Standard sirens for LISA

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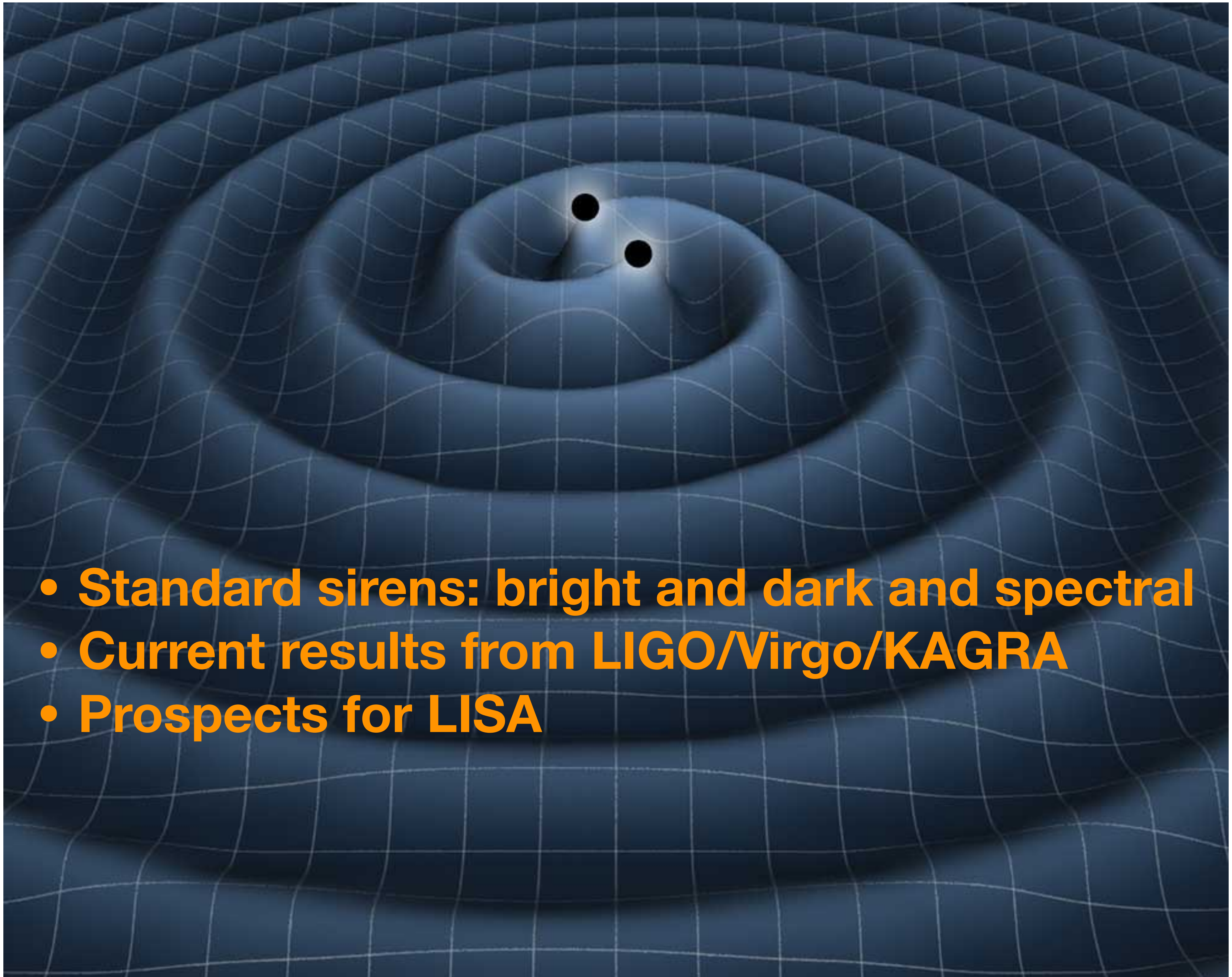
LISA CONSORTIUM

LIGO VIRGO KAGRA

ET EINSTEIN TELESCOPE

20/06/2024

Outline

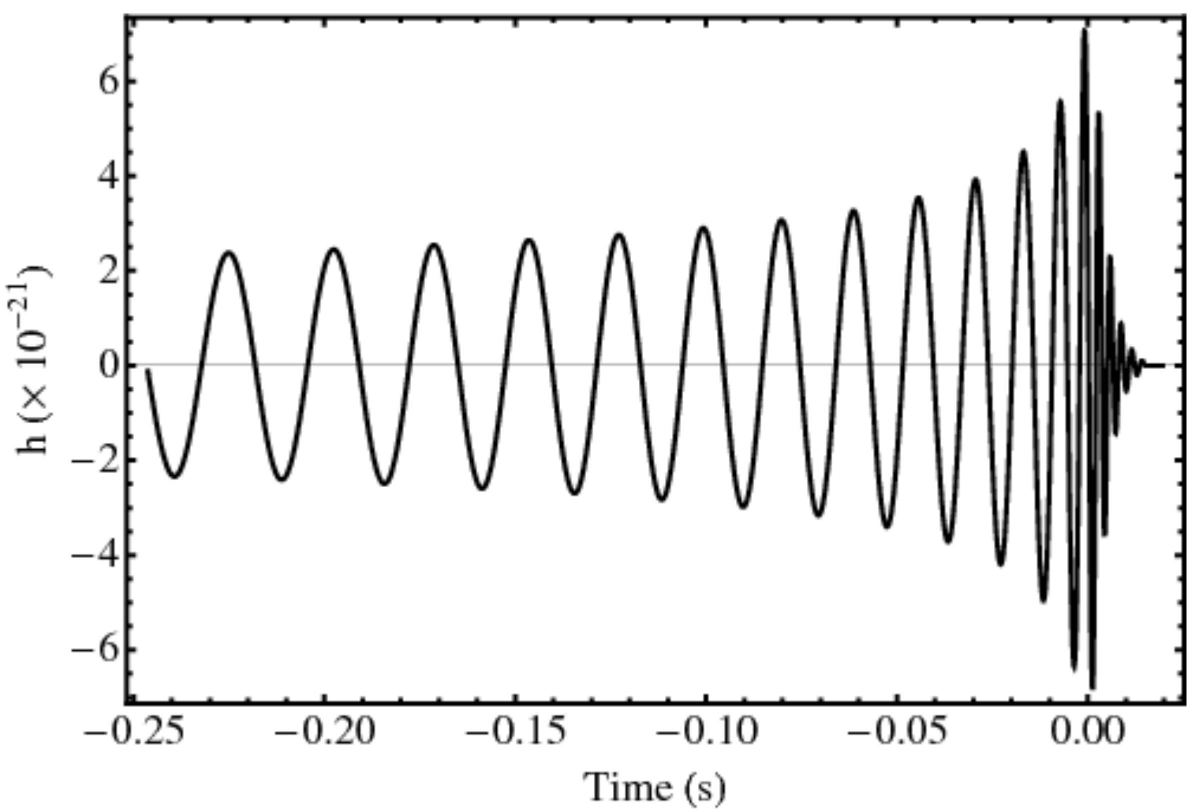


- **Standard sirens: bright and dark and spectral**
- **Current results from LIGO/Virgo/KAGRA**
- **Prospects for LISA**

Standard sirens

Standard sirens

How do we extract cosmological information from gravitational wave observations?



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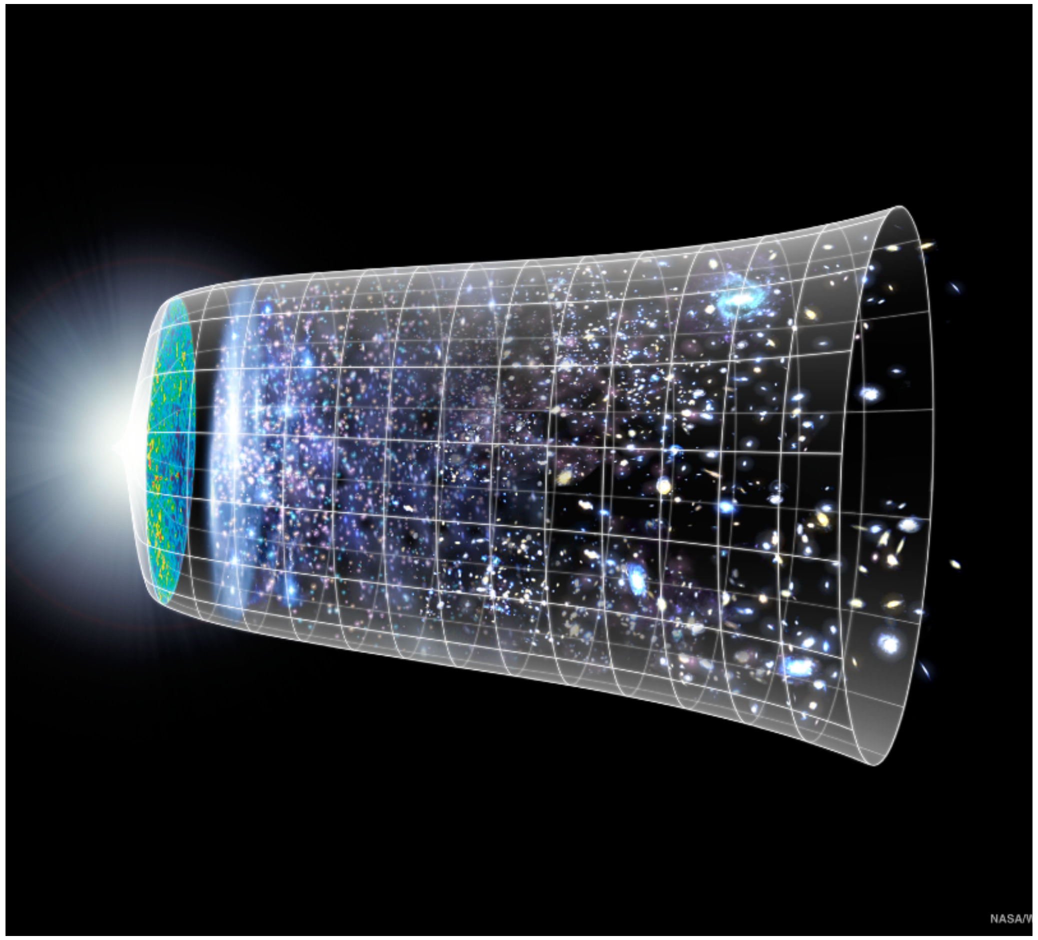
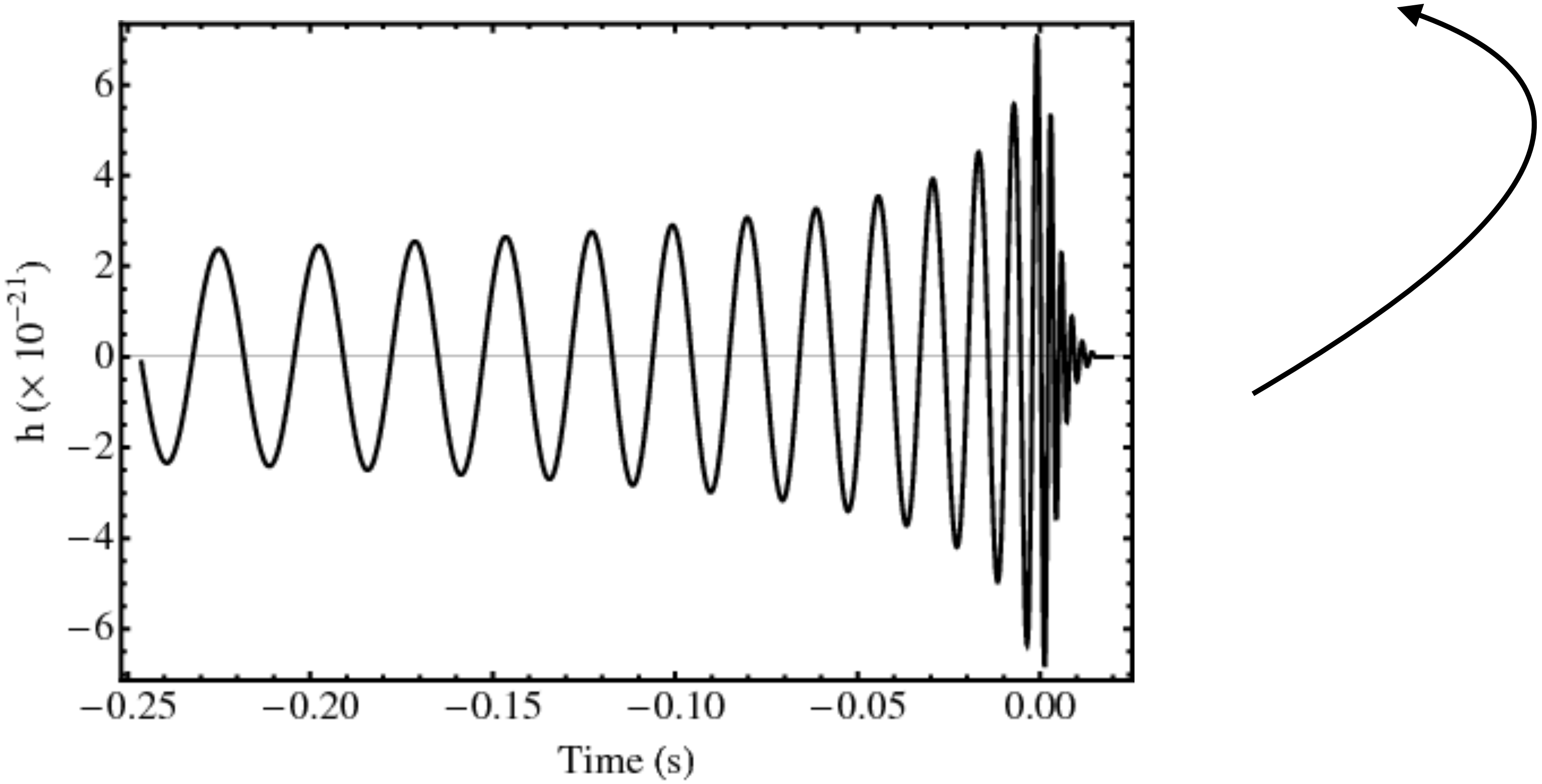


Standard sirens

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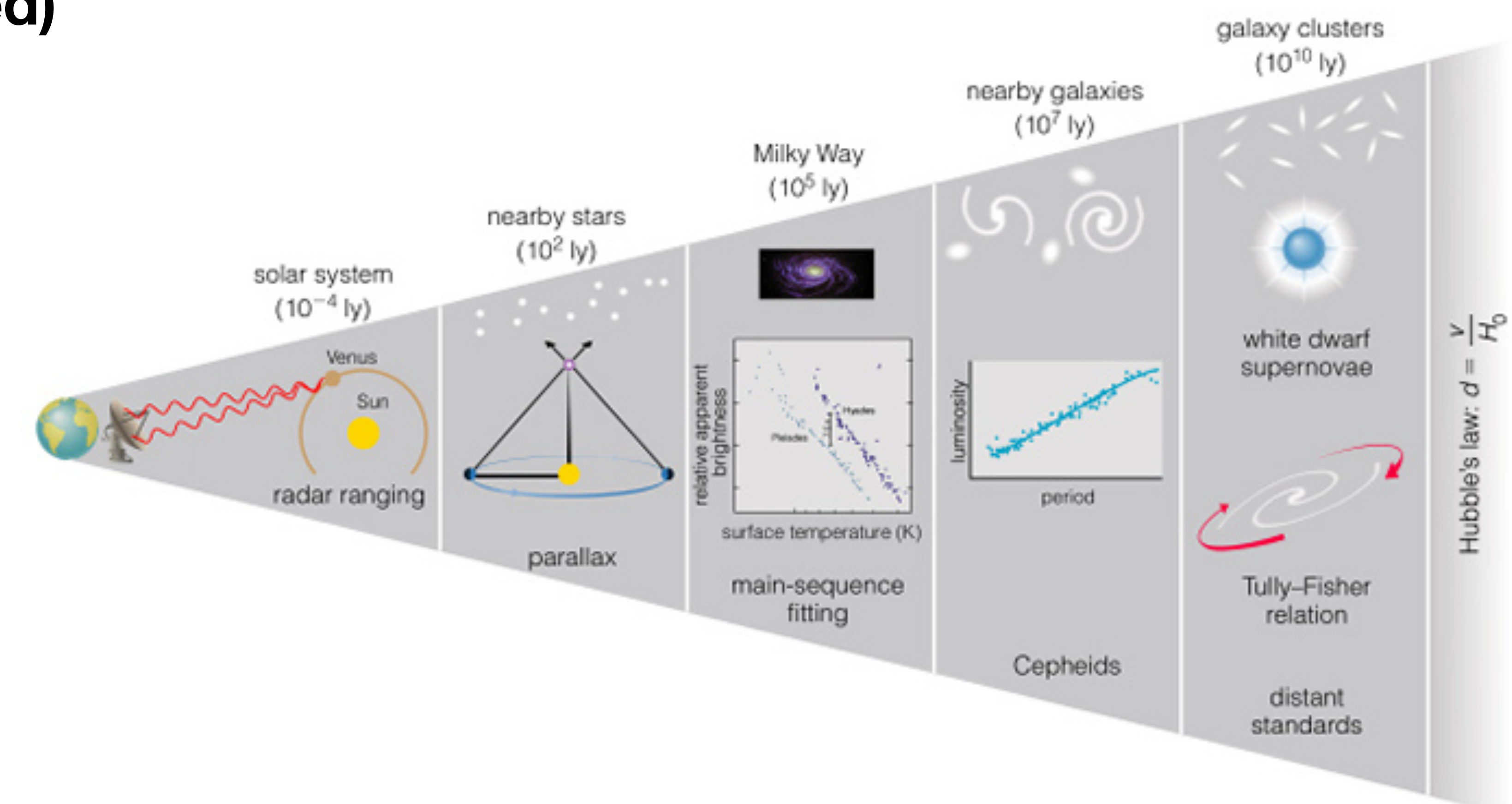
Most importantly for cosmology, one can measure the luminosity distance d_L of the source directly from the GW signal without relying on the *cosmic distance ladder* (only GR has been assumed)

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

↓

Free of possible calibration systematics



Standard sirens

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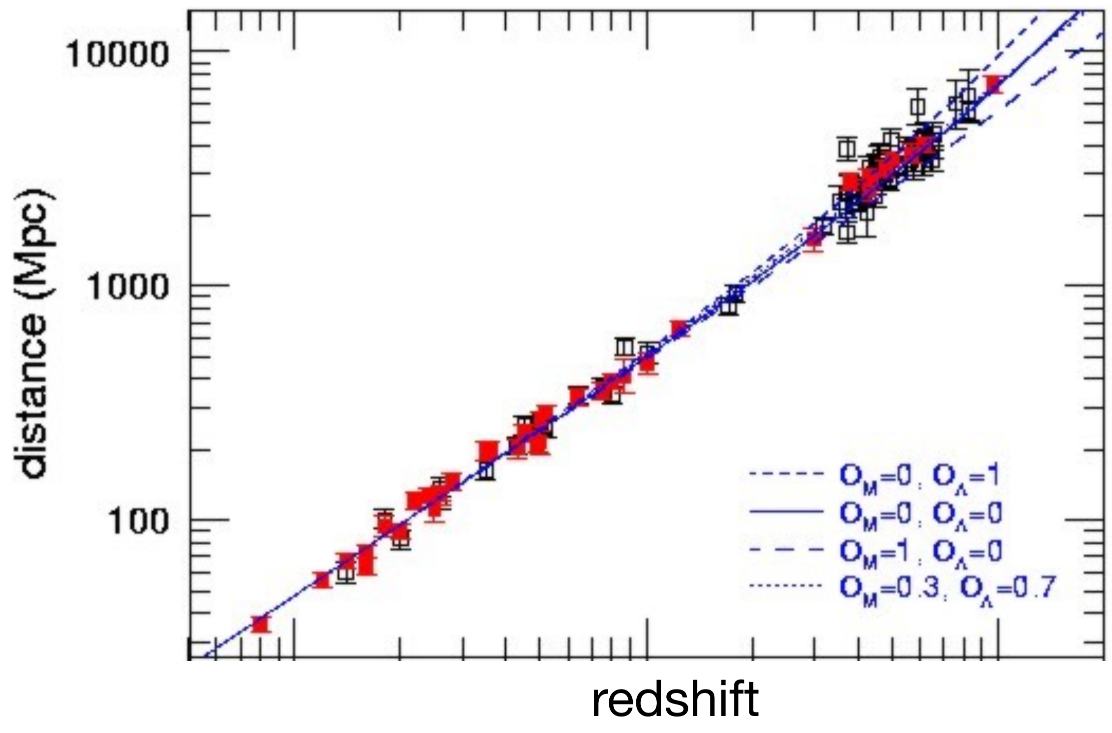
Note however that the waveform above does not depend explicitly on the redshift z, which cannot thus be measured directly from GWs

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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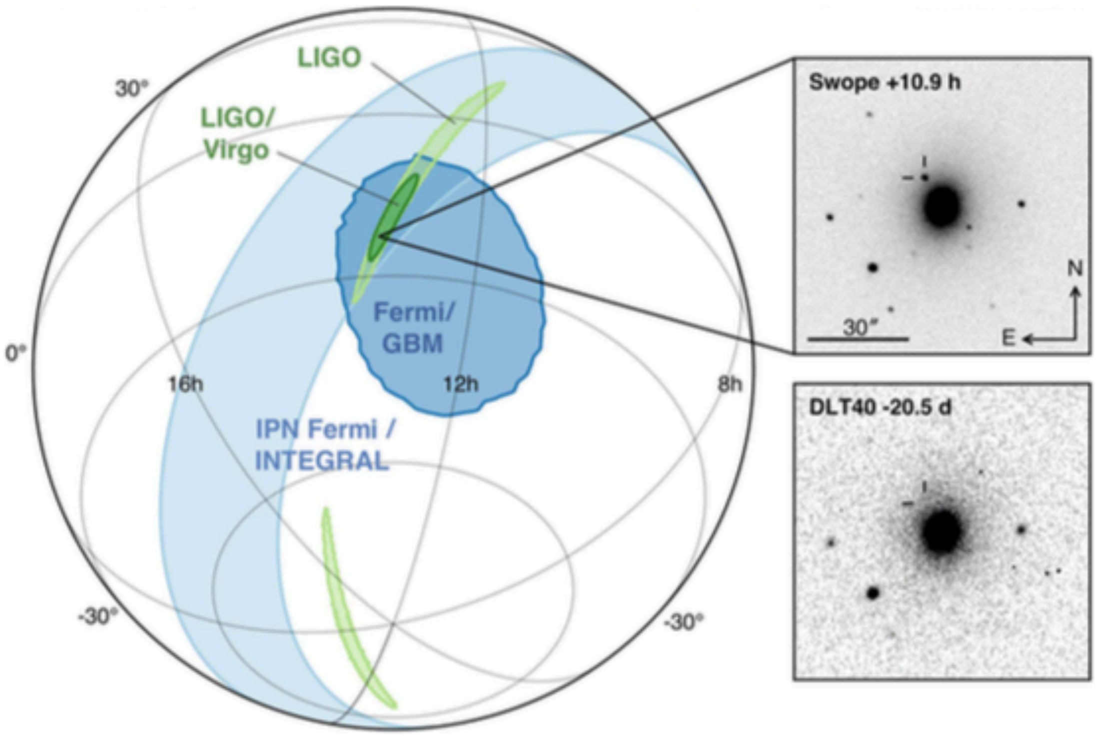

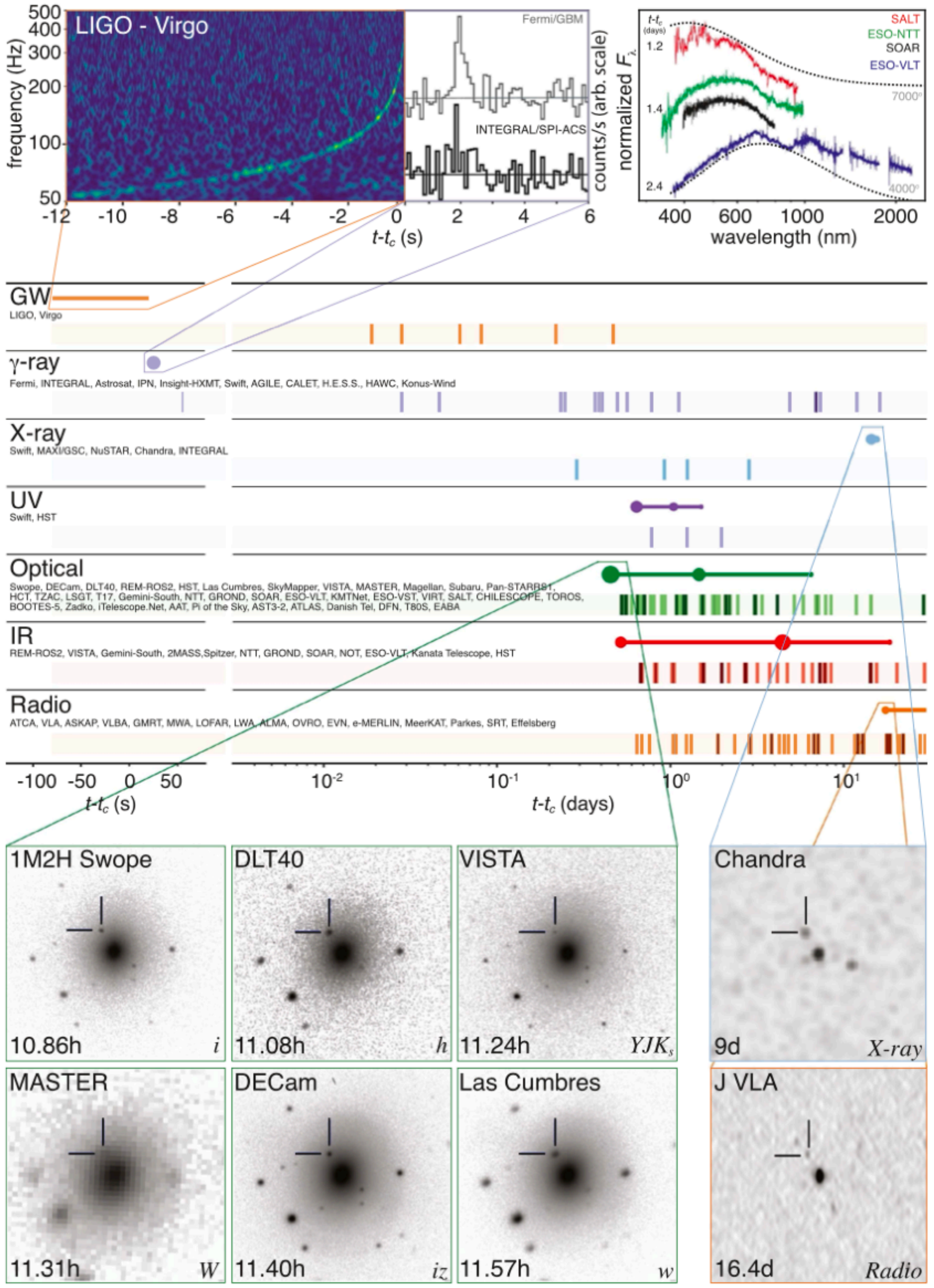

[Schutz, *Nature* (1986)] **Example: GW170817** [LVC+, *ApJL* (2017)]

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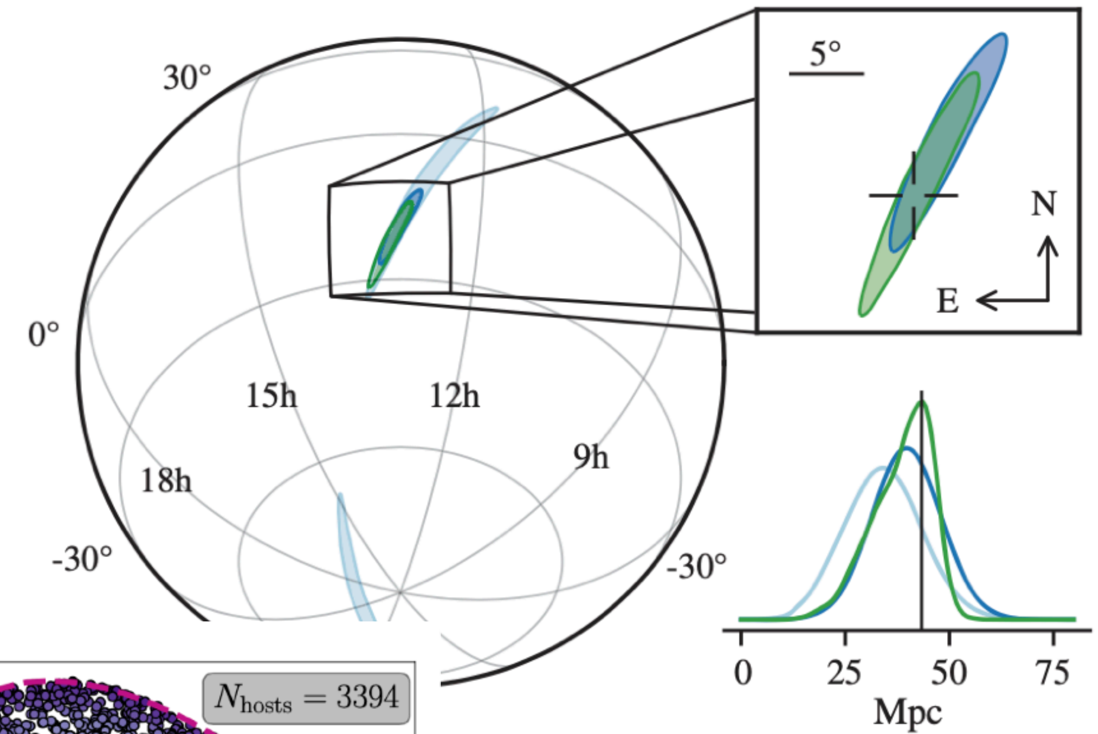

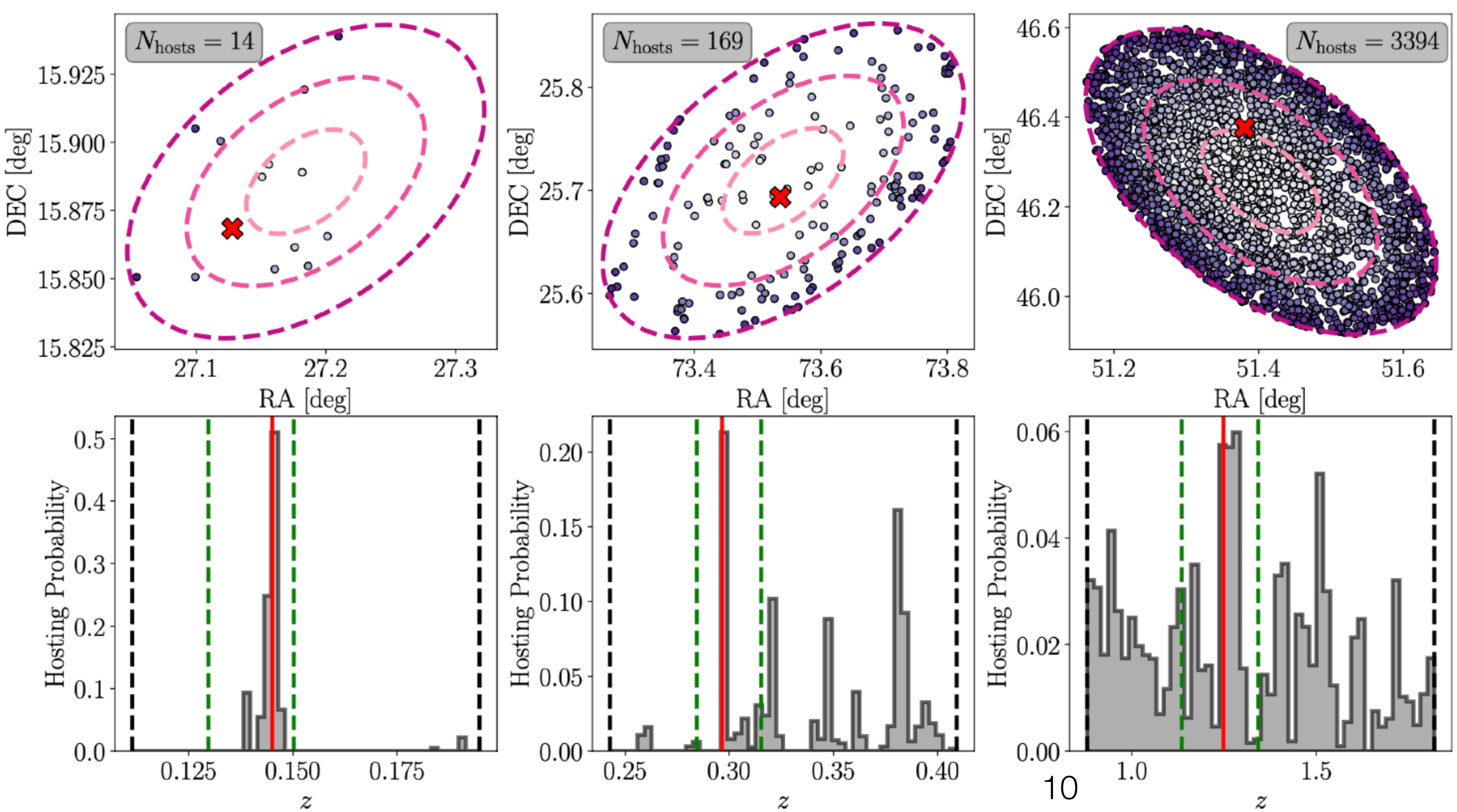

[Schutz, *Nature* (1986)]
[Del Pozzo, *PRD* (2012)]
[Gray+, *PRD* (2020)]
[Gray+, *JCAP* (2023)]

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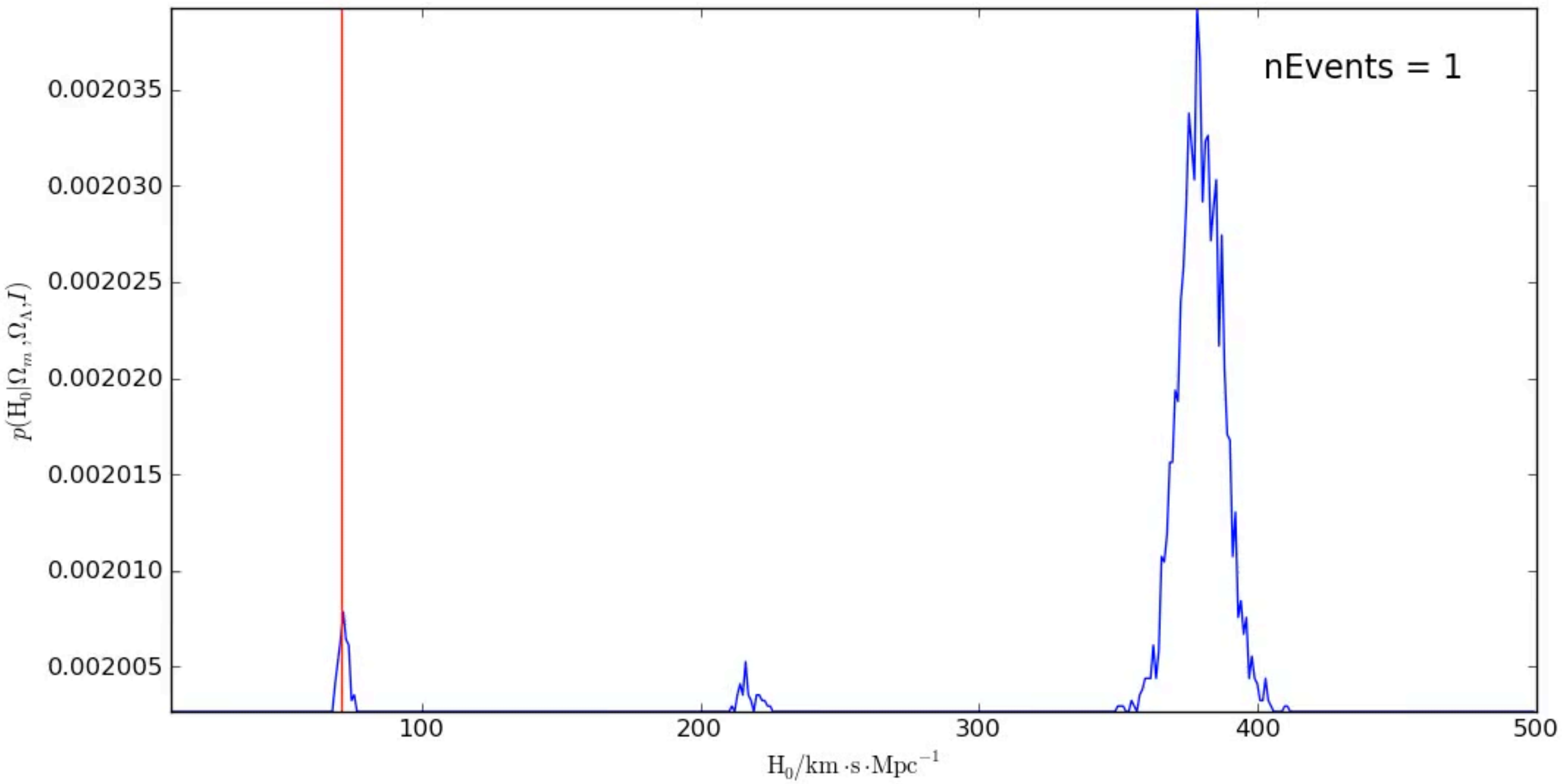
By stacking together the results from many events, the values given by the spurious galaxies cancel out and the true cosmological parameters emerge



Credit: W. Del Pozzo

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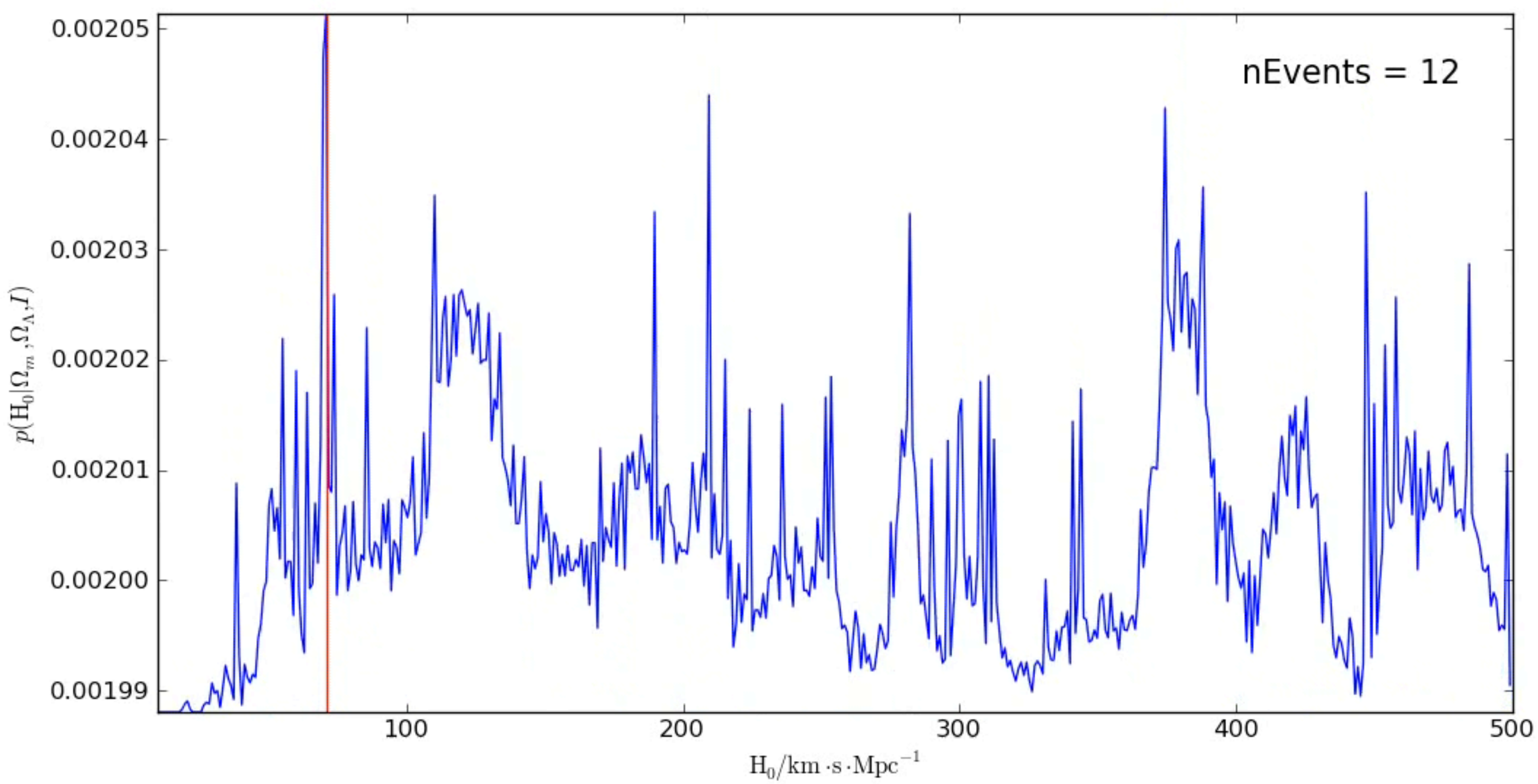

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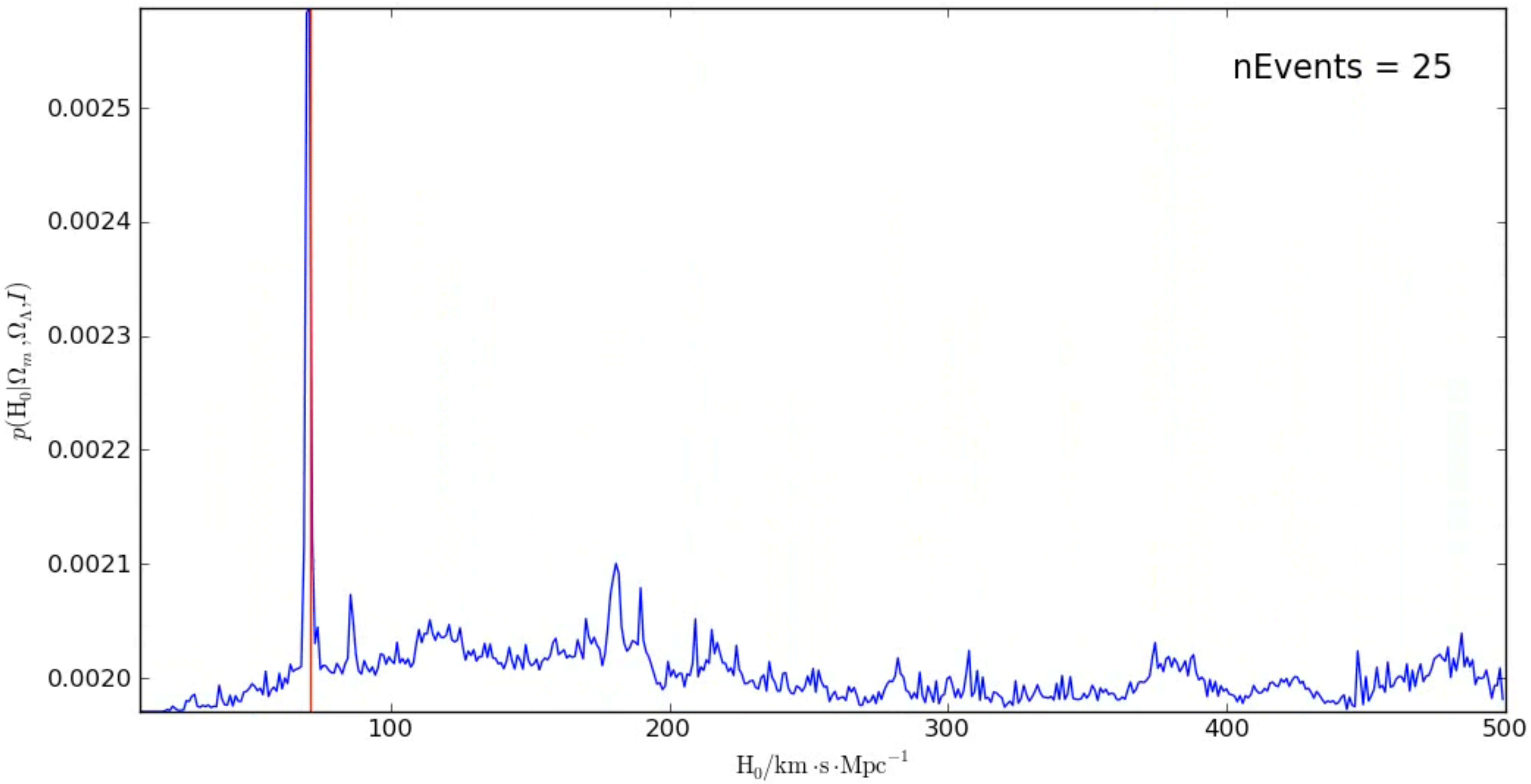

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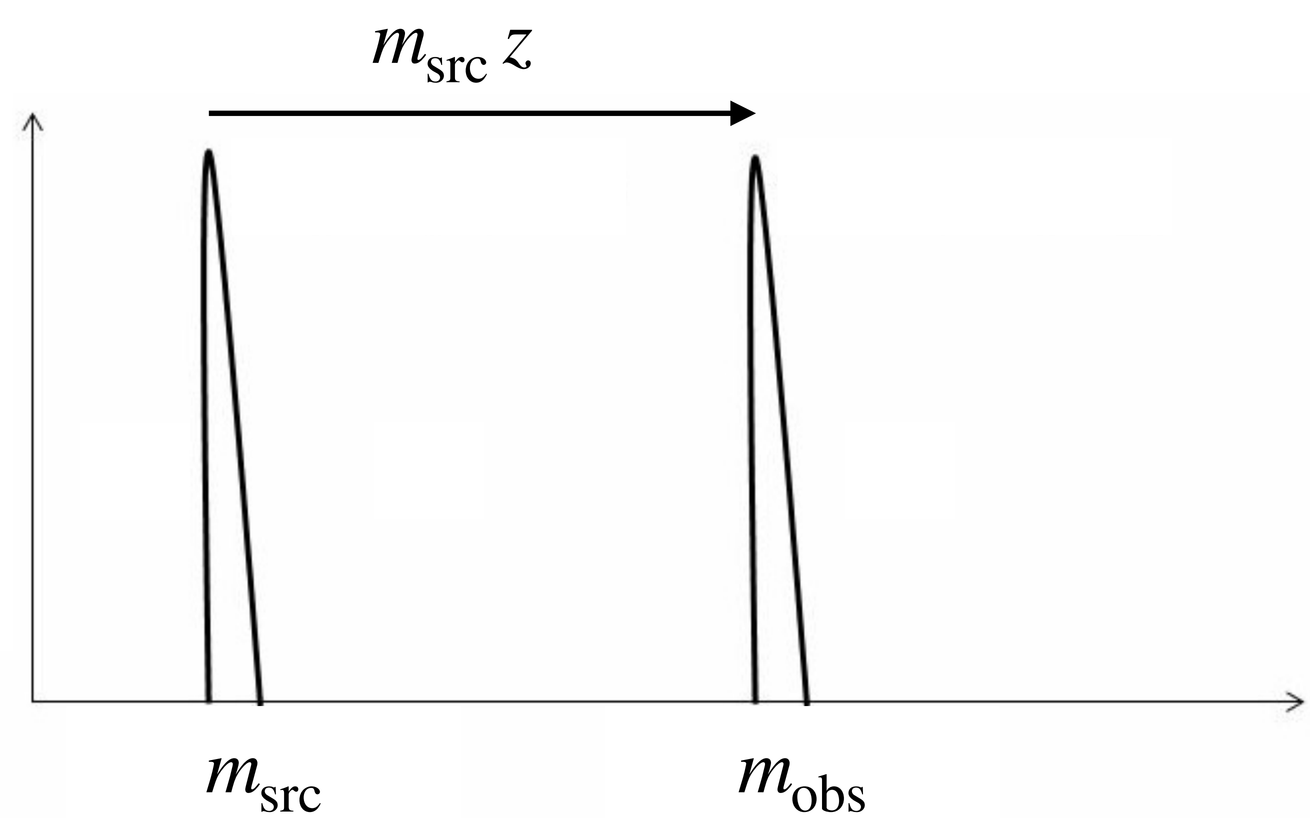

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Redshifted chirp mass

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

[Taylor+, *PRD* (2012)]

[Mastrogiovanni+, *PRD* (2021)]

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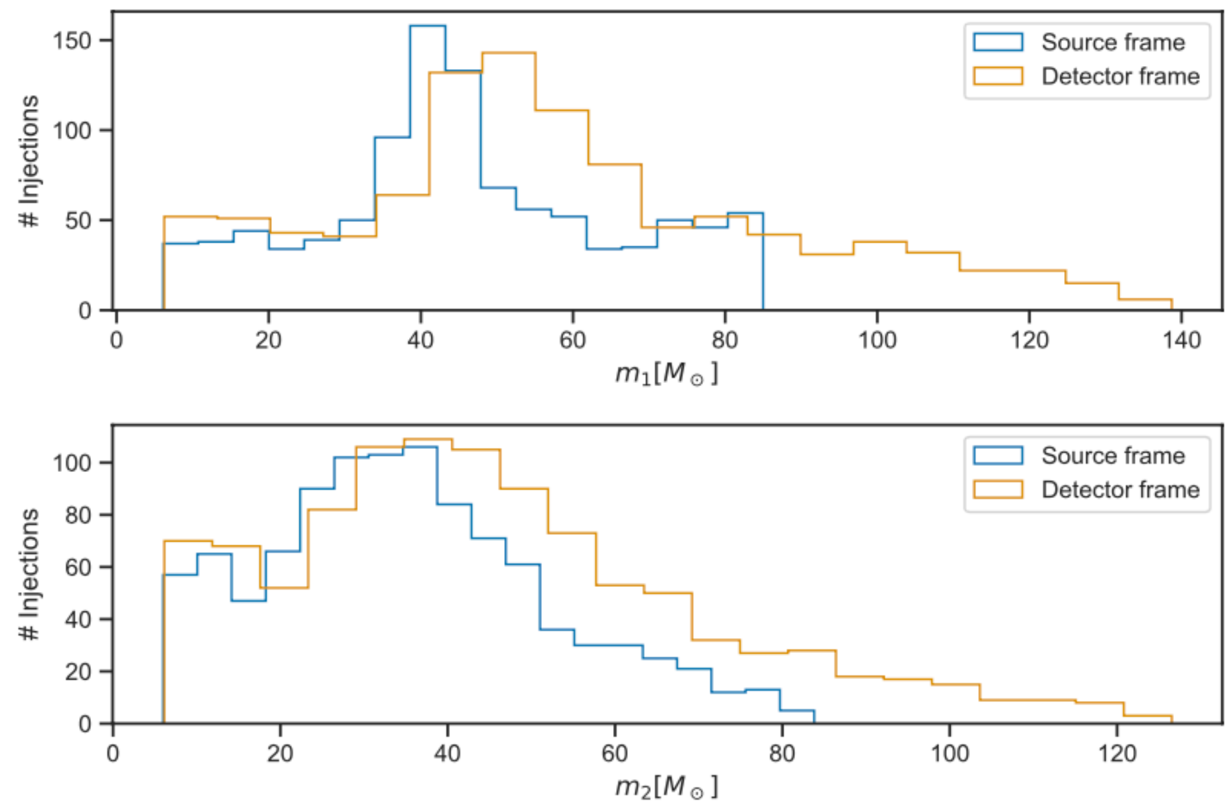
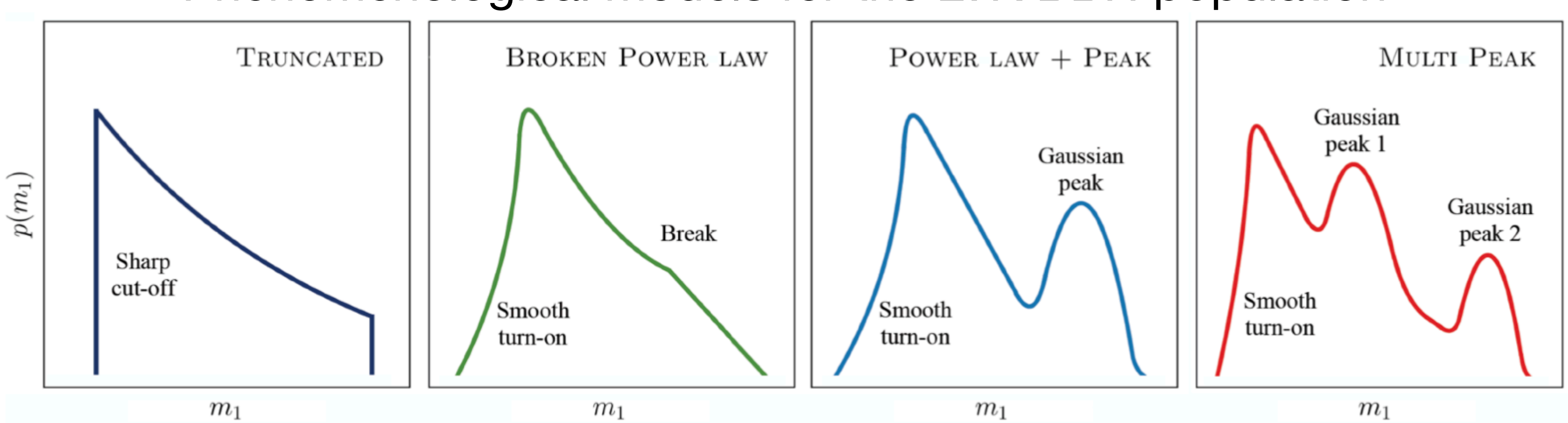


Phenomenological models for the LVK BBH population



[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

Slide curtesy of S. Mastrogiovanni

Current results from LVK

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Status of Earth-based GW observations:

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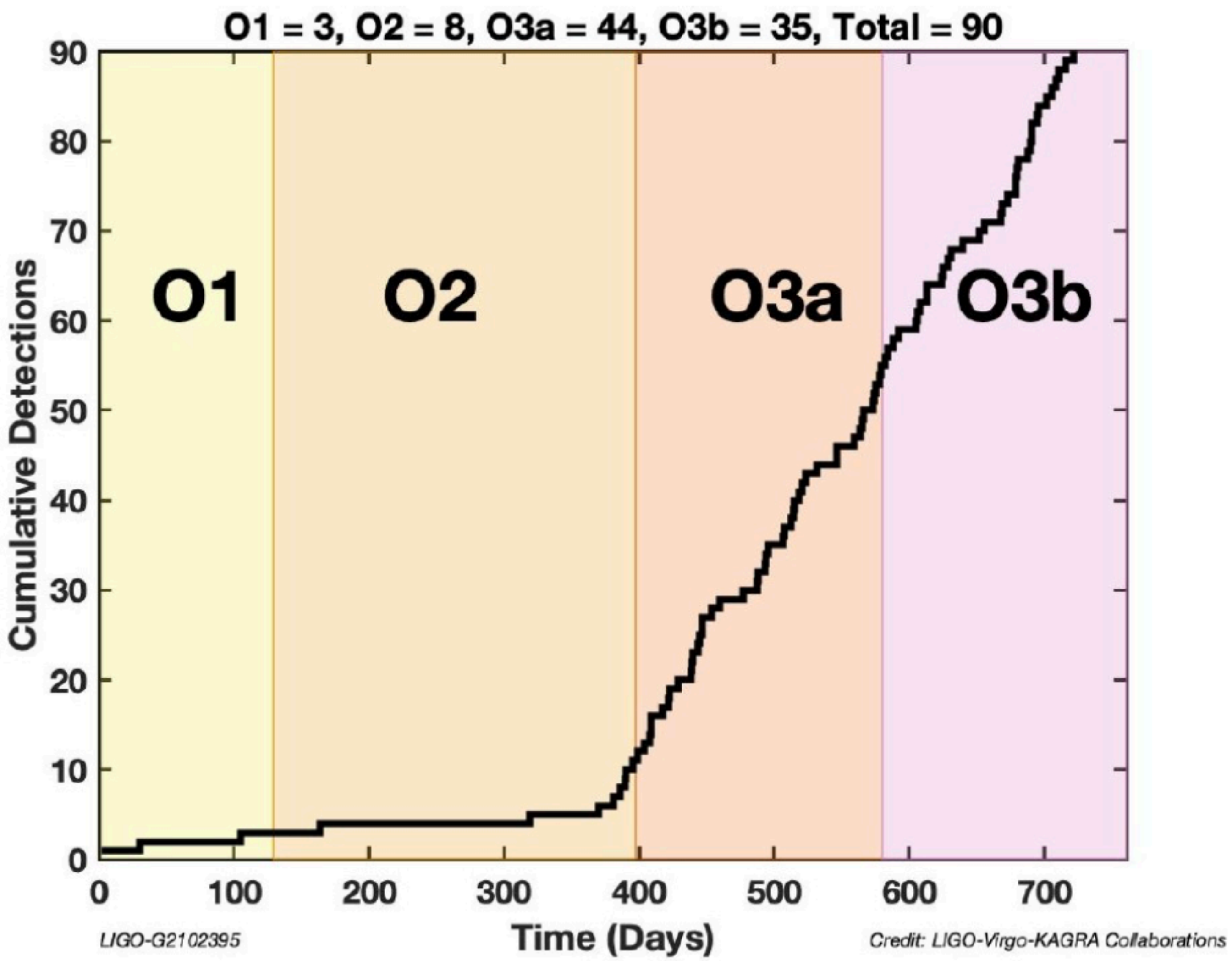
- O1: 2015 (completed), LIGO only, 4 months of data, 3 BBHs detected
- O2: 2017 (completed), LIGO(+VIRGO for GW1708xx only), 6 months of data, 7 BBHs + 1 BNS with EM counterpart (GW170817) [LVC, *PRX* (2019)]
- O3: 2019 (completed), LIGO+VIRGO, ~1 year of data, 79 events, 73 BBHs + 2 BNSs + 4 NSBHs [LVK, *PRX* (2020)] [LVK, *ApJL* (2021)] [LVK, *arXiv* (2021)]
- O4: started May 2023 LIGO+VIRGO(+KAGRA)
- O5: ~2027

90 high-significance* GW events in total so far

*for additional lower-significance events see arXiv:2108.01045



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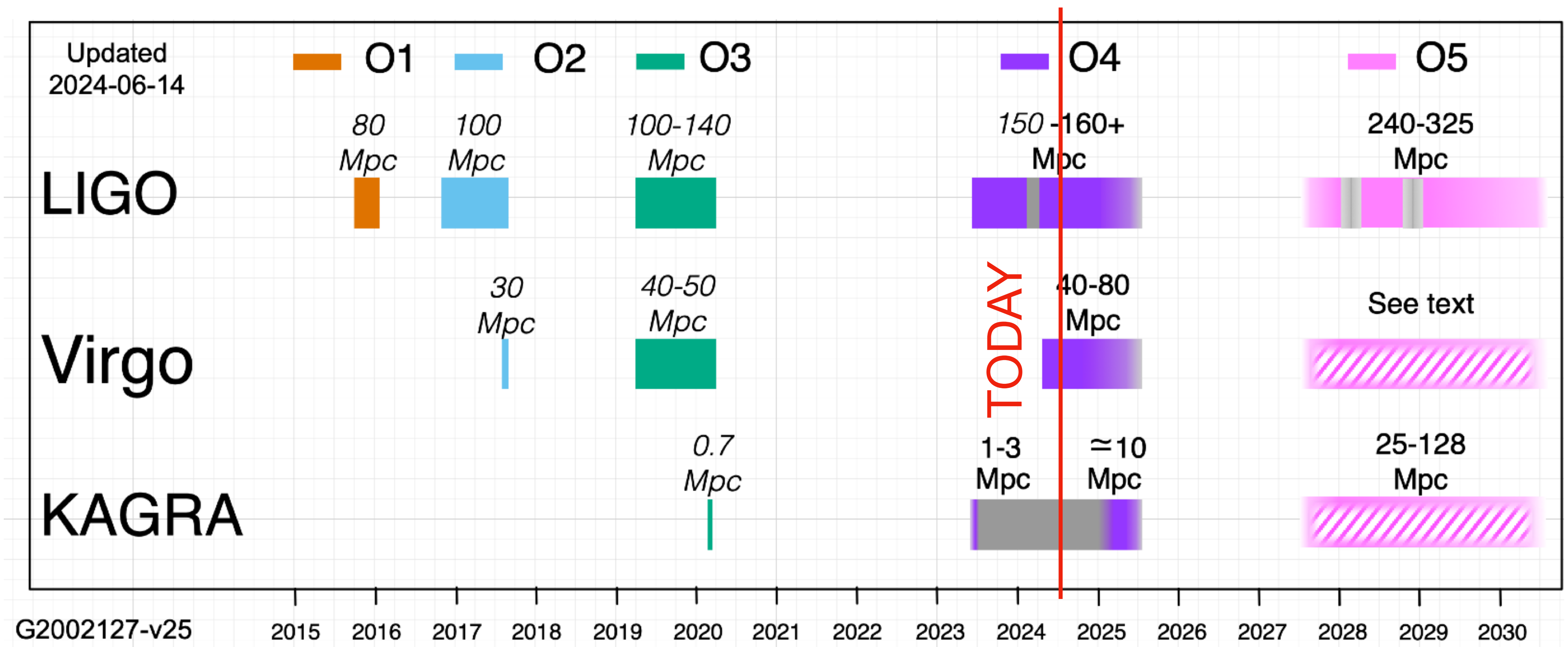
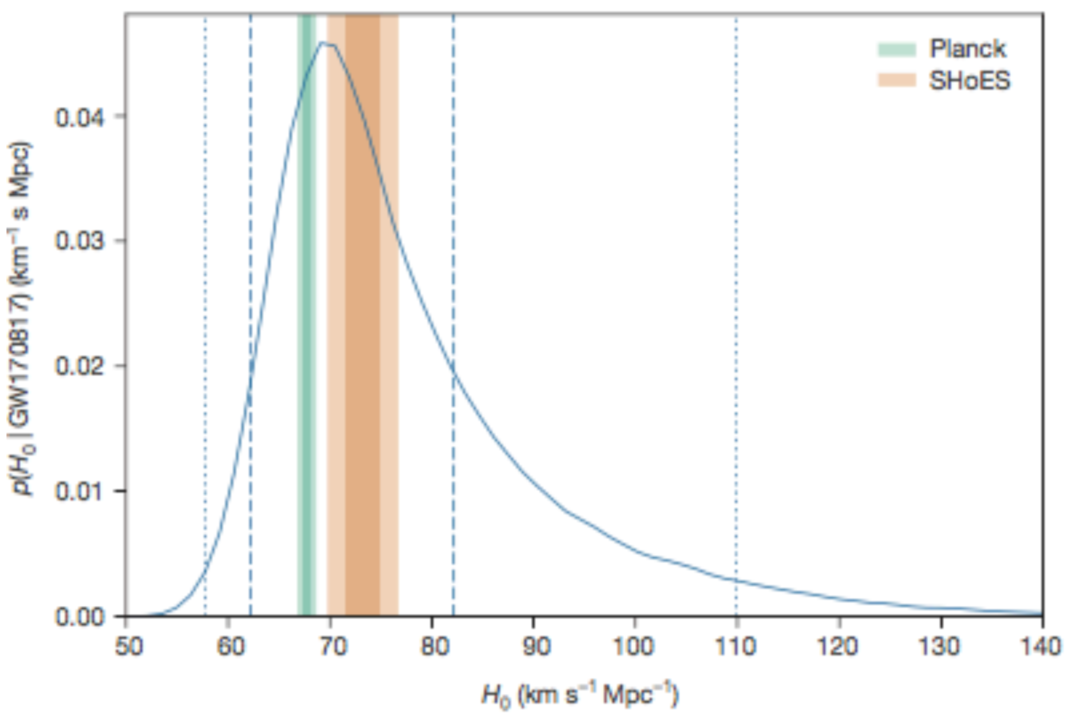
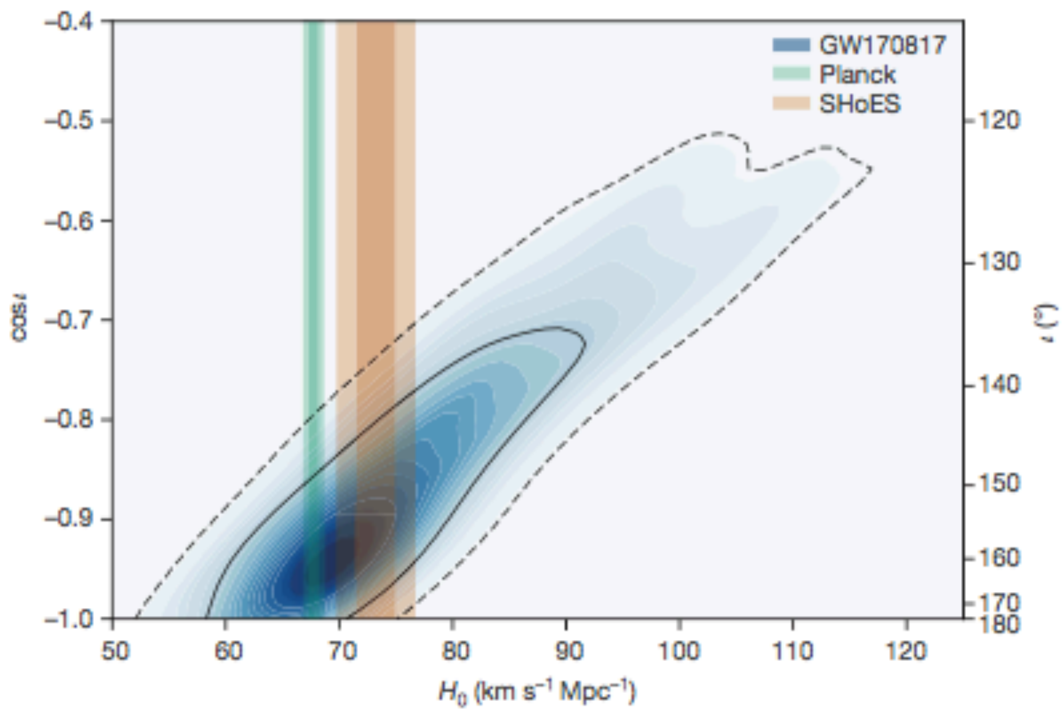
https://observing.docs.ligo.org/plan



Current results from LVK

GW170817: the first ever (bright) standard siren





The identification of an EM counterpart yielded the <u>first cosmological measurements with GW standard sirens</u>

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

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

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

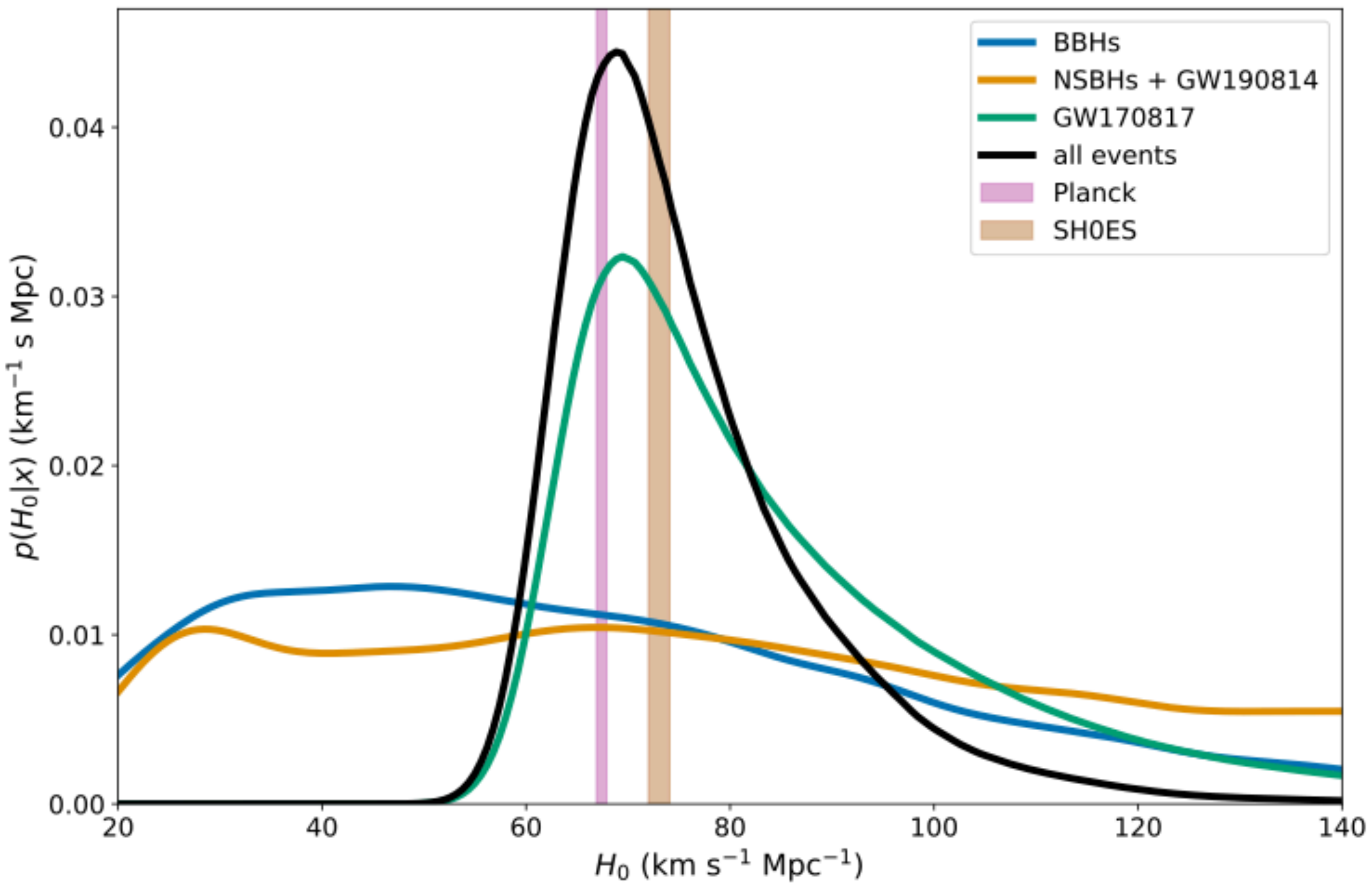
Current dark and spectral standard siren

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

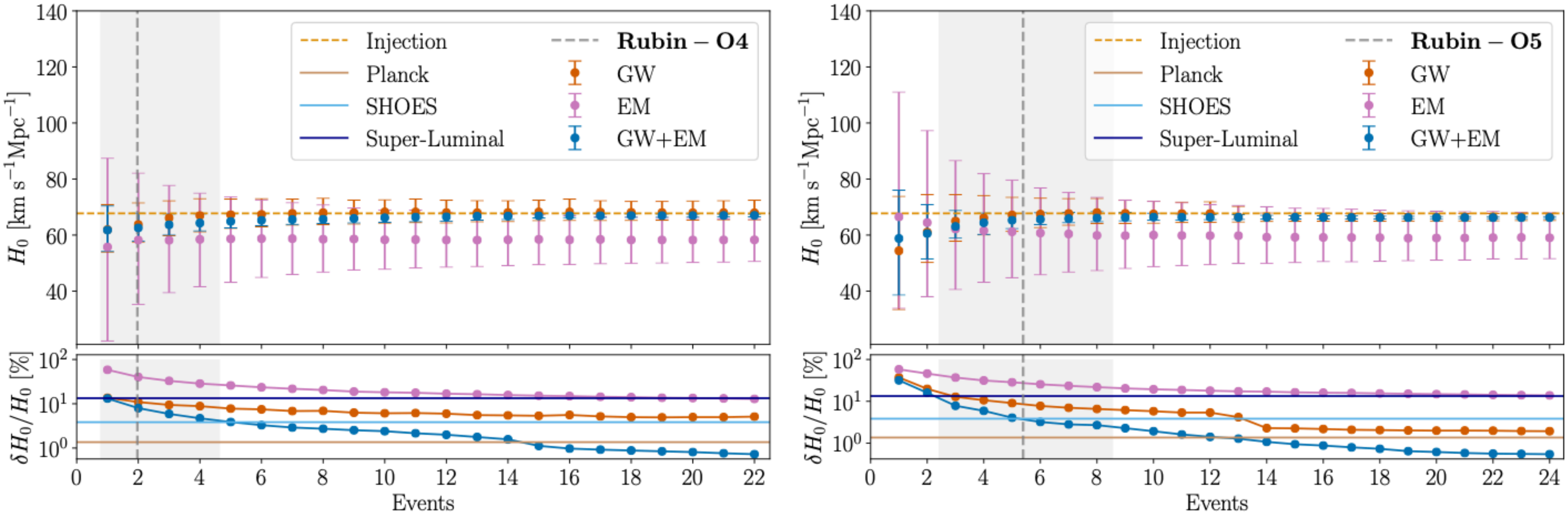
LVK O4 cosmological results will combine all standard siren methods (bright+spectral+statistical) for the first time



[LVK, *ApJ* (2023)]
[Gray+, *JCAP* (2023)]

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.



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	$5.39^{+6.59}_{-2.99}$	$0.43^{+0.59}_{-0.28}$

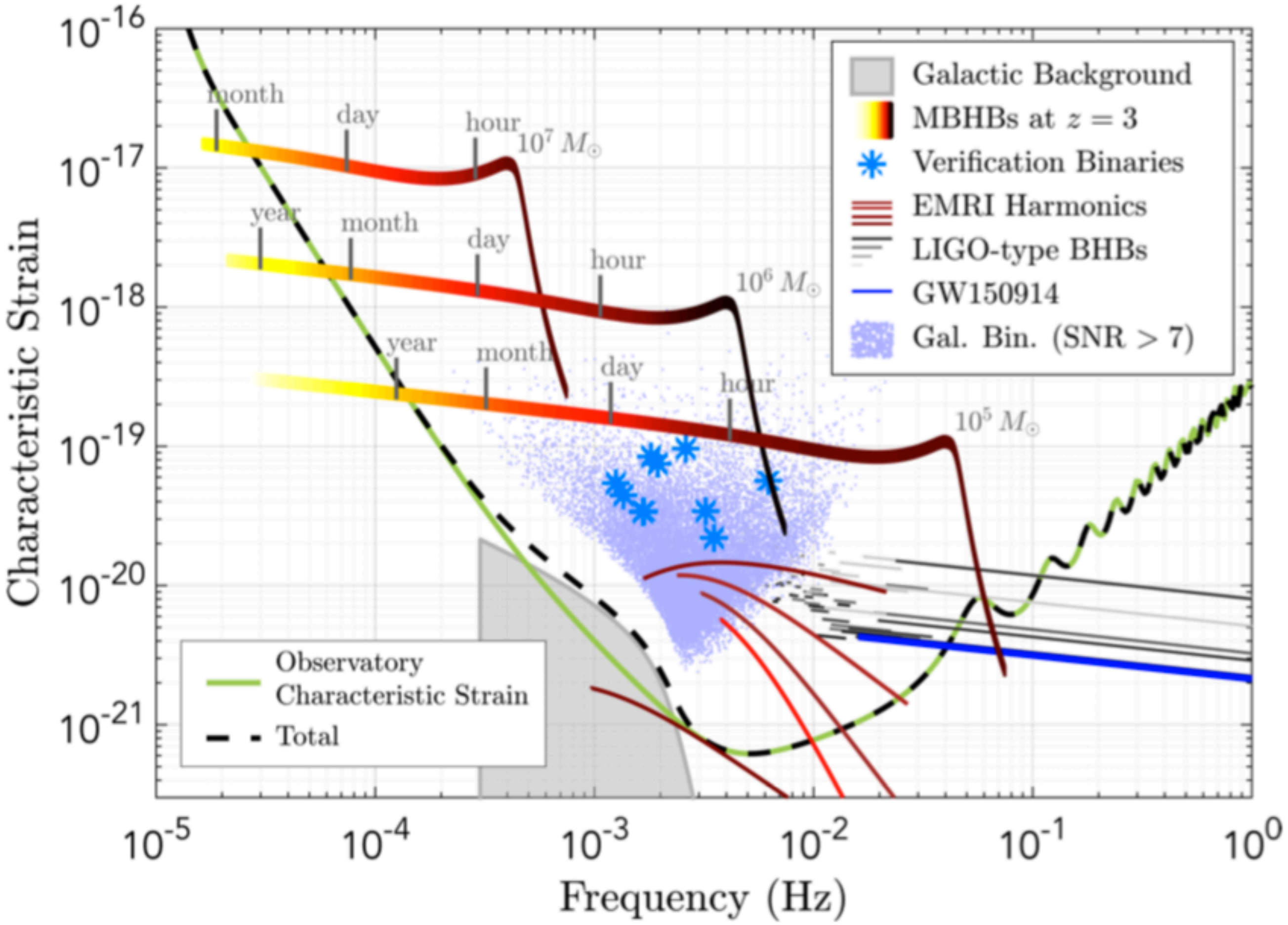
Few % accuracy on H_0 possible only in the most optimistic O5 scenario

[Kiendrebeogo+, *ApJ* (2023)]

LISA Standard Sirens

LISA Standard Sirens

Laser Interferometer Space Antenna



[LISA, *ArXiv* (2017)]

Design:

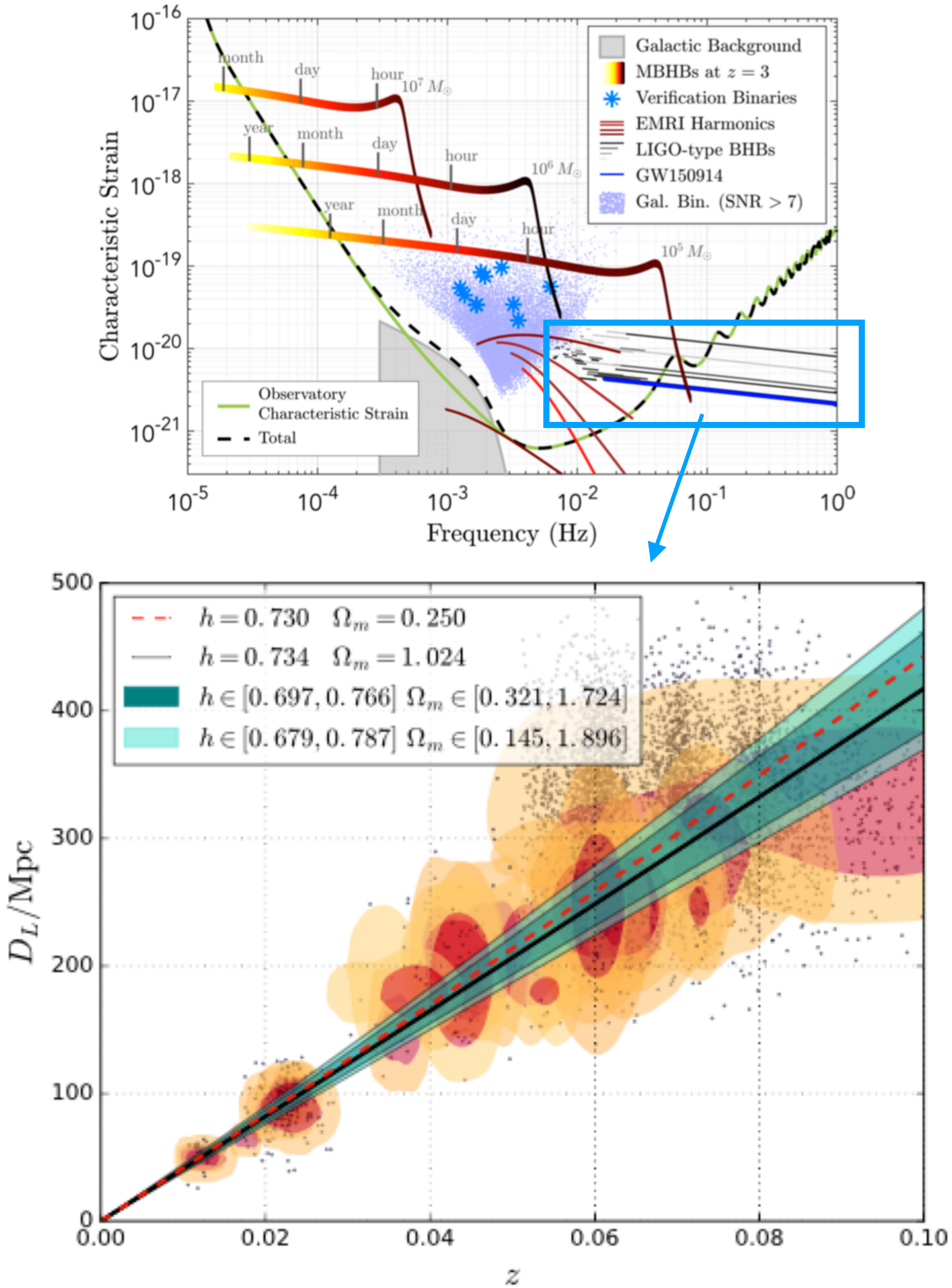
- Near equilateral triangular formation in heliocentric orbit
- 6 laser links (3 active arms)
- Arm-length: 2.5 million km
- Mission duration: 4 to 10 yrs
- **Adopted by ESA in 2024 !**
- Launch: mid-2030s

Standard siren sources:

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

*EM counterparts expected

LISA Standard Sirens



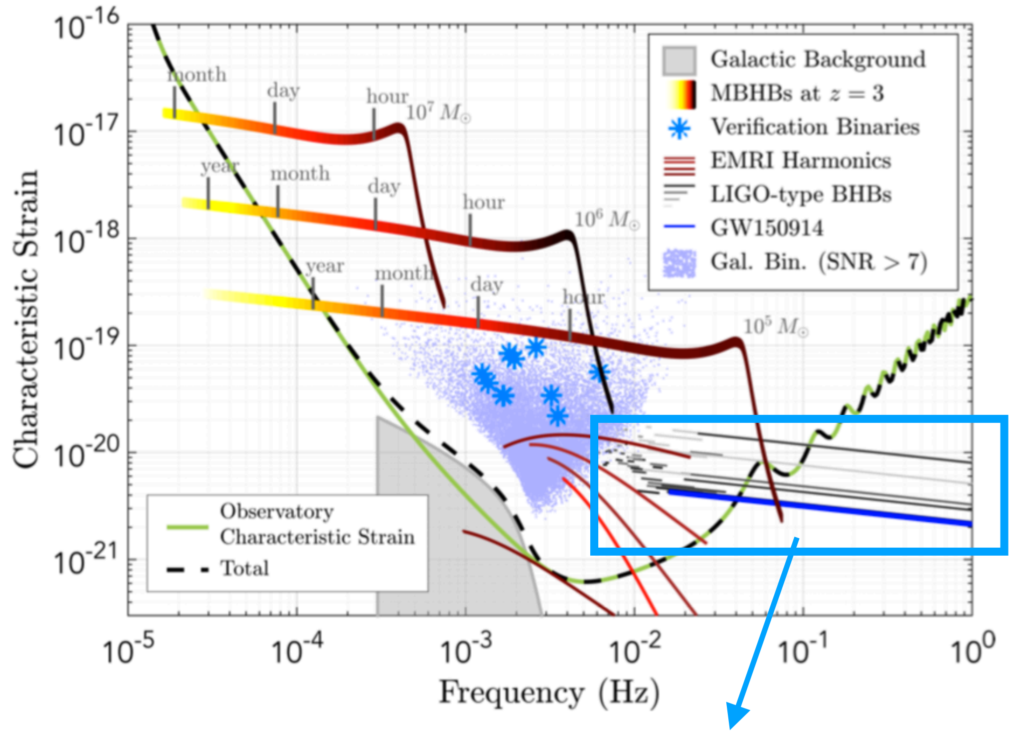
Stellar-mass BBHs

Dark Sirens

- 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
- <u>**Expected results:**</u>
  - ~~H_0 to few %~~
    H_0 not measured

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

LISA Standard Sirens

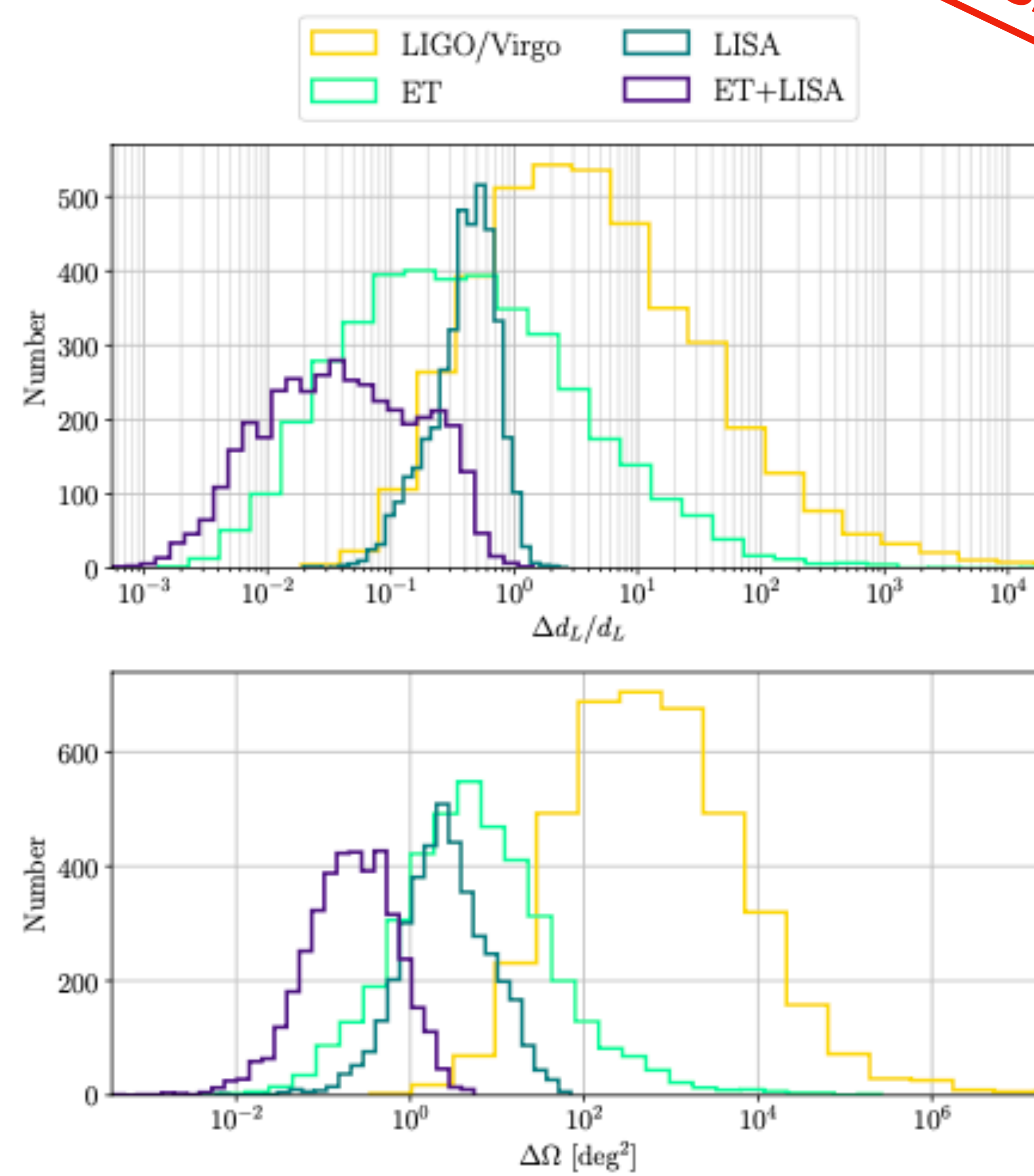


IMBHs can be used in **multi-band analyses** since their merger can be observed by ground-based detectors and their inspiral by LISA

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

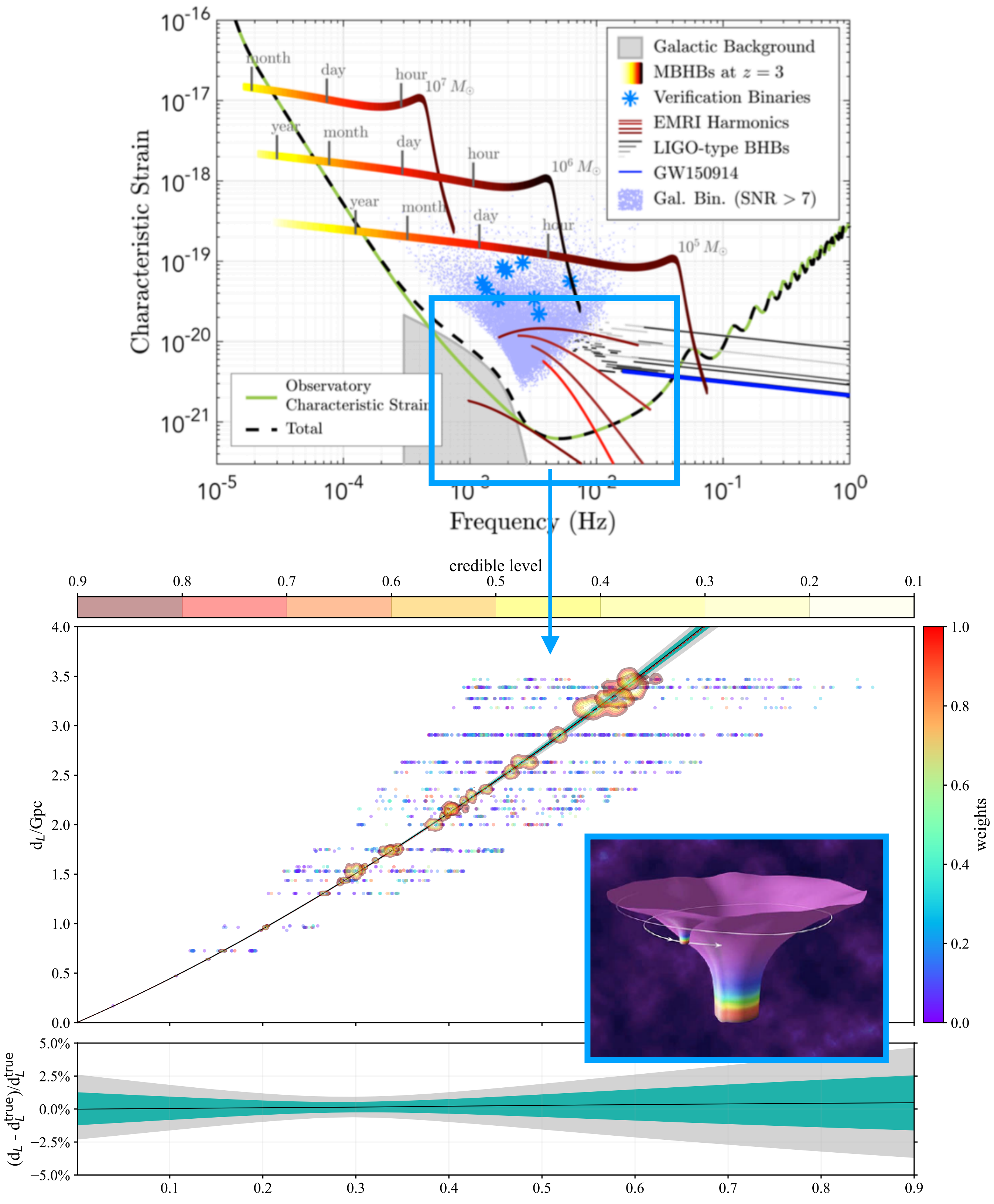
Multi-band IMBHs ?

Dark Sirens



[Muttoni+, *PRD* (2022)]

LISA Standard Sirens



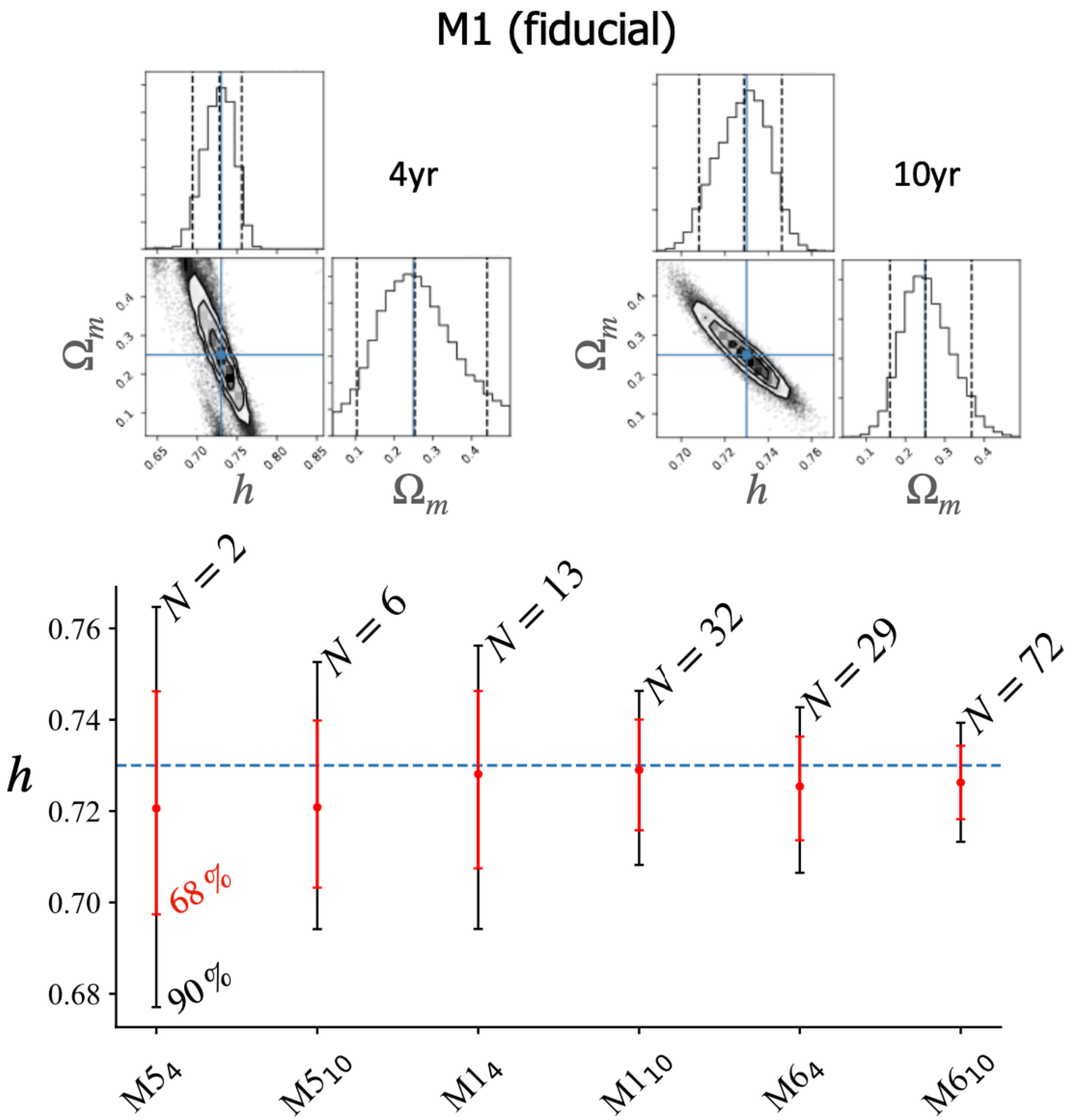
EMRIs

Dark Sirens

- 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 $\Delta\Omega < 2 \text{ deg}^2$
  - $\Rightarrow$ ~ 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)]

LISA Standard Sirens



Laghi et al., *MNRAS* (2021)

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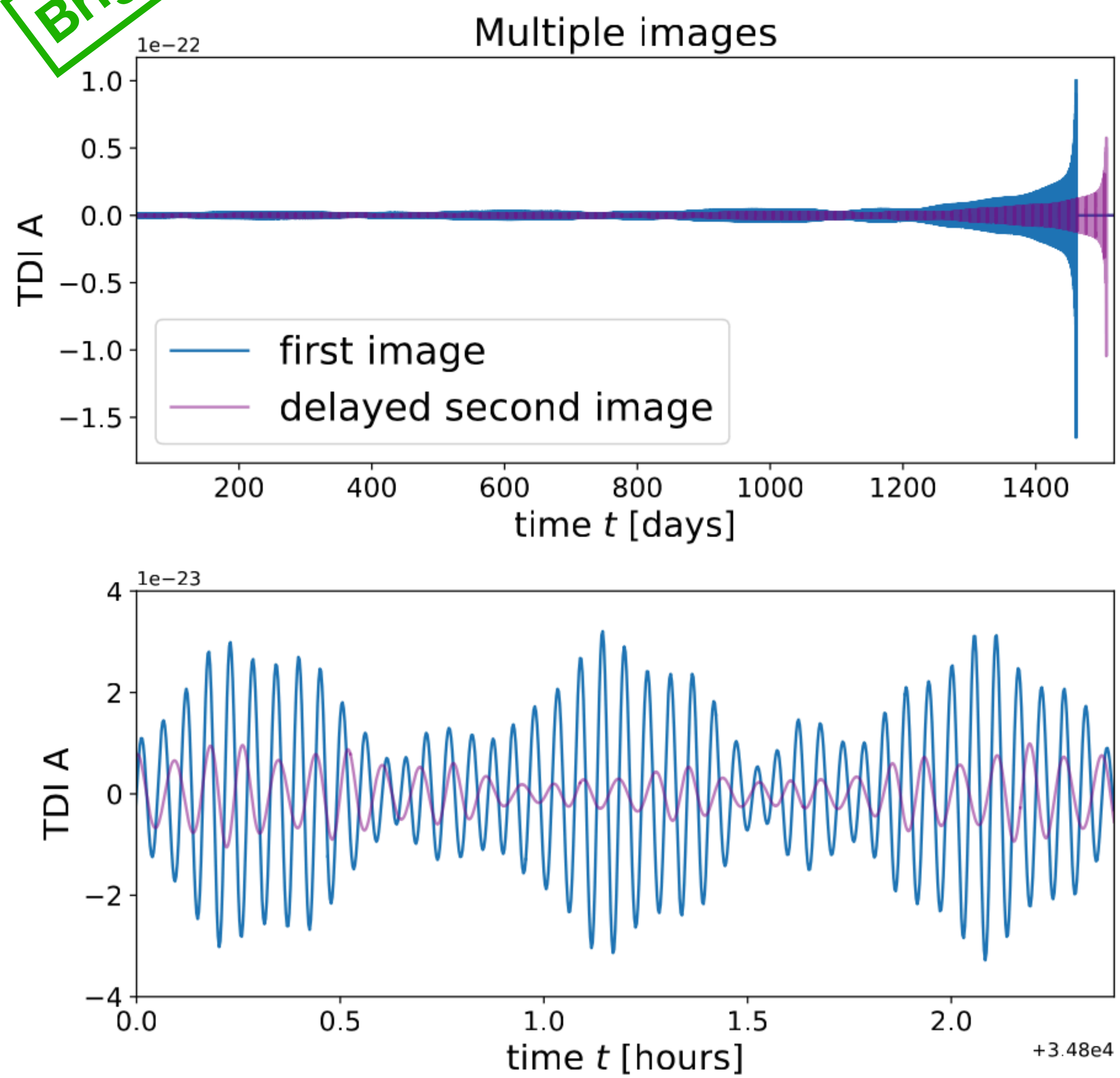
LISA Standard Sirens

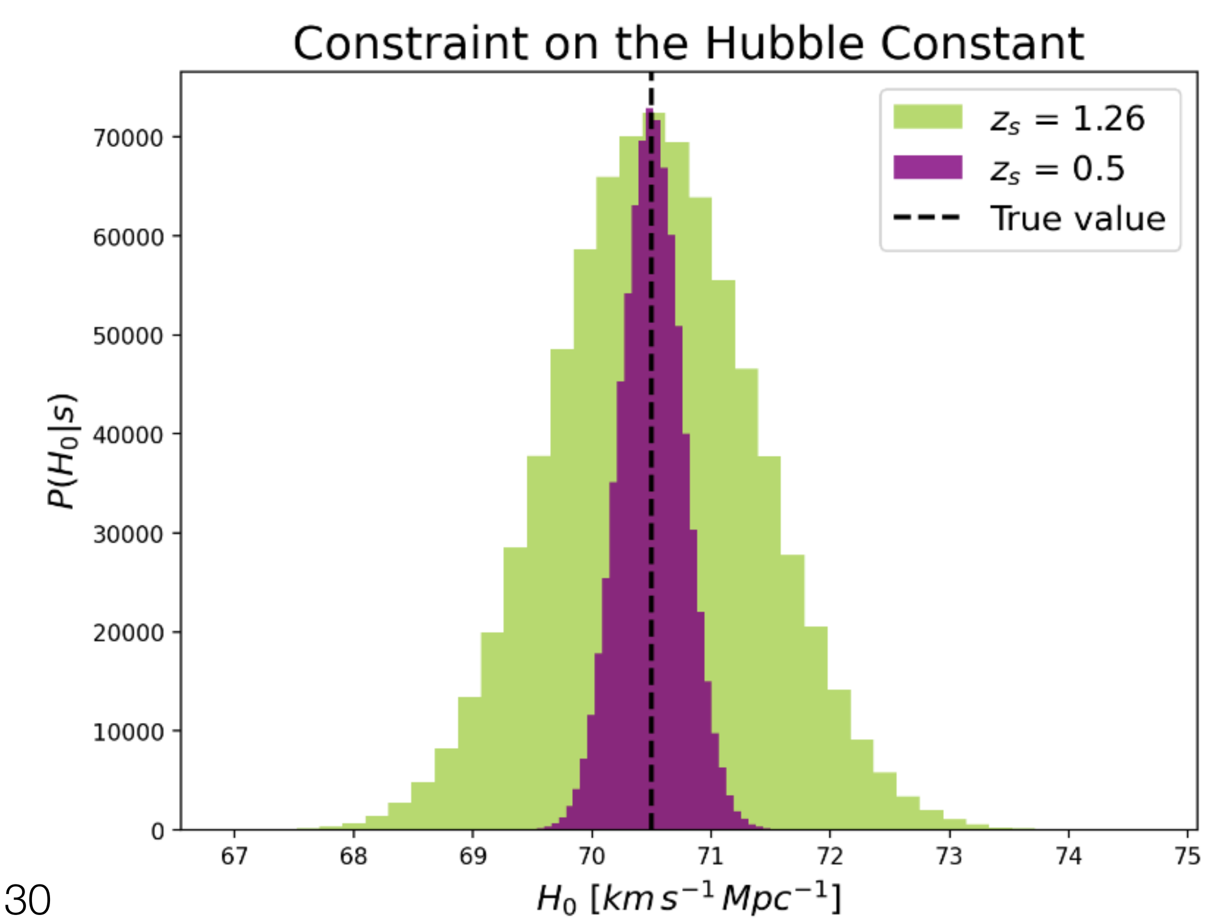
Bright Sirens

Strongly lensed EMRIs



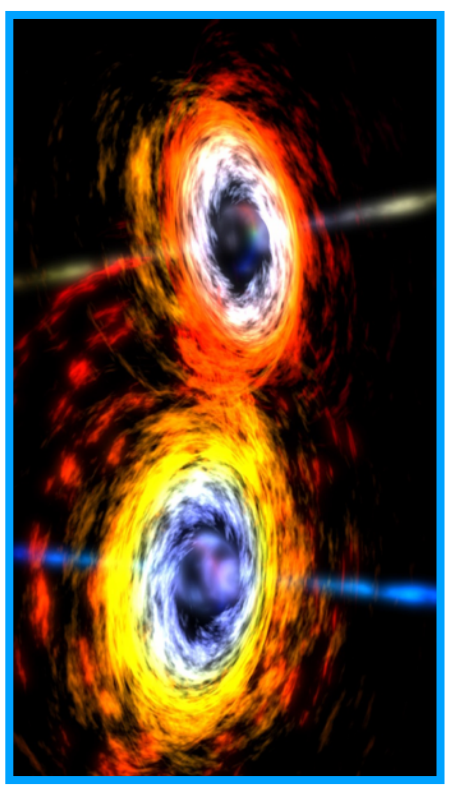
[Toscani+, *PRD* (2024)]

- 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:</u>**
  - H_0 at 1% or better (assuming Ω_m)

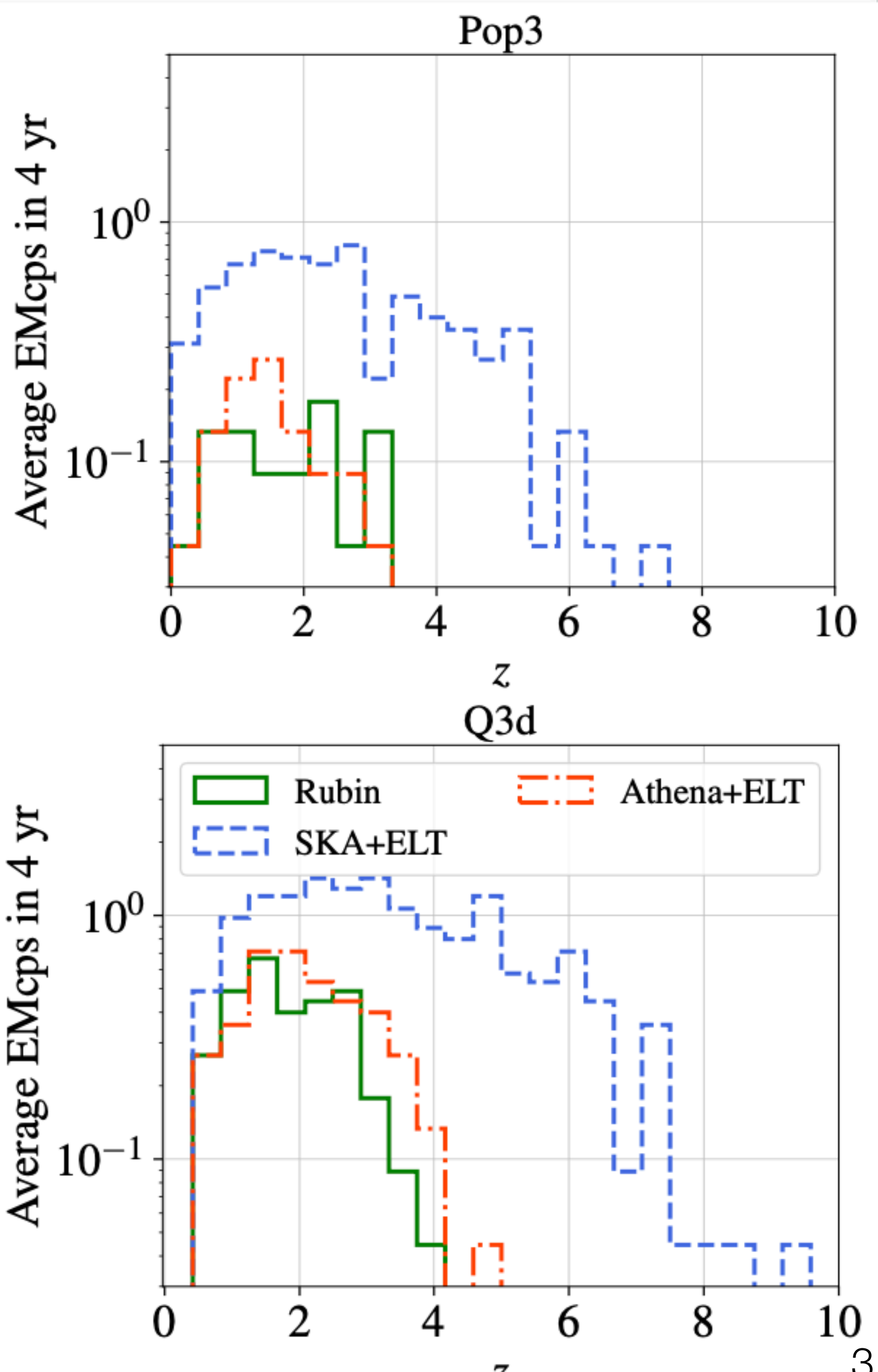


LISA Standard Sirens

(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)]



MBHBs

Bright Sirens

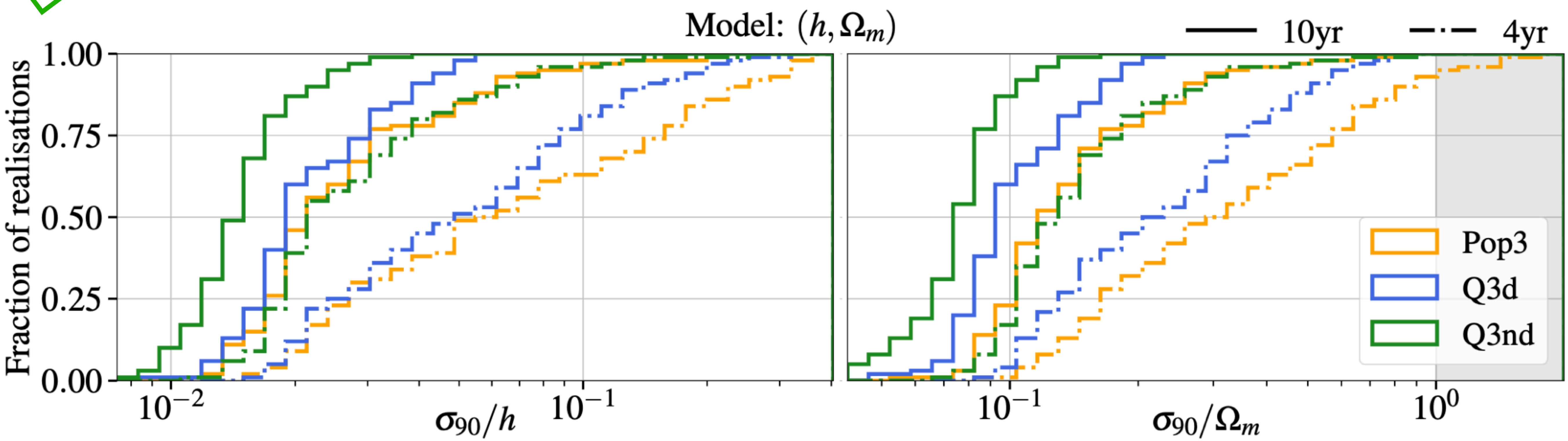
- Redshift range: $z \lesssim 20$
- <u>EM counterparts expected</u>
- LISA detections: 1 to 100/yr
- Useful as standard sirens:
  - $z \lesssim 7$
  - If $\Delta d_L / d_L \lesssim 0.1$ (include lensing)
  - If $\Delta \Omega < 10 \text{ deg}^2$
  - $\Rightarrow$ 1 to 5 standard sirens / yr **(with EM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

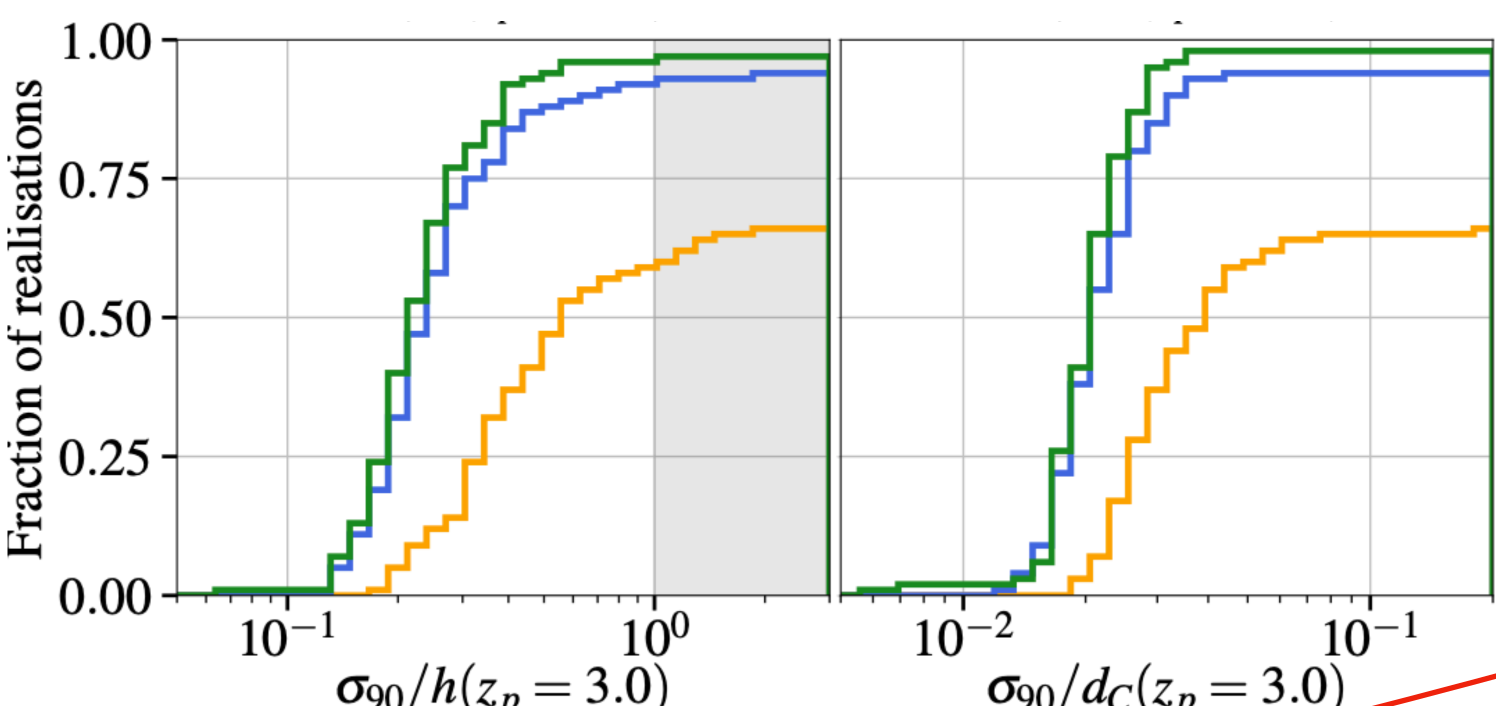
[Tamanini+, *JCAP* (2016)]
[Mangiagli+, *ArXiv* (2023)]

LISA Standard Sirens

Bright Sirens

MBHBs





- **<u>Expected results:</u>**
  - H_0 to few %
  - "Precise" high-z cosmography
    - $H(z = 3)$ at ~20%

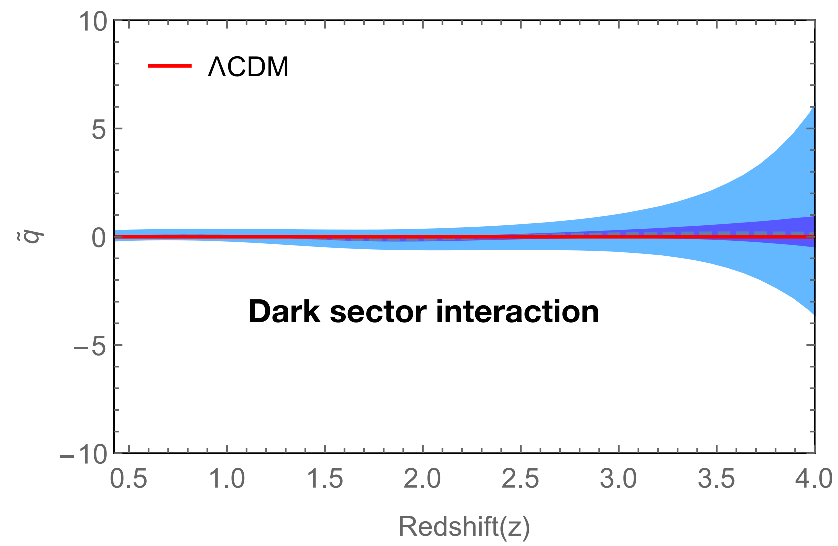
[Mangiagli+, *ArXiv* (2023)]

LISA Standard Sirens

Bright Sirens

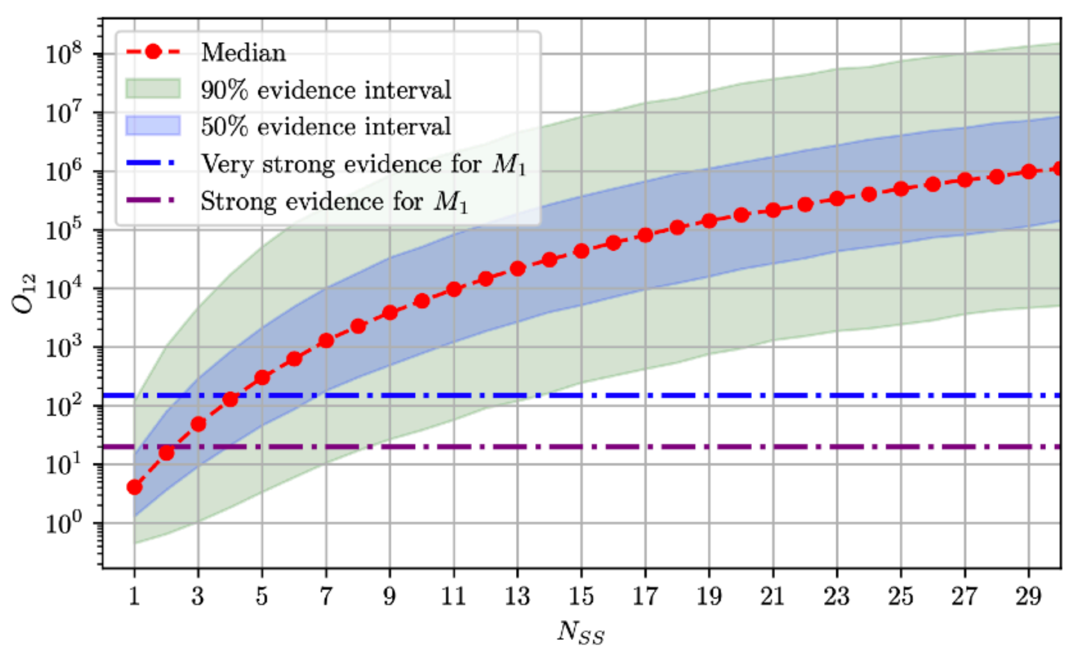
LISA MBHB data will be very useful to probe ΛCDM at high-redshift

Test alternative cosmological models



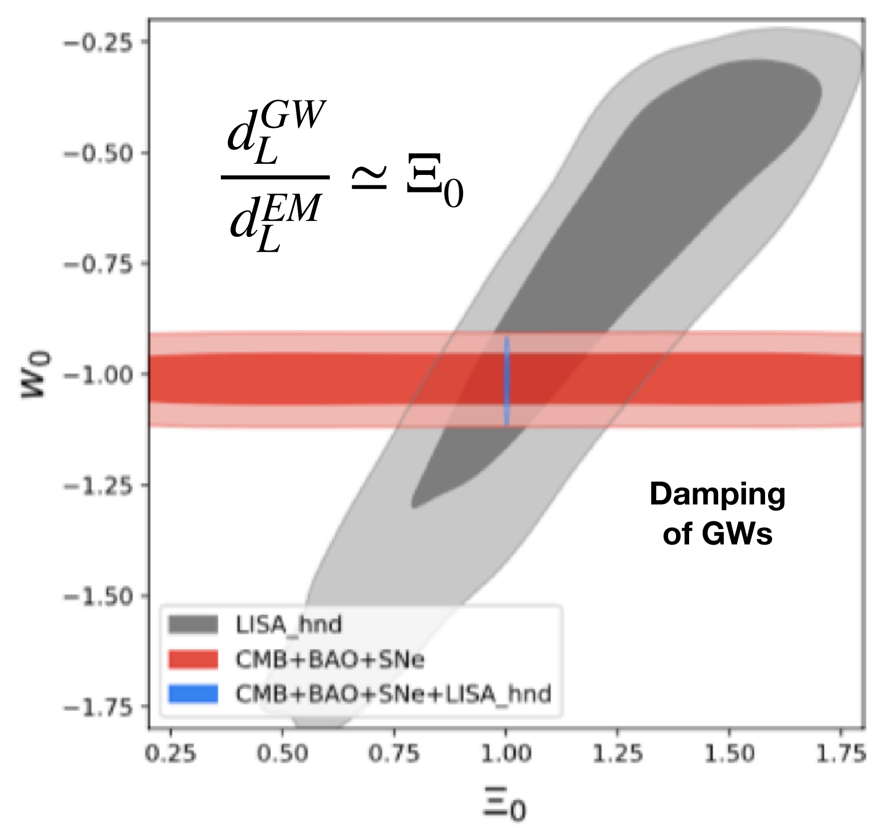
[Caprini & Tamanini, *JCAP* (2016)]
[Cai+, *JCAP* (2017)]

Test quasars Hubble diagram



[Speri+, *PRD* (2021)]

Test modified gravity

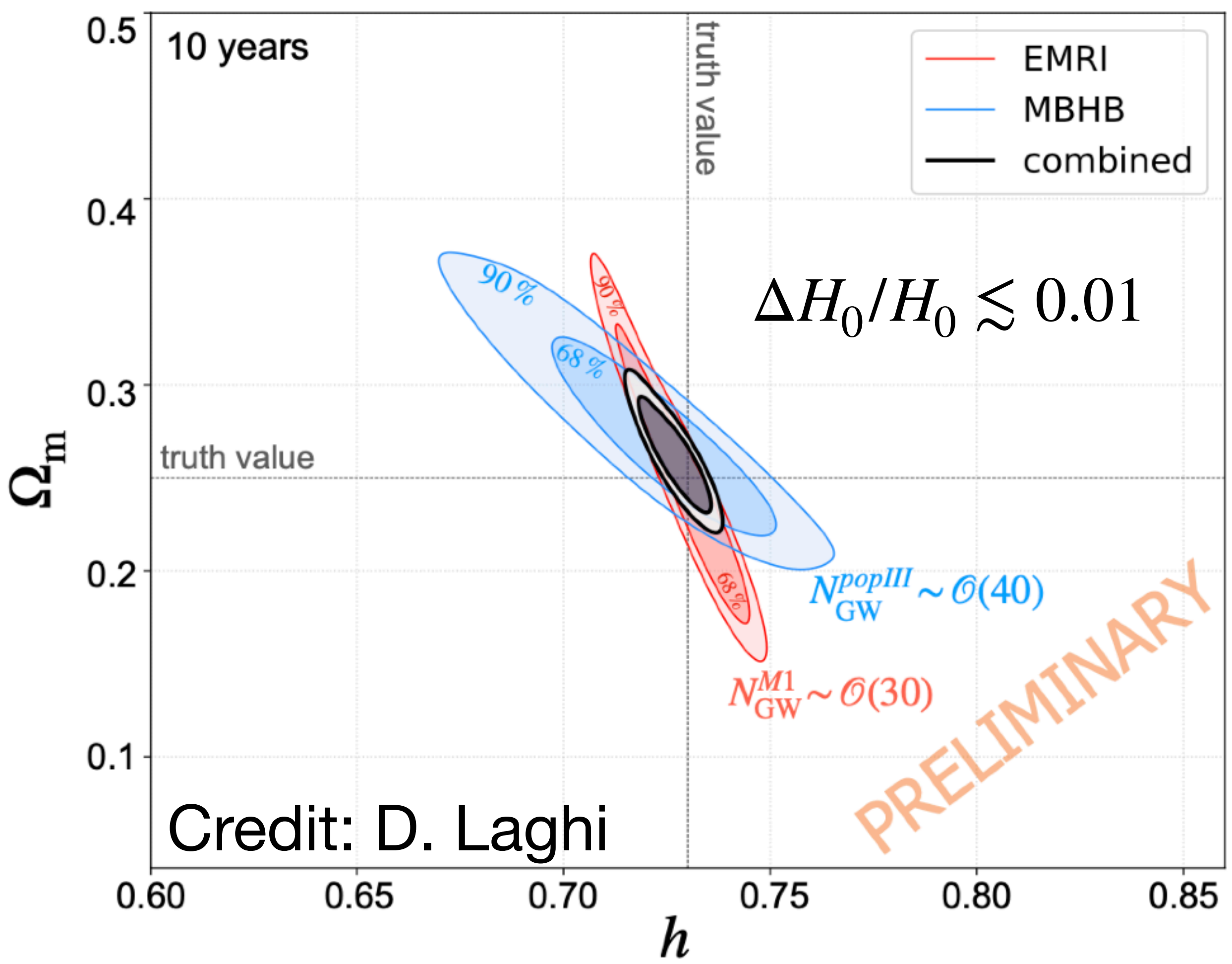


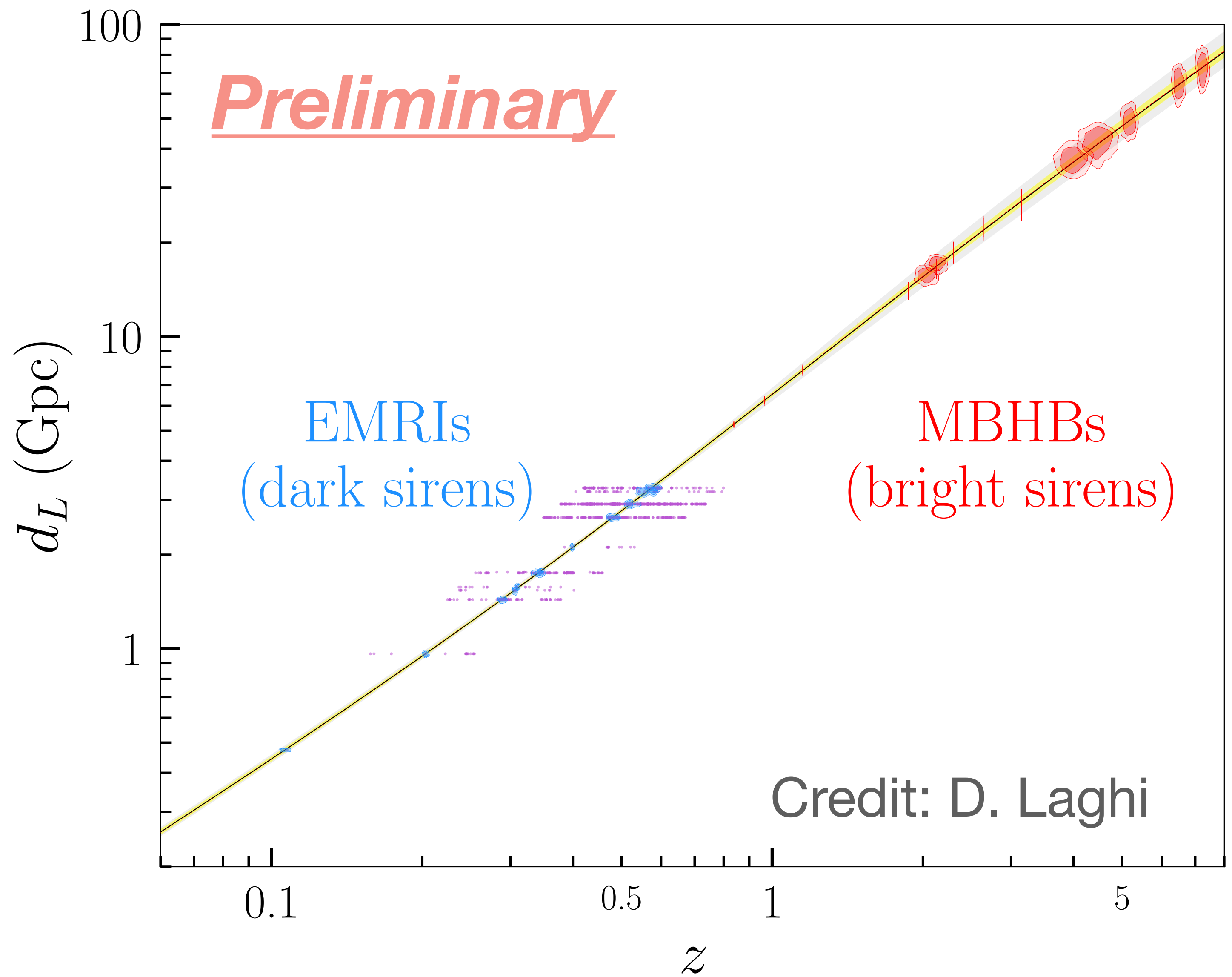
[LISA CosmoWG, *JCAP* (2019)]
[Corman+, *PRD* (2022)]

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.*]

LISA Standard Sirens

LISA Source	Redshift Range	Detection Rates	Redshift Measure (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 and Dark 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
  - Dark sirens results currently not competitive, but significant improvement on top of GW170817

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