Sub-GeV Dark Matter Detection with Dark Rates in Liquid Scintillators

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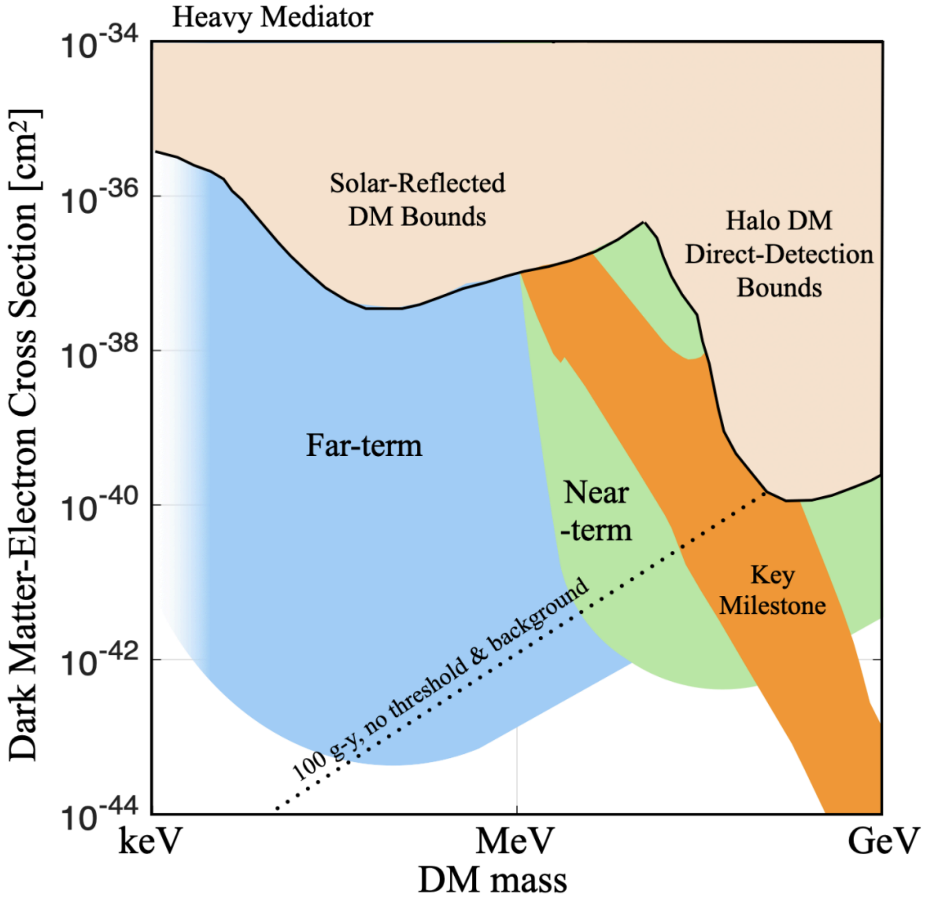
Pheno May 11, 2026

Phys.Rev.D 113 (2026) 10, 2512.13779

Motivation for sub-GeV DM

One main goal of the community is to improve sensitivity to sub-GeV DM:

- Well-motivated
- More open parameter space
- Search for sub-GeV DM is difficult in standard direct detection experiments



Essig et al (2203.08297)

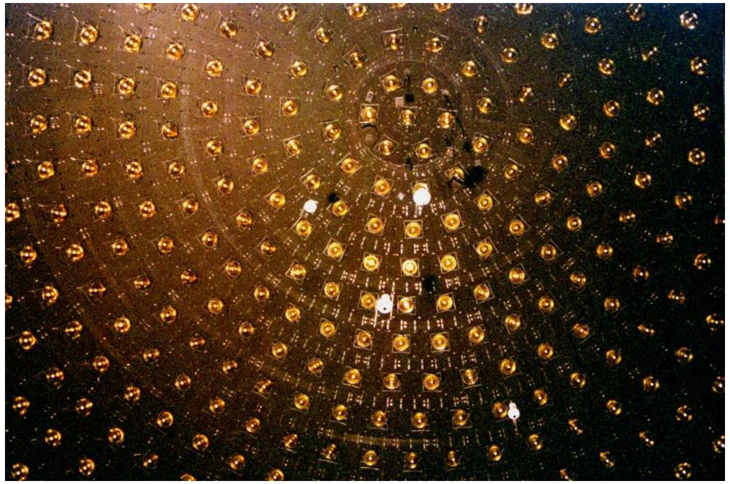
Neutrino observatories as DM detectors

What about using neutrino observatories to search for sub-GeV DM? Benefits include

- Large target volume
- Materials with low excitation thresholds
- High light yield in liquid-scintillator detectors

Neutrino observatories as DM detectors

Why had neutrino observatories not been used to search for standard (halo) sub-GeV DM before?



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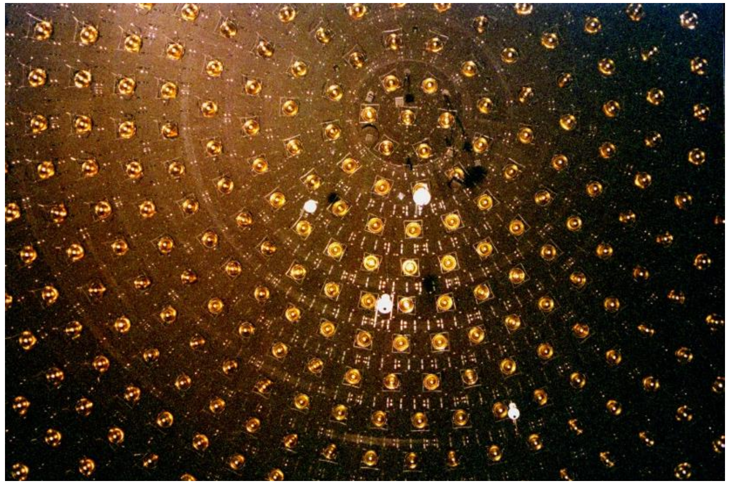
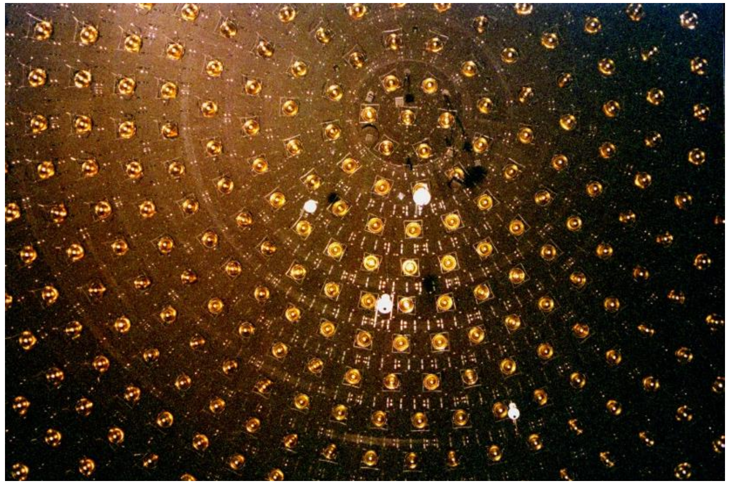
- Neutrino observatories have thresholds of order ~MeV (even more restrictive than ~keV threshold of direct detection)



Neutrino observatories as DM detectors

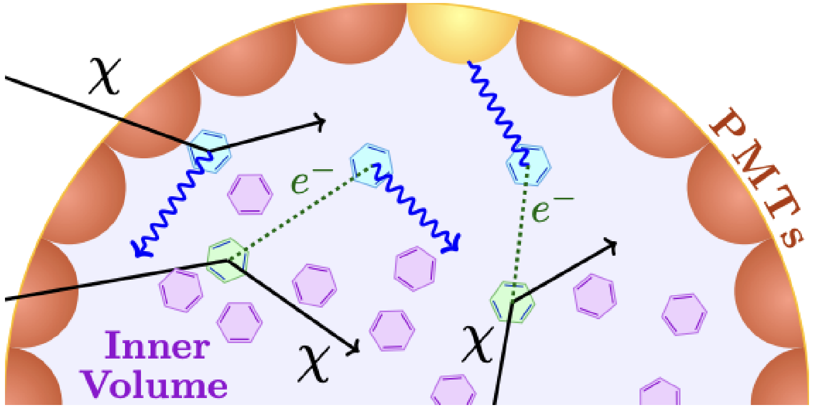
Why had neutrino observatories not been used to search for standard (halo) sub-GeV DM before?

- Neutrino observatories have thresholds of order ~MeV (even more restrictive than ~keV threshold of direct detection)
- Previous work on neutrino observatories as DM detectors focused on DM that could reach these thresholds, such as
  - Heavy DM
  - Boosted sub-GeV DM



Neutrino observatories as DM detectors

New way of using neutrino observatories to search for DM:



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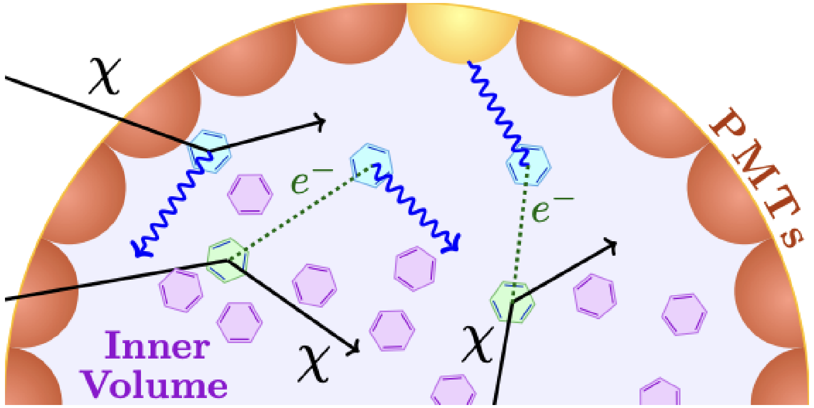
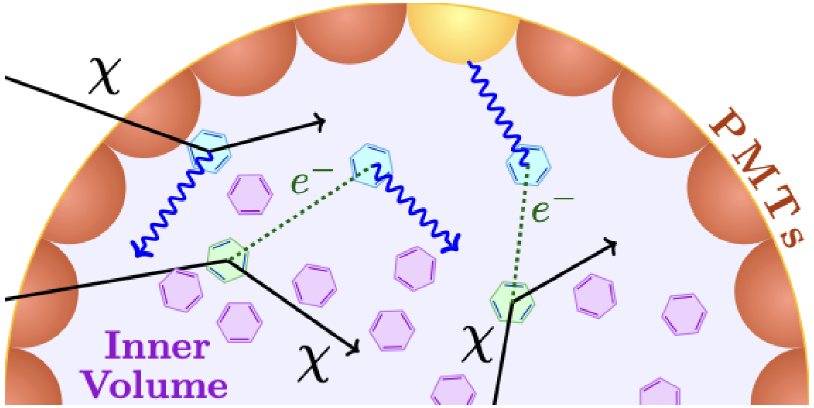
- **Instead of looking for events greater than ~MeV, see if DM directly excites or ionizes target molecules**



Neutrino observatories as DM detectors

New way of using neutrino observatories to search for DM:

- **Instead of looking for events greater than ~MeV, see if DM directly excites or ionizes target molecules**
- Consider DM-electron scattering
- As a result of excitation or ionization of the target molecules, photons may be produced and detected by photomultiplier tubes (PMTs)



Neutrino observatories as DM detectors

New way of using neutrino observatories to search for DM:

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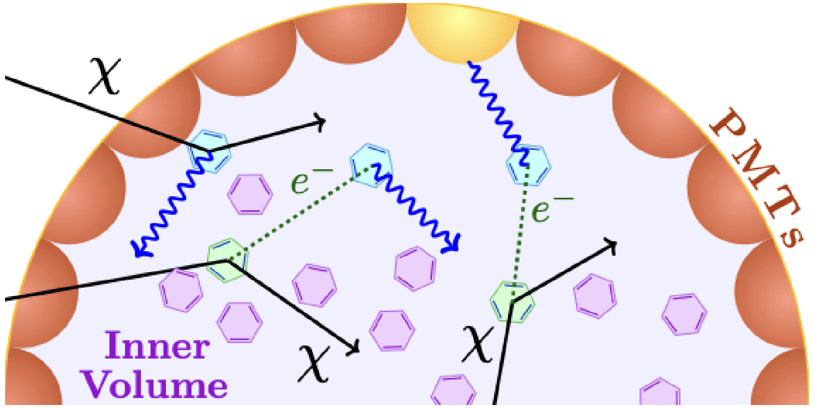
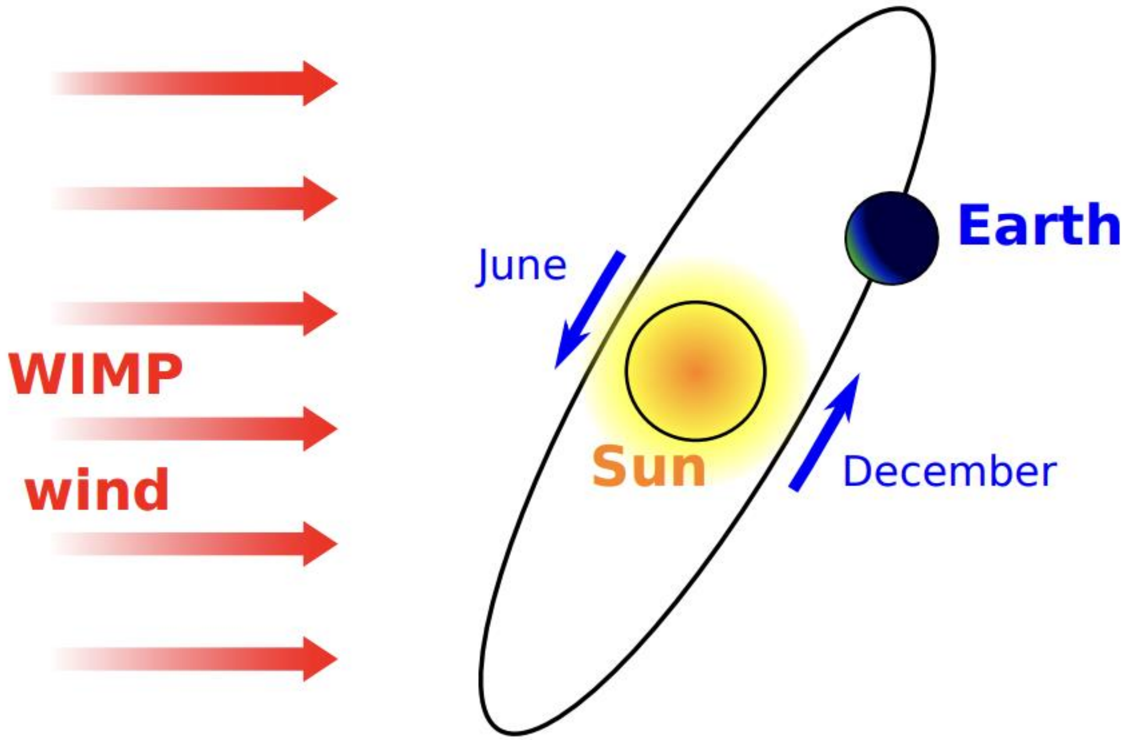
- Consider DM-electron scattering
- As a result of excitation or ionization of the target molecules, photons may be produced and detected by photomultiplier tubes (PMTs)
- Signal is small compared to background – need a way to extract it



Annual modulation

Signal can be distinguished using the annual modulation of the relative DM-Earth velocity

- Throughout the year, the average DM velocity relative to Earth varies by $\pm 15\ km/s$
- Highest velocity: June 2
- Lowest velocity: Dec 2



Freese, Lisanti, Savage (1209.3339)

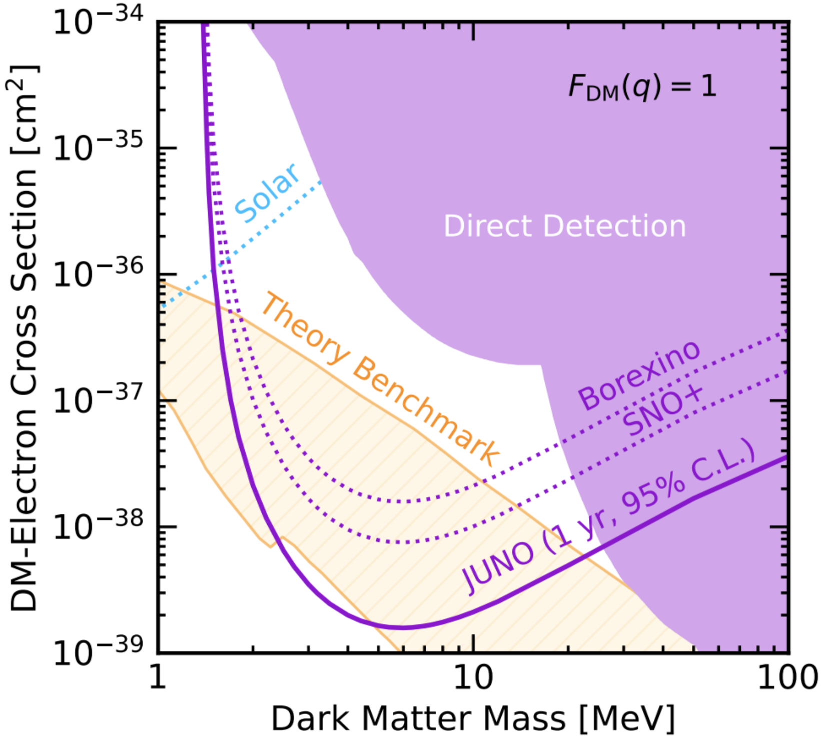
Background

- Background is the dark rate: total rate of PMT hits; dominated by thermal noise
- Dark rates are recorded for monitoring purposes
- Modulating backgrounds:
  - Different phase from DM modulation
  - Can be tracked using independent measurements

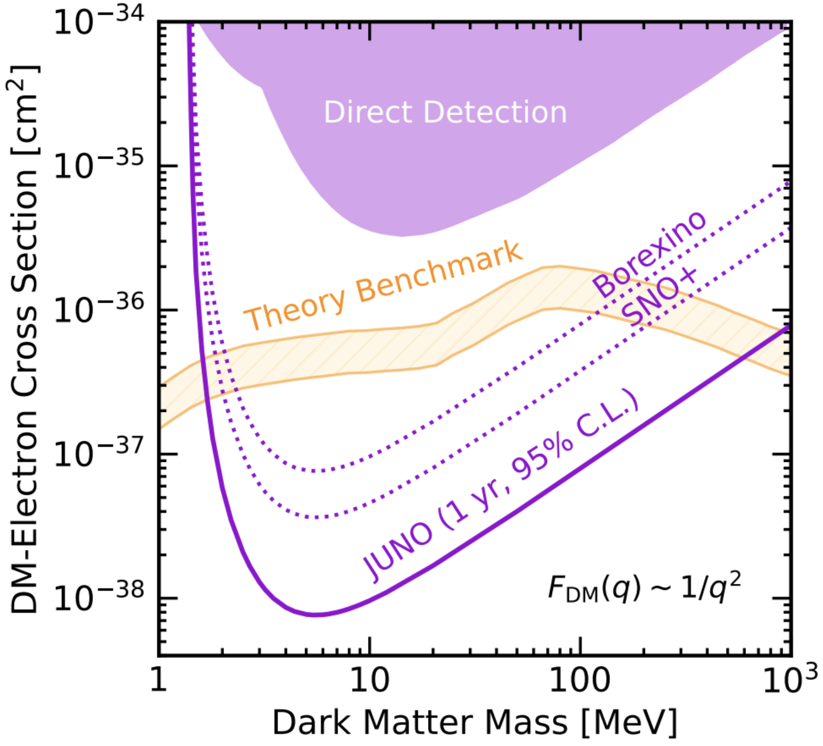
Previous work

Projected sensitivity from excitation in JUNO:

Heavy mediator



Light mediator



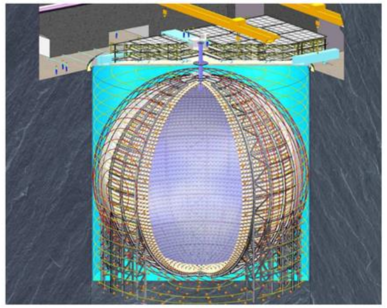
Leane, Beacom (2503.09685)

This work

Includes ionization and more detectors

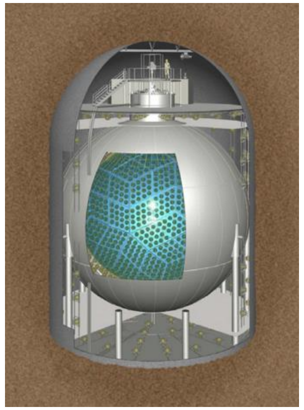
- Ionization improves sensitivity for heavier DM masses in the case of a heavy mediator
- We improve the calculation for JUNO and extend it to other detectors
- Multiple detectors can validate each other's results

JUNO



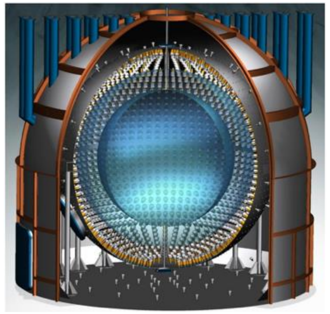
The JUNO Collaboration
(2103.09908)

KamLAND



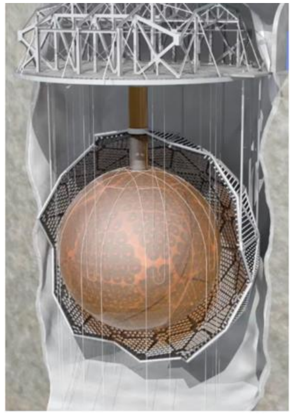
Inoue 2004

Borexino



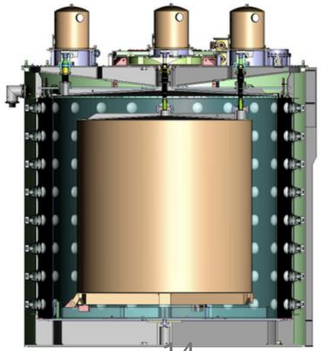
Ranucci et al. 2016

SNO+



Albanese et al.
(2104.11687)

Daya Bay



An et al. (2006.15386)

Signal rate

Signal rate

Ionization rate:

$$R_{ion} = \int dE_{er}\, \xi_{ion}(E_{er}) \frac{\rho_\chi\, \bar{\sigma}_{e\chi} F_{Fermi}(E_{er})}{8\, m_\chi \mu_{e\chi}^2} \sum_i N_T^i \int dq\, q\, |f_{ion}^i(E_{er}, q)|^2\, |F_{DM}(q)|^2\, \eta(v_{min})$$

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- Astrophysics: info about DM velocity distribution

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- Particle physics: info about interaction between DM and electron

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- Astrophysics: info about DM velocity distribution
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- Atomic/molecular physics: target info and response to ionization/excitation

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- Astrophysics: info about DM velocity distribution
- Particle physics: info about interaction between DM and electron
- Atomic/molecular physics: target info and response to ionization/excitation
- Detector physics: light yield and detection efficiency

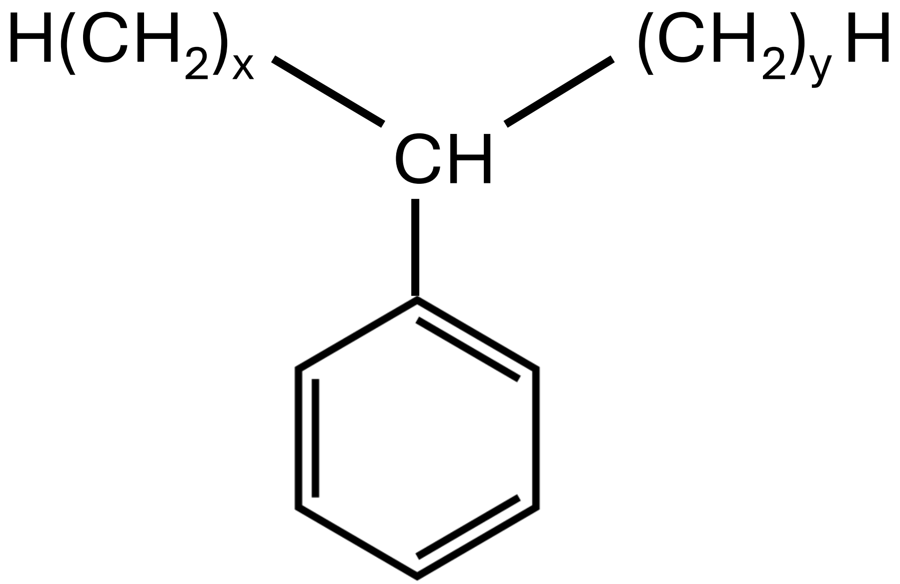
Targets

We consider three different materials:

- Linear alkylbenzene (LAB): used in JUNO, SNO+, and Daya Bay
- Pseudocumene (PC): used in Borexino and KamLAND
- Dodecane: used in KamLAND

All are made up of carbon and hydrogen atoms

LAB molecule:



Comparison of ionization and excitation

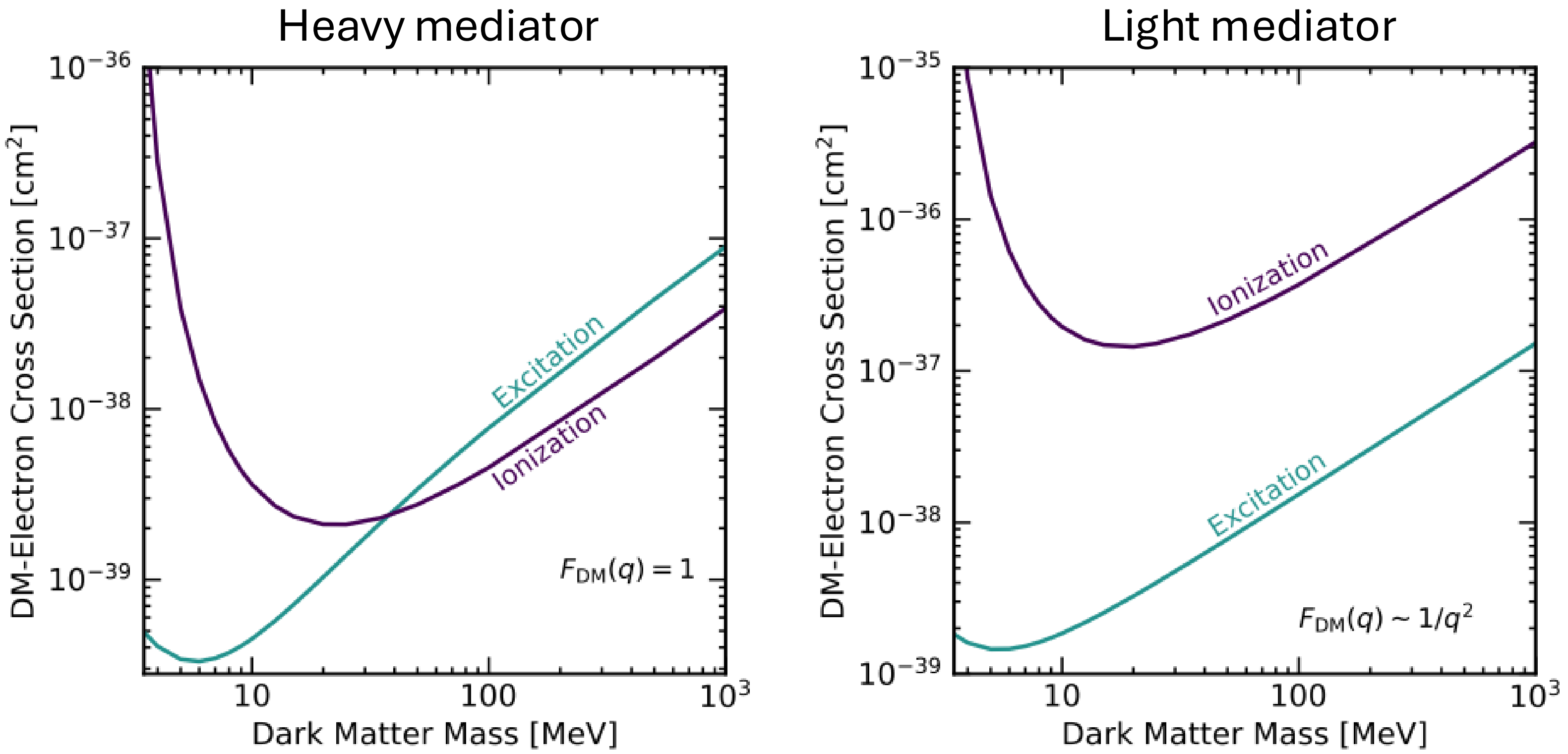
Heavy mediator:

- At low masses, excitation dominates due to lower threshold

Light mediator:

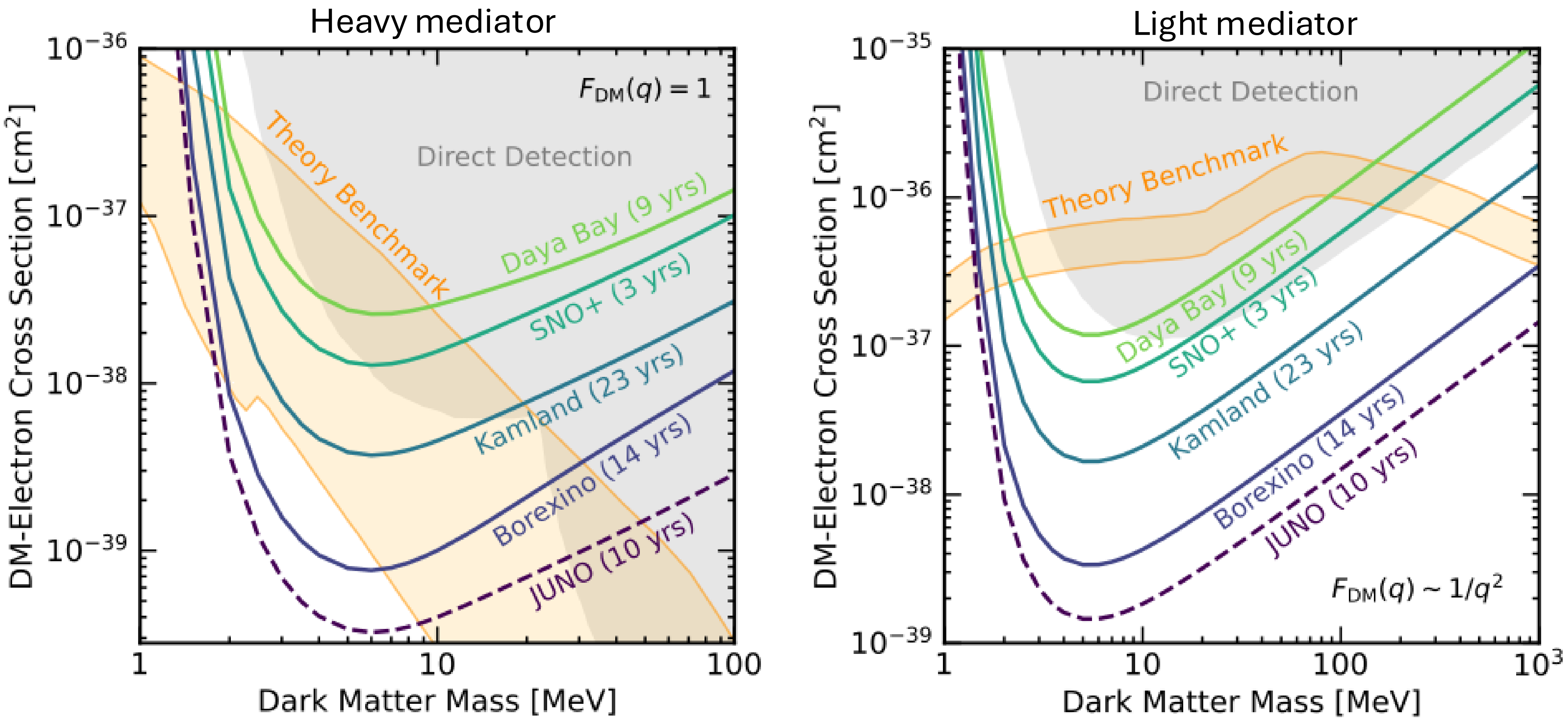
- Lower threshold is more important due to suppression at high momentum transfer

Comparison for JUNO


Heavy mediator

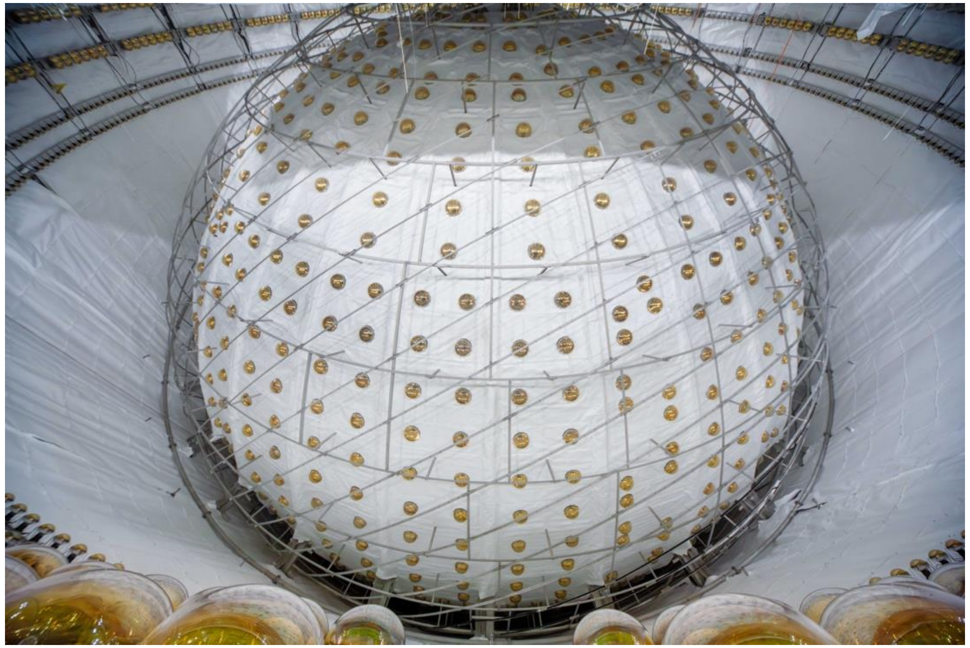
Light mediator

Projected sensitivity



Summary and Outlook

- Neutrino observatories are ideal for searching for sub-GeV DM
- Multiple liquid scintillators reach competitive sensitivity
- Experimental validation can already be done with years of existing data from SNO+, Daya Bay, Borexino, and Kamland
  - JUNO came online last year and will soon contribute
  - We can create a robust search program with all five detectors, where they can test this technique and cross check each other!



JUNO Collaboration

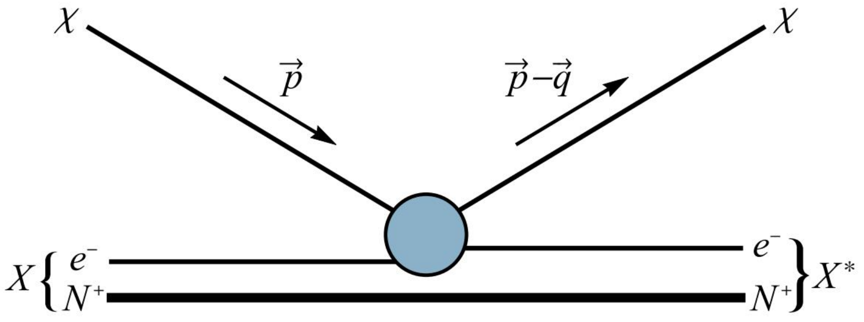
BACKUP

Why DM-electron scattering?

- Lighter DM is more kinematically matched with electron mass (~0.1 MeV) than nucleon mass (~GeV)
- The typical electron speed ($\sim \alpha$) is an order of magnitude larger than the typical DM speed ($\sim 10^{-3}$)

High relative speed between DM and electron

Increases probability of large enough momentum transfer for excitation or ionization

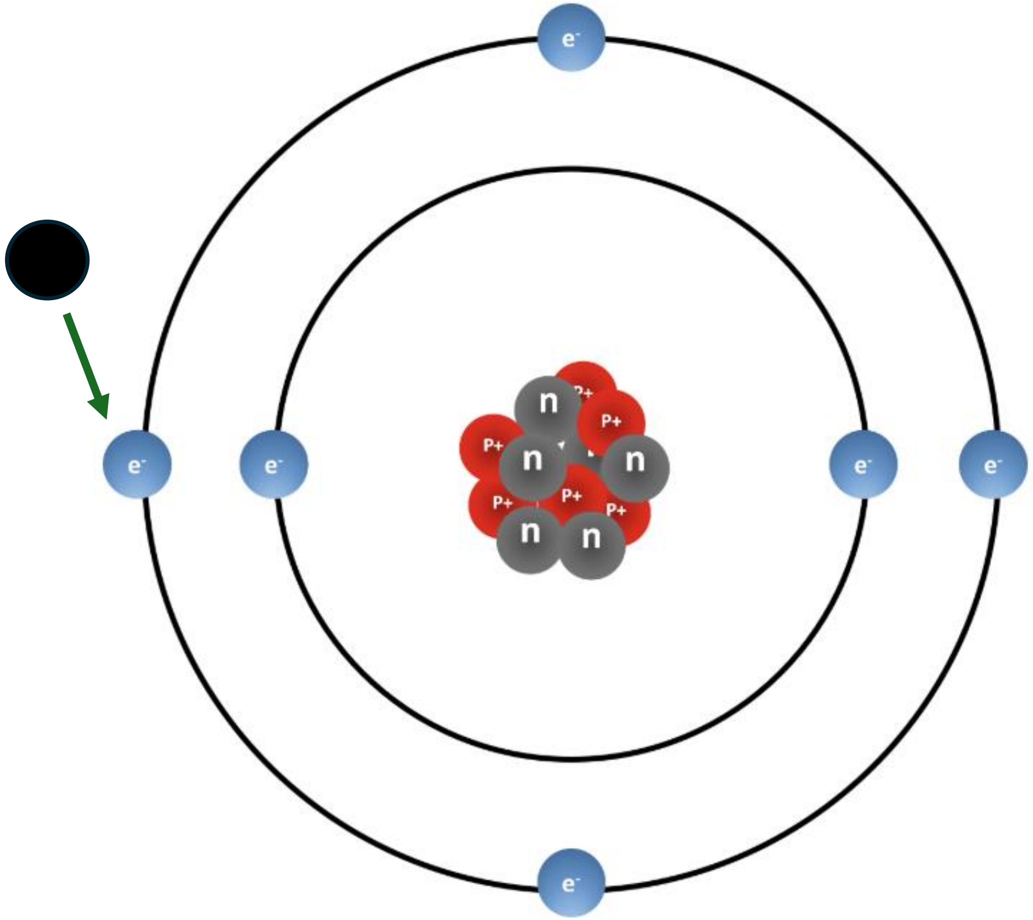


Essig et al (1509.01598)

Energy conservation:

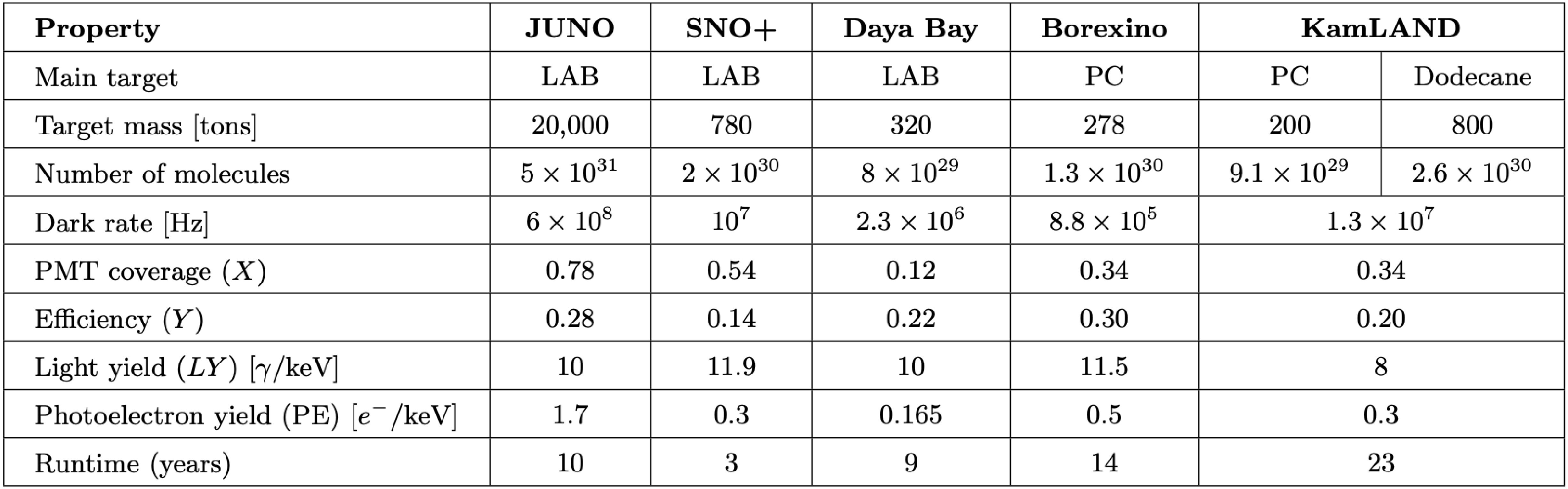
$$\underbrace{\Delta E_e}_{\text{Energy gained by electron}} = \underbrace{\vec{q}\cdot\vec{v} - \frac{q^2}{2\,m_\chi}}_{\text{Energy lost by DM}}$$

Kinematics



- The DM transfers a certain amount of energy to the electron, depending on its mass and speed
  - DM speed comes from velocity distribution in the halo
- Deposited energy must overcome binding energy for ionization to occur

Neutrino detector properties



Property	**JUNO**	**SNO+**	**Daya Bay**	**Borexino**	**KamLAND**	
Main target	LAB	LAB	LAB	PC	PC	Dodecane
Target mass [tons]	20,000	780	320	278	200	800
Number of molecules	5×10^{31}	2×10^{30}	8×10^{29}	1.3×10^{30}	9.1×10^{29}	2.6×10^{30}
Dark rate [Hz]	6×10^{8}	10^{7}	2.3×10^{6}	8.8×10^{5}	1.3×10^{7}	
PMT coverage (X)	0.78	0.54	0.12	0.34	0.34	
Efficiency (Y)	0.28	0.14	0.22	0.30	0.20	
Light yield (LY) [γ/keV]	10	11.9	10	11.5	8	
Photoelectron yield (PE) [e^-/keV]	1.7	0.3	0.165	0.5	0.3	
Runtime (years)	10	3	9	14	23	

DM sensitivity

95% confidence level sensitivity: $S = \frac{2\sqrt{B}}{f_{mod}}$

- Signal (S): DM-electron scattering event rate per year:

$$R = R_{ion} + R_{exc}$$

$$R_{ion} = \int \xi_{ion}(E_{er}) \frac{dR}{d \ln E_{er}} dE_{er}$$

- Annual Modulation (f_{mod})

- Background (B)

Integrated velocity distribution

$$\frac{dR}{d\ln E_{er}} = \frac{\rho_\chi\,\bar{\sigma}_{e\chi}}{8\,m_\chi \mu_{e\chi}^2} F_{Fermi}(E_{er}) \sum_i N_T \int dq\; q\,|f_{ion}^i(E_{er},q)|^2\,|F_{DM}(q)|^2 \eta(v_{min})$$

Integrated DM velocity distribution above v_{min}: $\eta(v_{min}) = \int dv\;\; 4\pi v^2\,\frac{g_\chi(v)}{v}\,\Theta(v - v_{min})$

$g_\chi(v)$: DM velocity distribution (Maxwell-Boltzmann)

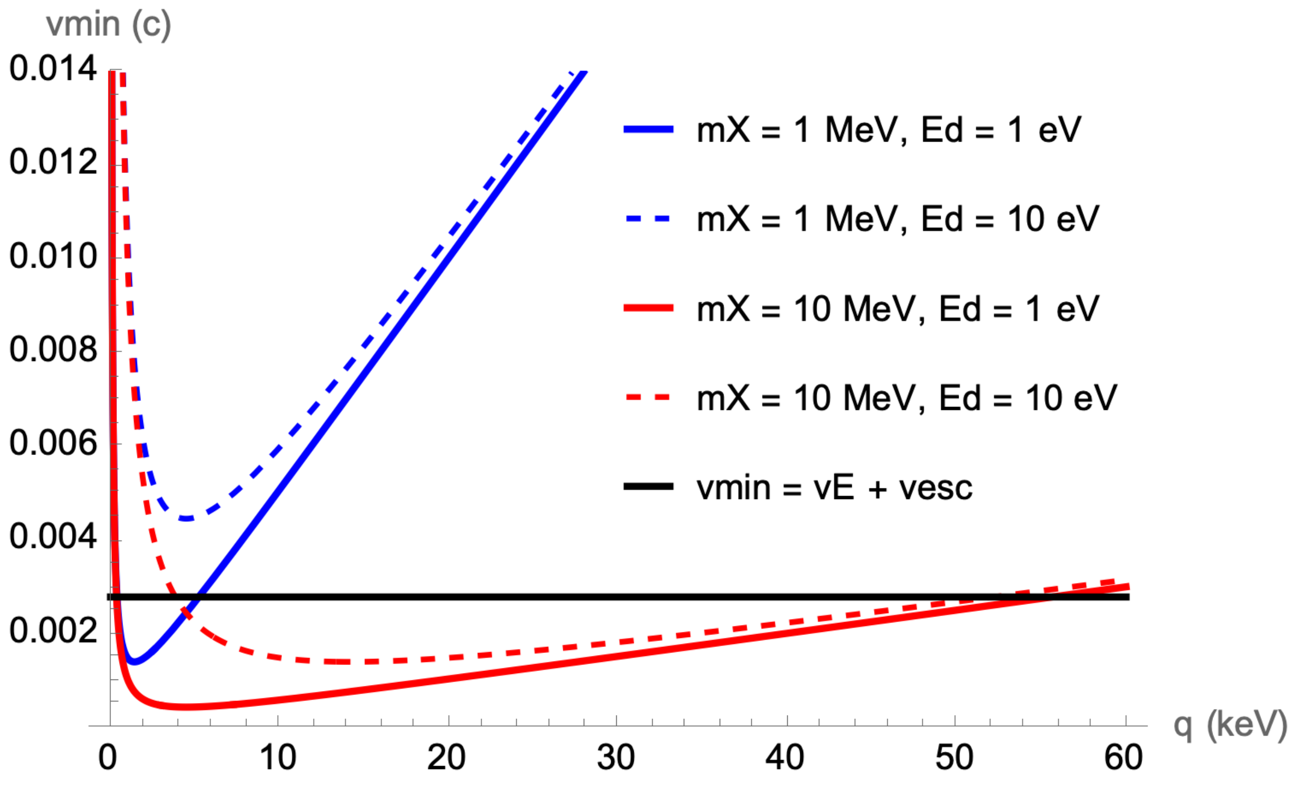
v_{min} is the minimum velocity needed to transfer energy E_d to the electron with momentum transfer q:

$$v_{min} = \frac{E_d}{q} + \frac{q}{2m_\chi}$$

The electron recoil energy E_{er} is the electron's energy after ionization: $E_{er} = E_d - E_b$

↳ Binding energy

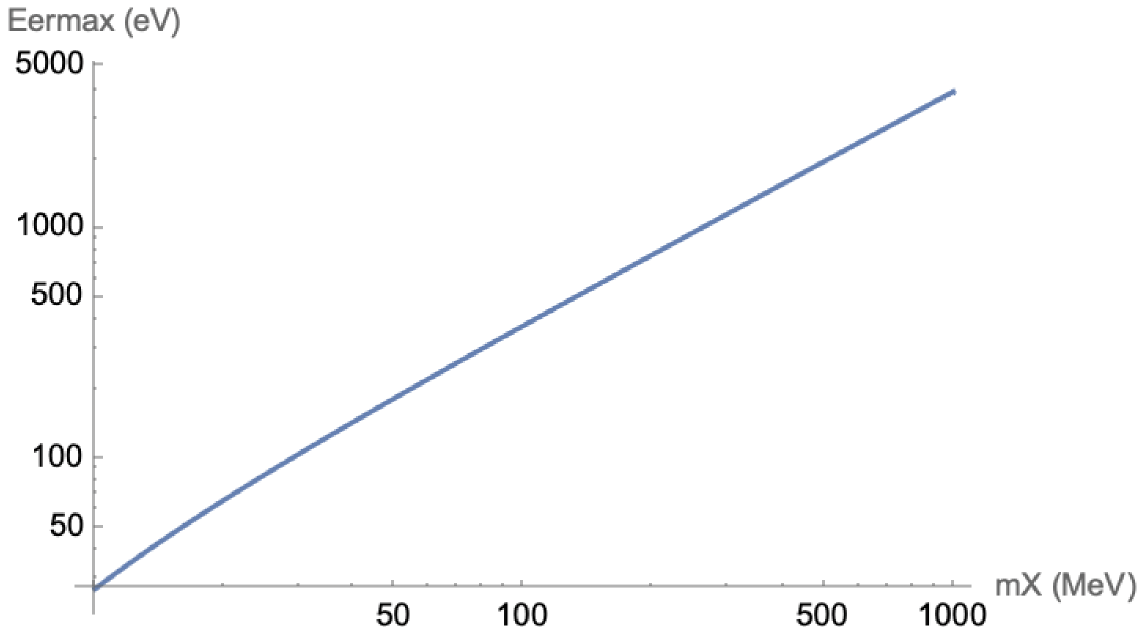
Minimum velocity



- $v_{min} = v_E + v_{esc}$ is the maximum kinematically allowed value of the DM velocity
- v_E is the Earth's velocity in the galactic rest frame
- v_{esc} is the galactic escape velocity
- The q range increases for higher masses and lower energy
- For each mass there is a maximum energy that can be reached

Maximum deposited energy

For each DM mass there is a maximum deposited energy that can be reached, based on the maximum possible speed of DM bound to our galaxy



Minimum DM mass: $m_\chi \gtrsim 0.26\ \text{MeV} \left(\frac{2.8 \times 10^{-3}}{v_E + v_{\text{esc}}}\right)^2 \left(\frac{E_d^{\min}}{\text{eV}}\right)$

Particle Physics: cross section and form factor

$$R_{exc} = \xi_{exc} \frac{\rho_\chi \bar{\sigma}_{e\chi} N_T^{exc}}{8\pi m_\chi \mu_{e\chi}^2} \sum_{i,j} \int \frac{d^3q}{q} |f_{exc}^{ij}(\vec{q})|^2 \, |F_{DM}(q)|^2 \, \eta(v_{min})$$

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$\bar{\sigma}_{e\chi}$ is the DM−electron cross section evaluated at $q = \alpha m_e$

The DM form factor $F_{DM}(q)$ specifies the momentum scaling of dark matter interactions

Our results are framed model-independently in terms of a generic heavy or light mediator:

$F_{DM}(q) = 1$ (Heavy)

$F_{DM}(q) = \frac{(\alpha m_e)^2}{q^2}$ (Light)

Dark matter form factor

Non-relativistic scattering rate between dark matter and free electrons evaluated at $q = \alpha m_e$:

$$\bar{\sigma}_e \equiv \frac{\mu_{e\chi}^2}{16\pi m_\chi^2 m_e^2} \left. \overline{|\mathcal{M}_{e\chi}(q)|^2} \right|_{q^2=\alpha^2 m_e^2}$$

$$|F_{\mathrm{DM}}(q)|^2 = \overline{|\mathcal{M}_{e\chi}(q)|} / \overline{|\mathcal{M}_{e\chi}(\alpha m_e)|}$$

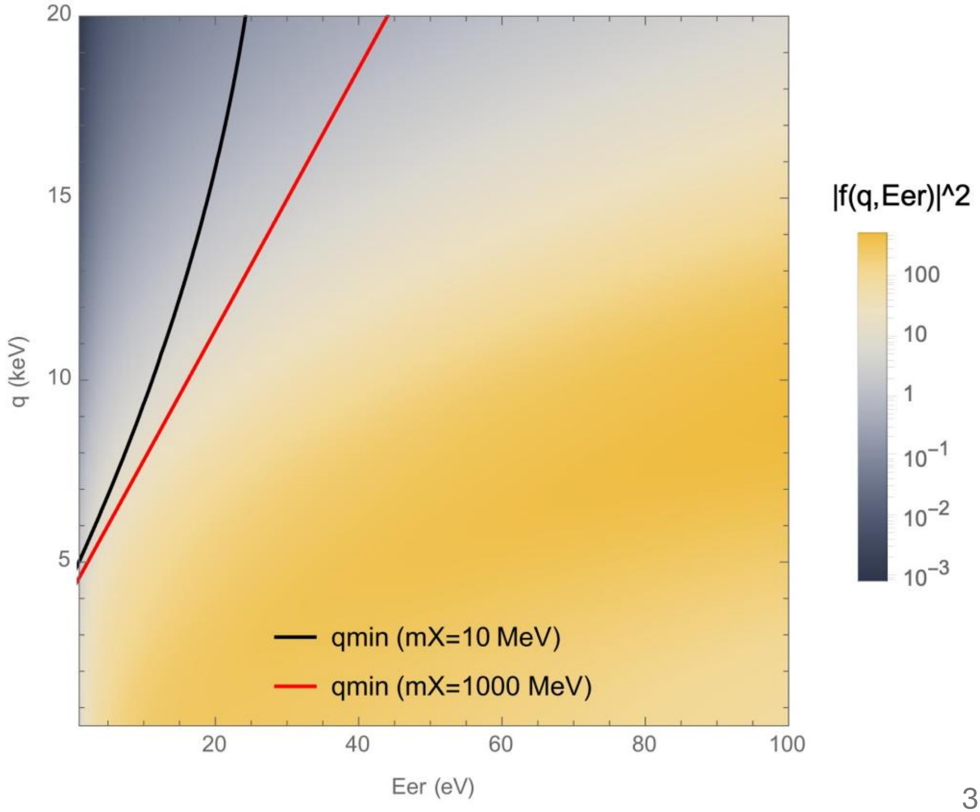
Spin-averaged matrix element

$$|F_{DM}(q)|^2 = \frac{m_\phi^2 + (\alpha m_e)^2}{m_\phi^2 + q^2}$$

Ionization form factor

$$\frac{dR}{d\ln E_{er}} = \frac{\rho_\chi \, \bar{\sigma}_{e\chi}}{8\, m_\chi \mu_{e\chi}^2} F_{Fermi}(E_{er}) \sum_i N_T \int dq\, q\, |f^i_{ion}(E_{er}, q)|^2 \, |F_{DM}(q)|^2 \eta(v_{min})$$

- The ionization form factor represents the probability of ionization
- The form factor generally peaks at low momentum transfer
- The peak shifts to higher momentum transfer for higher recoil energies
- Most of the peak is not included in the kinematically allowed parameter space



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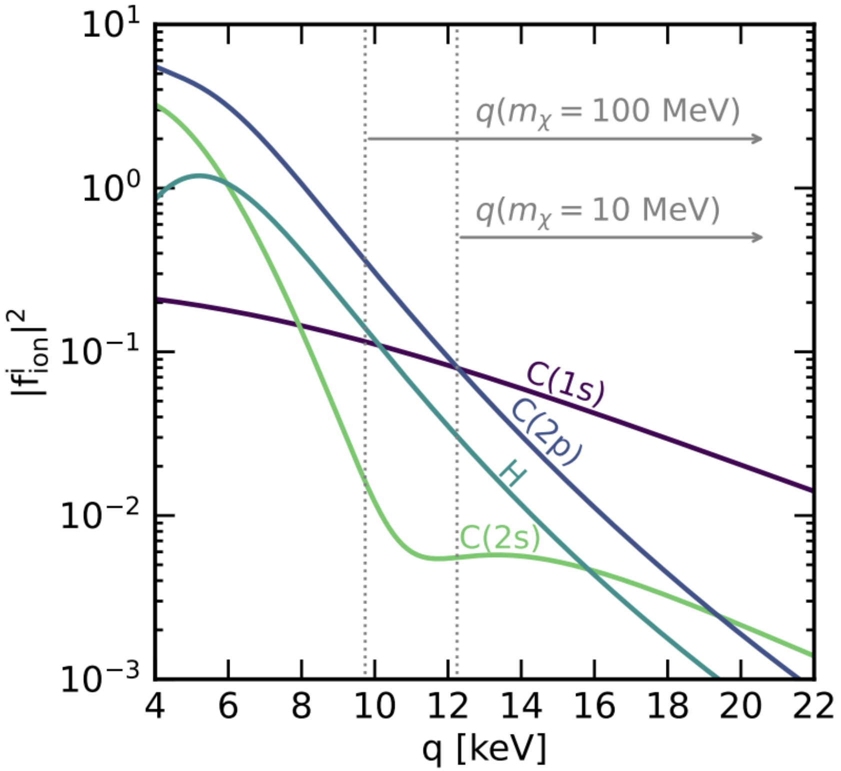

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$$\chi_{n\ell}(r) = \sum_j c_{j\ell n} N_{j\ell} r^{n_{j\ell}-1} \exp(-Z_{j\ell} r)$$

$$|f_{\mathrm{ion}}^i(k', q)|^2 = \frac{(2\ell+1)k'^2}{4\pi^3 q} \int_{|k'-q|}^{k'+q} dk\; k|\tilde{\chi}_{n\ell}(k)|^2$$

Final state approximated as plane wave

Fermi factor and number of targets

$$\frac{dR}{d\ln E_{er}} = \frac{\rho_\chi\,\bar{\sigma}_{e\chi}}{8\,m_\chi \mu_{e\chi}^2} F_{Fermi}(E_{er}) \sum_i N_T^i \int dq\, q\, |f_{ion}^i(E_{er},q)|^2\, |F_{DM}(q)|^2 \eta(v_{min})$$

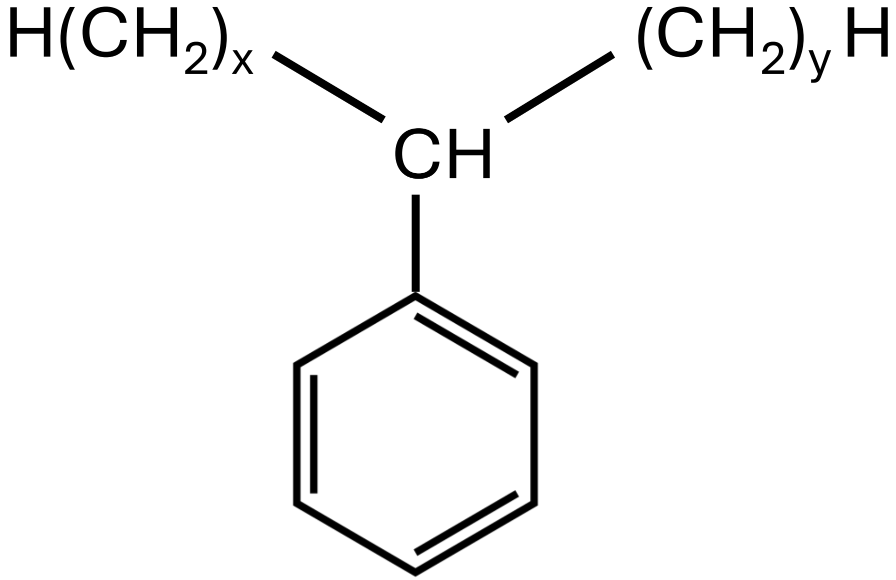
- Fermi factor $F_{Fermi}(E_{er})$: accounts for electron proximity to atom
- Number of targets N_T^i =

(# of LAB molecules)*(# of atoms in LAB)*(# of electrons in orbital)

  - # of LAB molecules in JUNO: 5×10^{31}
  - # of carbon atoms: 16
  - # of hydrogen atoms: 26
  - # of electrons: 2 in carbon orbitals, 1 for hydrogen

Chemical structure of LAB

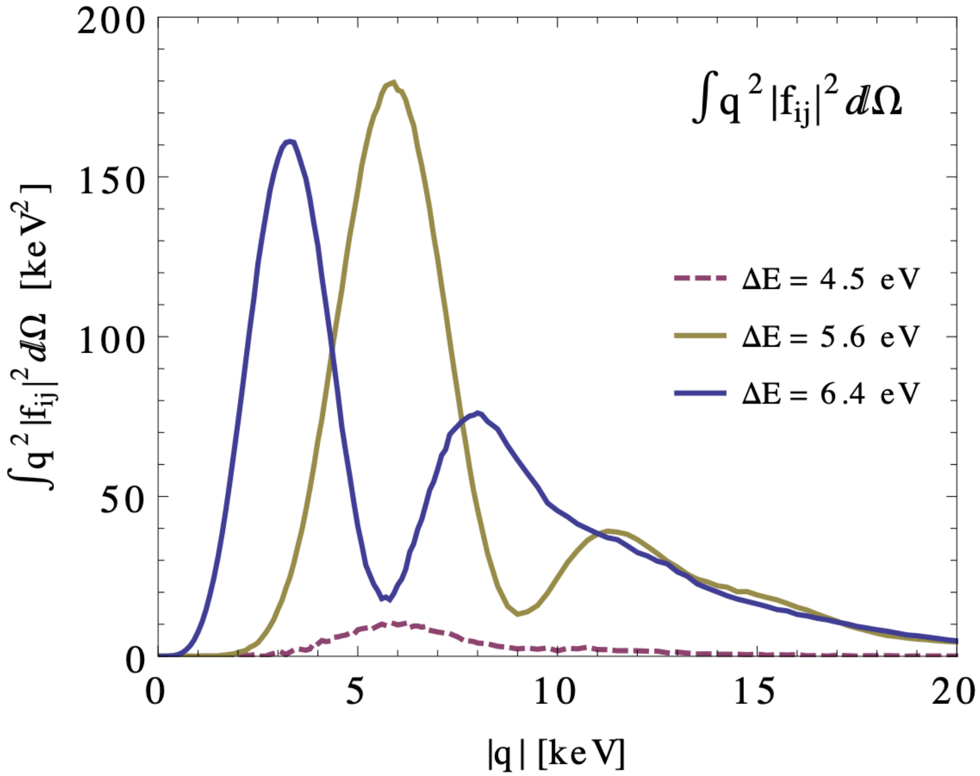
- LAB is made up of carbon and hydrogen atoms, arranged in a benzene ring and alkyl chain
- Chemical formula: $C_6H_5C_nH_{2n+1}$ $(n = x + y + 1)$
- In JUNO: $n = 10 - 13$



Excitation form factor

$$R_{exc} = \xi_{exc} \frac{\rho_\chi \bar{\sigma}_{e\chi} N_T^{exc}}{8\pi m_\chi \mu_{e\chi}^2} \sum_{i,j} \int \frac{d^3q}{q} |f_{exc}^{ij}(\vec{q})|^2 \, |F_{DM}(q)|^2 \, \eta(v_{min})$$

- Used benzene form factor for LAB and PC
  - LAB and PC are benzene based
  - The dominant transitions occur for electrons in the benzene ring
- Dodecane is not benzene based, so for KamLAND we only consider excitation of PC
- There are 6 delocalized electrons in the benzene ring that participate in the dominant transitions

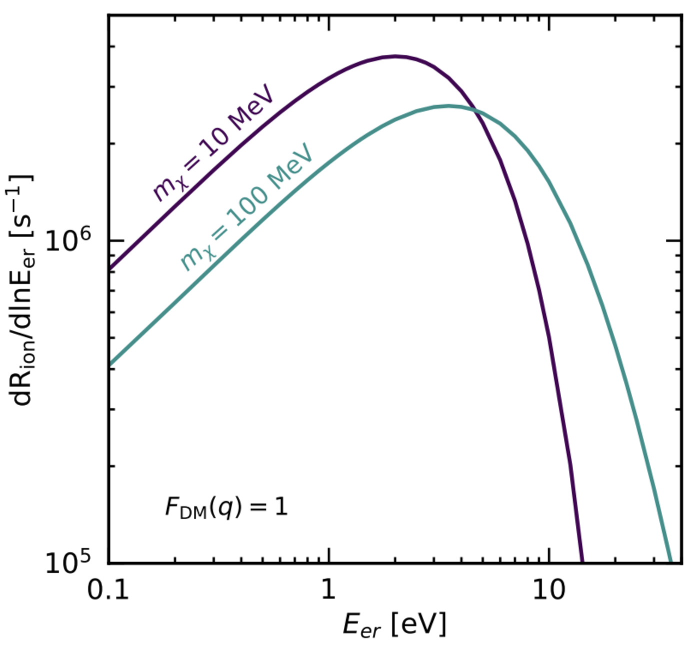


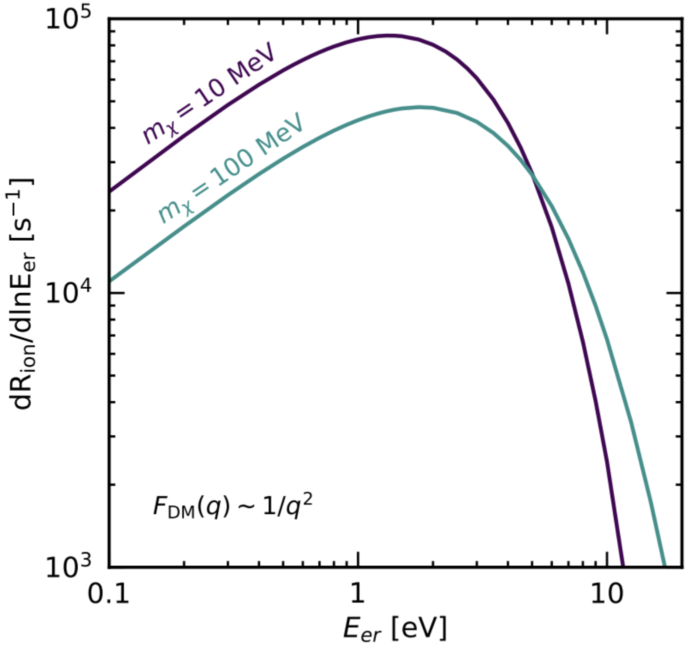
Blanco et al. (1912.02822)

Differential ionization rate

$$\frac{dR_{ion}}{d\ln E_{er}} = \frac{\rho_\chi\,\bar{\sigma}_{e\chi}}{8\,m_\chi \mu_{e\chi}^2} F_{Fermi}(E_{er}) \sum_i N_T^i \int dq\; q\; |f_{ion}^i(E_{er}, q)|^2\; |F_{DM}(q)|^2 \eta(v_{min})$$

- Sum over carbon orbitals and hydrogen
- Peak of differential rate is higher for lower masses due to number density
- At higher recoil energies, the differential rate is suppressed for lower masses due to limited energy deposition





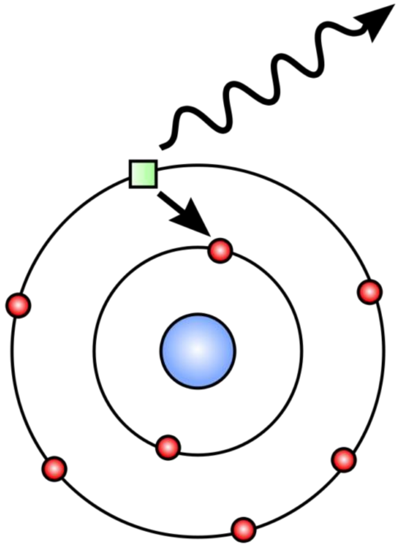
Light yield and efficiency

$$R_{ion} = \int \xi_{ion}(E_{er}) \frac{dR}{d\ln E_{er}} dE_{er}$$

$$R_{exc} = \xi_{exc} \frac{\rho_\chi \bar{\sigma}_{e\chi} N_T^{exc}}{8\pi m_\chi \mu_{e\chi}^2} \sum_{i,j} \int \frac{d^3q}{q} |f_{exc}^{ij}(\vec{q})|^2 \, |F_{DM}(q)|^2 \, \eta(v_{min})$$

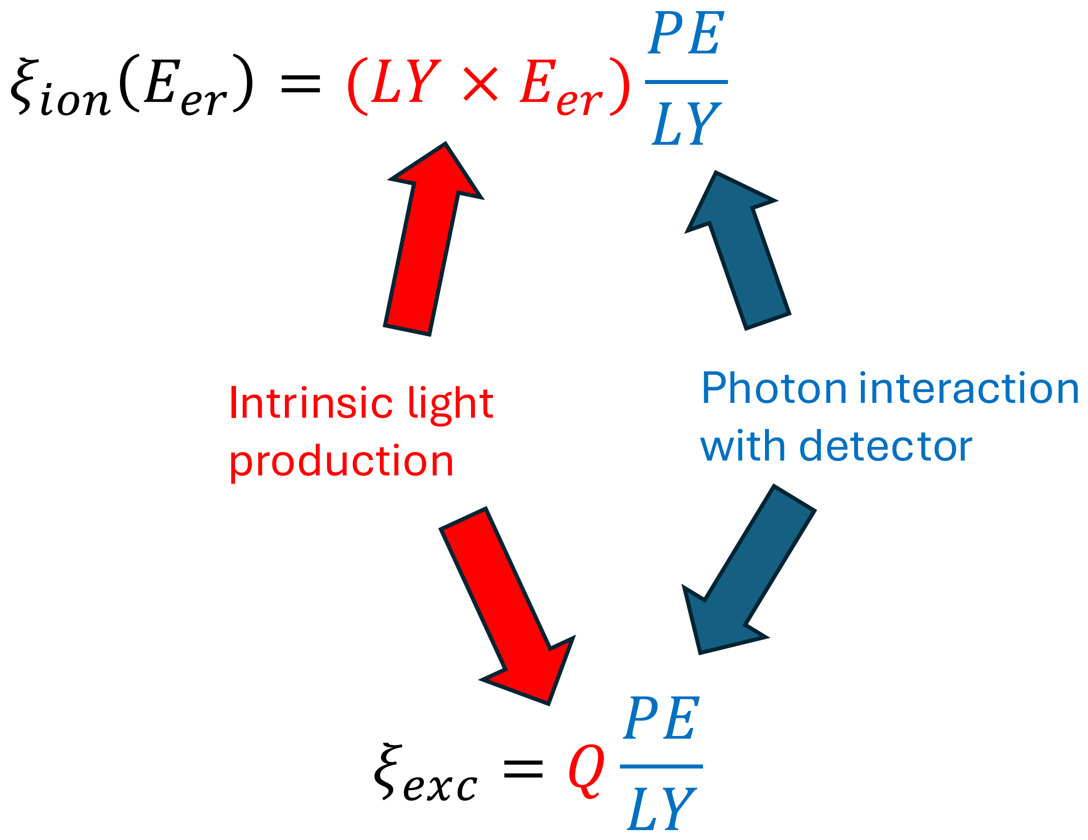
The efficiency factors ξ_{ion} and ξ_{exc} account for

- The intrinsic light production of the medium resulting from ionization or excitation
- The propagation of photons in the medium and their detection by PMTs



Light yield and efficiency

- Light yield (*LY*): rate of intrinsic light production from ionization
- Quantum fluorescence yield (*Q*): rate of intrinsic light production from excitation
- Photoelectron yield (*PE*): rate of successful detection of photoelectrons



$$\xi_{ion}(E_{er}) = (LY \times E_{er})\frac{PE}{LY}$$

Intrinsic light production

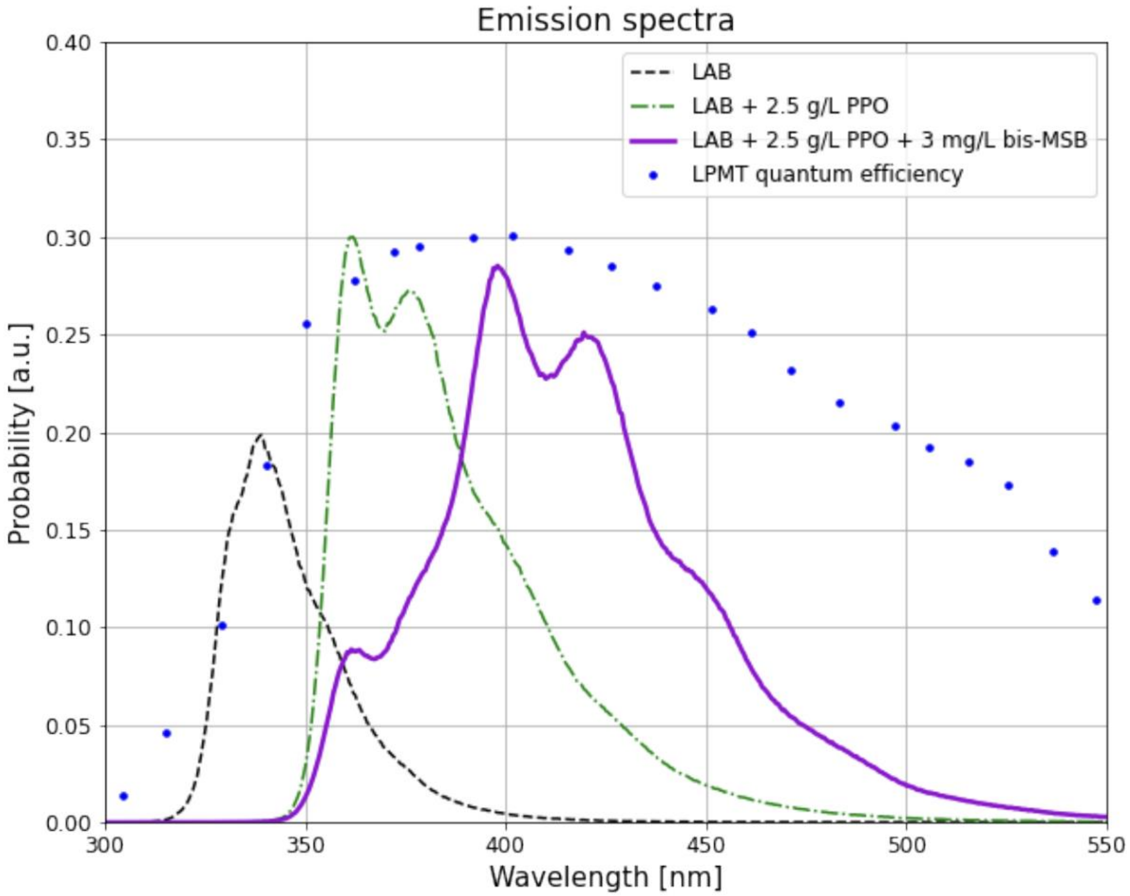
Photon interaction with detector

$$\xi_{exc} = Q\frac{PE}{LY}$$

Light yield and efficiency

PE/LY accounts for

- PMT wall coverage
- PMT quantum efficiency
- emission and absorption of photons in the medium



Beretta et al. (2501.09988)

Light yield and efficiency for ionization

- Not every DM-electron scattering event will lead to a PMT hit

    Need to account for photon yield and efficiency factors related to the PMTs and medium

- In JUNO, the medium is LAB + small percentage of other compounds (PPO and bis-MSB)

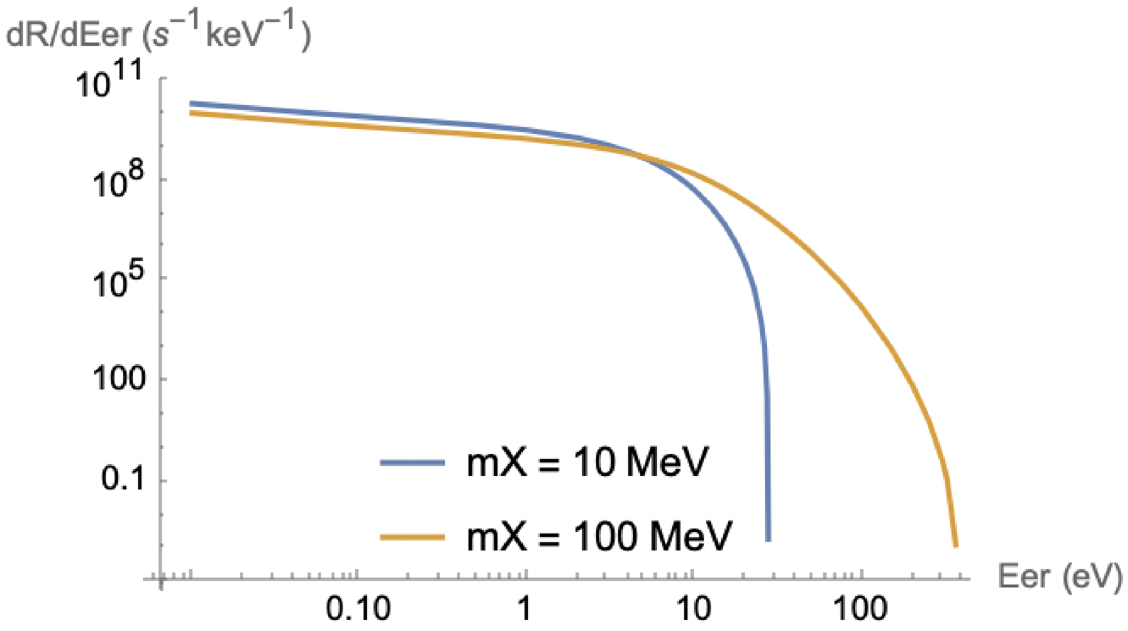
- After ionization, free electrons interact with the medium, leading to the production of photons

    In LAB, the number of photons produced per keV of electron energy is ~10

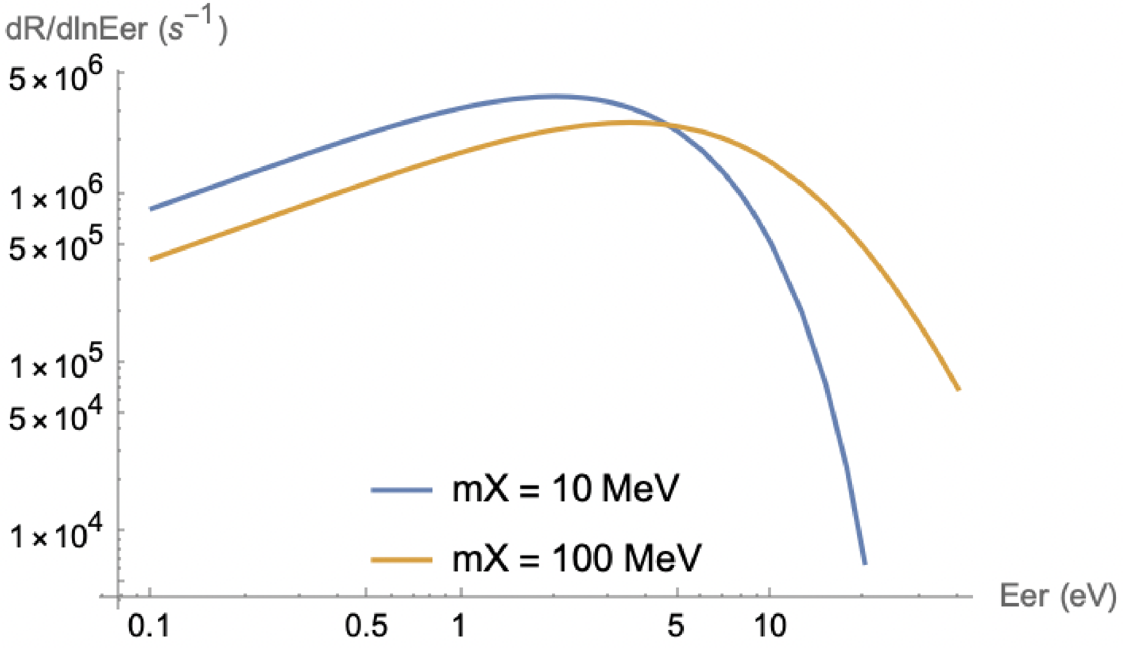
        Multiply the differential rate by $10\ E_{er}$

Light yield and efficiency for ionization

No photon yield



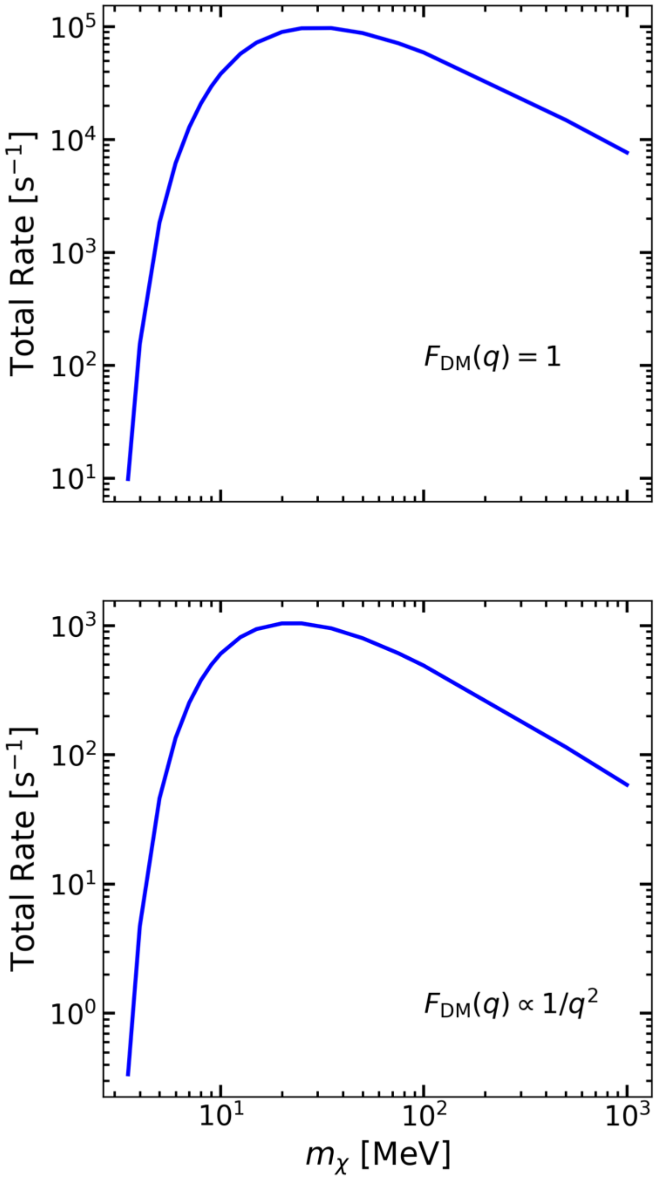
Photon yield included



For lower recoil energies, it’s less likely that a photon will be produced

Total ionization rate

- Integrate over differential rate (including photon yield and efficiency factor)
- Rate scales roughly as $1/m_\chi$ for high masses, aside from mass dependence of photon yield



Comparison between ionization and excitation

Factors that help ionization dominate:

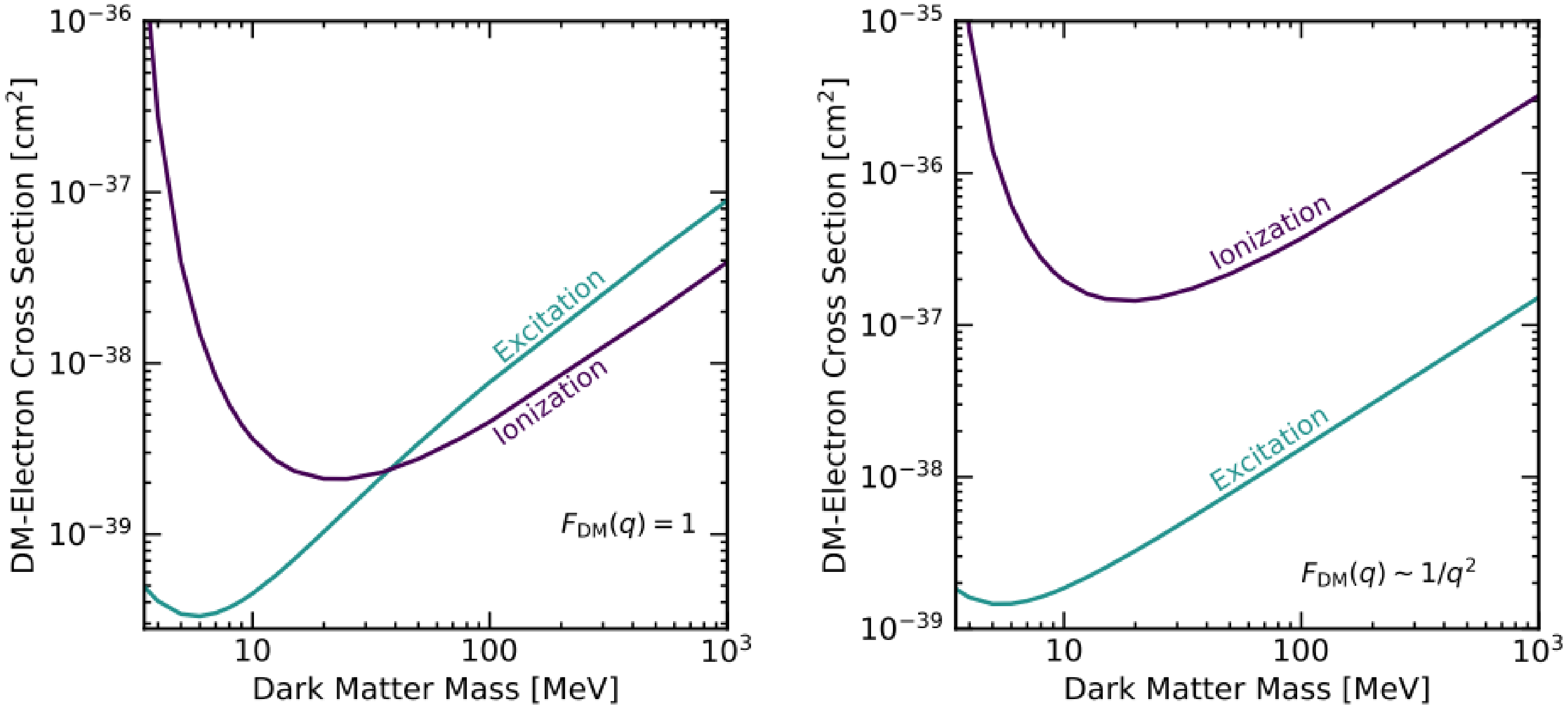
- Number of targets
- Annual modulation

Factors that help excitation dominate:

- Lower threshold
- Higher light yield

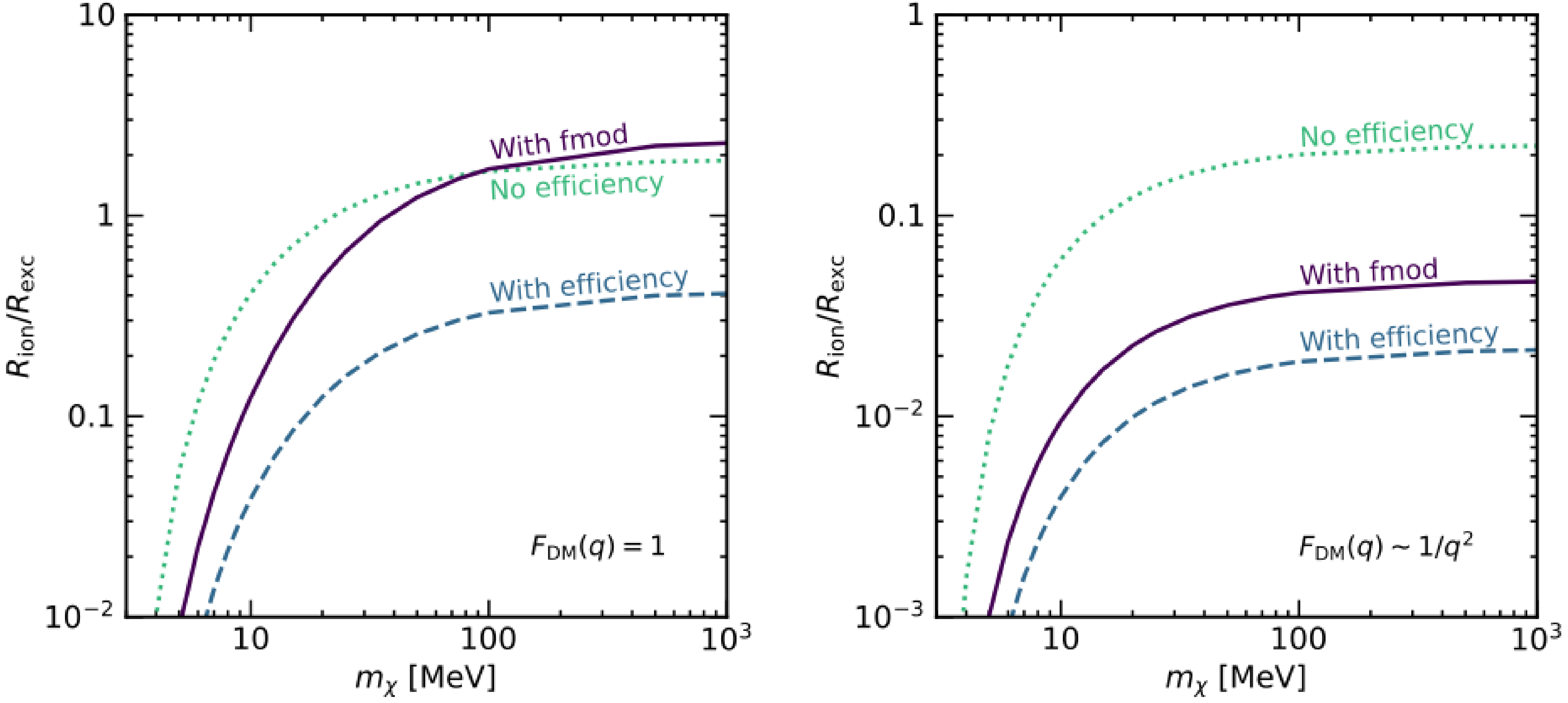
Light mediator:

- Lower threshold more important due to suppression at high momentum transfer



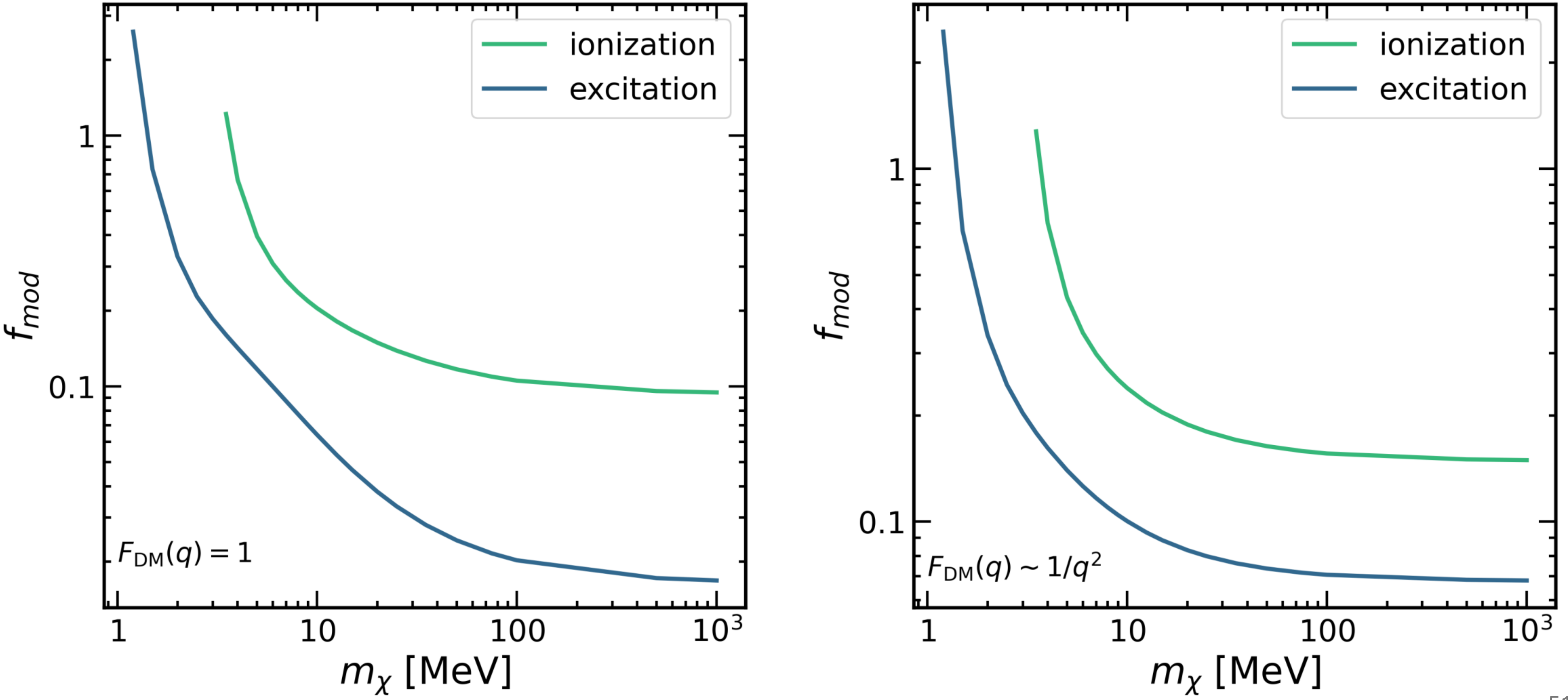
Comparison for JUNO

Comparison between ionization and excitation

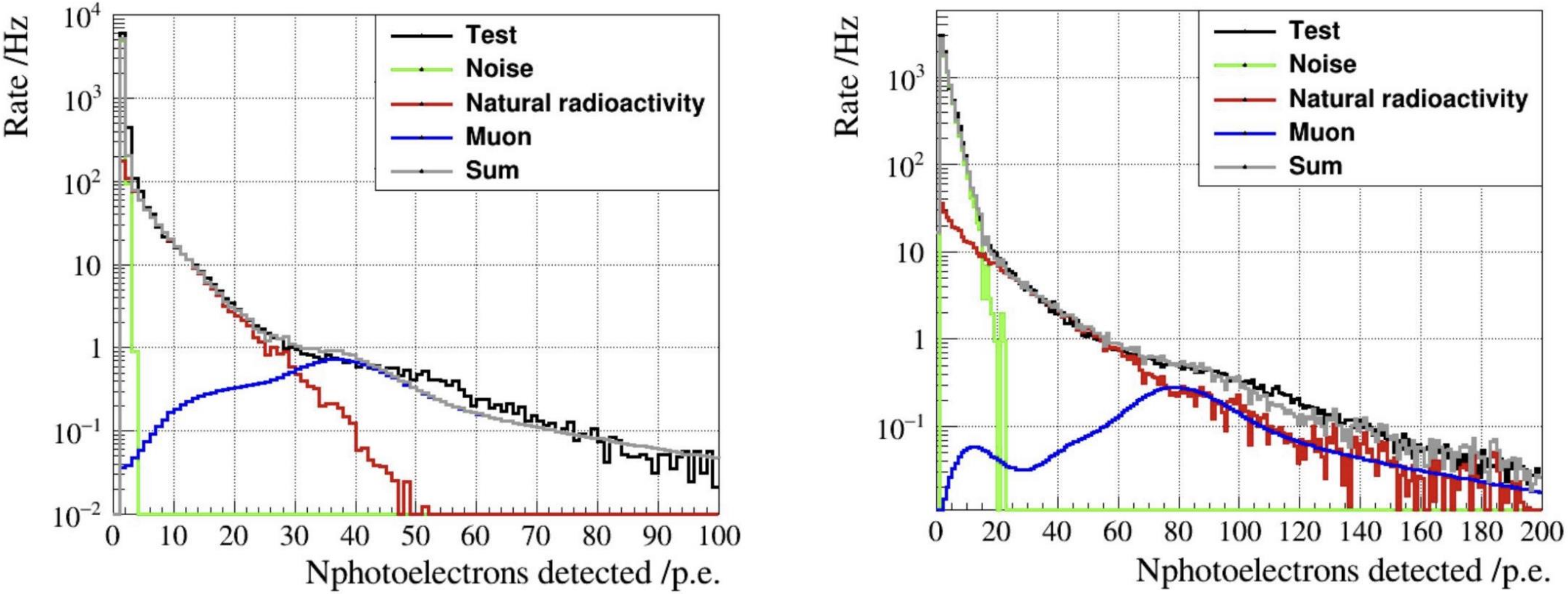


Annual Modulation

$$f_{mod} = \frac{R_{high} - R_{low}}{2\,R_0}$$



Background

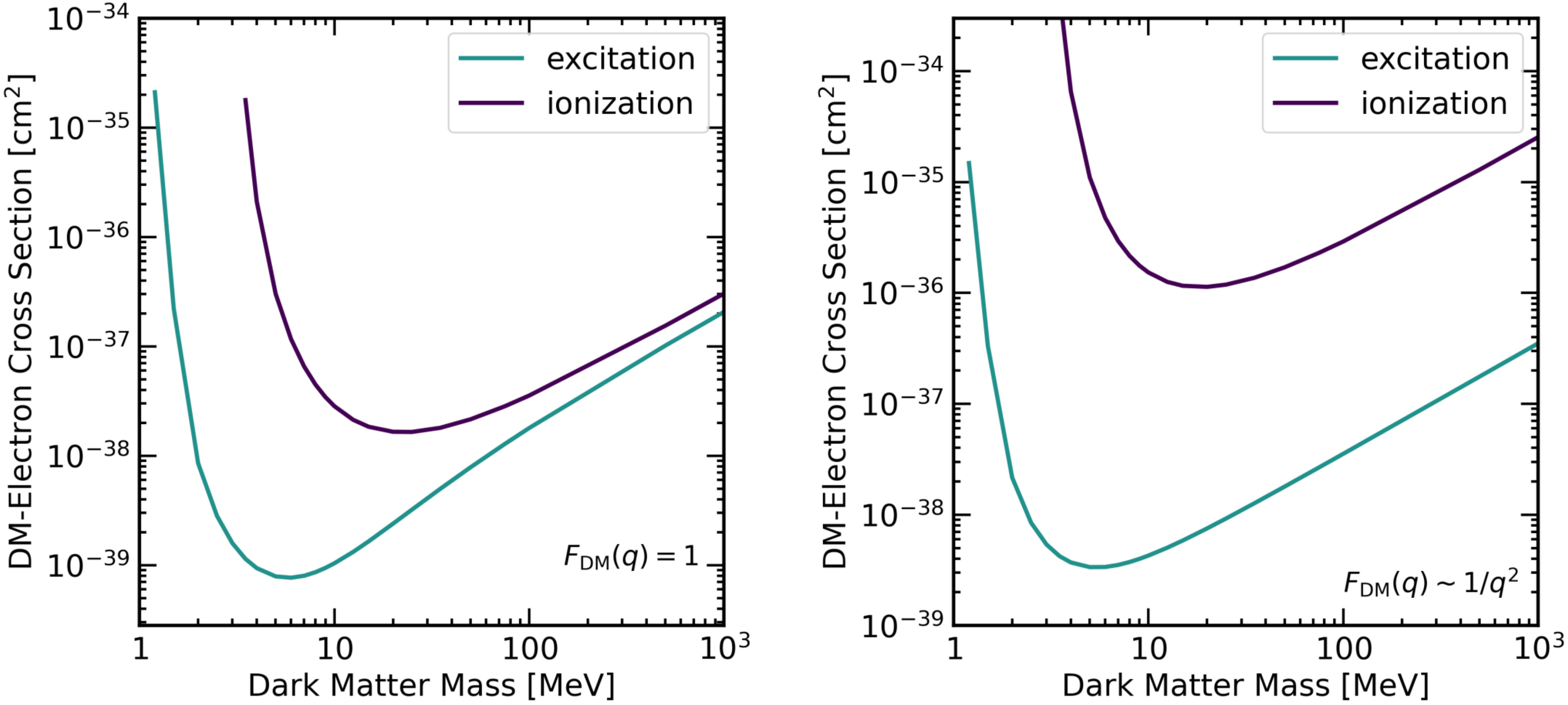


(a) HPK PMT fitted curves

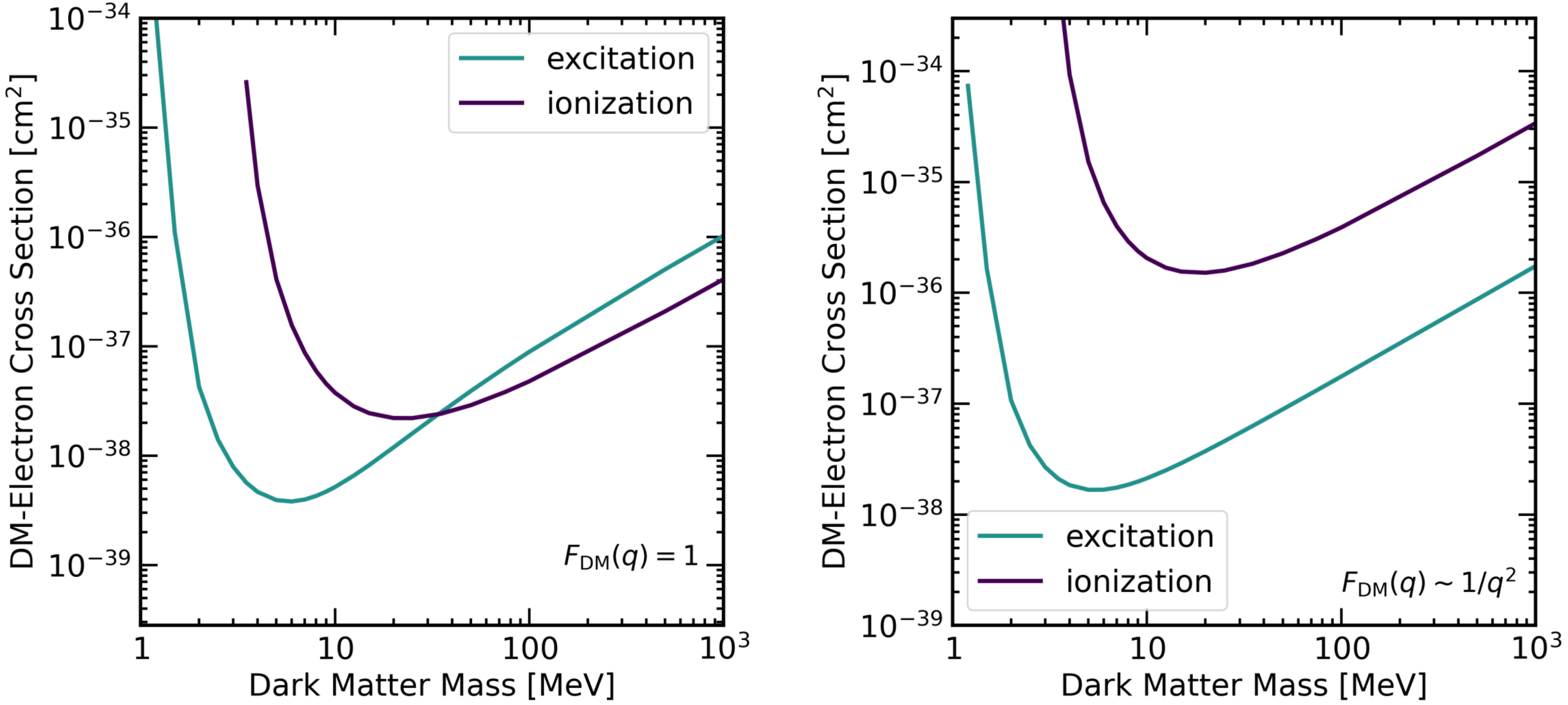
(b) NNVT PMT fitted curves

Zhang et al. (2307.15104)

Borexino


DM-Electron Cross Section [cm^2]
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
1
10
100
10^3
Dark Matter Mass [MeV]
excitation
ionization
$F_{\rm DM}(q) = 1$
DM-Electron Cross Section [cm^2]
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
1
10
100
10^3
Dark Matter Mass [MeV]
excitation
ionization
$F_{\rm DM}(q) \sim 1/q^2$

KamLAND



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