Norwegian Particle, Astroparticle & Cosmology Theory network

NPACT meeting Ålesund,
19-21 June 2024

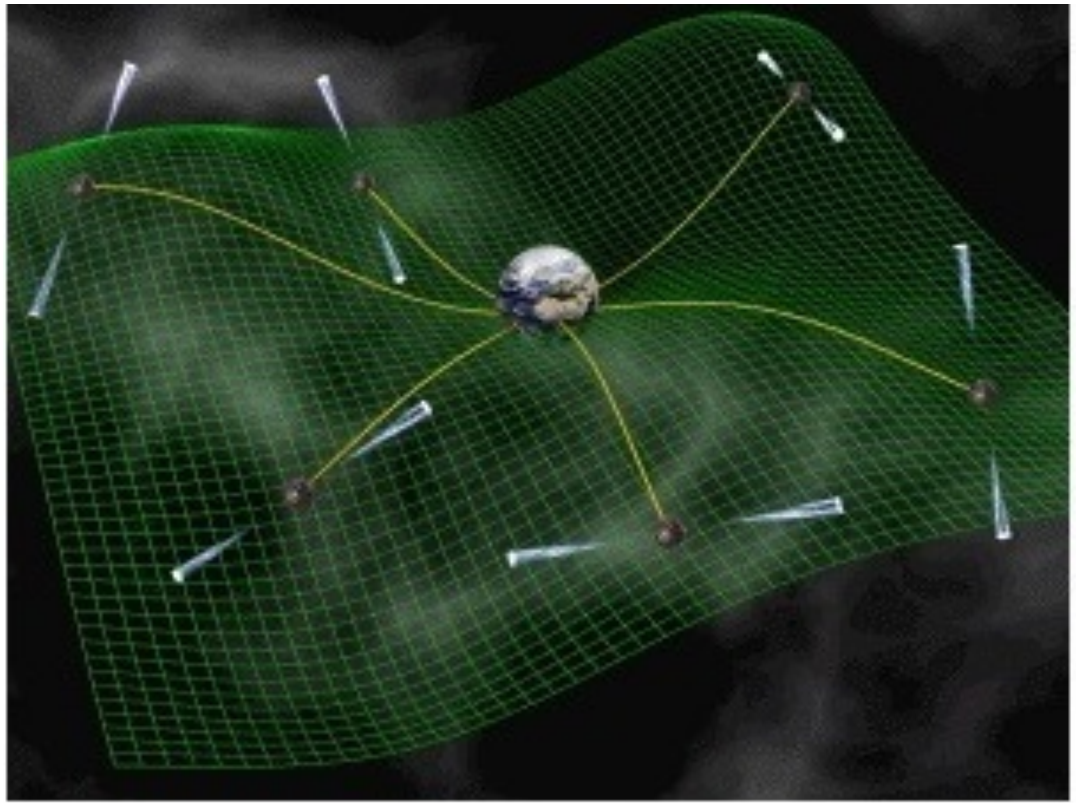
Gravitational waves from nHz to GHz frequencies

Based on

TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23

TB, Gonzalo, Kahlhoefer, Matuszak & Tasillo, JCAP '24

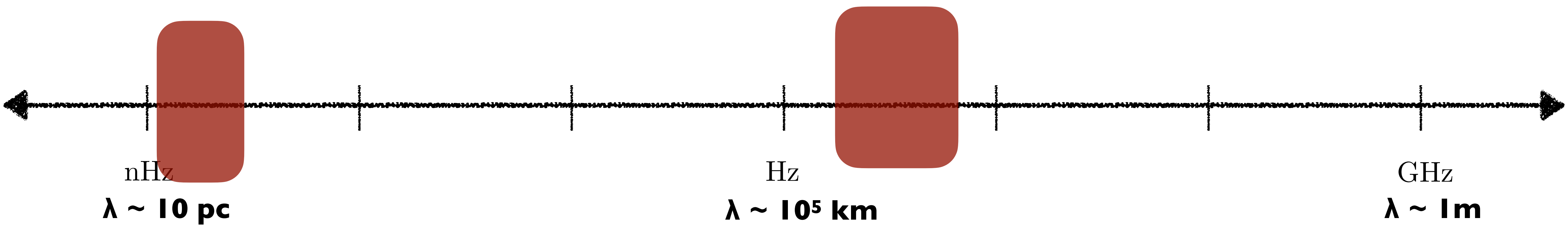
TB, Domcke, Fuchs & Kopp, PRD '23

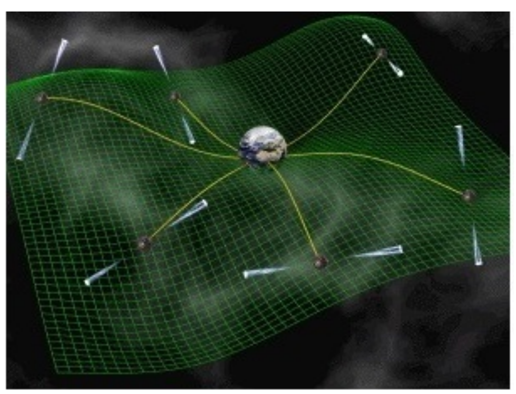


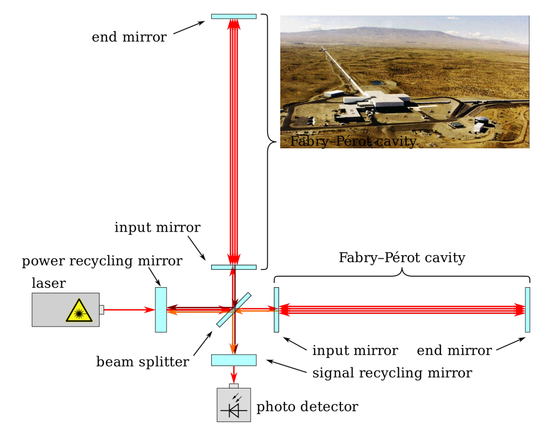
UiO : University of Oslo (Torsten Bringmann)

Gravitational waves: status 2024

- Confirmed observations in two frequency ranges







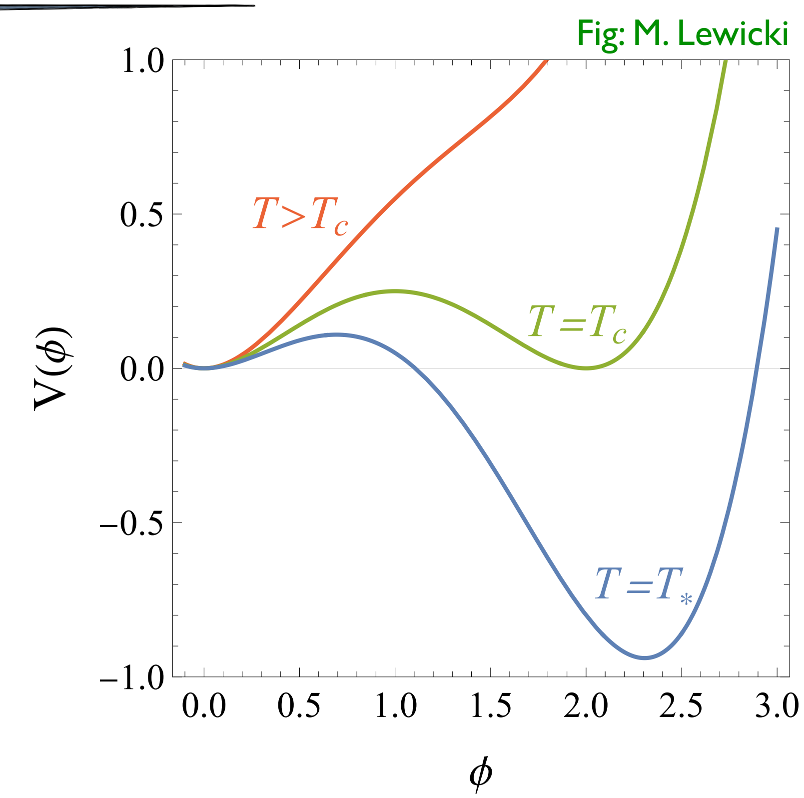
- Stochastic BG:
  - SMBH mergers ?
  - New physics?

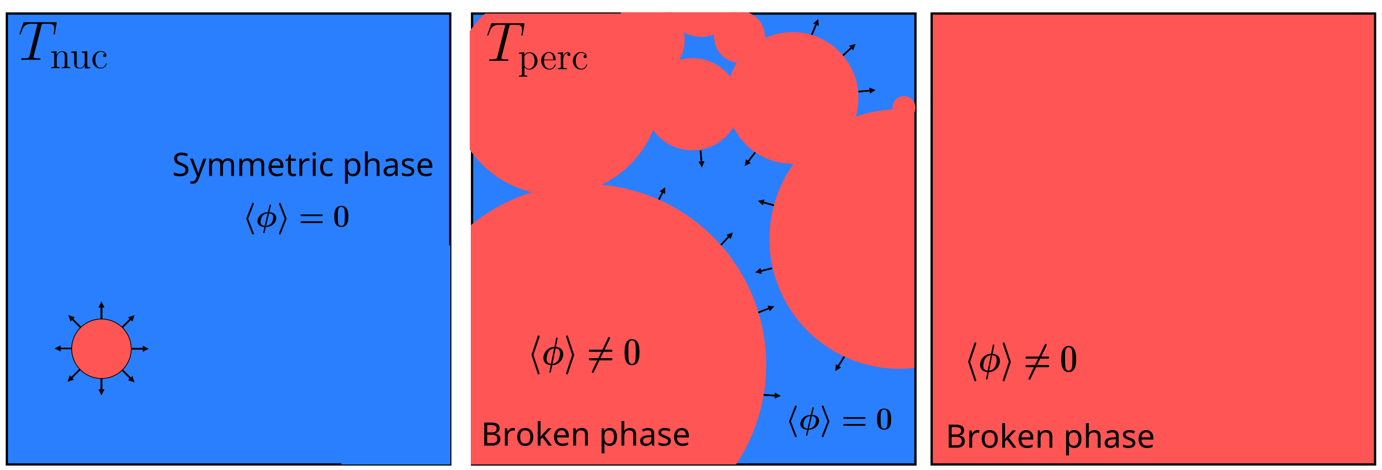
- Individual mergers:
  - BH-BH 
  - BH-NS
  - NS-NS

Cosmological phase transitions

- We need a (strong) first-order transition
  - Not in the standard model: new physics… !
  - Triggered by temperature corrections to the potential

$$V(\phi, T) = \frac{g_{m^2}}{24}\left(T^2 - T_0^2\right)\phi^2 - \frac{g_m}{12\pi}T\phi^3 + \lambda\phi^4$$

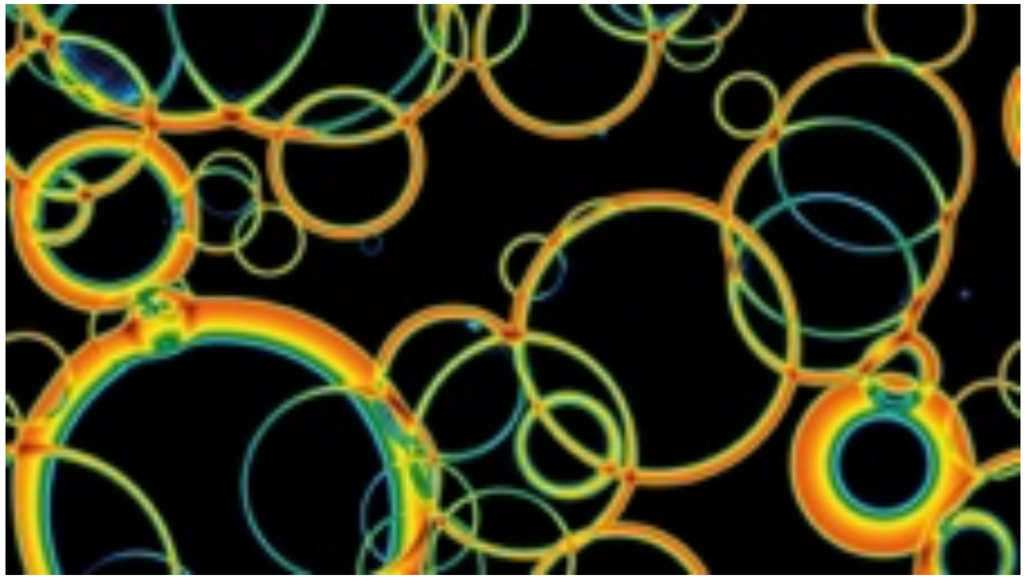




J. Matuszak, ‘23

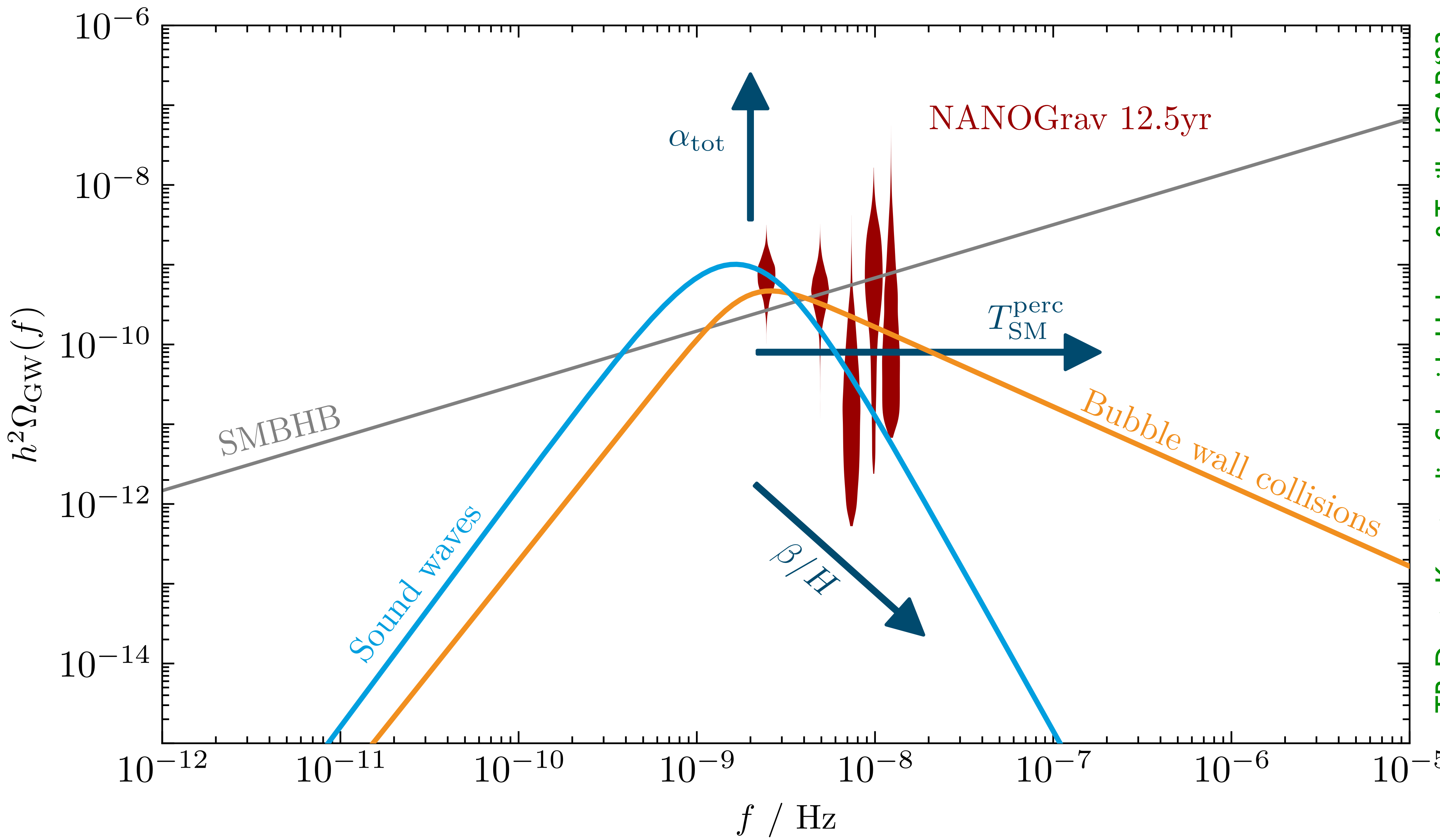
- Bubbles of new vacuum phase
  - nucleate spontaneously
  - quickly expand and percolate

- Need numerical simulations
  - highly non-linear dynamics
  - GWs produced through bubble wall collisions, sound waves and plasma turbulence



Resulting GW spectrum

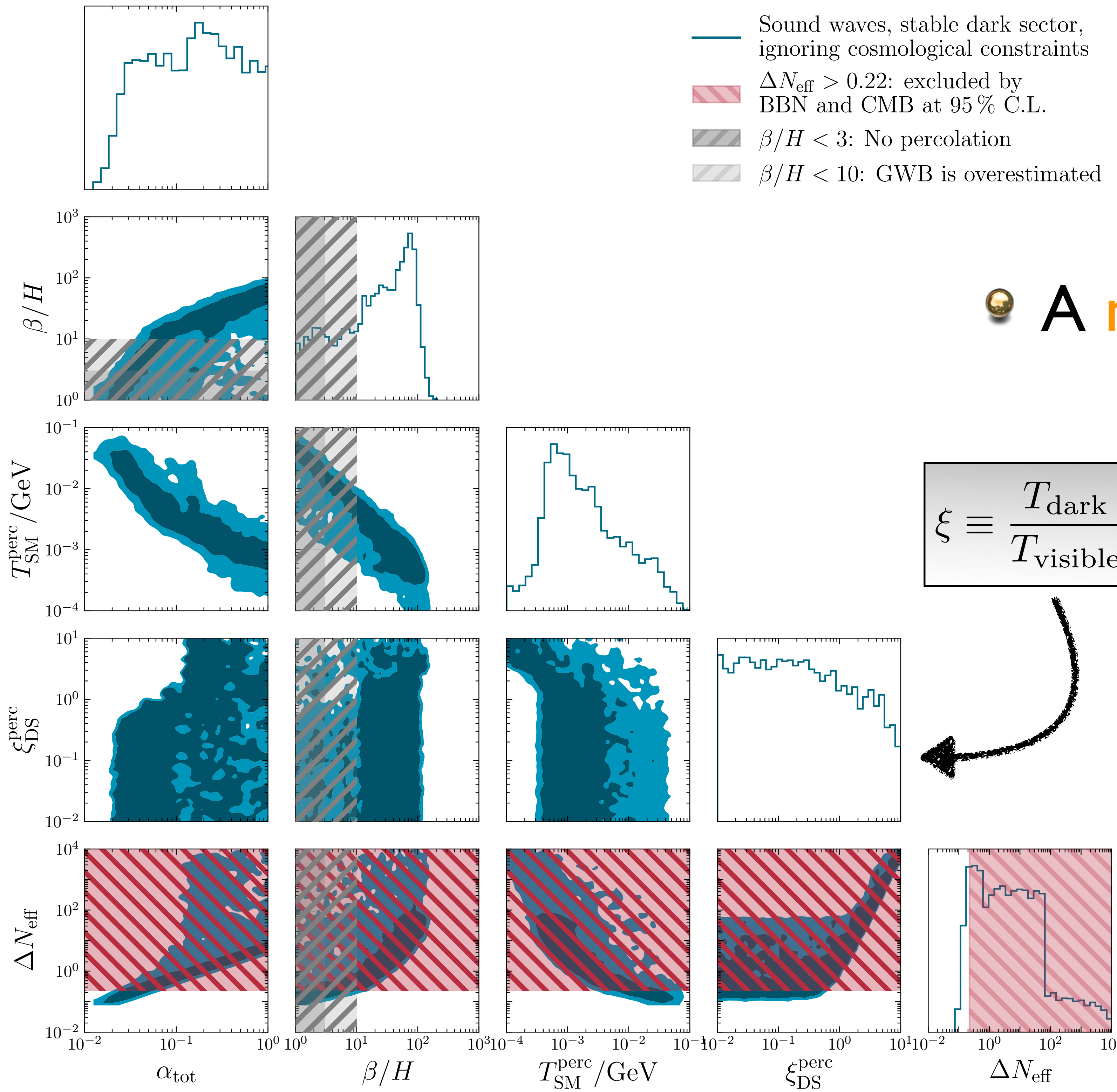
- Main phenomenological parameters:
  - nucleation/percolation temperature
  - PT strength
    $$\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$$
  - Characteristic scale (inverse time)
    $$\Gamma \propto e^{-\frac{S_3(T)}{T}} = e^{\beta\,(t-t_0)} \implies \frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Big|_{T=T_p}$$



TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23

A PT explanation of NANOGrav ?

TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23



$$\xi \equiv \frac{T_{\rm dark}}{T_{\rm visible}}$$

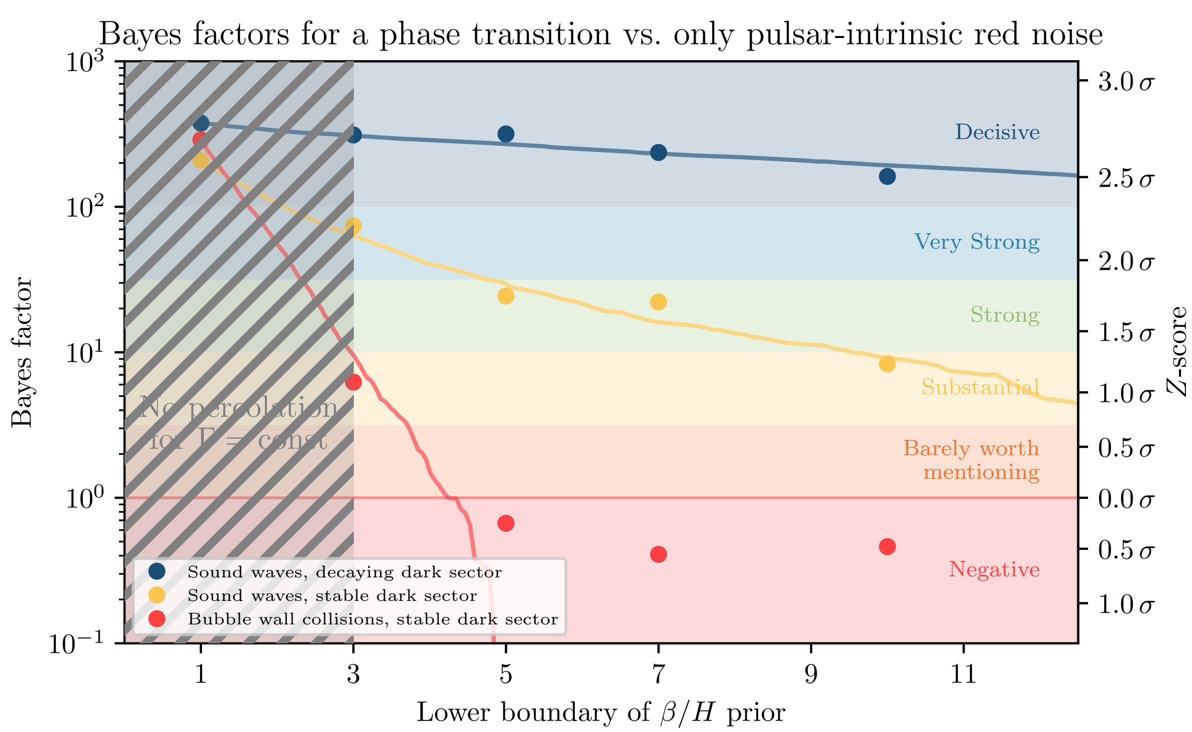
- A naive fit looks good…
- …but is incompatible with cosmology
  - confirmed by full global fit

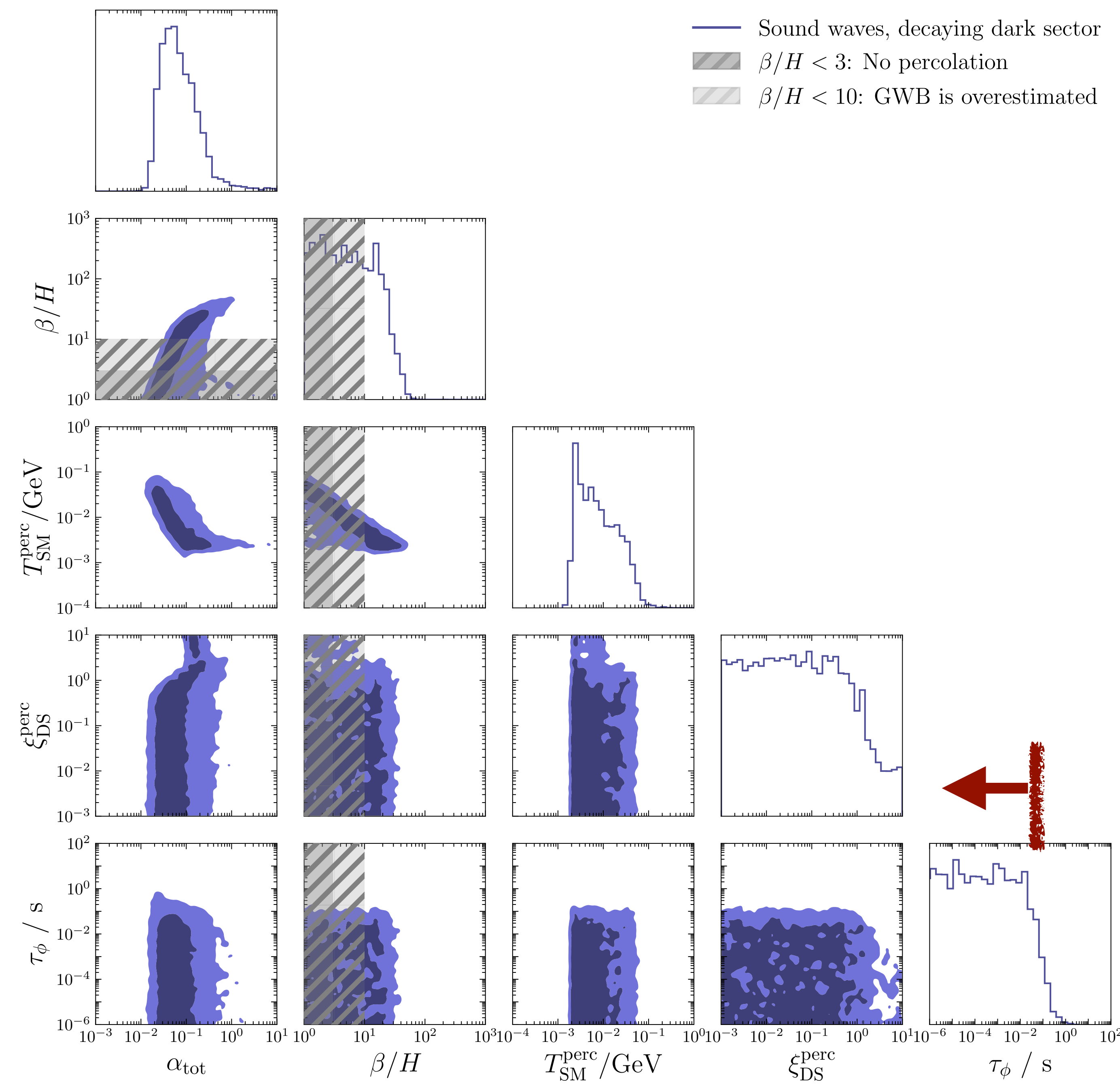
A decaying dark sector

TB, Depta, Konstandin, Schmidt-Hoberg & Tasillo, JCAP '23

- Simplest way out : allow $\phi \to \mathrm{SM}$ decays before BBN

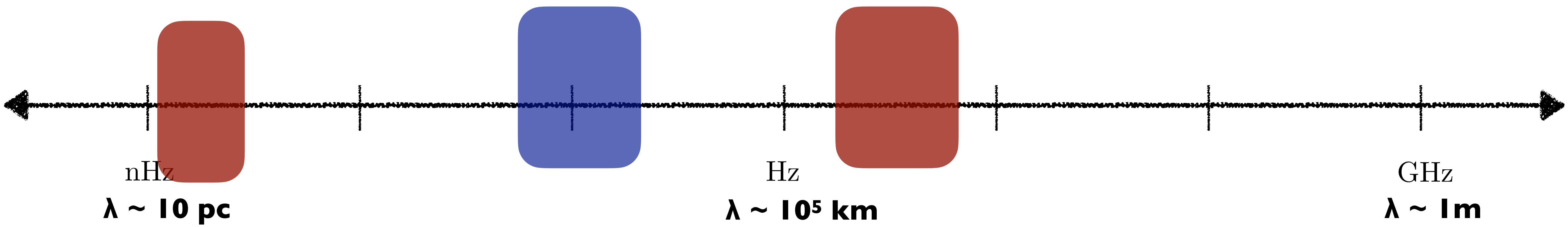
- Problem solved — results in good fit to data
  - Conclusions strengthened with 15yr data: w.i.p. …

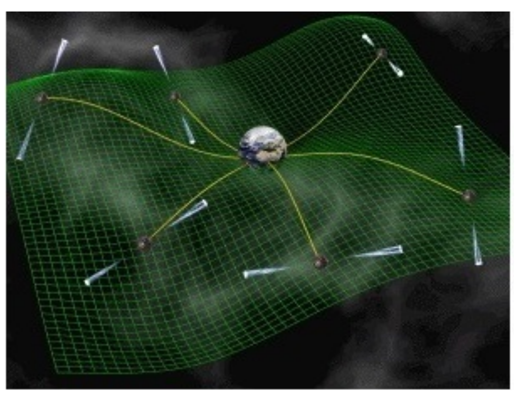


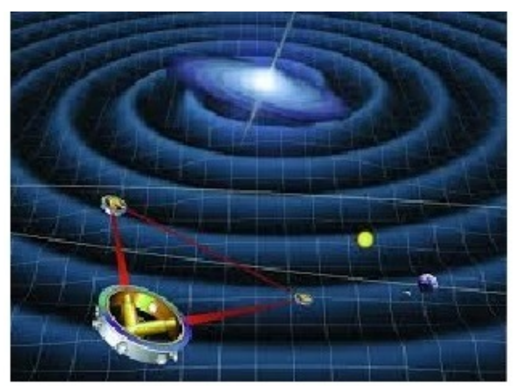


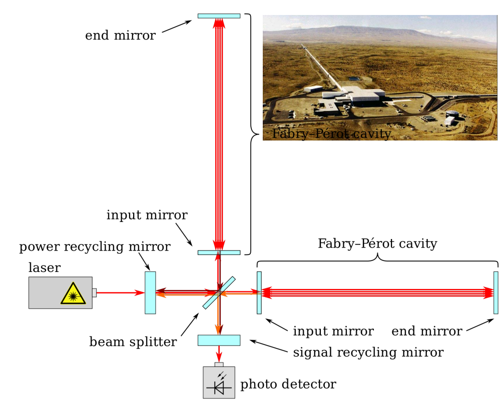
Gravitational waves: looking ahead

- Confirmed observations in two frequency ranges









- ESA has now formally adopted the LISA mission

  ⇨ *Large potential to probe new physics*

A concrete model

TB, Gonzalo, Kahlhoefer, Matuszak & Tasillo, JCAP '24

$$\mathcal{L} = |D_\mu \Phi|^2 - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2$$
$$+ \chi_L^\dagger i \not{D} \chi_L + \chi_R^\dagger i \not{D} \chi_R - y \Phi \chi_L^\dagger \chi_R - y \Phi^* \chi_R^\dagger \chi_L$$

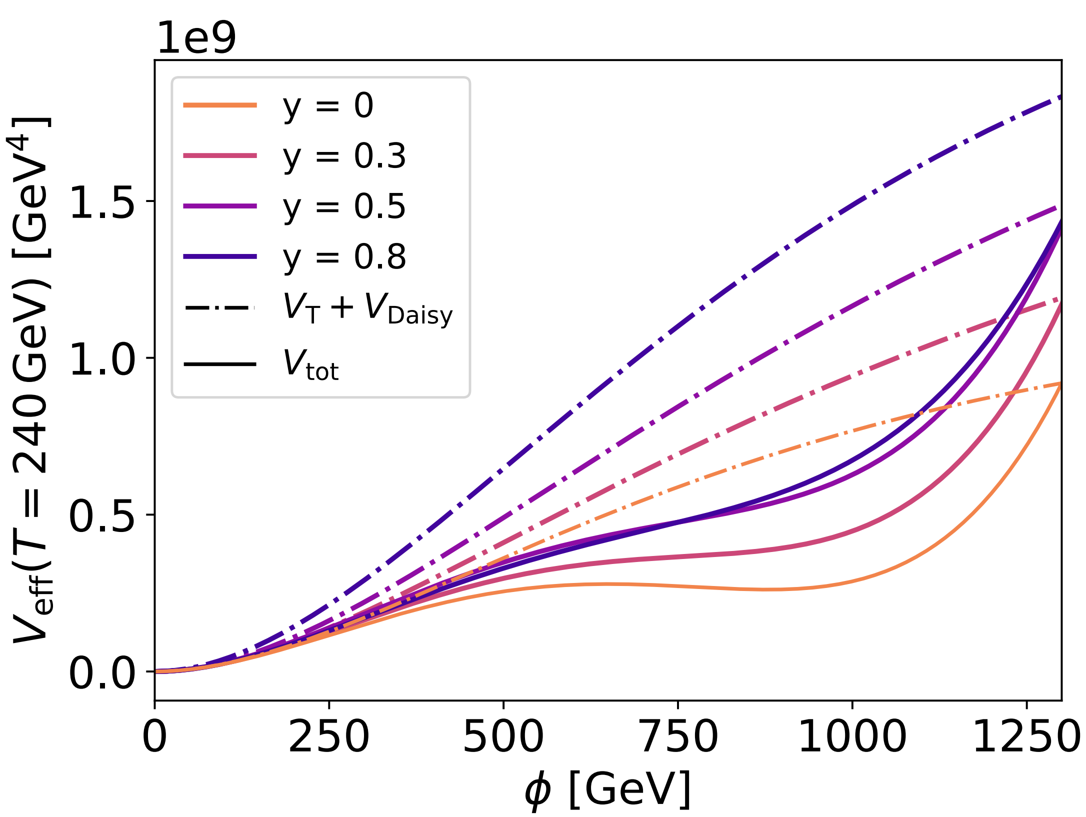
- scalar field charged under U(1)'
- (Chiral) dark matter fermion

→ (after PT) mass & thermal freeze-out

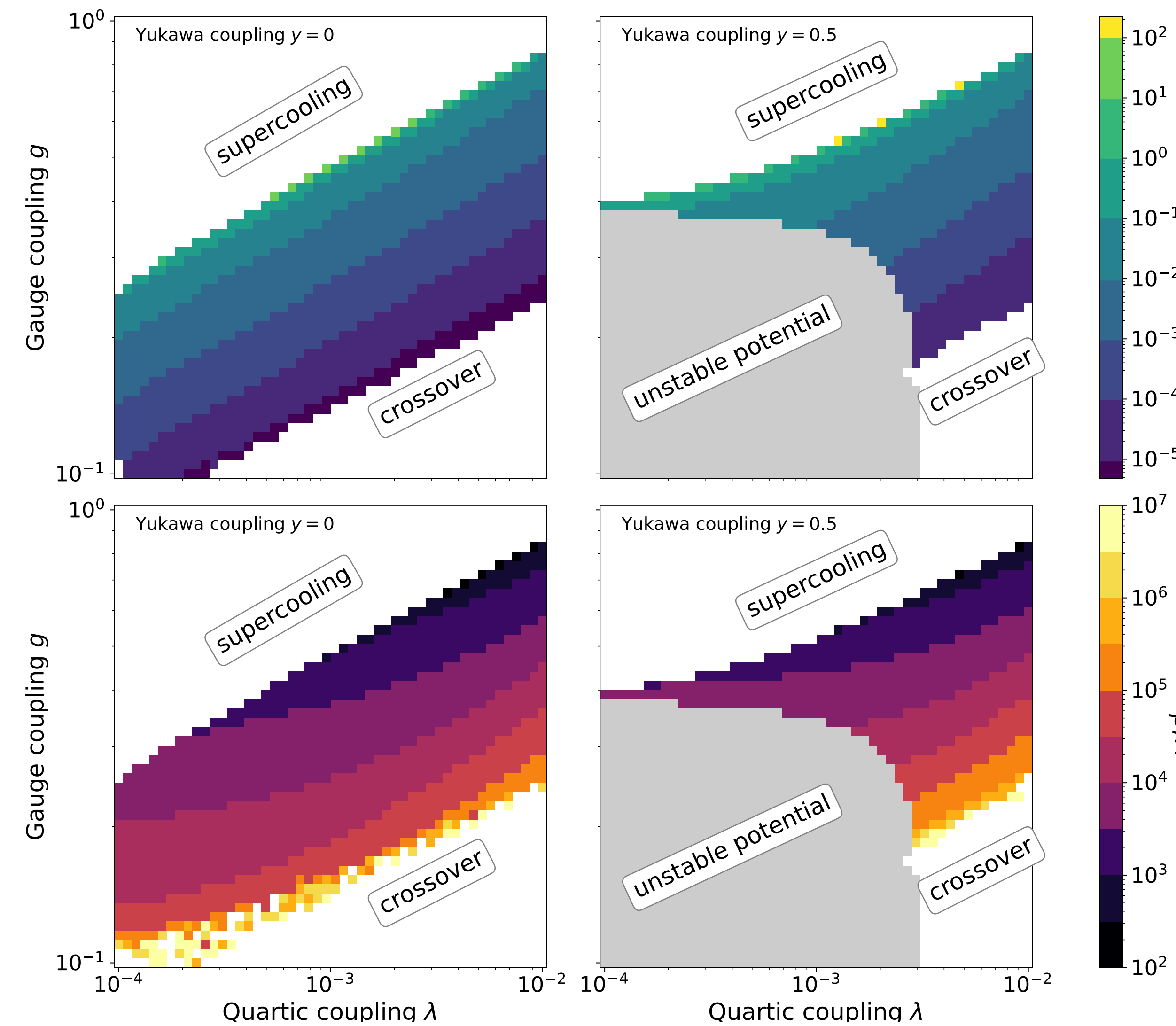
- tree-level masses from SSB:

$$m_\phi^2 = -\mu^2 + 3\lambda v_\phi^2 = 2\lambda v_\phi^2, \quad m_\varphi^2 = 0, \quad m_{A'}^2 = g^2 v_\phi^2, \quad m_\chi^2 = \frac{y^2}{2} v_\phi^2$$

- loop (CW) + thermal corrections:



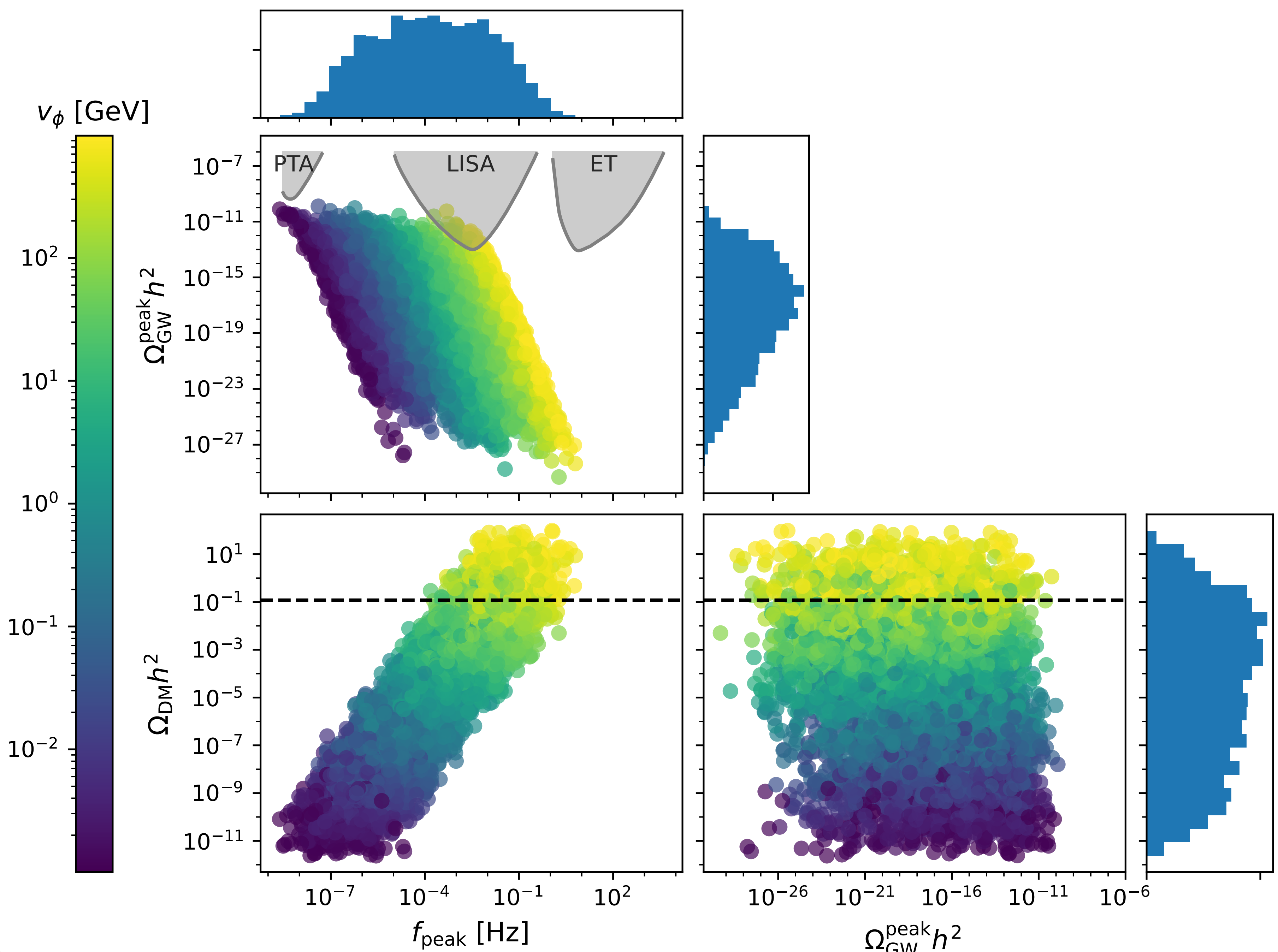
$g = 0.67, \lambda = 0.0035, v_\phi = 1000\,\text{GeV}$ and $T = 240\,\text{GeV}$



A LISA miracle ?

TB, Gonzalo, Kahlhoefer, Matuszak & Tasillo, JCAP '24

- Striking correlation between GW peak frequency and DM abundance



- Why ??
  - strong PT + large GW signal

    $g \sim \lambda \sim \mathcal{O}(1) \rightsquigarrow m_\phi \sim v_\phi$
  - freeze-out

    $m_\chi \gtrsim m_\phi, m_{A'} \rightsquigarrow y \gtrsim 0.1$

    $\Omega_{DM} \simeq 0.1 \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\langle\sigma_{ann}v\rangle}$

    $\langle\sigma_{ann}v\rangle \sim \frac{y^4}{m_{DM}^2} \sim \frac{y^2}{v_\phi^2}$

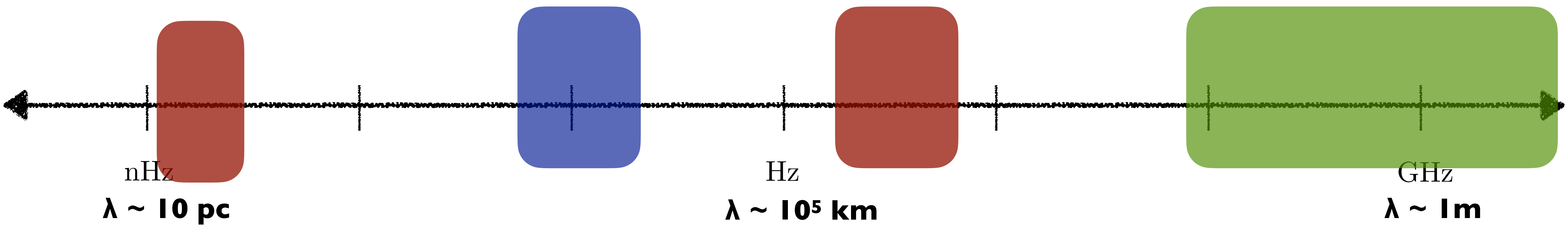
    $\rightsquigarrow v_\phi \sim \mathrm{TeV}$
  - $f_{peak} \simeq 10\,\mathrm{mHz}\left(\frac{\beta/H}{100}\right)\left(\frac{T_p}{1\,\mathrm{TeV}}\right)$

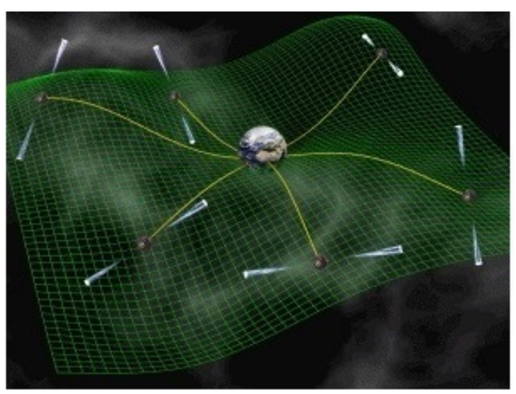
    $\sim 10\,\mathrm{mHz}\left(\frac{v_\phi}{1\,\mathrm{TeV}}\right)$

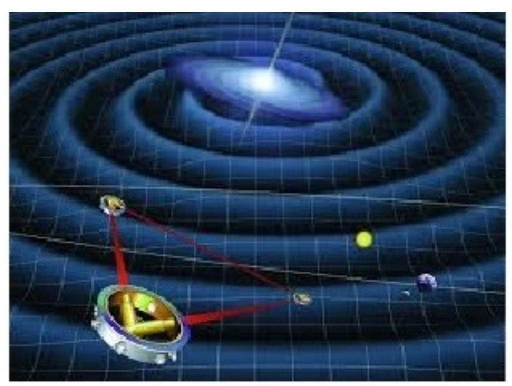
    for (not too strong) supercool PT

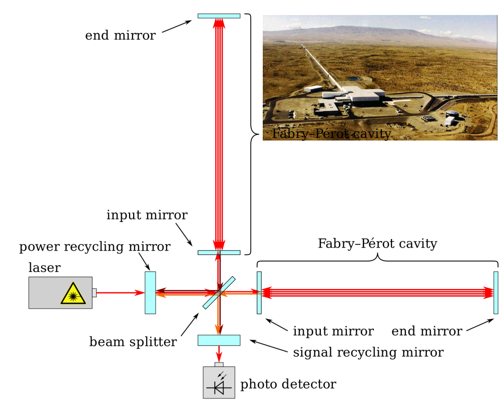
Gravitational waves: science fiction (?)

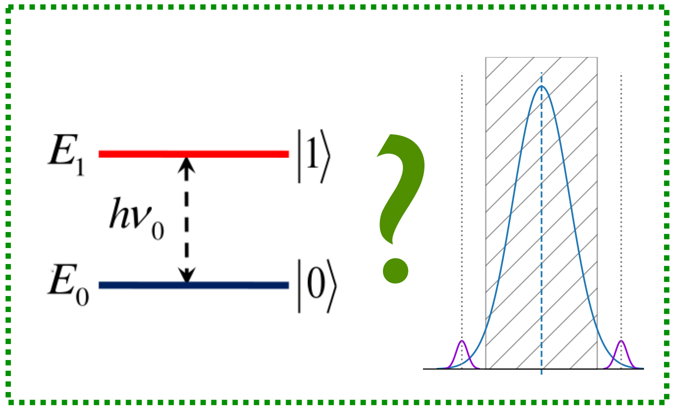
- Confirmed observations in two frequency ranges











- ESA has now formally adopted the LISA mission
- Some recent interest in exploring ultra-high frequency GWs
  - Table-top GW detectors ?
  - No known sources — smoking gun for new physics

Optical Frequency modulation

TB, Domcke, Fuchs & Kopp, PRD '23

- Frequency measured by observer with 4-velocity u^μ :

$$\omega_\gamma = -g_{\mu\nu} p^\mu u^\nu$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
$$p^\mu = (\omega_0, \omega_0, 0, 0) + \delta p^\mu$$
$$u^\mu = (1, 0, 0, 0) + \delta u^\mu,$$

' *trivial* '

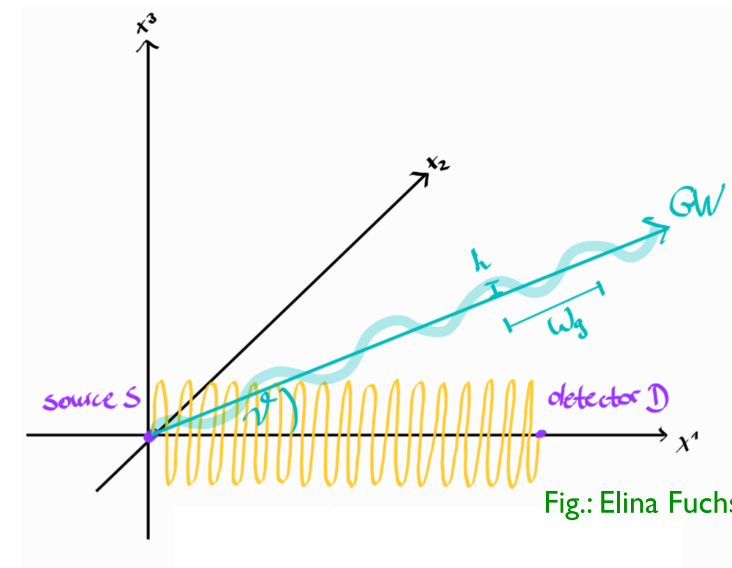
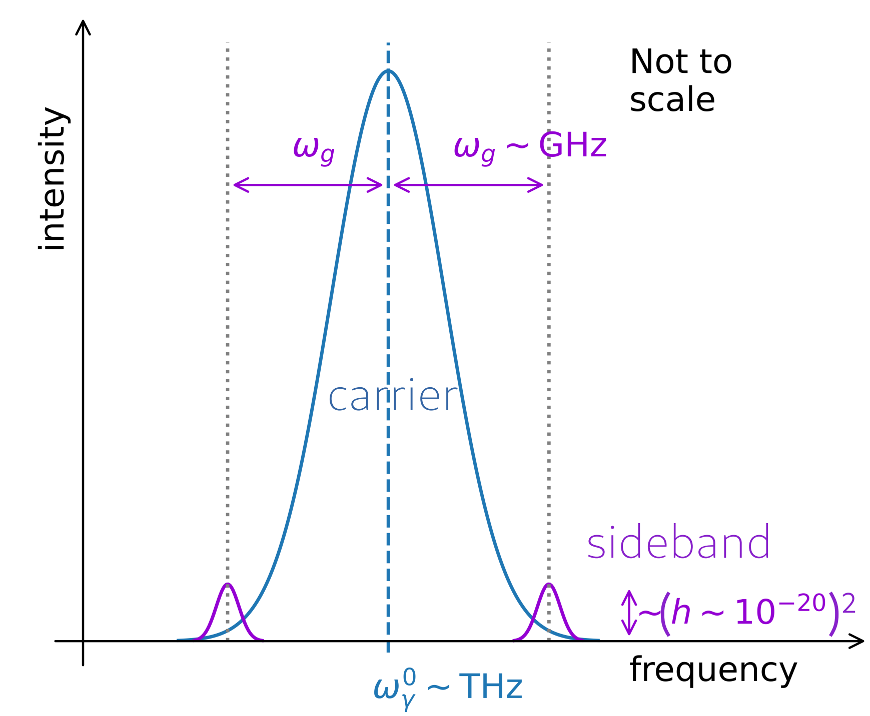


Fig.: Elina Fuchs

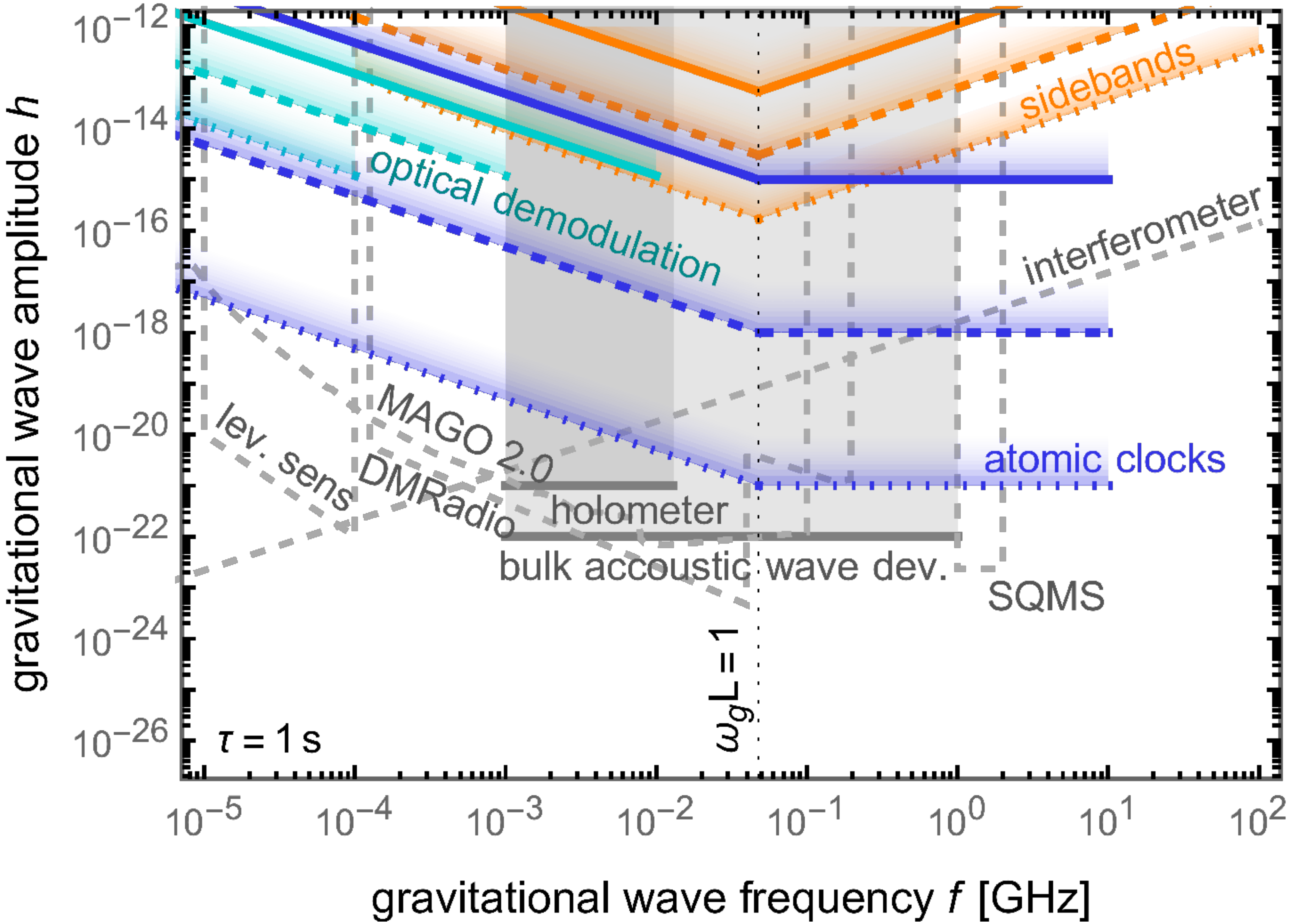
- Lessons learned:
  - Apparently, *nothing* is trivial…
  - Calculation in different frames shows intriguing cancellations
  - A rigid experimental setup $(\delta u^\mu = 0)$ naively gives frequency shifts $\propto (\omega_g L)^2$ … but a rigid ruler is impossible $\omega_g L \gg v_s$!

- Bottom line:
  - Signal with main (carrier) frequency ω_γ
  - Sidebands at $\omega_\gamma \pm \omega_g$
  - Tiny amplitudes $\sim h(\omega_\gamma/\omega_g)$



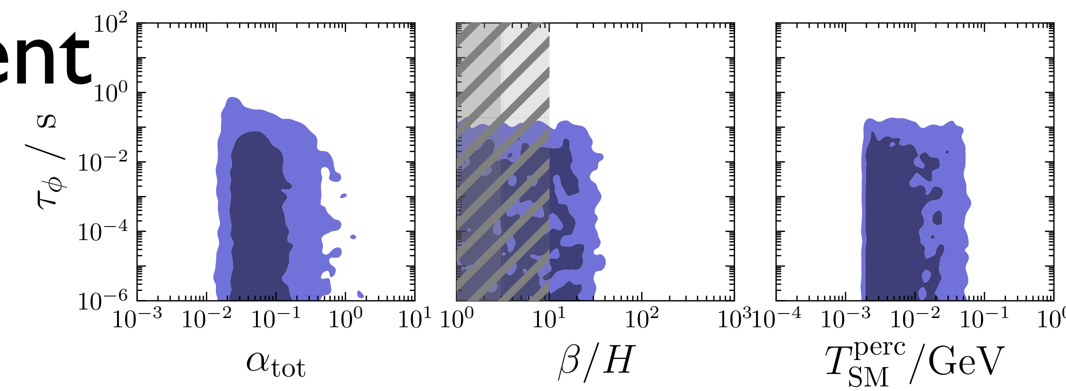
Sensitivities

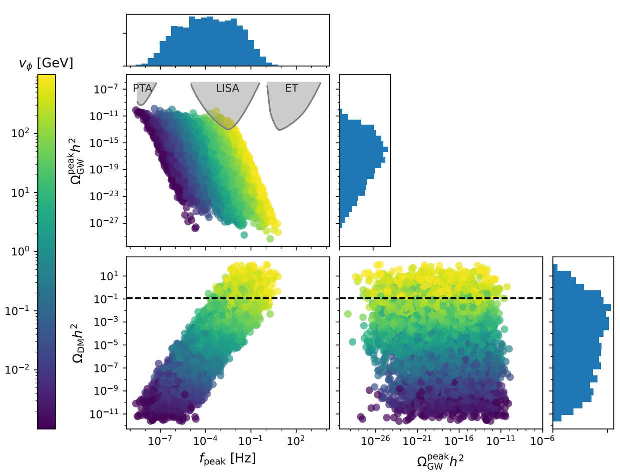
TB, Domcke, Fuchs & Kopp, PRD '23



Conclusions

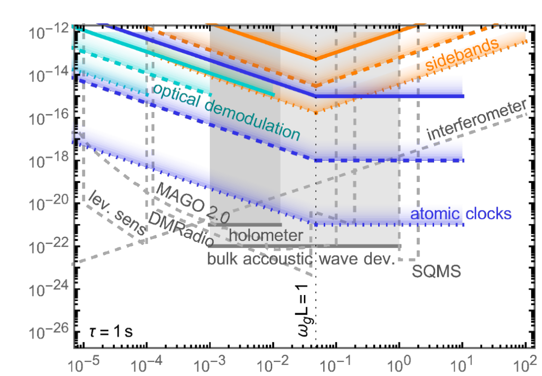
- The ***nHz*** GW background is consistent with a dark sector phase transition
  - but only if the dark sector is not 'too' dark !





- The observation of a ***mHz*** signal might indicate thermal dark matter production in a secluded dark sector
  - … the WIMP miracle in disguise?

- Rapid progress in developing ideas for 'table-top' detectors of ***GHz*** GWs
  - now we just need good ideas for signals…



Thanks for listening! Questions?