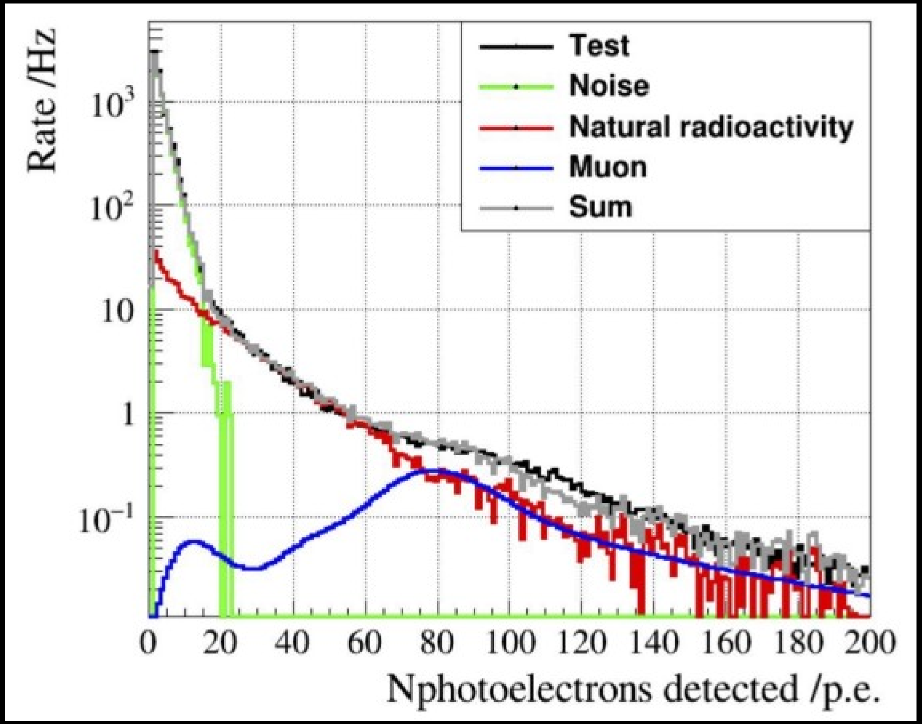
Sub-GeV Dark Matter Direct Detection with Neutrino Observatories

REBECCA LEANE
SLAC National Accelerator Laboratory

W/ JOHN BEACOM, 2503.09685

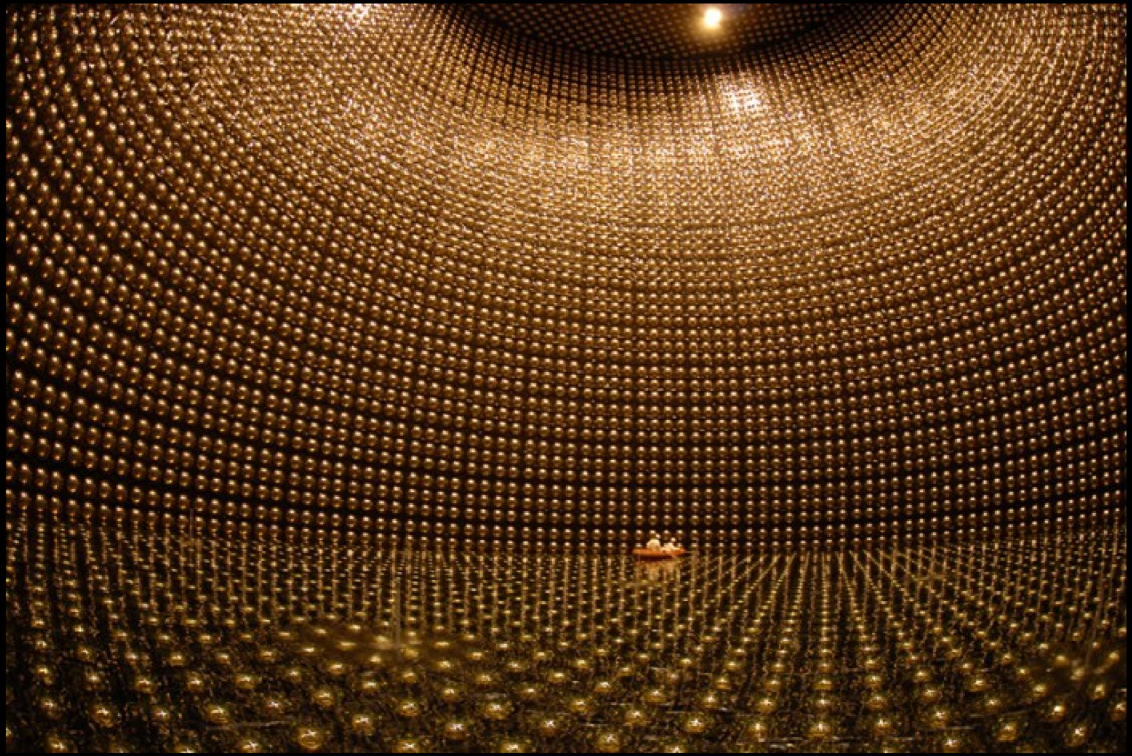
DARK MATTER AND NEUTRINOS 2025, PARIS
MAY 15TH 2025

Two new ideas for sub-GeV DM discovery



2307.15104

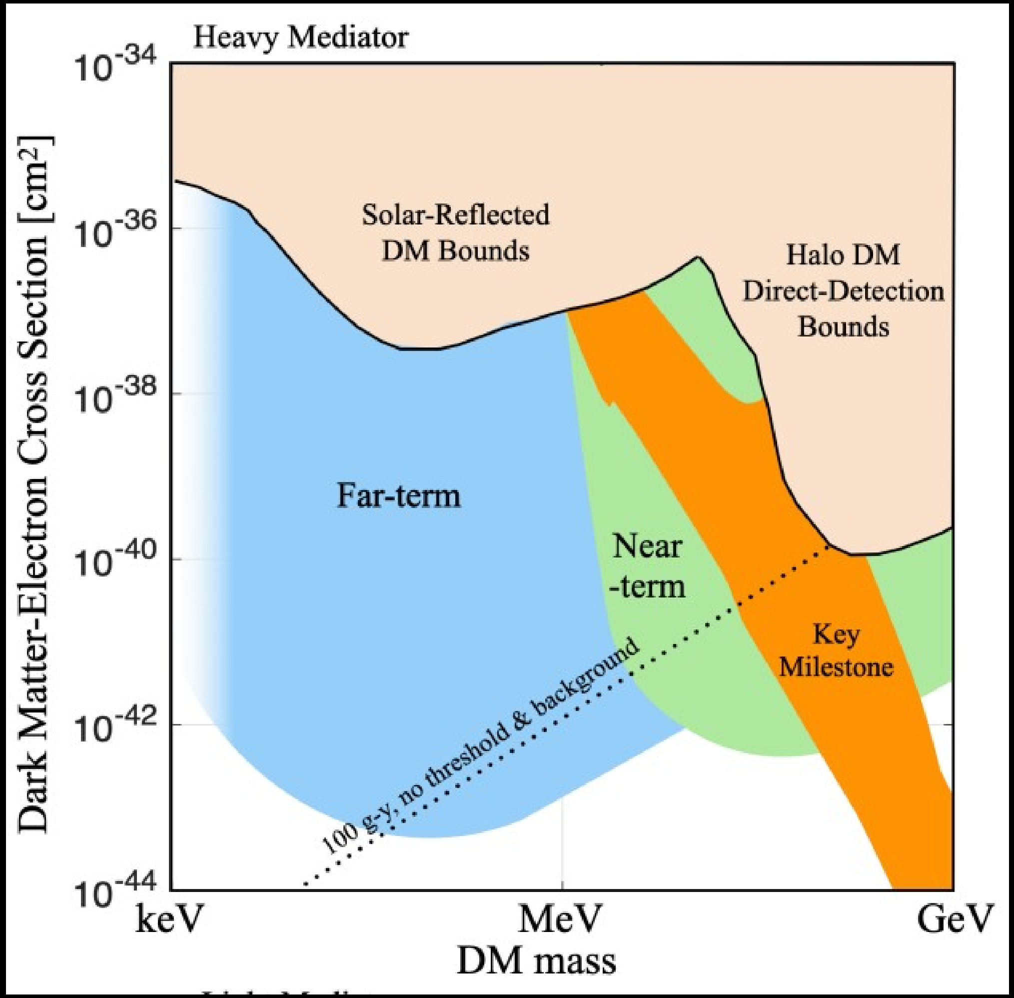
A new technique for sub-GeV DM searches



A new use of neutrino detectors

Sub-GeV Dark Matter

- Tantalizing targets
  - Wide open compared to GeV scale DM
  - Well motivated benchmark models
- Testing Sub-GeV DM is difficult
  - Low recoil energies
- Improving sensitivity is a major goal of the community
- Surge of interest in new technologies and techniques to push this frontier



Snowmass Community Paper, Essig et al 2203.08297

Direct Detection 101

- Traditional direct detection experiments search for energy deposited when dark matter scatters off detector materials
- Reconstruct observables such as recoil energy, ionization, backgrounds mitigated through fiducial cuts, energy windows, etc
- Strong constraints for DM above the GeV scale, where energy deposition is keV scale

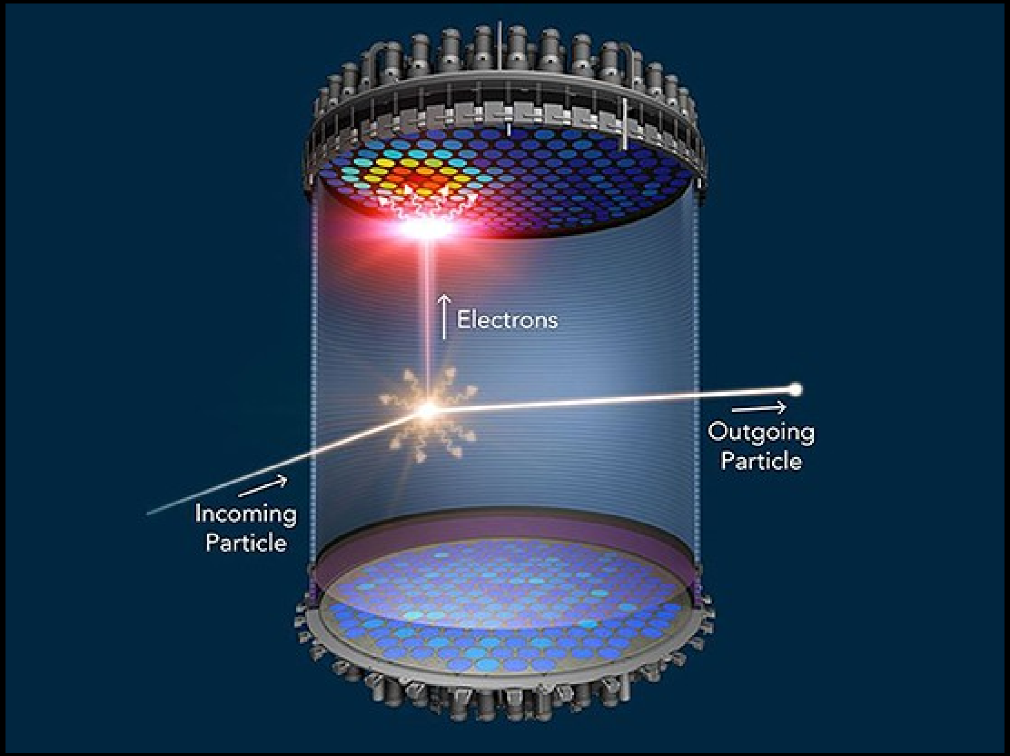
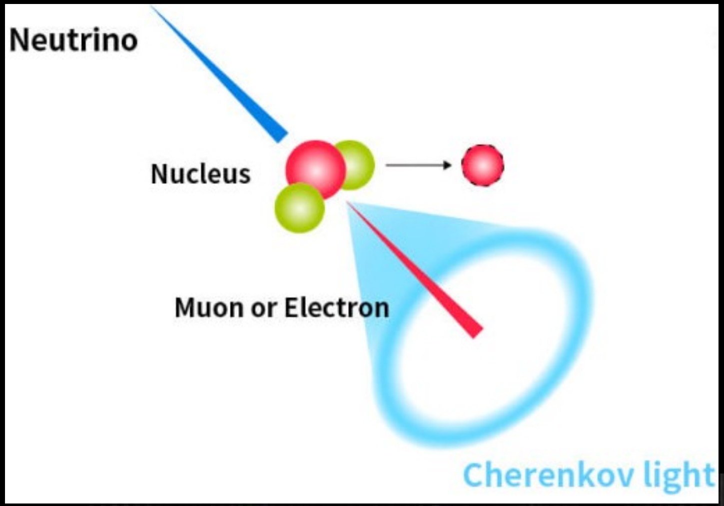
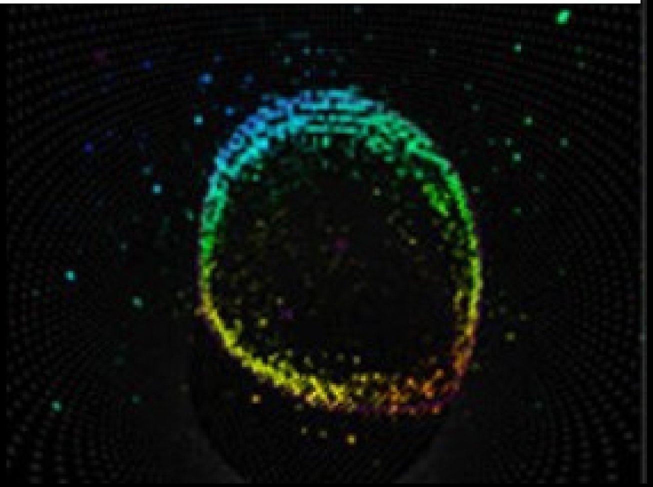


Image: U. Albany

Neutrino Observatories 101

- Detect scintillation or Cherenkov light from neutrinos, often using photomultiplier tubes (PMTs)
- Usual thresholds ~MeV. Comes from sufficient PMT hits to resolve events.
- Consequently, prior DM searches in neutrino detectors have focused on scenarios where DM is heavy, boosted, or using annihilation products





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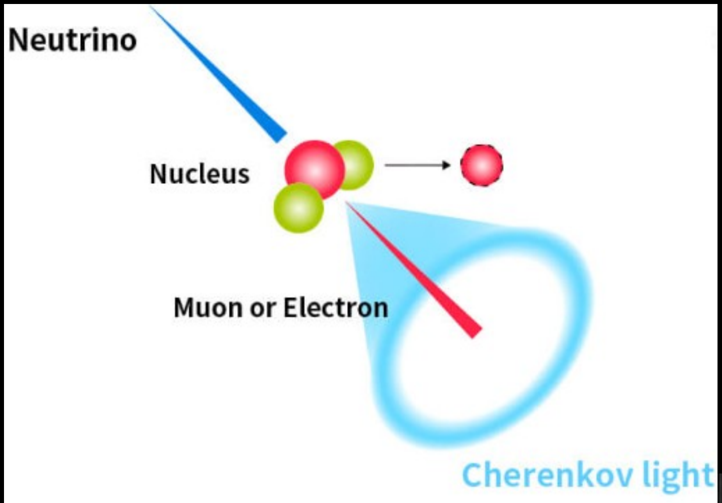
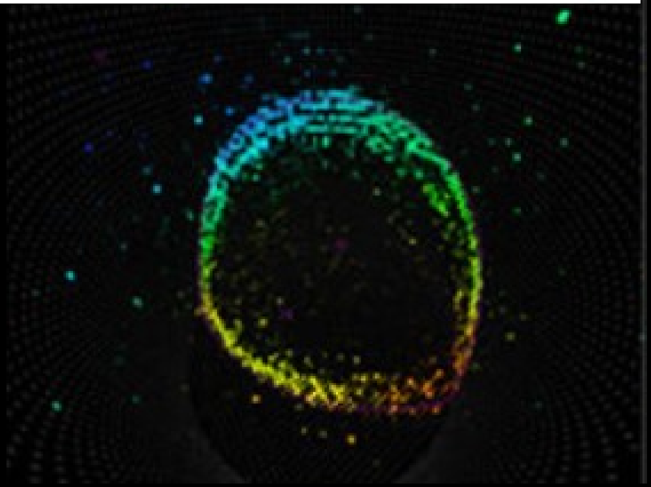
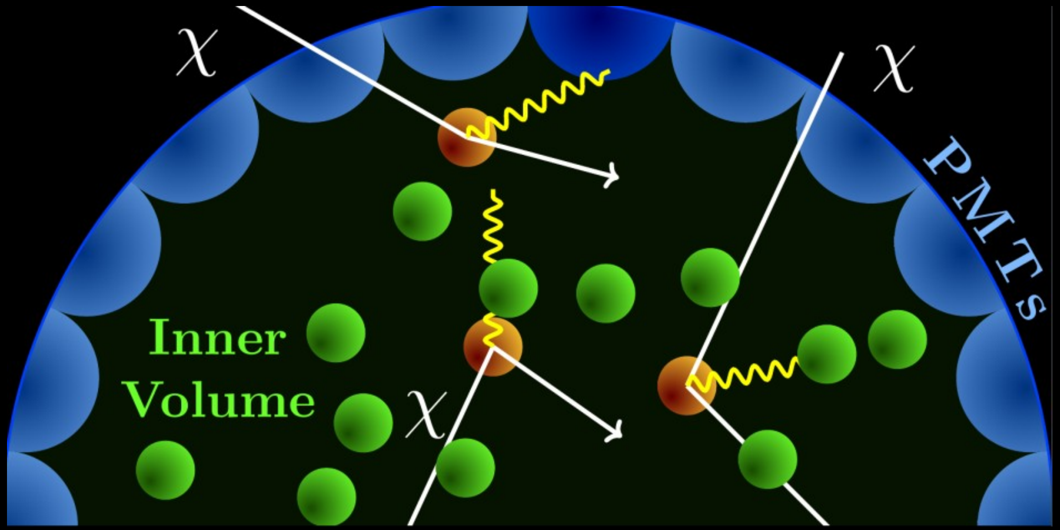




Neutrino observatories can detect standard sub-GeV dark matter scattering, opening new parameter space for DM discovery

The basic ideas

- **Use neutrino telescopes like direct detection experiments.**
- DM scatters with target particles, excites or ionizes them, creating eV-range photons
- These can be detected by PMTs



Leane+Beacom 2025

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- Search for measurable excess in total PMT hit rate, known as the detector's “dark rate”.
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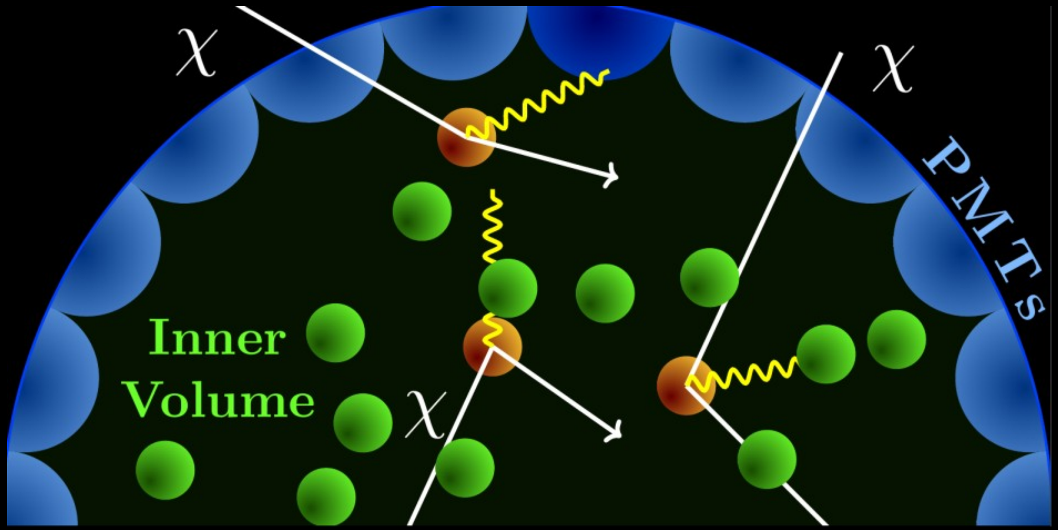
  - Individual events can't be seen
  - But aggregate signal from many independent scattering events can be



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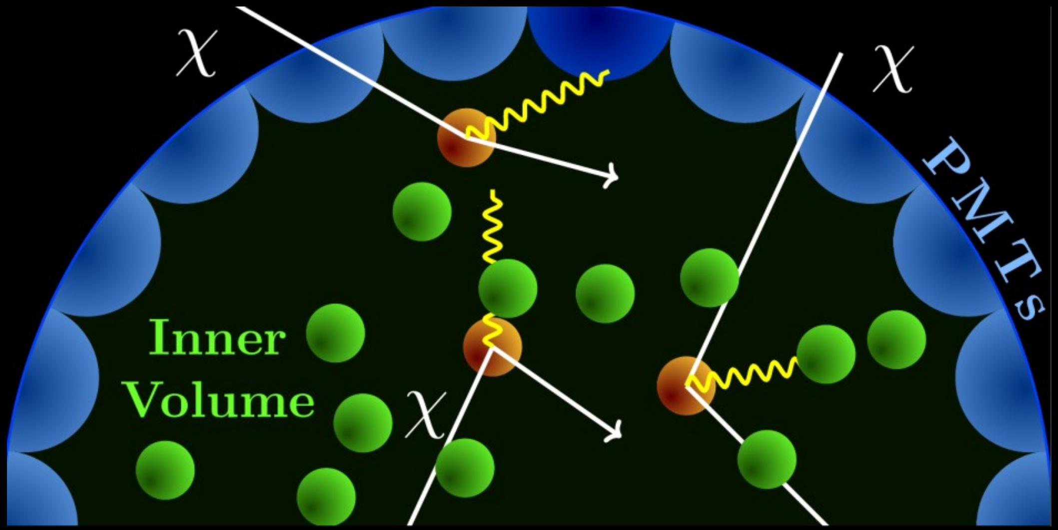
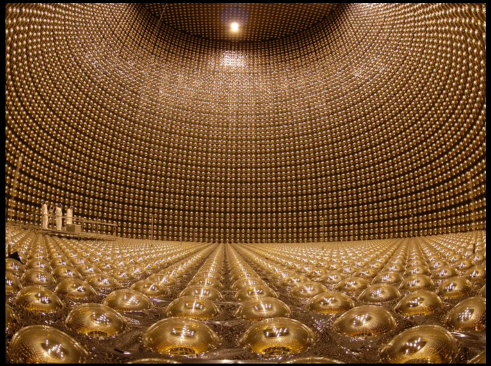


Leane+Beacom 2025

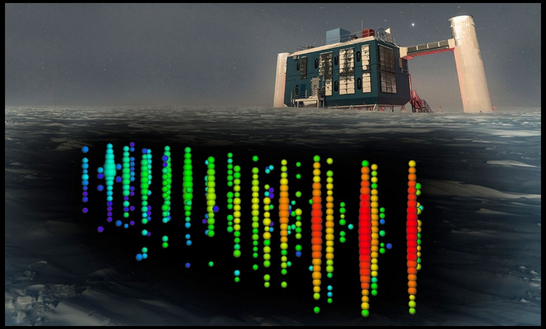
HUGE statistics → annual modulation can be extracted even under the dark rate

Reasons to Use Neutrino Observatories

1) They're huge → enormous exposure.

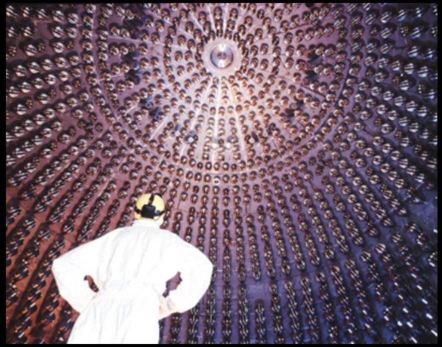


SuperK: 50,000 tons



IceCube: 10^9 tons

JUNO: 20,000 tons



Borexino: 300 tons

2) Many contain organic materials with low excitation thresholds, ~few eV
→ excellent sensitivity to light DM

3) Many are liquid scintillators
→ excellent light yield, optimal detectable photons per DM scattering.

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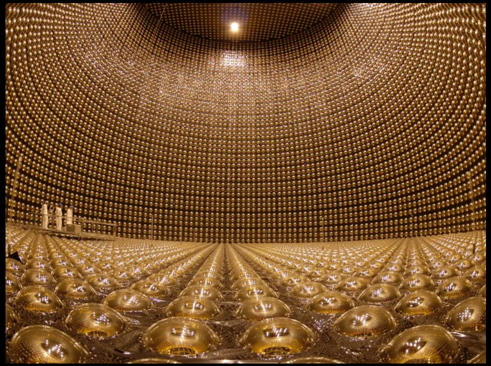

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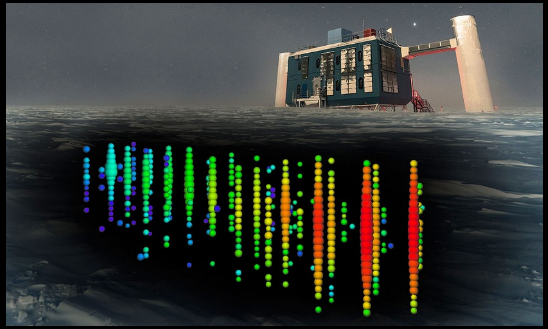

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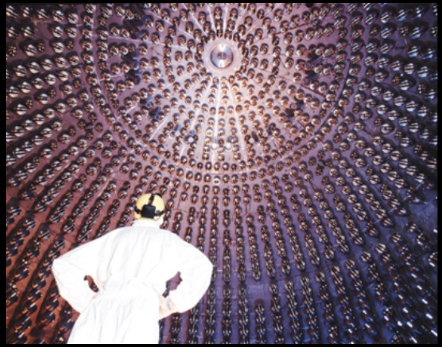

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These factors together can provide world-leading sensitivity to sub-GeV dark matter.

Illustration of new technique using JUNO

Focus on JUNO, but general ideas can be adapted to other detectors.

- Located in China
- 20,000 ton liquid scintillator, linear alkylbenzene
- Data taking starts this year!

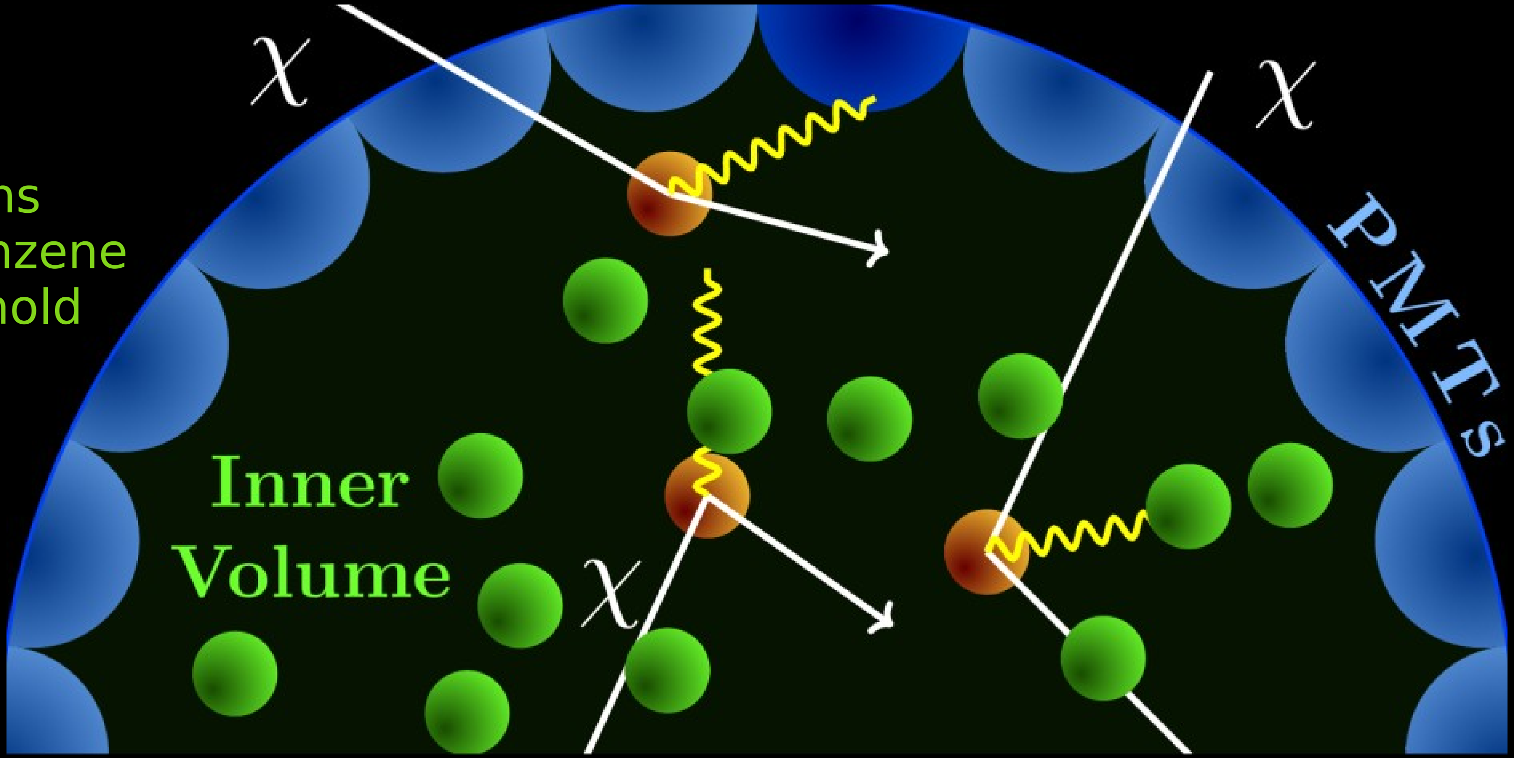
Dark Matter Signal in JUNO

Rebecca Leane (SLAC)

DM-Signal Rate

- Upon scattering with a molecule, DM can excite an electron from the ground state into one of several low-lying unoccupied orbitals that can de-excite by photon emission.
- In the medium, this de-excitation photon can be absorbed and re-emitted as a longer-wavelength fluorescence photon → propagates through volume to the PMTs.

20,000 tons
Linear alkylbenzene
~5 eV threshold



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- JUNO signal rate:

$$R_{\rm sig} = \xi \frac{N^e_{\rm LAB}\rho_\chi \bar{\sigma}_e}{8\pi m_\chi \mu^2_{\chi e}} \sum_{i,j} \int \frac{d^3\vec{q}}{q} \eta(v^{ij}_{\rm min}(q)) F^2_{\rm DM}(q) |f_{ij}(\vec{q})|^2$$

LAB target number

DM-electron cross section

Detection efficiency

DM number density

DM velocity information

DM form factor

Molecular form factor

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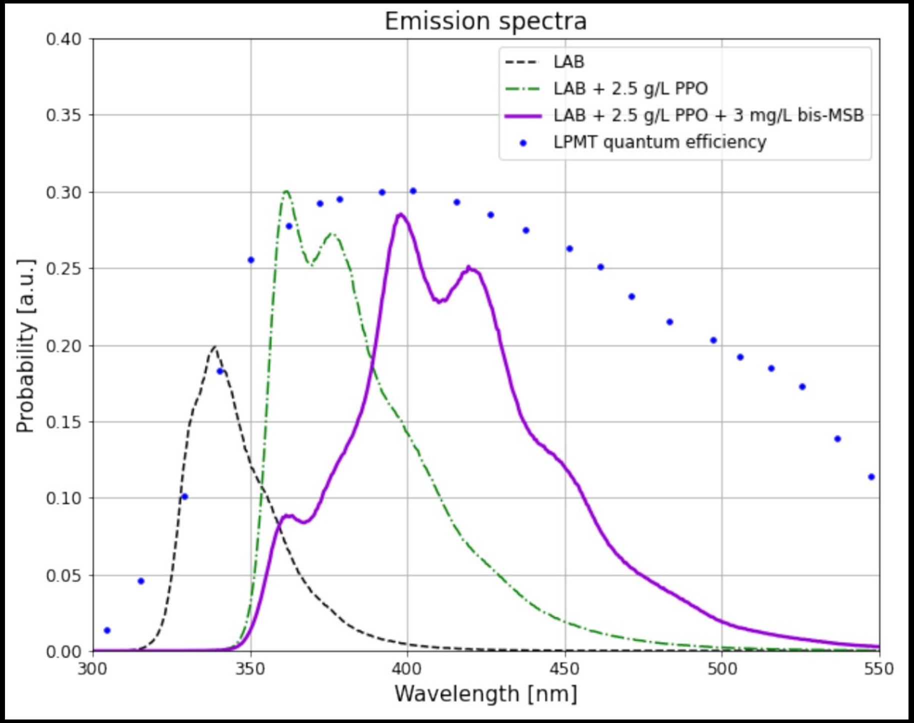
Detection Efficiencies

- Fluorescence factors
  - LAB fluorescence quantum yield: 0.1
  - Admixture of fluors, ensures medium excitations overlap w/ detector efficiencies
  - Gives an in-medium emission spectrum



Beretta et al 2501.09988

Detection Efficiencies

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  - LAB fluorescence quantum yield: 0.1
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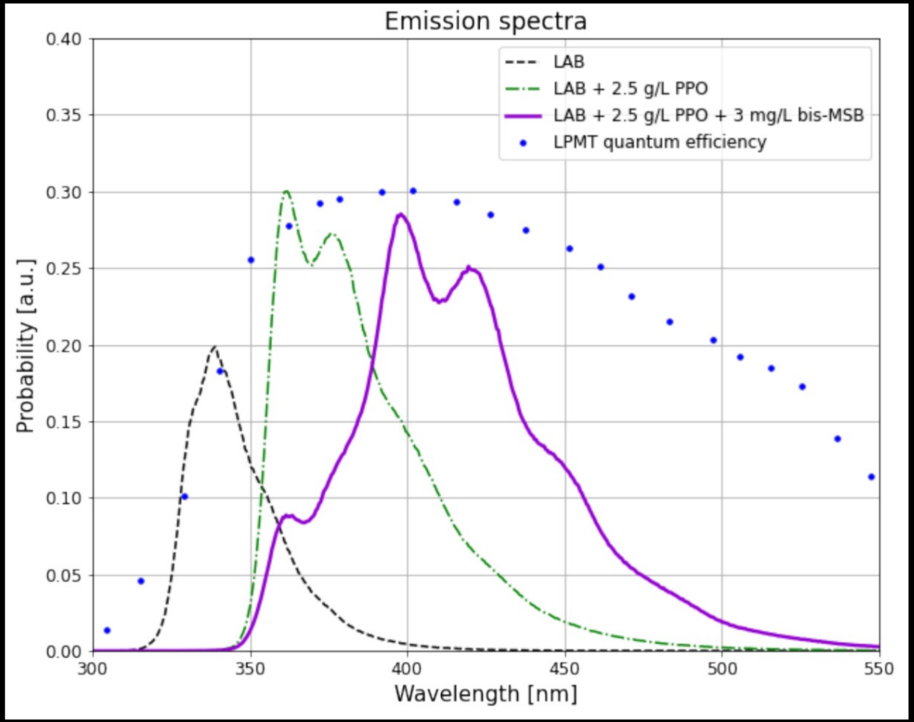
  - Gives an in-medium emission spectrum
- PMT inputs
  - Wall coverage: 78 %
  - Quantum efficiency: ~28 %
  - Integrate in-medium spectrum over PMT efficiencies

Detection efficiency: 0.02

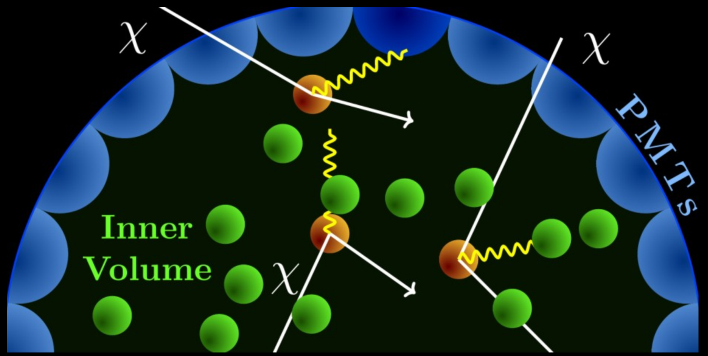


Beretta et al 2501.09988

Signal Extraction from Dark Rates

Rebecca Leane (SLAC)

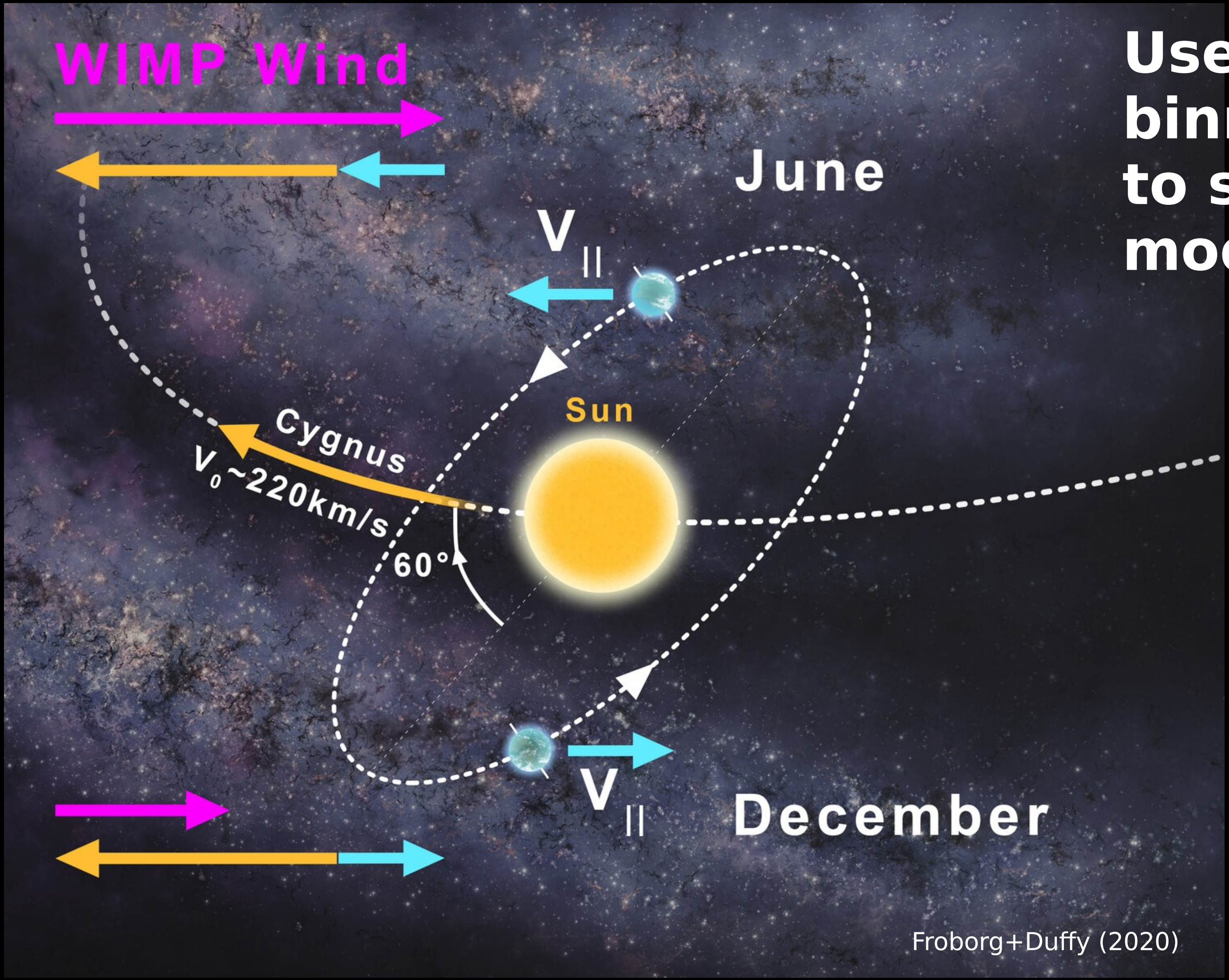
DM Signal Extraction



- Regular DM detectors usually have low backgrounds after cuts
  - e.g. using a fiducial volume, target energy range
- Such cuts not possible here: only observable is total PMT hits
- Huge background rate
  - JUNO has ~40,000 PMTs with dark rates ~5-25 kHz each → 10^16 counts/yr
  - Not expected to be known to high precision→ need a good handle on signal

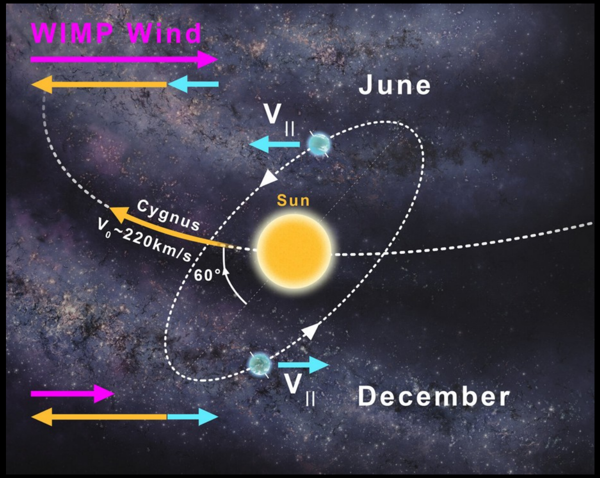
We point out dark matter hits under dark rate can be seen via annual modulation

Annual Modulation



Use time-binned data to search for modulation

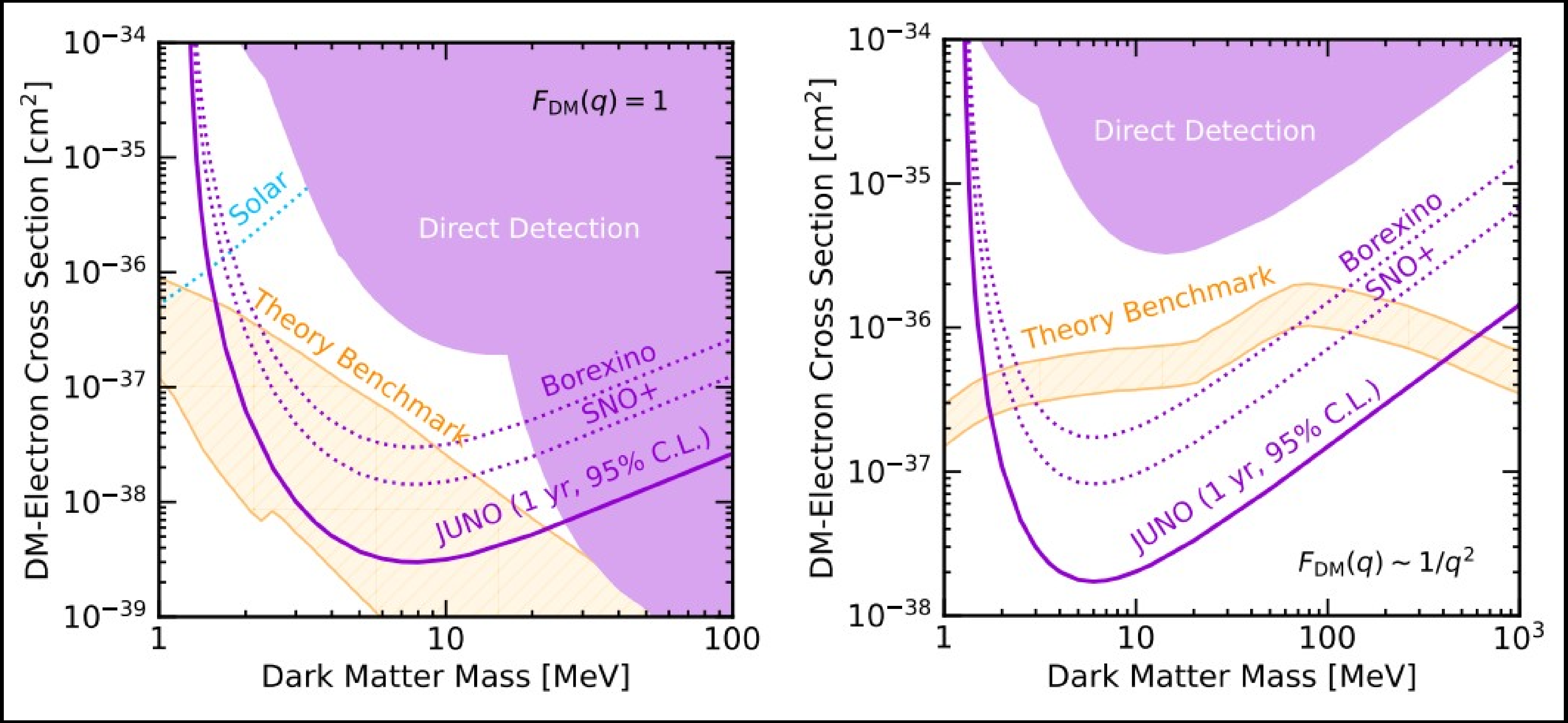
Backgrounds



Froborg+Duffy (2020)

- PMT dark rate: ~10^16
  - These have been measured in e.g. SuperK, IceCube, Borexino
  - Have non-statistical fluctuations, that integrate out over the year
  - Show secular trends: shift analysis window by half year would flip sign of DM signal
- Modulating backgrounds?
  - Muons, radon, nuclear reactors, temperature of PMTs
  - Can be precisely monitored with independent data
  - Even if could not, are shifted from DM phase by weeks or months, with order seconds or less uncertainties
- Use of multiple detectors would serve as cross check

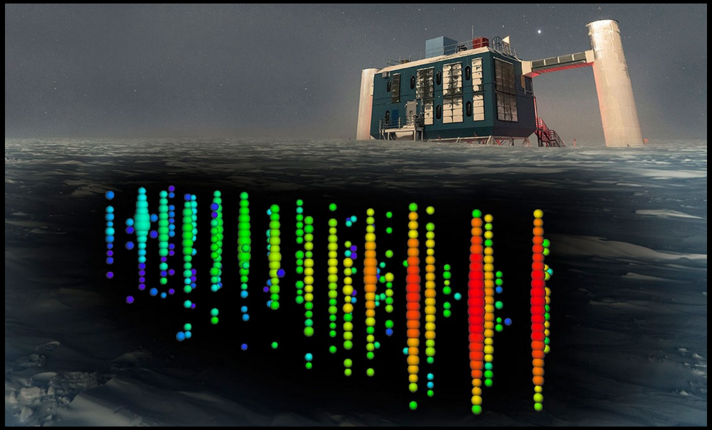
New Sub-GeV DM Sensitivities

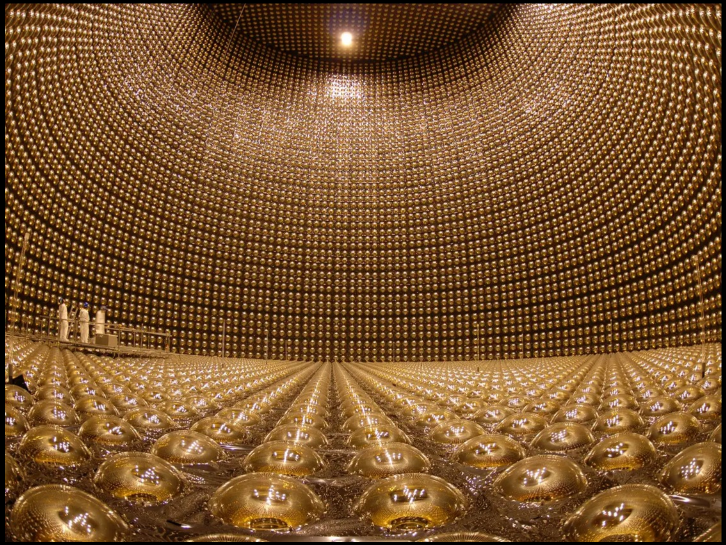


Leane+Beacom 2503.09685

Next Steps

- Theoretical Steps
  - Include ionization in signal rate
  - Improved form factor for linear alkylbenzene
  - Calculation of rates in other detectors. Less light emission, but lower dark rates. Serves two purposes:
    - (1) Robustness check
    - (2) Extracting more detailed DM properties
  - Application to dedicated DM detectors





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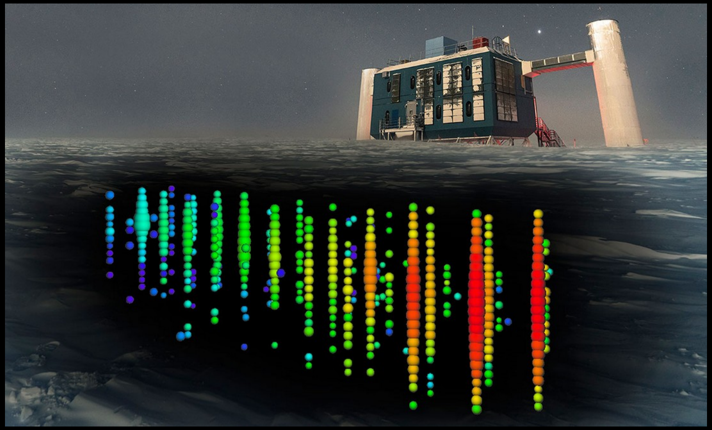
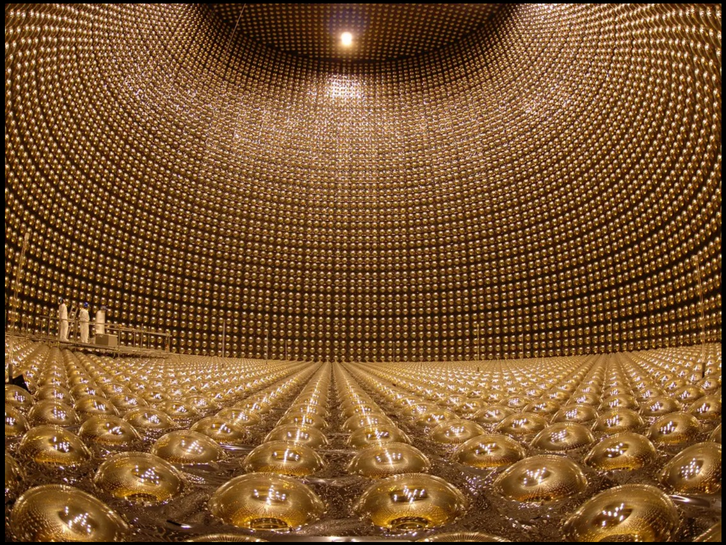
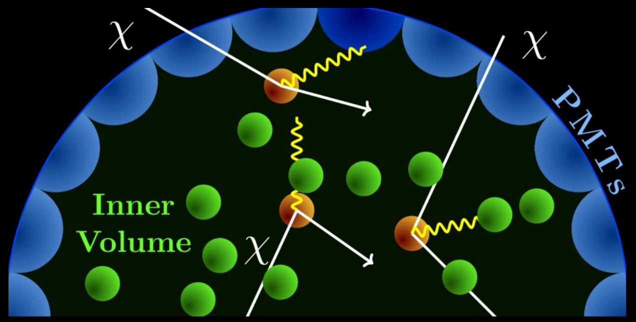




- Experimental Steps
  - JUNO starts this year, early validation
  - Co-ordinated multi-detector searches
  - There will be experimental challenges in implementing our new technique, but optimistic that they can be surmounted, given the importance of the task

Conclusions and Outlook



- Detecting sub-GeV DM is notoriously difficult
- We propose a new technique to probe sub-GeV DM and a new use of neutrino observatories
- DM-electron scattering in neutrino observatories: detectable signals w/ molecular excitation
  - Individual scattering events are undetectable, but the **aggregate rate** is
  - With JUNO, world-leading sensitivity to DM-electron scattering
- Next steps: refinement of theoretical and experimental details, operation!

Neutrino telescopes, designed for different physics, may hold the key to sub-GeV DM.
Just need to start looking!

Back Ups

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LAB target number

DM-electron cross section

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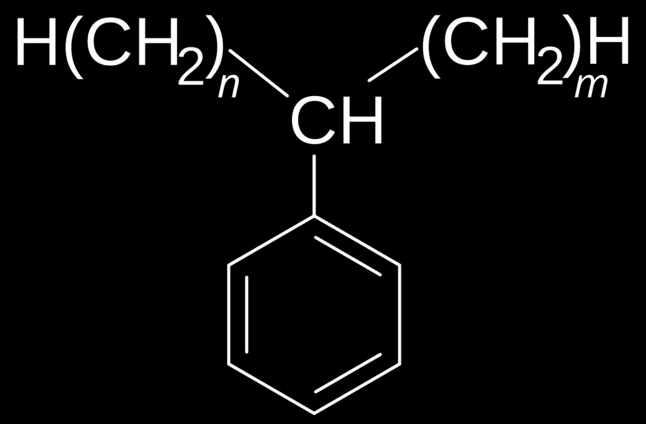
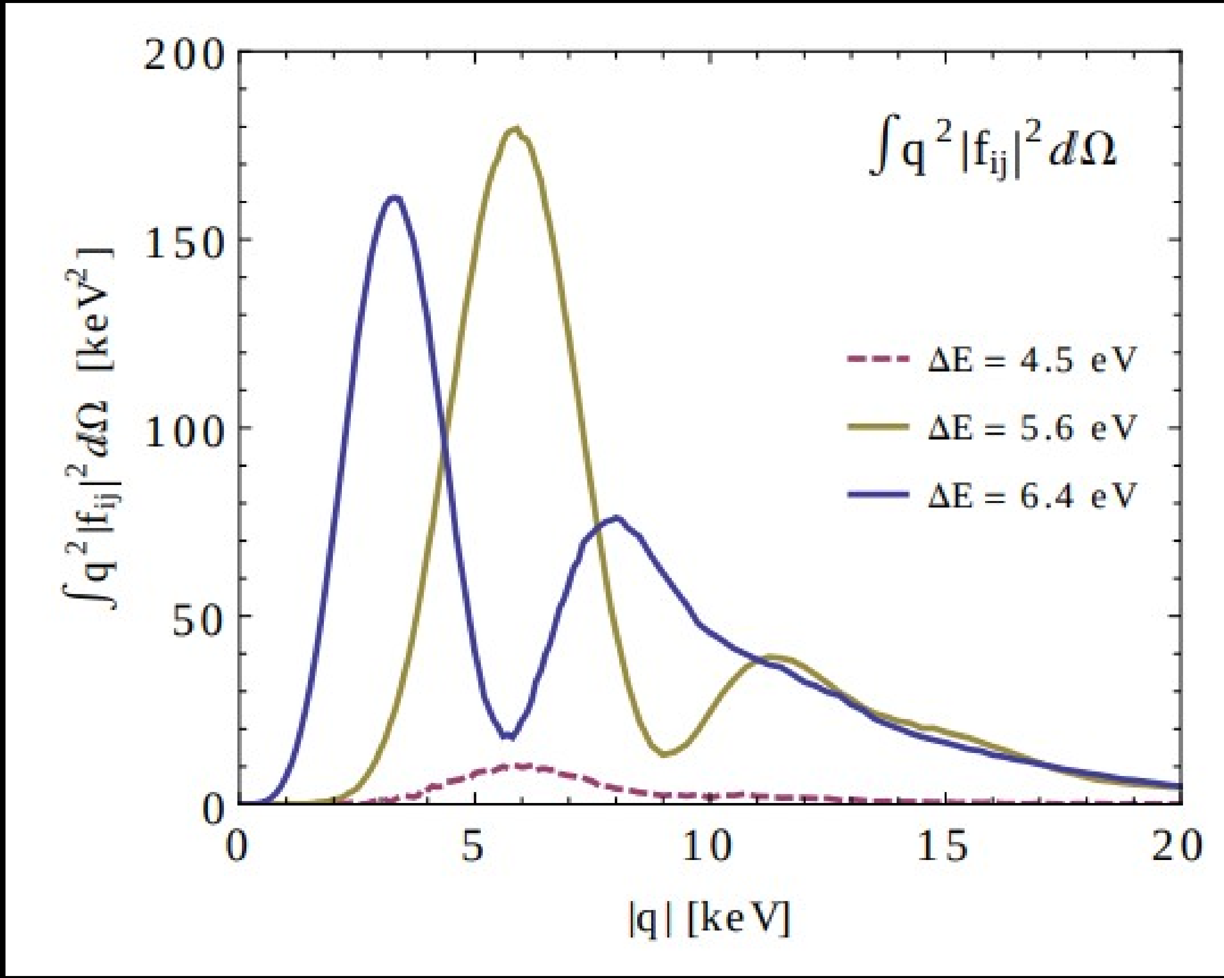


- Parametrizes the molecular response to excitation

- LAB contains a benzene ring, which features alternating double bonds, resulting in a system of conjugated π-bonds
  - The electrons occupying these π-orbitals are effectively delocalized, allowing them to move freely around the aromatic ring
  - Scintillation occurs due to electronic transitions where these π-electrons are excited into higher-energy molecular orbitals and then de-excite by photon emission

- LAB has not been considered as a sub-GeV DM detection material, but similar aromatic organic targets have been, e.g., EJ-301. which also has a benzene ring.
  - The π-electrons in the benzene ring are expected to dominate the rate, so we use the benzene from factor from Blanco et al 2019 → conservative

Benzene form factor



Blanco, Collar, Kahn, Lillard
1912.02822

Calculation details

$$(\sigma v)_{ij} = \int \frac{d^3\vec{q}}{(2\pi)^3}(2\pi)\delta(\Delta E_{ij} - \omega)\frac{|\mathcal{M}_{\rm free}|^2 |f_{ij}(\vec{q})|^2}{16 m_\chi^2 m_e^2},$$

$$\frac{|\mathcal{M}_{\rm free}|^2}{16 m_\chi^2 m_e^2} \equiv \frac{\pi \bar{\sigma}_e}{\mu_{\chi e}^2} F_{\rm DM}^2(q),$$

$$R_{\rm scatter} = \sum_{i,j} N_{\rm LAB}^e \frac{\rho_\chi}{m_\chi} \int d^3\vec{v} g_\chi(\vec{v})(\sigma v)_{ij}\,,$$

$$g_\chi(v) = \frac{1}{K}\exp\left(-\frac{|\vec{v}+\vec{v_E}|^2}{v_0^2}\right)\Theta(v_{\rm esc} - |\vec{v}+\vec{v_E}|)\,,$$

$$\eta(v_{\rm min}^{ij}) = \int \frac{4\pi v^2 dv}{v} g_\chi(v)\Theta(v - v_{\rm min}^{ij}(q))\,, \quad (7)$$

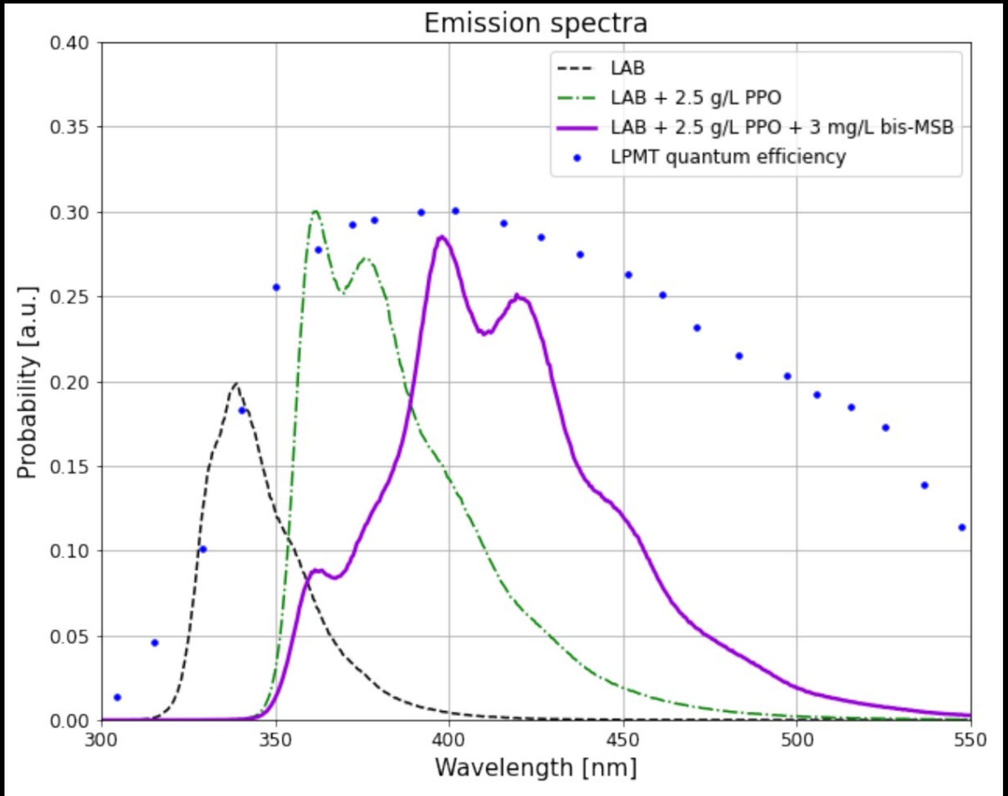
$$v_{\rm min}^{ij}(q) = \frac{\Delta E_{ij}}{q} + \frac{q}{2m_\chi}\,, \quad (8)$$

where $\eta(v_{\rm min}^{ij})$ is the integrated velocity distribution of DM particles above the threshold $v_{\rm min}^{ij}(q)$, which is the minimum speed DM needs for the electron to gain an energy ΔE_{ij} with momentum transfer q.

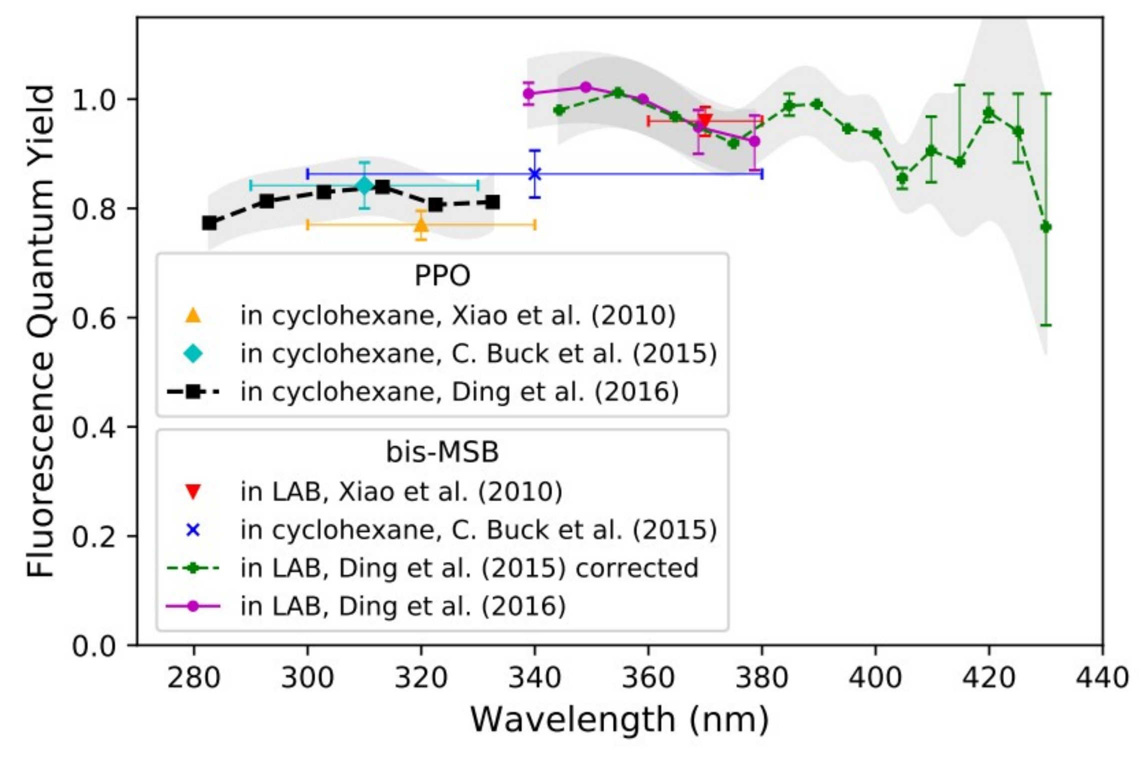
$$A = \frac{N_{\rm inc} - N_{\rm dec}}{N_{\rm inc} + N_{\rm dec}} = \frac{S_{\rm tot} f_{\rm mod}}{B_{\rm tot}}\,,$$

$$S_{\rm tot} \gtrsim \sqrt{B_{\rm tot}}/f_{\rm mod} \sim 10\sqrt{B_{\rm tot}}$$

Fluorescence yields

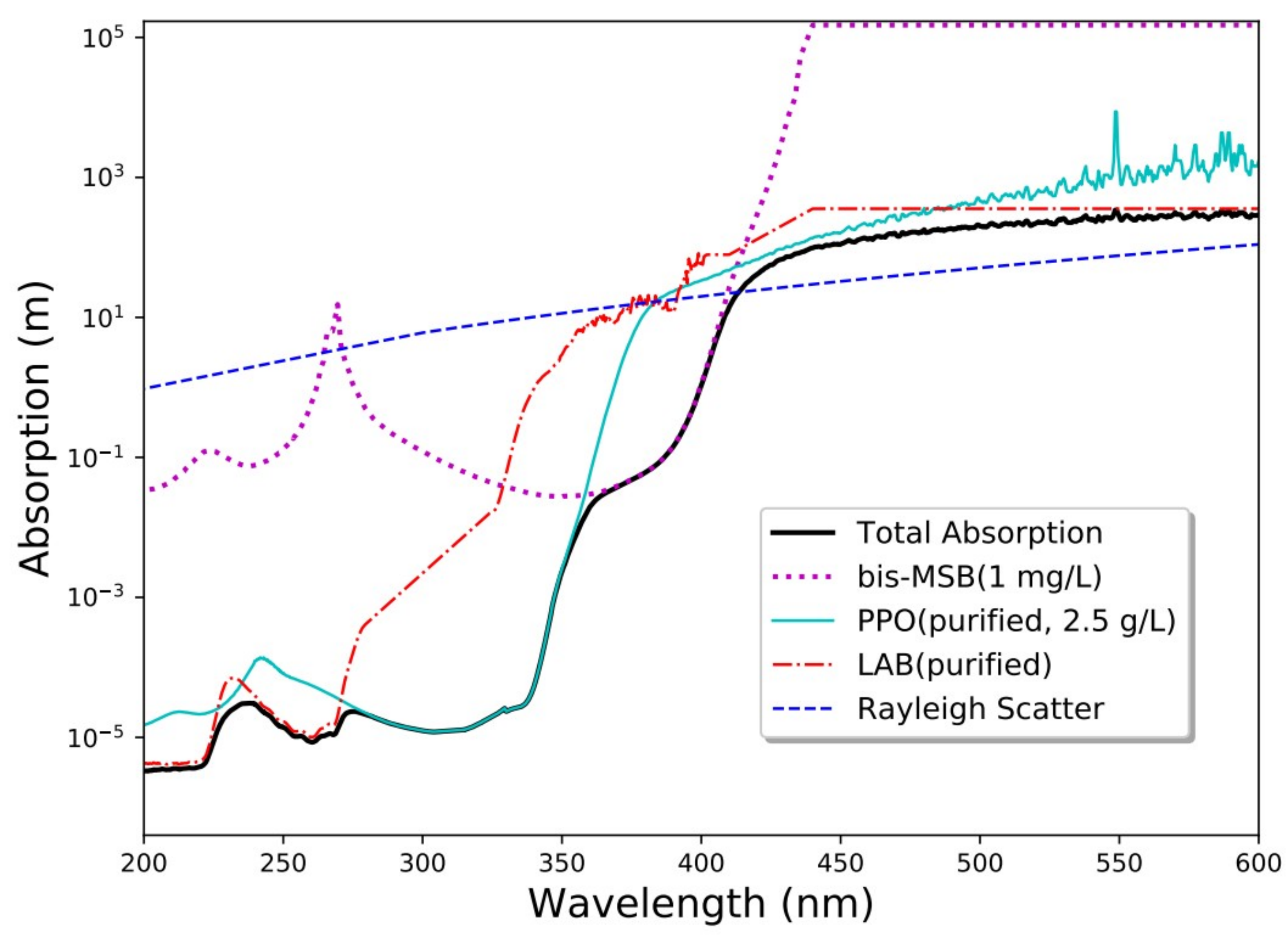


Beretta et al
2501.09988



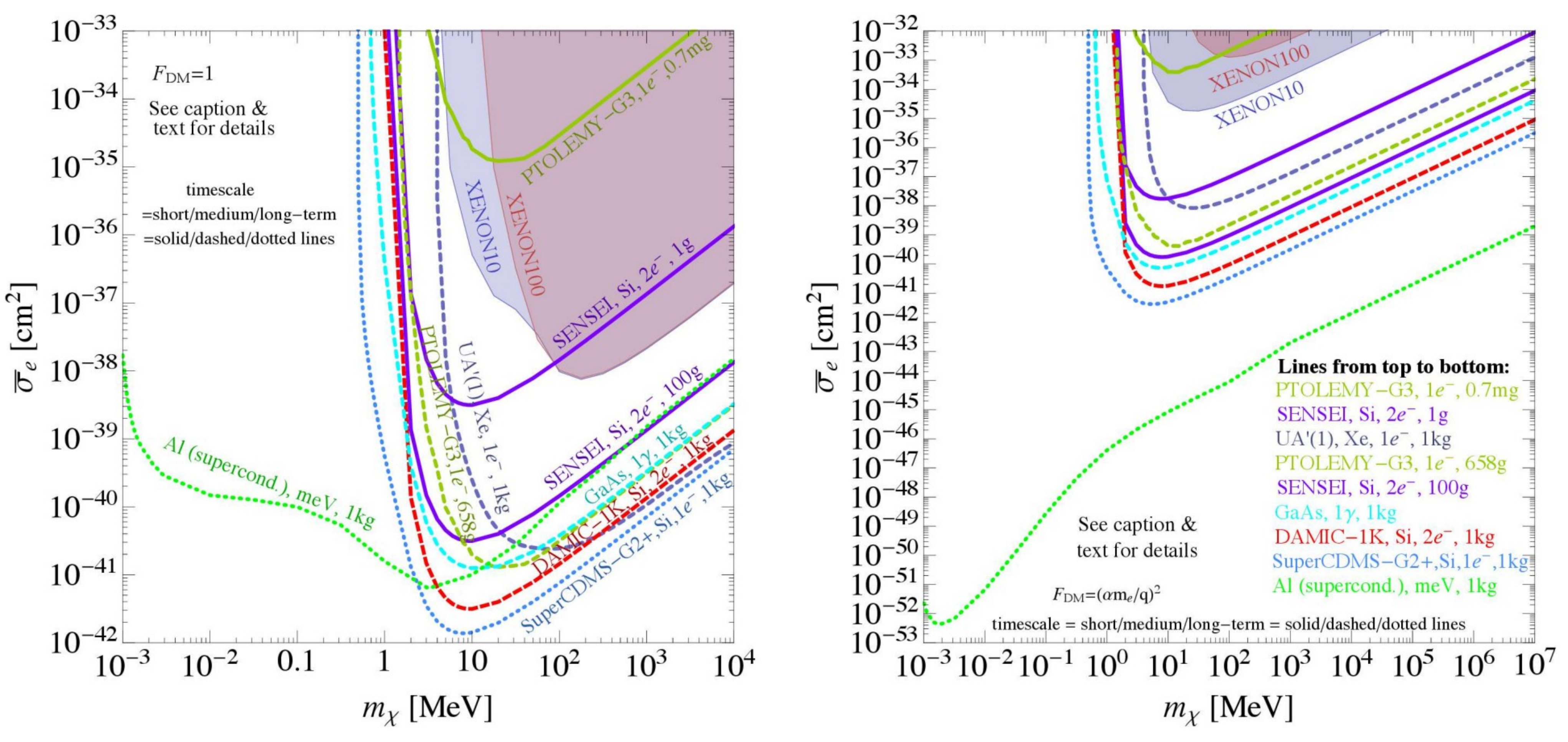
Zhang et al 2003.12212

Absorption length



Zhang et al 2003.12212

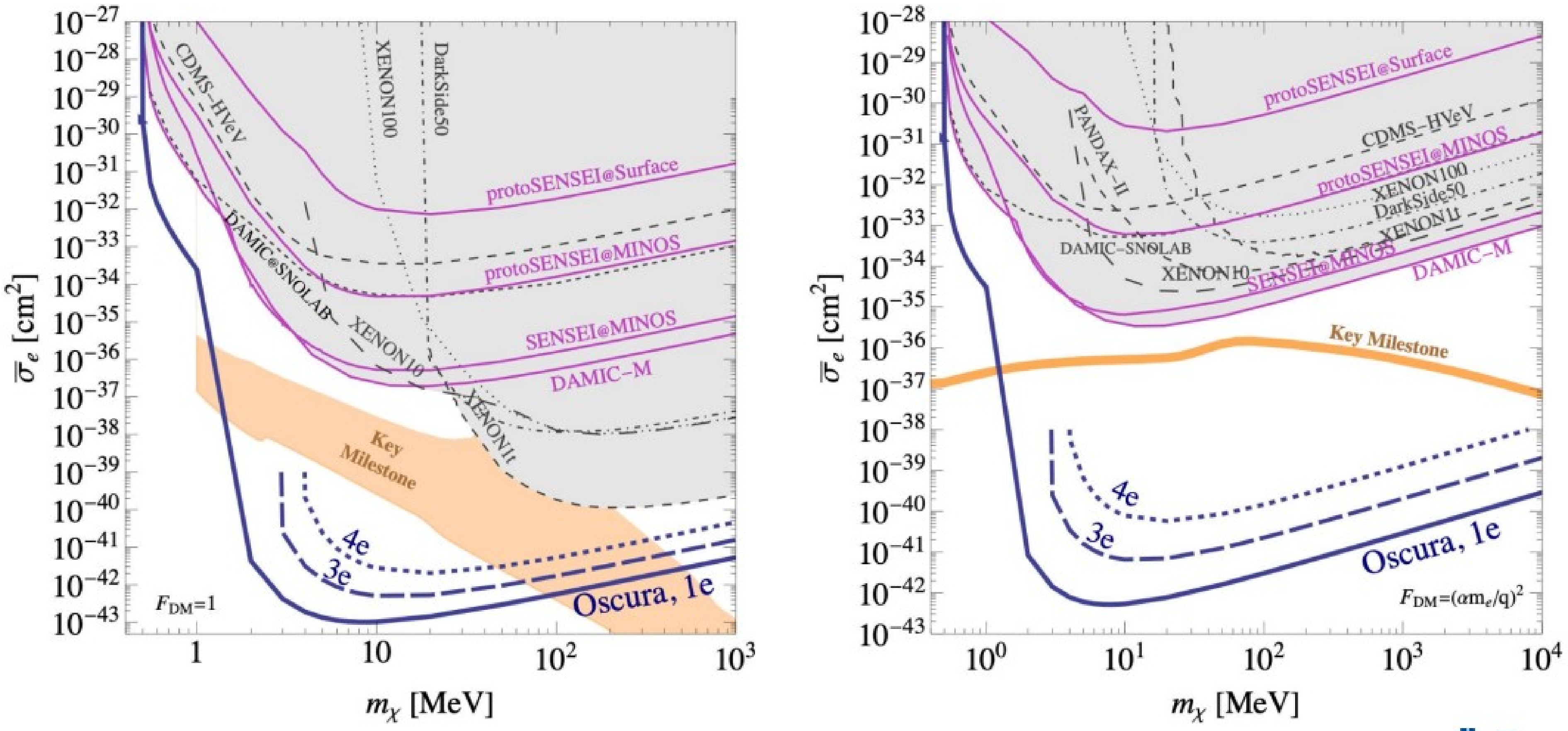
Comparison with projections



Battaglieri et al, Cosmic Visions Report (2017) [arXiv:1707.04591]

Oscura: Sensors performance to science reach

With current sensors performance, projected sensitivities lie between the 3e- and 4e- threshold curves.



Fermilab

Aguilar-Arevalo et al, (OSCURA Collaboration) [arXiv:2202.10518]

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