Diego Blas

ICREA

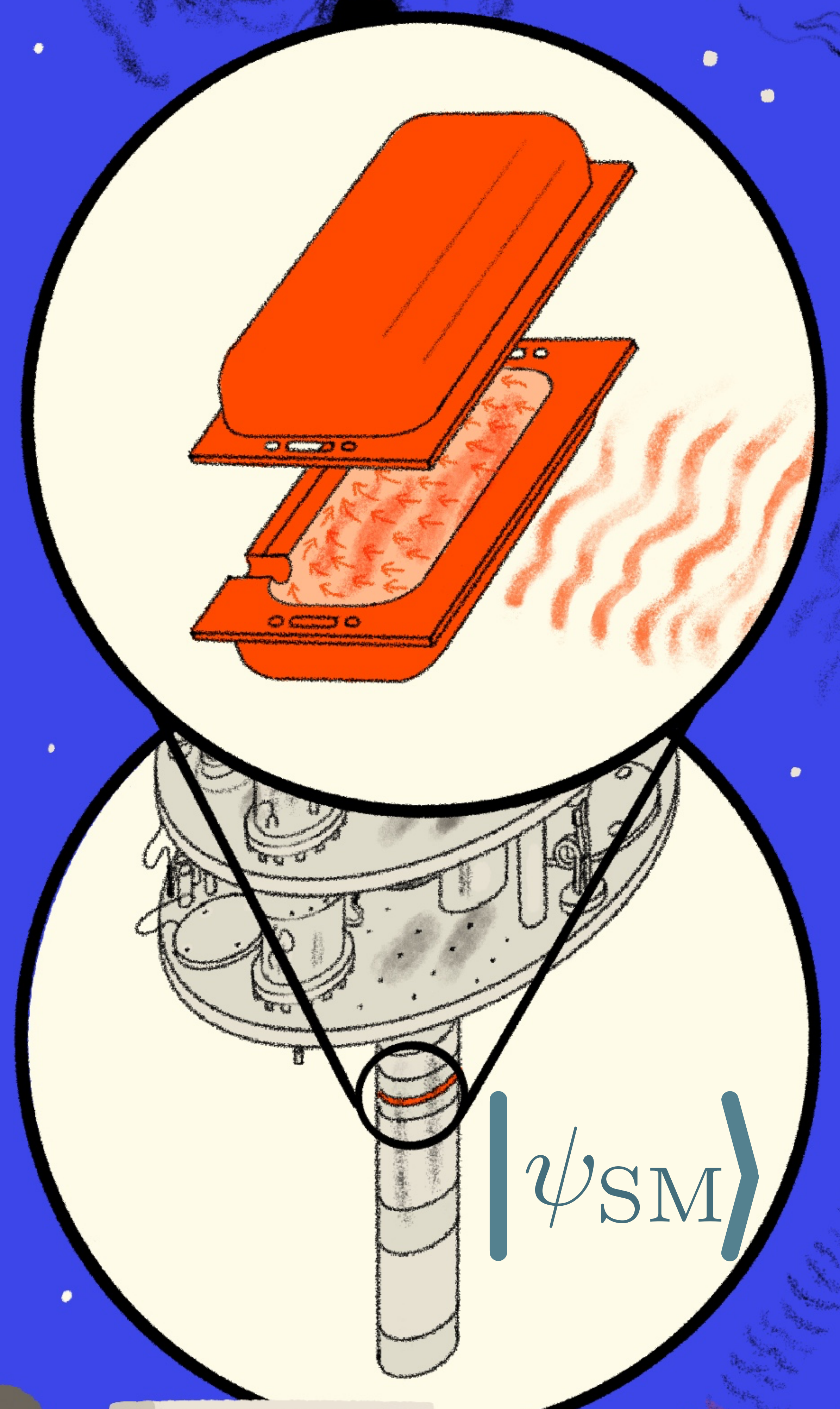
IFAE Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

bist SCIENTIFIC COMMUNITY

CERCA Centres de Recerca de Catalunya

Quantum Sensors for Fundamental Physics



European Research Council
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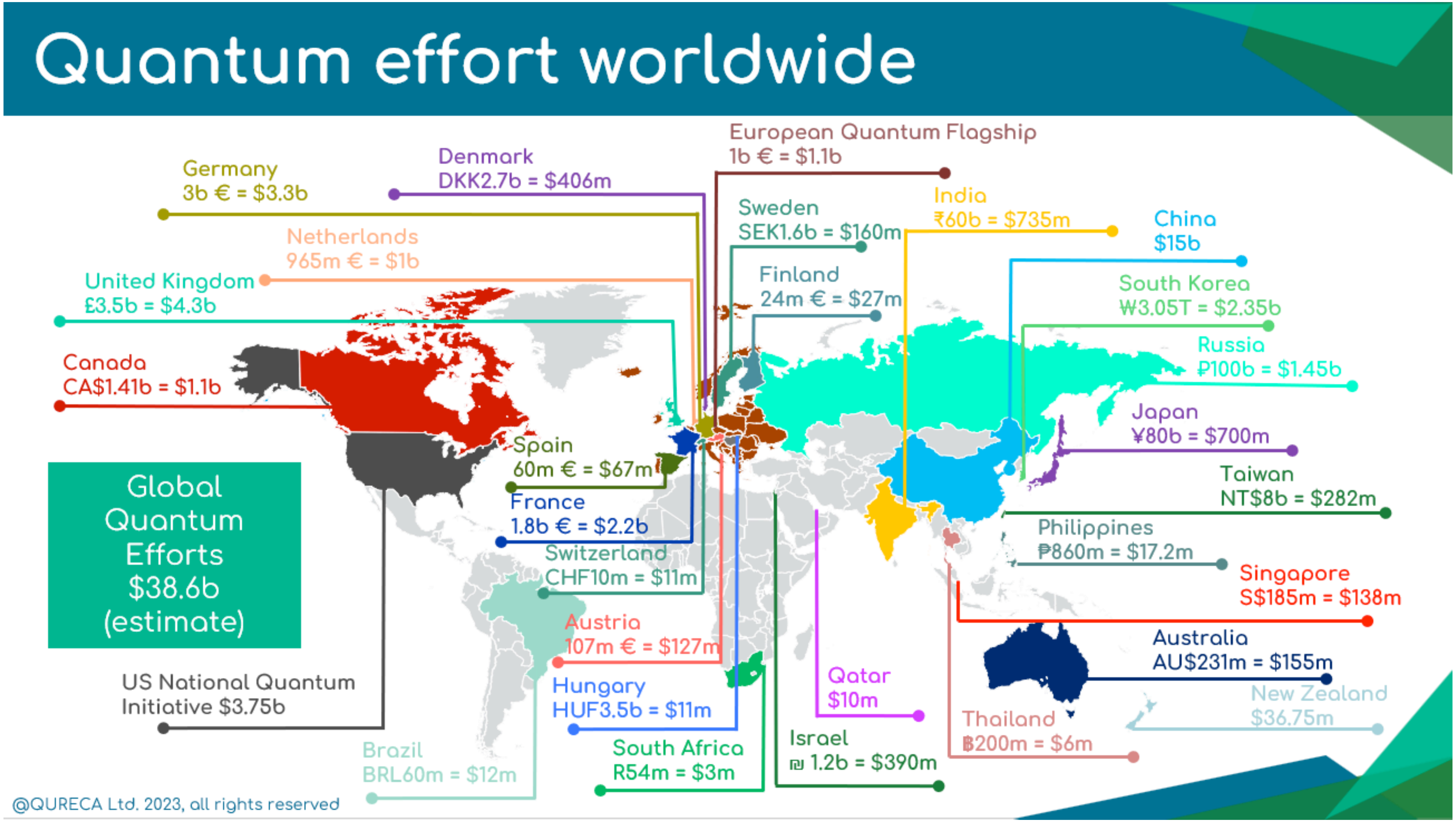
Fundación BBVA

Why QS? I

Quantum technologies everywhere…



https://thequantuminsider.com/

https://www.qureca.com/quantum-initiatives-worldwide/

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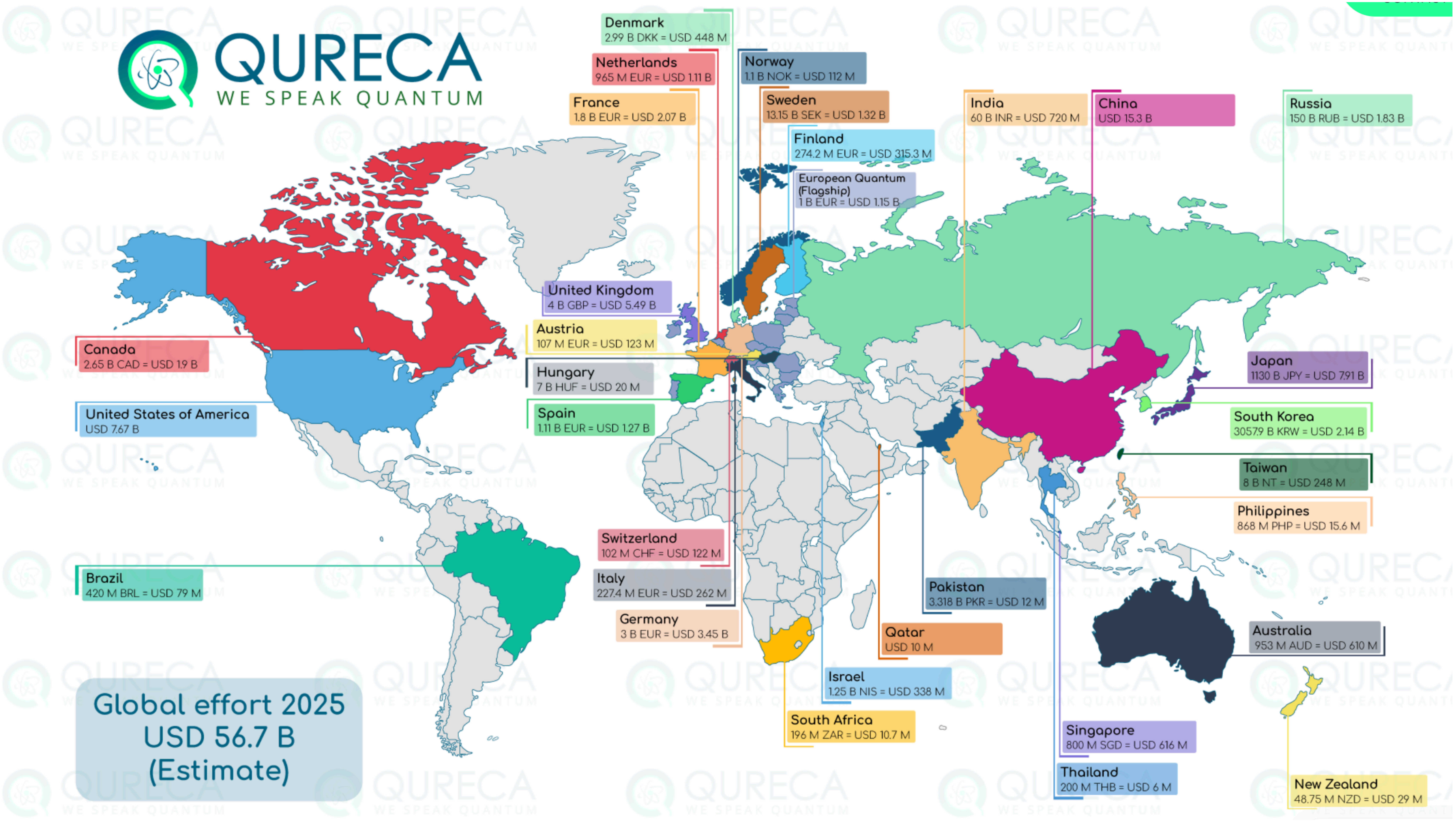

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Quantum-HEP/Grav/Cosmo: A growing field

CERN

https://quantum.cern/

QUANTUM TECHNOLOGY INITIATIVE

- Quantum computing and algorithms
- Quantum theory and simulation
- Quantum sensing, metrology and materials
- Quantum communication and networks

Quantum sensing for particle physics
Steven D. Bass (Jagiellonian U.), Michael Doser (CERN)
e-Print: 2305.11518 [quant-ph]

https://pbc.web.cern.ch/

Physics Beyond Colliders

Feebly Interacting Particles Physics Centre
Forward Physics Facility
Gamma Factory
LHC fixed target
QCD Physics Group
Technology
Accelerator Complex Capabilities
Beam Dump Facility
BSM Physics Working Group
Charged particle Electric Dipole Moment (cpEDM) measurement
Conventional Beams

https://indico.cern.ch/event/999818/

ECFA
European Committee for Future Accelerators

https://phystev.cnrs.fr/

https://quantum.fnal.gov/

Fermilab Quantum Institute
Solving the challenges of quantum sciences and technology for the benefit of all

- Quantum computing applications and simulations
- Quantum sensing
- Quantum communication
- Electronics and controls for quantum
- Quantum Science Center

Quantum Sensing for High Energy Physics
Zeeshan Ahmed (SLAC) *et al.*. Mar 29, 2018. 38 pp.
FERMILAB-CONF-18-092-AD-AE-DI-PPD-T-TD
Conference: C17-12-12
e-Print: arXiv:1803.11306 [hep-ex] | PDF

https://uknqt.ukri.org/our-programme/qtfp/

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME (NQTP)

Quantum Sensors for Fundamental Physics

QI · QSNET · QSHS · AION · QUEST DMC · QSimFP

NASA

https://www.jpl.nasa.gov/go/funpag

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UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
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Quantum Sensors for Fundamental Physics

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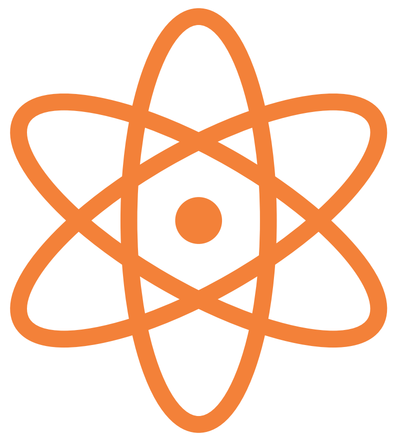
NASA

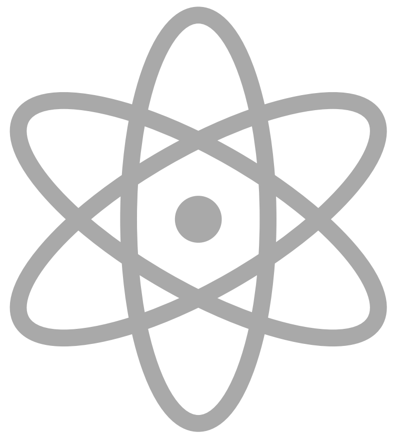
https://www.jpl.nasa.gov/go/funpag

Why Quantum Sensing for HEP: II

$|1\rangle$



$|2\rangle$

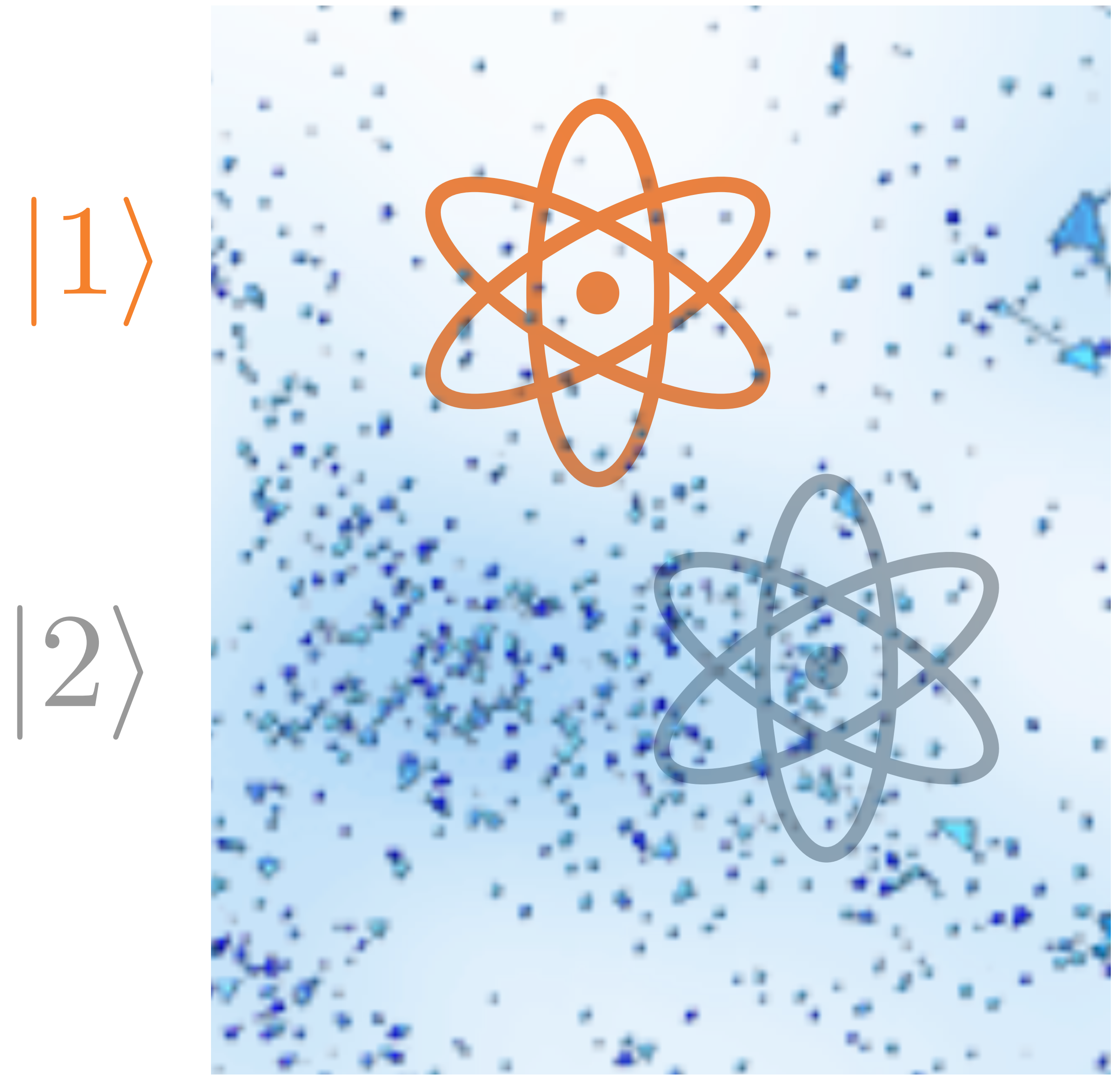


$$|\psi(t)\rangle = e^{-i\int \mathrm{d}\tau\, H(\tau)}\,|\psi_0\rangle$$

Sensor

- **System** — H_0
- **Noise** — H_n

Why Quantum Sensing for HEP: II



$$|\psi(t)\rangle = e^{-i\int d\tau\, H(\tau)}\,|\psi_0\rangle$$

In the real world there are also **fundamental backgrounds**

$$\int \mathrm{d}t H_{\rm sig} \sim \text{flux}$$

Sensor

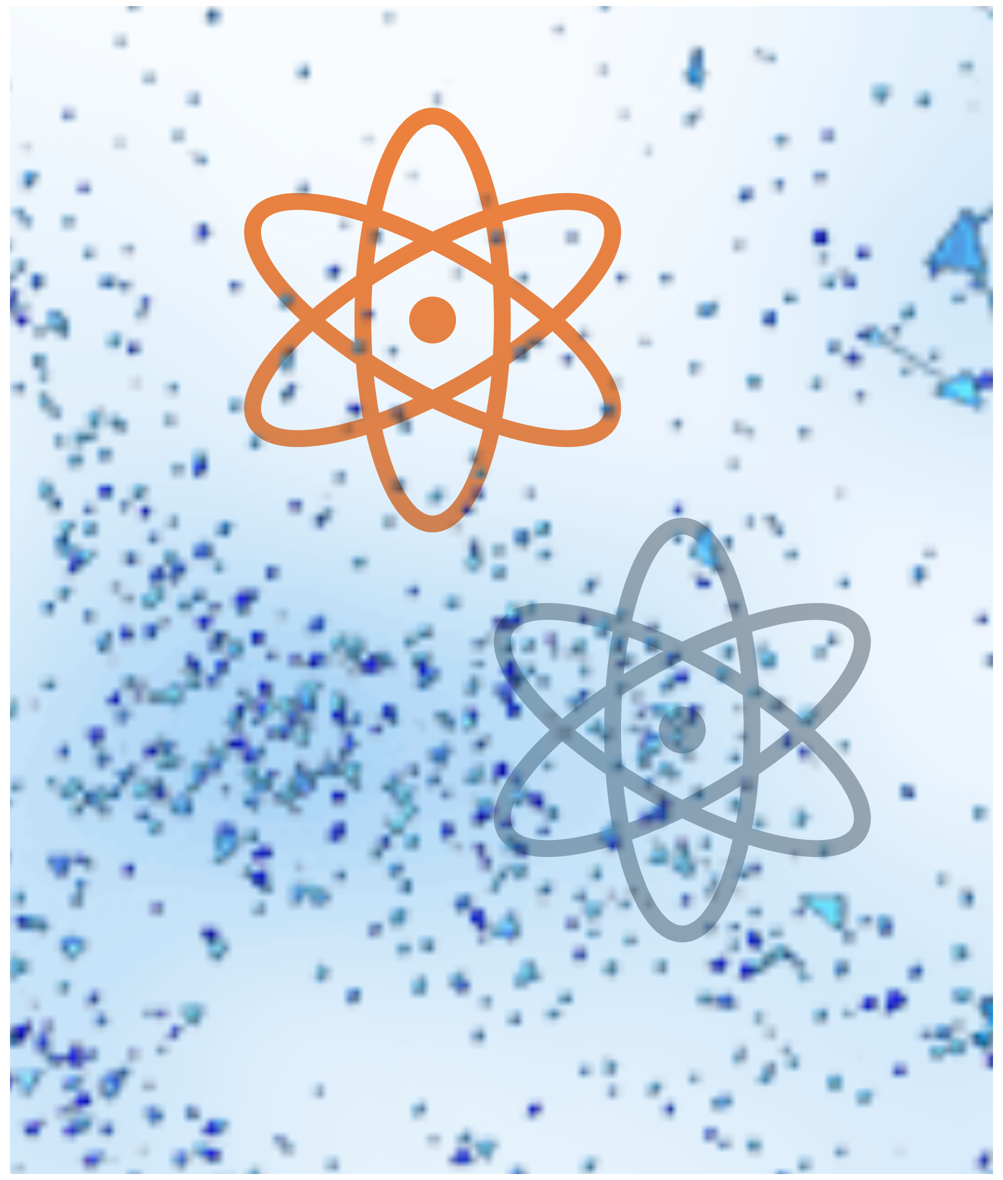
- **System** — H_0
- **Noise** — $H_{\rm n}$
- **Signal** — $H_{\rm sig}$

There are **no thresholds**: the larger the flux the better!

Why Quantum Sensing for HEP: II

$|1\rangle$

$|2\rangle$



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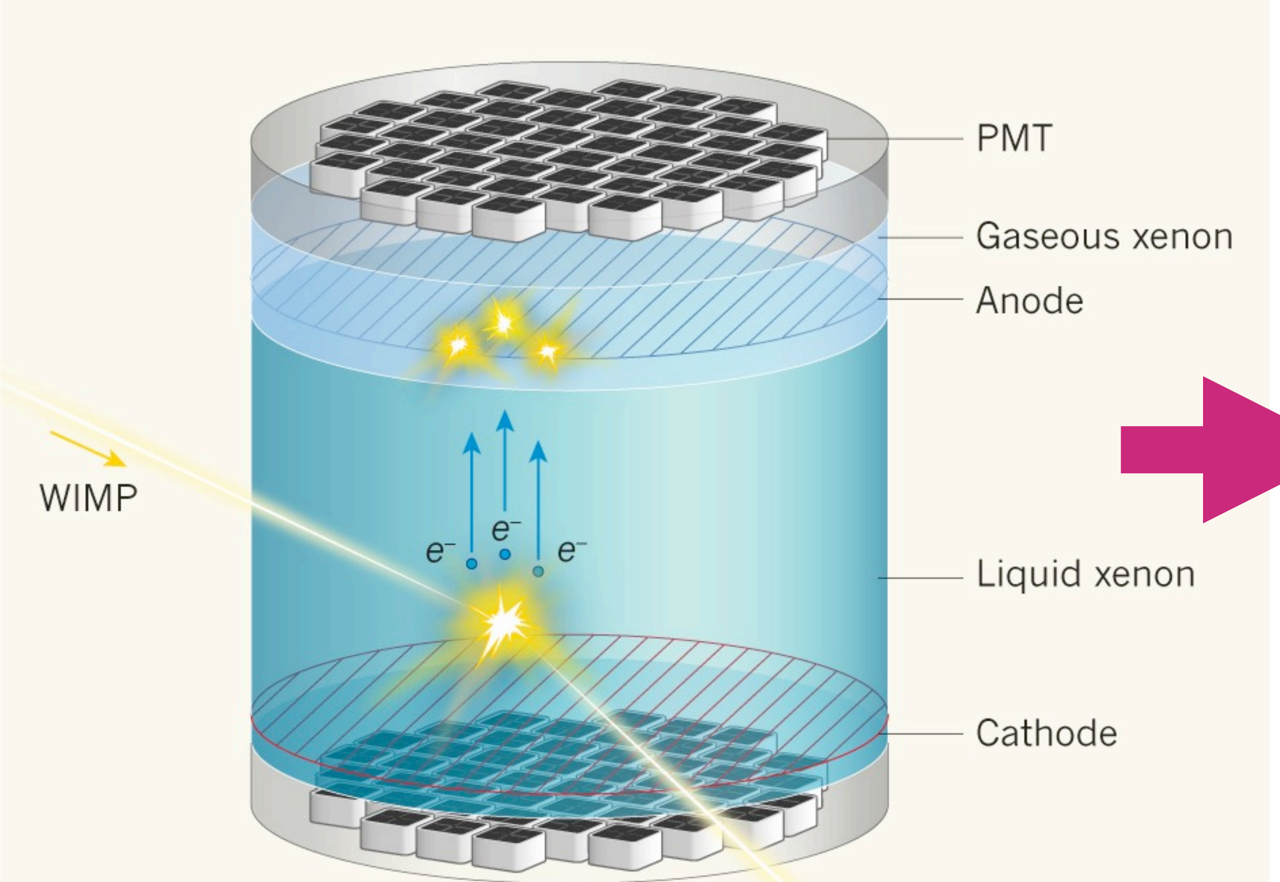
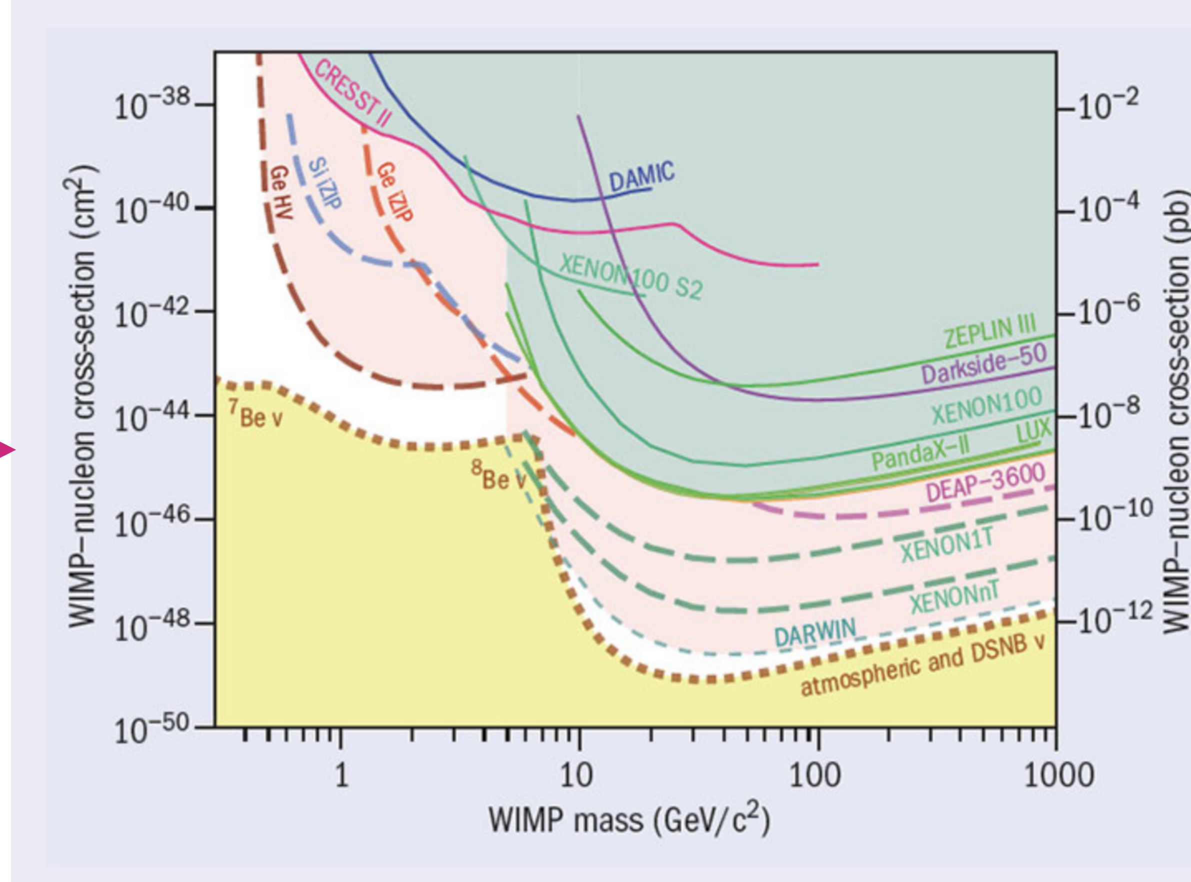
Sensor

- **System** — H_0
- **Noise** — H_{n}
- **Signal** — H_{sig}

There are **no thresholds**: the larger the flux the better!

Several other techniques have a **minimum momentum transfer**



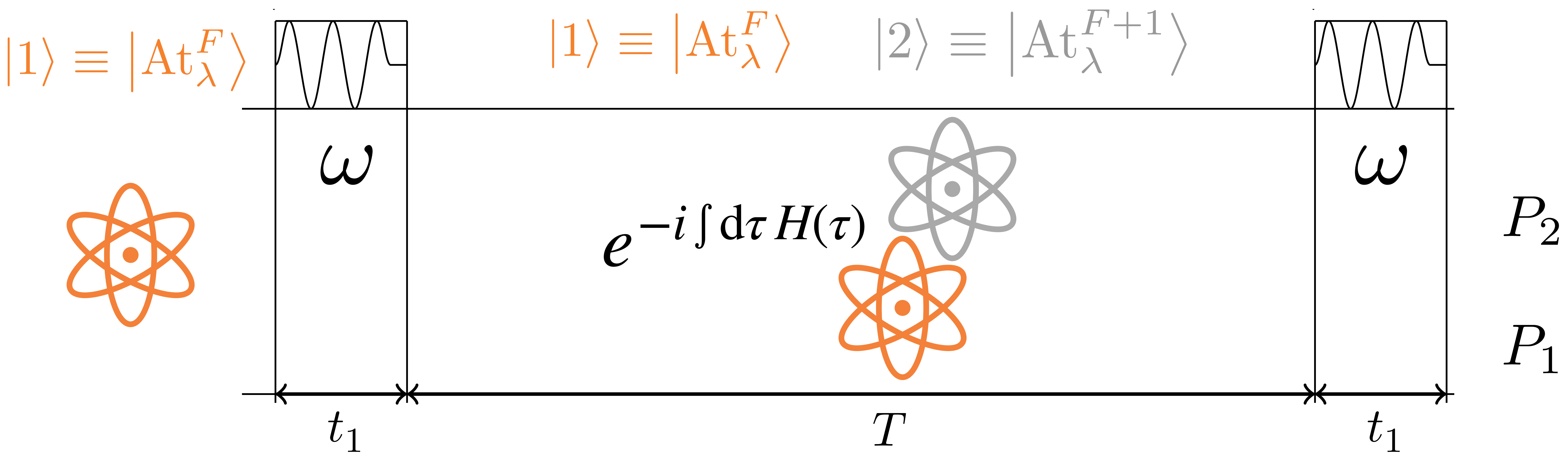


Measuring at $q = 0$: phase shifts in atomic systems

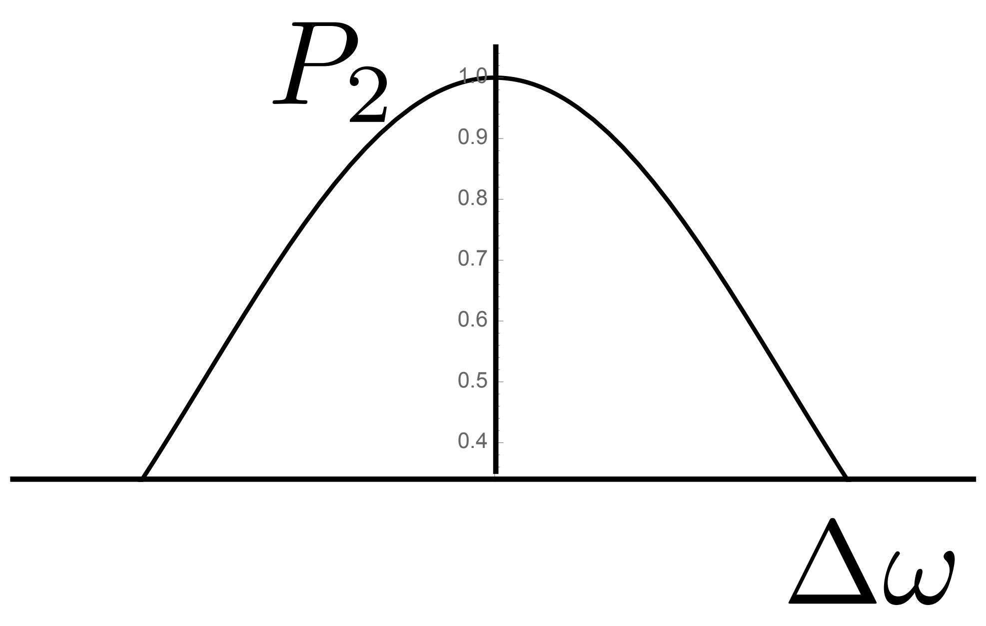
R. Alonso, DB and P. Wolf
1810.00889 & 1810.01632

Du et al. 2205.13546

Ramsey sequence



$$P_2 = \cos[\Delta\omega\, T/2]^2 \quad \text{with} \quad \Delta\omega \equiv \omega - (E_2 - E_1)$$



$$\partial P_2 = 0 \Rightarrow \omega_{\max} = \Delta E$$

We want : **long coherence**, small noise.

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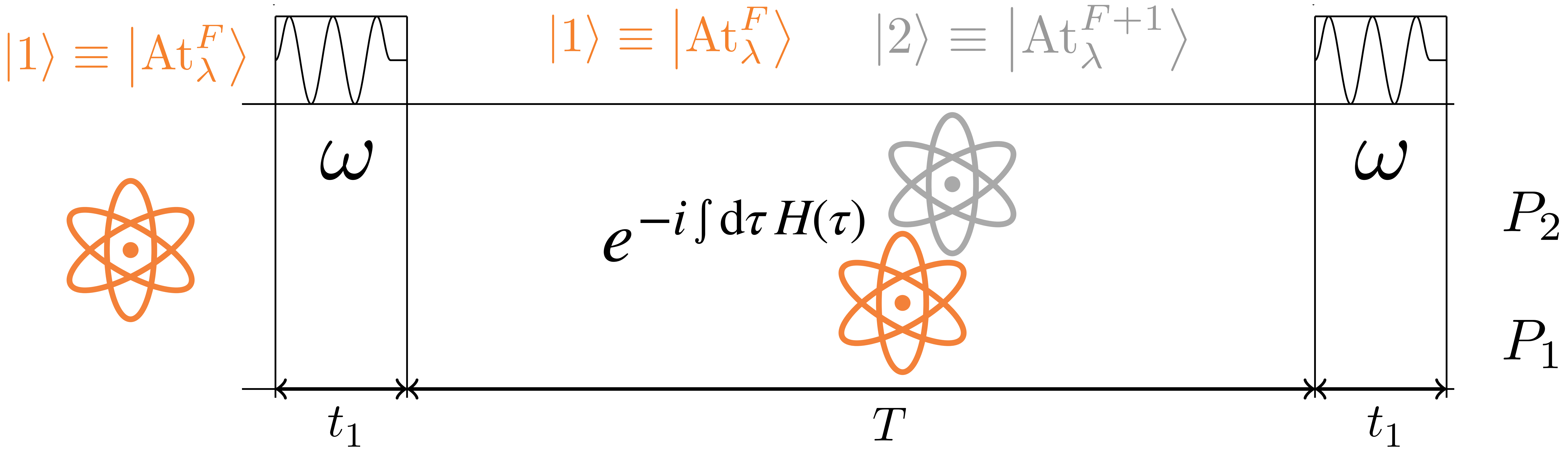

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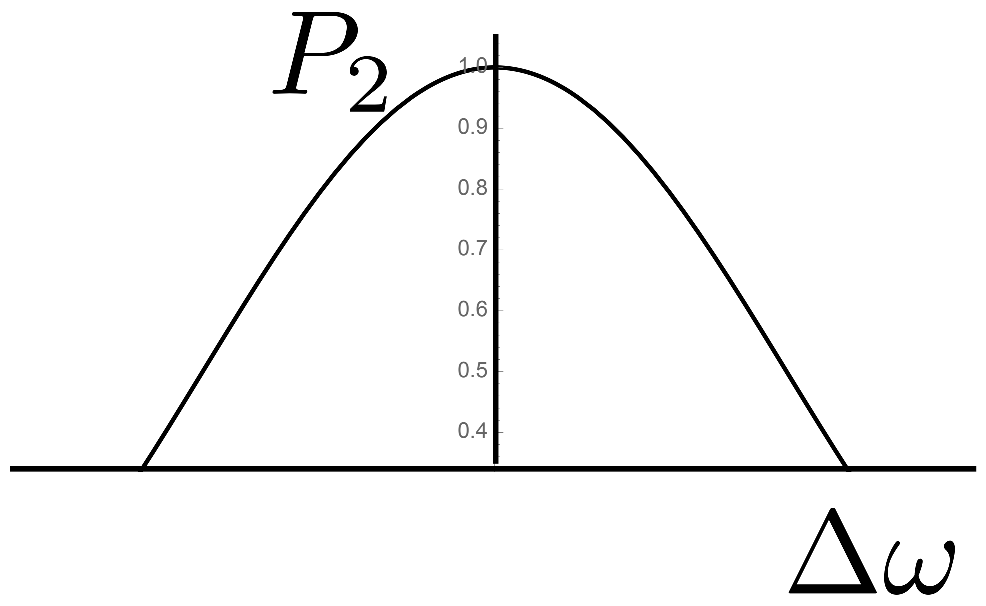


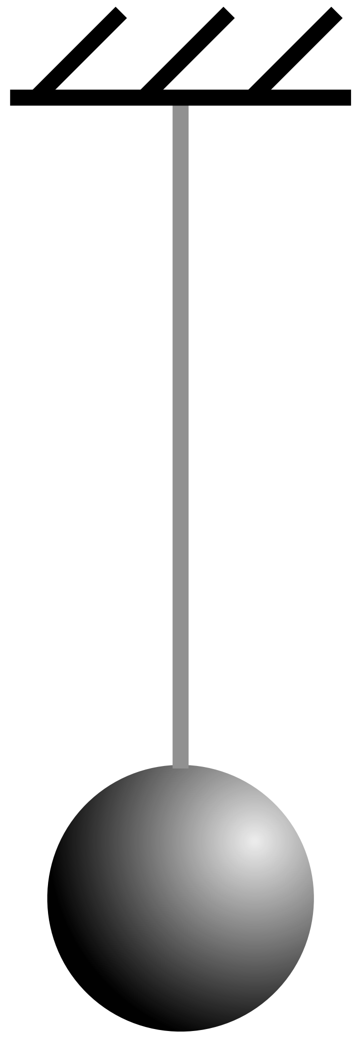
$$\partial P_2 = 0 \;\Rightarrow\; \omega_{\max} = \Delta E$$

We want : **long coherence**, small noise. ⇒ **Standard quantum limit** may be important

$$[\hat{\phi}, \hat{N}] = i \qquad \Delta\phi\Delta N \geq 1/2$$

Quantum noise vs classical measurements

To understand sensitivity, need to know about noise



Consider a simple harmonic oscillator:

$$x(t) = x(0)\cos(\Omega t) + \frac{p(0)}{m\Omega}\sin(\Omega t)$$

Autocorrelation

$$G_{xx}(t) = \langle x(0)x(0)\rangle\cos(\Omega t) + \frac{\langle p(0)x(0)\rangle}{m\Omega}\sin(\Omega t)$$

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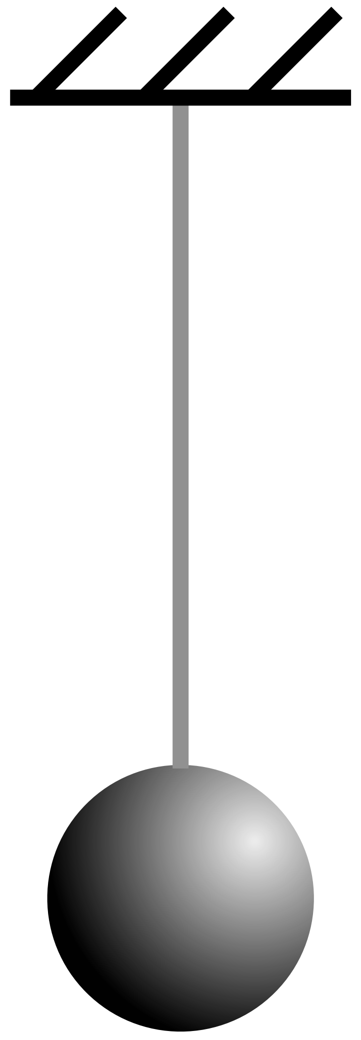

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Classically zero

Quantum noise vs classical measurements

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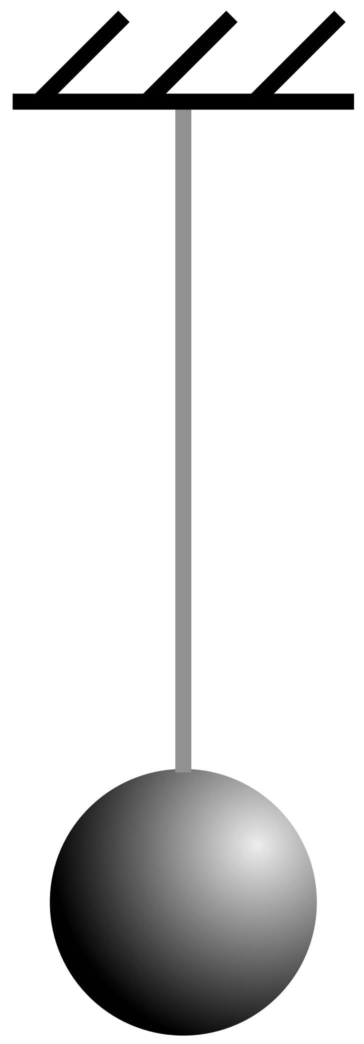

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QM $[\hat{x}, \hat{p}] = i\hbar$ $\Delta x \Delta p \geq \hbar/2$

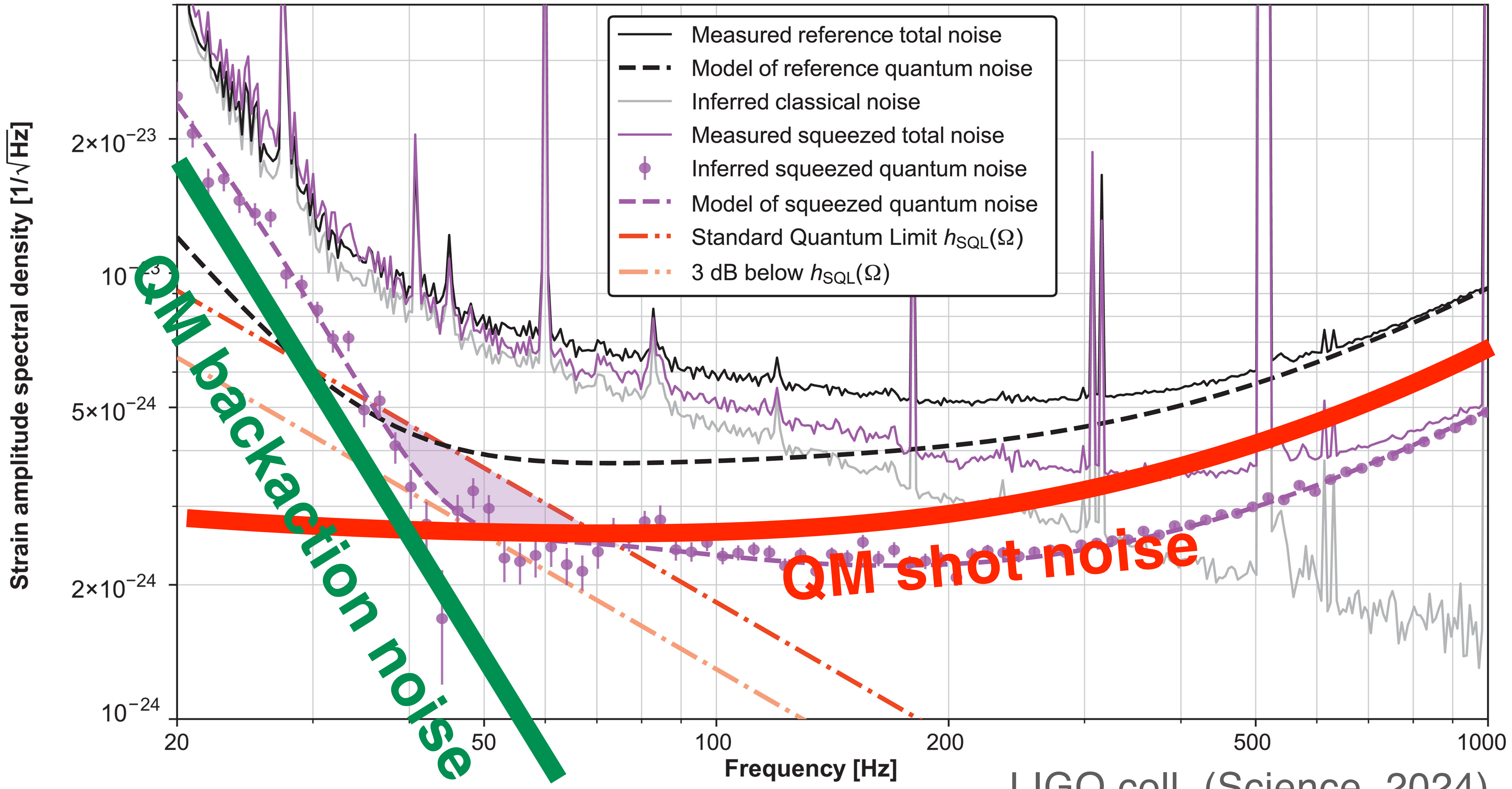
Independently of the state

This source of noise is called **back-action**

Quantum noise is already around

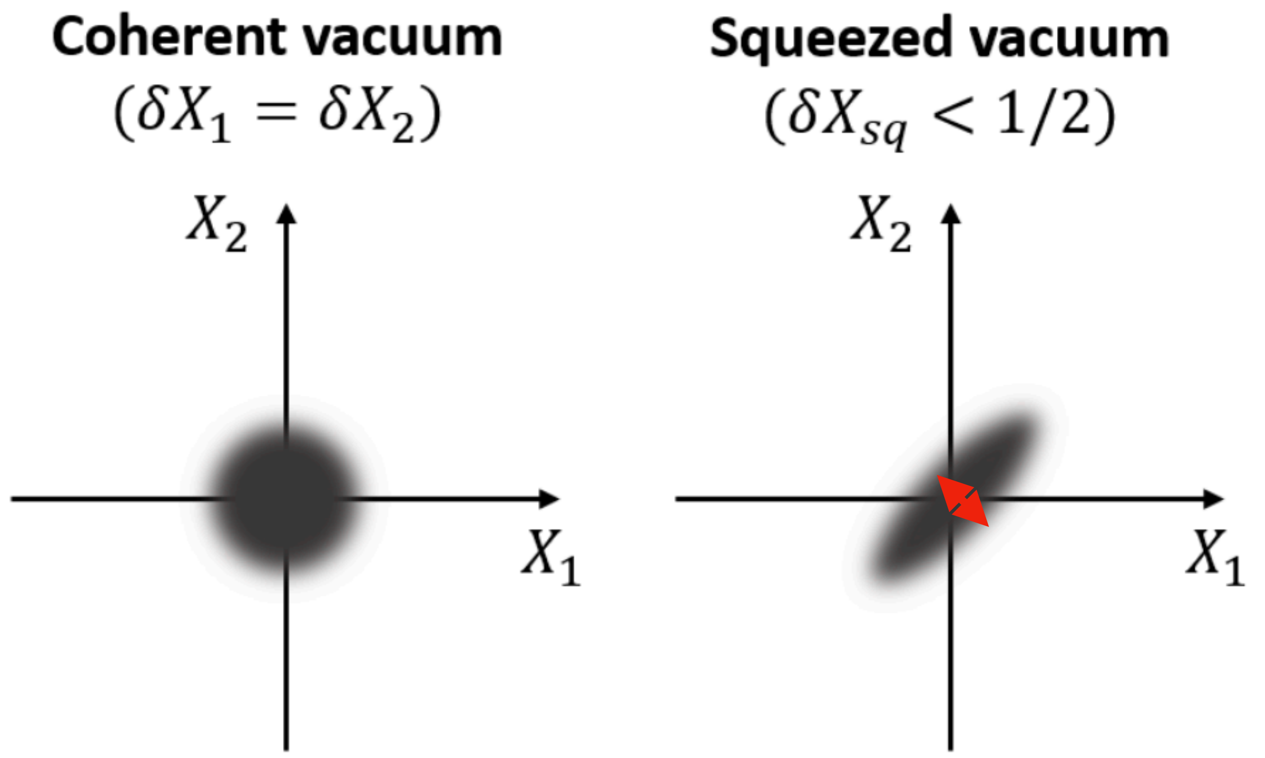
Even in a measurement with zero inserted photons, QM imposes a minimal noise level

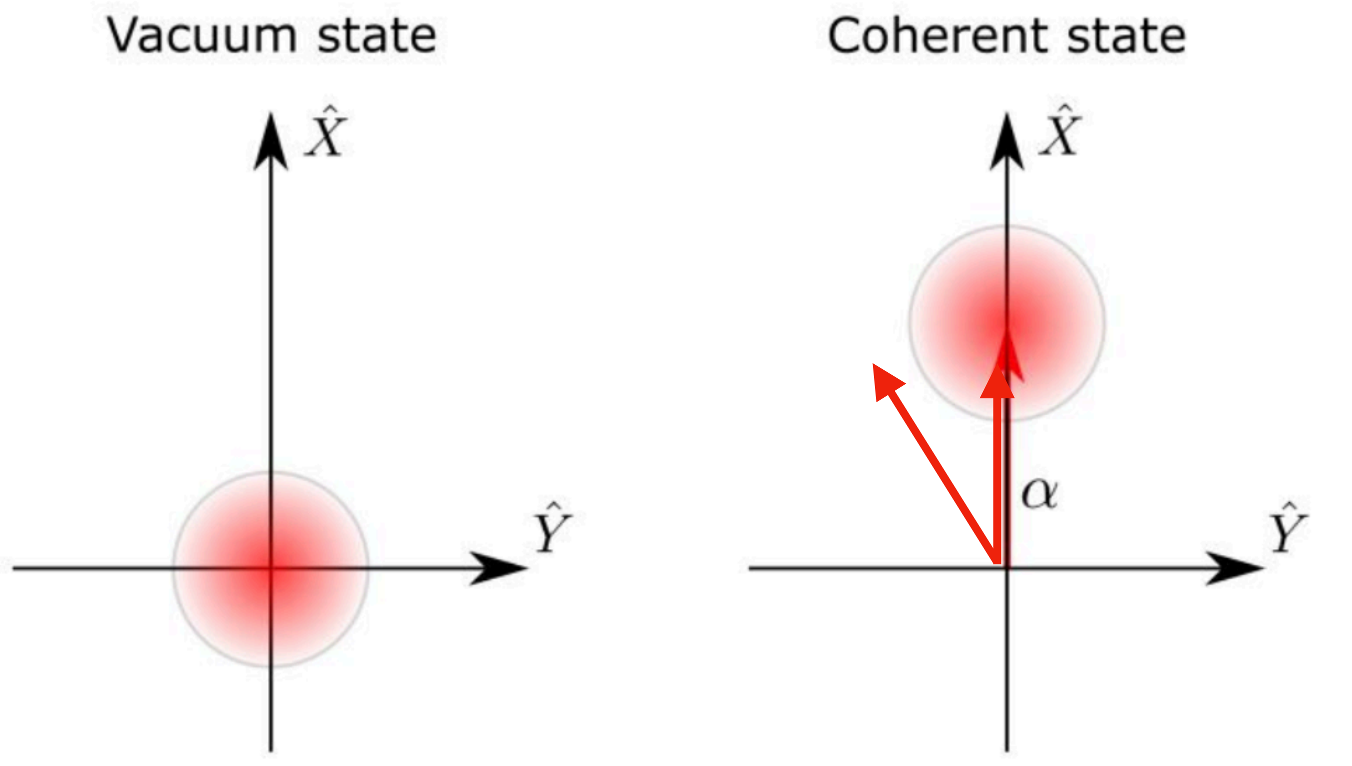
Standard Quantum Limit (SQL)
usually defined as regime where QM shot noise and back-action noise are simultaneously minimised



LIGO coll. (Science, 2024)

How to beat it? Squeezing or phase-space displacement





Measuring at $q = 0$: phase shifts in atomic systems

R. Alonso, DB and P. Wolf
1810.00889 & 1810.01632

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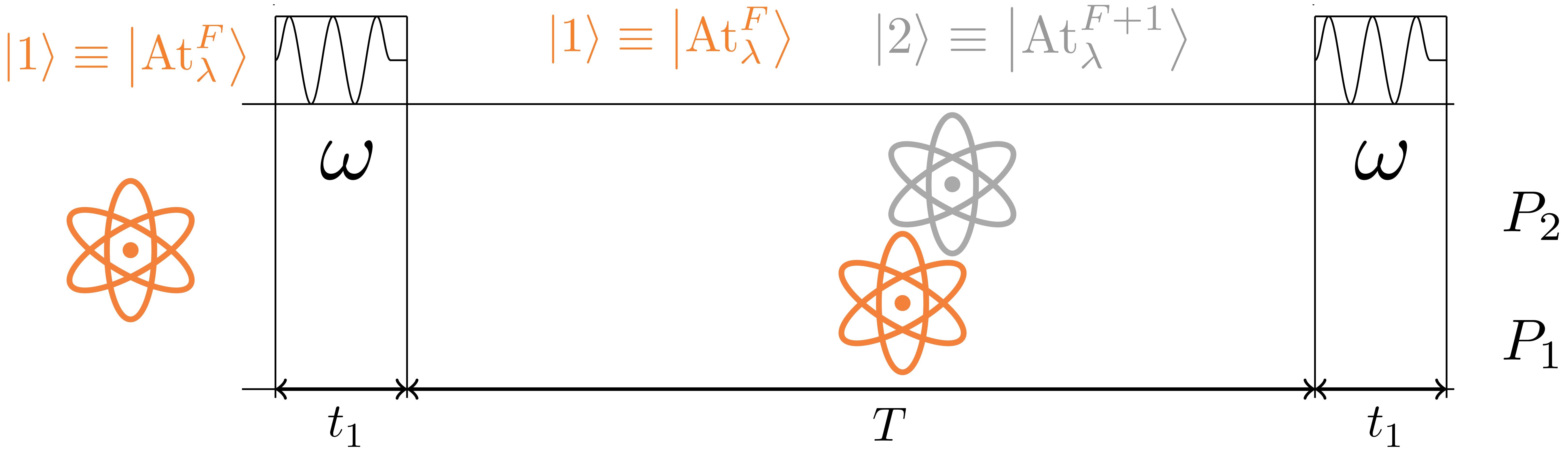

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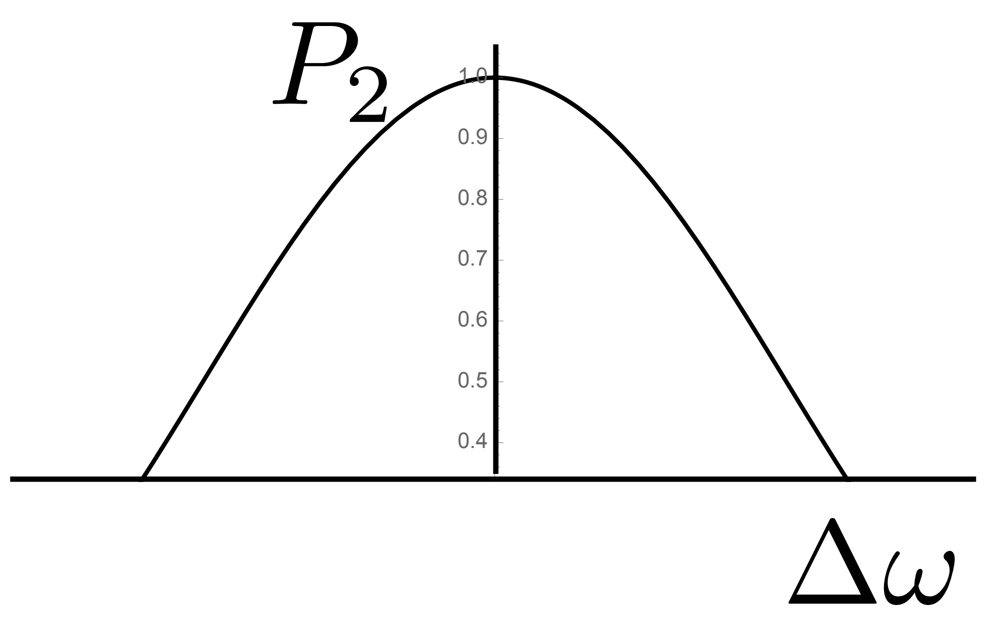

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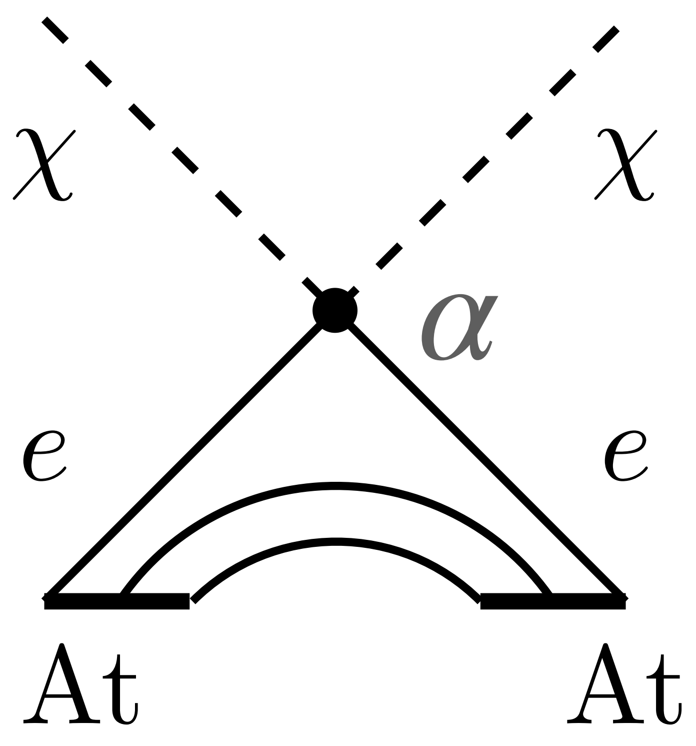
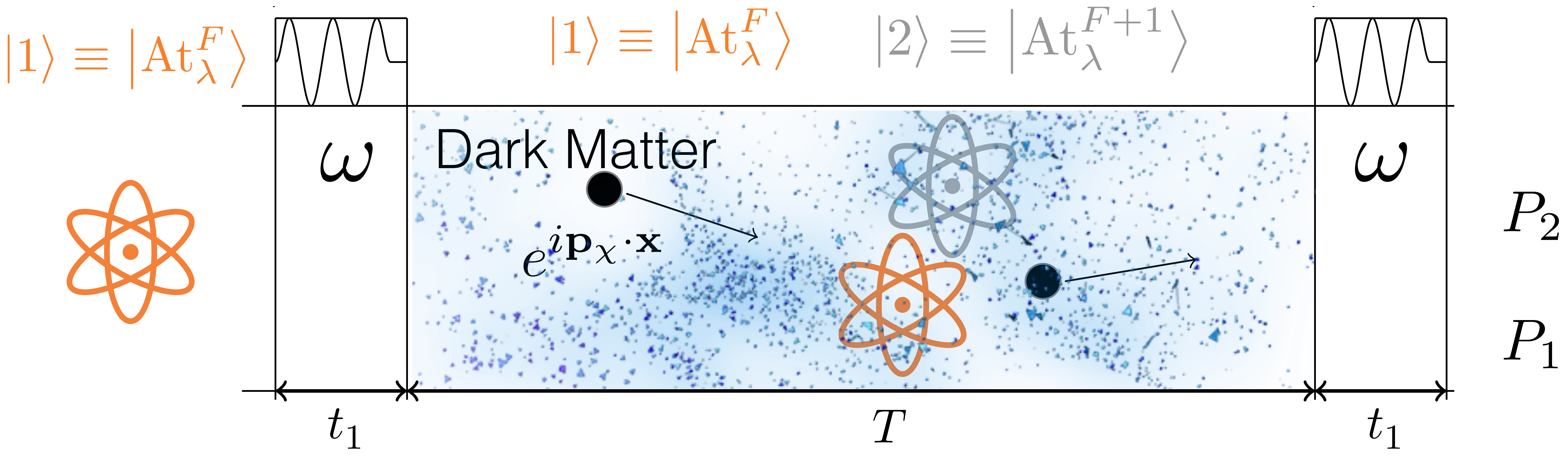
Du et al. 2205.13546

Ramsey sequence in the presence of DM





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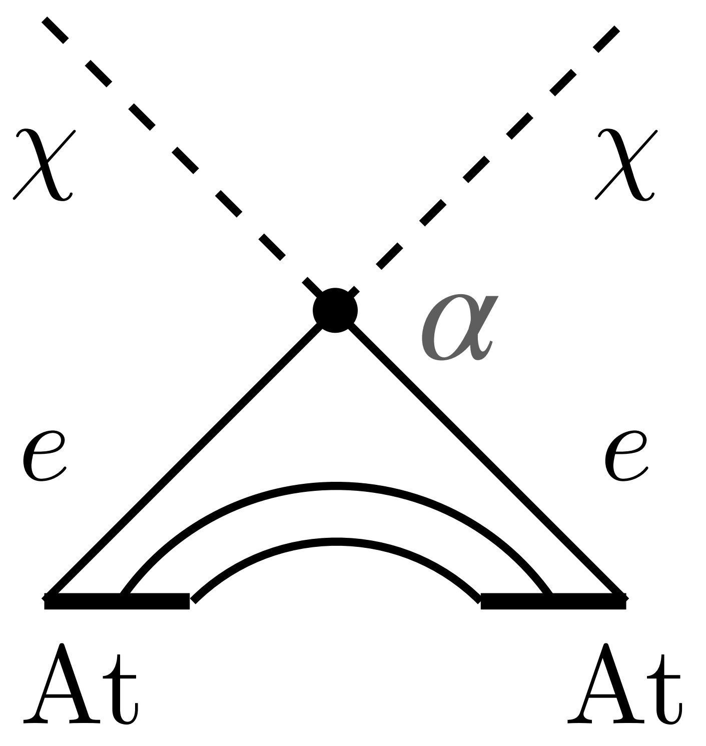
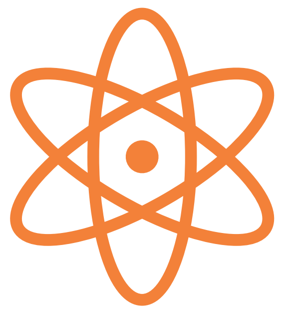
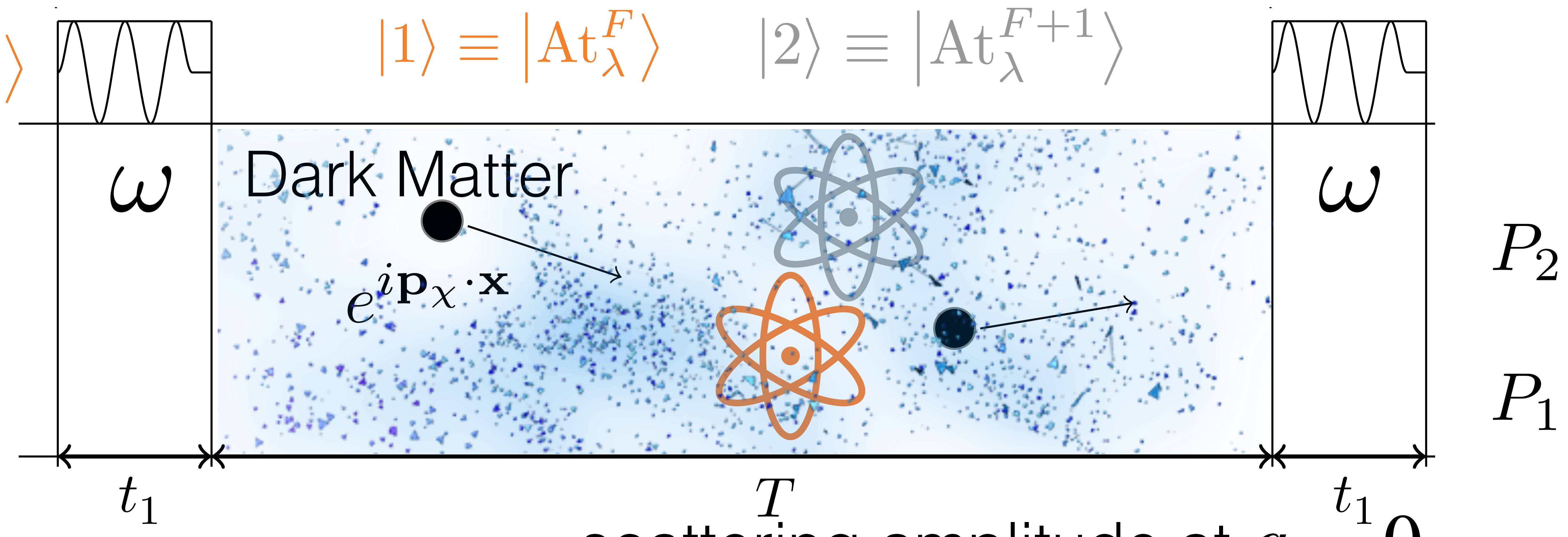


$m_{\rm DM} \ll m_{\rm atom}$





scattering amplitude at $q = 0$

$$P_2 = \cos[\Delta\omega T/2]^2 + \frac{\pi n_\chi v T}{p_\chi} {\rm Re}[\bar{f}_1(0) - \bar{f}_2(0)] \sin[\Delta\omega T]$$

$$\partial P_2 = 0 \quad \Rightarrow \quad \omega_{\rm max} = \Delta E + \delta_{\rm DM}$$

QM allows us to measure $q = 0$ and move to **low DM masses**!

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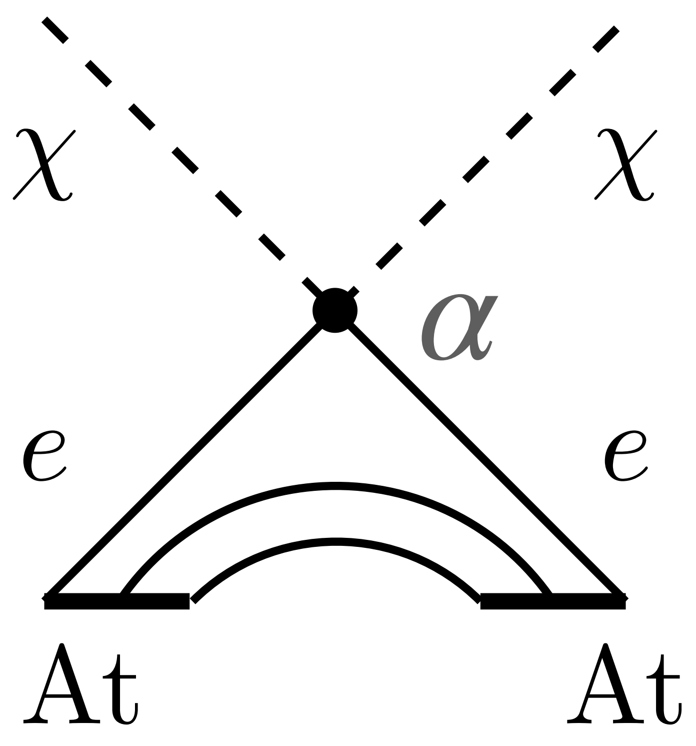
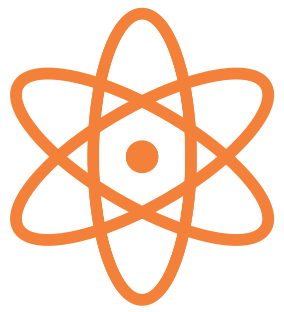
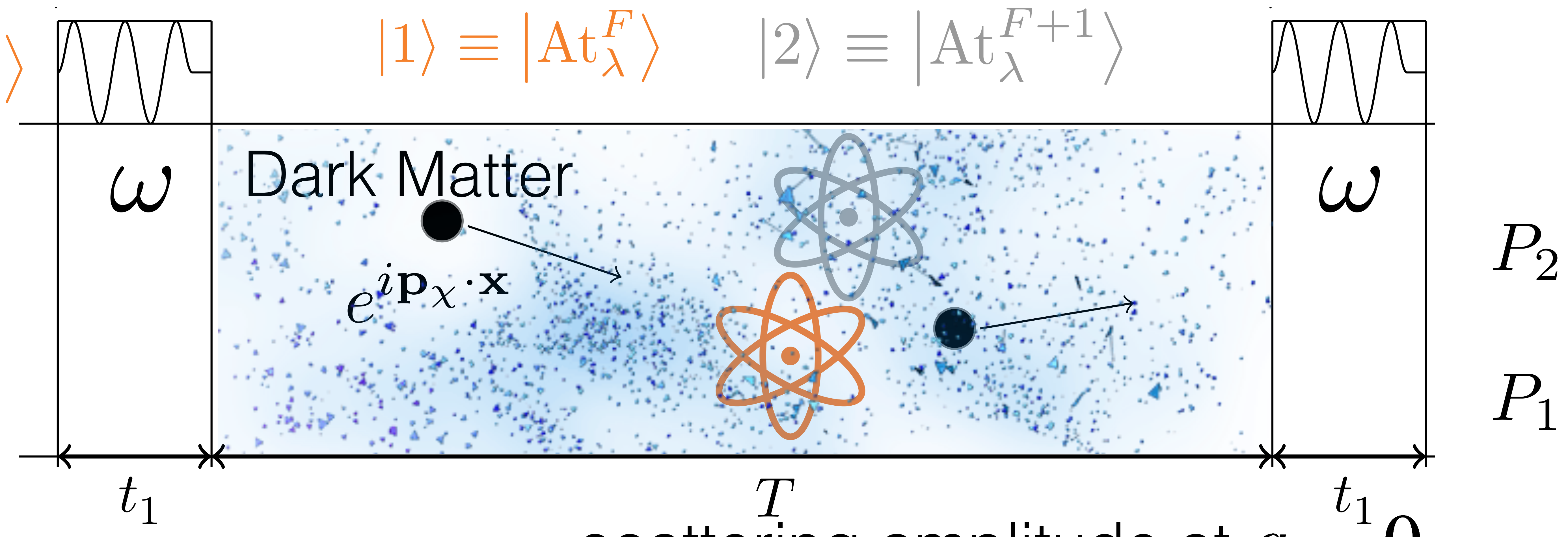


$m_{\rm DM} \ll m_{\rm atom}$

$|1\rangle \equiv |{\rm At}_\lambda^F\rangle$





scattering amplitude at $q = 0$ $\sim \alpha$

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$$\partial P_2 = 0 \quad \Rightarrow \quad \omega_{\rm max} = \Delta E + \delta_{\rm DM}$$

QM allows us to measure $q = 0$ and move to **low DM masses**!

Scalability is an issue:

$\Delta\phi\Delta N \geq 1/2$
$N \sim 10^8$

Also extra source of decoherence.

[Riedel, Yavin, 2016] [Du, Murgui, Pardo, Wang, Zurek, 20
[Badurina, Murgui, Plestid, 2024]

Better use density matrices

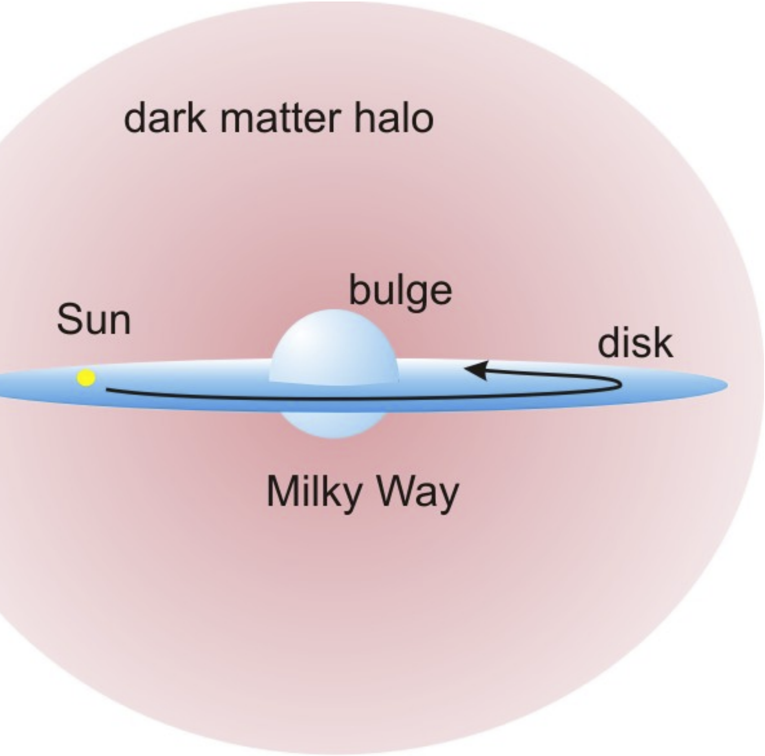
$$\rho = \frac{1}{2}\begin{pmatrix} 1 & \gamma e^{i\phi} \\ \gamma^* e^{-i\phi} & 1 \end{pmatrix} \qquad \gamma \sim \alpha^2$$

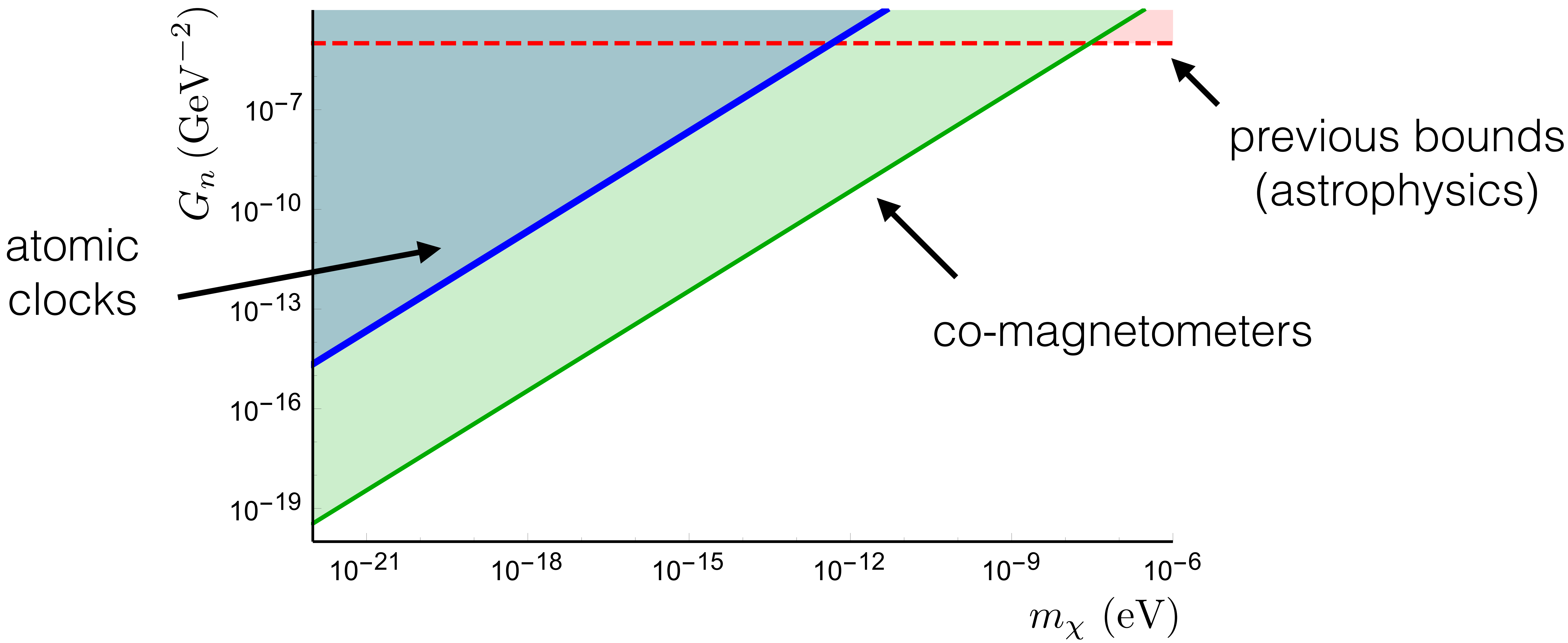
One example: complex scalar DM

Alonso, DB, Wolf 1810.00889

nucleons DM

$$L_{\rm int} = -G_n \int \mathrm{d}^3x\, (\bar{n}\gamma^\mu\gamma_5 n)\, (i\chi^\dagger\partial_\mu\chi + \mathrm{h.c.}) \quad \Rightarrow \quad \vec{S}_n \cdot \vec{v}_\chi$$





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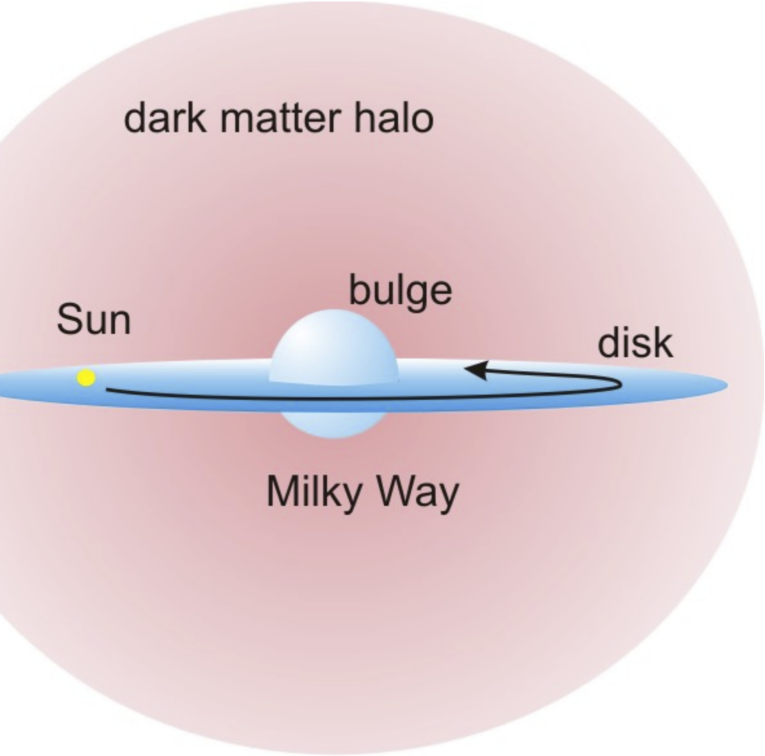
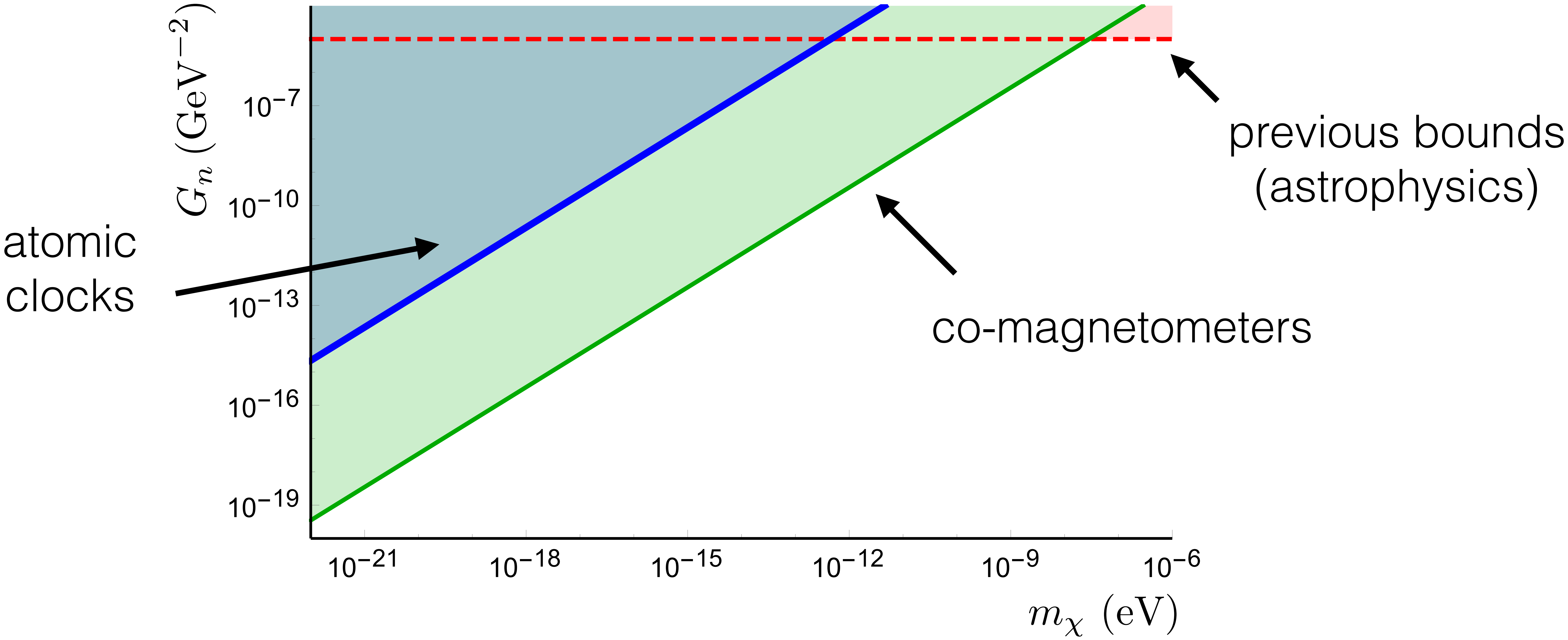
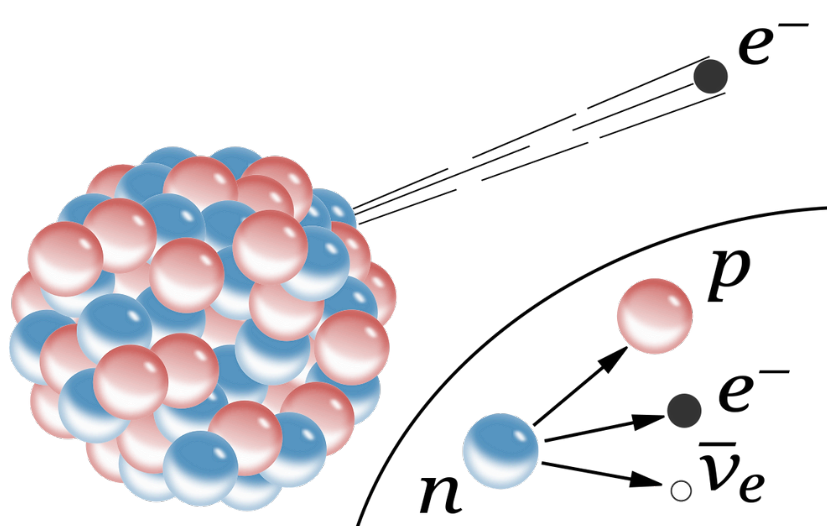


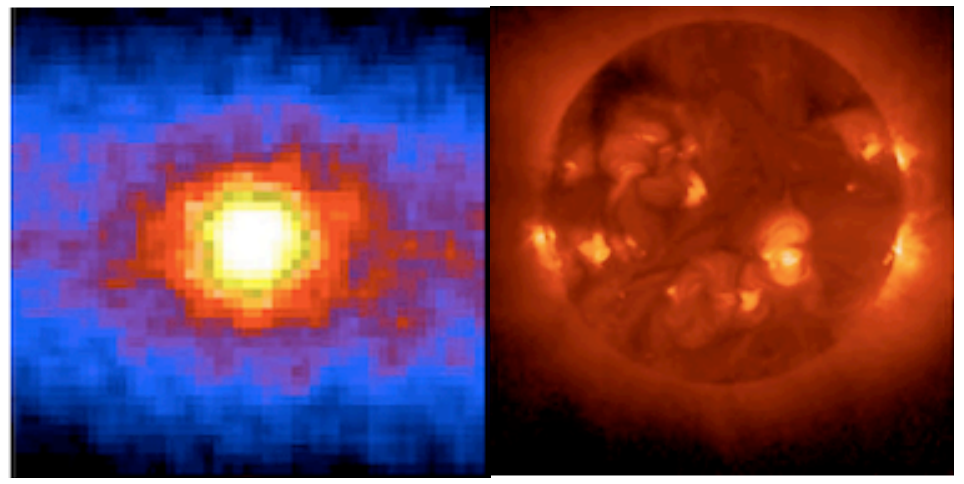


for cosmic neutrinos see Alonso, DB, Wolf 1810.00889
Bauer & Shergold 2207.12413

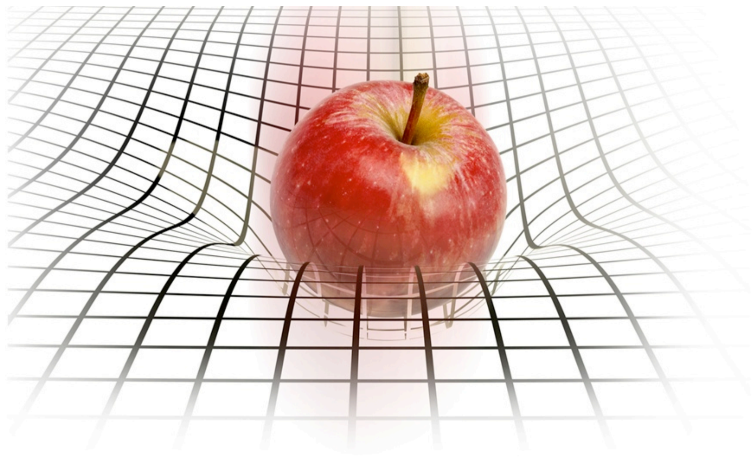
Fundamental signals of ‘high’ flux



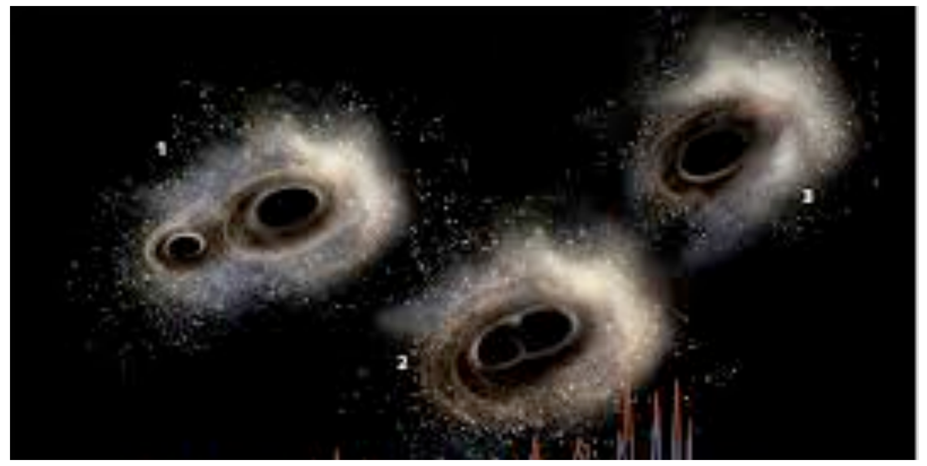
Neutrinos (Standard Model + new physics portal)



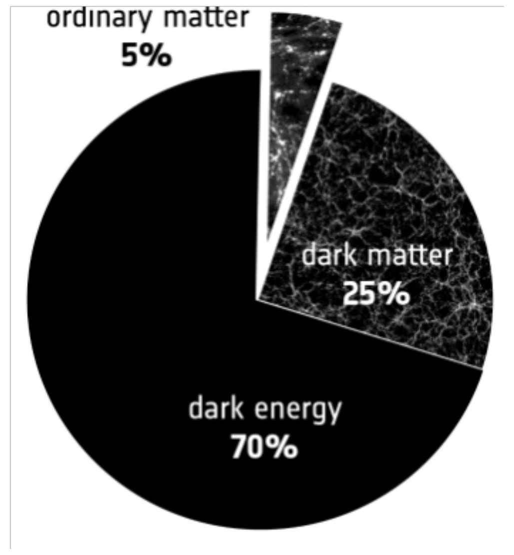
Produced in **nuclear** reactions
(**inside stars/ early Universe**)



Gravitational waves (SM + new physics portal)

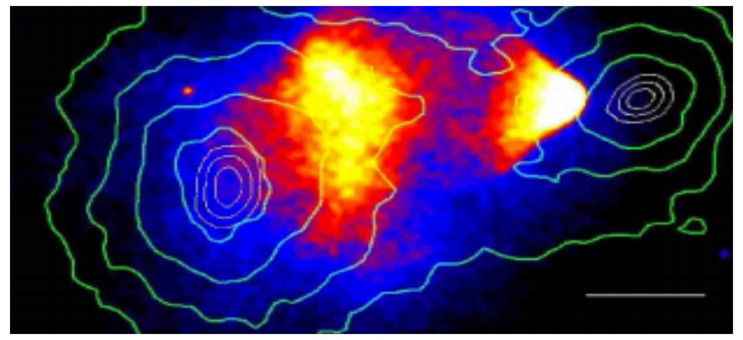


Distortions of gravitational field
Universally produced by **all** energetic events



Dark matter & Dark Energy(BSM)

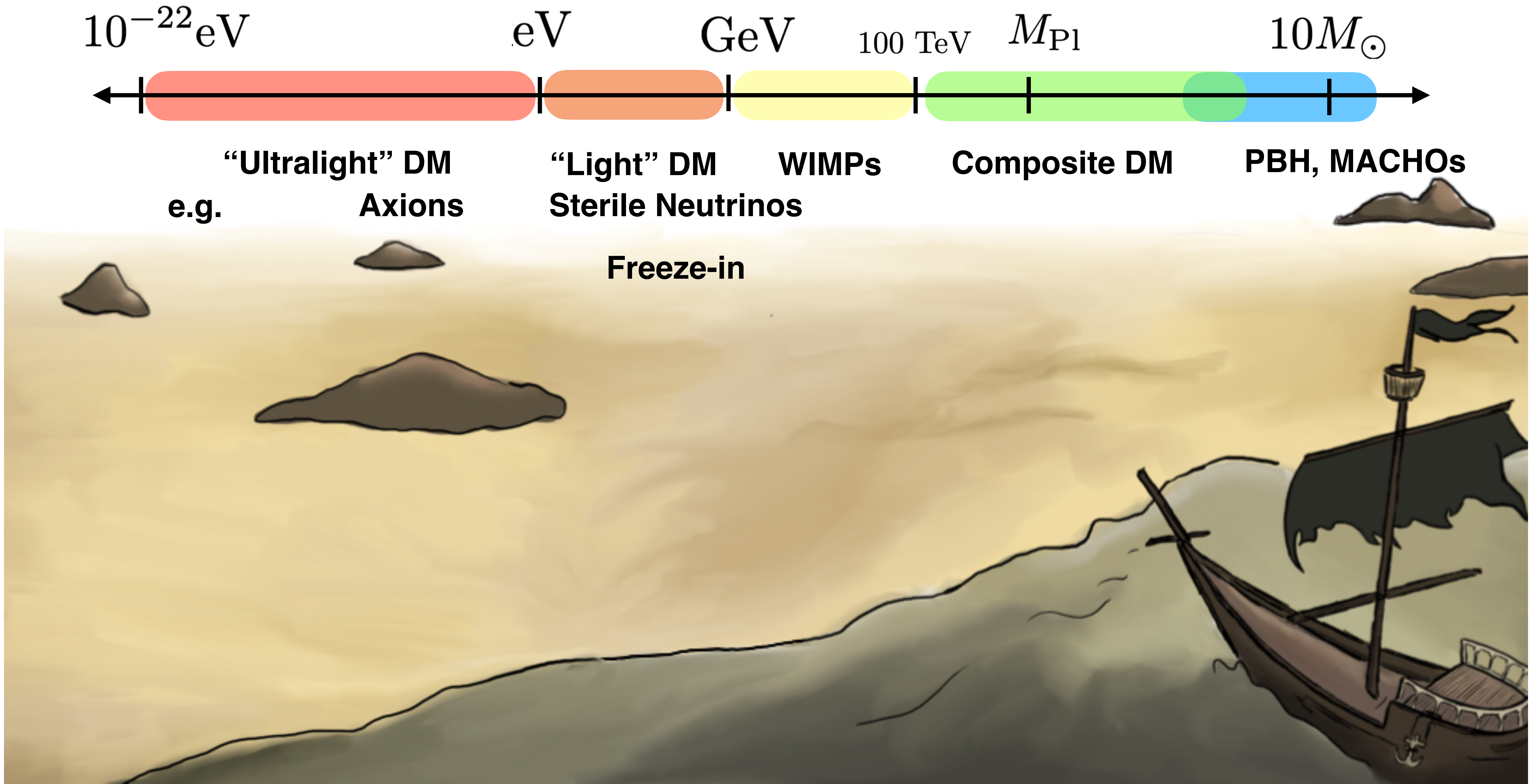
Permeates the Universe, in particular the laboratory.
Doesn’t emit light, but interacts with matter



Dark matter candidates beyond WIMP

Mass and *particle vs macroscopic nature*

are the most universal ones



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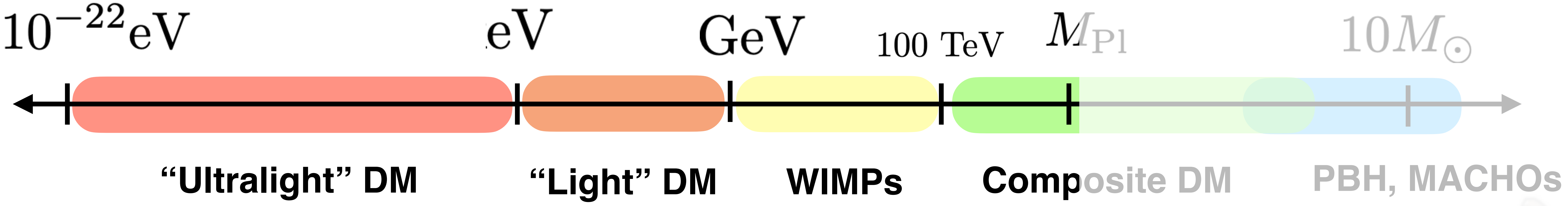

Most relevant different for laboratory searches: high occupancy per state

- typical **distance** between particles

$$d \sim n^{-1/3} \sim (M_{\rm gal}/(mV_{\rm gal}))^{-1/3} \sim 10^{-19}\,{\rm pc}\frac{r_{\rm gal}}{100\,{\rm kpc}}\left(\frac{10^9 M_\odot}{M_{\rm gal}}\frac{m}{\rm eV}\right)^{1/3}$$

- typical **size** of particle wavepacket in the halo

$$|\phi(x)\rangle = \int d^3p\, \phi(p)\,|p\rangle$$

$$L \gtrsim 1/p_{\rm max} \sim 1/(mv_{\rm esc}) \approx 190\left(\frac{10^{-22}{\rm eV}}{m}\right){\rm pc}$$

particles overlap for $d \lesssim L$

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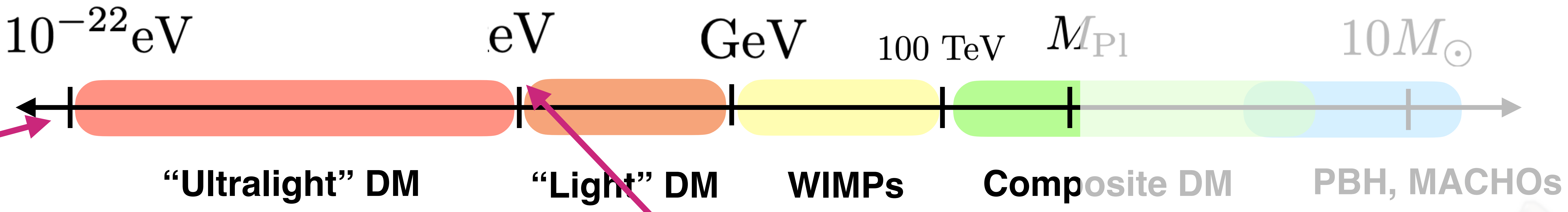
are the most universal ones



For minimum mass, see extra slide

Most relevant different for laboratory searches: high occupancy per state

- typical **distance** between particles $$d \sim n^{-1/3} \sim (M_{\rm gal}/(mV_{\rm gal}))^{-1/3} \sim 10^{-19}\,{\rm pc}\frac{r_{\rm gal}}{100\,{\rm kpc}}\left(\frac{10^9 M_\odot}{M_{\rm gal}}\frac{m}{\rm eV}\right)^{1/3}$$

- typical **size** of particle wavepacket in the halo $$L \gtrsim 1/p_{\rm max} \sim 1/(mv_{\rm esc}) \approx 190\left(\frac{10^{-22}{\rm eV}}{m}\right){\rm pc}$$

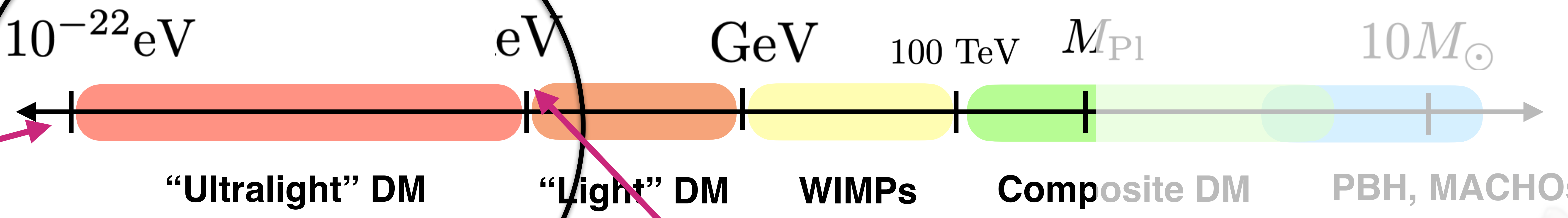
$$|\phi(x)\rangle = \int {\rm d}^3p\, \phi(p)\,|p\rangle$$

particles overlap for $d \lesssim L$ → For the Milky Way this is $m \sim 1$ eV (necessarily boson)

Dark matter candidates beyond WIMP

Mass and *particle* *vs macroscopic nature*

are the most universal ones



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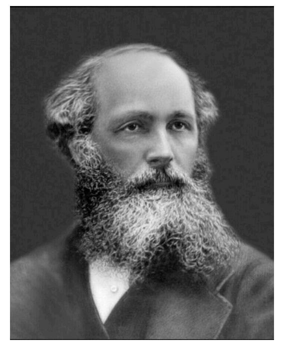
Detecting ultralight dark matter

When particles overlap in phase space, they start behaving collectively.

https://arxiv.org/abs/2408.04696

$\langle \hat{\phi}_{\rm DM} \rangle \equiv \phi_{\rm DM}$ starts behaving as **classical** field satisfying **classical** equations of motion



(as happens for quantum optics)

$$\mathscr{L} = \frac{1}{2}\left[(\partial_\mu \hat{\phi})^2 - m^2 \hat{\phi}^2\right] \rightarrow (\Box + m^2)\phi_{\rm DM} = 0 \rightarrow \phi_k \sim e^{i(\omega t - kx)}$$

(with suppressed fluctuations)

Non-relativistic

$$\omega_v \approx m(1 + v^2/2)$$

$$\vec{k}_v = m\vec{v}$$

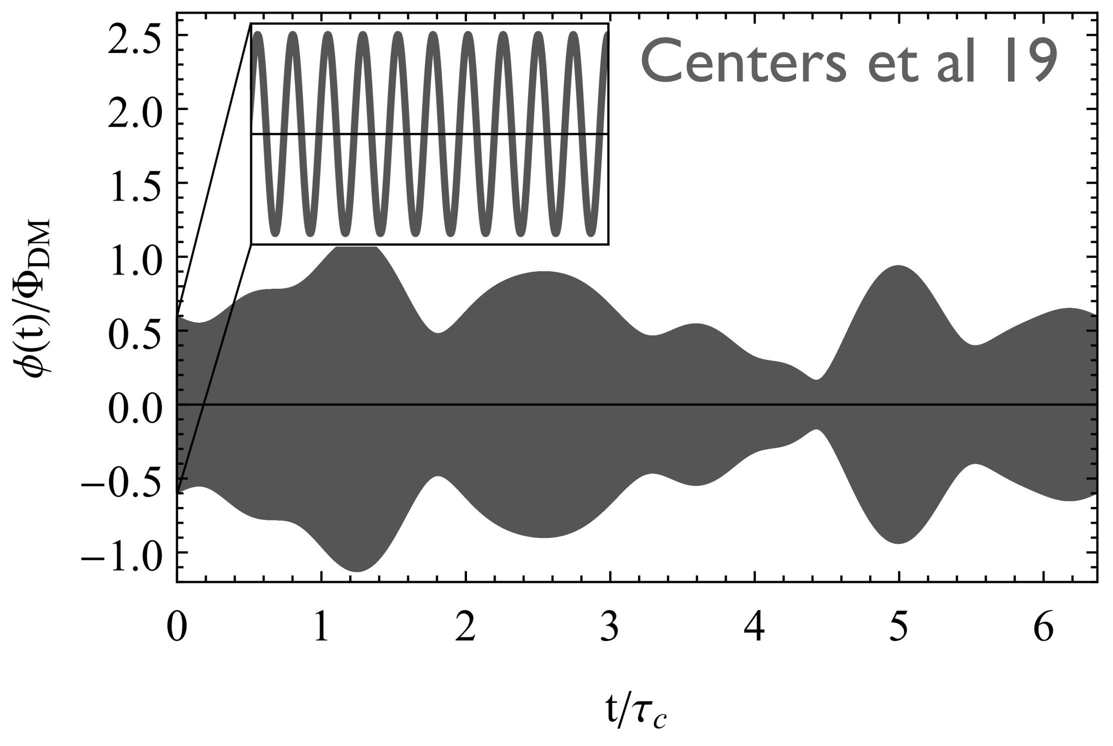
$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v\, f(\vec{v})\, e^{i\omega_v t}\, e^{-im\vec{v}\cdot\vec{x}}\, e^{if_{\vec{v}}} + c.c.$$

distribution of waves interacting gravitationally in a virtualized halo

$$f(v) = \begin{cases} \frac{1}{N_{esc}} \left(\frac{3}{2\pi\sigma_0^2}\right)^{3/2} e^{-\frac{3}{2}\frac{v^2}{2v_0^2}} & , v^2 < v_{esc} \\ 0 & , v > v_{esc} \end{cases}$$

Detecting ultralight dark matter

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3v\, e^{-\frac{3v^2}{2v_0^2}}\, e^{im(1+v^2/2)t}\, e^{-im\vec{v}\cdot\vec{x}}\, e^{if_{\vec{v}}} + c.c. \propto e^{imt} \int_0^{v_{max}} \mathrm{d}^3v\, e^{-\frac{3v^2}{2v_0^2}}\, e^{imv^2/2t}\, e^{-im\vec{v}\cdot\vec{x}}\, e^{if_{\vec{v}}} + c.c.$$



common part of oscillation

$$t_m \sim 1/m \sim \frac{10^{-15}\mathrm{eV}}{m} s$$

adds dispersion after

$$\tau_c \sim \frac{10^6}{m}\left(\frac{10^{-6}}{\sigma_0^2}\right) \sim 10^6\mathrm{yr}\left(\frac{10^{-22}\mathrm{eV}}{m}\right) \gg t_c$$

space independent at

$$d \lesssim \lambda_{\mathrm{dB}} \sim \frac{10^{-22}\mathrm{eV}}{m}\frac{10^{-3}}{v}\mathrm{kpc}$$

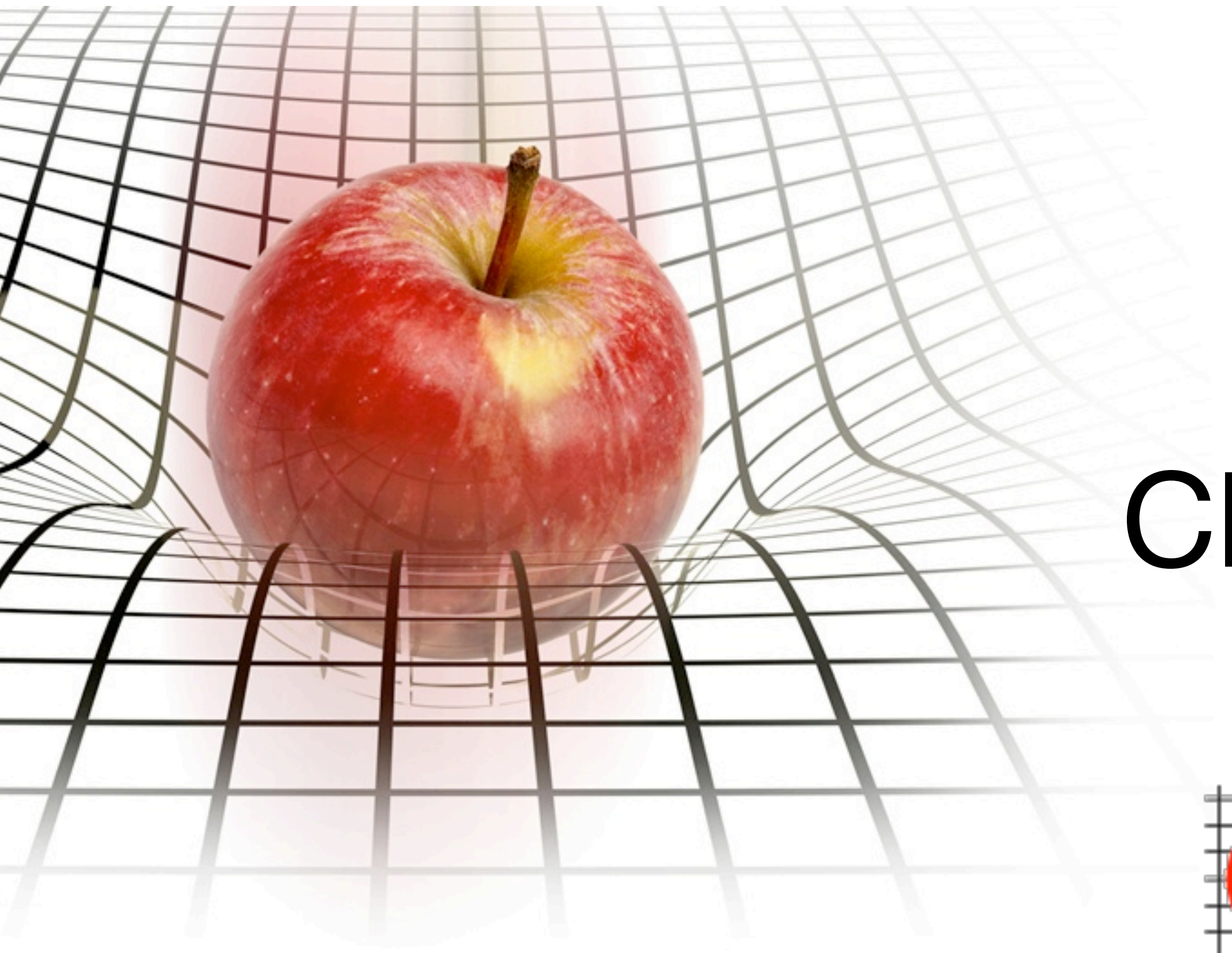
So, at ‘short’ times and ‘small’ distances

$$\phi = \phi_0 \cos(mt + m\vec{v}\cdot\vec{x} + \varphi_0)$$

For this field, its energy density is

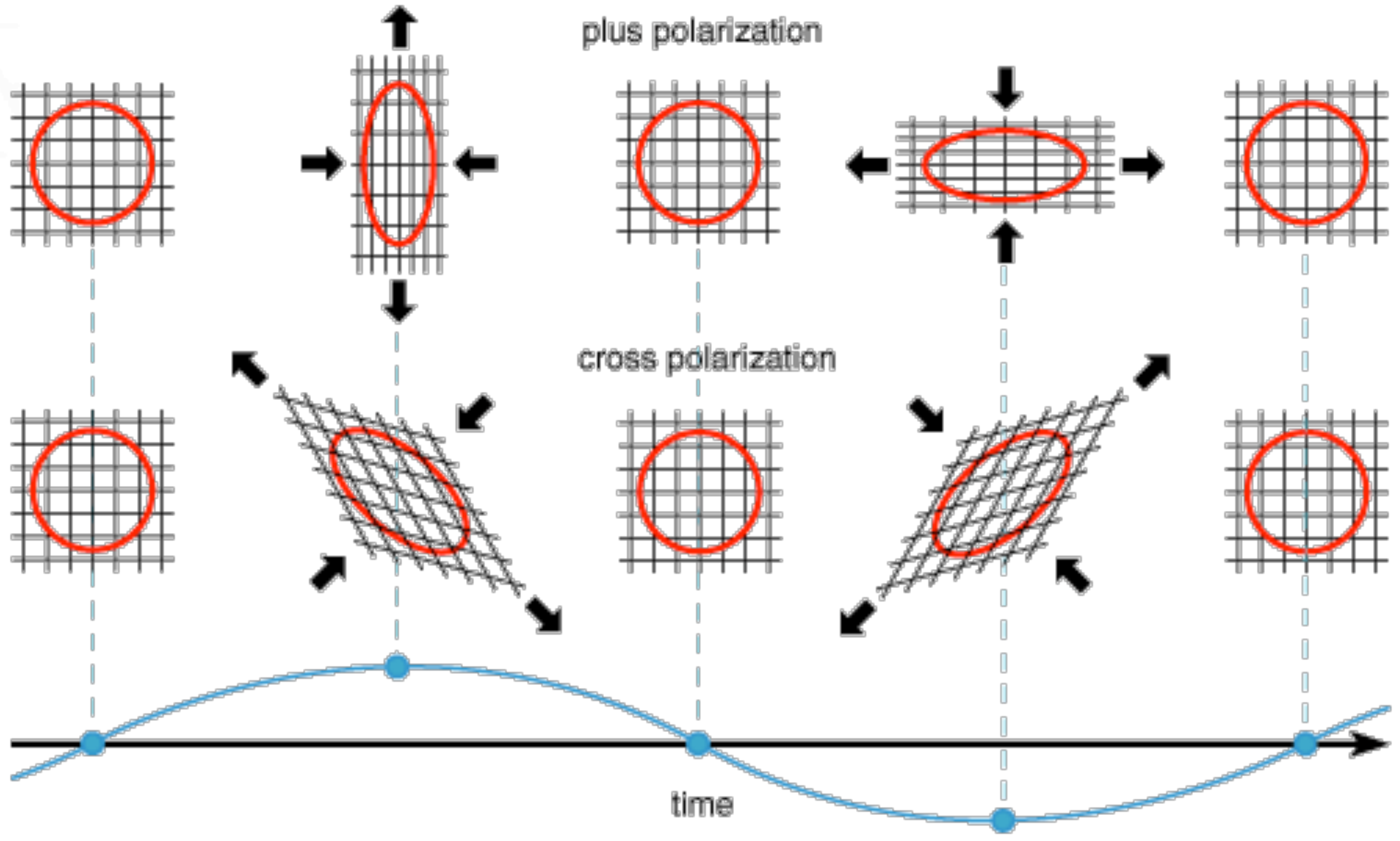
$$\langle\rho\rangle_t = \frac{1}{2}\langle\left(\dot{\phi}^2 + (\partial_i\phi)^2 + m^2\phi^2\right)\rangle_t \approx m^2\phi_0^2\langle\cos(mt+\varphi_0)^2\rangle_t = \frac{m^2}{2}\phi_0^2$$

GWs (essentials)



Perturbations of space-time
travelling as waves of frequency f

Characterised by 2 polarizations $h_{+,\times}$ (dimensionless)



$$h_{+,\times} \overset{c=1}{\approx} h_0 \cos\left(2\pi f(t-z)+\phi\right)$$

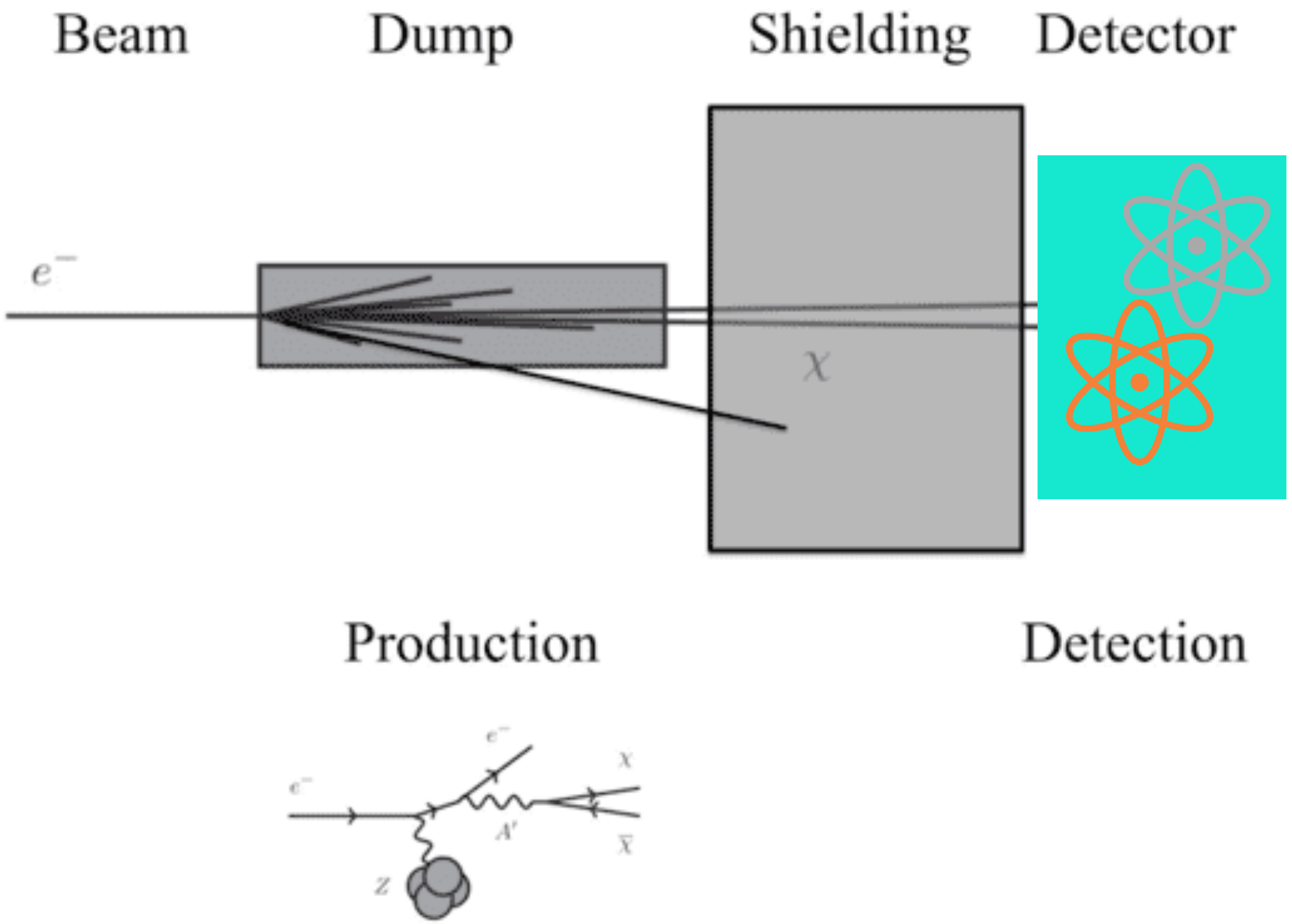
$$h_0 \approx \delta L/L \approx \delta E/E....$$

GWs carry energy. They have **energy density**

GWs couple to **ANYTHING** in your lab!

May also be relevant for machine made backgrounds

advantage of being table top

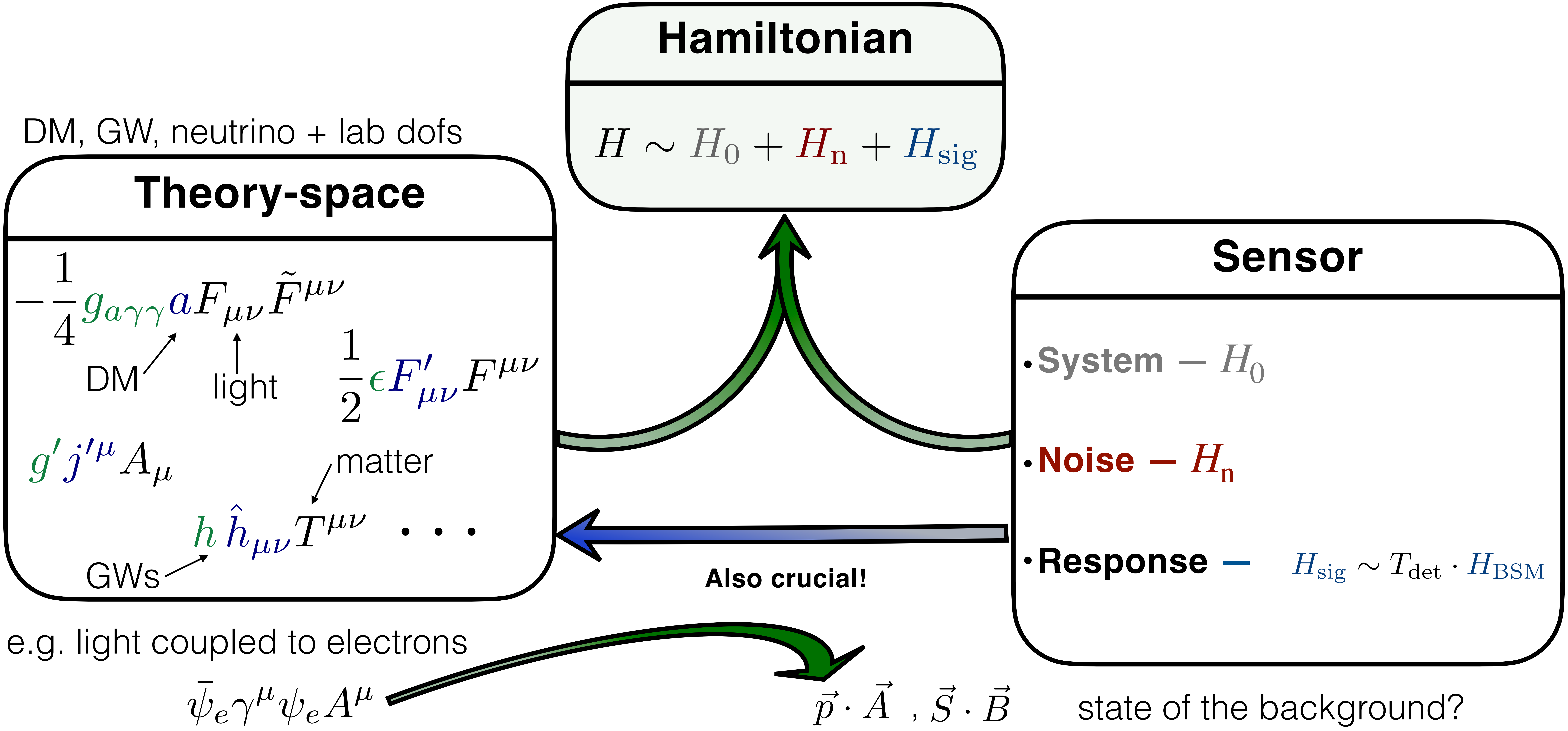


"no" energy-threshold: sensitive to whole flux

fig. adapted from 1712.01518

Searching for fundamental backgrounds with QS

How do these backgrounds affect precision measurements



Searching for fundamental backgrounds with QT

How do these backgrounds affect precision measurements

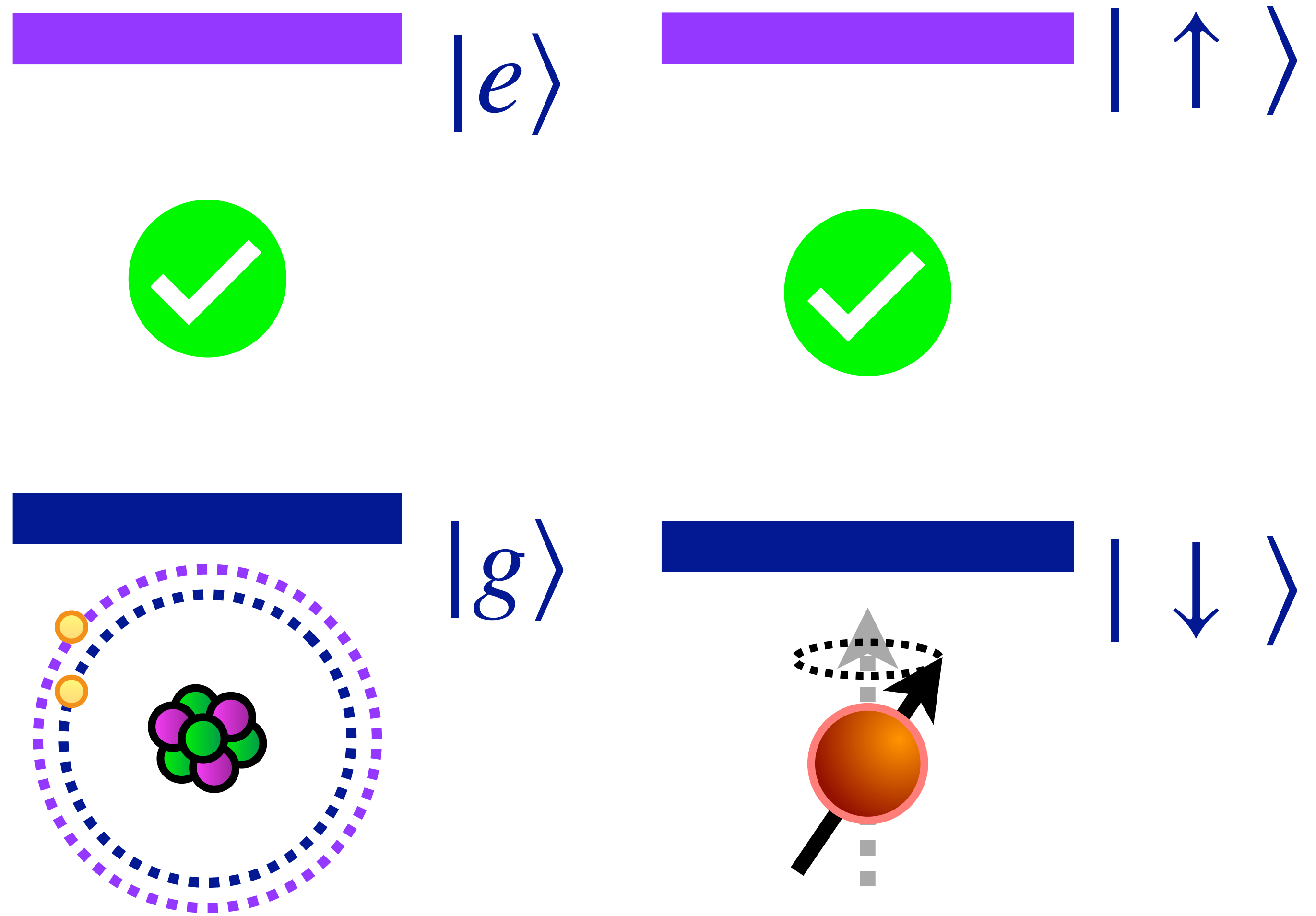
Part II: three (biased) examples

i) DM & cosmic neutrinos w/ atomic clocks and co-magnetometers

(see before)

ii) Large atomic interferometers

iii) GWs & axions in (superconducting radio-frequency) cavities



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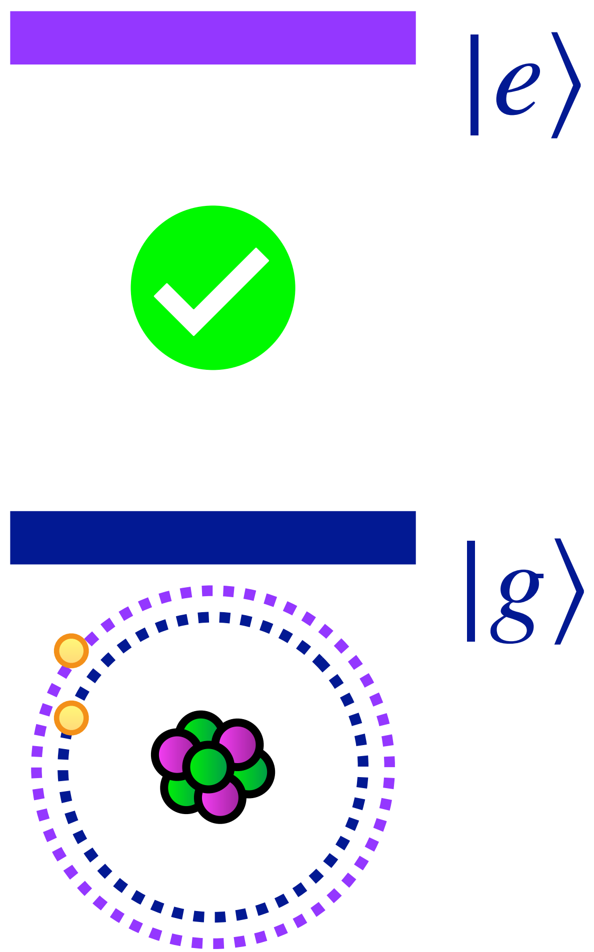
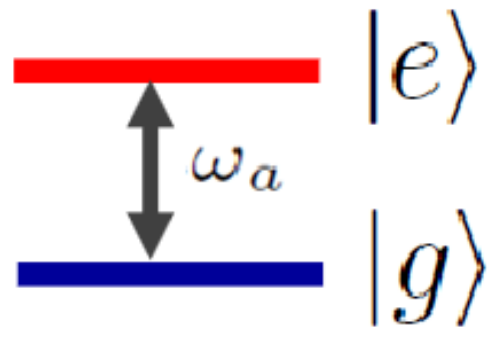


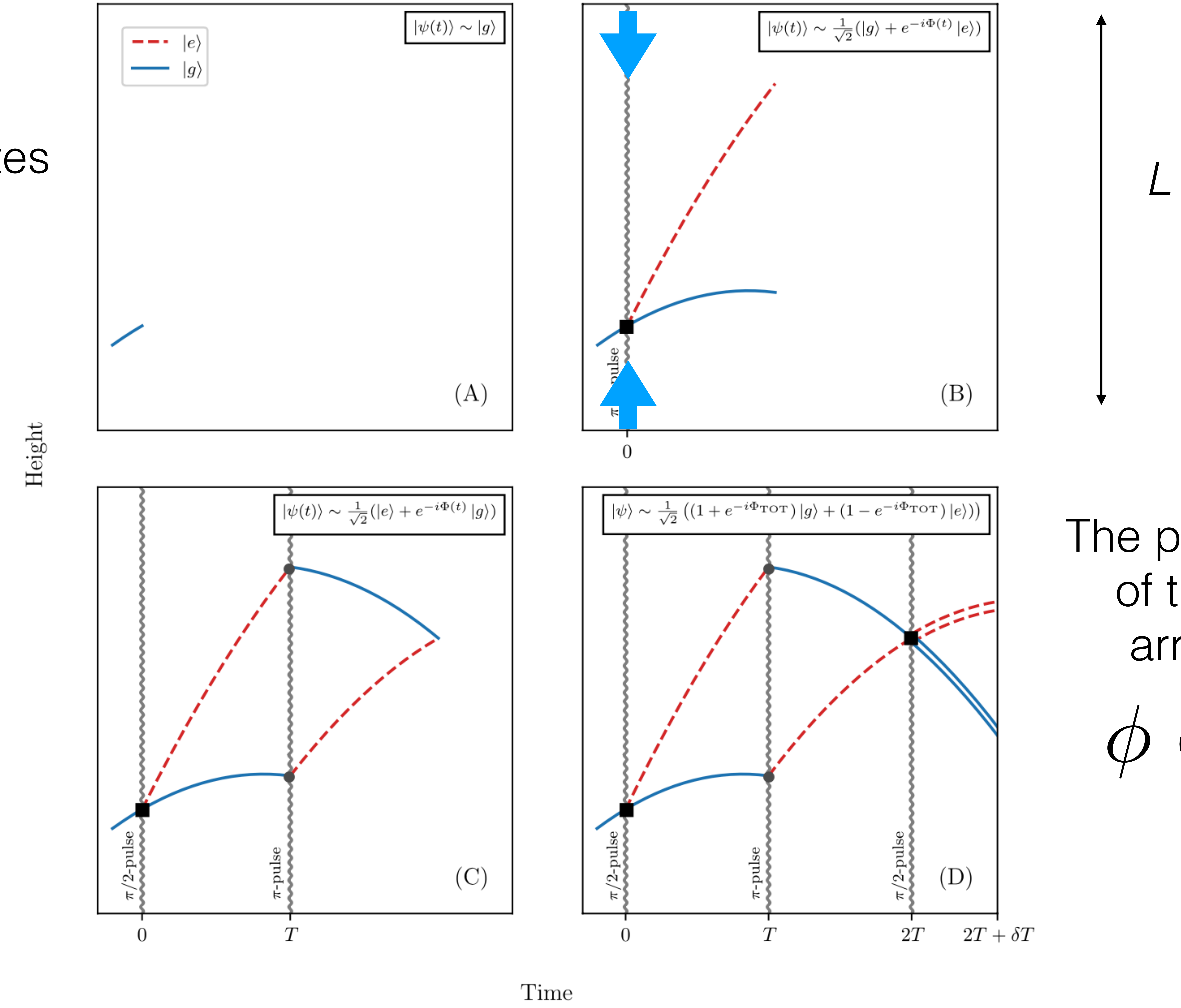
Long-baseline atomic interferometers

Dimopoulos et al 0712.1250
0806.2125
Arvanitaki et al 1606.04541

Basic concept:
atoms in free fall
with two possible states



$$|\psi(t)\rangle = e^{-iHt}|\psi(0)\rangle$$

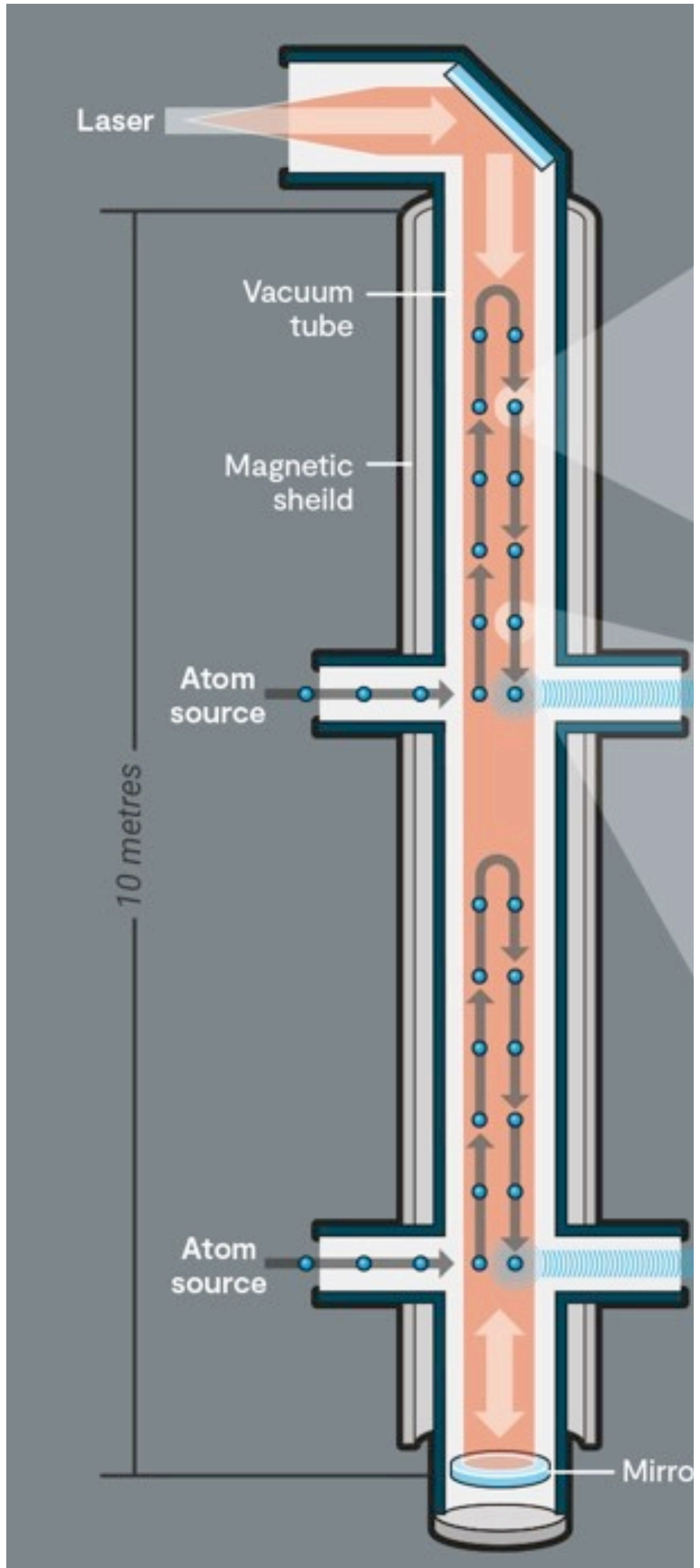


The phase difference
of the two states
arranged to be

$$\phi \propto \omega_A L/c$$

Optimized with more than one AI

Dimopoulos et al 0712.1250
0806.2125
e.g. Badurina et al 2108.02468



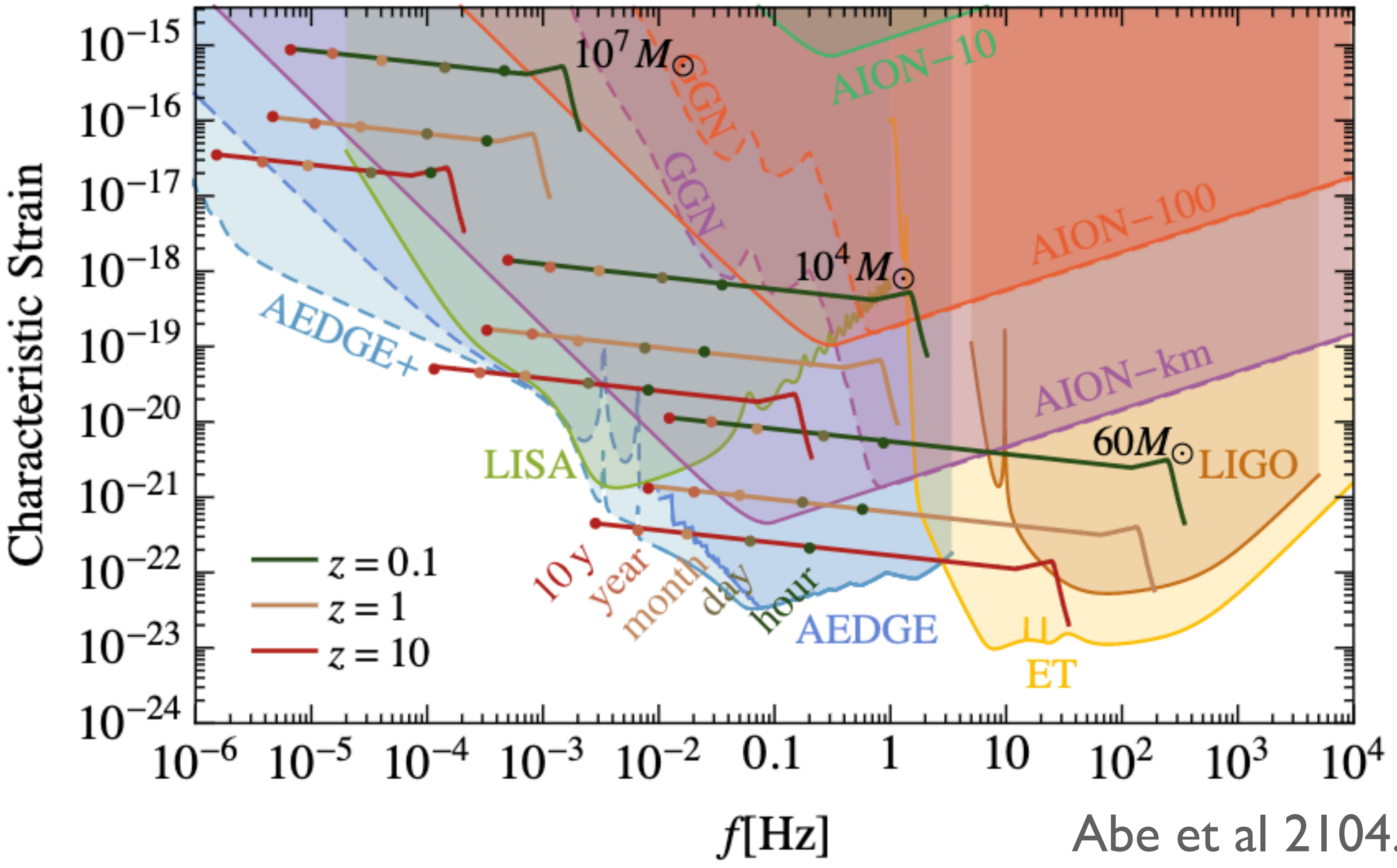
GWs (h) change distances

$$\delta L \sim hL$$

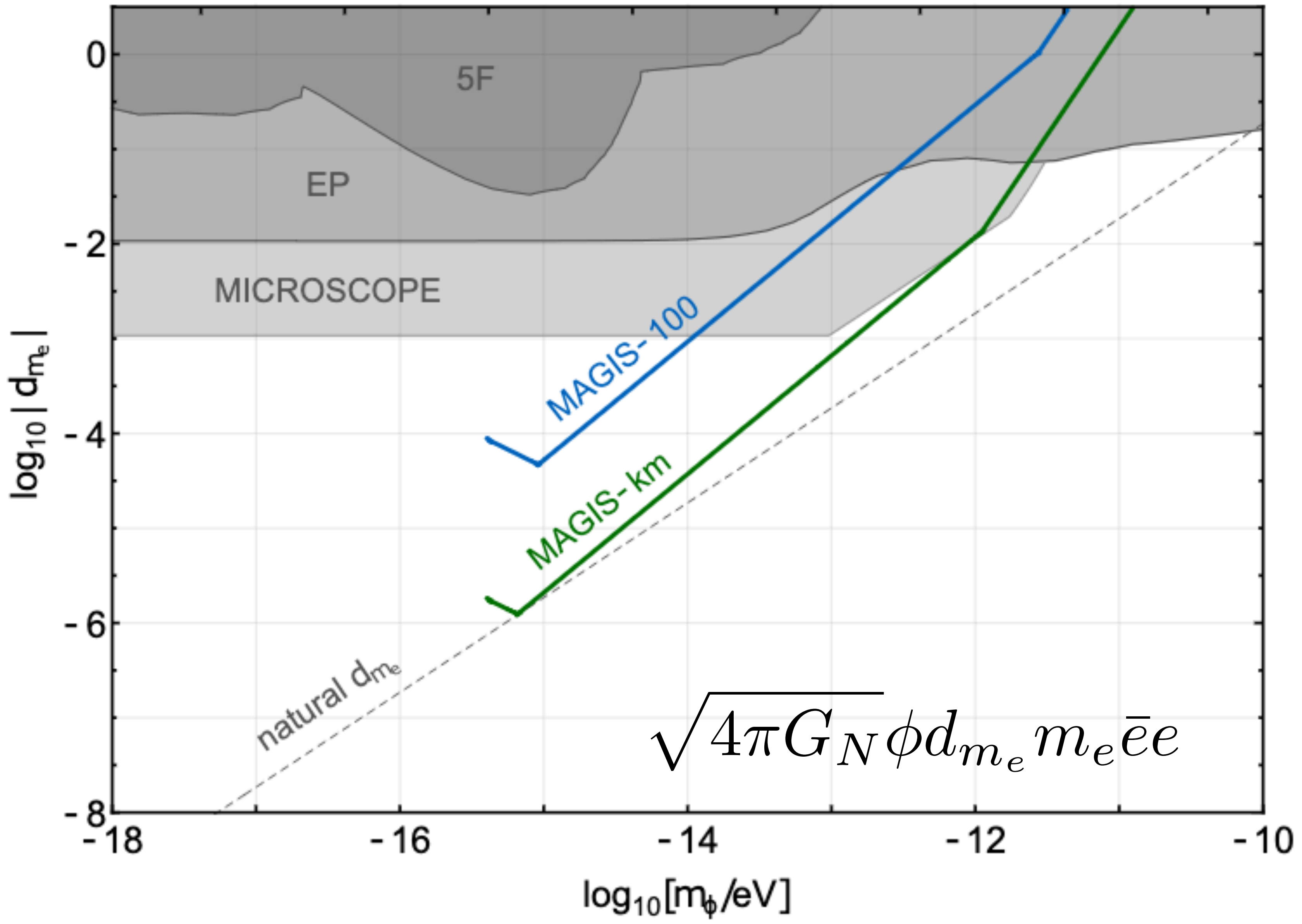
$$\phi \propto \omega_A L/c$$

DM (ϕ_{DM}) may change the “energy” levels

$$\delta\omega_a \sim g_c \omega_a \phi_{DM}$$



Abe et al 2104.02835



Current status

Site location:

Status

M. Abe et al., *Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)*, arXiv:2104.02835. — 100 m

B. Canuel et al., *Exploring gravity with the MIGA large scale atom interferometer*, *Sci. Rep.* **8** (2018), no. 1 14064, [arXiv:1703.02490]. — ~ 200 m?

B. Canuel et al., *ELGAR—a European Laboratory for Gravitation and Atom-interferometric Research*, *Class. Quant. Grav.* **37** (2020), no. 22 225017, [arXiv:1911.03701]. — ?

M.-S. Zhan et al., *ZAIGA: Zhaoshan Long-baseline Atom Interferometer Gravitation Antenna*, *Int. J. Mod. Phys.* **D28** (2019) 1940005, [arXiv:1903.09288]. — ~ 300 m?

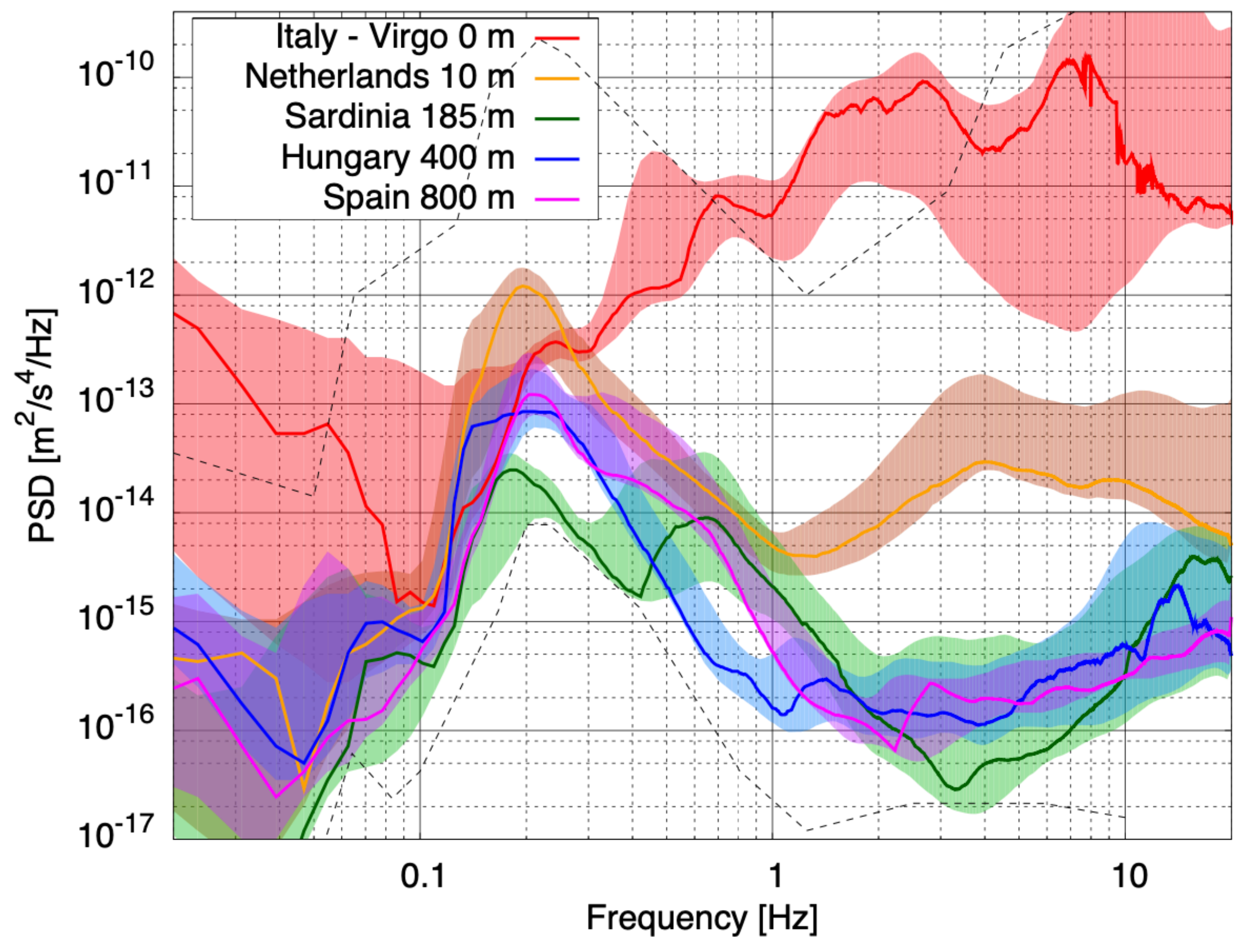
L. Badurina et al., *AION: An Atom Interferometer Observatory and Network*, *JCAP* **05** (2020) 011, [arXiv:1911.11755]. — 10 m

AEDGE Collaboration, Y. A. El-Neaj et al., *AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space*, *EPJ Quant. Technol.* **7** (2020) 6, [arXiv:1908.00802]. — 40 km?

talk to me!

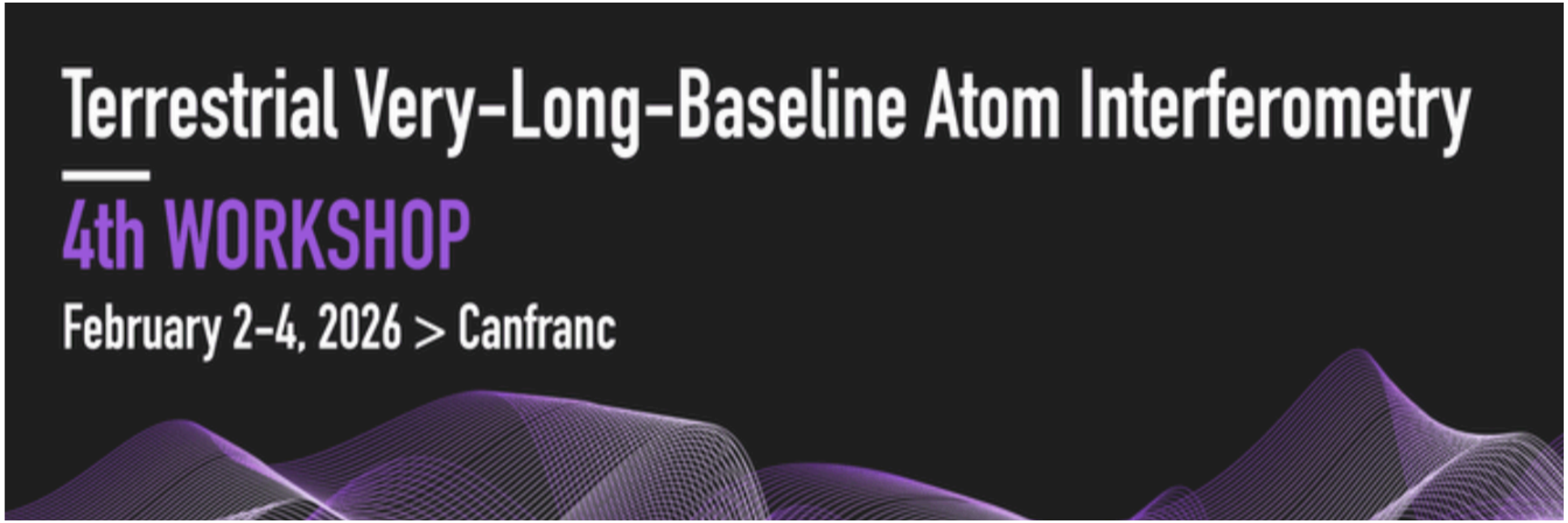
Current search for vertical shafts with right conditions (**Canfranc** (Spain)?)

M G Beker *et al* 2012 *J. Phys.: Conf. Ser.* **363** 012004



Join us!

https://indico.cern.ch/event/1599454/



Local Organisation Committee:

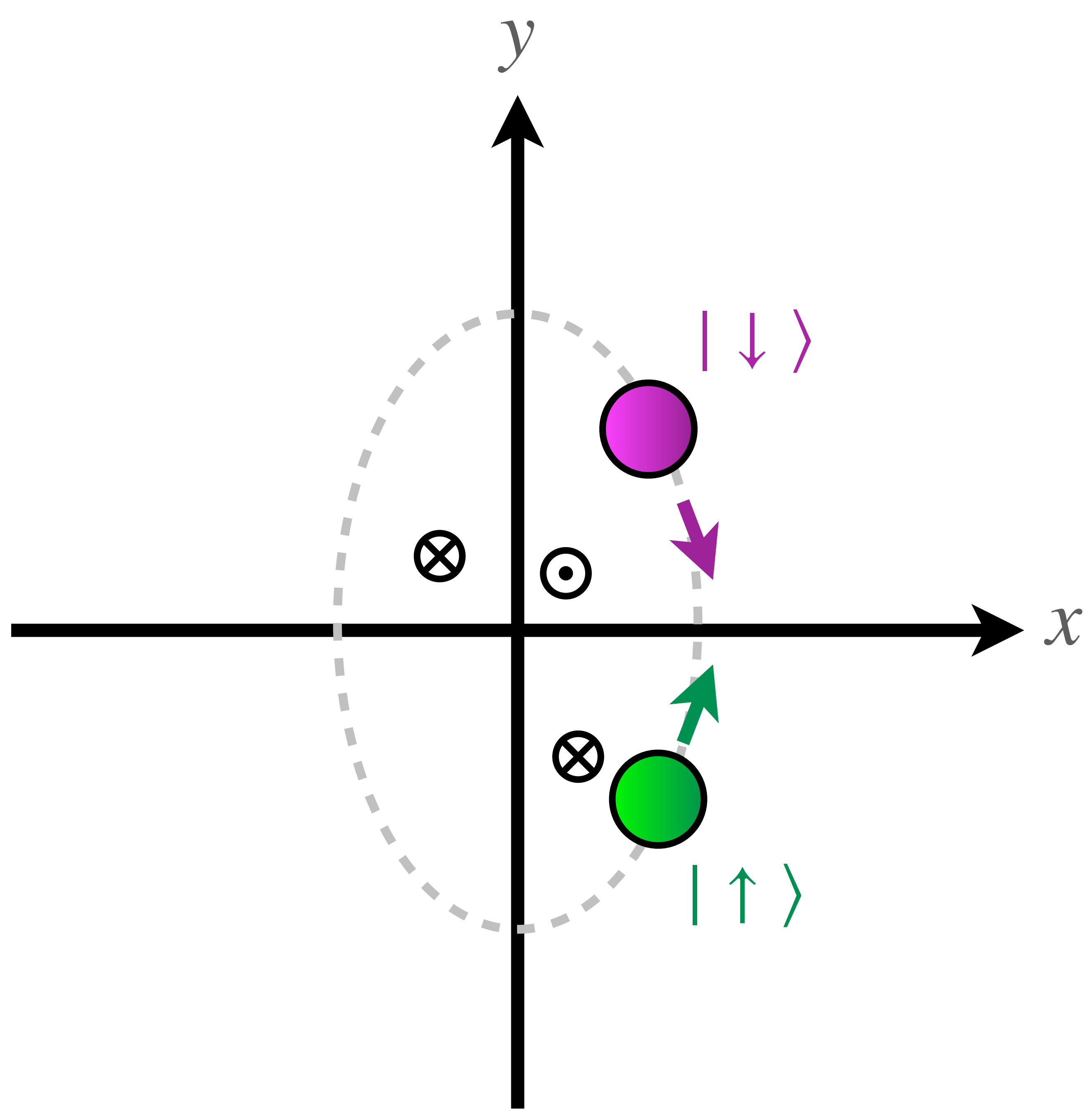
Diego Blas, Institut de Fisica de Altes Energies (IFAE), Spain
David Cerdeño, Instituto de Fisica Teorica (IFT), Spain
David Keitel, Universitat de les Illes Balears (UIB), Spain
Yolanda Labarta, Laboratorio Subterraneo de Canfranc (LSC), Spain
Elias Lopez Asamar, Universidad Autonoma de Madrid (UAM), Spain
Maria Moreno Llacer, Instituto de Fisica Corpuscular (IFIC), Spain
Carlos Peña Garay, Laboratorio Subterraneo de Canfranc (LSC), Spain

A more recent proposal: Trapped ions

hep-ph/2507.17825
L. Badurina, DB, J. Ellis, S. Ellis

States evolving in the presence of a vector potential pick up a phase

$$\varphi = \oint d\boldsymbol{l} \cdot \boldsymbol{A}$$



Counter-propagation of entangled spin & position state means relative phase of $\varphi_\uparrow - \varphi_\downarrow$ measurable

$$\Delta\varphi = 2\int_0^T \frac{d\boldsymbol{S}}{dt} \cdot \boldsymbol{B}\, dt \qquad \frac{d\boldsymbol{S}}{dt} \simeq \frac{y_d N \Delta k}{m_{\text{ion}}}$$

Morally equivalent to a motional magnetic moment

$$\mu \sim \mu_B y_d N \Delta k \frac{m_e}{m_{\text{ion}}}$$

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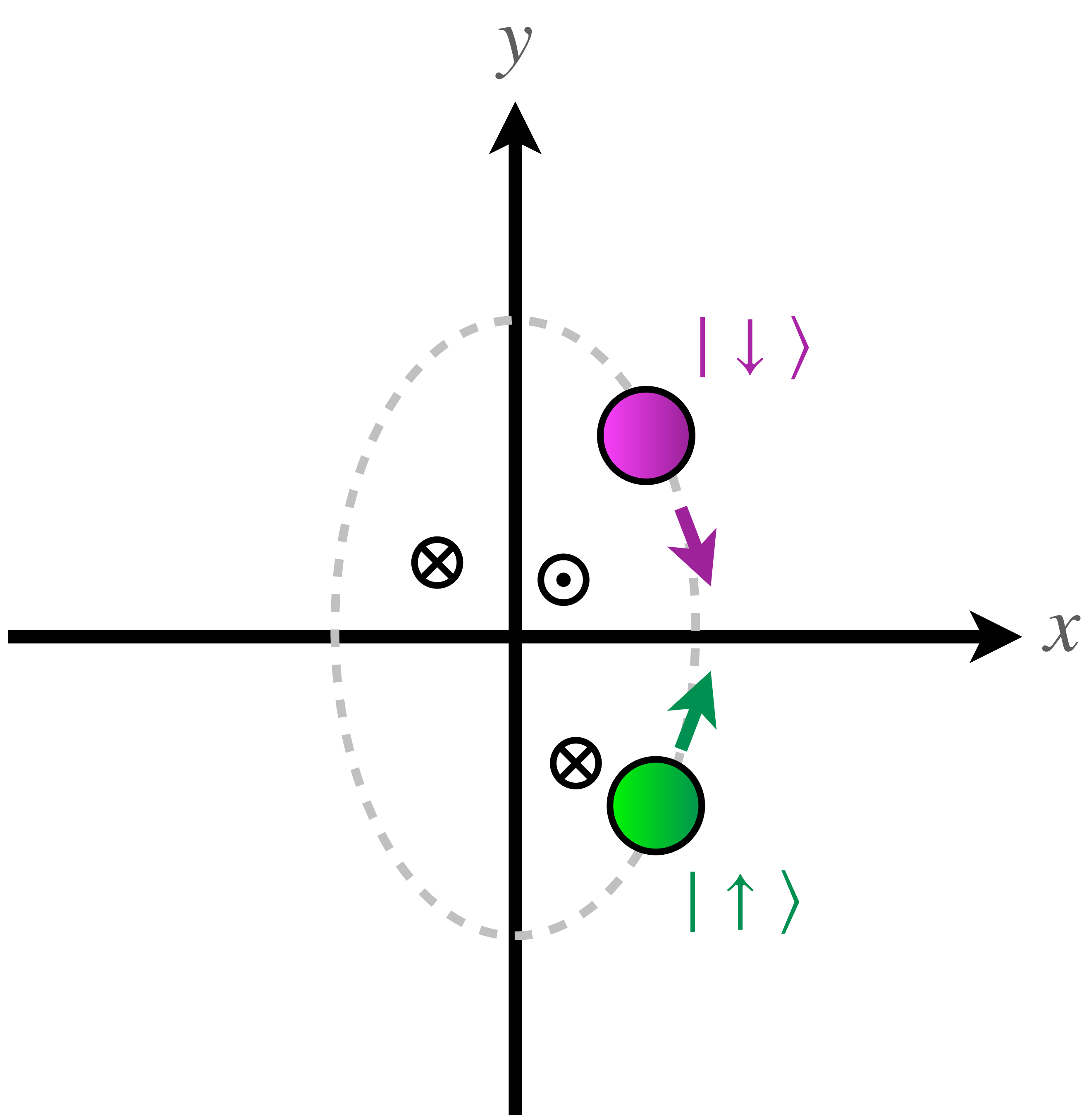

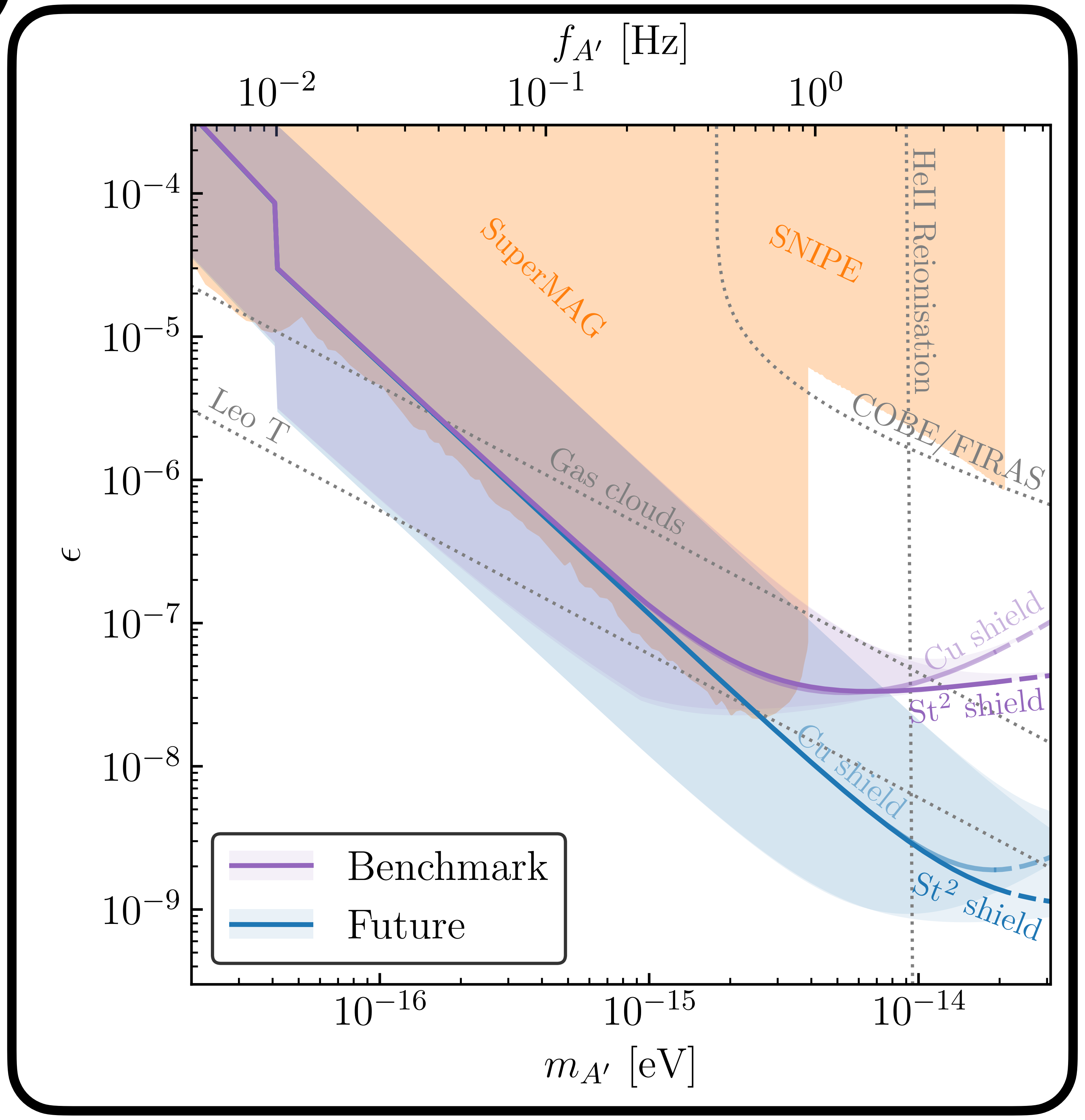

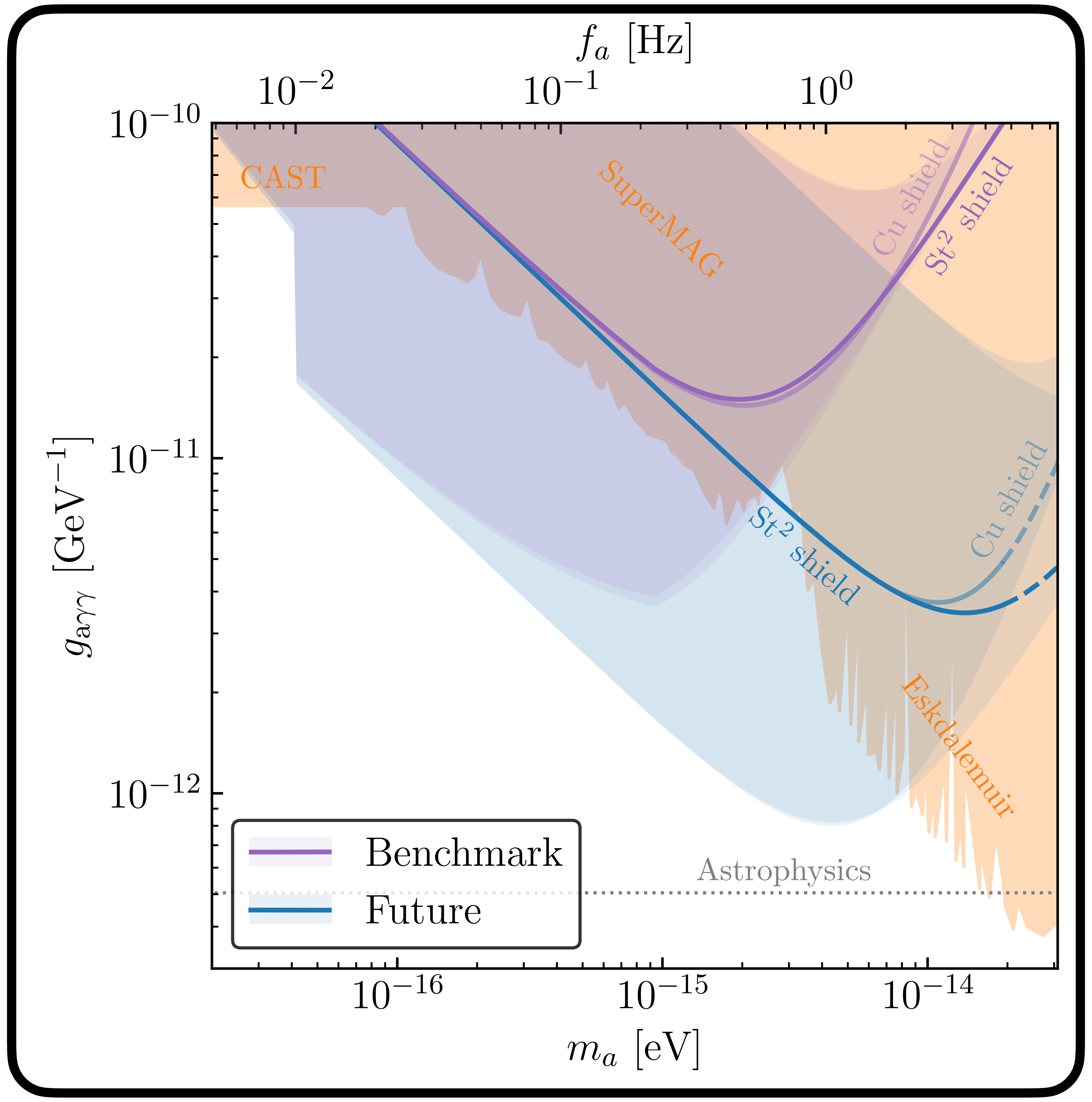

$$B_{A'} \sim \epsilon(m_{A'}R_\oplus)\sqrt{\rho_{\mathrm{DM}}}$$

$$B_a \sim g_{a\gamma\gamma}(m_a R_\oplus)\frac{\sqrt{\rho_{\mathrm{DM}}}}{m_a}B_\oplus$$

Entangling multiple ions increases sensitivity* linearly in N_{ion}

Searching for fundamental backgrounds with QT

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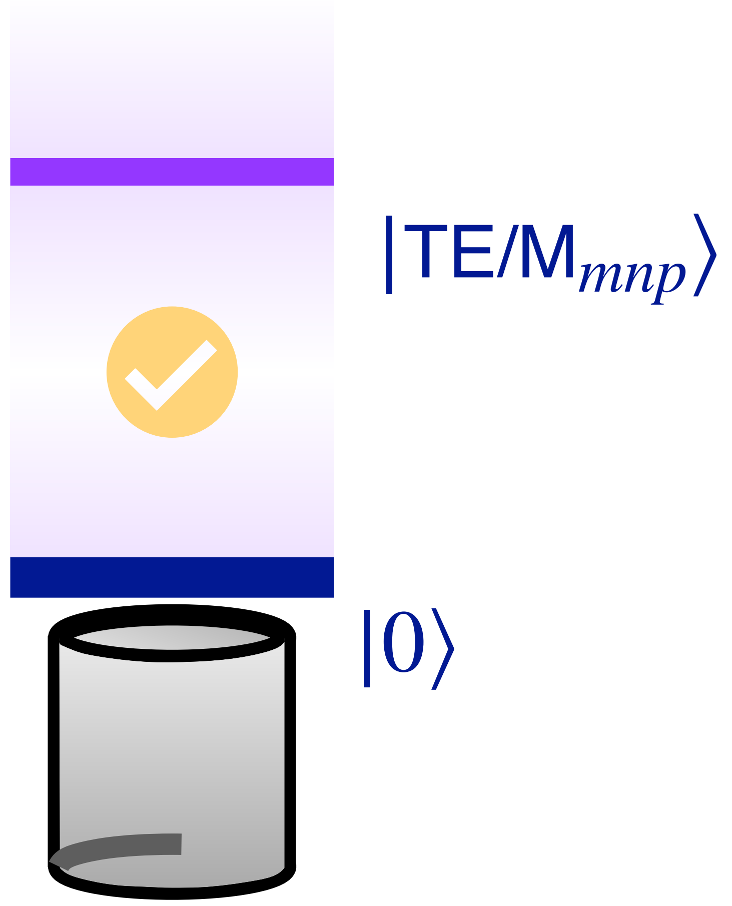
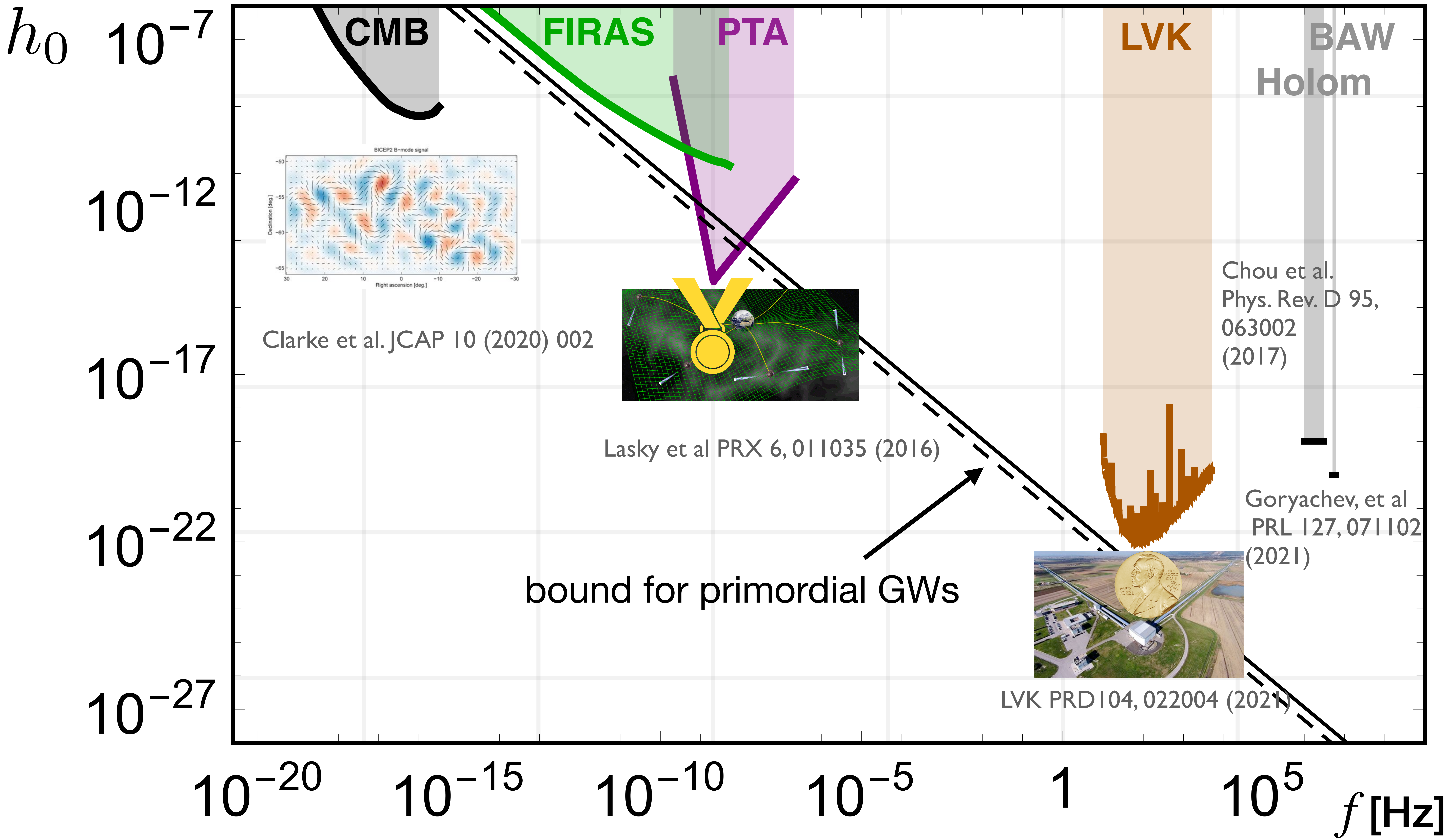
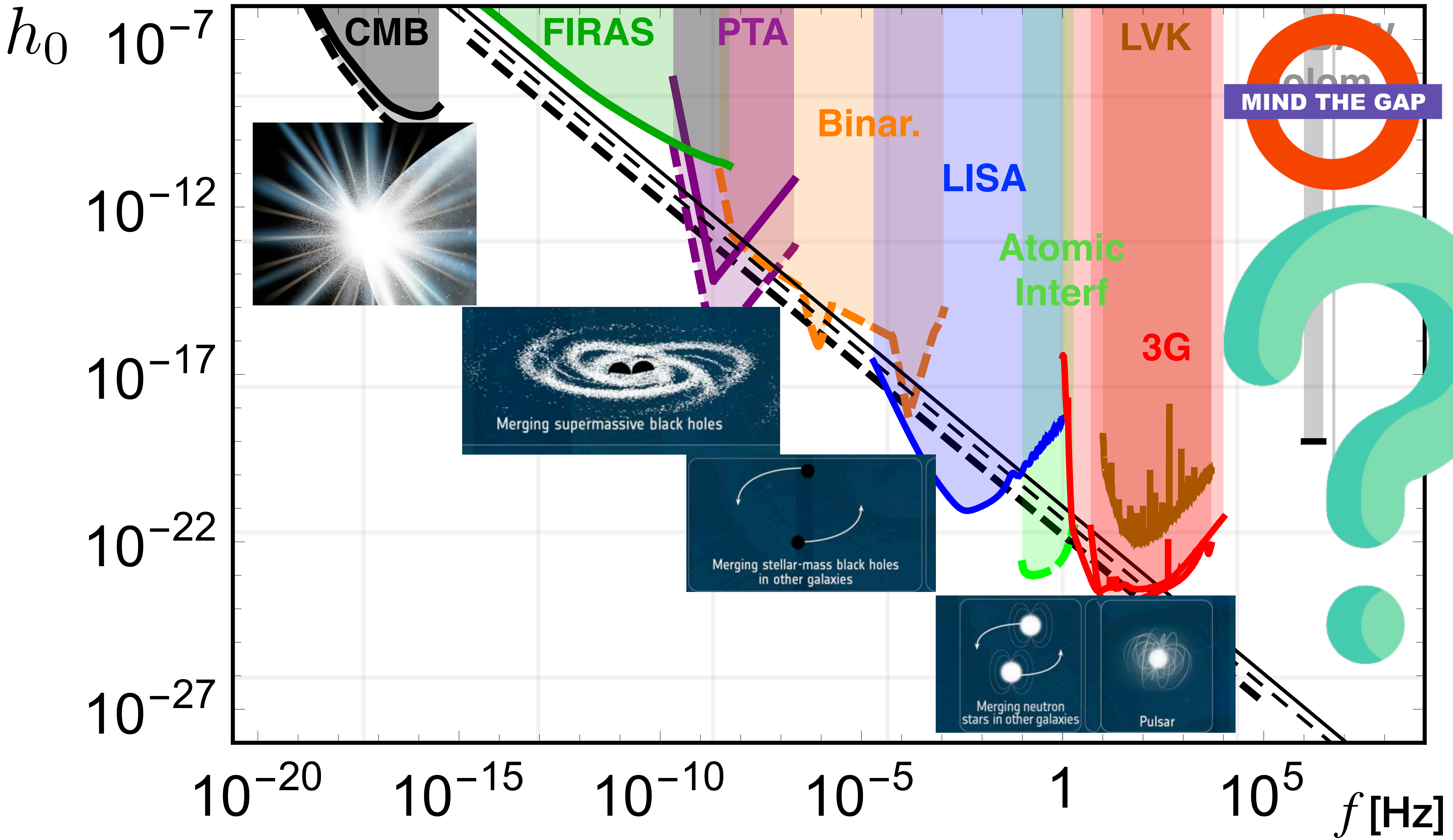


GWs soundscape today

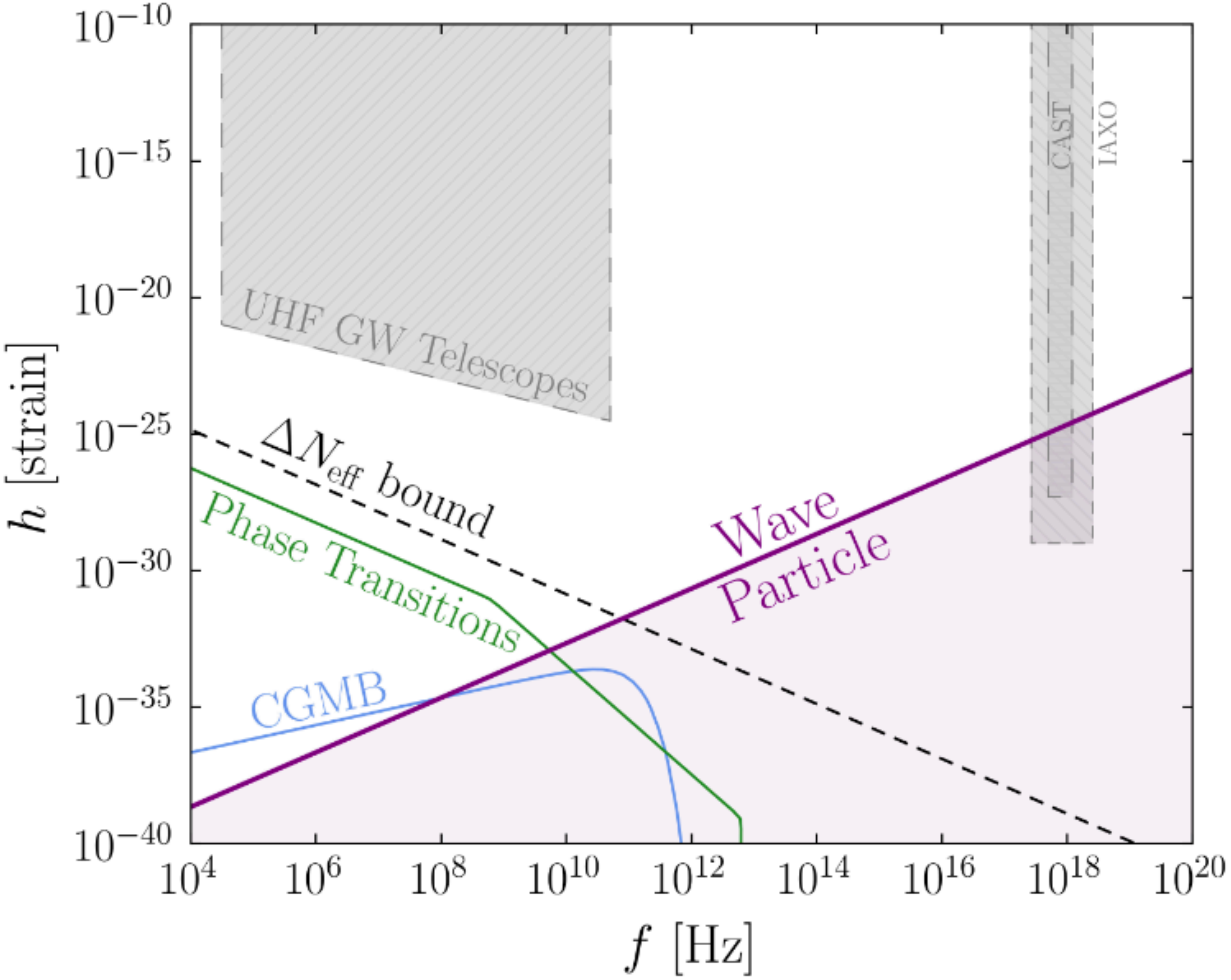


GWs soundscape ca. 2040

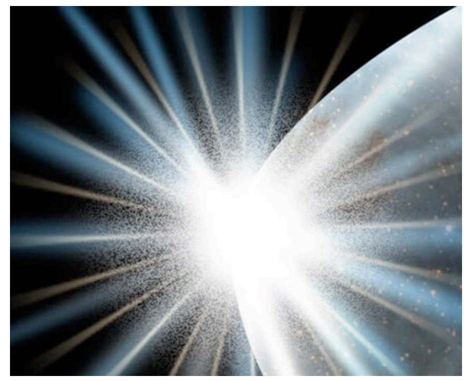


Where are gravitons hiding?

Carney et al. 2308.12988

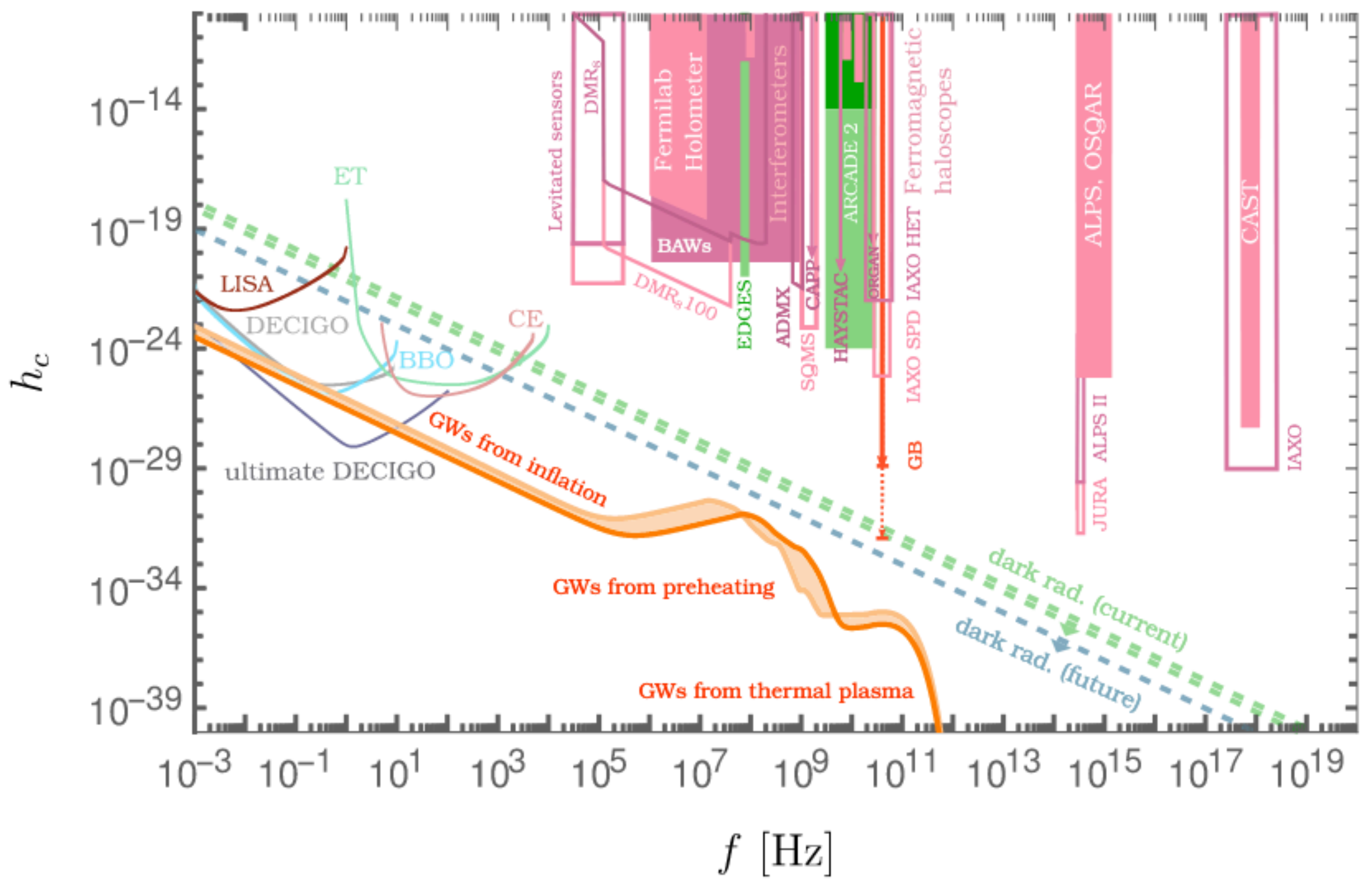


Sources of UHFGW: where to aim



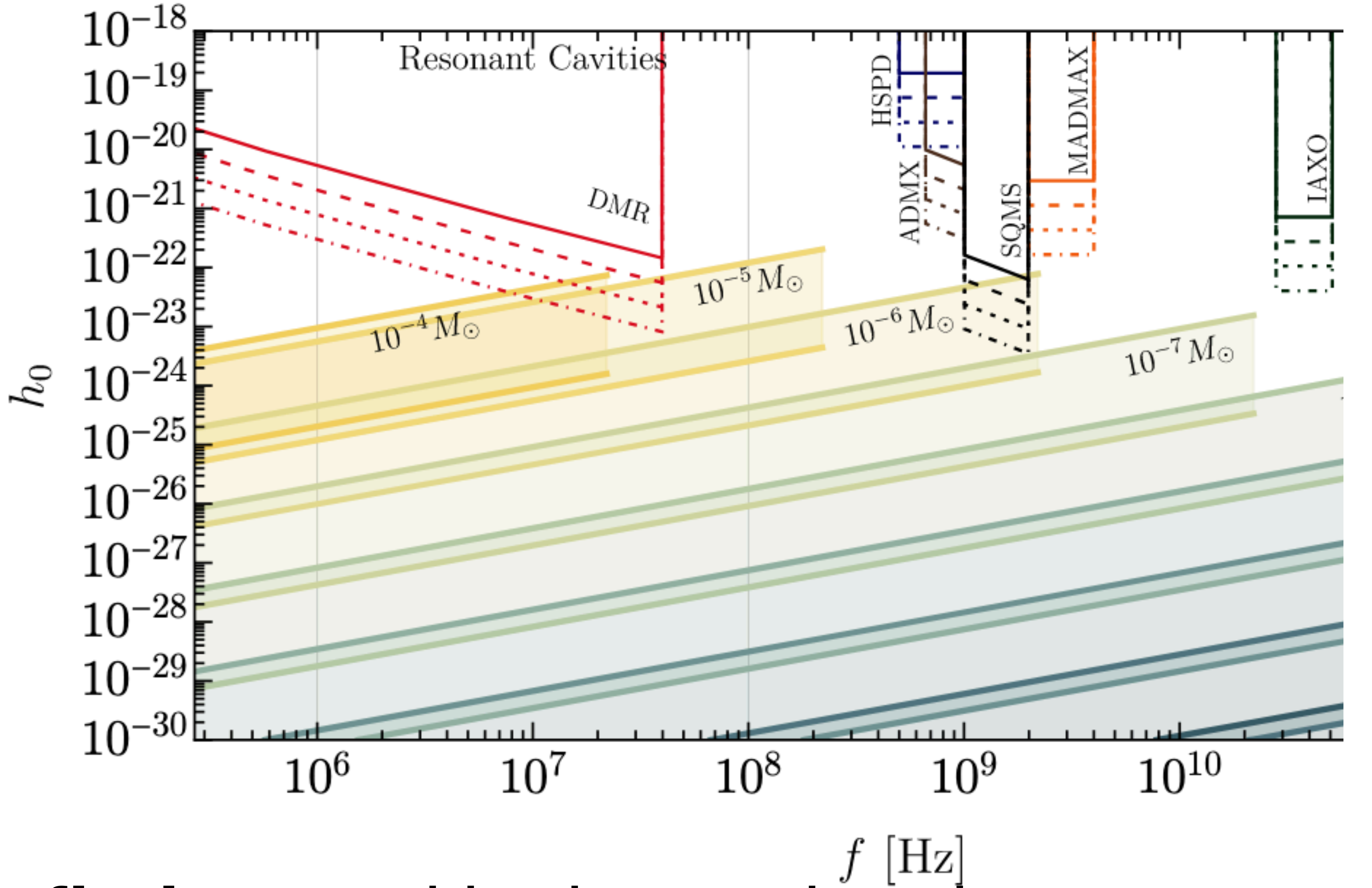
Inflation model full spectrum

Ringwald Tamarit 22

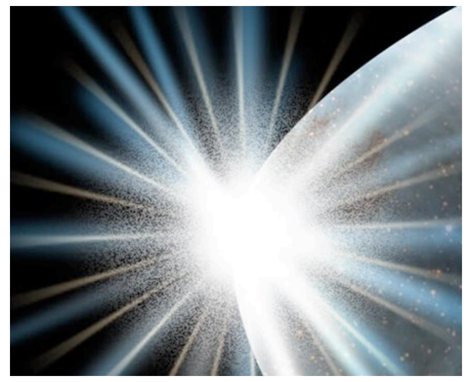


GWs from PBHs of **DM**

Franciolini et al 2205.02153



Lesson: there is a signal from **inflation**, and in the getting there we can detect **dark matter**!



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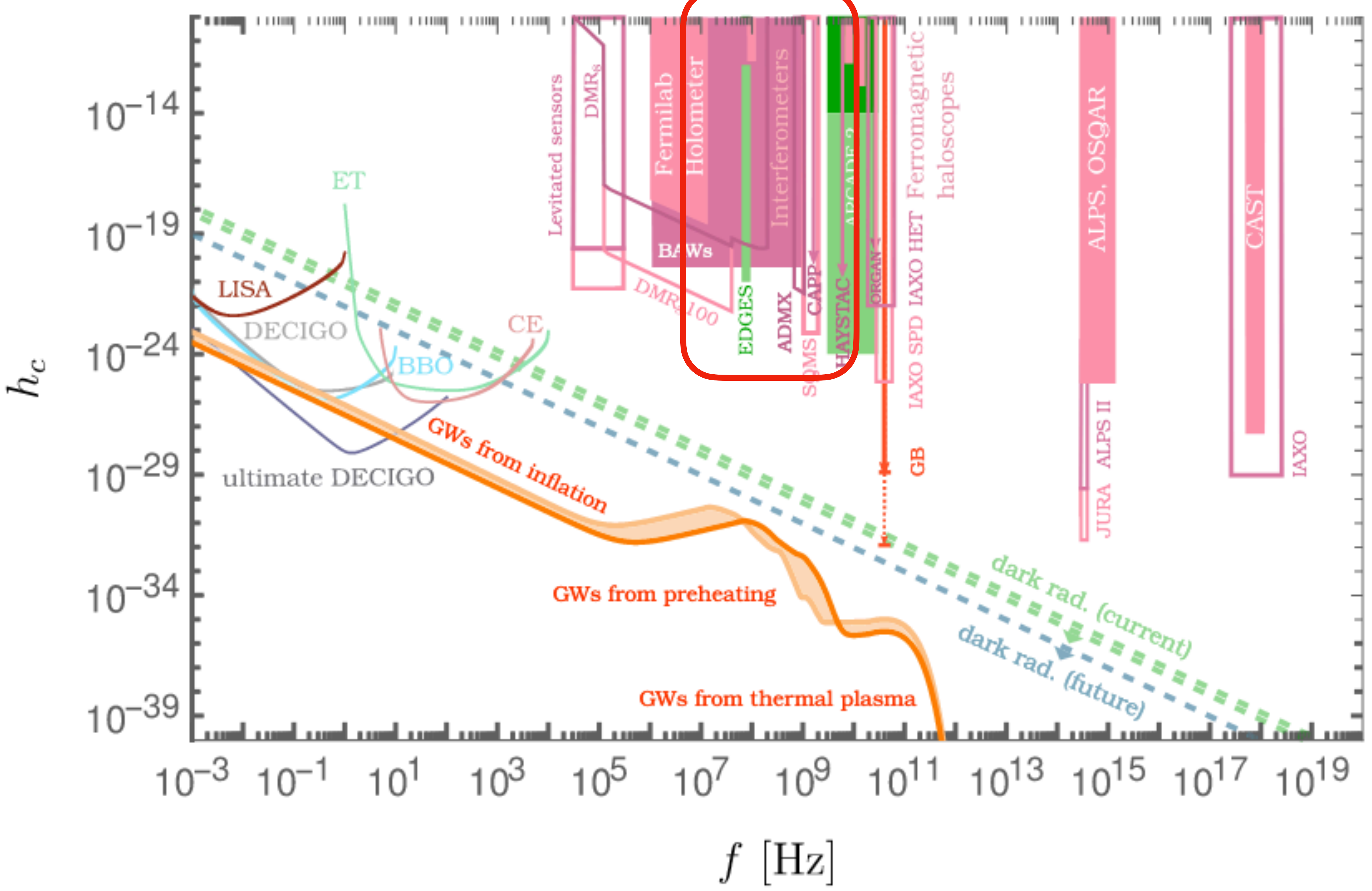

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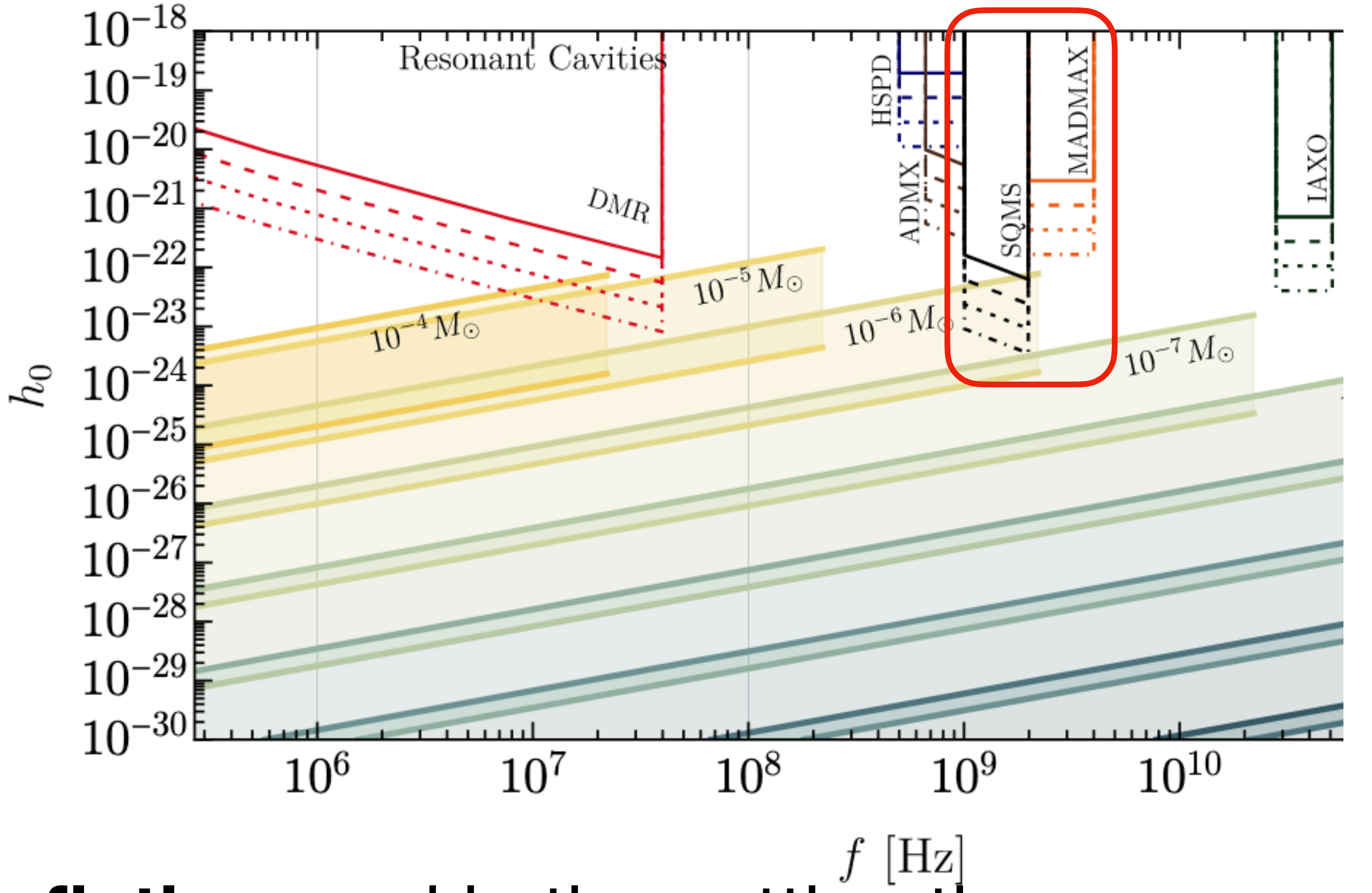
Franciolini et al 2205.02153



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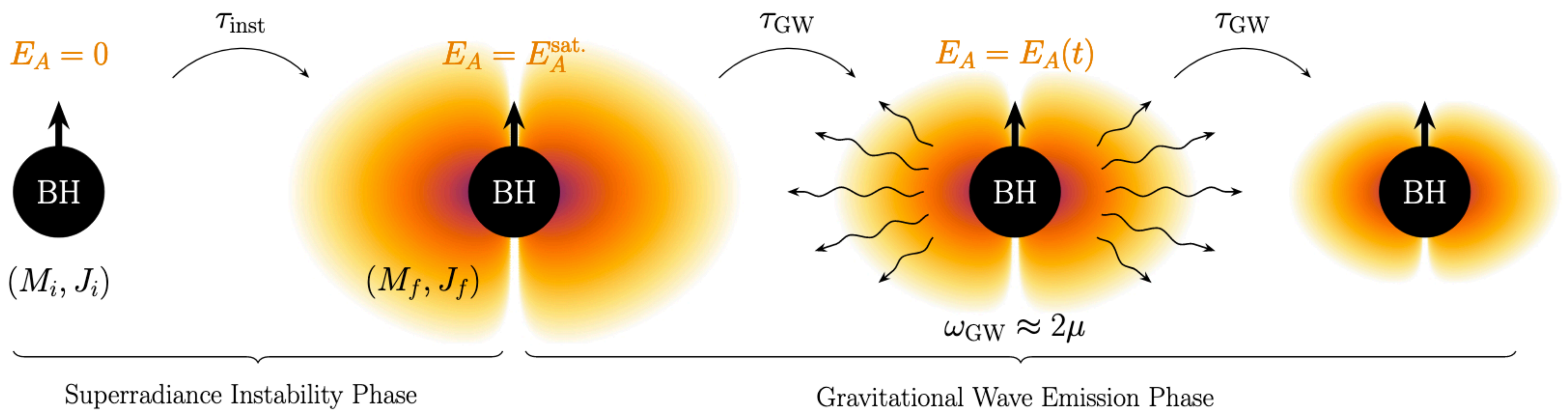
All transient sources

- SR

from Tsukada et al, ‘20



$$h \sim 10^{-23} \left(\frac{\Delta a_*}{0.1}\right)\left(\frac{1\text{kpc}}{D}\right)\left(\frac{M_b}{1M_\odot}\right)\left(\frac{\alpha}{0.2}\right)^7$$

$$(M_b/M_\odot) \sim (10^3\text{Hz}/\omega_{\rm gw})$$

$$t \sim 10^5\text{yrs} \times (\text{MHz}/\omega_g)^2$$

- BBH merger

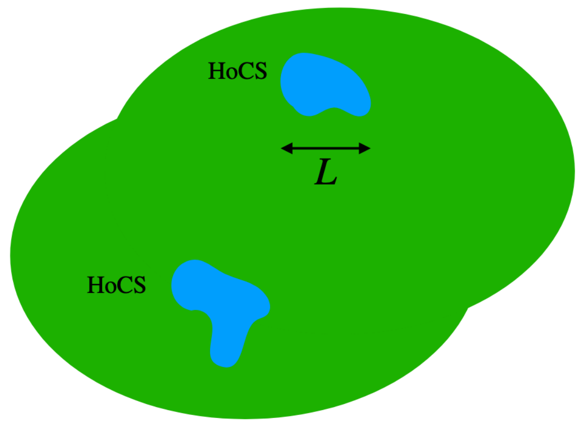
Franciolini et al 2205.02153

$$h_0 \sim 10^{-29} \times \left(\frac{1\text{pc}}{D}\right)\left(\frac{M_b}{10^{-11}M_\odot}\right)^{5/3}\left(\frac{\omega_g}{1\text{GHz}}\right)^{2/3}$$

$$\tau_b \sim 10^{-3}\ \text{s} \left(\frac{10^5}{Q}\right)\left(\frac{10^{-11}M_\odot}{M_b}\right)^{5/3}\left(\frac{1\text{GHz}}{\omega_g}\right)^{8/3}$$

- NS/NS mergers

Casalderrey et al. 2210.03171



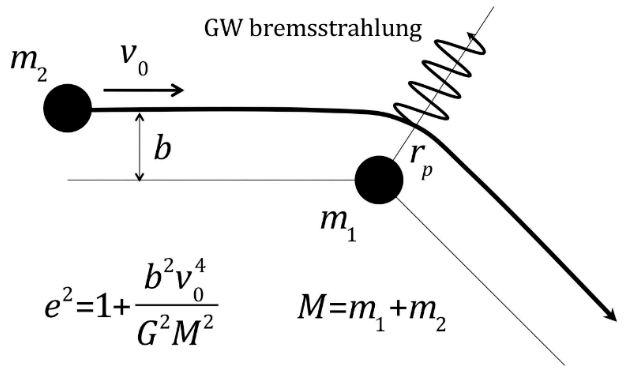
MHz

$$h_c^{\rm obs} \simeq 2.1 \times 10^{-24} v_f^2 \left(\frac{100\text{Mpc}}{d}\right)$$

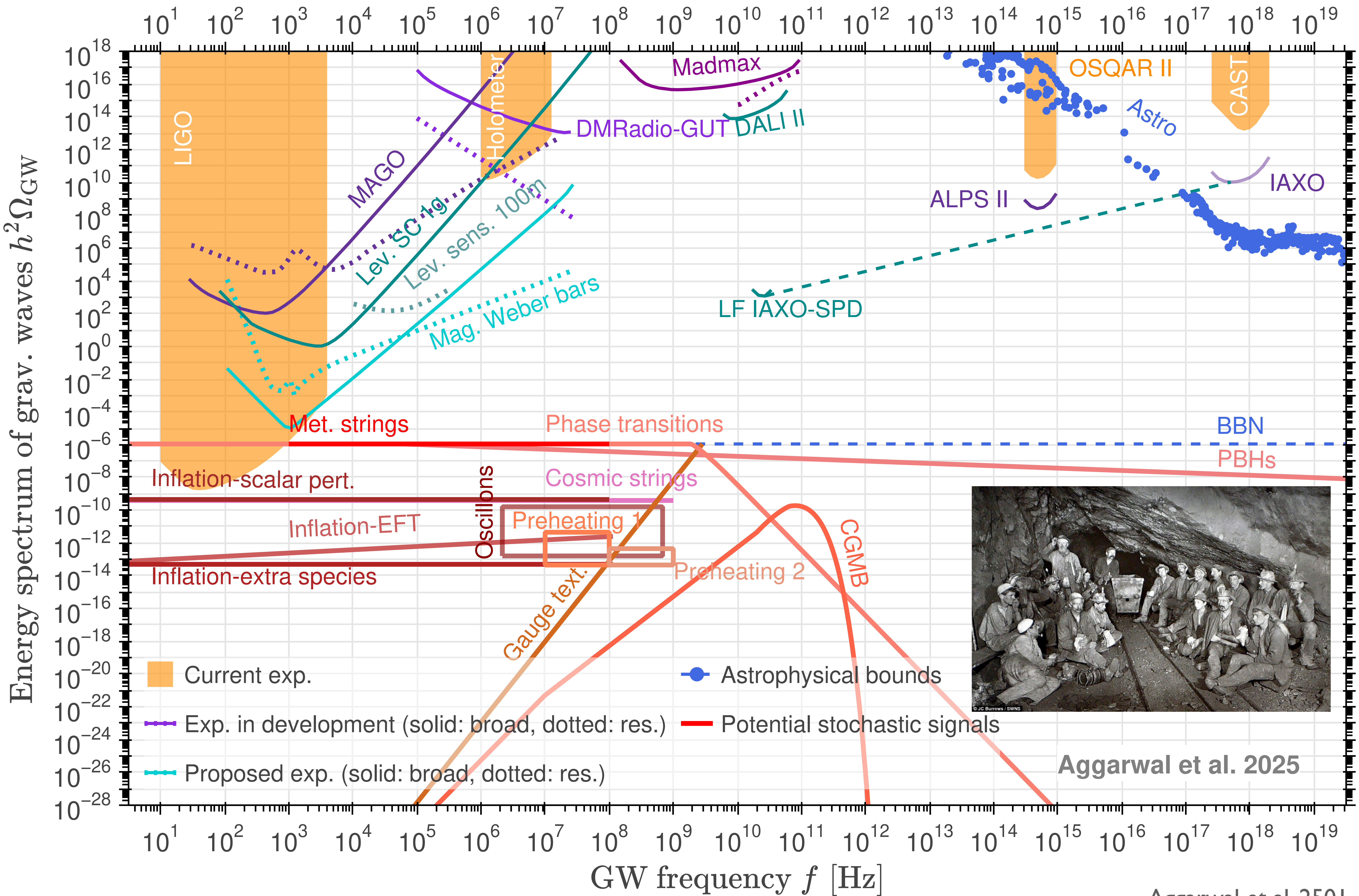
$$\Delta t \simeq L \simeq 1.7 \times 10^{-2}\ \text{ms}$$

- Hyperbolic encounters of PBH

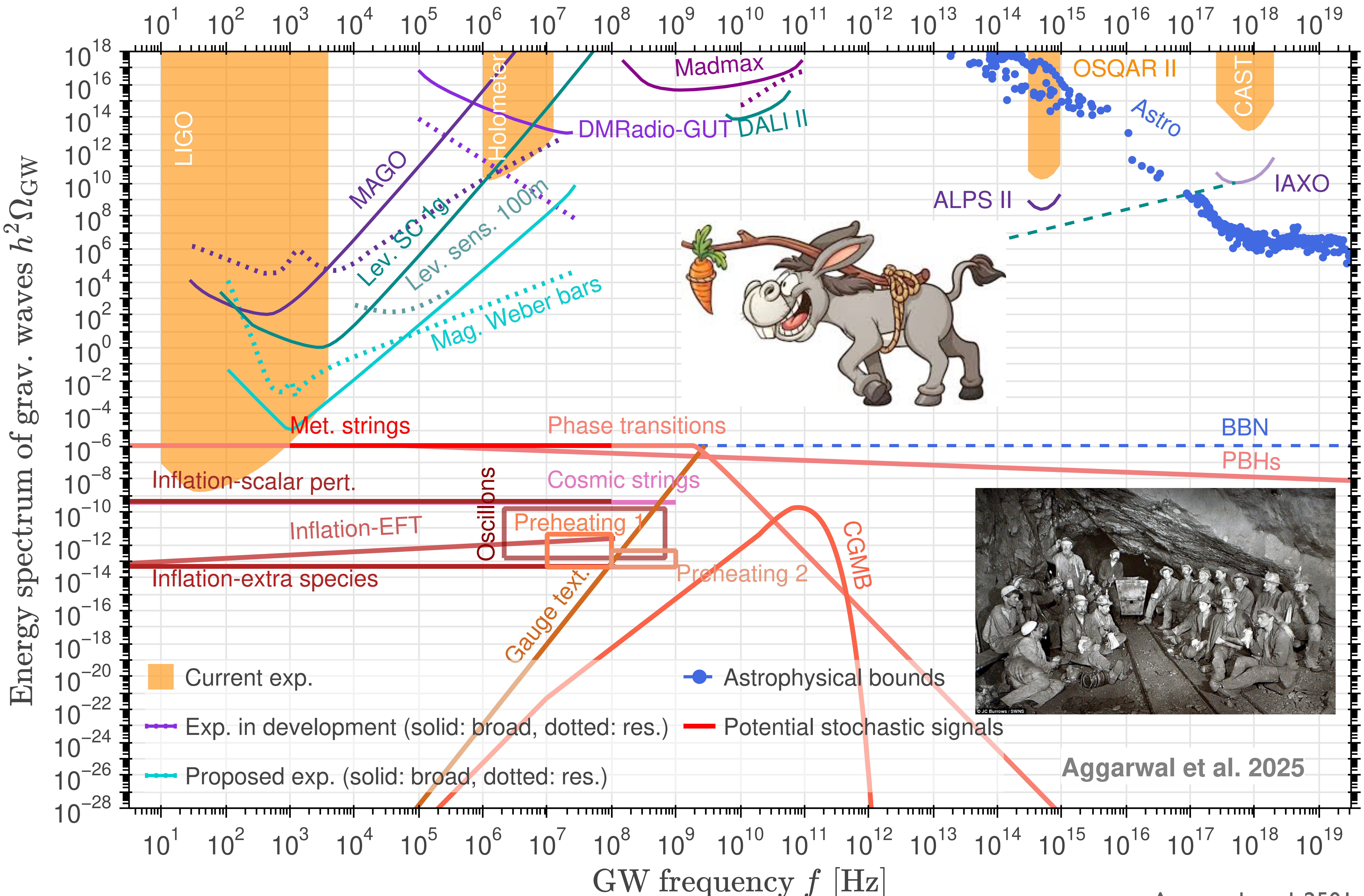
Garcia Bellido & S. Nesseris 1706.02111



$$t_{1/2} \simeq 1ms \left(\frac{b}{10^{-8}\text{AU}}\right)\left(\frac{0.01}{\beta}\right)(e-1)\sqrt{\frac{3\ln 2}{e+35(1+e)e}}$$

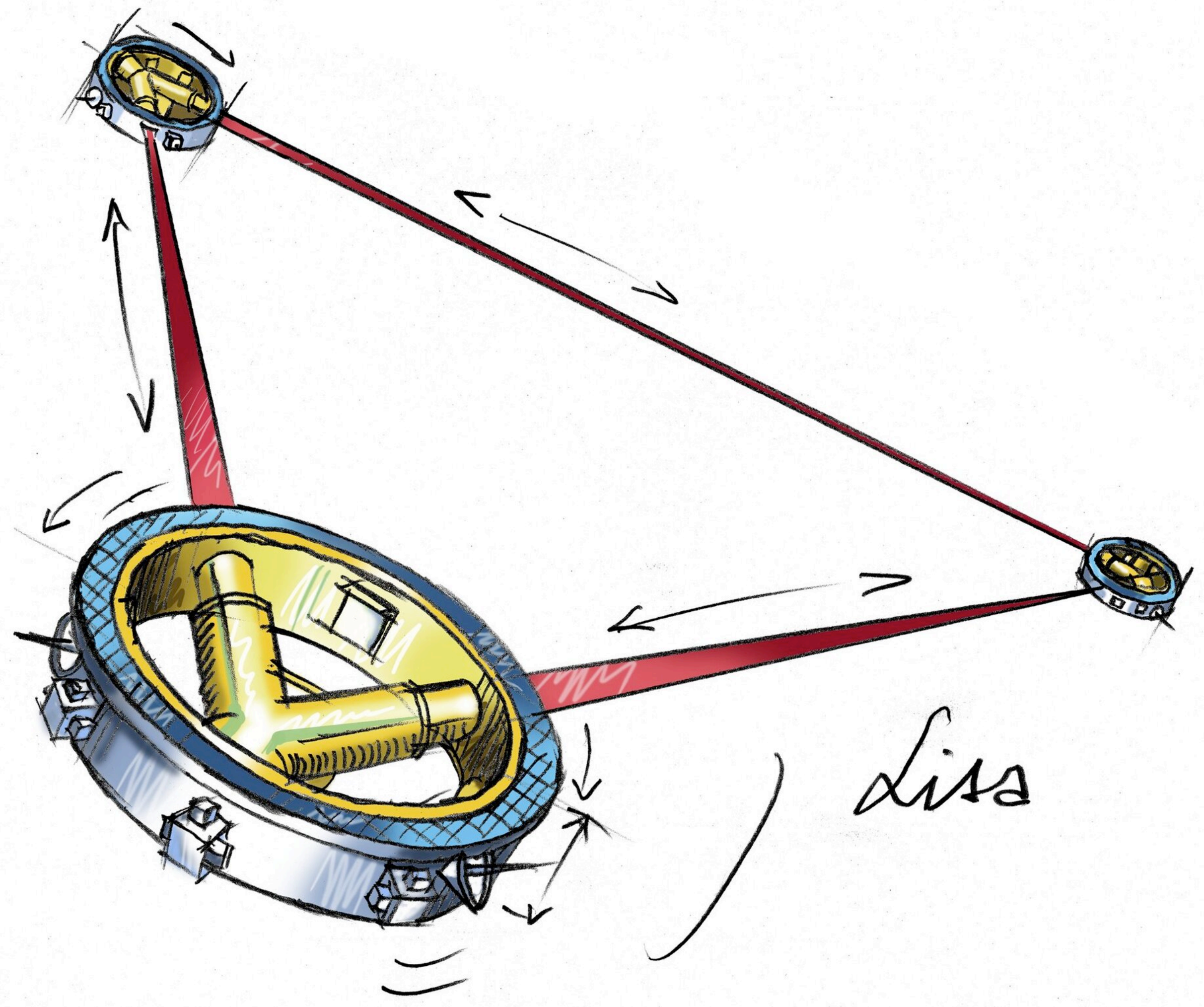


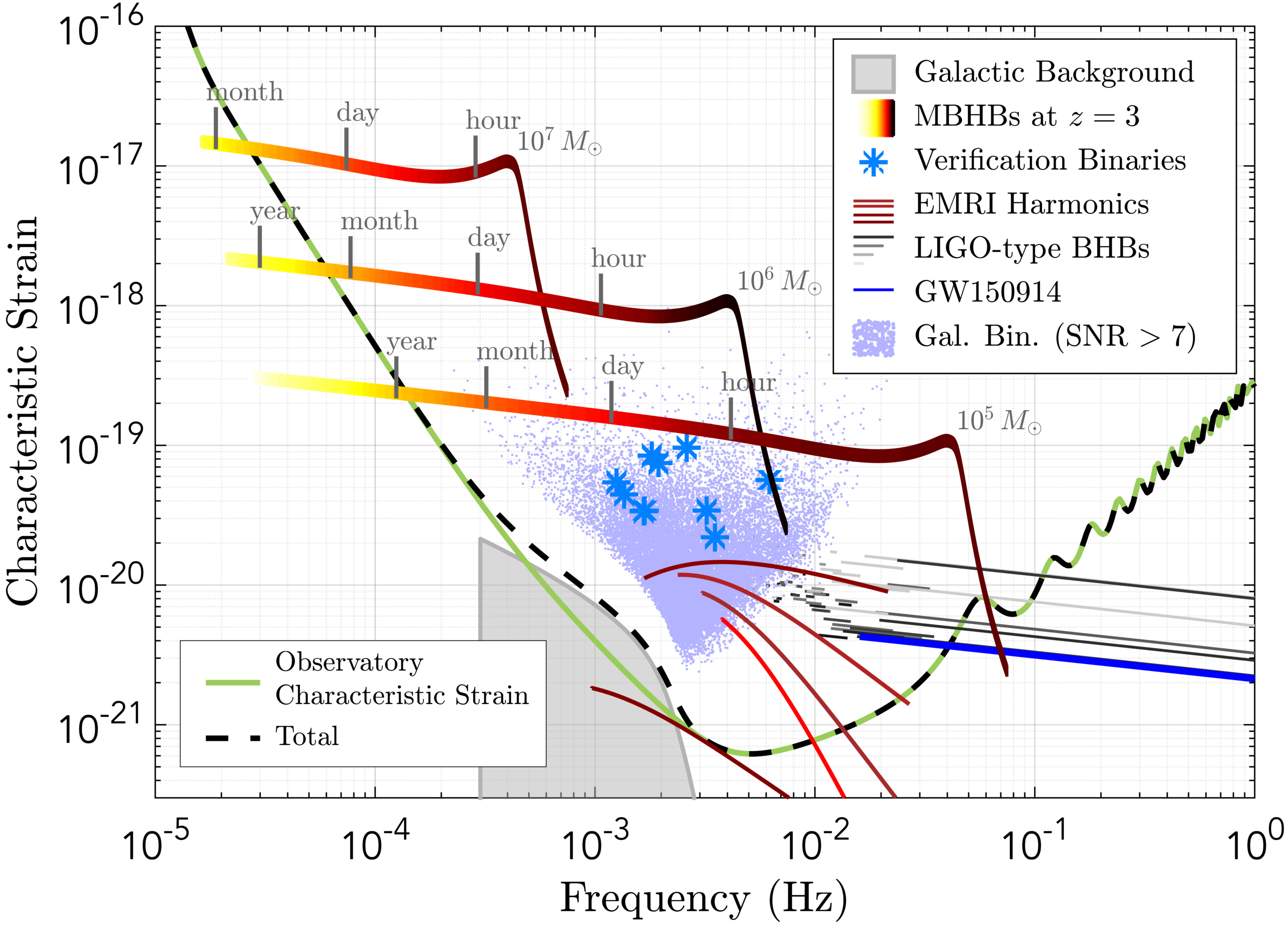
Aggarwal et al. 2501.11723 [gr-qc])

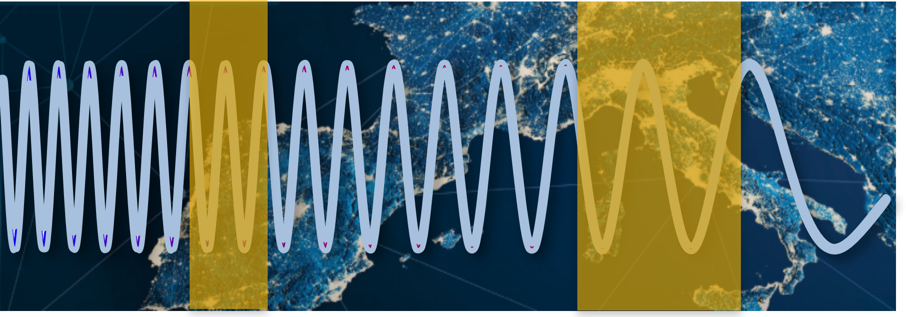


Aggarwal et al. 2501.11723 [gr-qc])

Compare with LISA







Interaction of GWs with your sensors

$$h_{+,\times} \approx h_0 \cos\left(2\pi f (t - z) + \phi\right)$$

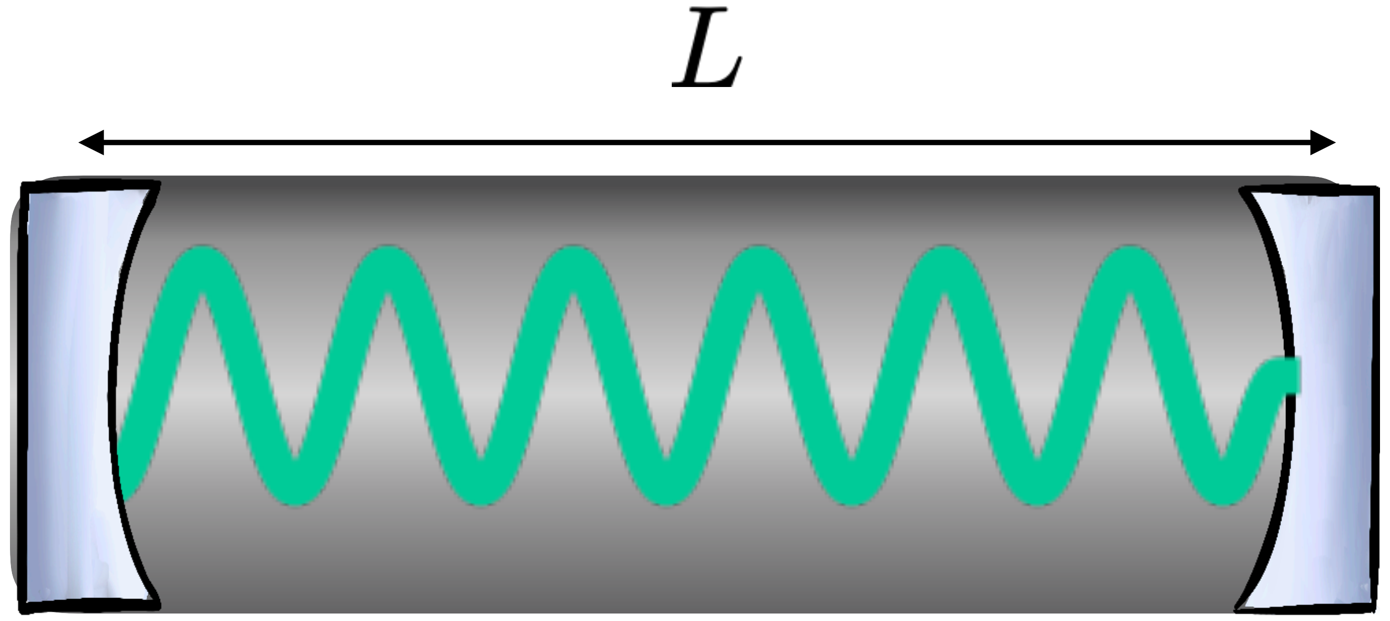
EM coupling **Spin coupling** **Energy/mechanical coupling**

$$\mathcal{H}_{gw}^{lab} \supset A^\nu \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h^\nu_\alpha F^{\alpha\mu} - h^\mu_\alpha F^{\alpha\nu} \right) + B_i h_{ij}(t_\psi)\, \Sigma^j + E_\psi \ddot{h}_{ij}(t_\psi)\, x^i_\psi x^j_\psi$$

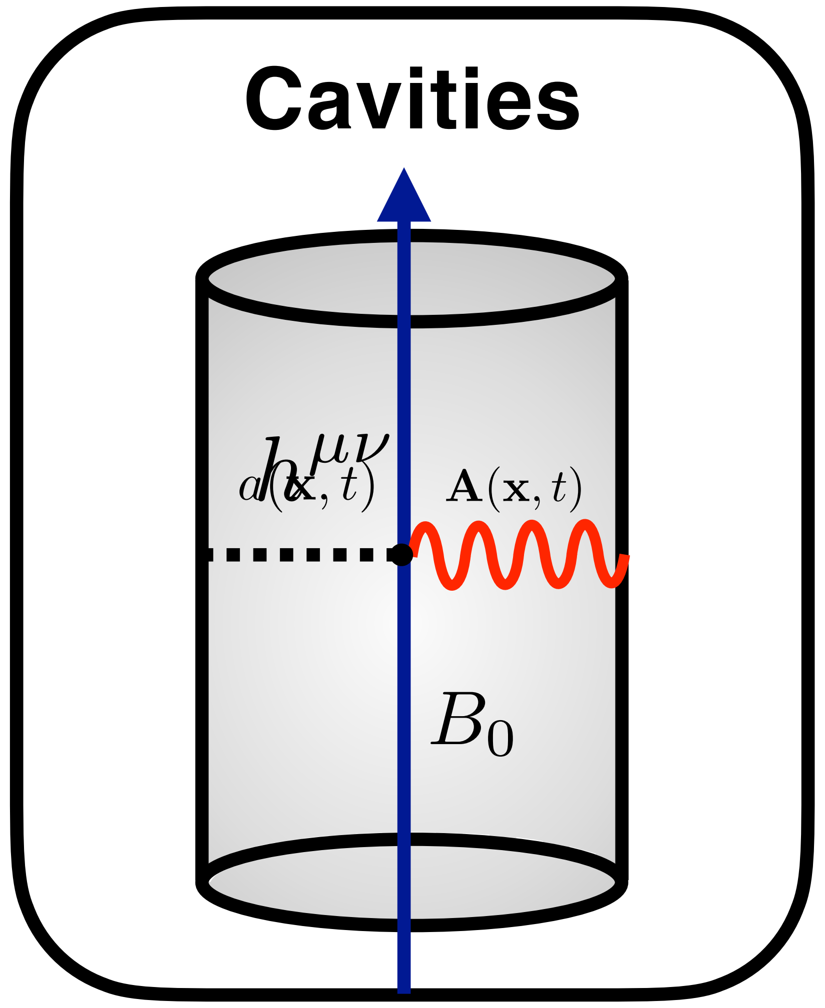
h+EM field = current!

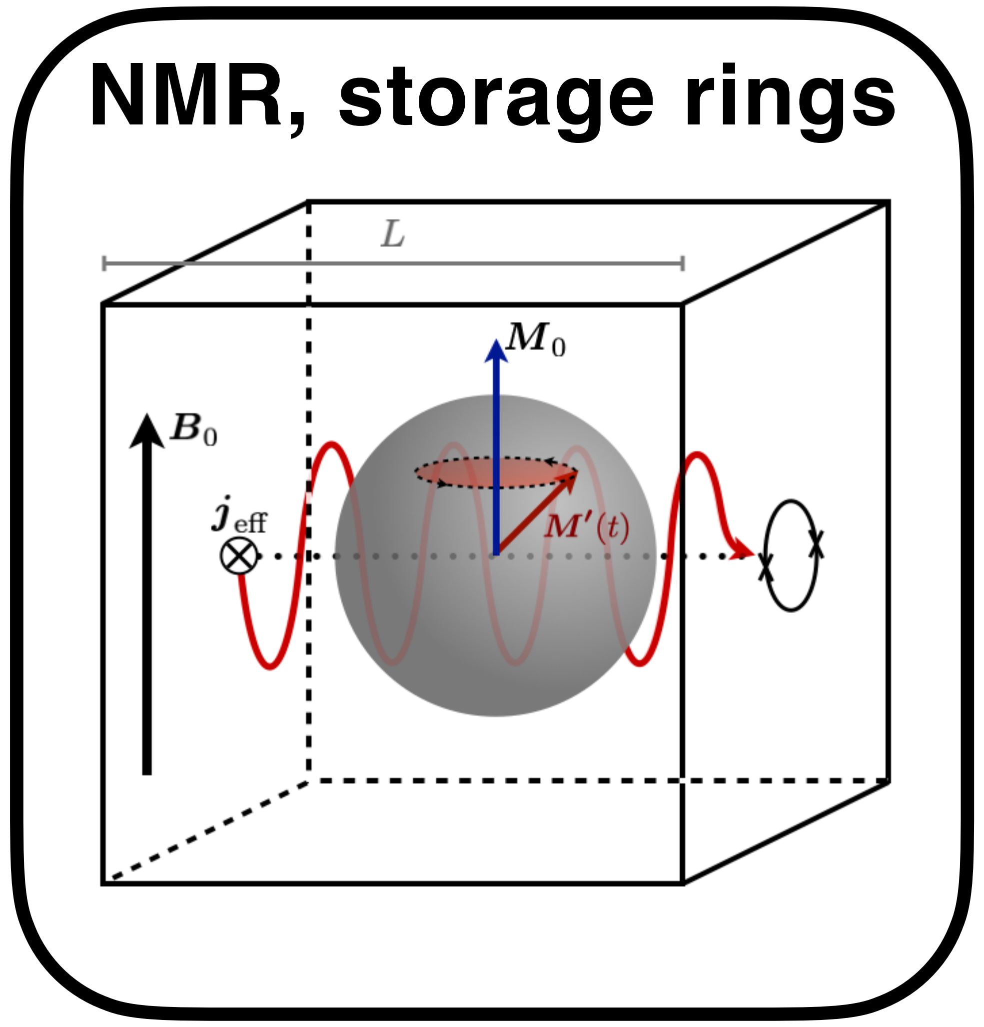
NMR anomalous B

$\delta L \sim hL$ (shaking walls)

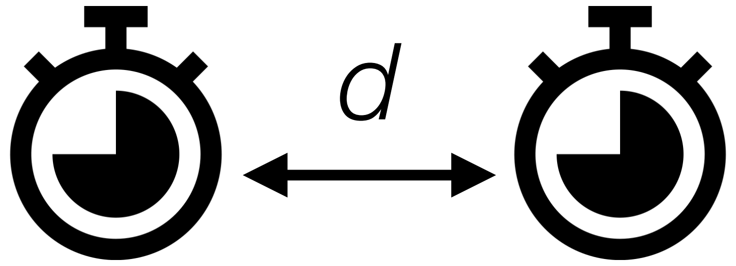


mode mixing when boundaries move





$\delta\omega \sim h\,\omega$



modify clocks at different locations

Ex1. GWs interact with light

$$\mathcal{H}_{gw}^{lab} \supset \quad A^{\nu}\partial_{\nu}\left(\frac{1}{2}hF^{\mu\nu} + h^{\nu}_{\alpha}F^{\alpha\mu} - h^{\mu}_{\alpha}F^{\alpha\nu}\right)$$

$j^{\mu}_{\rm eff}$

High Q cavities seem in strong $\overrightarrow{B}_0$ seem a good idea!

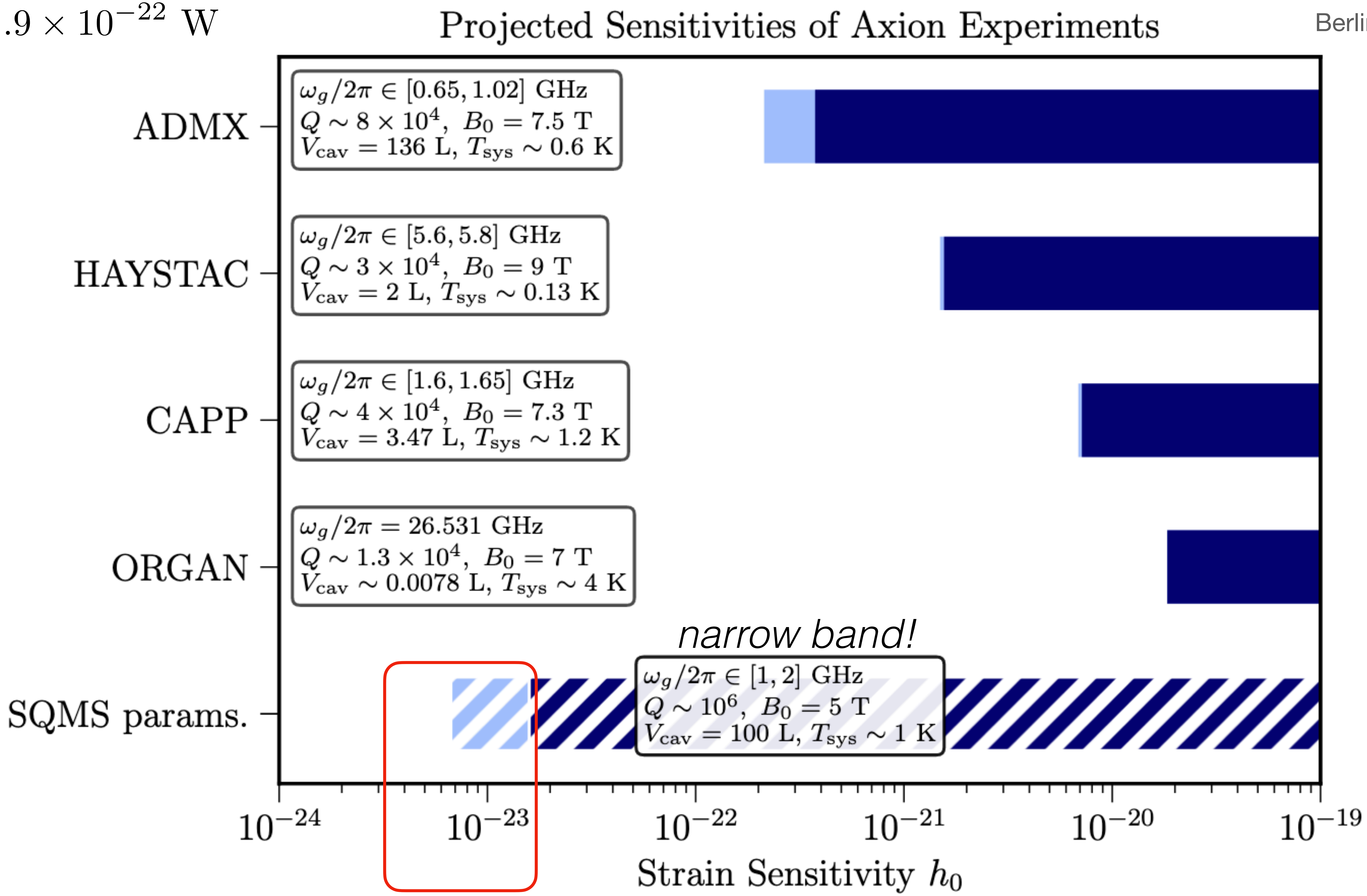
Berlin, DB et al 2112.11465

$$\partial_{\nu}F^{\mu\nu} = j^{\mu}_{\rm eff} = (-\nabla\cdot\mathbf{P},\ \nabla\times\mathbf{M} + \partial_t\mathbf{P})$$

Power $\leq\ 1.9\times 10^{-22}$ W

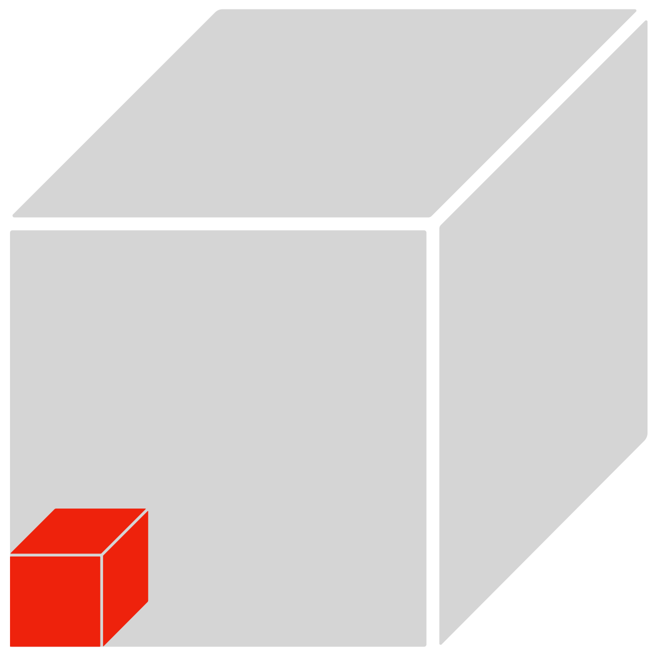
$P_{\text{axion}} = 1.9 \times 10^{-22}$ W

Berlin, DB et al arXiv:2112.11465



$$h_0 \gtrsim 3 \times 10^{-22} \times \left(\frac{1\ \text{GHz}}{\omega_g/2\pi}\right)^{3/2} \left(\frac{0.1}{\eta_n}\right) \left(\frac{8\ \text{T}}{B_0}\right) \left(\frac{0.1\ \text{m}^3}{V_{\text{cav}}}\right)^{5/6} \left(\frac{10^5}{Q}\right)^{1/2} \left(\frac{T_{\text{sys}}}{1\ \text{K}}\right)^{1/2} \left(\frac{\Delta\nu}{10\ \text{kHz}}\right)^{1/4} \left(\frac{1\ \text{min}}{t_{\text{int}}}\right)^{1/4}$$

Ex2. GWs exciting solids



$dm(x+u(x,t))$

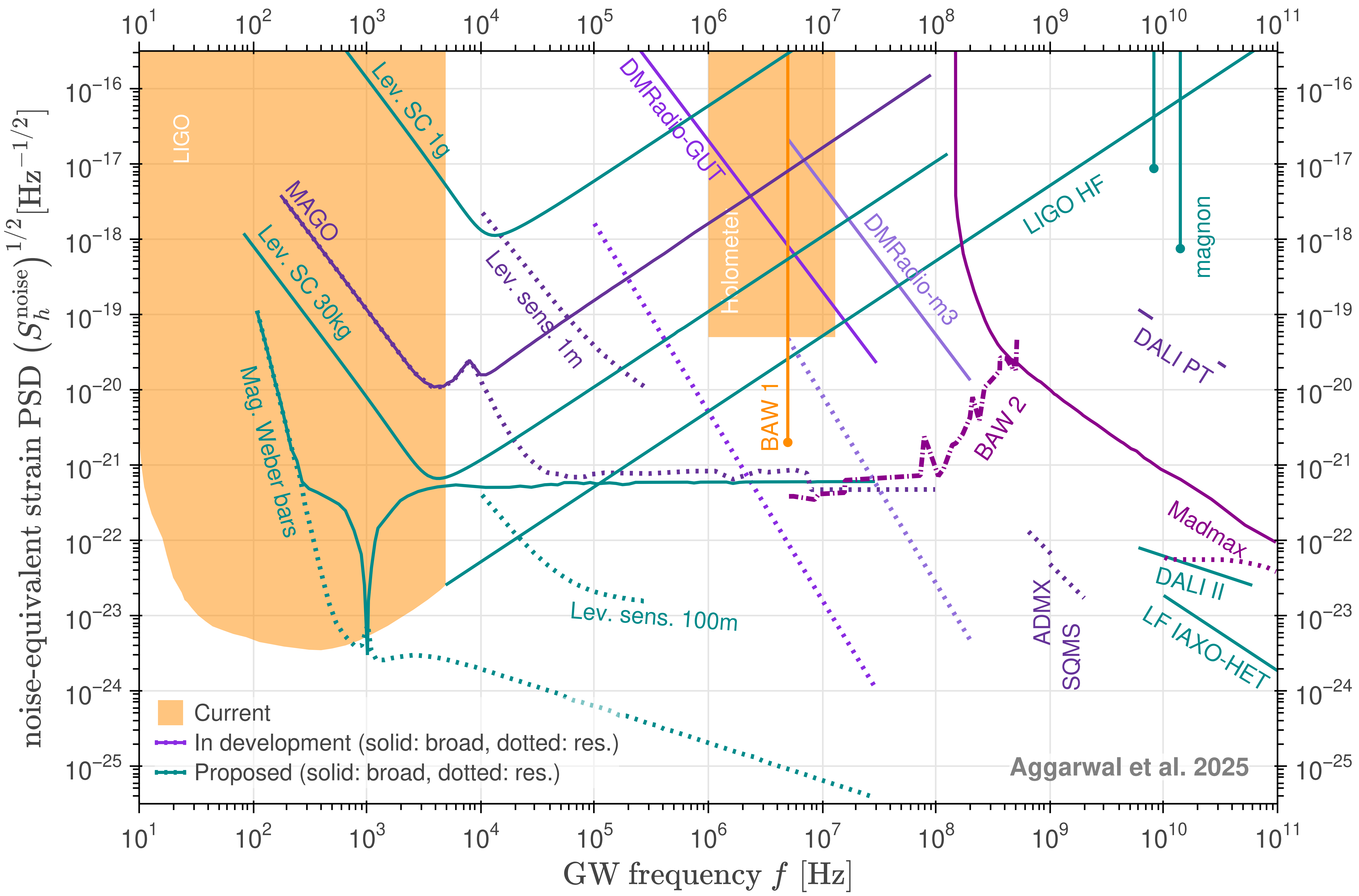
a solid affected by a external source (e.g. *x* direction)

$$dm\left(\frac{\partial^2 u}{\partial t^2} - v_s^2\frac{\partial^2 u}{\partial x^2}\right) = dF_x(t,x),$$

$$dF_i = \frac{1}{2}\ddot{h}_{ij}^{TT}x^j dm$$

searched for many years (Weber bars)

One can use any
mechanical resonator



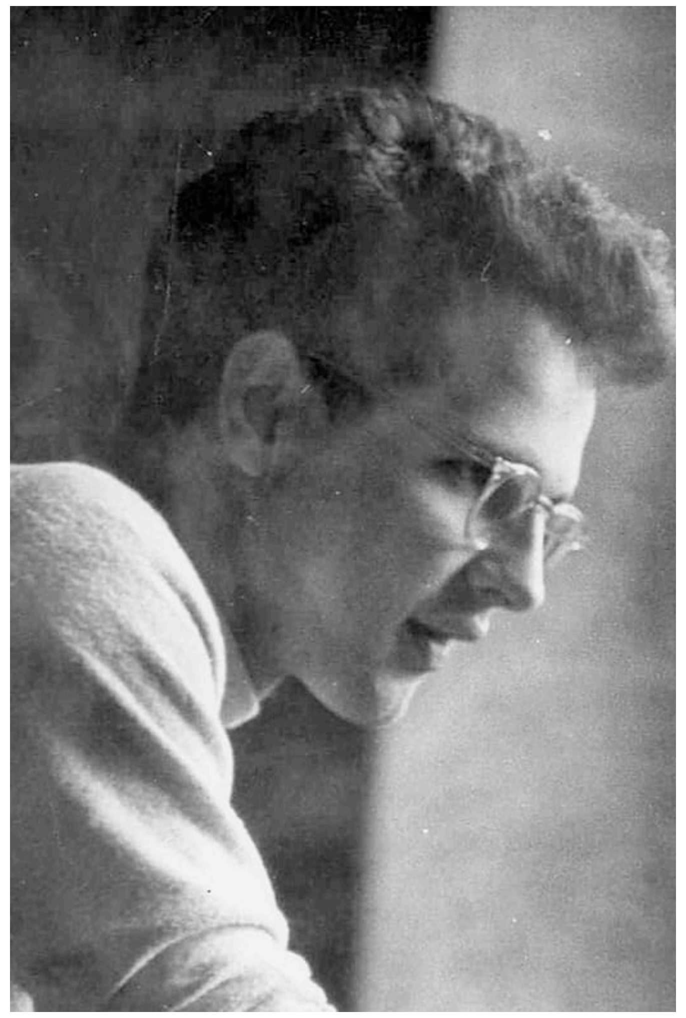
Aggarwal et al. 2501.11723 [gr-qc])

LIGO lesson for prospects

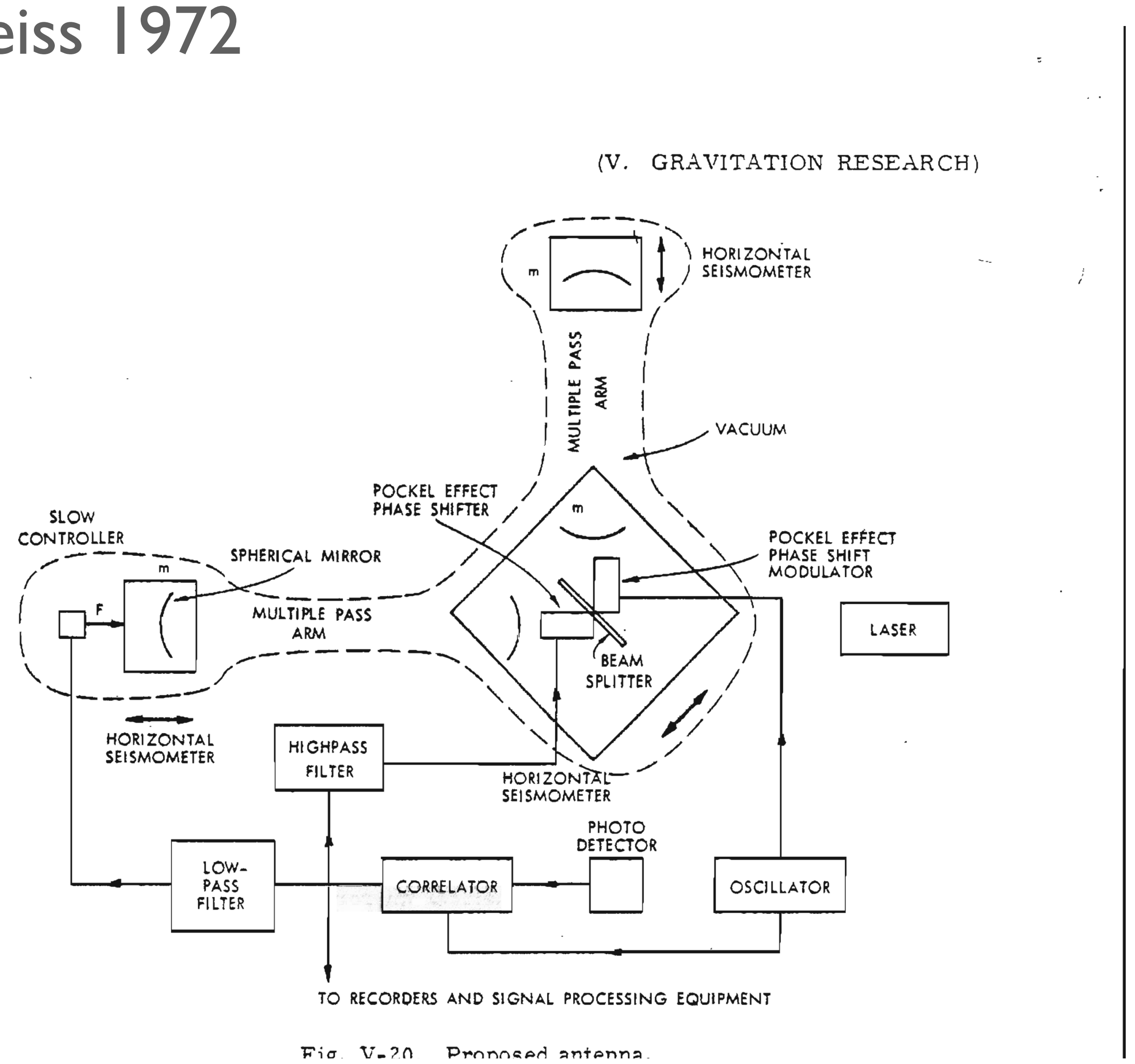
A very exploratory field…

we still need to **deeply think what's better** for the future

Rainer Weiss, ca. 1972

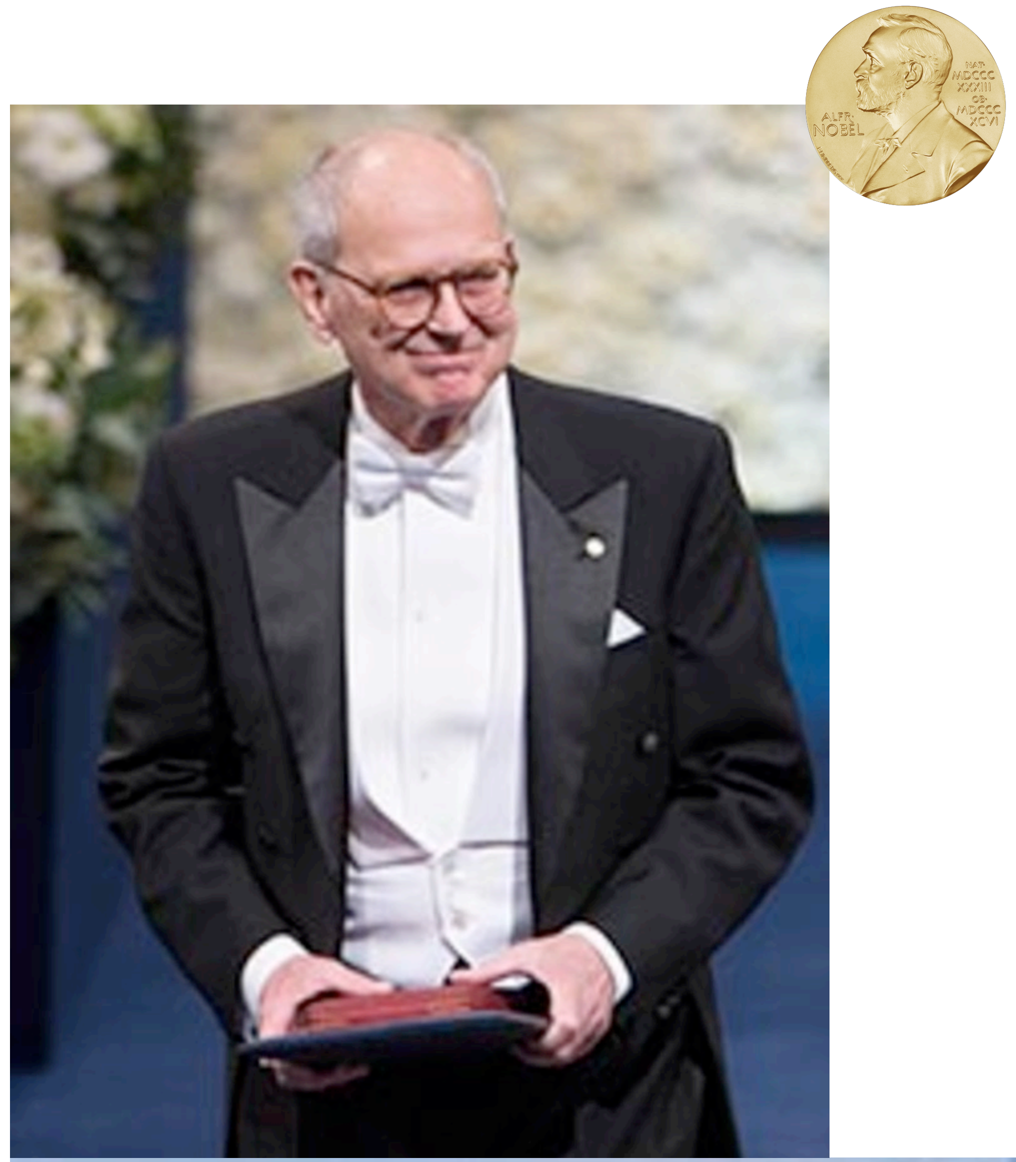


LIGO concept
Weiss 1972

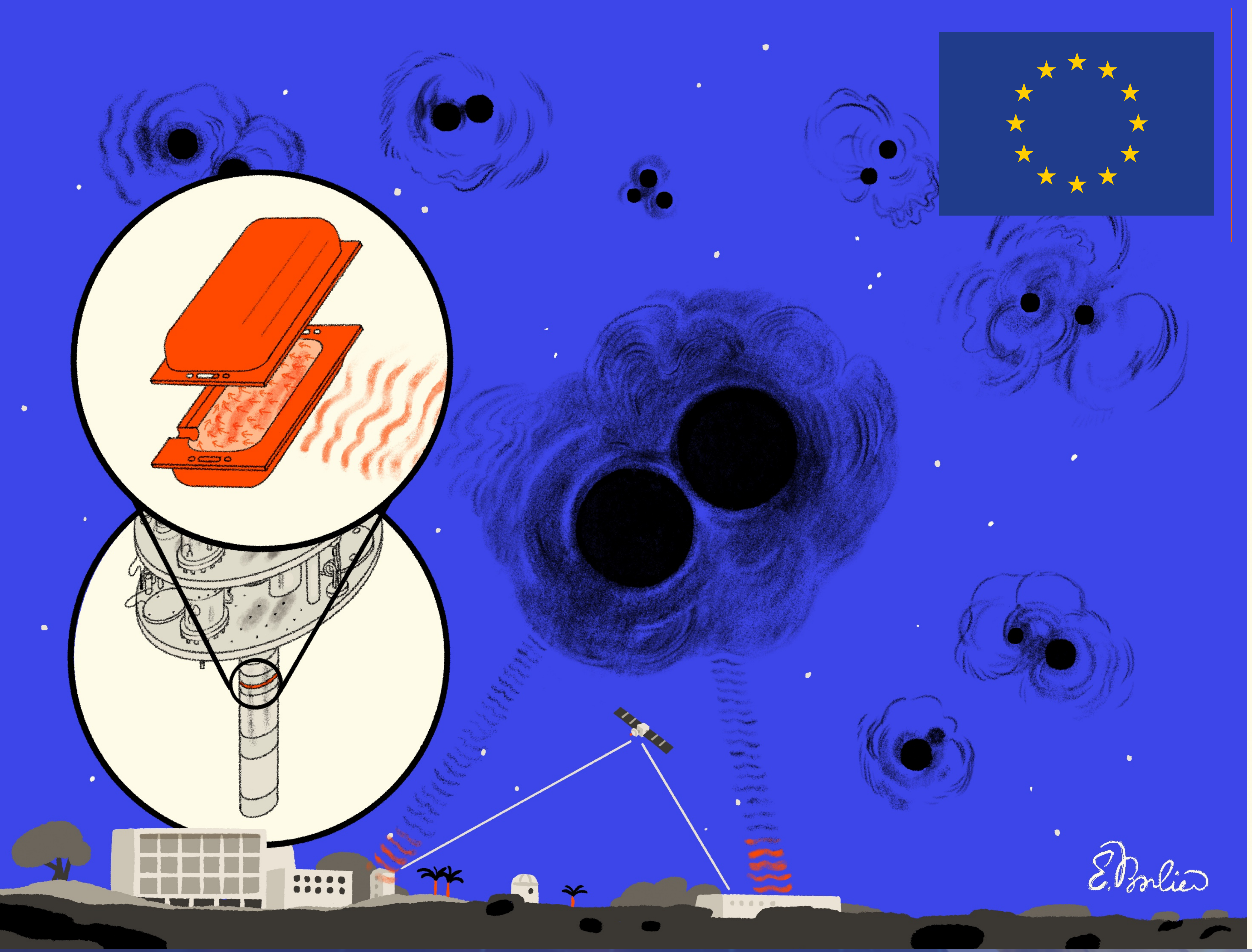


For continuous gravitational waves, the minimum detectable gravitational wave metric spectral density is then

$$h^2(f) > \frac{4}{f^2}\,\frac{\Delta x_n^2(f)}{\Delta f} \approx \frac{4\times 10^{-33}}{f^2(\mathrm{cm})} \qquad \mathrm{Hz}^{-1}.$$



Rainer Weiss &
LIGO , 2017



GravNet

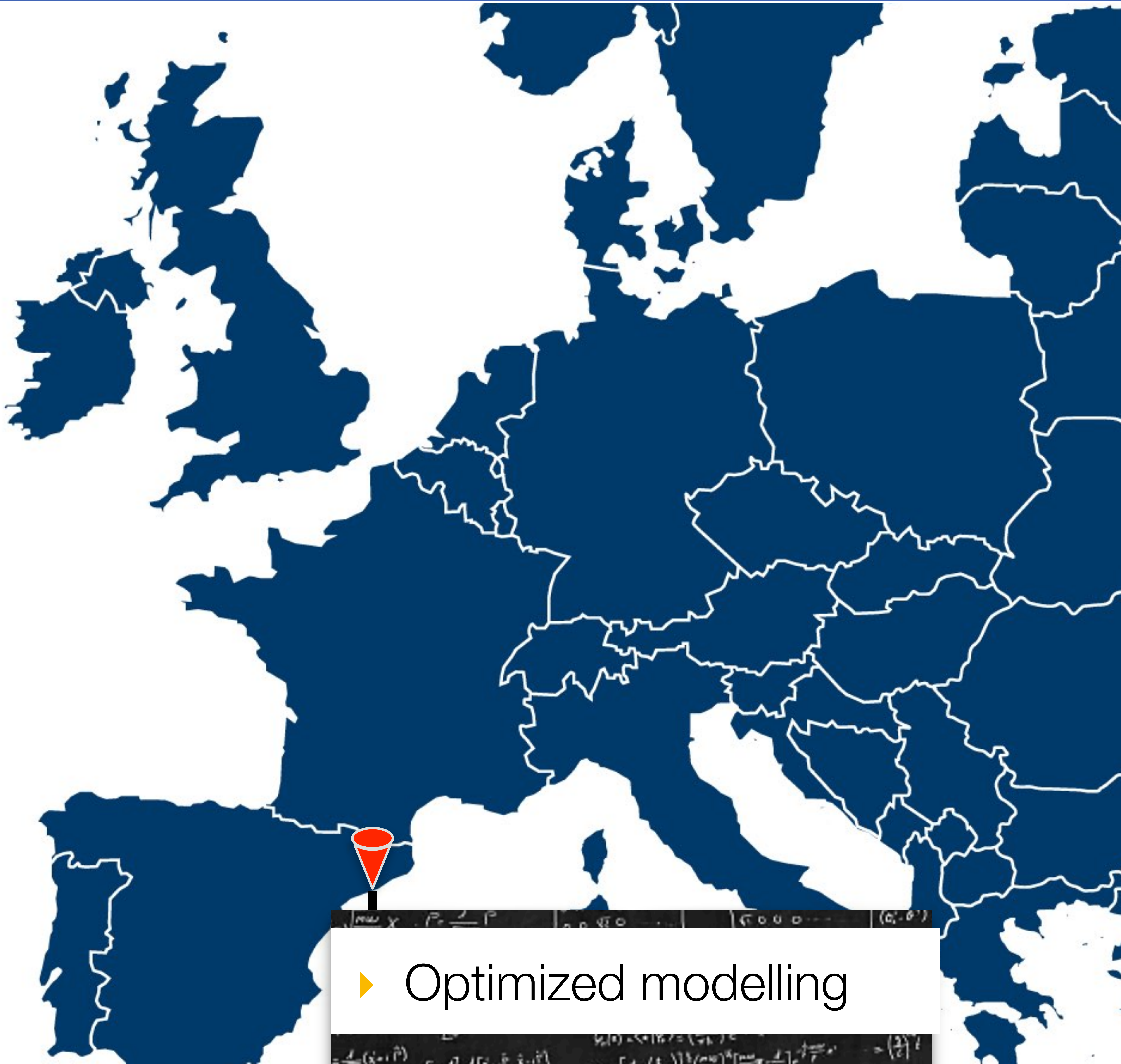
A Global Network for the Search for High Frequency Gravitational Waves

New eyes to explore the dark universe

Claudio Gatti (INFN)
Diego Blas (IFAE)
Matthias Schott (Bonn)
Dmitry Budker (Mainz)

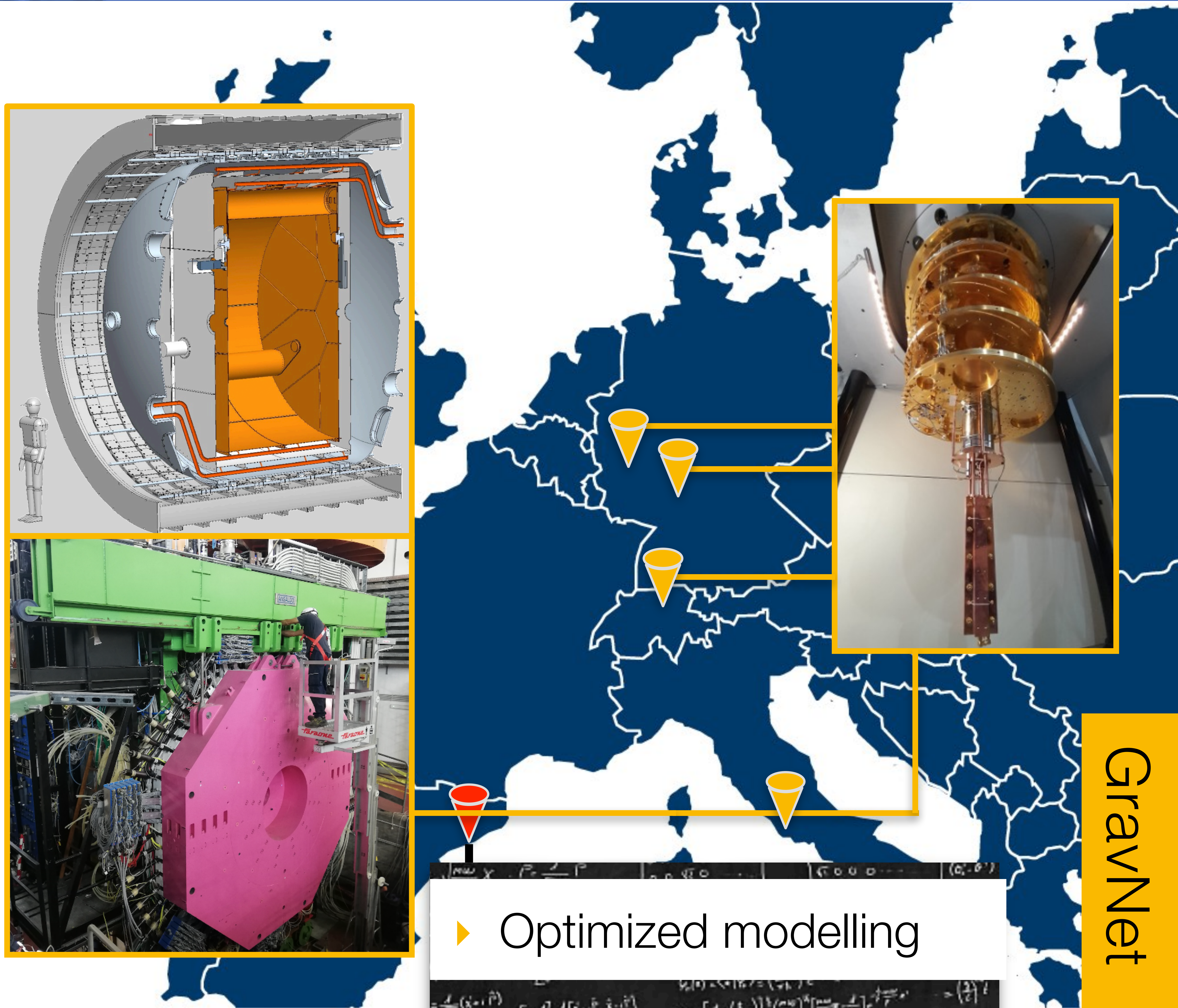
GravNet project (ERC funded)

- Further enhance sensitivity by combining HFGW detectors
  - Initial sites: Bonn, Mainz, Frascati, PSI

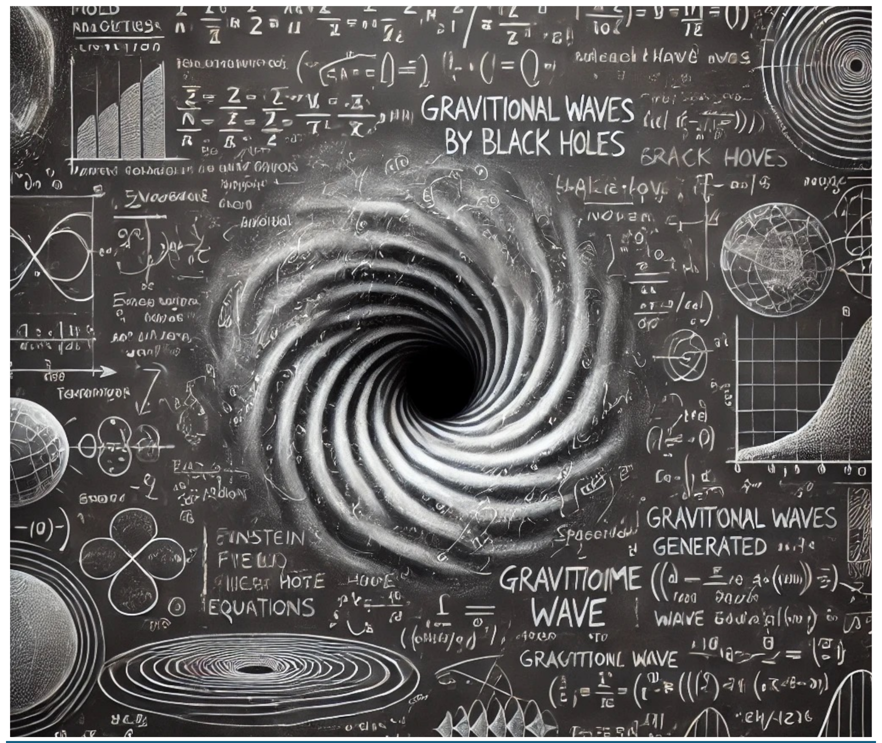


GravNet project (ERC funded)

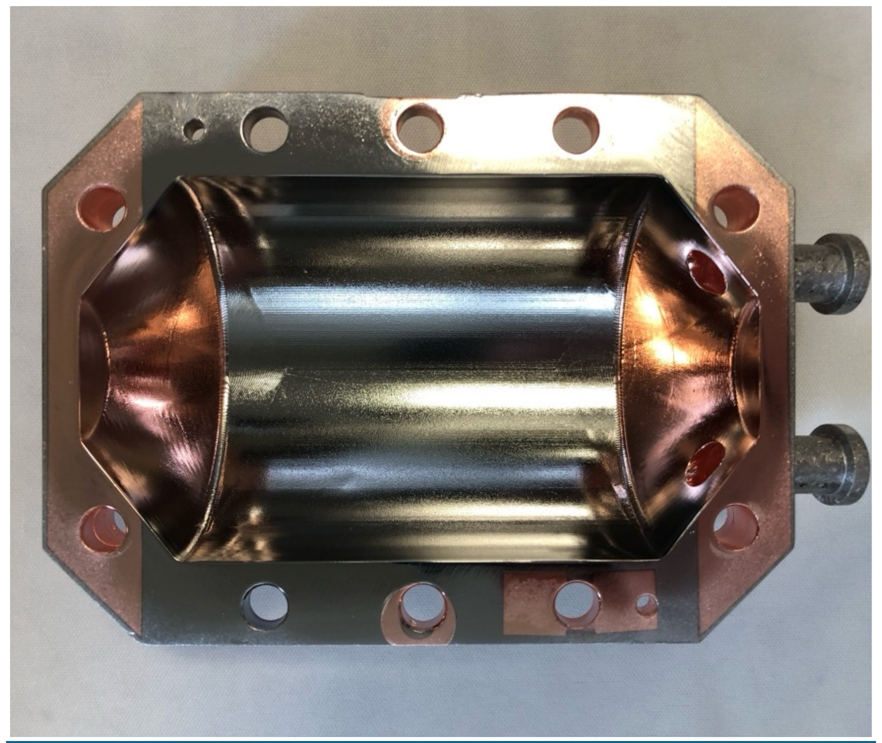
- Further enhance sensitivity by combining HFGW detectors
  - Initial sites: Bonn, Mainz, Frascati, PSI
- GPS based data-acquisition scheme
  - Experience from GNOME Network
- Nine small resonant cavities (5-9 GHz)
  - operation of three cavities in one magnet
- One large resonant cavity (100 MHz)



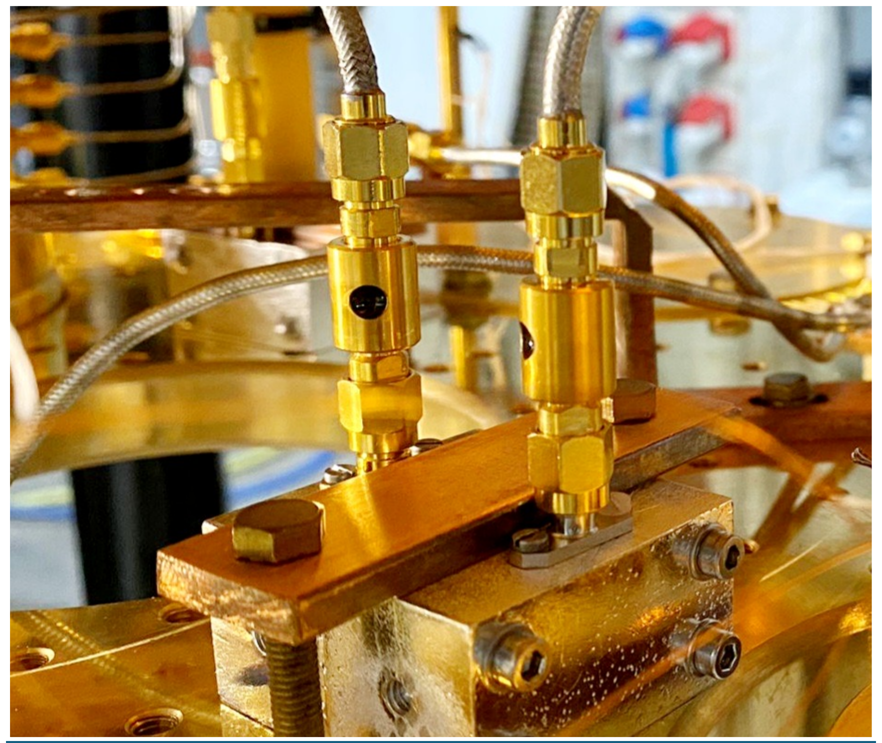
GravNet



Source Modeling and Data Analysis



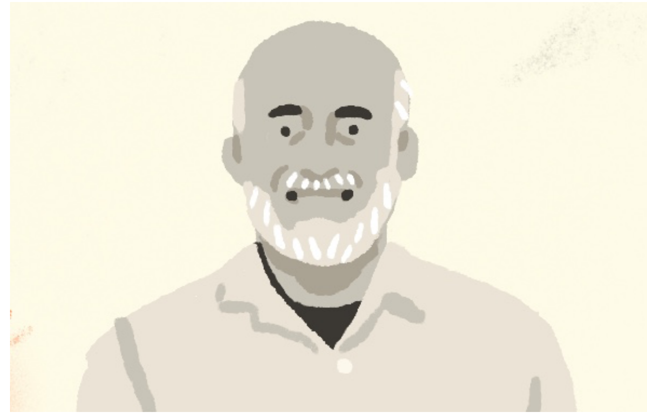
Resonant Cavities



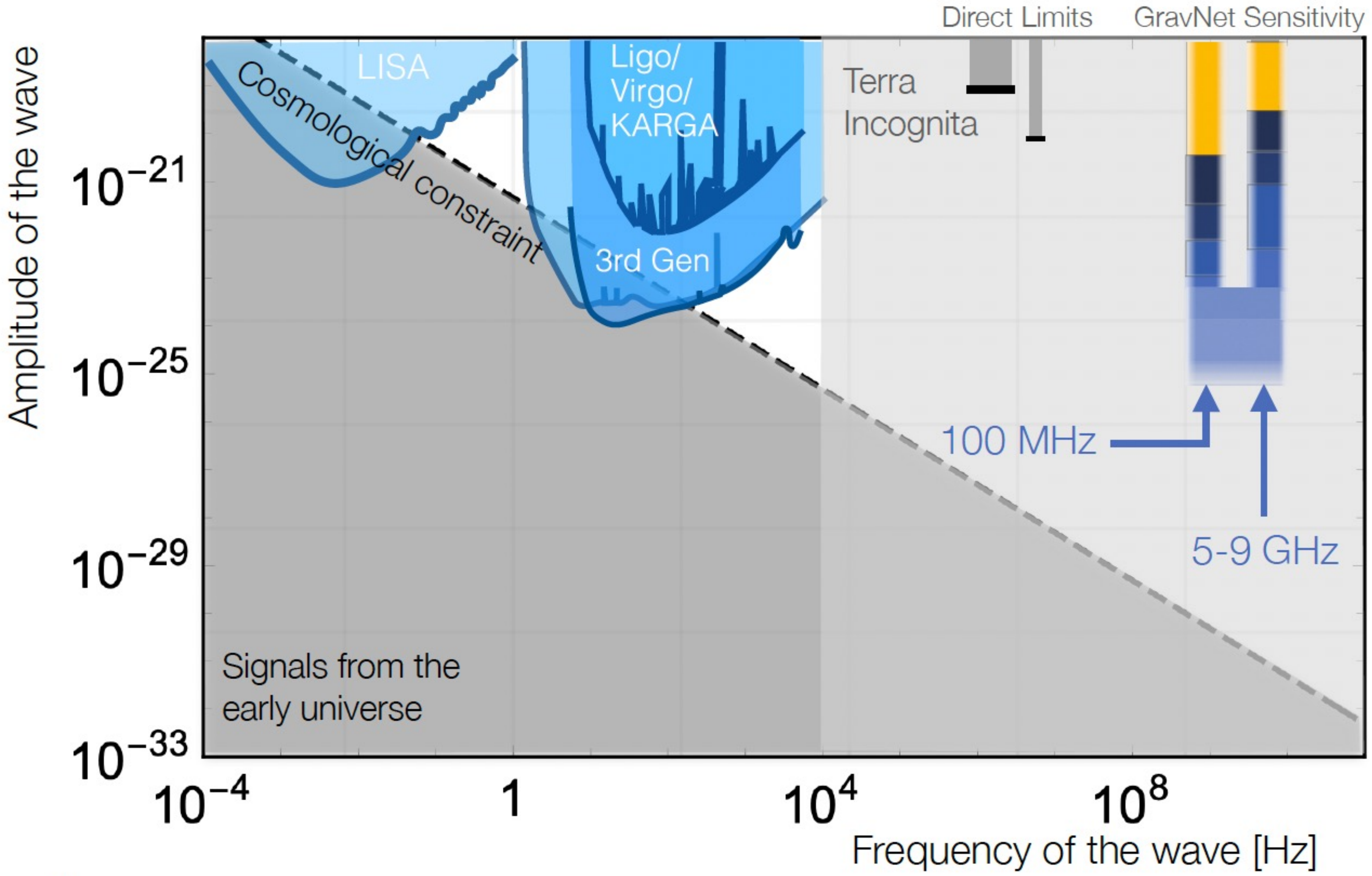
Quantum Sensing

Network Operation



EM coupling



GravNet

- GravNet Baseline
- Modelling and Data Analysis
- Cavity Design & Construction
- Quantum Amplifiers and Sensors
- Network Operation
- Combination of different frequencies
- Adding further detectors to network

$$h_0 \approx 6.0 \times 10^{-23} \left(\frac{1\,\mathrm{T}}{B_0}\right) \left(\frac{0.14}{\eta}\right) \left(\frac{\mathrm{m}^3}{V}\right)^{5/6} \left(\frac{10^6}{Q_{\mathrm{eff}}}\right)^{1/2}$$
$$\times \left(\frac{T_{\mathrm{sys}}}{\mathrm{K}}\right)^{1/2} \left(\frac{\Delta f}{\mathrm{kHz}} \frac{1\,\mathrm{min}}{t_{\mathrm{eff}}^{\mathrm{int}}}\right)^{1/4} \left(\frac{\mathrm{GHz}}{\omega_n/2\pi}\right)^{3/2},$$

GravNet collaboration

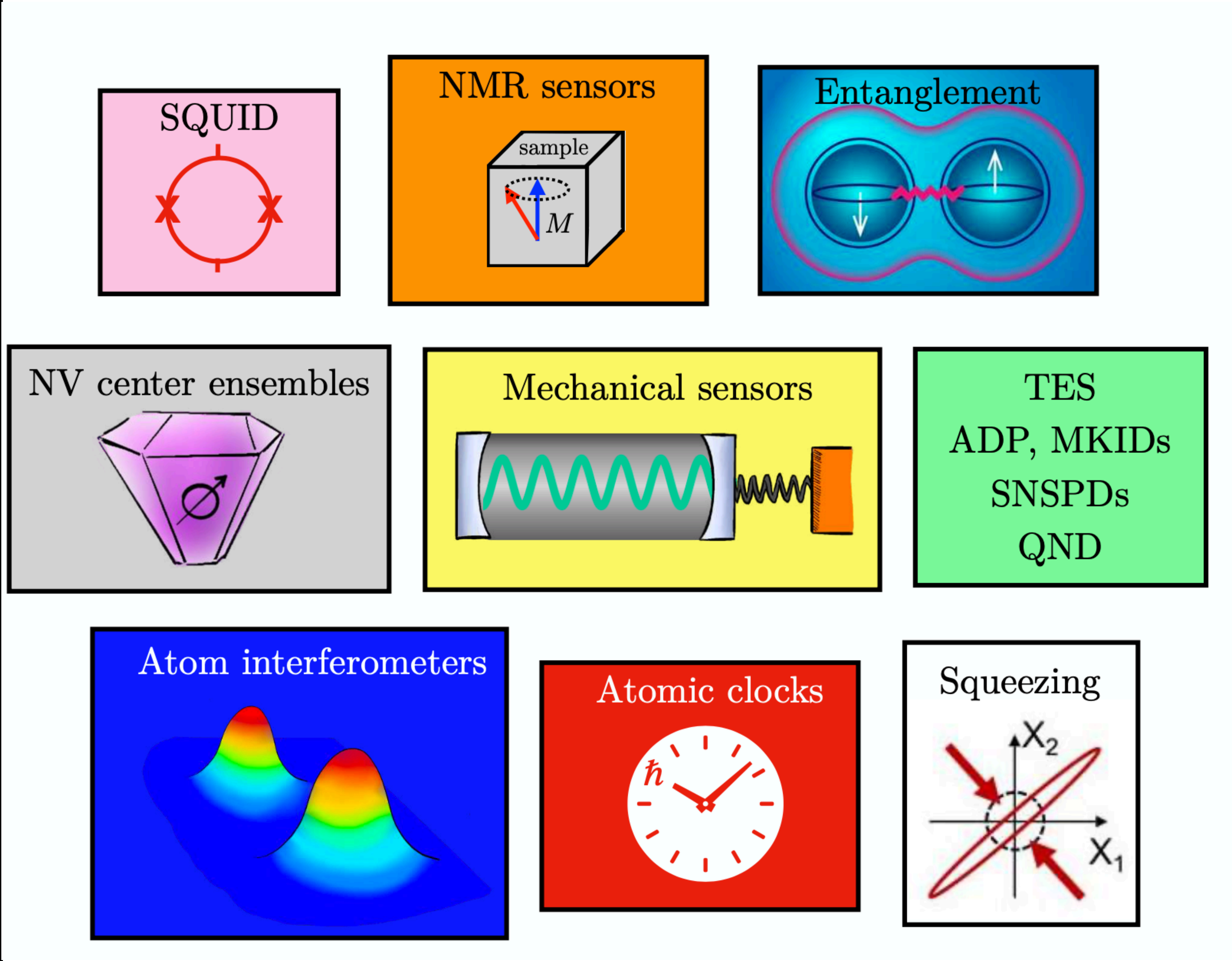
- Since March 2025:
  - We extend the project to a global collaboration
  - GWs generate peculiar signals in all detectors
    - Generate a global network of detectors getting as many sites/expertise/techniques as possible
      - Challenges to combine data
      - Common data taking campaigns to start in 2026
      - MoU ready, first global activities happening, first formalities about to happen
    - Talk to us! (There are not entry requirements beyond having a device/theoretical expertise/sensing/network… etc expertise)

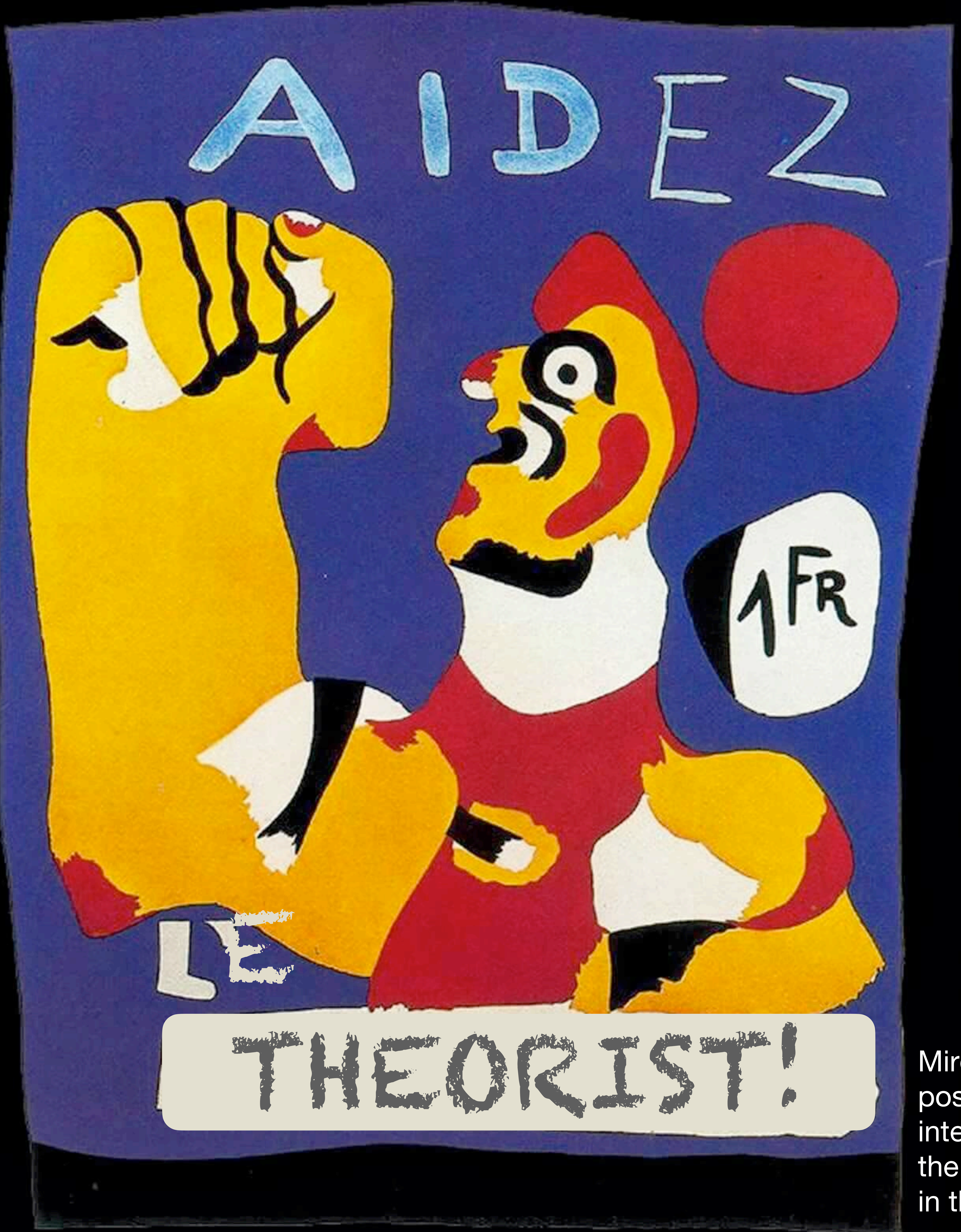
Quantum sensing (metrology) for HEP/Grav/Cosmo

- Quantum sensing/devices
  - Provide new ways to detect backgrounds
  - **Low thresholds** ideally for "substantial" fluxes with **tiny cross-sections**.
- Tasks for HEP/Grav/Cosmo practicioners
  - Going **from HEP/Grav/Cosmo dofs** to **QSen dofs**
  - Evaluate them to provide $H = H_0 + H_{\rm int}$
- Some examples: dark matter, neutrino and GW searches in
  - Co-magnetometers (maybe also for beam-dumped? neutrino searches?)
  - Large baseline interferometers
  - SRF Cavities

- Many more to come: we are **not** fully exploiting the quantum world!
  - Playing with **entanglement**, **squeezing**, **q network**, etc still at its infancy.

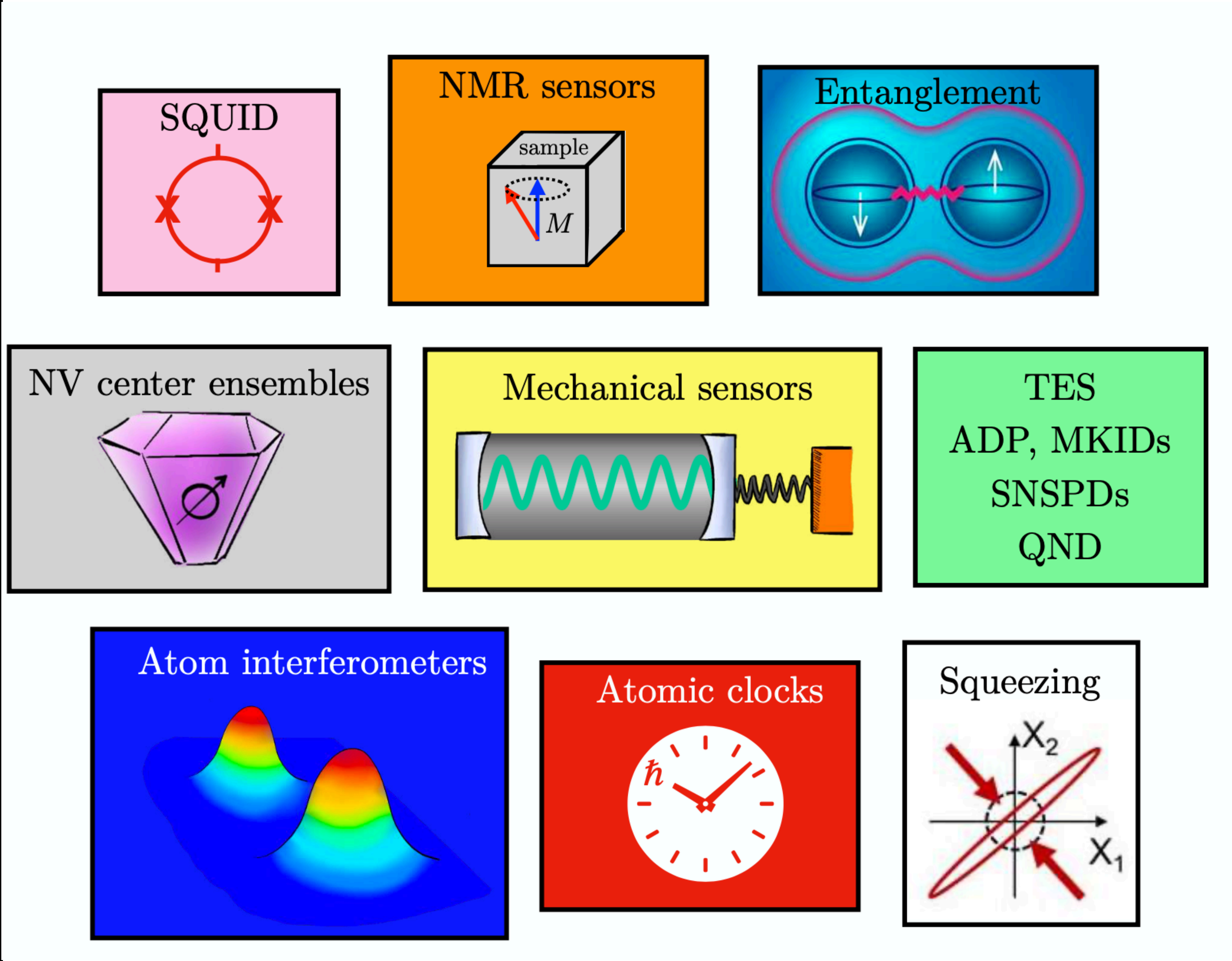
Quantum Device



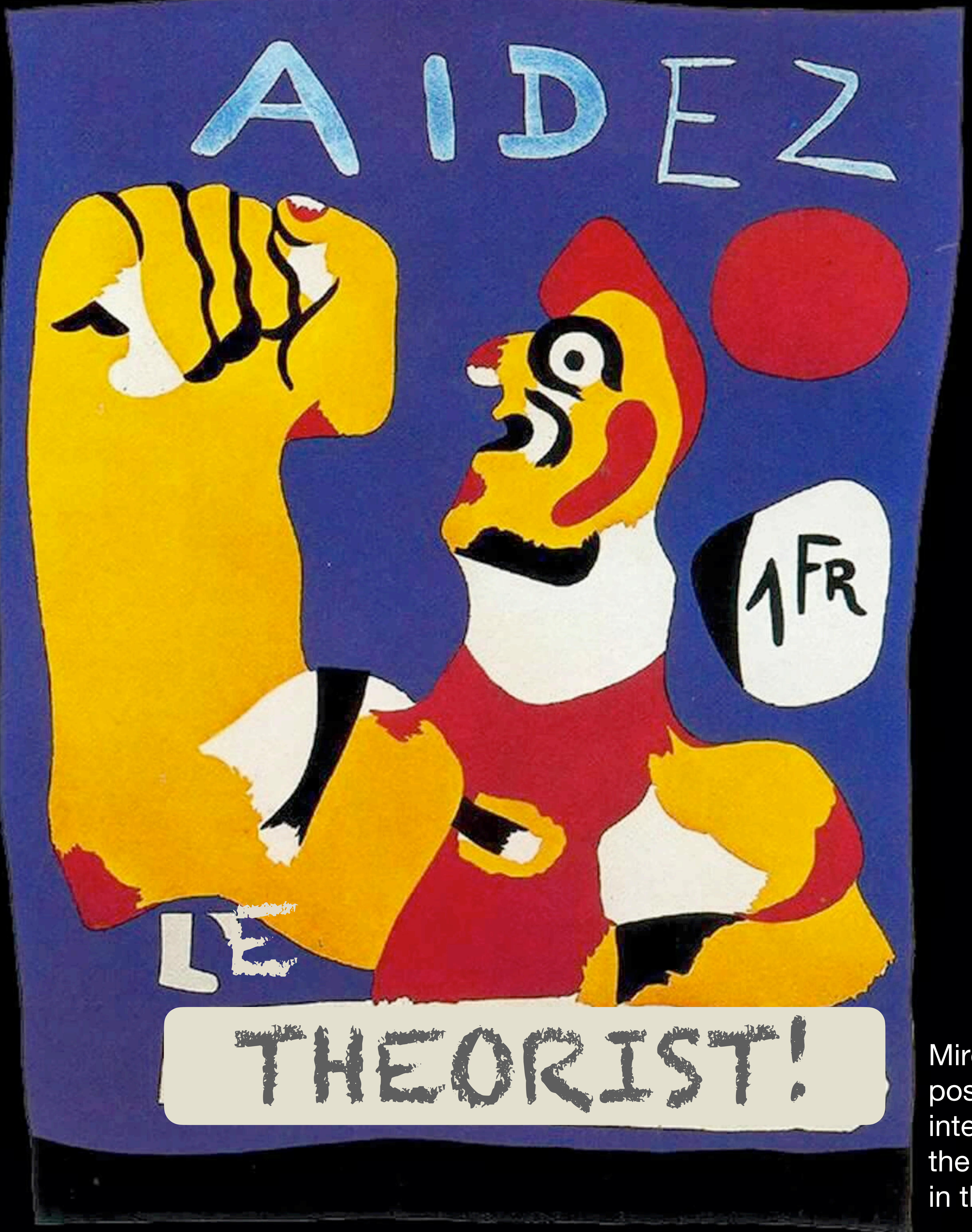


Miró, 1937. “Help Spain” poster calling for international help to support the democratic republic in the Spanish Civil war.

Quantum Device



And more…



Miró, 1937. "Help Spain" poster calling for international help to support the democratic republic in the Spanish Civil war.

Very recent references!

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz #1

Nancy Aggarwal (Northwestern U.), Odylio D. Aguiar (Sao Jose, INPE), Diego Blas (Barcelona, IFAE and ICREA, Barcelona), Andreas Bauswein (Darmstadt, GSI), Giancarlo Cella (INFN, Pisa) et al. (Jan 20, 2025)

e-Print: 2501.11723 [gr-qc]

Terrestrial Very-Long-Baseline Atom Interferometry: Summary of the Second Workshop #2

Adam Abdalla (Darmstadt, Tech. Hochsch.), Mahiro Abe (Stanford U., Phys. Dept.), Sven Abend (Leibniz U., Hannover), Mouine Abidi (Leibniz U., Hannover), Monika Aidelsburger (Munich, Max Planck Inst. Quantenopt. and Munich U. and Munich U., ASC and MCQST, Munich) et al. (Dec 19, 2024)

Proceedings of: TVLBAI 2024 • e-Print: 2412.14960 [hep-ex]