Extreme mass-ratio inspirals to probe modified gravitational-wave propagation and LCDM

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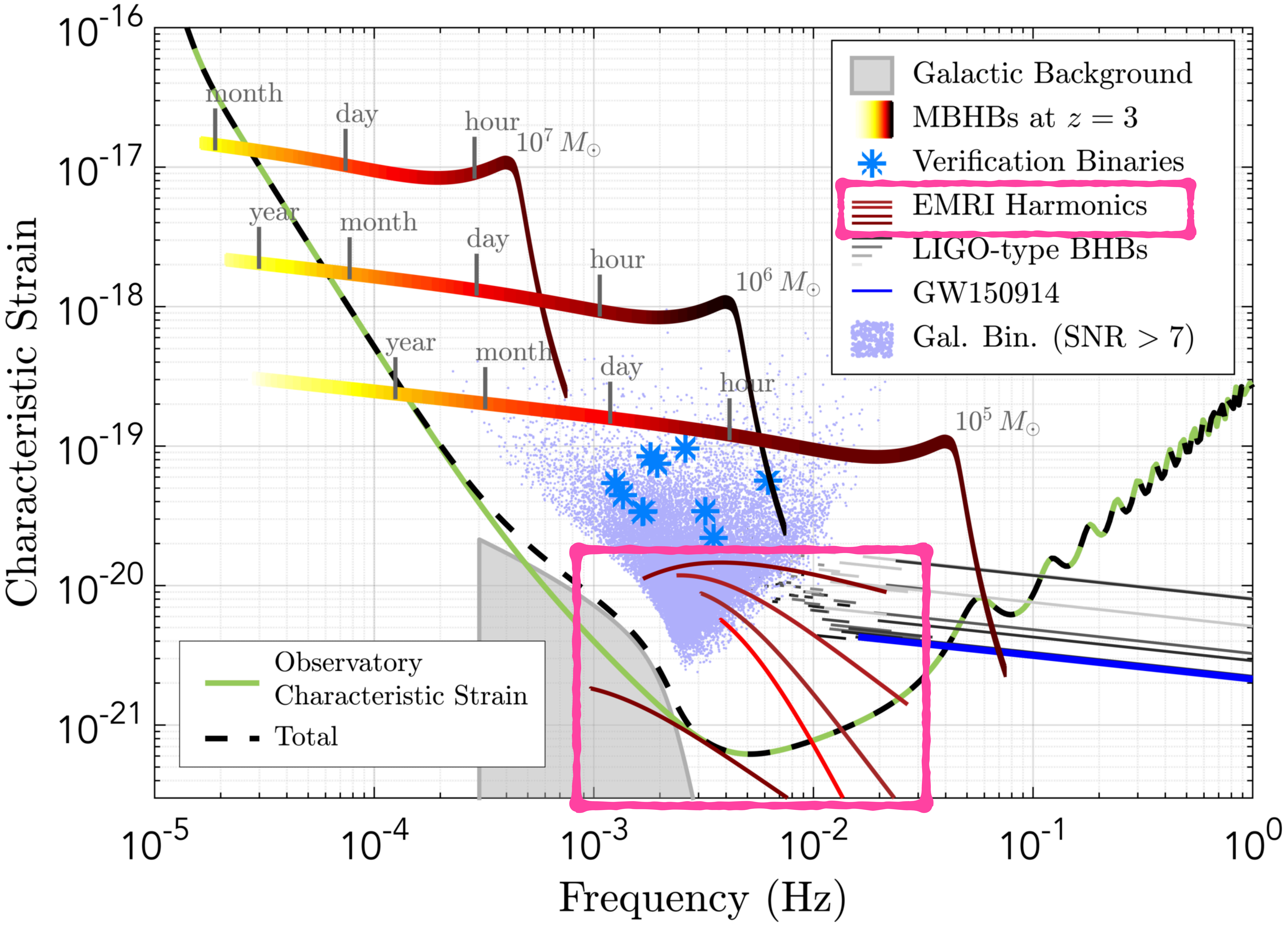
Based on **C. Liu**, **DL**, **N. Tamanini**, arXiv:2310.12813

[†]This research is directly supported by the CNES

LISA gravitational wave sources



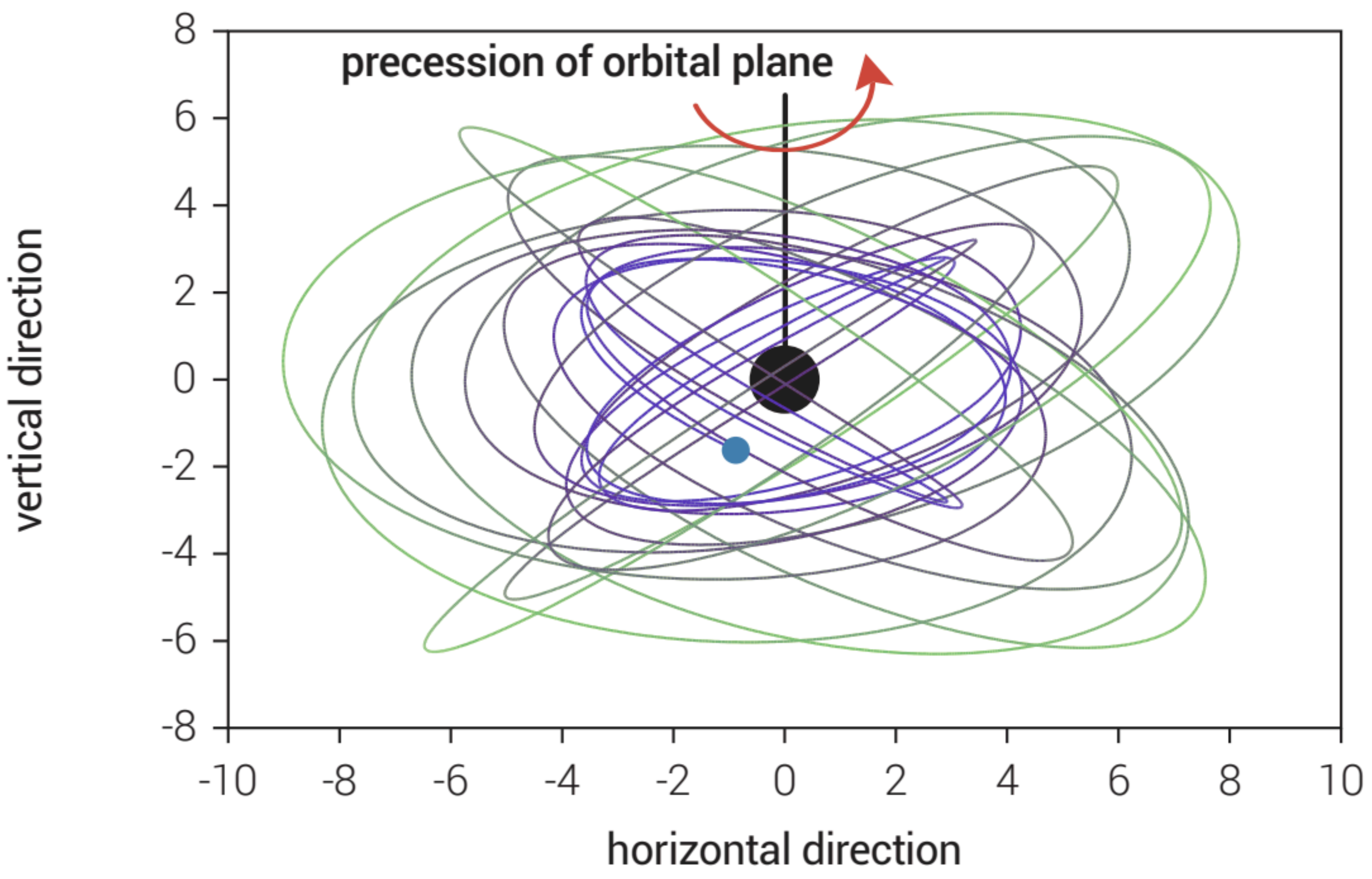
Amaro-Seoane et al., arXiv:1702.00786

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



Babak et al., PRD (2017)

Credit: eLISA White Paper, arXiv:1305.5720

GWs to probe late-time FLRW cosmology

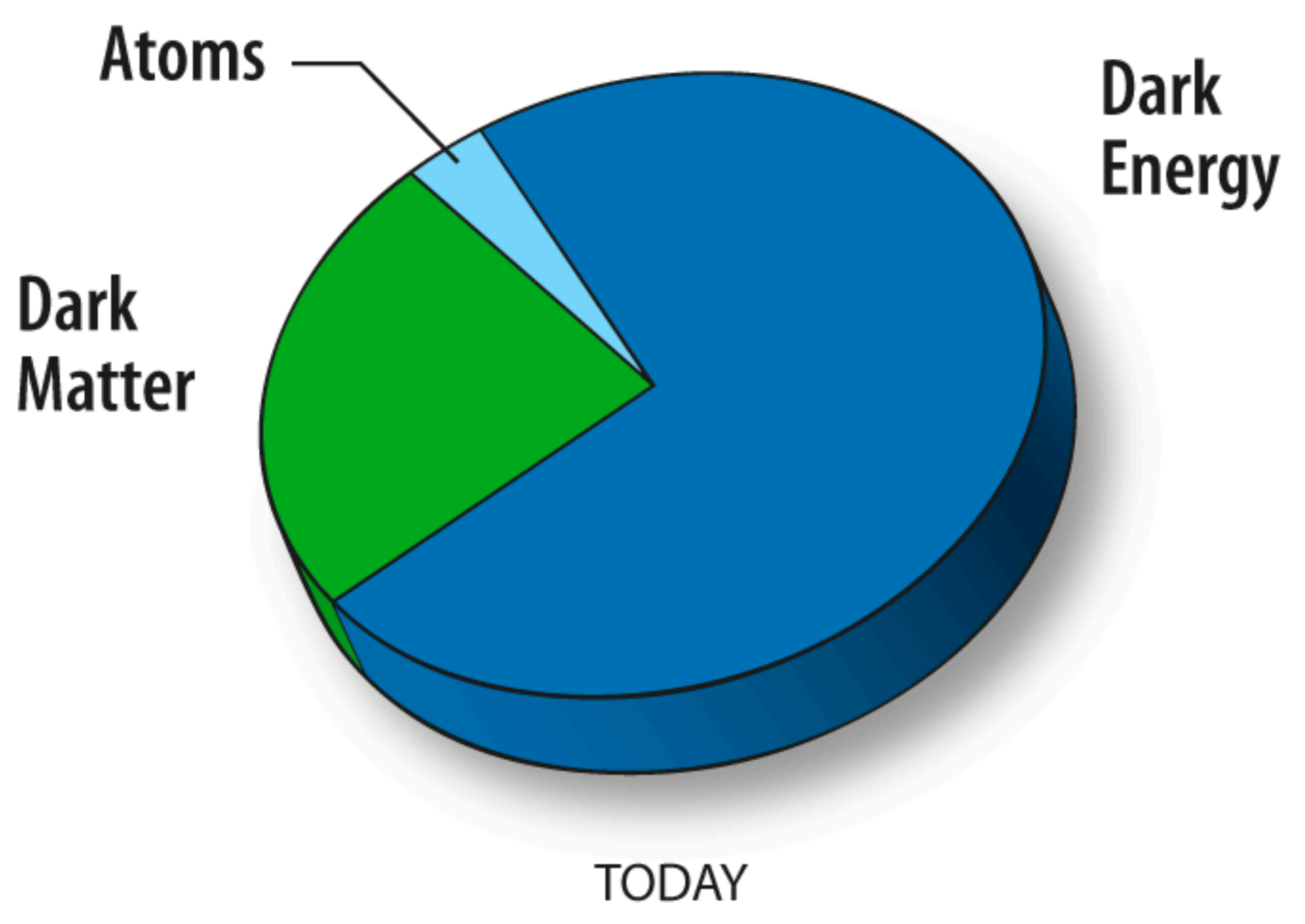
Individual GW sources at cosmological distances are "**standard sirens**"

- Hubble parameter

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

Hubble constant

fraction of matter/DE density today



Credit: WMAP

- Luminosity distance-redshift relation

$$d_L^{\mathrm{EM}}(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

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**":

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

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

Belgacem et al., PRD (2018)

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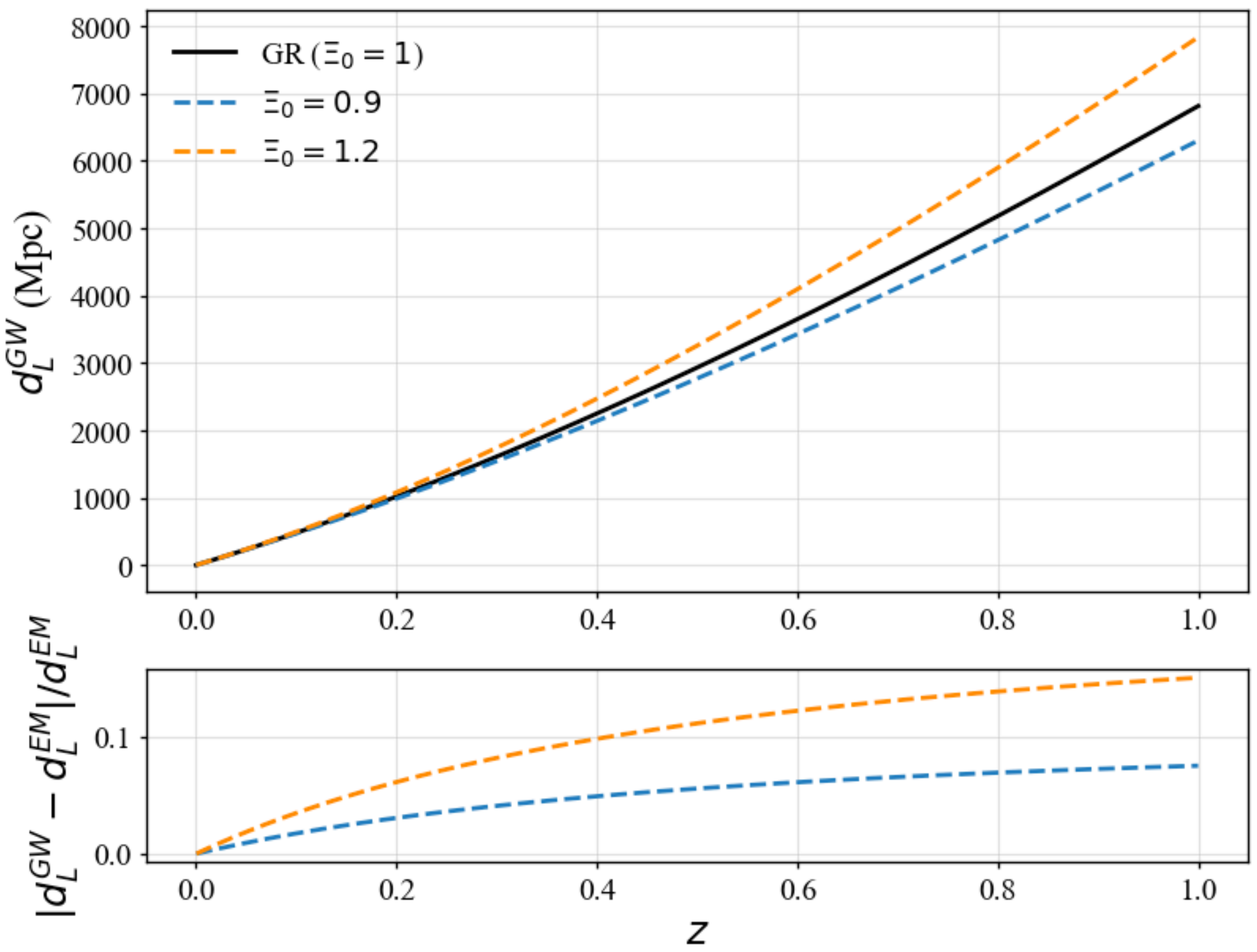
- A convenient phenomenological parametrisation (Ξ_0, n):

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



Belgacem et al., PRD (2018)

EMRIs as dark standard sirens

- Macleod, Hogan, PRD (2008)
  Proof-of-principle study

- Laghi+, MNRAS (2021)
  Bayesian constraints (90% CI) on H_0 (2-6%) and w_0 (<10%)

  EMRIs as dark sirens
  up to $z \sim 1$

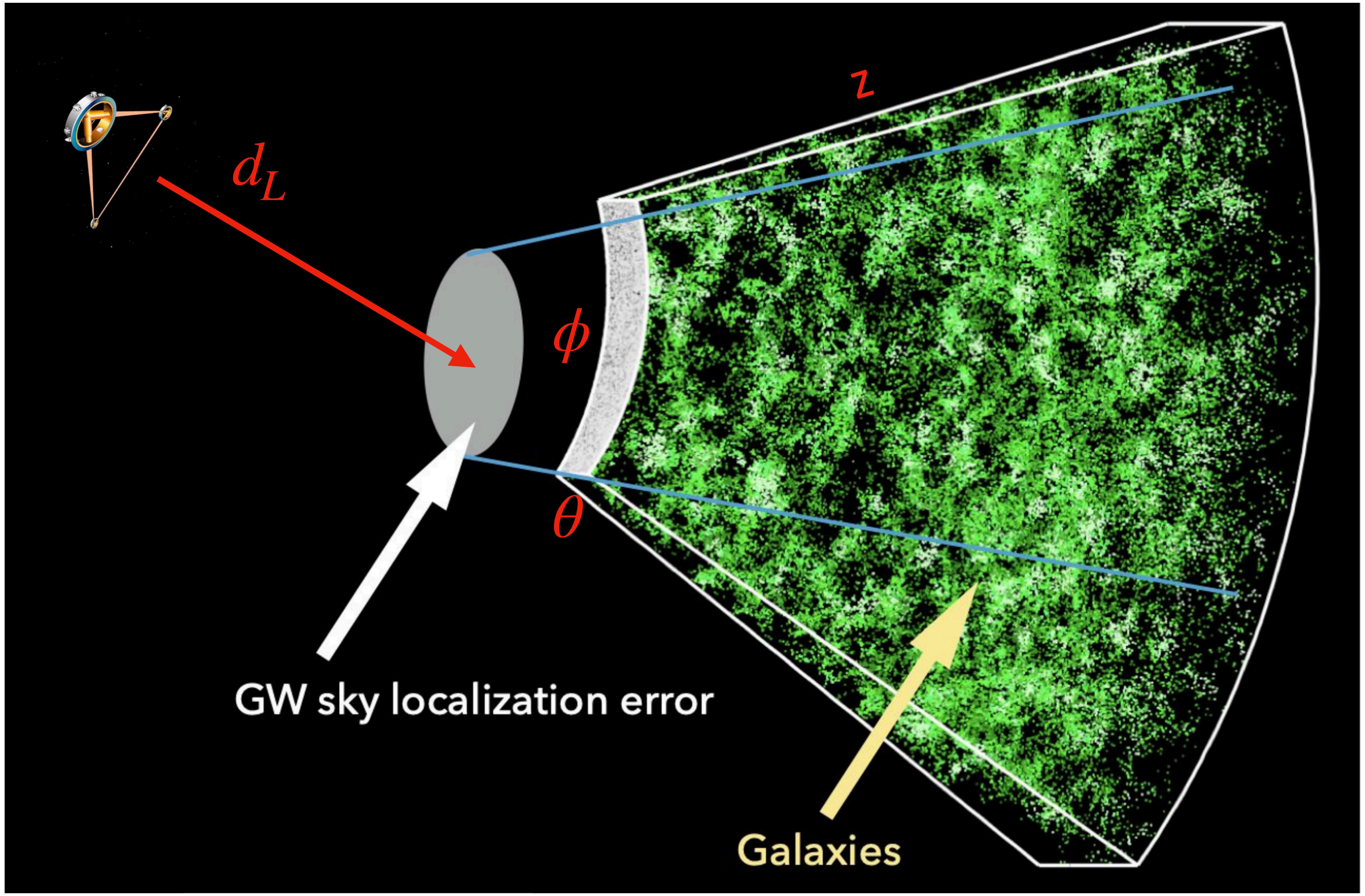


Image credit: Jeremy Tinker and the SDSS-III collaboration

Can we use EMRIs to constrain Ξ_0 + LCDM parameters ?

- In Liu, Laghi, Tamanini arXiv:2310.12813 we explored:

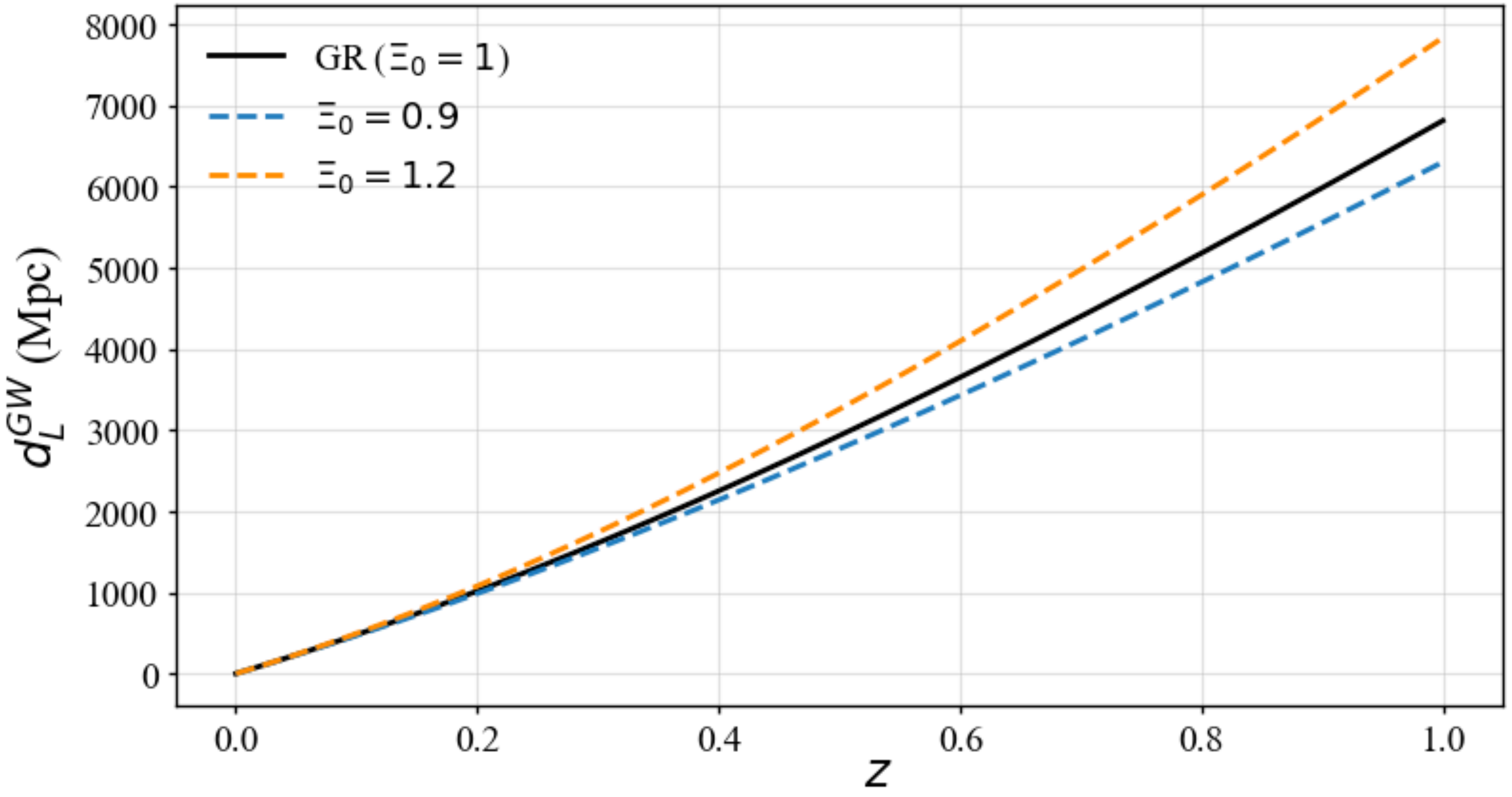
  - Different astrophysical EMRI models and waveforms (M1/M5/M6 + AKS/AKK) from Babak et al., PRD (2017)

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

Model	EMRI rate [yr^{-1}] Total	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 et al., PRD (2017)

Example: $\Xi_0 \sim 0.934$ (6.6% dev. from GR)
Belgacem et al., JCAP (2019)



Analysis Setup

- 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 et al., MNRAS (2019)
  Izquierdo-Villalba et al., A&A (2019)

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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, arXiv:2310.12813

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	$h + \Xi_0$	3	6
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Liu, DL, Tamanini, arXiv:2310.12813

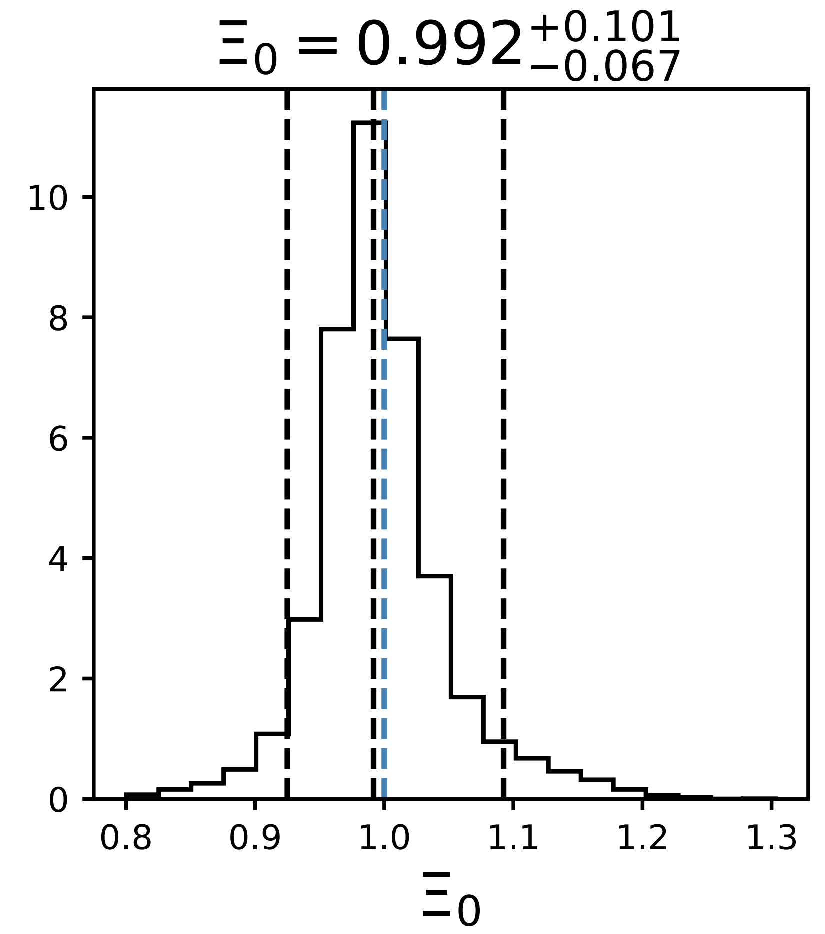
Bayesian inference with **`cosmoLISA`**

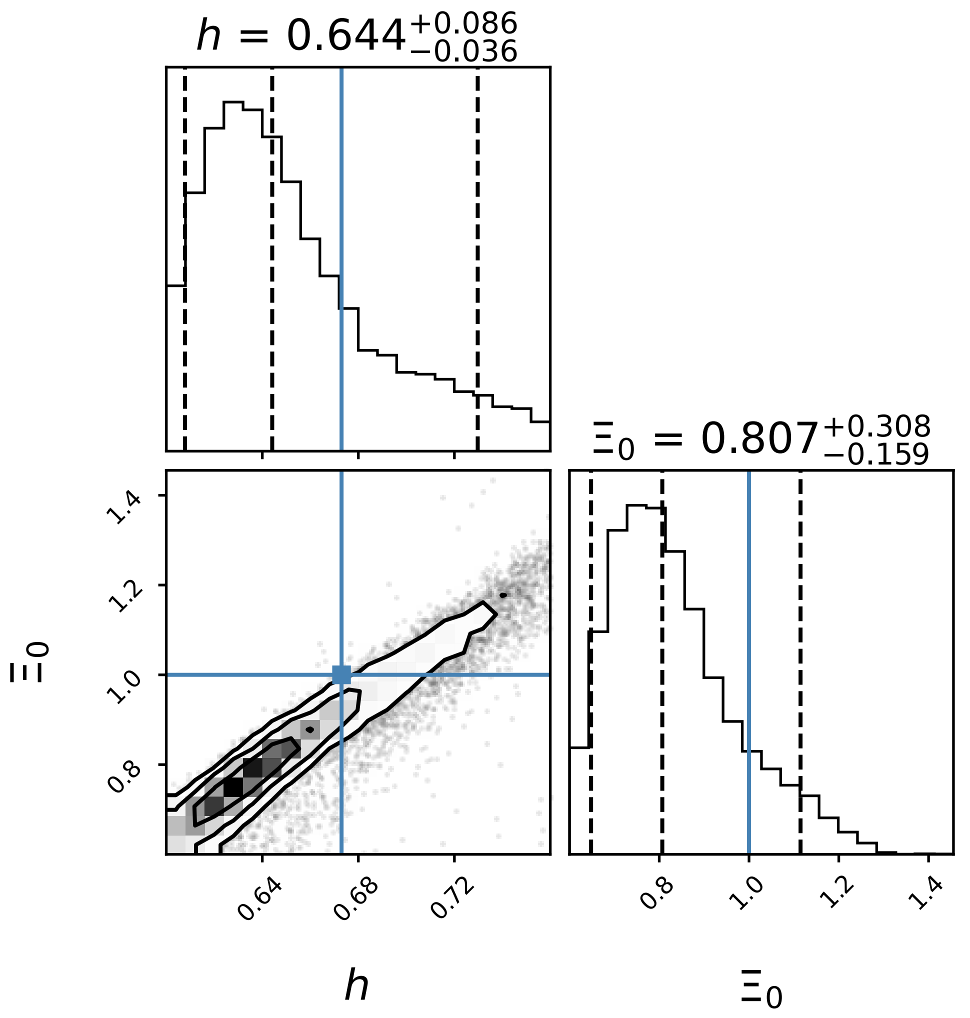
Del Pozzo, Laghi [github.com/wdpozzo/cosmolisa]

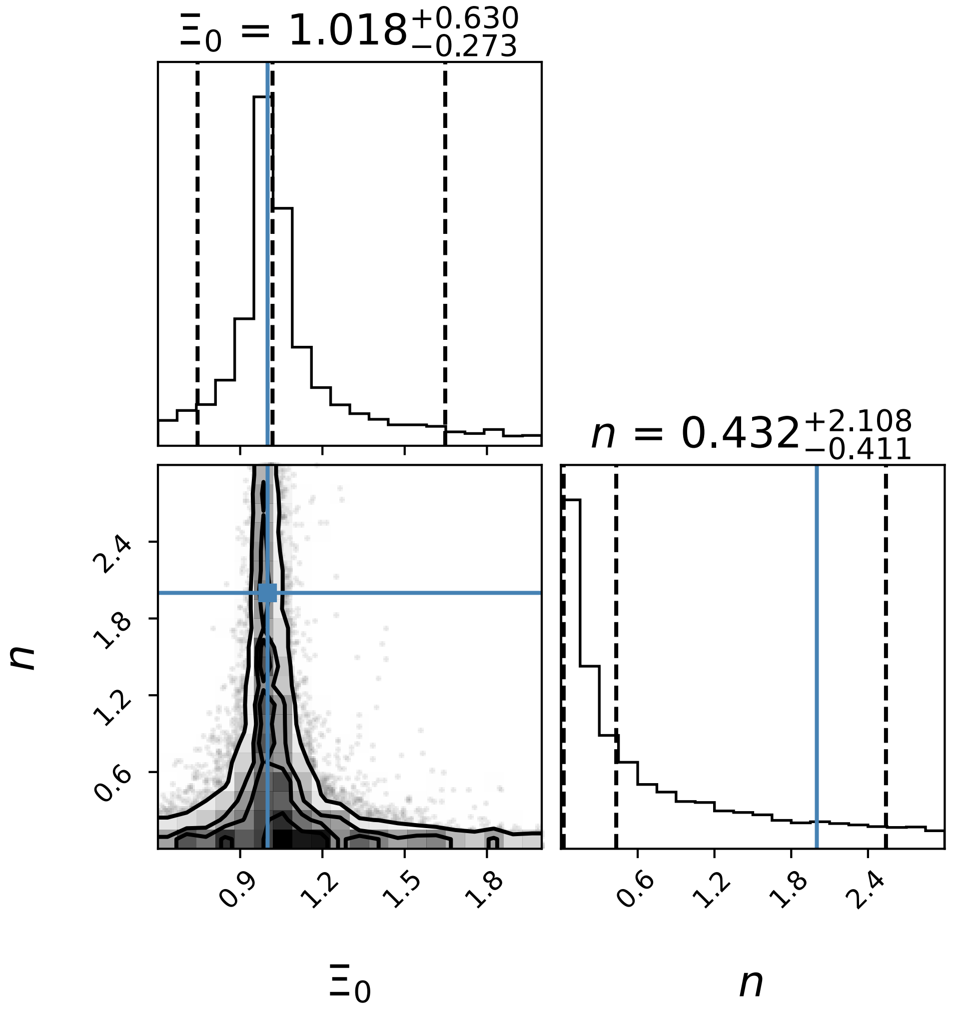
EMRIs with LISA can constrain Ξ_0 in several scenarios

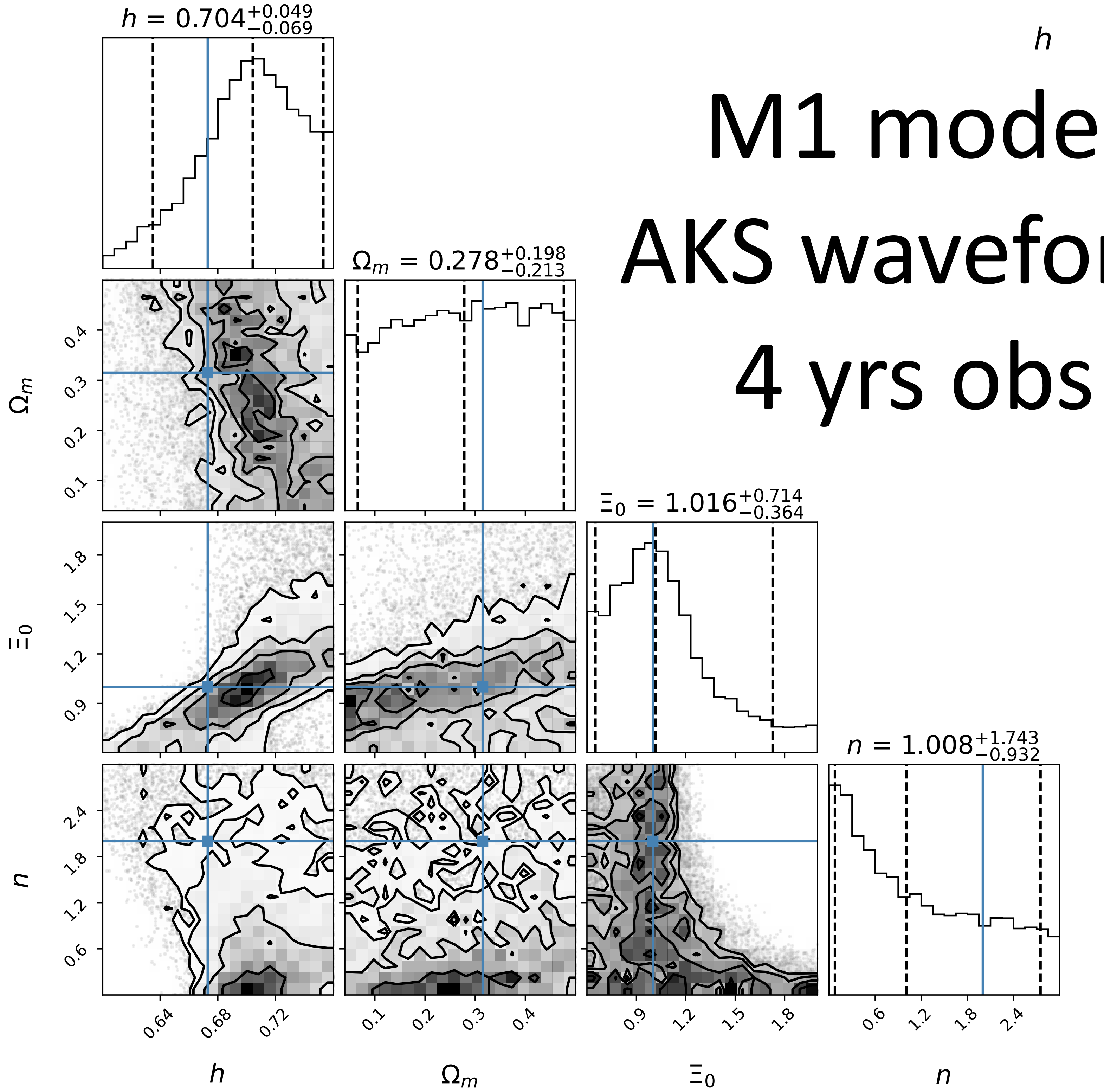
Liu, DL, Tamanini, arXiv:2310.12813

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





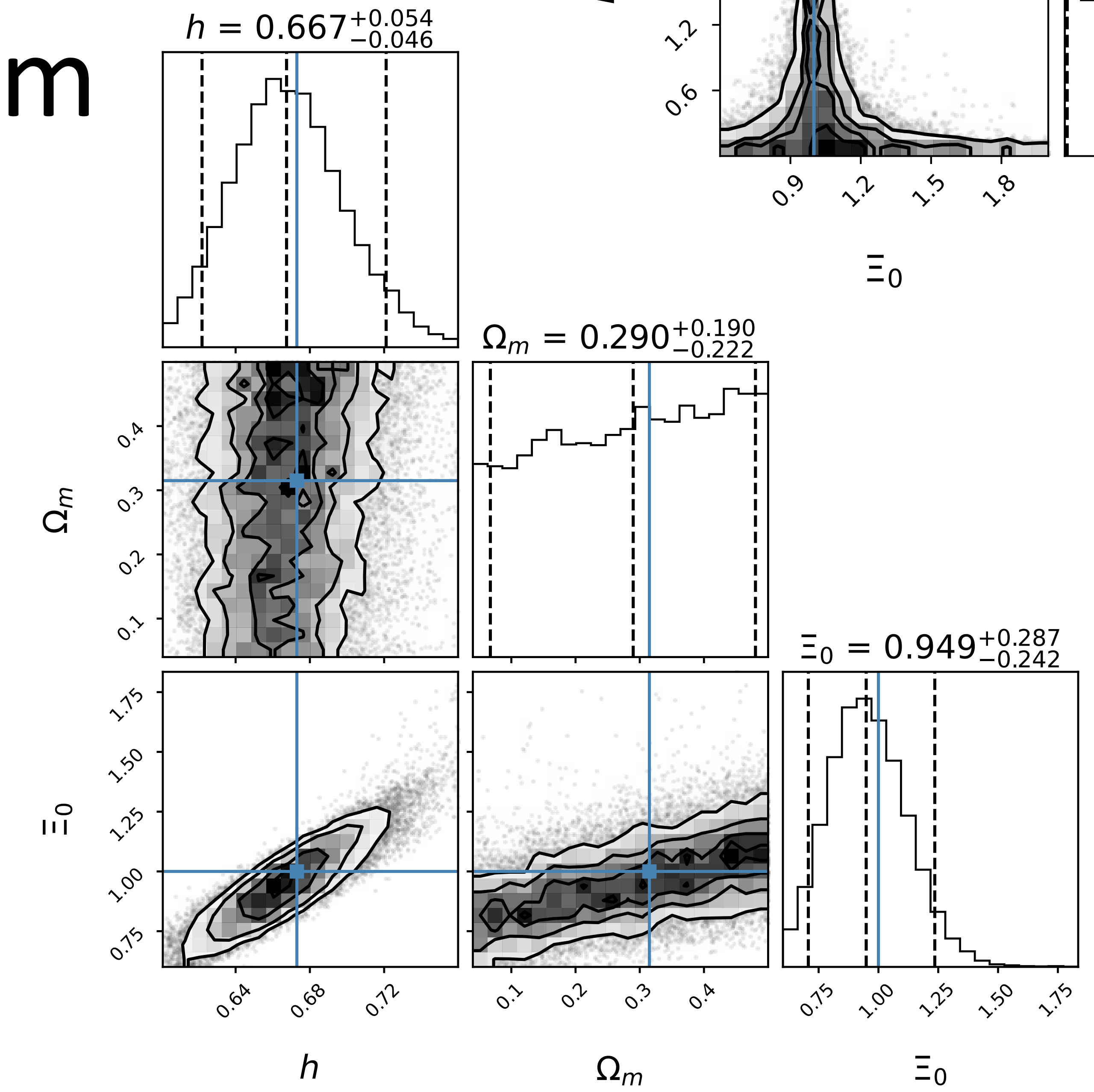




M1 model

AKS waveform

4 yrs obs



EMRIs with LISA can constrain Ξ_0 in several scenarios

Liu, DL, Tamanini, arXiv:2310.12813

- Overall, **AKK better** than AKS

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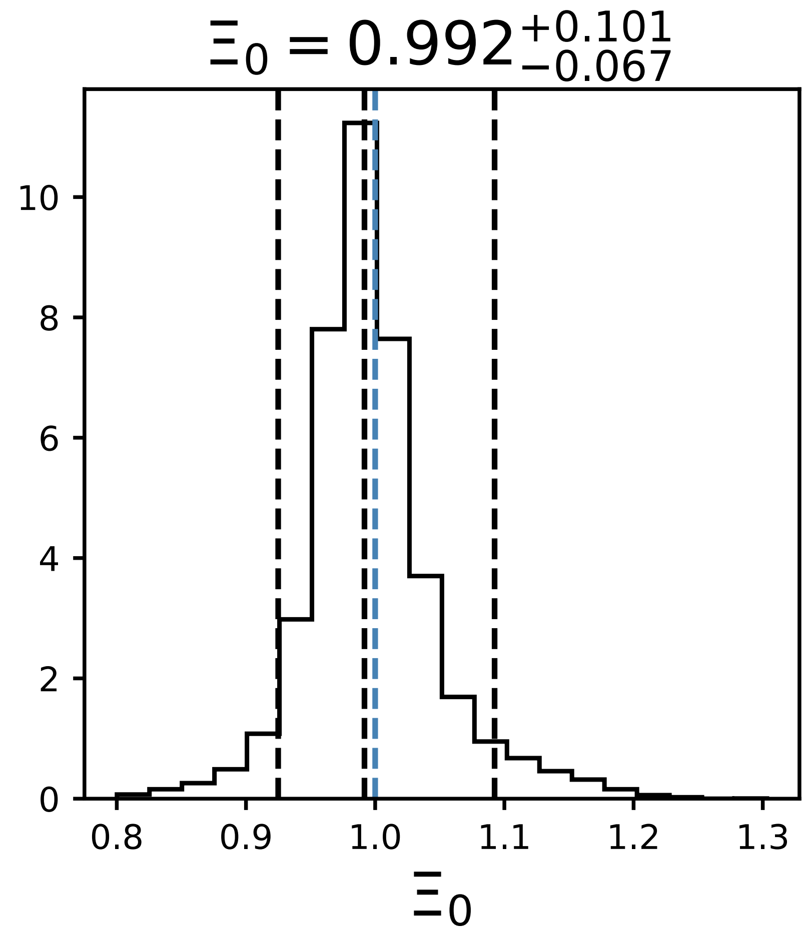

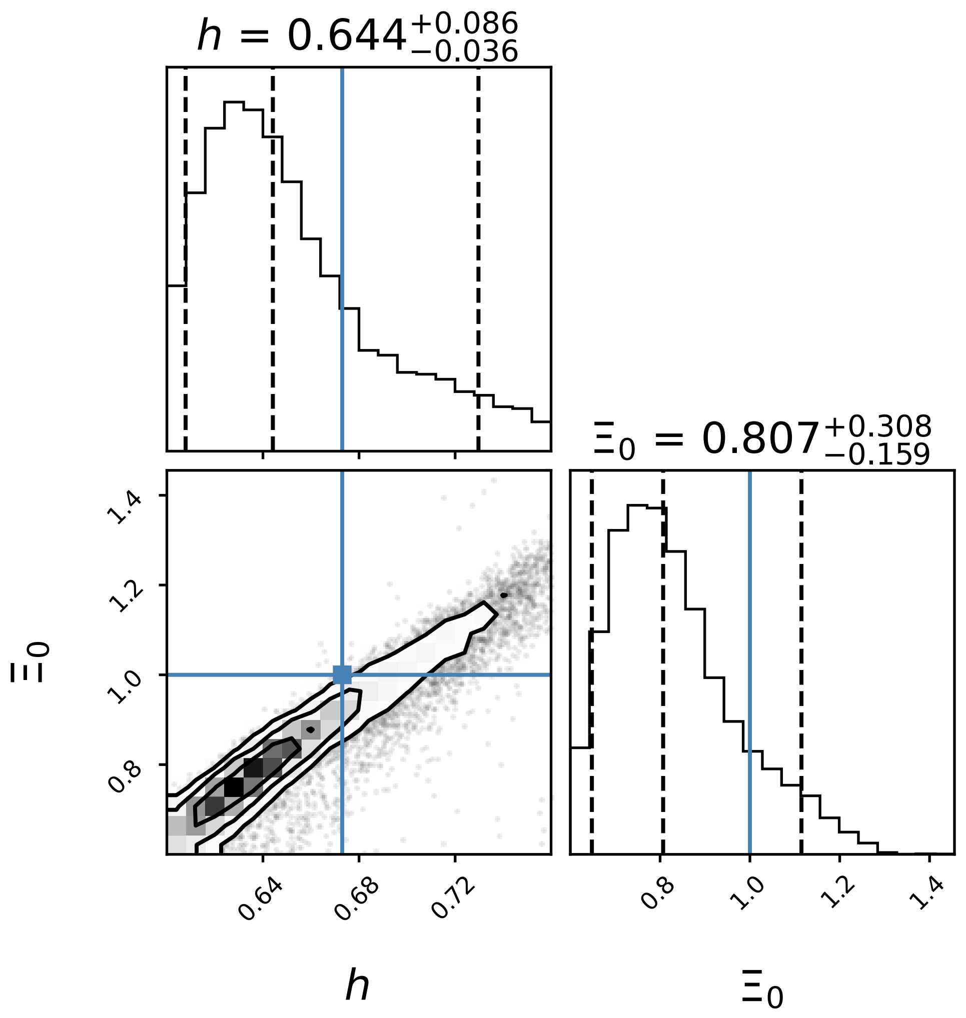

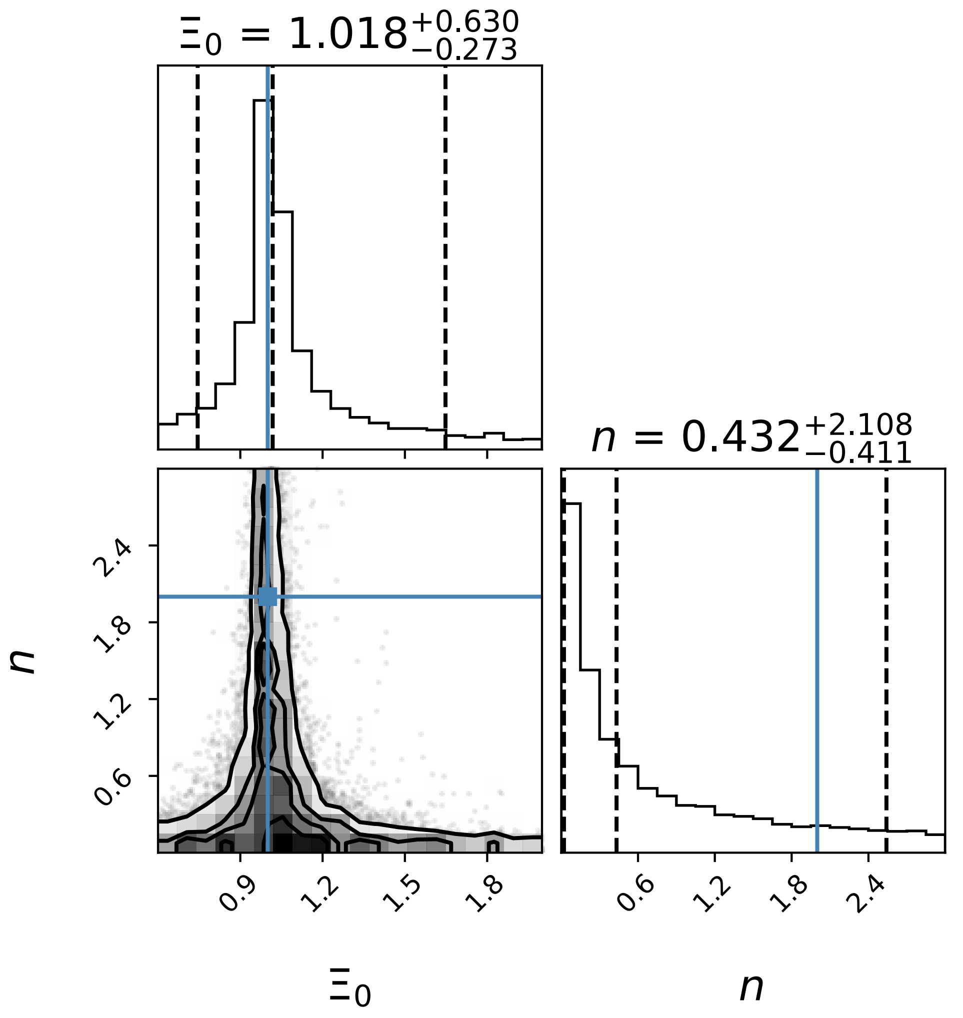

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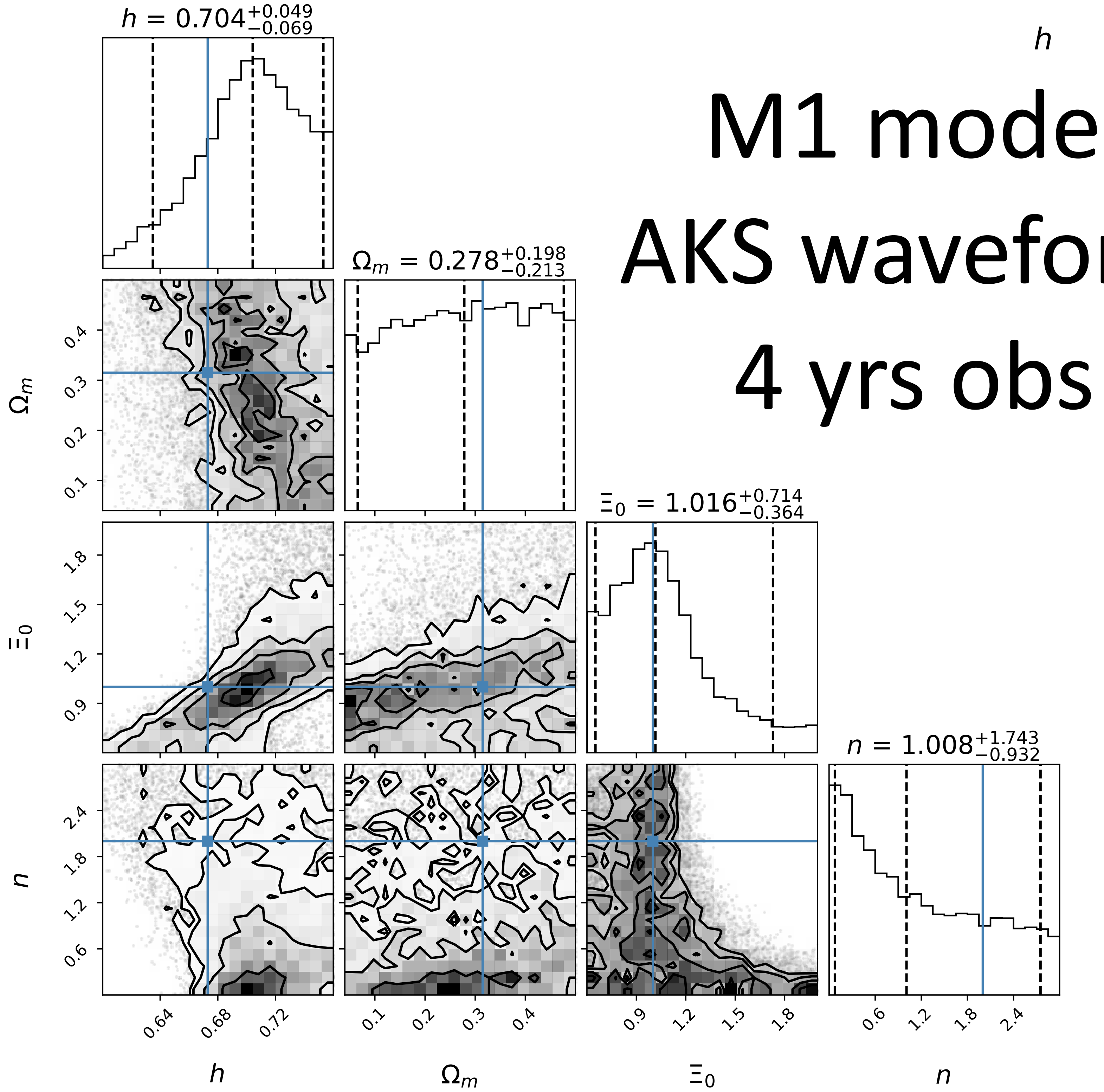

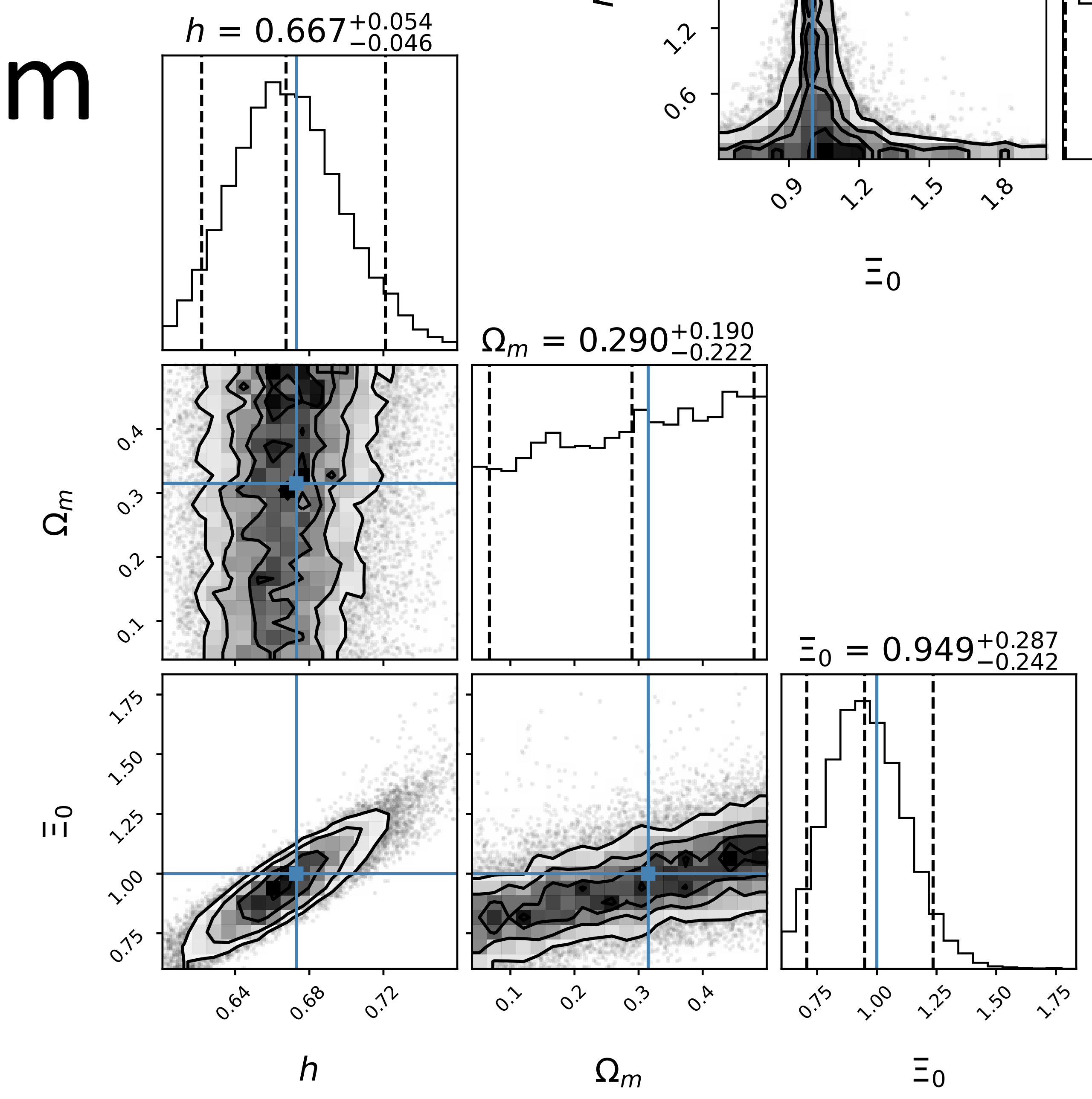

EMRIs with LISA can constrain Ξ_0 in several scenarios

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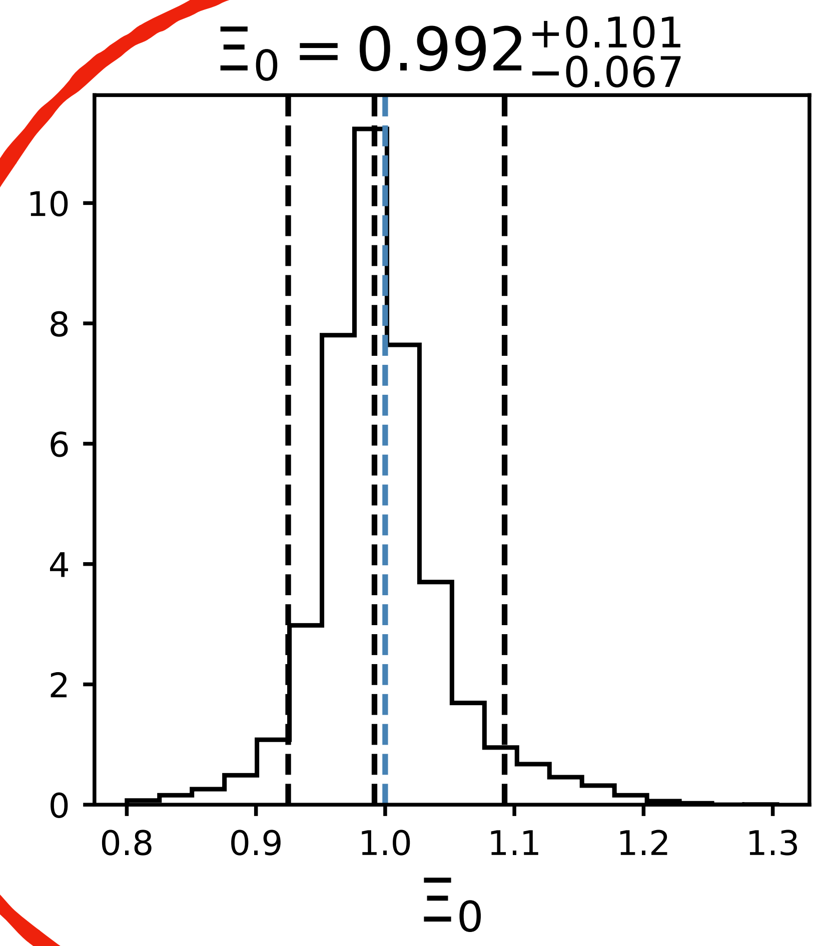
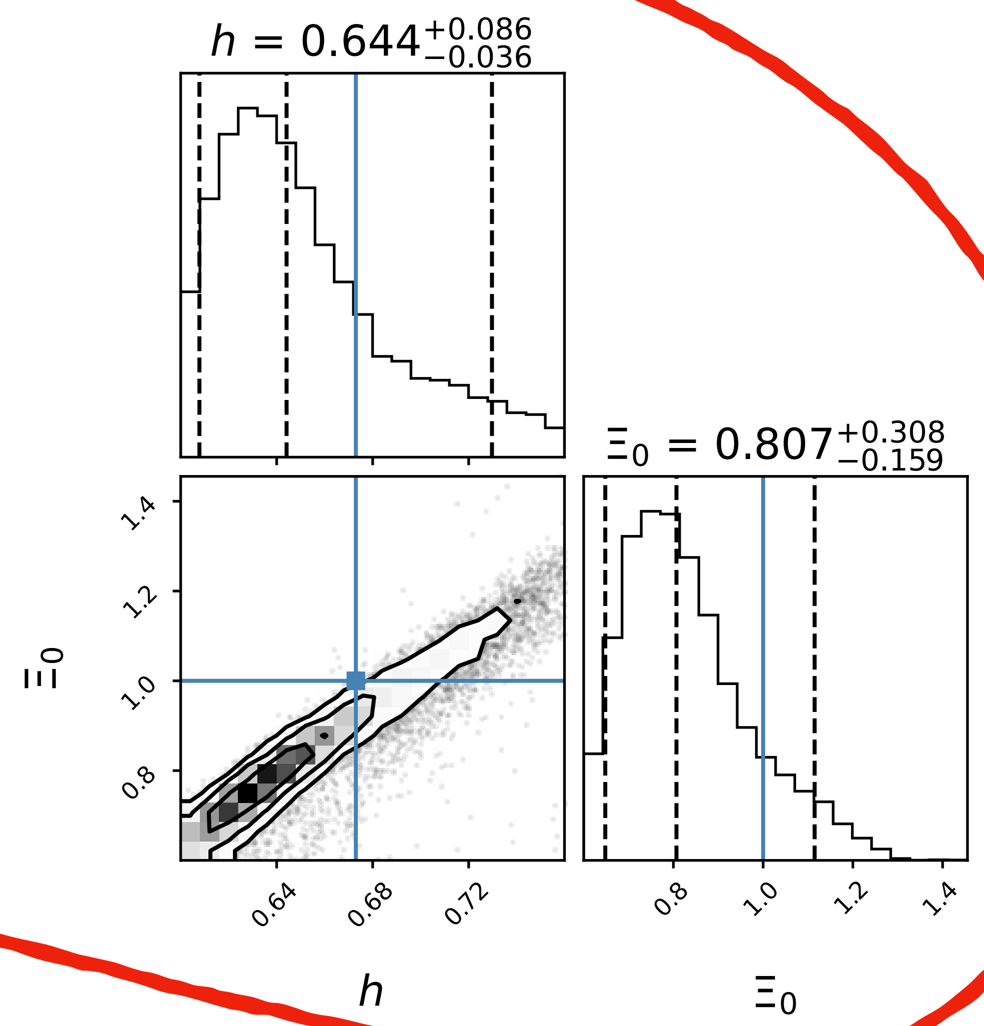
- Overall, **AKK better** than AKS
- Ξ alone: > 2 - 8% (90% CI)
- Ξ_0+h: > 9 - 29% and > 4 - 10% respectively





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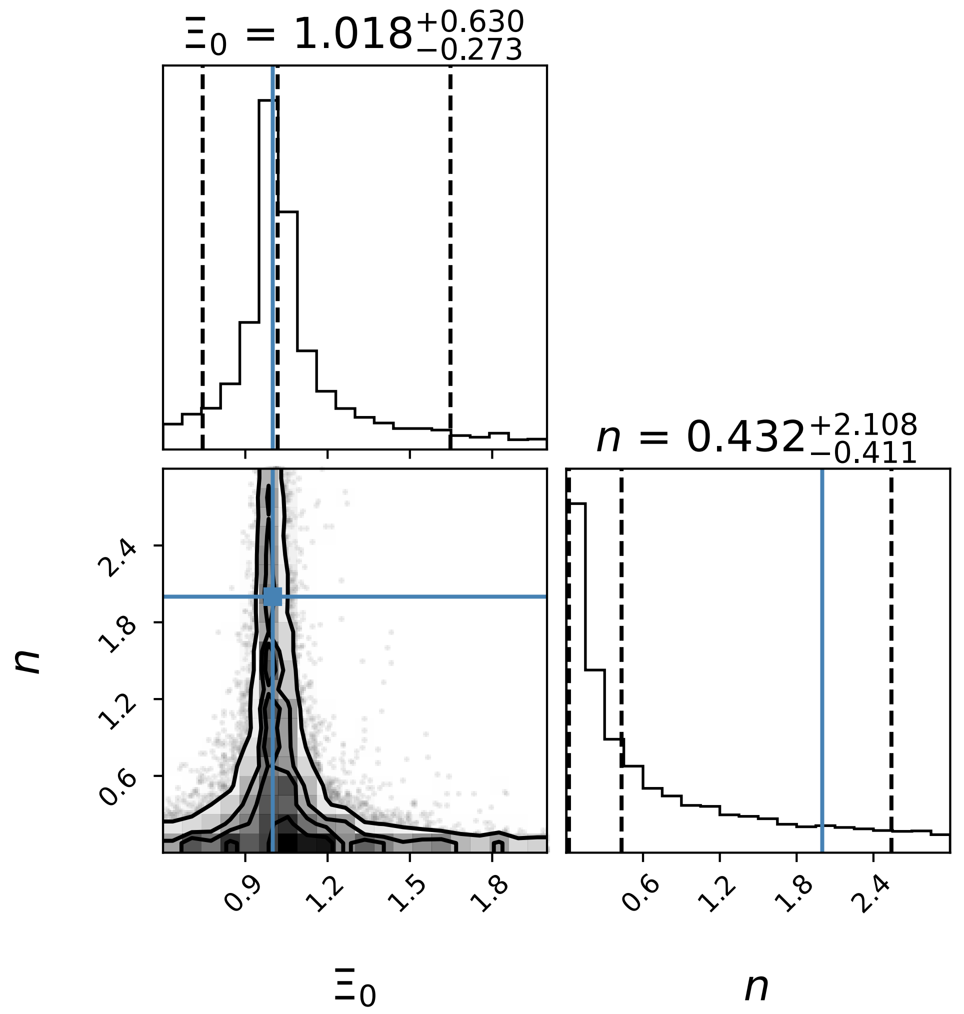

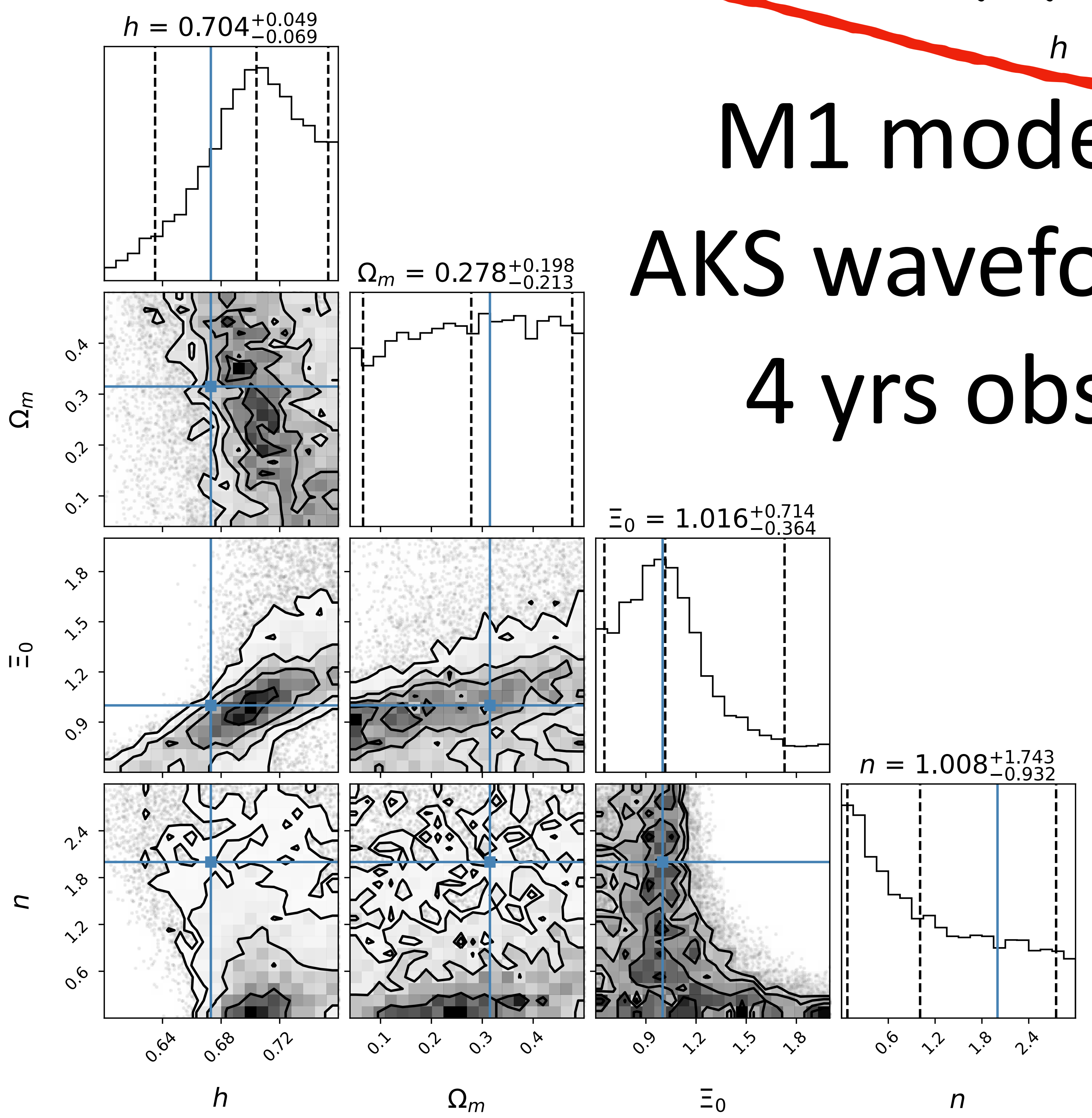

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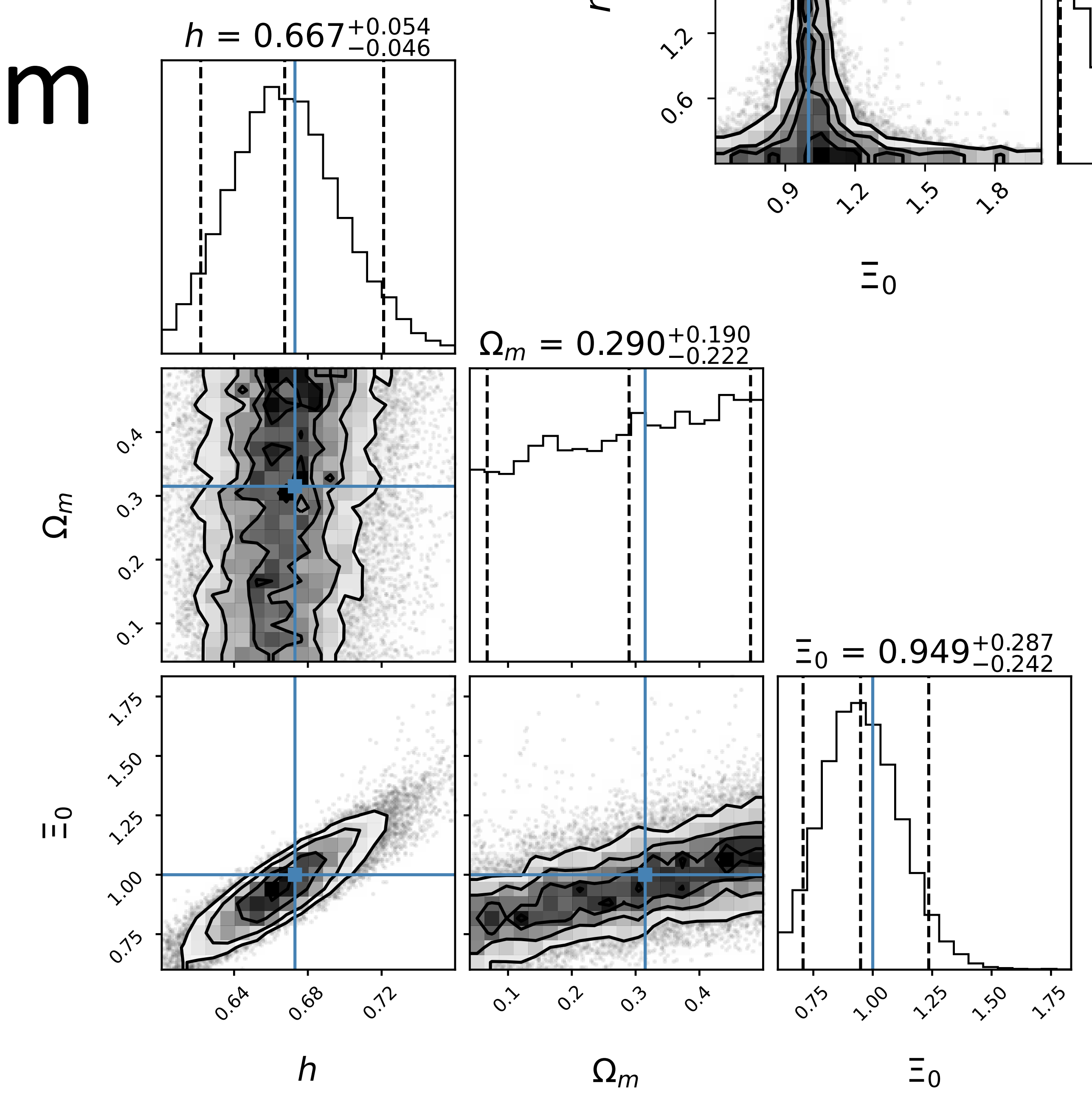

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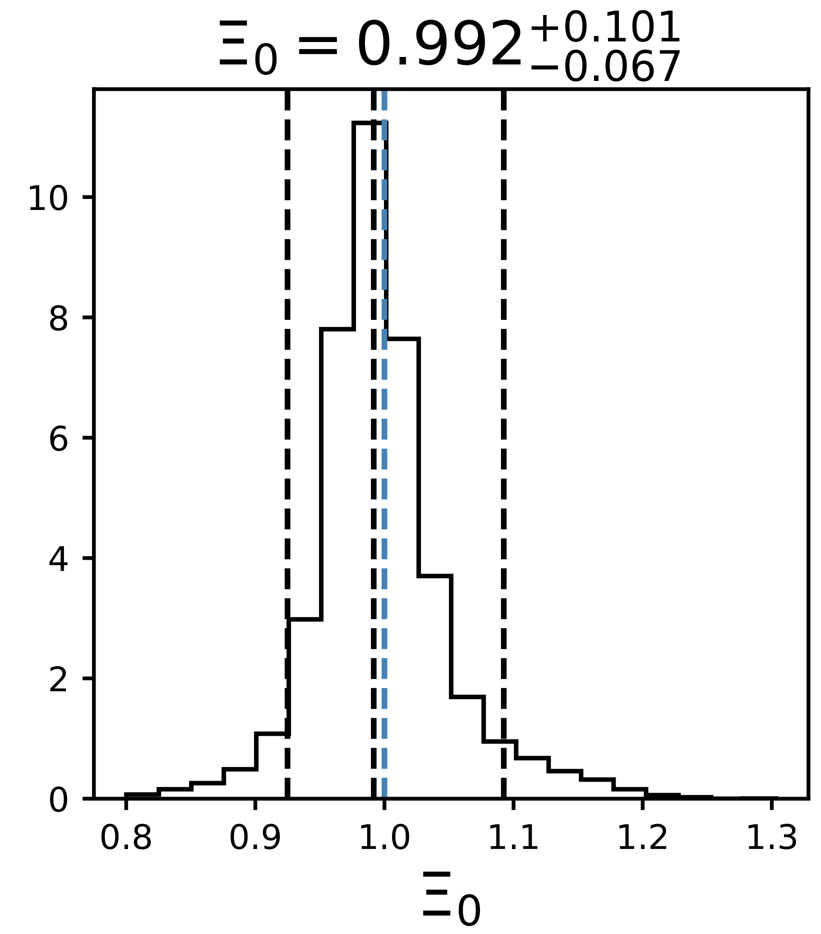
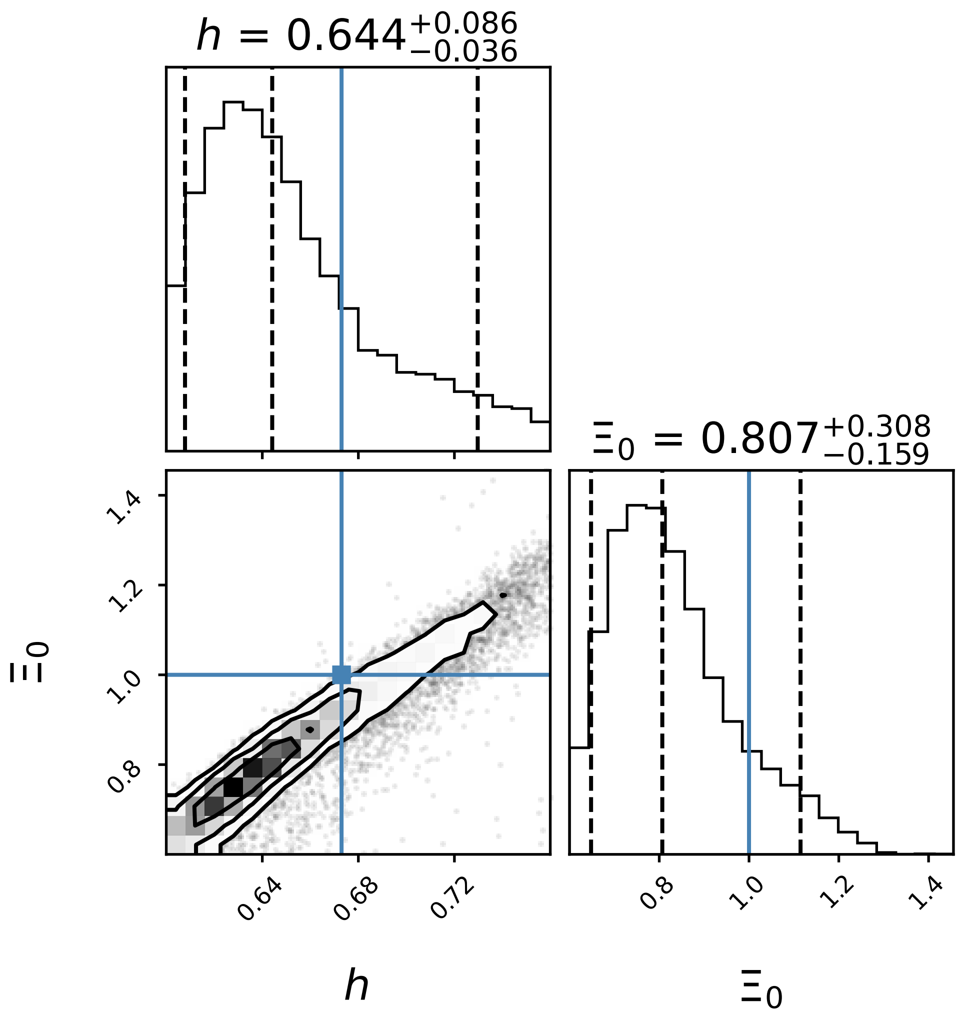
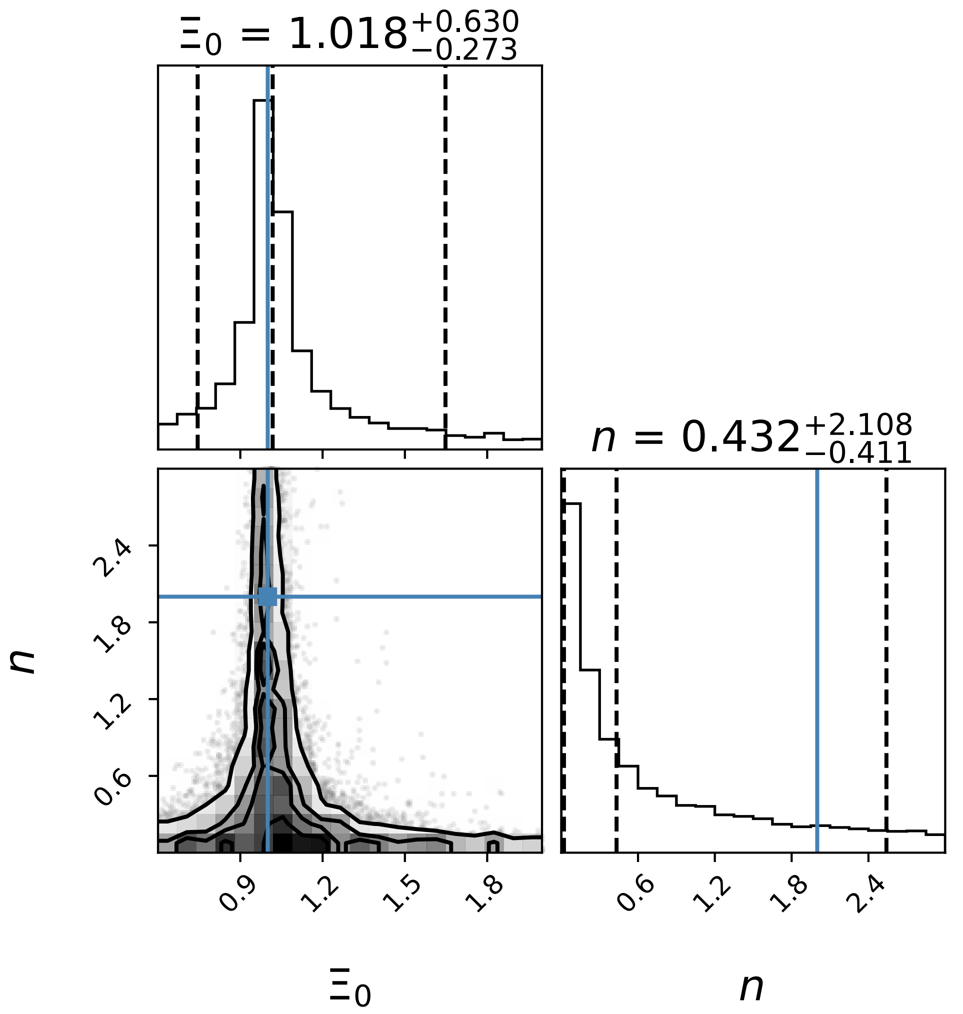
Liu, DL, Tamanini, arXiv:2310.12813

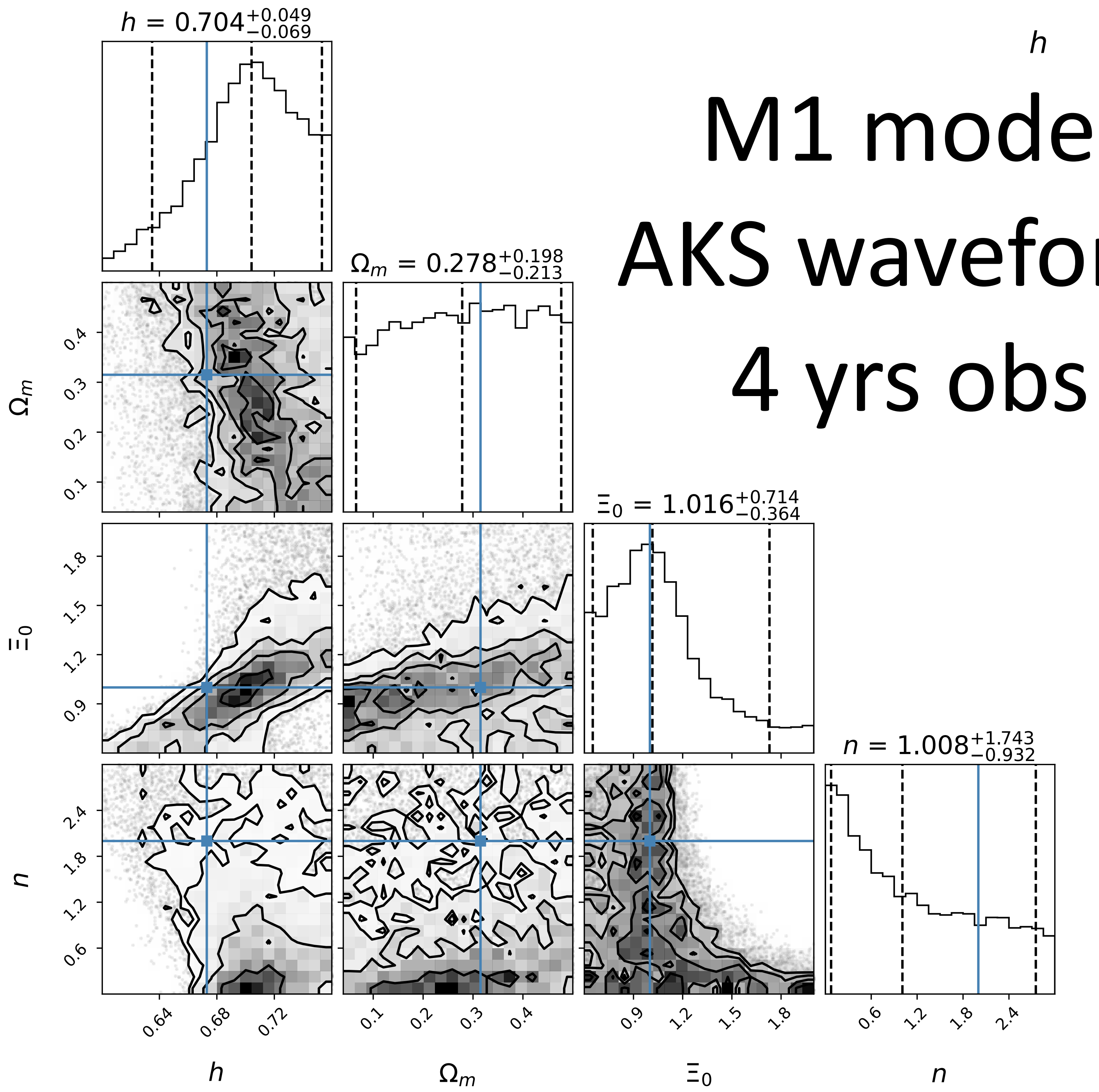
$$\frac{d_L^{\rm GW}(z)}{d_L^{\rm EM}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

- Overall, **AKK better** than AKS
- Ξ alone: > 2 - 8% (90% CI)
- Ξ_0+h: > 9 - 29% and > 4 - 10% respectively
- **M5** 10x **worse** than M1
- **10 yrs** 1.4x **better** than 4 yrs
- Similar constraints for $\Xi_0 \neq 1$









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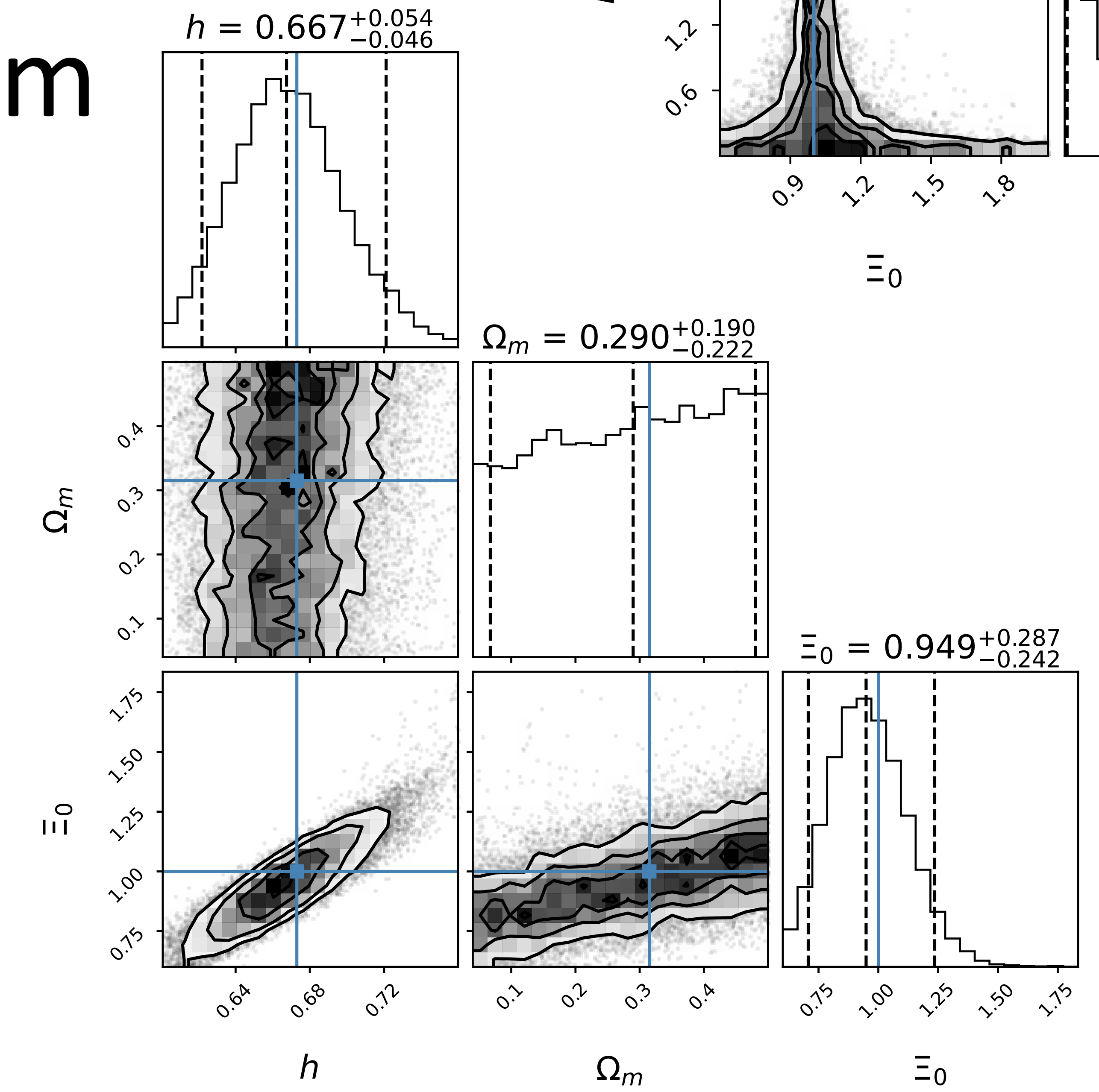

Conclusion

- **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, arXiv:2309.03833
  - In general as not as good as 3G detector forecasts Belgacem+, JCAP (2019)

- **Full details and results** in Liu, Laghi, Tamanini, arXiv:2310.12813

Thank you!

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