Quantum technologies for fundamental physics

Diego Blas

$\mathcal{O}_{\mathrm{BSM}}|\psi_{\mathrm{SM}}\rangle$

ICREA
IFAE
BIST Barcelona Institute of Science and Technology
AGENCIA ESTATAL DE INVESTIGACIÓN
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Generalitat de Catalunya
Departament de Recerca i Universitats

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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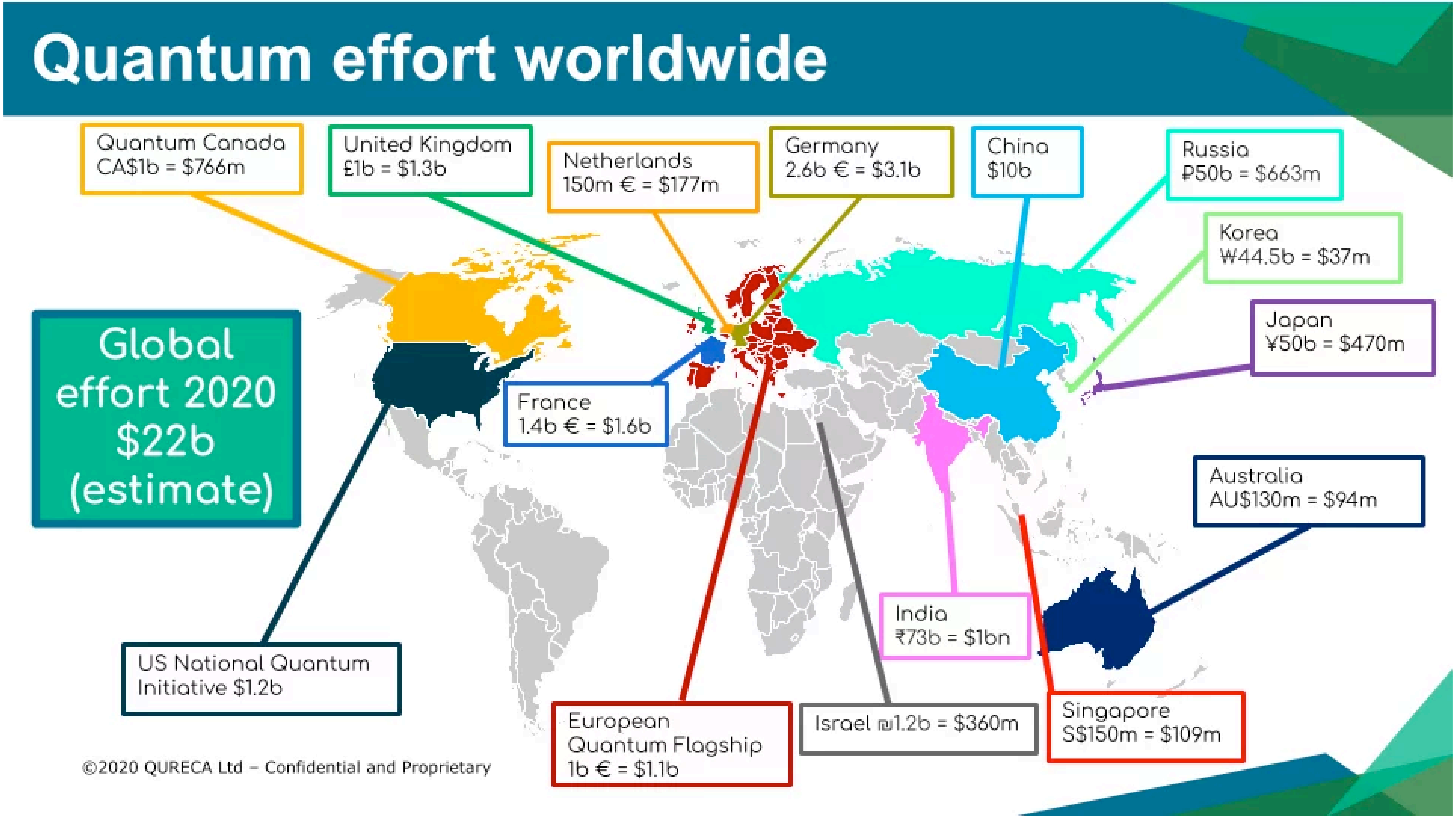
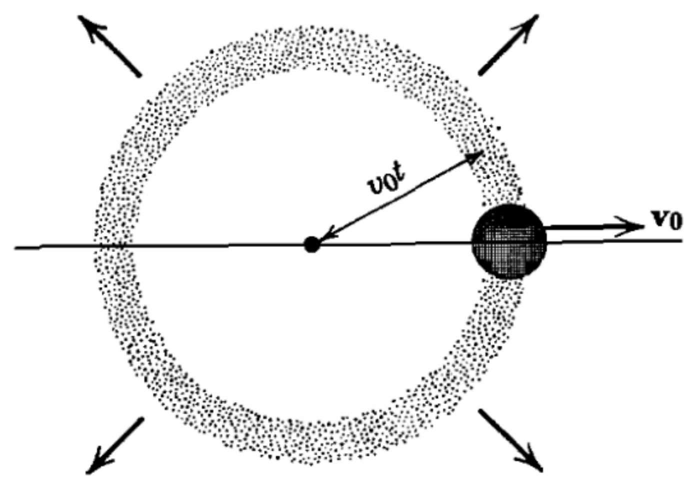
Quantum technologies everywhere…



https://thequantuminsider.com/

Quantum sensing (metrology) for HEP/Grav/Cosmo



- Quantum sensing/devices

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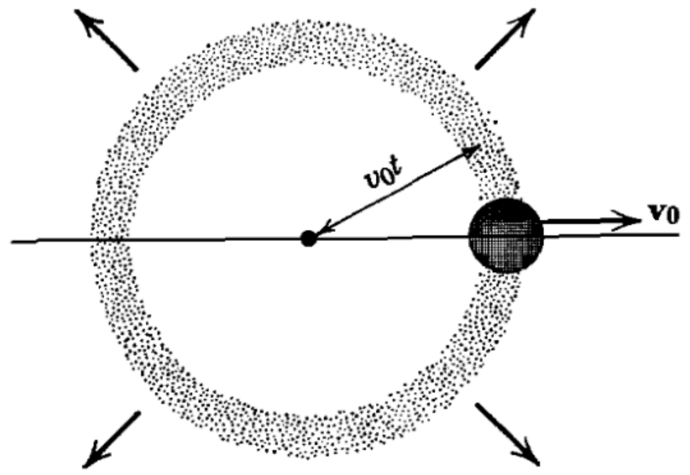

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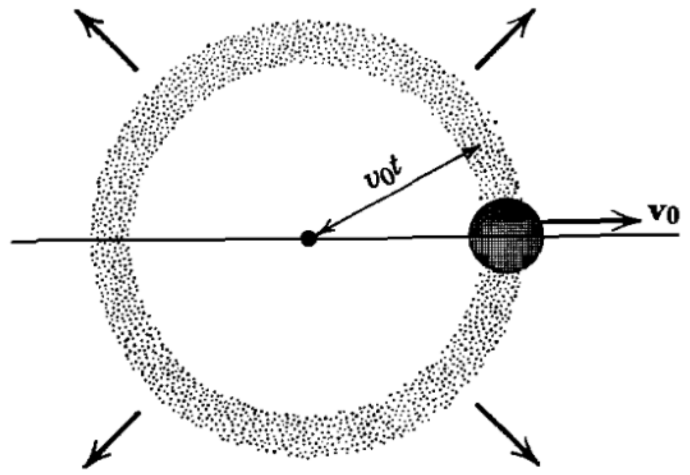

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  - **Coherent effects $\Rightarrow$ *enhance detection sensitivity***

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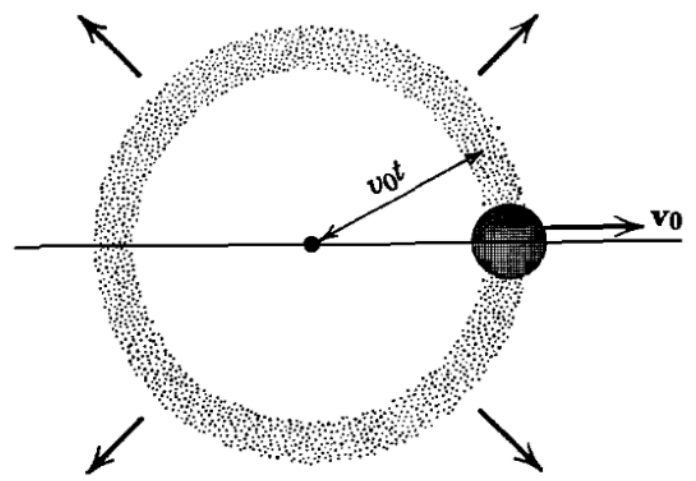

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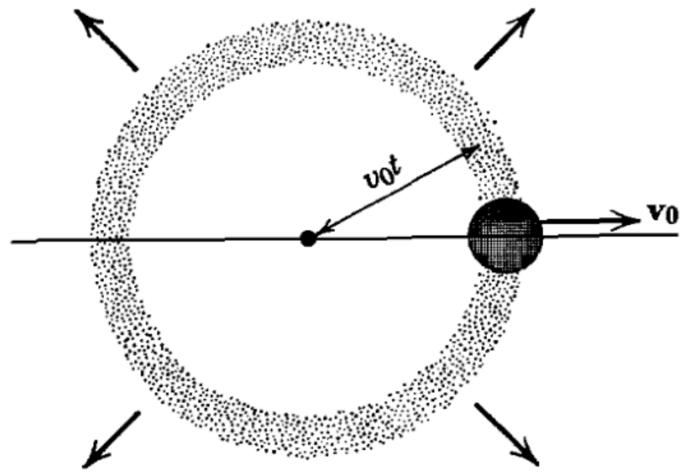

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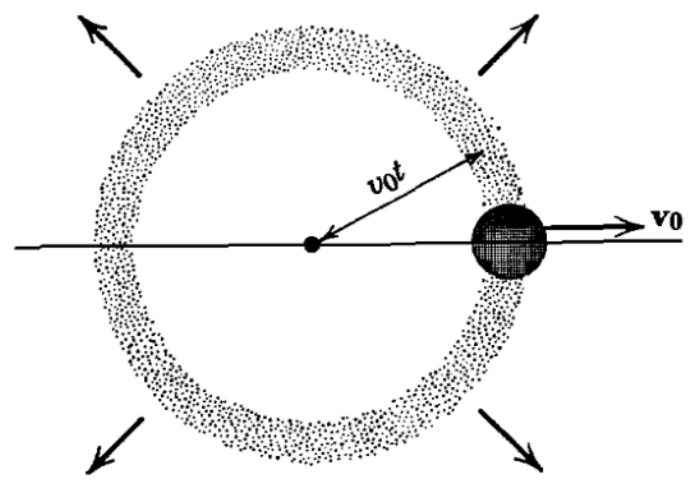

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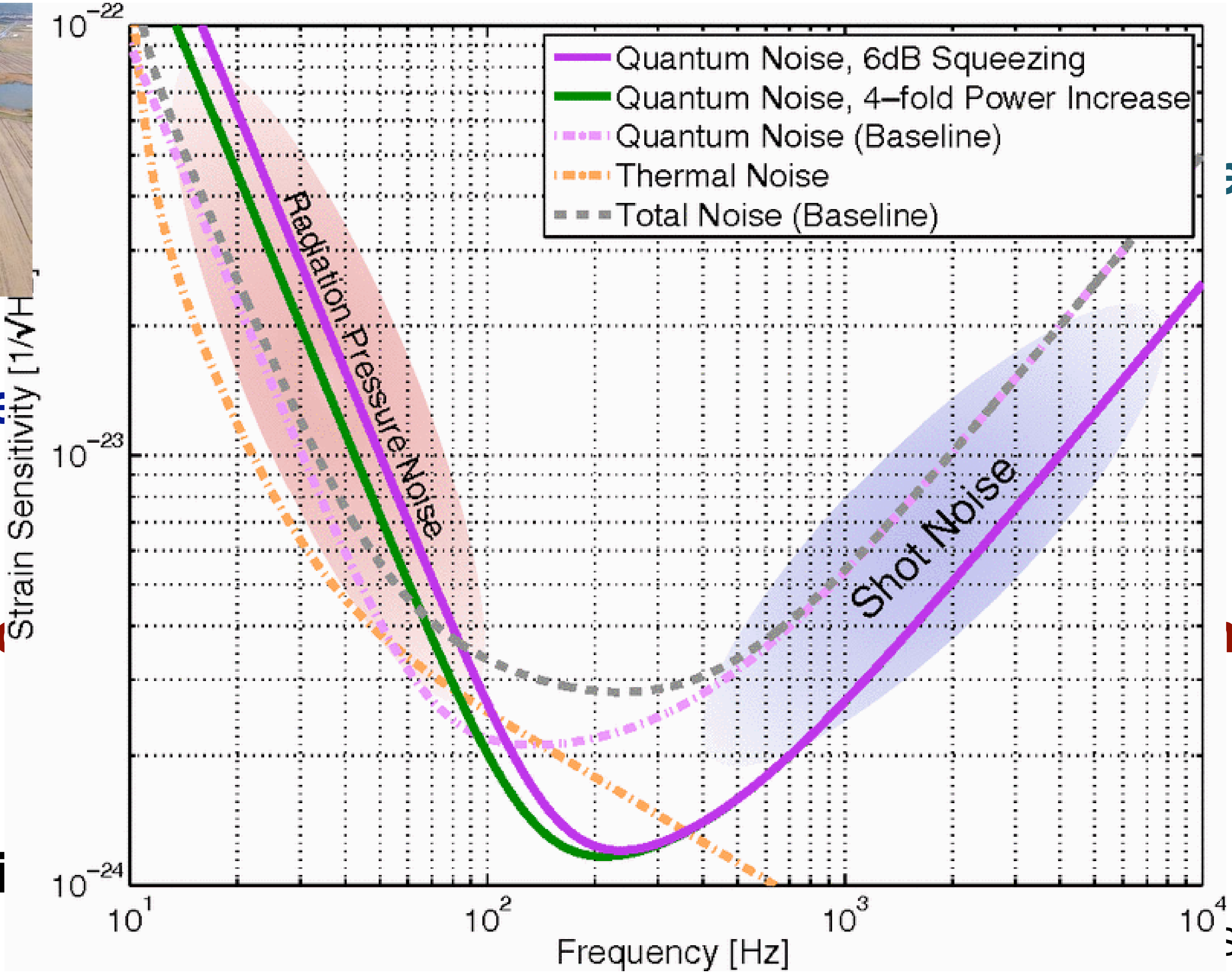
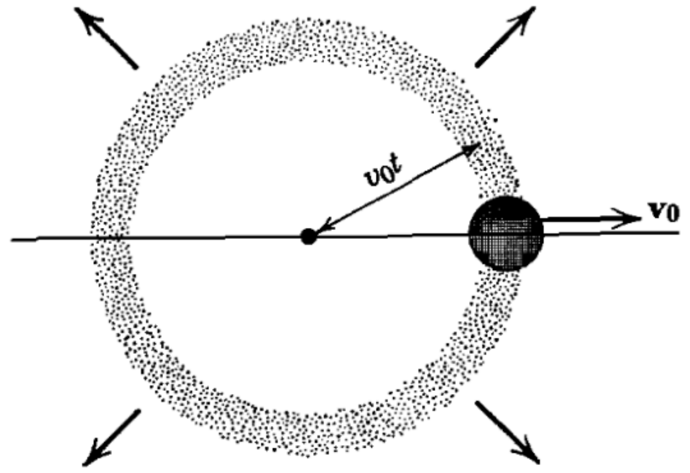
Quantum Sensing for Fundamental Physics
A. Chou et al, hep-ex/2311.01930

Quantum sensing (metrology) for HEP/Grav/Cosmo

already used in many measurements.



LIGO sensitivity to GWs $\delta L/L$



ed signals

- **Coherent e**
- **Current te** **tum Limit***
- **Tabletop(-i**

Sensing for Fundamental Physics
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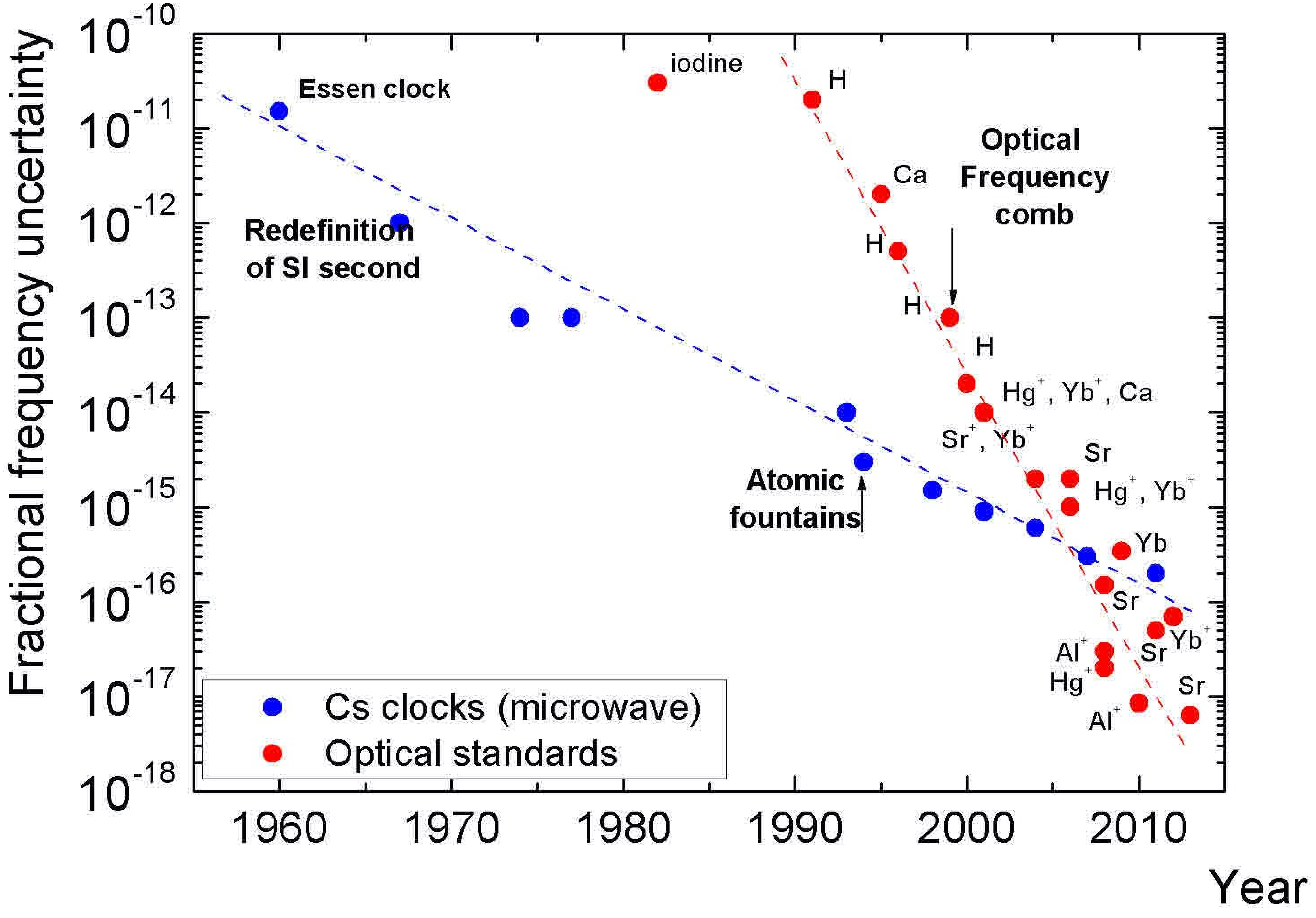
E.g. improvement in atomic clocks

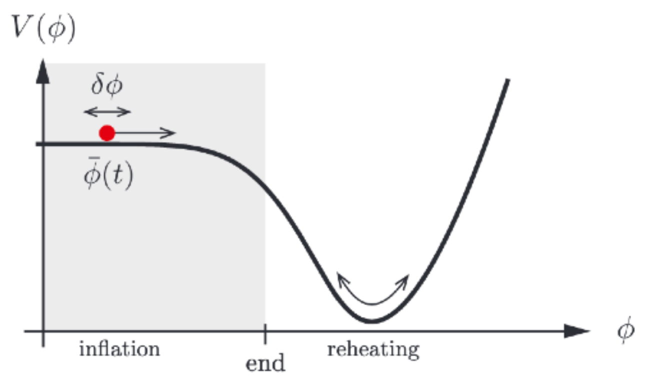
Poli et al. 1401.2378
Safronova et al. 1710.01833
Riehle et al. (CIPM) 2018

$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$

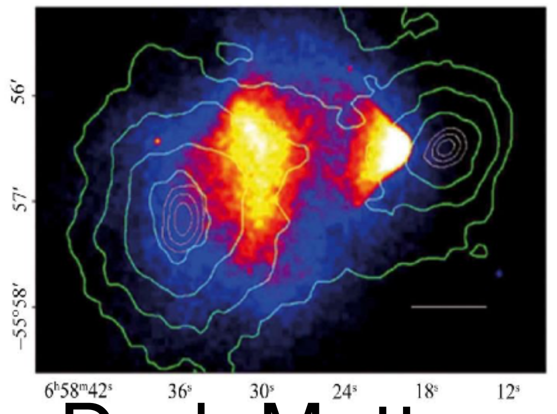


Mapping TH to Quantum Sensing

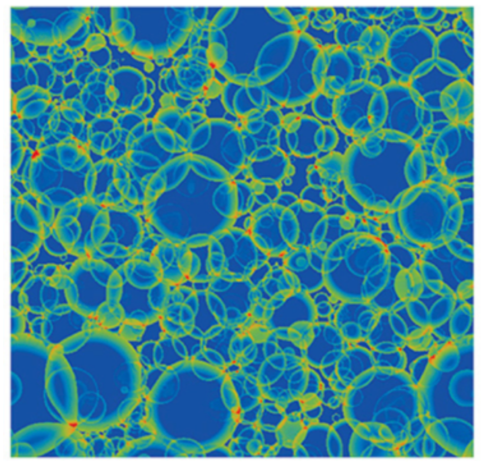
Open Questions



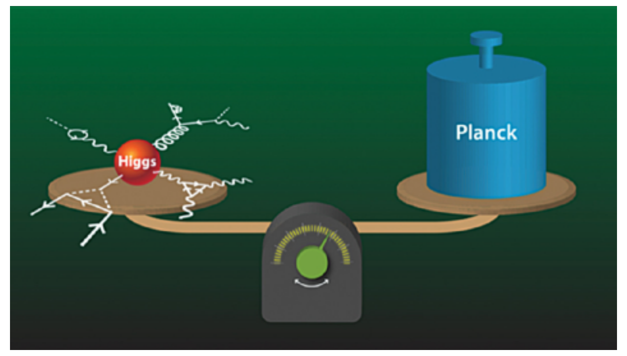
Cosmic Evolution



Dark Matter



Baryogenesi



Higgs Physics

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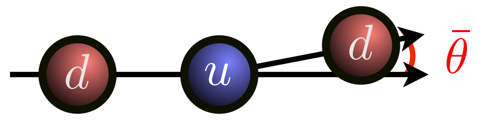
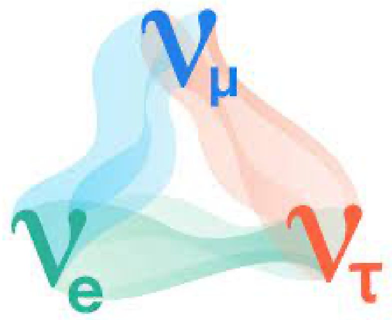


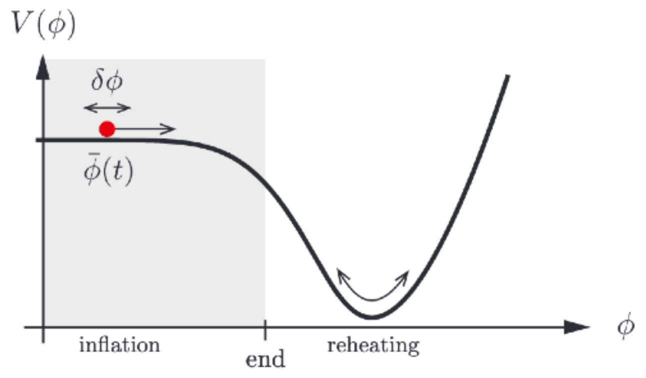
CP Violation



Neutrino masses

Mapping TH to Quantum Sensing

Open Questions



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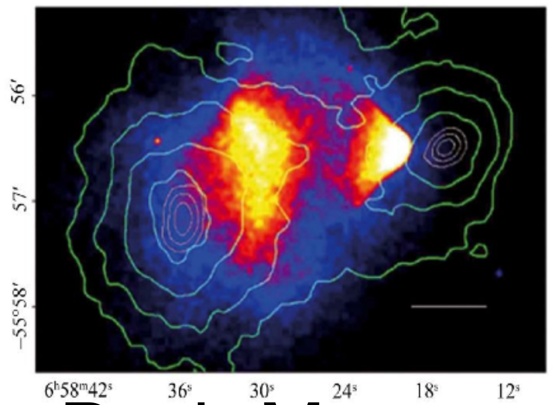

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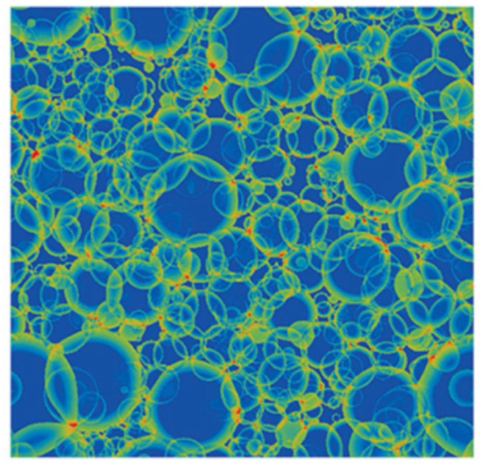

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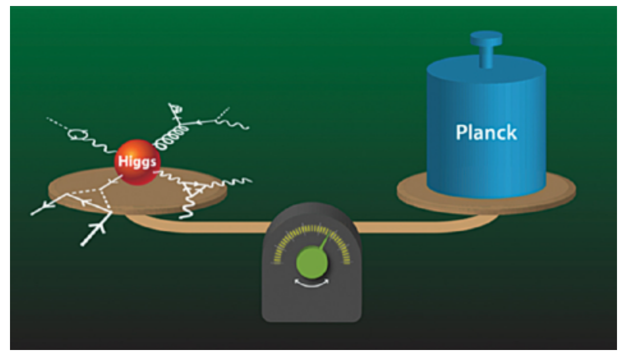

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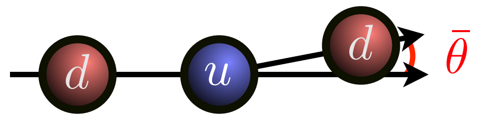

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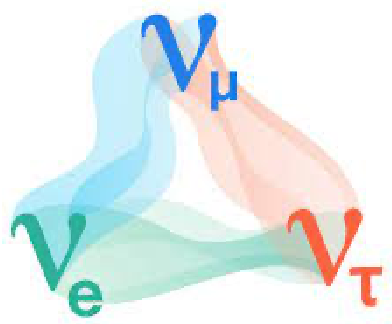

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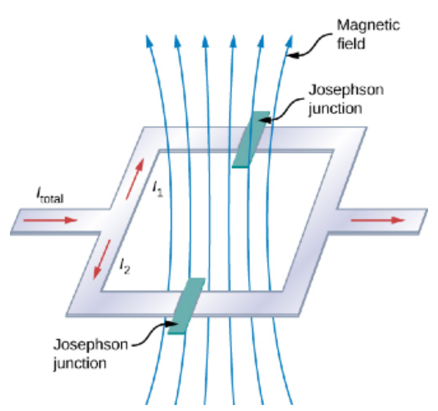
Quantum Device



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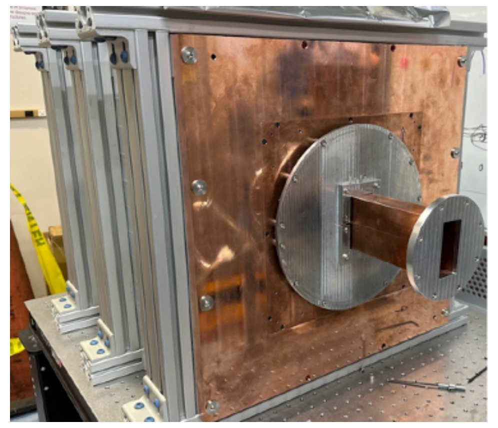
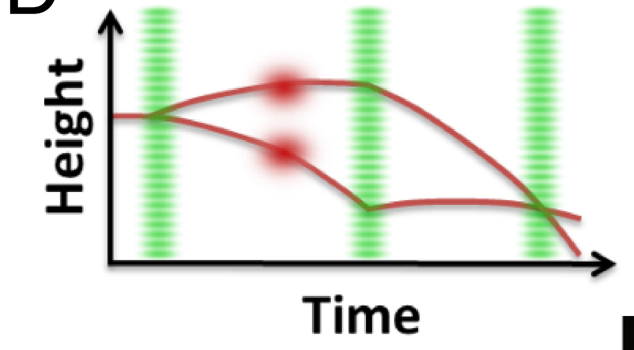
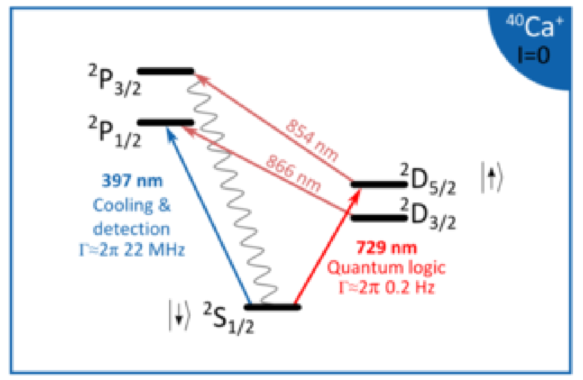


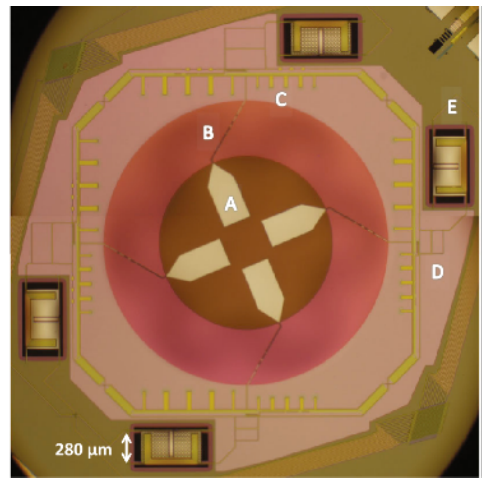
Cavity



Atom Interf.



Atomic Clock.



TES

And more…

Mapping TH to Quantum Sensing

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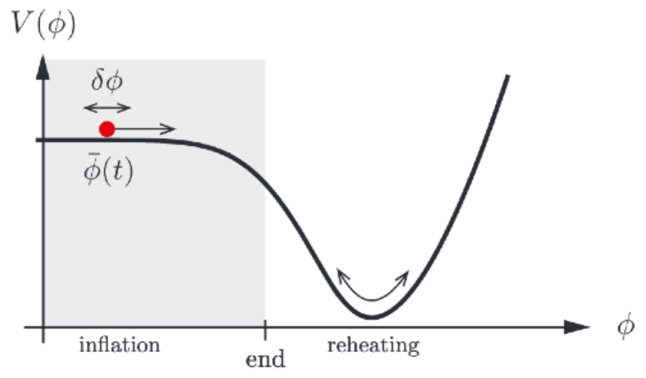

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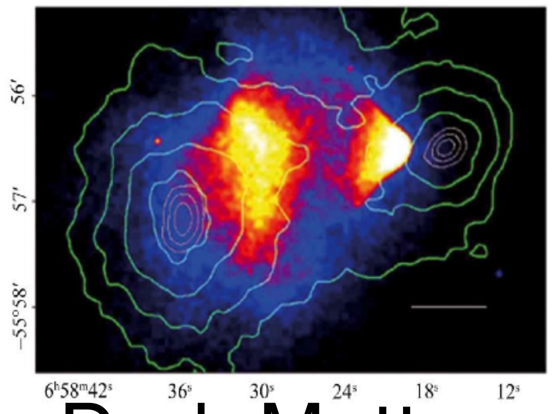

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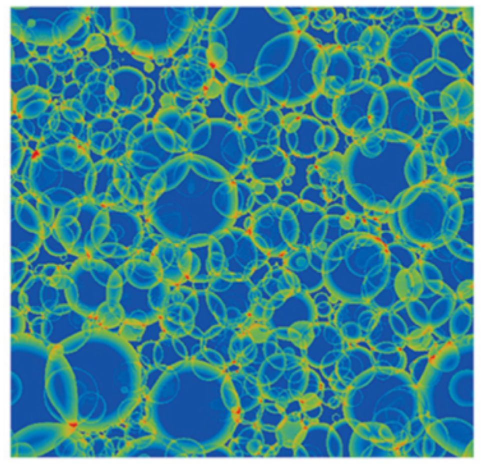

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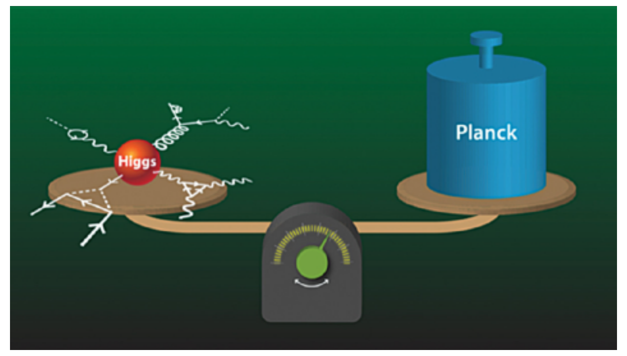

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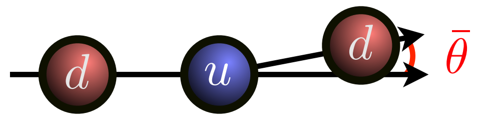

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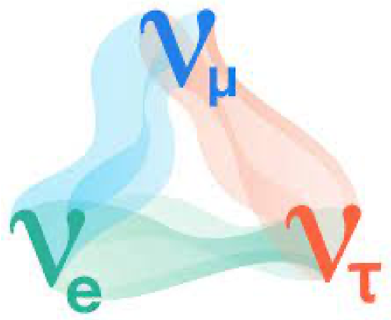

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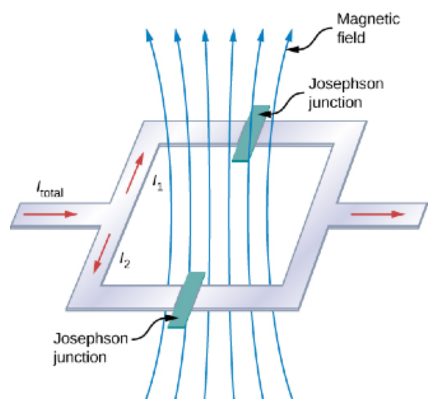

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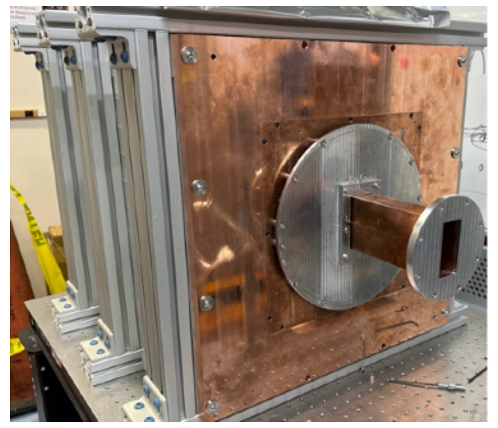

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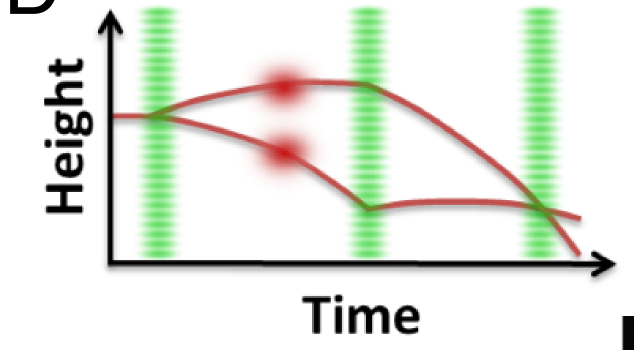

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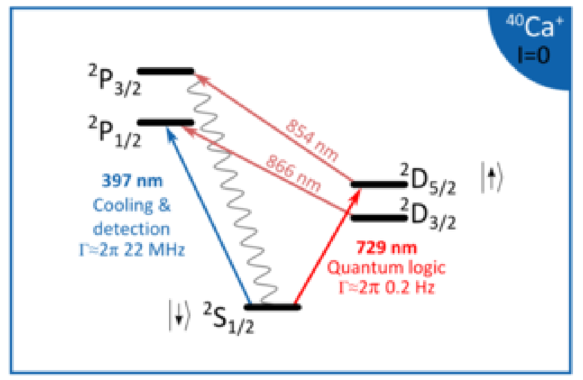

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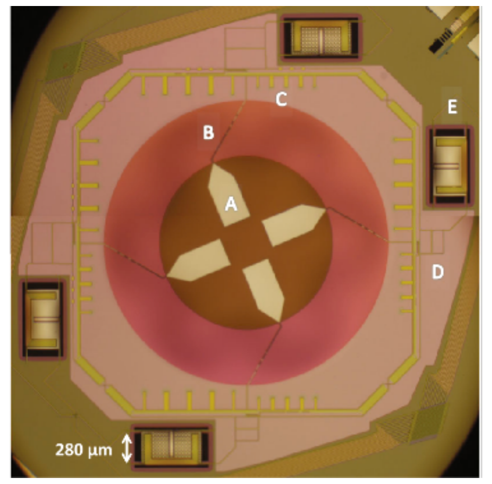

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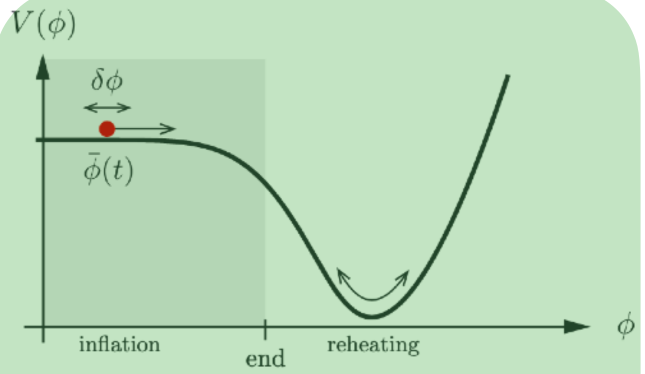

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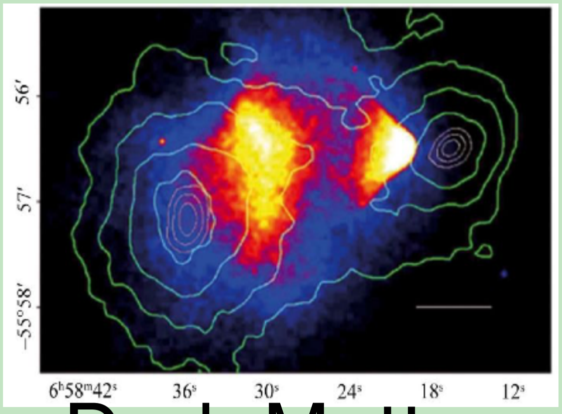

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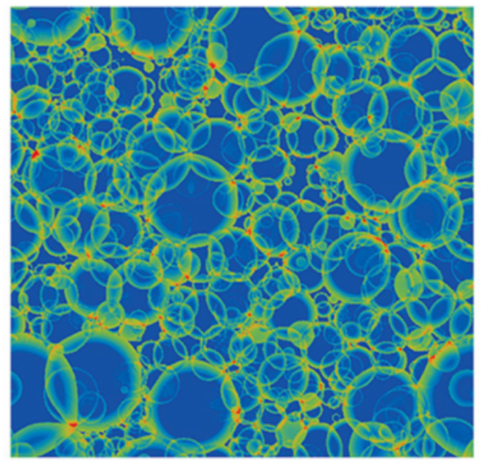

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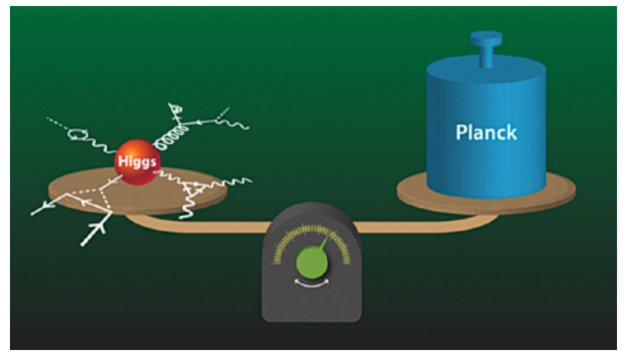

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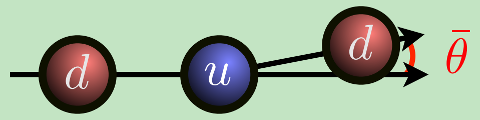

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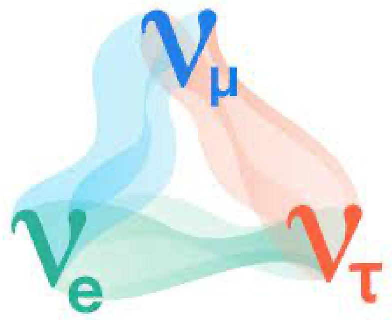

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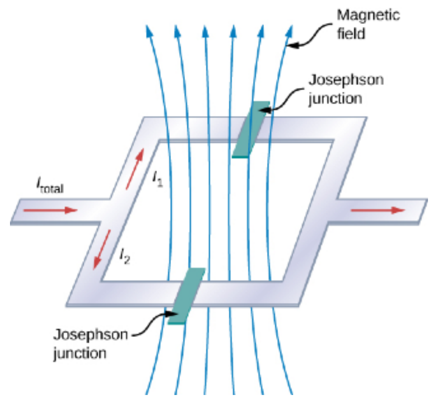

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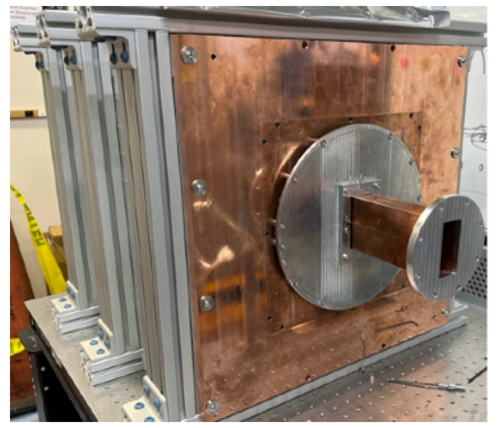

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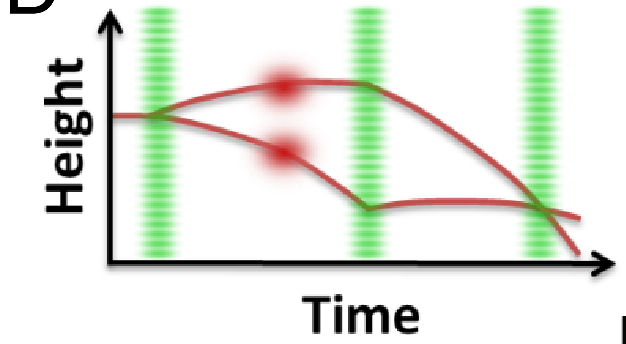

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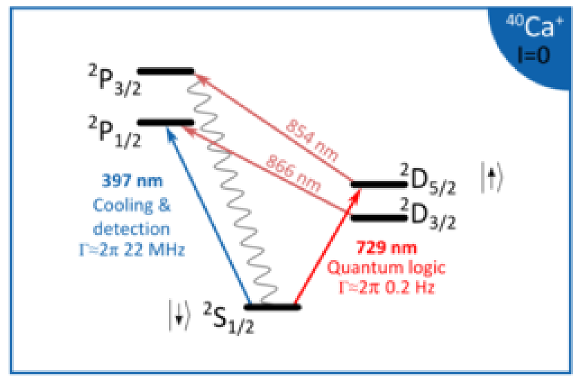

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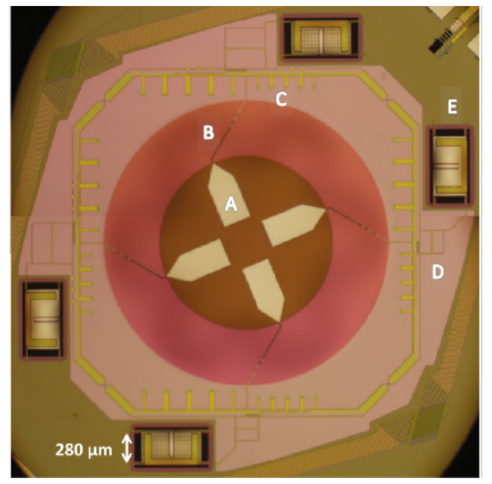


TES

And more…

A possibility: looking for backgrounds

Neutrinos (Standard Model + new physics portal)

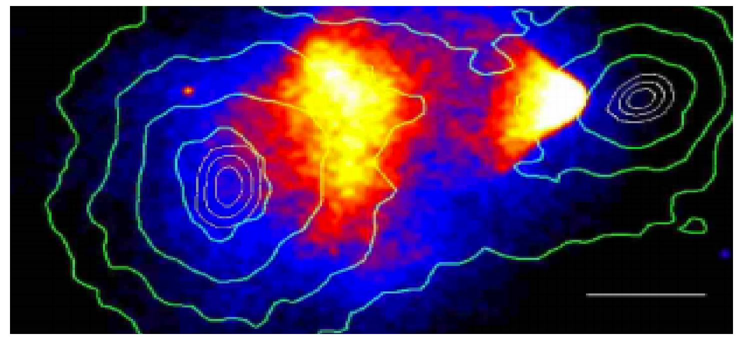
Produced in **nuclear** reactions (astrophysical **dense objects/ early Universe**)

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

Gravitational waves (SM + new physics portal)

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

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



Dark matter (BSM)

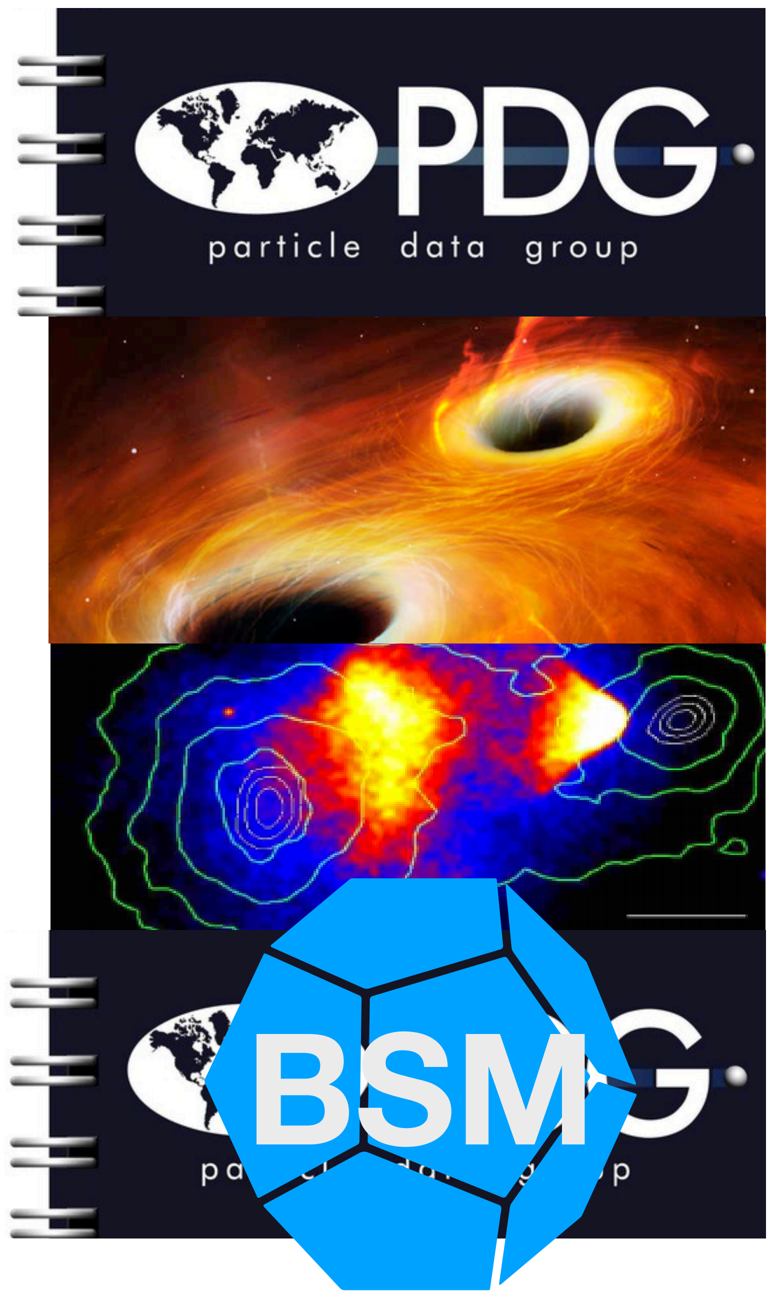
Permeates the Universe, in particular the precision devices

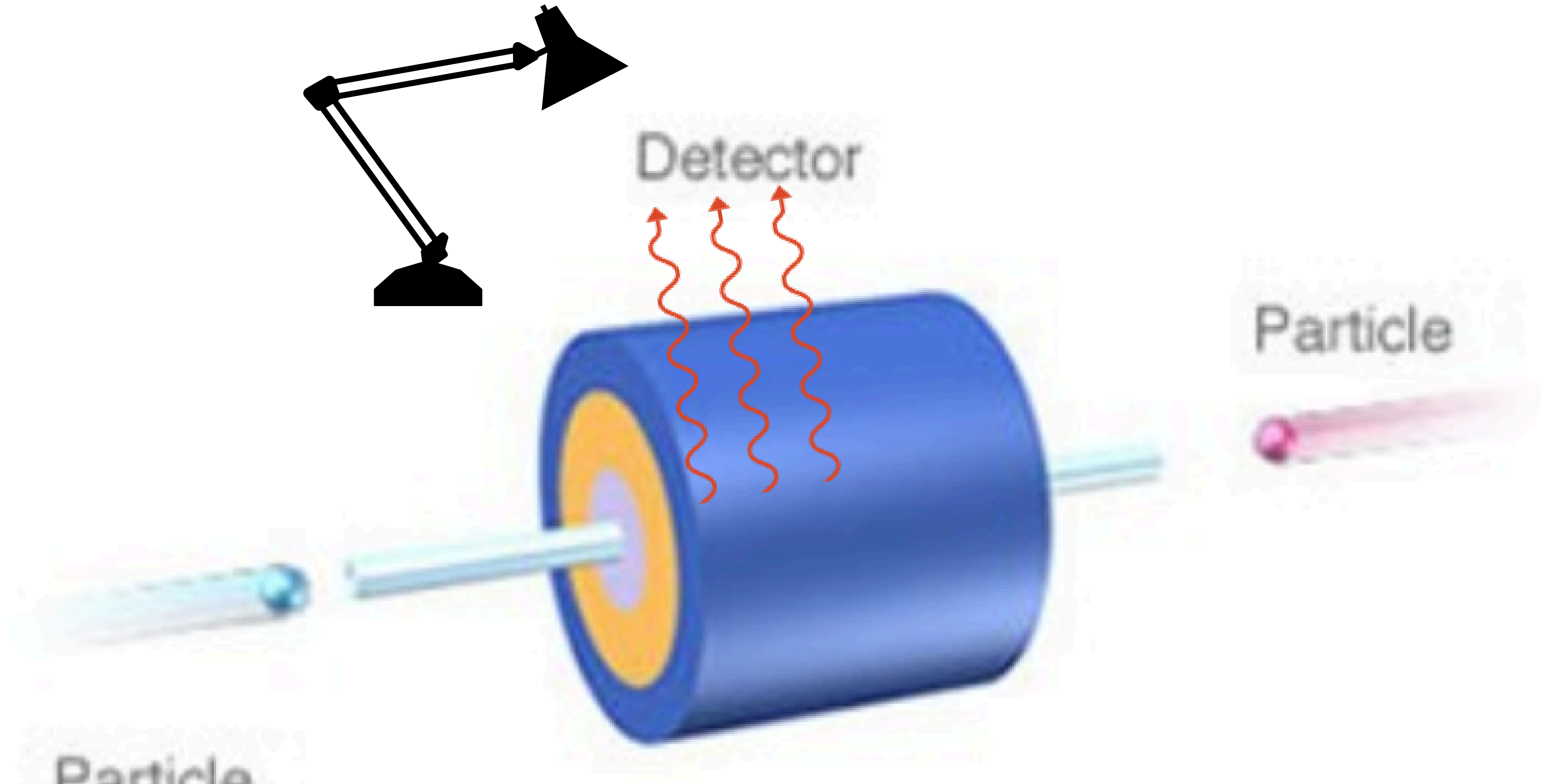
OPEN QUESTIONS its direct detection/ its mass/ its nature (wave, particle, compact object)/ interactions

New particles and more

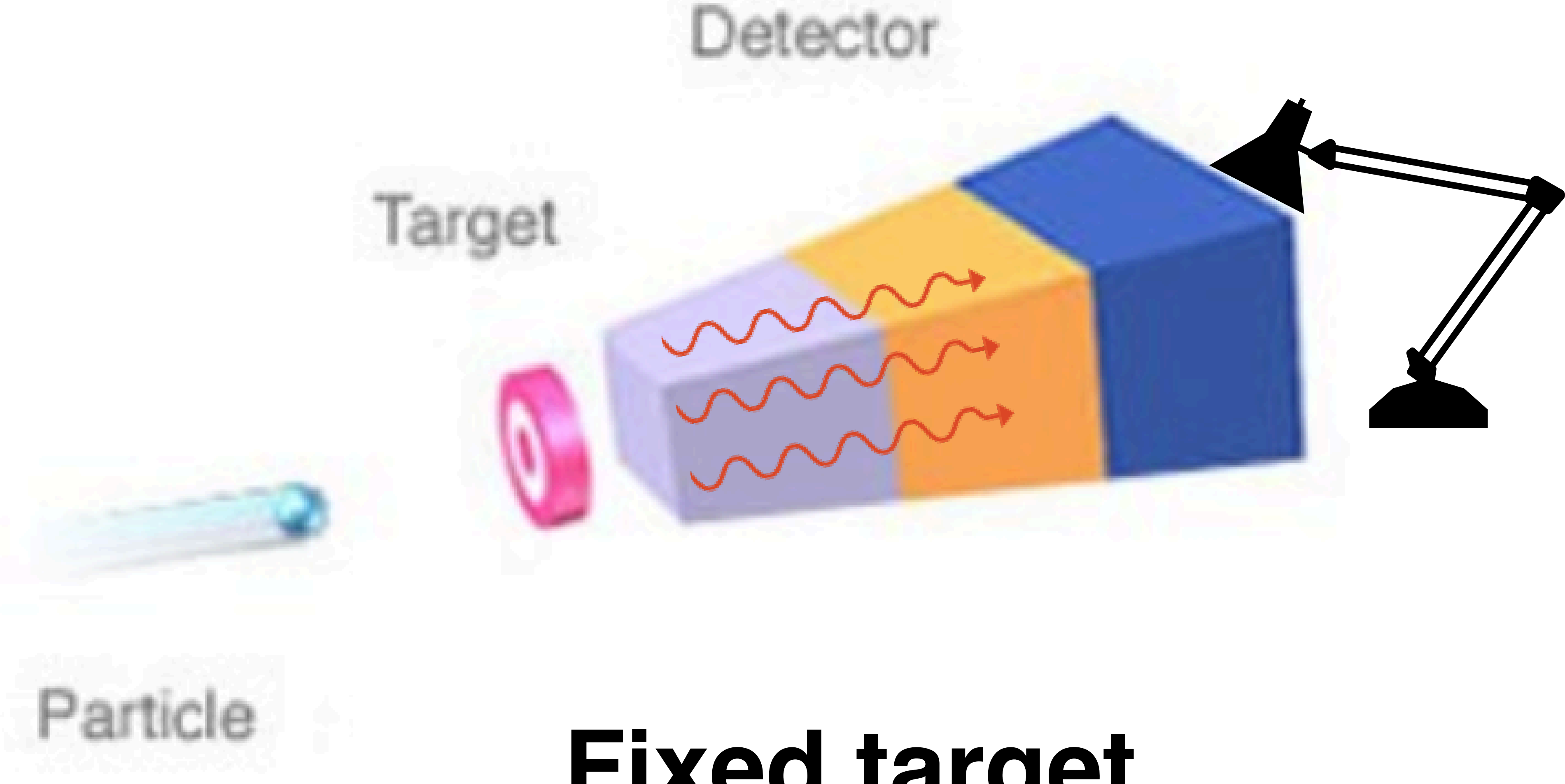
Cosmological/Astrophysical

Machine-made backgrounds

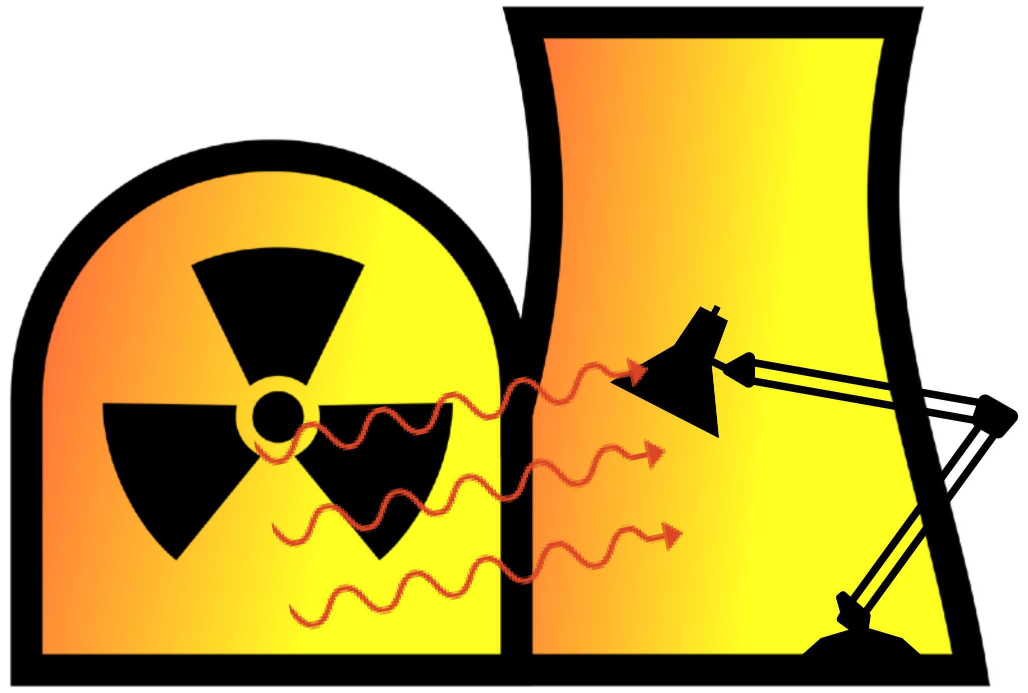




Colliders



Fixed target



Reactors

Bridging QSens-HEP/Grav/Cosmo

How do these backgrounds affect precision measurements

As a theorist:

Bridging QSens-HEP/Grav/Cosmo

How do these backgrounds affect precision measurements

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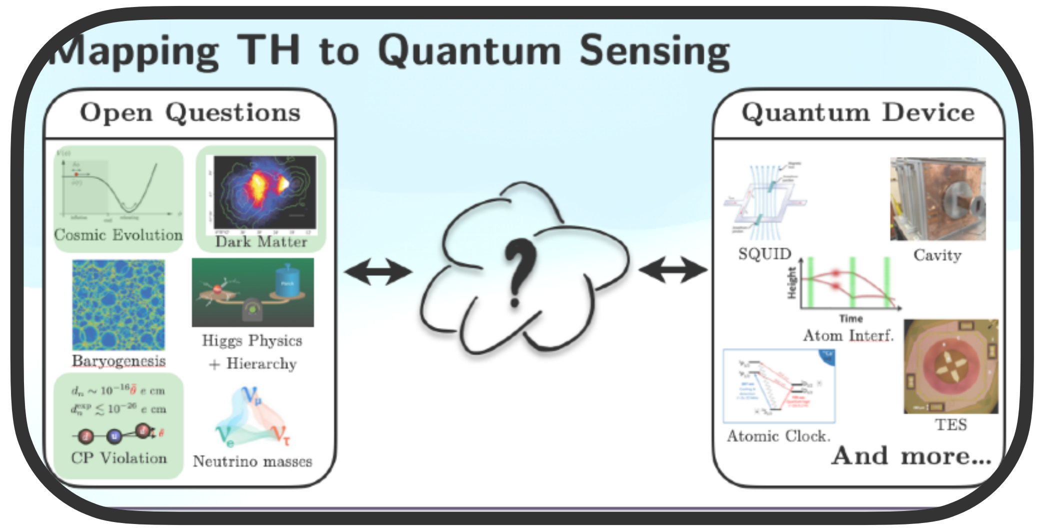
Bridging QSens-HEP/Grav/Cosmo

How do these backgrounds affect precision measurements

As a theorist:

- ▸ **Map theory-space onto detector-space**

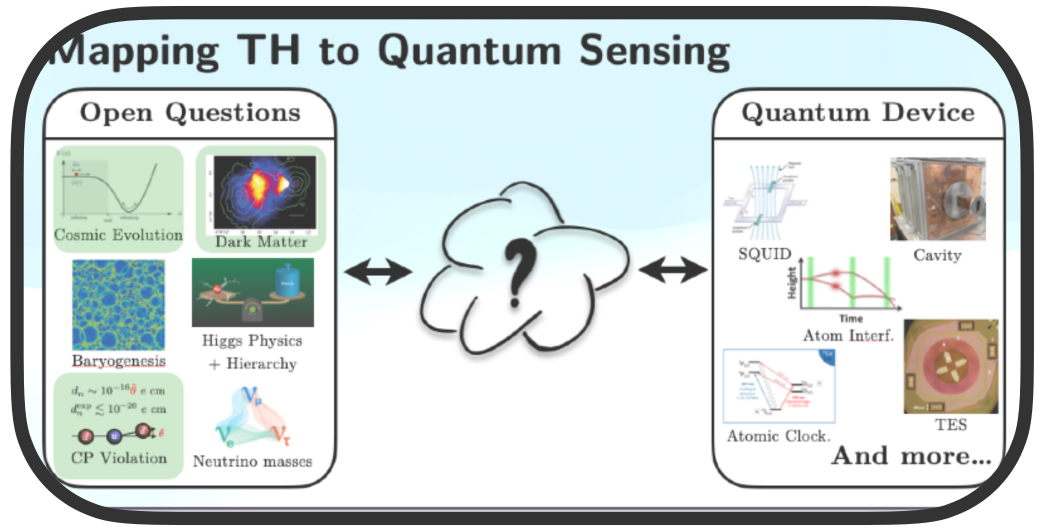


Bridging QSens-HEP/Grav/Cosmo

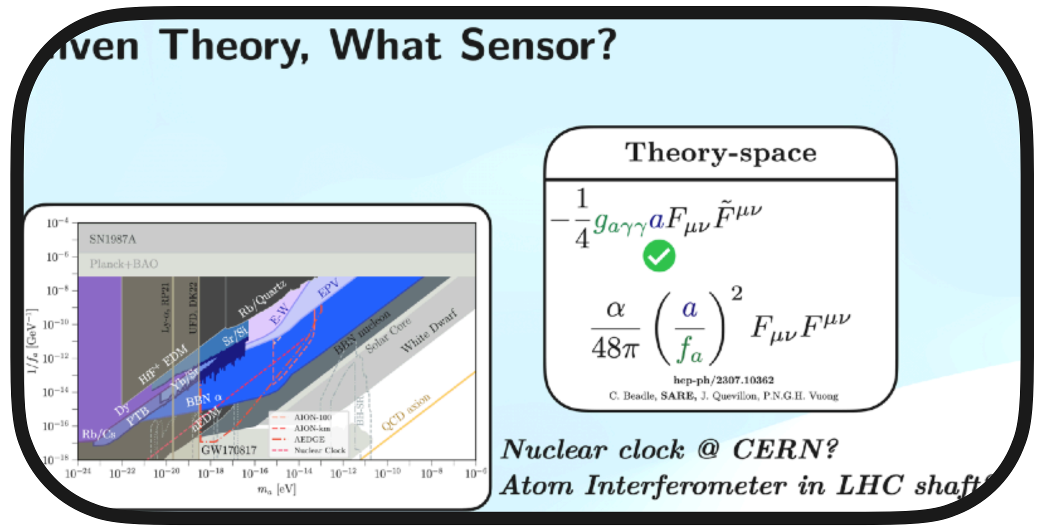
How do these backgrounds affect precision measurements

As a theorist:

- ▸ **Map theory-space onto detector-space**



- ▸ **Extend theory-space & detector-space**

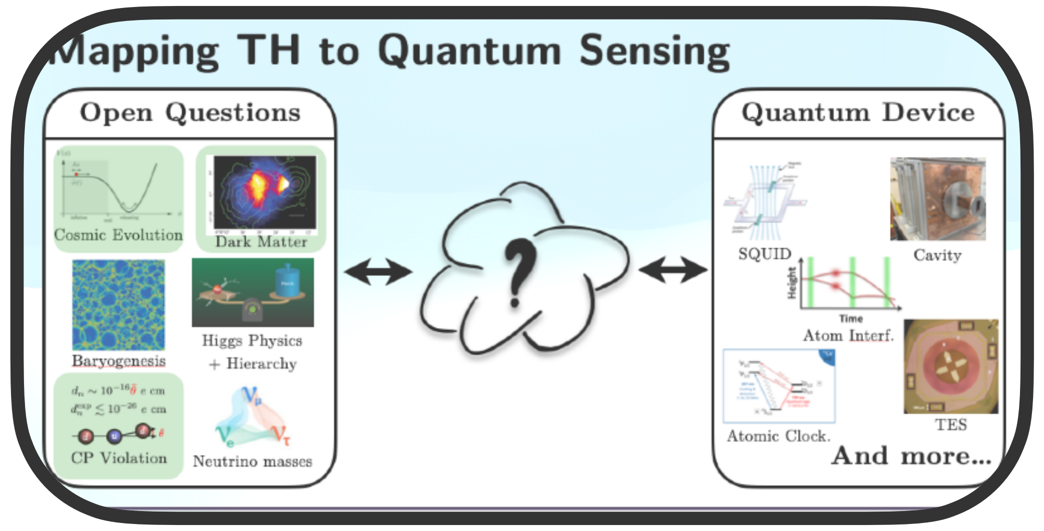


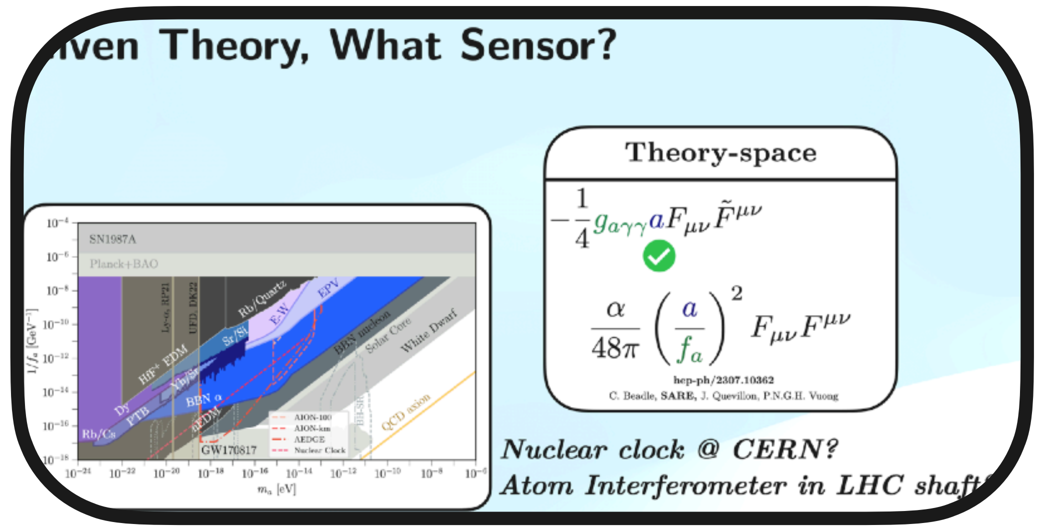
Bridging QSens-HEP/Grav/Cosmo

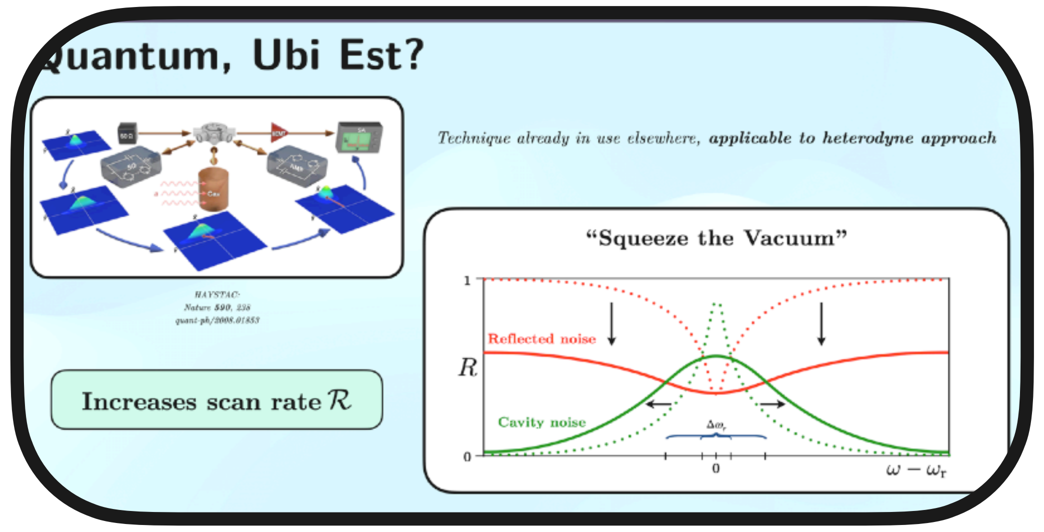
How do these backgrounds affect precision measurements

As a theorist:

- ▸ **Map theory-space onto detector-space**
- ▸ **Extend theory-space & detector-space**
- ▸ **Push back/circumvent experimental limitations**

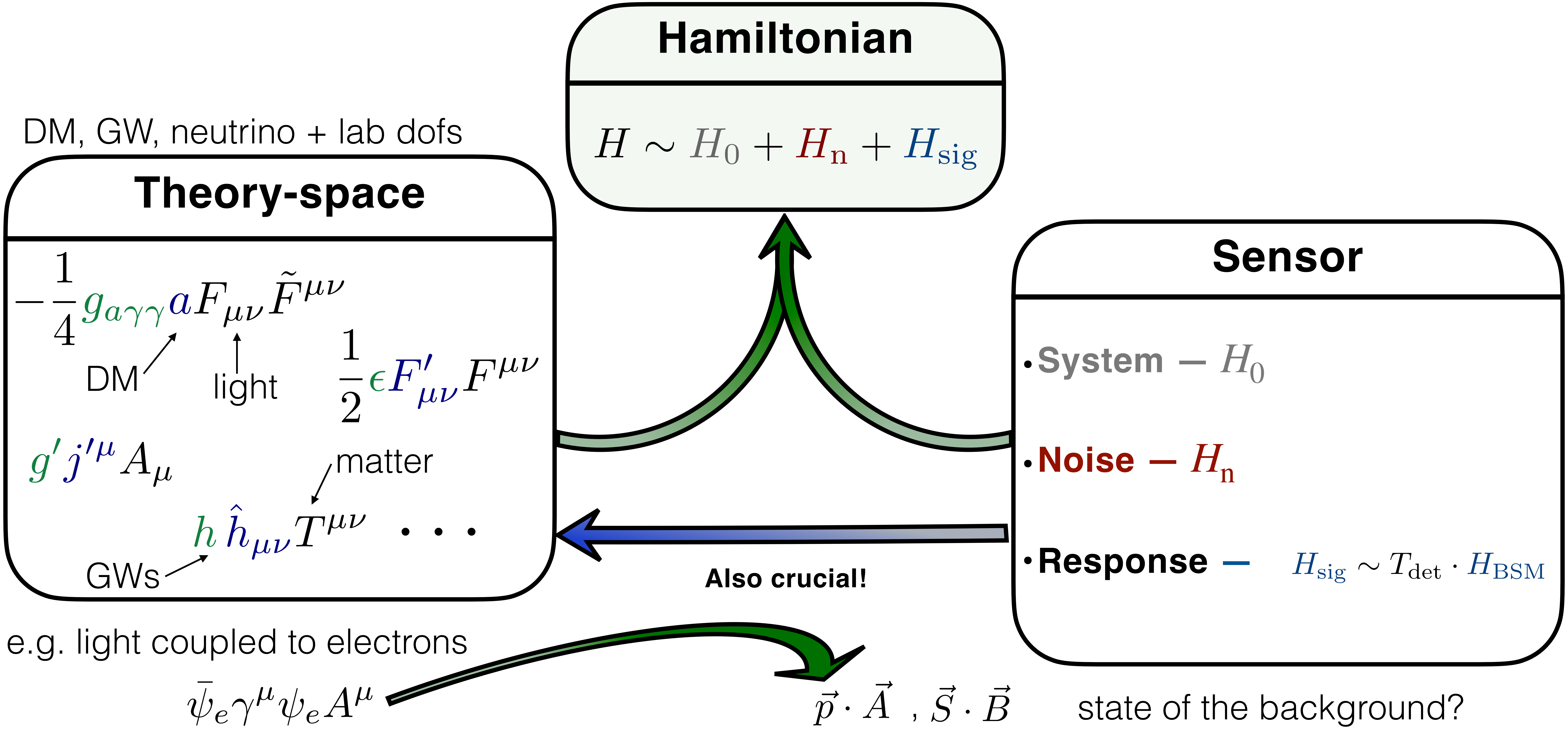




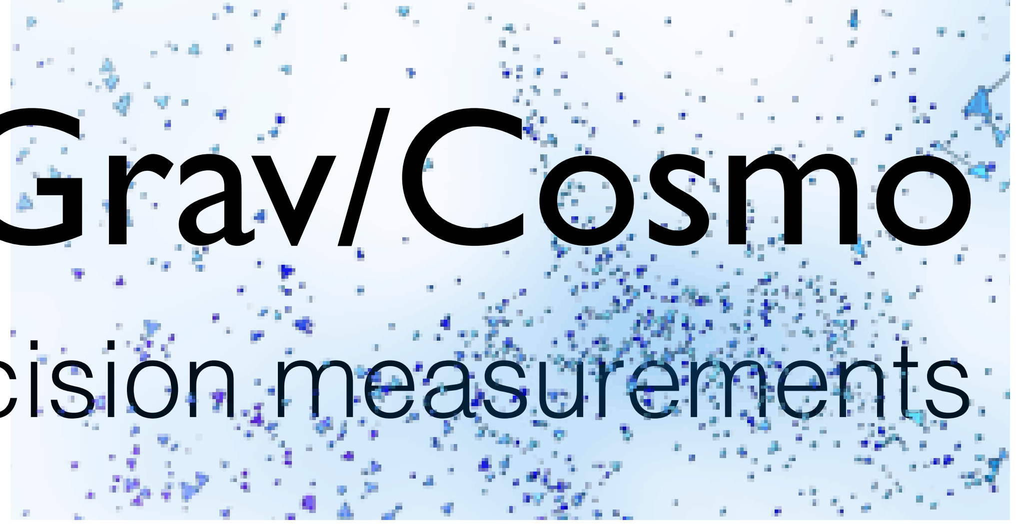


Bridging QSens-HEP/Grav/Cosmo

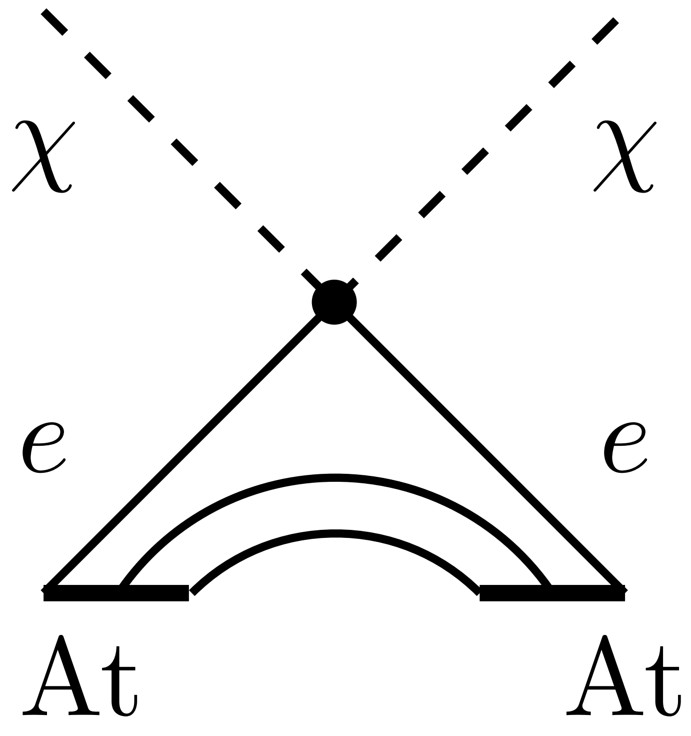
How do these backgrounds affect precision measurements



Bridging QSens-HEP/Grav/Cosmo



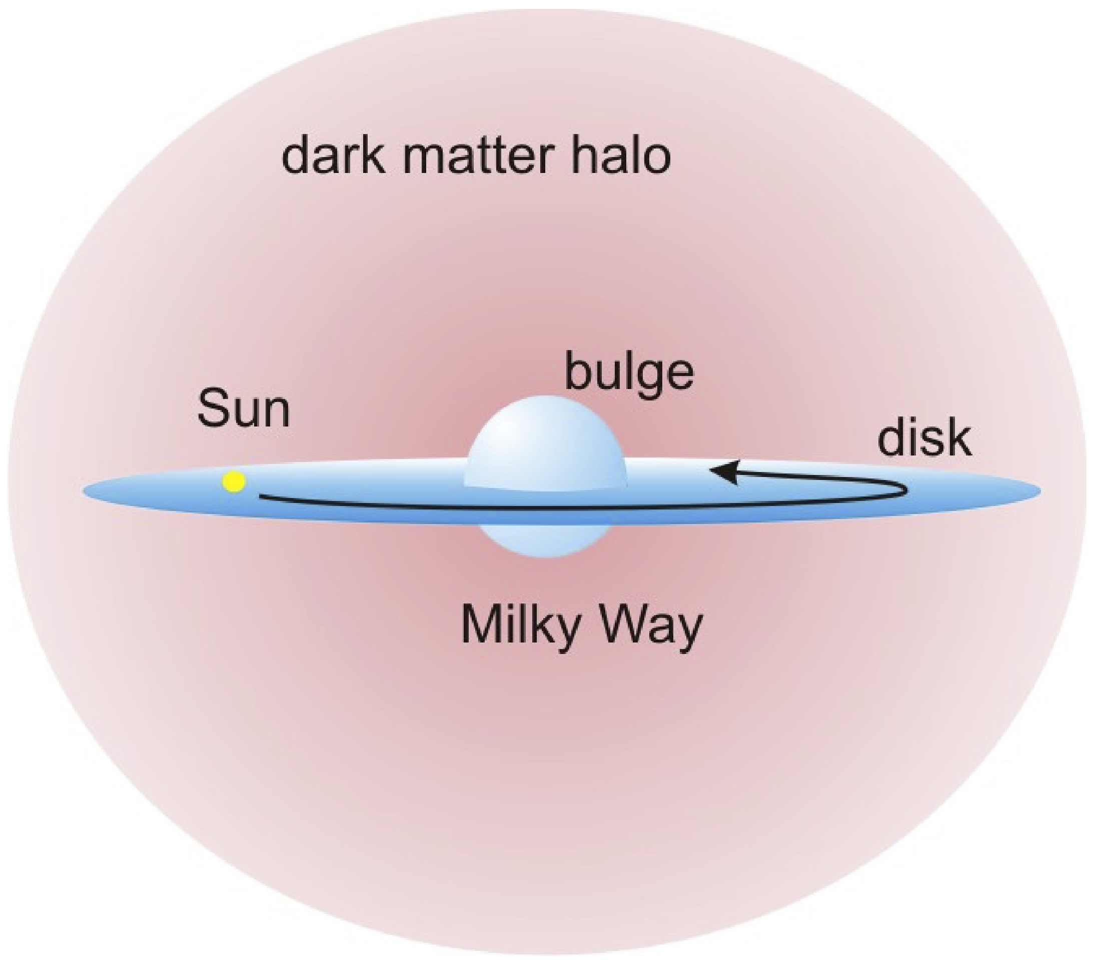
How do these backgrounds affect precision measurements



e.g. $\lambda \bar{\psi}_e \gamma^\mu \gamma_5 \psi_e \bar{\chi} \gamma_\mu \chi$

NR limit (lab)
$\lambda \, \vec{S}_e \cdot \vec{p}_\chi$

state of the background?



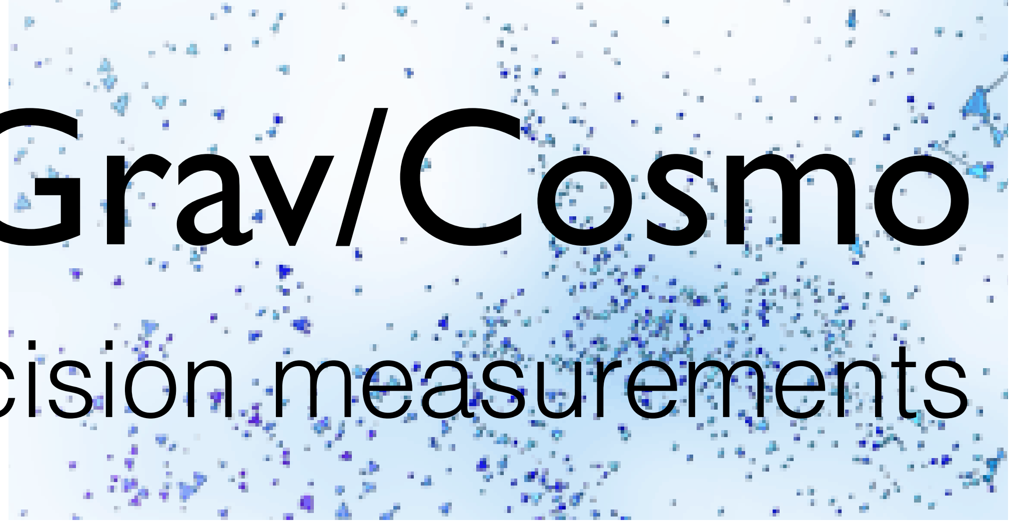
e.g. if χ behaves as PARTICLE dark matter

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

ii) with average momentum $\langle \vec{p}_\chi \rangle \approx \; m_\chi \langle v_\odot \rangle \sim 10^{-3} m_\chi c$
(annually modulated)

$$H_{\mathrm{sig}} \sim \lambda \, \vec{S}_e \cdot \langle \vec{p}_\chi \rangle$$

compare with standard EM interactions $g_e \vec{S}_e \cdot \vec{B}$ DM may affect measurements of $\vec{B}$



Bridging QSens-HEP/Grav/Cosmo

How do these backgrounds affect precision measurements

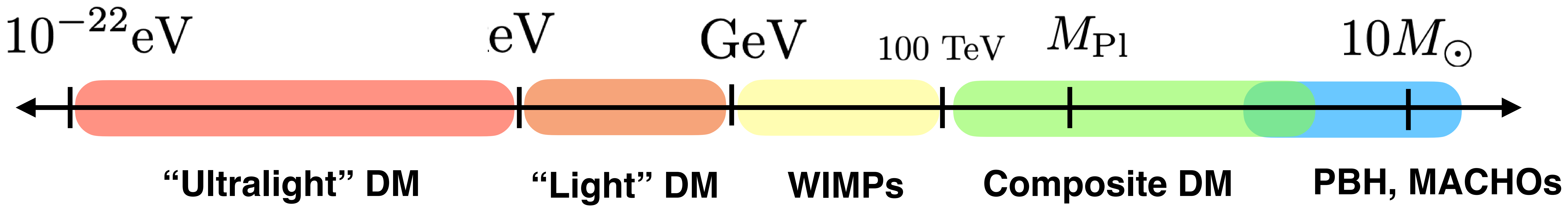
Part II: three (biased) examples as apetizer

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

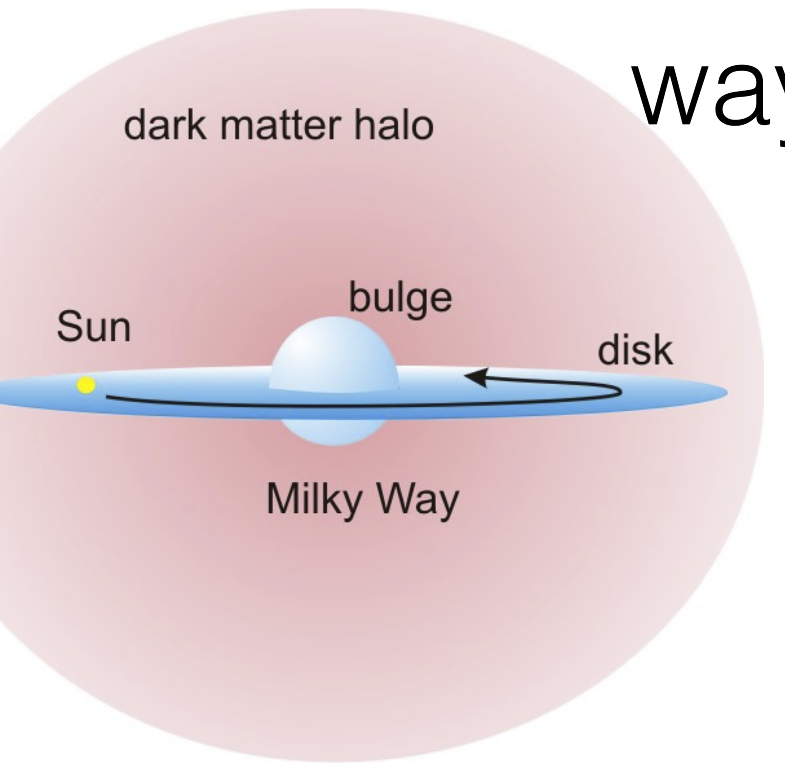
ii) Large atomic interferometers

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

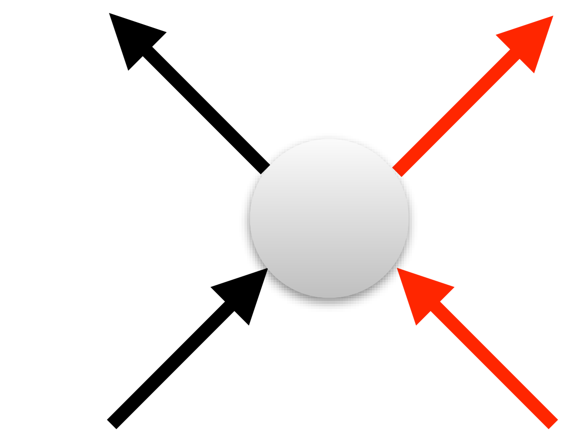
Dark Matter: where to look?



Problems to detect DM at low masses



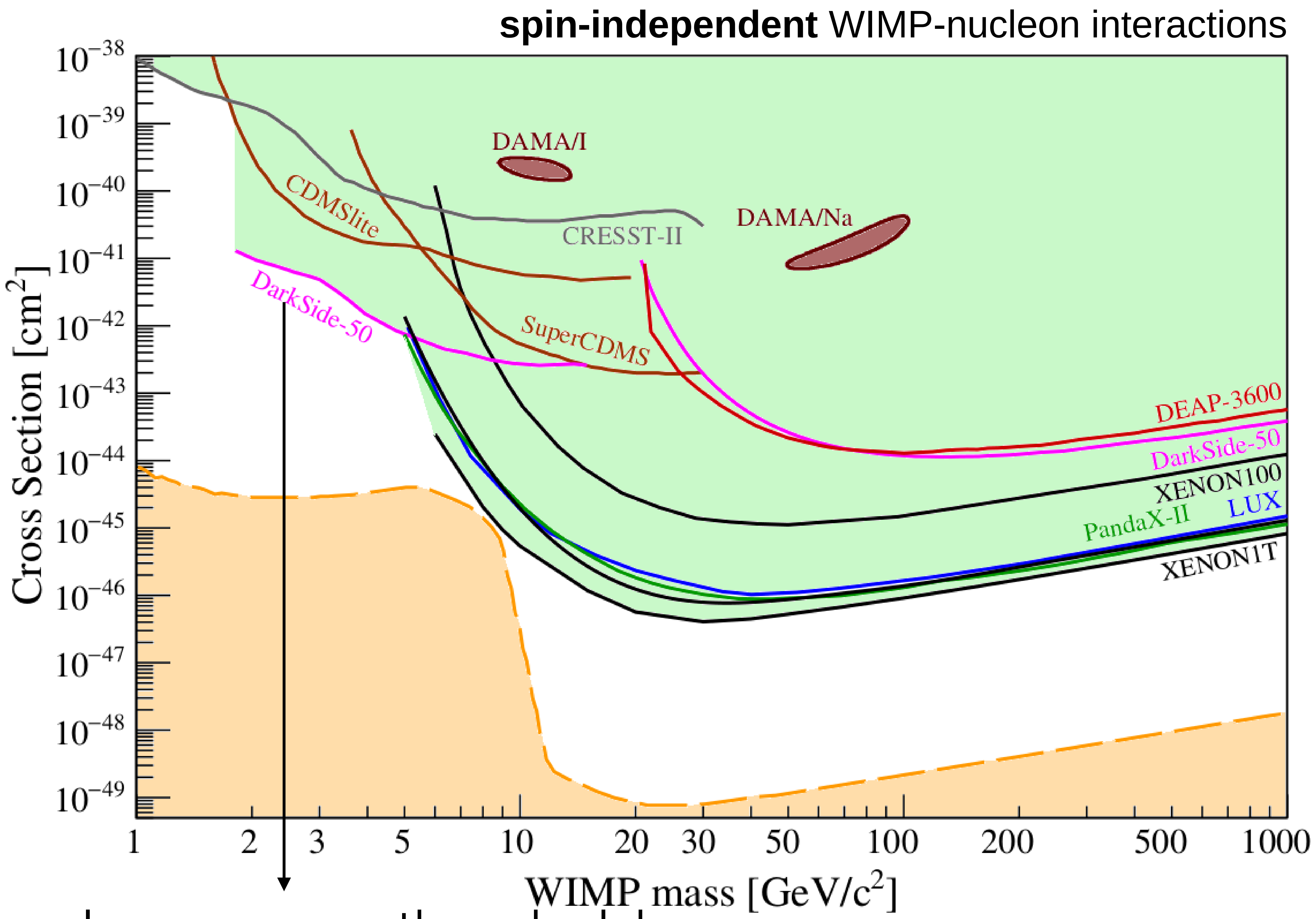
Leading
way to search for DM



DM nucleus

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

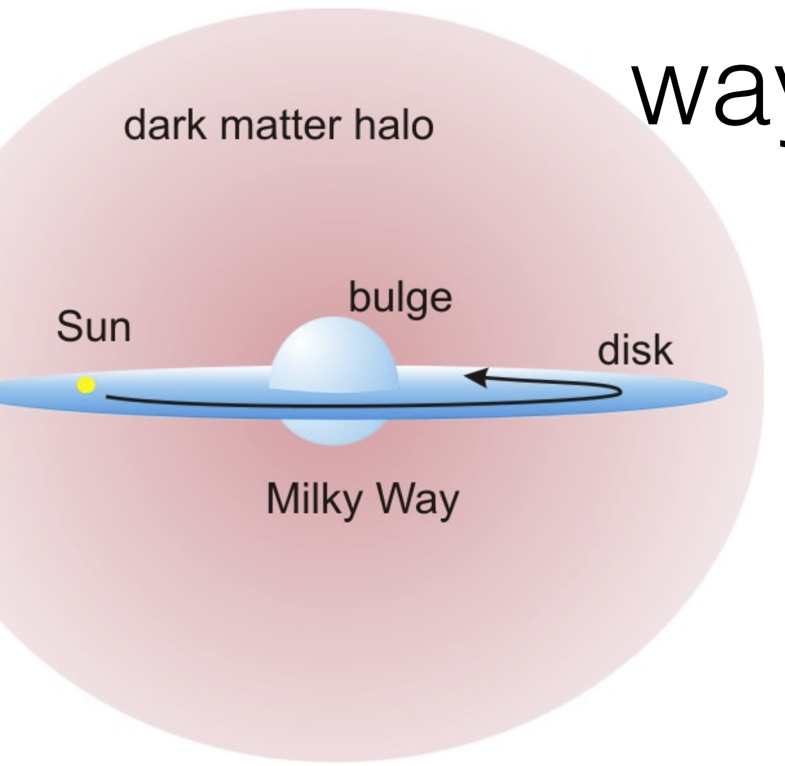
energy of the recoiled
(observed) nucleus



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 at low masses



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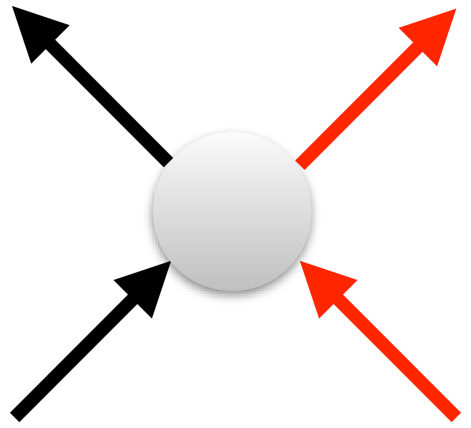
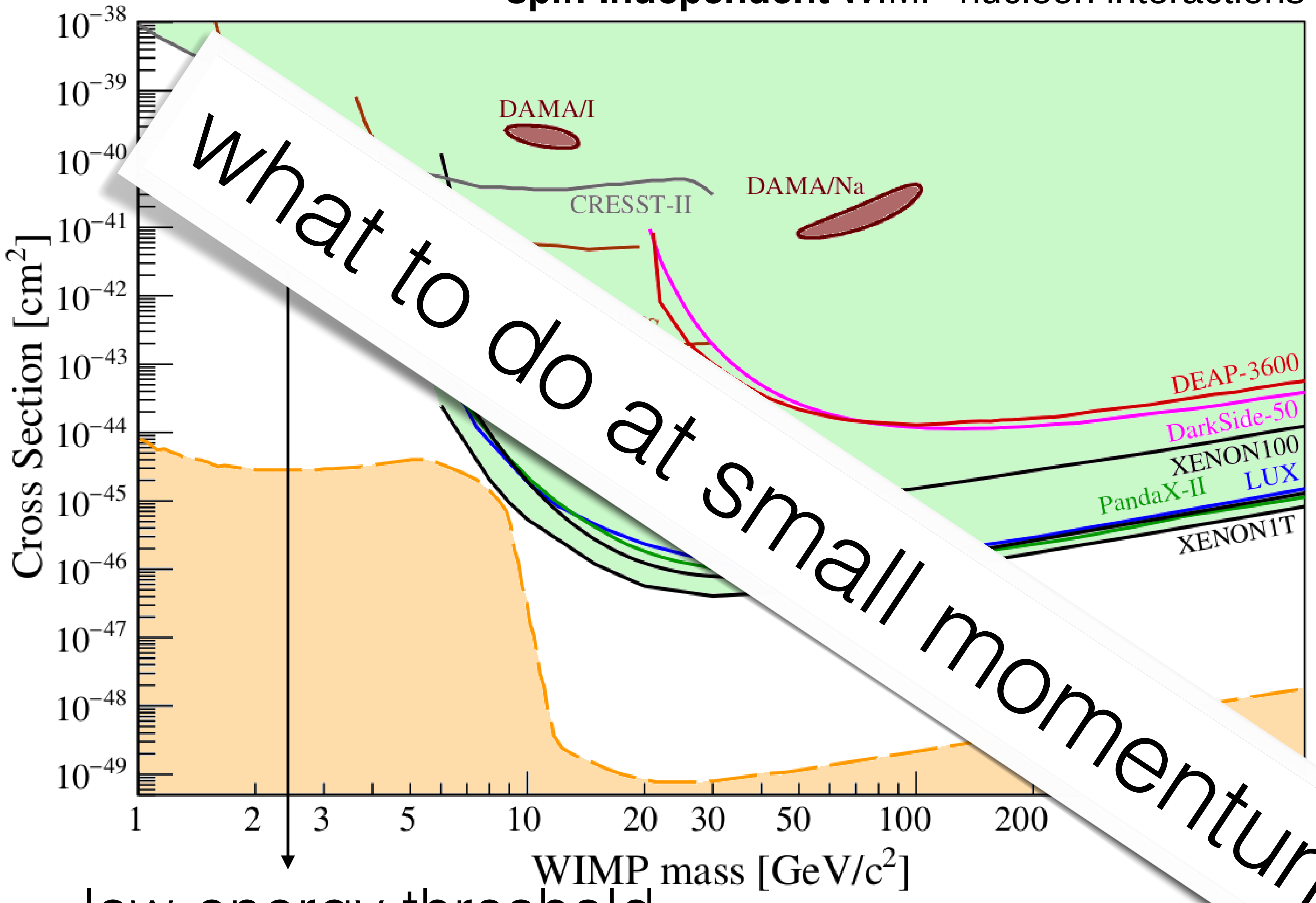


DM nucleus

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

energy of the recoiled
(observed) nucleus

spin-independent WIMP-nucleon interactions



what to do at small momentum transfer?

low-energy threshold

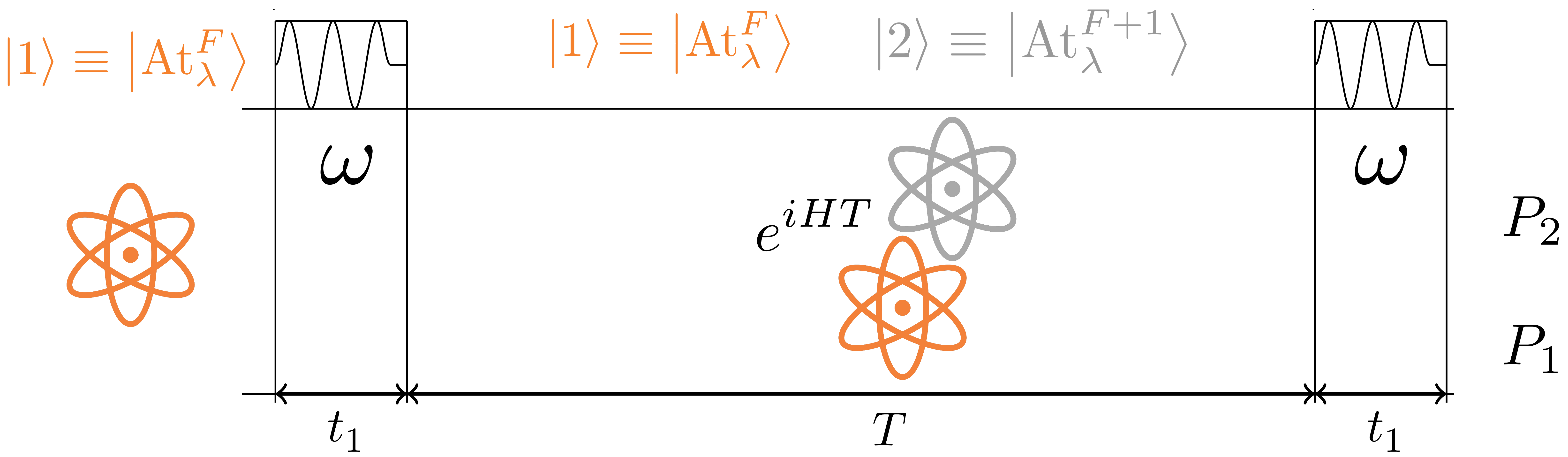
dramatic loss of sensitivity at low mass
when the momentum transfer is too small to generate a 'recoil'

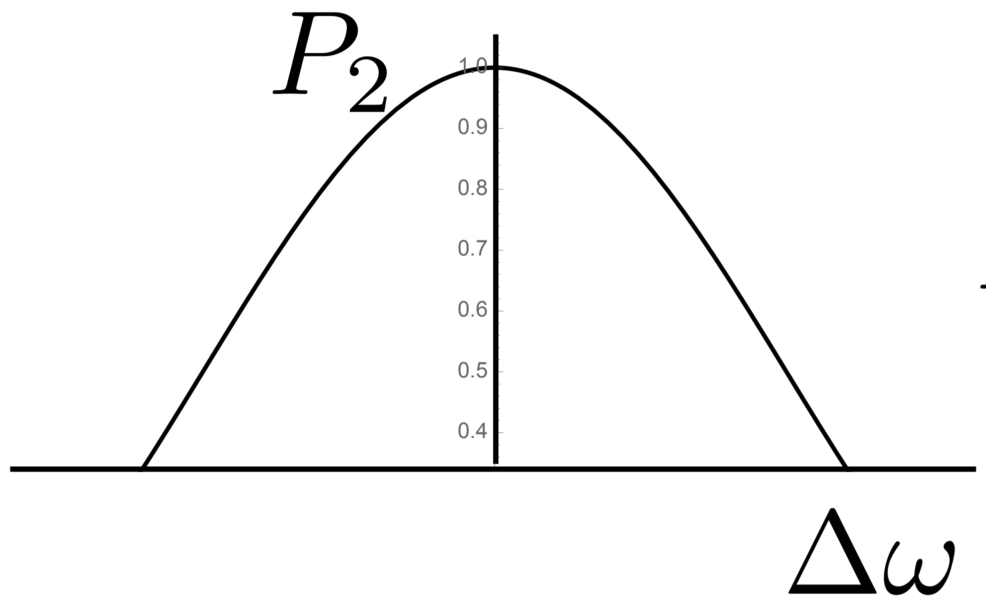
Measuring at $q = 0$: phase shifts in atomic systems

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

Du et al. 2205.13546

Ramsey sequence





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

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

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

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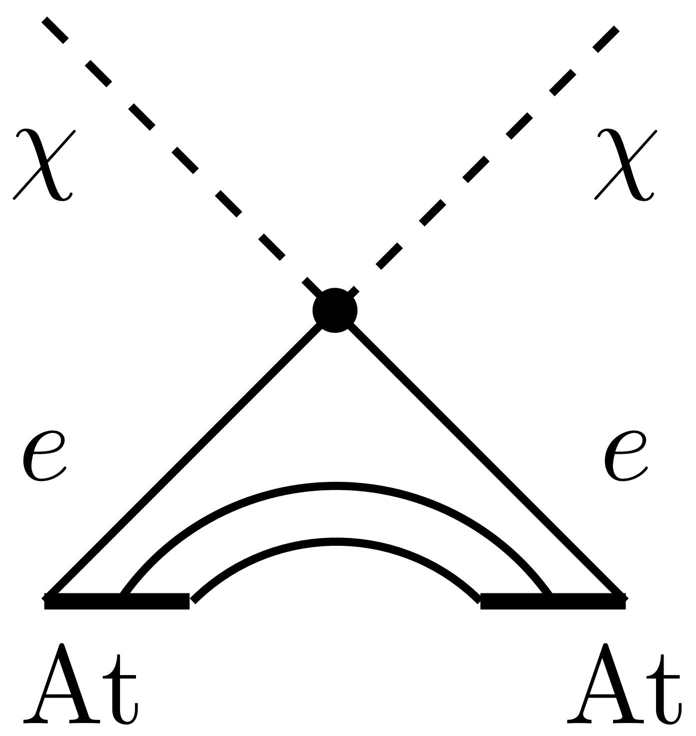
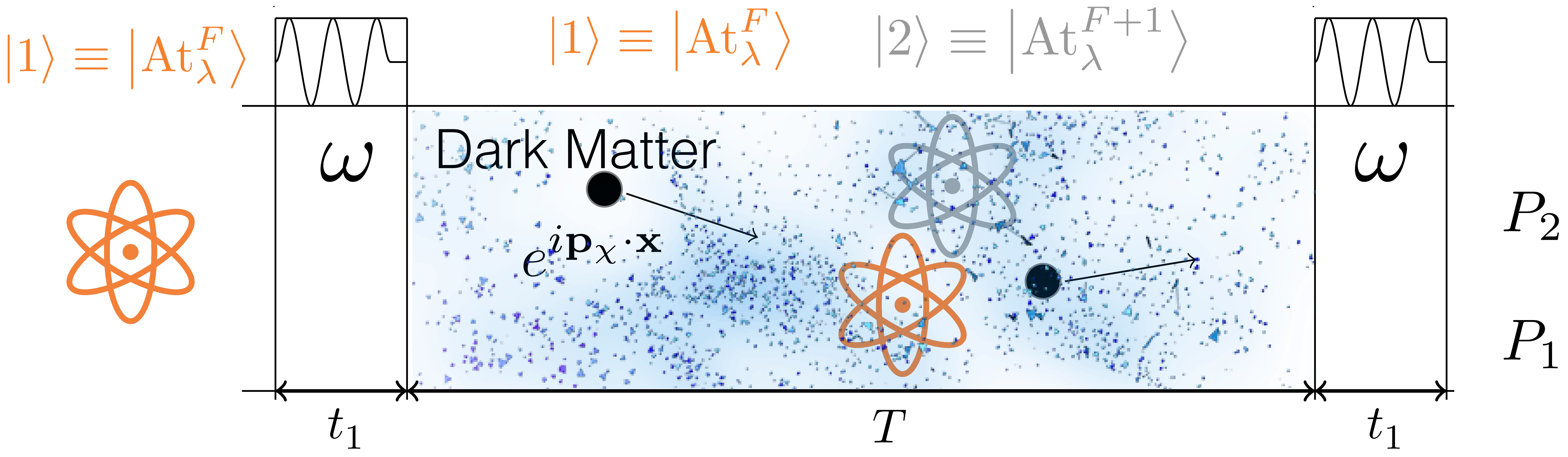
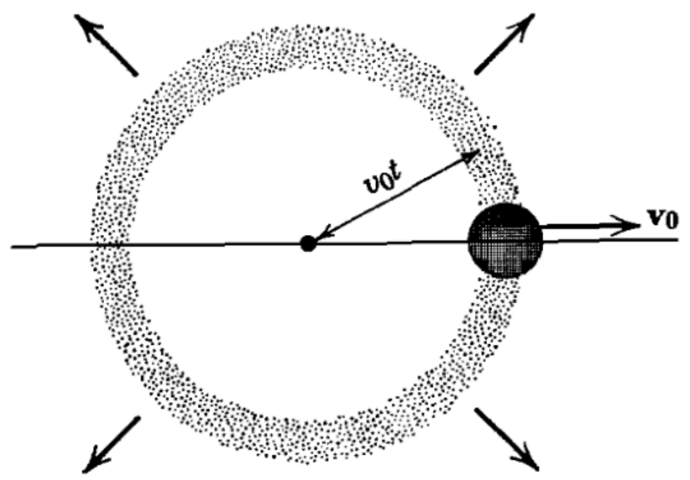
Ramsey sequence in the presence of DM







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

scattering amplitude at $q = 0$

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

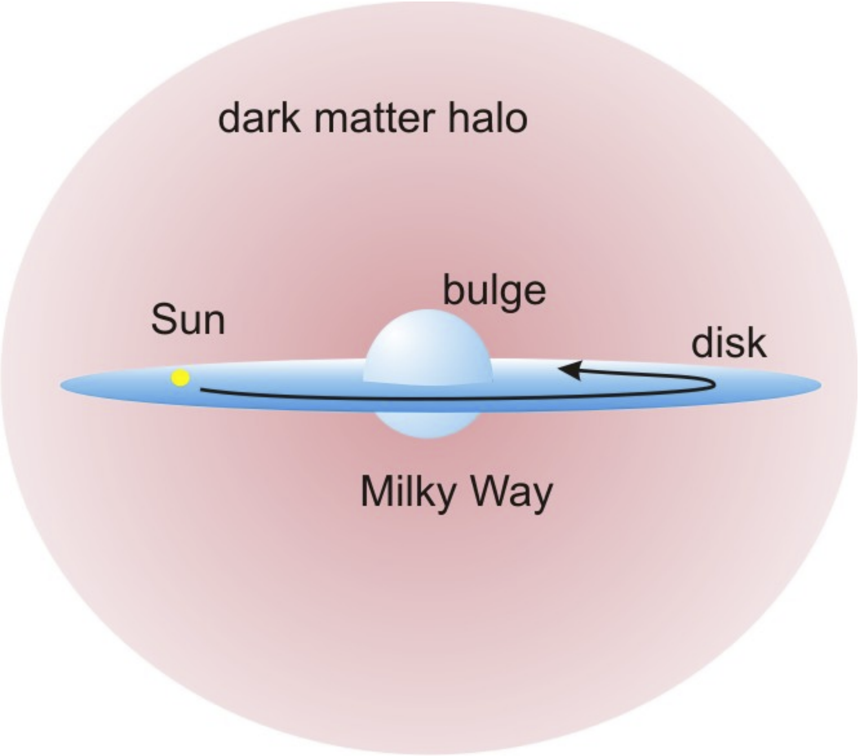
$$\partial P_2 = 0 \quad \Rightarrow \quad \omega_{\max} = \Delta E + \delta_{\mathrm{DM}}$$

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

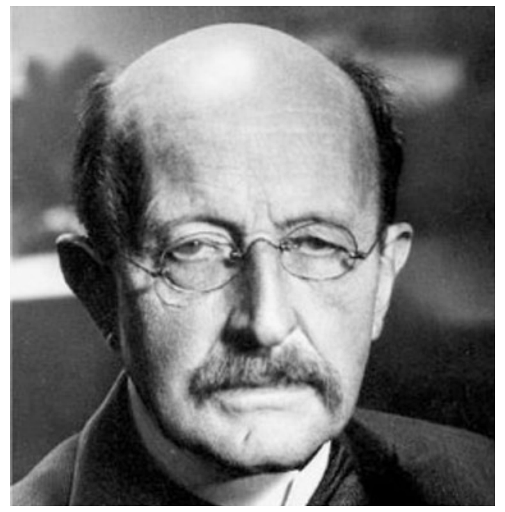
* axions are other DM candidates generating anomalous *B*. Also extra source of decoherence. Ask me!

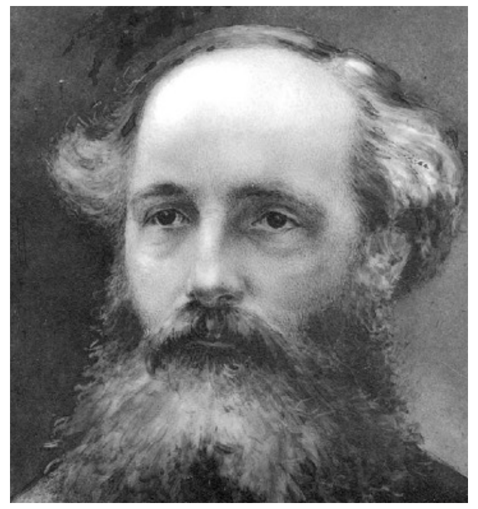
[Du, Murgui, Pardo, Wang, Zurek, 2023]

Dark Matter: which state?

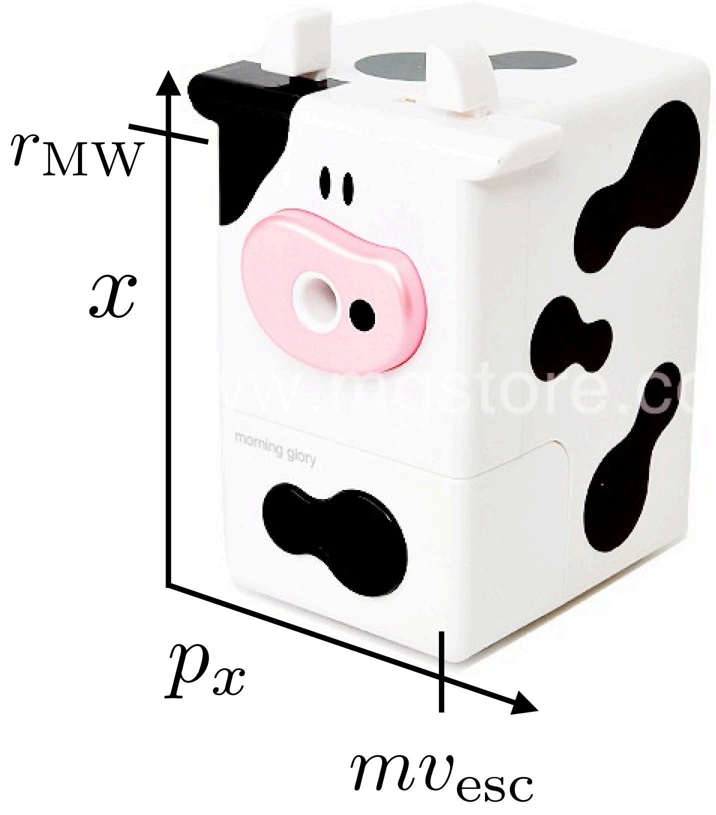


$\hbar\omega$





$F_{\mu\nu}$



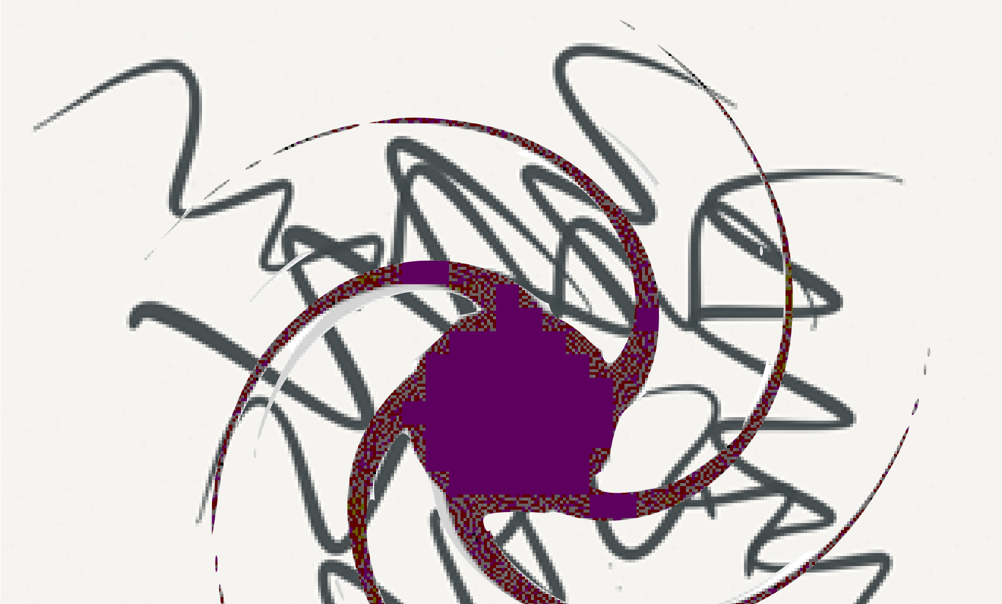
i) escape velocity $\sim 2\times 10^{-3}c$ ii) size $100\ \mathrm{kpc}$

$$\Delta x\Delta p \gtrsim \hbar \rightarrow N_s \sim 10^{75}\left(\frac{m}{\mathrm{eV}}\right)^3 \qquad N_p = \frac{M_{MW}}{N_s m} \sim 10^3\left(\frac{\mathrm{eV}}{m}\right)^4$$

$$m \lesssim 1\,\mathrm{eV} \rightarrow n^{-1/3} \lesssim \lambda_{\rm dB}$$

For ULDM, field has huge occupation numbers with random phases:

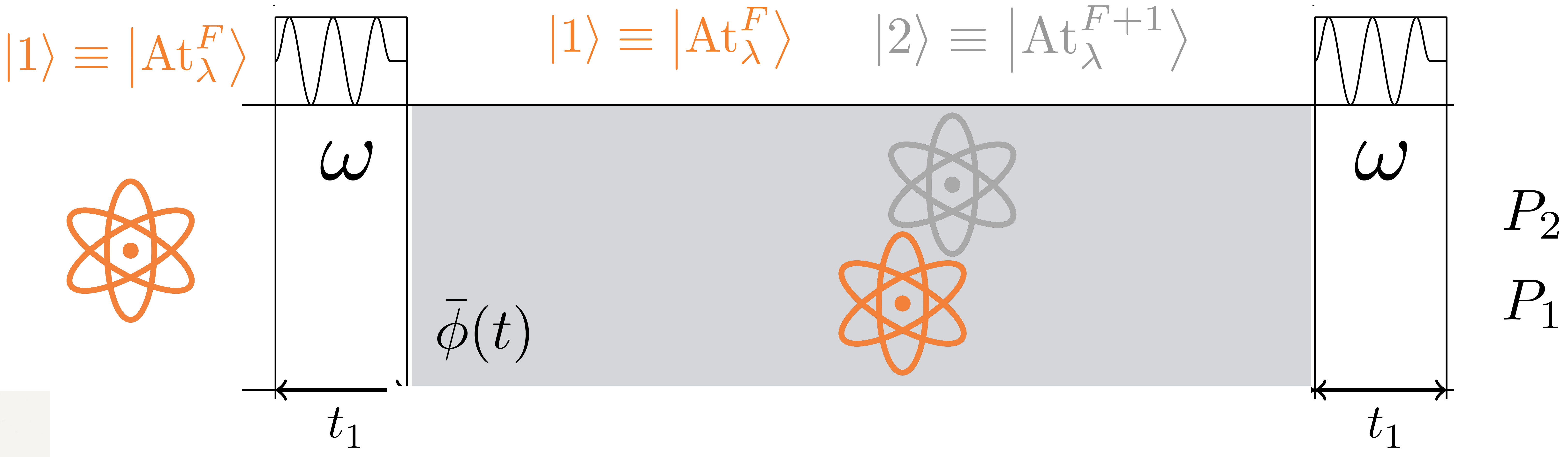
it can be treated as a classical field



$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu\phi)^2 - m^2\phi^2\right] \rightarrow \phi_k \sim e^{i(\omega t - kx)}$$

in a virialized halo

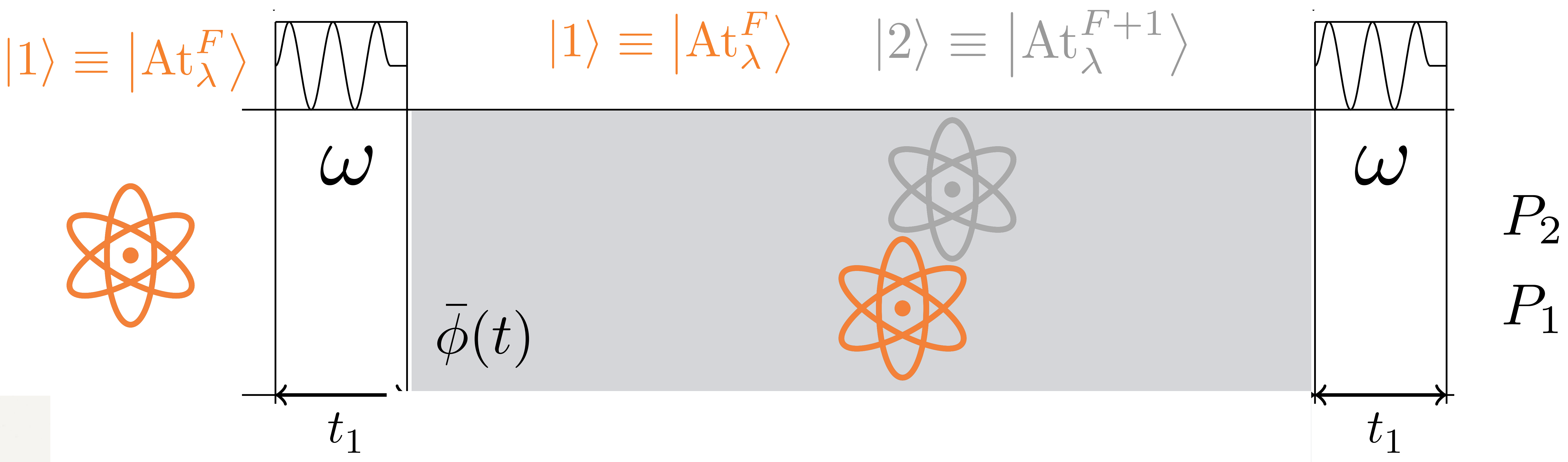
ULDM case



The atoms live in a background with some coherent features and for certain dark matter models

$$V_2 - V_1 \neq 0$$

ULDM case



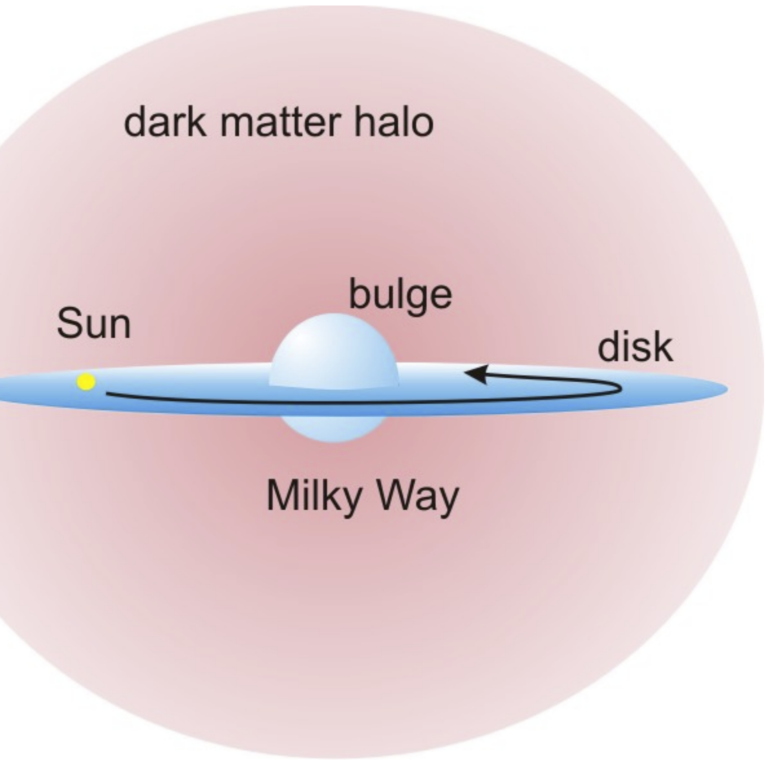
The atoms live in a background with some coherent features and for certain dark matter models

$$V_2 - V_1 \neq 0$$

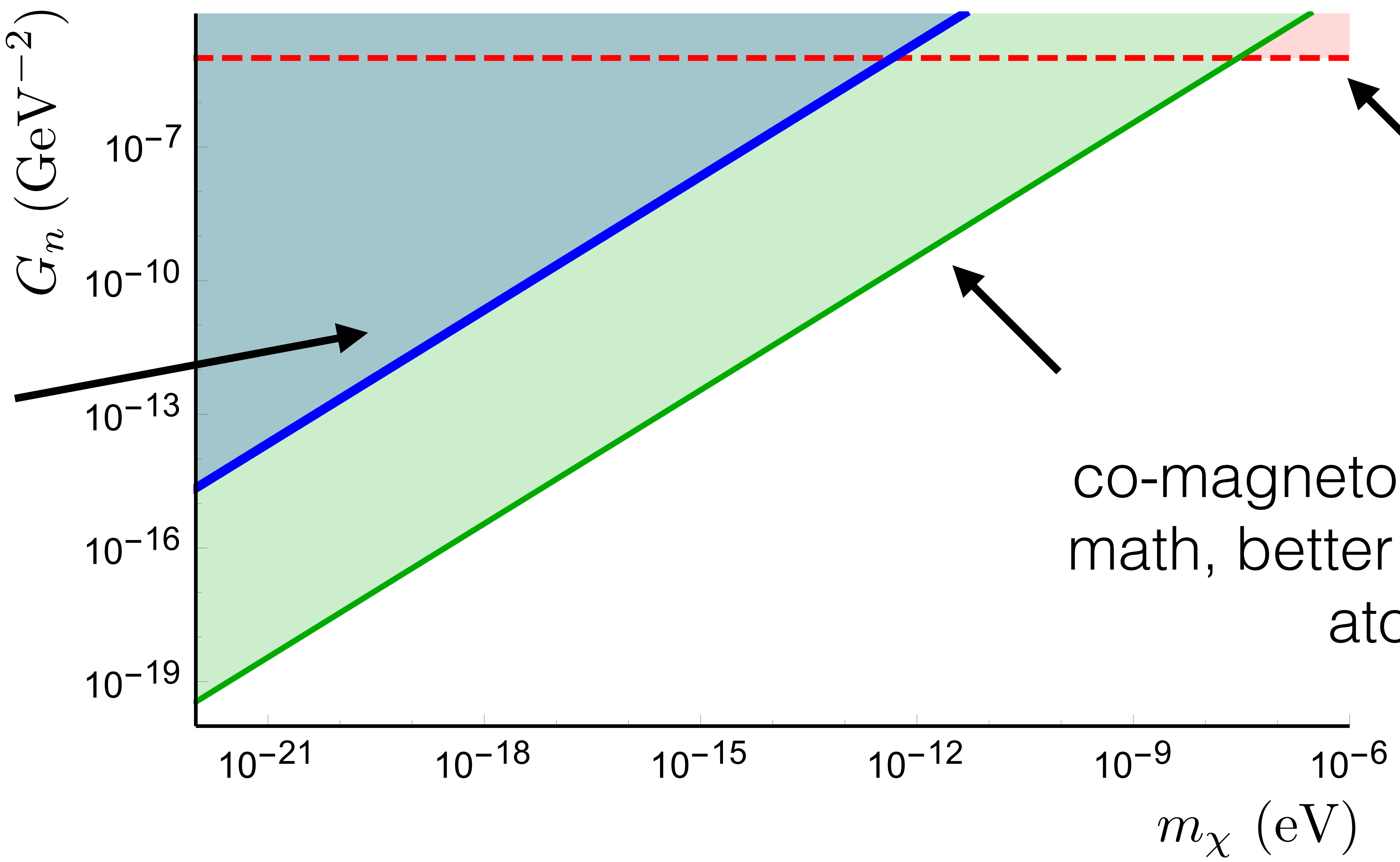
One example: complex scalar DM

Alonso, DB, Wolf 1810.00889

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



atomic clocks



previous bounds (astrophysics)

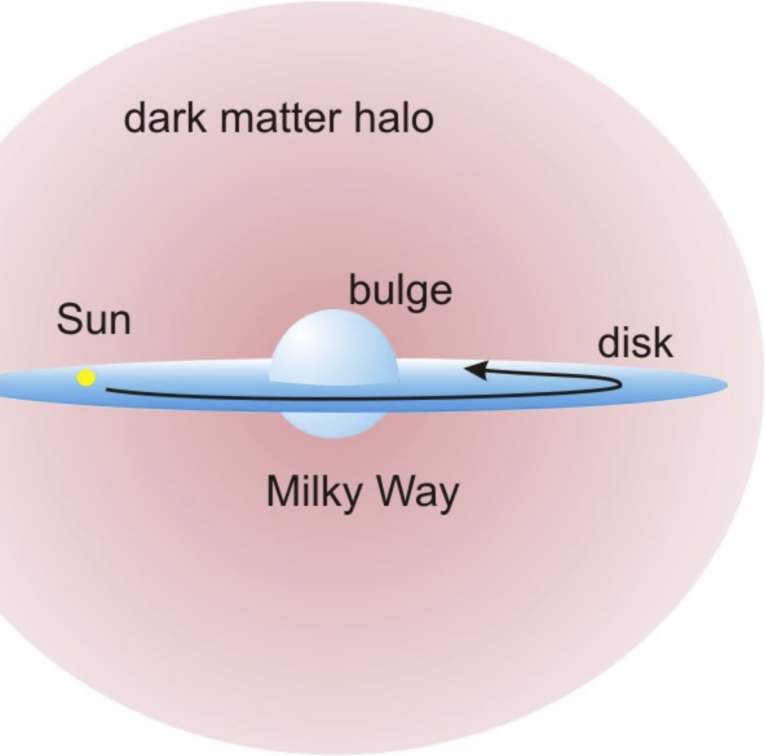
co-magnetometers (same math, better system. More atoms)

One example: complex scalar DM

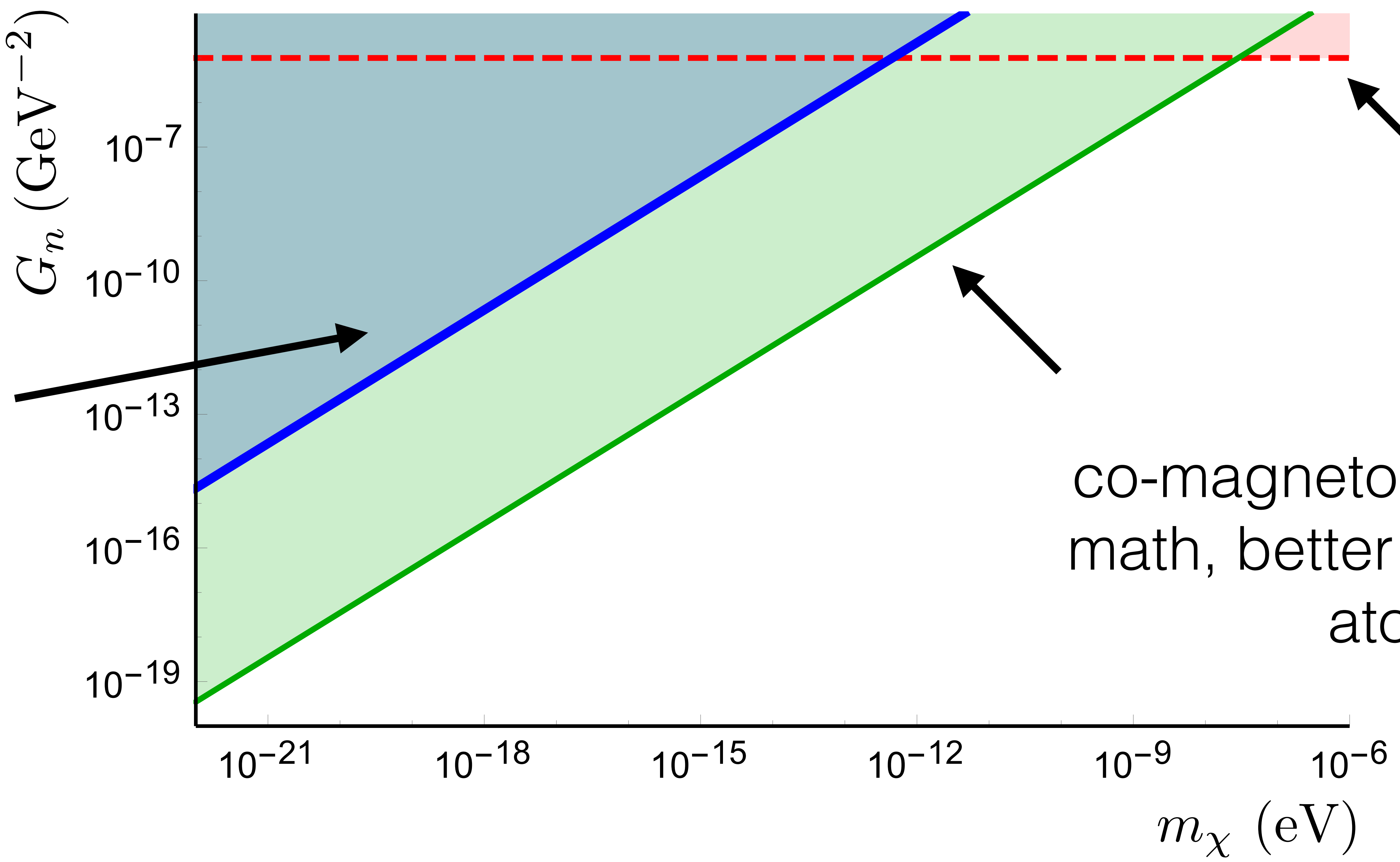
Alonso, DB, Wolf 1810.00889

nucleons DM

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



atomic clocks



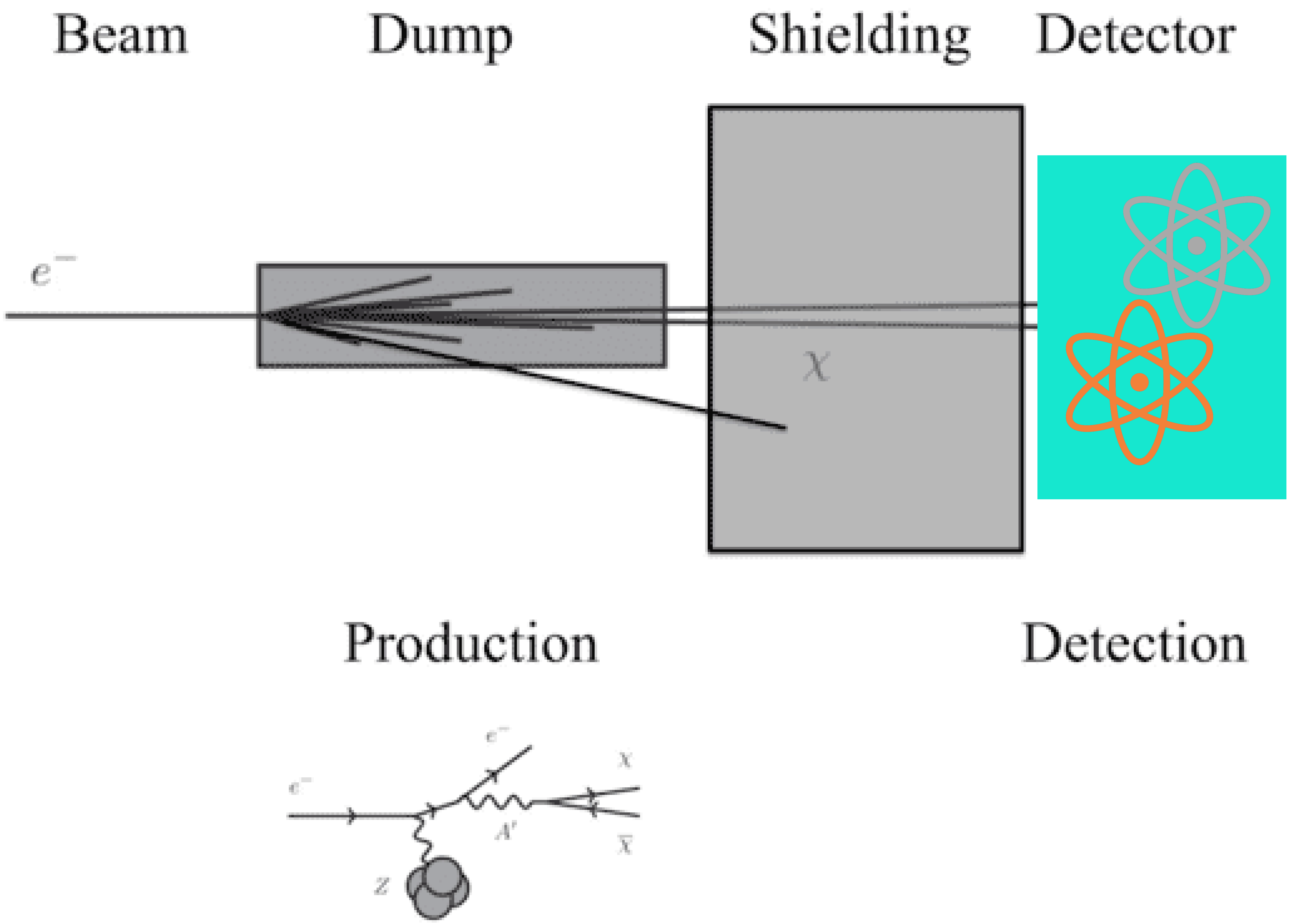
previous bounds (astrophysics)

co-magnetometers (same math, better system. More atoms)

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

May also be relevant for machine made backgrounds

advantage of being table top

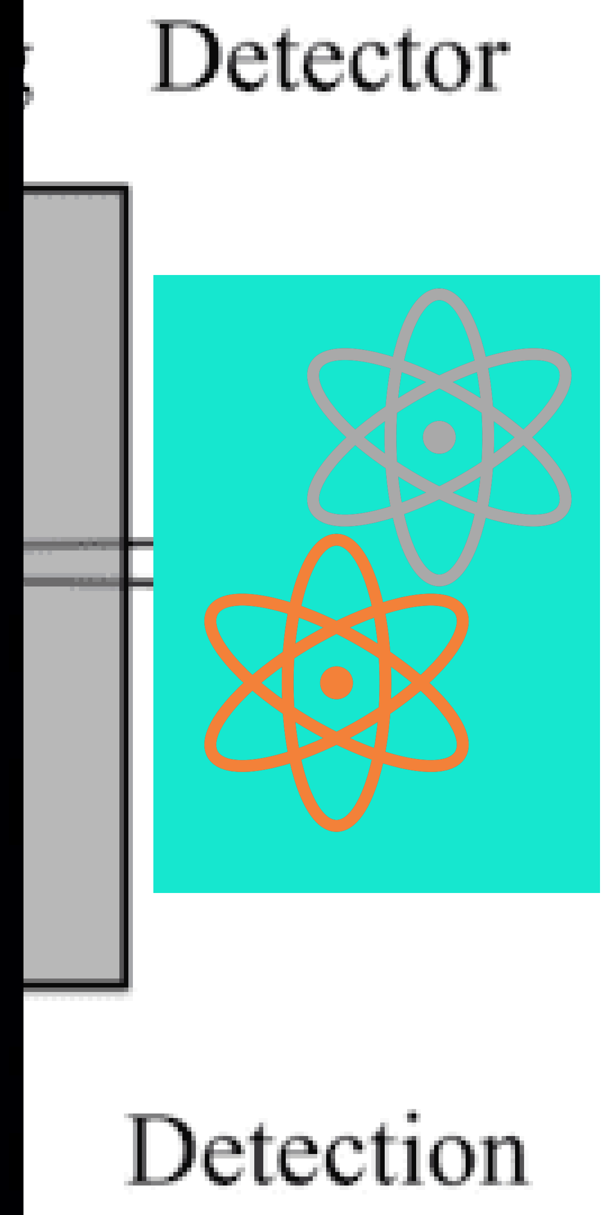


“no” energy-threshold:
sensitive to whole flux

fig. adapted from 1712.01518

May als… e made backgrounds

e top

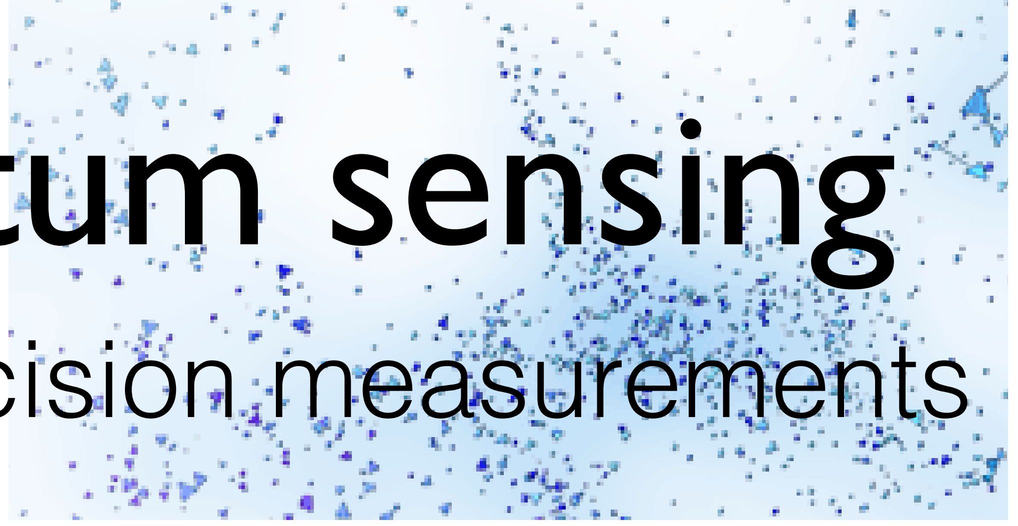


"no" energy-threshold: sensitive to whole flux

fig. adapted from 1712.01518

Connection to quantum sensing

How do these backgrounds affect precision measurements



Part II: three (biased) examples

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

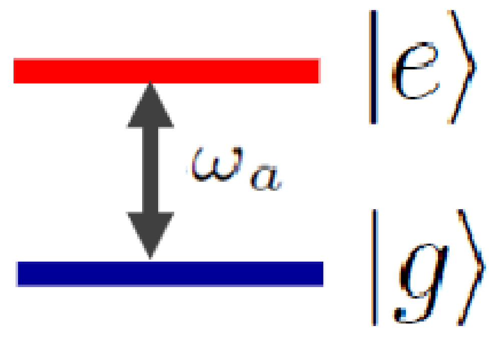
ii) Large atomic interferometers

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

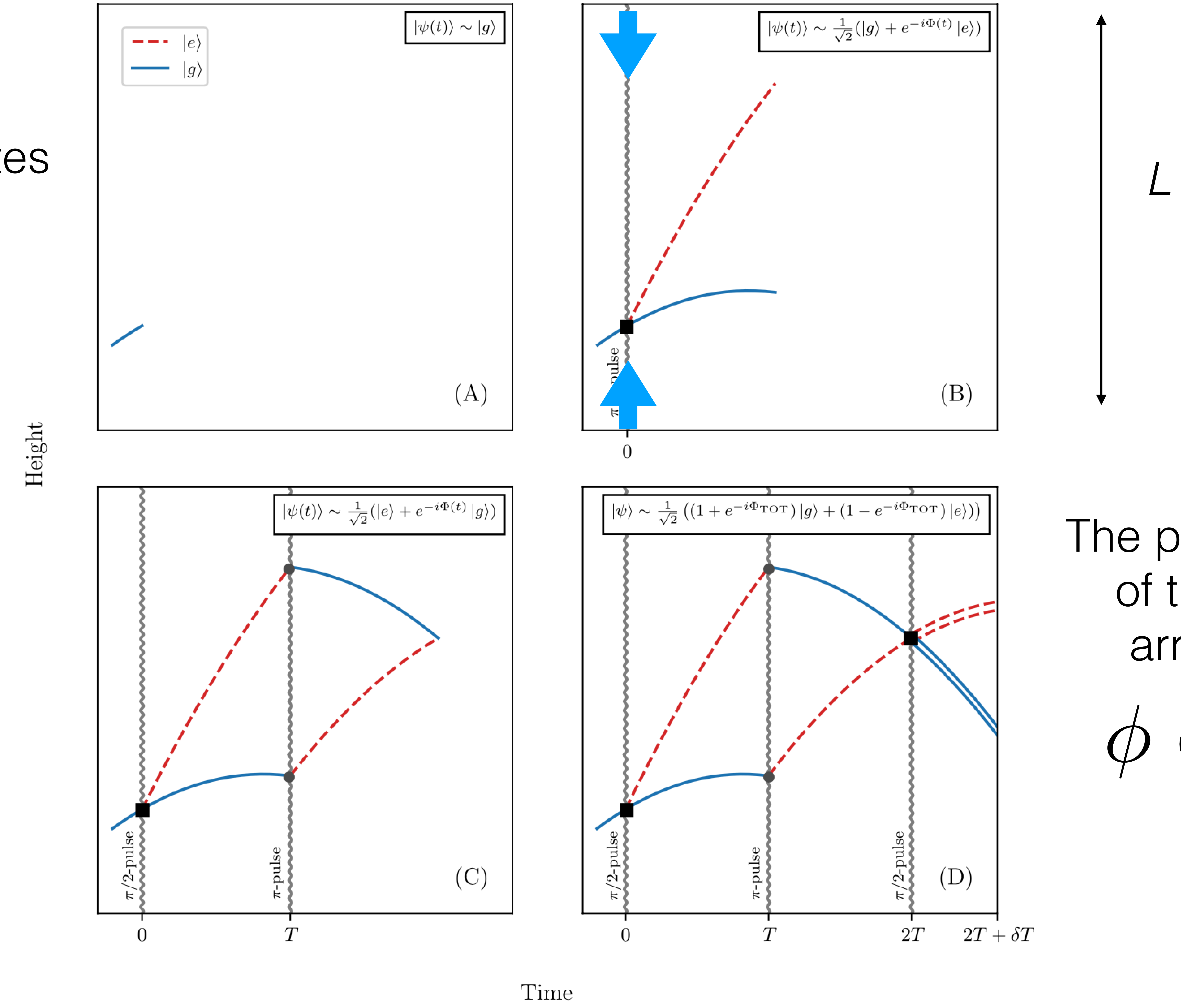
Long-baseline atomic interferometers

Dimopoulos et al 0712.1250
0806.2125
Arvanitaki et al 1606.04541

Basic concept:
atoms in free fall
with two possible states



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

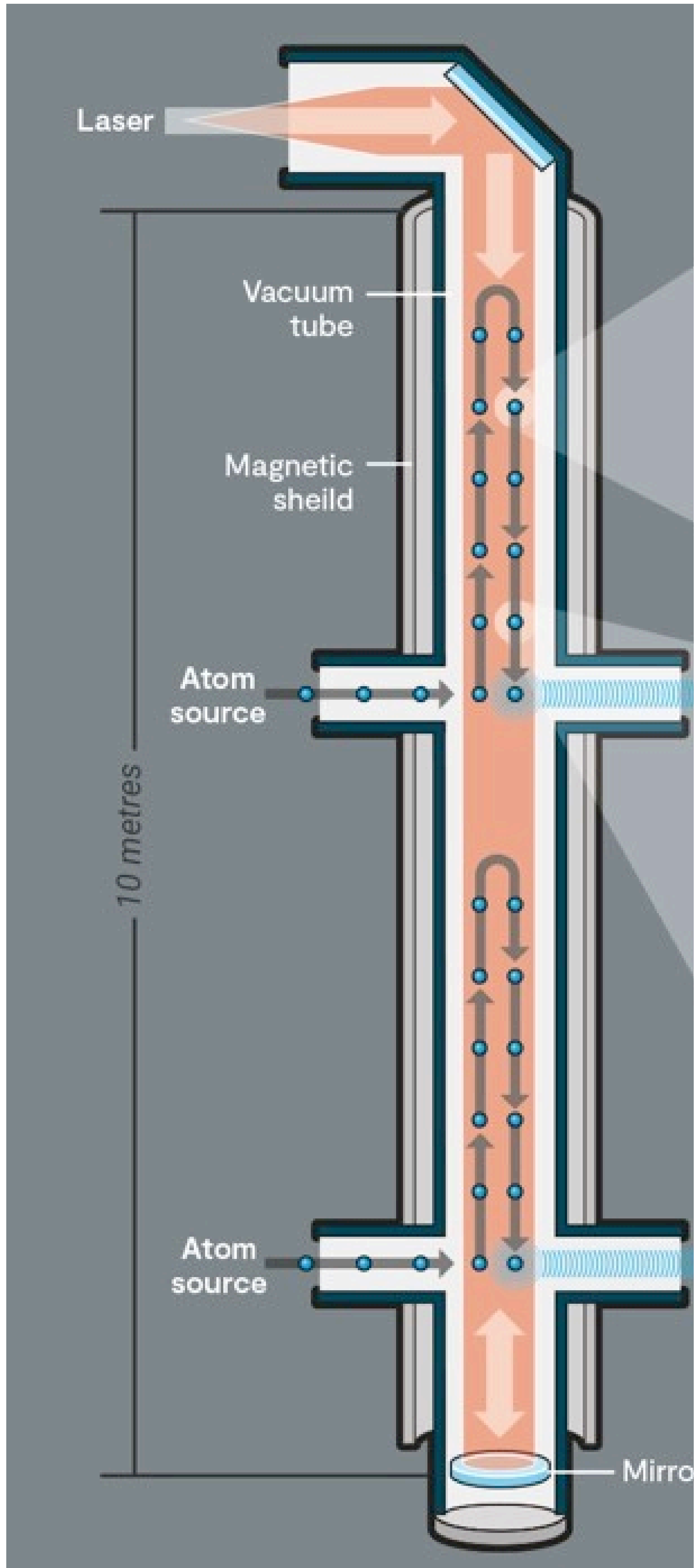


The phase difference
of the two states
arranged to be

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

Optimized with more than one AI

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



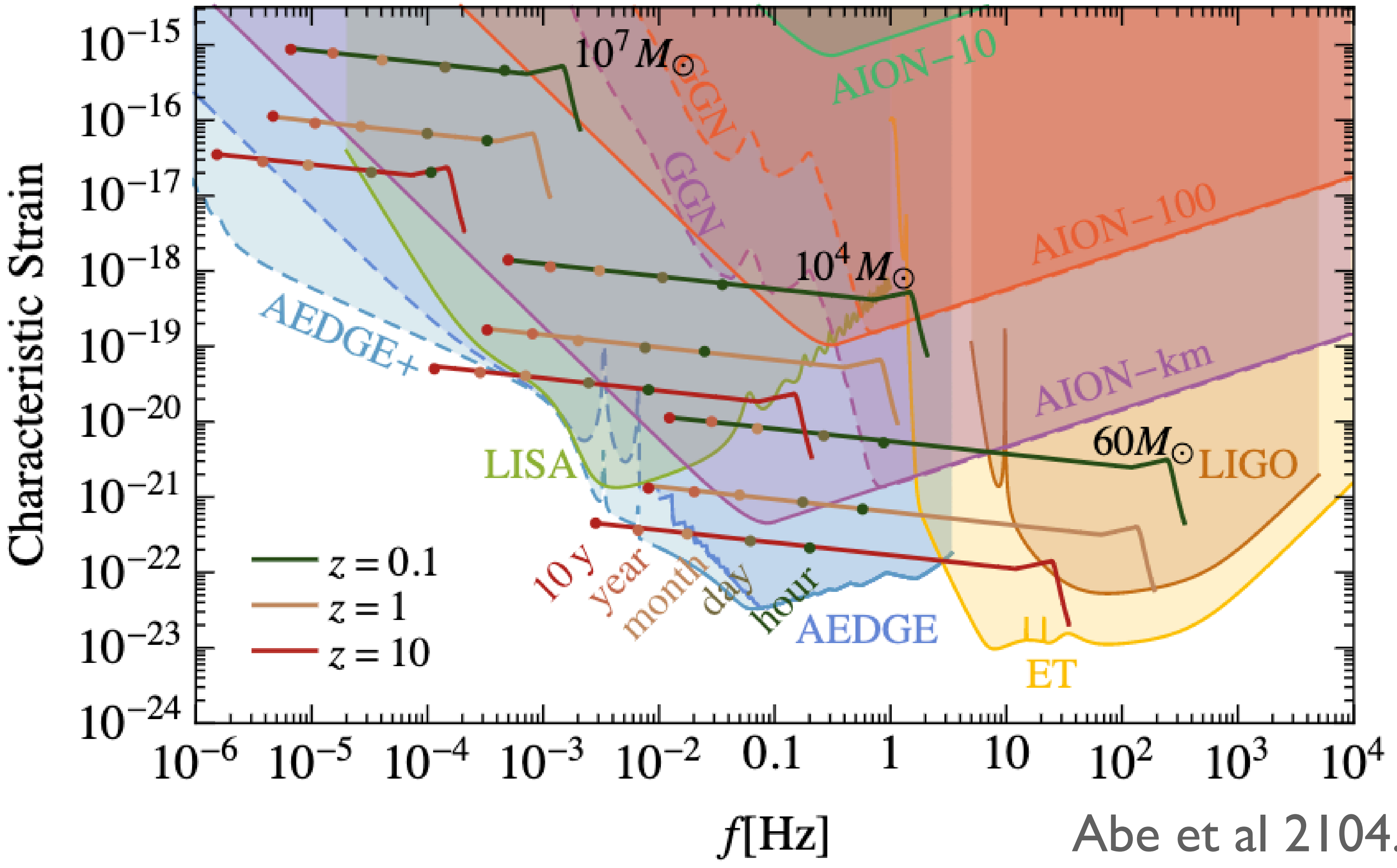
GWs (h) change distances

$$\delta L \sim hL$$

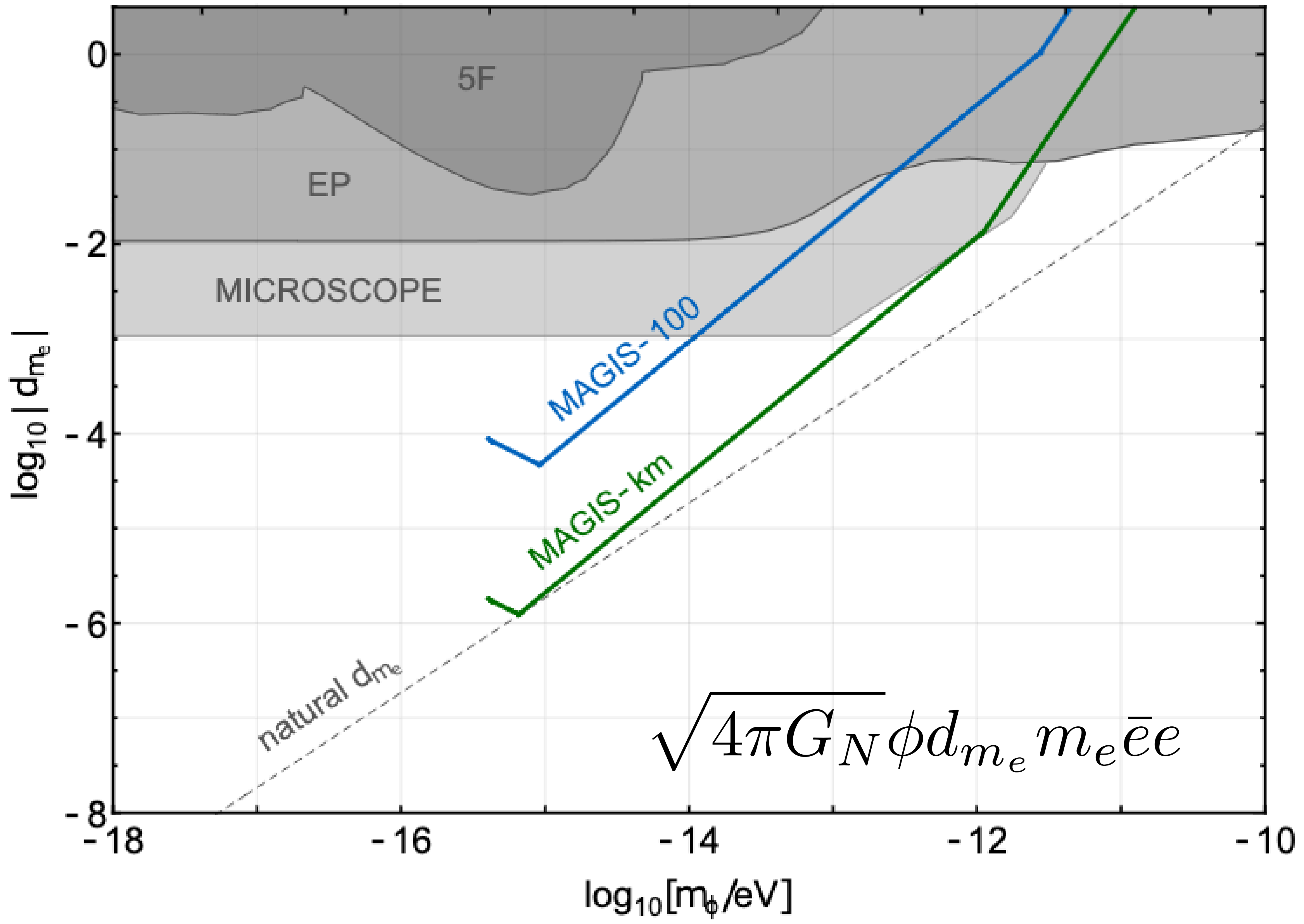
$$\phi \propto \omega_A L/c$$

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

eg. Arduini et al 2304.00614
Buchmuller et al 2306.17726

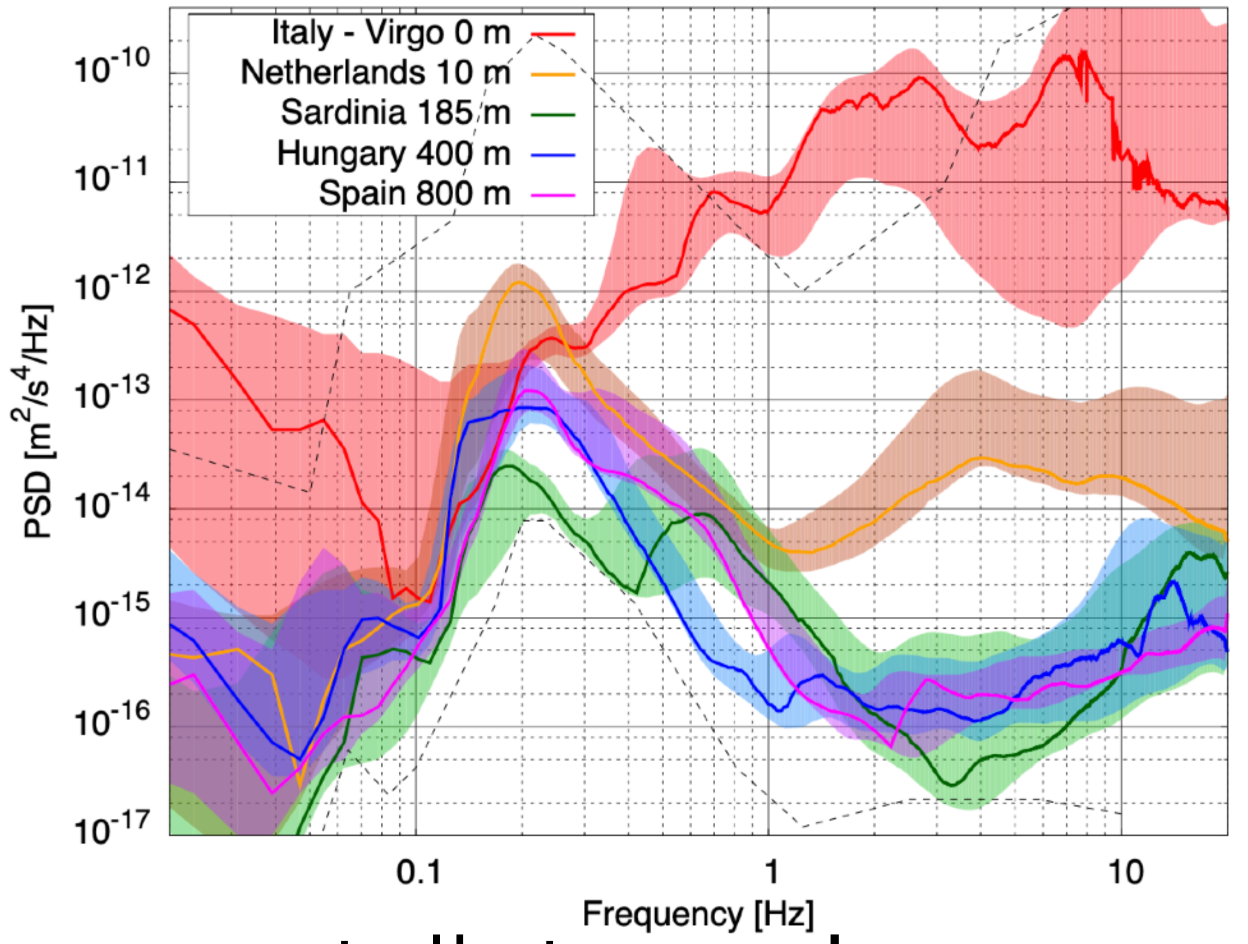
Site location:

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?

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

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



talk to me!

eg. Arduini et al 2304.00614
Buchmuller et al 2306.17726

Site

Status

IS

etric Sensor (MAGIS-100), 100 m

ale atom interferometer, Sci. Rep. **8** ~ 200 m?

itation and Atom-interferometric
rXiv:1911.03701]. ?

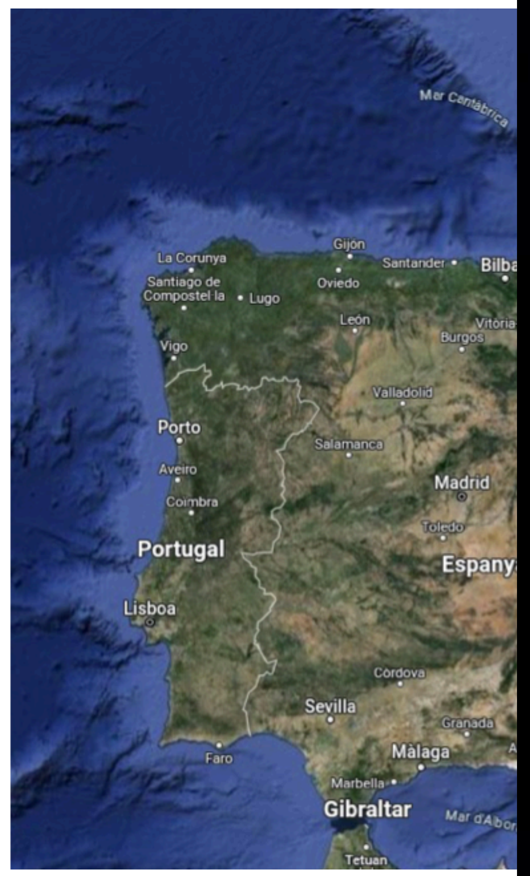
nterferometer Gravitation Antenna, Int.
3]. ~ 300 m?

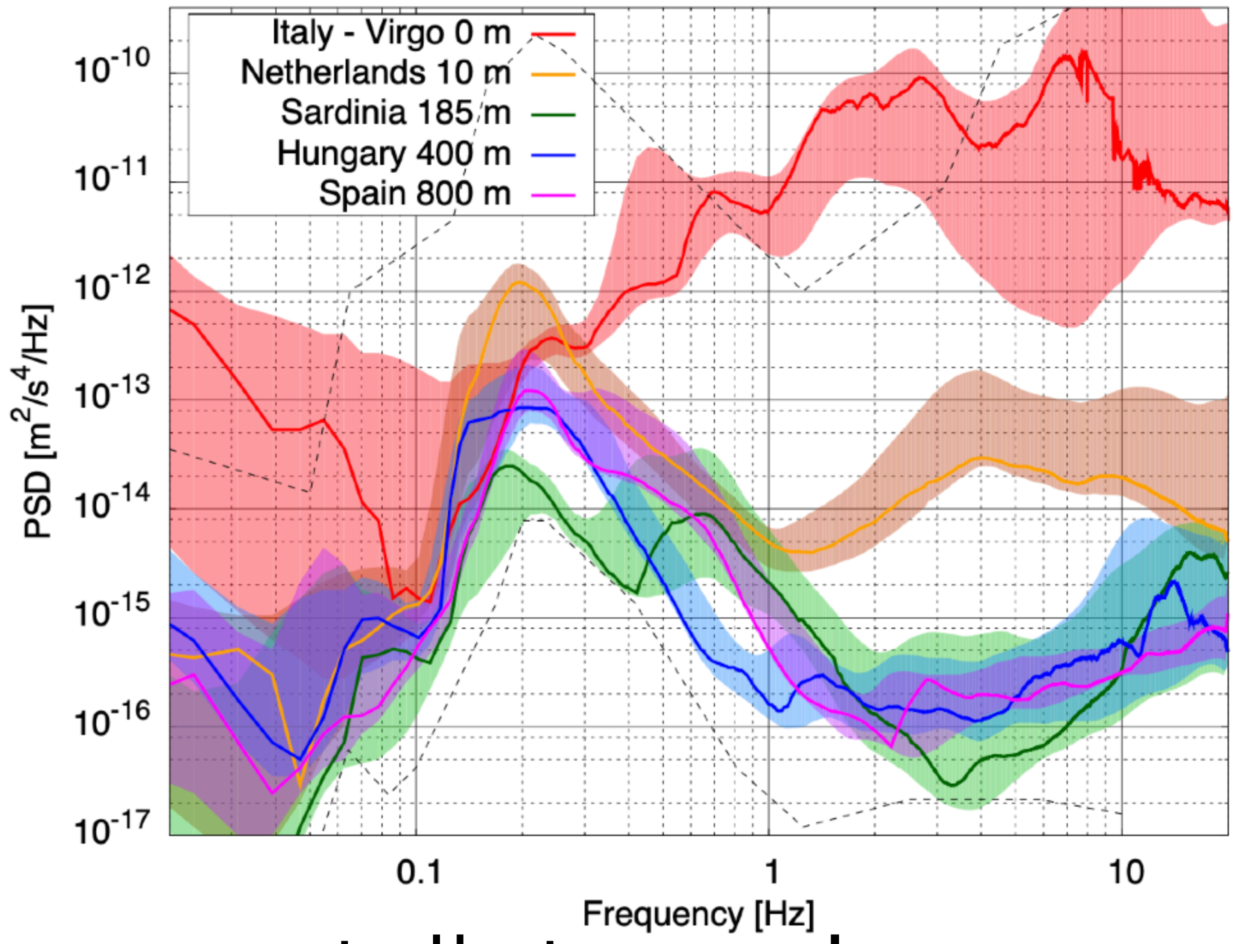
atory and Network, JCAP **05** (2020) 10 m

mic Experiment for Dark Matter and
6, [arXiv:1908.00802]. 40 km?

Current sear ... ERN? Boulby (UK)? **Canfranc** (Spain)?)

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

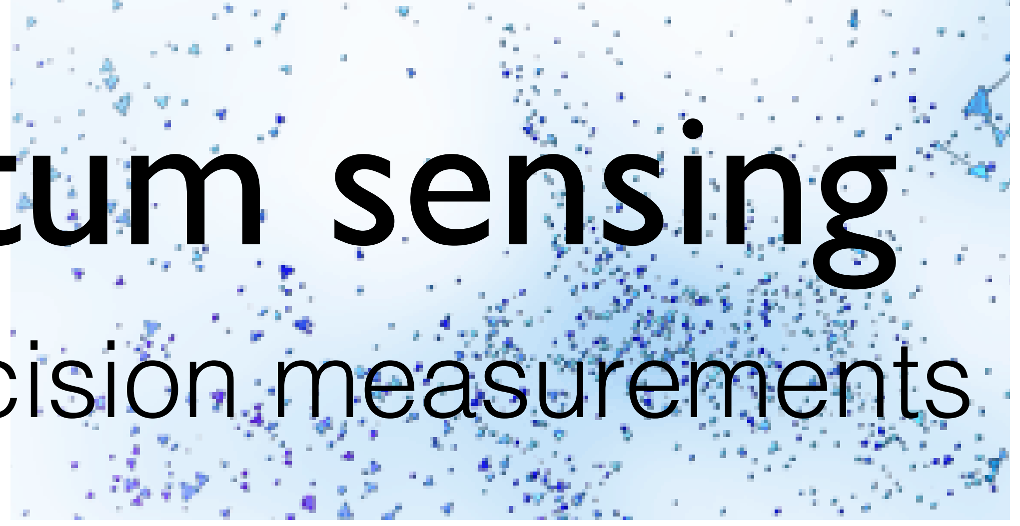




talk to me!

Connection to quantum sensing

How do these backgrounds affect precision measurements



Part II: three (biased) examples

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

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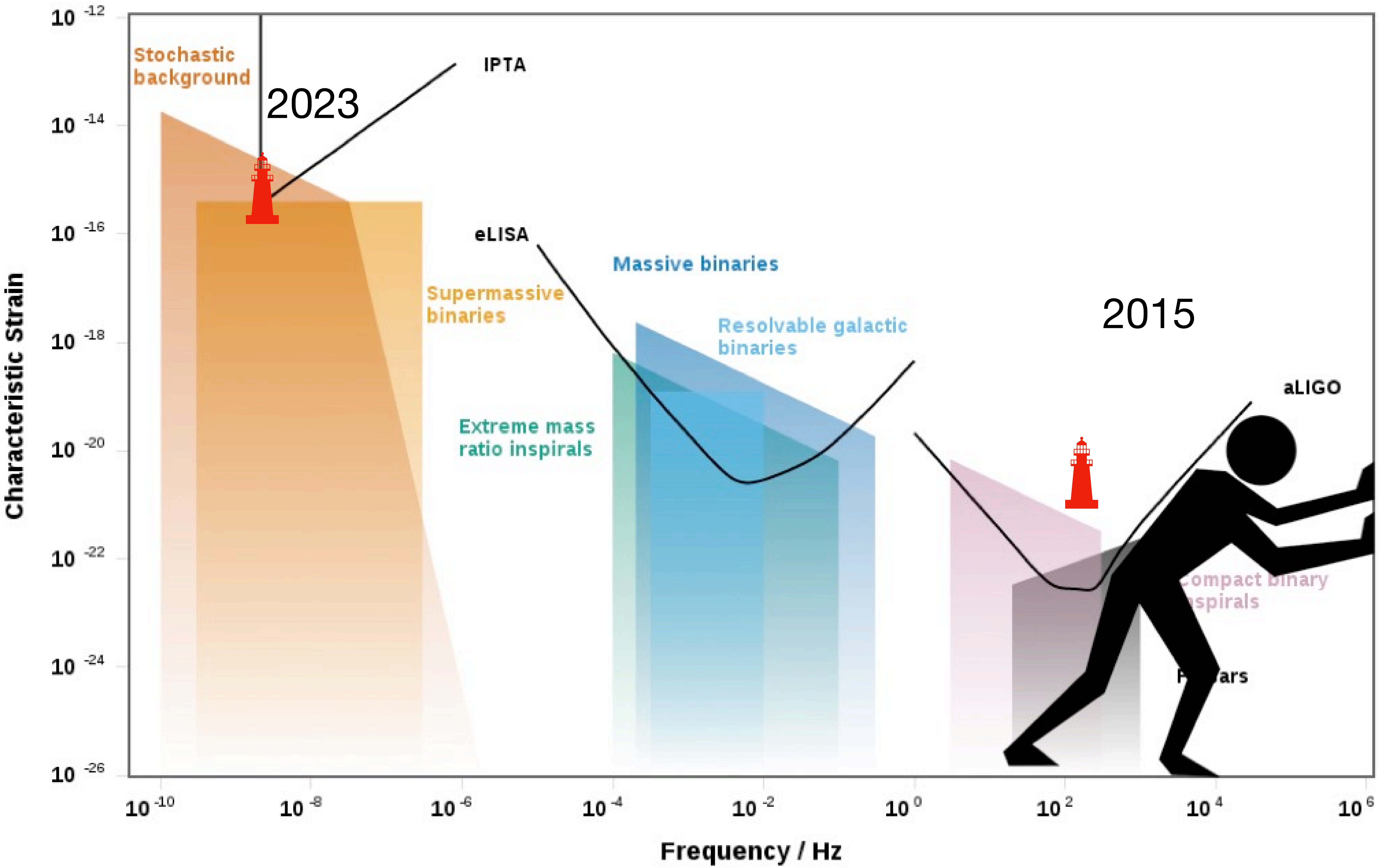
Detection of high frequency gravitational waves?



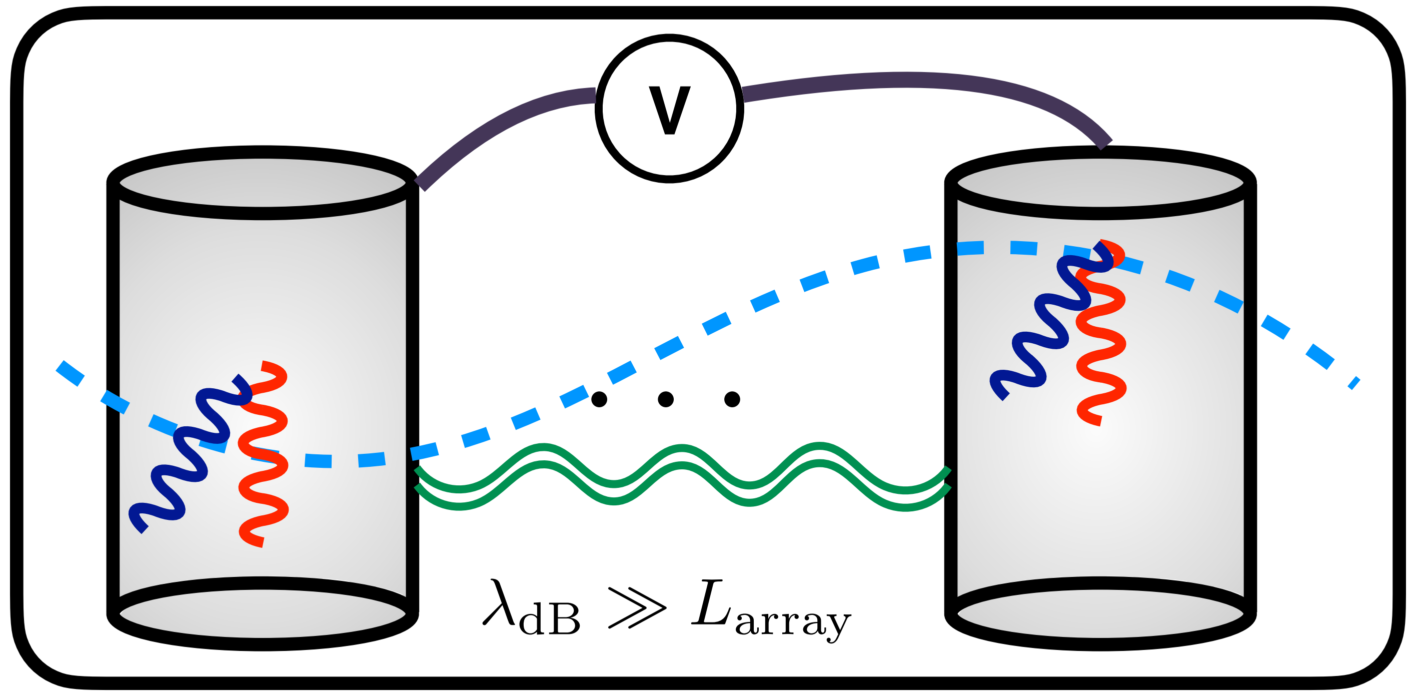
https://www.ctc.cam.ac.uk/activities/UHF-GW.php

High frequency implies small wavelength

GWs interact with everything in the laboratory!

Cavities (cm -> GHz)

coherent measures are also possible



Interaction of GWs & axions with cavities: 2 cases

axion $\mathcal{H}_a \supset \boxed{-g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}} \boxed{- g_{a\psi} (\nabla a) \cdot \mathbf{\Sigma}_\psi} \boxed{- d_{a\psi} a \mathbf{E} \cdot \mathbf{\Sigma}_\psi}$

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

EM coupling

Mechanical coupling

Spin coupling

Interaction of GWs & axions with cavities: 2 cases

axion $\mathcal{H}_a \supset \boxed{-g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}} \boxed{-\, g_{a\psi}(\nabla a)\cdot \mathbf{\Sigma}_\psi} \boxed{-\, d_{a\psi} a \mathbf{E}\cdot\mathbf{\Sigma}_\psi}$

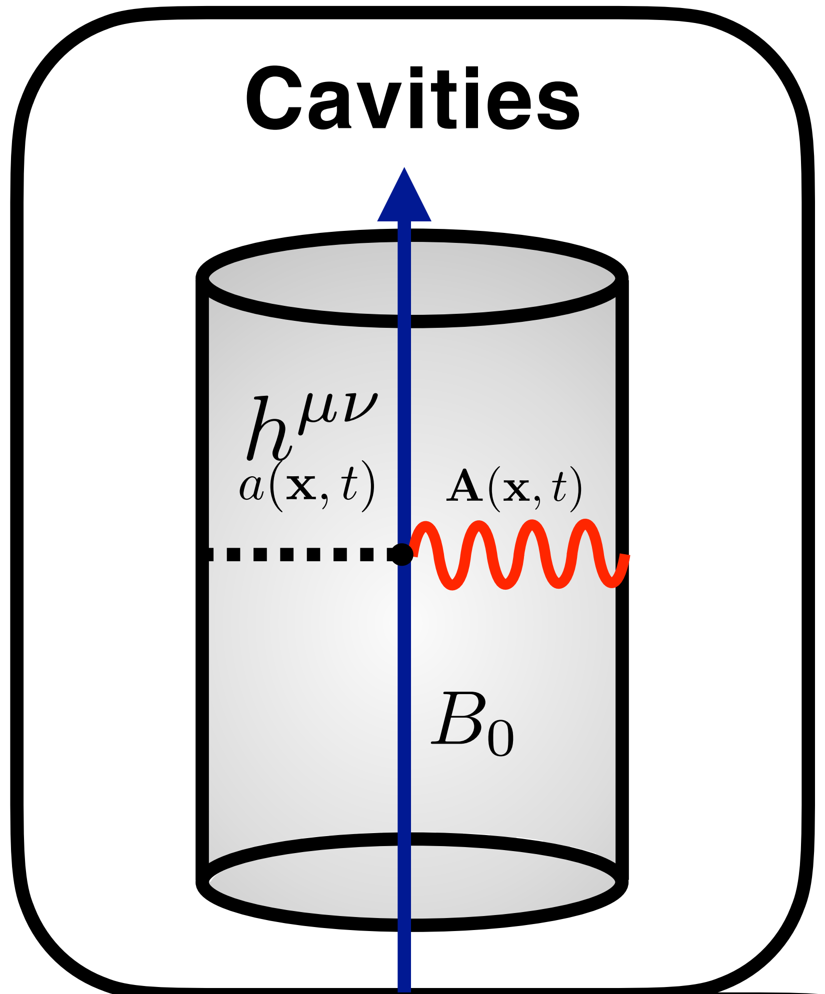
gws $\mathcal{H}_{gw} \supset \boxed{A^\nu \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h^\nu_\alpha F^{\alpha\mu} - h^\mu_\alpha F^{\alpha\nu}\right)} \boxed{+ B_i h_{ij}(t_\psi)\Sigma^j} \boxed{+ m_\psi \ddot{h}_{ij}(t_\psi) x^i_\psi x^j_\psi}$

EM coupling

h+EM field = current!

axion+B = current

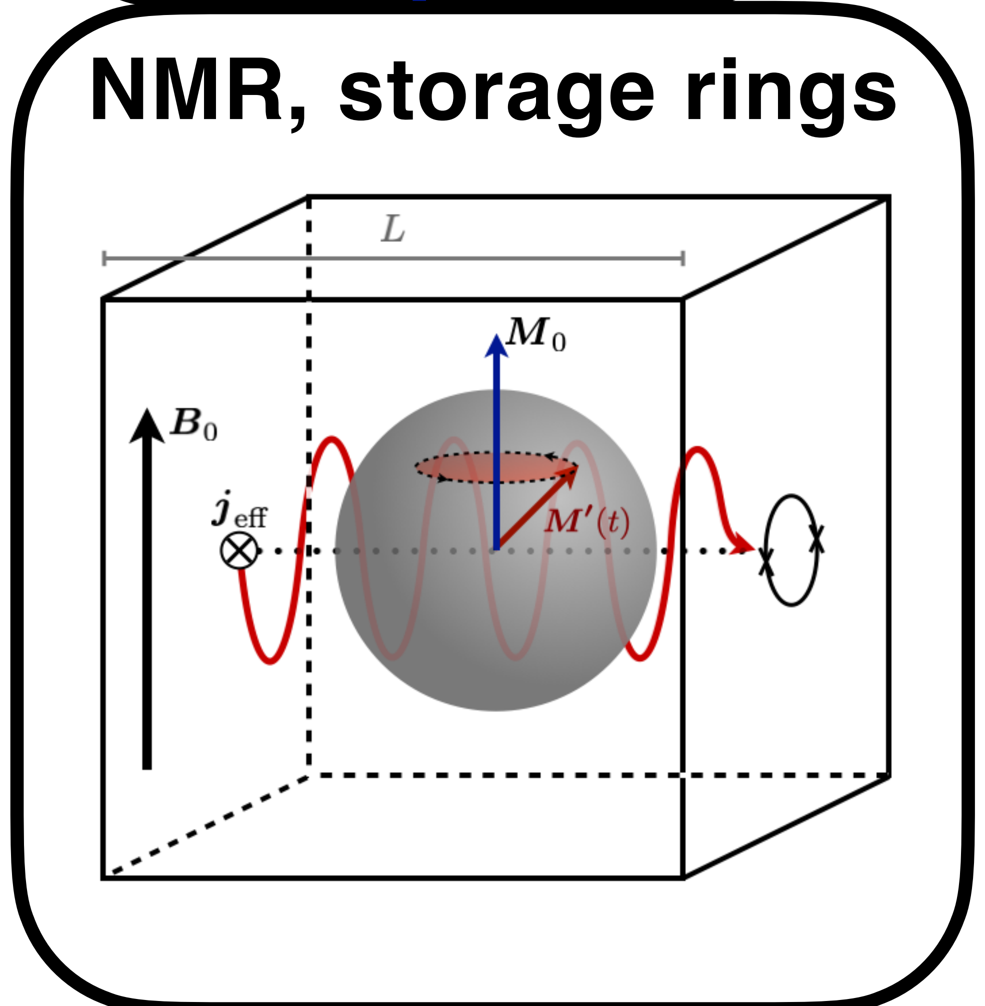
Raffelt Stodolsky 87



Spin coupling

anomalous B

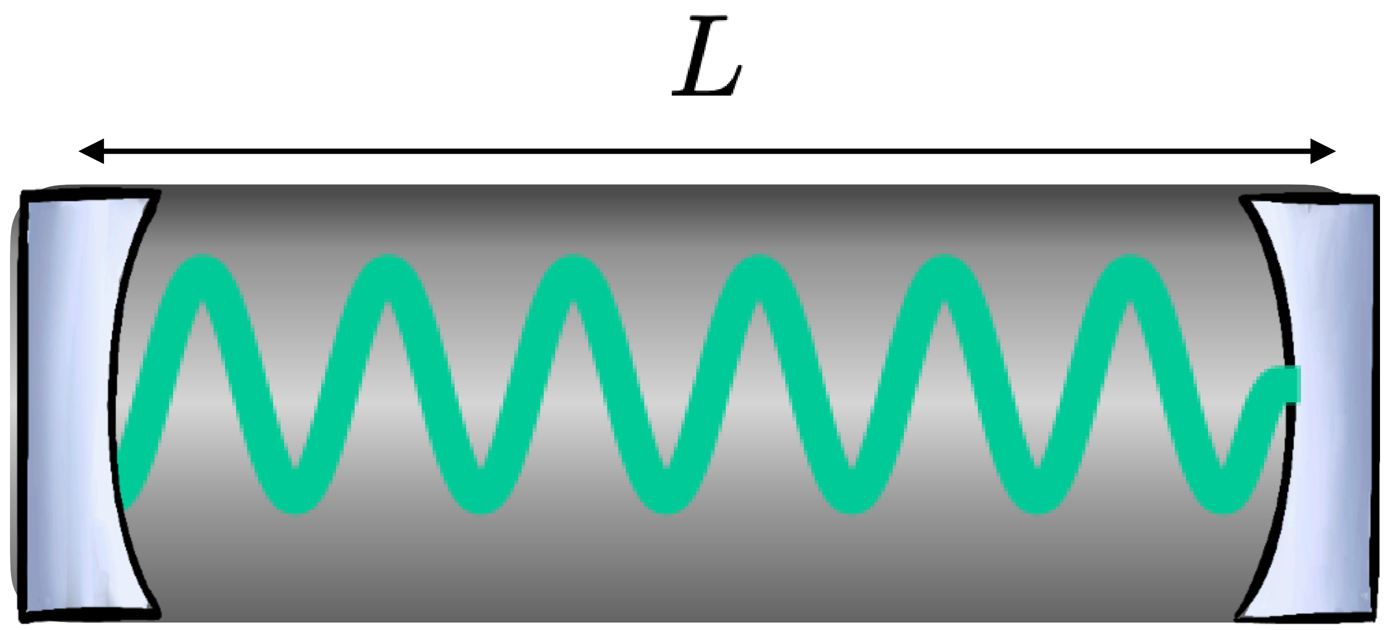
NMR



Mechanical coupling

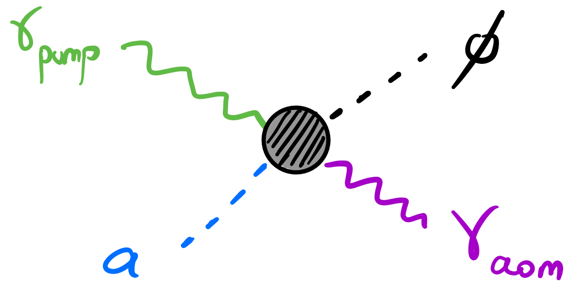
$$\delta L \sim hL$$

(shaking the walls)



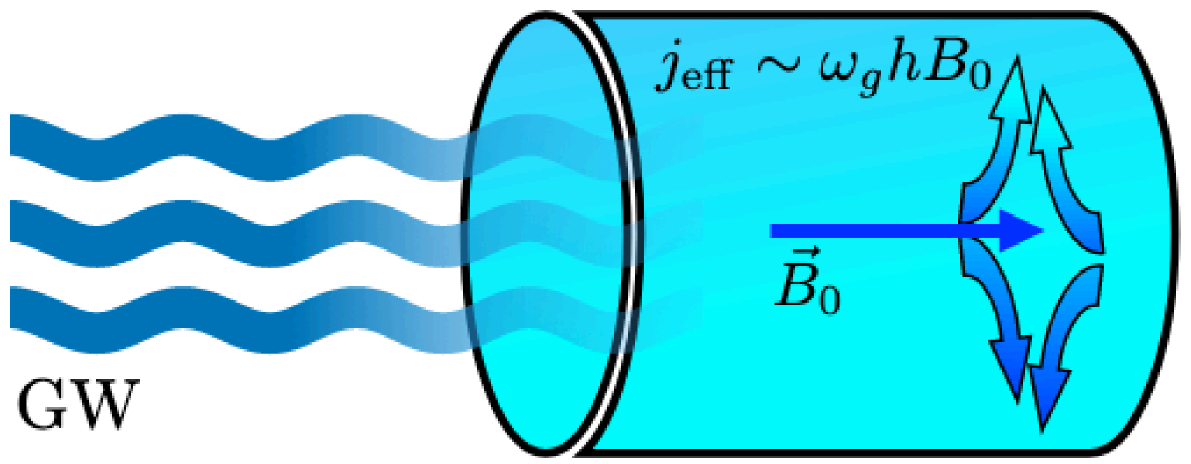
mode mixing when boundaries move

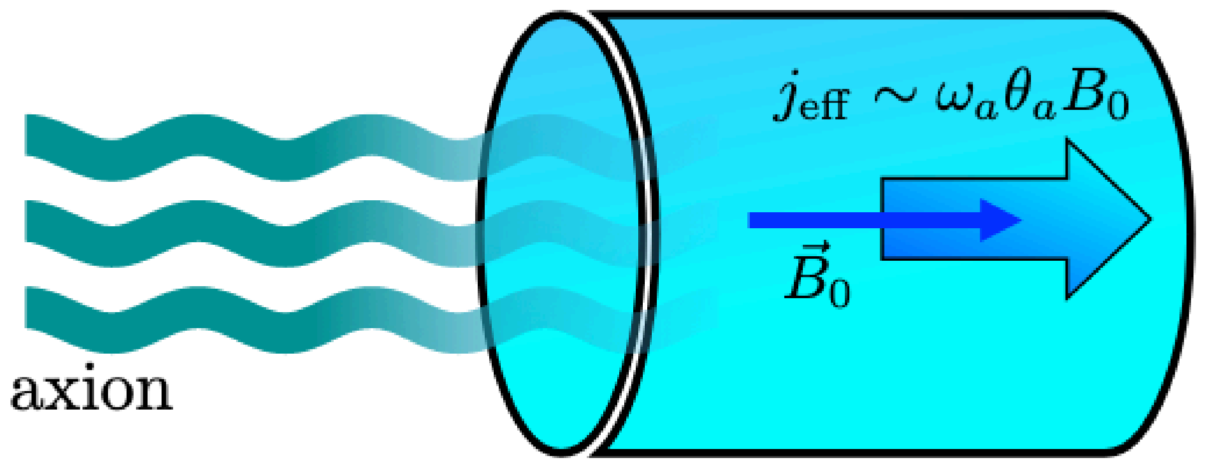
* *axions may modify amplitude*



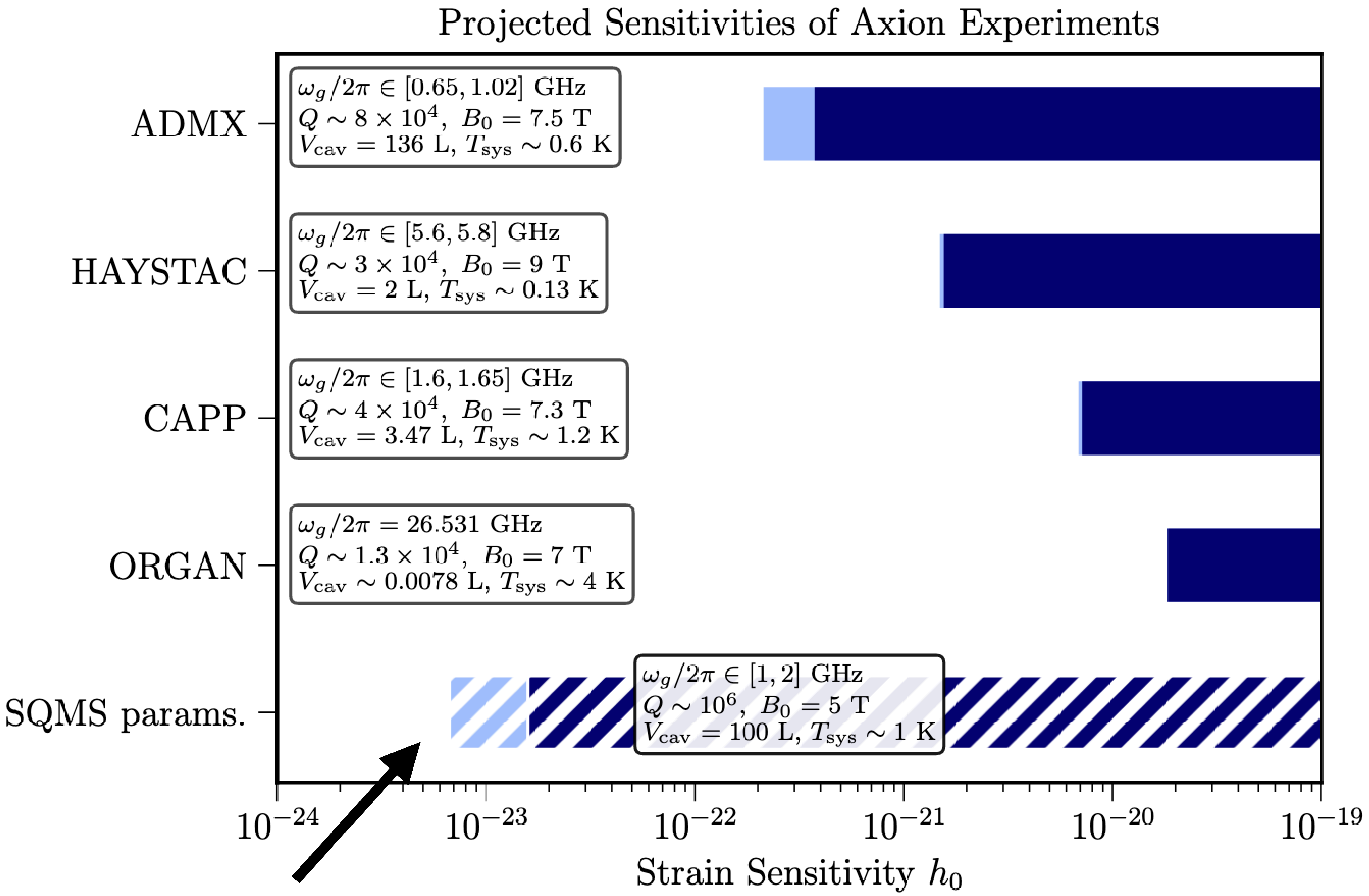
Murgui, Y. Wang, K. M. Zurek. 2022]

EM coupling





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

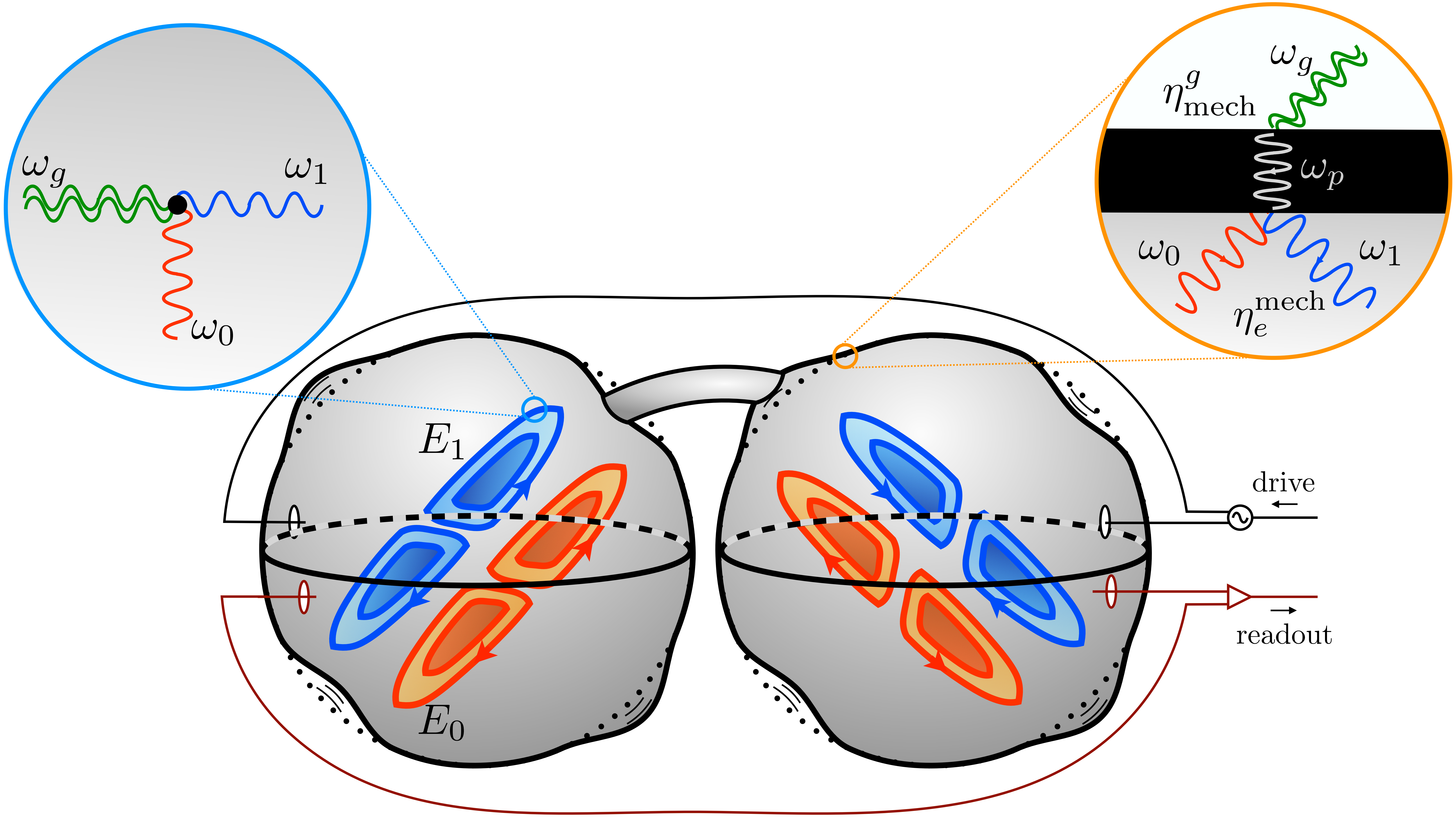


Amplitude of the GW

(same as in LVK)

Mechanical coupling

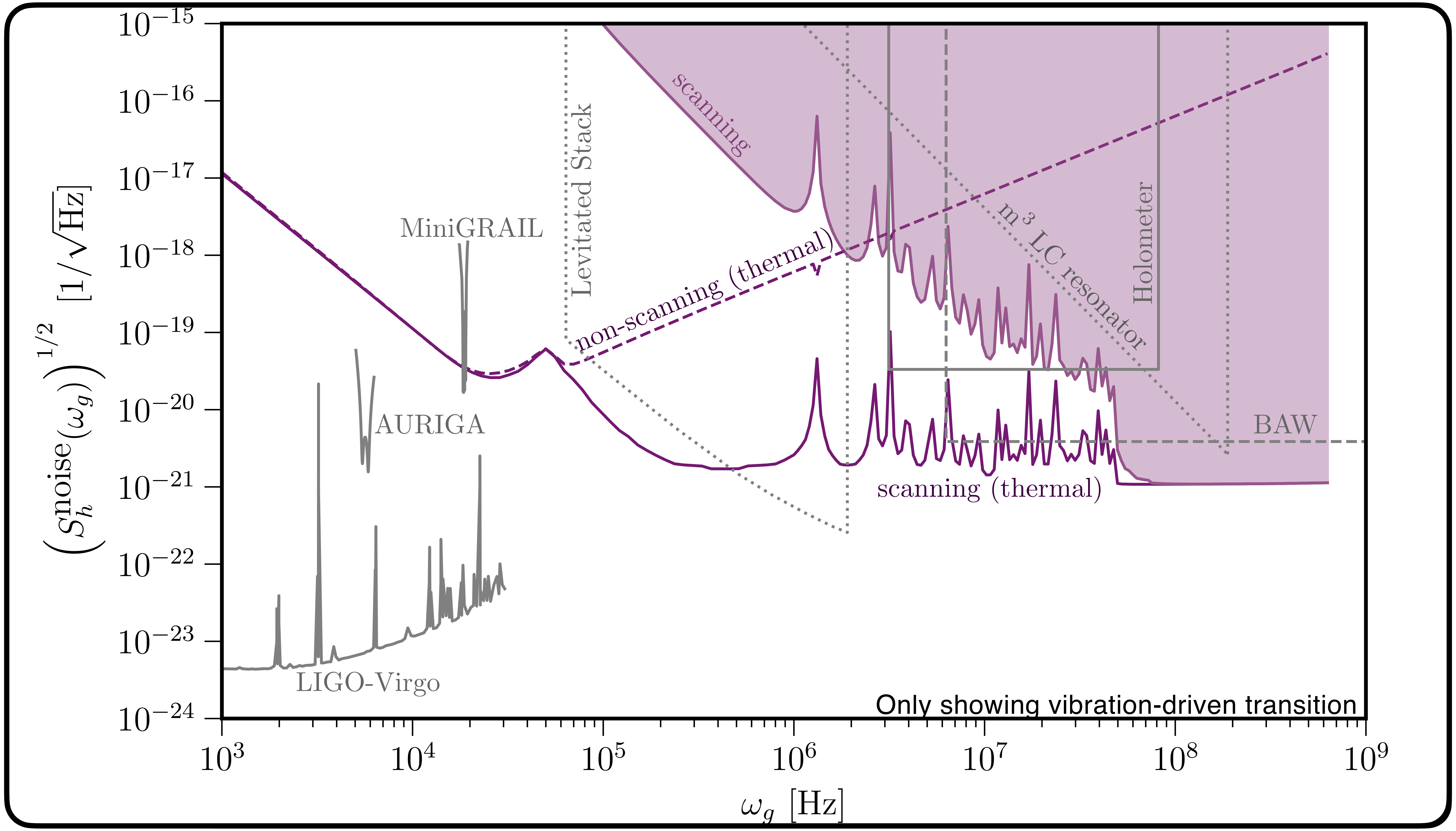
A. Berlin, DB, R.T. D'Agnolo, S. Ellis, R. Harnik,
Y. Kahn, J. Schütte-Engel, M.Wentze 2303.01518



MAGO design from
CERN (gr-qc/0502054)

Mechanical coupling

A. Berlin, DB, R.T. D'Agnolo, S. Ellis, R. Harnik,
Y. Kahn, J. Schütte-Engel, M.Wentze 2303.01518



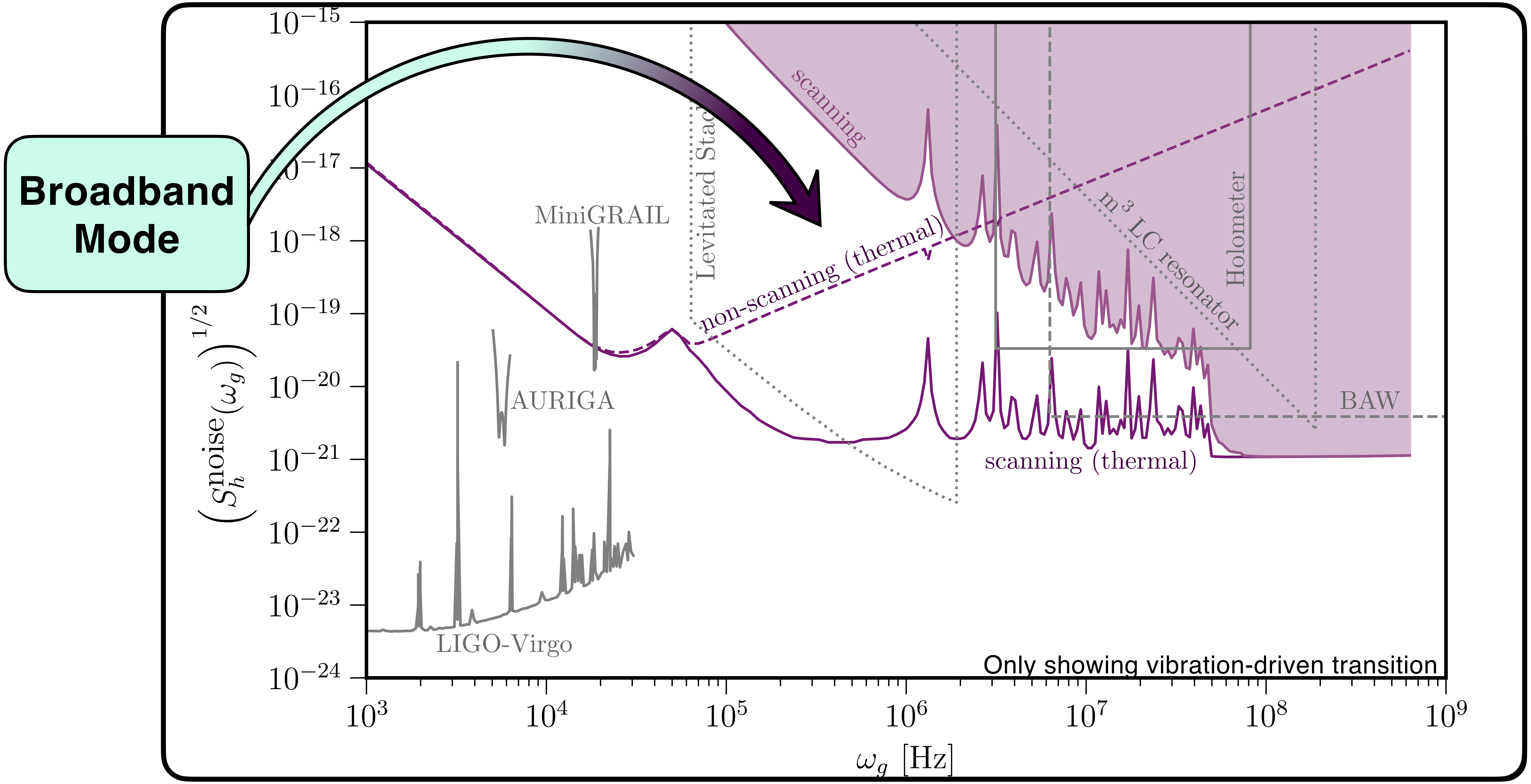
MAGO design from
CERN (gr-qc/0502054)

PRD 108 8, 084058
hep-ph/2303.01518
A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

1 yr integration in band!

Mechanical coupling

A. Berlin, DB, R.T. D'Agnolo, S. Ellis, R. Harnik,
Y. Kahn, J. Schütte-Engel, M. Wentze 2303.01518



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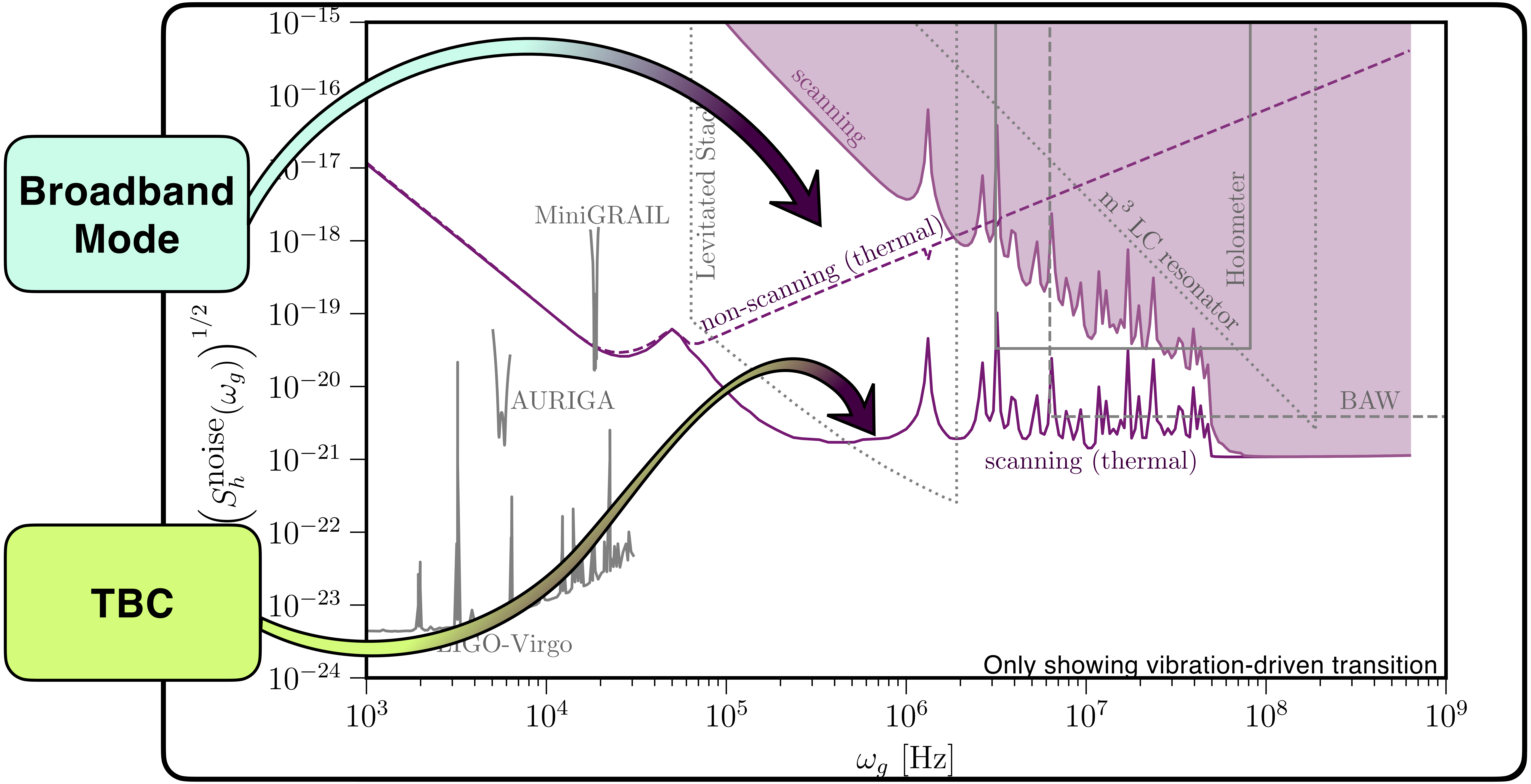

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PRD 108 8, 084058
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A. Berlin, D. Blas, R. T. D'Agnolo, **SARE,** R. Harnik, Y. Kahn, J. Schütte-Engel, M. Wentzel

1 yr integration in band!

Continuation of R&D efforts

DESY/UHH - FNAL - INFN collaboration

DESY	June 2023	**Cavity at DESY** • Mechanical characterisation and RF measurements at room temperature (done)
	Today	
FNAL		**Cavity at FNAL** • Treatment of cavity, construction of a support structure and RF antennas, first cryogenic characterisation
DESY	Mid. 2024	**Cavity back at DESY** • Cryogenic test with (initial) LLRF system
FNAL	End 2024	**Cavity back at FNAL** • First GW search in existing cryostats at Fermilab

In parallel, work started on an LLRF system to drive and read-out the cavity

University Genova

Living Reviews in Relativity manuscript No.
(will be inserted by the editor)

Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

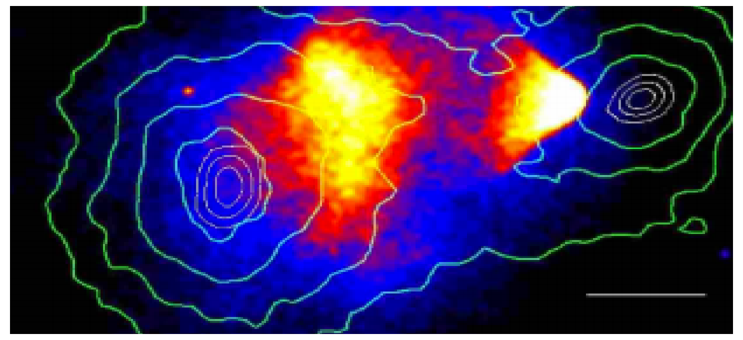
Quantum sensing (metrology) for HEP/Grav/Cosmo

- 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! + machine-made!

neutrino physics

dark matter



gravitational waves

new physics

Back-up slides

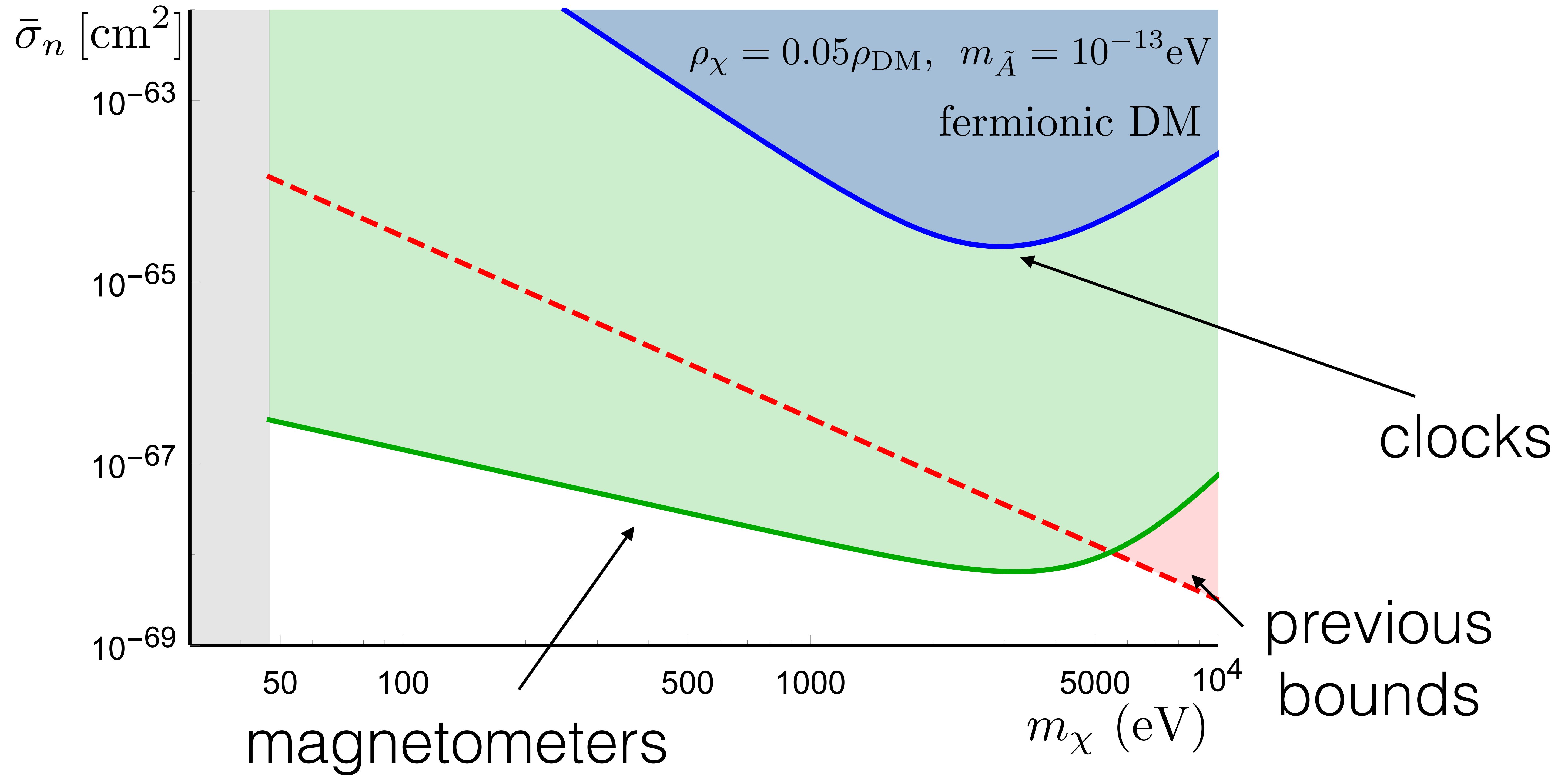
Constraints: three examples

Alonso, DB, Wolf 18

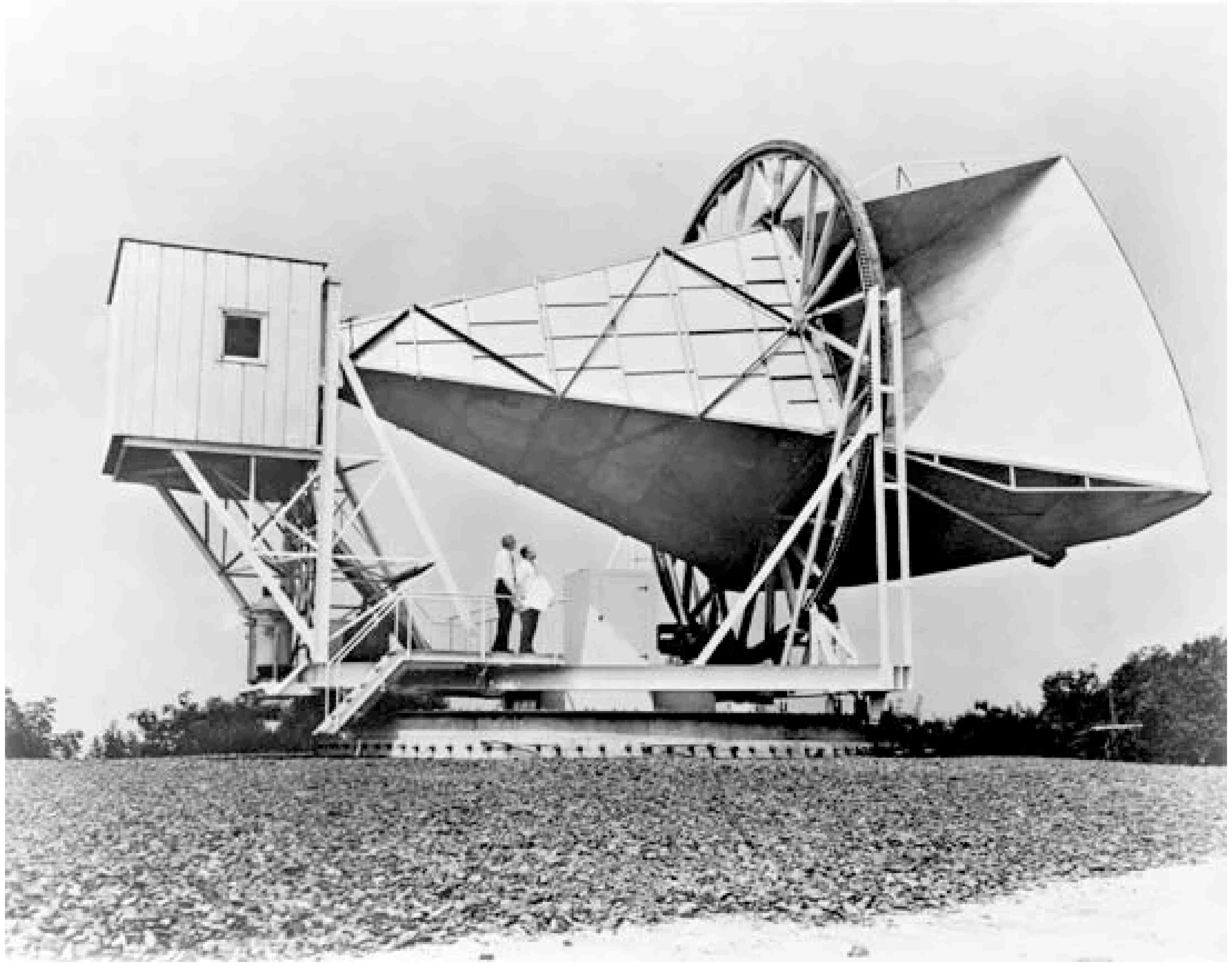
fermionic DM with light mediator

$$L_{\rm int} = -g_{\tilde{A}} g_\chi \int \mathrm{d}^3x \, (\bar{n}\gamma^\mu\gamma_5 n) \frac{1}{m_{\tilde{A}}^2 + \Box} (\bar{\chi}^\dagger \gamma^\mu \gamma_5 \chi)$$

$$\vec{S}_n \cdot \vec{S}_\chi / m_{\tilde{A}}^2$$



This was initially considered noise…



R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

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——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
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A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

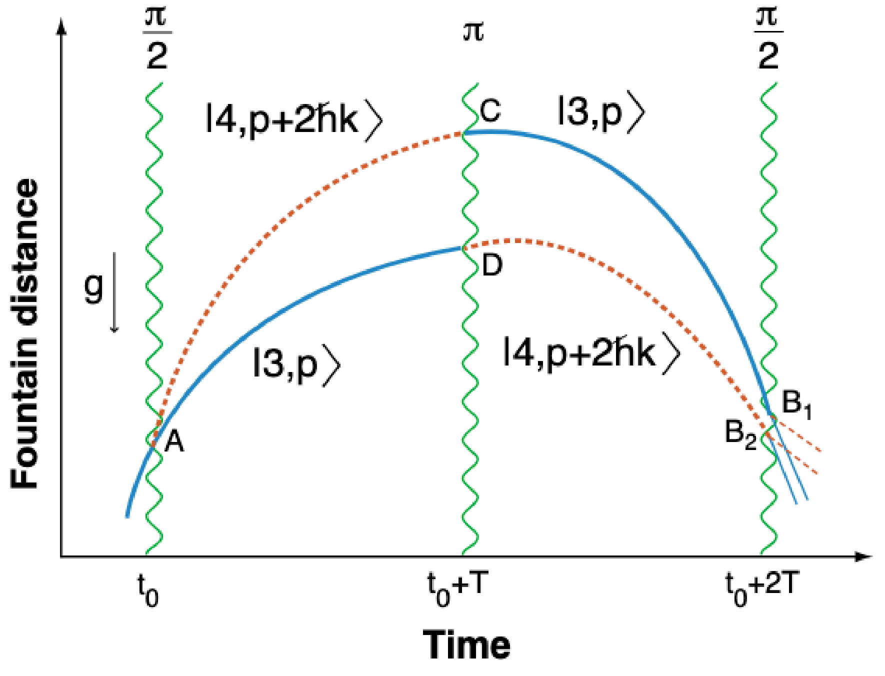
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

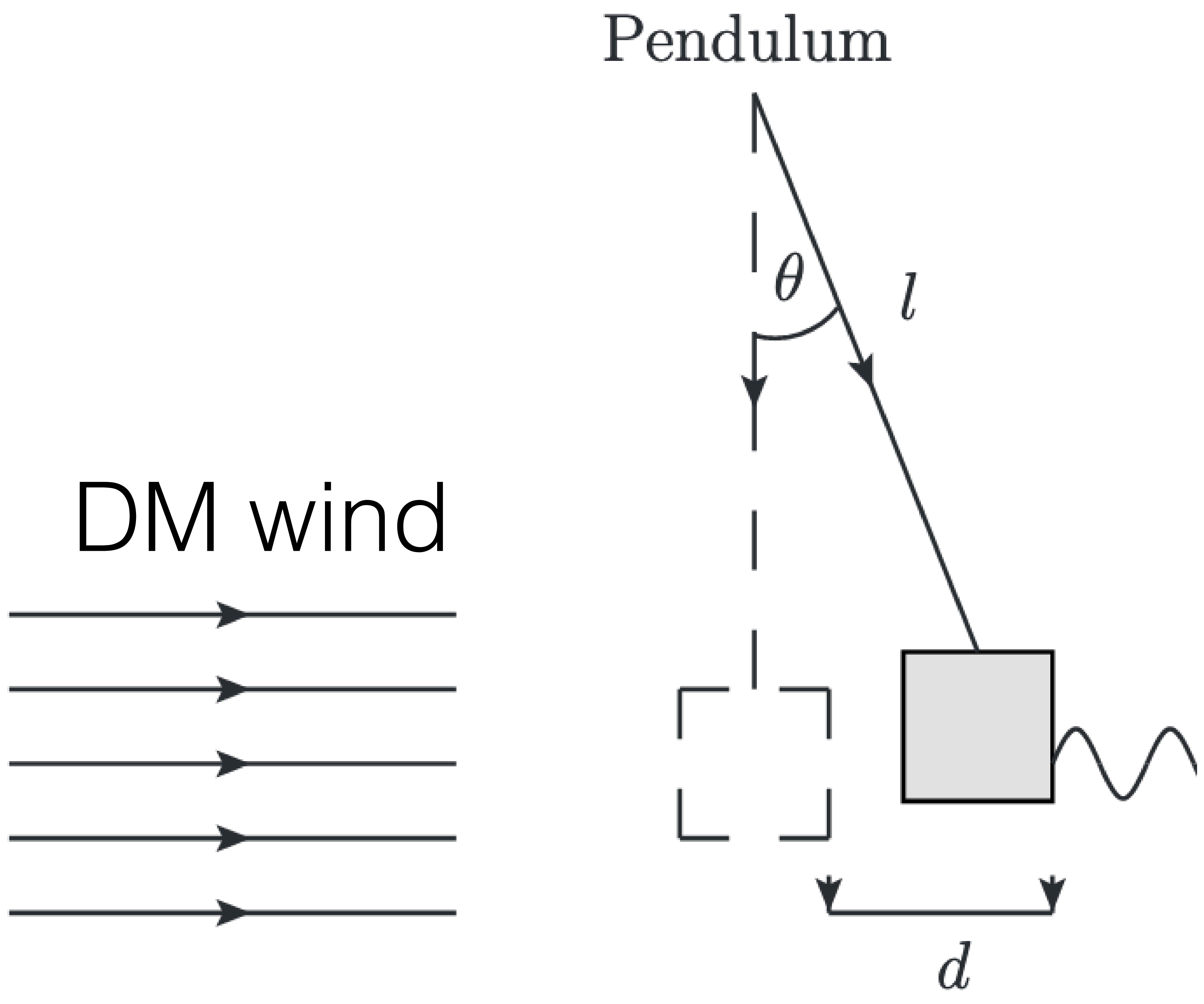
i) Accessing DM of higher mass



AION measures acceleration (gravimeter)

Given the DM wind, if it scatters with an atom it will also transfer momentum (accelerate)

g $\theta(t)$



https://arxiv.org/pdf/1703.08629.pdf

$$a_{G_F^2} \approx 10^{-18}\ \mathrm{cm/s^2}\,, \quad m_X = 10\ \mathrm{GeV}\,, \quad \sigma_{X-N} = 3\cdot 10^{-34}\ \mathrm{cm^2}\,,$$
$$a_{G_F^2} \approx 10^{-20}\ \mathrm{cm/s^2}\,, \quad m_X = 0.1\ \mathrm{GeV}\,, \quad \sigma_{X-N} = 3\cdot 10^{-36}\ \mathrm{cm^2}\,,$$
$$a_{G_F^2} \approx 10^{-22}\ \mathrm{cm/s^2}\,, \quad m_X = 1\ \mathrm{MeV}\,, \quad \sigma_{X-N} = 1\cdot 10^{-40}\ \mathrm{cm^2}\,.$$

Can we reach these numbers?

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

(also atomic clocks)

E.g. Atomic co-magnetometers

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

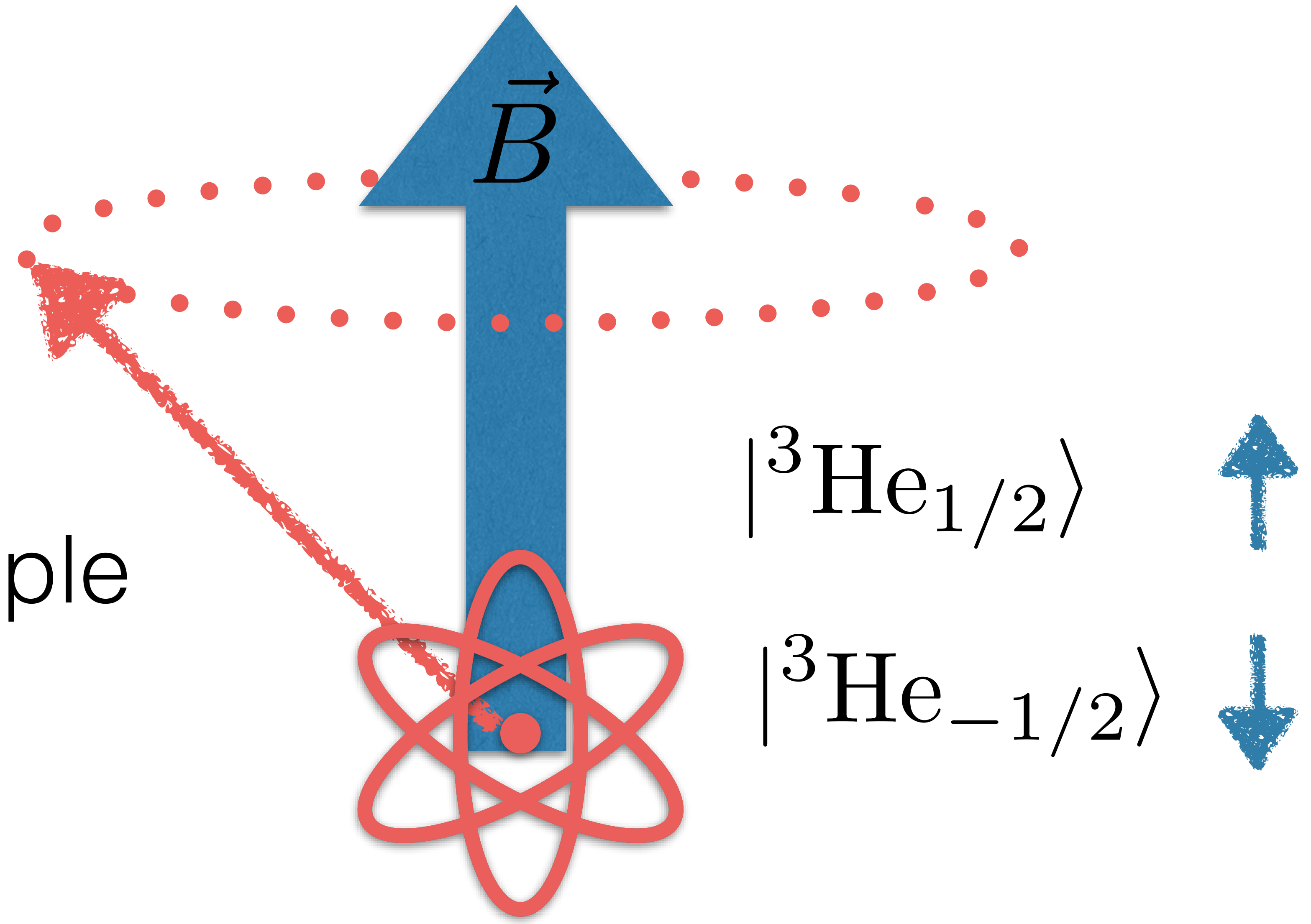
Du et al. 2205.13546
Block et al 1907.03767
Dror et al 2210.06481
Terrano et al 2106.09210

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

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

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

polarized sample



$$\omega \equiv \gamma \beta = \gamma \left(B \qquad\qquad\qquad\qquad\qquad \right)$$

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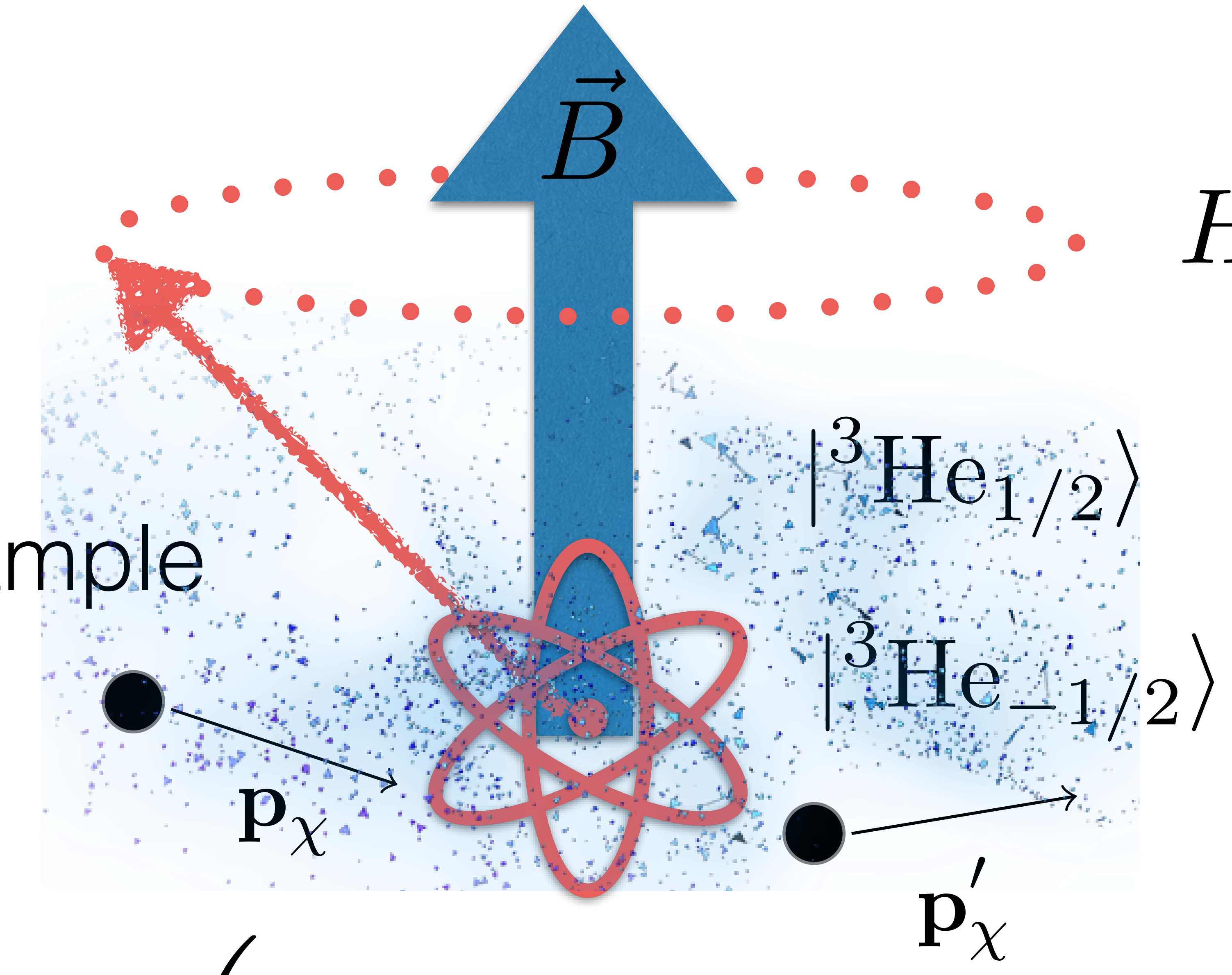

$$H_{\pm 1/2} = H_{\mathrm{int}} + V_{\pm 1/2}$$

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

$$e^{i\mathbf{p}_\chi \cdot \mathbf{x}} + \frac{f_{\mathrm{i}}(p_\chi \hat{\mathbf{x}}\,,\, \mathbf{p}_\chi) e^{i\,p_\chi |\mathbf{x}|}}{|\mathbf{x}|}$$

$V_{\pm 1/2}$

$$\omega \equiv \gamma \beta = \gamma \left(B \qquad\qquad\qquad\qquad \right)$$

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

(also atomic clocks)

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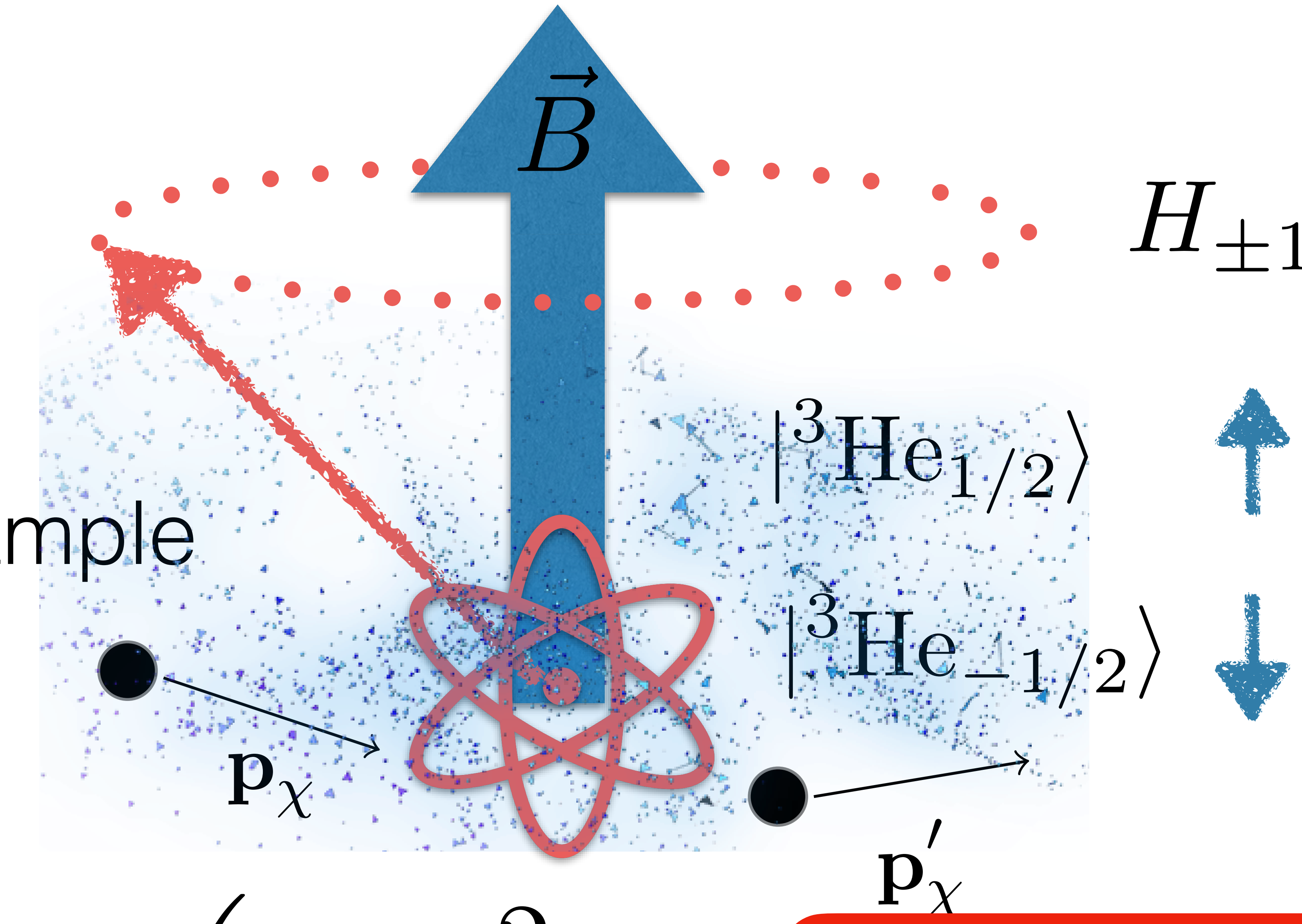

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$V_{\pm 1/2}$

scattering amplitudes at $q = 0$

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

* axions are other DM candidates generating anomalous *B*. Also extra source of decoherence. Ask me!

[Du, Murgui, Pardo, Wang, Zurek, 2023]