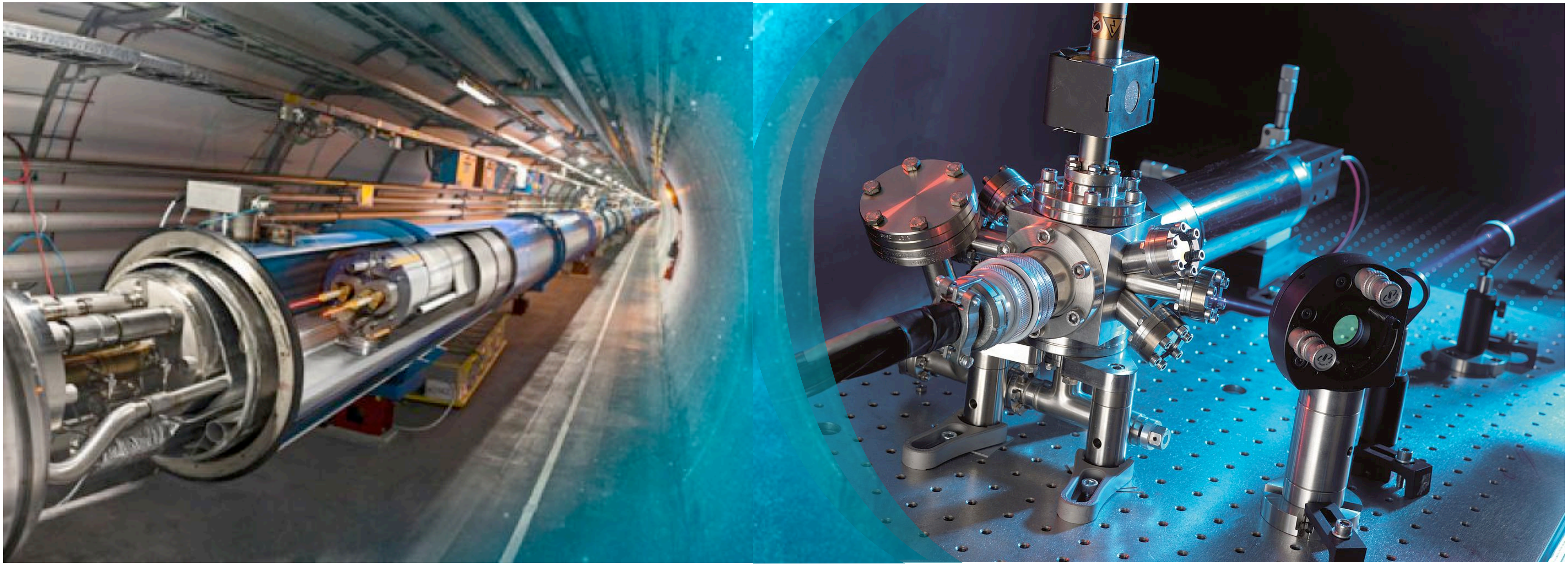
Light dark matter: from colliders to quantum sensors



Martin Bauer

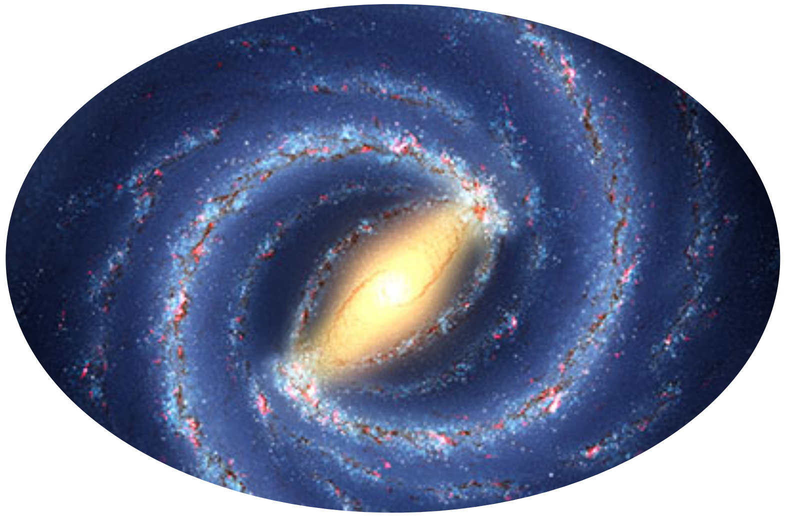
ECFA-UK, Durham 25.9.2024

IP3

Durham University

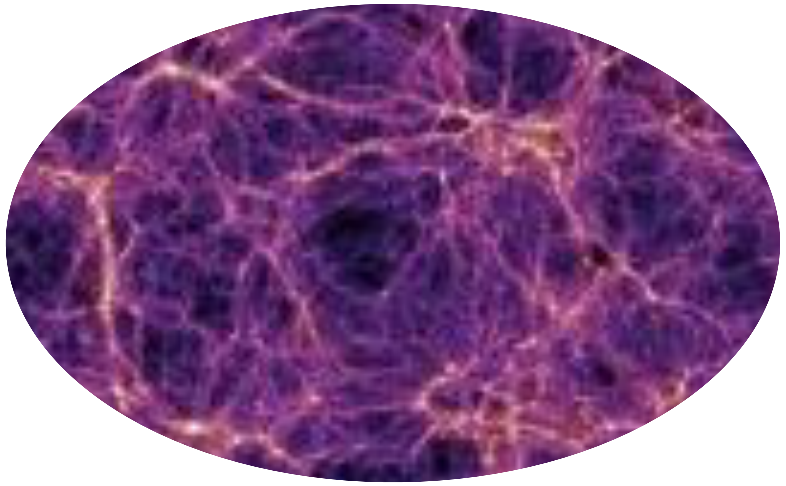
Light dark matter

Overwhelming evidence for dark matter, but its mass scale is unknown



Rotation curves

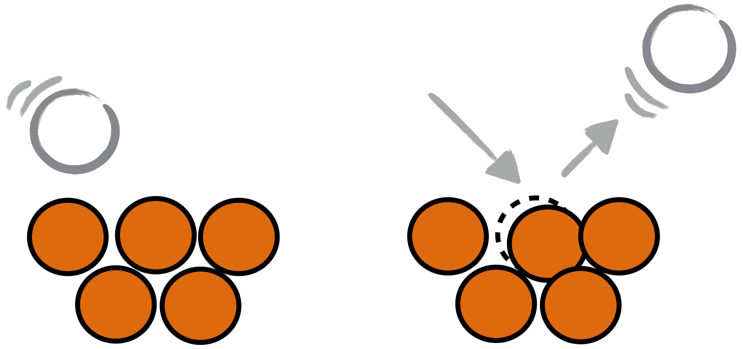
gravitational lensing



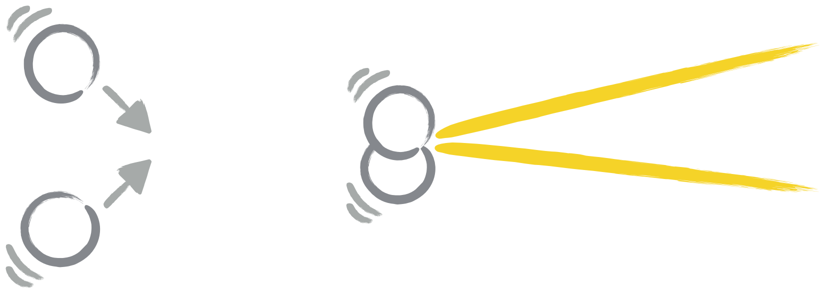
Structure formation

Light dark matter

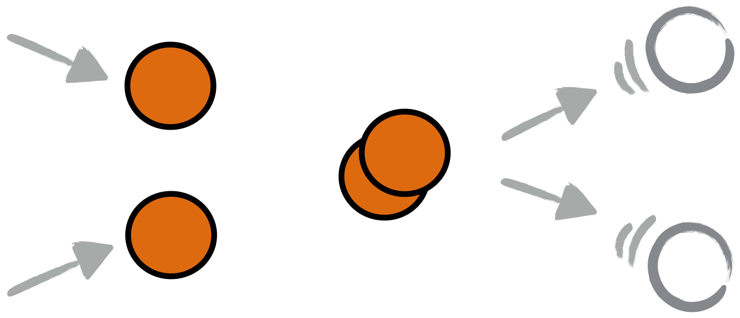
Direct
detection



Indirect
detection

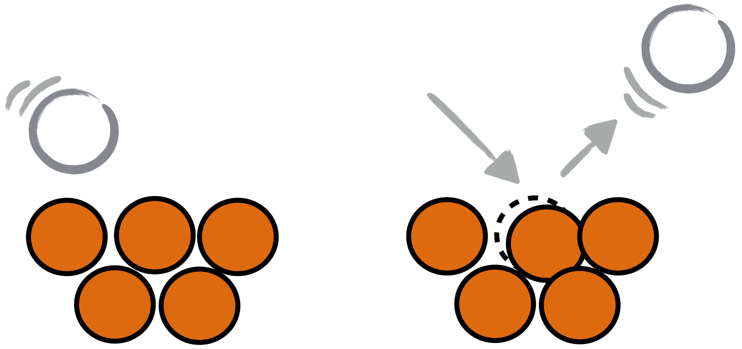


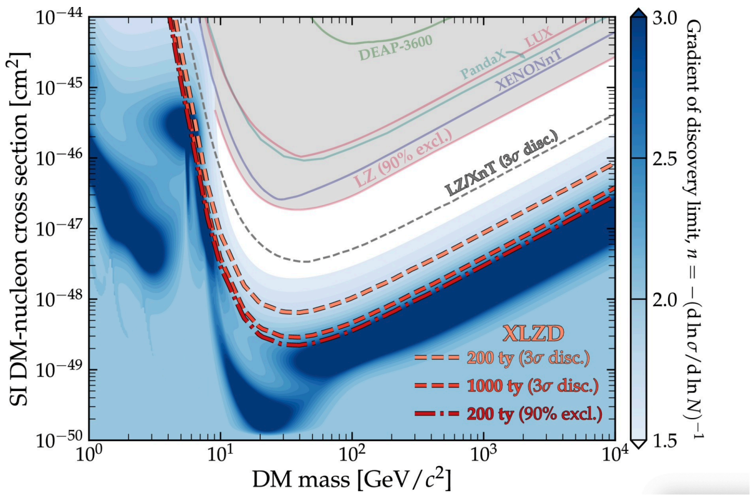
Collider
searches



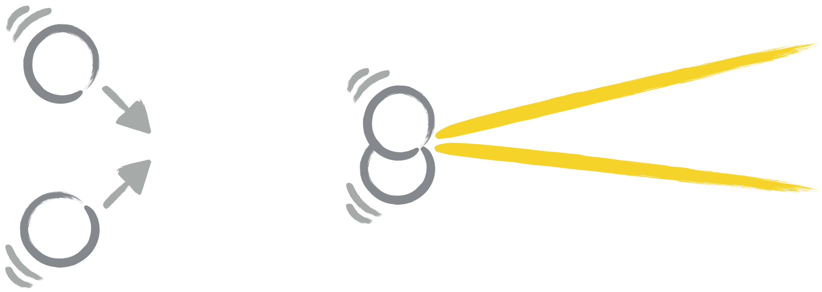
Light dark matter

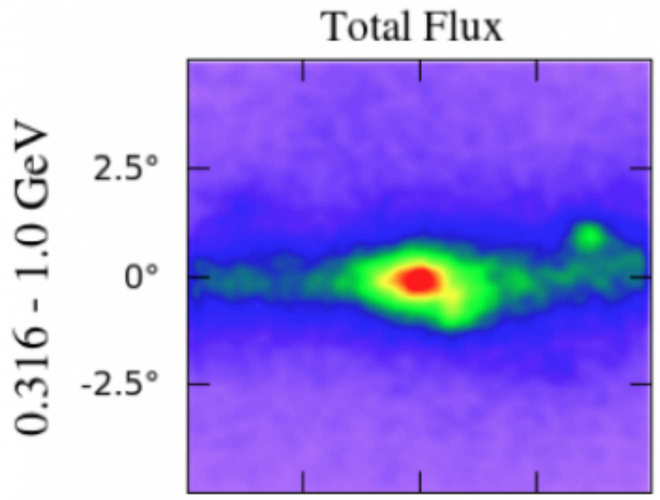
Direct detection



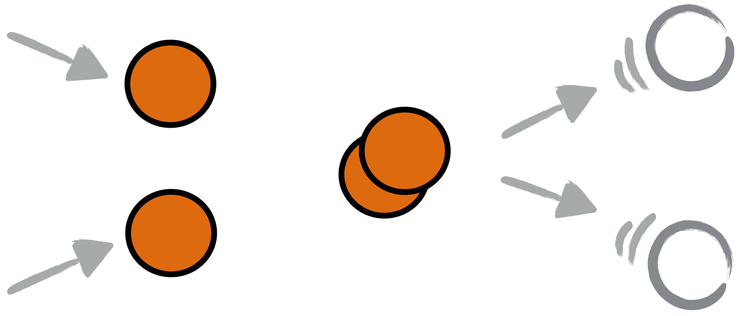


Indirect detection



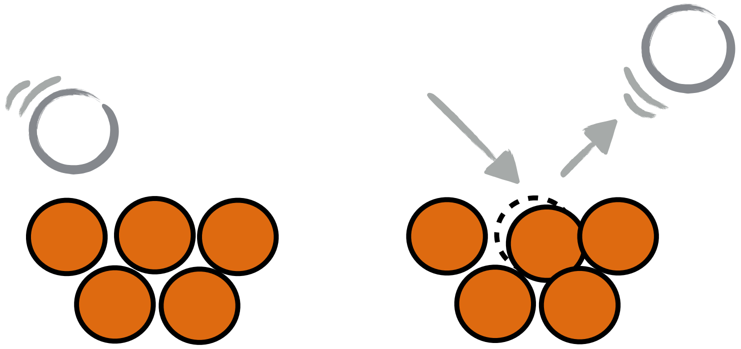


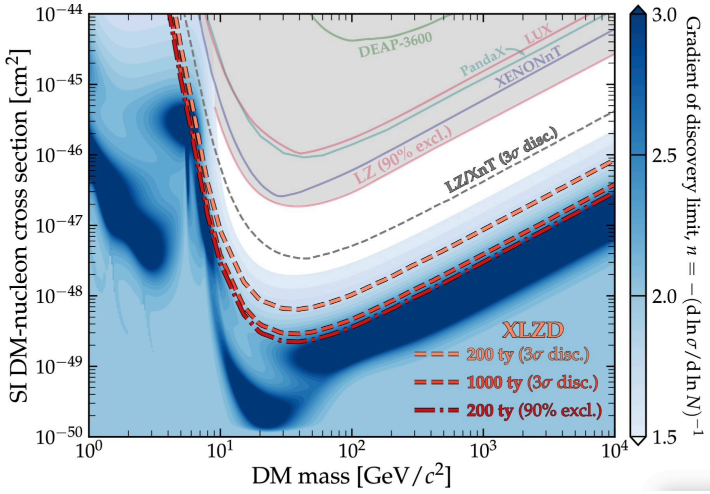
Collider searches



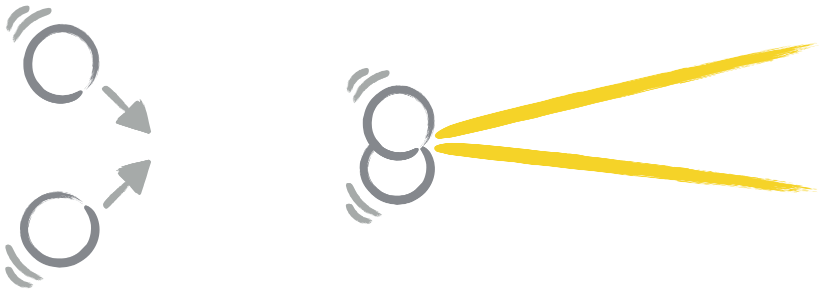
Light dark matter

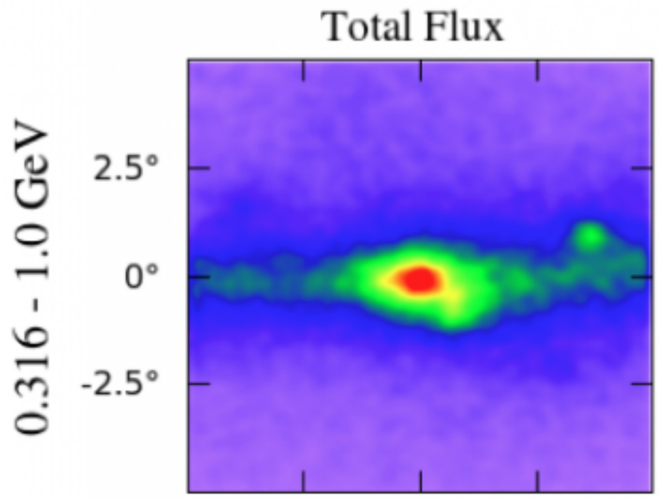
Direct detection



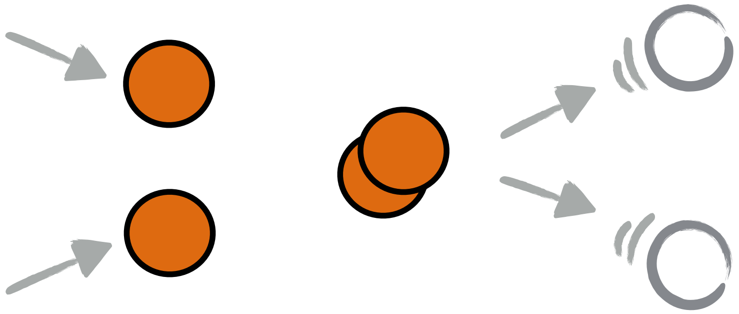


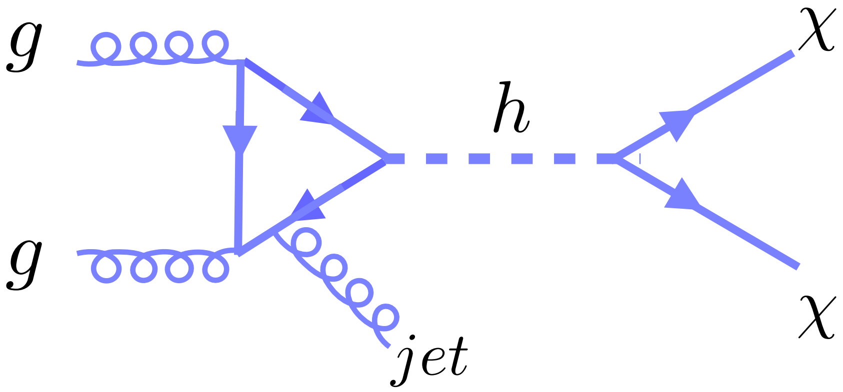
Indirect detection





Collider searches





Light dark matter

Searches for dark matter with masses < 1-10 GeV require new strategies

What can we learn about dark matter in this mass range?

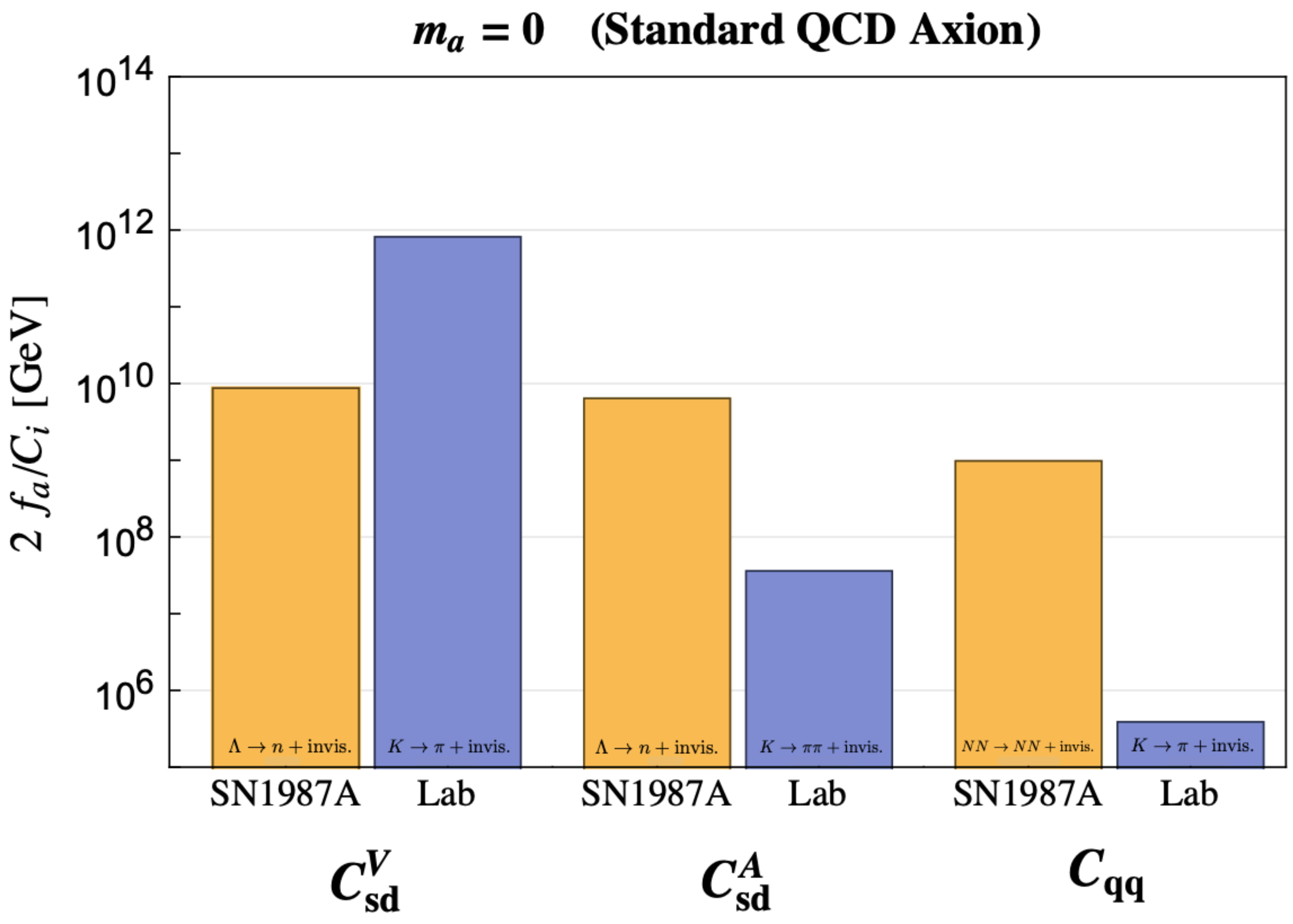
- Rare decays
- Long-lived particles
- Spin measurements
- Quantum sensors

Rare meson decays

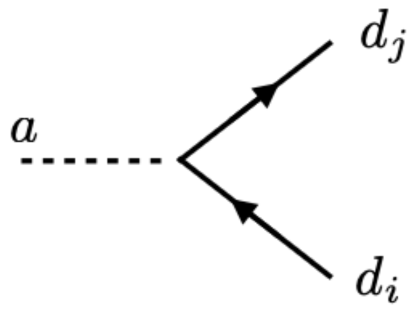
Rare meson decays

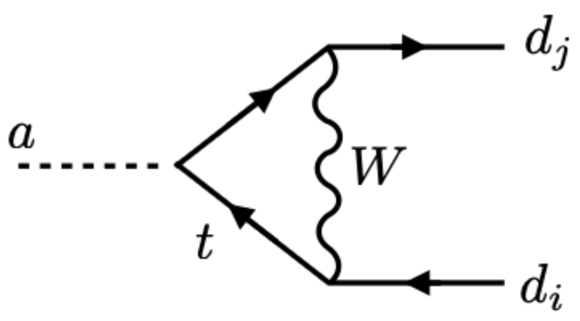
Rare decays, especially rare meson decays are the best probes for axions with flavor-violating couplings

$$\mathcal{L}_{\text{ALP-f}} = \frac{\partial_\mu a}{2 f_a}\, \bar{f}_i \gamma^\mu \left(C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5\right) f_j$$



Even in absence of FV couplings they're induced by the SM



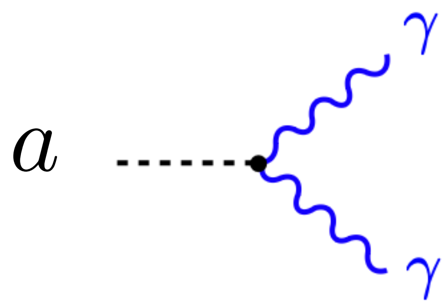


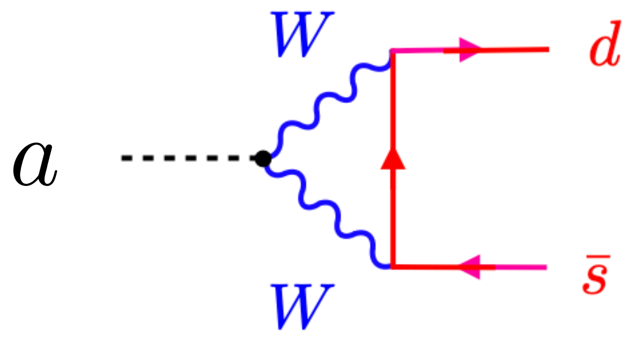
E.~Goudzovski et al.``New physics searches at kaon and hyperon factories”, Rept. Prog. Phys. **86** (2023) no.1, 016201

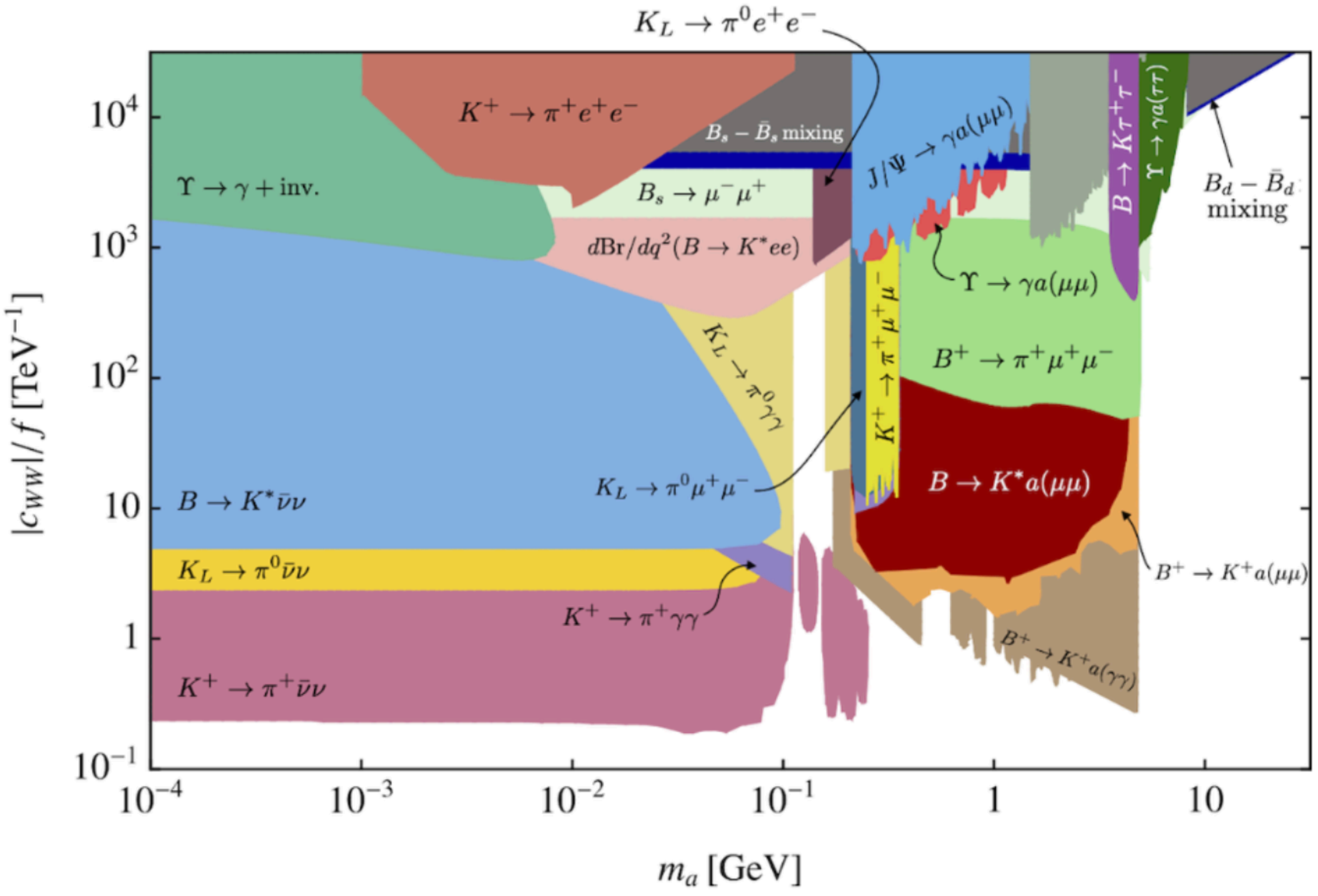
Rare meson decays

If the axion decays, rare meson decays are even more powerful

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W_{\mu\nu}\tilde{W}^{\mu\nu}$$

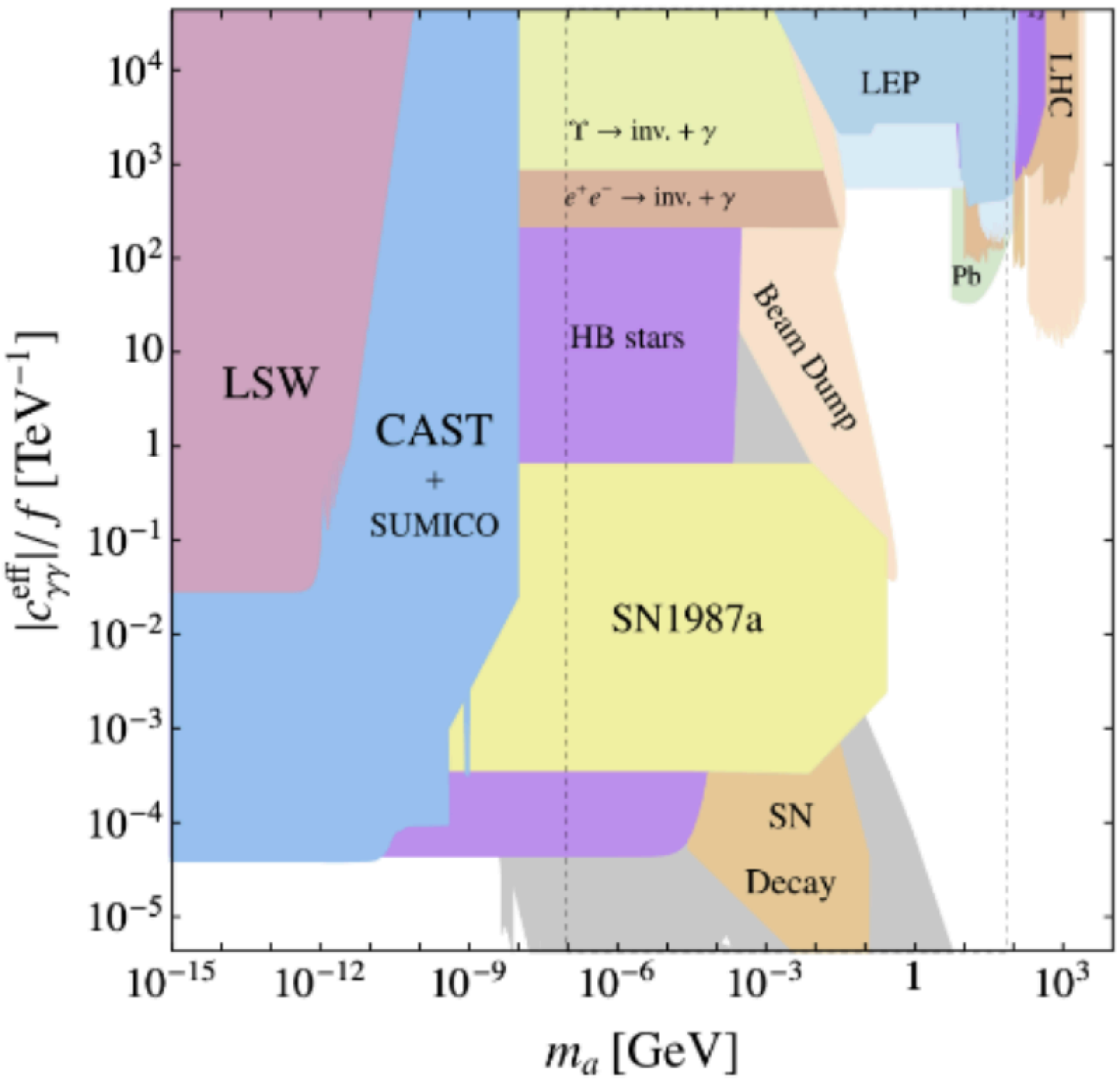






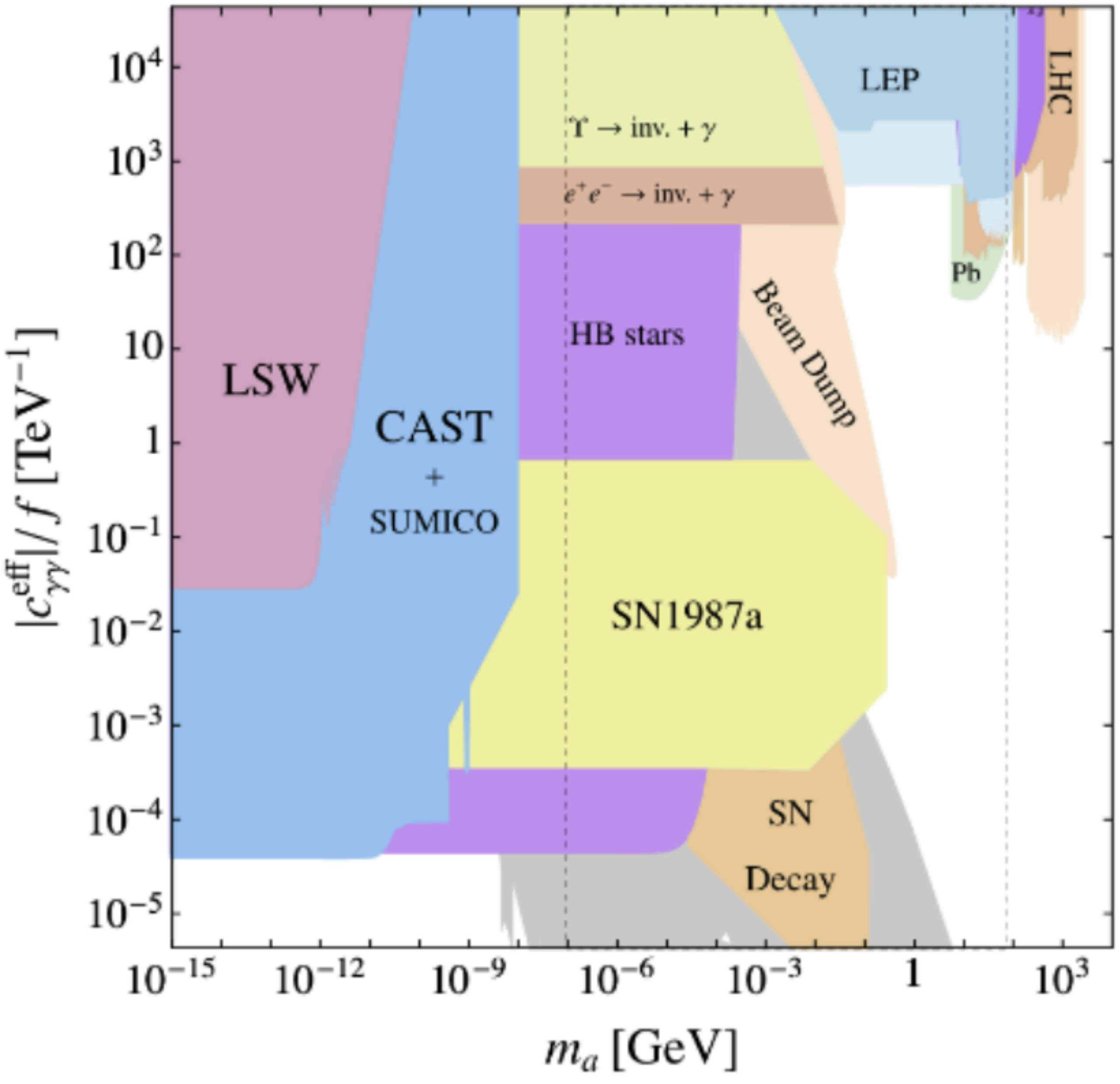
Rare meson decays

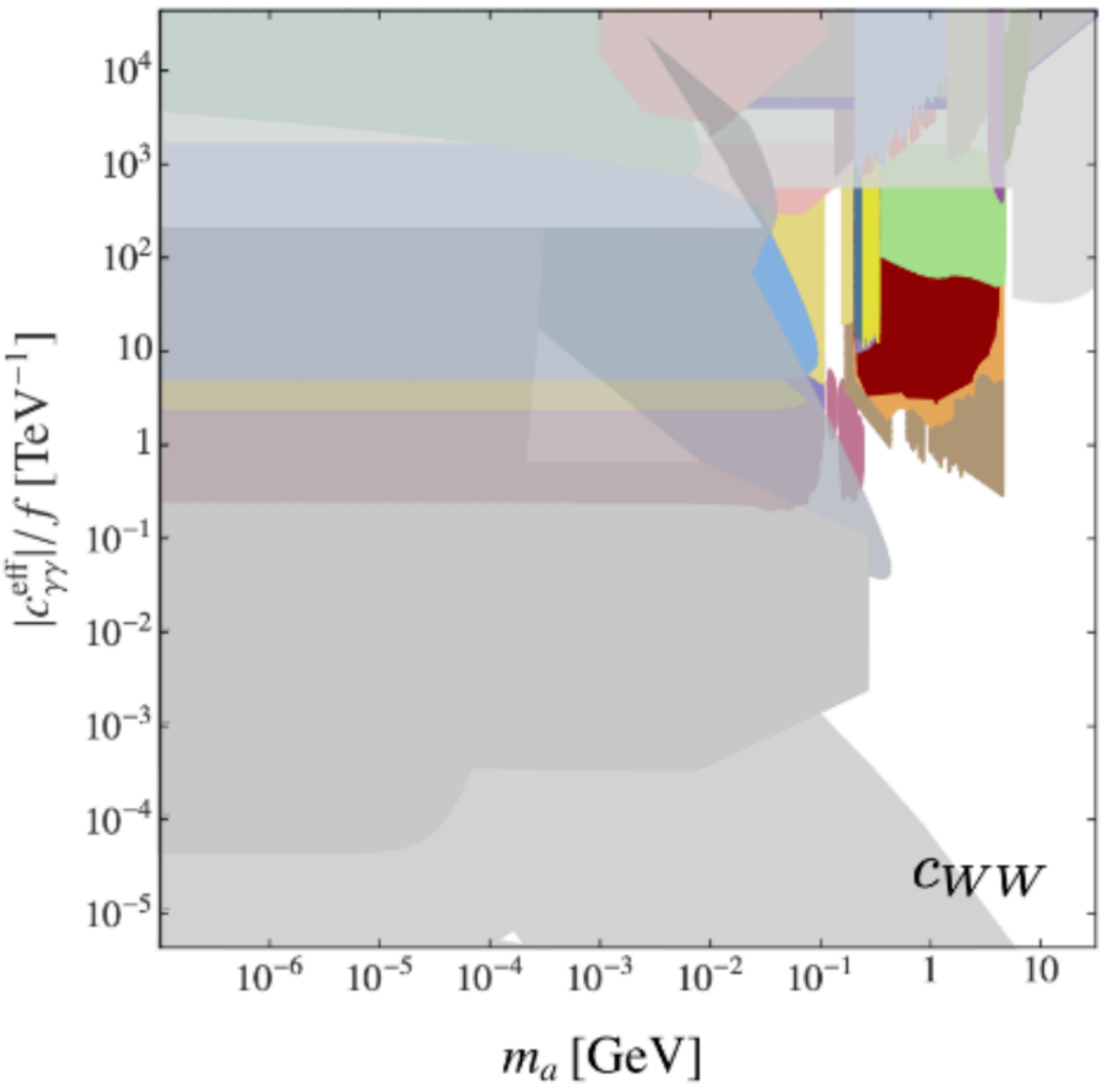
Offer a unique test of the parameter space unconstrained by astrophysical, beam dump and collider searches



Rare meson decays

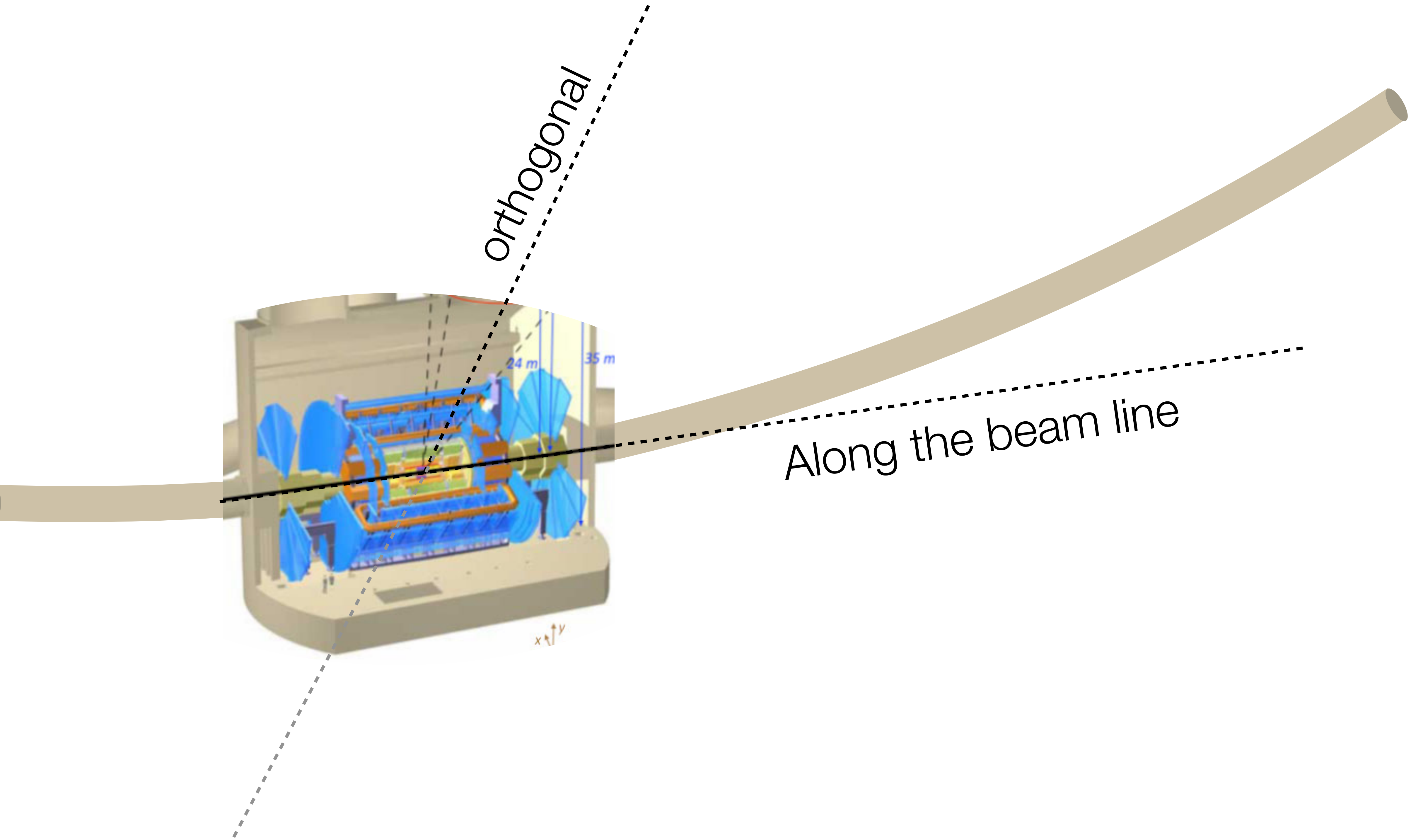
Offer a unique test of the parameter space unconstrained by astrophysical, beam dump and collider searches





Long-lived particles

Long-lived particles



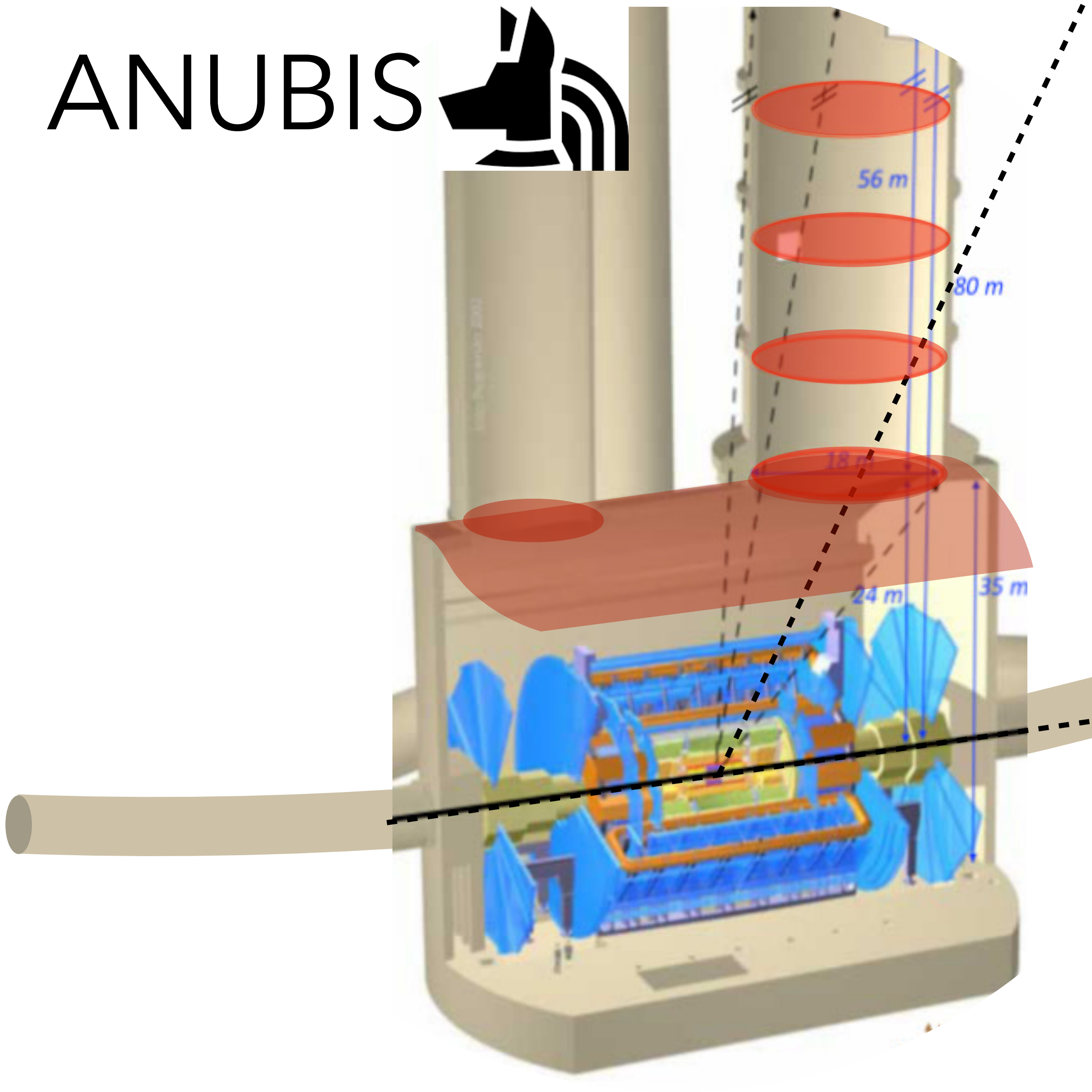
orthogonal

Along the beam line

The lifetime reach of LHC detectors is limited by their size and backgrounds

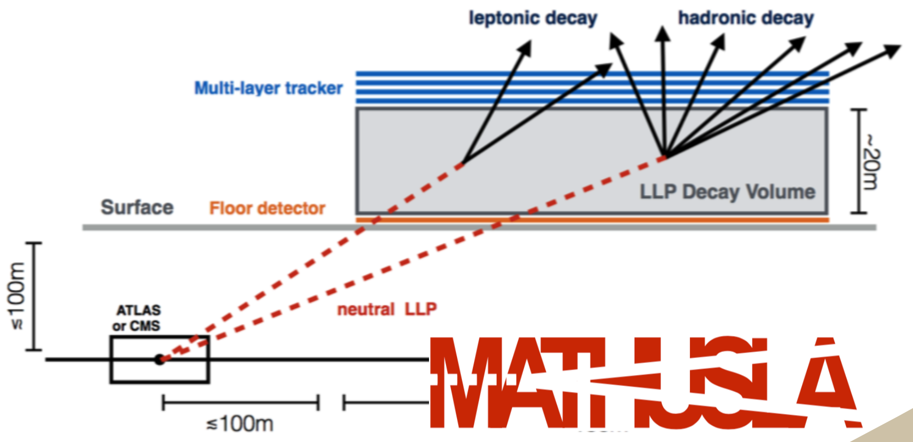
Long-lived particles

ANUBIS

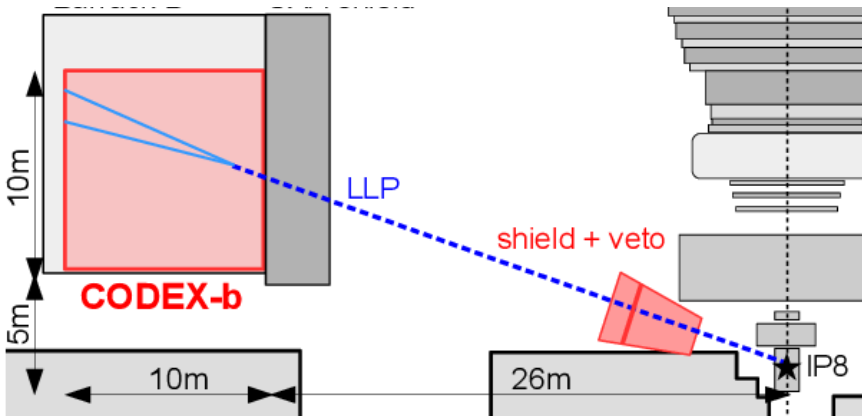


We propose to instrument the ATLAS service shaft or ceiling

MB, Brandt, Lee, Ohm 1909.13022

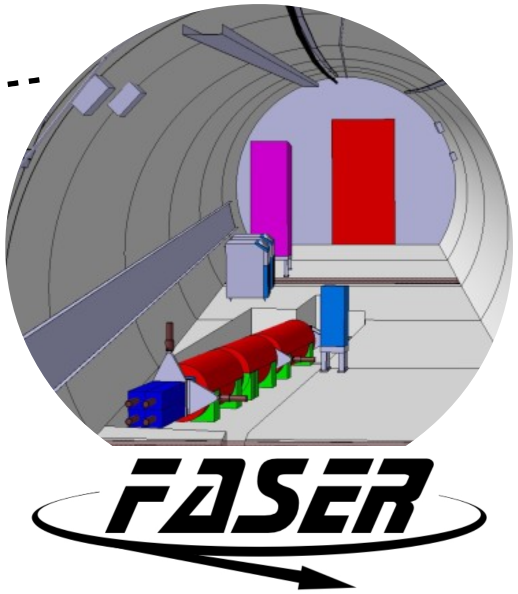


Chou et al 1606.06298



CODEX-b

Gligorov et al 1708.09395

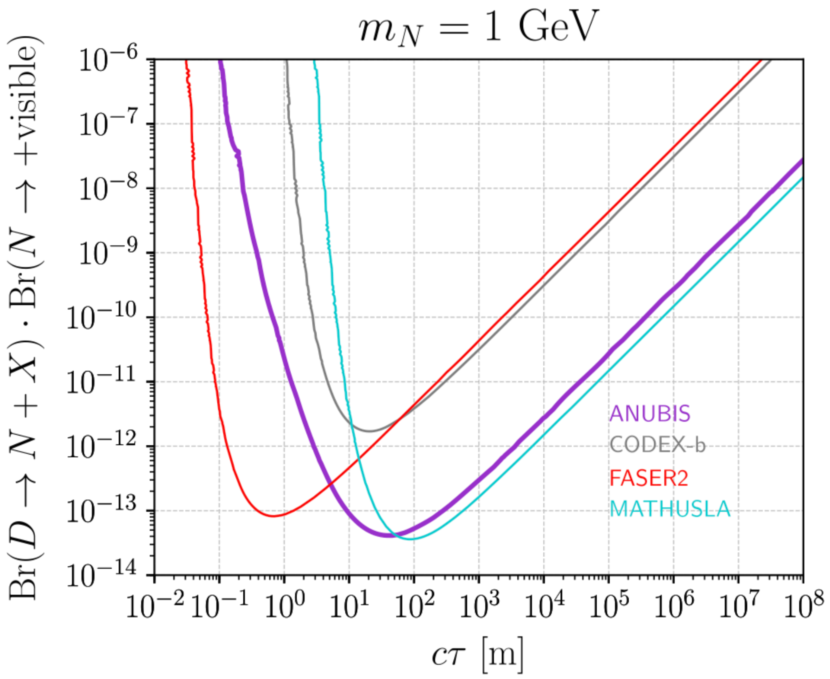


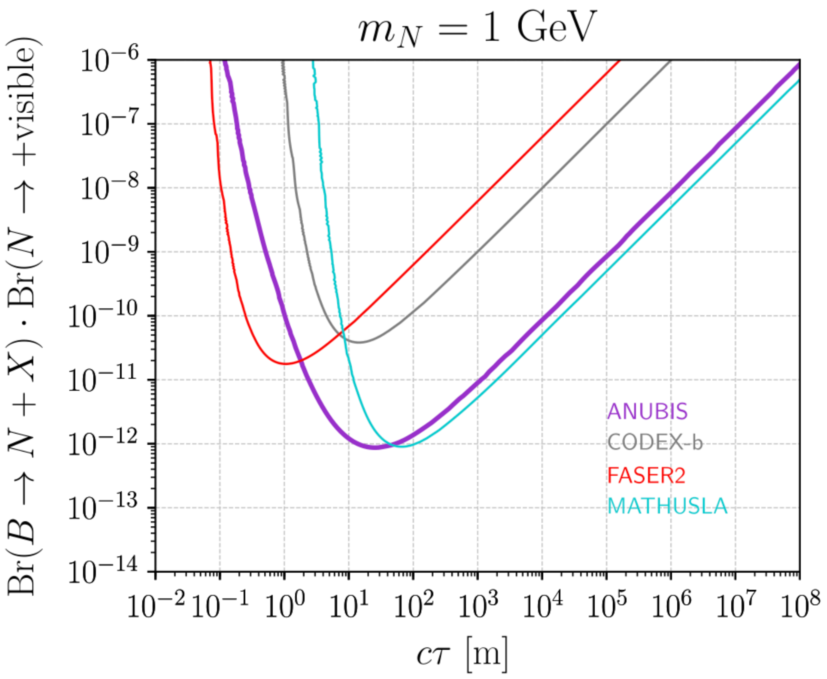
Feng, et al 1710.09387

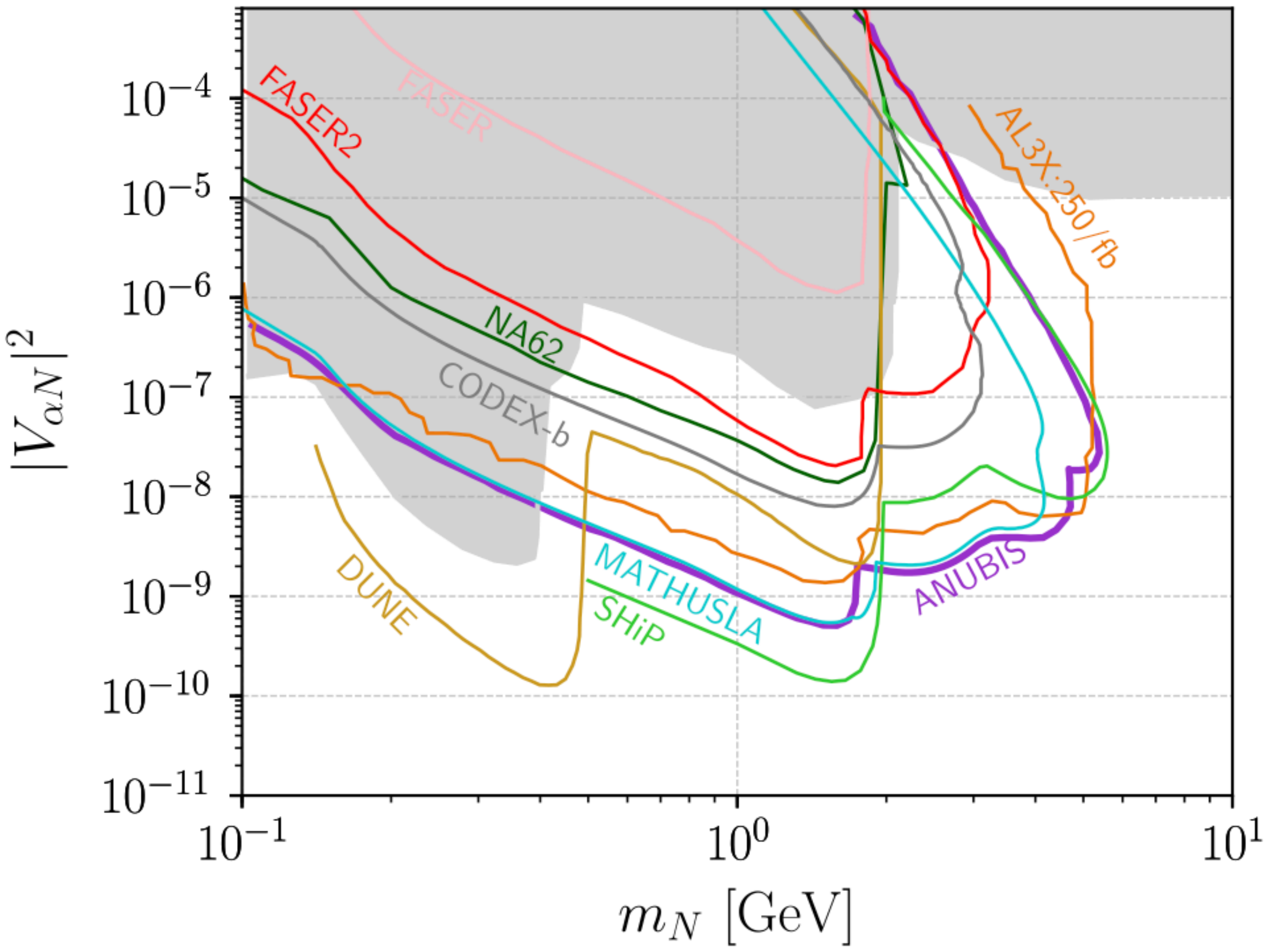
Long-lived particles

Sensitivity to heavy neutral leptons

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{\alpha N_j} \bar{\ell}_\alpha \gamma^\mu P_L N_j W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} V^L_{\alpha i} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$

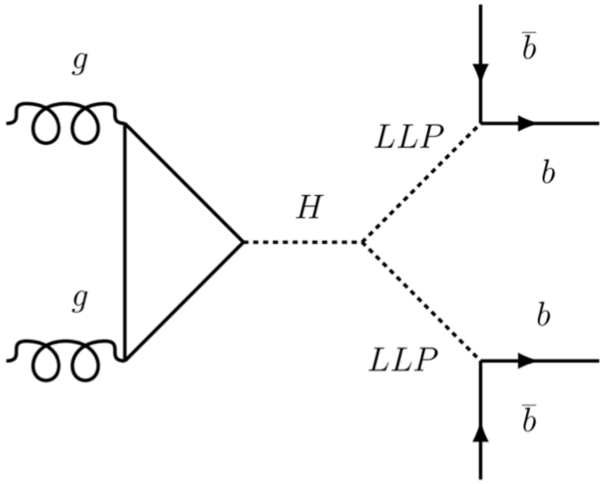




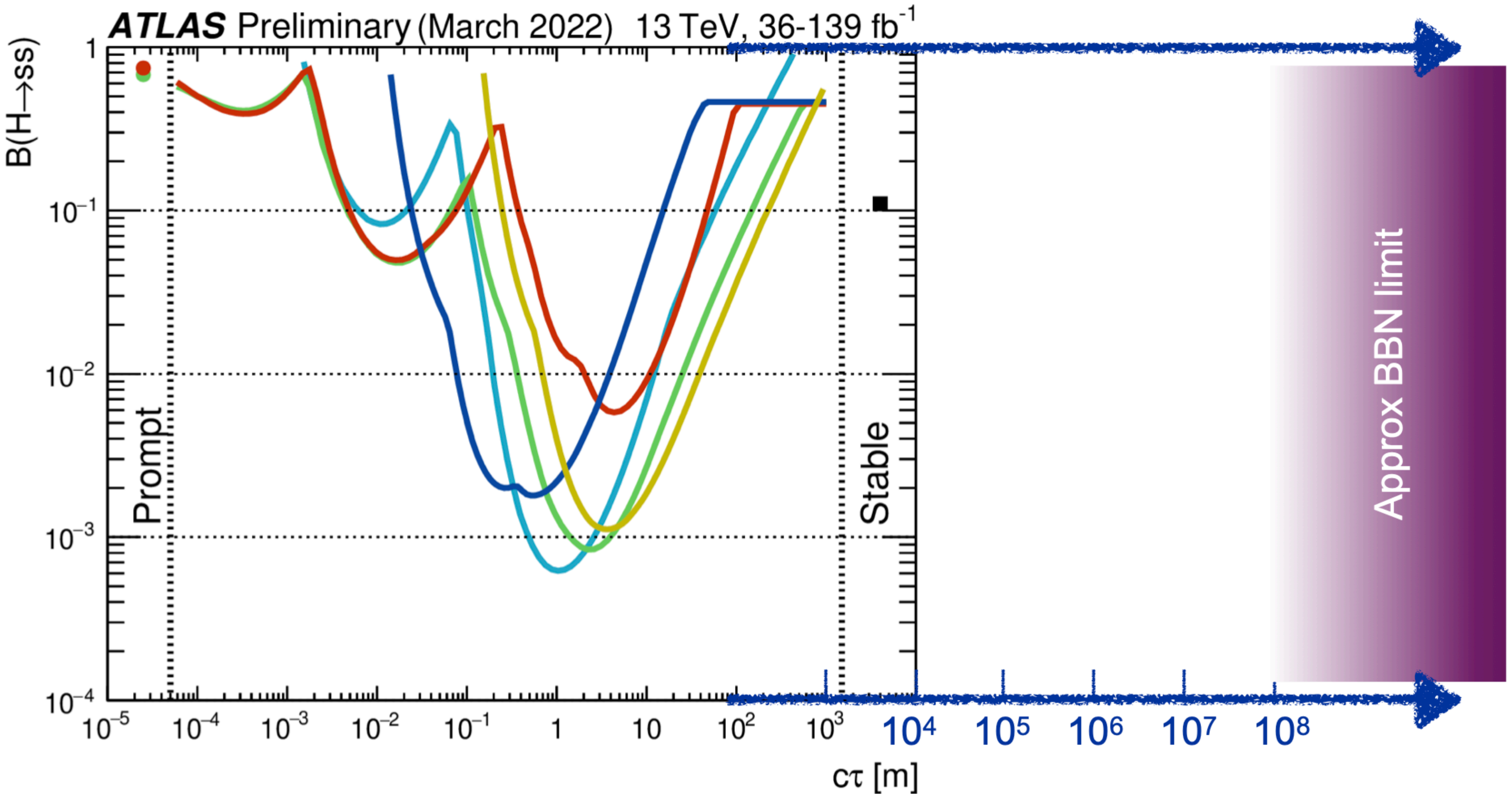


Hirsch, Wang ``Heavy neutral leptons at ANUBIS,''
Phys. Rev. D **101** (2020) no.5, 055034

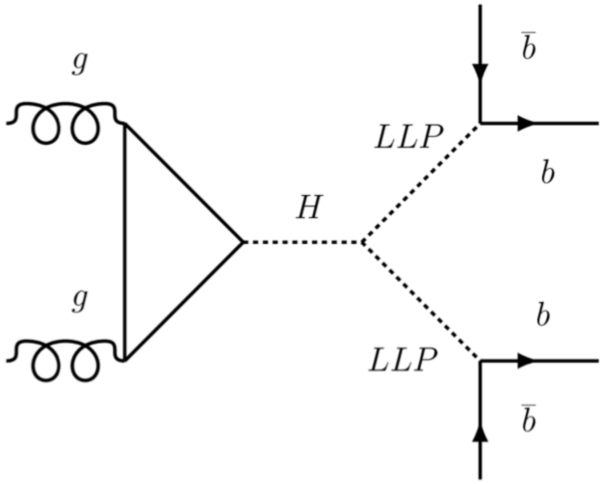
Long-lived particles



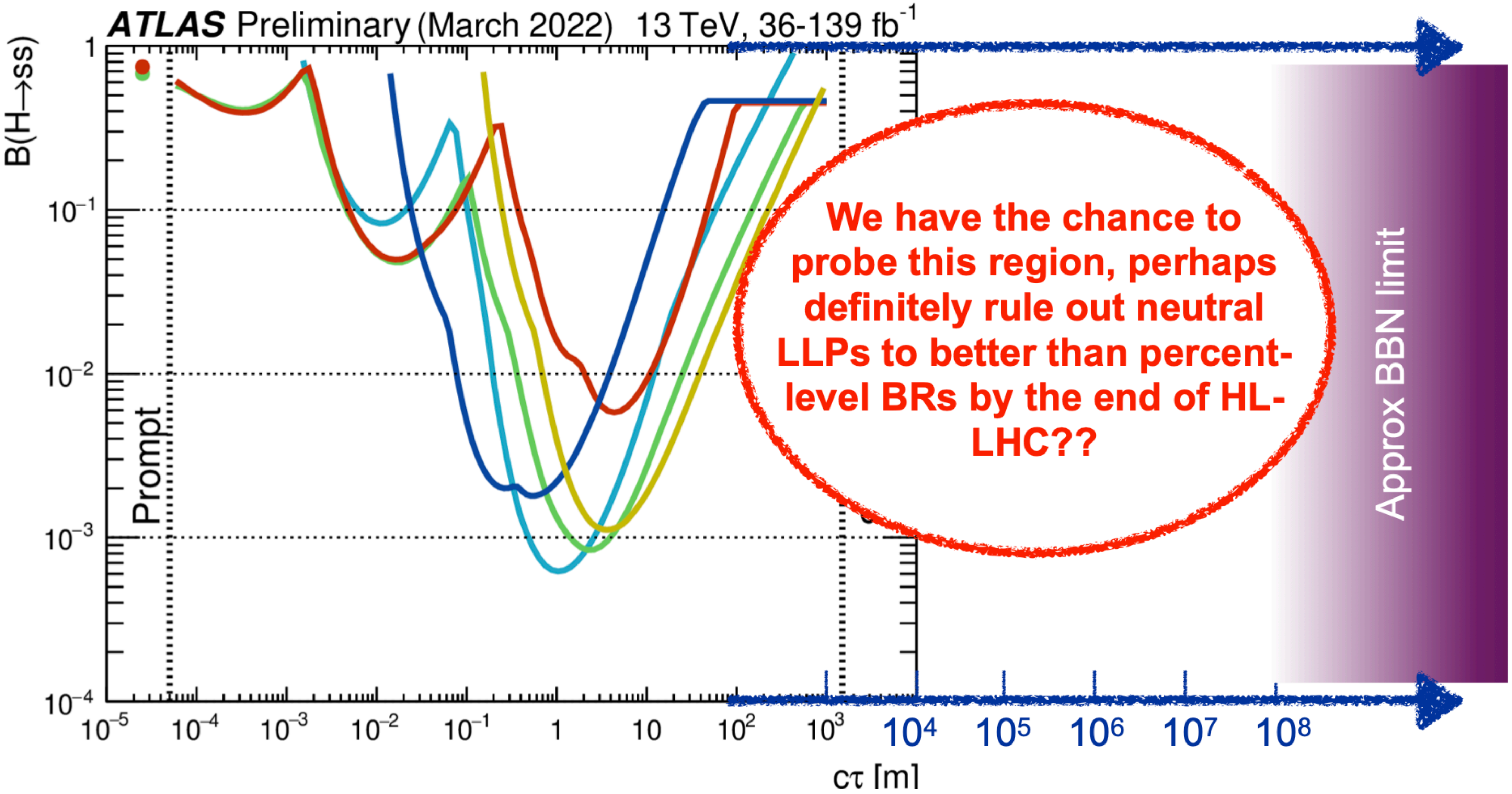
The most important target is the Higgs boson: only produced at the LHC!



Long-lived particles



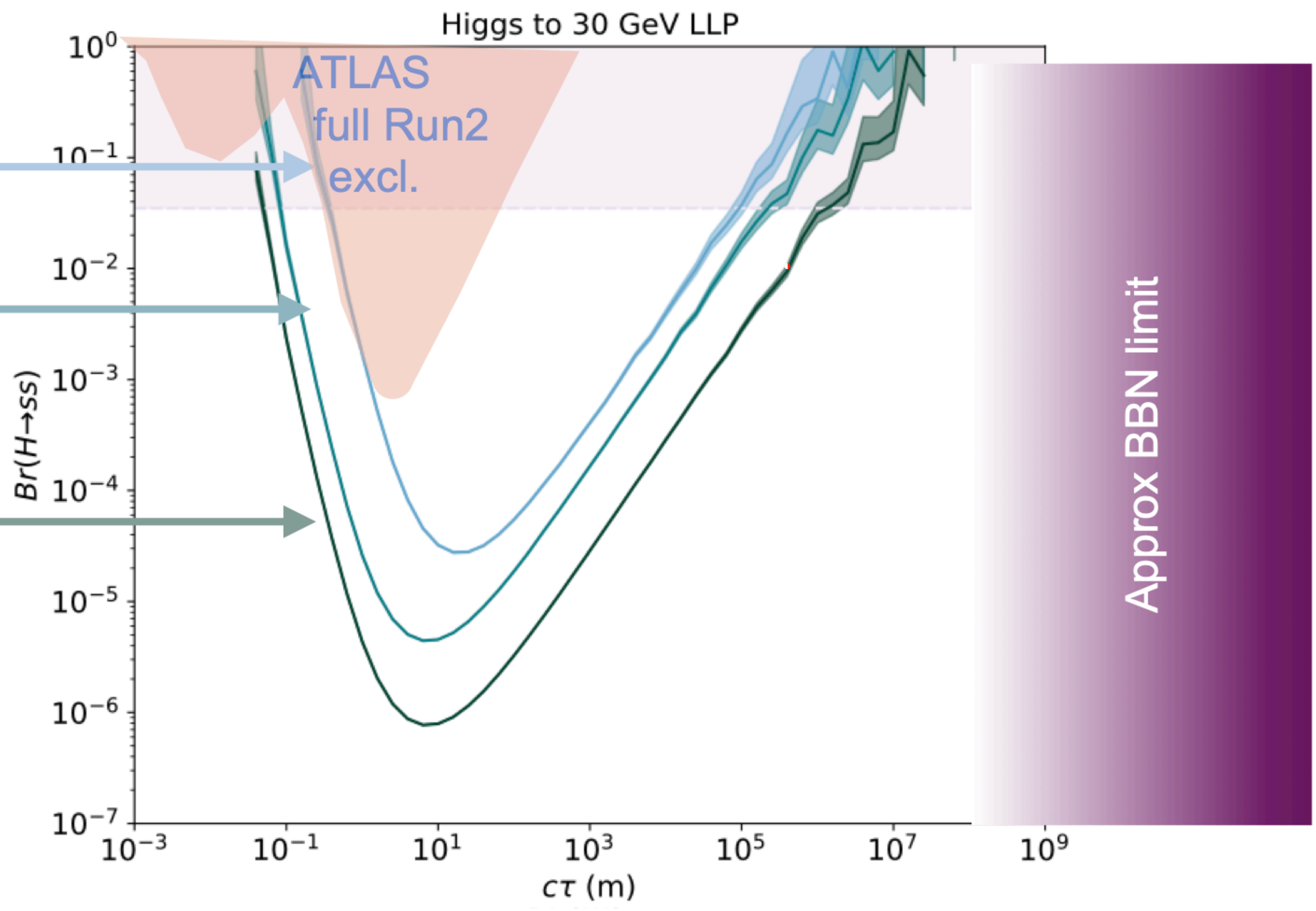
The most important target is the Higgs boson: only produced at the LHC!



We have the chance to probe this region, perhaps definitely rule out neutral LLPs to better than percent-level BRs by the end of HL-LHC??

Long-lived particles

The ‘lifetime reach’ of LHC detectors is limited by their size and backgrounds



Original ANUBIS shaft-only proposal

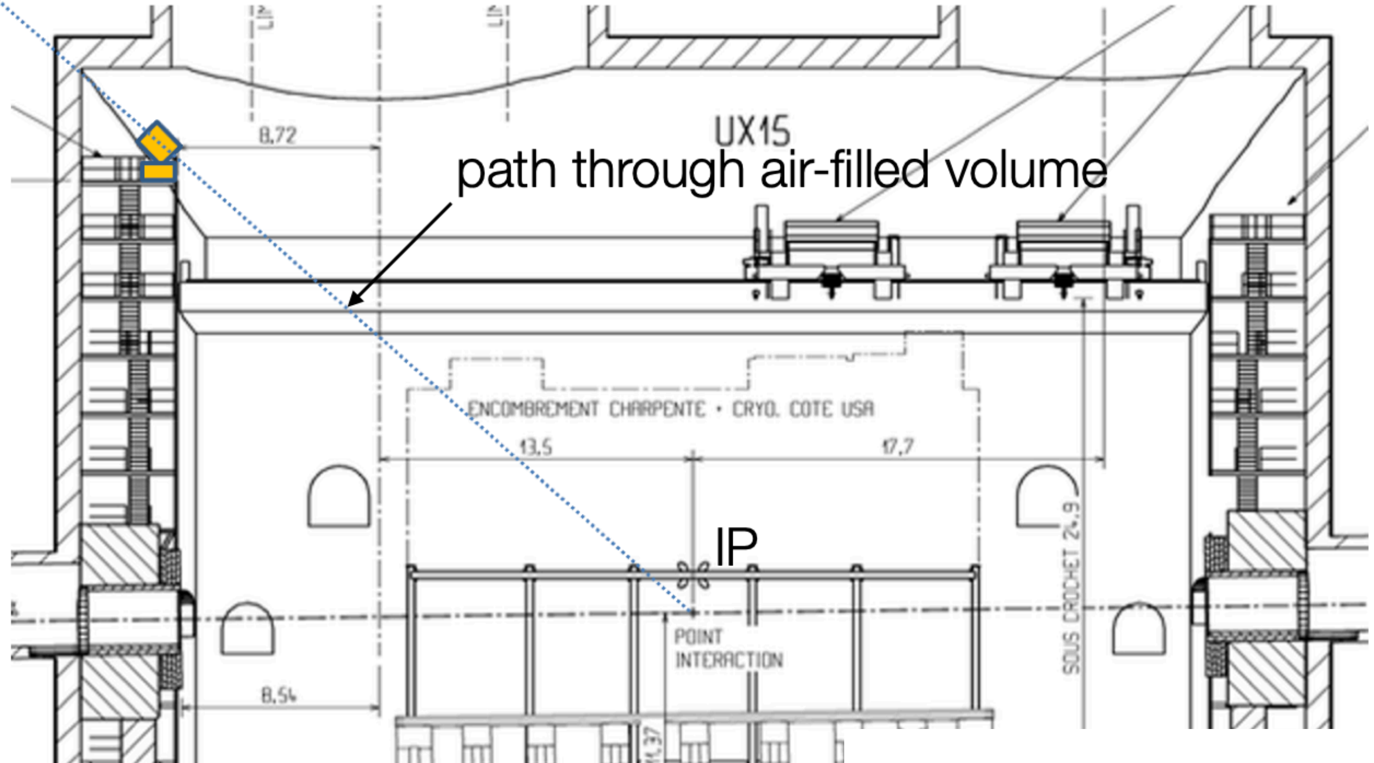
ANUBIS shaft, including cavern decays

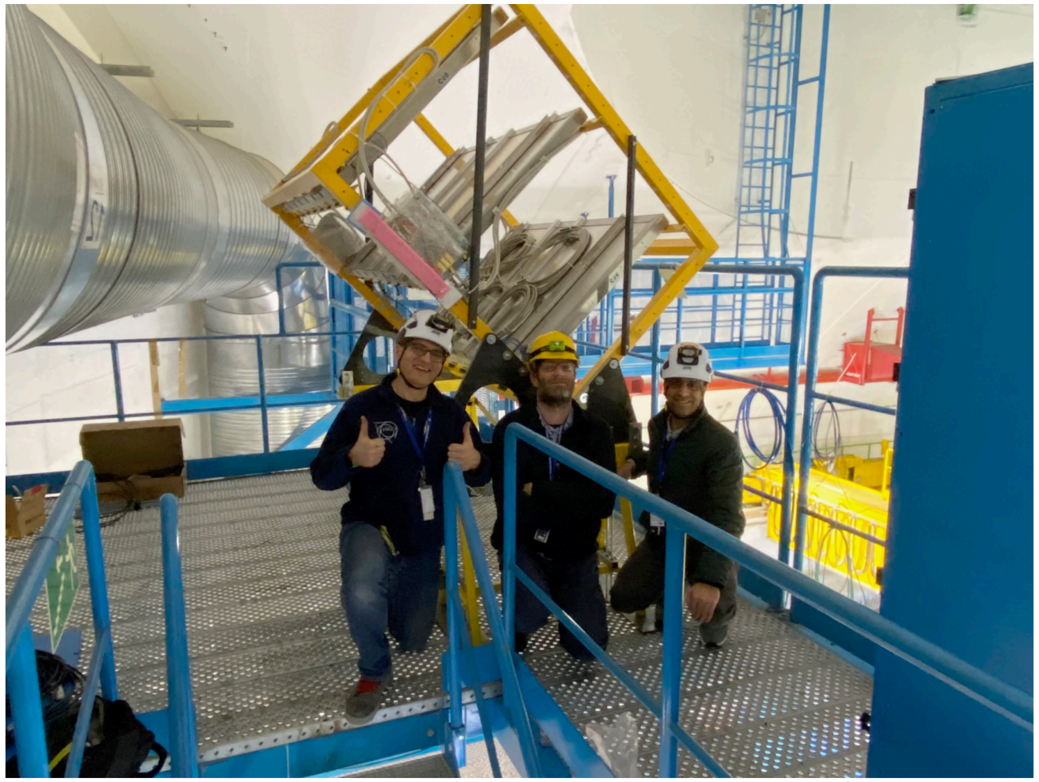
Current proposal: ANUBIS ceiling configuration

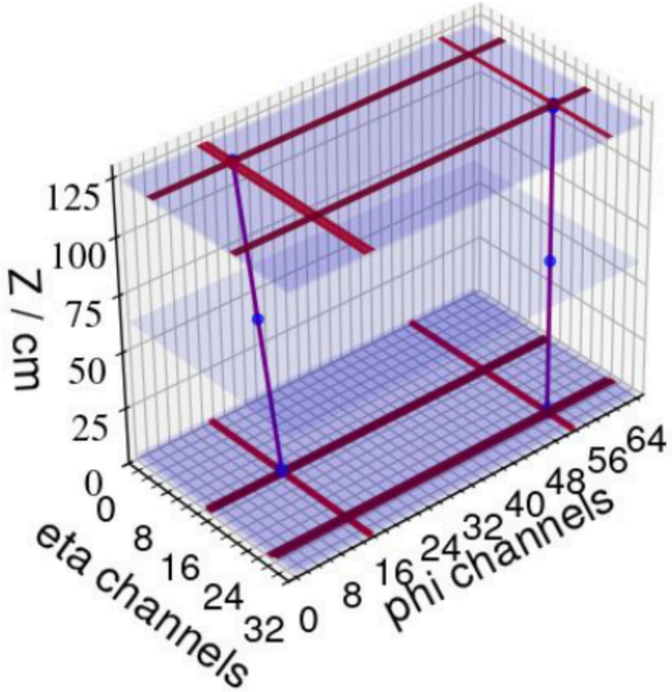
Long-lived particles

Pro-ANUBIS demonstrator installed during run 3 to show feasibility and understand backgrounds

Synchronised with ATLAS clock to provide an active veto





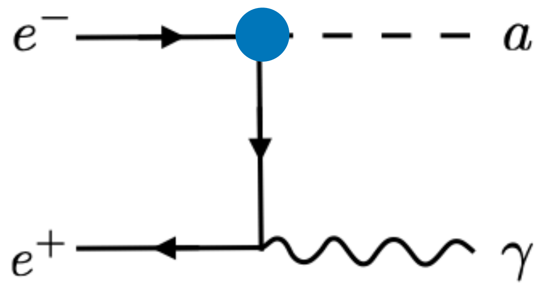


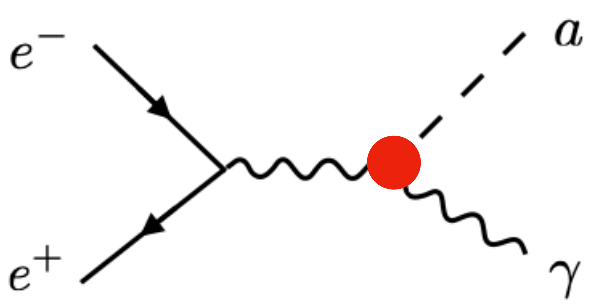
Measuring the spin of invisible states

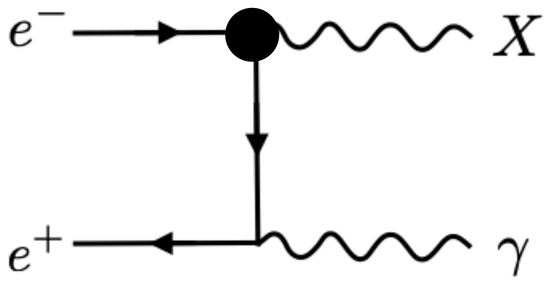
Measuring the spin of invisible states

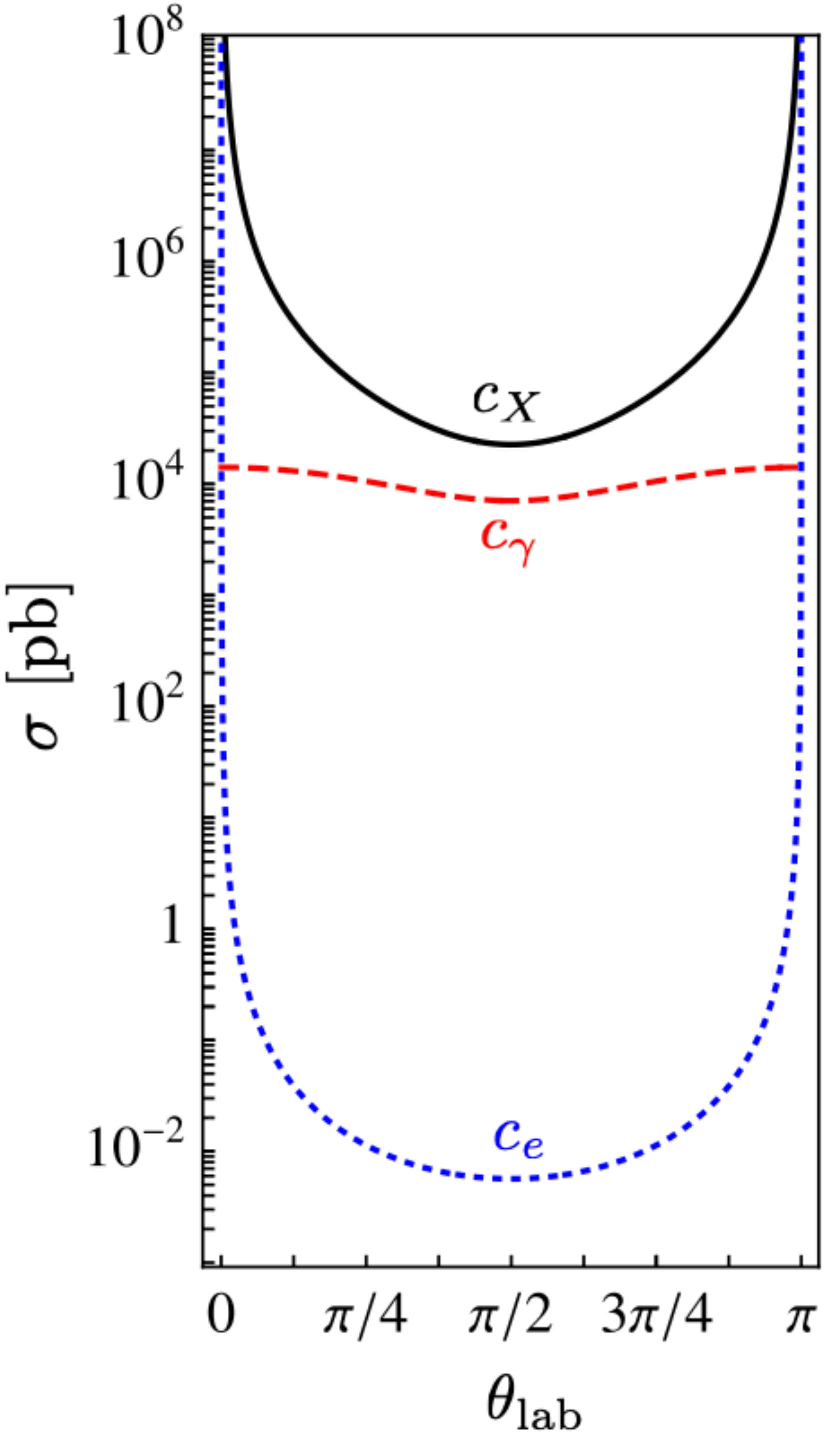
What if the ALP, dark photon is stable?

Angular distribution can distinguish t-channel from s-channel





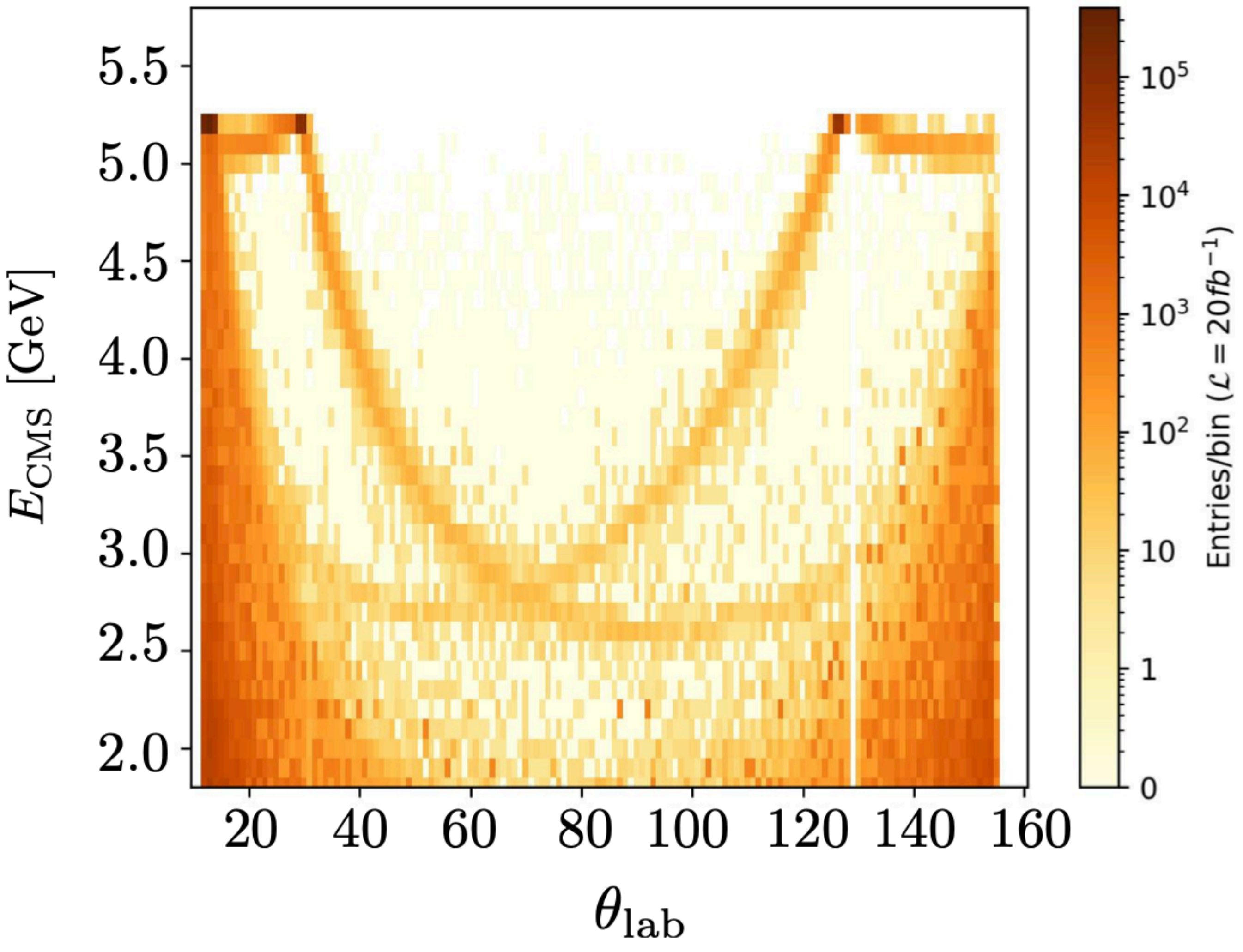


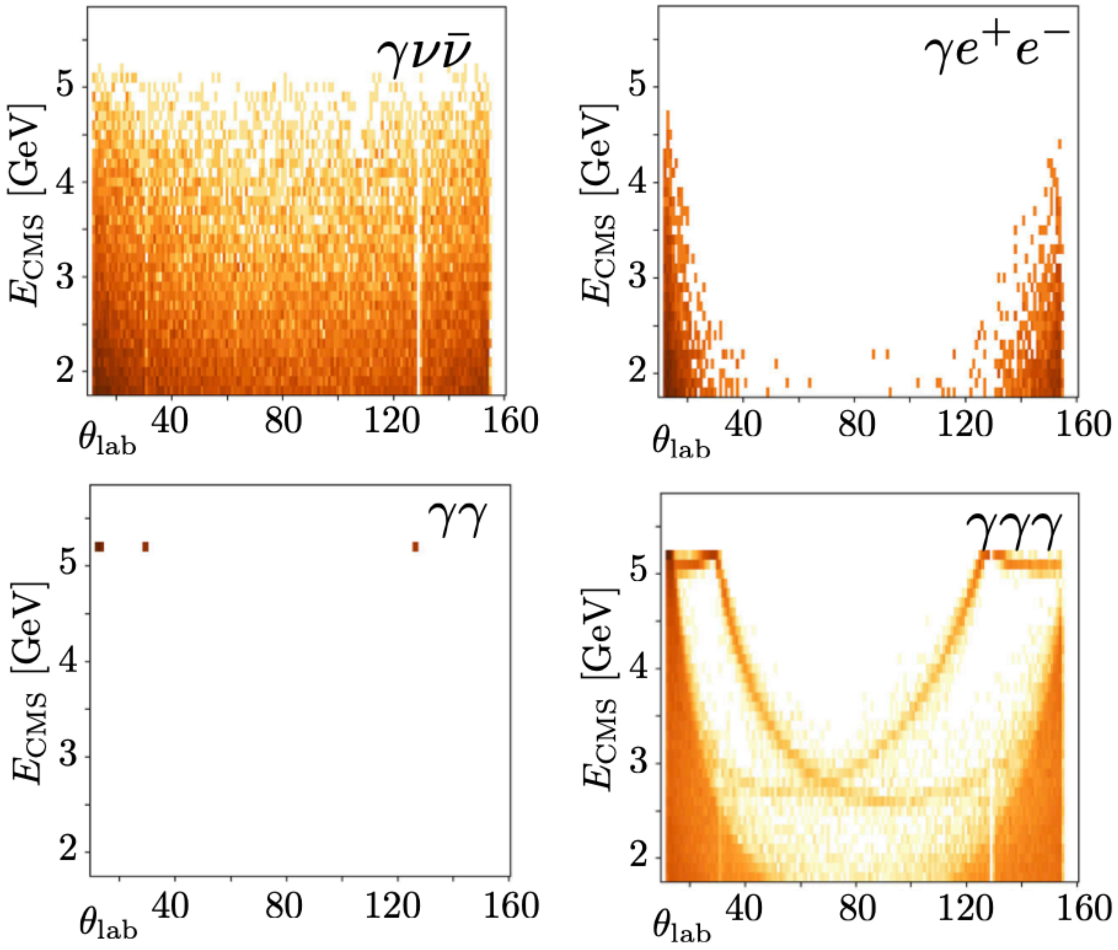


MB, Erner, *Phys.Rev.D* 108 (2023) 11

Invisible decays and polarisation

Backgrounds for e+e- -> X + ɣ at Belle II



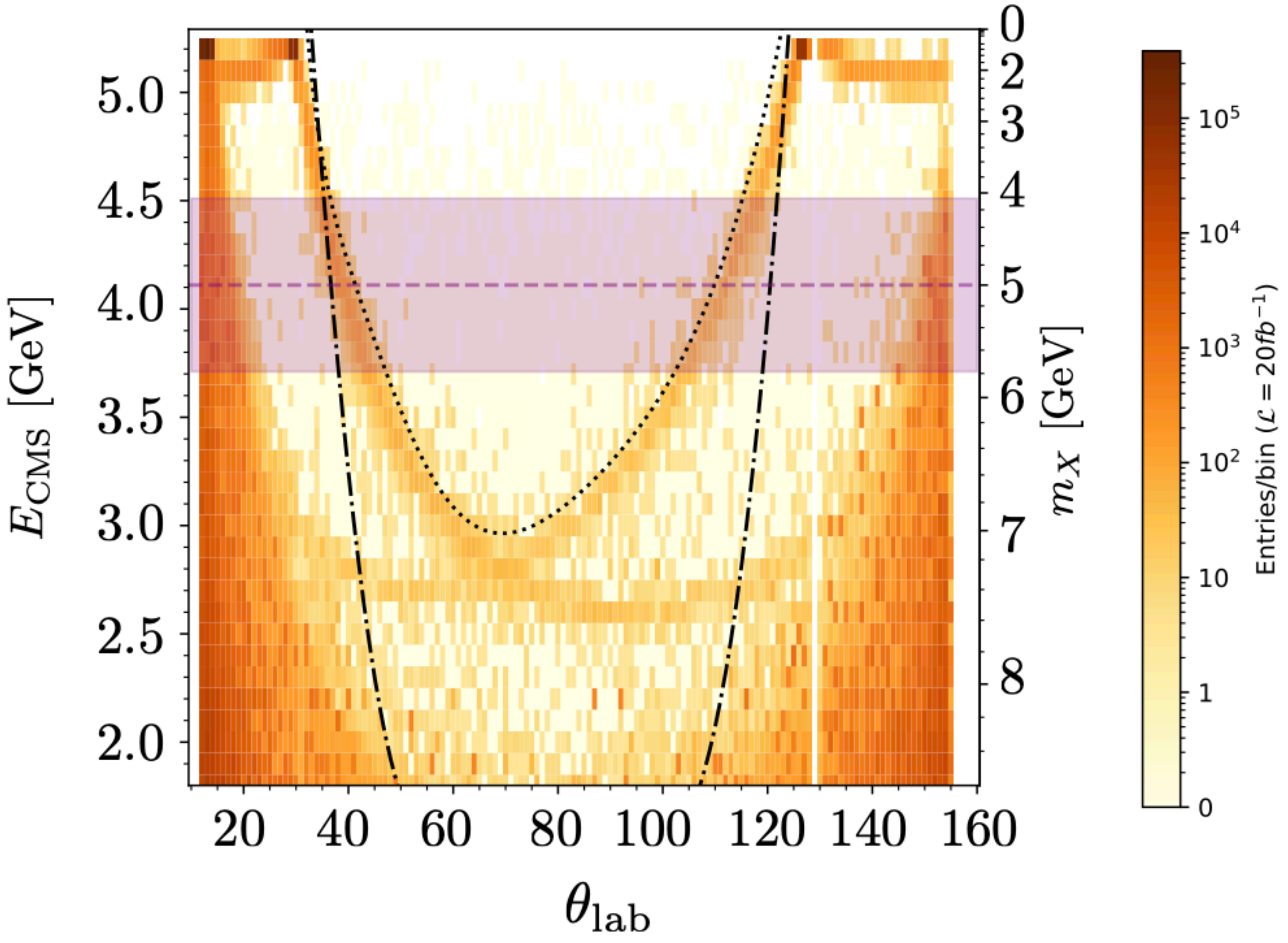


MB, Erner, *Phys.Rev.D* 108 (2023) 11

Invisible decays and polarisation

Polarised beams eliminates background and distinguishes ALP-electron and photon interactions

Unpolarised

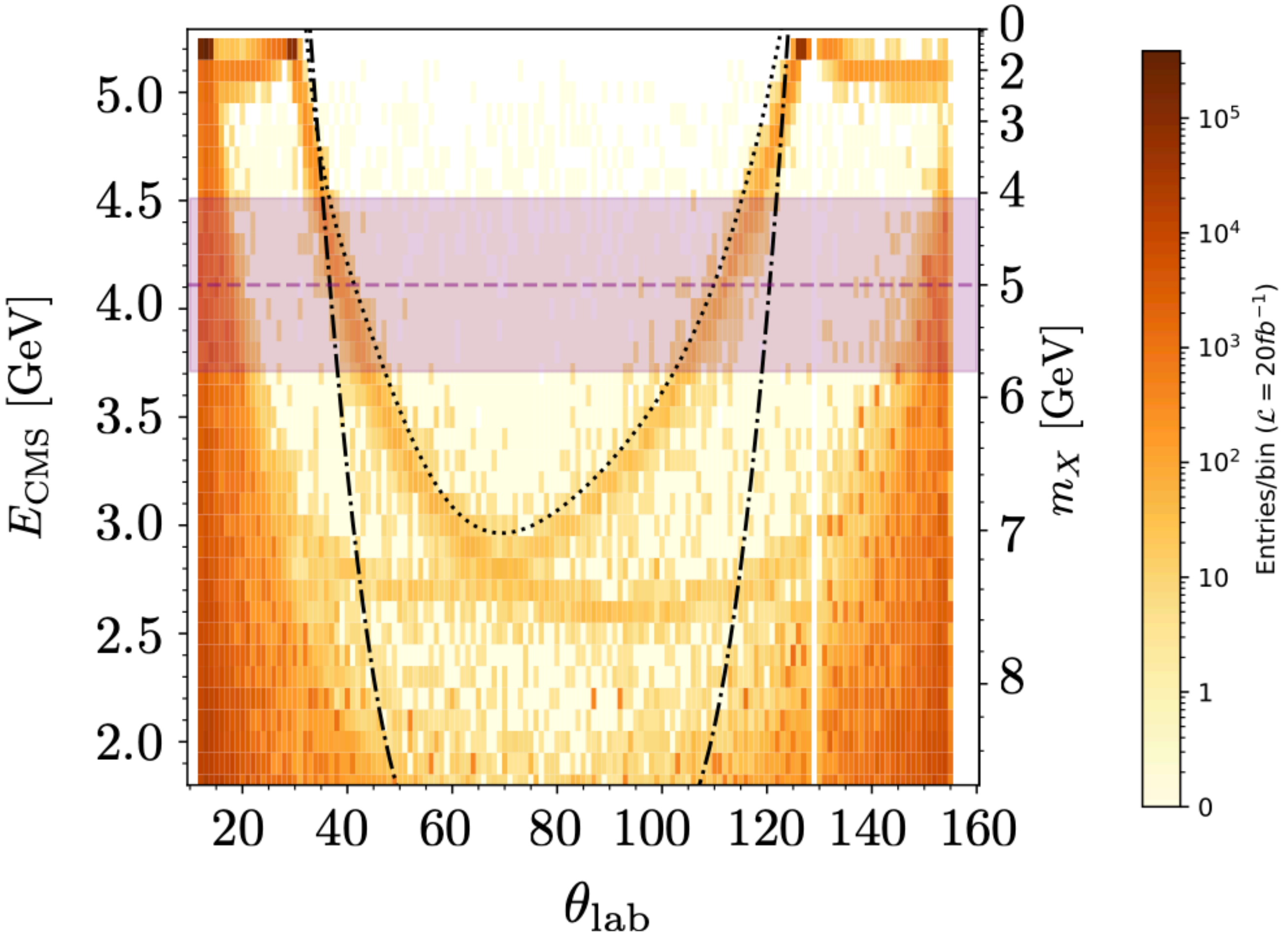


MB, Erner, *Phys.Rev.D* 108 (2023) 11

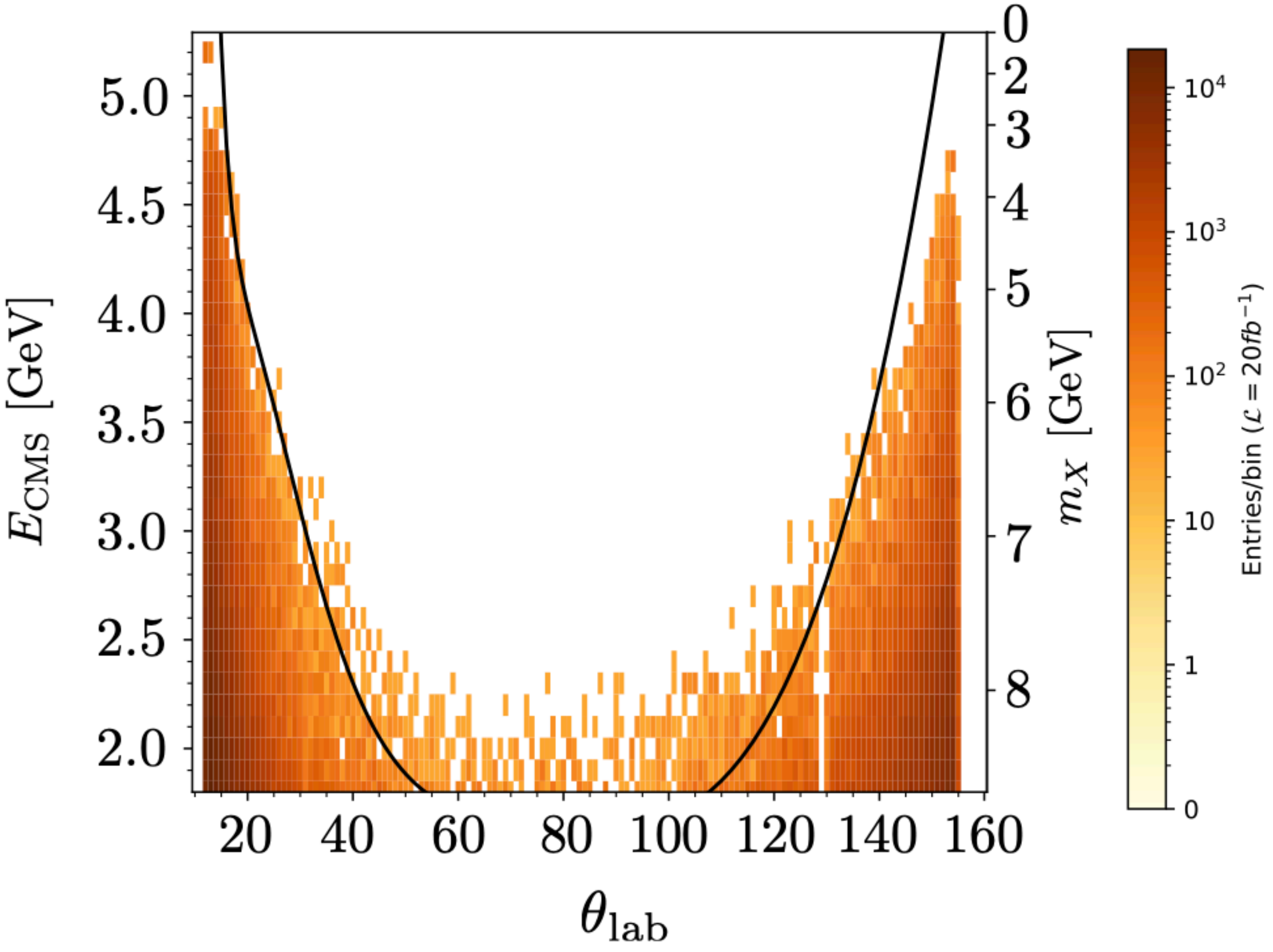
Invisible decays and polarisation

Polarised beams eliminates background and distinguishes ALP-electron and photon interactions

Unpolarised



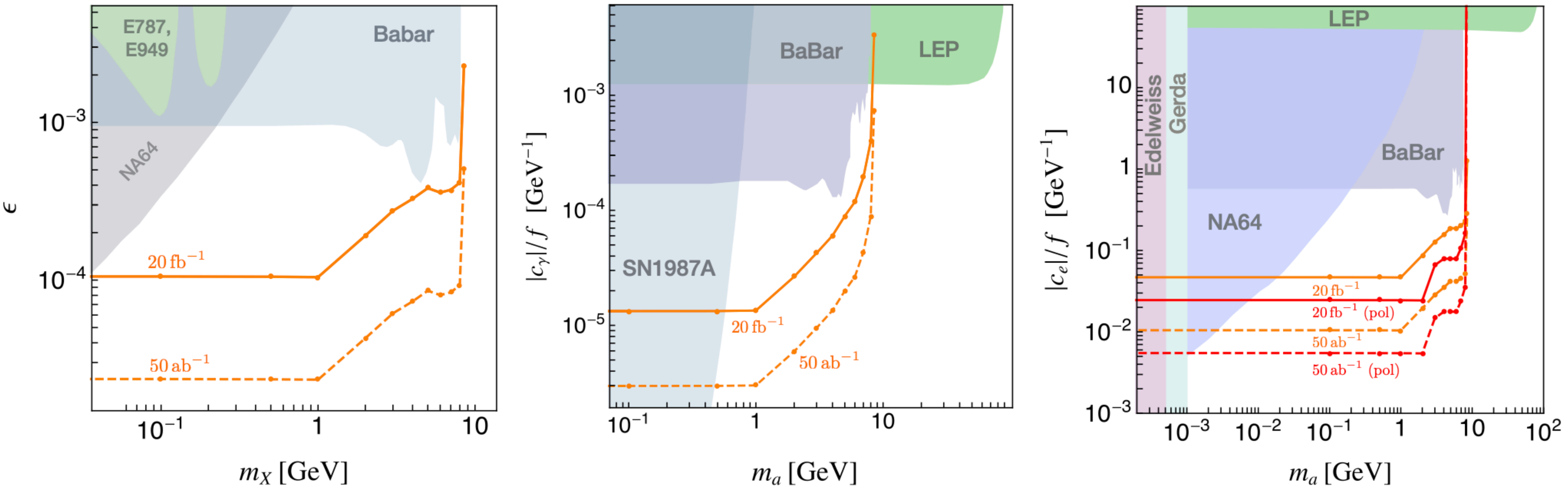
Polarised beams



MB, Erner, *Phys.Rev.D* 108 (2023) 11

Invisible decays and polarisation

Polarised beams eliminates background and distinguishes ALP-electron and photon interactions



MB, Erner, *Phys.Rev.D* 108 (2023) 11

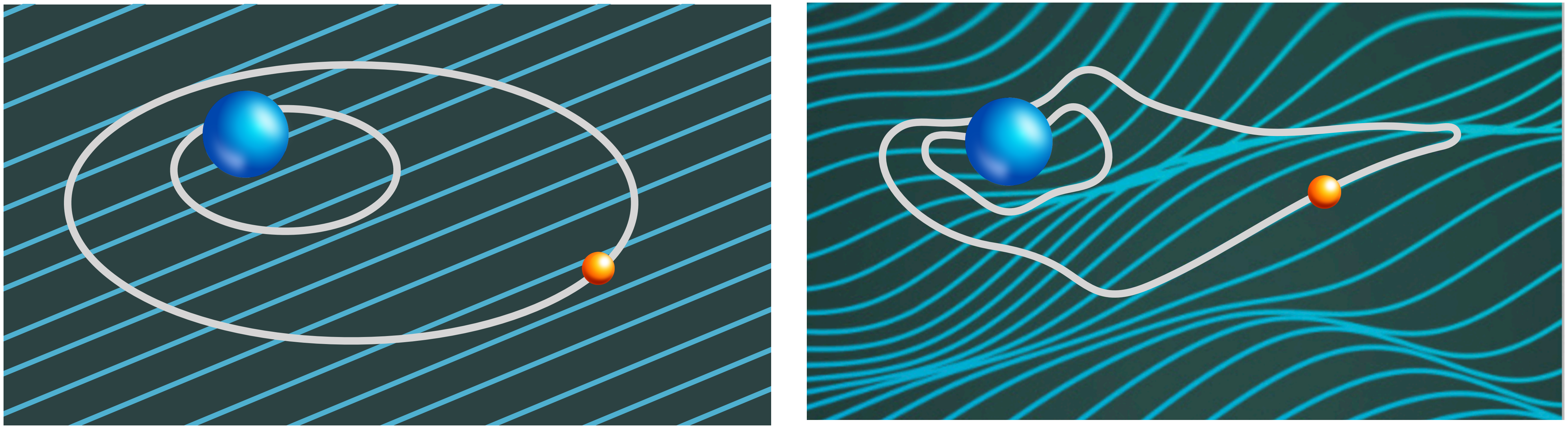
Ultra-light dark matter

Ultra-light dark matter

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

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

Sketch of an atom in a wavelike DM background



Ultra-light dark matter

Mass is fixed by halo size $m_a \gtrsim 10^{-22}\,\mathrm{eV}$

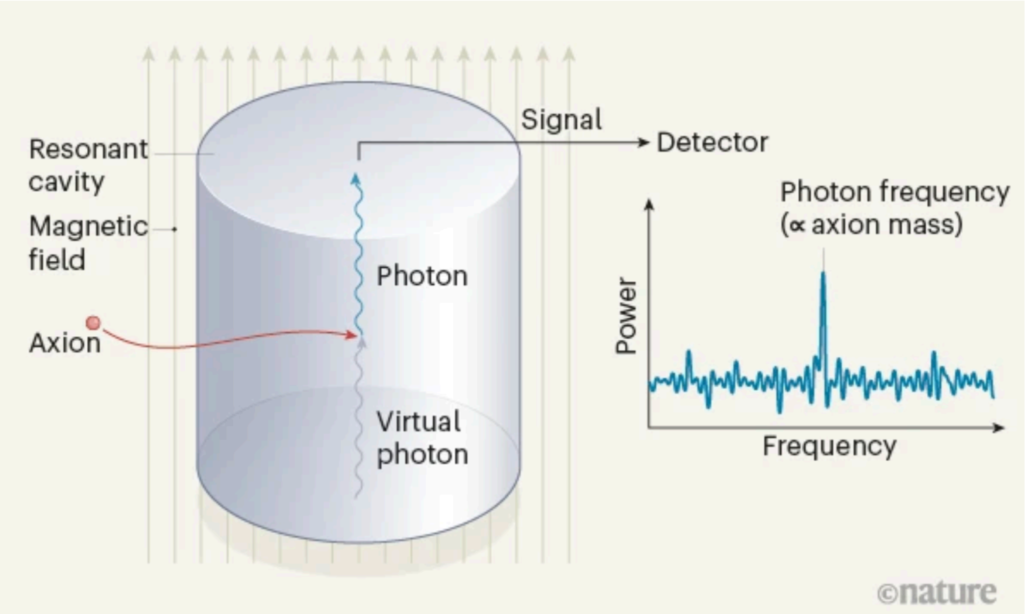
Amplitude is fixed by the dark matter energy density $\rho_a = \frac{1}{2} m_a^2 a_0^2 \overset{!}{=} \rho_{\mathrm{DM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$

The angular frequency is determined by the rest mass. $\omega \sim m_a$

Small corrections from the kinetic energy $\frac{\Delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$

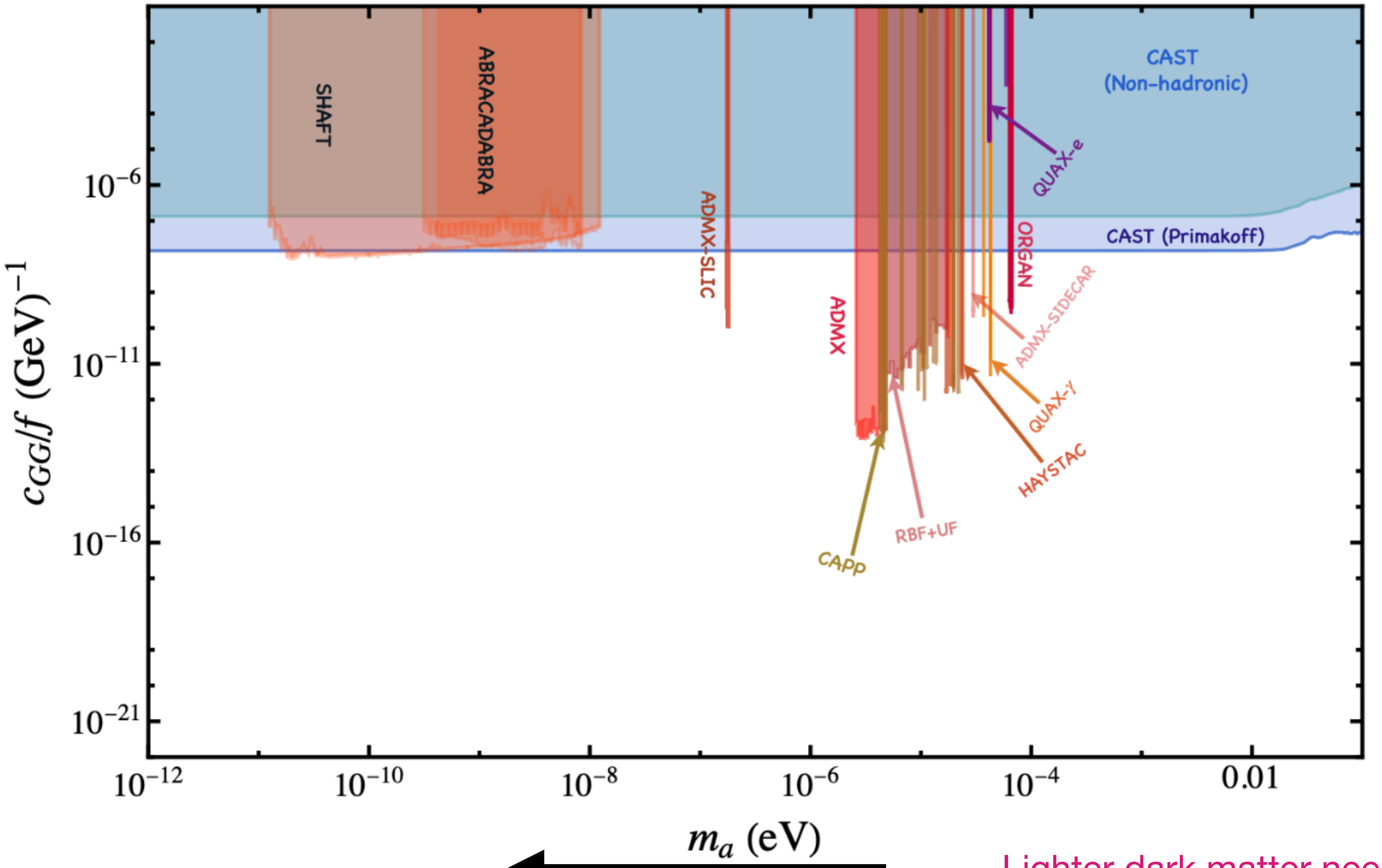
Coherence time is set by the frequency spread $\tau_c = \frac{2\pi}{\Delta\omega} = \frac{2\pi}{m_a v^2} \approx 1\mathrm{s} \left(\frac{\mathrm{MHz}}{m_a}\right)$

Ultra-light dark matter



Resonant cavities

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



Probes axion interactions with photons

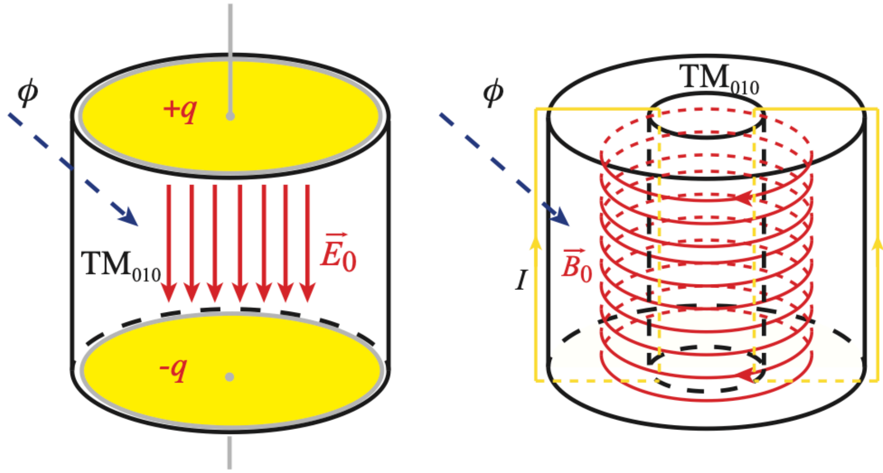
$$c^{\text{eff}}_{\gamma\gamma}\,\frac{\alpha}{4\pi}\,\frac{a}{f}\,F_{\mu\nu}\,\tilde{F}^{\mu\nu} = c^{\text{eff}}_{\gamma\gamma}\,\frac{\alpha}{\pi}\,\frac{a}{f}\,\vec{E}\cdot\vec{B}$$

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

Lighter dark matter needs larger cavities

Flambaum et al, 2207.14437

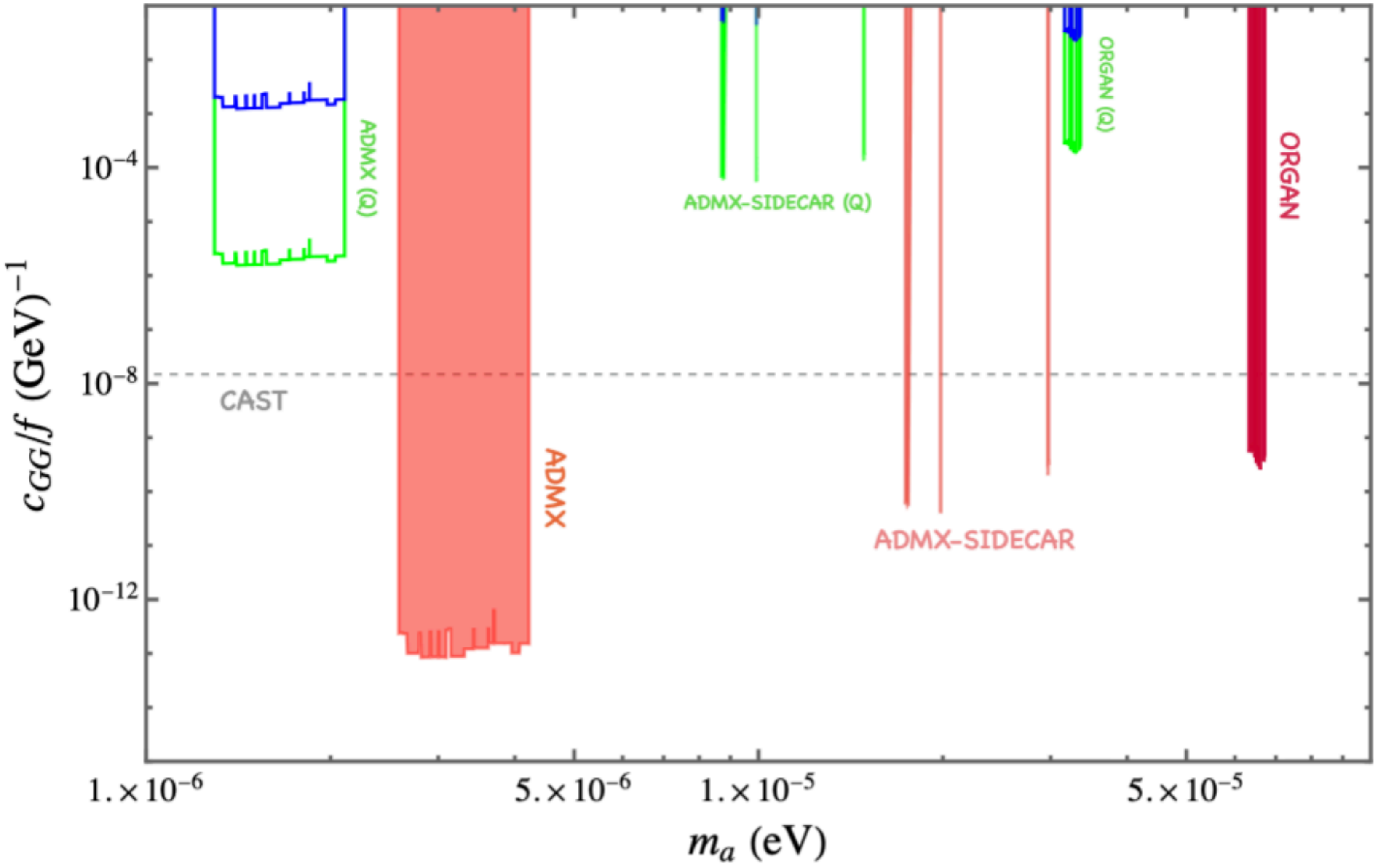
Ultra-light dark matter



Quadratic axion interactions allow to extend the parameter space

$$C_\gamma \frac{a^2}{4f^2}F_{\mu\nu}F^{\mu\nu} = C_\gamma \frac{a^2}{2f^2}(E^2 - B^2)$$

$$P_{aa\to\gamma} \propto \left(\frac{C_\gamma}{f^2}\frac{\rho_{\mathrm{DM}}}{m_a}\right)^2 (B_0^2+E_0^2)VC_\phi \min(Q_L, Q_a)$$



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

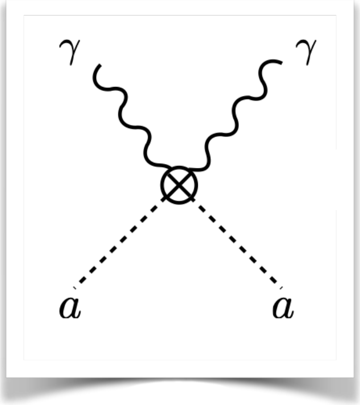
Ultra-light dark matter

Standard model fields in this background

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

Can be described with time-dependent masses and coupling constants

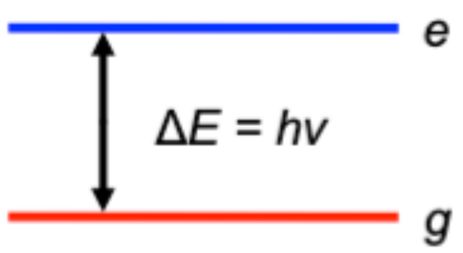
$$m_e^{\text{eff}}(a) = m_e \left(1 + \frac{a_0}{m_e} \cos(\omega t - \delta)\right)$$



For axions these are quadratic interactions

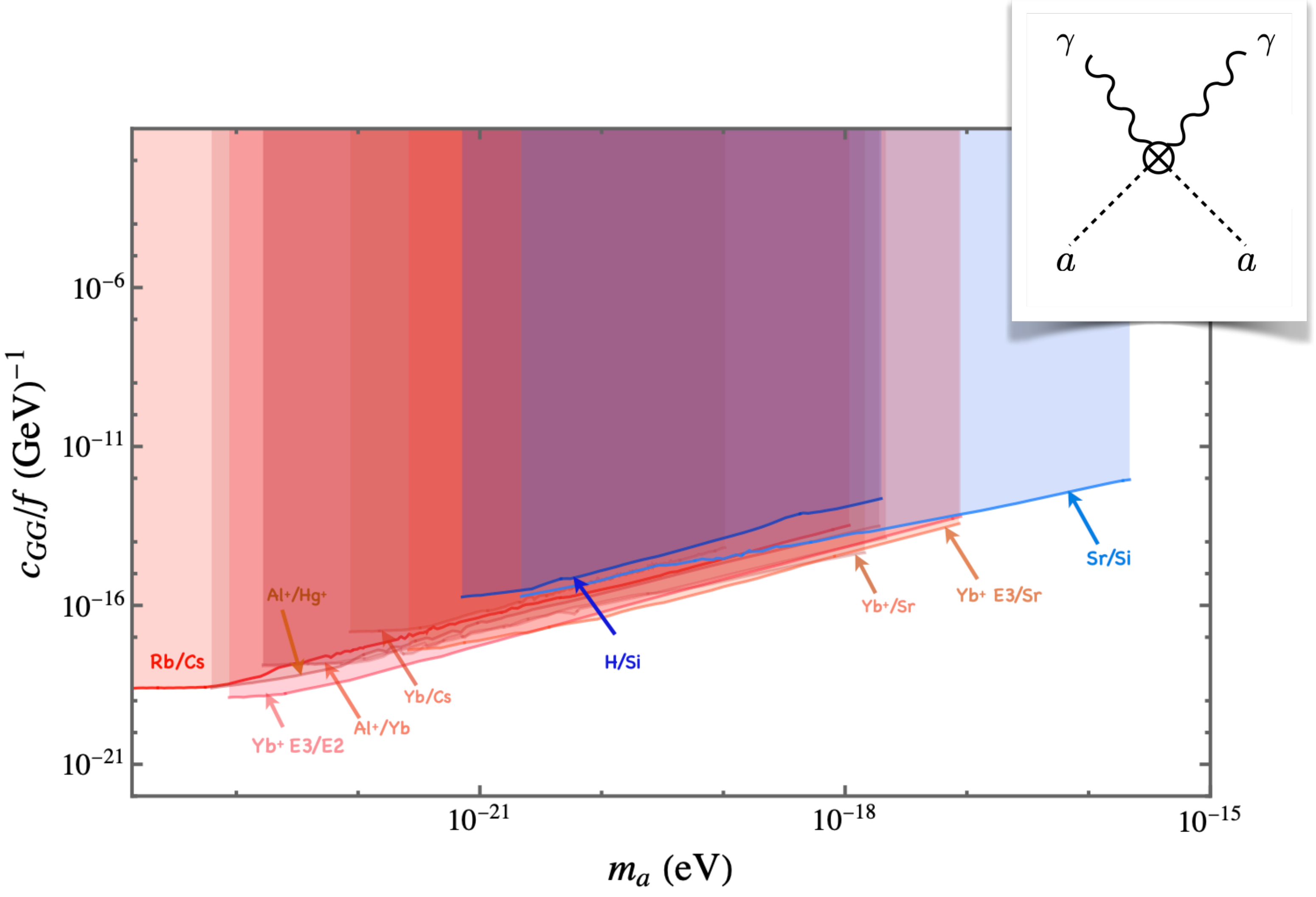
Ultra-light dark matter

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



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

Ultra-light dark matter

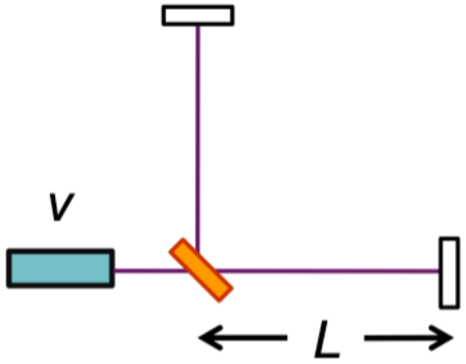
Ion clocks

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

Laser interferometers

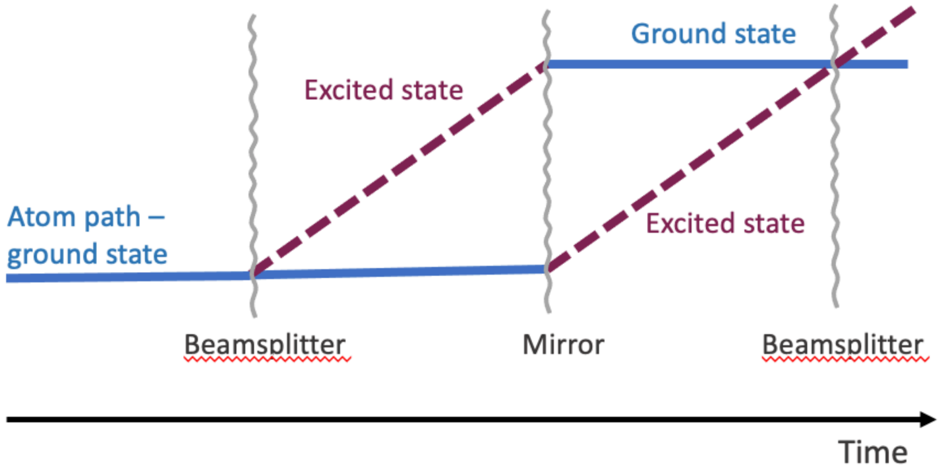
$$\frac{\delta l}{l} = -\left(\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right)$$

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

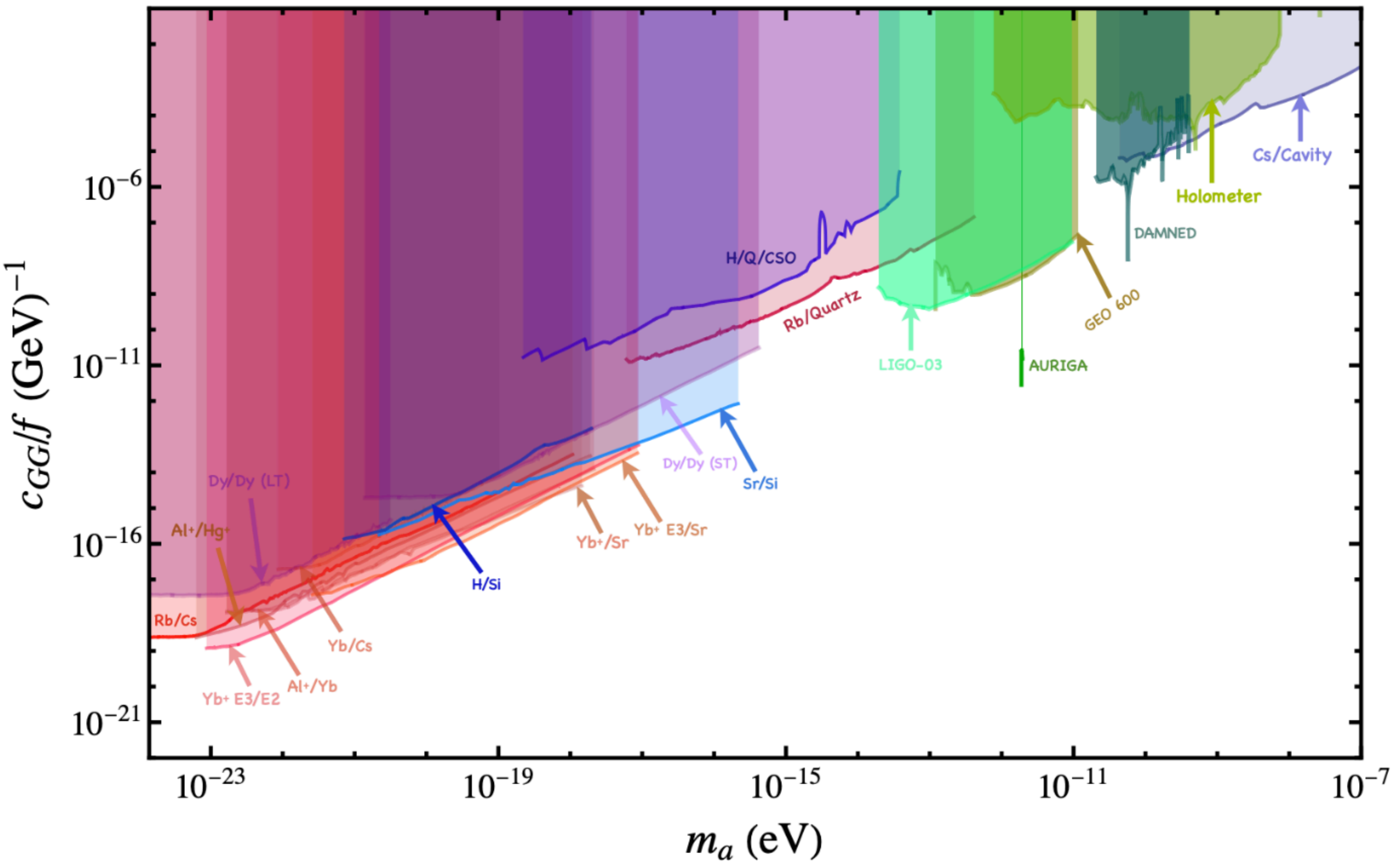


Atom interferometers

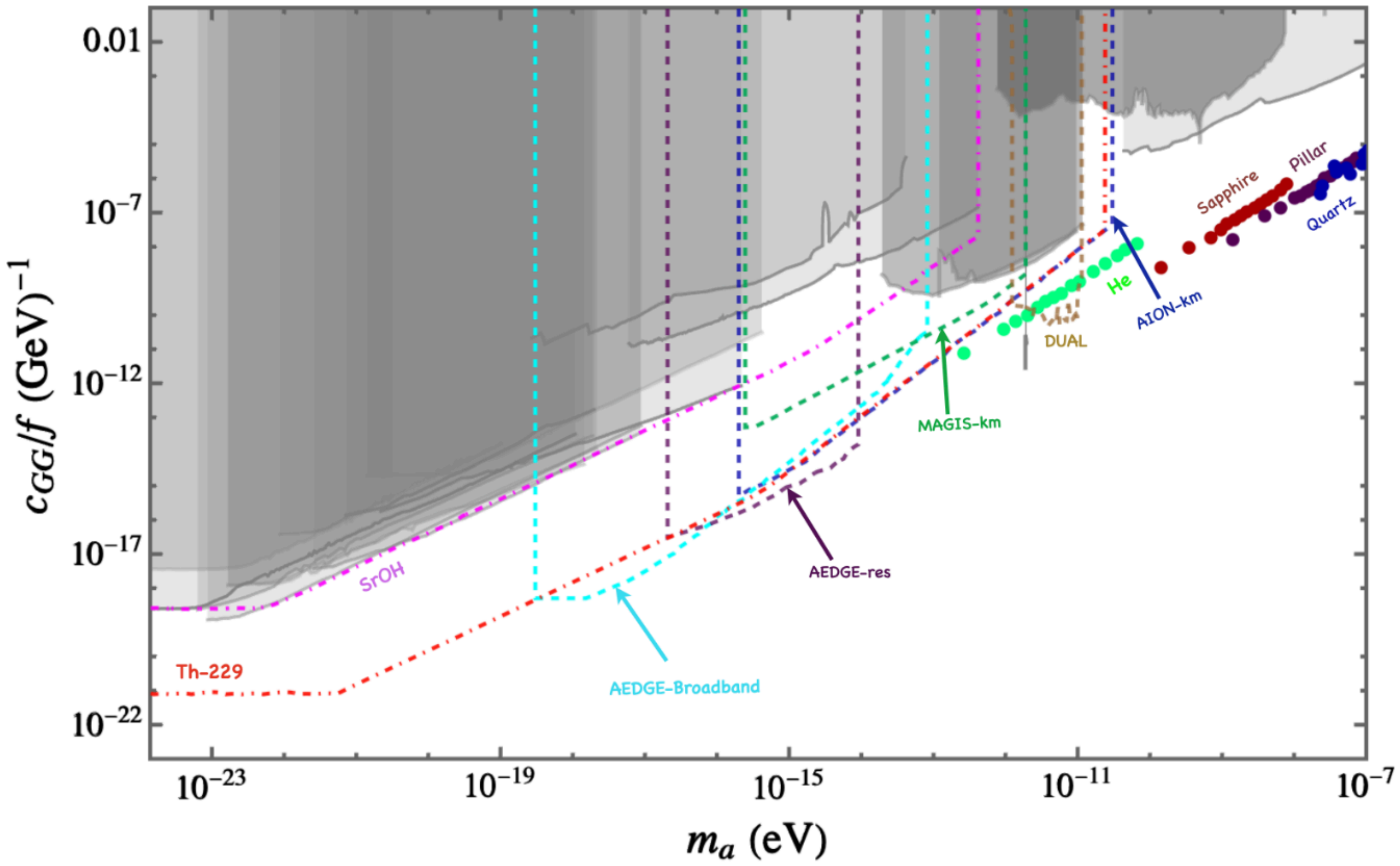
$$\Phi_s = 4\,\overline{\omega_a} n \Delta r \sin^2(m_a T)$$



Ultra-light dark matter

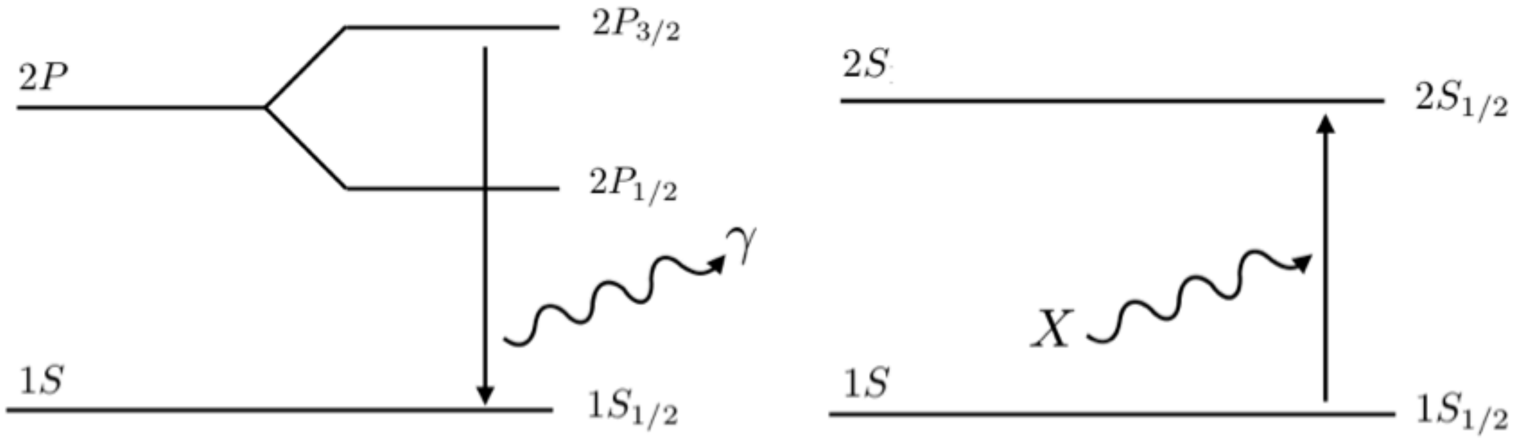


Ultra-light dark matter



Ultra-light 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]].

Summary

Searches for light dark matter and mediators require new strategies beyond established searches

Rare meson decays, polarised beams, future detectors and quantum sensors explore complementary scenarios that are hard or impossible to test otherwise