Parameter estimation for gravitational waves from the early universe

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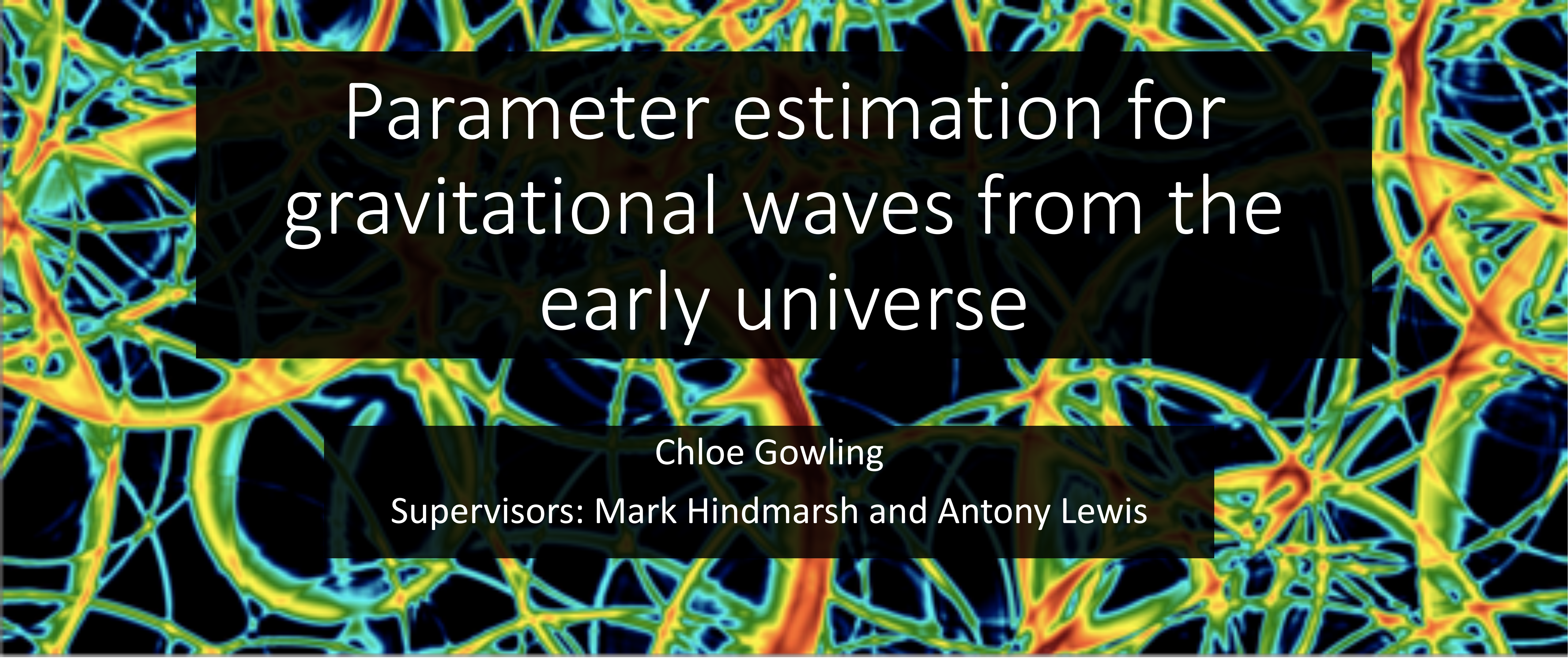
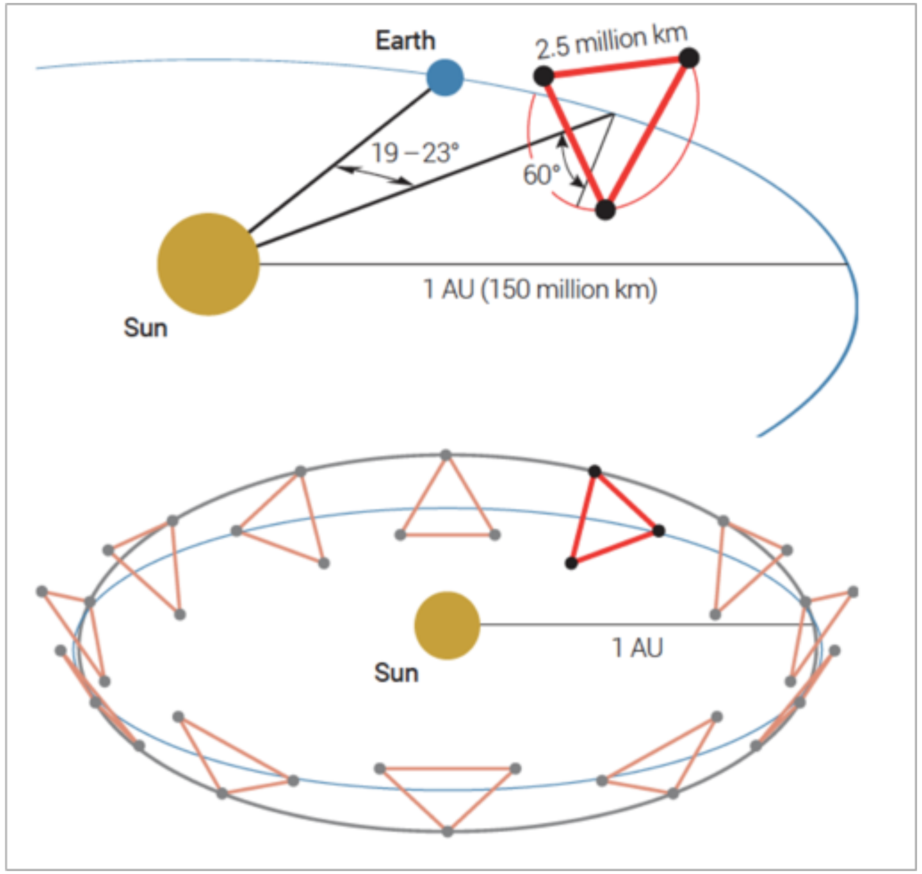


Laser Interferometer Space Antenna - LISA



- Expected launch: **2034**
- Duration: **4 years**
- Frequency sensitivity: $\mathbf{10^{-4} - 10^{-1}}\boldsymbol{Hz}$
- 3 spacecrafts - **6 laser links**
- Design successfully tested in LISA pathfinder mission (2016)

Figure credit: K. Danzmann et al. LISA proposal (2017)

What will LISA see?

- $\Omega_{GW} = \frac{2\pi^2}{3{H_0}^2} f^2 [h_c(f)]^2$
- Where H_0 is the Hubble constant and f is the frequency.
- $h_c(f)$ is the characteristic strain.

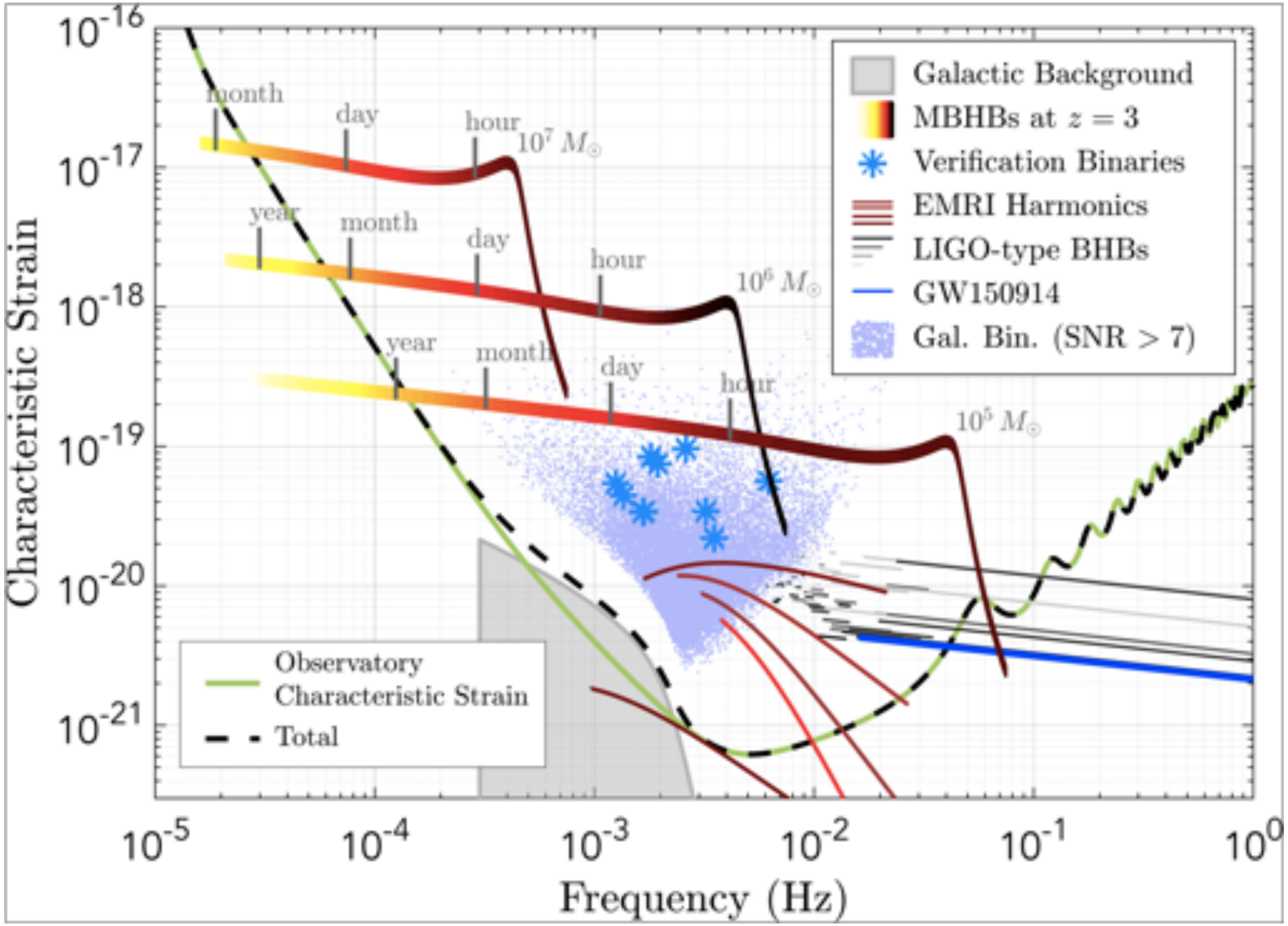


Figure credit: K. Danzmann et al. LISA proposal (2017)

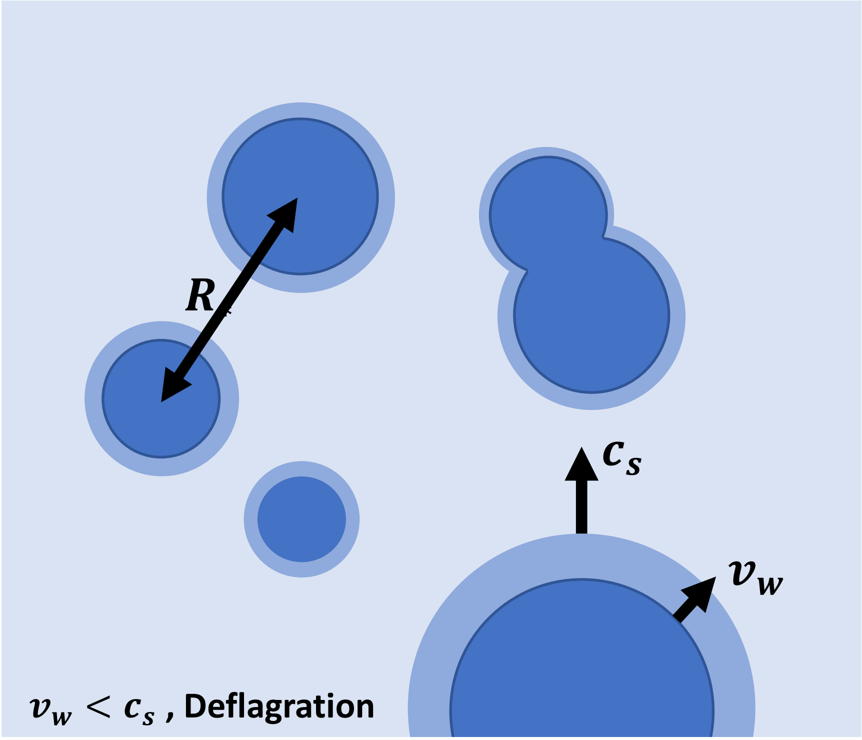
Phase transition parameters

- Nucleation temperature - $\boldsymbol{T_n}$
- Inverse duration of the PT relative to the Hubble rate - $\frac{\boldsymbol{\beta}}{\boldsymbol{H_*}}$
- Transition strength - $\boldsymbol{\alpha} \sim \frac{\Delta V}{\rho_{th}}$
- Phase boundary speed- $\boldsymbol{v_w}$

Length scales

- Mean bubble separation - R_*
- Sound shell thickness ~ $|v_w - c_s|\, R_*$

- $\Omega_{GW} \propto {KE_{frac}}^2$



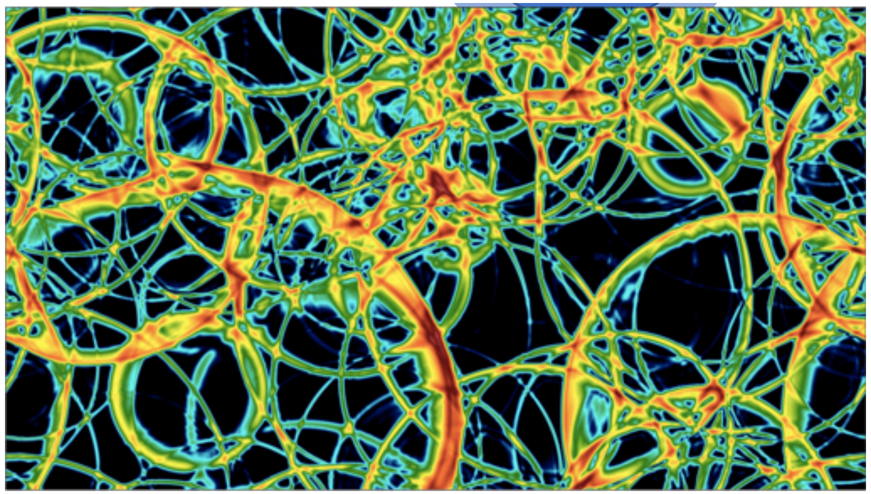
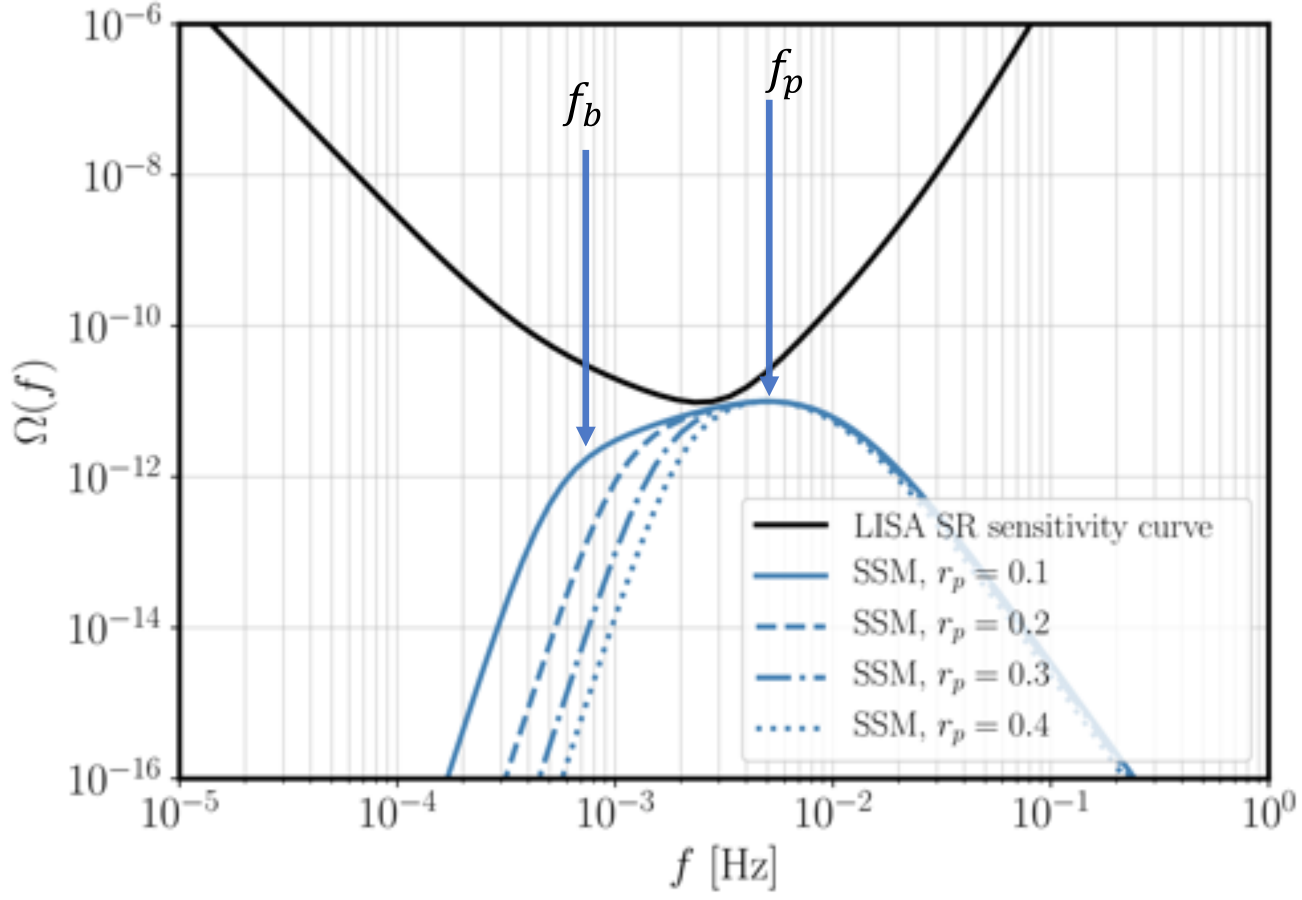


Image credit: David Weir, **arXiv:1705.01783**

Sound shell model power spectrum

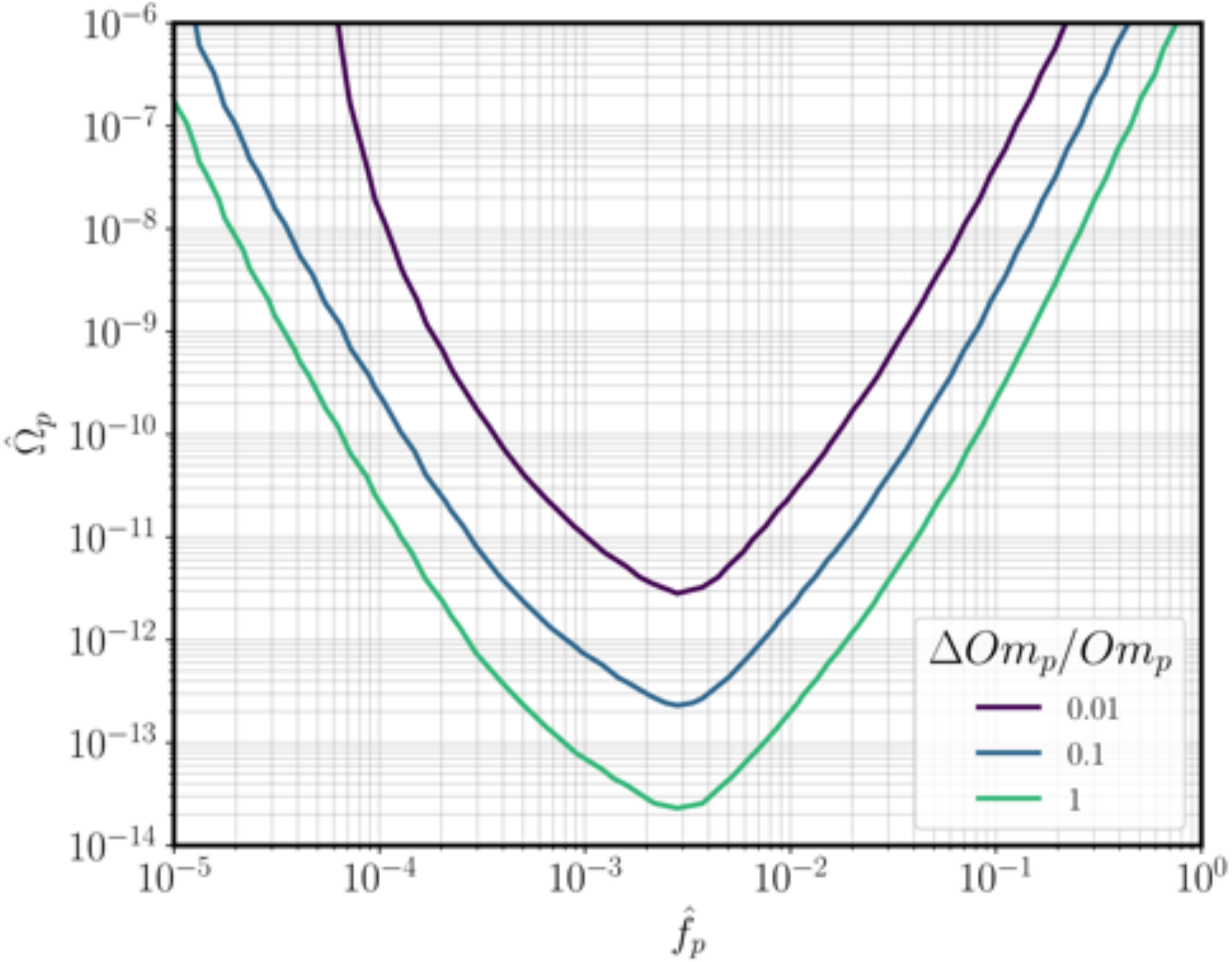


Mark Hindmarsh and Mulham Hijazi: arXiv:1909.10040v1

- GW power spectrum can be calculated from the velocity power spectrum of the fluid.
- Velocity power spectrum from sound shells.
- $\Omega_{GW}(f) = \Omega_p M\,(s, r_p)$
- $s = \frac{f}{f_p}, \quad r_p = \frac{f_b}{f_p}$
- Observable parameters Ω_p, f_p and r_p

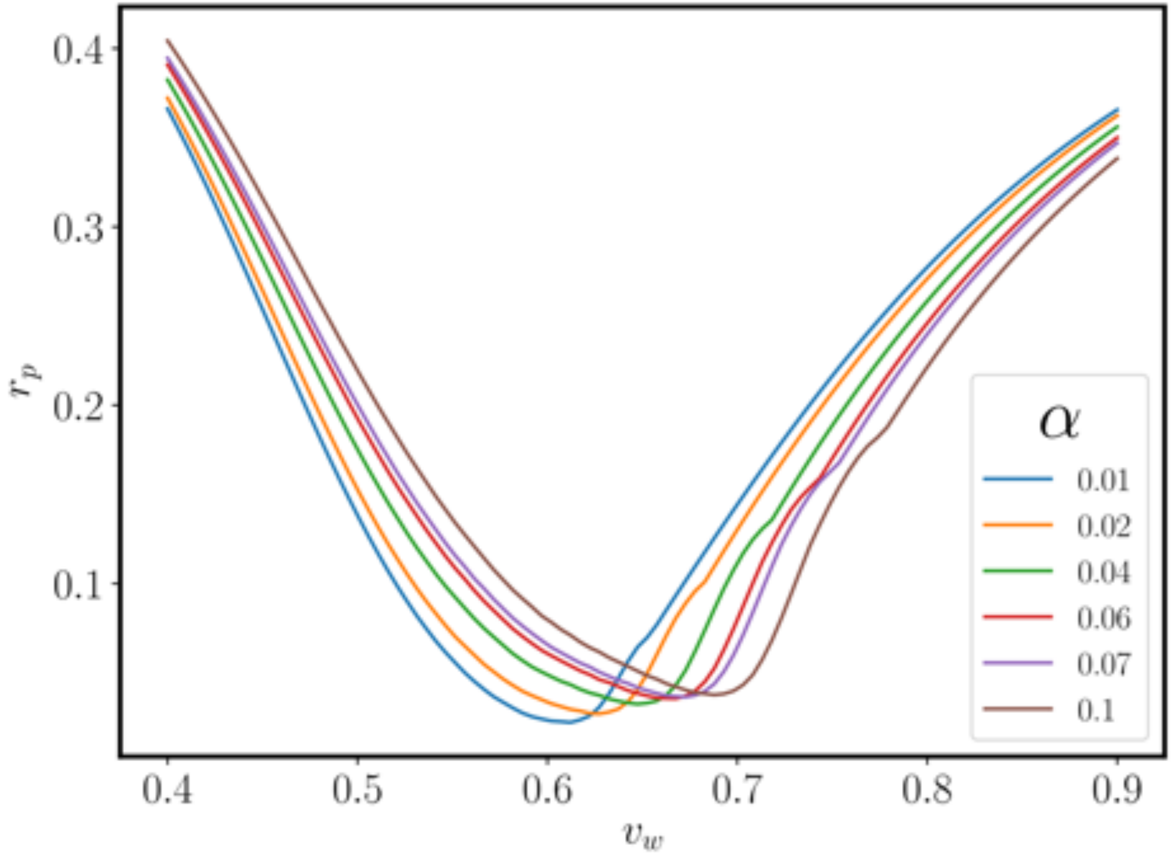
Sensitivity forecasts: $\boldsymbol{\Omega_p}$

- Performing Fisher matrix analysis
- $\frac{\Delta\Omega_p}{\Omega_p}$ relative uncertainty in $\boldsymbol{\Omega_p}$
- $r_p = 0.1$



Connection to phase transition parameters

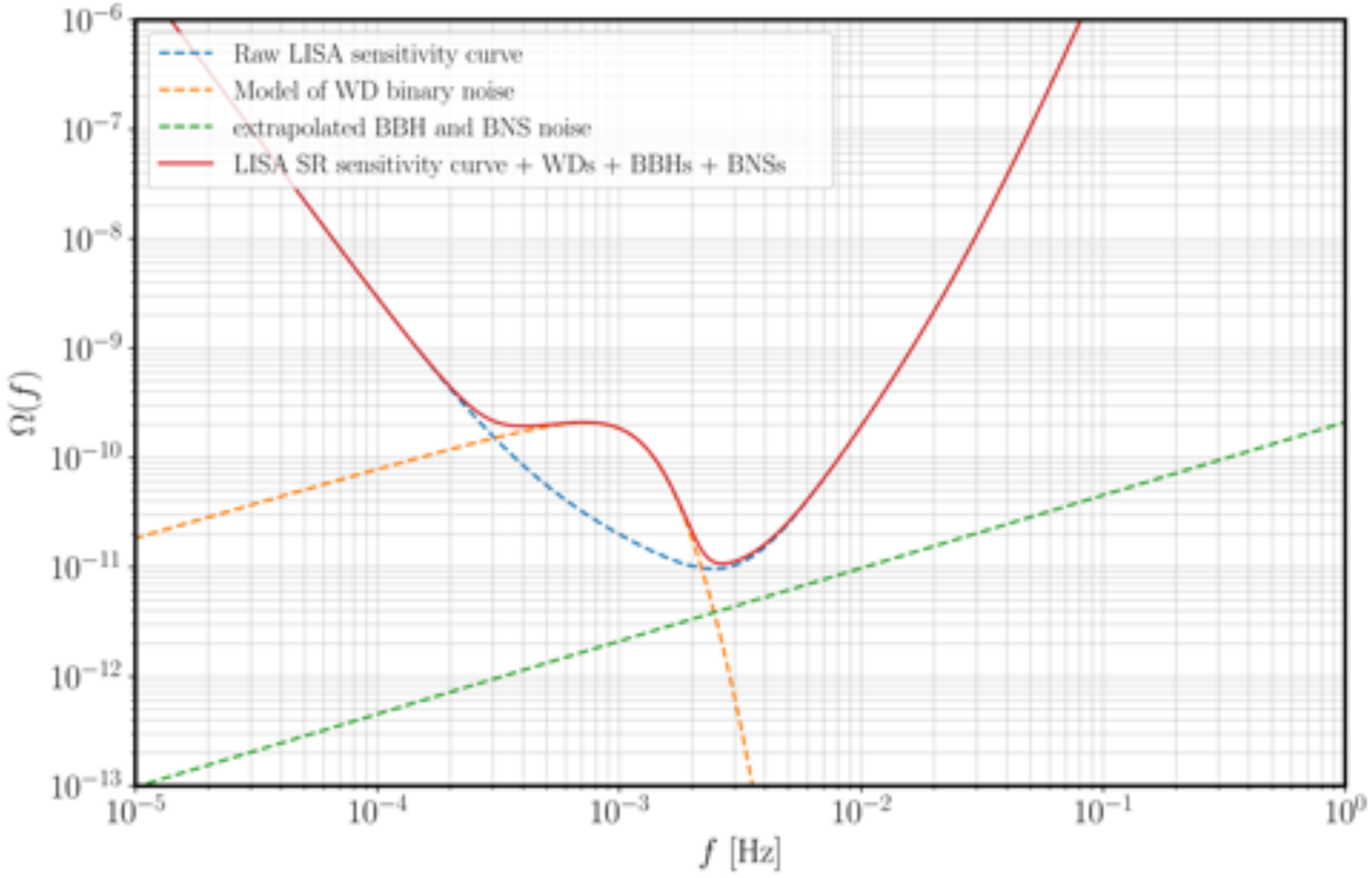
- $\Omega_p \longleftrightarrow \alpha, v_w, \frac{\beta}{H_*}$
- $f_p \longleftrightarrow |v_w - c_s|, \frac{\beta}{H_*}, T_n$
- $r_p \longleftrightarrow |v_w - c_s|, (\alpha)$



Conclusions

- LISA, opens a window onto early universe cosmology and potentially new particle physics.
- Here we have demonstrated LISA's sensitivity to Ω_p, f_p and r_p .
- Motivates continued study of v_w in different particle physics models.
- Better modelling of astrophysical foregrounds required (white dwarfs and compact binaries)

Incorporating astrophysical noise



White dwarf binaries : arXiv:1703.09858v2, Compact binaries: PhysRevLett.120.091101