LISA cosmology vs L3 catalogs

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Outline

- **Standard sirens: bright & dark & more**
- **LISA standard siren sources and results**
- **LISA early universe SGWB**
- **L3 catalogs for cosmology?**

Standard sirens

Standard sirens

$$h_\times(t_o) = \frac{4}{d_L}\left(\frac{G\mathcal{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\sin\left[-2\left(\frac{5G\mathcal{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

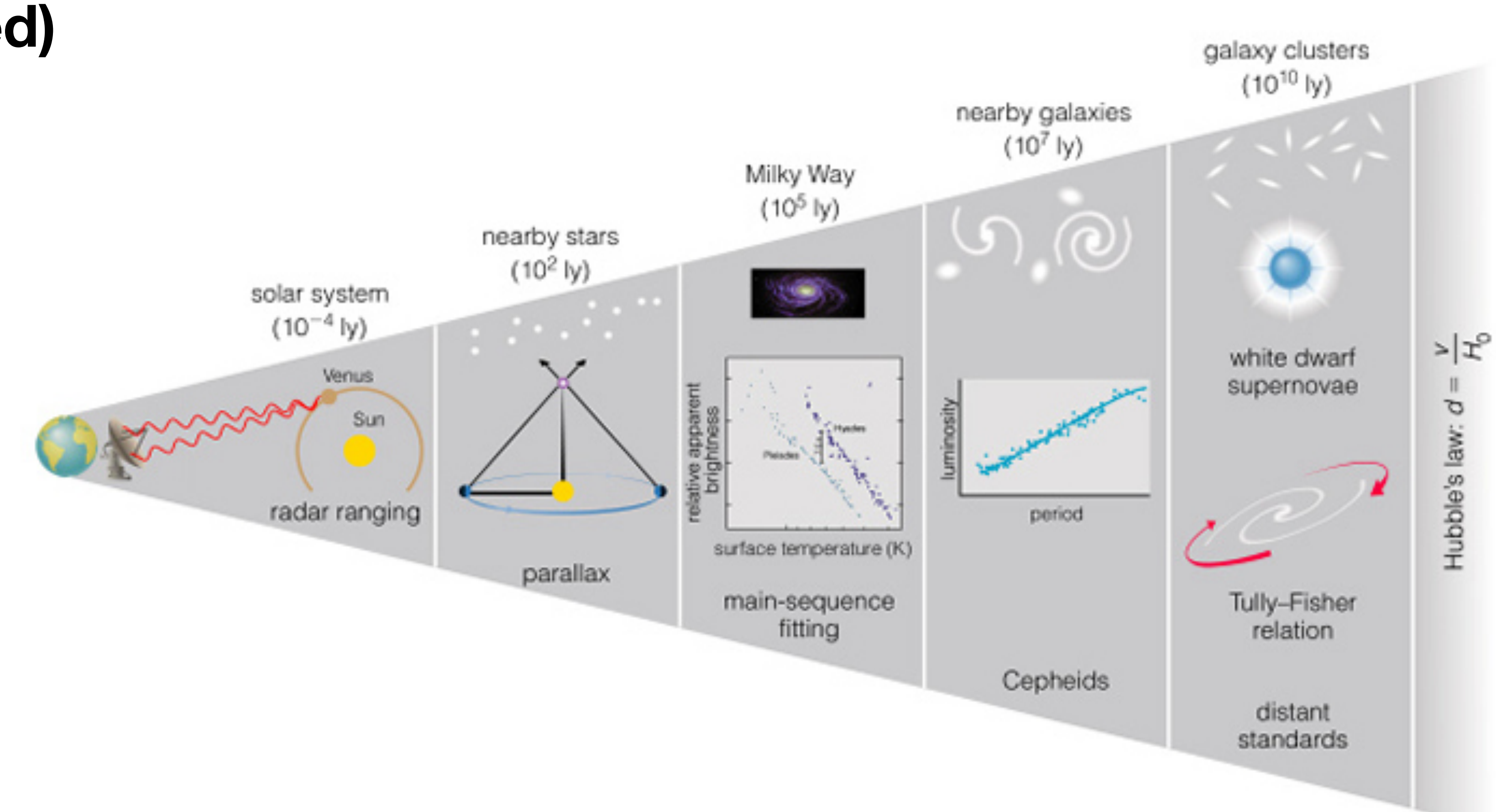
This is the very waveform (in time-domain at the lowest Newtonian order) used to detect GWs and measure the parameters of the system

Most importantly for cosmology, one can measure the luminosity distance d_L of the source directly from the GW signal without relying on the *cosmic distance ladder* (only GR has been assumed)

This means that <u>GW binaries are absolute cosmological distance indicators!</u>

↓

Free of possible systematics



Standard sirens

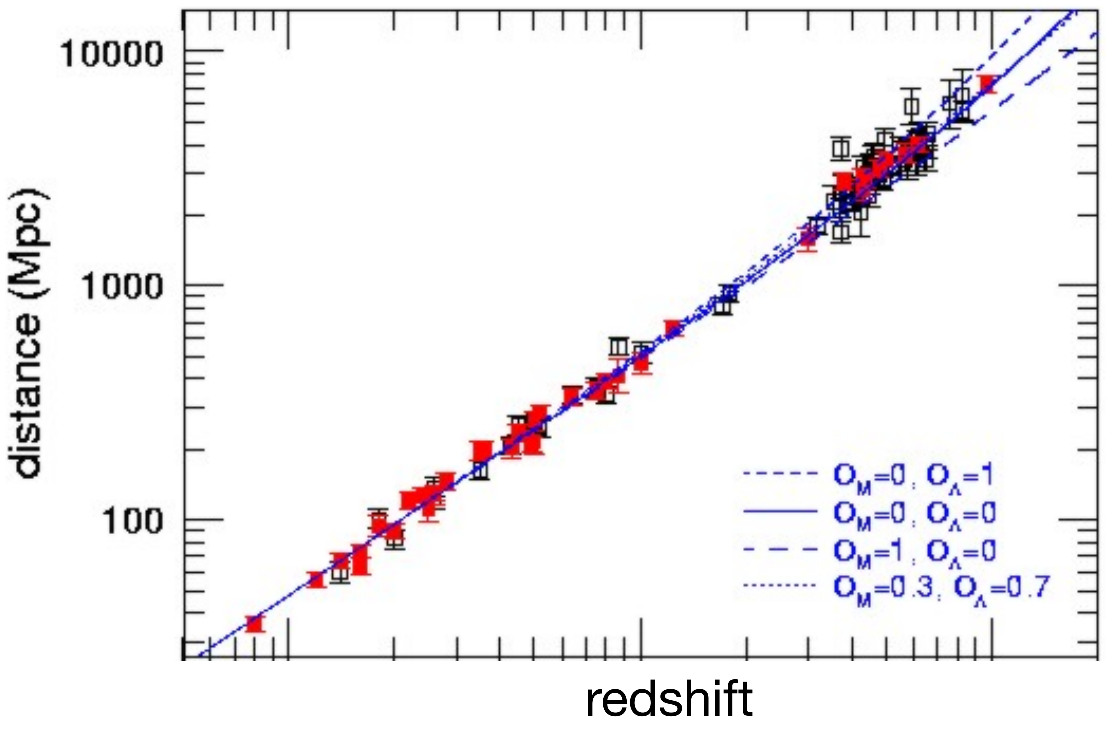
$$h_\times(t_o) = \frac{4}{d_L}\left(\frac{G\mathscr{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\sin\left[-2\left(\frac{5G\mathscr{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

Note however that the waveform above does not depend explicitly on the redshift z, which cannot thus be measured directly from GWs

One needs independent information on the redshift of the source to do cosmology: if both d_L and z are known one can fit the *distance redshift relation*

$$d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]$$

This is very similar to standard candles (supernovae type-Ia), from which the name standard sirens (using the analogy between GWs and sound waves)



[Schutz, *Nature* (1986)]

Standard sirens

How can we determine the redshift of a GW source? Three main methods:

- **By identifying an EM counterpart (*bright sirens*)**
- **By cross-correlating sky-localisation with galaxy catalogs (*statistical dark sirens*)**
- **By exploiting features in the source mass distribution (*spectral dark sirens*)**

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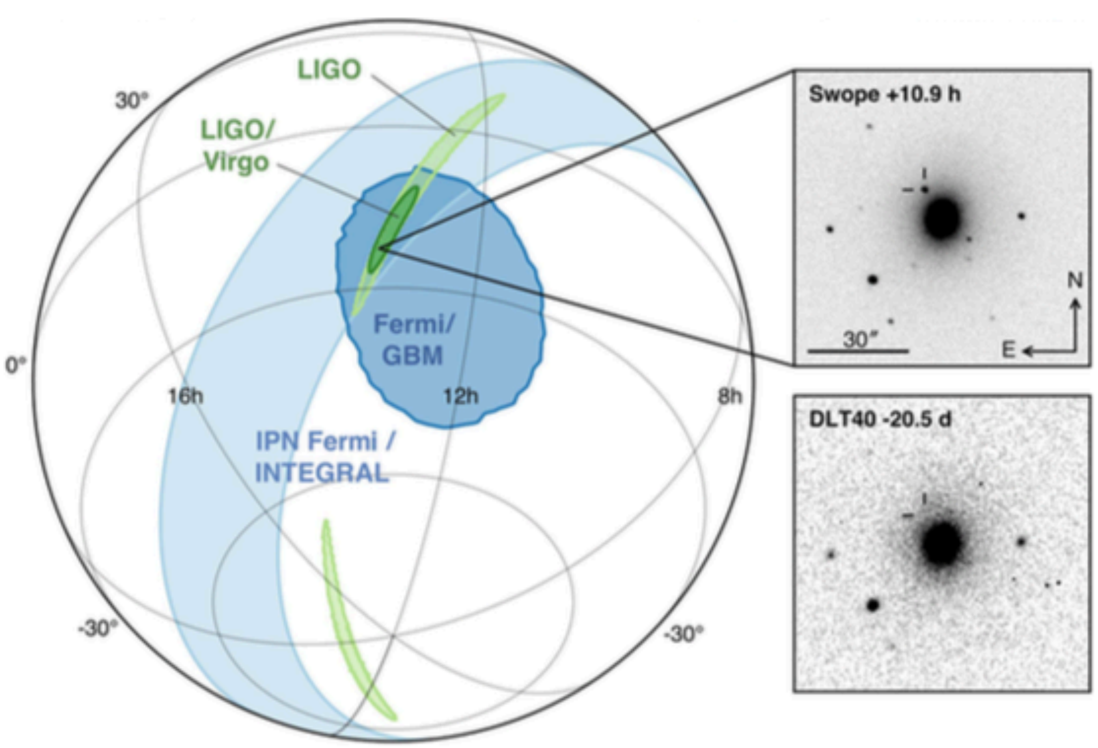

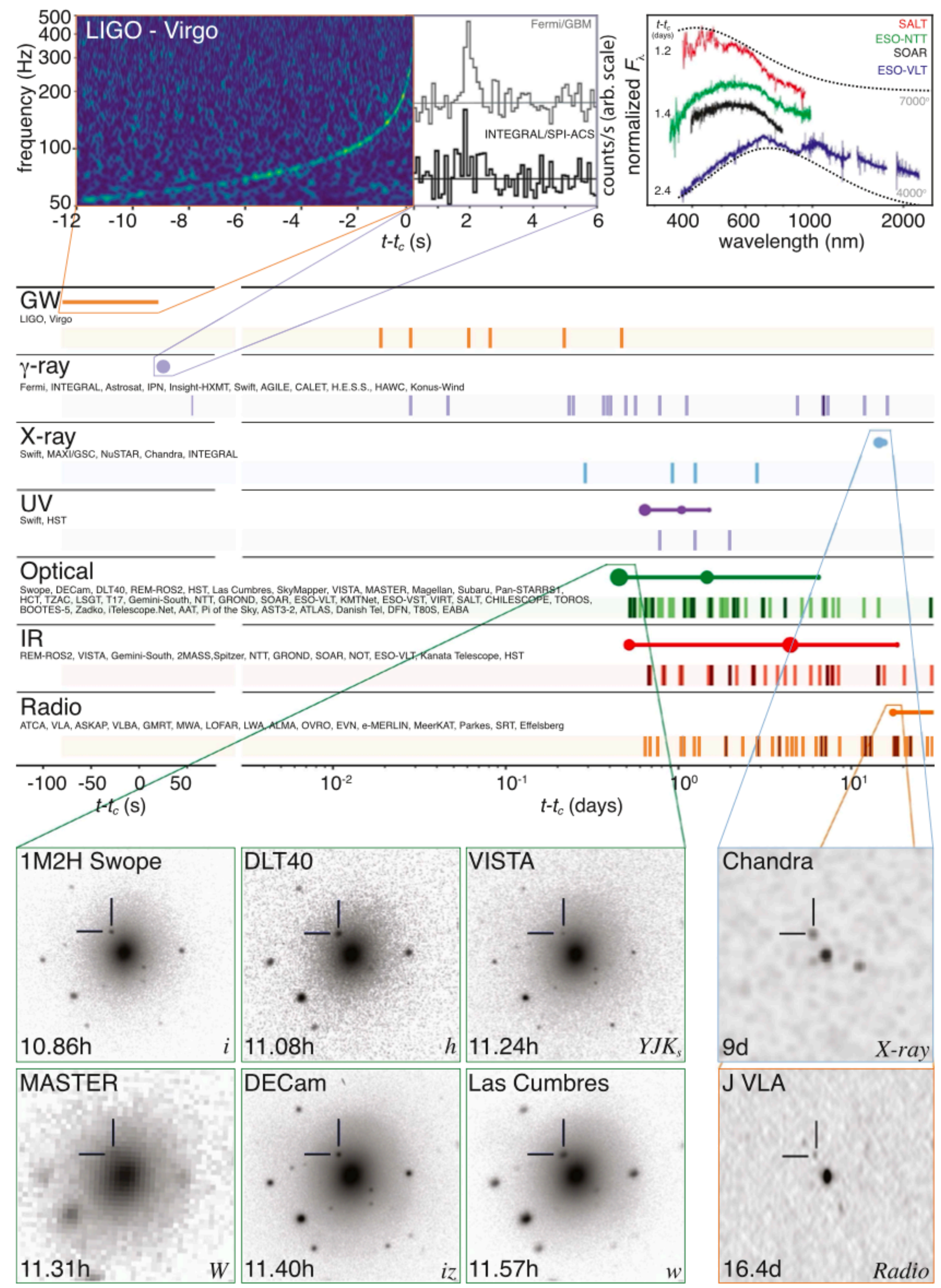

[Schutz, *Nature* (1986)]

Example: GW170817

[LVC+, *ApJL* (2017)]

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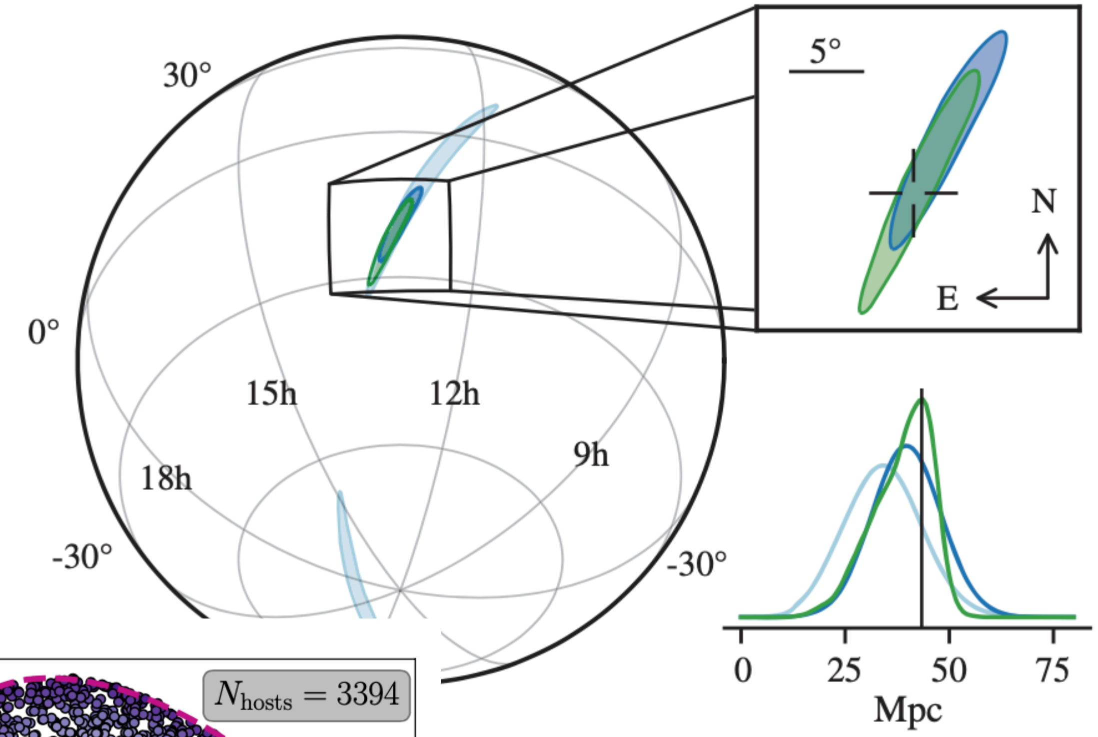

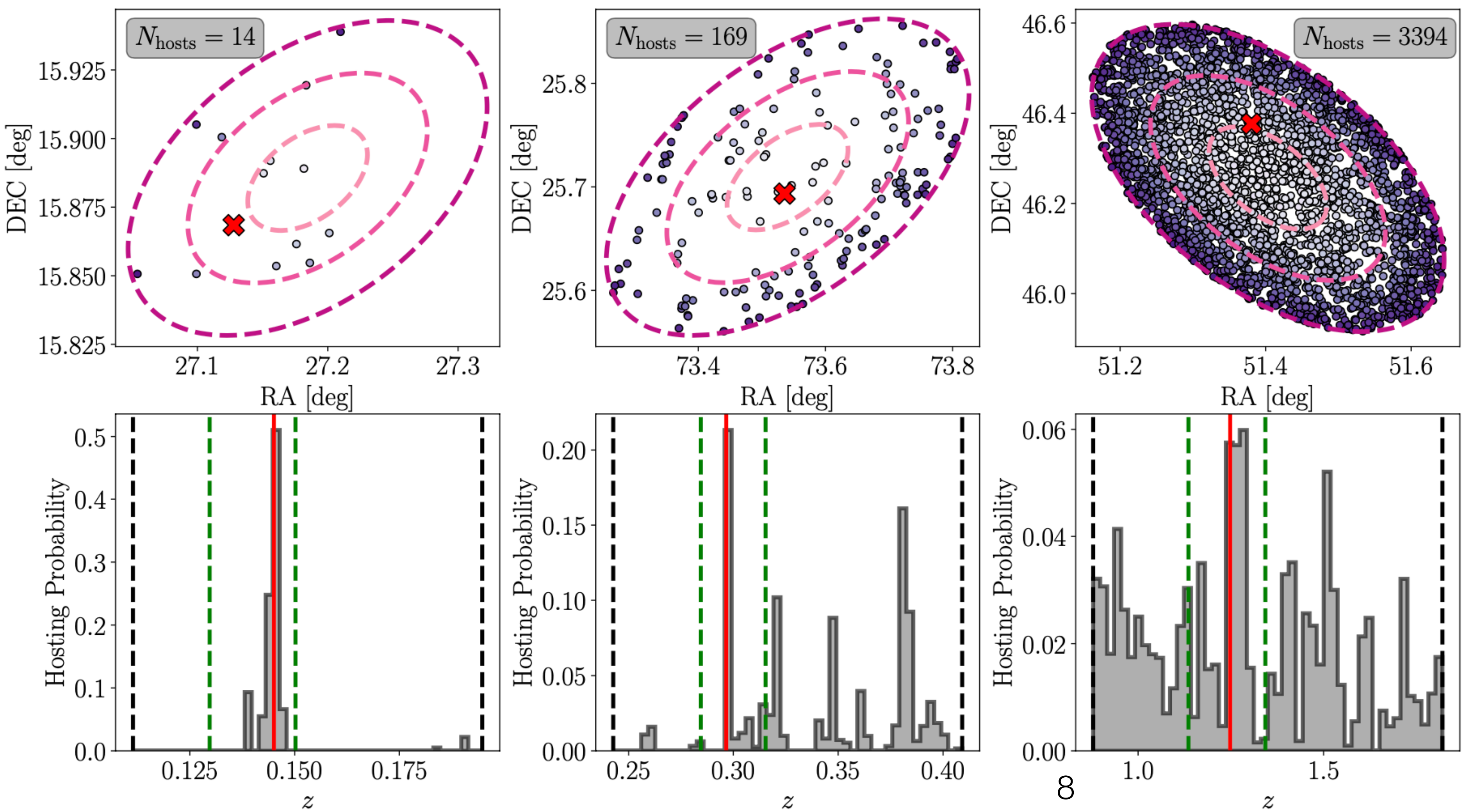

[Schutz, *Nature* (1986)]
[Gray+, *PRD* (2020)]
[Muttoni+, arXiv (2023)]

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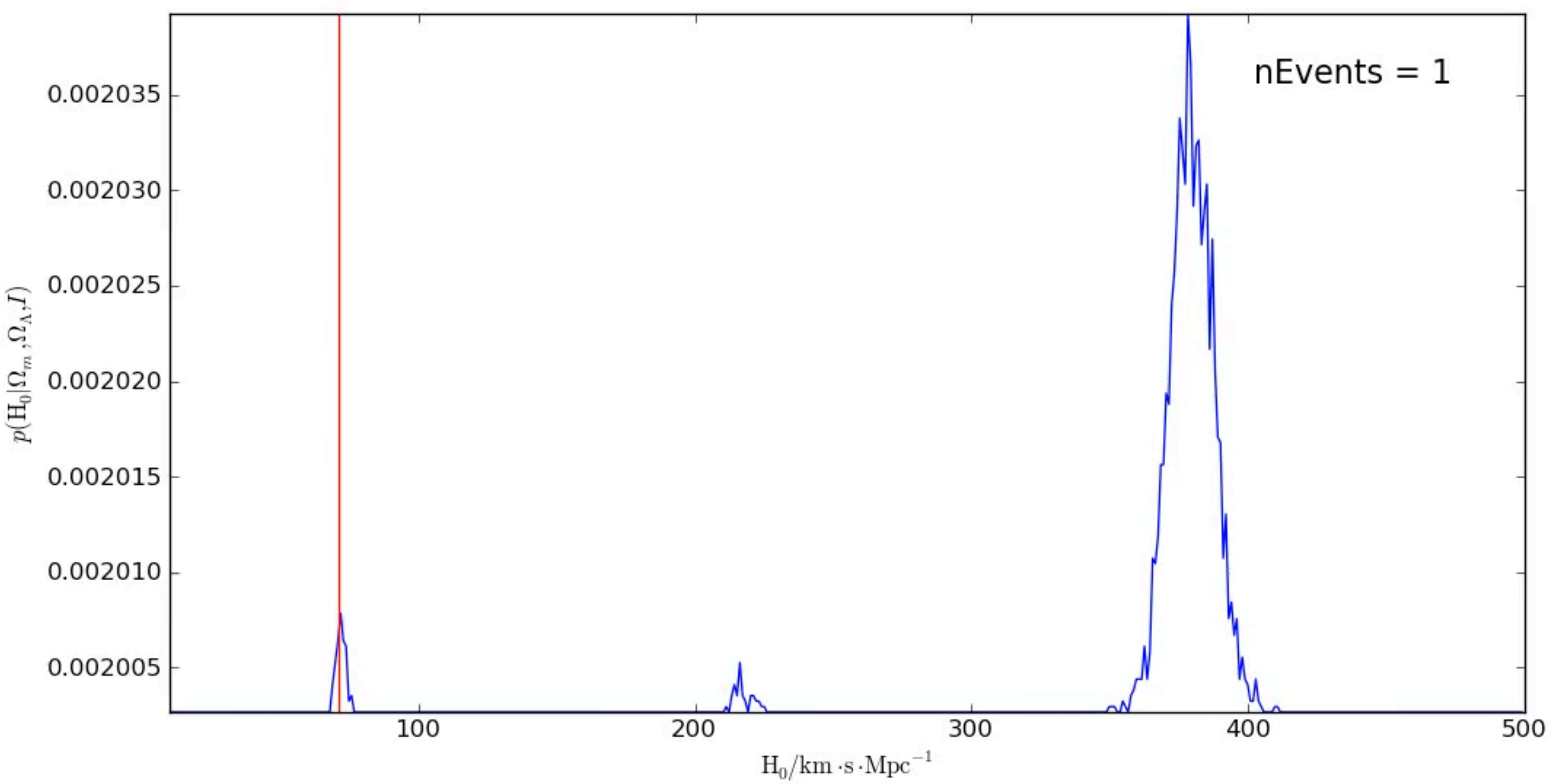
By stacking together the results from many events, the values given by the spurious galaxies cancel out and the true cosmological parameters emerge



Credit: W. Del Pozzo

[Schutz, *Nature* (1986)]
[Gray+, *PRD* (2020)]
[Muttoni+, arXiv (2023)]

Standard sirens

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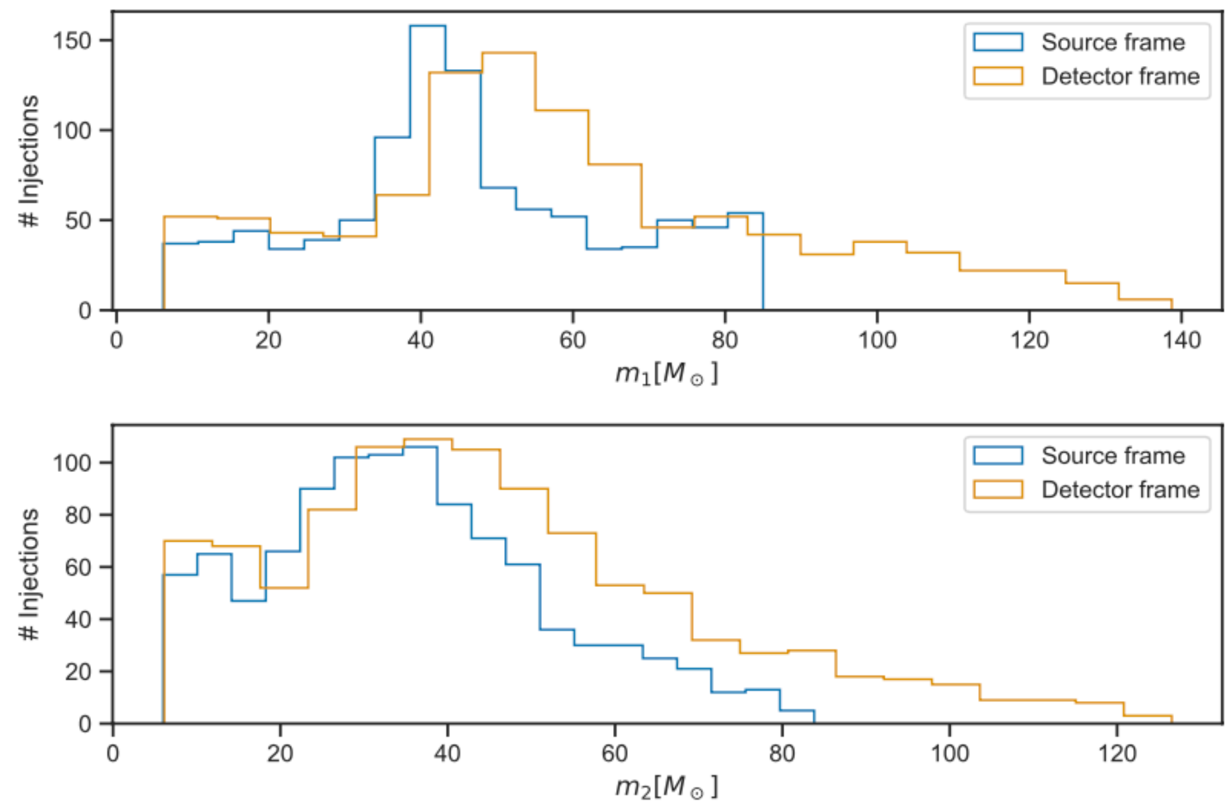
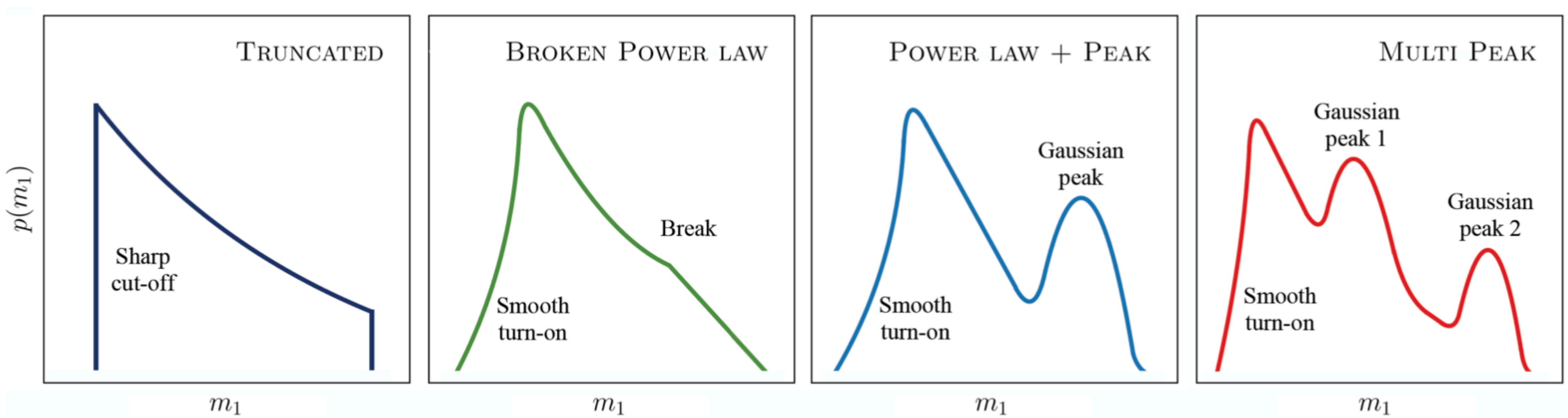
$$m_{\rm obs} = (1+z)m_{src}$$





[Taylor+, *PRD* (2012)]

[Mastrogiovanni+, *PRD* (2021)]

Standard sirens

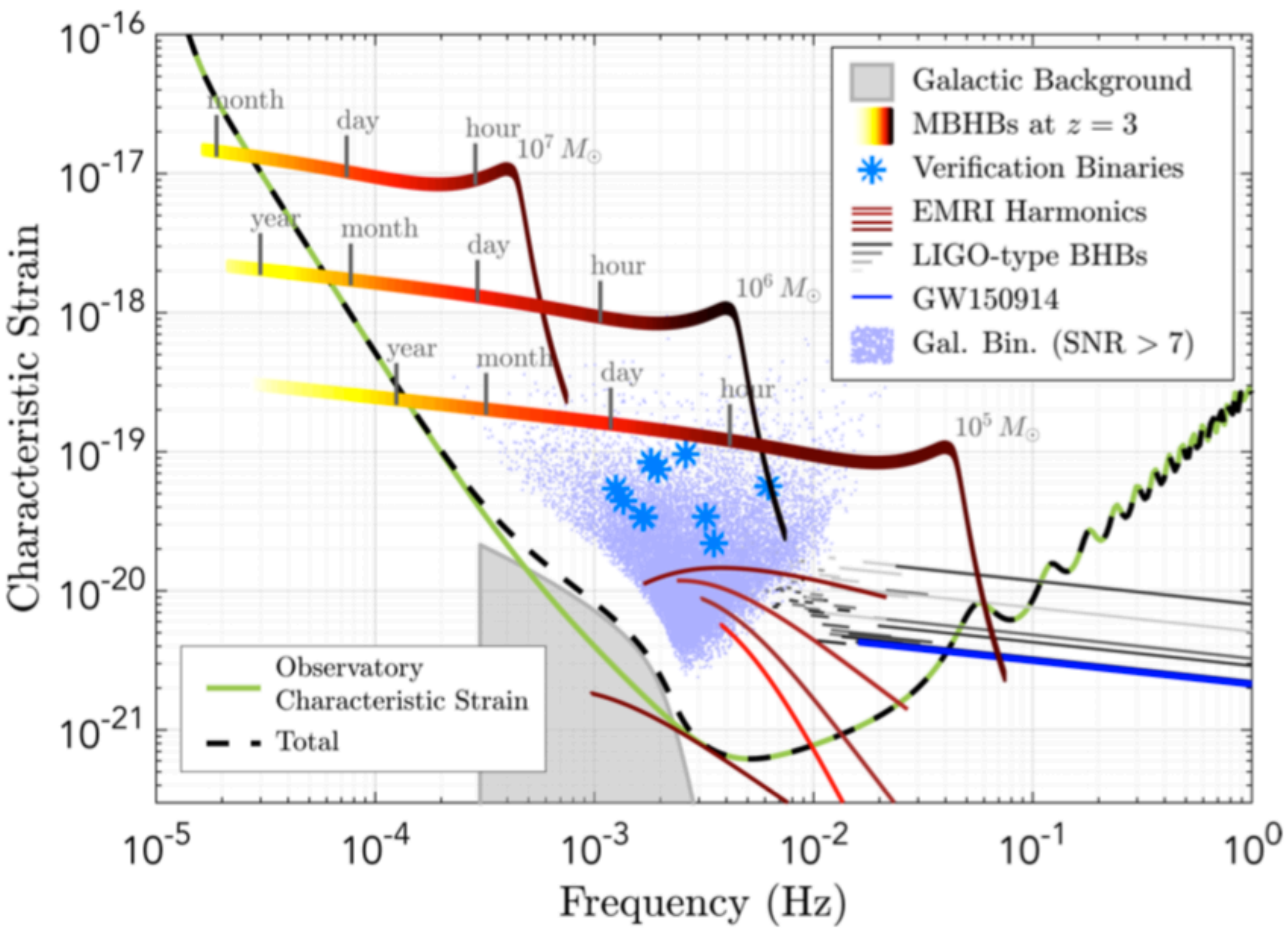
Method	Pros	Cons
EM counterpart	Accurate redshift estimation, golden sirens	Infrequent and rare events, tentative associations
Galaxy catalogs	Available even for BBHs, several EM bands to check consistency	Less and less incomplete, less constraining for poorly localized events
Clustering	No EM counterpart needed, more efficient for poorly localized events	Needs to know the dark matter density field. Incompleteness issue
Quadruple lensing	Provides 4 bright golden sirens at the price of one.	Could be rare events and lensing follow-up could be difficult
Source-frame mass	No needs of EM counterparts, can fit conjointly cosmology and astrophysics	Needs to be driven by some astrophysical expectation
Rate evolution	As above	As above
Tidal deformation	No need of EM counterpart, detectable from the waveform.	Needs to obtain a Universal EOS from few calibrators

Curtesy of S. Mastrogiovanni

Standard sirens with LISA: Late-universe cosmology

Standard sirens with LISA

Laser Interferometer Space Antenna



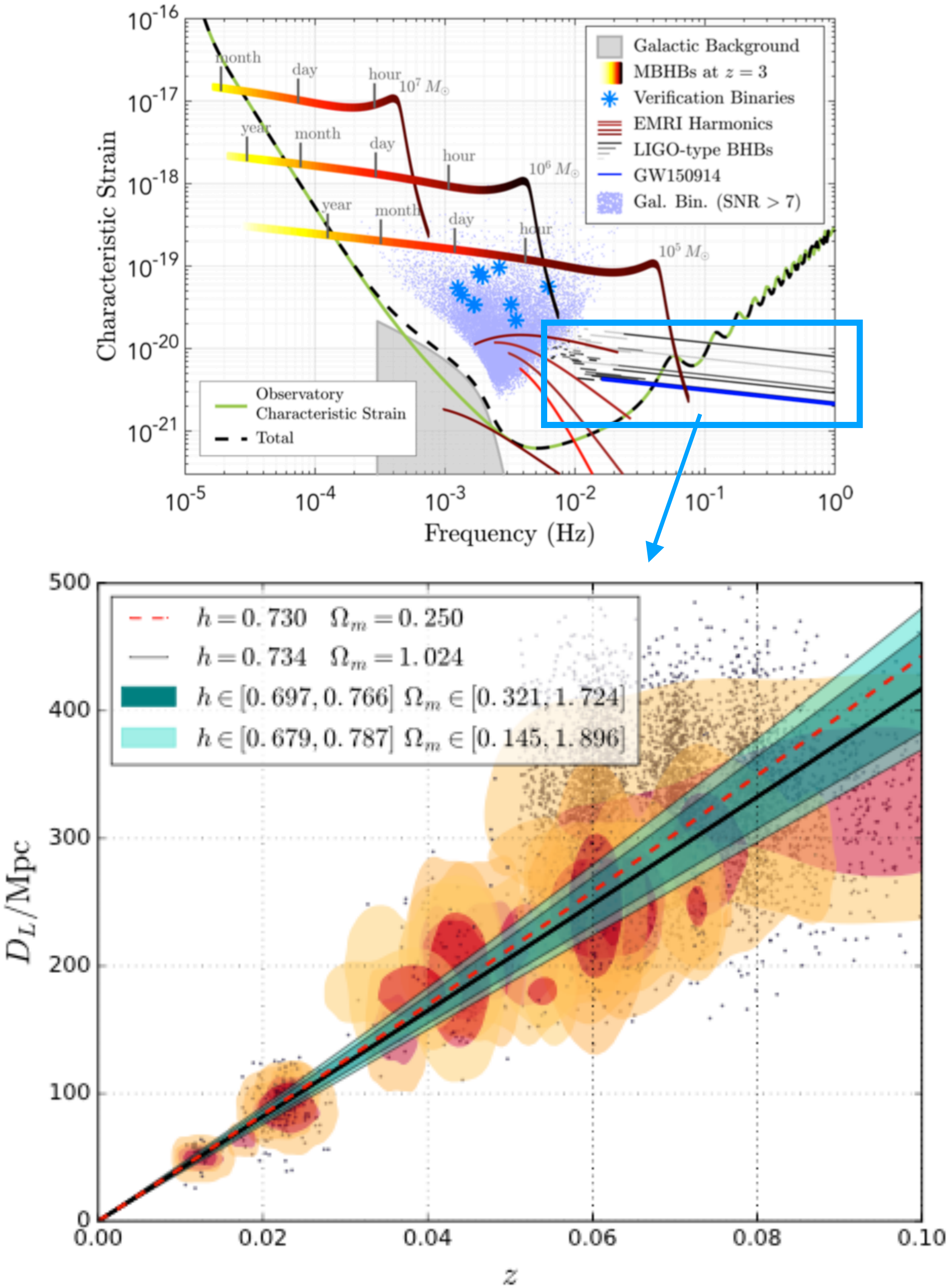
[LISA, *ArXiv* (2017)]

Standard siren sources:

- Stellar-mass BBHs $(10 - 100\,M_\odot)$
- Extreme mass ratio inspirals (EMRIs)
- MBHBs $(10^4 - 10^7\,M_\odot)$
- Intermediate-mass BBHs? ($\gtrsim 100\,M_\odot$)

*EM counterparts expected

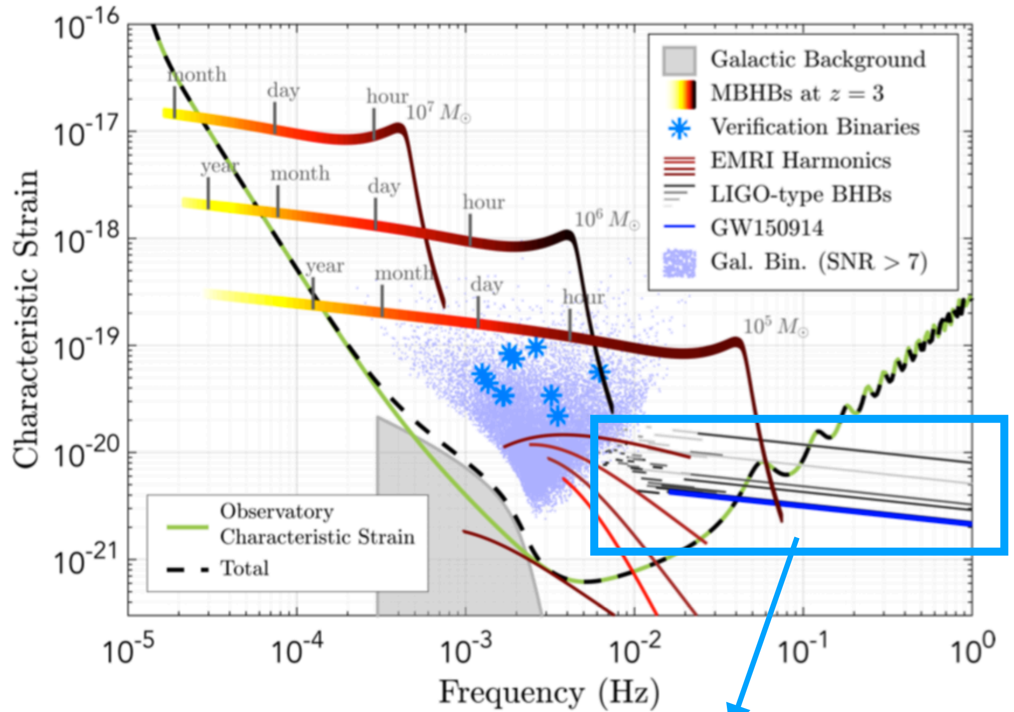
Stellar-mass BHBs

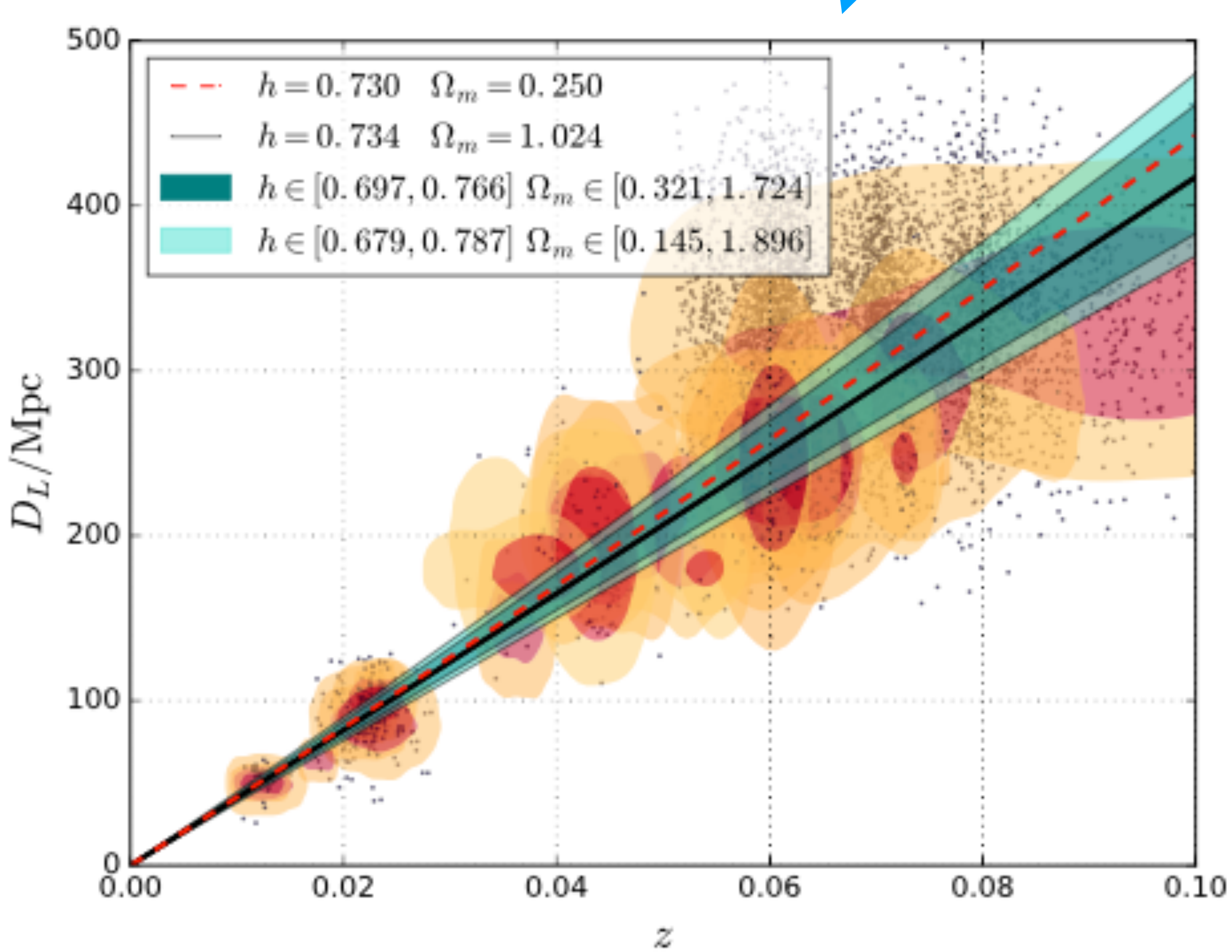


- Redshift range: $z \lesssim 0.5$
- No EM counterparts expected
- LISA detections: ~50/yr (optimistic)
- Useful as standard sirens:
  - $z \lesssim 0.1$
  - If $\Delta d_L / d_L < 0.2$
  - If $\Delta\Omega \sim 1 \text{ deg}^2$
  - $\Rightarrow$ ~ 5 standard sirens / yr
- **Expected results:**
  - H_0 to few % (very optimistic - depend on LISA high-f sensitivity)

[Kyutoku & Seto, *PRD* (2017)]
[Del Pozzo+, *MNRAS* (2018)]

Stellar-mass BHBs

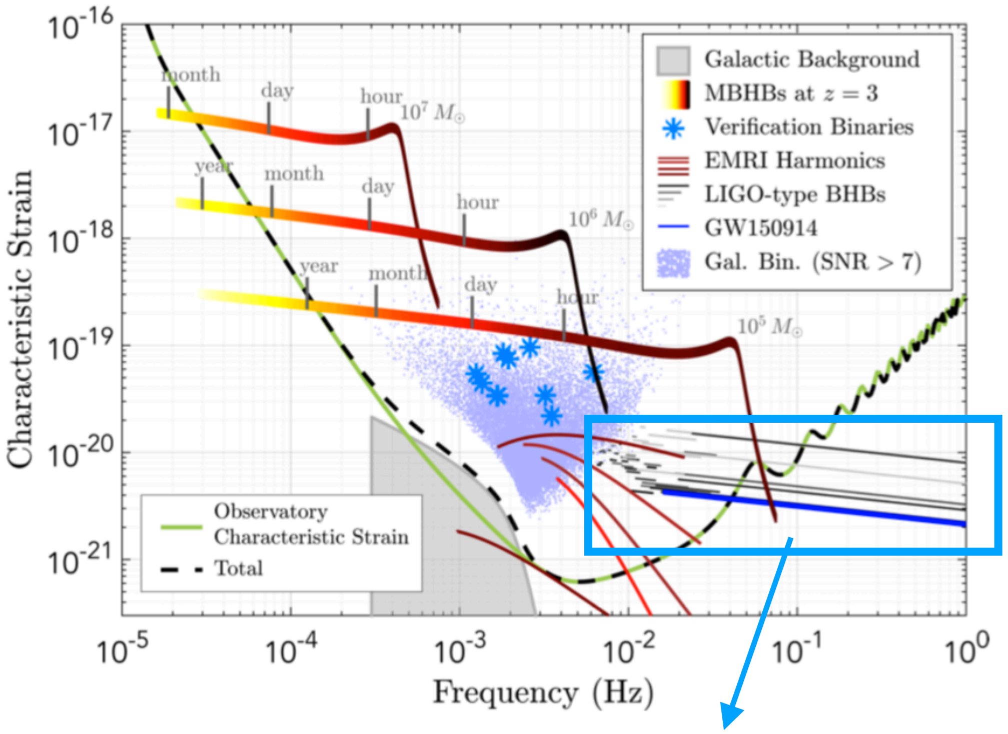


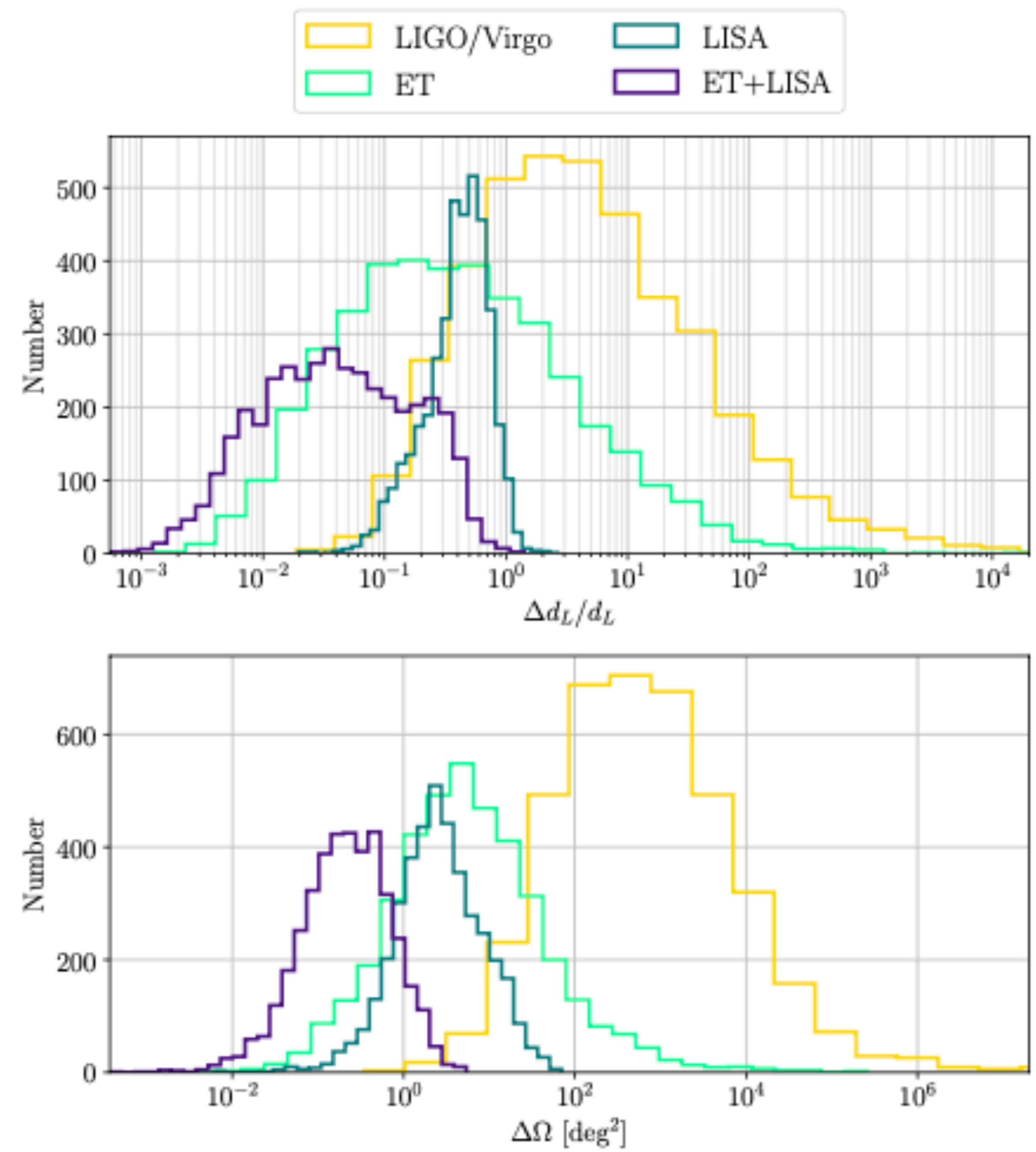


- Redshift range: $z \lesssim 0.5$
- No EM counterparts expected
- LISA detections: ~~~50/yr (optimistic)~~
  ~few/yr
- Useful as standard sirens:
  - $z \lesssim 0.1$
  - If $\Delta d_L / d_L < 0.2$
  - If $\Delta\Omega \sim 1\ \mathrm{deg}^2$
  - $\Rightarrow$ ~~~ 5 standard sirens / yr~~
    ~0.1 standard sirens / yr
- **Expected results:**
  - ~~H_0 to few %~~
    H_0 not measured

[Kyutoku & Seto, *PRD* (2017)]
[Del Pozzo+, *MNRAS* (2018)]

Stellar-mass BHBs



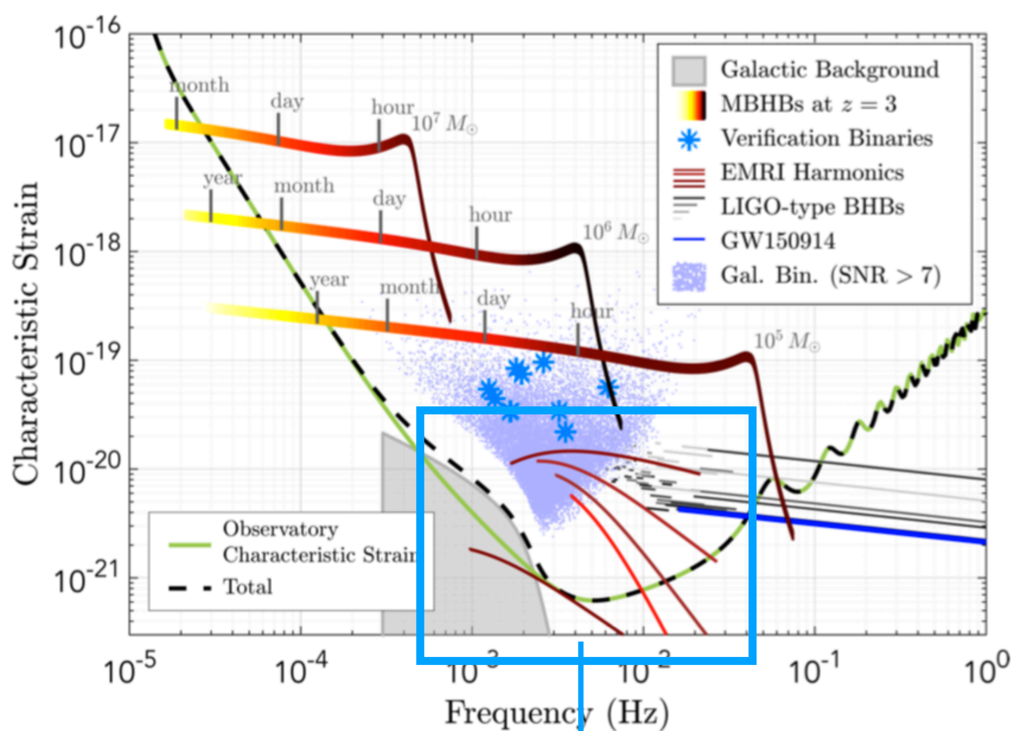


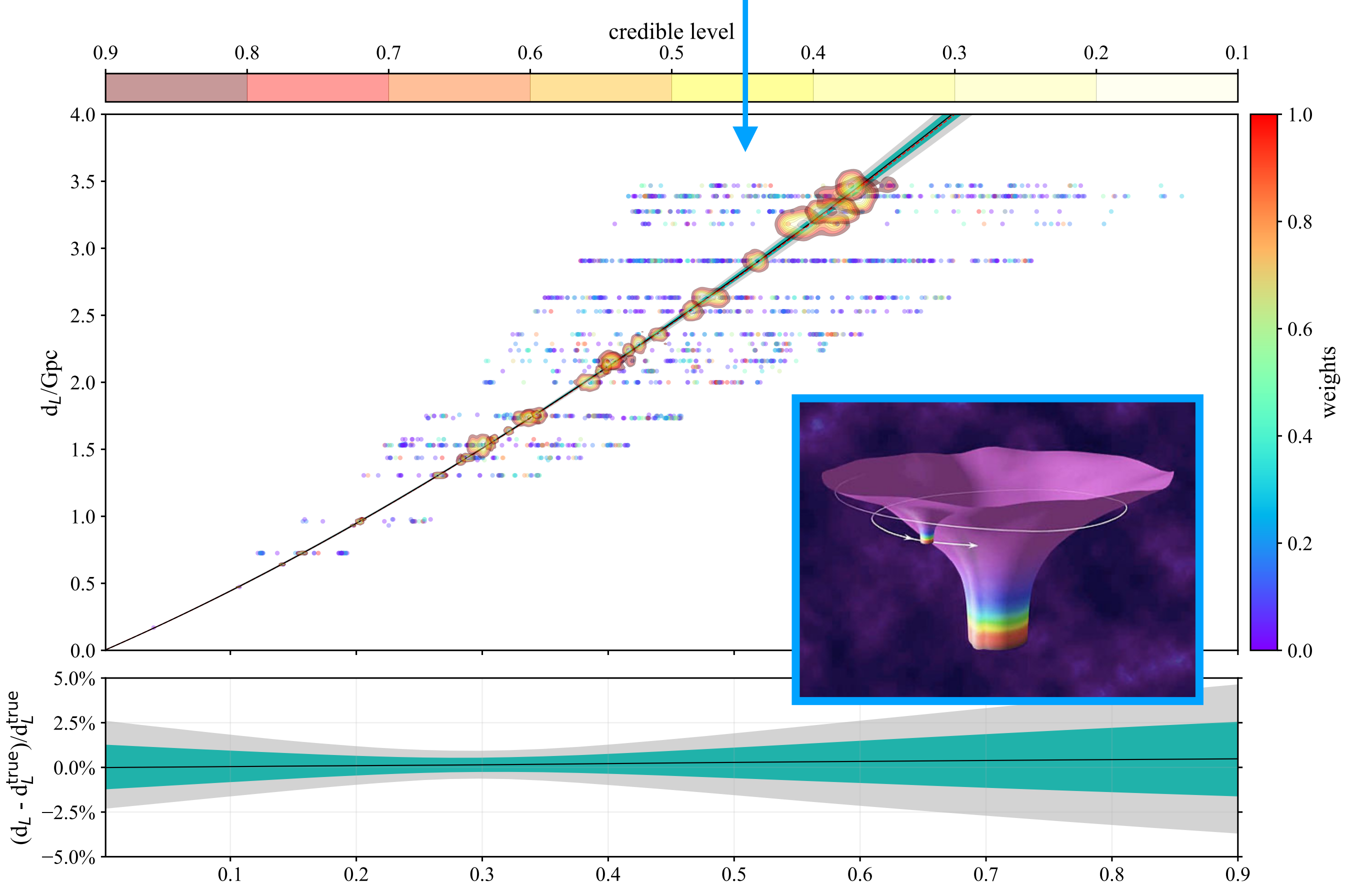
Stellar-mass BHs (and IMBHs) can also be used in **multi-band analyses** since their merger can be observed by ground-based detectors

- **Expected results:**
  - H_0 to few %
    (with IMBHs "above the gap")

[Muttoni+, *PRD* (2022)]

EMRIs

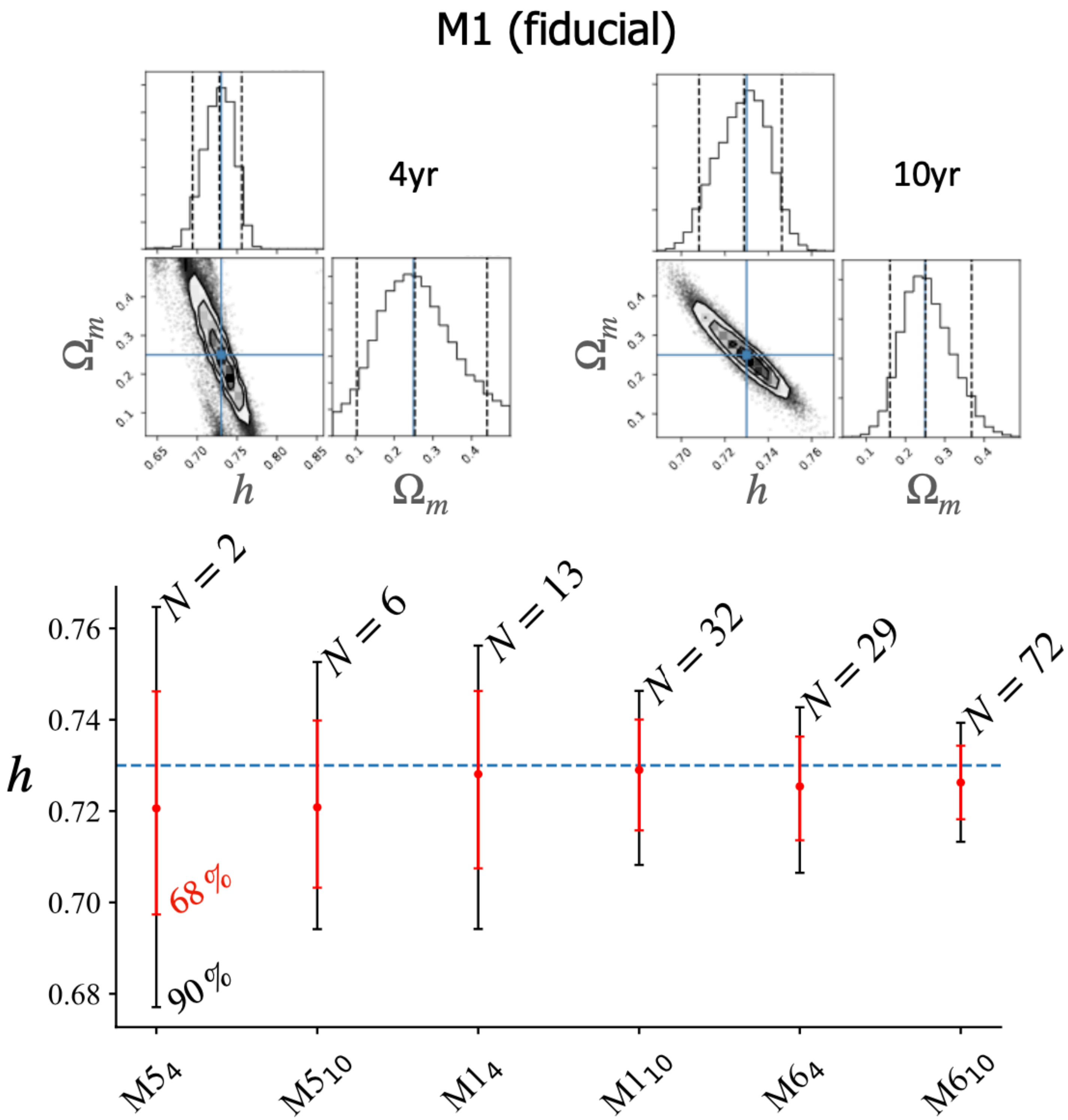




- Redshift range: $0.1 \lesssim z \lesssim 4$
- No EM counterparts expected
- LISA detections: from 1 to 1000/yr
- Useful as standard sirens:
  - $0.1 \lesssim z \lesssim 1$
  - If $\Delta d_L / d_L < 0.1$
  - If $\Delta\Omega < 2\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 1 to 100 standard sirens / yr
- **<u>Expected results:</u>**
  - H_0 between 1 and 10 %
  - w_0 between 5 and 10 %

[MacLeod & Hogan, *PRD* (2008)]
[Babak+, *PRD* (2017)]
[Laghi+, *MNRAS* (2021)]

EMRIs



Laghi et al., *MNRAS* (2021)

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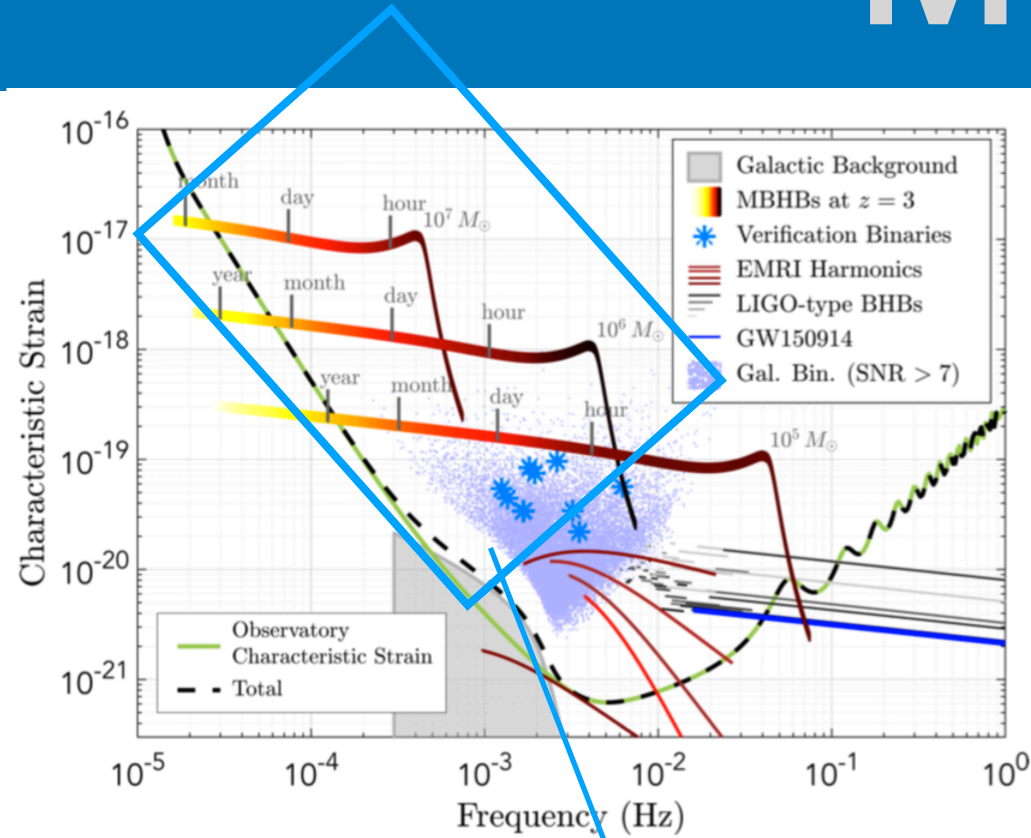
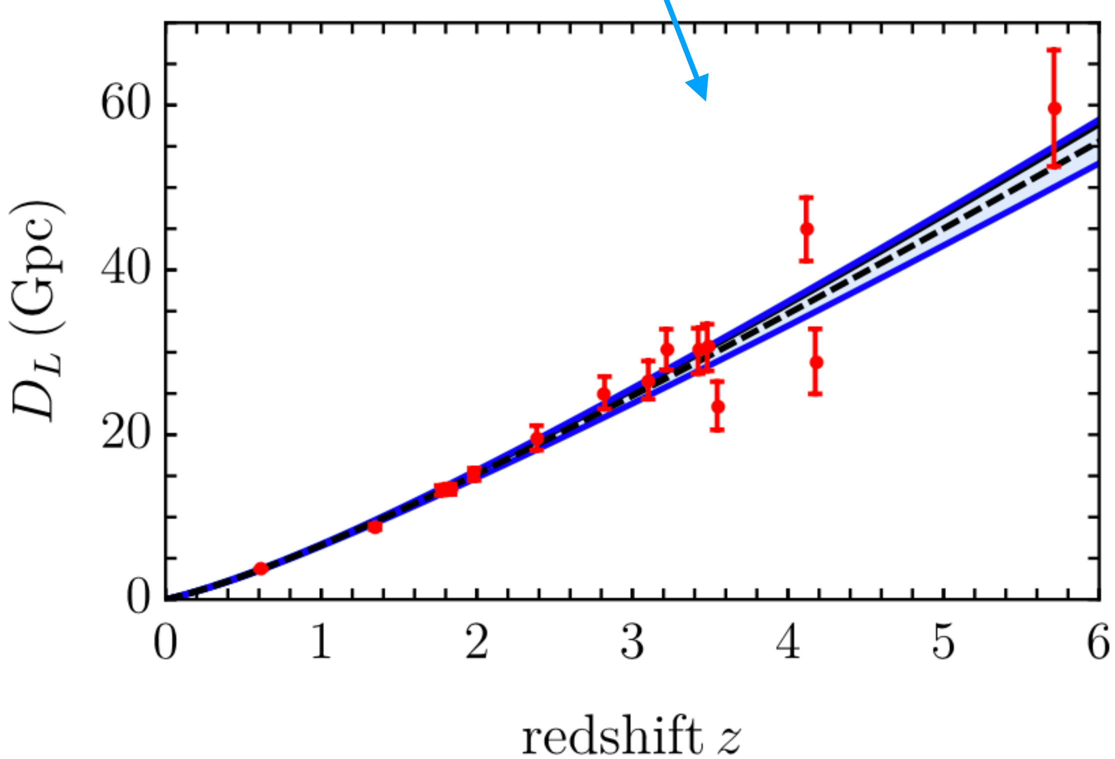
MBHBs





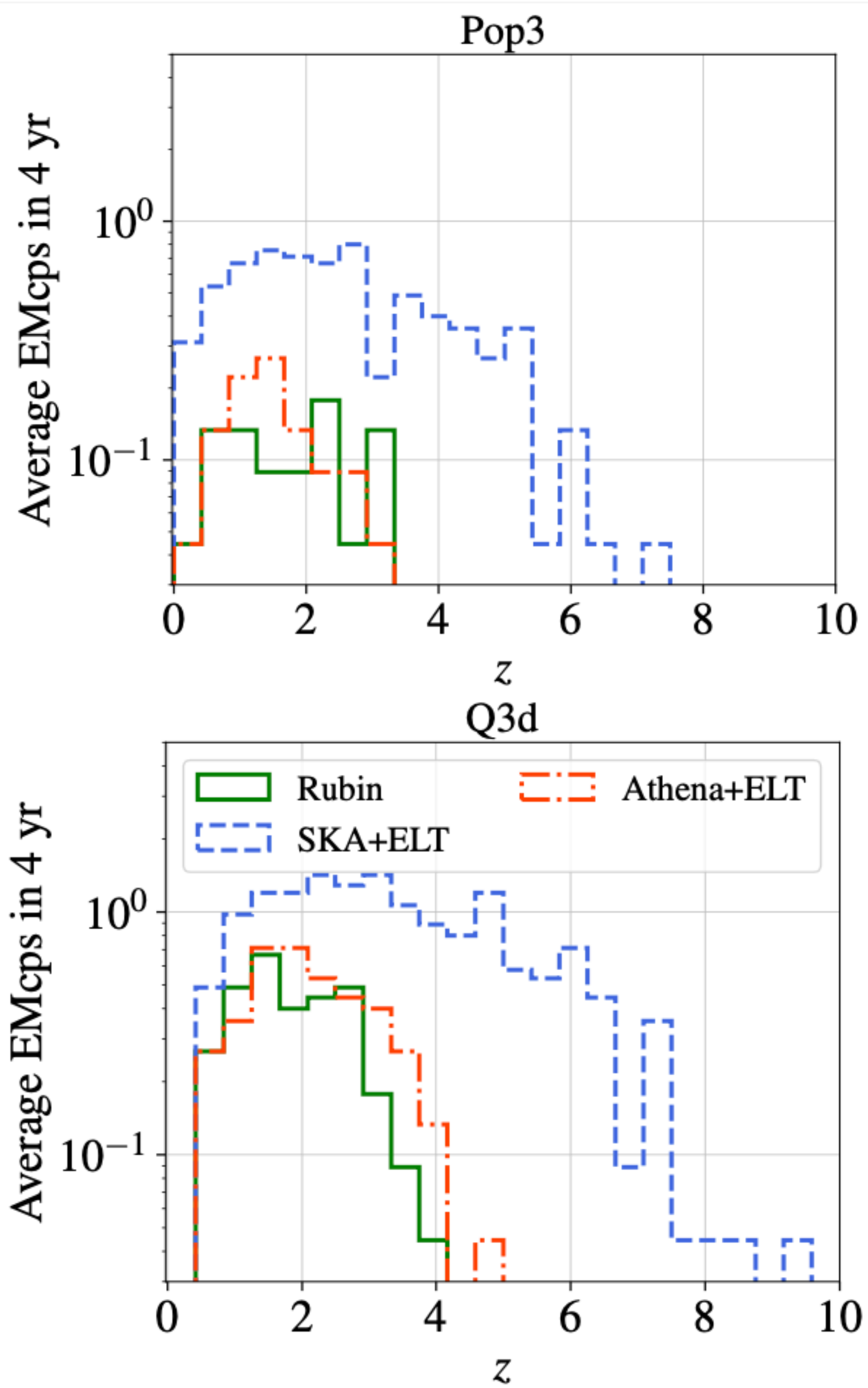
- Redshift range: $z \lesssim 20$
- EM counterparts expected
- LISA detections: 1 to 100/yr
- Useful as standard sirens:
  - $z \lesssim 7$
  - If $\Delta d_L / d_L \lesssim 0.1$ (include lensing)
  - If $\Delta\Omega < 10 \text{ deg}^2$
  - $\Rightarrow$ ~ 3 standard sirens / yr (with EM counterpart)
- **Expected results:**
  - H_0 to few %
  - “Precise” high-z cosmography

[Tamanini+, *JCAP* (2016)]
[Mangiagli+, *in prep*]

[Speri+, *PRD* (2021)]

MBHBs

(In 4 yr)	Standard	w Obsc./Colli. radio
Light	6.4	1.6
Heavy	14.8	3.3
Heavy-no-delays	20.7	3.5



[Mangiagli+, *PRD* (2022)]

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[Mangiagli+, *in prep*]

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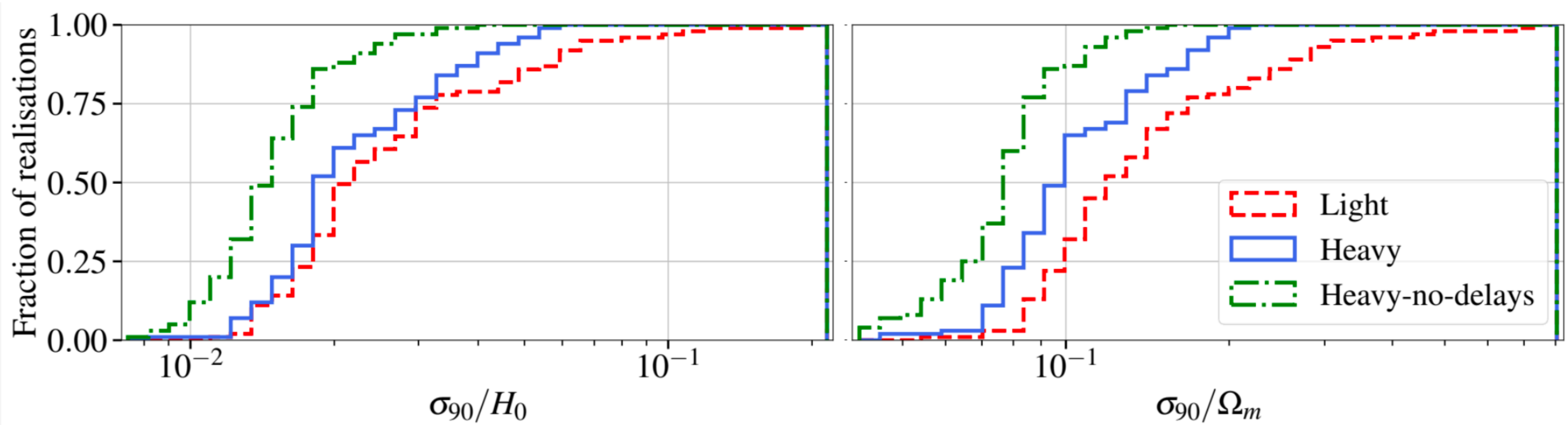
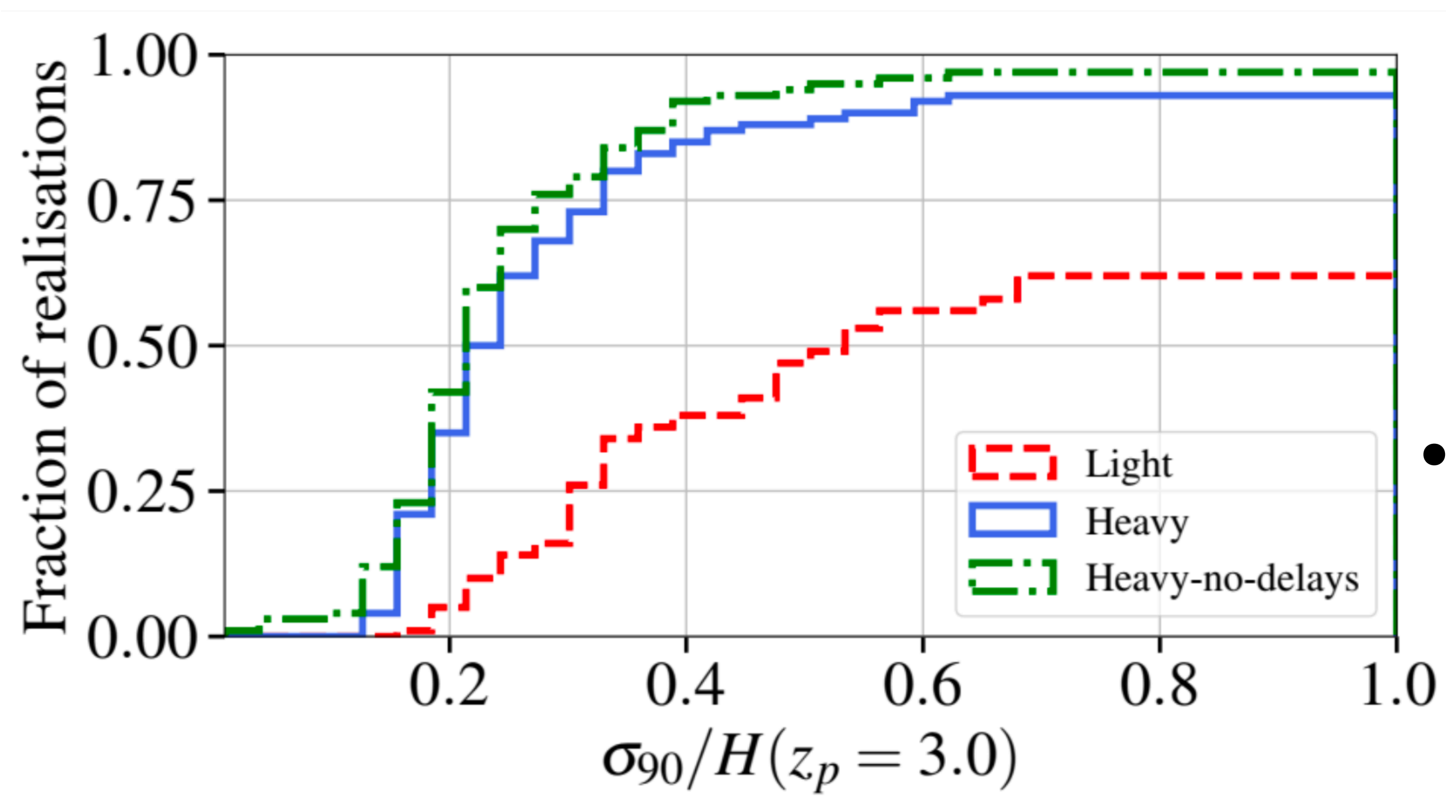




Preliminary!

(10 yr of LISA observation)

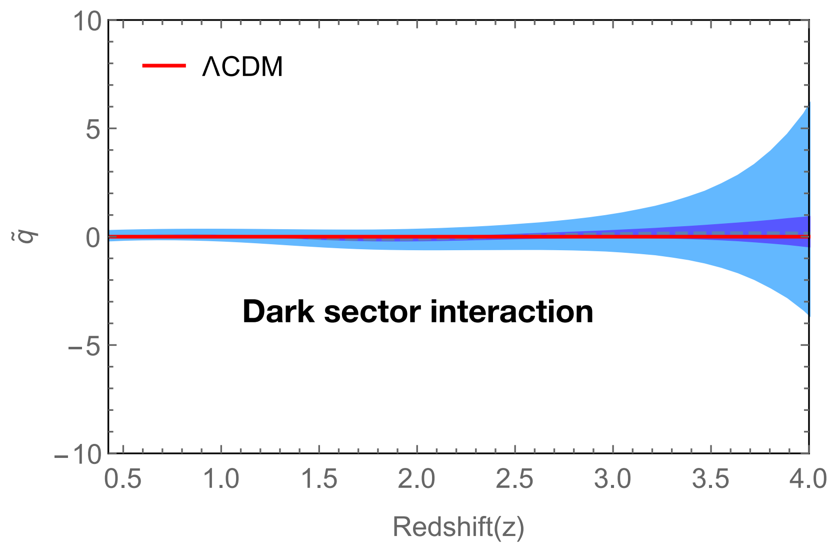
- **Expected results:**
  - H_0 to few %
  - “Precise” high-z cosmography

[Mangiagli+, *in prep*]

Standard sirens with LISA

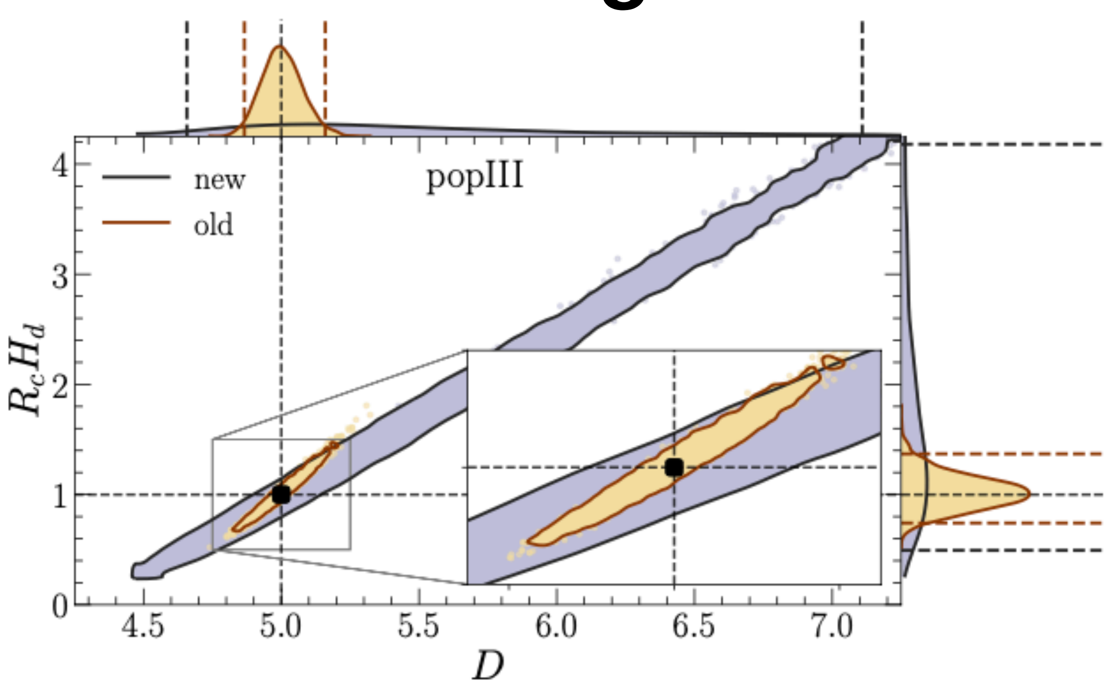
LISA MBHB data will be very useful to probe <u>ΛCDM</u> at high-redshift

Test alternative cosmological models



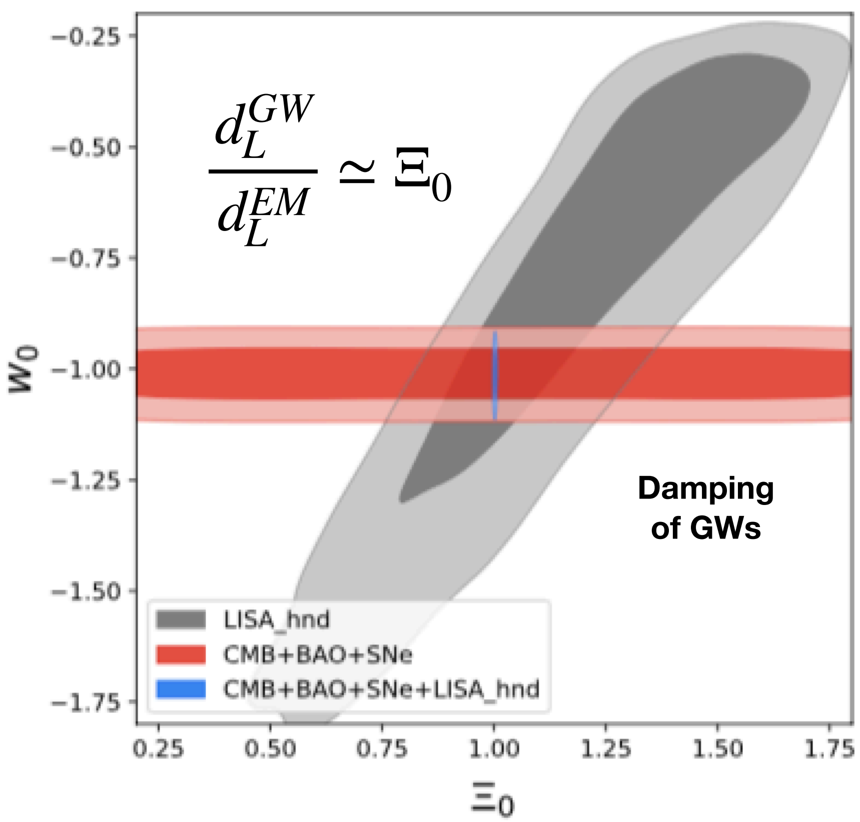
[Caprini & Tamanini, *JCAP* (2016)]
[Cai+, *JCAP* (2017)]

Test cosmological extra-dimensions



[Corman+, *PRD* (2022)]

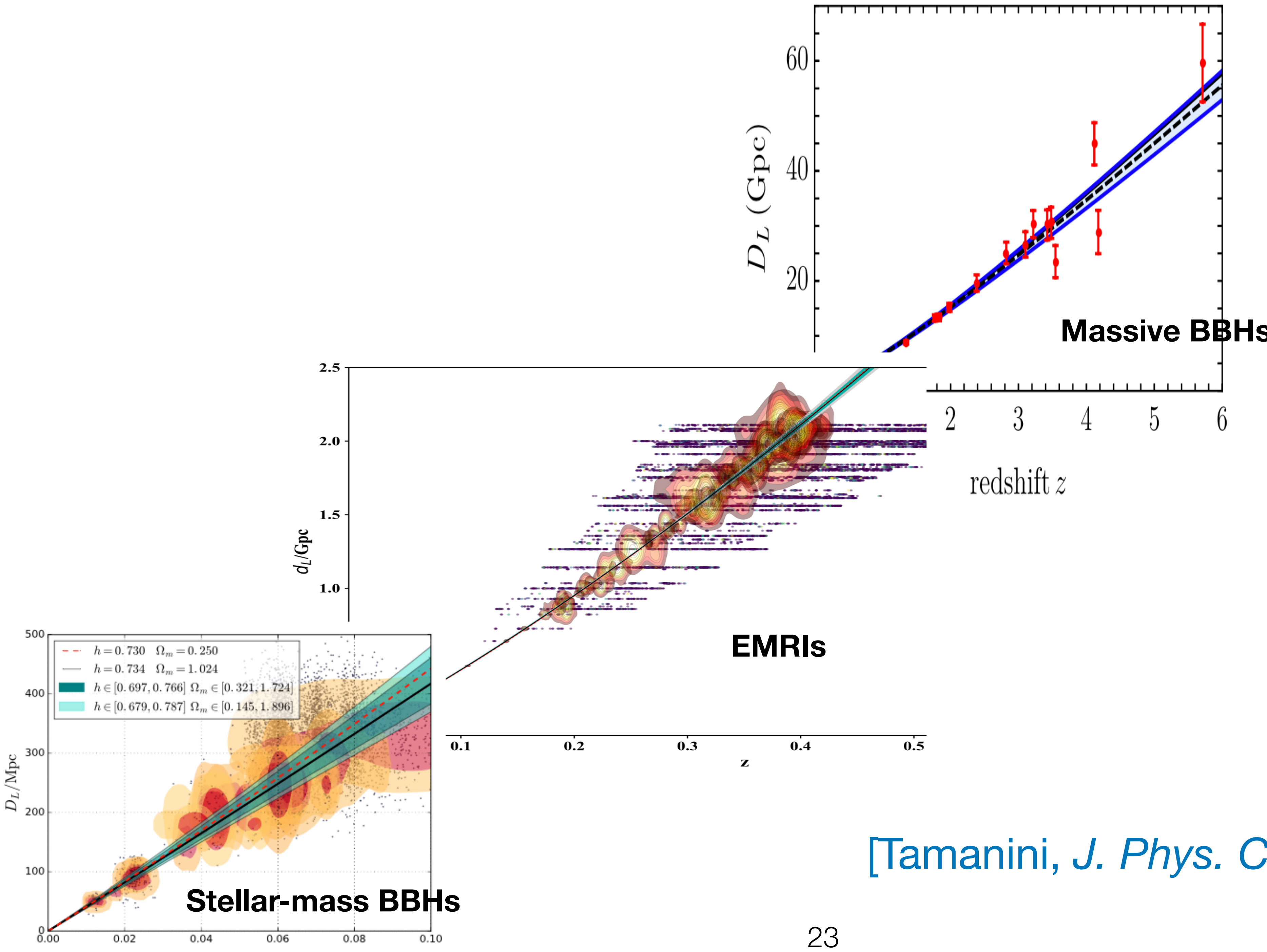
Test modified gravity



[LISA CosmoWG, *JCAP* (2019)]

Standard sirens with LISA

The combination of different standard sirens will allow LISA to measure the expansion of the universe from $z \sim 0.01$ to $z \sim 10$



[Tamanini, *J. Phys. Conf. Ser.* (2017)]

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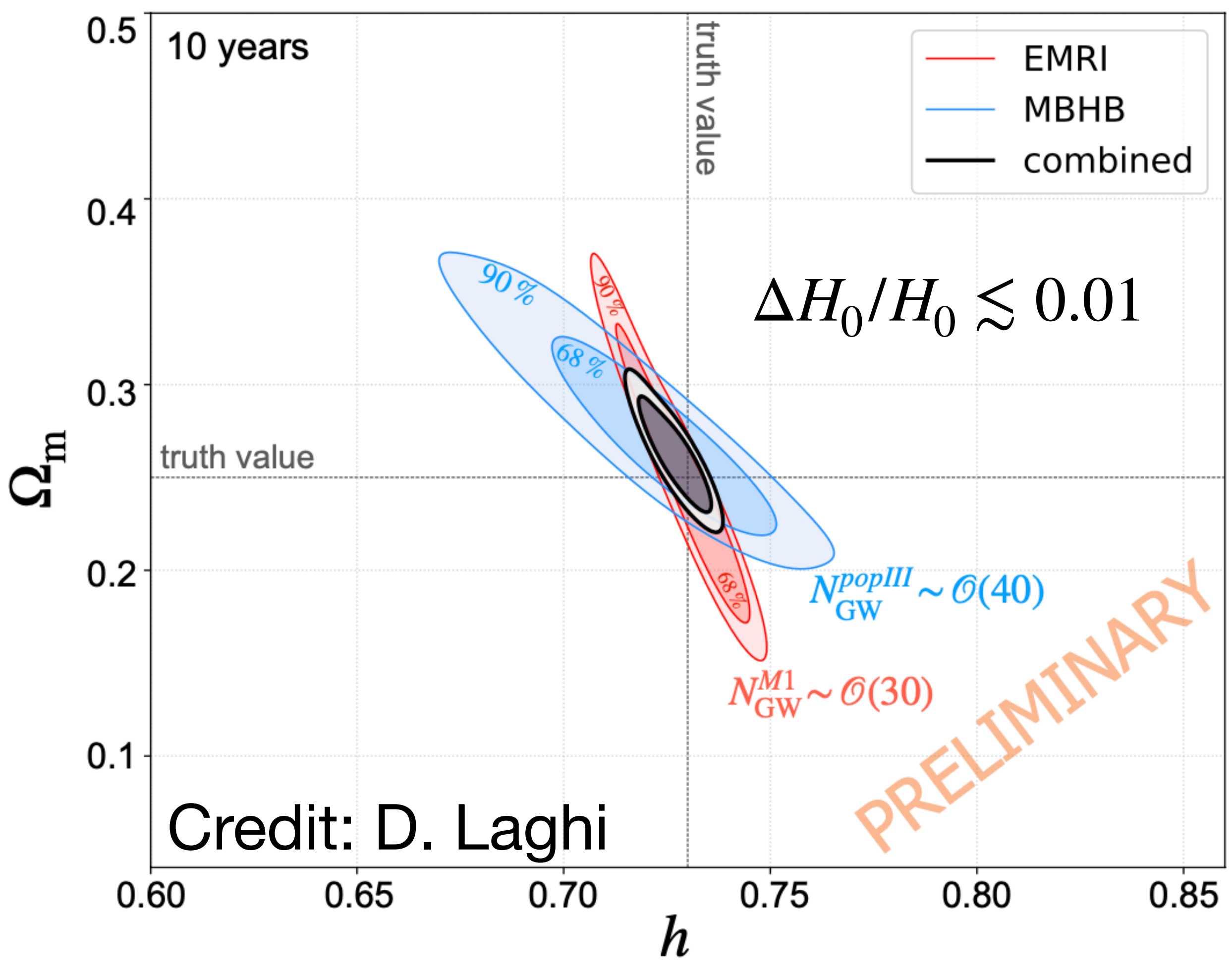
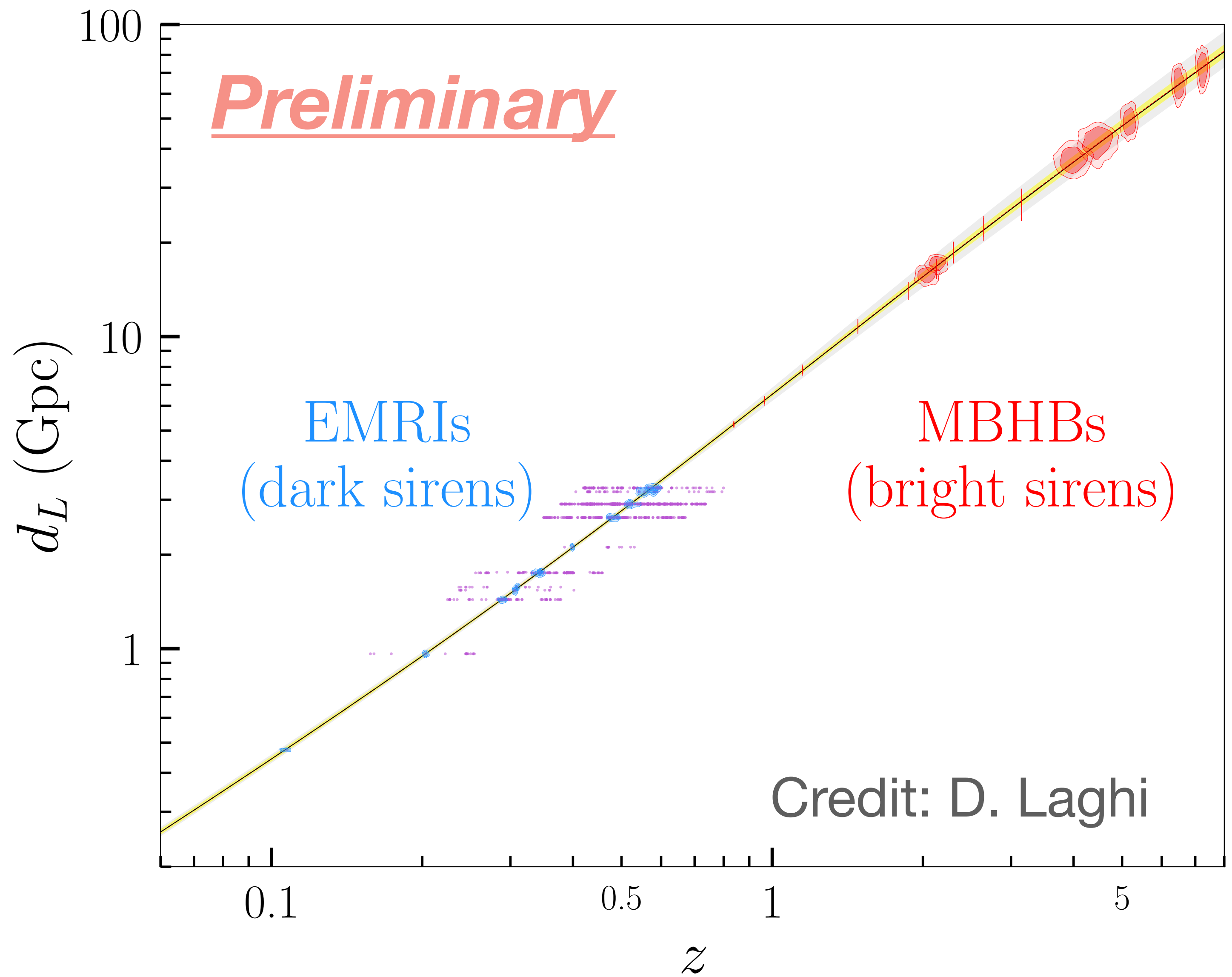
Expected results for ΛCDM:



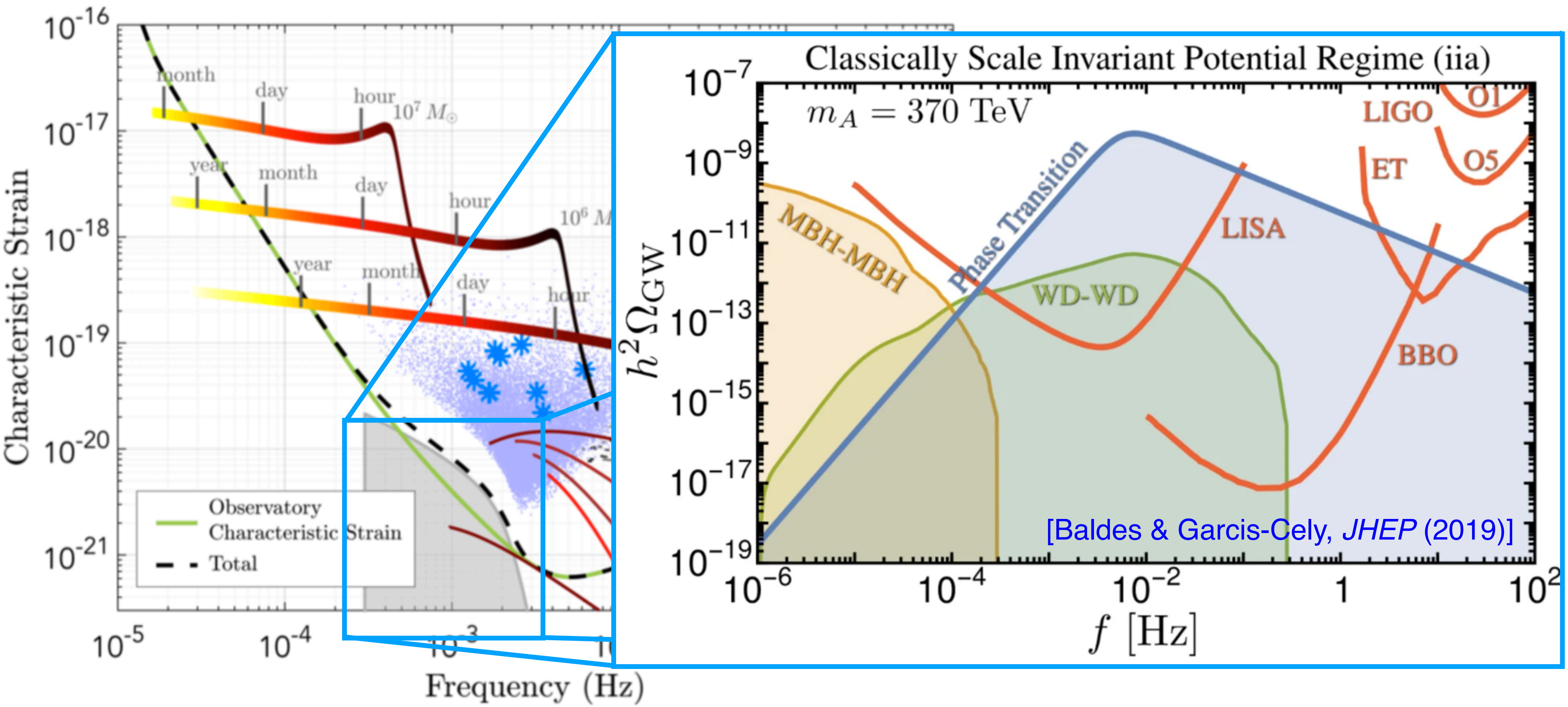


[Tamanini, *J. Phys. Conf. Ser.* (2017)]
[Laghi+, *in prep.* (2023)]

Early universe science with LISA

Early universe science with LISA

LISA can detect stochastic backgrounds of GW of both astrophysical and cosmological origin



[LISA (2017), arXiv:1702.00786]

[Caprini & Figueroa, *CQG* (2018)]

Early universe science with LISA

Possible mechanisms to produce a primordial SBGW:

- Inflation:
  - quantum tensor fluctuations (at first and second order)
  - tensor modes from additional fields (scalar, gauge…)
  - GWs from primordial BHs
  - preheating
  - modifications of gravity
  - …

- Other phase transitions:
  - stable topological defects (in particular strings)
  - *first order* phase transitions
    - bubble wall collisions
    - bulk fluid motion (compressional and vortical)
    - magnetic fields

LISA CosWG White Paper

arXiv:2204.05434

LISA CosWG-22-03

Cosmology with the Laser Interferometer Space Antenna

- 200 authors
- 176 pages
- 1346 references

1. Introduction
2. Tests of cosmic expansion and acceleration with standard sirens
3. Gravitational lensing of gravitational wave signals
4. Constraints on modified gravity theories
5. Stochastic gravitational wave background as a probe of the early universe
6. First order phase transitions
7. Cosmic Strings
8. Inflation
9. Tests of non-standard pre-Big-Bang nucleosynthesis cosmology via the SGWB
10. Primordial black holes
11. Tools/pipelines for the analysis of transient signal data in cosmology
12. Tools/pipelines for the analysis of stochastic gravitational wave background data

Accepted by Liv. Rev. Rel. (2023) !!!

L3 catalogs for cosmology?

Cosmo L3 catalogs

- <u>Basic questions:</u>
  - Do we need/want to produce L3 catalogs for cosmology?
  - Will cosmological analyses be included in the DDPC products? (if yes we'll need cosmological catalogs)
  - Do we need anything more than standard source catalogs? Yes if we need EM information or estimation of section effects
  - What about beyond LCDM/GR analyses?
  - How will we provide information on a possible SGWB? (lessons to be learned from PTA?)
  - What about strong lensing events?

Cosmo L3 catalogs

- Cosmo catalogs main features
  - Need catalogs not relying on any cosmological model
  - Source selection (high SNR, good sky-loc or distance estimate, …)
  - Estimation of selection effects (needed for cosmo/astro population analyses)
  - Need complementary EM information
    - EM counterparts
    - Galaxy catalogs
    - Weak lensing maps

Cosmo L3 catalogs

- Sources for cosmology

  - **MBHBs**: high-z, (de-)lensing, well localised only, EM counterparts, EM galaxy catalogs?
  - **EMRIs**: intermediate-z, (de-)lensing?, well localised only, EM galaxy catalogs
  - **SOBHBs**: low-z, multi-band analyses only?
  - **SGWBs**: distinguishable from noise or astro SGWBs?, what about marginal detection?

Cosmo L3 catalogs

- Needed data
  - **GW**:
    - *Standard cosmology*: distances, sky-loc, masses, …
    - *Cosmology beyond GR/LCDM*: just L1 data?, resampling L2 data?, same problem as TGR analyses?
  - **EM**: redshifts, sky-loc, galactic masses/luminosities, weak lensing maps, information on orbital inclination?, …
    - Which to use? Where to get them? Who to ask?
    - Strong synergy with *DDPC WP "External Data"* (L2IT/IRAP)