宇宙の進化と素粒子模型

平成２９年度宇宙線研究所共同利用研究成果発表会

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国内旅費：10万円

2017 業績一部

1) Oscillons from Pure Natural Inflation.
By Jeong-Pyong Hong, Masahiro Kawasaki, Masahito Yamazaki.
[arXiv:1711.10496 [astro-ph.CO]].

2) Primordial Black Holes for the LIGO Events in the Axion-like Curvaton Model.
By Kenta Ando, Keisuke Inomata, Masahiro Kawasaki, Kyohei Mukaida, Tsutomu T. Yanagida.
[arXiv:1711.08956 [astro-ph.CO]].

3) Double Inflation as a single origin of PBHs for all dark matter and LIGO.
By Keisuke Inomata, Masahiro Kawasaki, Kyohei Mukaida, Tsutomu T. Yanagida.
[arXiv:1711.06129 [astro-ph.CO]].

4) Cogenesis of LIGO Primordial Black Holes and Dark Matter.
By Fuminori Hasegawa, Masahiro Kawasaki.
[arXiv:1711.00990 [astro-ph.CO]].

5) Domain wall and isocurvature perturbation problems in a supersymmetric axion model.
By Masahiro Kawasaki, Eisuke Sonomoto.
[arXiv:1710.07269 [hep-ph]].

6) $\mathcal O(10) M_\odot$ primordial black holes and string axion dark matter.
By Keisuke Inomata, Masahiro Kawasaki, Kyohei Mukaida, Yuichiro Tada, Tsutomu T. Yanagida.
[arXiv:1709.07865 [astro-ph.CO]].

7) Revisiting Big-Bang Nucleosynthesis Constraints on Long-Lived Decaying Particles.
By Masahiro Kawasaki, Kazunori Kohri, Takeo Moroi, Yoshitaro Takaesu.
[arXiv:1709.01211 [hep-ph]].

8) Adiabatic suppression of the axion abundance and isocurvature due to coupling to hidden monopoles.
By Masahiro Kawasaki, Fuminobu Takahashi, Masaki Yamada.
[arXiv:1708.06047 [hep-ph]].

9) Migdal Effect in Dark Matter Direct Detection Experiments.
By Masahiro Ibe, Wakutaka Nakano, Yutaro Shoji, Kazumine Suzuki.
[arXiv:1707.07258 [hep-ph]].

10) Oscillating Affleck-Dine condensate and its cosmological implications.
By Fuminori Hasegawa, Masahiro Kawasaki.
[arXiv:1706.08659 [hep-ph]].
10.1103/PhysRevD.96.063518.
Phys.Rev. D96 (2017) no.6, 063518.

11) Foreground effect on the J-factor estimation of ultra-faint dwarf spheroidal galaxies.
By Koji Ichikawa, Shun-ichi Horigome, Miho N. Ishigaki, Shigeki Matsumoto, Masahiro Ibe, Hajime Sugai, Kohei Hayashi.
[arXiv:1706.05481 [astro-ph.GA]].

12) Dynamical Clockwork Axions.
By Rupert Coy, Michele Frigerio, Masahiro Ibe.
[arXiv:1706.04529 [hep-ph]].
10.1007/JHEP10(2017)002.
JHEP 1710 (2017) 002.

13) Gauged Q-ball Decay Rates into Fermions.
By Jeong-Pyong Hong, Masahiro Kawasaki.
[arXiv:1706.01651 [hep-ph]].
10.1103/PhysRevD.96.103526.
Phys.Rev. D96 (2017) no.10, 103526.

14) A "gauged" $U(1)$ Peccei–Quinn symmetry.
By Hajime Fukuda, Masahiro Ibe, Motoo Suzuki, Tsutomu T. Yanagida.
[arXiv:1703.01112 [hep-ph]].
10.1016/j.physletb.2017.05.071.
Phys.Lett. B771 (2017) 327-331.

15) New type of charged Q -ball dark matter in gauge mediated SUSY breaking models.
By Jeong-Pyong Hong, Masahiro Kawasaki.
[arXiv:1702.00889 [hep-ph]].
10.1103/PhysRevD.95.123532.
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16) Charged Q-Balls in Gauge Mediated SUSY Breaking Models.
By Jeong-Pyon Hong, Masahiro Kawasaki, Masaki Yamada.
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17) Dark Matter Candidates in a Visible Heavy QCD Axion Model.
By Hajime Fukuda, Masahiro Ibe, Tsutomu T. Yanagida.
[arXiv:1702.00227 [hep-ph]].
10.1103/PhysRevD.95.095017.
Phys.Rev. D95 (2017) no.9, 095017.

18) Inflationary Primordial Black Holes as All Dark Matter.
By Keisuke Inomata, Masahiro Kawasaki, Kyohei Mukaida, Yuichiro Tada, Tsutomu T. Yanagida.
[arXiv:1701.02544 [astro-ph.CO]].
10.1103/PhysRevD.96.043504.
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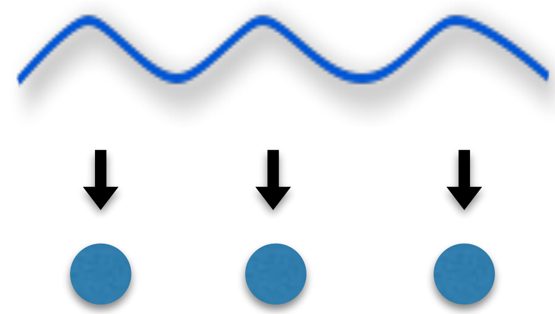
$\boldsymbol{O(10)M_\odot}$ primordial black holes and string axion dark matter

Inomata, Kawasaki, Mukaida, Tada, Yanagida

✓ ***Primordial Black Hole***

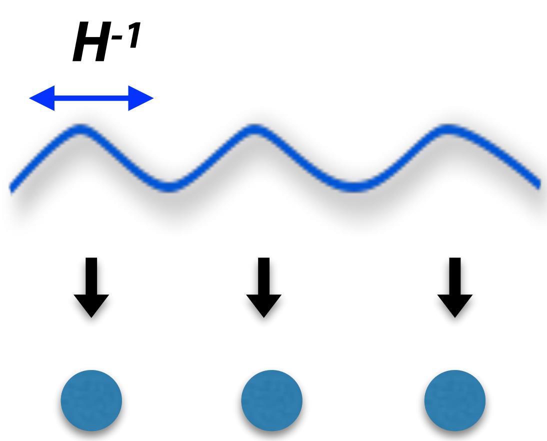
The density fluctuations of $\boldsymbol{\delta = (\rho - \rho_{average})/\rho_{average} = O(1)}$ collapse.



$\boldsymbol{\delta = O(1)}$

Collapsed objects

If $\boldsymbol{\delta = O(1)}$ for the fluctuation with a spacial size $\boldsymbol{\sim H^{-1}}$



$\boldsymbol{\delta = O(1)}$

Collapsed objects : Mass $\boldsymbol{\sim 4\pi/3\, \rho\, H^{-3}}$

Schwarzschild Radius of : G Mass $\sim H^{-1} >$ *Object Size !*

$\boldsymbol{\delta = O(1)}$ of a spacial size $\boldsymbol{\sim H^{-1}} \rightarrow$ Black Hole

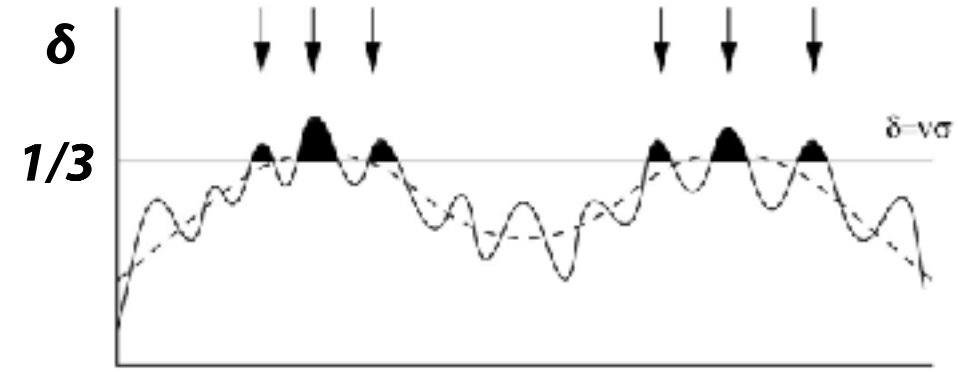
Primordial Black Hole

- Mass of the PBH formed at $H \sim T^2/M_{PL}$

$$M_{BH} \sim 4\pi/3\, \rho\, H^{-3}$$

$$\sim 0.066 M_\odot \left(\frac{\text{GeV}}{T}\right)^2$$

- Energy fraction at the formation



https://ned.ipac.caltech.edu/level5/Sept03/Peacock/Peacock6_2.html

Energy fraction at the formation

$$\beta_*(M_*) = \int_{1/3}^{1} \frac{d\delta}{\sqrt{2\pi}\bar{\delta}(M_*)} \exp\left(-\frac{\delta^2}{2\bar{\delta}^2(M_*)}\right) \simeq \bar{\delta}(M_*) \exp\left(-\frac{1}{18\bar{\delta}^2(M_*)}\right),$$

Abundance

$$\Omega_{BH} h^2 \simeq 5.6 \times 10^7 \beta_* \qquad \bar{\delta}^2 \sim 0.01$$

- LIGO-Virgo Events By PBH ?

O(10)M$_\odot$ Black hole merger ~ ***12 - 213 / Gpc³ / year***

→ ***O(10)M***$_\odot$ ***PBH with*** $\Omega_{PBH}/\Omega_{DM} \sim 10^{-3} - 10^{-2}$

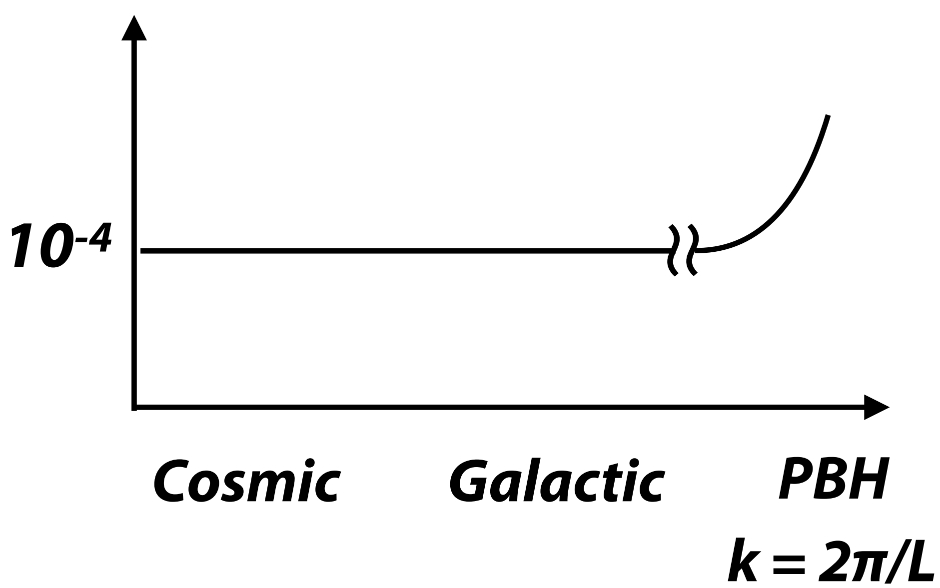
✓ ***Primordial Black Hole***

At large scales, the fluctuations are

$$\delta(\text{CMB, galaxy cluster}) \sim 4(\Delta T/T)_{CMB} \sim 10^{-4}$$

We prepare large fluctuation at very small structure scale !

$$\delta^2(\text{PBH}) \sim 0.01 \qquad \text{at } H^{-1} \ll \text{CMB, galaxy cluster sizes}$$



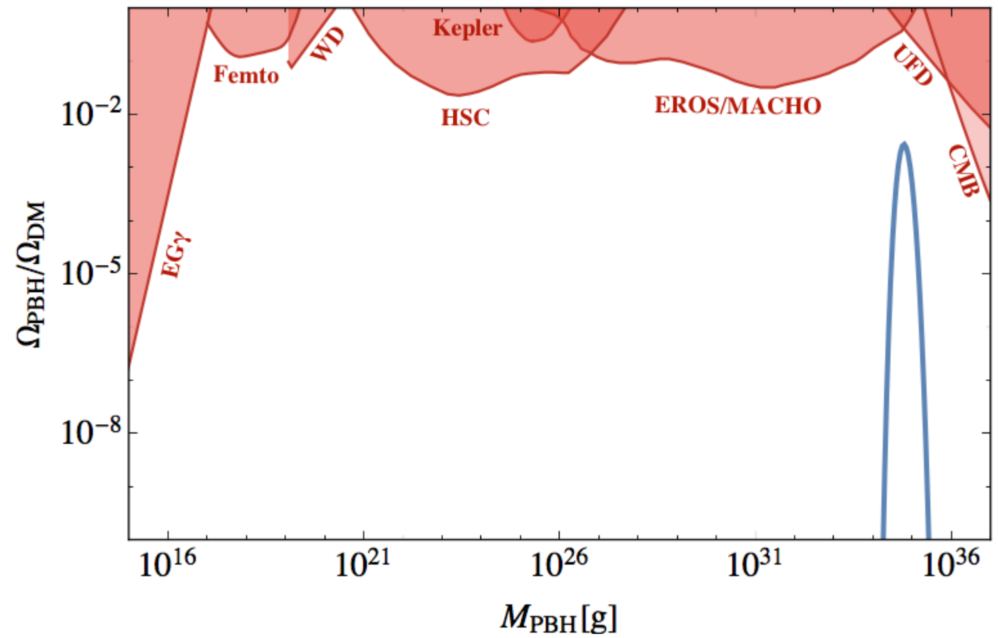


FIG. 3. The PBH mass spectrum for parameters given in Eq. (41). Red shaded regions are excluded by extragalactic gamma rays from Hawking radiation (EGγ) [75], femtolensing of known gamma ray bursts (Femto) [76], white dwarfs existing in our local galaxy (WD) [77], microlensing search with Subaru Hyper Suprime-Cam (HSC) [78], Kepler micro/millilensing (Kepler) [79], EROS/MACHO microlensing (EROS/MACHO) [80], dynamical heating of ultra faint dwarf galaxies (UFD) [51], and accretion constraints from CMB (CMB) [50]. See also [23] for a recent summary of observational constraints on PBHs.

Inomata, Kawasaki, Mukaida, Tada, Yanagida

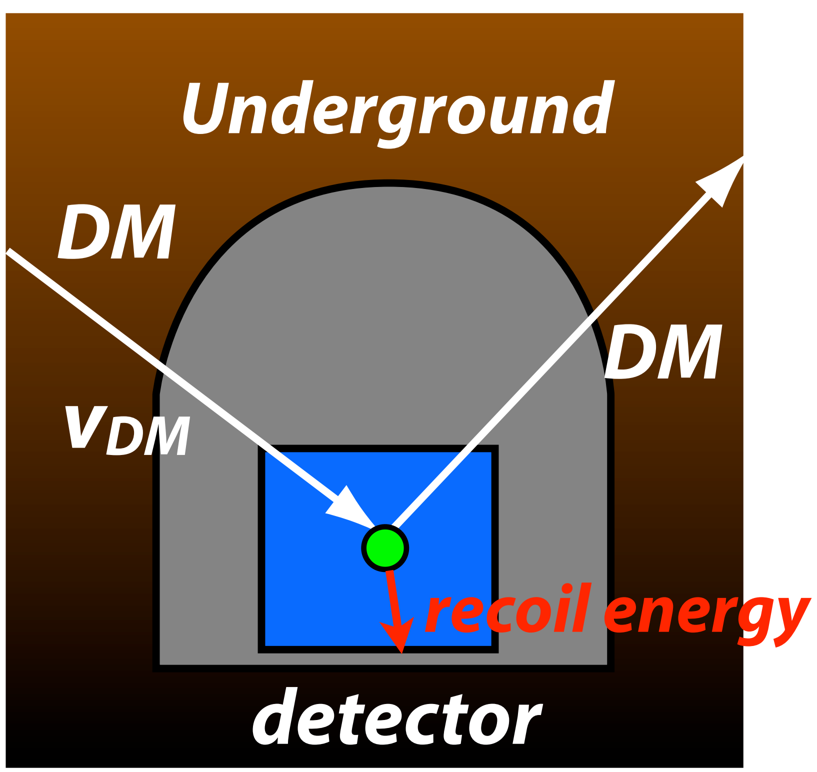
Migdal Effect in Dark Matter Direct Detection Experiments

Ibe, Nakano, Shoji, Suzuki

Dark Matter Direct Detection Experiment

- The Earth is immersed in a dark matter halo (***ρ_{DM} ~ 0.4 GeV/cm^3***)
- Dark Matter in such a halo has a velocity distribution (***$\langle v_{DM} \rangle$~220km/s***)
- The Sun moves at a speed of ***232 km/s*** around the Galaxy.

  (The Earth moves around the Sun with a speed of ***30 km/s***)



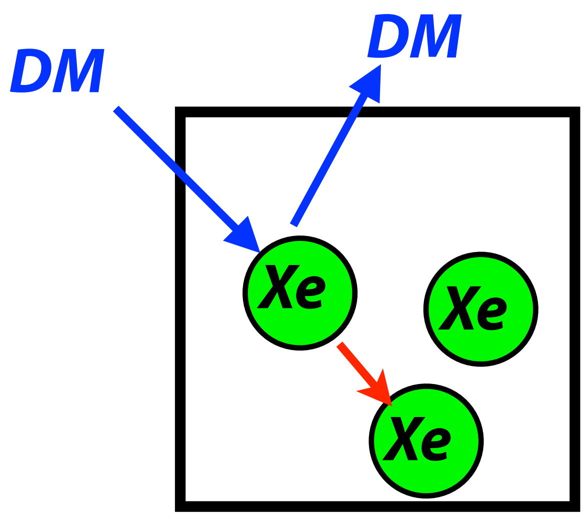
- Dark matter scatters off a nucleus of the detector material and deposits ***recoil energy (O(10)keV)***

↓

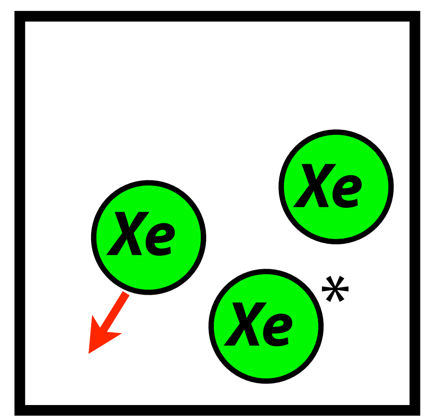
- The recoil energy is detected through ***ionization***, ***scintillation***, and the production of ***heat*** in the detectors.

✓ *How is the Nucleus Scattering detected ?*

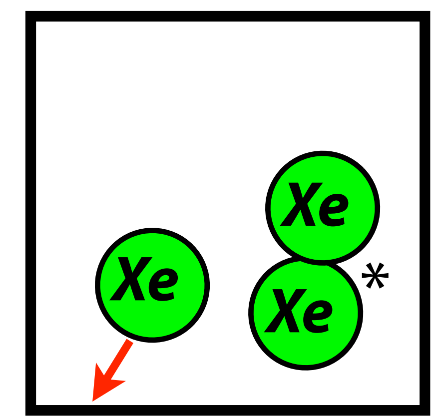
e.g. Liquid Xenon (LXe) Detector



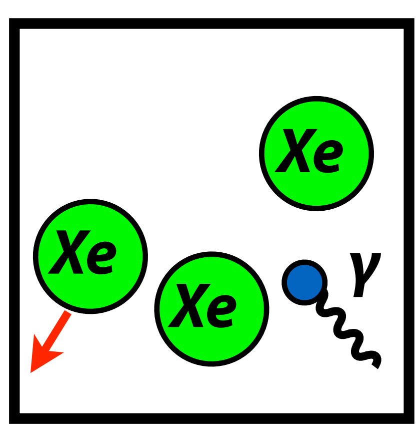
Recoiled ***Xe*** lose its energy via (in)elastic scattering with other ***Xe***.



Inelastic scattering leads to excite/ionize ***Xe's.***



The ***excited/ionized Xe***'s form excited molecular (excimer).



Excimer eventually decays by emitting a photon with a characteristic wave length (***~ 175nm***)

= scintillation photon !

(Typical Time Scale ~ ***O(1)ns - O(10)ns***)

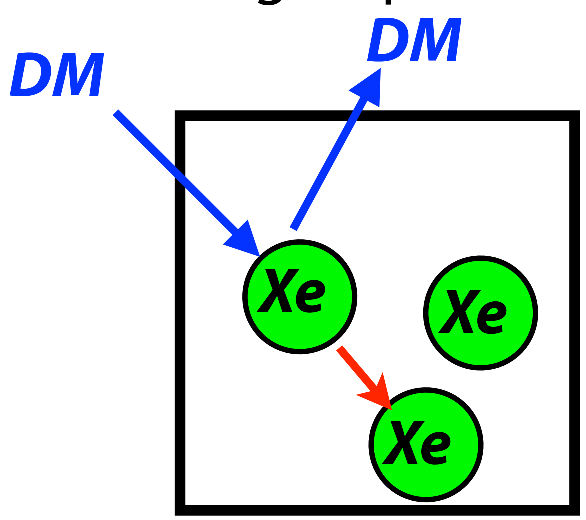
 # scintillation photon ∝ Recoil Energy

Nuclear recoil is detected by looking for

Scintillation photons &/ emitted electrons @ ionizations

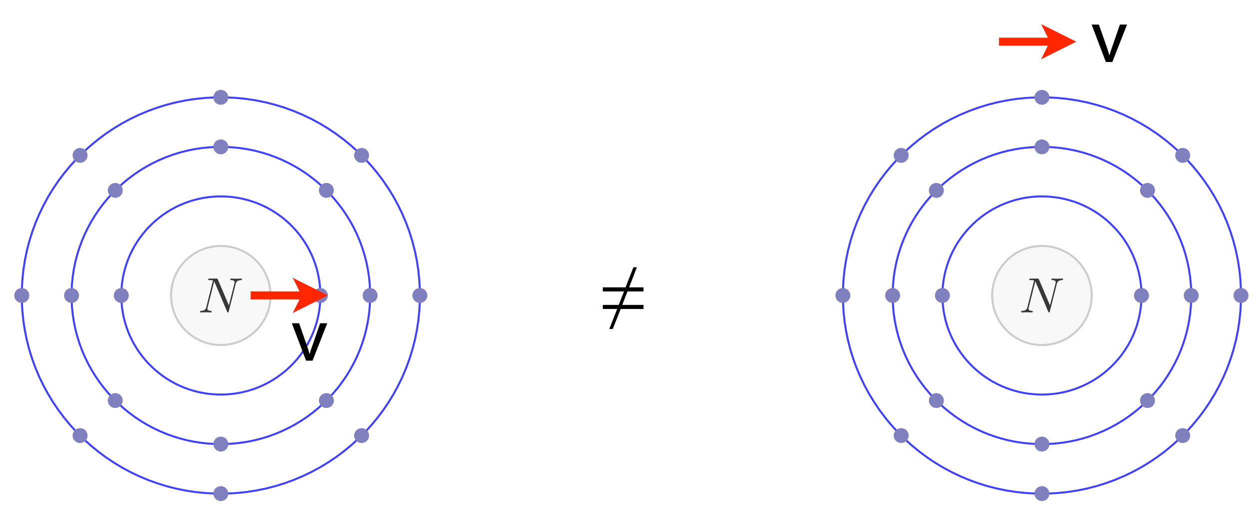
What is missing in this analysis?

e.g. Liquid Xenon (LXe) Detector



In conventional analysis, the ***recoiled nucleus*** is treated as a ***recoiled neutral atom***.

- In reality, it takes some time for the electrons to catch up…



- The process to catch up causes electron excitations/ionizations!

→ ***Migdal Effect ! [1939, Migdal]***

['05 Vergados&Ejiri, '07 Bernabei et al. Application to DM detection]

✓ "Atomic" Recoil Cross Section

After phase space integration :

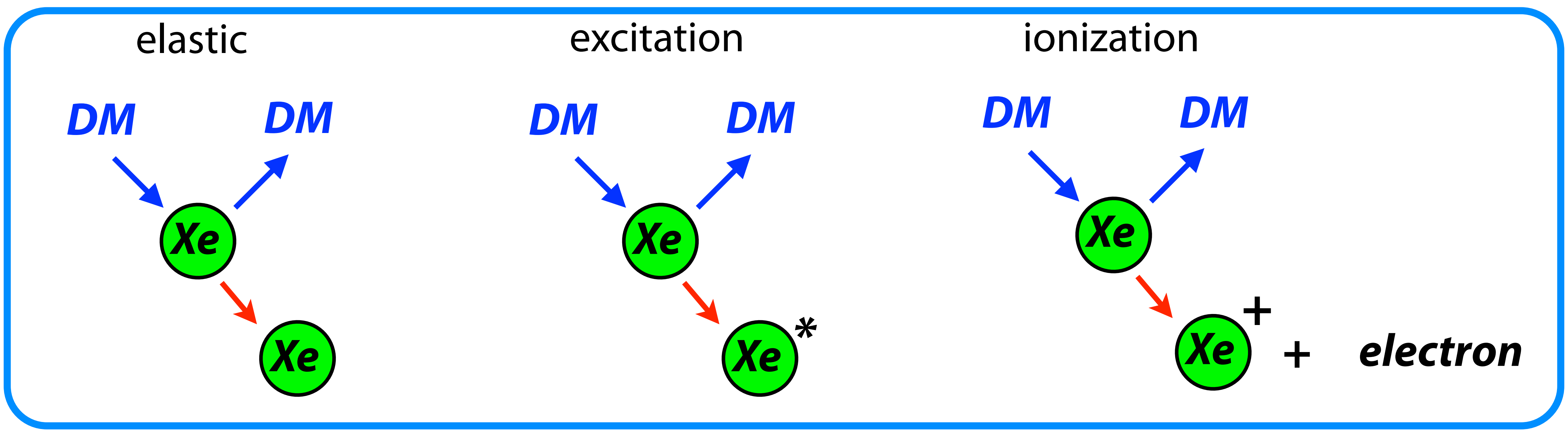
$$\frac{d\sigma}{d\cos\theta_{CM}} \simeq \sum_{E^F_{ec}} \frac{1}{32\pi} \frac{|\mathbf{p}_F|}{(p^{I\,0}_A + p^{I\,0}_{DM})^2|\mathbf{p}_I|} |\mathcal{M}|^2 |Z_{FI}(q_e)|^2$$

$$Z_{FI}(\mathbf{q}_e) = \int \prod_i d^3\mathbf{x}_i\, \Phi^*_{E^F_{ec}}(\{\mathbf{x}\}) e^{-i\sum_i \mathbf{q}_e\cdot\mathbf{x}_i} \Phi_{E^I_{ec}}(\{\mathbf{x}\})$$

$$\mathbf{p}^I_{DM} = -\mathbf{p}^I_A = \mathbf{p}_I \simeq \mu_N \mathbf{v}^I_{DM} \qquad (p_A^{I\,0} = m_A,\ p_{DM}^{I\,0} = m_{DM})$$

The process is not elastic for $E_{ec}^F \neq E_{ec}^I$!

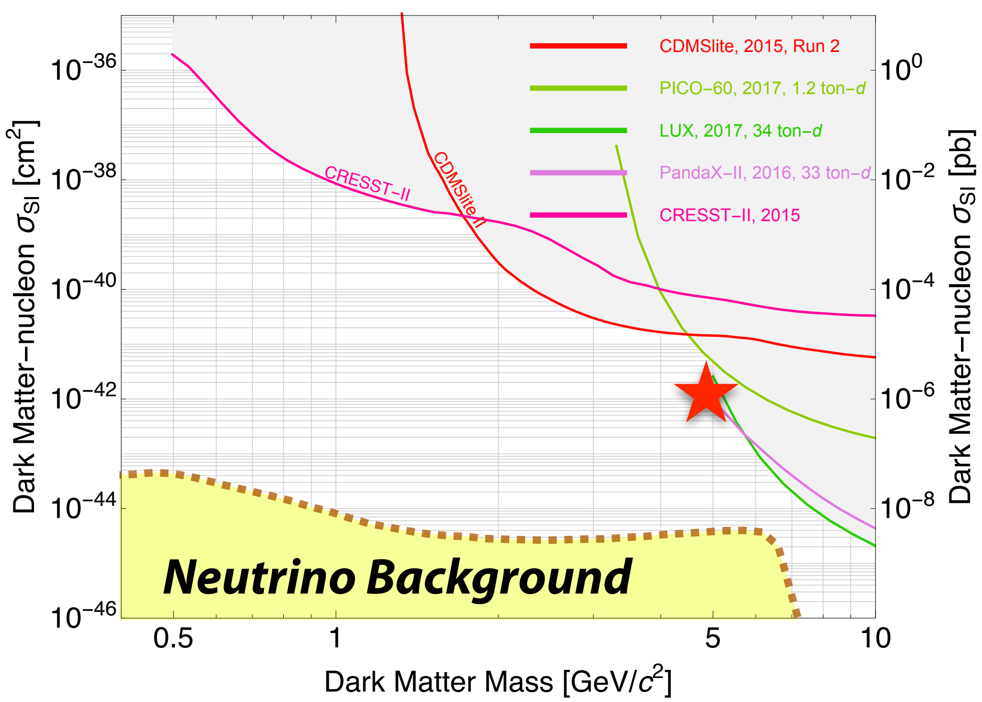
$$|\mathbf{p}_F|^2 \simeq |\mathbf{p}_I|^2 - 2\mu_N(E^F_{ec} - E^I_{ec}) \qquad v^{(th)}_{DM} = \sqrt{\frac{2(E^F_{ec} - E^I_{ec})}{\mu_N}}$$

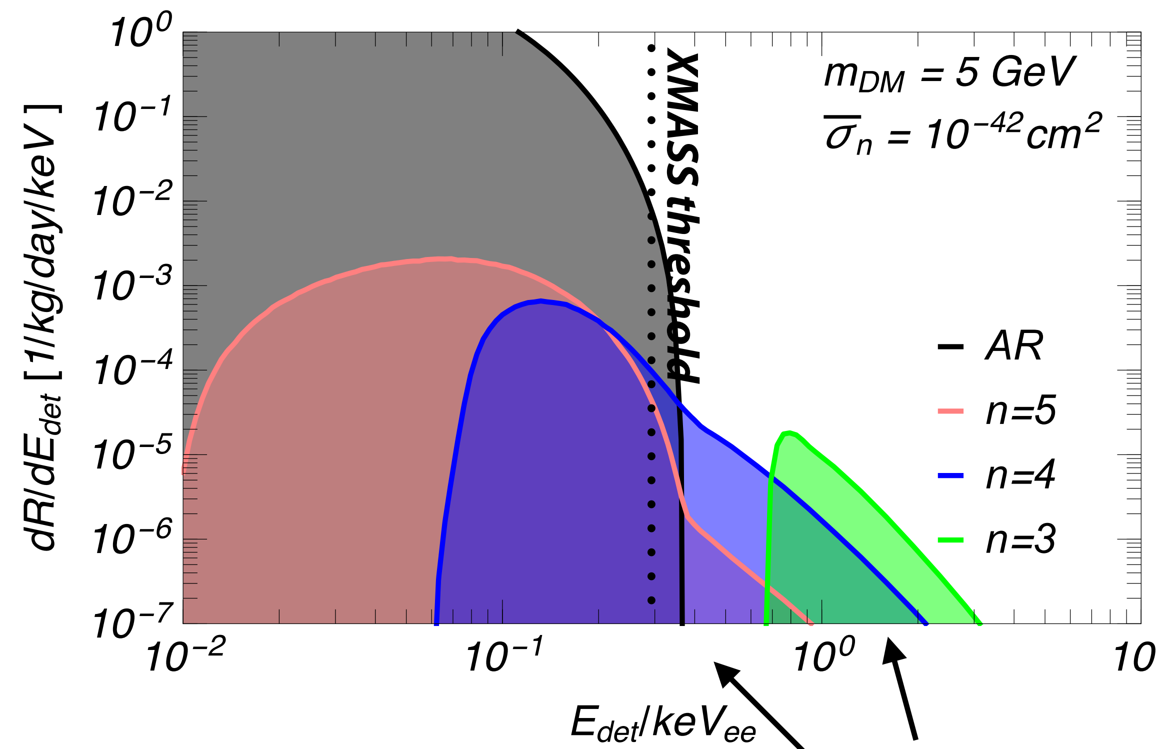


✓ Implication on Dark Matter Direct Detection Experiments

✓ Migdal Effect single-phase Liquid Xe detectors

WIMP Limit Plotter





de-excitation energy is added

$$\frac{dR}{dE_{\rm det}} \simeq \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/o\ Migdal} + \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/\ Migdal}$$

$E_{det} = (0.1\text{-}0.2)\, E_R + E_{EM}$ $\quad$ $E_{EM} = E_e + E_{dex} \sim E_e - E_n$

A few events with E_{det} = O(1)keV are expected for 10^5 kg days !

The atom recoil energy is lower than threshold $E_R < M_{DM}^2 / M_A \times v_{DM}^2 < O(1)$keV

Migdal Effect might opens up new detection channel of the DM-NUCLEAR scattering !

Backup

✓ Numerical Transition Rate (by using Flexible Atomic Code)

Xe ($q_e = m_e \times 10^{-3}$)

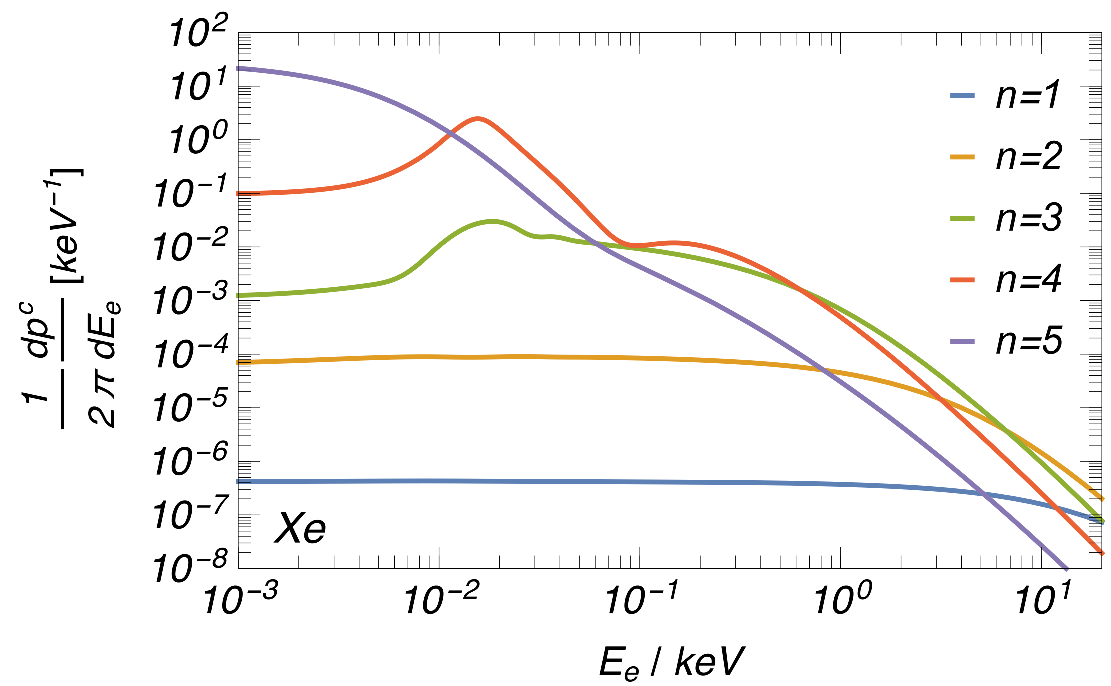
(n,ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^{4}	4.6×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^{3}	2.9×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^{3}	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^{3}	8.7×10^{-5}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^{2}	5.2×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^{2}	3.5×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^{2}	3.4×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^{2}	1.4×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.4×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.1×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	1.0×10^{-1}

initial state

(n,ℓ)	$4f$	$5d$	$6s$	$6p$
$E_{n\ell}$[eV]	0.85	1.6	3.3	2.2

(transition is possible only for $|\Delta\ell| = 1$)

ionization spectrum



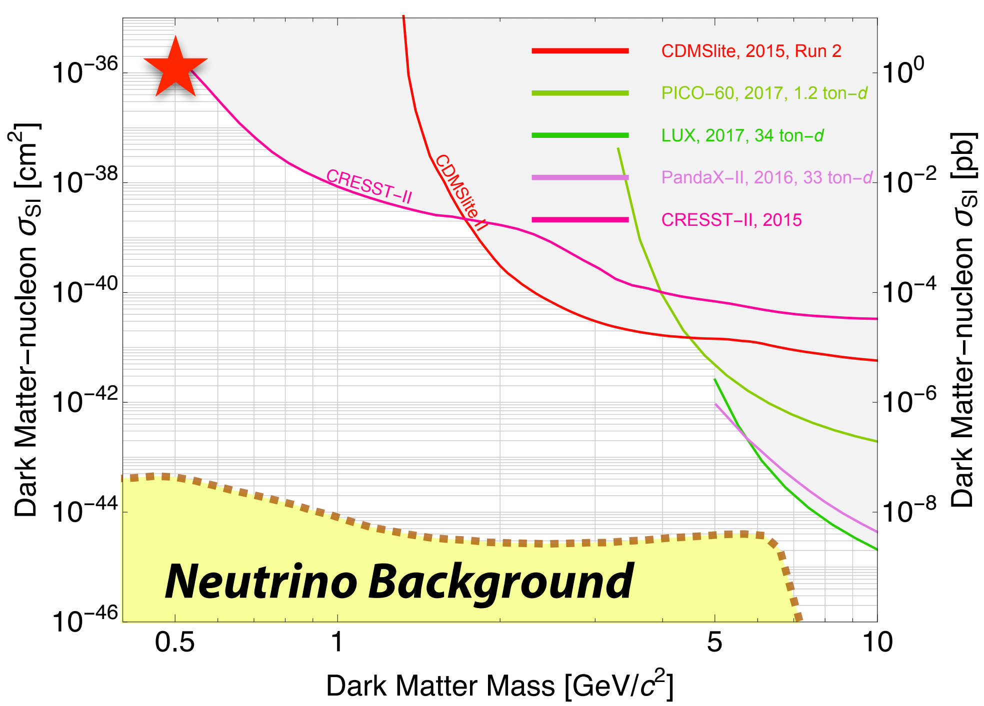
✓ The ionization rate from ***n* = 3** state can be ***O*(10^{-3})**.
→ leading to ***O*(1)keV** electronic energy deposition !

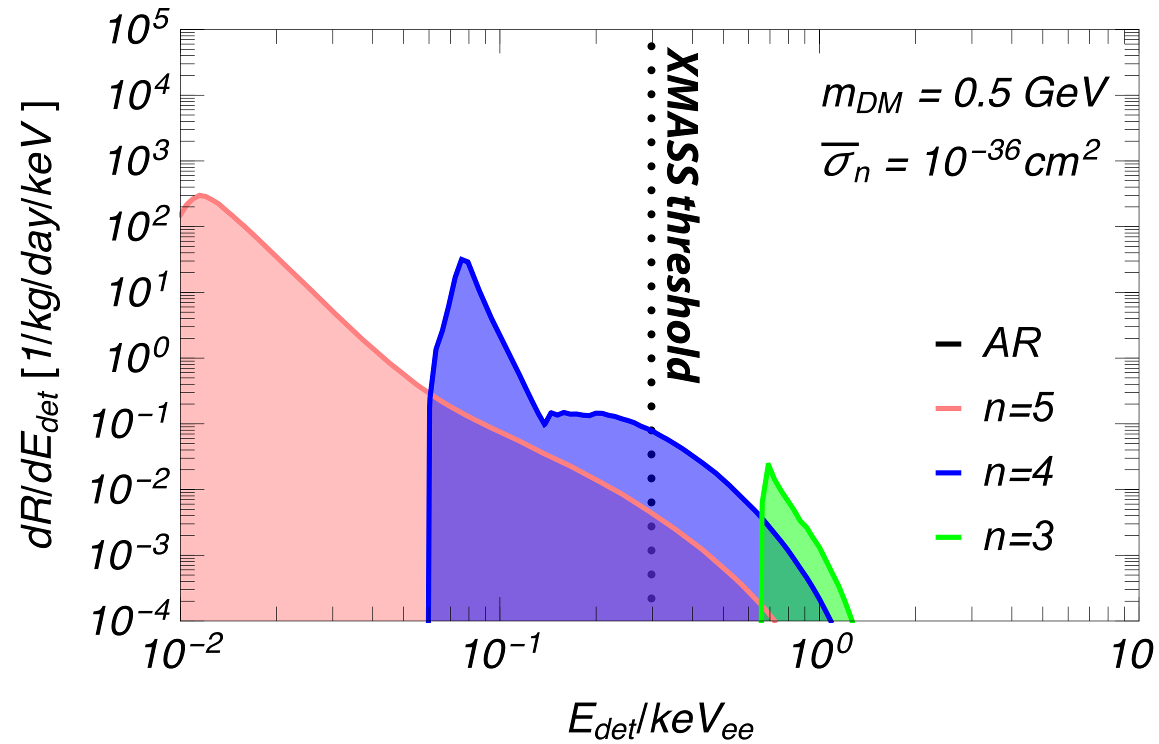
✓ The excitation rates are smaller.

✓ Implication on Dark Matter Direct Detection Experiments

✓ Migdal Effect single-phase Liquid Xe detectors

WIMP Limit Plotter





$$\frac{dR}{dE_{\rm det}} \simeq \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/o\ Migdal} + \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/\ Migdal}$$

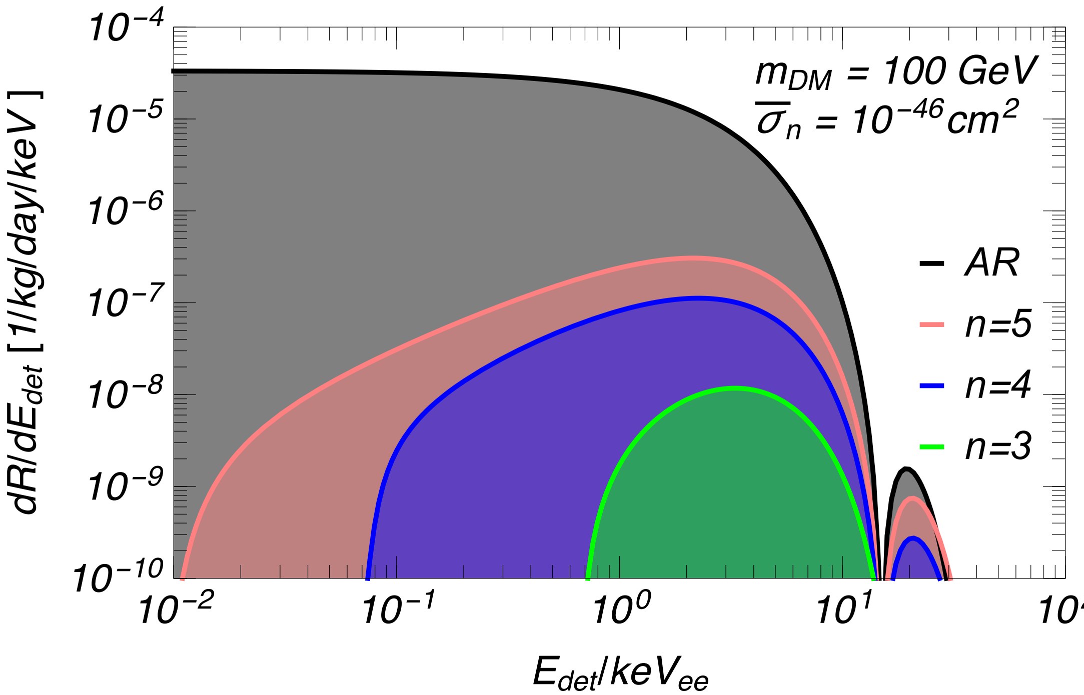
$E_{det} = (0.1\text{-}0.2)\ E_R + E_{EM}$ $\quad E_{EM} = E_e + E_{dex} \sim E_e - E_n$

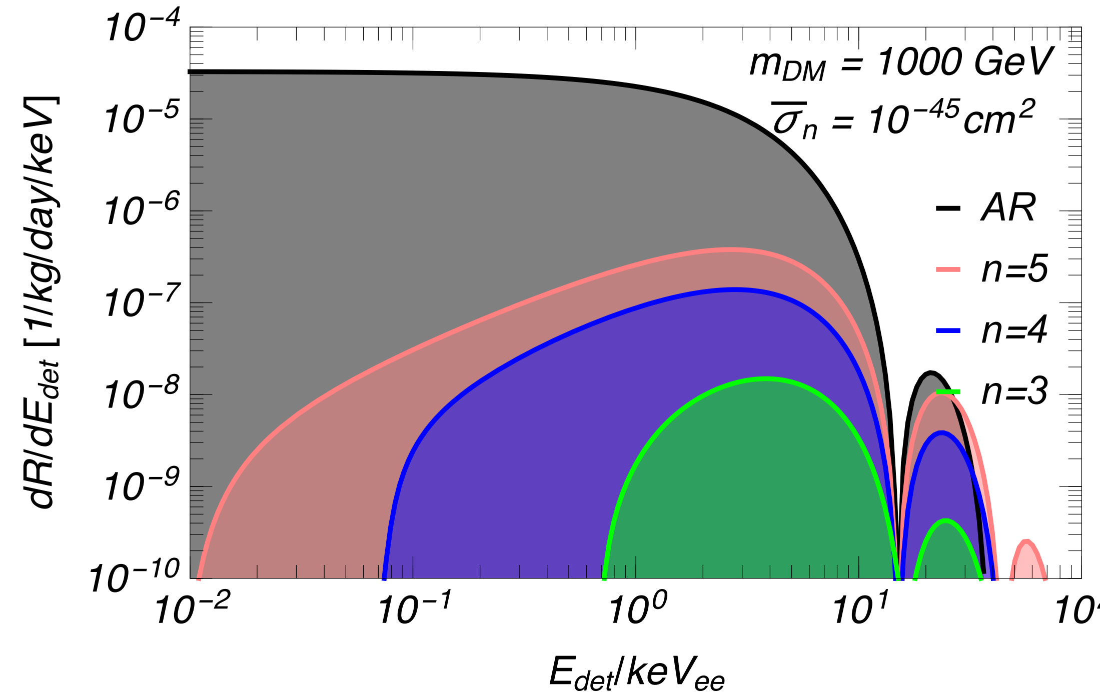
A few hundred events with $E_{det} = O(1)$keV are expected for 10^5 kg days !

The atom recoil energy is much lower than threshold $E_R < M_{DM}^2 / M_A \times v_{DM}^2 = O(1)$eV

✓ Implication on Dark Matter Direct Detection Experiments

✓ Migdal Effect single-phase Liquid Xe detectors





$$\frac{dR}{dE_{\rm det}} \simeq \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/o\ Migdal} + \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/\ Migdal}$$

$E_{det} = (0.1\text{-}0.2)\, E_R + E_{EM}$ $\quad$ $E_{EM} = E_e + E_{dex} \sim E_e - E_n$

For heavier dark matter, the atom recoil energy is much lower than threshold

$E_R < M_A^2 \times v_{DM}^2 = O(10\text{-}100)$ keV

The Migdal effect is submerged below the conventional nuclear recoil spectrum.