Gravitational Waves from the Early Universe

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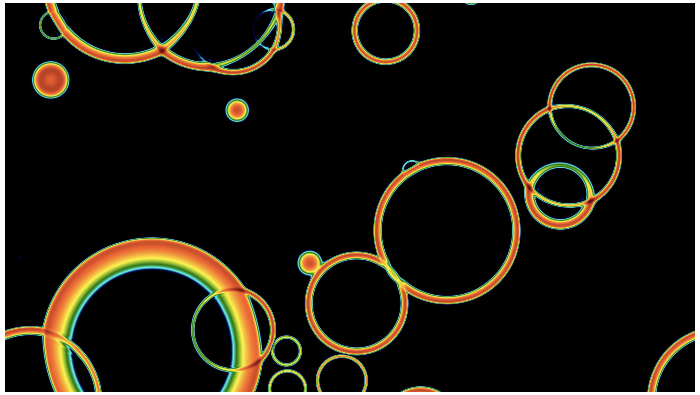
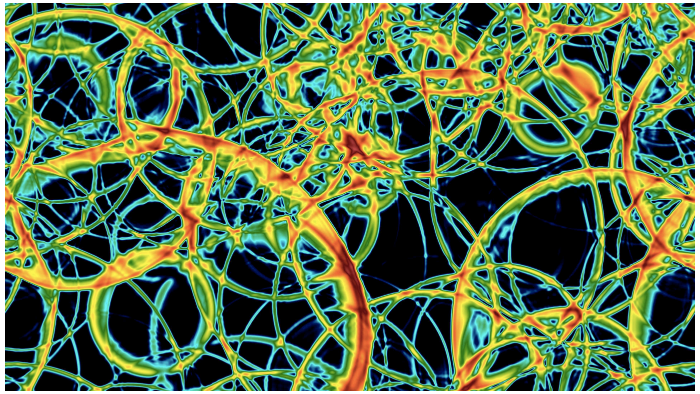
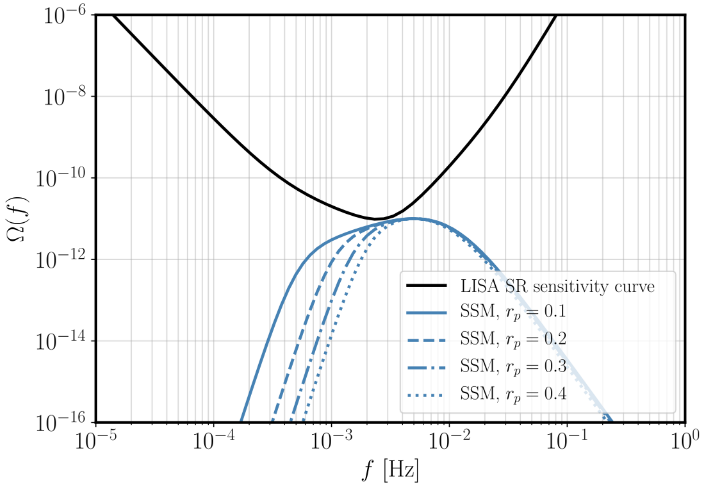
Overview

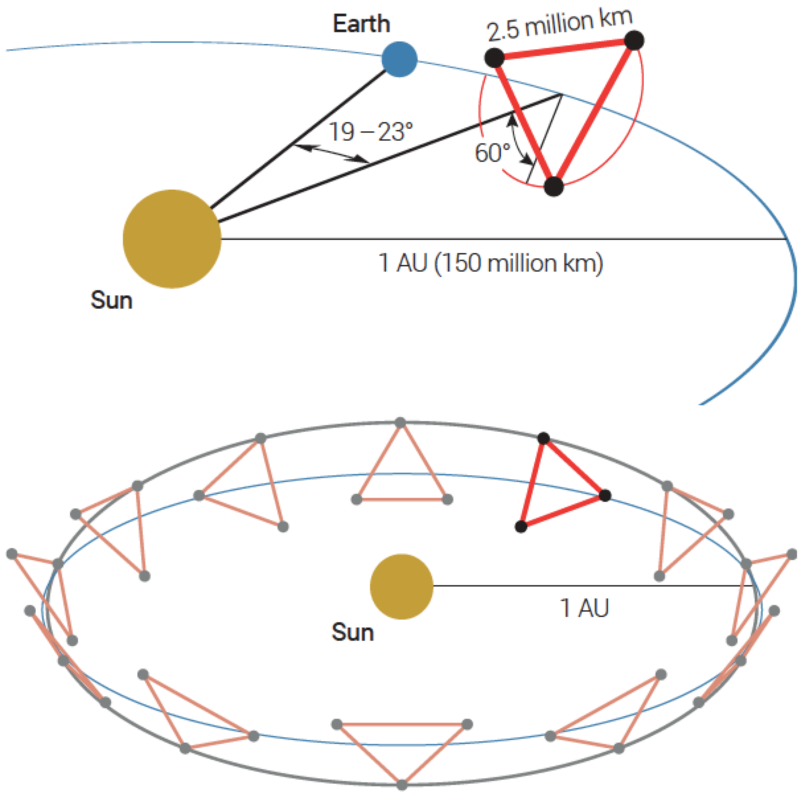
- LISA
- Gravitational waves (GWs) from the early universe.
- First order electroweak phase transition.
- The sound shell model.
- Current work
    - Connecting observables to model parameters.
    - How can we extract parameters from a GW power spectrum?







Laser Interferometer Space Antenna



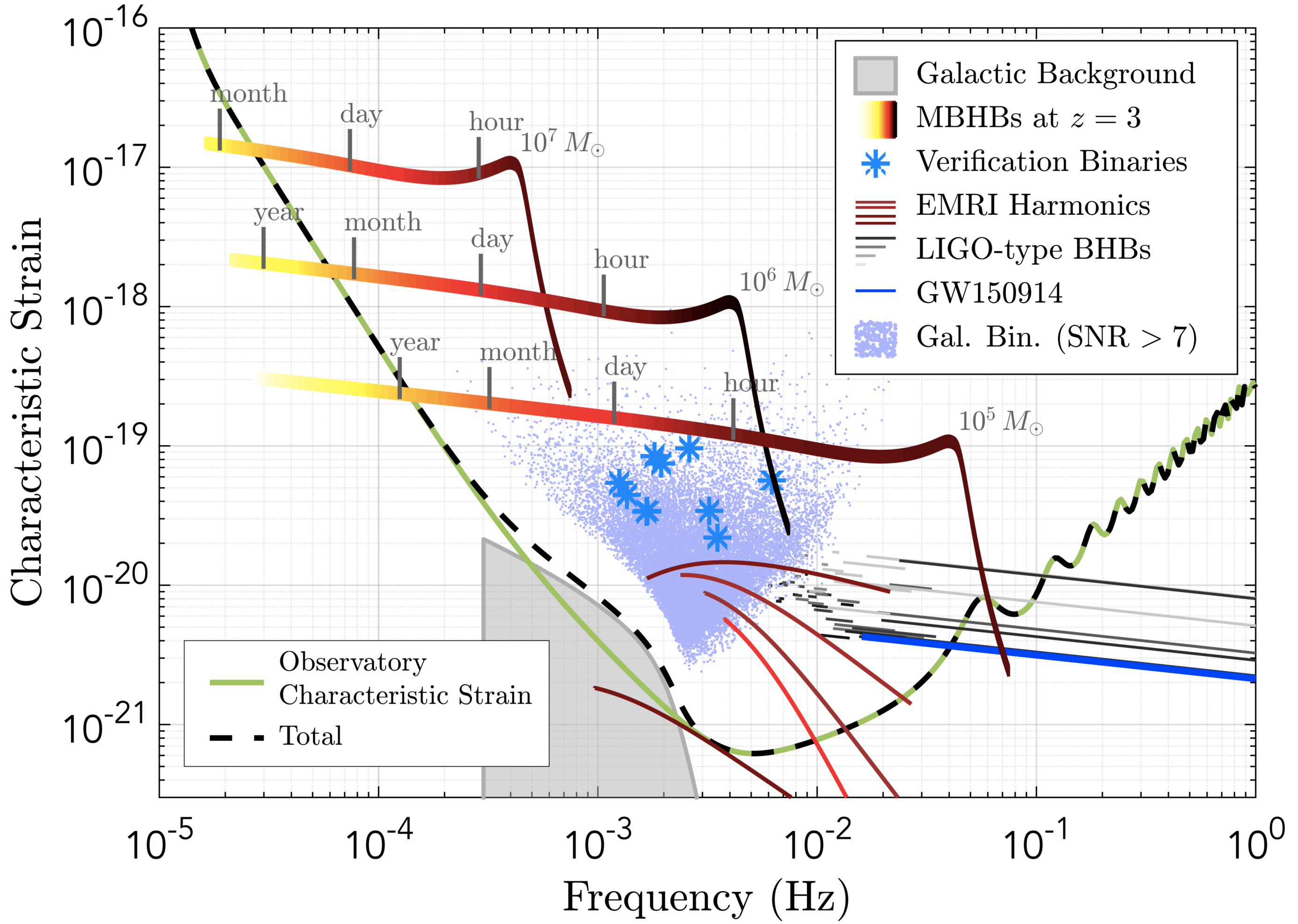
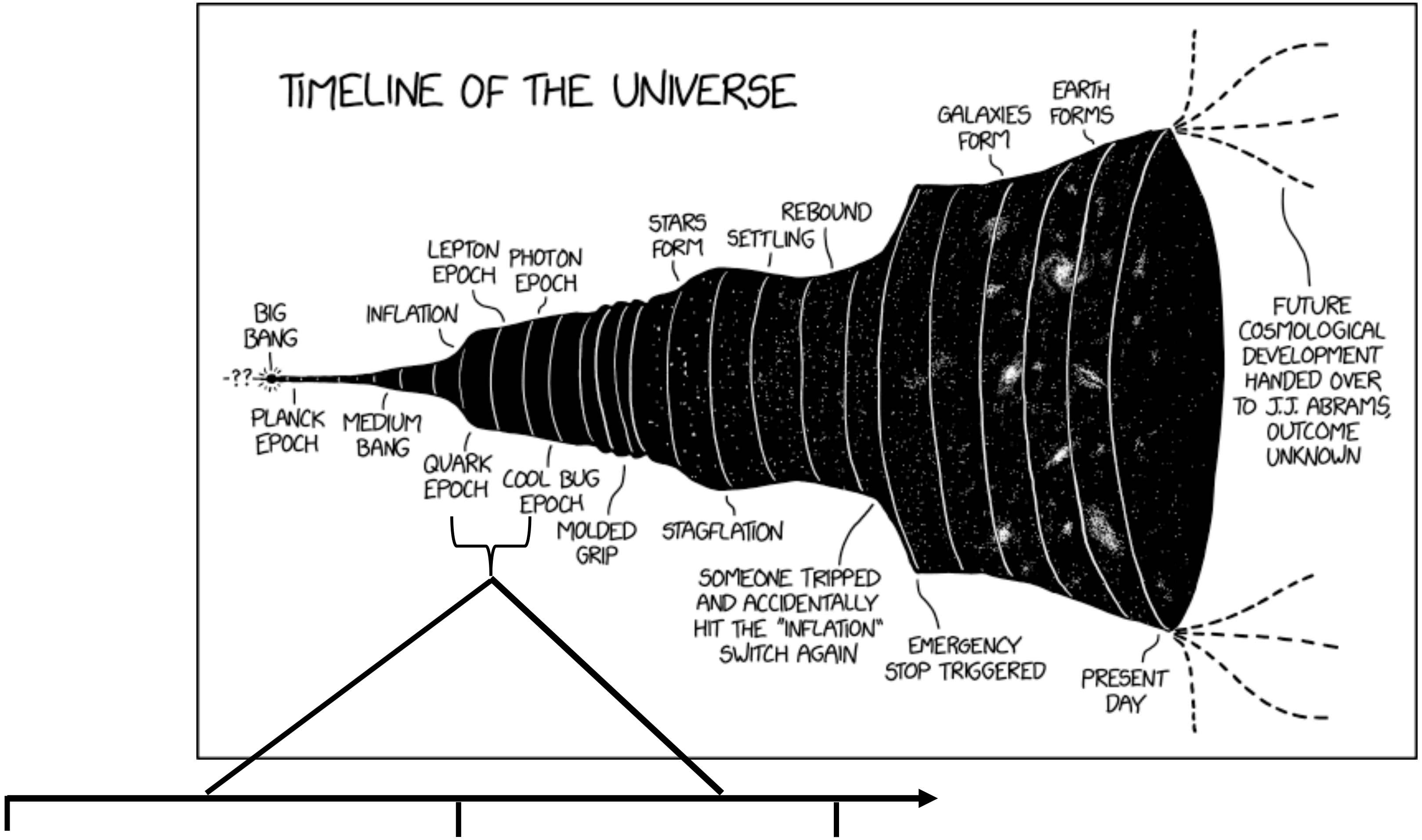


Figure credit: K. Danzmann et al. LISA proposal (2017)

Cosmological phase transitions



$\leq 10^{16} GeV$ — End of inflation

$\sim 100 GeV$ — EW phase transition

$\sim 0.1 GeV$ — QCD phase transition

Credit xkcd comics: https://xkcd.com/2240/

Frequency today of GWs from the early universe

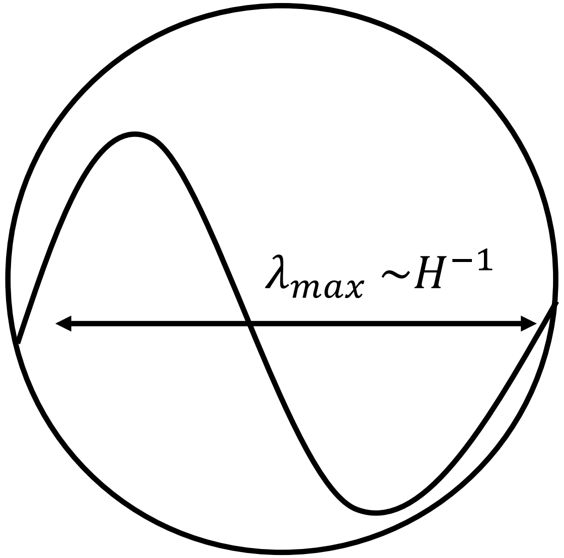
- The minimum frequency of a GW generated at time t

$$f_{min} = H = \frac{1}{t}.$$

- Today, taking into account redshift, this corresponds to:

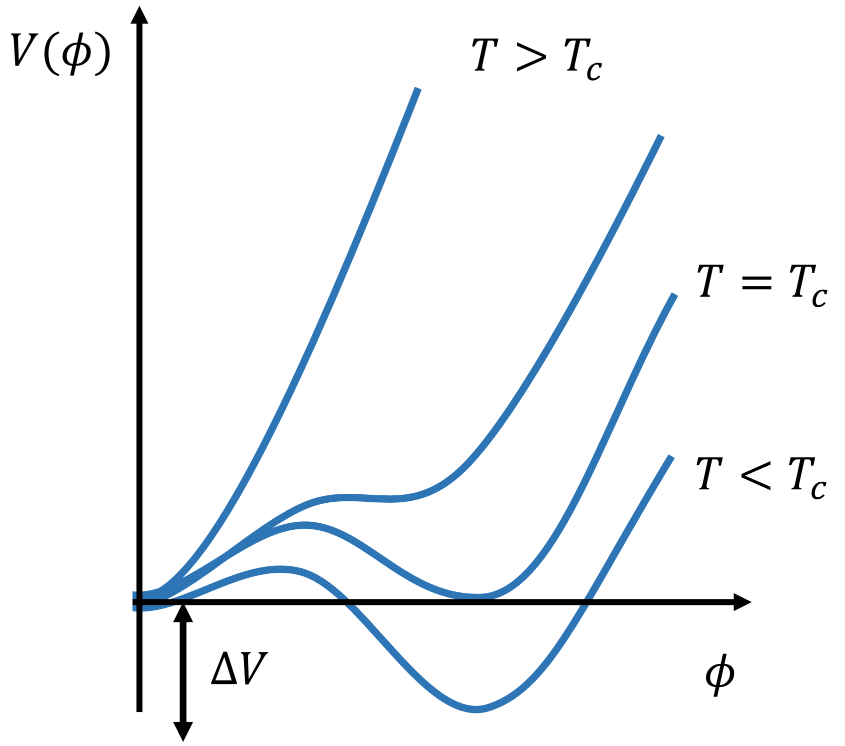
$$f_{min,0} = H_{T,0} = \frac{a}{a_0} H_T$$

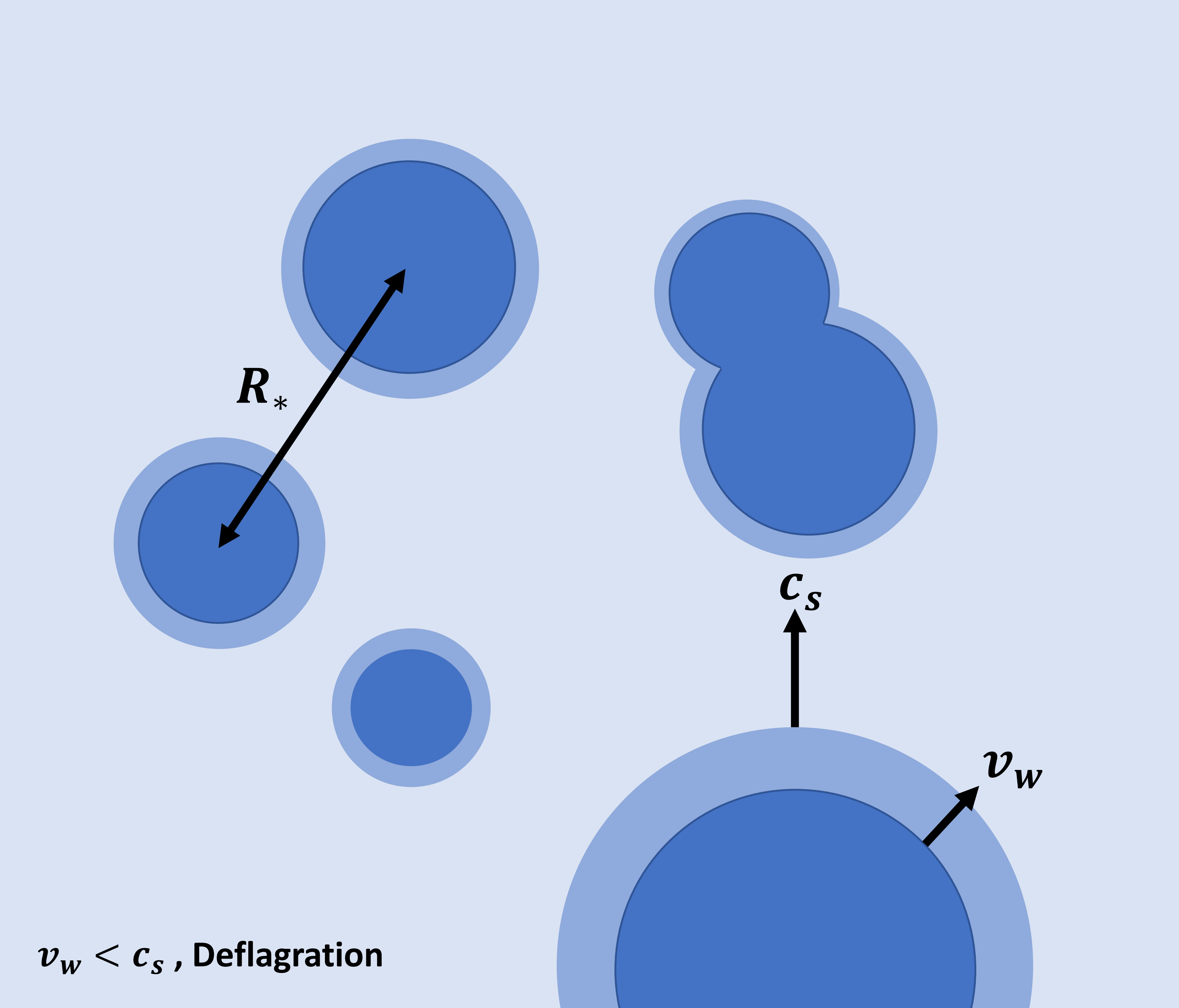
$$f_{min,0} = H_{T,0} = 1.6{\times}10^{-5} \left(\frac{g_*}{100}\right)^{\frac{1}{6}} \left(\frac{T}{100GeV}\right) [Hz]$$



Gravitational waves from the EWPT

- When $T < T_c$ bubbles of broken phase Higgs nucleate.
- Sources of gravitational waves
  - Collision of bubble walls
  - **Sound waves**
  - Other hydrodynamic modes





Broken phase

Symmetric phase

Sound shell

R_* = mean bubble separation
v_w = wall velocity
c_s = speed of sound

Potential energy in the scalar field is converted into **kinetic energy** of the plasma.

Thermodynamic parameters

- Transition strength - $\boldsymbol{\alpha} \sim \frac{\Delta V}{\rho_{th}}$
- Wall speed- $\boldsymbol{v_w}$
- Transition rate- $\boldsymbol{\beta}$
- Nucleation temperature - $\boldsymbol{T_n}$

Derived parameters

- Mean bubble separation - $R_* = (8\pi)^{\frac{1}{3}} \frac{\boldsymbol{v_w}}{\beta}$
- Sound shell thickness $\sim |v_w - c_s|$
- Kinetic energy fraction - $K^2(v_w, \alpha)$

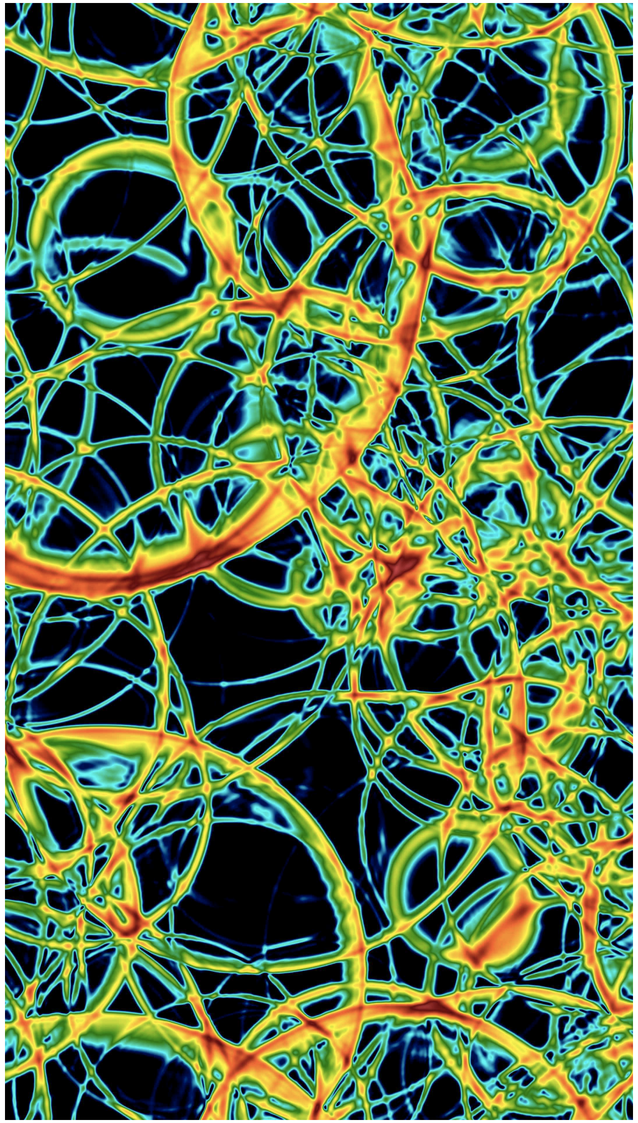
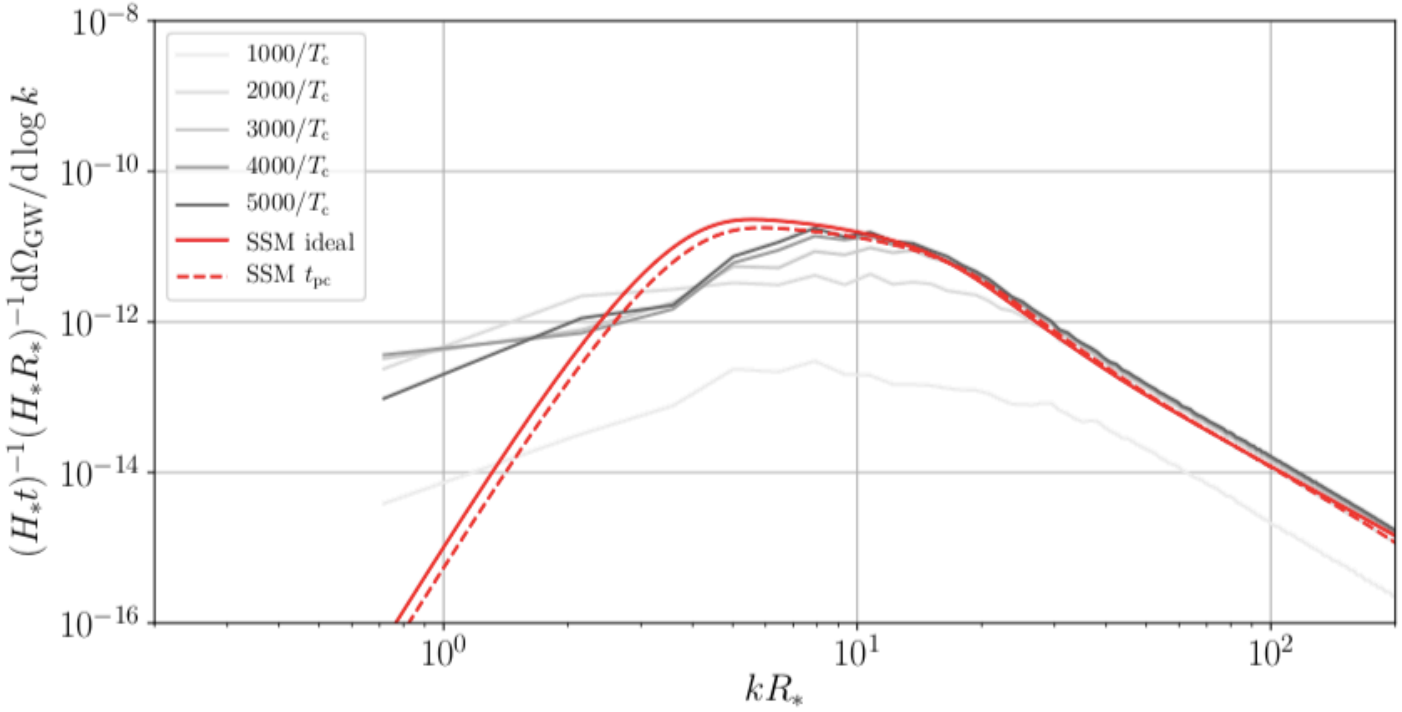


Image credit: David Weir, **arXiv:1705.01783**

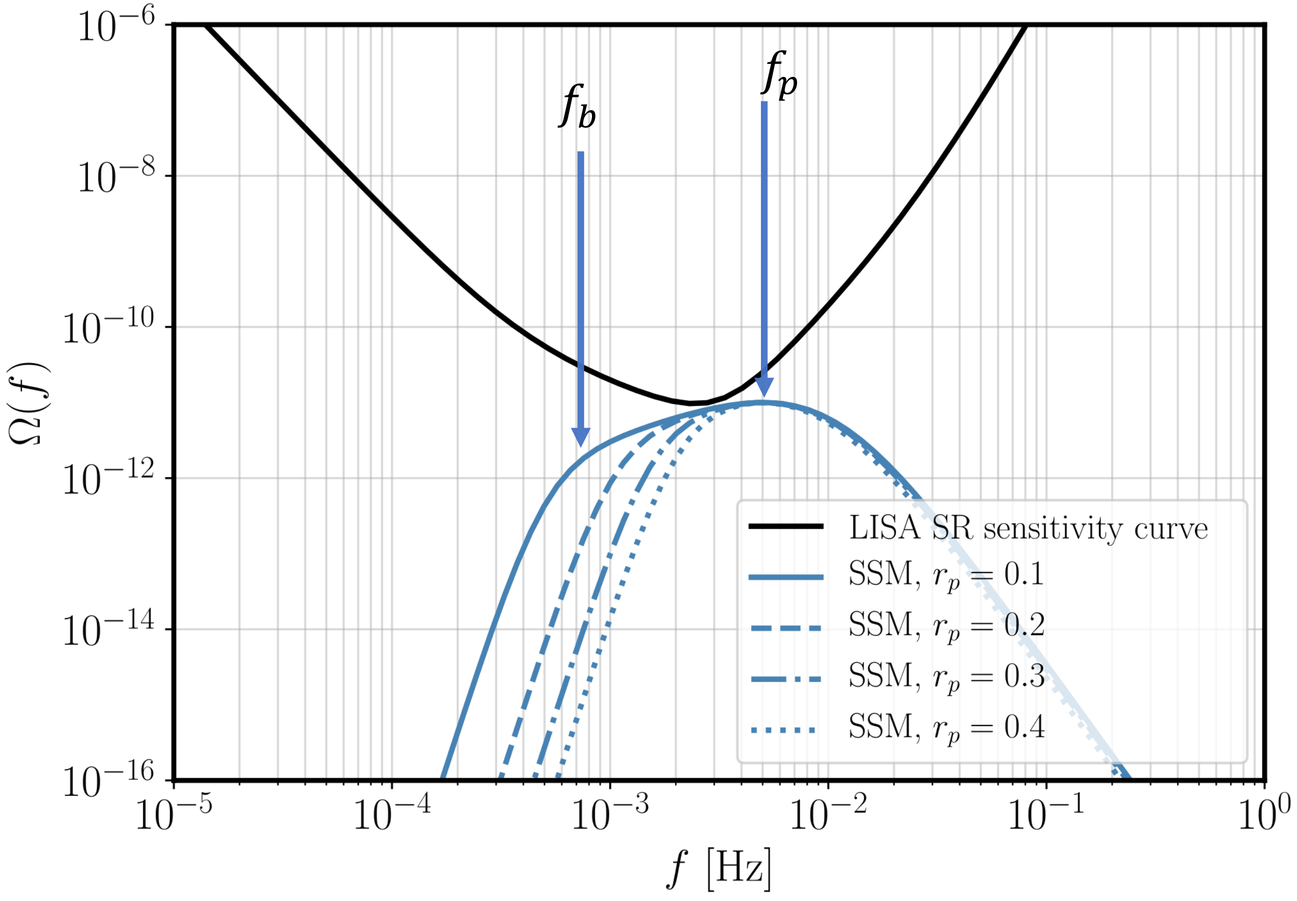
Sound shell model



- GW power spectrum can be computed form the velocity power spectrum of the fluid.
- SSM proposes the velocity PS can be calculated from the sound shells.
- Analytic approximation of simulation results is shown in red.

Figure credit: M.Hindmarsh, slides from Nordita workshop 2019

Simplified sound shell model

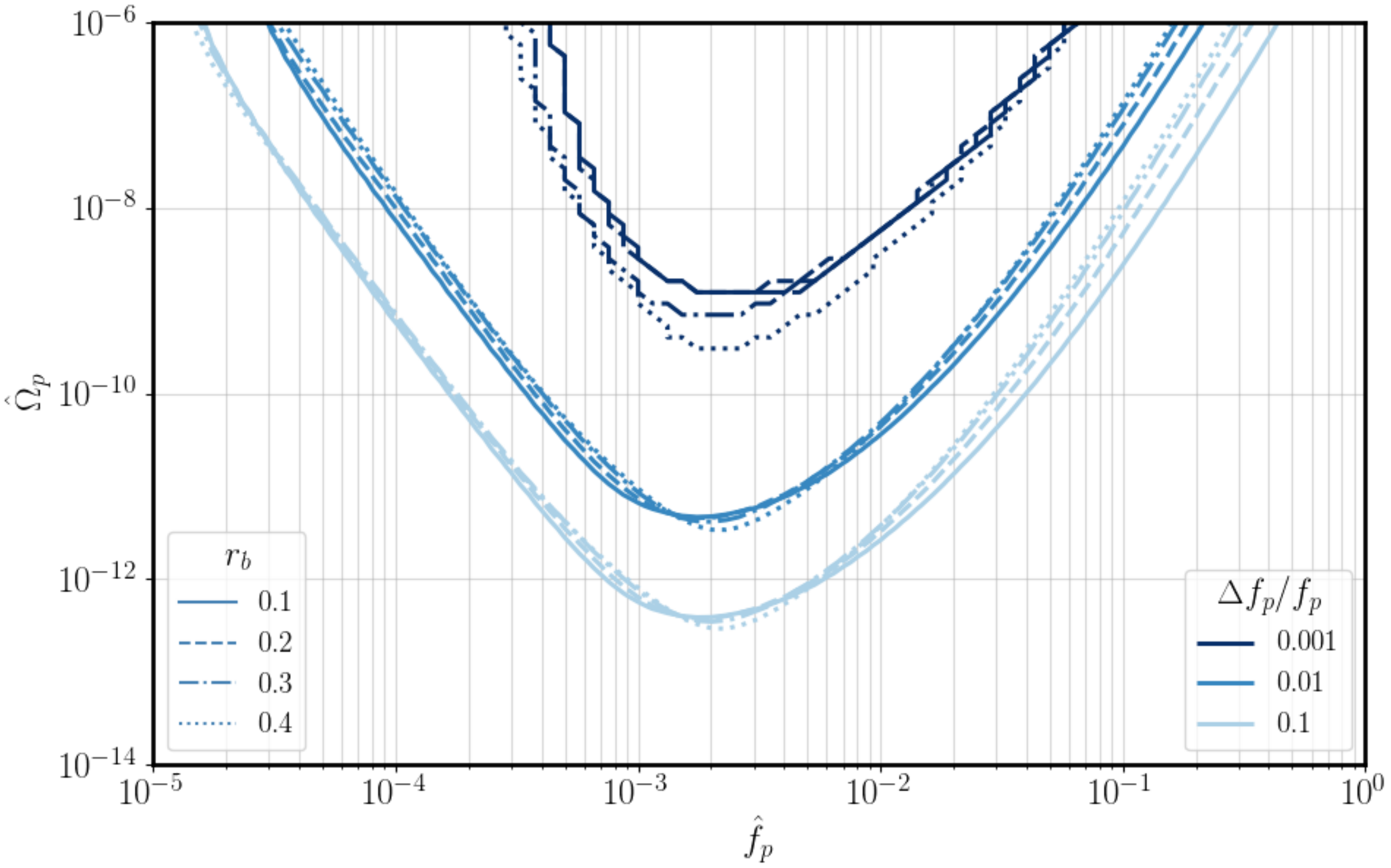


arXiv:1909.10040v1

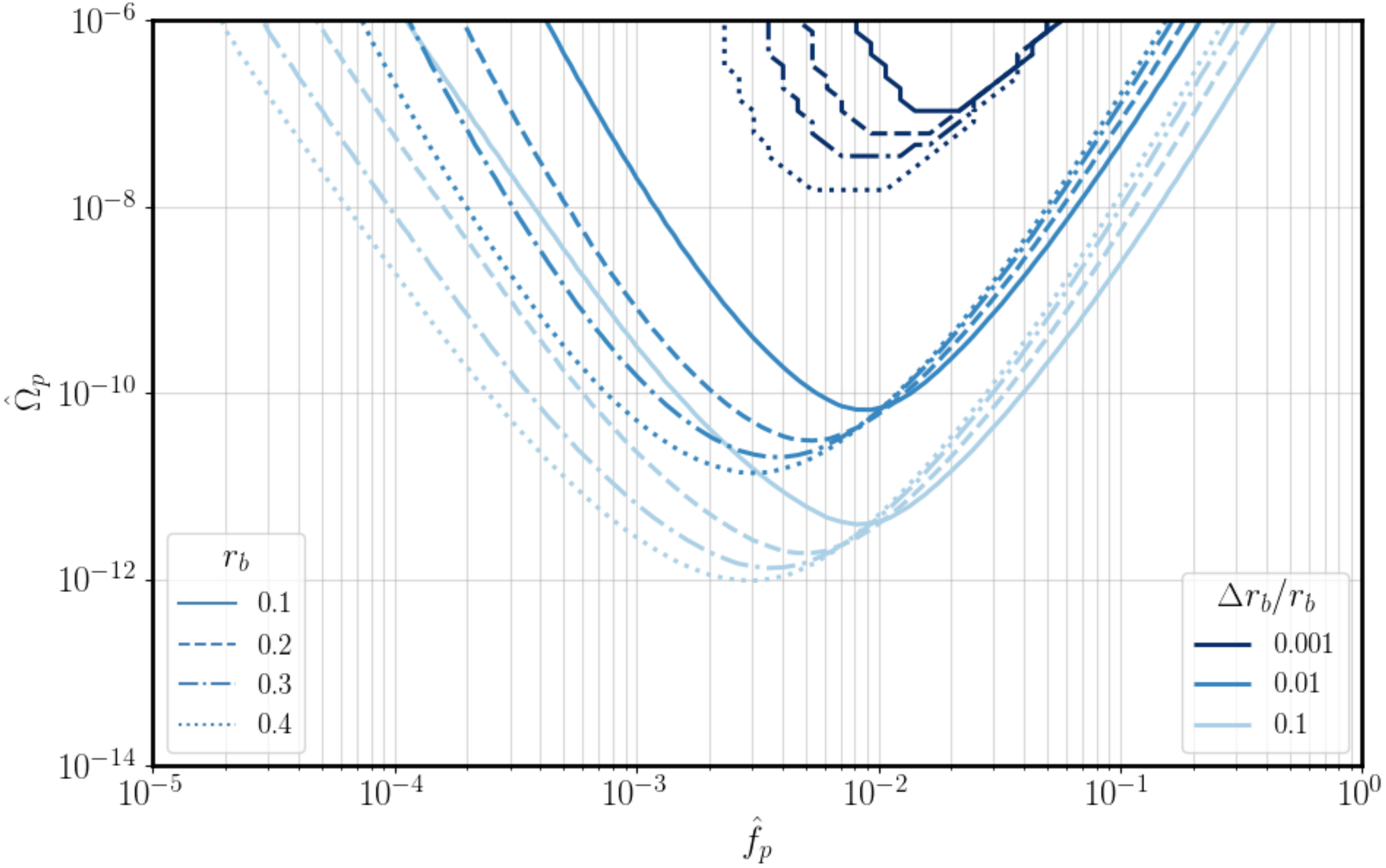
- $\Omega_{GW}(f) = \Omega_p M\,(s, r_b)$
- $M = s^9 \left(\frac{1 + {r_b}^4}{{r_b}^4 + s^4}\right)^2 \left(\frac{5}{5 - m + m s^2}\right)^{\frac{5}{2}}$
- $m = \frac{1 + 9\,{r_b}^4}{1 + {r_b}^4}, \quad s = \frac{f}{f_p}, \quad r_b = \frac{f_b}{f_p}$
- Observable parameters Ω_p, f_p and r_b

Sensitivity forecasts: $\boldsymbol{f_p}$

- $\chi^2 = T_{obs} \int \frac{(\Omega_{GW}(f,\theta) - \Omega_n(f,\widehat{\theta}))}{{\Omega_n}^2}$
- $\mathcal{L} = e^{-\frac{1}{2}\chi^2}$
- $F_{ij} = \frac{\partial^2 \ln(\mathcal{L})}{\partial\theta_i \partial\theta_j} = \frac{1}{2}\frac{\partial^2\chi^2}{\partial\theta_i\partial\theta_j}$
- $\frac{\Delta f_p}{f_p}$ relative uncertainty in f_p



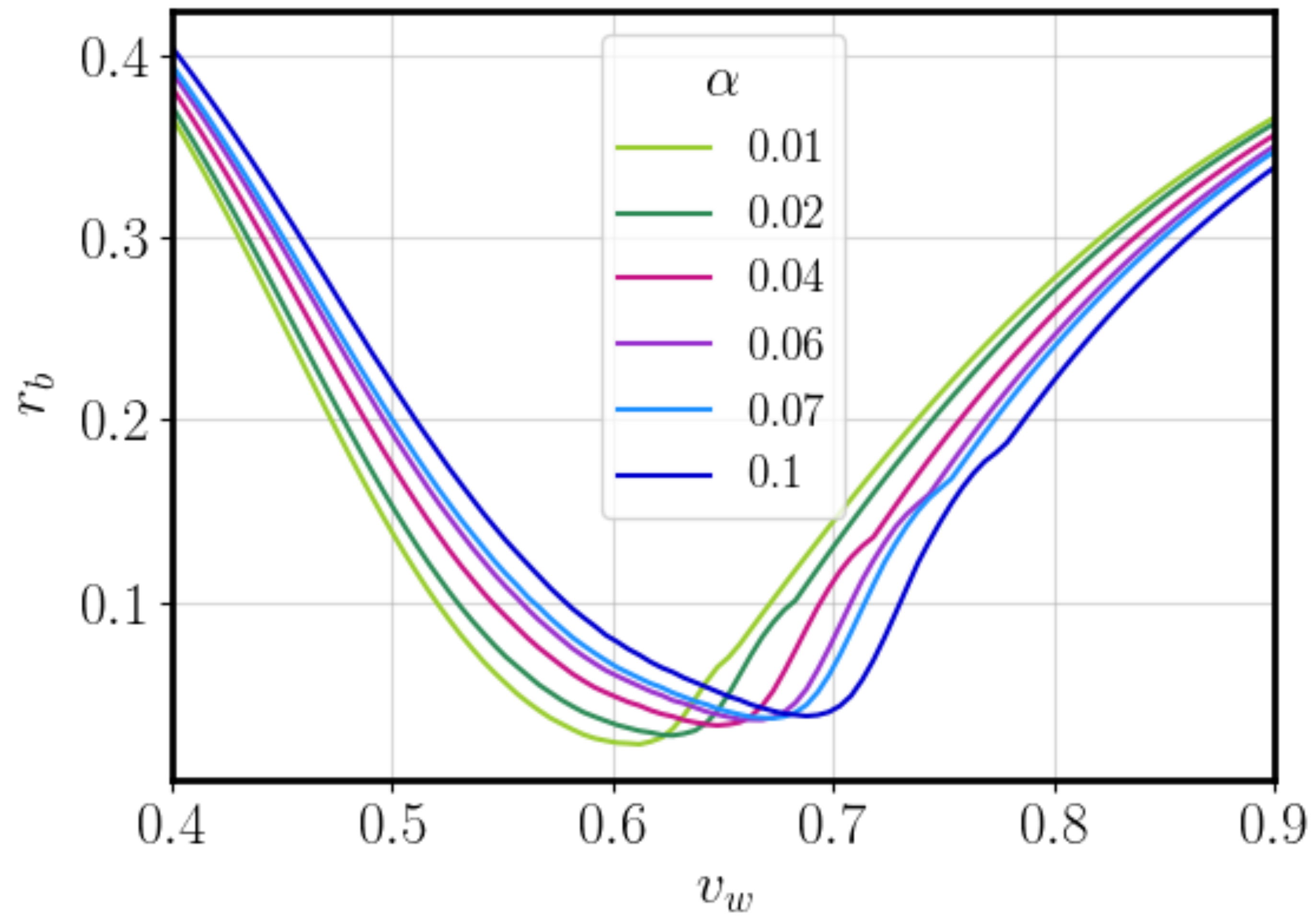
Sensitivity forecasts: $\boldsymbol{r_b}$



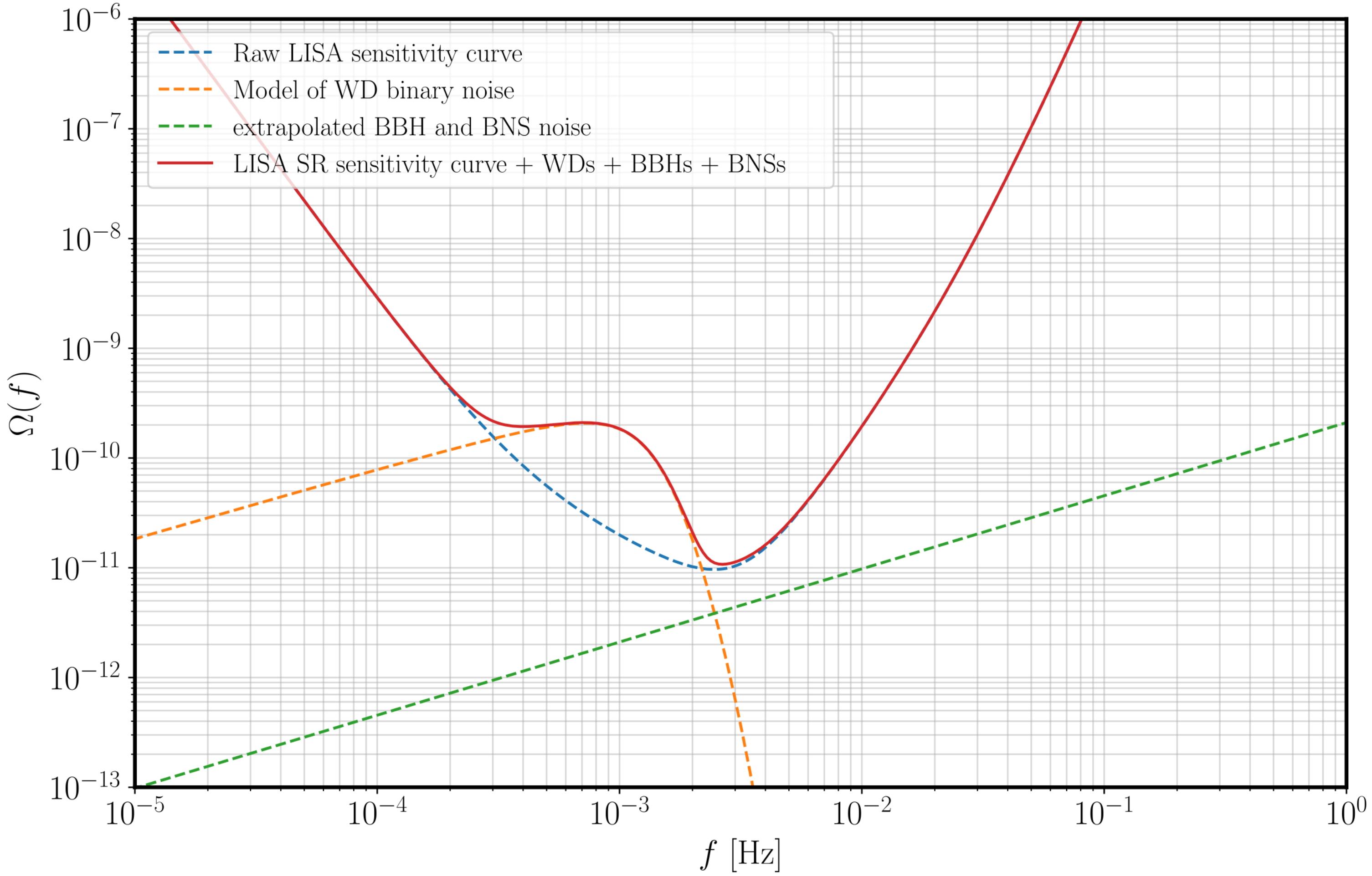
- $r_b = \frac{f_b}{f_p}, \quad 0 < r_b < 1$
- Larger r_b corresponds to a narrower power spectrum.

Connection to thermodynamic parameters

- $\Omega_p\ (v_w\ ,\alpha, H_n R_*)$
- $f_p(v_w, \alpha, H_n R_*)$
- $r_b\ (v_w, \alpha)$
- fixed T_n



Astrophysical noise



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

Next steps

- Better understanding of the sources of noise
  - Astrophysical noise, white dwarfs, BBHs and BNSs
- Further investigate the relationship between $(\Omega_p, f_p\ , r_p)$ and thermodynamic parameters $(v_w, \alpha, H_n R_*, T_n)$.
- Perform Monte Carlo analysis on for thermodynamic parameters.