(Some) Open questions in fundamental physics

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Ivan Esteban

EHU

EHU Quantum Center

About this talk

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I am **no expert on quantum technologies**.
I work on *weakly coupled fundamental physics* (neutrinos, Dark Matter).

I am here to learn!

The driving questions

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- **What are the fundamental constituents of the Universe?**
- **How do they interact?**

We can study these questions *scientifically*!

Enormous progress

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Thomson, 1906.
Discovery of the electron

Englert, Higgs, 2013.
Last particle of the Standard Model

There is work to do

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- What is Dark Matter?
- What is Dark Energy?
- Are there additional interactions? ("Fifth forces")
- What is the nature of neutrinos?

Shedding light on these questions probably requires *new detector technologies*.

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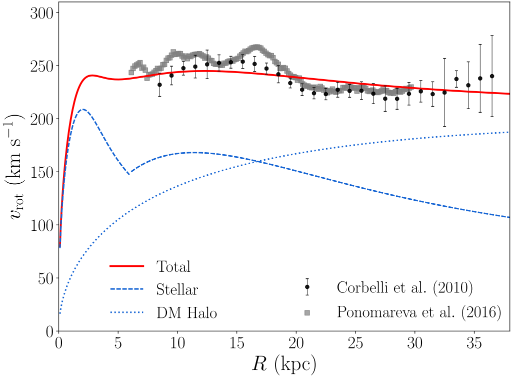
Evidence



More matter than stars

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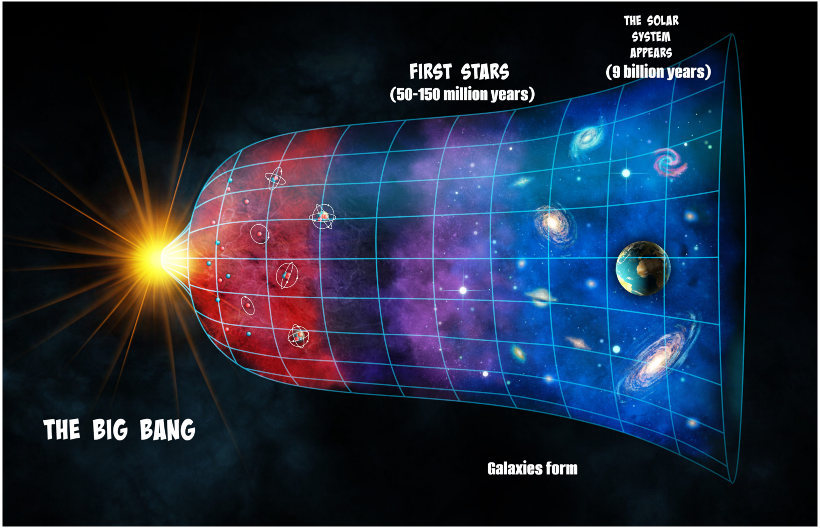

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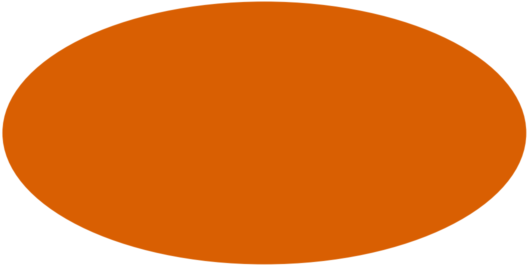
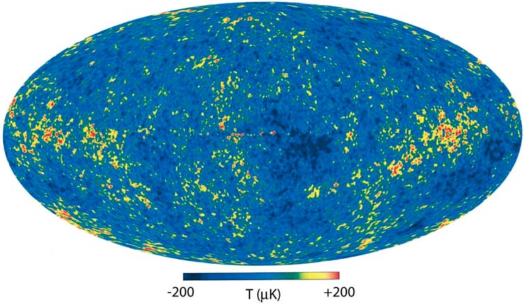


$$T \sim 2.7\,\mathrm{K}$$



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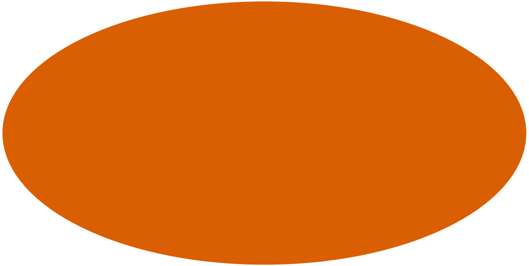

$T \sim 2.7\,\mathrm{K}$

There is already structure at $t \sim 5 \times 10^8\,\mathrm{years}$.
Inhomogeneities only grow by $\sim 10^2$ since the CMB!

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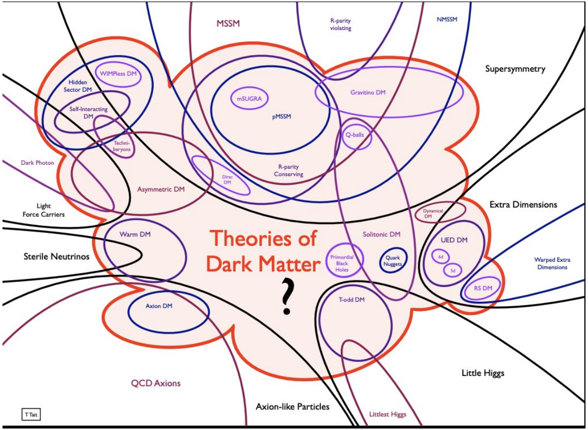
What is Dark Matter?



Cartoon by Tim Tait

Searches for non-gravitational interactions of Dark Matter are worth it because **Dark Matter must have been produced somehow!**

Searches for Dark Matter are **a benchmark for sensitivity to rare/weak processes!**

(Reusable in, e.g., neutrino detectors, long-lived particle production in colliders, search for new forces. . .)

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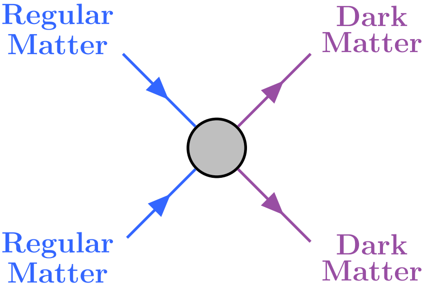
Thermal relic



- When the Universe was dense, even feeble interactions would **thermally produce Dark Matter**
- At some point, these interactions *freeze out*
- *Naturally large abundance today*!

(We think this is the origin of all regular matter in the Universe)

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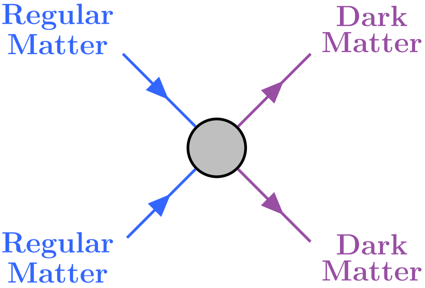
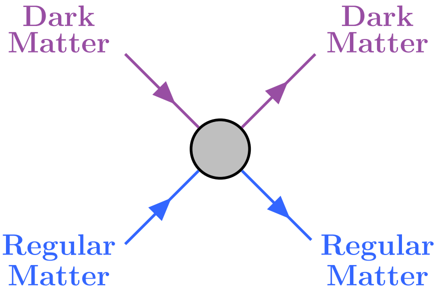
Thermal relic





Dark Matter interacts with regular matter, with a cross section that can, **on a model-by-model basis**, be predicted! $\sigma \sim 10^{-35}$–$10^{-45}\,\mathrm{cm}^2$

Dark Matter

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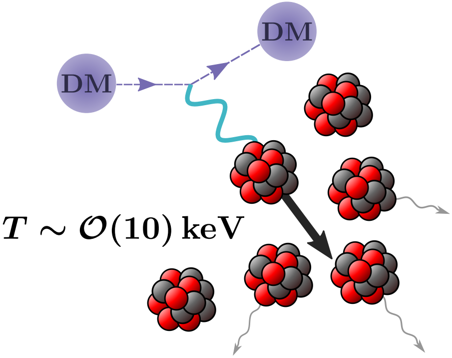
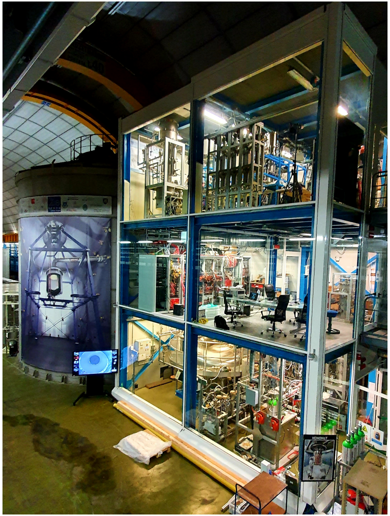
Direct detection





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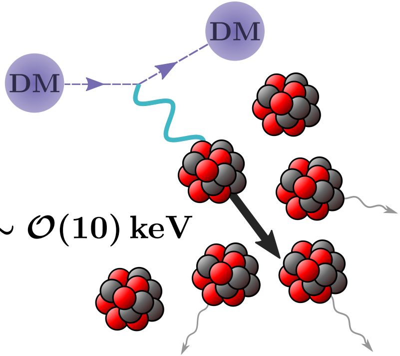
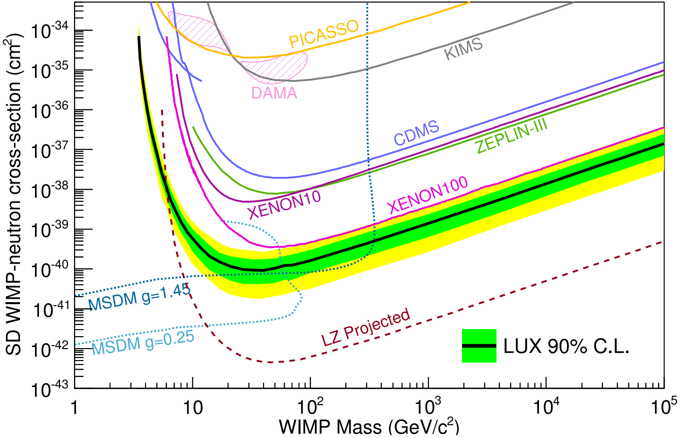
Direct detection: limitations



$T \sim \mathcal{O}(10)\ \mathrm{keV}$



Sensitivity loss at Dark Matter masses $\lesssim$ 10 GeV

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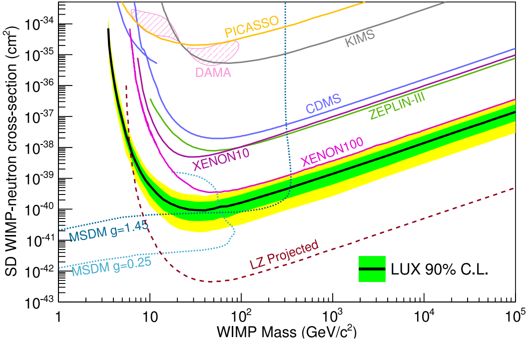
Direct detection: limitations

We need sensitivity to deposited energies

$$T \sim \mathbf{100\,eV} \left(\frac{m_{\mathrm{DM}}}{\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{GeV}}{m_{\mathrm{Target}}}\right)$$



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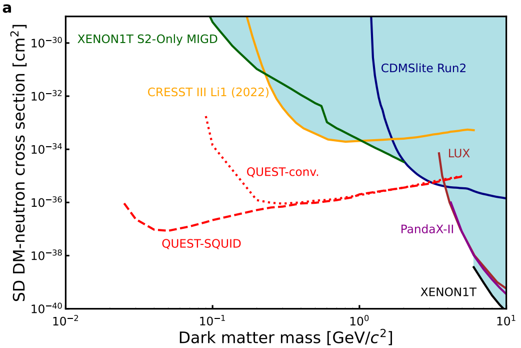

Bolometric: broken Cooper pairs in superfluid ^{3}He, detected with a nanomechanical resonator (NEMS), readout with a SQUID. (QUEST-DMC)

Defects? Color centers?

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Even smaller masses: wavelike Dark Matter

- We can go to the other side of the spectrum: $m_{\rm DM} \ll \mathrm{eV}$.
- The number density of Dark Matter in the solar system would be

$$n_{\rm DM} = \frac{\rho_{\rm DM}}{m_{\rm DM}} = 3 \times 10^8\,\mathrm{cm}^{-3}\left(\frac{1\,\mathrm{eV}}{m_{\rm DM}}\right)\,,$$

  i.e., interparticle distances $r \lesssim 10^{-3}\,\mathrm{cm}$. To be compared with the de Broglie wavelength $\lambda \gtrsim 10^{-2}\,\mathrm{cm}$.

- *Large occupation number* $\Rightarrow$ (bosonic) **classical field!**
  (See `arXiv:2408.04696` for a derivation with techniques from Quantum Optics)

(AKA axion-like Dark Matter)

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Hunting for wavelike Dark Matter

There are generically *feeble* interactions with regular matter.
Some consequences

- Birefringence even in vacuum
- Stimulated conversion into photons in cavities that resonate with the Dark Matter wavelength ($f \sim m_{\mathrm{DM}} \sim \mathrm{GHz}\ \frac{m_{\mathrm{DM}}}{10^{-6}\,\mathrm{eV}}$)
- Time-dependent nuclear electric/magnetic dipole moments ($f \sim m_{\mathrm{DM}} \sim \mathrm{GHz}\ \frac{m_{\mathrm{DM}}}{10^{-6}\,\mathrm{eV}}$)
- Time-dependent fundamental constants
- . . .

(See, e.g., `arXiv:1306.6088`)

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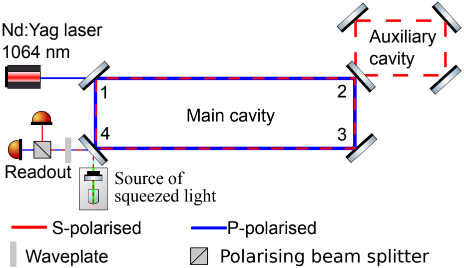
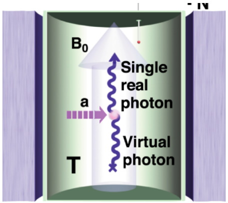
Hunting for wavelike Dark Matter





Interferometry with squeezed light for vacuum birefringence `arXiv:1911.00429`

$\Delta\phi \sim 10^{-15}\,\mathrm{rad}$ for $t = 10\,\mathrm{ns}$.

Resonant cavities with quantum-limited amplifier to reduce noise `arXiv:2504.07279`

Superconducting qubits for single-microwave-photon detection `arXiv:1711.05479, 2008.12231`

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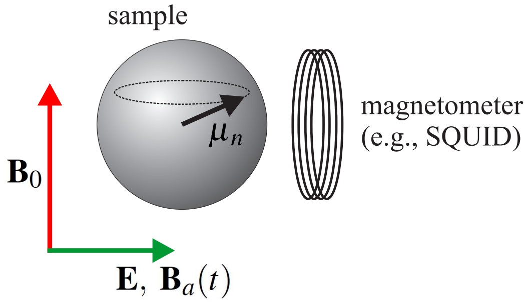
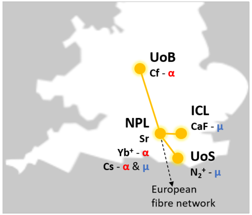
Hunting for wavelike Dark Matter





Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

Nuclear electric/magnetic dipole moments arXiv:1711.08999

$B \sim 10^{-13}\,\mathrm{T}$

Atomic clock networks for time-dependent fundamental constants arXiv:2112.10618

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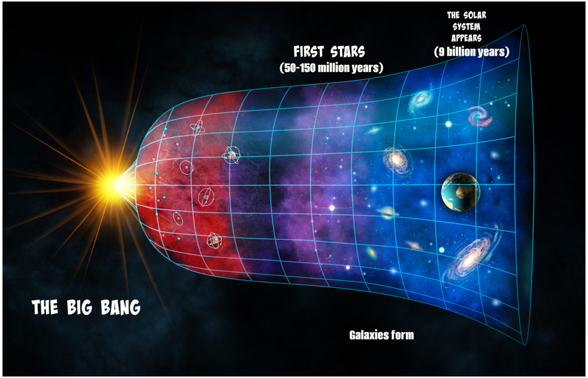

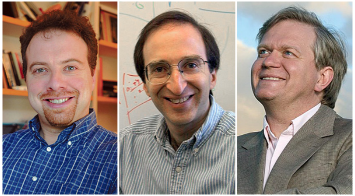

The expansion of the Universe is accelerating!

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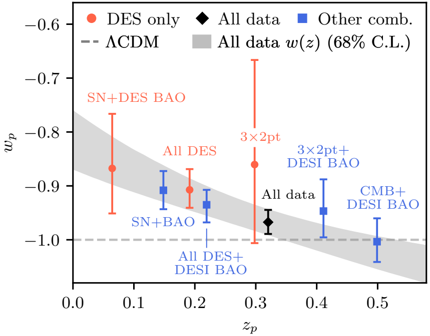
And ultralight scalar fields

A very light scalar field that permeates the Universe could cause accelerated expansion.
The smoking gun would be time-dependent acceleration rate. . .



arXiv:2605.27221

Dark Energy and fifth forces

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- In the very same way that a vector field (electromagnetism) mediates attractive/repulsive forces, a scalar field would mediate **universally attractive forces**.
- "Fifth forces" are a generic prediction of **extensions of General Relativity**.
- $a \sim 10^{-11}\,\mathrm{m/s^2}$, testable with atom interferometers, arXiv:1408.1409, arXiv:2511.09750 ...

A final word on neutrinos

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- In the Standard Model of particle physics, *all particles are massless*. The observed mass is only a consequence of interactions with the Higgs.

- With no new particles, *neutrinos do not interact with the Higgs*.

We only know $\Delta m \sim 0.1\,\mathrm{eV}\ldots$

A final word on neutrinos

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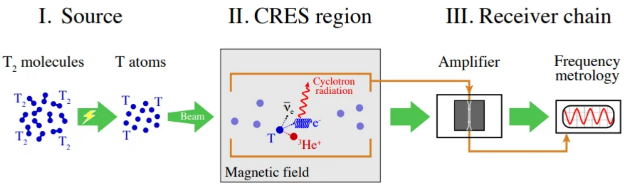
QTNM
Quantum Technologies for Neutrino Mass



$$B \sim 10^{-6}\,\mathrm{T}$$

Concluding words

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- There are pressing open questions in fundamental physics (Dark Matter? Dark Energy? Neutrinos?).
- There is a lot of room for looking at **feeble effects**.
- Quantum sensing may be the way forward,
  - Tiny energy depositions
  - Tiny magnetic fields
  - Single-photon detection
  - Atom interferometry
  - ...
- Potential for new avenues!