Quantum sensing
&
fundamental backgrounds

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MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

Fundamental cosmological backgrounds

Fundamental cosmological backgrounds

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Fundamental cosmological backgrounds

very weak backgrounds, of fundamental origin, permeate the Universe…

To-be-detected fundamental backgrounds

Neutrinos (Standard Model + Beyond SM portal)

Known but puzzling particles

Produced in nuclear reactions (astrophysical dense objects/ early Universe)

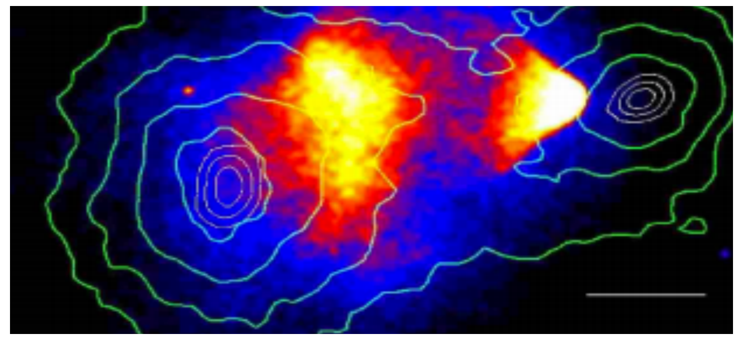
OPEN QUESTIONS: it's mass (why so light?)/ nature/ why their family structure/ new interactions/messengers of early cosmological times

Gravitational waves (SM + BSM)

Ripples of space time so far **detected** only in a narrow band (~100 Hz)

Universally produced in **all** energetic events (e.g. dark universe)

OPEN QUESTIONS: what happens at other frequencies?/ will we detect GWs from early Universe?/ new events beyond SM?



Dark matter (BSM)

Leading explanation of lots of astrophysical data.

Permeates the Universe, in particular your laboratory.

OPEN QUESTIONS: its direct detection
its mass/ its nature (wave, particle, compact object)/ interact.

Connection to your laboratory

How can I add these backgrounds to my analysis?

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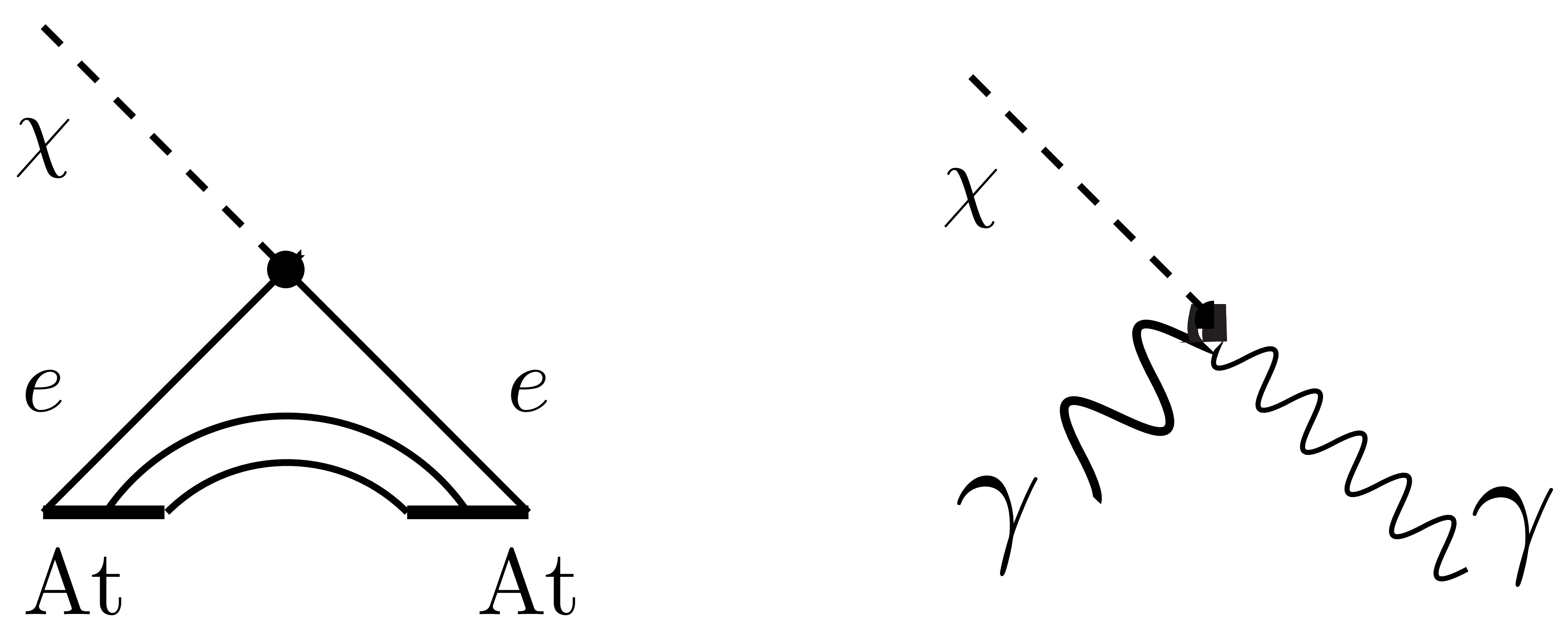
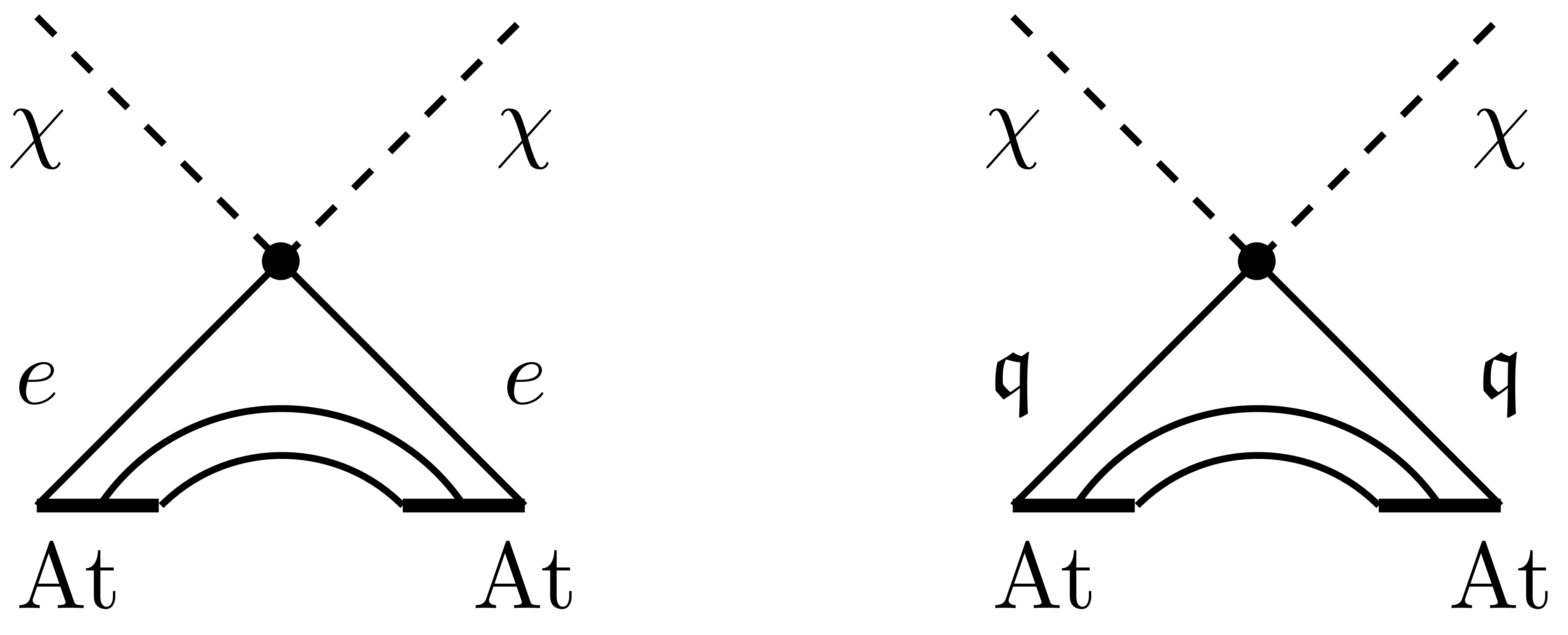
e.g. **absorption** process

gw, nu, dm



scattering process



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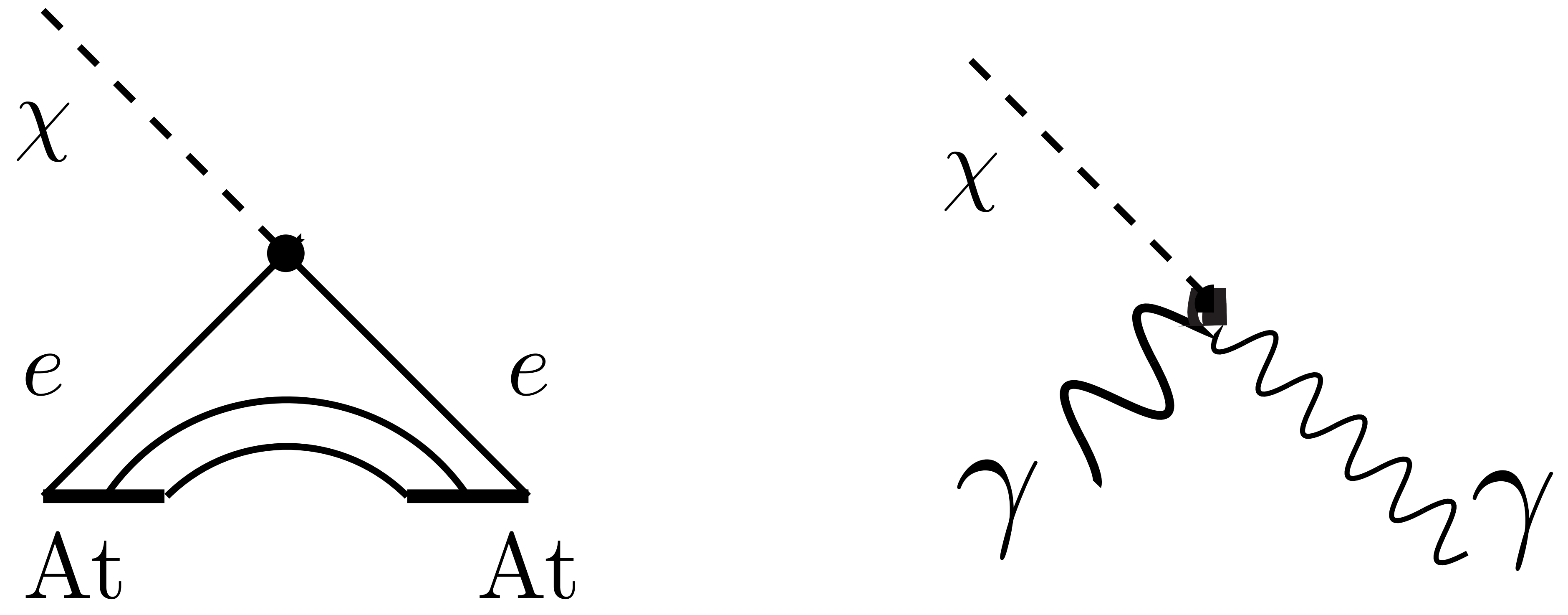

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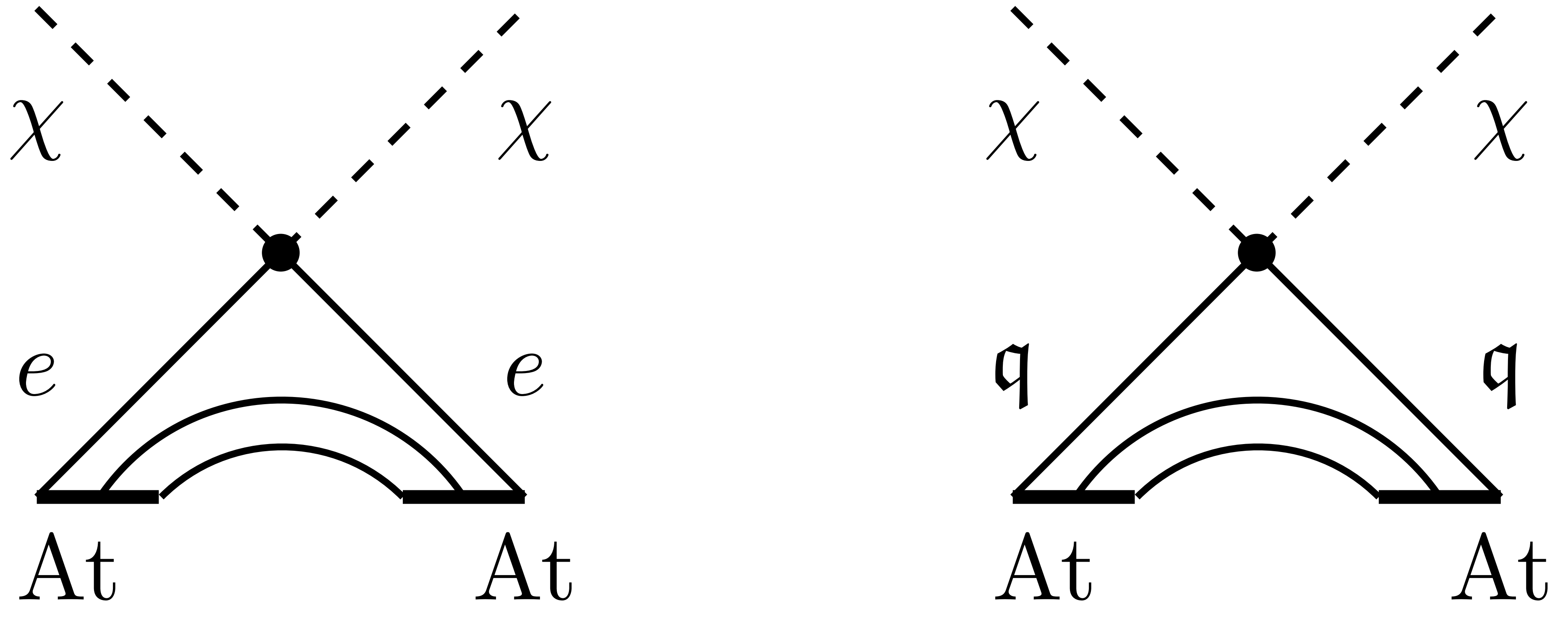


The ***first*** job of the theorist:

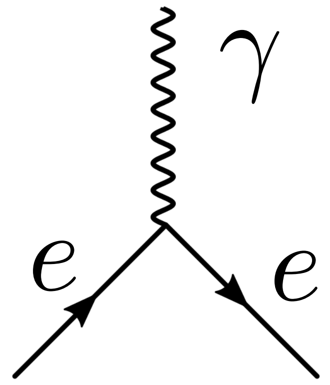
classify the possible relevant interactions (from different motivations)

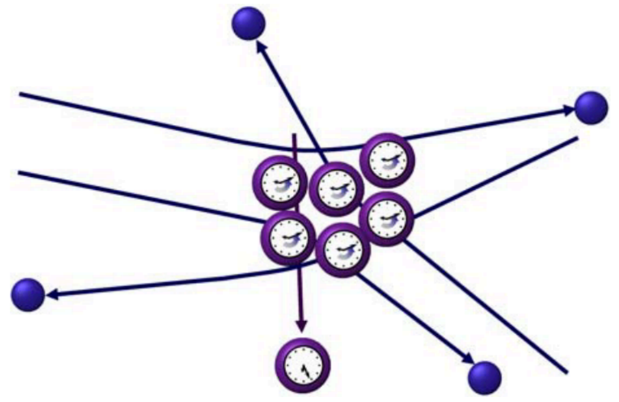
e.g. $\bar{\psi}_e \, O \, \psi_e \chi$ $\bar{\psi}_e \bar{\chi} \, O \, \psi_e \chi$

compare with standard model interactions

$\bar{\psi}_e \gamma^\mu \psi_e A^\mu$

electron-photon





atoms with surrounding gas

Kibble 1304.3486

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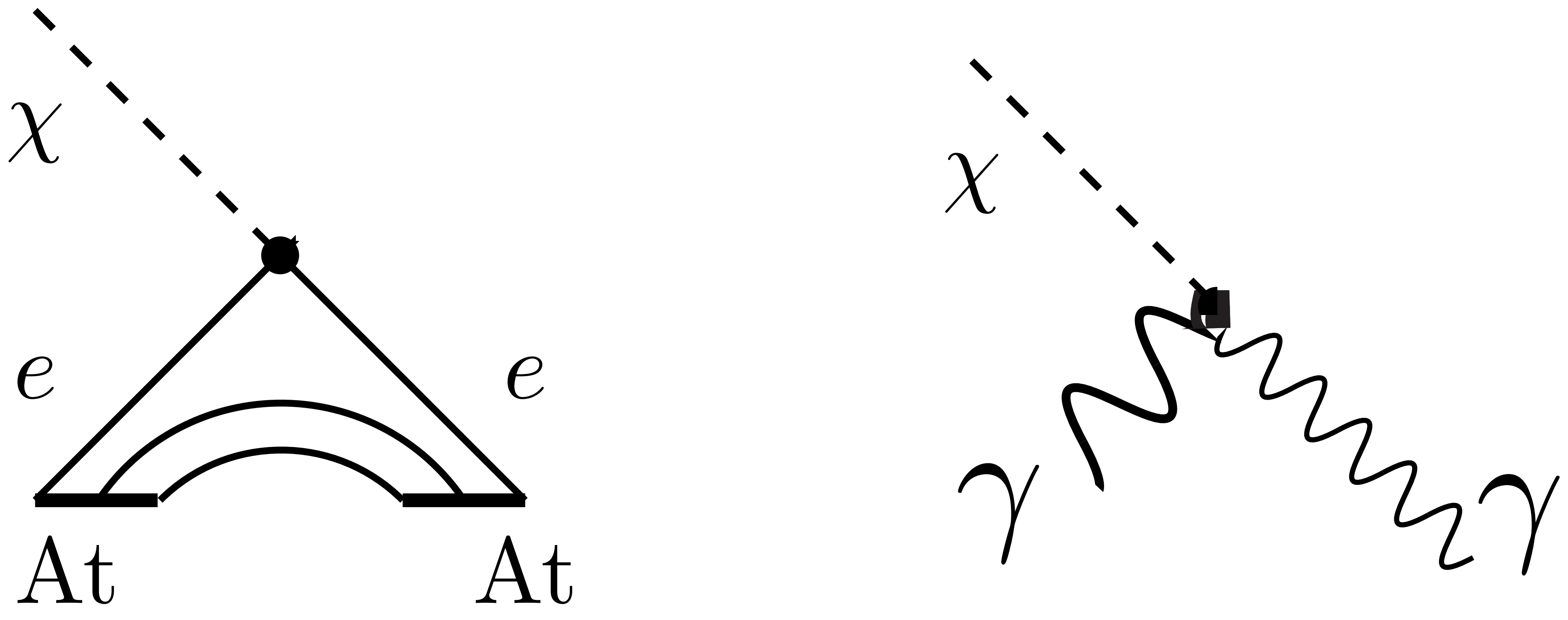

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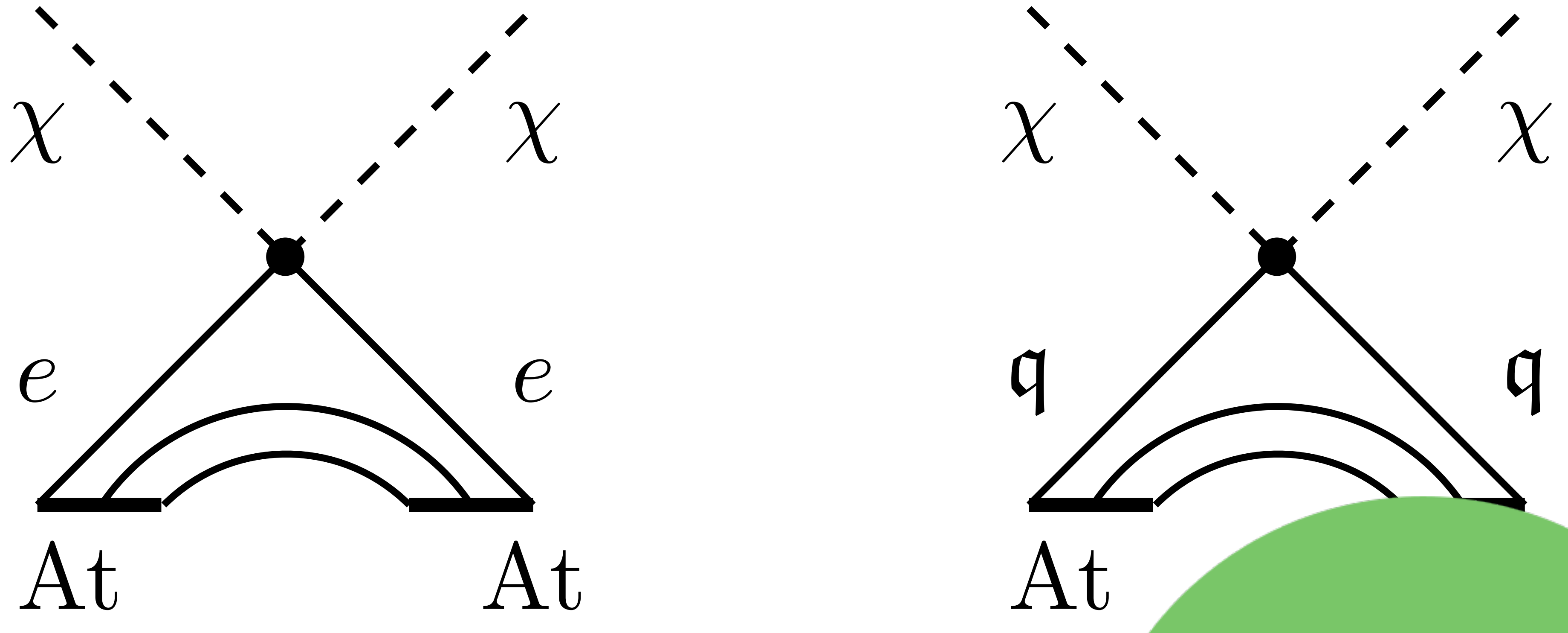

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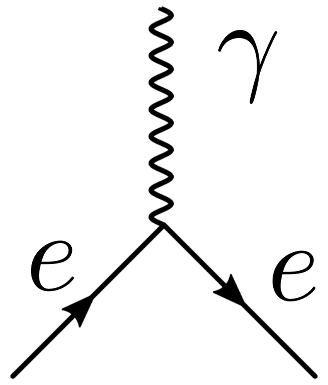

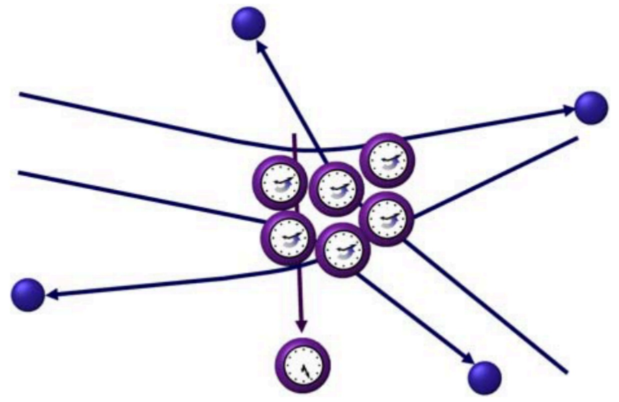

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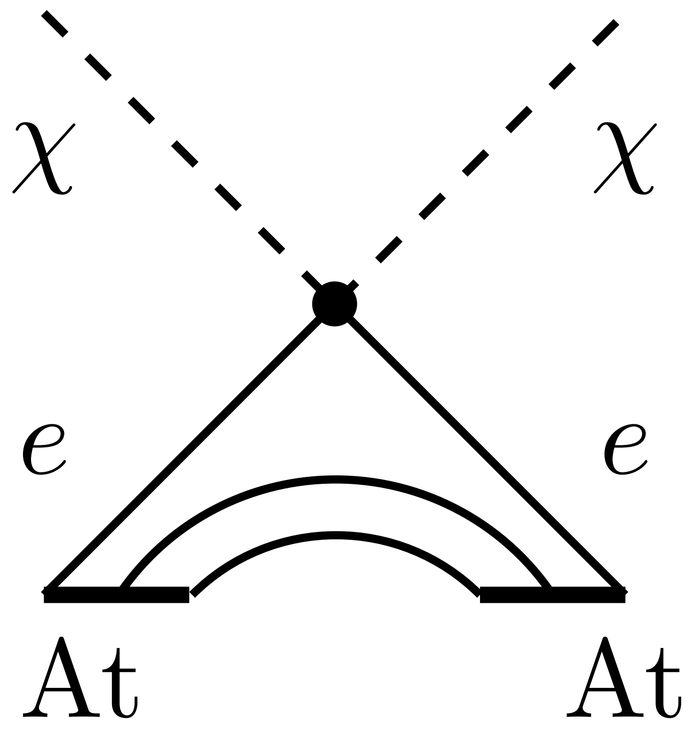
Connection to your laboratory

How can I add these backgrounds to my analysis?

The ***second*** job of the theorist:

connect fundamental terms to the **effective theory** relevant for the experiment



e.g. $\bar{\psi}_e \gamma^\mu \gamma_5 \psi_e \bar{\chi} \gamma_\mu \chi \quad \rightarrow \quad \vec{S}_e \cdot \vec{p}_\chi$

compare with standard EM interactions

$\bar{\psi}_e \gamma^\mu \psi_e A_\mu \quad \rightarrow \quad \vec{p}_e \cdot \vec{A} \; , \quad g_e \vec{S}_e \cdot \vec{B}$

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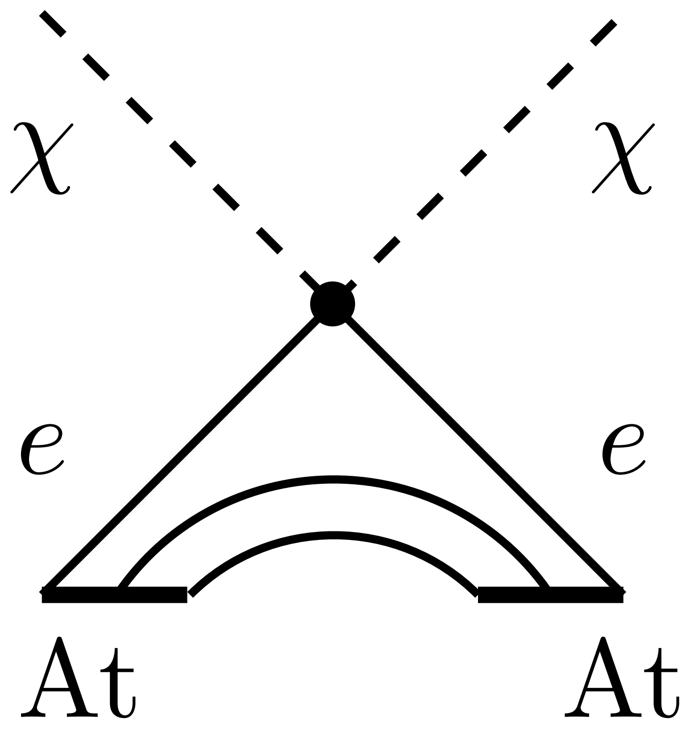

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doing this **comprehensively** is a pending task!

Connection to your laboratory

How can I add these backgrounds to my analysis?

The ***third*** job of the theorist:

evaluate the operators of the **effective theory** for the **fundamental background**

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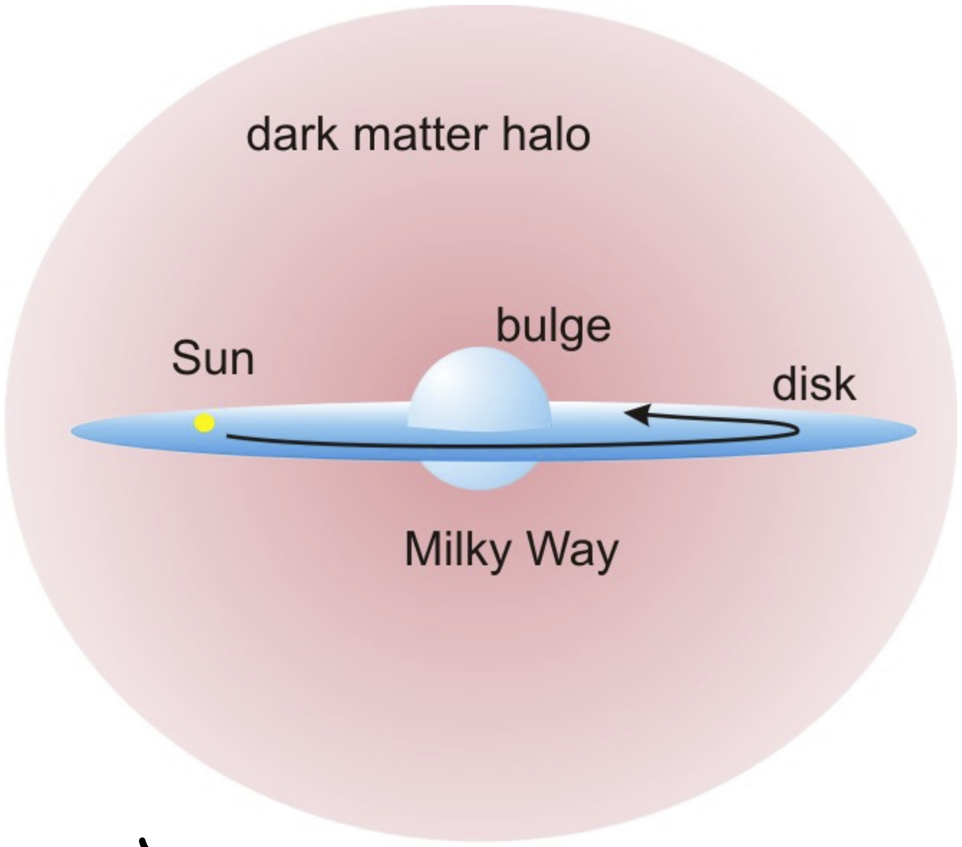
e.g. if χ is the dark matter



i) flux on Earth

$$10^{10}\left(\frac{\mathrm{MeV}}{m_\chi}\right)\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$g\,\bar{\psi}_e\gamma^\mu\gamma_5\psi_e\bar{\chi}\gamma_\mu\chi \;\longrightarrow\; \tilde{g}\,\vec{S}_e\cdot\vec{p}_\chi \;\longrightarrow$$

$$\langle\vec{p}_\chi\rangle$$

ii) each with momentum

$$p_\chi \approx m_\chi\langle v_\odot\rangle \sim 10^{-3}m_\chi c$$

(annually modulated)

compare with standard EM interactions

$$\bar{\psi}_e\gamma^\mu\psi_e A_\mu \;\longrightarrow\; \vec{p}_e\cdot\vec{A} \;\longrightarrow$$

e.g. if $\vec{A}$ is a GHz photon from a certain source

Connection to your laboratory

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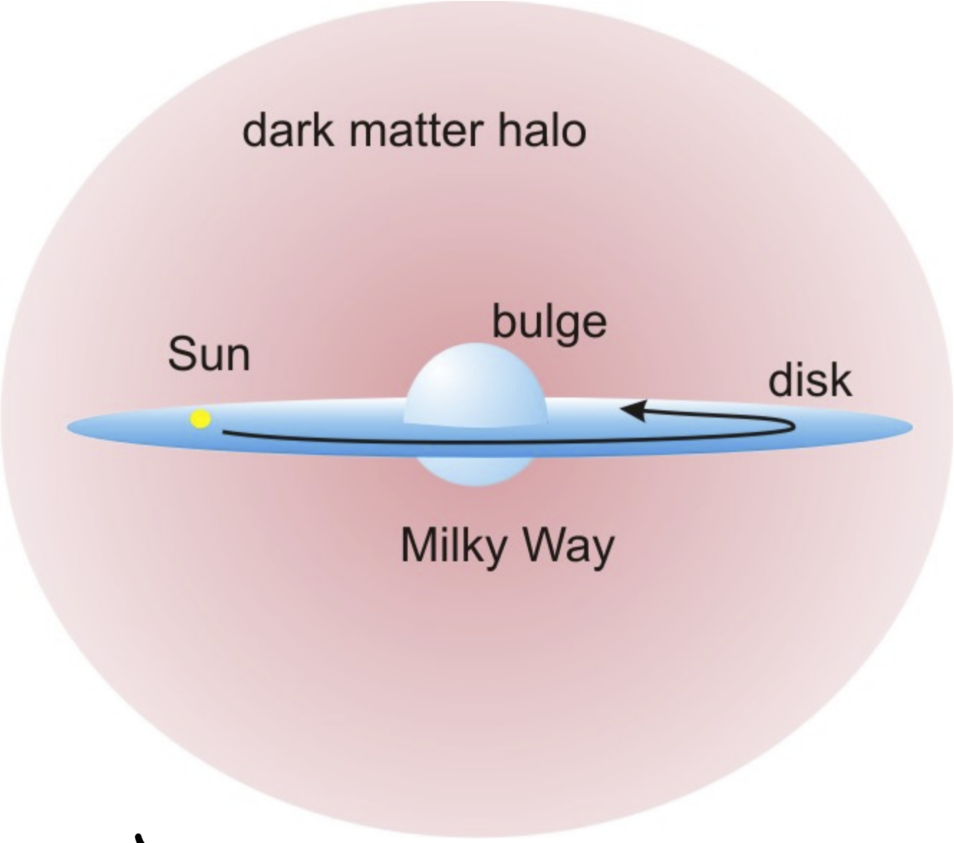

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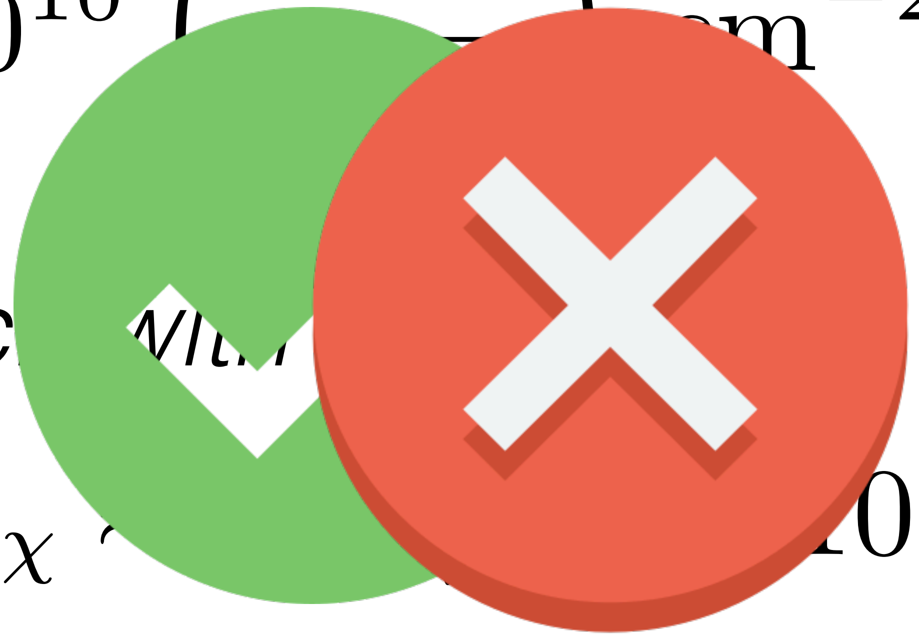
$10^{10}\left(\text{MeV}\right.$ … $\text{cm}^{-2}\text{s}^{-1}$

$$g\,\bar{\psi}_e\gamma^\mu\gamma_5\psi_e\bar{\chi}\gamma_\mu\chi \;\rightarrow\; \tilde{g}\,\vec{S}_e\cdot\vec{p}_\chi \;\rightarrow\; \langle\vec{p}_\chi\rangle$$

ii) eac… wit…

p_χ … $0^{-3}m_\chi c$



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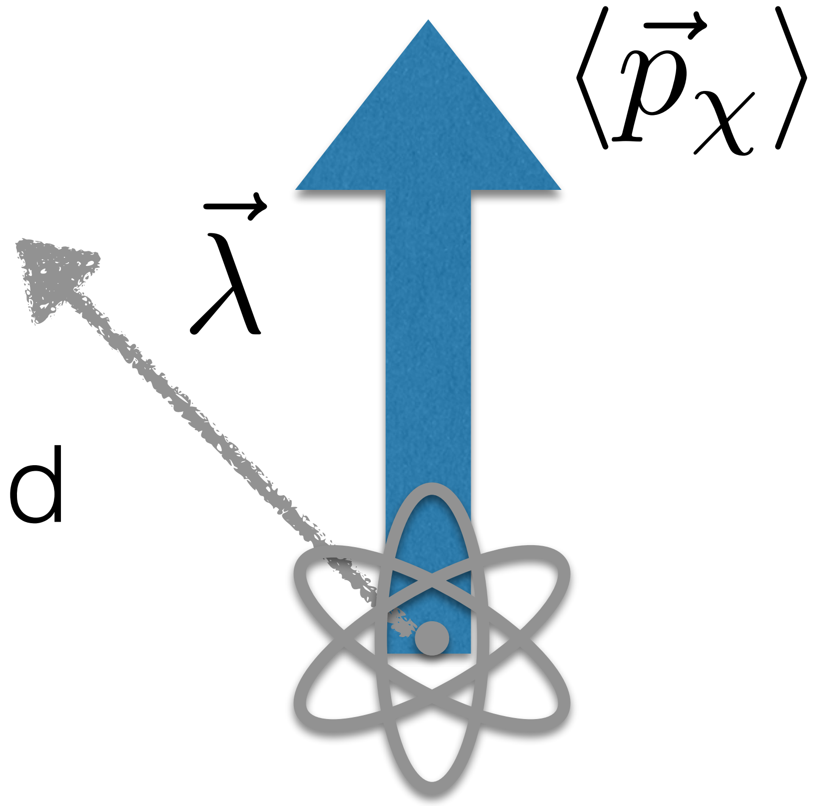
1st Conclusion

We need the comprehensive map between
fundamental backgrounds and **new interaction terms of Hamiltonians**
relevant for the laboratory

fundamental backgrounds → $H = H_0 + H_{\rm int}$

e.g. $\tilde{g}\ \vec{S}_e \cdot \langle \vec{p}_\chi \rangle$

'anomalous' magnetic field



This is something **feasible** and will be extremely **useful**
for the next steps in the field!

e.g. with bounds on $\tilde{g}$ we can already explore several models.

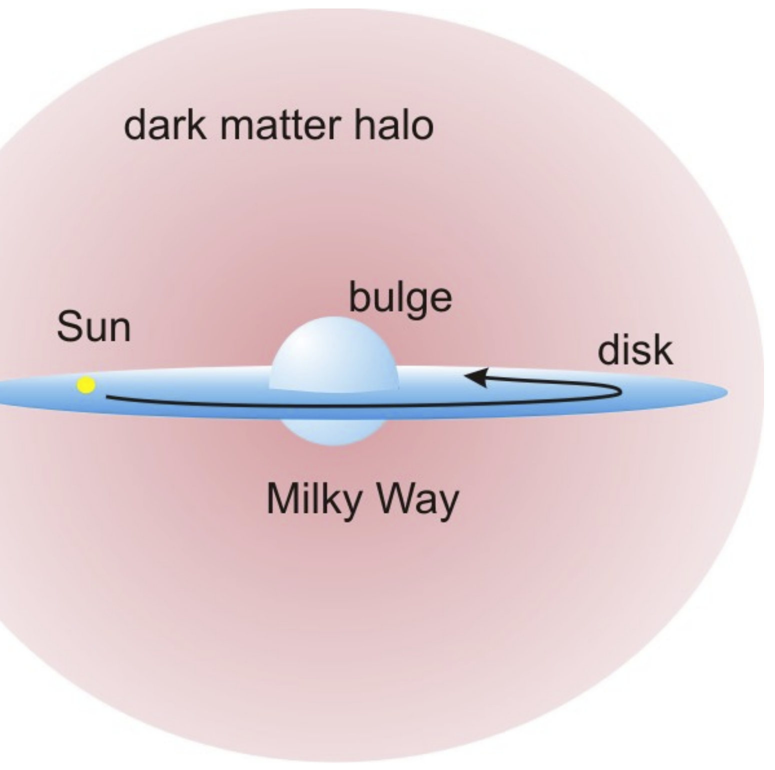
important: the fundamental background may
offer **new handles** (e.g. anual modulation, oscillations…)

Part II: two examples

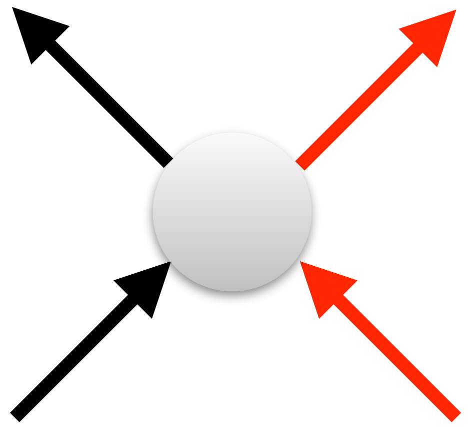
i) DM and cosmic neutrinos w/ atomic clocks and co-magnetometers

ii) GWs in (superconducting radio-frequency) cavities

Problems to detect DM



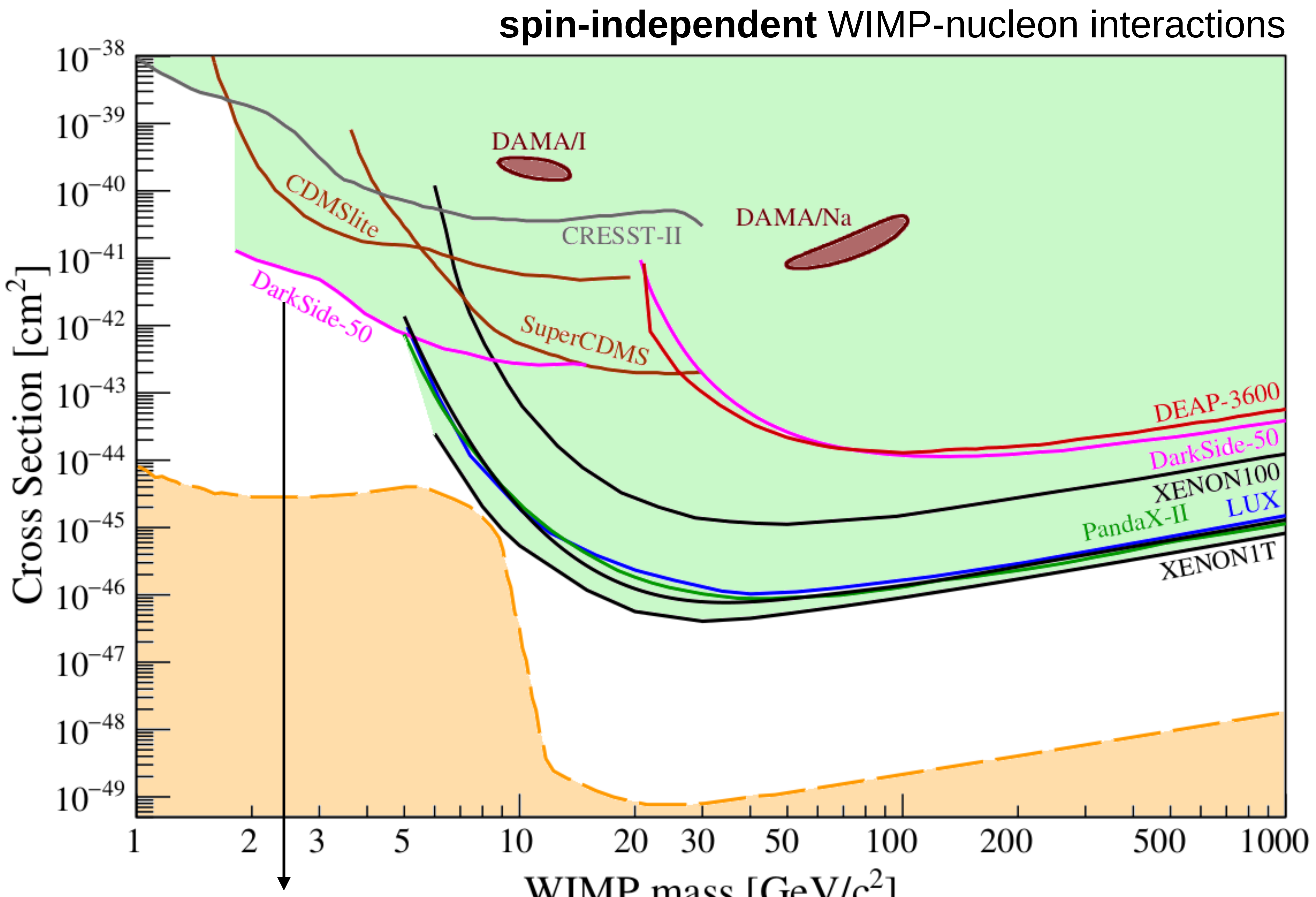
scattering



DM nucleus

$$E_R^{\max} \sim \left(\frac{m_\chi}{\mathrm{GeV}}\right) \mathrm{keV}$$

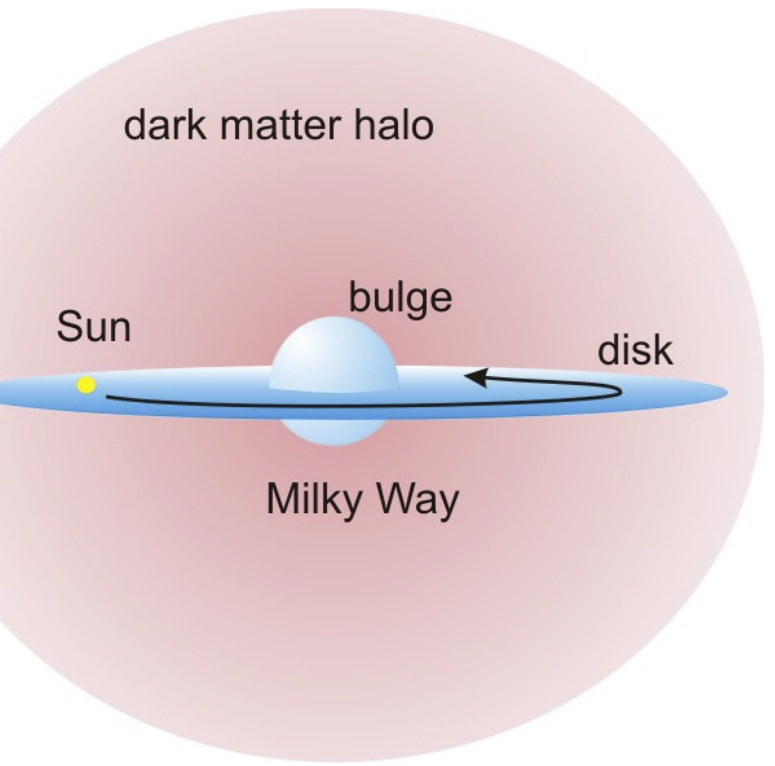
energy of the recoiled (observed) nucleus



low-energy threshold

dramatic loss of sensitivity at low mass
when the momentum transfer is too small to generate a ‘recoil’

Problems to detect DM



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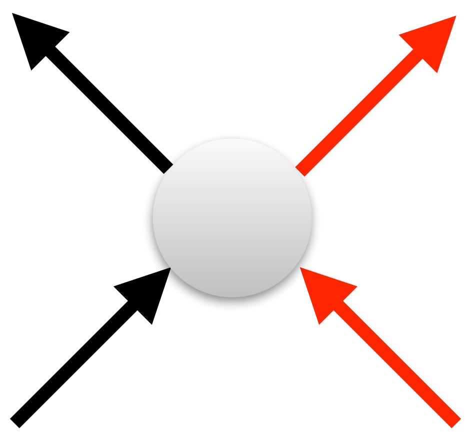

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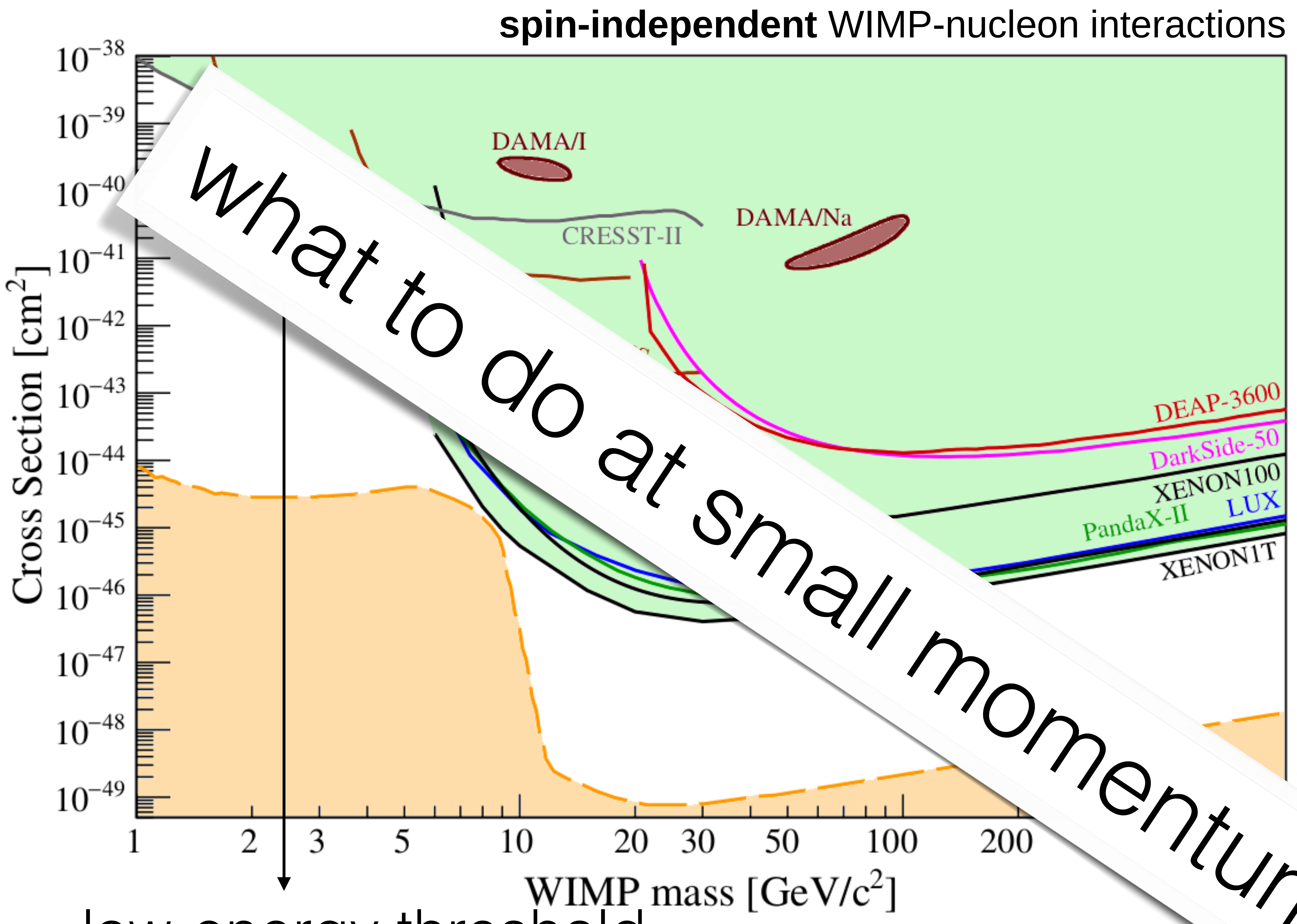


low-energy threshold

what to do at small momentum transfer?

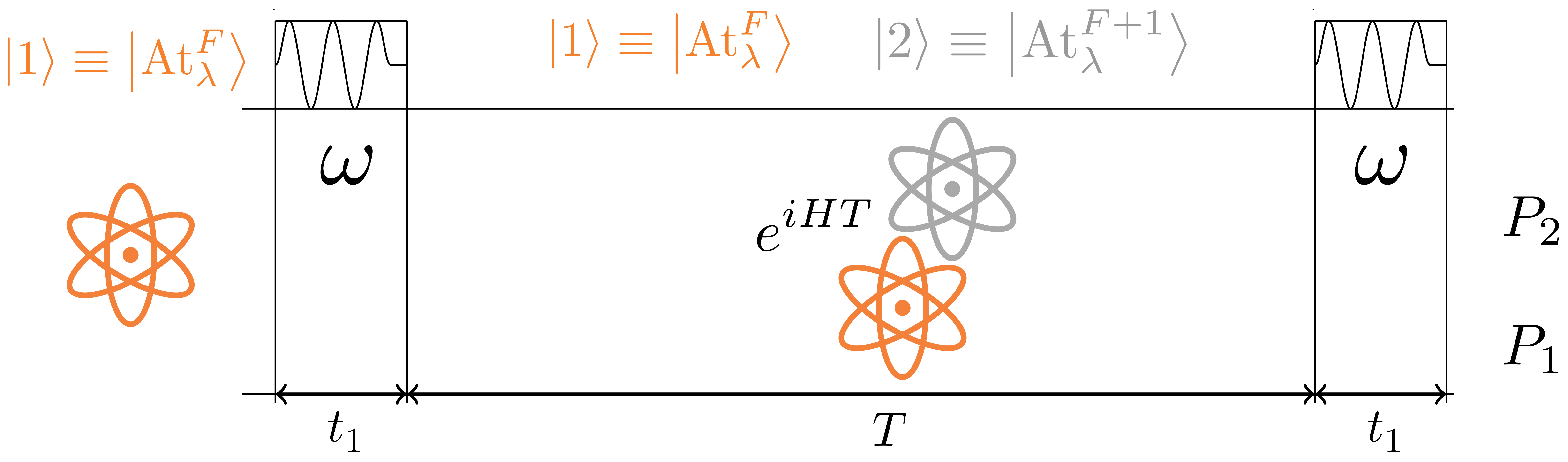
dramatic loss of sensitivity at low mass
when the momentum transfer is too small to generate a 'recoil'

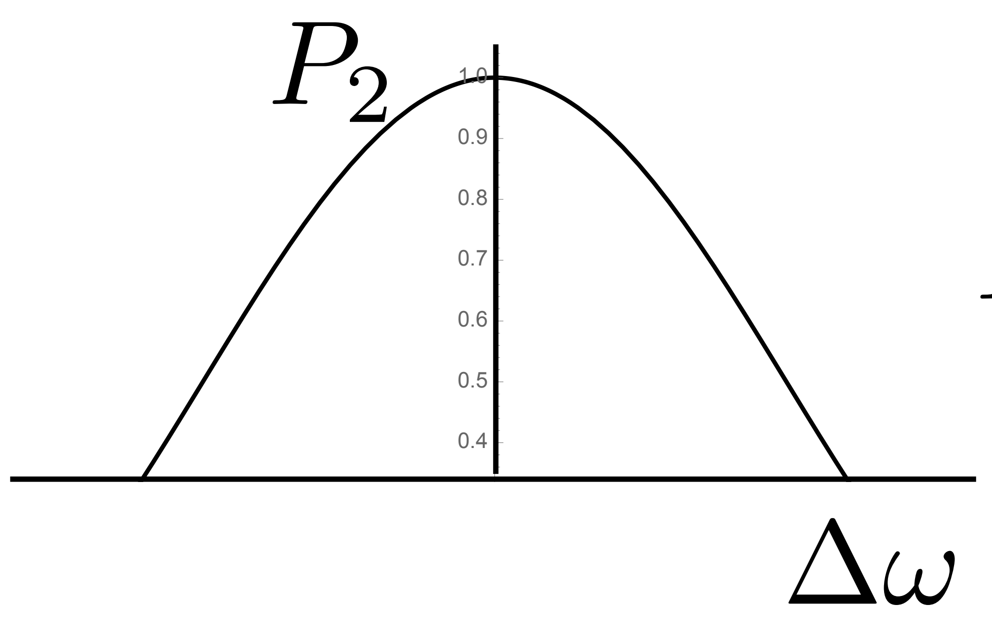
Measuring at $q = 0$: phase shifts in atomic clocks

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

Du et al. 2205.13546

Ramsey sequence





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

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

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

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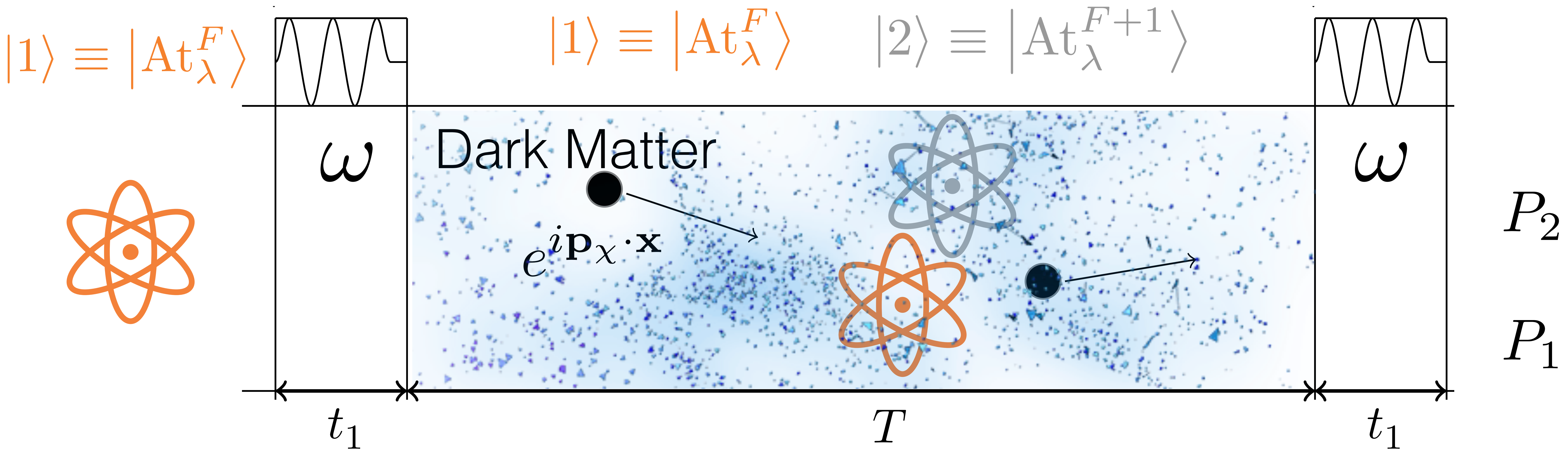
Ramsey sequence in the presence of DM



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

scattering amplitude at $q = 0$

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

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

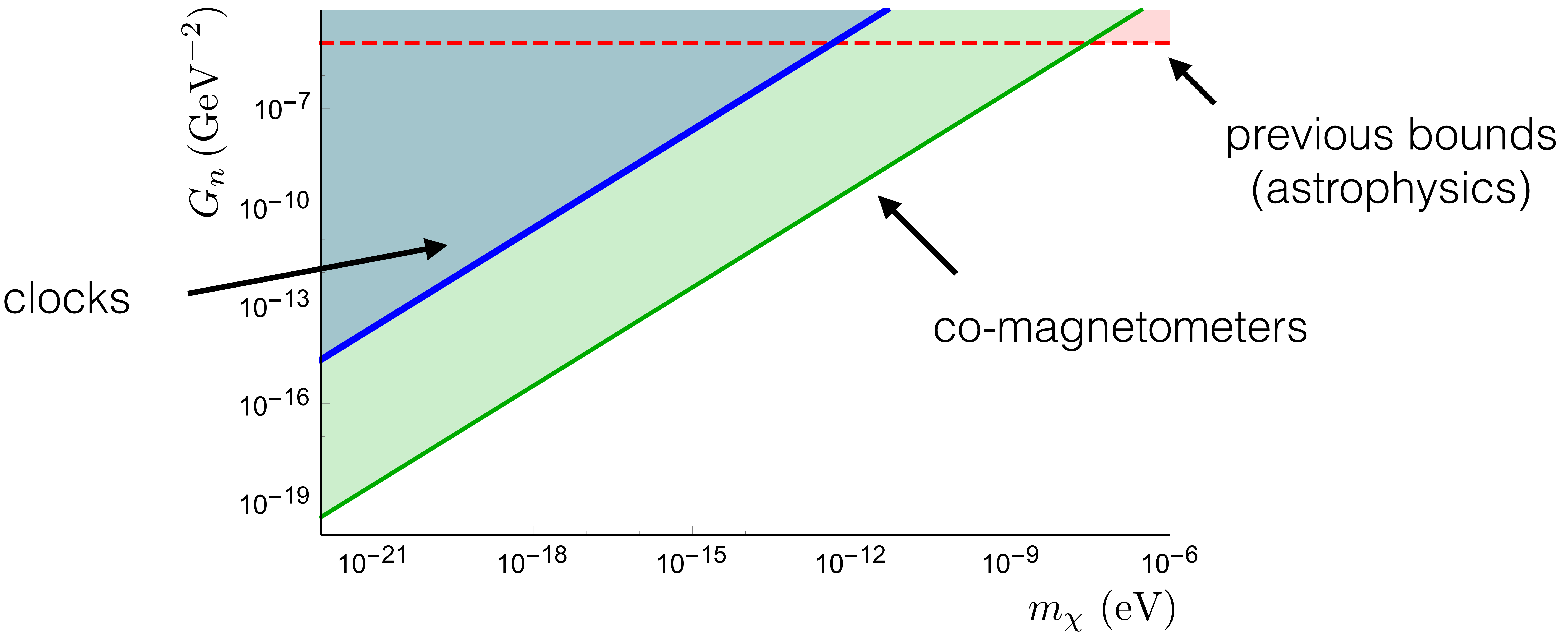
QM allows us to measure at $q = 0$ and hence move to **low DM masses**!

One example: complex scalar DM

Alonso, DB, Wolf 1810.00889

nucleons DM

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

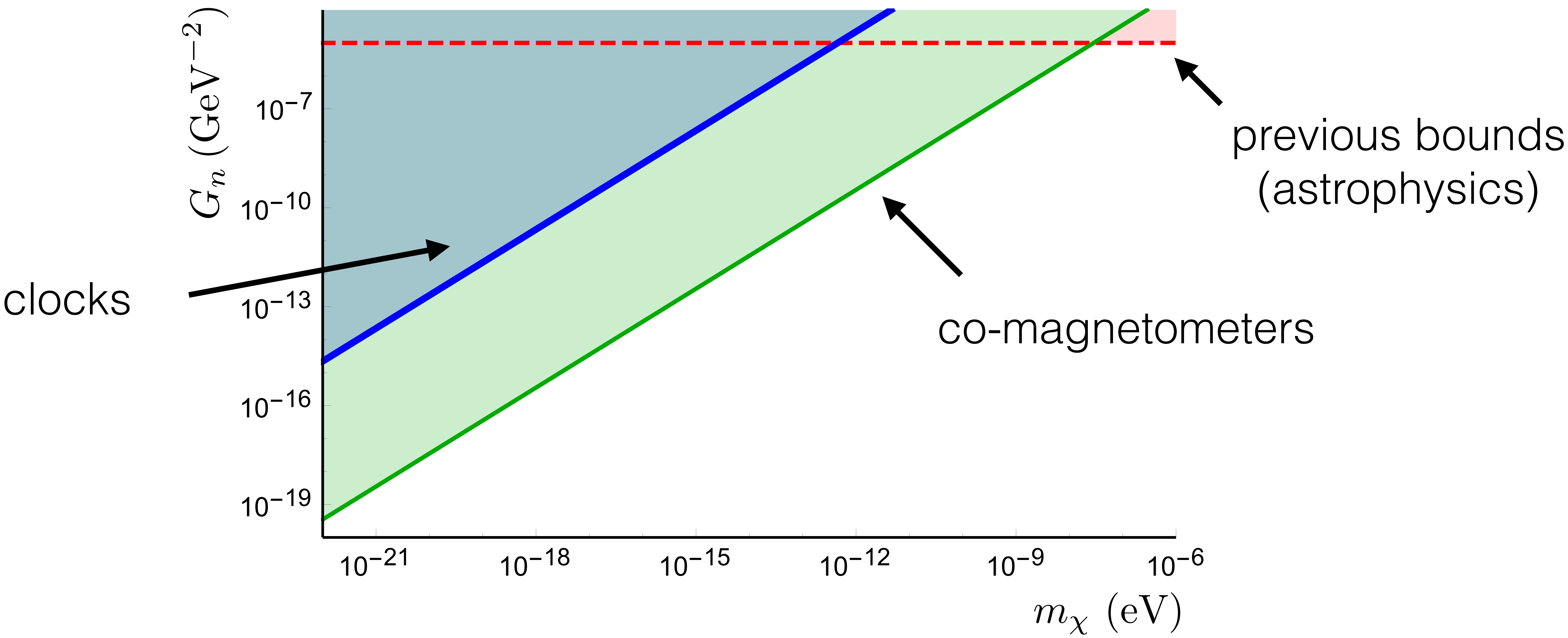


One example: complex scalar DM

Alonso, DB, Wolf 1810.00889

nucleons → $\bar{n}\gamma^\mu\gamma_5 n$, DM → $i\chi^\dagger\partial_\mu\chi$

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



for cosmic neutrinos see Alonso, DB, Wolf 1810.00889

Bauer & Shergold 2207.12413

Part II: two examples

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

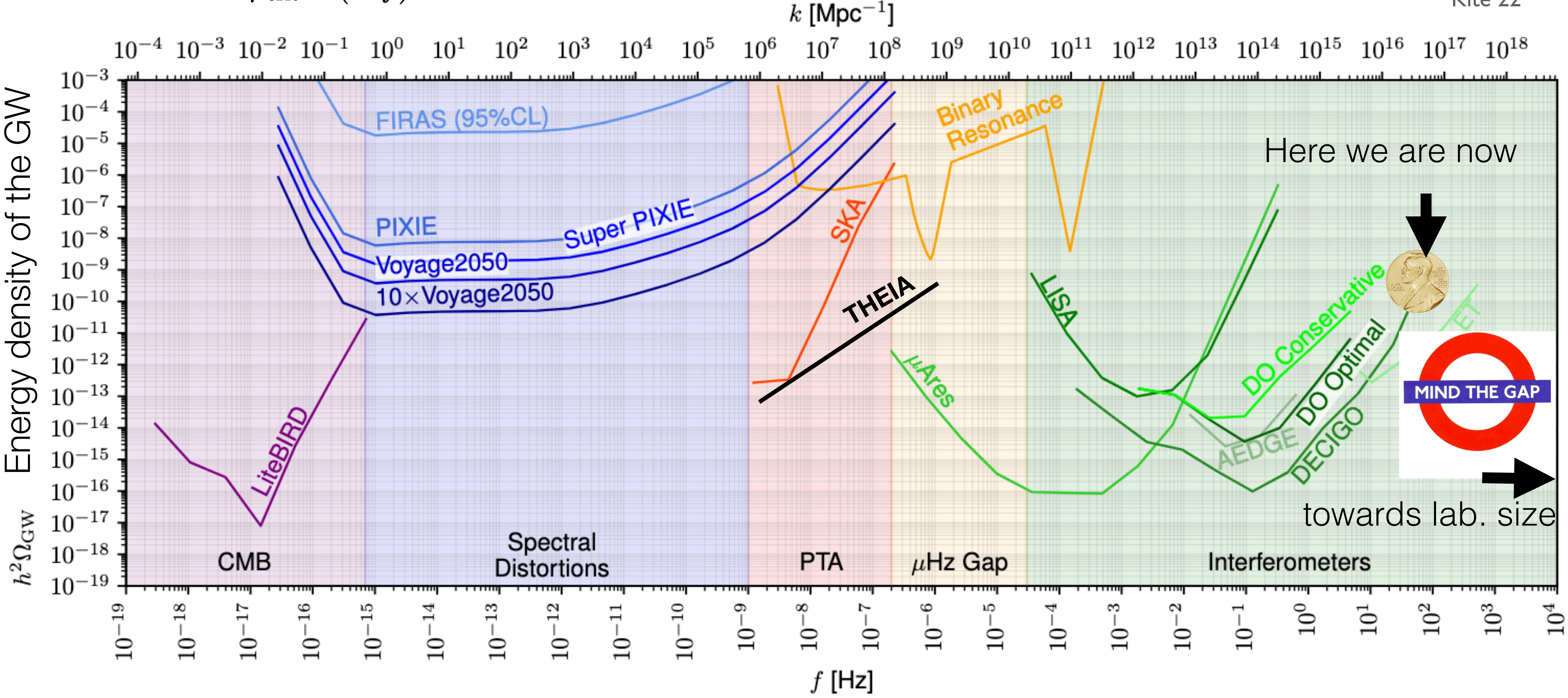
ii) GWs in (superconducting radio-frequency) cavities

The first direct detection of GWs is a great achievement, but…

Expected gravitational soundscape ca. 2040

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

Kite 22



Milky Way in visible band


Milky Way in X rays

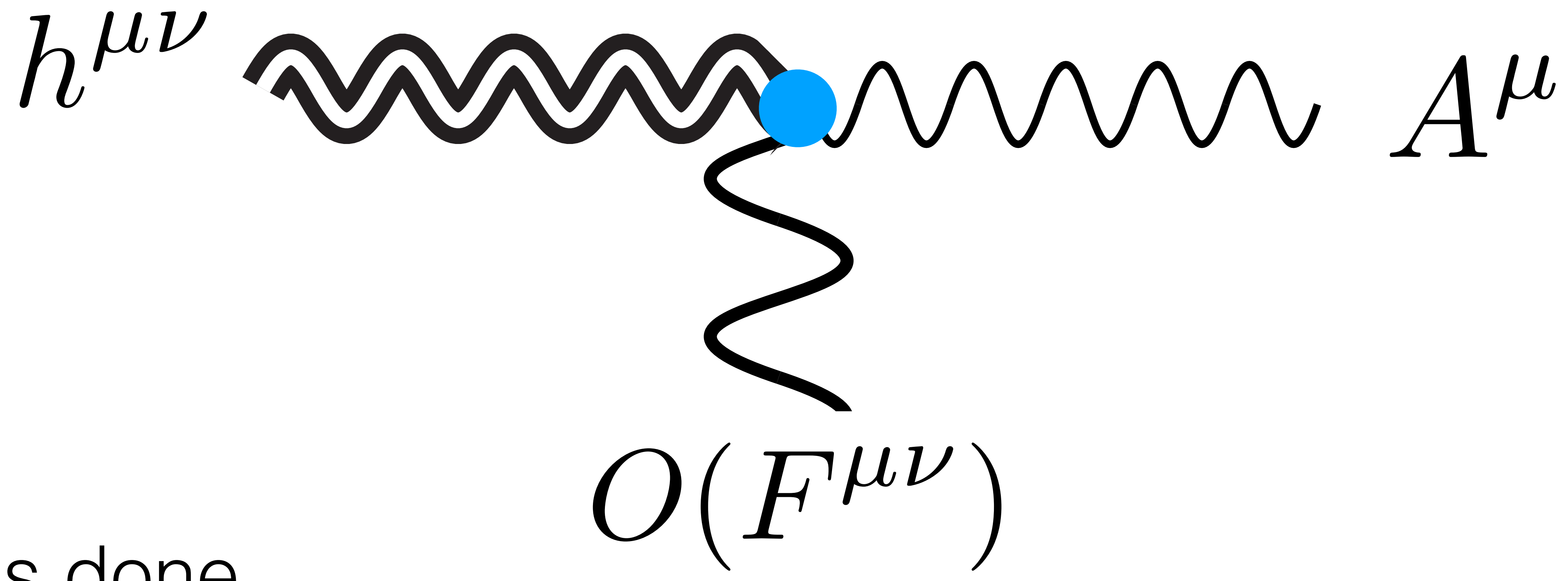
Our control of light in the lab is excellent!

Interaction of GWs with light?

Interaction GWs with light!

fundamental backgrounds/interactions

gravitational wave + EM field = current!



The ***first*** and ***second*** jobs done

$$\mathcal{L} \approx \frac{1}{2} A_\mu j^\mu_{\rm eff}(h) + \eta^{\mu\alpha}\eta^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}\,.$$

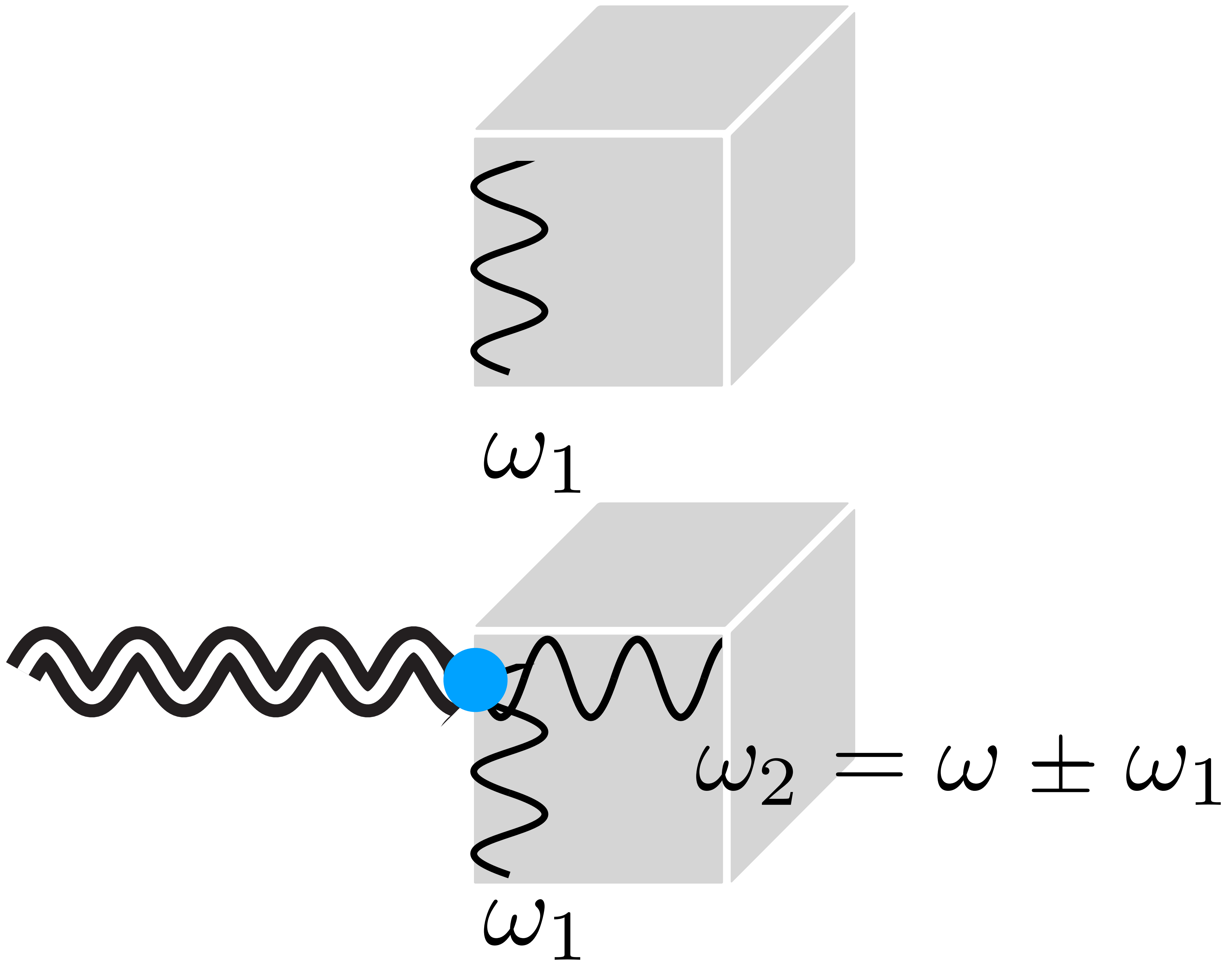
$$j^\mu_{\rm eff} = -\partial_\beta\left(\frac{1}{2}hF^{\mu\beta} + h^\beta_\alpha F^{\alpha\mu} - h^\mu_\alpha F^{\alpha\beta}\right)$$

Interaction GWs with light: loaded cavities

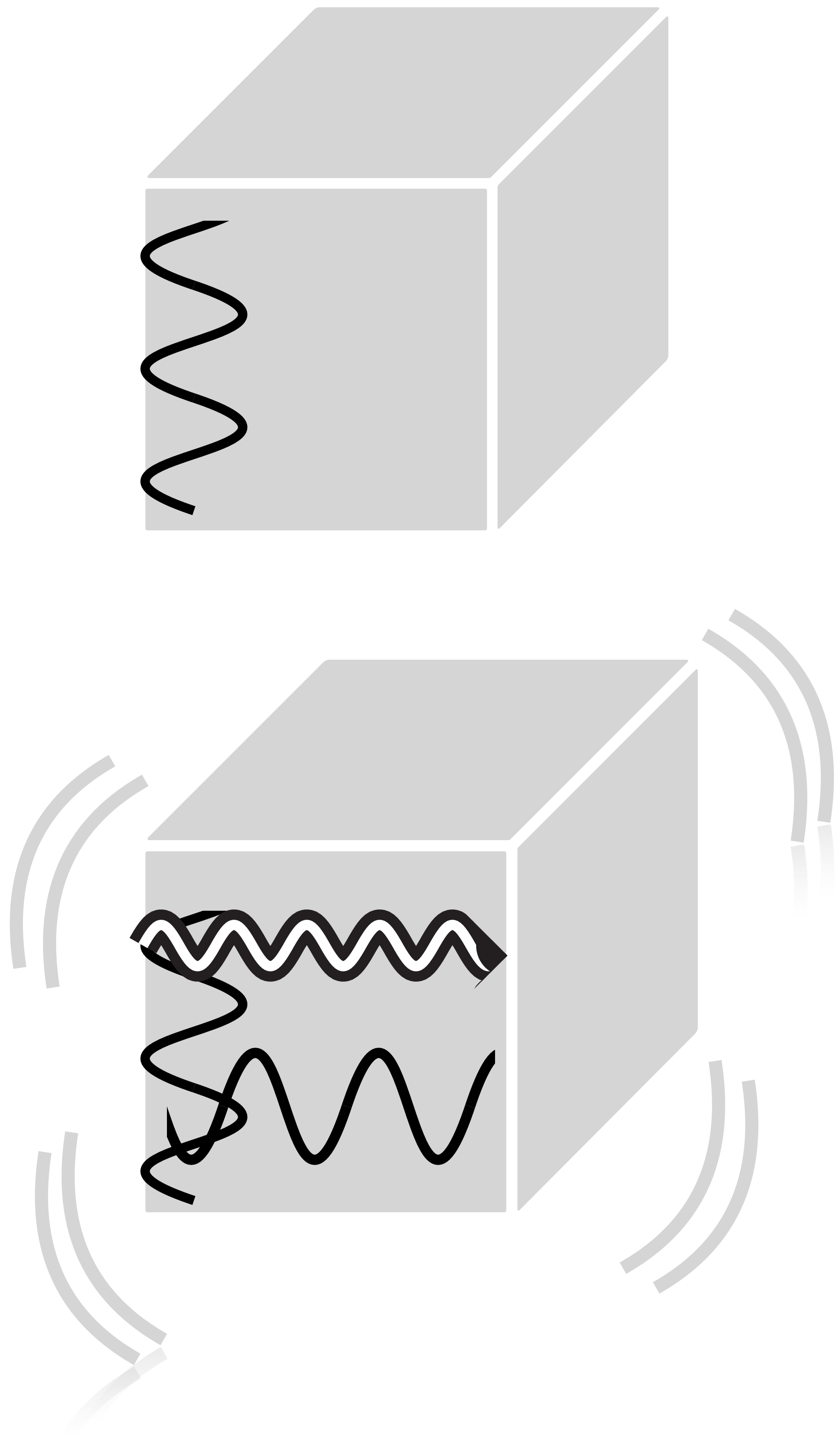
h+EM field = current!

MAGO design from CERN (gr-qc/0502054)

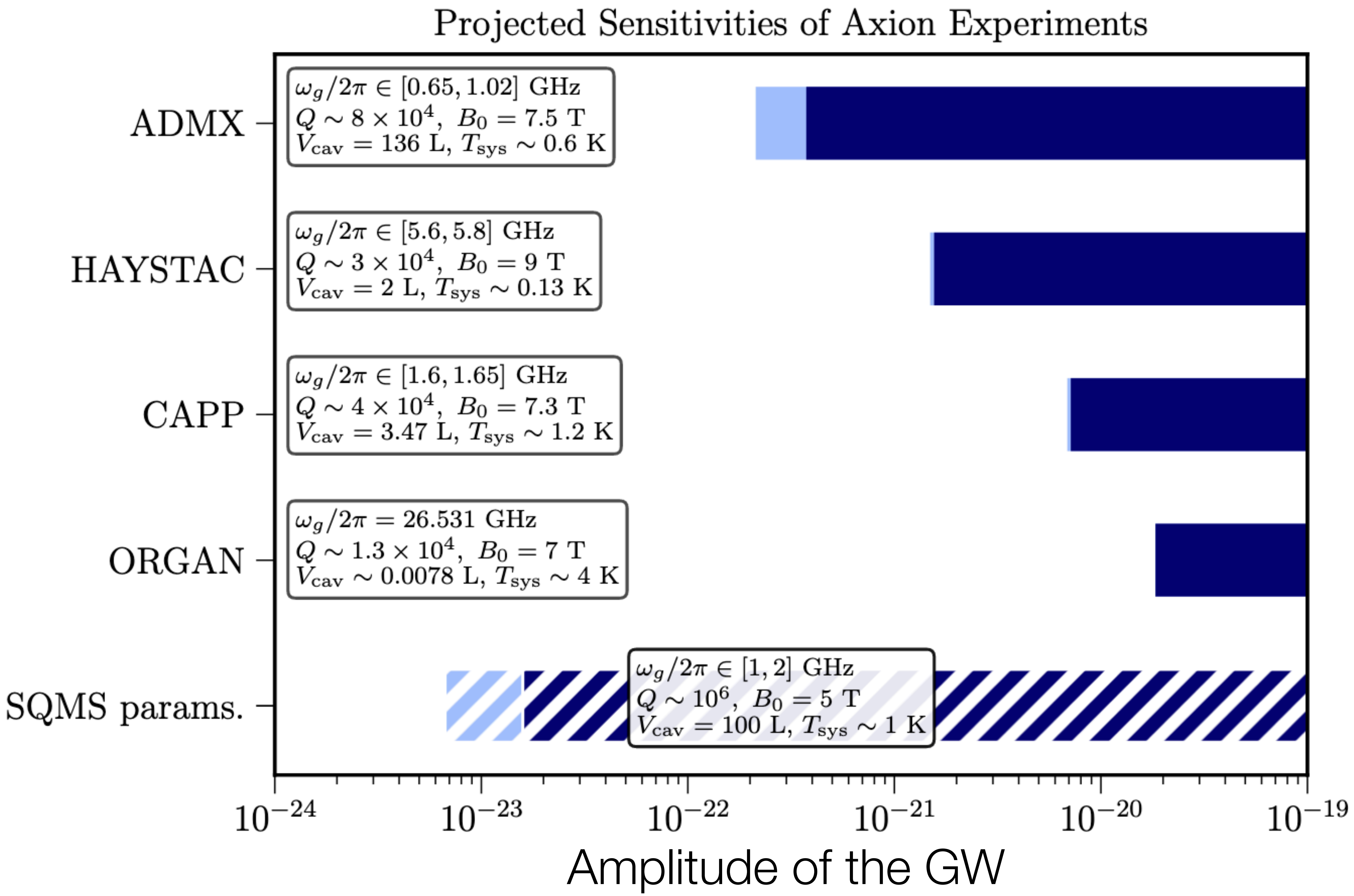
EM-coupling



Mechanical-coupling
(shaking the walls)



A. Berlin, DB, R.T. D'Agnolo, S. Ellis, R. Harnik, Y. Kahn, J. Schütte-Engel
2112.11465 (PRD)& To appear



+ it's directional and not degenerate with axions

2nd Conclusion

- Dark matter and cosmic neutrinos may leave impact in **quantum devices** (e.g. atomic clocks/magnetometers) even if the momentum transfer is ≈ 0
  - This opens new exiting possibilities
- SRF cavities is a mature technology to look for GWs at GHz either
  - Still far from getting to expected backgrounds, but there may be surprises

Road ahead

- Our first task: *dictionary*

fundamental backgrounds FP → QT $H = H_0 + H_{\rm int}$

(high) flux, (low) momentum and small coupling

(in)coherent/modulated/material dep/CP odd…

- Our second task: *genuine symmetric dialogue*

we have been (mostly) recycling techniques ♻

we need a more fluid **dialogue with QT** colleagues for more **genuine ideas**

$H = H_0 + H_{\rm int}$ QT → FP **backgrounds**

  - The most promising set-ups and dedicated improvements (e.g. read-outs)
  - Dedicated resources (dedicated simulations, theory + exp work, schools, time)

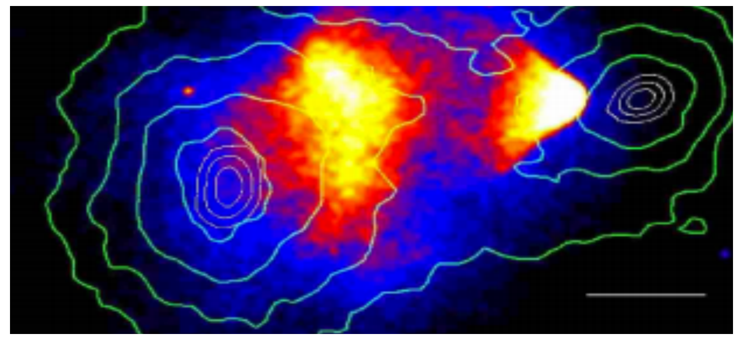
✳ Sub-task: we are far from the limit: e.g. **get more quantum**

e.g. single-photon detectors,
using entangled samples…

neutrino physics

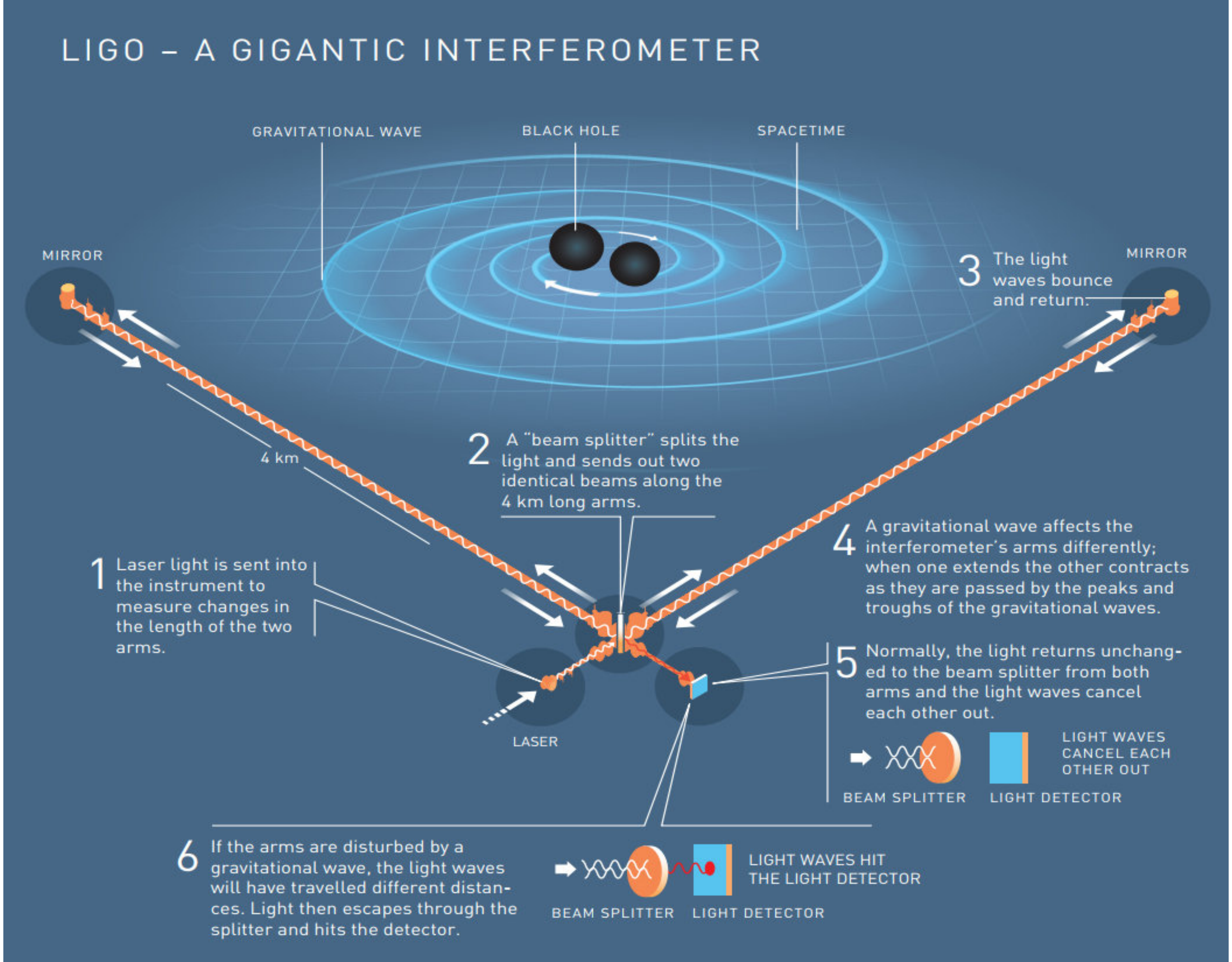
particle data group

dark matter



gravitational waves

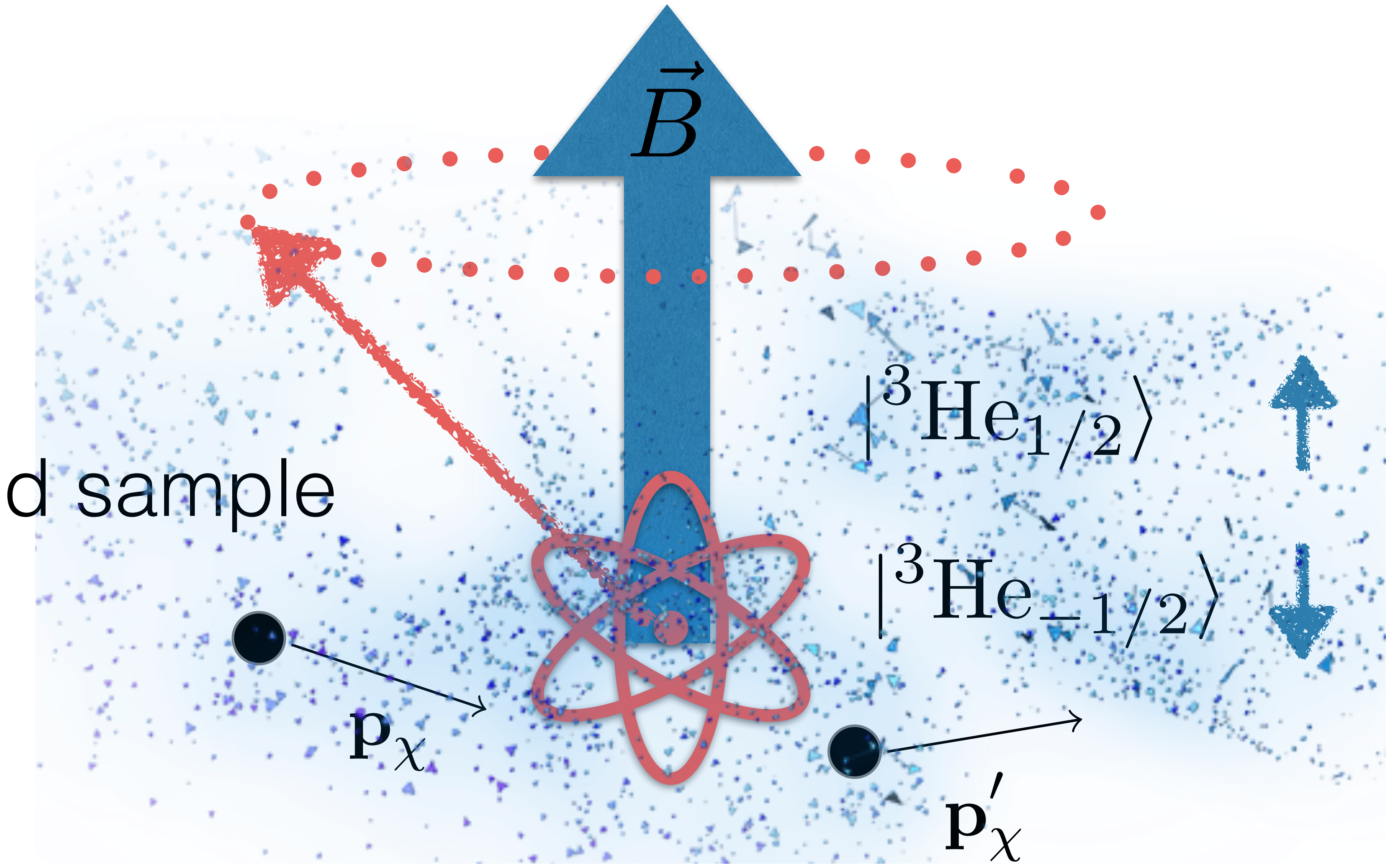
Back-up slides


LIGO – A GIGANTIC INTERFEROMETER
GRAVITATIONAL WAVE
BLACK HOLE
SPACETIME
MIRROR
MIRROR
3 The light waves bounce and return.
4 km
2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.
4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.
1 Laser light is sent into the instrument to measure changes in the length of the two arms.
5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.
LASER
LIGHT WAVES CANCEL EACH OTHER OUT
BEAM SPLITTER
LIGHT DETECTOR
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.
LIGHT WAVES HIT THE LIGHT DETECTOR
BEAM SPLITTER
LIGHT DETECTOR

DM-atom interaction in co-magnetometers

$$H_{\rm int} = -\gamma \vec{B}\cdot\vec{\lambda}$$

$N_{\rm at} \sim 10^{22}$



polarized sample

same with ^{129}Xe

$$\omega \equiv \gamma\beta = \gamma\left(B + \frac{2\pi n_\chi}{m_\chi\gamma}\left(\bar{f}(0)_1 - \bar{f}(0)_2\right)\right)$$

Modified Larmor frequencies

Can be also understood as a phase difference

Co-magnetometer: eliminates *B*

$\Delta\omega \lesssim 10^{-9}\,\mathrm{Hz}$ Brown et al. 2010

The Gravitational Soundscape *at high frequencies*

Crucial question: what sources above kHz?

review
Aggarwal et al, 2011.12414

	Stochastic	**Coherent**
Standard Model:	✓ Thermal plasma fluctuations Ghiglieri & Laine (2015) Ghiglieri et al (2020) Ringwald et al (2020)	✗ ?
BSM:	✓ Inflation Phase transitions Cosmic Strings ...	✓ PBH inspirals Superradiance Exotic objects ...