Title: Direct Detection of Classically Undetectable Dark Matter through Quantum Decoherence

Date: Dec 04, 2013 04:00 PM

URL: http://pirsa.org/13120053

Abstract: Although various pieces of indirect evidence about the nature of dark matter have been collected, its direct detection has eluded experimental searches despite extensive effort. If the mass of dark matter is below 1 MeV, it is essentially imperceptible to conventional detection methods because negligible energy is transferred to nuclei during collisions. Here I propose directly detecting dark matter through the quantum decoherence it causes rather than its classical effects such as recoil or ionization. I show that quantum spatial superpositions are sensitive to low-mass dark matter that is inaccessible to classical techniques. This provides new independent motivation for matter interferometry with large masses, especially on spaceborne platforms. The apparent dark matter wind we experience as the Sun travels through the Milky Way ensures interferometers and related devices are directional detectors, and so are able to provide unmistakable evidence that decoherence has galactic origins.

Direct Detection of Classically Undetectable Dark Matter Through Quantum Decoherence

C. Jess Riedel

IBM Research

Material from arXiv:1212.3061, forthcoming PRD
Slides will be made available at jessriedel.com

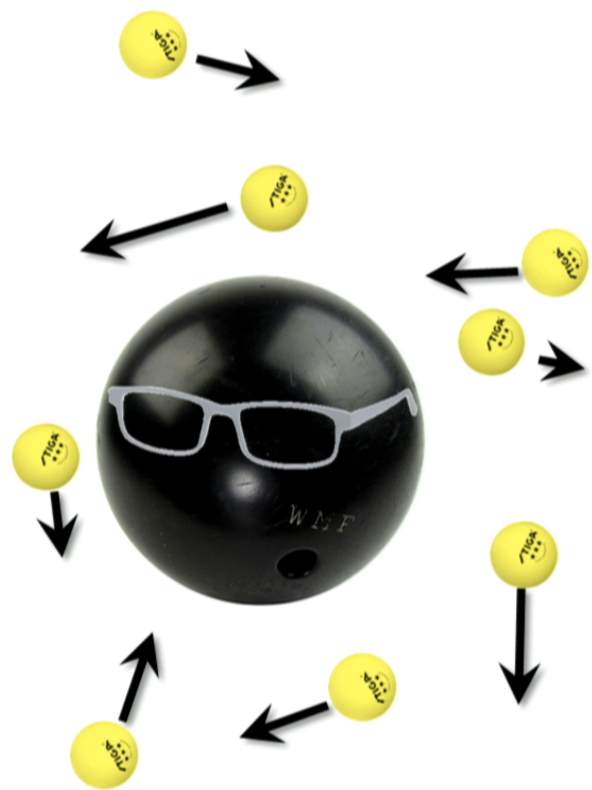
Perimeter Institute 4 December 2013

Bowling balls and ping-pong balls

- Suppose everything in the universe—including us—were made of bowling balls

Bowling balls and ping-pong balls

- Suppose everything in the universe—including us—were made of bowling balls
- Now suppose we were surrounded by a sea of slow-moving ping-pong balls



Outline

Decoherence without classical influence

Intro to low-mass dark matter

Collisional decoherence by dark matter

Feasibility and contributing effects

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Collisional Decoherence Observed in Matter Wave Interferometry

Klaus Hornberger, Stefan Uttenthaler, Björn Brezger, Lucia Hackermüller, Markus Arndt, and Anton Zeilinger
Universität Wien, Institut für Experimentalphysik, Boltzmanngasse 5, A-1090 Wien, Austria
(Received 7 October 2002; published 22 April 2003)

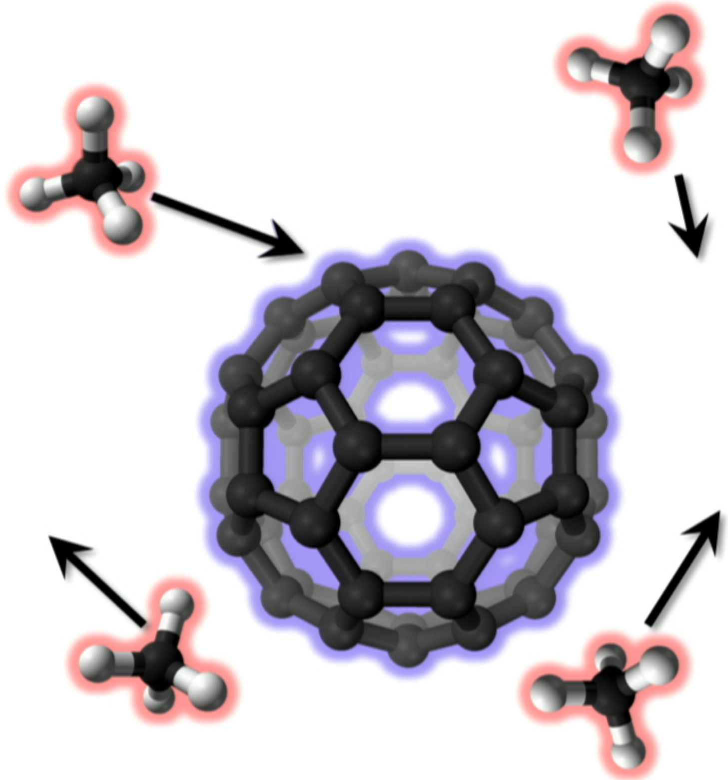
We study the loss of spatial coherence in the extended wave function of fullerenes due to collisions with background gases. From the gradual suppression of quantum interference with increasing gas pressure we are able to support quantitatively both the predictions of decoherence theory and our picture of the interaction process. We thus explore the practical limits of matter wave interferometry at finite gas pressures and estimate the required experimental vacuum conditions for interferometry with even larger objects.

DOI: 10.1103/PhysRevLett.90.160401 PACS numbers: 03.75.–b, 03.65.Yz, 39.20.+q

Matter wave interferometers are based on *quantum* superpositions of spatially separated states of a single particle. However, as is well known, the concept of wave-particle duality does not apply to a *classical* object which by definition never occupies macroscopically distinct states simultaneously. By performing interference decoherence effects were not observed in these experiments, since the *detected* atoms did not change the state of the colliding gas sufficiently to leave behind the required path information for decoherence. In contrast to that, our experiment uses *massive* C_{70}-fullerene molecules, and is based on a Talbot-Lau interferometer

Collisional decoherence in experiment

- Molecule being interfered:
  - Carbon fullerene (C_{70})
  - 840 amu



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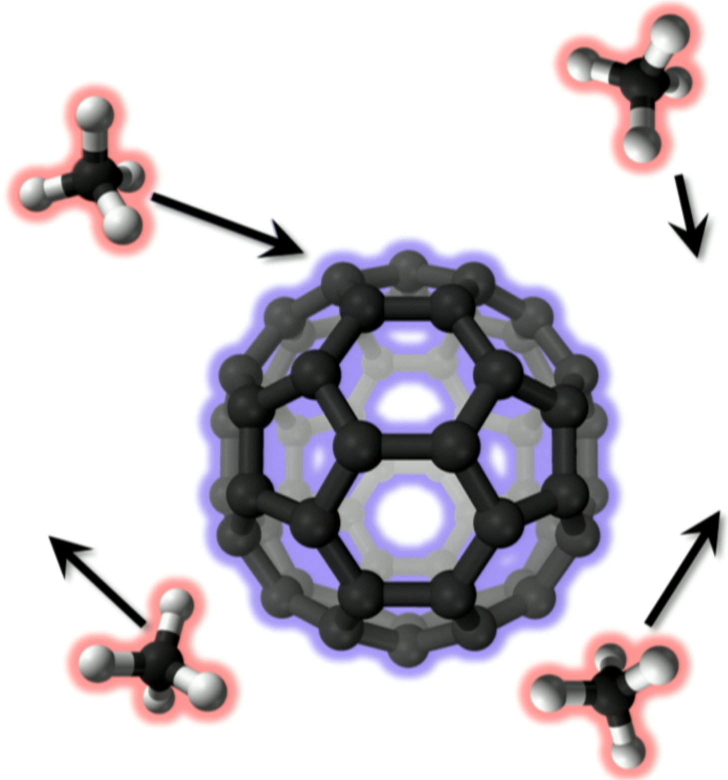

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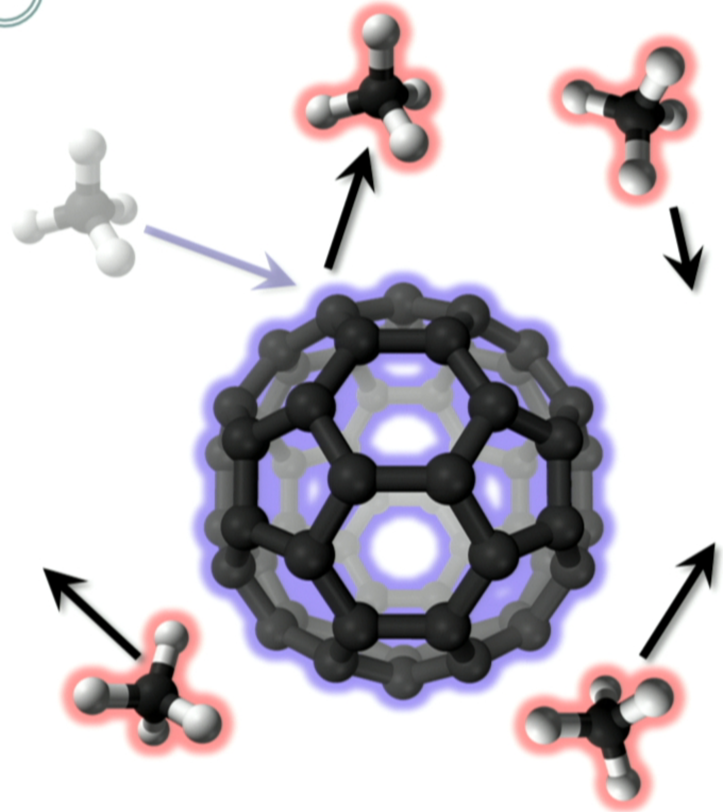
- Deflection of much heavier fullerenes is small



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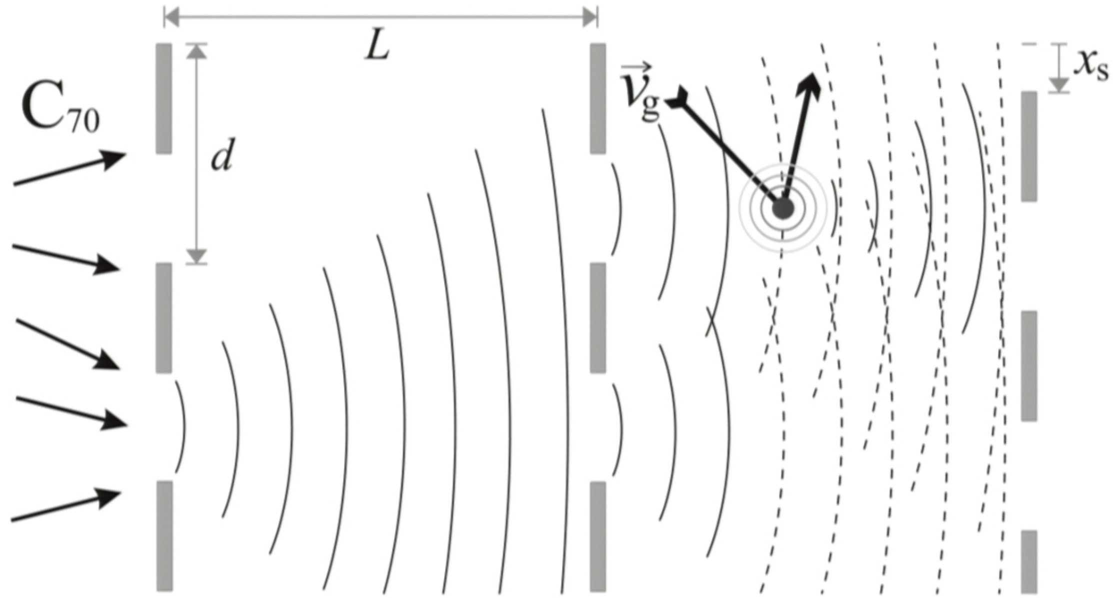

Image source: K. Hornberger et al. *Phys. Rev. Lett.* **90**, 160401 (2003)

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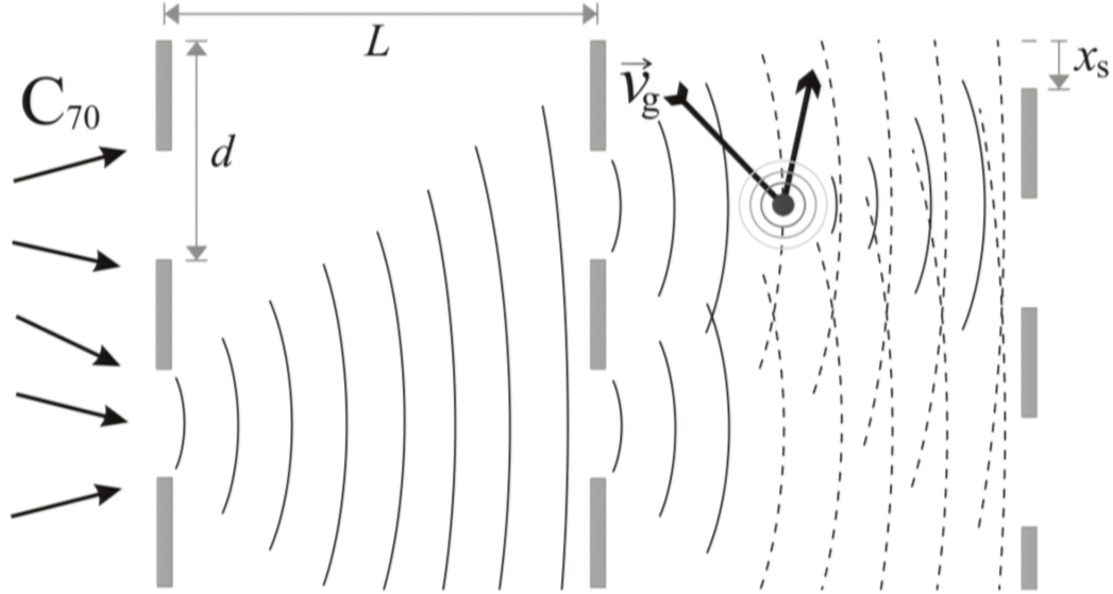

- Key idea: varying gas pressure in experiment controls interference fringe visibility

Image source: K. Hornberger et al. *Phys. Rev. Lett.* **90**, 160401 (2003)

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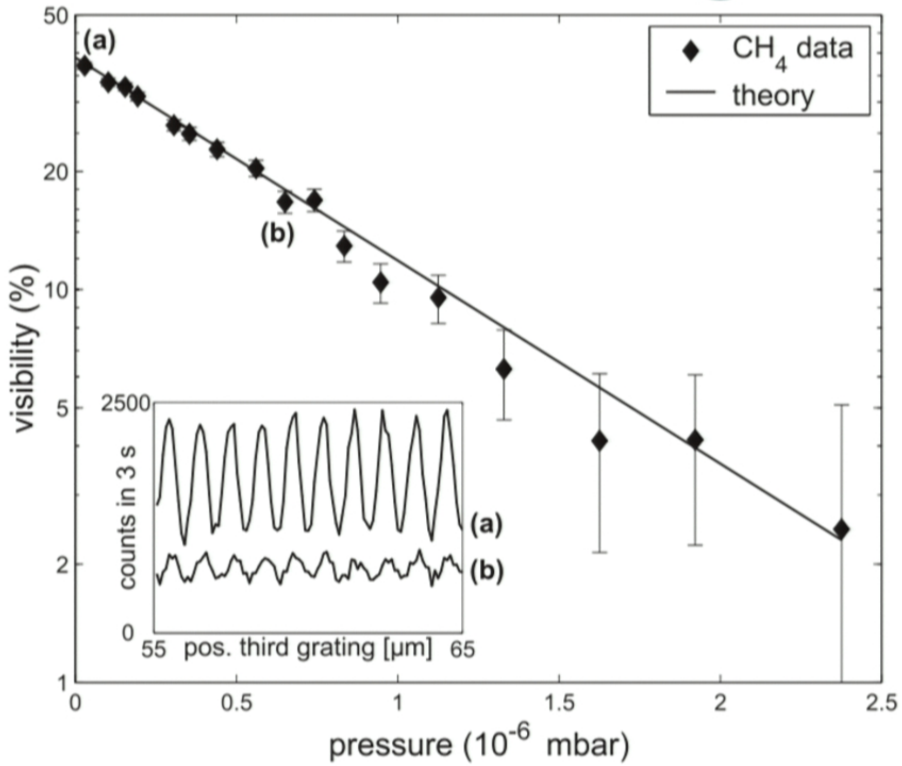

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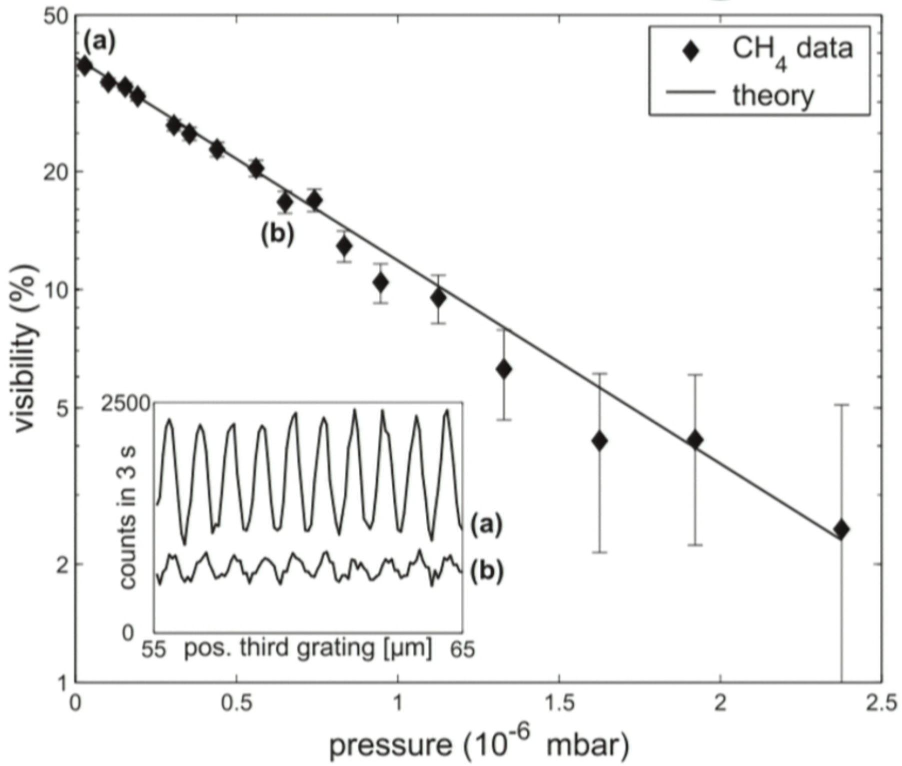

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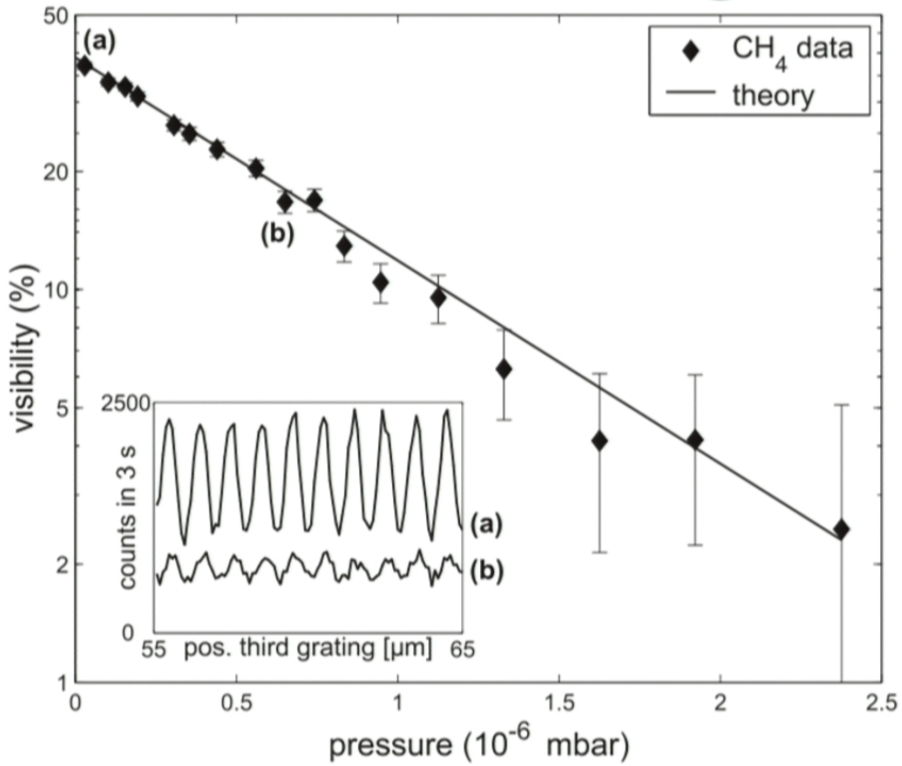

$$\text{visibility} = \frac{\text{amplitude}}{\text{average}}$$

- Visibility *and* count rate fall exponentially
- Sufficiently dense methane knocks fullerenes out of experiment

Image source: K. Hornberger et al. *Phys. Rev. Lett.* **90**, 160401 (2003)

Limits of detection

- But what if we dial down the mass of methane molecules while holding their velocity constant?
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- Apparently, we can detect the presence of *arbitrarily* light particles transferring *arbitrarily* little momentum and energy
- Quantum measurements can detect particles which are classically *undetectable*

Bowling-ball interferometry

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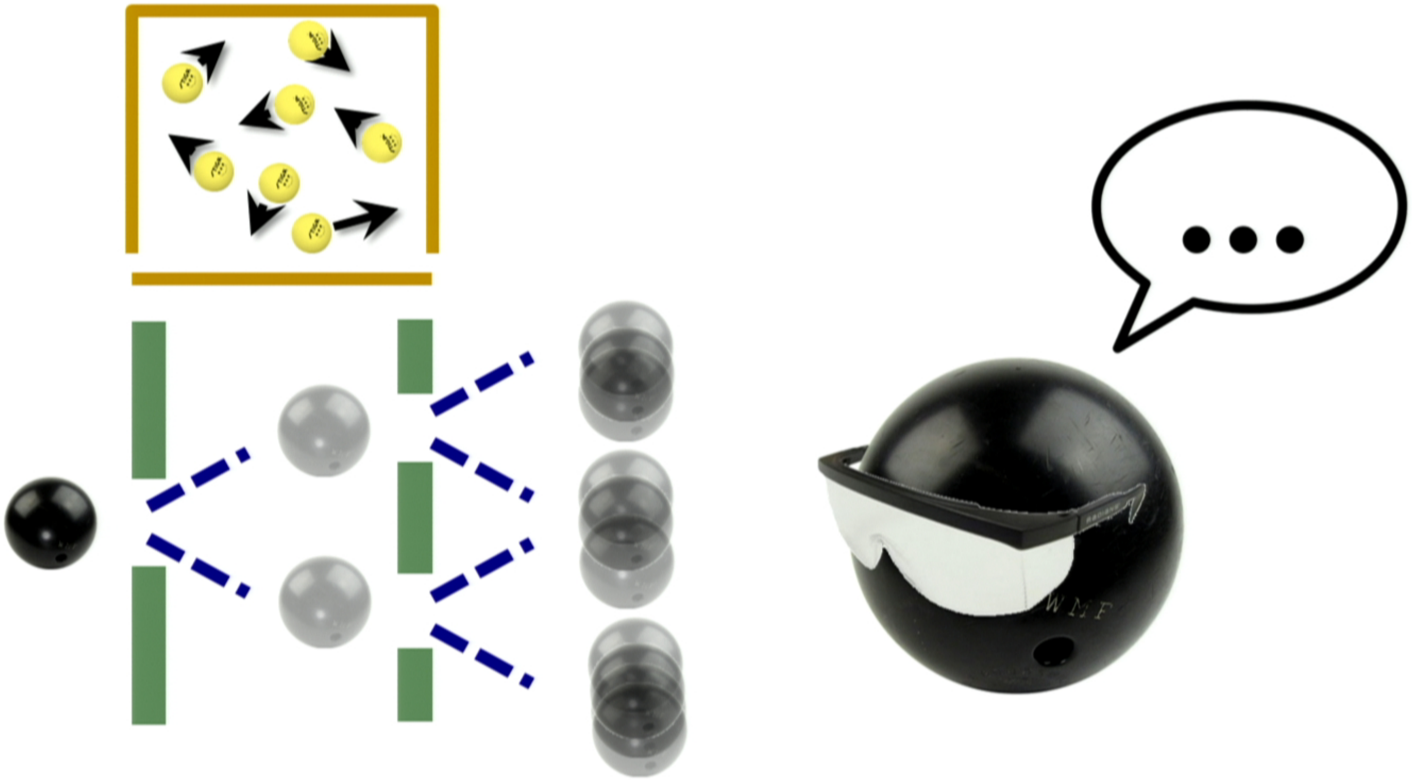

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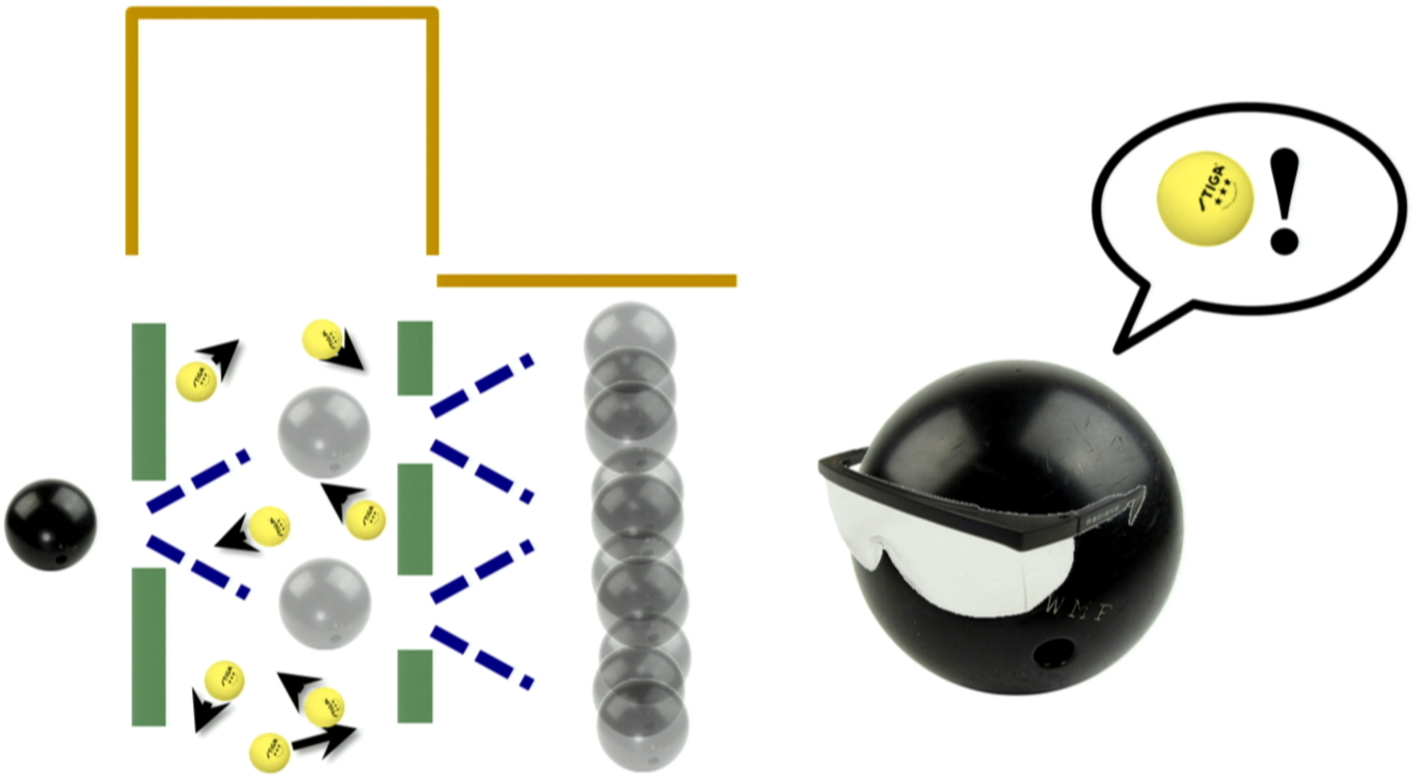

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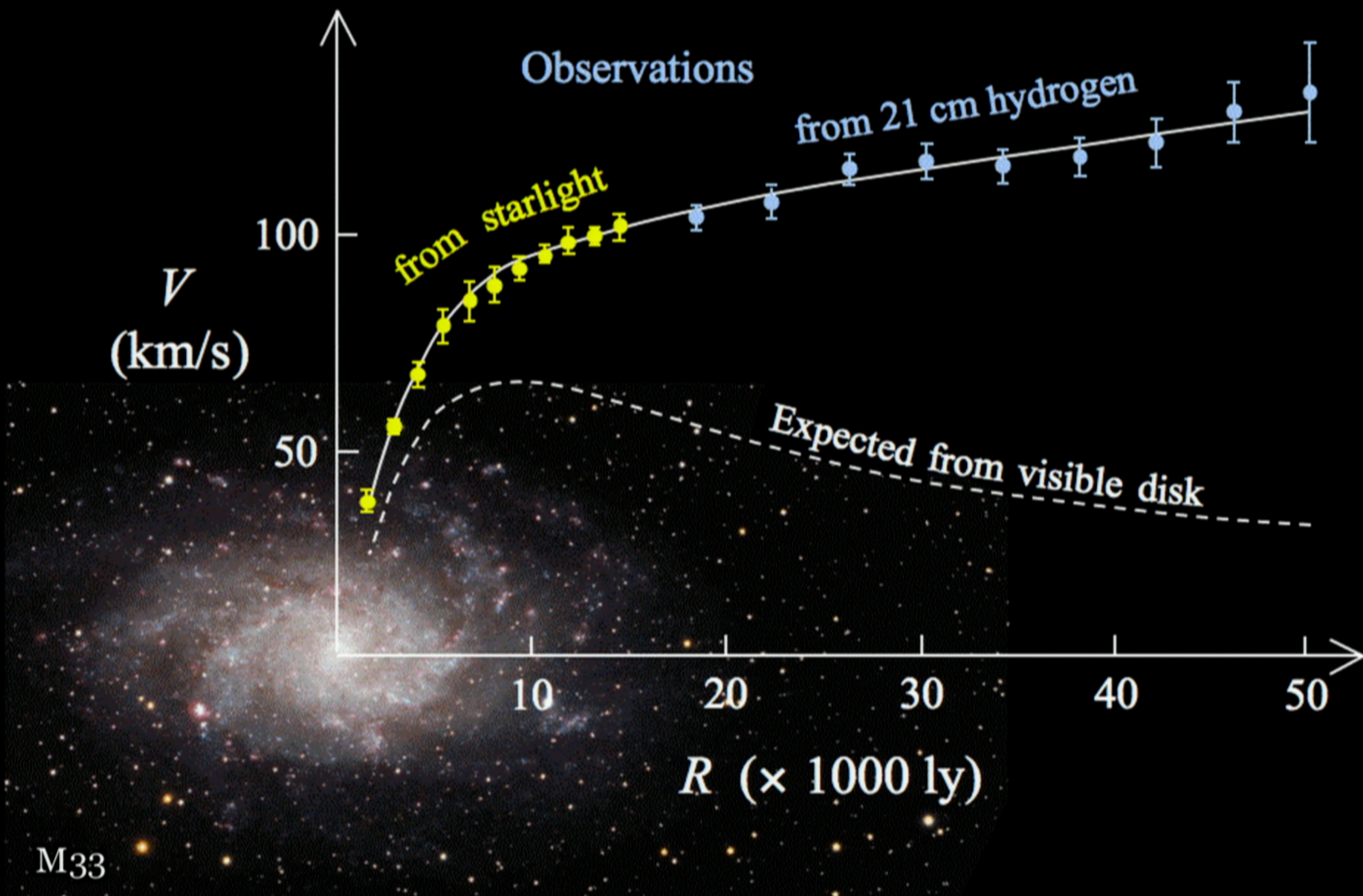

Image source: Mark Wittle; U. of Sheffield (UK), Particle Physics and Astrophysics Group

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- Evidence comes from sub-galactic scales and above, e.g.
  - Galactic rotation curves
  - Bullet cluster


X-ray emissions [Interstellar hydrogen: normal matter (90%)]
Gravitational lensing [Mass density: dark matter]
Image source: NASA [X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.]

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- Evidence comes from sub-galactic scales and above, e.g.
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  - Bullet cluster
  - Large-scale structure

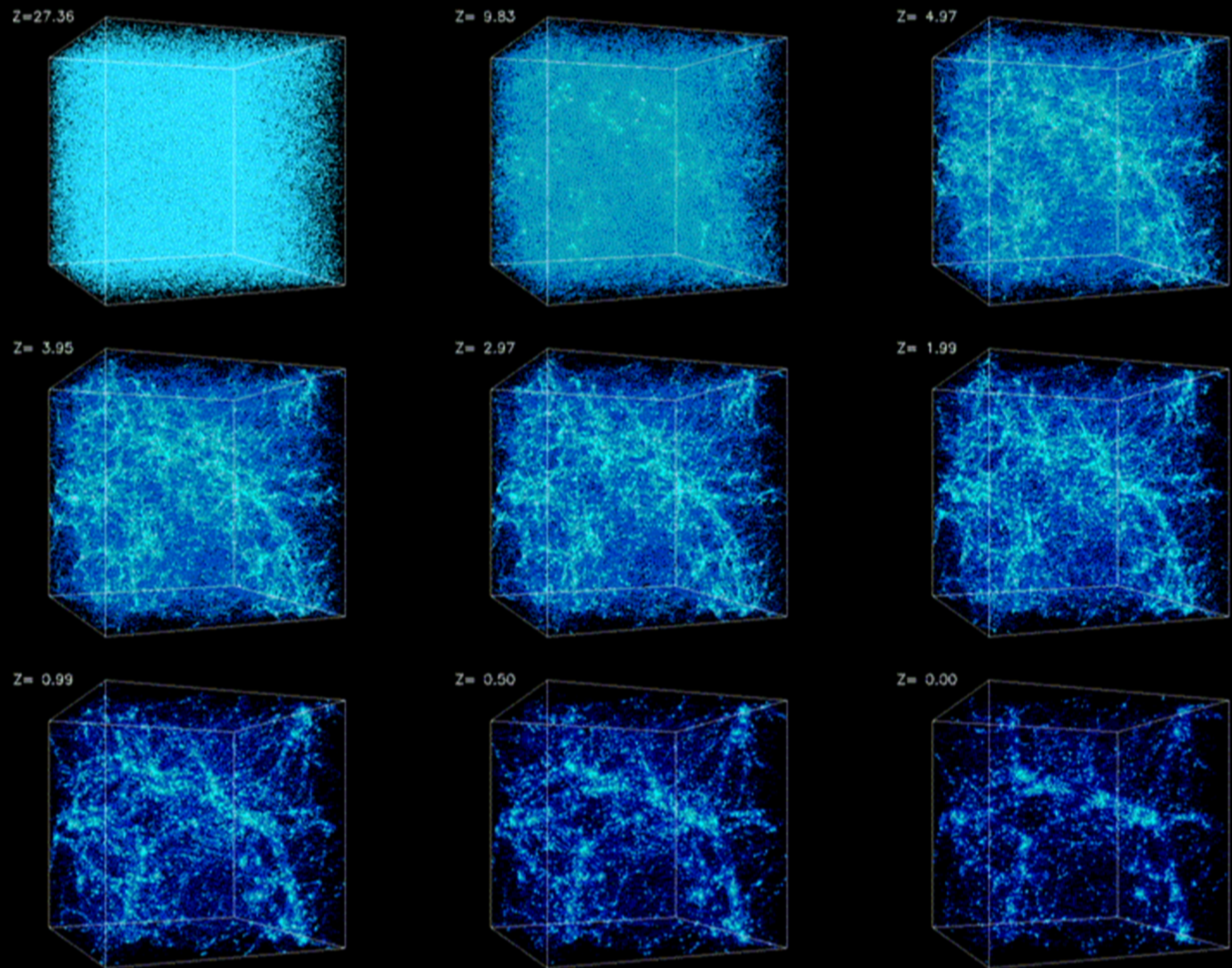

Image source: Andrey Kravtsov and Anatoly Klypin

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- All evidence is essentially gravitational
- Many, many competing ideas
- Candidate explanations must satisfy a wide range of experiments and observations stretching back decades
  - Many indirect, model-dependent restrictions
- Relatively few model-independent results

The dark matter halo

- But we have a **generic** local prediction: roughly spherical, virialized halo of dark matter enveloping the Milky Way

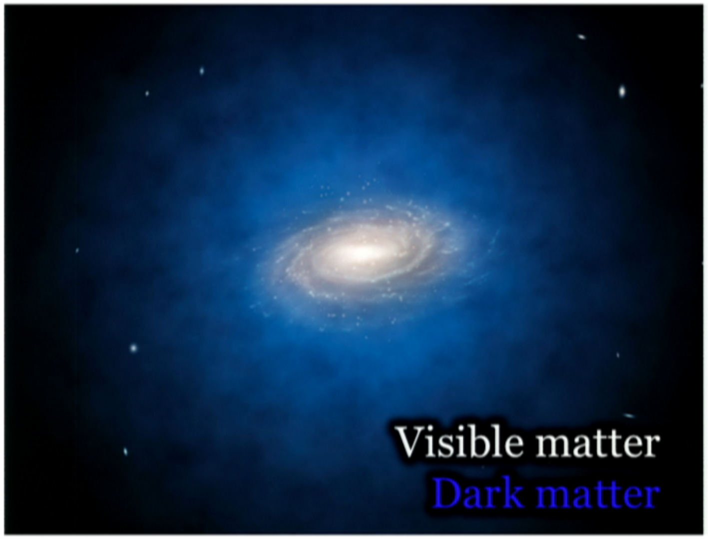
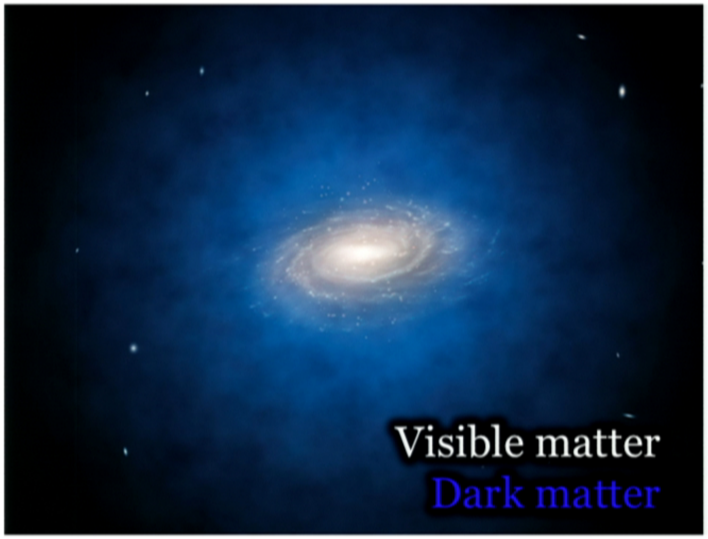


Image source: European Southern Observatory (artist impression, duh)

The dark matter halo

- But we have a **generic** local prediction: roughly spherical, virialized halo of dark matter enveloping the Milky Way
  - Isotropic in galactic rest frame
  - Maxwellian velocity distribution
  - Local density ~ 0.4 GeV/cm^3
  - Typical velocity ~ 230 km/s
- Assumed for limits set by underground detectors
- Based only on local, present-day observation
  - (no cosmology necessary)



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  - Key plot: m_{DM} vs. σ

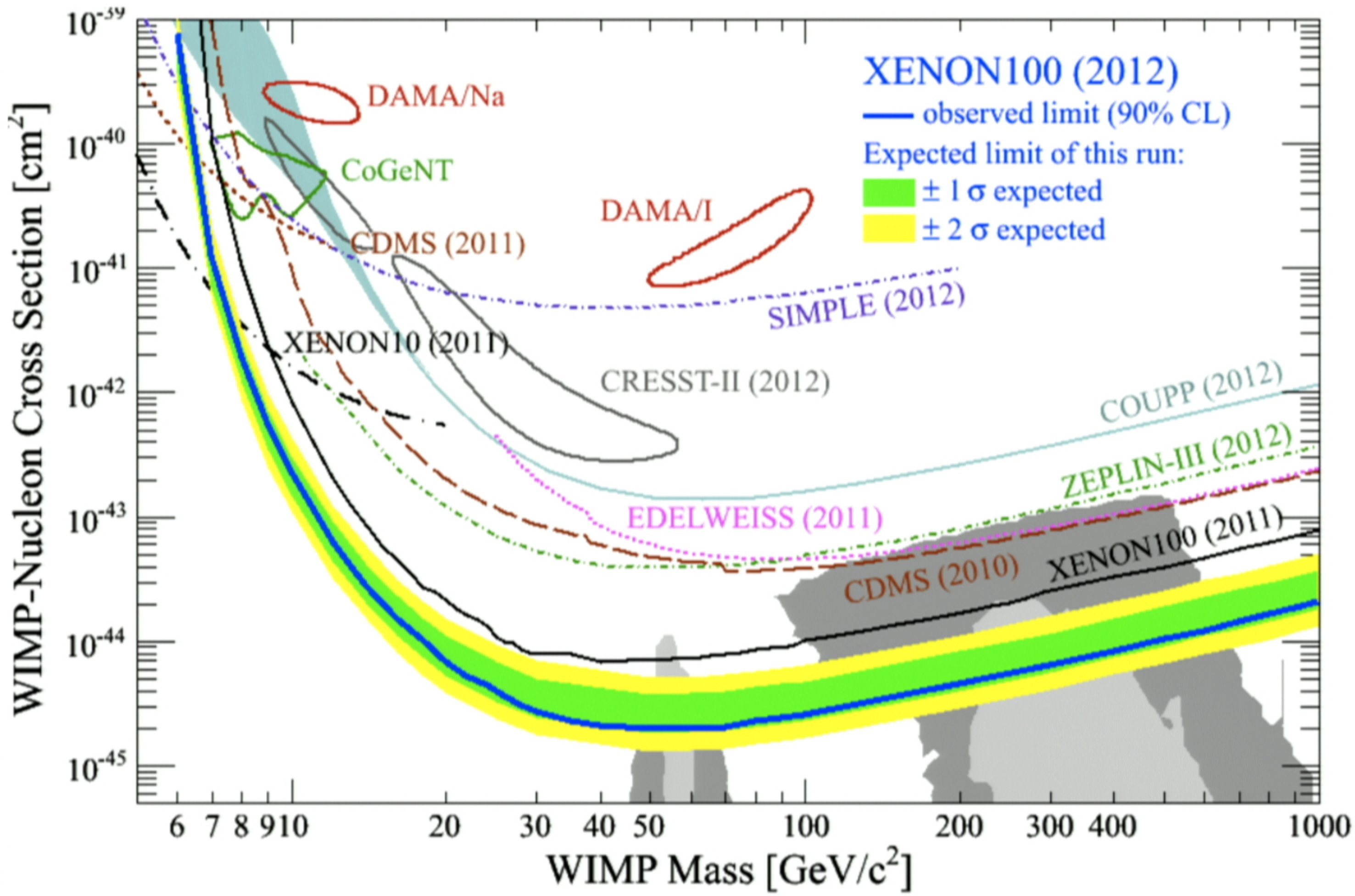
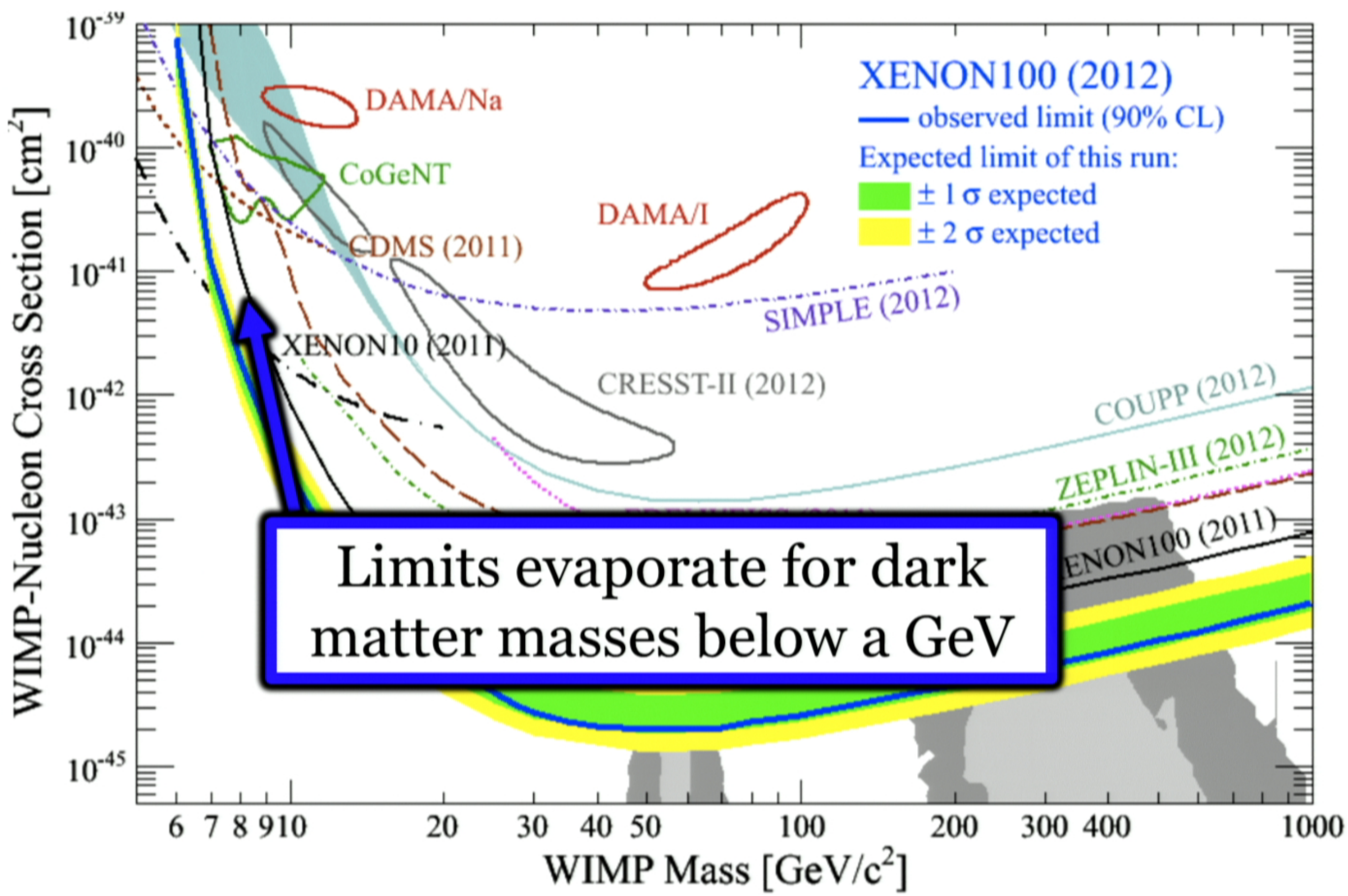


Image source: XENON Collaboration. *Phys. Rev. Lett.* **109**, 181301 (2012)



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- But experimental exclusions on traditional WIMPs are becoming uncomfortable
  - See recent LUX results
- Many proposed sub-GeV models are not constrained by Lee-Weinberg bound
- Can we look for lighter masses?

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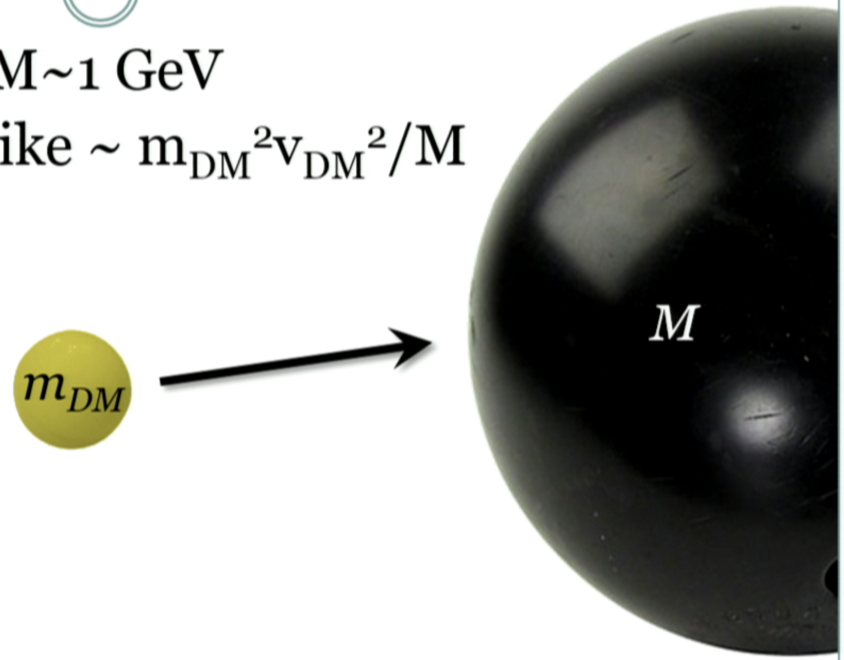

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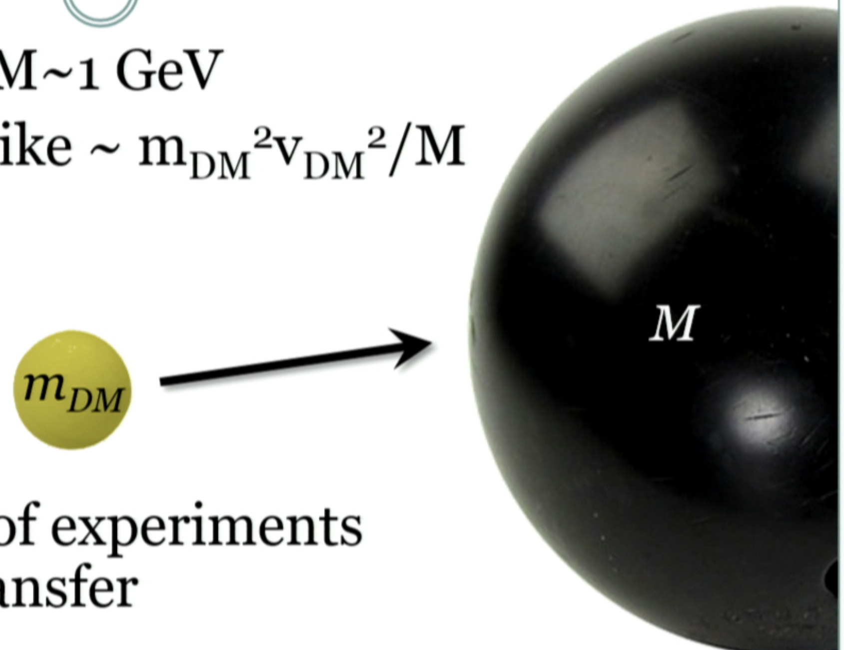

- Minimum sensitivity of experiments
  ~ 1 keV energy transfer
- Corresponds to M ~ m_{DM}

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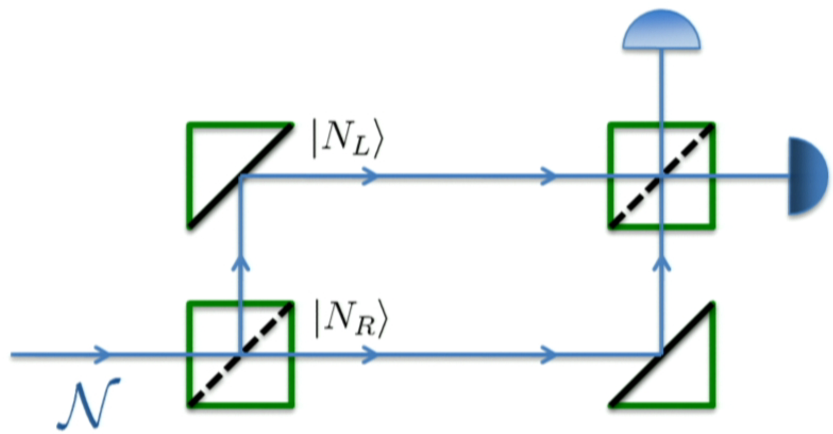
Alternative: detection through decoherence

- Initial state: $|\mathcal{N}_L\rangle + |\mathcal{N}_R\rangle$



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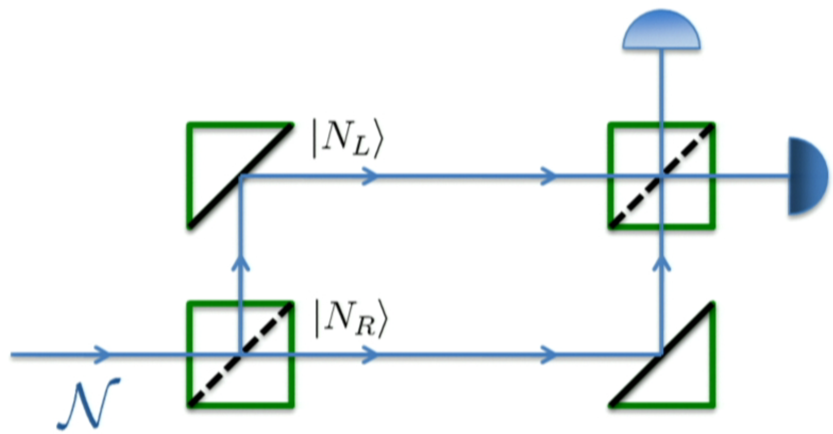

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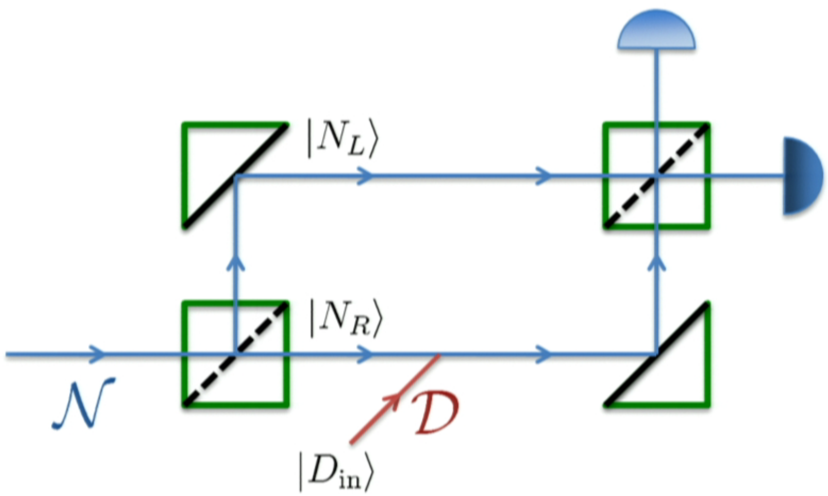

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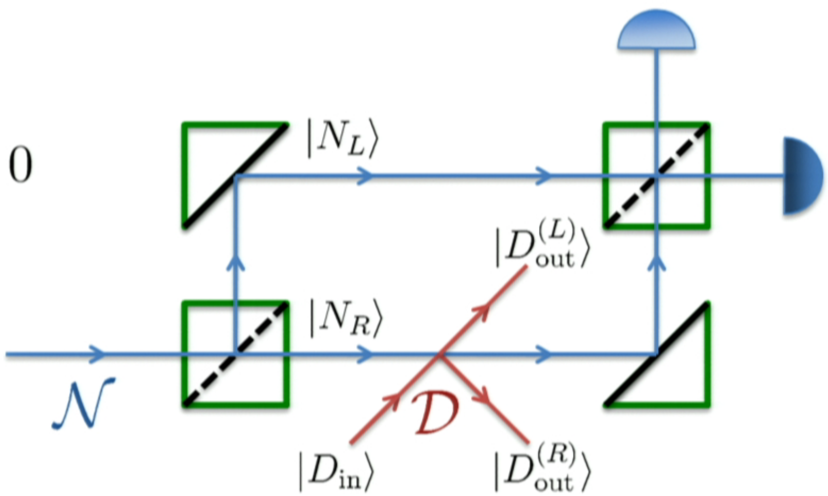
- Measurement:

$$\langle D_{\text{out}}^{(L)}|D_{\text{out}}^{(R)}\rangle \approx 0$$



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- Measurement: $\{|\mathcal{N}_\pm\rangle = |\mathcal{N}_L\rangle \pm |\mathcal{N}_R\rangle\}$

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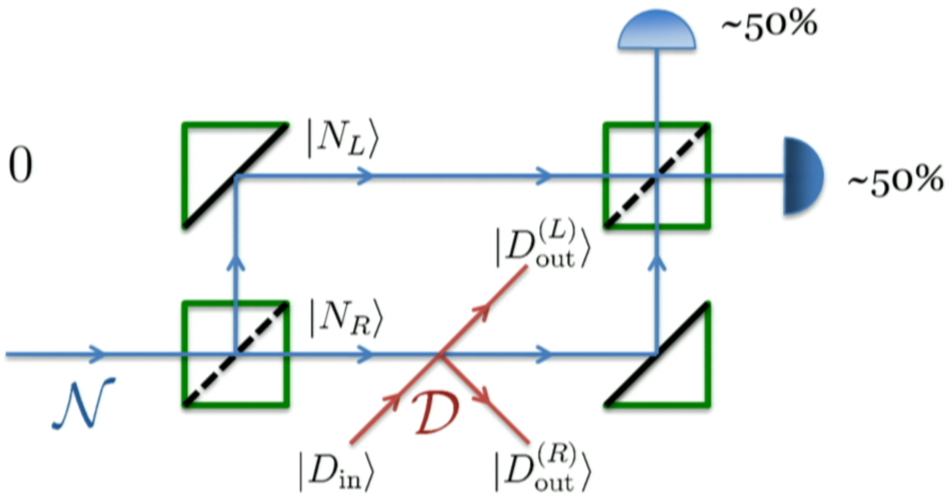

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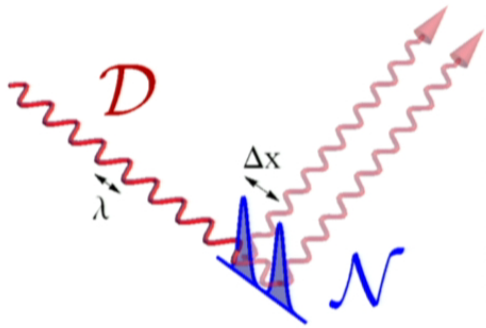
- Full information: $\langle D_{\text{out}}^{(L)} | D_{\text{out}}^{(R)} \rangle \approx 0$
  - Complete decoherence
  - Short-wavelength dark matter
  - Zero interference visibility
  - One scattering event required



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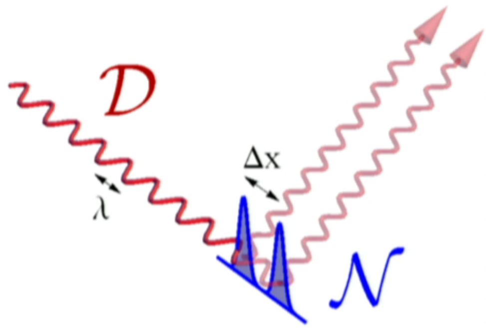

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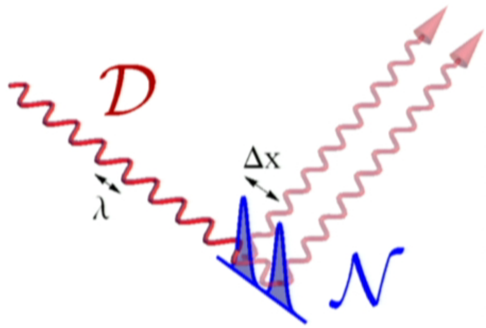

- Minimal information: $\langle D_{\text{out}}^{(L)} | D_{\text{out}}^{(R)} \rangle = 1 - \epsilon$
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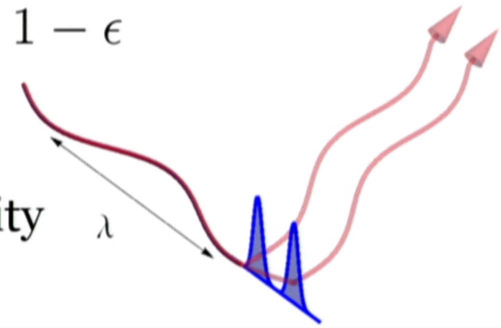

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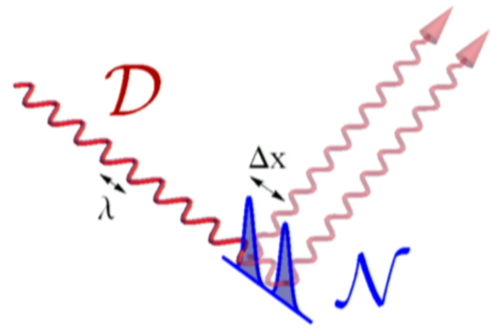

- Minimal information: $\langle D_{\text{out}}^{(L)} | D_{\text{out}}^{(R)} \rangle^N = (1-\epsilon)^N \approx e^{-\epsilon N}$
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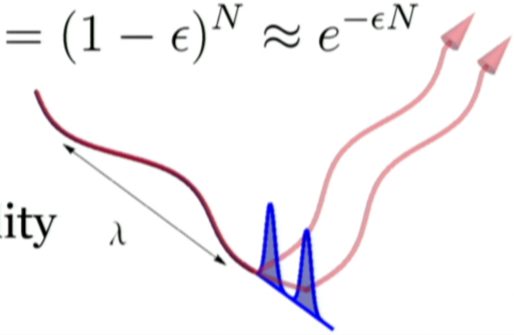
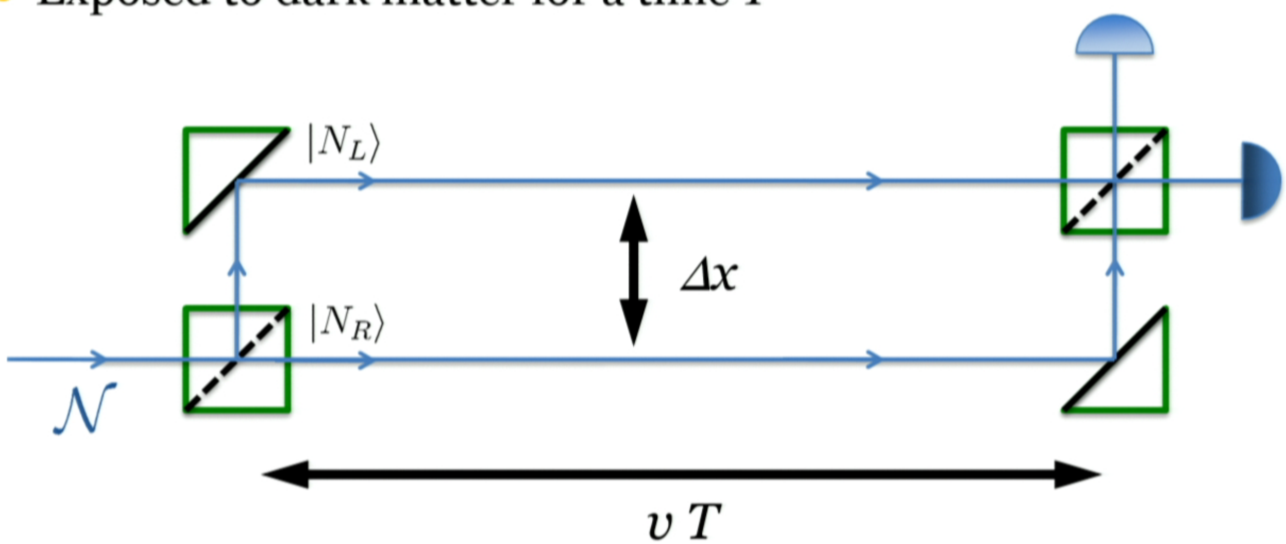


Collisional decoherence

- We consider a single nucleon placed in a superposition of two localized wavepackets
  - Separated by a distance Δx
  - Exposed to dark matter for a time T



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$n(\vec{q})$: Dark matter phase space density

$\hat{r}$: Momentum out states

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  - Modifying angular cross section gives only order-unity correction (see paper for details)

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- But creating large superpositions is too hard, right? Won't N always be small, or unity?

Matter interferometry

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Image source: Gerlich, S. et al. *Nat. Commun.* **2**, 263 (2011)

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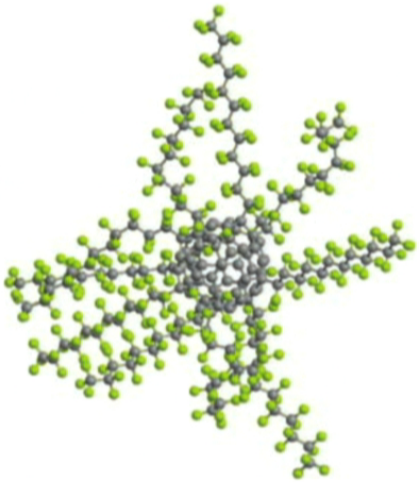

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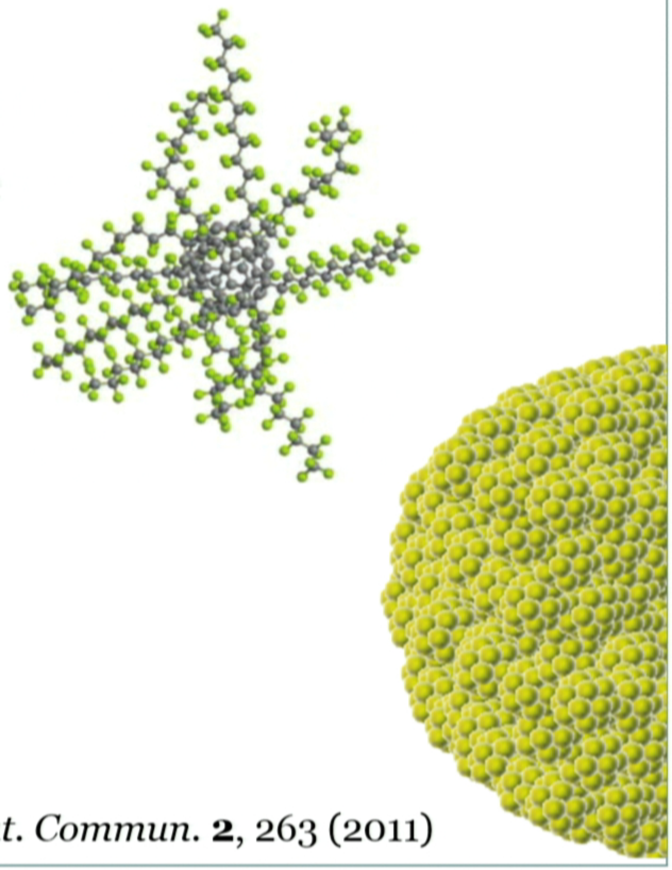
- Experiments in Vienna have superposed molecules of almost 10^4 amu
- The next generation of interferometers should tickle 10^7 amu



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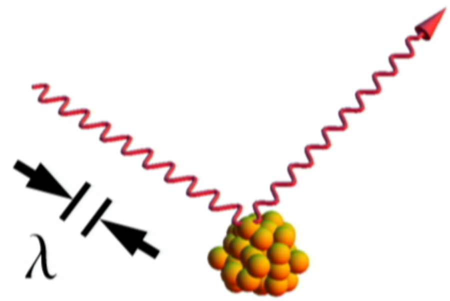

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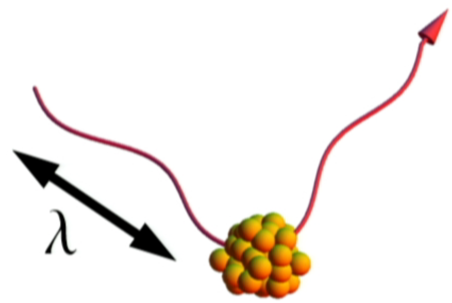

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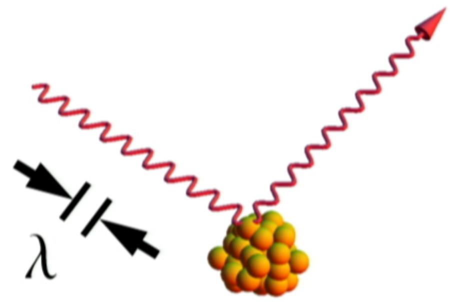

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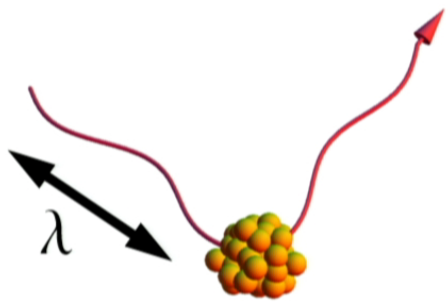

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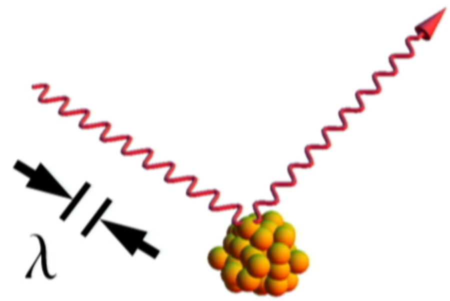

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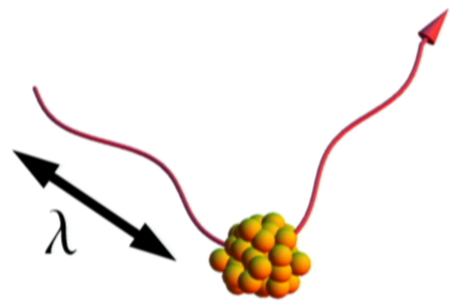

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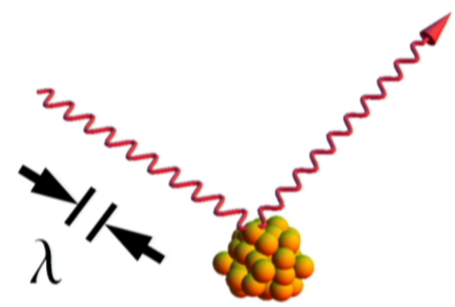

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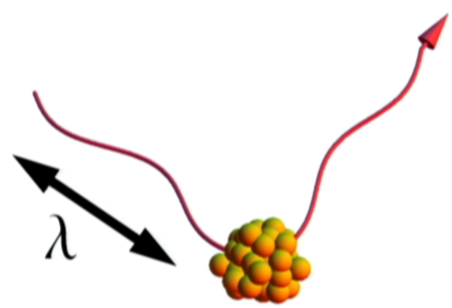

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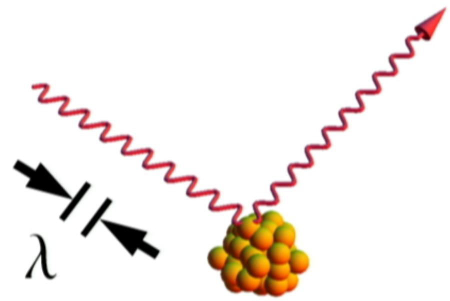
- Yields *additional* boost of factor N



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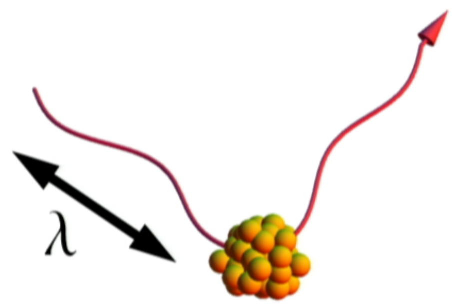

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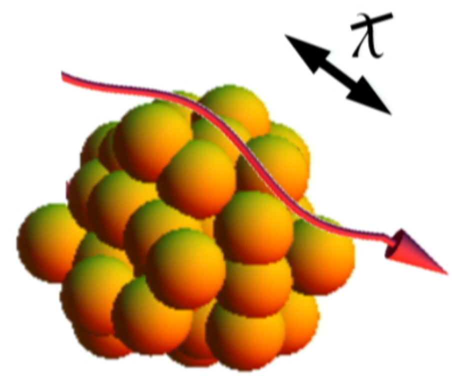

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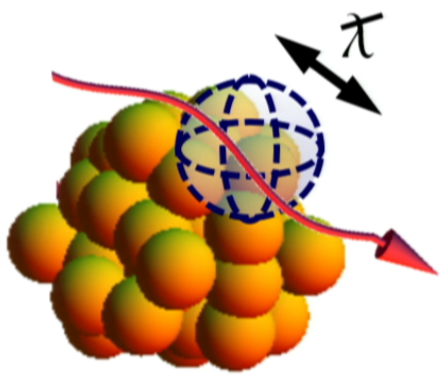
- Good approximation: boost is proportional to number of nucleons in "coherent scattering volume" $ƛ^3$
  - See paper for details



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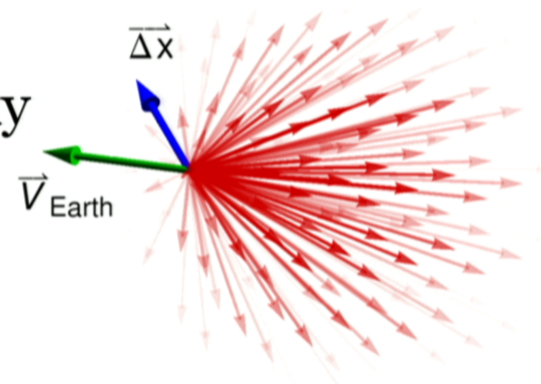

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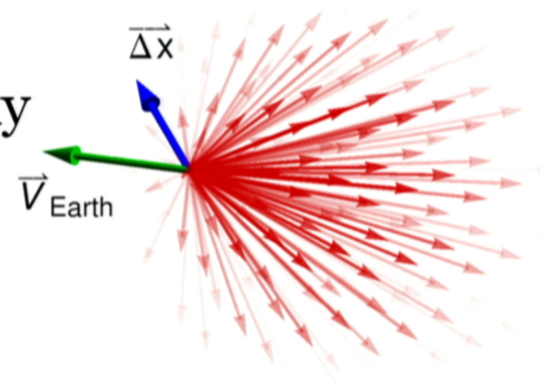

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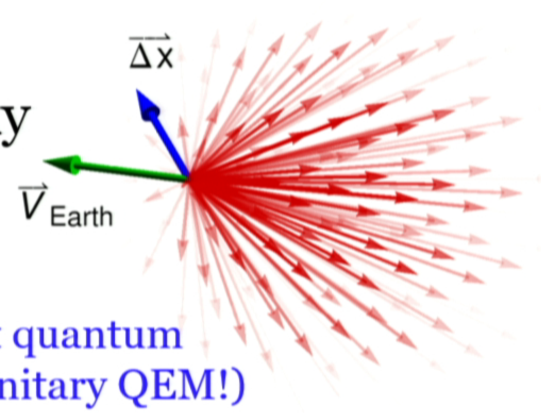

(Teaser: smooth link between "decoherent quantum enhanced measurement" and conventional, unitary QEM!)

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- However, the inverse statement is true: a successful interferometer implies *all* sources of decoherence have been eliminated
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- But if we think anomalous decoherence might be due to dark matter, how could we be sure?

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- But for low-mass dark matter, constraints are very weak

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- The other generic constraint arises from requiring…
  - stability of the dark matter halo from collisions with the Milky Way disk and
  - consistency with temperature of interstellar hydrogen

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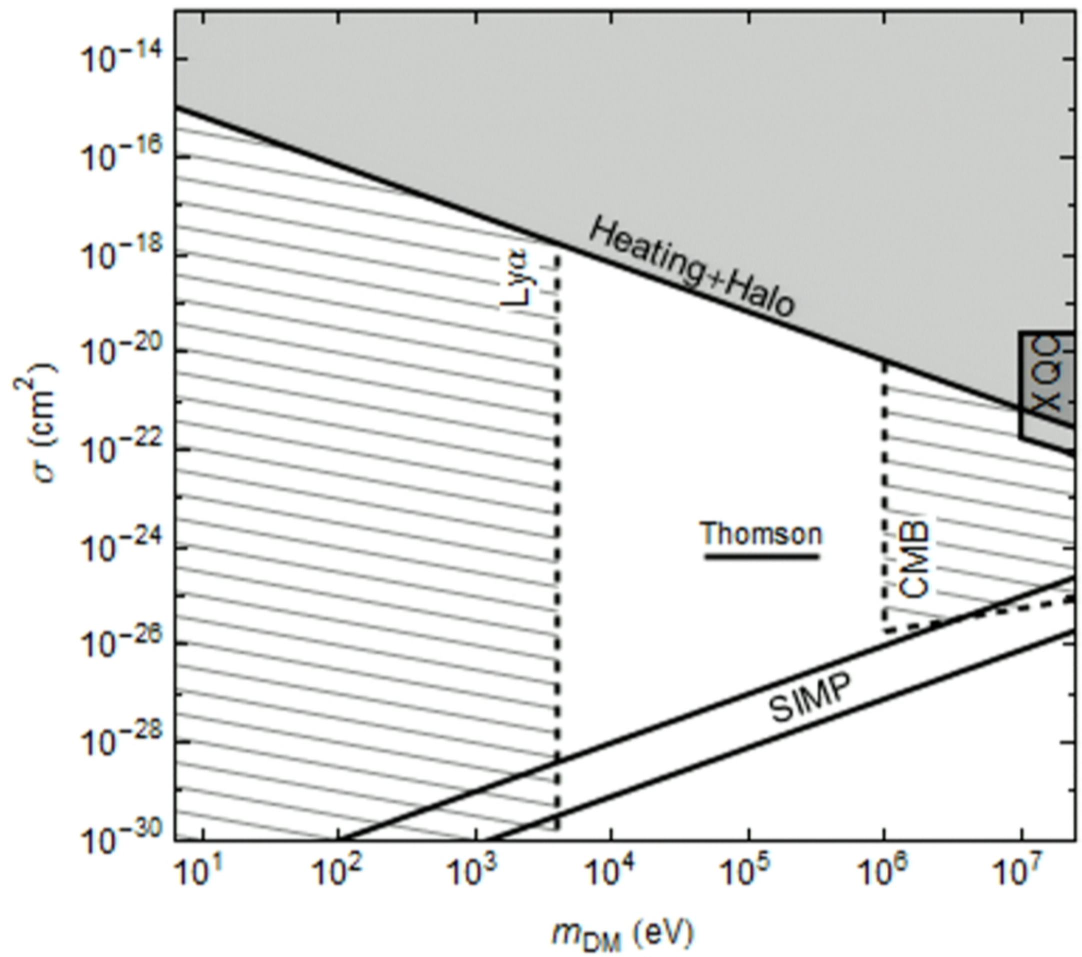
  - Cosmic microwave background (CMB)

Low-mass dark matter models

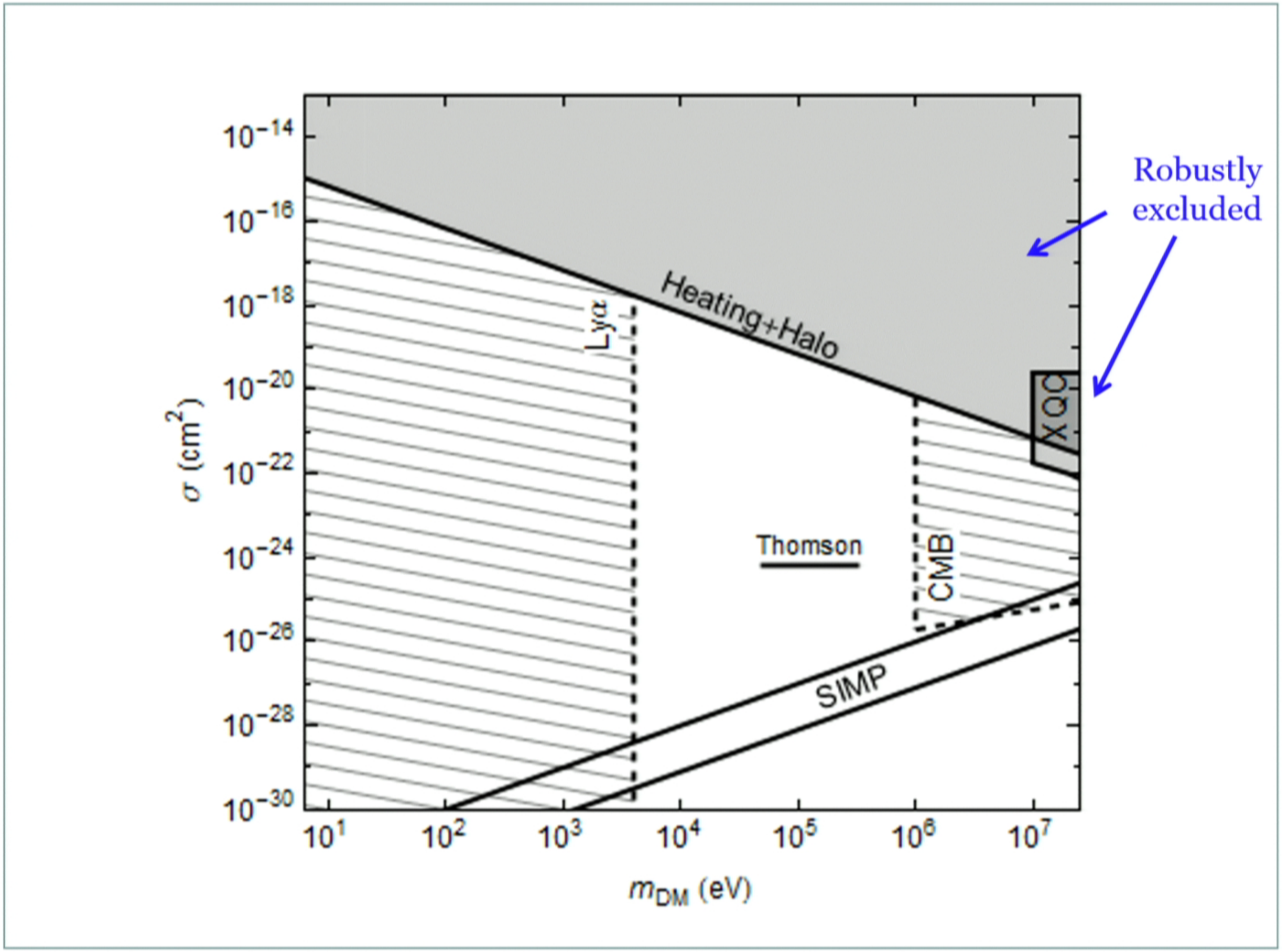
- Very little theoretical attention paid to low-mass possibility
  - Generally assumed to be depressingly undetectable
  - Recent increase in model-building, probably due to negative WIMP results

Low-mass dark matter models

- Very little theoretical attention paid to low-mass possibility
  - Generally assumed to be depressingly undetectable
  - Recent increase in model-building, probably due to negative WIMP results
- Best-known toy models are the so-called Strongly Interacting Massive Particles (SIMPs)
  - Characterized by m_{DM}/σ ratio which could help explain so-called "cusp" problem (among others)
  - Not very attractive these days for large masses (m_{DM} > GeV)
  - Provides good landmark for Not-Totally-Crazy theories



10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
σ (cm^2)
Heating+Halo
Lyα
XQC
Thomson
CMB
SIMP
10^1
10^2
10^3
10^4
10^5
10^6
10^7
m_{DM} (eV)



Robustly
excluded
Heating+Halo
Lyα
XQC
Thomson
CMB
SIMP
σ (cm²)
m_{DM} (eV)
10^{-14}
10^{-16}
10^{-18}
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10^{-22}
10^{-24}
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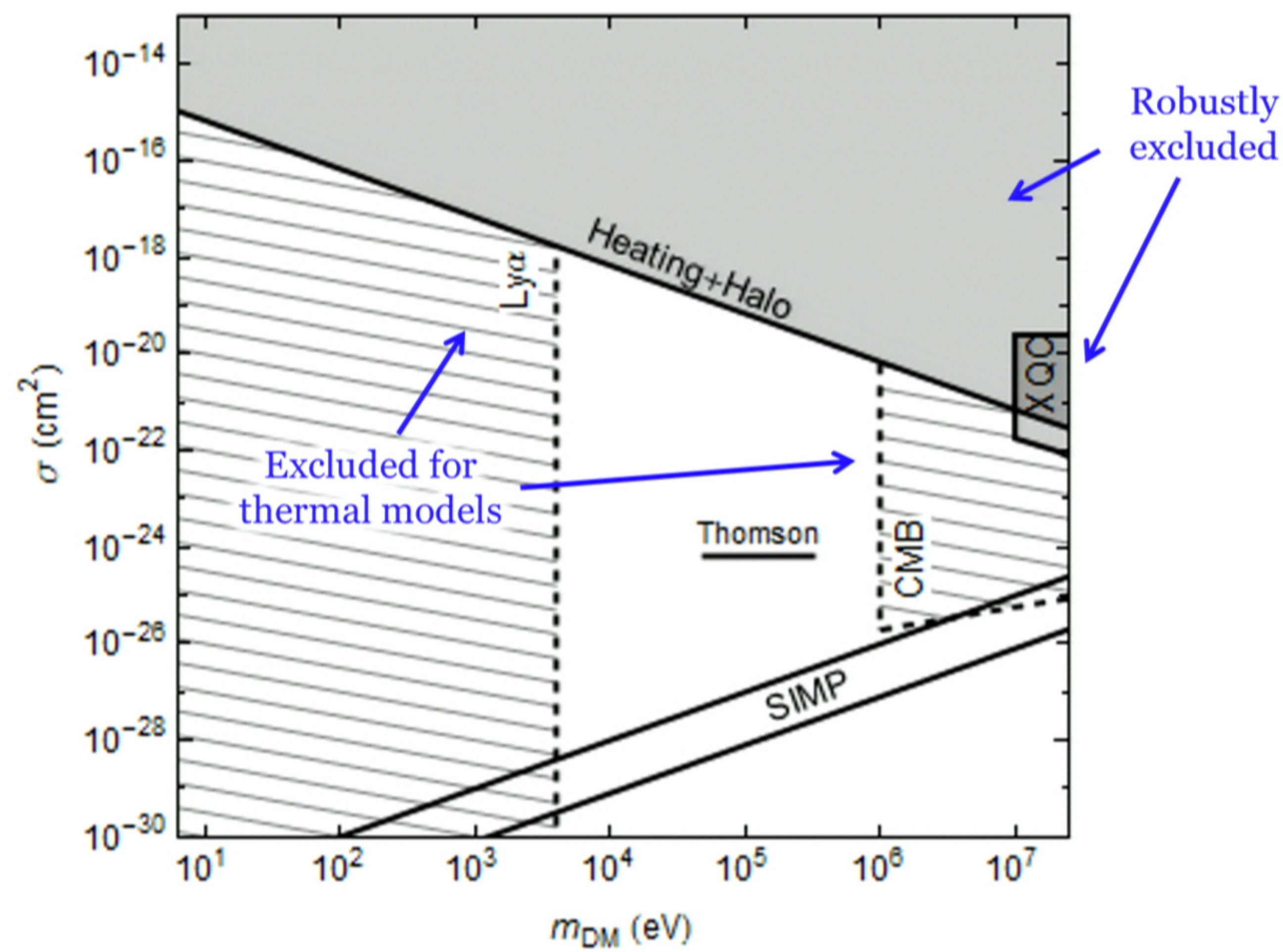
10^{6}
10^{7}


Robustly excluded
Excluded for thermal models
Heating+Halo
Lyα
XQC
Thomson
CMB
SIMP
σ (cm²)
m_{DM} (eV)
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10^{-16}
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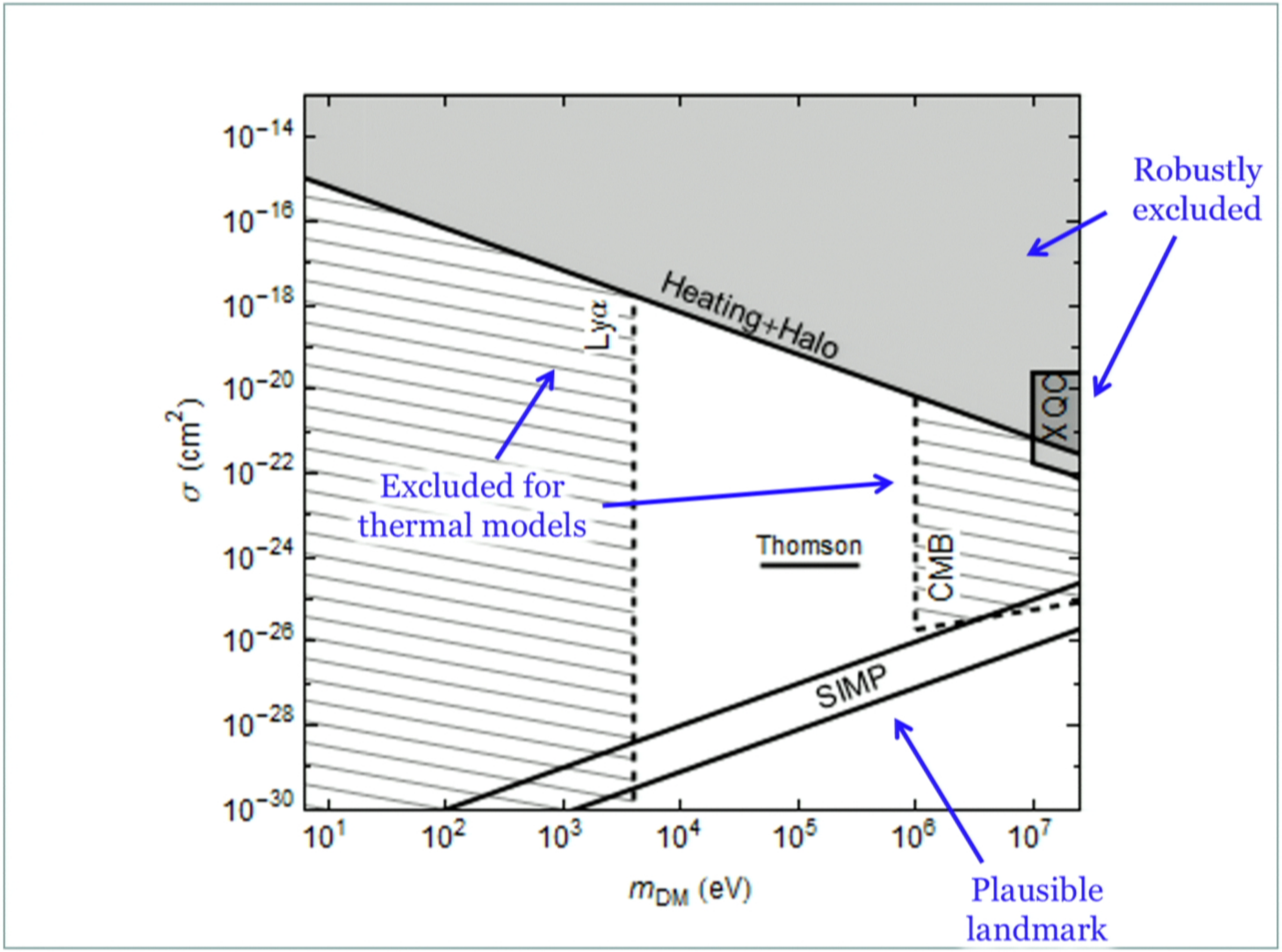
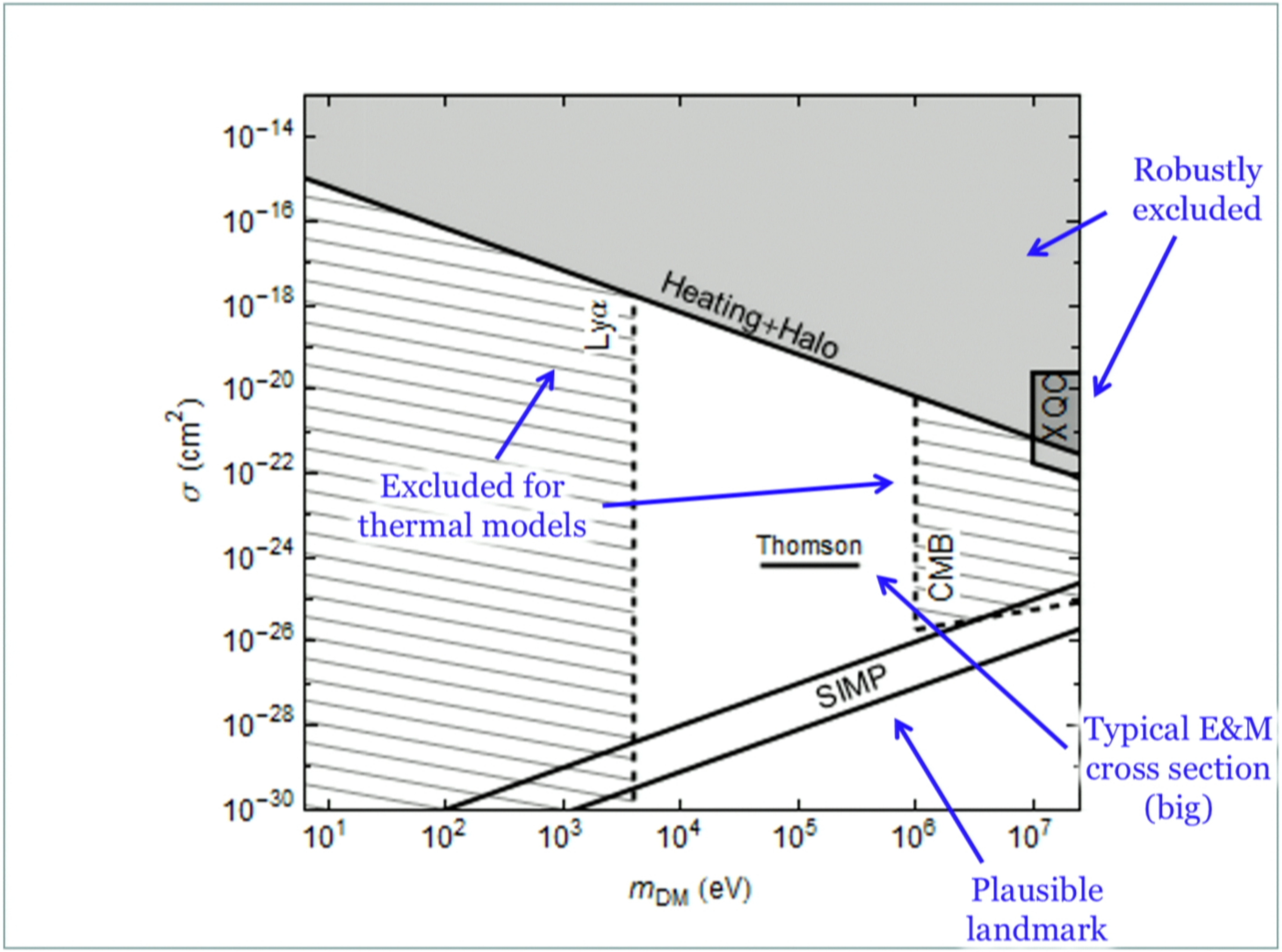


Robustly excluded
Heating+Halo
Lyα
XQC
Excluded for thermal models
Thomson
CMB
SIMP
Plausible landmark
σ (cm²)
m_{DM} (eV)
10⁻¹⁴ 10⁻¹⁶ 10⁻¹⁸ 10⁻²⁰ 10⁻²² 10⁻²⁴ 10⁻²⁶ 10⁻²⁸ 10⁻³⁰
10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10⁷


Robustly excluded
Heating+Halo
XQC
Lyα
Excluded for thermal models
Thomson
CMB
SIMP
Typical E&M cross section (big)
Plausible landmark
σ (cm²)
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
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10^1 10^2 10^3 10^4 10^5 10^6 10^7
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Proposed experiments as benchmarks

- Consider proposals for three next-generation matter interferometers in order to estimate sensitivity to dark matter

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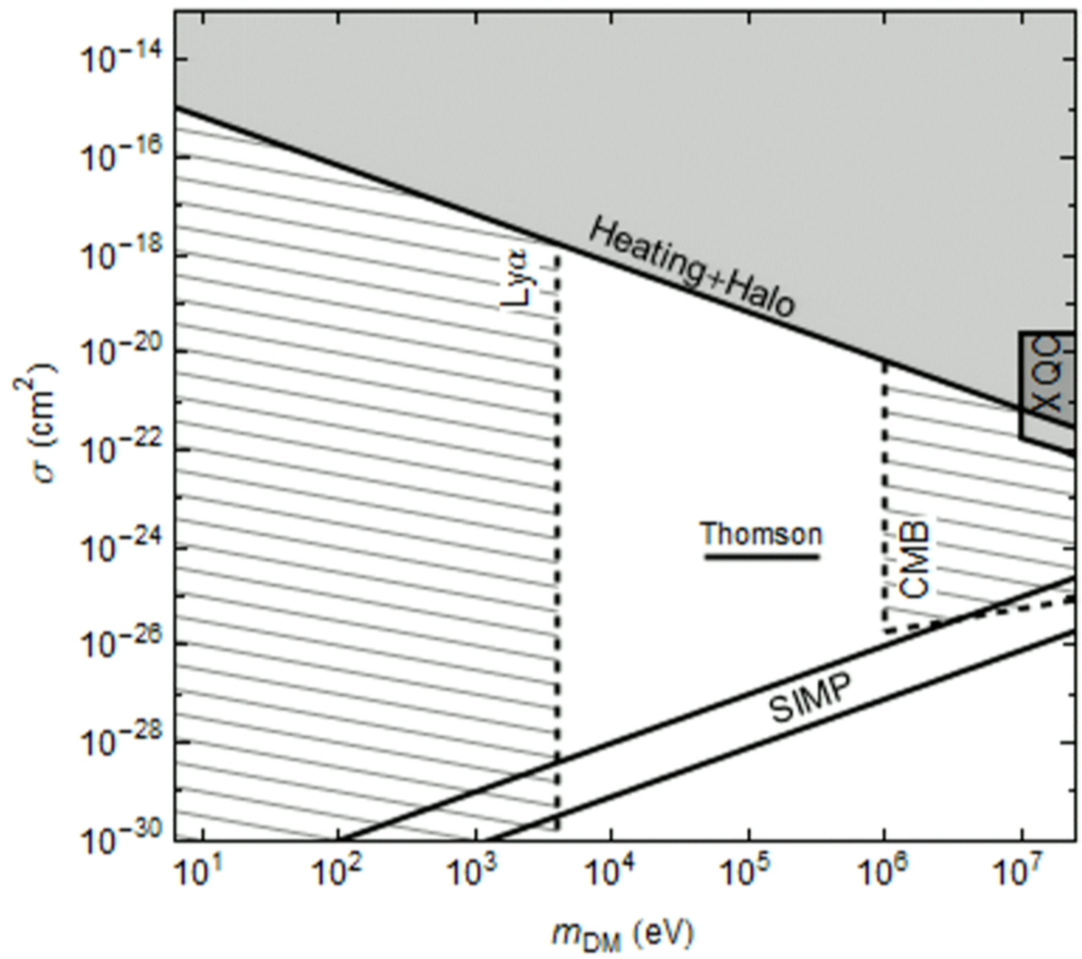
- Atomic Gravitational-wave Interferometric Sensor (AGIS) satellite experiment proposal
  - Single atoms (so minimal coherence boost) interfered in open vaccuum of space (so no atmospheric shielding)
  - J. Hogan et al. *General Rel. Grav.* **43**, 1953 (2011)



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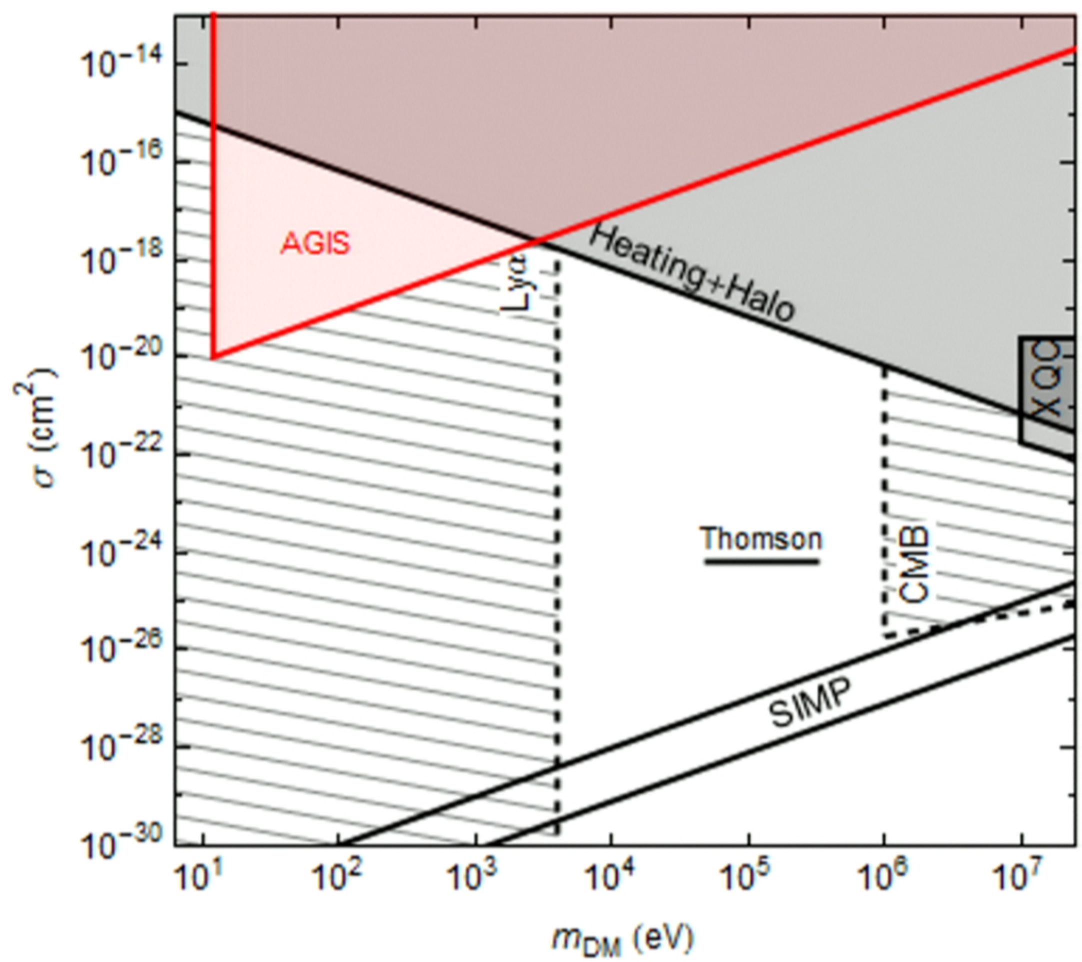
m_{DM} (eV)



AGIS
Heating+Halo
Lyα
XQC
Thomson
CMB
SIMP
σ (cm²)
m_DM (eV)

Proposed experiments as benchmarks

- Optical Time-domain Ionizing Matter-wave (OTIMA) Interferometer proposal
  - Improved technology applied to previously mentioned matter interferometry experiment
  - S. Nimmrichter et al. *New Journal of Physics* **13**, 075002 (2011)

Atmospheric shielding

- Problem: Atmospheric shielding is real concern at sea level ($\sim 10^{-27}$ cm^2)
  - Can't look for dark matter if it is stopped by atmosphere

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- Or, create a superposition so large it's sensitive to smaller dark matter
  - Not possible for terrestrial experiments in foreseeable future

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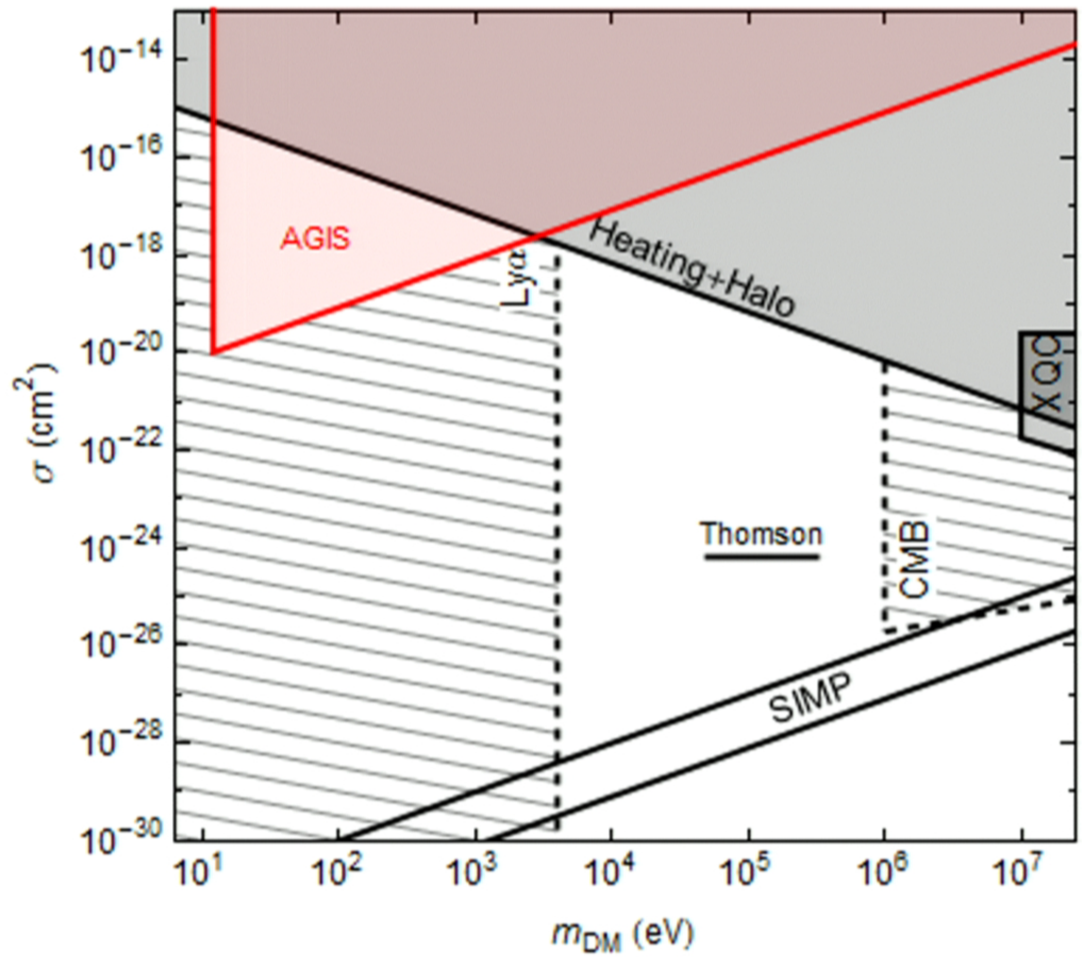
  - Satellite
- Or, create a superposition so large it's sensitive to smaller dark matter
  - Not possible for terrestrial experiments in foreseeable future
- For now: assume sounding rocket platform (200 km)



AGIS
Heating+Halo
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σ (cm^2)
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10^{-14}
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10^6
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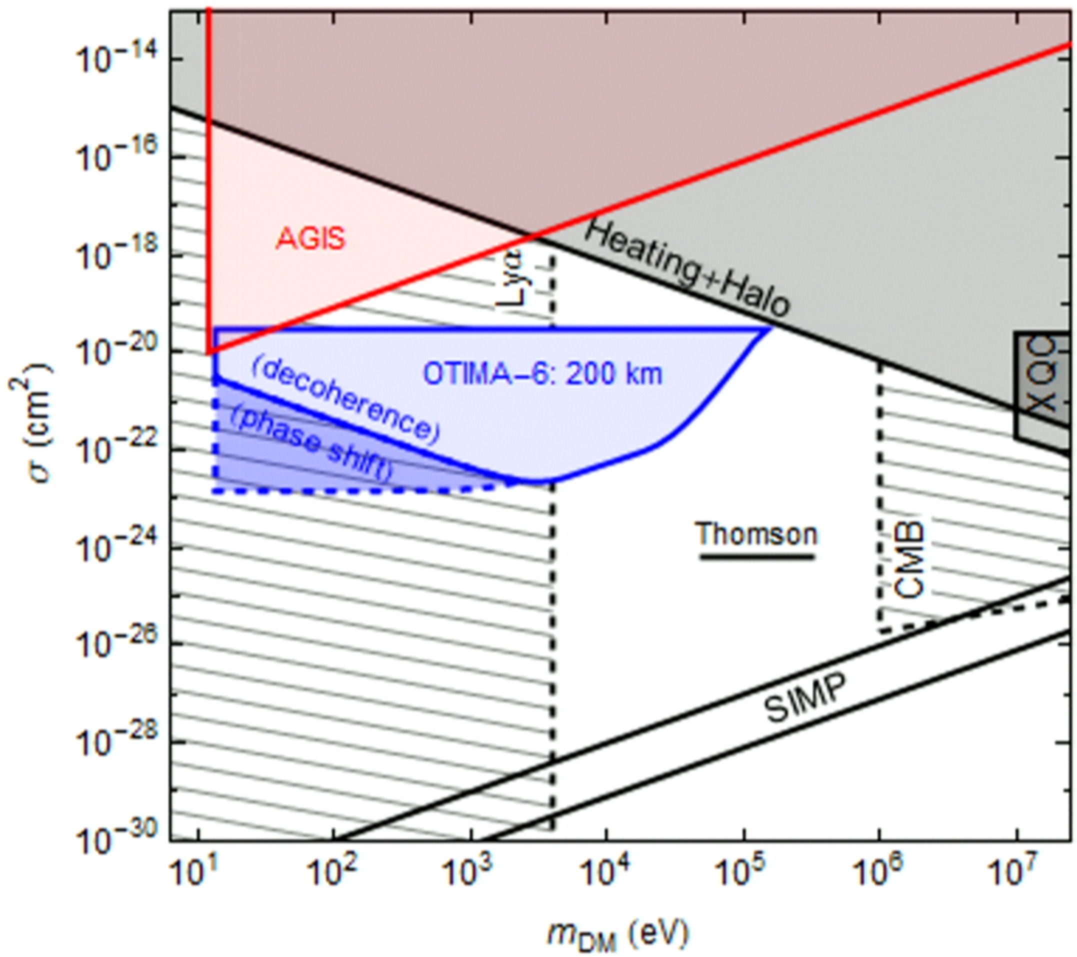

10^{-14}
10^{-16}
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10^{-22}
10^{-24}
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σ (cm^2)
AGIS
Lyα
Heating+Halo
OTIMA–6: 200 km
(decoherence)
(phase shift)
XQC
Thomson
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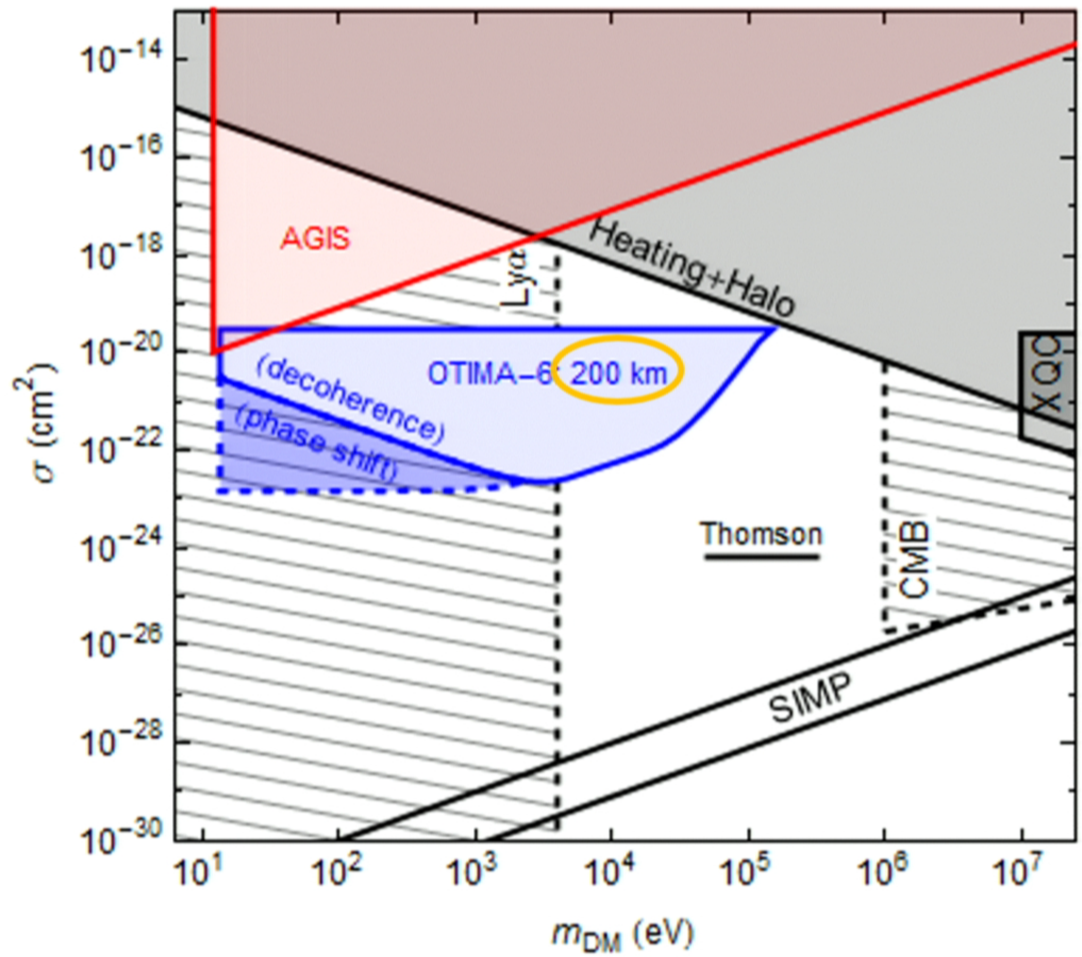
10^1
10^2
10^3
10^4
10^5
10^6
10^7
m_{DM} (eV)



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m_{DM} (eV)
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OTIMA−6: 200 km
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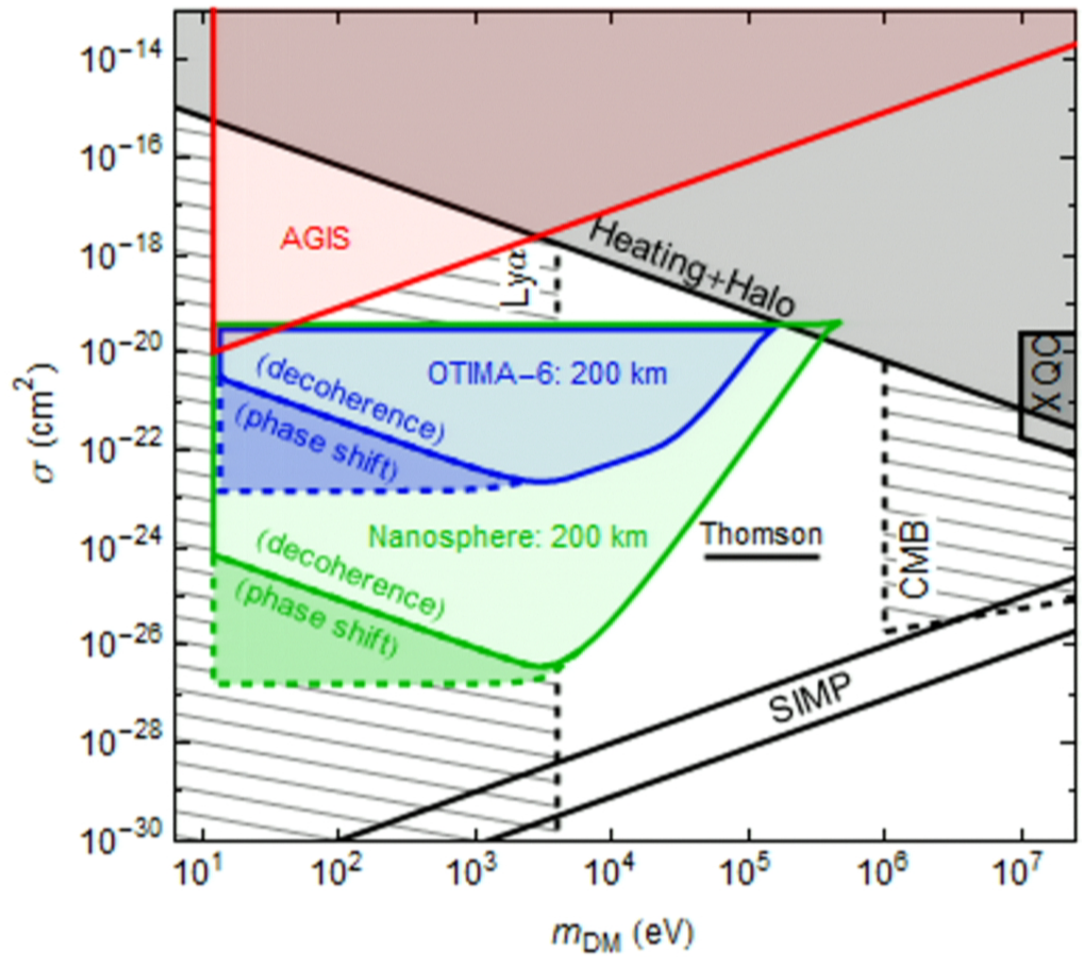
Proposed experiments as benchmarks

- Optically trapped 40 nm silica 'Nanosphere' proposal
  - Nanometer sized ball of silicon suspended and brought into superposition optically; very different than traditional interferometry
  - O. Romero-Isart et al. *Phys. Rev. Lett.* **107**, 020405 (2011).



AGIS
Lyα
Heating+Halo
XQC
OTIMA−6: 200 km
(decoherence)
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Nanosphere: 200 km
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Thomson
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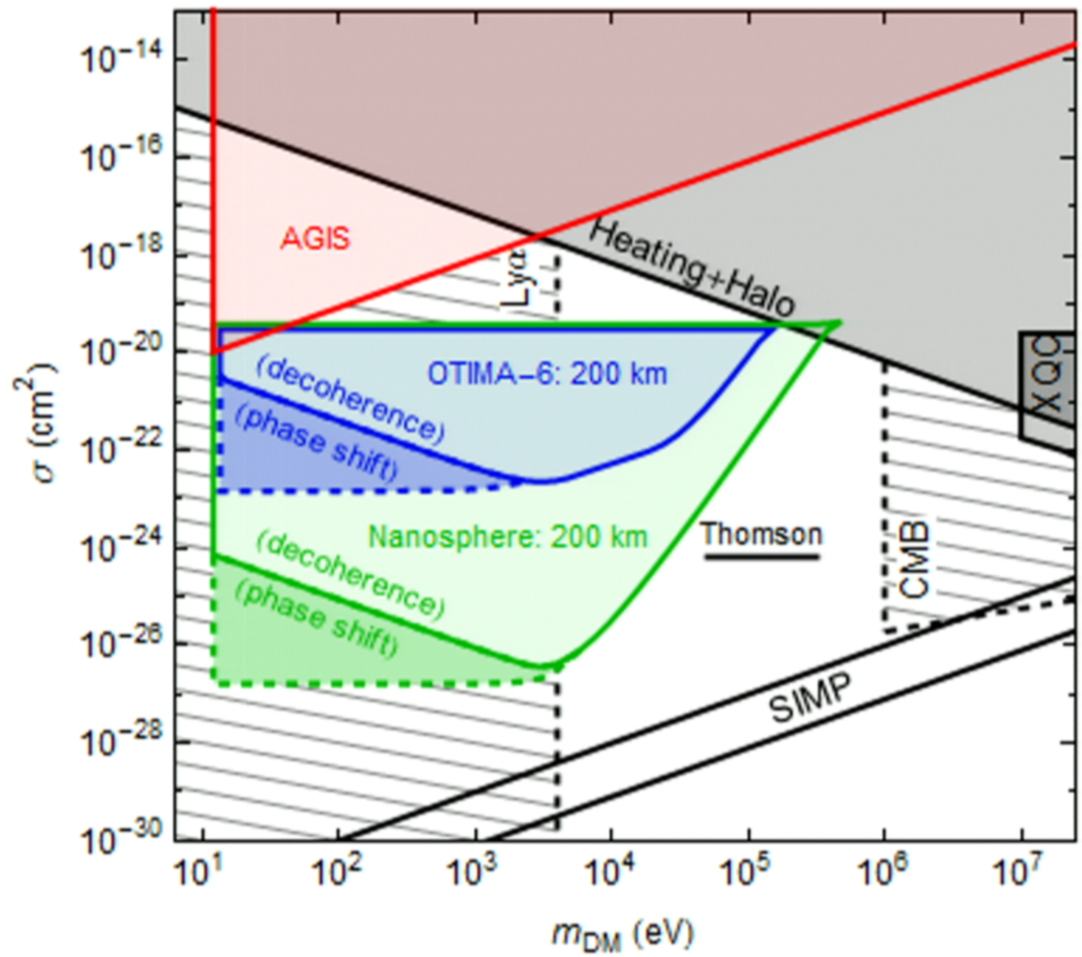

AGIS
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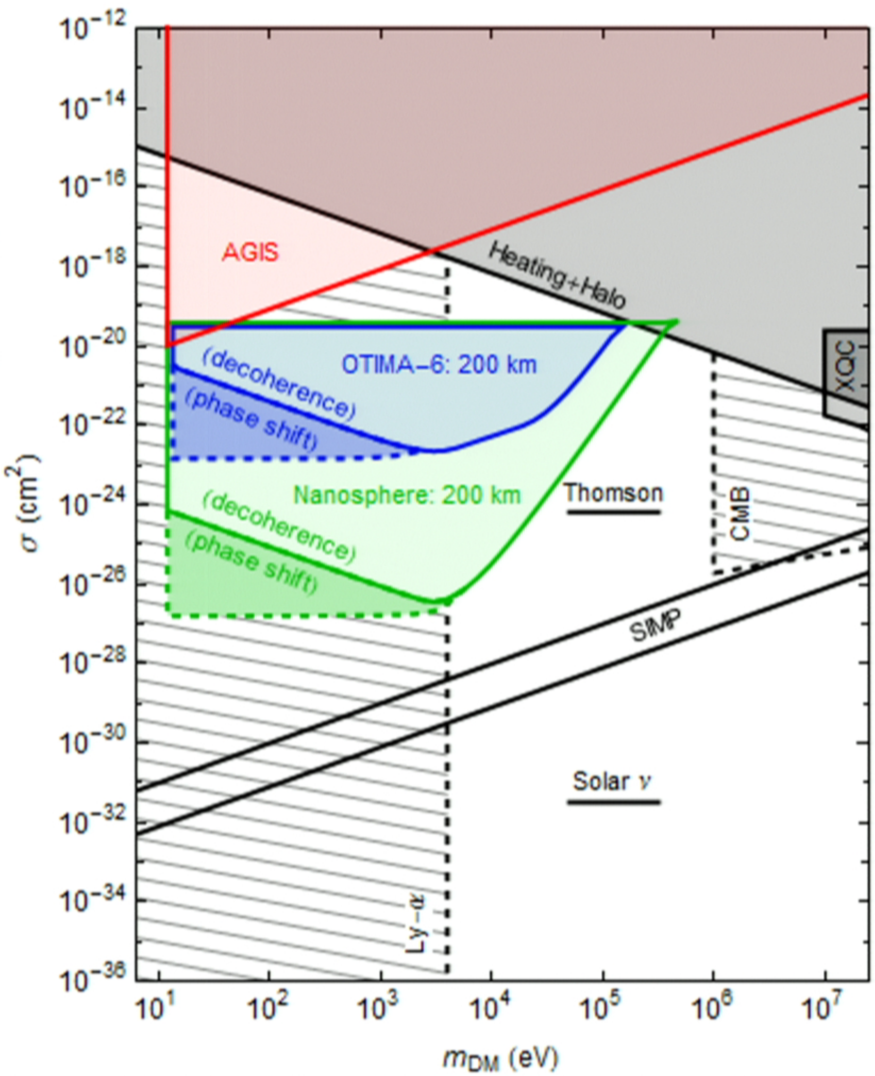
10^7

- DECIDE satellite experiment (speculative)
  - “Macroscopic quantum experiments in space using massive mechanical resonators”



- DECIDE satellite experiment (speculative)
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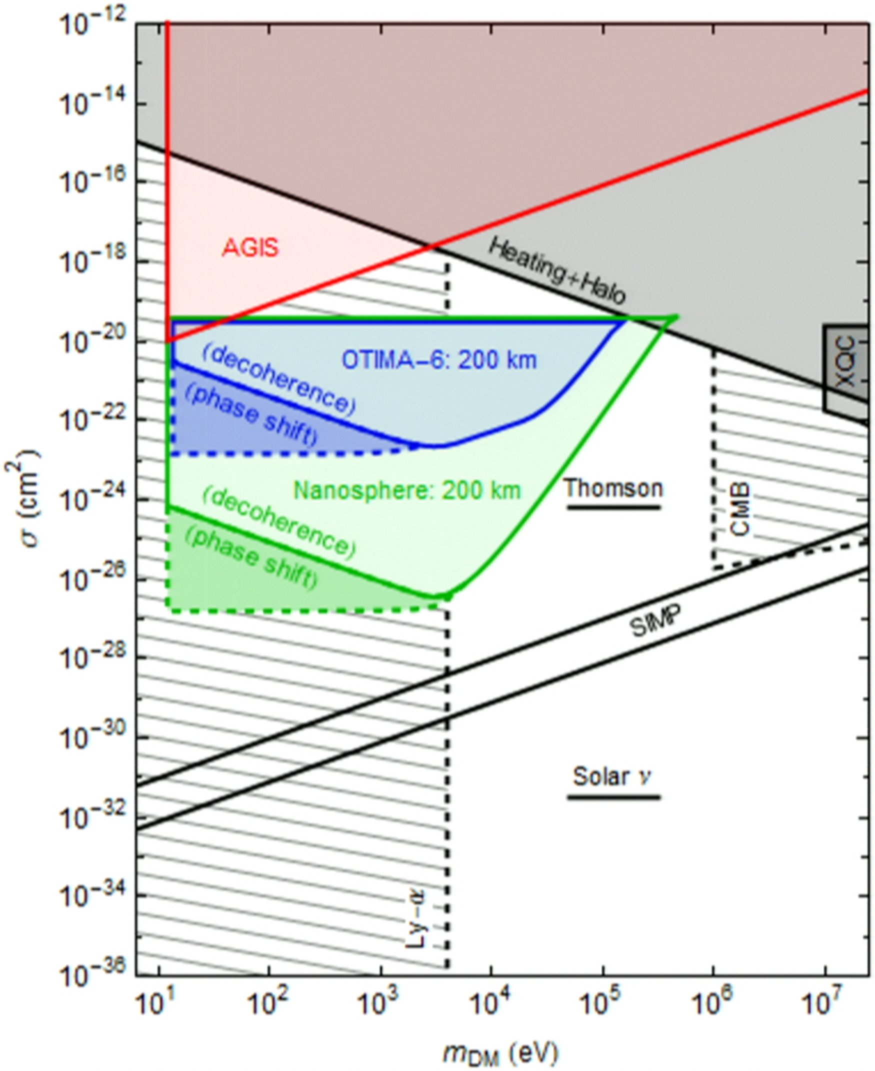
- Timespan*:
  - **10^3**



* Compared to terrestrial 'Nanosphere' experiment

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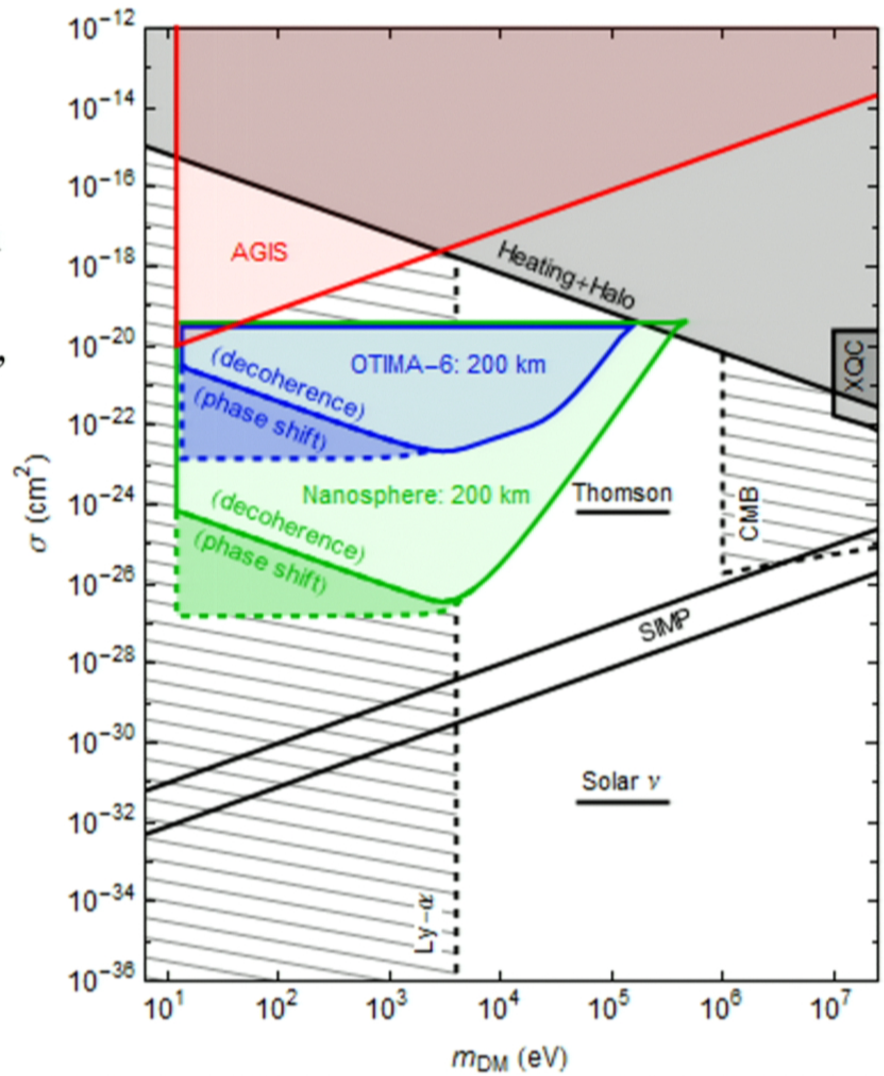
  - $[10^2]^2 = 10^4$



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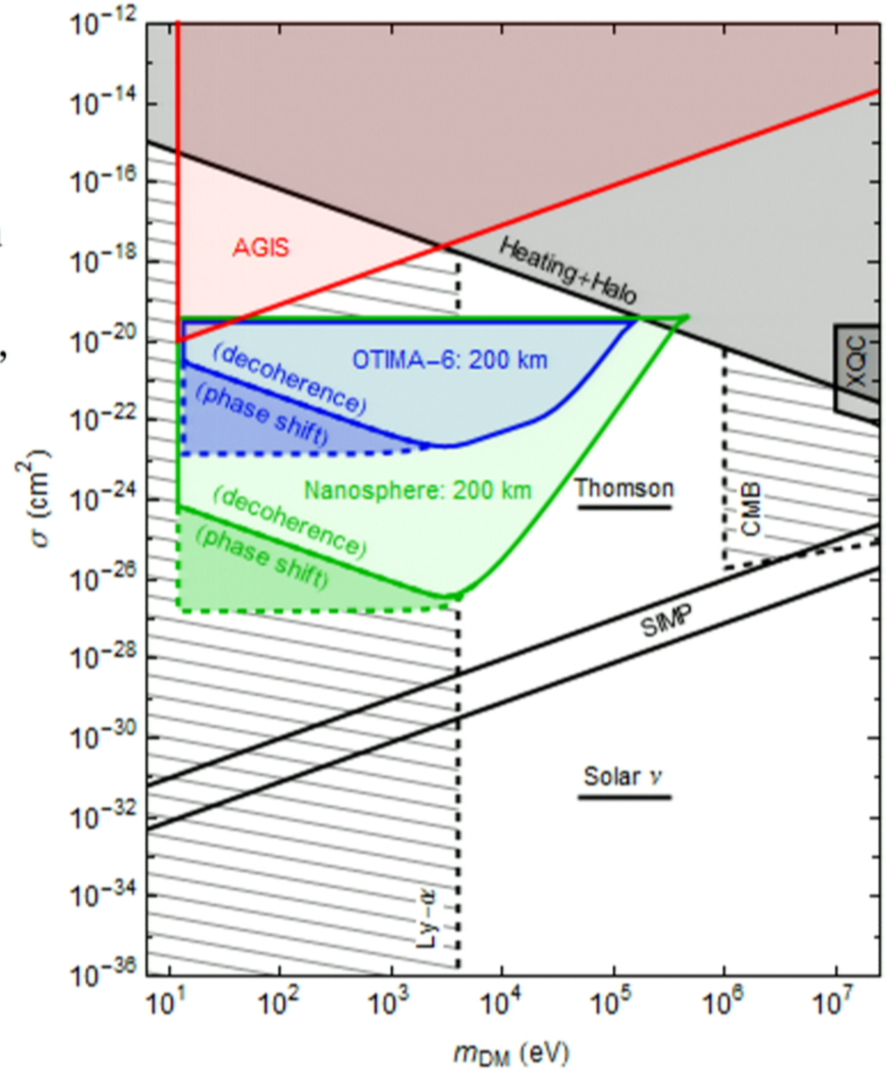

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- Total*: **7** to **10** orders of magnitude

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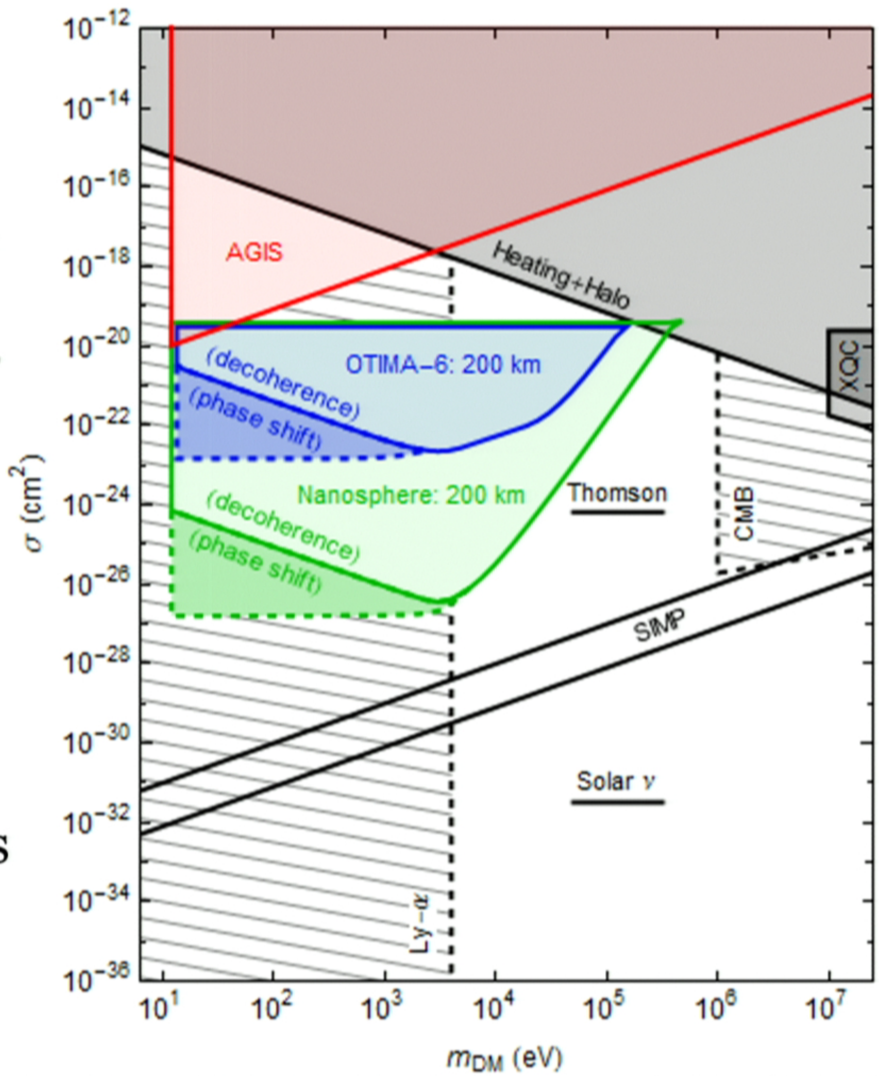

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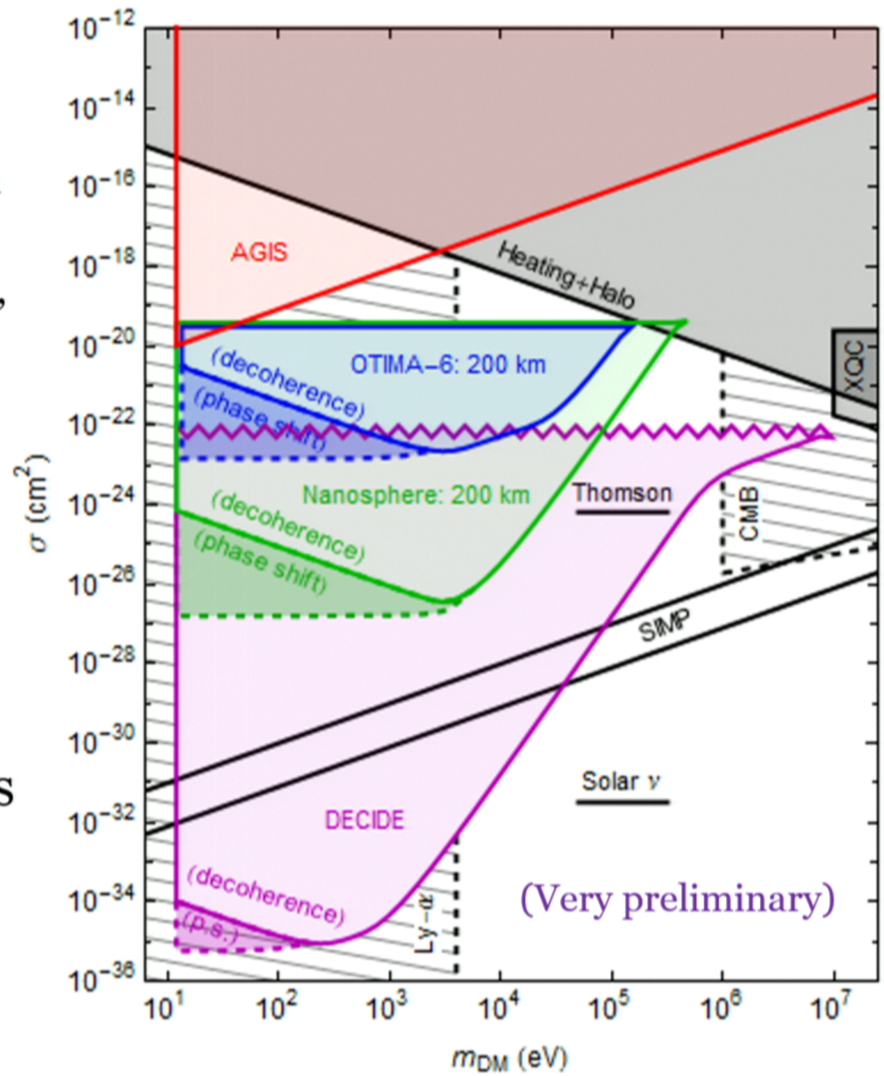

Progress in masses

- Compare to some existing interferometers:

Progress in masses

- Compare to some existing interferometers:
  - Neutron
  - Helium
  - C_{70} fullerene
  - PFNS10 ($C_{60}[C_{12}F_{25}]_{10}$; a fullerene derivative)

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Progress in masses

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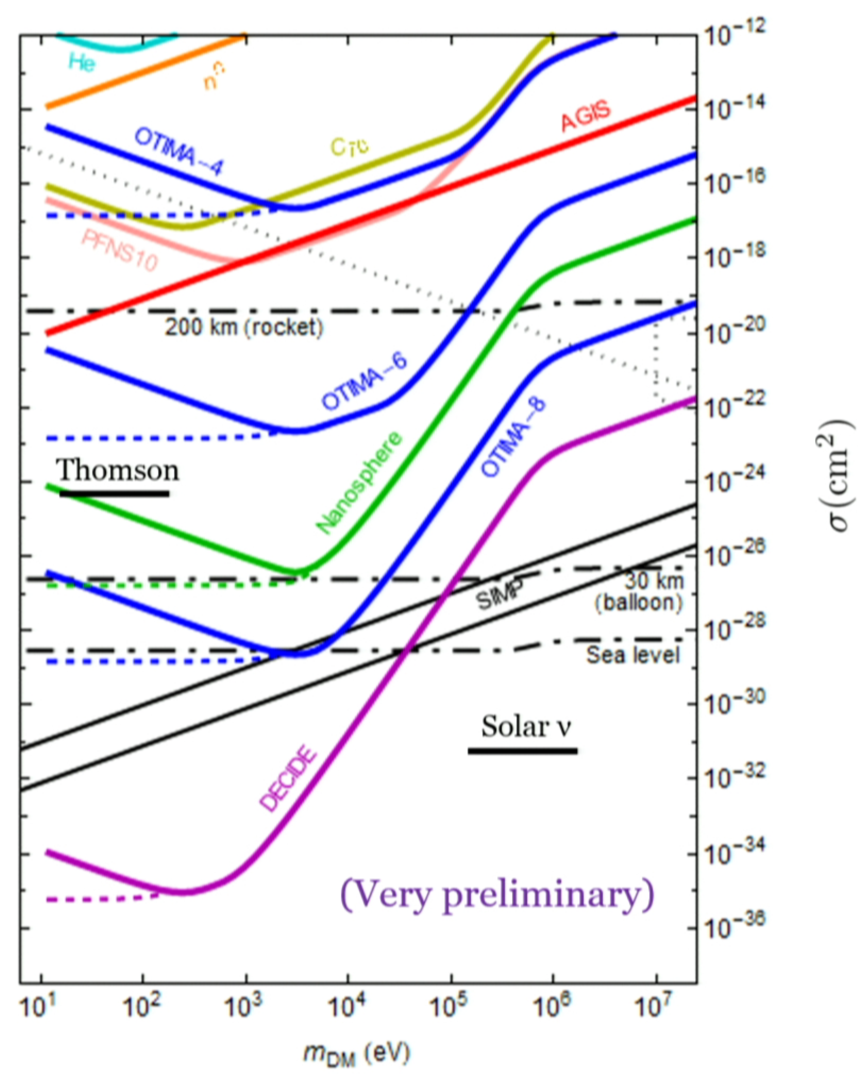
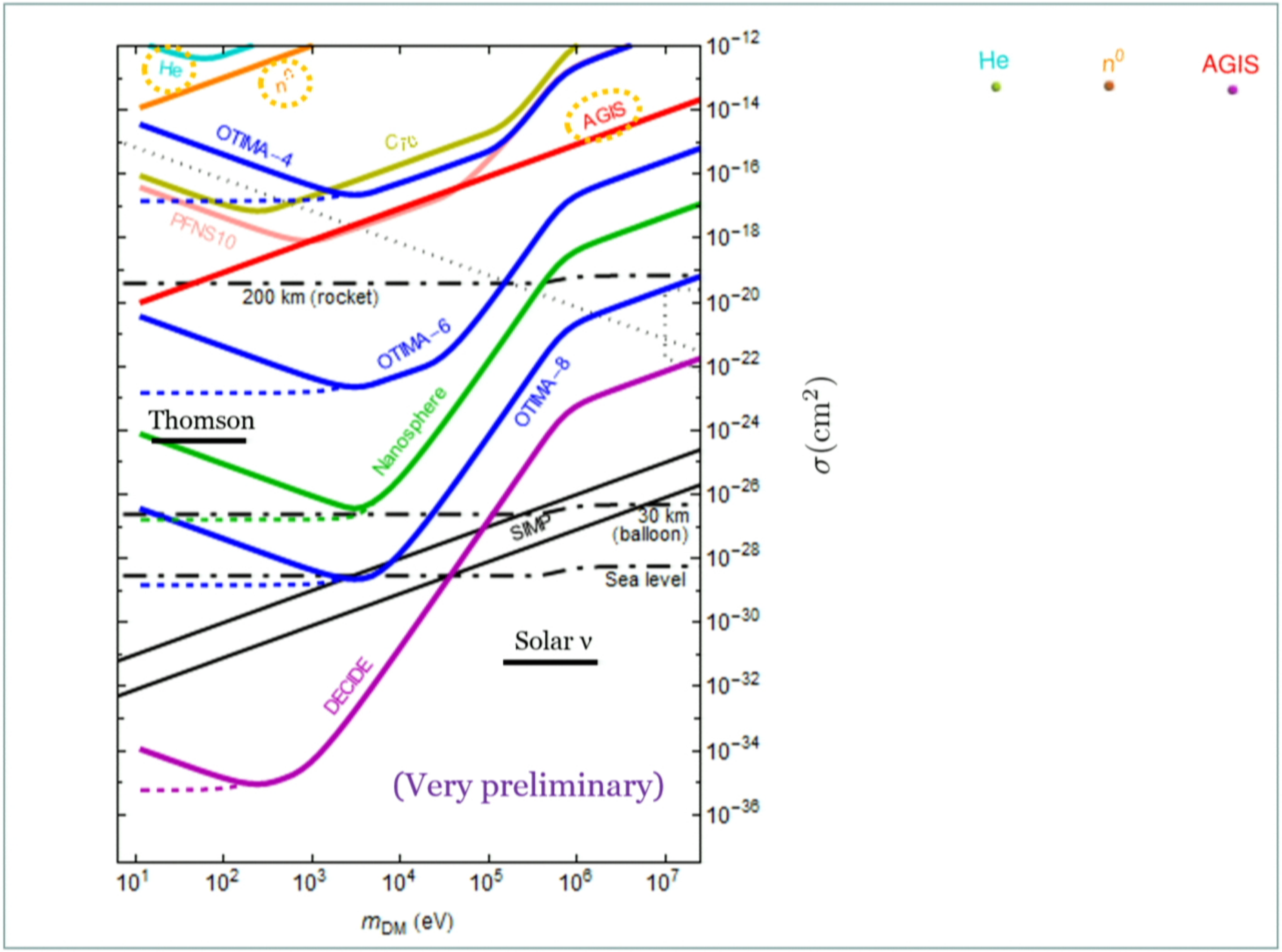
  - PFNS10 ($C_{60}[C_{12}F_{25}]_{10}$; a fullerene derivative)
- Also consider three OTIMA masses:
  - 10^4 amu (done)
  - 10^6 amu (hard but likely to be achieved in next few years)
  - 10^8 amu (not possible on Earth because of gravity; same techniques may work in orbit)


He
n?
OTIMA-4
C70
AGIS
PFNS10
200 km (rocket)
OTIMA-6
Thomson
Nanosphere
OTIMA-8
SIMP
30 km
(balloon)
Sea level
Solar ν
DECIDE
(Very preliminary)
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
$\sigma(\mathrm{cm}^2)$
10^1
10^2
10^3
10^4
10^5
10^6
10^7
m_{DM} (eV)


He
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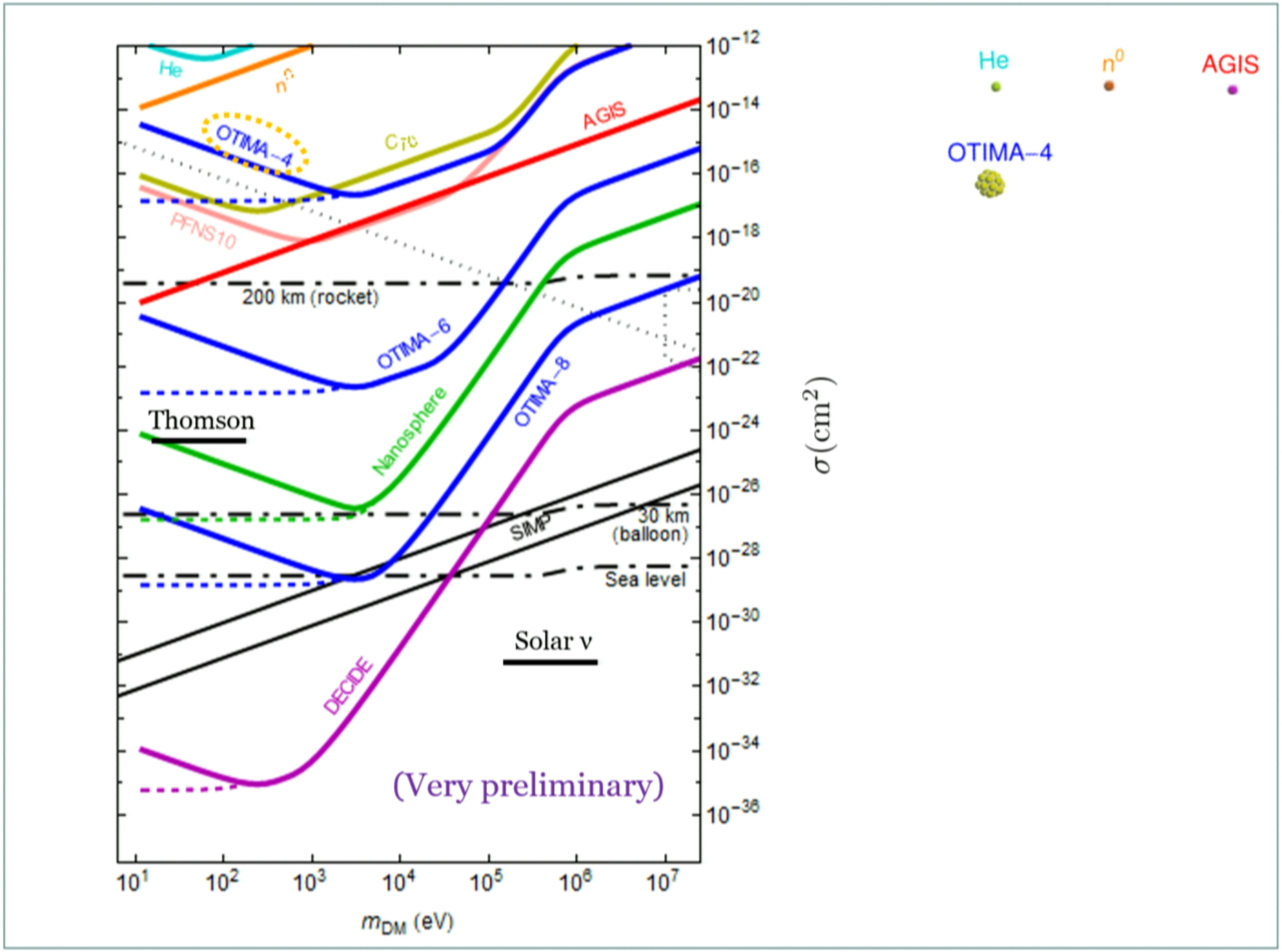
10^1 10^2 10^3 10^4 10^5 10^6 10^7
m_{DM} (eV)
He
n^0
AGIS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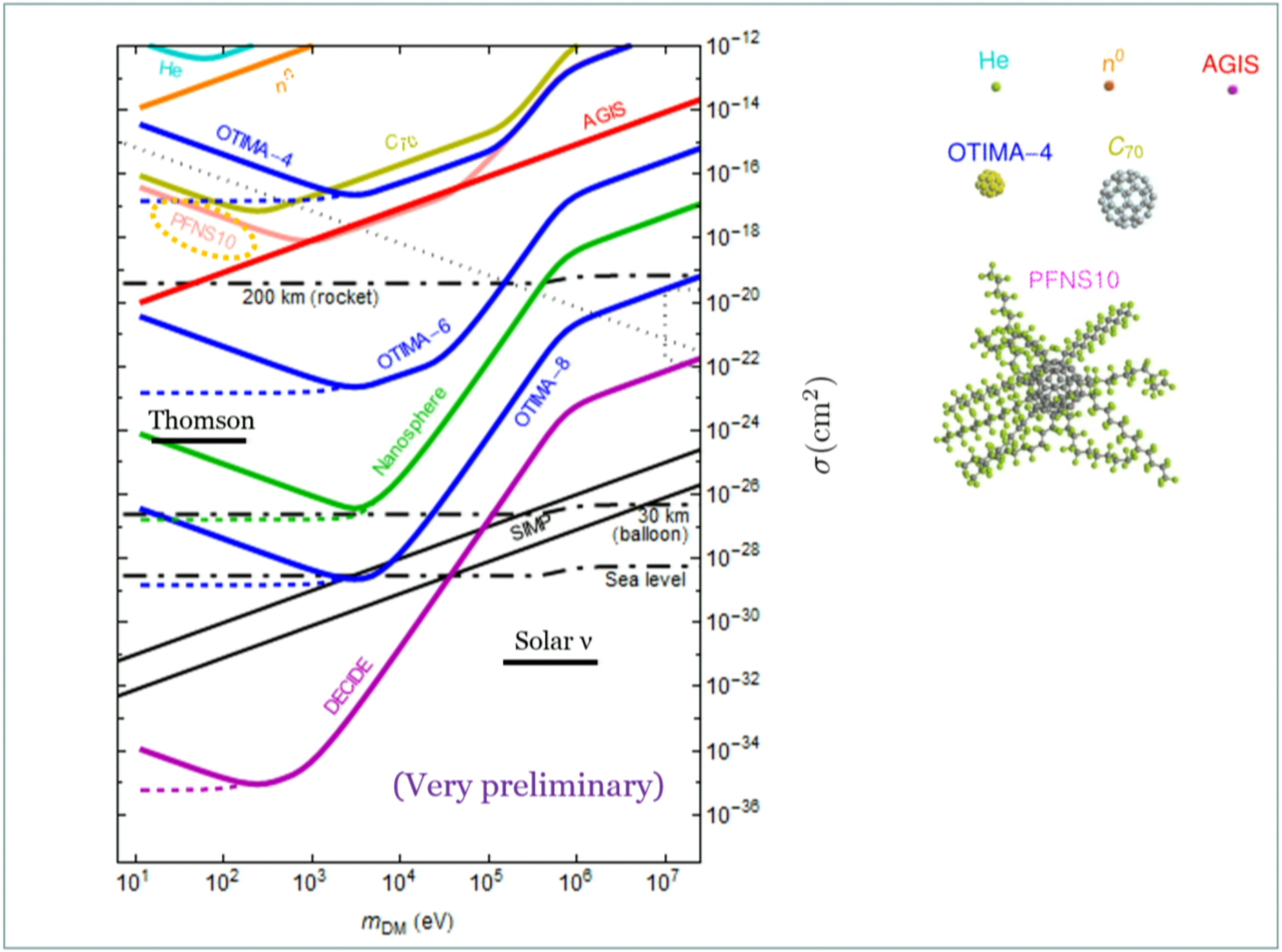
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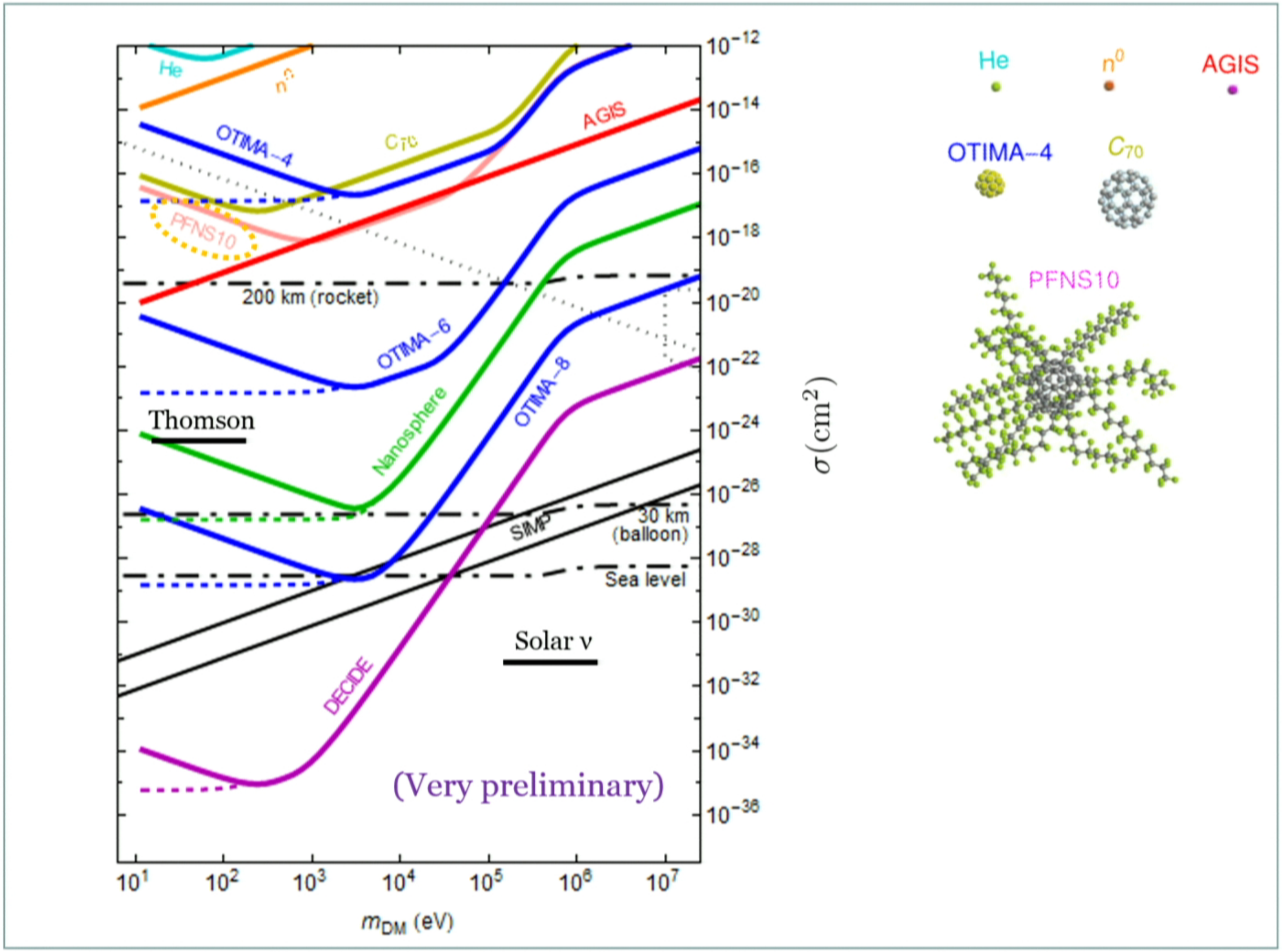

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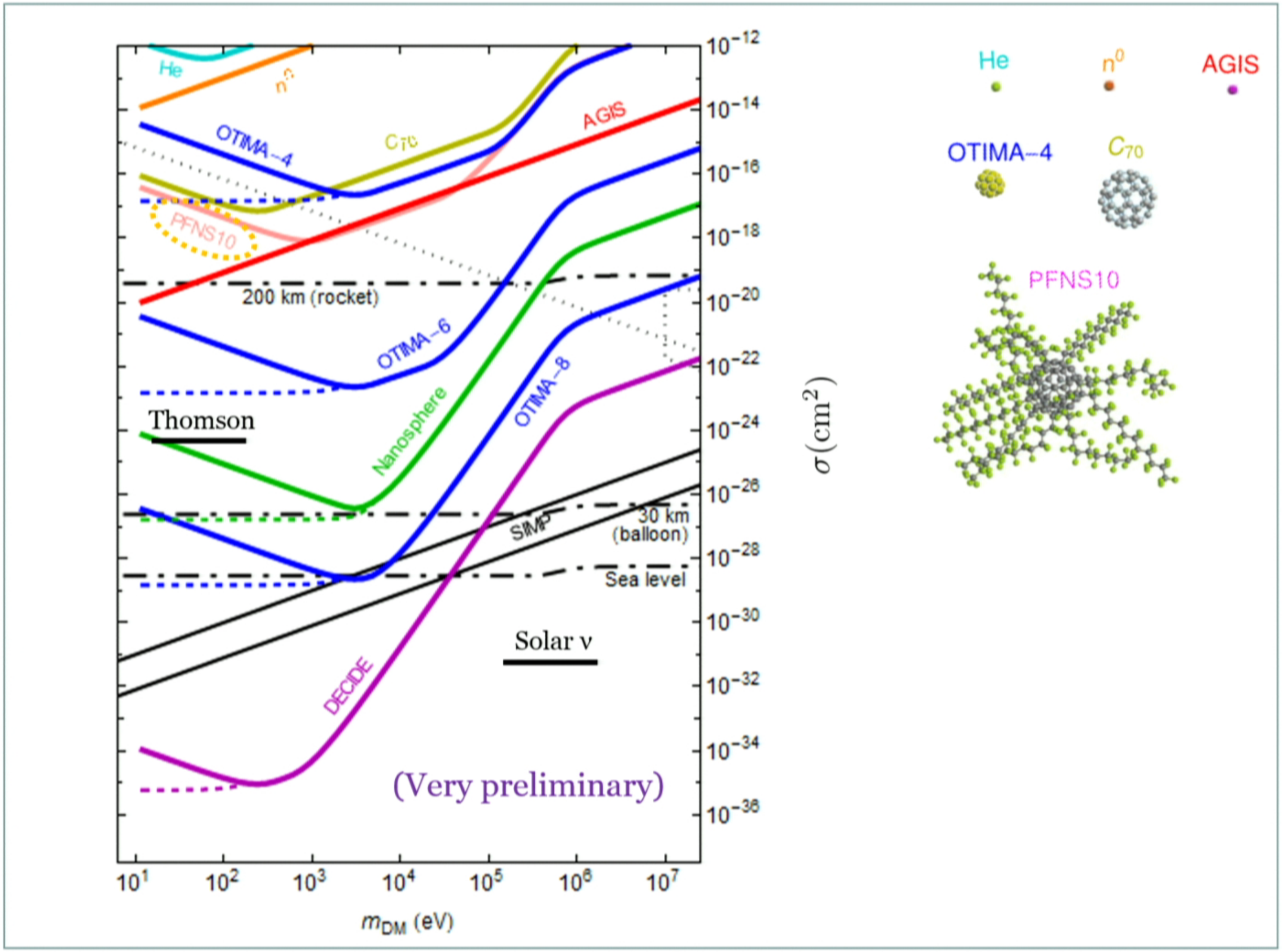
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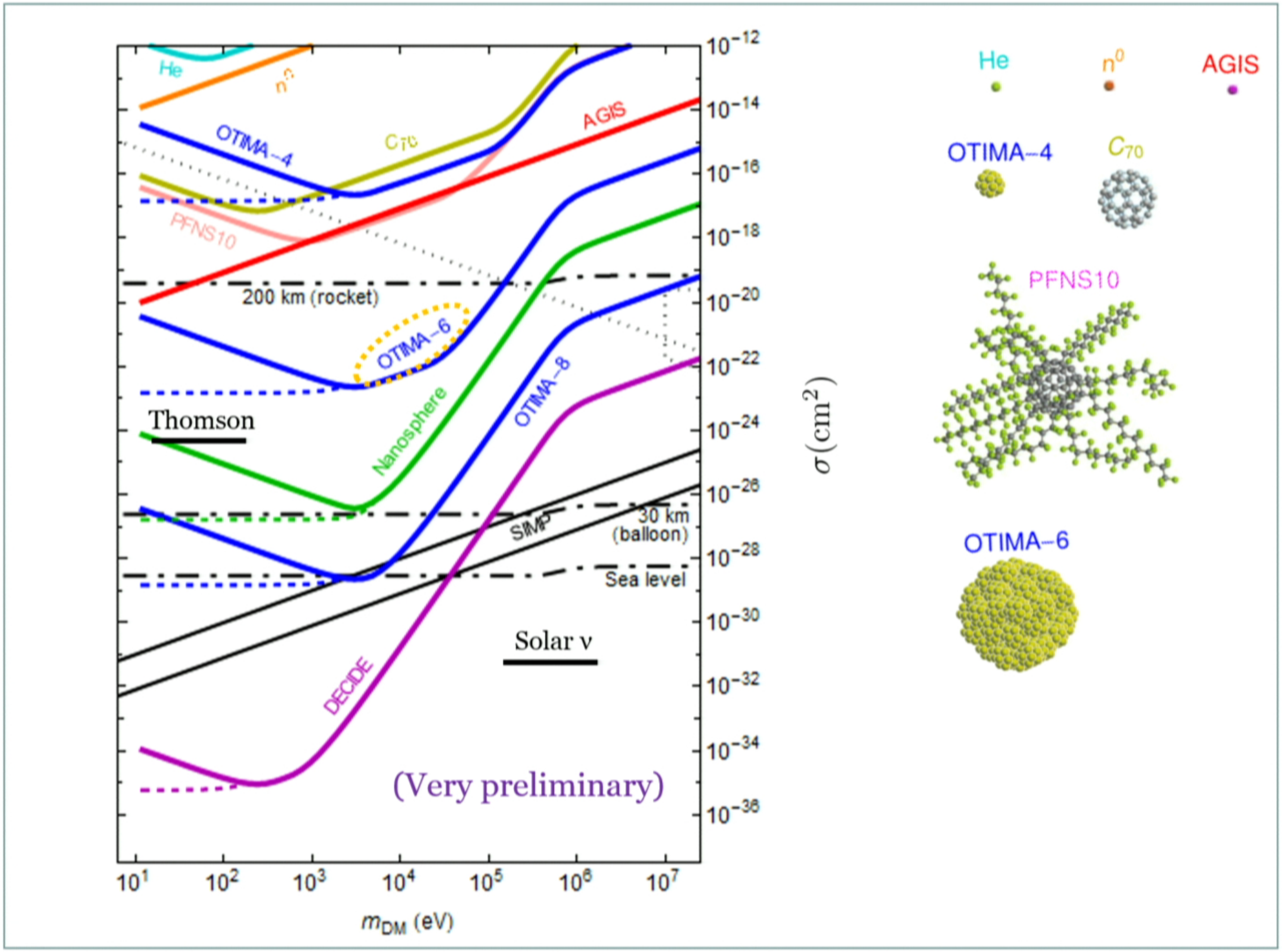
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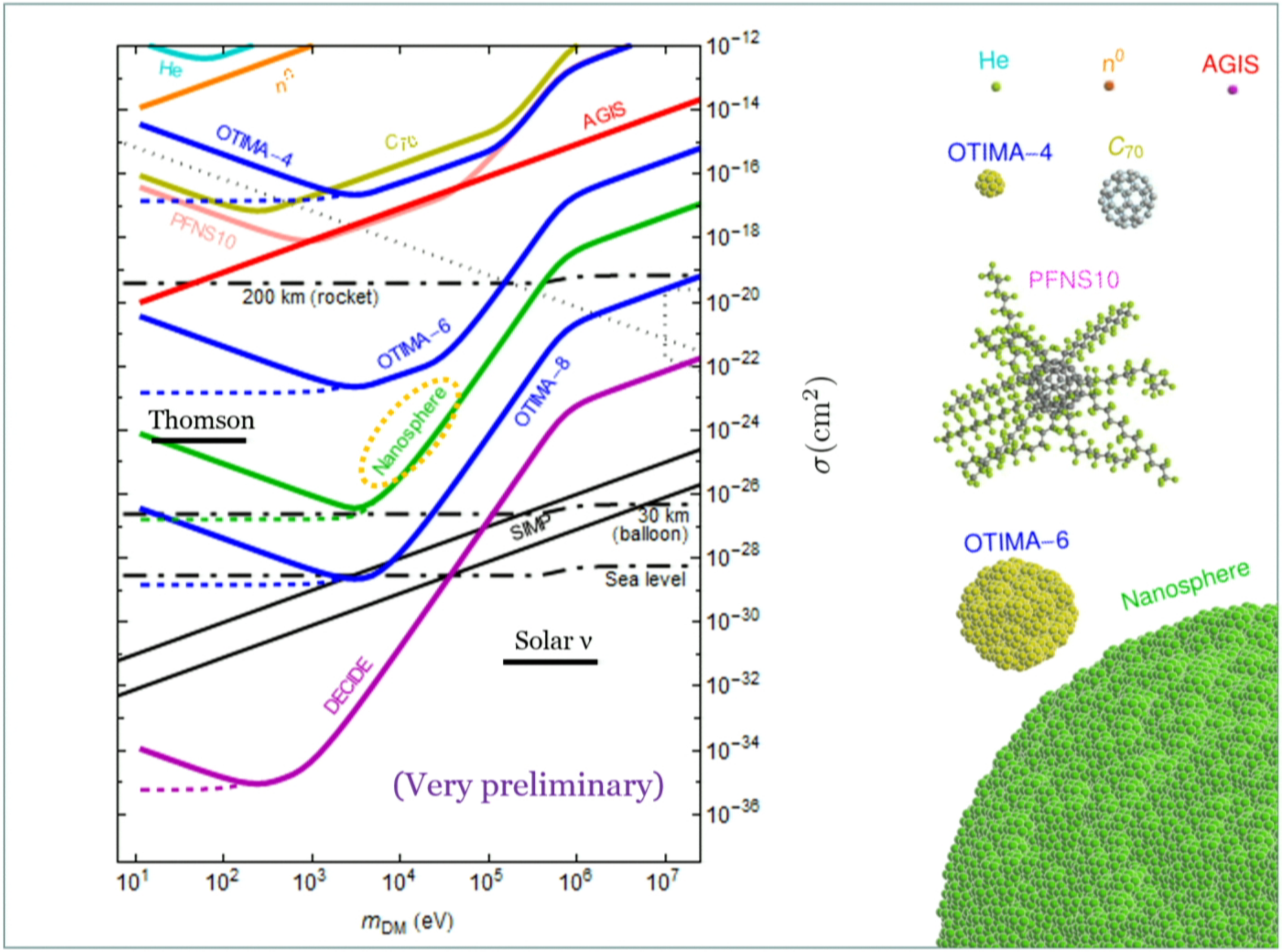

He
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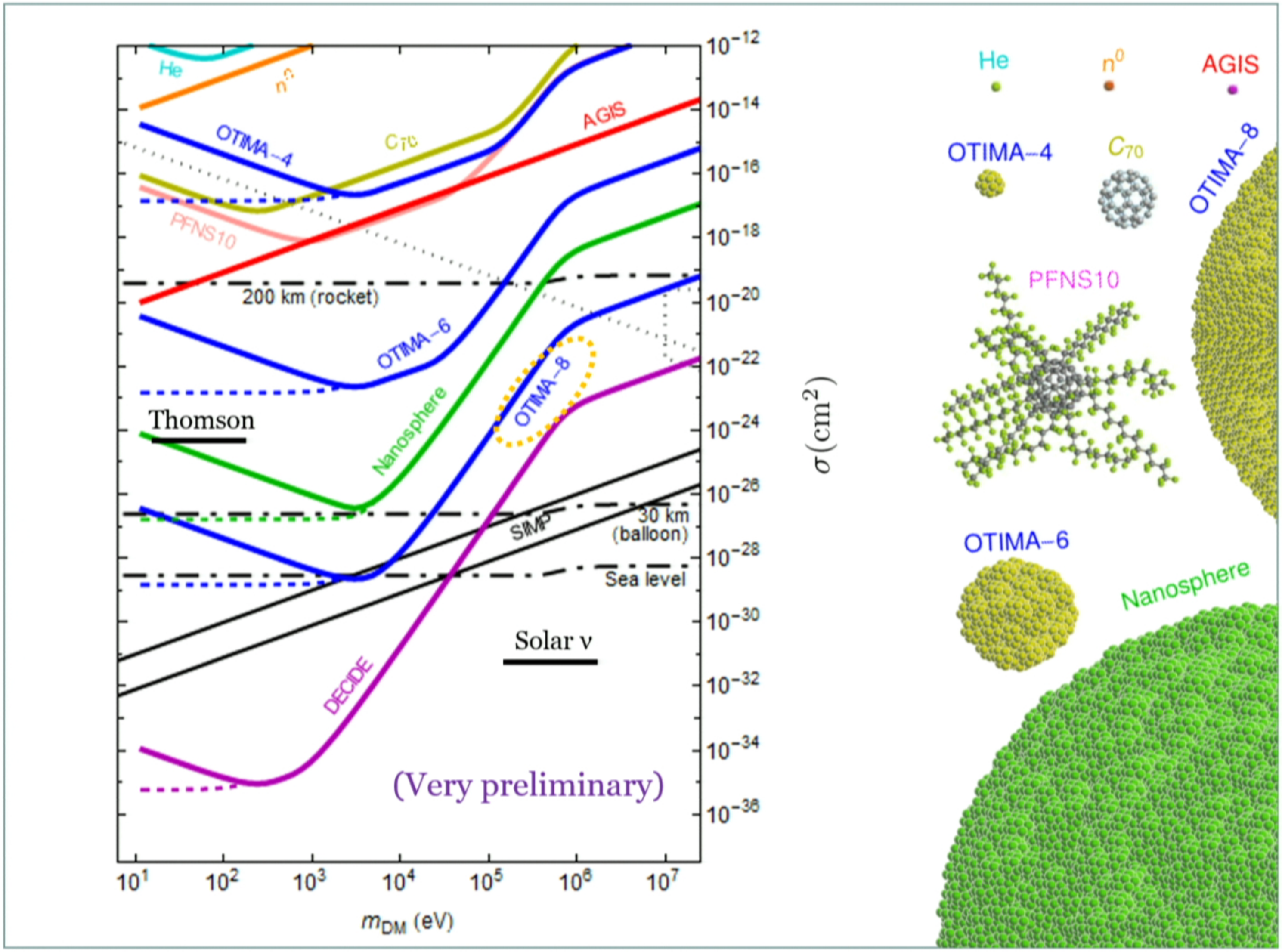

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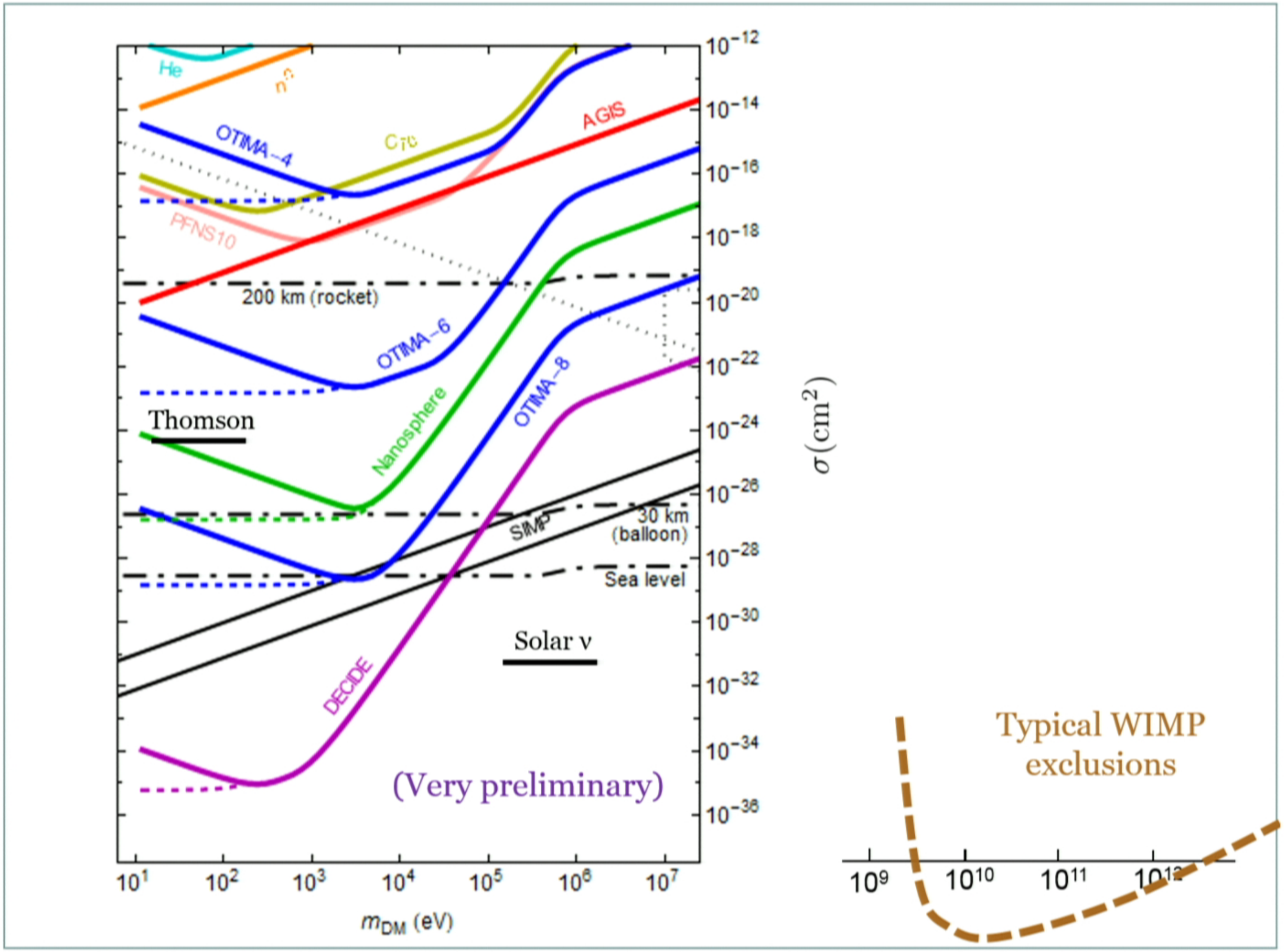

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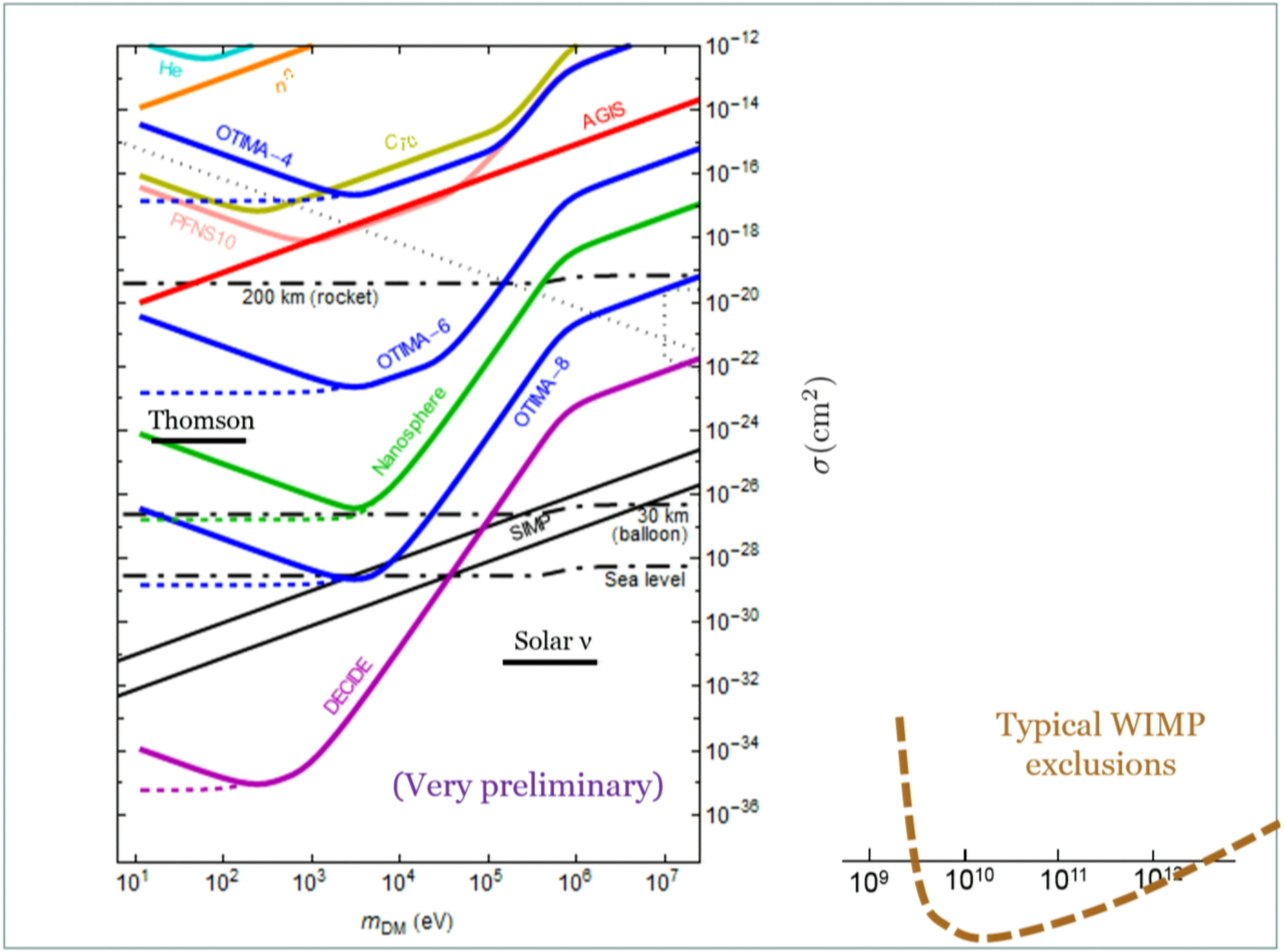
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^1 10^2 10^3 10^4 10^5 10^6 10^7
m_{DM} (eV)
$\sigma(\mathrm{cm}^2)$
Typical WIMP
exclusions
10^9 10^{10} 10^{11} 10^{12}

Dark matter conclusions

- Next generation of matter interferometers will probably need to get above the atmosphere to see dark matter


He
n?
OTIMA−4
C70
AGIS
PFNS10
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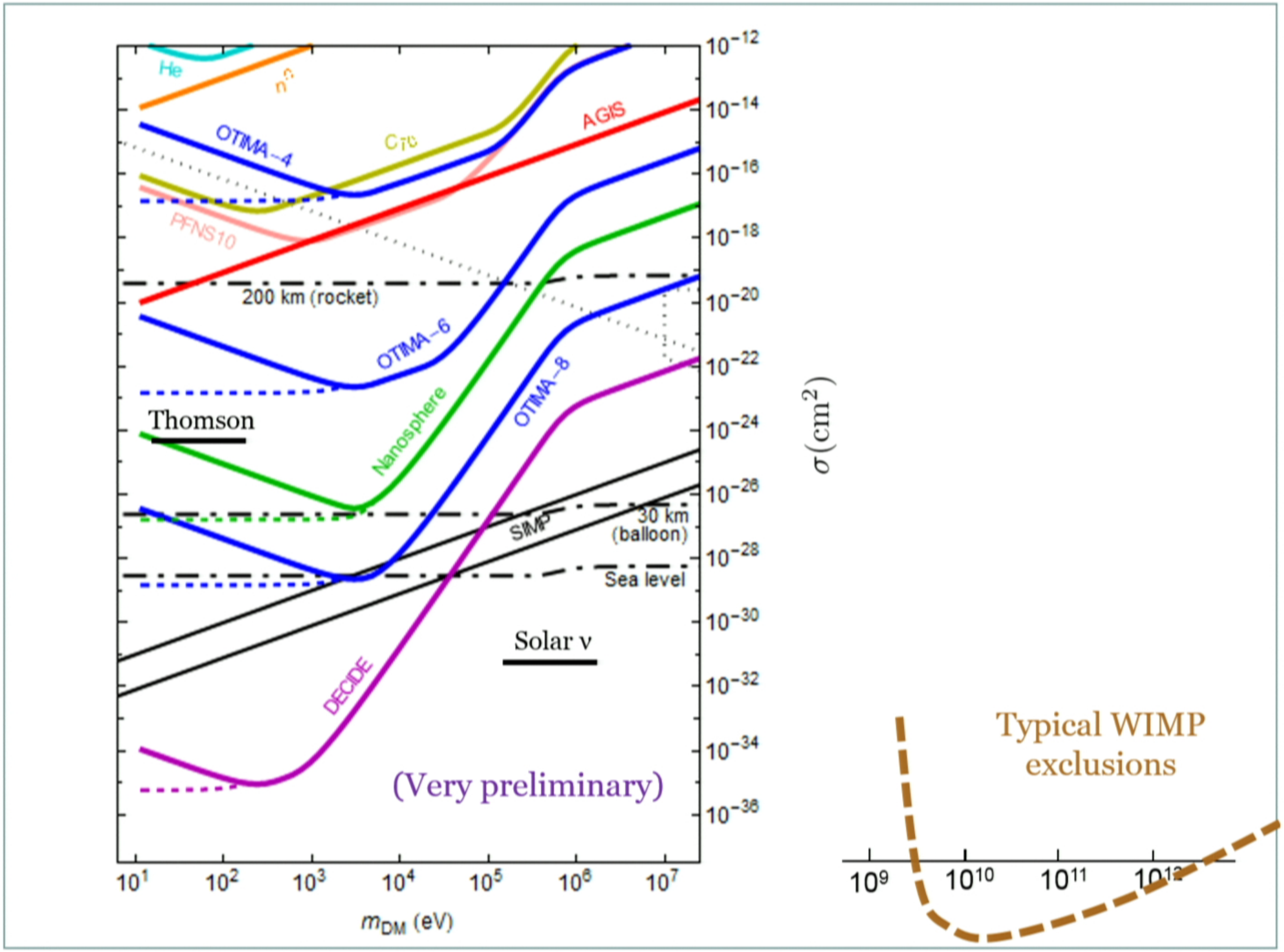

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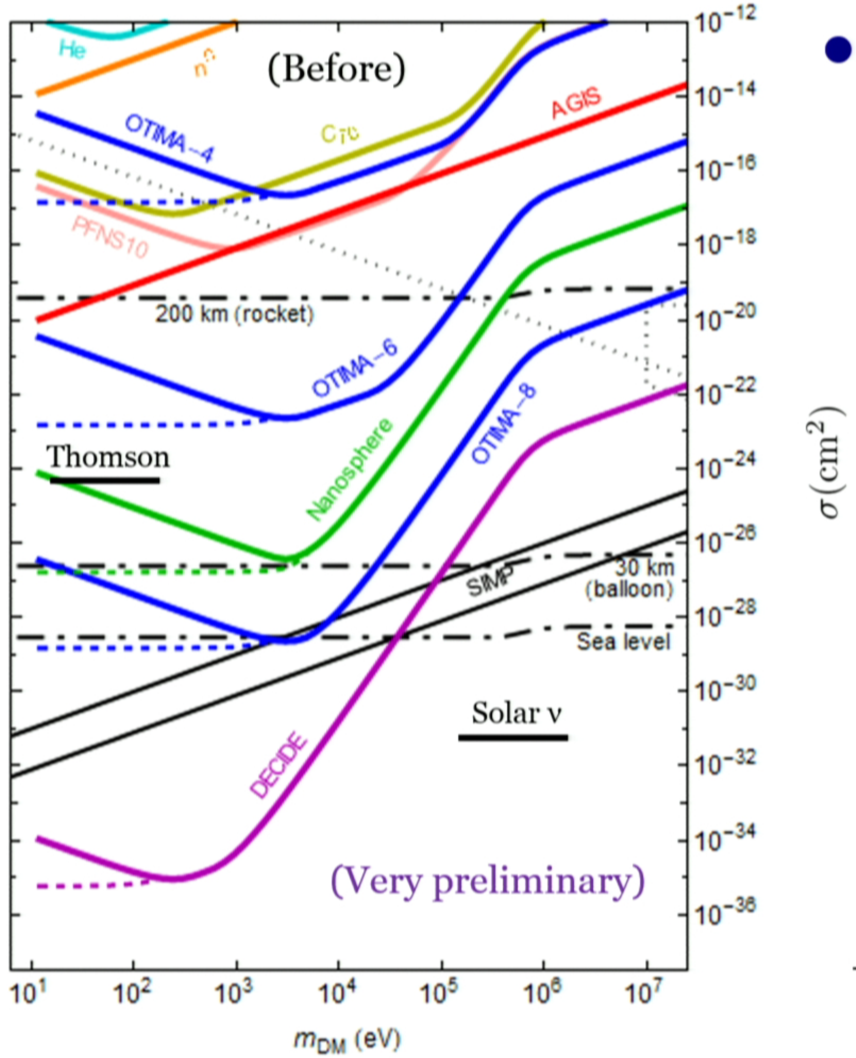
- Rapid improvement in masses superposed translates to *squared* increases in sensitivity
- Satellite experiments can open up 5 orders of magnitude in previously inaccessible dark matter masses
- What if we relax requirement for complete decoherence?
  - Can pick up orders of magnitude with statistics: $\sqrt{M}$ scaling



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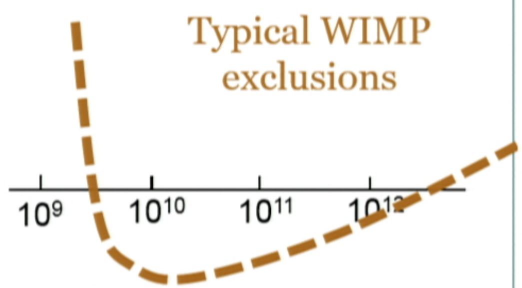

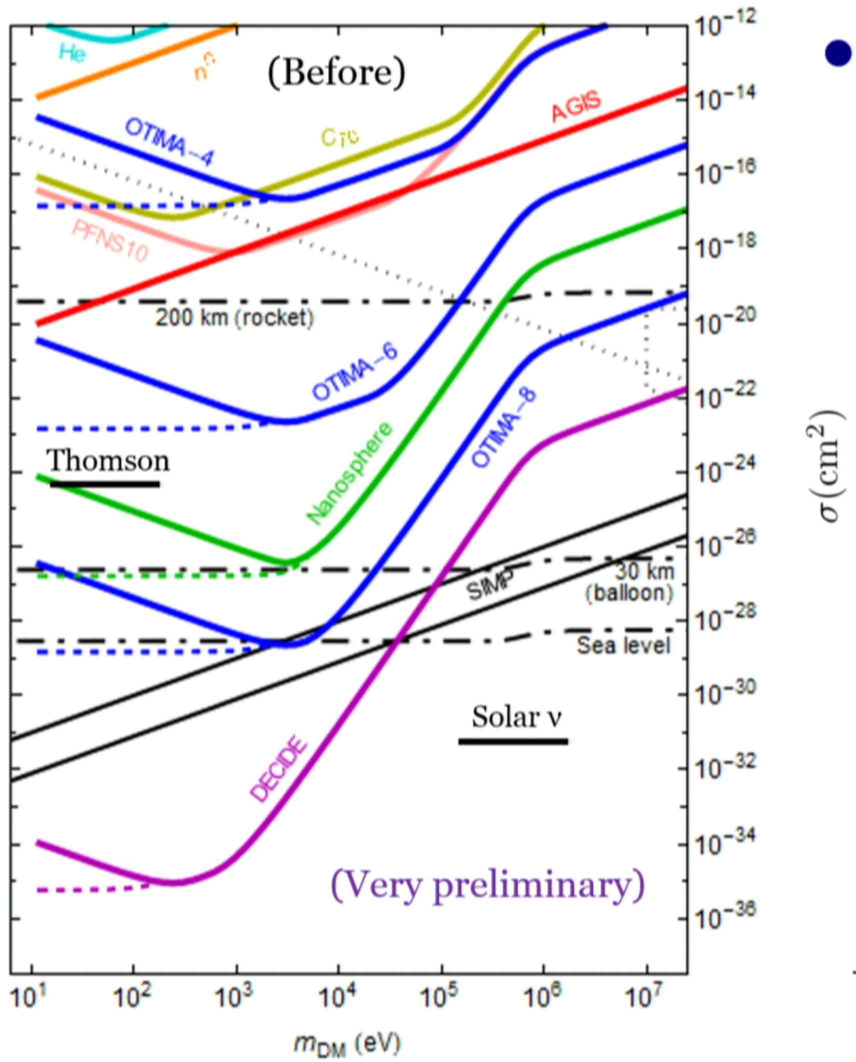

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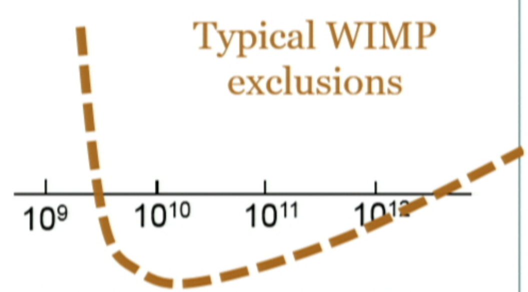

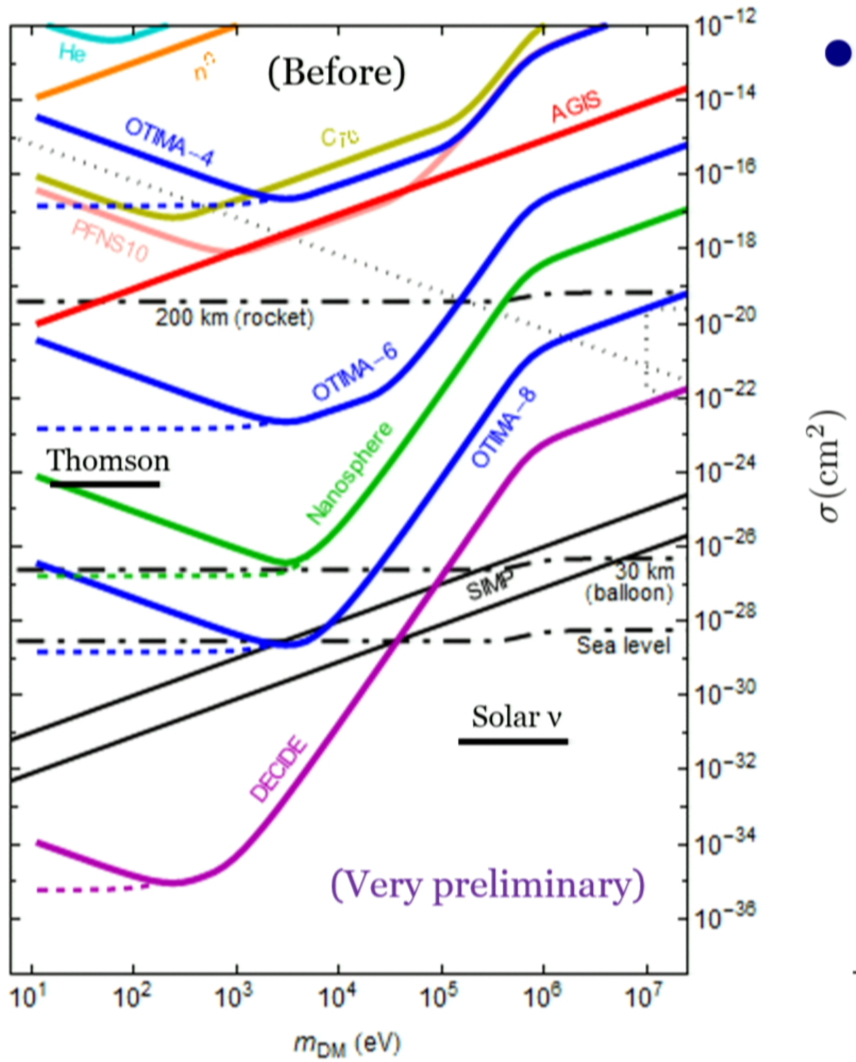

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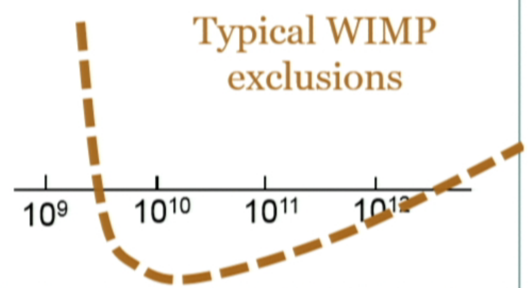

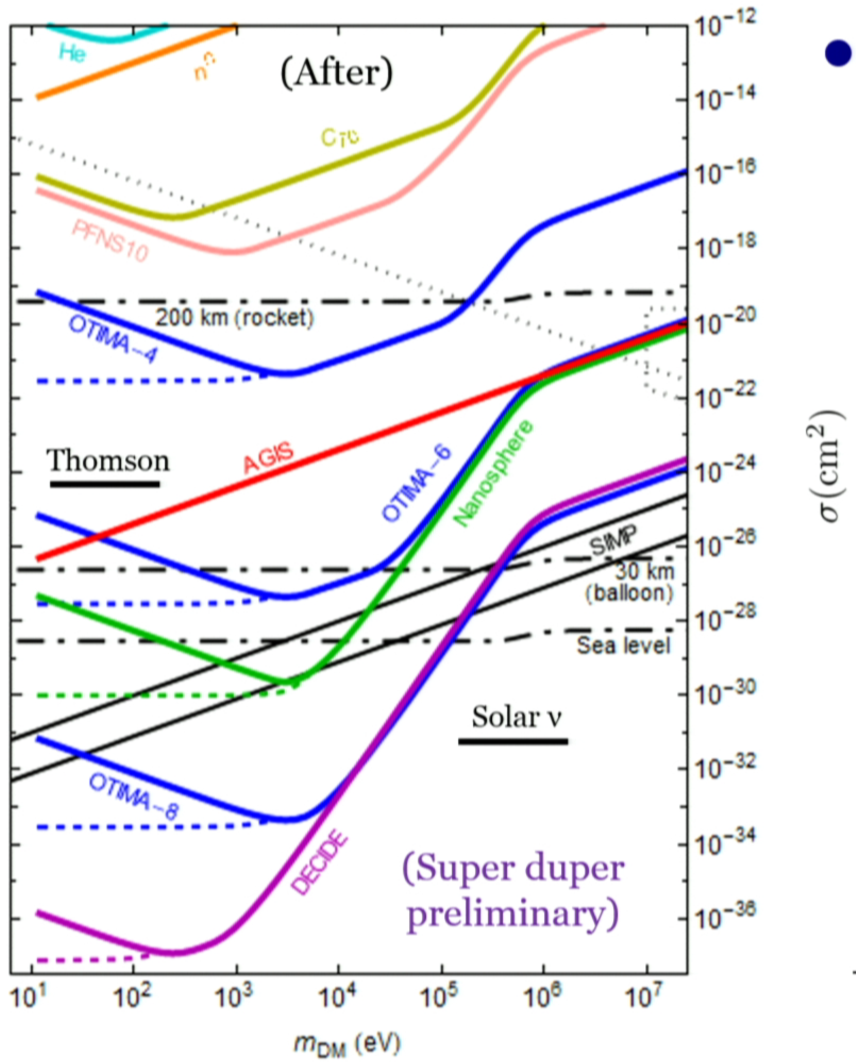

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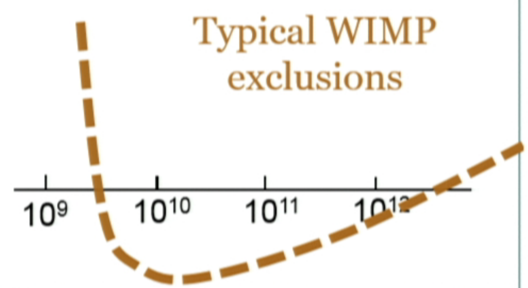

Outline

Decoherence without classical influence

Intro to low-mass dark matter

Collisional decoherence by dark matter

Feasibility and contributing effects

Dark matter search potential

Conclusions and outlook

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  - Much more mass, but not separated on scale of object
- Normal BEC interferometers don't work well
  - Not entangled, so no coherence boost
  - Could squeezed states or NOON states?

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- Graviton existence?
  - Well, not any time soon
  - Relativistic Planck mass superpositions decohere through gravitational bremsstrahlung
  - See arXiv:1310.6347 or bonus slide

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- **New motivation for pursuing macroscopic quantum superpositions of all kinds**

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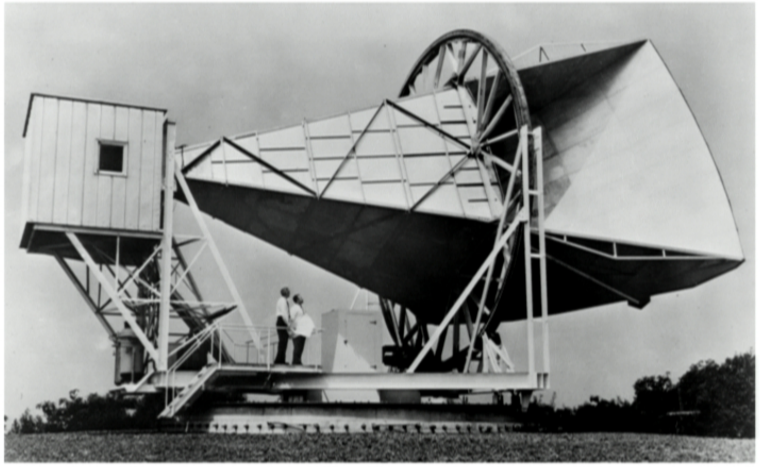

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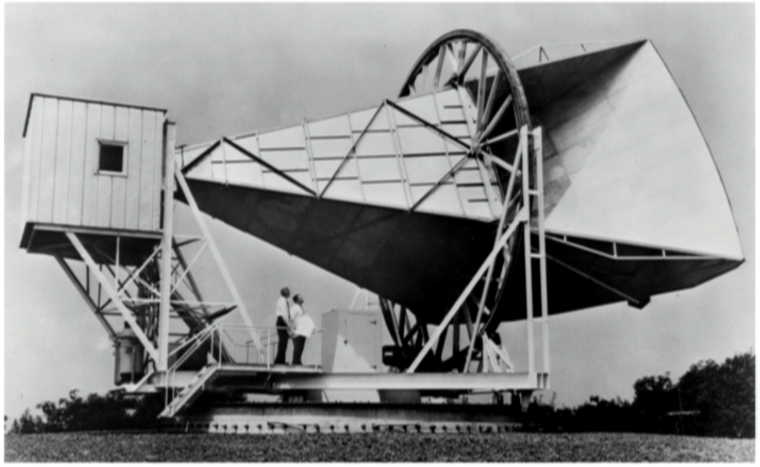
(Bird droppings?)



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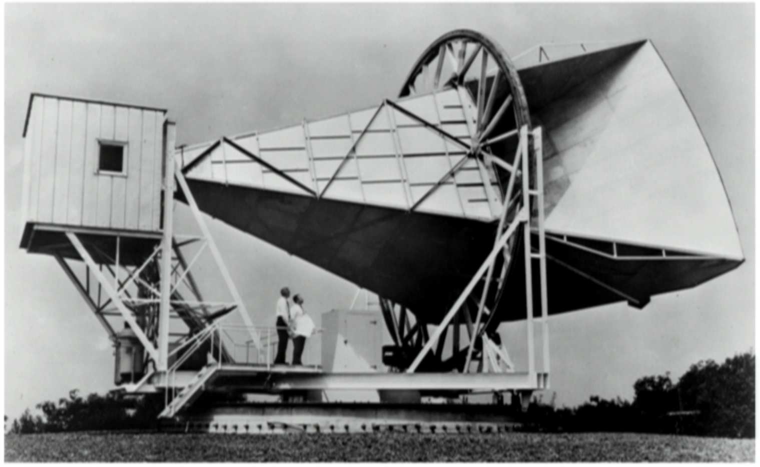

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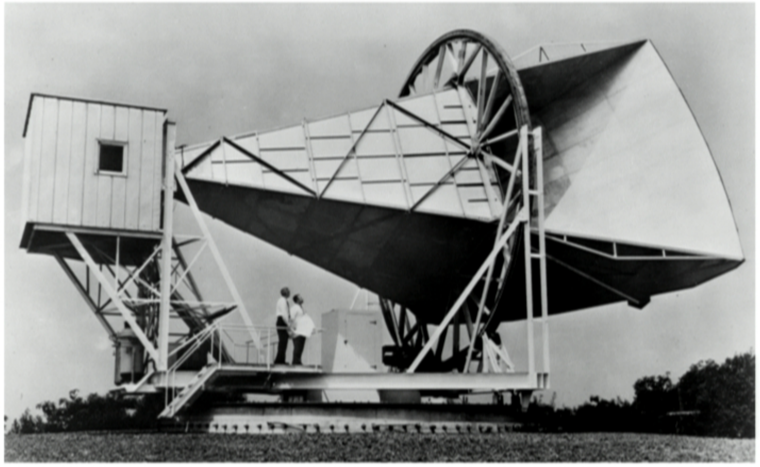

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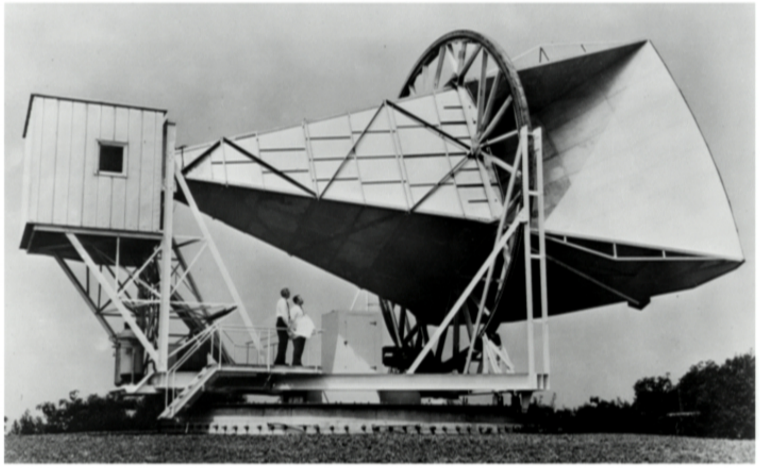
- Keep your eyes open!



The End

ArXiv:1212.3061
Slides: jessriedel.com