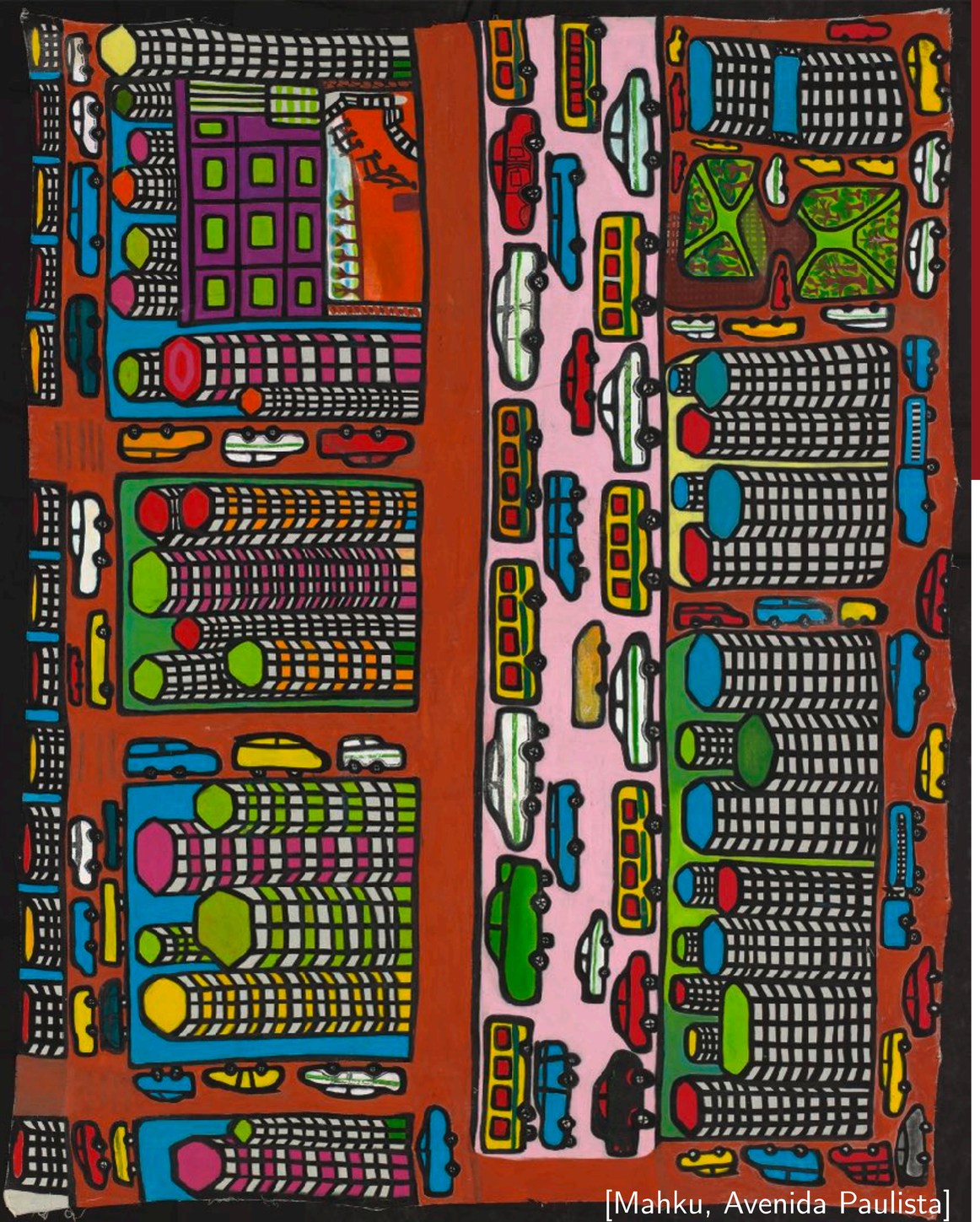


[Mahku, Avenida Paulista]

Jose María Ezquiaga

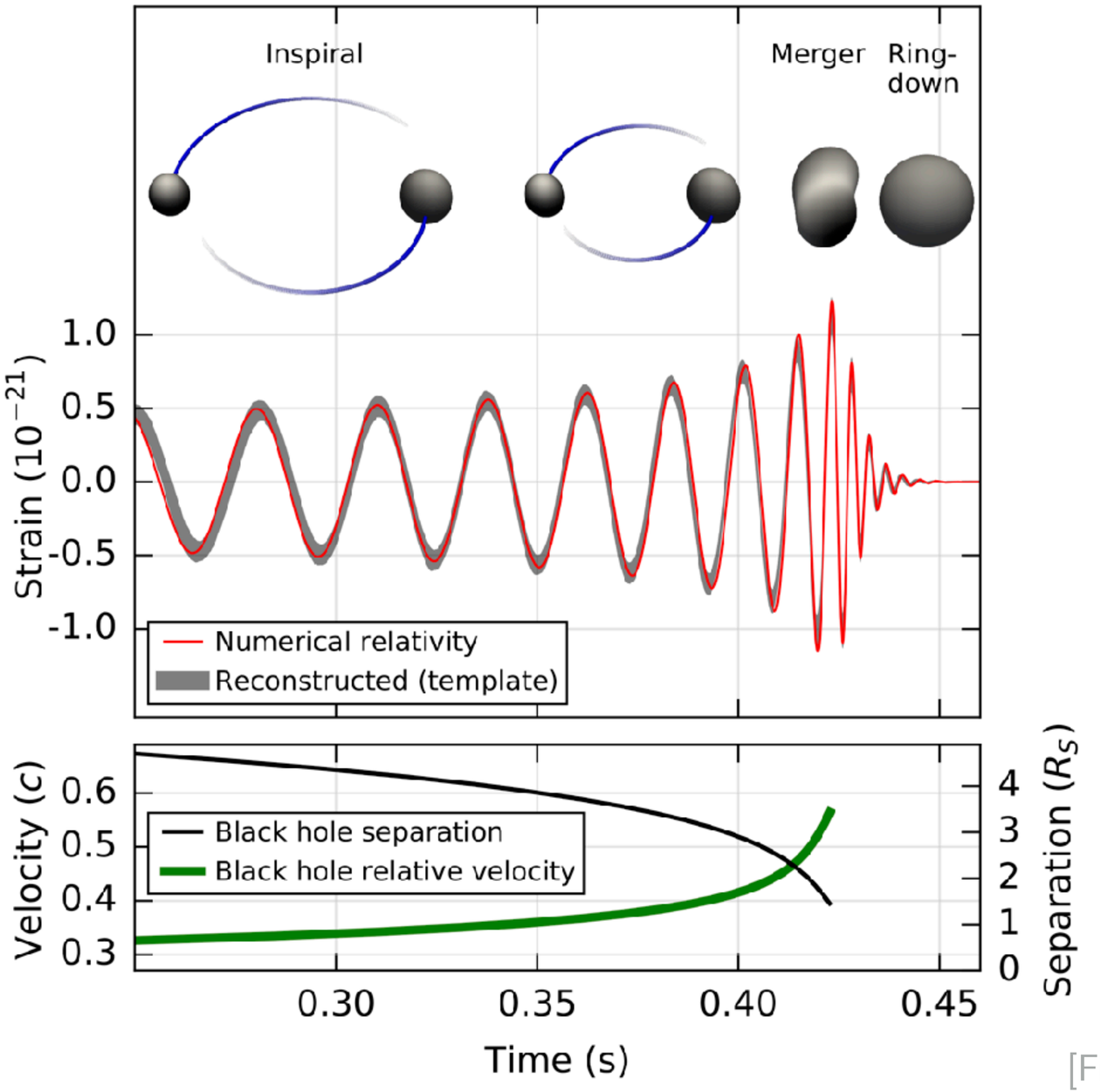
Niels Bohr Institute

ezquiaga.github.io

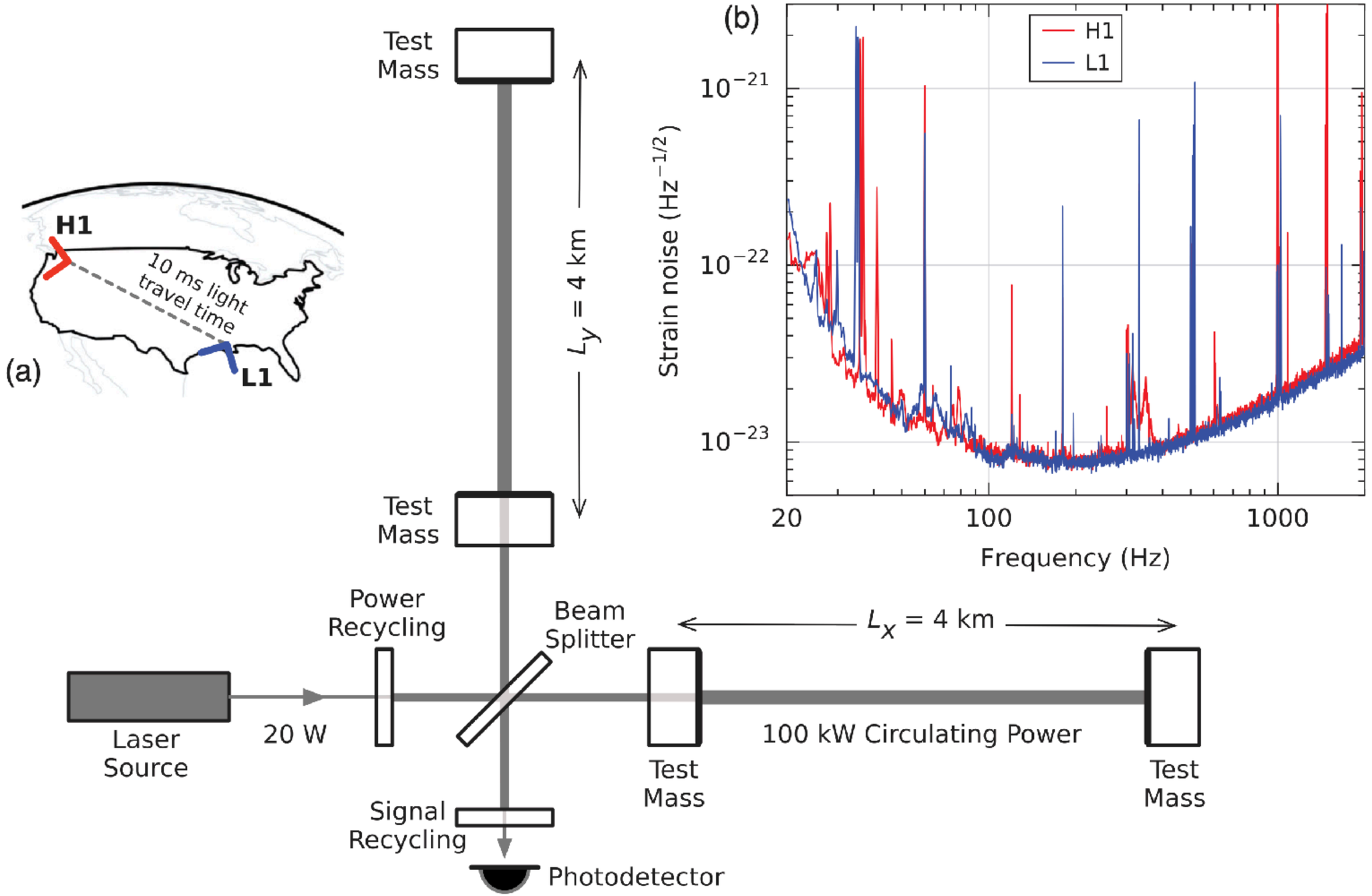
THE CENTER OF GRAVITY

VILLUM FONDEN

Gravitational waves from stellar-mass **binary black holes**

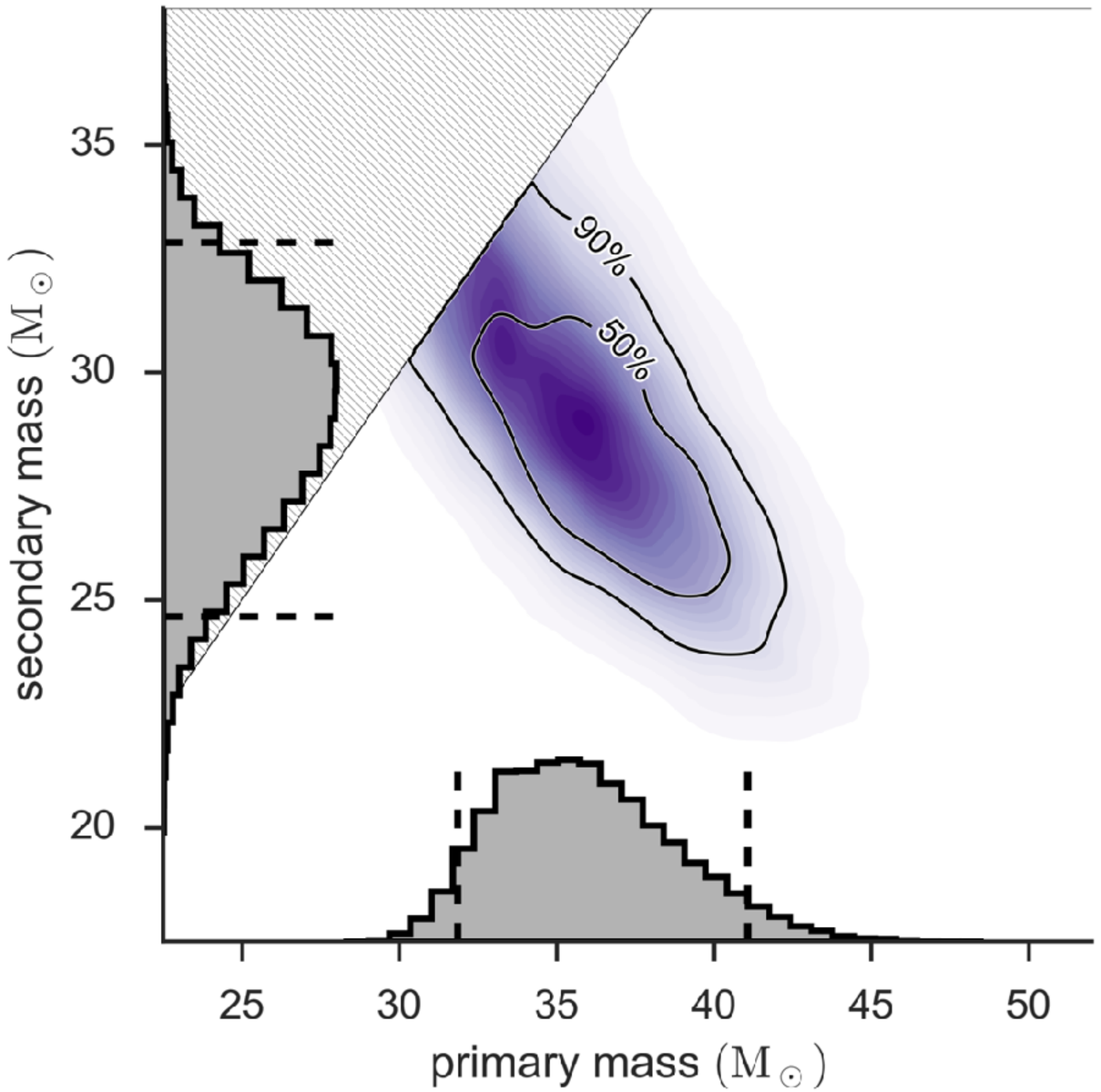


[First detection, GW150914]


H1
10 ms light travel time
L1
(a)
Test Mass
L_y = 4 km
Test Mass
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
(b)
H1
L1
10^{-21}
10^{-22}
10^{-23}
Strain noise ($Hz^{-1/2}$)
20
100
1000
Frequency (Hz)

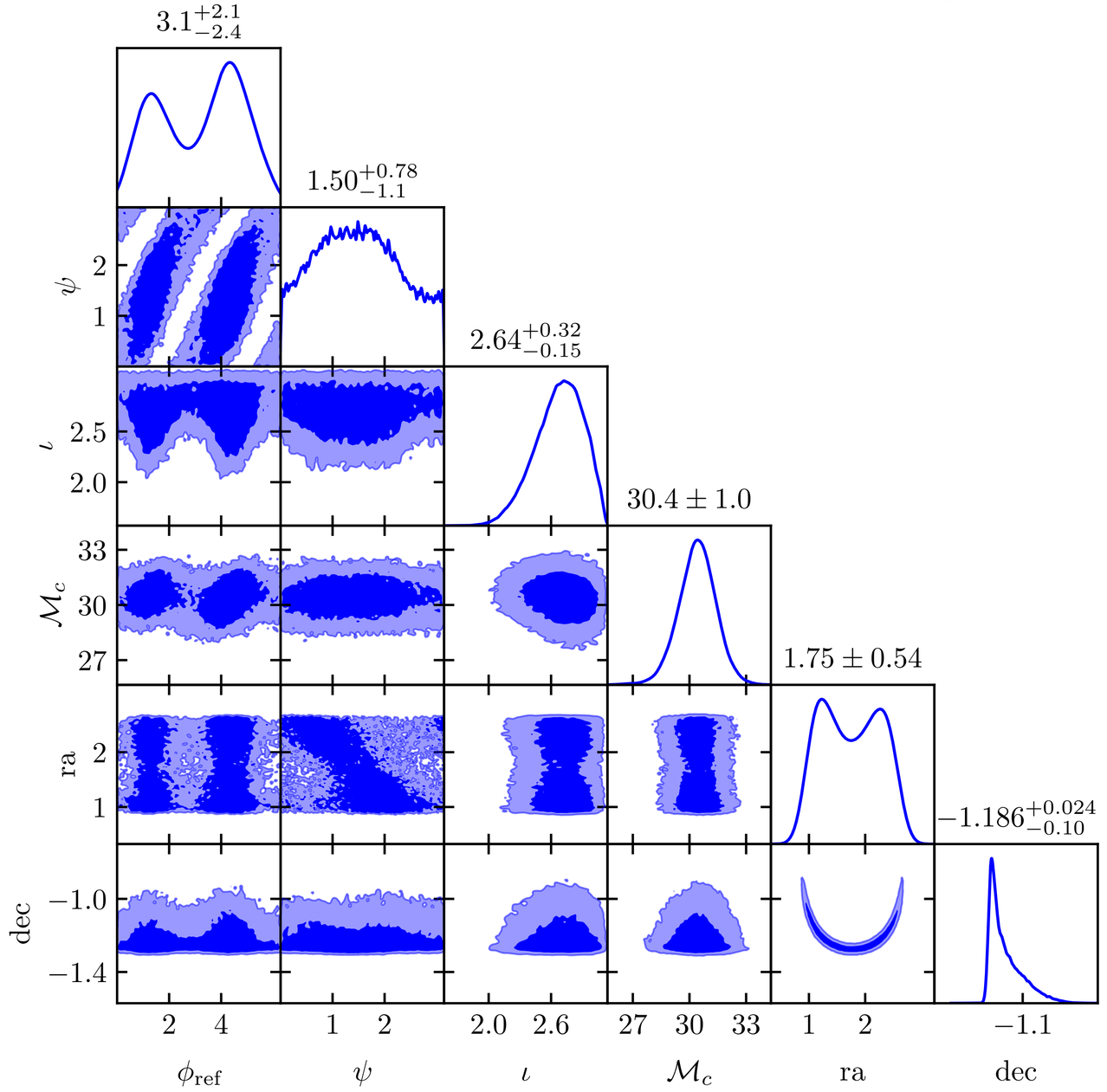
[Credit: LIGO]

Parameter estimation: masses are degenerate



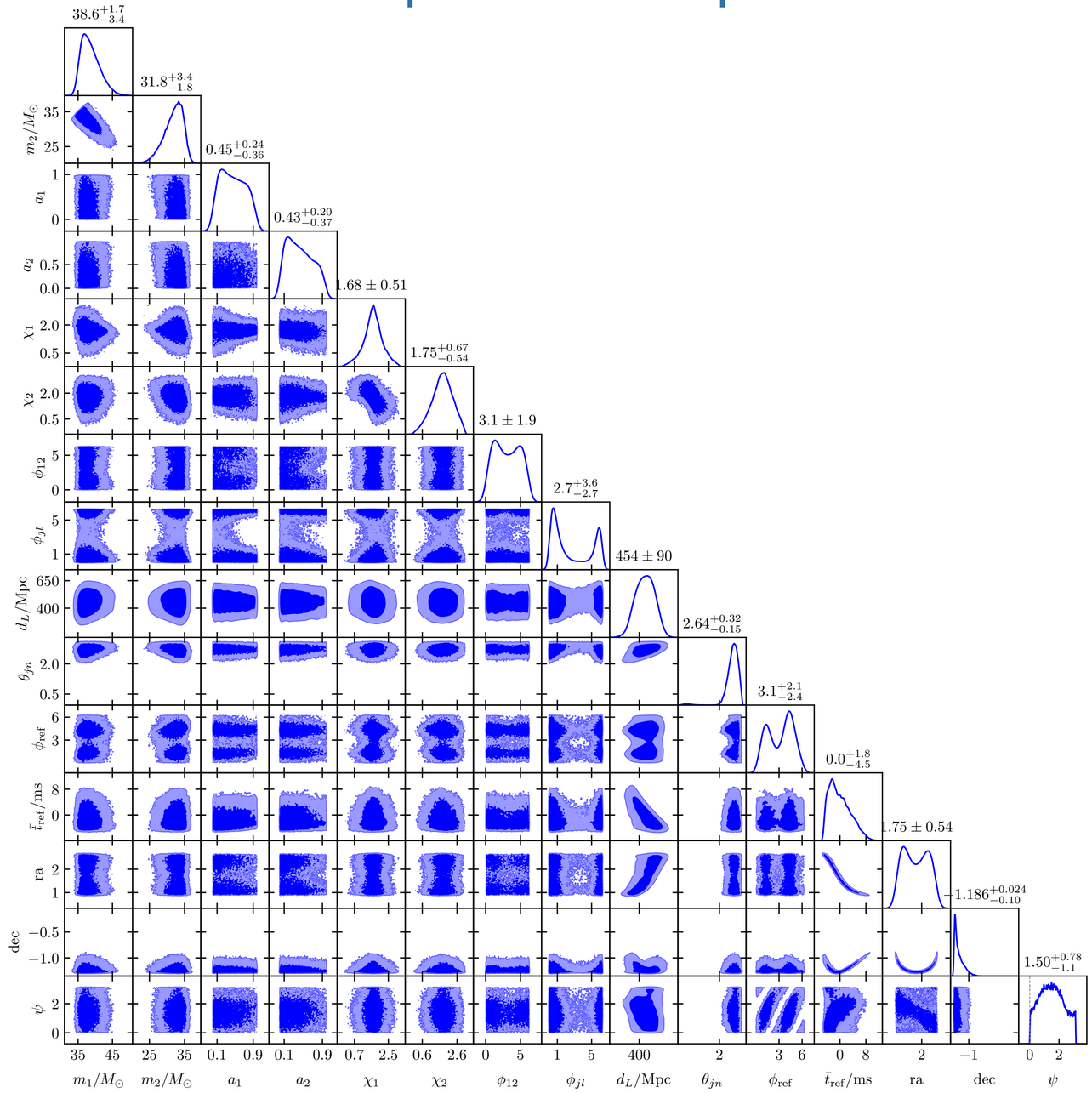
[GW150914]

Parameter estimation: chirp mass, phase & angles

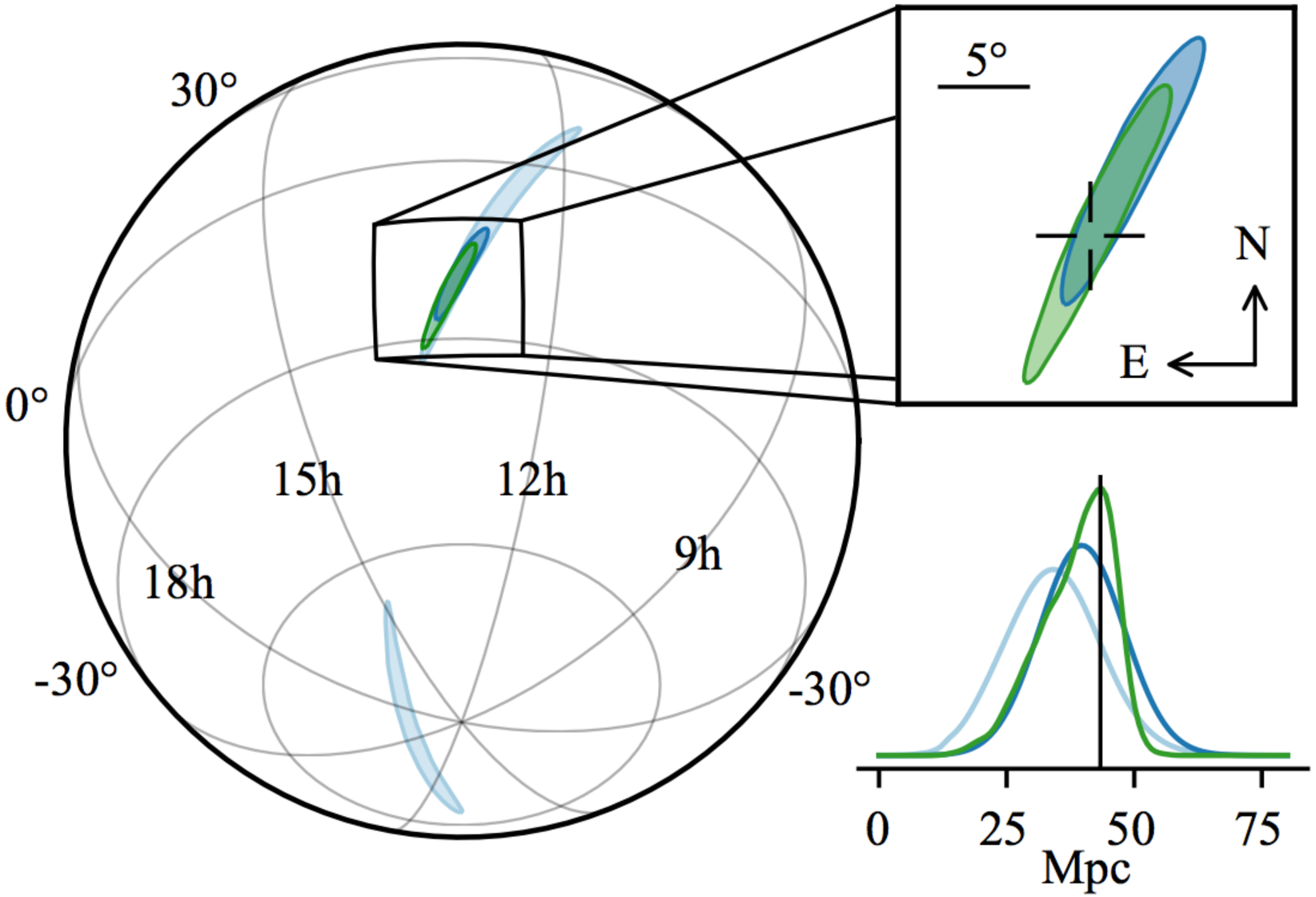


[GW150914]

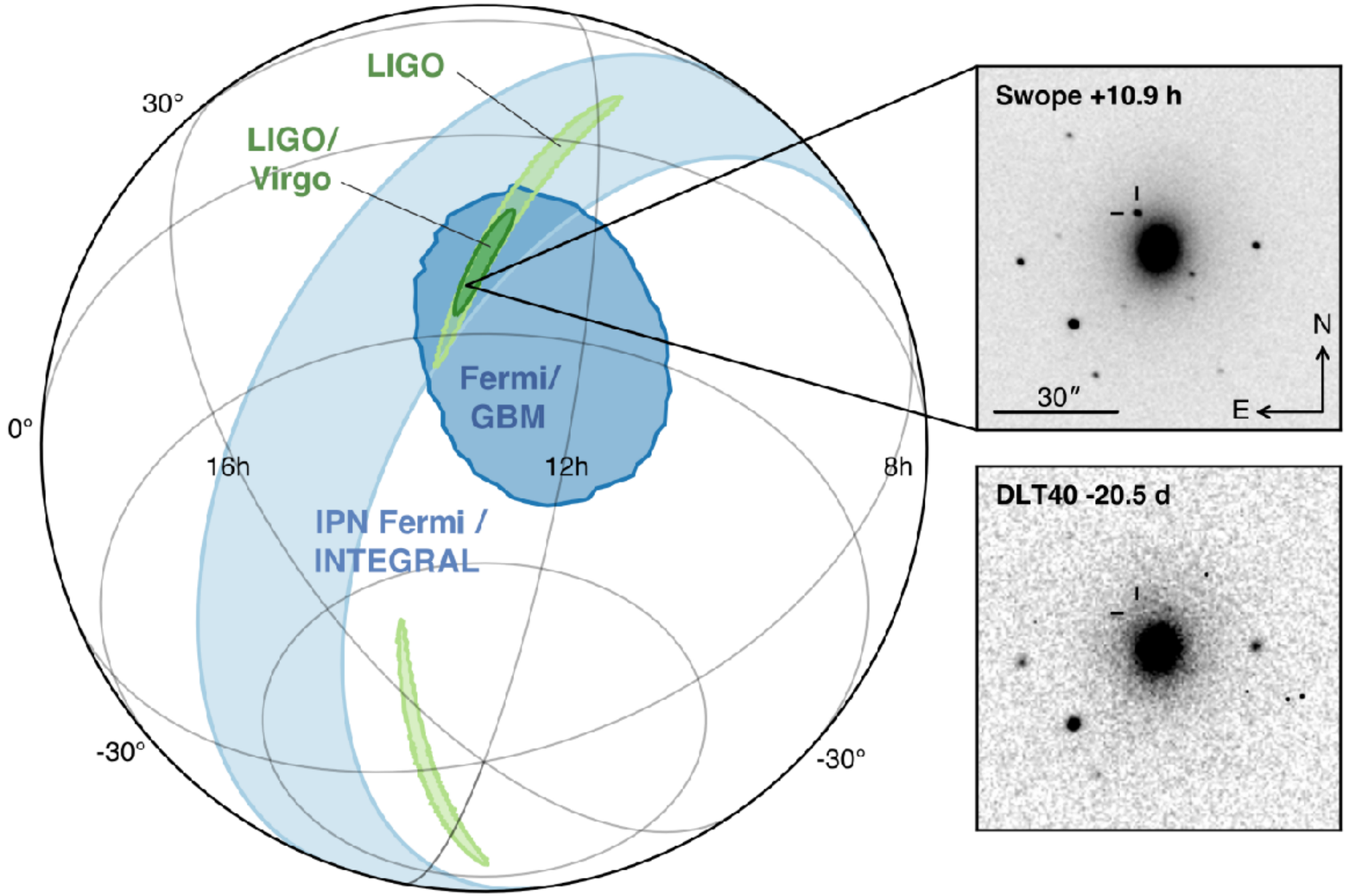
Parameter estimation: 15D parameter space!



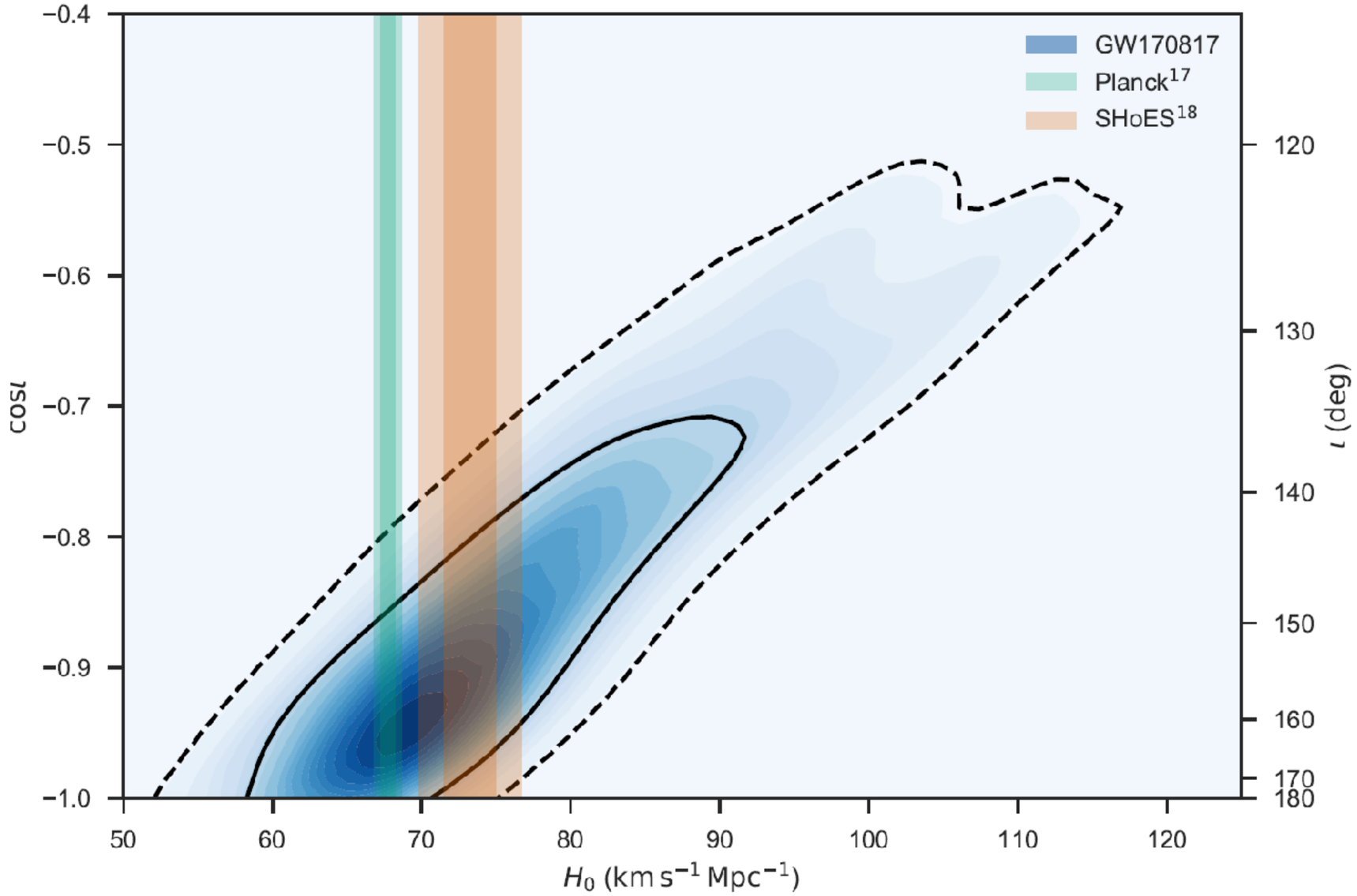
Localizing GW sources



Localizing GW sources: finding electromagnetic counterparts

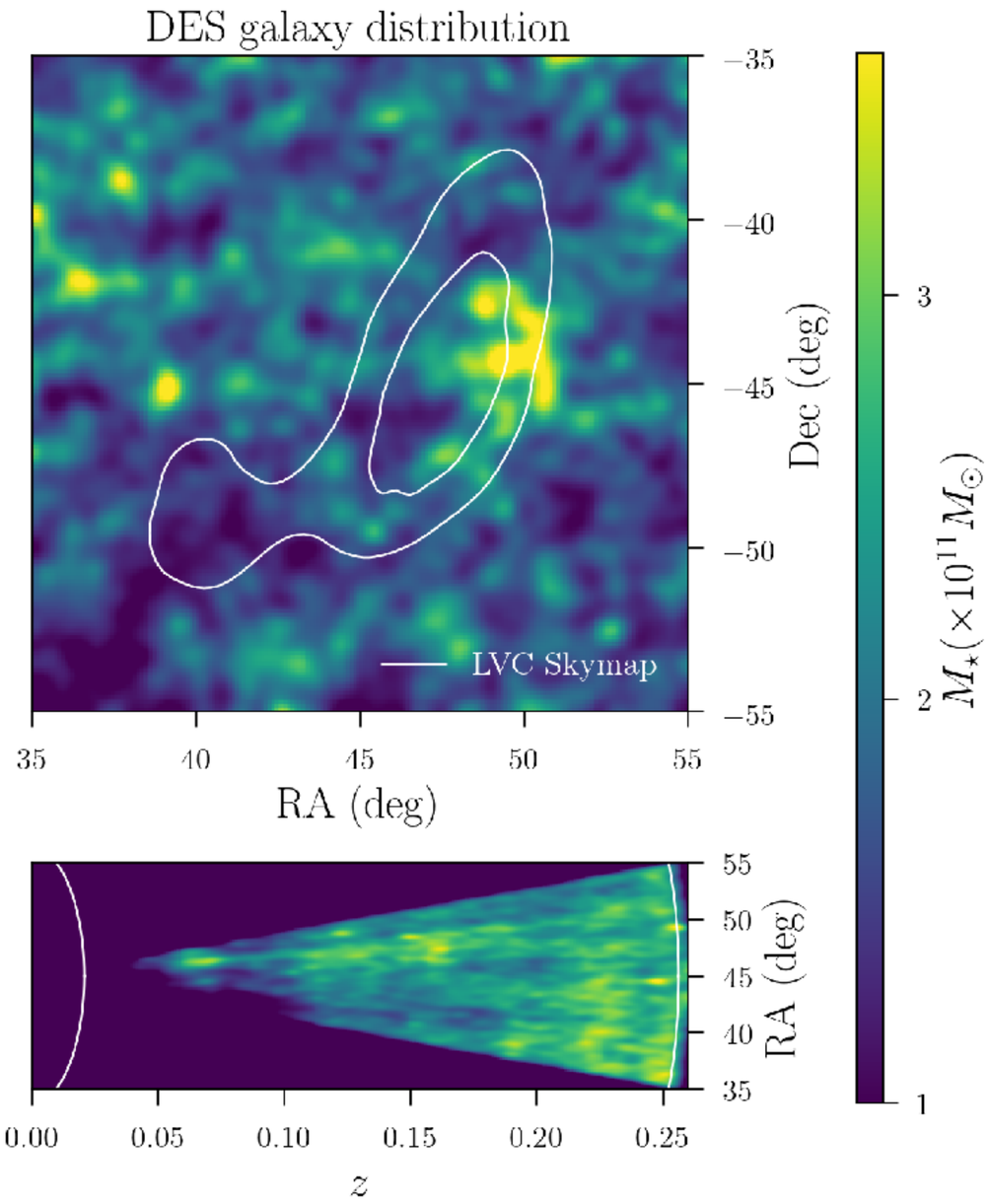


Distance-inclination: enlarged H_0 errors



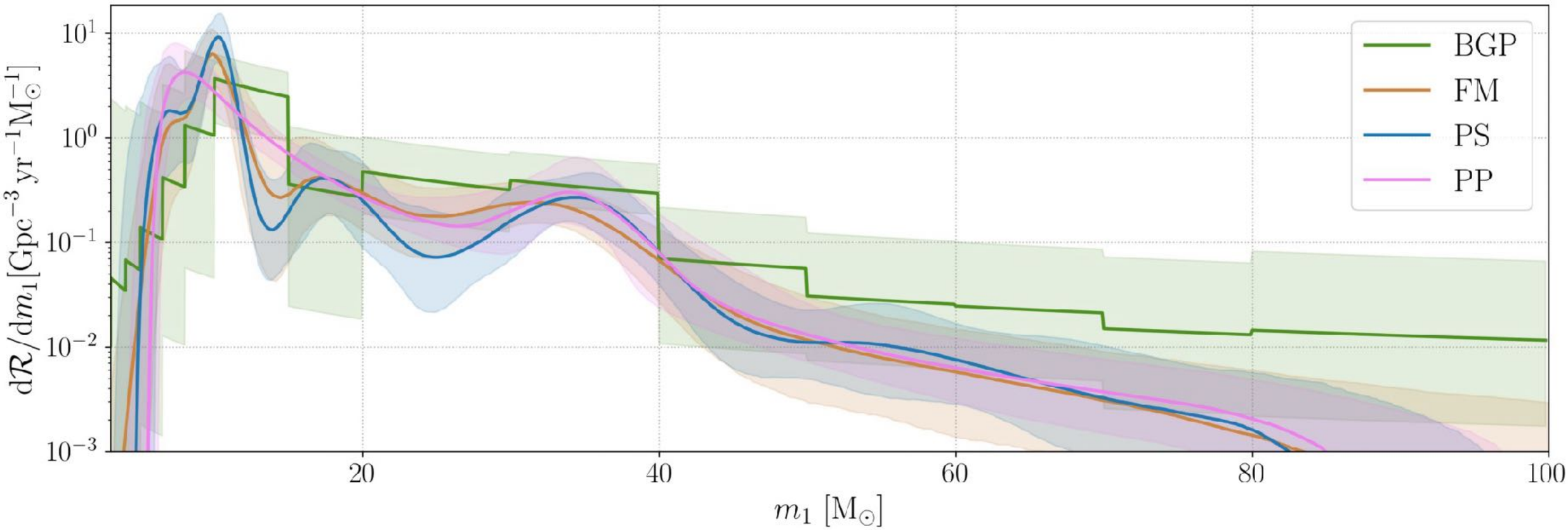
[GW170817]

Localizing GW sources: using galaxy catalogs



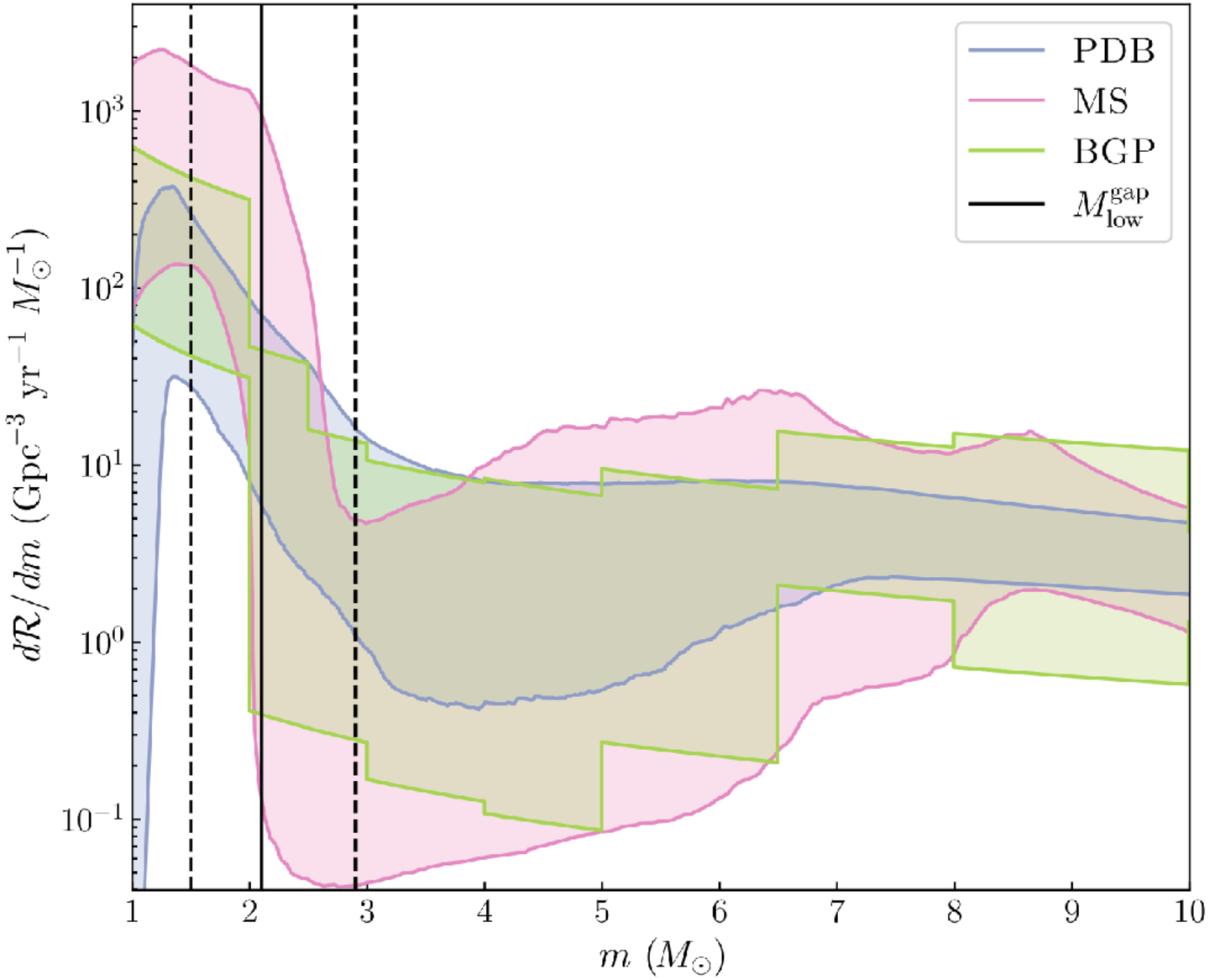
[LIGO,DES; ApJ'19]

Population inference: black hole mass spectrum



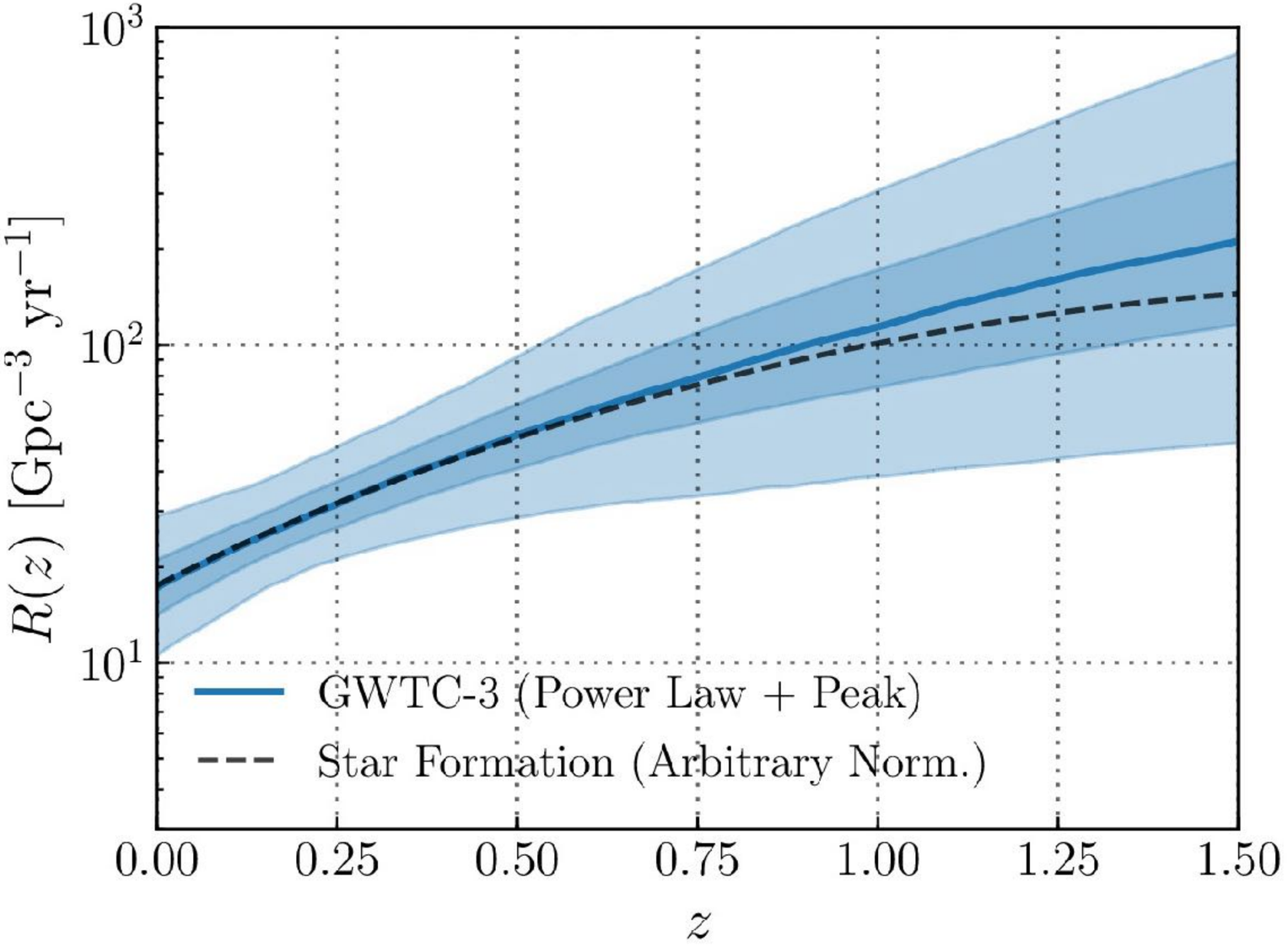
[LVK GWTC3 pop]

Population inference: low-mass spectrum



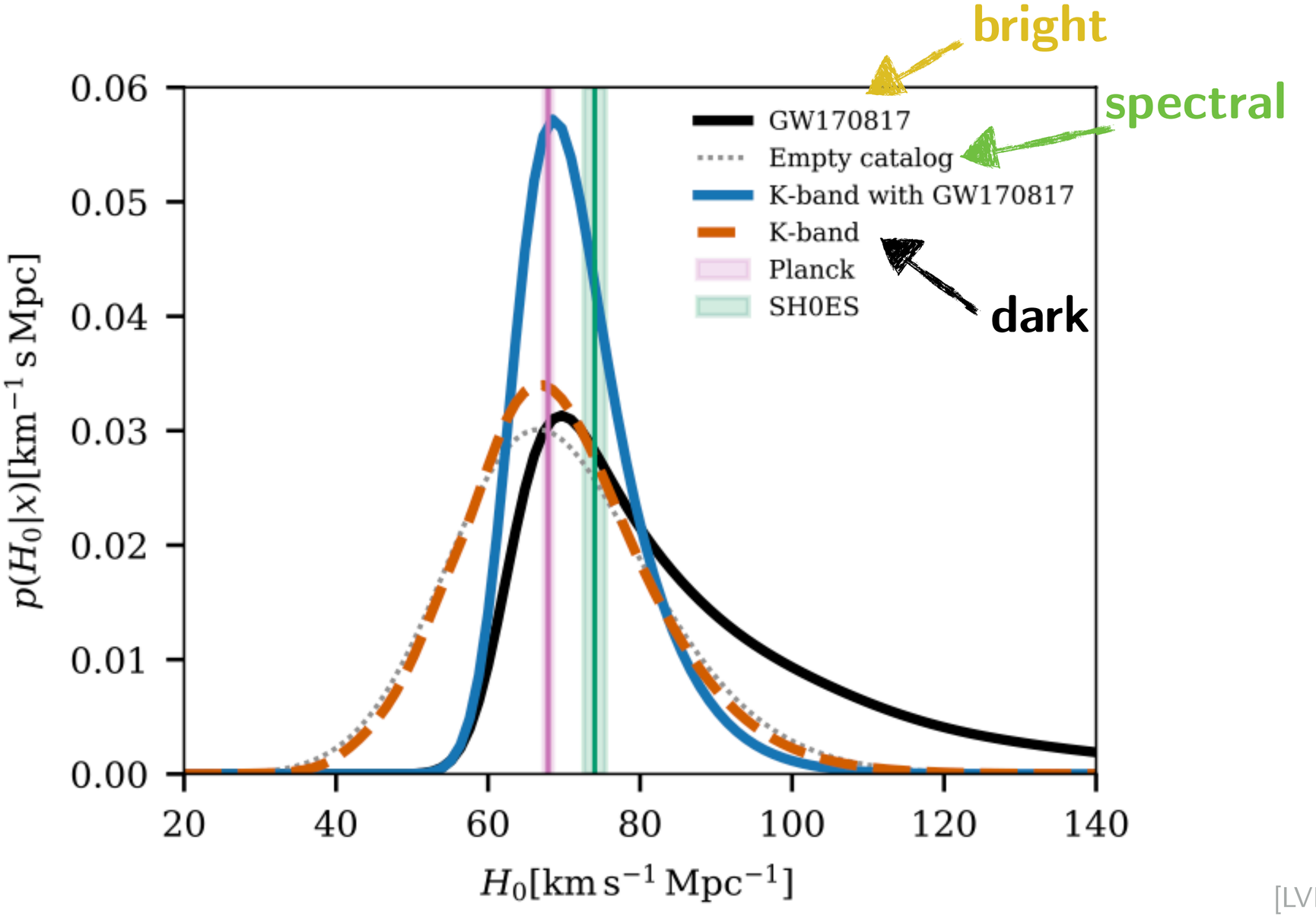
[LVK GWTC3 pop]

Population inference: black hole merger rate history



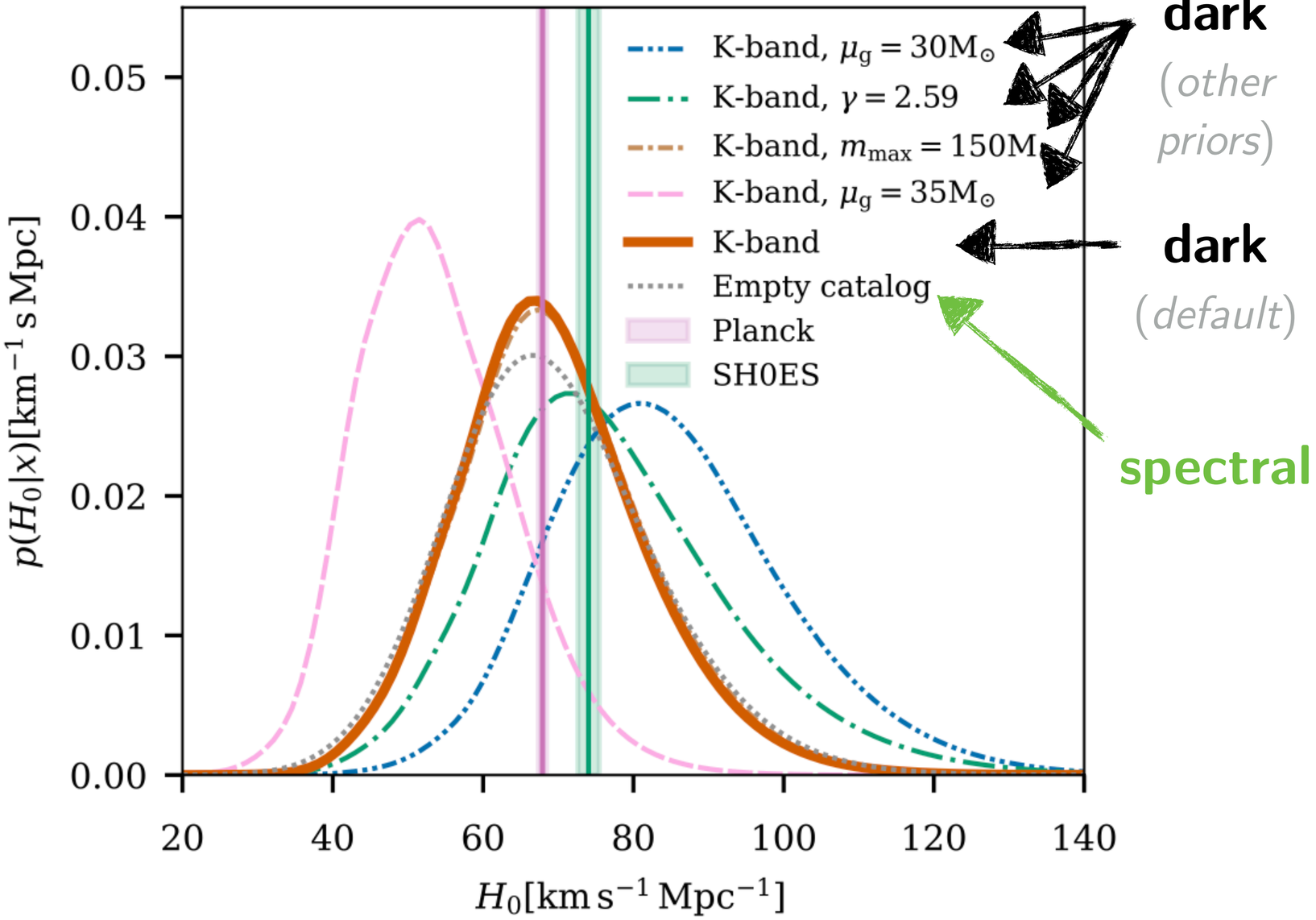
[LVK GWTC3 pop]

Standard sirens: *current results*



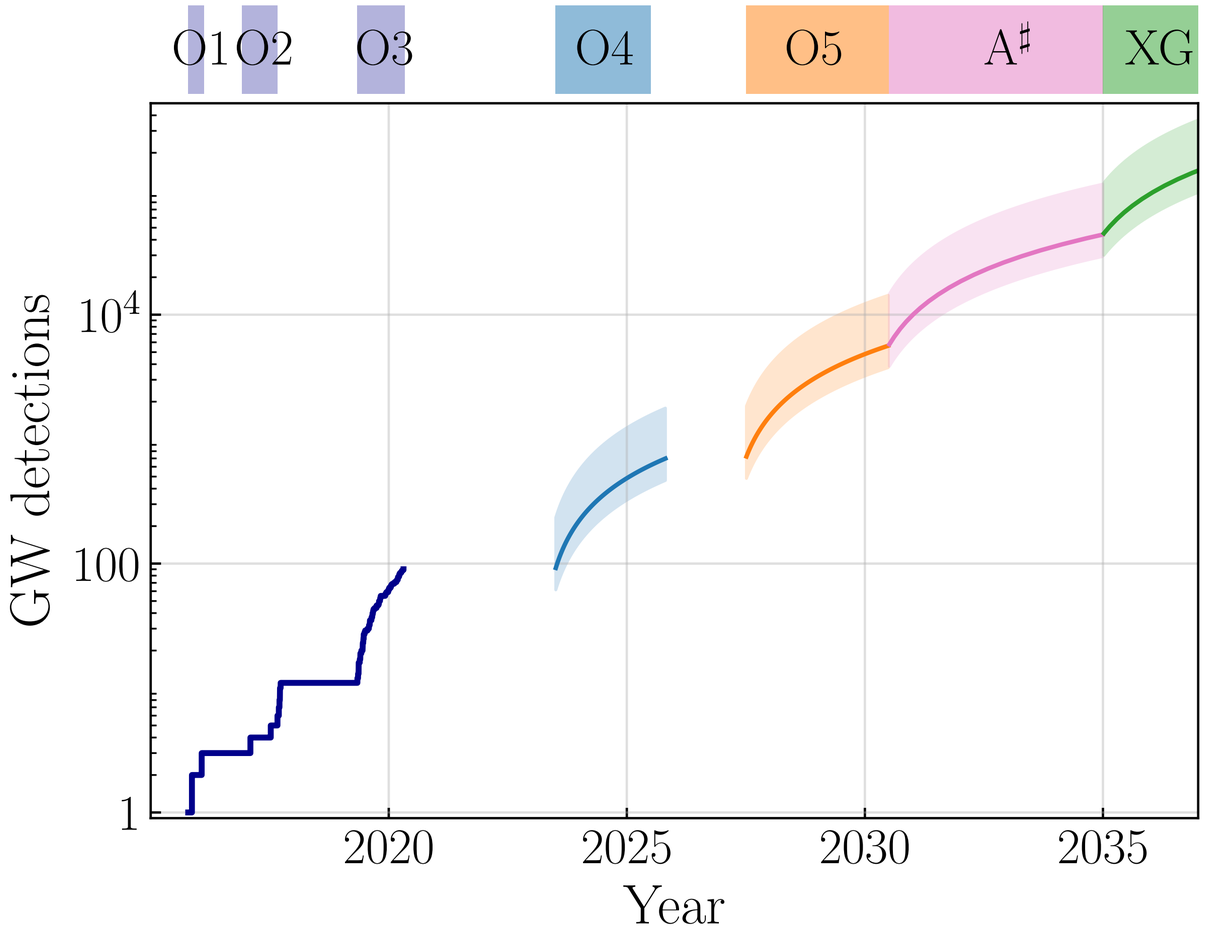
[LVK GWTC-3]

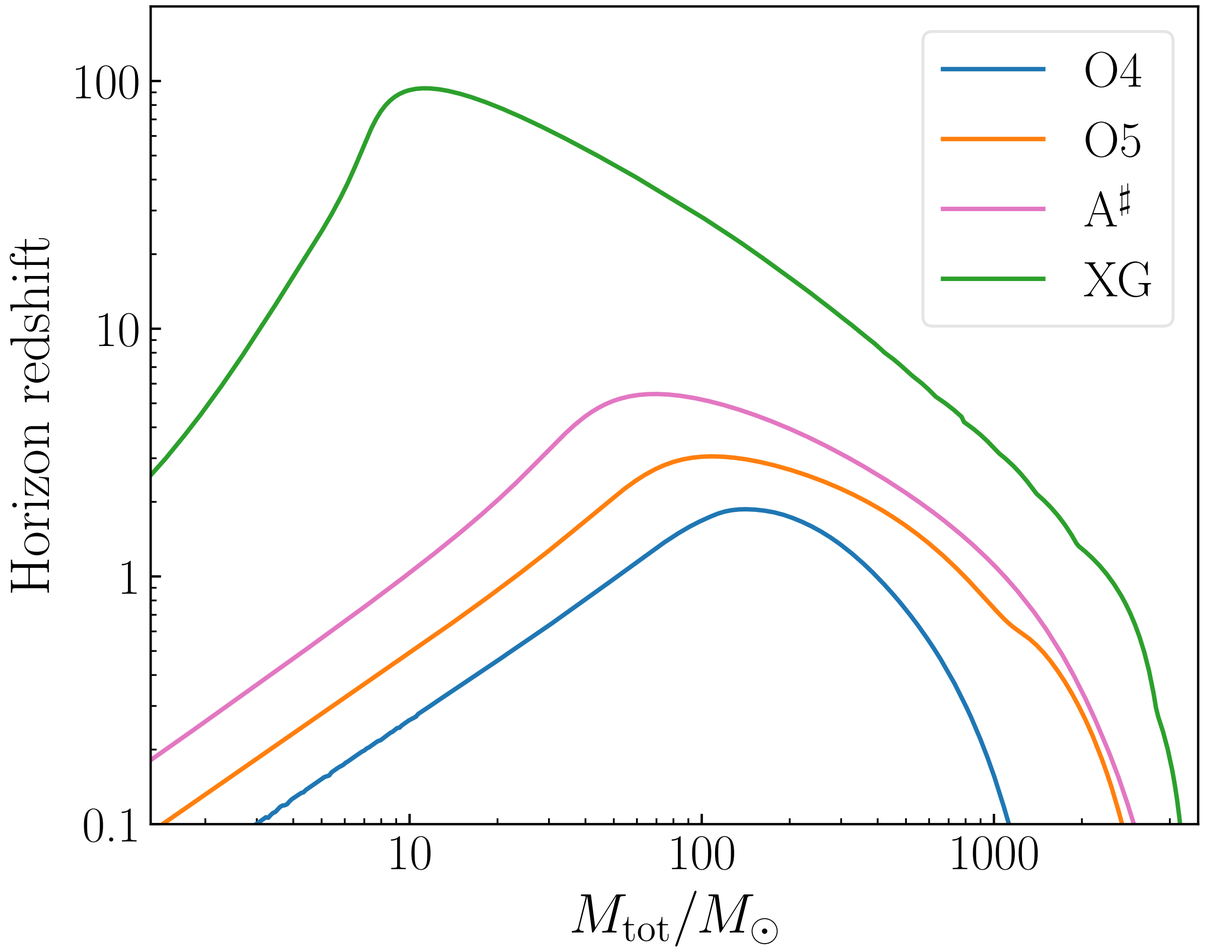
Standard sirens: *current results*



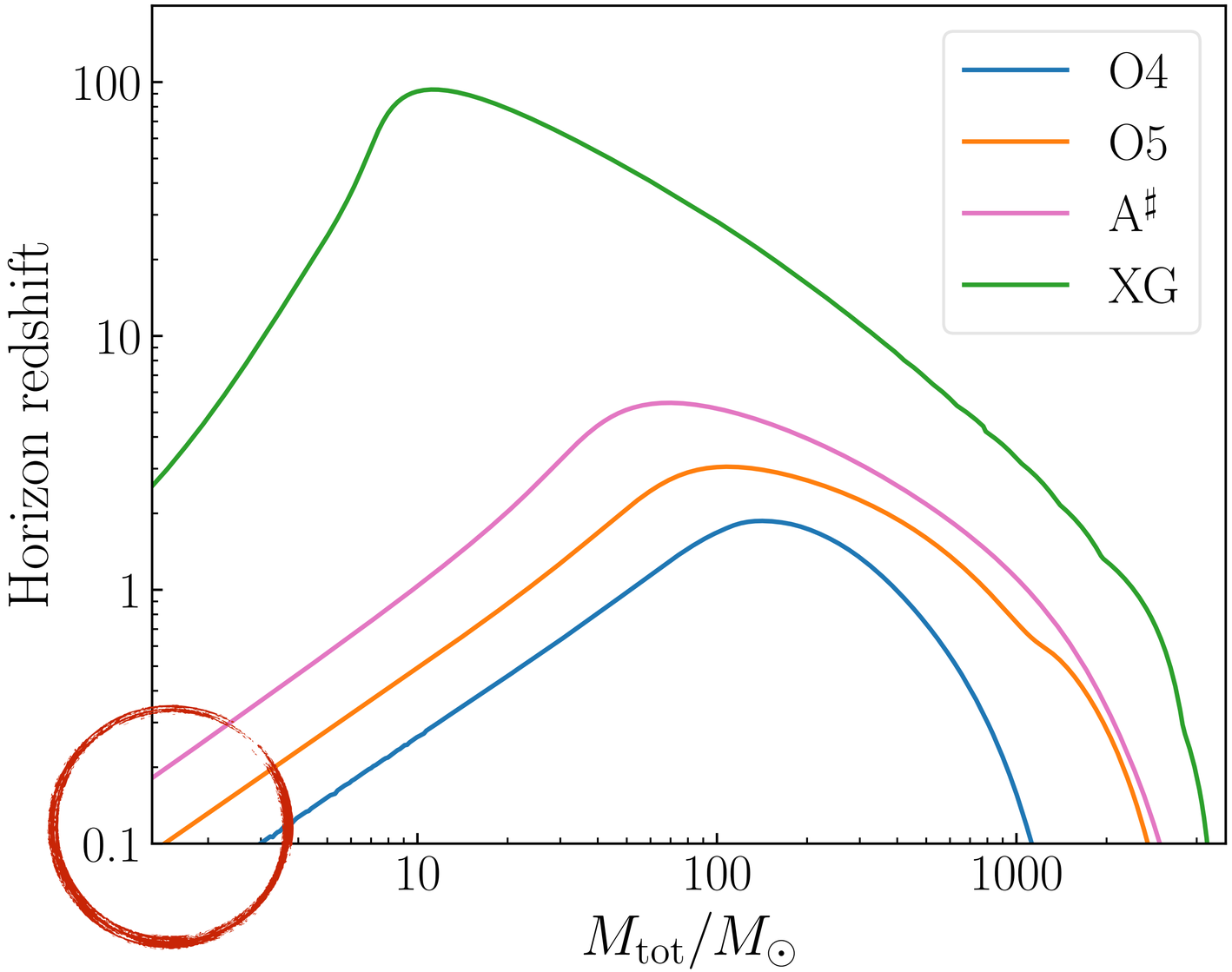
[LVK GWTC-3]

The future: big data & distant Universe





Bright sirens: *forecasts*



Bright sirens: *forecasts (kilonovae)*

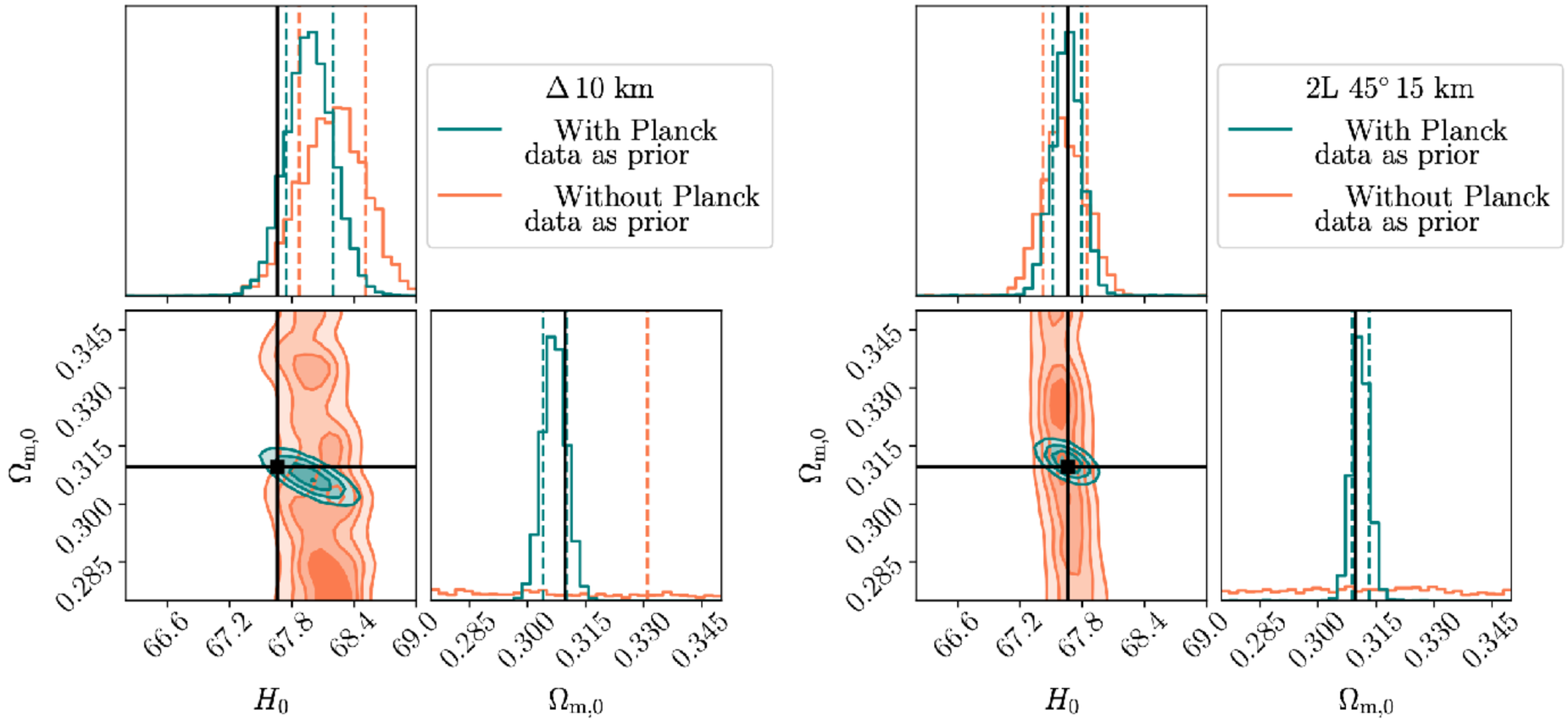


Figure 2.25: Results of the joint inference on the cosmological parameters H_0, $\Omega_{m,0}$, employing GW+KN events detected in one year of observations by the 10 km triangular (left panel) or the 2L-15km-45° (right panel) ET configurations, with the EM counterpart detected by the Vera Rubin Observatory. Vertical dashed lines represent the 68% CI of each distribution, while the black solid lines label the fiducial values.

Bright sirens: *forecasts (short GRB)*

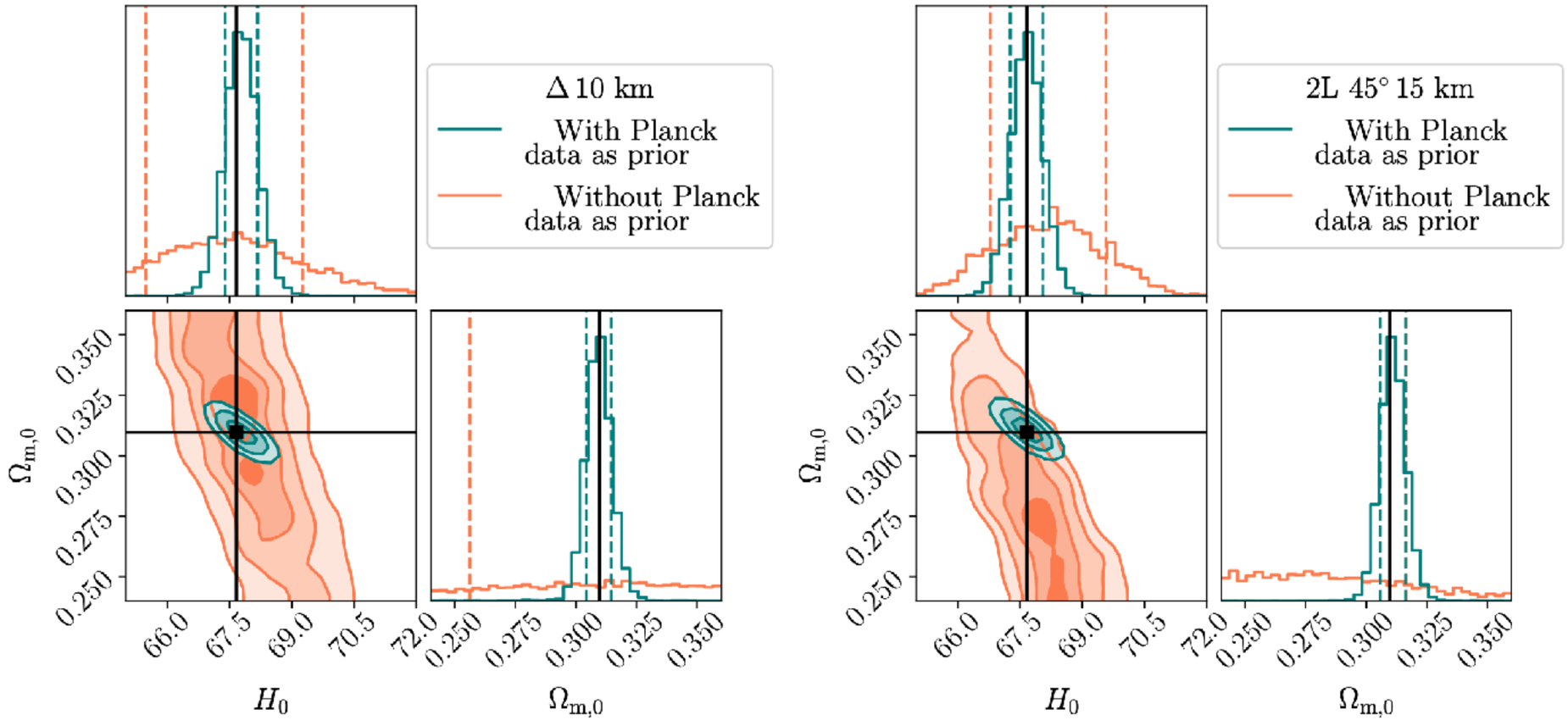
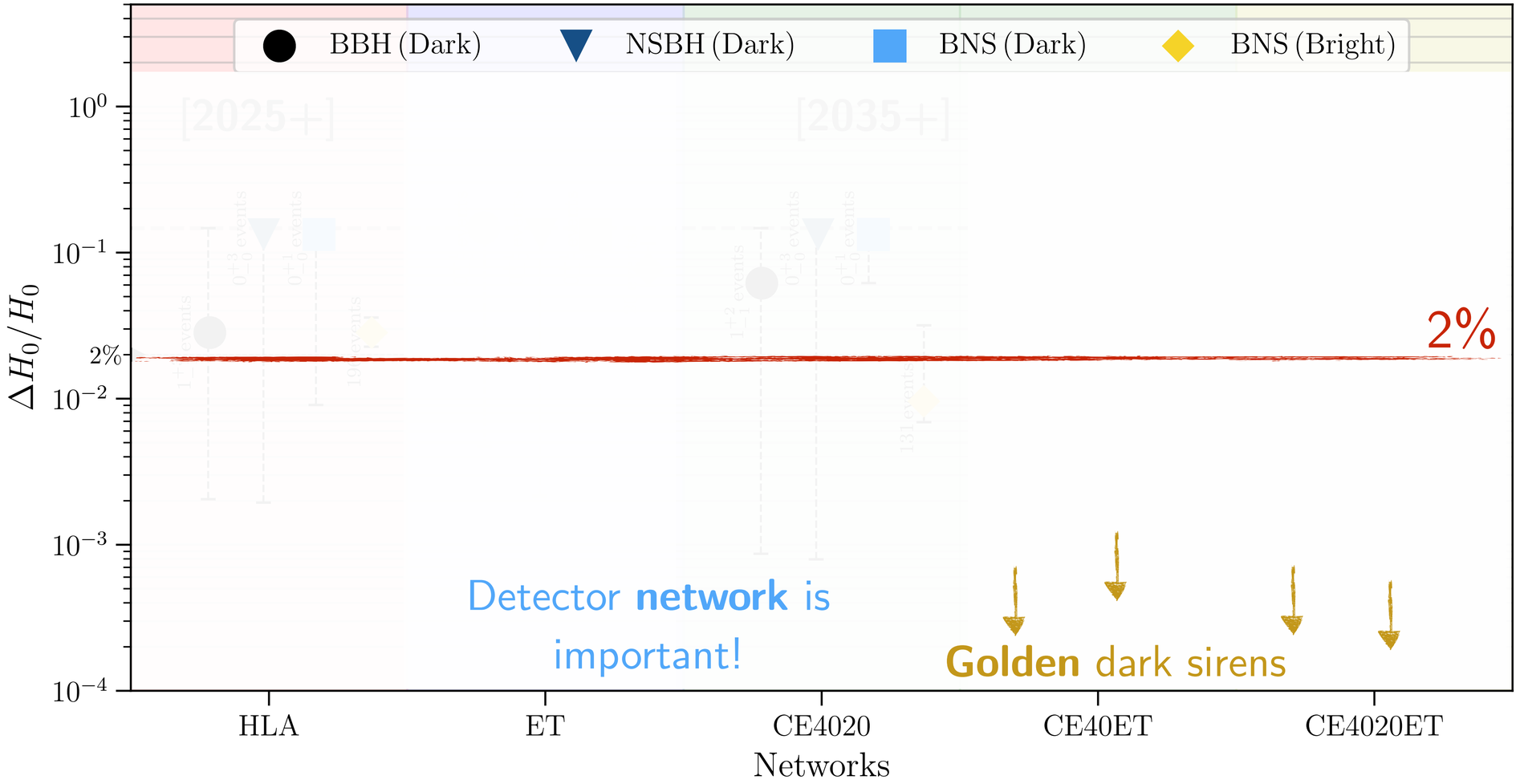


Figure 2.26: Results of the joint inference on the cosmological parameters H_0, $\Omega_{m,0}$ employing GW+GRB events detected in 5 years of observations by the 10 km triangular (left panel) or the 2L-15km-45° (right panel) ET configurations, with the EM counterpart detected by THESEUS. Vertical dashed lines represent the 68% CI of each distribution, while the black solid lines label the fiducial values.

Dark sirens: *forecasts*

H: Hanford (US)
L: Livingston (US)
A: Aundha (India)
ET: Einstein Telescope (EU)
CE: Cosmic Explorer (US)

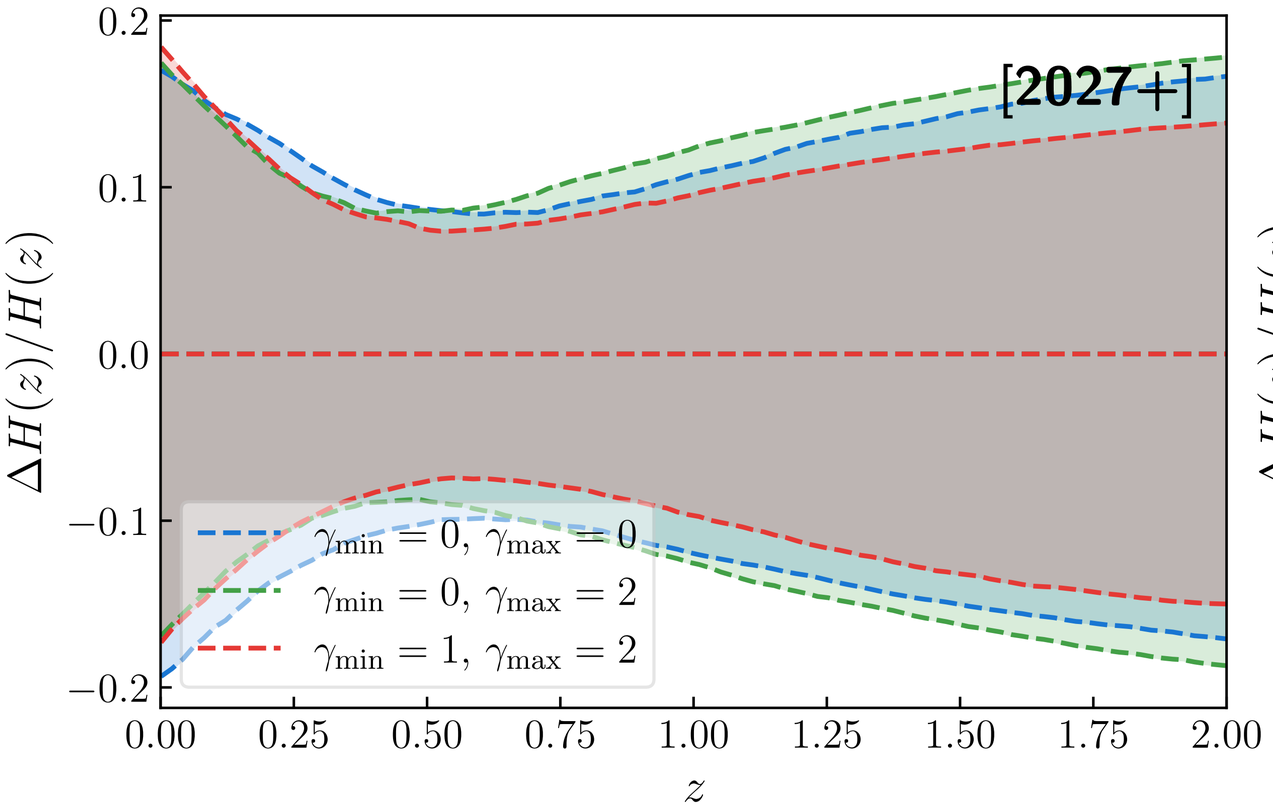
H_0 (also) with dark sirens

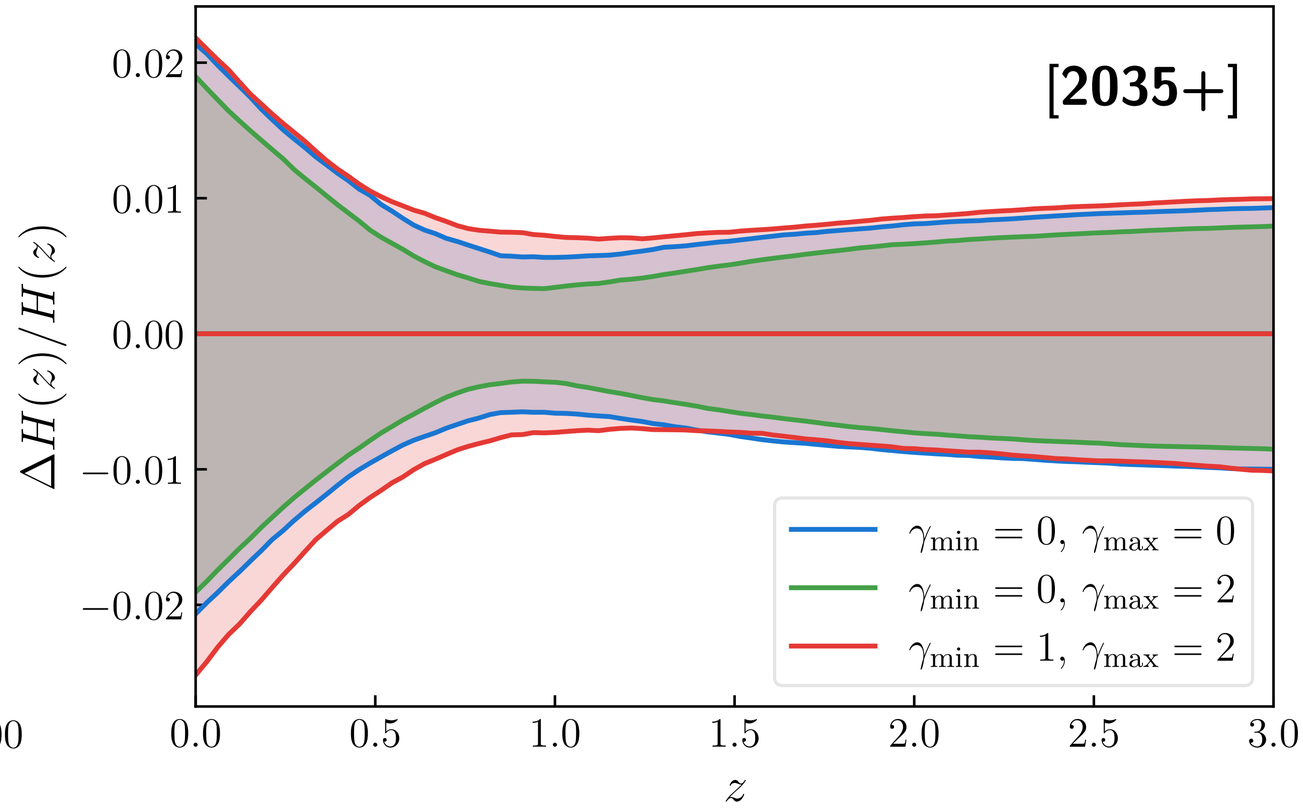


[Chen, **Ezquiaga** & Gupta (CQG'24)]

Spectral sirens: *forecasts*

[binary black hole population]





2G: **<10%** within 1 year at approx. z=0.7

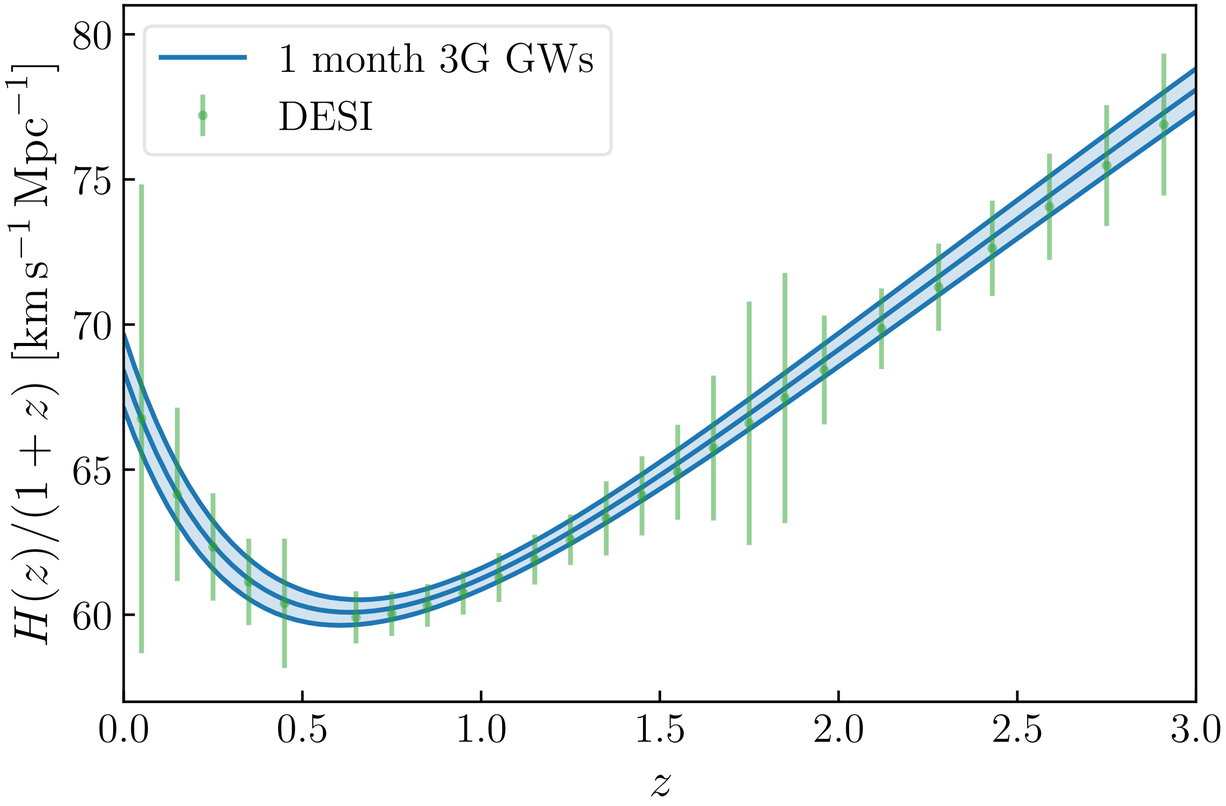
3G: **Sub-percent** within 1 month. High-redshift!

[**Ezquiaga** & Holz (PRL'22)]

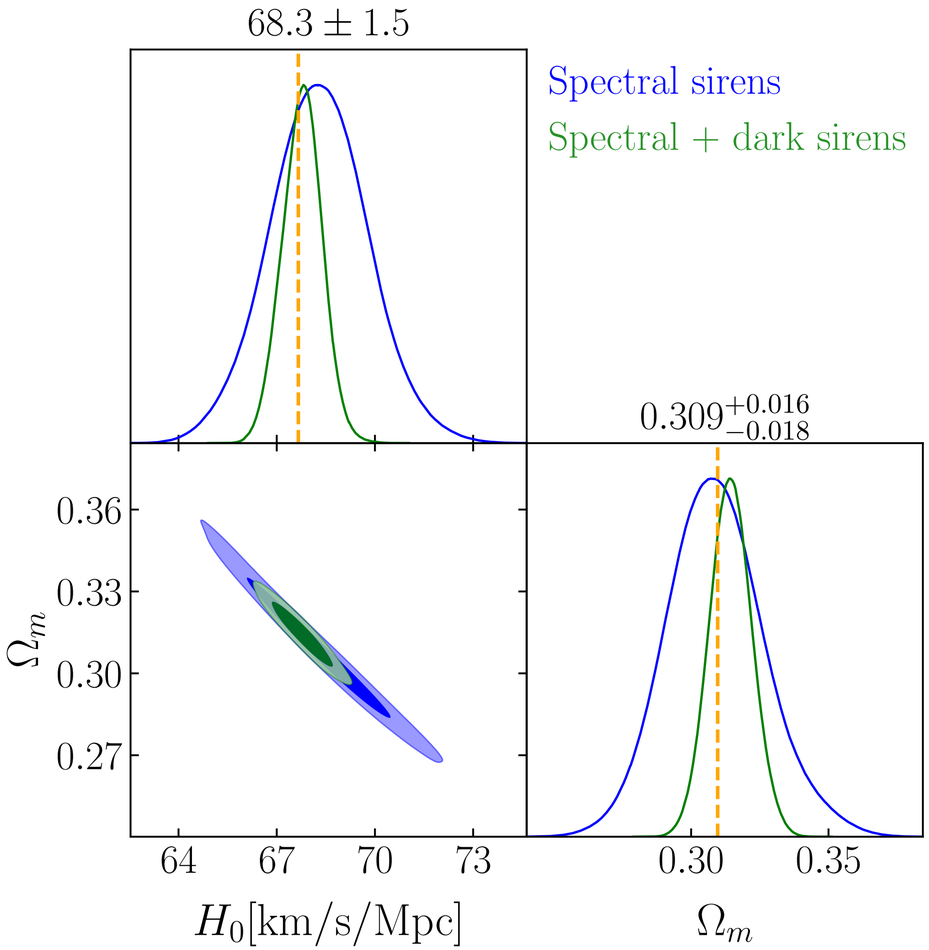
Standard siren cosmology: *forecasts*

Combining sirens **sub-percent** precision across cosmic history!

Spectral sirens are competitive with cosmic surveys

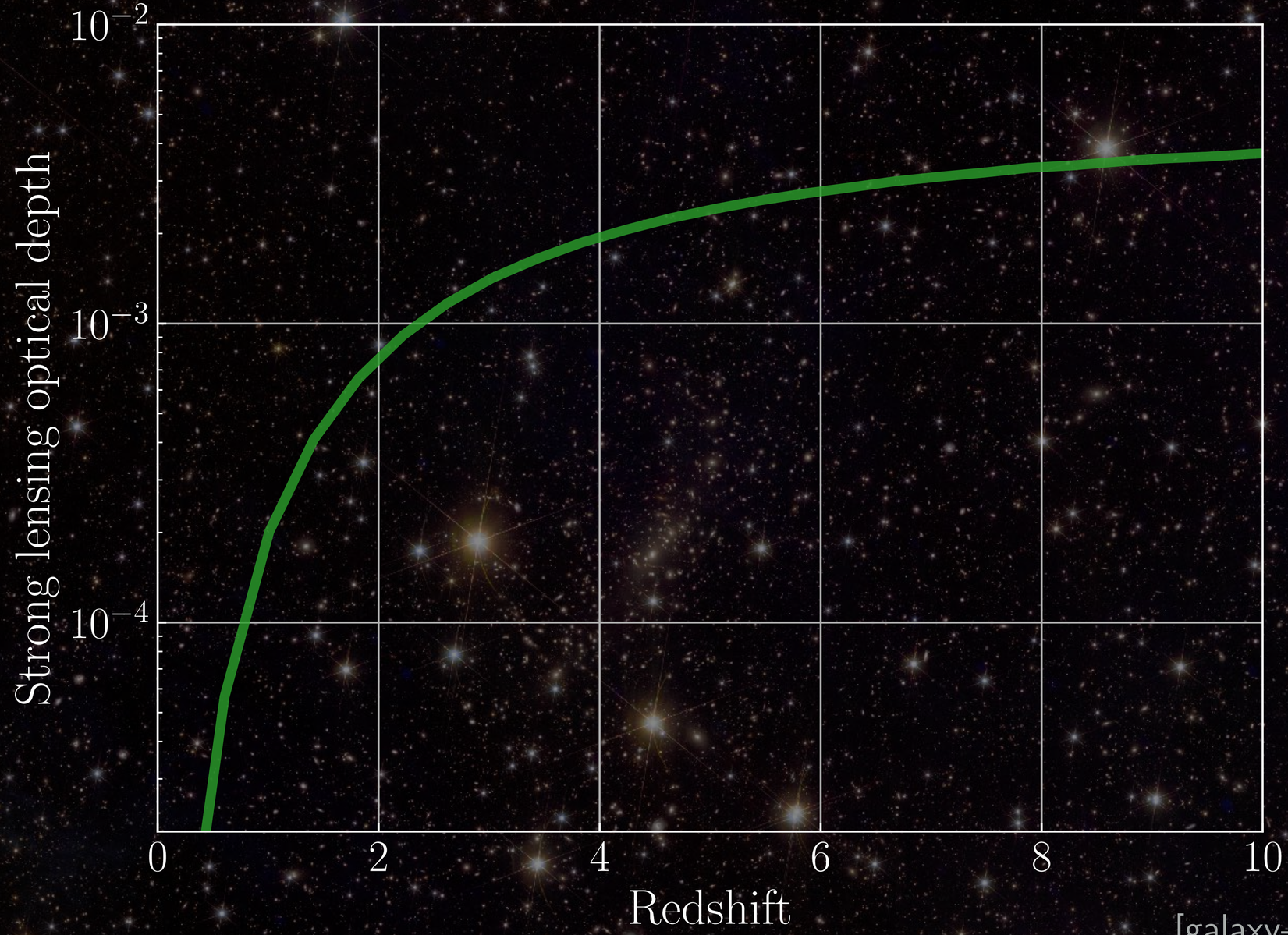


[**Ezquiaga** & Holz (PRL'22)]

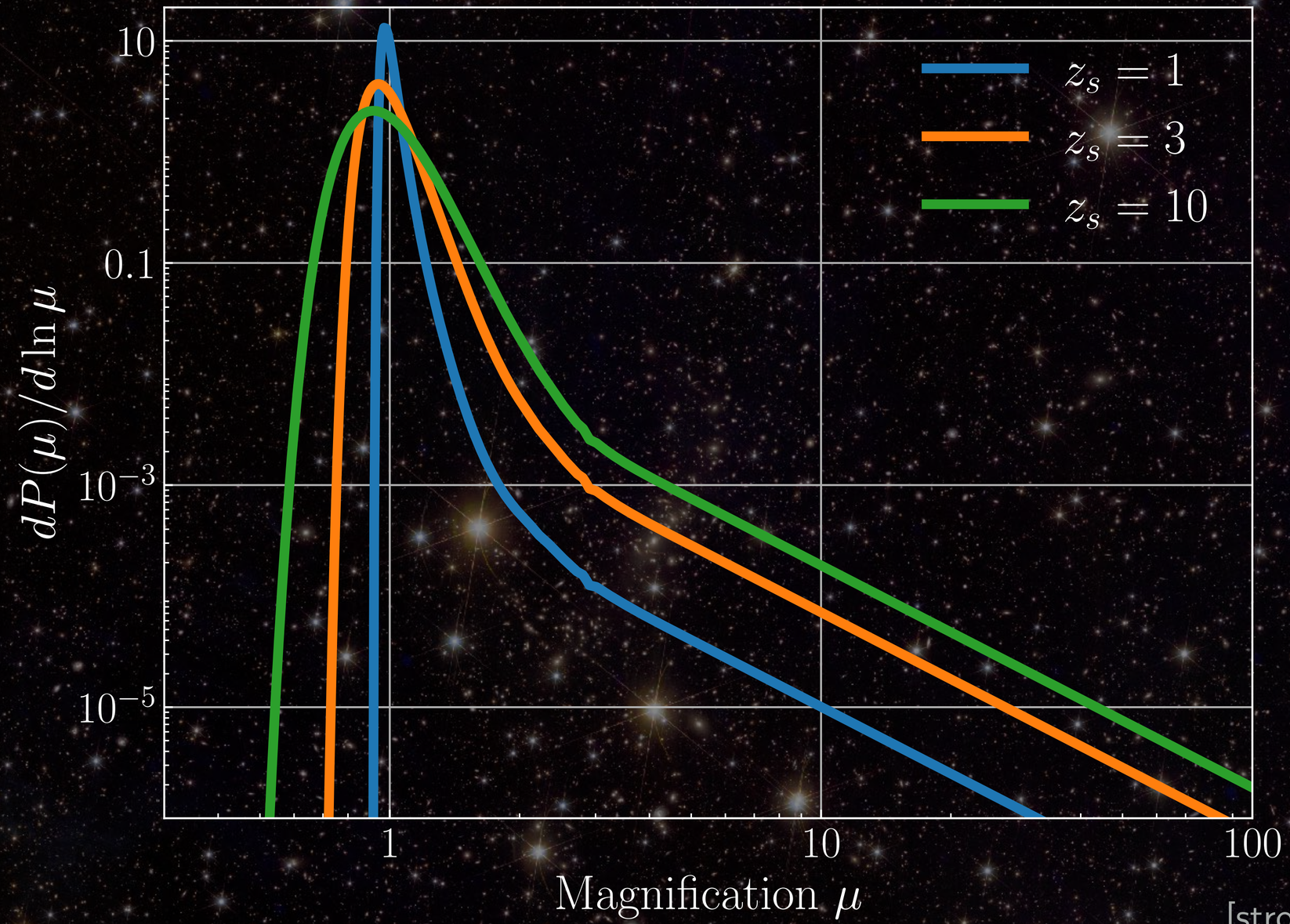


[Chen, **Ezquiaga** & Gupta (CQG'24)]

Gravitational lensing only becomes **more** probable at *higher* redshifts

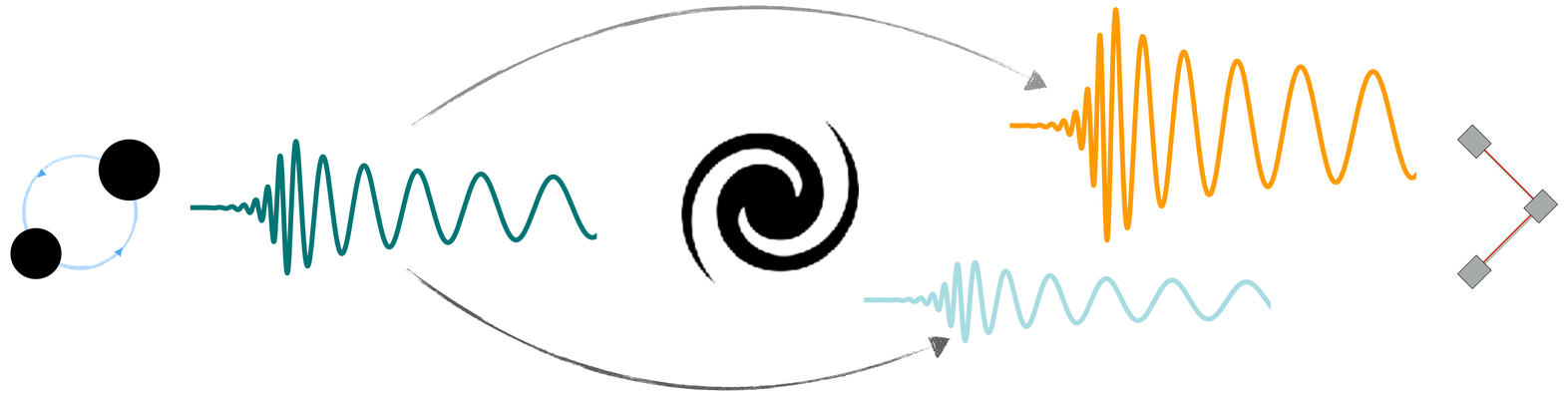


All sources are lensed. A fraction of them with large **magnifications**

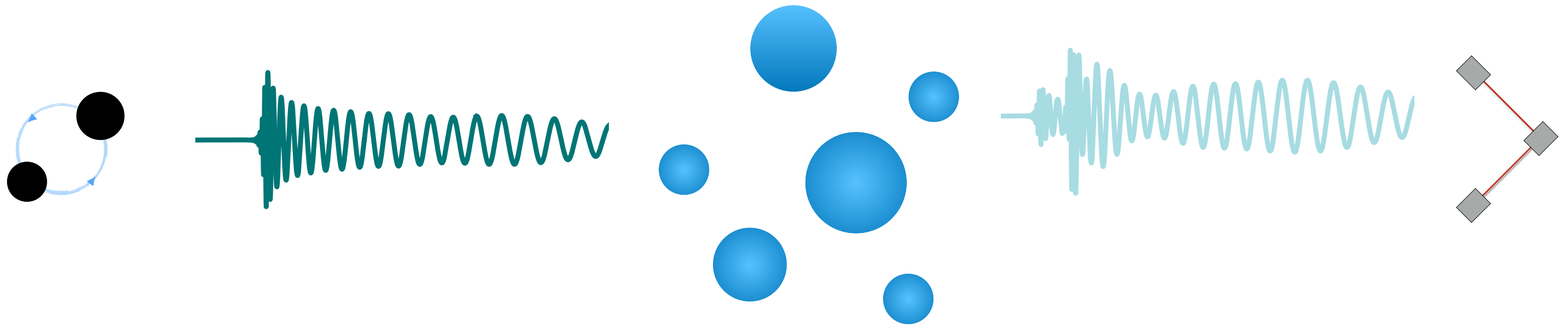


Gravitational lensing - gravitational wave spectrum

Repeated chirps due to strong lensing



Waveform *distortions* by substructures



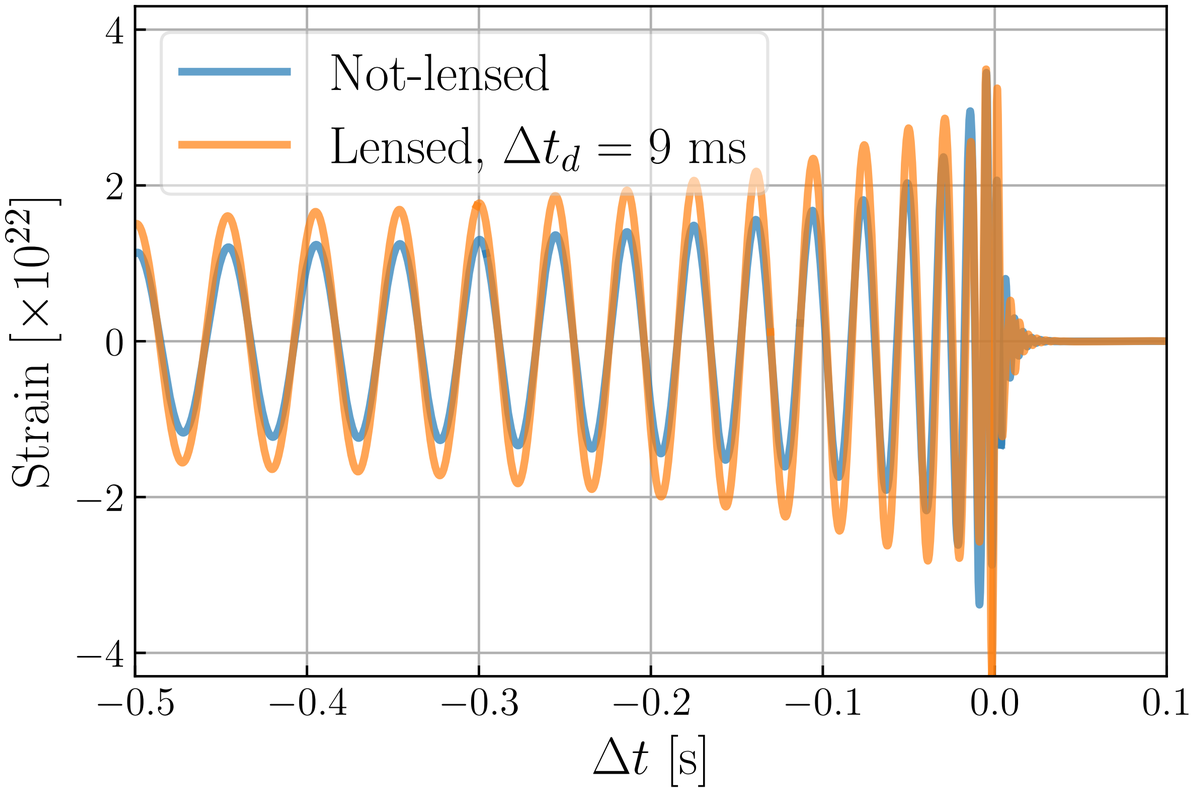
Source Lens Detector

Probing cosmic (sub)structures: GWs are sensitive to time delays from millisecond (solar mass objects) to years (clusters of galaxies)

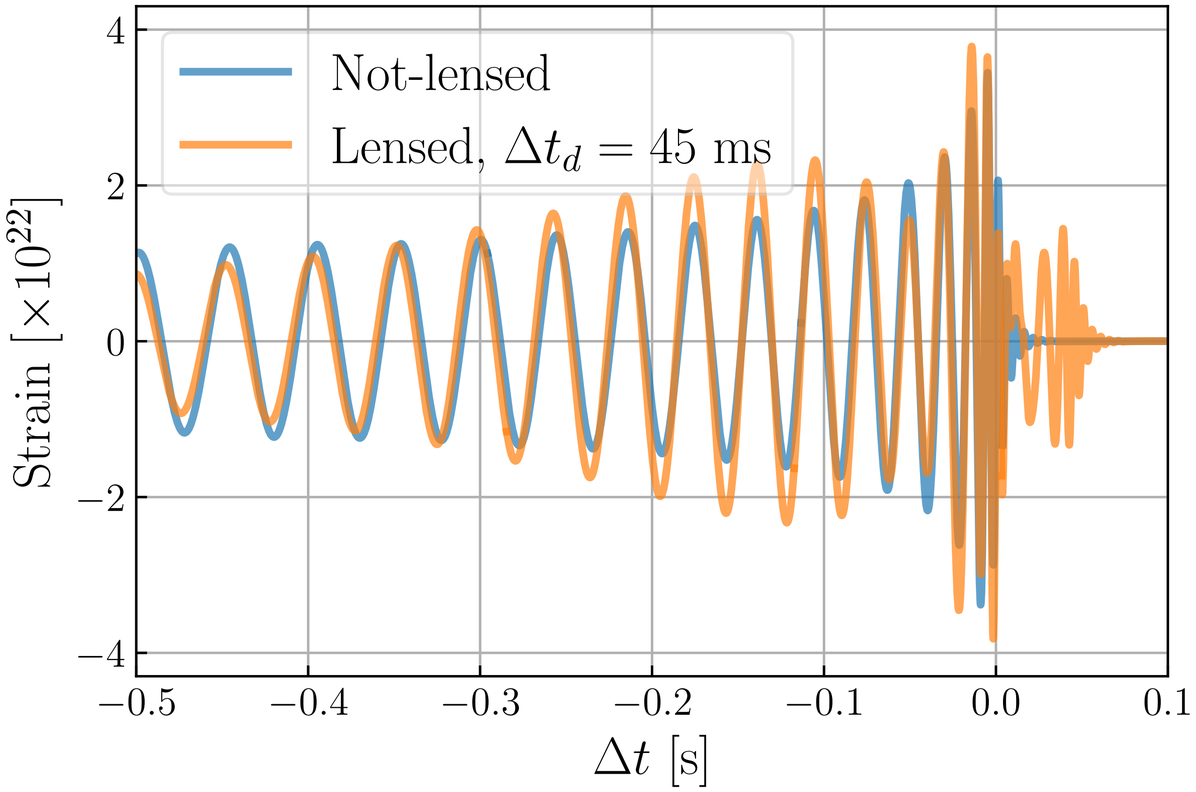
E.g. compact (point) lenses

$$\Delta t_d(y=1) \simeq 4\left(\frac{(1+z_L)M_L}{100M_\odot}\right)\ \mathrm{ms}$$

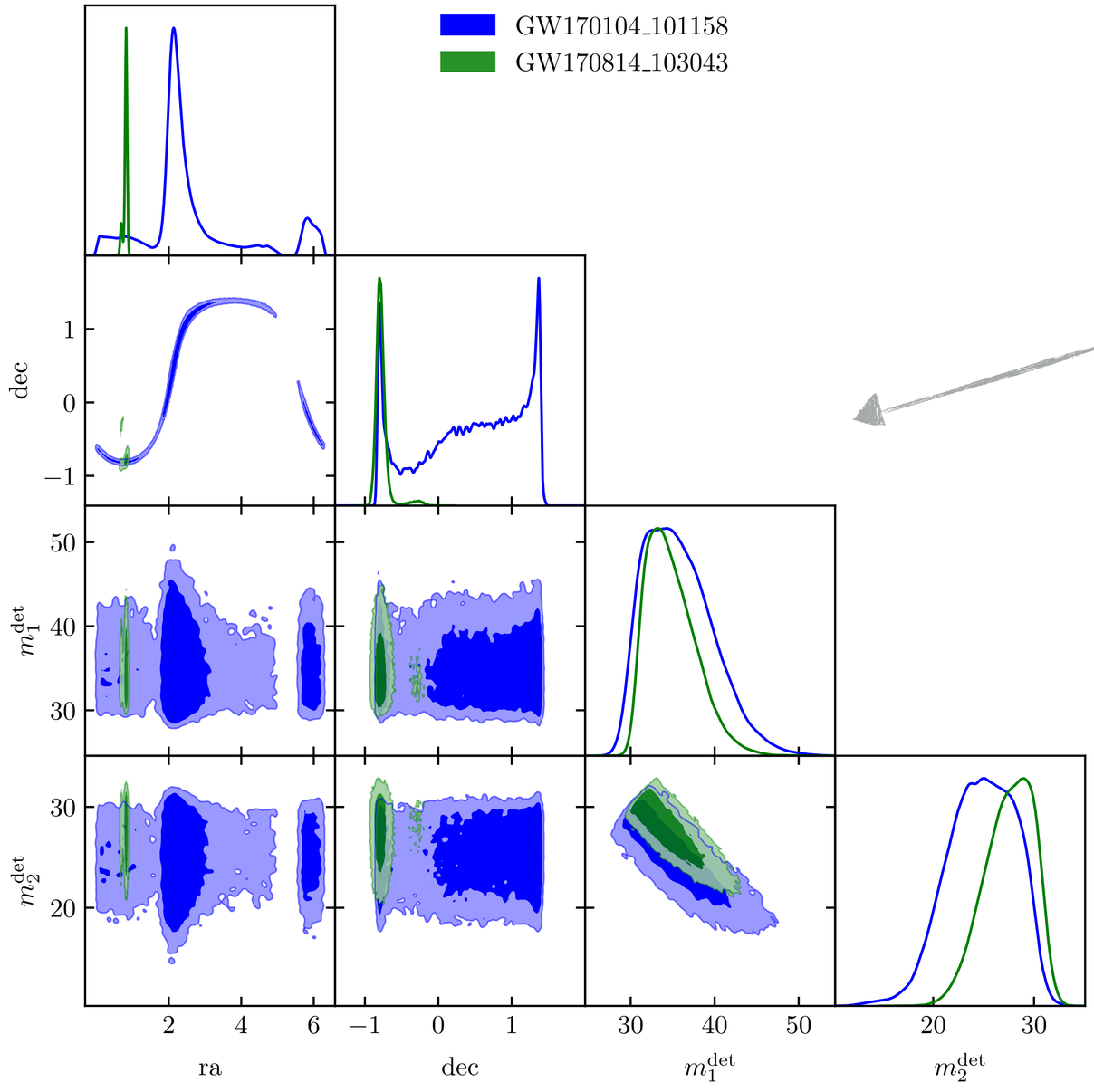
Diffraction



Interference



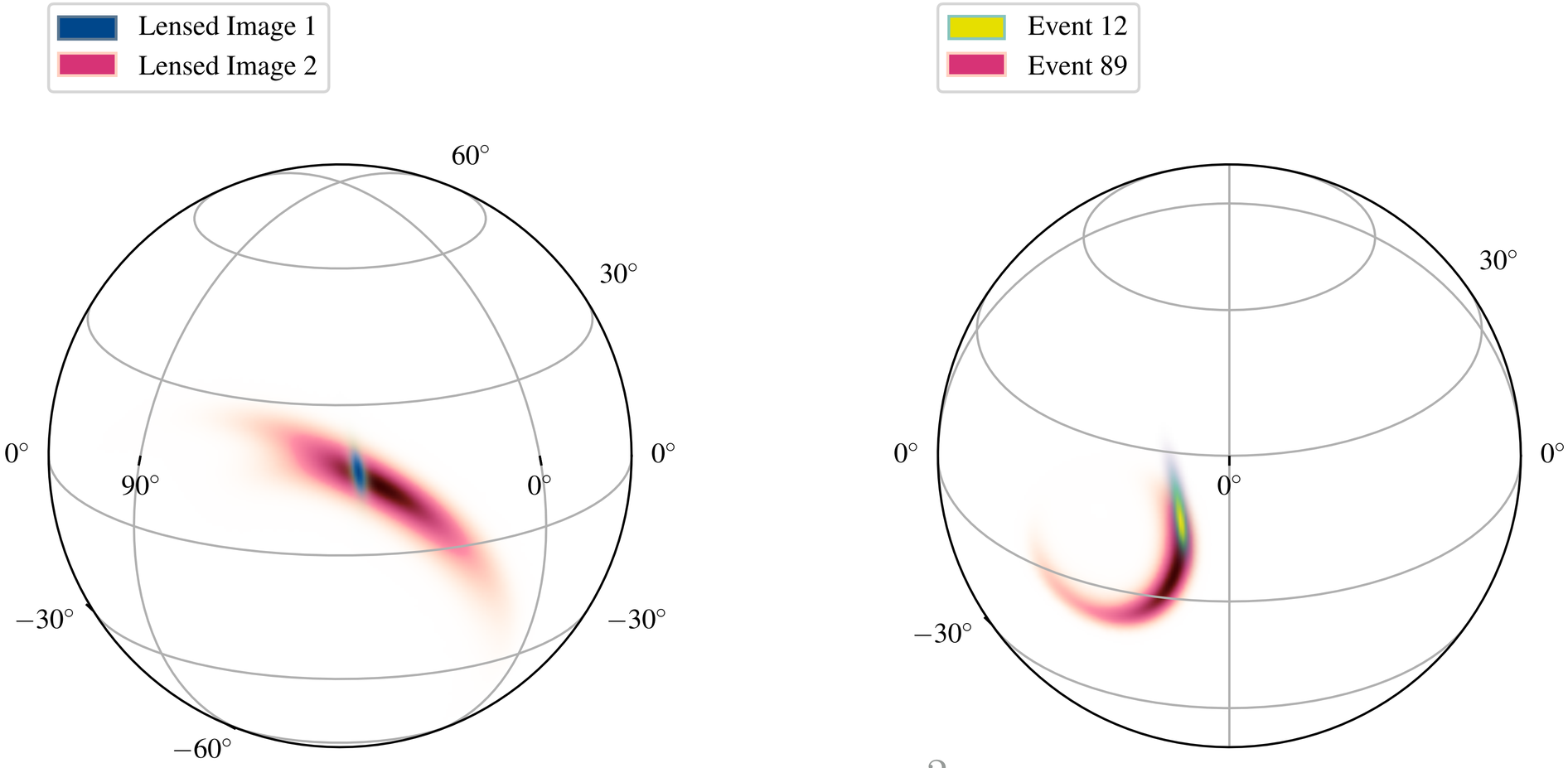
Searching for repeated chirps



Look for events with similar properties: masses, sky positions, spins...

... many parameters are degenerate and poorly constrained ...

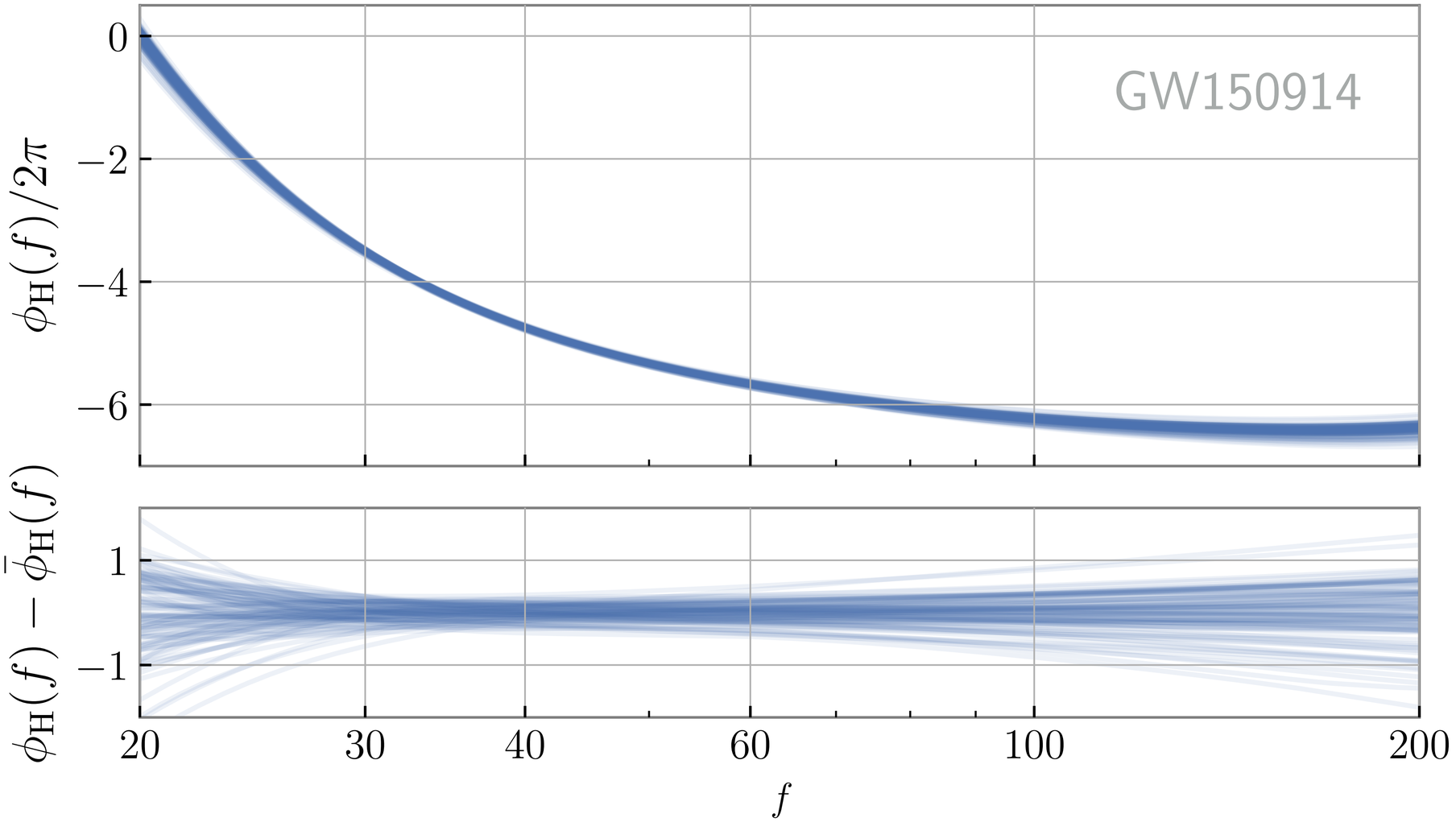
Searching for repeated chirps: false alarms



$$N_{\text{false alarm}} \sim N^2$$

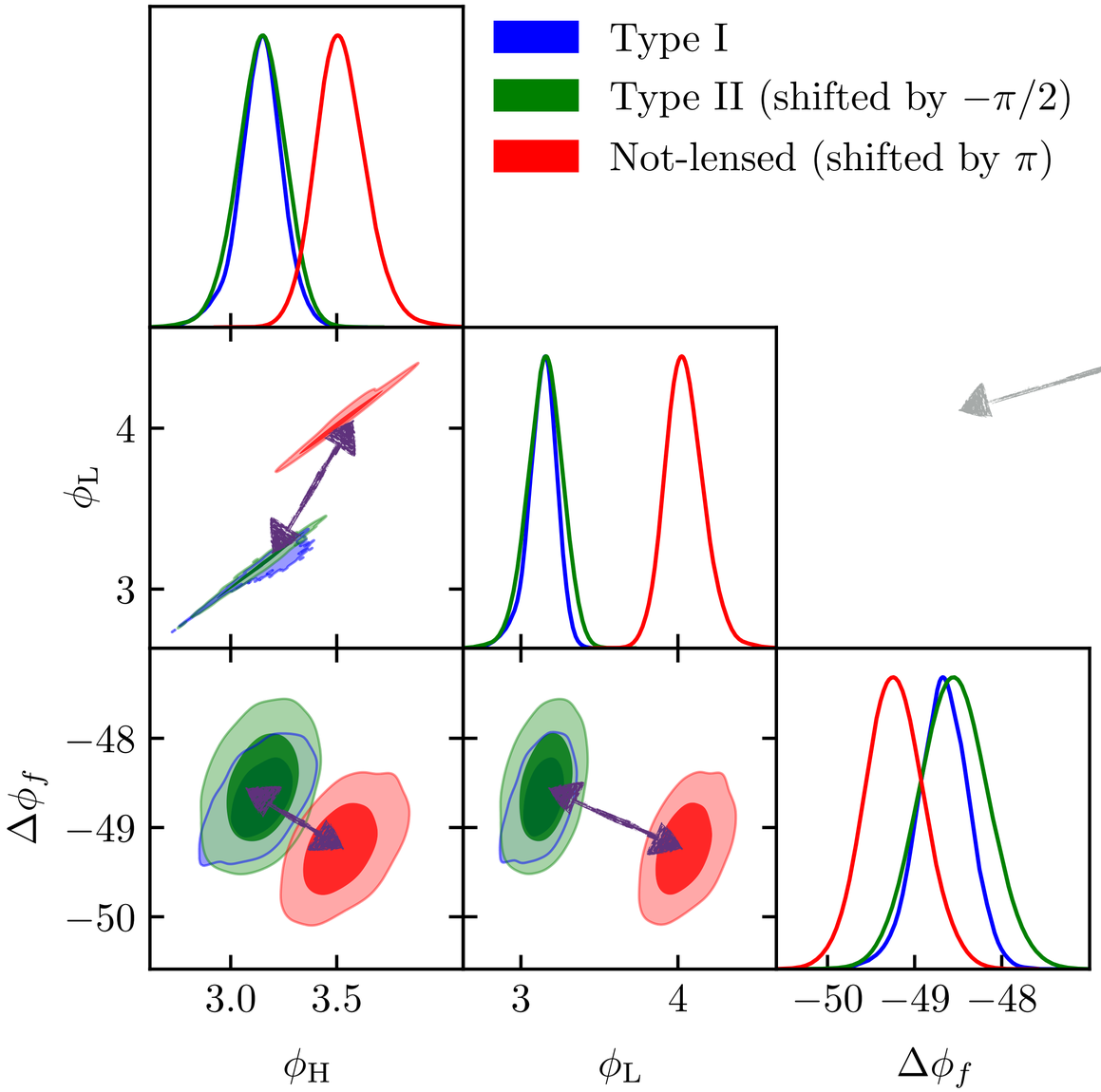
[*Çalışkan*, **Ezquiaga**, Hannuksela and Holz; PRD'22]

Fighting the false alarms: **phase consistency**



[**Ezquiaga**, Hu, Lo; PRD'23]

Fighting the false alarms: **phase consistency**

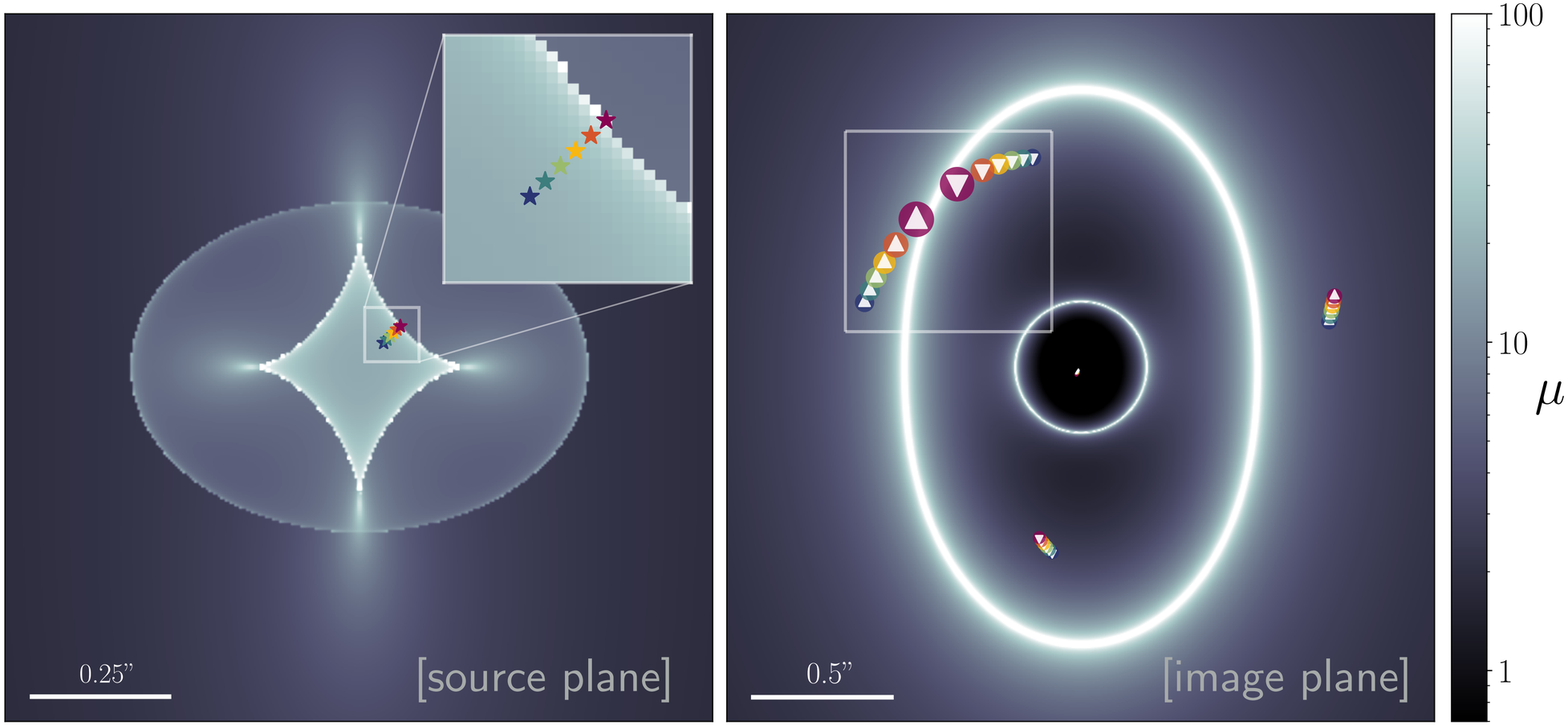


Look for events with consistent detector phases

- Best measured quantities!
- Check consistency from *distance* in phase space (similar to cosmological tensions)

[**Ezquiaga**, Hu, Lo; PRD'23]

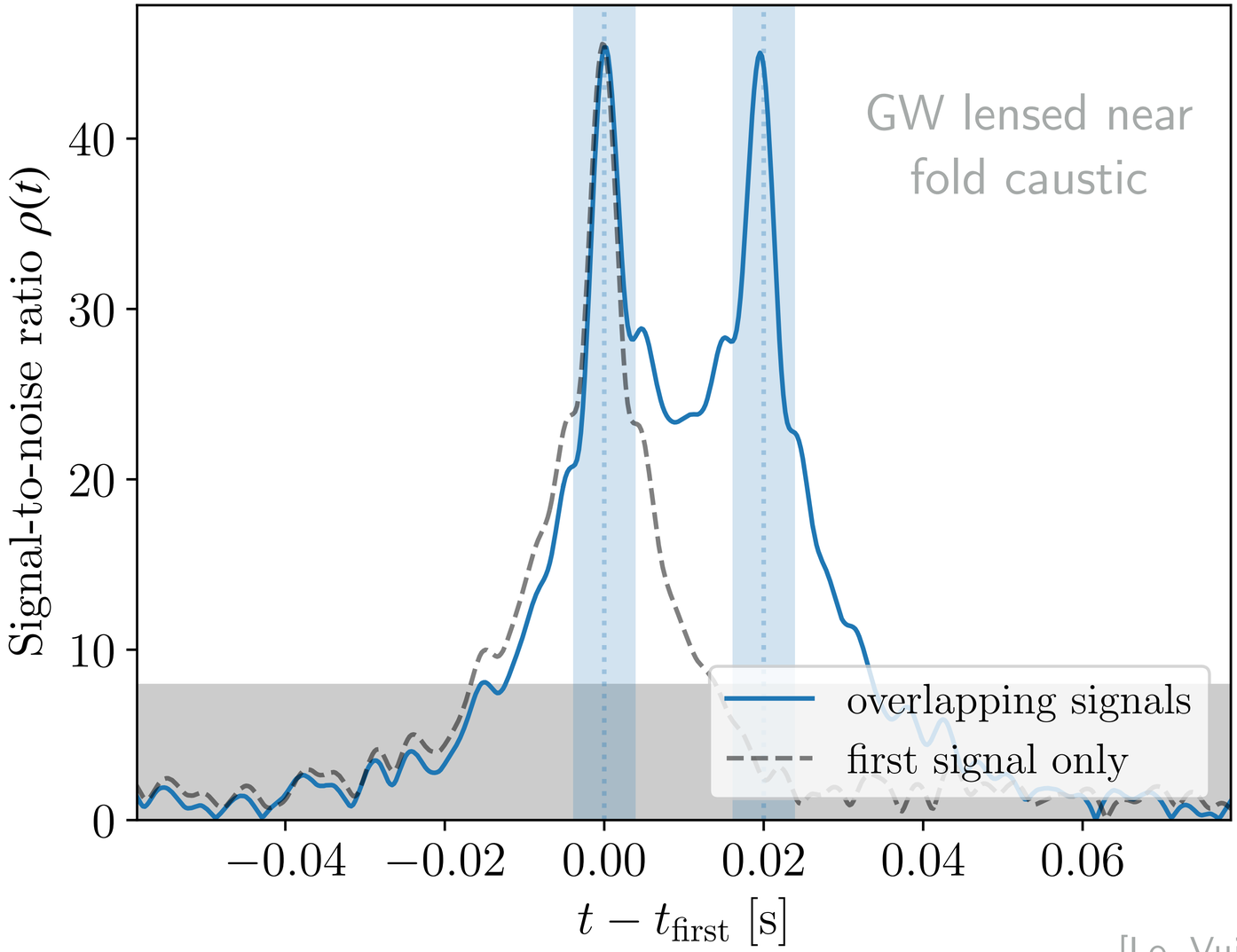
Searching for lensing: *caustics* are the regions of highest magnification



[galaxy lens with a cored singular isothermal ellipsoid density profile]

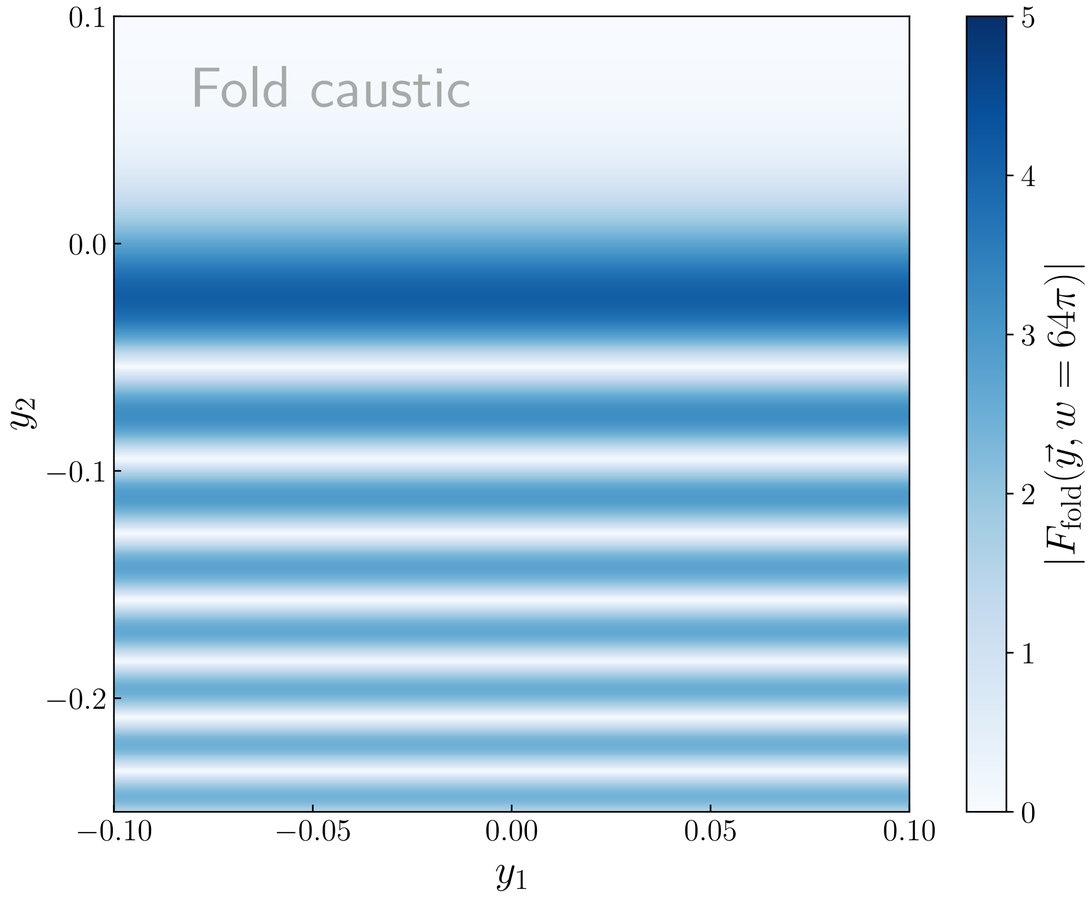
[Lo, Vujeva, **Ezquiaga**, Chan; PRL'25]

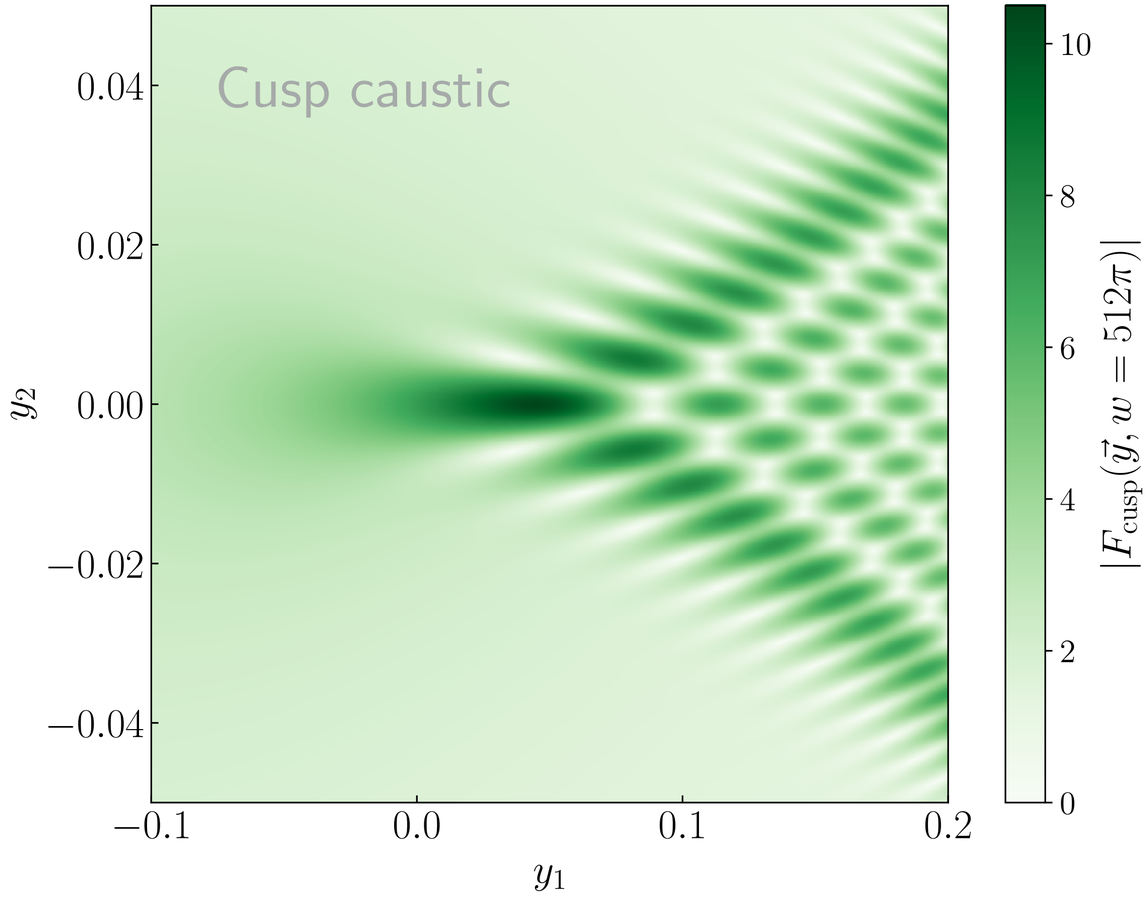
Searching for lensing: universality around *caustics* is a smoking-gun!



[Lo, Vujeva, **Ezquiaga**, Chan; PRL'25]

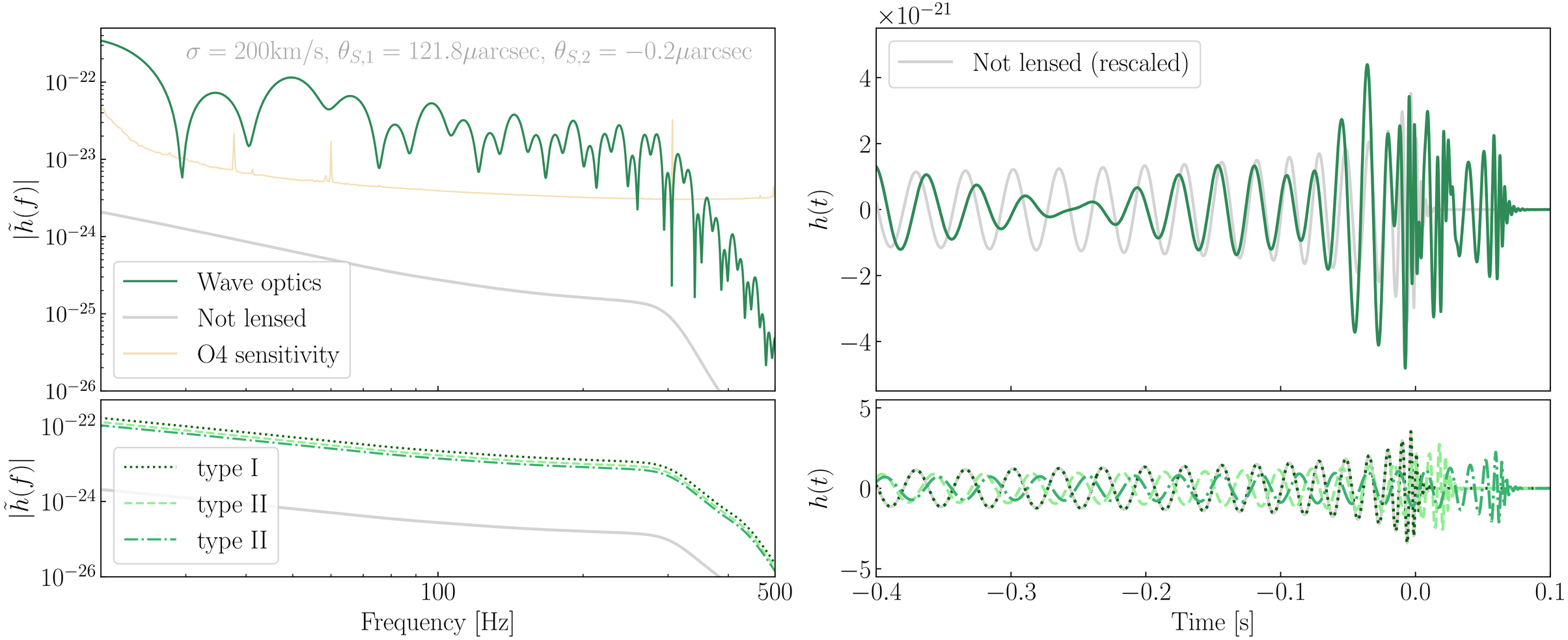
Searching for lensing: diffraction around *caustics* sets maximum magnification and leads to waveforms distortions





[**Ezquiaga**, Lo, Vujeva; 2025]

Searching for lensing: diffraction around *caustics* sets maximum magnification and leads to waveforms distortions



[**Ezquiaga**, Lo, Vujeva; 2025]