

Quantum sensing & fundamental backgrounds

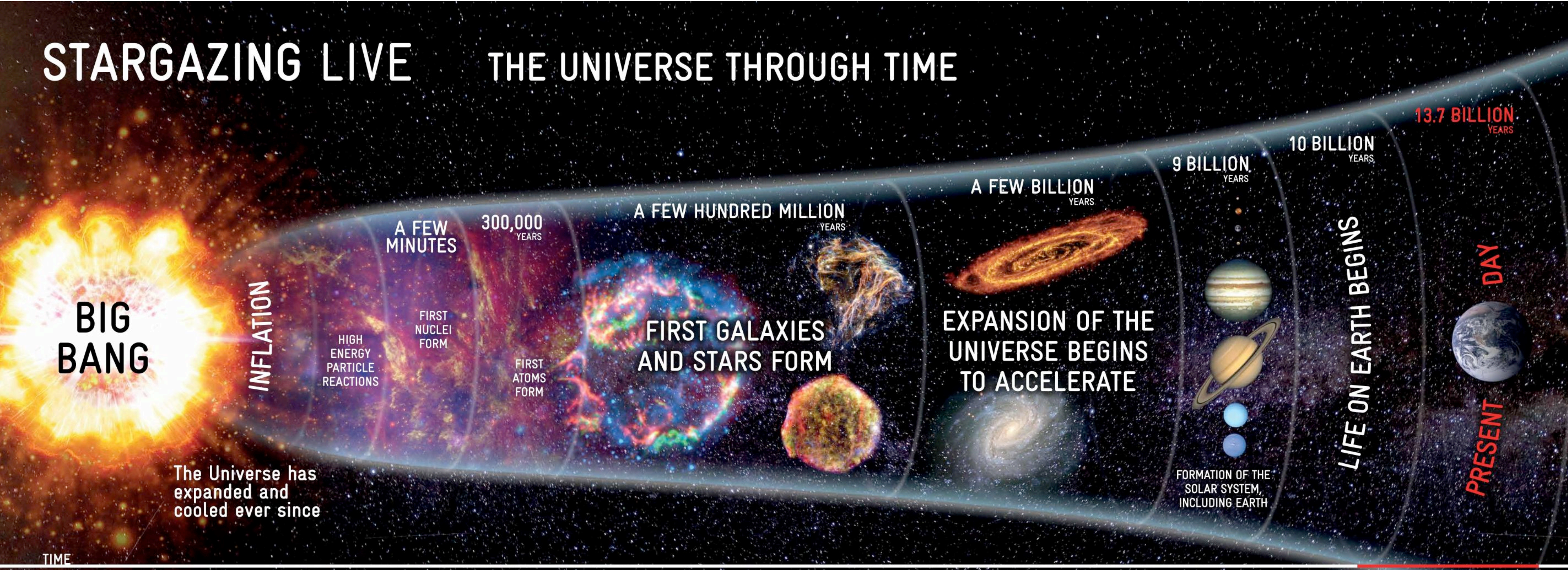
Diego Blas



Fundamental cosmological backgrounds

STARGAZING LIVE

THE UNIVERSE THROUGH TIME



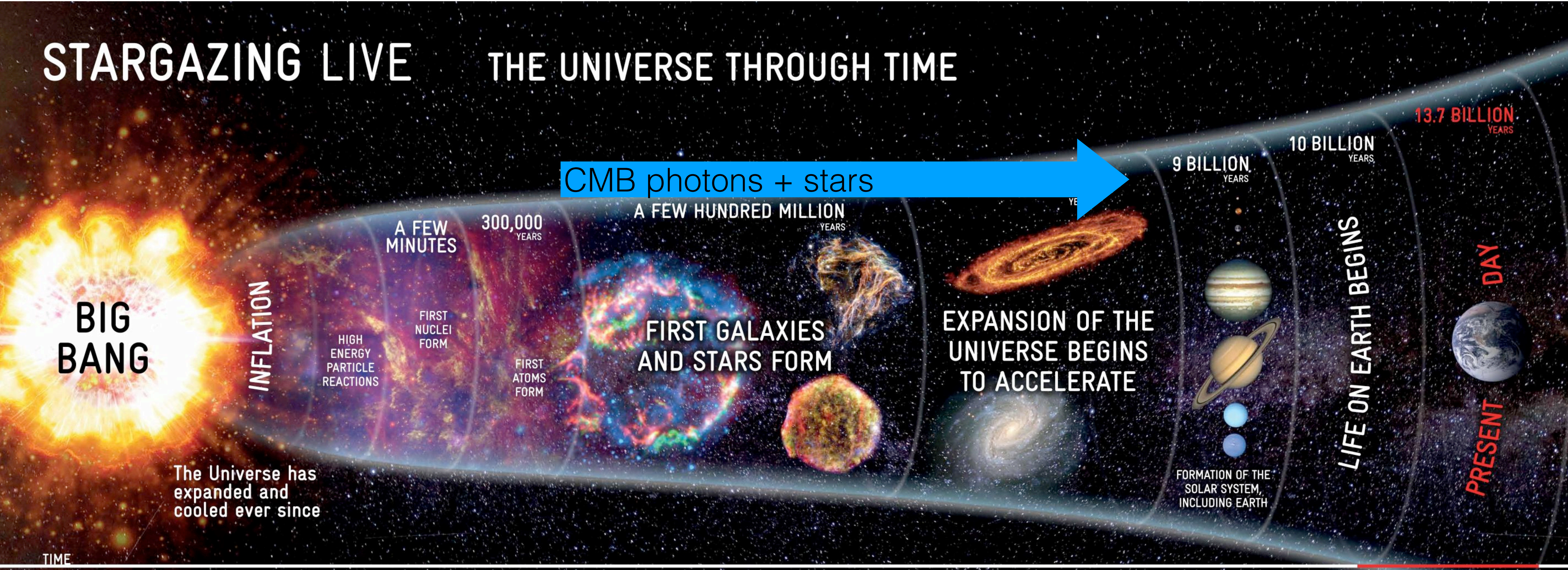
Fundamental cosmological backgrounds

BBC
TWO

The Open
University

STARGAZING LIVE

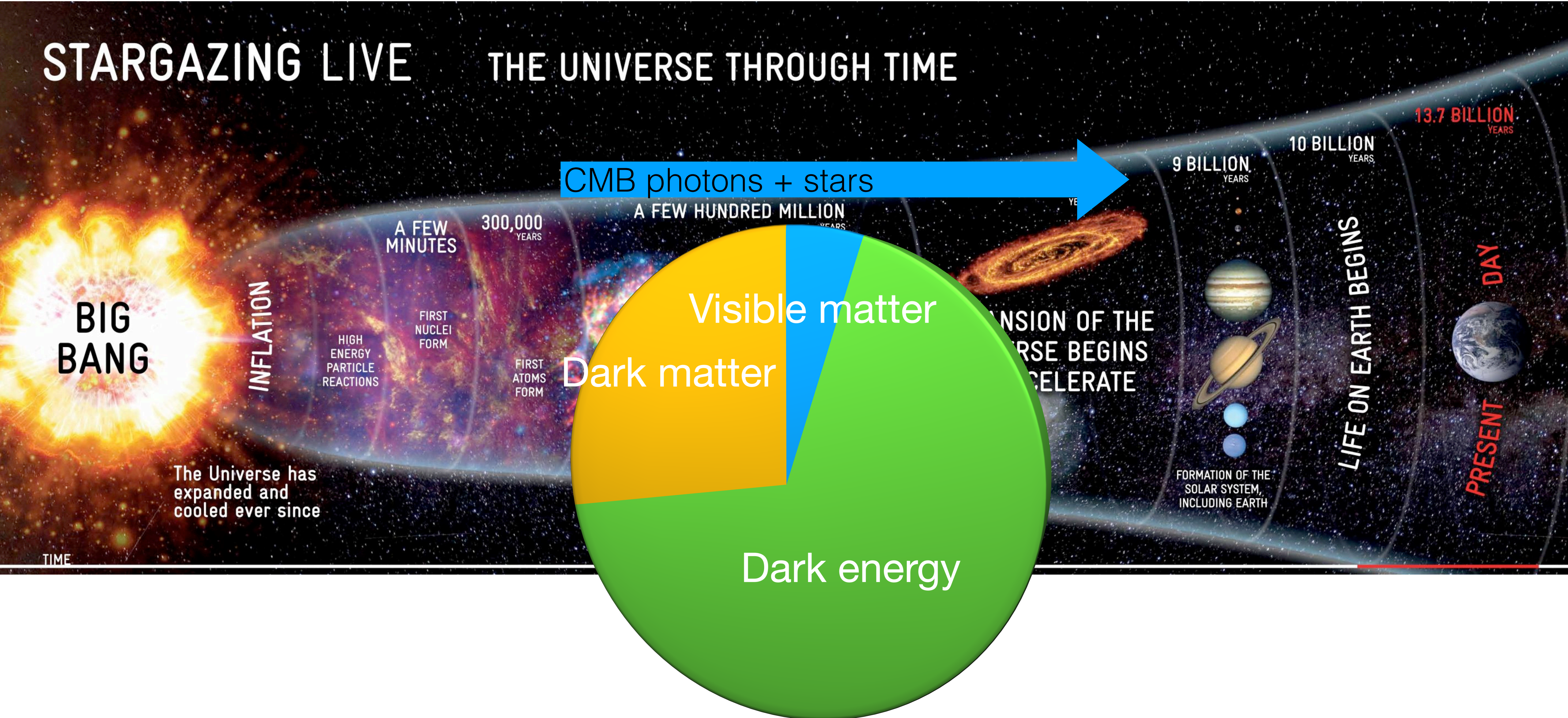
THE UNIVERSE THROUGH TIME



Fundamental cosmological backgrounds

STARGAZING LIVE

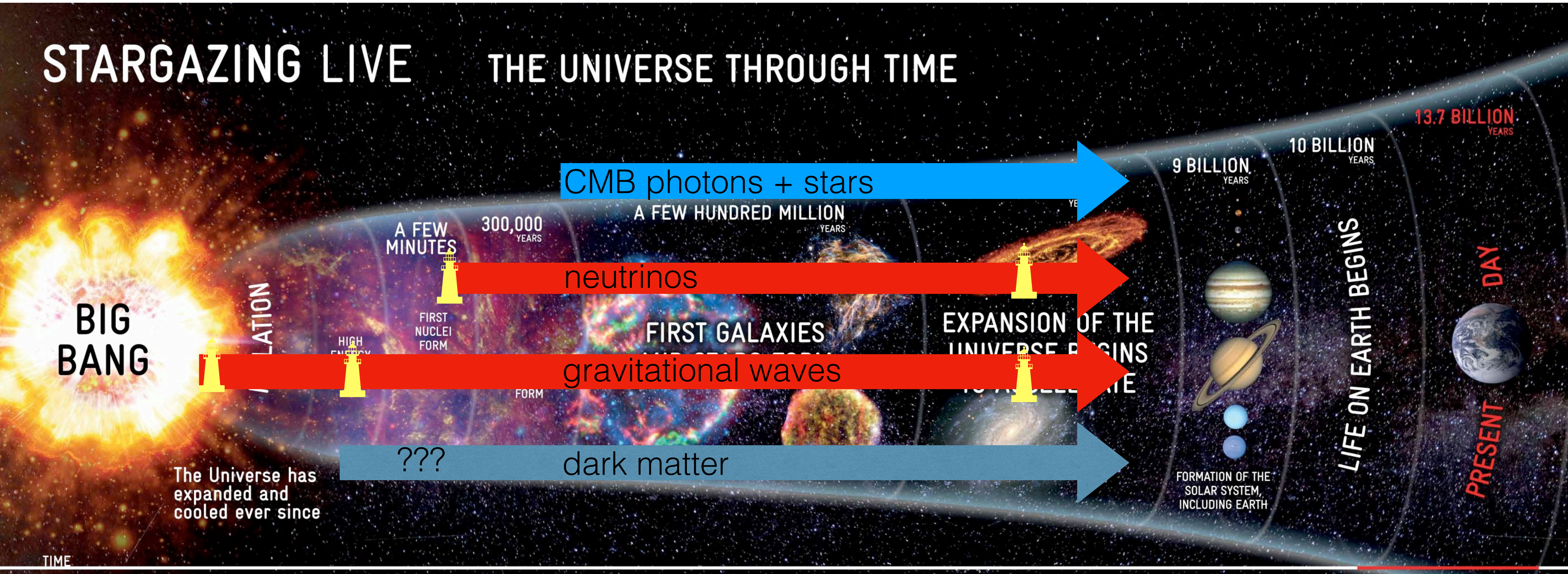
THE UNIVERSE THROUGH TIME



Fundamental cosmological backgrounds

STARGAZING LIVE

THE UNIVERSE THROUGH TIME



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



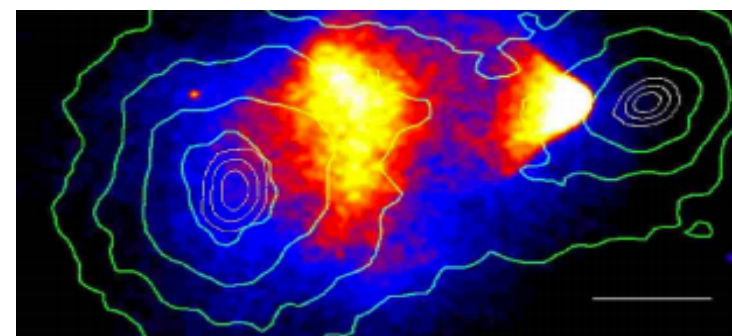
Gravitational waves (SM + BSM)



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?

Connection to your laboratory

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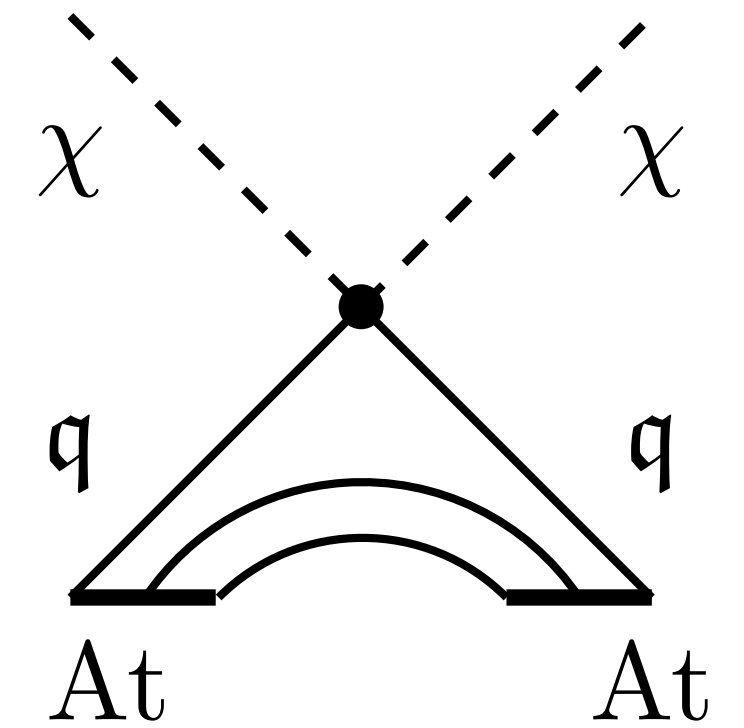
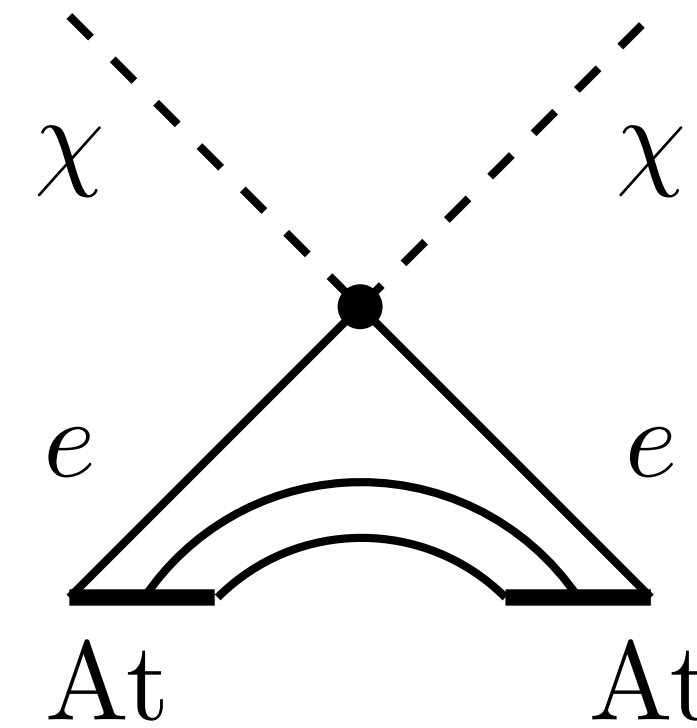
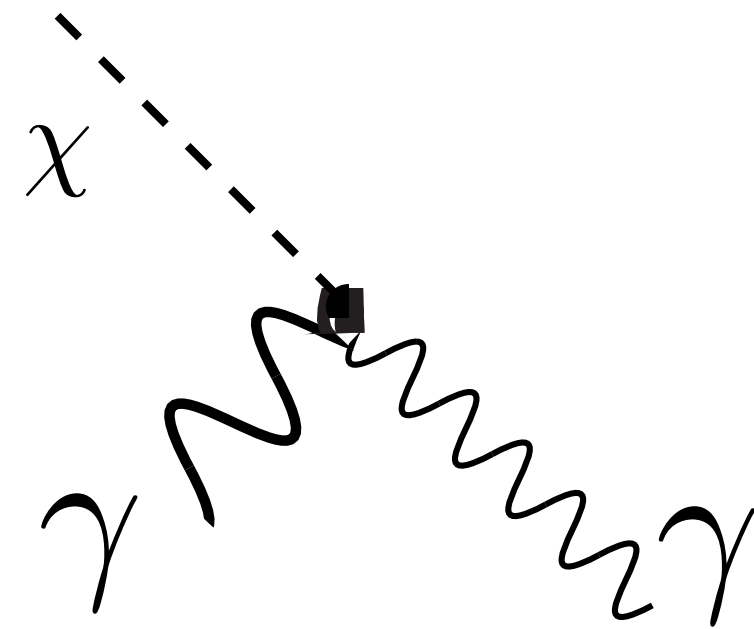
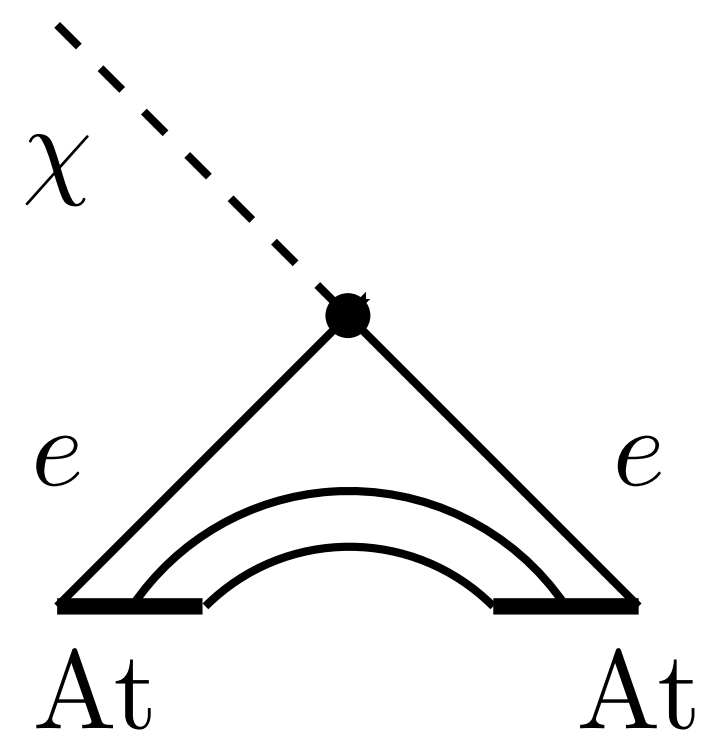
Connection to your laboratory

How can I add these backgrounds to my analysis?

e.g. **absorption** process

scattering process

gw, nu, dm



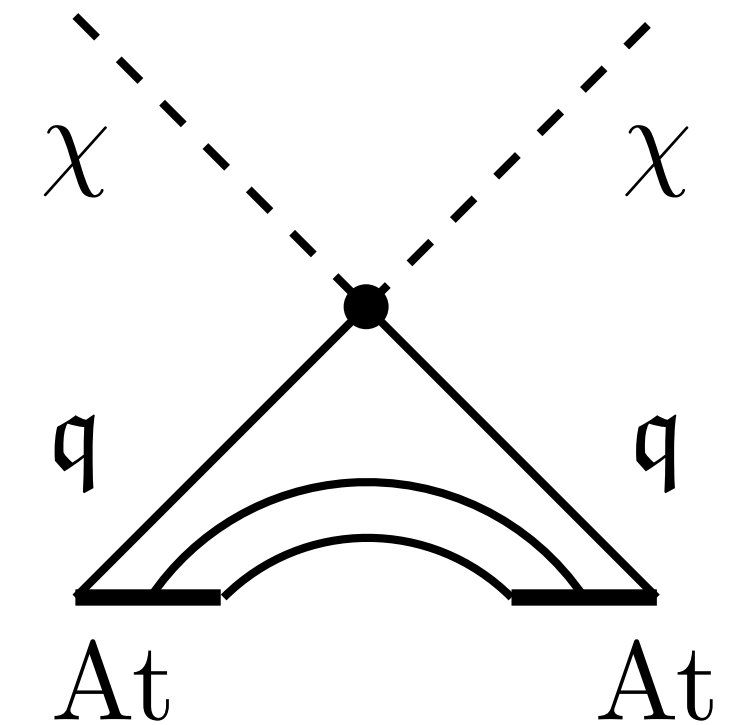
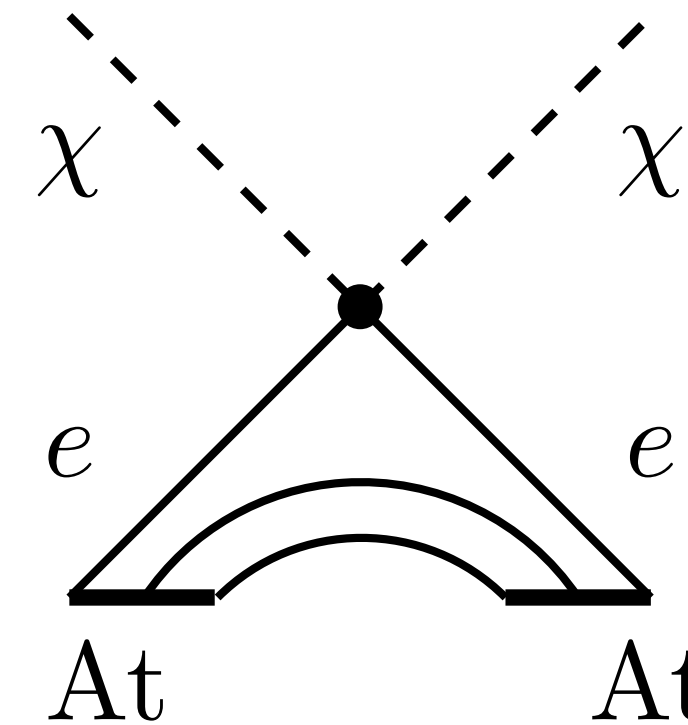
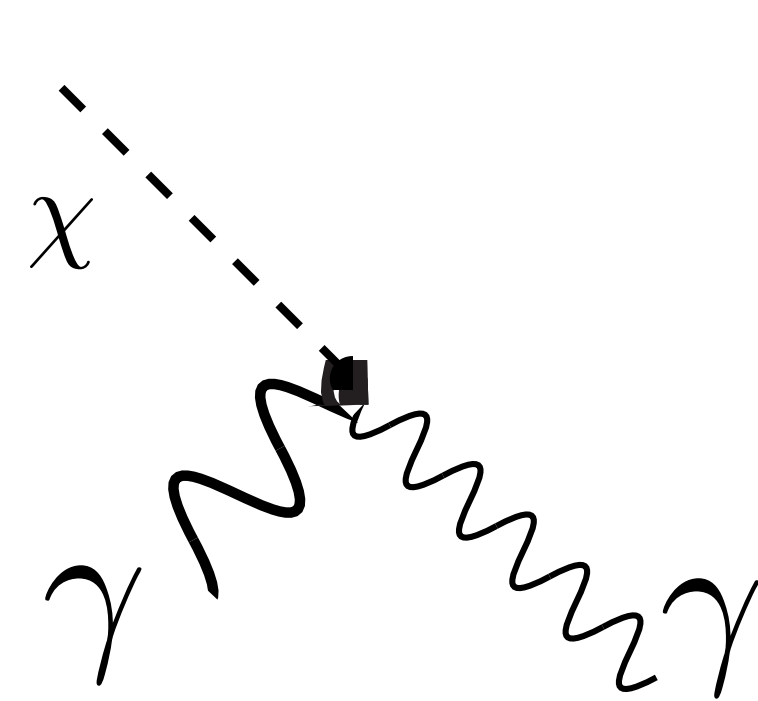
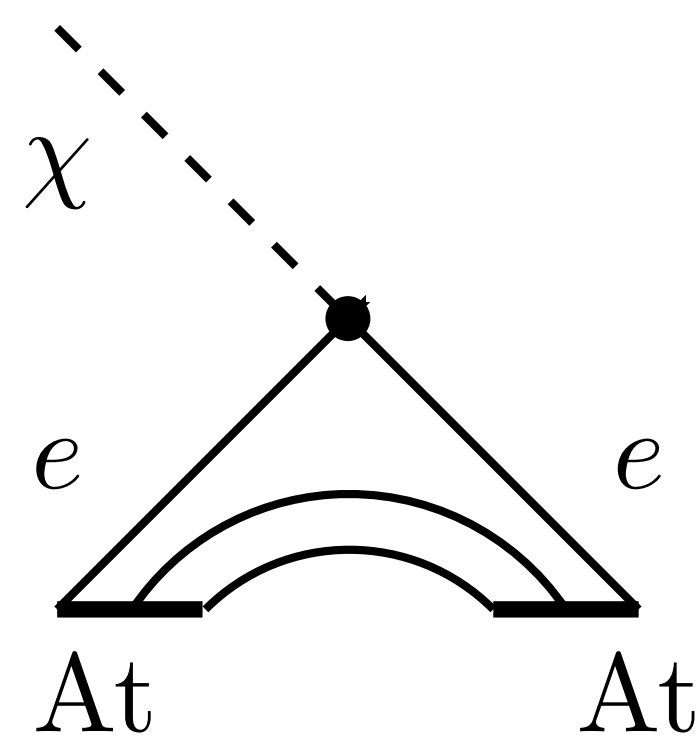
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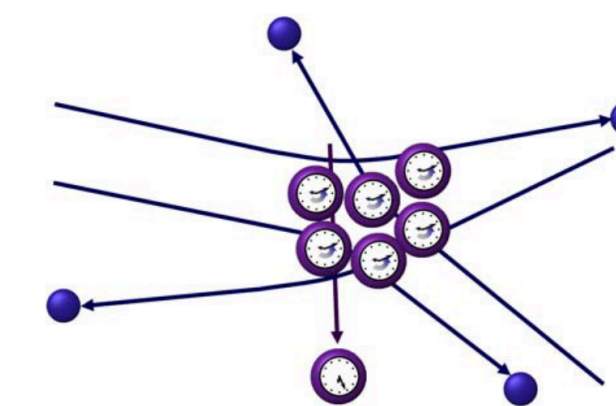
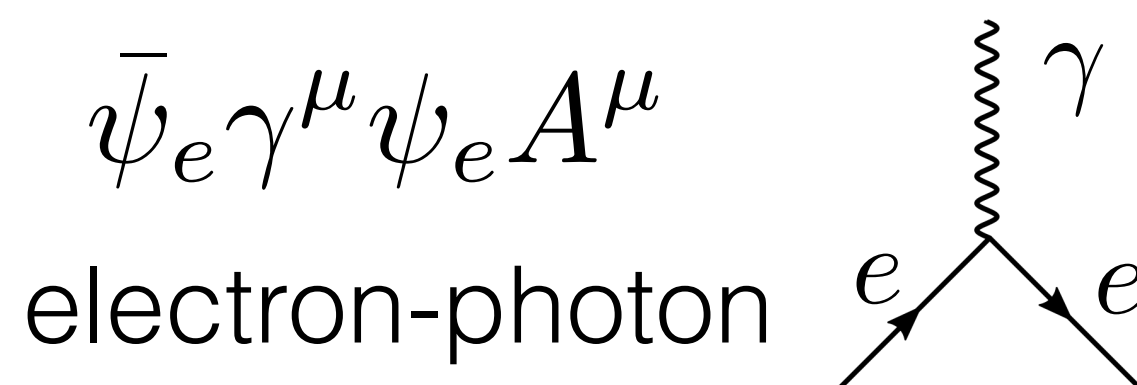
The **first** job of the theorist:

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



atoms with surrounding gas

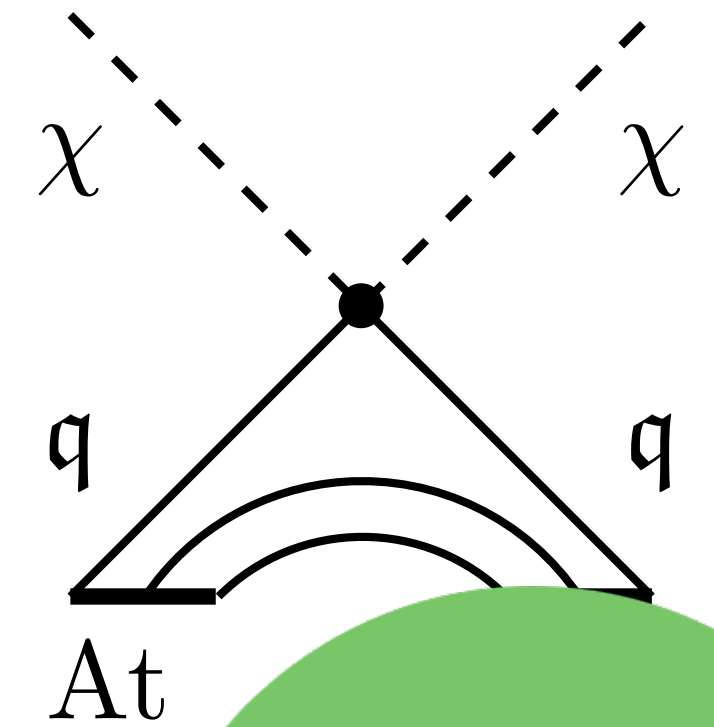
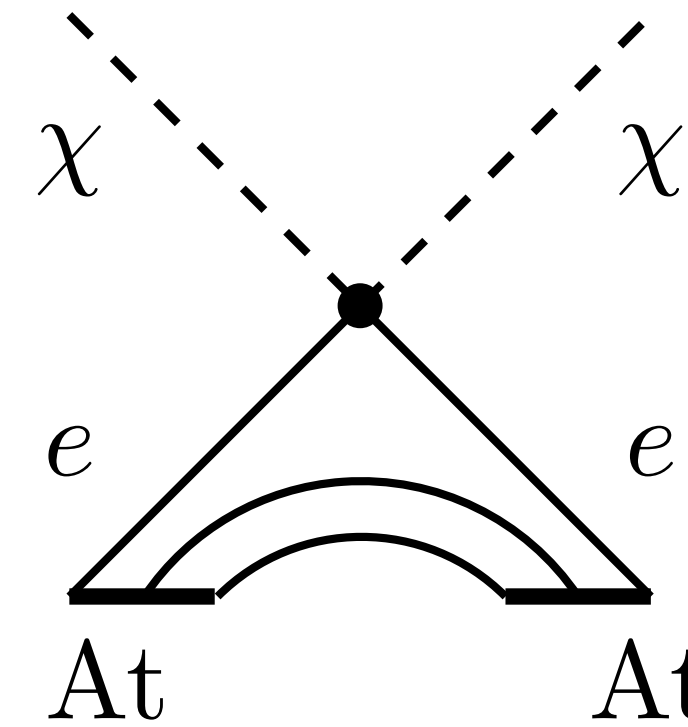
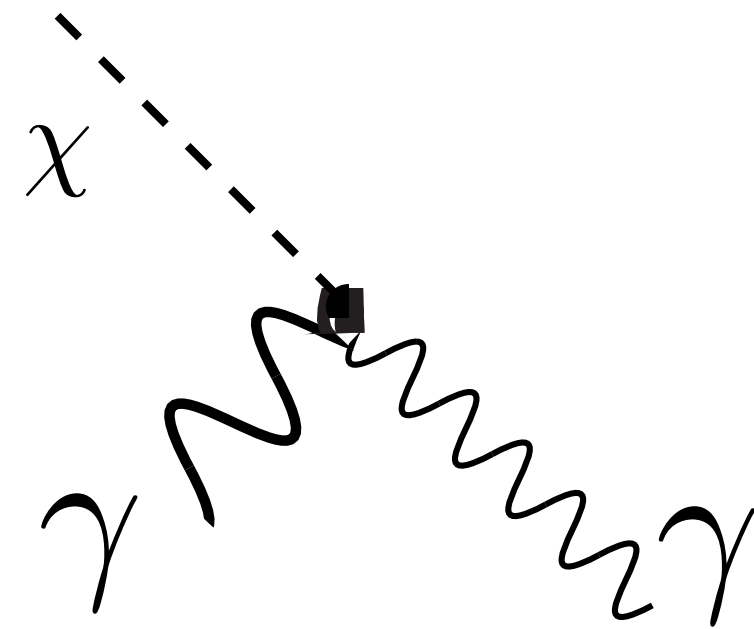
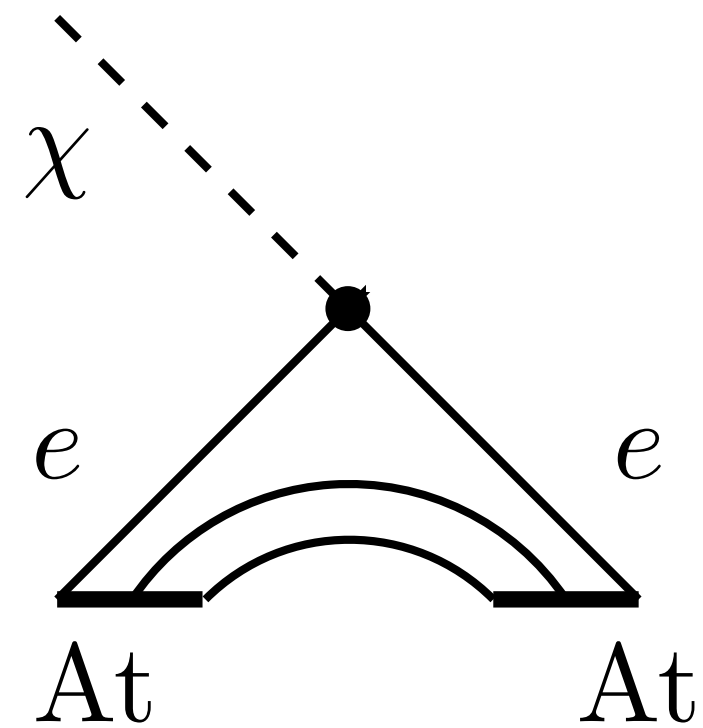
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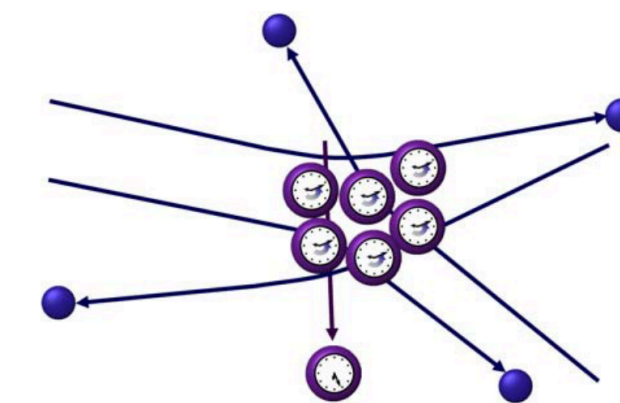
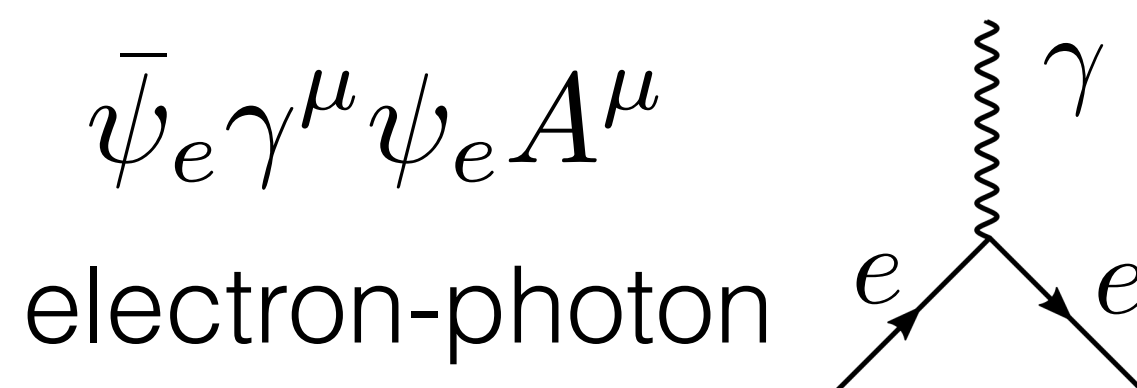
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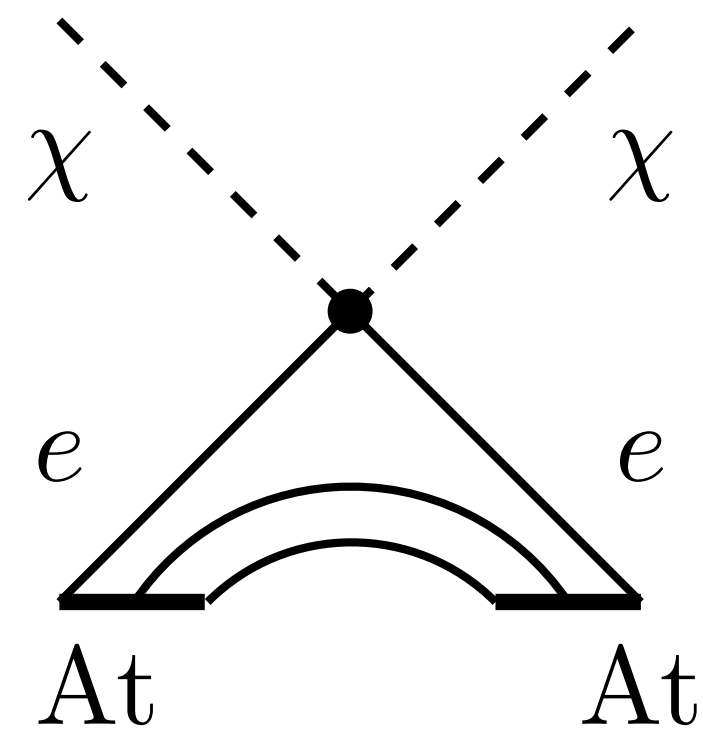
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Connection to your laboratory

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The **second** job of the theorist:

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



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

compare with standard EM interactions

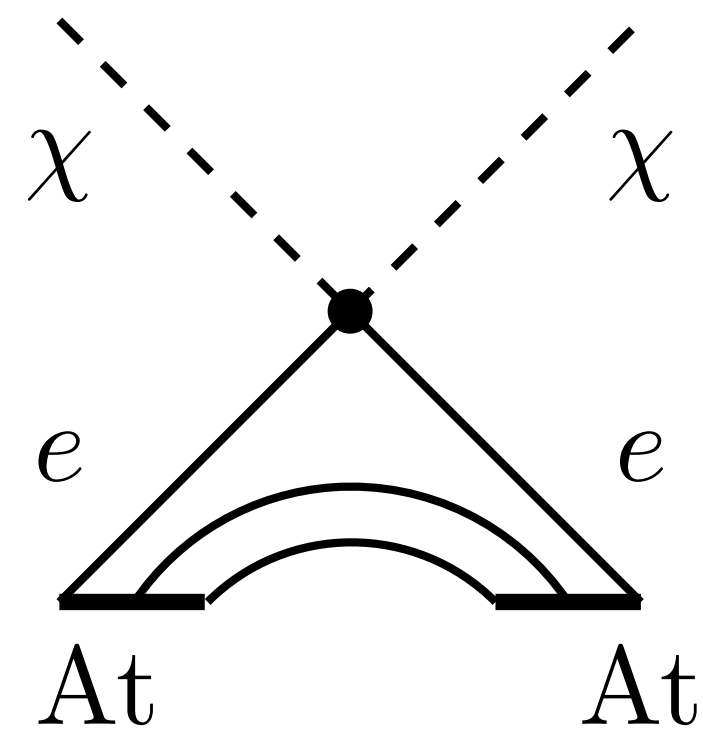
$\bar{\psi}_e \gamma^\mu \psi_e A_\mu \longrightarrow \vec{p}_e \cdot \vec{A} \quad , \quad g_e \vec{S}_e \cdot \vec{B}$

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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**

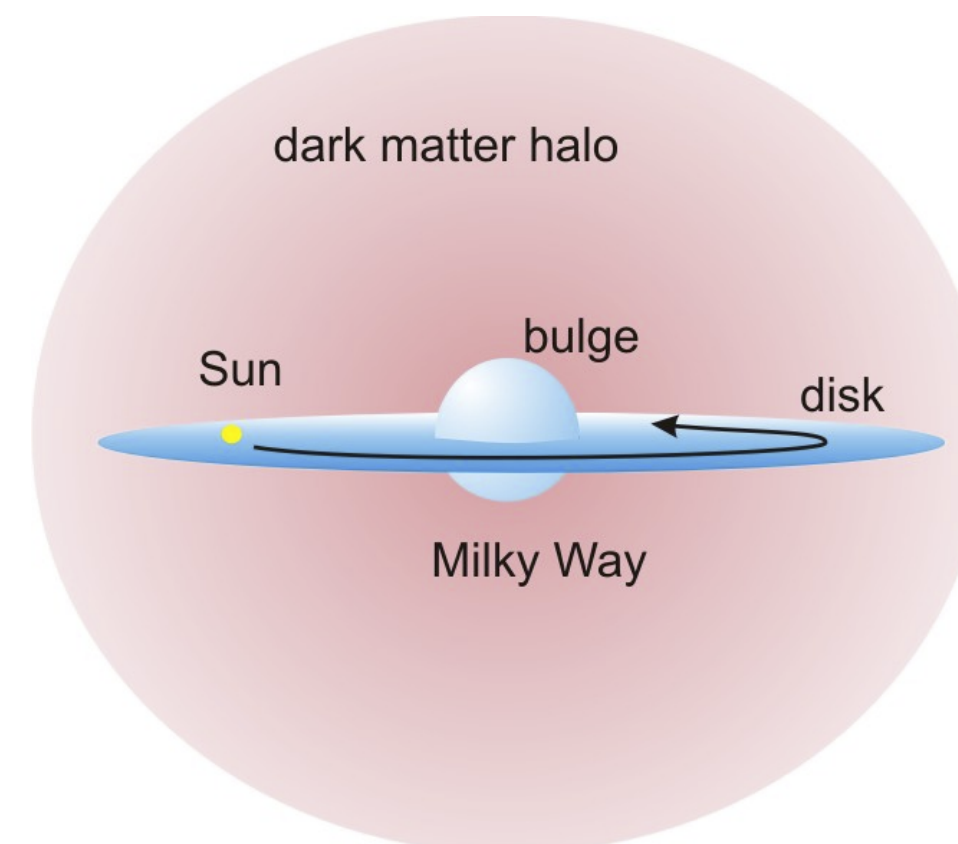
Connection to your laboratory

How can I add these backgrounds to my analysis?

The **third** job of the theorist:

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e.g. if χ is the dark matter



i) flux on Earth

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

ii) each with momentum

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

(annually modulated)

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

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

compare with standard EM interactions

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

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

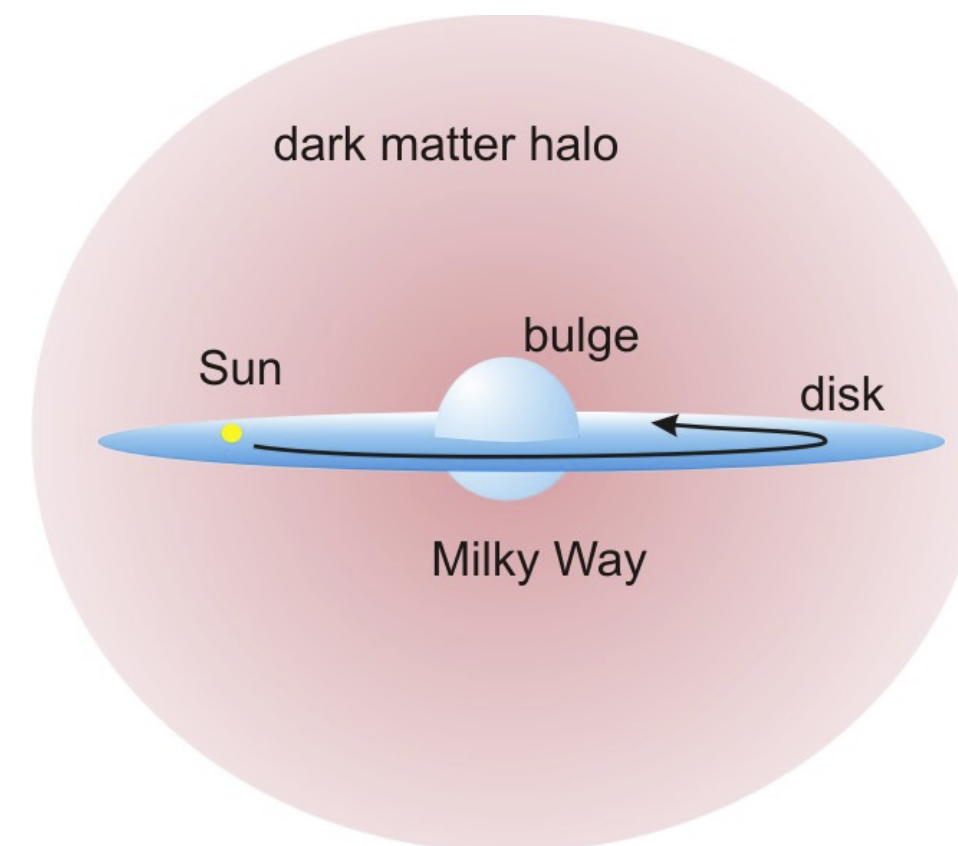
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1st Conclusion

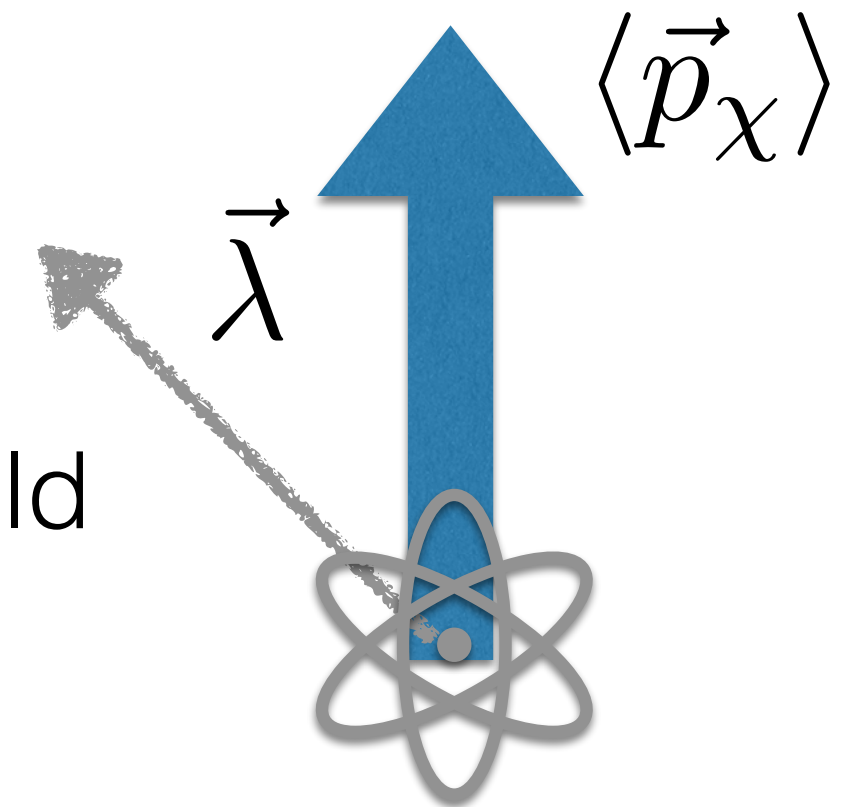
We need the comprehensive map between **fundamental backgrounds** and **new interaction terms of Hamiltonians** relevant for the laboratory

fundamental backgrounds



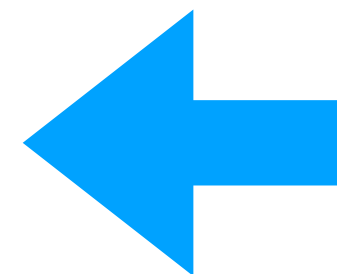
$$H = H_0 + H_{\text{int}}$$

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.

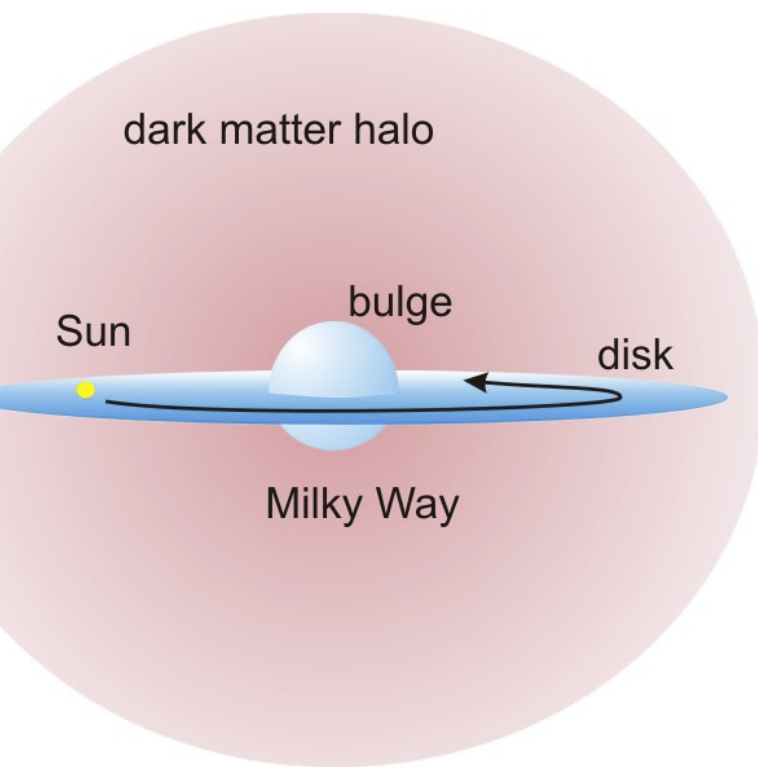


important: the fundamental background may offer **new handles** (e.g. anual modulation, oscillations...)

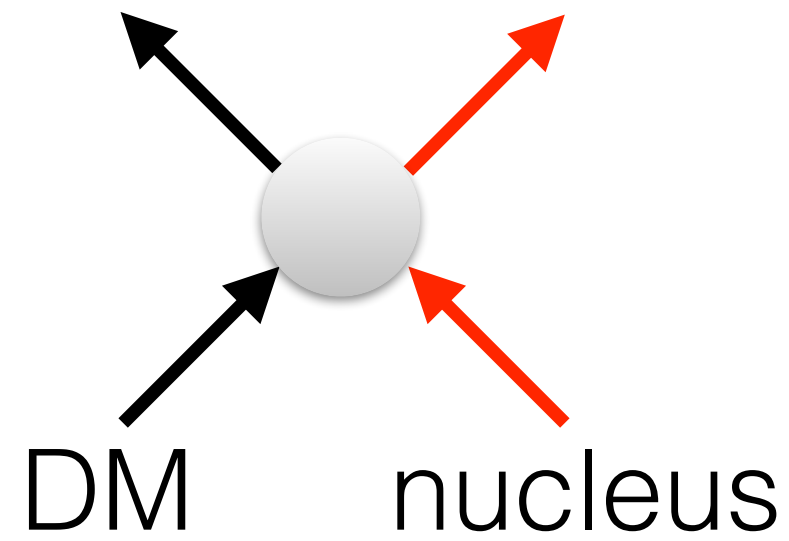
Part II: two examples

- i) DM and cosmic neutrinos w/ atomic clocks and co-magnetometers
- ii) GWs in (superconducting radio-frequency) cavities

Problems to detect DM

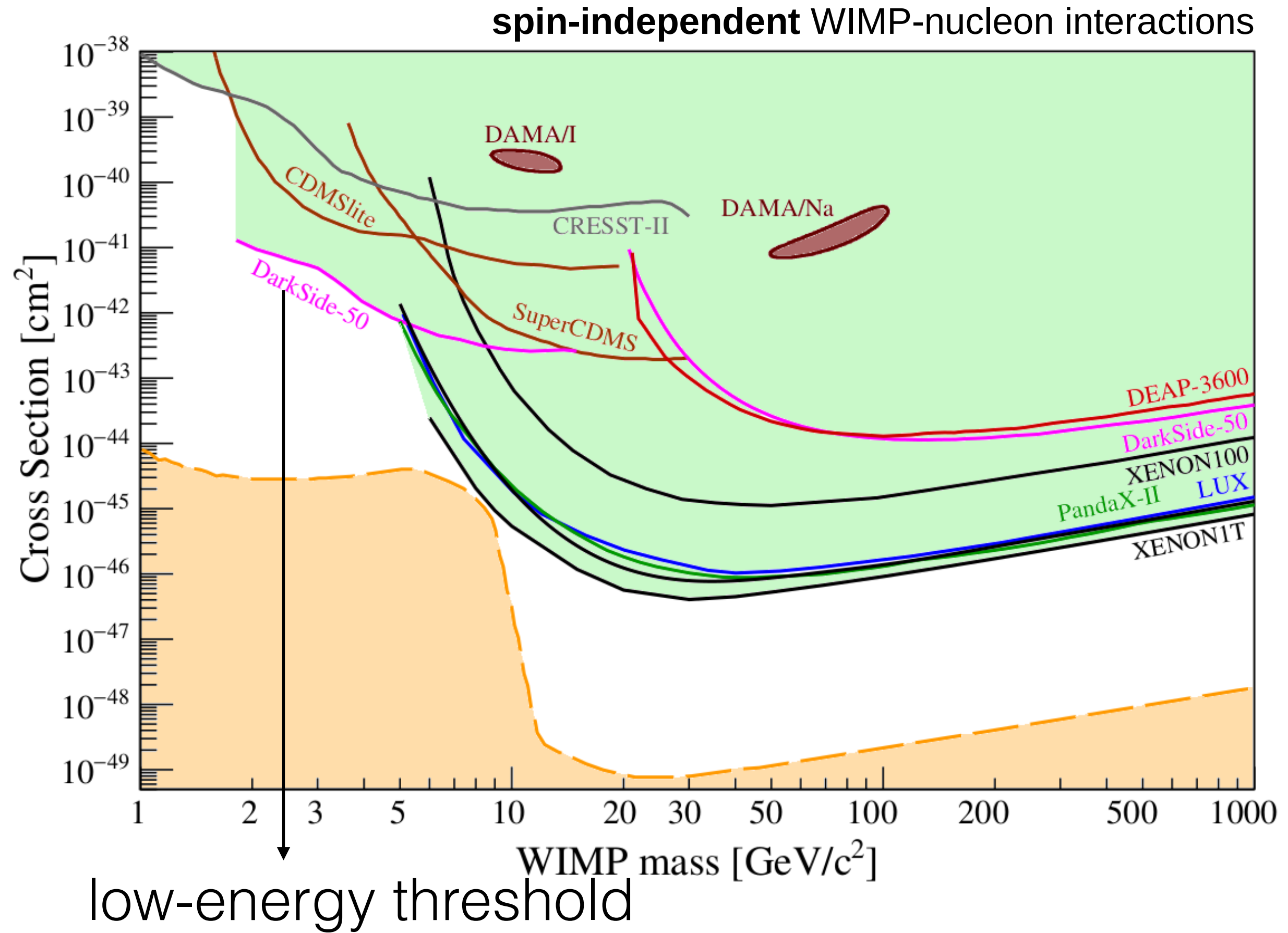


scattering



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

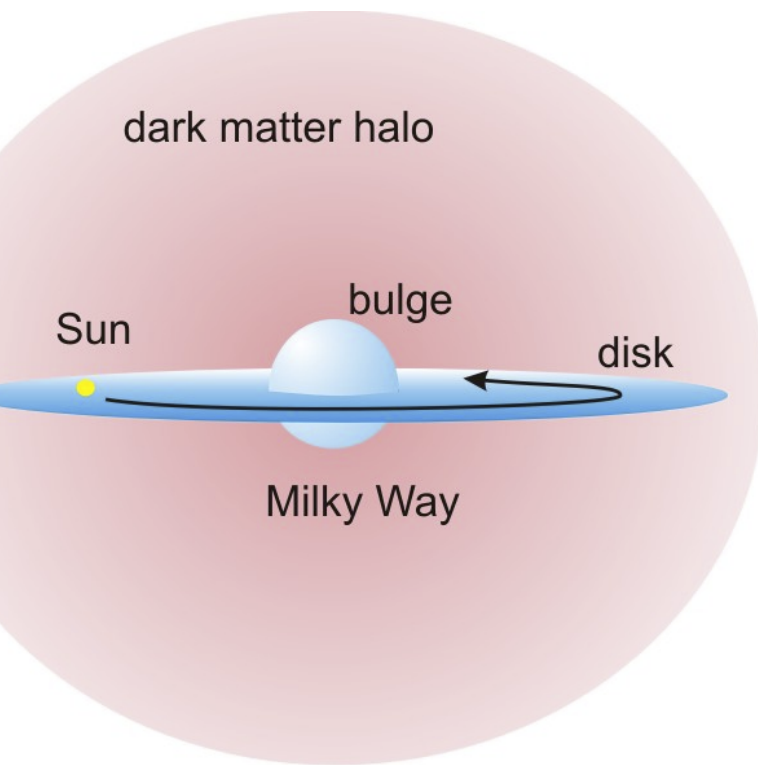
energy of the recoiled
(observed) nucleus



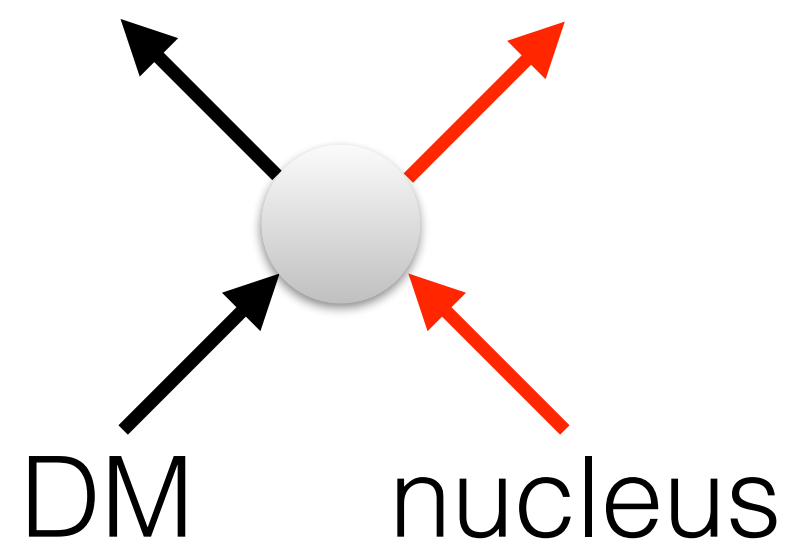
dramatic loss of sensitivity at low mass

when the momentum transfer is too small to generate a 'recoil'

Problems to detect DM

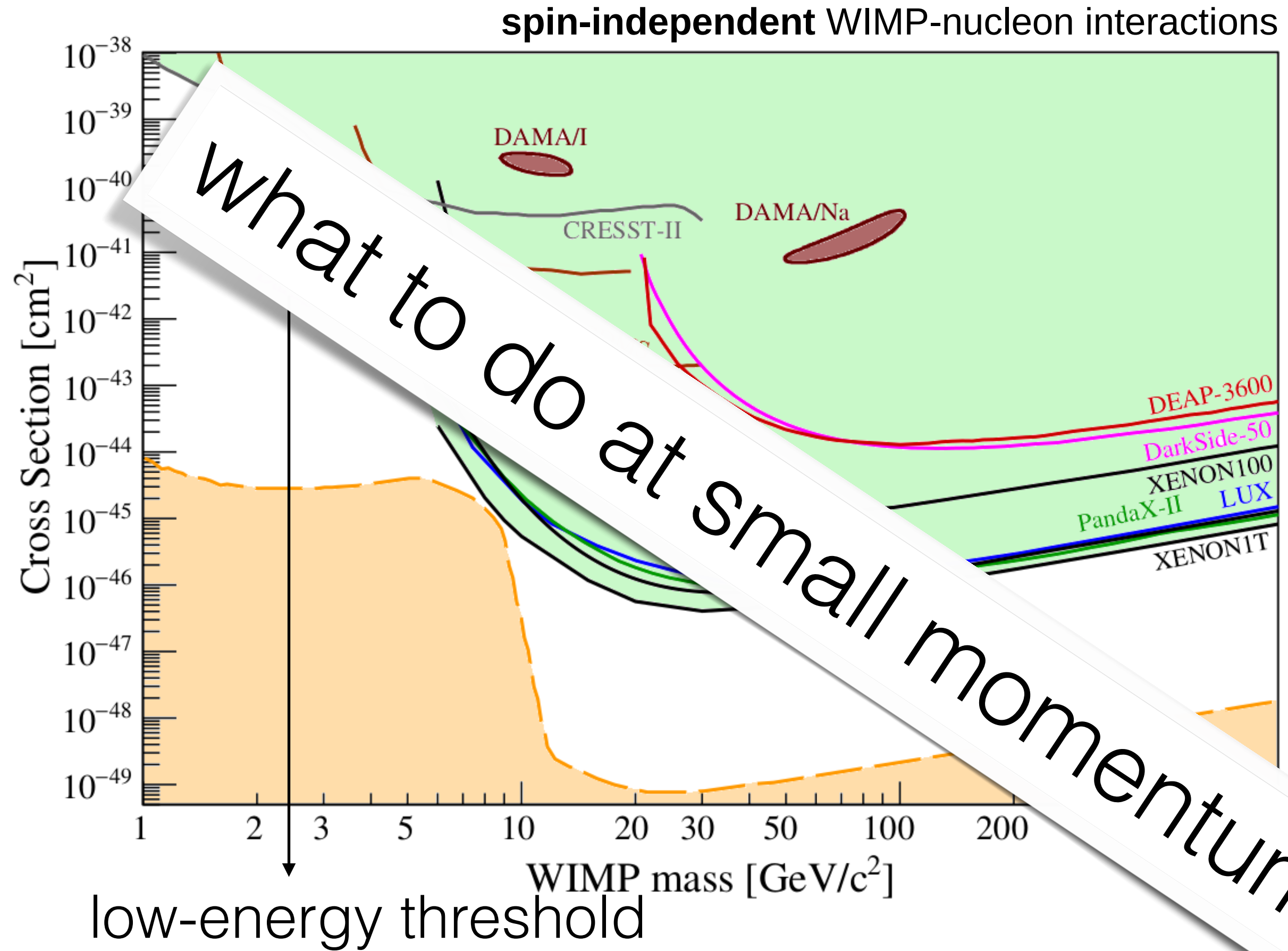


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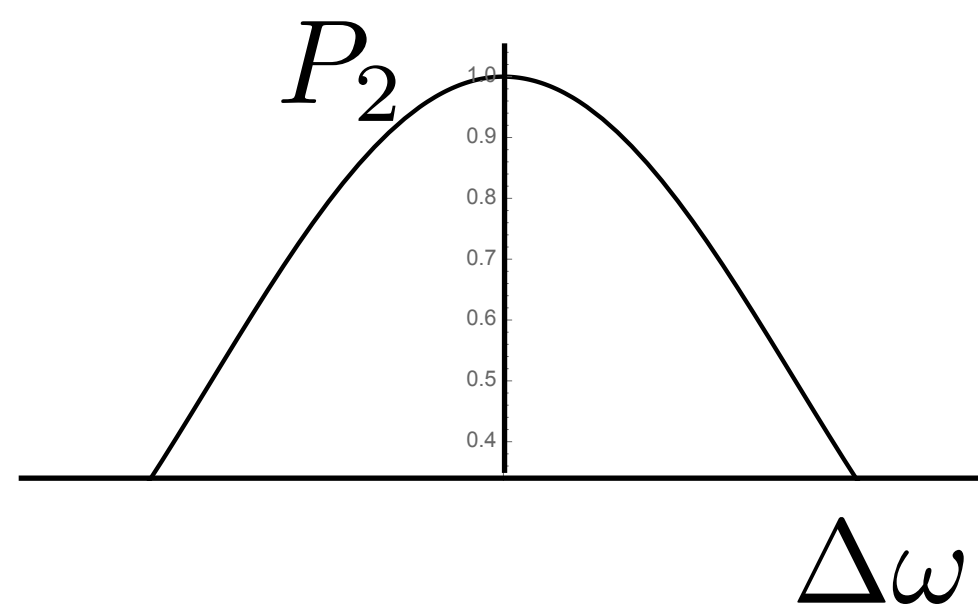
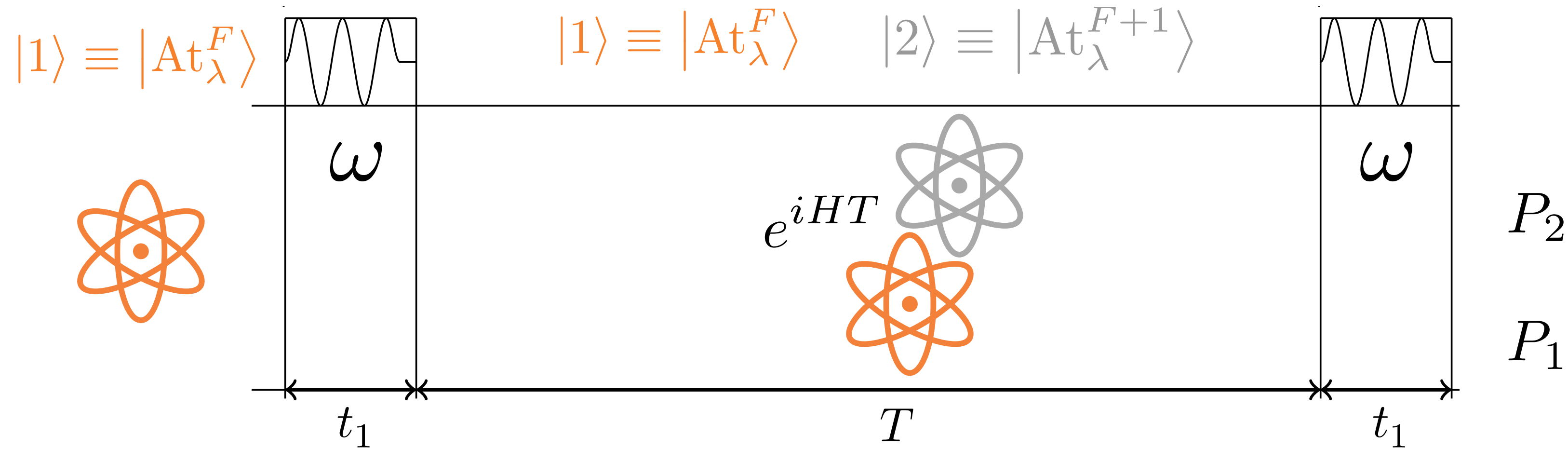
What to do at small momentum transfer?

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



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

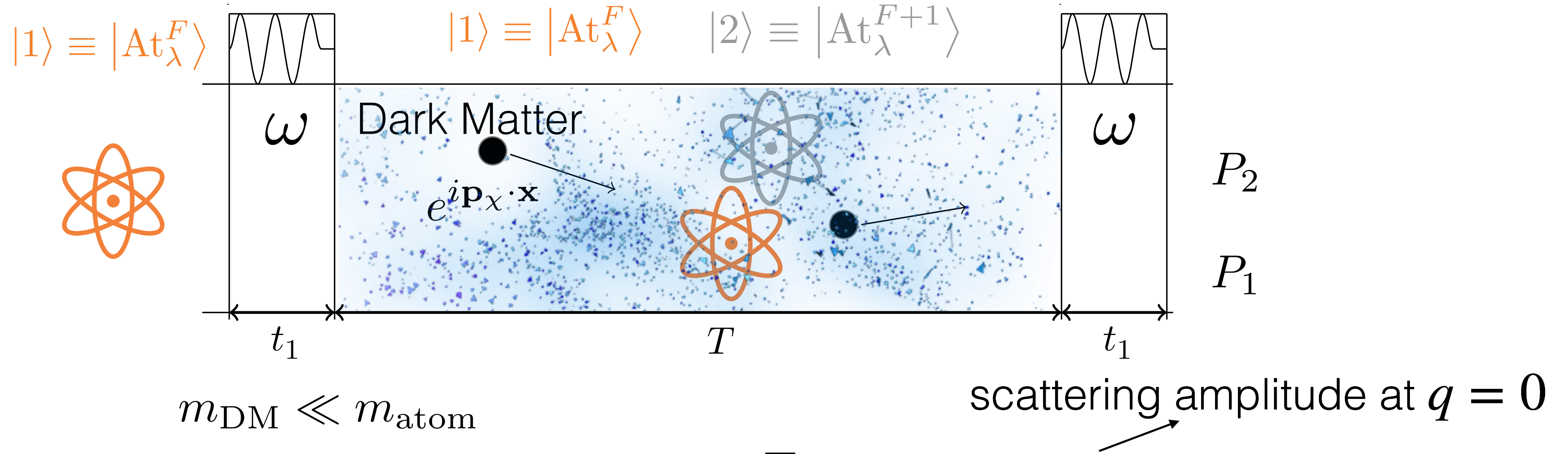
$$\partial P_2 = 0 \quad \rightarrow \quad \omega_{\max} = \Delta E$$

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

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Ramsey sequence in the presence of DM



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

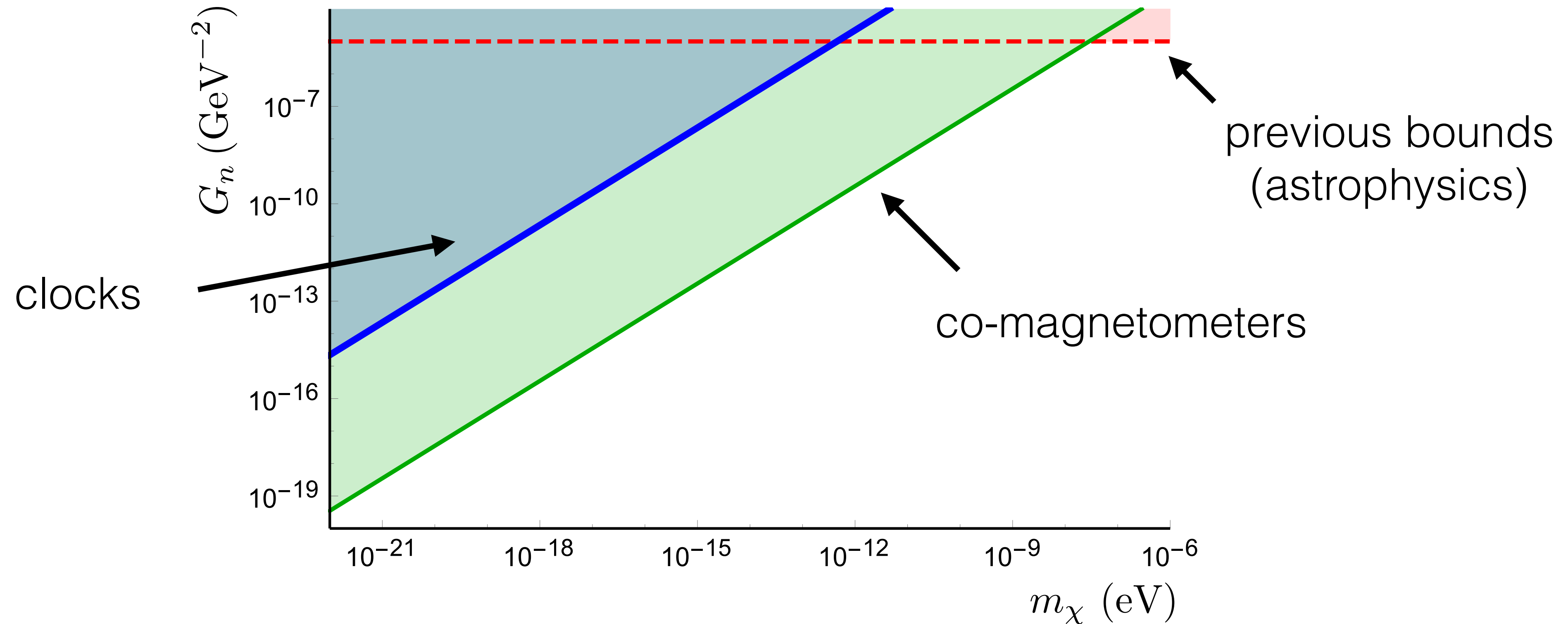
$$\partial P_2 = 0 \quad \longrightarrow \quad \omega_{\text{max}} = \Delta E + \delta_{\text{DM}}$$

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

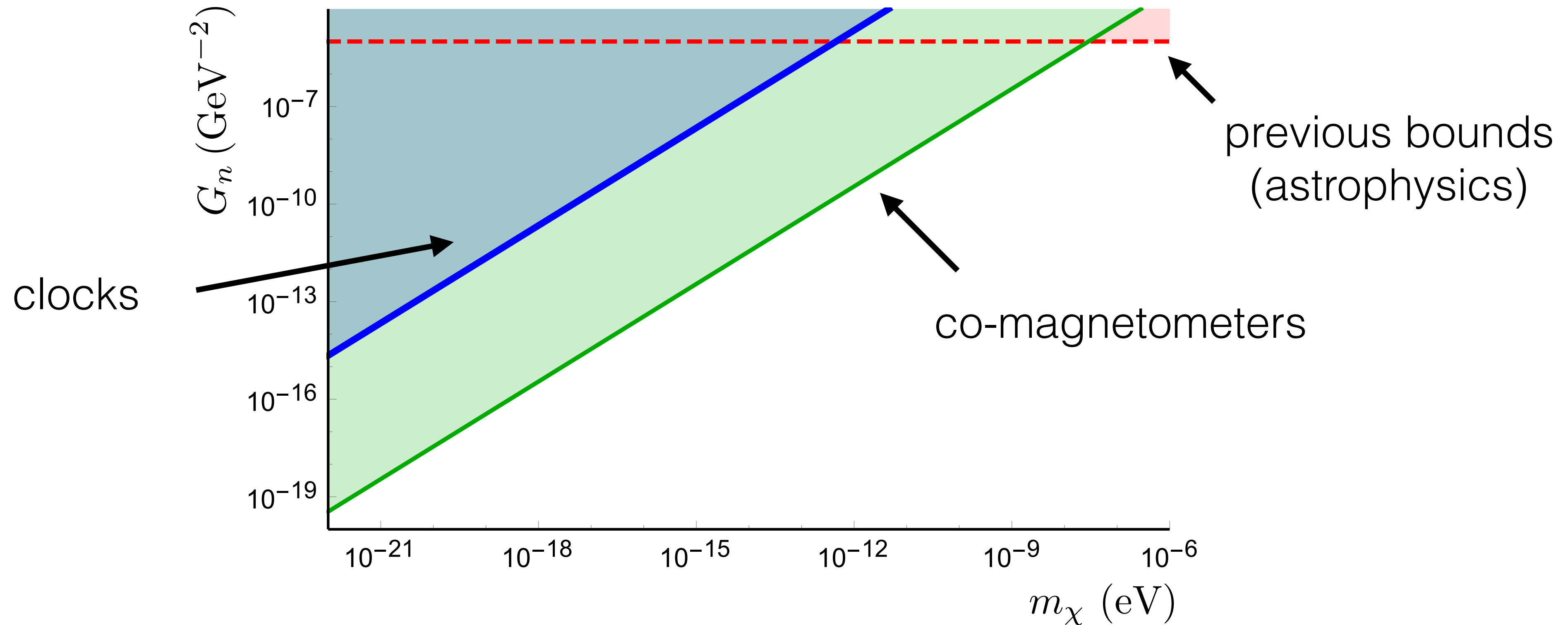
$$L_{\text{int}} = -G_n \int d^3x (\bar{n} \overset{\text{nucleons}}{\downarrow} \gamma^\mu \gamma_5 n) (\overset{\text{DM}}{\downarrow} i\chi^\dagger \partial_\mu \chi + \text{h.c.}) \quad \rightarrow \quad \vec{S}_n \cdot \vec{v}_\chi$$



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Alonso, DB, Wolf 1810.00889

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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...



Clinton Paints Sanders Plans As Unrealistic
New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY
MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.



A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

Long in Clinton's Corner, Blacks Notice Sanders

By RICHARD FAUSSET
ORANGEBURG, S.C. — When Helen Daley was asked whom she would vote for in the South Carolina primary, she answered as if the very question were absurd.

"What I'm seeing is a bunch of confusion, hearsay and foolishness," said Ms. Daley, 60, a retired nursing assistant who is African-American, shortly after finishing breakfast at the downtown McDonald's. "What I also see is a white man who's already been in the White House eight years. A veteran of the Clinton administration."

Continued on Page A16

Last Occupier In Rural Oregon Is Coaxed Out

This article is by Dave Semura, Richard Pérez-Peña and Kirk Johnson.
PRINCETON, Ore. — They implored the last holdout in the armed occupation of a wildlife refuge here to think about the Holy Spirit. They explained that the First Amendment was about freedom of speech and the Second was about the right to bear arms, and said that they were in that order for a reason.

Continued on Page A16

Late Edition
Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A16.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle.

More generally, it means that a century of innovation, testing, questioning and plain hard work after Einstein imagined it on paper, scientists have tapped into the deepest register of physical reality, where the weirdest and wildest implications of Einstein's universe became manifest.

Conveyed by these gravitational waves, power 50 times greater than the output of all the stars in the universe combined vibrated a pair of L-shaped antennas in Washington State and Louisiana known as LIGO on Sept. 14.

If replicated by future experiments, that simple chirp, which rose to the note of middle C before abruptly stopping, seems destined to take its place among the great sound bites of science, ranking with Alexander Graham Bell's "Mr. Watson — come here" and Sputnik's first beeps from orbit.

"We are all over the moon and back," said Gabriela González of Louisiana State University, a spokeswoman for the LIGO Scientific Collaboration, short for Laser Interferometer Gravitational-Wave Observatory.



La sombra de una nueva crisis bancaria hunde los mercados

El Ibex cae un 4,88% y la prima de riesgo llega a 169, máximo desde 2010

CLAUDI PÉREZ / IGNACIO FARIZA
Bruselas / Madrid
Las dudas sobre la salud de la banca europea hundieron ayer los mercados, temerosos de que se repita una crisis como la de 2008, que llevó a Lehman Brothers a la quiebra. En esta ocasión las miradas de los inversores están puestas principalmente sobre el mayor banco alemán, el Deutsche Bank, cuyos títulos cayeron un 6,1%. También existen dudas sobre la entidad francesa Société Générale, que se dejó un 12,57%, y sobre la fortaleza del sector italiano en conjunto.

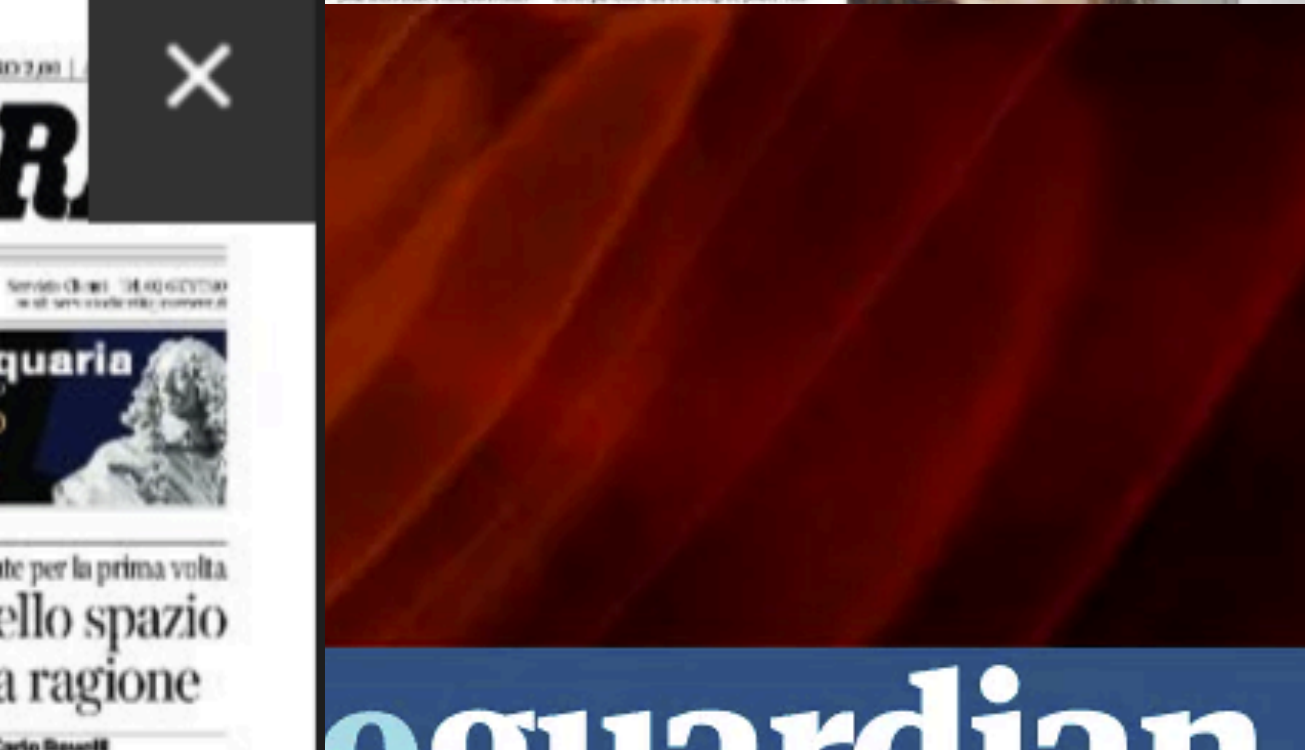
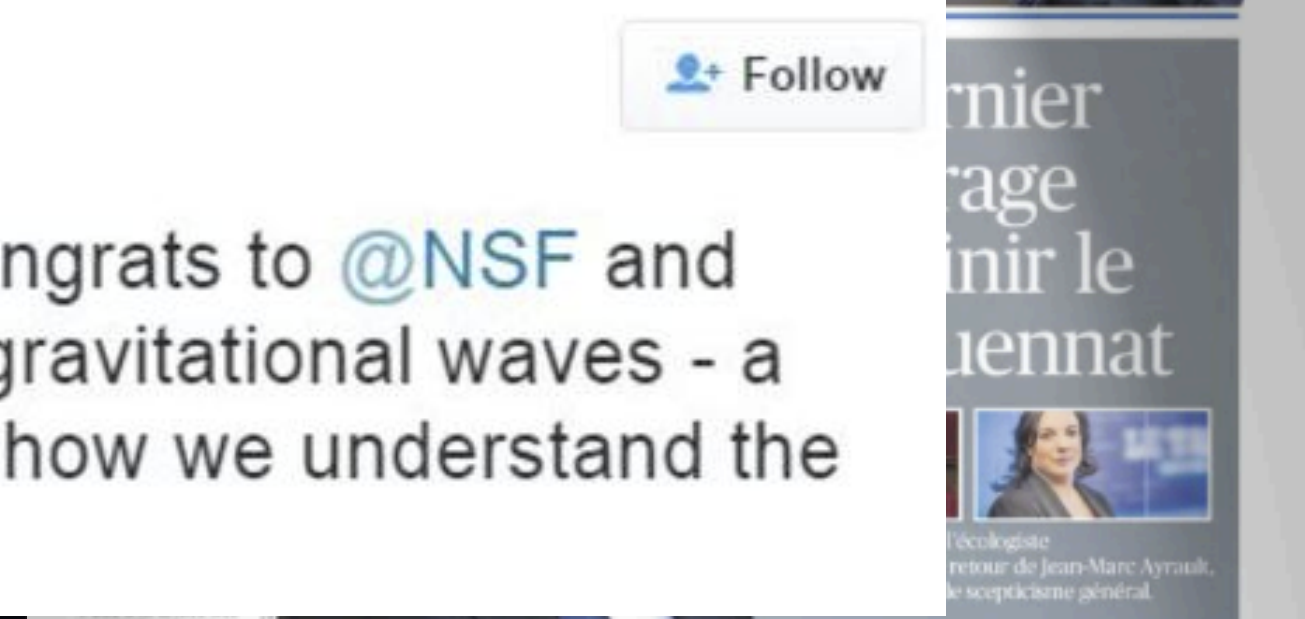
La caída de la Bolsa española —un 4,88%, la mayor desde agosto— solo fue superada por el desplome en Milán, del 5,63%. París se dejó un 4,05%. Londres un 2,39% y Fráncfort un 2,93%. El diferencial entre el bono español a 10 años y el alemán, llegó a los 169 puntos básicos, por encima del nivel que en 2010 llevó al expresidente del Gobierno José Luis Rodríguez Zapatero a acometer un duro plan de ajuste.

Los líderes europeos trataron



President Obama @POTUS

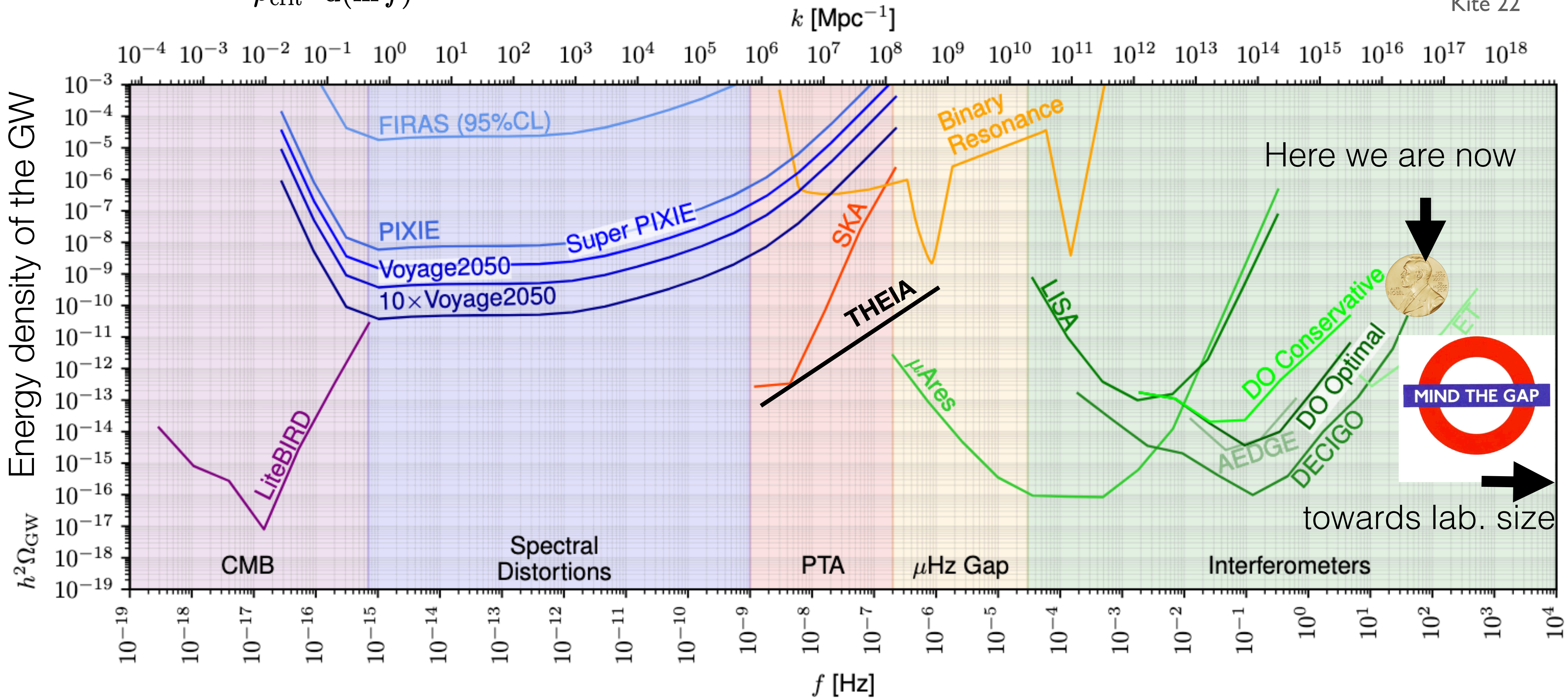
Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.



Expected gravitational soundscape ca. 2040

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

Kite 22



Milky Way in visible band



Milky Way in X rays



Our control of light in the lab is excellent!

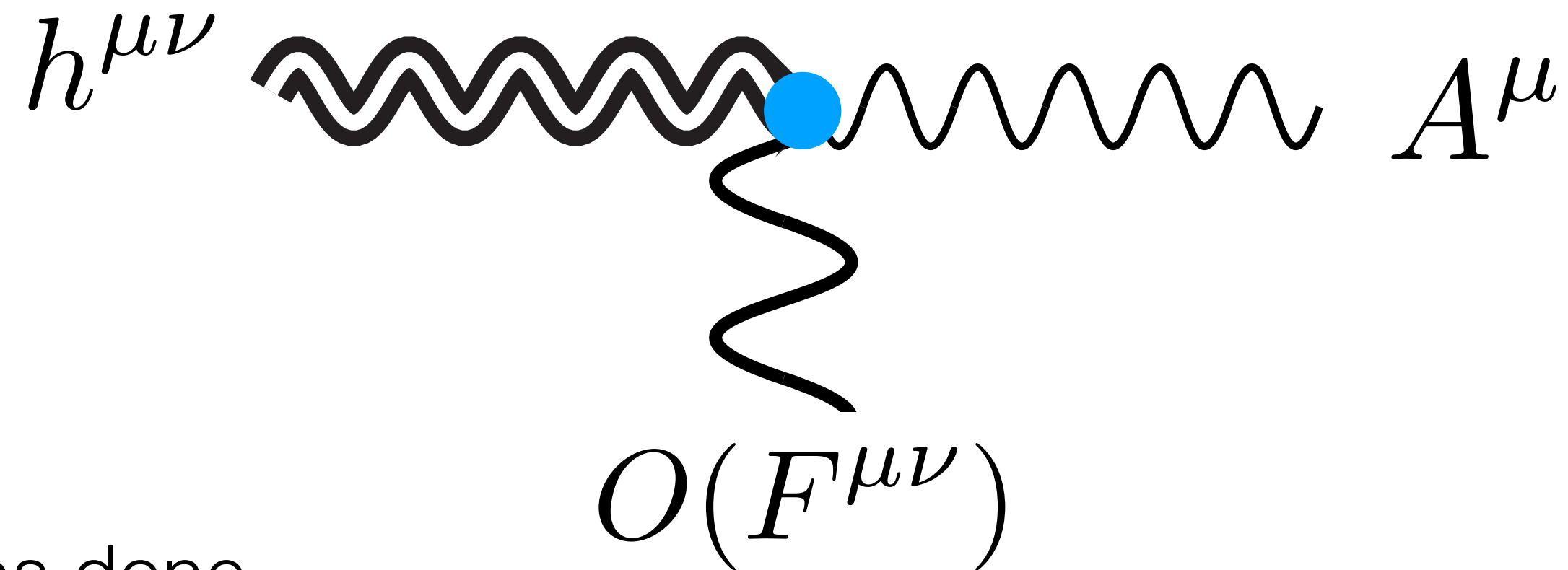


Interaction of GWs with light?

Interaction GWs with light!

fundamental backgrounds/interactions

gravitational wave + EM field = current!



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

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

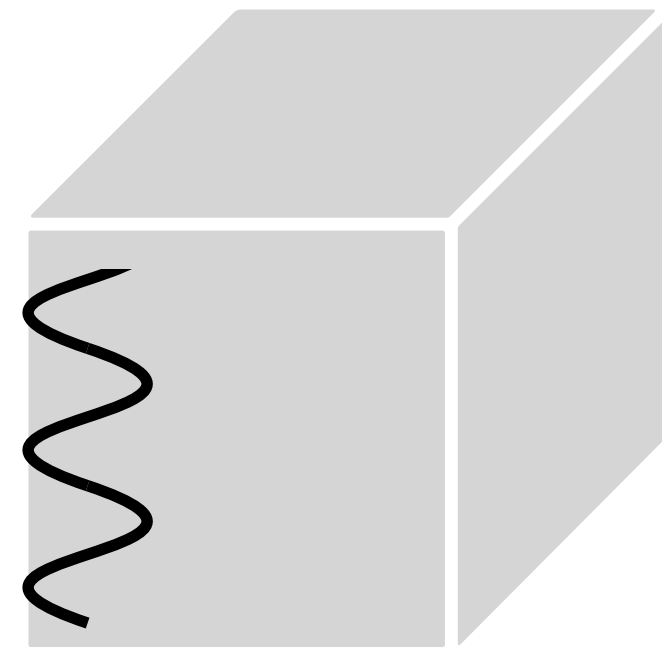
$$j_{\text{eff}}^\mu = -\partial_\beta \left(\frac{1}{2} h F^{\mu\beta} + h_\alpha^\beta F^{\alpha\mu} - h_\alpha^\mu F^{\alpha\beta} \right)$$

Interaction GWs with light: loaded cavities

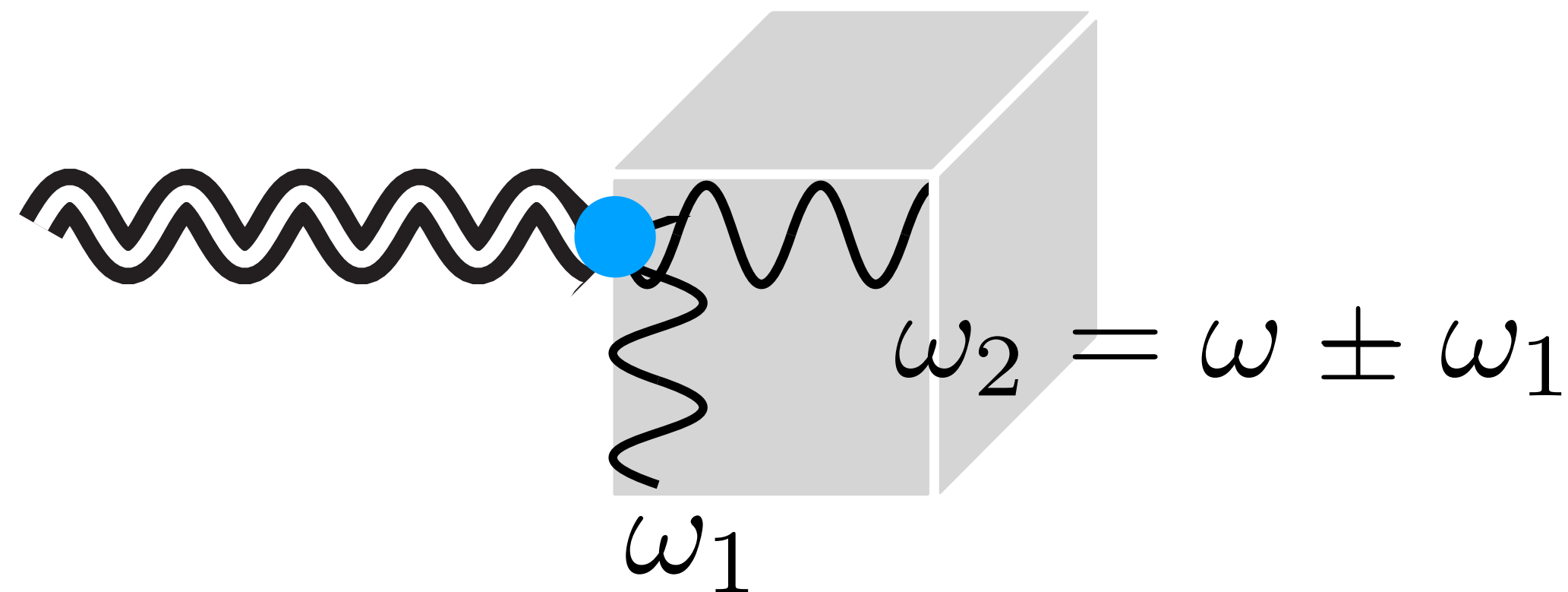
$h+EM$ field = current!

MAGO design from CERN (gr-qc/0502054)

EM-coupling

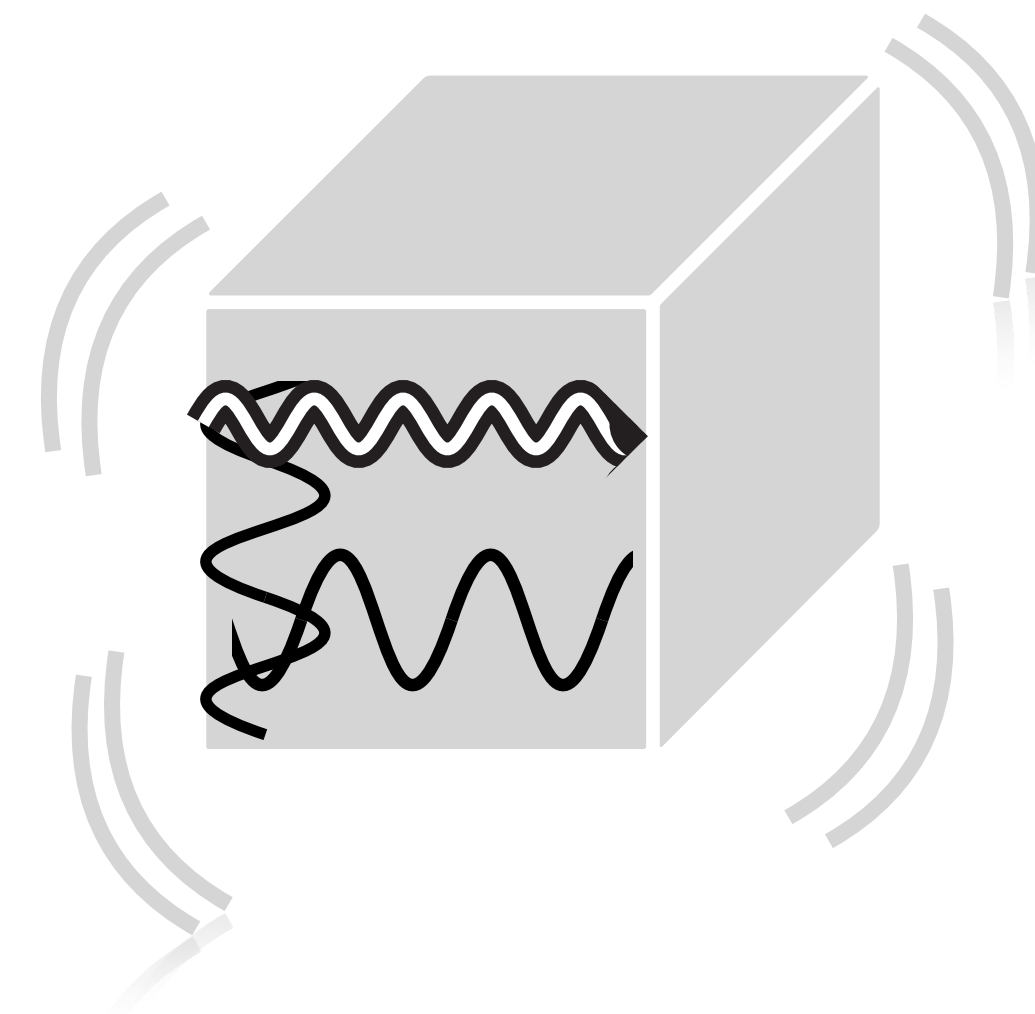
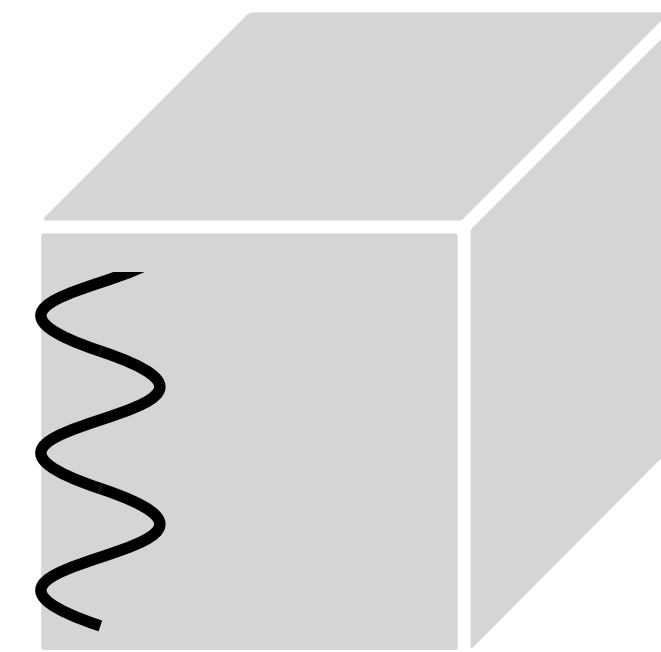


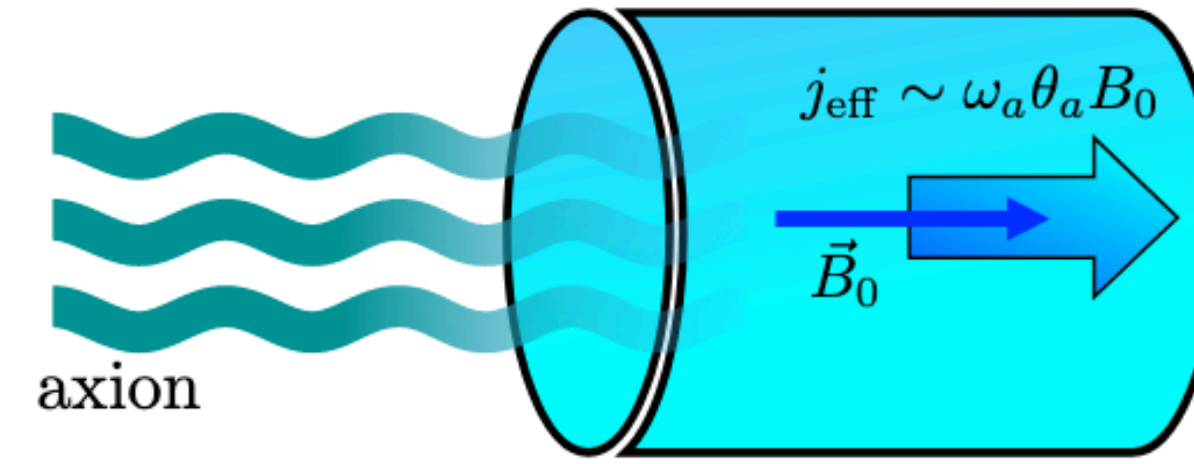
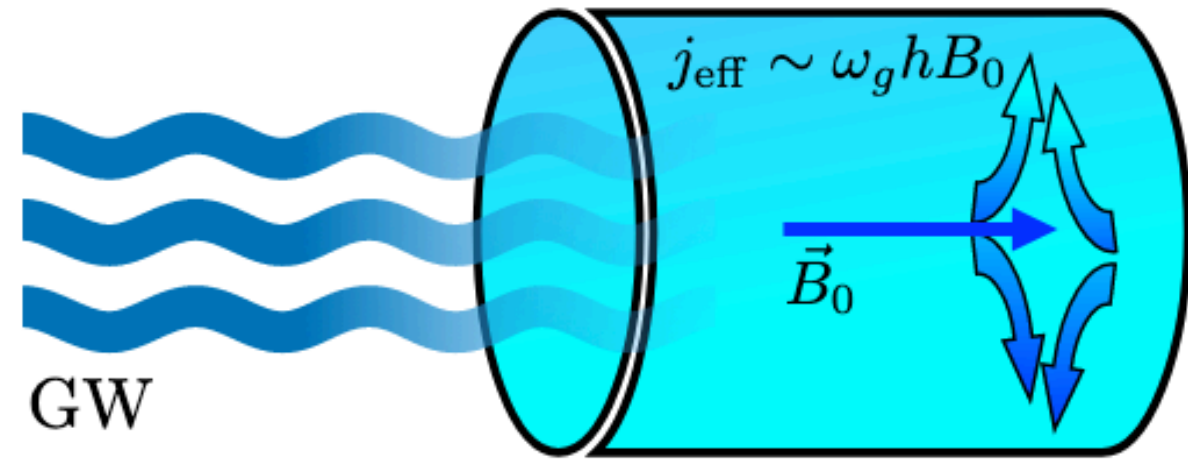
ω_1



ω_1

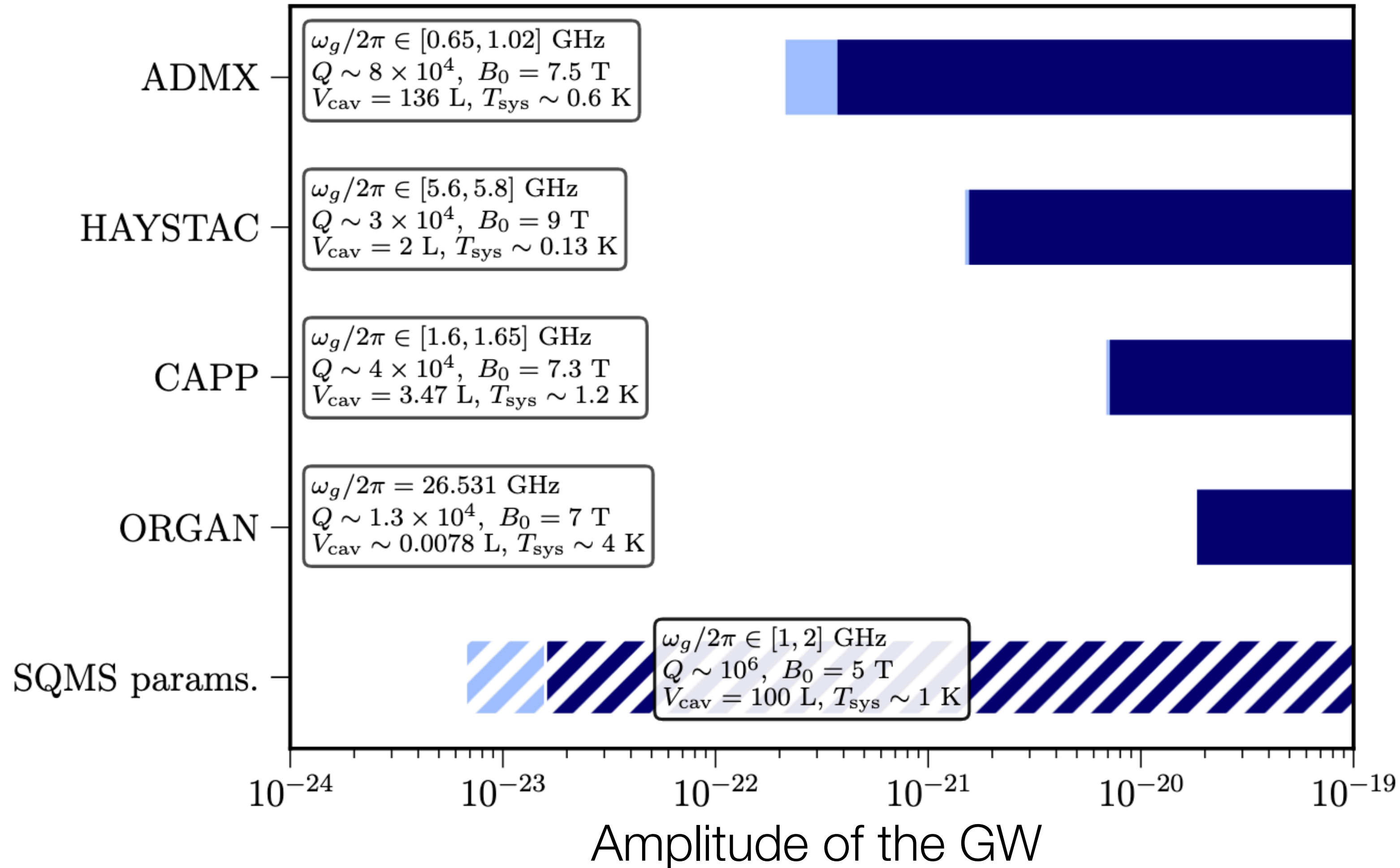
Mechanical-coupling
(shaking the walls)





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

Projected Sensitivities of Axion Experiments



+ it's directional and not degenerate with axions

2nd Conclusion

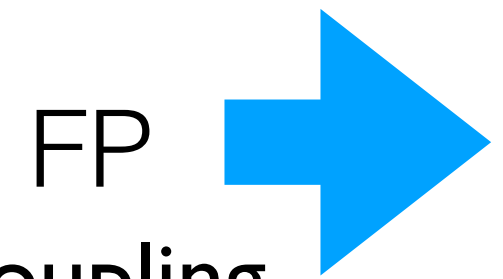
- Dark matter and cosmic neutrinos may leave impact in **quantum devices** (e.g. atomic clocks/magnetometers) even if the momentum transfer is ≈ 0
 - This opens new exiting possibilities
- SRF cavities is a mature technology to look for GWs at GHz either
 - Still far from getting to expected backgrounds,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

Road ahead

- Our first task: *dictionary*

fundamental backgrounds

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



QT

$$H = H_0 + H_{\text{int}}$$

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

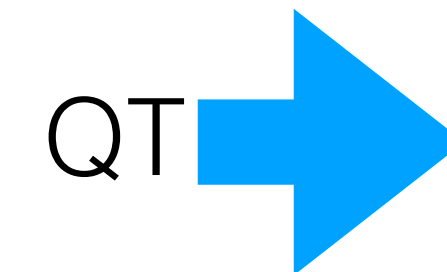
- Our second task: *genuine symmetric dialogue*

we have been (mostly) recycling techniques



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

$$H = H_0 + H_{\text{int}}$$



FP

backgrounds

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

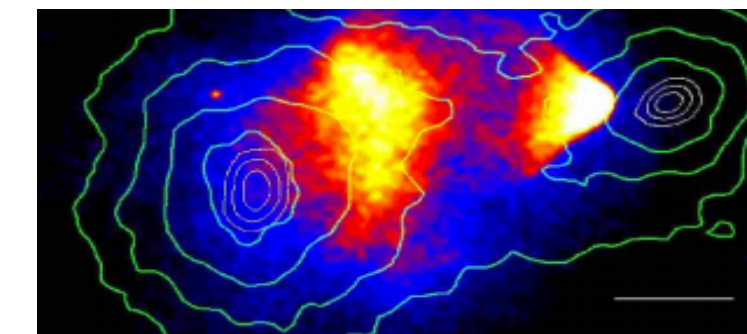
- ✳ Sub-task: we are far from the limit: e.g. **get more quantum**

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

neutrino physics



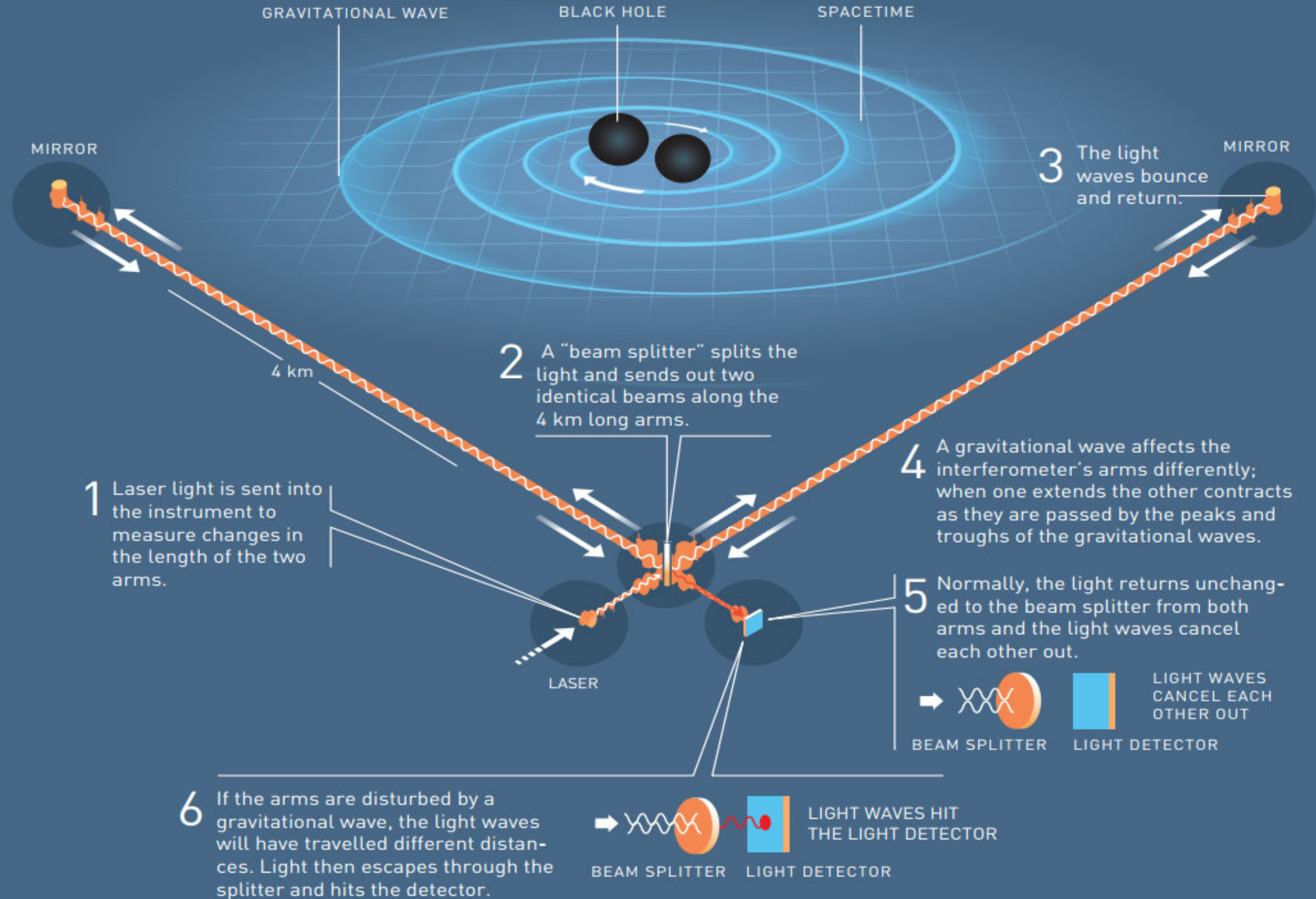
dark matter



gravitational waves

Back-up slides

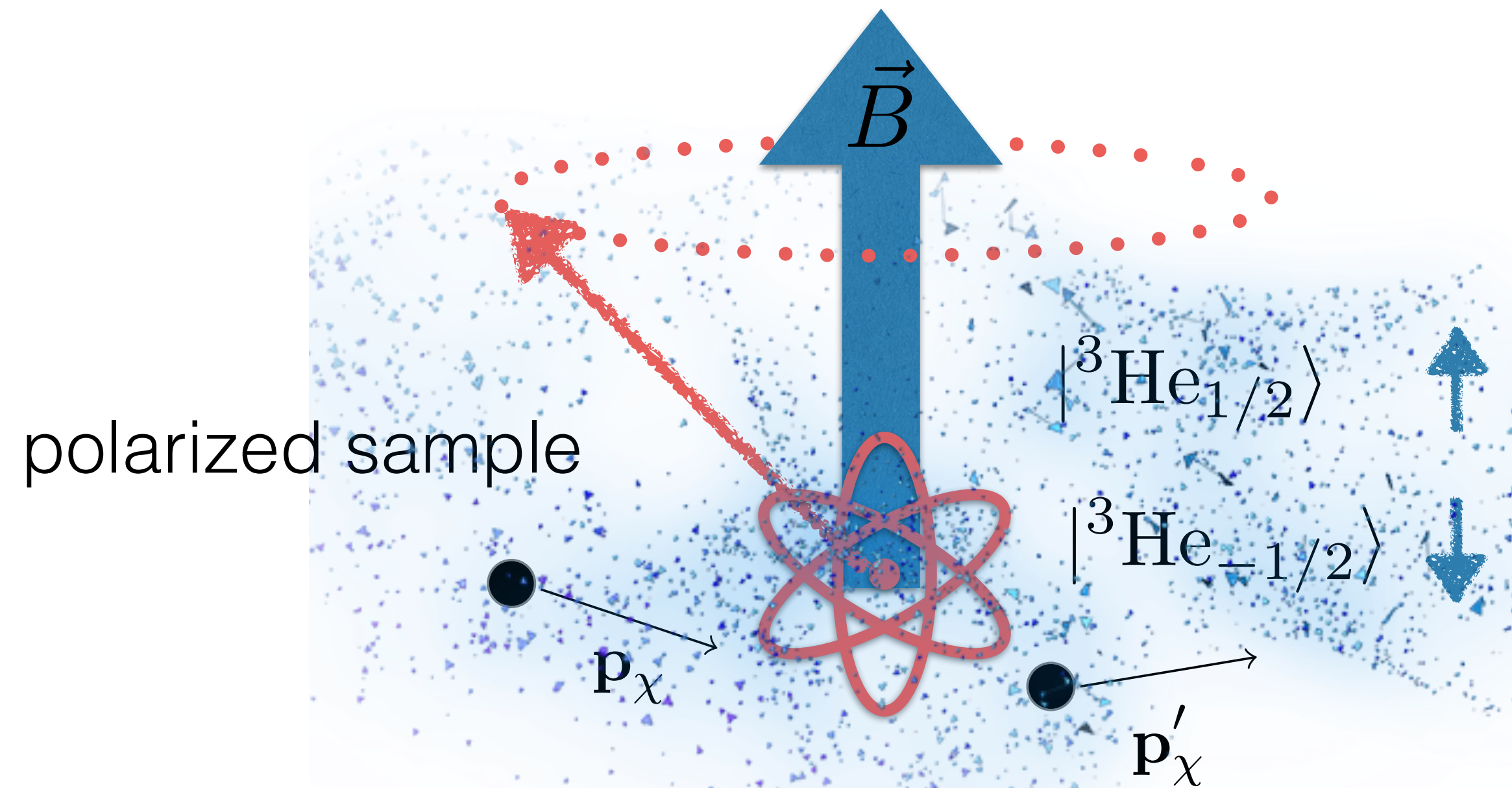
LIGO – A GIGANTIC INTERFEROMETER



DM-atom interaction in co-magnetometers

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

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



same with
 ^{129}Xe

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

Modified Larmor frequencies

Can be also understood as a phase difference

Co-magnetometer: eliminates B






$$\Delta\omega \lesssim 10^{-9} \text{ Hz}$$

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 ...