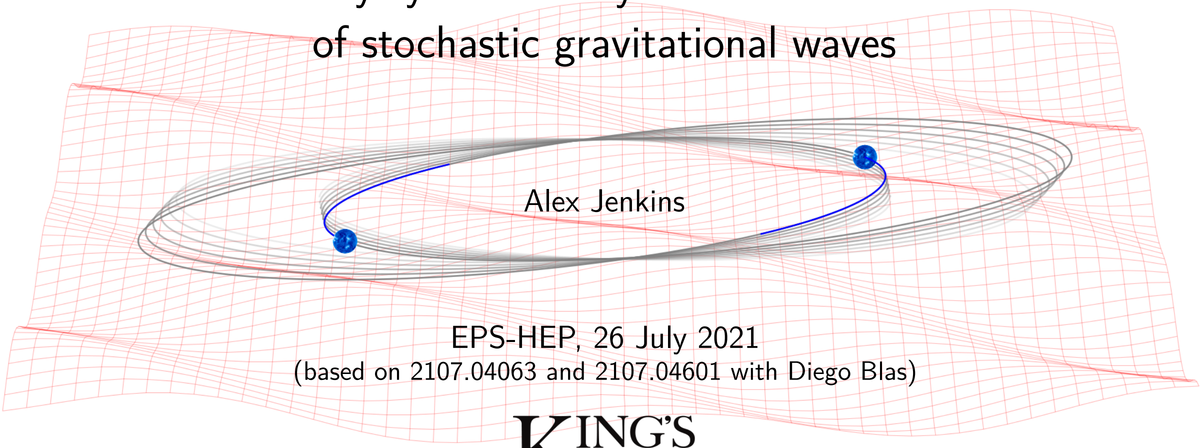
Binary systems as dynamical detectors of stochastic gravitational waves



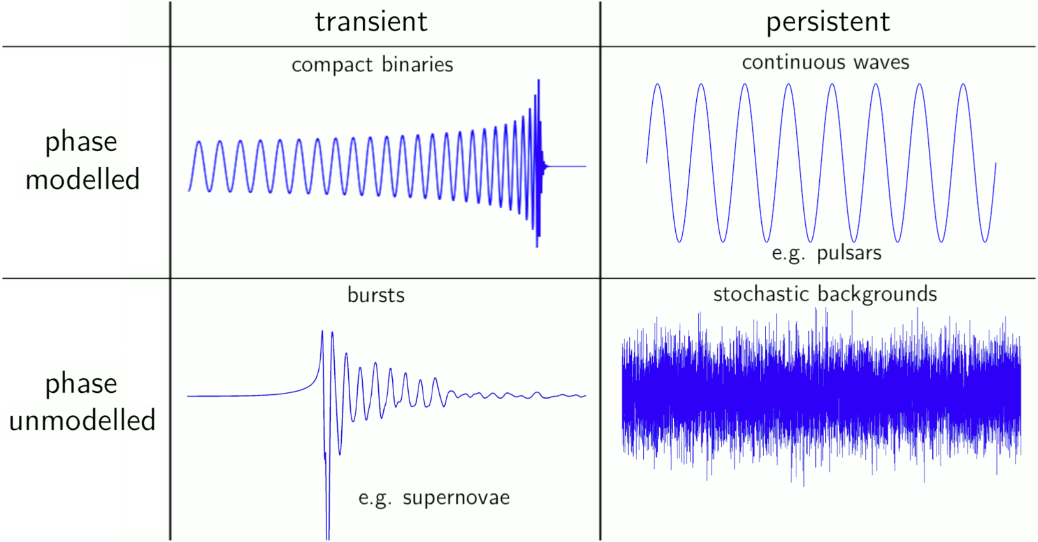
Alex Jenkins

EPS-HEP, 26 July 2021

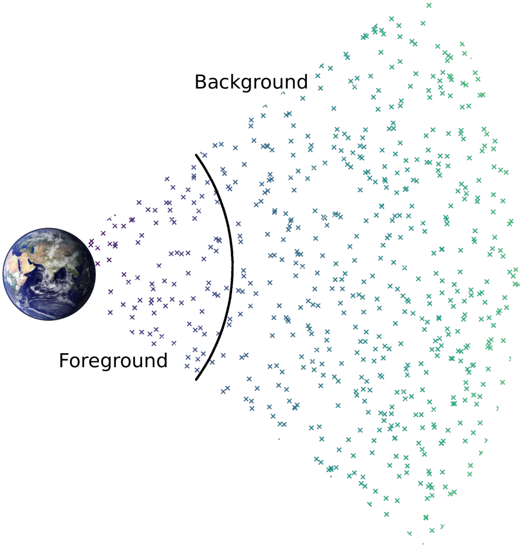
(based on 2107.04063 and 2107.04601 with Diego Blas)

KING'S College LONDON

A taxonomy of GW signals



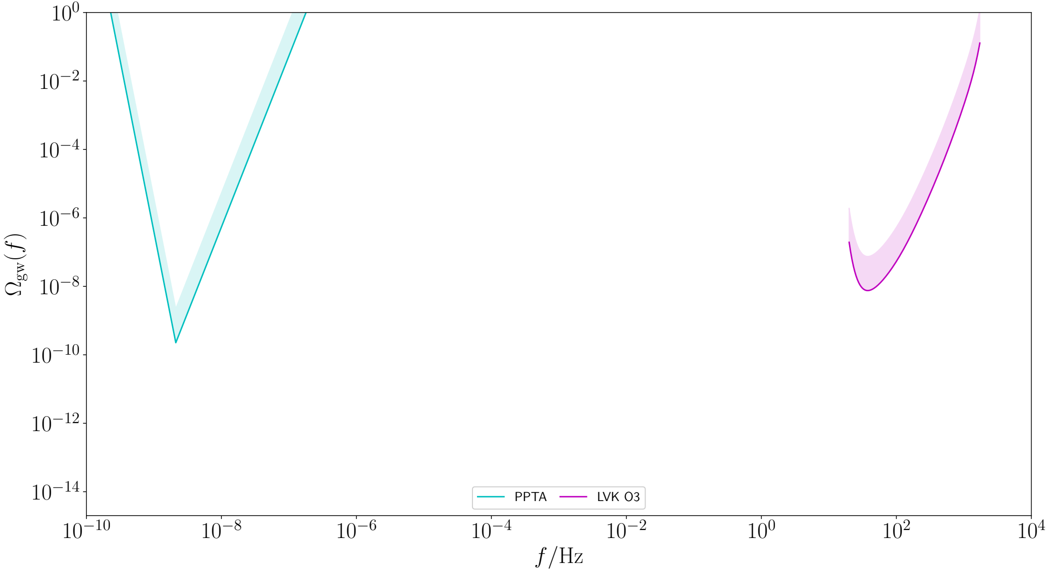
Stochastic gravitational-wave background (SGWB)



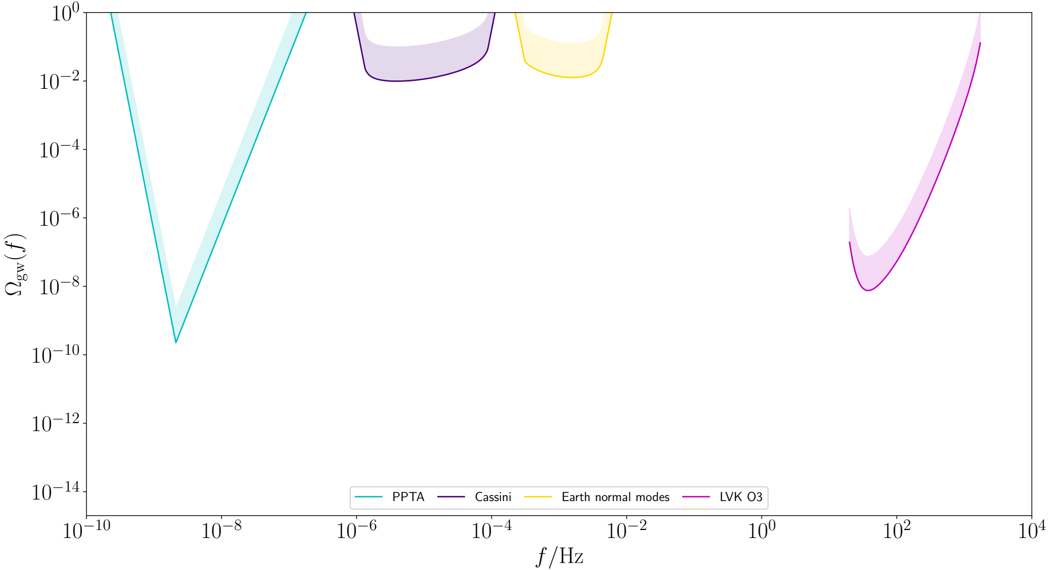
- incoherent, persistent GW signal
- faint/numerous sources
- astrophysical and cosmological
- GW density parameter:

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_{\mathrm{crit}}} \frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}(\ln f)}$$

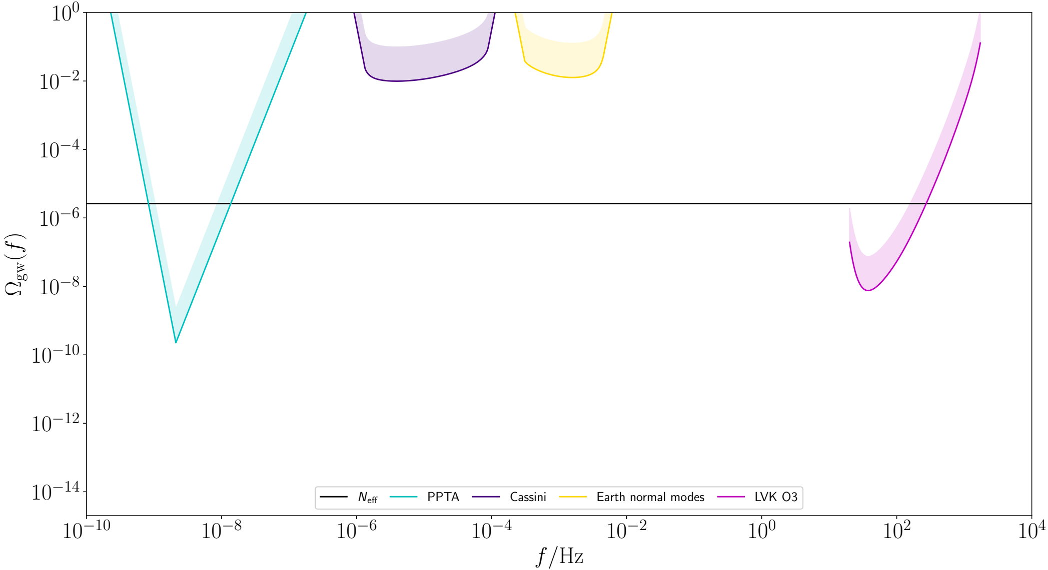
Current SGWB constraints



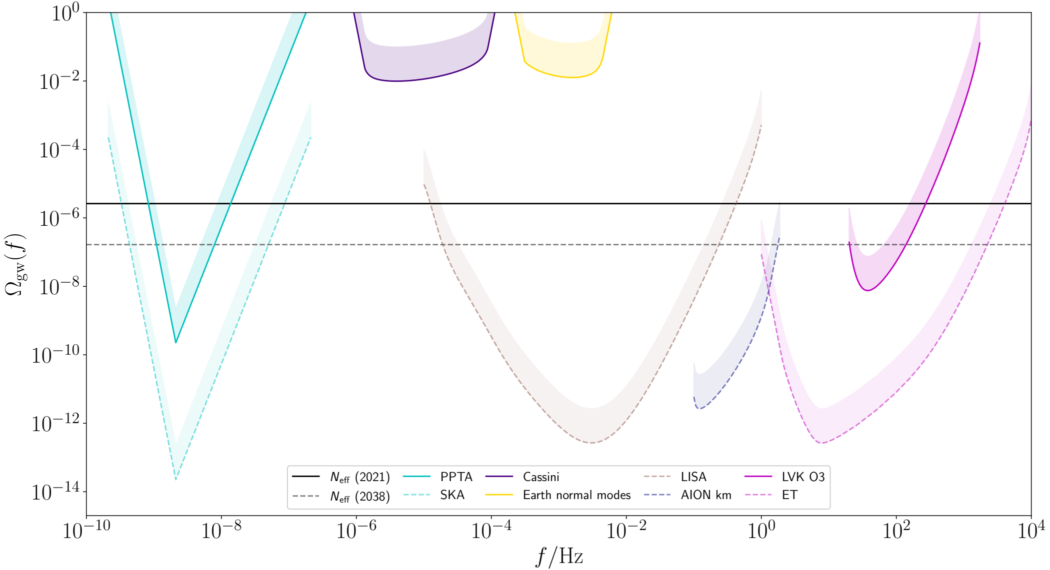
Current SGWB constraints



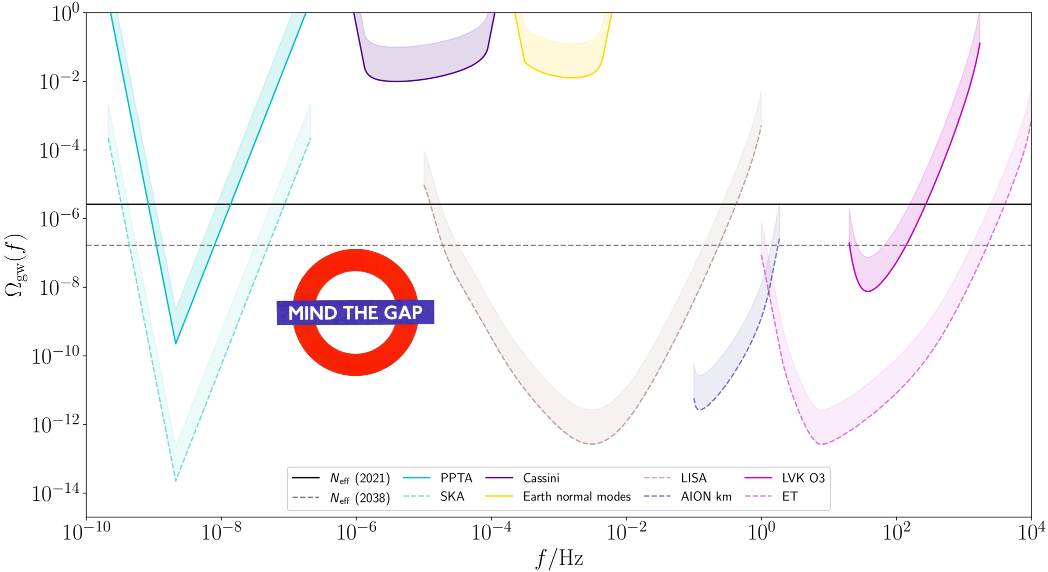
Current SGWB constraints



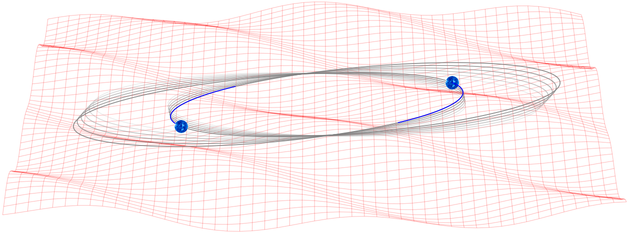
Future SGWB constraints



Future SGWB constraints



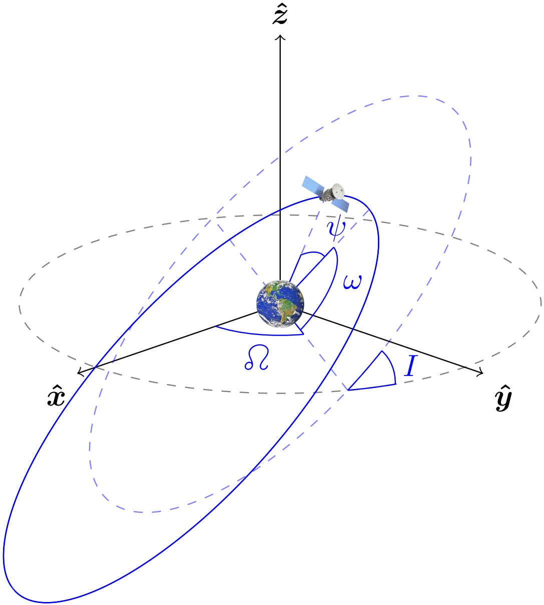
A way forward: binary resonance



- GWs cause oscillations between orbiting bodies
- resonant for frequencies $f = n/P$, where P is the period
- imprints on the orbit accumulate over time

Orbital elements

- **period** P**, eccentricity** e:
  size and *shape* of orbit
- **inlination** I**, ascending node** Ω:
  orientation in space
- **pericentre** ω**,**
  mean anomaly at epoch ε:
  radial and angular *phases*



Binary resonance: a brief history

discussed by Misner, Thorne, and Wheeler. . .

1. The Relative Motions of Two Freely Falling Bodies

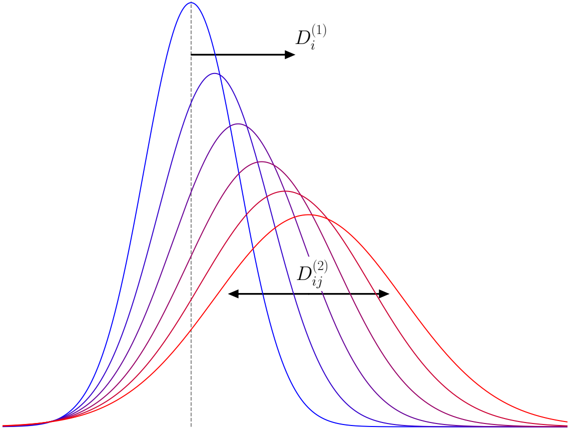
As a gravitational wave passes two freely falling bodies, their proper separation oscillates (Figure 37.3). This produces corresponding oscillations in the redshift and round-trip travel times for electromagnetic signals propagating back and forth between the two bodies. Either effect, oscillating redshift or oscillating travel time, could be used in principle to detect the passage of the waves. Examples of such detectors are the Earth-Moon separation, as monitored by laser ranging [Fig. 37.2(a)]; Earth-spacecraft separations as monitored by radio ranging; and the separation between two test masses in an Earth-orbiting laboratory, as monitored by redshift measurements or by laser interferometry. Several features of such detectors are explored in exercises 37.6 and 37.7. As shown in exercise 37.7, such detectors have so low a sensitivity that they are of little experimental interest.

. . . but that was *50 years ago!*

investigated more recently by Lam Hui *et al*, PRD (2013),
similar ideas used to search for dark matter by Blas *et al*, PRL (2017)

time for a closer look?

Our new approach



- track distribution function $W(\boldsymbol{X}, t)$ of orbital elements $\boldsymbol{X} = (P, e, I, \Omega, \omega, \varepsilon)$
- evolves through *Fokker-Planck eqn.*

$$\frac{\partial W}{\partial t} = -\frac{\partial}{\partial X_i}\left(D_i^{(1)} W\right) + \frac{\partial}{\partial X_i}\frac{\partial}{\partial X_j}\left(D_{ij}^{(2)} W\right)$$

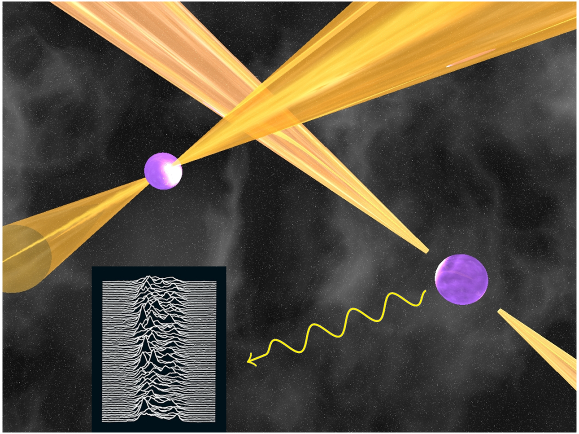
- *drift* and *diffusion* coefficients

$$D_i^{(1)}(\boldsymbol{X}) = V_i(\boldsymbol{X}) + \sum_{n=1}^{\infty} \mathcal{A}_{n,i}(\boldsymbol{X}) \Omega_{\mathrm{gw}}(n/P)$$

$$D_{ij}^{(2)}(\boldsymbol{X}) = \sum_{n=1}^{\infty} \mathcal{B}_{n,ij}(\boldsymbol{X}) \Omega_{\mathrm{gw}}(n/P)$$

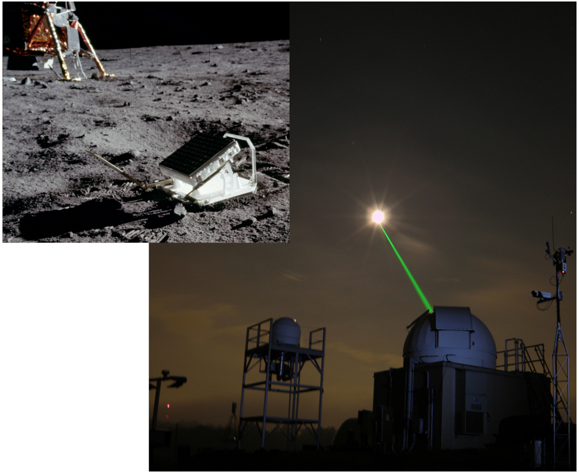
Two binary probes

timing of binary pulsars



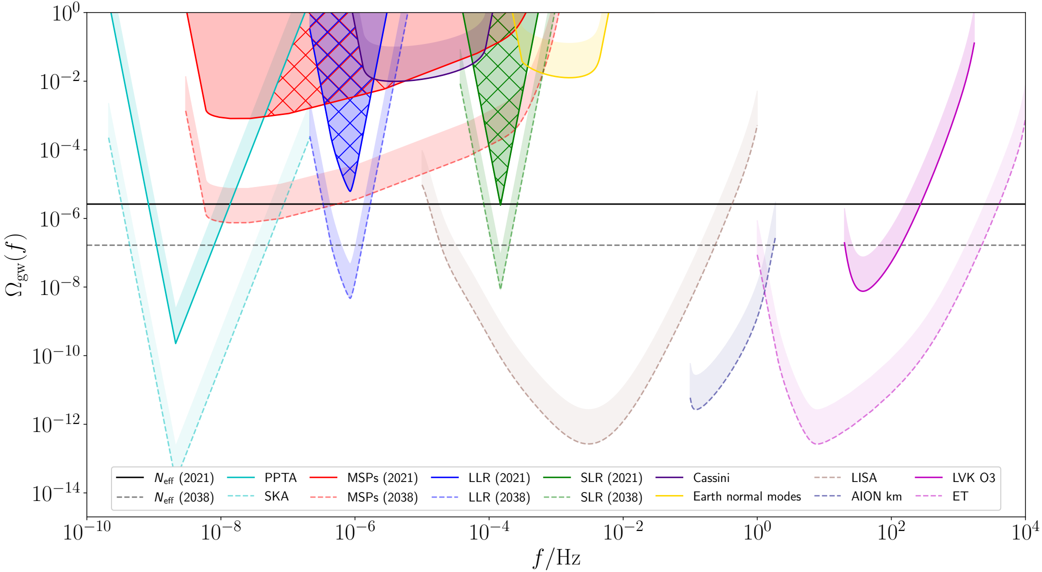
(pulsar animation credit: Michael Kramer)

lunar and satellite laser ranging

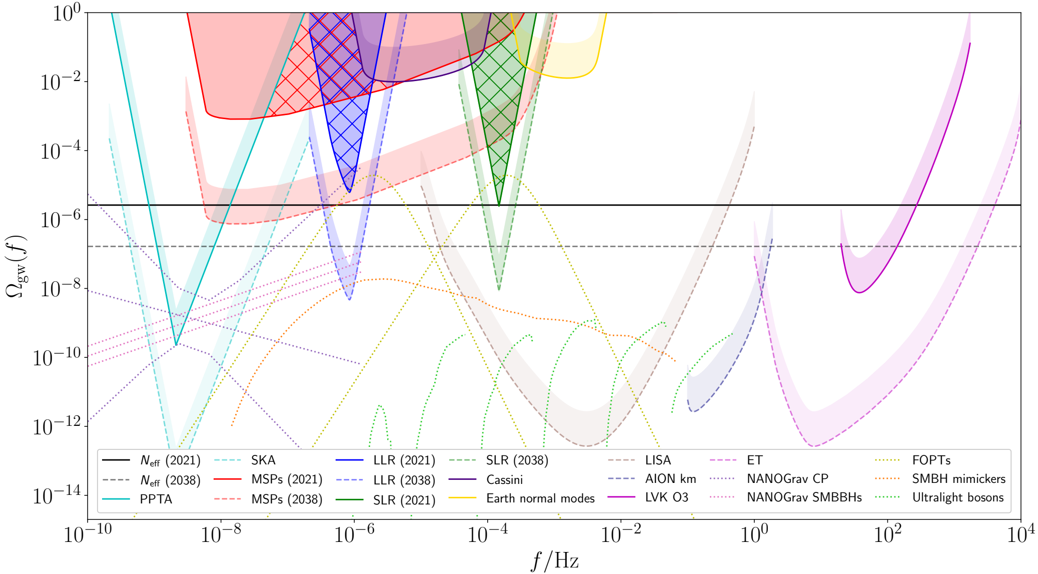


(image credit: NASA)

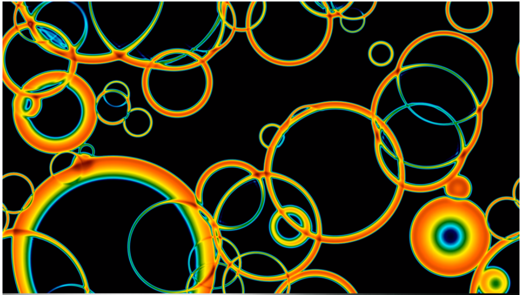
Our forecast constraints



Signals in the μHz band



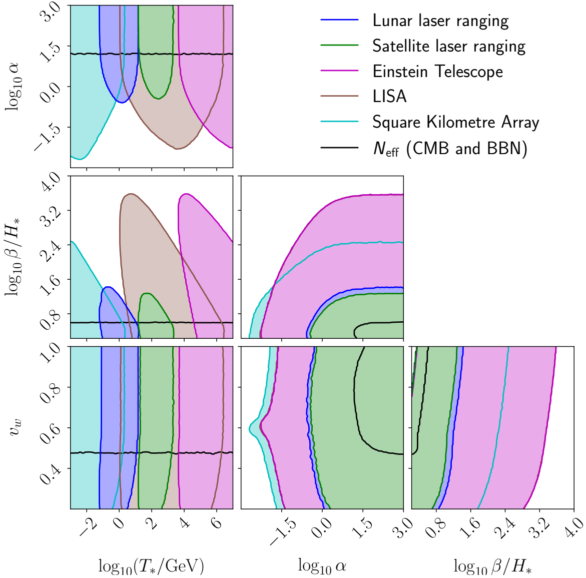
An example signal: cosmological phase transitions



- key prediction of many particle physics models
- four parameters:
  - temperature T_*
  - strength α
  - rate β/H_*
  - bubble-wall velocity v_w
- peak frequency

$$f_* \approx 19\,\mu\mathrm{Hz} \times \frac{T_*}{100\ \mathrm{GeV}} \frac{\beta/H_*}{v_w}$$

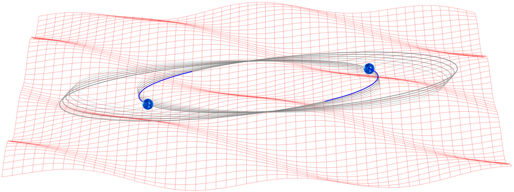
Phase transition constraints



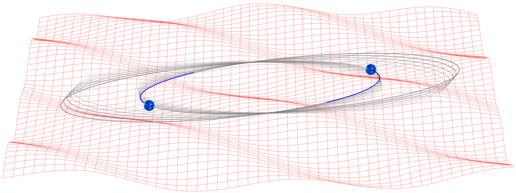
Summary and outlook

- binary resonance can probe a unique GW frequency band
- we have developed a powerful new formalism
- unique constraints on phase transitions (and more)
- plenty more work to do! more signals, more systems, plus running on real data

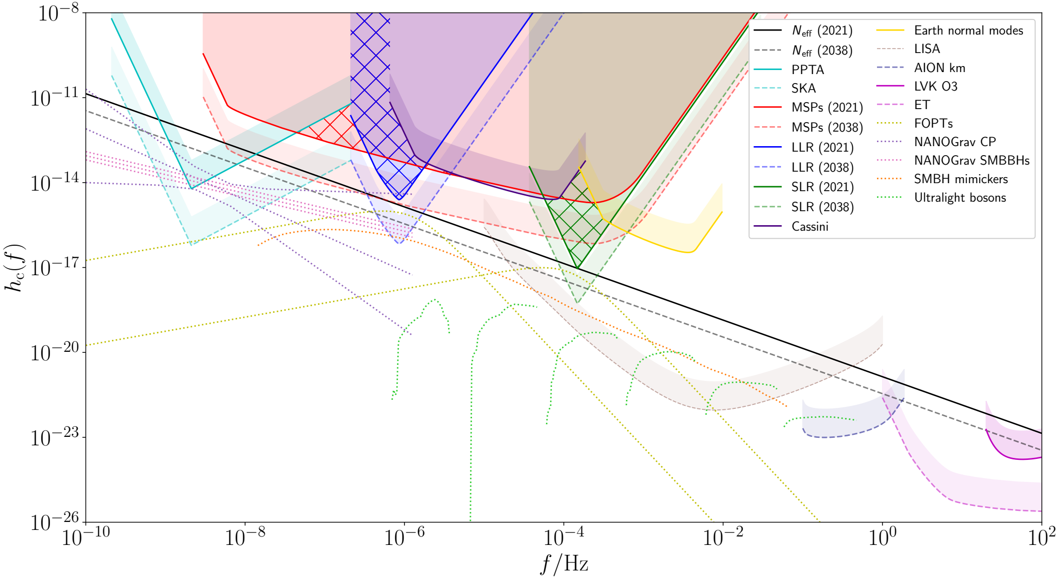
thanks for listening!



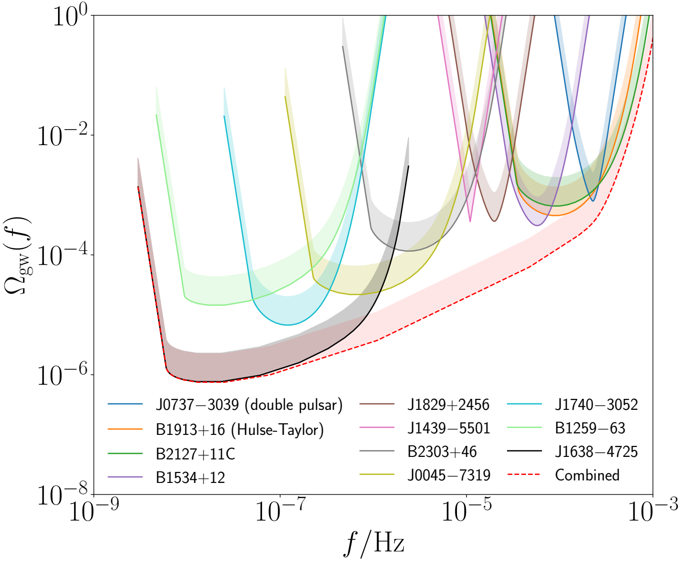
Backup Slides



Characteristic strain

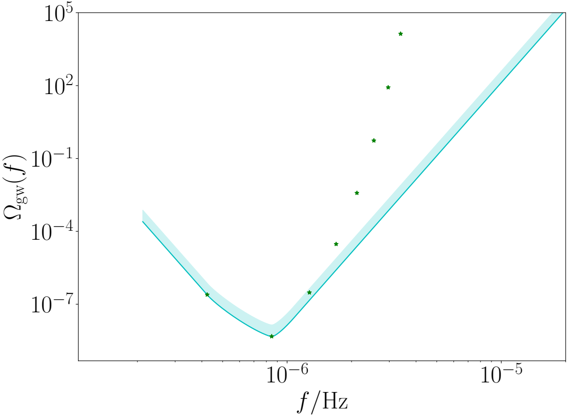


Combining binary pulsar bounds

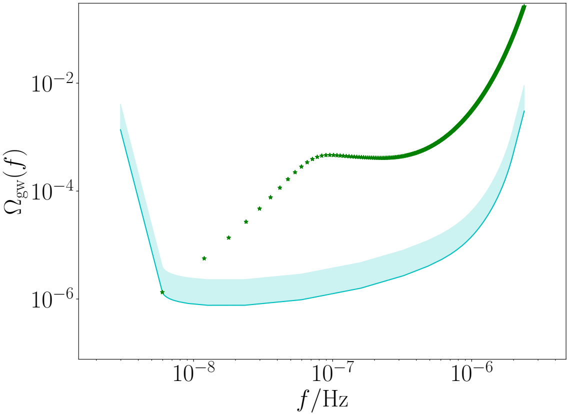


Power-law sensitivity vs. monochromatic sensitivity

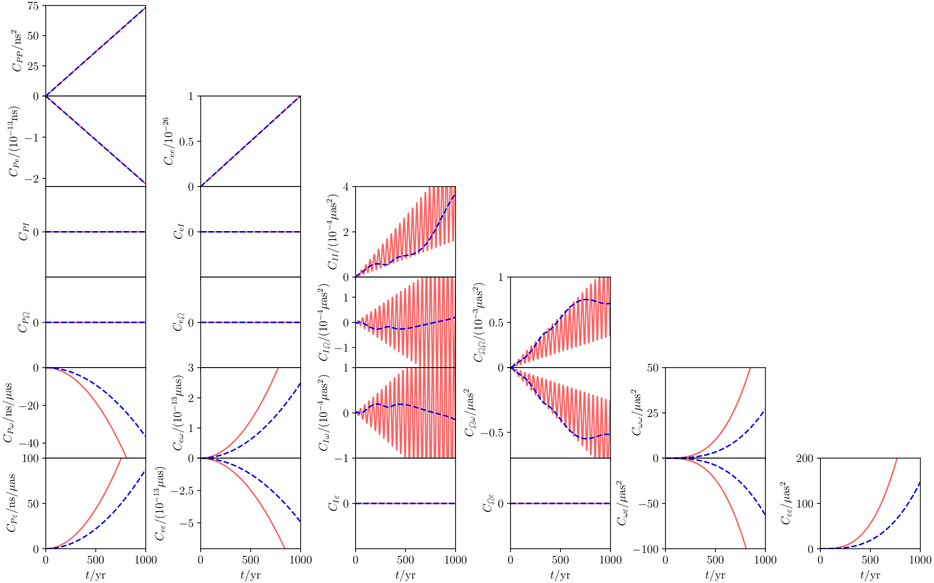
lunar laser ranging, $e \approx 0.055$



pulsar timing (J1638-4725), $e \approx 0.955$



Covariance matrix over time



Solar system bounds