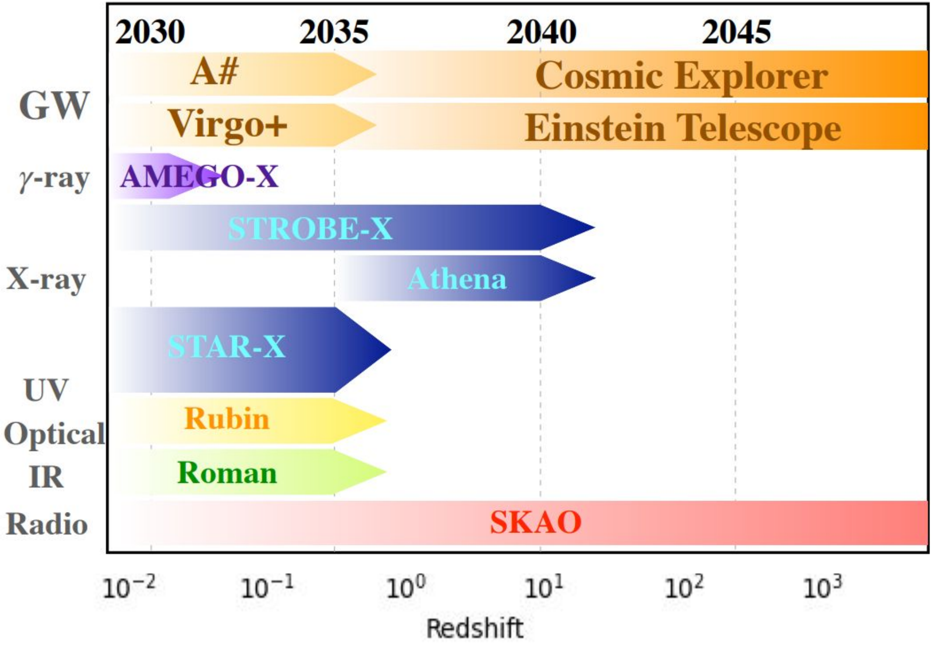
LISA 2035+



Moving forward with ground-based GW detectors



S. Mastrogiovanni (generated from prospective horizons)

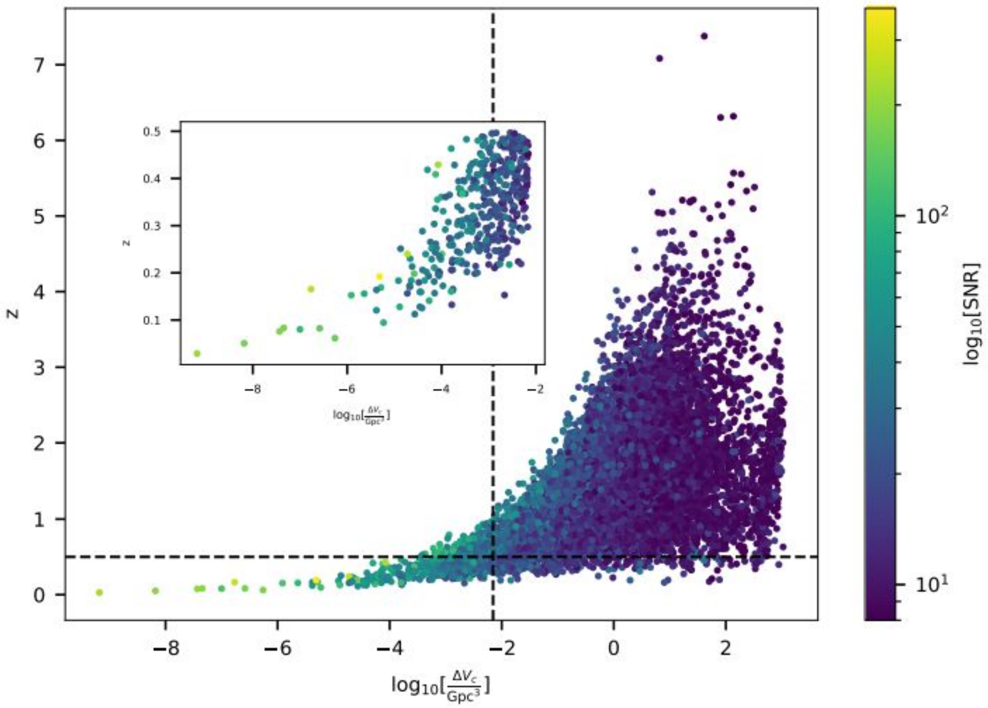


H. Chen et al 2024

Dark sirens with 2.5 Generation GW detectors

Localization is of crucial importance for the galaxy catalog method.

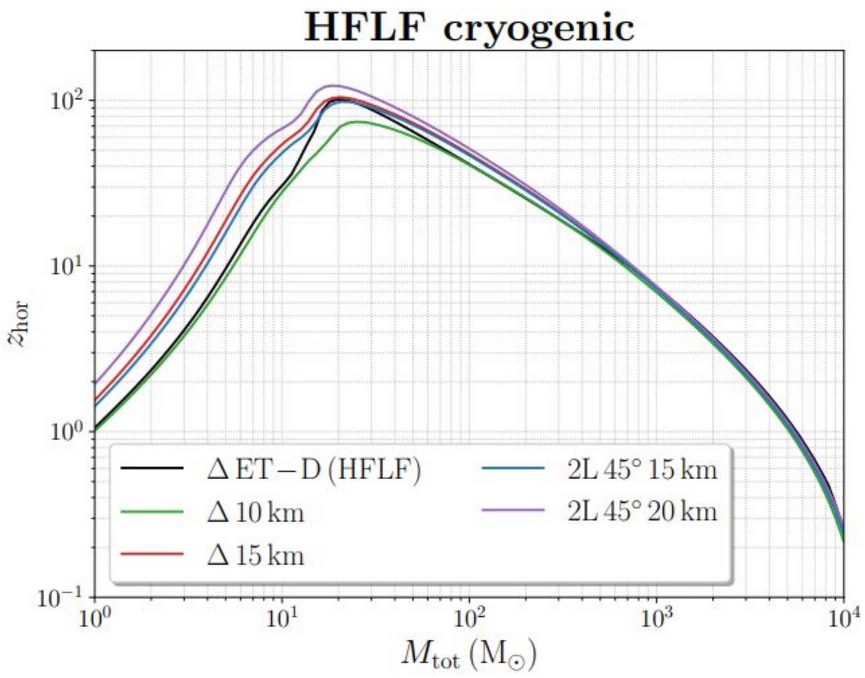
- About 3000 dark sirens will be localized better than GW190814.
- ~5 dark sirens will be so well localized to have ~1 galaxy in their localization volume.
- ~100 dark sirens will have less than 1000 galaxies in their localization paper.
- With one year of observation, constraint on H0 at the 5% precision



Virgo NeXT, Concept study, VIR-0497D-22

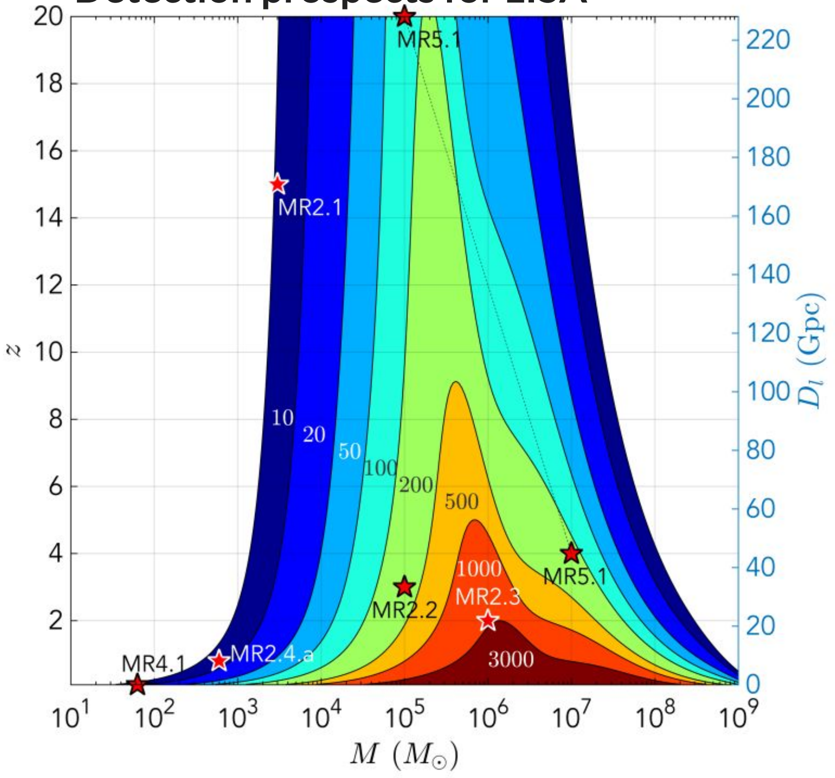
Detection ranges of 3G detectors

Detection prospects for Einstein Telescope



M. Branchesi, JCAP07 (2023) 068

Detection prospects for LISA



P. Amaro-Seoane arXiv 1702.00786

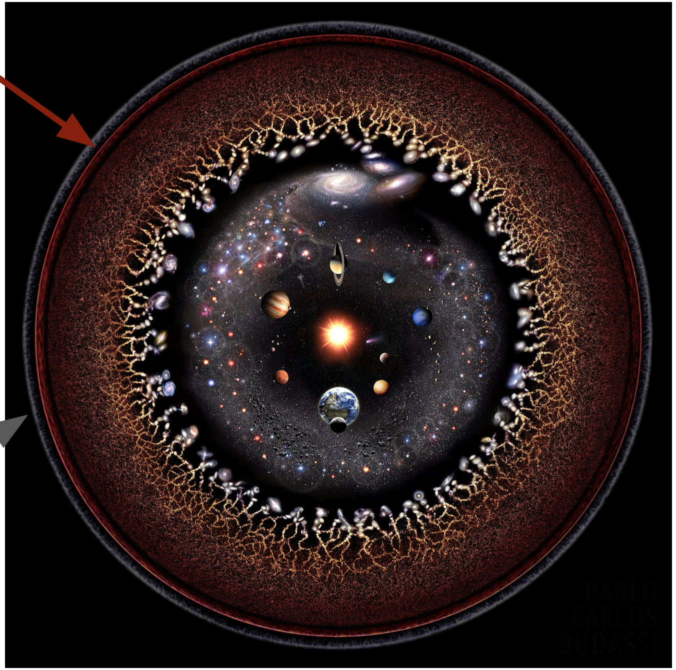
Gravitational wave backgrounds

Why care about the background?

["Astronomie 1", Camille Flammarion, 1888]

CMB

GWB?

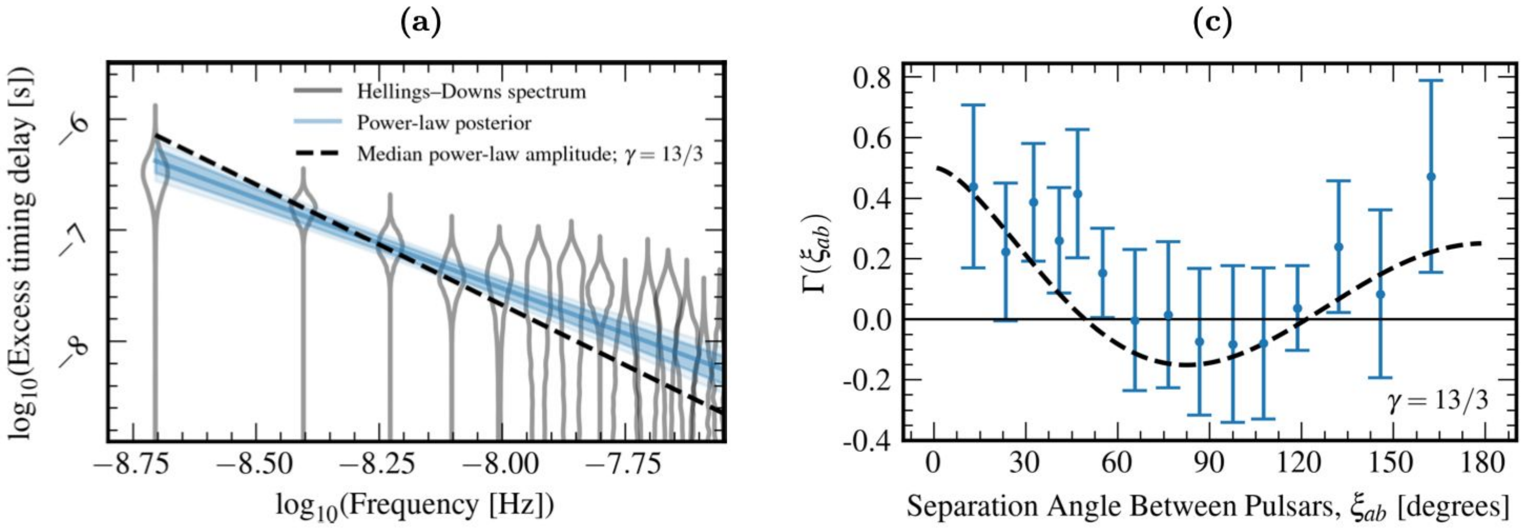


[Pablo Carlos Budassi, 2018]

In case you haven't heard the news

21

In case you haven't heard the news…



[NANOGrav, Astrophys.J.Lett. 951 (2023)]

Several pulsar timing arrays found a gravitational wave background at O(10 nHz) in June 2023!

See: Sarah's talk earlier today

What sourced the pulsar timing signal?

Supermassive black hole binaries?

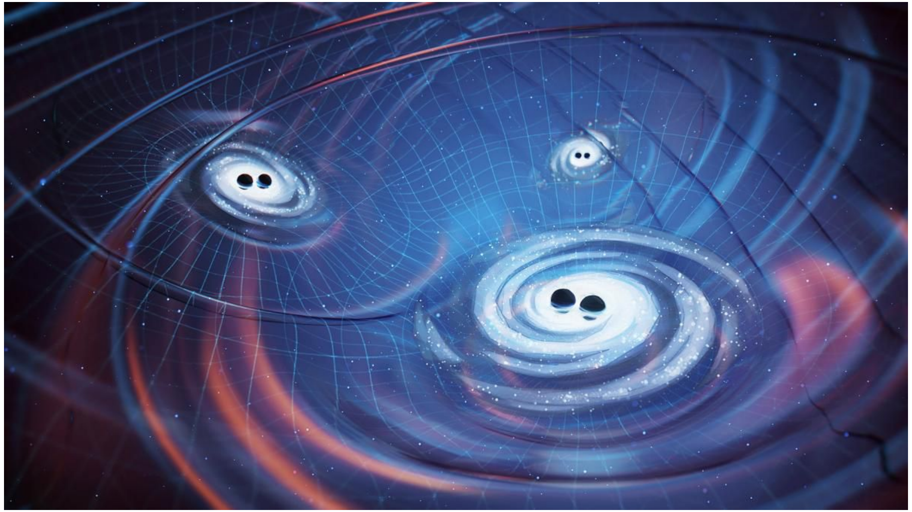


Image credit: NANOGrav collaboration

Individual SMBH mergers have not been observed so far. The precise spectral shape of the GW signal is unknown, but its existence is a robust prediction.

The Big Bang?

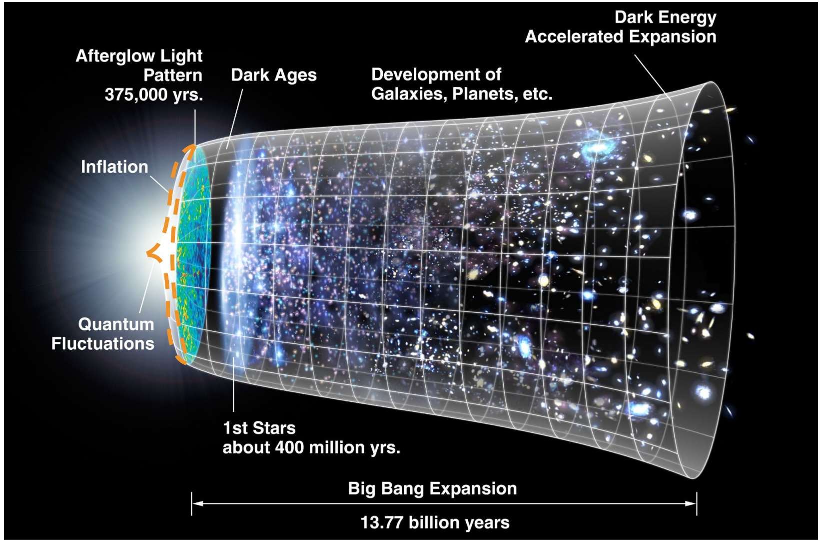
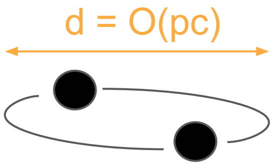
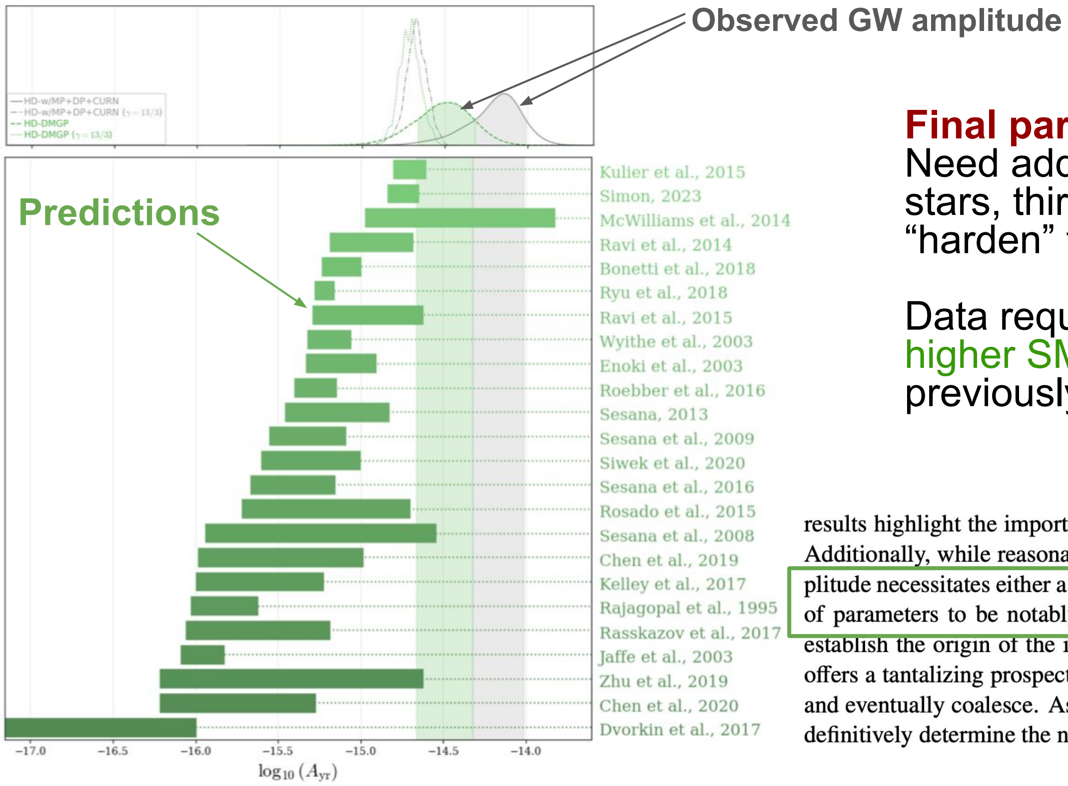


Image credit: NASA

Many speculative signal sources and predictions exist. *See: talks by Rishav, Gabriele, Antonino & CT*

What sourced the pulsar timing signal?





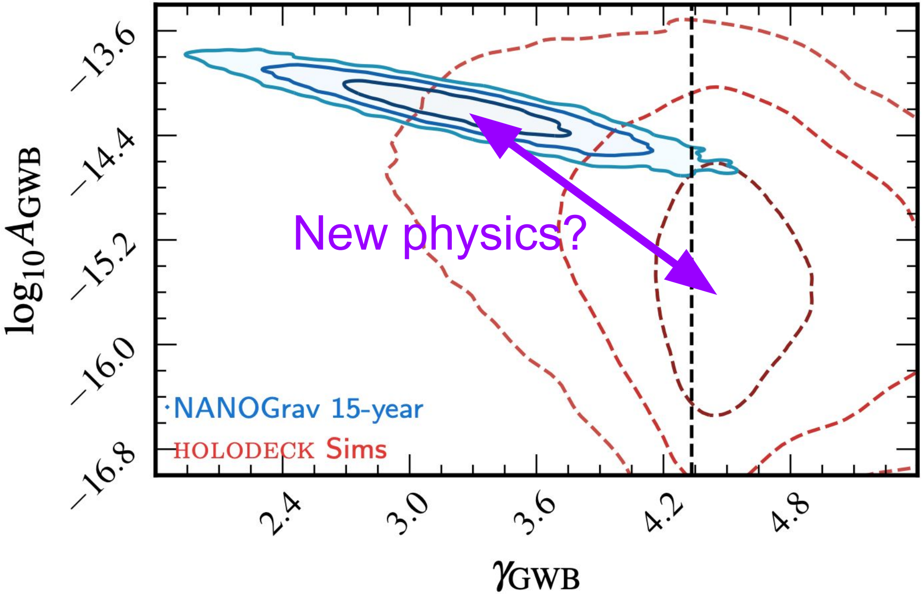
Final parsec problem
Need additional feedback (scattering of individual stars, third SMBH, …) to extract energy and "harden" the binary to dissipate energy.

Data requires shorter hardening timescales, higher SMBH number densities and masses than previously expected.

results highlight the importance of accurately modeling binary evolution for producing realistic GWB spectra. Additionally, while reasonable parameters are able to reproduce the 15 yr observations, the implied GWB amplitude necessitates either a large number of parameters to be at the edges of expected values, or a small number of parameters to be notably different from standard expectations. While we are not yet able to definitively establish the origin of the inferred GWB signal, the consistency of the signal with astrophysical expectations offers a tantalizing prospect for confirming that SMBH binaries are able to form, reach sub-parsec separations, and eventually coalesce. As the significance grows over time, higher-order features of the GWB spectrum will definitively determine the nature of the GWB and allow for novel constraints on SMBH populations.

[NANOGrav, Astrophys.J.Lett. 952 (2023)]

What sourced the pulsar timing signal?



[NANOGrav, Astrophys.J.Lett. 951 (2023)]

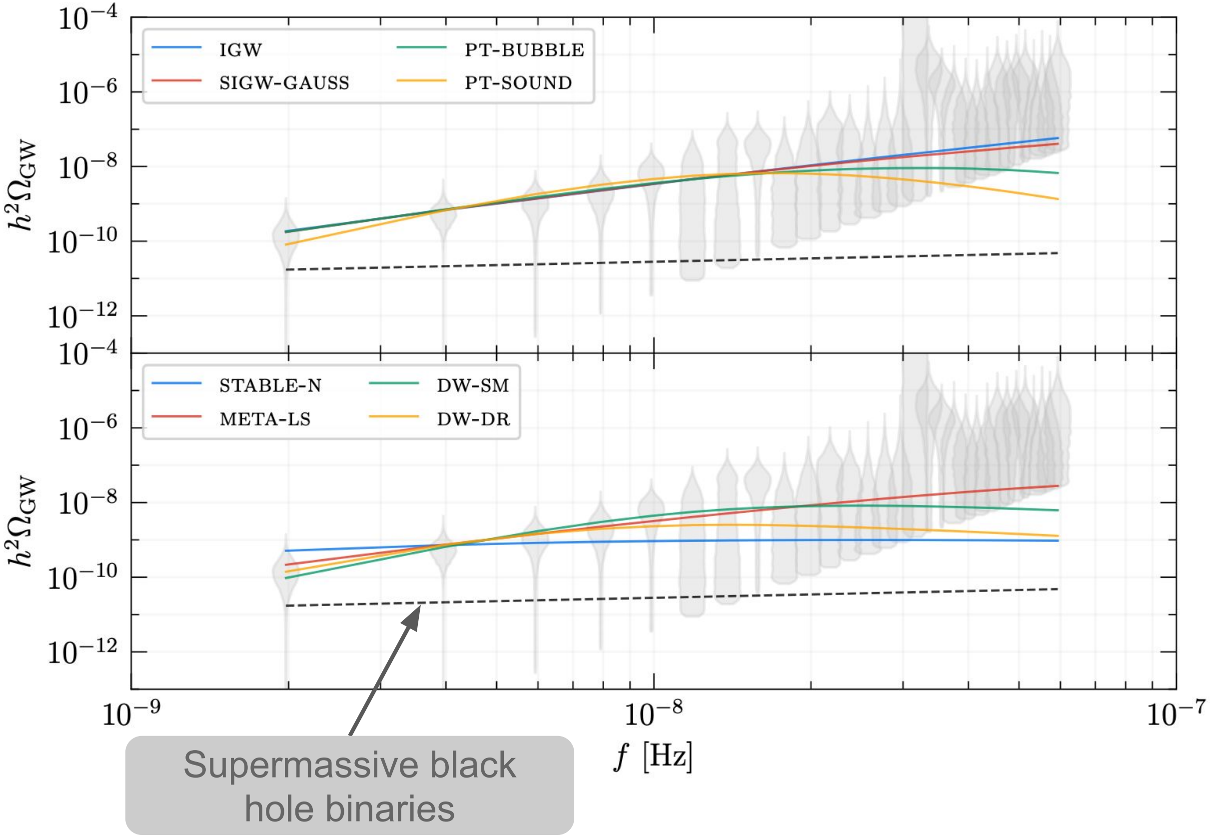
The observed signal is consistent with a power-law of amplitude A and slope γ.

Simulations assuming realistic SMBH populations yield too-low GW amplitudes and favor steeper slopes.

Cosmological sources of nHz gravitational waves

- Inflationary GWs
- Phase Transitions
- Scalar-induced GWs
- Domain Walls
- Cosmic strings
- Audible axions
- Supermassive PBHs

[see also Rishav's talk yesterday and Gabriele's talk earlier today]

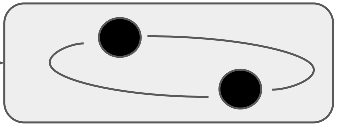


[NANOGrav, Astrophys.J.Lett. 951 (2023), L11]

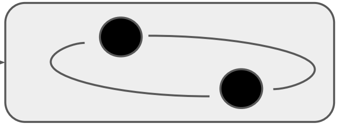
Quo vadis pulsar timing?

We are here!

Anisotropies? ❌ / ✅

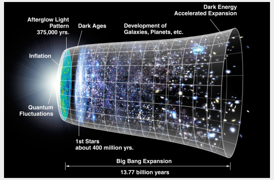


Continuous wave signals? ❌ / ✅



Incl. multi-messenger detection?

Possibly:

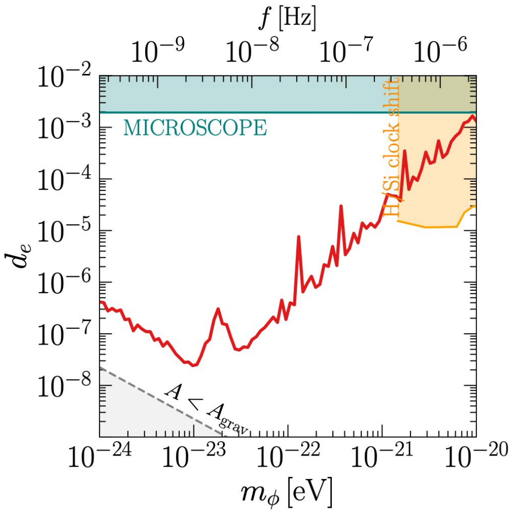


If the signal is indeed from SMBHBs, we will find anisotropies and individual events. Else: look out for signals from the early cosmos! Spectral shapes might help.

[Thanks to A. Mitridate for the flowchart idea!]

Novel bounds on new physics models from PTAs

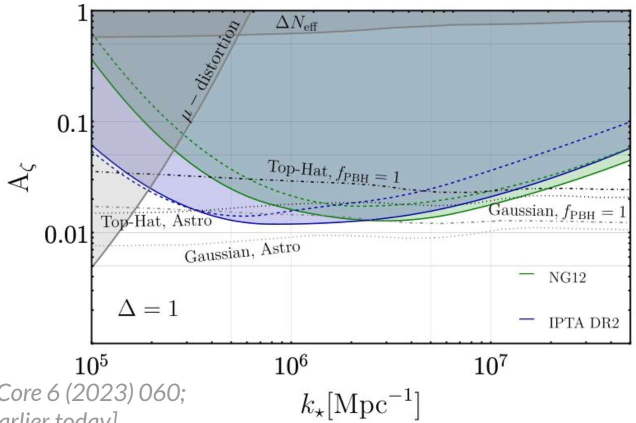
Ultralight dark matter



[NANOGrav, Astrophys.J.Lett. 951 (2023) 1, L11; See also Cristiano's talk yesterday]

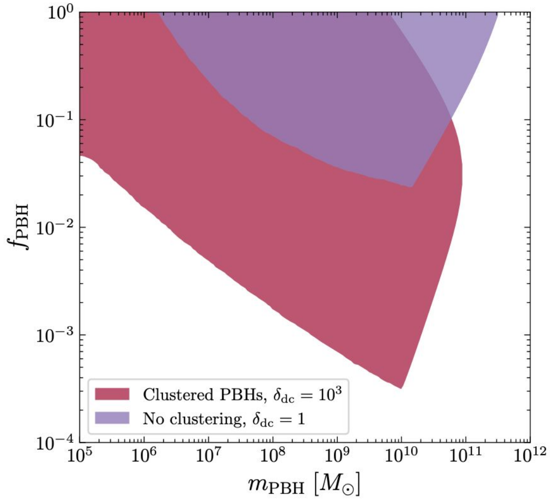
Even if SMBH mergers are indeed responsible for the nHz signal, we can still use it to put **bounds on new physics!**

Primordial scalar power-spectrum



[Dandoy+, SciPost Phys.Core 6 (2023) 060; See also Gabriele's talk earlier today]

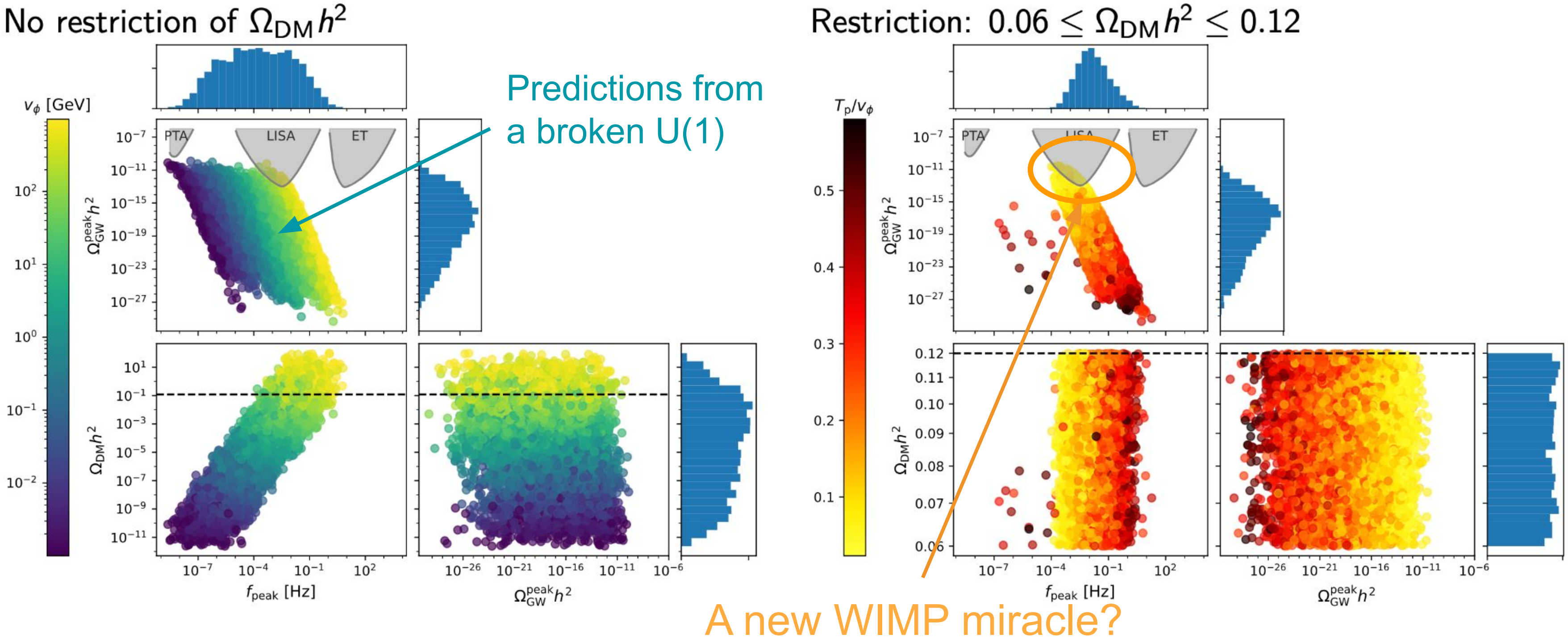
(Clustered) supermassive, primordial black holes



[CT+, 2306.17836; See also Theodoros' talk later today]

LISA and ET: finding the dark big bang

If LISA finds a mHz background, it might be due to a dark sector phase transition giving rise to dark matter!
There might be an **intimate correlation between the LISA frequency band and the DM** abundance.

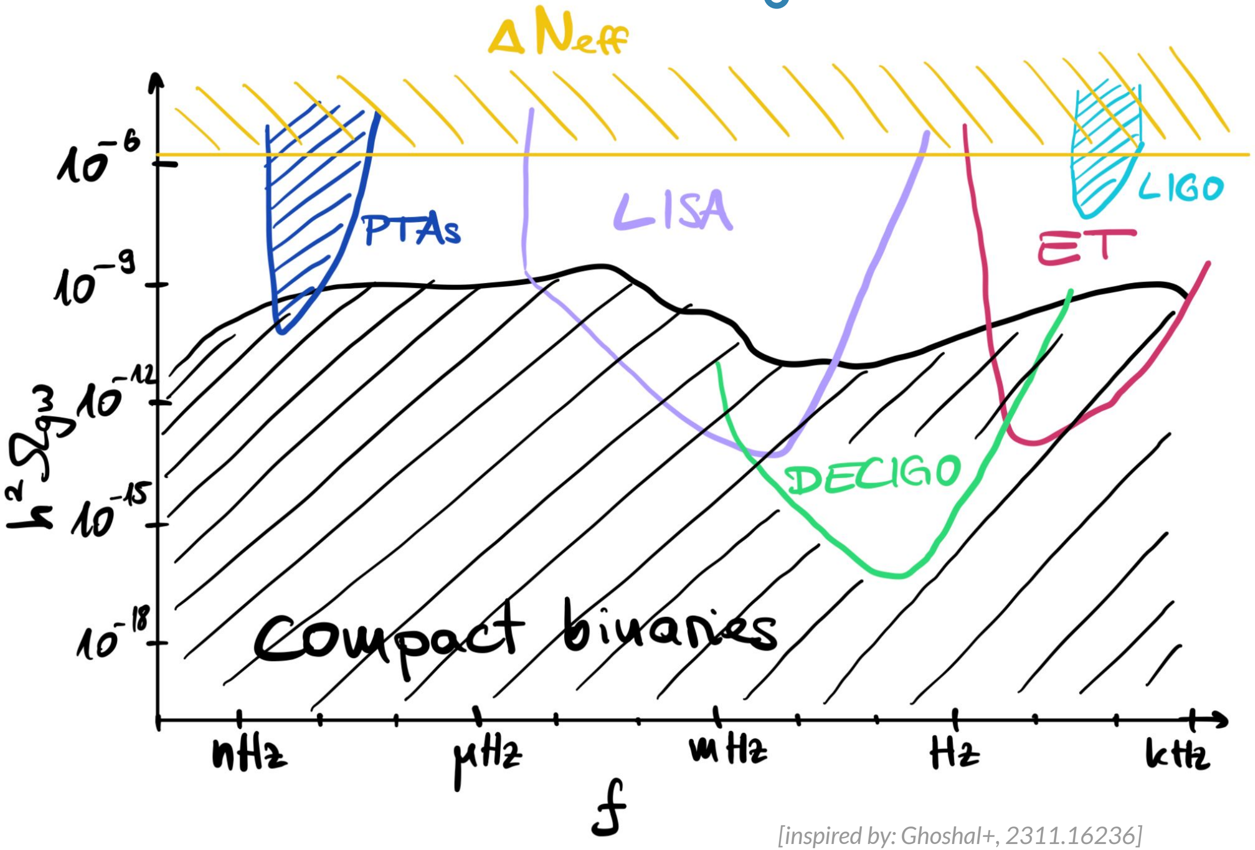


[CT+, 2311.06346; thanks to J. Matuszak for slide]

A sketch of the future of GWBs

To search for cosmic backgrounds, we will need to learn how to subtract the astrophysical background (= foreground)

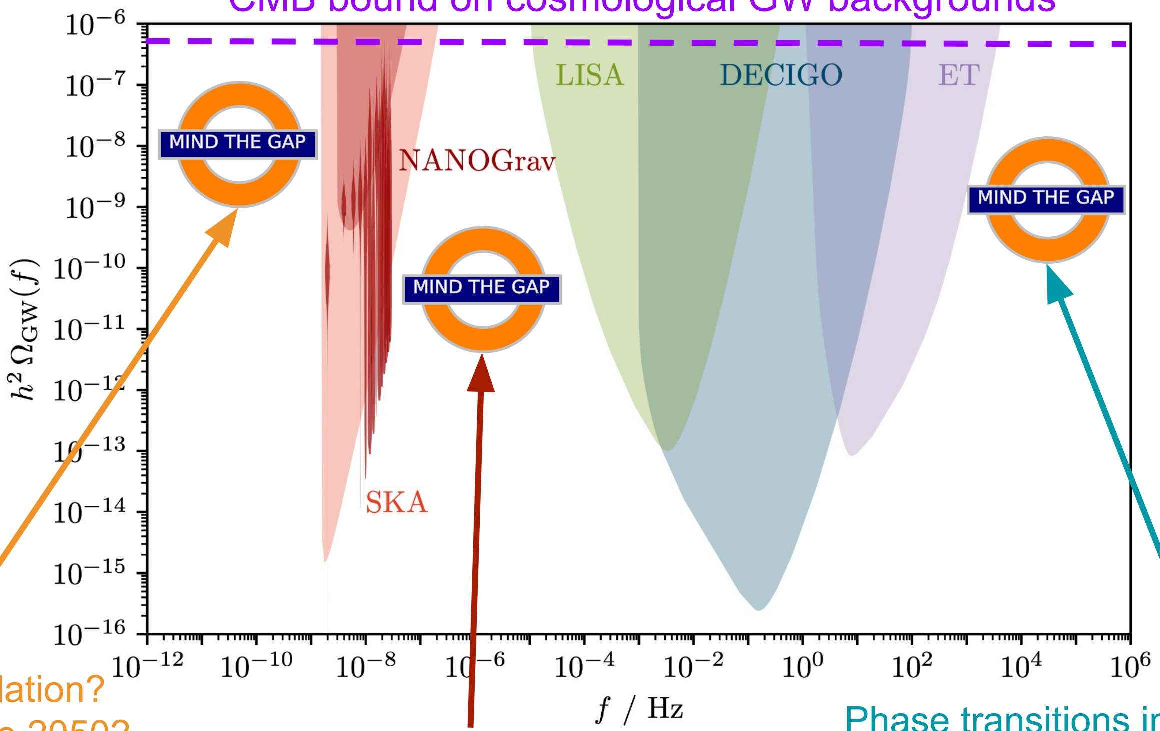
→ Utopia: a joint fit?



[inspired by: Ghoshal+, 2311.16236]

The need for new GW observatories

CMB bound on cosmological GW backgrounds



[See Diego's talk tomorrow]

GWs from inflation?
→ Pixie/Voyage 2050?

How does the PTA signal evolve at μHz?
→ μAres, astrometry?

Phase transitions in the very early universe?
Merging PBHs with tiny masses?
→ Reuse of axion experiments?

Summary

- We are at the dawn of GW cosmology
- First direct probes of pre-CMB times!
- PTAs push SMBHBs to border of considered parameter space
- Anisotropies and continuous waves will decide on the PTA data interpretation
- Novel constraints on BSM physics
- The fight “astro vs. cosmo” just started
- We need new ideas for GW detection <nHz, @μHz, >MHz