Gravitational wave cosmology: present and future

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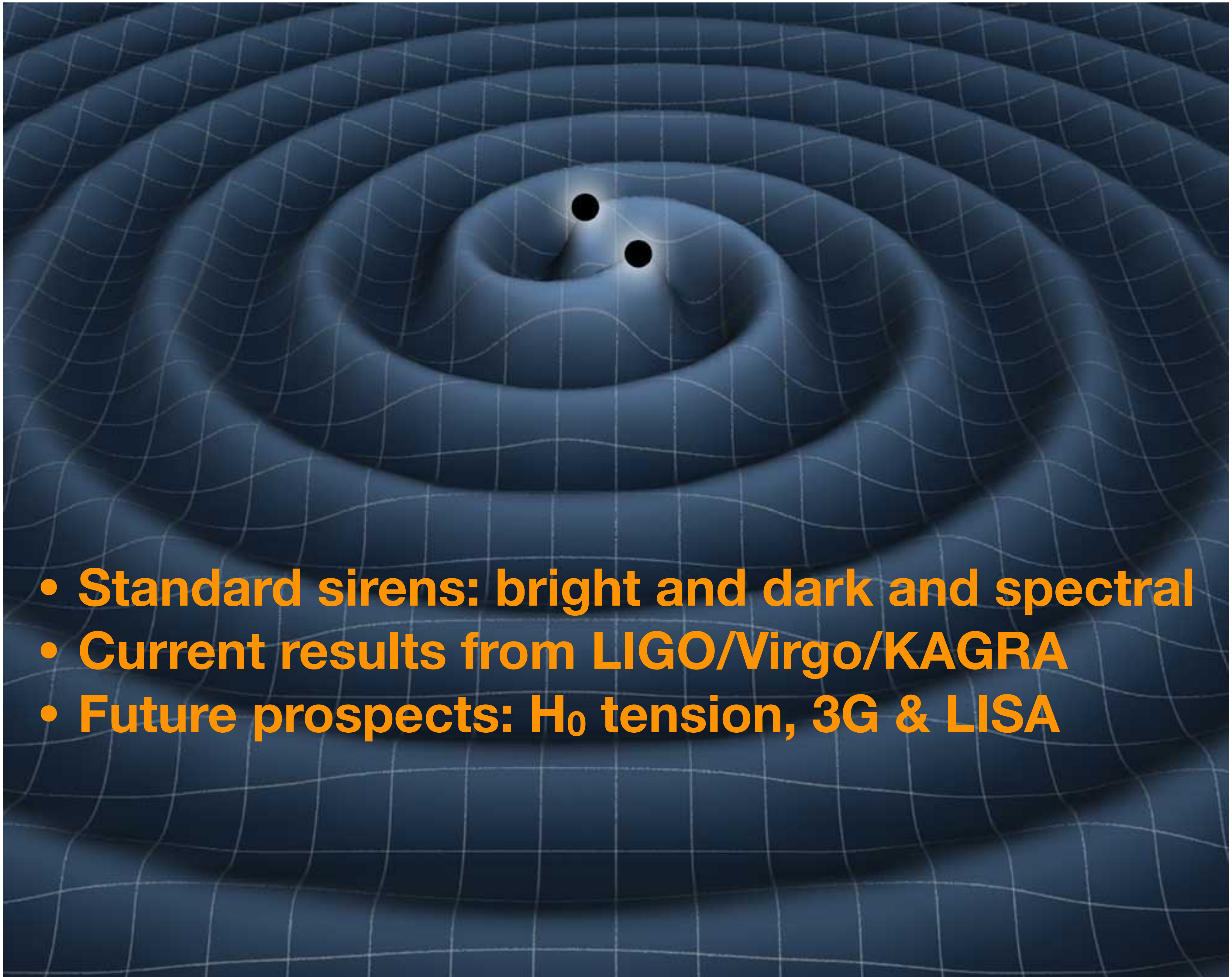
Outline

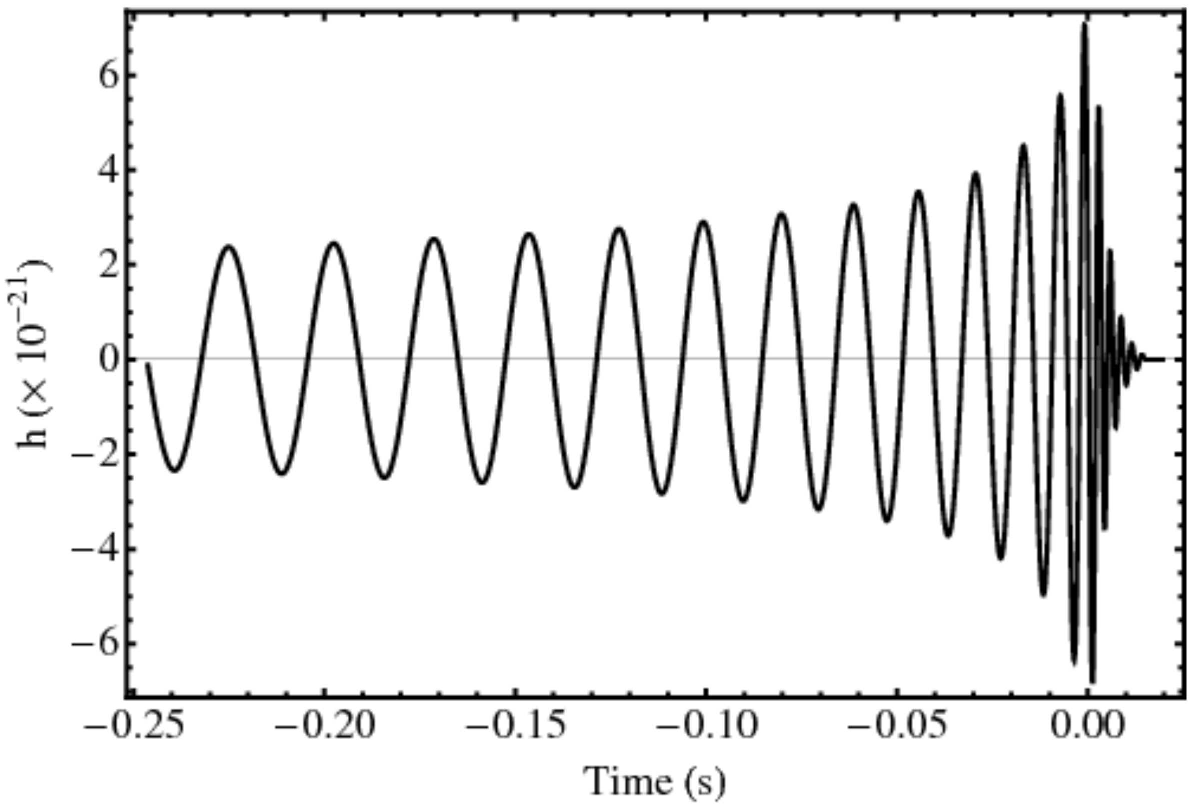


- Standard sirens: bright and dark and spectral
- Current results from LIGO/Virgo/KAGRA
- Future prospects: H_0 tension, 3G & LISA

Standard sirens

Standard sirens

How do we extract cosmological information from gravitational wave observations?



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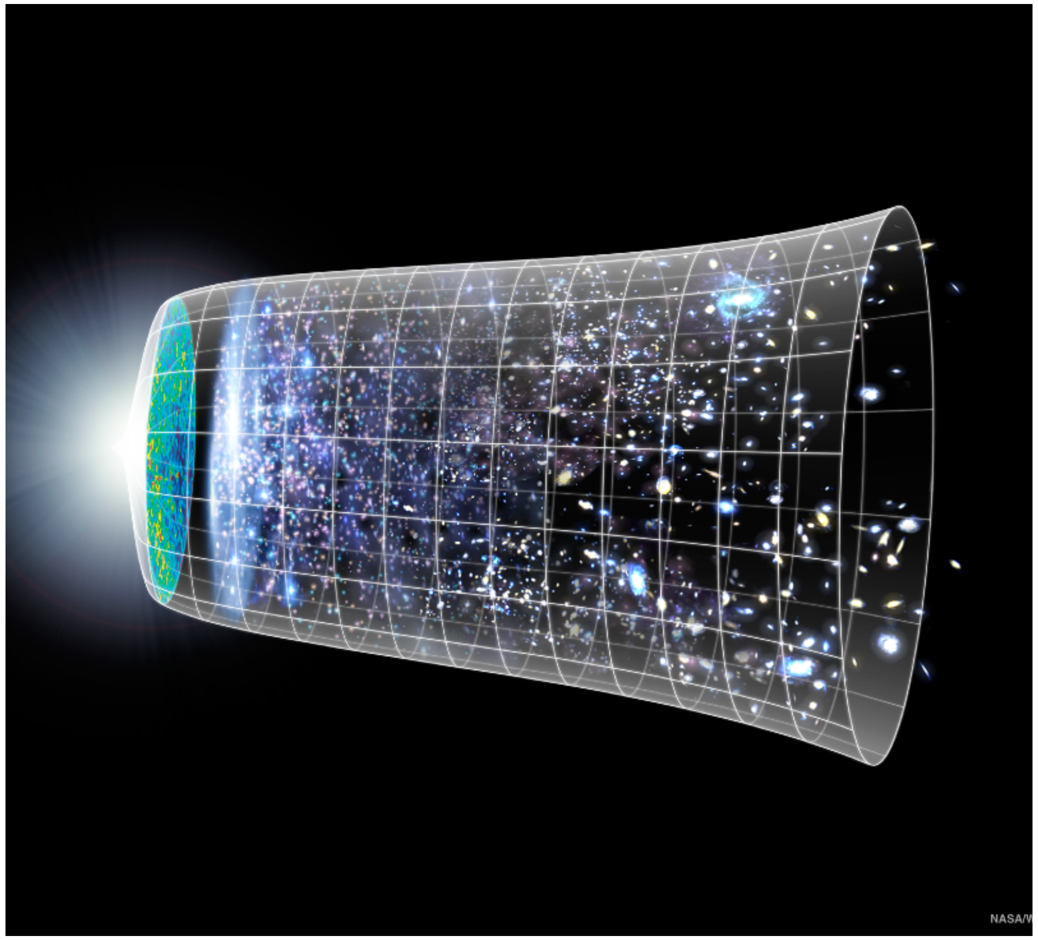
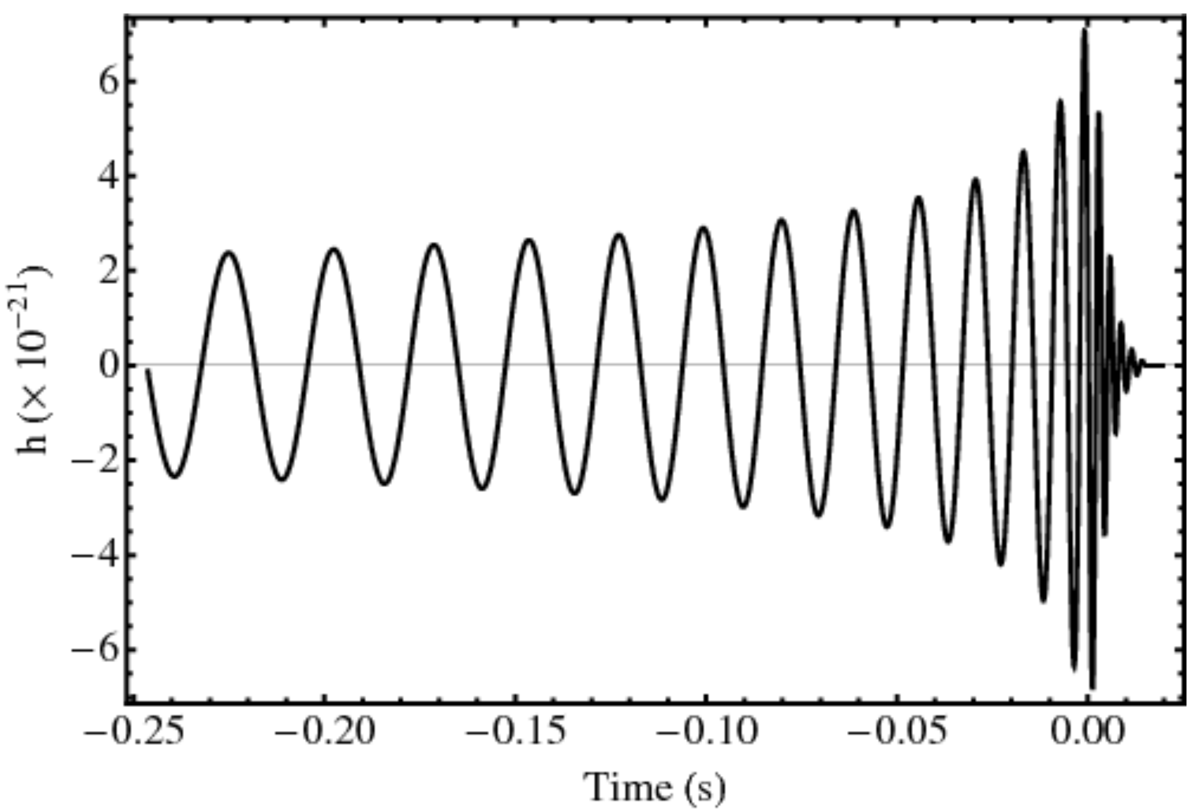


Standard sirens

The GW waveform (in time-domain at the lowest Newtonian order) used to detect GWs and measure the parameters of the system is (for the $\times$ polarisation)

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



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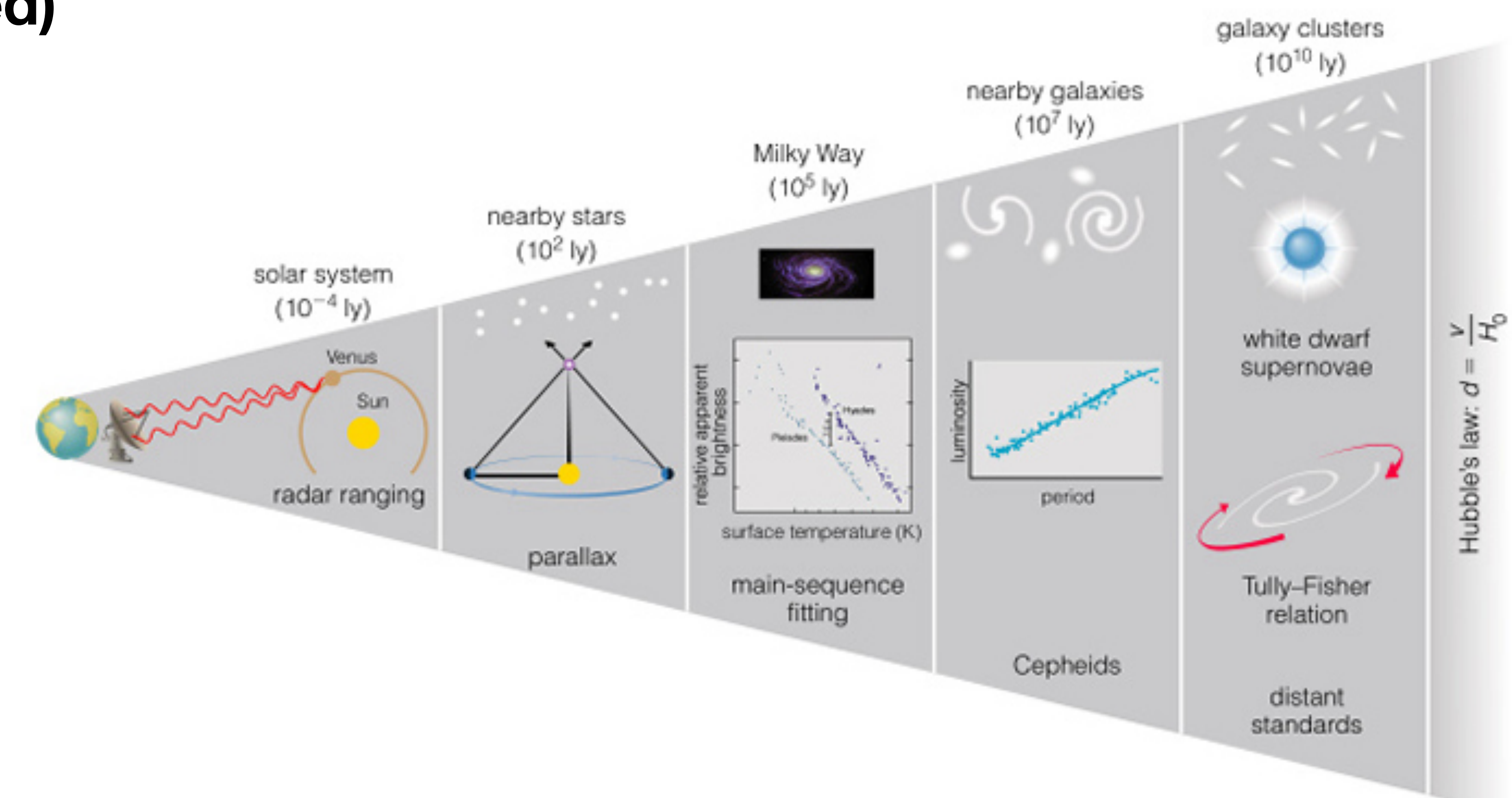
Most importantly for cosmology, one can measure the luminosity distance d_L of the source directly from the GW signal without relying on the *cosmic distance ladder* (only GR has been assumed)

This means that GW binaries are absolute cosmological distance indicators!

Free of possible calibration systematics



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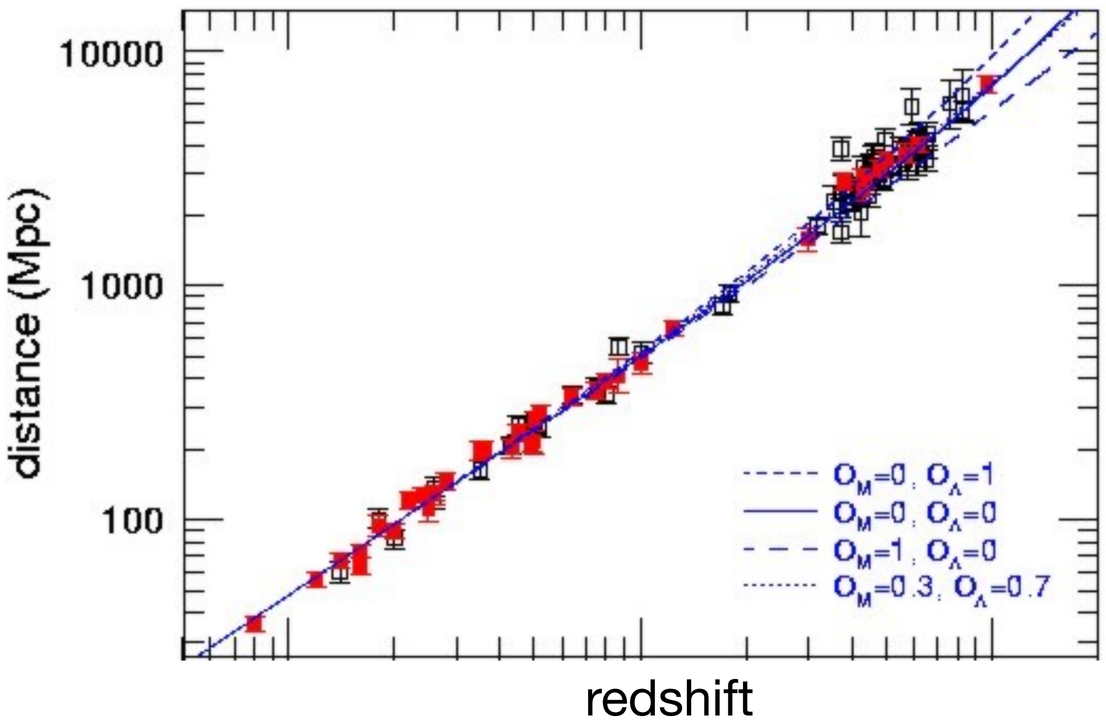
Note however that the waveform above does not depend explicitly on the redshift z, which cannot thus be measured directly from GWs

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)

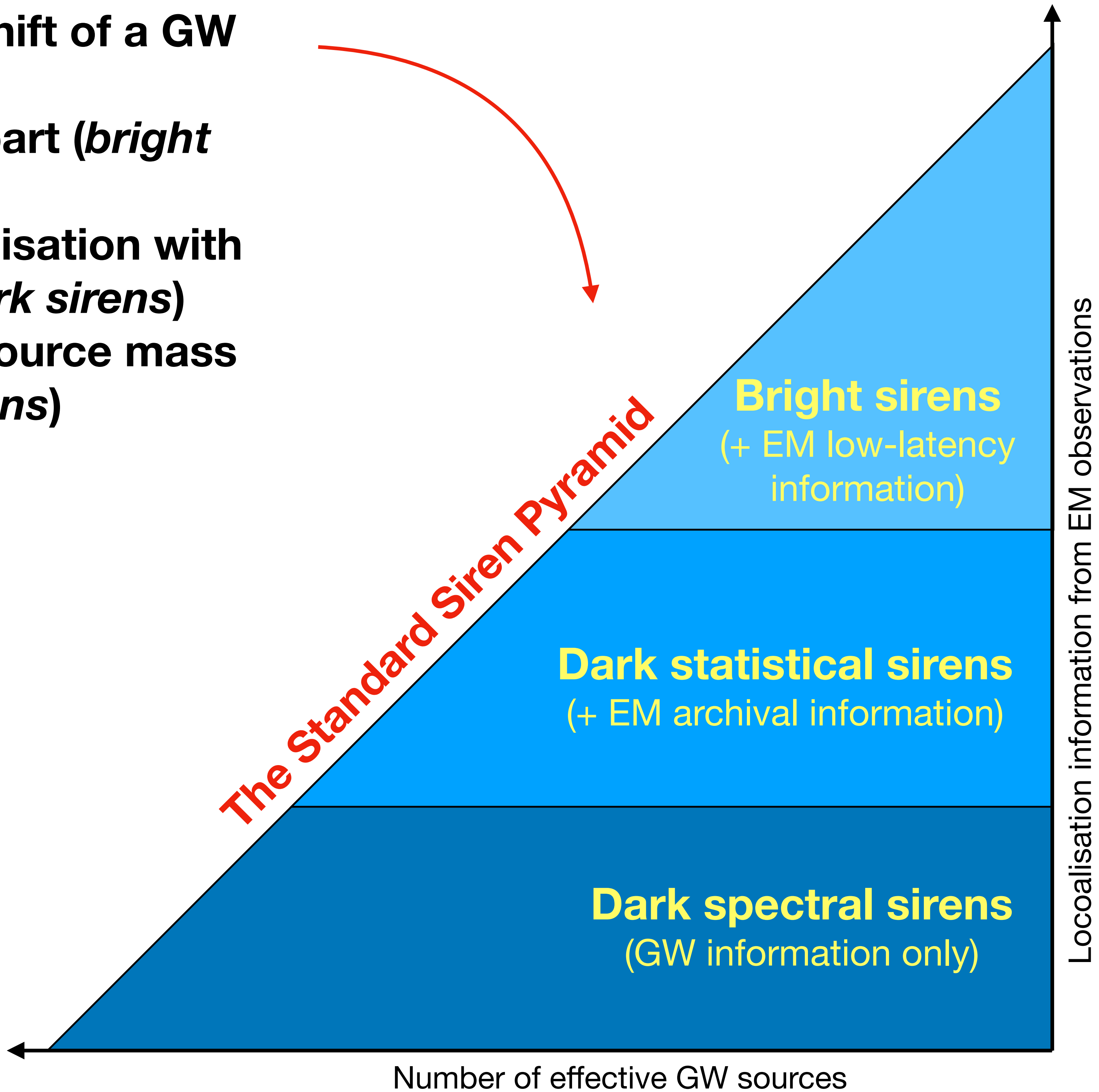


[Schutz, *Nature* (1986)]

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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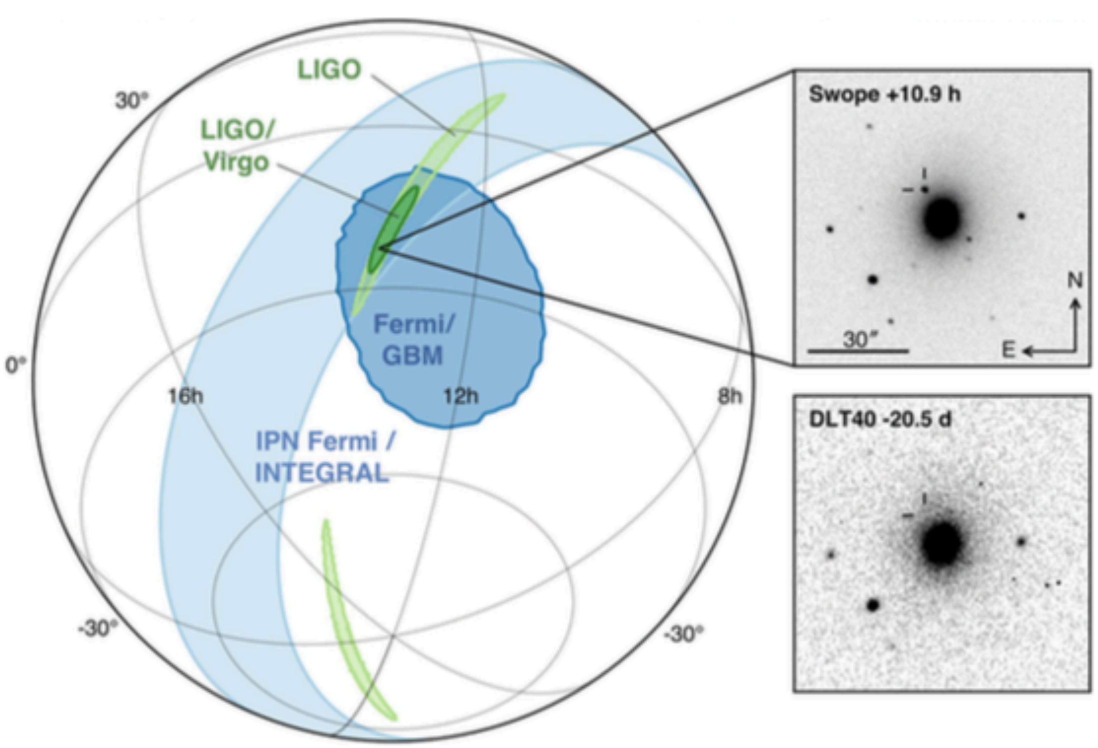
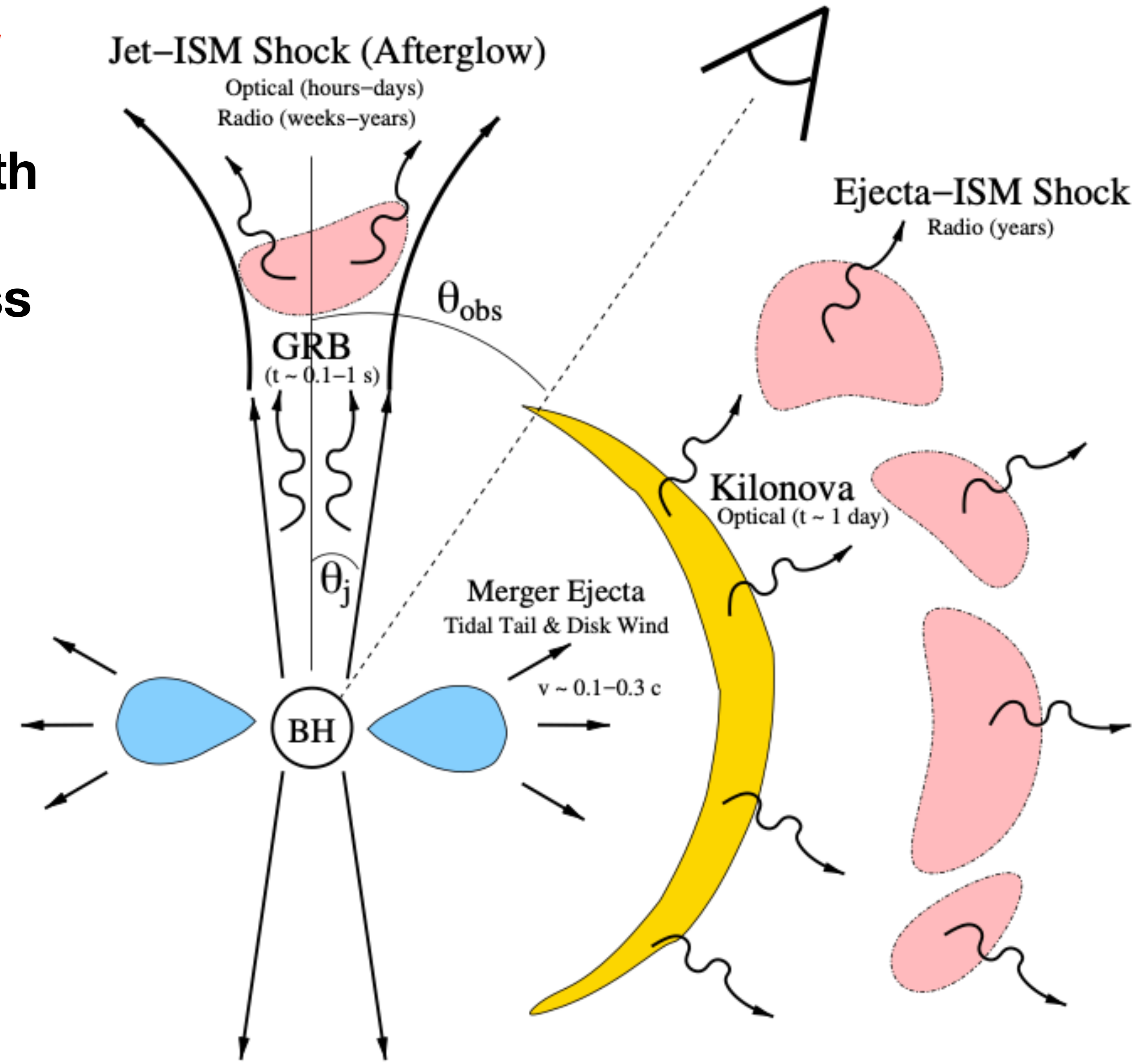


[Schutz, *Nature* (1986)]
[LVC+, *ApJL* (2017)]

Example: BNS mergers



[Metzger&Berger, *ApJ* (2012)]

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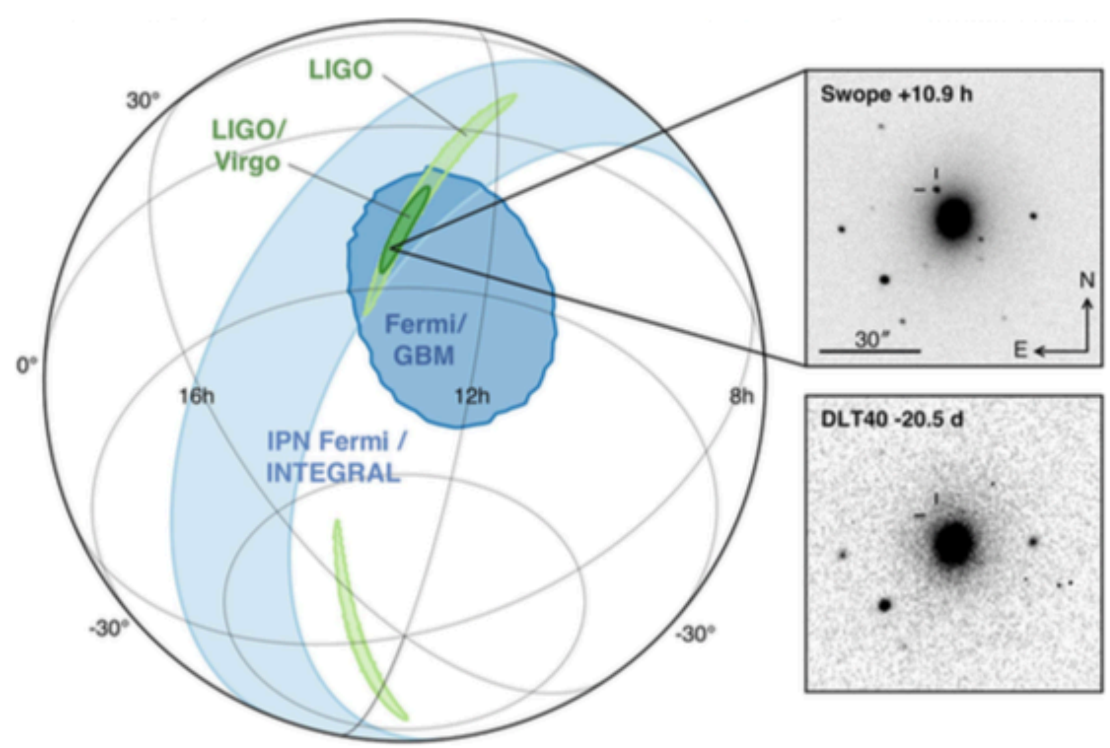

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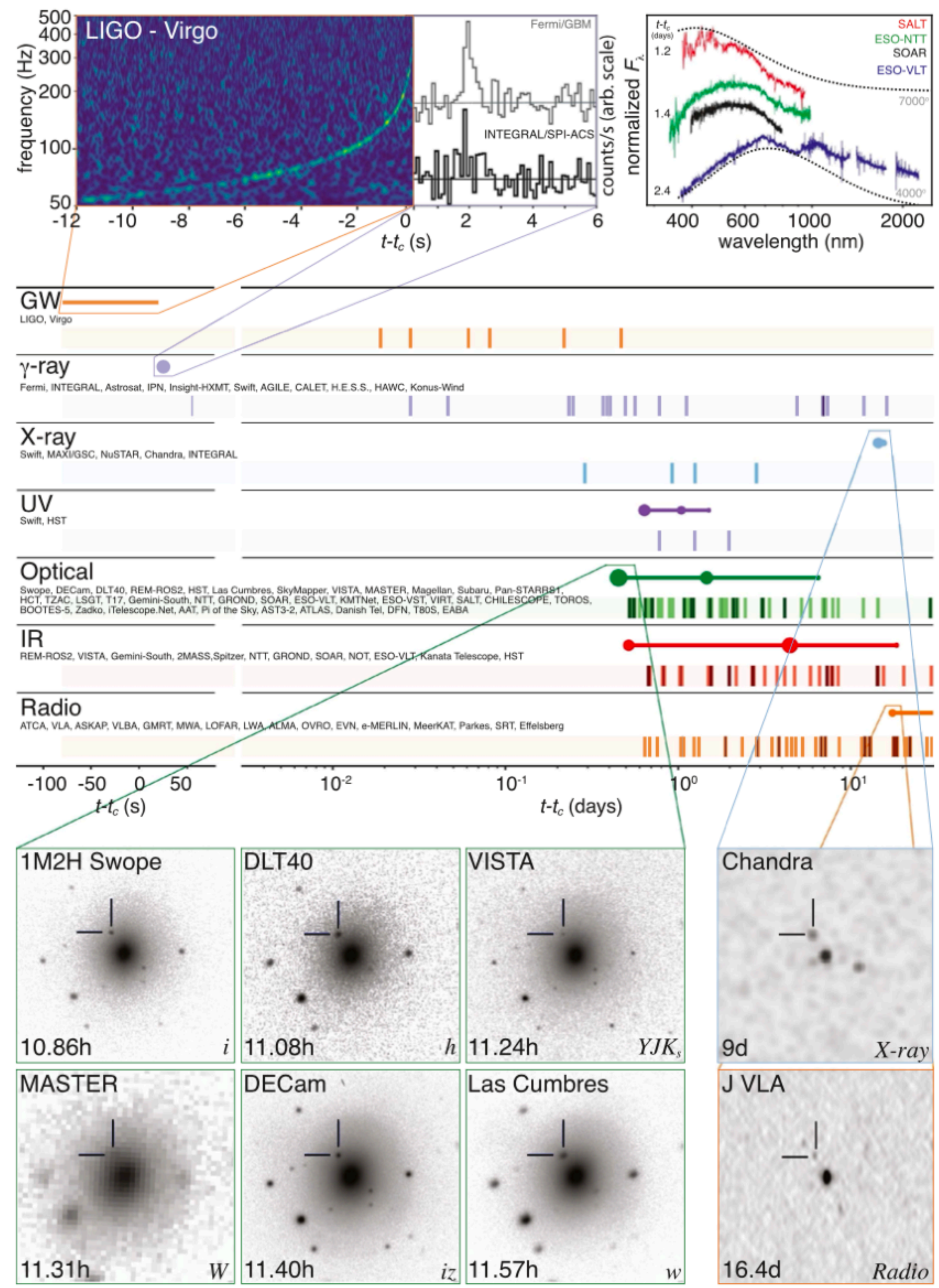

Example: GW170817

[LVC+, *ApJL* (2017)]

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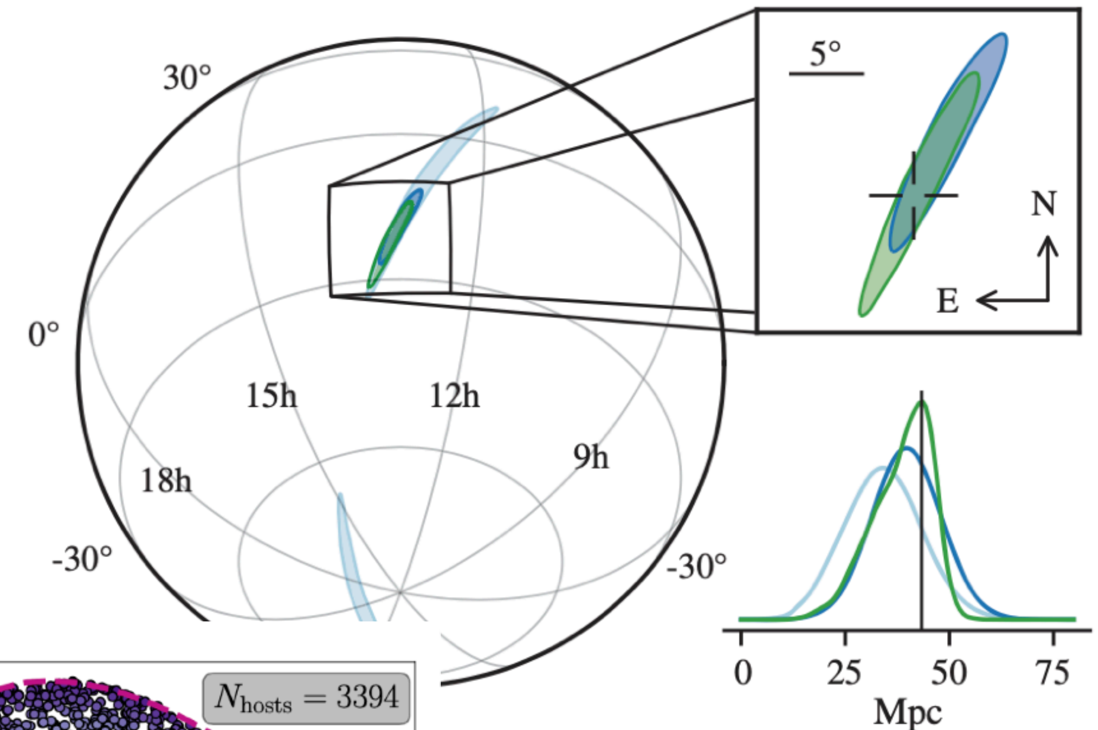

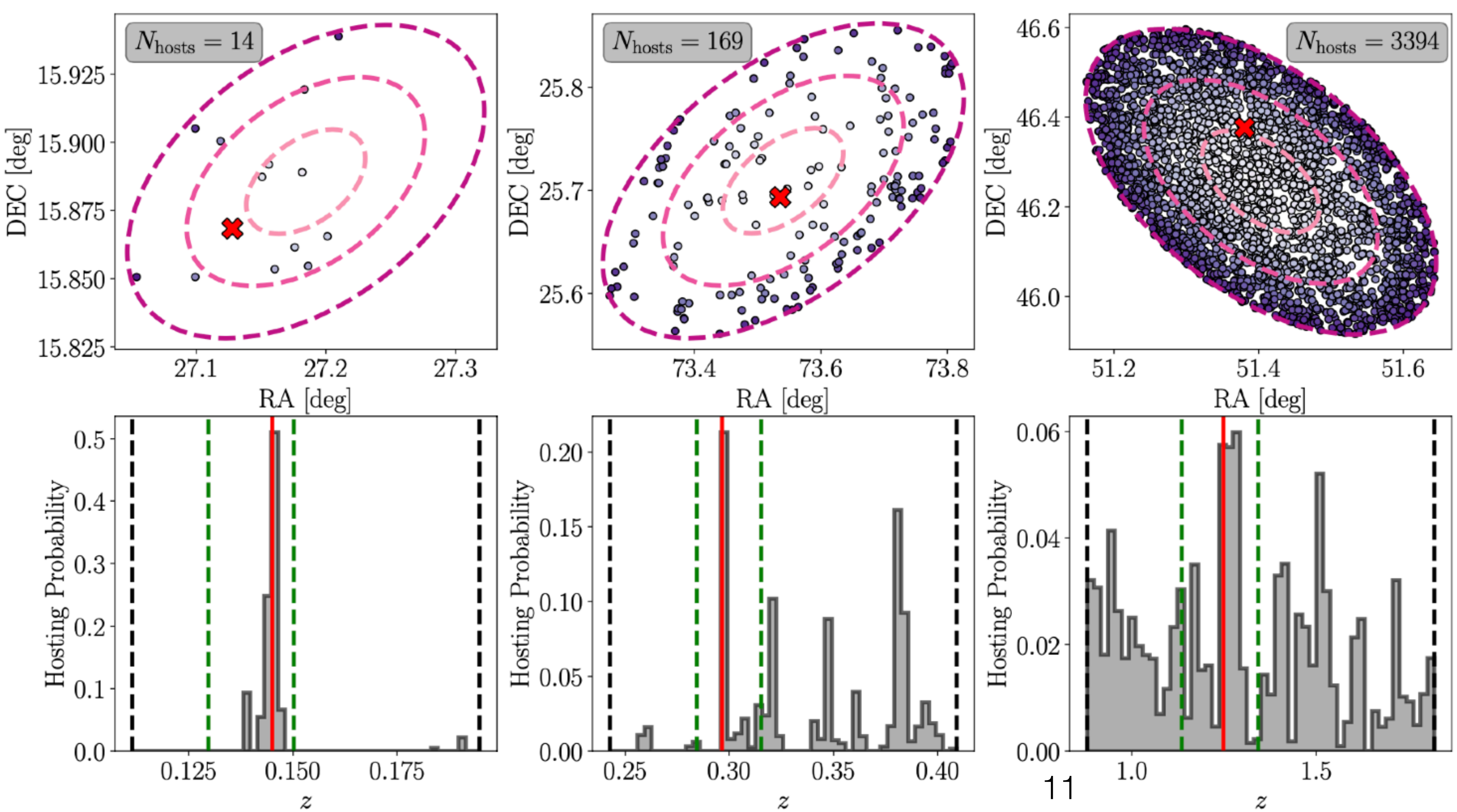

Every galaxy gives a redshift value which in turns gives possible values for the cosmological parameters

[Schutz, *Nature* (1986)]
[Del Pozzo, *PRD* (2012)]
[Gray+, *PRD* (2020)]
[Gray+, *JCAP* (2023)]

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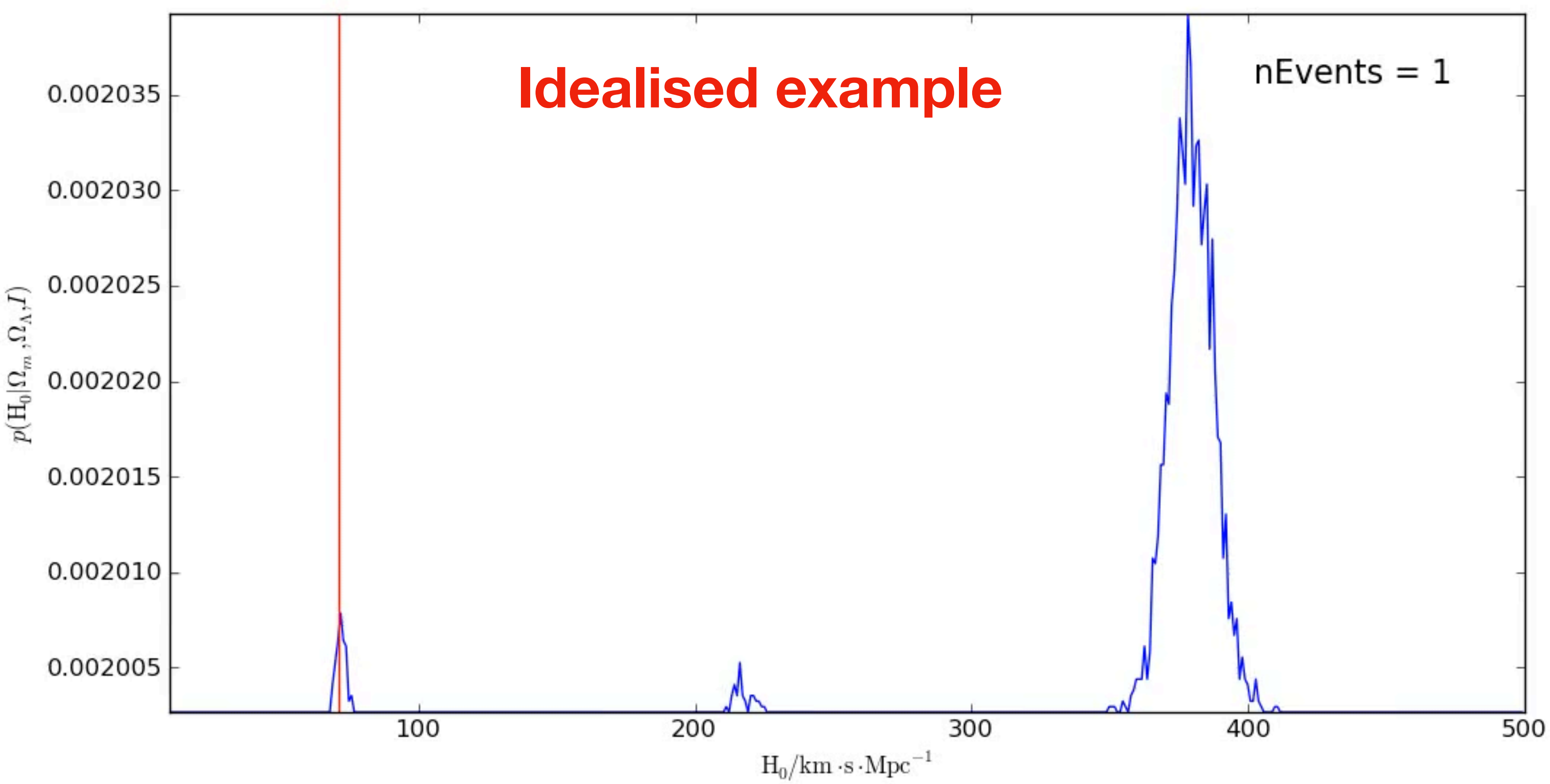

Credit: W. Del Pozzo

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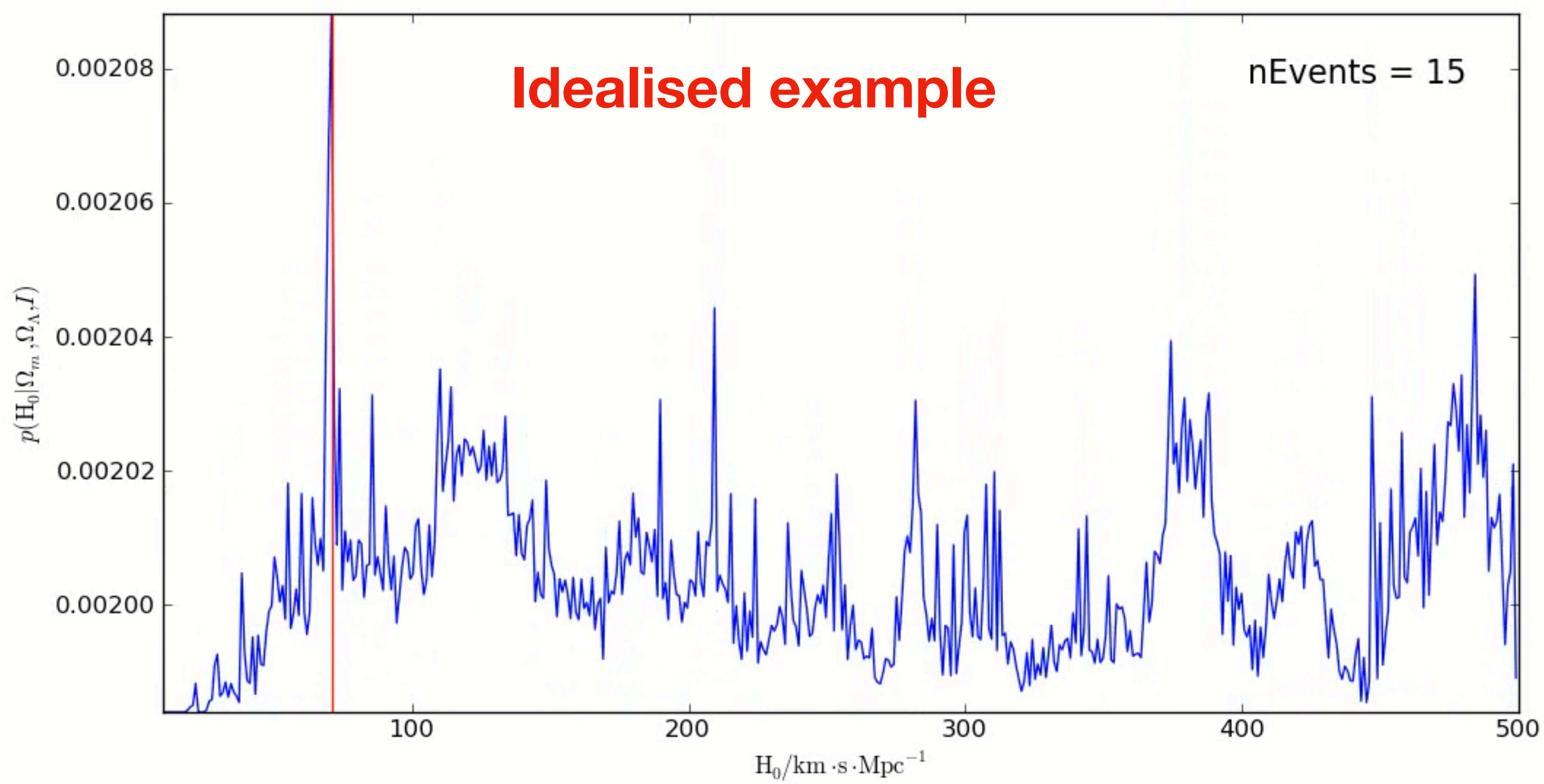

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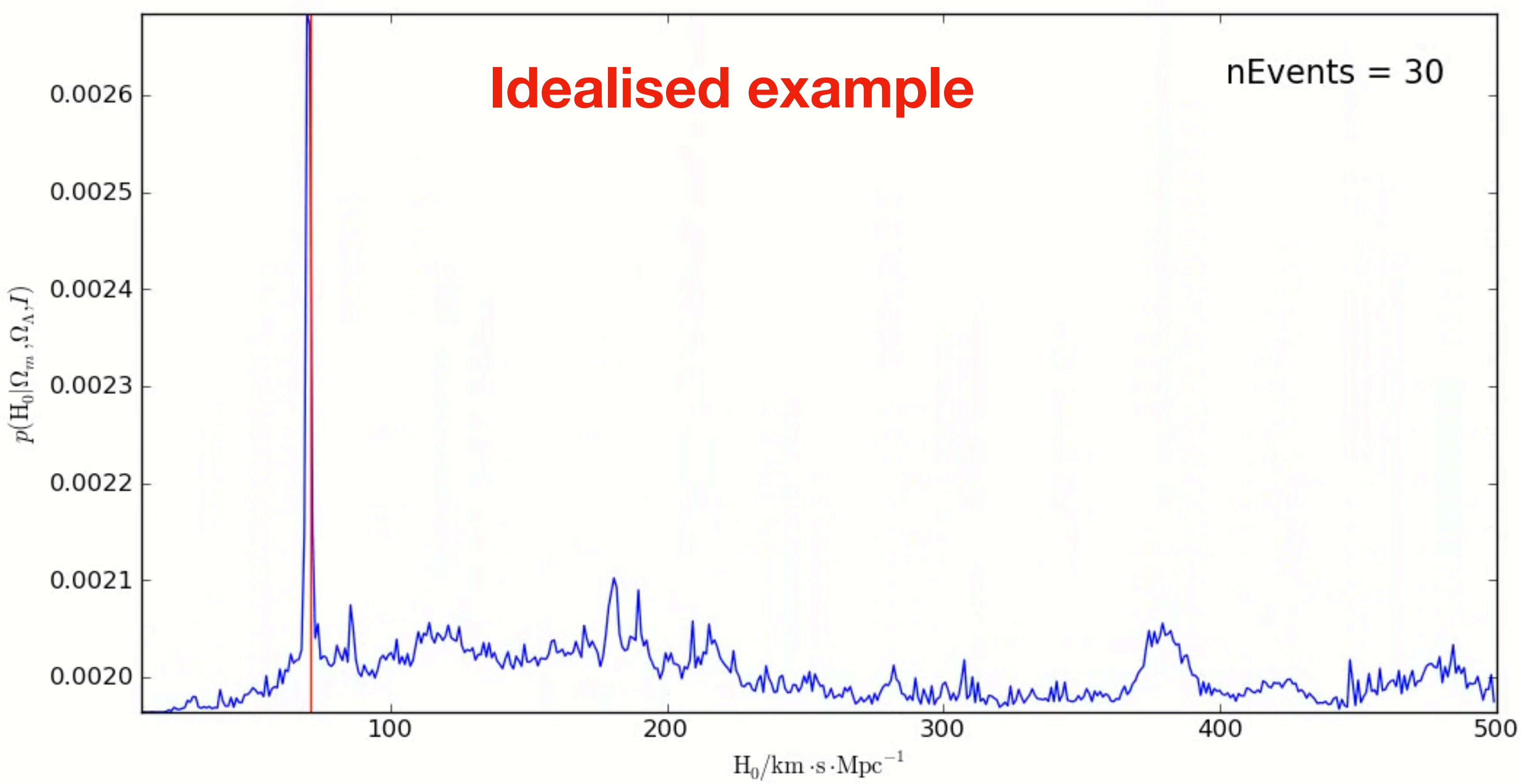

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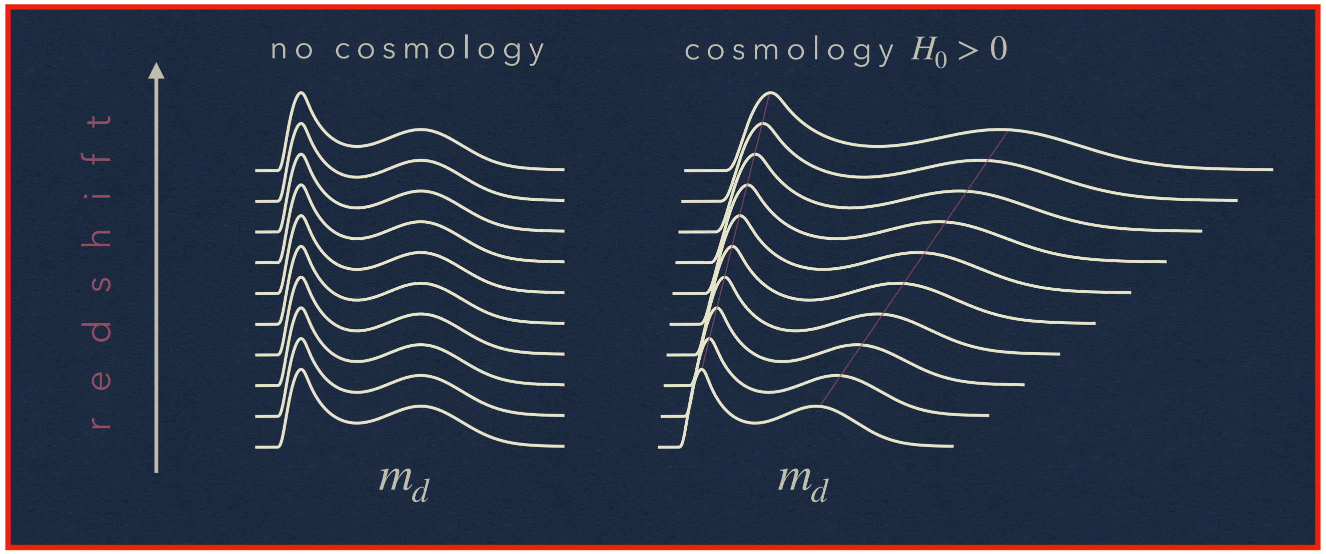
Credits: V. Gennari



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

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Redshifted chirp mass

$$\mathcal{M}_{cz} = (1+z)\mathcal{M}_c$$

[Taylor+, *PRD* (2012)]

[Mastrogiovanni+, *PRD* (2021)]

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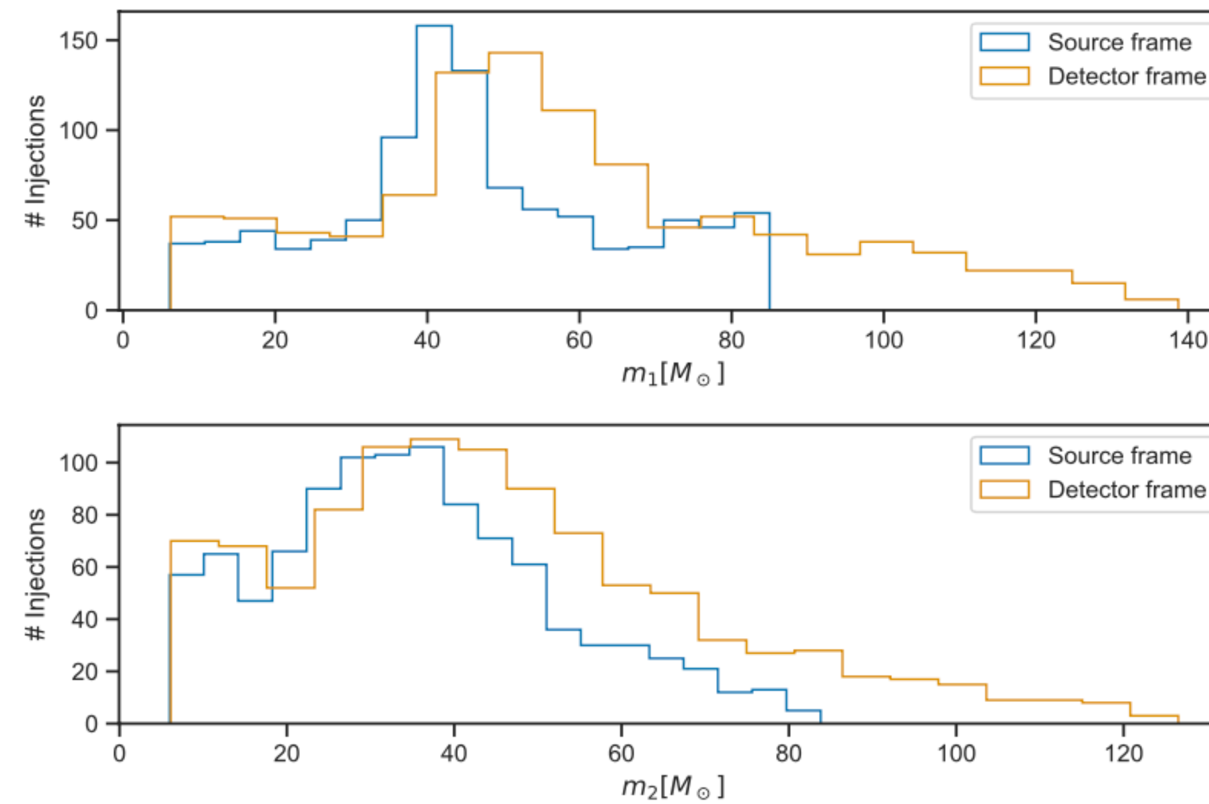
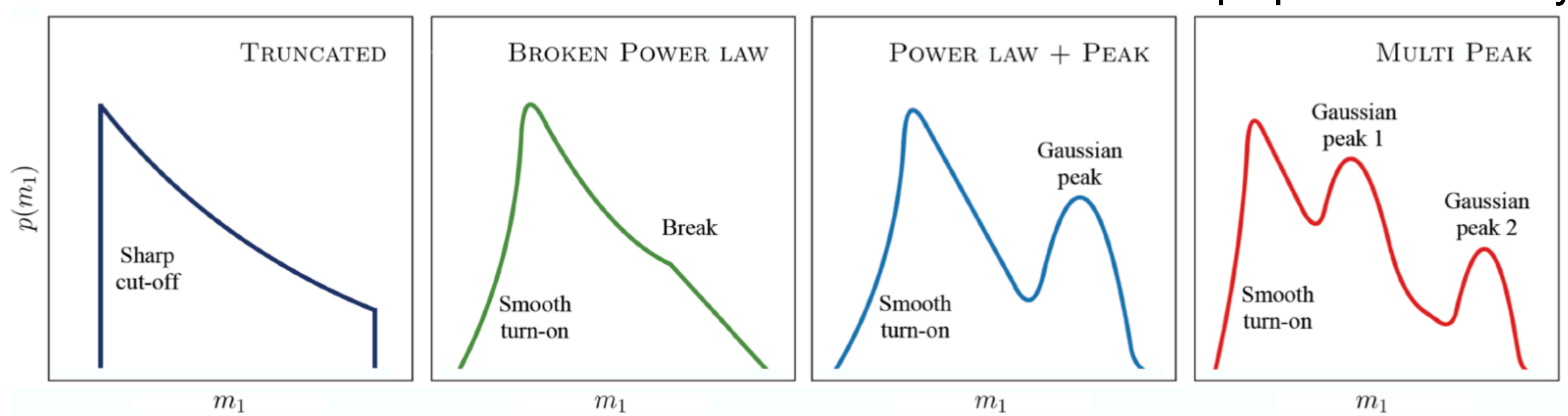


Source-frame mass distributions used for the LVK O3 BBH population analyses



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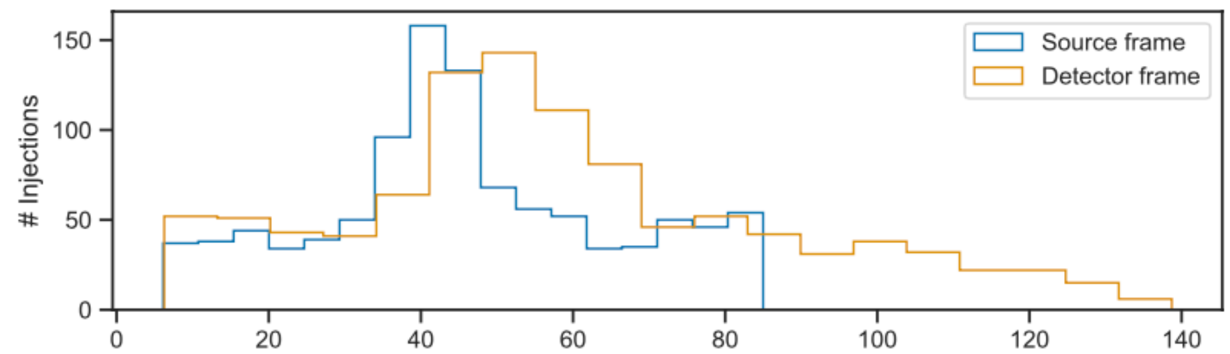
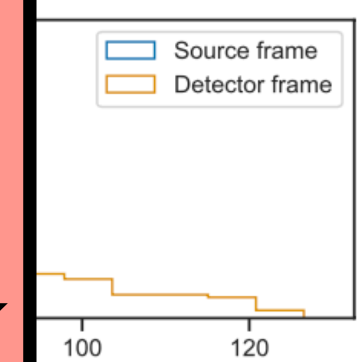
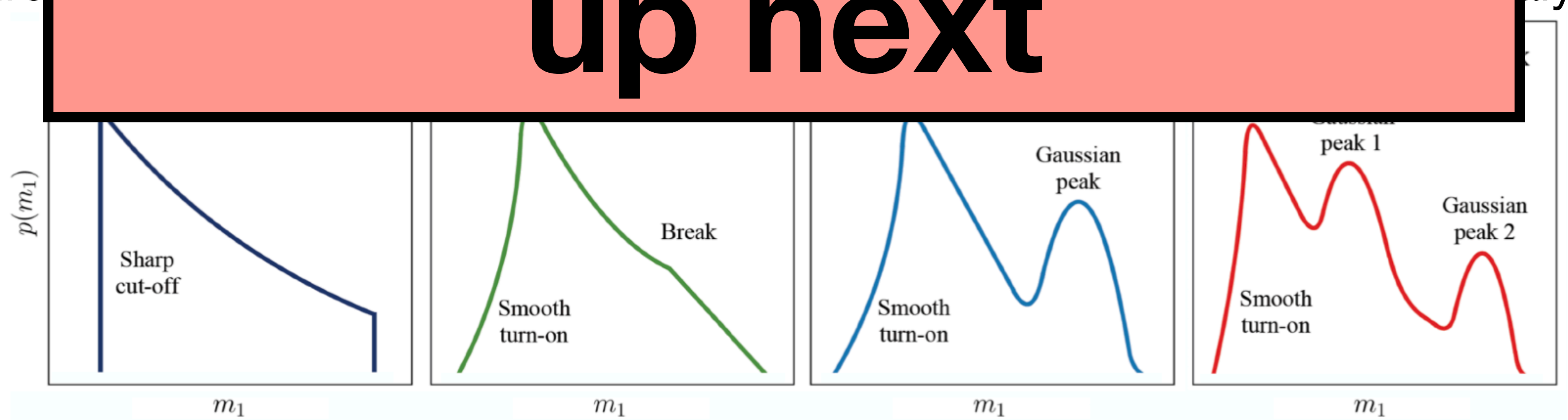




More details in Vasco Gennari's Talk up next

Sourc alyses



[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

Current results from LVK

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Status of Earth-based GW observations:

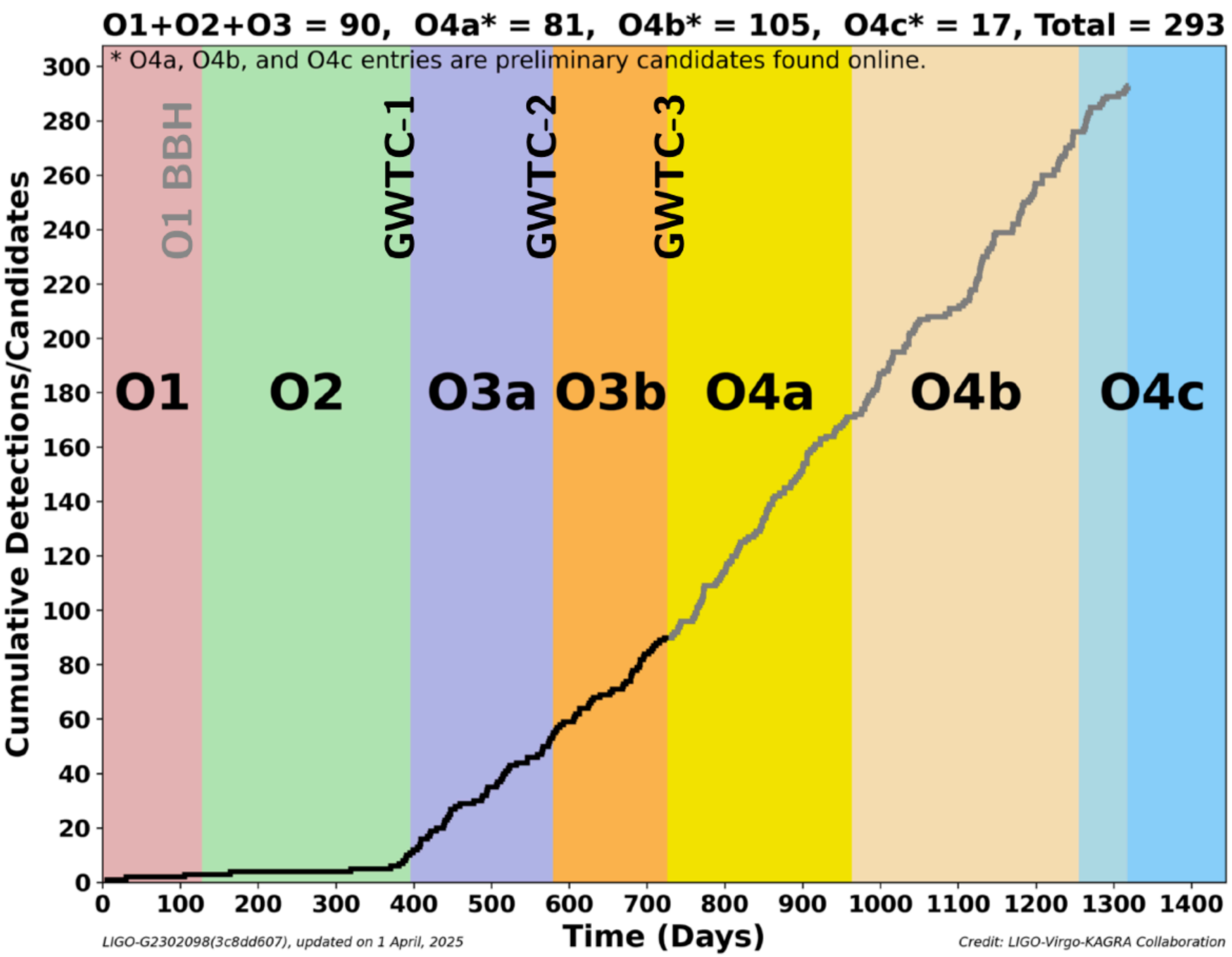
Current results from LVK

<u>Status of Earth-based GW observations:</u>

- O1: 2015 (completed), LIGO only, 4 months of data, 3 BBHs detected
- O2: 2017 (completed), LIGO(+VIRGO for GW1708xx only), 6 months of data, 7 BBHs + 1 BNS with EM counterpart (GW170817)
- O3: 2019 (completed), LIGO+VIRGO, ~1 year of data, 79 events, 73 BBHs + 2 BNSs + 4 NSBHs
- O4: May 2023 -> Oct 2025 LIGO+VIRGO(+KAGRA)
- O5: ~2027

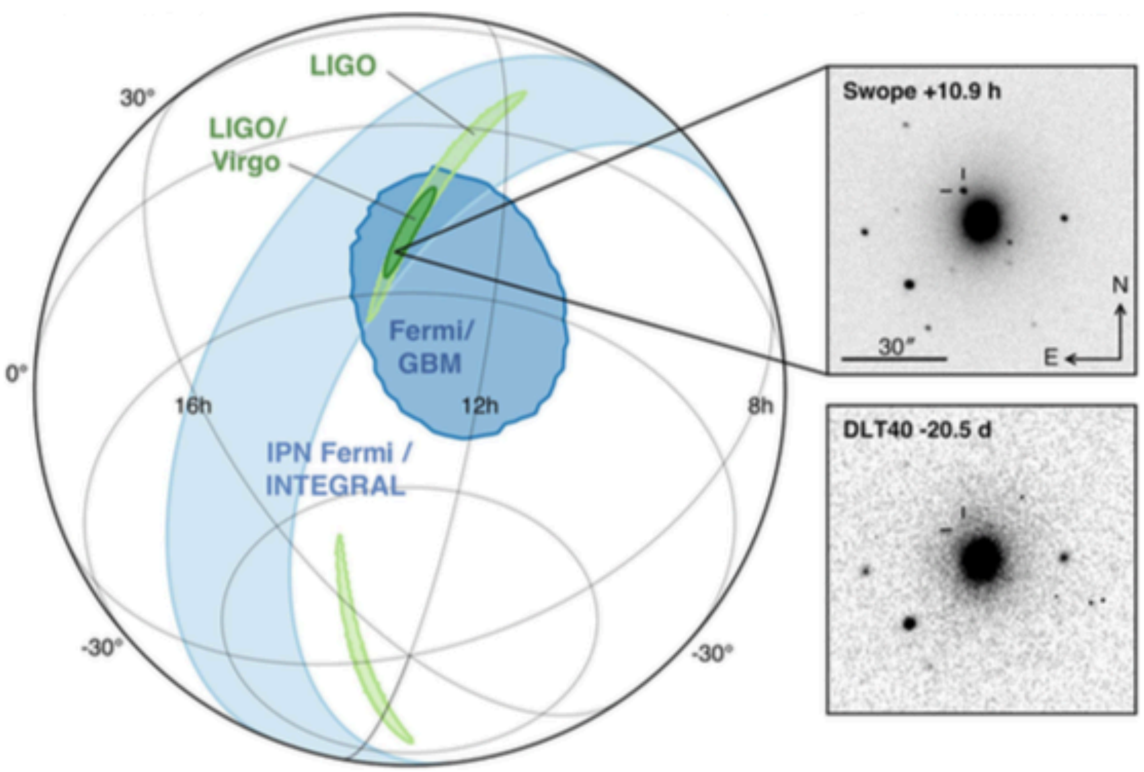
90 high-significance GW events from O1/O2/O3

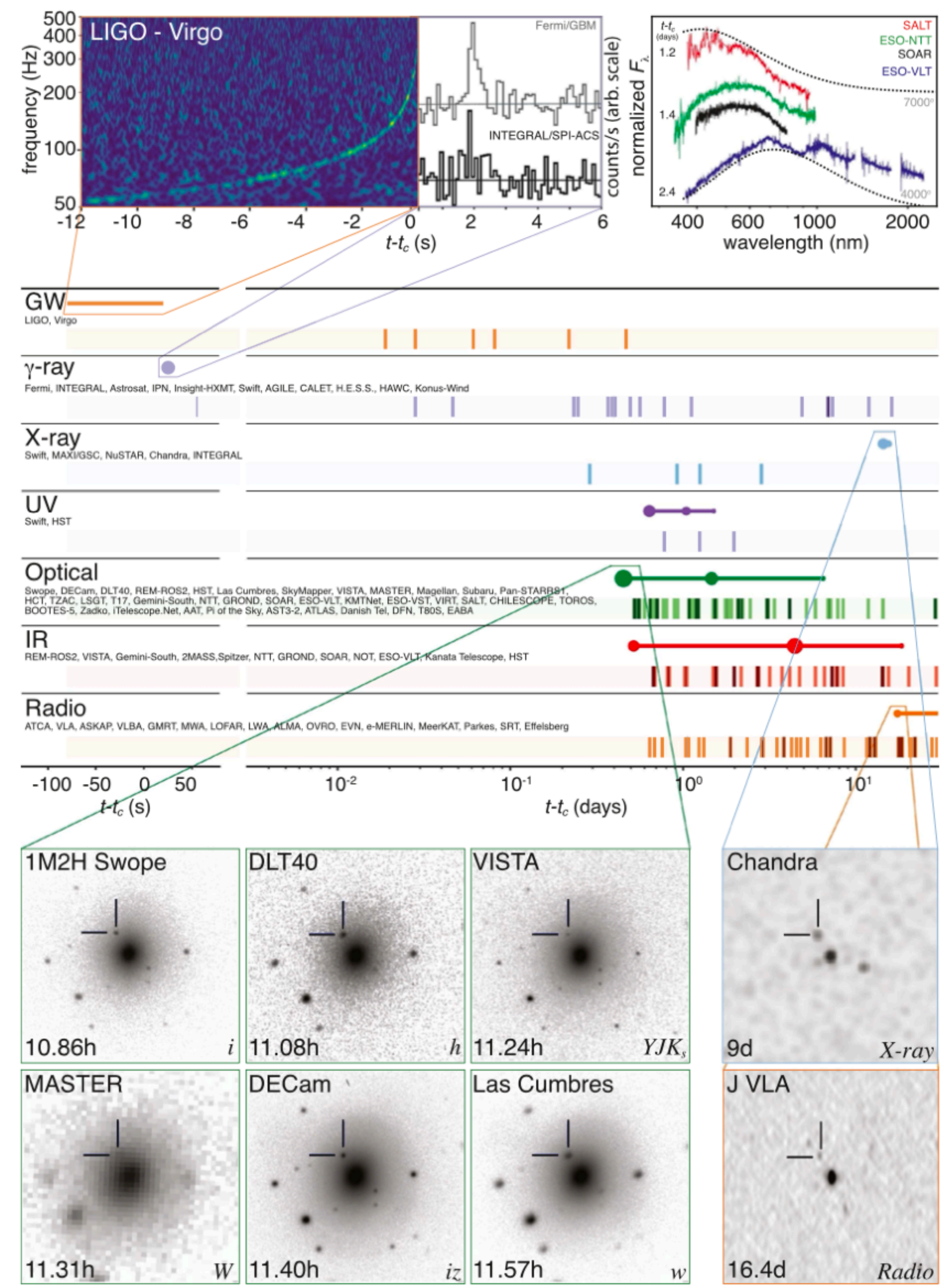
More than 200 preliminary detections from O4



Current results from LVK

GW170817: the first ever (bright) 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)]
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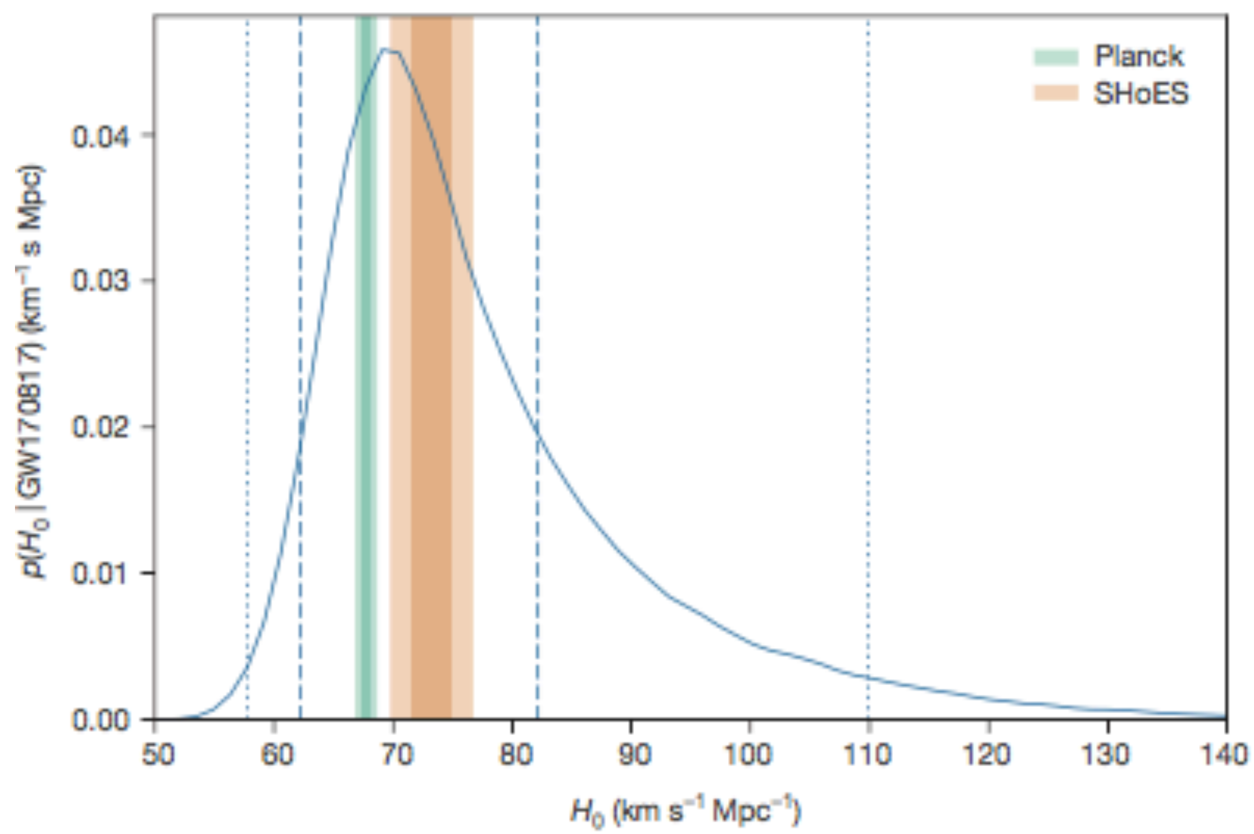

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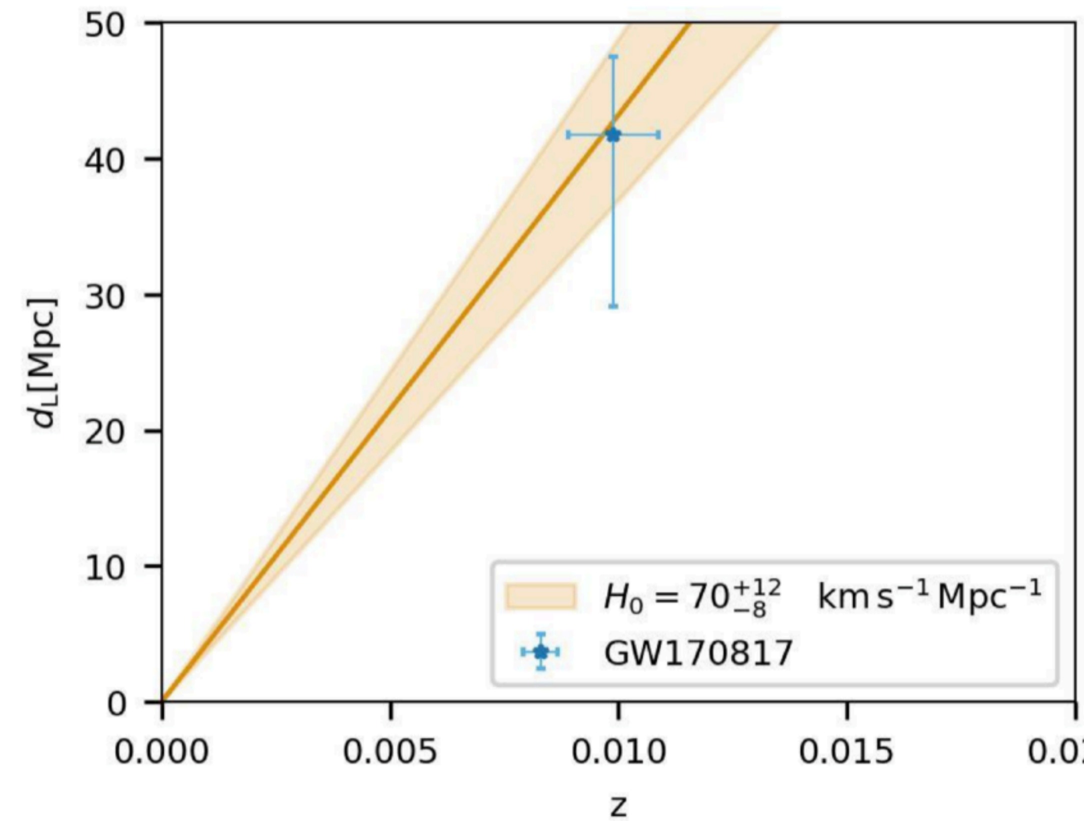


Low-redshift event ($z = 0.01$): only H_0 can be measured (**Hubble law**)

$$d_L(z) \simeq \frac{c}{H_0} z \quad for \;\; z \ll 1$$

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

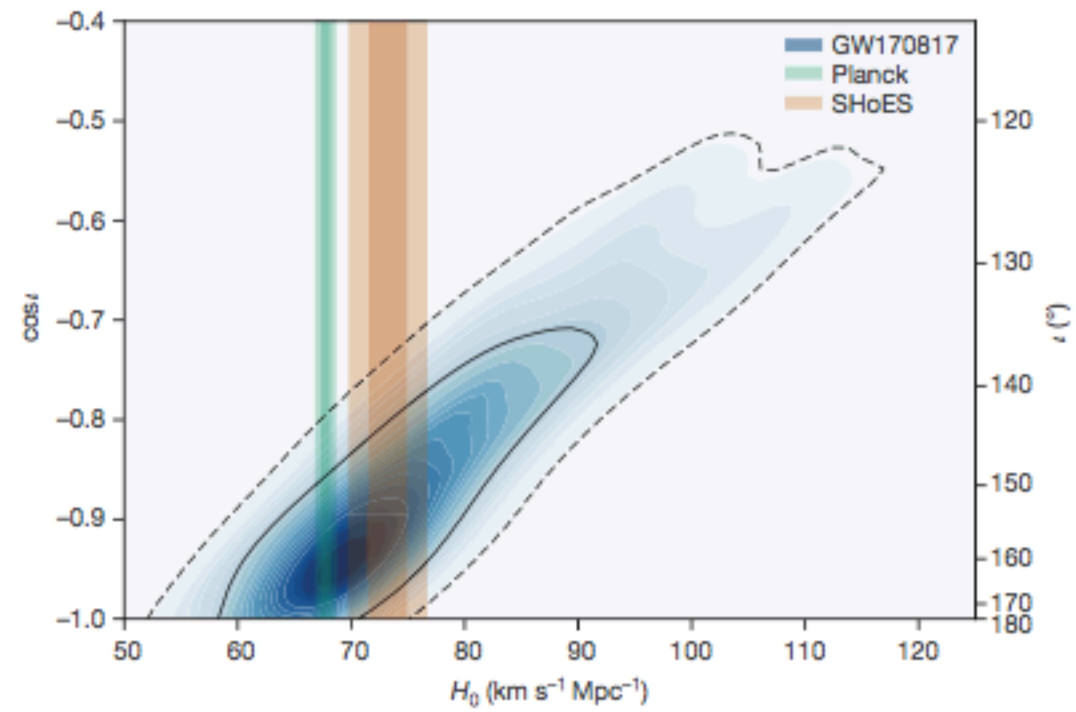
Current results from LVK

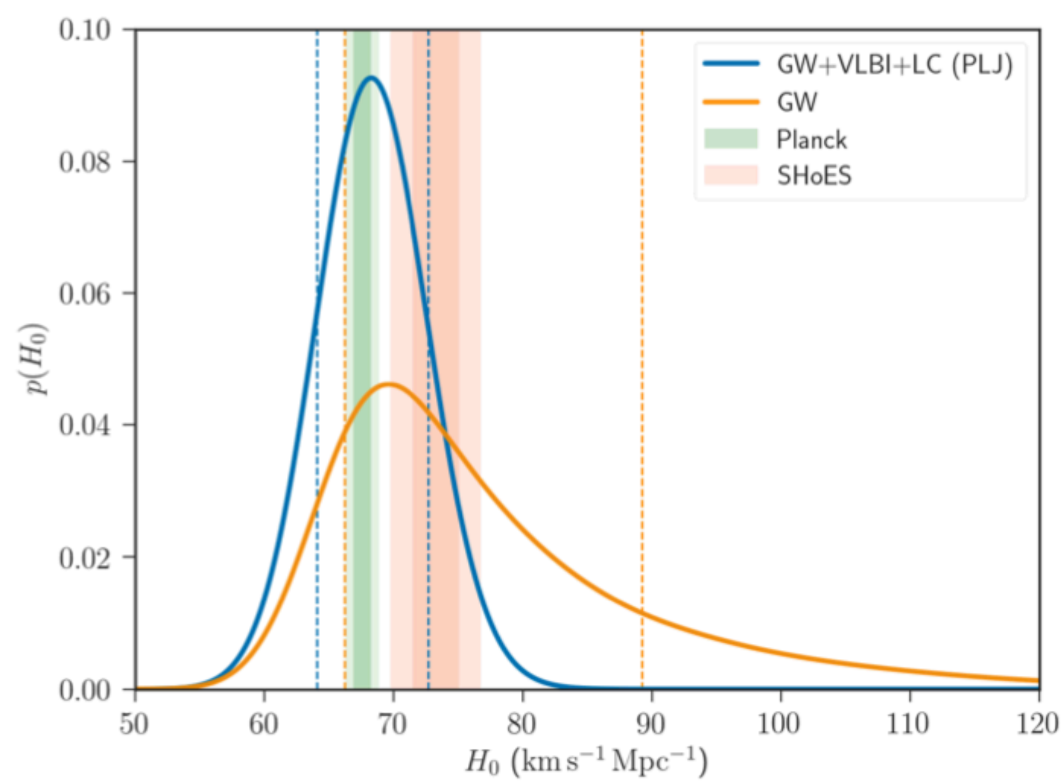
GW170817: the first ever (bright) standard siren

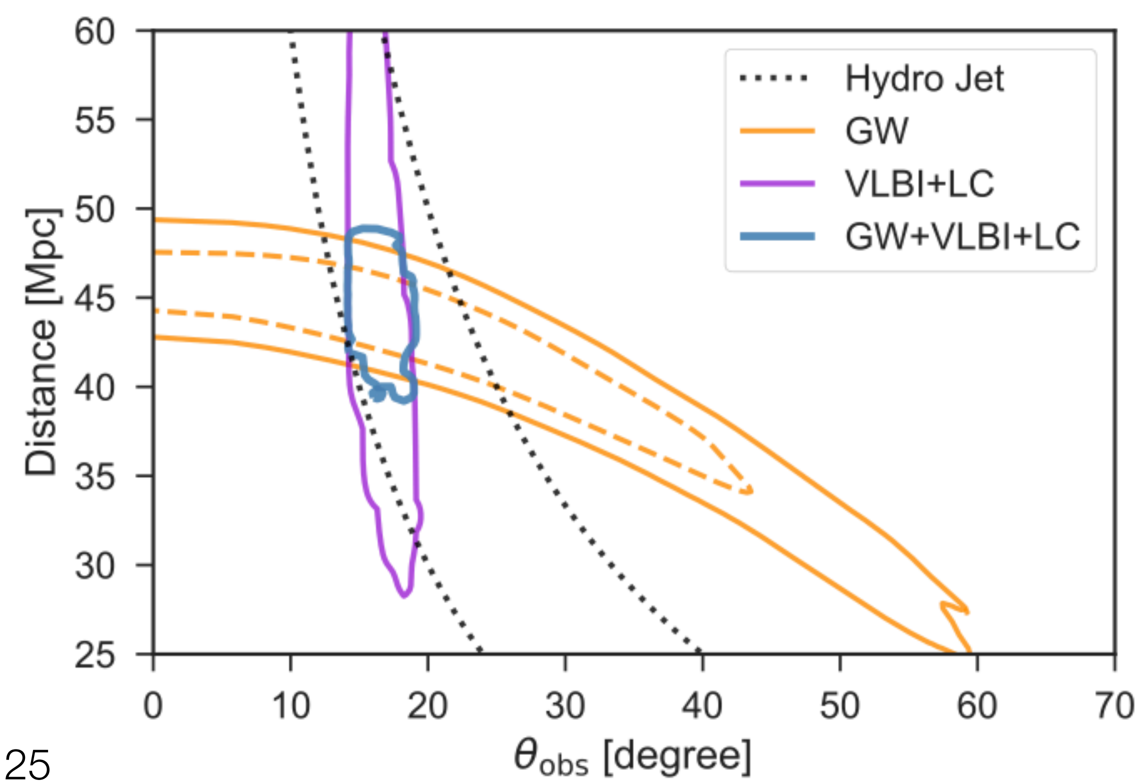
The distance-inclination degeneracy can be broken/alleviated with EM measurements of the viewing angle of the emitted radio jet.

H_0 measured at 7% level, but dependent on jet modelling.

[Hotokezaka+, *Nature* (2019)]







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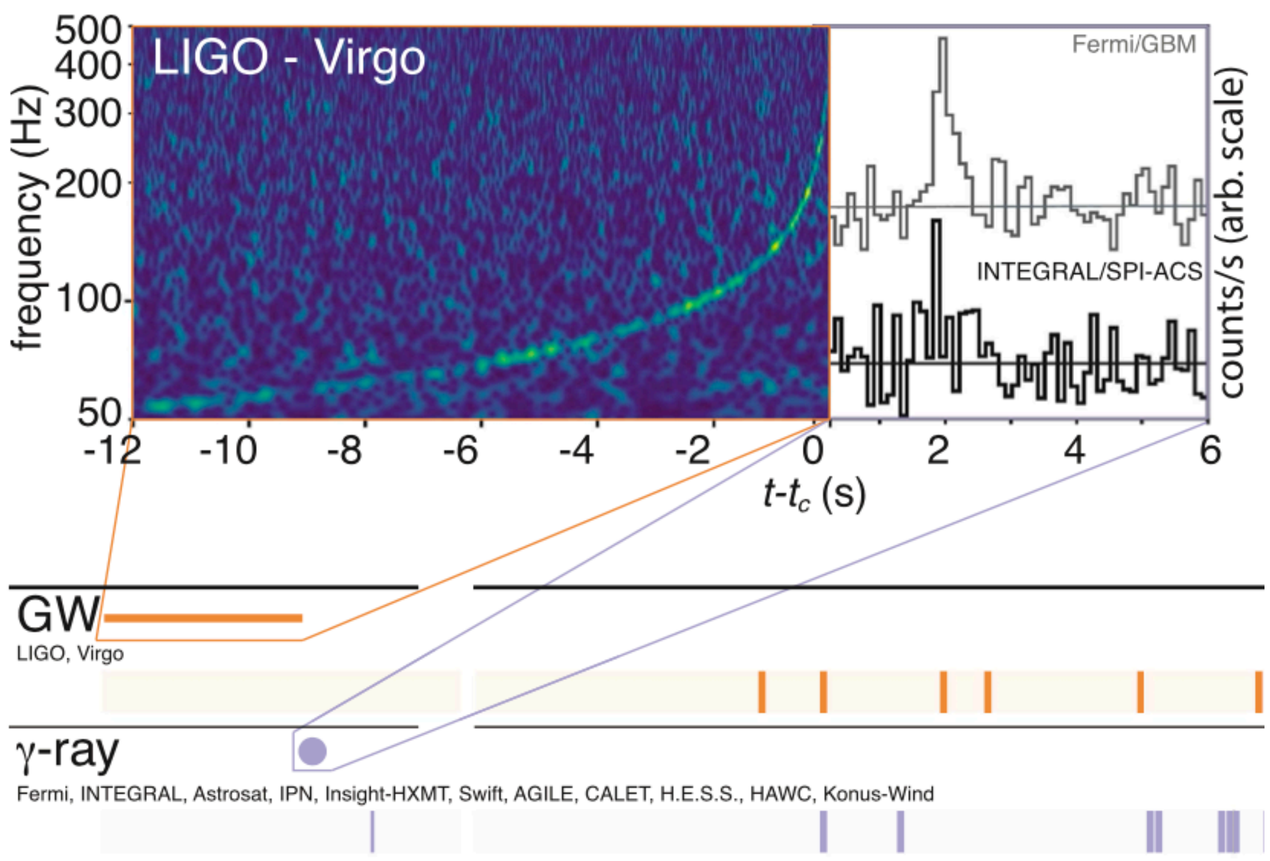


[LVC+, *ApJL* (2017)]

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

$$c_T = c^{+7\times10^{-16}}_{-3\times10^{-15}}$$

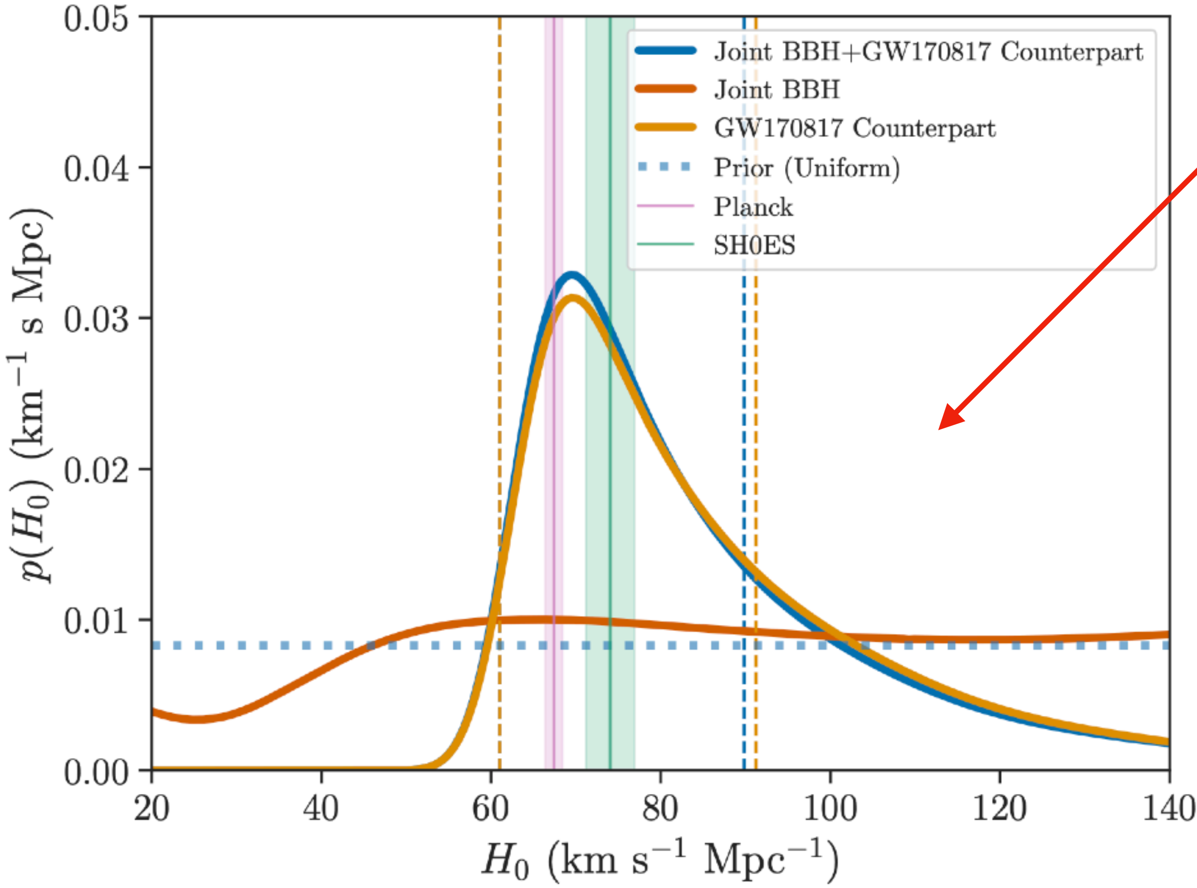
This observation rules out several modified gravity models predicting $c_T \neq c$ [see e.g. 1807.09241 and refs therein]

The low redshift of GW170817 however do not allow for any relevant constraints on the GW friction ν

[Belgacem+, *PRD* (2018)]

Current results from LVK

The <u>statistical dark siren method</u> has then been applied to combine BBHs events:



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

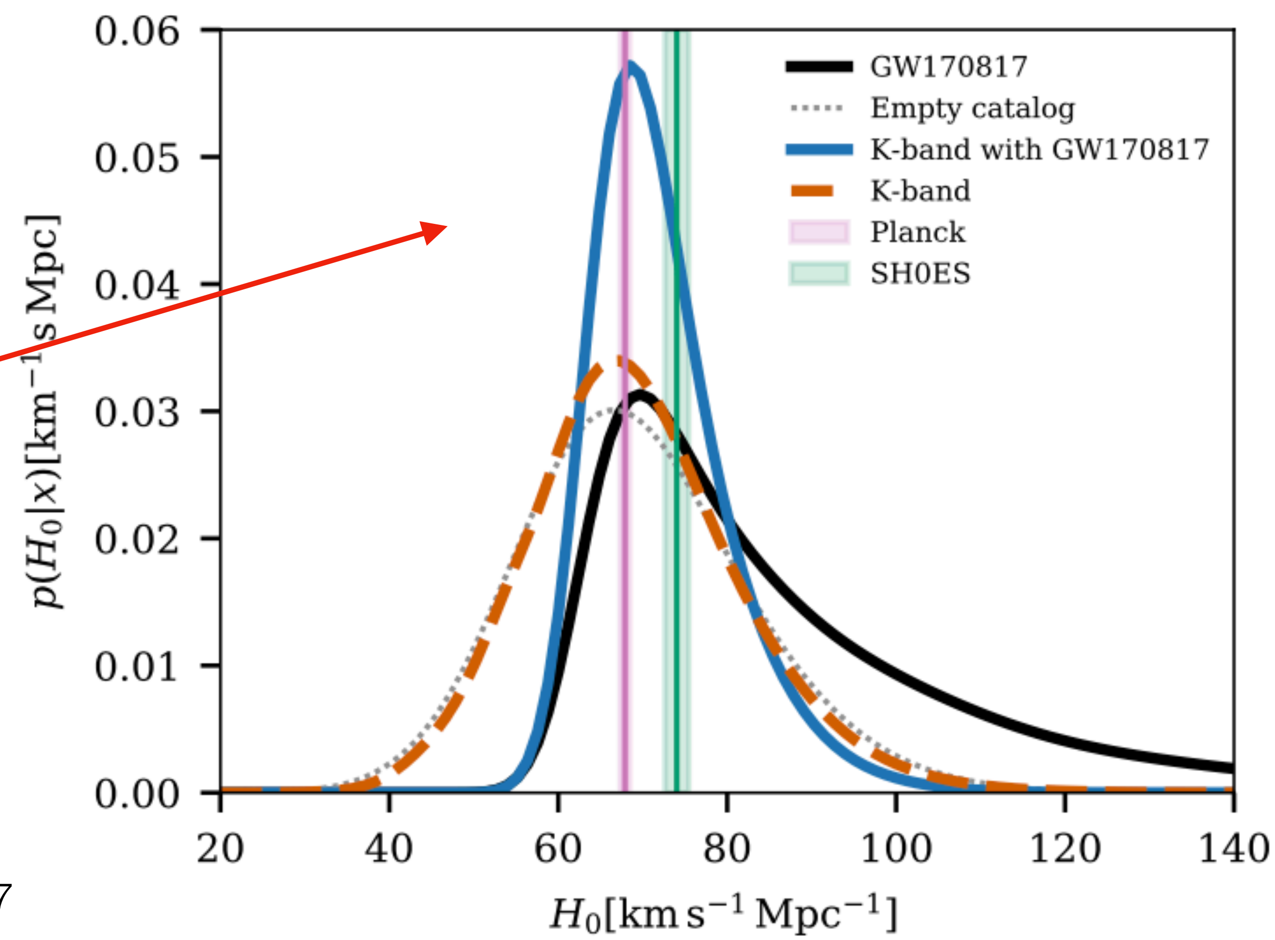
$$H_0 = 69^{+16}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(4% improvement over GW170817 only)

LVC results with all events so far combined (O1+O2+O3): [LVK, *ApJ* (2023)]

$$H_0 = 68^{+8}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(20% improvement over O2 results)



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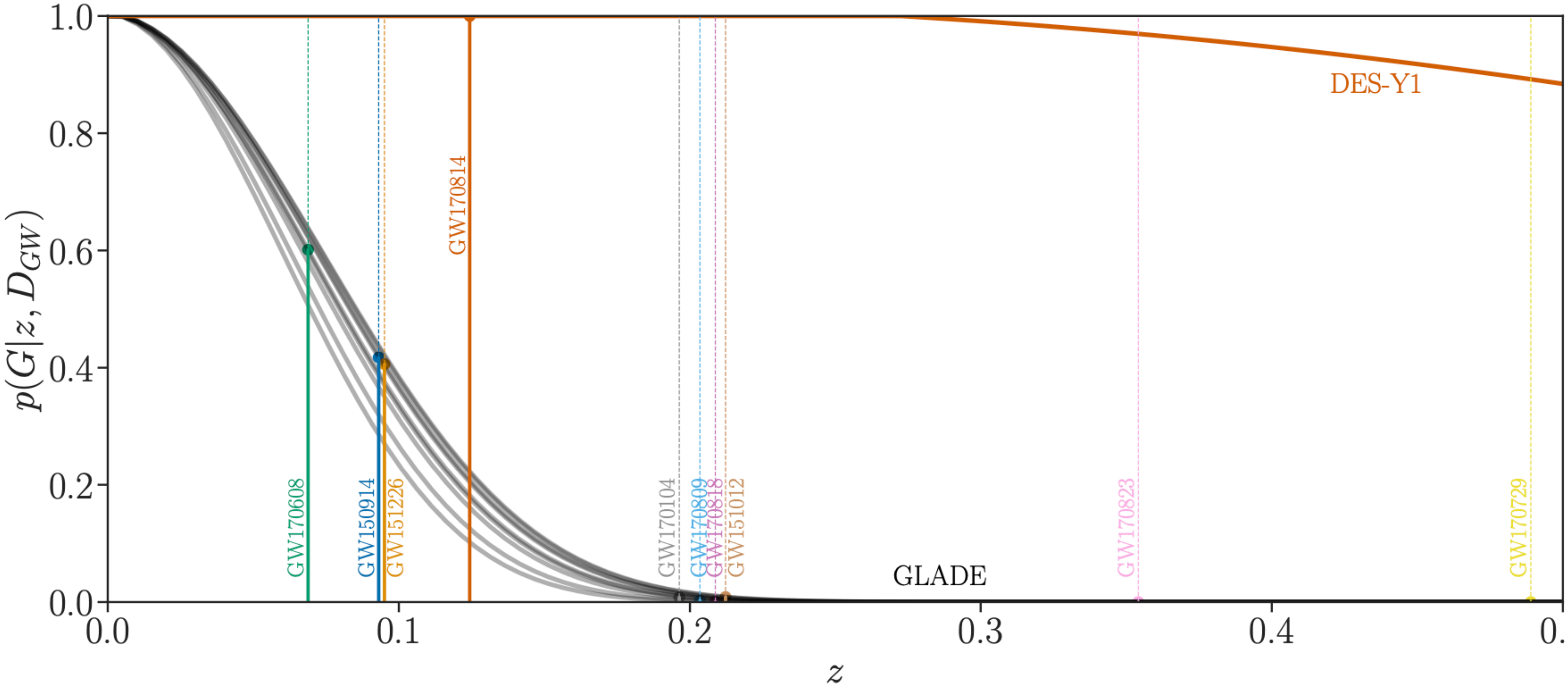

Completeness of galaxy catalogs is the main limitation for statistical dark sirens

[LVC, *ApJ* (2020)]

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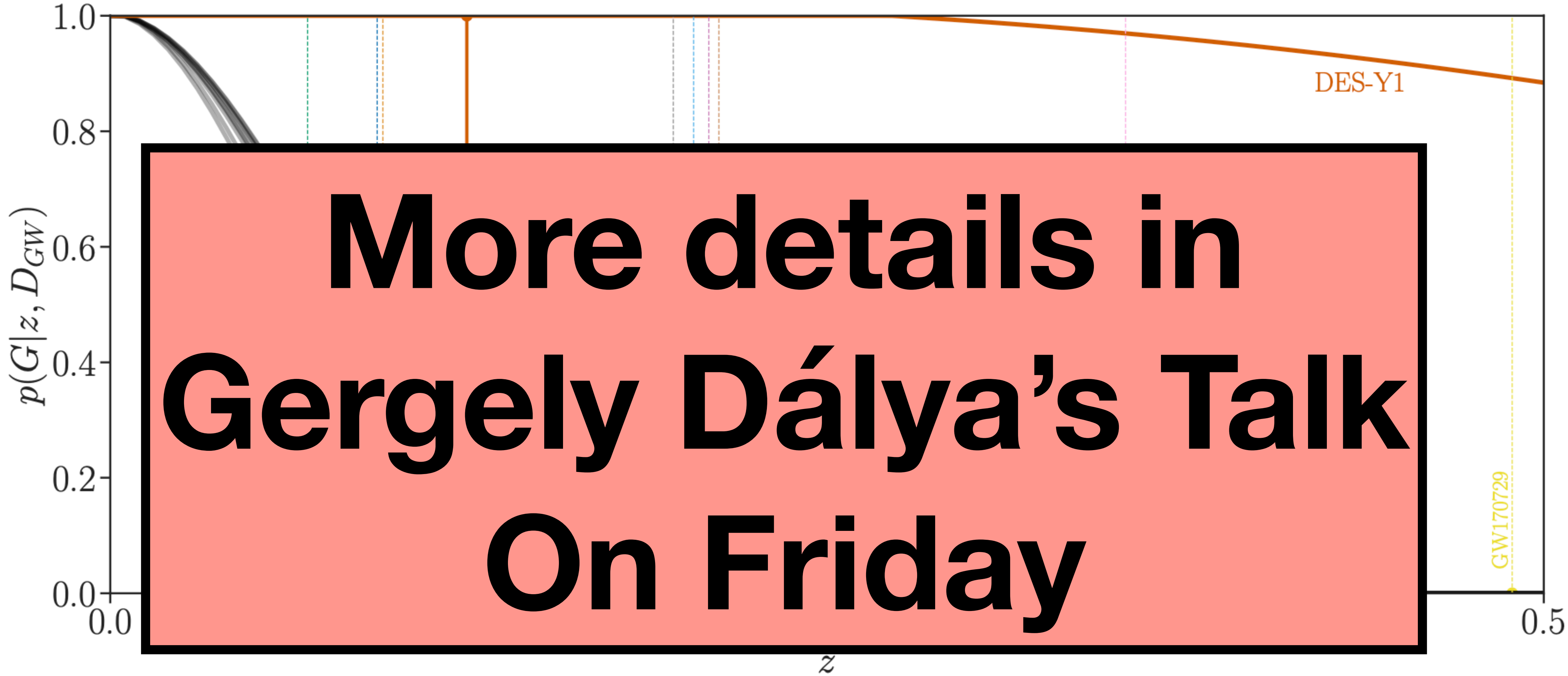

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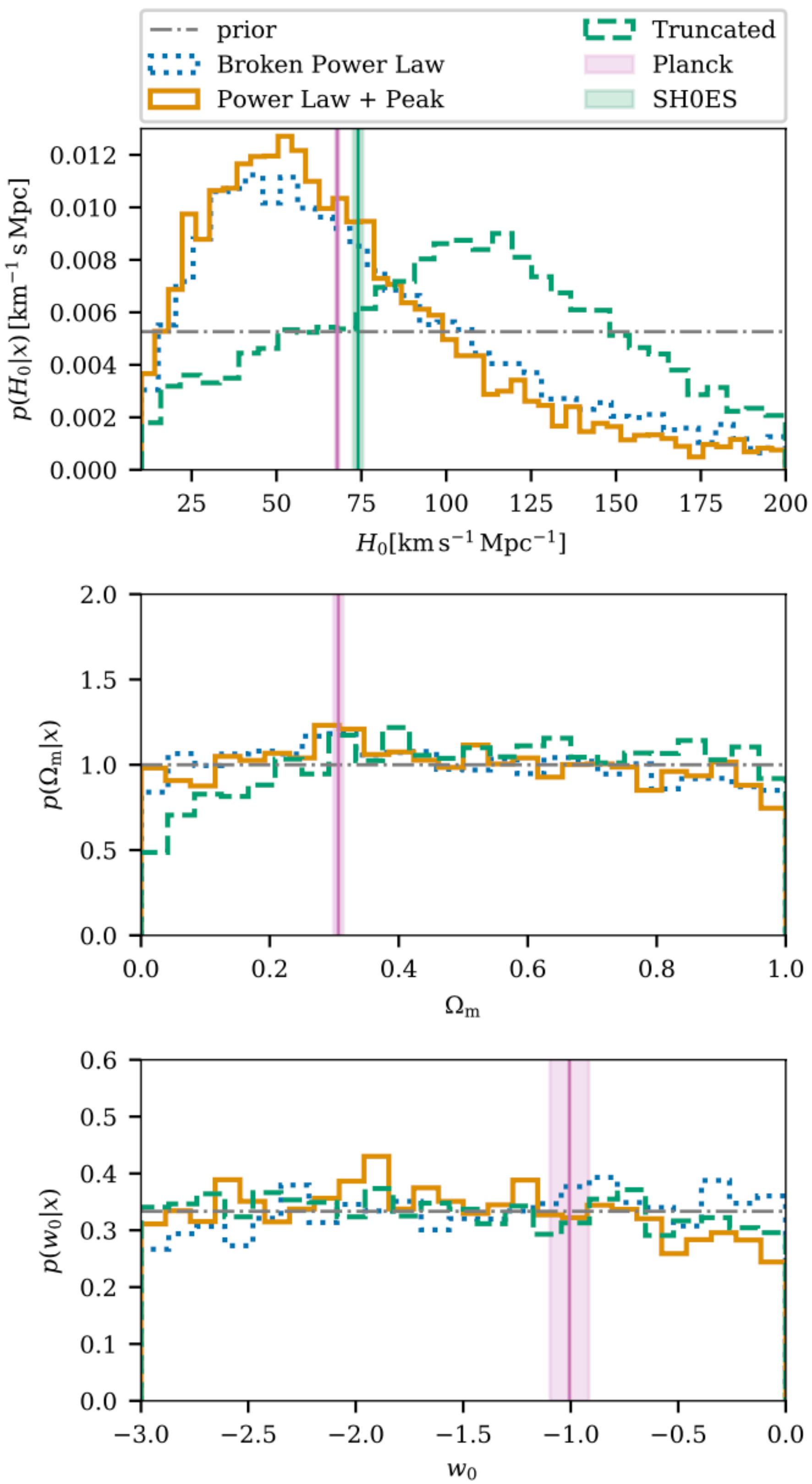
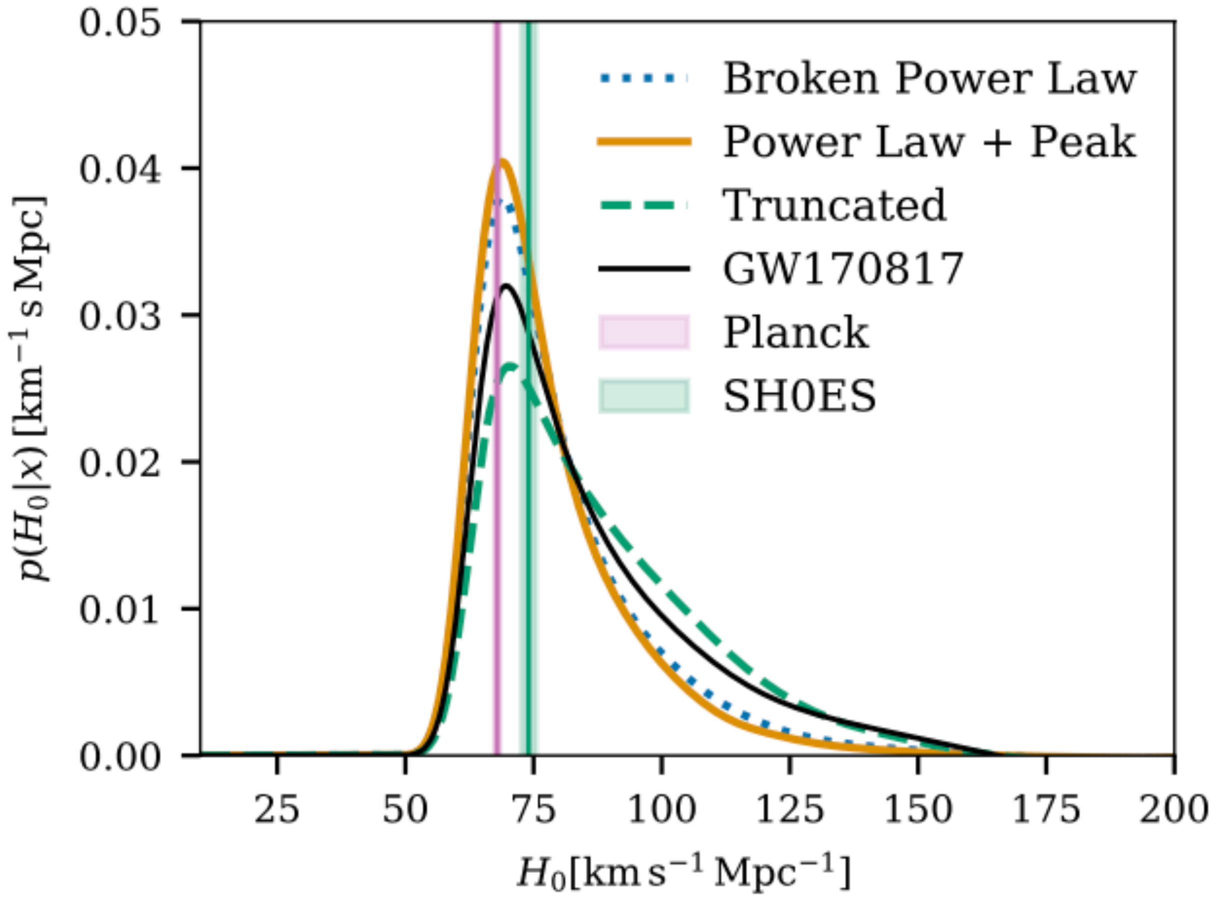
[LVC, *ApJ* (2020)]

Current results from LVK

Finally the <u>spectral dark siren method</u> has been applied to current events (O1+O2+O3):





Posteriors are informative on H_0 (not on other cosmo parameters) but strongly depend on population model

$$H_0 = 68^{+12}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

[LVK, *ApJ* (2022)]

(17% improvement over O2 results)

Current results from LVK

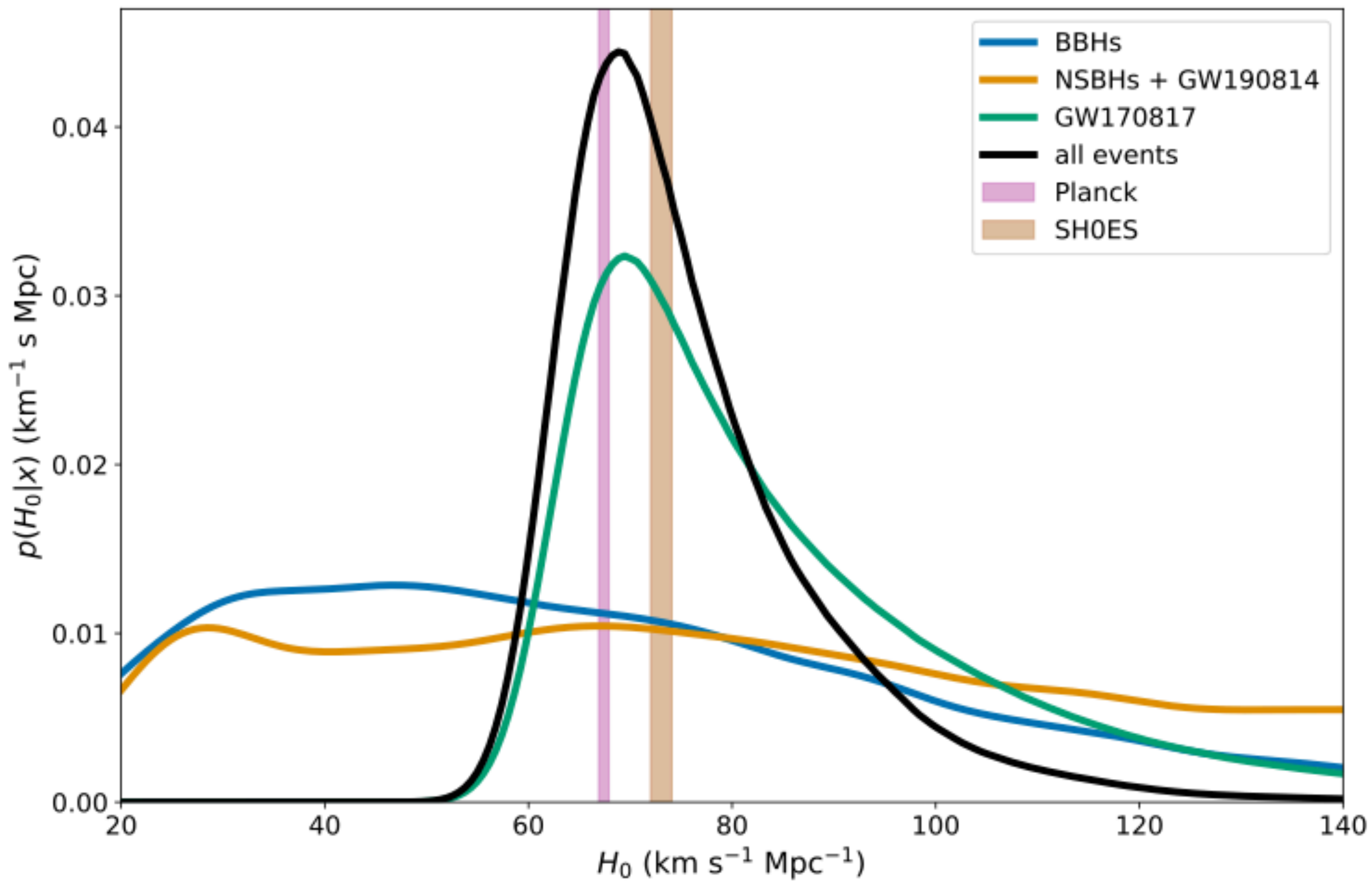
Latest observational results obtained by combining all sirens methods

A joint analysis combining all dark sirens methods (statistical+spectral) + GW170817 provides the best constraint so far (including marginalisation over population parameters)

$$H_0 = 69^{+12}_{-7}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

This represents a ~20% improvement over GW170817 only results

LVK O4 cosmological results will combine all standard siren methods (bright+spectral+statistical) for the first time



[Gray+, *JCAP* (2023)]
[Mastrogiovanni+, *PRD* (2023)]

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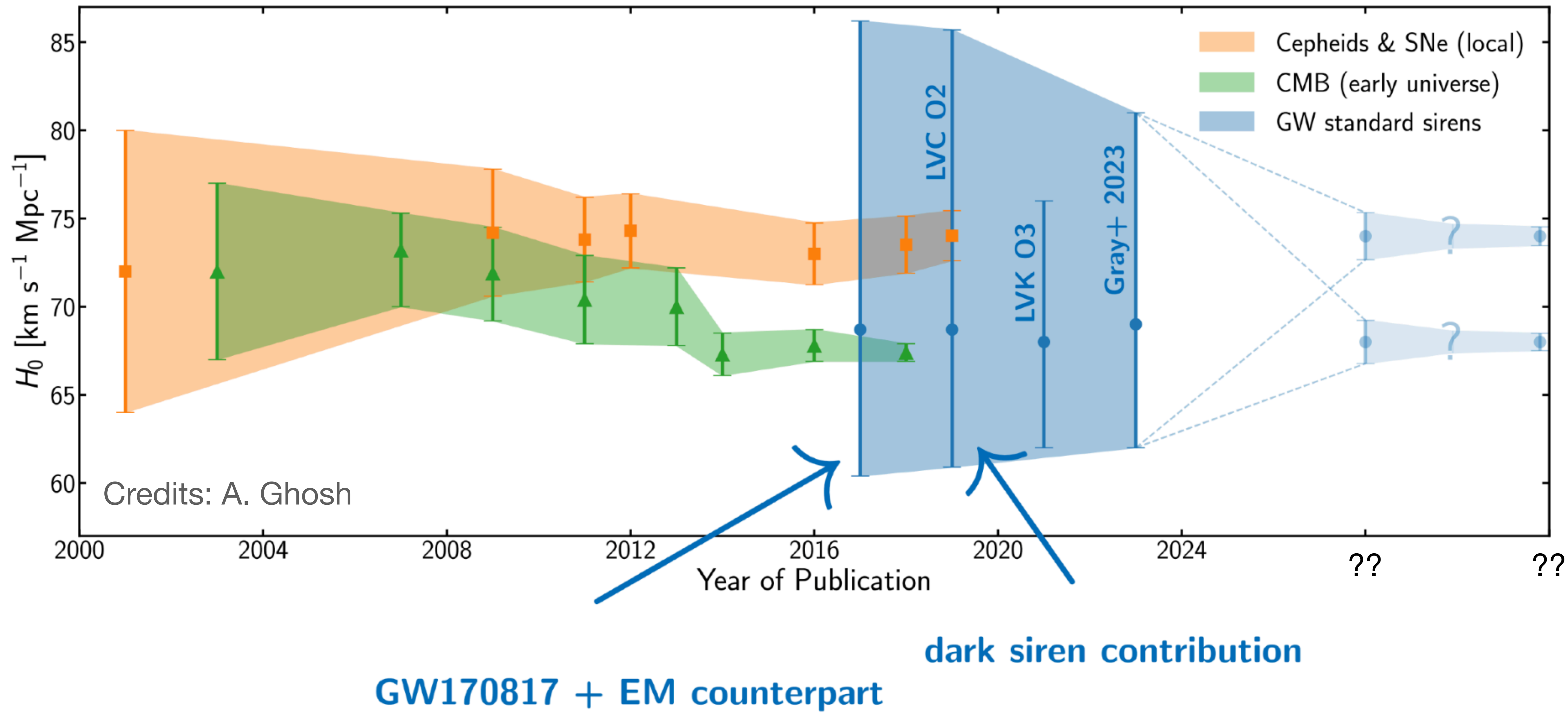

Few % accuracy on H_0 possible only in the most optimistic O5 scenario

[Kiendrebeogo+, *ApJ* (2023)]

Post-O5 (>2030) observations needed to solve the <u>Hubble tension</u>

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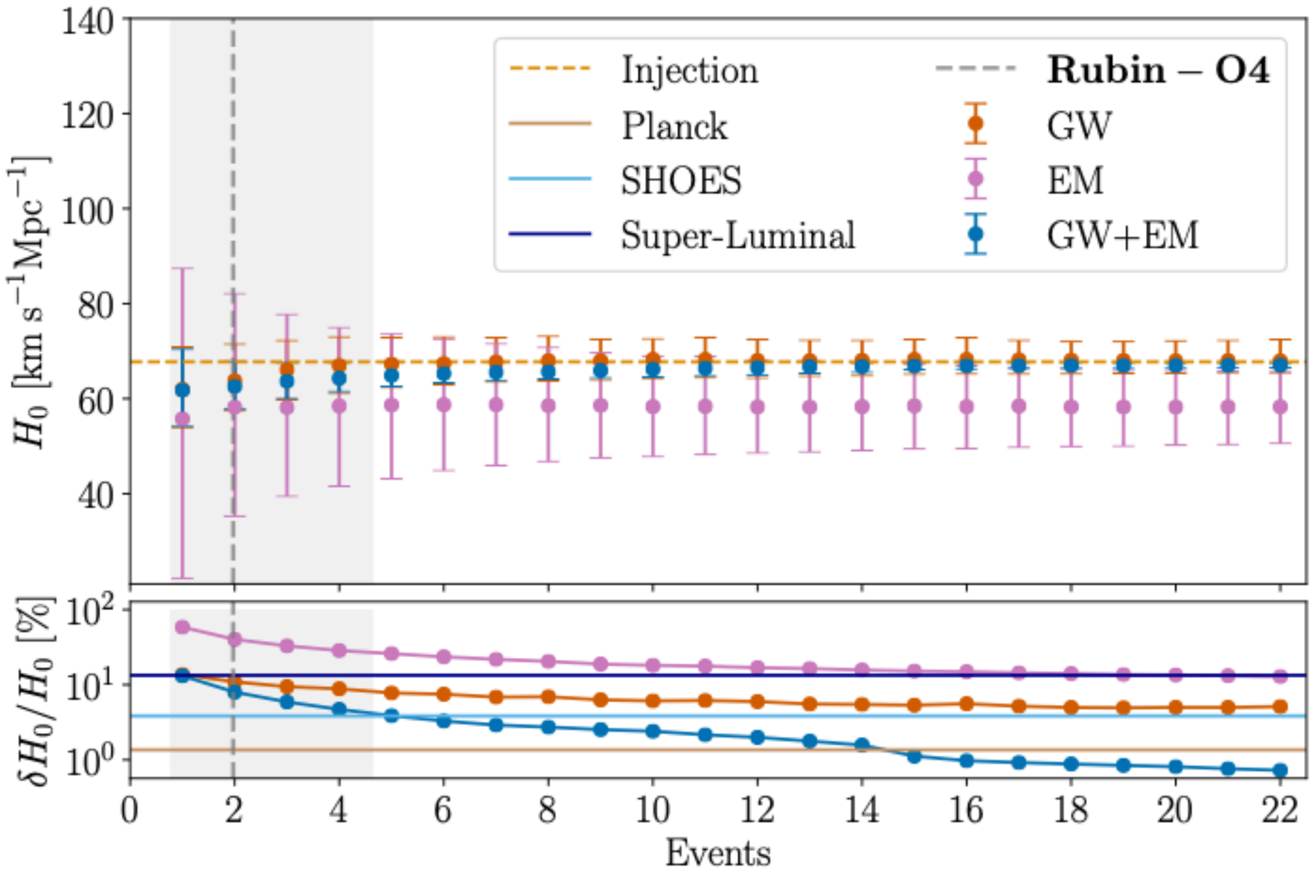
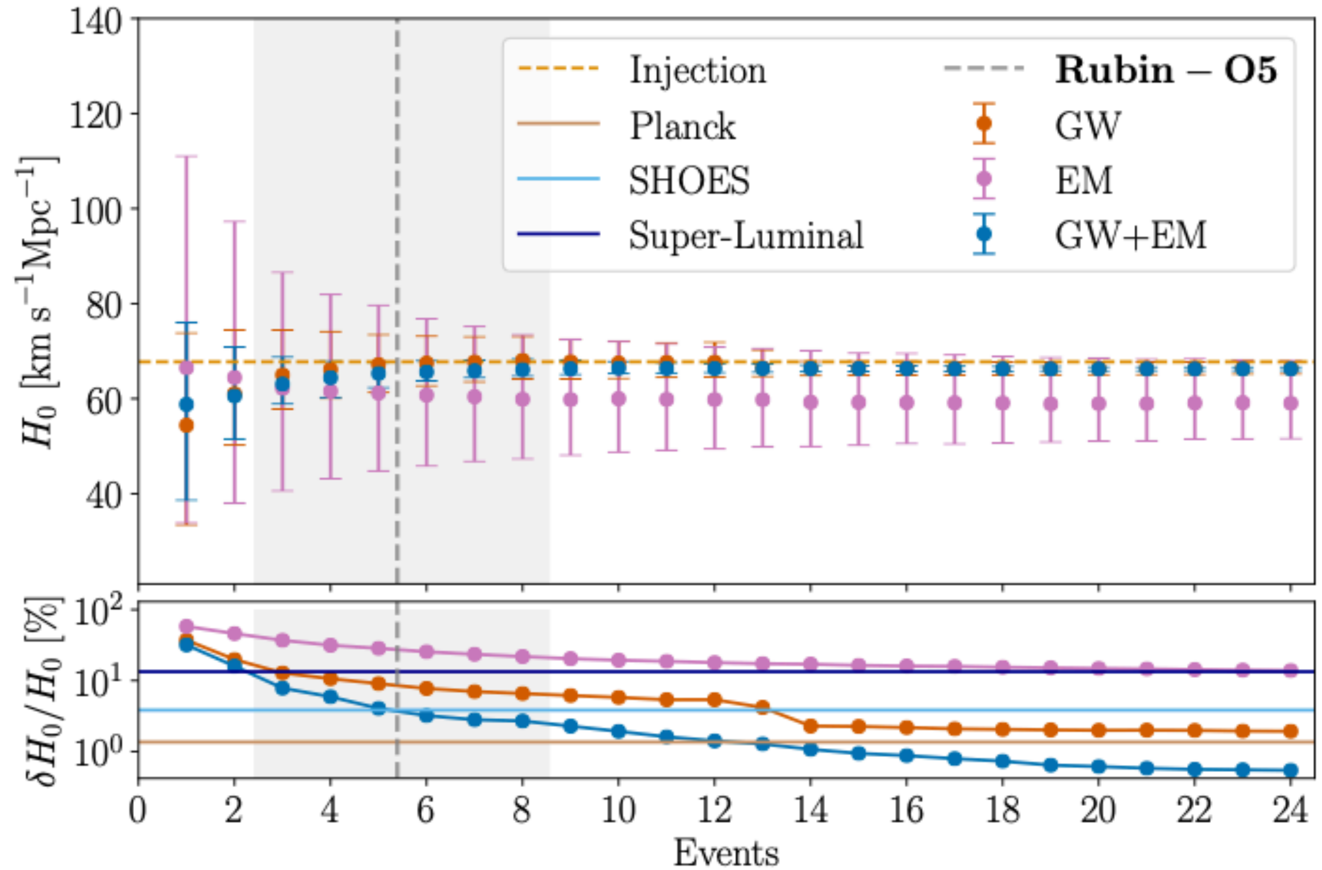




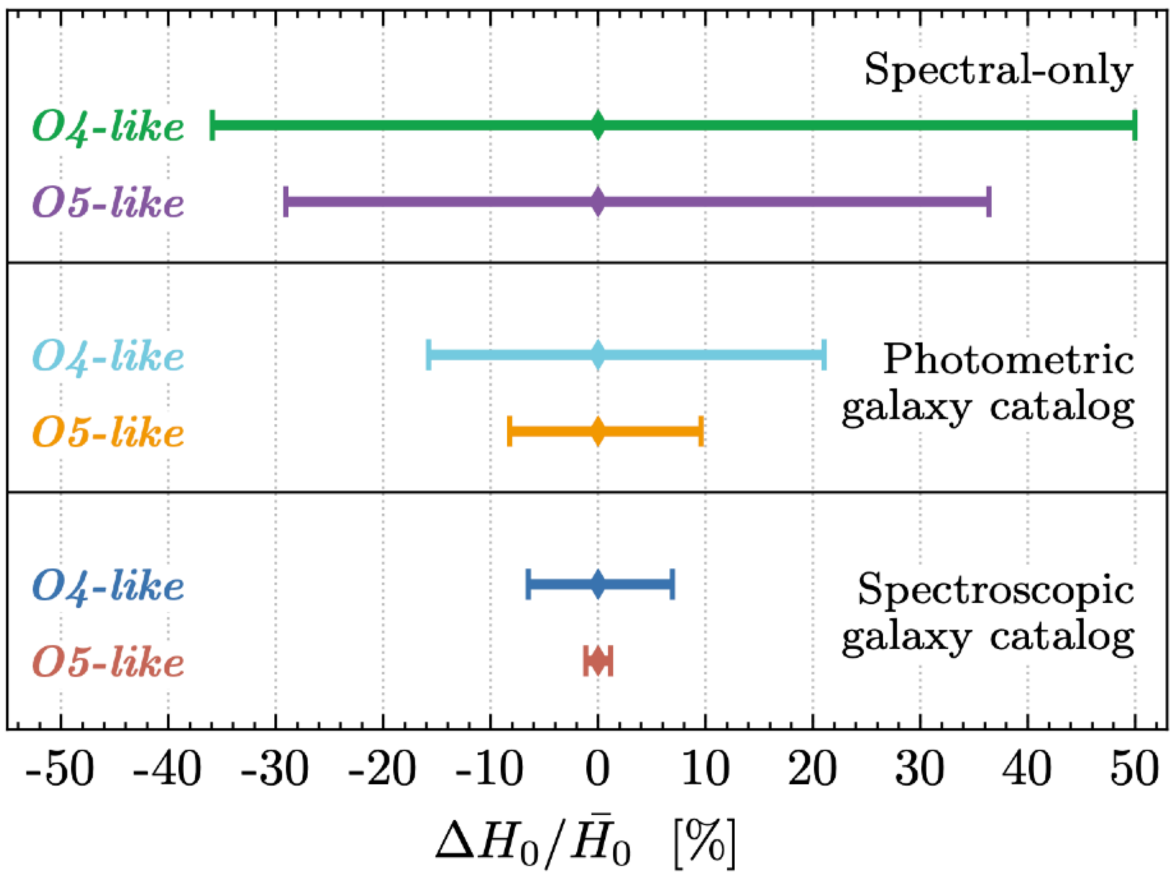
Few % accuracy on H_0 possible only in the most optimistic O5 scenario

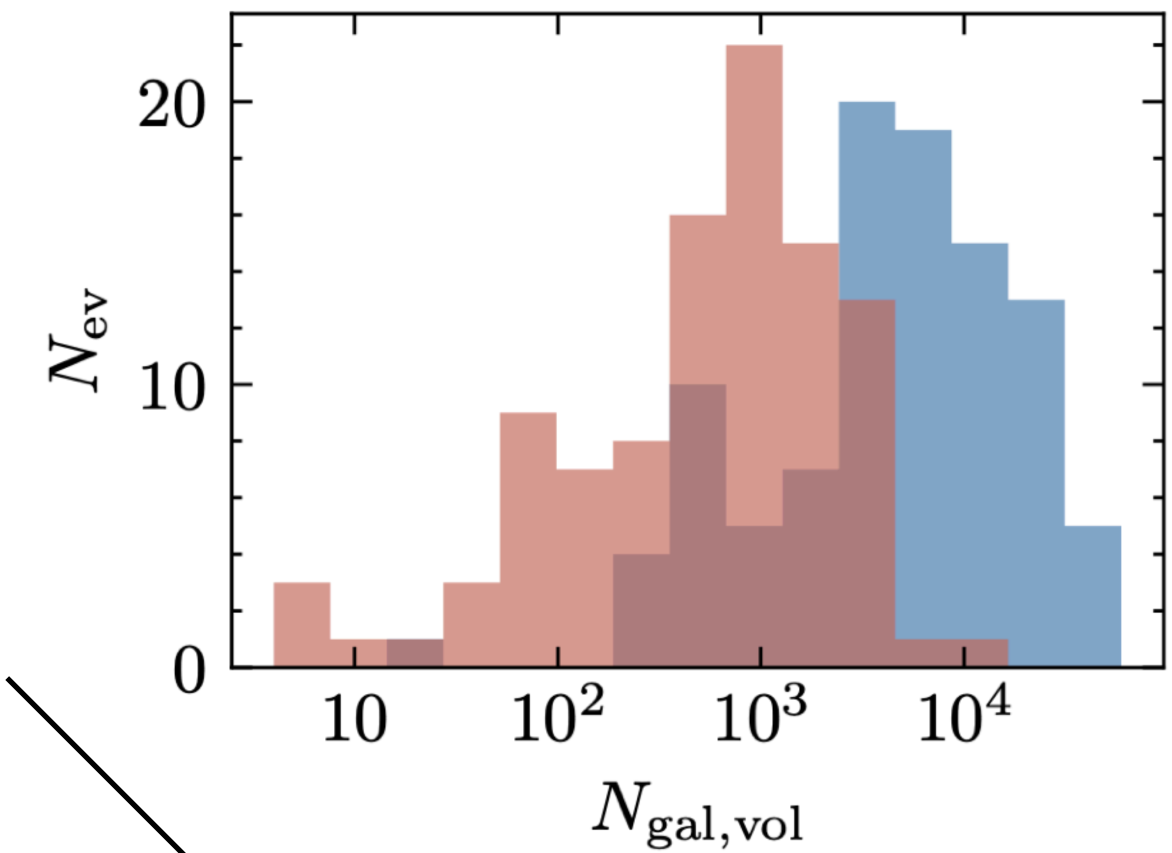
[Kiendrebeogo+, *ApJ* (2023)]

Run	Telescope	BNS	NSBH
EM annual number of detections			
O4	ZTF	$0.43^{+0.58}_{-0.26}$	$0.13^{+0.24}_{-0.11}$
	Rubin	$1.97^{+2.68}_{-1.2}$	$0.03^{+0.06}_{-0.03}$
O5	ZTF	$0.43^{+0.44}_{-0.2}$	$0.09^{+0.12}_{-0.06}$
	Rubin	$5.39^{+6.59}_{-2.99}$	$0.43^{+0.59}_{-0.28}$

Future prospects

<u>FUTURE PROSPECTS WITH LVK:</u> The current network of ground-based detectors is not expected to measure H_0 at few % accuracy before ~2030-2035.





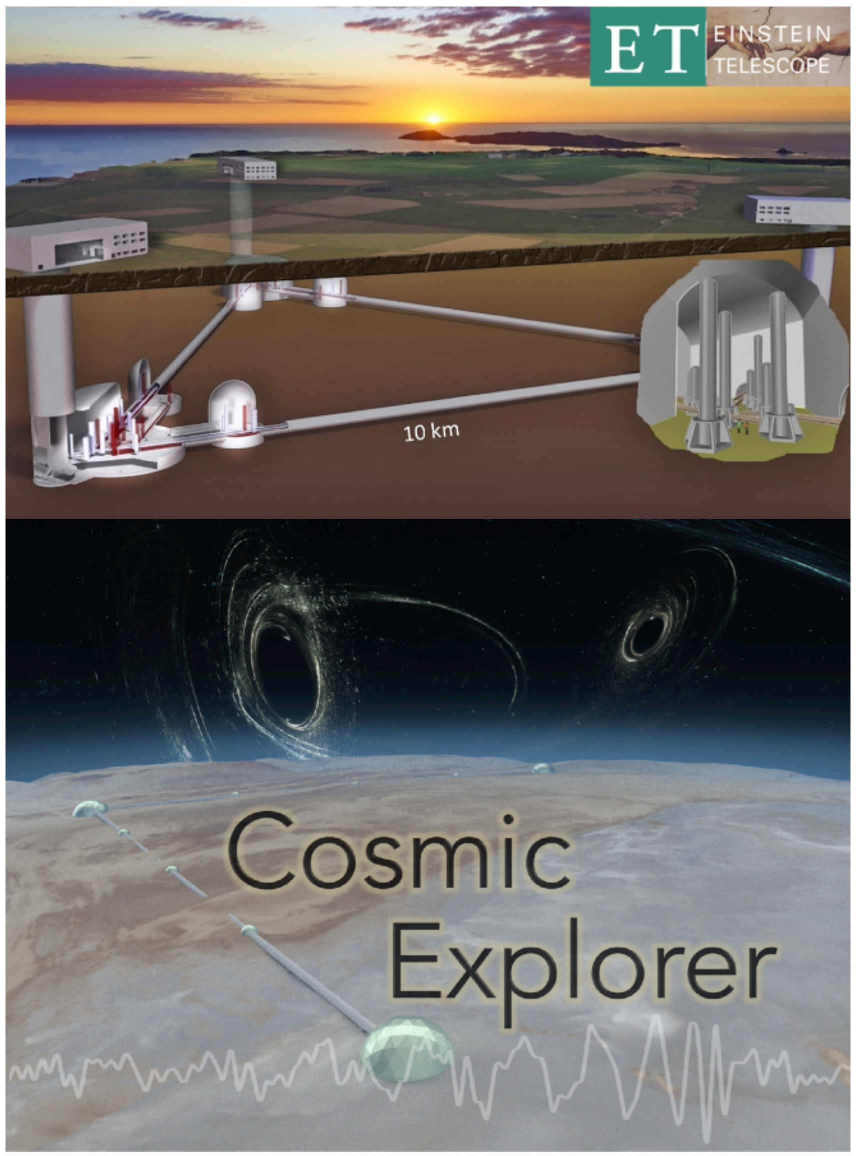
Few % accuracy on H_0 possible only in the most optimistic O5 scenario

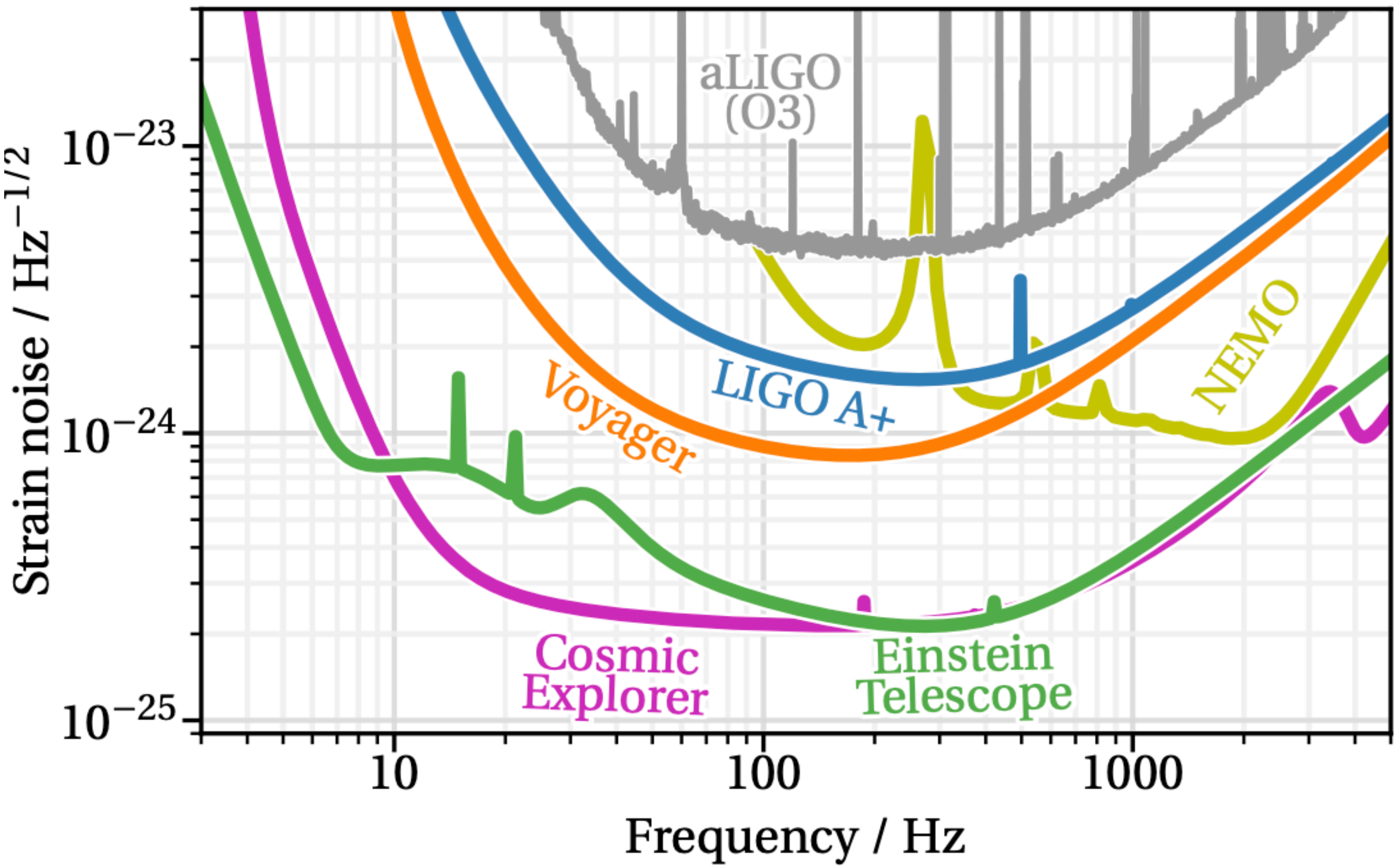
Optimistic! Galaxy catalogs fully complete, 5 detectors (HLVKI), simplified GW PE, …

[Borghi+, *ApJ* (2024)]

Future prospects

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

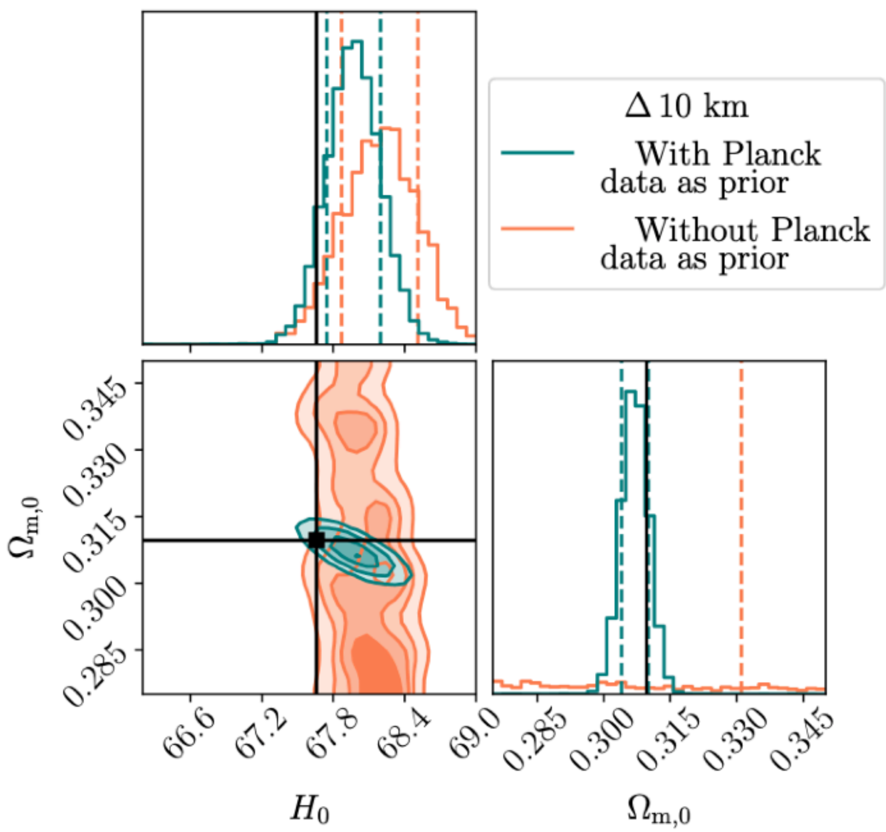


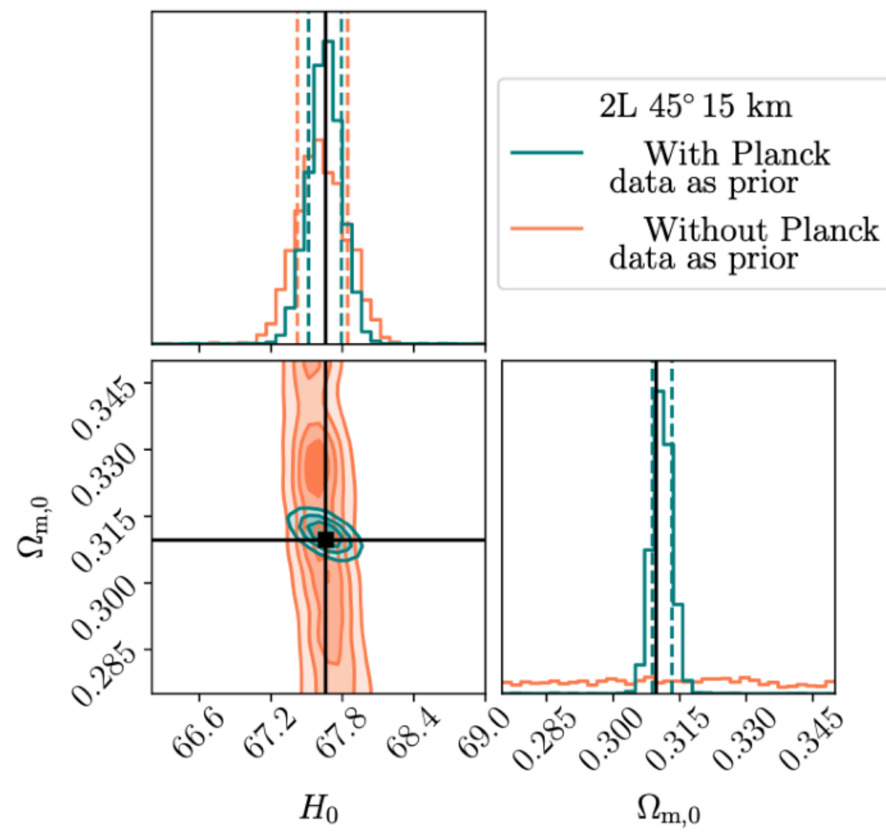


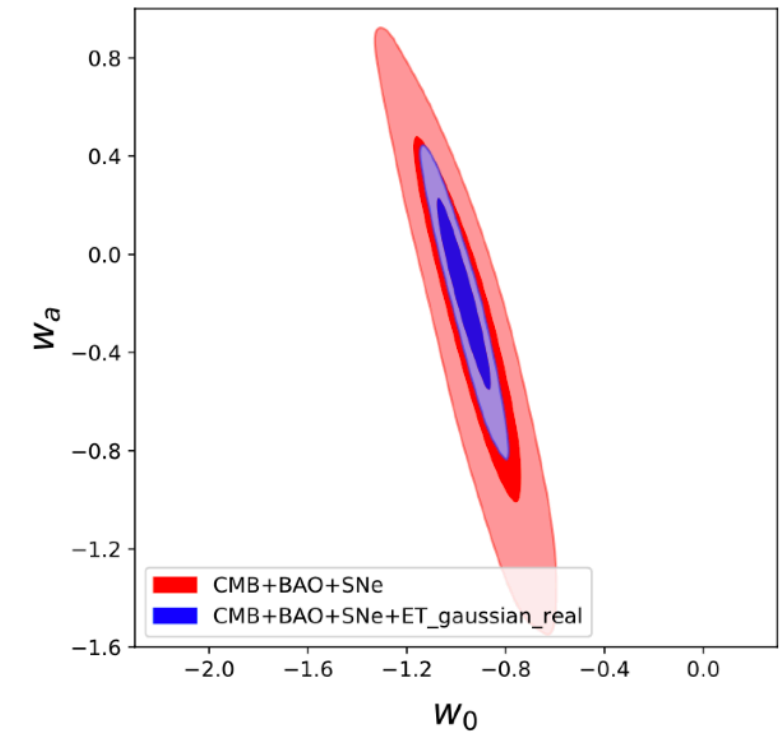
One order of magnitude sensitivity improvement w.r.t. LIGO, similar frequency range

Future prospects

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







Einstein Telescope and *Cosmic Explorer* will guarantee:

- % constraints on H_0 or better
- Improved constraints on dark energy
- Strong GW-only tests of GR at cosmic distances

Forecasts with bright sirens

[Belgacem+, *JCAP* (2019)]
[ET Blue Book, arXiv (2025)]

Future prospects

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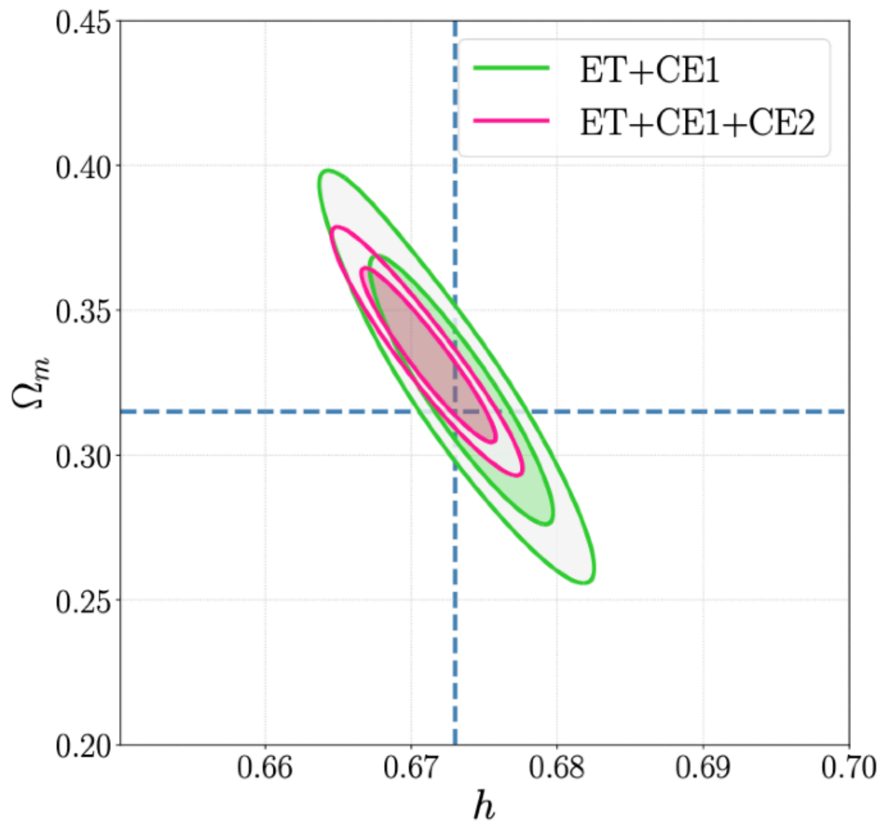
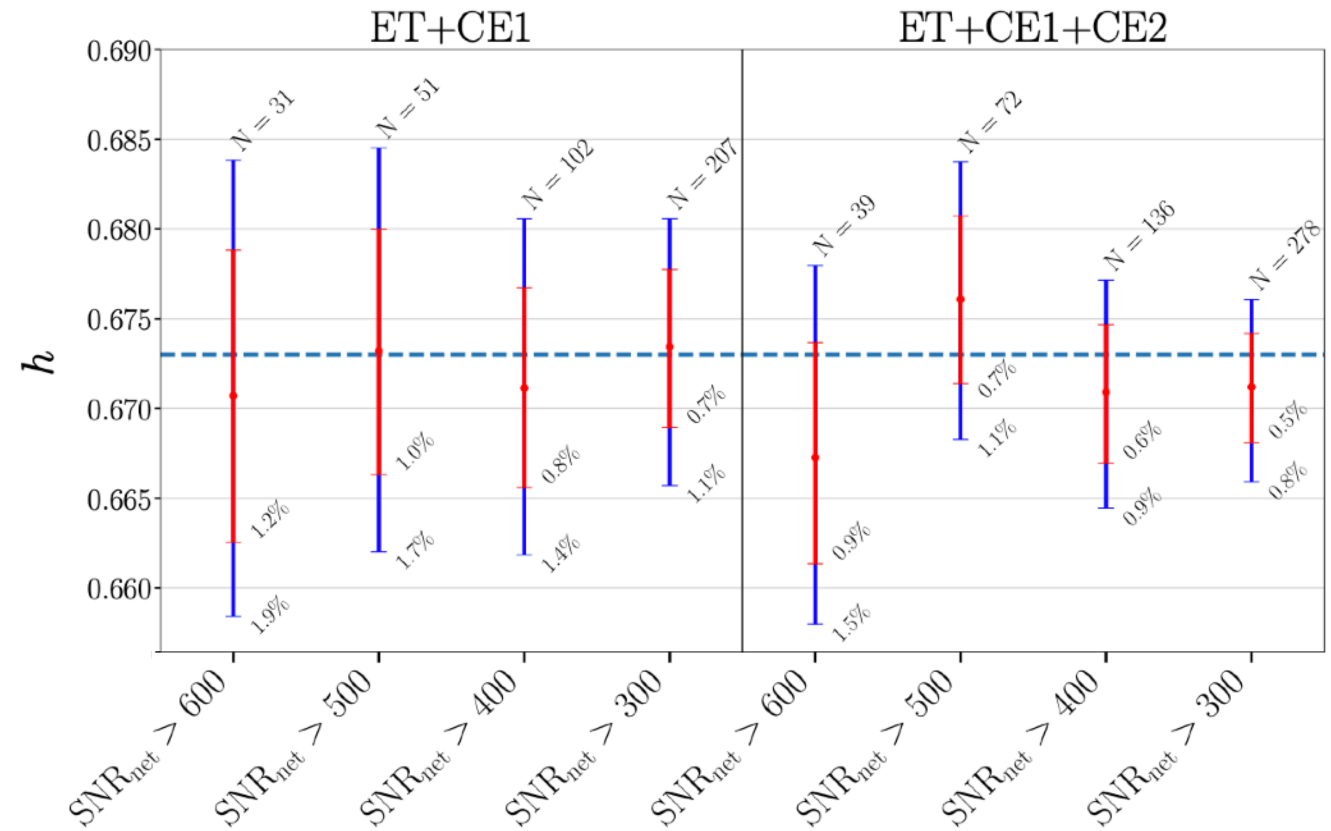




<u>Einstein Telescope</u> and *<u>Cosmic Explorer</u>* will guarantee:

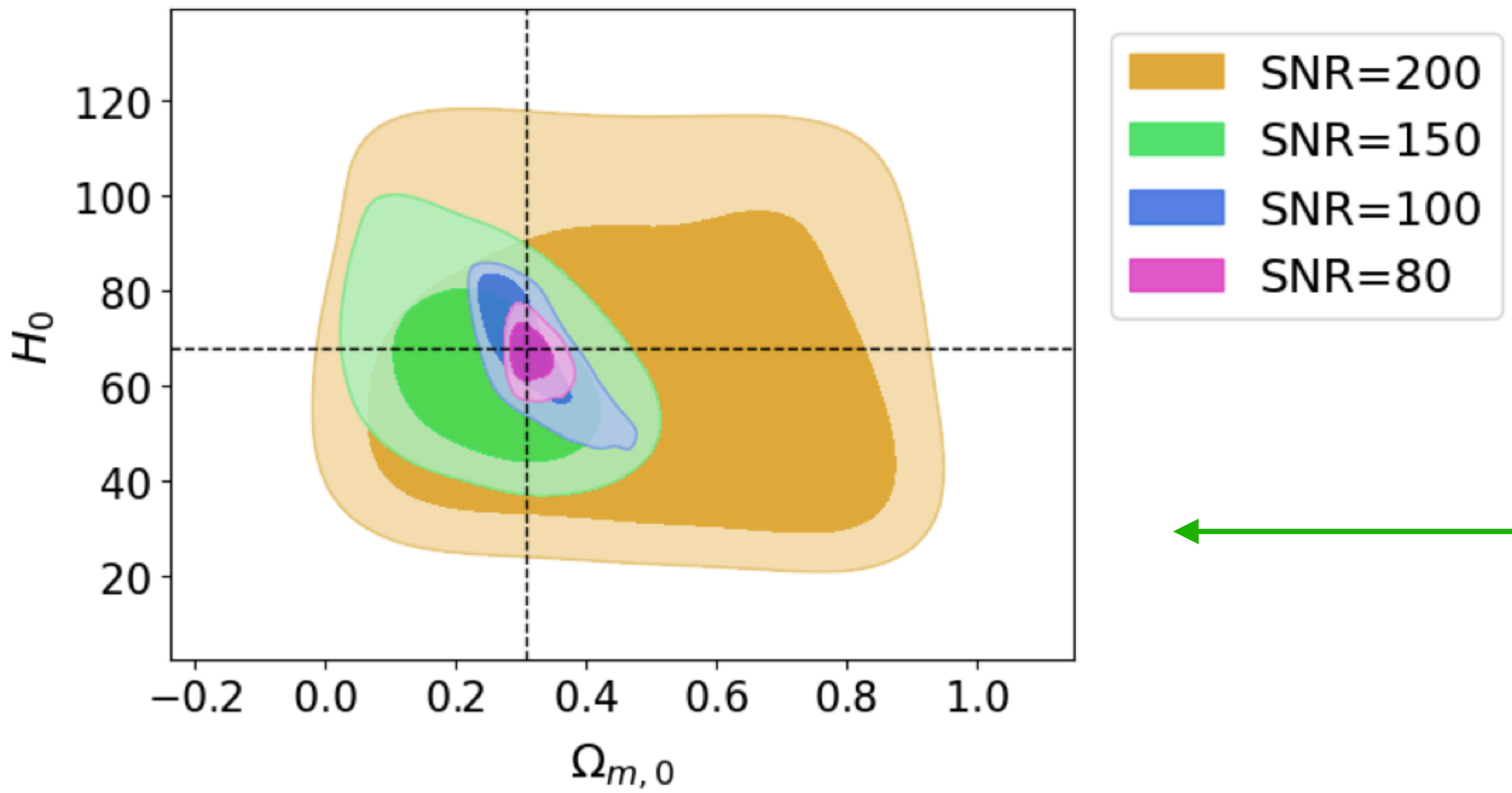
- % constraints on H_0 or better
- Improved constraints on dark energy
- Strong GW-only tests of GR at cosmic distances

Forecasts with statistical <u>dark</u> sirens

[Muttoni+, *PRD* (2023)]
[ET Blue Book, arXiv (2025)]

Future prospects

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



Forecasts with spectral siren method (limited to high SNR events)

Einstein Telescope and *Cosmic Explorer* will guarantee:

- % constraints on H_0 or better
- Improved constraints on dark energy
- Strong GW-only tests of GR at cosmic distances

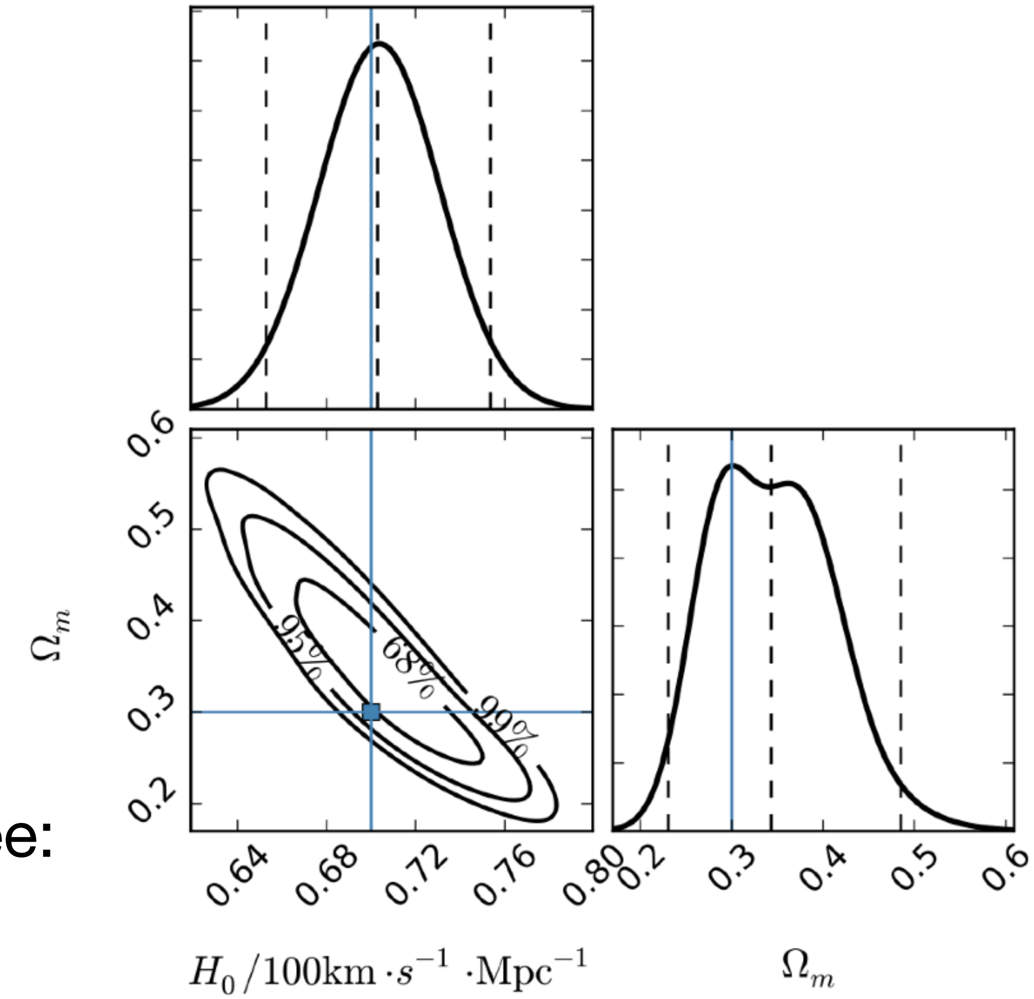
Moreover 3G detectors may not need EM information to get the redshift of BNSs, but use their mass function and/or the EoS to do cosmology and test GR/LCDM

[Califano+, *ArXiv* (2025)]

Future prospects

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

Forecasts with <u>Neutron Star EoS</u> siren method



Einstein Telescope and *Cosmic Explorer* will guarantee:

- % constraints on H_0 or better
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- Strong GW-only tests of GR at cosmic distances

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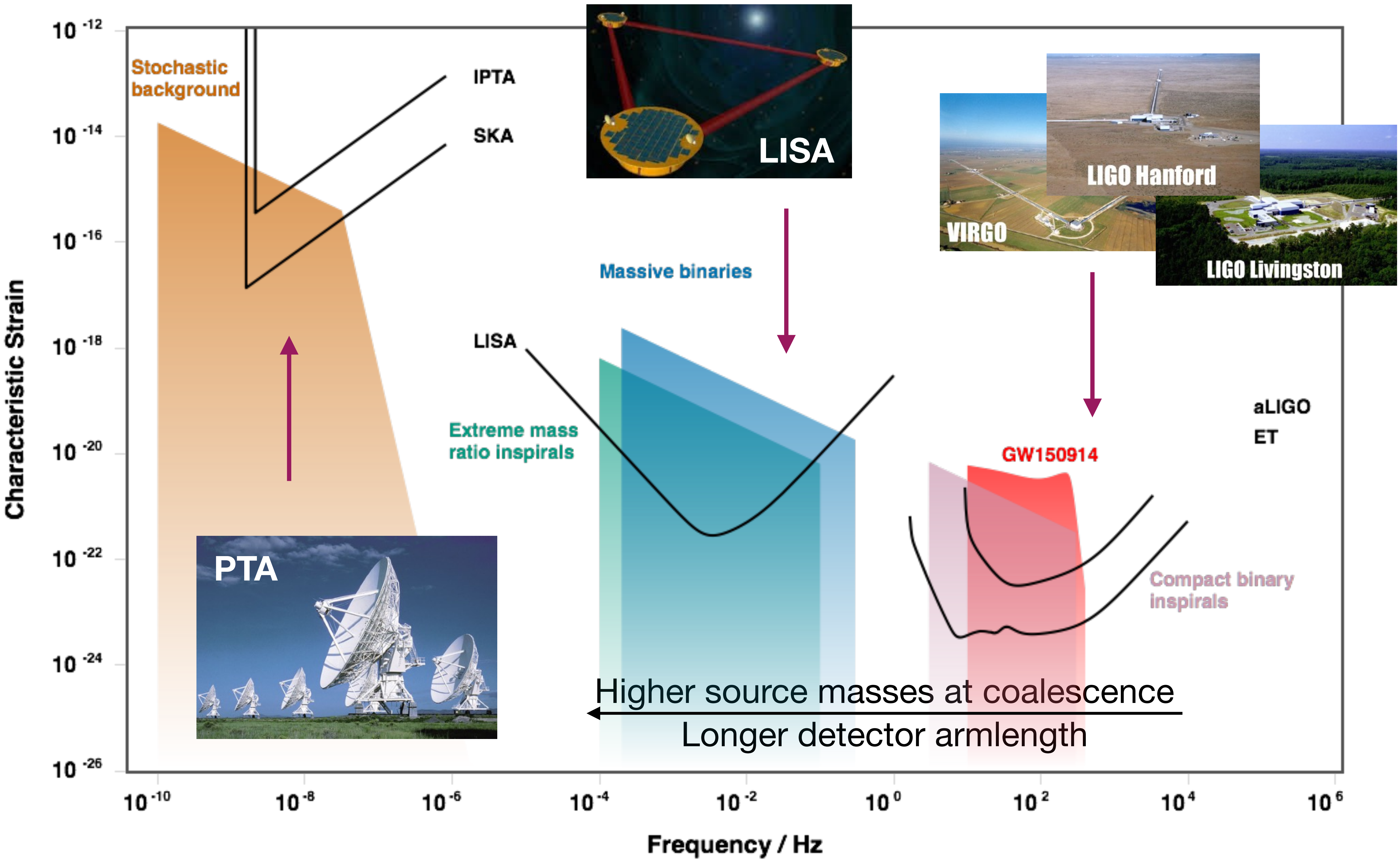
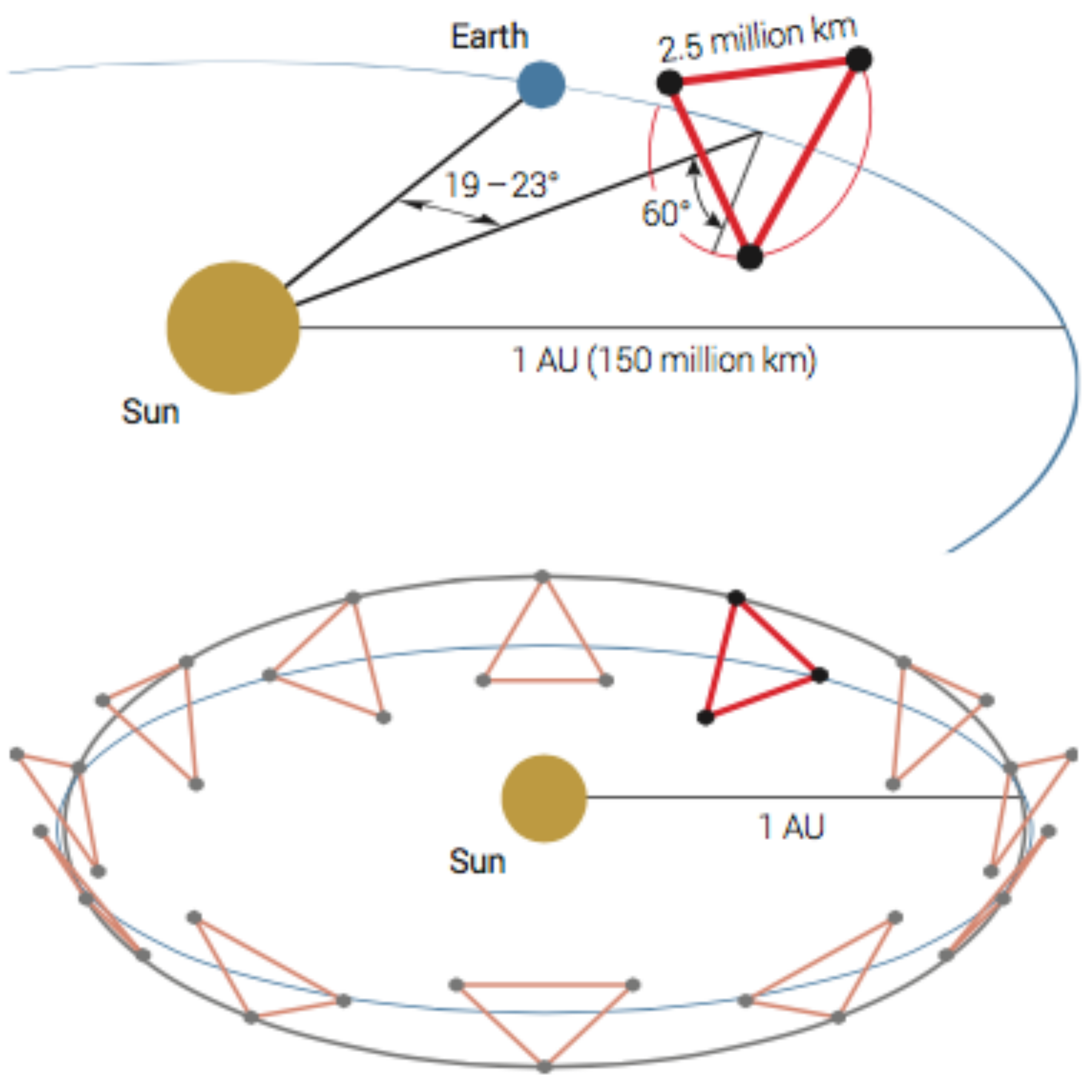
[Taylor&Gair, *PRD* (2012)]
[Del Pozzo+, *PRD* (2017)]
[Finke+, *Phys. Dark Univ.* (2021)]

Future prospects



Future prospects

Laser Interferometer Space Antenna



[LISA, *ArXiv* (2017)]
[LISA, *ArXiv* (2024)]

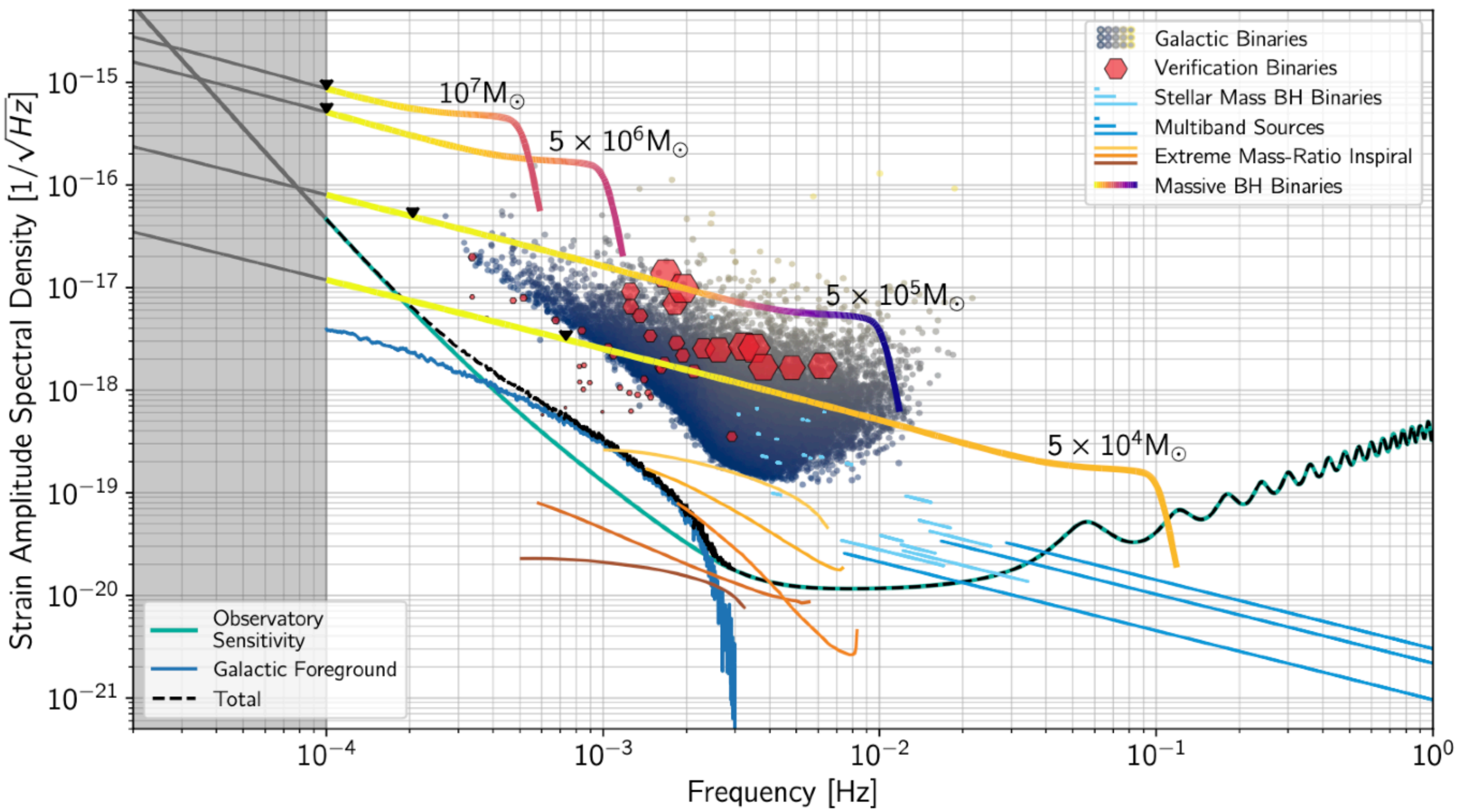
Design:

- Near equilateral triangular formation in heliocentric orbit
- 6 laser links (3 active arms)
- Arm-length: 2.5 million km
- Scince observations: 4 to 10 yrs
- **Adopted by ESA in 2024 !**
- Launch: mid-2030s

Review on
Cosmology with LISA
LISA CosWG, Liv. Rev. Rel. (2023)
arXiv:2204.05434

Future prospects

Laser Interferometer Space Antenna



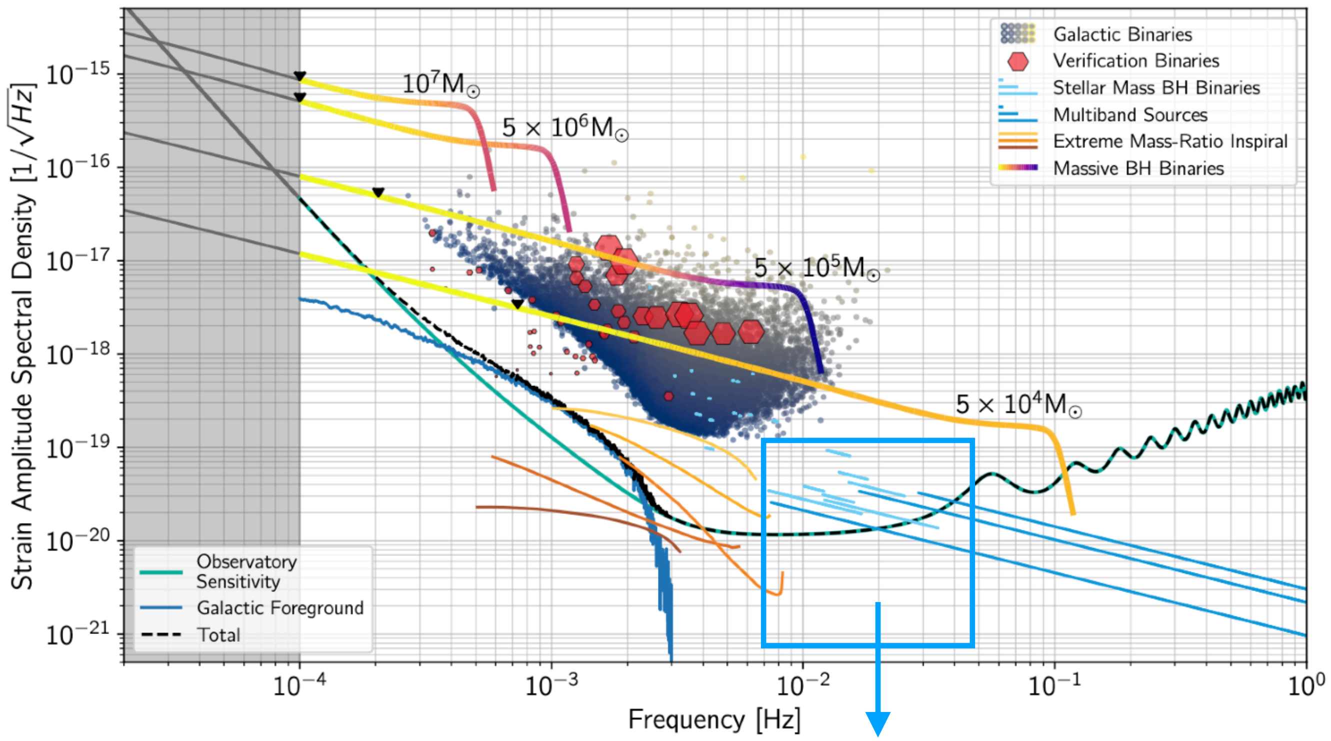
Standard siren sources:

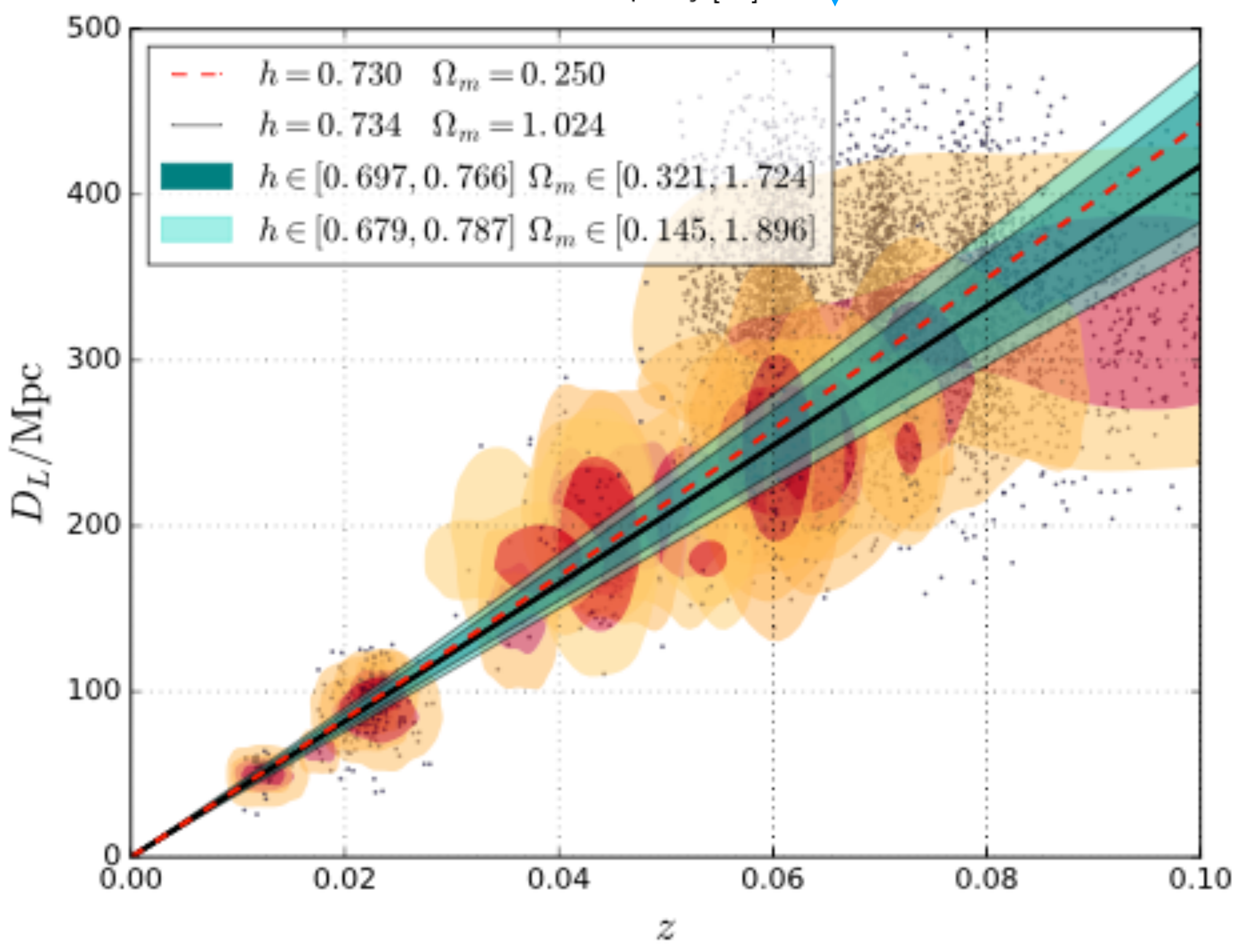
- ~~Stellar-mass BBHs~~ ~~$(10 - 100\,M_\odot)$~~
- Intermediate-mass BBHs? ($\gtrsim 100\,M_\odot$)
- Extreme mass ratio inspirals (EMRIs)
- Massive Black Hole Binaries* $(10^4 - 10^7\,M_\odot)$

[LISA, *ArXiv* (2017)]
[LISA, *ArXiv* (2024)]

*EM counterparts expected

Future prospects



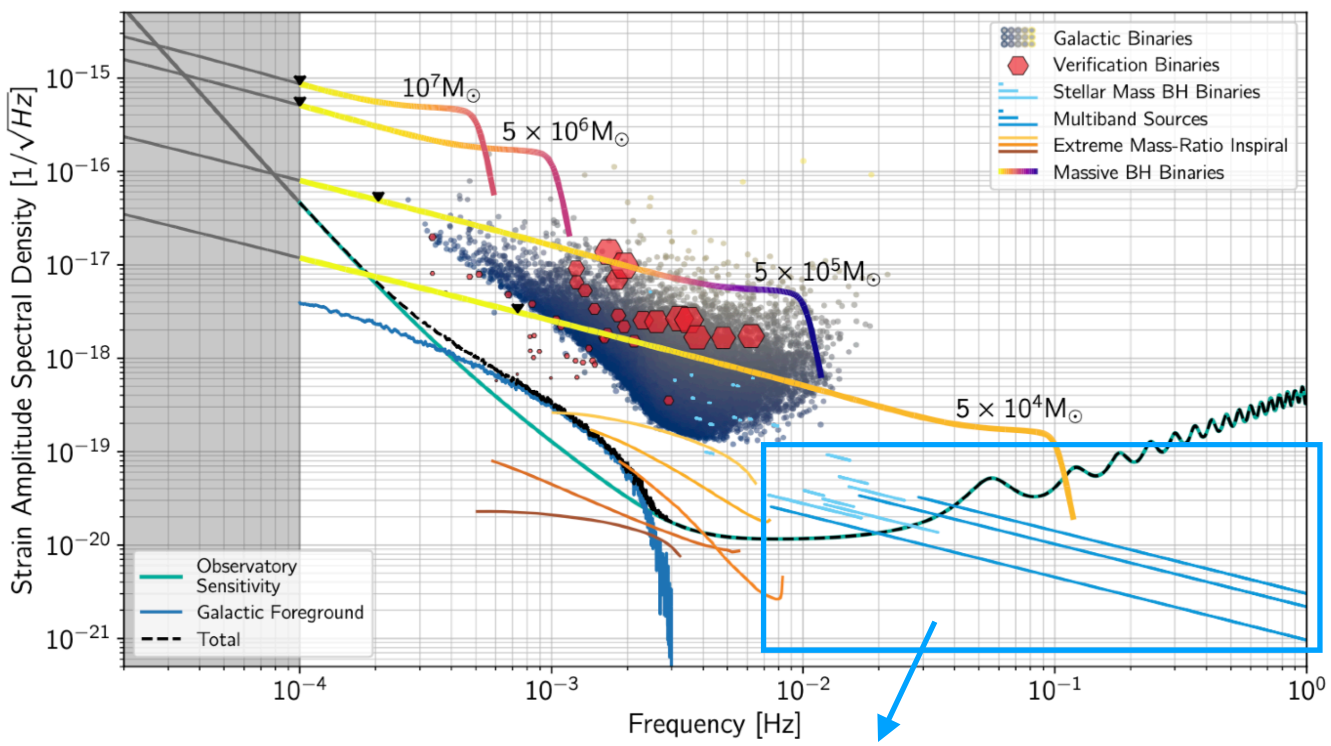


Stellar-mass BBHs

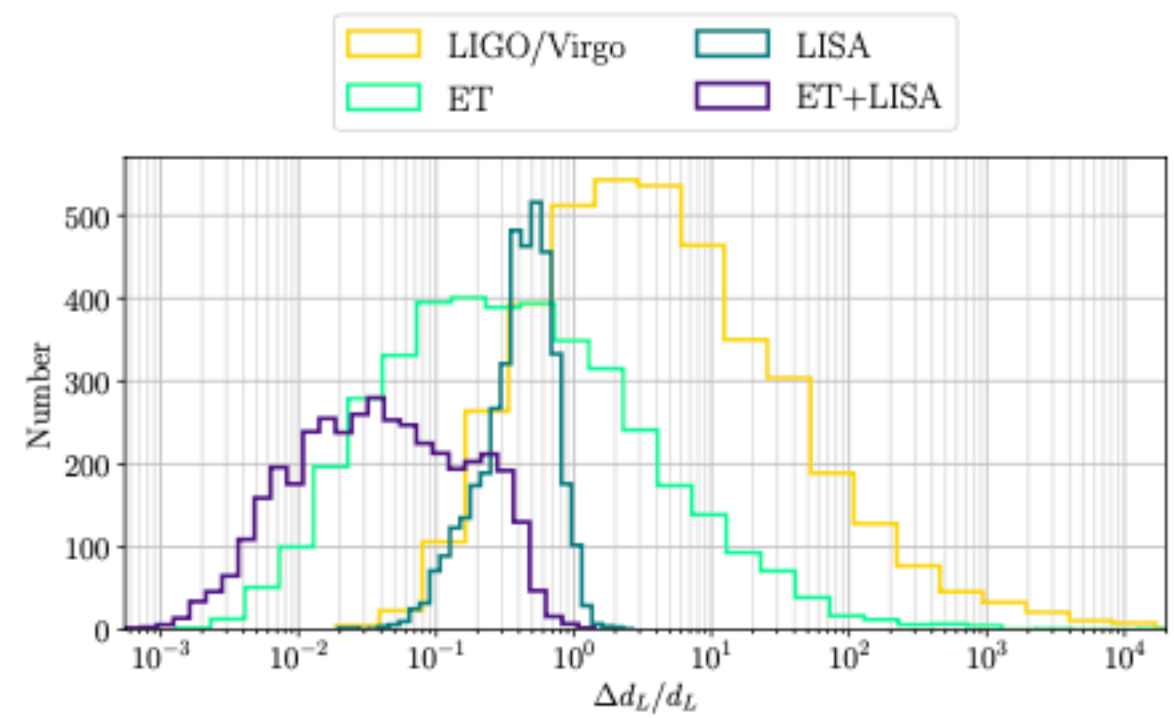
- Redshift range: $z \lesssim 0.1$
- No EM counterparts expected
- LISA detections: ~~~50/yr (optimistic)~~
  ~few/yr
- Useful as standard sirens:
  - If $\Delta d_L/d_L < 0.2$
  - If $\Delta\Omega \sim 1\ \mathrm{deg}^2$
  - $\Rightarrow$ ~~~ 5 standard sirens / yr~~
    ~0.1 standard sirens / yr
-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

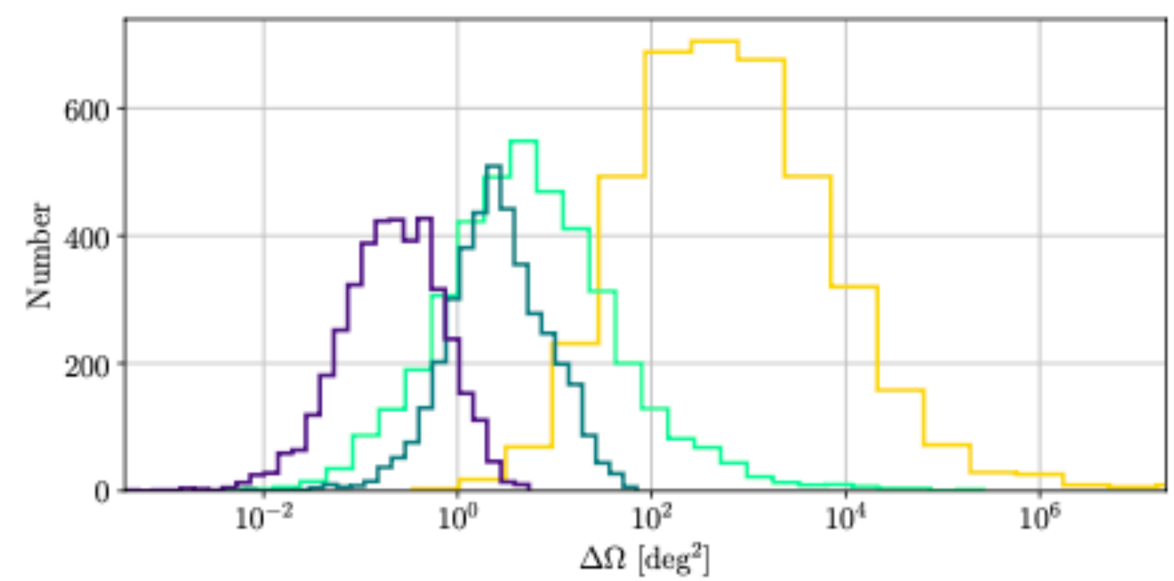
[Kyutoku & Seto, *PRD* (2017)]
[Del Pozzo+, *MNRAS* (2018)]

Future prospects



Multi-band IMBHs ?





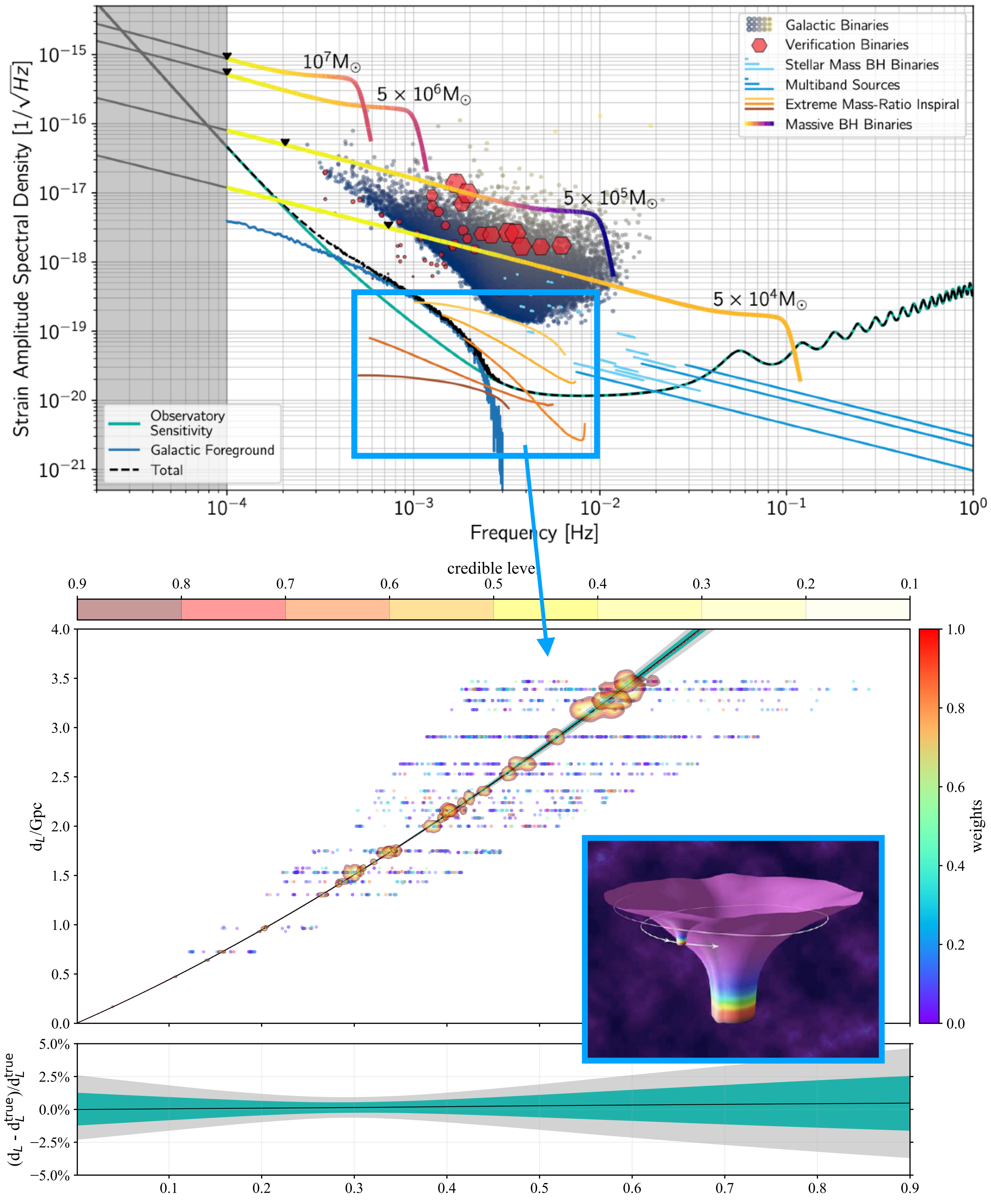
Intermediate mass black holes (IMBHs) can be used in **multi-band analyses** since their merger can be observed by ground-based detectors and their inspiral by LISA

Expected results:

- H_0 to few % with $\mathcal{O}(10)$ IMBHs (rates yet unknown)

[Muttoni+, *PRD* (2022)]

Future prospects



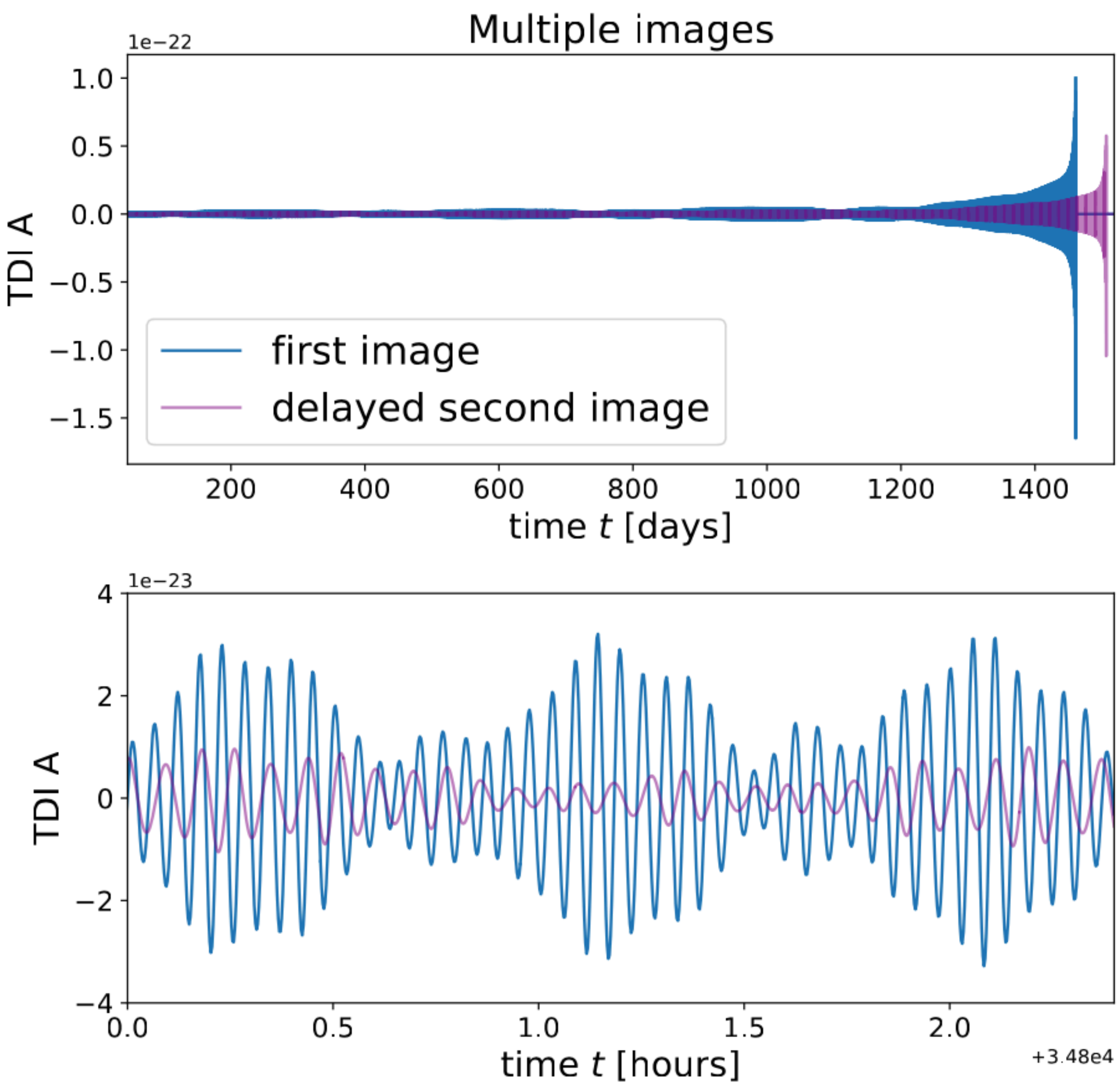
EMRIs

- 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
- **Expected results:**
  - H_0 between 1 and 10 %
  - w_0 between 5 and 10 %

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

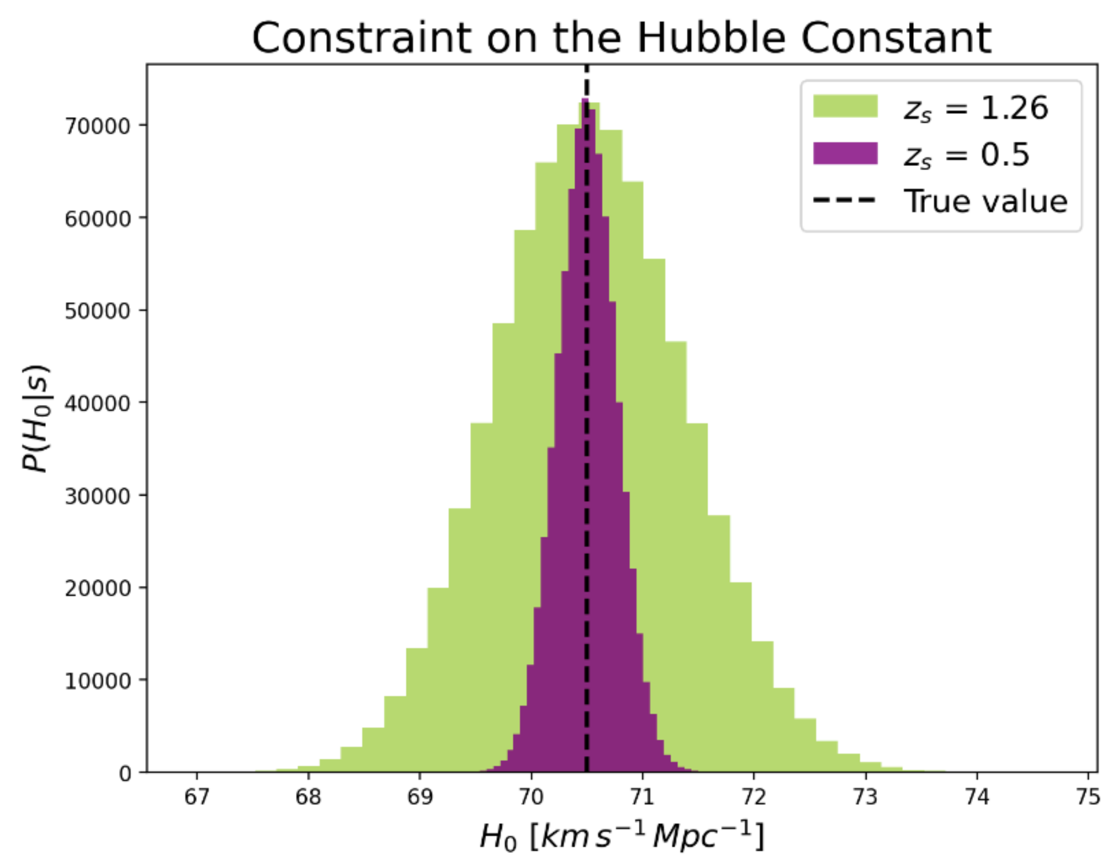
Future prospects

Strongly lensed EMRIs

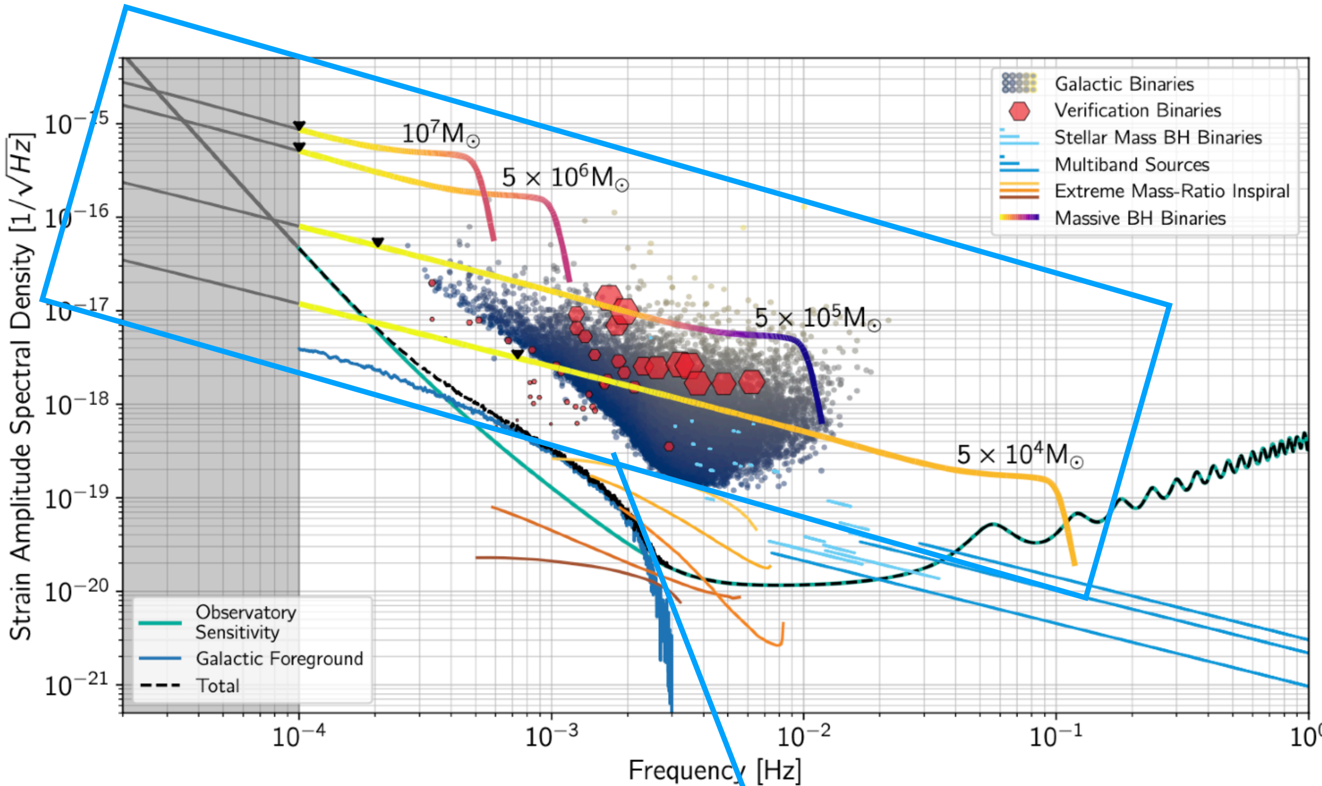


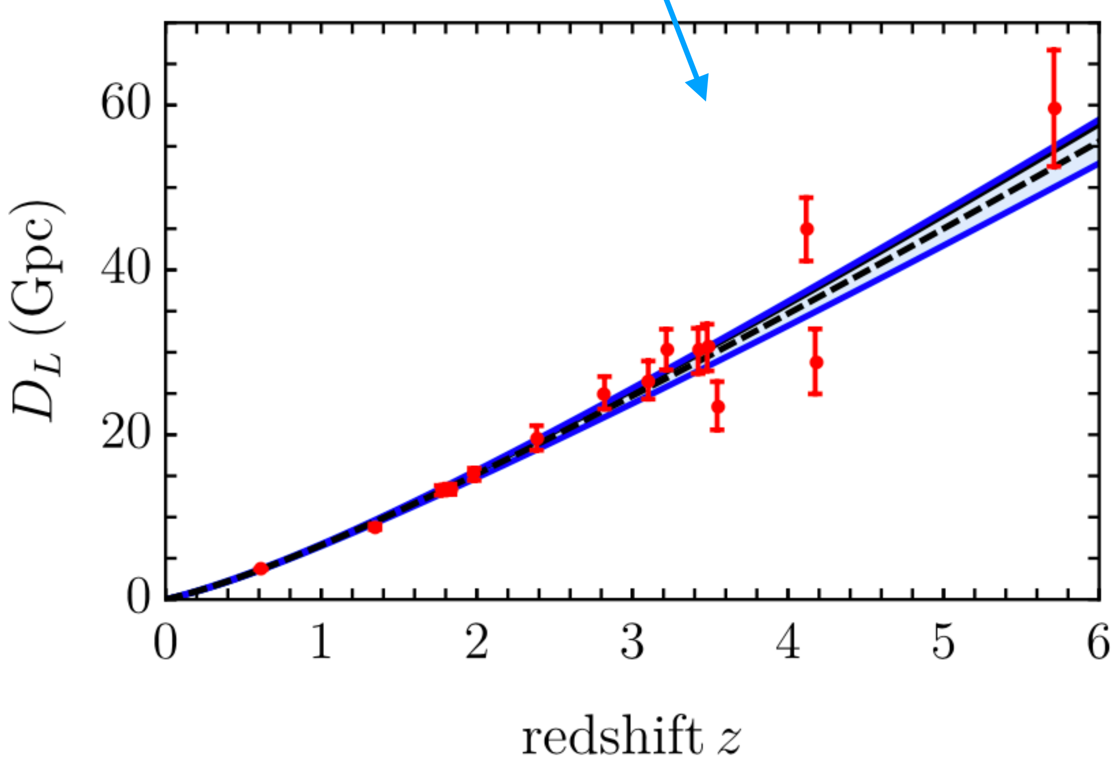
[Toscani+, *PRD* (2024)]

- Redshift range source: $0.5 \lesssim z \lesssim 2$
- <u>Lensed host galaxy may be identified</u>
- LISA detections: 0 to 10/yr
- <u>**Expected results with one LEMRI (with host galaxy identified):**</u>
    - H_0 at 1% or better (assuming Ω_m)



Future prospects





[Speri+, *PRD* (2021)]

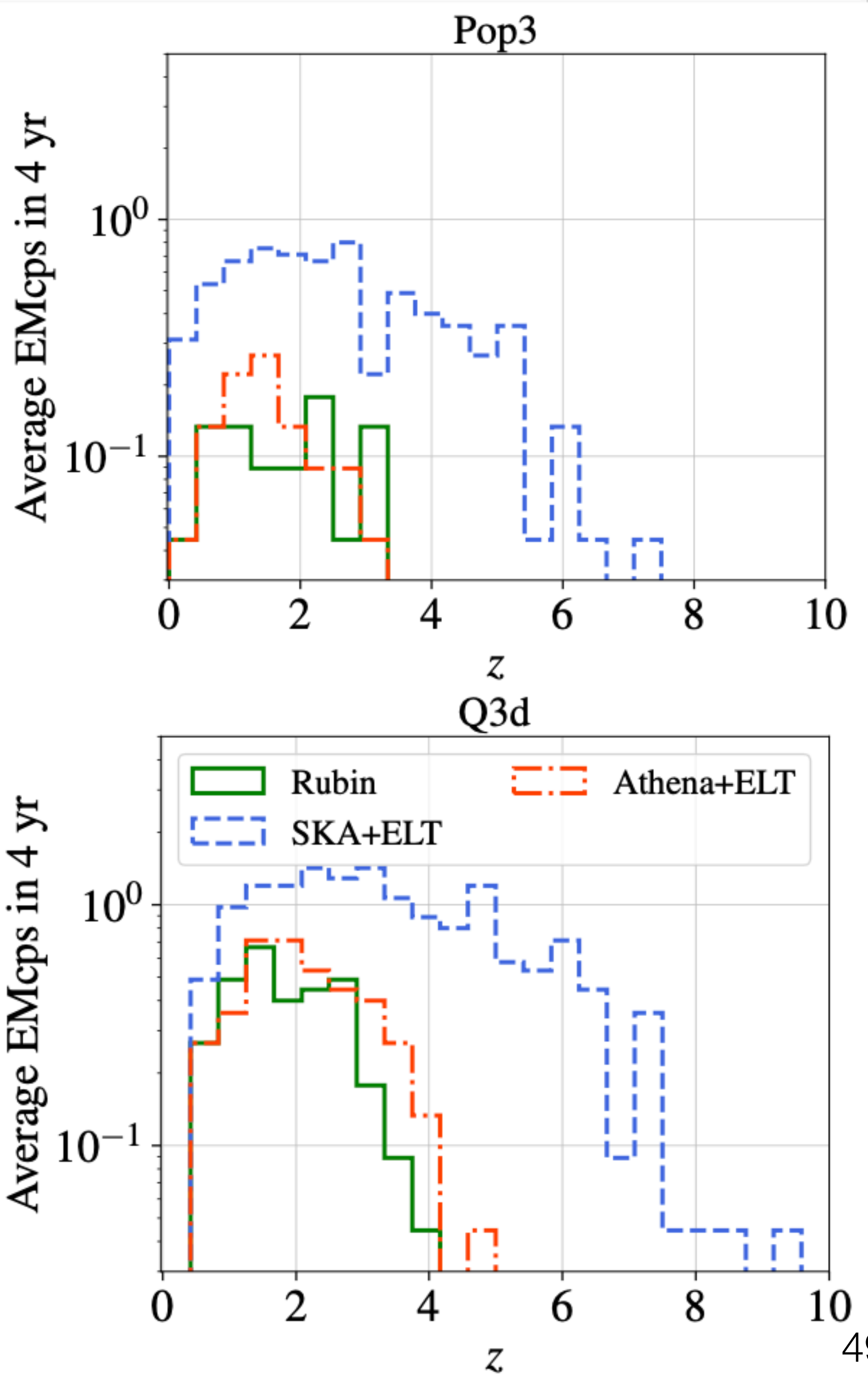
MBHBs

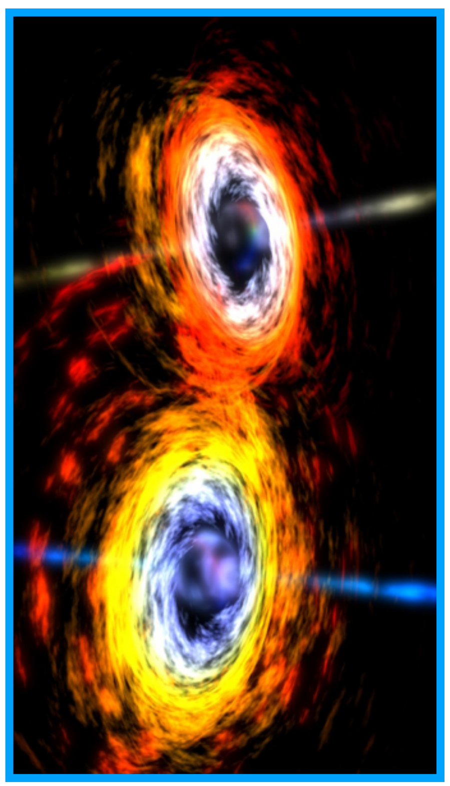
- Redshift range: $z \lesssim 20$
- EM counterparts expected
- LISA detections: 1 to 100/yr
- Useful as standard sirens:
  - $z \lesssim 7$
  - If $\Delta d_L / d_L \lesssim 0.1$ (include lensing)
  - If $\Delta\Omega < 10\ \mathrm{deg}^2$
  - $\Rightarrow$ 1 to 5 standard sirens / yr (with EM counterpart)
- **Expected results:**
  - H_0 to few %
  - “Precise” high-z cosmography

[Tamanini+, *JCAP* (2016)]
[Mangiagli+, *ArXiv* (2023)]

Future prospects

(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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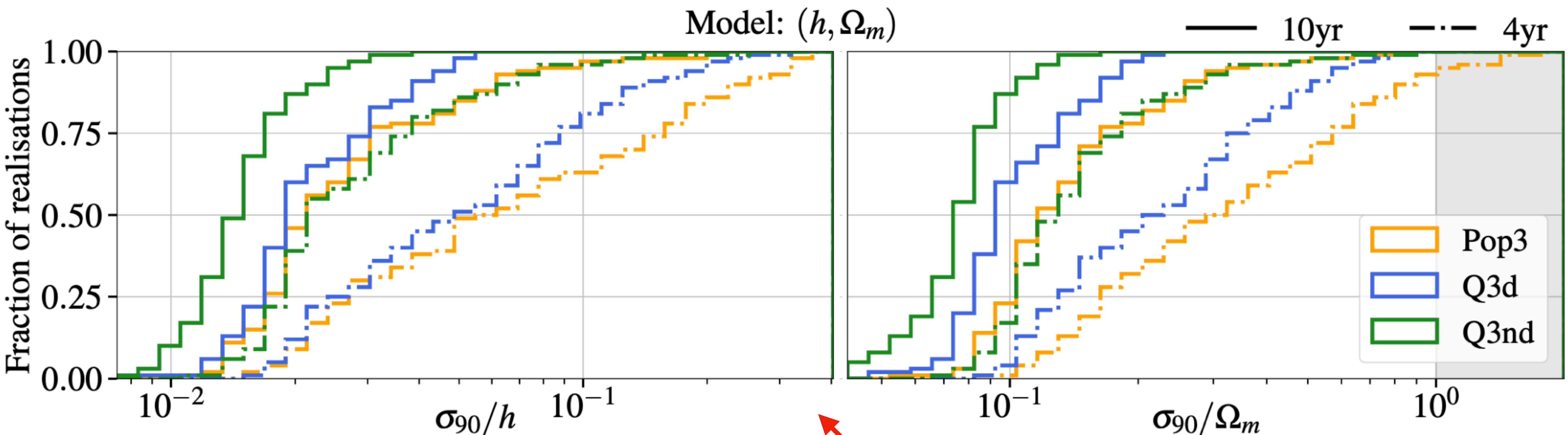
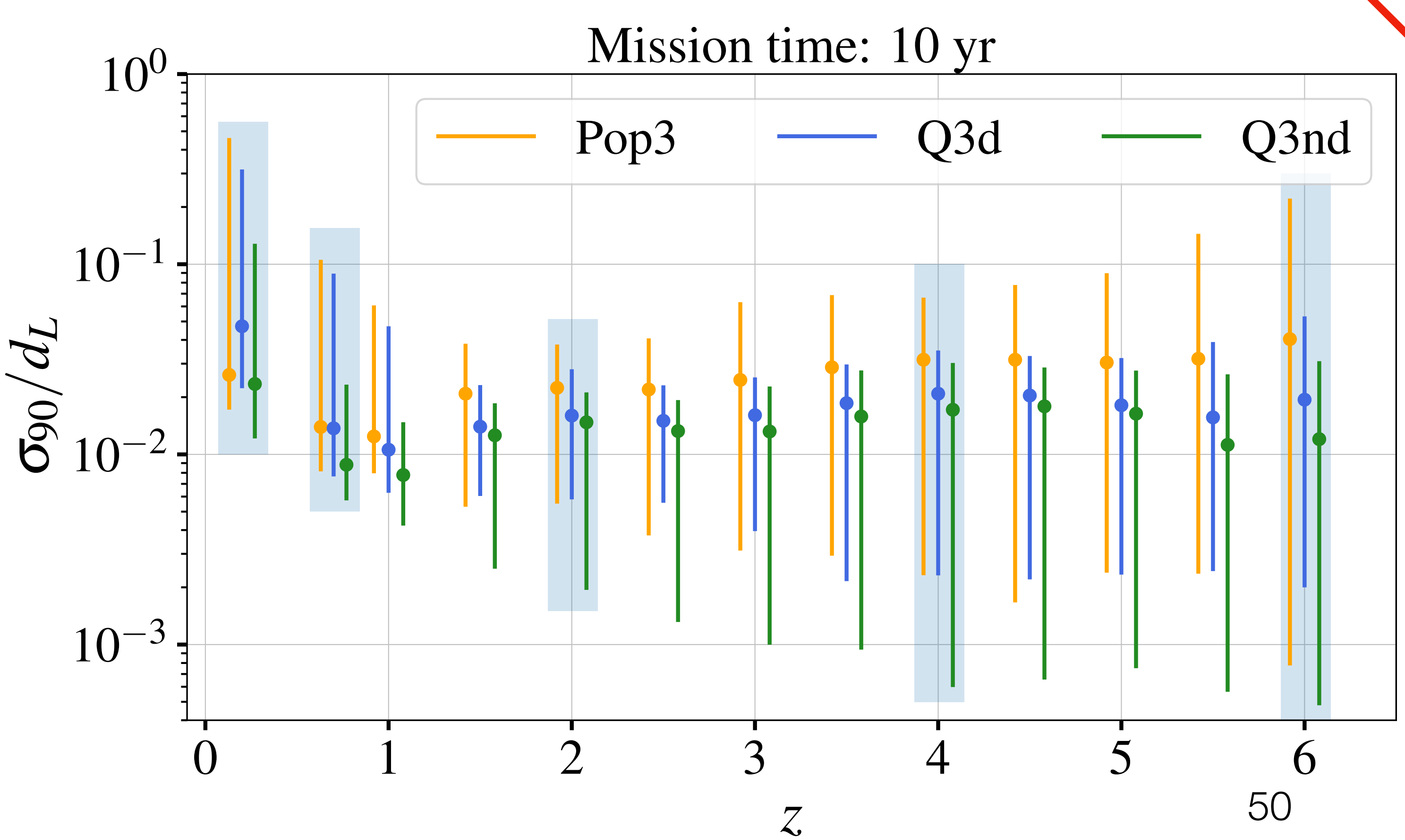
[Tamanini+, *JCAP* (2016)]
[Mangiagli+, *ArXiv* (2023)]

Future prospects

MBHBs





Expected results:

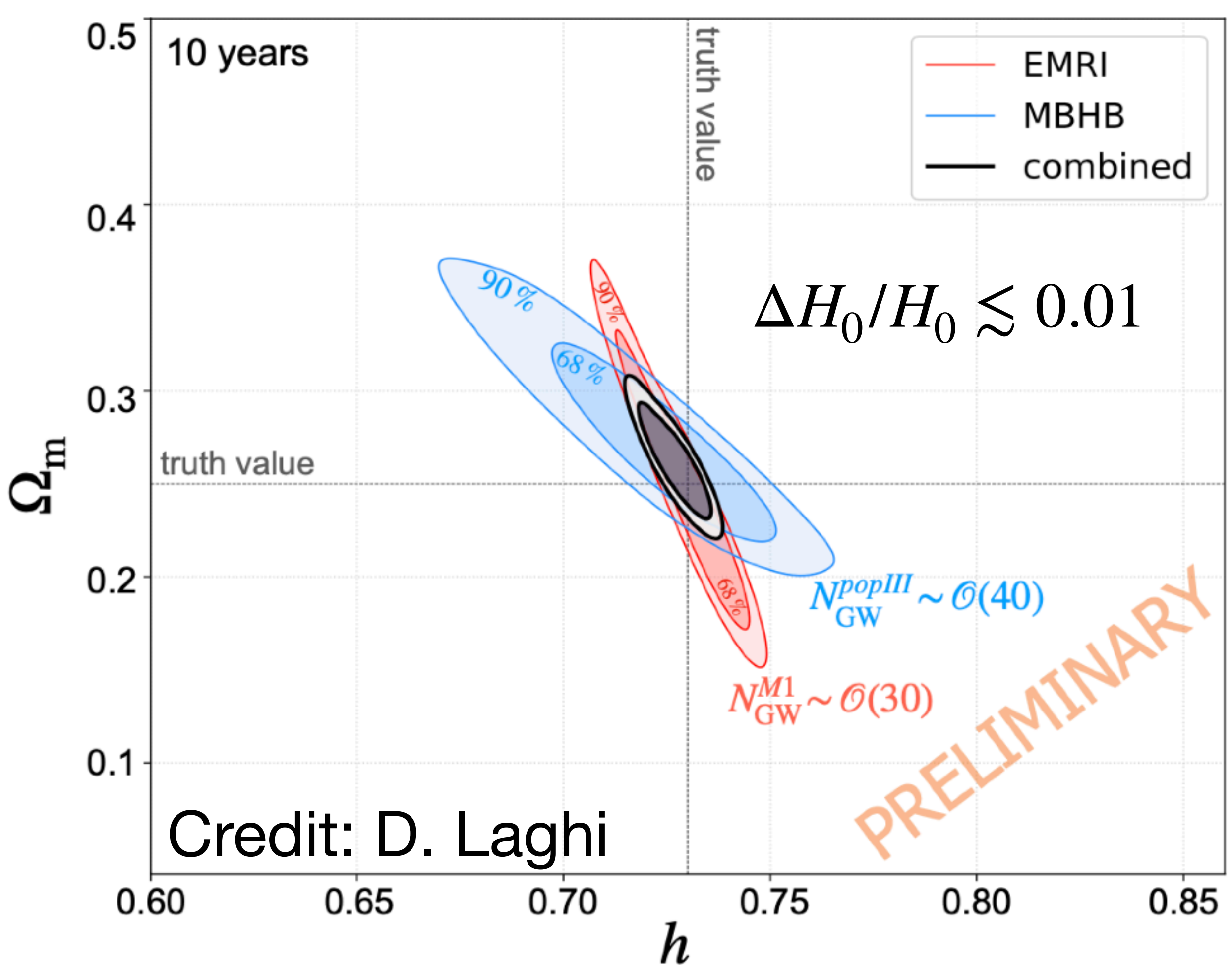
- H_0 to few %
- "Precise" high-z cosmography
  - $d_L(z)$ to few % @ $z \gtrsim 2$

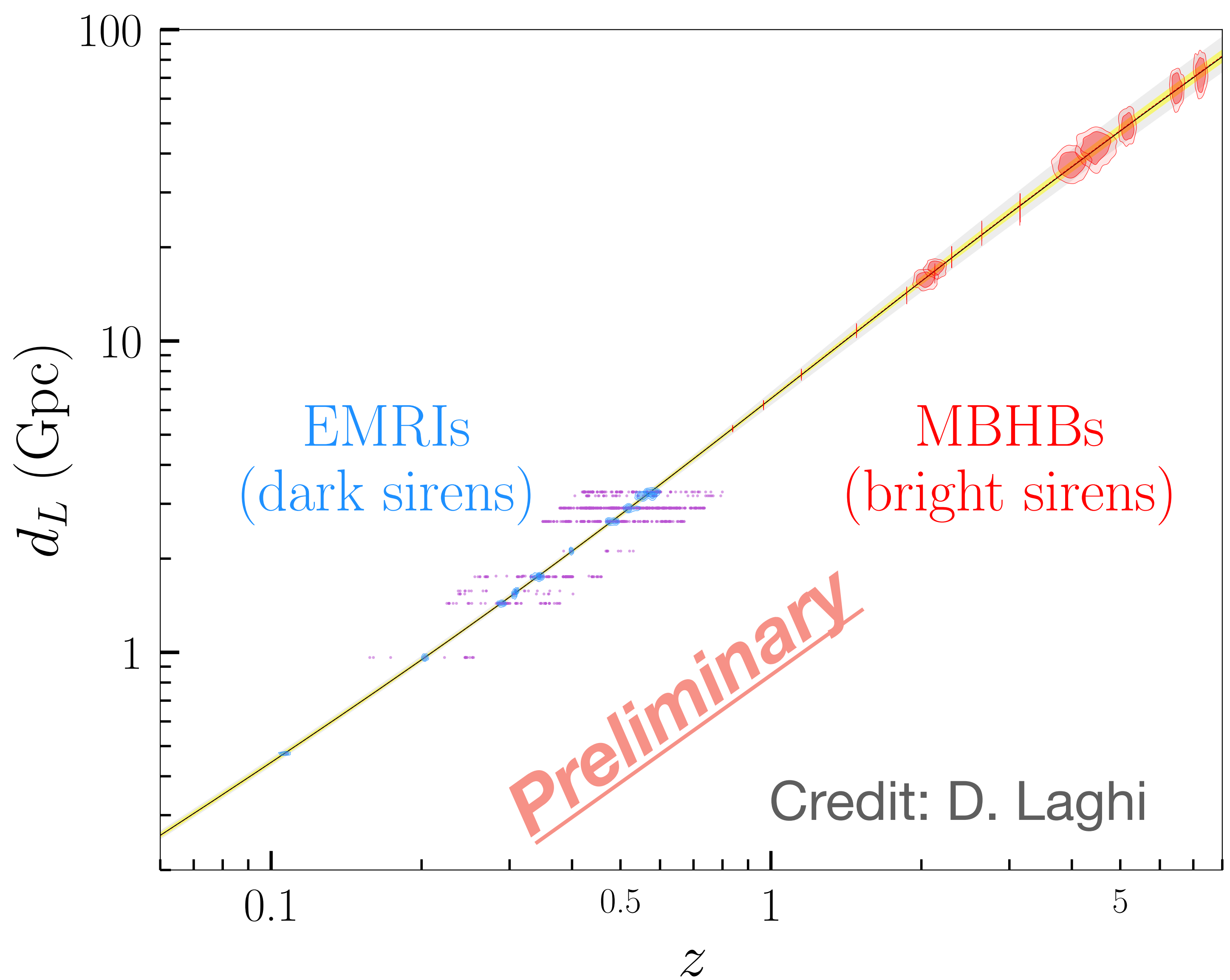
[Mangiagli+, *ArXiv* (2023)]

Future prospects

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)]
[Laghi, Tamanini+, *in prep.*]

Future prospects

LISA Source	Redshift Range	Detection Rates	Redshift Measured (Bright Sirens)	Well Localised (Dark Sirens)	$\frac{\Delta H_0}{H_0}$	More
SOBHBs	$\lesssim 0.1$	$\lesssim 1$/yr	None	$\lesssim 0.1$/yr	None	
IMBHs?	$\lesssim 0.1$	$\lesssim 10$/yr (?)	None	$\lesssim 2$/yr (?)	~2%	Multiband
EMRIs	$\lesssim 4$	$\lesssim 1000$/yr	None	$\lesssim 100$/yr @ $z \lesssim 1$	1-10%	$\Delta w_0 \lesssim 0.1$
LEMRIs	$\lesssim 4$	$\lesssim 10$/yr	$\lesssim 1$/yr @ $z \lesssim 2$	$\lesssim 10$/yr (?) @ $z \lesssim 1$	~1%	
MBHBs	$\lesssim 20$	$\lesssim 100$/yr	$\lesssim 3$/yr @ $z \lesssim 7$	$\lesssim 10$/yr (?) @ $z \lesssim 2$	2-10%	High-z Analyses
LMBHBs	$\lesssim 20$	$\lesssim 1$/yr	$\lesssim 0.1$/yr (?) @ $z \lesssim 2$	$\lesssim 0.1$/yr (?) @ $z \lesssim 2$	~10%	High-z Analyses
Combined			$\lesssim 3$/yr	$\lesssim 100$/yr	$\lesssim 1$ %	High-z and dark energy Analyses

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
    - Bright, Dark and Sirens
  - New cosmological tests complementary to EM observations

- Current observations with ground-based detectors:
  - First standard siren discovered: GW170817
    - First GW measurement of H_0
    - Strong constraints on GW speed of propagation
  - Dark sirens results currently not competitive, but significant improvement on top of GW170817

- Future prospects:
  - Future observations useful to solve tension on H_0
  - 3G detectors and LISA will bring precise GW cosmology and will test LCDM at high-redshift