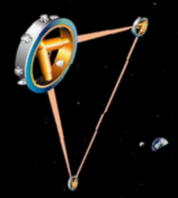
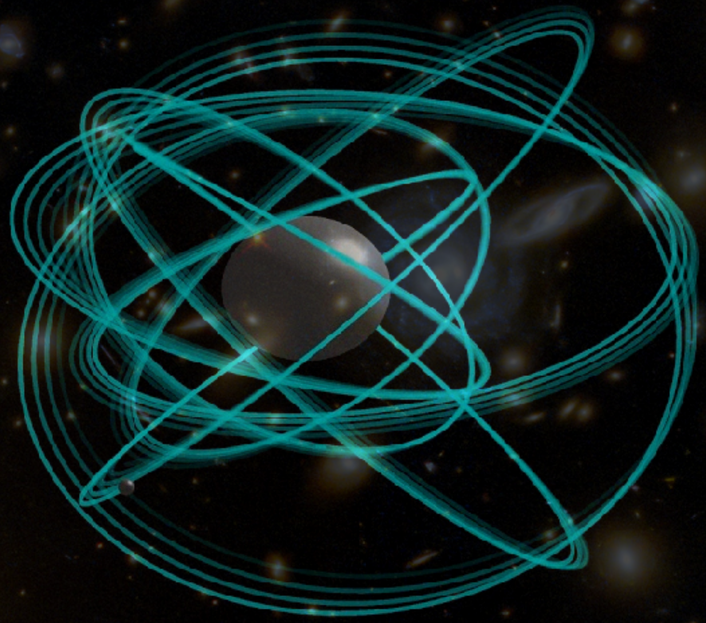


Extreme Mass-Ratio Inspirals as dark standard sirens

Danny Laghi



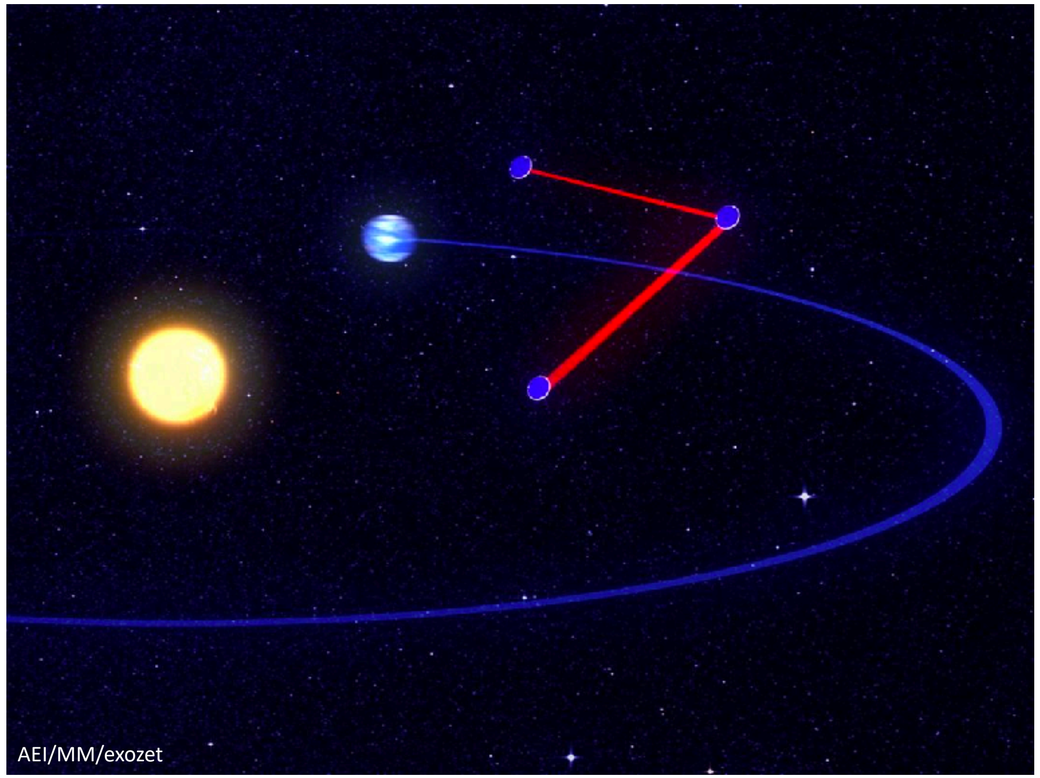
Laghi, Tamanini, Del Pozzo, Sesana, Gair, Babak, Izquierdo-Villalba - MNRAS **508**, 4512 (2021)

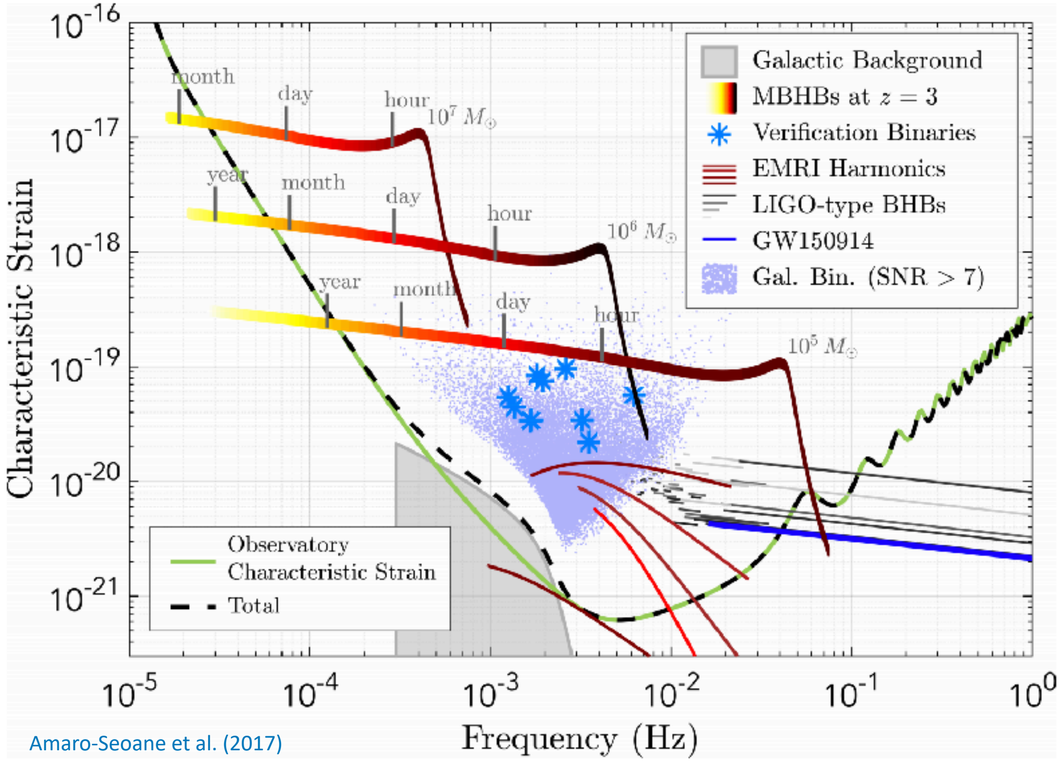
IRAP/L2IT mini-symposium - 10/12/2021

Credits: Steve Drasco/ESA-HUBBLE

LASER INTERFEROMETER SPACE ANTENNA

- LISA will be the **first space-based** GW detector (expected launch in 2034)
- LISA will observe GWs in a yet **unexplored** frequency range (10^{-4} – 10^{-1} Hz)
- LISA will be sensible to **new** exciting GW sources up to high redshift





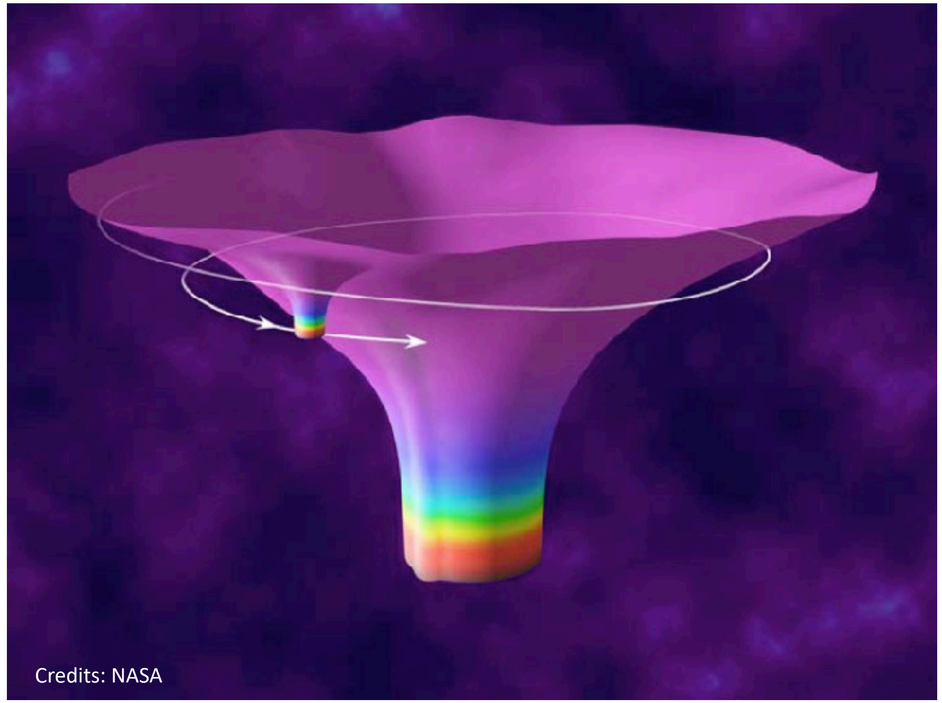
Amaro-Seoane et al. (2017)

EXTREME MASS-RATIO INSPIRALS

- Systems with **mass-ratio** $q \sim 10^{-5} - 10^{-3}$
- **Compact object** $(M \sim 10 M_\odot)$ orbiting a **massive BH** $(10^4 M_\odot \lesssim M \lesssim 10^6 M_\odot)$
- EMRIs emit GWs in the '**sweet spot**' of LISA's sensitivity $\sim$ mHz
- **Slow inspiral**, $10^4 - 10^5$ orbital cycles in the final year before plunge
- **Extremely accurate** measurements of the system parameters:

$$\Delta M_{MBH}/M_{MBH} < 10^{-4} \qquad \Delta d_L/d_L \sim 10^{-1}$$
$$\Delta S_{MBH}/S_{MBH} < 10^{-4} \qquad \Delta\Omega/\Omega \sim 10\ \mathrm{deg}^2$$

Babak et al., *PRD* (2017)


Credits: NASA

- We expect several events to be **well-localised**
- We can use these events as "**dark sirens**"

GW COSMOGRAPHY WITHOUT EM COUNTERPART

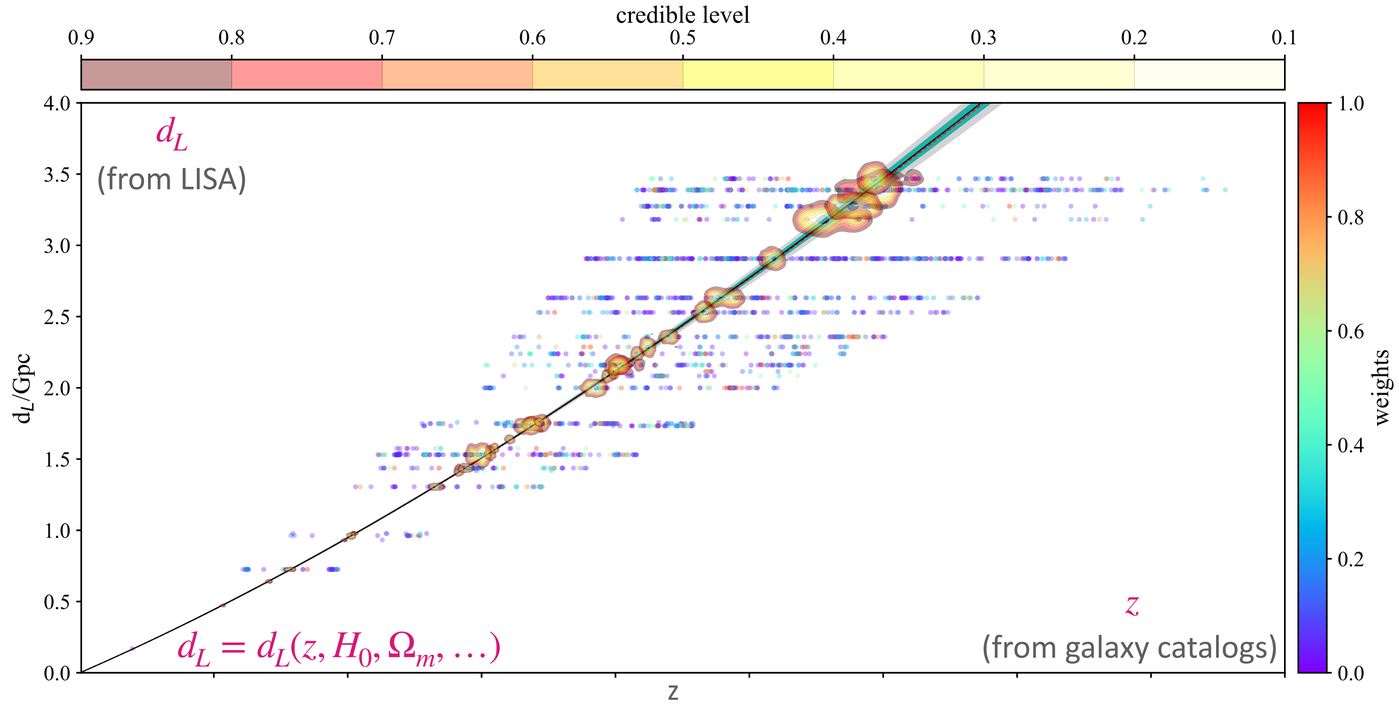
Schutz, *Nature* (1986)

- GWs are "**self-calibrated**": $h \sim d_L^{-1}$
  - GWs encode the luminosity distance
  - No need for distance scale ladder ("standard sirens")
  - No redshift measurement from GWs

Krolak, Schutz, *GRG* (1987)

Macleod, Hogan, *PRD* (2008)

- EMRIs can be used as "**dark standard sirens**"
  - Infer z by **statistically matching** GW sky position with galaxy catalogs
  - Compute the **probability** of each galaxy to be the true EMRI host



EMRI & GALAXY CATALOGS

- Use EMRI catalogs for 10 years of LISA observation from Babak et al., *PRD* (2017)
- Investigate three models: **pessimistic** (M5), **fiducial** (M1), **optimistic** (M6)
- Use flux-limited, full-sky simulation of Henriques et al., *MNRAS* (2012)

$(M_* > 10^{10} M_\odot)$

- Require **SNR>100**:
  - Well-localised, most-informative events
  - $N_g \lesssim 10^3$

→ Analysed events

$M5 \sim O(5)$

$M1 \sim O(30)$

$M6 \sim O(70)$

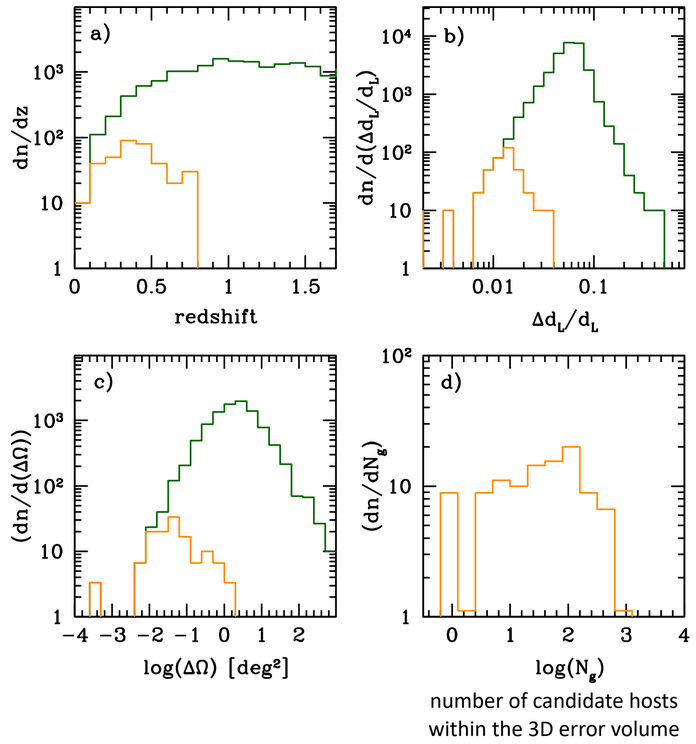
$\Delta d_L/d_L \lesssim 0.04$

$\Delta\Omega_{sky} \lesssim 2\ \mathrm{deg}^2$

Green: 10yrs

Orange: 10yrs & SNR>100

M1 model



number of candidate hosts within the 3D error volume

BAYESIAN INFERENCE

- **Posterior PDF**: $p(\Omega \mid D\,\mathscr{H}\,I) \propto p(\Omega \mid \mathscr{H}\,I)\,p(D \mid \Omega\,\mathscr{H}\,I)$
- **Parameter space**: $\Omega = \{h, \Omega_m, \ldots\}$

$h = H_0/100\,\mathrm{km^{-1}s\ Mpc}$

- **Data**: $D = \{D_1, \ldots, D_N\}$, with $D_i = \{\hat{d}_L \pm \Delta\hat{d}_L,\ \hat{\theta}_{GW} \pm \Delta\hat{\theta}_{GW},\ \hat{\phi}_{GW} \pm \Delta\hat{\phi}_{GW}\}_i$
- **Cosmological model** $\mathscr{H}$: flat ($\kappa = 0$) FLRW metric:

$$d(\Omega, z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{E(z')}$$

$$E(z') = \sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda\, g(z', w_0, w_a)}$$

$$g(z', w_0, w_a) = (1+z')^{3(1+w_0+w_a)} e^{-3\frac{w_a z'}{1+z'}}$$

Linder, *PRL* (2003)

$w(z) = w_0 + w_a\, z/(1+z)$

- **GW redshift prior**: dictated by LISA 3D error volume and galaxy catalog
- **LISA likelihood**: multivariate Gaussian distribution

COSMOLOGICAL SCENARIOS

- We investigate two cosmological scenarios:

ΛCDM

"Classical" LambdaCDM model

$$\Omega = \{h, \Omega_m\}$$
$$p(h \,|\, \mathscr{H} I) = \mathscr{U}(0.6, 0.86)$$
$$p(\Omega_m \,|\, \mathscr{H} I) = \mathscr{U}(0.04, 0.5)$$

DE

Dynamical Dark Energy model

$$\Omega = \{w_0, w_a\}$$
$$p(w_0 \,|\, \mathscr{H} I) = \mathscr{U}(-3, -0.3)$$
$$p(w_a \,|\, \mathscr{H} I) = \mathscr{U}(-1, 1)$$

- Our 'reference' cosmology is based on the **Millennium Run**:

Henriques et al., *MNRAS* (2013)
Springel et al., *Nature* (2005)

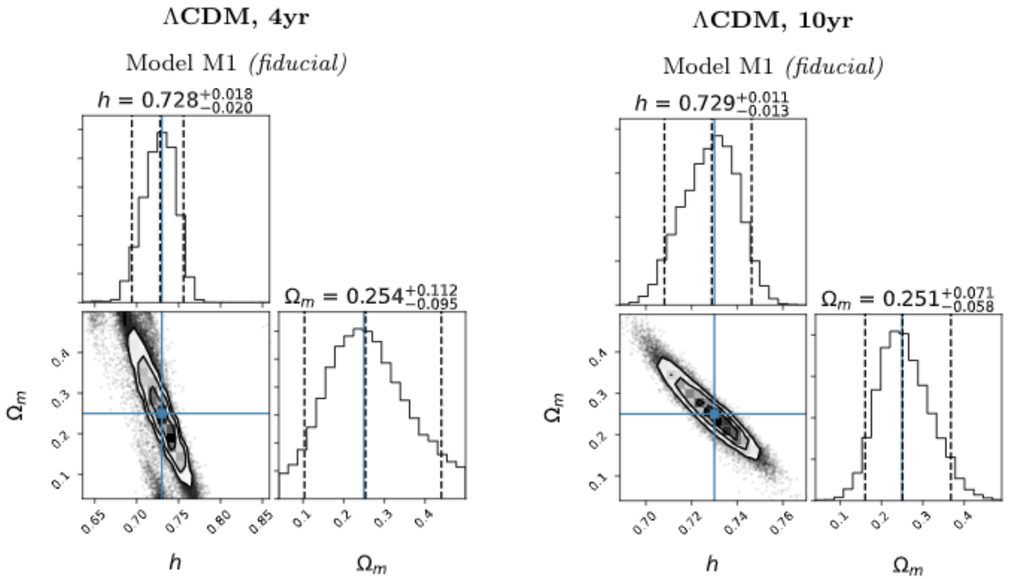
$$h = 0.73$$
$$\Omega_m = 0.25$$
$$\Omega_\Lambda = 0.75$$
$$w_0 = -1$$
$$w_a = 0$$

- Cosmological parameter inference pipeline: **`cosmoLISA`**

Del Pozzo, Laghi [https://github.com/wdpozzo/cosmolisa]

ΛCDM & DE

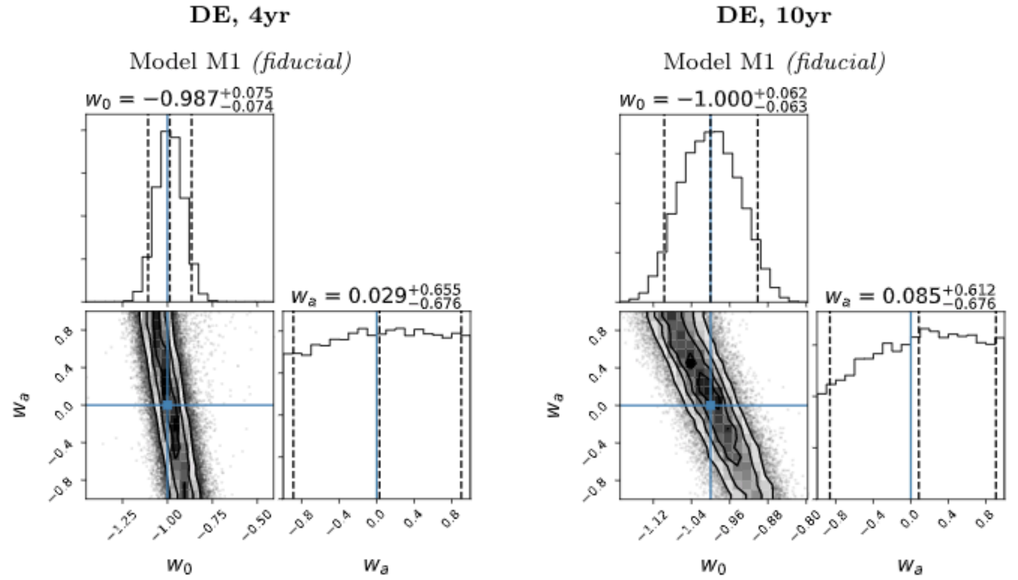
1. EMRIs will be excellent probes of H_0



h accuracy of 1-4%

Ω_m accuracy of 25-60%

2. EMRIs can constrain w_0

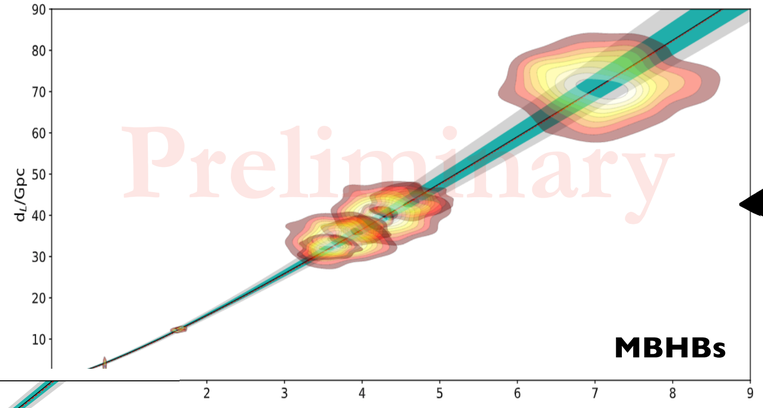


w_0 accuracy of 5-10%

GW cosmology with LISA well-localised EMRIs is going to be **highly rewarding**

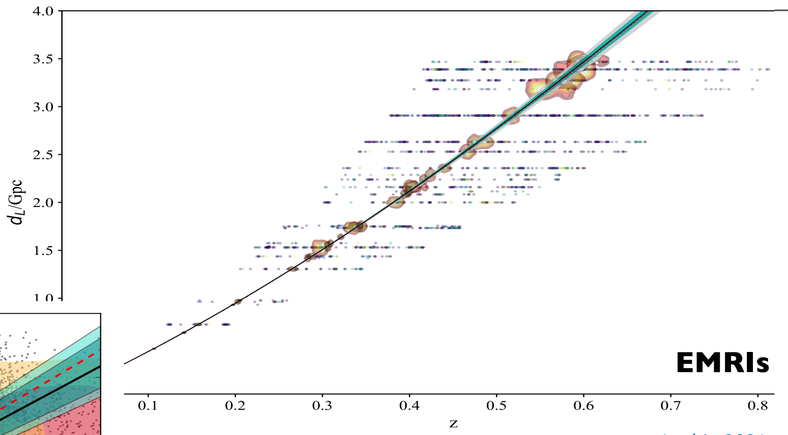
FUTURE PROSPECTS

- Cosmological **enchilada** (SOBHBs + EMRIs + MBHBs)



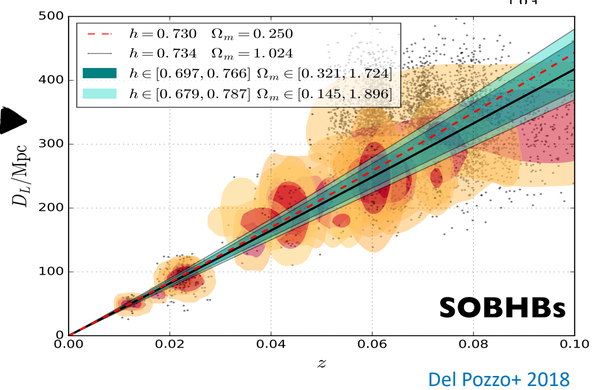
"Bright sirens"
with
EM counterpart

[In preparation]



Laghi+ 2021

"Dark sirens"
without
EM counterpart



Del Pozzo+ 2018

Low z Intermediate z High z