Gravitational wave cosmology with LISA (and TianQin)

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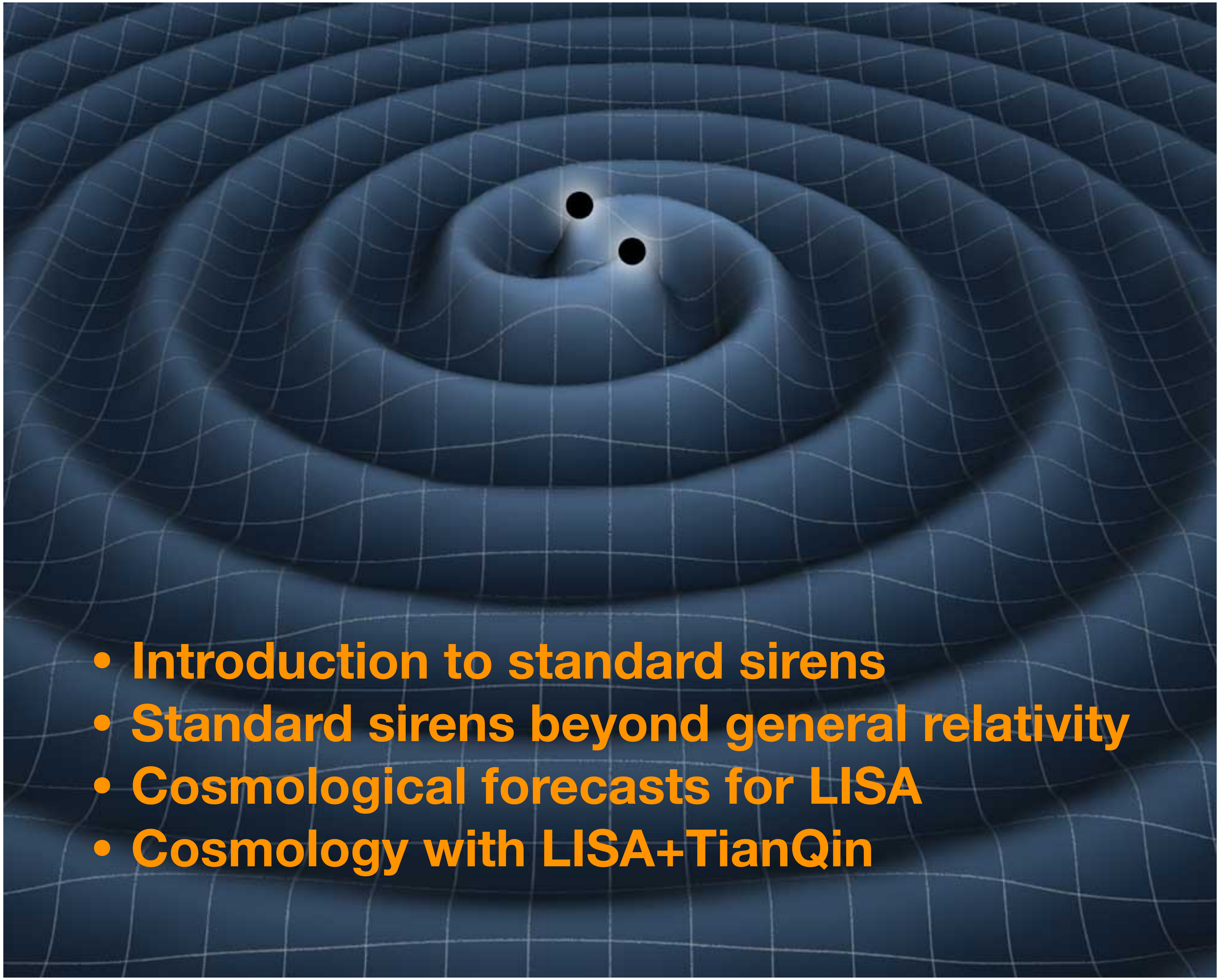
24/08/2022

Outline



- Introduction to standard sirens
- Standard sirens beyond general relativity
- Cosmological forecasts for LISA
- Cosmology with LISA+TianQin

Introduction to standard sirens

Standard sirens

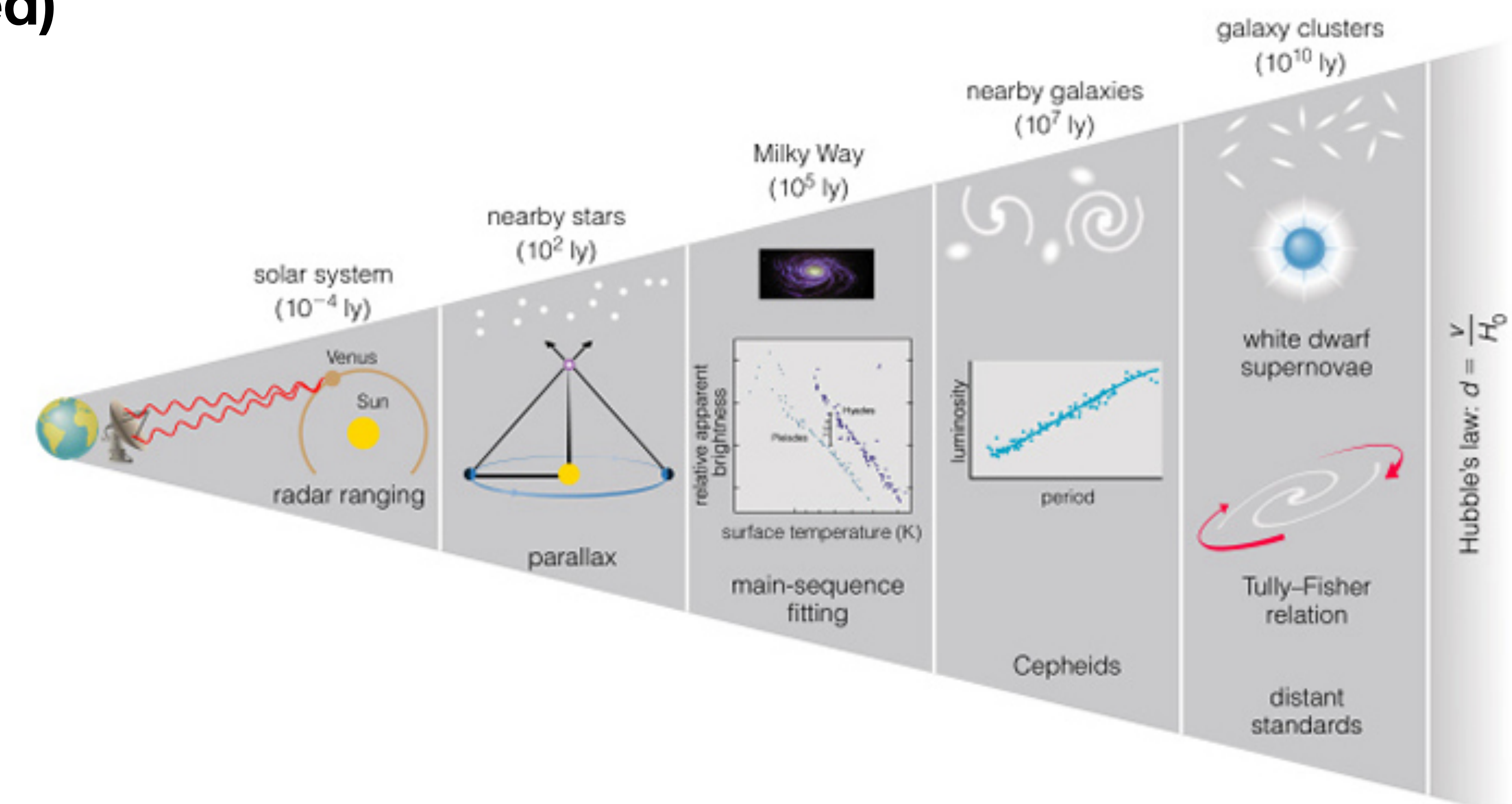
$$h_\times(t_o) = \frac{4}{d_L}\left(\frac{G\mathscr{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\sin\left[-2\left(\frac{5G\mathscr{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

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 GW binaries are absolute cosmological distance indicators!

Free of possible systematics



Standard sirens

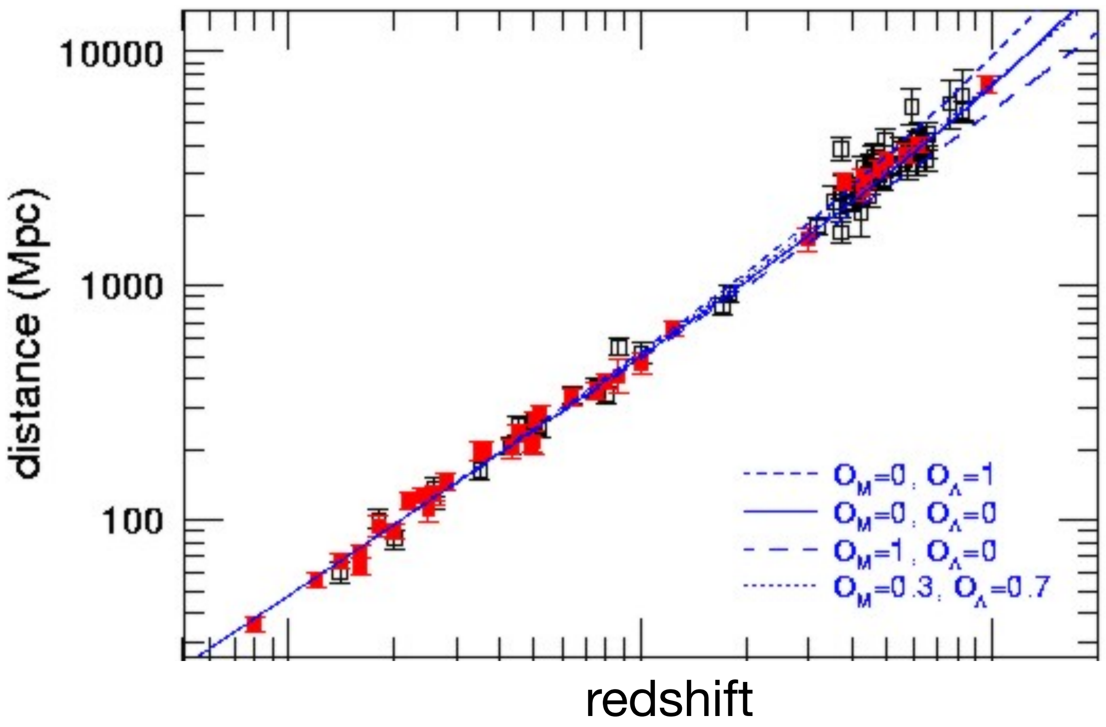
$$h_\times(t_o) = \frac{4}{d_L}\left(\frac{G\mathcal{M}_{cz}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw},o}}{c}\right)^{2/3}\cos\theta\sin\left[-2\left(\frac{5G\mathcal{M}_{cz}}{c^3}\right)^{-5/8}\tau_o^{5/8}+\Phi_0\right]$$

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/spectral sirens*)**

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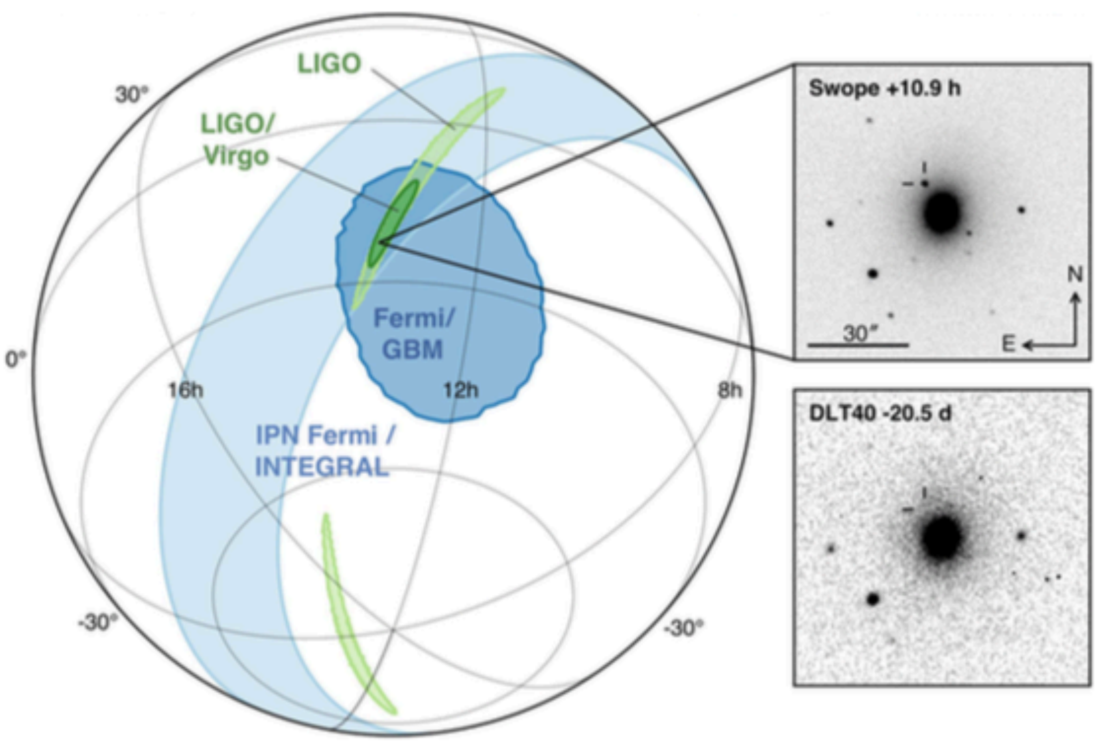

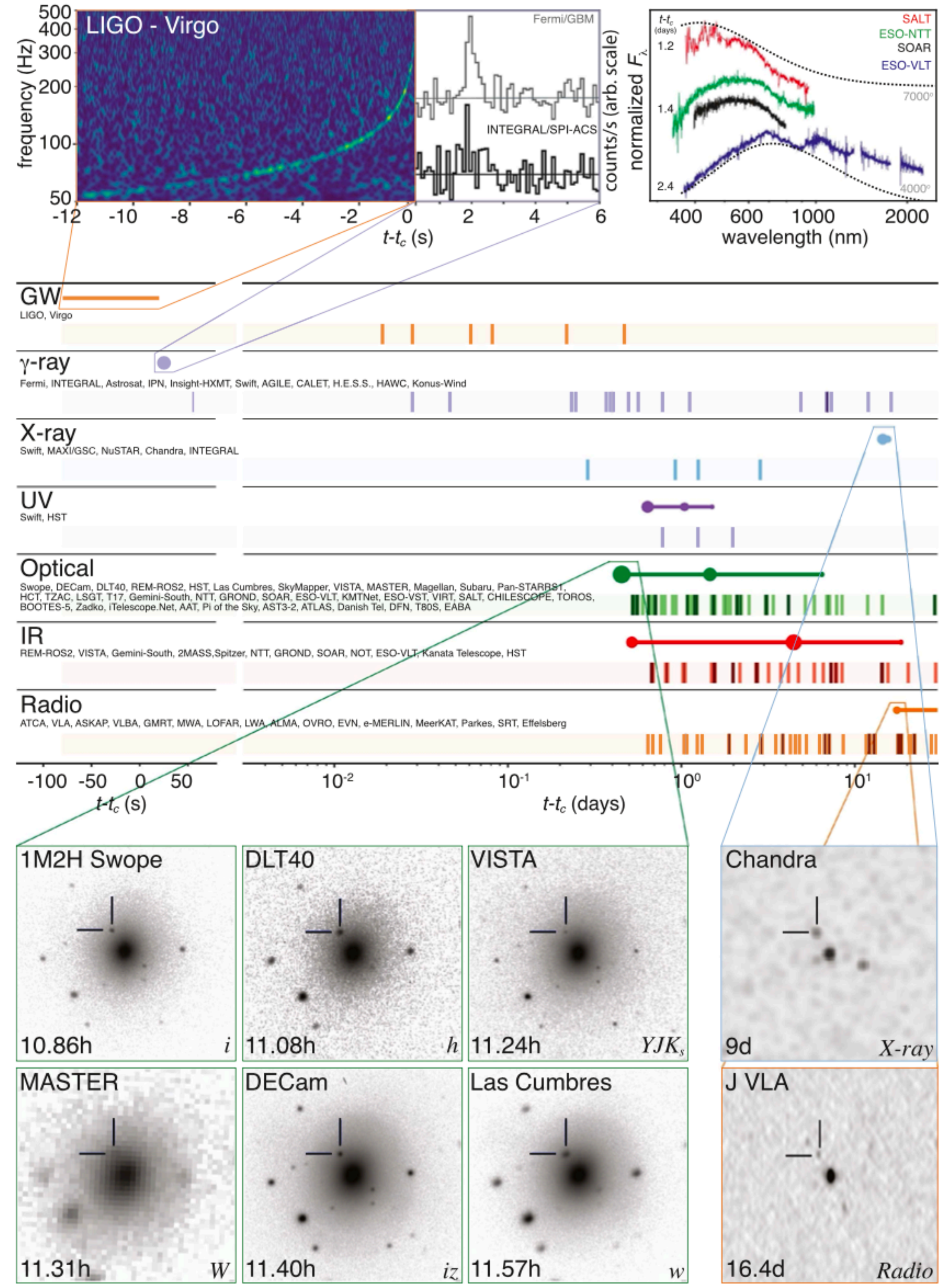

[Schutz, *Nature* (1986)]

Example: GW170817

[LVC+, *ApJL* (2017)]

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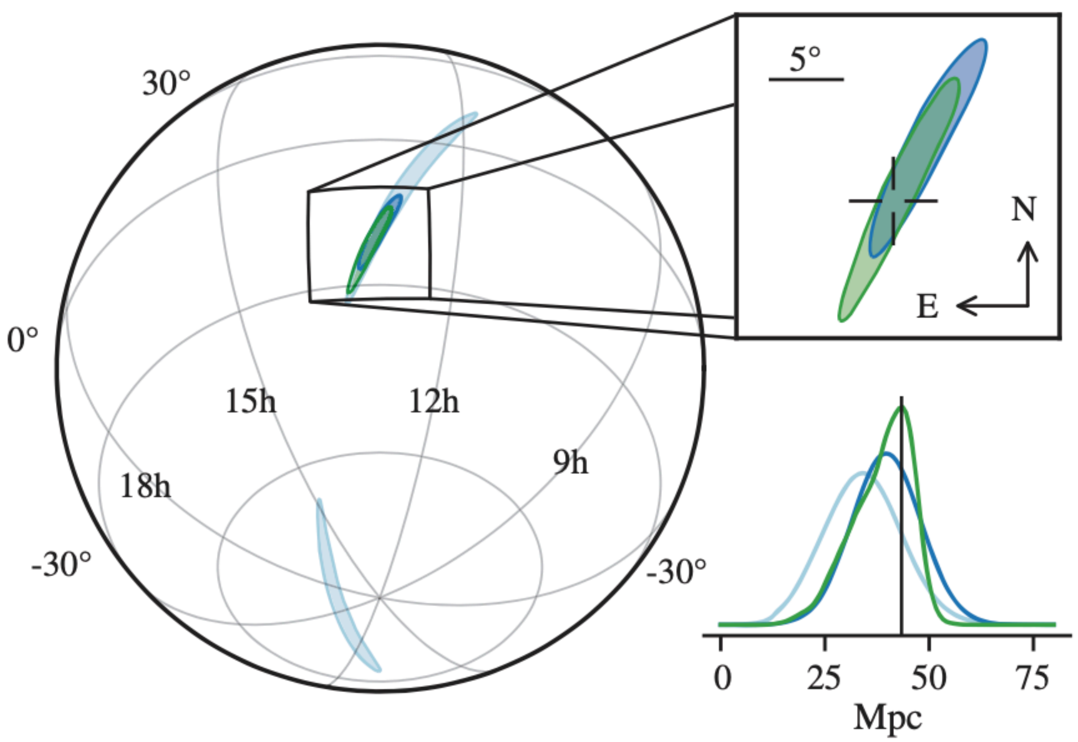

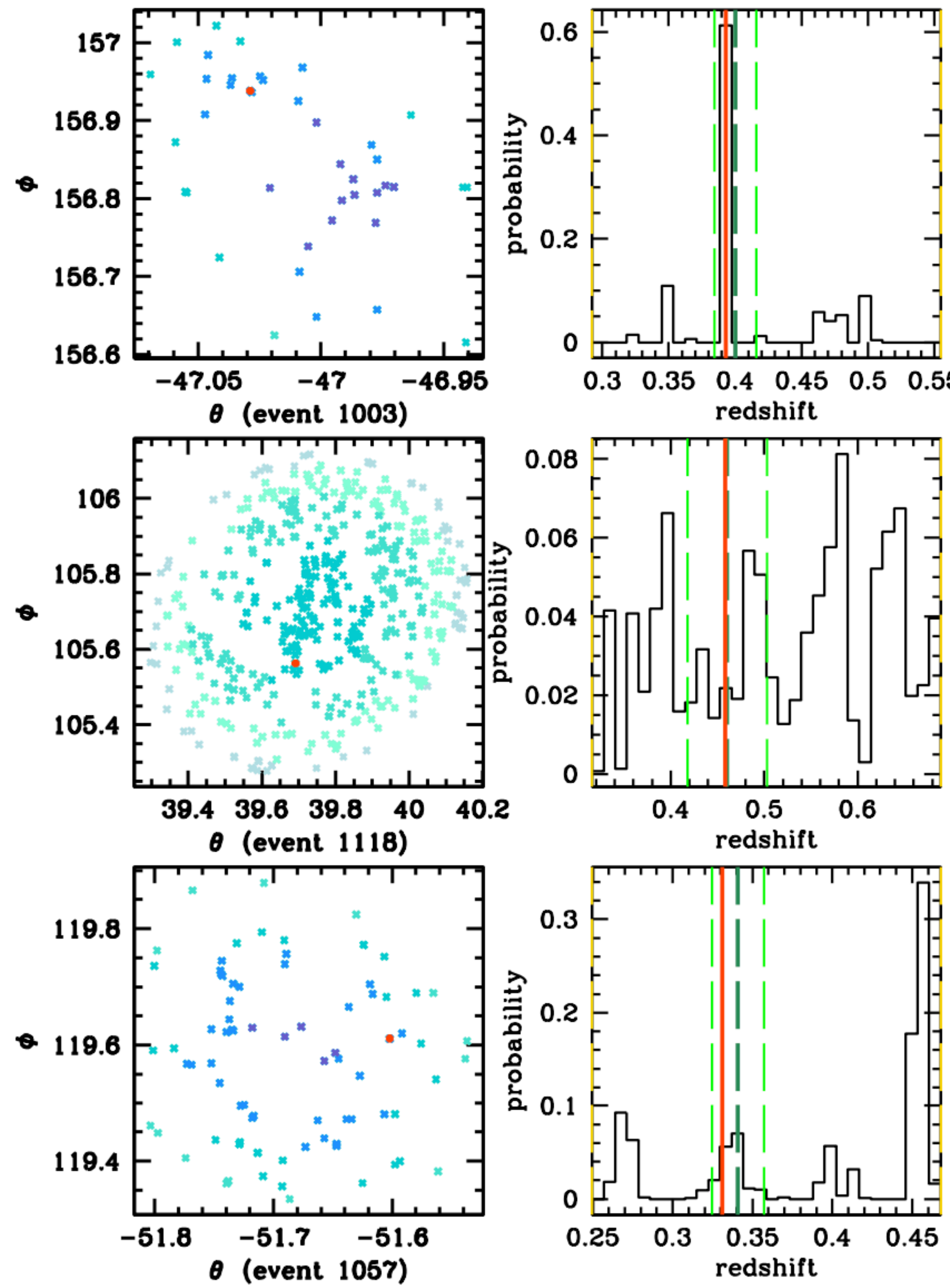

[Schutz, *Nature* (1986)] [Del Pozzo, *PRD* (2012)] [Gray+, *PRD* (2020)]

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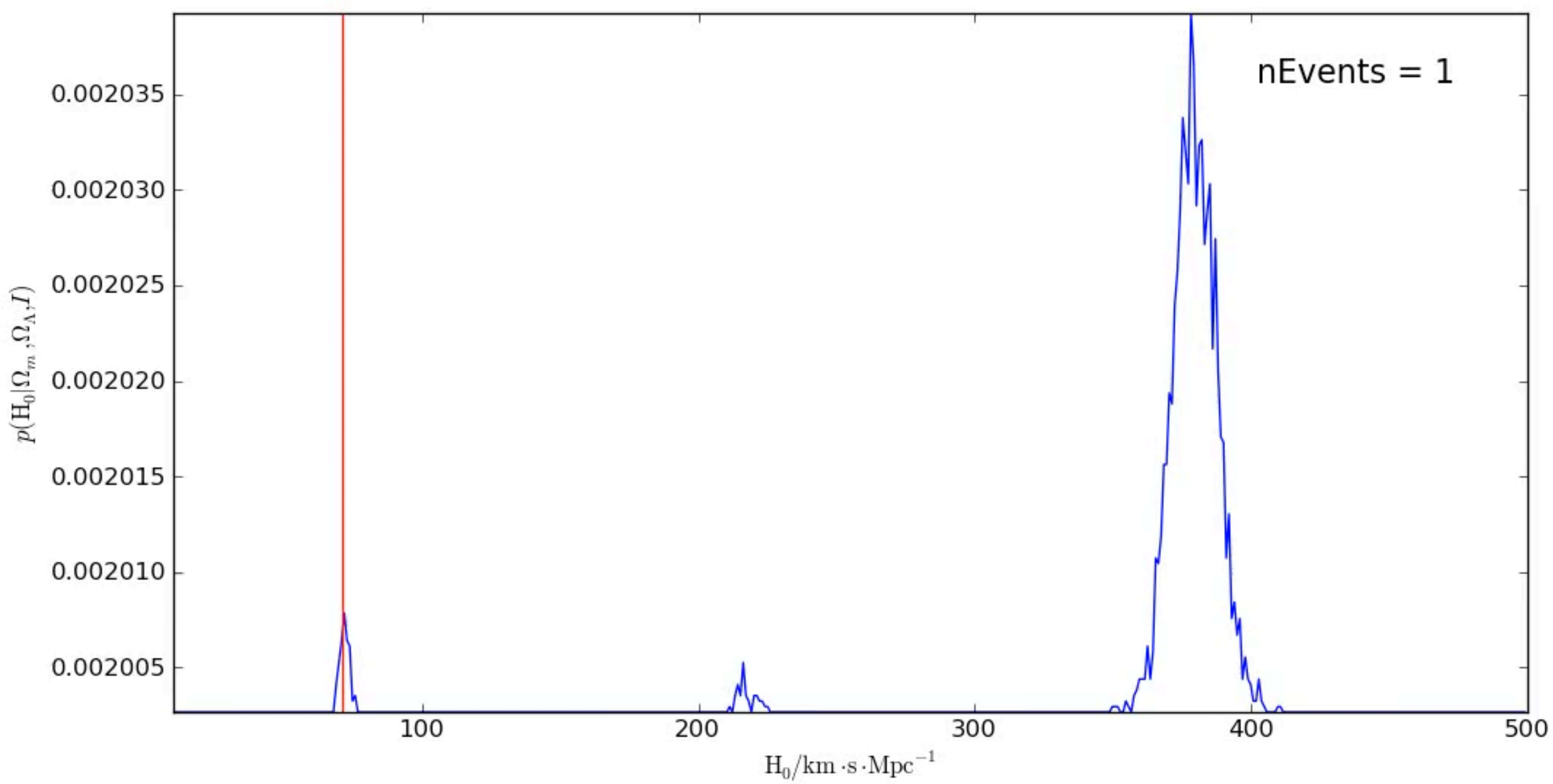
By stacking together the results from many events, the values given by the spurious galaxies cancel out and the true cosmological parameters emerge



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

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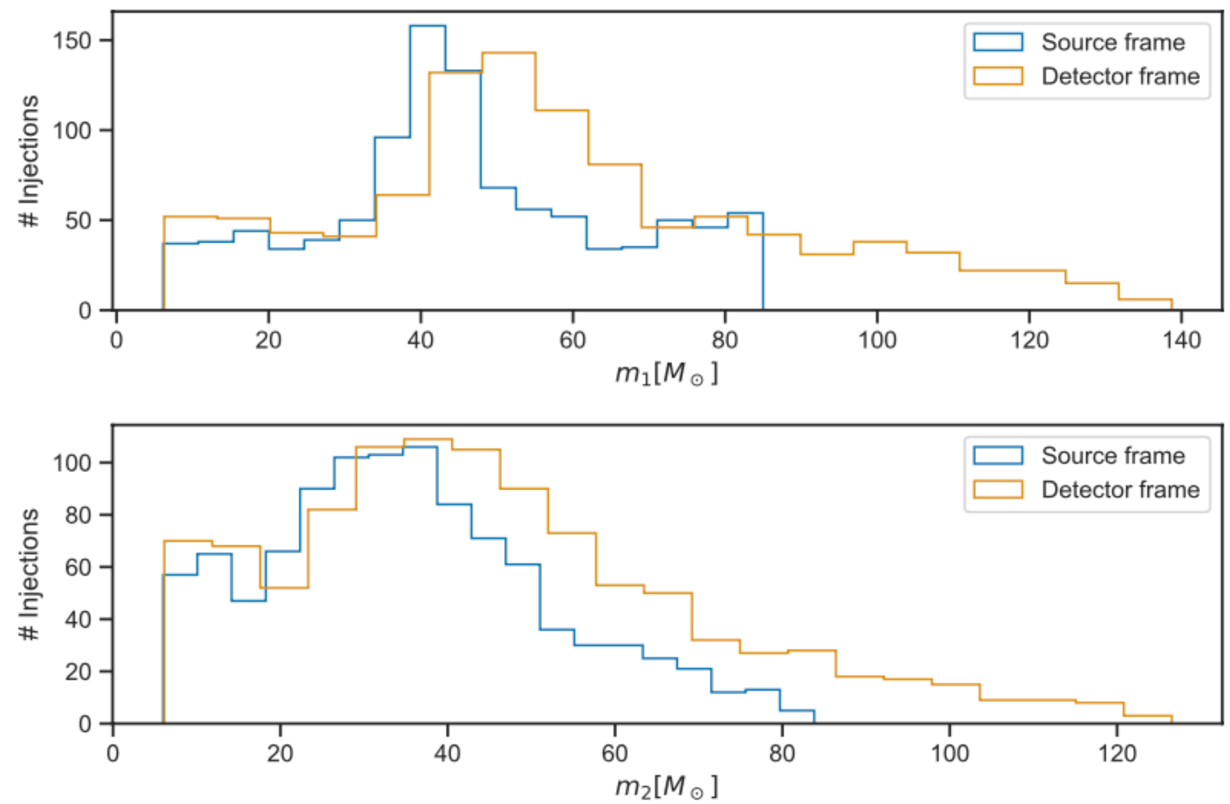
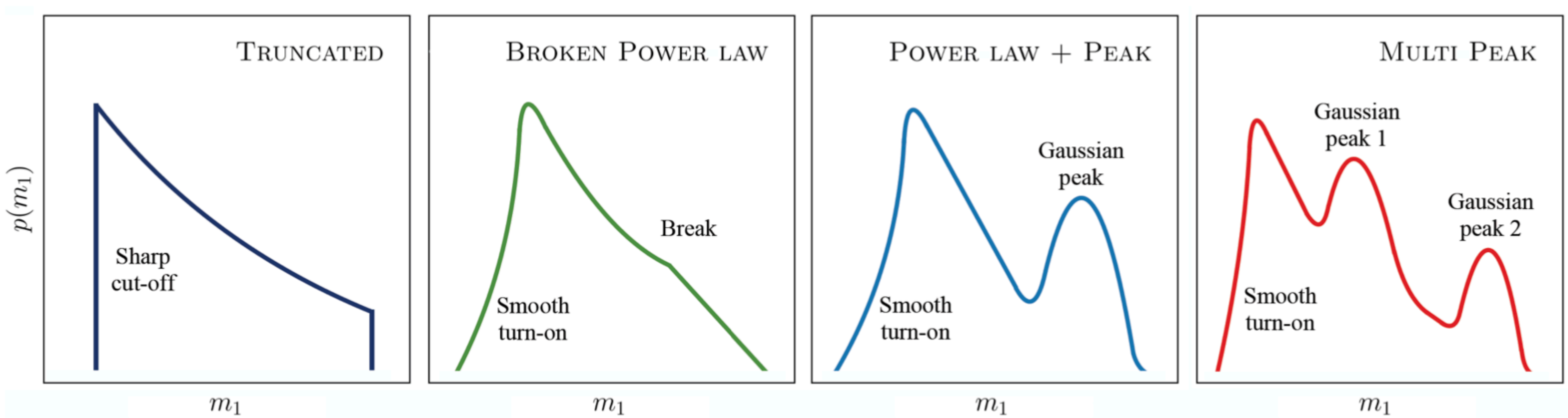
$$m_{\rm obs} = (1+z)m_{src}$$





[Taylor+, *PRD* (2012)]

[Mastrogiovanni+, *ArXiv* (2020)]

Standard sirens

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All these approaches are affected by different systematic uncertainties:

Peculiar velocities and tentative association of EM counterpart may give possible selection effects

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

Source population parameters must be inferred simultaneously, introducing dependence on astrophysical models and possible systematics

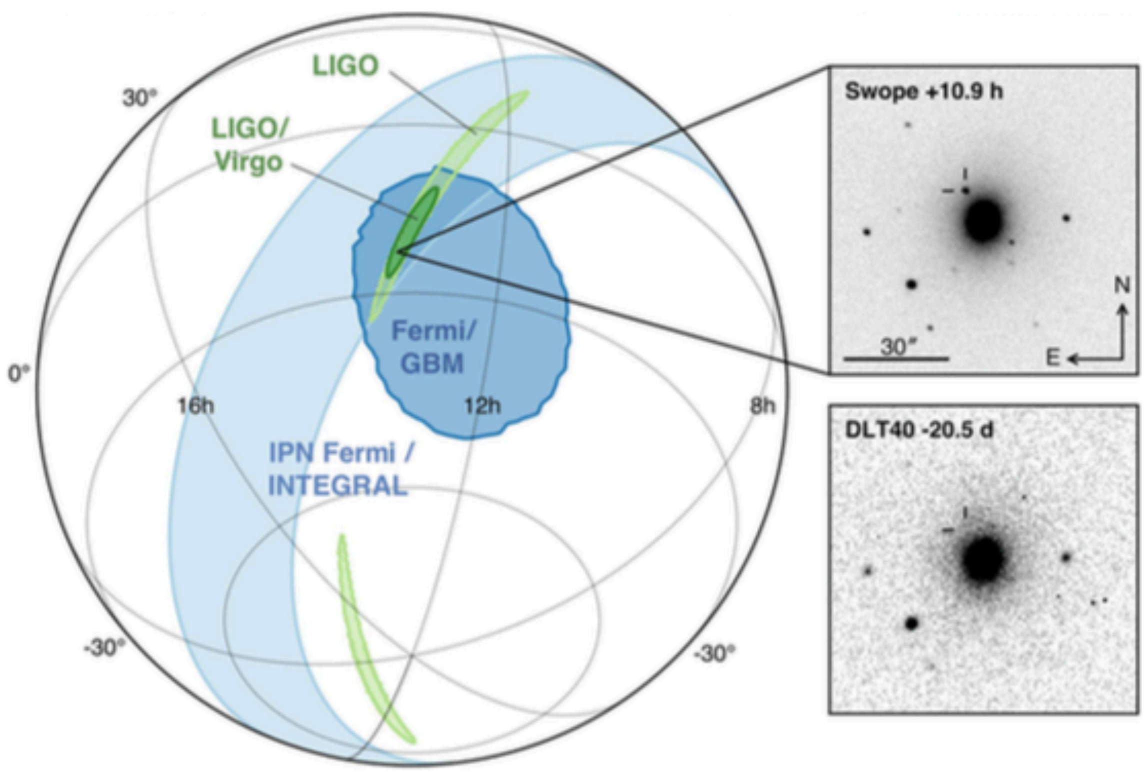
Standard sirens

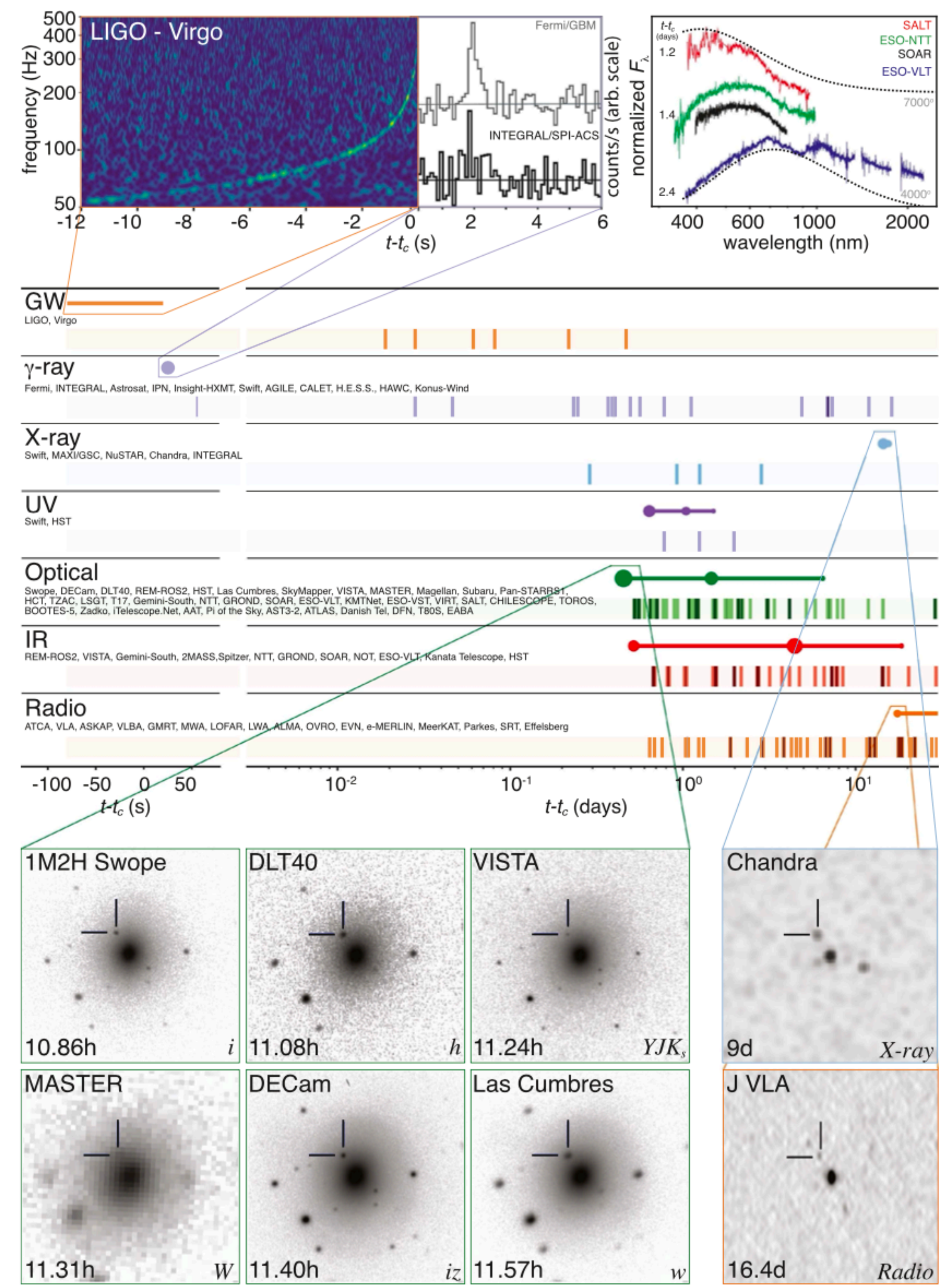
Method	Pros	Cons
EM counterpart	Accurate redshift estimation, golden sirens	Infrequent and rare events, tentative associations
Galaxy catalogs	Available even for BBHs, several EM bands to check consistency	Less and less incomplete, less constraining for poorly localized events
Clustering	No EM counterpart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

Curtesy of S. Mastrogiovanni

Standard sirens

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)]

Standard sirens

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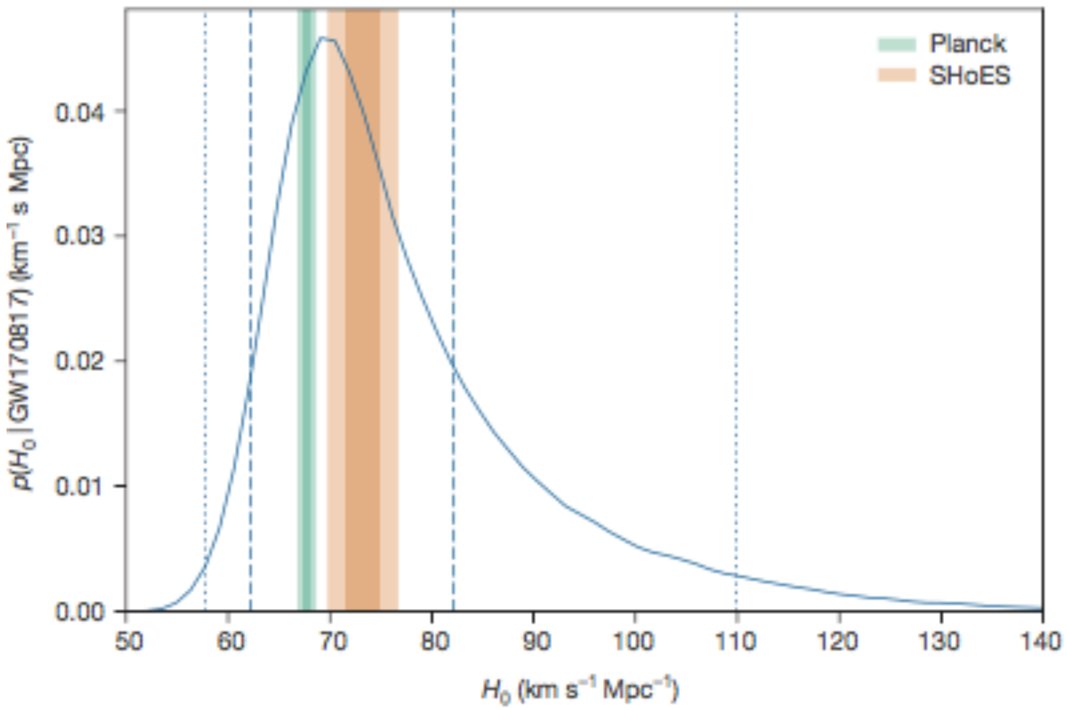
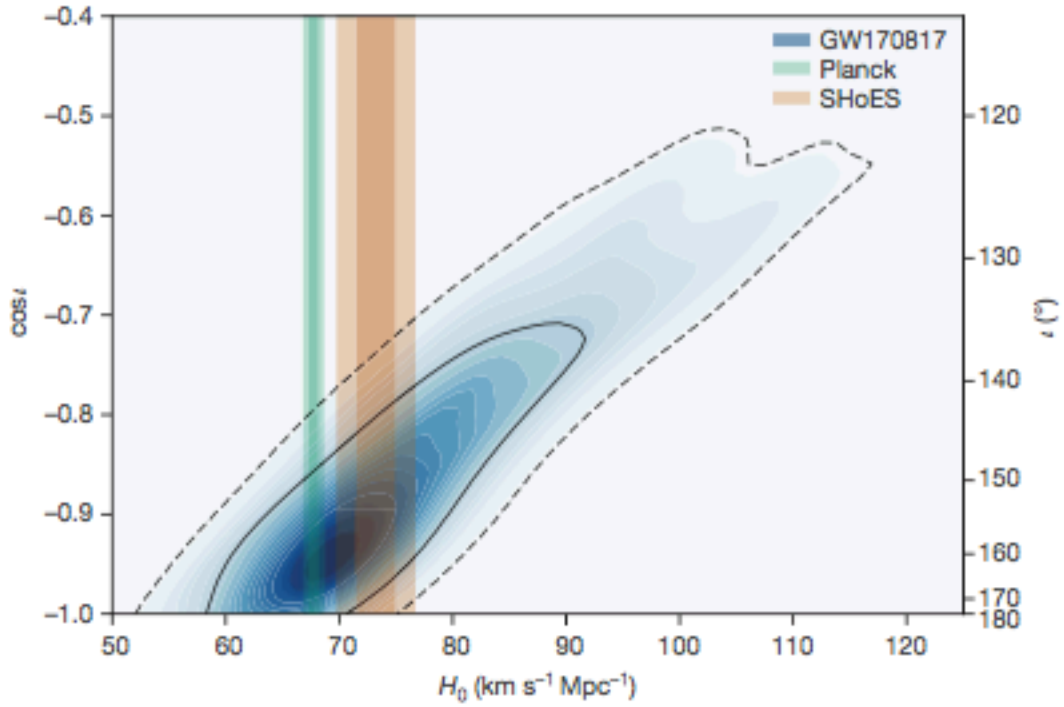




The identification of an EM counterpart yielded the first cosmological measurements with GW standard sirens

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

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

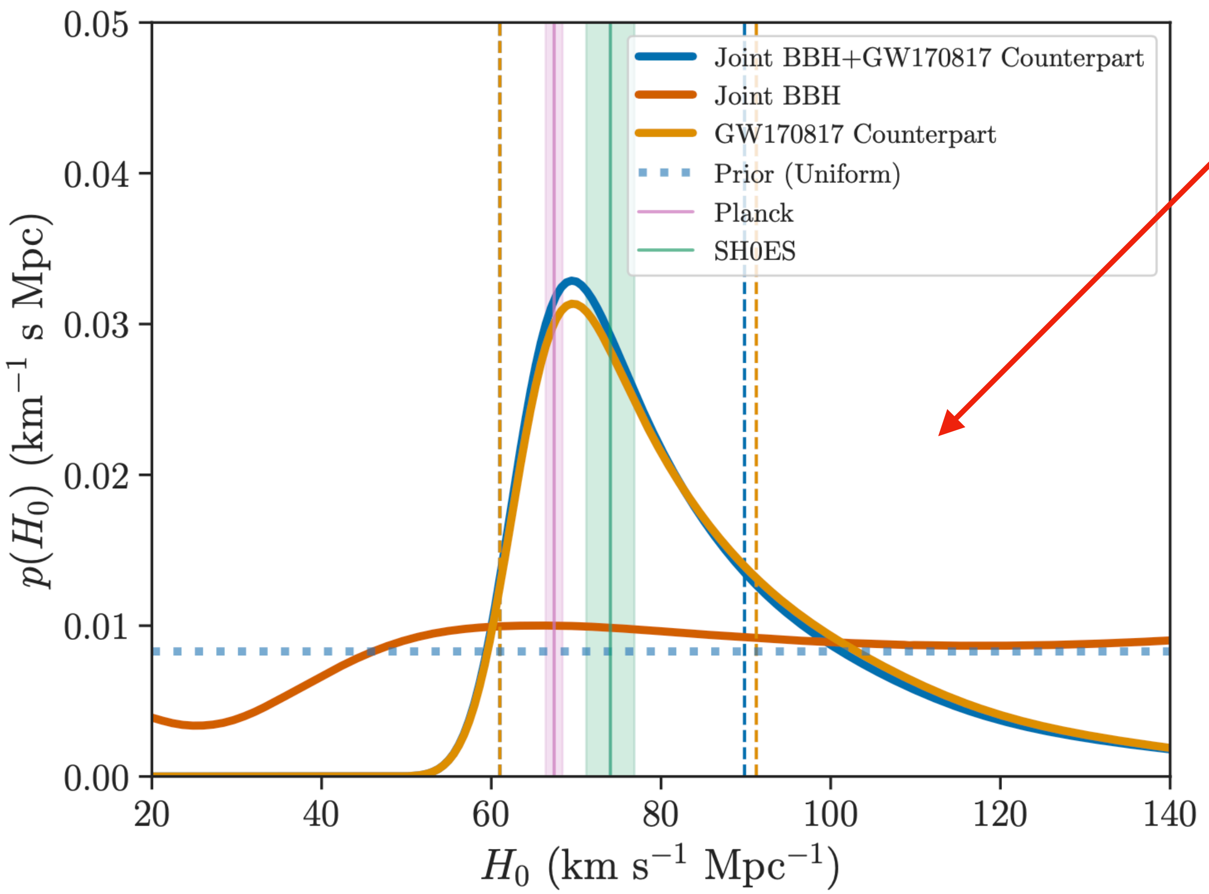
Low-redshift event ($z = 0.01$): only H_0 can be measured (**Hubble law**)

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

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

Standard sirens

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



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

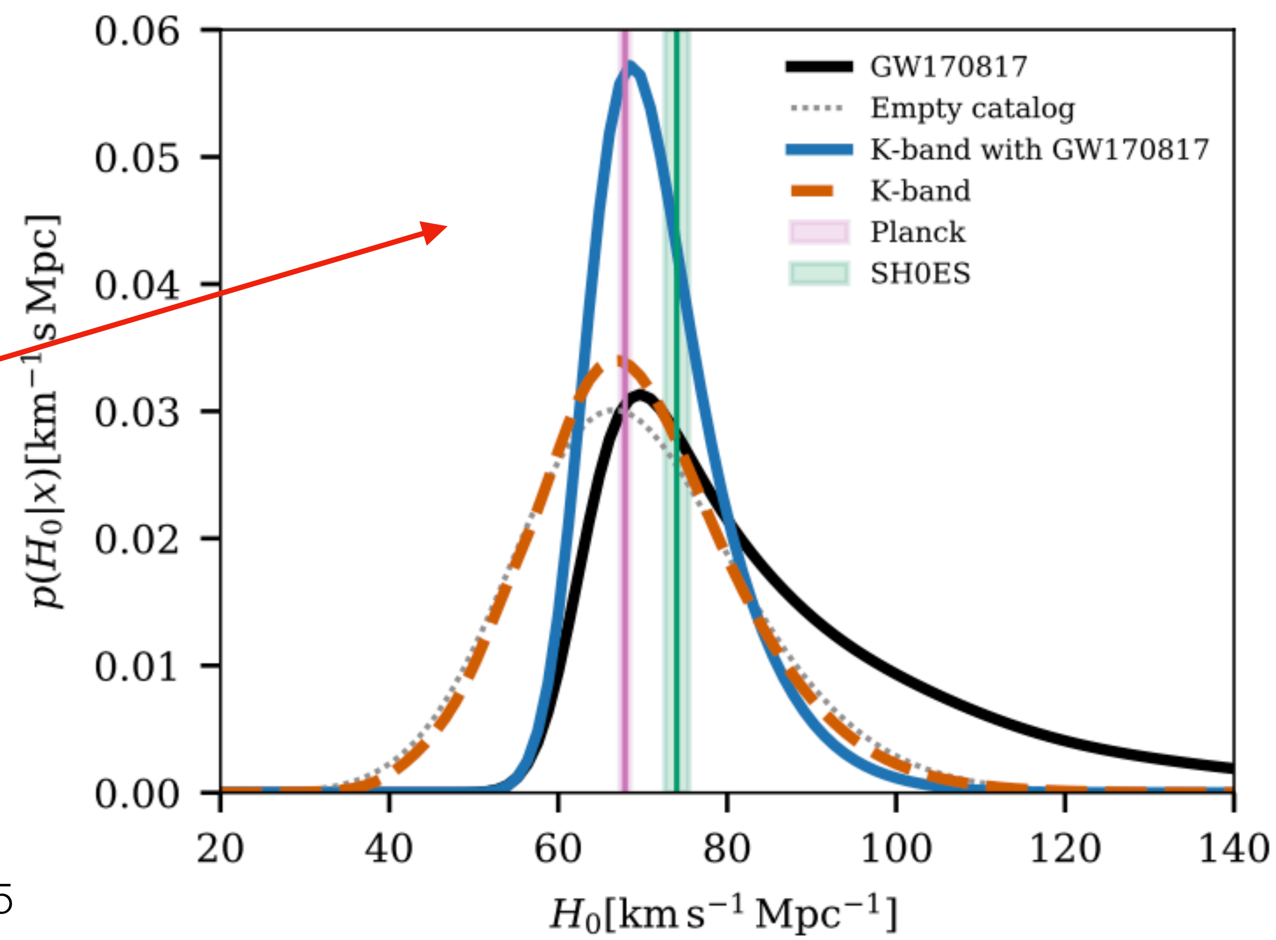
$$H_0 = 69^{+16}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

(4% improvement over GW170817 only)

LVC results with all events so far combined (O1+O2+O3): [LVK, *ApJ* (2022)]

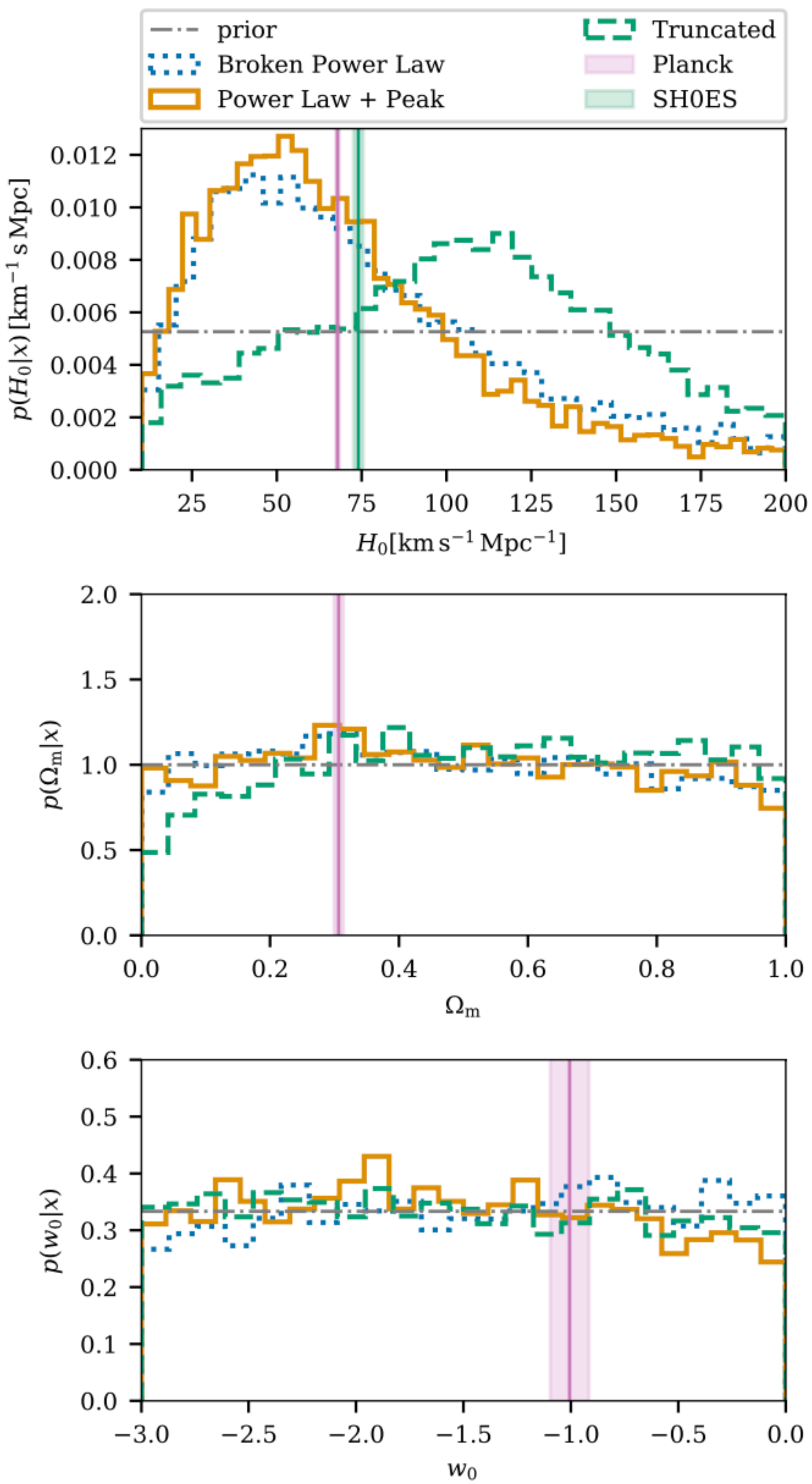
$$H_0 = 68^{+8}_{-6}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

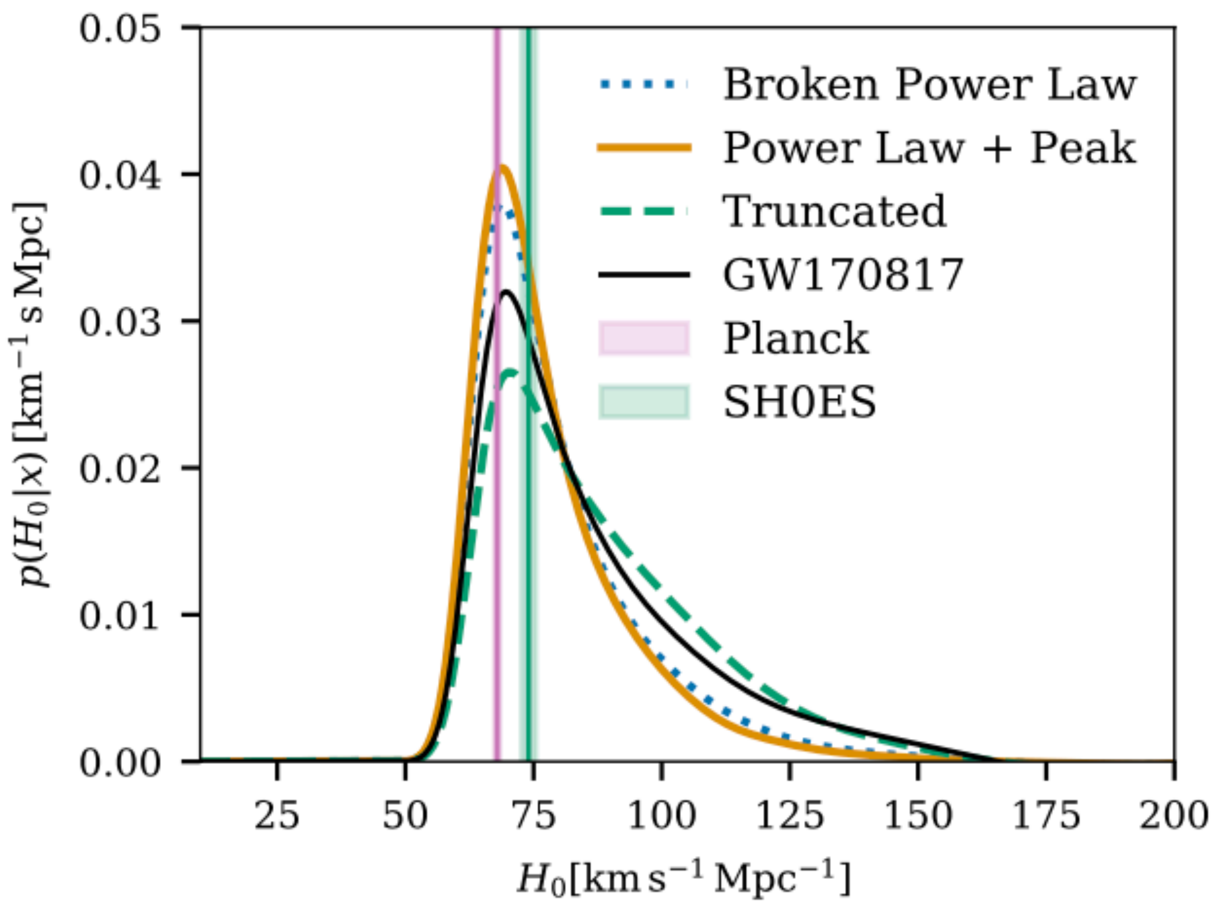
(20% improvement over O2 results)



Standard sirens

Finally the mass-distribution method 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)

Standard sirens beyond general relativity

Standard sirens beyond general relativity

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

$$h''_{ij} + 2\mathcal{H}h'_{ij} + c^2k^2h_{ij} = 0$$

Derivative w.r.t conformal time:

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

Hubble constant:

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

Wavenumber:

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

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

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

which implies

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

GW propagation speed

Standard sirens beyond general relativity

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

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

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	$c_T^2 - 1$	μ	Γ
General relativity	0	0	0	0
Extra-dimensional theory	$(D-4)(1+\frac{1+z}{\mathcal{H}d_L})$	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	$(n_{\rm mdr}-1)\mathbb{A}E^{n_{\rm mdr}-2}$	when $n_{\rm mdr}=0$	0
Bimetric massive gravity theory	0	0	m^2f_1	m^2f_1

[Nishizawa, *PRD* (2018)]

Standard sirens beyond general relativity

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

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

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

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

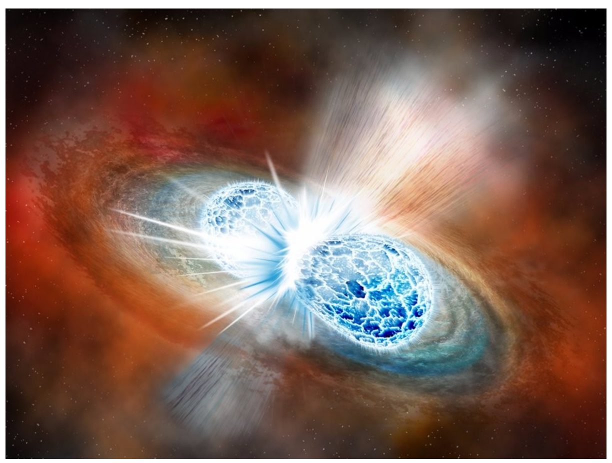
Delay of GW propagation w.r.t. the speed of light

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)]

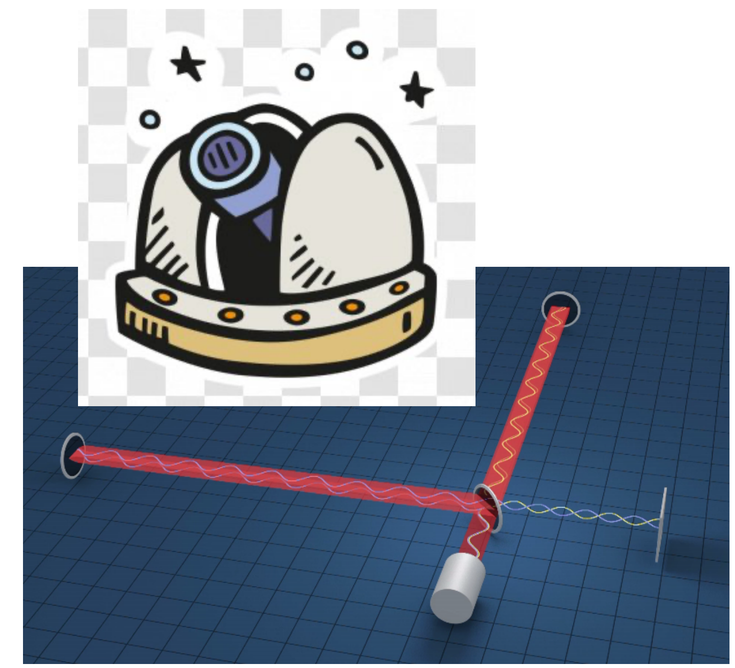
Standard sirens beyond general relativity

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 general relativity

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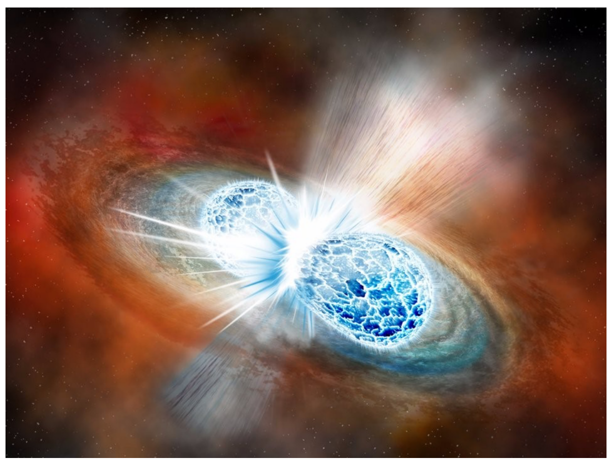

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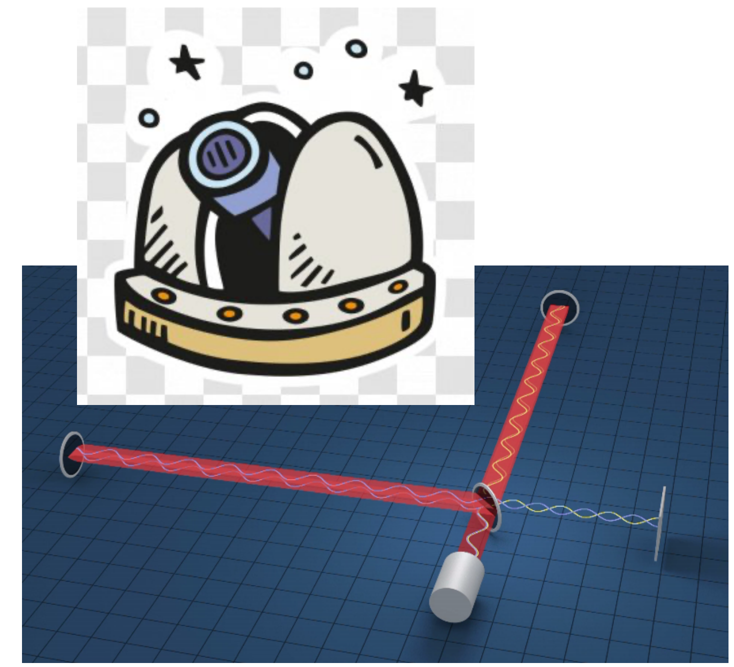
EM radiation (photons)

Gravitational waves

d_L^{EM}

d_L^{GW}



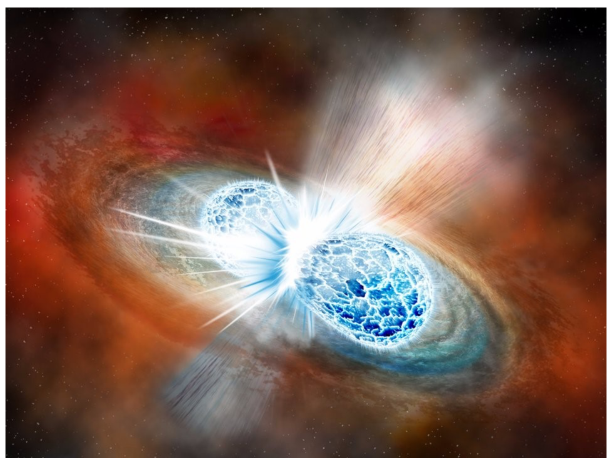
GW and EM detectors

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 general relativity

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



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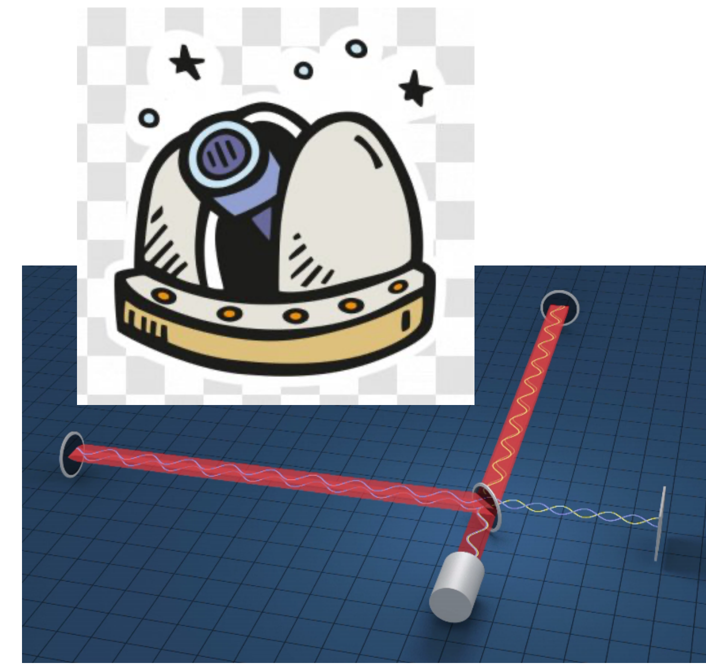


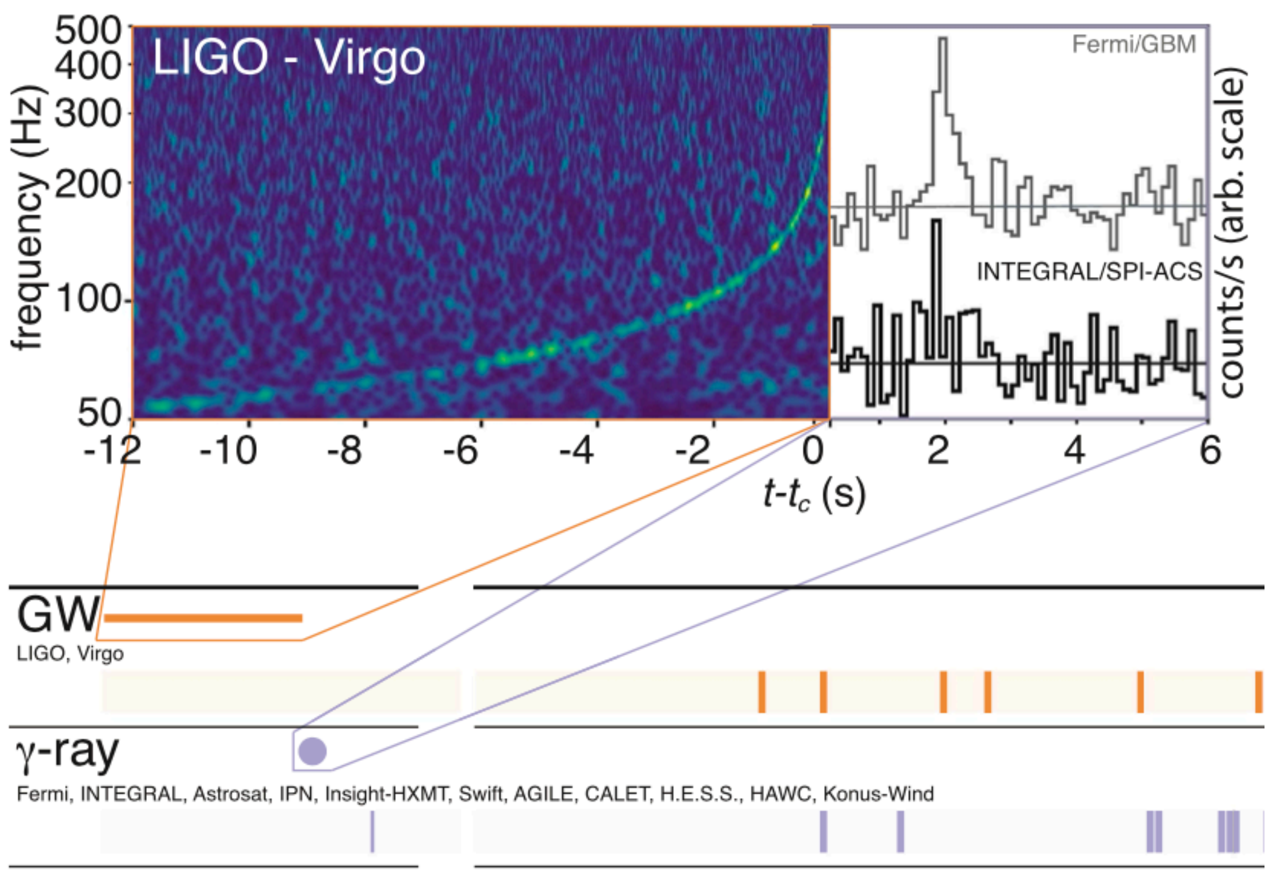
GW and EM detectors

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 general relativity

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)]

Standard sirens with LISA

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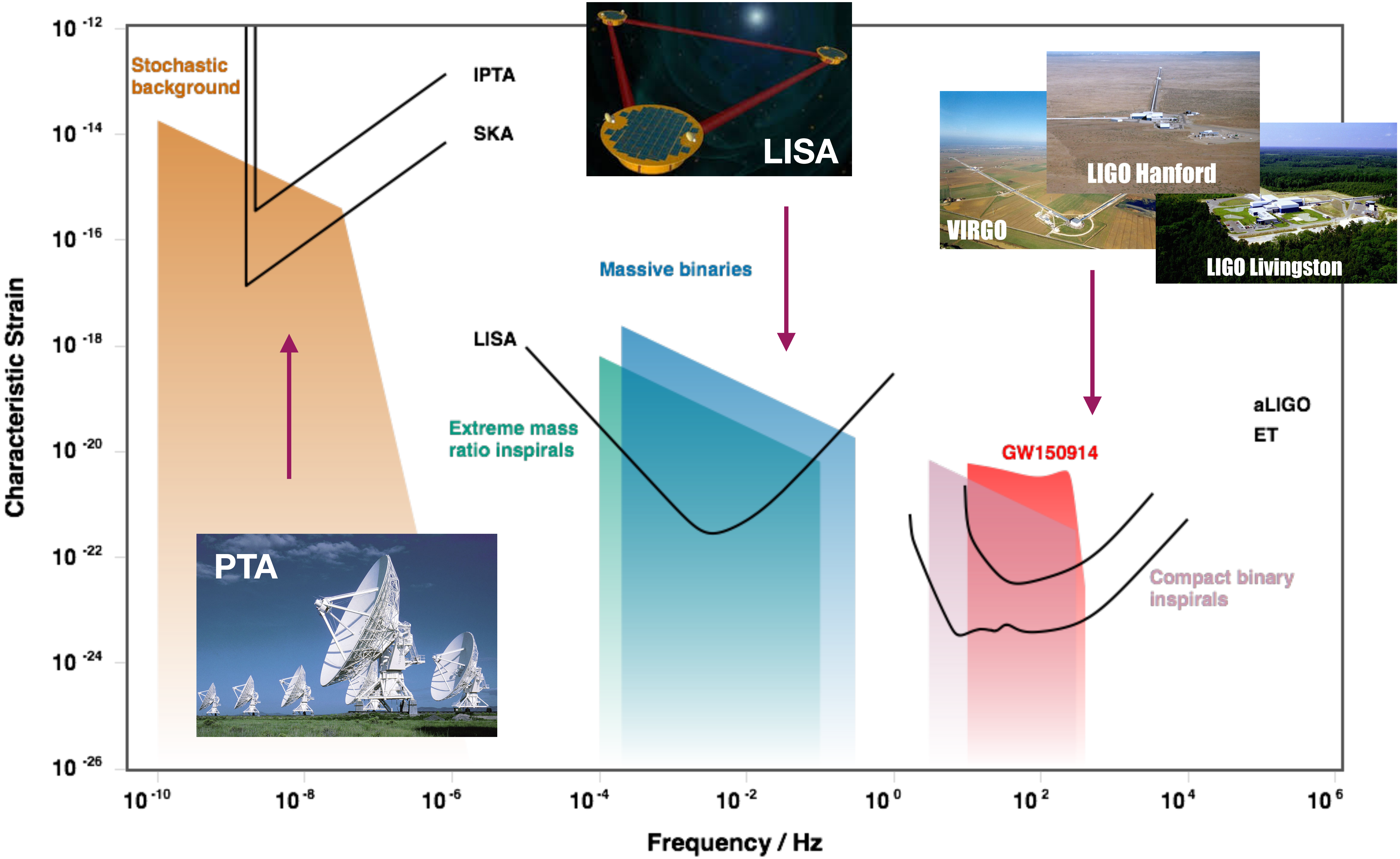

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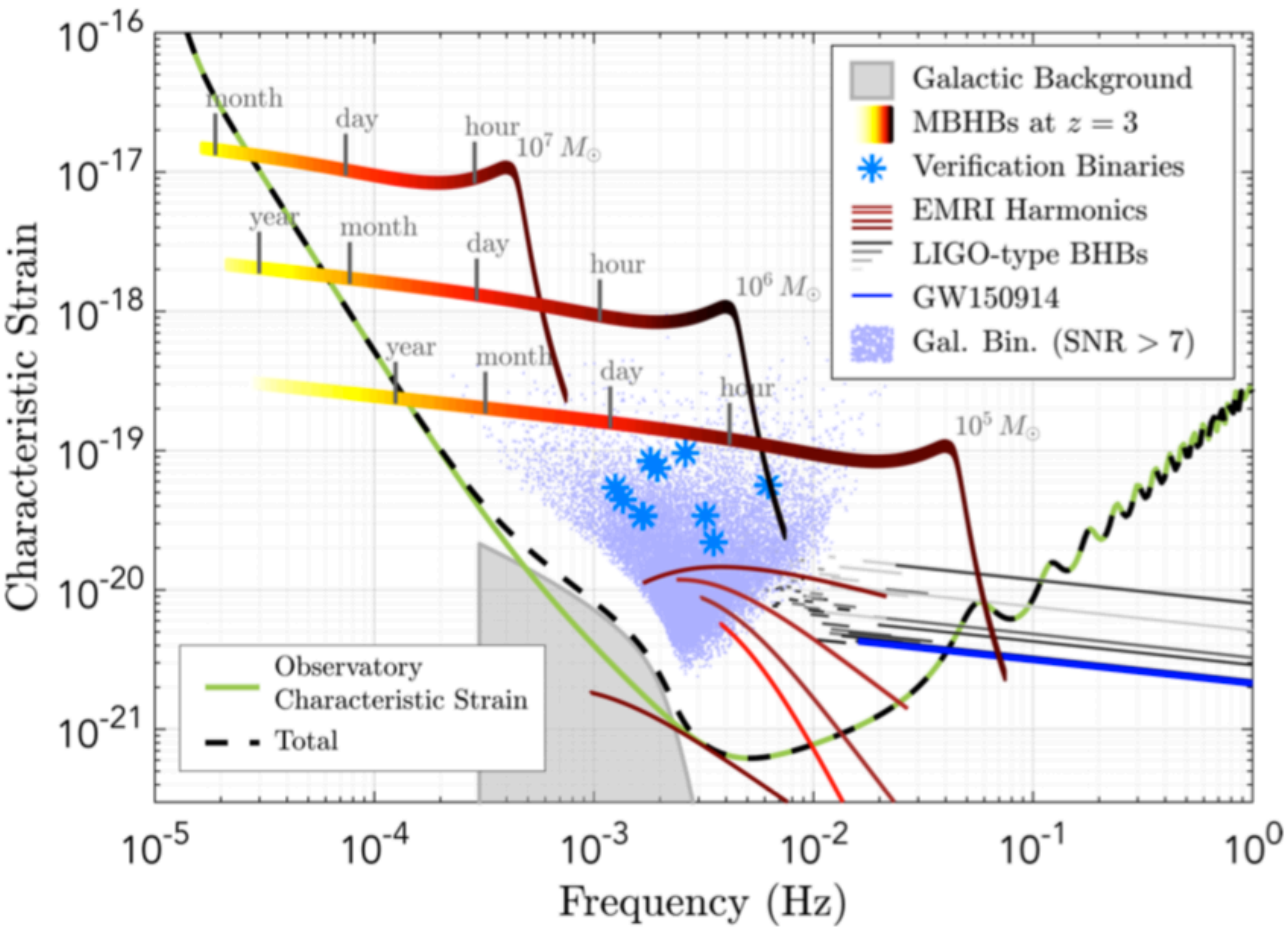


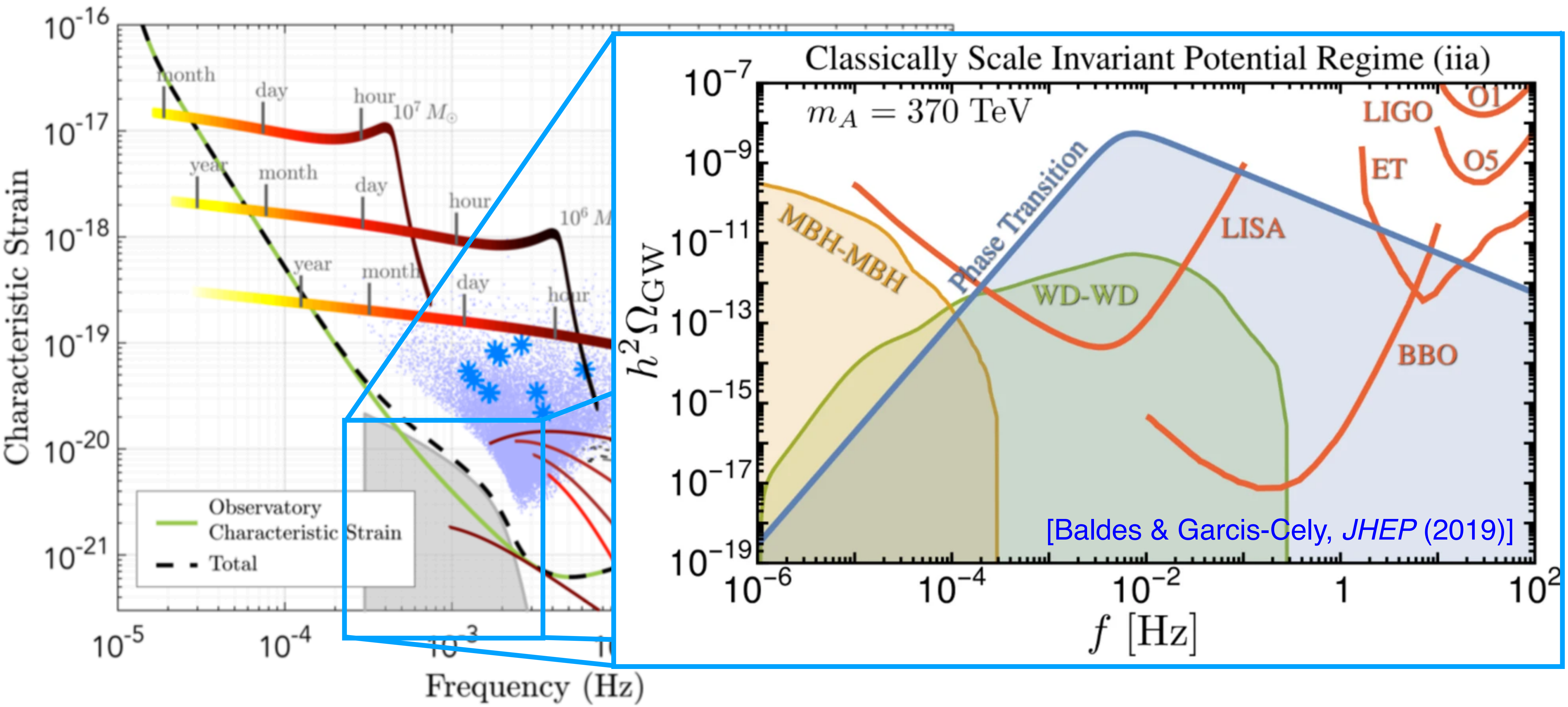
LISA GW target sources:

- **Massive BBHs**
- **Extreme mass ratio inspirals**
- **Stellar-mass (and intermediate-mass) BBHs**
- **Galactic binaries/multiples**
- **Stochastic GW backgrounds**

[LISA (2017), arXiv:1702.00786]

Standard sirens with LISA

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

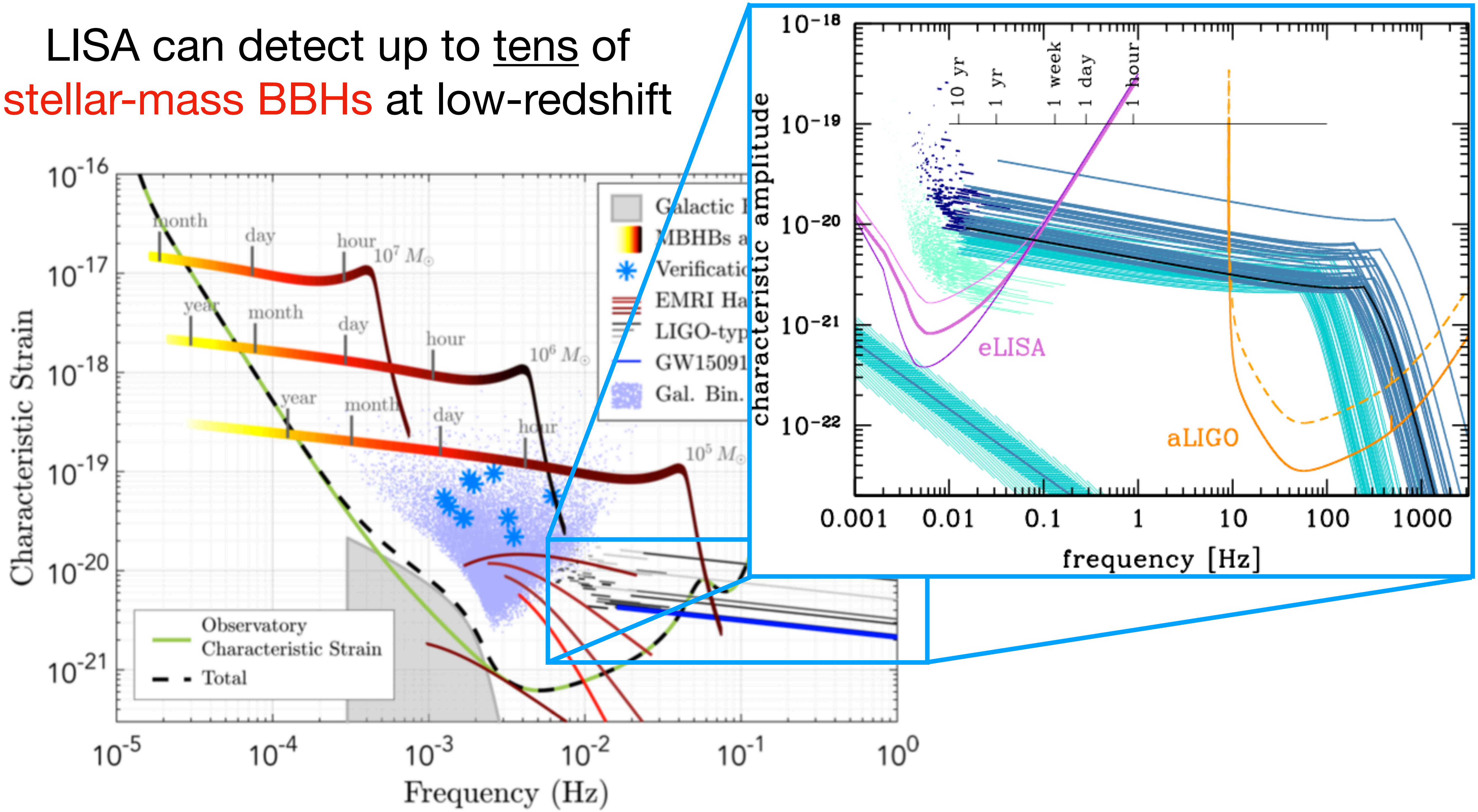


[LISA (2017), arXiv:1702.00786]

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

Standard sirens with LISA

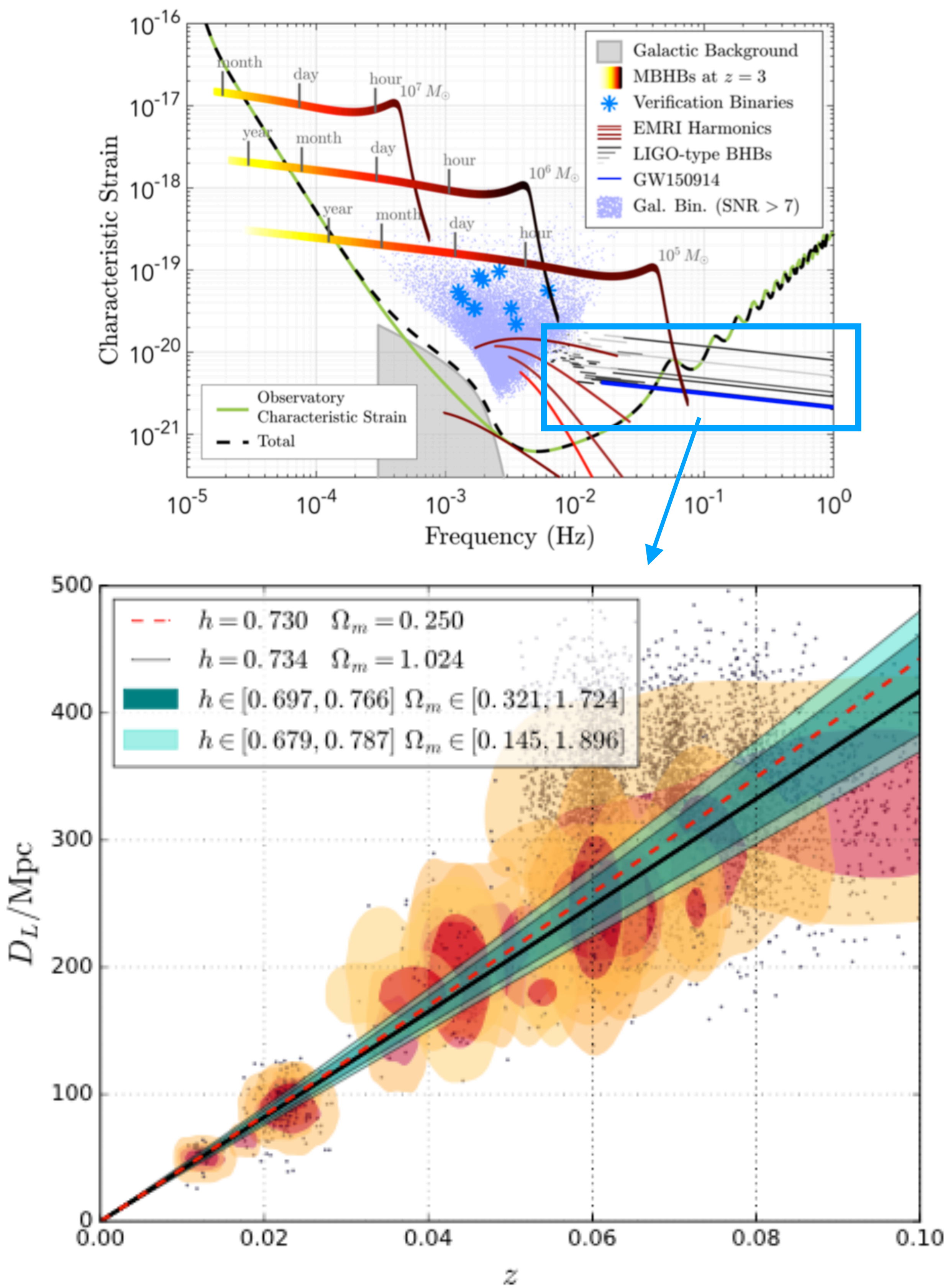
LISA can detect up to tens of stellar-mass BBHs at low-redshift



[LISA (2017), arXiv:1702.00786]

[Sesana, *PRL* (2016)]

Standard sirens with LISA

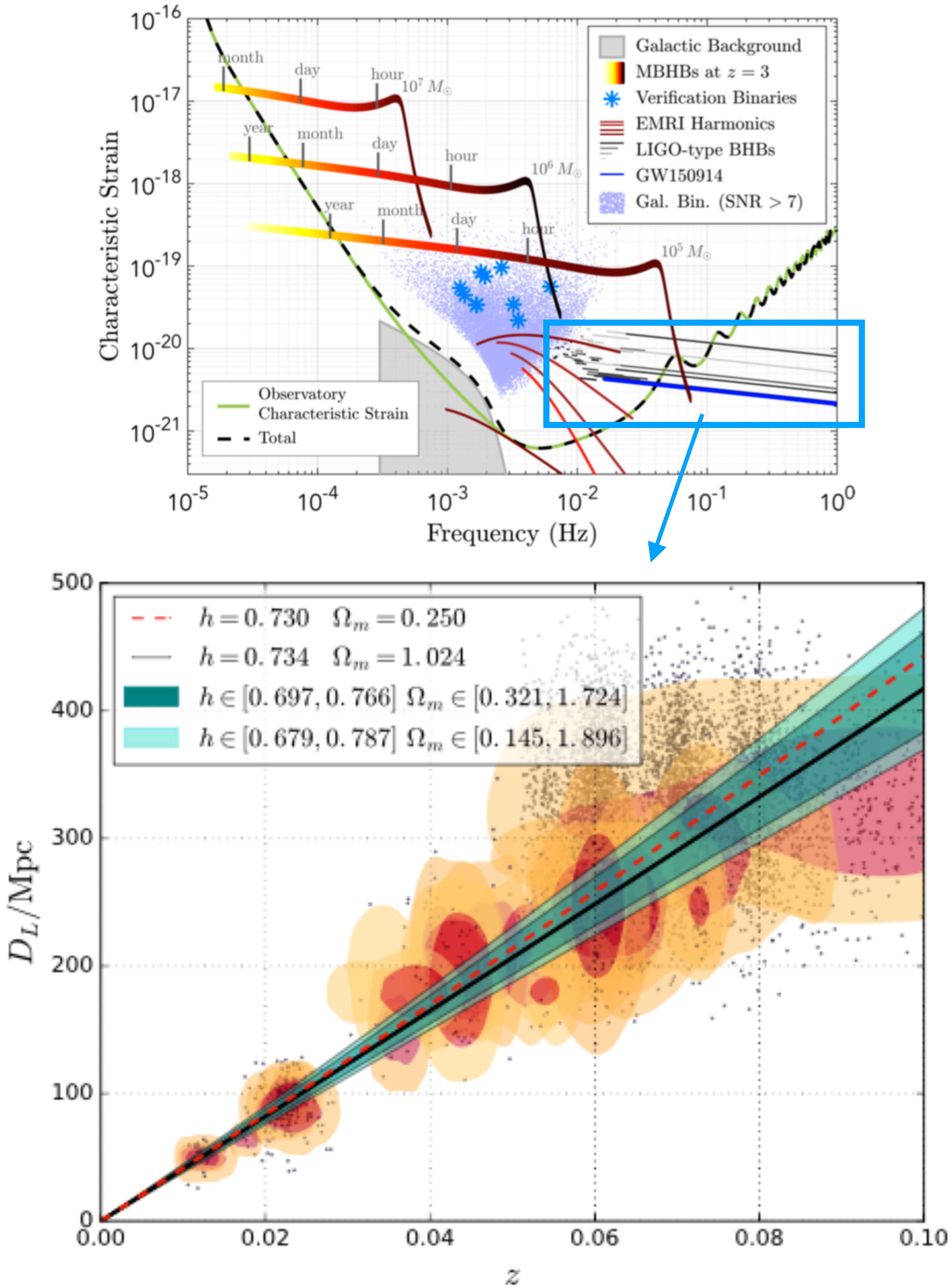


Stellar-mass BBHs

- 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 $\Delta\Omega \sim 1\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 5 standard sirens / yr
- **Expected results:**
  - H_0 to few % (very optimistic - depend on LISA high-f sensitivity)

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

Standard sirens with LISA



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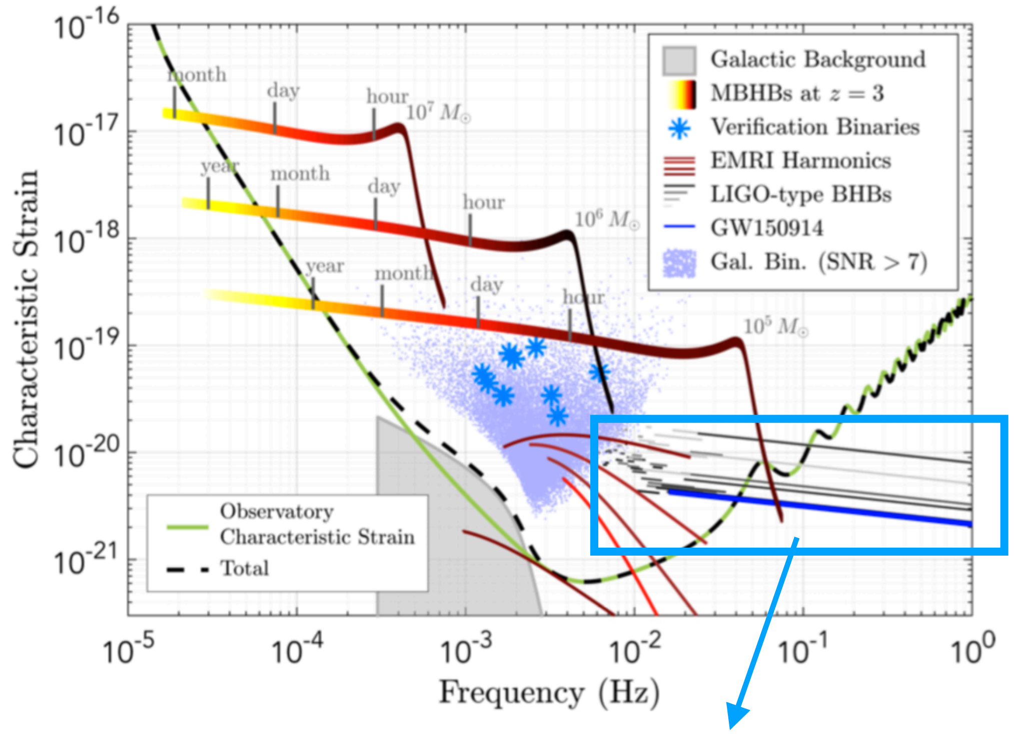
- Redshift range: $z \lesssim 0.1$
- No EM counterparts expected
- LISA detections: ~~~50/yr (optimistic)~~
  ~few/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L < 0.2$
  - If $\Delta\Omega \sim 1\ \mathrm{deg}^2$
  - $\Rightarrow$ ~~~ 5 standard sirens / yr~~
    ~0.1 standard sirens / yr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

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

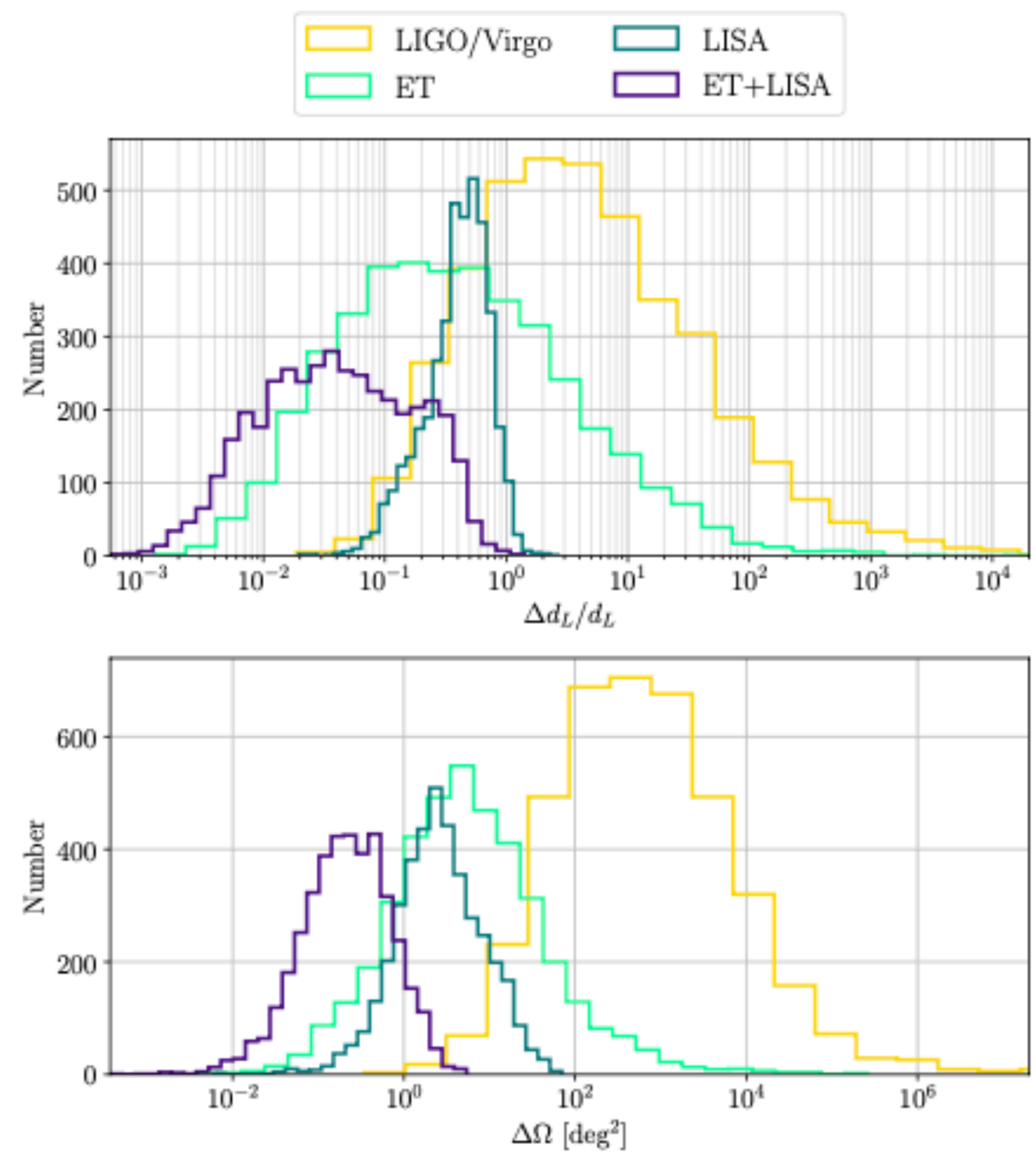
Standard sirens with LISA



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

- **<u>Expected results:</u>**
  - H_0 to few %
    (with BHs "above the gap" whose rate is yet unknown)

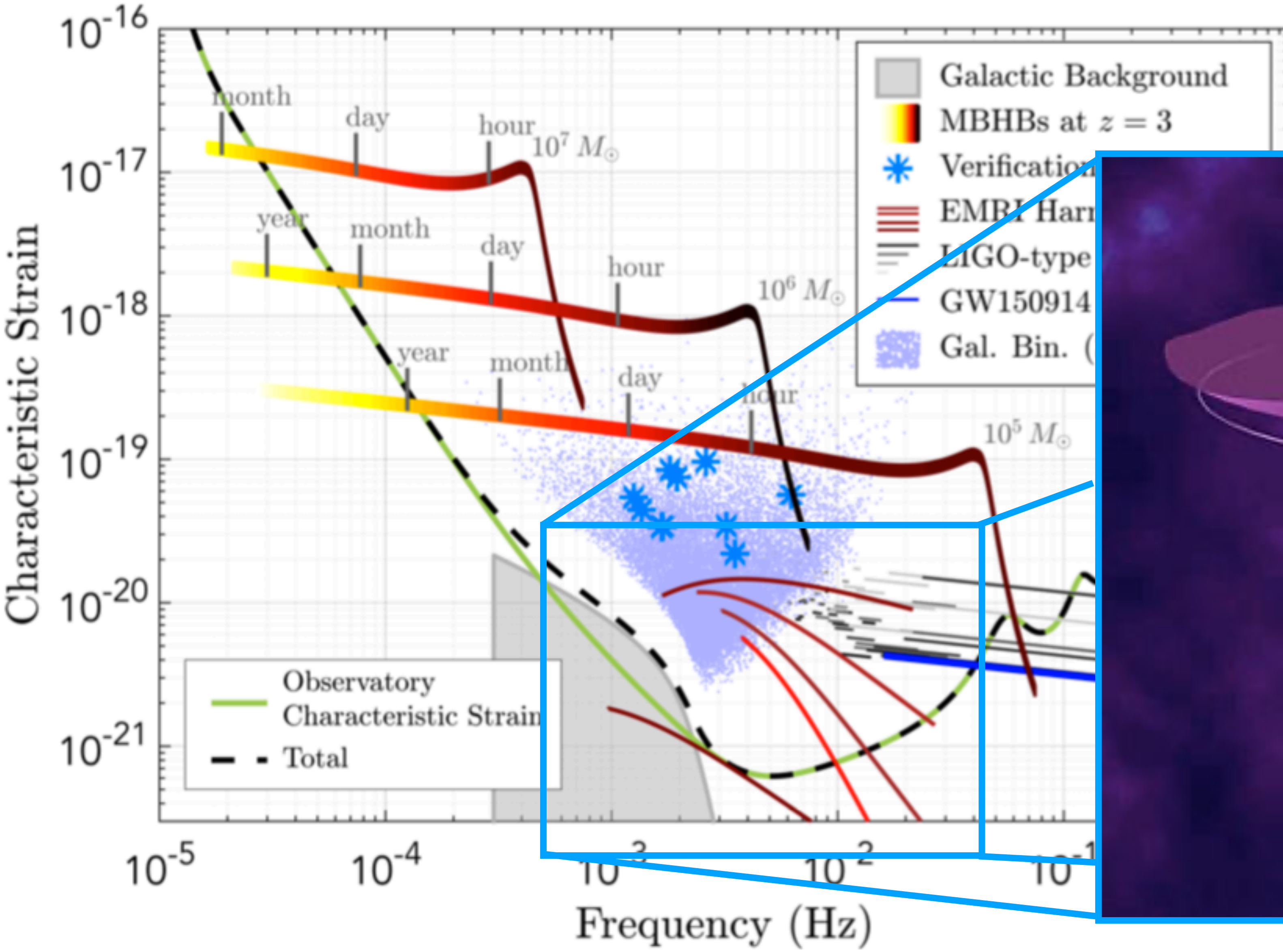
Multi-band stellar-mass BBHs

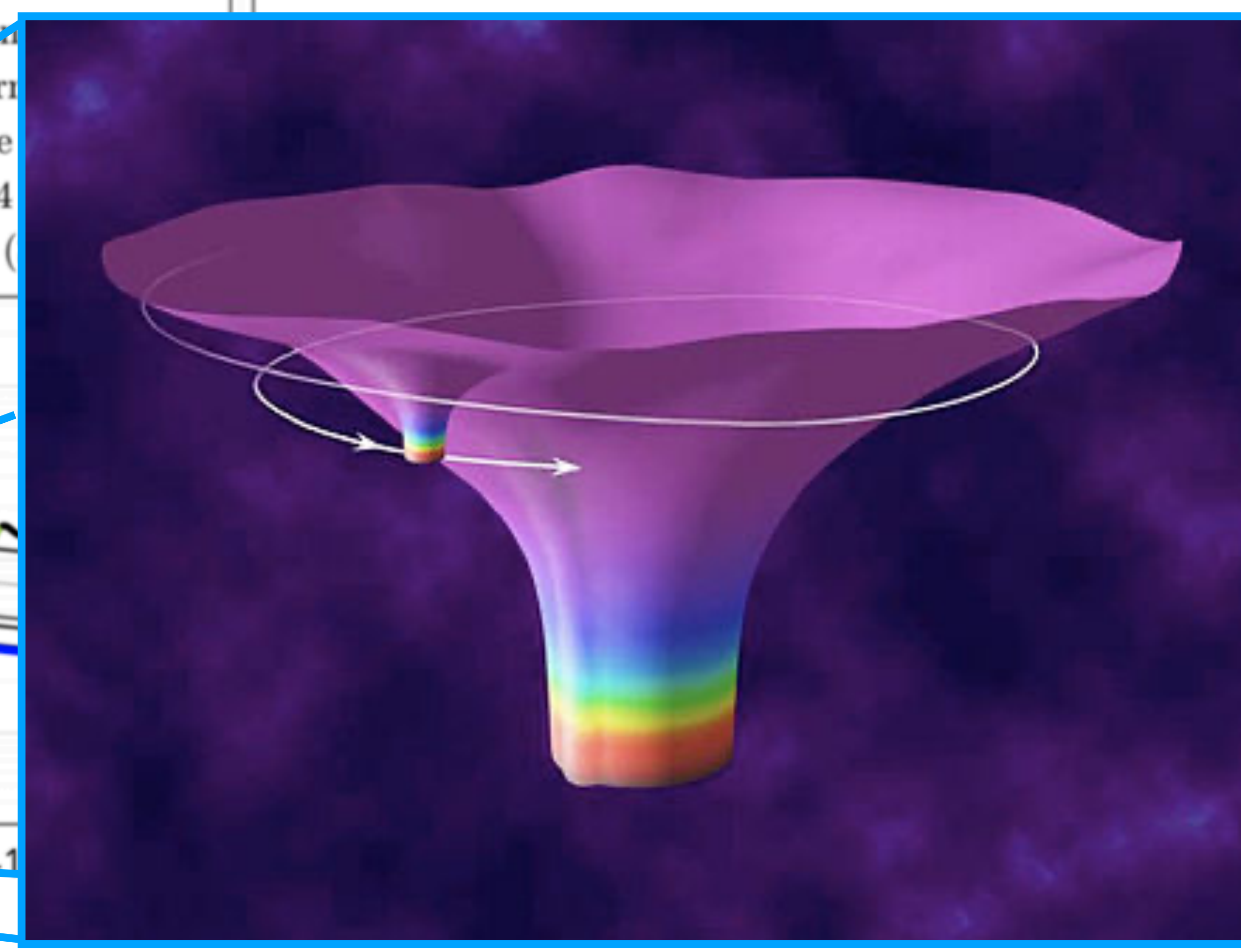


[Muttoni+, *PRD* (2022)]

Standard sirens with LISA

LISA can detect up to thousands of extreme mass ratio inspiral (EMRI) events up to $z \sim 4$

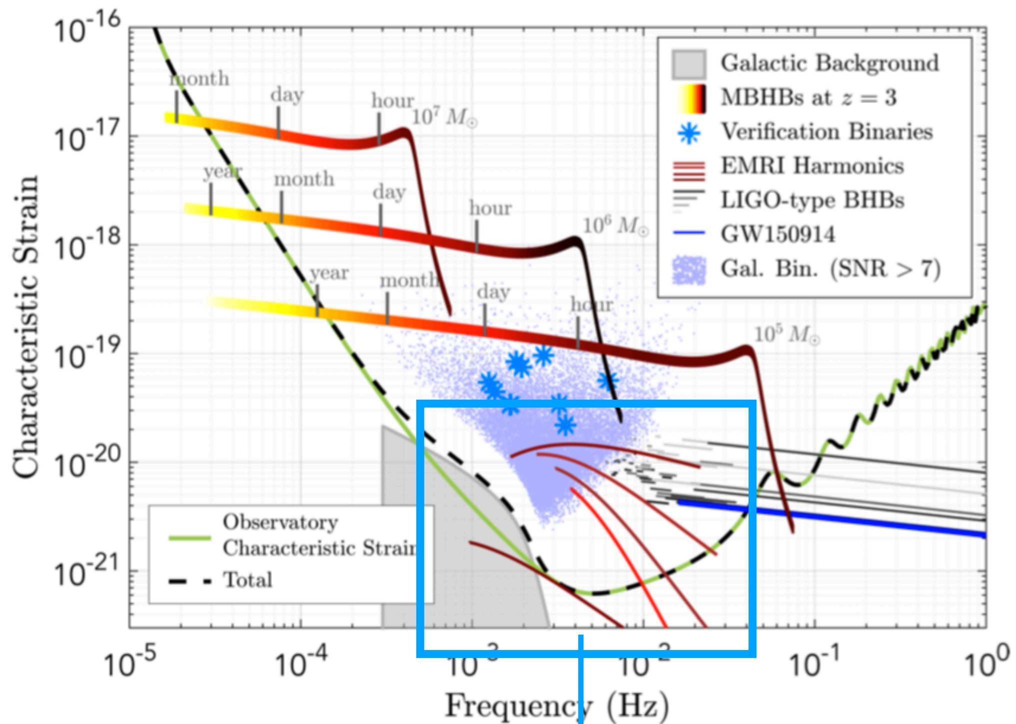


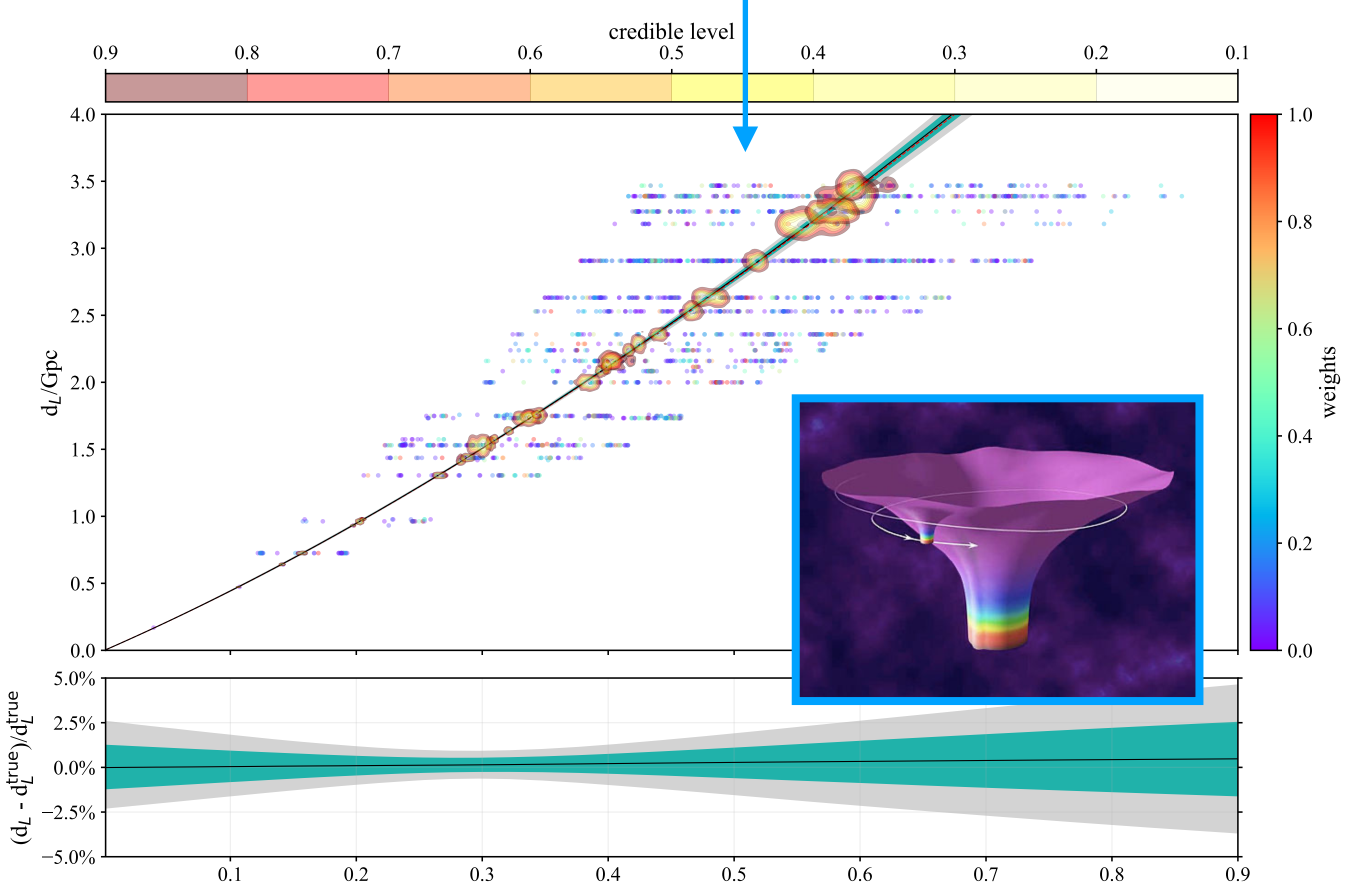


[LISA (2017), arXiv:1702.00786]

[Babak+, PRD (2017), arXiv:1703.09722]

Standard sirens with LISA





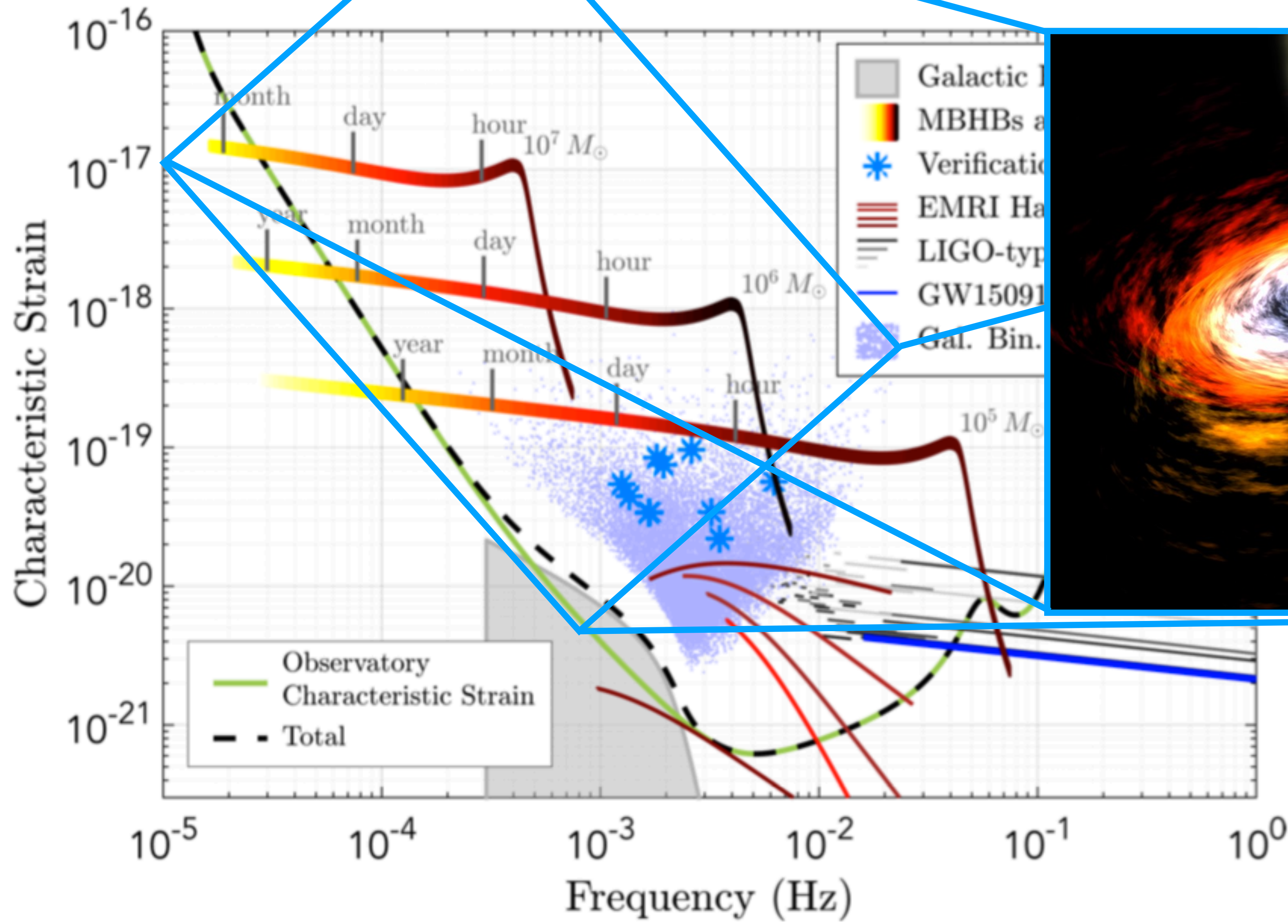
EMRIs

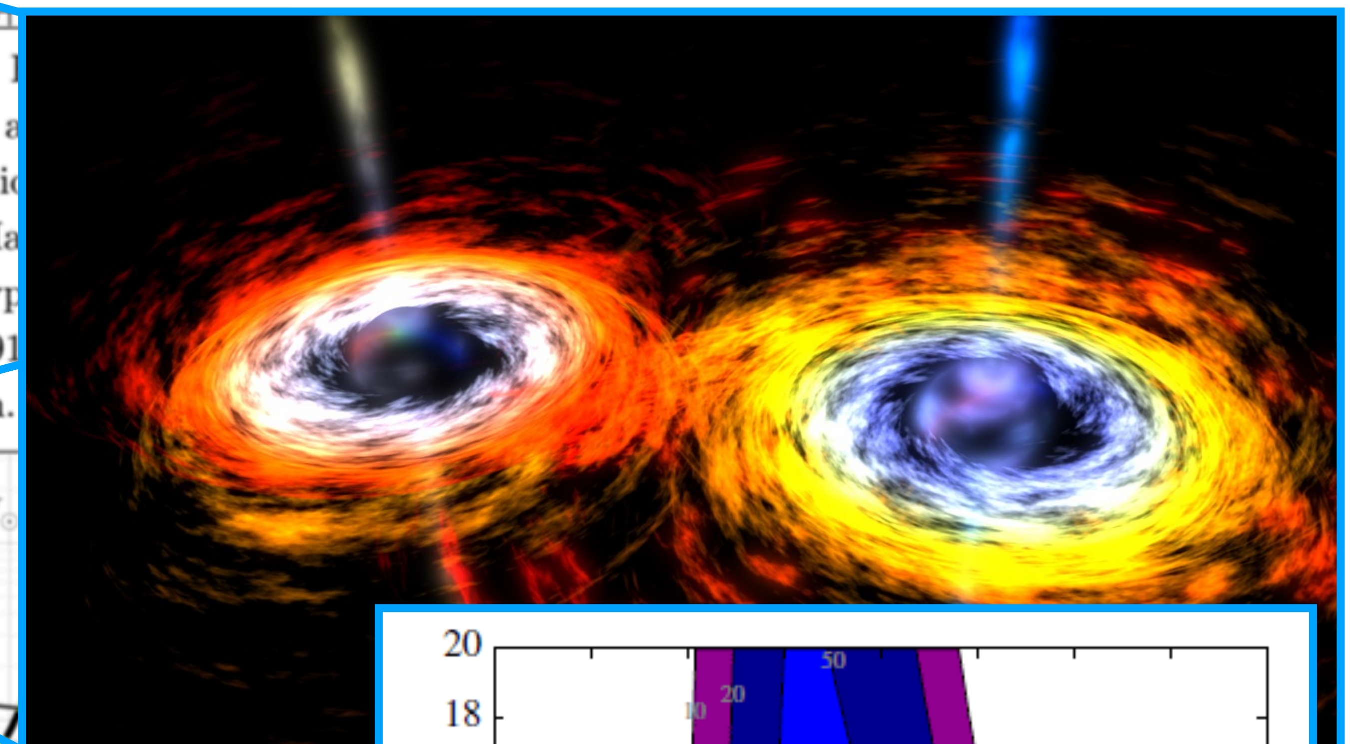
- Redshift range: $0.1 \lesssim z \lesssim 1$
- No EM counterparts expected
- LISA detections: from 1 to 1000/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L < 0.1$
  - If $\Delta\Omega < 2\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 1 to 100 standard sirens / yr
- <u>**Expected results:**</u>
  -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

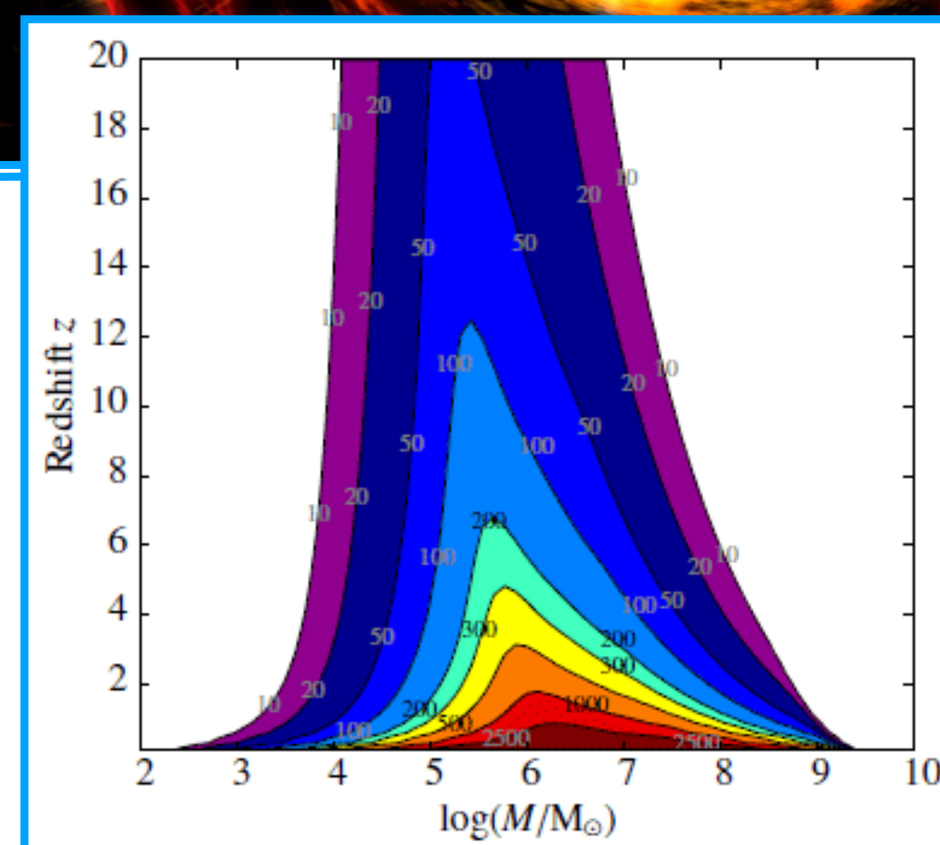
[MacLeod & Hogan, *PRD* (2008)]
[Babak+, *PRD* (2017)]
[Laghi+, *MNRAS* (2021)]

Standard sirens with LISA

LISA can detect up to <u>hundreds</u> of massive black hole binary mergers up to $z \sim 20$



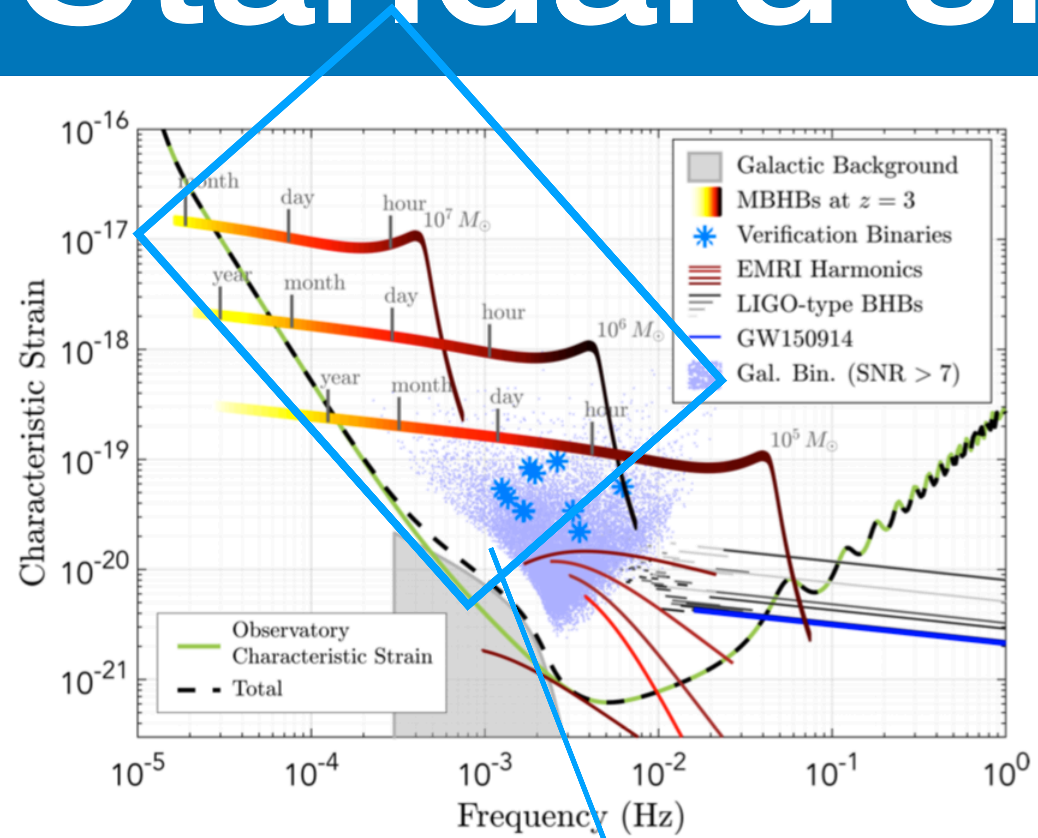


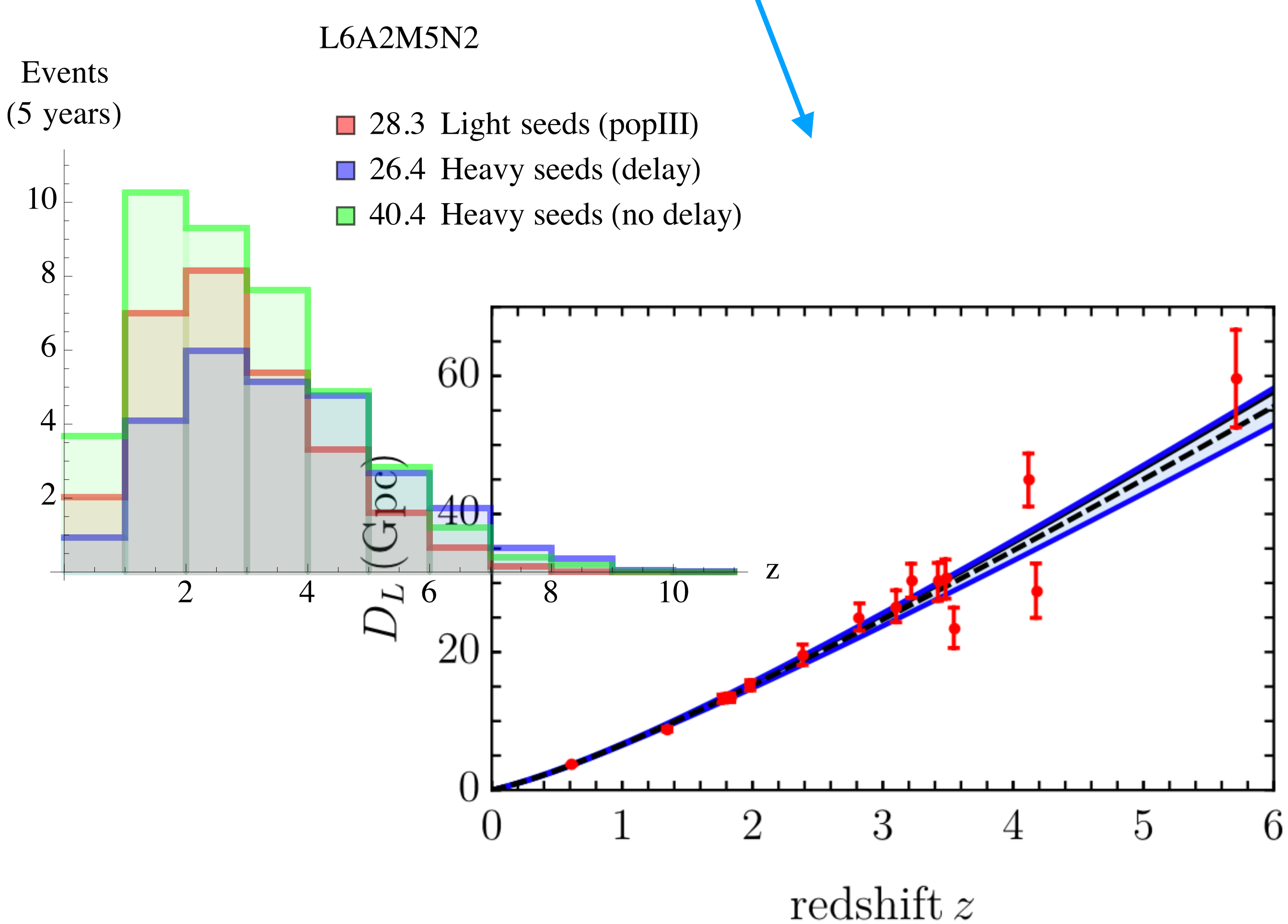


[LISA (2017), arXiv:1702.00786]

[Klein+, PRD (2016)]

Standard sirens with LISA





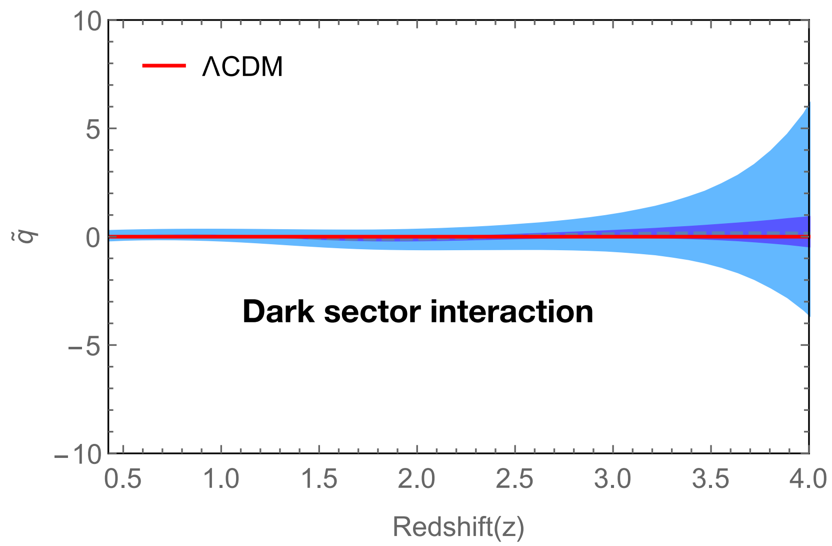
- Redshift range: $z \lesssim 10$
- EM counterparts expected
- LISA detections: 1 to 100/yr
- Useful as standard sirens:
  - If $\Delta d_L / d_L \lesssim 0.1$ (include lensing)
  - If $\Delta\Omega < 10\ \mathrm{deg}^2$
  - $\Rightarrow$ ~ 4 standard sirens / yr (with EM counterpart)
- **Expected results:**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

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

Standard sirens with LISA

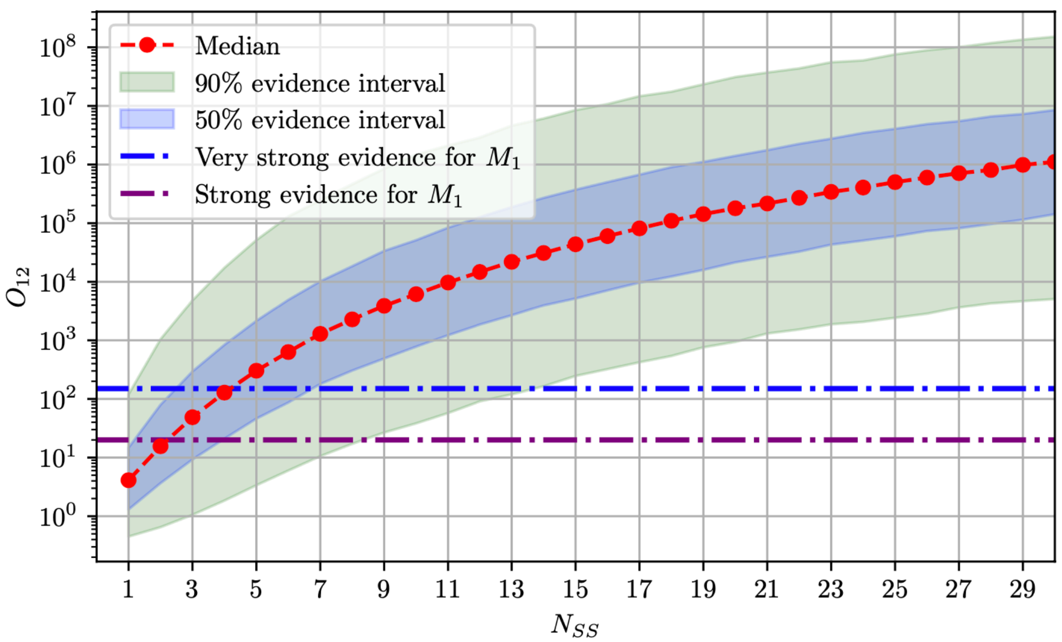
LISA MBHB data will be very useful to probe ΛCDM at high-redshift

Test alternative cosmological models



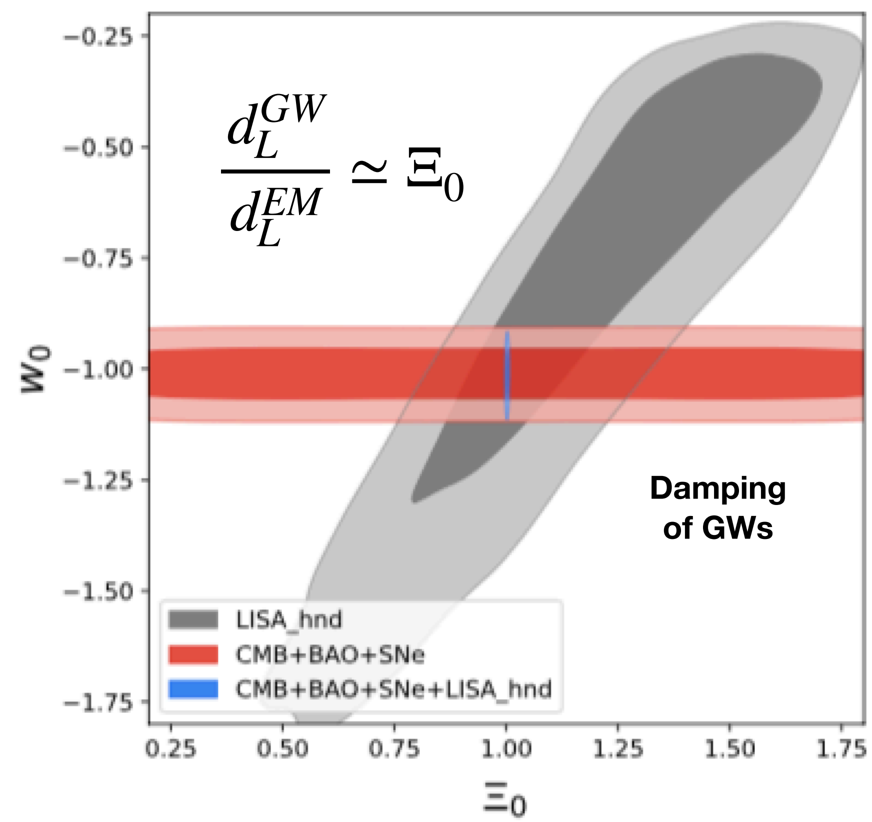
[Caprini & Tamanini, *JCAP* (2016)]
[Cai+, *JCAP* (2017)]

Test quasars Hubble diagram



[Speri+, *PRD* (2021)]

Test modified gravity



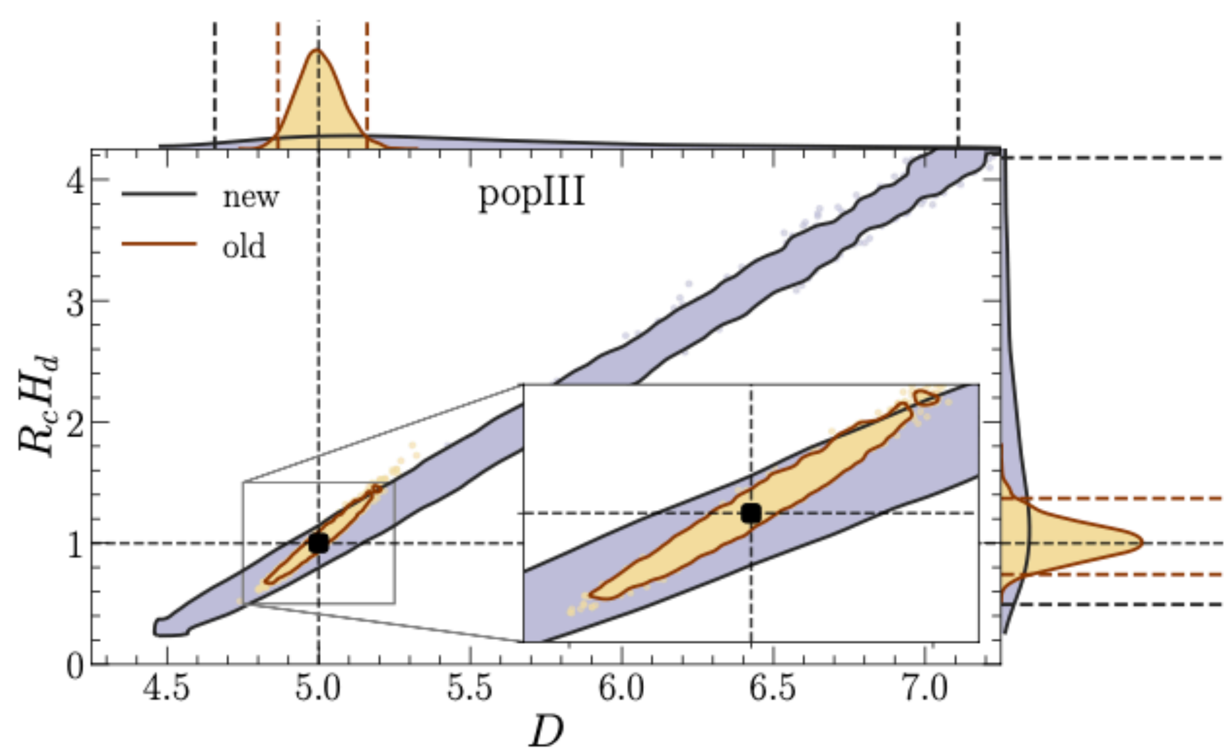
[LISA CosmoWG, *JCAP* (2019)]

Standard sirens with LISA

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

Test cosmological extra-dimensions

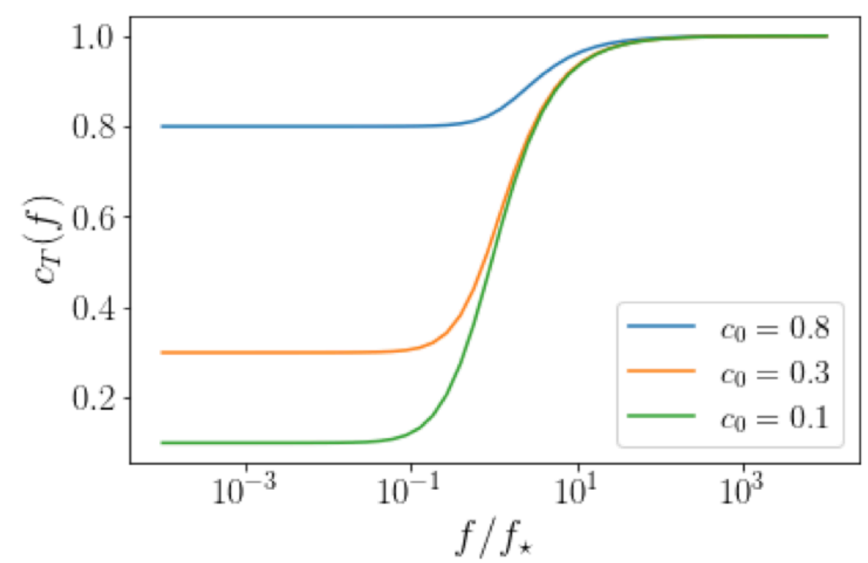
$$\frac{d_L^{\mathrm{GW}}}{d_L^{\mathrm{EM}}} = \left[1 + \left(\frac{d_L^{\mathrm{EM}}}{(1+z)R_c}\right)^n\right]^{\frac{D-4}{2n}}$$



[Corman+, *PRD* (2022)]

Test GW speed

At both larger distance and lower frequency (and possibly higher accuracy)

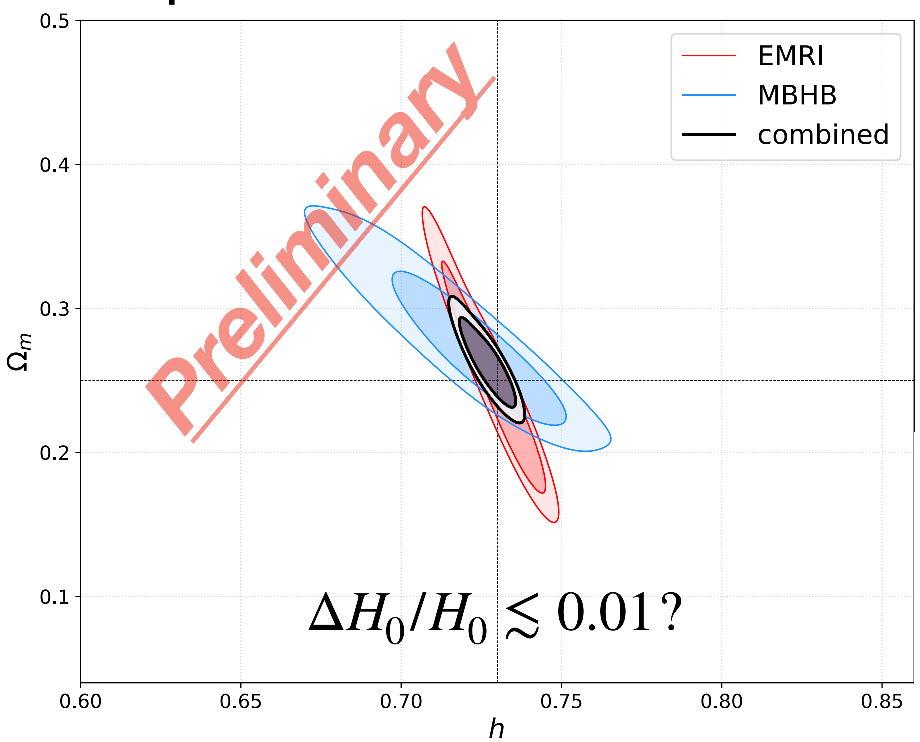


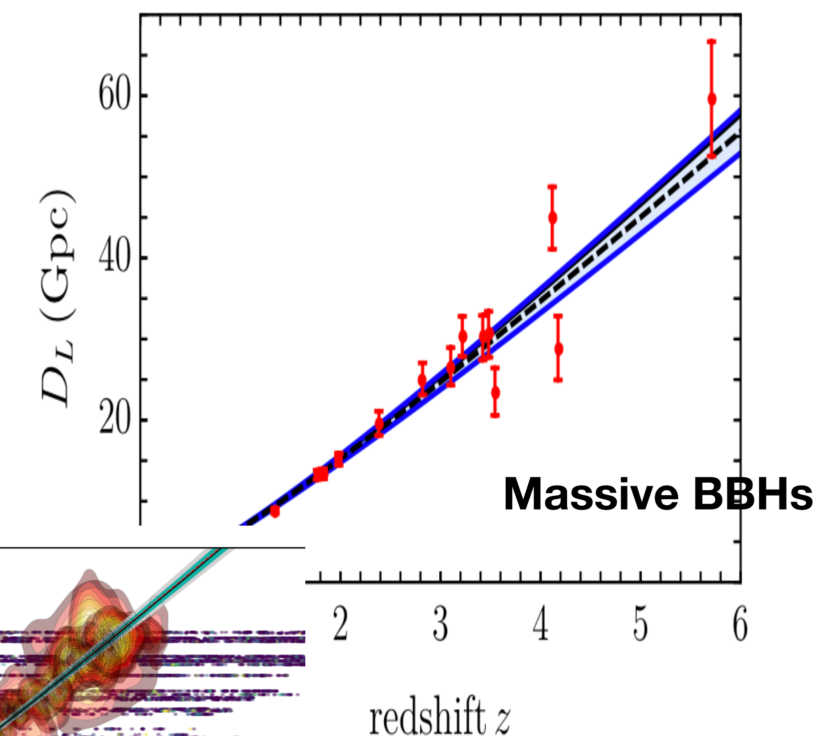
[LISA CosmoWG, *arXiv* (2022)]

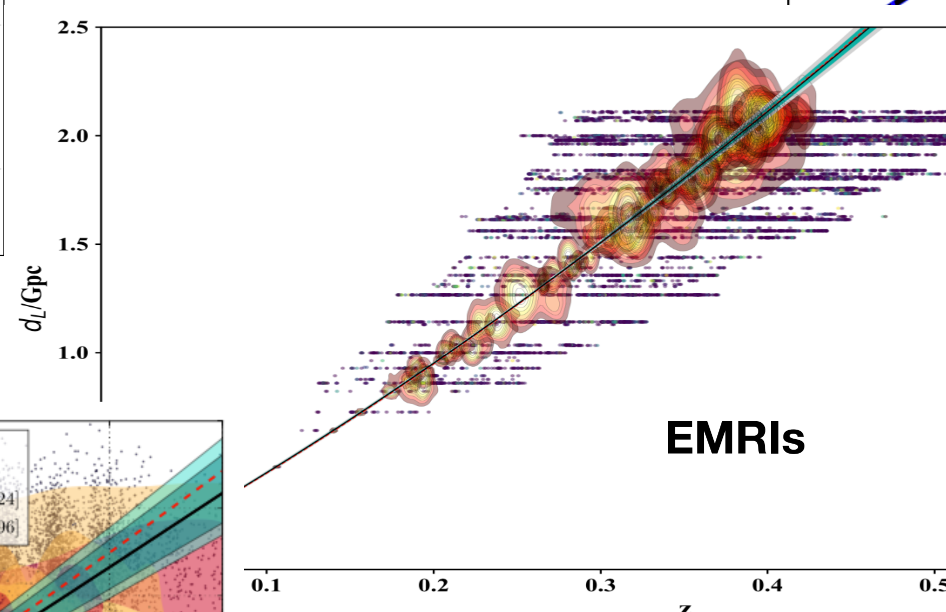
Standard sirens with LISA

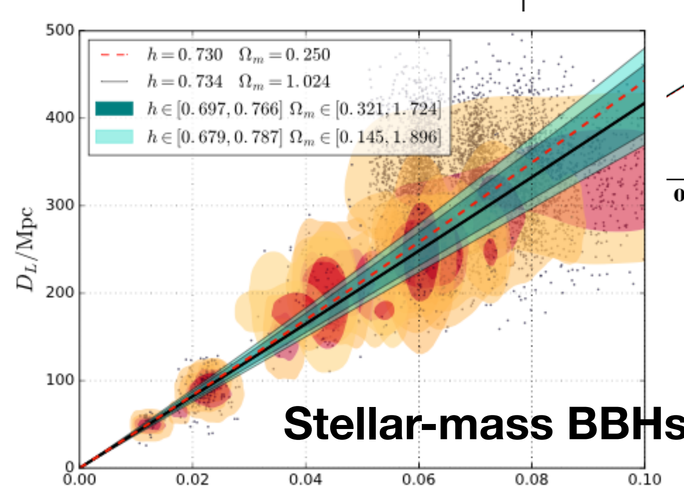
The combination of different standard sirens will allow LISA to measure the expansion of the universe from $z \sim 0.01$ to $z \sim 10$

Expected results for ΛCDM:





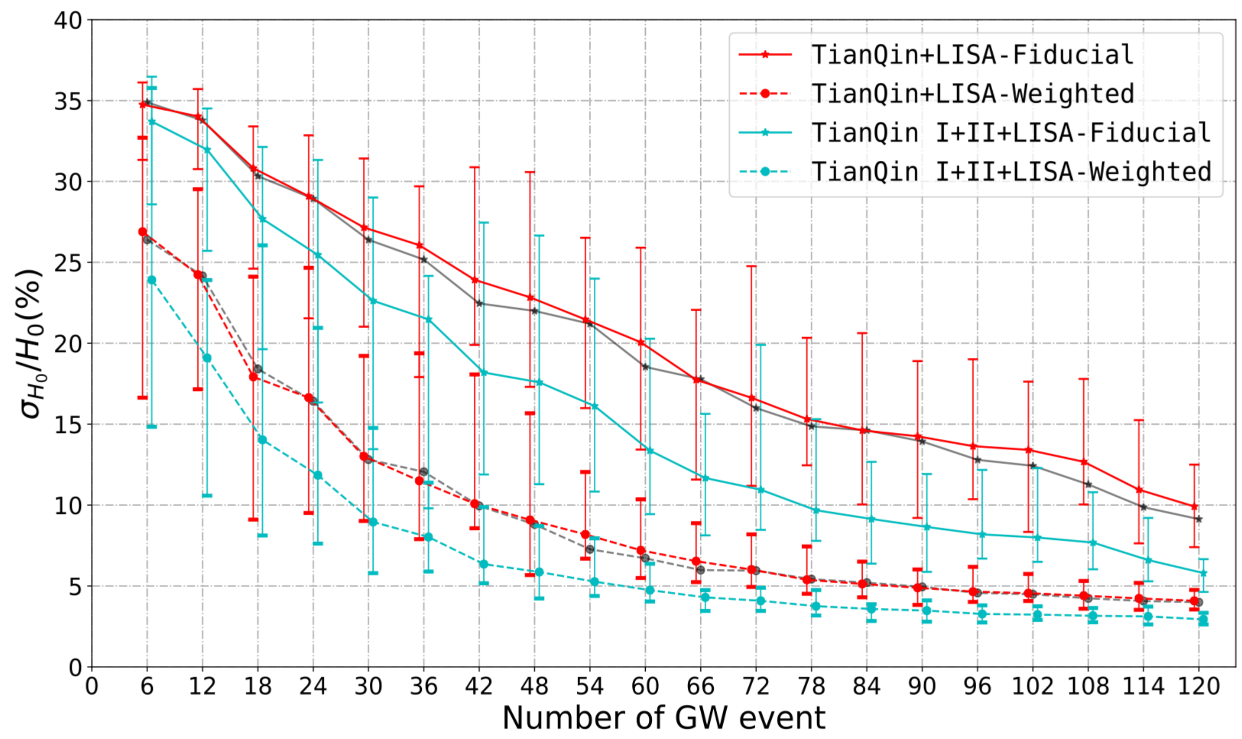


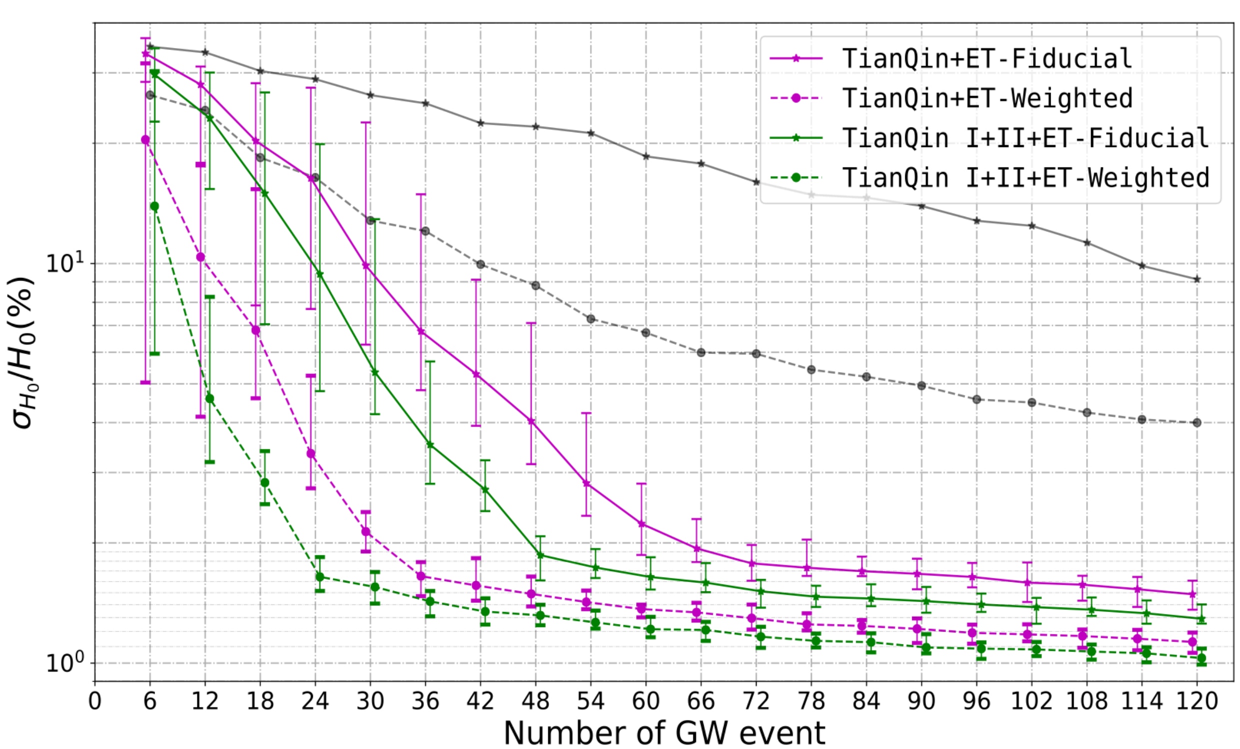


[Tamanini, *J. Phys. Conf. Ser.* (2017)]
[Tamanini+, *in prep.* (2022)]

Cosmology with LISA+TianQin

Cosmology with LISA+TianQin





Stellar-mass BBHs have been analysed in the LISA + TainQin network

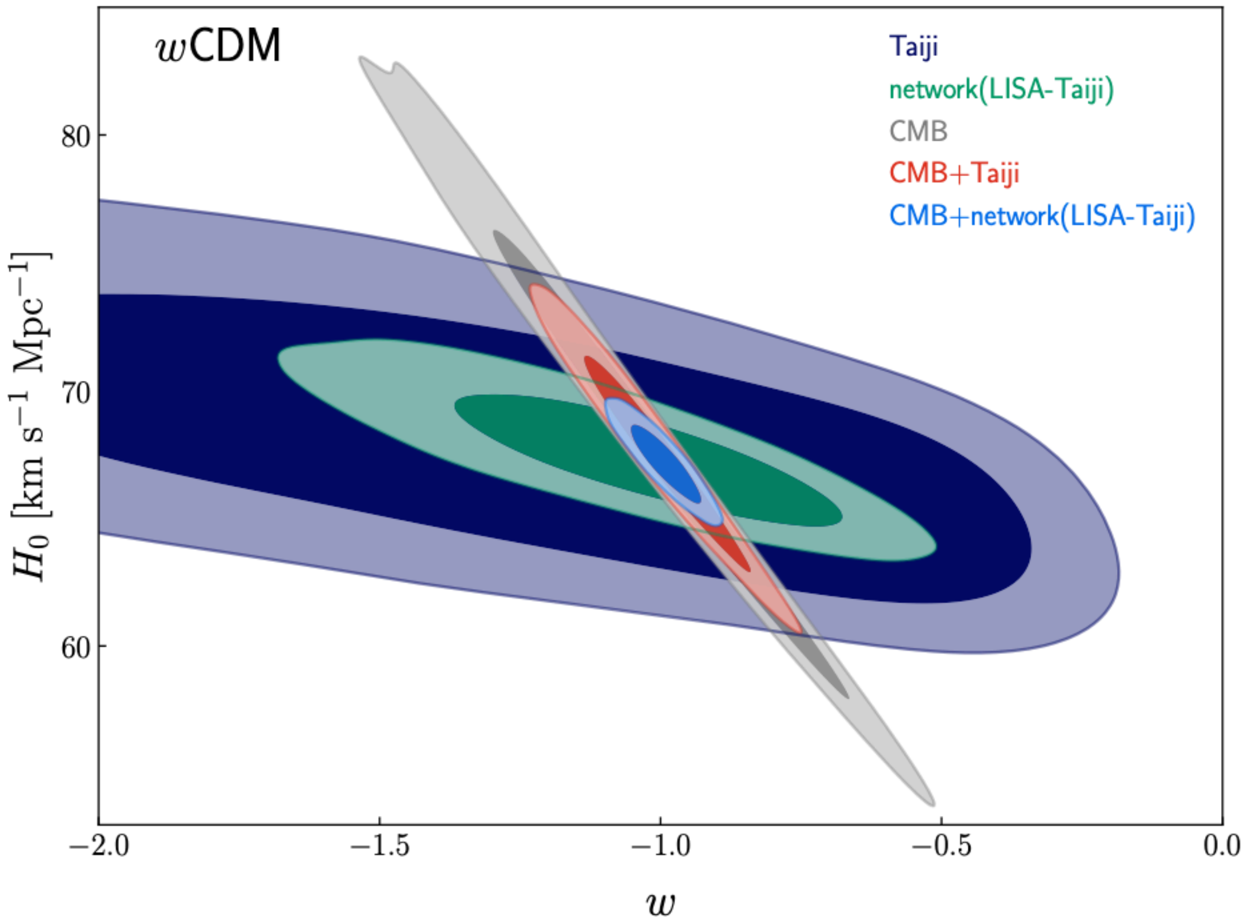
Percent constraints on H0 remains challenging, unless multi-band analyses are taken into account

LISA+TainQin : H0 at ~10%
LISA/TainQin+ET : H0 at few %

[Liu+, *PRD* (2022)]
[Zhu+, *Sci. China Phys. Mech. Astron.* (2022)]

Cosmology with LISA+TianQin

Model	Number of standard sirens	
	Taiji	network
pop III	25	50
Q3d	12	20
Q3nod	24	44



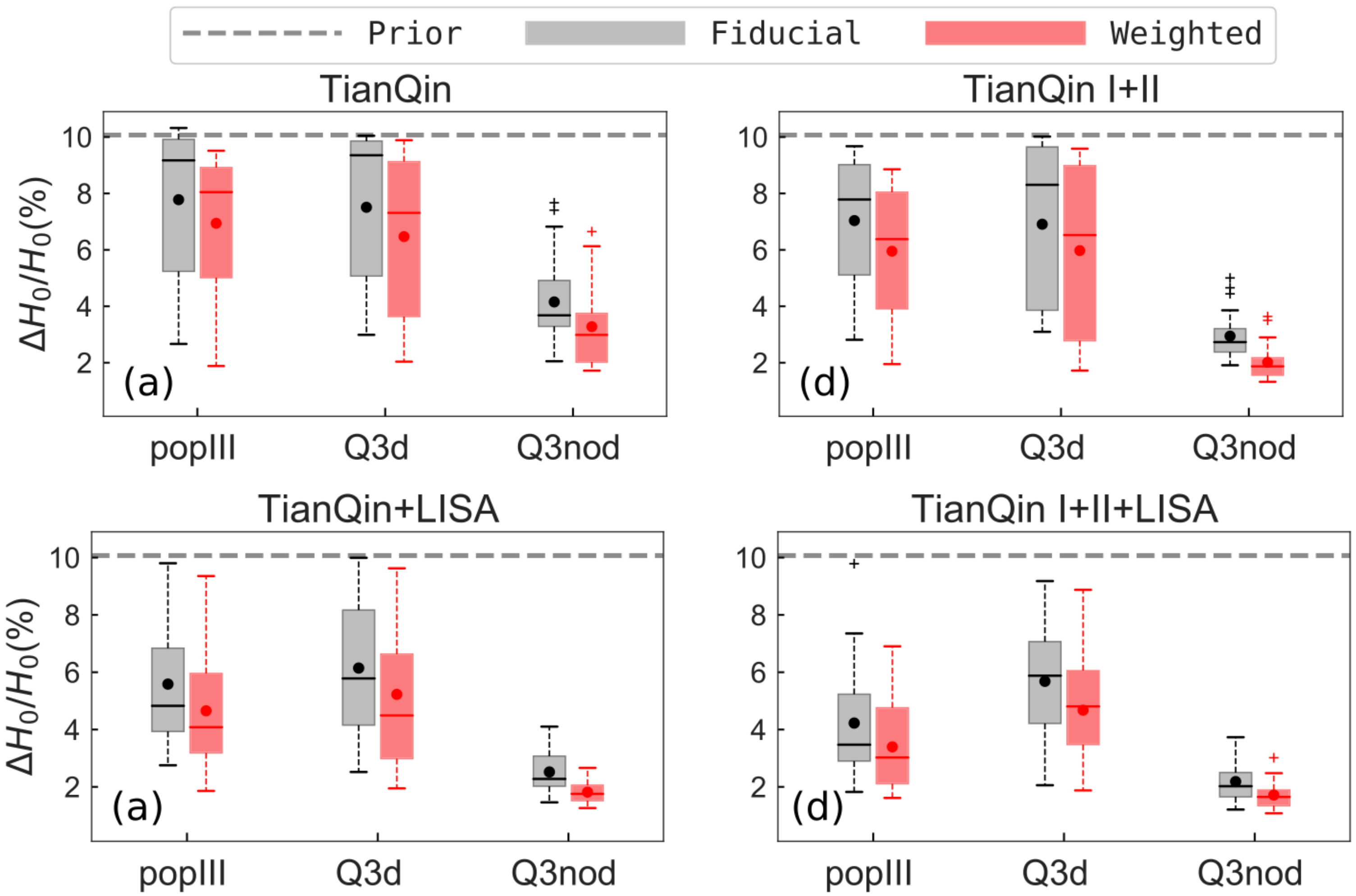
MBHBs with EM counterpart have also been investigated with LISA+TianQin

The number of detected standard sirens double thanks to the better sky-localisation

LISA or TainQin alone : H0 at ~few %
LISA + TainQin : H0 at ~1 %

[Wang+, *JCAP* (2022)]
[Wang+, *Sci. China Phys. Mech. Astron.* (2022)]

Cosmology with LISA+TianQin



MBBHs have also been investigated as dark sirens with LISA+TianQin.

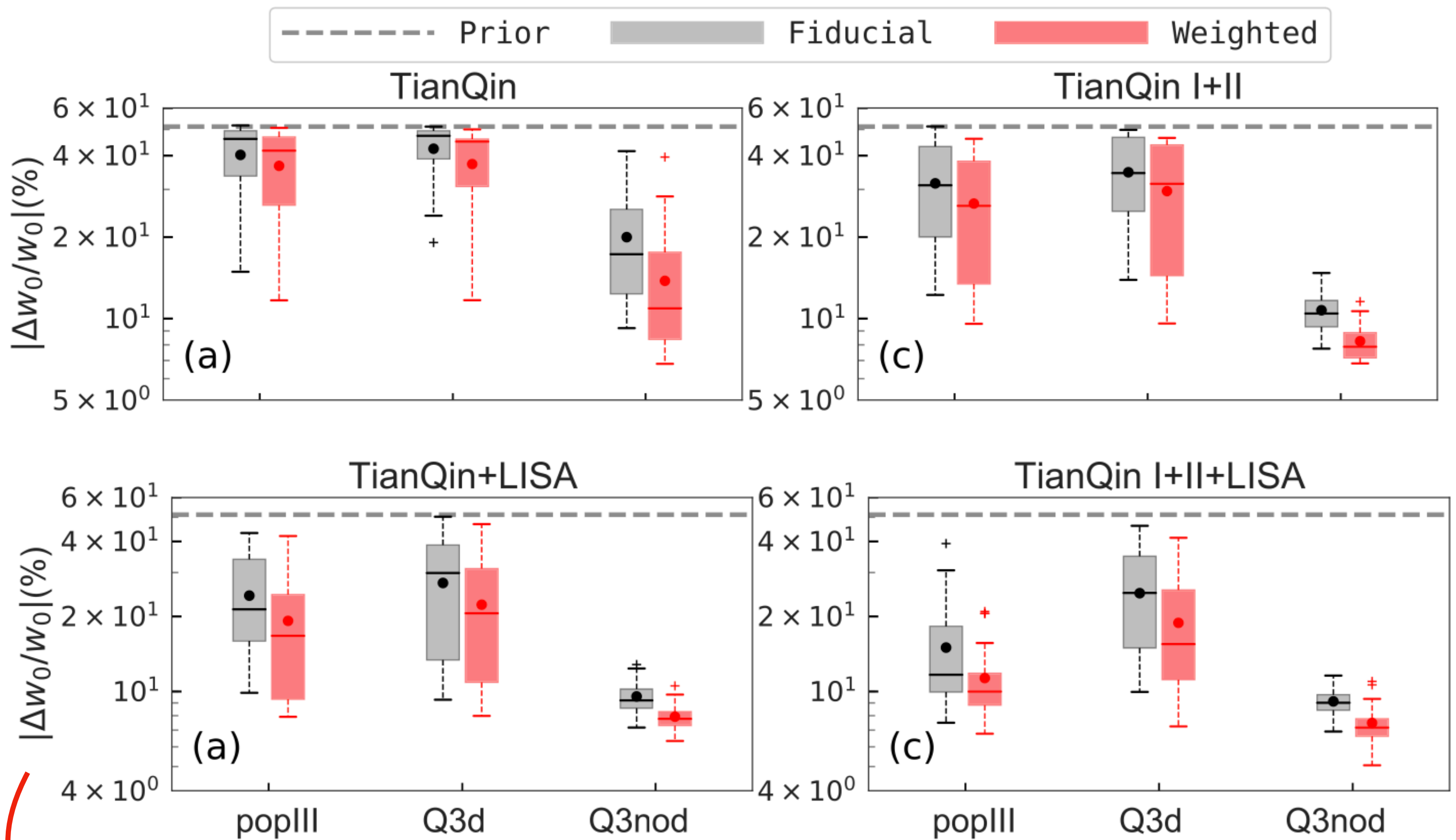
Using strong population assumptions/properties (clustering, black hole mass-host galaxy bulge luminosity relationship, …).

Results seems to improve roughly by $\sqrt{2}$ in agreement with doubling number of standard sirens.

LISA or TainQin only : H0 at ~10%
LISA+TainQin.   : H0 at few %

[Zhu+, *PRD* (2022)]

Cosmology with LISA+TianQin



Similar conclusions apply to constraints on the EoS of dark energy

MBBHs have also been investigated as dark sirens with LISA+TianQin.

Using strong population assumptions/properties (clustering, black hole mass-host galaxy bulge luminosity relationship, …).

Results seems to improve roughly by $\sqrt{2}$ in agreement with doubling number of standard sirens.

LISA or TainQin only : H0 at ~10%
LISA+TainQin. : H0 at few %

[Zhu+, *PRD* (2022)]

Cosmology with LISA+TianQin

Some points for discussion

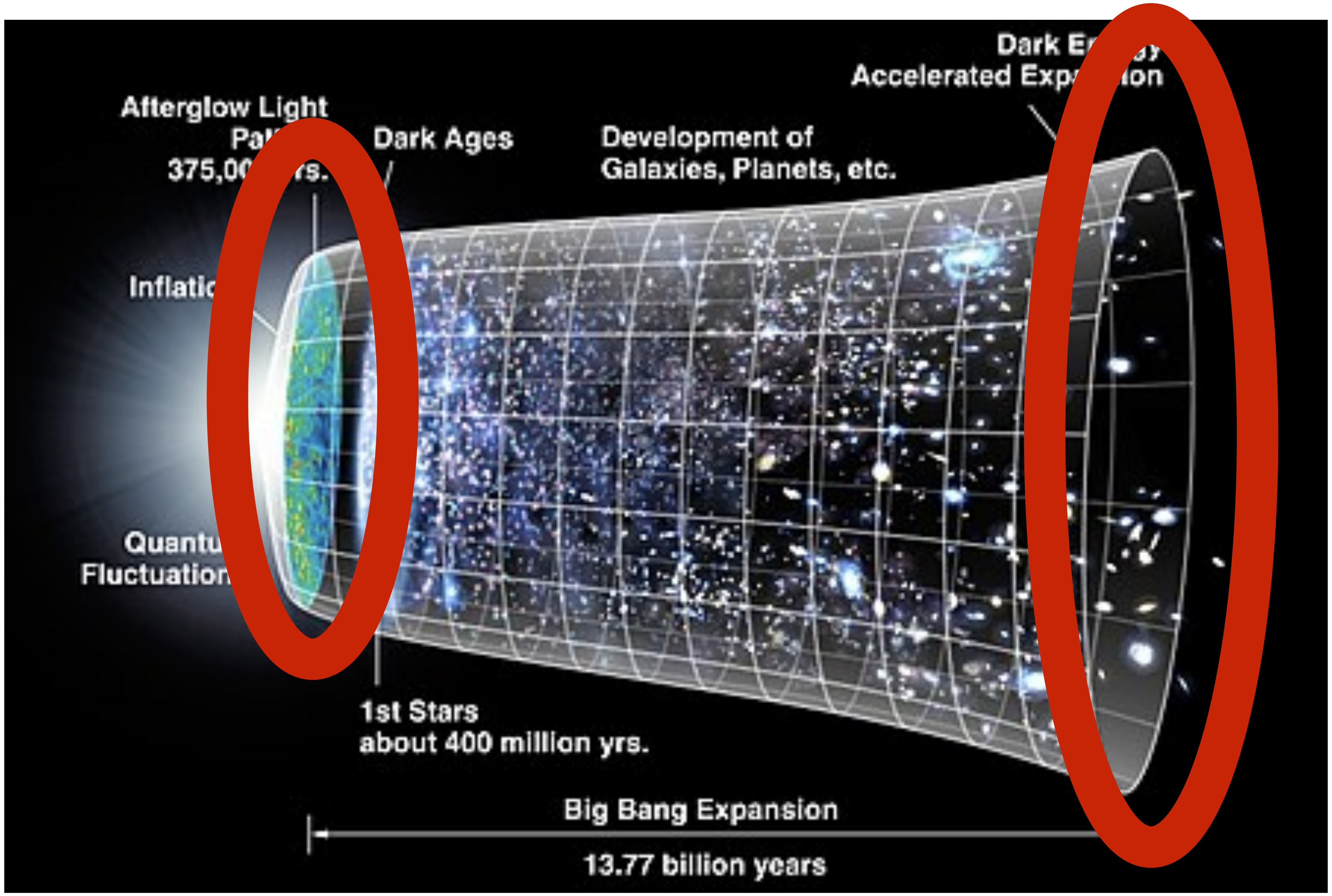
- The LISA+TianQin network can drastically improve sky-localisation w.r.t. a single detector. Can we use this to get more standard sirens (beyond the $\sqrt{2}$ gain)?
- Can TianQin help LISA with stellar-origin BBHs and their cosmological analysis?
- Can the LISA+TianQin network help investigating the nature of dark energy and beyond-LCDM models?
- What about cosmology with EMRIs with LISA+TianQin ?
- Can we cross-check detector's systematics (e.g. calibration errors) between LISA and TianQin?

Conclusions

- Many cosmological discoveries expected from LISA and TianQin:
  - Independent and complementary estimates of H_0
  - Probes of the cosmic expansion history between $0.01 < z < 10$
  - New tests of dark energy and modified gravity
- New insights into:
  - H_0 tension (if still around)
  - The nature of dark energy
  - Possible deviations from LCDM at high redshift
- Many other investigations and much more work still do be done:
  - Fully understand the potential of LISA and TianQin standard sirens
    - Cosmological forecasts from combination of all GW sources
  - Fully assess what we gain with the LISA+TianQin network
  - Investigate GW lensing, primordial BHs, modified gravity, …

Early universe science with LISA

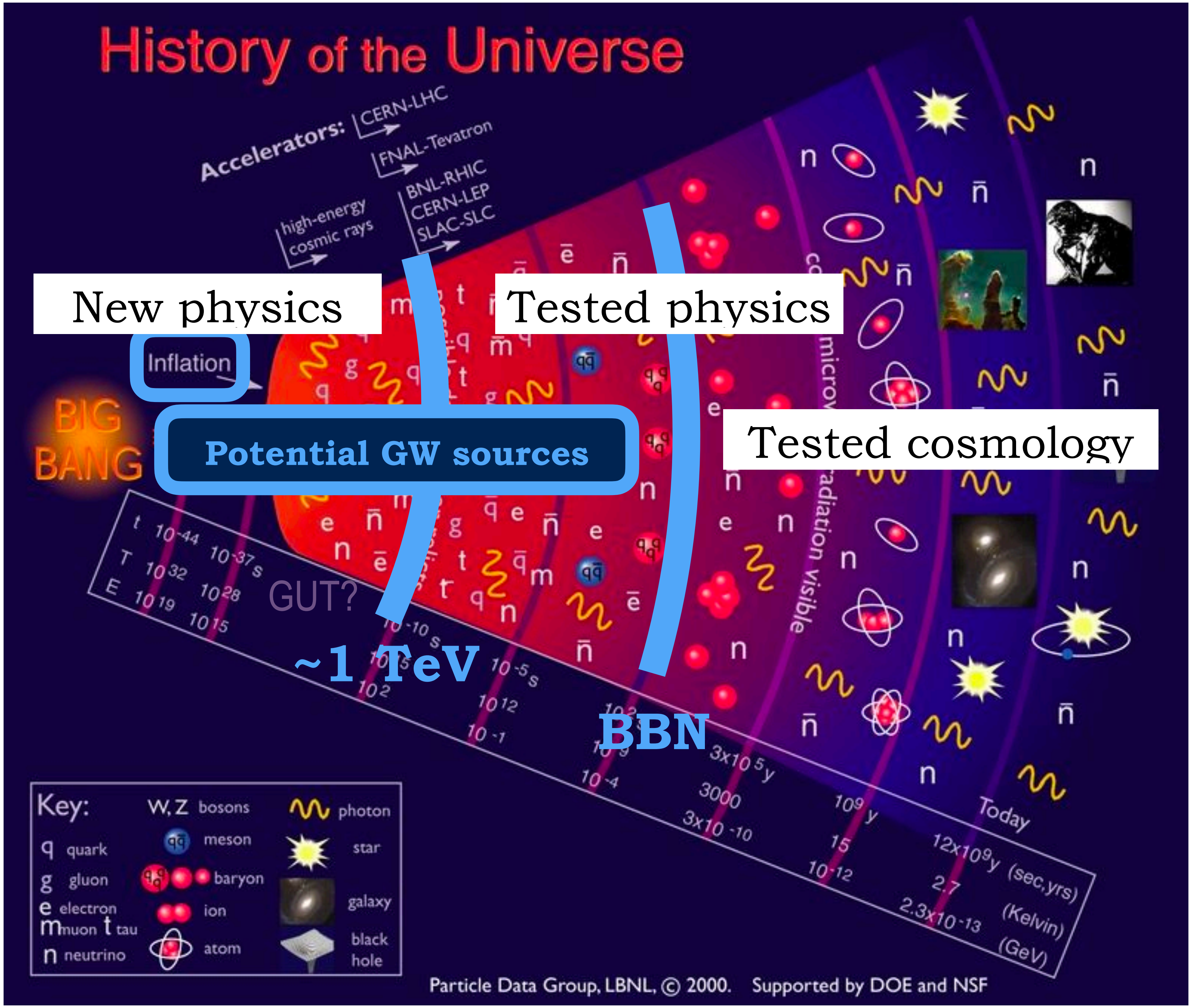
Early universe science with LISA



the stochastic GW background from primordial sources: test of early universe and high energy phenomena

use of GW emission from binaries to probe late-time dynamics and content of the universe

Early universe science with LISA



GWs can bring direct information from very early stages of the universe evolution, to which we have no direct access through em radiation —> amazing discovery potential

Early universe science with LISA

In the early universe there are two main mechanism to generate a **stochastic background of GWs**:

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

STANDARD INFLATION:
amplification of tensor metric vacuum fluctuations by the exponential expansion

ACTIVE GW SOURCE:
tensor anisotropic stress can act an any time in the universe

A GW source acting at time t_* in the early universe cannot produce a signal correlated on length/time scales larger than the causal horizon at that time

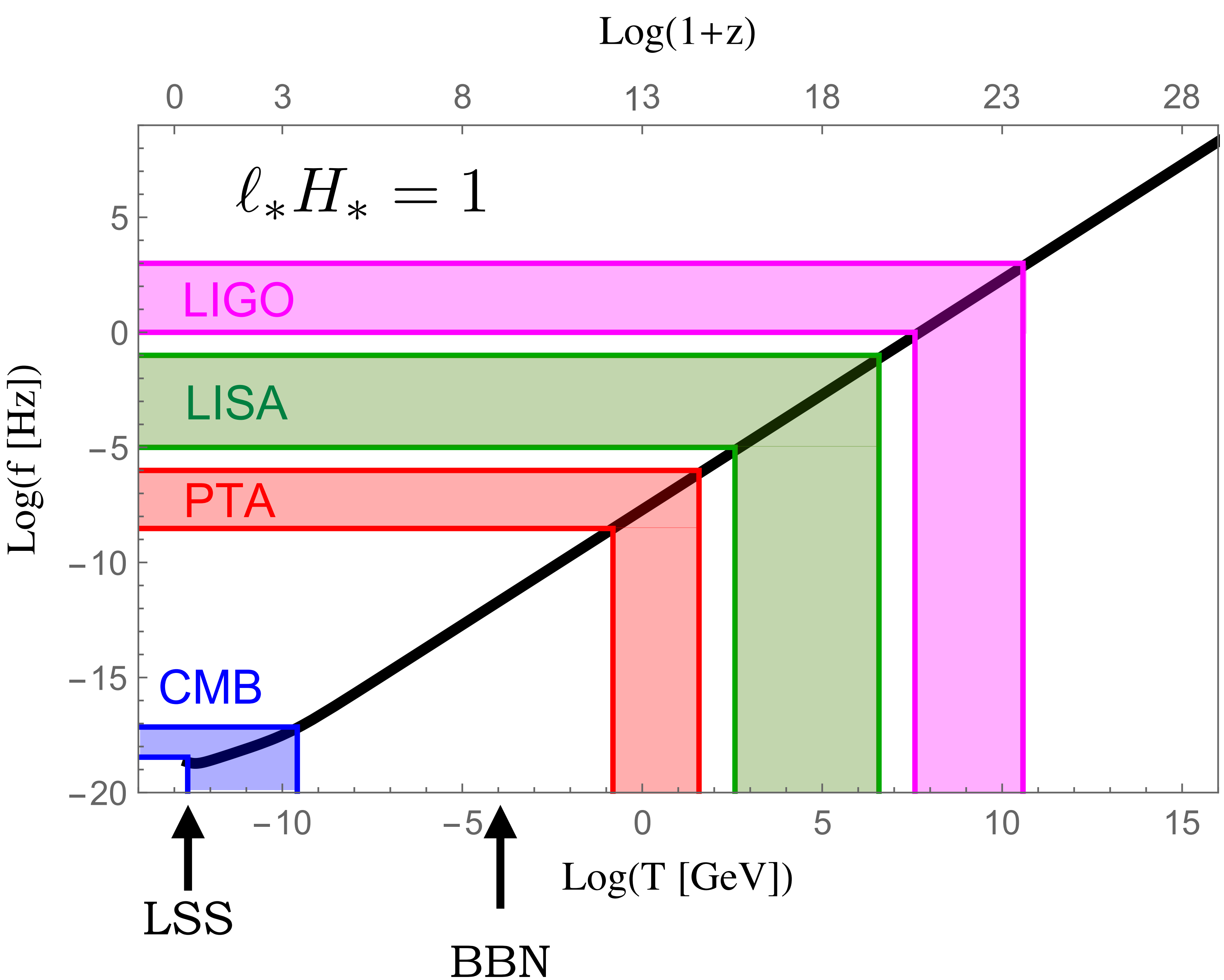
$$\ell_* \leq H_*^{-1}$$

$\Rightarrow$ characteristic frequency of the GW signal $\qquad f_* = \frac{1}{\ell_*} \geq H_*$

Early universe science with LISA

$T_{\rm QCD} \sim 100\,\text{MeV}$ $\quad \ell_* H_* \sim 0.1$ $\longrightarrow$ $f \sim 10\,\text{nHz}$ PTA

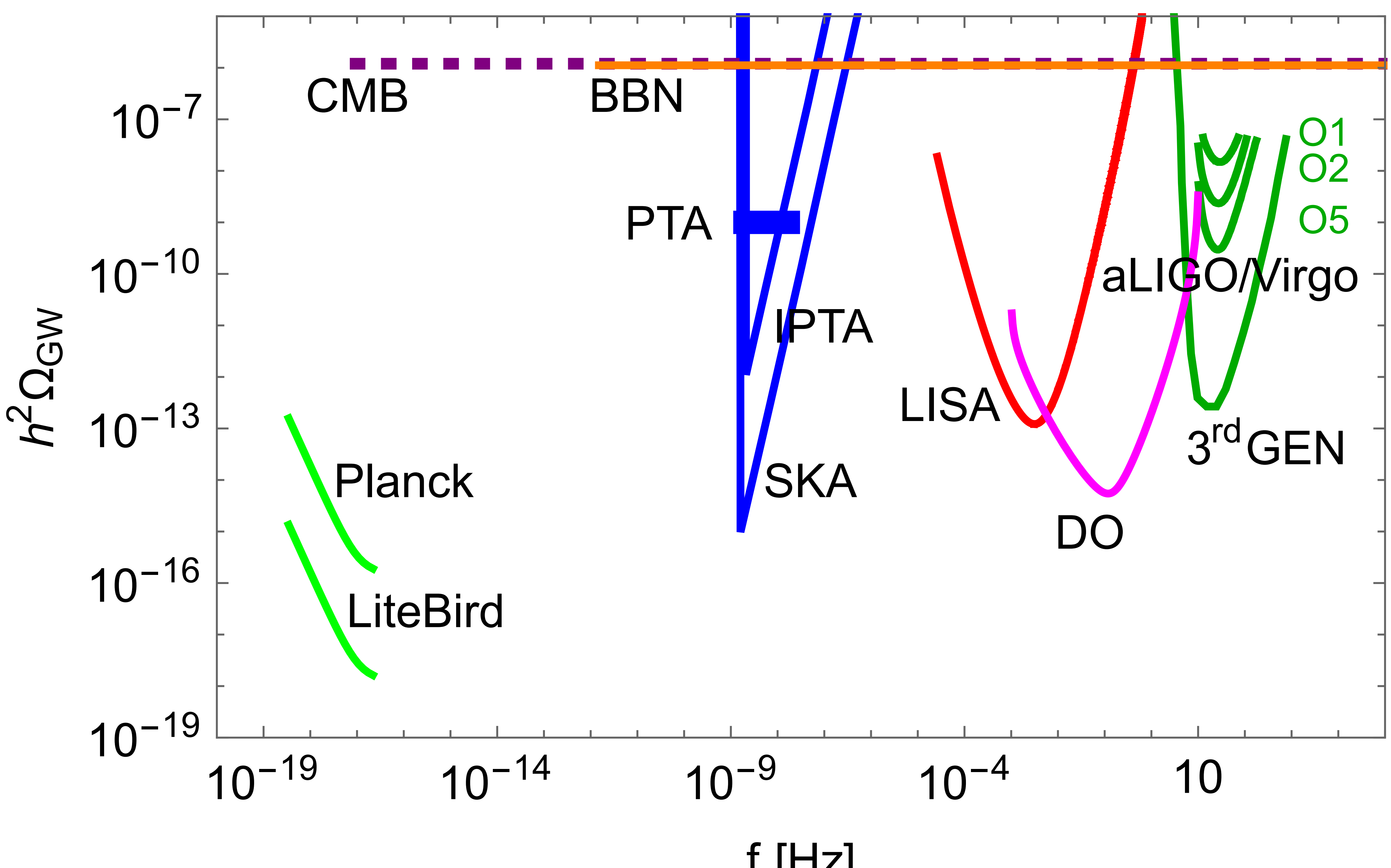
$T_{\rm EW} \sim 100\,\text{GeV}$ $\quad \ell_* H_* \sim 0.01$ $\longrightarrow$ $f \sim \text{mHz}$ LISA



Characteristic frequency of the GW signal

Early universe science with LISA

Current and future constraints on SBGW:



Early universe science with LISA

Possible mechanisms to produce a primordial SBGW:

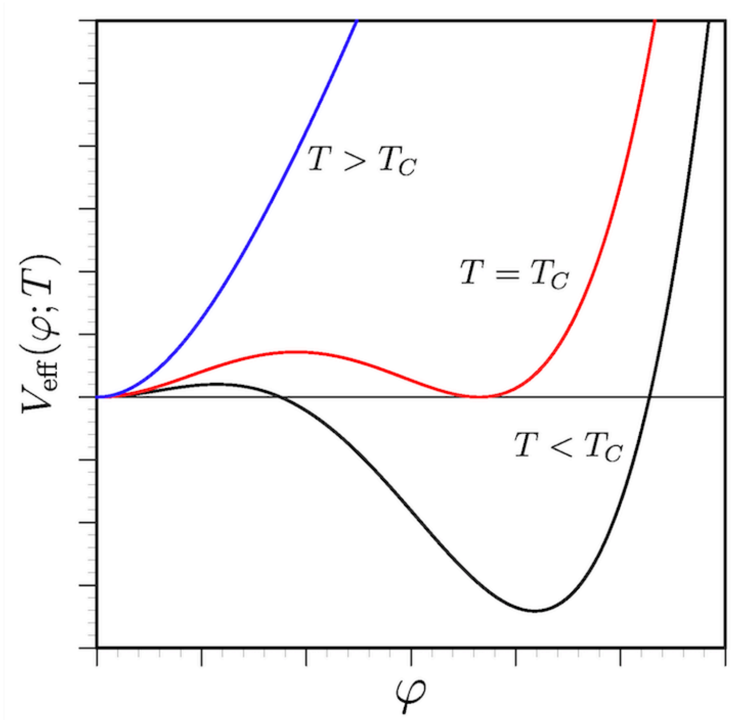
- Inflation:
  - quantum tensor fluctuations (at first and second order)
  - tensor modes from additional fields (scalar, gauge…)
  - GWs from primordial BHs
  - preheating
  - modifications of gravity
  - …

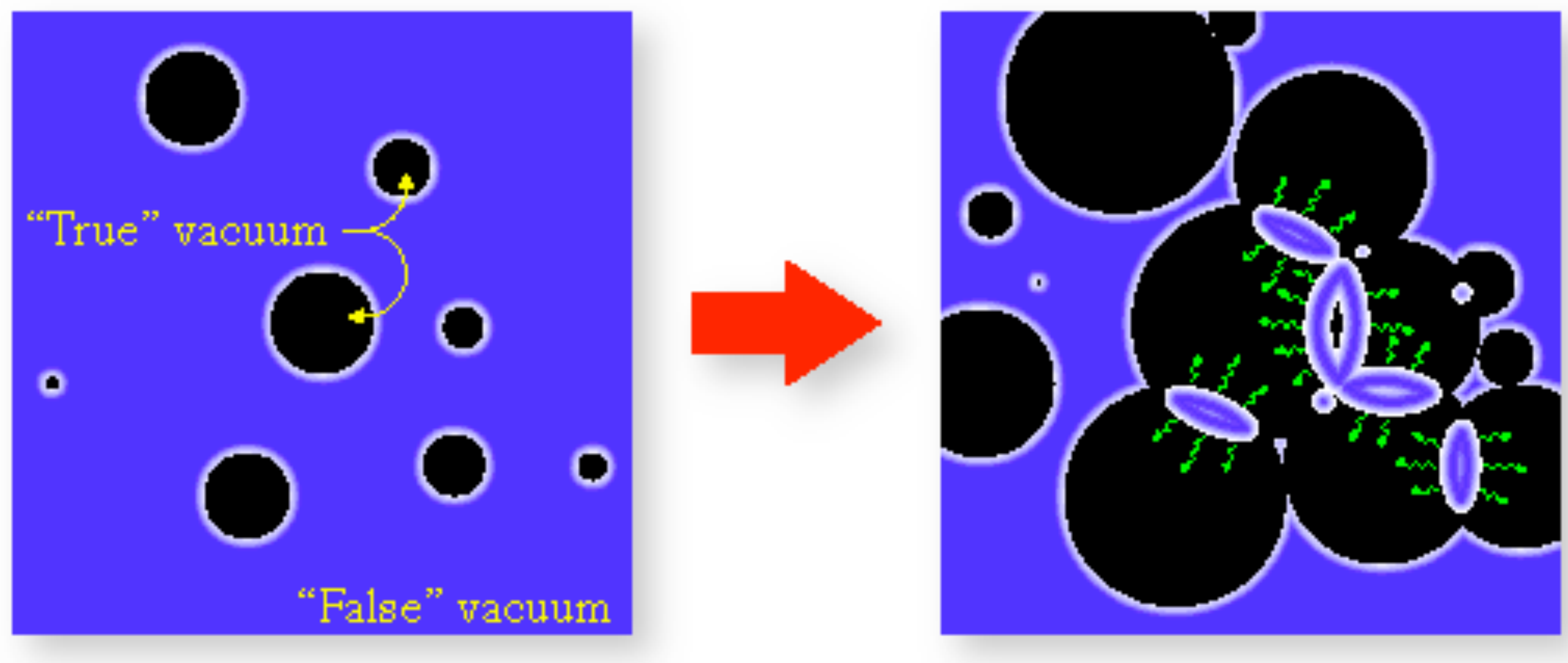
- Other phase transitions:
  - stable topological defects (in particular strings)
  - *first order* phase transitions
    - bubble wall collisions
    - bulk fluid motion (compressional and vortical)
    - magnetic fields

Early universe science with LISA

Sources of tensor anisotropic stress at a first order PT:

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$





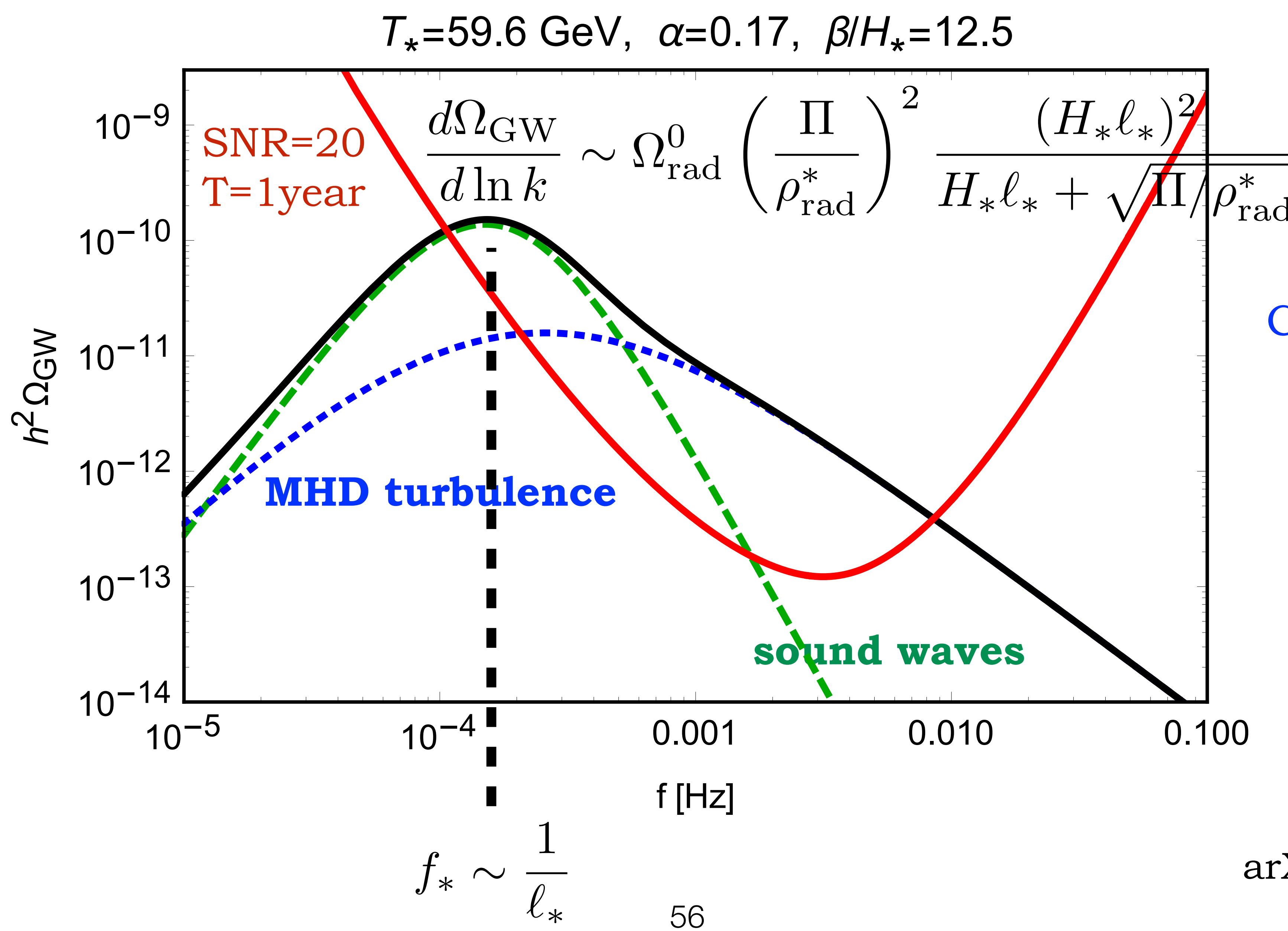
- Bubble collision (scalar field gradients) $\quad \Pi_{ij}^{TT} \sim [\partial_i\phi\partial_j\phi]^{TT}$
- Bulk fluid motion $\quad \Pi_{ij}^{TT} \sim [\gamma^2(\rho+p)v_iv_j]^{TT}$
- Electromagnetic fields $\quad \Pi_{ij}^{TT} \sim [-E_iE_j - B_iB_j]^{TT}$

Early universe science with LISA

LISA (mHz) is sensitive to energy scales around the TeV scale, so it can probe the EWPT in Beyond Standard models and more exotic PTs at higher energies

LISA can probe of Beyond Standard Model physics complementary to colliders

One example of GW signal from the EW phase transition: “Higgs portal” scenario



CAREFUL NOTE: The spectral shape is still under investigation

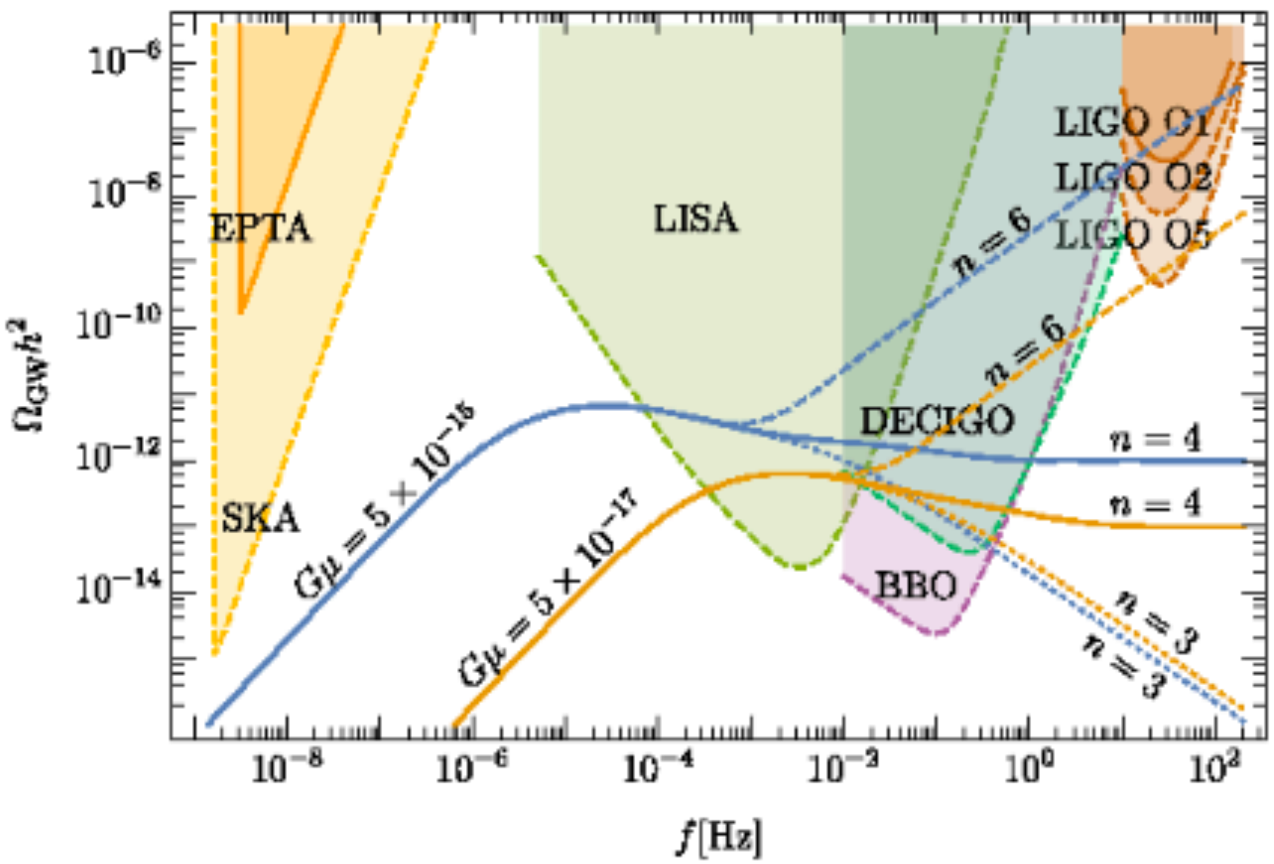
Caprini et al, arXiv:1910.13125

Early universe science with LISA

Other commonly studied possible sources of a primordial SBGW:

Topological defects (cosmic strings)

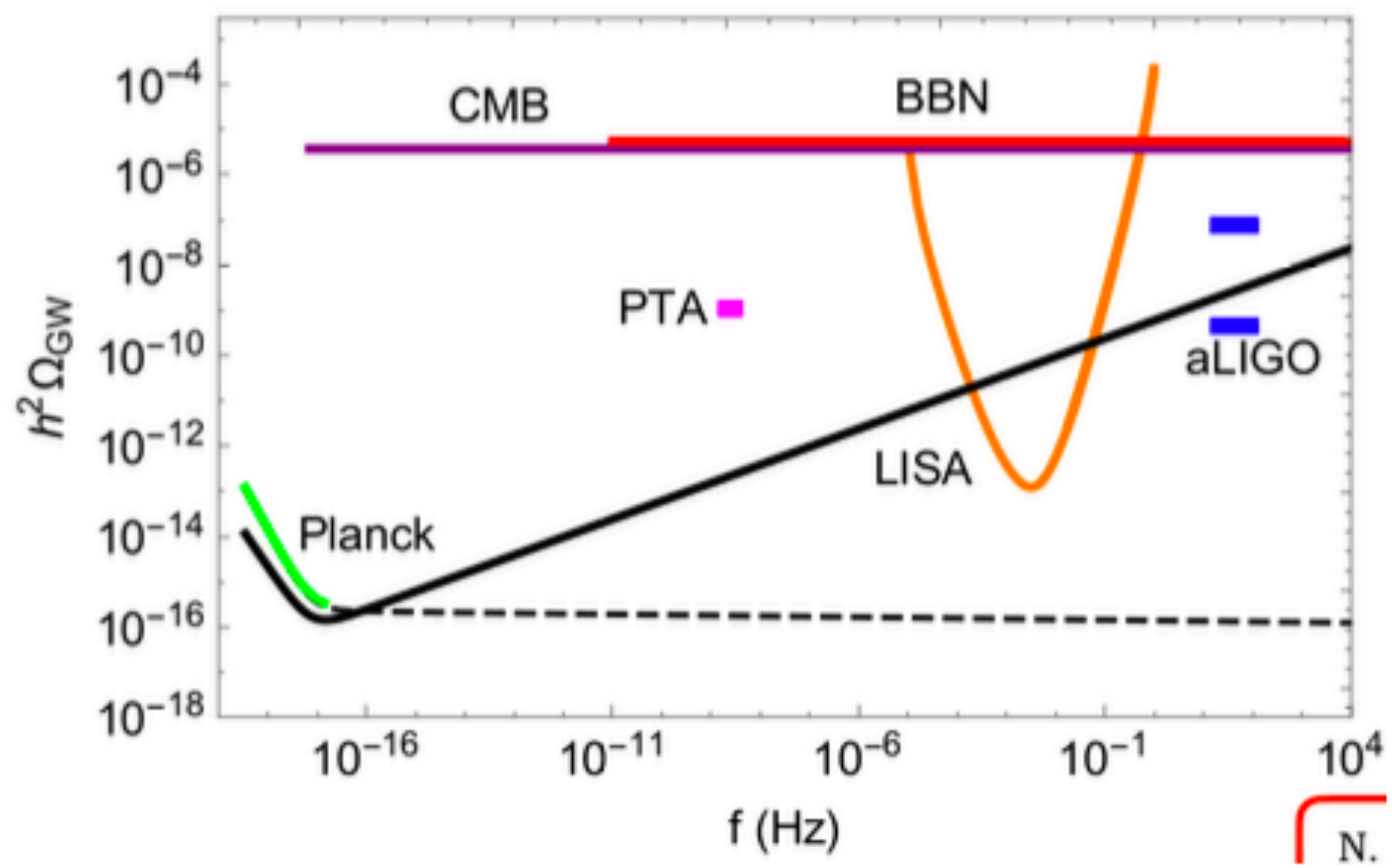
Nambu-Goto string



Y. Cui et al.'17

Non-standard models of inflation

Beyond the vanilla slow-roll case



Review: N. Bartolo et al.'17