Gravitational wave cosmology

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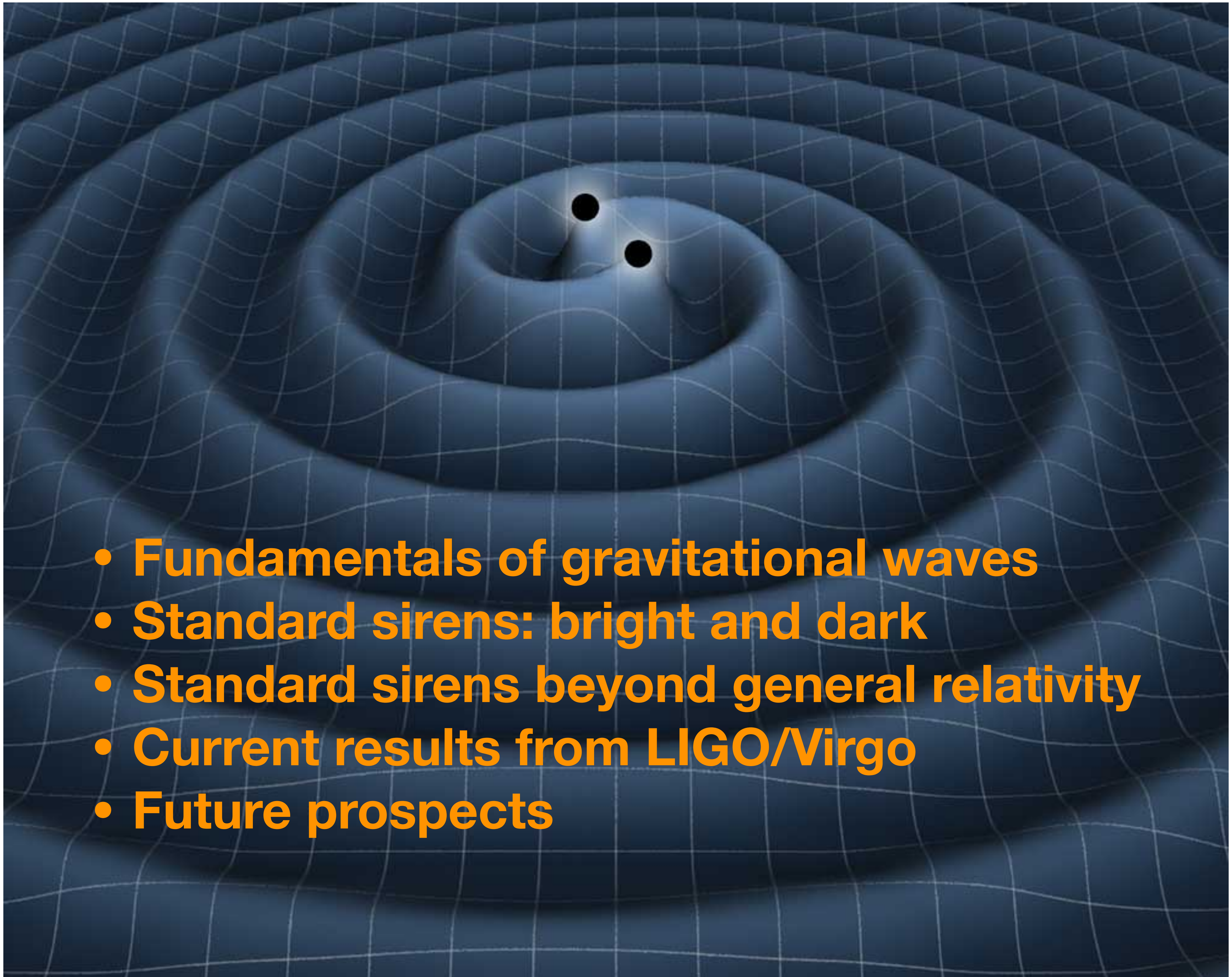
Outline



- **Fundamentals of gravitational waves**
- **Standard sirens: bright and dark**
- **Standard sirens beyond general relativity**
- **Current results from LIGO/Virgo**
- **Future prospects**

Outline

Full of equations, if you get lost just read the text in red

- Fundamentals of gravitational waves
- Standard sirens: bright and dark
- Standard sirens beyond general relativity
- Current results from LIGO/Virgo
- Future prospects

Fundamentals of GWs

Fundamentals of GWs

Gravitational waves (GWs) are dynamical solutions of the Einstein field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Einstein tensor
(determines spacetime curvature)

Stress-energy tensor
(depends on matter distribution and motion)

obtained by expanding the metric over a fixed background (for simplicity Minkowski)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad \text{with} \quad |h_{\mu\nu}| \ll 1$$

which indeed provides (with a suitable gauge choice) the following wave equation

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu} \quad \text{with} \quad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu} h$$

Wave operator $\partial_\mu \partial^\mu$

[Maggiore, vol.1 (2008)]

Fundamentals of GWs

In vacuum, i.e. for $T_{\mu\nu} = 0$, one can impose the so-called *transverse-traceless (TT) gauge* which reduces the GW equation simply to

$$\Box\, h_{\mu\nu} = 0$$

This gauge eliminates all spurious degrees of freedom of $h_{\mu\nu}$ leaving only the two physical degrees of freedom which, for a GW propagating along z, can be written as

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Only two GW polarisation in vacuum: h_+ and $h_\times$

[Maggiore, vol.1 (2008)]

Fundamentals of GWs

One can solve the GW equation for a general $T_{\mu\nu}$ in the limit of weak gravitational field and small velocities

$$r \gg R_s \quad \text{and} \quad v \ll c$$

Observer located at much larger distance than Schwarzschild radius (= weak field)

Velocities much smaller than speed of light

In the TT gauge, one then finds (latin indices = spatial components)

$$h_{ij}(t, \underline{x}) = \frac{1}{r}\frac{2G}{c^4}\Lambda_{ijkl}(\hat{n})\ddot{Q}_{kl}(t - r/c)$$

Einstein's quadrupole formula for the generation of GWs

Projector tensor to TT gauge component along $\hat{n}$ (direction of propagation of the GW)

$$Q_{ij} = \frac{1}{c^2}\int d^3x T^{00}(t, \underline{x})(x_i x_j - \frac{1}{3}r^2\delta_{ij})$$

Quadrupole momentum of the mass density

[Maggiore, vol.1 (2008)]

Fundamentals of GWs

By applying the quadrupole formula to a Newtonian binary system in circular orbit one finds

$$h_+(t,r,\theta,\varphi) = \frac{1}{r}\frac{4G\mu\omega_s^2R^2}{c^4}\frac{1+\cos^2\theta}{2}\cos(2\omega_s t_{\rm ret} + 2\phi_0)$$

$$h_\times(t,r,\theta,\varphi) = \frac{1}{r}\frac{4G\mu\omega_s^2R^2}{c^4}\cos\theta\sin(2\omega_s t_{\rm ret} + 2\phi_0)$$

where

$\omega_s = 2\pi f_s = \dfrac{2\pi}{P_s}$ → orbital frequency

GW frequency is twice the orbital frequency!

$\mu = \dfrac{m_1 m_2}{m_1+m_2}$ → reduced mass

R → separation between m_1 and m_2

[Maggiore, vol.1 (2008)]

Fundamentals of GWs

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GW frequency is twice the orbital frequency!

The separation of the two orbiting bodies must be at minimum of the order of the system's Schwarzschild radius (otherwise the binary merges), implying that

$$\omega_{gw} = 2\omega_s = 2\sqrt{\frac{Gm_{\rm tot}}{R^3}} \lesssim 2\sqrt{\frac{Gm_{\rm tot}}{R_s^3}} = \frac{\sqrt{2}\,c}{Gm_{\rm tot}}$$

The more massive the system, the lower the maximum (merger) frequency!

$$R_s = \frac{2Gm_{\rm tot}}{c^2} \lesssim R$$

Schwarzschild radius

Fundamentals of GWs

From the quadrupole formula one can also compute the total power transported by GWs, which carries away energy from the Newtonian system

$$P_{\rm gw} = \frac{32}{5}\frac{G\mu R^4 \omega_s^6}{c^5} = -\frac{dE_{\rm orbit}}{dt} = \frac{d}{dt}\left(\frac{Gm_1 m_2}{2R}\right)$$

From this equation one find the evolution of the GW frequency $f_{\rm GW} = 2f_s = \omega_s/\pi$

$$\frac{df_{\rm gw}}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3} f_{\rm gw}^{11/3} \quad \text{with} \quad \mathcal{M}_c = \mu^{3/5} m_{\rm tot}^{2/5}$$

chirp mass

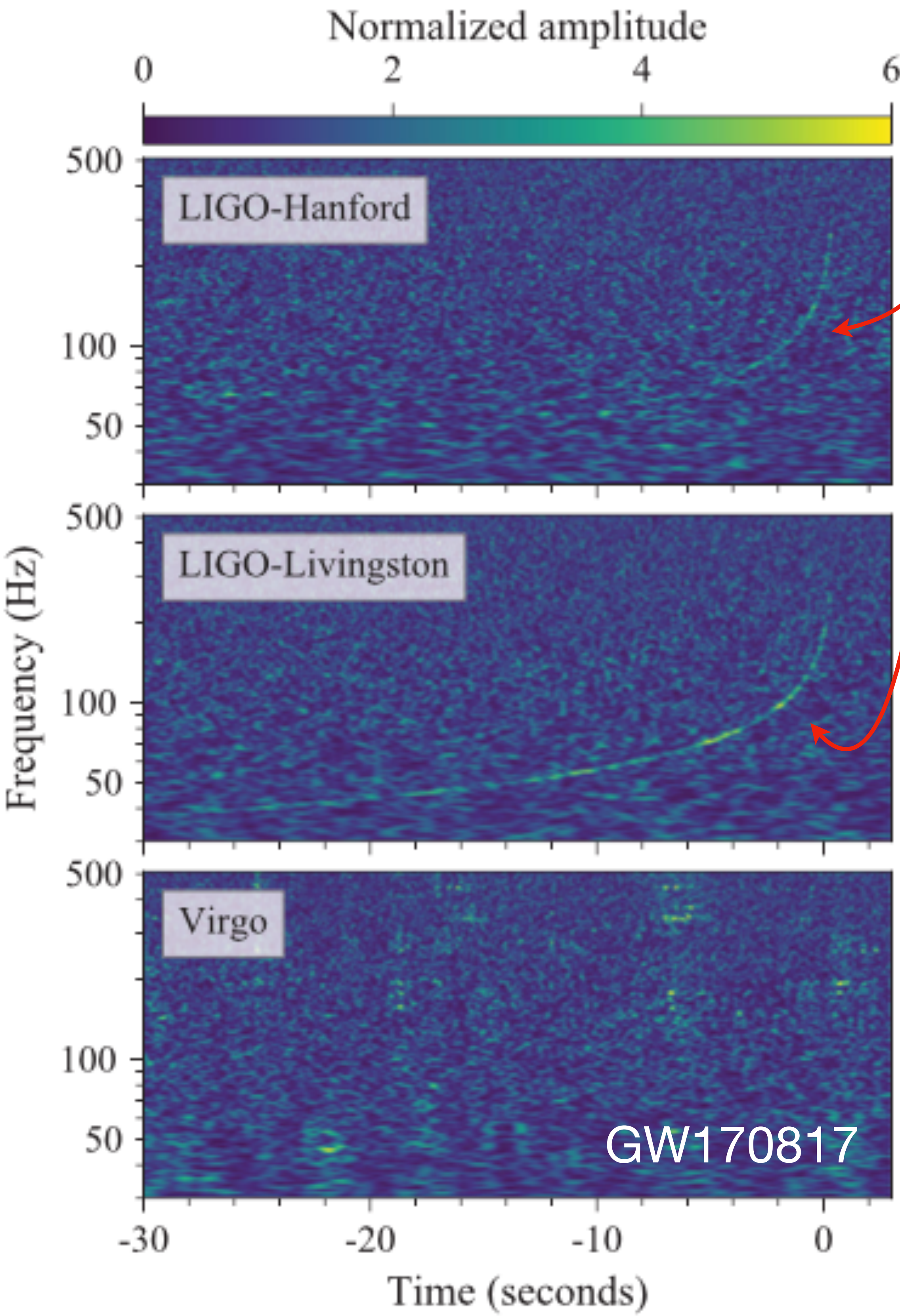
whose solution is

$$f_{\rm gw}(t) = \frac{1}{\pi}\left(\frac{5}{256}\right)^{3/8}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{-5/8}\left(\frac{1}{t-t_c}\right)^{3/8}$$

Time of coalescence: $f_{\rm gw}(t_c) \to \infty$

[Maggiore, vol.1 (2008)]

Fundamentals of GWs



$$f_{\rm gw}(t) = \frac{1}{\pi}\left(\frac{5}{256}\right)^{3/8}\left(\frac{G\mathscr{M}_c}{c^3}\right)^{-5/8}\left(\frac{1}{t-t_c}\right)^{3/8}$$

This is the (leading order of) the very frequency evolution looked for in GW detectors data stream

Measuring this trace one can directly infer the chirp mass $\mathscr{M}_c$ of the system

By directly integrating the frequency one can finally find the phase evolution

$$\Phi(t) = -2\left(\frac{5G\mathscr{M}_c}{c^3}\right)^{-5/8}\tau^{5/8} + \Phi_0$$

Time to coalescence

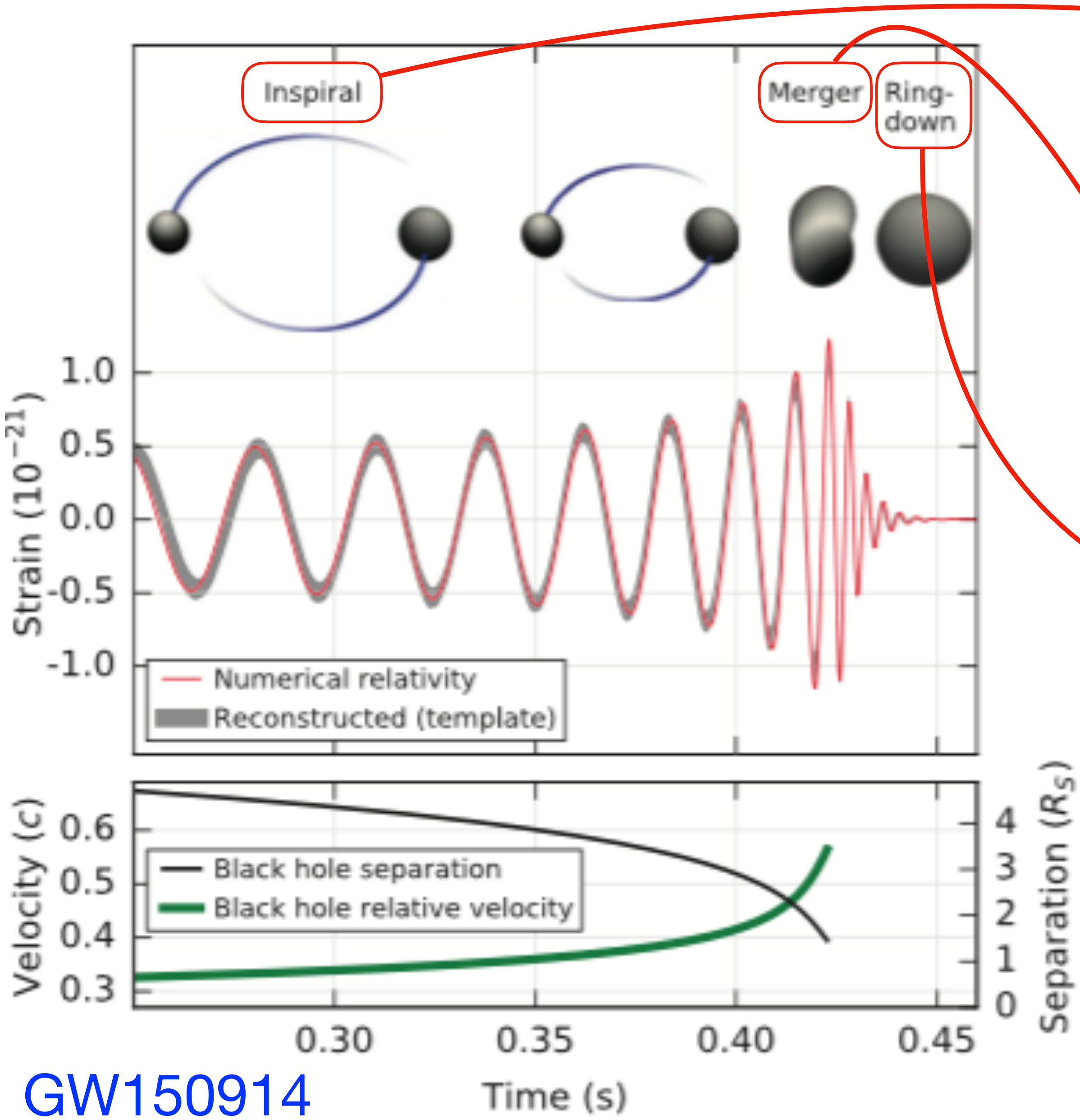
$$\tau = t_c - t$$

[Maggiore, vol.1 (2008)]

Fundamentals of GWs

Close to coalescence however, velocities become relativistic and the leading-order solution no longer applies

The full GW signal of a coalescing binary system cannot be found fully analytically, and different phases of the GW signal need different techniques



GW150914

Needs Post-Newtonian corrections to well describe signal as closer as possible to merger

Can only be computed with numerical relativity (no analytic solution)

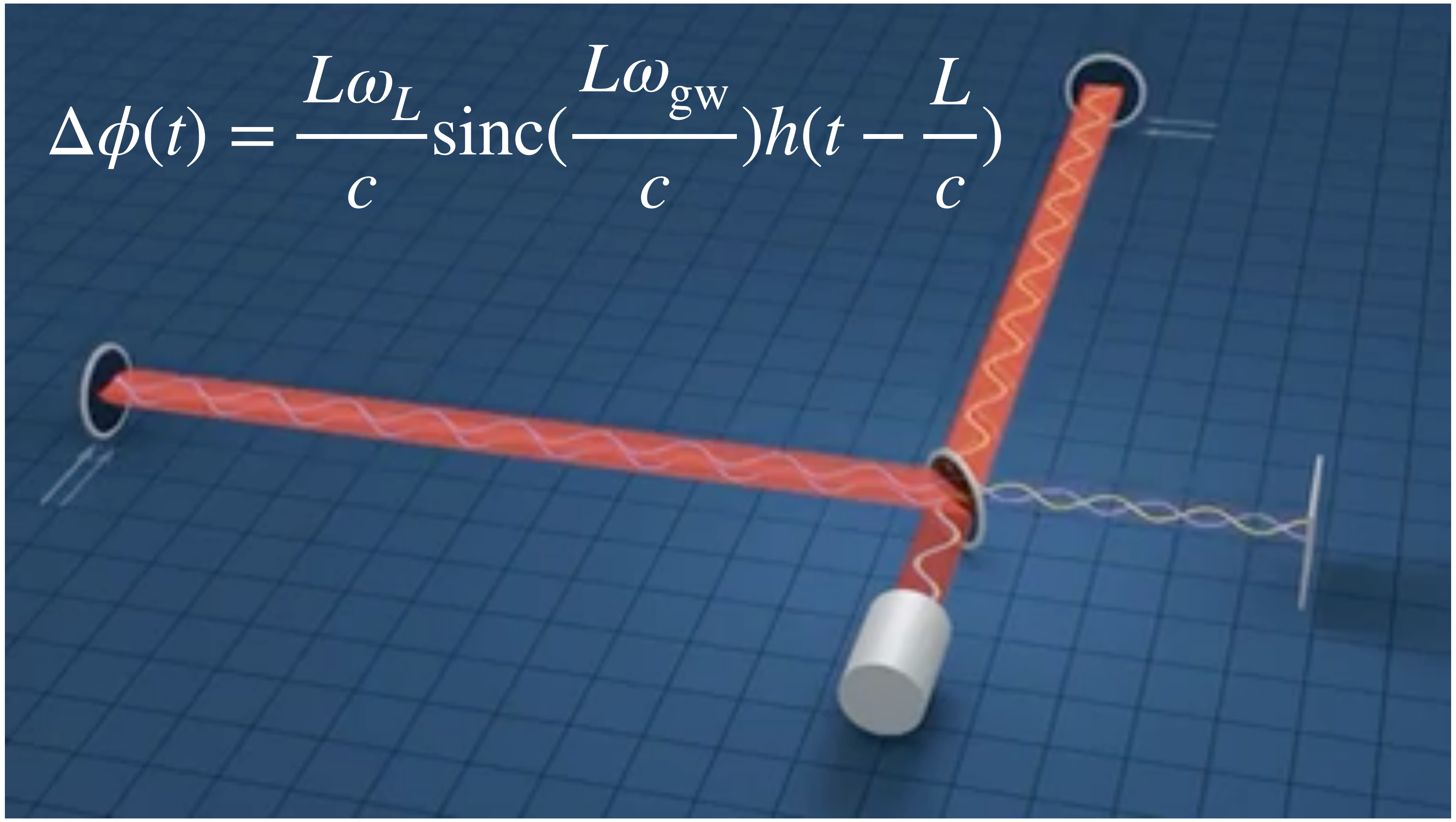
Can be computed using perturbations techniques around single black hole for black hole binaries, but needs numerical relativity for neutron stars binaries

Fundamentals of GWs

To detect a GW signal one can measure the proper distance $s = \hat{n}_i s_i$ between two free-falling test masses. From the geodesic deviation equation one finds

$$\frac{d^2 s_i}{dt^2} = \frac{1}{2}\frac{d^2 h_{ij}}{dt^2} s_j$$

meaning that by precisely measuring s_i over time, one can infer h_{ij}



This is the principle at the basis of *interferometric GW detectors*

The output phase difference depends on the proper distance travelled in each arms, which is affected by GWs

[Maggiore, vol.1 (2008)]

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$$\Delta\phi(t) = \frac{L\omega_L}{c}\mathrm{sinc}(\frac{L\omega_{\mathrm{gw}}}{c})h(t-\frac{L}{c})$$

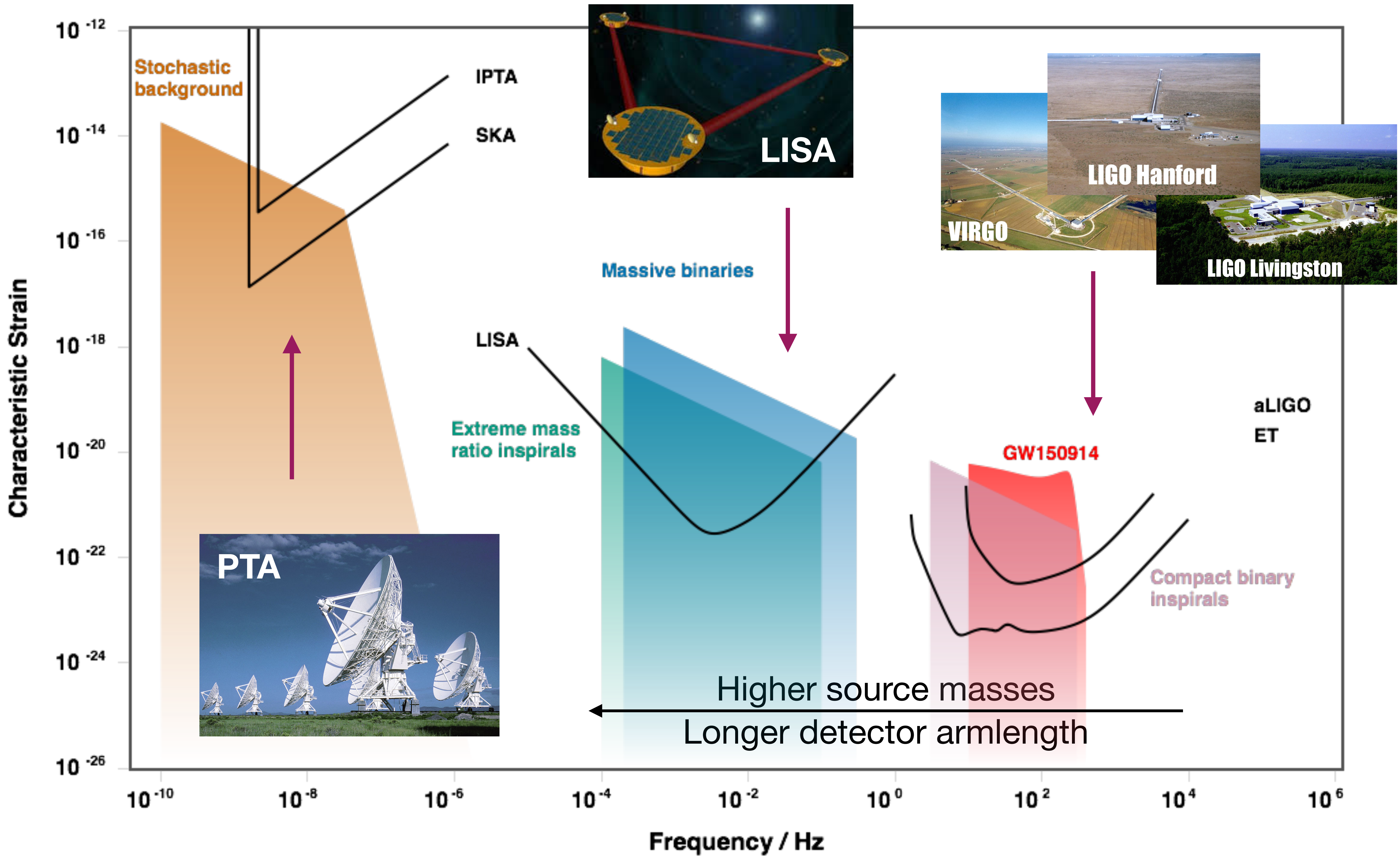
To optimise the response one must maximise the factor in front of $h(t - L/c)$

$$\mathrm{Max}\left[\frac{L\omega_L}{c}\mathrm{sinc}(\frac{L\omega_{\mathrm{gw}}}{c})\right] \Rightarrow L \approx \frac{\pi c}{2\omega_{\mathrm{gw}}} = \frac{\lambda_{\mathrm{gw}}}{4} \longrightarrow$$

The armlength of an interferometers is best suited to detect GW of comparable wavelength!

[Maggiore, vol.1 (2008)]

Fundamentals of GWs



Standard sirens

Standard sirens

Let's now consider again the GW emitted by a binary system in circular orbit, which we can rewrite as (only one polarisation considered for simplicity)

$$h_\times(t_s) = \frac{4}{r}\left(\frac{G\mathcal{M}_c}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},s}}{c}\right)^{2/3}\cos\theta\,\sin\left[-2\left(\frac{5G\mathcal{M}_c}{c^3}\right)^{-5/8}\tau_s^{5/8}+\Phi_0\right]$$

If the source is at cosmological distances we need to take into account that the expansion of the universe will stretch distances and redshift time and frequency

$$r \mapsto a(t_o)r \qquad f_s = (1+z)f_o \qquad dt_s = dt_o/(1+z)$$

implying that the waveform at the observer becomes

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

Luminosity distance

$$d_L = (1+z)a(t_o)r$$

Redshifted chirp mass

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

[Maggiore, vol.1 (2008)]

Standard sirens

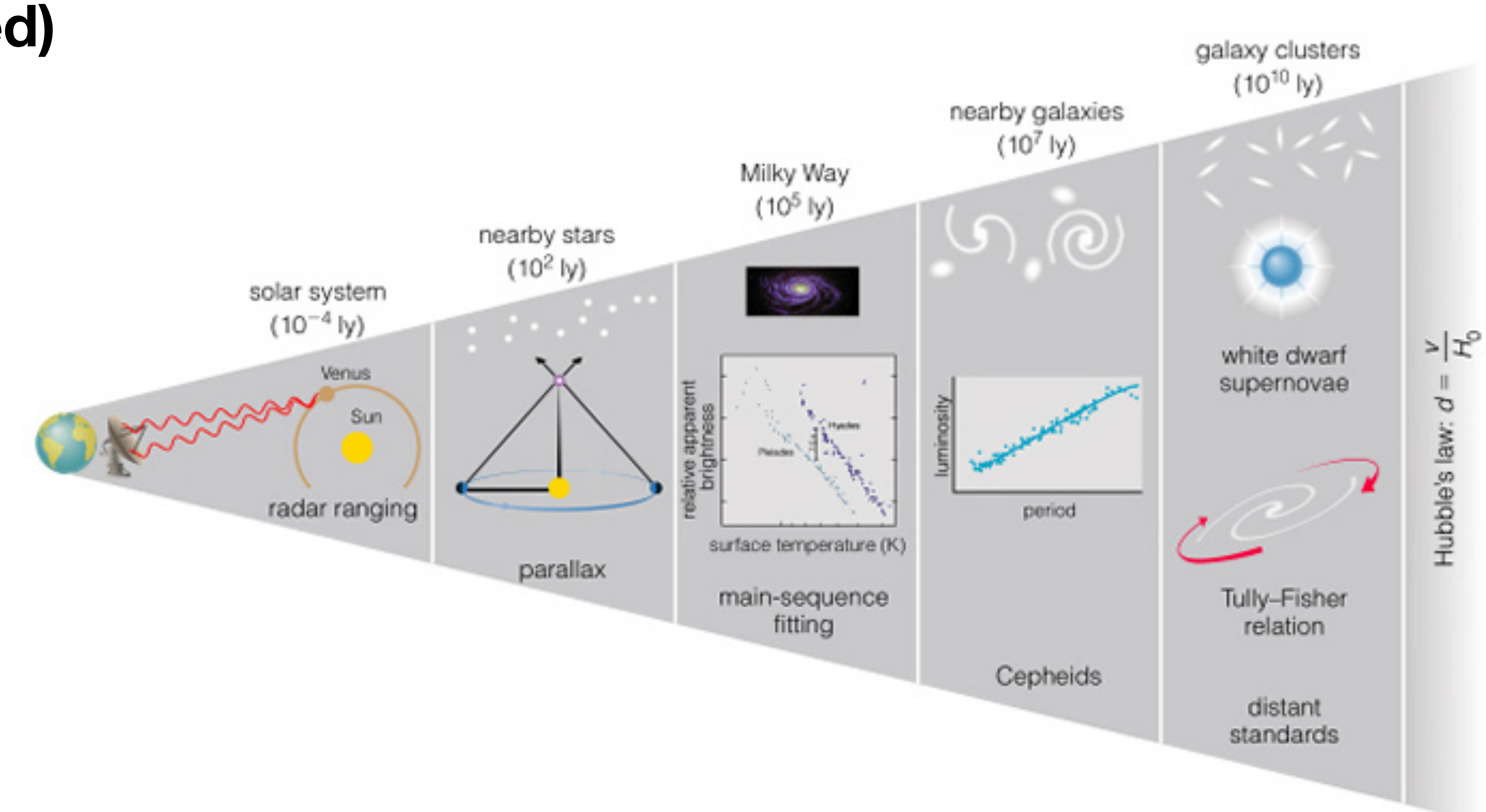
$$h_{\times}(t_o) = \frac{4}{d_L}\left(\frac{G\mathcal{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\,\sin\left[-2\left(\frac{5G\mathcal{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

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

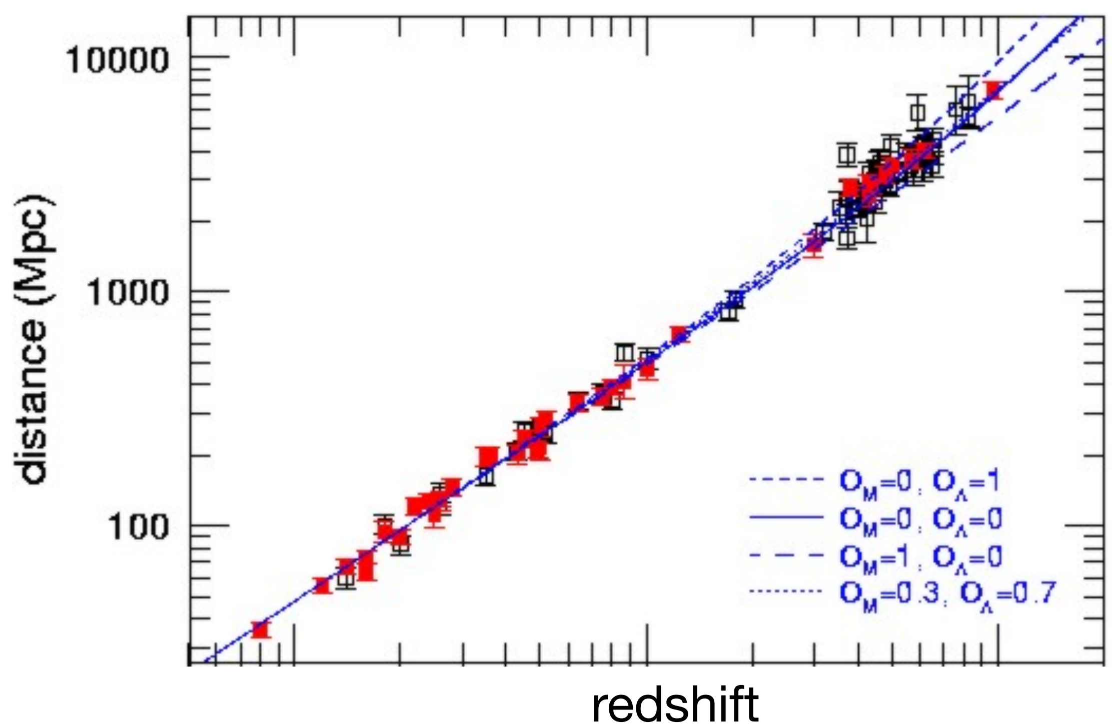
$$h_\times(t_o) = \frac{4}{d_L}\left(\frac{G\mathcal{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\sin\left[-2\left(\frac{5G\mathcal{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

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 (*dark sirens*)**
- **By exploiting features in the source mass distribution (*dark sirens*)**

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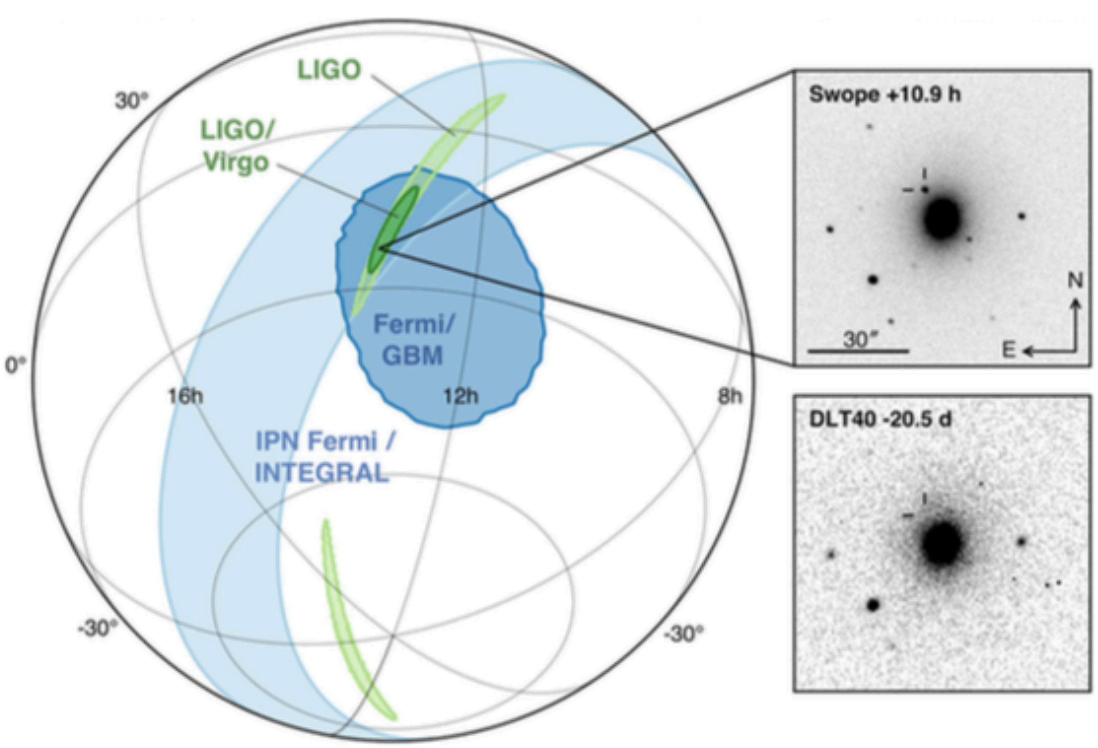

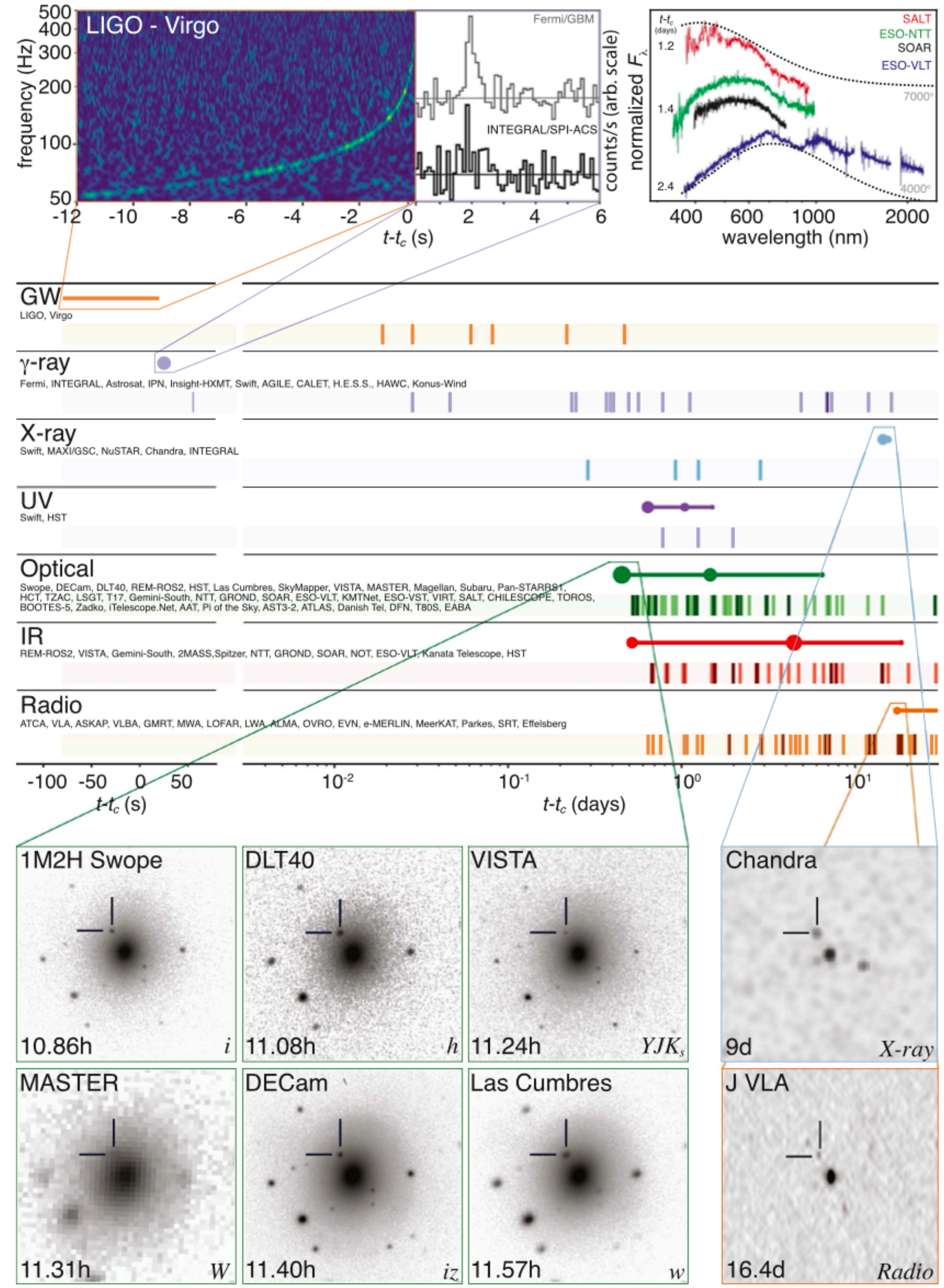

[Schutz, *Nature* (1986)]

Example: GW170817

[LVC+, *ApJL* (2017)]

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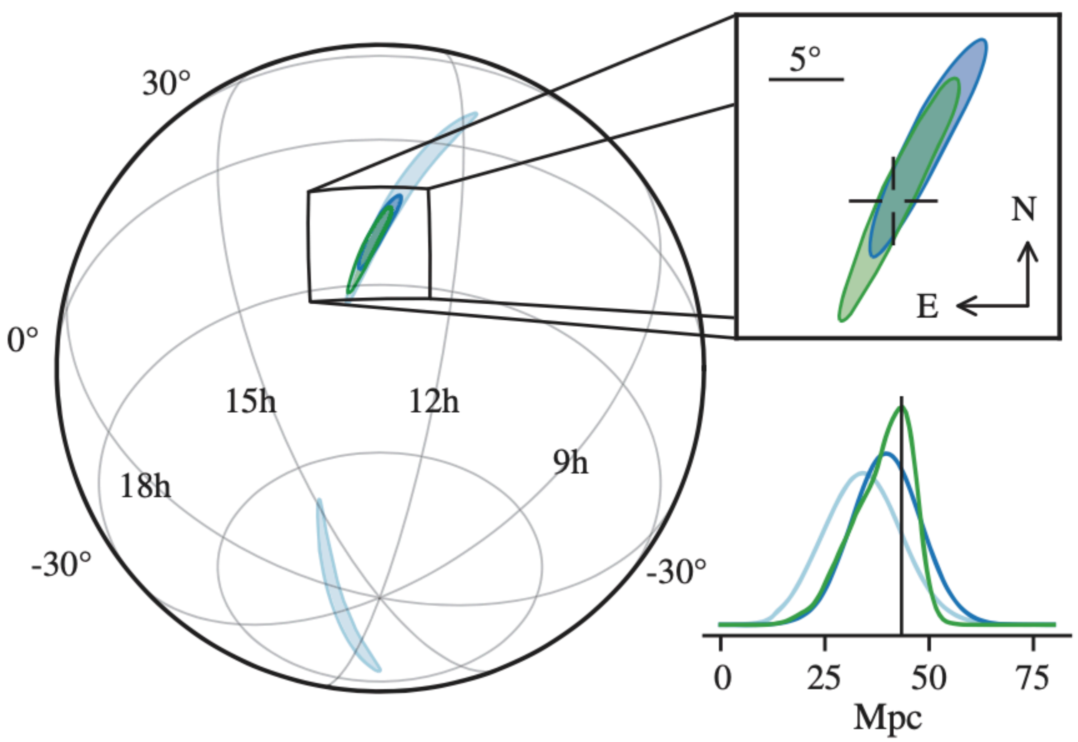

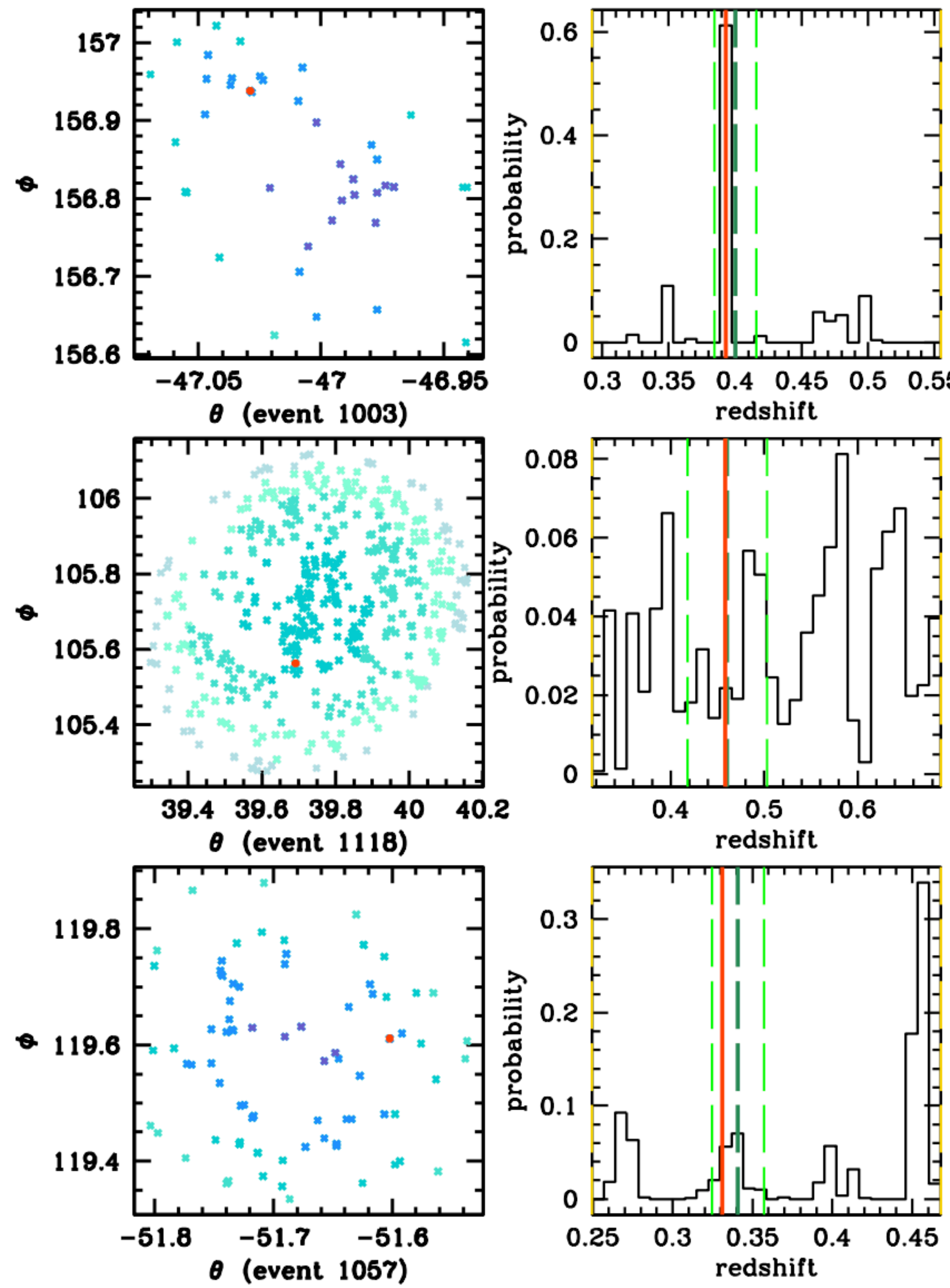

[Schutz, *Nature* (1986)] [Del Pozzo, *PRD* (2012)] [Gray+, *PRD* (2020)]

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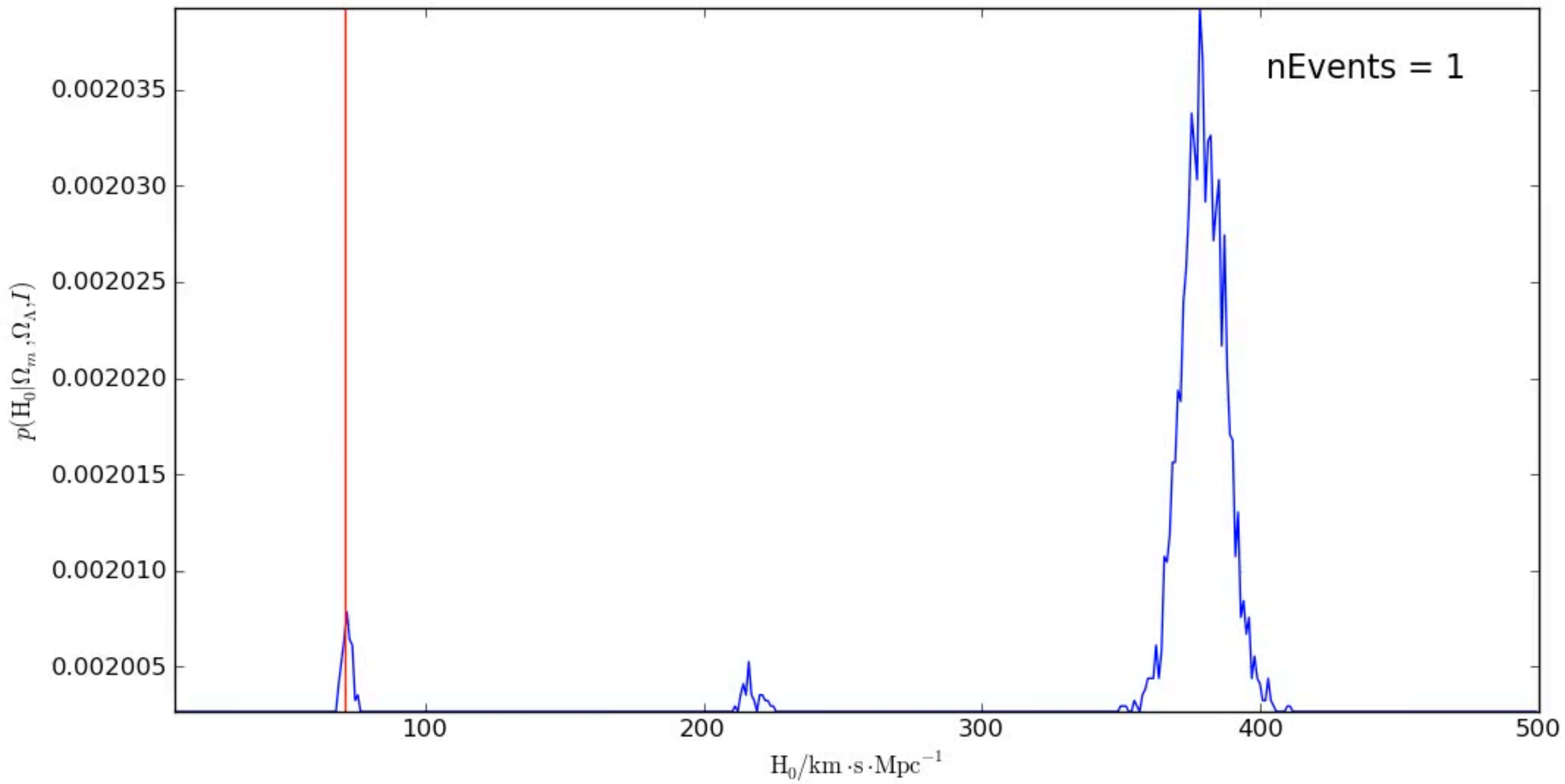
By stacking together the results from many events, the values given by the spurious galaxies cancel out and the true cosmological parameters emerge



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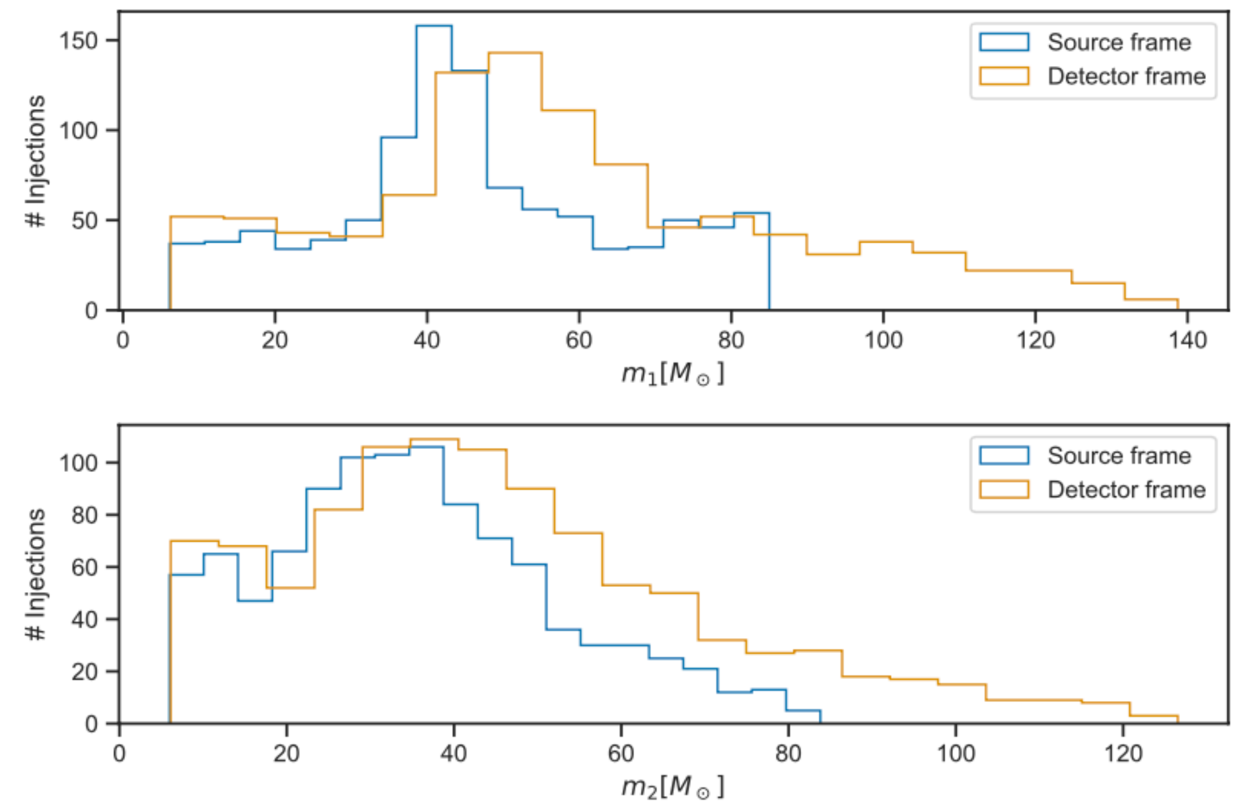
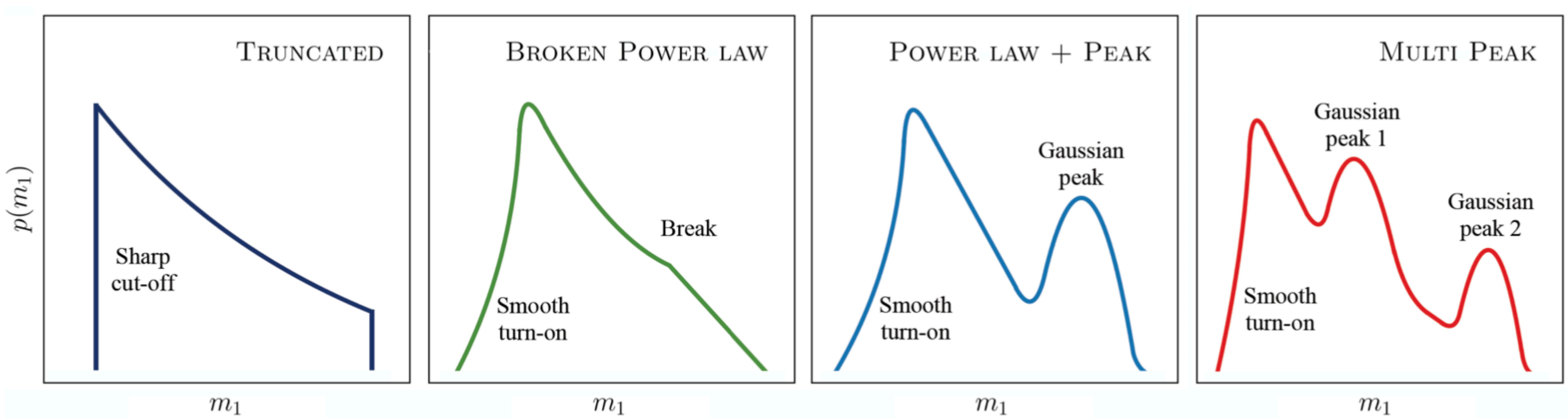
$$m_{\rm obs} = (1+z)m_{src}$$





[Taylor+, *PRD* (2012)]

[Mastrogiovanni+, *ArXiv* (2020)]

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All these approaches are affected by different systematic uncertainties:

Weak lensing and peculiar velocities degrade distance and redshift measurements

Source population parameters must be inferred simultaneously, degrading cosmological measurements and introducing possible systematics

Galaxy catalogs are subject to selection effects and incompleteness (host galaxy may be missed)

Standard sirens beyond general relativity

Standard sirens beyond GR

Let's consider how GWs propagate through the universe. Assuming GR one can find the equation of GW propagation in FRW universe starting from the Einstein equations

$$h''_{ij} + 2Hh'_{ij} + c^2k^2h_{ij} = 0$$

Derivative w.r.t conformal time:

$$h' = \frac{\partial h}{\partial \eta}$$

Hubble constant:

$$H = \frac{a'}{a}$$

Wavenumber:

$$k = \frac{2\pi}{\lambda}$$

At sub-horizon scales ($k\eta \gg 1$) the general solution of this equation is

$$h_{\rm GR} \propto \exp\left(-\int H d\eta\right) \exp\left(\pm ik\int d\eta\right)$$

which implies

$$h_{\rm GR} \propto \frac{1}{d_L} \quad \text{and} \quad c_T = c$$

GW propagation speed

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$$h''_{ij} + 2Hh'_{ij} + c^2k^2h_{ij} = 0$$

For an arbitrary gravitational theory beyond-GR this equation is modified by four general functions of η (time) and k (wavenumber)

$$h''_{ij} + 2H(1+\nu)h'_{ij} + (c_T^2k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

GW "friction"
Connected e.g. to running of the gravitational constant G or GW propagation in higher dimensions
- *Scalar-tensor theories*
- *Brane models*

GW speed
Velocity of propagation of GWs (= c in GR)
- *Scalar-tensor theories*
- *Massive gravity*
- *…*

Graviton's mass
Mass associated to gravity's propagating modes (gravitons in QFT terms)
- *Massive gravity*

Matter coupling
Interactions with other matter matter modes
- *Massive bi-gravity*

[Nishizawa, *PRD* (2018)]

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Gravity theory	ν	$c_\mathrm{T}^2 - 1$	μ	Γ
General relativity	0	0	0	0
Extra-dimensional theory	$(D-4)(1+\frac{1+z}{\mathcal{H}d_\mathrm{L}})$	0	0	0
Horndeski theory	α_M	α_T	0	0
f(R) gravity	$F'/\mathcal{H}F$	0	0	0
Einstein-aether theory	0	$c_\sigma/(1+c_\sigma)$	0	0
Modified dispersion relation	0	$(n_\mathrm{mdr}-1)\mathbb{A}E^{n_\mathrm{mdr}-2}$	when $n_\mathrm{mdr}=0$	0
Bimetric massive gravity theory	0	0	m^2f_1	m^2f_1

[Nishizawa, *PRD* (2018)]

Standard sirens beyond GR

$$h''_{ij} + 2H(1+\nu)h'_{ij} + (c_T^2 k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

For $\Gamma = 0$ the general solution of this equation can be written as

$$h \propto e^{-\mathscr{D}} e^{-ik\Delta T} h_{\mathrm{GR}}$$

where

$$\mathscr{D} = \frac{1}{2}\int \nu H d\eta \quad \text{and} \quad \Delta T = \int \left(1 - c_T - \frac{a^2\mu^2}{2k^2}\right) d\eta$$

Additional damping of the GW amplitude

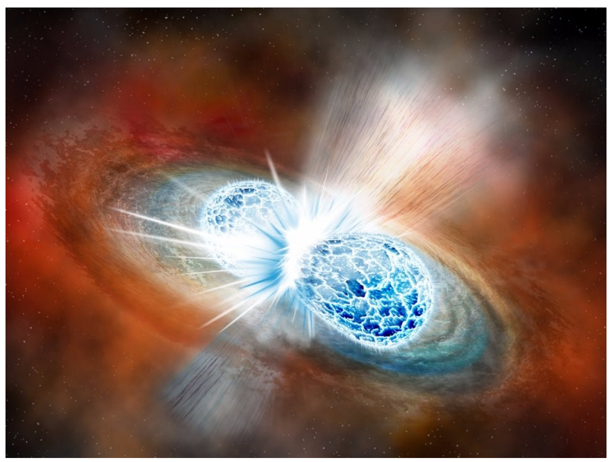
Delay of GW propagation w.r.t. the speed of light

The general solution for $\Gamma \neq 0$ is more complicated and involves a mixing between the two GW polarisations h_+ and $h_\times$

[Nishizawa, *PRD* (2018)]

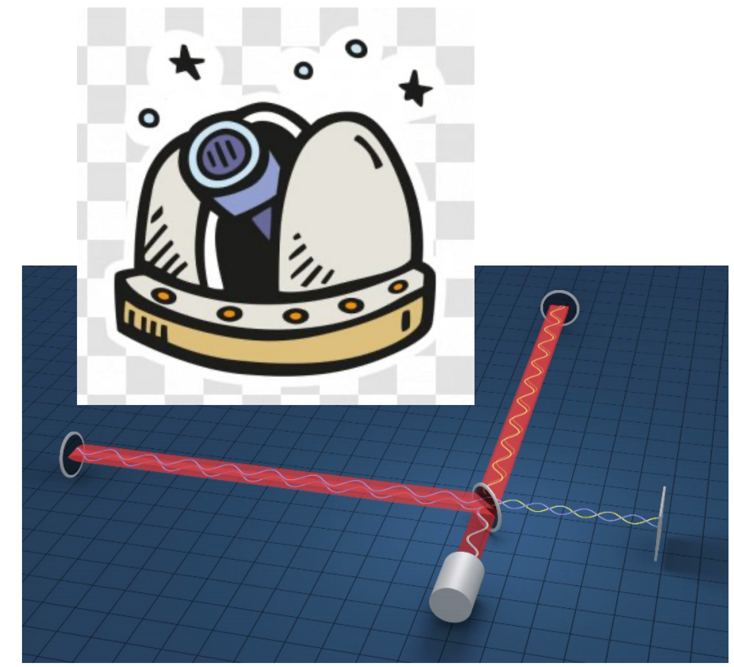
Standard sirens beyond GR

To test these deviations from GR we can use multi-messenger events, namely *bright standard sirens*



EM radiation (photons)

Gravitational waves



Source emitting both GW and EM radiation

GW and EM detectors

- Binary neutron star mergers
- NS-BH mergers (?)
- Massive BBH mergers (?)
- Supernovae (?)
- …

- LIGO / Virgo / Kagra
- LISA

- Radio / gamma / optical / X-ray telescopes

Standard sirens beyond GR

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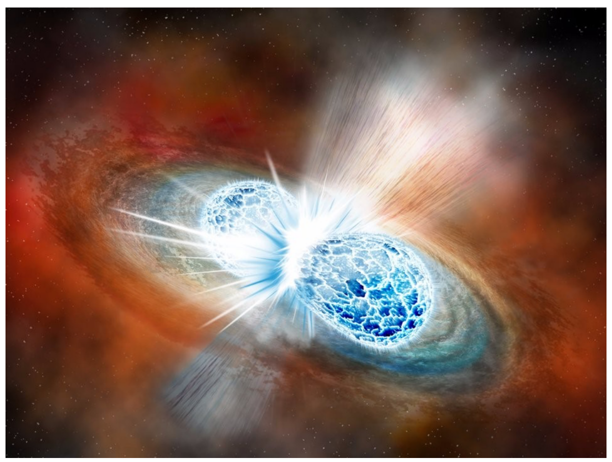

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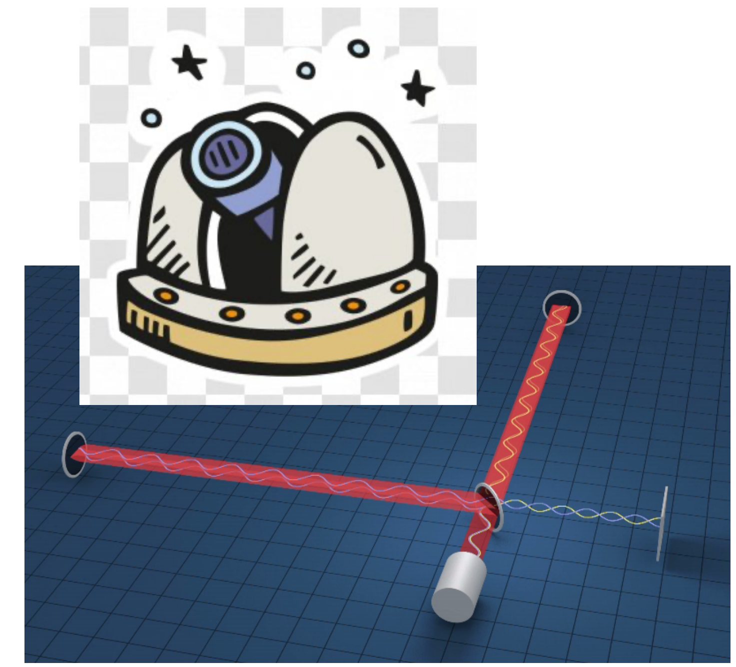

GW and EM detectors

A delay in the time of arrival of GW w.r.t. EM radiation can be used to constrain c_T and μ

$$\Delta T = \int \left(1 - c_T - \frac{a^2 \mu^2}{2k^2} \right) d\eta$$

Standard sirens beyond GR

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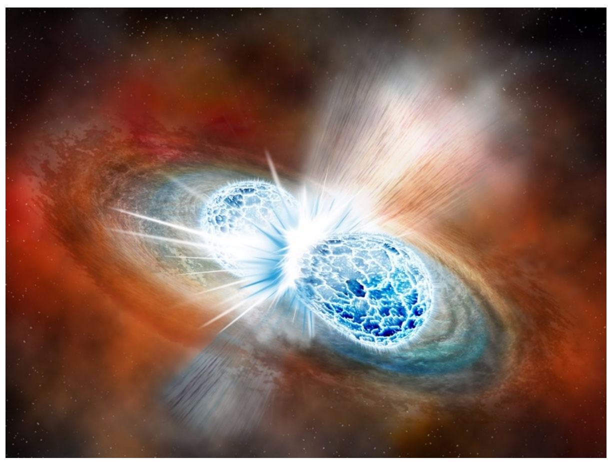


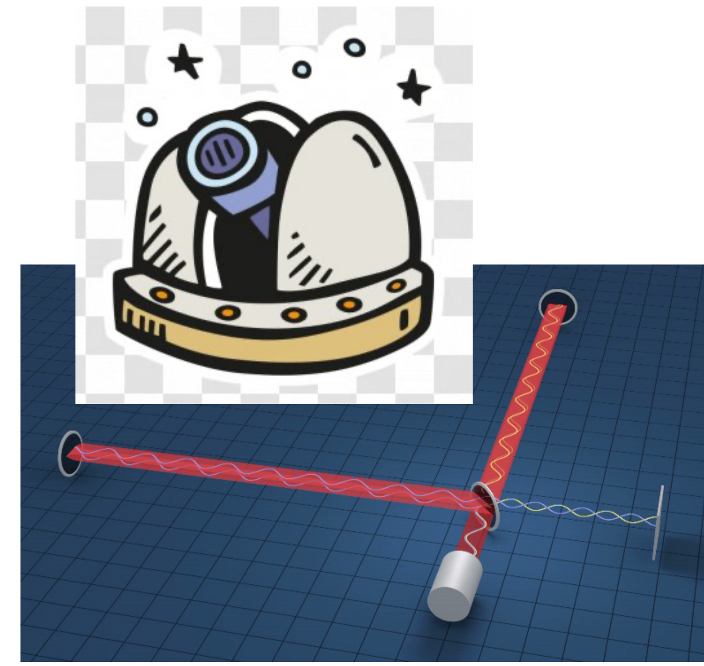
Source emitting both GW and EM radiation

EM radiation (photons)

Gravitational waves

d_L^{EM}

d_L^{GW}



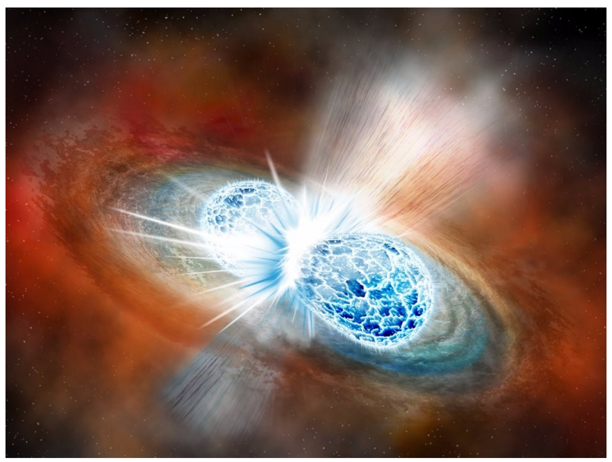
GW and EM detectors

An additional amplitude damping of GWs translates into a different (luminosity) distance inferred by EM and GW measurements which allows to test ν

$$d_L^{\mathrm{GW}} = d_L^{\mathrm{EM}} \exp\left\{ \int_0^z \frac{\nu(z')}{1+z'} dz' \right\}$$

Standard sirens beyond GR

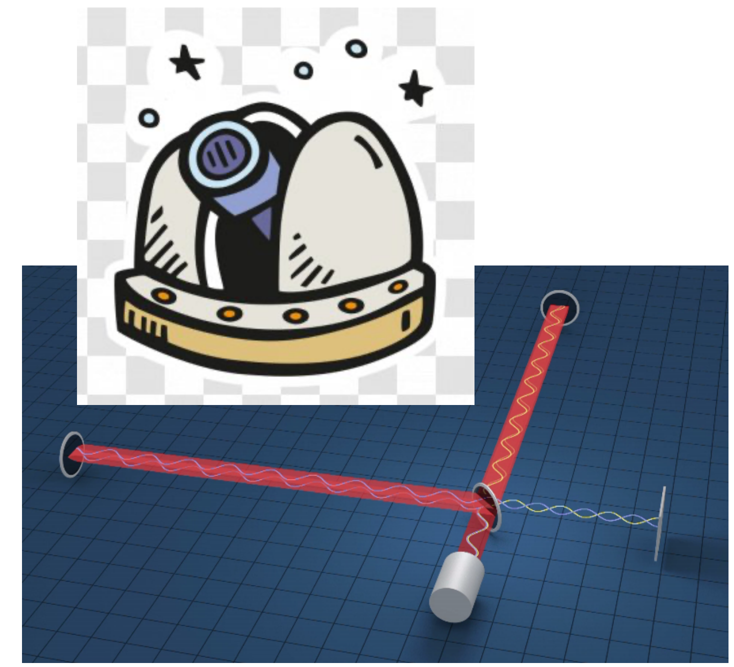
To test these deviations from GR we can use multi-messenger events, namely *bright standard sirens*



Source emitting both GW and EM radiation

EM radiation (photons)

Gravitational waves



GW and EM detectors

Hence bright standard sirens allow us to test/constrain

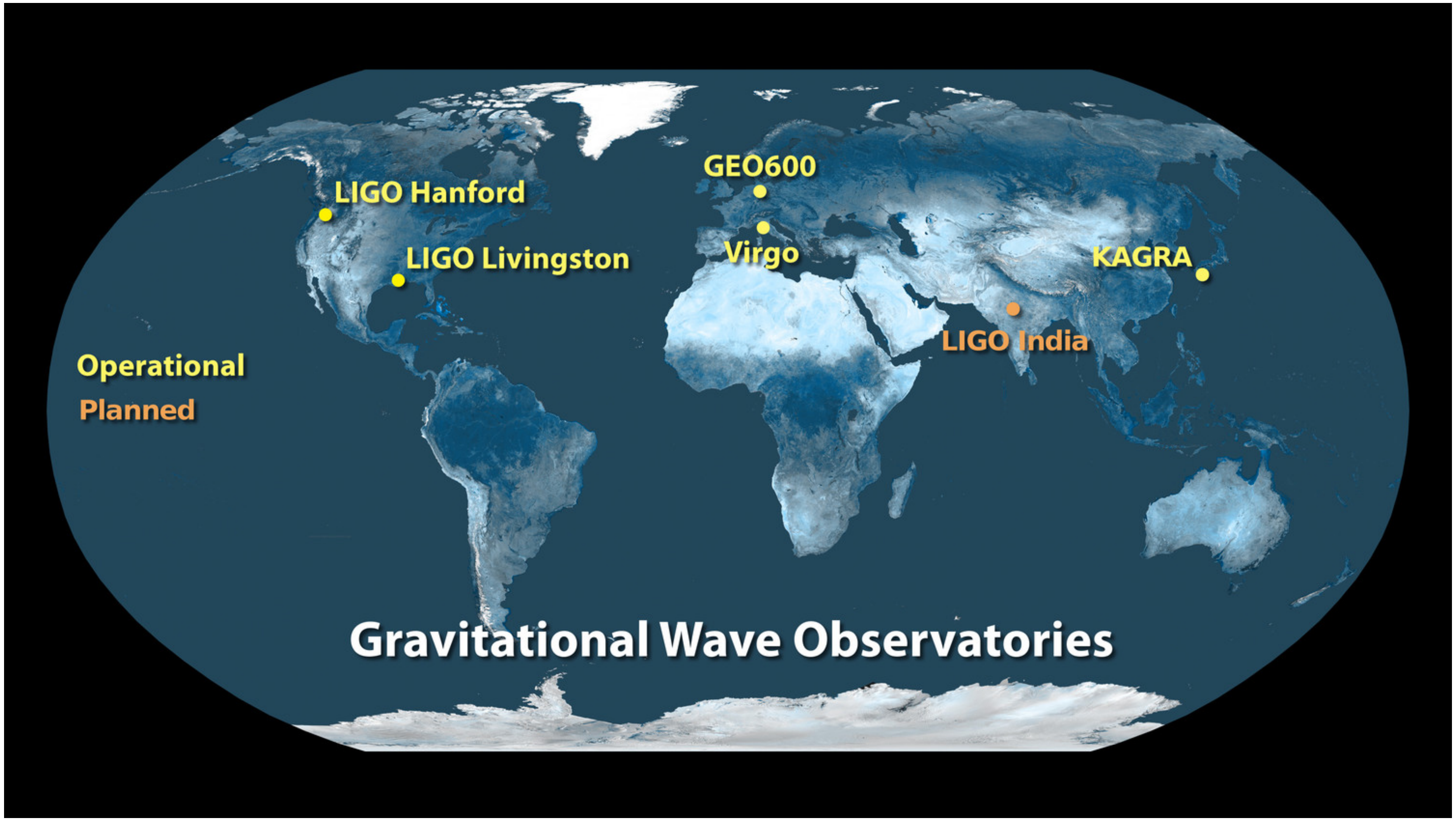
- **the speed of propagation of GWs**
- **an anomalous amplitude damping**

→ **Direct tests of deviations from GR**

Current results from LIGO/Virgo

Current results from LIGO/Virgo

Status of Earth-based GW observations:



Current 2nd generation GW detector network

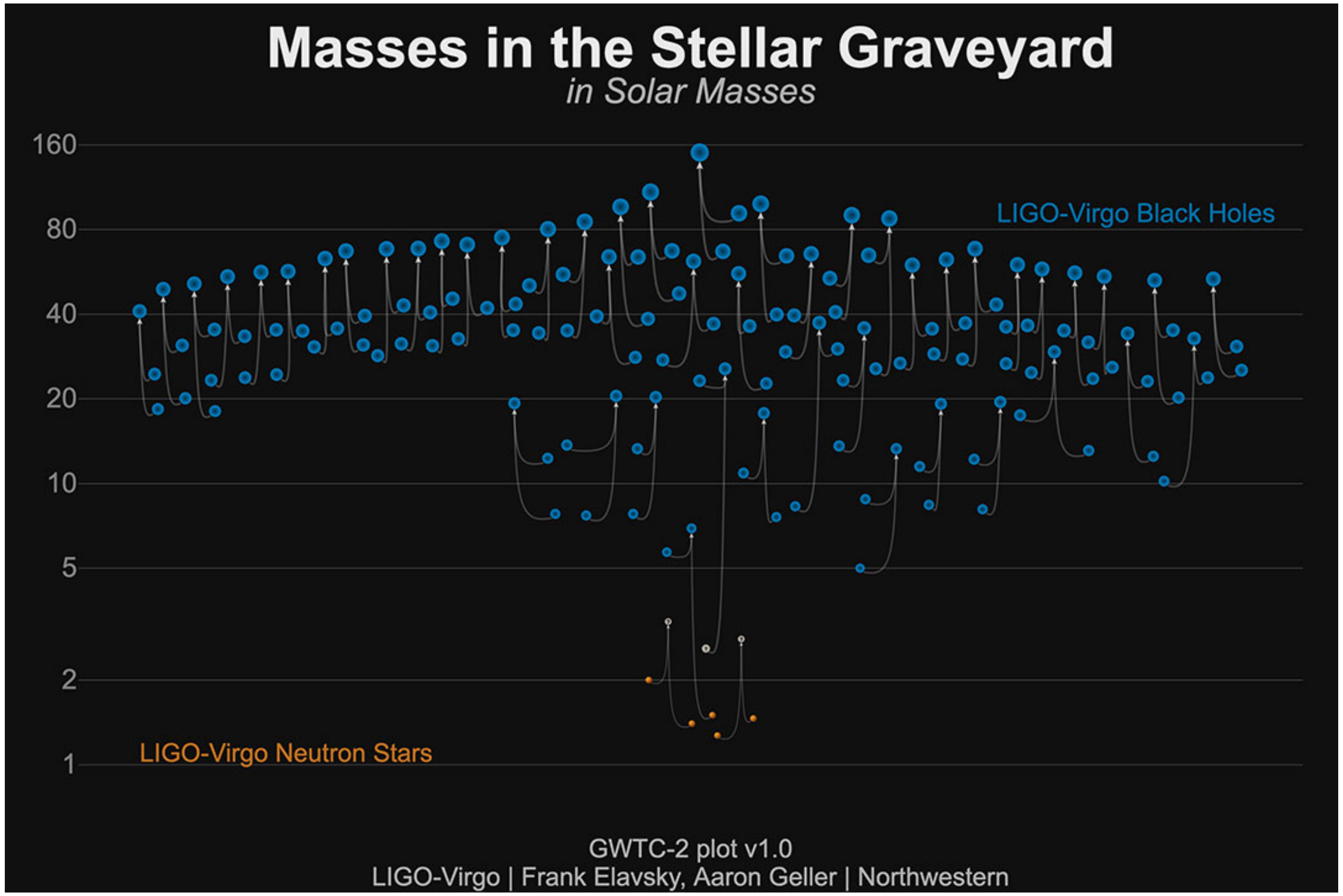
Current results from LIGO/Virgo

Status of Earth-based GW observations:

- O1: 2015 (completed), LIGO only, 4 months of data, 3 BBHs detected
- O2: 2017 (completed), LIGO(+VIRGO 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, 41 events so far (O3a only), 36 BBHs + 2 BNSs + 2 NSBHs + 1 BBH/NSBH [LVC, *PRX* (2020)] [LVC, *ApJL* (2021)]
- O4: mid-2022 LIGO+VIRGO+KAGRA
- O5: ~2024/2025? LIGO India should join

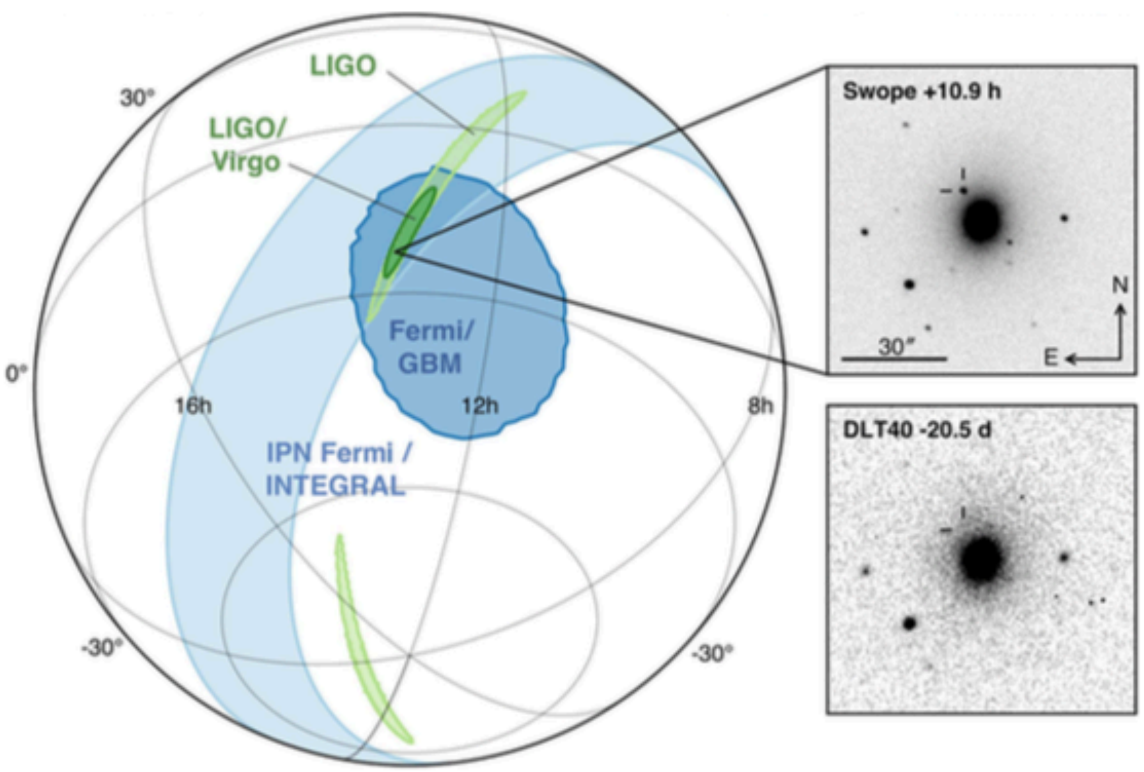
52 high-significance* GW events in total so far

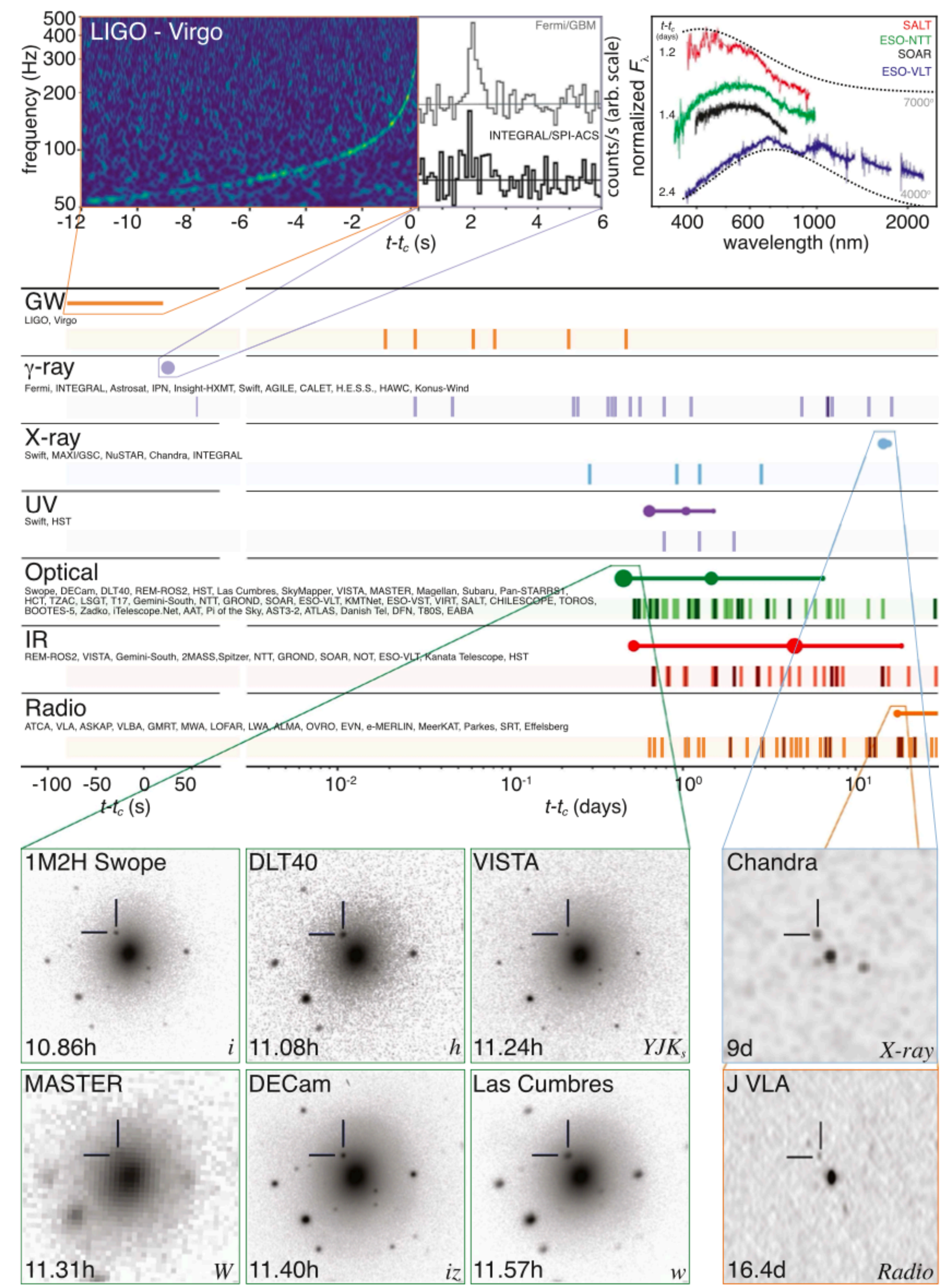
*for additional lower-significance events see arXiv:2108.01045



Current results from LIGO/Virgo

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)]

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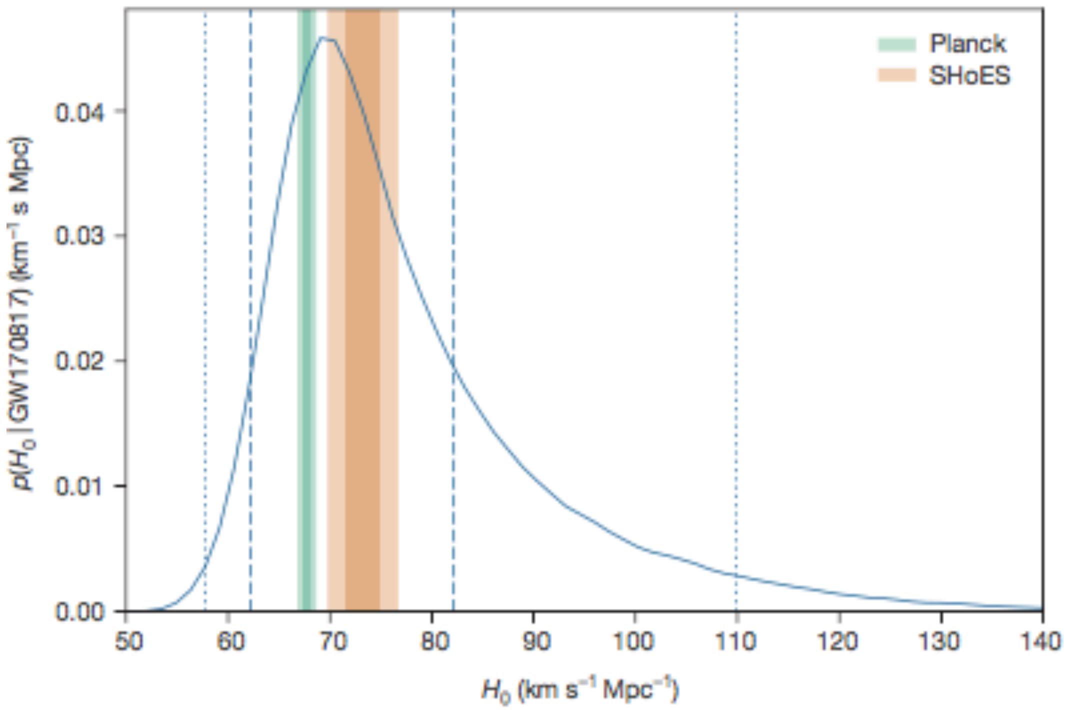

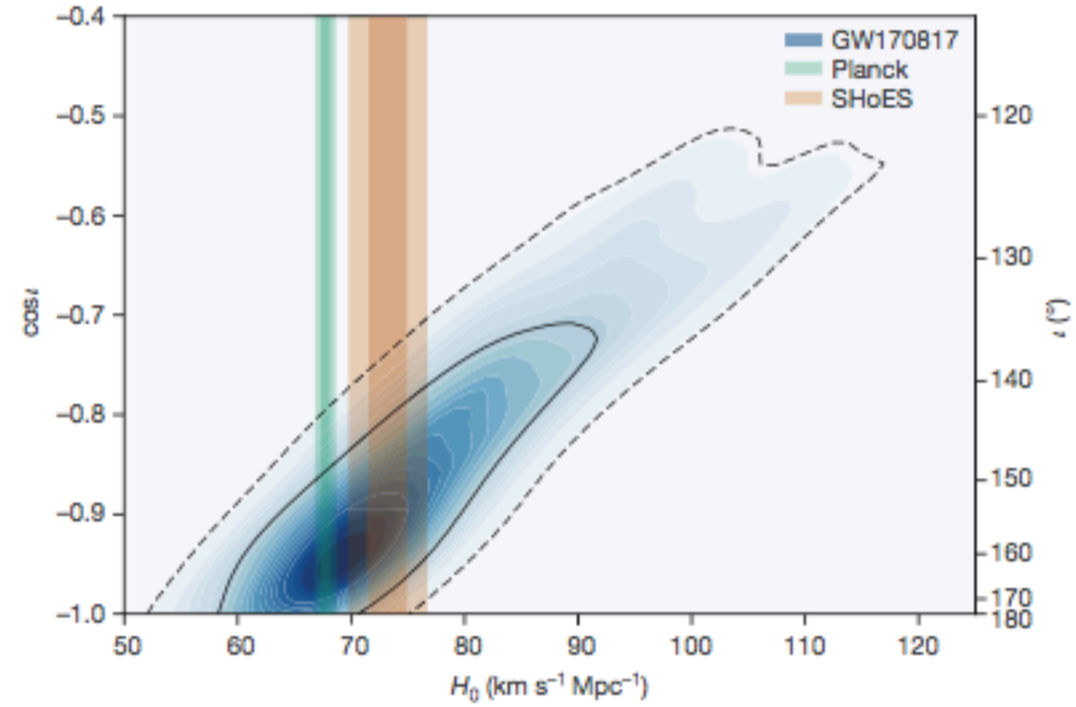

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$$H_0 = 69^{+17}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

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

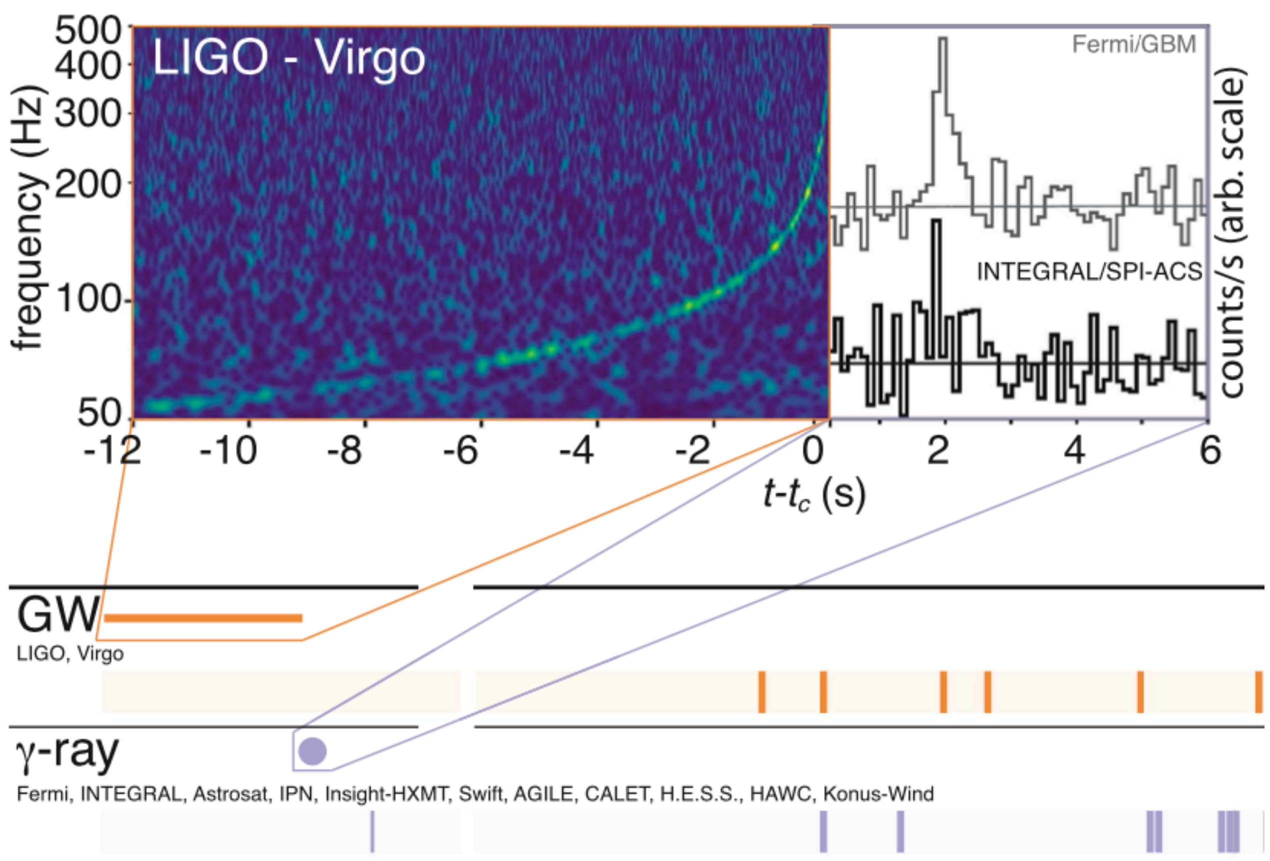
Low-redshift event ($z = 0.01$): only H_0 can be measured (**Hubble law**)

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

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

Current results from LIGO/Virgo

GW170817: the first ever (bright) standard siren



[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)]

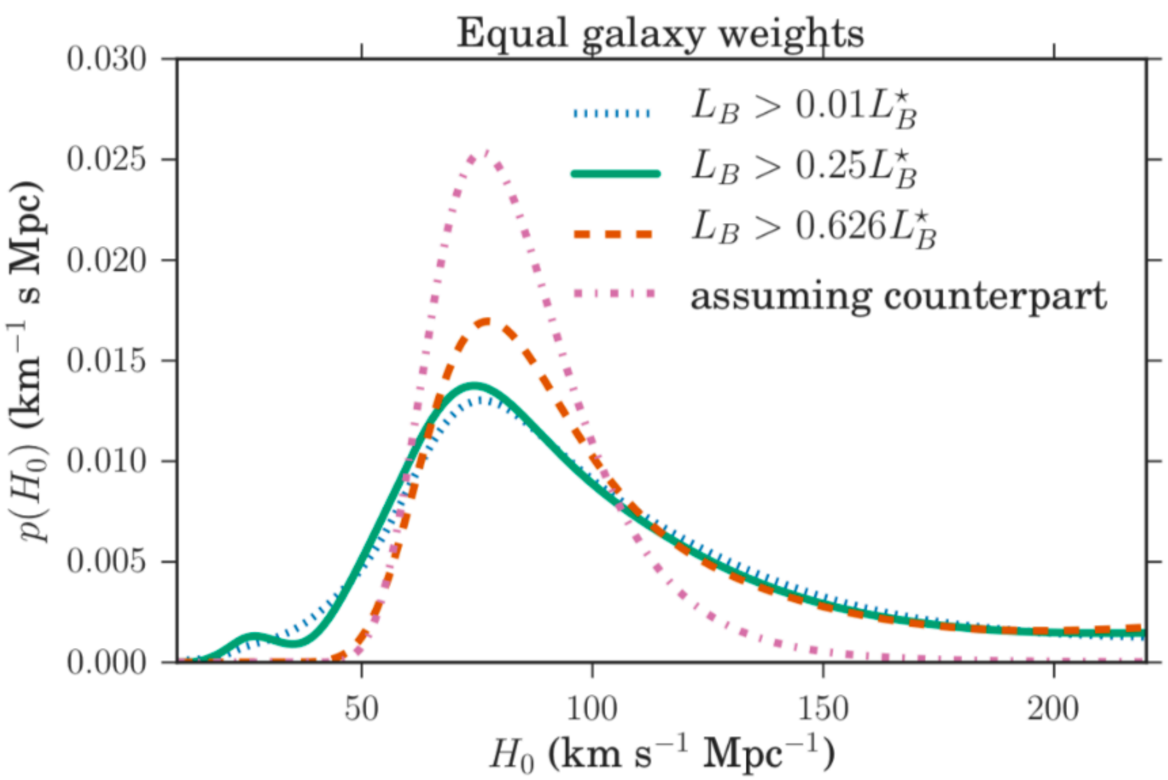
Current results from LIGO/Virgo

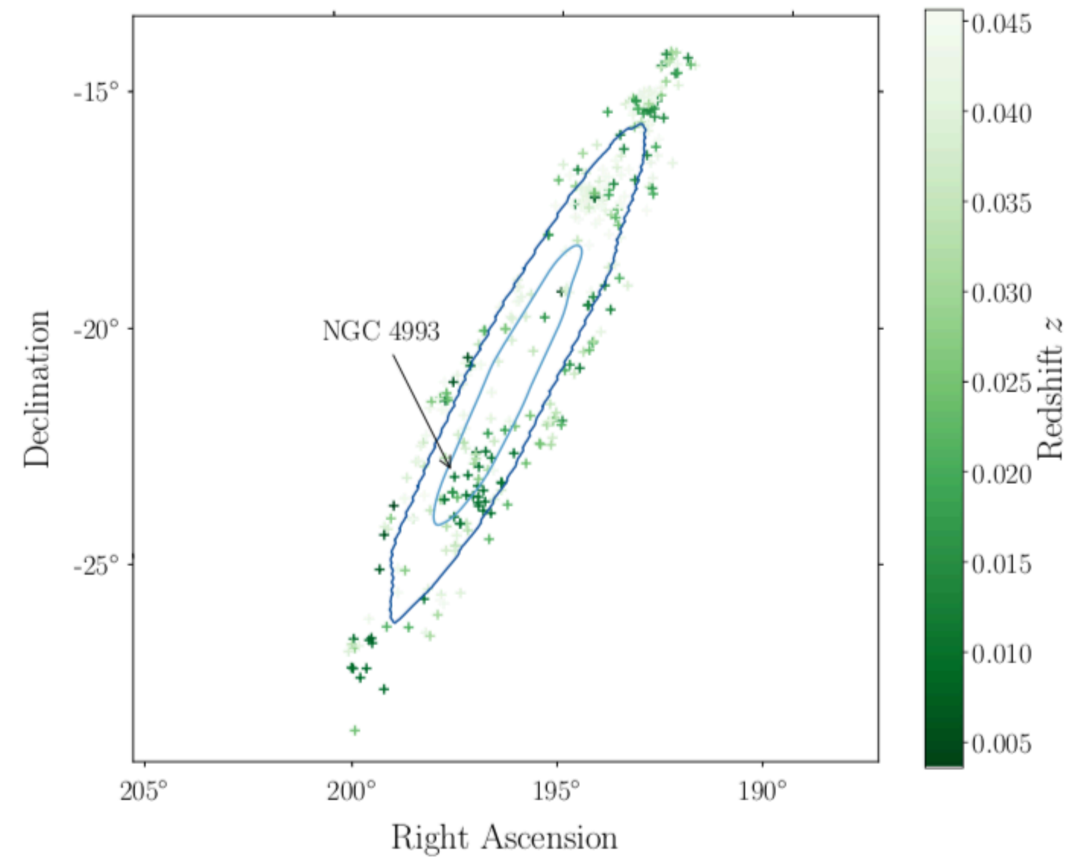
GW170817: the first ever (bright) standard siren

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

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

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



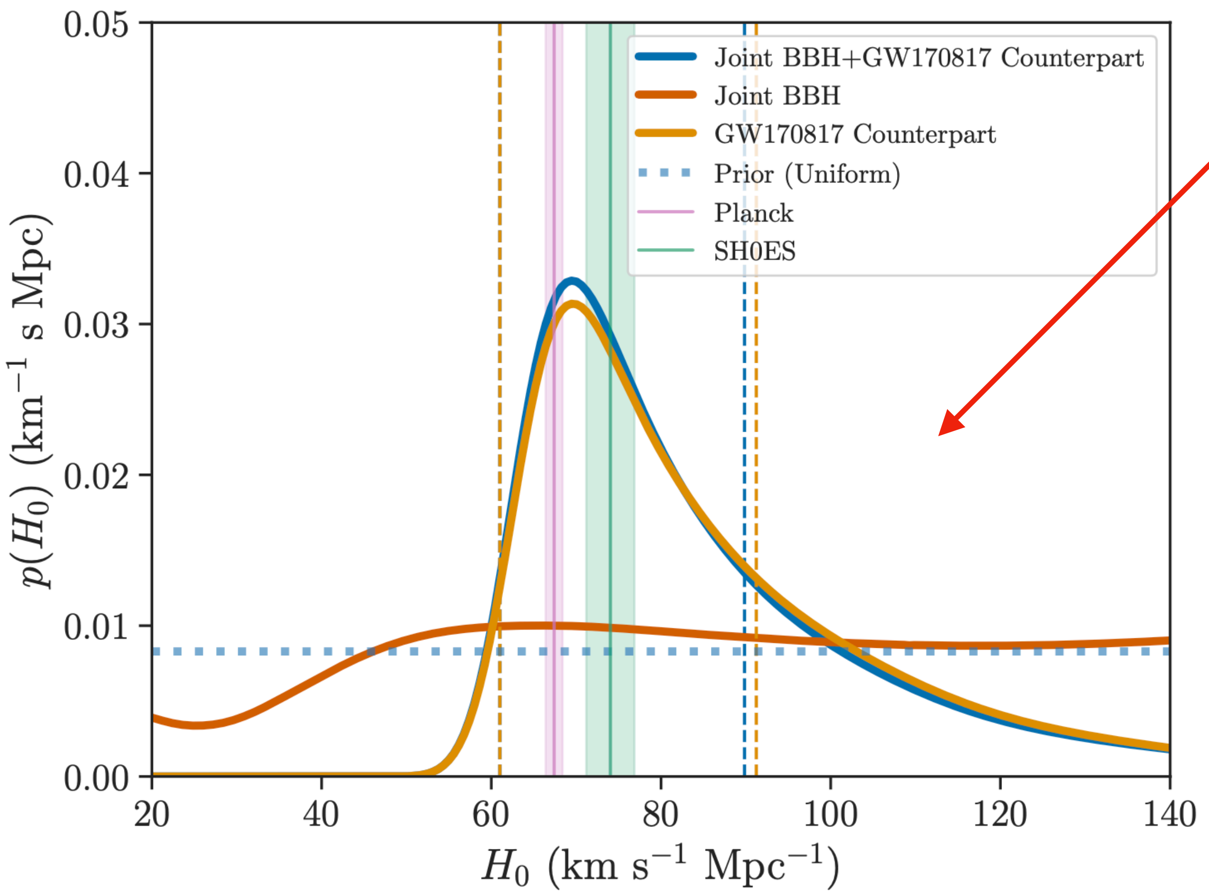


<u>Some lesson learnt however</u>: Strong dependence on the completeness and characteristics of the used galaxy catalogs

[Fishbach+, *ApJL* (2019)]

Current results from LIGO/Virgo

The galaxy-catalogs method has then been applied to combine BBHs events:



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

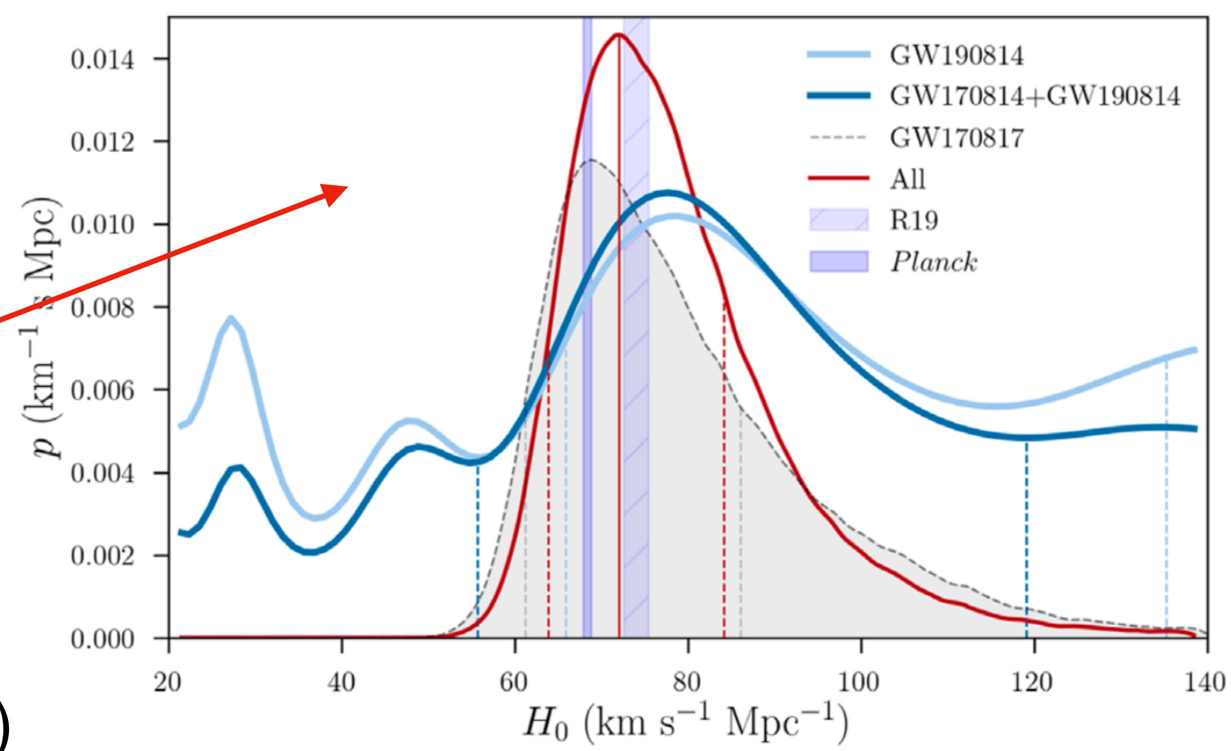
$$H_0 = 69^{+16}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(4% improvement over GW170817 only)

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)



Current results from LIGO/Virgo

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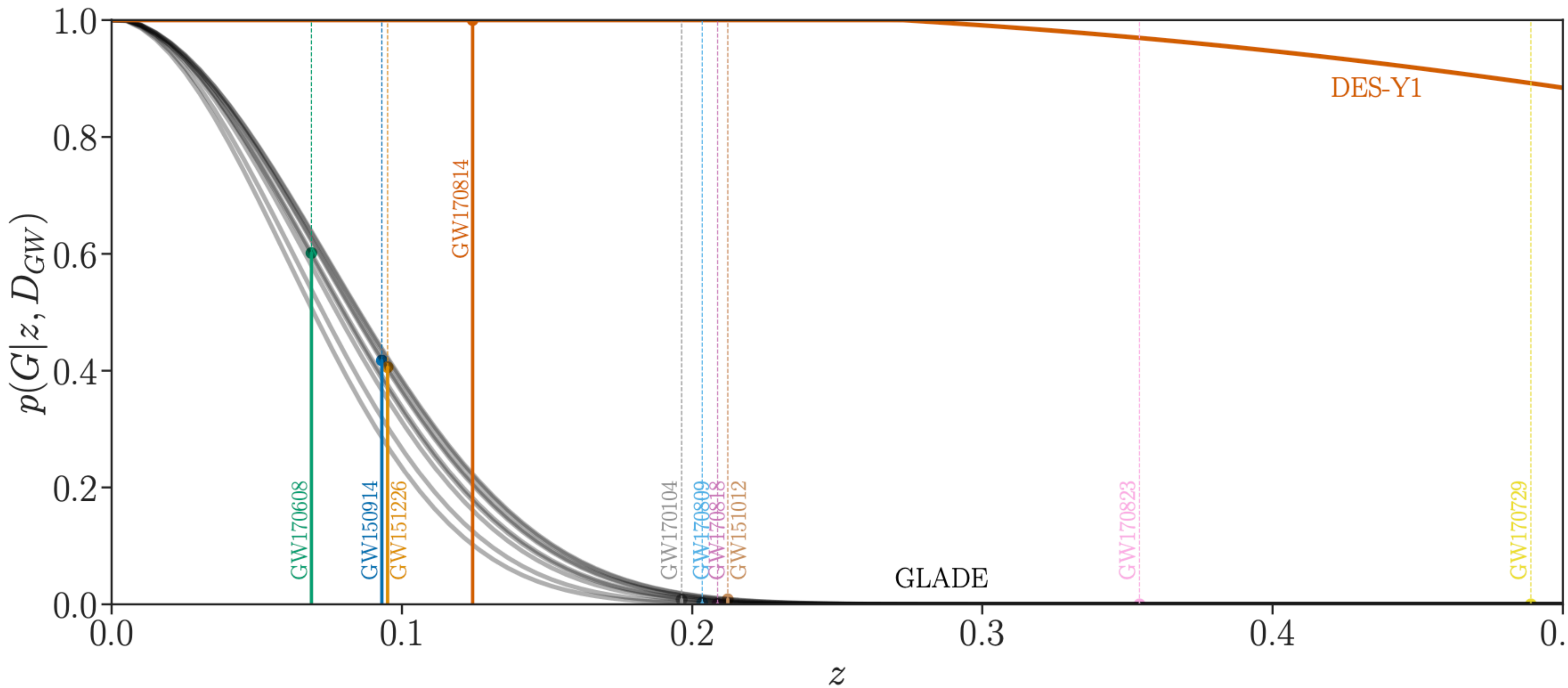
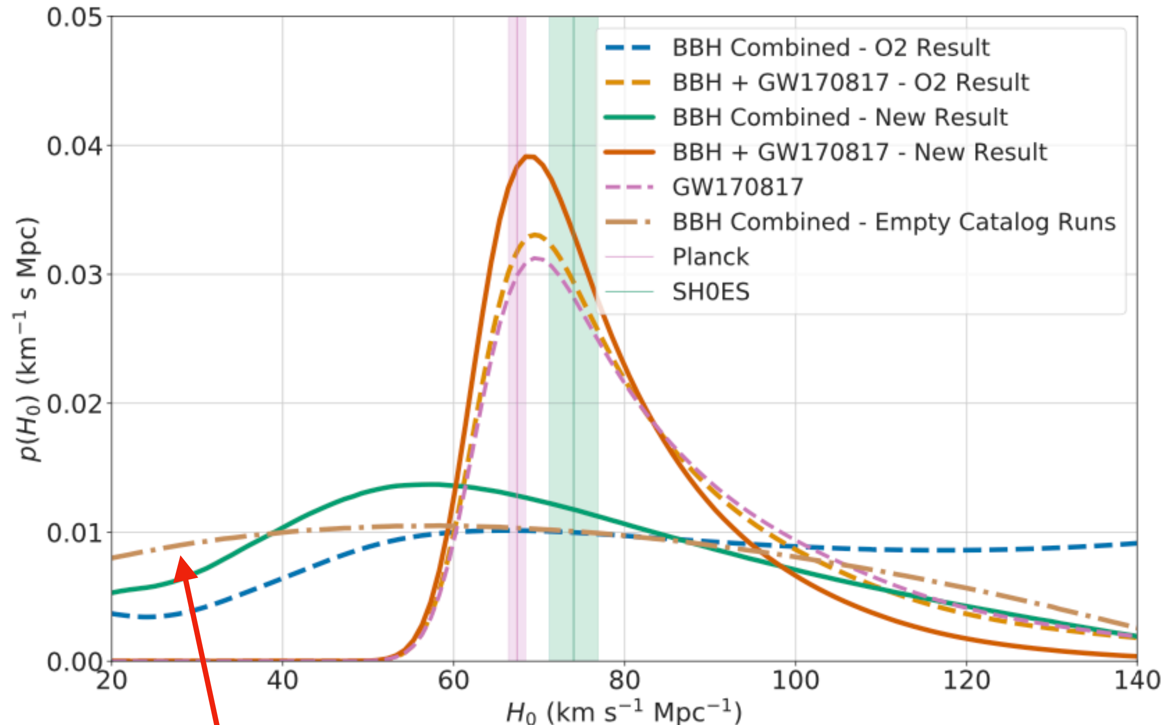


Completeness of galaxy catalogs is the main limitation for this method

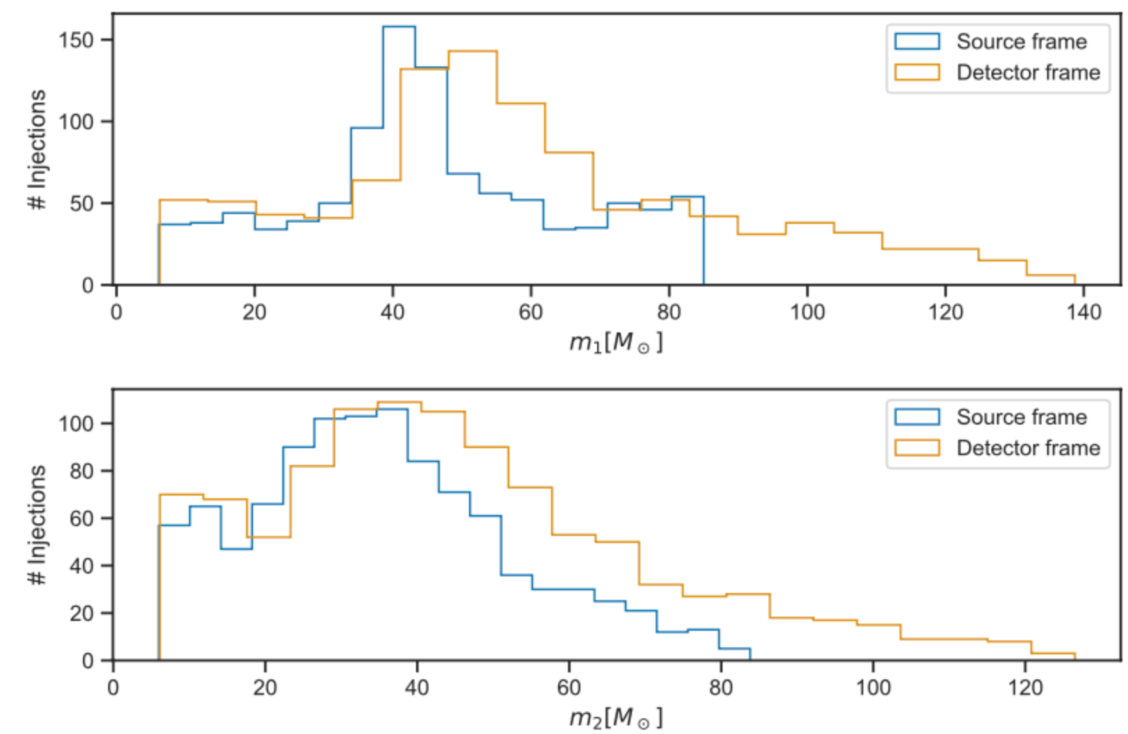
[LVC, *ApJ* (2020)]

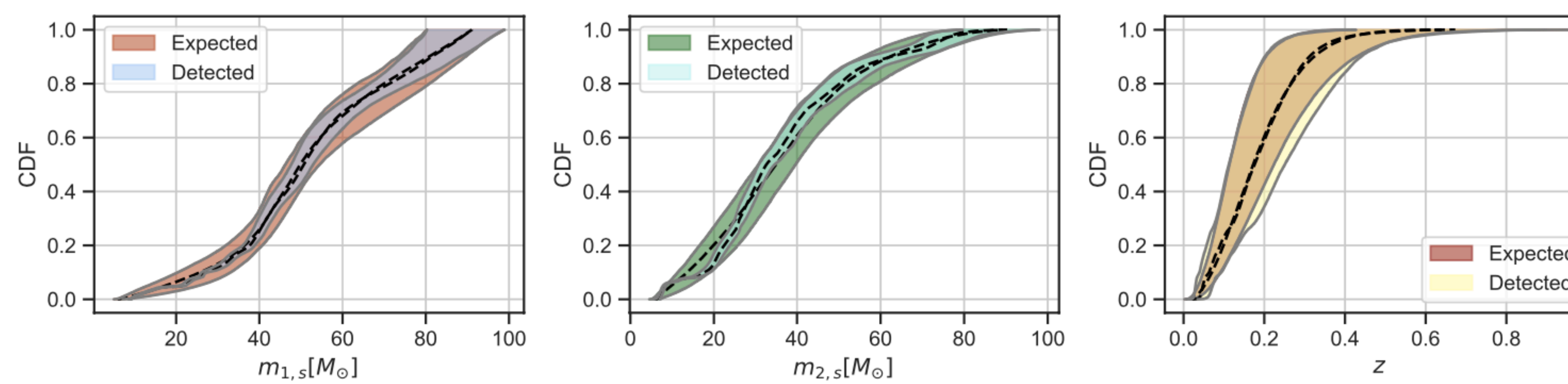
Current results from LIGO/Virgo

Finally the mass-distribution method has been applied to O2 BBHs events*:



Current results with O2 are largely uninformative on the value of H_0





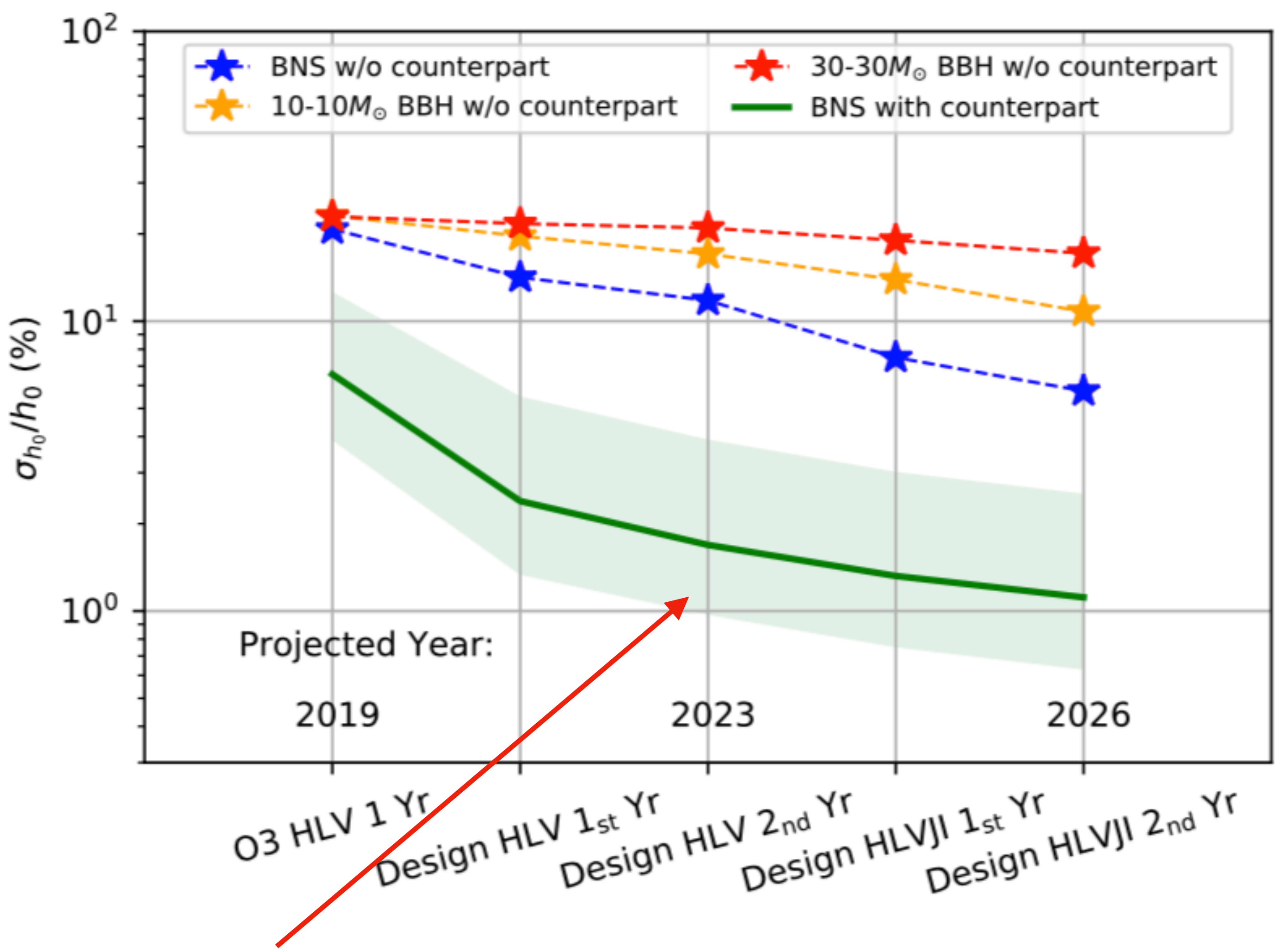
*new analysis with O3 events coming soon!

[Mastrogiovanni+, *ArXiv* (2021)]

Future prospects

Future prospects

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+, *ApJL* (2020)]

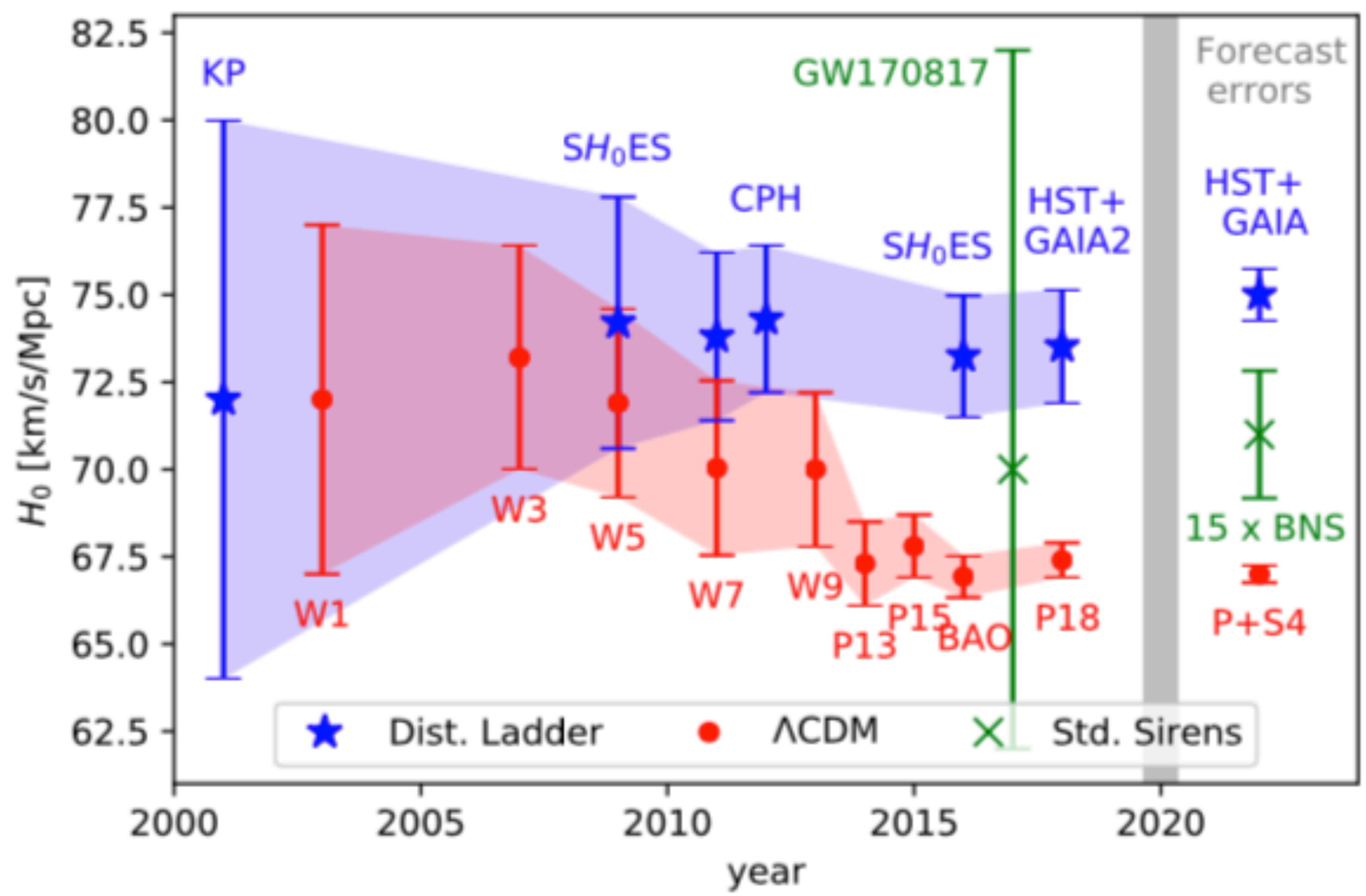
Forecasts for LIGO/Virgo/Kagra+:

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

Future prospects

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

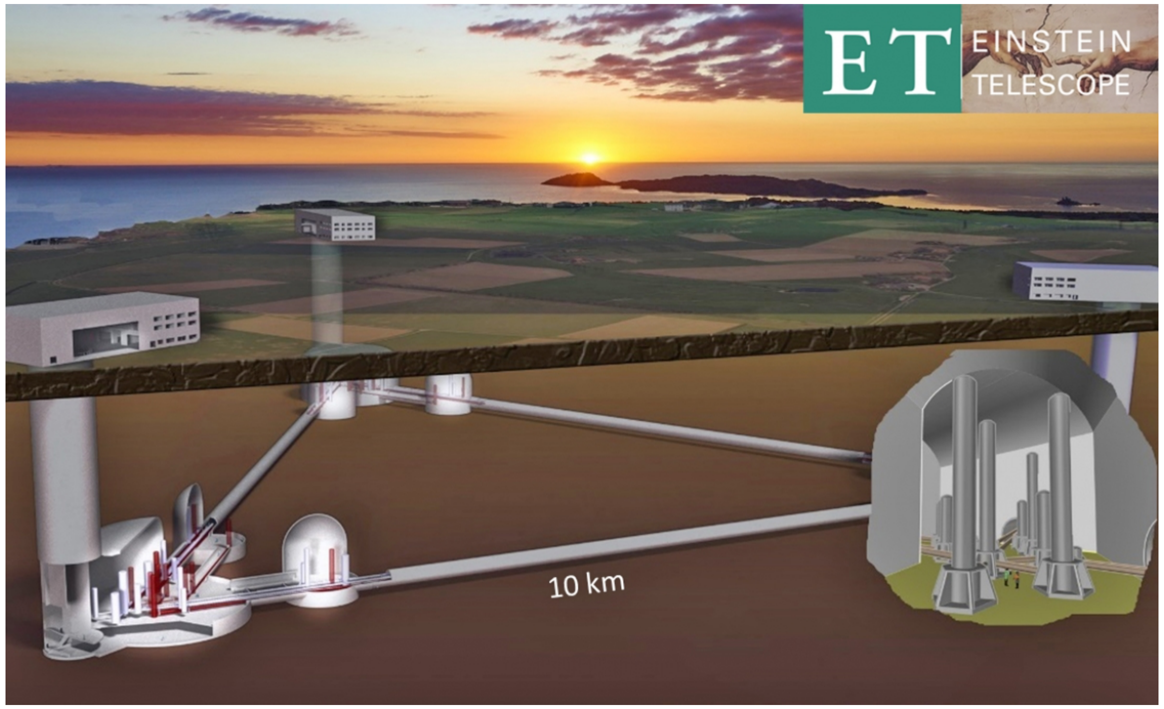
A few % constraints on H0 with GWs could solve the current <u>tension</u> between local and CMB measurements

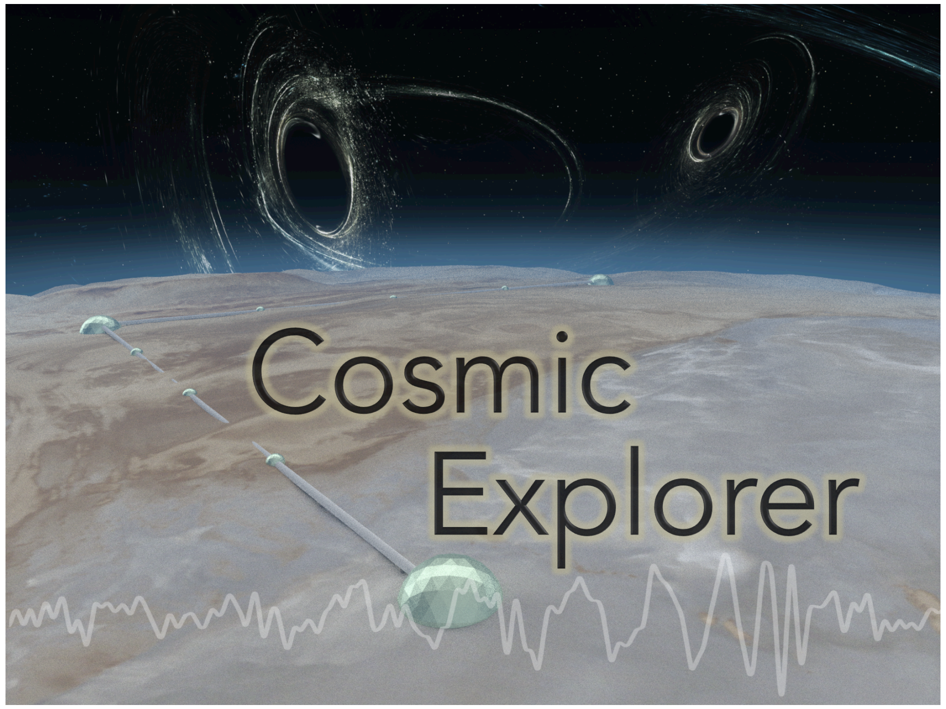


[Ezquiaga & Zumalacarregui, *Front. Astron. Space Sci.* (2018)]

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

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

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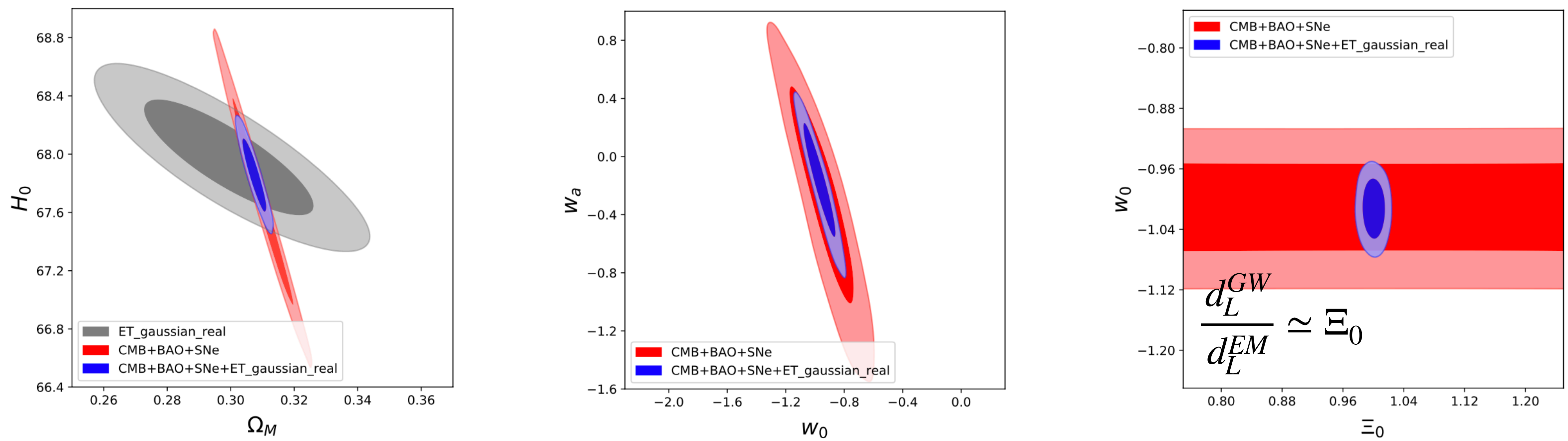

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[Belgacem+, *JCAP* (2019)]

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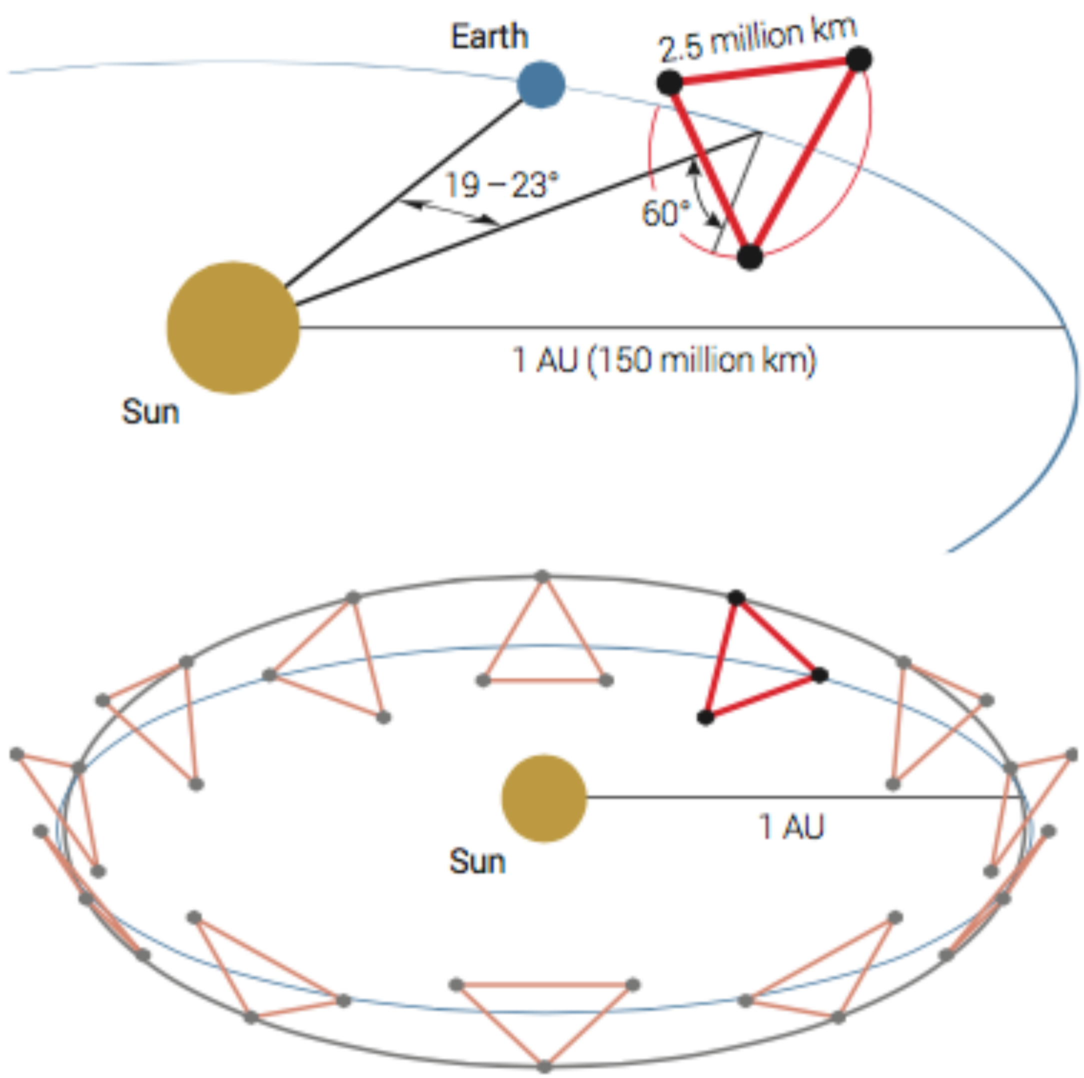
[Taylor&Gair, *PRD* (2012)]
[Del Pozzo+, *PRD* (2017)]
[Finke+, *ArXiv* (2021)]

Future prospects

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

Future prospects

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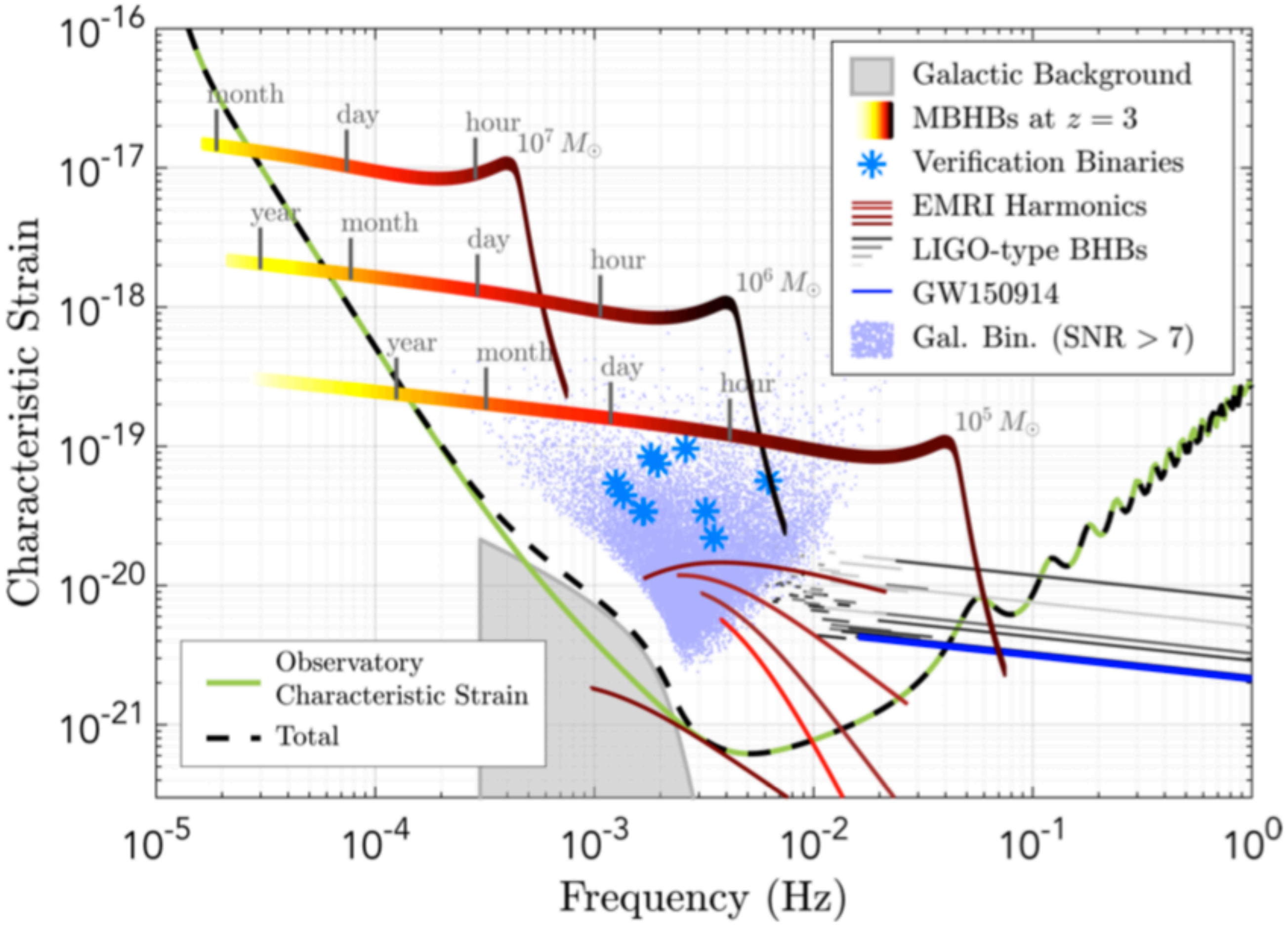

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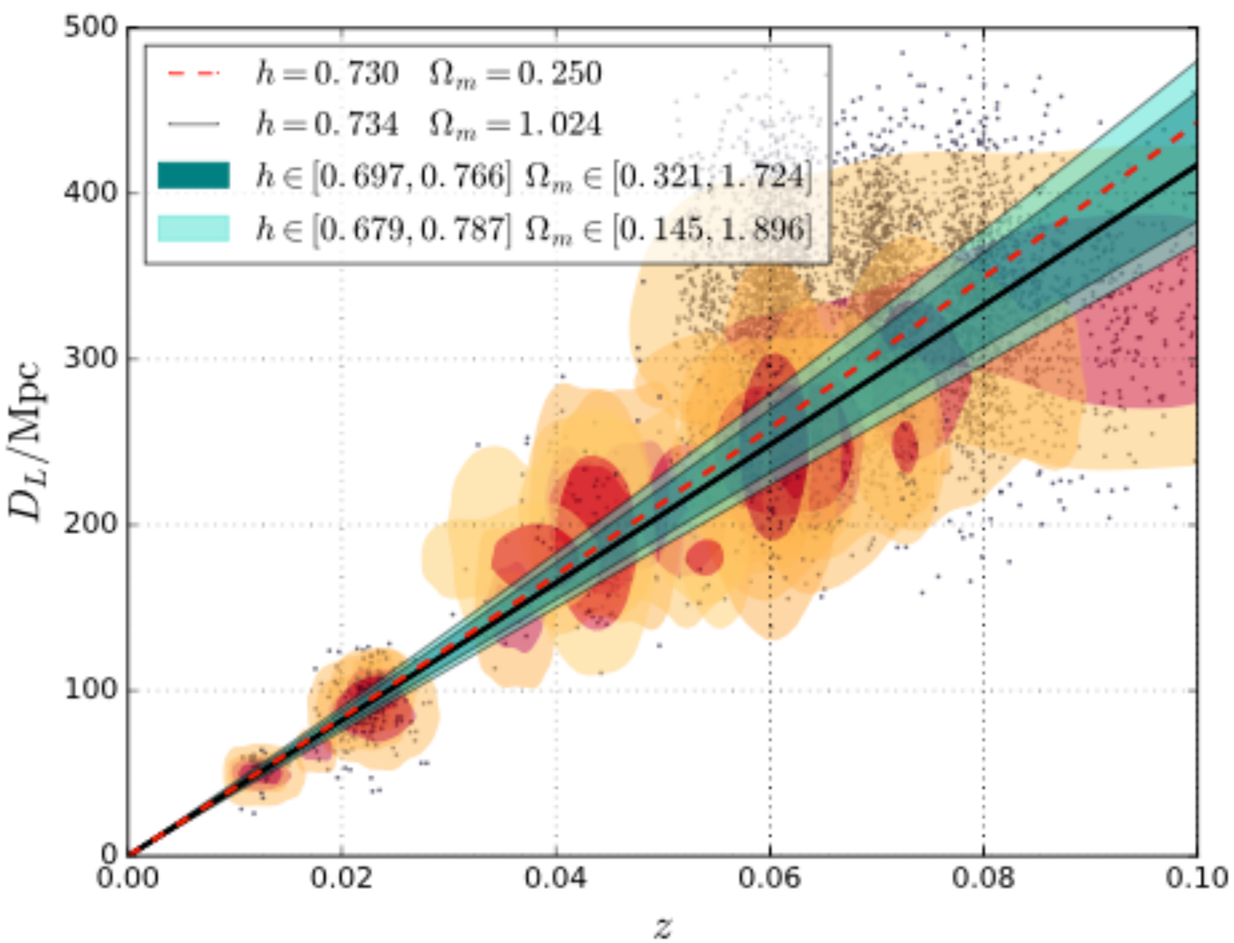
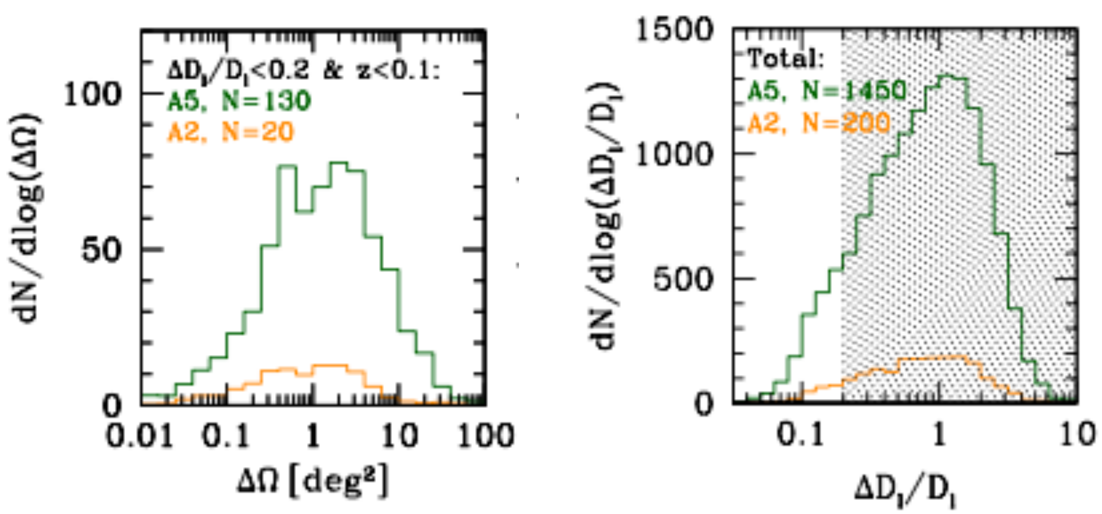
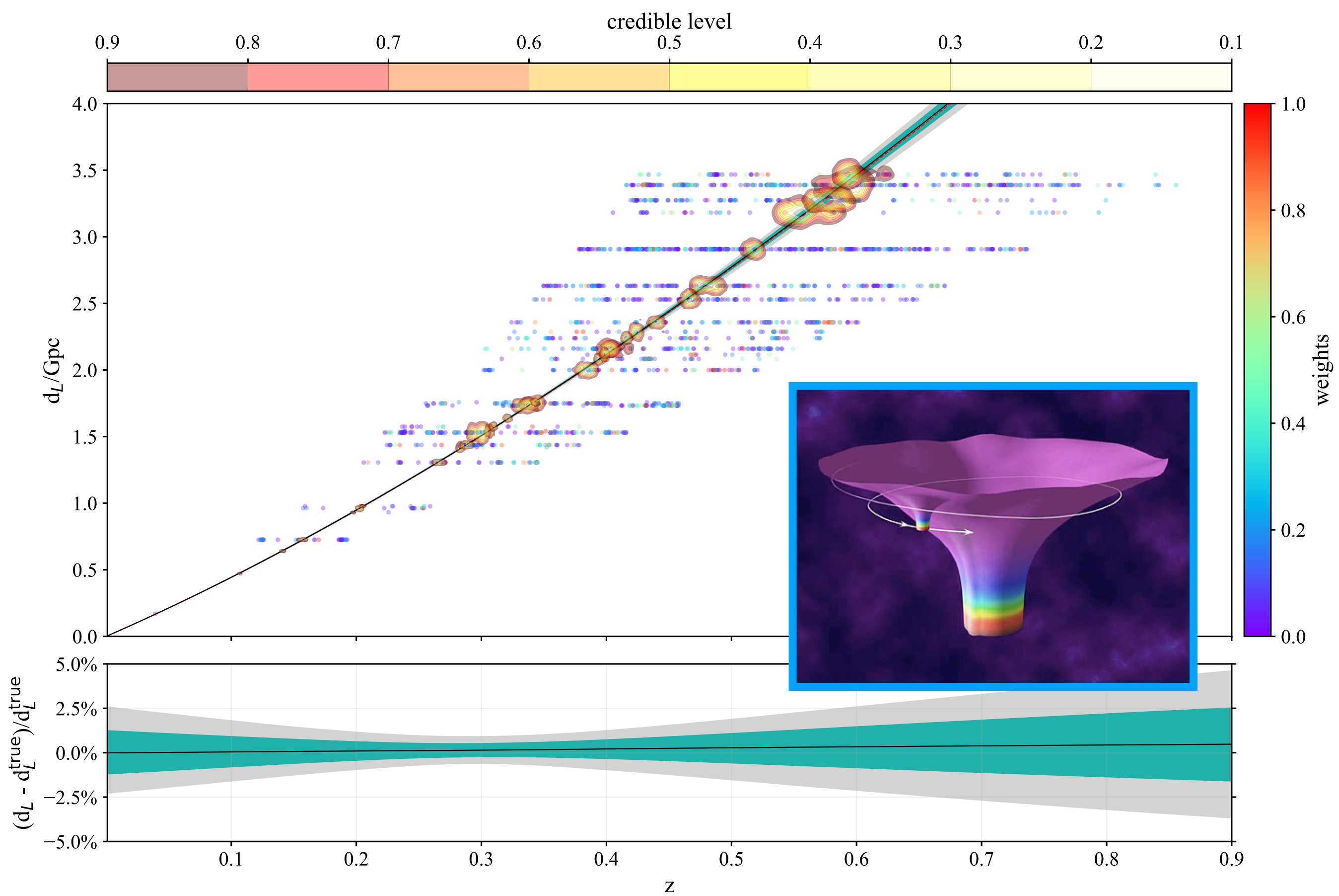


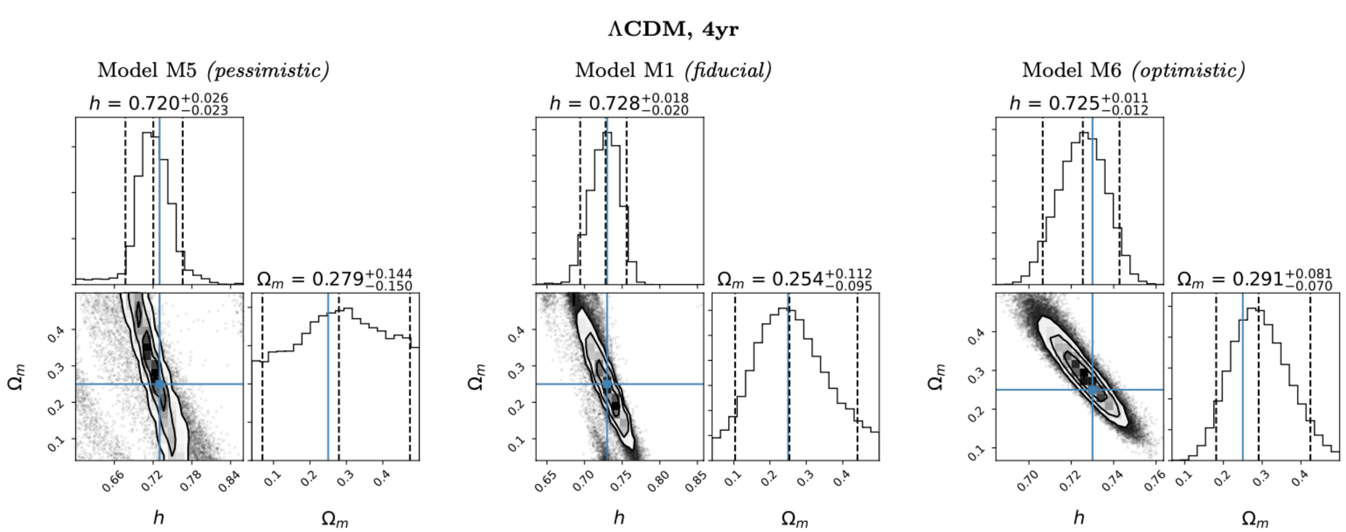


- Redshift range: $z \lesssim 0.1$
- No EM counterparts expected
- LISA detections: ~50/yr (optimistic)
- Useful as standard sirens:
  - If $\Delta d_L/d_L < 0.2$
  - If $\Delta\Omega \sim 1 \ \mathrm{deg}^2$
  - ⇒ ~ 5 standard sirens / yr
- **Expected results:**
  - H_0 to few % (very optimistic - depend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

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

Future prospects

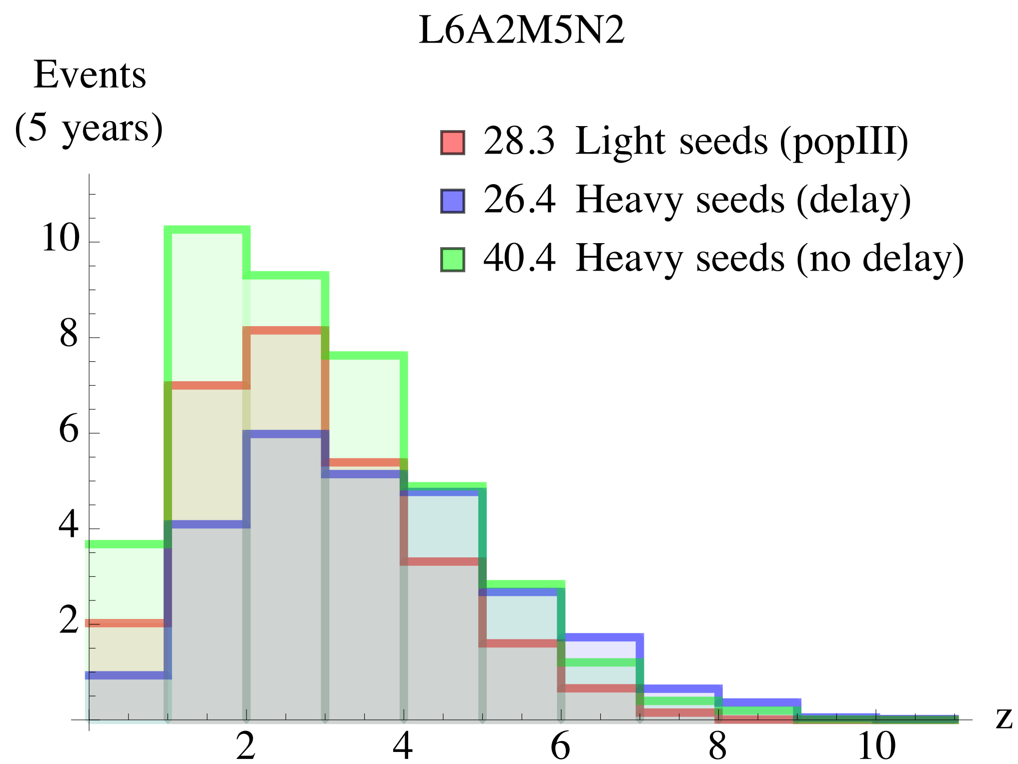


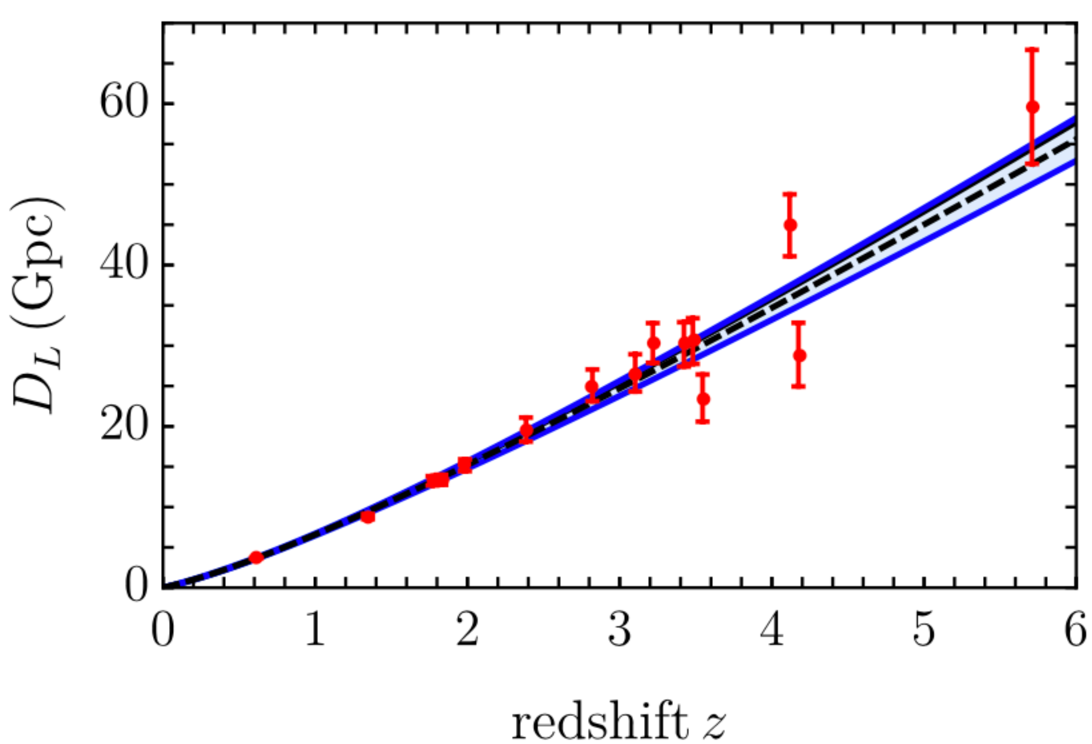


- Redshift range: $0.1 \lesssim z \lesssim 1$
- No EM counterparts expected
- LISA detections: 1 to 1000/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L < 0.1$
  - If $\Delta\Omega < 2\ \mathrm{deg}^2$
  - ⇒ ~ 1 to 100 standard sirens / yr
- **Expected results:**
  - H_0 between 1 and 10 %
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

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

Future prospects





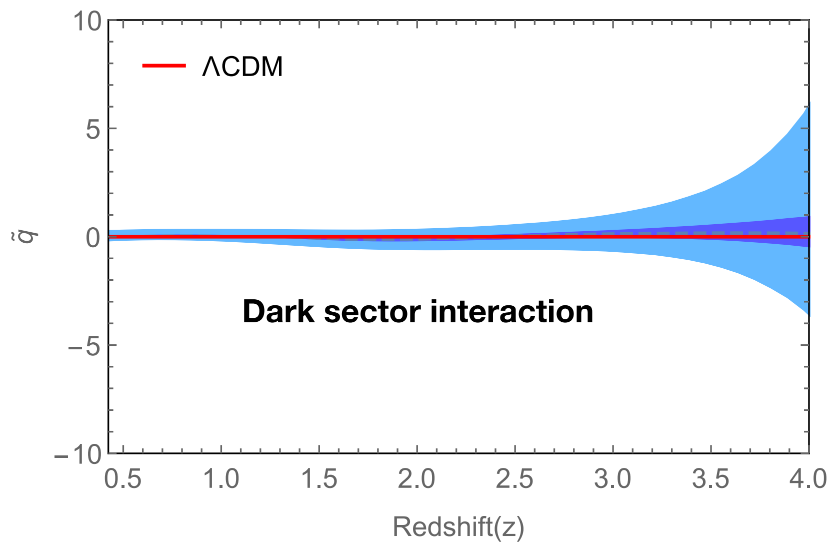
- Redshift range: $z \lesssim 10$
- EM counterparts expected
- LISA detections: 1 to 100/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L \lesssim 0.1$ (include lensing)
  - If $\Delta\Omega < 10\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 4 standard sirens / yr (with EM counterpart)
- <u>**Expected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

[Tamanini+, *JCAP* (2016)]
[LISA CosmoWG, *JCAP* (2019)]
[Speri+, *PRD* (2021)]

Future prospects

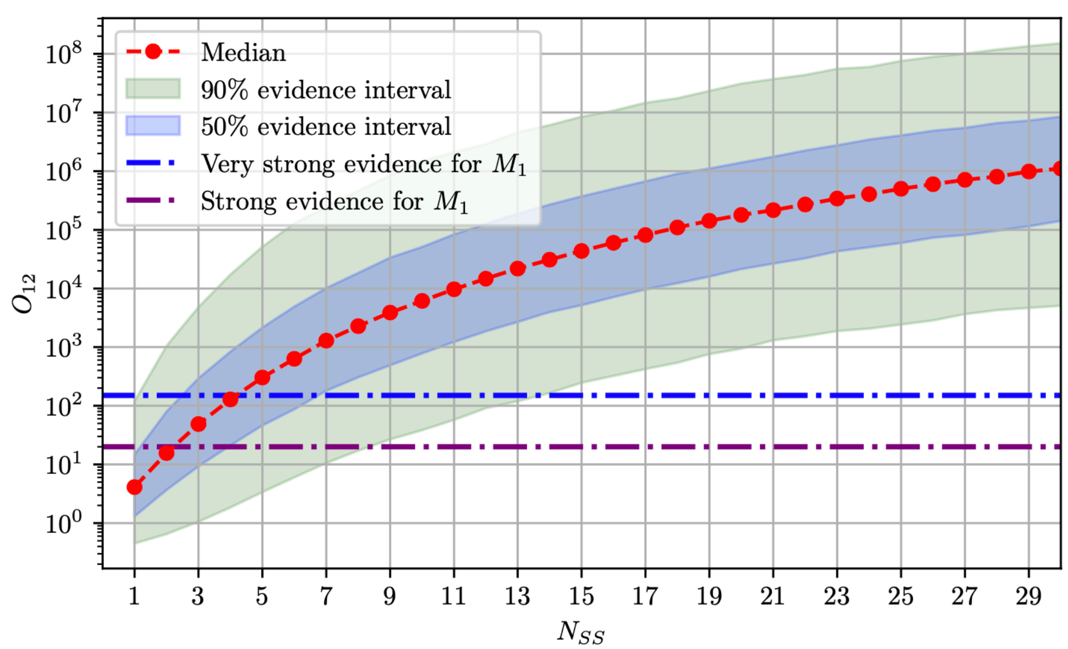
LISA MBHB data will be very useful to probe $\underline{\Lambda\mathrm{CDM}}$ at high-redshift

Test alternative cosmological models



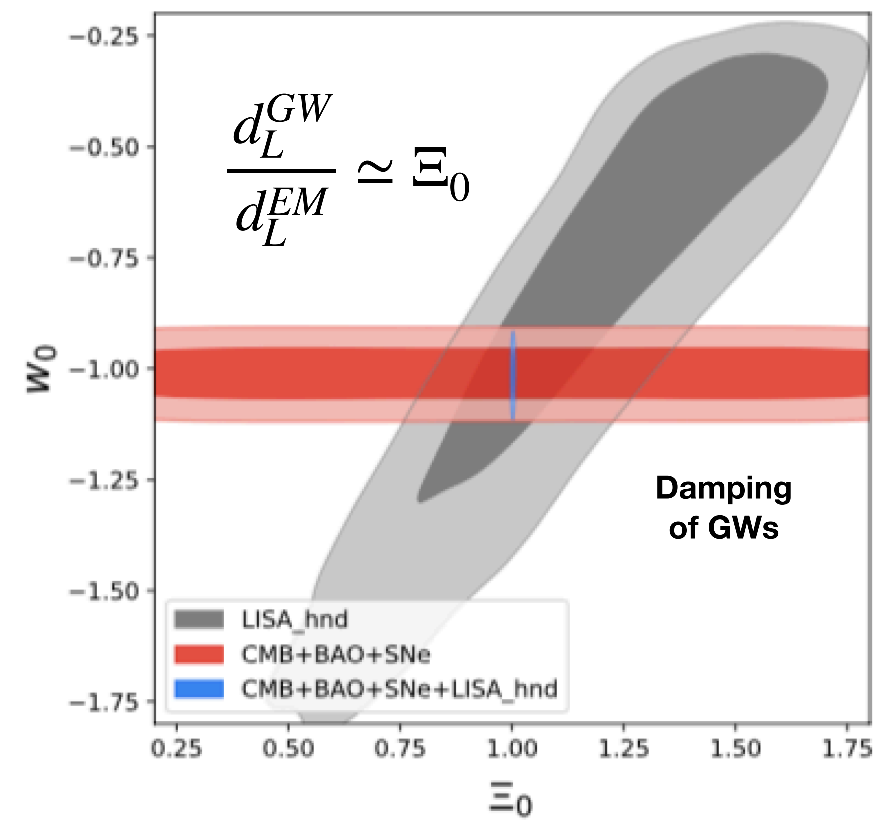
[Caprini & Tamanini, *JCAP* (2016)]
[Cai+, *JCAP* (2017)]

Test quasars Hubble diagram



[Speri+, *PRD* (2021)]

Test modified gravity

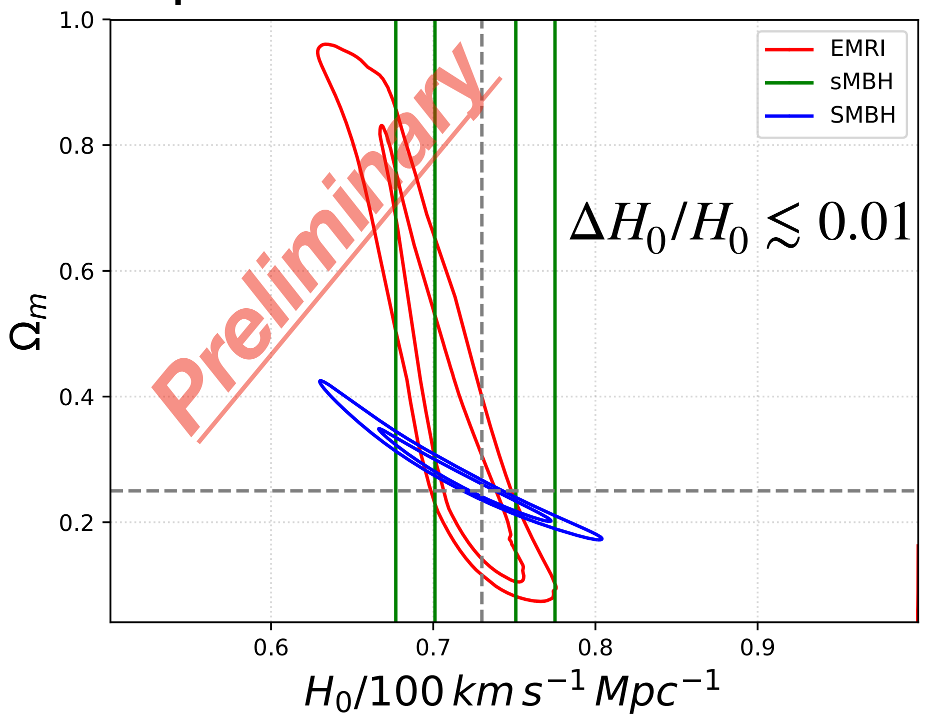


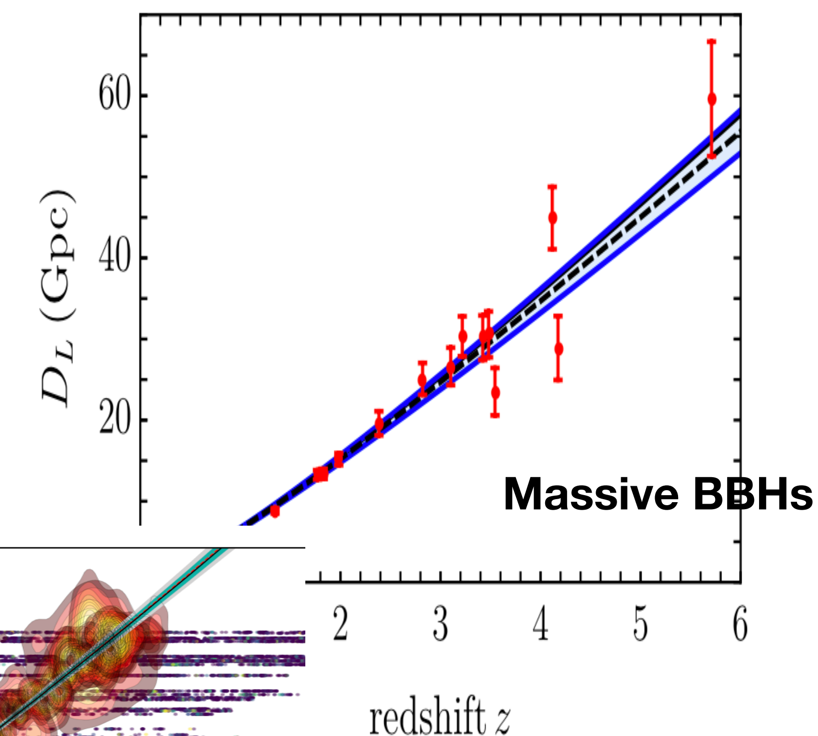
[LISA CosmoWG, *JCAP* (2019)]

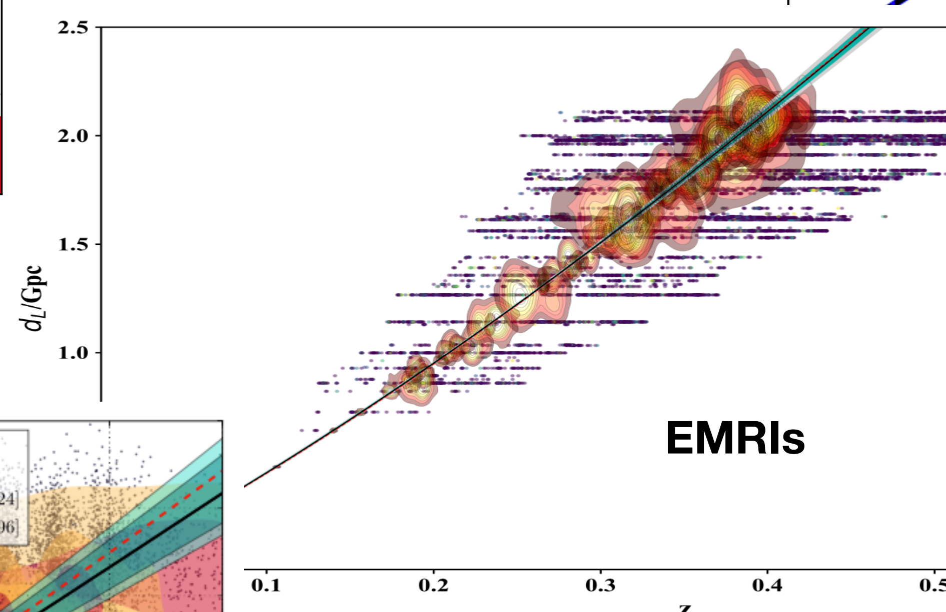
Future prospects

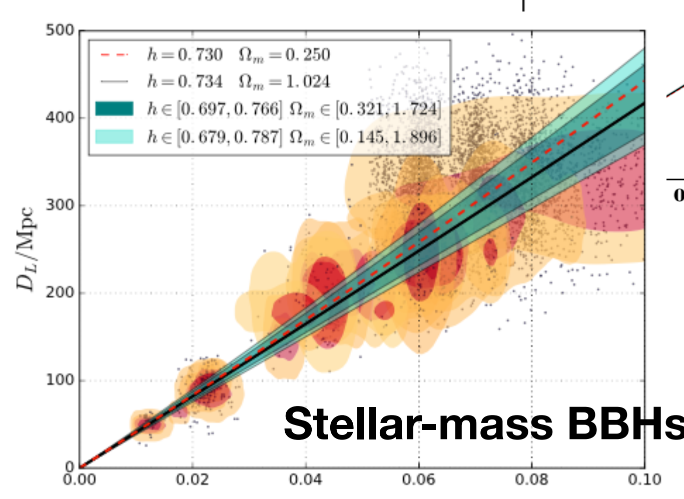
The combination of different standard sirens will allow LISA to measure the expansion of the universe from $z \sim 0.01$ to $z \sim 10$

Expected results for ΛCDM:









[Tamanini, *J. Phys. Conf. Ser.* (2017)]
[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
  - Will allow for new tests of GR/LCDM

- 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

- Future prospects:
  - Future observations useful to solve tension on H_0
  - 3G detectors and LISA will bring high-redshift tests of alternative cosmological models and modified gravity