Tests of LCDM from WP perspective: methods and pipelines

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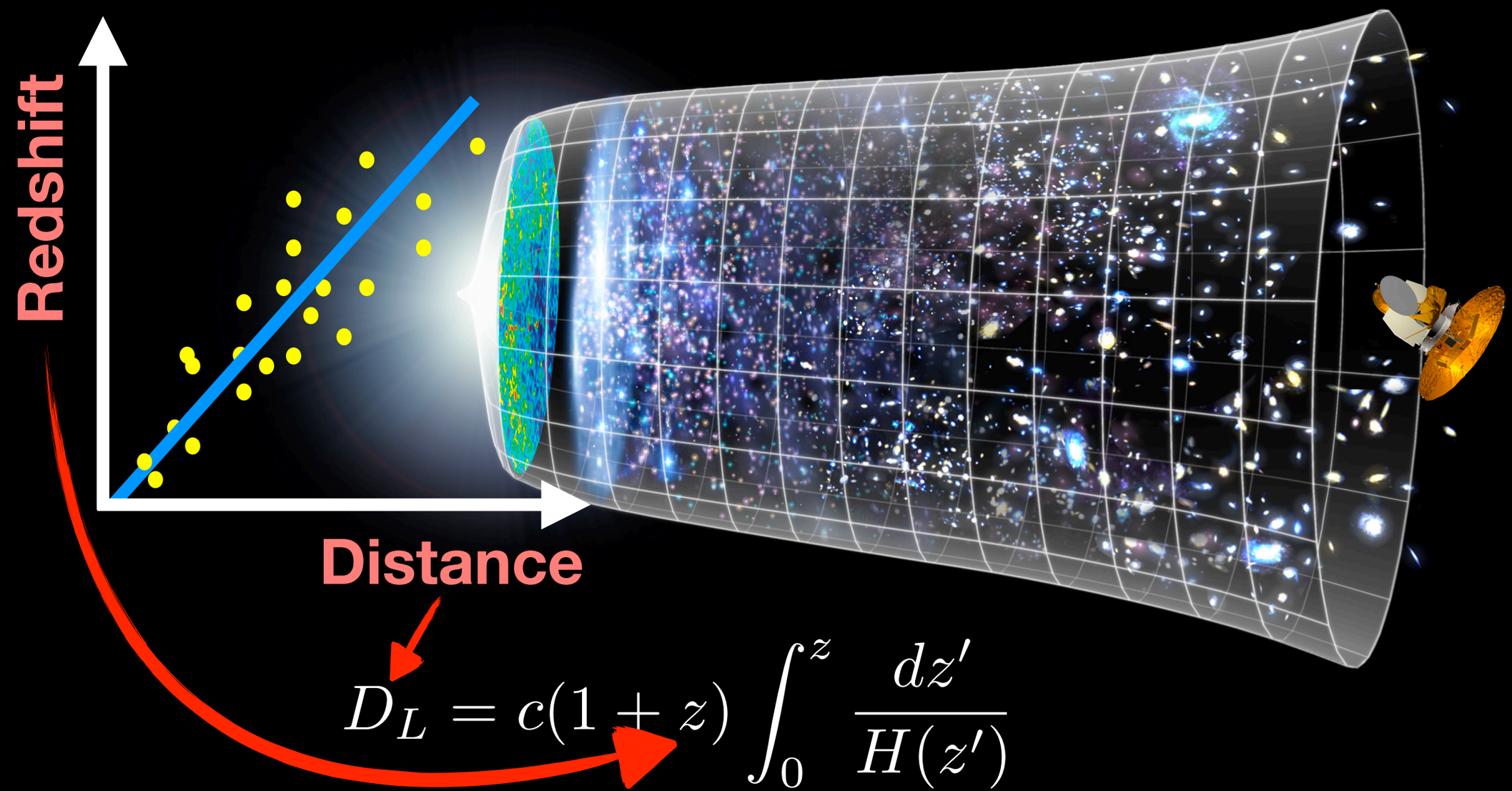
TEXAS
The University of Texas at Austin

Fundamental Physics with LISA, August 2023

The expansion history of the Universe

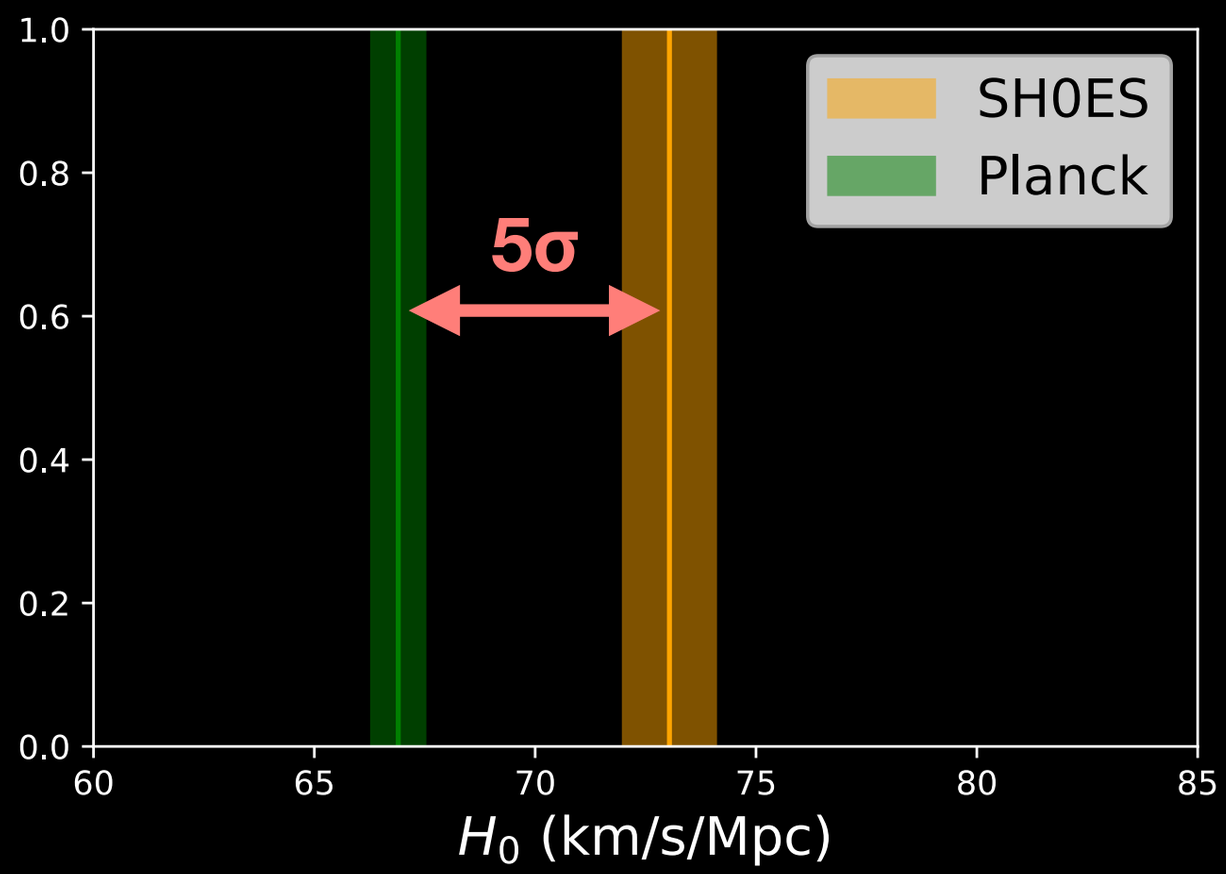


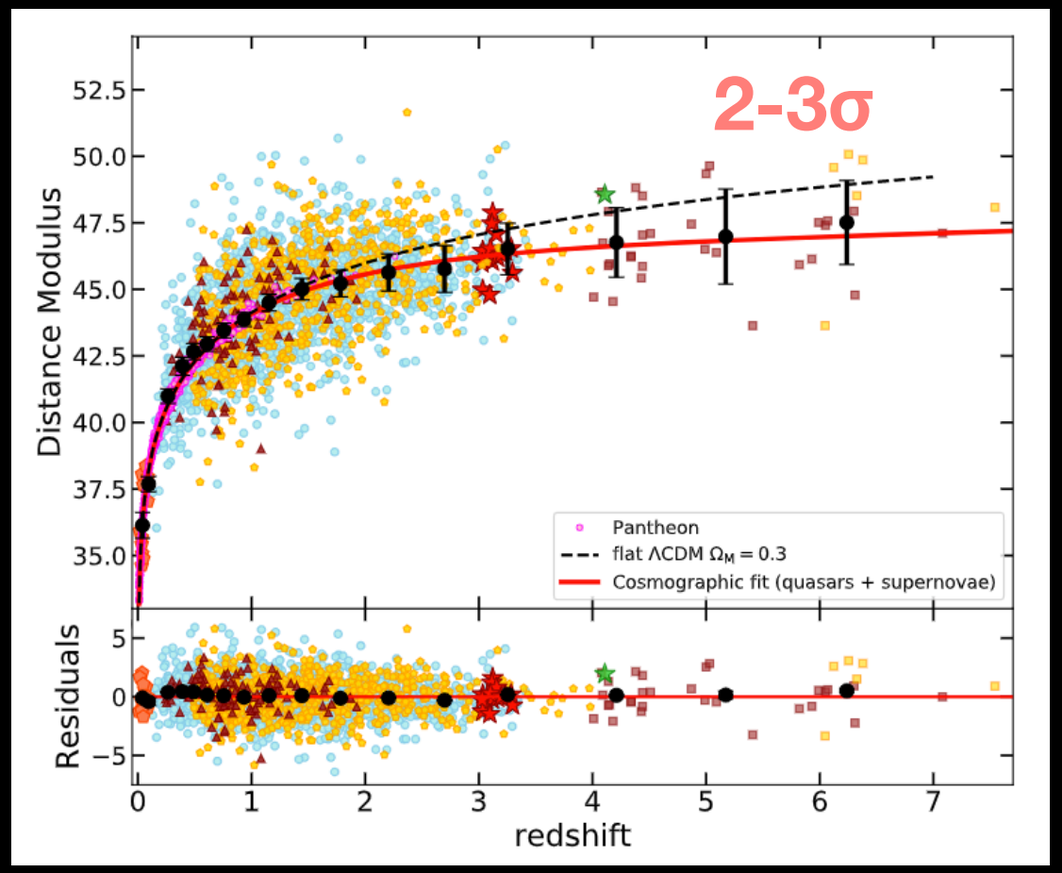
$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}}$$

Astrophysical sources at different redshift range constrain different part of the expansion history.

Tensions in cosmological measurements



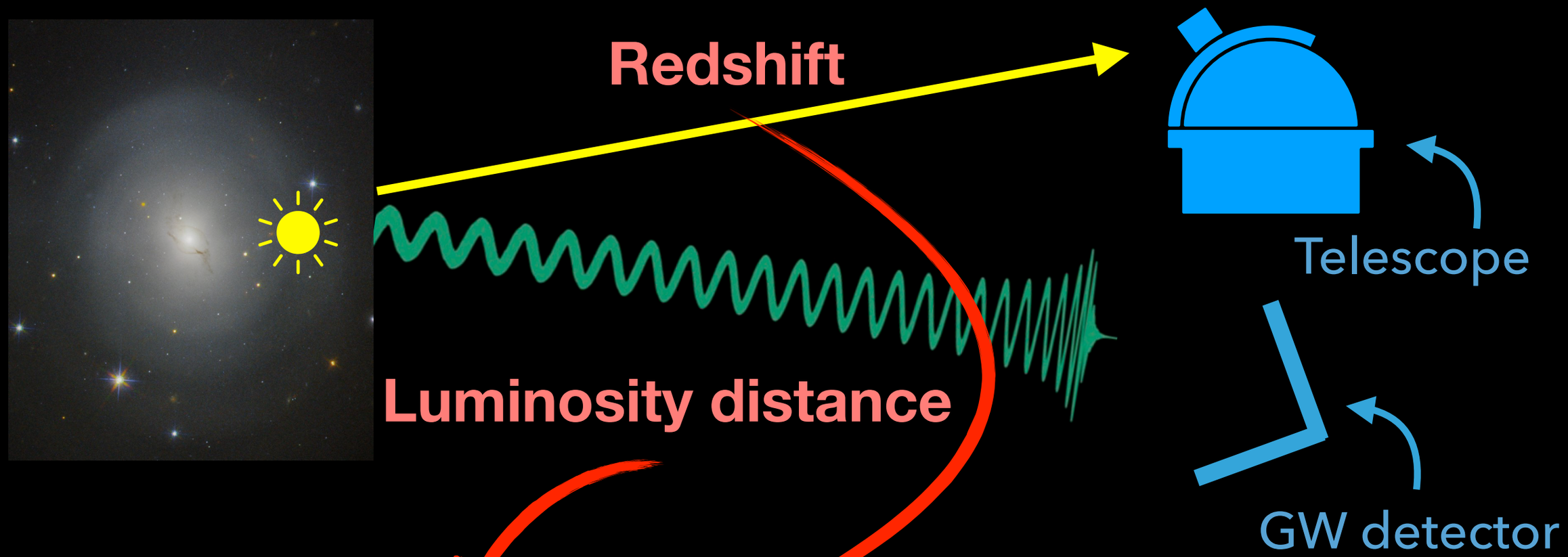


Lusso et al., A&A, 2020

Independent measurement of the cosmological parameters—Standard siren method

BRIGHT SIREN

Standard siren with electromagnetic counterparts—determine the redshift of gravitational-wave source with the *host galaxy*



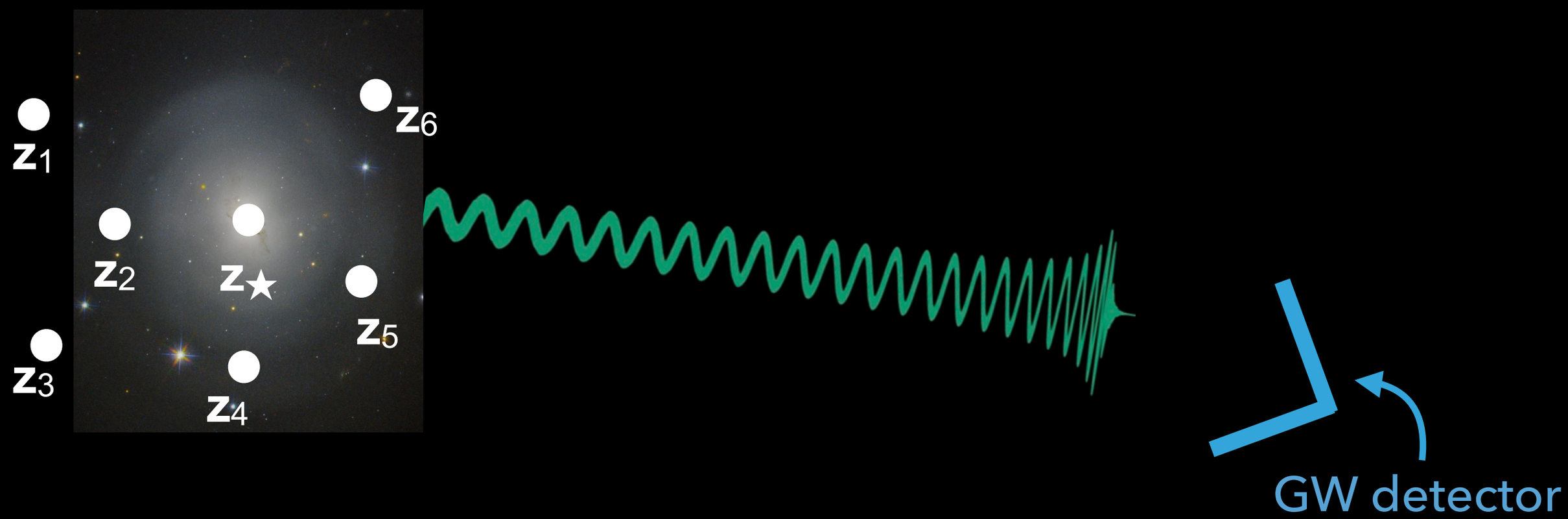
$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = H_0\sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}}$$

Schutz, Nature, 1986 / Holz & Hughes, ApJ, 2005

DARK SIREN

When there's no electromagnetic counterpart–it's difficult to identify the host galaxy



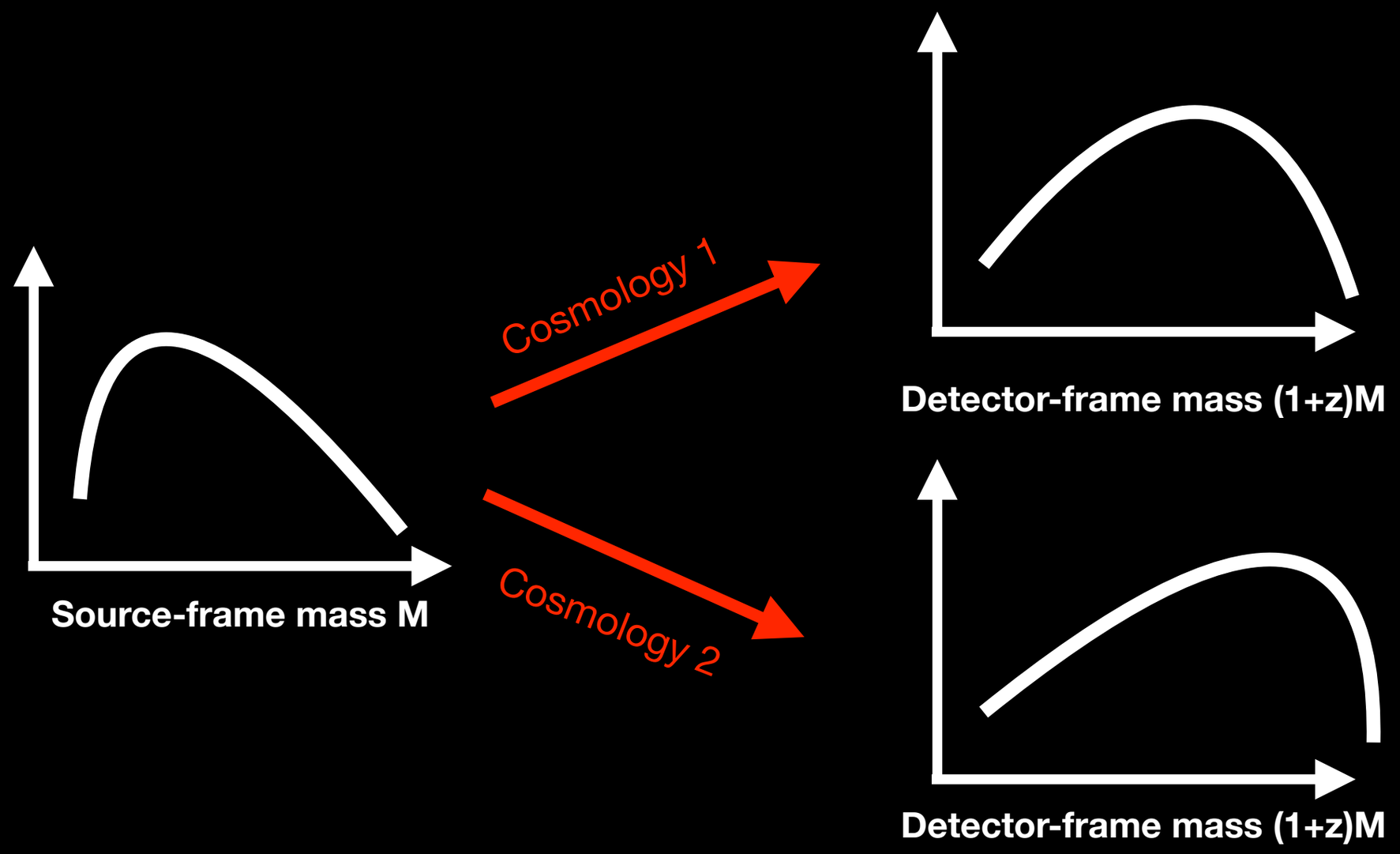
Combine the redshifts of all possible host galaxies.

Schutz, Nature, 1986/ Del Pozzo,PRD, 2011

Heavily relies on the availability/completeness of galaxy catalog.

SPECTRAL SIREN

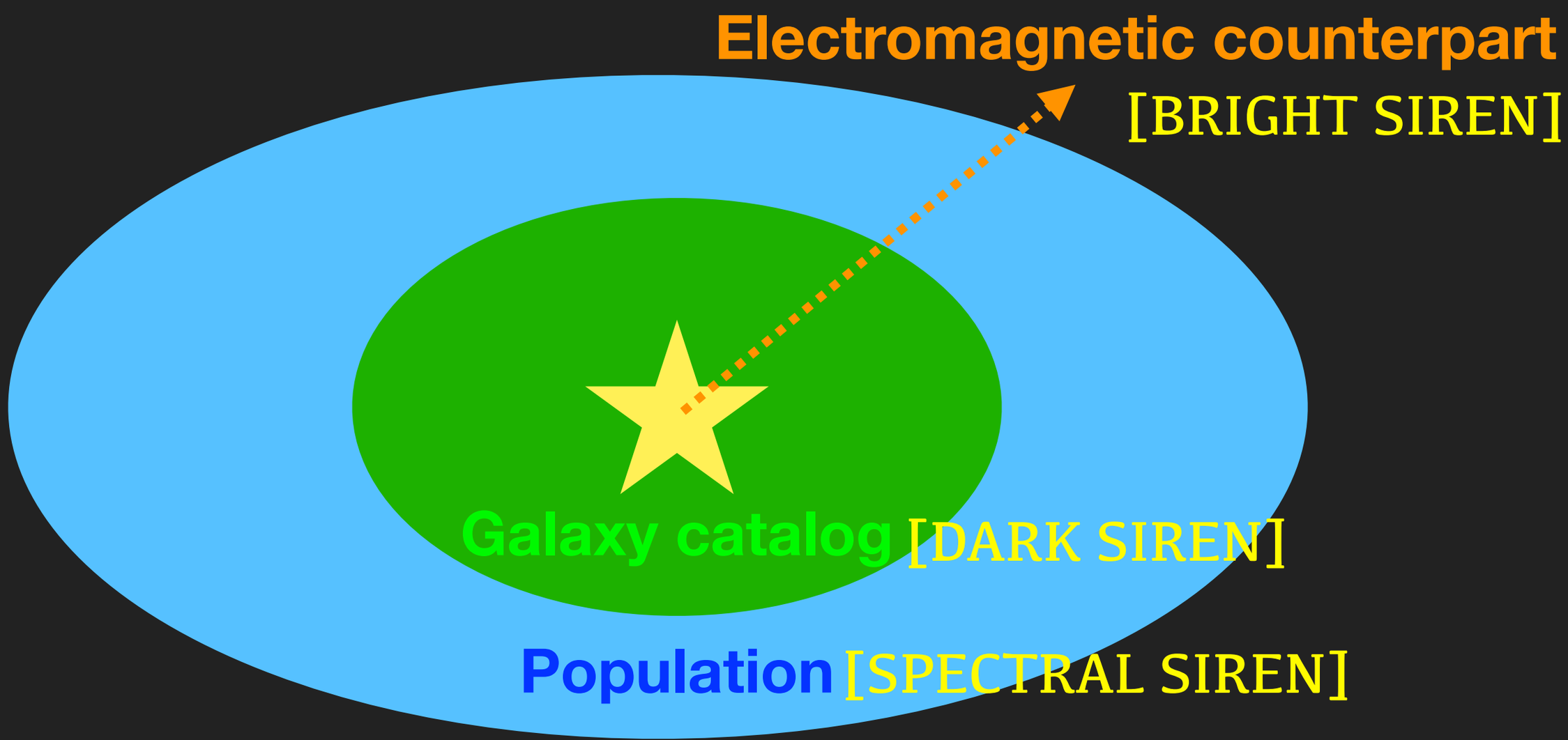
The detected mass and distance distribution of the binaries carries cosmological information too



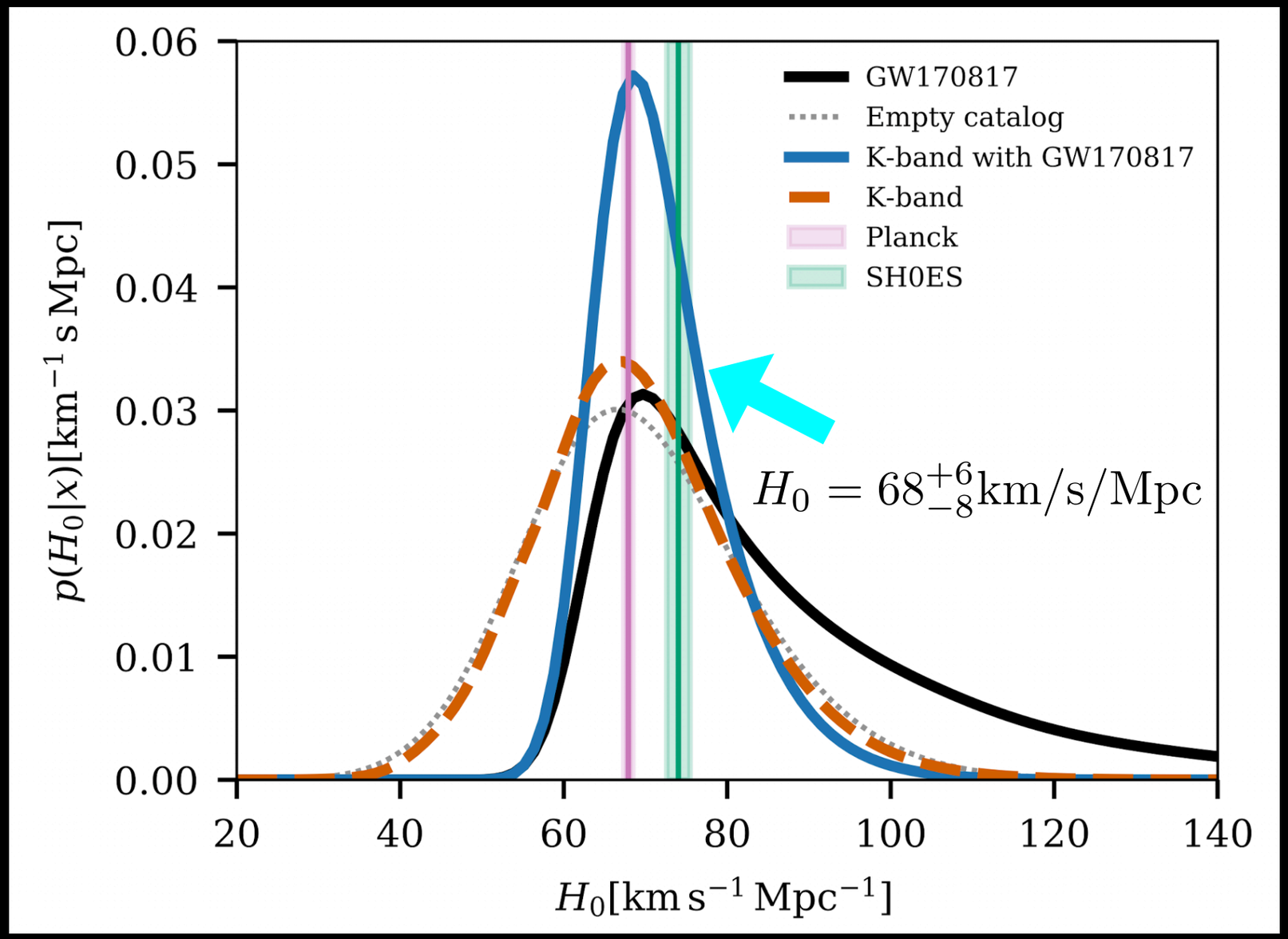
Taylor et al., PRD, 2012/Farr et al., ApJL, 2019/Mastrogiovanni, PRD, 2021/ Ezquiaga&Holz, PRL, 2022

The as ... *to be*
consis

The cosmological and population parameters have to be inferred jointly.


Electromagnetic counterpart
[BRIGHT SIREN]
Galaxy catalog [DARK SIREN]
Population [SPECTRAL SIREN]

Latest LIGO-Virgo-KAGRA standard siren measurement



LVK, 2111.03604

$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

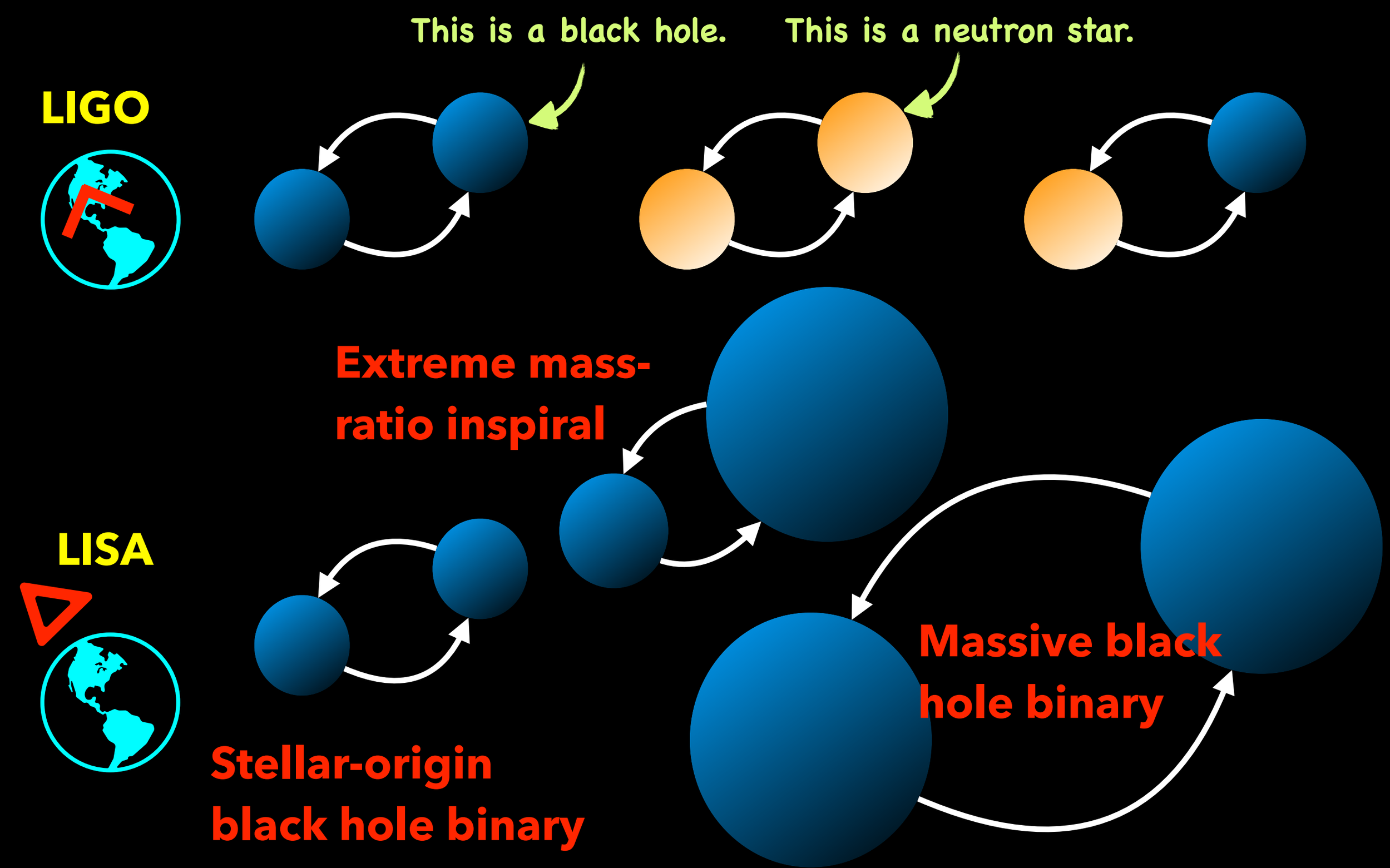
42 binary black hole mergers + 2 binary neutron star mergers + 2 neutron star-black hole mergers +GW190814

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}}$$

What will be different in the LISA era?

Standard siren sources

Gravitational-wave sources for standard sirens

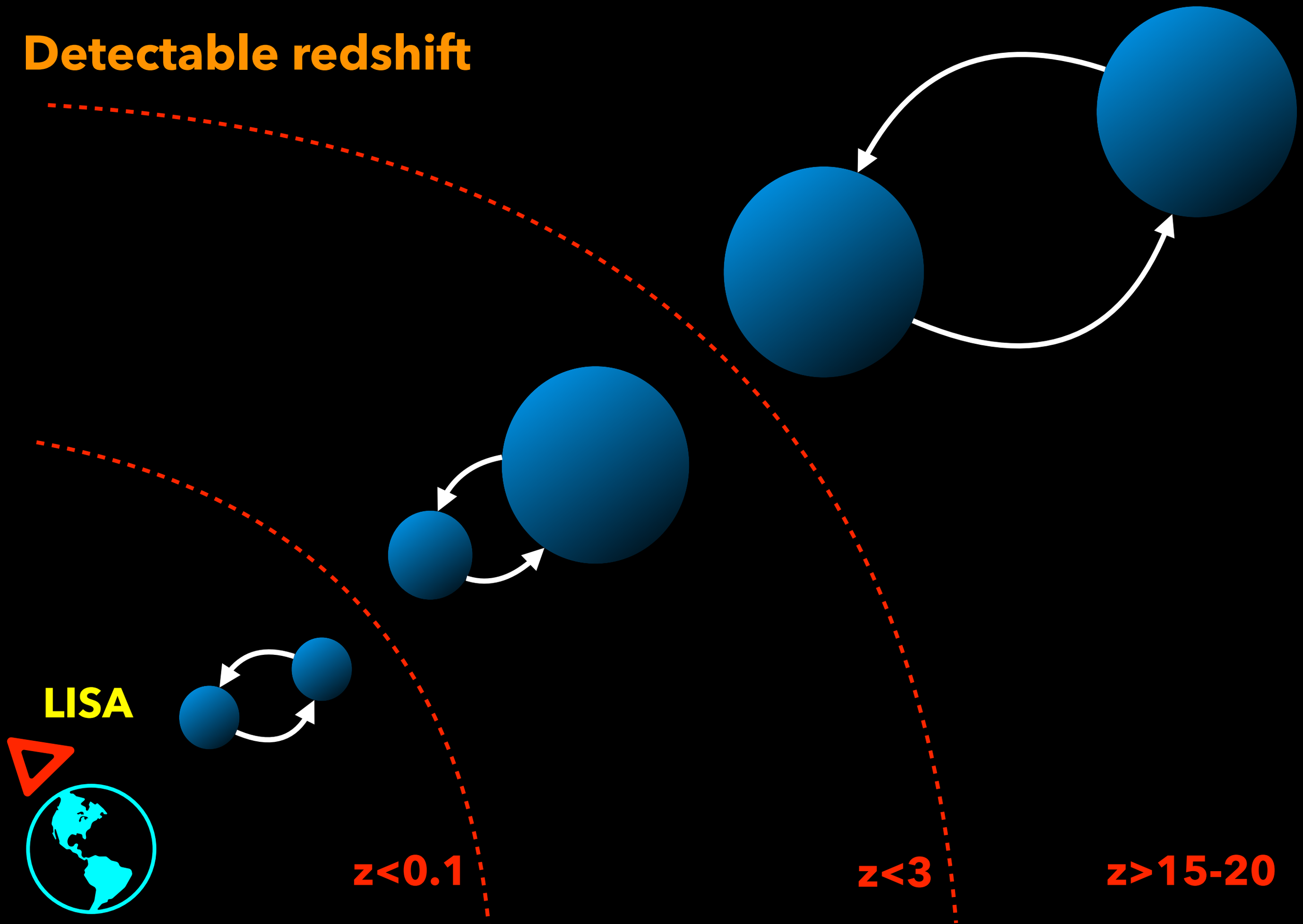


What will be different in the LISA era?

Standard siren sources

Redshift range

Detectable redshift



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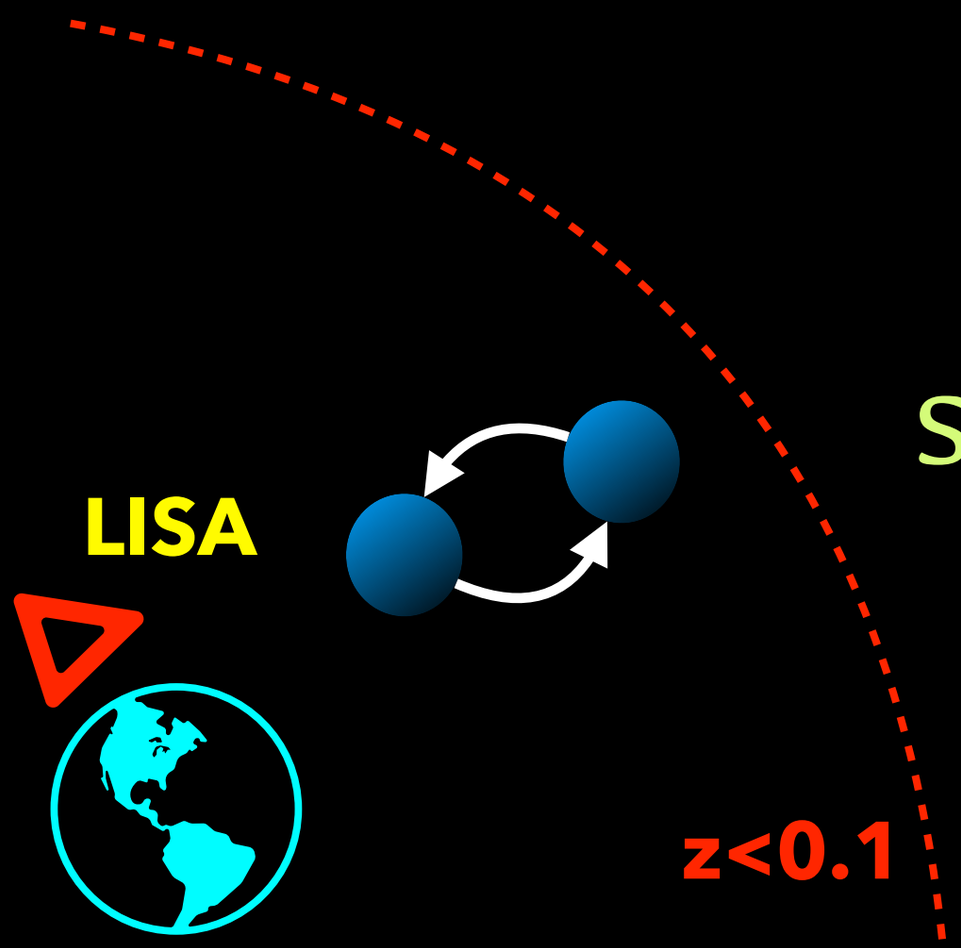
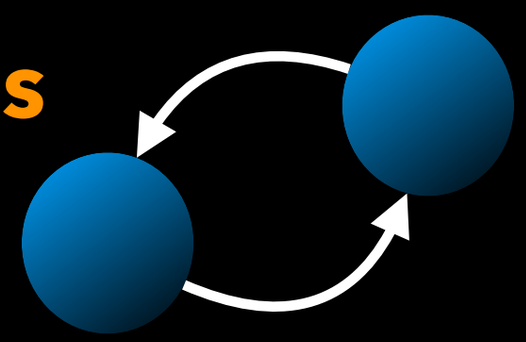


Stellar-origin black hole binaries

Stellar-origin binary black hole binaries



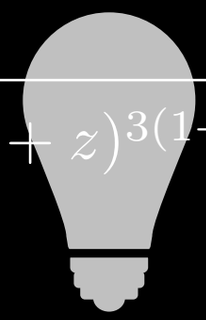
-LISA will detect them in the local Universe

*→**Best for H_0 measurement***

$$D_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

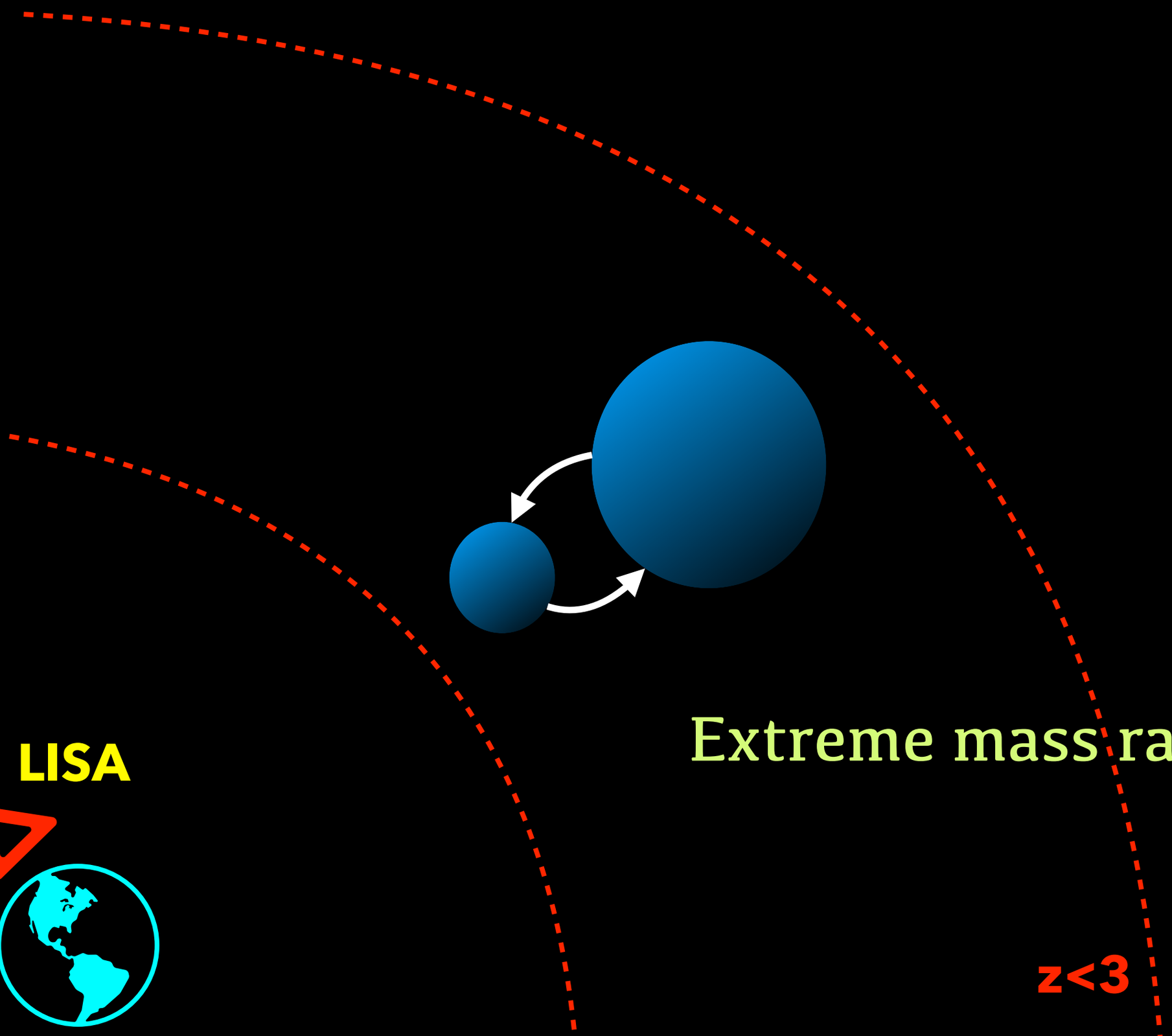
*-No widely accepted electromagnetic counterpart identified so far→**Dark Siren***

$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}}$$



[Need further verification: intermediate-mass black hole mergers may produce light.]

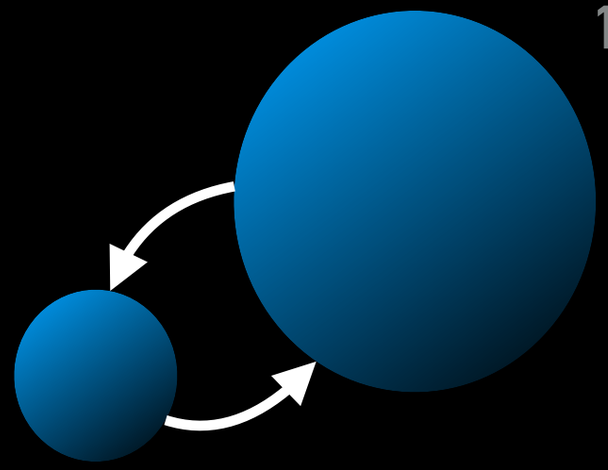
Graham et al., PRL (2020)



Extreme mass ratio inspirals

LISA

Extreme mass ratio inspirals

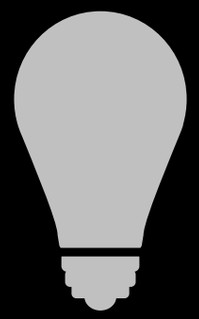


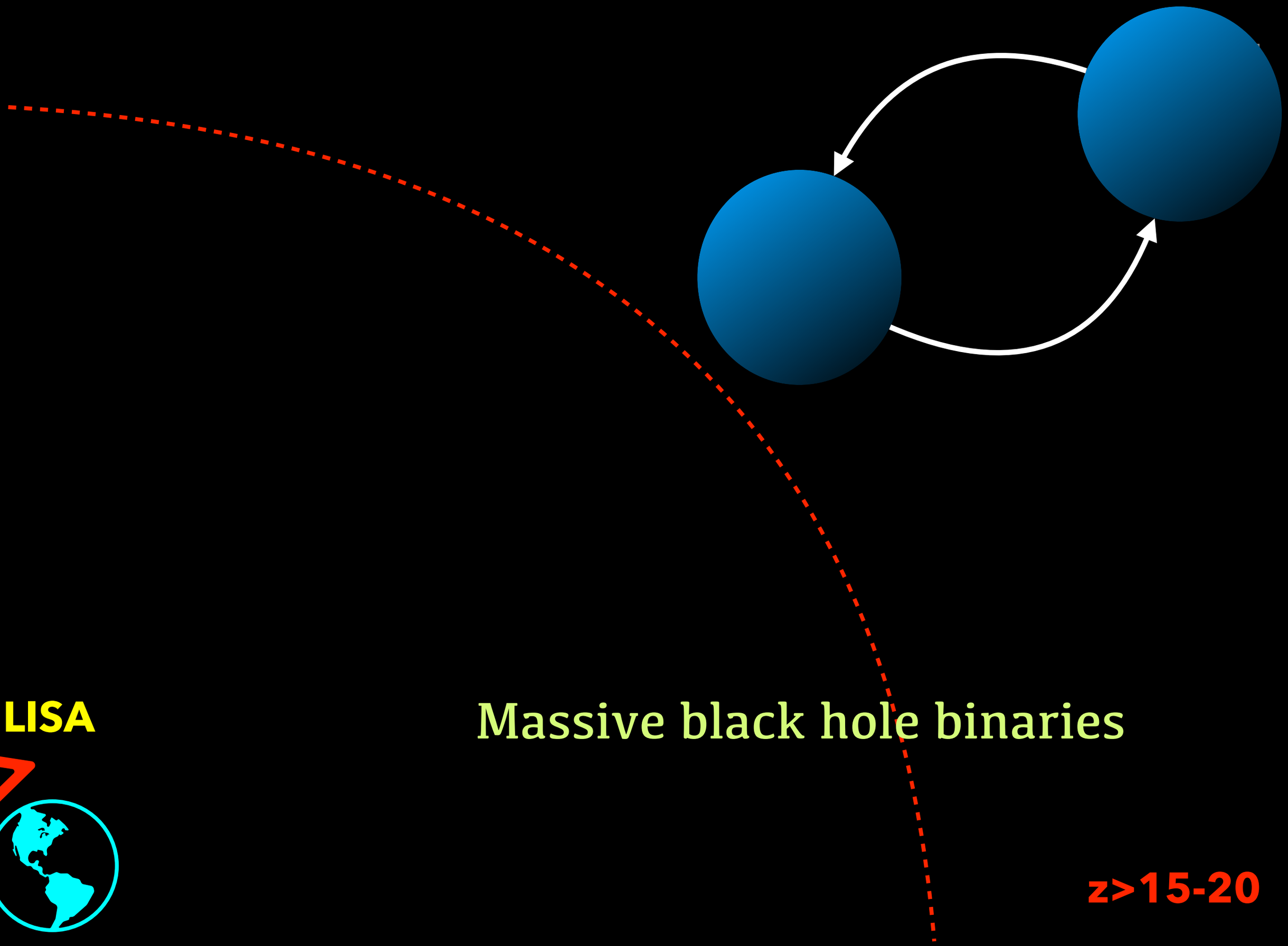
-LISA will detect them further away

→***Measurement of dark energy equation-of-state (w) in addition to H_0***

-No electromagnetic counterpart expected

→***Dark Siren***





LISA

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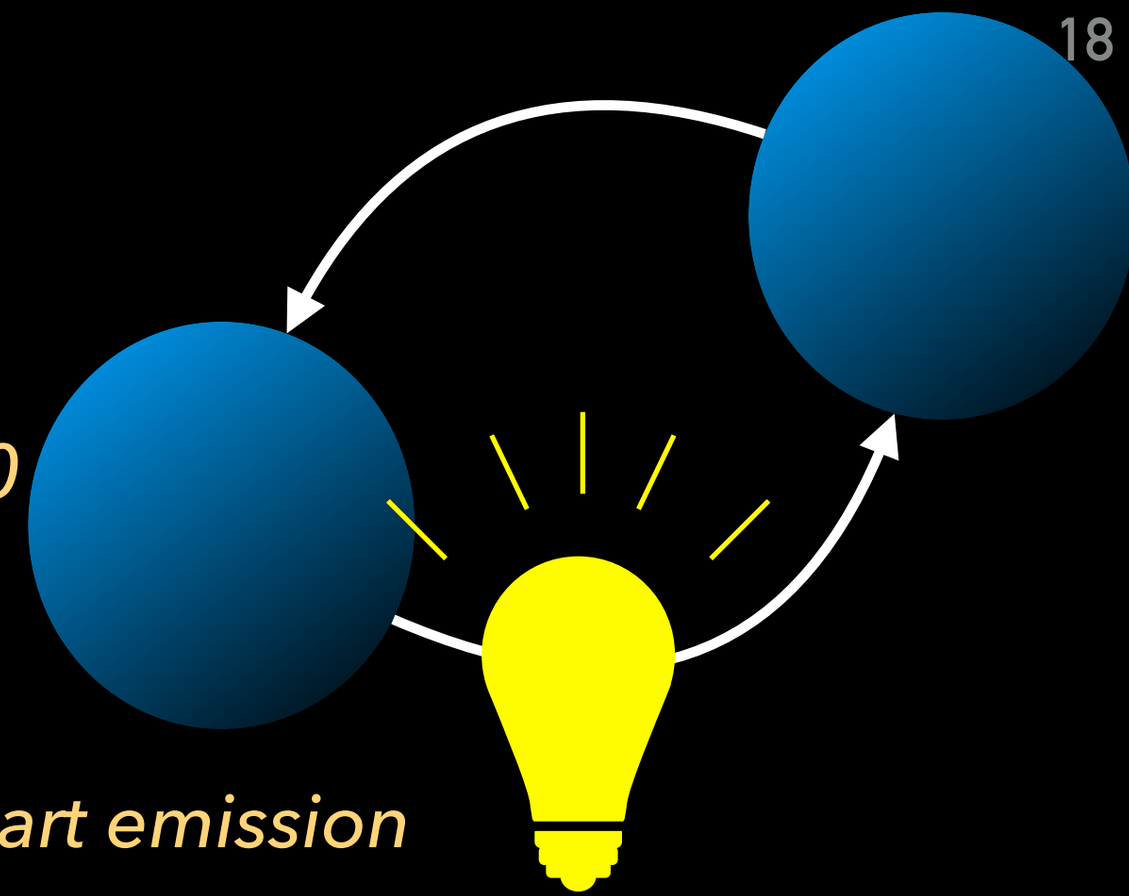
Massive black hole binaries



-LISA will detect them up to z=15-20
*→**Constraint on H(z) at high z***

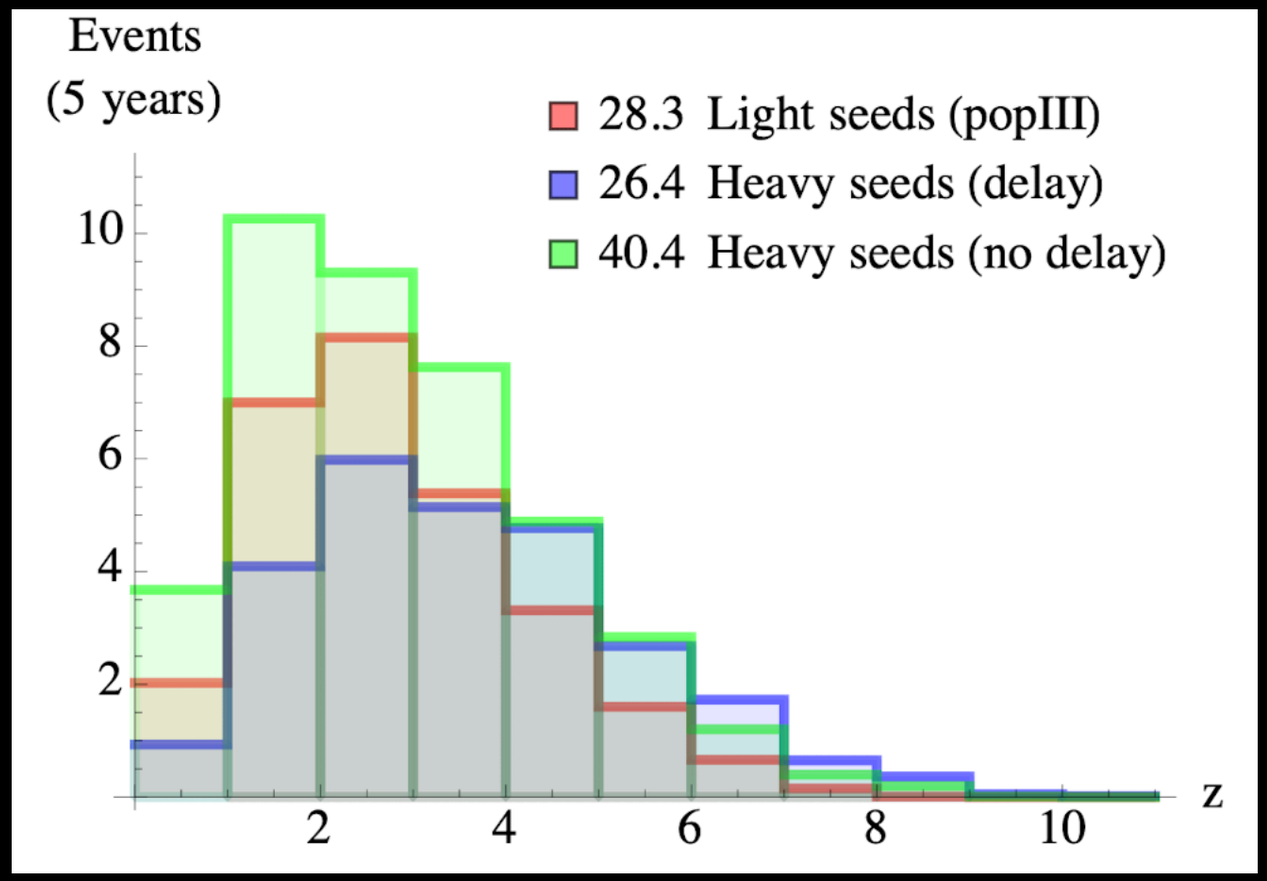
*-Potential electromagnetic counterpart emission in optical/x-ray/radio→**Bright Siren***

Tamanini et al., JCAP, 2016

-The number of bright sirens is highly uncertain:

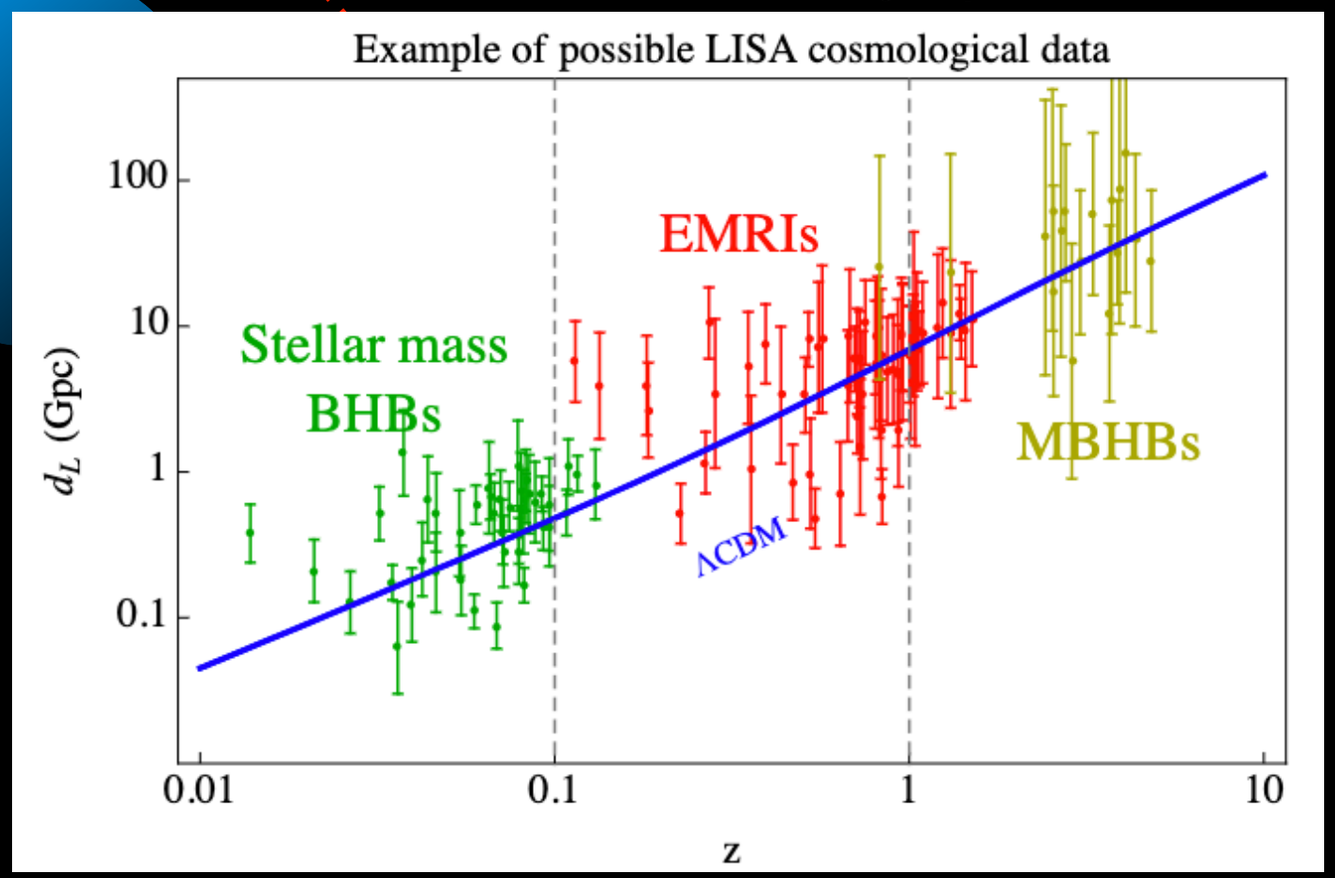
–Black hole seeding models

–EM emission models



Independent cosmological measurement across cosmic history

Tamanini, LISA Symposium, 2016



LISA

z<0.1

z<3

z>15-20

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Accuracy of the measurements

Systematic uncertainties

Potential sources of systematics

Distance

Waveform

Calibration

Lensing

Population

Population distribution

EM selection

Potential sources of systematics

Distance

Waveform

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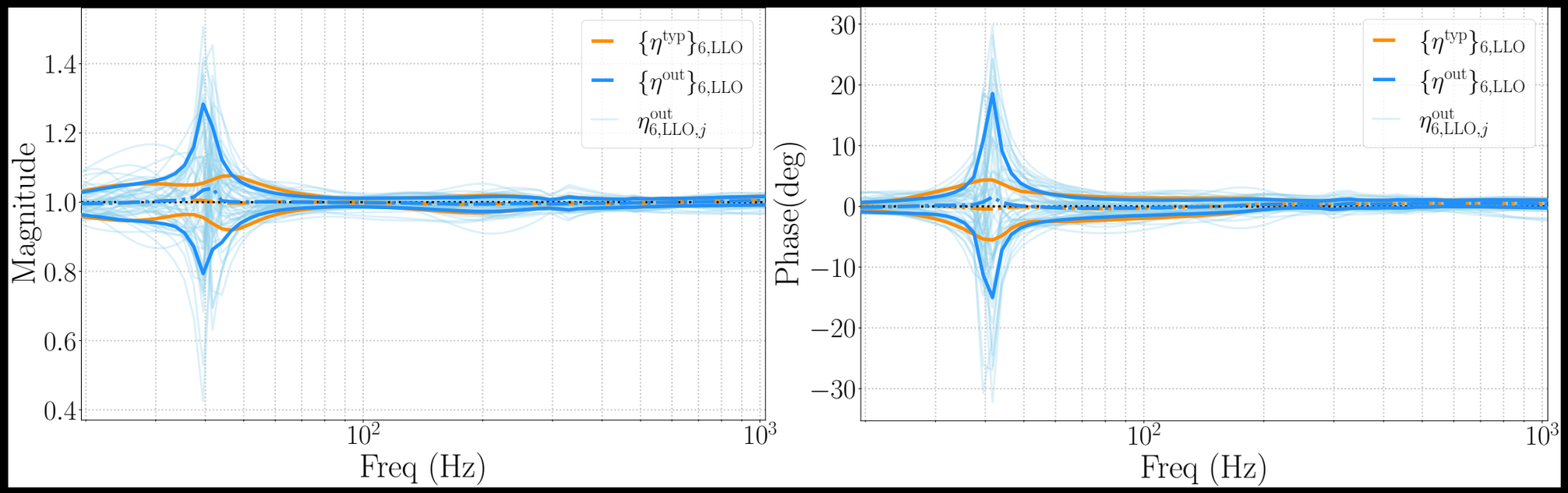
Systematics associated with the distance measurement

Instrumental calibration uncertainty

Sun et al., CQG (2020) / Sun et al., 2107.00129

-Imperfect conversion from the voltage signals to the data stream.



Potential sources of systematics

Distance

Waveform

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Systematics associated with the distance measurement

Weak Lensing

-$D_L' = (1-\kappa)D_L$

κ is the convergence for the lensing by large scale structure

-2% for z<1, 5% at z=2

-Can be reduced with galaxy survey

Hilbert et al, MNRAS (2011)/ Hilbert et al, PRD (2010)

-Selection effect for high-redshift sources

Cusin and Tamanini, MNRAS (2021)

-Redshift+LISA luminosity distance measurement can be used to constrain the clustering parameters.

Cutler and Holz, PRD (2009)/Camera and Nishizawa, PRL (2013)/
Congedo and Taylor, PRD (2019)

Potential sources of systematics

Distance

Waveform

Calibration

Lensing

Population

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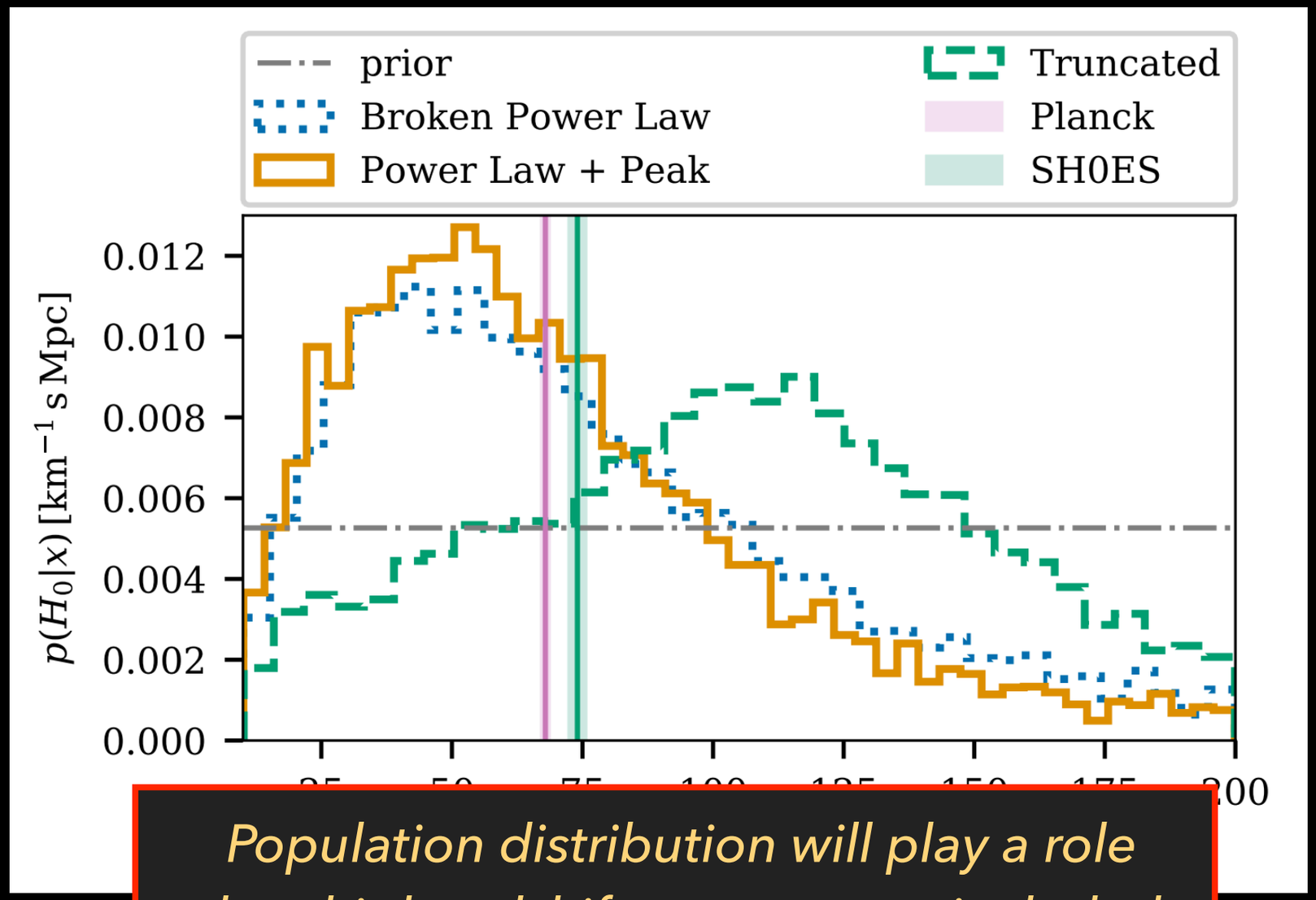
Systematics associated with the population

Distribution of the merger population



Population distribution will play a role when high redshifts sources are included.

Abbott et al., ApJ in press

Potential sources of systematics

Distance

Waveform

Calibration

Lensing

Population

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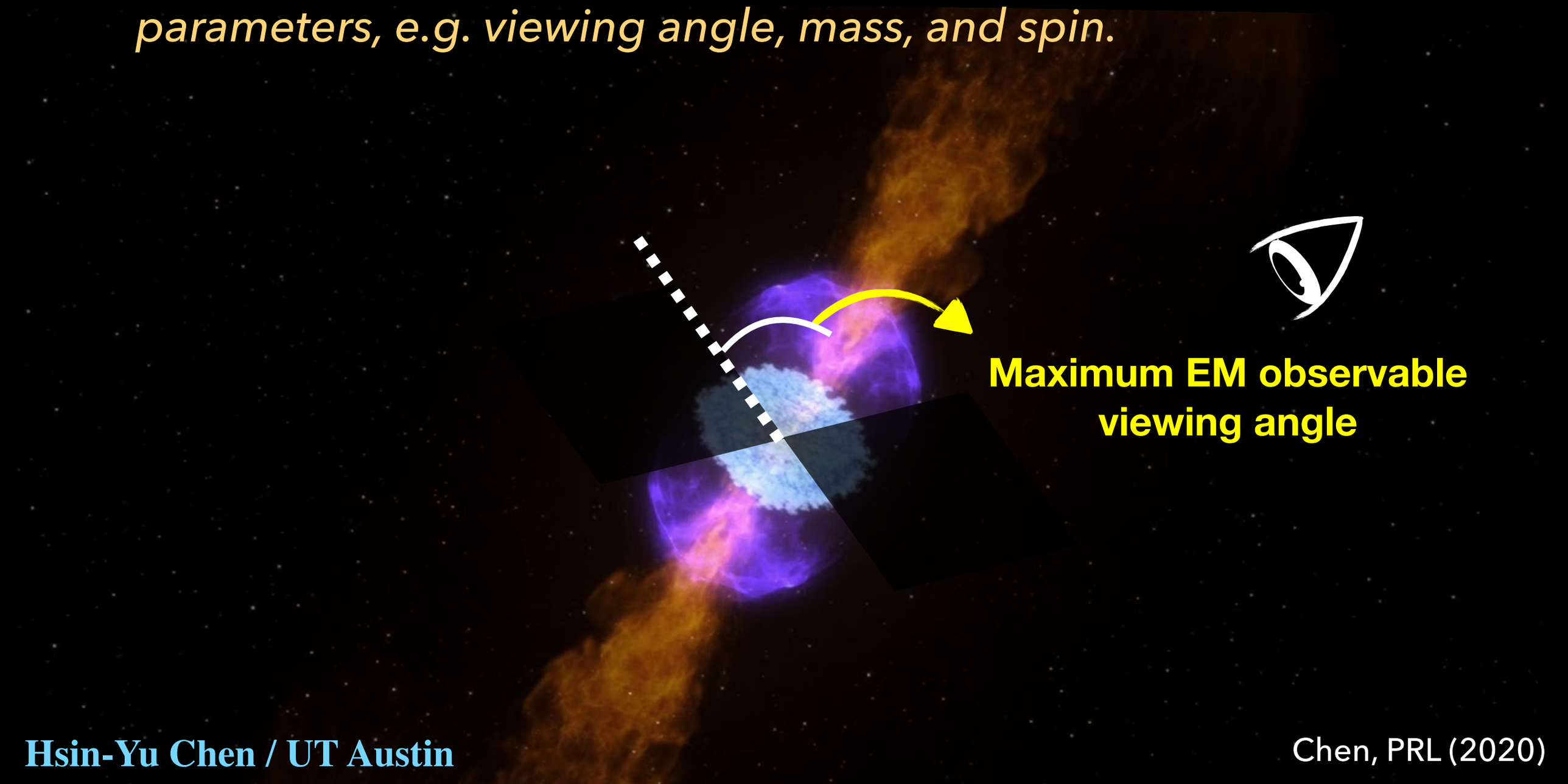
EM selection

Systematics associated with the population

Counterpart selection effect

-Variation of counterpart observability as a function of the binary parameters, e.g. viewing angle, mass, and spin.

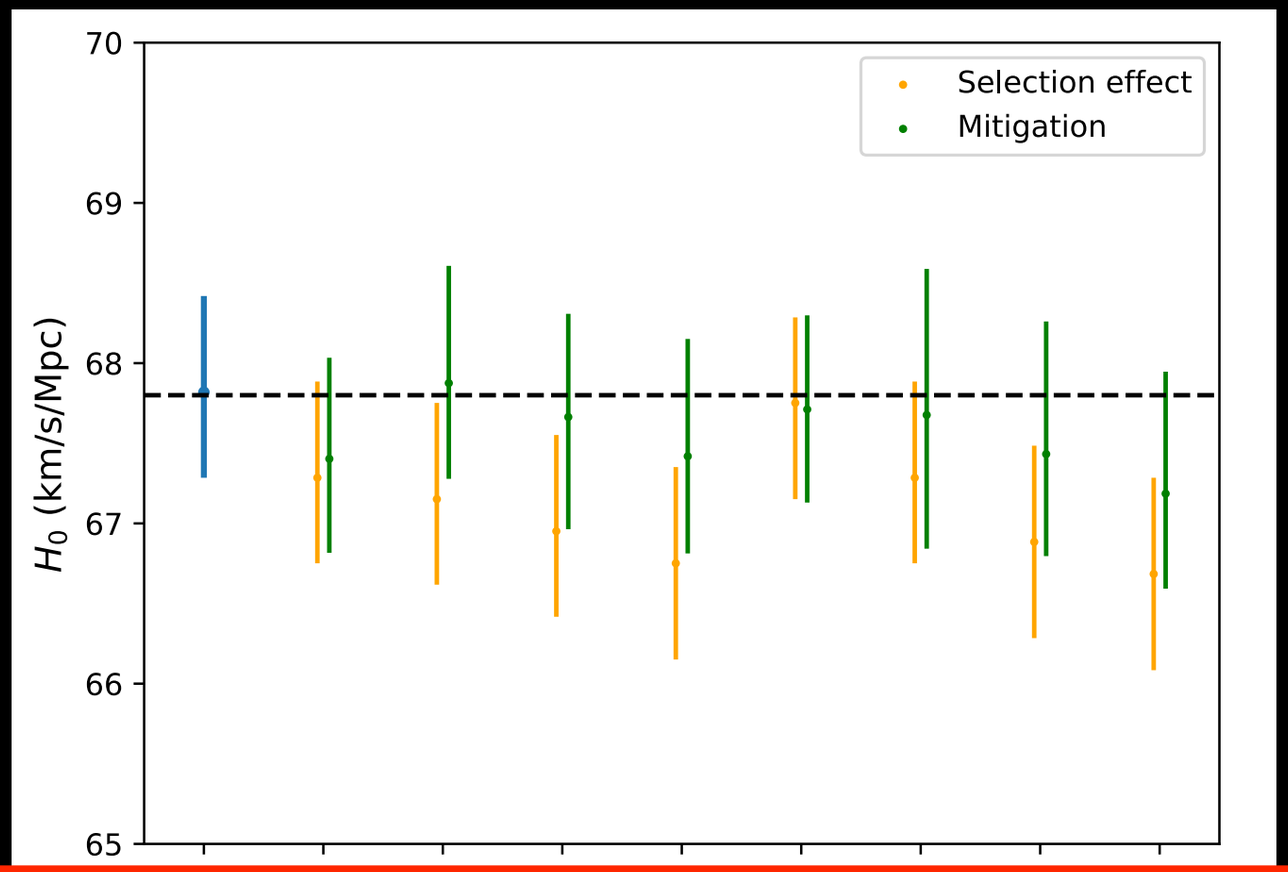


Chen, PRL (2020)

Systematics associated with the population

Counterpart selection effect

-Variation of counterpart observability as a function of the binary parameters, e.g. viewing angle, mass, and spin.



Mitigation of the effect could be easier for LISA given better parameter estimation.

Chen, Talbot, Chase, 2307.10402

Potential sources of systematics

Distance

Waveform

Calibration

Lensing

We currently are lack of comprehensive estimate/mitigation for many of these systematics in standard siren measurements.

Population

Population distribution

EM selection

Science Objectives of the WP

-Map the expansion rate of the Universe at all redshifts

-Test the standard cosmological model

Available Tools: for LISA

CosmoLISA

Laghi et al, MNRAS (2021)

-LISA (and 3G) bright and dark siren forecast.

-Publicly available: github.com/wdpozzo/cosmolisa

Laghi & Del Pozzo

-Proposed to be a colalborative project for LISA working group.

-Still need to implement spectral siren and several necessary technical details (e.g., selection effect, incompleteness of galaxy catalogue).

Available Tools: for LIGO/Virgo/KAGRA

-***ICAROGW*** Mastrogiovanni et al, PRD (2023)

Dark siren + Spectral siren

-***GWCOSMO*** Gray et al, to be on arXiv

Dark siren + Spectral siren

-***DarkSirensStat*** Finke et al, JCAP (2021)

Dark sirens and modified GW propagation.

To be developed

-Bright+dark+spectral siren inference.

-Comprehensive estimate of the systematics.

-Mitigation of the systematics.

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Horizon/PE uncertainty for stellar mass BBH

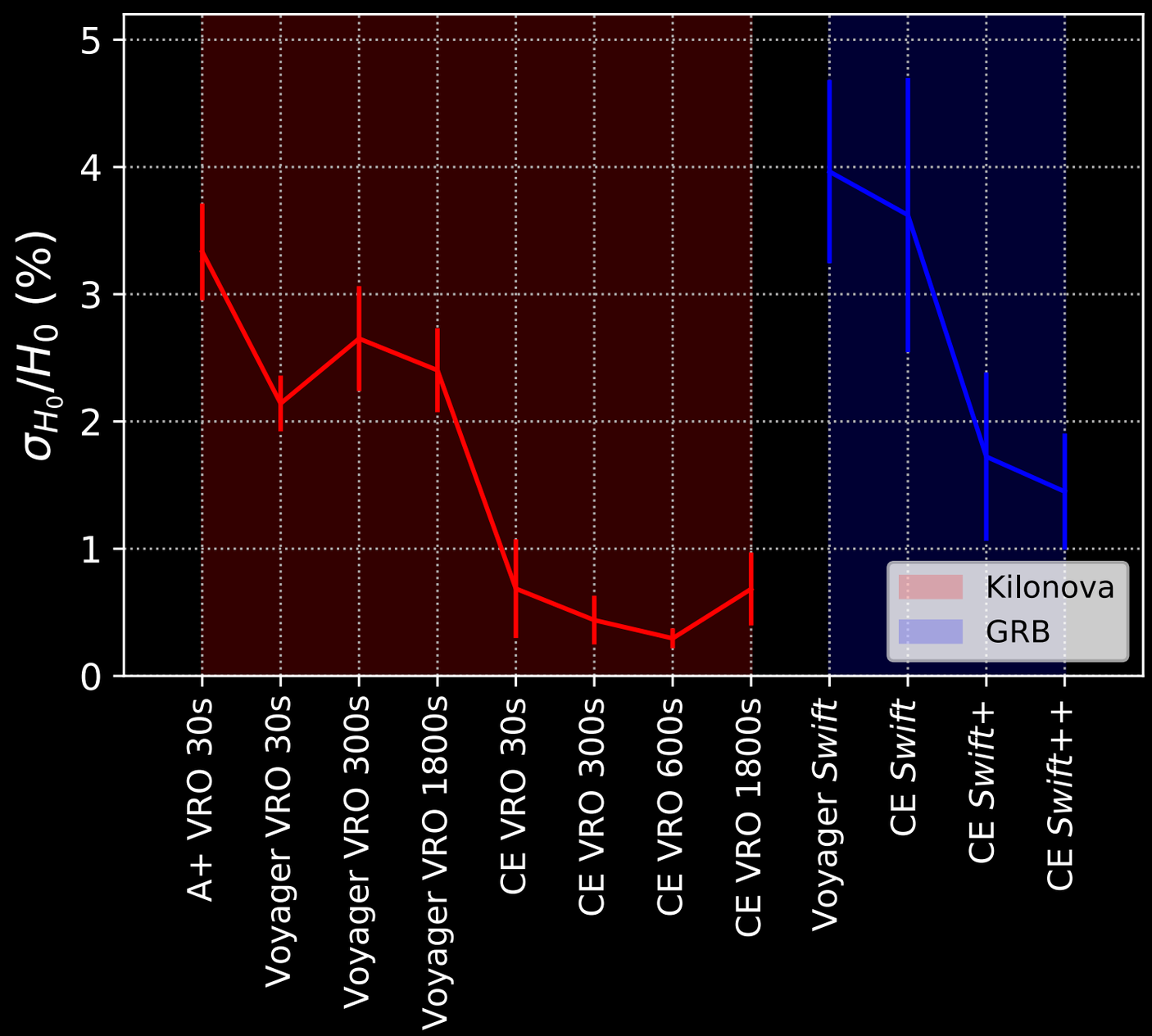
Source type	Masses [$M_\odot$]	red D_L [kpc]	yellow D_L [kpc]	green D_L [kpc]
BBH low	$5+5$	580	1164	2330
BBH mid	$10+10$	1849	3697	7396
GW150914	$36+29$	13031	26062	52129
GW190814	$85+65$	52875	105749	214603

Table 2: Maximum luminosity distances for T_{obs}= 4 yr (6 yr at 75% duty cycle) assuming an averaged sky location, polarization, and inclination. The green FoM is assuming the current mission design, yellow (red) is current mission design but T_{obs}= 1 yr (3 mo) to mimic sensitivity degradation

	LIGO/Virgo	**ET**	**LISA**	**ET+LISA**
$\Delta\Omega$ [deg^2]	5.6×10^{2}	5.1	2.5	2.2×10^{-1}
$\Delta d_L/d_L$	3.6	3.4×10^{-1}	4.3×10^{-1}	3.9×10^{-2}
$\Delta\mathcal{M}/\mathcal{M}$	3.6×10^{-1}	3.3×10^{-3}	4.1×10^{-7}	2.0×10^{-7}
$\Delta\iota/\iota$	5.9	4.7×10^{-1}	9.3×10^{-1}	6.5×10^{-2}
$\Delta\chi_1/\chi_1$	3.9	2.8×10^{-2}	3.3×10^{-1}	8.6×10^{-4}
$\Delta\chi_2/\chi_2$	3.8	3.0×10^{-2}	4.6×10^{-1}	1.4×10^{-3}

TABLE III. Medians of the uncertainty distributions of each parameter for LIGO/Virgo, ET, LISA and the network ET+LISA, assuming 10 years LISA mission time. Here $\mathcal{M}$ represents the *chirp mass* of the system, defined as $\mathcal{M} = (M_1M_2)^{(3/5)}/(M_1+M_2)^{(1/5)}$ and its uncertainty is obtained through error propagation formulas.

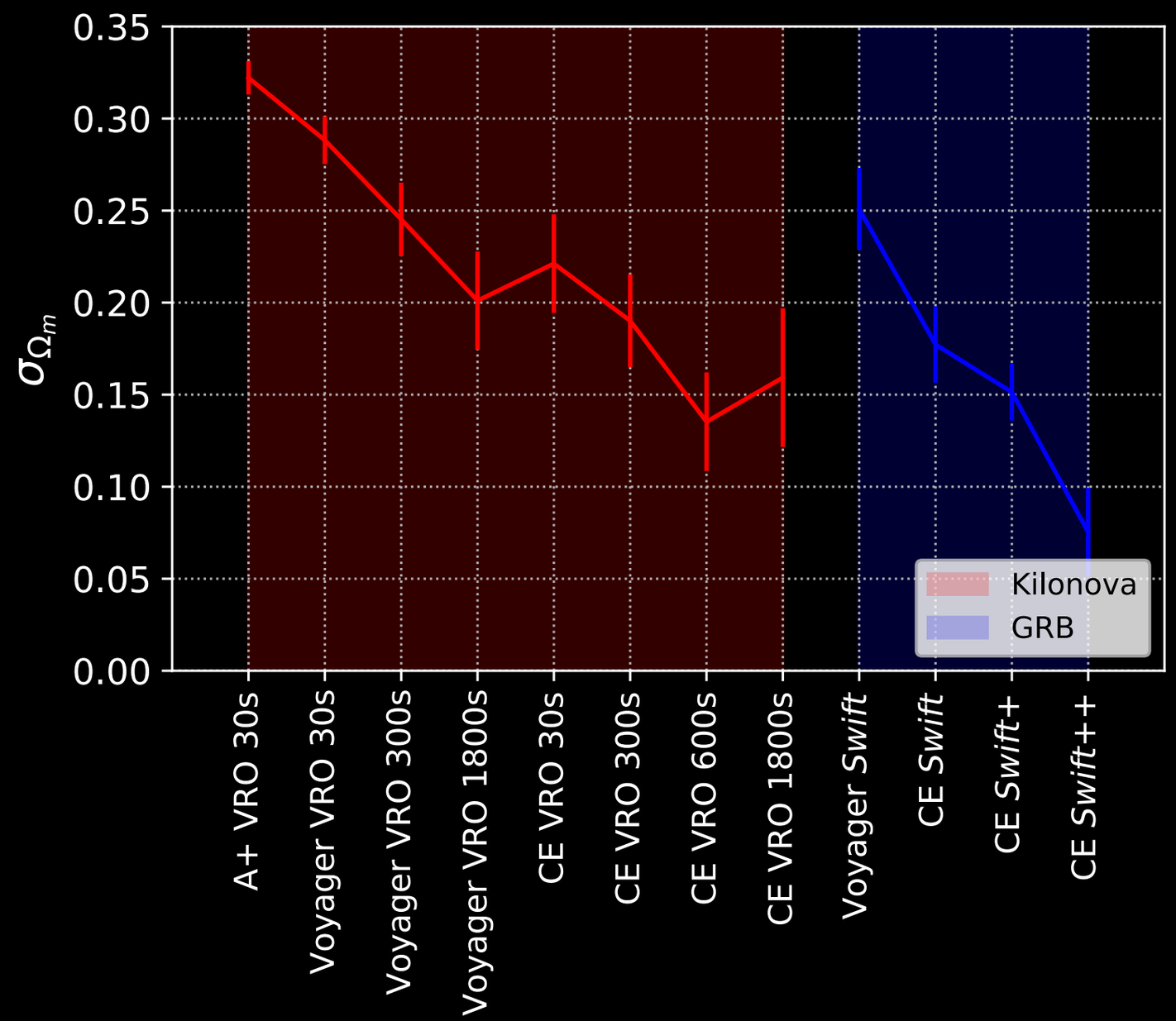
Cosmological constraints from bright sirens in 2.5-3G



-A+ and Voyager still at percent level. Sub-percent level precision is possible in CE era.

-Kilonovae are better than GRBs for H_0 constraint.

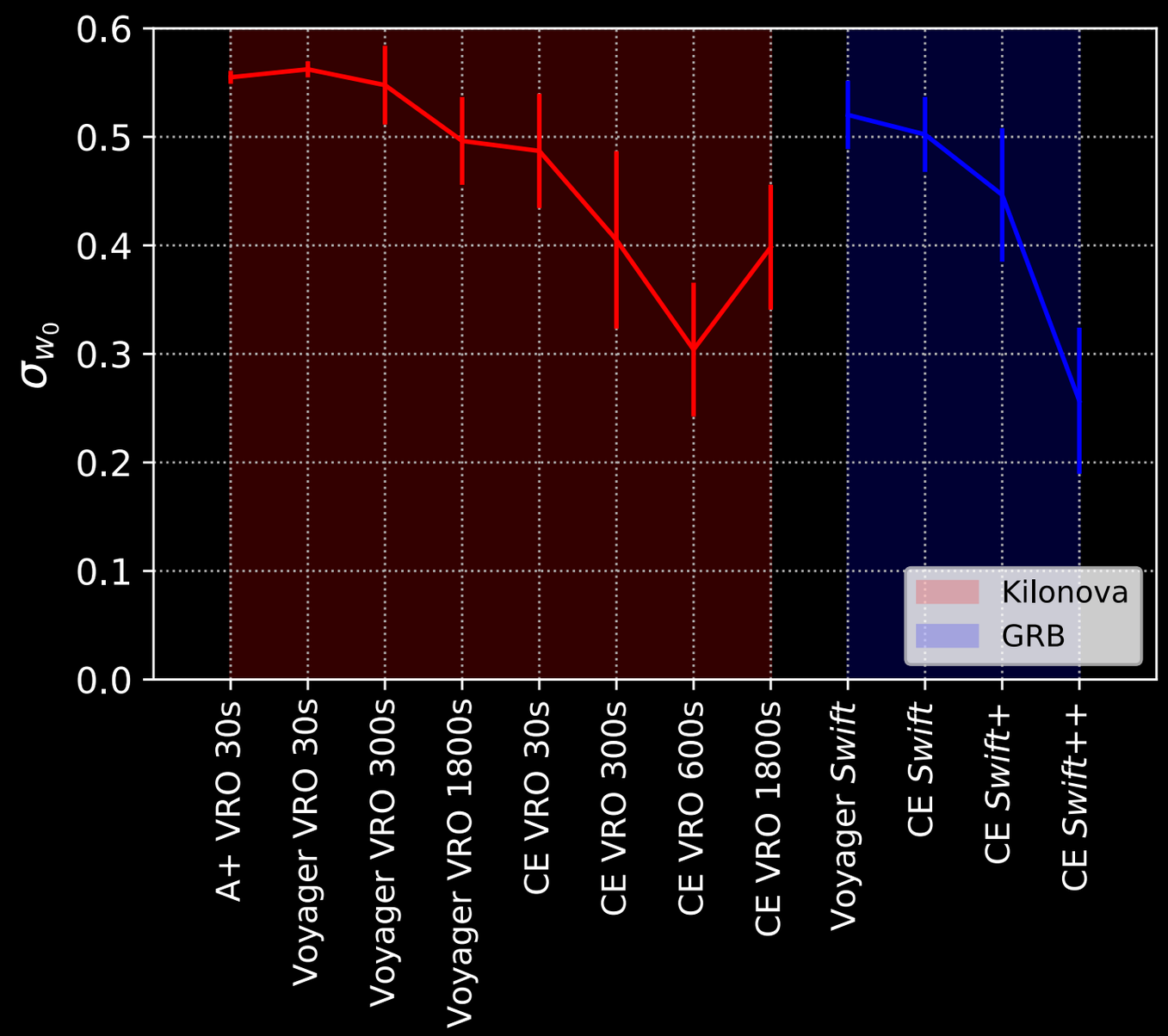
Cosmological constraints from bright sirens in 2.5-3G



-GRBs are better than kilonovae to constrain Ω_m and w.

-One order of magnitude fewer GRBs (with beaming) is needed to achieve the same precision as kilonovae.

Cosmological constraints from bright sirens in 2.5-3G

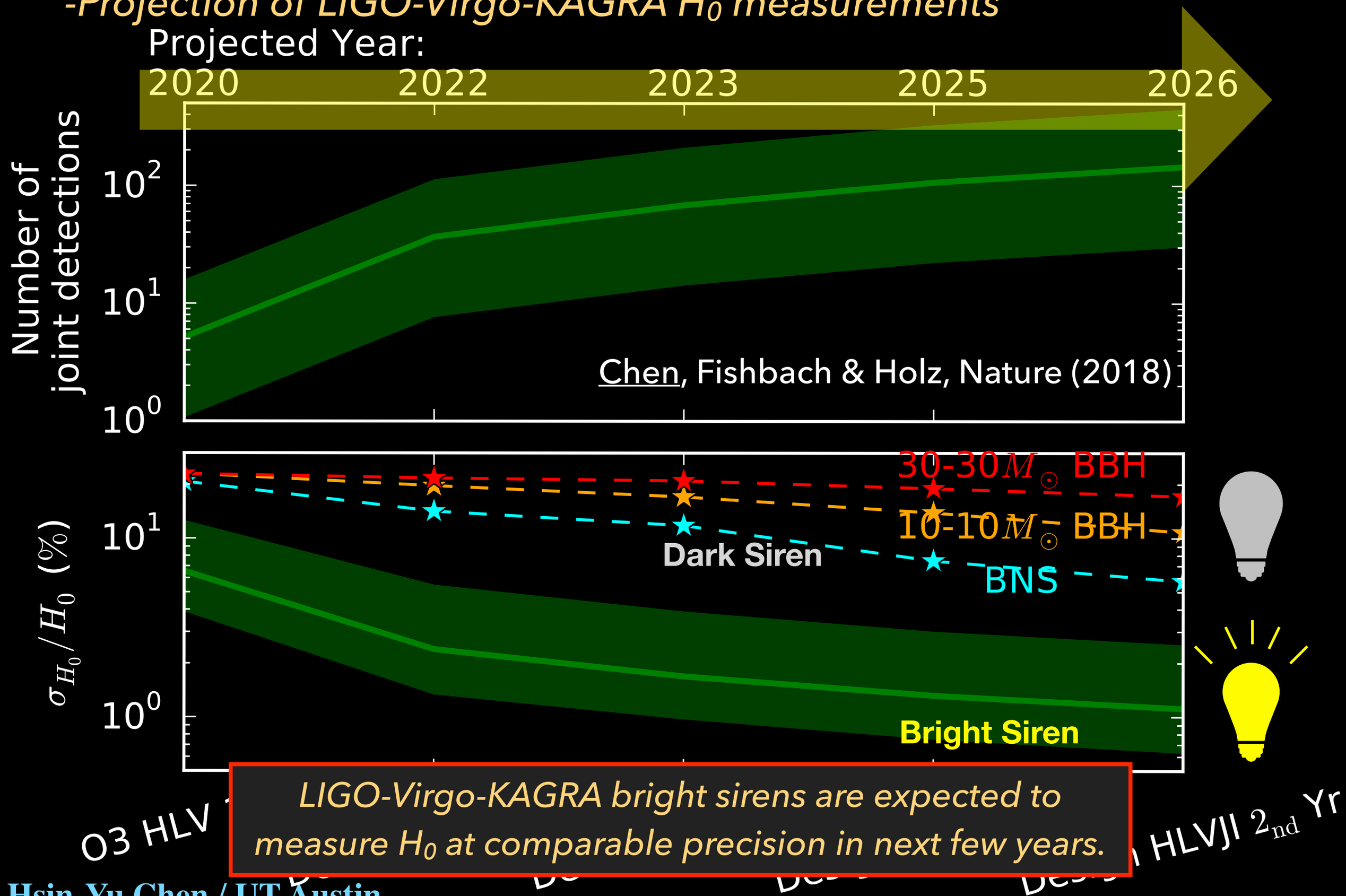


-Swift-like GRB telescope with larger field-of-view and better sensitivity is in need in the CE era.

-Otherwise, dedicated VRO-like telescope is needed in absence of the GRB telescope described above.

Comparison with GW/EM observations in the future

-Projection of LIGO-Virgo-KAGRA H_0 measurements



LIGO-Virgo-KAGRA bright sirens are expected to measure H_0 at comparable precision in next few years.