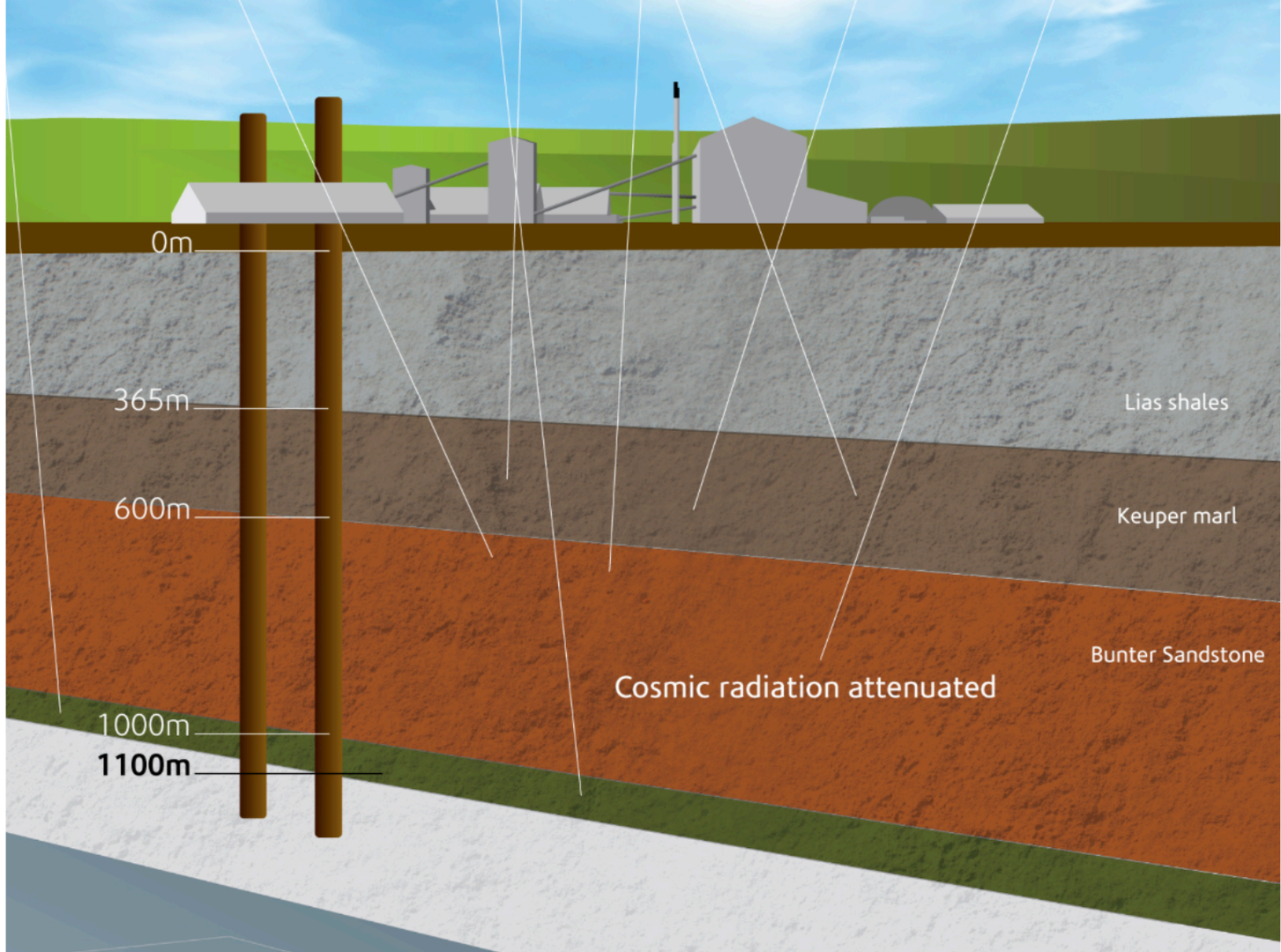
Quantum Technology for Fundamental Physics

Martin Bauer, 16.9.2024



Quantum Technology…

..is technology that exploits the fundamental principles of quantum mechanics.

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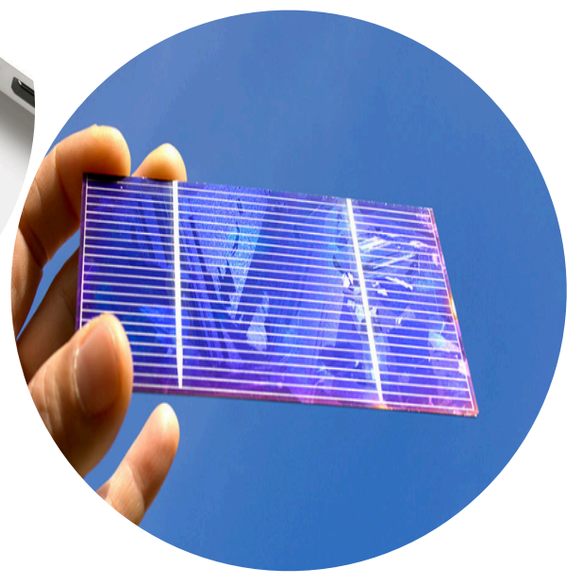
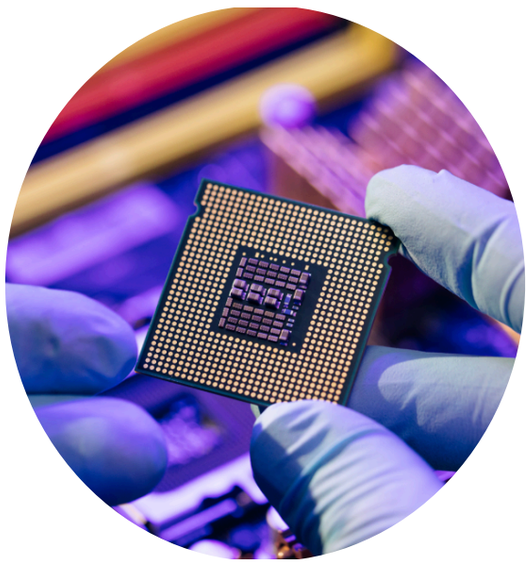
Tunneling, particle nature of photons, energy quantisation…





…entanglement, superposition and coherence

Quantum Technology…

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Tunneling, particle nature of photons, energy quantisation…

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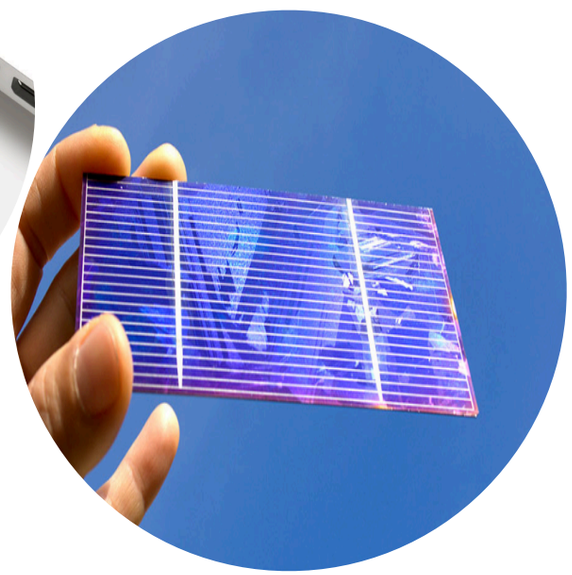
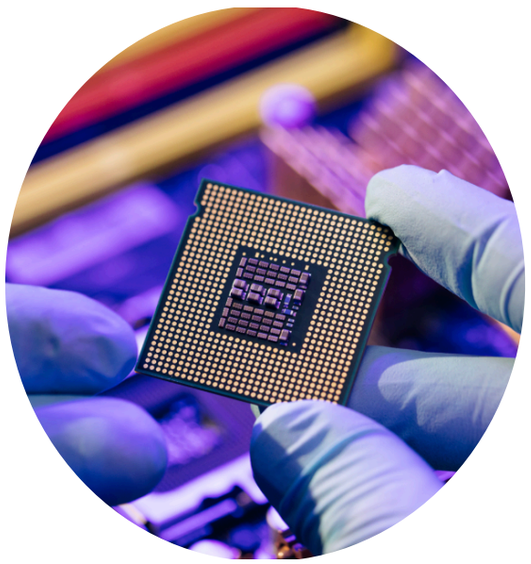
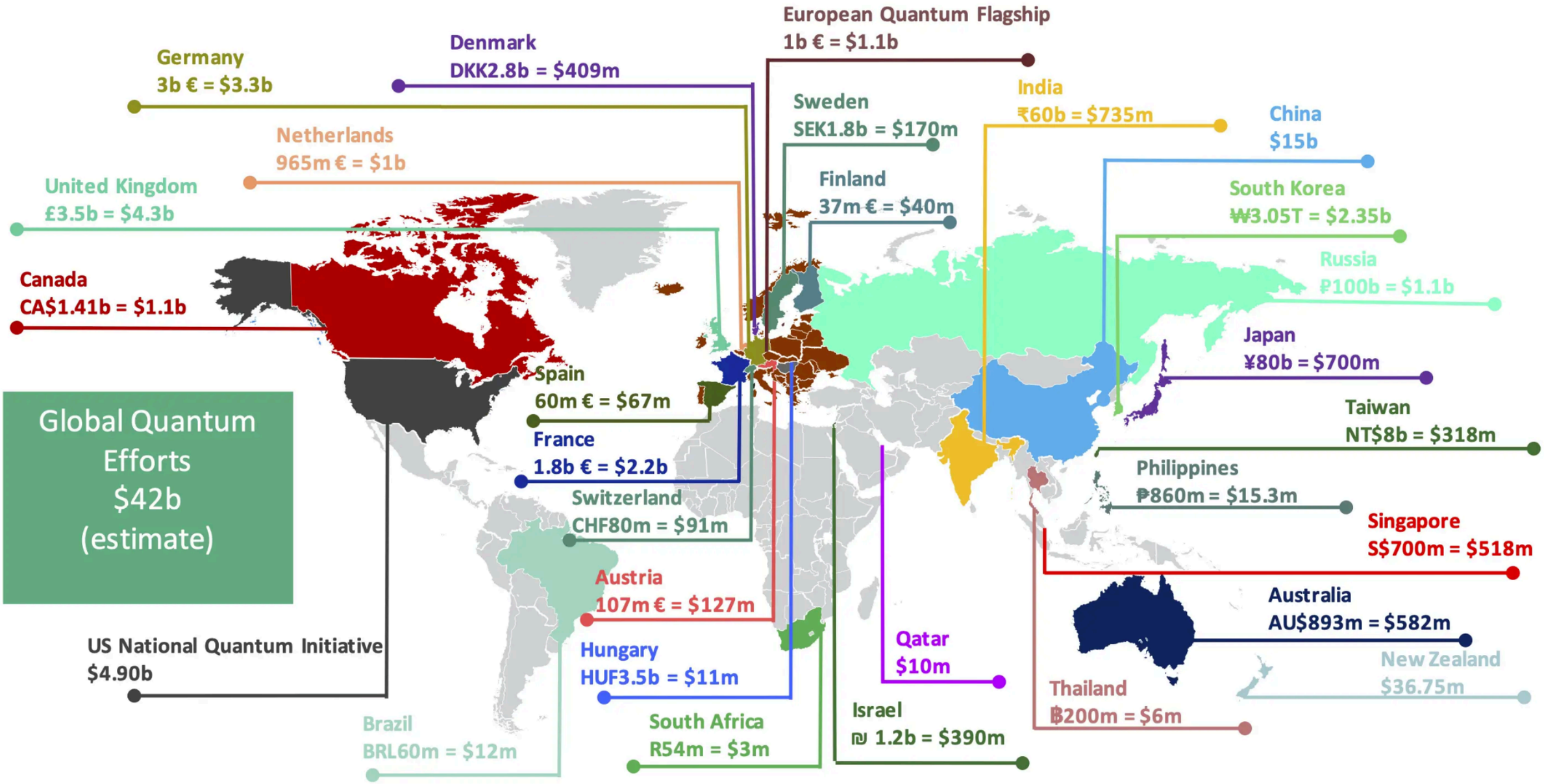




Quantum technology public investment



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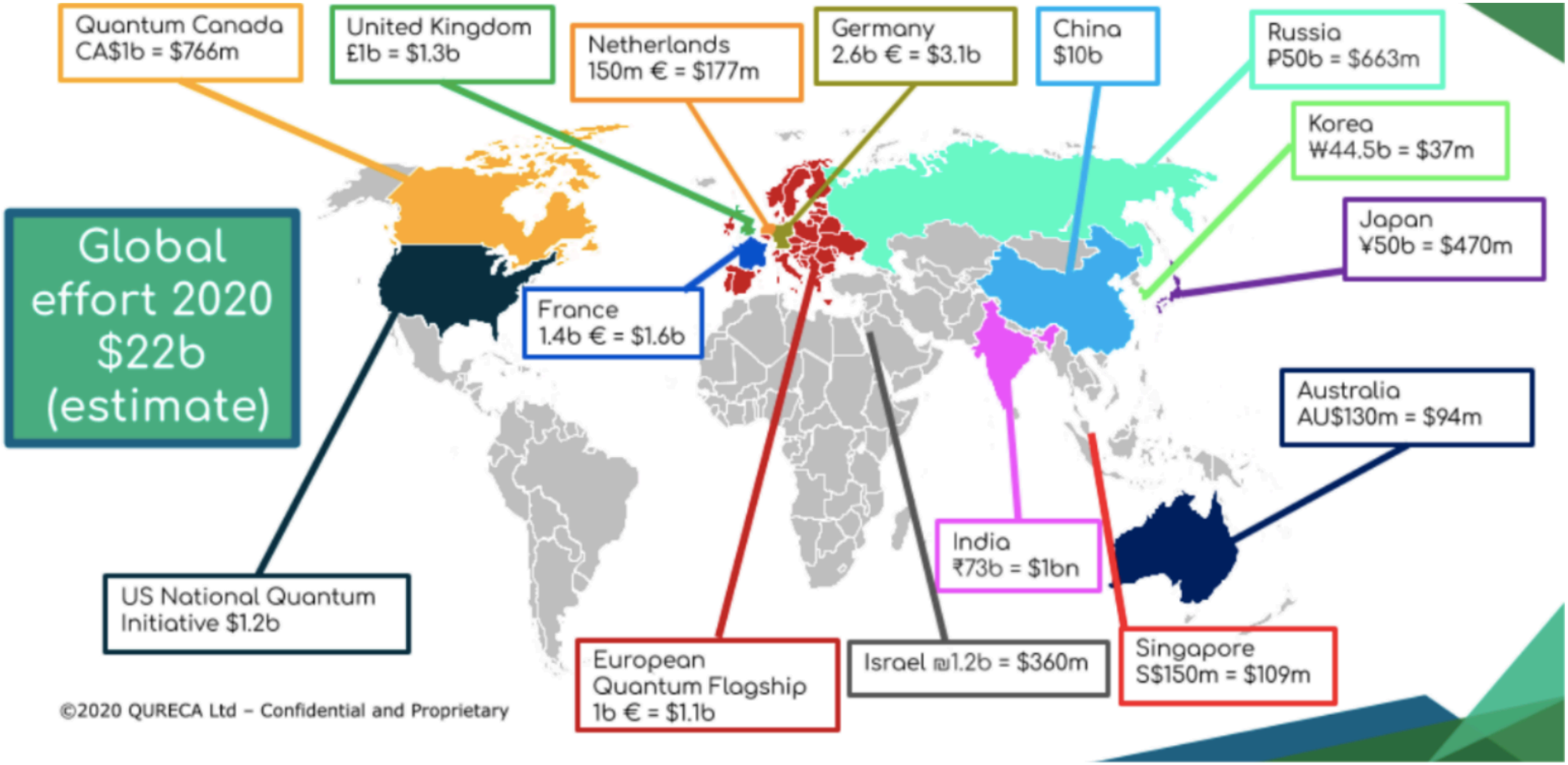
Quantum technology public investment



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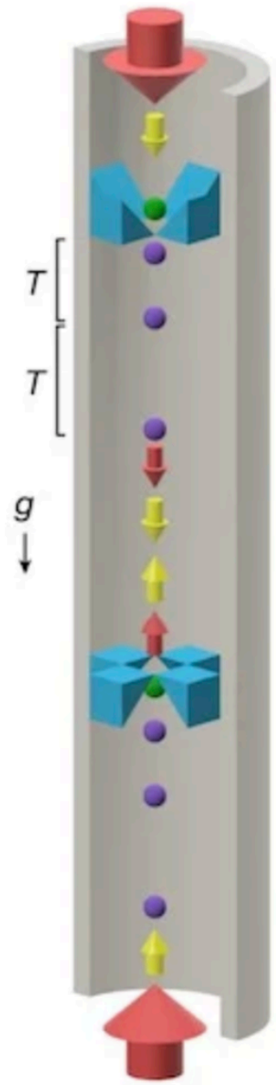
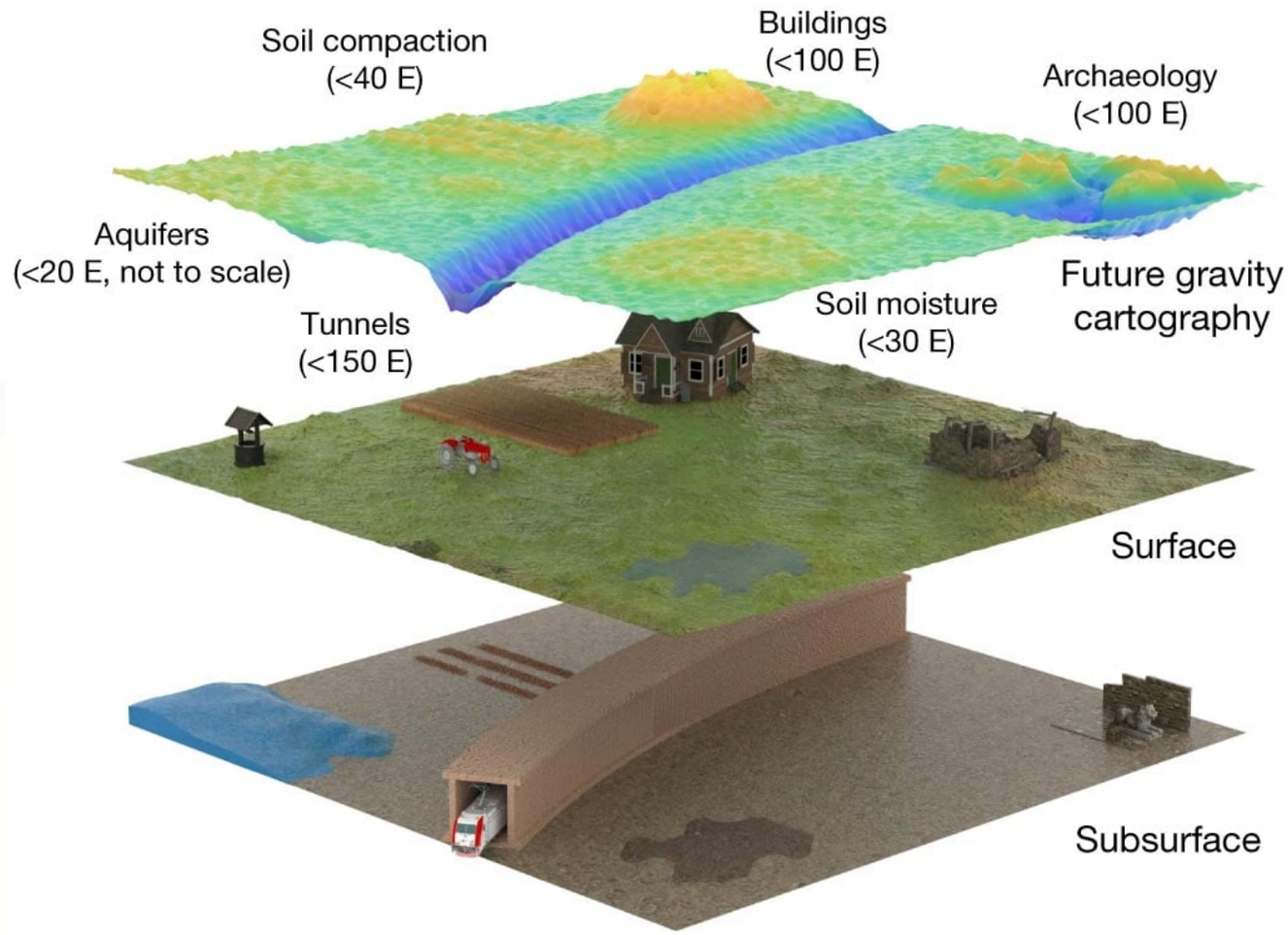
Quantum technology applications

First example:

Quantum gravitometers

Measures acceleration via the interference pattern that results when atom waves recombine after splitting into different paths





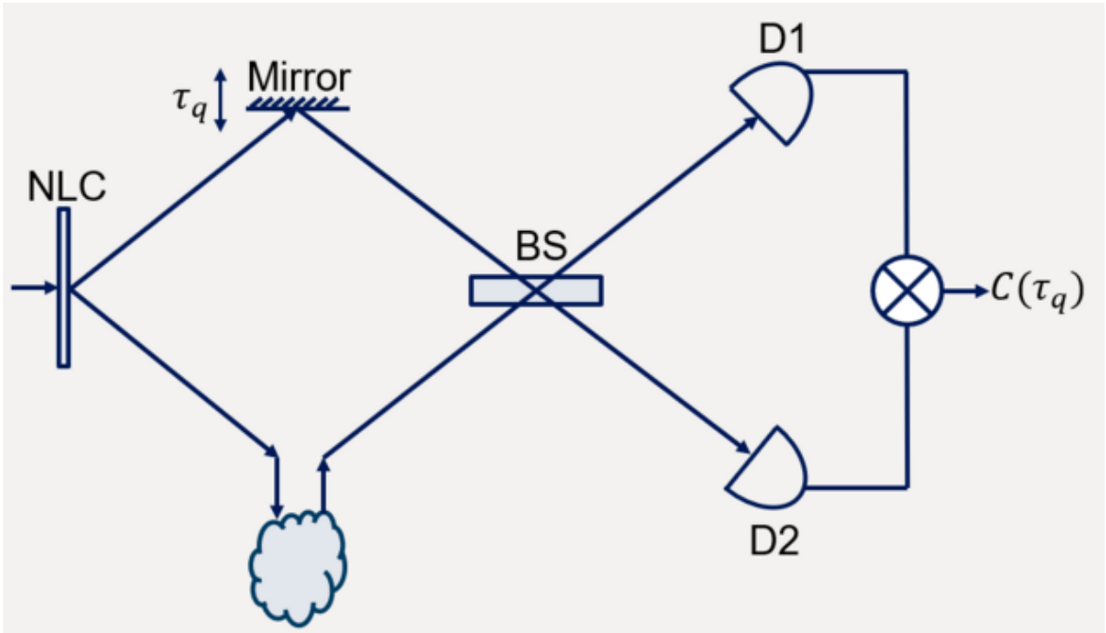
Stray, B., Lamb, A., Kaushik, A. *et al.* Quantum sensing for gravity cartography. *Nature* **602**, 590–594 (2022)

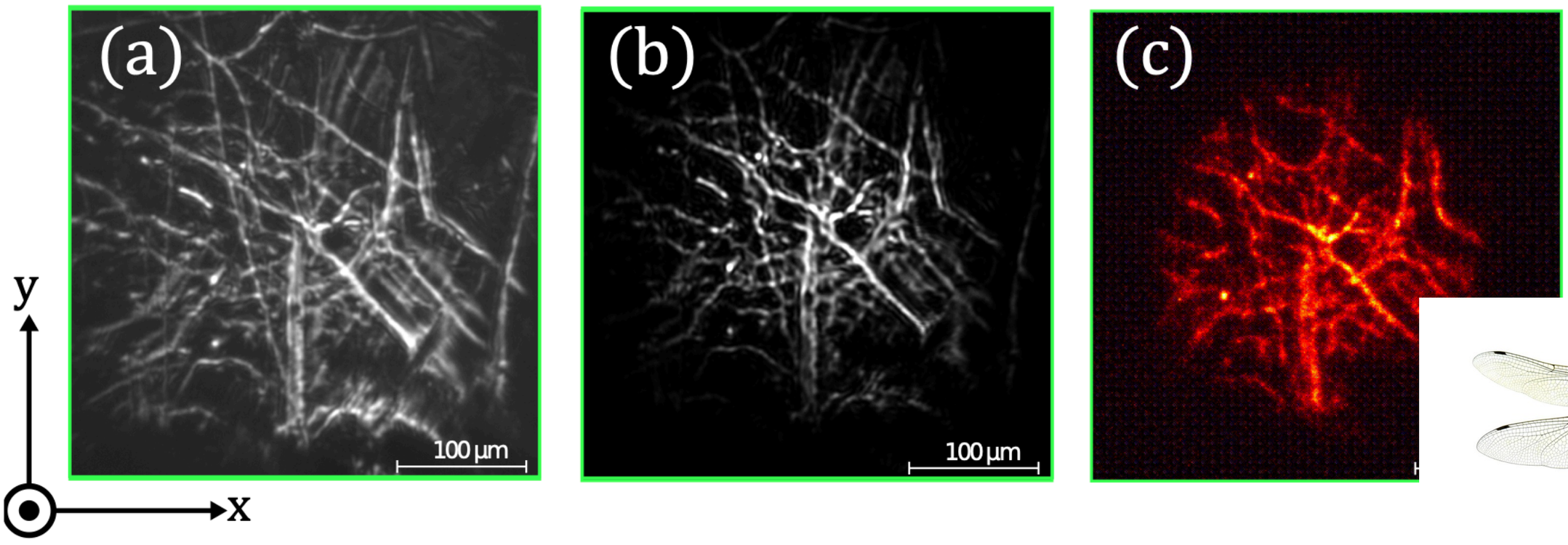
Quantum technology applications

Second example:

Quantum-optical tomography

Interference of entangled photons to measure surface structures





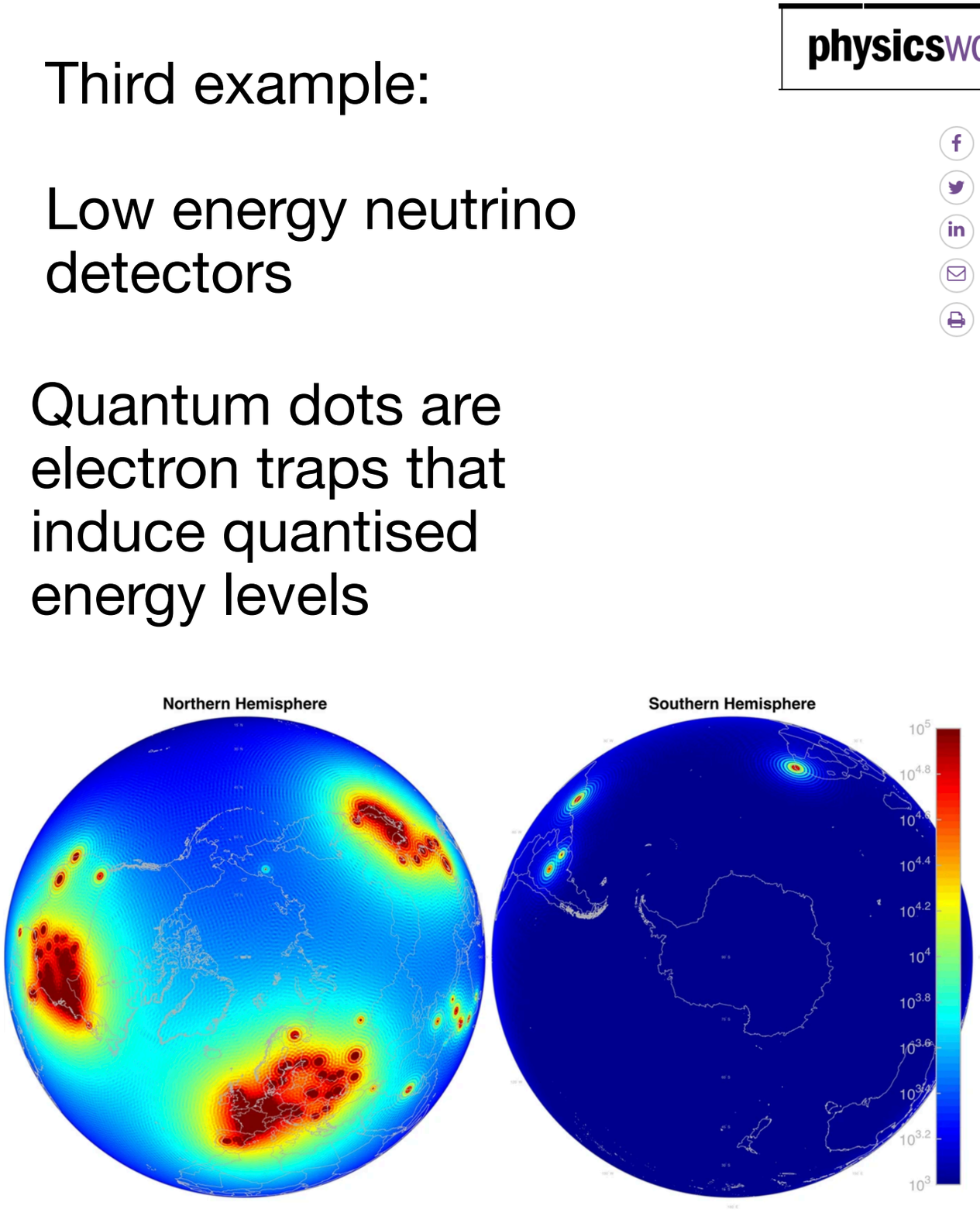
Yepiz-Graciano, Pablo, et al. "Quantum optical coherence microscopy for bioimaging applications." *Physical Review Applied* 18.3 (2022): 034060.

Quantum technology applications

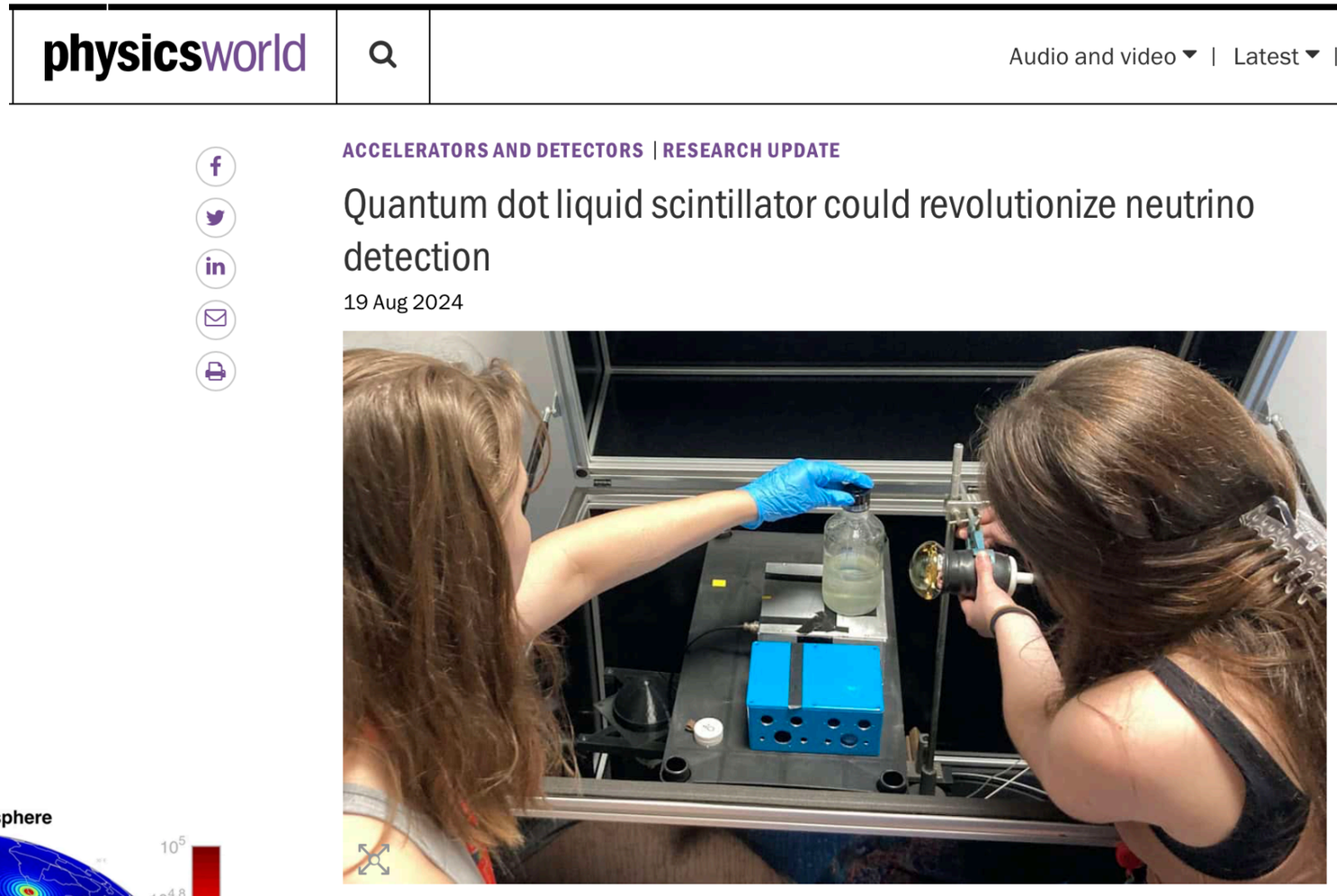
Third example:

Low energy neutrino detectors

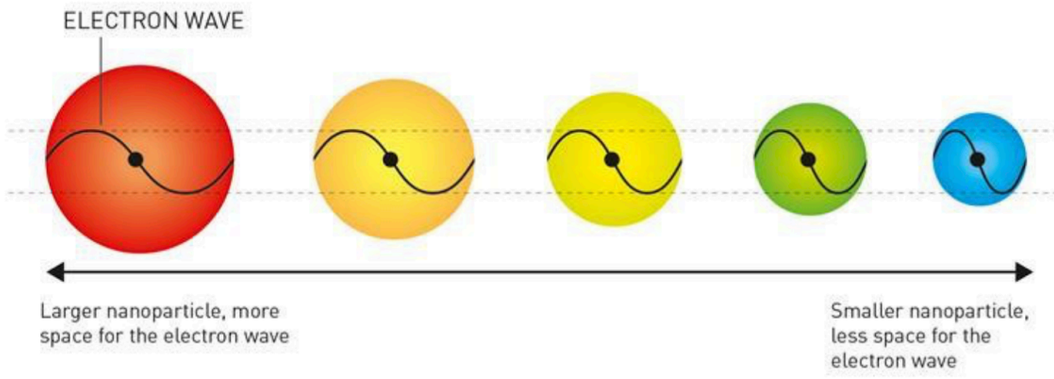
Quantum dots are electron traps that induce quantised energy levels



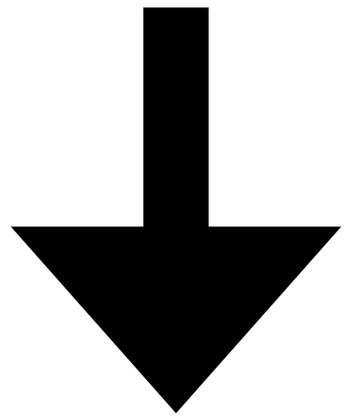
AGM2015 reactor-$\bar{\nu}_e$ flux in the 3.00–3.01 MeV energy bin (in logspace color).



Safer scintillator Researchers at King's College London are developing a water-based scintillator made from quantum dots for neutrino detection. The experimental setup shows a sample of quantum dots in water solution placed in front of a photomultiplier tube. (Courtesy: King's College London)



Quantum Technology for Fundamental Physics



Quantum Technology from Fundamental Physics

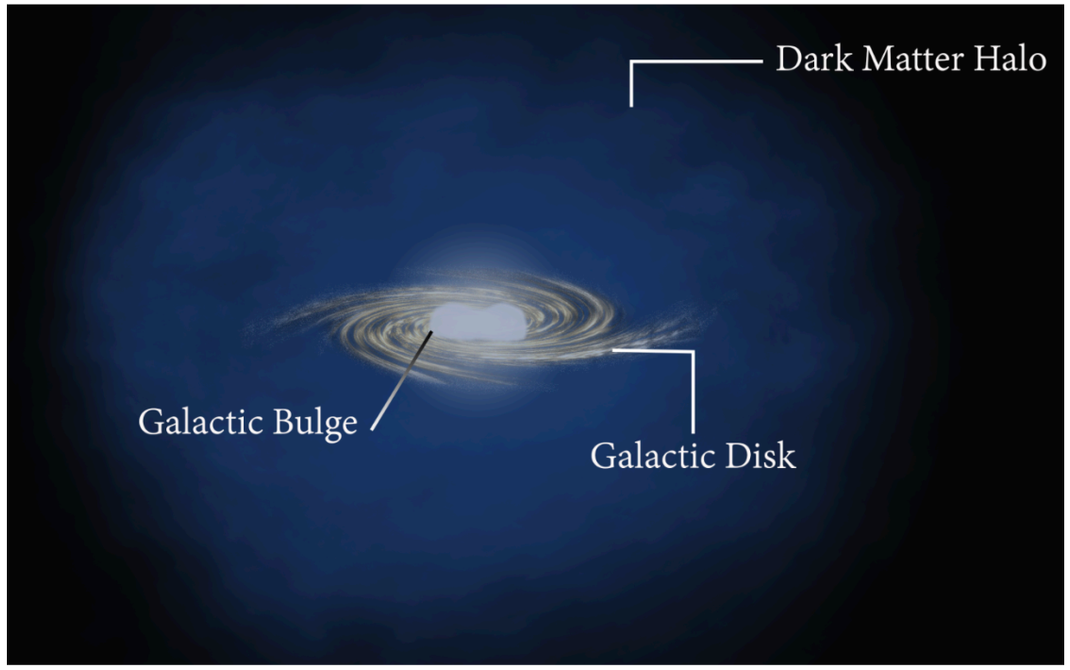
Fundamental Physics

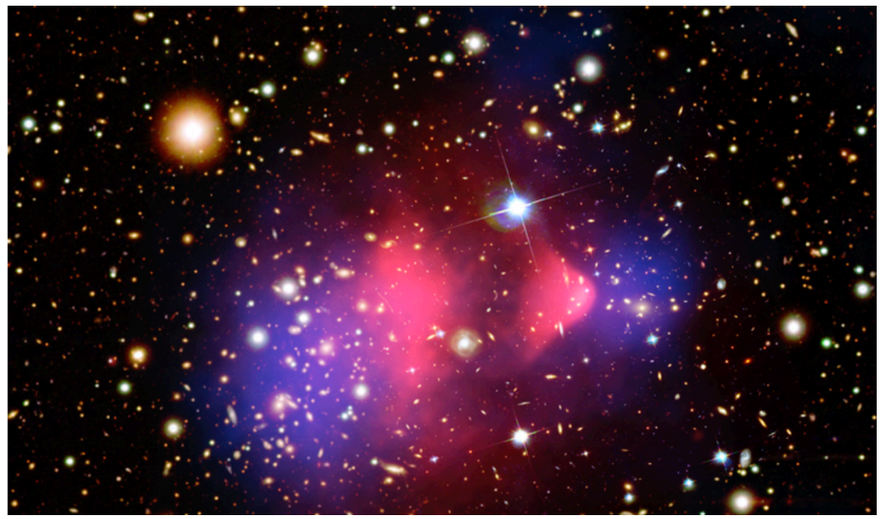
We want to answer fundamental questions…

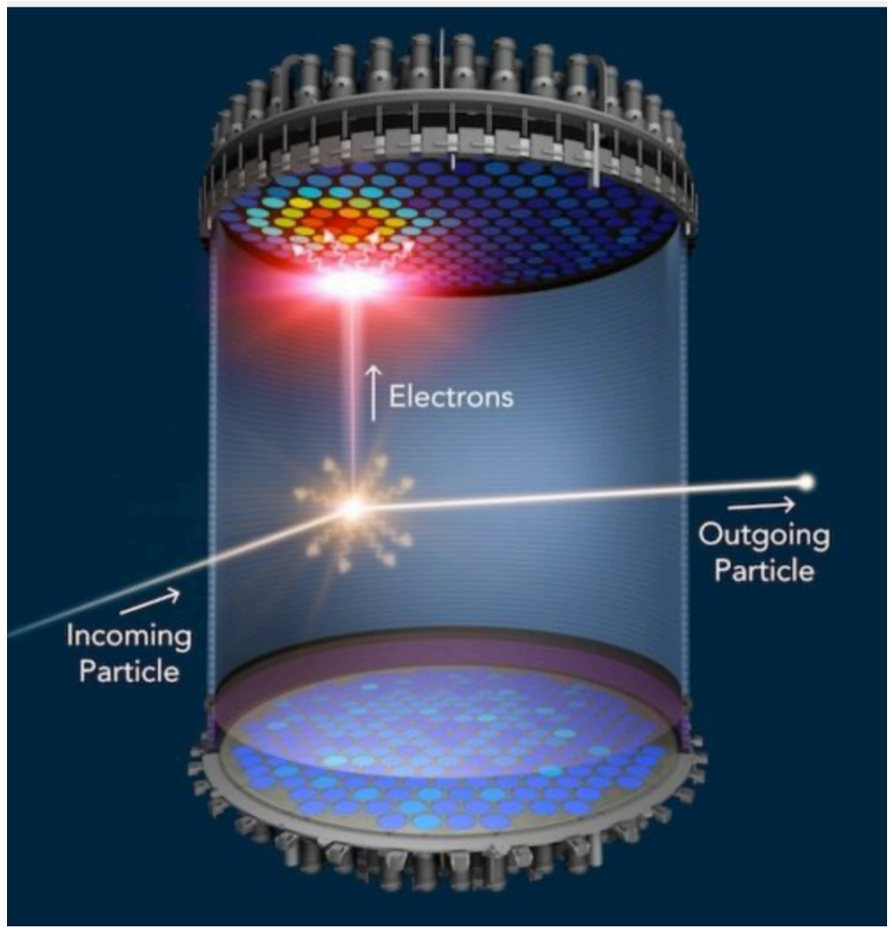
- What is dark matter ?
- Is there a fifth force ?
- Are there extra dimensions ?
- Where is the anti-matter ?
- Is gravity a quantum theory ?
- …

What is dark matter ?

We know a lot about dark matter from cosmology and astrophysics.



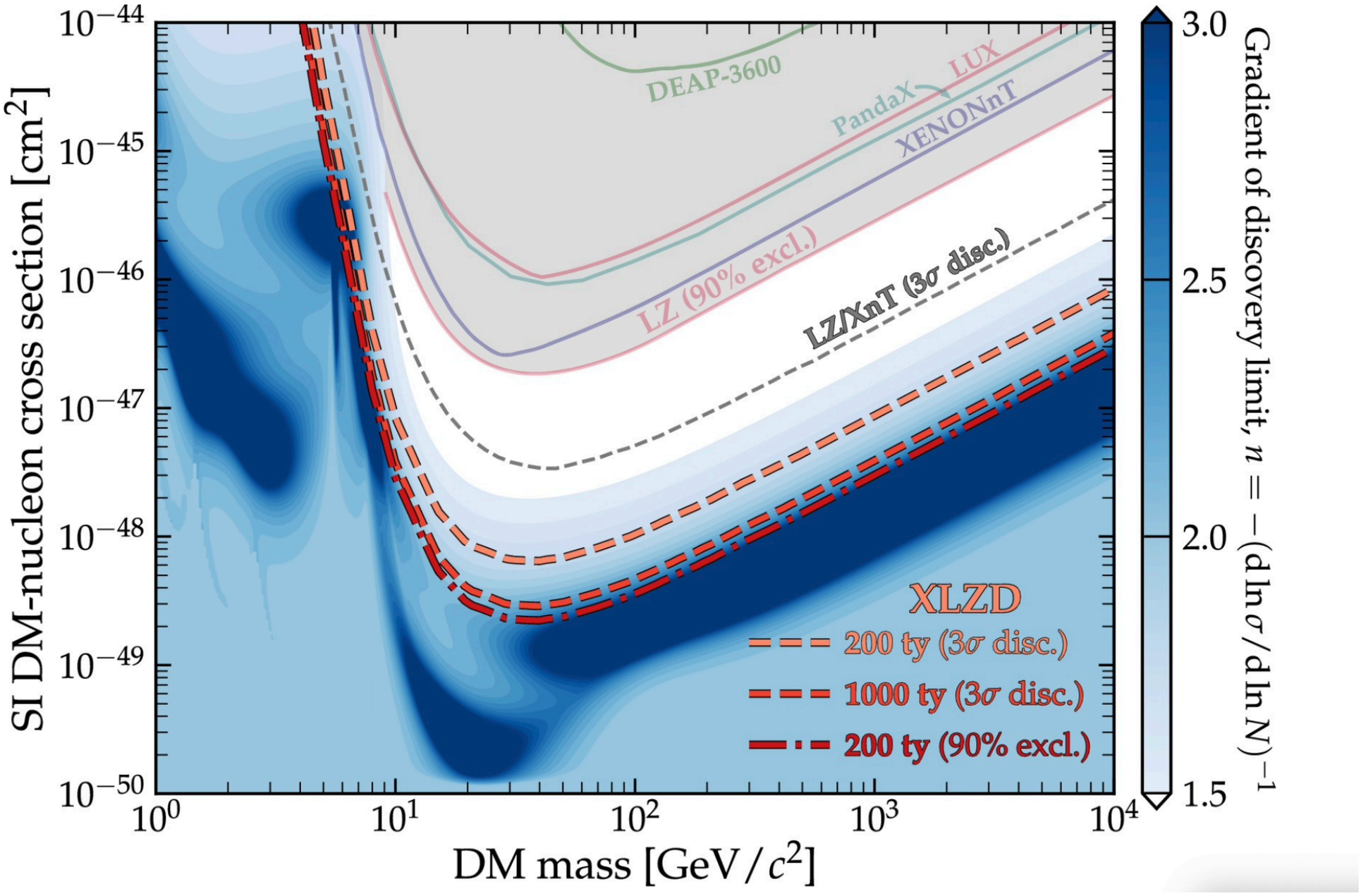




But what is dark matter at a fundamental level?

If dark matter was in thermal equilibrium in the early Universe it interacts like a particle today

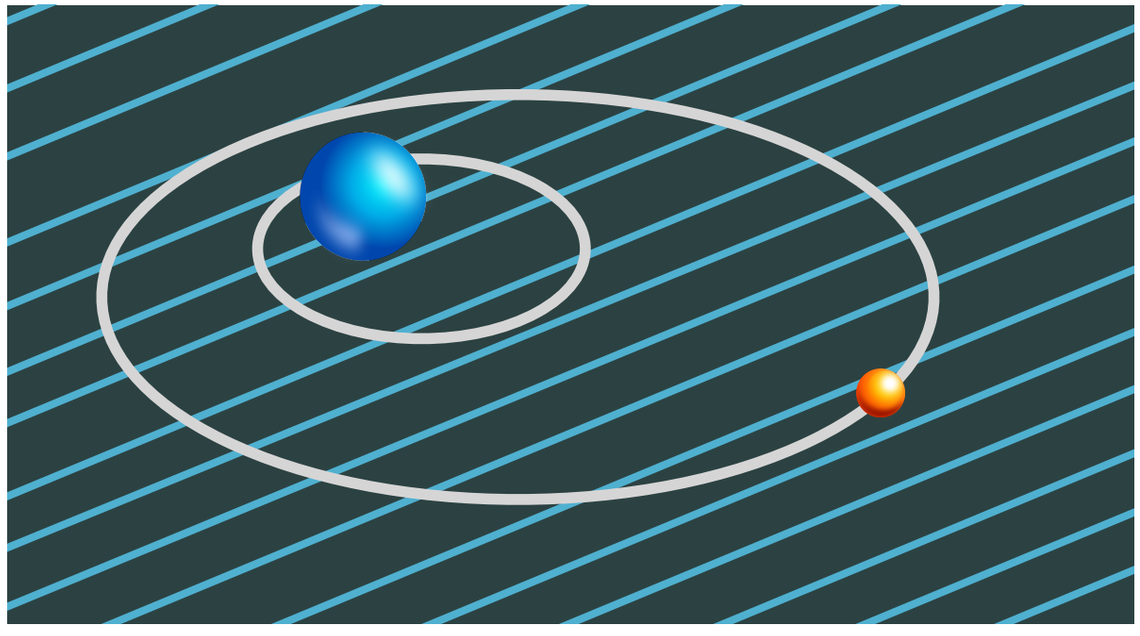
What is dark matter ?

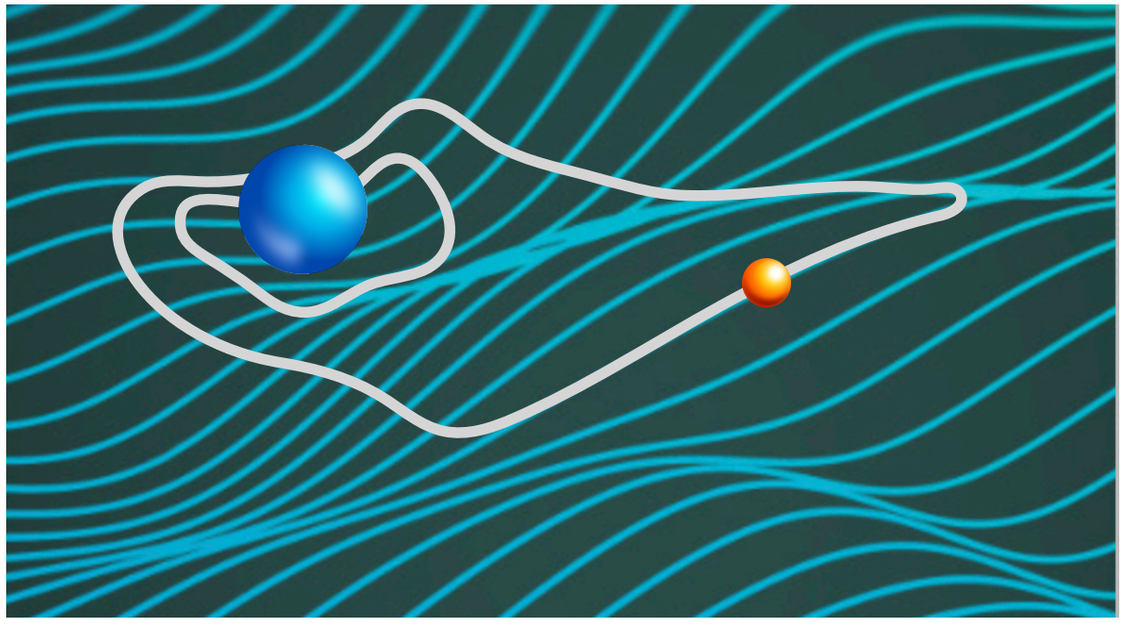


What is dark matter ?

What if dark matter is very light? It behaves like a wave

$$a(x,t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\cos(\omega t - \delta)$$





What is dark matter ?

Mass is fixed by halo size

$$m_a \gtrsim 10^{-22}\,\mathrm{eV}$$

Amplitude is fixed by the dark matter energy density

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \stackrel{!}{=} \rho_{\mathrm{DM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

The angular frequency is determined by the rest mass.

$$\omega \sim m_a$$

Small corrections from the kinetic energy

$$\frac{\Delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$$

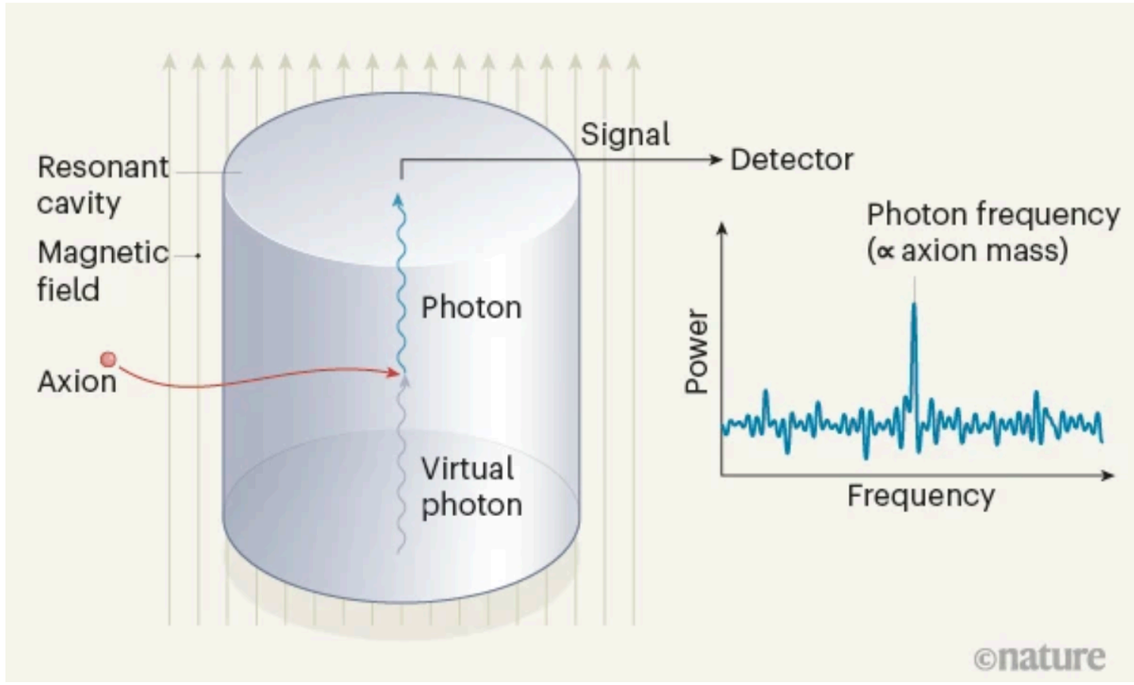
Coherence time is set by the frequency spread

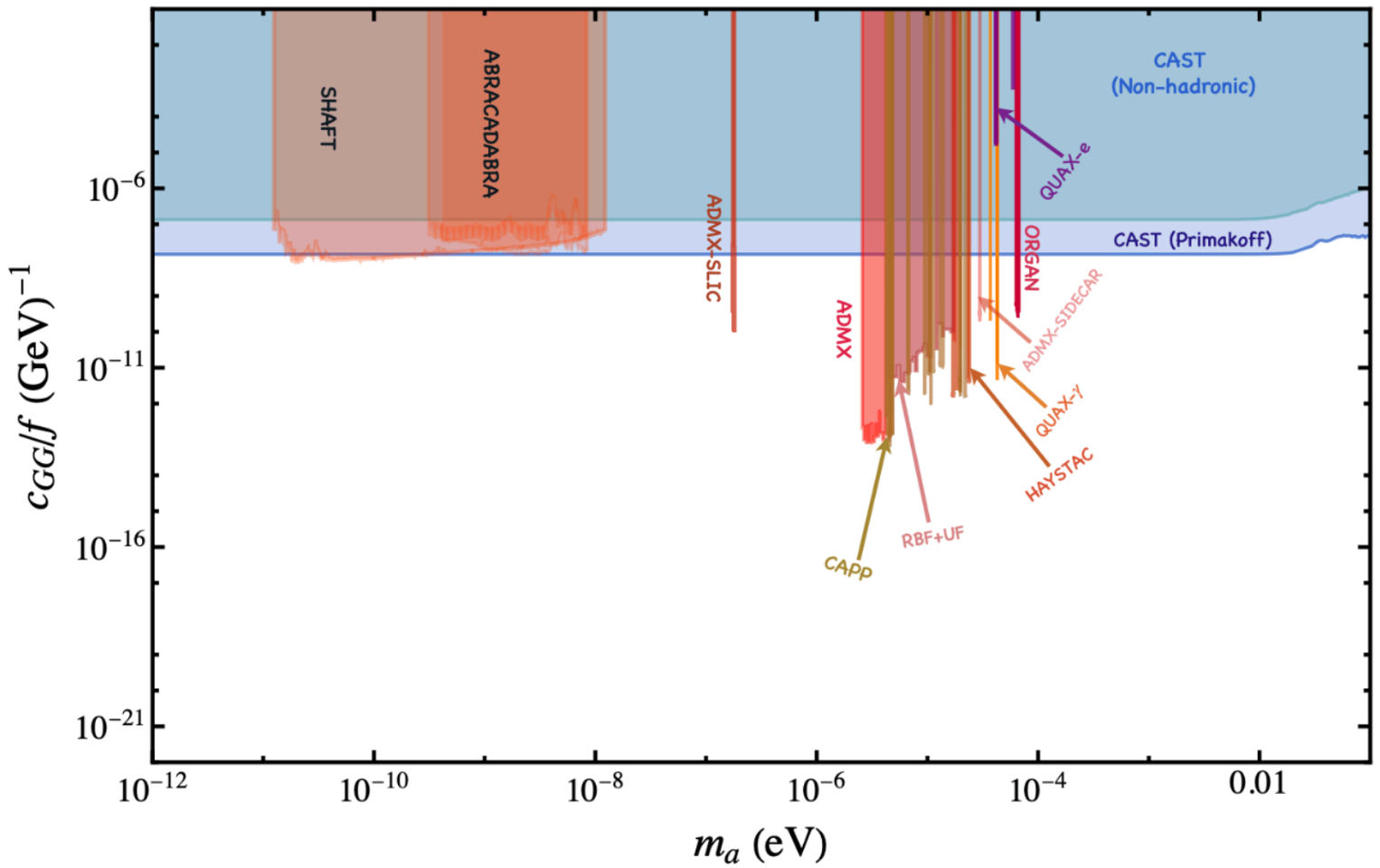
$$\tau_c = \frac{2\pi}{\Delta\omega} = \frac{2\pi}{m_a v^2} \approx 1\mathrm{s} \left(\frac{\mathrm{MHz}}{m_a}\right)$$

What is dark matter ?

Resonant cavities

$$P_{a\to\gamma} = \frac{\alpha^2}{\pi^2}\frac{\left(c_{\gamma\gamma}^{\rm eff}\right)^2}{f^2}\frac{\rho_{\rm DM}}{m_a}B_0^2 V C \min(Q_L, Q_a)$$





MB, Chakraborti, Rostagni,``Axion Bounds from Quantum Technology,', [arXiv:2408.06412 [hep-ph]]

Lighter dark matter needs larger cavities

What is dark matter ?

Standard model fields in this background

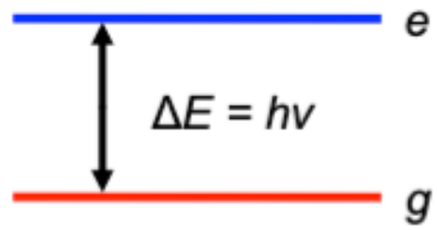
$$\begin{aligned}\mathcal{L} &= -m_e \bar{\psi}_e \psi_e + g\, a \bar{\psi}_e \psi_e \\ &= (-m_e + g a)\, \bar{\psi}_e \psi_e \\ &= -m_e^{\mathrm{eff}}(a)\, \bar{\psi}_e \psi_e\end{aligned}$$

Can be described with time-dependent masses and coupling constants

$$m_e^{\mathrm{eff}}(a) = m_e \left(1 + \frac{a_0}{m_e} \cos(\omega t - \delta)\right)$$

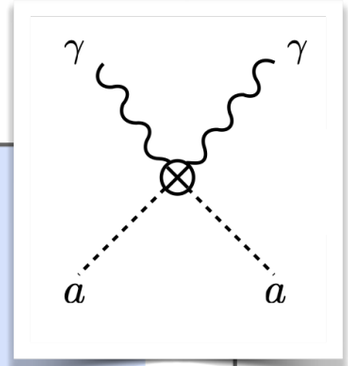
What is dark matter ?

Clocks and clock-cavity bounds



$$\frac{\delta\nu_{A/B}}{\nu_{A/B}} = k_\alpha \frac{\delta\alpha}{\alpha} + k_e\left(\frac{\delta m_e}{m_e} - \frac{\delta m_p}{m_p}\right) + k_q\left(\frac{\delta m_q}{m_q} - \frac{\delta\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}}\right)$$

Unique sensitivity to ultra-light states via precision measurements of transition frequencies



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What is dark matter ?

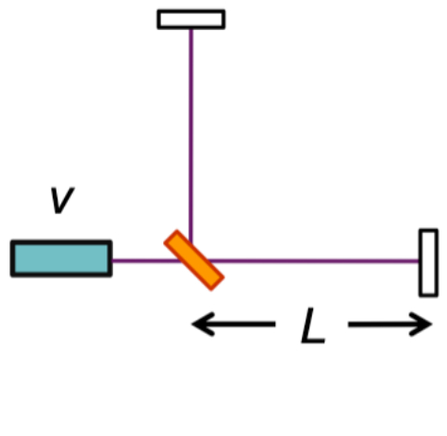
Ion clocks

$$\frac{\delta\nu_{A/B}}{\nu_{A/B}} = k_\alpha \frac{\delta\alpha}{\alpha} + k_e \left(\frac{\delta m_e}{m_e} - \frac{\delta m_p}{m_p} \right) + k_q \left(\frac{\delta m_q}{m_q} - \frac{\delta \Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} \right)$$

Laser interferometers

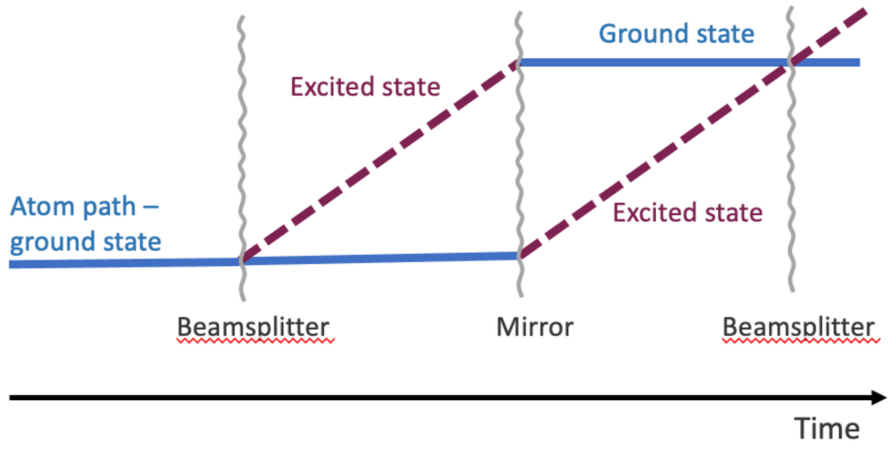
$$\frac{\delta l}{l} = -\left(\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e} \right)$$

$$\frac{\delta n}{n} = -5 \times 10^{-3} \left(2\,\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e} \right)$$



Atom interferometers

$$\Phi_s = 4\,\overline{\omega_a} n \Delta r \sin^2\left(m_a T\right)$$



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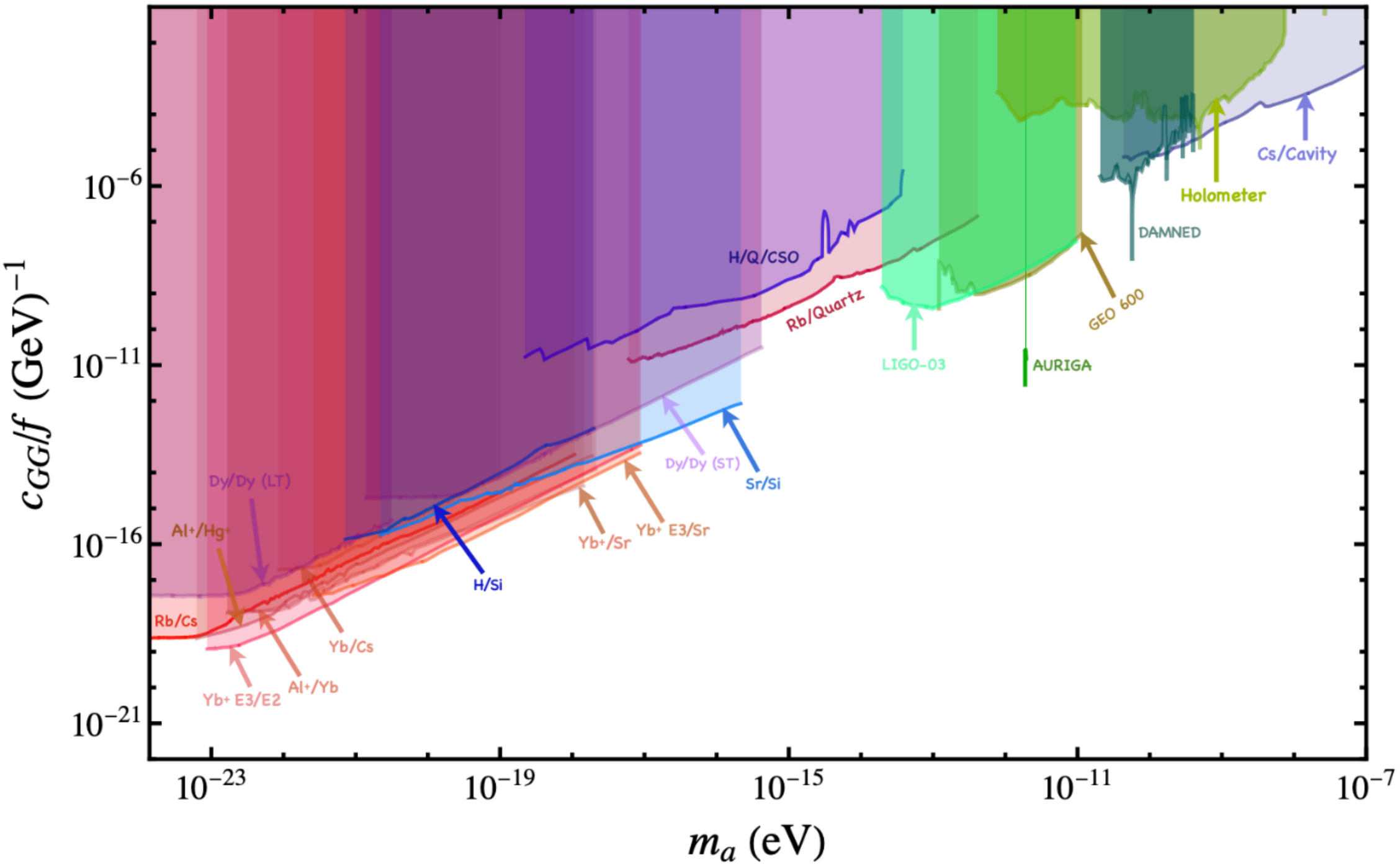

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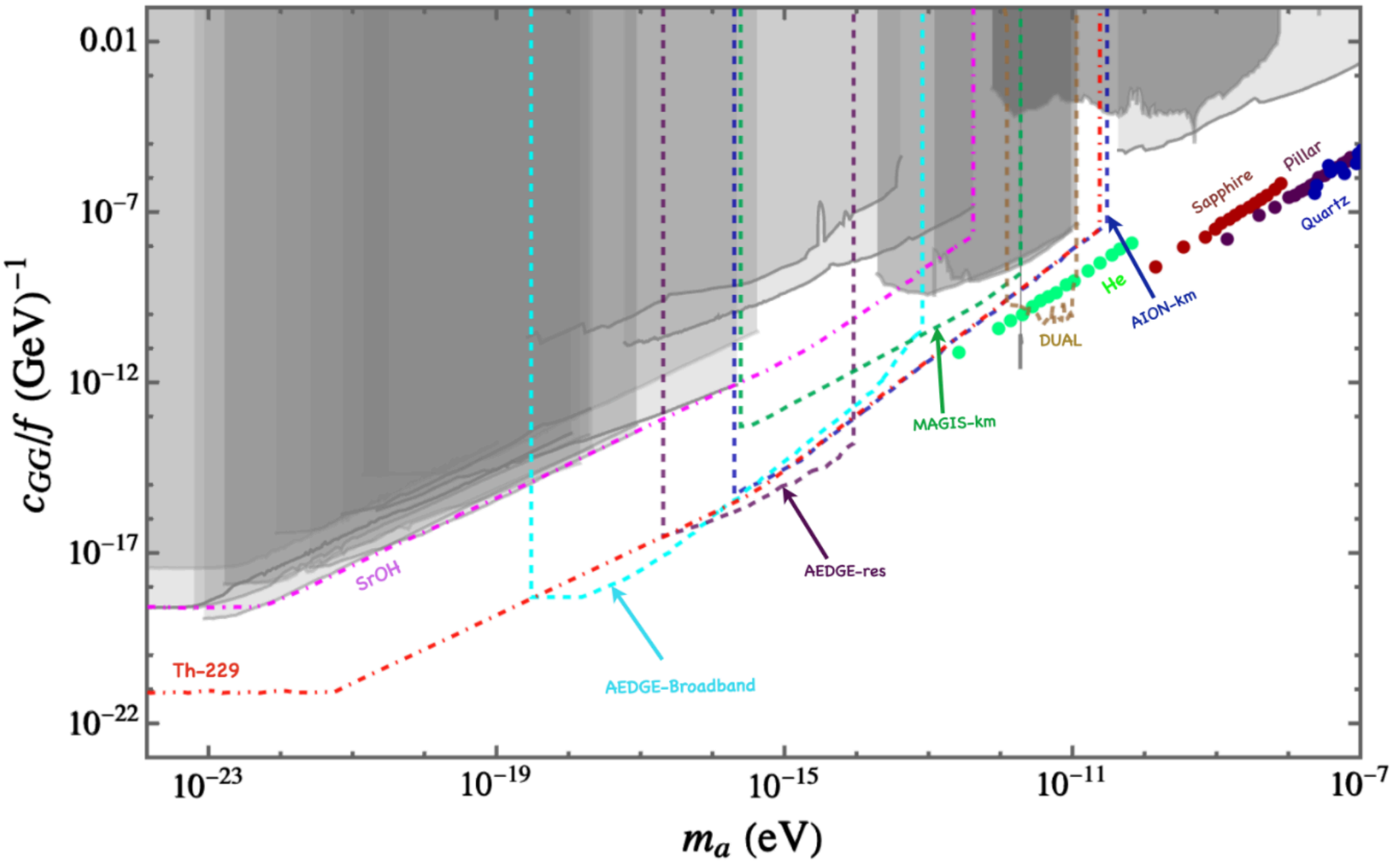
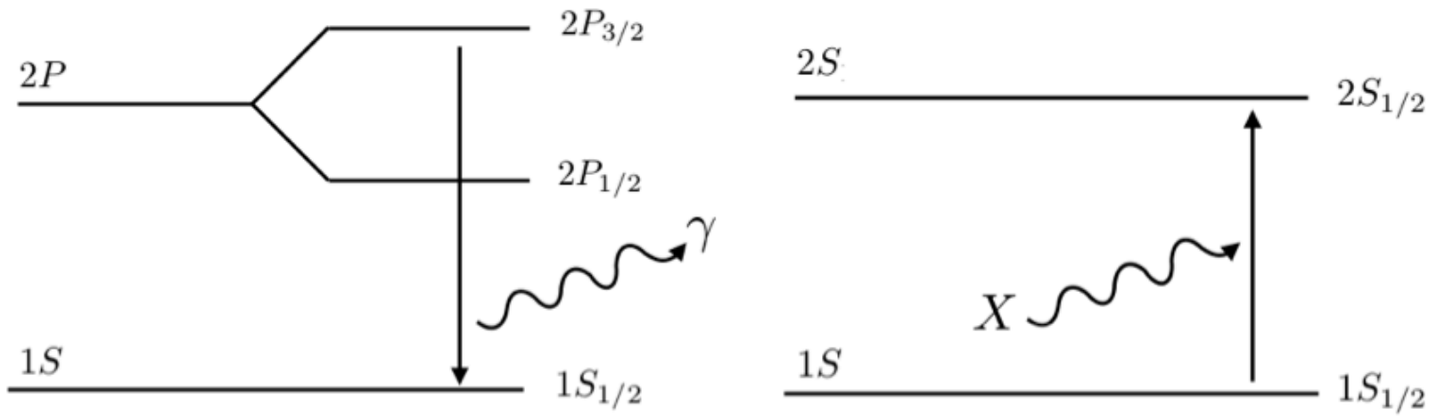


What is dark matter ?

Another way to observe dark matter is via absorption



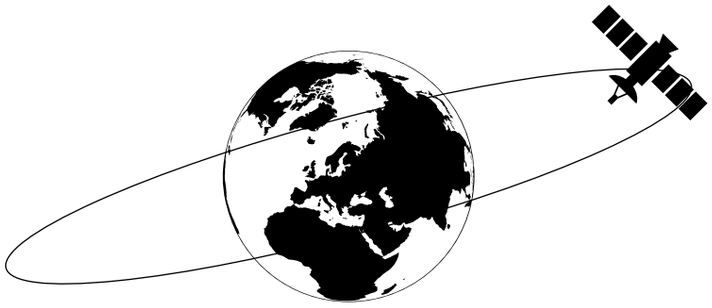
Depending on the quantum numbers of the dark matter states these can be forbidden transitions

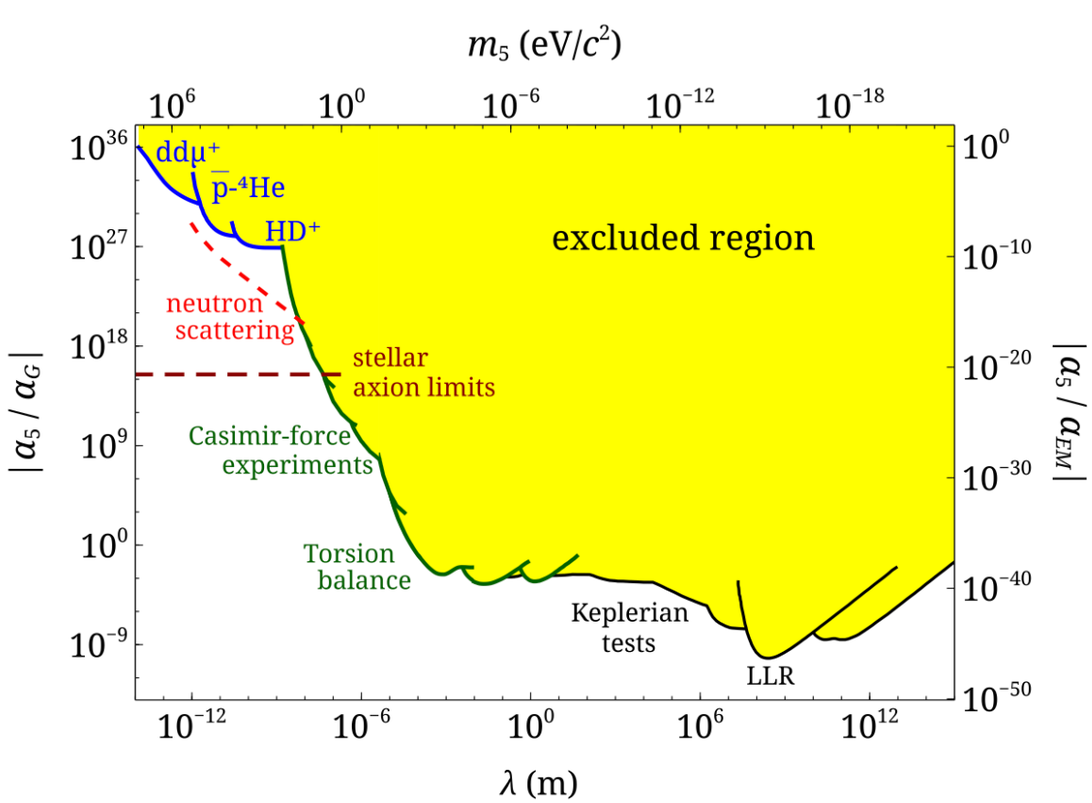
Software to automate the calculation of the overlap integrals and transition rates covering all dark matter candidates is now available

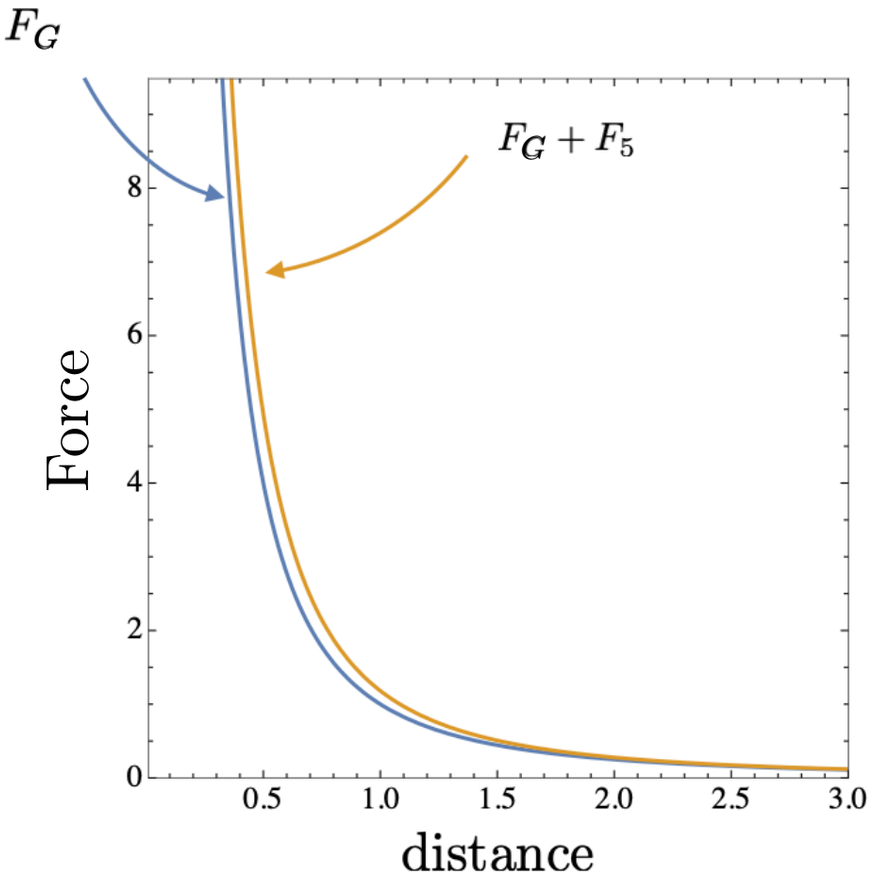
MB, Perez-Soler and Shergold,``Generalised hydrogen interactions with **CINCO**: a window to new physics,''[arXiv:2407.12913 [hep-ph]].

Is there a fifth force ?

Fifth forces $$V_5 = N_1 N_2 \alpha_5 \frac{\exp(-r/\lambda)}{r} \hbar c$$







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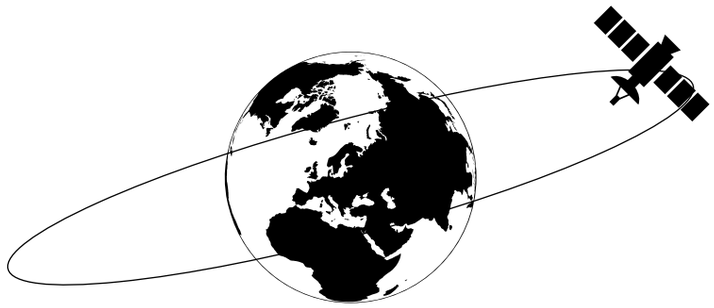
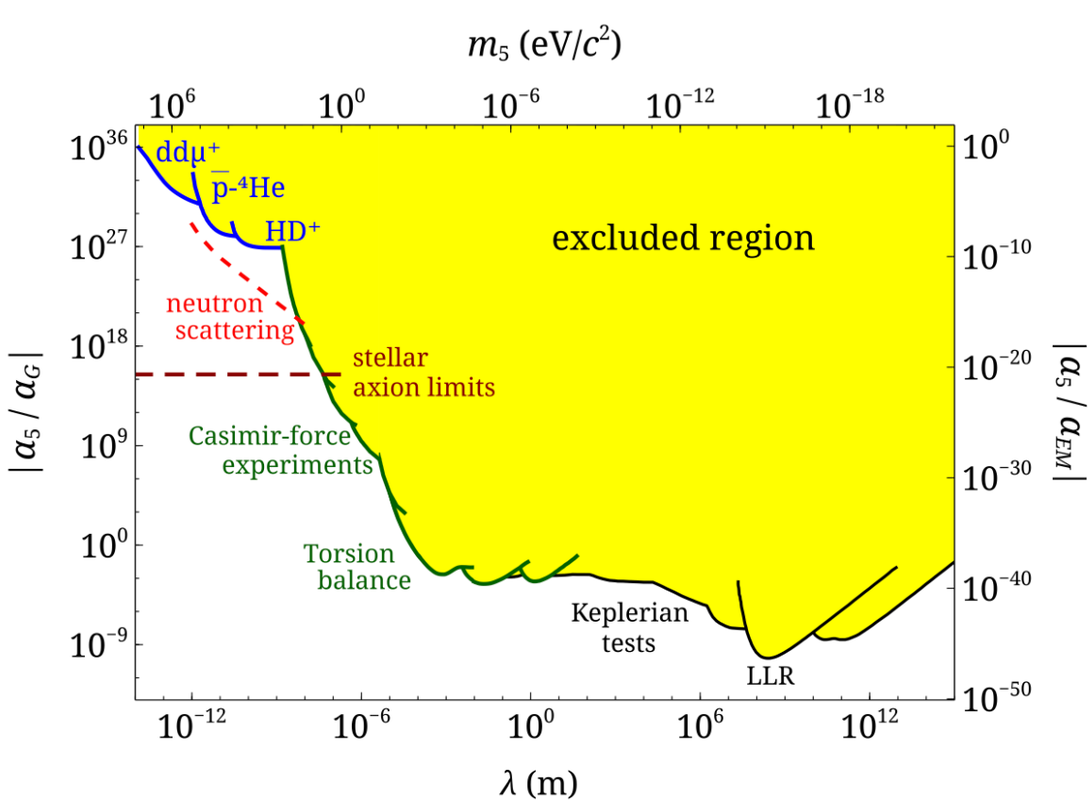
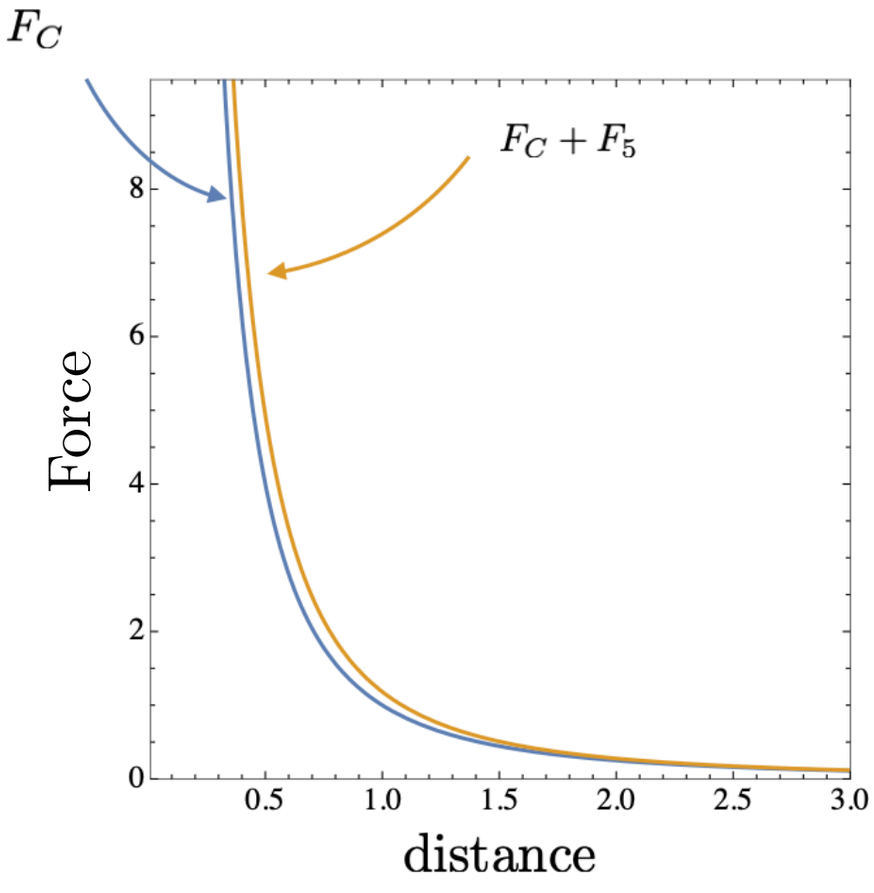
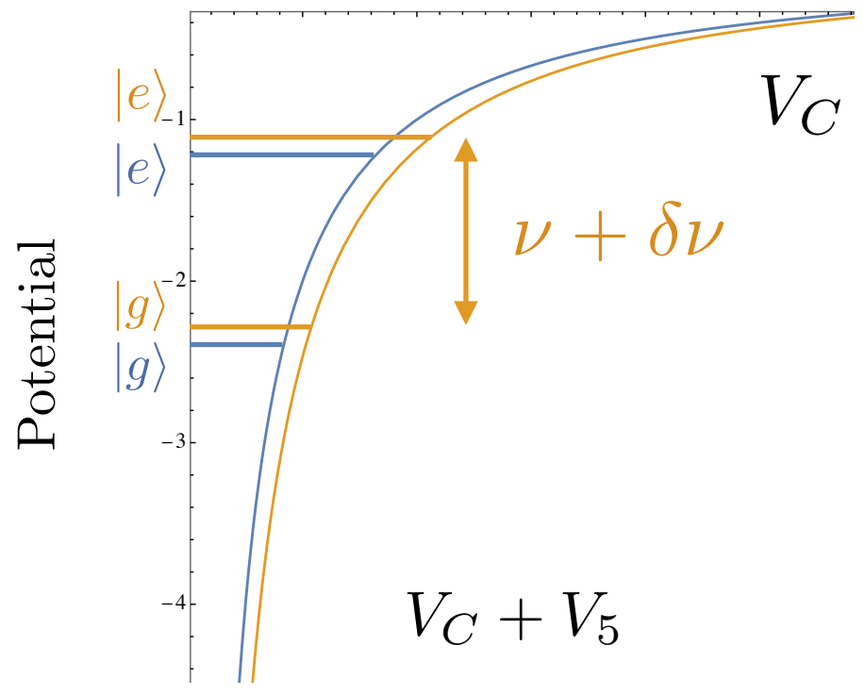
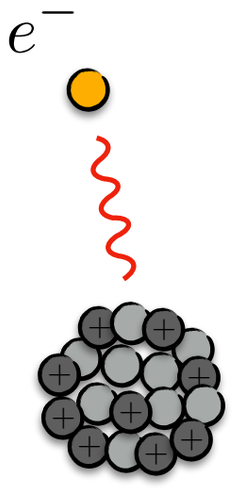








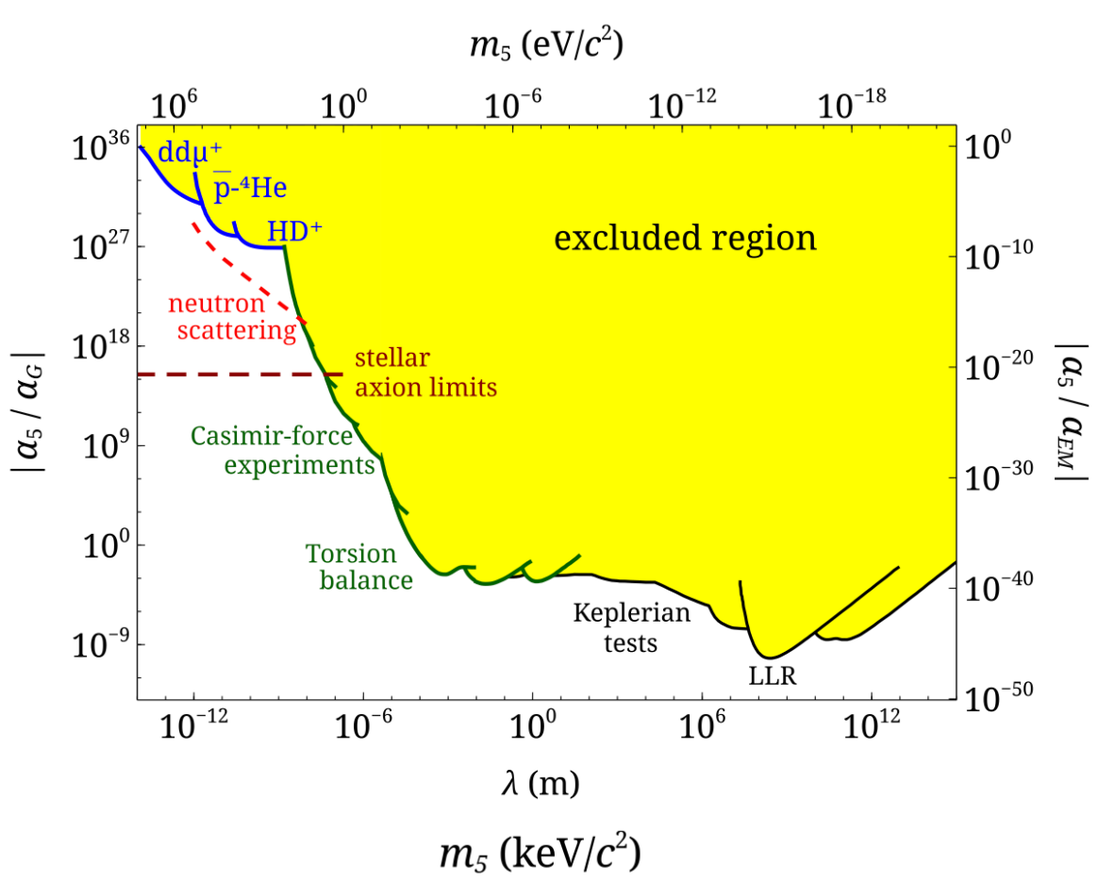


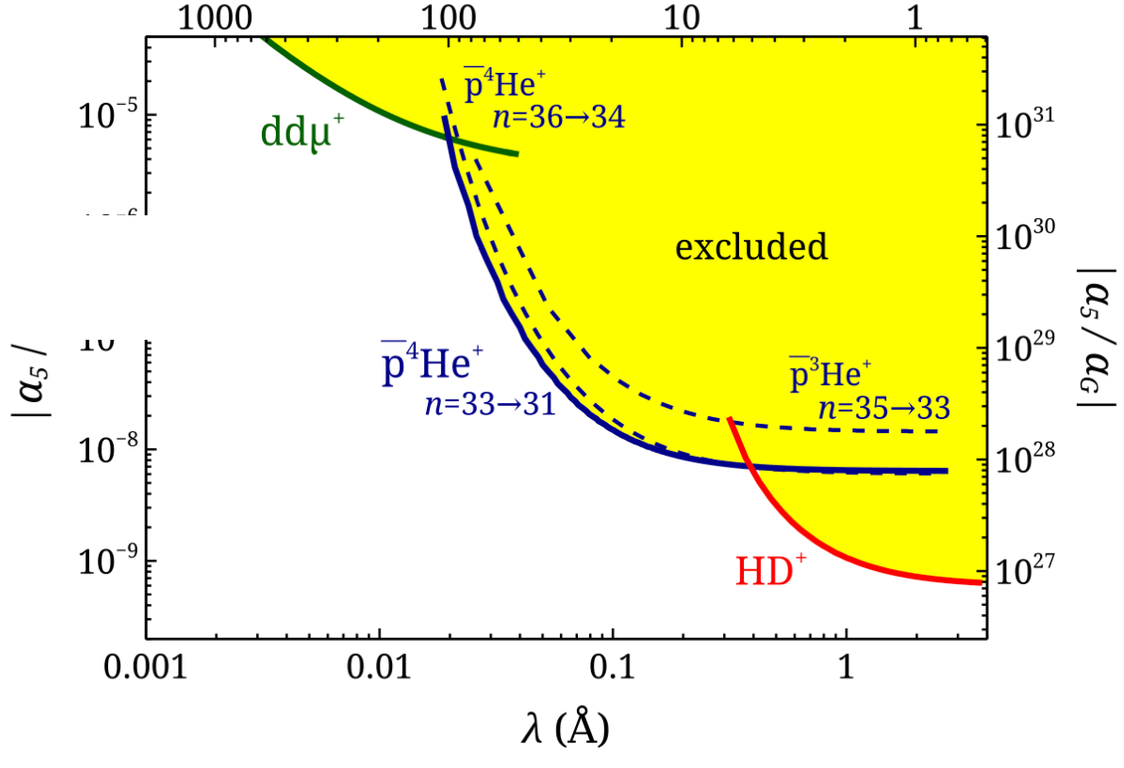
Is there a fifth force ?

Fifth forces $$V_5 = N_1 N_2 \alpha_5 \frac{\exp(-r/\lambda)}{r} \hbar c$$

Induces a change in energy levels that can be probed with atomic and molecular spectroscopy

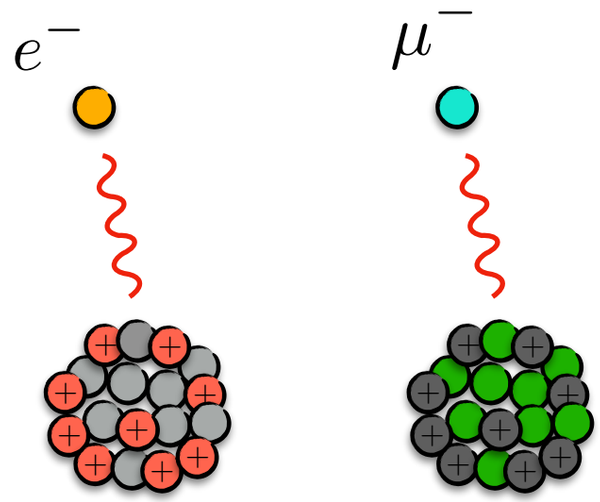
$$\langle \Delta V_{5,\lambda} \rangle = \alpha_5 N_1 N_2 \left[\langle \Psi_{n',\ell'}(r) | Y(r,\lambda) | \Psi_{n',\ell'}(r) \rangle - \langle \Psi_{n'',\ell''}(r) | Y(r,\lambda) | \Psi_{n'',\ell''}(r) \rangle \right] \hbar c = \alpha_5 N_1 N_2 \Delta Y_\lambda \hbar c$$





Is there a fifth force ?

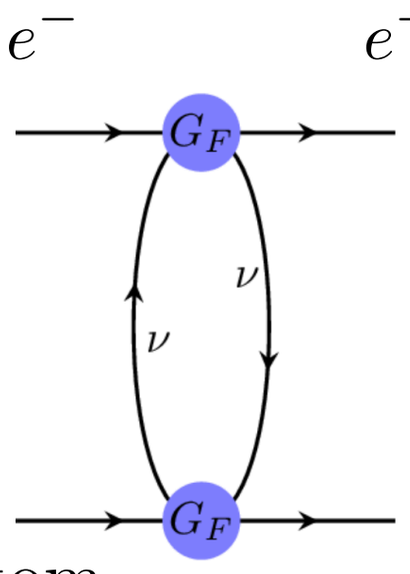
Isotope differences can determine how the fifth force couples to up- or down-type quarks, electrons or muons

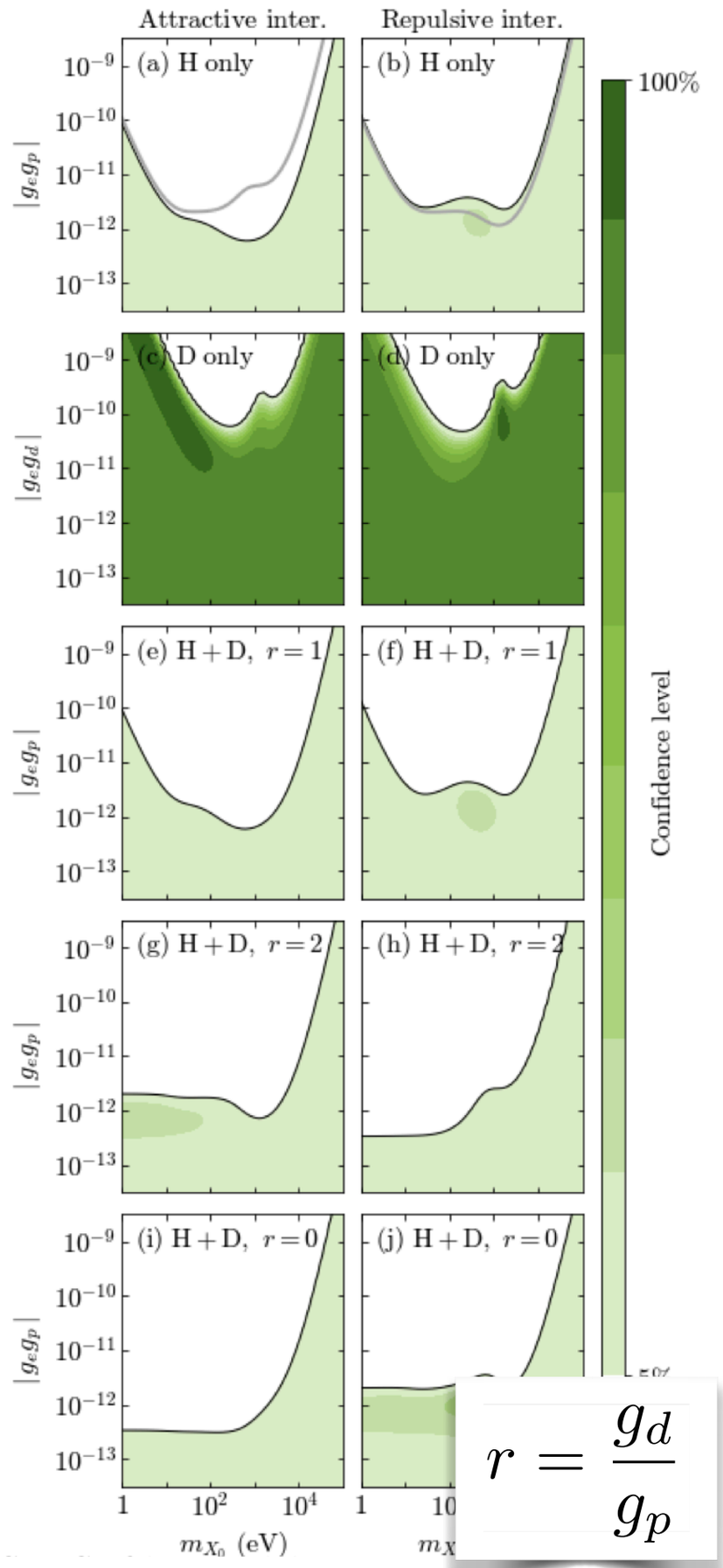


Combined data improves sensitivity

Many forces are much more important at short distances

$$V_\nu(r) \sim \frac{1}{r^5}\, e^{-m_\nu r}$$





Potvliege et al. “Deuterium spectroscopy for enhanced bounds on physics beyond the standard model,” Phys.Rev.A 108 (2023) no.5, 05282

Are there extra dimensions ?

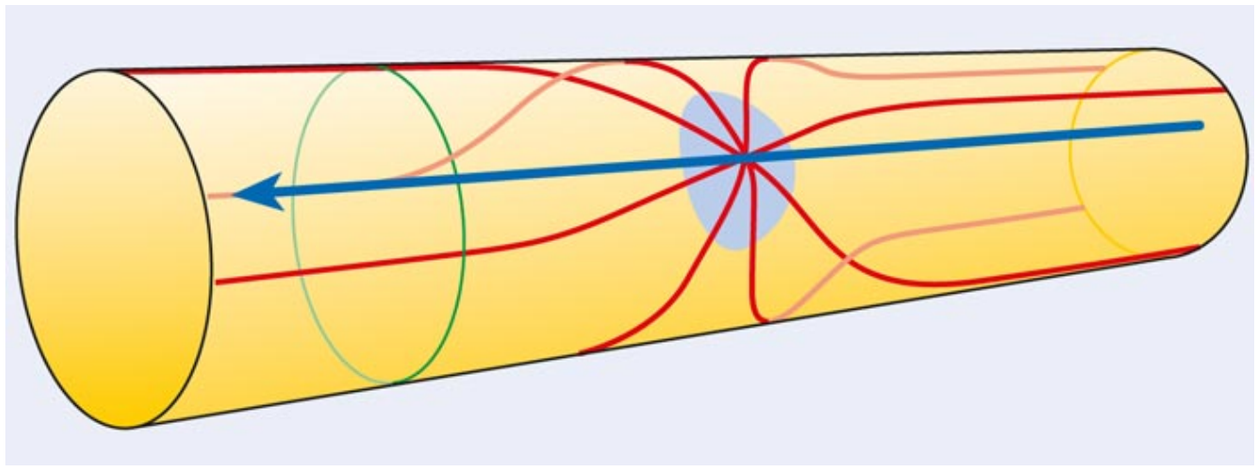
Additional dimensions change the way gravity propagates

Large distances $r \gg R_n$

$$V_{\mathrm{N}}(r) = -\alpha_G N_1 N_2 \frac{1}{r}$$

Small distances $r < R_n$

$$V_{\mathrm{ADD}}(r) = -\alpha_G N_1 N_2 R_n^n \frac{1}{r^{n+1}}$$



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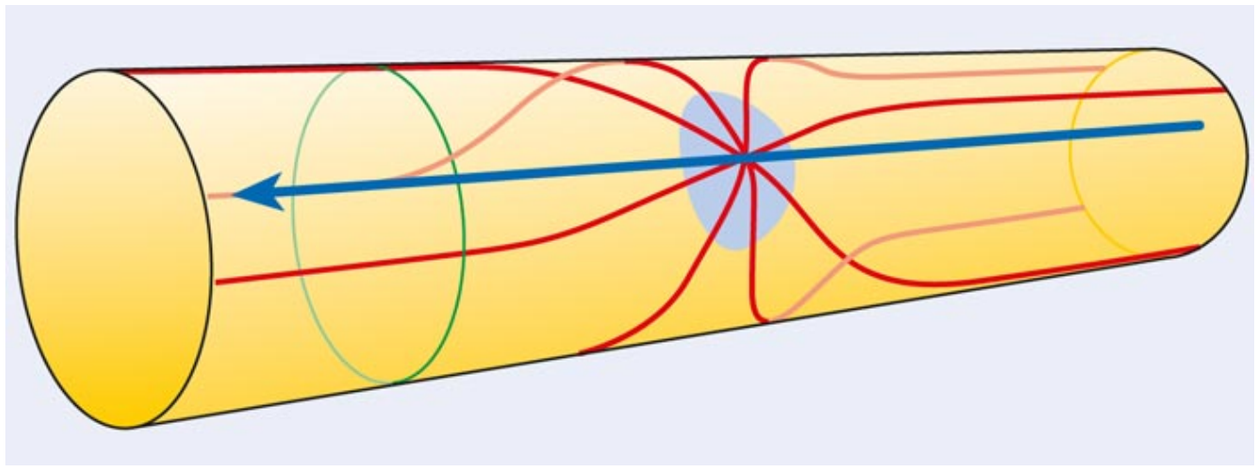
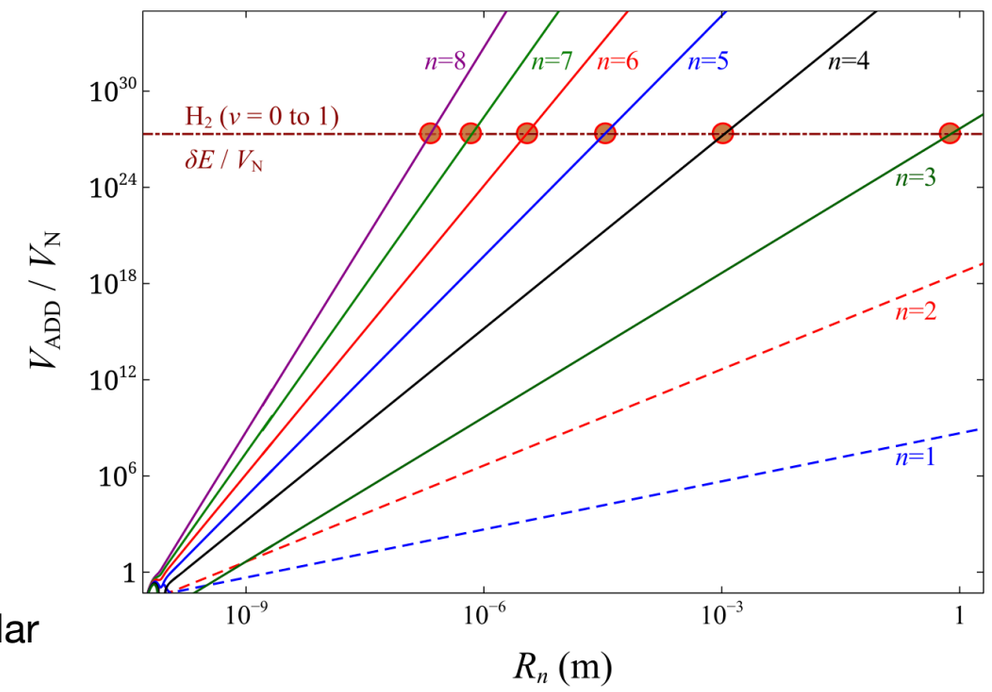
$$V_{\mathrm{ADD}}(r) = -\alpha_G N_1 N_2 R_n^n \frac{1}{r^{n+1}}$$

$$\left\langle V_{\mathrm{ADD}} \right\rangle = -\alpha_G N_1 N_2 \left[\int_{R_n}^{\infty} \Psi^*(r) \frac{1}{r} \Psi(r) r^2 \mathrm{d}r + R_n^n \int_0^{R_n} \Psi^*(r) \frac{1}{r^{n+1}} \Psi(r) r^2 \mathrm{d}r \right]$$





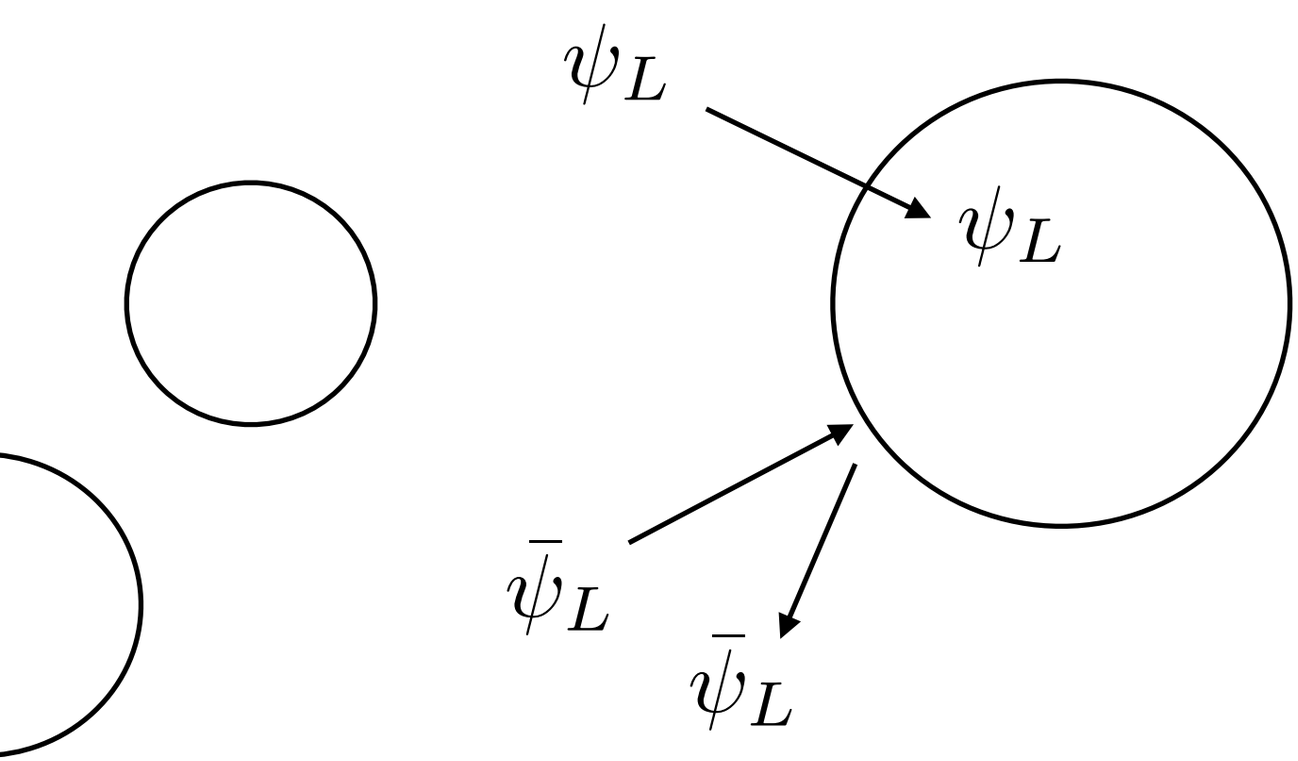
Salumbides et al., ``Constraints on extra dimensions from precision molecular spectroscopy,''New J. Phys**. 17** 2015, 3 3015

Where is the anti-matter ?

The university has much more matter than anti-matter. How did it get there?

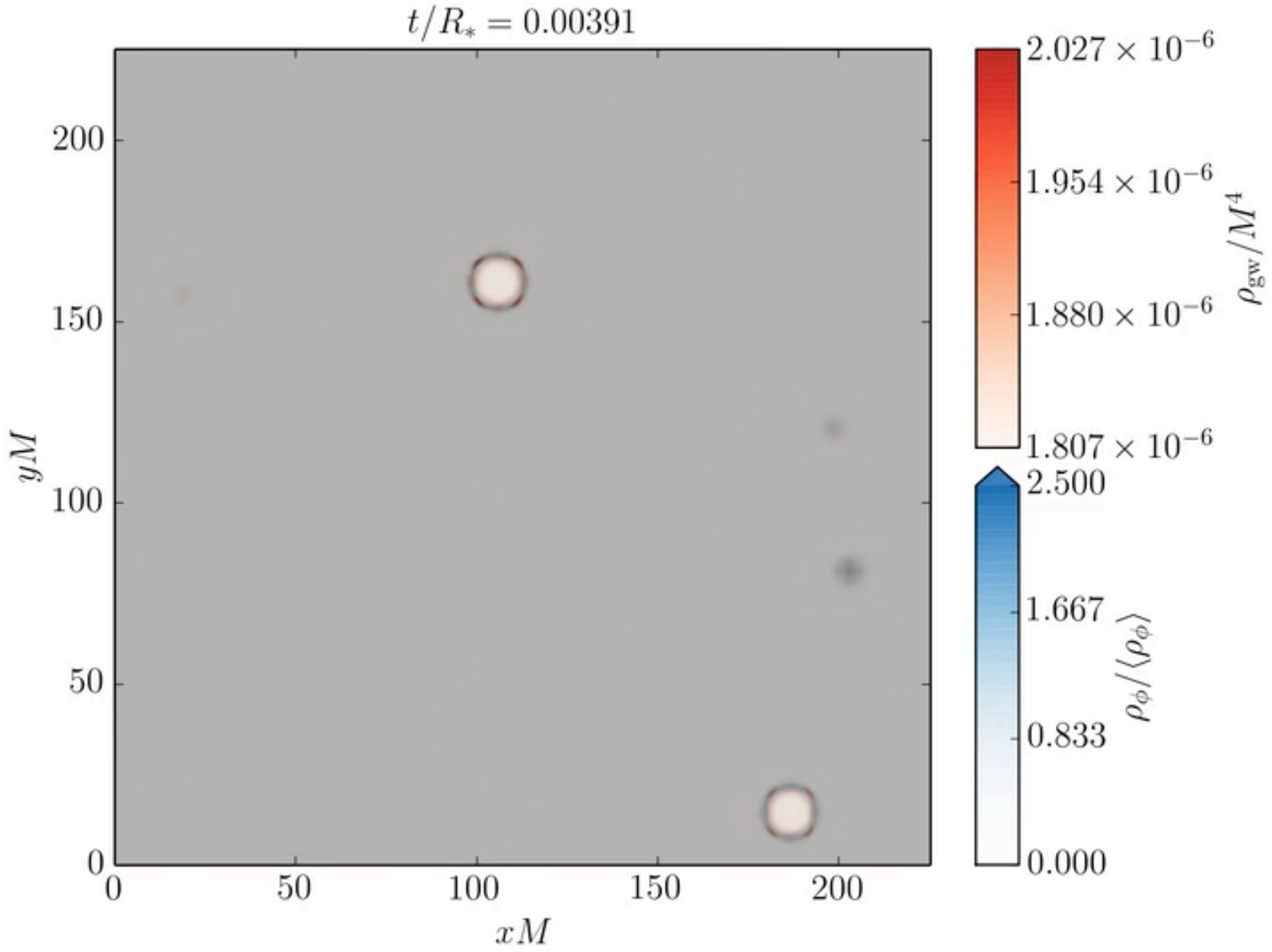
The laws of nature need to distinguish between the two: CP violation

An asymmetry can be generated via baryogenesis



Where is the anti-matter ?

Bubble collisions generate gravitational waves



Cutting, Hindmarsh,Weir, “Gravitational waves from vacuum first-order phase transitions: from the envelope to the lattice,” Phys. Rev. D **97** (2018) no.12, 123513

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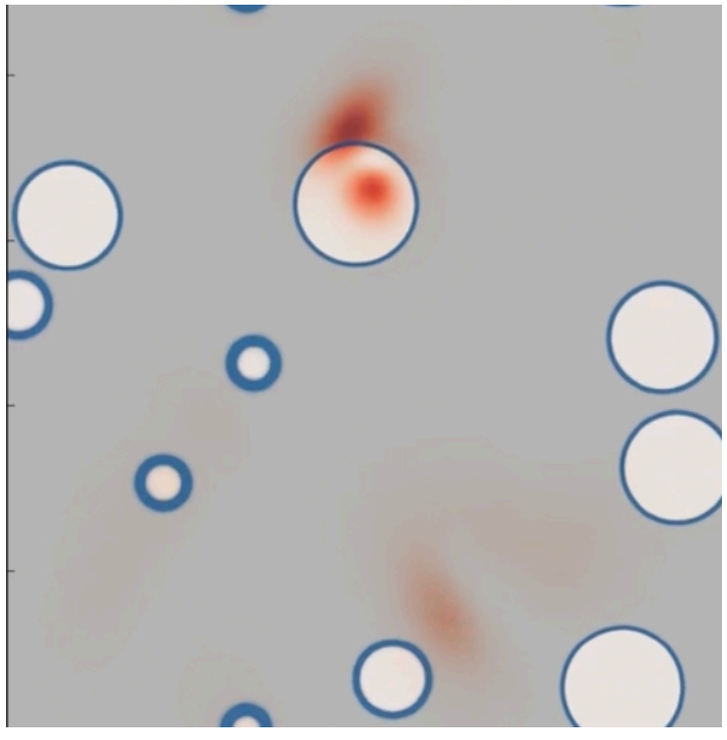
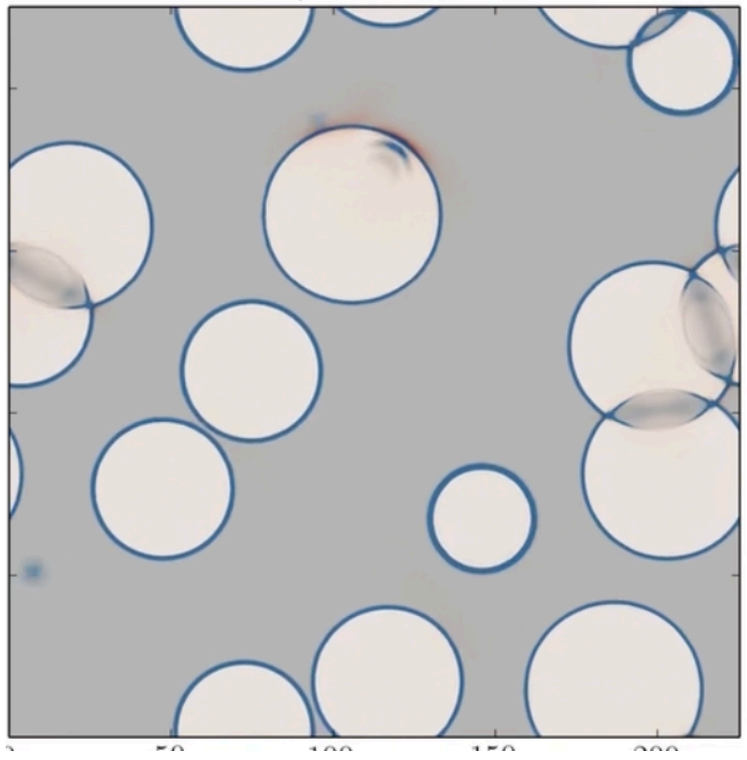
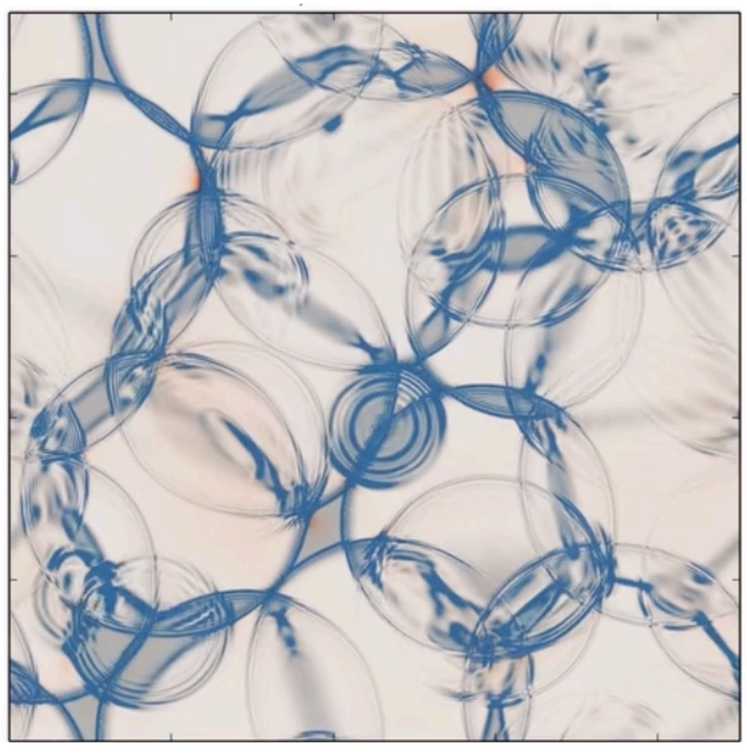




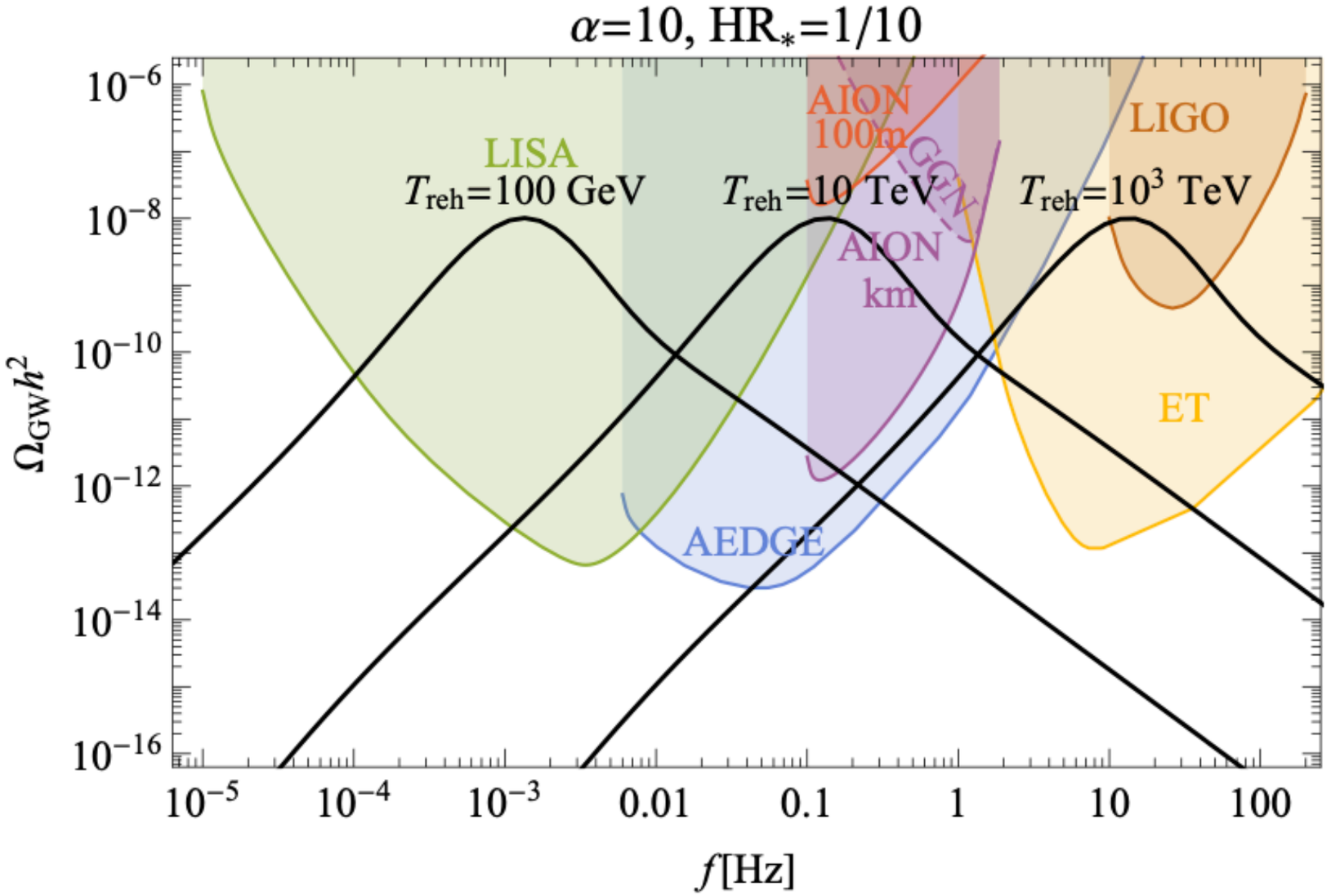


Cutting, Hindmarsh,Weir, “Gravitational waves from vacuum first-order phase transitions: from the envelope to the lattice,” Phys. Rev. D **97** (2018) no.12, 123513

Where is the anti-matter ?

Bubble collisions generate stochastic gravitational waves with a peak frequency determined by the percolation temperature

AION covers a frequency band not covered by existing and future laser interferometers

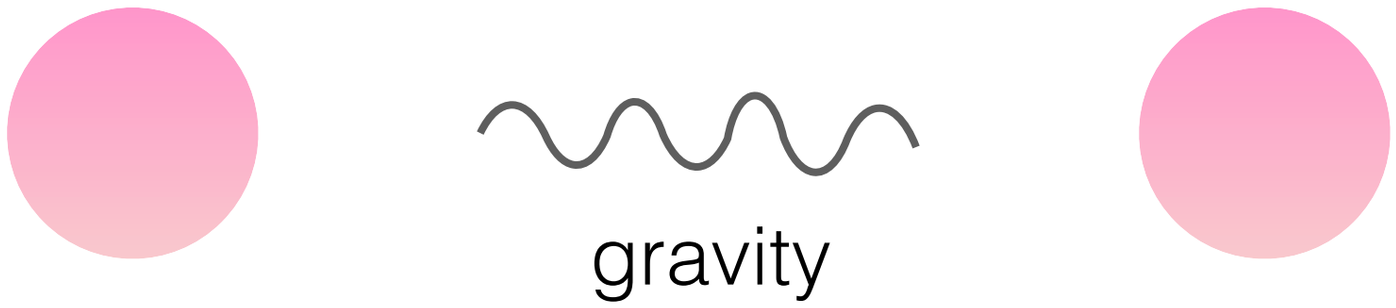


Badurina et al,"AION: An Atom Interferometer Observatory and Network", JCAP **05** (2020), 011

Is gravity a quantum theory ?

What -if any- quantum features does gravity have?

Some properties can be tested by entangled macroscopic states



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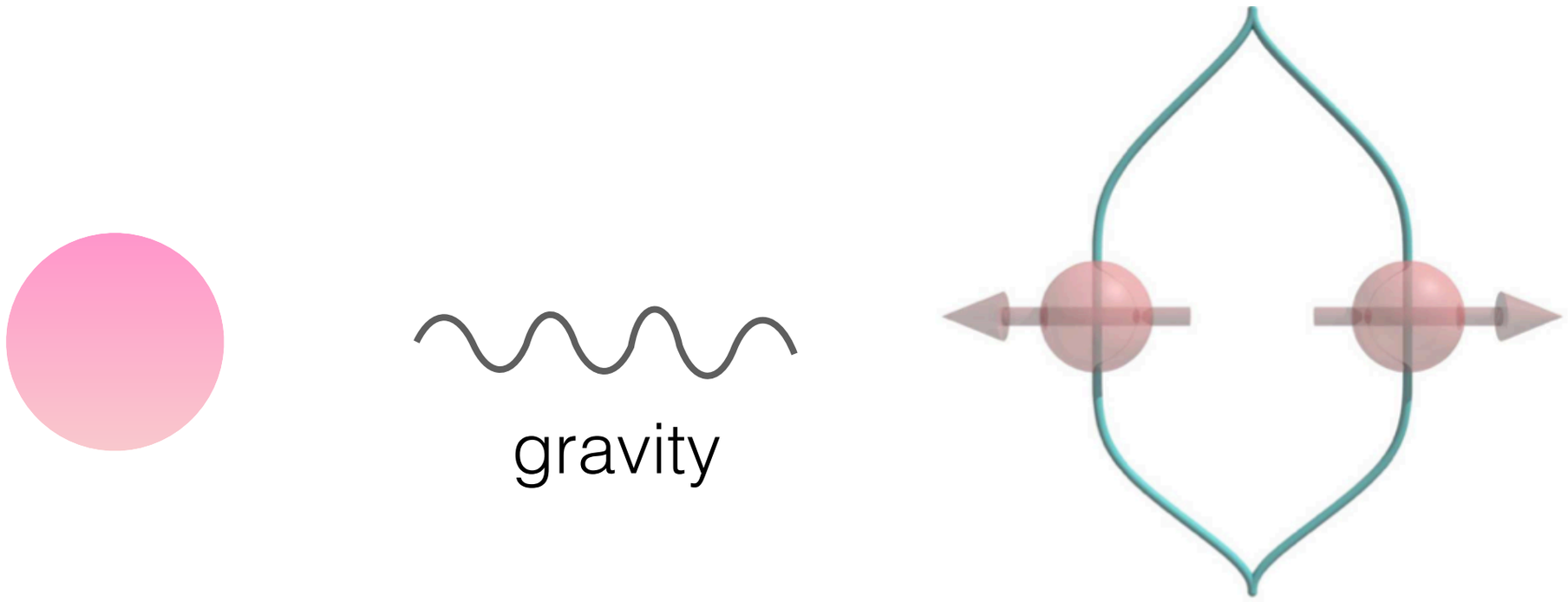
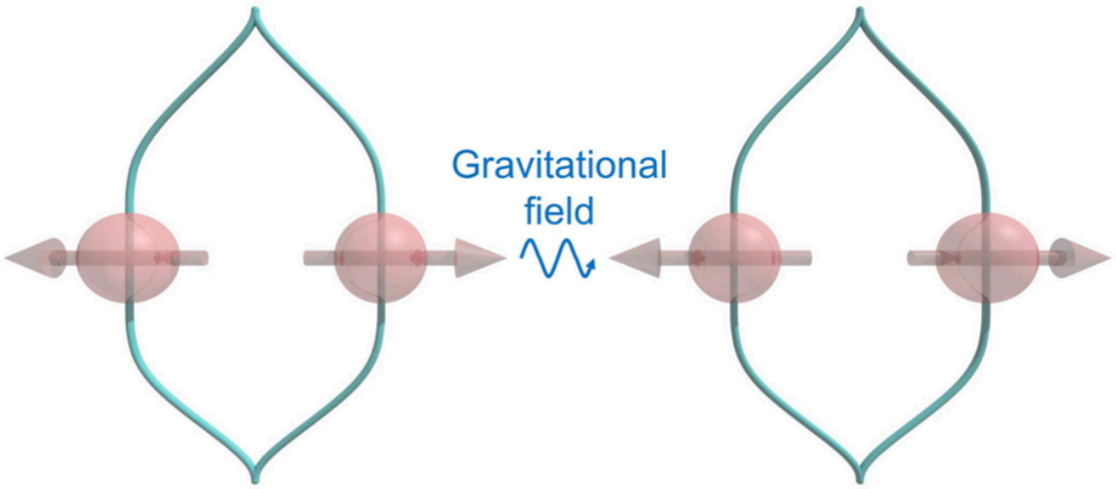
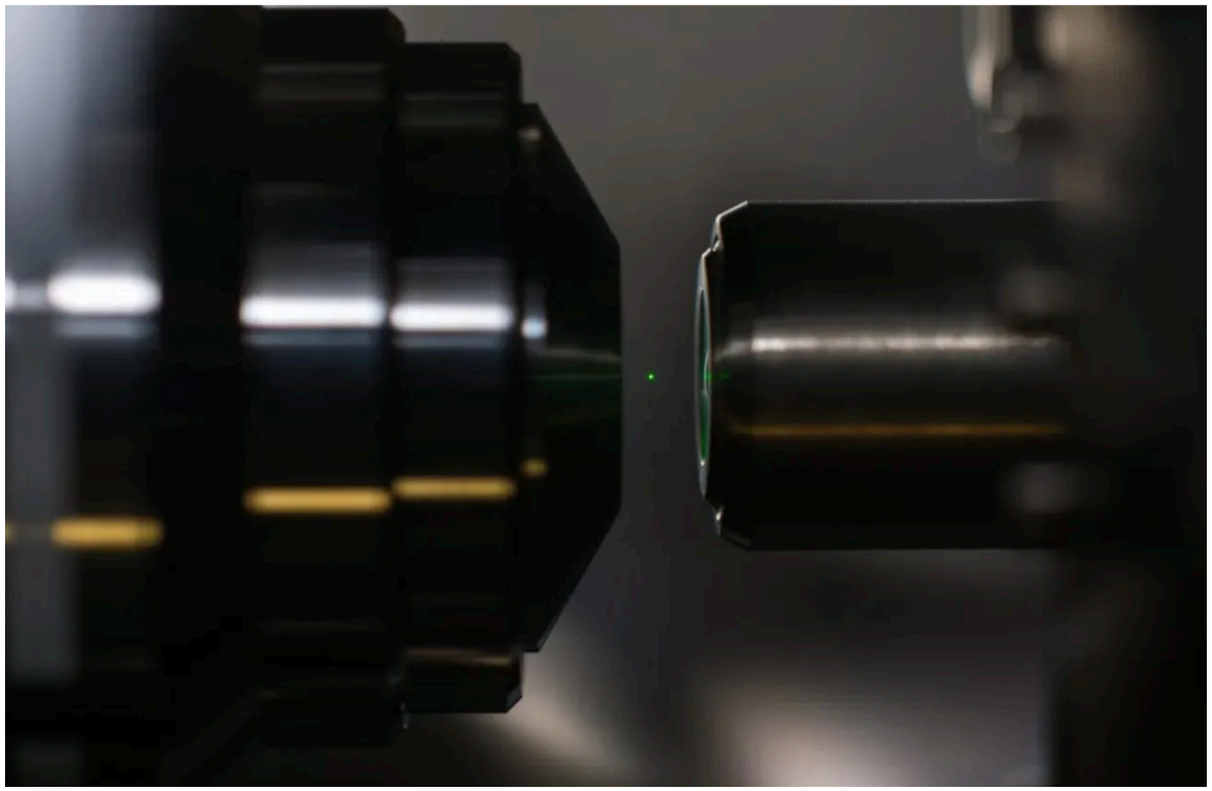


Is gravity a quantum theory ?

Entangled nanodiamonds to probe quantum properties of gravity





Wood, Morley,
“Towards a test of quantum gravity with a levitated nanodiamond containing a spin,”
Proc. SPIE Int. Soc. Opt. Eng. **11881** (2021), 71

Conclusions

Quantum technology is both a product of and a driving force for advancements in fundamental physics

Fundamental questions push technology to it’s limits and trigger novel technology

The UK has a unique opportunity to lead in this field. Boulby could play a central role