Fast Moving Dark Matter at Direct Detection Experiments

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In colaboration with
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Nov. 14th 2022

arXiv:2006.16252
arXiv:22xx.xxxx

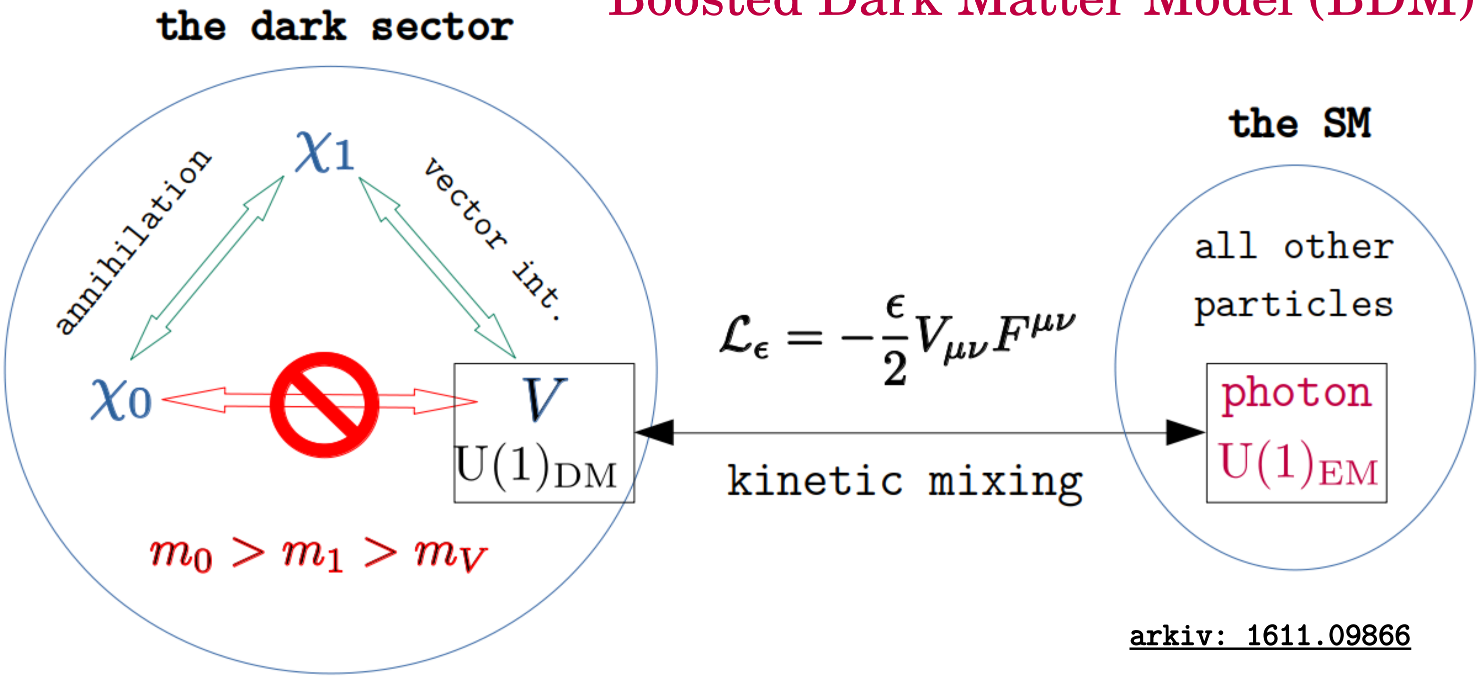
Dark Interactions

New Perspectives from Theory and Experiment

This workshop will be held as a virtual event.
November 14–16, 2022

Boosted Dark Matter Model (BDM)

- Multi-component
- Interactions
- Mass splitting
- Stability
- Self Interaction
- Abundances



the dark sector

χ_1

annihilation

vector int.

χ_0

V

$U(1)_{DM}$

$m_0 > m_1 > m_V$

the SM

all other particles

photon

$U(1)_{EM}$

$$\mathcal{L}_\epsilon = -\frac{\epsilon}{2} V_{\mu\nu} F^{\mu\nu}$$

kinetic mixing

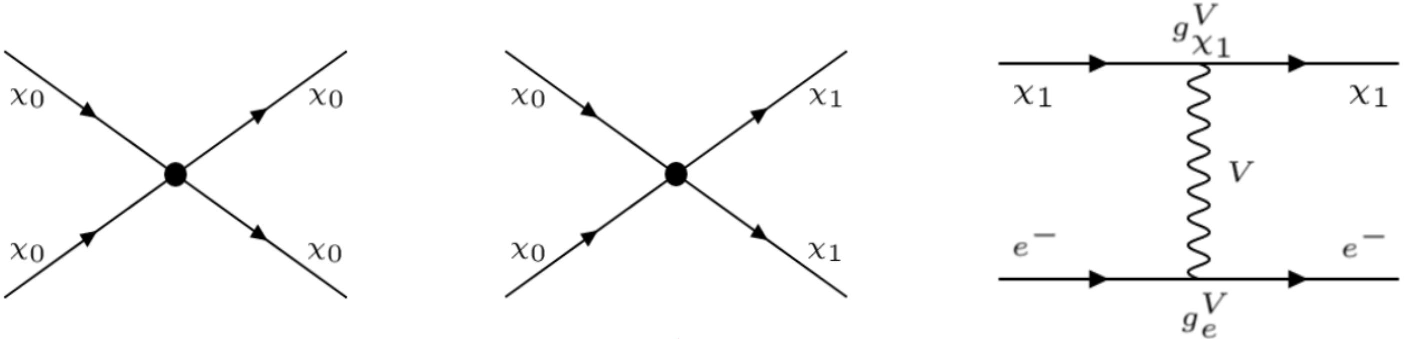
arkiv: 1611.09866

assisted freeze out mechanism

$$\sigma_{11\to XX} \gg \sigma_{00\to 11}$$

$$\Omega_{\chi_1}/\Omega_{\chi_0} \ll 1$$

arXiv:1112.4491



model parameters: $\{\sigma^{\text{self}}_{00}, g^V_e\, g^V_{\chi_1}, m_0, m_1, m_V\}$

Summary of Boosted Dark Matter Studies

Ref.	Boost Mechanism			Source			Interaction		Phenomenology at				
(ArXiv)	A	D	semi-A	GC	Sun	dSps	e^-	N	SK/HK	DUNE	IceCube	Sur.	DD
1405.7370 [1]	✓			✓			E		✓		✓		
1407.3280 [2]		✓		✓				E			✓		
1410.2246 [3]	✓		✓		✓			E	✓				
1411.6632 [4]	✓				✓		E		✓		✓		
1501.03166 [5]	✓			✓				E					✓
1610.03486 [6]	✓			✓		✓	E		✓	✓			
1611.09866 [7]	✓			✓	✓		E		✓	✓			
1612.06867 [8]							IE		✓	✓			
1712.07126 [9]	✓			✓			IE						✓
1803.03264 [10]	✓			✓			IE					✓	
1804.07302 [11]	✓	✓		✓	✓		E					✓	
1806.09154 [12]	✓			✓			IE		✓				
1903.05087 [13]	✓			✓			IE			✓			

Abbreviations

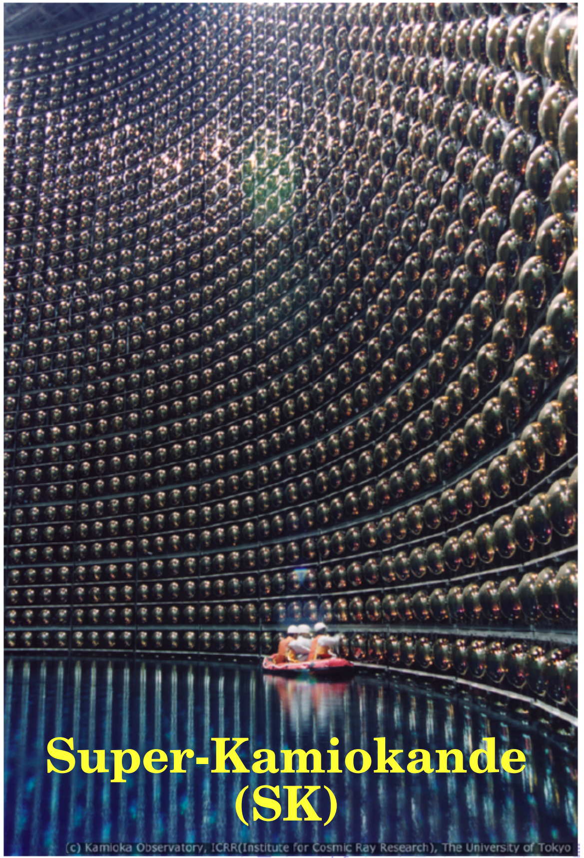
A: annihilation [14, 15], D: decay [16, 17], semi-A: semi-annihilation [18–22].

dSphs: dwarf spheroidal galaxies, e-: electron, N: nucleon.

E: elastic, IE: inelastic, SK: Super-Kamiokande, HK: Hyper-Kamiokande, DUNE: Deep Underground Neutrino Experiments.

Sur.: surface neutrino detectors, DD: direct detection experiments.

Large Volume Neutrino Experiments



Super-Kamiokande (SK)

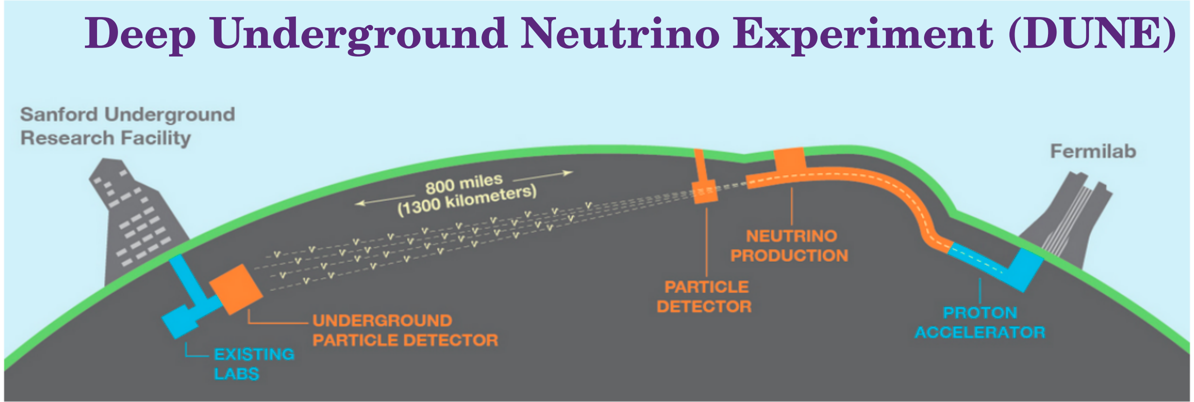
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

	Volume (kTon)	$E_{\rm th}$ (MeV)	$\theta_{\rm res}$	Running Time (years)
SK [109]	22.5	100	3°	~ 18
HK [110]	560	100	3°	
DUNE [111]	$40-50$	30	1°	

$\frac{N_{\rm bkg}}{\rm year}$		DUNE20	DUNE40	SK	HK
	GC	2 with 10°	4 with 10°	7.01 with 10°	174 with 10°
	Sun	0.02 with 1°	0.04 with 1°	0.632 with 3°	15.7 with 3°

BDM signal sources: $N_{\rm sig} = \Delta T \times N_{\rm target} \times \Phi \times \sigma_{1e}$

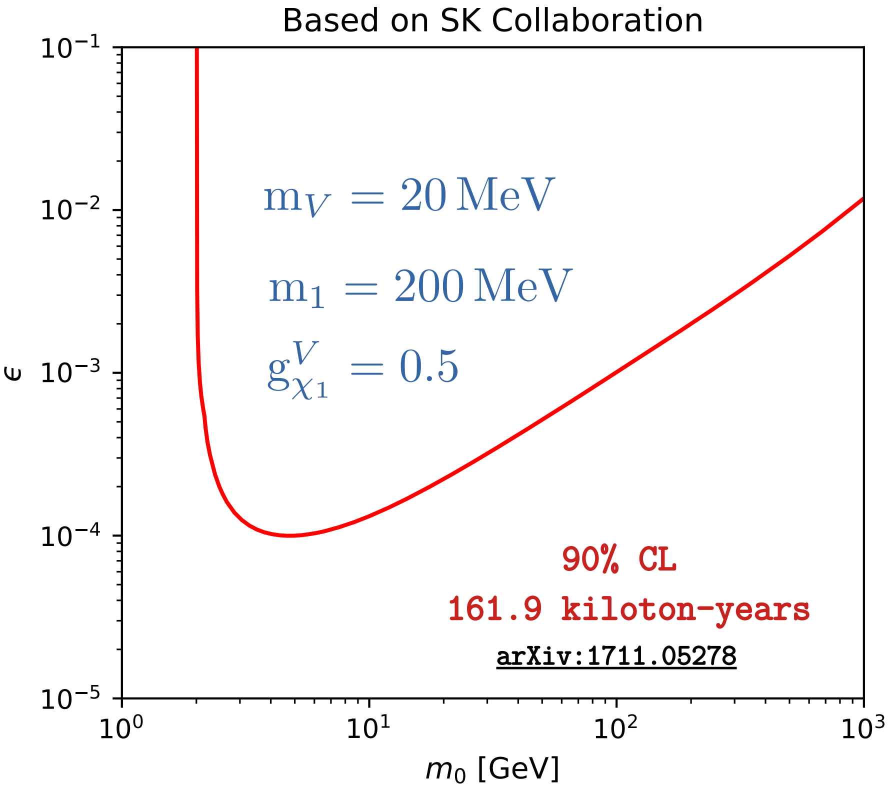
$E_{\rm th}$ `requires sufficiently high electron recoil energies.` ⇒ $m_0/m_1 \gtrsim \mathcal{O}(10)$ `electrons: free-at-rest`



Deep Underground Neutrino Experiment (DUNE)

Fast Moving Dark Matter at Direct Detection Experiments

Experimental Study



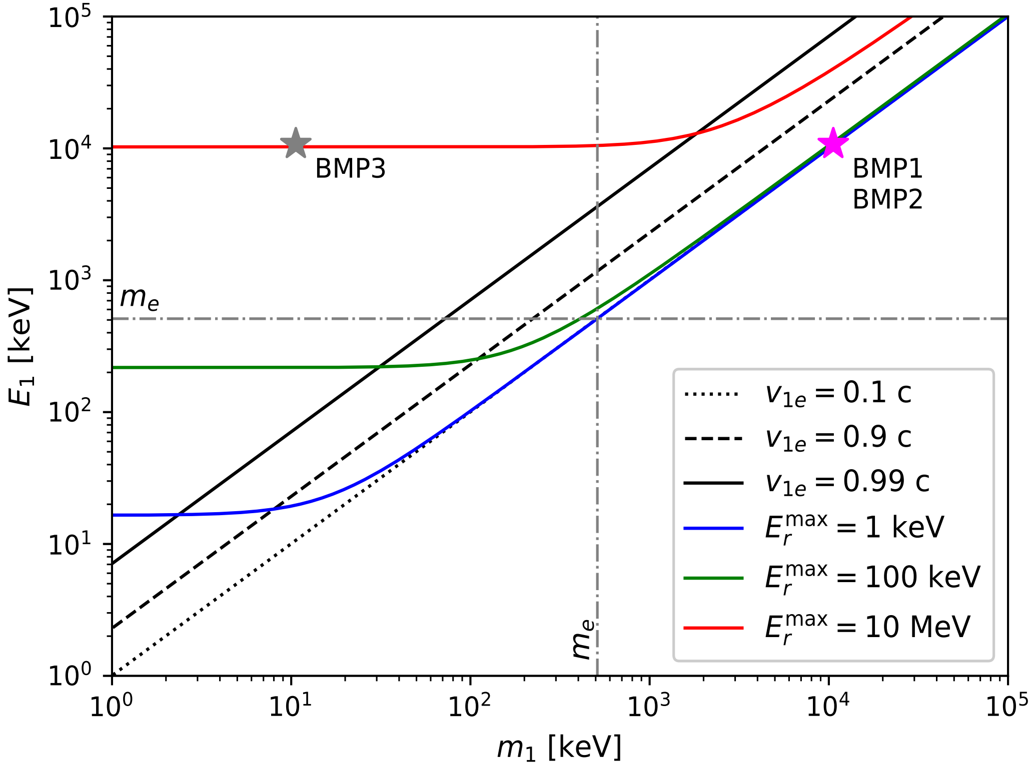
After proving the principle, how can we generalize?

- High recoil vs low recoil: necessity to exploit the full parameter space.
- Revisiting the free-at-rest electron assumption.
- Exploring different models of BDM.
- Generalization to boost mechanism independent framework.

We can discuss all the above at once by considering BDM or fast moving dark matter at low energy electron recoil such as DD experiments.

Fast Moving Dark Matter at Direct Detection Experiments

anatomy of the mass-energy space



Recoil energy: E_r

spin classification

Mediators: V, A, P and S.

DM particles: F and S.

⇩

7 different combinations

Atomic Physics Effects

$$\text{DM}(p) + e^-(k) \to \text{DM}(p') + e^-(k')$$

- **Electrons are bound to the target atoms, treating them as free is effectively valid only at high E_r.**
- **At low E_r, atomic effects become very important.**
- **We shall re-derive the scattering cross section to accommodate such effects.**
- **Star wit free scattering, replace:** $\delta^3(\mathbf{p}+\mathbf{k}-\mathbf{p}'-\mathbf{k}')$ **with** $\left|f_{e_i\to e_f}\right|^2$.

different considerations for the transition factor, $\lvert f_{e_i\to e_f}\rvert$.				
method	regiem	$\lvert e_i\rangle$ wave functions initial e^- $(n\ell)$	$\langle e_f\rvert$ final e^- $(E_r\ell')$	mediator
1 (PW)	non-relativistic	RHF	PW	S,V
2 (SCE)		RHF	Schrodinger	S,V
3 (DCE)	relativistic	Dirac (DHFS)		S,V P, A
4 (DCE)		Dirac (erf)		S,V P, A
5 (DCE)		Dirac (exp)		S,V P, A

transition factor

$$\left|f_{e_i\to e_f}(\mathbf{q})\right| = \langle e_f|e^{i\mathbf{q}\cdot\mathbf{r}}|e_i\rangle$$

ionization form factor

$$|f_{ion}(E_r,|\mathbf{q}|)|^2 = \frac{2\,|\mathbf{k}'|^3}{(2\pi)^3}\int d\Omega_{\hat{\mathbf{k}}'}\,|f_{e_i\to e_f}(\mathbf{q})|^2.$$

non-rel. $(n\ell)$

rel. $(n\kappa)$

binding energy

$$\frac{d\sigma_{1e}^{n\ell}}{dE_r} = \frac{1}{64\pi v_{1e}}\,\frac{1}{E_1E_r(2m_e+E_r)(m_e-\boxed{|E^B_{n\ell}|})\sqrt{E_1^2-m_1^2}}\int_{|\mathbf{q}|^{\min}}^{|\mathbf{q}|^{\max}} d|\mathbf{q}|\;\;|\mathbf{q}|\,|\mathcal{M}|^2\boxed{|f_{ion}(E_r,\,|\mathbf{q}|)|^2}$$

$$\left|f_{e_i\to e_f}\right|^2 \to \delta^3(\mathbf{p}+\mathbf{k}-\mathbf{p}'-\mathbf{k}')\;\text{ and }\;|E^{\text{B}}_{n\ell}| = 0 \quad\Longrightarrow\quad \frac{d\sigma_{1e}}{dE_r} = \frac{m_e\,|\mathcal{M}|^2}{8\pi\,\lambda\,(s,m_e^2,m_1^2)}$$

Fast Moving Dark Matter at Direct Detection Experiments

Example rel. wave functions

$$\hat{h} = \boldsymbol{\alpha} \cdot \mathbf{p} + m_e\,(\beta - 1) + V_{\text{eff}}(r)$$

numerical solution: `RADIAL`, `dtfatom`

Example potential

$$\mathrm{V}^{\mathrm{DHFS}}_{\mathrm{eff}}(r) = V_{\mathrm{nuc}}(r) + V_{\mathrm{el}}(r) + V_{\mathrm{ex}}(r)$$

state			Xe absolute ionization energy in atomic units.				
$n_{\ell j}$	n	κ	-Z/r	[129]	V_{eff}^{ERF} [125, 126]	V_{eff}^{EXP} [127]	V_{eff}^{DHFS} [128]
$1_{s_{1/2}}$	1	-1	1519	1277	1261	1263	1270
$2_{s_{1/2}}$	2	-1	383.8	202.5	196.4	196.2	199.1
$2_{p_{1/2}}$	2	1	383.8	189.7	184.5	184.2	187.6
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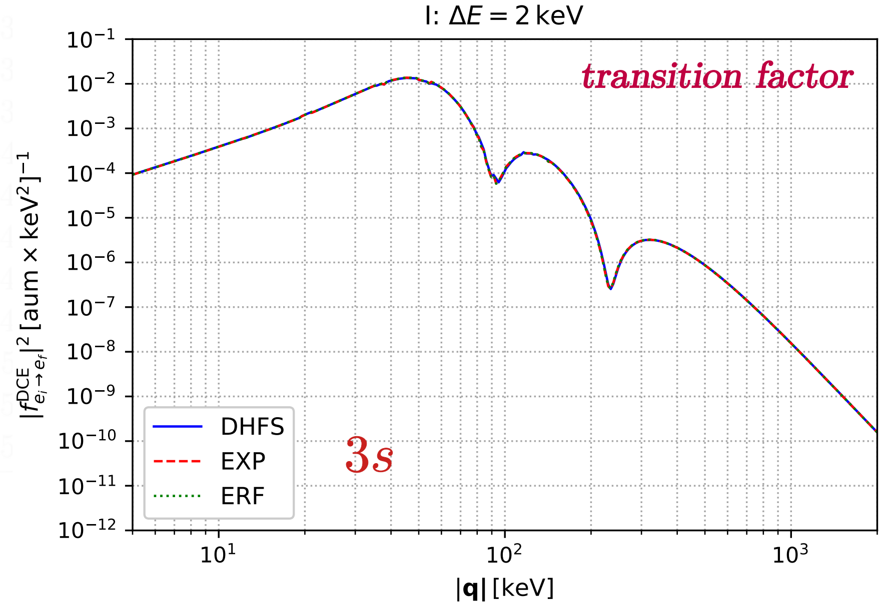
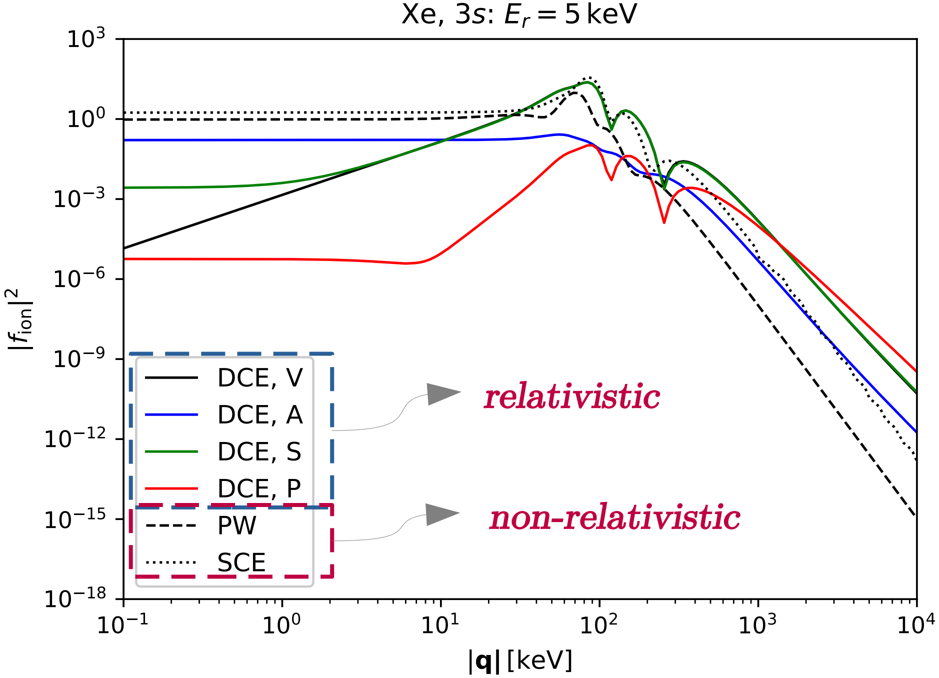
$3_{s_{1/2}}$	3	-1	168.8	43.01	40.39	40.36	41.24

ionization form factor
relativistic vs non-relativistic



transition factor

3s



relativistic

non-relativistic

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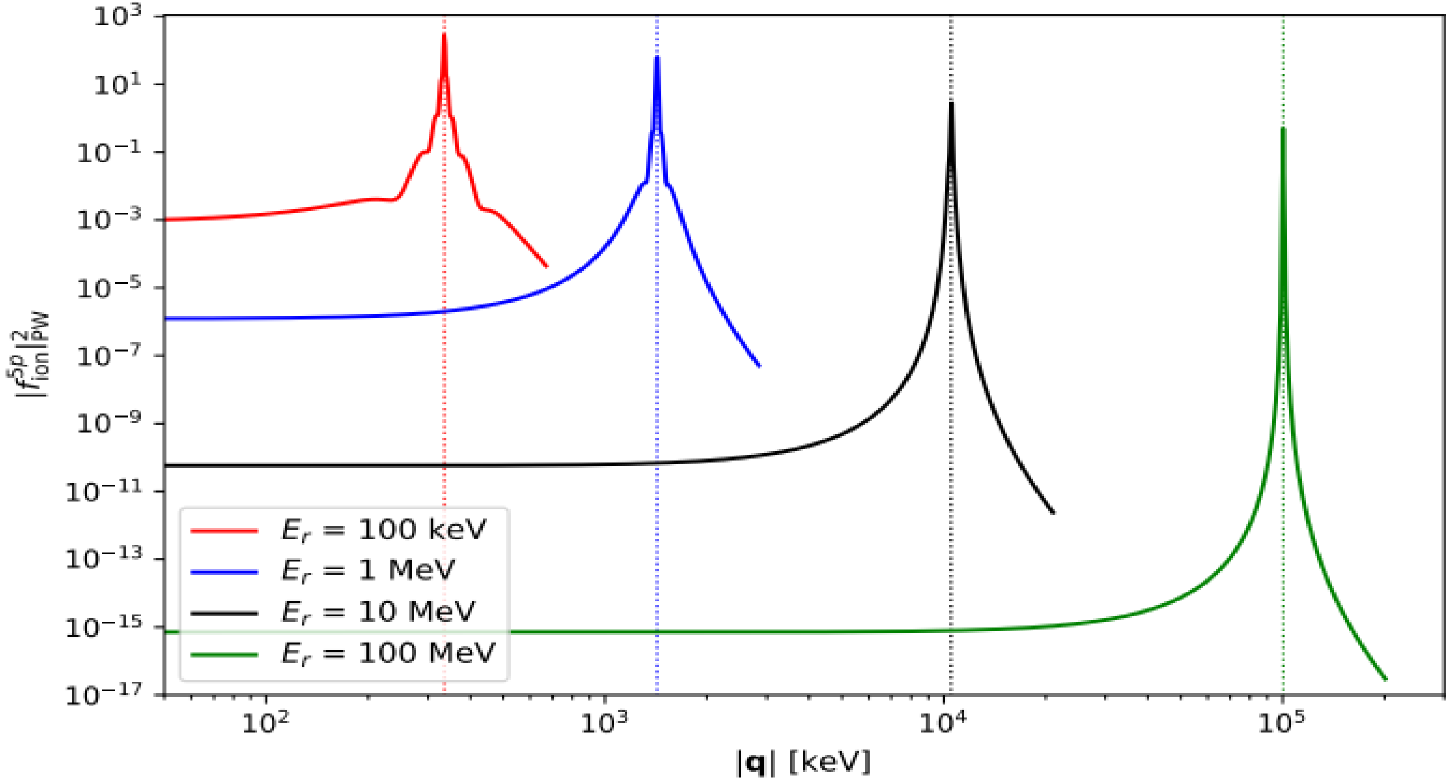
Does the ionization form factor restore the asymptotic freedom of electrons at high recoil energies?

$$\text{as } E_r \text{ increases:} \quad |f_{ion}(E_r, |\mathbf{q}|)|^2 \to \delta(|\mathbf{q}| - |\mathbf{k}'|)$$

DD Exps. ⇠ ⇢ LVnu Exps.



This behavior of the ionization form factor at high electron recoils justifies an earlier assumption "free-at-rest" electrons when considering experiments with energy threshold above ~10 MeV.

dotted lines

$$|\mathbf{k}'| = \sqrt{2m_e E_r + E_r^2}$$

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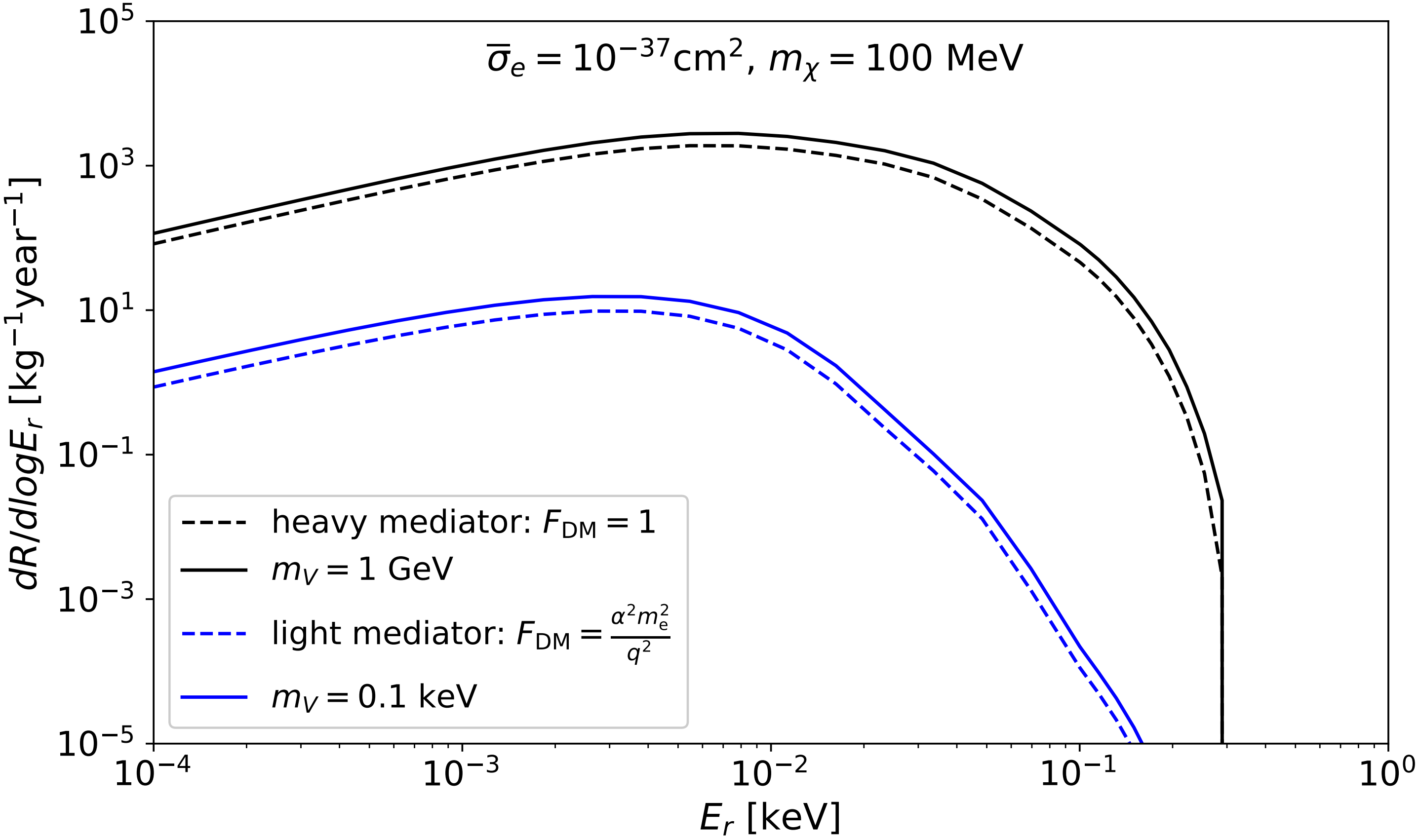
$$\frac{d\sigma}{dE_r} = \frac{1}{64\pi}\int_{q^-}^{q^+}\frac{q\,dq}{pk'^2 E E_e}\,|f_{ion}|^2\,|\mathcal{M}|^2$$

$$\frac{d\langle\sigma v\rangle}{d\log E_r} = \frac{\overline{\sigma}_{\mathrm{B}}}{8\mu^2}\int_{q^-}^{q^+} q\,dq\,|f_{ion}|^2\,|F_{\mathrm{DM}}|^2(q)\,\eta(v_{\min})$$

arXiv:1108.5383

arXiv:1508.07361



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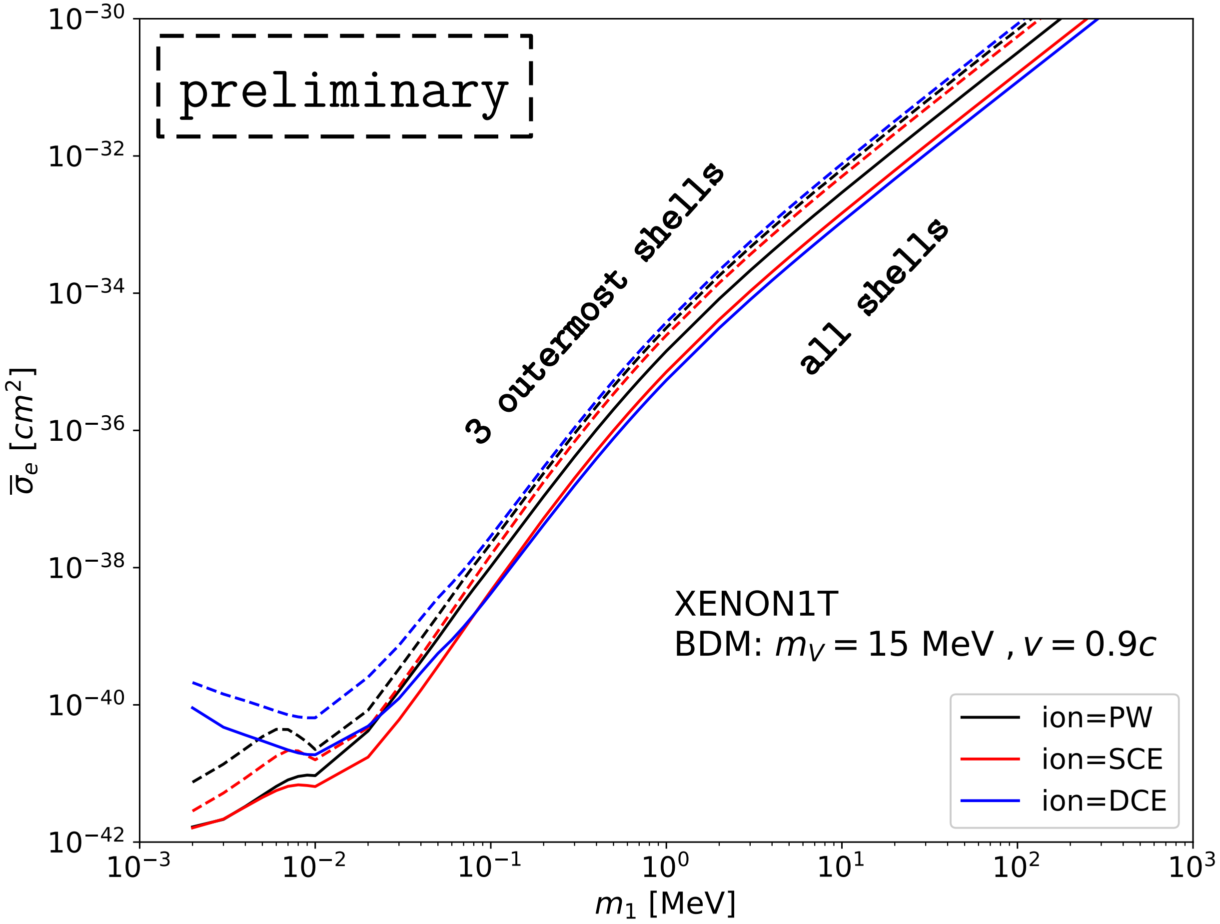
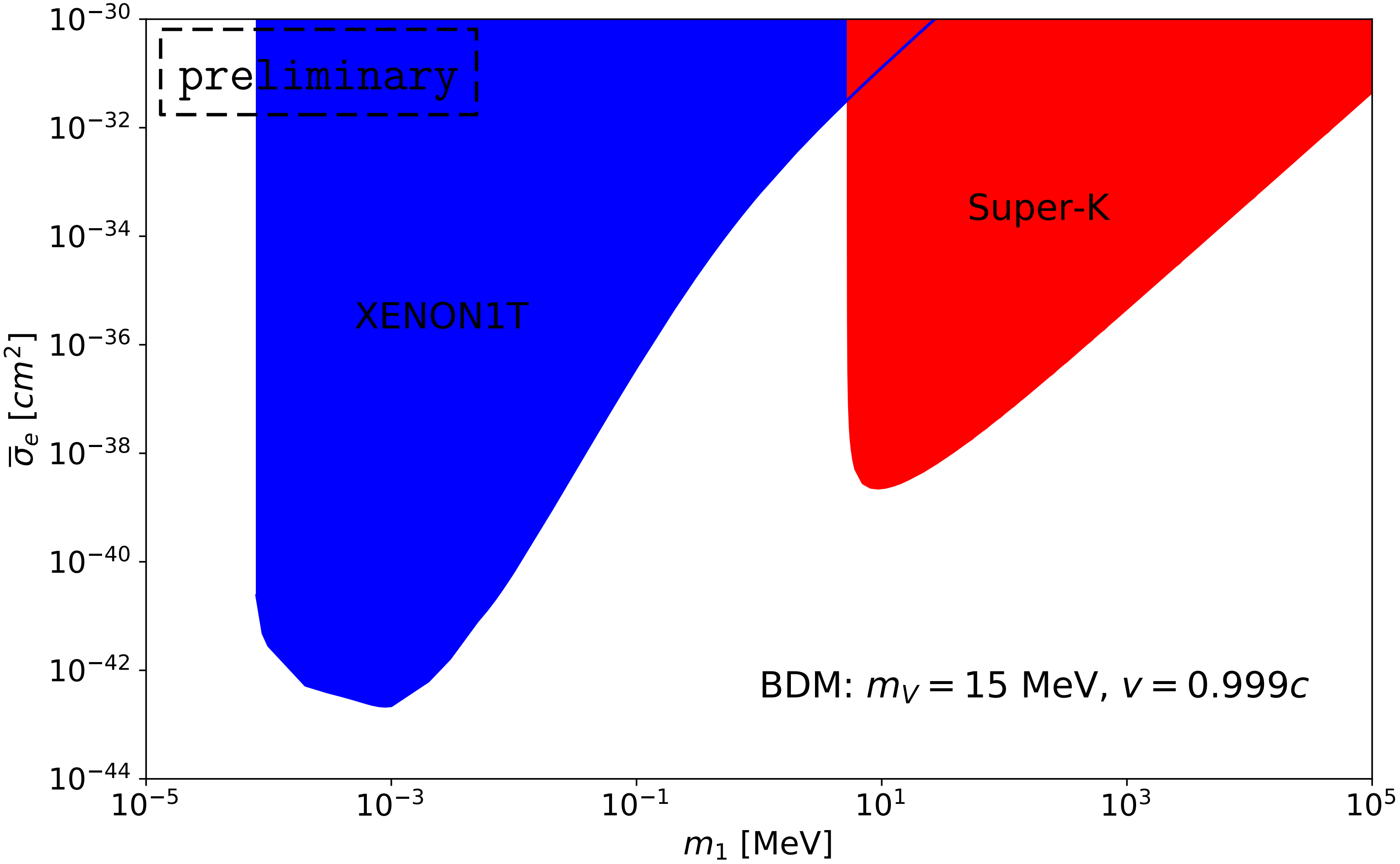
- `Taking the XENON1T experiment as an example.`
- `Uses the reported number of events between 1.5 keV and 30 keV electron recoil as a background.` **arXiv:2006.09721**
- `The analysis could be improved by studying the number of Photo-electrons instead of the recoil energy.`

90% exclusion



90% exclusion at two example experiments



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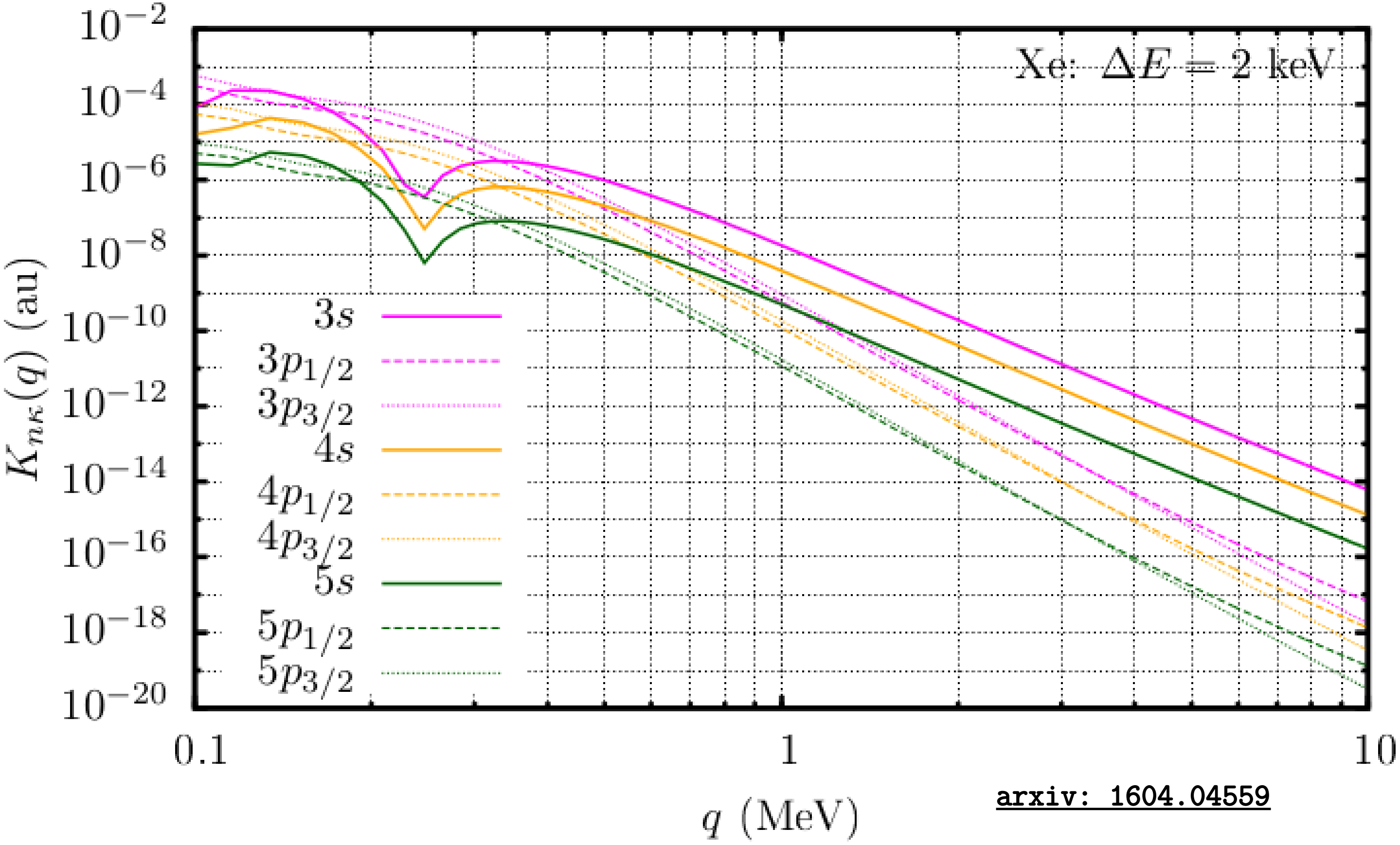
Questions

Thank you

Fast Moving Dark Matter at Direct Detection Experiments

Backup Slides

Fast Moving Dark Matter at Direct Detection Experiments



arxiv: 1604.04559

Fast Moving Dark Matter at Direct Detection Experiments

transition factor: $\left| f_{e_i \to e_f} \right| \propto \int_0^\infty R_{n\ell} R_{E_r \ell'} j_L(qr) r^2 dr.$

Schrodinger:

$$\mathrm{R^S} \propto r^\ell \left(1 - \frac{Z}{\ell+1} r + \cdots\right)$$

LO $\propto \frac{1}{q^{\ell+\ell'+3}} \boxed{\int_0^\infty x^{\ell+\ell'+2} j_L(x) dx.} = 0$

NLO $\propto \boxed{\frac{1}{q^{\ell+\ell'+4}}} \int_0^\infty x^{\ell+\ell'+3} j_L(x) dx.$

Dirac:

NR: $Z\alpha \to 0, \gamma \simeq |\kappa| (1 - \boxed{\frac{1}{2} Z^2 \alpha^2})$

$$\mathrm{R^D_{NR}} \propto r^{1-\gamma} (\gamma - \kappa + Cr + \cdots)$$

LO $\propto \boxed{\frac{1}{q^{\gamma+\gamma'+1}}} \int_0^\infty x^{\gamma+\gamma'} j_L(x) dx.$

for example: $\ell = \ell' = s = 0.$ $\left| f^{\mathrm{S}}_{\mathrm{ion}} \right|^2 \propto \frac{1}{q^8}$ **vs** $\left| f^{\mathrm{D}}_{\mathrm{ion}} \right|^2 \propto \frac{1}{q^{(6-2Z^2\alpha^2)}}$

In non rel. approx., Dirac large component is dominant since the small component is linearly proportional to $Z\alpha$.

$$\kappa = \mp (j + \tfrac{1}{2}) \text{ for } j = \ell \pm \tfrac{1}{2}$$

$$\gamma = \sqrt{\kappa^2 - Z^2 \alpha^2}$$

Phys. Rev. Lett. 116, 023201 (2016)

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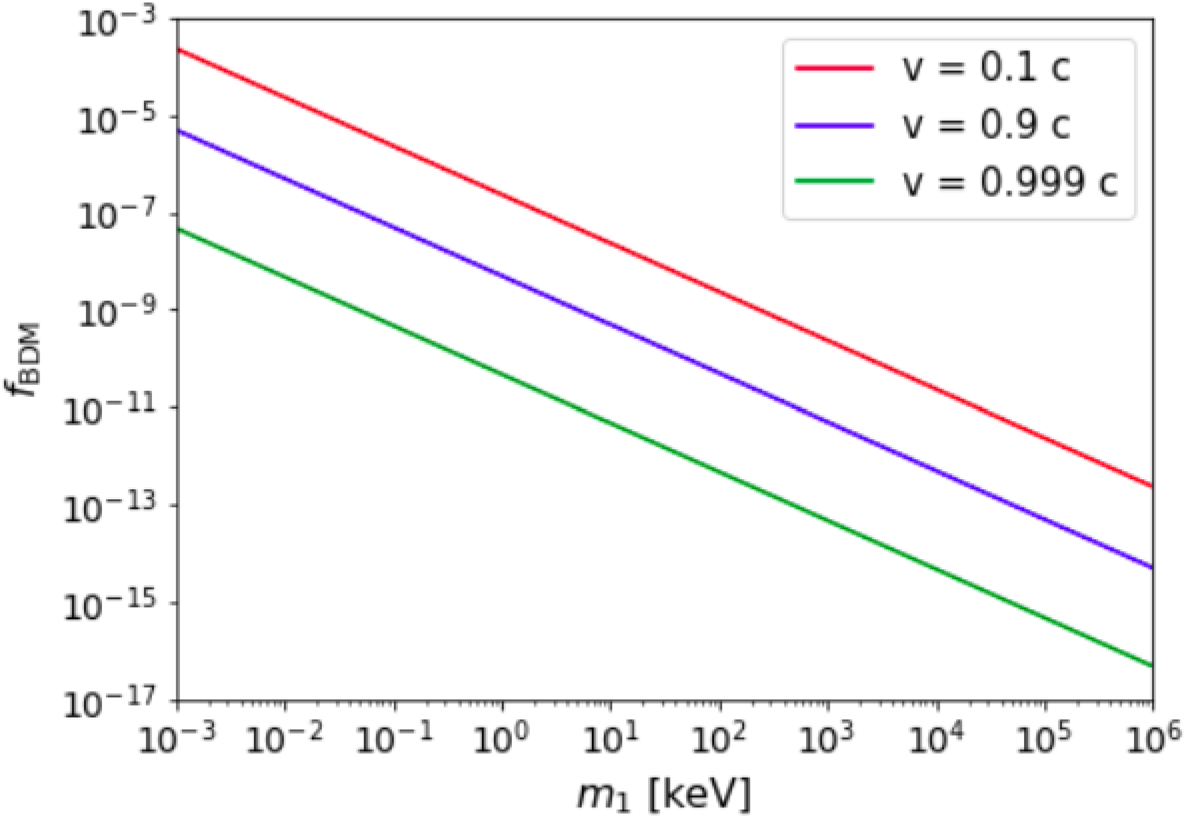
$$f = \frac{m\Phi}{v\rho_{\rm DM}}$$



Fast Moving Dark Matter at Direct Detection Experiments

Example rel. wave functions

$$\hat{h} = \boldsymbol{\alpha}\cdot\mathbf{p} + m_e\,(\beta - 1) + V_{\rm eff}(r)$$

numerical solution: `RADIAL`, `dtfatom`

Example potential

$$V_{\rm eff}^{\rm DHFS}(r) = V_{\rm nuc}(r) + V_{\rm el}(r) + V_{\rm ex}(r)$$

state			Xe absolute ionization energy in atomic units.				
$n_{\ell j}$	n	κ	-Z/r	[129]	$V_{\rm eff}^{ERF}$ [125, 126]	$V_{\rm eff}^{EXP}$ [127]	$V_{\rm eff}^{DHFS}$ [128]
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$3_{p_{3/2}}$	3	-2	164.1	35.33	33.17	33.15	34.05
$3_{d_{3/2}}$	3	2	164.1	26.02	24.48	24.50	25.39
$3_{d_{5/2}}$	3	-3	162.7	25.54	24.00	24.03	24.89
$4_{s_{1/2}}$	4	-1	94.21	8.430	7.401	7.445	7.662
$4_{p_{1/2}}$	4	1	94.21	6.453	5.649	5.701	5.909
$4_{p_{3/2}}$	4	-2	92.25	5.983	5.203	5.251	5.438
$4_{d_{3/2}}$	4	2	92.25	2.711	2.368	2.425	2.566
$4_{d_{5/2}}$	4	-3	91.65	2.634	2.296	2.353	2.488
$5_{s_{1/2}}$	5	-1	59.97	1.010	0.851	0.869	0.869
$5_{p_{1/2}}$	5	1	59.97	0.493	0.465	0.479	0.454
$5_{p_{3/2}}$	5	-2	58.97	0.440	0.422	0.434	0.403

- Identify the potential for a given Z value.
- Solve Dirac equation for a bound state electron $\psi_{n\kappa}$.
- Solve Dirac equation for an electron in the continuum state $\psi_{E_r\kappa'}$.
- Compute wave function overlap between above two states:

$$f^{\rm DCE}_{e_i\to e_f}(\mathbf{q}) = \int d^3\mathbf{r}\,\psi^{\dagger}_{E_r\kappa'}(\mathbf{r})\,e^{i\mathbf{q}\cdot\mathbf{r}}\,\psi_{n\kappa}(\mathbf{r}).$$

- Use the above to estimate the ionization form factor and then the differential cross section.

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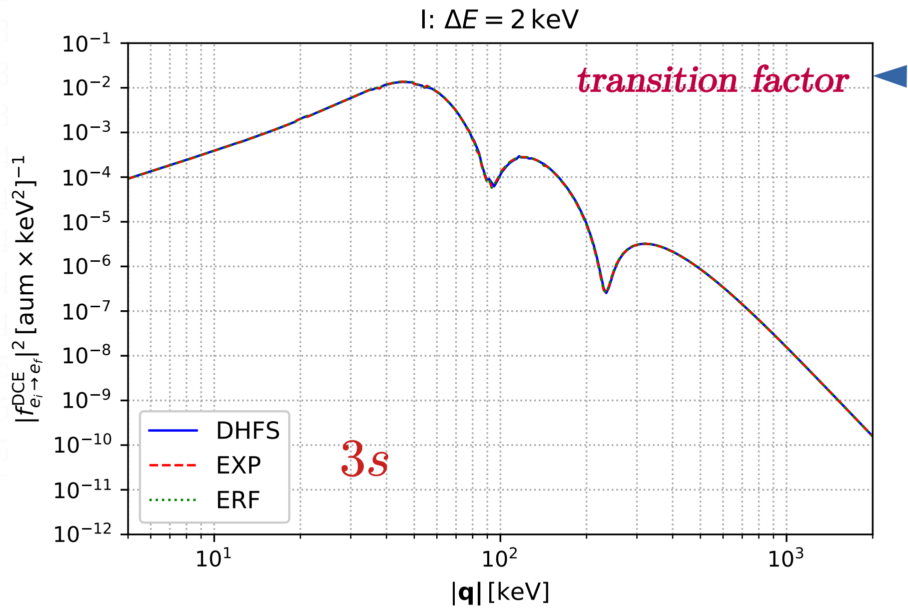

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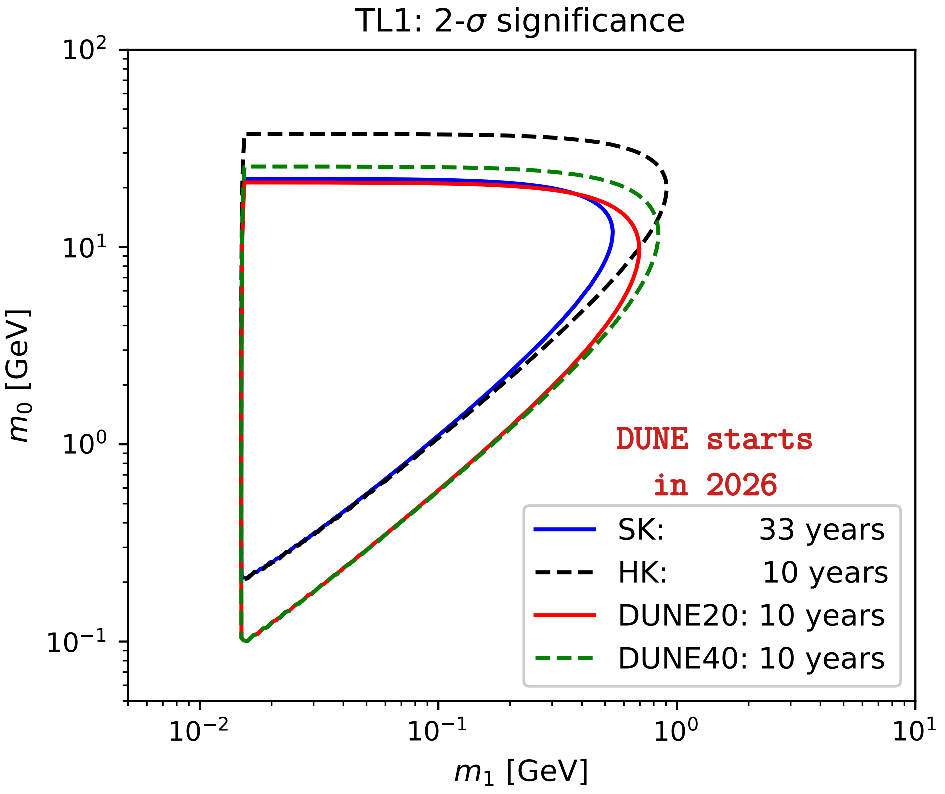
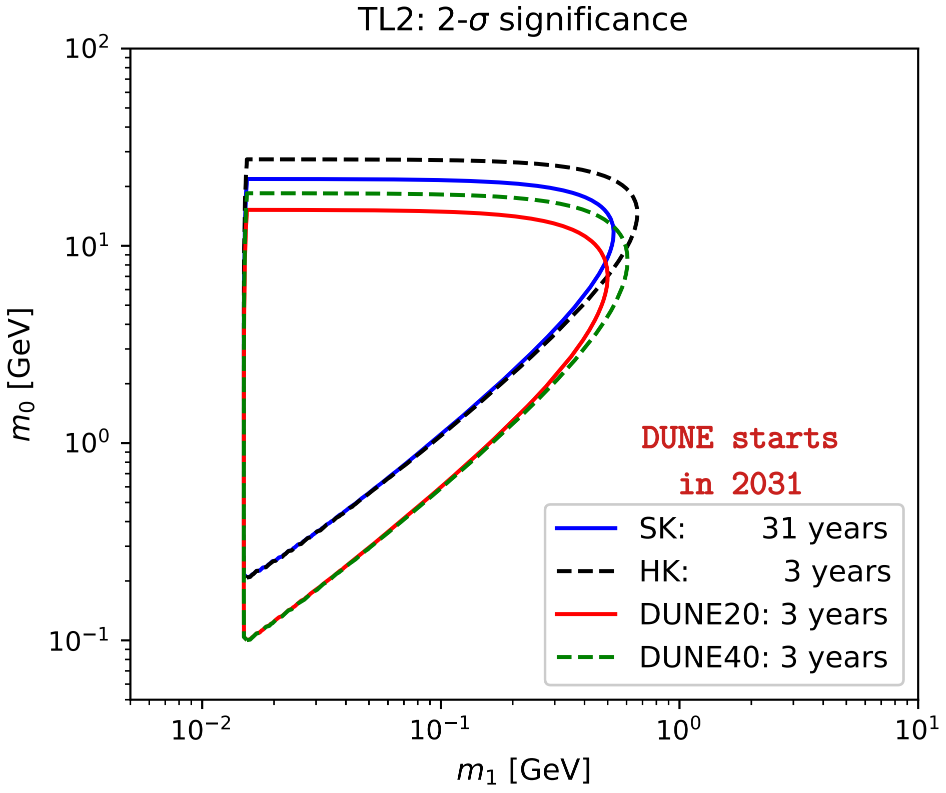
Signal Significance of BDM from the Galactic Center





$$\text{BMP}: \quad g_e^V = 3 \times 10^{-5}, g_{\chi_1}^V = 0.5 \ \text{and} \ m_V = 15\,\text{MeV}.$$

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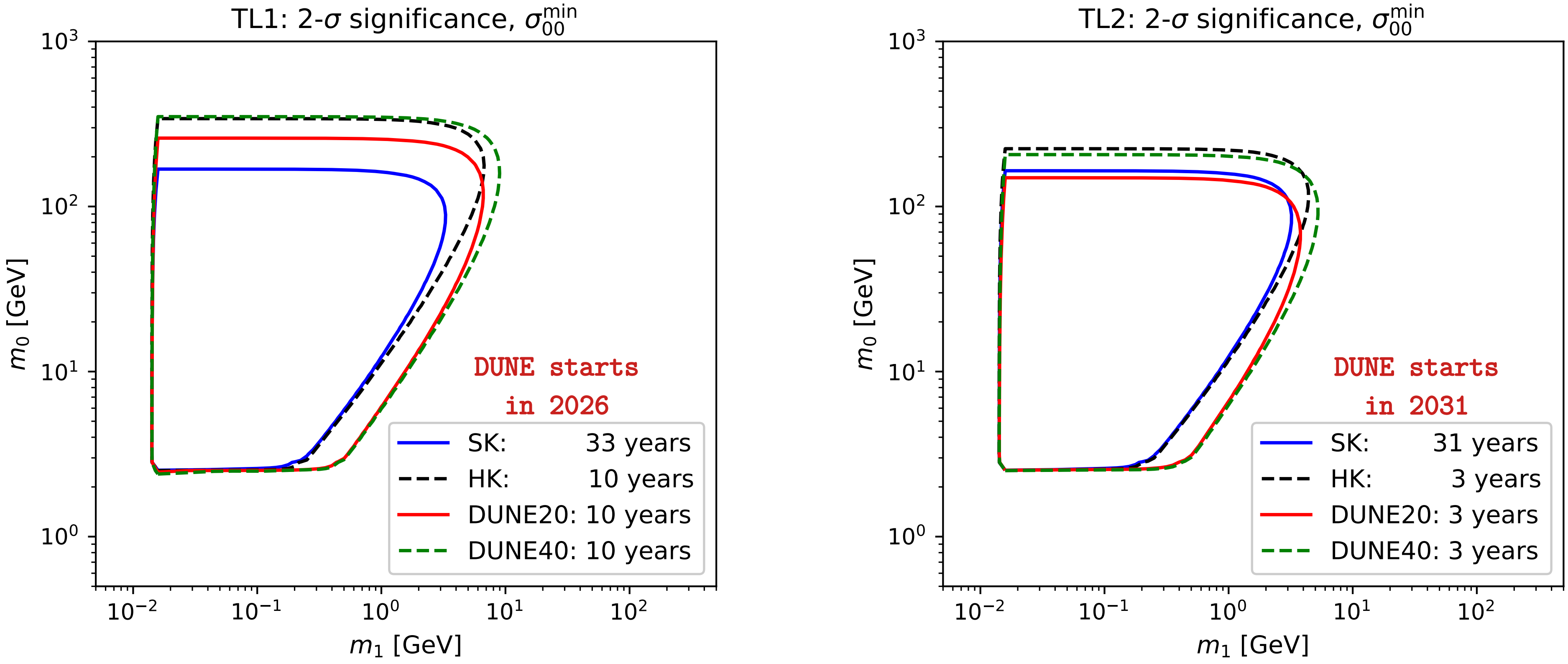
Signal Significance of BDM from the Sun



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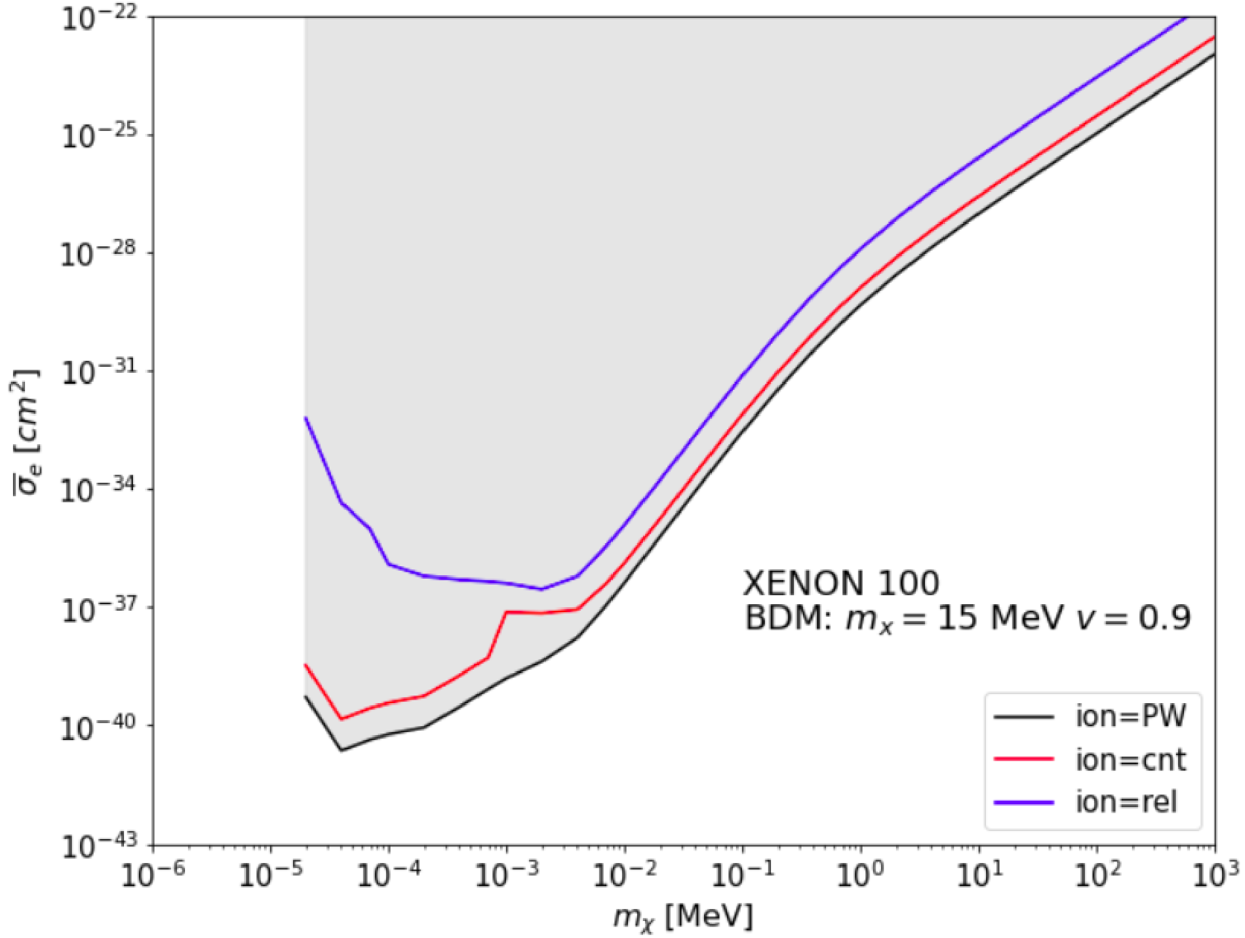
Fast Moving Dark Matter at Direct Detection Experiments



Fast Moving Dark Matter at Direct Detection Experiments

ArXiv:1405.7370

1. Limits on the dark photon.
2. Direct detection of non-relativistic Ψ_0.
3. Direct detection of non-relativistic Ψ_1.
4. Indirect detection of non-relativistic Ψ_1.
5. CMB constraints on Ψ_1 annihilation.
6. BBN constraints on Ψ_1 annihilation.
7. Dark matter searches at colliders.

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