Quantum Sensing For (Very) Light Dark Matter Direct Detection

RYAN PLESTID

THEORY FELLOW @ CERN --> UNIVERSITÉ DE MONTRÉAL IN 2027

MACDONALD INSTITUTE ANNUAL MEETING 2026

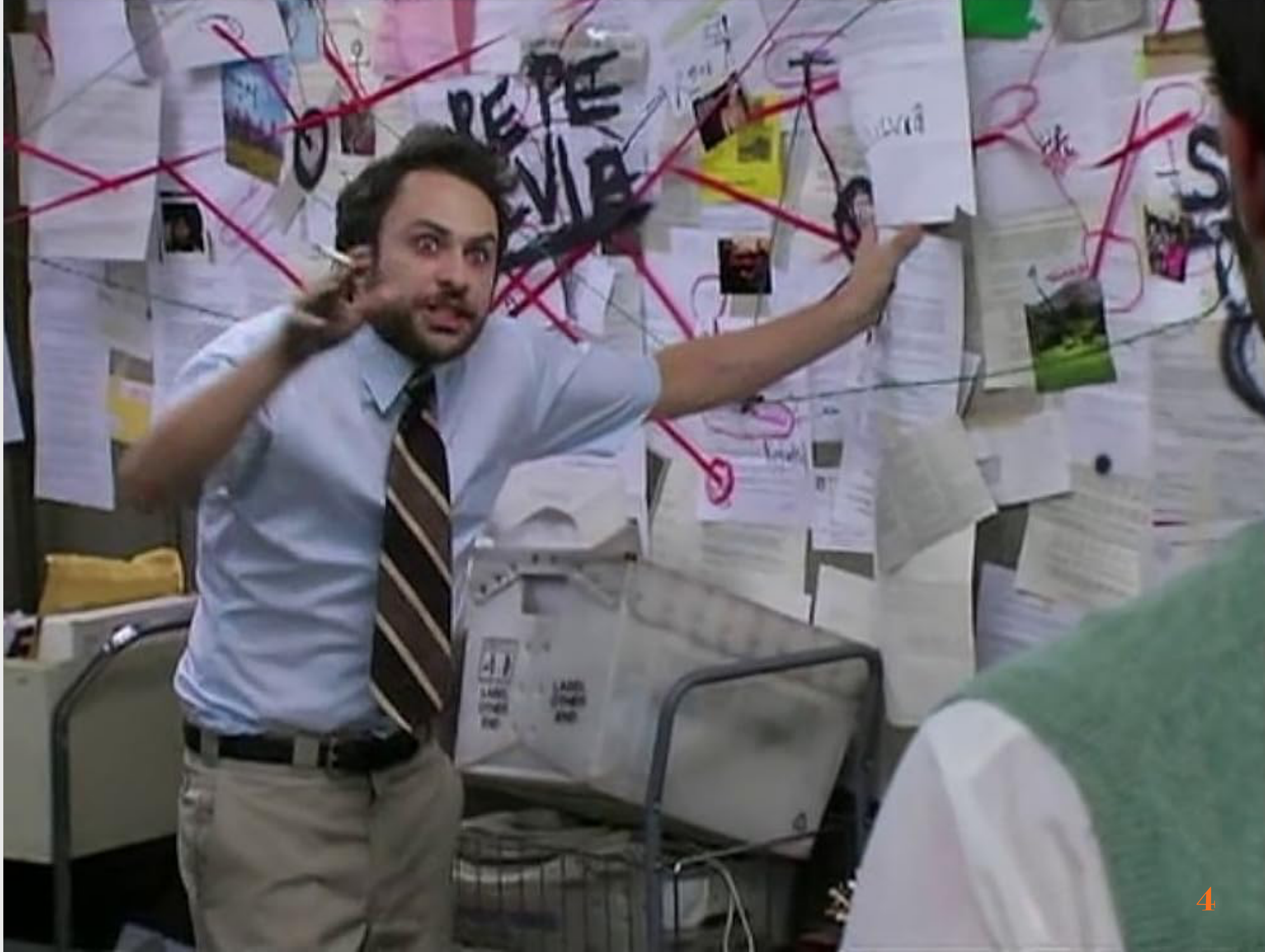
A Quick About Me

- Near Toronto
- Small(ish) hometown
- Undergraduate (4 yr) at U. of Guelph.
- M.Sc. & Ph.D. in Hamilton.

A Map!

2027
Université de Montréal
PERIMETER INSTITUTE
McMaster University
CERN
CALIFORNIA INSTITUTE OF TECHNOLOGY
1891
Greenland
Iceland
Northwestern Passages
Hudson Bay
Labrador Sea
Canada
United States
Mexico
Cuba
Puerto Rico
Guatemala
Nicaragua
Caribbean Sea
Venezuela
North Atlantic Ocean
Sweden
Finland
Norway
Denmark
United Kingdom
Ireland
Poland
Belarus
Ukraine
France
Italy
Spain
Portugal
Greece
Türkiye
Syria
Tunisia
Morocco
Algeria
Libya
Egypt
Western Sahara
Mauritania
Mali
Niger
Chad
Sudan
Burkina Faso
Guinea
Nigeria
Ghana
Ethiopia

Research Interests




COSMIC RAYS
PRECISION BETA DECAY
ASTRO-PARTICLE
DARK MATTER
EFFECTIVE FIELD THEORY
NEUTRINO PHYSICS
QU. SENSING
DETECTORS & NEW SIGNALS

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Université de Montréal

CERN

MOTIVATION

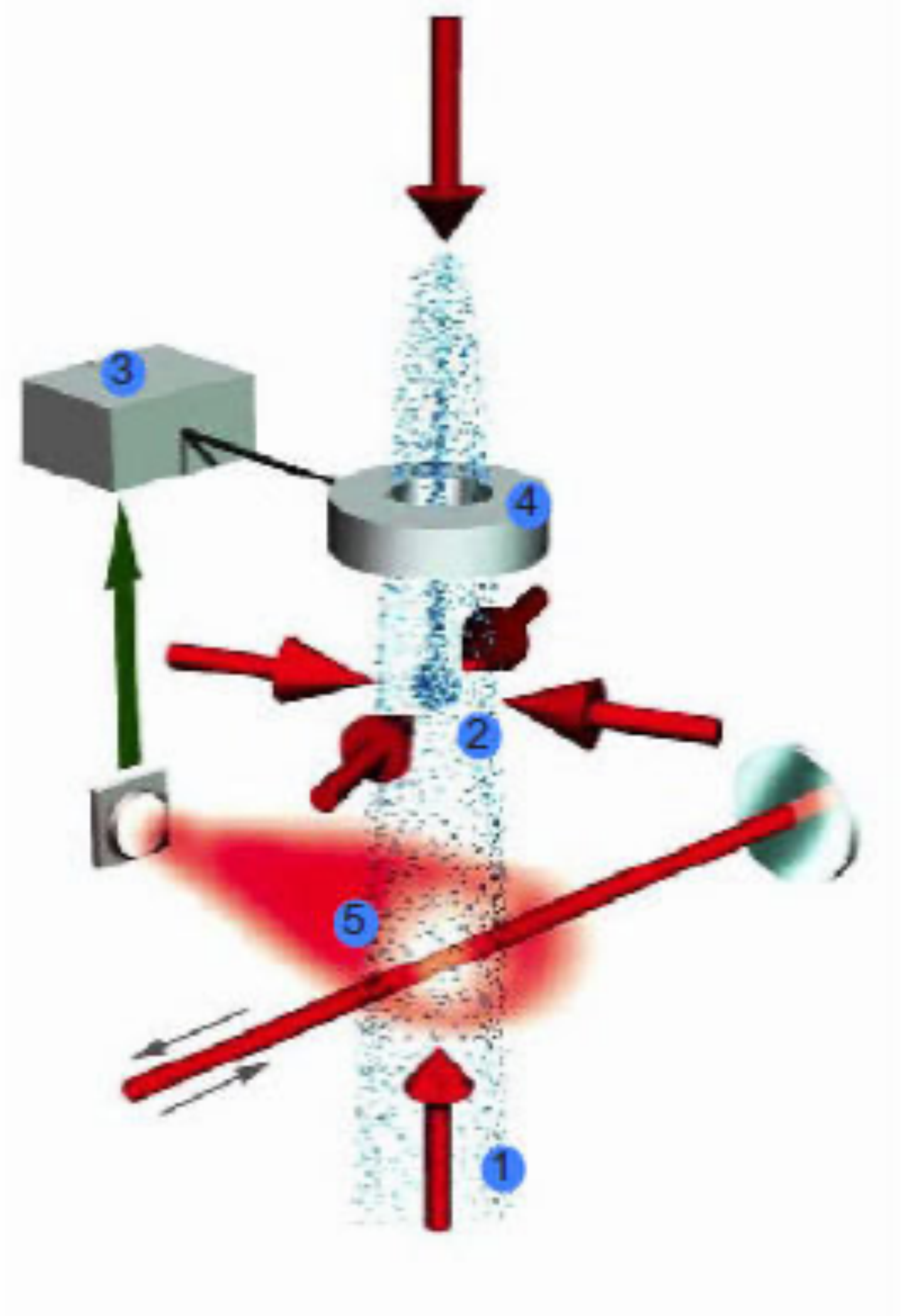
A DETECTOR FRONTIER

ZEN DETECTION

CHANGE WITHOUT CHANGE

ATOM INTERFEROMETERS

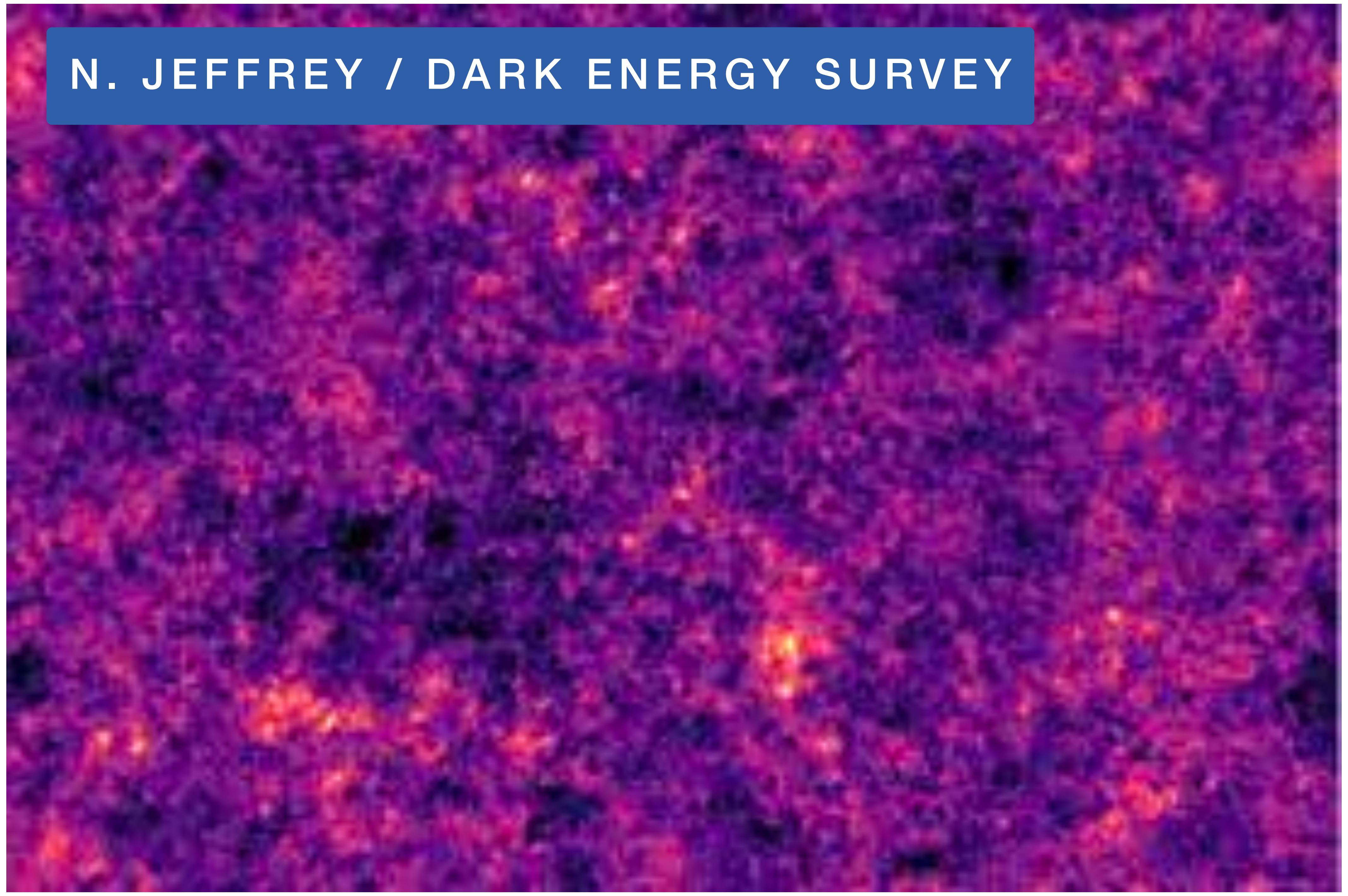
COHERENCE + DECOHERENCE



Principle of the atomic fountain

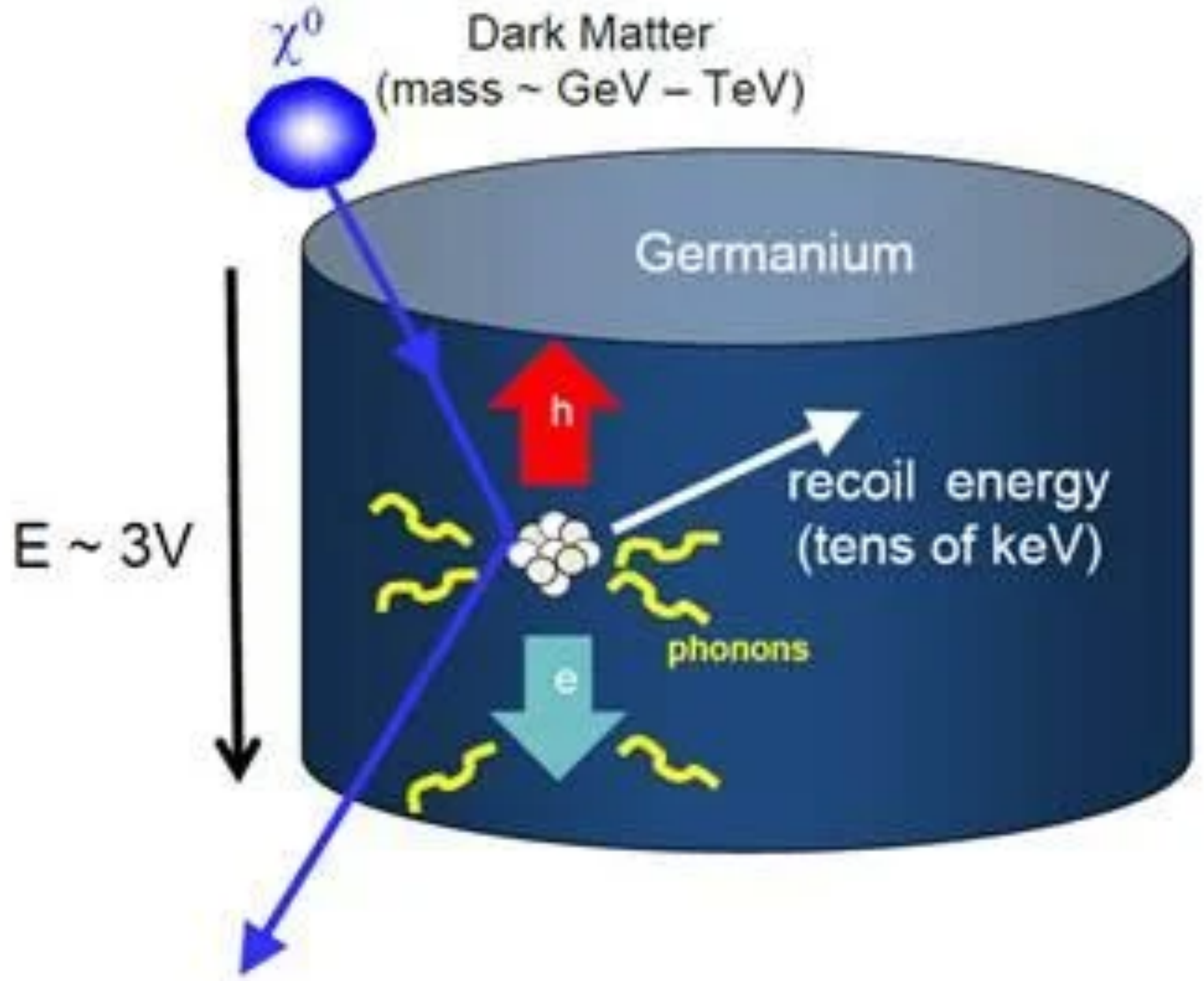
1. Stream of Caesium atoms
2. Optical molasses
3. Oscillator
4. Micro-wave interactions
5. Measurement of fluorescence

WHAT ***WE KNOW*** WE ***DON'T KNOW***.

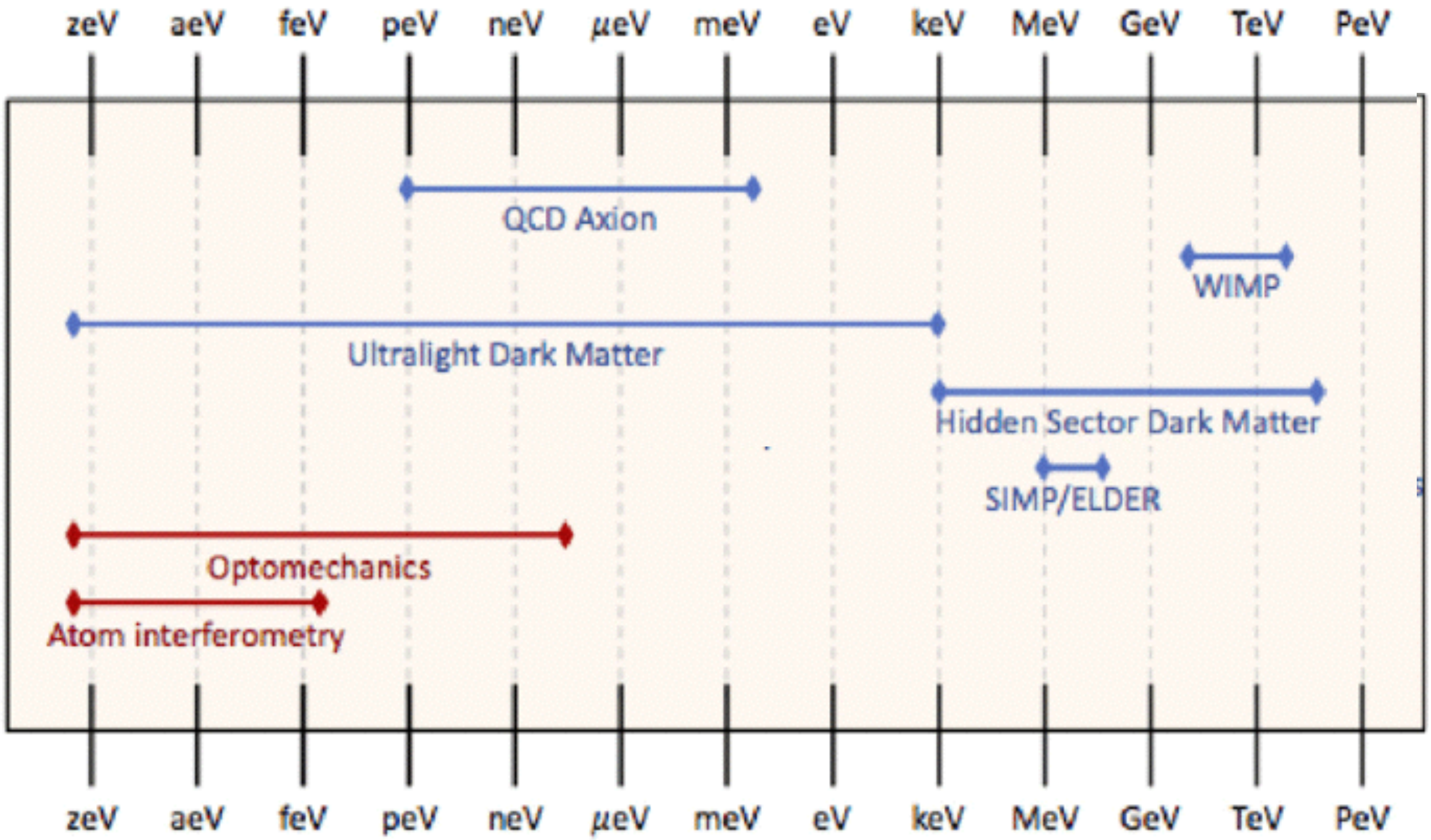


Dark matter direct detection

- We have big experimental blind-spots.
- ***Low-masses*** and/or ***soft-scatters***.
- Need new ideas even for ***large cross-sections.***

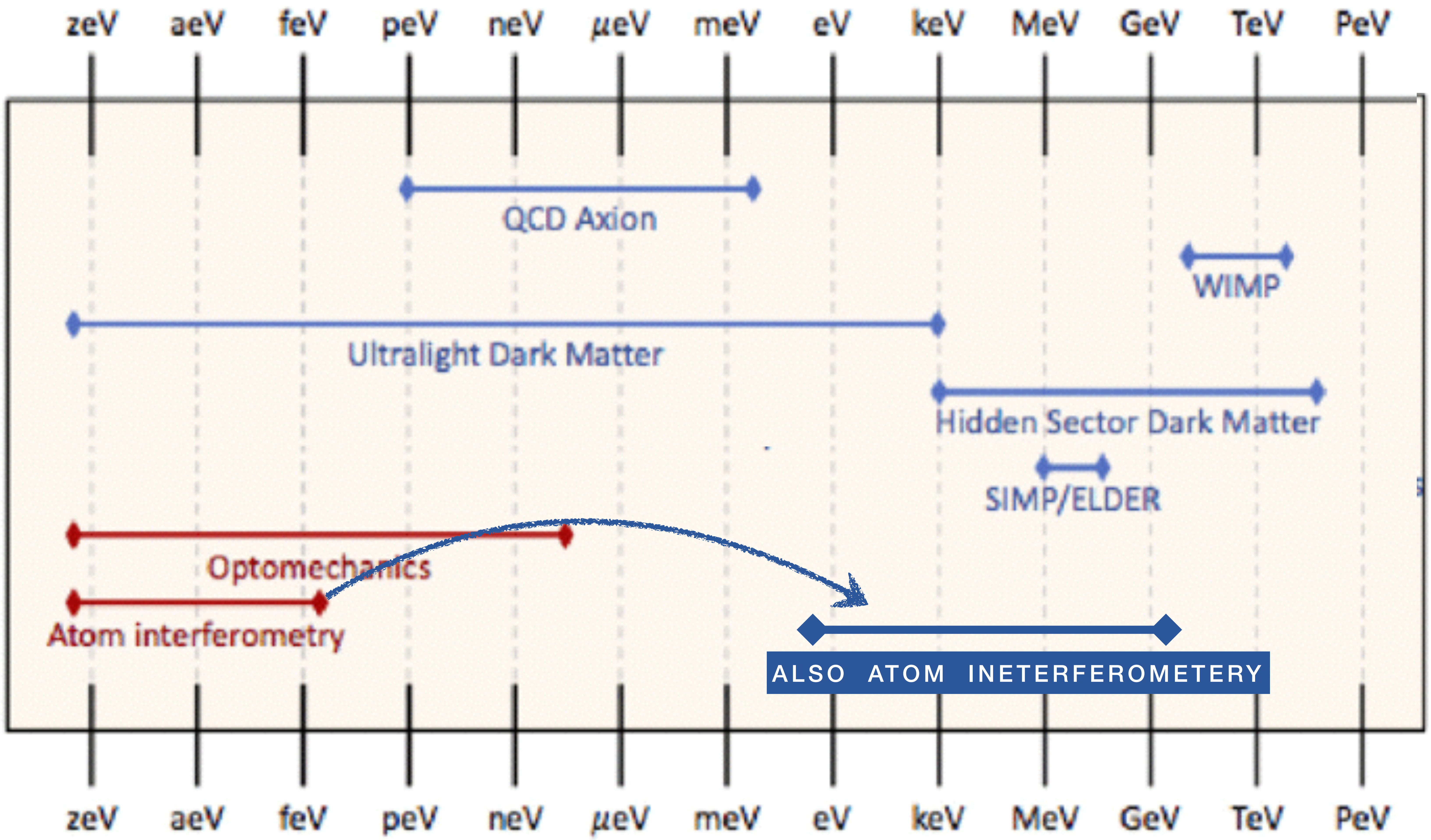


Dark Matter Landscape



- Mature literature attacking wave-like dark matter.
- Big potential for low-mass particle-like DM.
- See Riedel, Yavin (2016) 1609.04145.

Quantum Sensors



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QUANTUM MECHANICS

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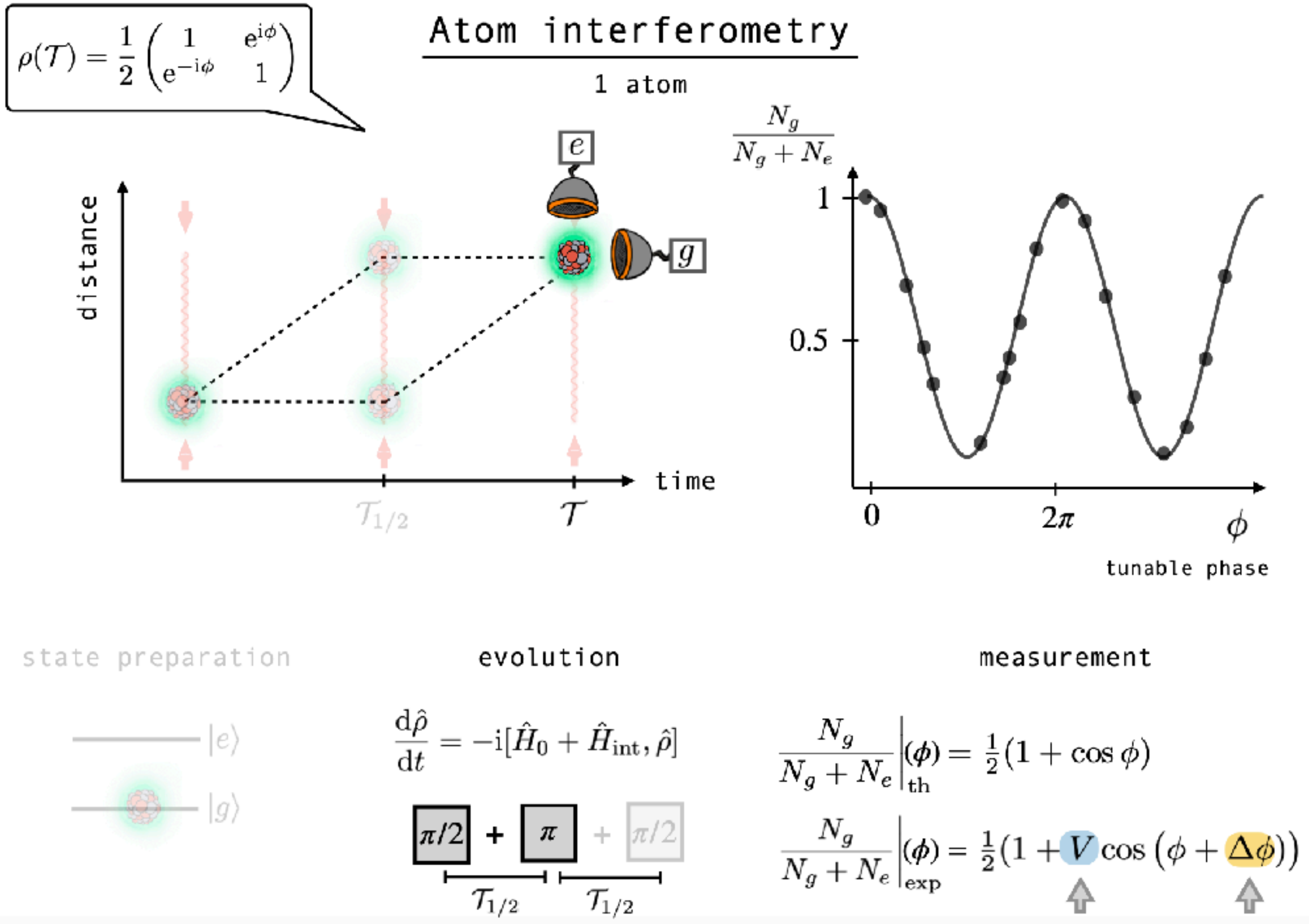
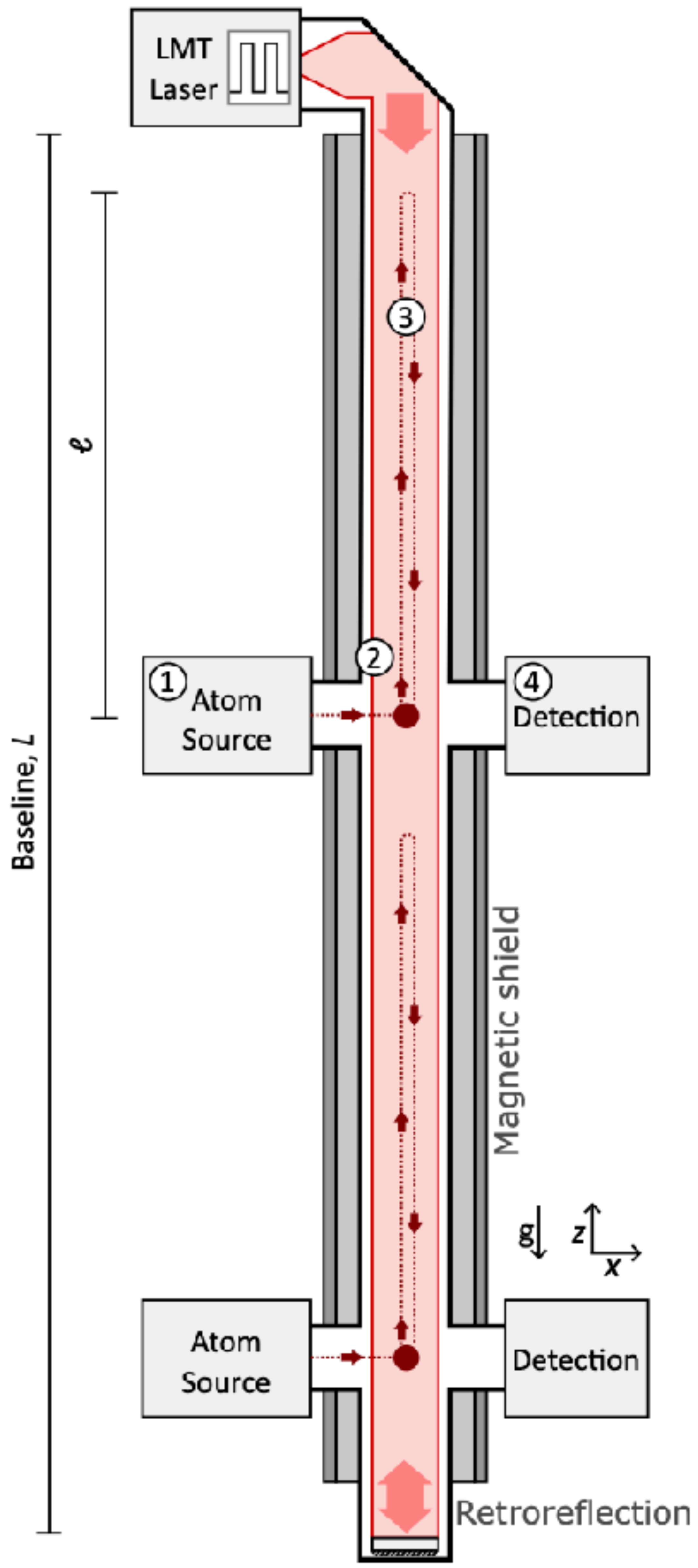
Atom Interferometers



SLIDE BY C. MURGUI

AICE PROPOSAL AT CERN



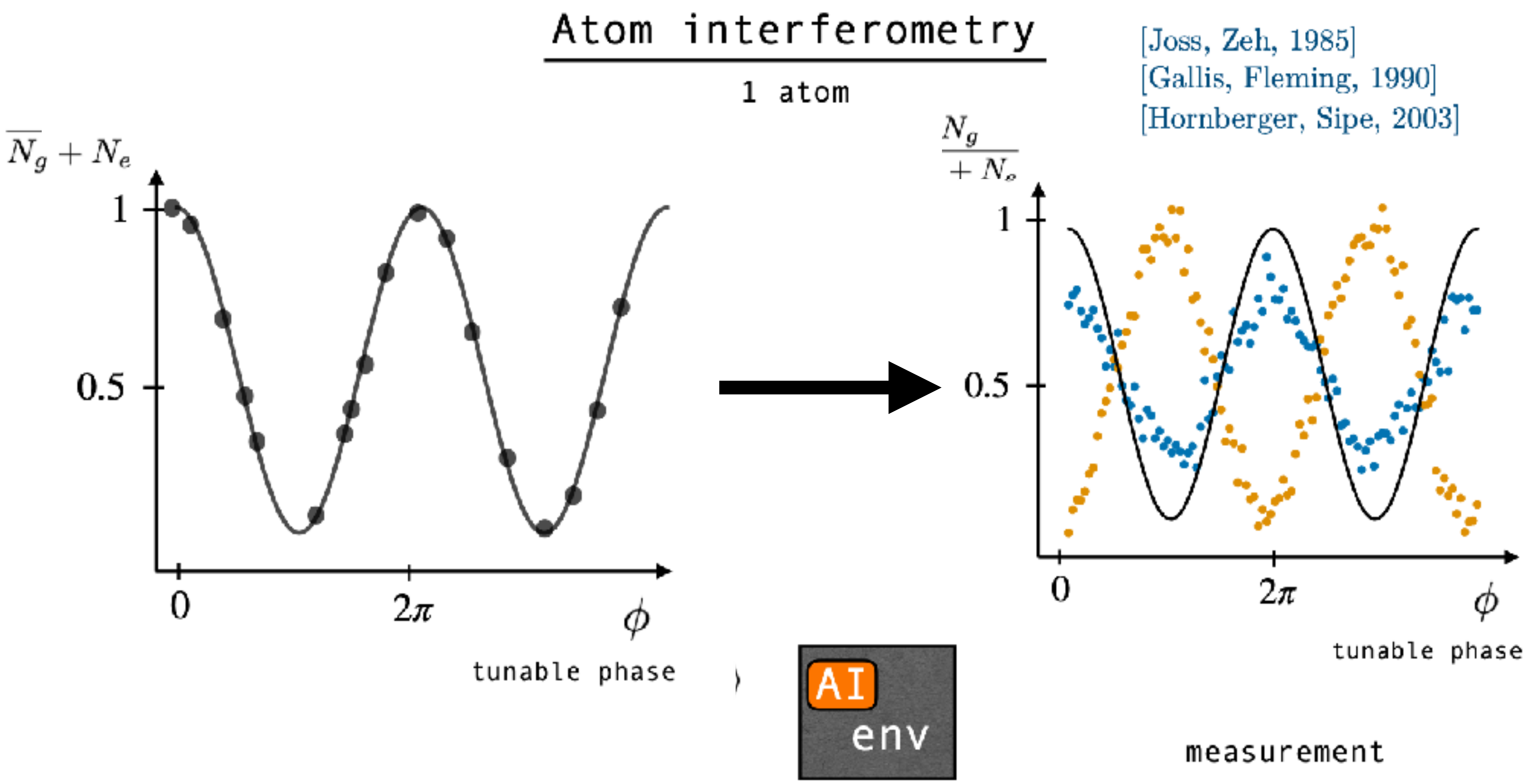
Decoherence

- Dark matter scattering from atom at position $\mathbf{x}$.

$$|A(\mathbf{x})\rangle\,|\chi(\mathbf{k})\rangle \to |A(\mathbf{x})\rangle \otimes \hat{S}_{\mathbf{x}}\,|\chi(\mathbf{k})\rangle$$

- ``Measure'' $\mathbf{x}$ without disturbing atom.
- Can be detected with atom intereferometer!

Decoherence & Interferometery



[Joss, Zeh, 1985]
[Gallis, Fleming, 1990]
[Hornberger, Sipe, 2003]

SLIDE BY C. MURGUI

$$|A(\mathbf{x})\rangle\,|\chi(\mathbf{k})\rangle \to |A(\mathbf{x})\rangle \otimes \hat{S}_{\mathbf{x}}\,|\chi(\mathbf{k})\rangle$$

- DM interacts with atom.
- Dark matter "bath" ***decoheres*** system.
- Phase shift/contrast loss.

REMARKABLE PROPERTIES

- No thresholds.
- Can probe lower masses than any other scheme.

QUANTUM MECHANICS

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ZEN DETECTION

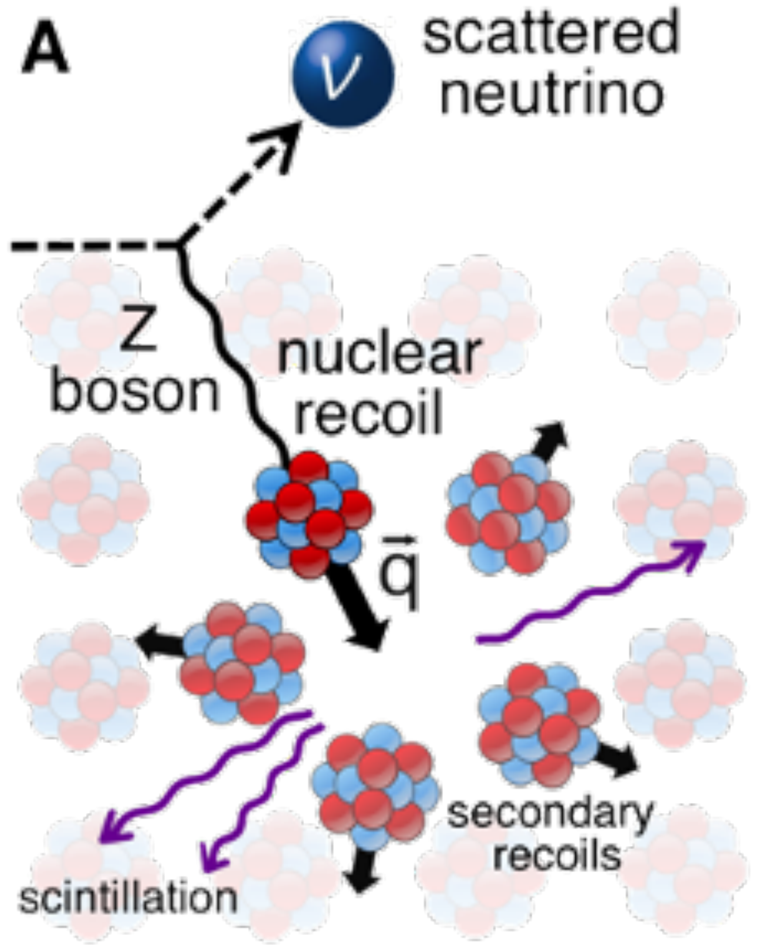
CHANGE WITHOUT CHANGE

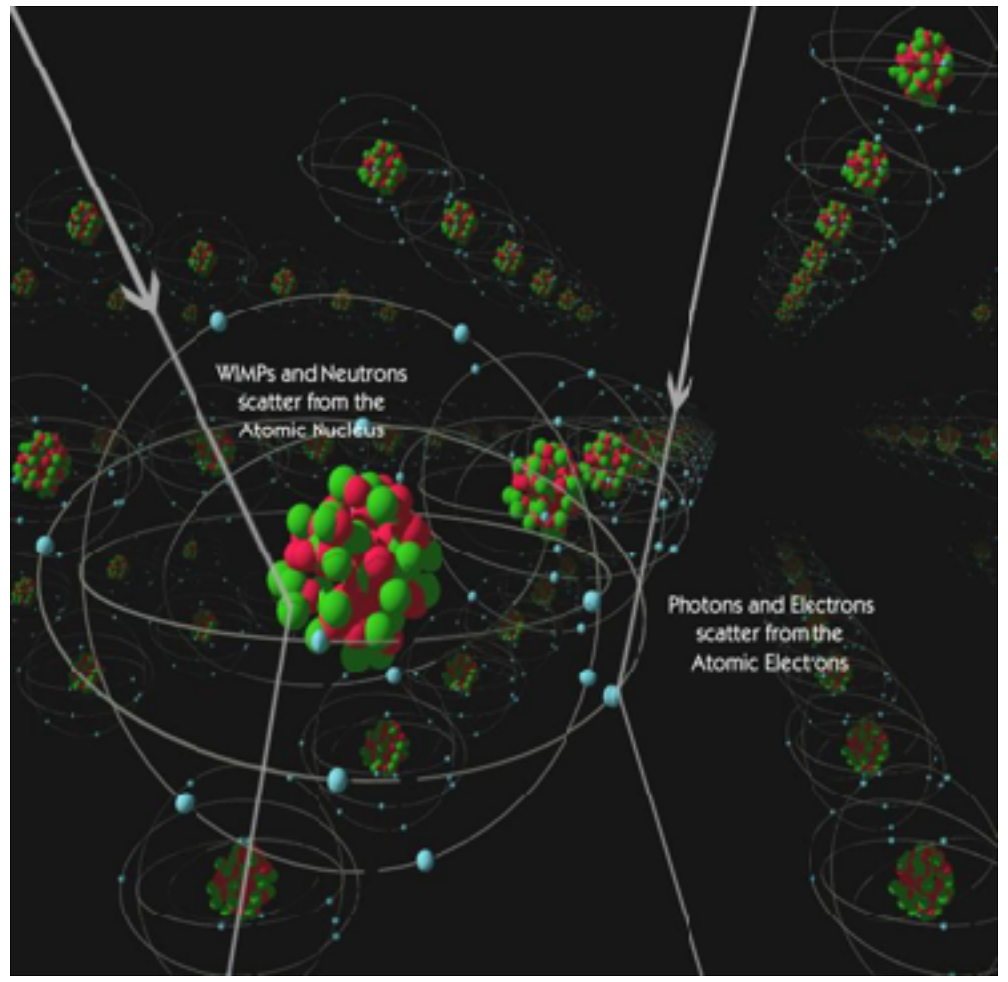
ATOM INTERFEROMETERS

COHERENCE + DECOHERENCE

A GAP IN THE LITERATURE

- All theory assumes one atom.
- Experiments use $10^6 - 10^9$.
- ***Enhancements*** $\sim N^p$.





Coherent Enhancements

- Well known in particle physics literature that cross sections can scale with number of targets as N_T^2
- Atom interferometers have $N_T \sim 10^6 - 10^9$ (i.e., huge).
- Can this be leveraged to enhance observables?

A GAP IN THE LITERATURE

- All theory assumes one atom.
- Experiments use $10^6 - 10^9$.
- ***Enhancements*** $\sim N^p$.

AS OF 2023 THIS WAS NOT KNOWN

Revisiting Foundations

PHYSICAL REVIEW A **110**, 033311 (2024)

Coherent collisional decoherence

Leonardo Badurina,[1,*] Clara Murgui,[2,†] and Ryan Plestid[1,‡]

[1] *Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*

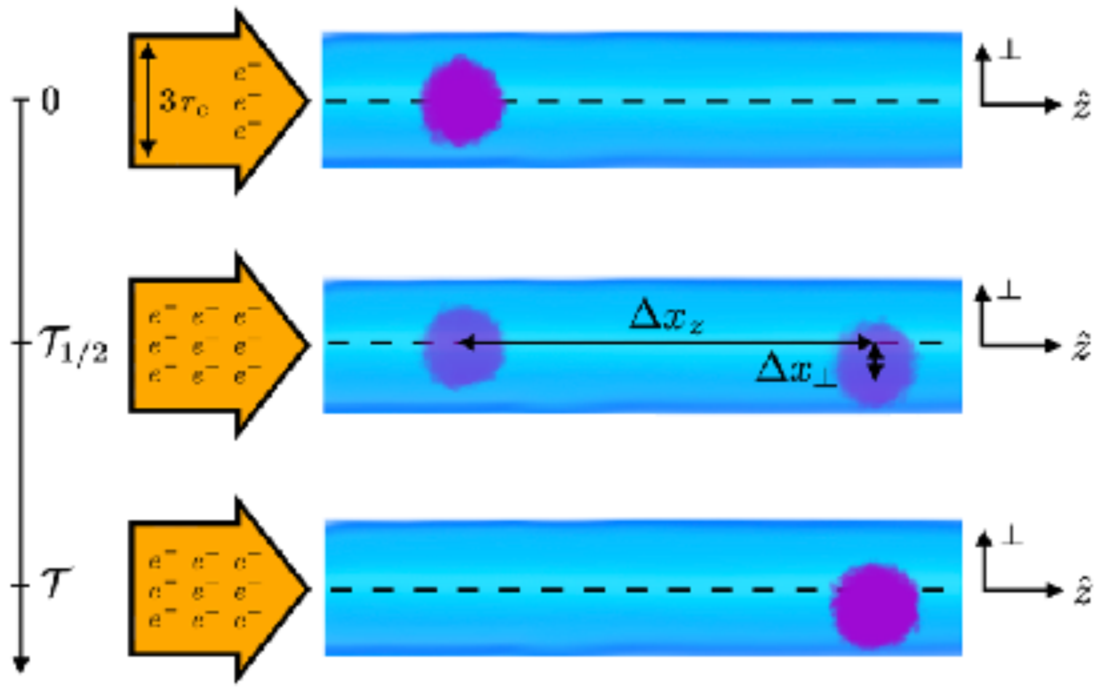
[2] *Departament de Física, Universitat Autonoma de Barcelona, 08193 Bellaterra, Barcelona, Spain*

(Received 9 February 2024; revised 23 July 2024; accepted 26 August 2024; published 10 September 2024)

$$\Delta\rho_A(\{\mathbf{x}\},\{\mathbf{x}'\}) = \rho_A(\{\mathbf{x}\},\{\mathbf{x}'\}) \int \frac{d^3p}{(2\pi)^3}\,\rho_\pi(\mathbf{p}) \Bigg(\frac{i}{2}\langle \mathbf{p}|(T_{\{\mathbf{x}\}} + T^\dagger_{\{\mathbf{x}\}} - T_{\{\mathbf{x}'\}} - T^\dagger_{\{\mathbf{x}'\}})|\mathbf{p}\rangle - \frac{1}{2}\langle \mathbf{p}|(T_{\{\mathbf{x}\}}T^\dagger_{\{\mathbf{x}\}} + T_{\{\mathbf{x}'\}}T^\dagger_{\{\mathbf{x}'\}})|\mathbf{p}\rangle + \langle \mathbf{p}|T^\dagger_{\{\mathbf{x}'\}}T_{\{\mathbf{x}\}}|\mathbf{p}\rangle \Bigg).$$

- Generalized to include N atoms.
- Identified coherently enhanced observables.
- Studied idealized limit with point-like cloud following classical trajectory.

Experimental Realities



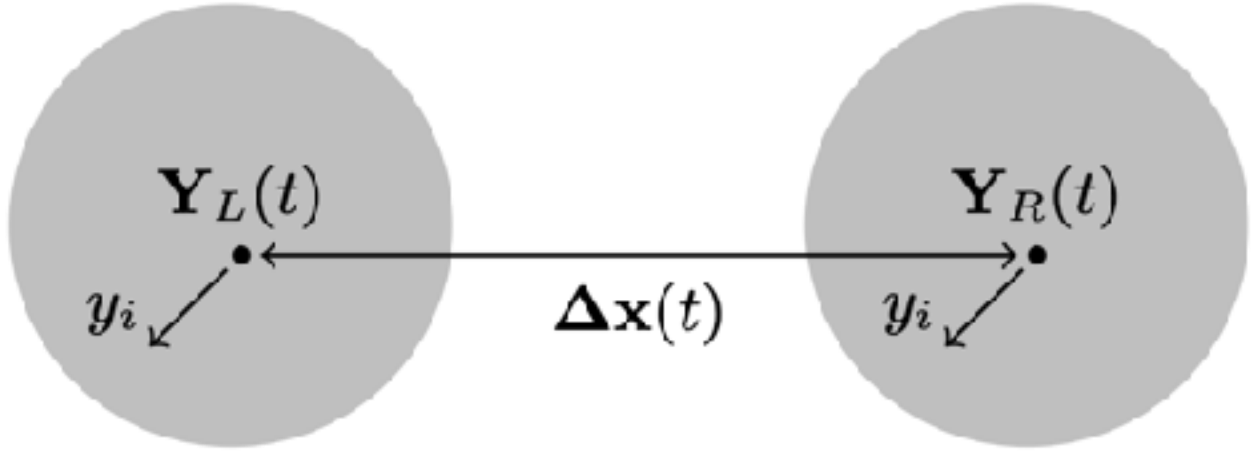
CALT-TH/2025-028 CERN-TH-2025-174

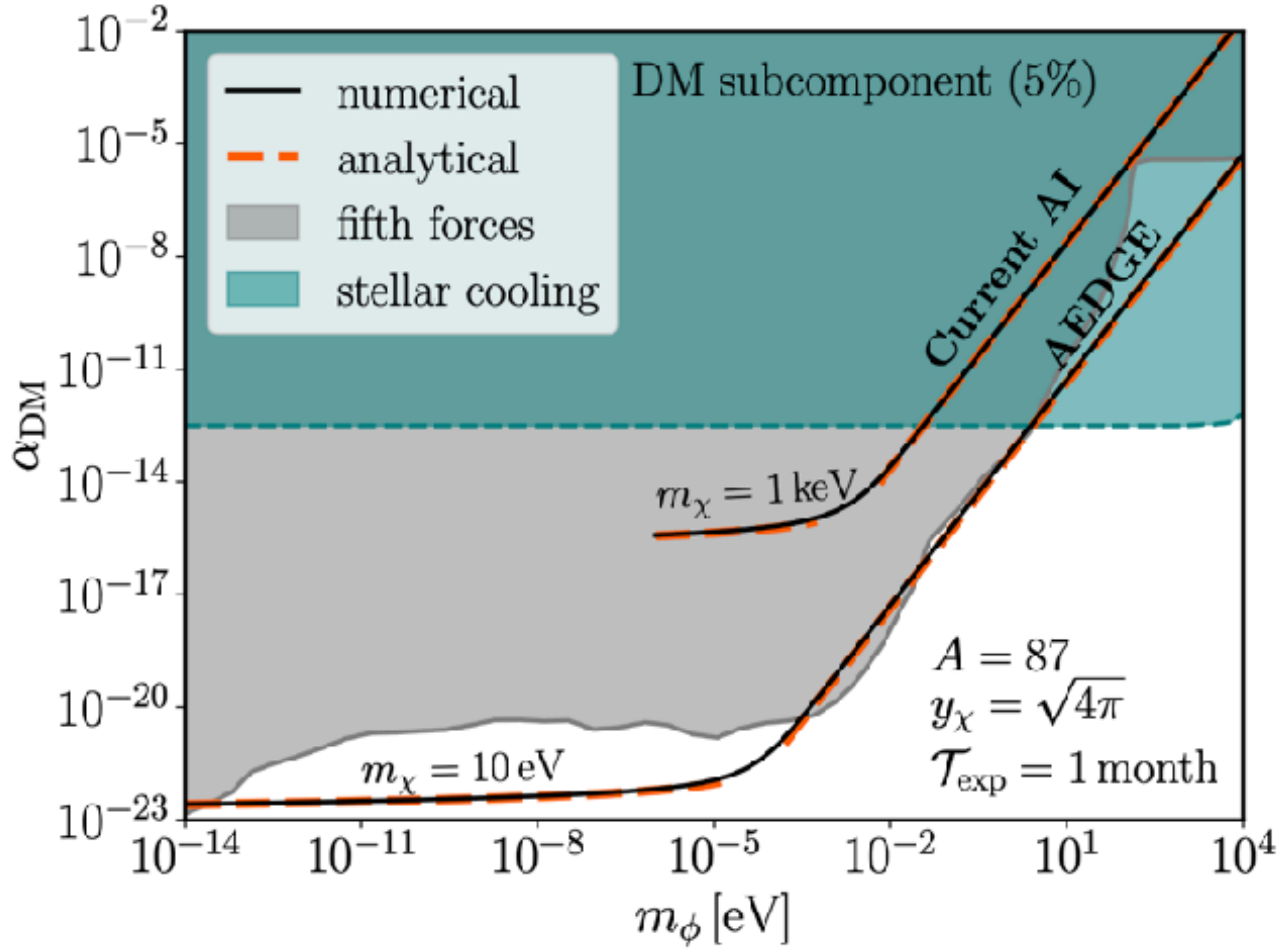
Coherently enhanced decoherence and cloud substructure of atom interferometers

Clara Murgui[1, *] and Ryan Plestid[2, 1, †]

[1] *Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*
[2] *Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA*

(Dated: September 18, 2025)



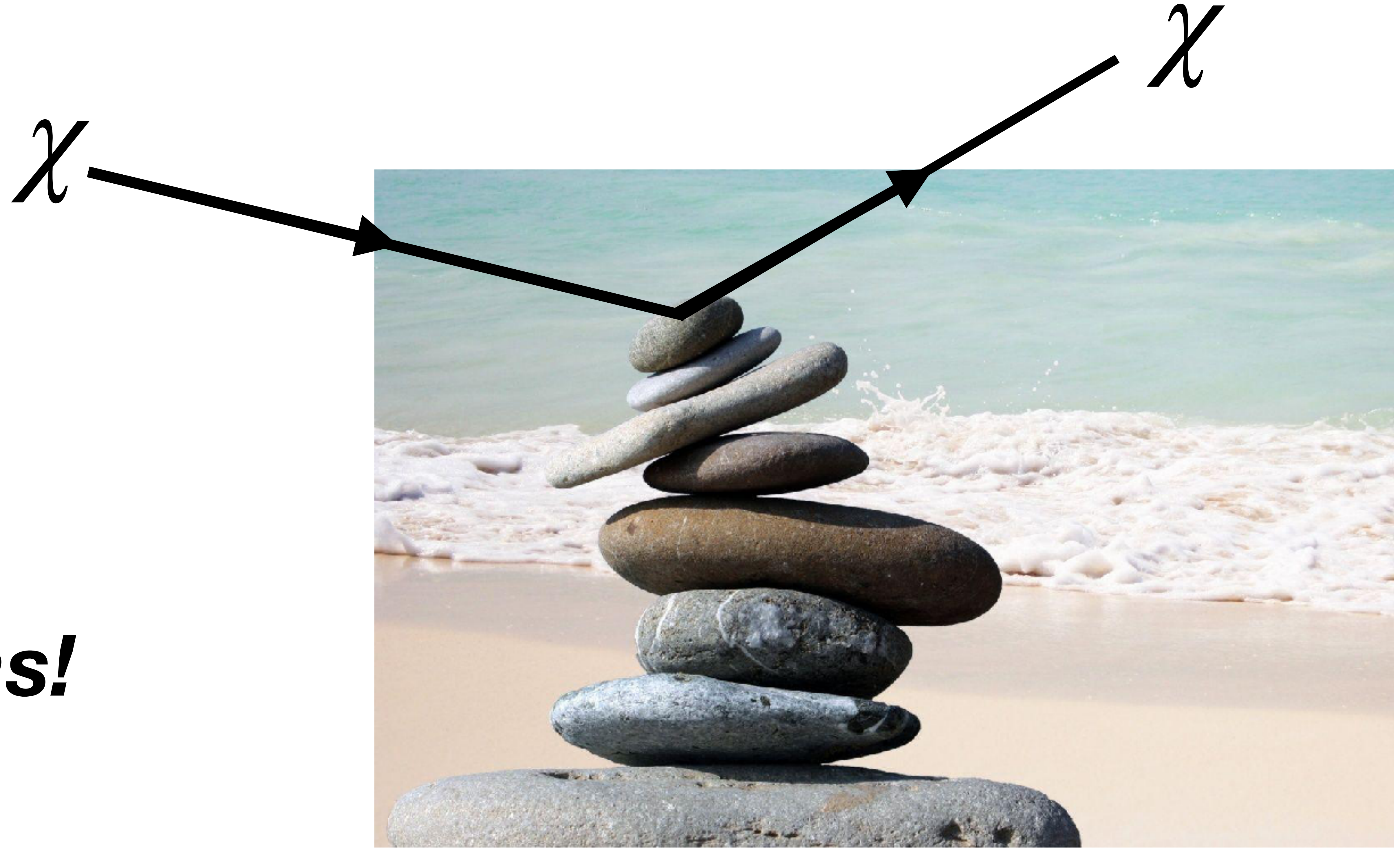


- Incorporated cloud-radius, temperature, and quantum spreading.
- Proposed experimental test with electron gun and photon lamp.
- First phenomenological application to DM.

New Observables & Models

$$|\mathrm{AI}\rangle = \bigotimes_{i=1}^{N} \frac{1}{\sqrt{2}} \left(|\uparrow\rangle + |\downarrow\rangle \right)$$

- Product state is ***very special***.
- Cancellations between terms leads variance scaling as N vs N^2.
- Dark matter can ***spoil cancellations!***



New Observables & Models

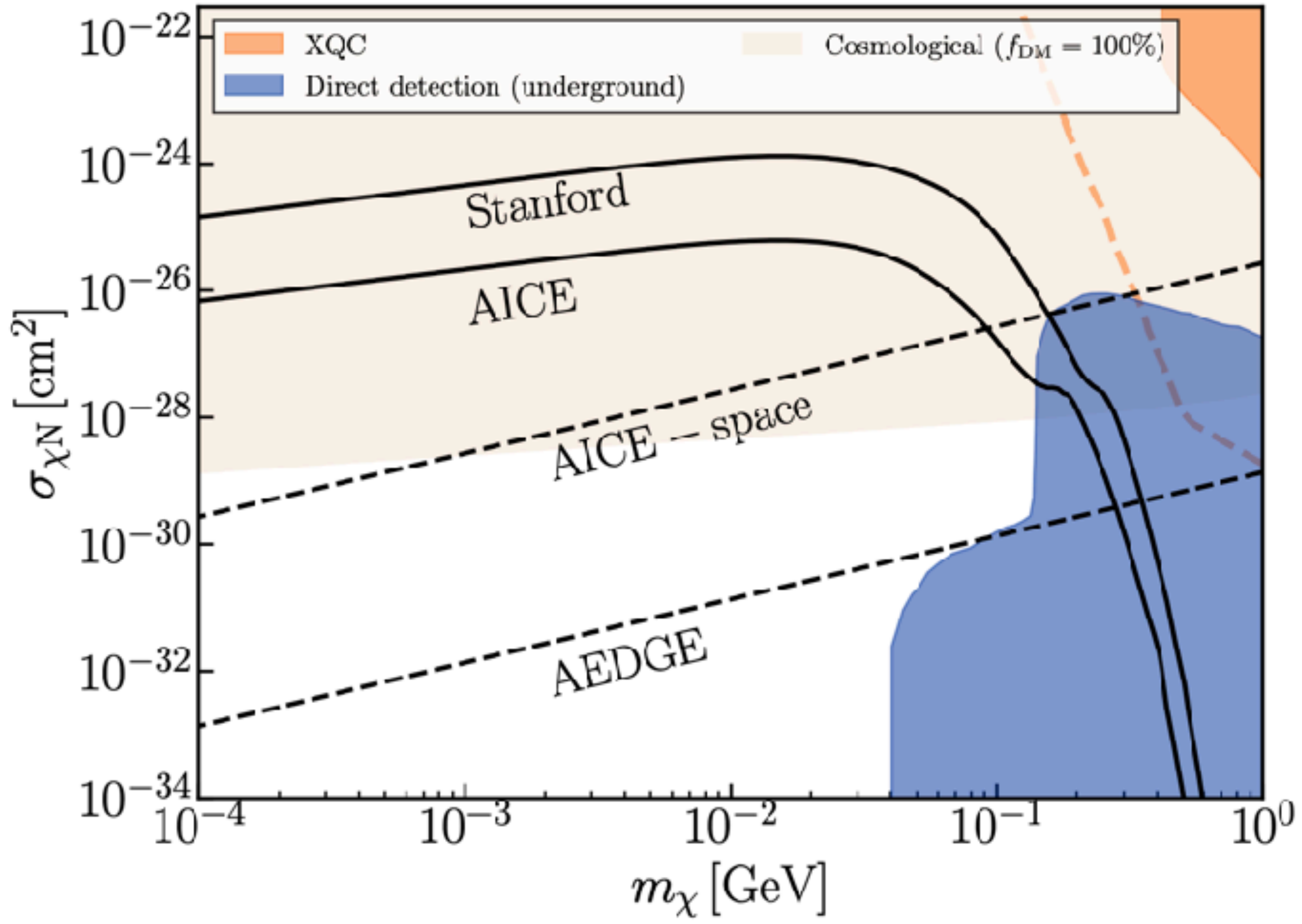
CERN-TH-2026-024

Fluctuations in atom interferometers as a new tool for dark matter

Clara Murgui[1,*] and Ryan Plestid[1,†]

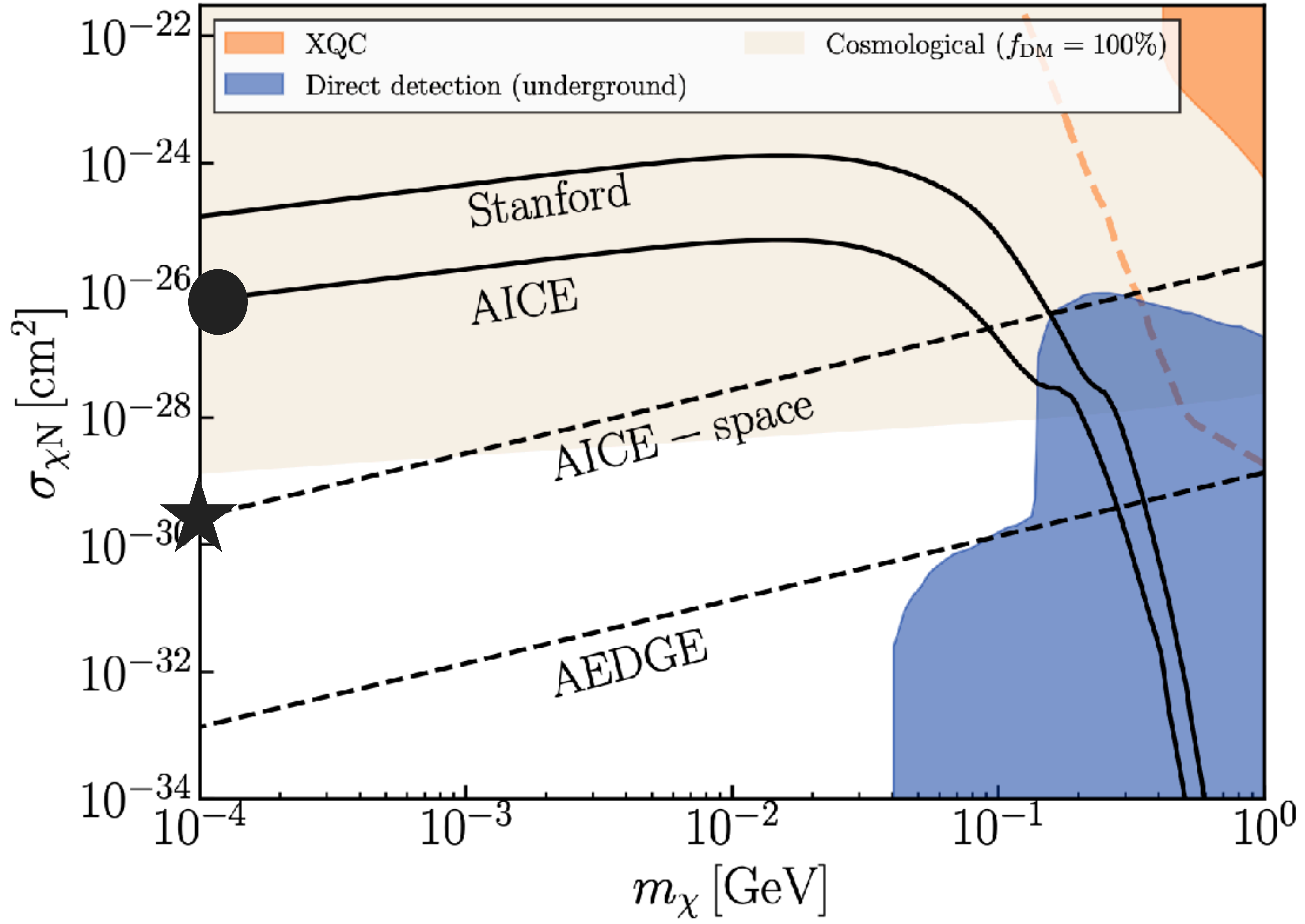
[1] *Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*

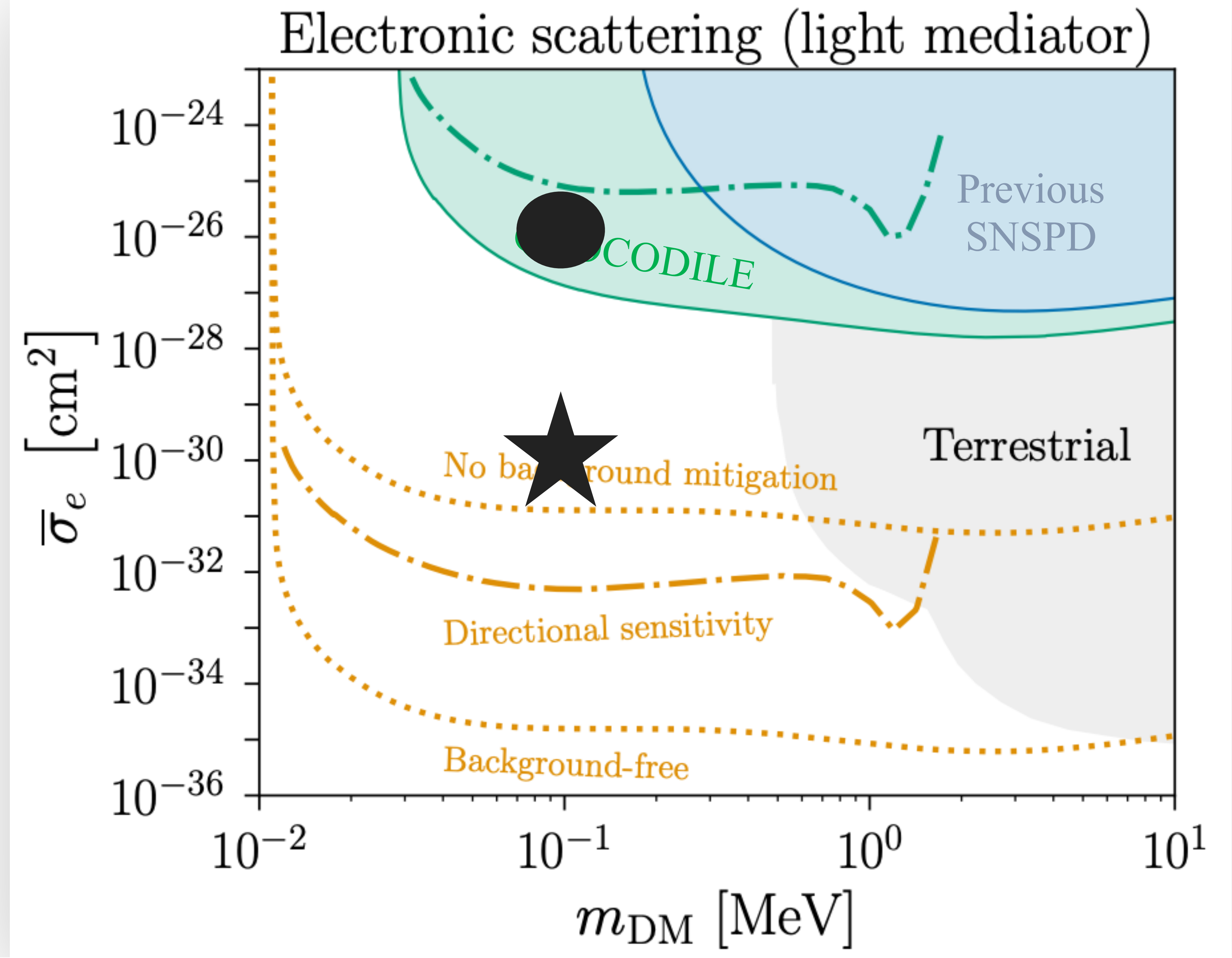
(Dated: March 2, 2026)



- Interactions with dark matter induces correlations between atoms.
- Can lead to non-binomial statistics.
- New observable! Well suited to a strongly interacting dark matter.

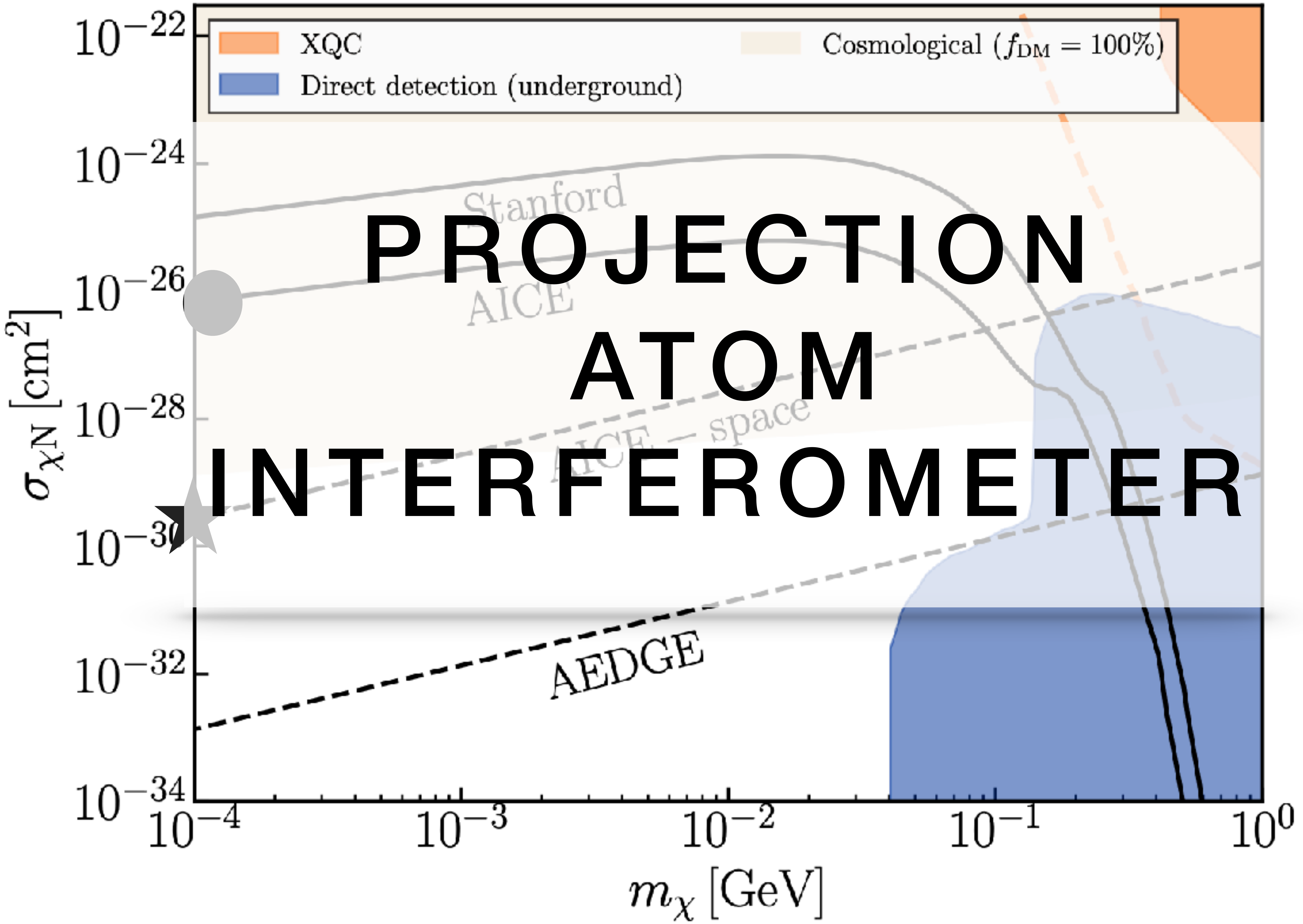
New Observables & Models

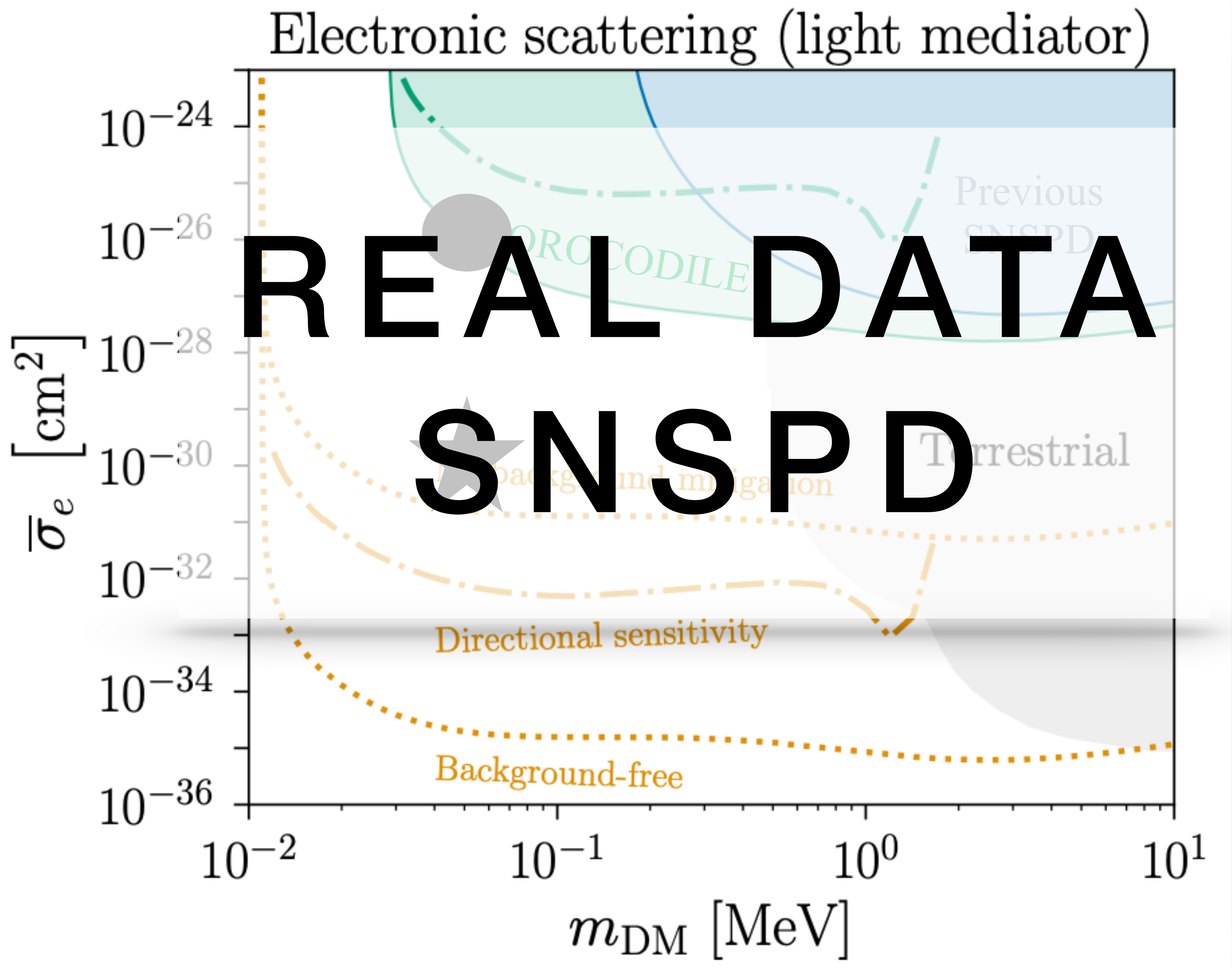




- Atom interferomter competitive with ng sensor.
- Has ***no*** threshold!

New Observables & Models





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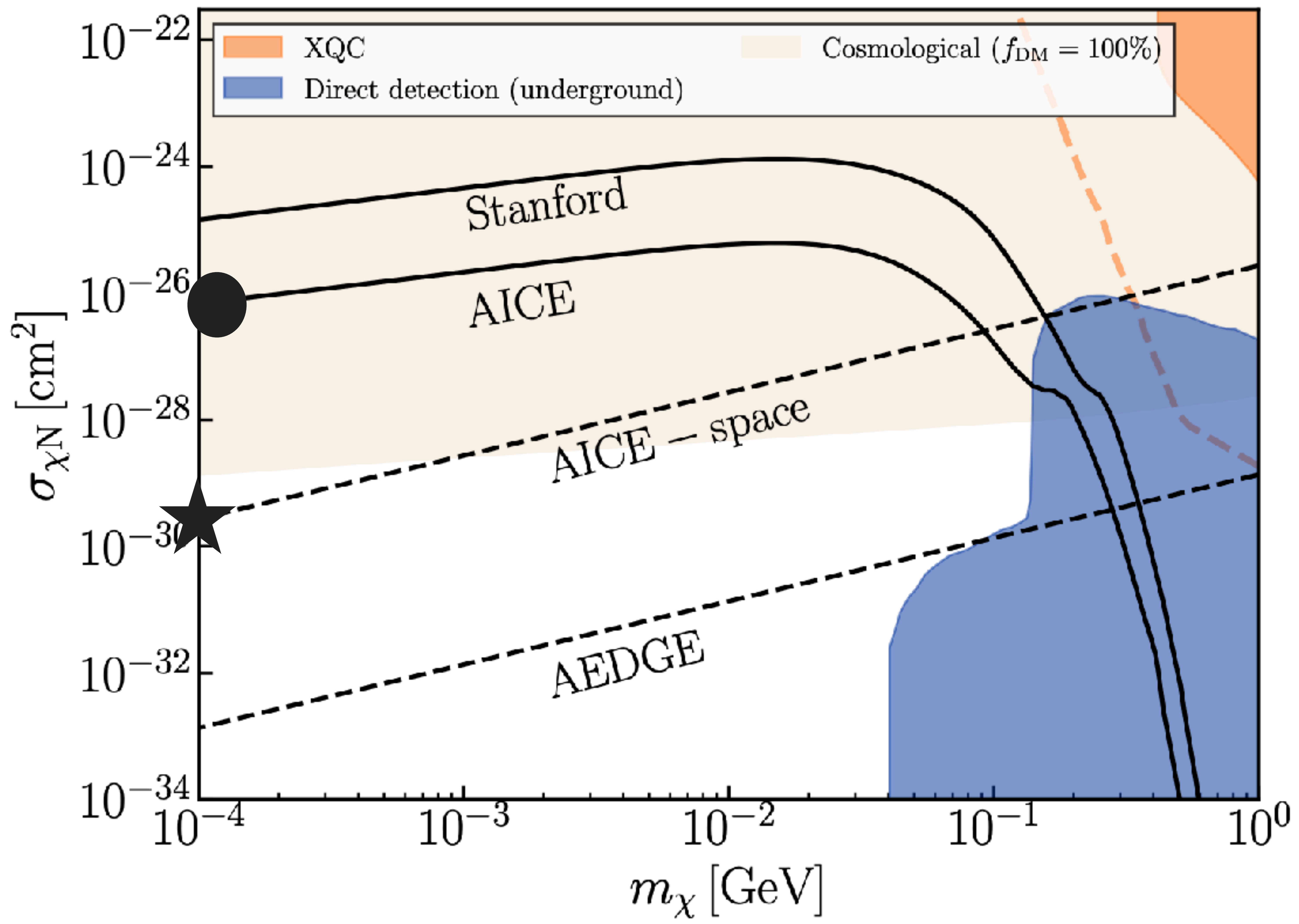
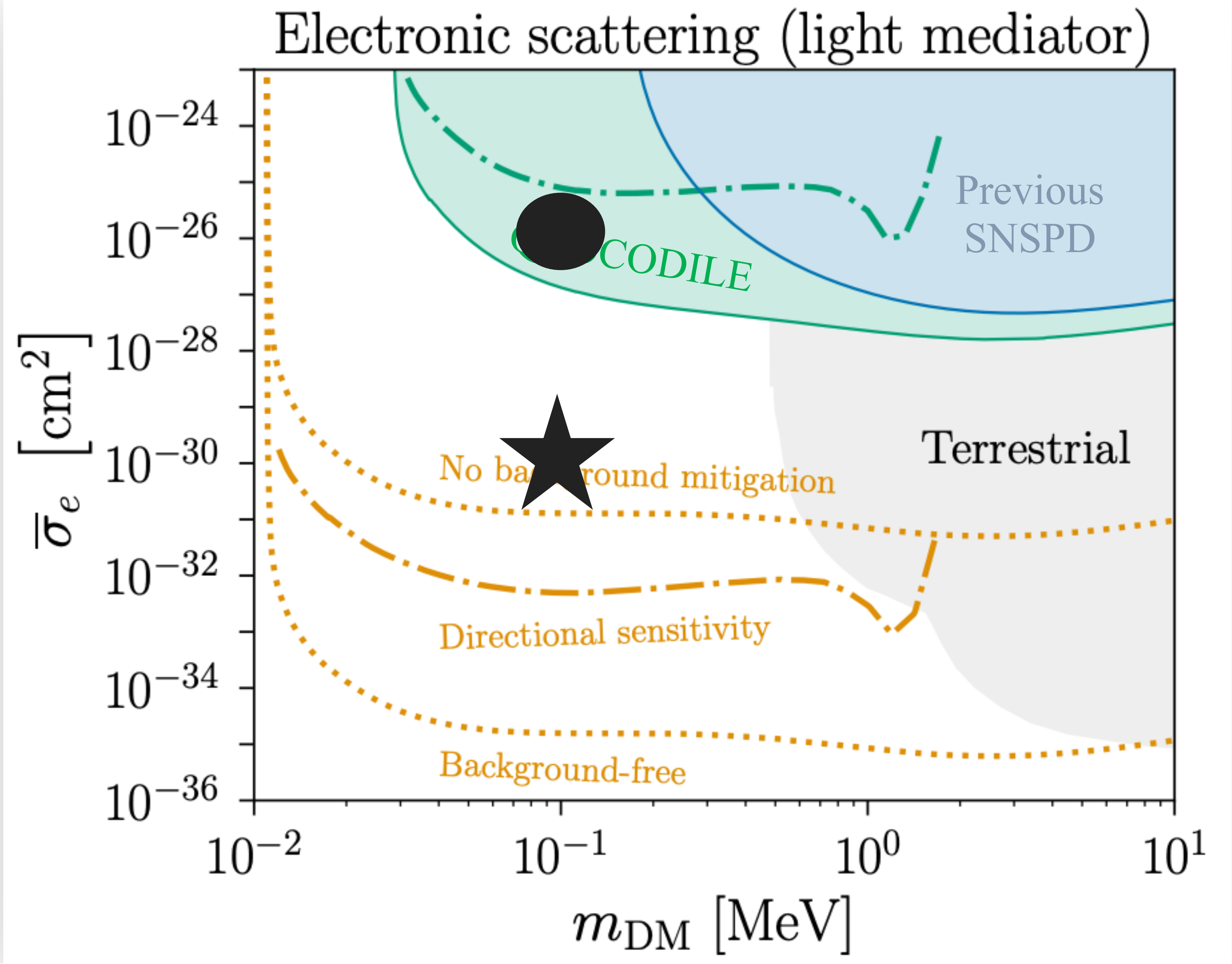


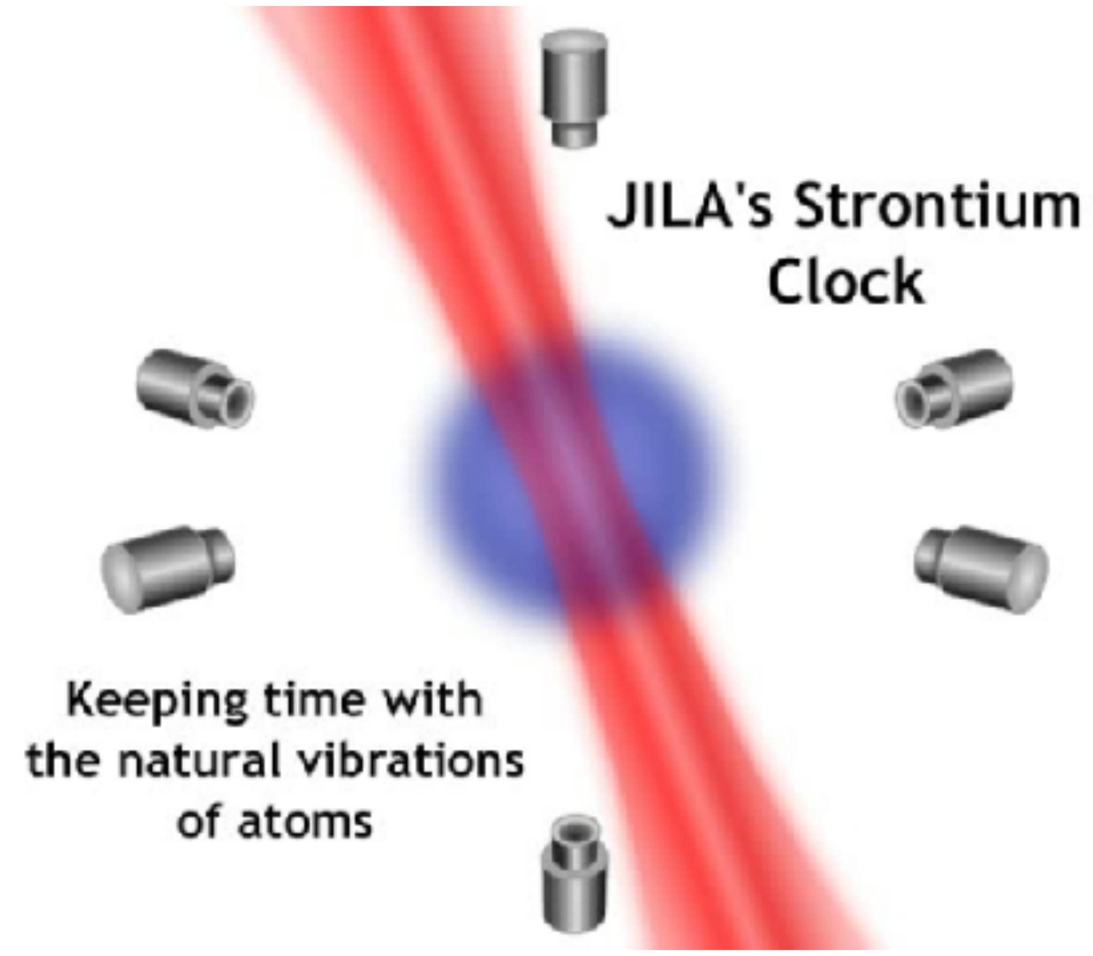


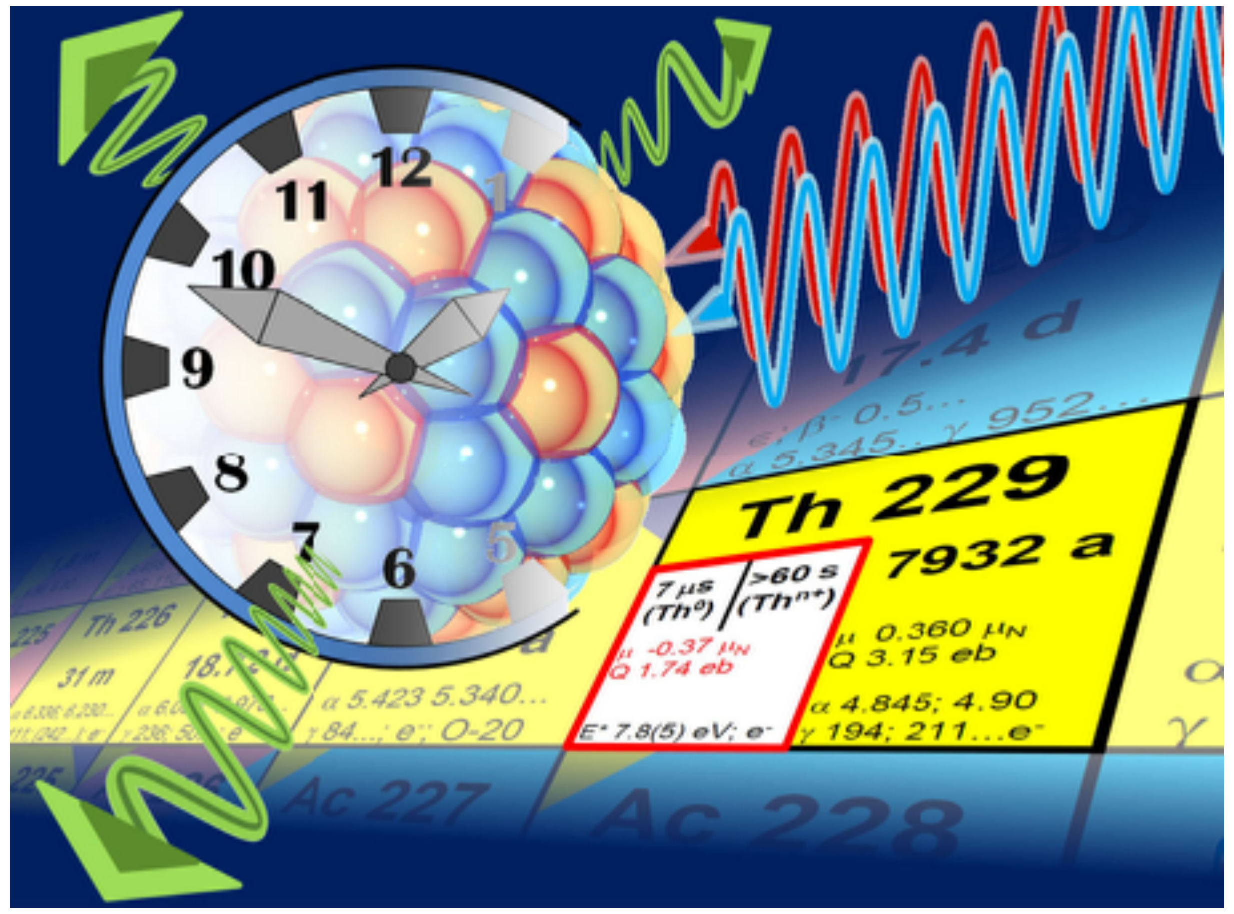
- Atom interferomter competitive with ng sensor.
- Has ***no*** threshold!

What's Next?

- Pablo Blanco (Ph.D. student visited May+June).
- Tentative plan is to study spin-dependent dark matter.
- May look at ***atomic clocks*** and or ***nuclear clocks***.

CERN





Conclusions

- Atom interferometers offer thresholdless detection!
- N-enhancements are a resource.
- Can probe otherwise unreachable parameter space.