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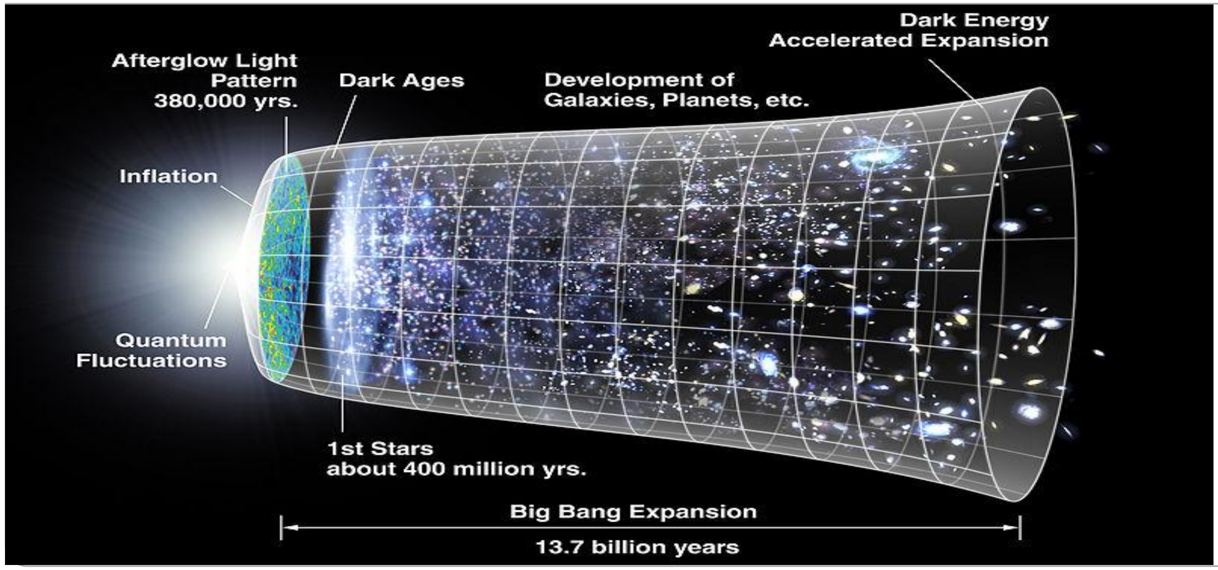
UNTERSTÜTZT VON / SUPPORTED BY

Alexander von HUMBOLDT STIFTUNG

Probing Sub-GeV Dark Matter via Migdal Effect-Induced Electron Excitations

Liangliang Su

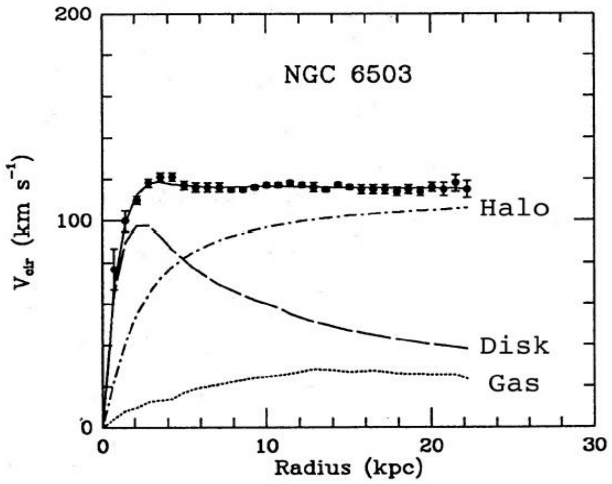
IDM2026, Zaragoza, Spain, 2 June, 2026



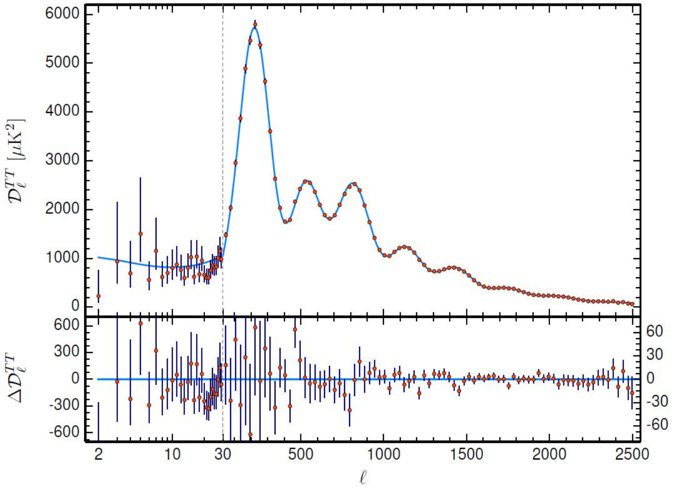
Based on **arXiv: 2604.26773** in collaboration with Felix Kahlhoefer

Gravitational Evidence of Dark Matter

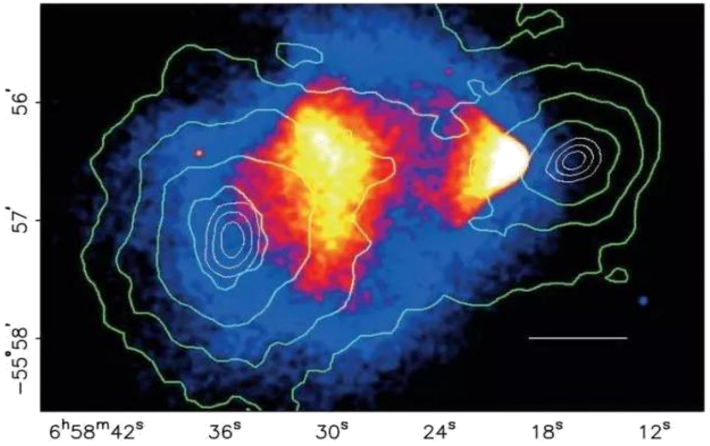
Galaxy rotation curve anomaly

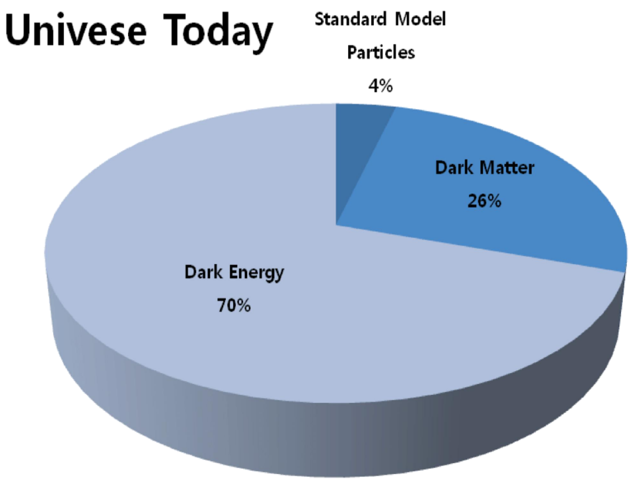


Cosmic microwave background



Bullet Cluster





DM Candidates and Direct Detection:

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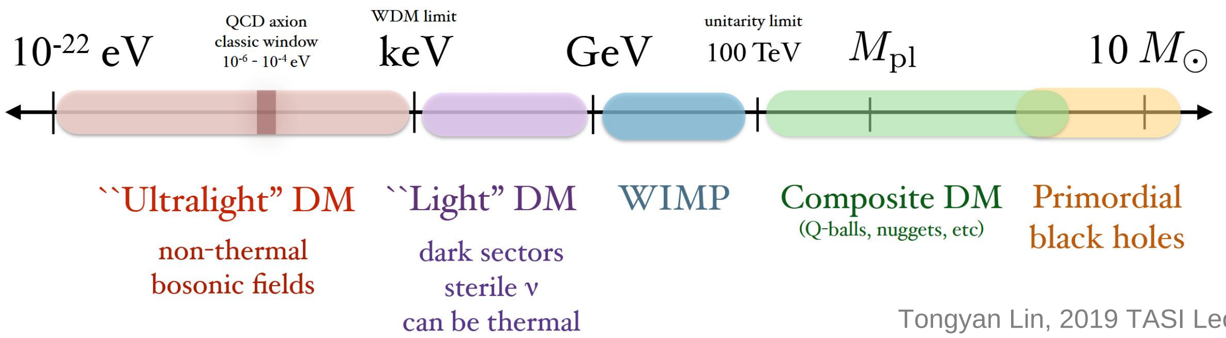


Tongyan Lin, 2019 TASI Lectures

- Current status of WIMPs

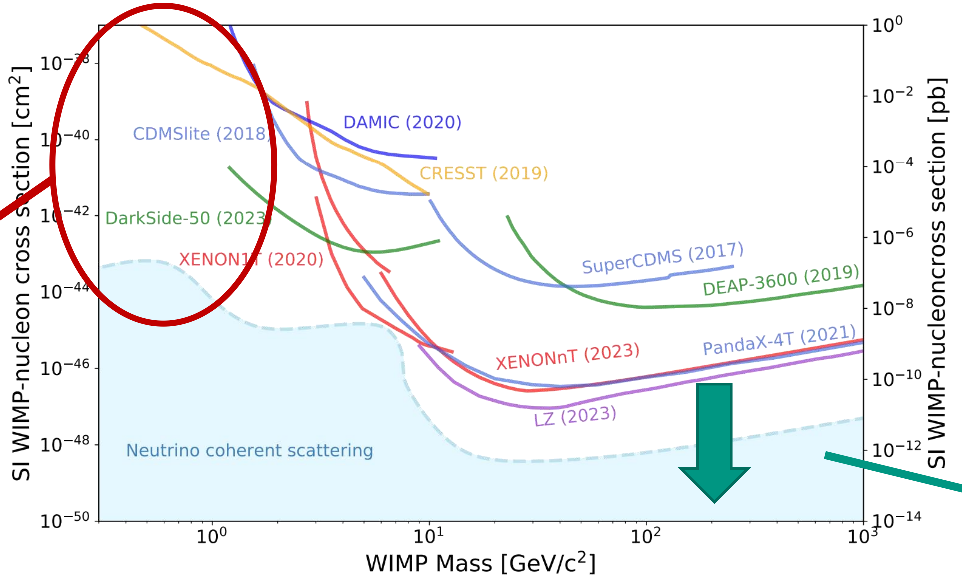
Light DM Detection:

1. Accelerated Dark Matter

2. Novel DM experiments

3. Electron signal

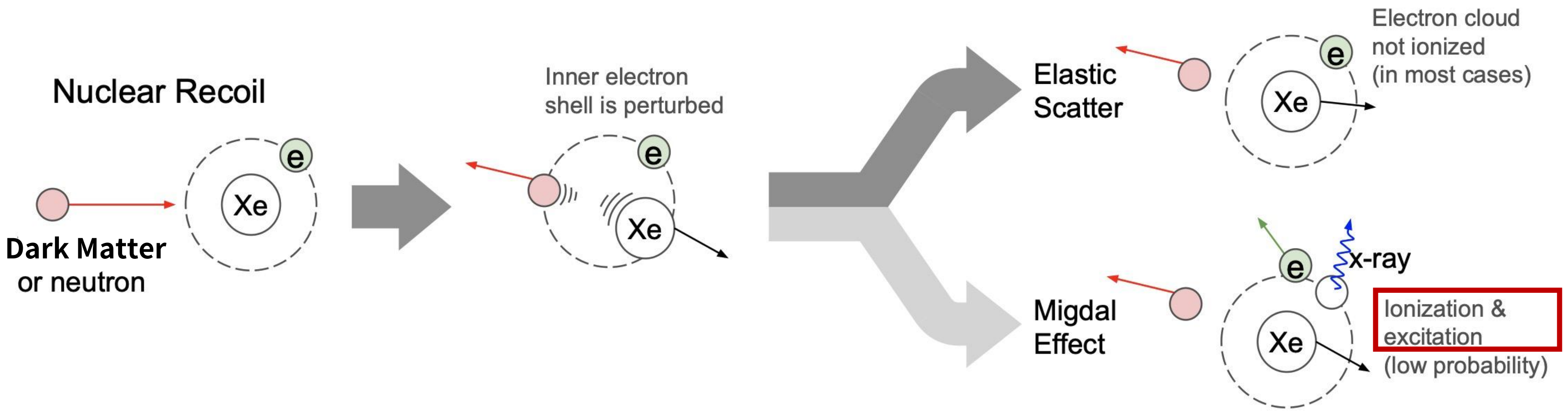
. . .



improve background discrimination:
Directional Detection

Migdal effect

The electrons of atoms or molecules are excited or ionized due to perturbations in the atom.



- Kinematics

$$v_{\min} = \frac{q}{2\mu_{\chi N}} + \frac{E_{\mathrm{EM}}}{q} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}} + \frac{E_{\mathrm{EM}}}{\sqrt{2 m_N E_R}} \Rightarrow \begin{cases} E_{\mathrm{NR}}^{\max} = \dfrac{2\mu_{\chi N}^2 v_{\max}^2}{m_N} \\ E_{\mathrm{EM}}^{\max} = \dfrac{1}{2}\mu_{\chi N} v_{\max}^2 \end{cases}$$

Migdal effect deposits more energy than the nuclear recoil for sub-GeV DM

Migdal effect in DM direct detection

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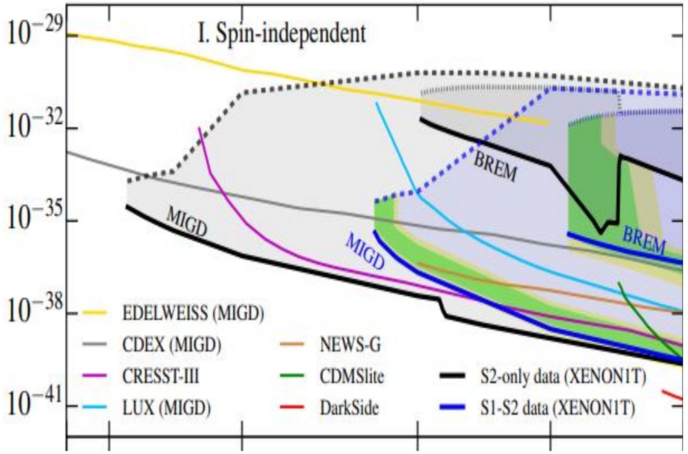
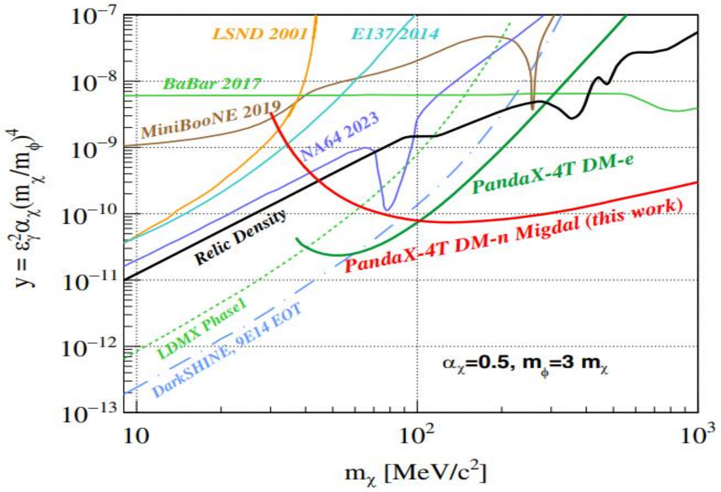
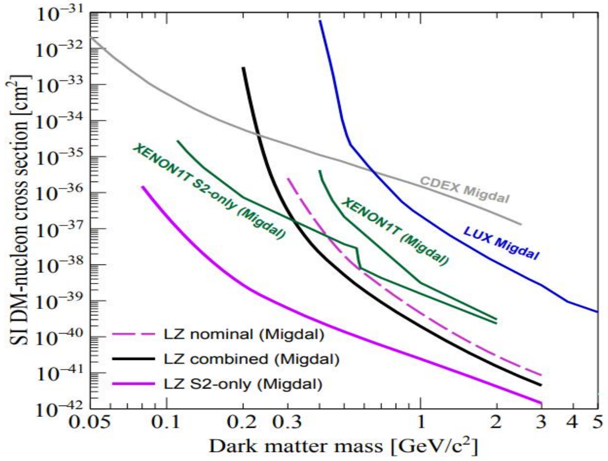
XENON1T PRL 23, 241803 (2019)



PandaX-4T PRL131, 191002 (2023)

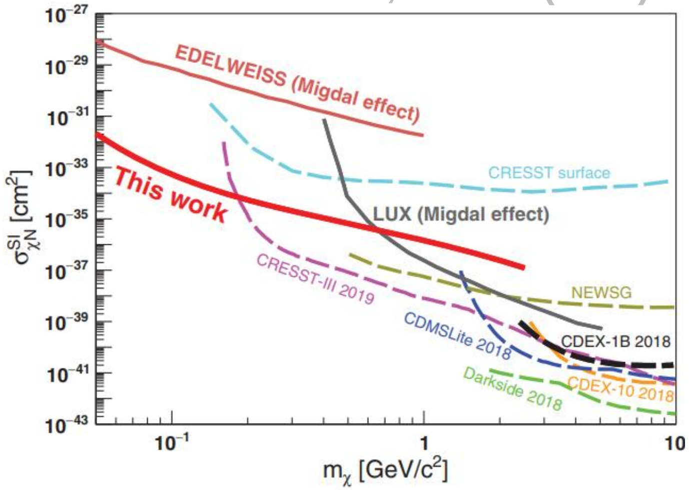


LZ arXiv:2101.08753

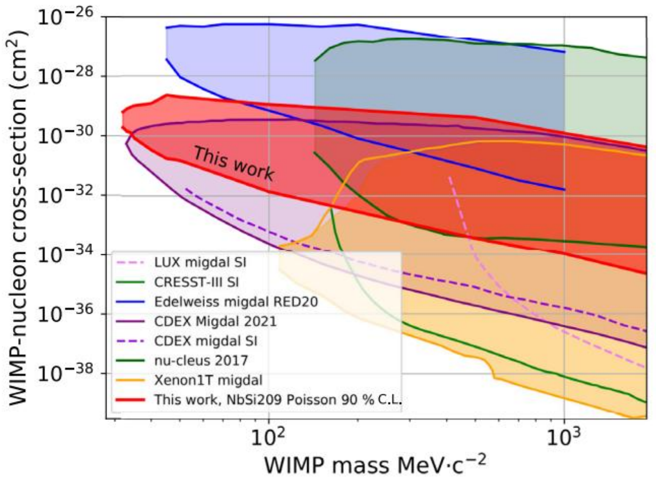


Electron Ionization

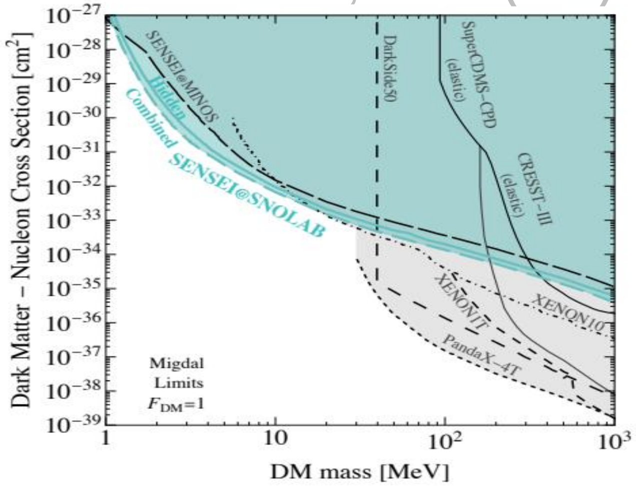
CDEX PRL 123, 161301 (2019)



EDELWEISS PRD 106, 062004 (2022)



SENSEI PRL 134, 011804 (2025)



Electron Excitation

?

Excitation Signal in Superfluid He-4 experiment

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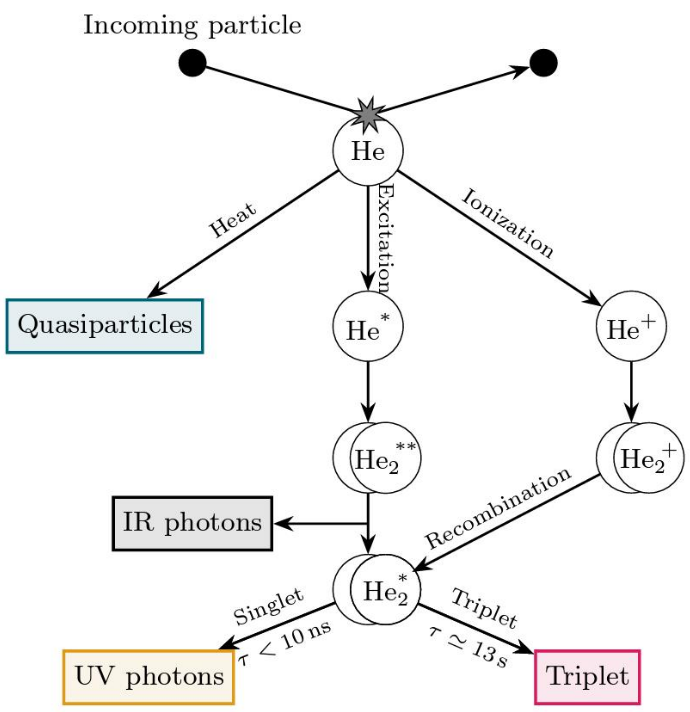


FIG. 1. Schematic representation of signal formation in LHe.

Francesco Toschi et al. arXiv:2410.13684

Excitation Signal: IR and UV photons

- **Electron Recoil:** DM-electron interaction

$$\chi + \mathrm{He} \to \chi + \mathrm{He}^*$$ Direct

- **Nuclear Recoil:** DM-nucleus interaction

$$\left.\begin{array}{l} \chi + \mathrm{He} \to \chi + \mathrm{He}^{0/1/2+} + ne^- \\ \mathrm{He}^{0/1/2+} + \mathrm{He} \to \mathrm{He}^{0/1/2+} + \mathrm{He}^* \end{array}\right\} \text{Indirect}$$

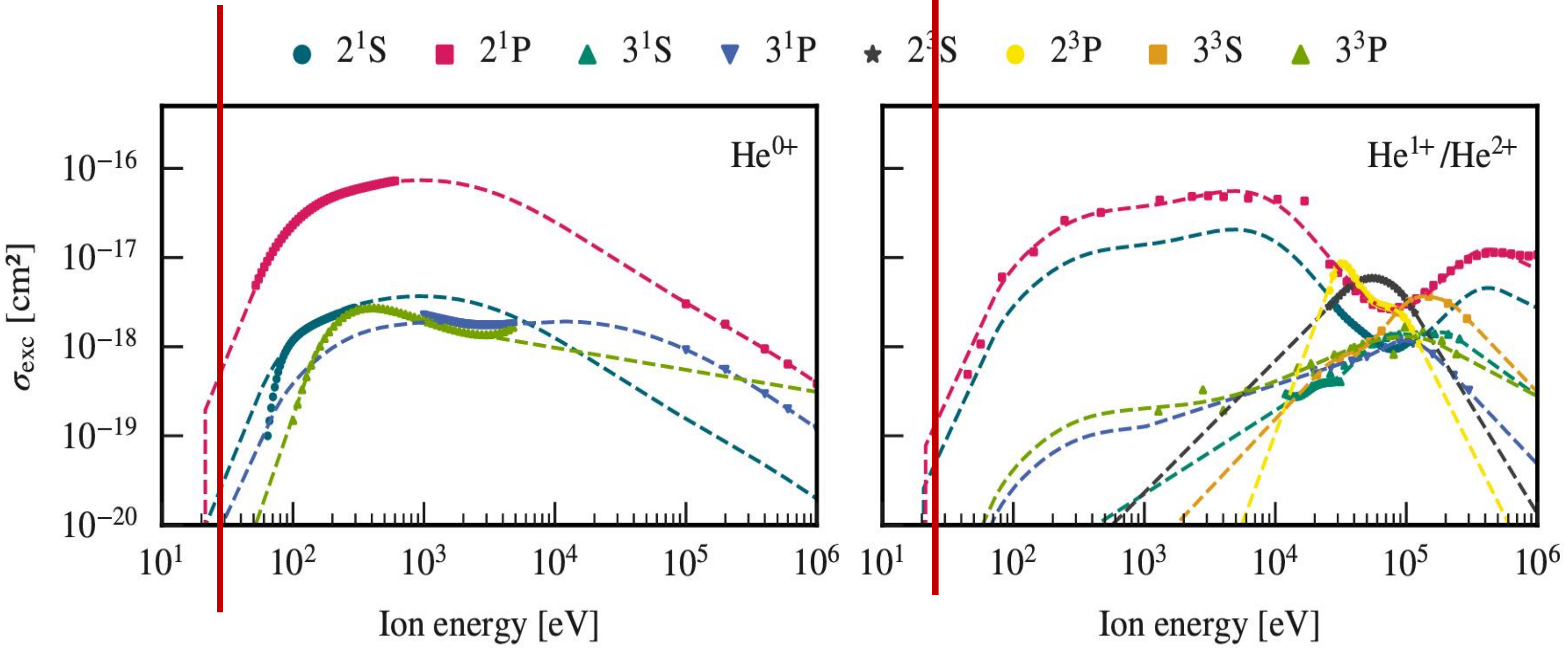
Can the DM-nucleus interaction directly induce excited atoms?

Migdal effect ✓

Excitation Signal in Superfluid He-4 experiment

- **Normal Nuclear Recoil:** $\mathrm{He}^{0/1/2+} + \mathrm{He} \to \mathrm{He}^{0/1/2+} + \mathrm{He}^*$

Francesco Toschi et al. arXiv:2410.13684



Excitation condition: the nuclear recoil energy must be larger than the excitation energy (~20 eV)

$$E_R^{\max} = \frac{2\mu_{\chi\mathrm{He}}^2 v_{\chi,\max}^2}{m_{\mathrm{He}}} \gtrsim 20\ \mathrm{eV} \quad \Rightarrow \quad m_\chi \gtrsim 0.1\ \mathrm{GeV}$$

Excitation Signal in Superfluid He-4 experiment

- **Migdal effect:** $\chi + \mathrm{He} \rightarrow \chi + \mathrm{He}^*$

Migdal can directly excite atoms in low nuclear recoil energy region

$$\boxed{E_{\mathrm{EM}}^{\mathrm{max}} = \frac{1}{2}\mu_{\chi\mathrm{He}} v_{\chi,\mathrm{max}}^2} > E_R^{\mathrm{max}} \quad \Longrightarrow \quad m_\chi \gtrsim 6\ \mathrm{MeV}$$

	Normal Nuclear Recoil	Migdal Effect
Excitation	**Indirect** (via Secondary ion collisions)	**Direct** (via sudden nuclear motion)
Recoil Req.	**High:** $E_R \gtrsim 20\mathrm{eV}$	**Low:** Sub-threshold E_R
Sensitivity	**Heavy DM:** $m_\chi \gtrsim 0.1\ \mathrm{GeV}$	**Light DM:** $m_\chi \gtrsim 6\ \mathrm{MeV}$

The Migdal effect bypasses the 20 eV recoil energy threshold, enabling **MeV-scale** DM detection.

Transition Probability of Migdal Effect

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Impulse Approximation

After the collision, the wave function of electronic states in rest frame of nucleus

$$|\Psi_i\rangle \xrightarrow[\text{Galilean boost}]{} |\Psi_i'\rangle = e^{i\mathbf{q}_e\cdot\sum_k \mathbf{r}_k}|\Psi_i\rangle$$

- $|\Psi_i\rangle$ is electonic wave function in the rest frame of nucleus before the interaction
- $\mathbf{r}_k$ is the position of k-th electon
- $\mathbf{q}_e = m_e\mathbf{v}_e = -m_e\mathbf{v}_A$

Transition probability induced by Migdal effect

$$P_{fi} = \left|\langle\Psi_f|\Psi_i'\rangle\right|^2 = \left|\langle\Psi_f|e^{i\mathbf{q}_e\cdot\sum_k \mathbf{r}_k}|\Psi_i'\rangle\right|^2$$

- $|\Psi_f\rangle$ is the final electronic wave function in rest frame of nucleus

Transition Probability of Migdal Effect

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Atomic wave function (Multiconfiguration Hartree–Fock method)

Atomic state functions (ASF) can be expanded by the configuration state functions (CSFs)

$$\underbrace{\boxed{\Psi(PJM_J)}}_{\text{ASF}} = \sum_{\gamma=1} \boxed{C_\gamma} \underbrace{\boxed{\Phi(\gamma PJM_J)}}_{\text{CSFs}}$$

Expansion (mixing) coefficients

Example:

$$|\Psi_{1s2s,J=0}\rangle = C_1|\Phi_{1s2s,J=0}\rangle + C_2|\Phi_{1s3s,J=0}\rangle + \cdots$$

The CSFs are given as coupled anti-symmetric products of one-electron orbitals

CG coefficients

$$|\Phi_{1s2s,J=0}\rangle = \boxed{\frac{1}{\sqrt{2}}}\mathrm{Det}(\psi_{1s_{1/2},+\frac{1}{2}}, \psi_{2s_{1/2},-\frac{1}{2}}) - \frac{1}{\sqrt{2}}\mathrm{Det}(\psi_{1s_{1/2},-\frac{1}{2}}, \psi_{2s_{1/2},\frac{1}{2}})$$

$$\mathrm{Det}(\psi_{a_1}, \phi_{a_2}) \equiv \frac{1}{\sqrt{2}}(\psi_{a_1}(1)\psi_{a_2}(2) - \psi_{a_1}(2)\psi_{a_2}(1))$$

$$\boxed{\psi_{n\kappa m}(r,\theta,\varphi) = \frac{1}{r}\begin{pmatrix} P_{n\kappa}(r)\Omega_{\kappa m}(\theta,\varphi) \\ iQ_{n\kappa}(r)\Omega_{-\kappa m}(\theta,\varphi) \end{pmatrix}}$$

Transition Probability of Migdal Effect

Transition probability

$$|\Psi_i\rangle = \sum_\gamma C_i^\gamma |\Phi_i^\gamma\rangle \quad |\Psi_f\rangle = \sum_\gamma C_f^\gamma \left|\Phi_f^\gamma\right\rangle \quad \Longrightarrow \quad p_v(|\Psi_i\rangle \to |\Psi_f\rangle) = \left| \sum_{\gamma,\gamma'} \left(C_f^{\gamma'}\right)^* C_i^\gamma \det\left(M^{\gamma'\gamma}\right) \right|^2$$

- $M^{\gamma'\gamma}$ is the $N \times N$ matrix of single-electron matrix elements

Single electron matrix elements

$$\begin{aligned} M_{n\kappa m}^{n'\kappa' m'} &\equiv \langle \psi_{n',\kappa',m'} | \exp(i\mathbf{q}_e \cdot \mathbf{r}) | \psi_{n,\kappa,m} \rangle \\ &= \sqrt{4\pi} \sum_{L,M} (-i)^L \sqrt{2L+1} Y_L^M(\hat{v}_A) \boxed{d_M^L(j', m'; j, m)} \\ &\times \int_0^\infty dr j_L(m_e v_A r)[P_{n,\kappa}(r) P_{n',\kappa'}(r) + Q_{n,\kappa}(r) Q_{n',\kappa'}(r)] \end{aligned}$$

Angular coefficients: Deciding to selection rules

$$\Delta s = 0$$

Only singlet excitation state for He-4

$$n\ {}^{2s+1}L:\ 2\ {}^1S, 2\ {}^1P \cdots$$

Transition Probability of Migdal Effect

Calculating Radial Electron wave function

GRASP : ground state and excited state

RATIP：ionization

- ground state

$1s^2_{1/2},{}^1S_0$: **Only** considering **this configuration** with no electron excitation

- Excited state Peter Cox *et al*. PRD 107, 035032 (2023)

Iterative procedure: 1. progressively **increase** the maximum **n**，

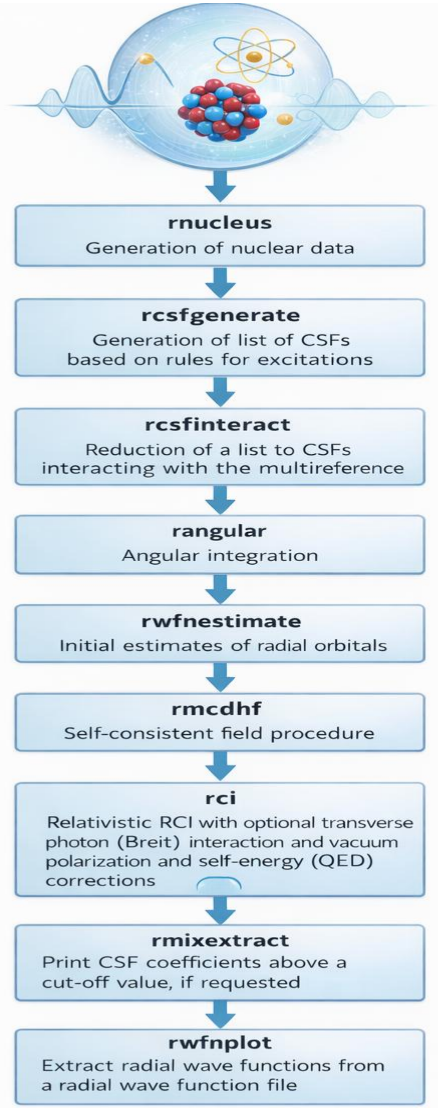
2. keeping **lower-*n*** radial functions **fixed**.

Fixed Fixed

$$1s^2 \rightarrow \{\boxed{1s^2}, 1s2s, 1s2p\} \rightarrow \{\boxed{1s^2, 1s2s, 1s2p}, 1s3s, 1s3p, 1s3d\}\cdots$$

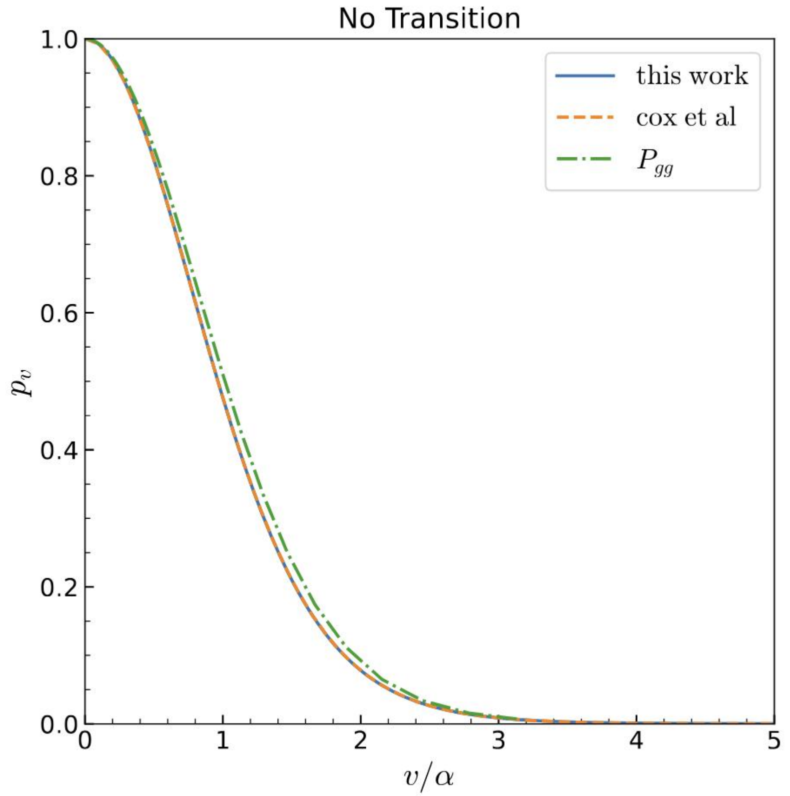
Dominant：$n \leq 3$

$$\boxed{2\,{}^1P_0, 3\,{}^1P_0, 2\,{}^1S_0, 3\,{}^1S_0}$$

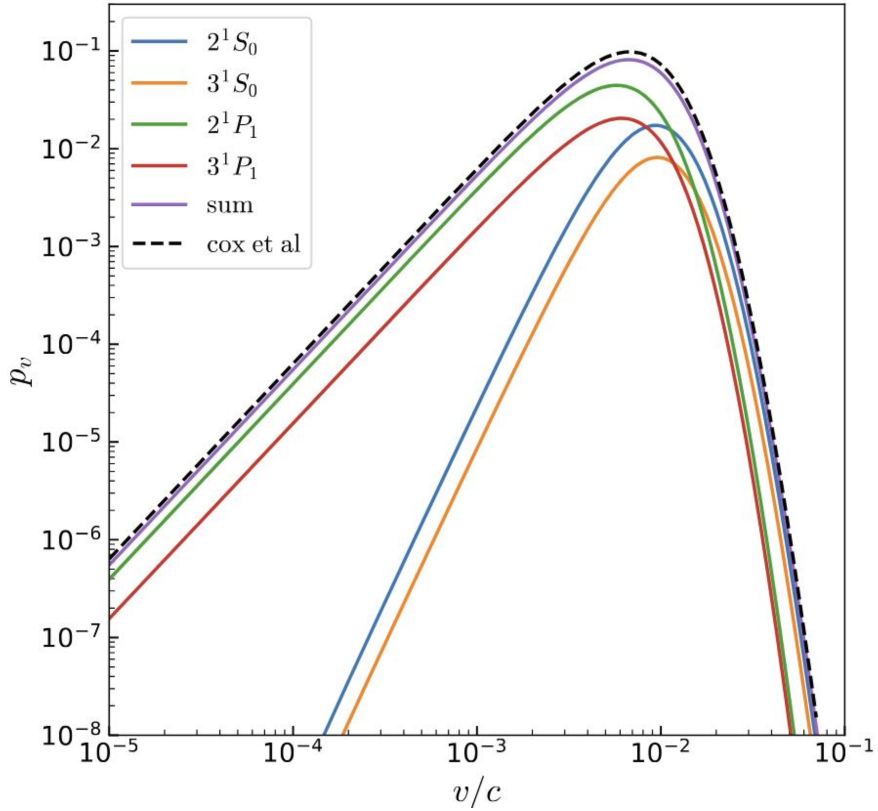


Transition Probability of Migdal Effect

Transition Probability Results



$$P_{gg} = \frac{1}{[1 + (8v/27\alpha)^2]^8},$$



Excitation Event from Migdal Effect

Differential Event Rate

Fermionic dark matter + Heavy vector mediator

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi A^2 \sigma_{\chi n}^{\mathrm{SI}}}{2 m_\chi \mu_{\chi n}^2} |F_{\mathrm{N}}(E_R)|^2 |F_{\mathrm{DM}}(E_R)|^2 p_{exc}(v_R) \eta_\chi(v_{\min})$$

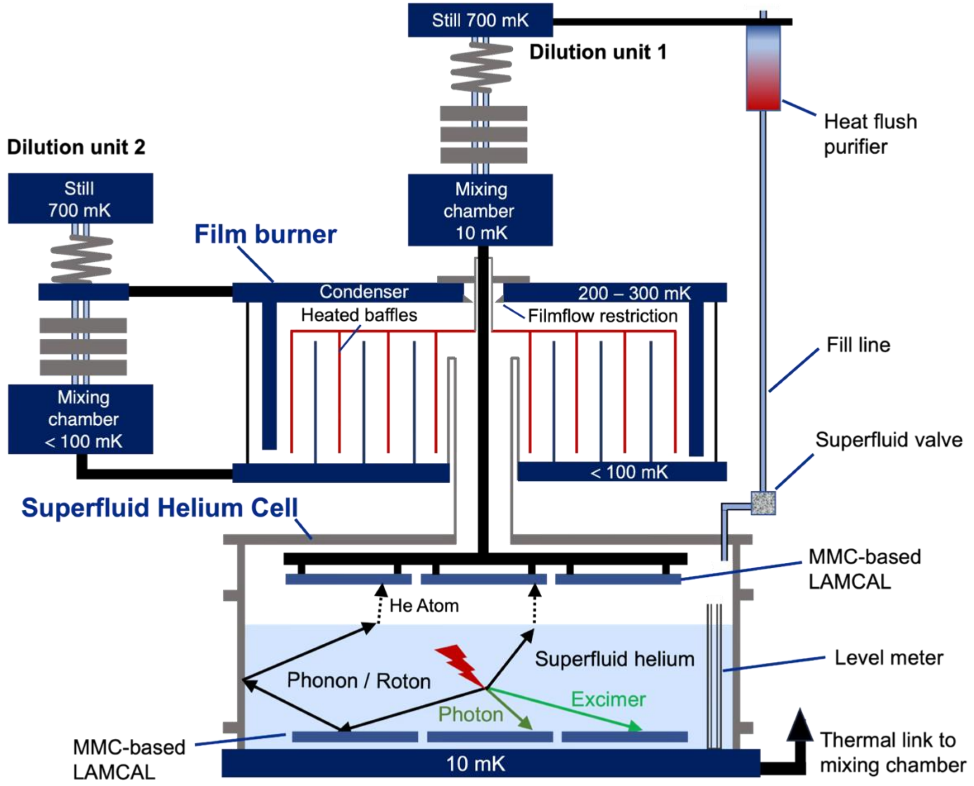
- $|F_{\mathrm{DM}}(E_R)|^2 = 1$ is DM Form factor for heavy mediator
- $F_{\mathrm{N}}(E_R)$: nuclear form factor of helium
- $p_{exc}(v_A)$: excitation probability
- Inverse mean speed:

$$\eta(v_{\min}) = \int \mathrm{d}^3 \vec{v}_\chi f(\vec{v}_\chi) \frac{1}{v_\chi} \Theta(v_\chi - v_{\min}) \qquad v_{\min} = \sqrt{\frac{m_{\mathrm{He}} E_{\mathrm{R}}}{2\mu_{\chi \mathrm{He}}^2}} + \frac{\boxed{|E_{\mathrm{exc}}|}}{\sqrt{2 m_{\mathrm{He}} E_{\mathrm{R}}}}$$

Excitation Energy

State	$\lvert E_{exc} \rvert$ [eV]
$2\,^1\mathrm{S}$	20.616
$2\,^1\mathrm{P}$	21.218
$3\,^1\mathrm{S}$	22.920
$3\,^1\mathrm{P}$	23.087

DELight Experiment



Superfluid He-4 experiment with MMCs sensor

See IDM2026 talk:

Francesco Toschi, Wed. 16:20

Sensitivity Projections

Results

- DELight is in its design phase
  currently operating demonstrator

- Frist Measurement Plan

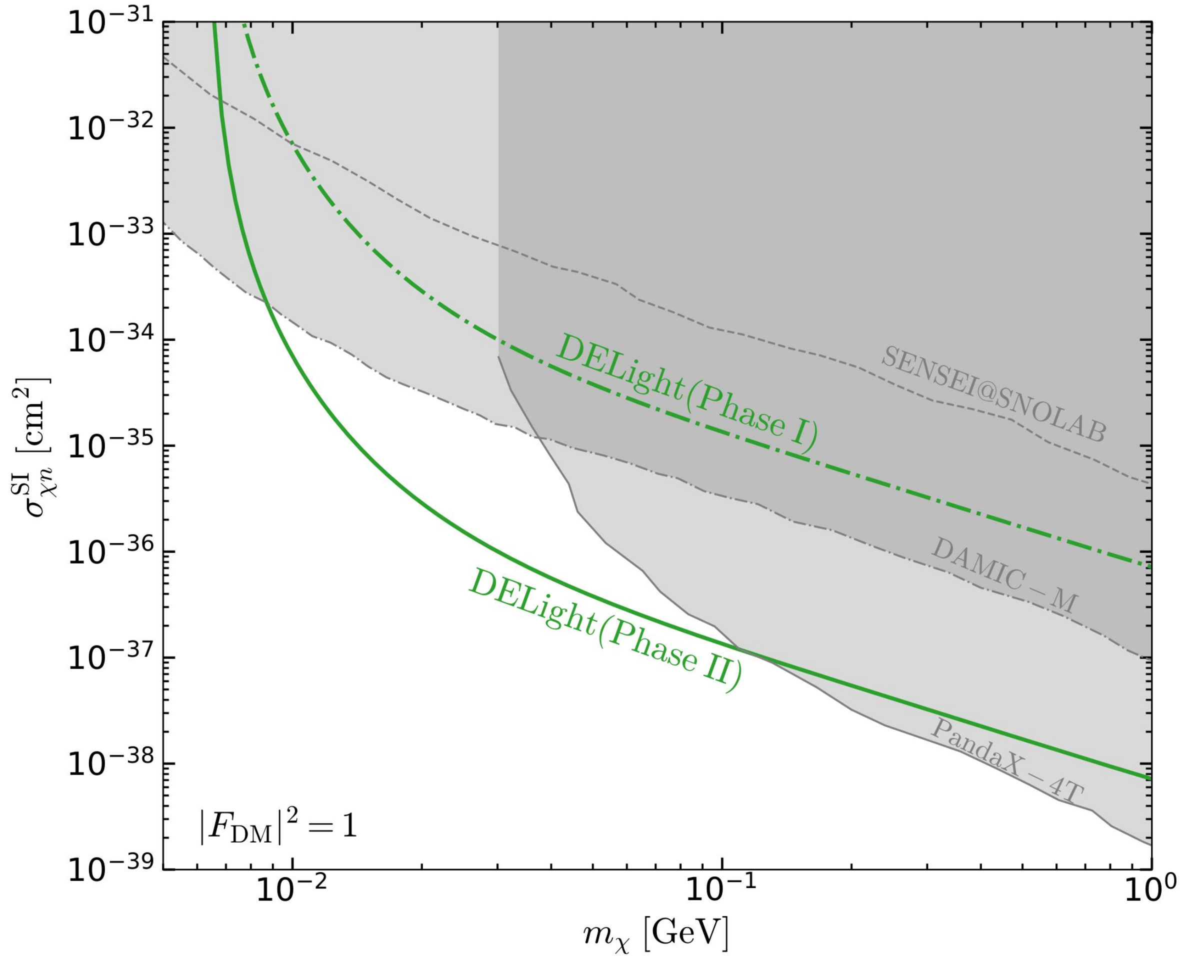
  Phase-I: 1 kg·d exposure and 20 eV threshold

  Phase-II: 100 kg·d exposure and 10 eV threshold

- Limits

  Poisson 90% C.L. upper limit (zero background)

  ***N* > 2.3 Events**



Migdal-induced electron excitation probes DM–nucleus scattering down to a few MeV.

Summary

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- Sub-GeV dark matter can be probed via the Migdal effect, which induces atomic excitation even for sub-threshold nuclear recoils.
- For superfluid He-4, only singlet excited states contribute to detectable signals.
- The resulting excitation rate provides competitive sensitivity to sub-GeV dark matter in experiments such as DELight.
- Migdal-induced excitation offers a powerful complementary probe beyond traditional nuclear recoil searches.

Probing Sub-GeV Dark Matter via Migdal Effect-induced Electron Excitations

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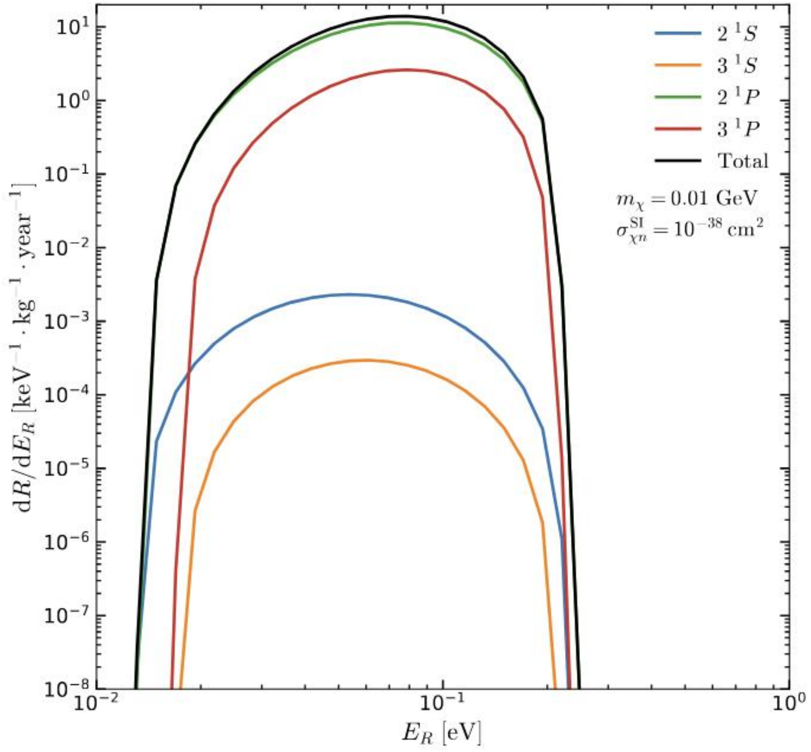
Thank you for your attention!

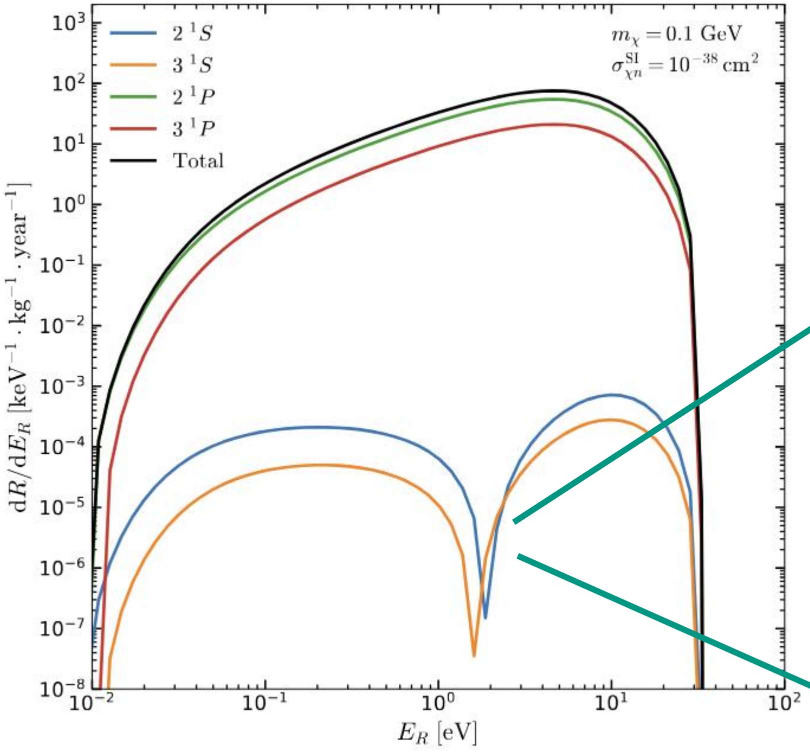
Questions, comments and collaborations are welcome.

Backup

Excitation Event from Migdal Effect

Results

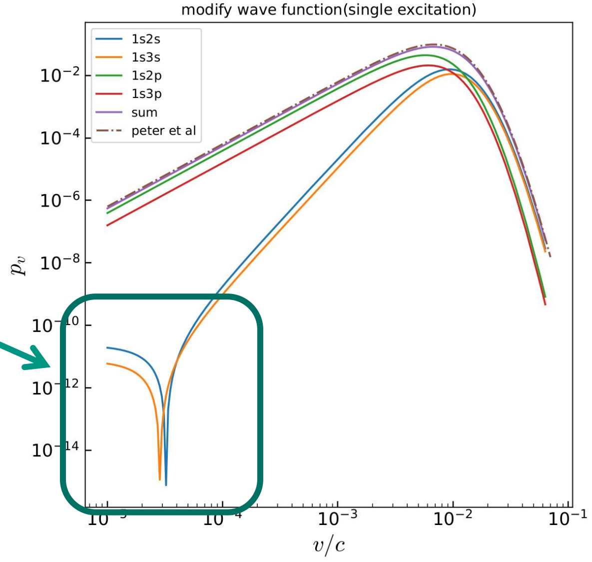




Orthogonality problem

- $L = 0$ term

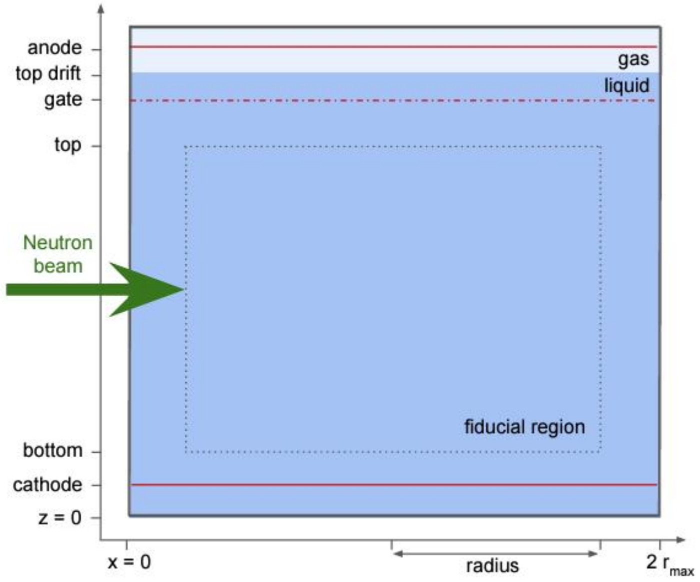
$$\int_0^\infty dr j_0(m_e v_A r)[P_{n,\kappa}(r)P_{n',\kappa'}(r) + Q_{n,\kappa}(r)Q_{n',\kappa'}(r)] \neq_{v_A \to 0} 0$$



The dominant process is ground state to 2 ^1P excited state.

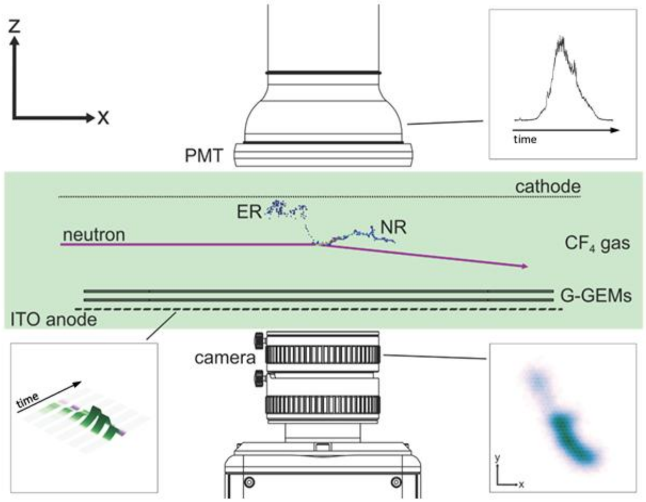
Proposal/Experiments to Discover Migdal Effect with Neutrons

Bell et al, PRD 105, 096015 (2022)



$E_{\mathrm{neutron}} \sim 15\ \mathrm{keV}$

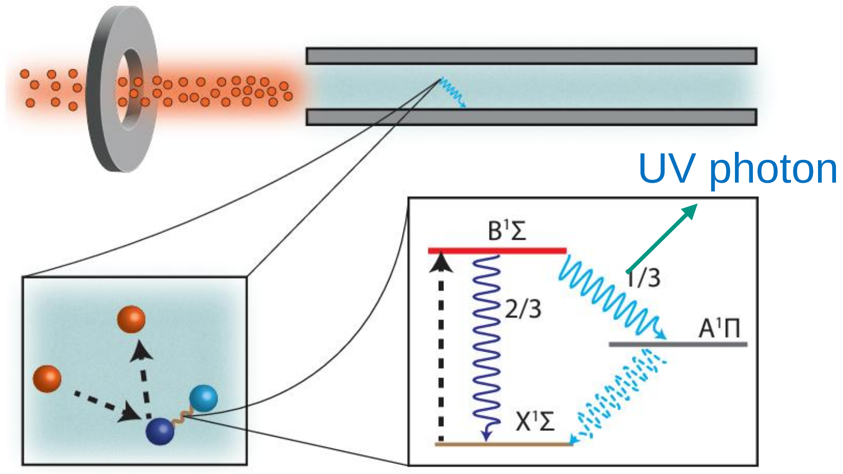
Araújo et al (MIGDAL), Astropart.Phys. 151 102853 (2023)



$E_{\mathrm{neutron}} \sim 2.5 - 15\ \mathrm{MeV}$

Based on ionization induced by Migdal

Kahn et al, PRD 110, 092012(2024)



$E_{\mathrm{neutron}} \sim 100\ \mathrm{eV}$

Based on excitation induced by molecular Migdal effect

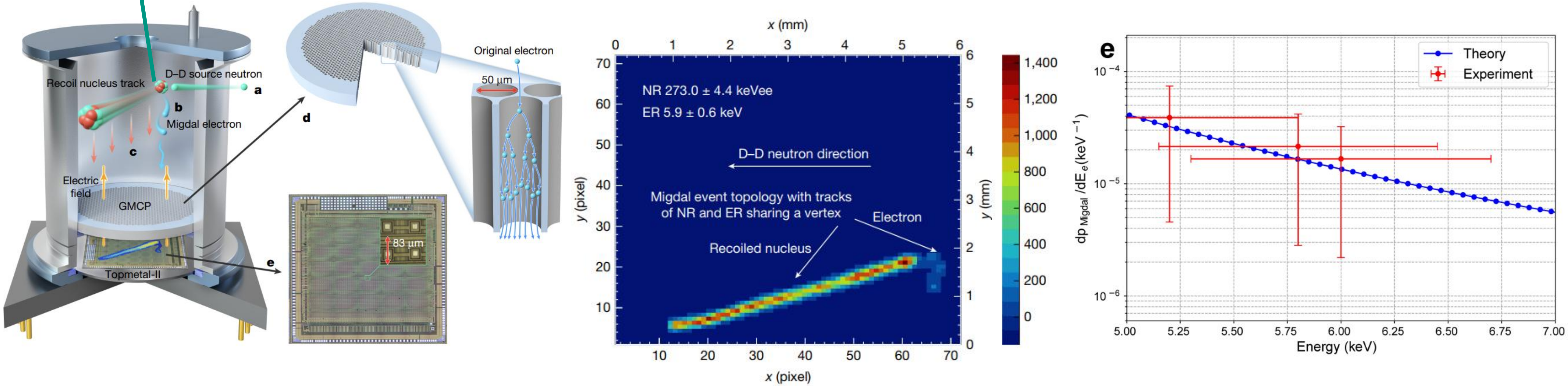
Proposal/Experiments to Discover Migdal Effect with Neutrons

MigdAI pRocess Validation by nEutruaL scattering (MARVEL group)

40% helium and

60% dimethyl ether (DME: CH3OCH3)

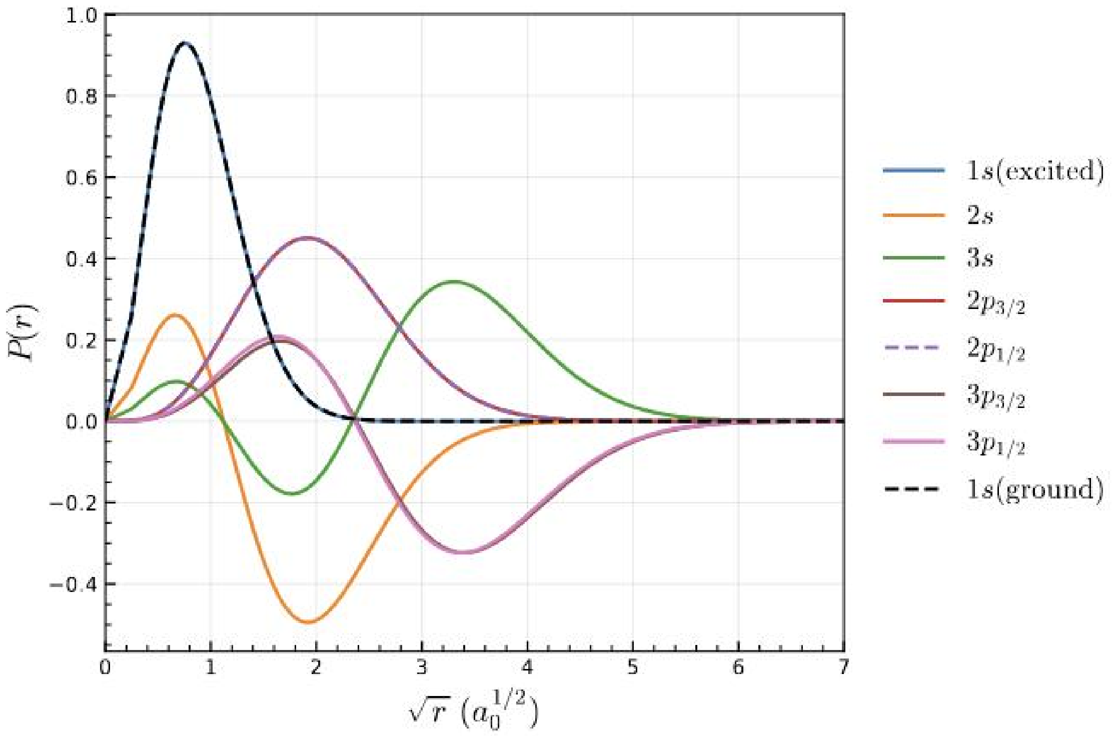
Yi et al (MARVEL), Nature 649, 580–583 (2026)

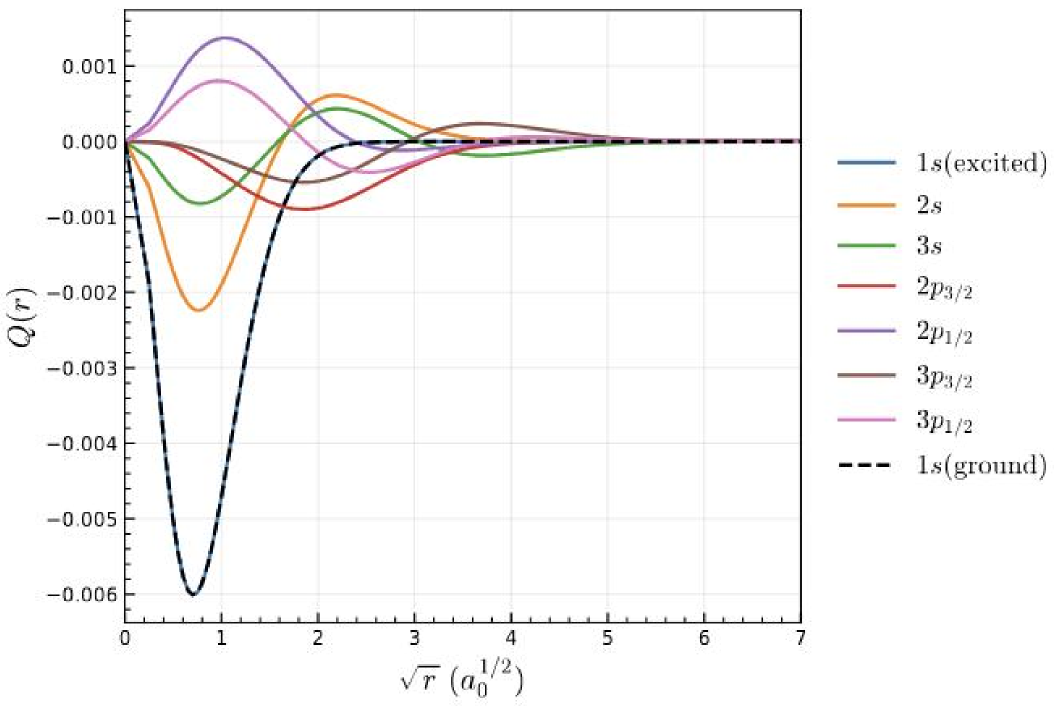


The first direct evidence of Migdal effect in neutron-nucleus collisions

Transition Probability of Migdal Effect

Calculating Radial Electron wave function





Different excited states share the same 1s orbital as the ground state.