Gravitational-wave cosmology with Extreme Mass Ratio Inspirals

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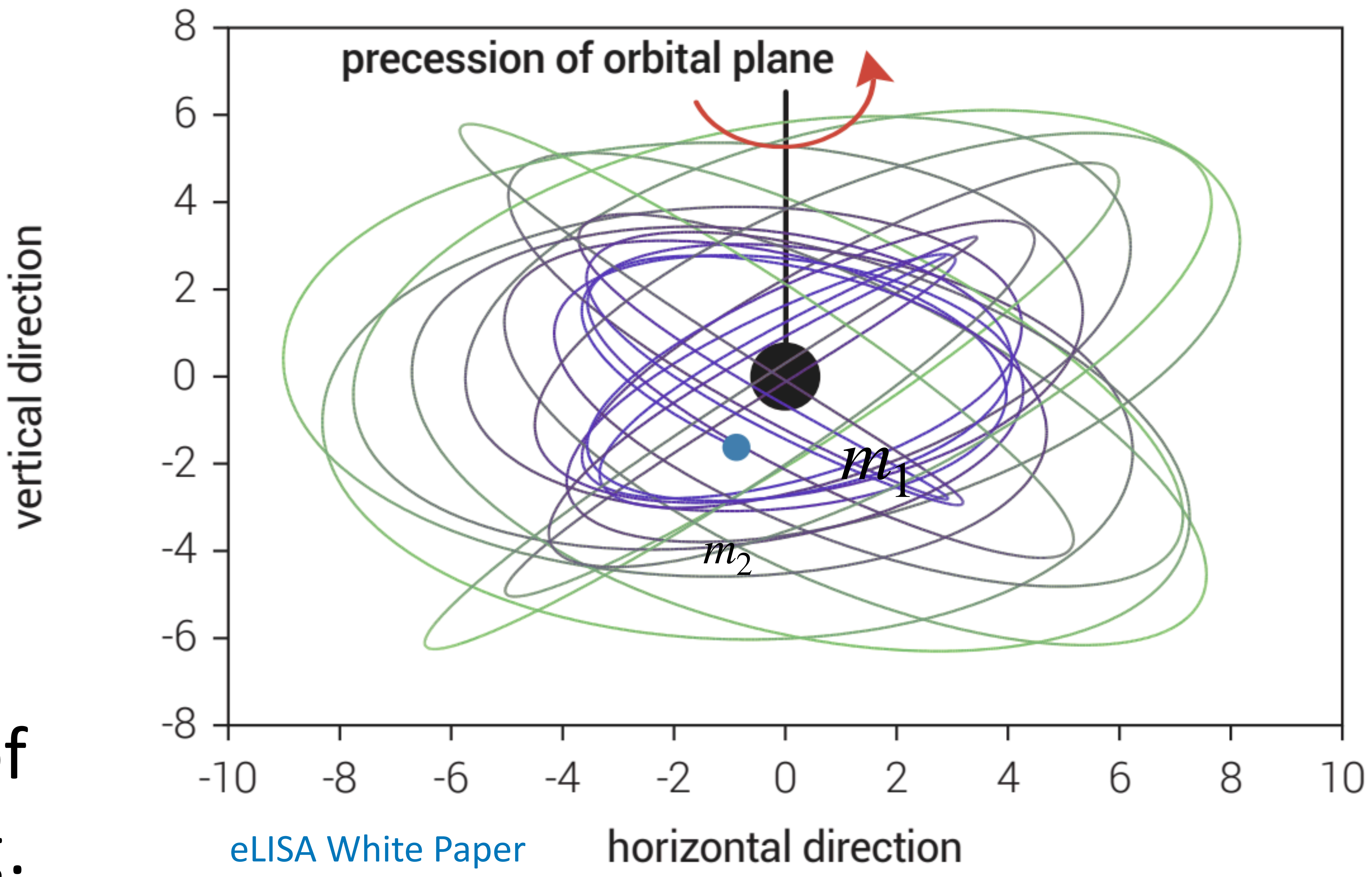
Extreme Mass Ratio Inspirals

- Binary systems with **mass ratio** $m_2/m_1 \sim 10^{-6} - 10^{-3}$
- **Slow inspiral**, $10^4 - 10^5$ orbital cycles in the final year before plunge
- **Very accurate** measurements of the system parameters, e.g. $\Delta d_L/dL \lesssim 10\,\%\,,\,\Delta\Omega \lesssim 10\,\mathrm{deg}^2$

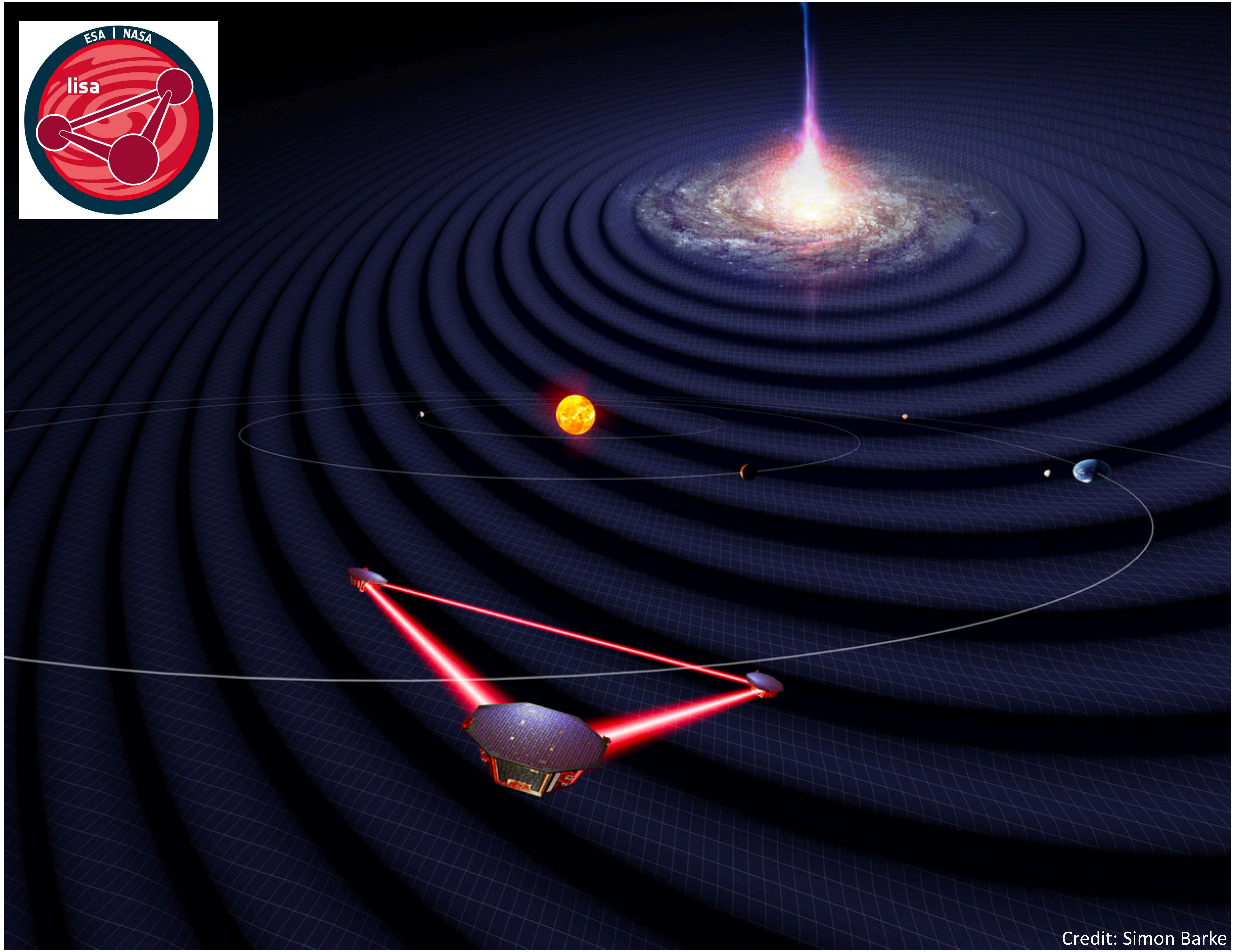
Babak+ PRD (2017)



eLISA White Paper

LASER INTERFEROMETER SPACE ANTENNA (LISA)

- Mission **adopted** by ESA in 2024 ⇒ Expected launch in 2035
- **LISA** will observe gravitational waves (GWs) in a yet **unexplored** frequency range ($10^{-4} - 10^{-1}$ Hz)
- Cartwheeling heliocentric orbit, average armlength ~2.5M km



GWs to probe late-time FLRW cosmology

Individual GW sources at cosmological distances are "**standard sirens**"

- **Complex multi-dimensional GW parameter space** explored with computationally intensive stochastic sampling techniques (e.g. MCMC, nested sampling)
- No need for distance scale ladder to obtain the **luminosity distance**
- GWs are standard sirens because they are **self-calibrated**

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

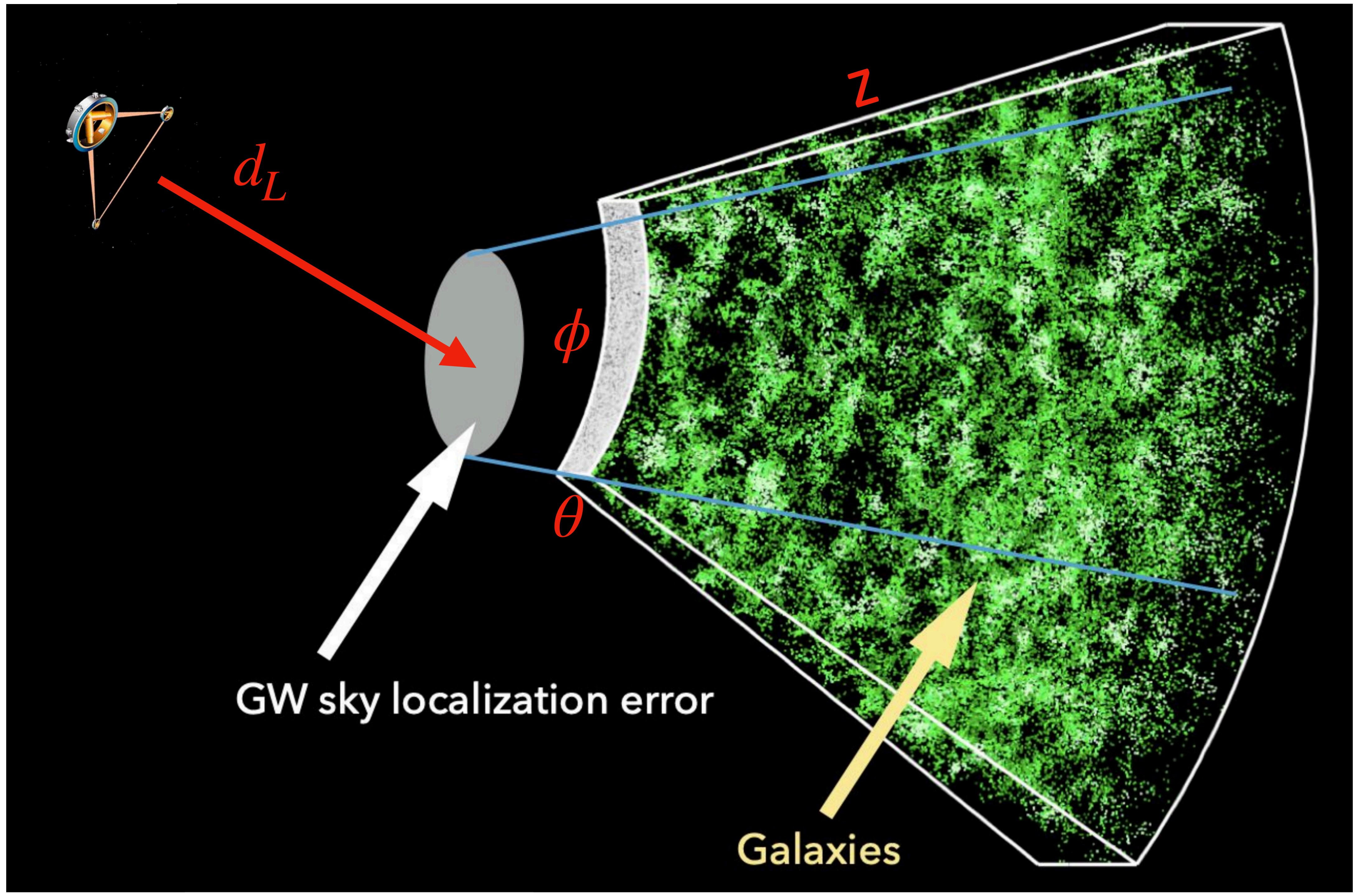
$$H(z)^2 = H_0^2\left(\Omega_m(1+z)^3 + \Omega_{DE}(1+z)^{3(1+w(z))}\right)$$

Hubble constant

fraction of matter/DE density today

EMRIs as dark standard sirens

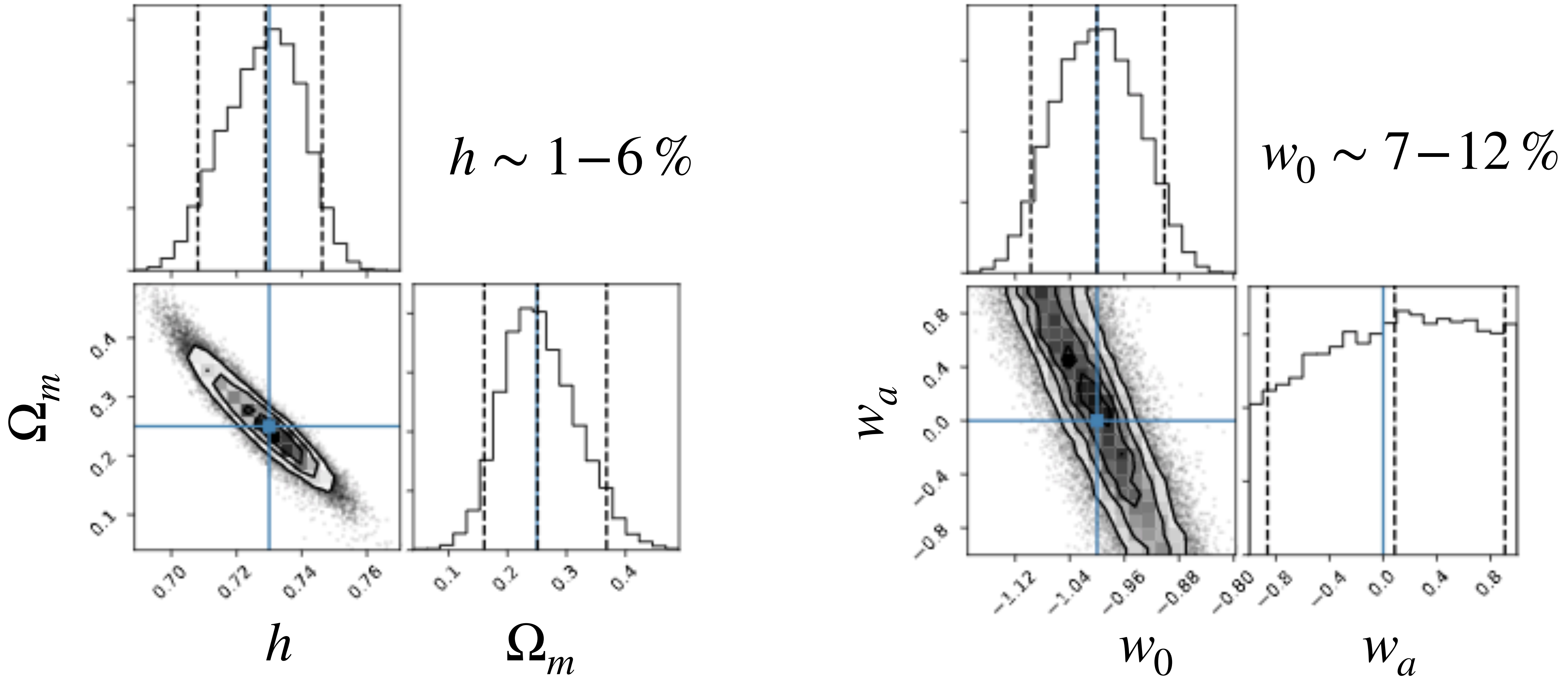
- Laghi+ MNRAS (2021)



- Cross-matching of state-of-the-art EMRI mock catalogues with full-sky simulated galaxy catalogue Babak+ PRD (2017) Henriques+ MNRAS (2012)

- Nested sampling to explore cosmological parameter space assuming LISA Fisher-Matrix likelihood on the GW luminosity distance

Laghi+ MNRAS (2021)



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

$w(z) = w_0 + \frac{z}{1+z} w_a$

Modified GW propagation

- In **General Relativity**, GW propagating on FLRW background:

$$\tilde{h}''_A + 2\mathcal{H}\tilde{h}'_A + k^2\tilde{h}_A = 0$$

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

$$A = +, \times$$

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- In **modified gravity**, GW propagating on FLRW background:

$$\tilde{h}''_A + 2\mathcal{H}\left[1 - \delta(\eta)\right]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

Saltas+ PRL (2014)   Nishizawa PRD (2018)   Belgacem+ PRD (2018)

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Modified "friction"

- This affects the **GW amplitude** across **cosmological distances**

Saltas+ PRL (2014) Nishizawa PRD (2018) Belgacem+ PRD (2018)

GW luminosity distance

- The net effect is that the quantity extracted from GW observations is a "**GW luminosity distance**":

$$\tilde{h}_A \propto \frac{1}{d_L^{EM}} \xrightarrow{\text{non-GR}} \tilde{h}_A \propto \frac{1}{d_L^{GW}}$$

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

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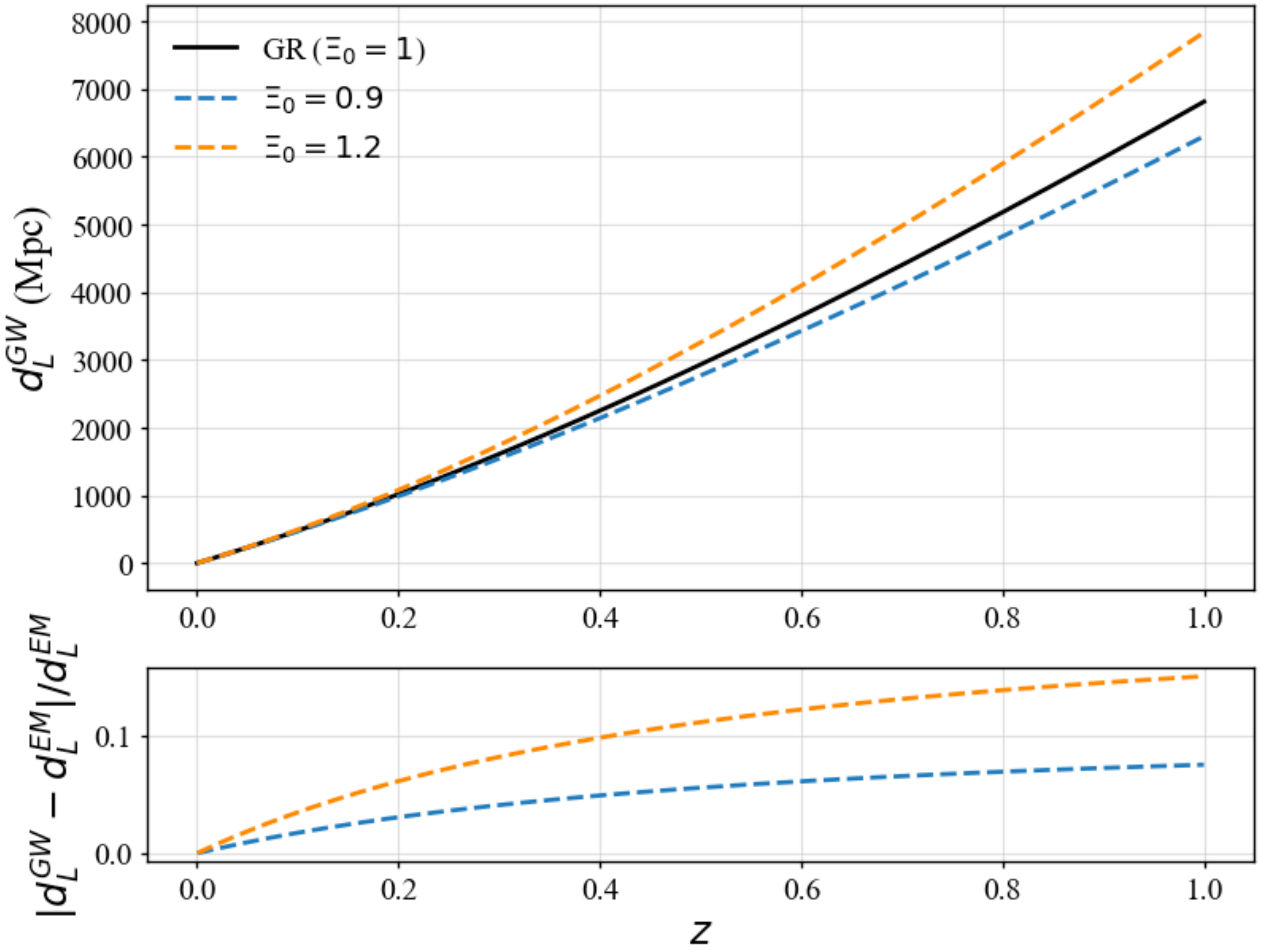
- A convenient phenomenological parametrisation (Ξ_0, n):

$$\frac{d_L^{\rm GW}(z)}{d_L^{\rm EM}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

Belgacem+ PRD (2018)



Can we use EMRIs to constrain Ξ_0 + LCDM parameters?

- In Liu, Laghi, Tamanini PRD (2024) we explored:

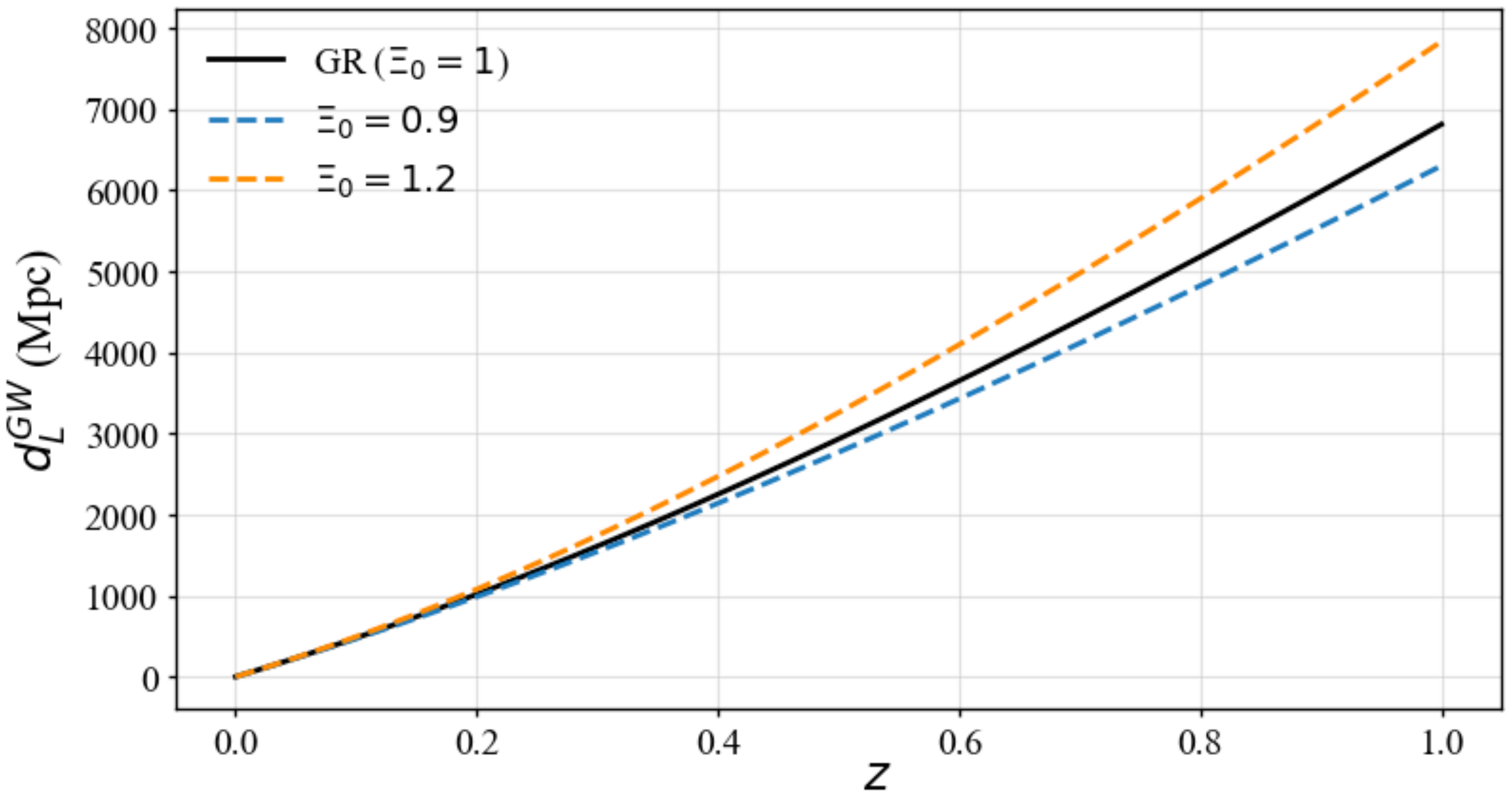
  - Different astrophysical EMRI models and waveforms (M1/M5/M6 + AKS/AKK) from Babak+ PRD (2017)

  - Different injected values of $\Xi_0 = 0.9, 1.0, 1.2\ (n = 2)$

Examples of deviations: O(<10%) Belgacem+ JCAP (2019)

Model	Total	EMRI rate [yr^{-1}] Detected (AKK)	Detected (AKS)
M1	1600	294	189
M2	1400	220	146
M3	2770	809	440
M4	520 (620)	260	221
M5	140	47	15
M6	2080	479	261
M7	15800	2712	1765
M8	180	35	24
M9	1530	217	177
M10	1520	188	188
M11	13	1	1
M12	20000	4219	2279

Babak+ PRD (2017)



Analysis Setup

- Gauge waveform uncertainty by considering two models (AKS, AKK)

- Select EMRIs at SNR>100

- Move to z-space using d_L^{GW} and assuming cosmological priors:
  $h \in [0.6, 0.76], \Omega_m \in [0.04, 0.5],$
  $\Xi_0 \in [0.6, 2.0], n \in [0.0, 3.0]$

- Cross-match EMRI sky locations with simulated galaxy light cone ($z < 1$)

Henriques+ MNRAS (2019)
Izquierdo-Villalba+ A&A (2019)

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Standard Sirens

Model	Parameters	Num of StSi	
		AKS	AKK
M1	$h + \Omega_M + \Xi_0 + n$	17	29
	$h + \Omega_M + \Xi_0$	19	30
	$h + \Xi_0$	19	30
	$\Xi_0 + n$	19	32
	Ξ_0	19	33
M5	$h + \Omega_M + \Xi_0 + n$	3	5
	$h + \Omega_M + \Xi_0$	3	6
	$h + \Xi_0$	3	6
	$\Xi_0 + n$	3	6
	Ξ_0	3	7
M6	$h + \Omega_M + \Xi_0 + n$	23	60
	$h + \Omega_M + \Xi_0$	23	65
	$h + \Xi_0$	23	68
	$\Xi_0 + n$	23	69
	Ξ_0	24	72

Liu, DL, Tamanini PRD (2024)

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Bayesian inference with **`cosmoLISA`**
Laghi+ MNRAS 2021

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Liu, DL, Tamanini PRD (2024)

EMRIs with LISA can constrain Ξ_0 in several scenarios

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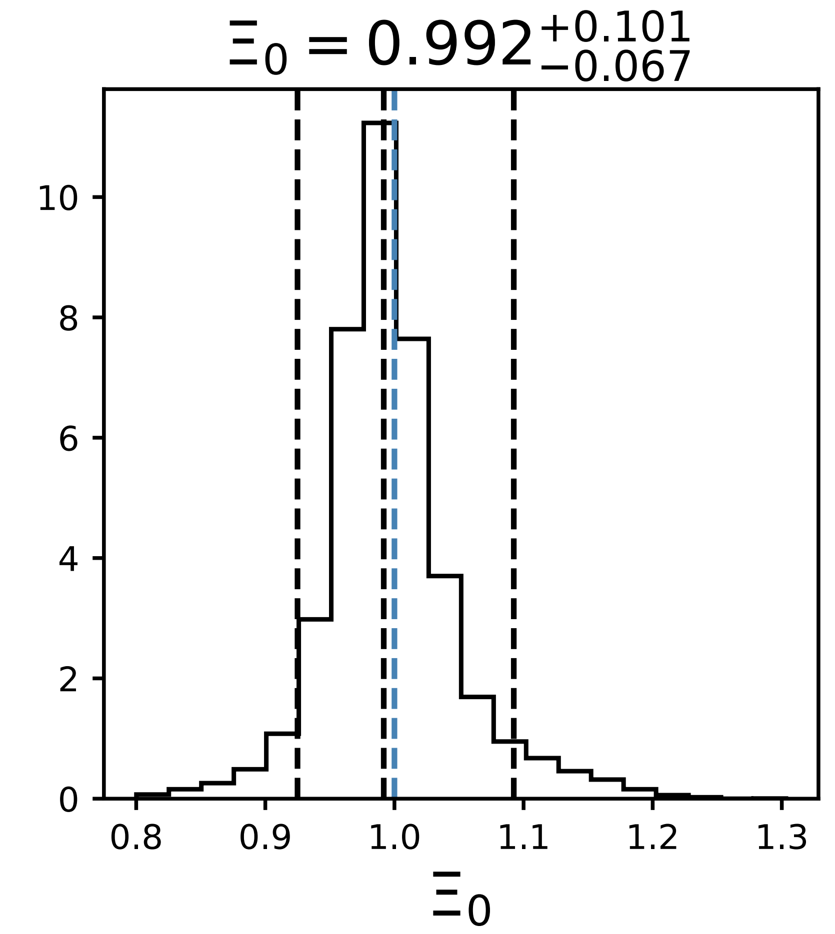

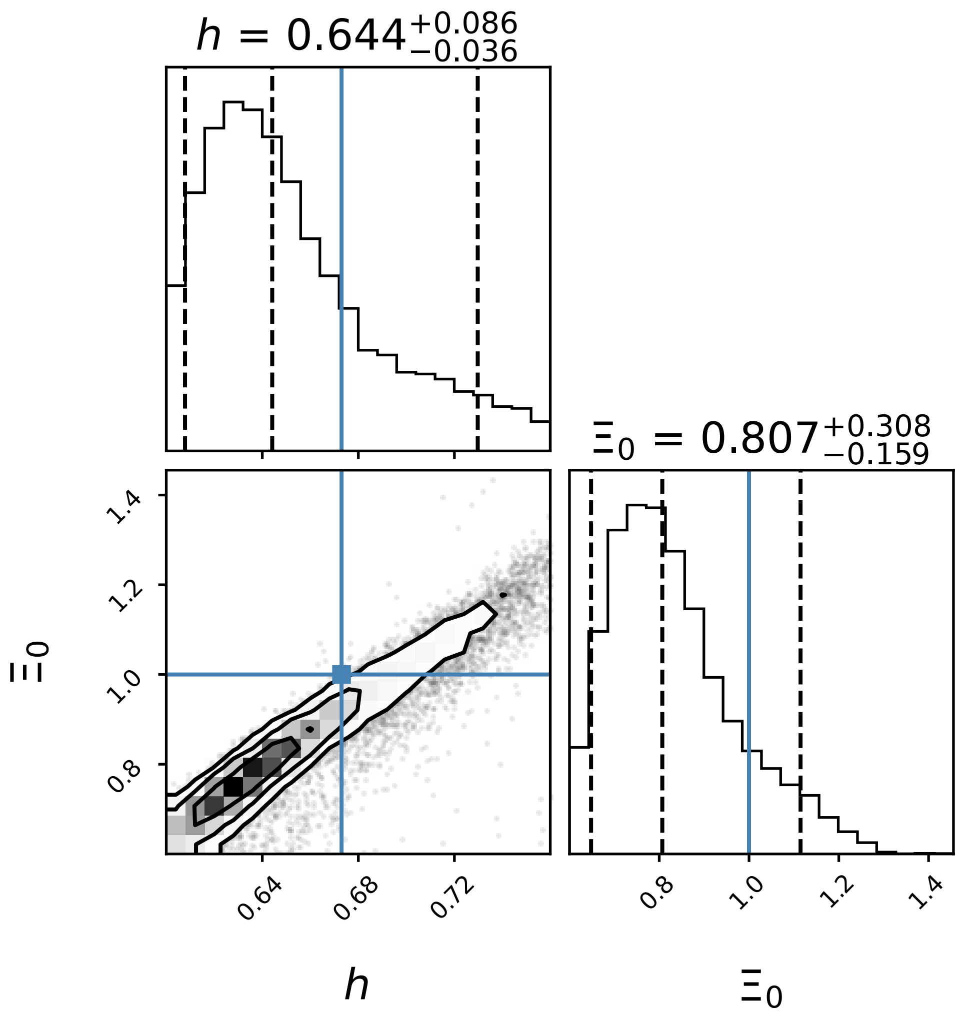

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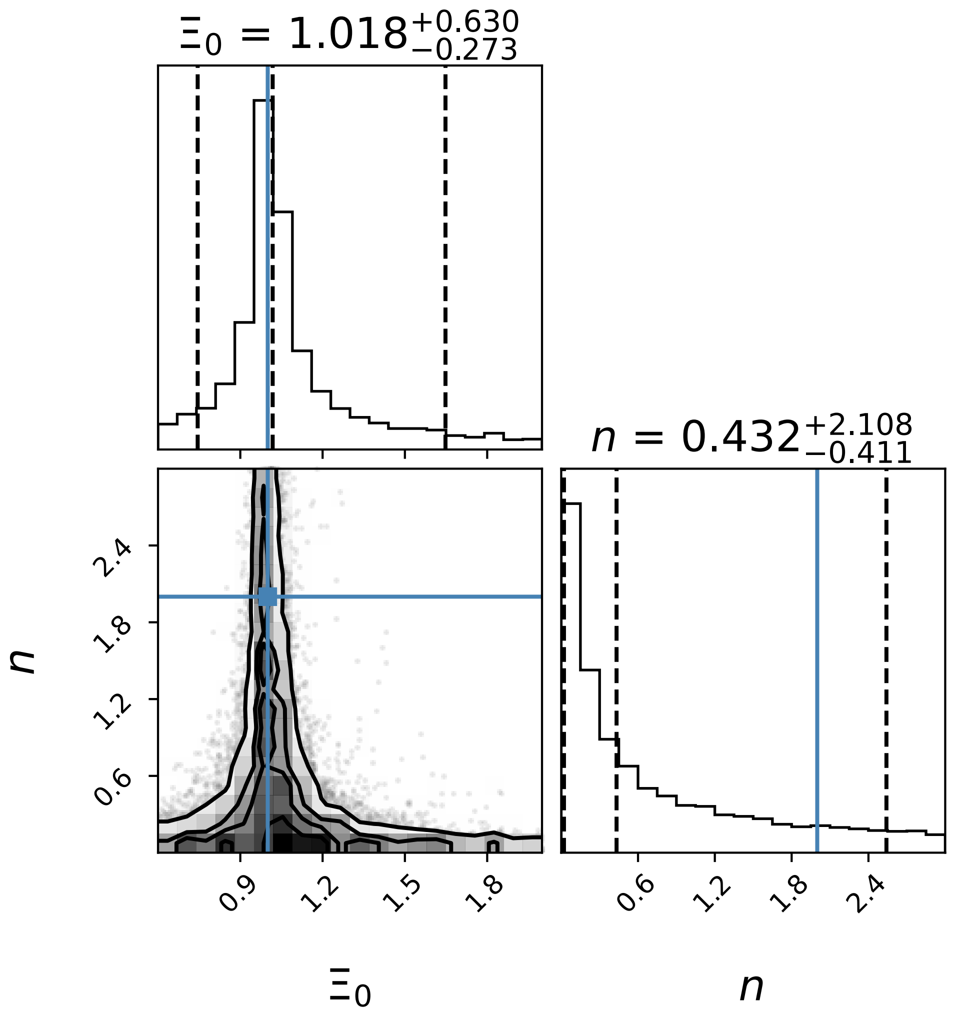
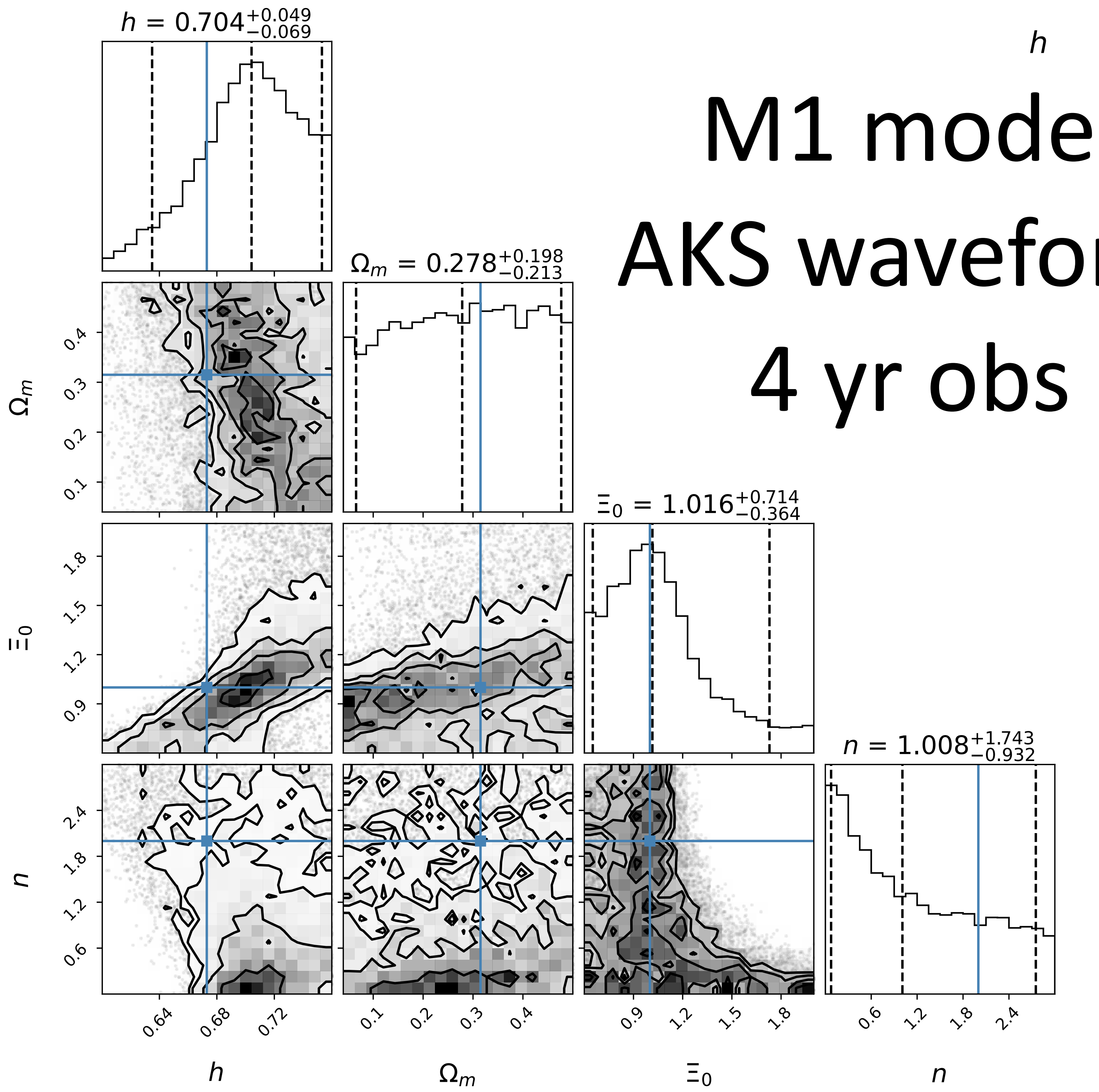
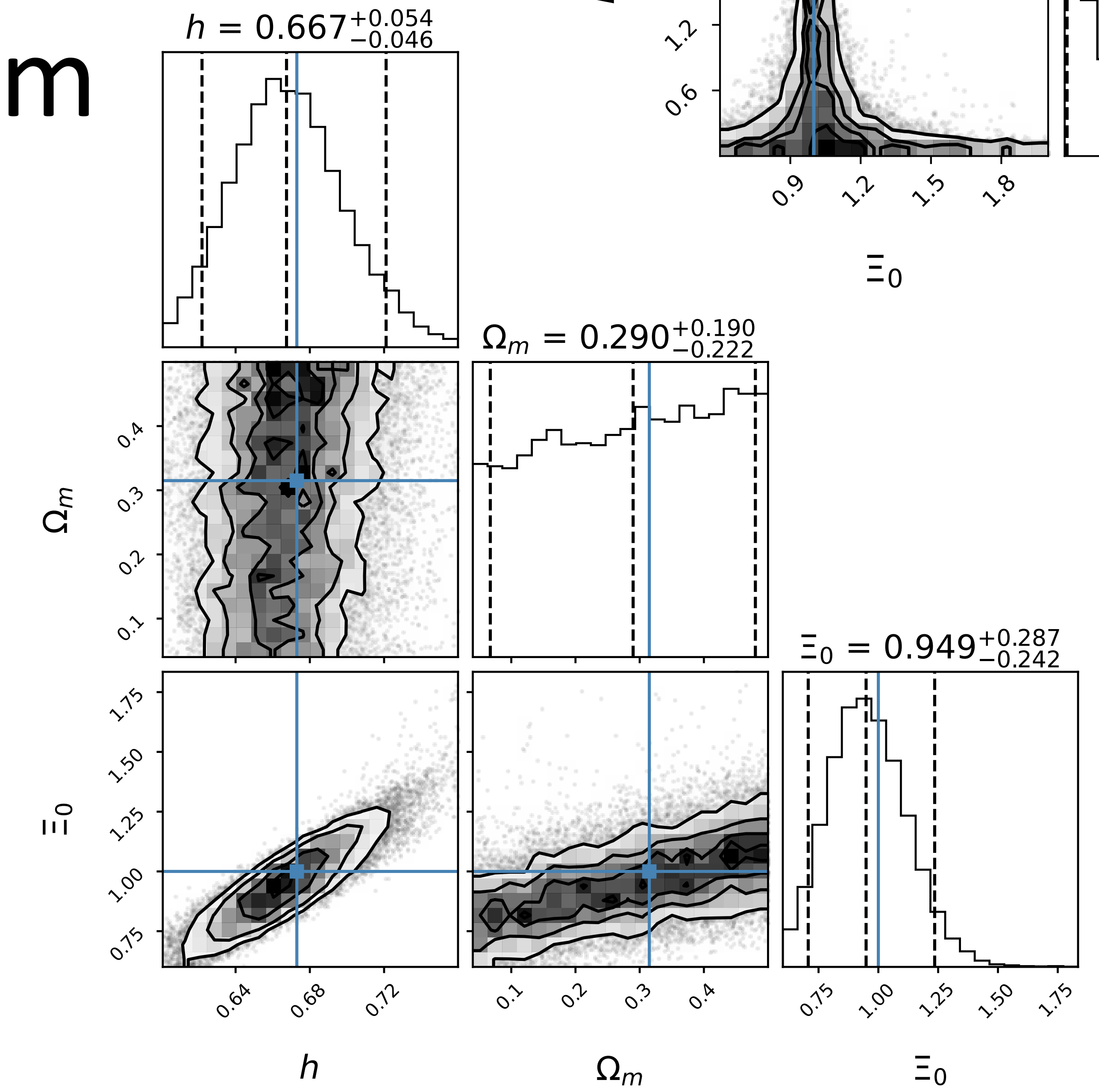




M1 model

AKS waveform

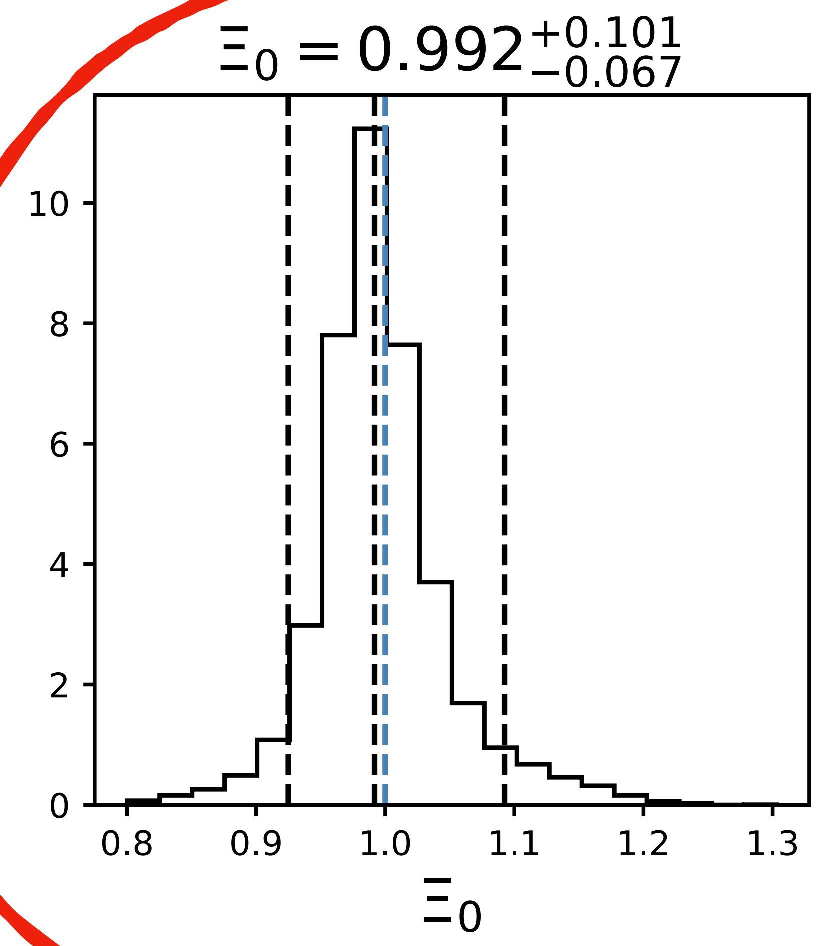
4 yr obs

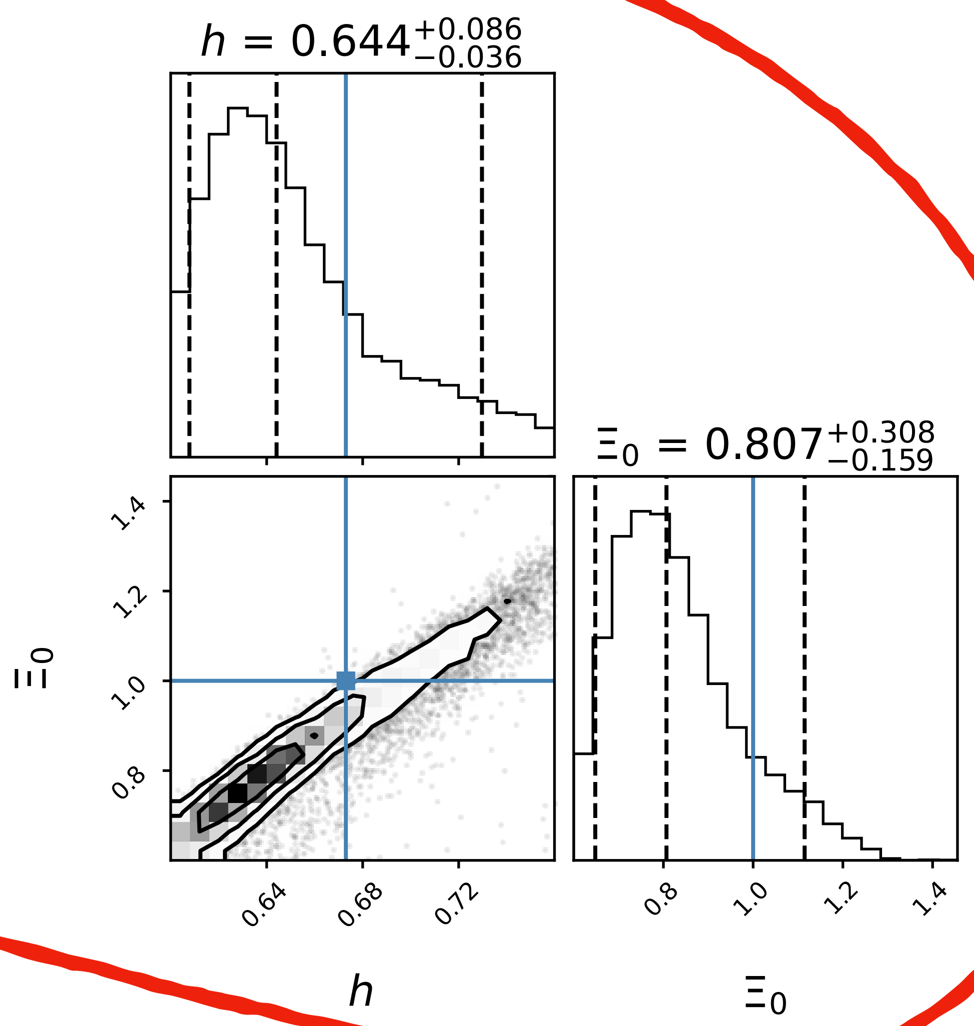


EMRIs with LISA can constrain Ξ_0 in several scenarios

Liu, DL, Tamanini PRD (2024)

- Ξ_0 alone: > 2 - 8% (90% CI)
- Ξ_0+h: > 9 - 29% and > 4 - 10% respectively





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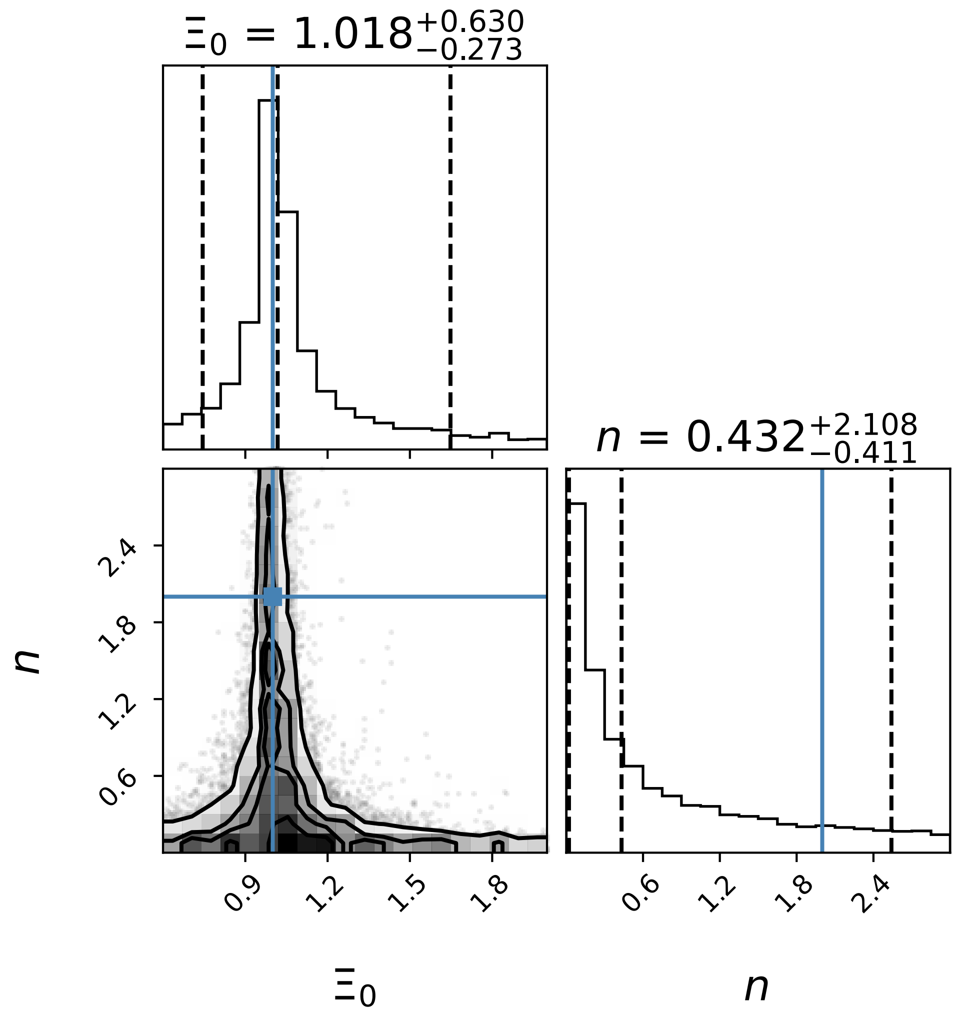

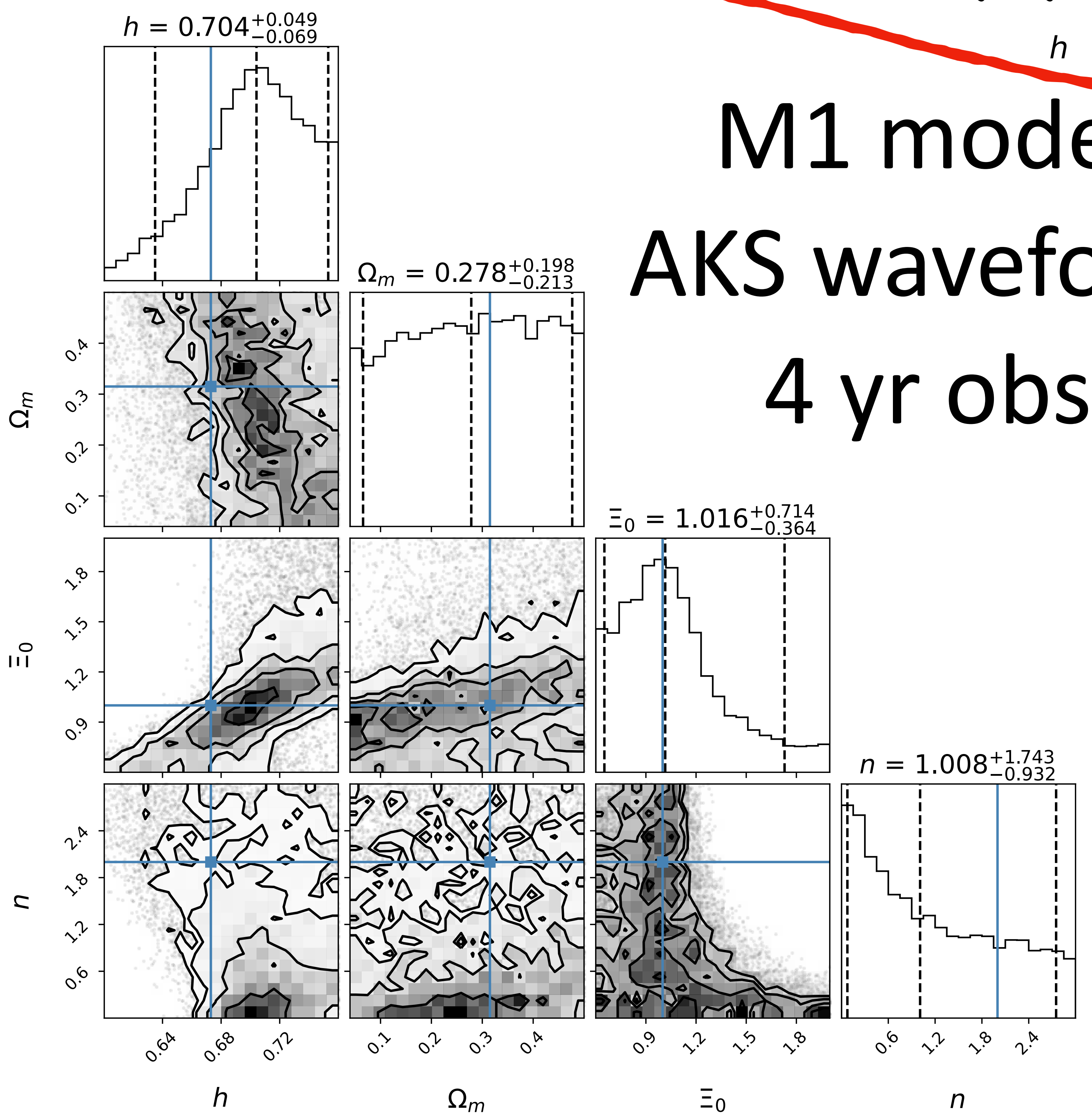

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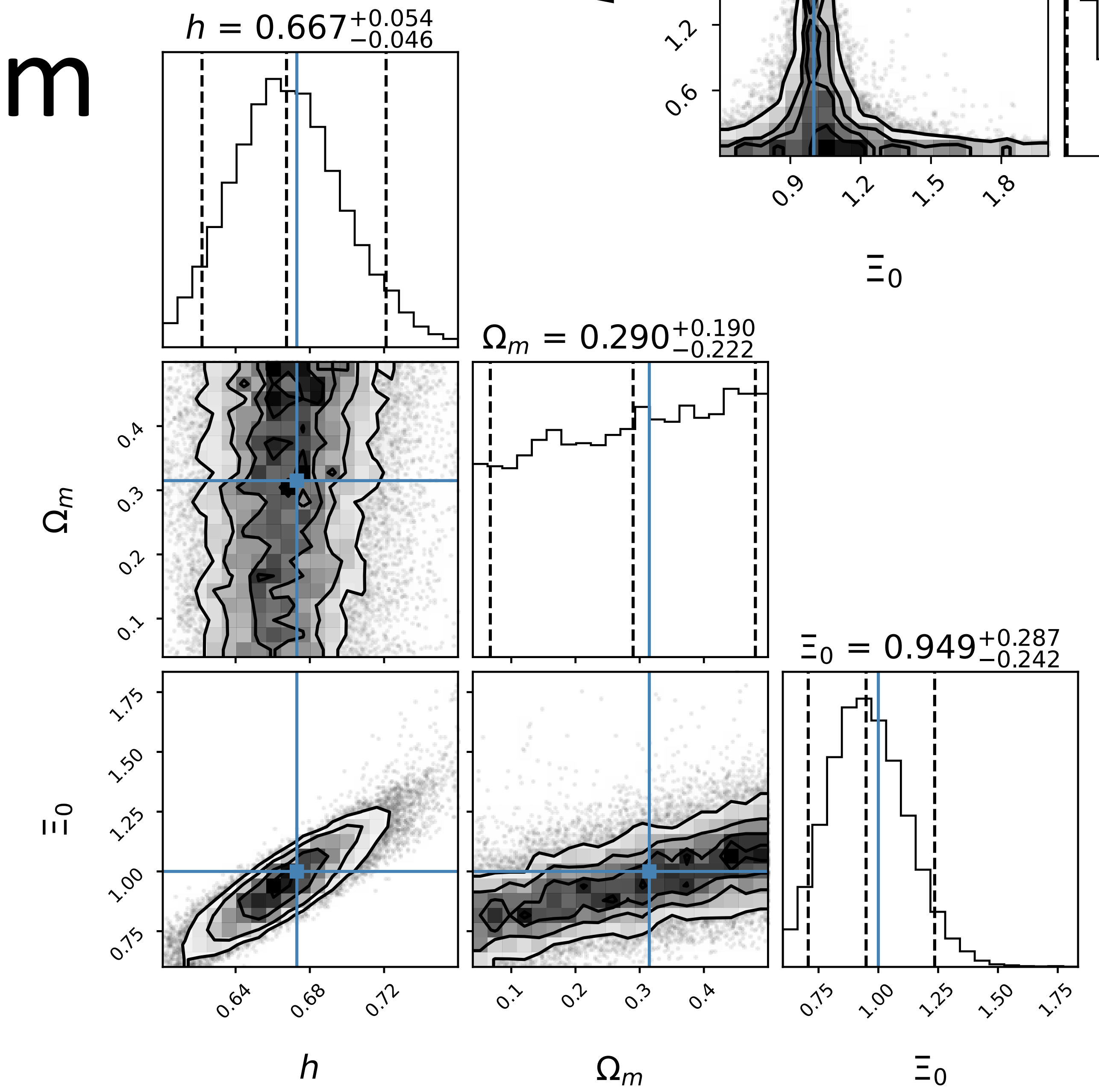

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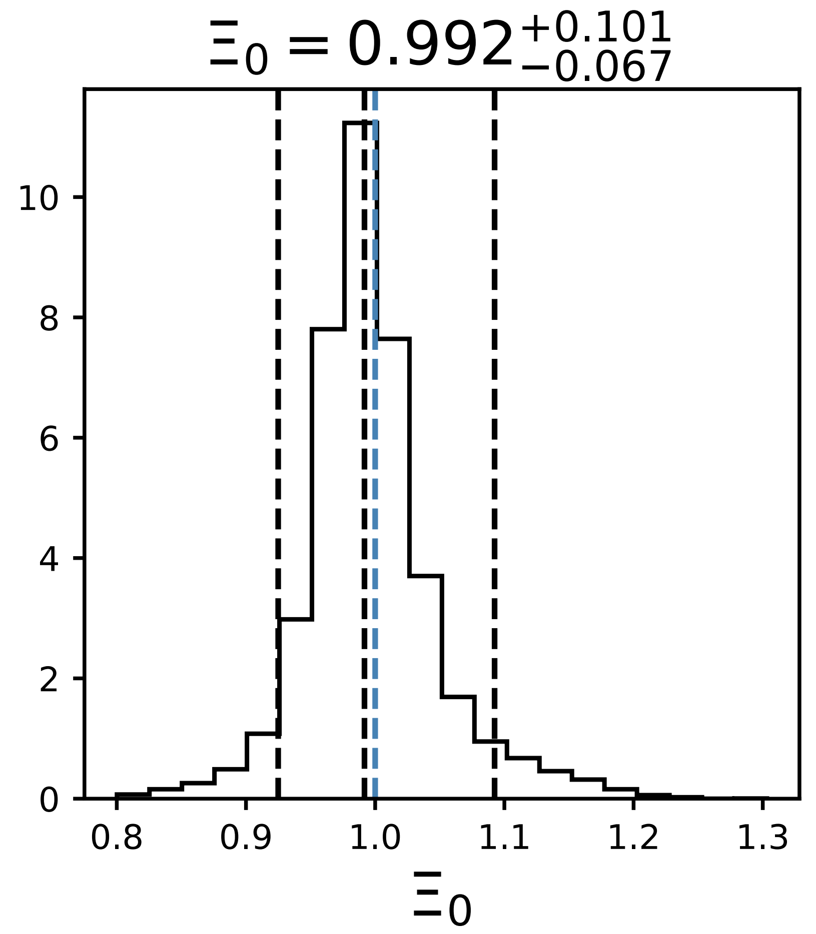

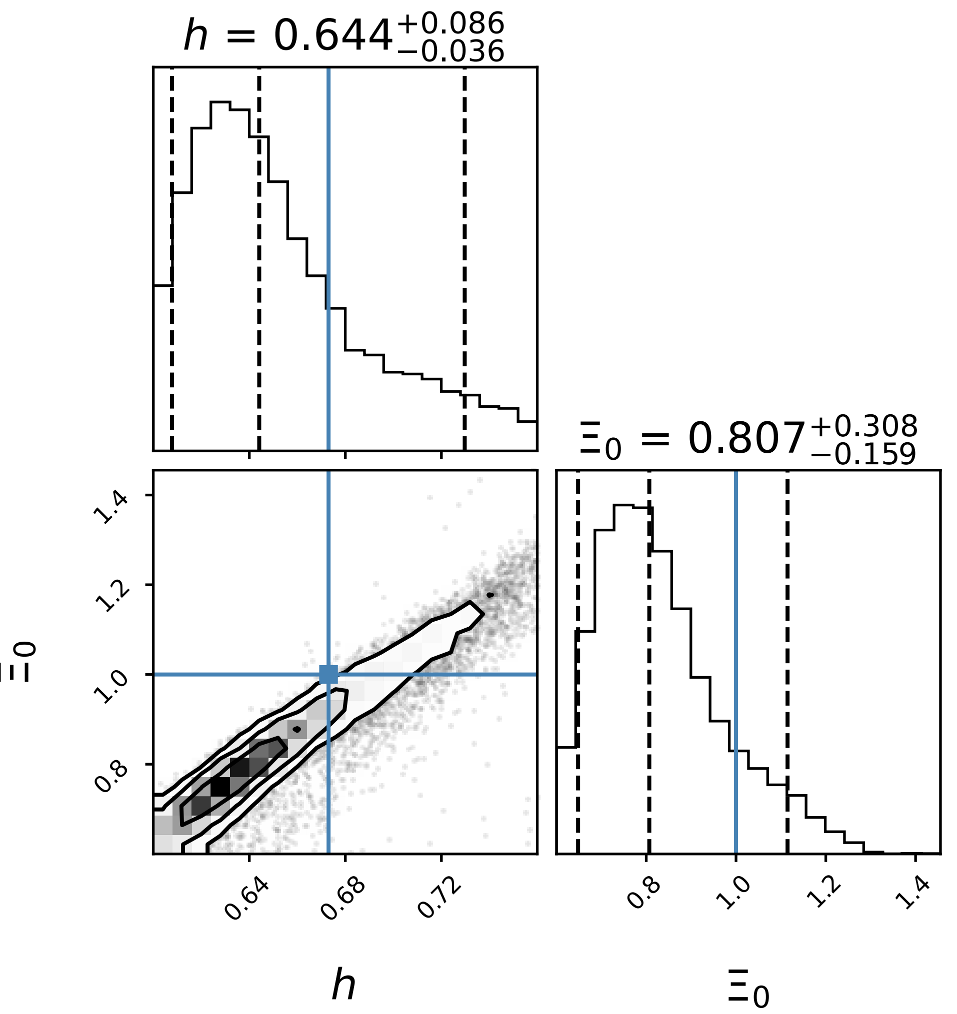

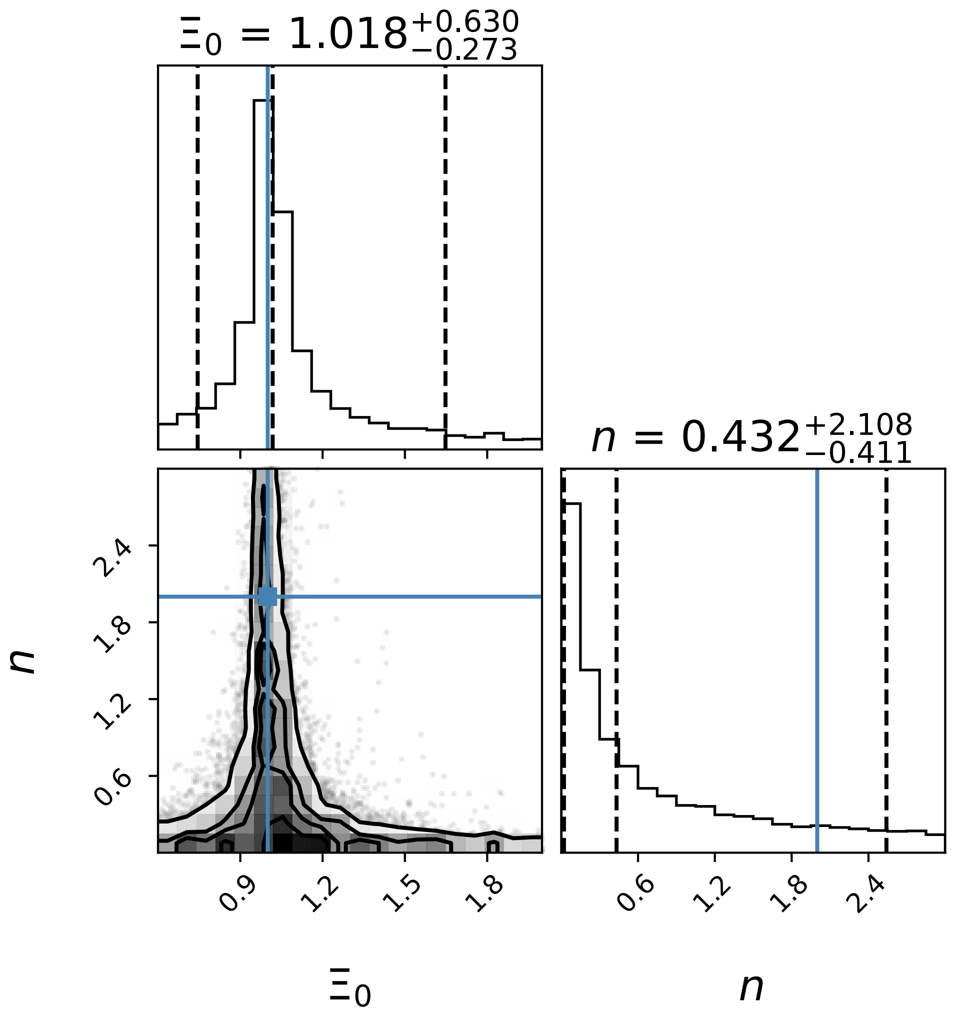

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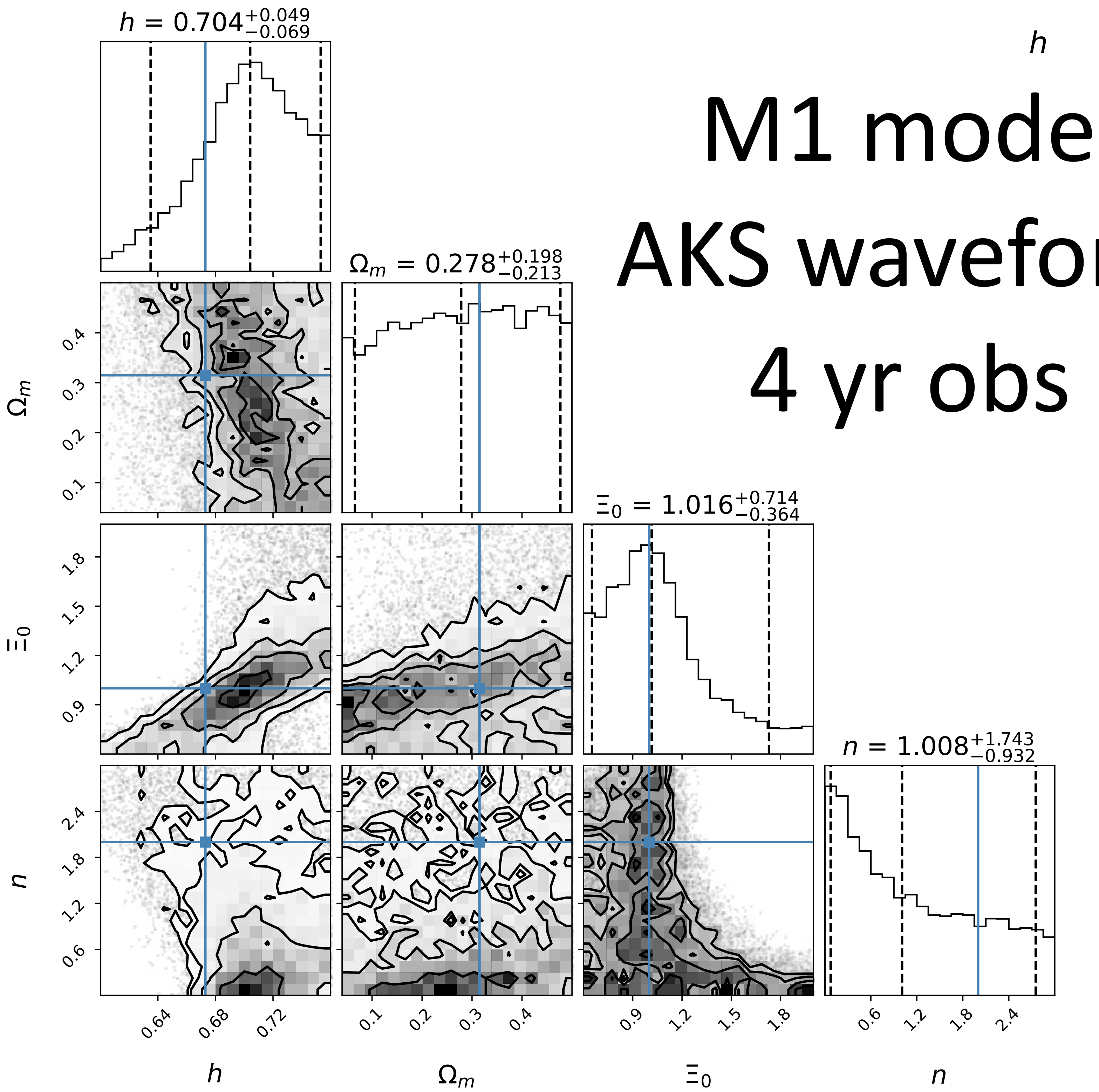

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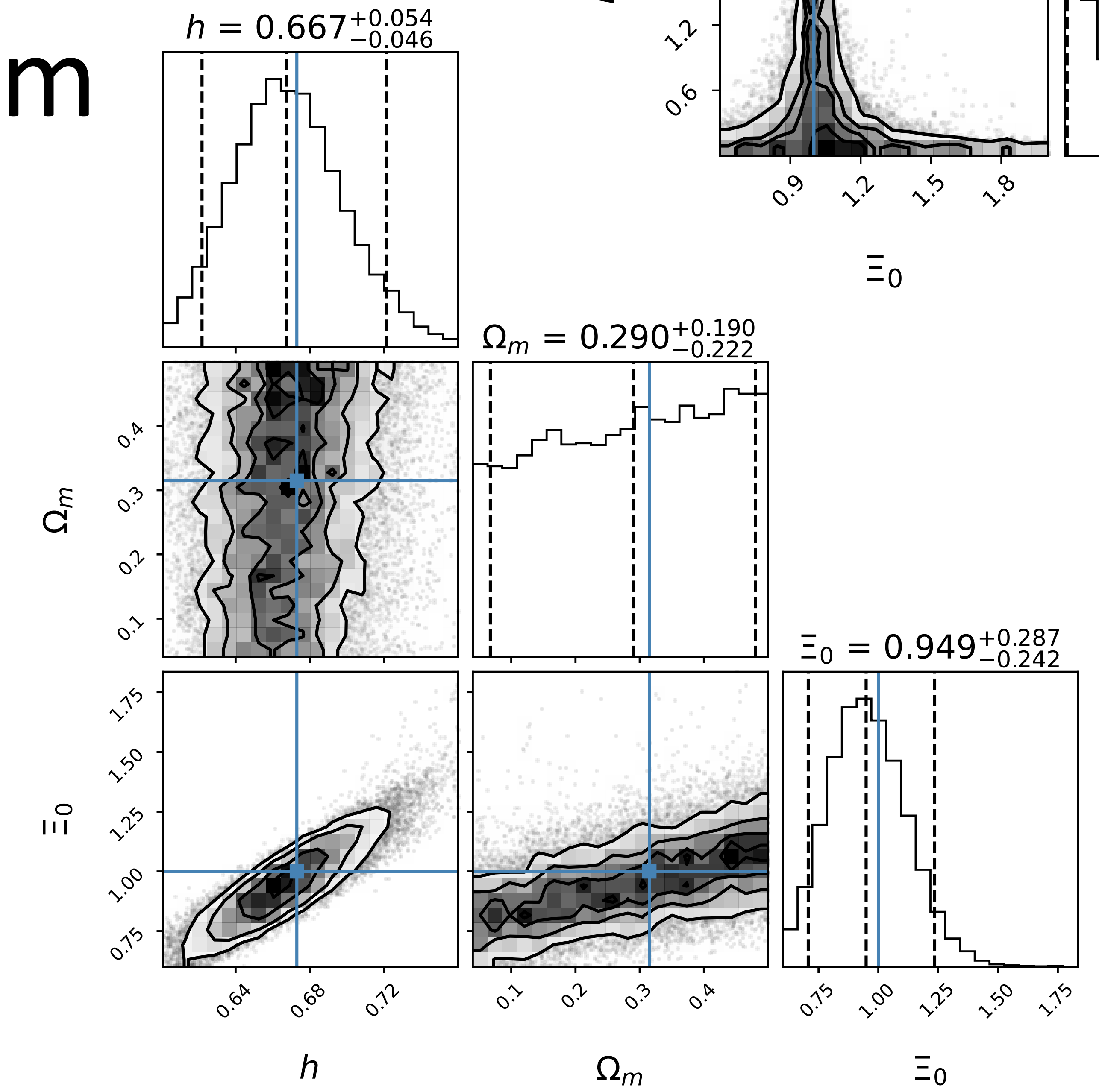
4 yr obs



- **M5** 10x **worse** than M1
- **10 yrs** 1.4x **better** than 4 yrs
- Similar constraints for $\Xi_0 \neq 1$

Conclusions and future prospects

- **LISA** can probe modified friction in GW propagation

- **EMRIs** used as dark sirens could constrain Ξ_0 at the few-% level
  - Better than current 2G detector constraints — Chen, Gray, Baker JCAP (2024)
  - In general as not as good as 3G detector forecasts — Belgacem+ JCAP (2019)

What's next?

- New EMRI detection rate and parameter estimation (Piarulli+ in prep.)

- LISA Cosmology Working Group Collaborative Project (Coordinator: DL):
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  2. Refined dark siren method: hierarchical likelihood approach to marginalise over EMRI population parameters while using galaxy redshift information (in prep.)

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Thank you!

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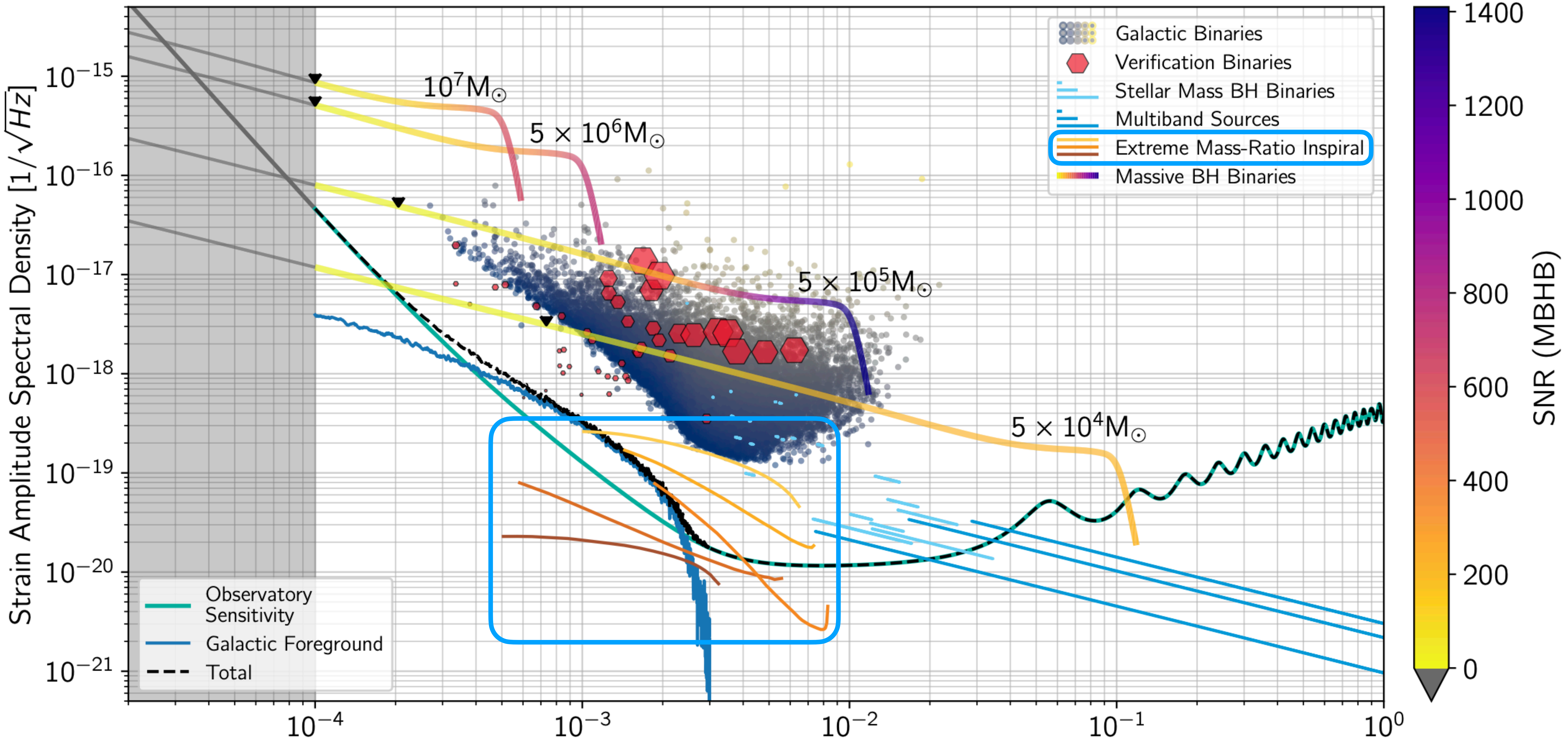
Extra-slides

LISA gravitational wave sources



LISA Red Book 2024