Cosmology with gravitational wave standard sirens: current results and future prospects

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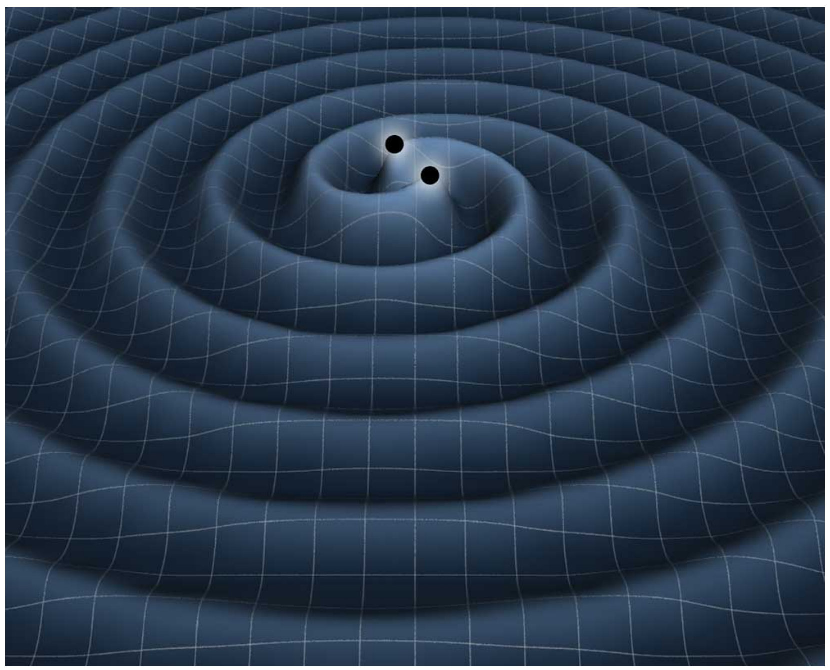
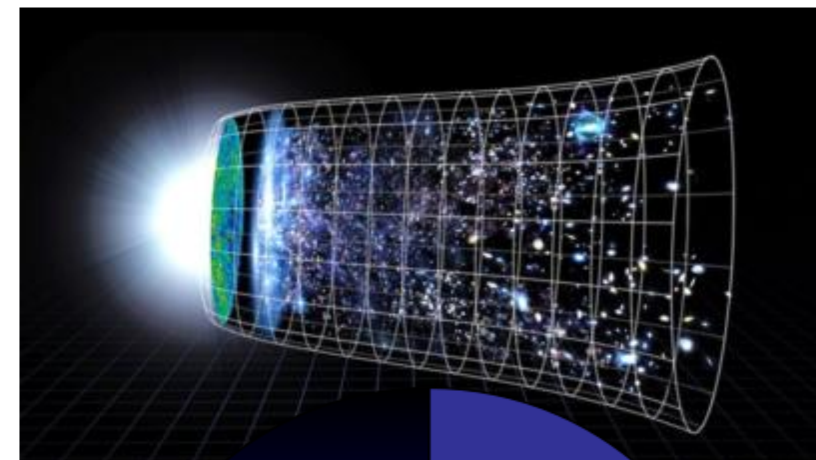
Outline

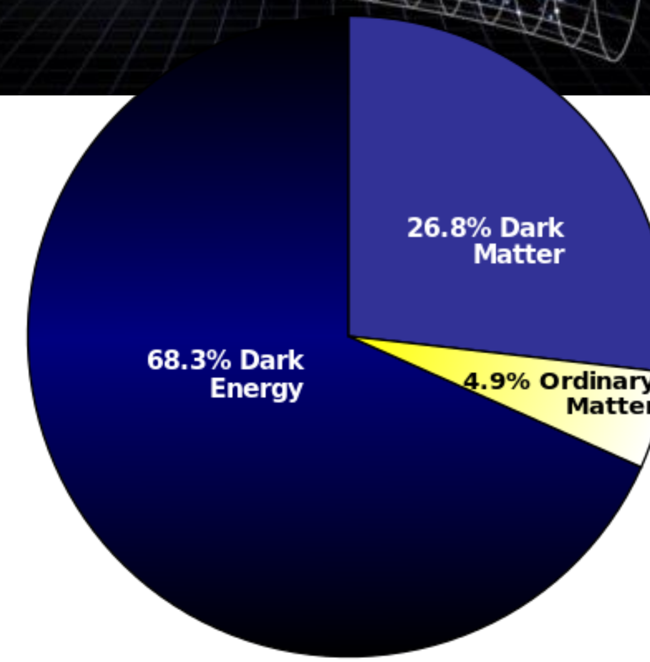
How can we use GW observations to probe the cosmic expansion?



Standard

Sirens





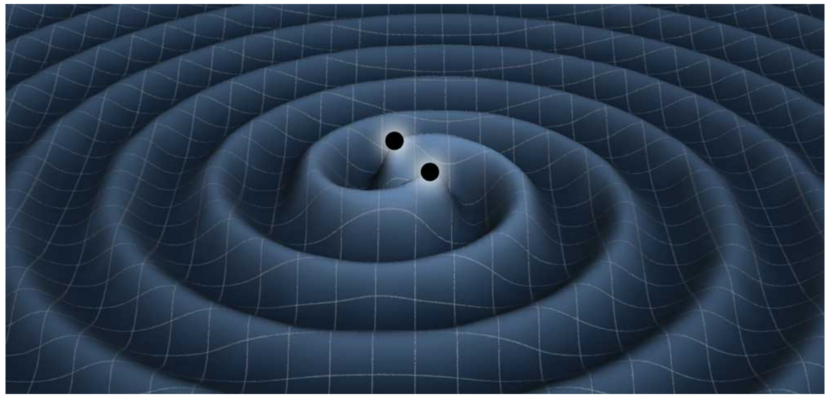
Outline:

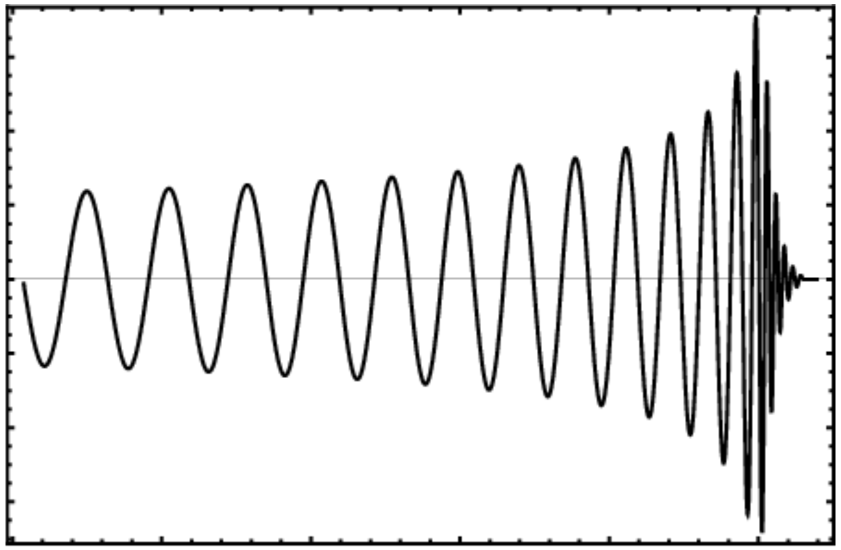
- **What are standard sirens?**
- **Current results from LIGO/Virgo**
- **Forecasts for ground-based detectors**
- **Forecasts for LISA**

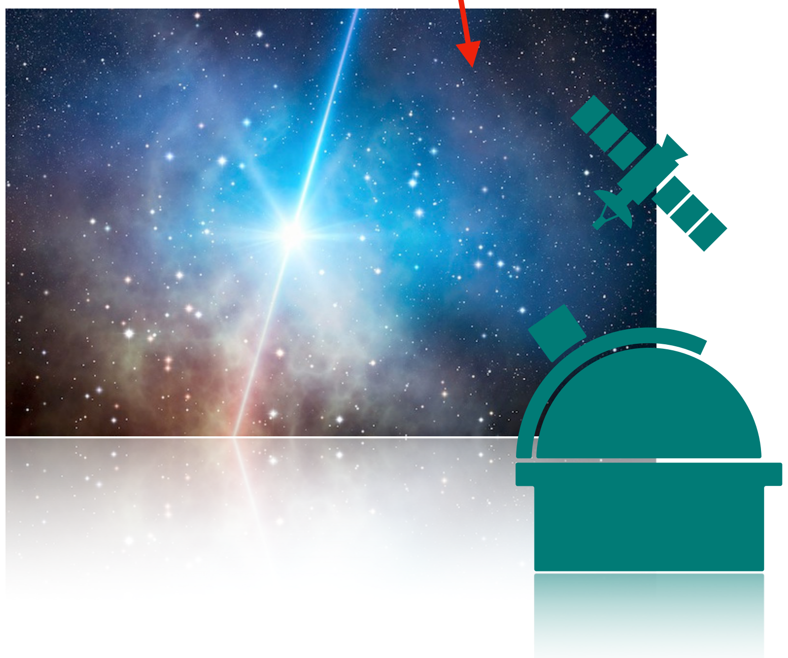
What are standard sirens?

<u>Standard sirens</u> are GW events that can be used as absolute cosmological distance indicators

- **Luminosity distance** estimated from GW signal
- **Redshift** obtained from EM observations







$$h_\times = \frac{4}{d_L}\left(\frac{GM_c}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi f}{c}\right)^{\frac{2}{3}}\cos\iota\sin\Phi(t)$$

[Schutz, *Nature* (1986)]

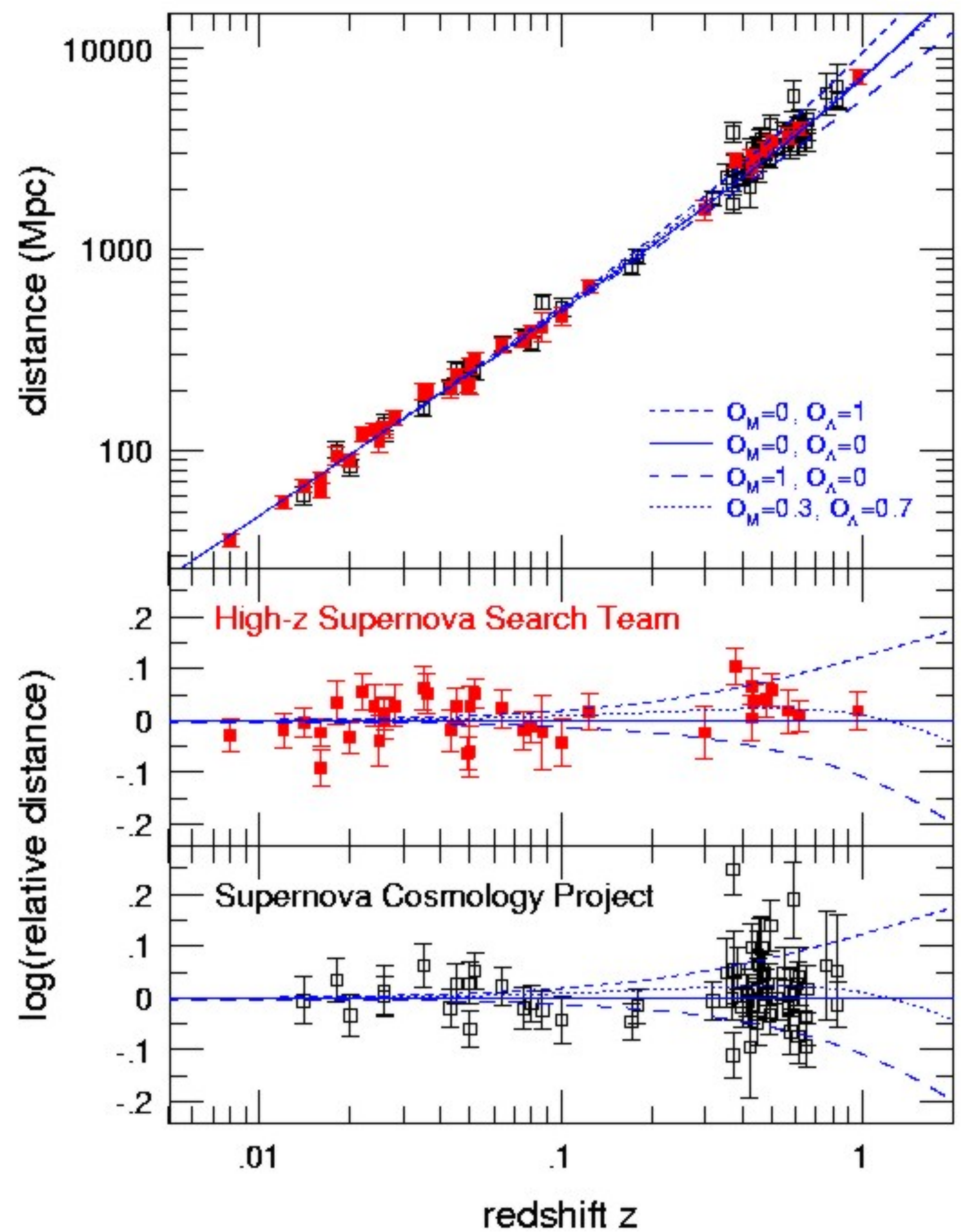
What are standard sirens?

<u>Standard sirens</u> are GW events that can be used as absolute cosmological distance indicators

- **Luminosity distance** estimated from GW signal
- **Redshift** obtained from EM observations

With these two measurements one can then fit the **distance-redshift relation** and obtain constraints on the **cosmological parameters** (similarly to *standard candles* ⇒ type-Ia SNs)

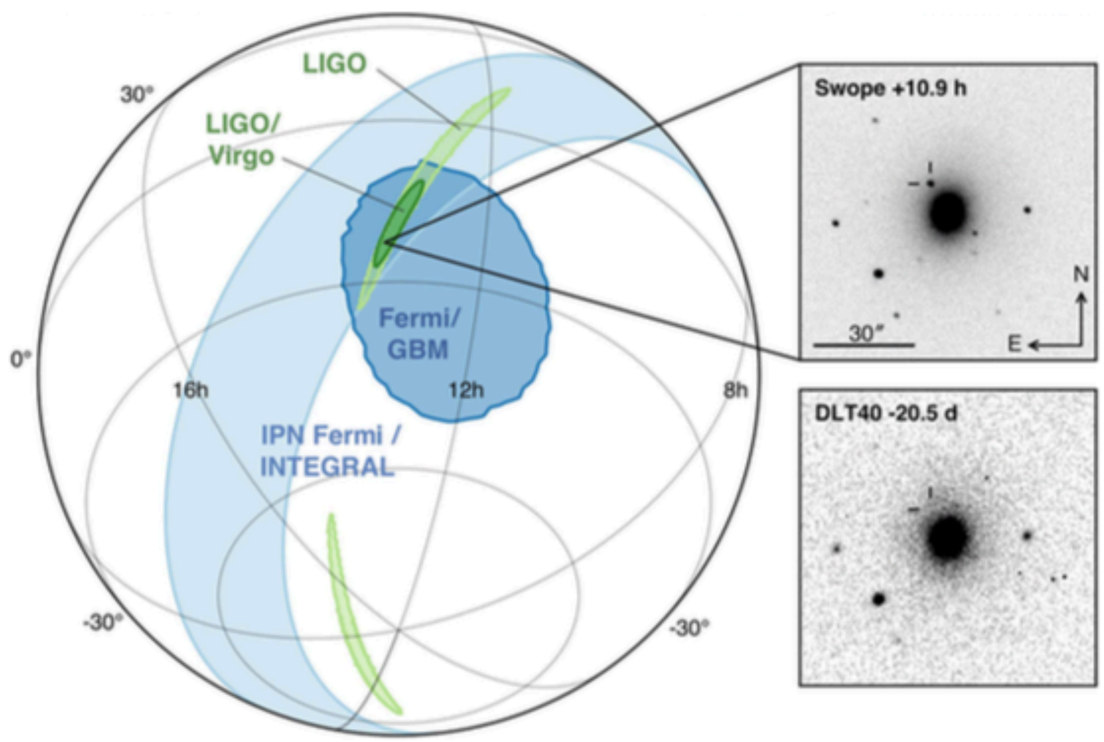
$$d_L(z) = \frac{c}{H_0}\frac{1+z}{\sqrt{\Omega_k}}\sinh\left[\sqrt{\Omega_k}\int_0^z \frac{H_0}{H(z')}dz'\right]$$

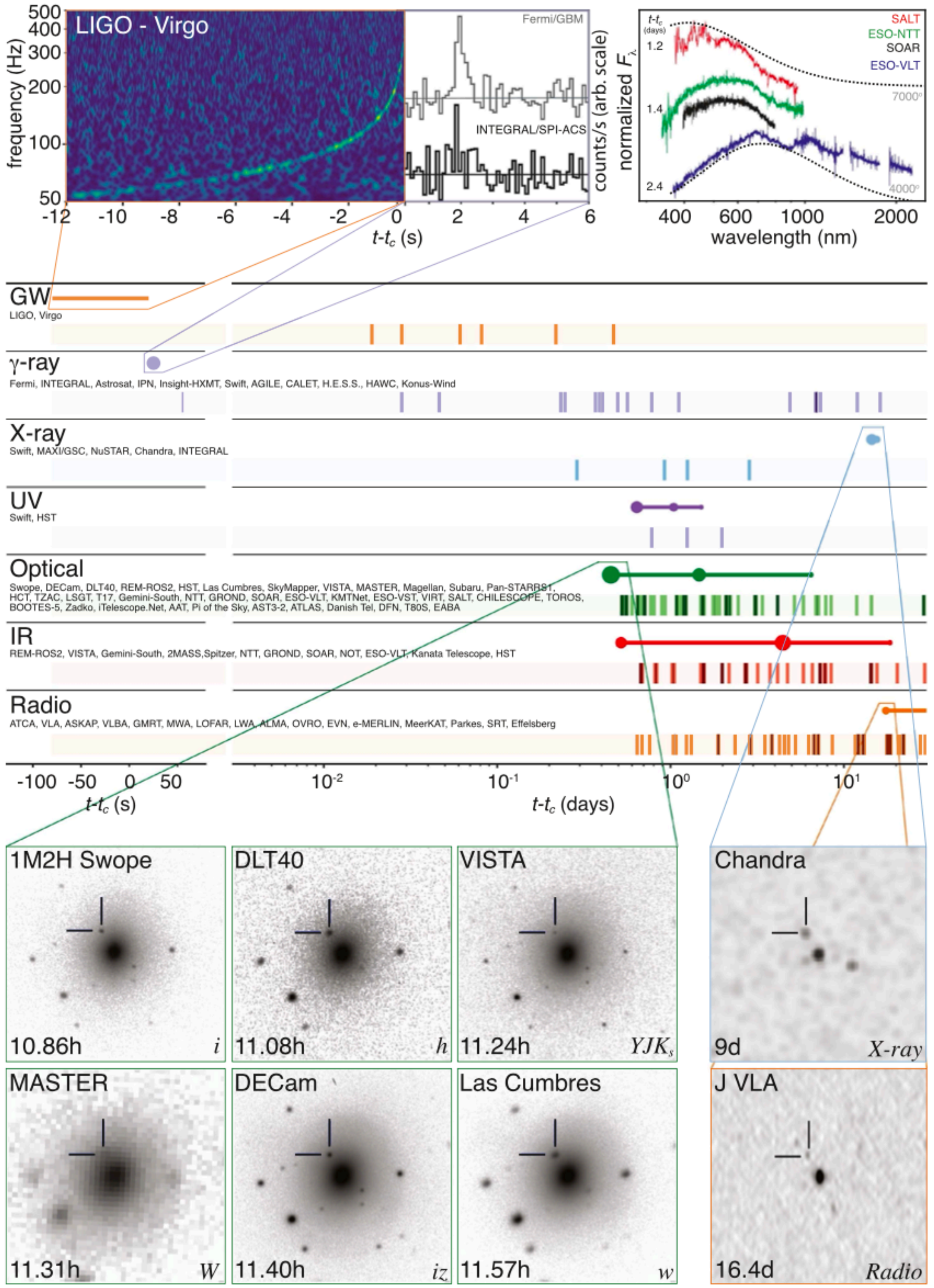


How to get redshift information

Two main approaches to obtain redshift information:

- Identify the host galaxy through a (transient) EM counterpart
- Cross-correlate sky position with galaxy catalogs





Example: GW170817 [LVC+, *ApJL* (2017)]

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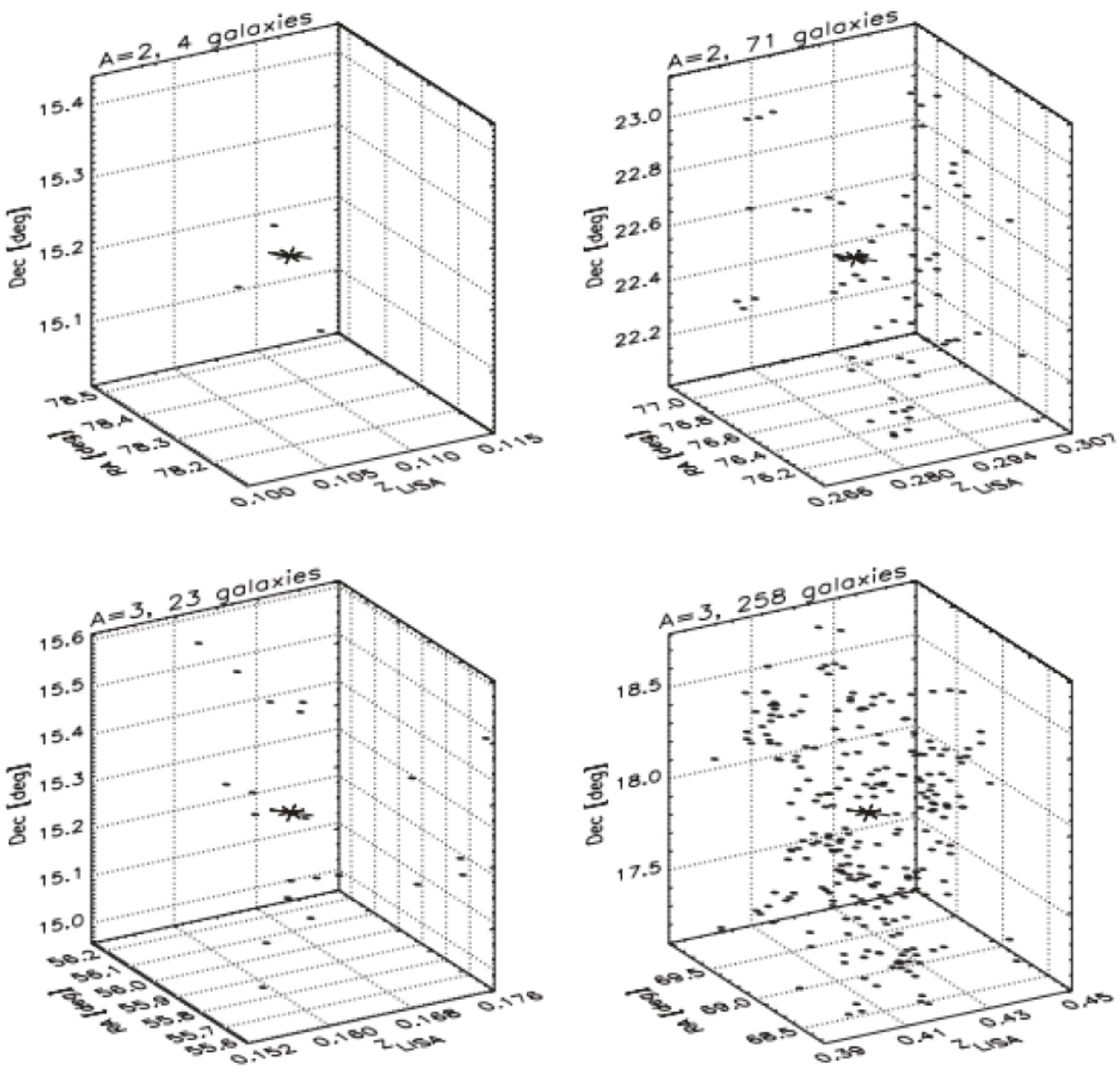
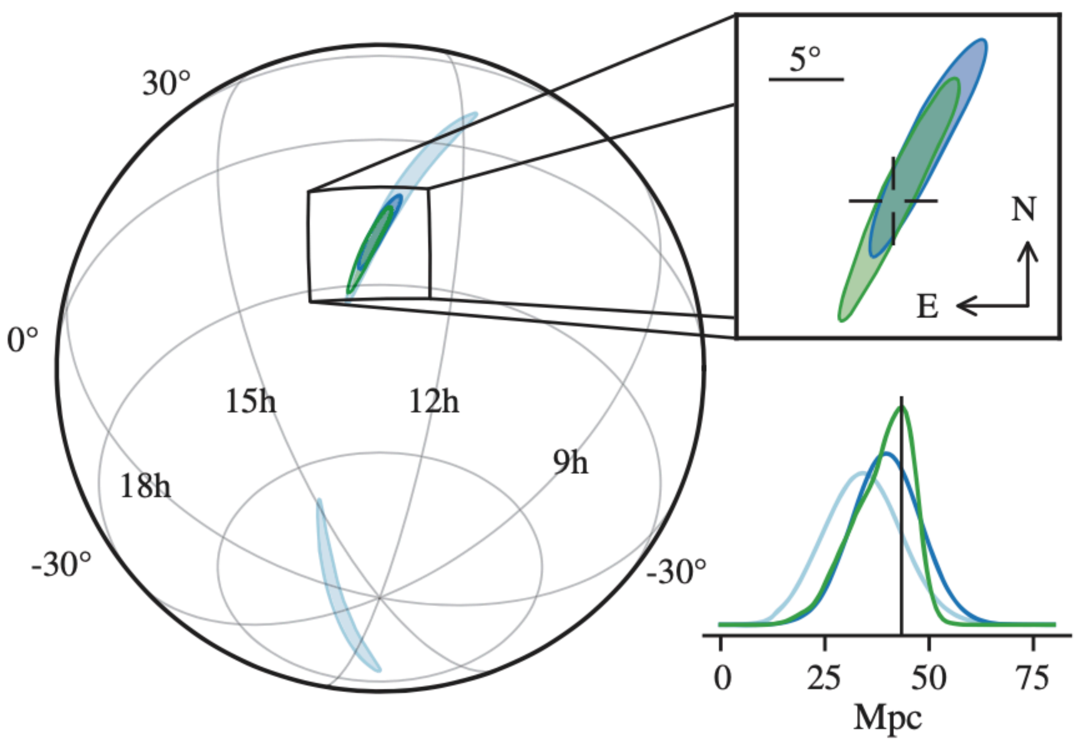
[MacLeod & Hogan, *PRD* (2008)]

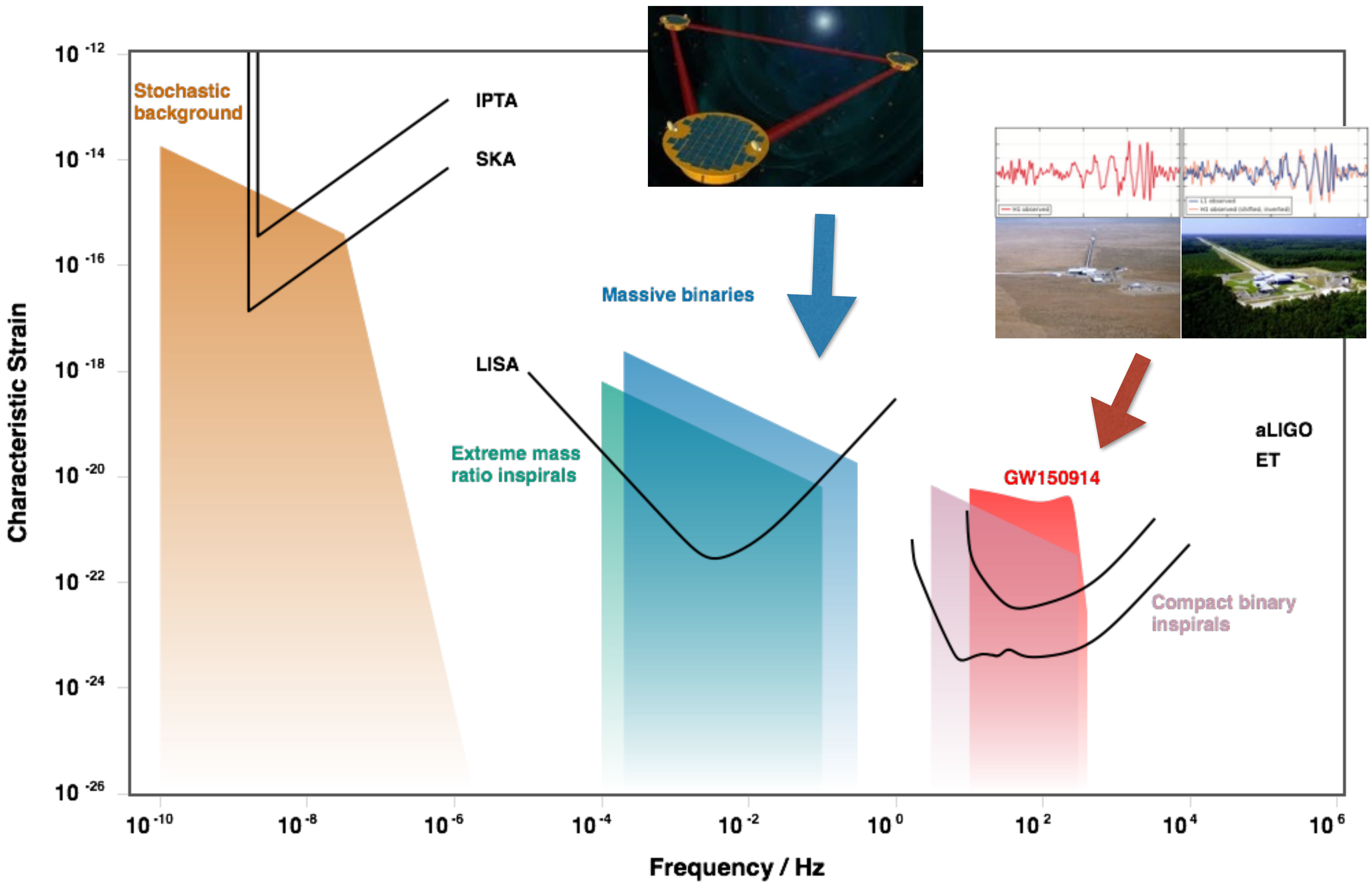




Example: GW170817 [LVC, *ApJL* (2019)]

Standard siren sources

The GW sources that can be used as standard sirens will in general be different for ground-based and space-based detectors



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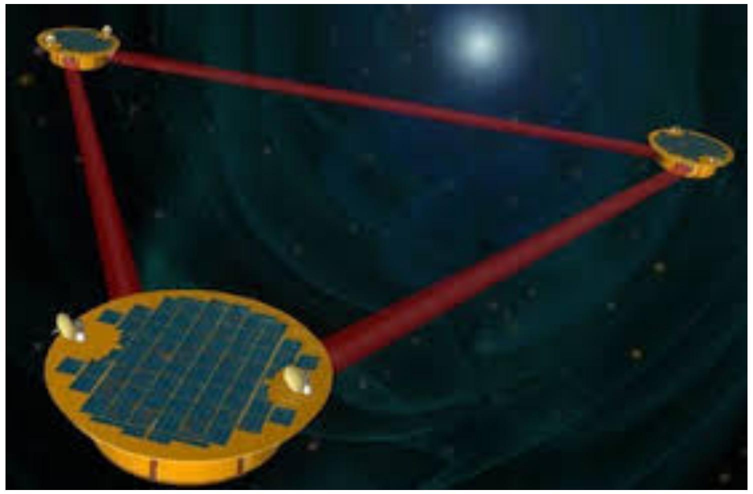


<u>Standard sirens for LISA:</u>

- **Stellar mass BBHs (inspiral only)**
- **Extreme mass ratio inspirals (EMRIs)**
- **Intermediate mass BBHs (?)**
- **Massive BBHs**

<u>Standard sirens for LIGO/Virgo/3G:</u>

- **Stellar mass BBHs**
- **Neutron star binaries**
- **NS-BH binaries**

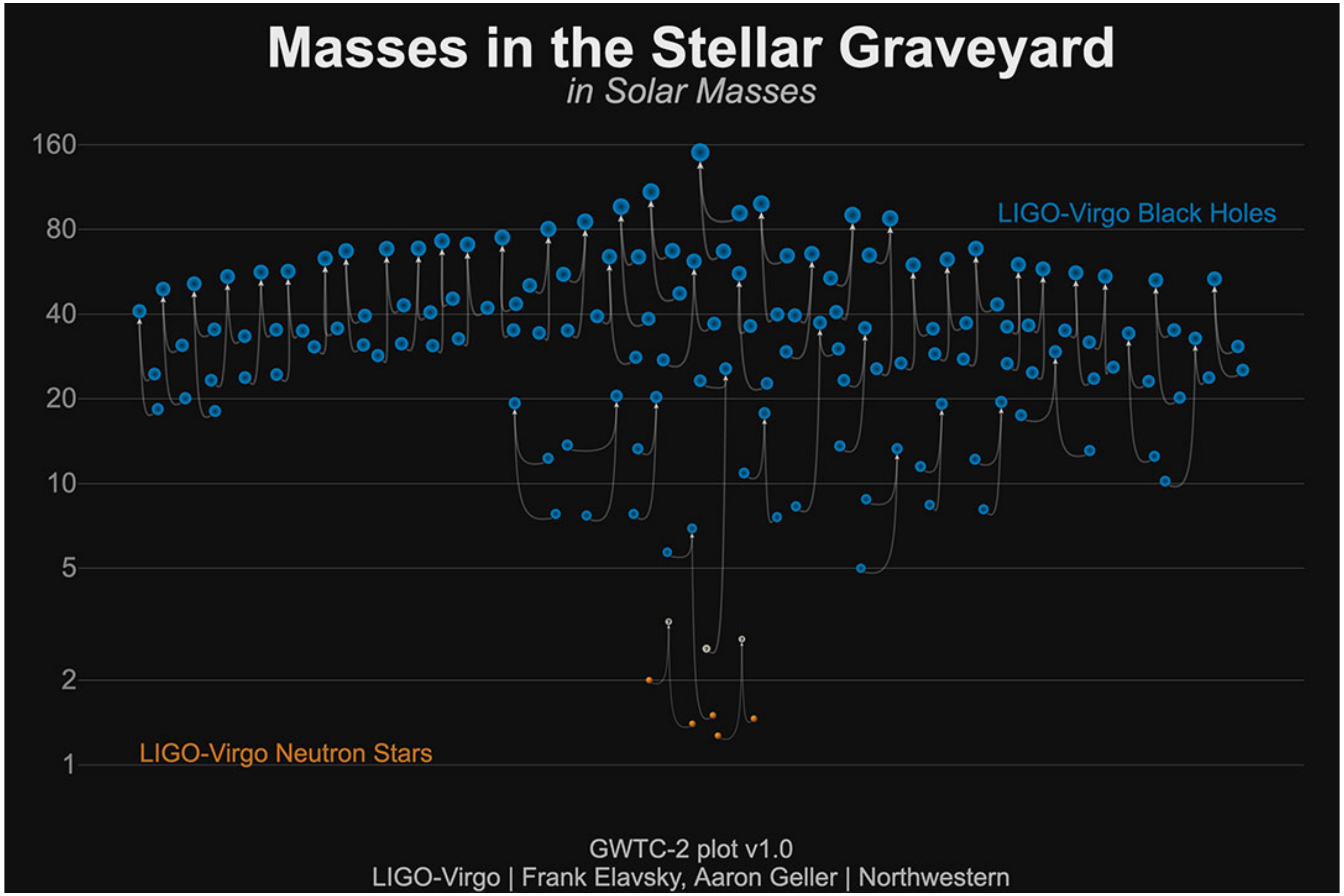
<u>*EM counterparts expected</u>

Current results from LIGO/Virgo

Status of Earth-based GW observations:

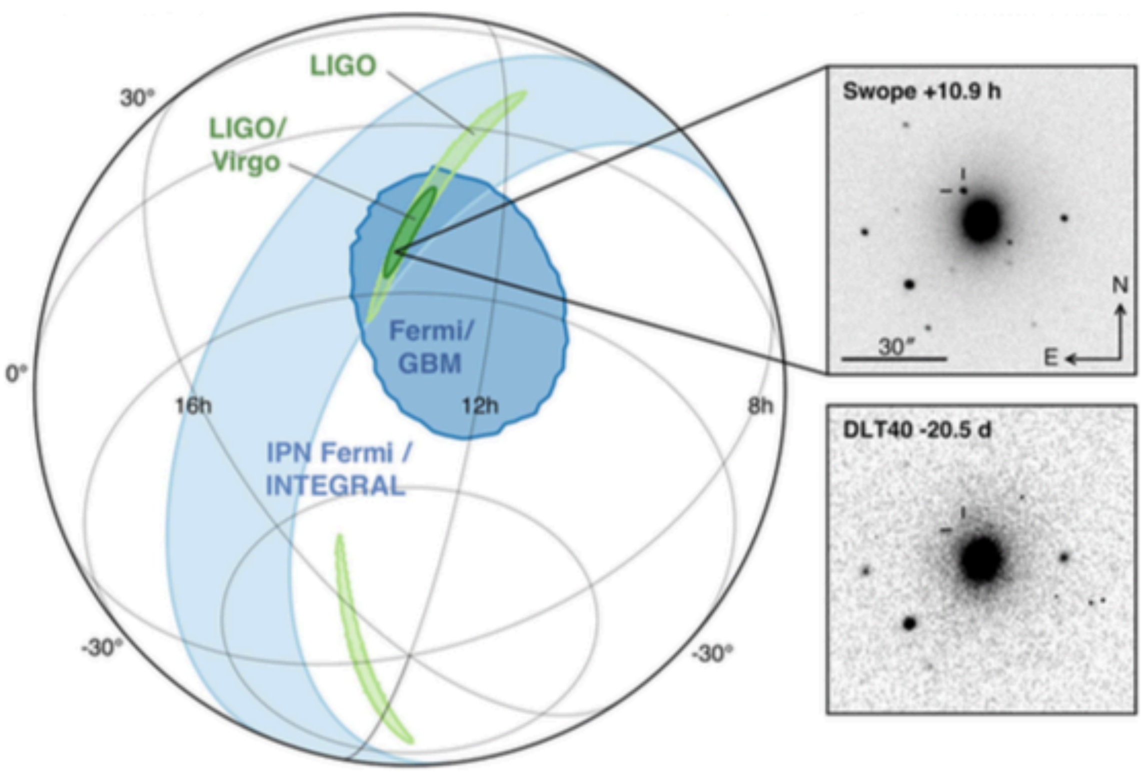
- O1: 2015 (completed), LIGO only, 4 months of data, 3 BBHs detected
- O2: 2017 (completed), LIGO+VIRGO(only for GW1708xx), 6 months of data, 7 BBHs + 1 BNS (GW170817) [LVC, *PRX* (2019)]
- O3: 2019 (completed), LIGO+VIRGO, 1 year of data, 39 events so far (only from O3a) [LVC, *ArXiv* (2020)]
- O4: 2022 LIGO+VIRGO+KAGRA
- O5: ~2024 LIGO India should join

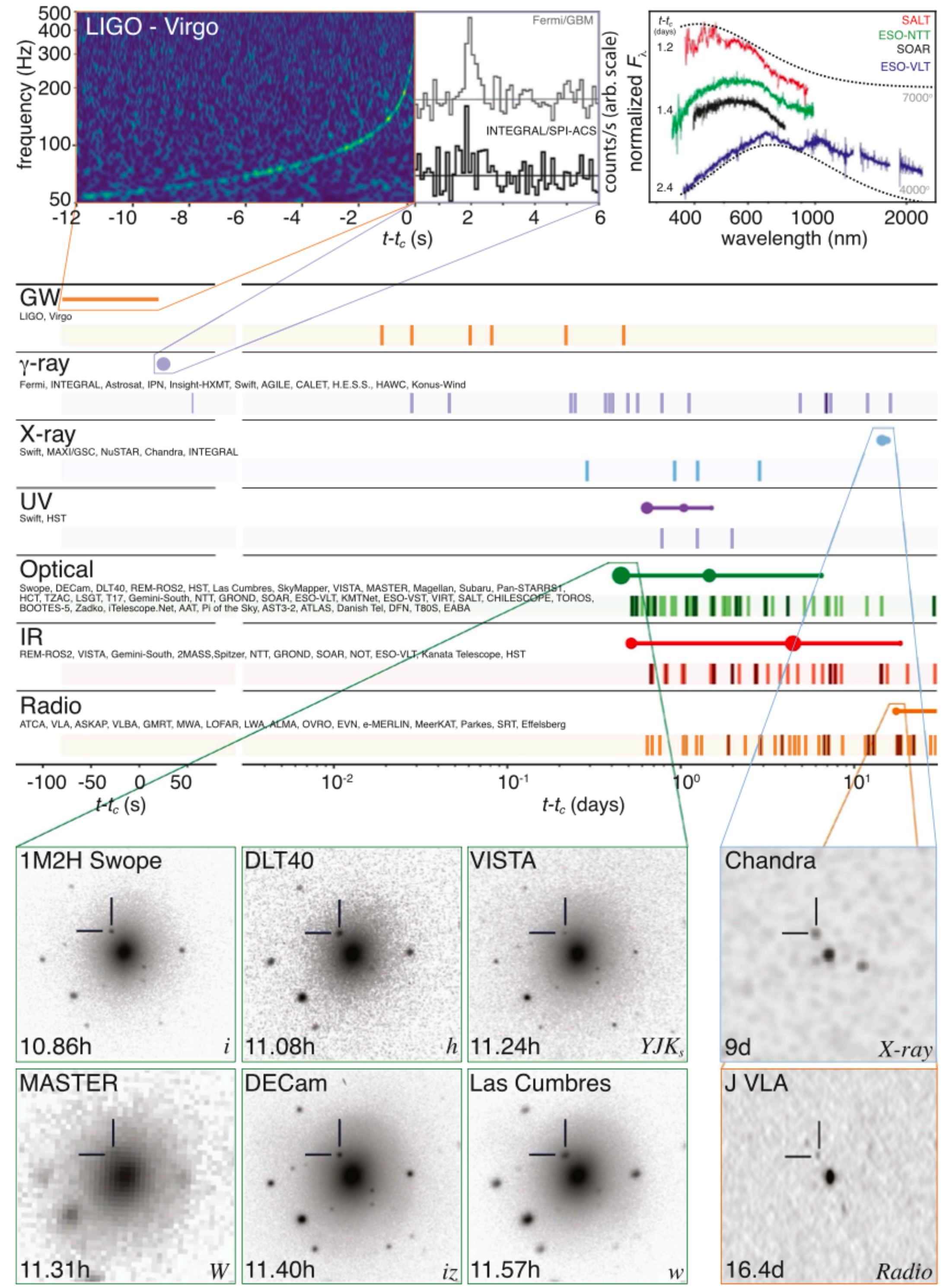
50 GW events in total so far



Current results from LIGO/Virgo

GW170817: the first ever standard siren





The identification of an EM counterpart yielded the first cosmological measurements with GW standard sirens

$$H_0 = 69^{+17}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[LVC+, *Nature* (2017)]
[LVC, *PRX* (2019)]

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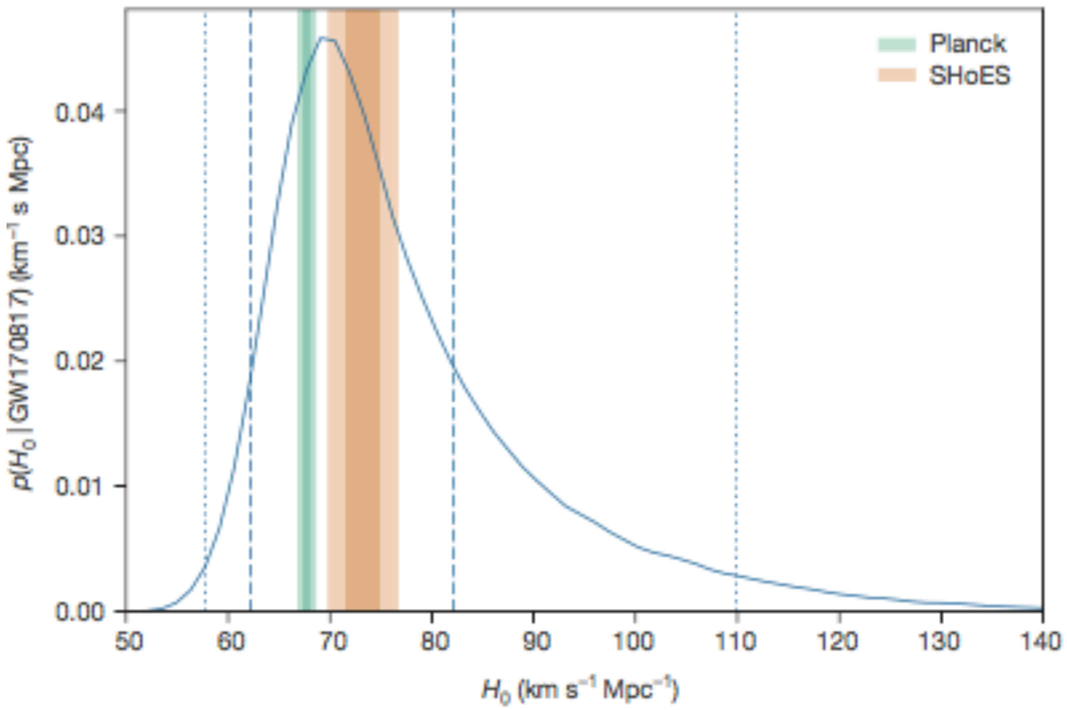

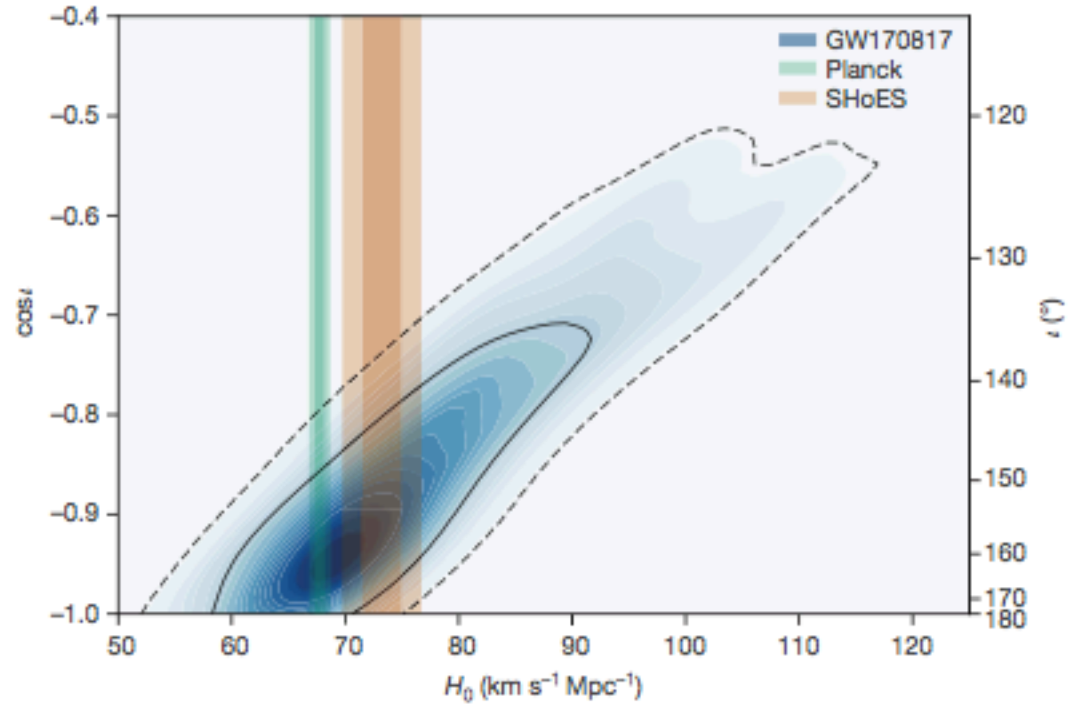

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$$H_0 = 69^{+17}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[LVC+, *Nature* (2017)]
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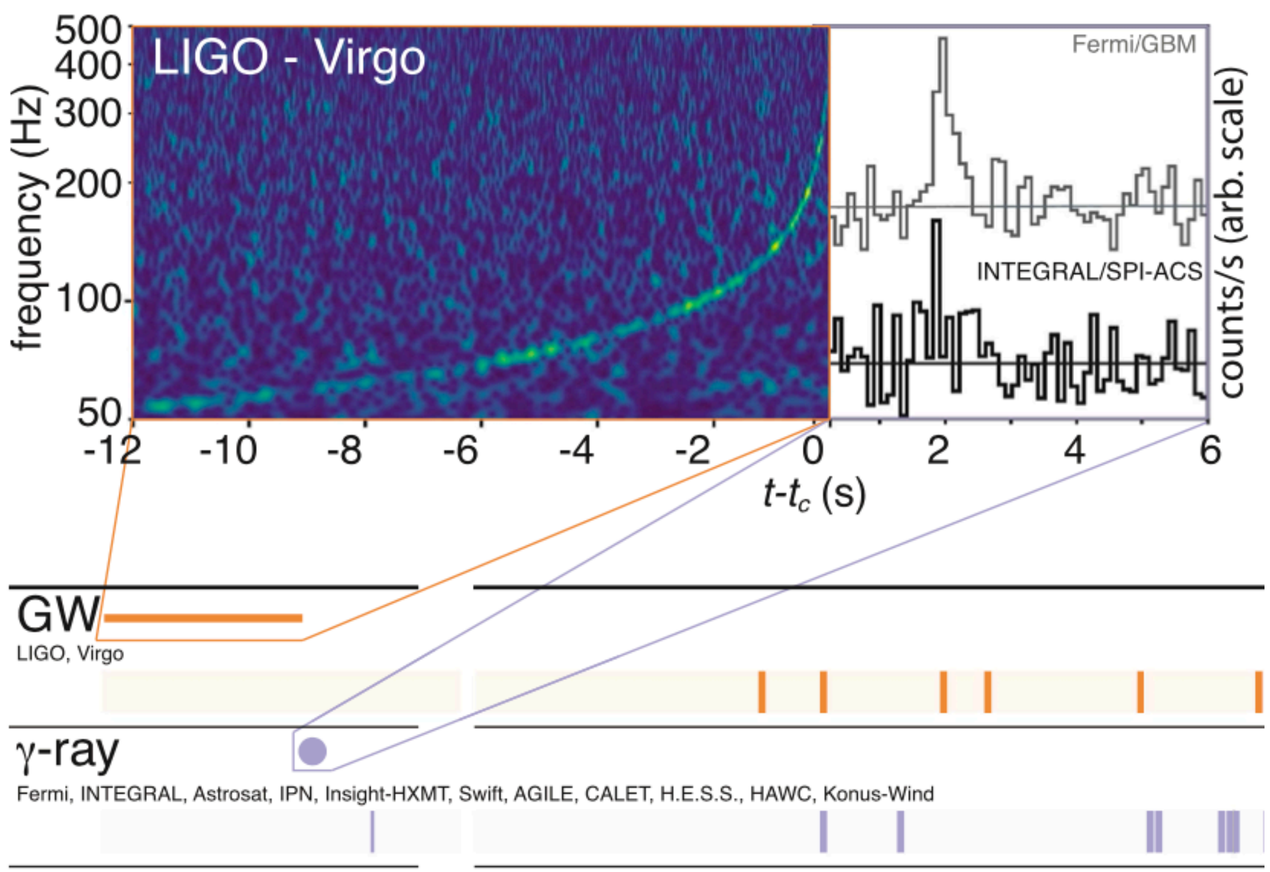
Low-redshift event ($z = 0.01$): only H_0 can be measured (Hubble law)

Results largely in agreement with EM constraints (SNIa/CMB), but not yet competitive with them

Current results from LIGO/Virgo

GW170817: the first ever standard siren



[LVC+, *ApJL* (2017)]

The coincident GW-EM detection of GW170817 puts stringent constraints on the speed of GW:

$$v_{\mathrm{gw}} = c^{+7\times10^{-16}}_{-3\times10^{-15}}$$

This observation rules out several modified gravity models predicting $v_{\mathrm{gw}} \neq c$ [see e.g. 1807.09241 and refs therein]

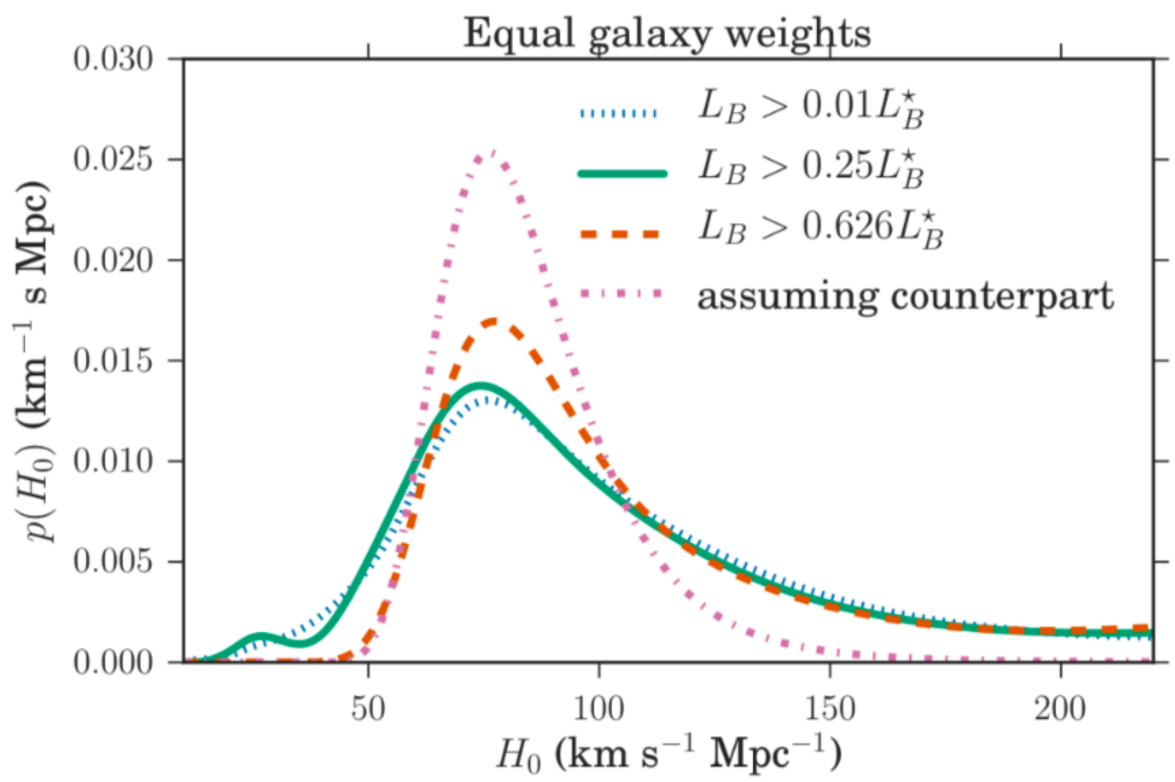
Current results from LIGO/Virgo

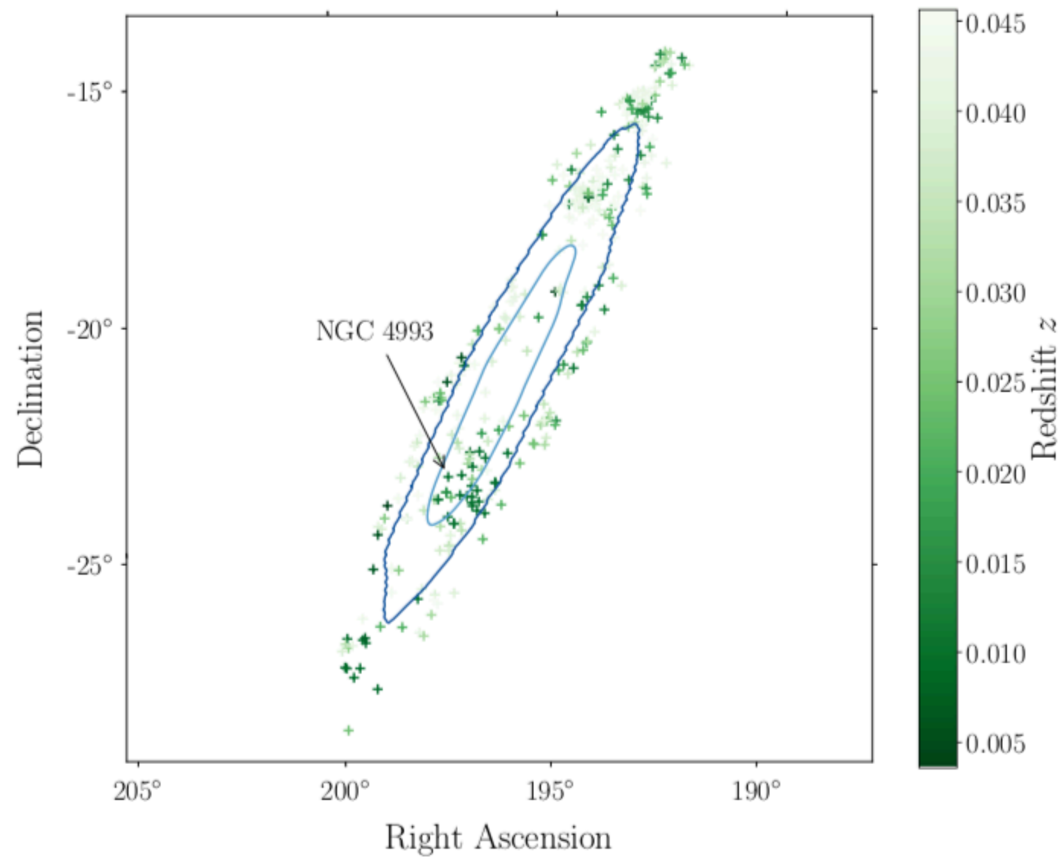
GW170817: the first ever standard siren

The statistical method has been first applied to GW170817 as a proof-of-principle, pretending that no EM counterpart was observed:

$$H_0 = 70^{+48}_{-23}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Results not comparable to assuming known host galaxy (EM counterpart)



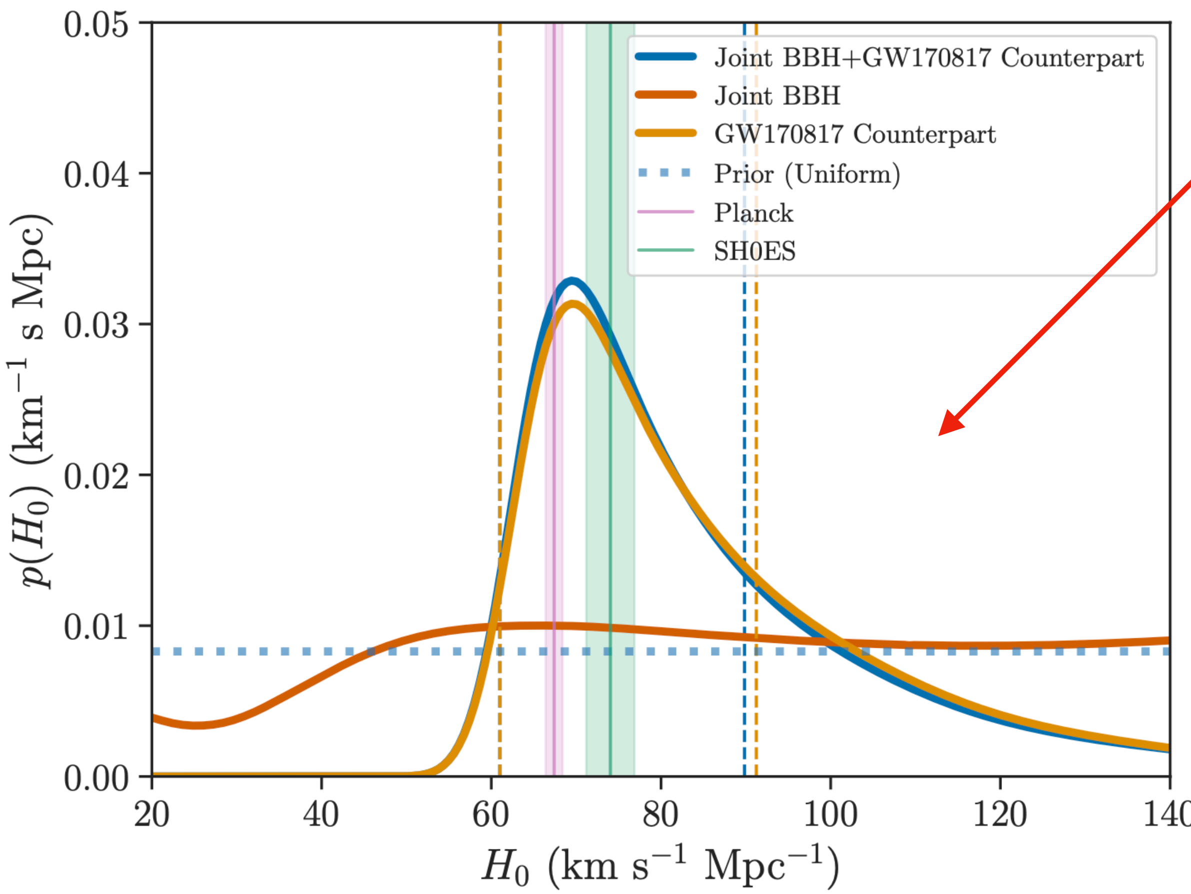


<u>Some lesson learnt however</u>: Strong dependence on the completeness and characteristics of the used galaxy catalogs

[Fishbach+, *ApJL* (2019)]

Current results from LIGO/Virgo

The statistical method has then been applied to combine BBHs events:



LVC results with all O1 and O2 events combined: [LVC, *ArXiv* (2020)]

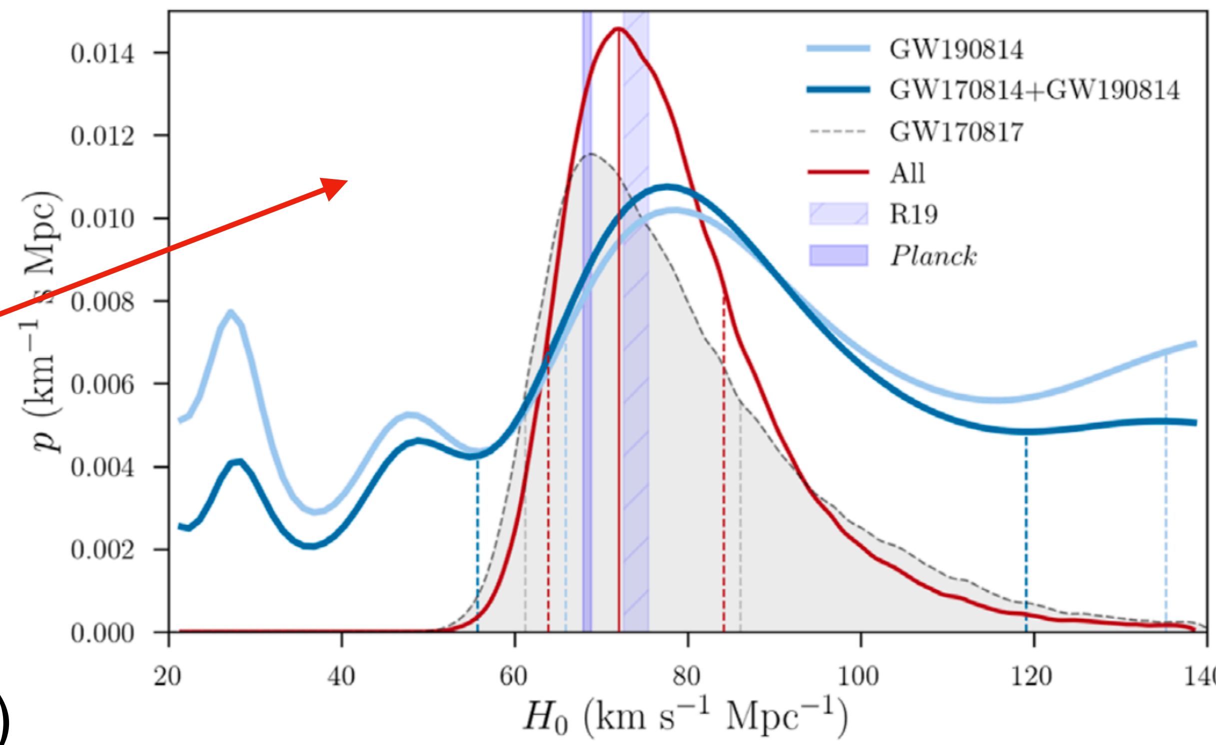
$$H_0 = 69^{+16}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(4% improvement over GW170817 only)

DES results with GW190814 and GW170814: [Palmese+, *ApJL* (2020)]

$$H_0 = 72^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(18% improvement over GW170817 only)



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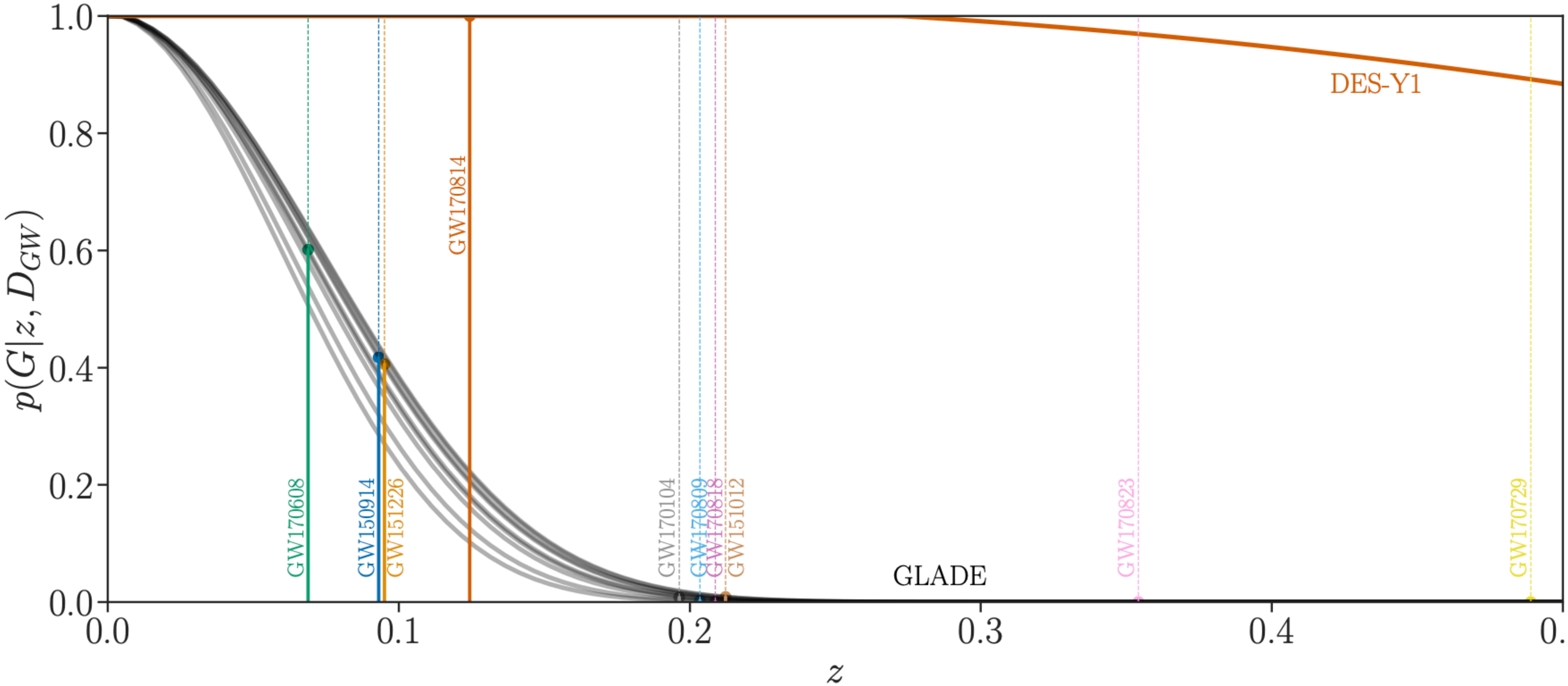
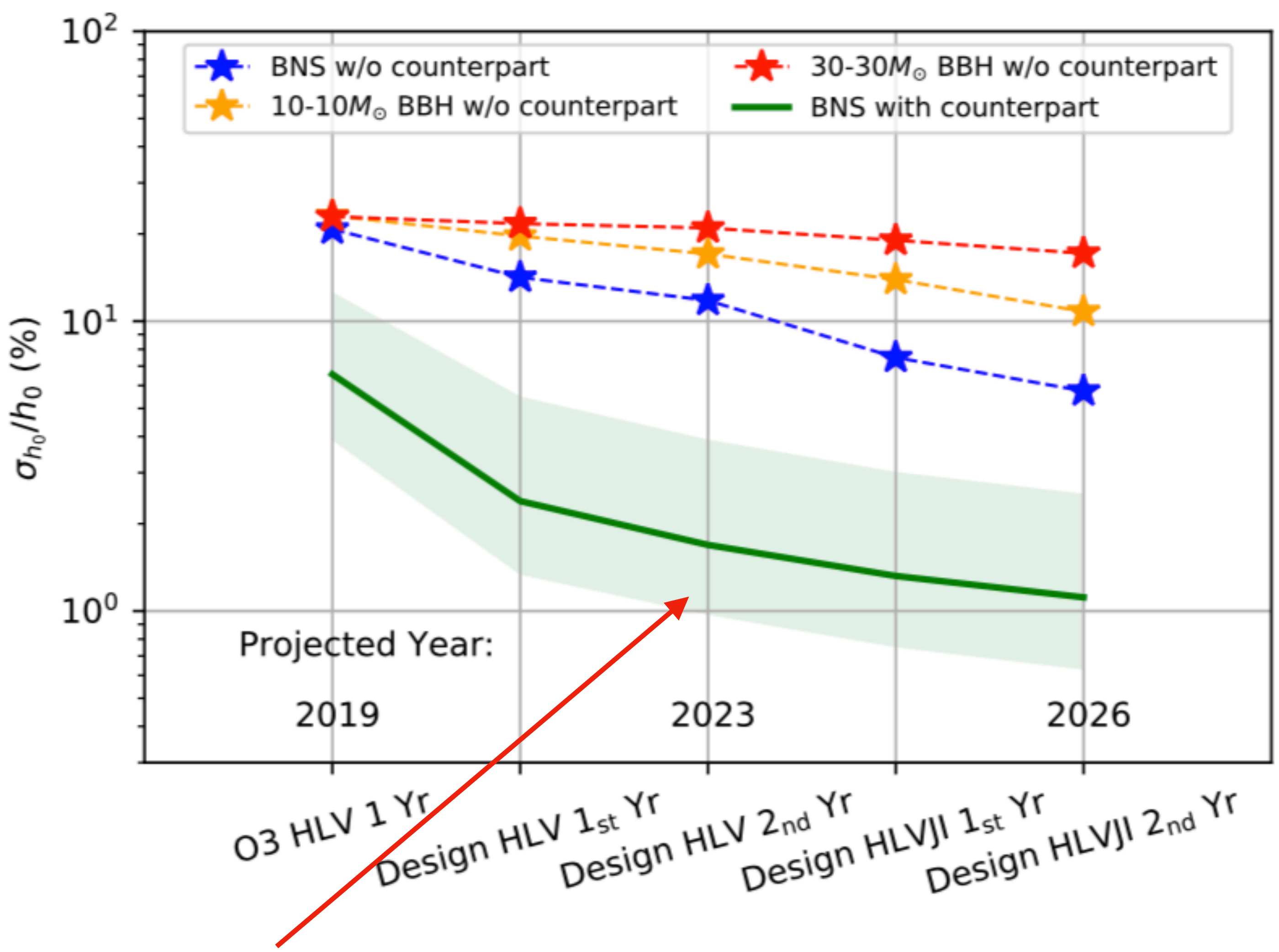


Completeness of galaxy catalogs is the main limitation for the statistical method

[LVC, *ArXiv* (2020)]

Forecasts for ground-based detectors

The network of ground-based detectors should be able to measure H_0 at few % accuracy before ~2030.



Very optimistic (based on pre-O3 BNS rates)

[Chen+, *Nature* (2018)]
[Chen+, *ArXiv* (2020)]

Forecasts for LIGO/Virgo/Kagra+:

- BNSs with EM counterpart: ~2% constraint on H_0 with ~50 events (but systematics!)
- BNSs without EM counterpart: ~10% constraint on H_0 with ~50 events
- BBHs without EM counterpart: ~10% constraint on H_0 with ~15 "well-localised" events ($\Delta V < 10^4\,\mathrm{Mpc}^3$)

Forecasts for ground-based detectors

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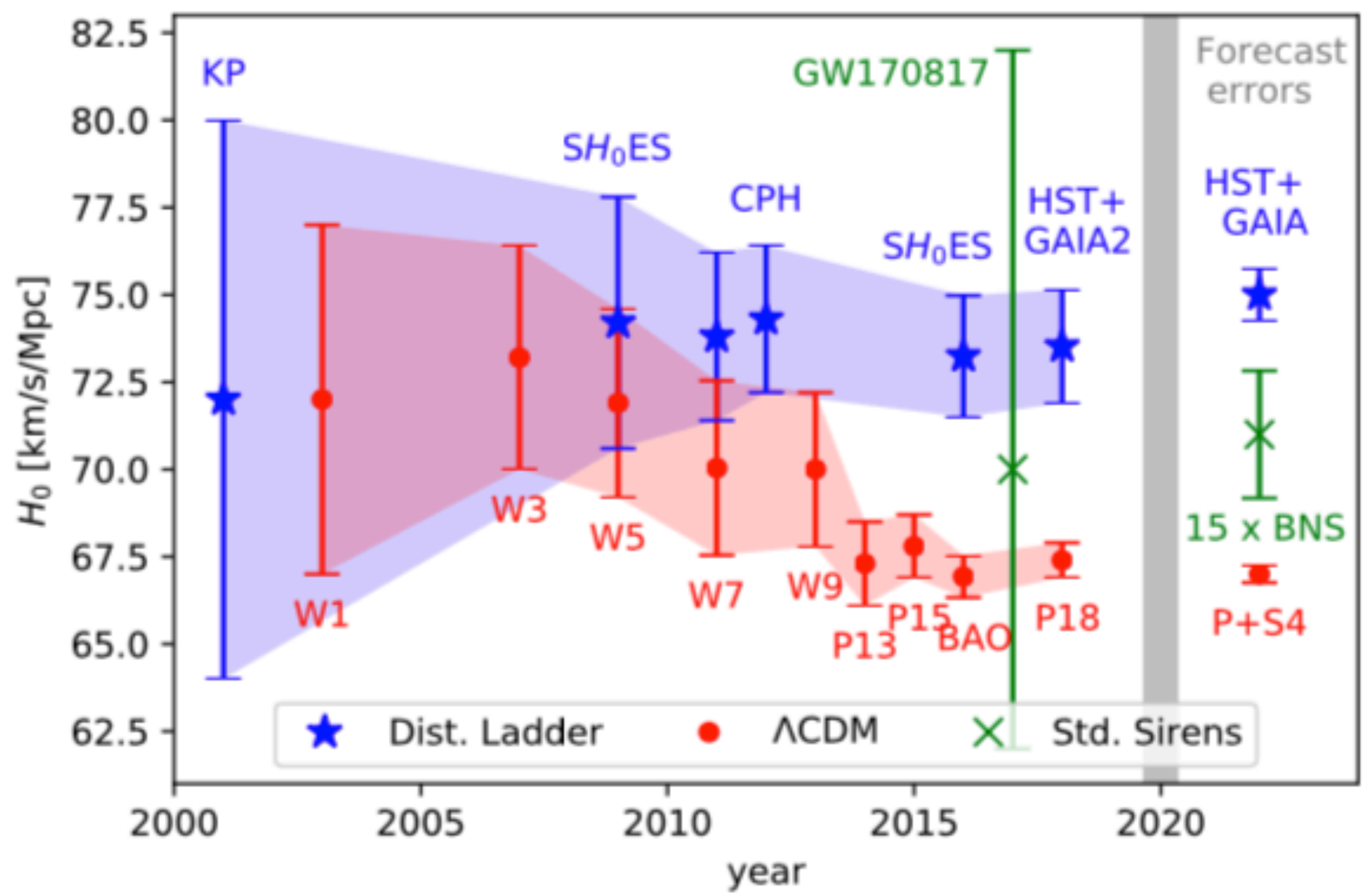
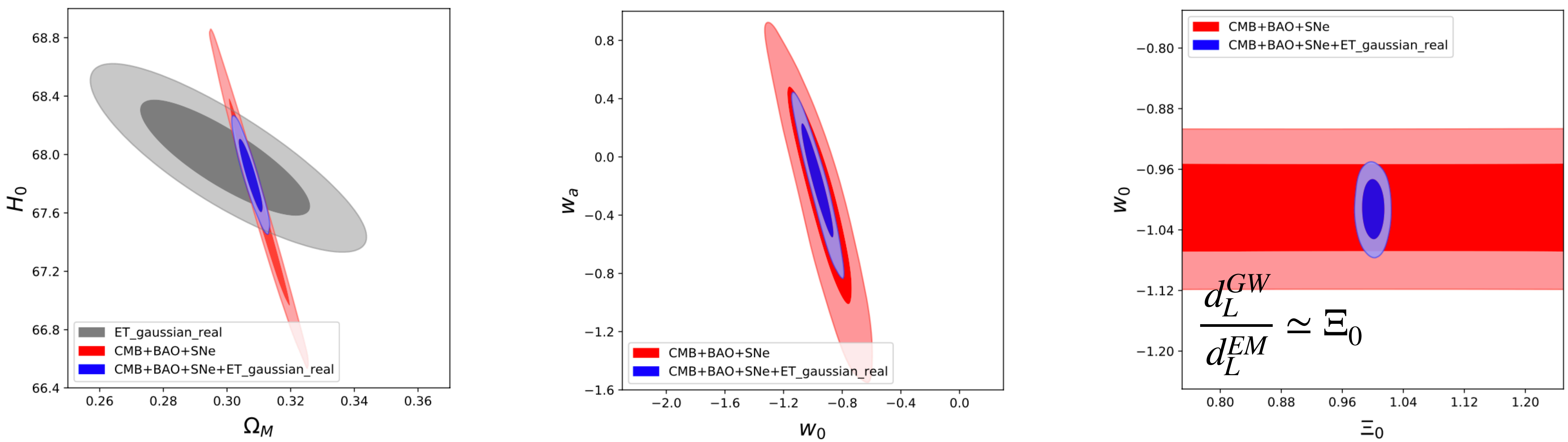
A few % constraints on H0 with GWs could solve the current tension between local and CMB measurements



[Ezquiaga & Zumalacarregui, *Front. Astron. Space Sci.* (2018)]

Forecasts for ground-based detectors

In the 2030s 3G detectors will turn GW observations into precise cosmological probes:



Einstein Telescope and *Cosmic Explorer* will guarantee: [Belgacem+, *JCAP* (2019)]

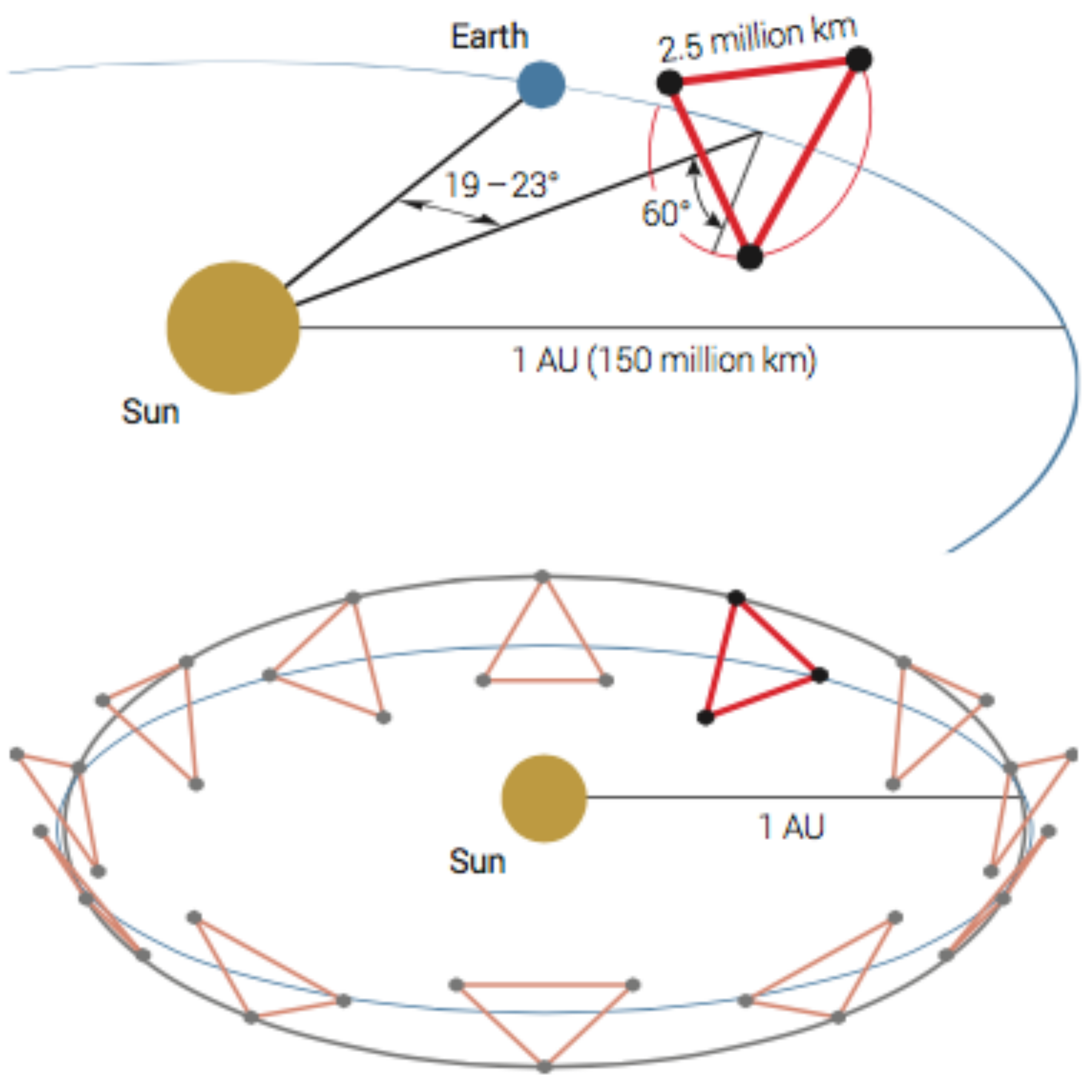
- % constraints on H_0 or better
- Improved constraints on dark energy
- Strong GW-only tests of GR at cosmic distances (see Zumalacarregui's talk)

Moreover 3G detectors may not need EM counterparts to get the redshift of BNSs, but use the information on their EoS to extract it from the GW signal

[Del Pozzo+, *PRD* (2017)]

Let’s go to space: LISA

Laser Interferometer Space Antenna



[LISA, *ArXiv* (2017)]

Design:

- Near equilateral triangular formation in heliocentric orbit
- 6 laser links (3 active arms)
- Arm-length: 2.5 million km
- Mission duration: 4 to 10 yrs
- Launch: 2034

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

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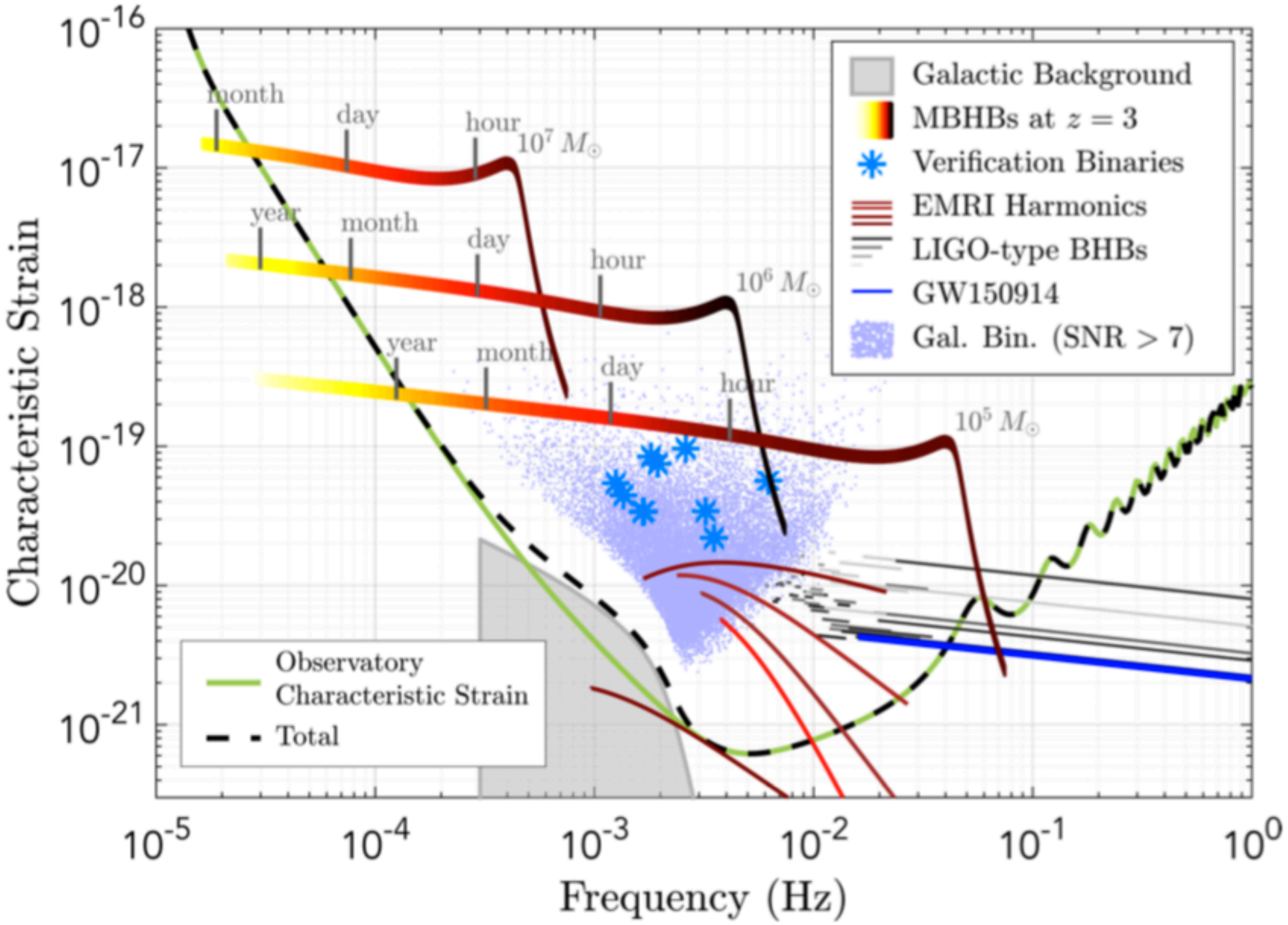

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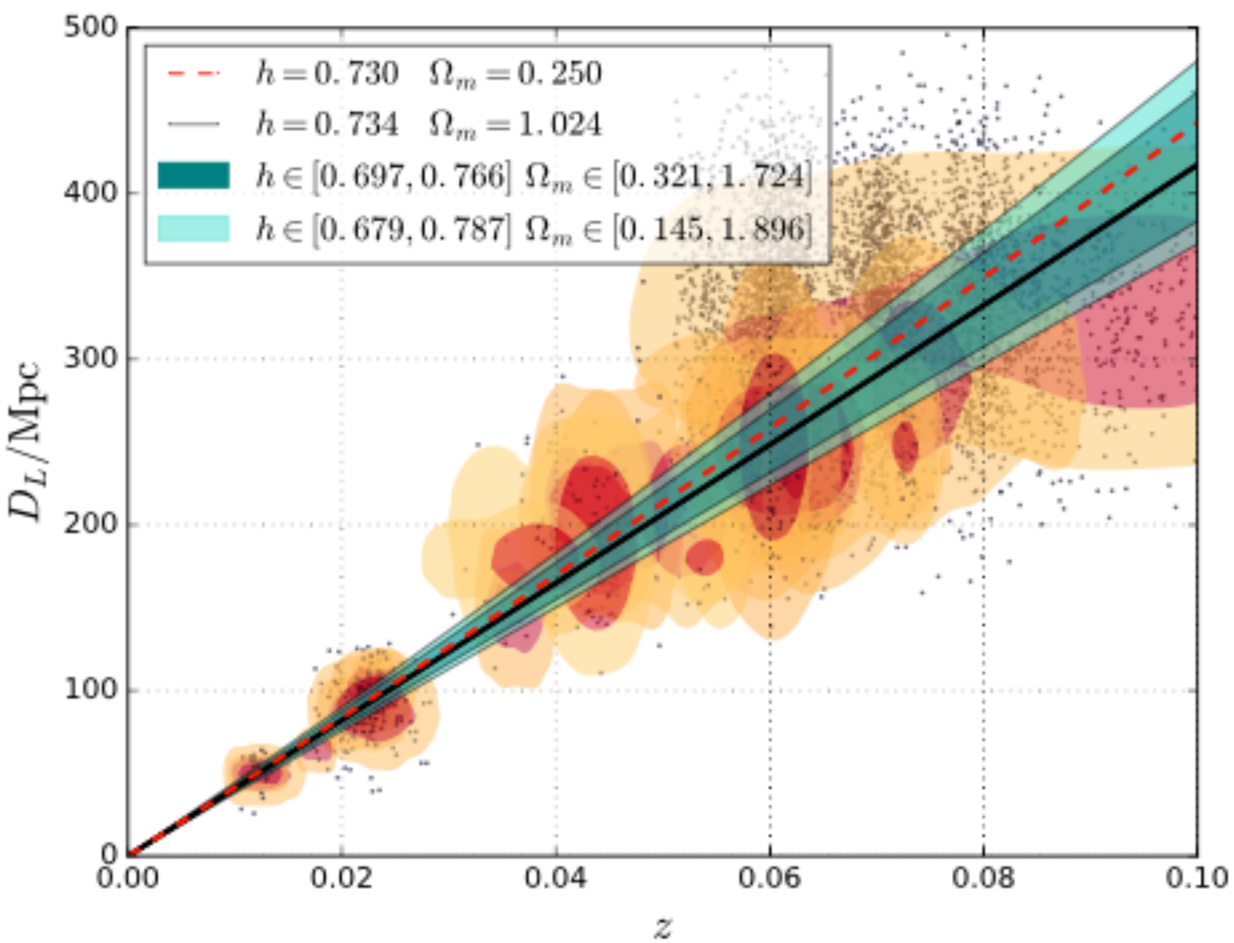
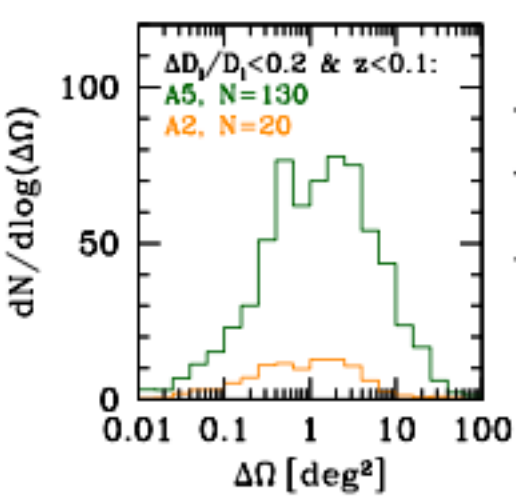
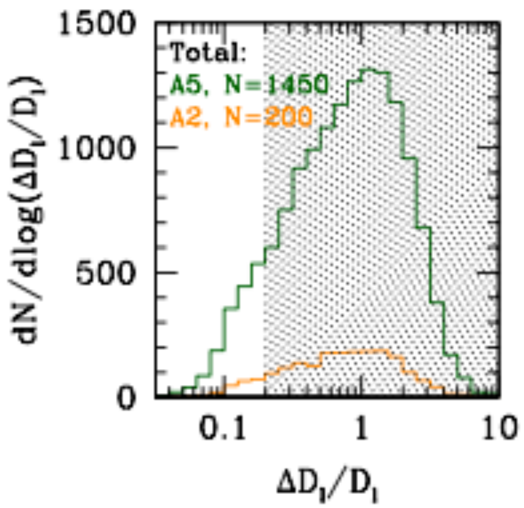
LISA: stellar-mass BBHs



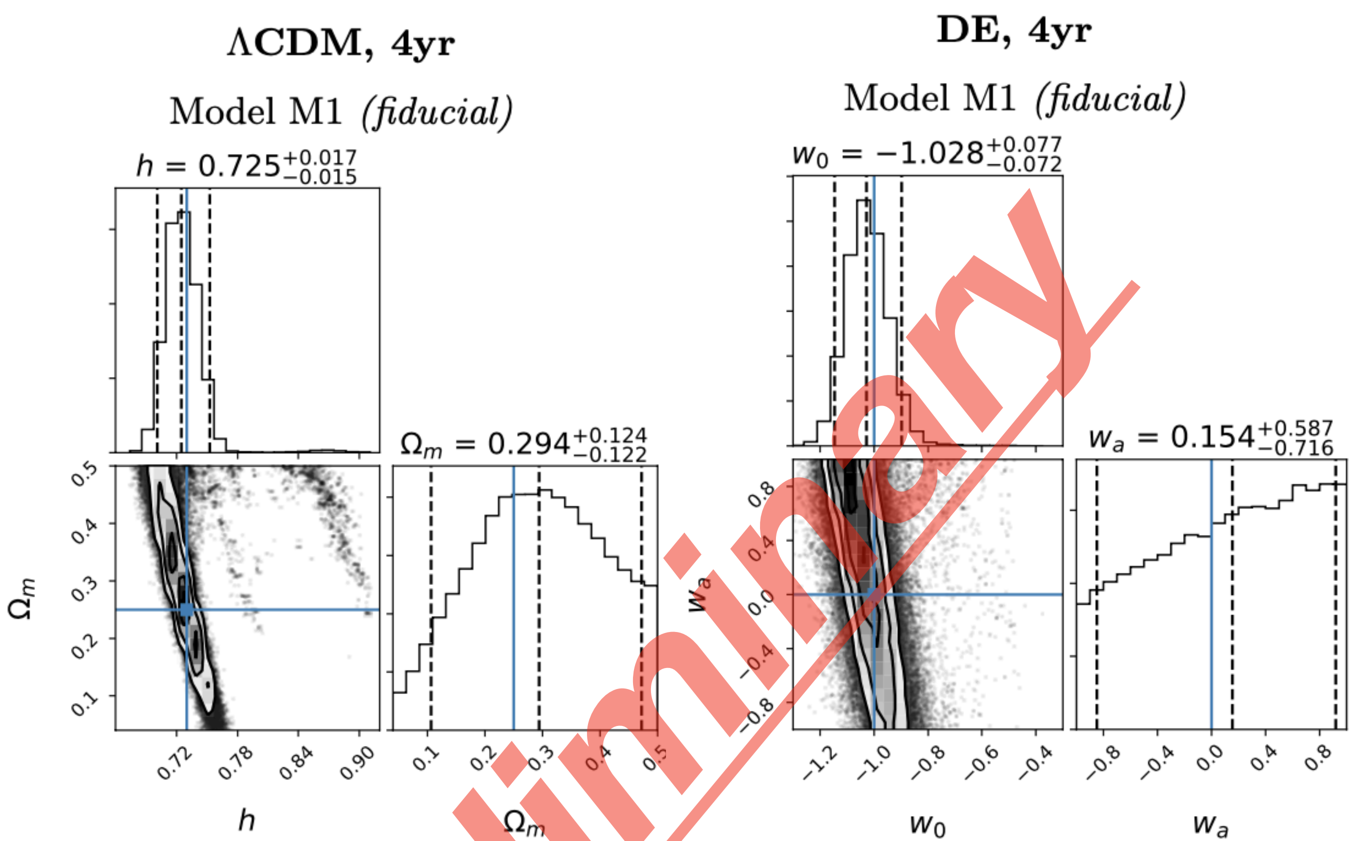


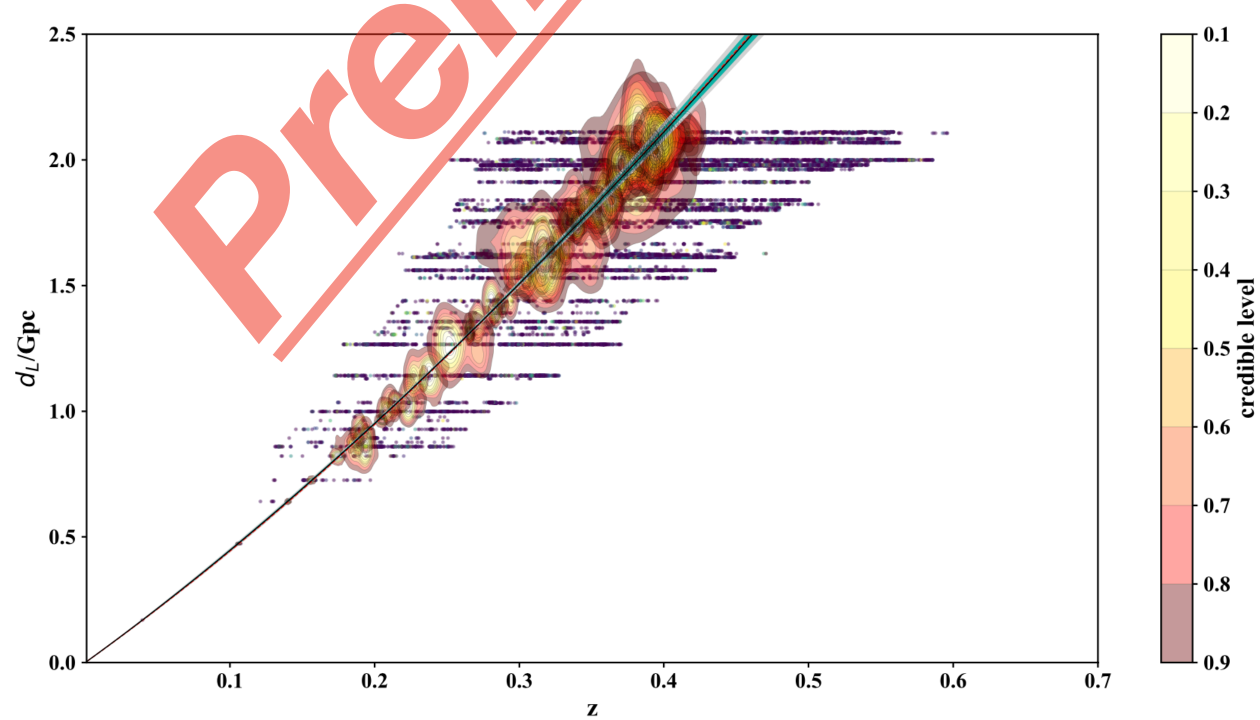


- Redshift range: $z \lesssim 0.1$
- No EM counterparts expected
- LISA detections: ~50/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L < 0.2$
  - If $\Delta\Omega \sim 1 \text{ deg}^2$
  - $\Rightarrow$ ~ 5 standard sirens / yr
- <u>**Expected results:**</u>
  - H_0 to few %

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

LISA: Extreme Mass Ratio Inspirals

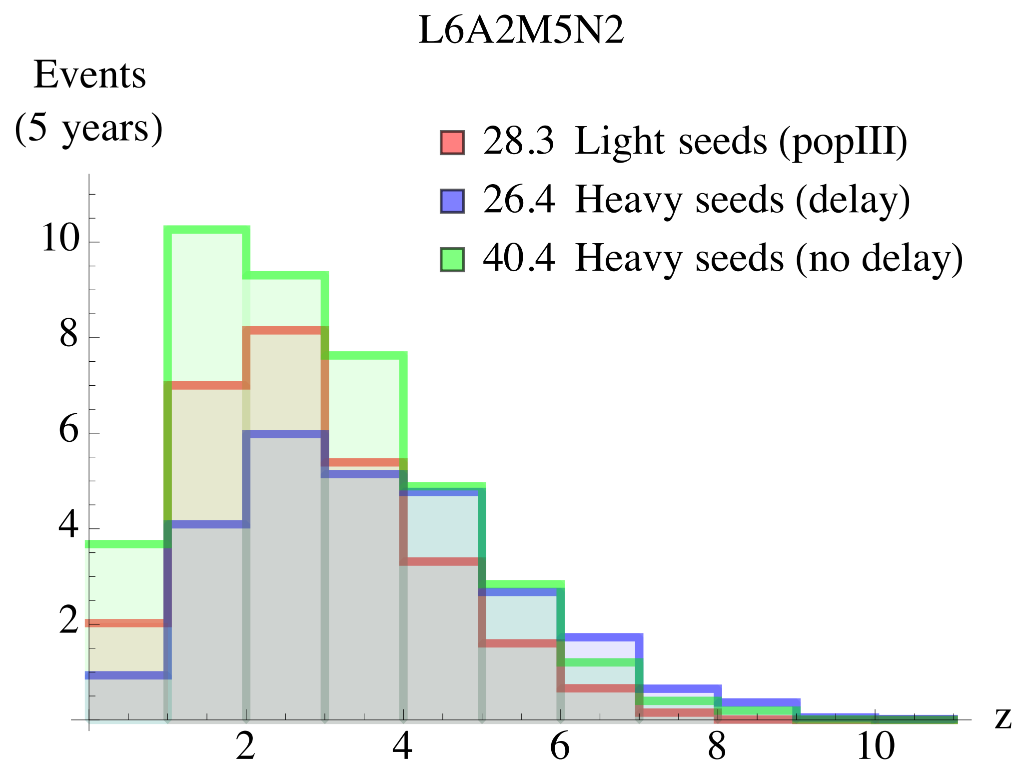


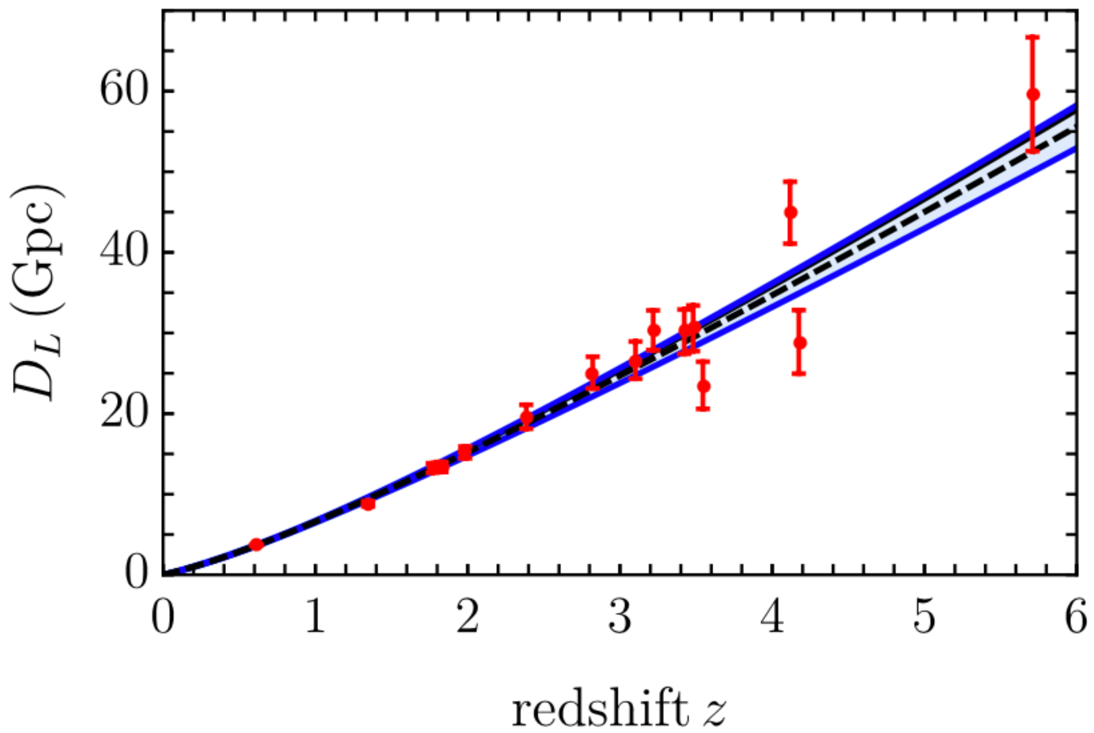


- Redshift range: $0.1 \lesssim z \lesssim 1$
- No EM counterparts expected
- LISA detections: 1 to 1000/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L < 0.1$
  - If $\Delta\Omega < 2\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 1 to 100 standard sirens / yr
- **Expected results (preliminary):**
  - H_0 between 1 and 10 %
  - w_0 between 5 and 20 %

[MacLeod & Hogan, *PRD* (2008)]
[Babak+, *PRD* (2017)]
[Laghi, Tamanini+, *in prep.* (2021)]

LISA: massive BBHs





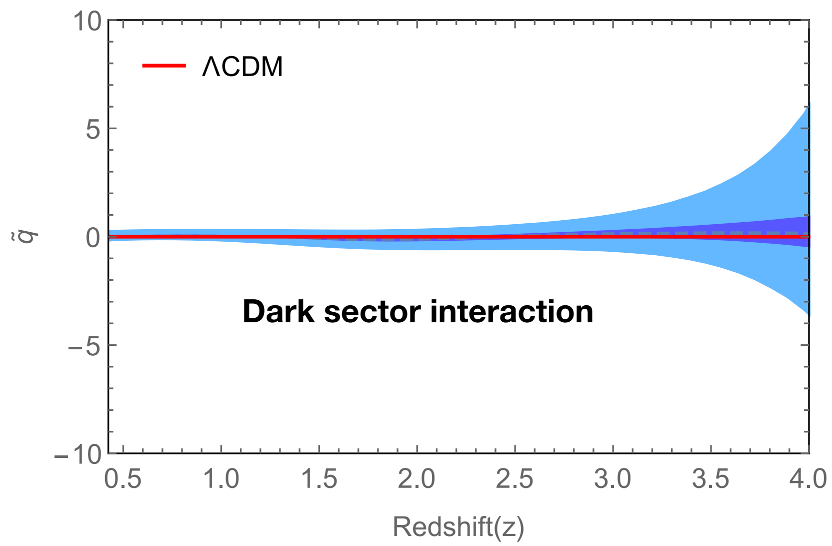
- Redshift range: $z \lesssim 10$
- EM counterparts expected
- LISA detections: 1 to 100/yr
- Useful as standard sirens:
  - If $\Delta d_L/d_L \lesssim 0.1$ (include lensing)
  - If $\Delta\Omega < 10\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 4 standard sirens / yr (with EM counterpart)
- **Expected results:**
  - H_0 to few %

[Tamanini+, *JCAP* (2016)]
[LISA CosmoWG, *JCAP* (2019)]
[Speri, Tamanini+, *ArXiv* (2020)]

LISA: massive BBHs

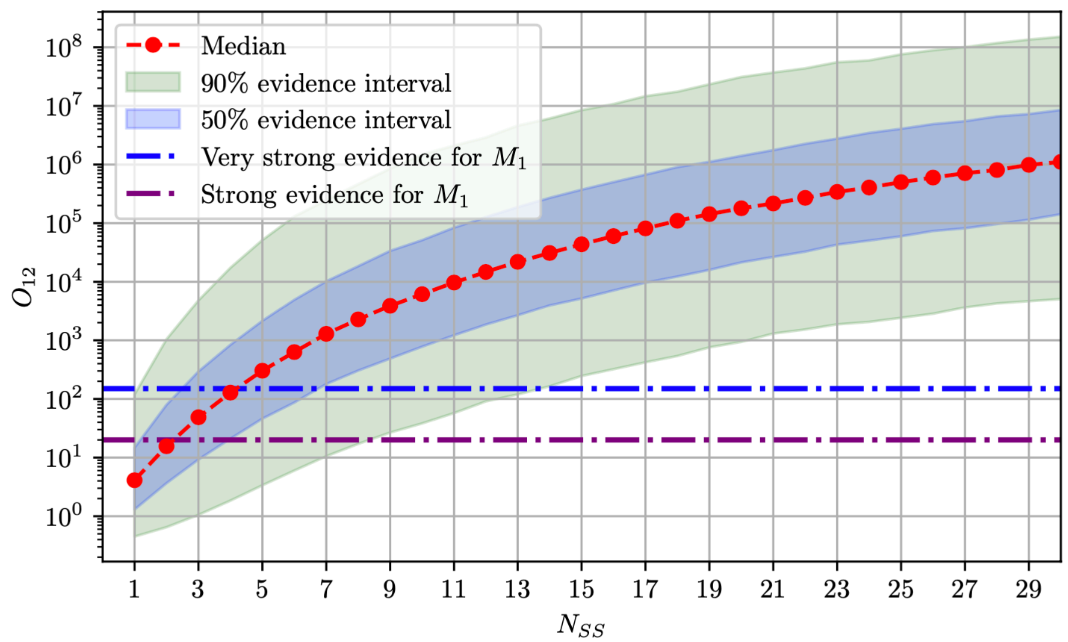
LISA MBHB data will be very useful to probe $\underline{\Lambda\text{CDM}}$ at high-redshift

Test alternative cosmological models



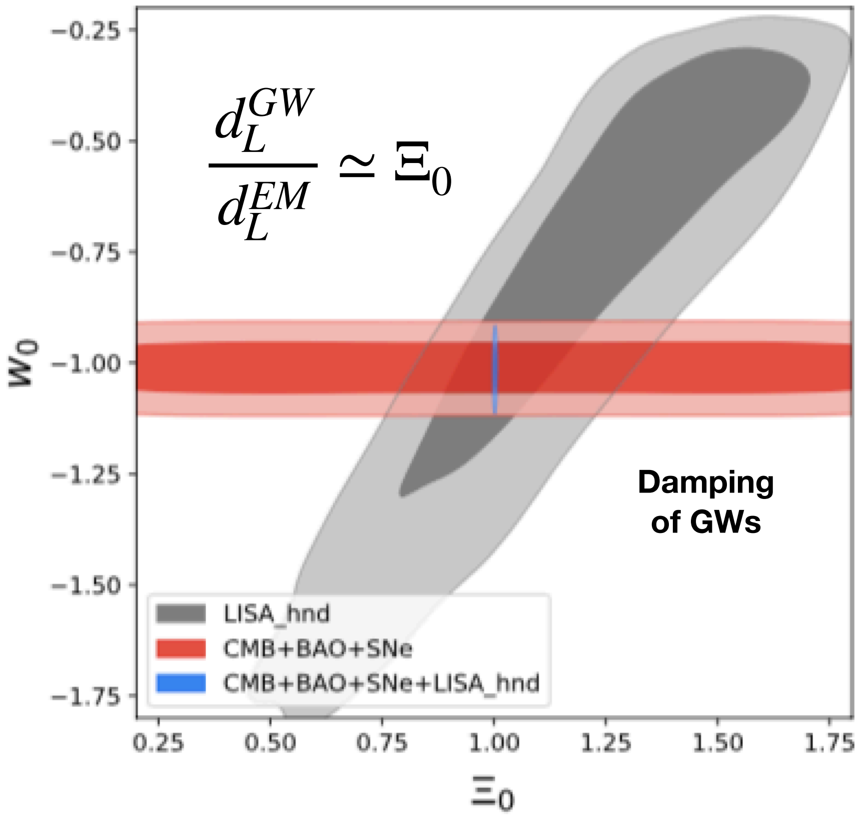
[Caprini & Tamanini, *JCAP* (2016)]
[Cai, Tamanini, Yang, *JCAP* (2017)]

Test quasars Hubble diagram



[Speri, Tamanini+, *ArXiv* (2020)]

Test modified gravity

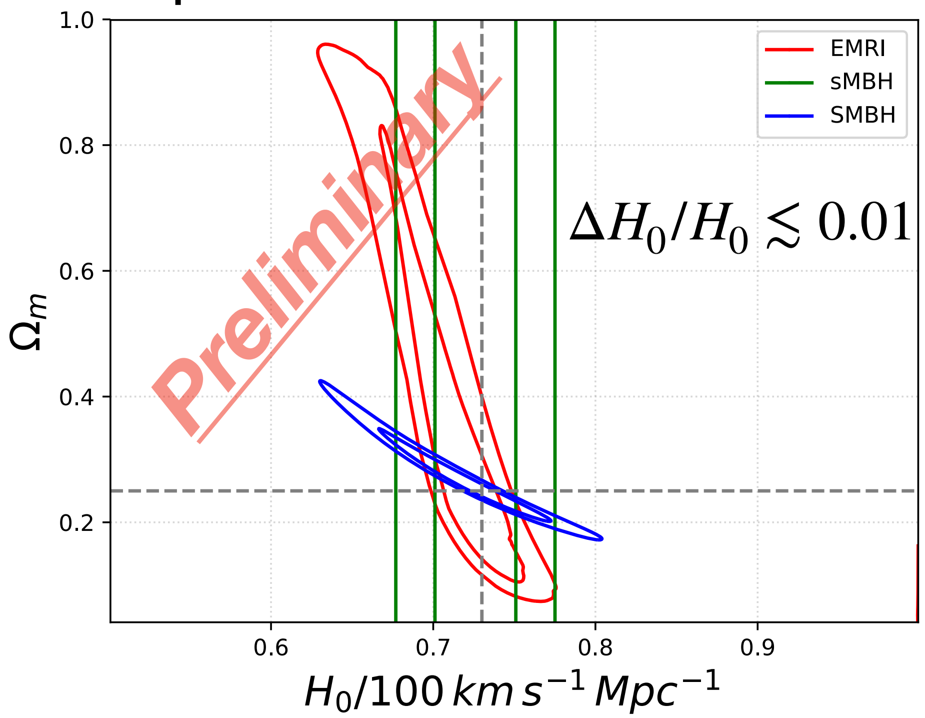


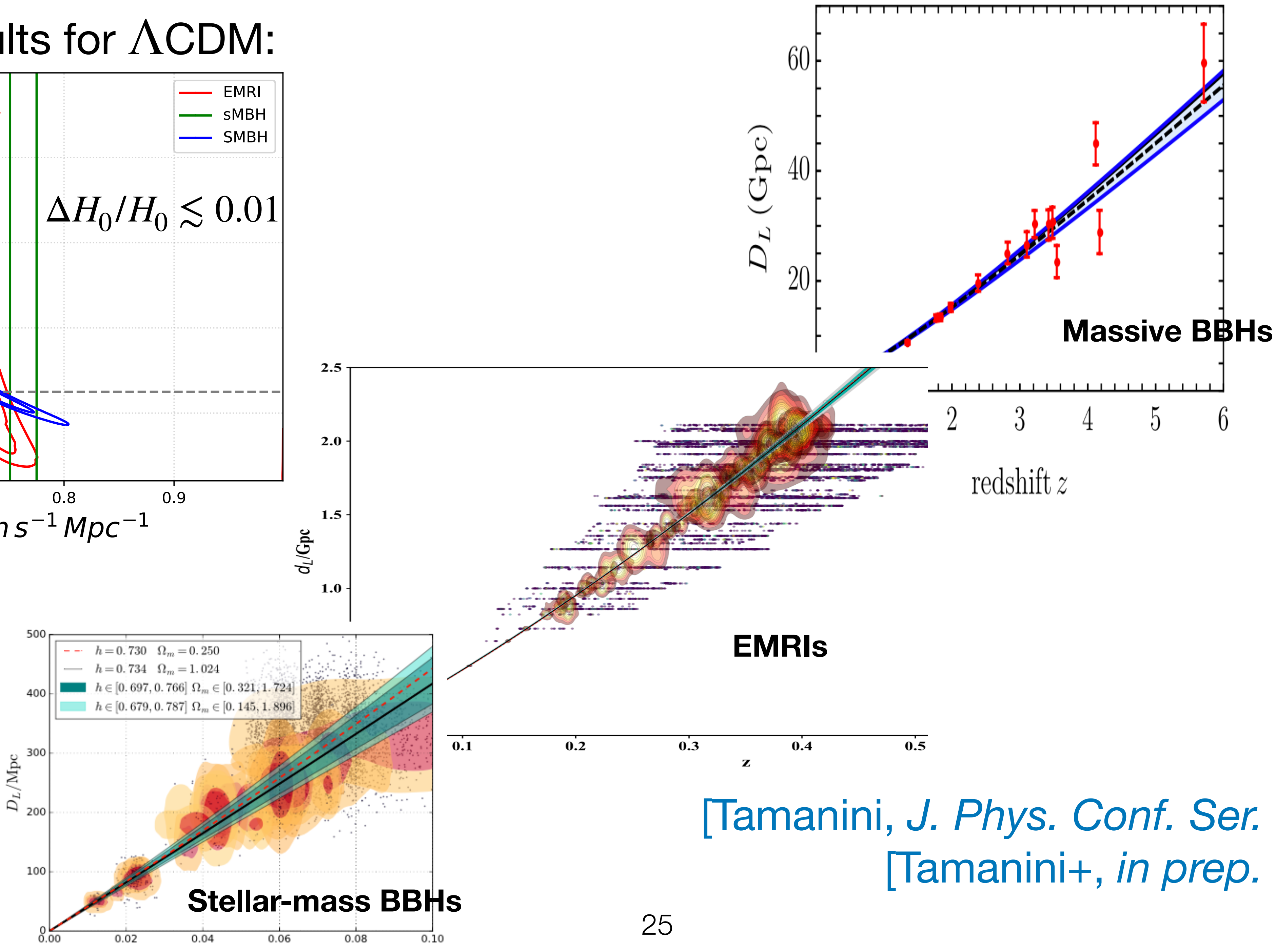
[LISA CosmoWG, *JCAP* (2019)]
(see Zumalacarregui's talk)

LISA as a cosmological probe

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

Expected results for ΛCDM:





[Tamanini, *J. Phys. Conf. Ser.* (2017)]
[Tamanini+, *in prep.* (2021)]

Conclusions

- Standard sirens are excellent distance indicators:
  - They do not require calibration and are not affected by systematics
  - Can be used with or without an EM counterpart

- Standard sirens with ground-based detectors:
  - Three possible sources:
    - SOBHBs (no EM cp), NSBs (EM cp) and NS-BH (?)
  - First standard siren discovered: GW170817
  - Future observations useful for tension on H_0

- Standard sirens with LISA:
  - Three possible sources:
    - SOBHBs (no EM cp), EMRIs (no EM cp), MBHBs (EM cp)
  - Probing the cosmic expansion from z~0.01 to z~10
  - High-redshift tests of alternative cosmological models and modified gravity