Title: Bridging gaps in the spectrum of GWs: new opportunities for fundamental physics.

Speakers: Diego Blas

Series: Particle Physics

Date: January 24, 2023 - 1:00 PM

URL: https://pirsa.org/23010058

Abstract: In this talk I'll highlight the existence of gaps in the spectrum of GWs poorly explored by current observations and that may contain information about BSM physics or primordial cosmology. I'll focus on the muHz gap, and explain how to use the resonance absorption of GWs by binary systems (as the Earth-Moon system or binary pulsars) to access this band. I'll also highlight the potential of high frequency (\omega > kHz) GWs. The focus of this second part will be the use of cavities to detect these signals, together with a brief discussion of sources and what can be learned from them.

Zoom Link: https://pitp.zoom.us/j/94501758748?pwd=amFsTjV5Z1c5SHJrVVBCanVCRHRMUT09

Bridging gaps in the spectrum of GWS:
new opportunities for fundamental physics

Diego Blas

based on 2107.04063/2107.04601 (PRL/PRD22), 2112.11465 (PRD22) + ongoing (2301.xxxx?)

(w. Alex Jenkins // A. Berlin, DB, R. T. D'Agnolo, S. Ellis, R. Harnik, Y. Kahn, J. Schütte-Engel)

Universitat Autònoma de Barcelona

Barcelona Institute of Science and Technology

Ayuda Beatriz Galindo Senior
BG20/00228

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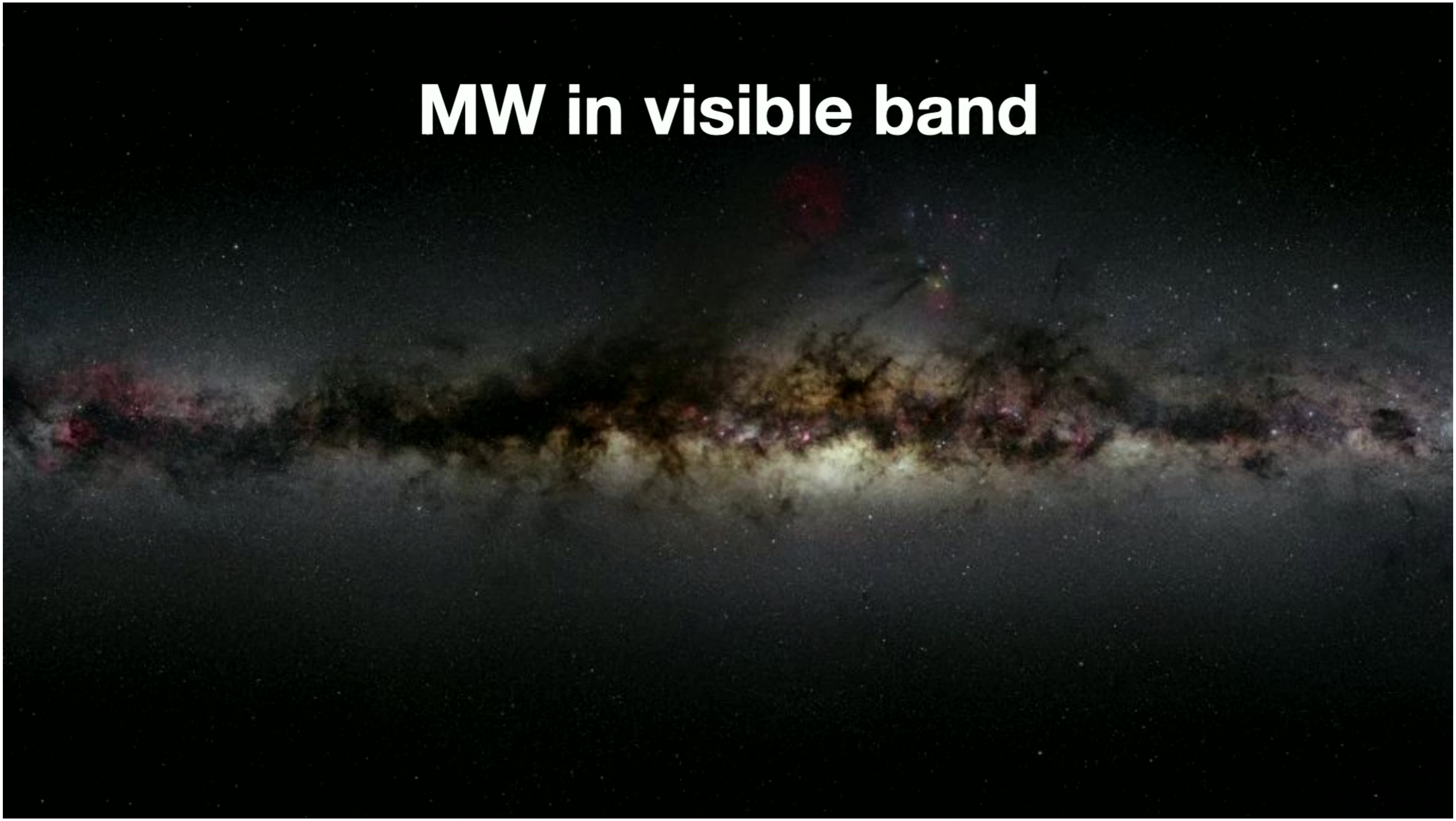
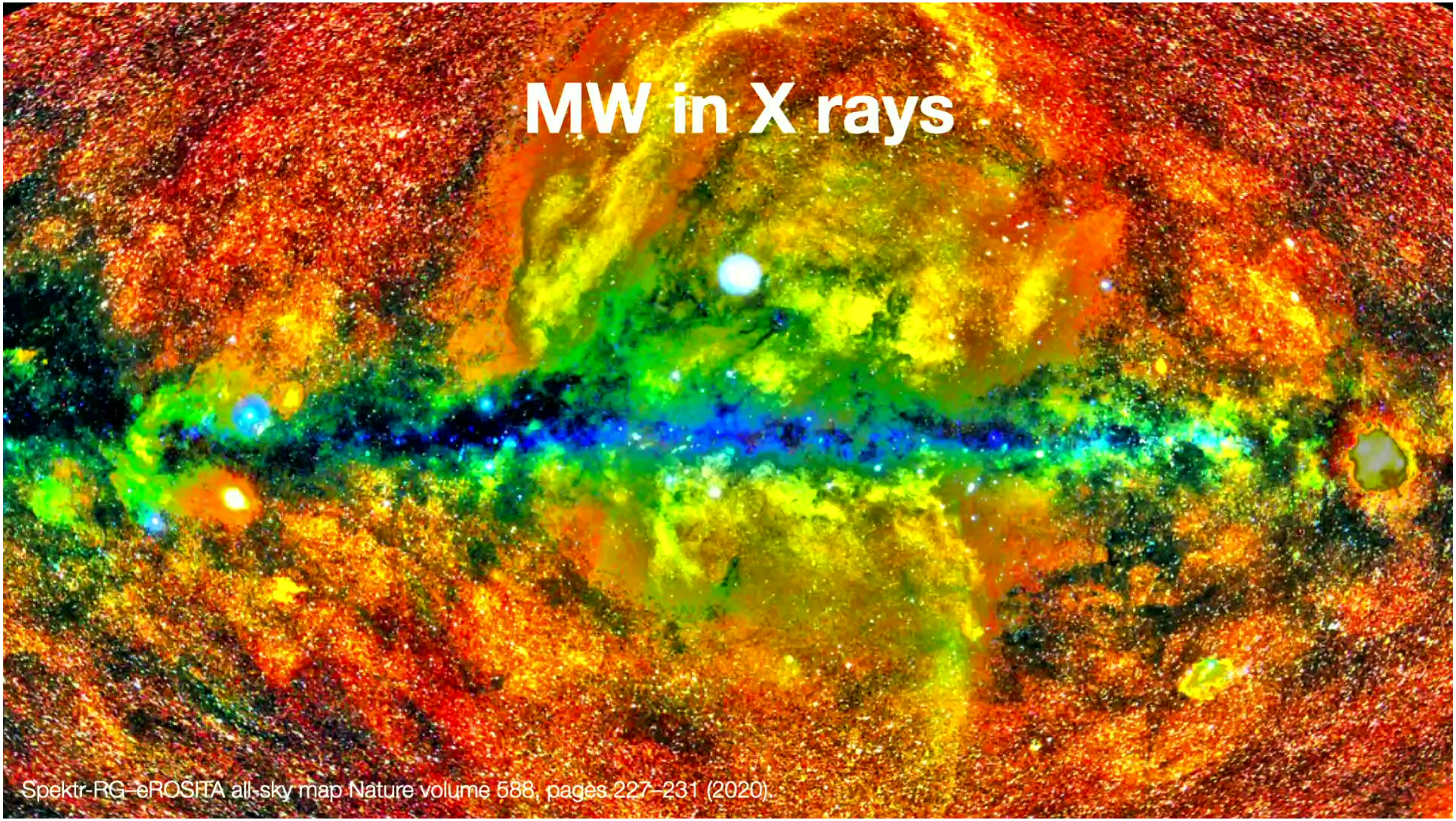
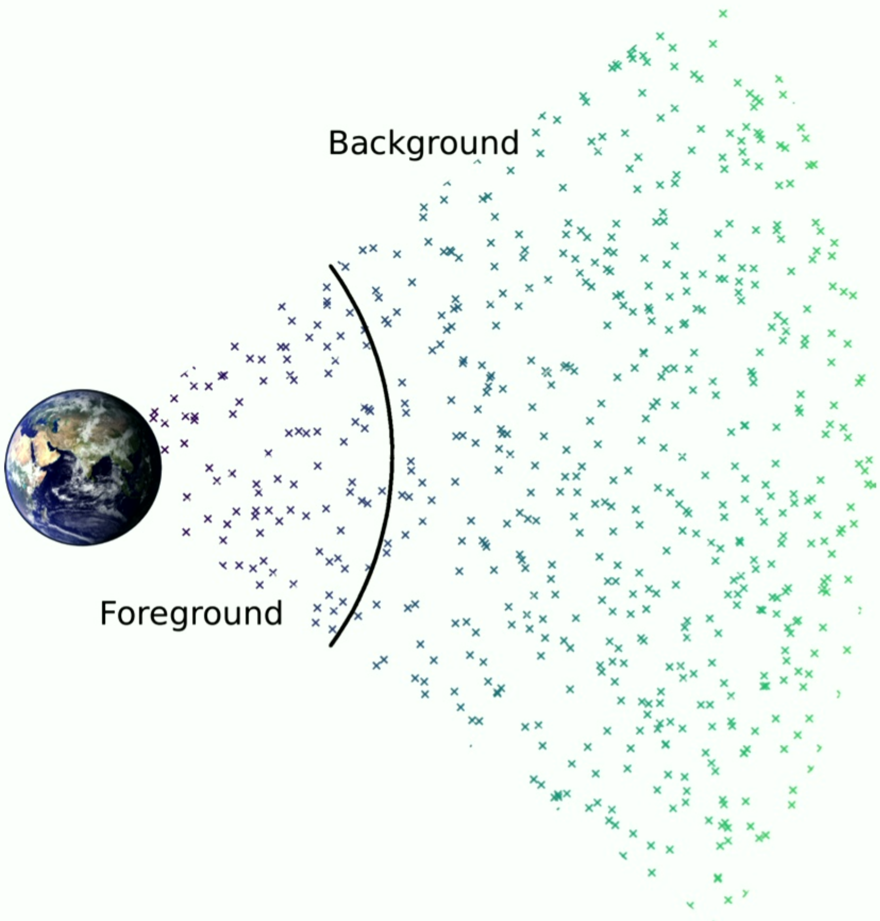

MW in visible band


MW in X rays
Spektr-RG eROSITA all-sky map Nature volume 588, pages 227–231 (2020).

GWs soundscape today

Stochastic gravitational-wave background (SGWB)



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

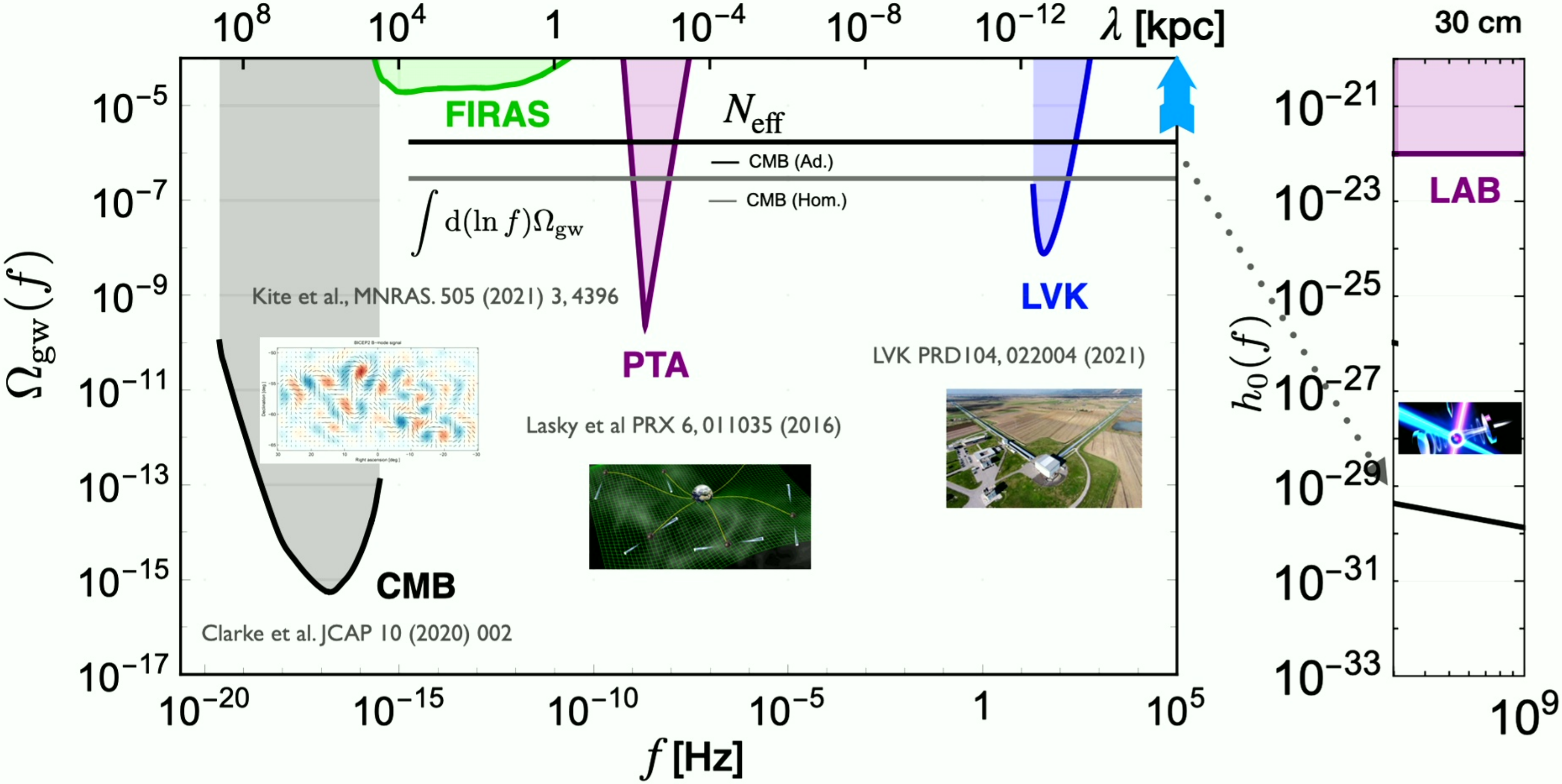
$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_{\mathrm{crit}}} \frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}(\ln f)}$$

$$\rho_{\mathrm{GW}} \sim M_P^2 \omega^2 h_{GW}^2$$

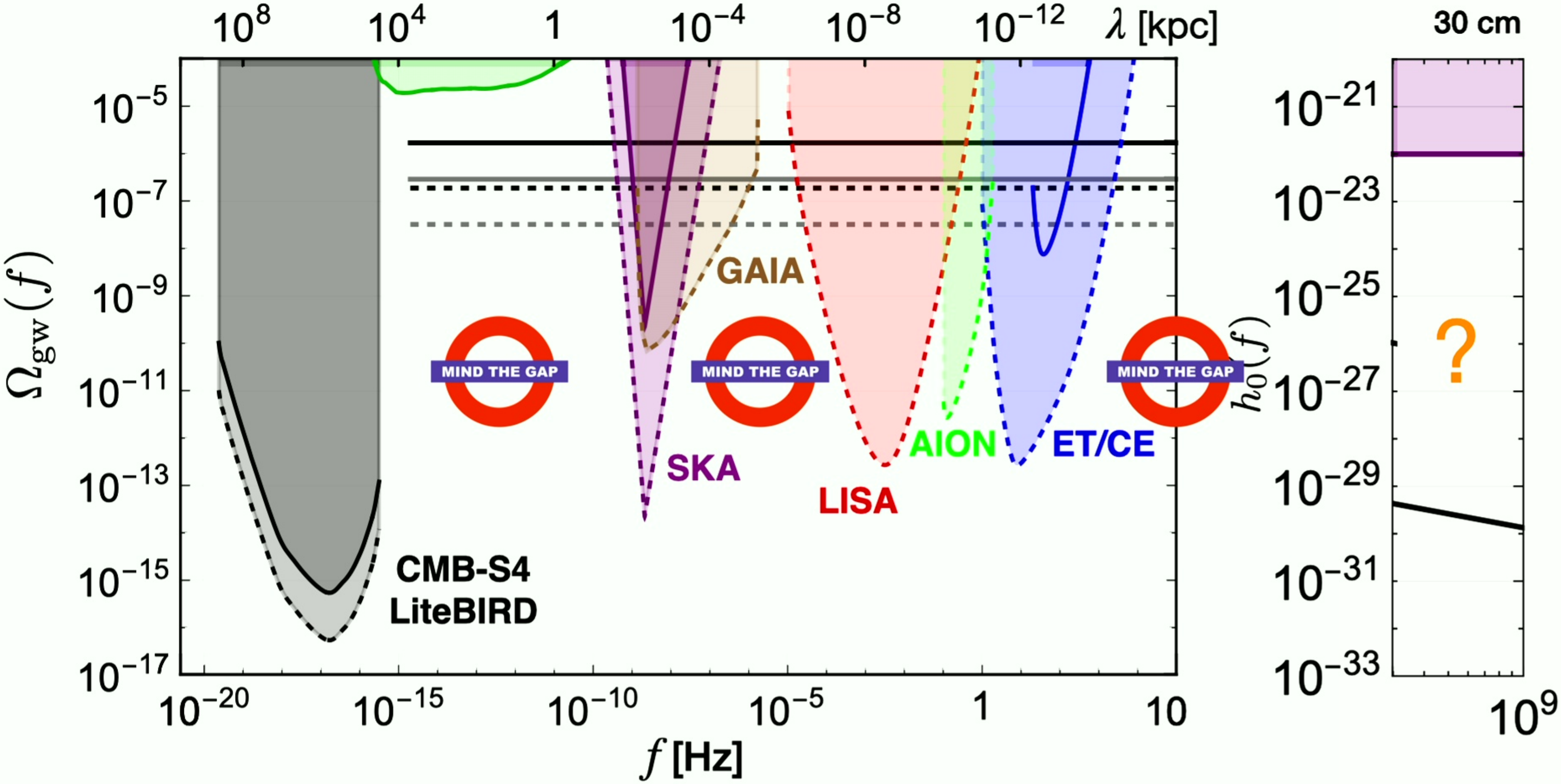
$$\rho_c = 1.2 \times 10^{11} M_{\odot} \mathrm{Mpc}^{-3}$$
$$\sim \mathrm{keV/cm}^3$$

dblas@ifae.es

GWs soundscape today



GWs soundscape ca. 2040



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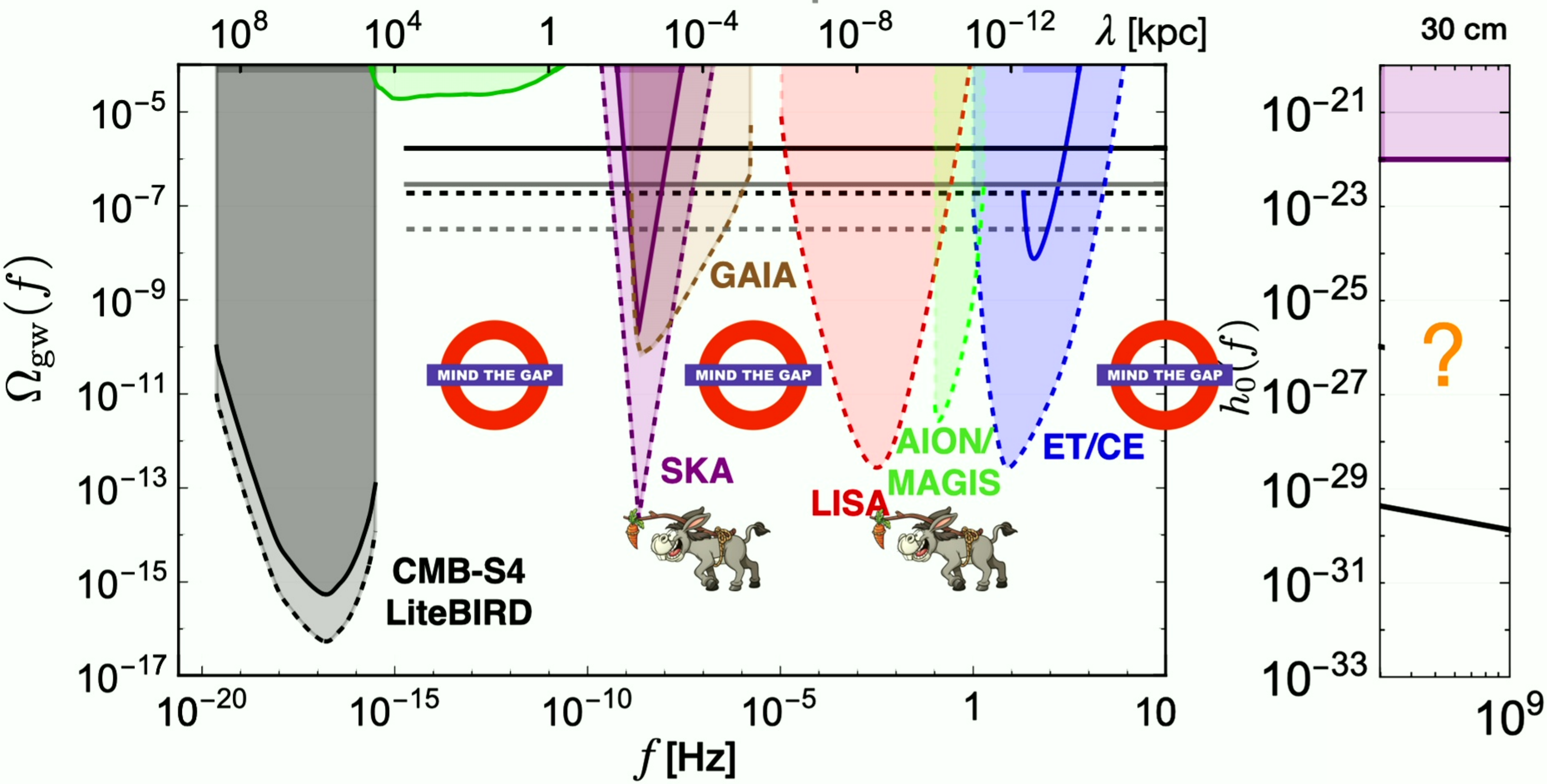

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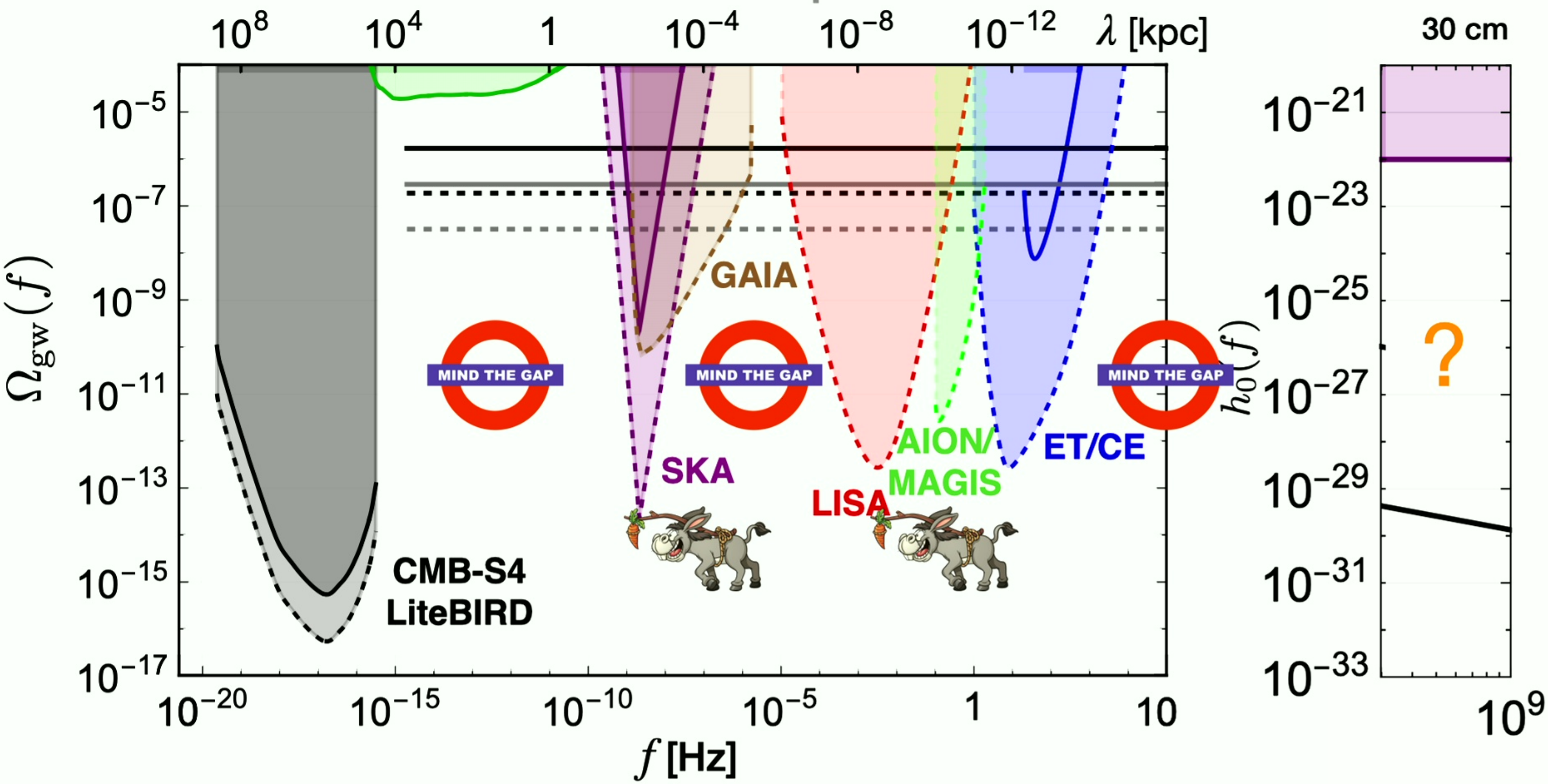

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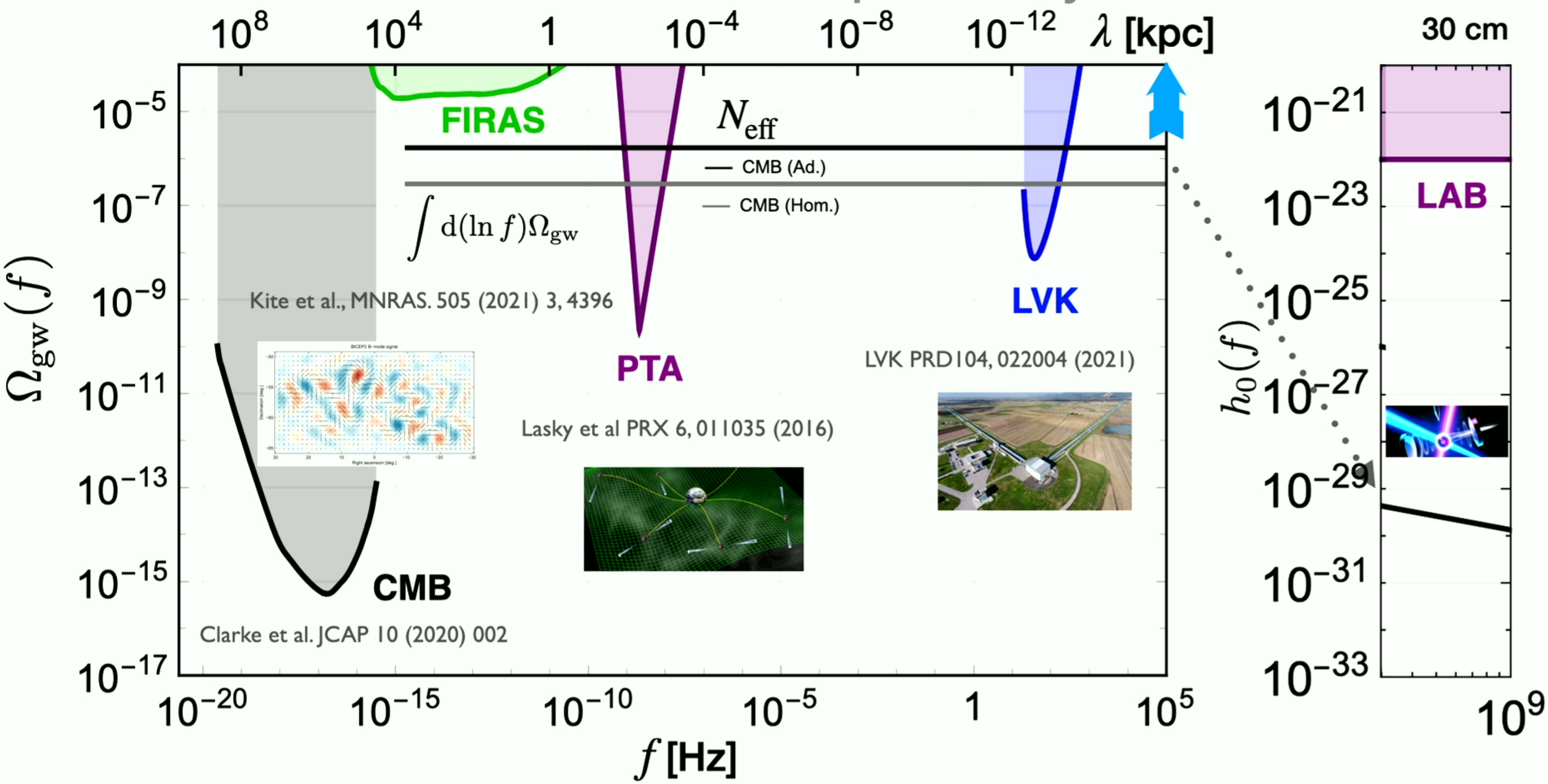
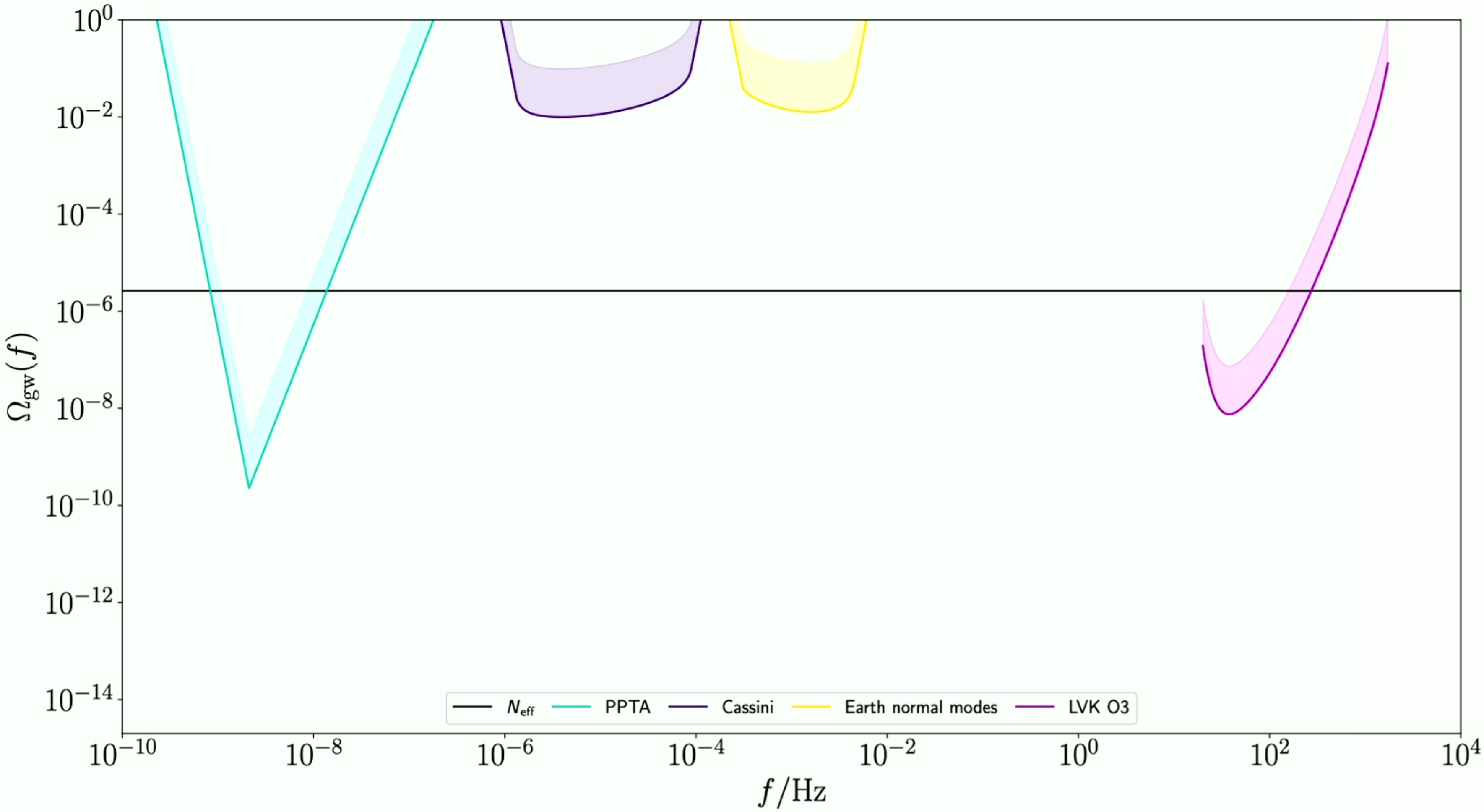


Current SGWB constraints



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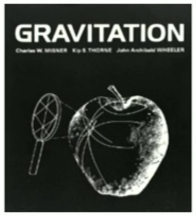
Absorption of GWs by binaries



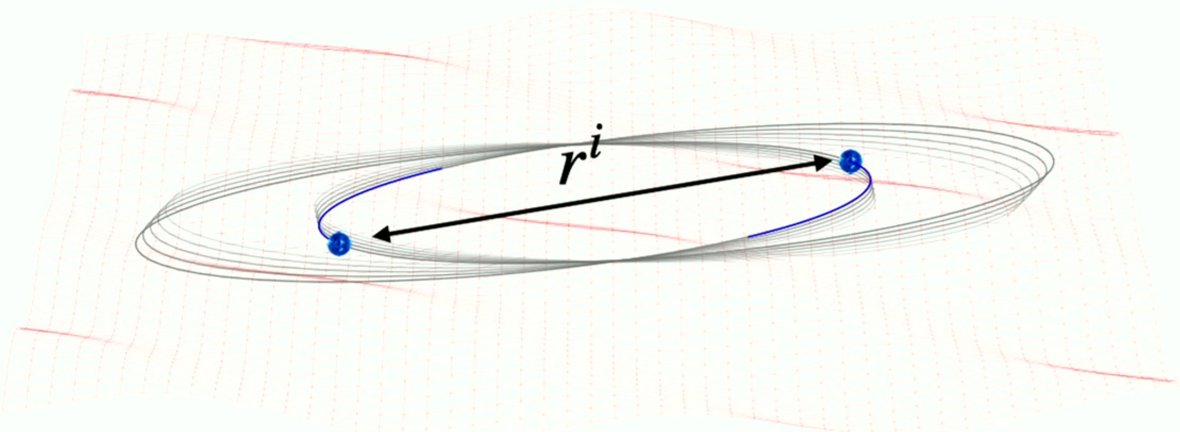
MWT
Hui et al 2013
DB, Lopez-Nacir, Sibiryakov 2017

Intuitive idea (from '60s)

Influence of a GW on a binary system (e.g. non-relativistic)

$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

Newtonian potential ⋯ GW

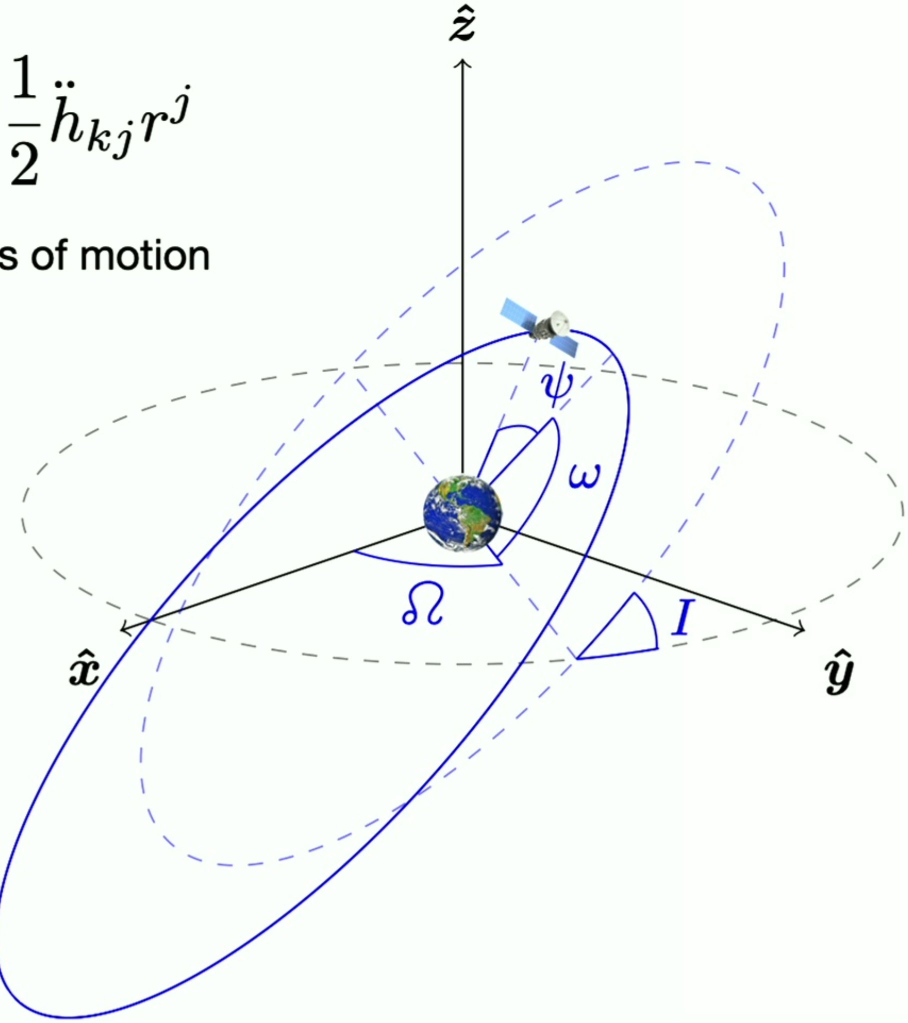


Absorption of GWs by binaries

$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

Better characterised for its 6 Newtonian constants of motion

- **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*



Absorption of GWs by binaries

$$\ddot{\boldsymbol{r}} + \frac{GM}{r^2}\hat{\boldsymbol{r}} = \boldsymbol{\delta}\ddot{\boldsymbol{r}}.$$

- for generic perturbation:

$$\boldsymbol{\delta}\ddot{\boldsymbol{r}} = r(\mathcal{F}_r\hat{\boldsymbol{r}} + \mathcal{F}_\theta\hat{\boldsymbol{\theta}} + \mathcal{F}_\ell\hat{\boldsymbol{\ell}}),$$

$$\dot{P} = \frac{3P^2\gamma}{2\pi}\left[\frac{e\sin\psi\mathcal{F}_r}{1+e\cos\psi} + \mathcal{F}_\theta\right],$$

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$$\dot{\varepsilon} = -\frac{P\gamma^4\mathcal{F}_r}{\pi(1+e\cos\psi)^2} - \gamma(\cos I\dot{\Omega} + \dot{\omega}),$$

For the SGWB… Fokker-Planck approach

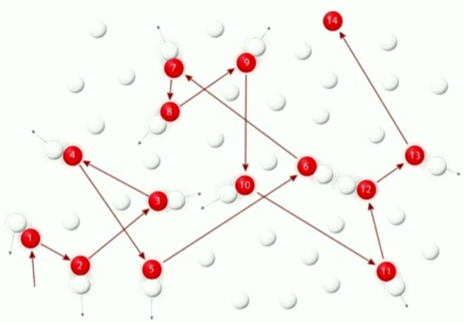
$$\ddot{r}^i + \frac{GM}{r^3} r^i = \delta^{ik} \frac{1}{2} \ddot{h}_{kj} r^j$$

deterministic

stochastic

$$\dot{X}_i(\boldsymbol{X}, t) = V_i(\boldsymbol{X}) + \Gamma_i(\boldsymbol{X}, t)$$

we move from dynamics of the variable to dynamics of the **distribution *W(X)***



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

with $\partial_i \equiv \partial / \partial X_i$

$$D_i^{(1)} = V_i + \lim_{\tau \to 0} \frac{1}{\tau} \int_t^{t+\tau} \mathrm{d}t' \int_t^{t'} \mathrm{d}t'' \left\langle \Gamma_j\left(\boldsymbol{x}, t''\right) \partial_j \Gamma_i\left(\boldsymbol{x}, t'\right) \right\rangle .$$

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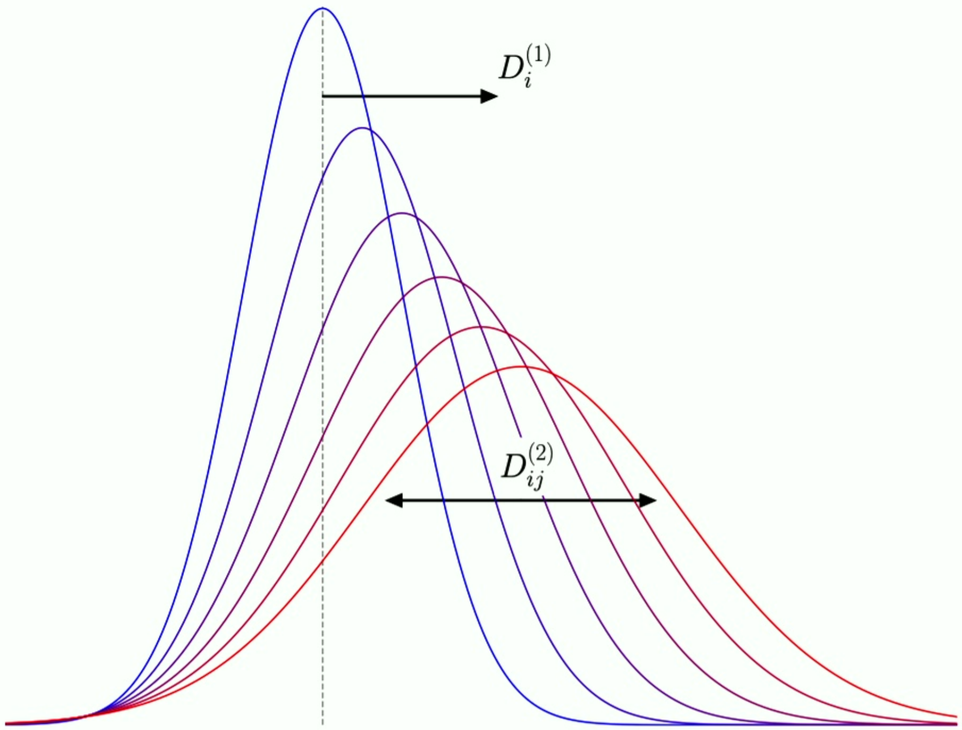
Our approach to the problem

Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103



- 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 (averaged over orbits)

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

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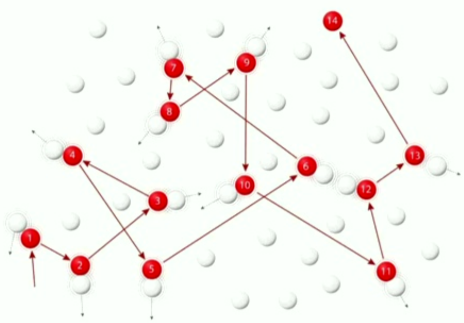

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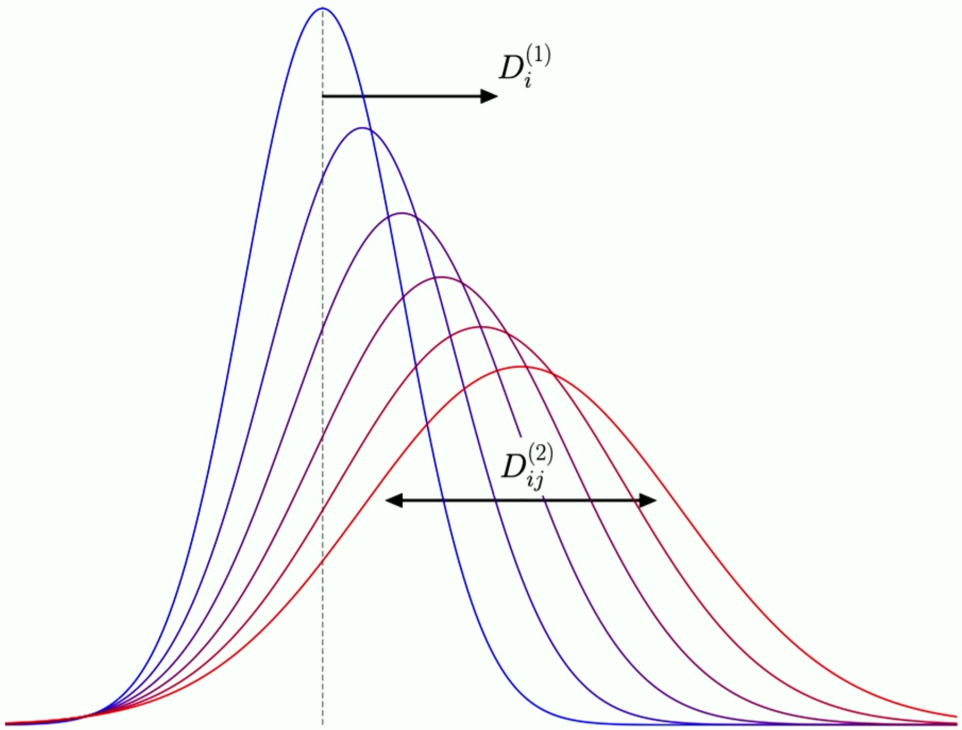

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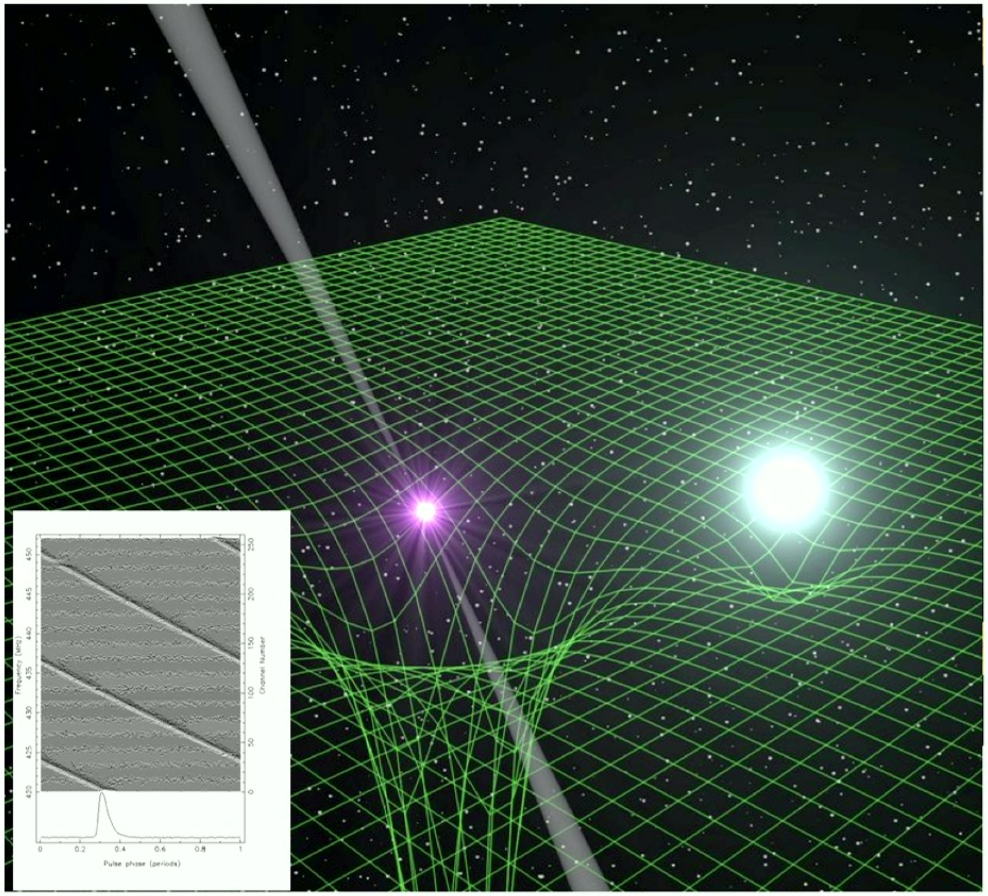
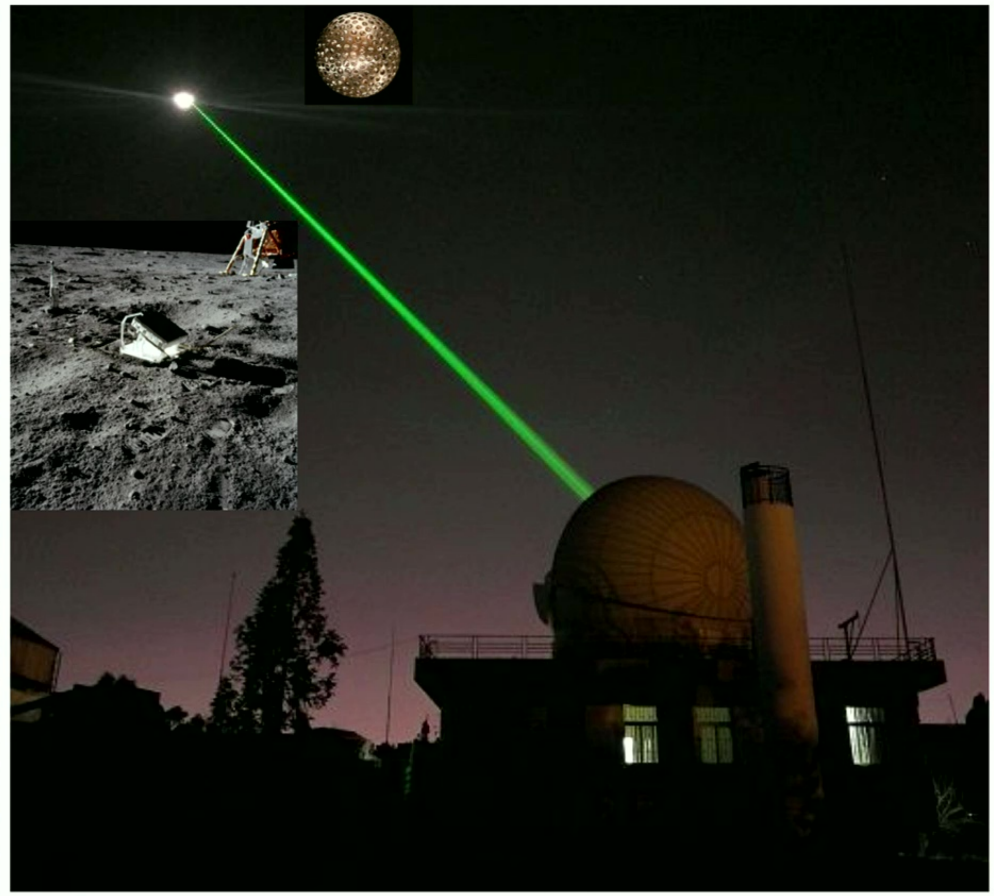
Two probes

timing of binary pulsars

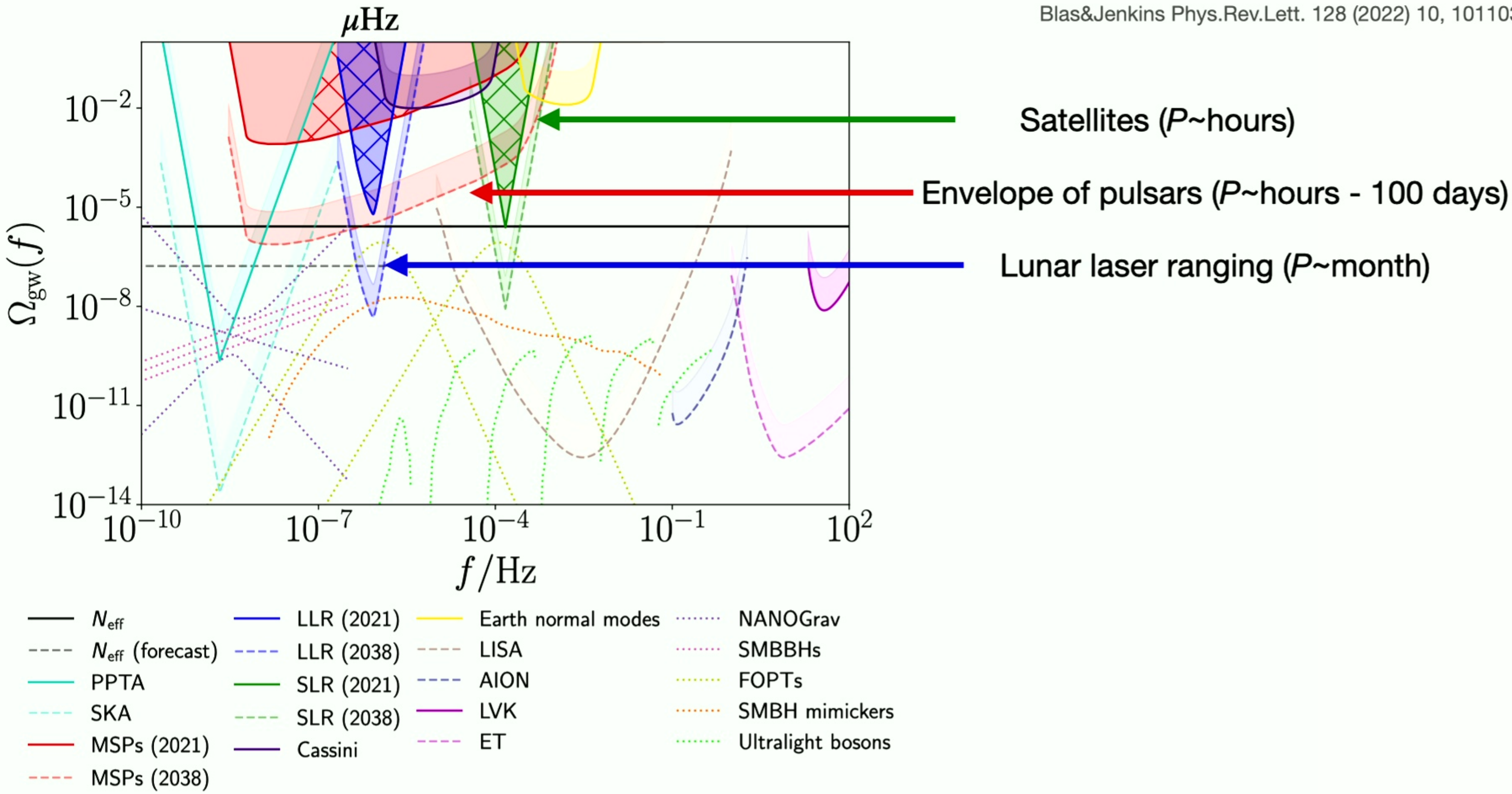


lunar and satellite laser ranging

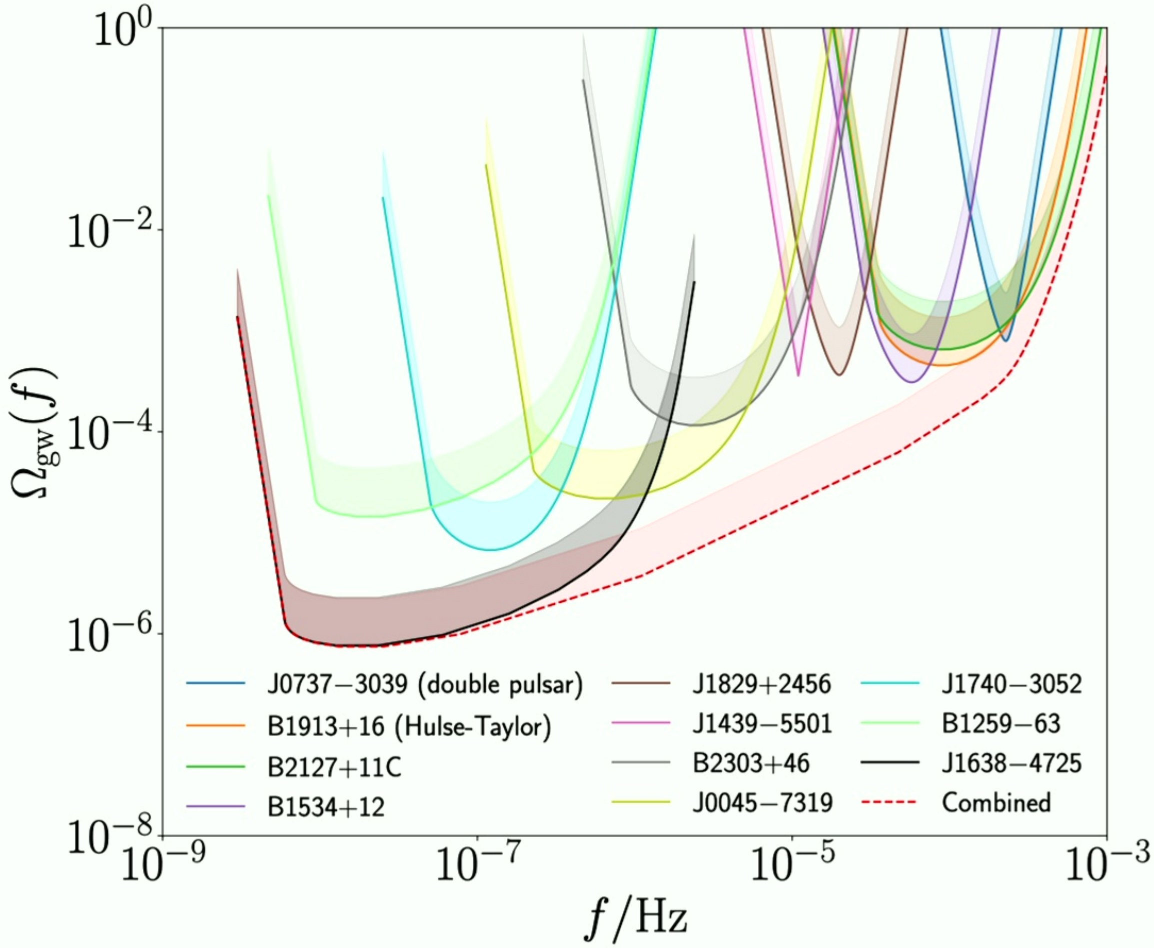


Our estimates

Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103



Combining binary pulsar bounds



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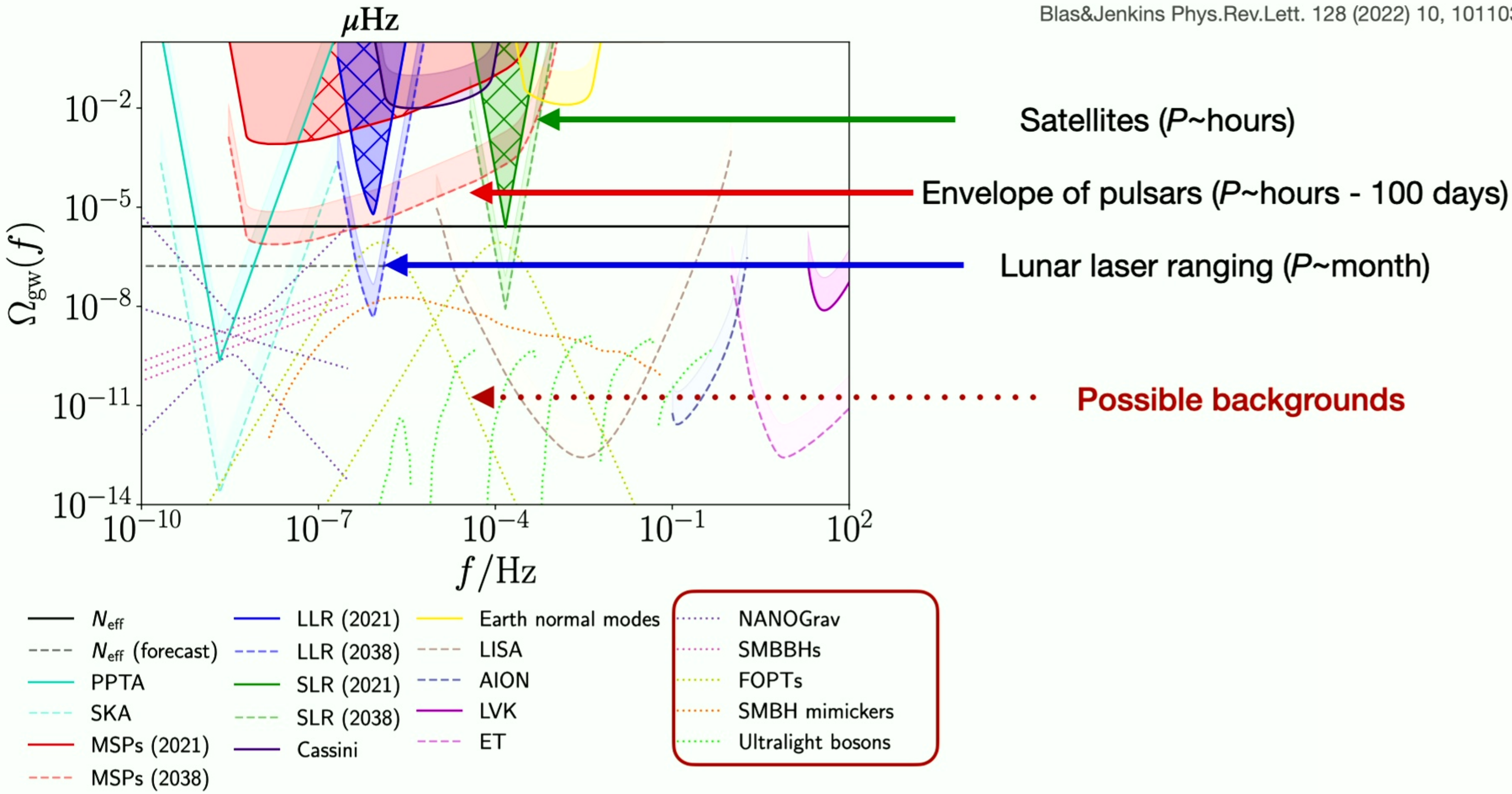

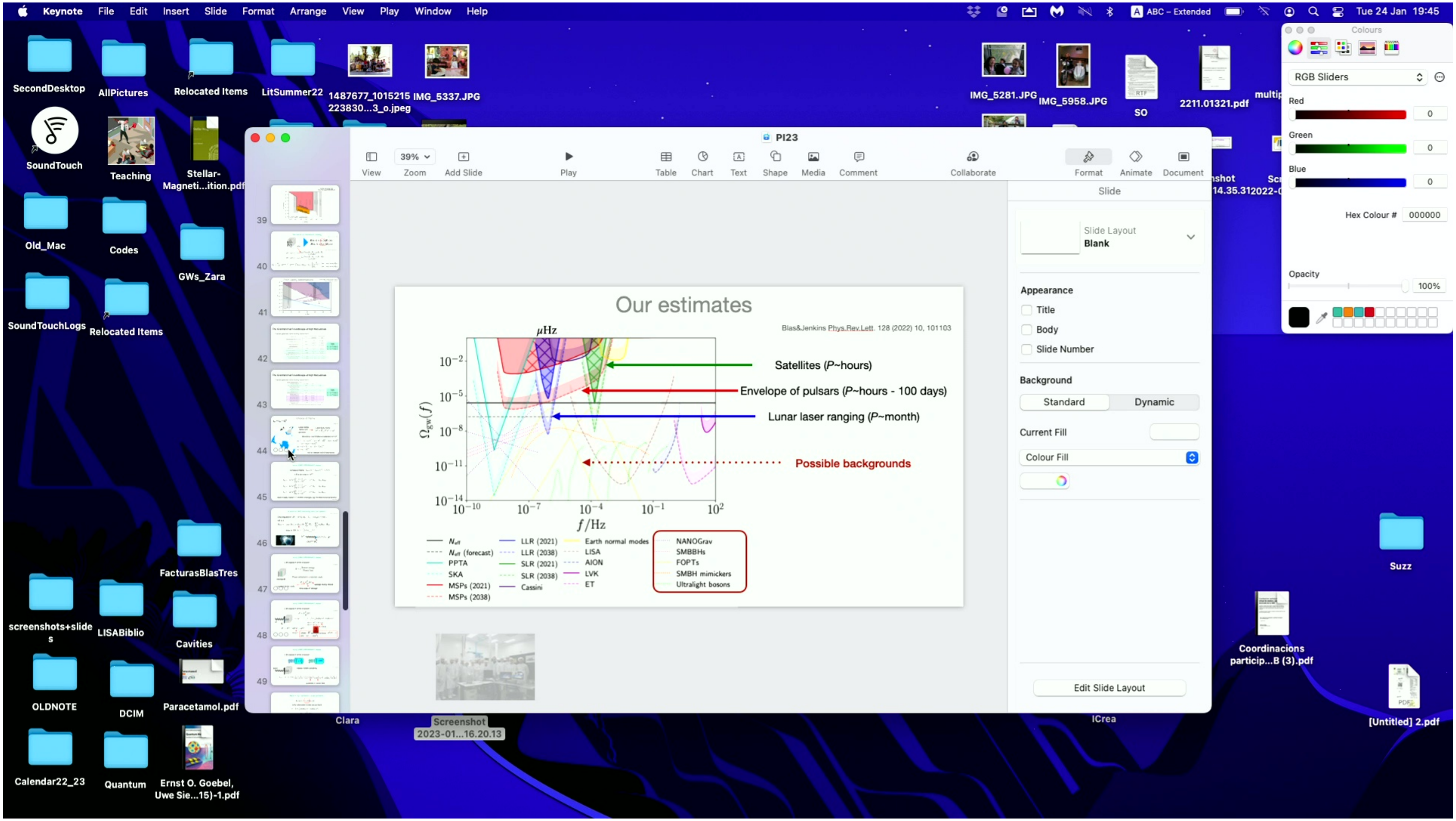
Our estimates
Blas&Jenkins Phys.Rev.Lett. 128 (2022) 10, 101103
μHz
Satellites (P~hours)
Envelope of pulsars (P~hours - 100 days)
Lunar laser ranging (P~month)
Possible backgrounds
f/Hz
NANOGrav
SMBBHs
FOPTs
SMBH mimickers
Ultralight bosons
LLR (2021)
LLR (2038)
SLR (2021)
SLR (2038)
Cassini
Earth normal modes
LISA
AION
LVK
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PPTA
SKA
MSPs (2021)
MSPs (2038)
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Hex Colour #
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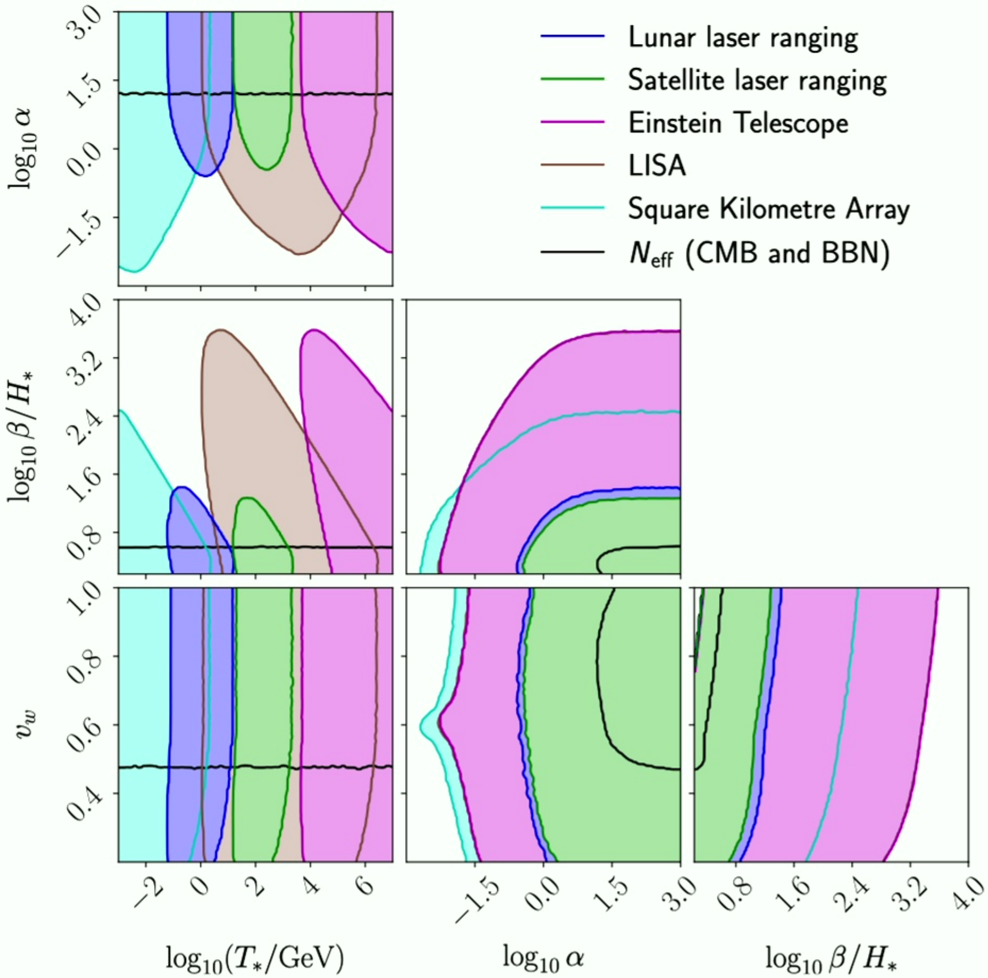
Opacity
100%

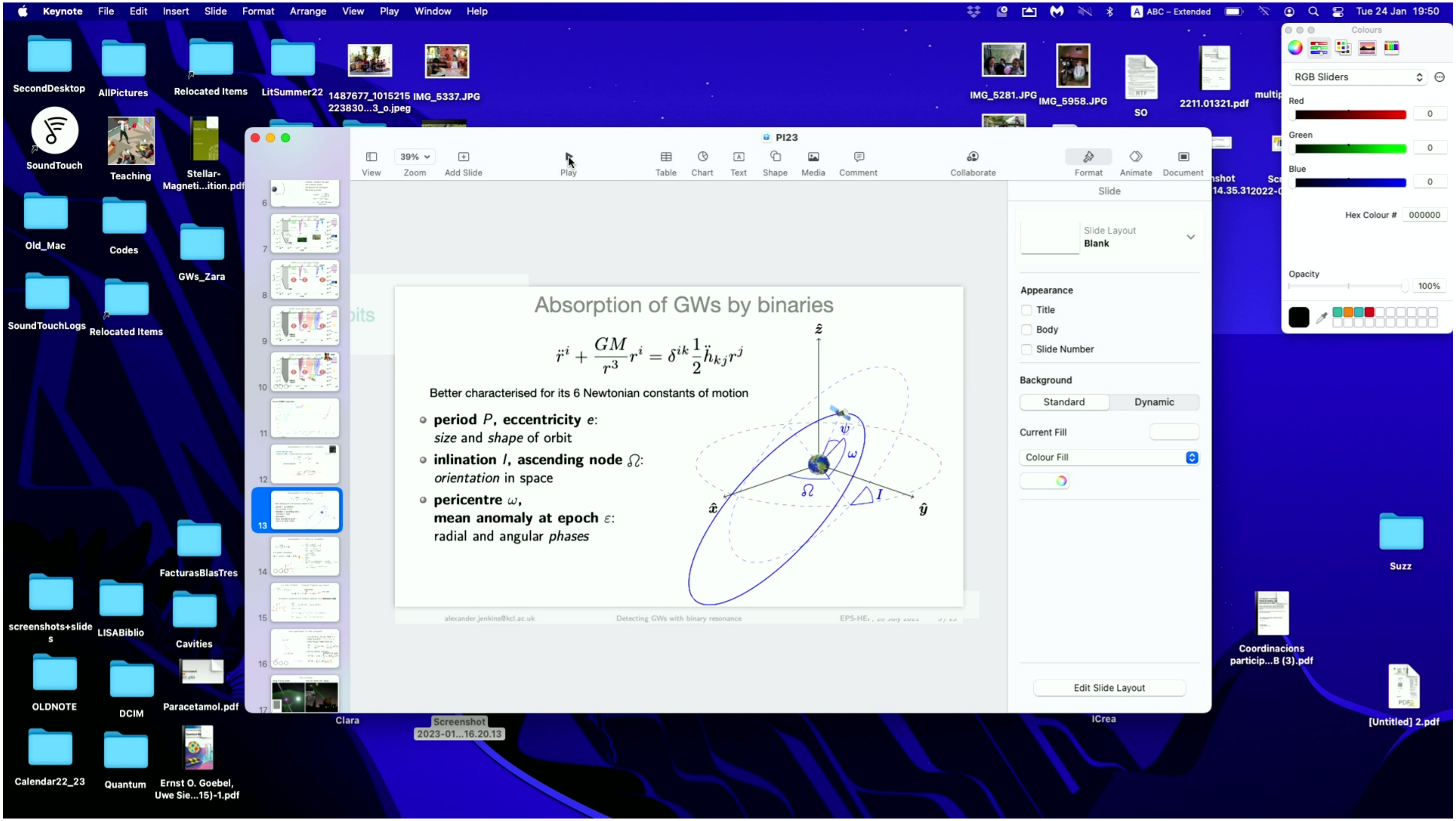
An example signal: cosmological phase transitions

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

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

Phase transition constraints

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radial and angular phases
$\hat{z}$
$\hat{x}$
$\hat{y}$
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alexander.jenkins@kcl.ac.uk
Detecting GWs with binary resonance
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Our estimates

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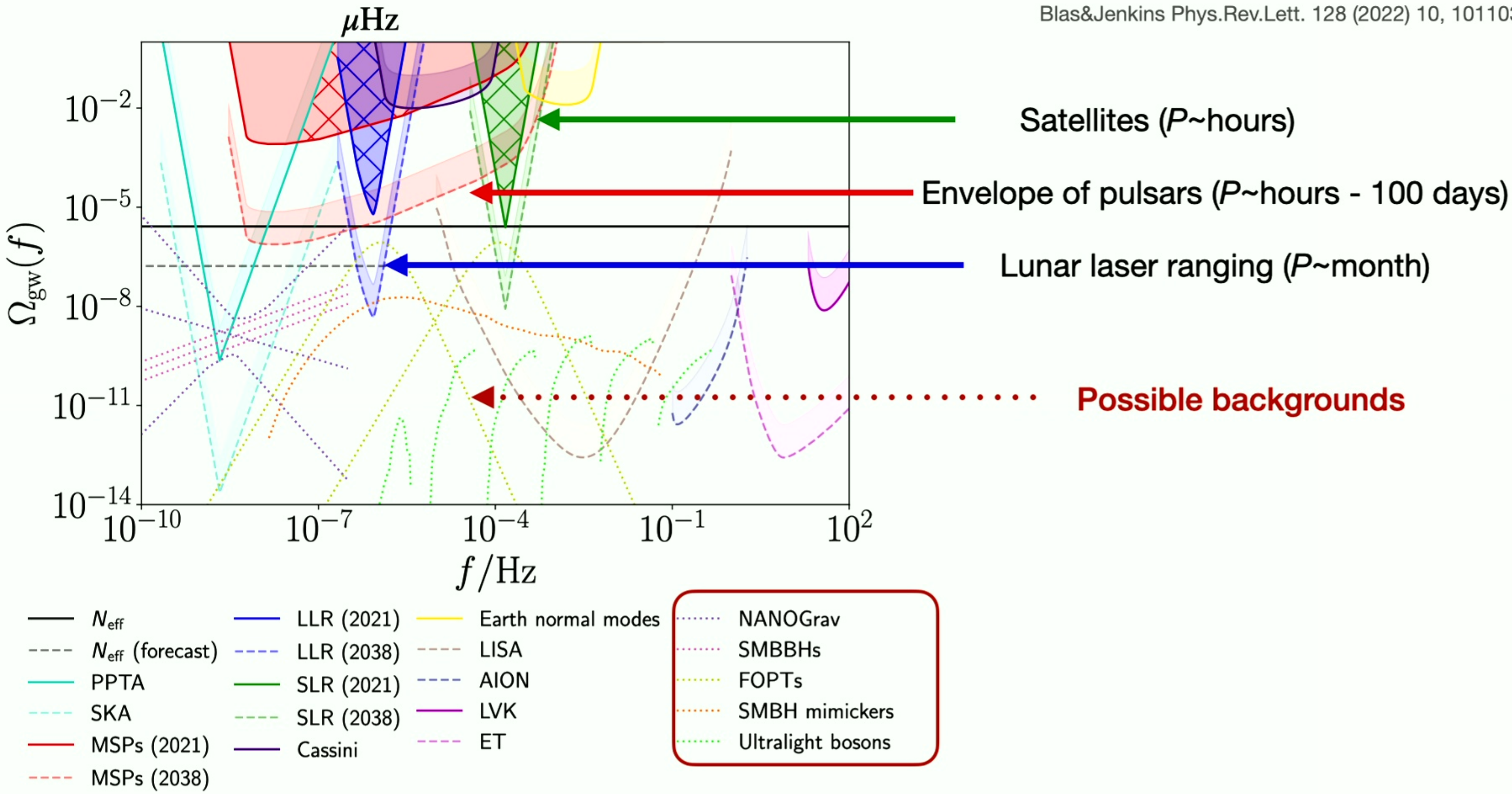
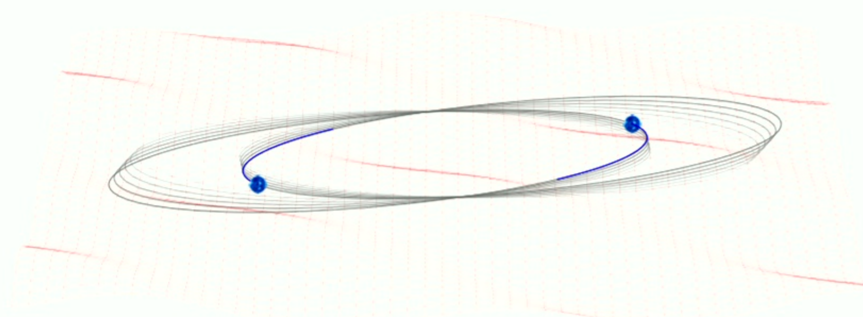


Summary and outlook @ $\mu\mathrm{Hz}$

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



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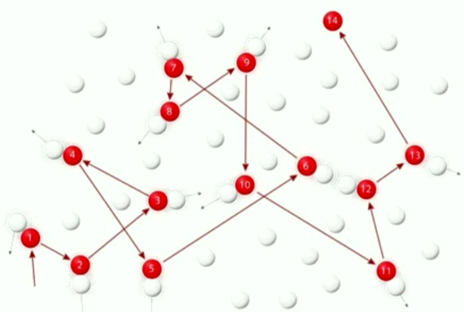

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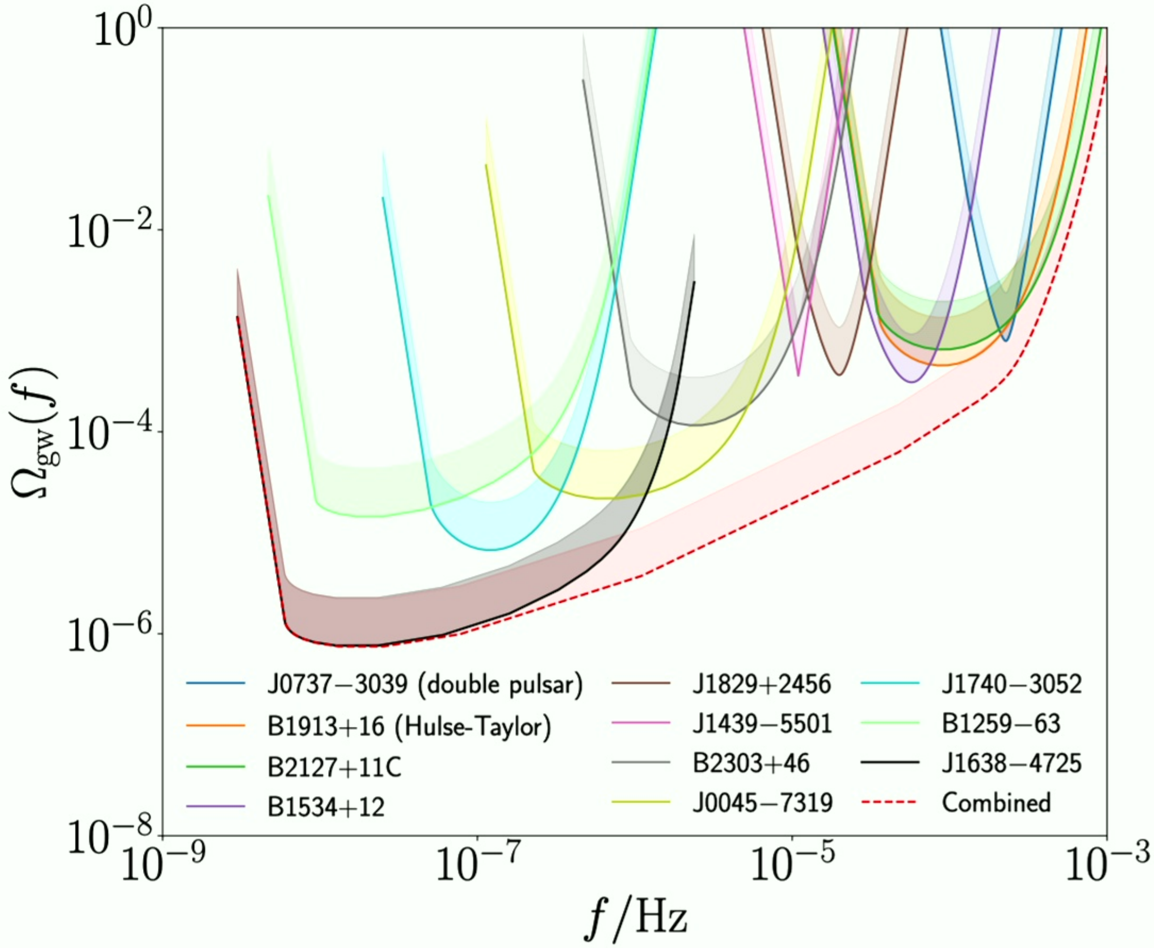

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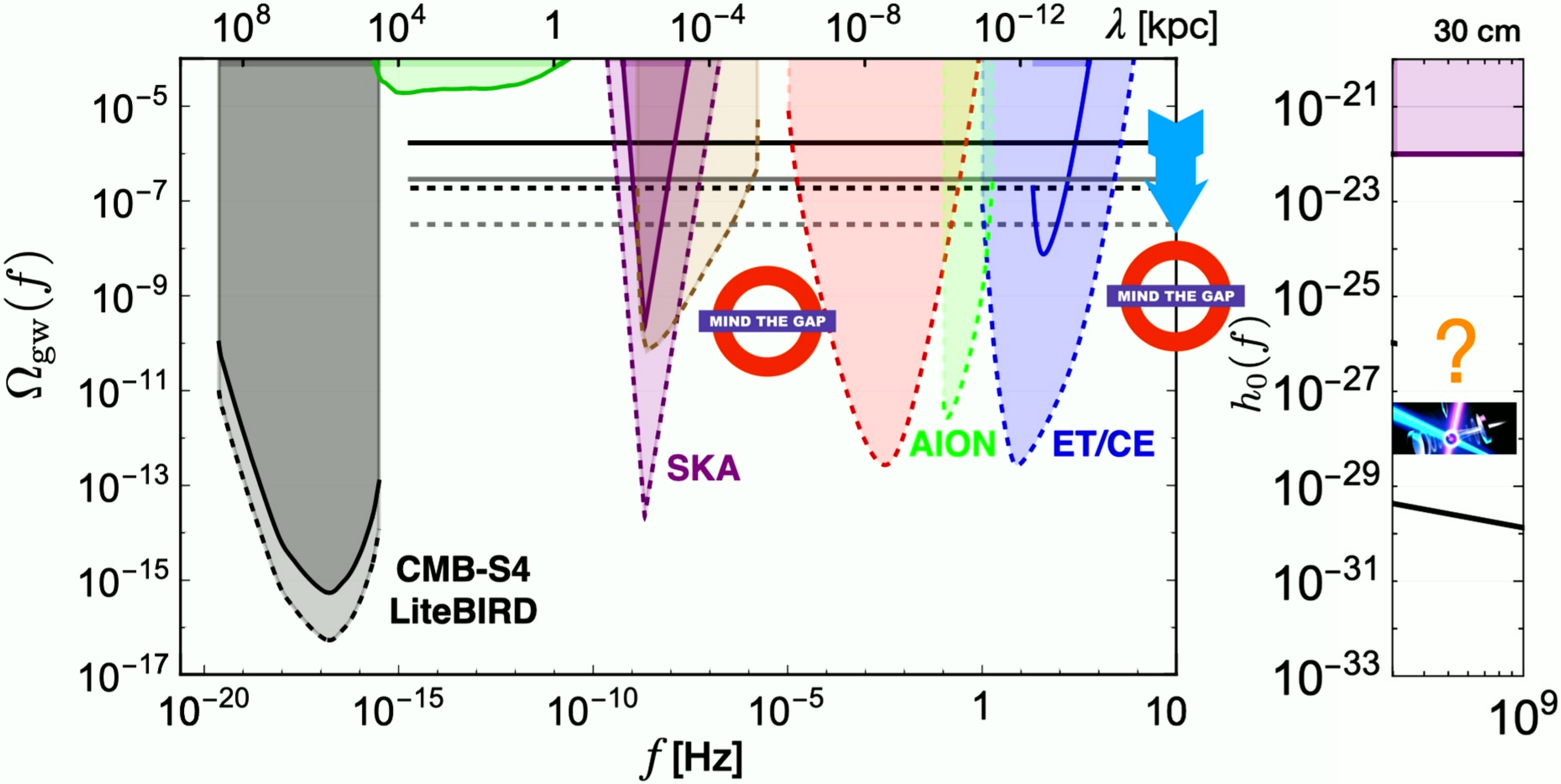
$$\dot{I} = \frac{P\gamma^3\cos\theta\mathcal{F}_\ell}{2\pi(1+e\cos\psi)^2},$$

$$\dot{\Omega} = \frac{\tan\theta}{\sin I}\dot{I},$$

$$\dot{\omega} = \frac{P\gamma^3}{2\pi e}\left[\frac{(2+e\cos\psi)\sin\psi\mathcal{F}_\theta}{(1+e\cos\psi)^2} - \frac{\cos\psi\mathcal{F}_r}{1+e\cos\psi}\right] - \cos I\dot{\Omega},$$

$$\dot{\varepsilon} = -\frac{P\gamma^4\mathcal{F}_r}{\pi(1+e\cos\psi)^2} - \gamma(\cos I\dot{\Omega} + \dot{\omega}),$$

UHFGWs



10^8
10^4
1
10^{-4}
10^{-8}
10^{-12}
λ [kpc]
30 cm
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
$\Omega_{\rm gw}(f)$
MIND THE GAP
MIND THE GAP
SKA
AION
ET/CE
CMB-S4
LiteBIRD
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
10
f [Hz]
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{-29}
10^{-31}
10^{-33}
$h_0(f)$
?
10^9

Sources of UHFGW

Very different picture comparing to EM spectrum

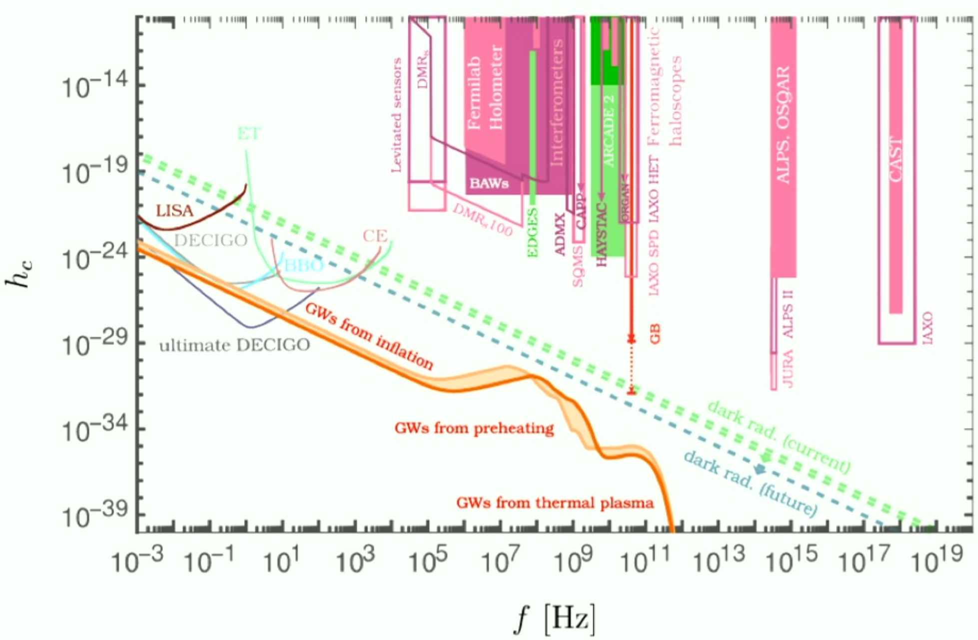
	Stochastic	Coherent
standard physics	Primordial plasma thermal fluctuations ✔ Ghiglieri et al JHEP 07 (2020) 092 Ringwald et al JCAP 03 (2021) 054	? ✘
	Inflation	
new physics	Phase transitions, Cosmic strings Close encounters of BHs ✔	Light PBHB Ultra-light DM Exotic objects ✔

The Gravitational Soundscape *at high frequencies*

$$\Omega_{GW}(f) = \frac{1}{\rho_{crit}} \frac{d\rho_{GW}}{d(\ln f)} \qquad \rho_{GW} \sim M_P^2 \omega^2 h_{GW}^2$$

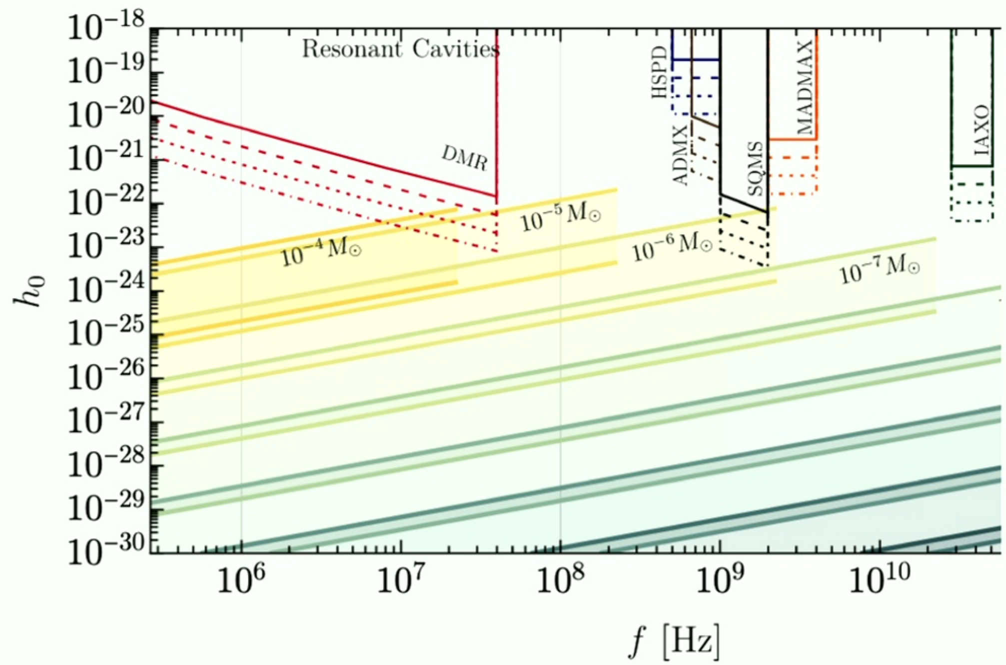
SMASH model full spectrum

Ringwald Tamarit 22



GWs from PBHs (rates 1/year)

Franciolini et al 2205.02153

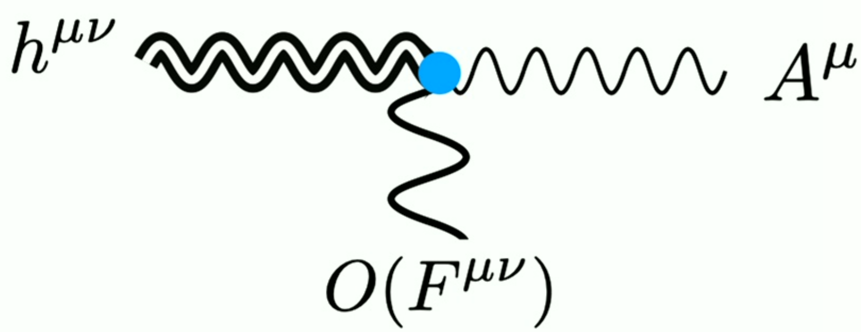


Searching for GWs with light

Interaction GWs with light

$$\mathcal{L} = \sqrt{-g}\,(R + F_{\mu\nu}F^{\mu\nu}) \supset \frac{1}{2}A_\mu j^\mu_{\rm eff}(h) + \eta^{\mu\alpha}\eta^{\nu\beta}F_{\mu\nu}F_{\alpha\beta} + O(h^2)$$

$$j^\mu_{\rm eff} = -\partial_\beta\left(\frac{1}{2}hF^{\mu\beta} + h^\beta_\alpha F^{\alpha\mu} - h^\mu_\alpha F^{\alpha\beta}\right)$$



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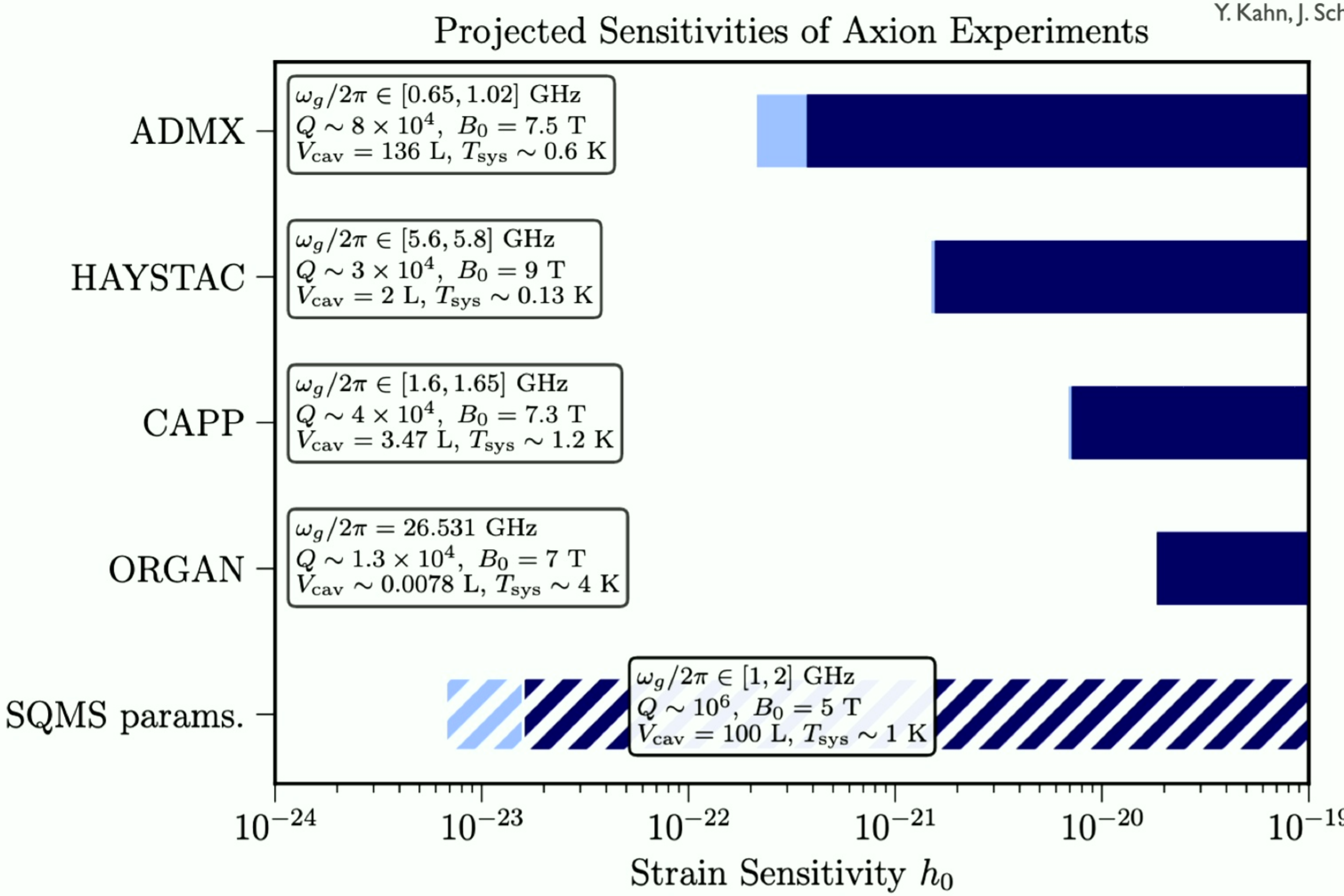
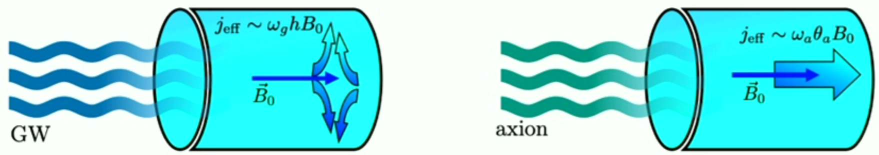


Summary and outlook @ GHz

- SRF cavities are a mature technology to look for GWs at GHz either
  - 'ADMX' like
  - Heterodyne



- As in any GR calculation: subtleties in working with a consistent gauge
  - TT gauge needs to be converted to laboratory frame
  - Reach of $h_0 \sim 10^{-23}$ possible, though far from known signals

- Stay tuned for the connection to real world… (noise estimates + prospects)

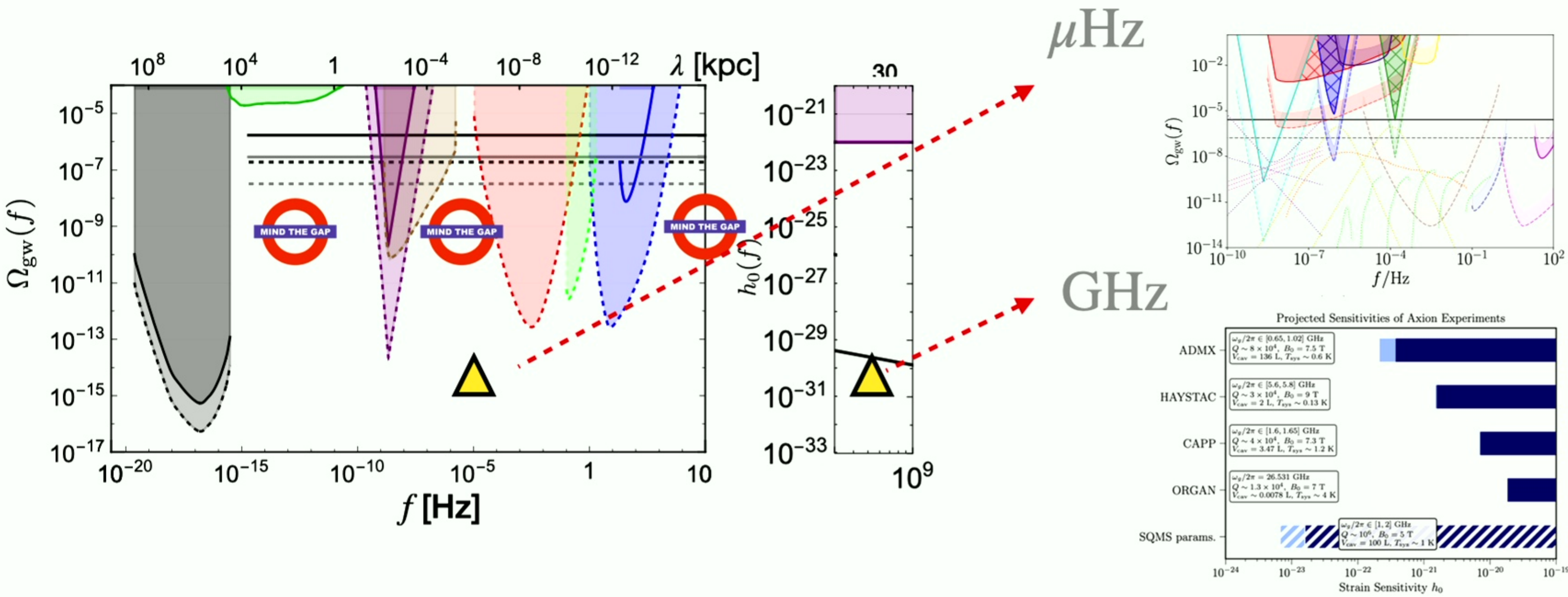
Conclusions

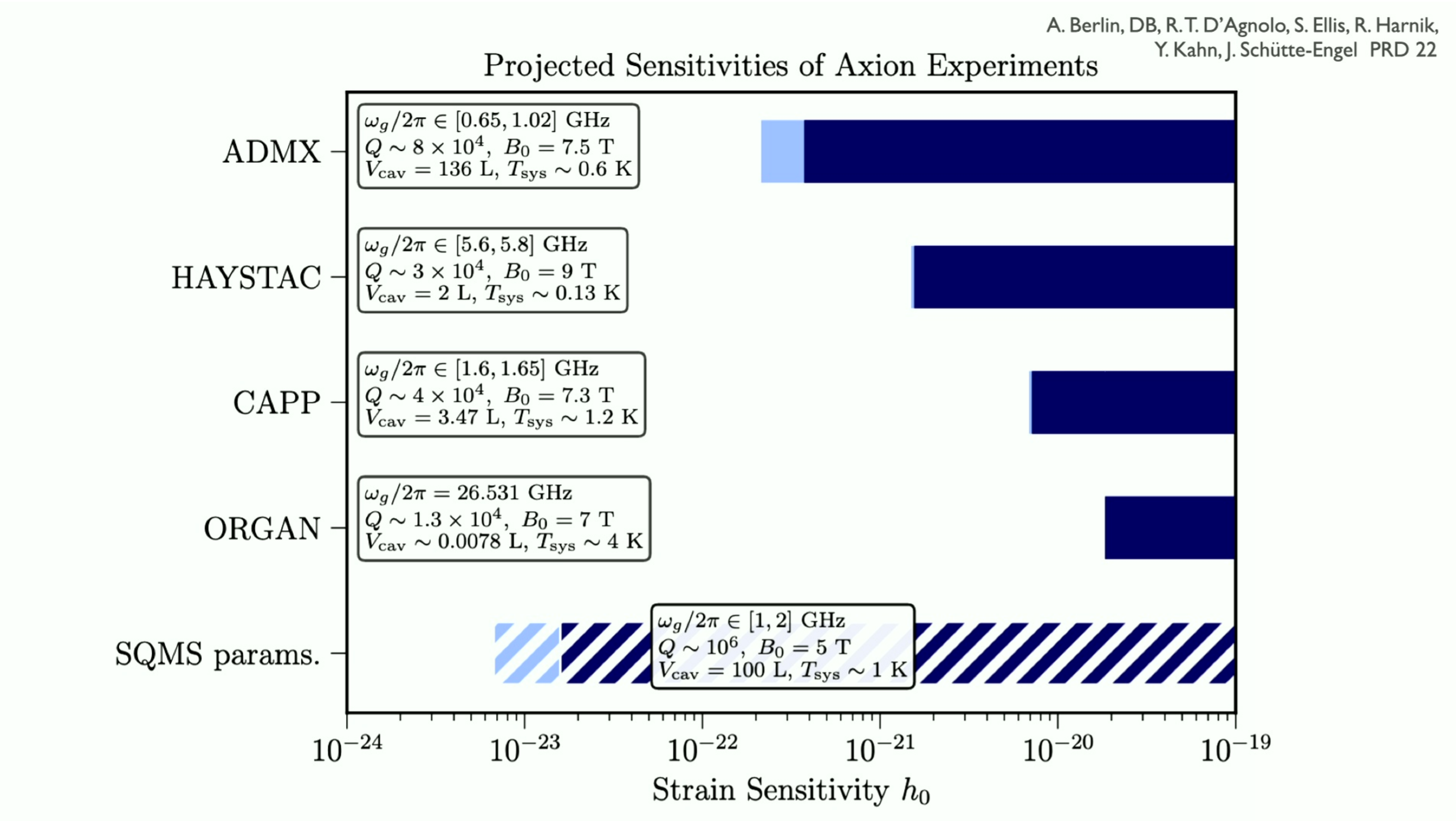
Multiband approach to GWs: great potential to transform both astrophysics and BSM

For this:

i) there is vigours effort to in four regions (CMB/PTA/LISA/LVK)

ii) new ideas are needed in other phenomenologically rich regions

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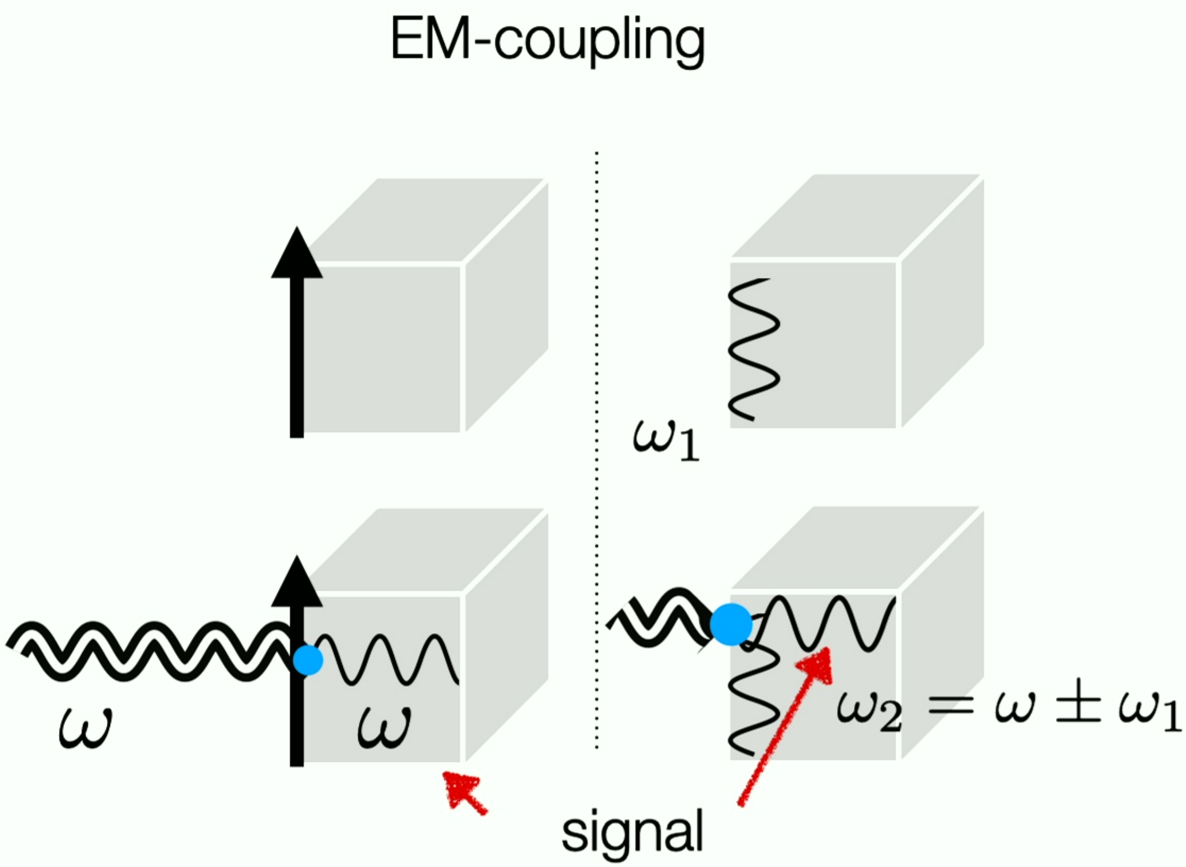
Y. Kahn, J. Schütte-Engel PRD 22
Projected Sensitivities of Axion Experiments
ADMX
$\omega_g/2\pi \in [0.65, 1.02]$ GHz
$Q \sim 8 \times 10^4,\ B_0 = 7.5$ T
$V_{\rm cav} = 136$ L, $T_{\rm sys} \sim 0.6$ K
HAYSTAC
$\omega_g/2\pi \in [5.6, 5.8]$ GHz
$Q \sim 3 \times 10^4,\ B_0 = 9$ T
$V_{\rm cav} = 2$ L, $T_{\rm sys} \sim 0.13$ K
CAPP
$\omega_g/2\pi \in [1.6, 1.65]$ GHz
$Q \sim 4 \times 10^4,\ B_0 = 7.3$ T
$V_{\rm cav} = 3.47$ L, $T_{\rm sys} \sim 1.2$ K
ORGAN
$\omega_g/2\pi = 26.531$ GHz
$Q \sim 1.3 \times 10^4,\ B_0 = 7$ T
$V_{\rm cav} \sim 0.0078$ L, $T_{\rm sys} \sim 4$ K
SQMS params.
$\omega_g/2\pi \in [1, 2]$ GHz
$Q \sim 10^6,\ B_0 = 5$ T
$V_{\rm cav} = 100$ L, $T_{\rm sys} \sim 1$ K
10^{-24} 10^{-23} 10^{-22} 10^{-21} 10^{-20} 10^{-19}
Strain Sensitivity h_0

Recycling axion experiments

Cavities (cm -> GHz)



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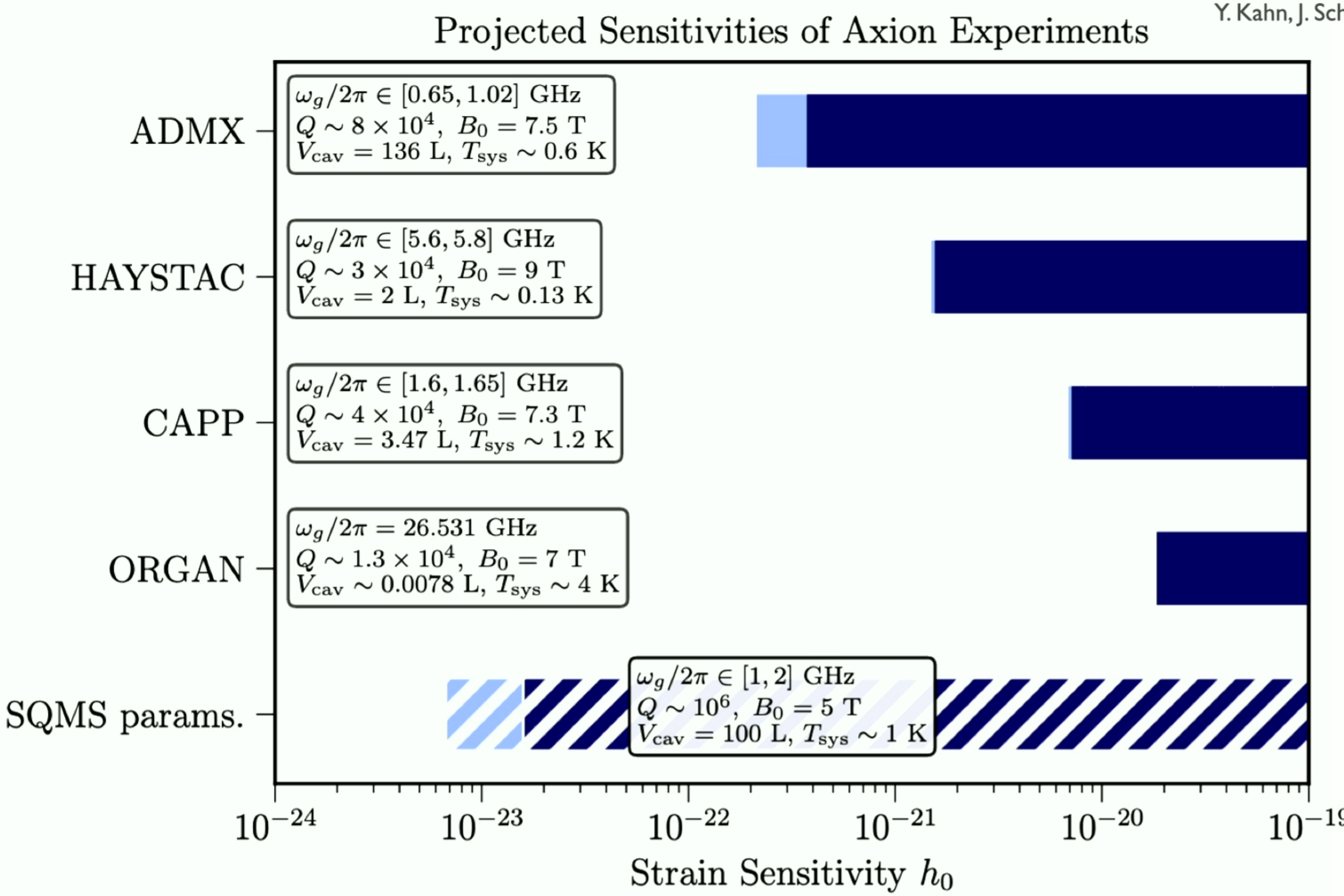

Summary and outlook @ GHz

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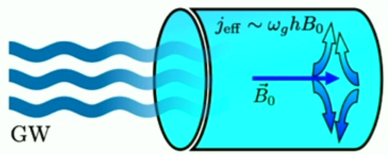

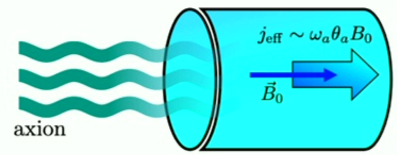

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Recycling axion experiments

Cavities (cm -> GHz)

EM-coupling