Cosmology

PAX IX, King’s College London, UK, July 23-25

B. S. Sathyaprakash, Ish Gupta, Archisman Ghosh, Daniel Holz, Matteo Fasiello

Cosmology with ground-based gravitational-wave detectors

Ish Gupta (Penn State)

Gravitational waves as standard sirens

Gravitational waves (GWs) from compact binaries can be described by a waveform that is characterized by the parameters that describe the system.

$$h(t, \boldsymbol{\mu}) = \sum_{i \in \{+, \times\}} F_i(\alpha, \delta, \psi, \boldsymbol{\beta})\, h_i(t, \boldsymbol{\lambda})$$

$$(\alpha, \delta) \qquad \boldsymbol{\lambda} = \{m_1, m_2, \chi_1, \chi_2, \iota, D_L\}$$

Among other parameters, the detection of GWs allows the estimation of the position of source in the sky, as well as the distance to the source.

As GWs allow for the estimation of the distance to the source by themselves, independent of an external distance calibrator, they are referred to as **standard sirens**.

Standard sirens to do cosmology

GWs already give us the luminosity distance. If we can obtain the redshift *in some way*, we can infer cosmological parameters, like H_0.

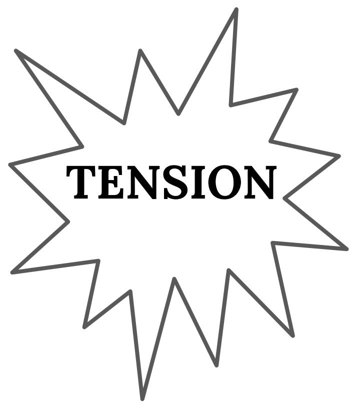
$$D_L = \frac{1+z}{H_0} \int_{1/(1+z)}^{1} \frac{dx}{x^2 \sqrt{\Omega_\Lambda + \Omega_m x^{-3}}}$$

Is that a big deal?

Planck 2018

$$H_0 = 67.4 \pm 0.5 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Using cosmic microwave background measurements



SH0ES

$$H_0 = 73.30 \pm 1.04 \,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Using Type 1A supernovae

Resolution

An independent measurement of H_0 using gravitational-wave observations!

Choir of sirens

Statistical Sirens

Schutz (1986)
Fishbach+ arXiv:1807.05667

Bright Sirens

Chen+ arXiv:1712.06531
LVC+ arXiv:1710.05835

Gray Sirens

Feeney+ arXiv:2012.06593
Gupta arXiv:2212.00163

Spectral Sirens

Ezquiaga and Holz arXiv:2202.08240
Chen, Ezquiaga and Gupta arXiv:2402.03120

Love Sirens

Messenger+ arXiv:1107.5725
Dhani+ arXiv:2212.13183

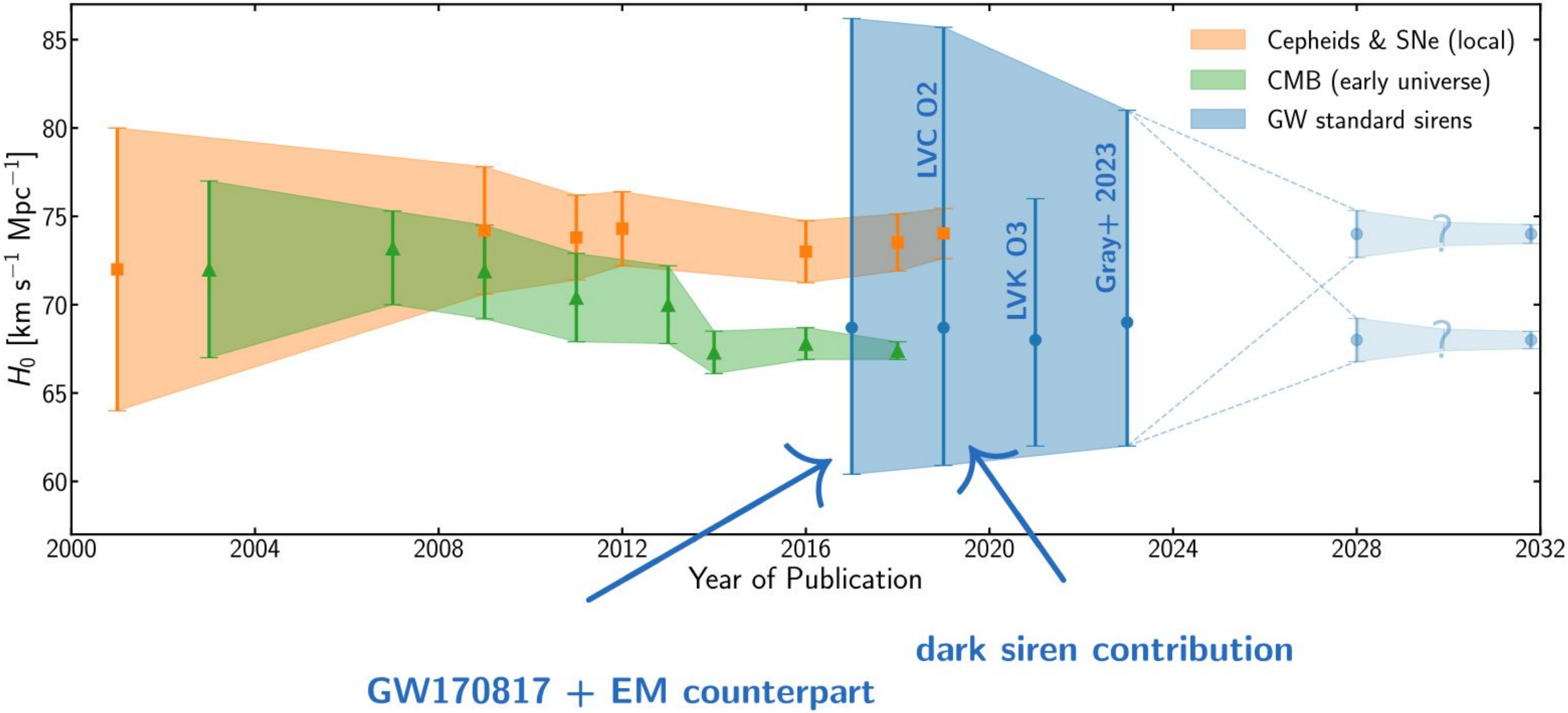
Golden Dark Sirens

Nishizawa arXiv:1612.06060
Borhanian+ arXiv:2007.02883

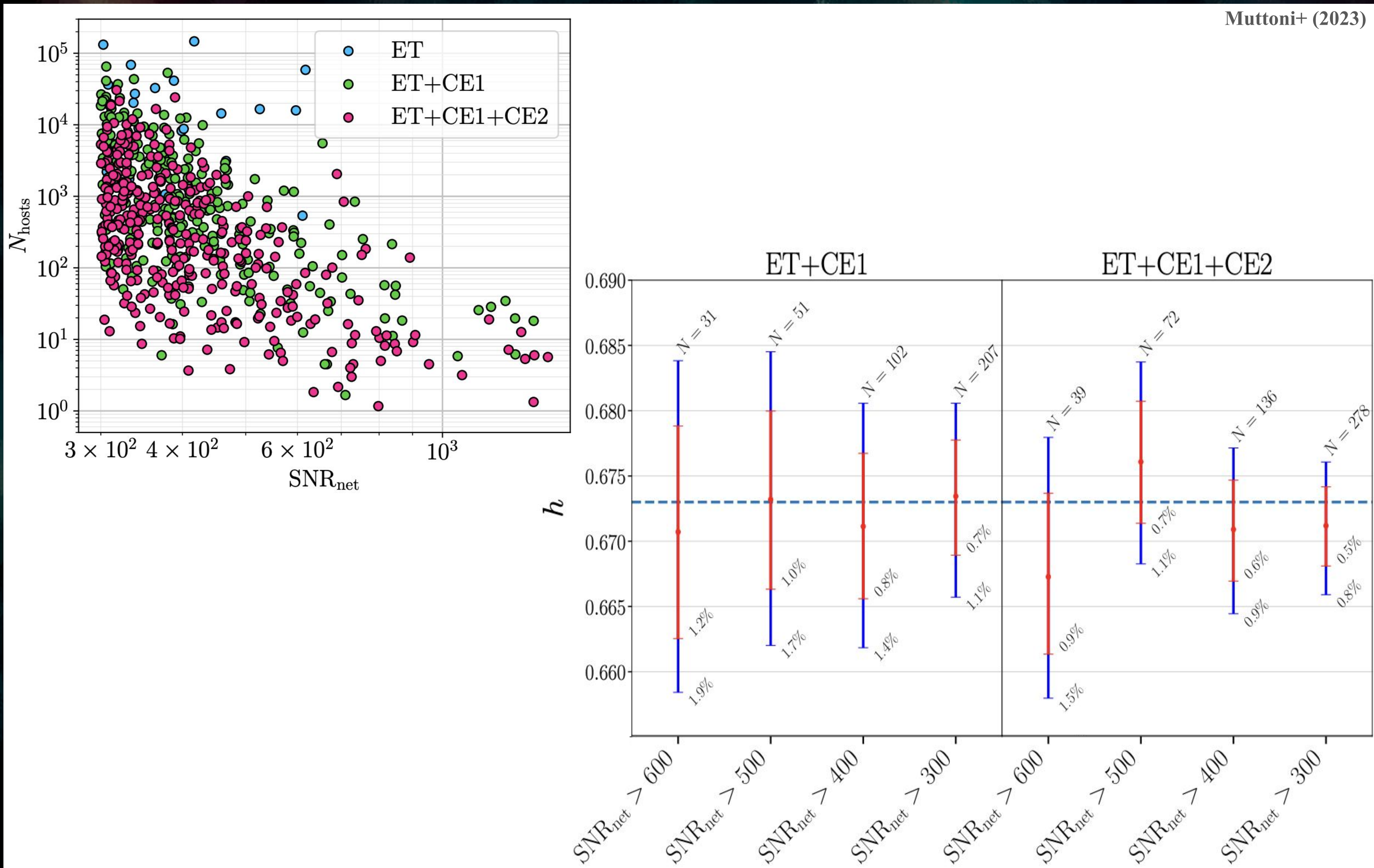
Clustering & Cross-correlations

Mukherjee+ arXiv:2007.02943
Diaz and Mukherjee arXiv:2107.12787

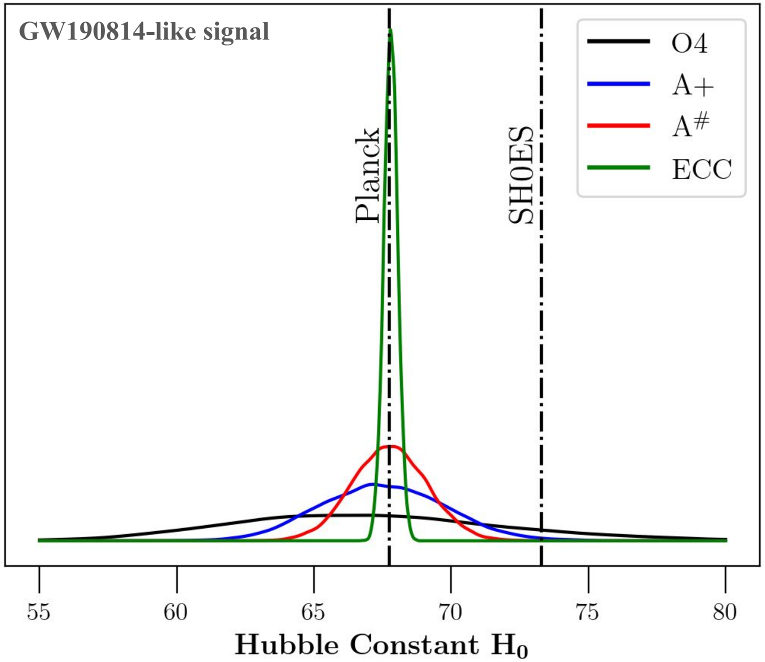
Current constraints



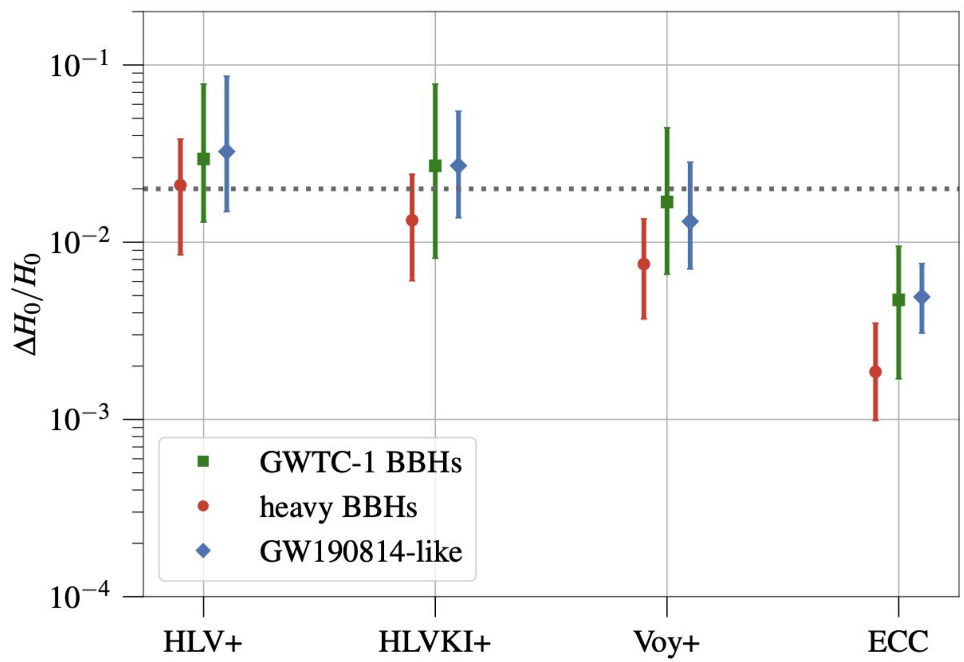
Forecasts with dark sirens



Forecasts with golden dark sirens

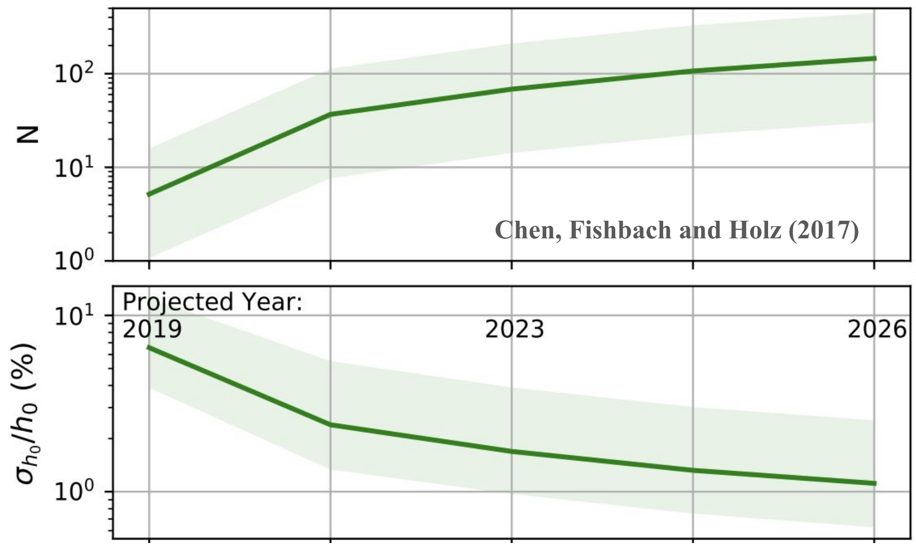


Borhanian+ (2023)

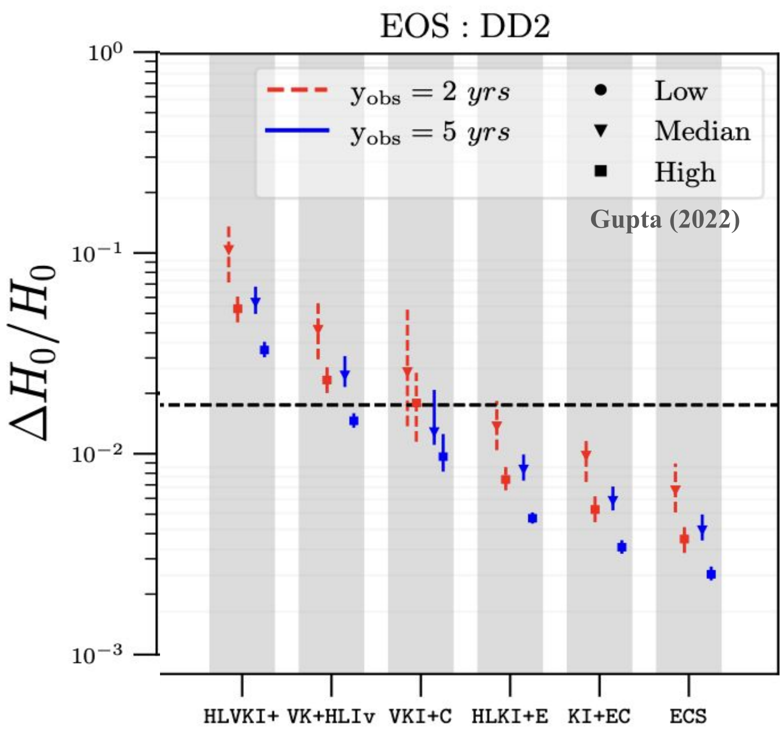


Forecasts with bright sirens

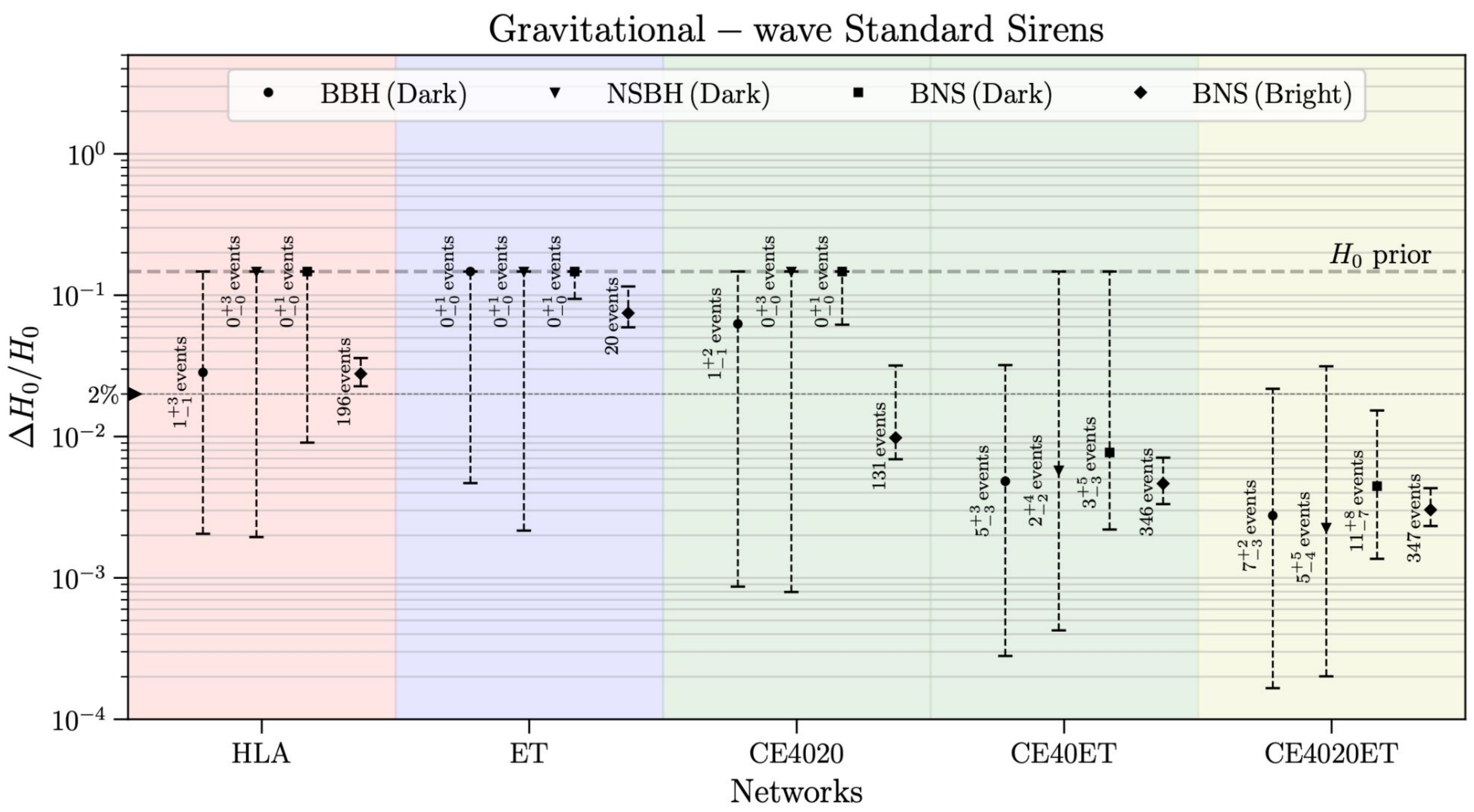
Binary neutron stars



Neutron star-black hole

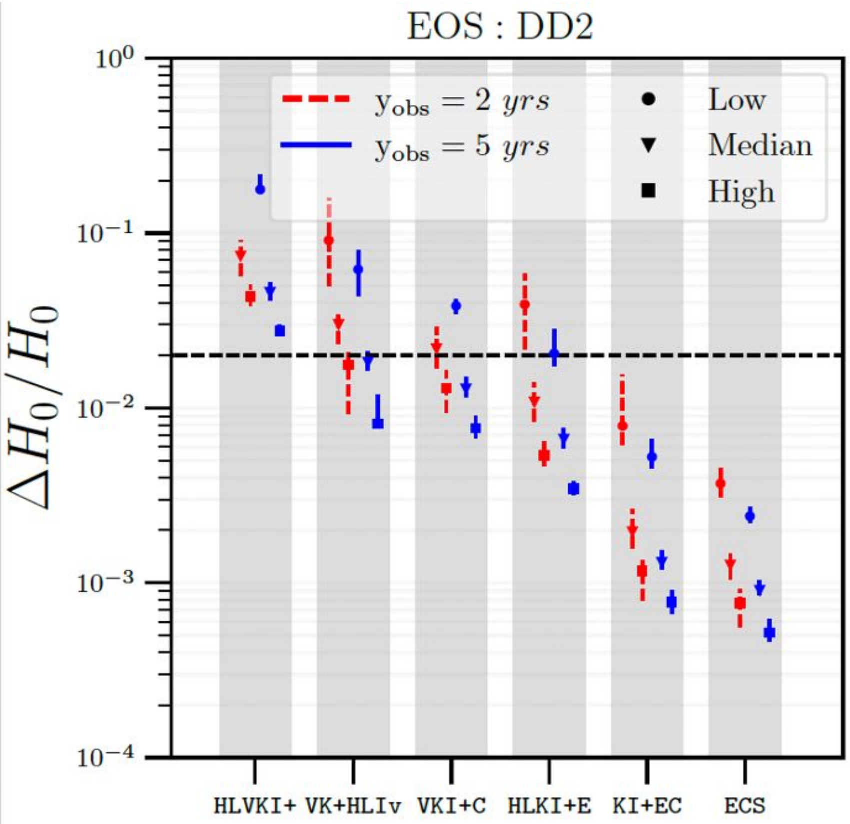


Comparing the sirens

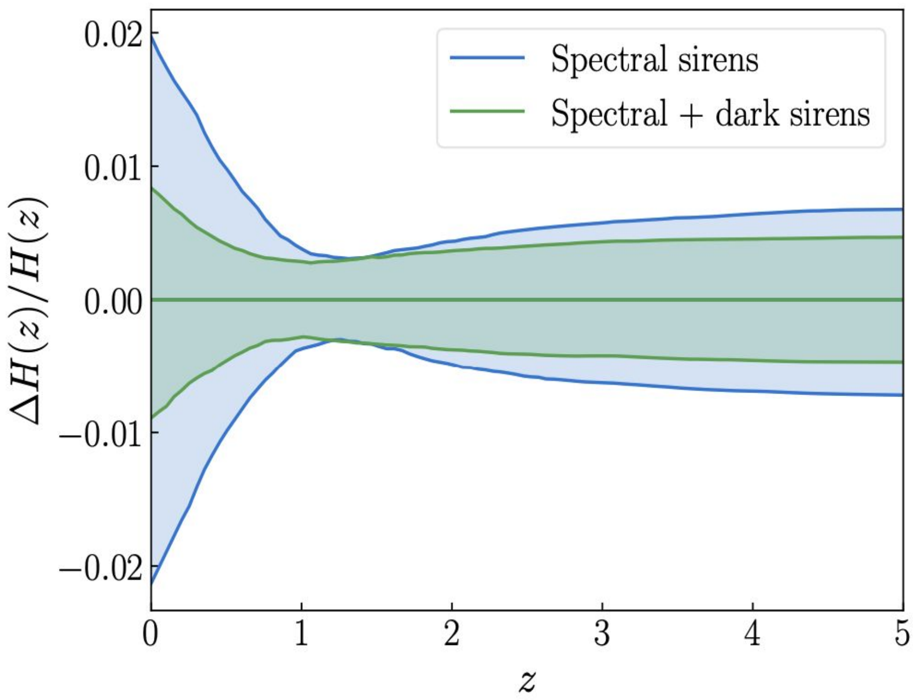


Chen, Ezquiaga and Gupta (2024)

Combining the sirens?



Gupta (2022)



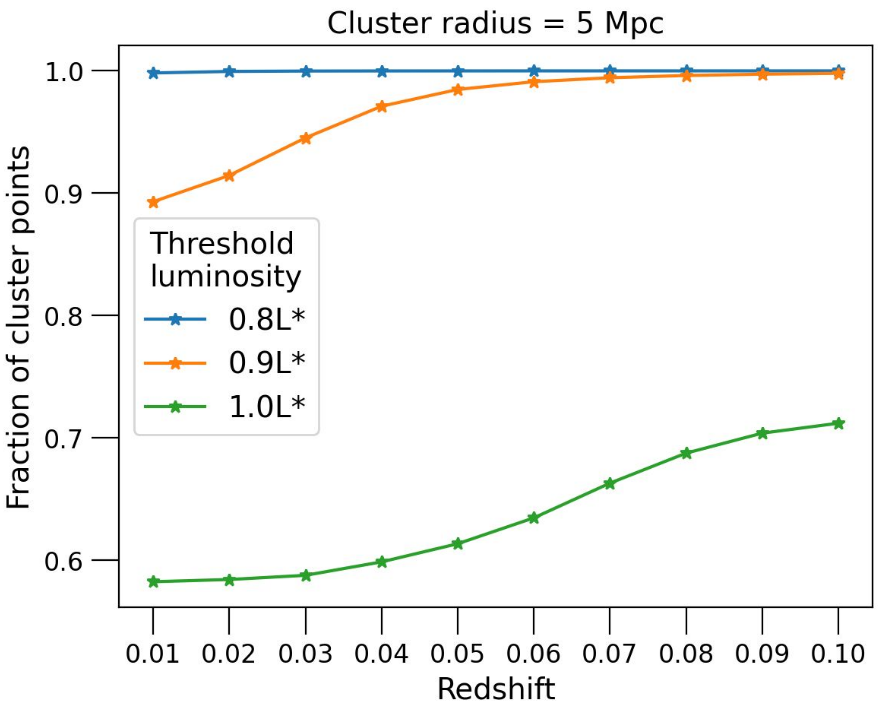
Chen, Ezquiaga and Gupta (2024)

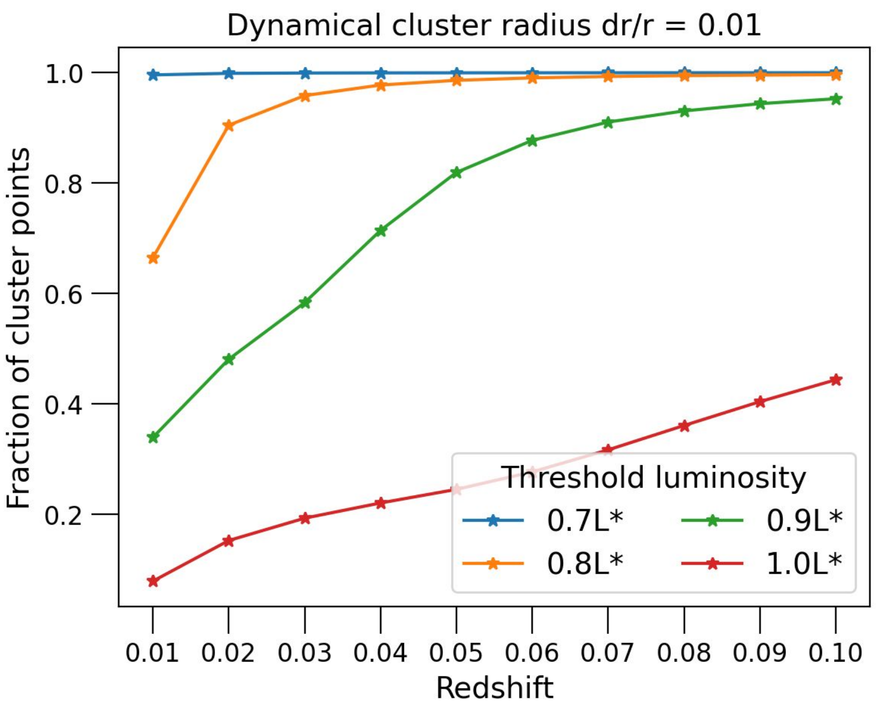
Food for thought...

- **What are the siren-specific systematics and how can they be mitigated?**
  galaxy weighting, inclination-angle bias, mass-spectrum, unique host identification
- **When spoiled for choice, can we only consider the golden events?**
- **Can waveform systematics play spoilsport in cosmological inference?**
- **What are the obstacles in achieving the forecasted precision measurements with next-generation networks?**
  calibration uncertainties, EM follow-up strategies, etc.

What if the host is not L*?

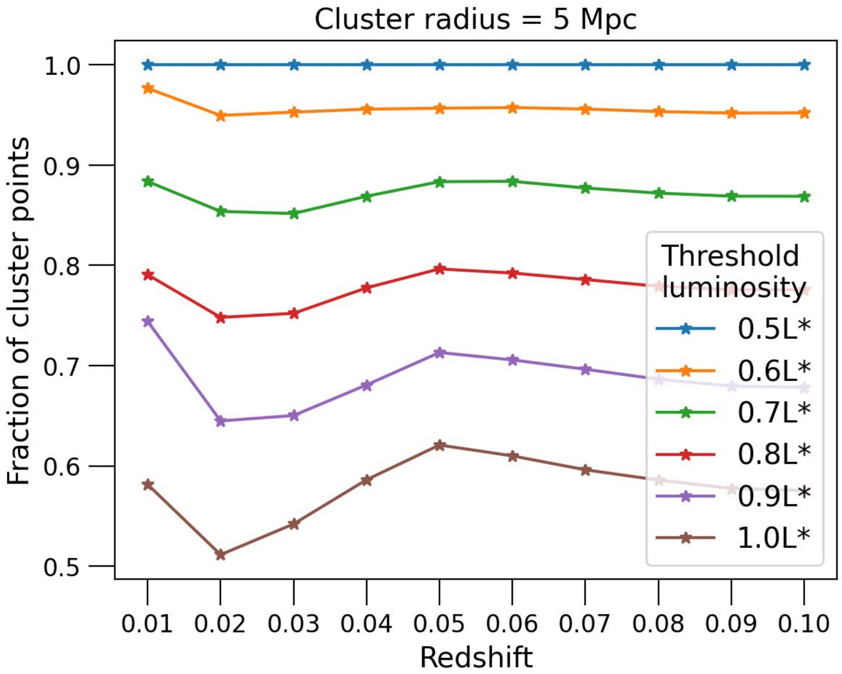
Are these non-L* hosts clustered around a bright galaxy?

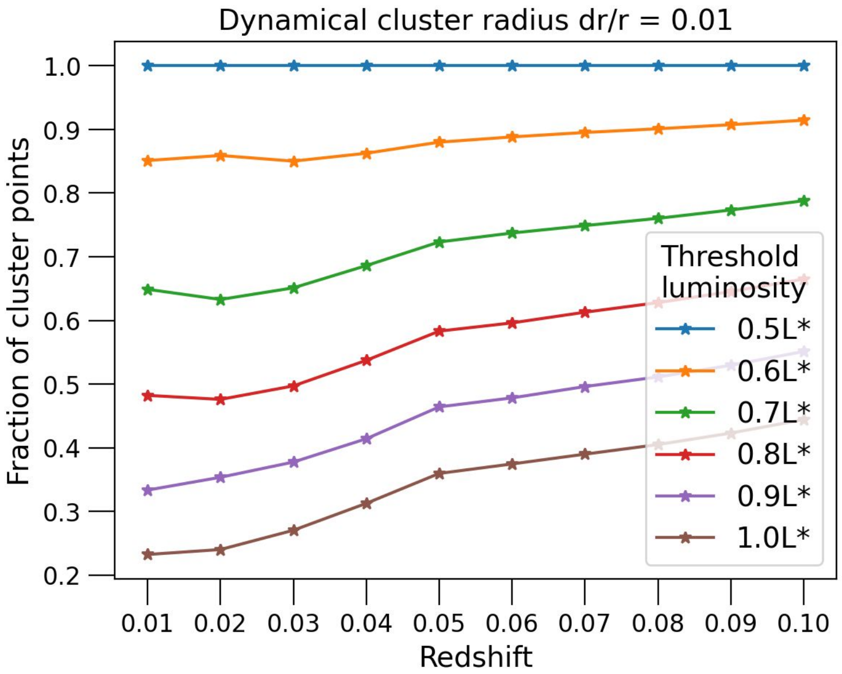




What if the host is not L*?

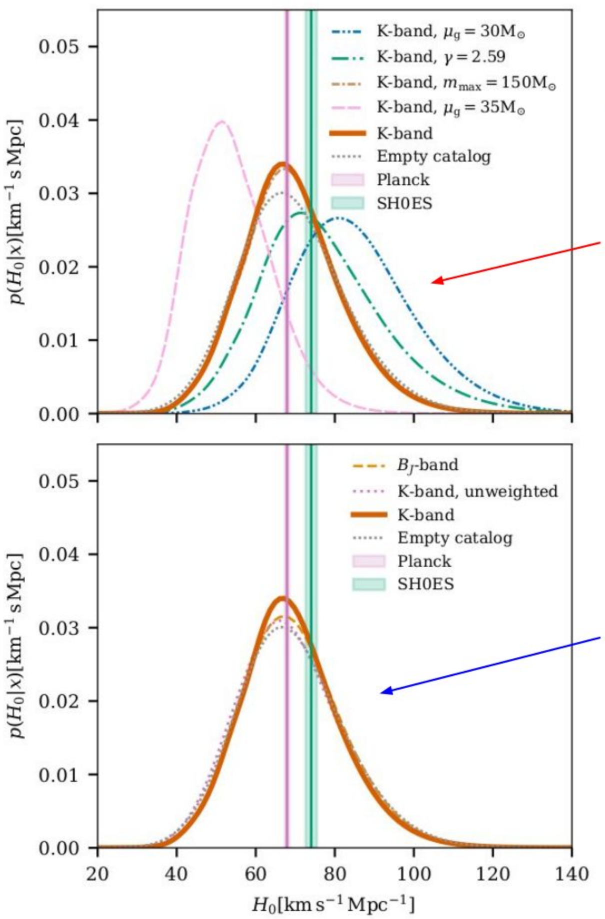
Tackling completeness with a simulated catalog (MICECAT)





Standard sirens: challenges

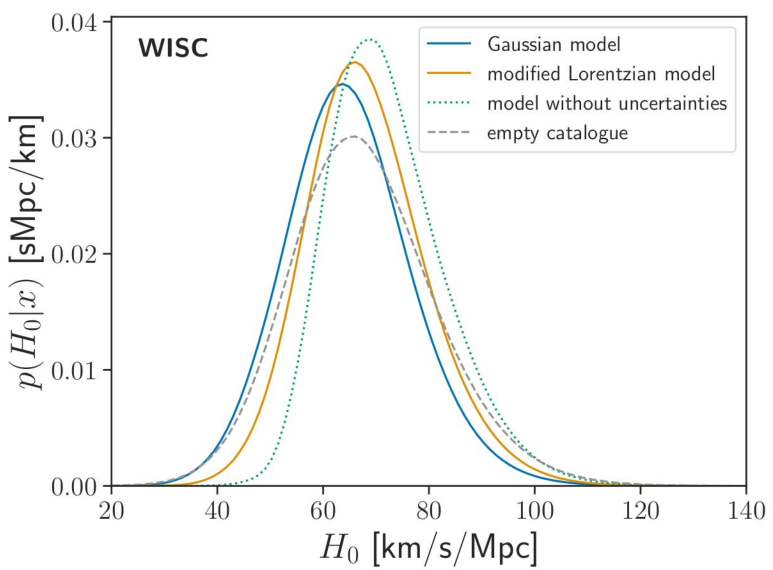
- Limited number of sources with bright counterparts
  - Can pre-merger analysis successfully aid follow-up campaigns?
- Incompleteness of galaxy catalogues
  - Upcoming observatories: VRO, DESI, SPHEREx
- Systematic effects:
  - Selection effects on GW and EM side
  - Peculiar velocities of nearby galaxies
  - Uncertainties from galaxy catalogues
  - Astrophysical assumptions
  - GW waveform modelling, GW detector calibration
  - Other detector artefacts



Varying certain population parameters affects the H0 posterior significantly

Varying galaxy catalog parameters affects the H0 posterior only marginally

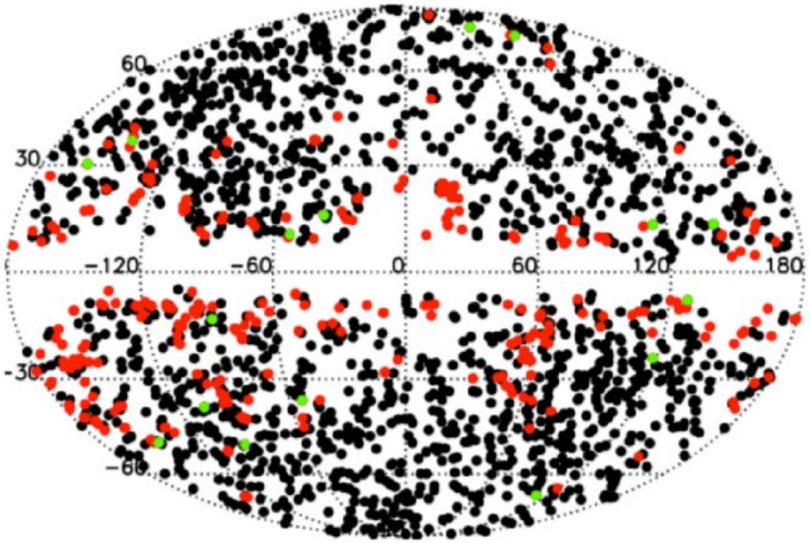
Situation expected to be different with more "in-catalogue" information.



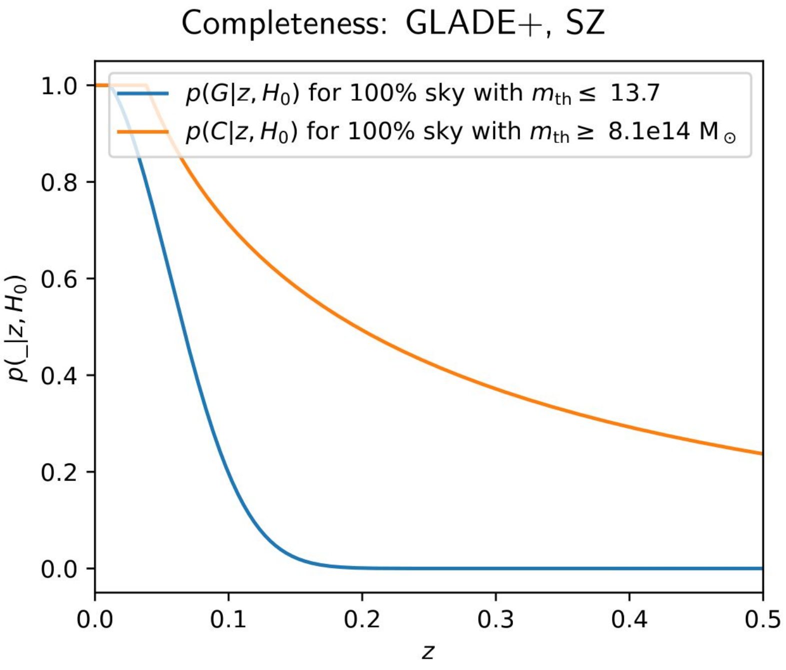
Impact of photo-z uncertainty profiles on H0 [Turski+ 2023]

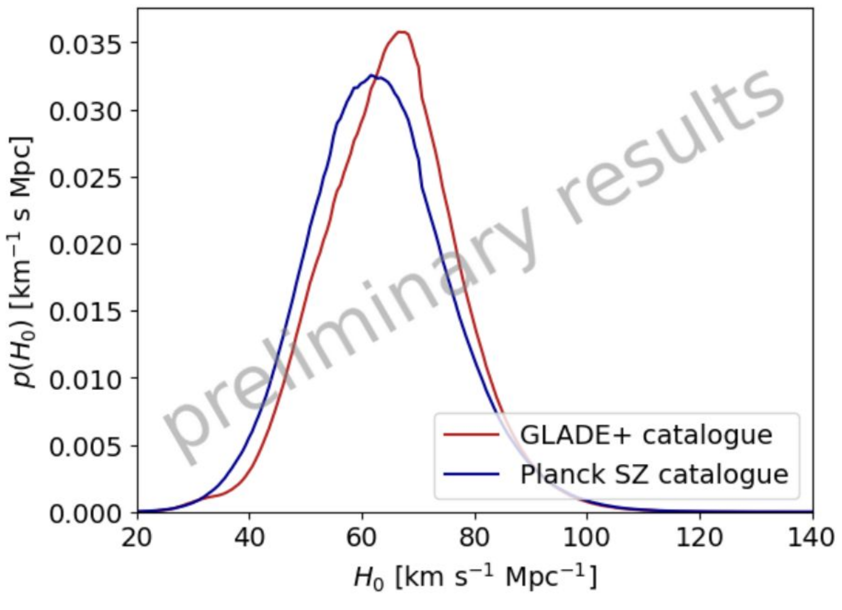
Recent developments and future directions

- Construction of line-of-sight redshift prior [Gray+ 2023]
  - probability density of GW mergers in redshift space
- Use of other probes as tracers in z-space
  - High-luminosity galaxies: L* galaxies, bright red galaxies
  - Galaxy clusters: X-ray surveys (eRosita), Sunayev-Zel’dovich (SZ)
  - Quasars
  - HI intensity mapping



Ongoing work by Freija Beirnaert: Cosmography using GWTC-3 events and Planck SZ cluster catalogue.





Questions for Slido

- What will win: bright sirens, dark sirens, spectral sirens?
- What is the most important challenge to overcome for standard sirens:
  - Search for EM counterparts
  - Limited depth of galaxy catalogues
  - GW distance / localization uncertainties
  - Unknown astrophysics: environment, evolution of merger rate, etc.
  - Other: ???
- Choose between:
  - GW standard sirens will provide meaningful information about cosmology beyond EM probes.
  - No, we will need to look for other aspects of cosmology with GWs.

Slido Code: 1925516

Discussion topics

-- What systematics are dominant for each method?

-- Bright: inclination distribution of GRBs?

-- Dark: galaxy weightings?

-- Spectral: mass distribution evolution?

- What is the role of golden (high SNR) sources in each of the siren methods? Can we only consider the very loudest events?

- Is there cosmology from GW source correlations/cross-correlations with galaxy catalogs?

Primordial GW

Matteo Fasiello, IFT

PAX IX, Physics & Astrophysics at the eXtreme,
July 24th 2024, London

Primordial GW Sources

- PGW, a universal prediction of inflation

  detection @ intermediate & small scales requires multi-field scenarios

- PGW from pre-heating dynamics

- PGW from 1st order phase transitions in the early universe

  need beyond Standard Model physics

- PGW from cosmic defects

Inflation, the minimal paradigm, SFSR

Simplest realization: single-scalar field in slow-roll

- Scalar field

$$p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi) \approx -V(\phi)$$

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi) \approx V(\phi)$$

$$\dot{\phi}^2 \ll V$$

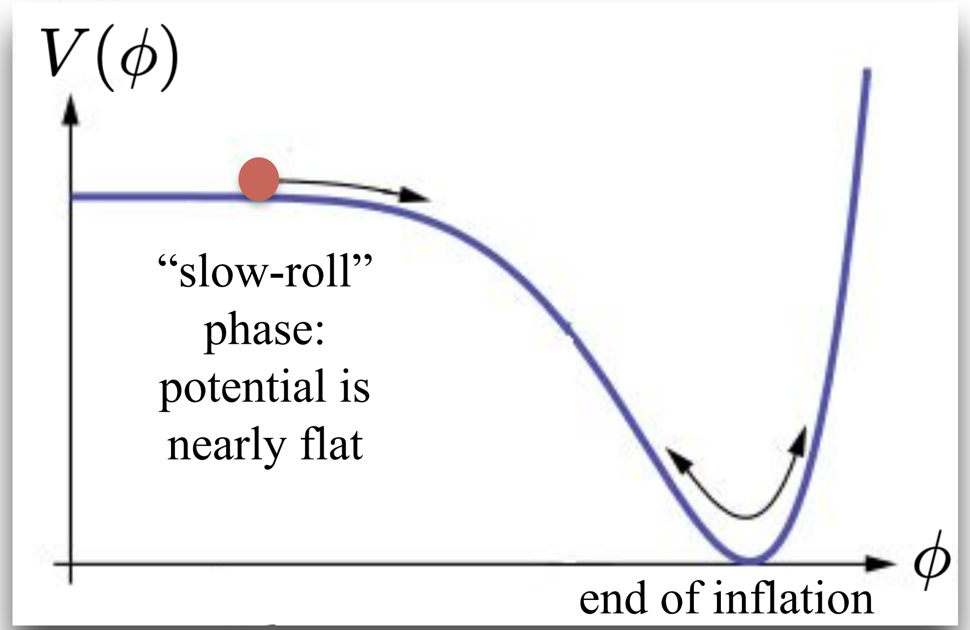
$$p_\phi \approx -\rho_\phi$$

start flat

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \simeq \frac{3}{2}\frac{\dot{\phi}^2}{V} \ll 1$$

stay flat

$$|\eta| \equiv \frac{|\dot{\epsilon}|}{H\epsilon} \simeq -\frac{2}{3}\left(\frac{V''}{H^2}\right) + 4\epsilon \ll 1$$



Primordial Fluctuations

(minimal scenario)

$$ds^2 = (-dt^2 + a(t)^2[e^{2\zeta}\delta_{ij} + \gamma_{ij}]dx^i dx^j)$$

scalar fluctuations

tensor perturbations

Primordial Fluctuations

(minimal scenario)

$$ds^2 = (-dt^2 + a(t)^2[e^{2\zeta}\delta_{ij} + \gamma_{ij}]dx^i dx^j)$$

scalar fluctuations

$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$n_s - 1 \simeq -2\epsilon - \eta$$

2.2×10^{-9}

0.9649 ± 0.0042

$[k_* = 0.05\,\mathrm{Mpc}^{-1}, 68\%\mathrm{C.L.}]$

from Planck measurements of CMB anisotropies

tensor perturbations

$$\mathcal{P}_\gamma^{\rm vacuum}(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_T}$$

energy scale of inflation

red tilt

$$n_T \simeq -2\epsilon \simeq -r/8$$

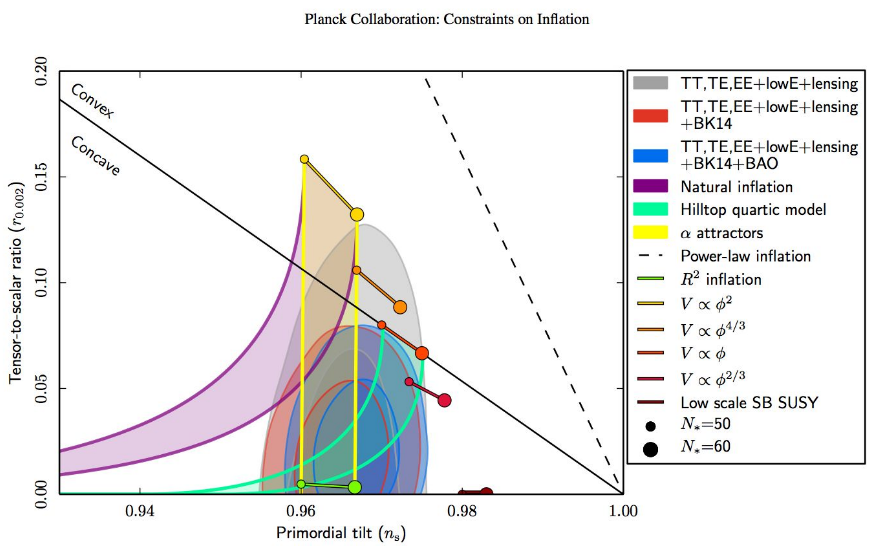
tensor-to-scalar ratio $\quad r \equiv \frac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta}$

bounds

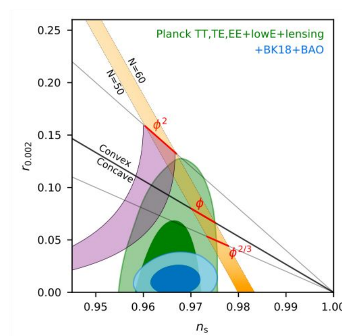
current: $r < 0.032\,(95\%\mathrm{CL, Planck}^+)$

future: $r < 0.01$ (CMB-S3); $r < 0.001$ (-S4) LiteBIRD

@ CMB scales

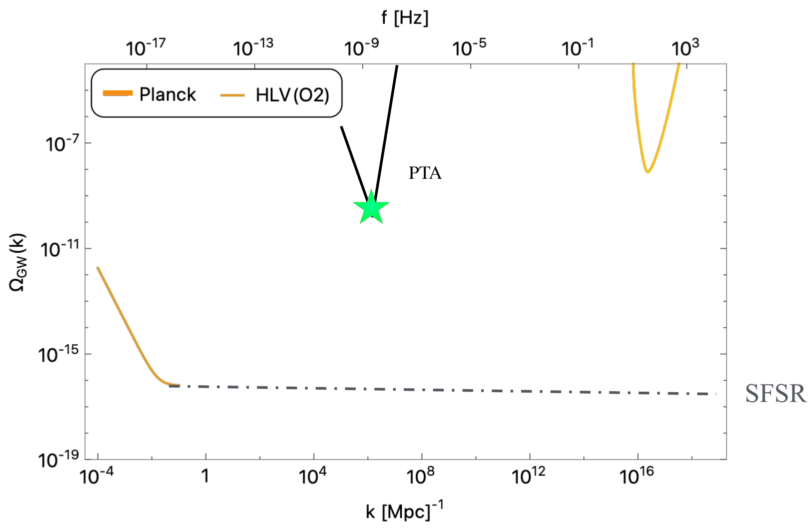


+BK update:



Hope for a little more (GW)

now



Hope for a little more (GW)

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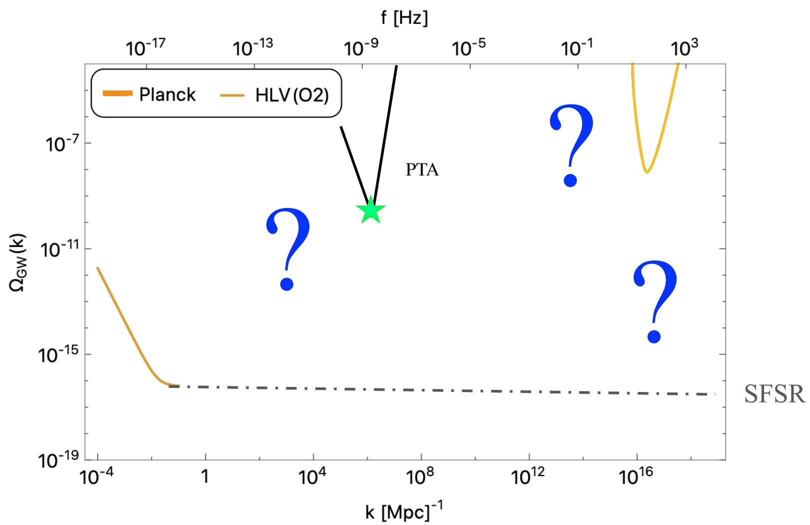
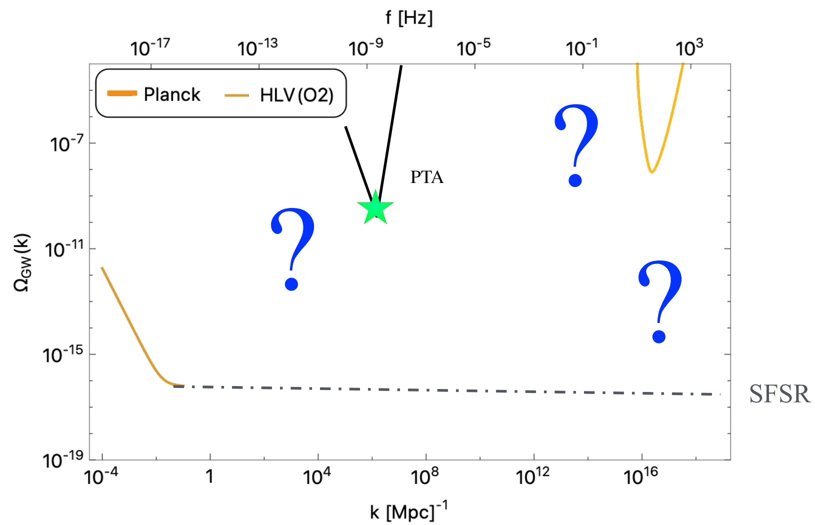


Hope for a little more (GW)

now



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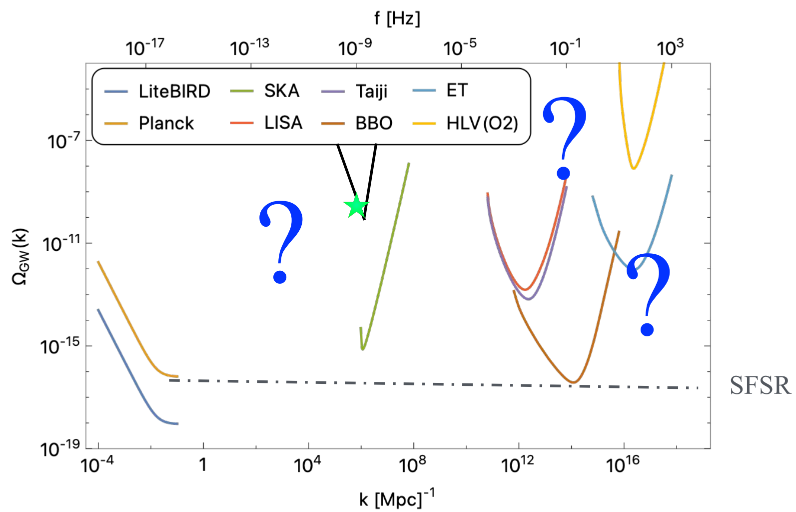
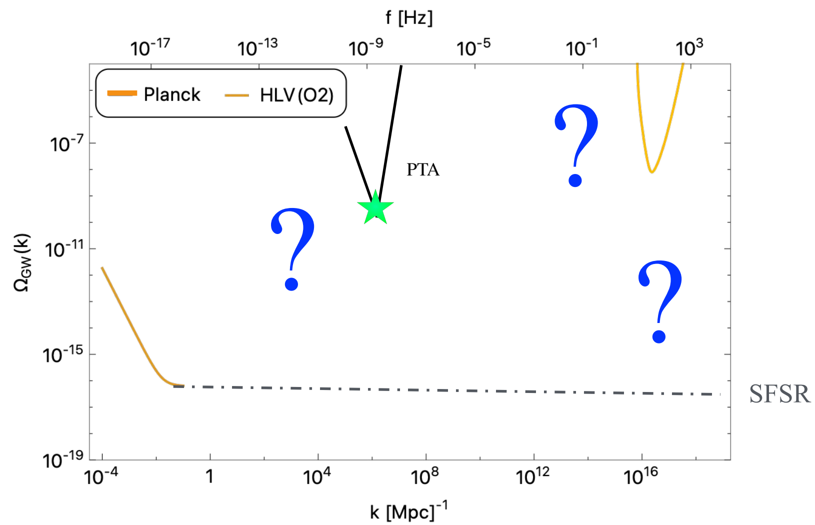


Hope for a little more (GW)

now



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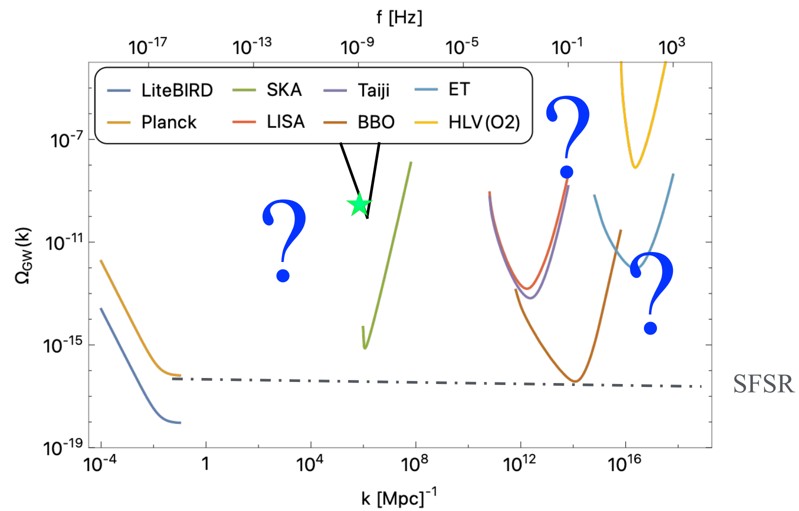
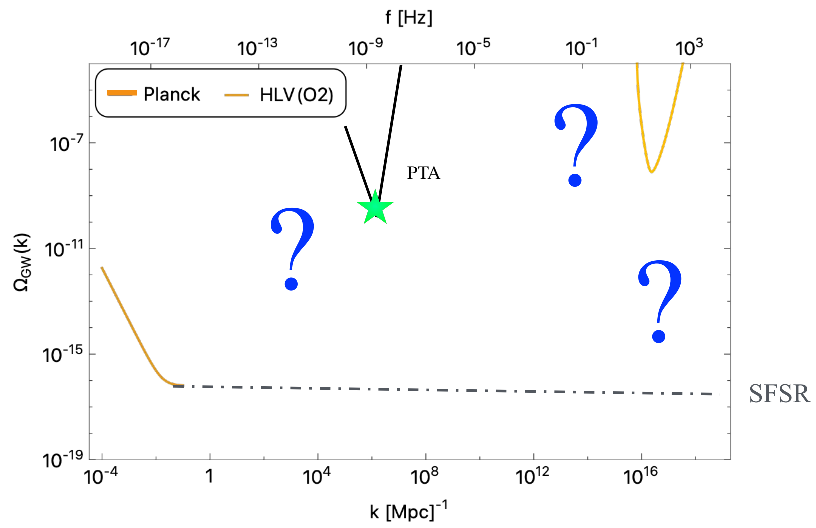


features!

Hope for a little more (GW)

now



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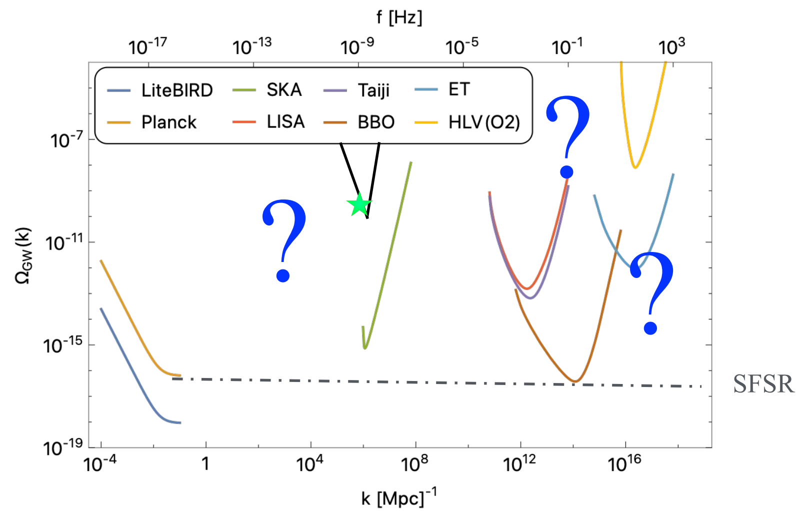


blue or bump-like GW spectrum testable @ PTA or via laser interferometers

Typically multiple fields required

why go beyond the single-field?

Likely

string theory
|
flux compactifications
|
4D EFT with many moduli fields

Testable

soon to cross key thresholds
$r < 0.001$ (CMB)
$f_{NL} < 1$ (LSS, 21cm)

GW signatures of new content:
PS: scale-dependence, chirality,
n-G: (amplitude, shape, angular)

Necessary

extraordinary claims
require extraordinary evidence

what to infer from
GW detection?
e.g. r <—> H relation

Many (classes of) models

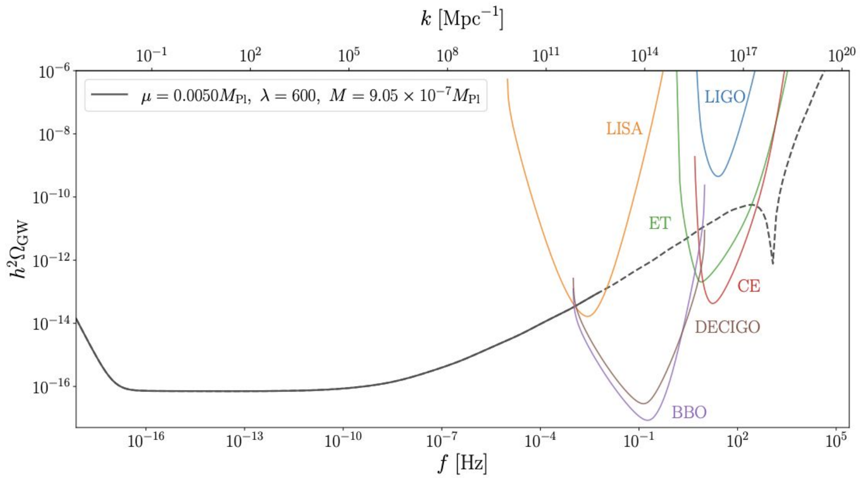
Natural Inflation + Gauge Sector

$$\mathcal{L} \supset -\frac{1}{4}F^2 + \frac{\lambda\phi}{4f}F\tilde{F} - (\partial\phi)^2 - U_{\rm axion}(\phi)$$

$U(\chi) \sim \mu^4[1+\cos(\chi/f)]$

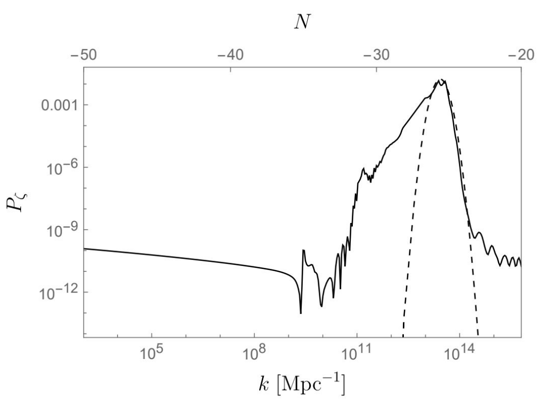
- friction/dissipation slows the roll
- $f \ll M_{\rm P}$ realization
- very interesting GW signatures !

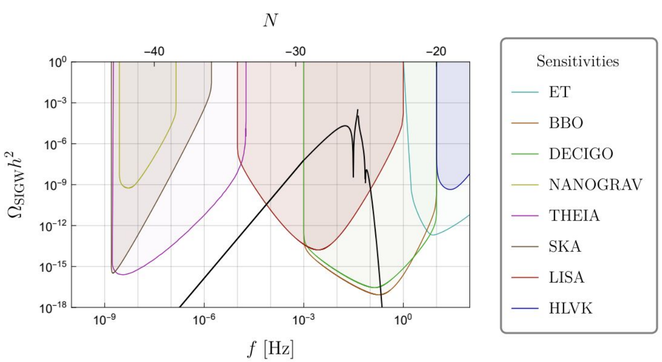
Axion-inflaton with non-minimal coupling



[Dimastrogiovanni, MF, Michelotti, Pinol]

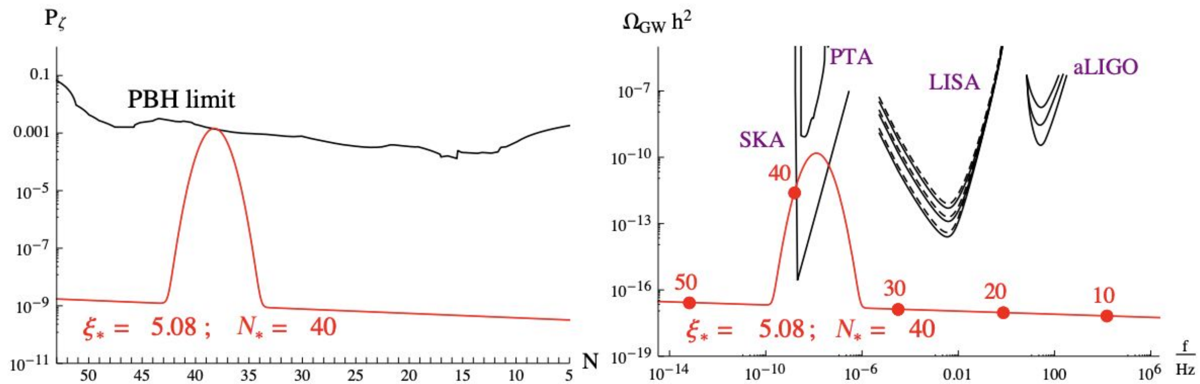
Axion inflaton in strong back-reaction regime



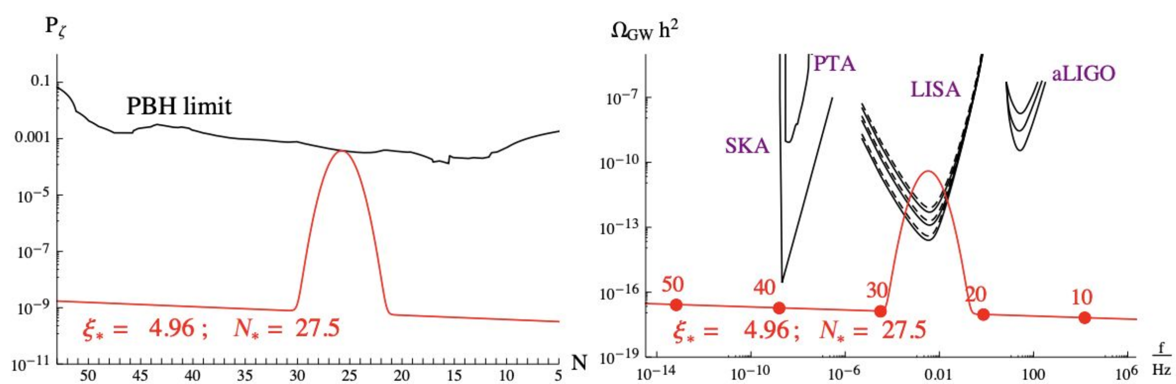


[Dimastrogiovanni, MF, Papageorgiou]

Spectator Axions



[Garcıa-Bellido, Peloso, Unal]



One unique signature: chirality

(background +) Chern-Simons coupling $\dfrac{\lambda\chi}{4f}F\tilde{F}$

$$\ddot{t}_{ij}^{L/R} \pm \lambda(\dots)t_{ij}^{L/R} + \dots = 0$$

$$\gamma_{ij}^{L} \neq \gamma_{ij}^{R}$$

chiral spectrum

$$\mathcal{P}_{\gamma}^{L} \neq \mathcal{P}_{\gamma}^{R}$$

Testable @ CMB (<EB>, <BT>) and @ interferometers
- cross-correlation @ different locations [Smith, Caldwell 2017]
- kinematically induced dipole [Seto 2006, Domcke et al 2019]

From Domcke et al 1910.08052:

“We find that both LISA and ET, despite operating at different frequencies, could detect net circular polarization with a signal-to-noise ratio of order 1 in a SGWB with amplitude $h^2 \Omega_{GW} \sim 10^{-11}$"

Appeal of axion-gauge field models

Model Building

"simple" ingredients

eta problem

UV complet-able

spectral shape

non-Gaussianity

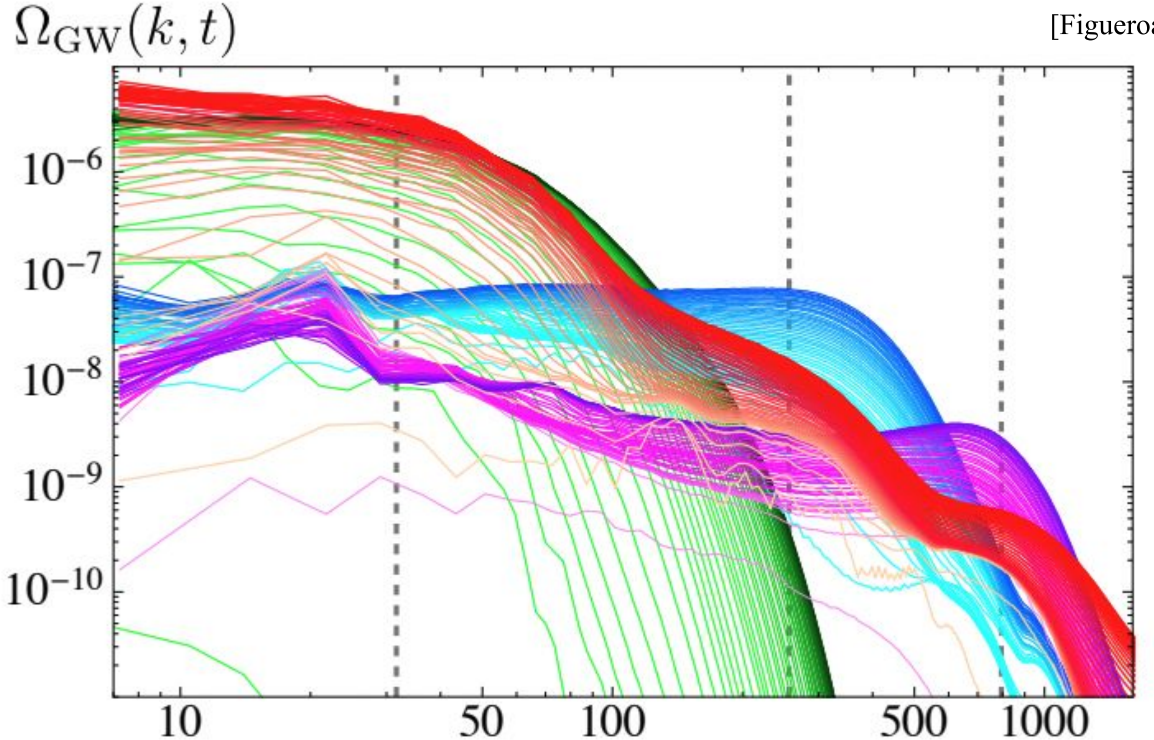
chirality

PBHs too!

Testing

GW from Pre-heating

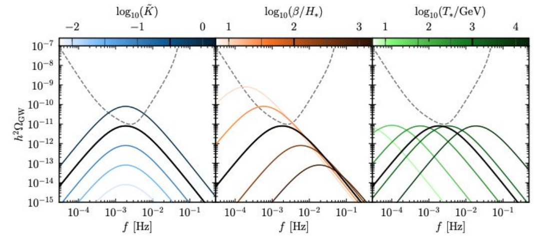
[Figueroa et al arXiv:2202.05805]



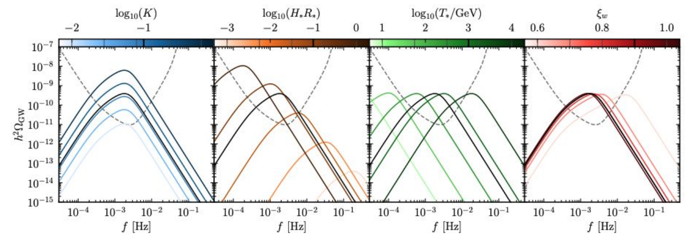
Typically at high (>>10^3 Hz) frequencies

GW from 1st order Phase Transitions

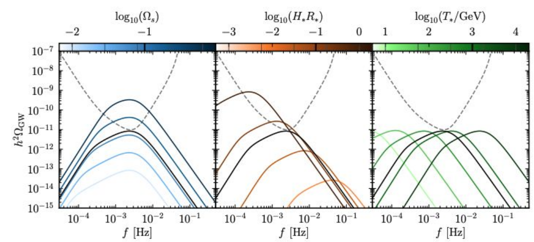
[Caprini et al 2403.03723]



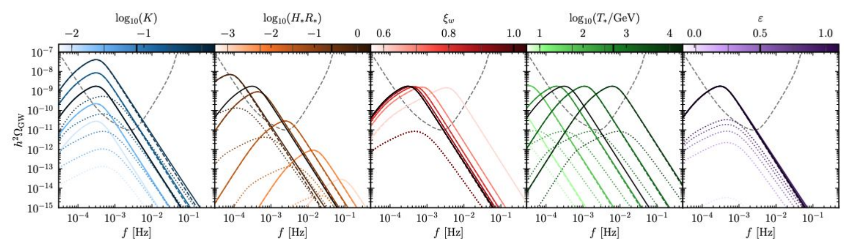
(a) bubble collisions and highly relativistic fluid shells (black: $\tilde{K} = 0.32$, $\beta/H_* = 100$, $T_* = 1\,\text{TeV}$)



(b) sound waves (black: $K = 0.1$, $H_*R_* = 0.1$, $\xi_w = 0.9$, $T_* = 1\,\text{TeV}$)



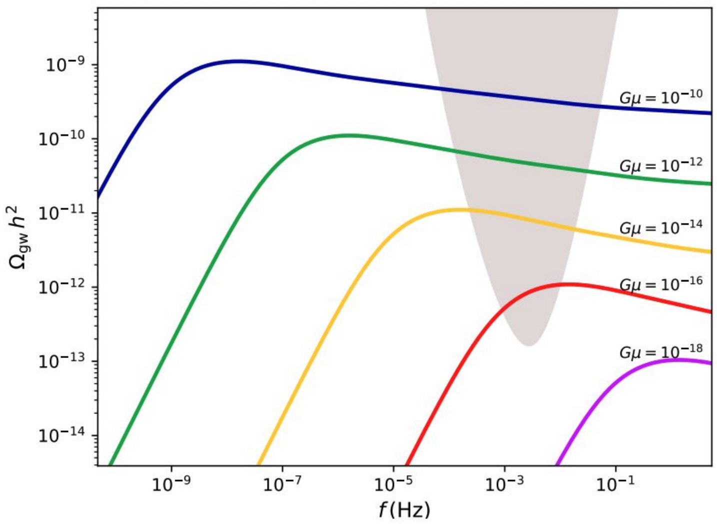
(c) turbulence (black: $\Omega_s = 0.1$, $H_*R_* = 0.1$, $T_* = 1\,\text{TeV}$)

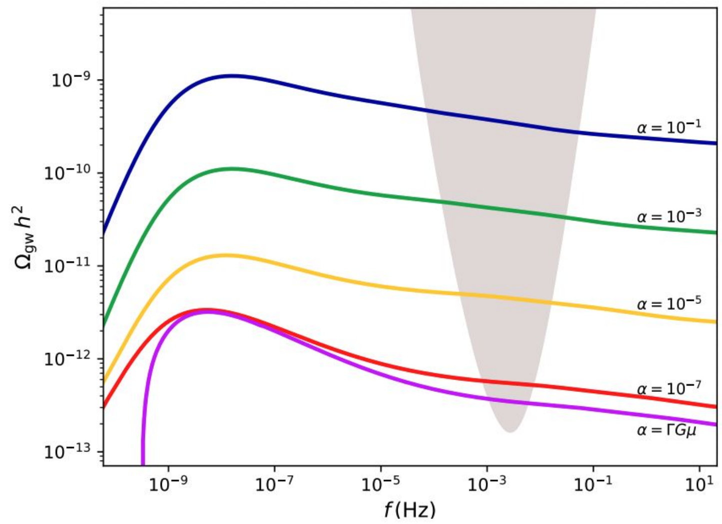


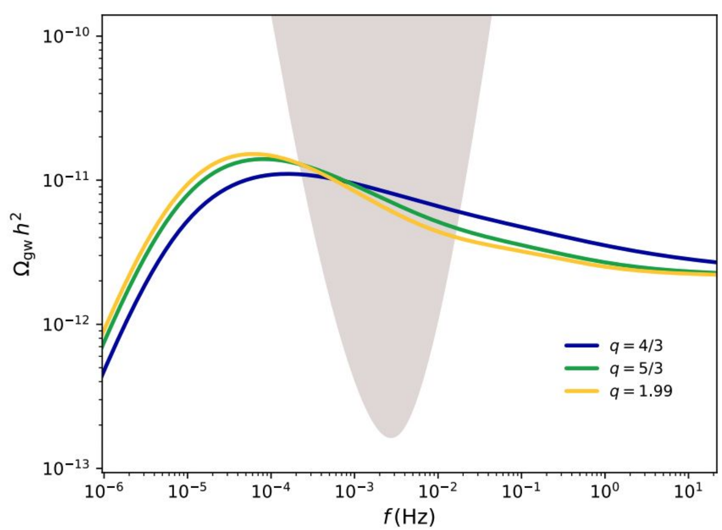
(d) sound waves + turbulence (black: $K = 0.08$, $H_*R_* = 0.25$, $\xi_w = 1$, $T_* = 500\,\text{GeV}$, $\varepsilon = 0.5$)

GW from Cosmic String Network

[Blanco-Pillado et al 2405.03740]







Recent Survey of PGW Templates (LISA-oriented)

Braglia et al, [arXiv:2407.04356]
Blanco-Pillado et al [arXiv:2405.03740]
Caprini et al [2403.03723]

Template	Class of models
Power law	- Axion-inflaton with gauge sector - massive spin-2 - time dependent sound speed
Log-normal bump	-Axion spectator models
Broken power law	- Models w/ USR phase followed by 2nd SR phase - hybrid inflation with mild waterfall stage
Double peak	- Single and multifield models with non-attractor stage - models with log-normal P_ζ (enhancement by resonance) - models with broken power law P_ζ (e.g. thermal inflation)
Excited states	- Strong & brief deviation from geodesic in field space (strong turn in 2-field inflation)
Linear oscillations	- single-field w/ step in the inflaton potential - multifield inflationary sharp turn in trajectory
Logarithmic resonant oscillations	- Axion monodromy models
Deformations thereof due to + physics	- e.g. kination era

inflation only

How do we test the primordial nature of the signal?

From arXiv:2407.04356*:

“If the primordial SGWB signal is not sufficiently strong to dominate over most of the transient, its reconstruction at LISA is planned to be achieved via a “global fit”, where all sources are simultaneously reconstructed in an iterative manner….

…A more feasible approach is to consider a global fit where the primordial SGWB is firstly isolated with an approximate template-free approach, and then use this reconstruction to shortlist the theoretically-motivated templates that best suit the reconstructed signal.”

Is this an optimistic take?

* Assumptions
i) ESA delivers a very accurate LISA noise model,
ii) The astrophysical community manages to precisely model the astrophysical foregrounds,
iii) The data analysis and waveform communities achieve binary waveform reconstruction with residuals that do not mimic too strongly a SGWB signal.

From arXiv:2405.03740

“…exploiting all possible means to isolate the primordial SGWB from the other sources, e.g., discriminators based on the signals’ statistical properties, anisotropic characteristics, et cetera…”

cross-correlations

SGWB x CMB

GW anisotropies

[Adshead, Afshordi, Dimastrogiovanni, MF, Lim, Tasinato]

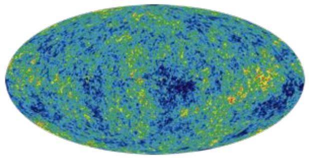
[…]

SGWB x LSS

[Scelfo, Bellomo, Raccanelli, Matarrese, Verde]

[…]

Galaxy x GW catalogues tease out nature of merging binary BH



Anisotropies
cosmological ***vs*** astrophysical

$\delta_{\rm GW}^{\rm cosmo} \propto f_{\rm NL}^{\zeta\gamma\gamma}\,\zeta$

$\delta_{\rm T}^{\rm CMB} \propto \zeta$

common primordial origin

<u>not true</u> for $\delta_{\rm GW}^{\rm astro}$ at large scales

$$\langle \delta_{\rm GW}^{?} | \delta_{\rm T}^{\rm CMB} \rangle$$

test primordial nature of $\delta_{\rm GW}$

constrain $f_{\rm NL}^{\zeta\gamma\gamma}$ at small scales

[Adshead, Afshordi, Dimastrogiovanni, MF, Lim, Tasinato]

SGWB x LSS

galaxy x GW catalogues tease out nature of merging binary BH

[Scelfo, Bellomo, Raccanelli, Matarrese, Verde]

From 1809.03528:

The cross-correlation of galaxy with gravitational wave catalogues carries information about whether black hole mergers trace more closely the distribution of dark matter – indicative of primordial origin – or that of stars harboured in luminous and massive galaxies – indicative of a stellar origin…

…Our results show that forthcoming experiments could allow us to test most of the parameter space of the still viable models investigated, and shed more light on the issue of binary black hole origin and evolution..

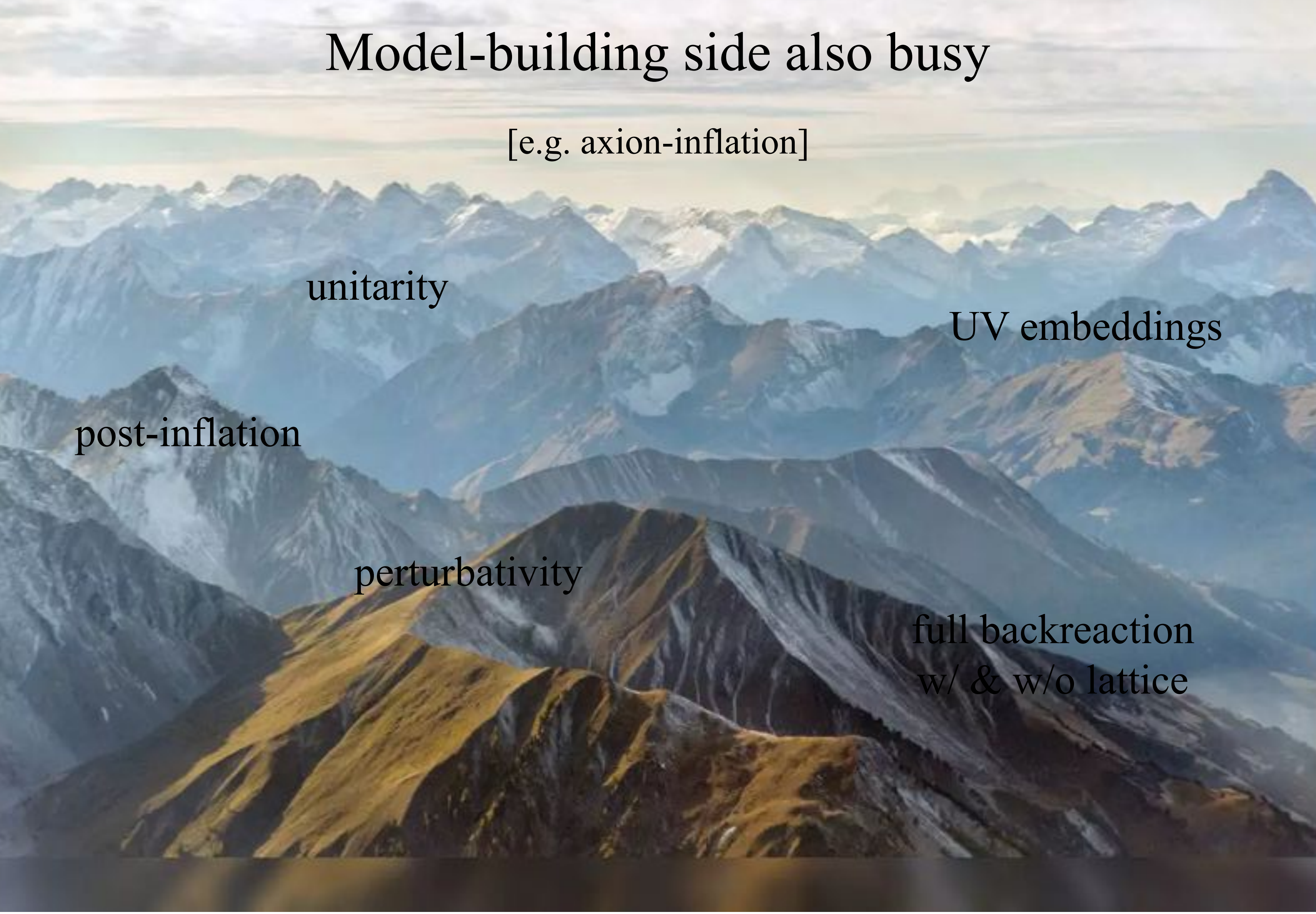
- Primordial vs Astrophysical SGWB dichotomy

- Prospect of detecting GW at high frequency

Thank you!

Model-building side also busy

[e.g. axion-inflation]



Template for participants, copy and edit.

- If you would like to bring up a topic for discussion in this session please include salient points with a figure or two.
- Please limit the text to three or four bullets.

Add your name if you think this is a good topic for discussion.

LSS from GW localization volumes.

- 3G detectors will have enough localization precision to probe large-scale structure features such as clustering bias or BAO peak.
- Prospects of combining the GW data with that of galaxy surveys (one is in z-space while the other is in luminosity-distance space).
- High redshift strategy: What can we expect from the future analysis? Apart from detector sensitivity, can we make better localization possible? For example, improvements in WF modeling, …