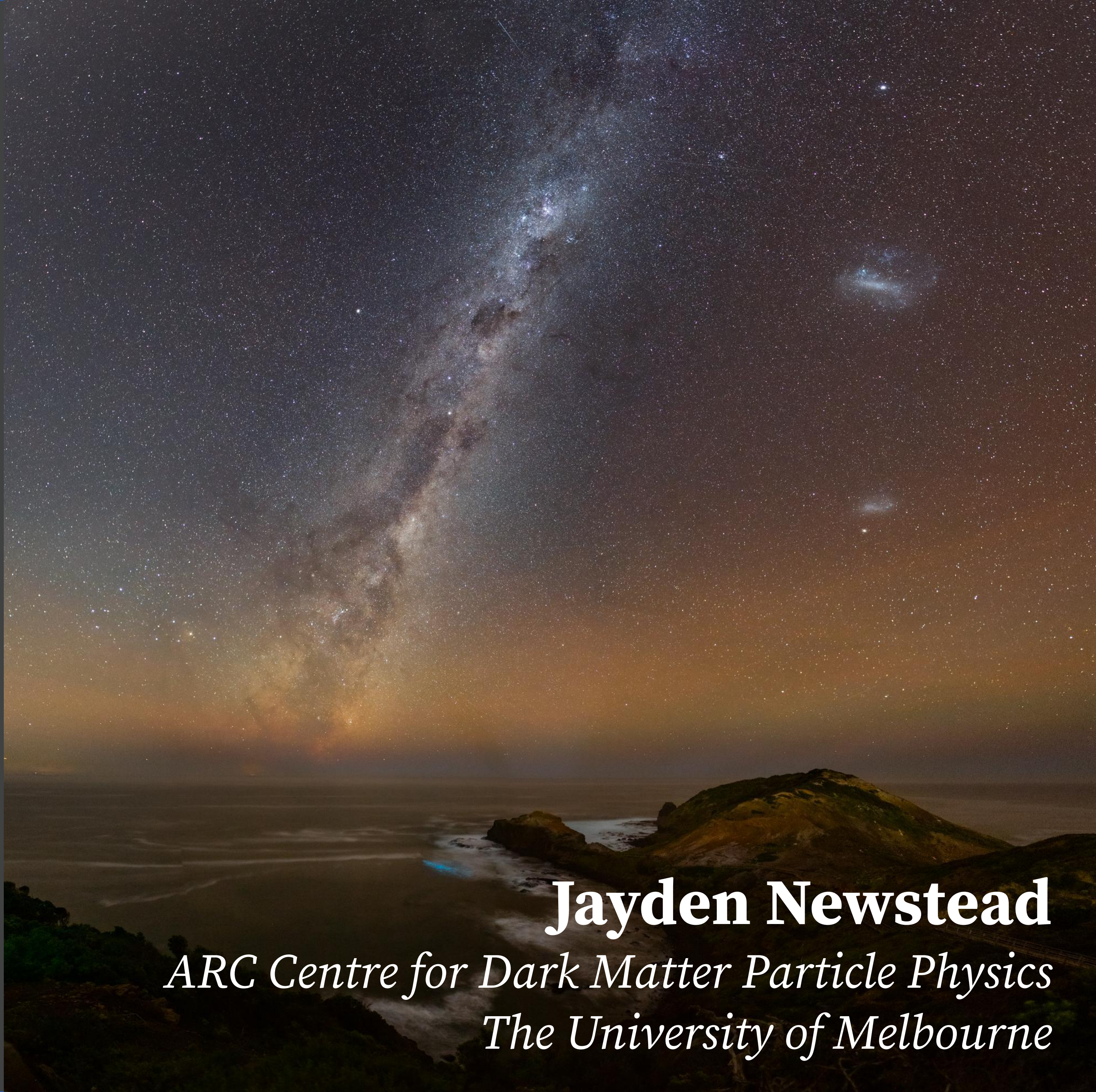
ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

The Migdal effect in liquid noble dark matter experiments

Mitchell Institute Workshop 2022



Jayden Newstead
ARC Centre for Dark Matter Particle Physics
The University of Melbourne

The Migdal effect in liquid noble dark matter experiments

Collaborators:
Nicole Bell (Uni Melb)
James Dent (SHSU)
Rafael Lang (Purdue)
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Jason Kumar (Hawaii U.)
Bhaskar Dutta (TAMU)
Sumit Ghosh (TAMU)

Mitchell Institute Workshop 2022

arXiv:2112.08514 - Calibrating the Migdal effect
arXiv:2103.05890 – The Migdal effect from inelastic scattering

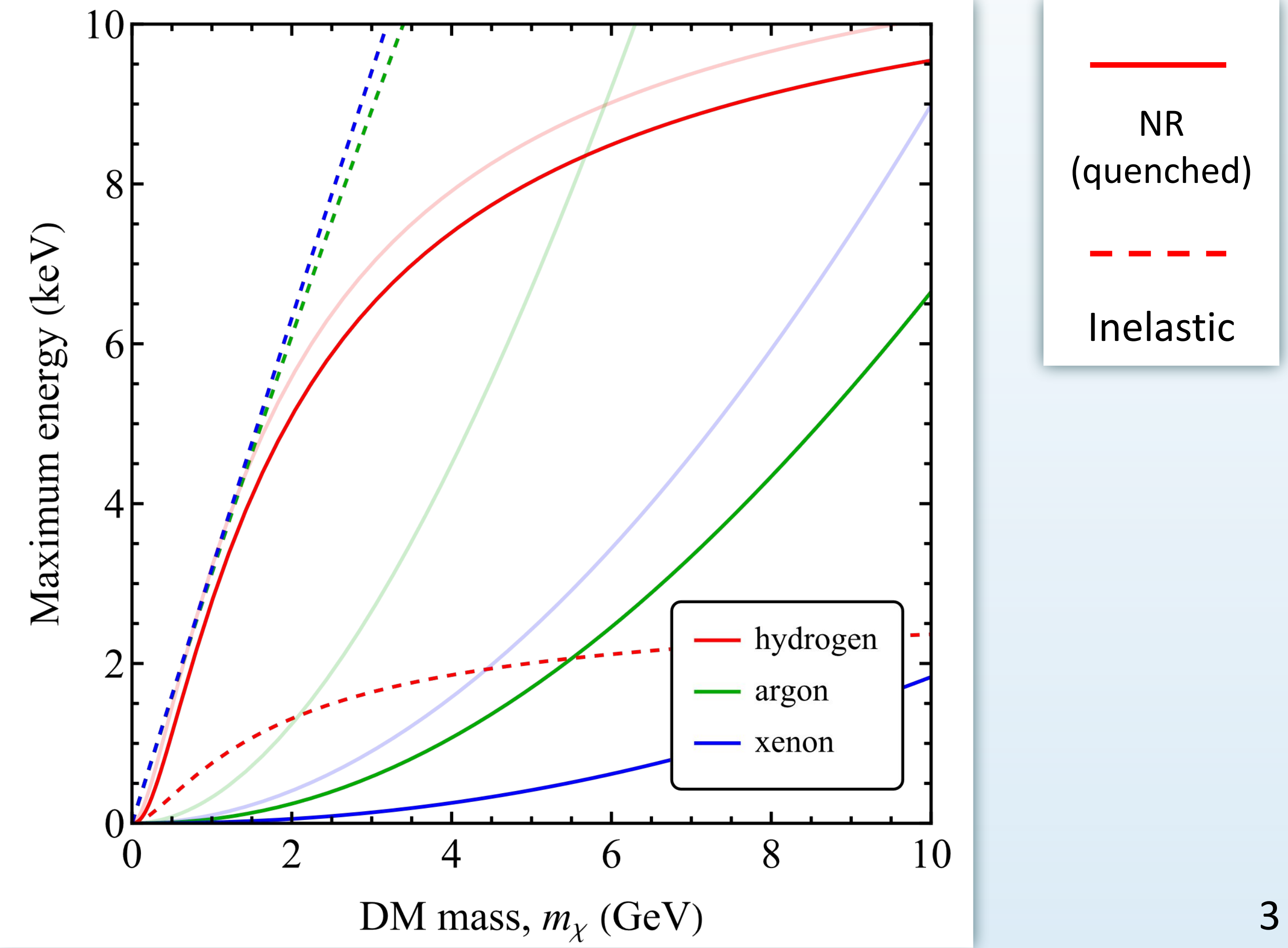
Direct detection's kinematic problem

- Light dark matter does not pack much of a punch:

$$E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$

$$E_{EM_{\max}} = \frac{\mu_T}{2} v_{\max}^2$$

take $v_{\max}$ = 760 km/s



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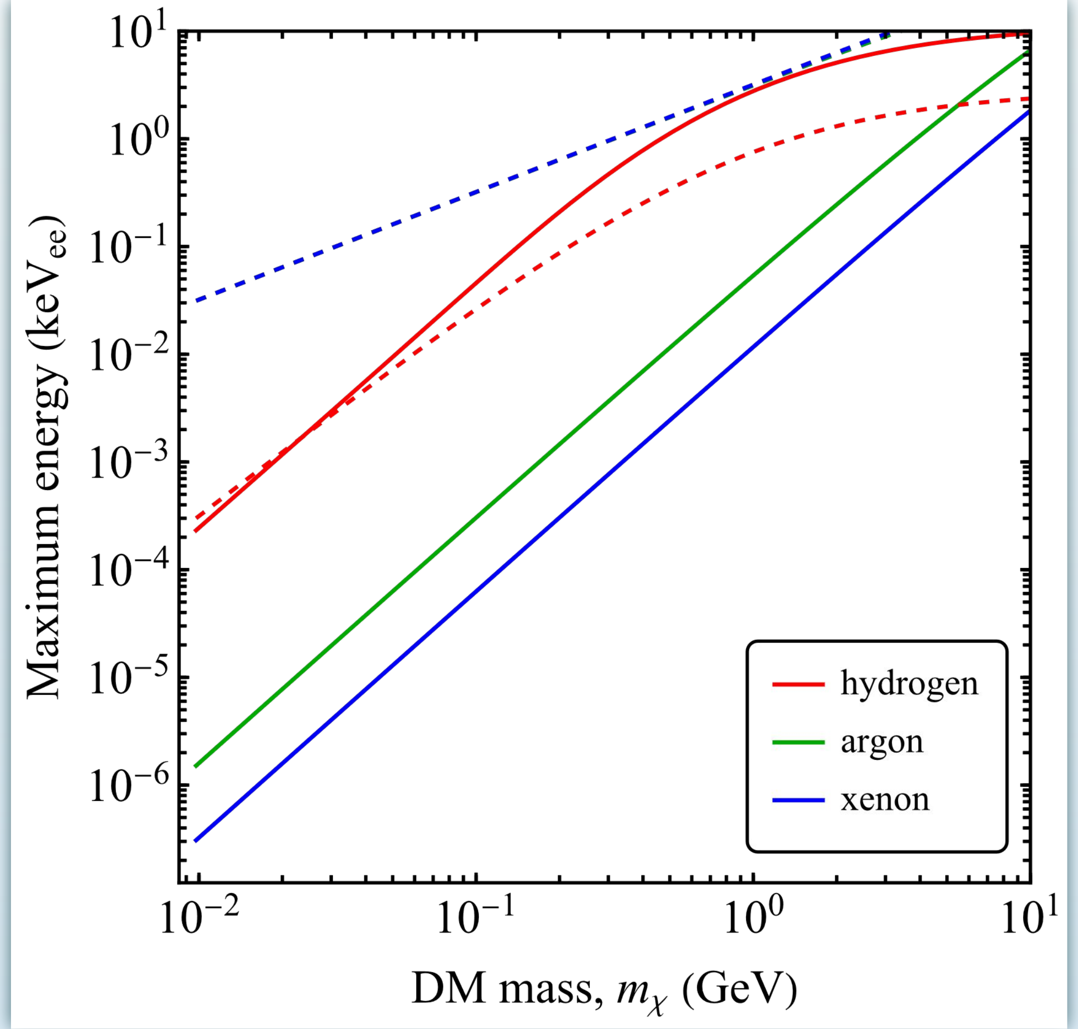
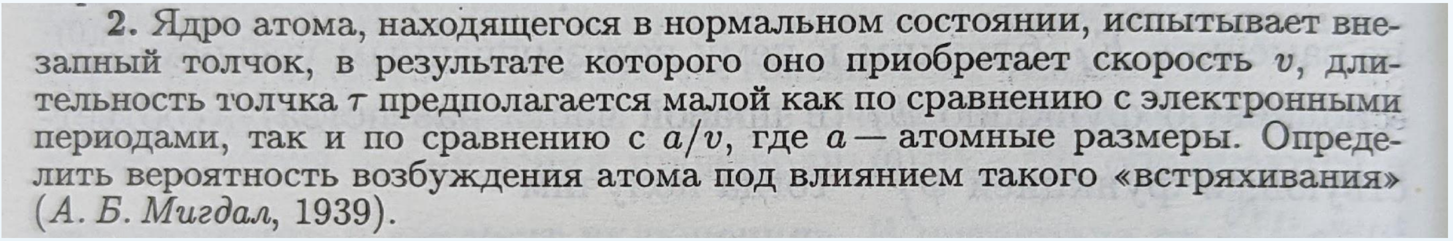


A brief history of the Migdal effect

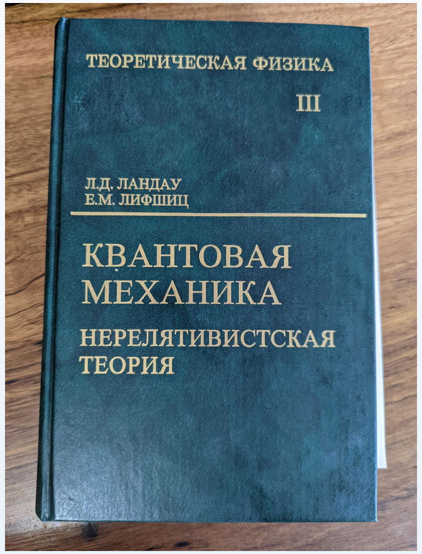
1939: A.B. Migdal, J. Phys. USSR 4 449

1958: Landau and Lifshitz Vol. 3: Quantum Mechanics, sec. 41:



2. Ядро атома, находящегося в нормальном состоянии, испытывает внезапный толчок, в результате которого оно приобретает скорость v, длительность толчка τ предполагается малой как по сравнению с электронными периодами, так и по сравнению с a/v, где a — атомные размеры. Определить вероятность возбуждения атома под влиянием такого «встряхивания» (*А. Б. Мигдал*, 1939).

2005: J.D. Vergados and H. Ejiri, Phys. Lett. B 606, 313, [hep-ph/0401151]



2018: M. Ibe, W. Nakano, Y. Shoji and K. Suzuki, JHEP 1803 (2018) 194 [arXiv:1707.07258]

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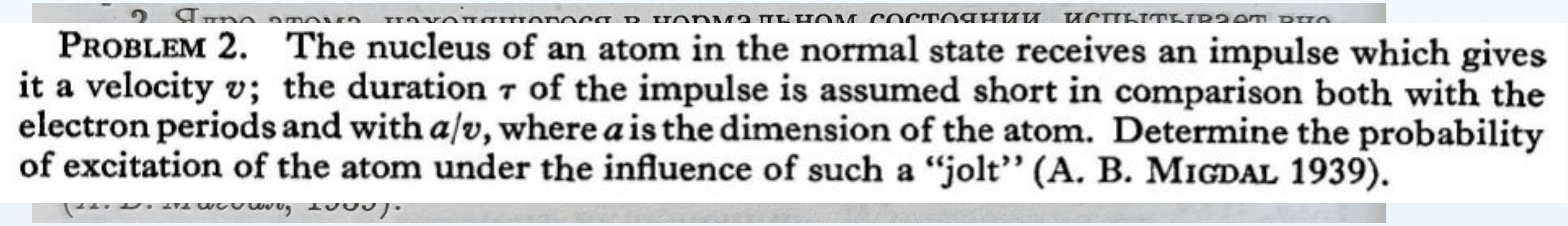
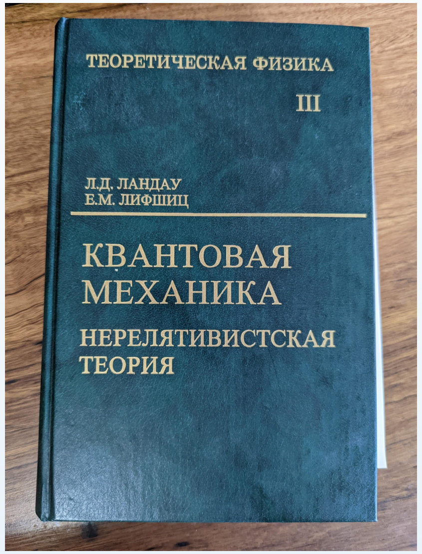


Problem 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. Migdal 1939).



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Migdal rate calculation

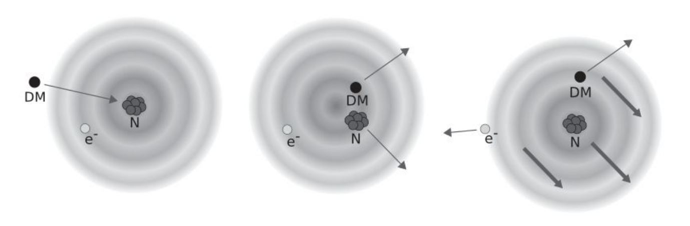
- What goes into the rate calculation?

$$\frac{d^2 R}{dE_{\mathrm{NR}} dE_i} = \frac{d^2 R_{iT}}{dE_{\mathrm{NR}} dE_i} \times |Z_{\mathrm{ion}}|^2$$

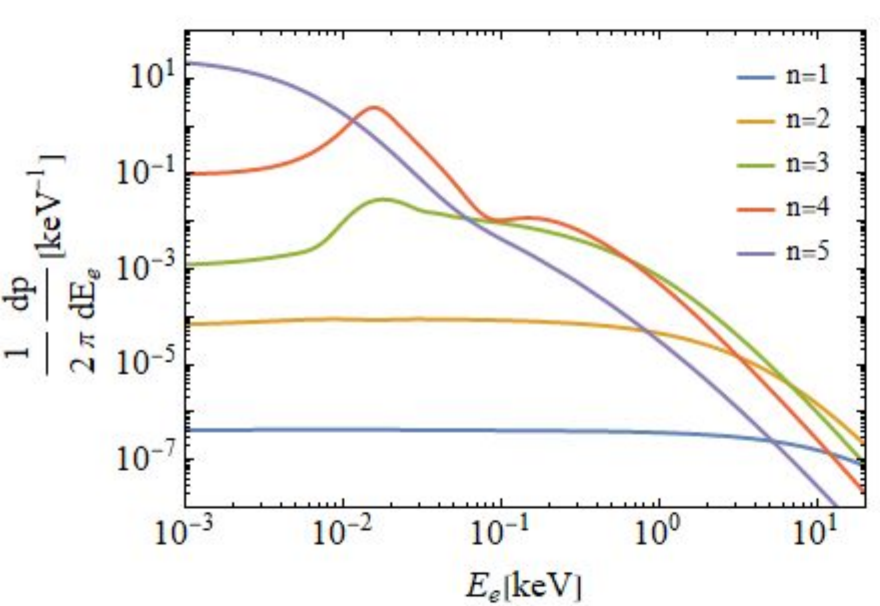
$$|Z_{\mathrm{ion}}|^2 = \frac{1}{2\pi} \sum_{n,\ell} \int dE_e \frac{d}{dE_e} p^c_{q_e}(n\ell \rightarrow (E_e))$$

- What does such an event look like?

$$E_{\mathrm{det}} = \mathcal{L} E_R + E_e + E_{nl}$$



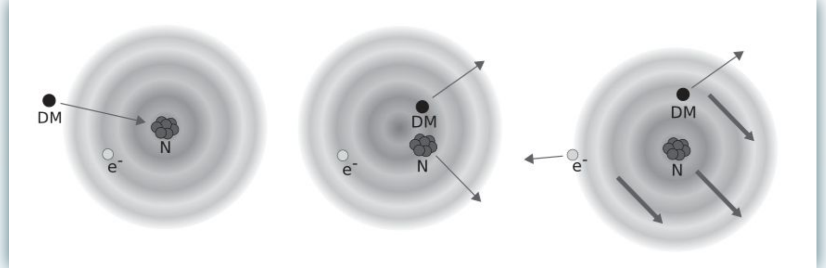
Dolan et al. PRL 2017



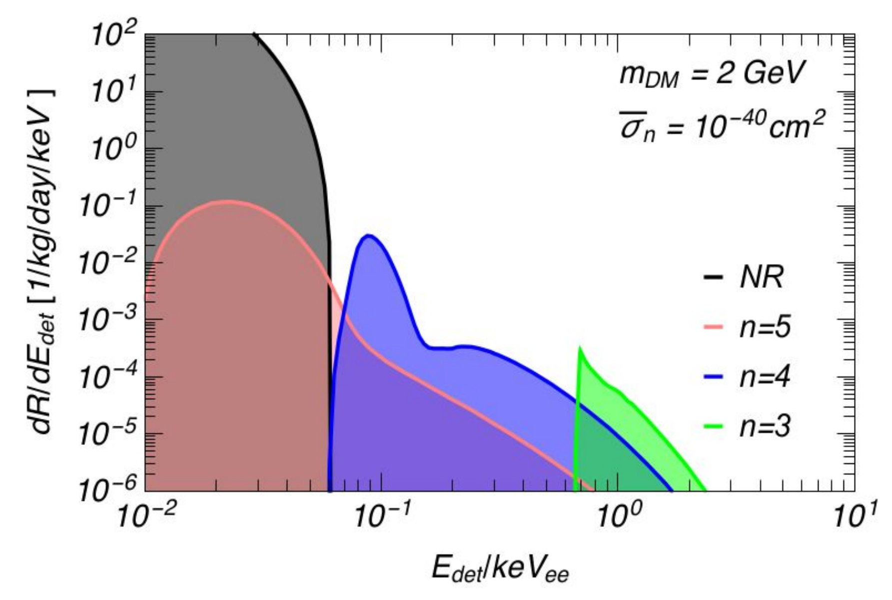
M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, arXiv:1707.07258

Migdal rates and Limits

- The Migdal effect is atomic ionization or excitation due to a nuclear recoil
- Electron shakeoff has been observed during nuclear decay, but not due to scattering



Dolan et al.



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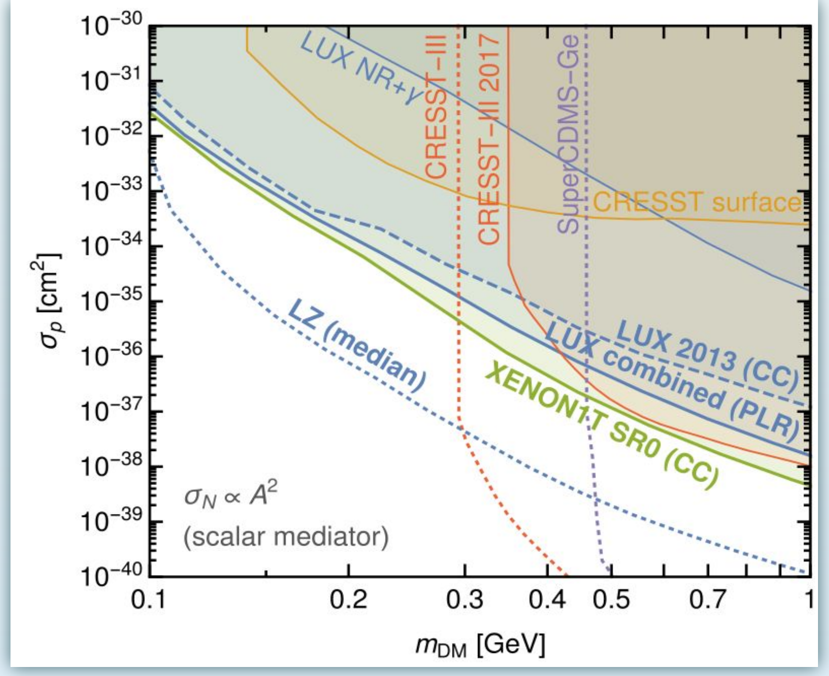

M. J. Dolan, F. Kahlhoefer, and C. McCabe, (PRL)
arXiv:1711.09906

Migdal rates and Limits

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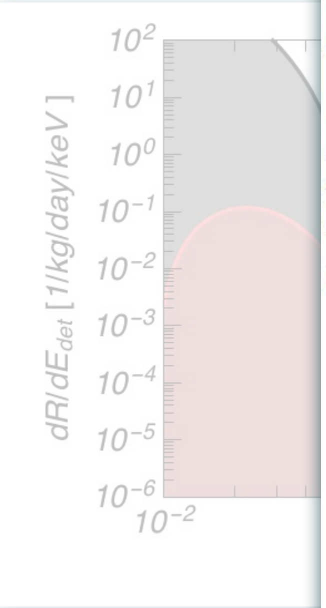

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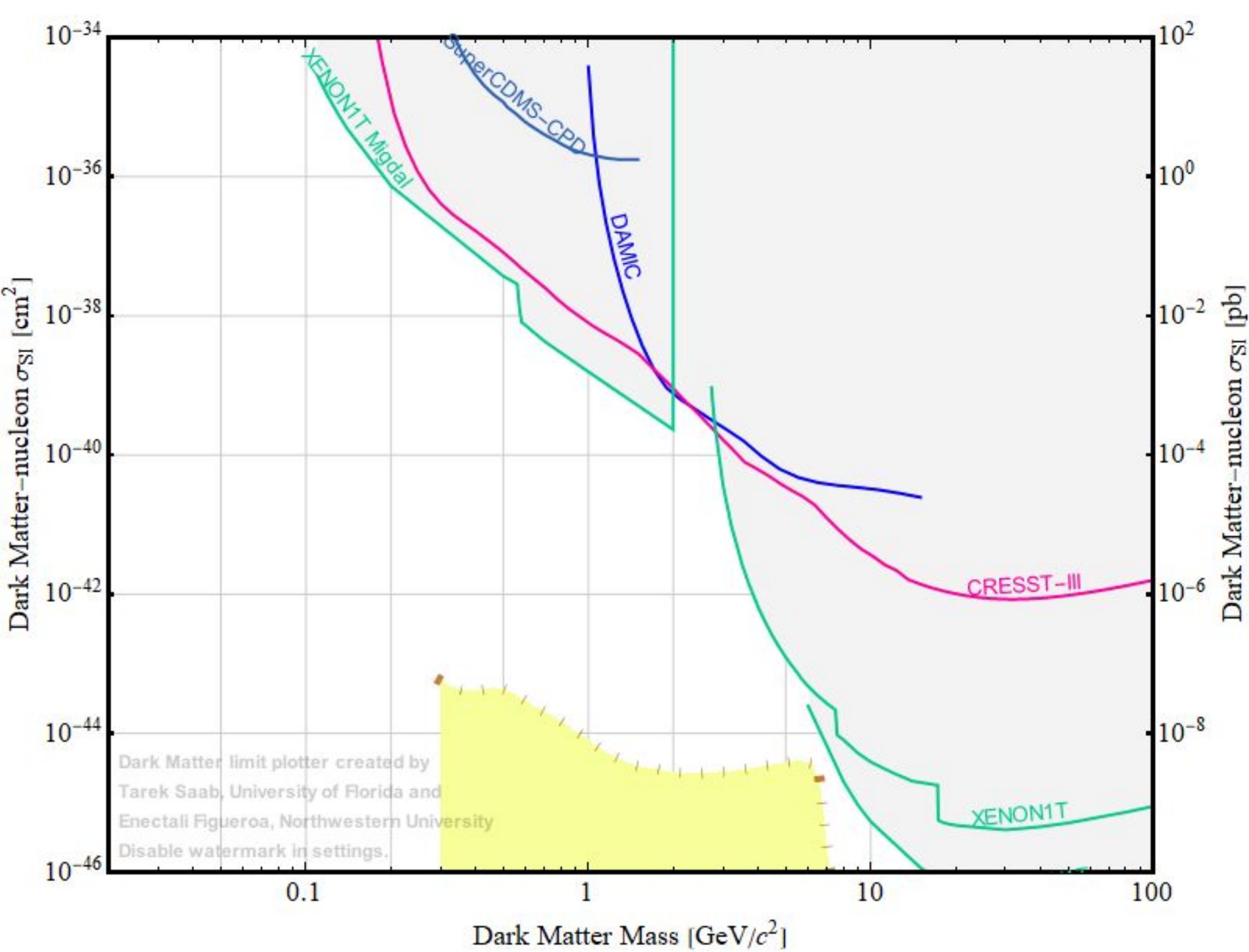

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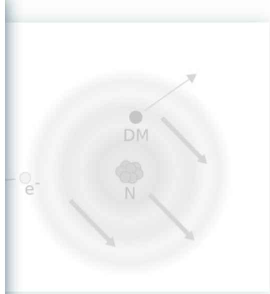
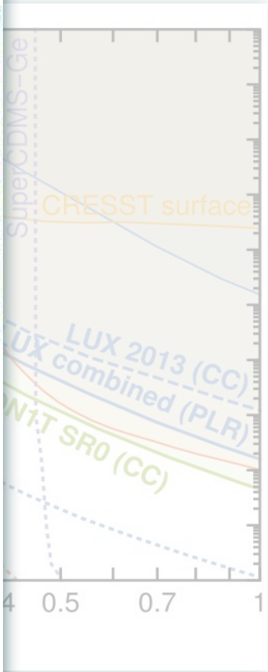


Dolan et al.



McCabe, (PRL)

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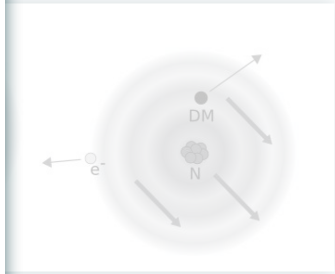
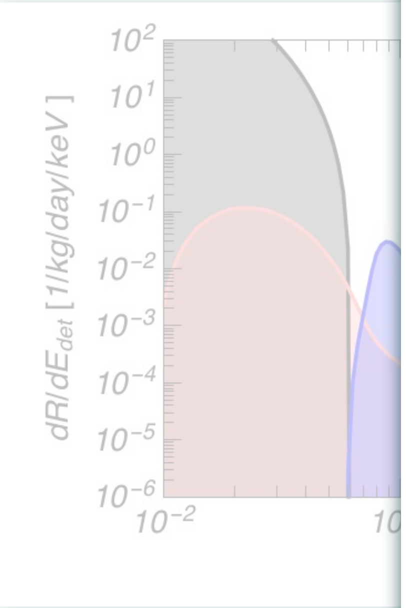


Dolan et al.



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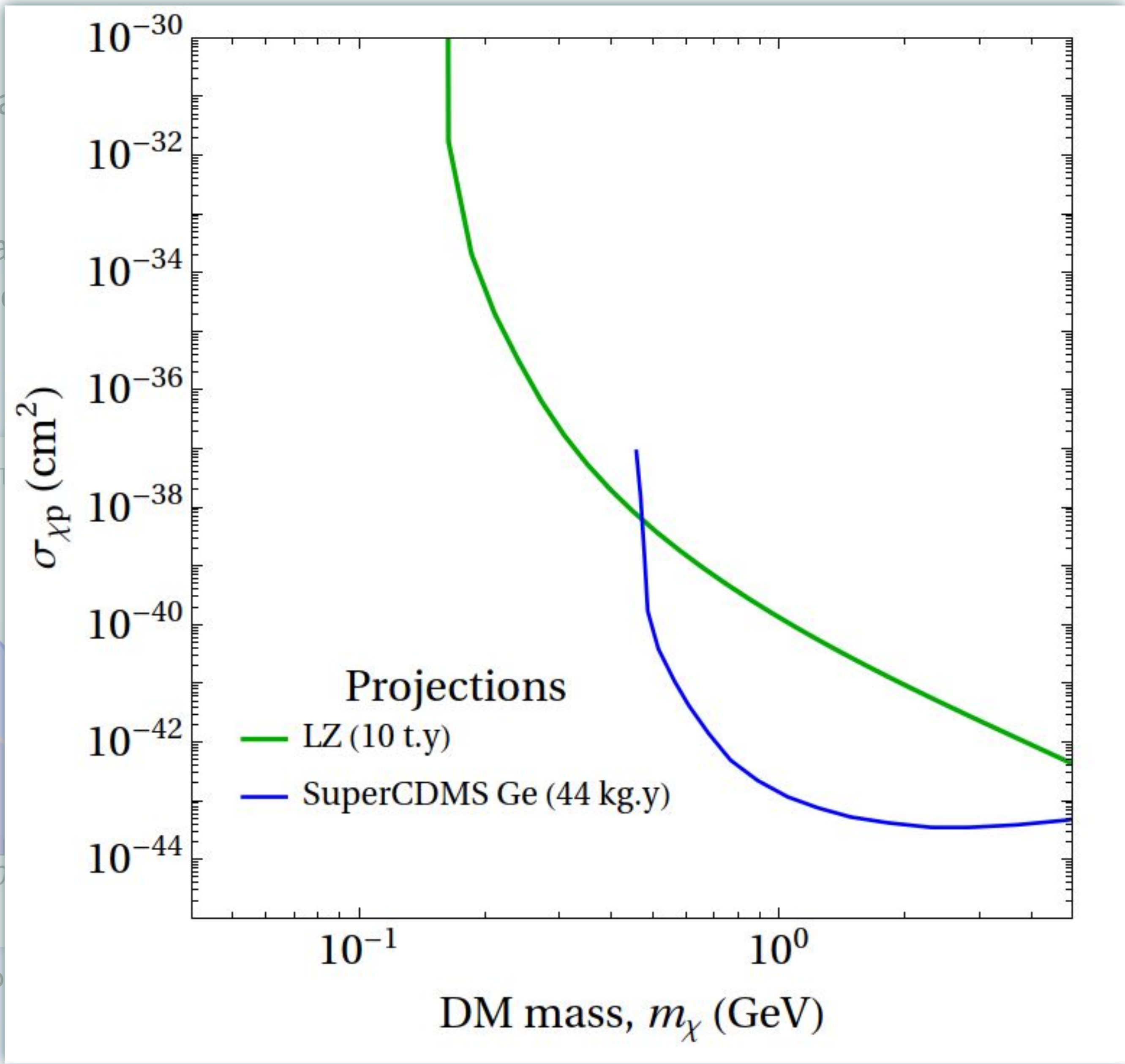
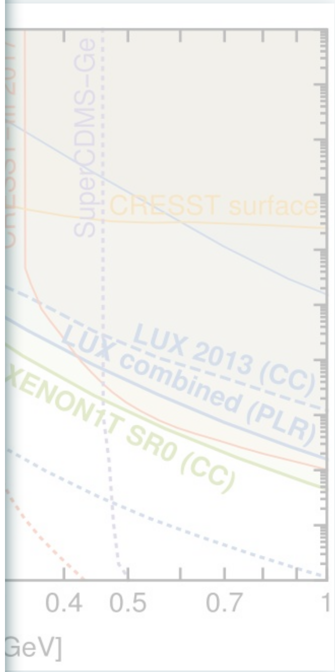
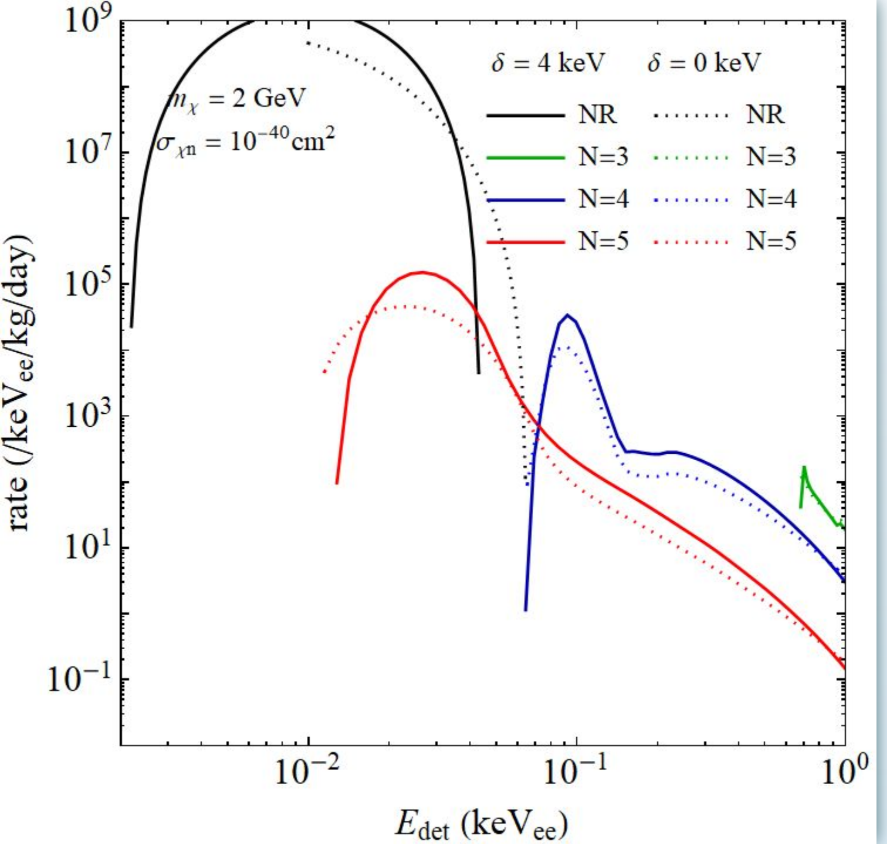




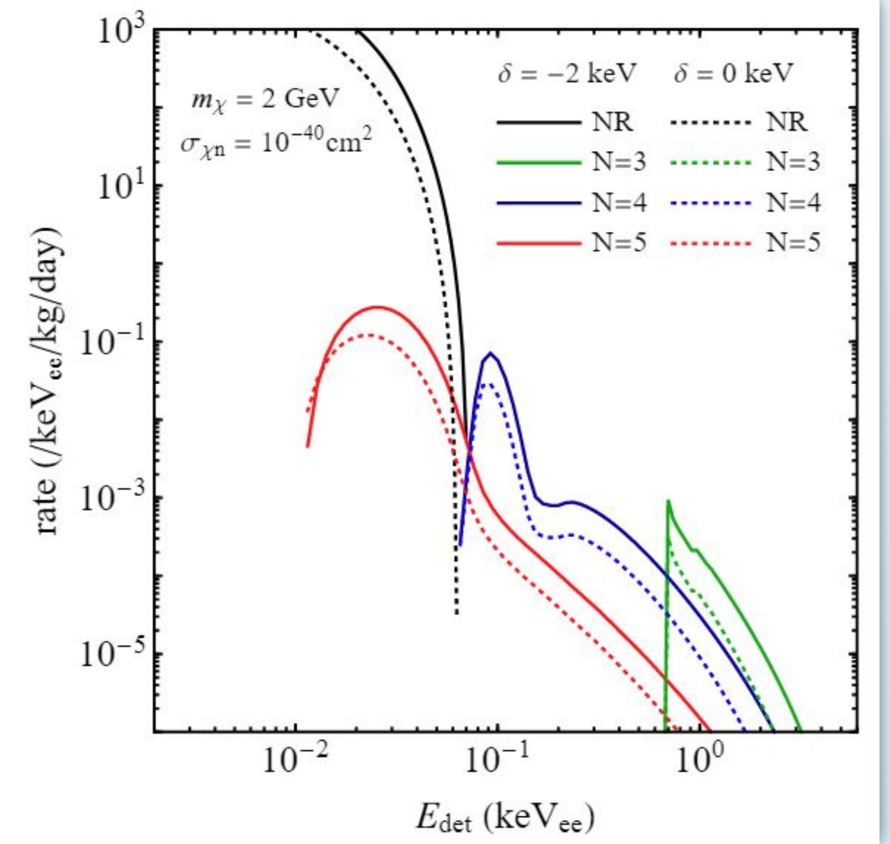
d C. McCabe, (PRL)

The Migdal effect with inelastic DM

- Keeping mass and cross section constant, the largest effect is on the kinematic endpoint



endothermic



exothermic

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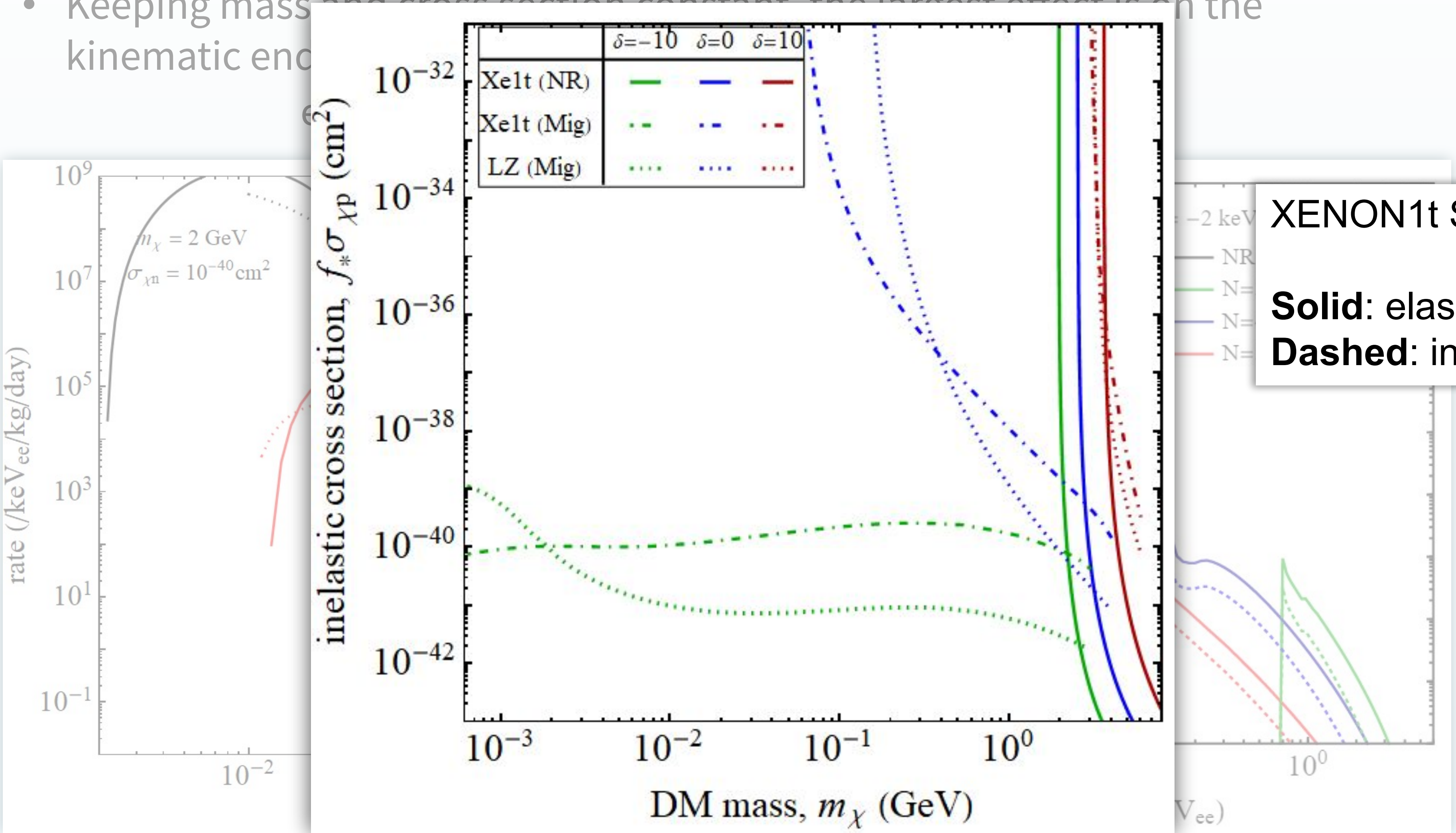
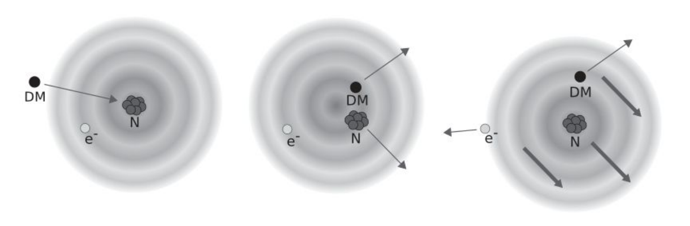


XENON1t S2-only

Solid: elastic
Dashed: inelastic

Migdal rate calibration

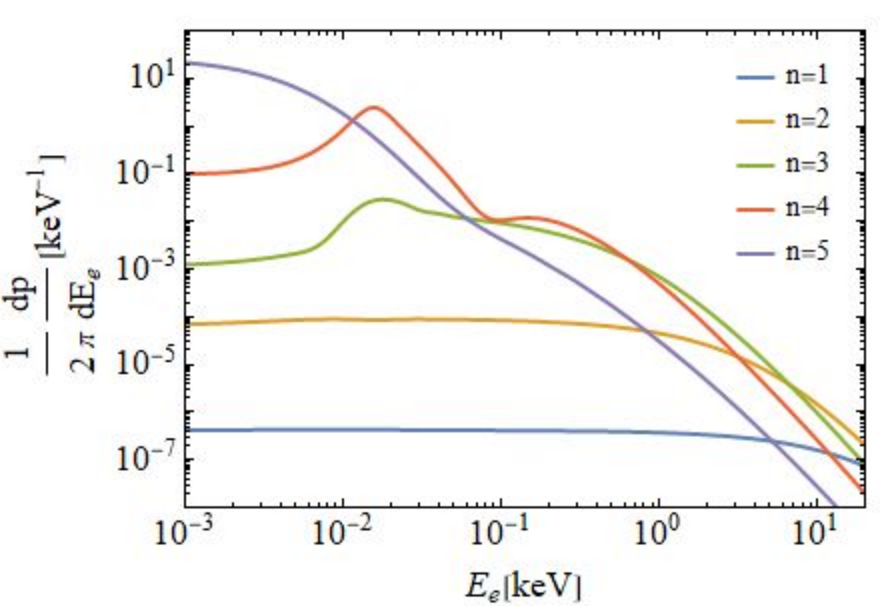


Two components of the calculation we want to calibrate:

1. The atomic ionization factors
   (Data driven methods exist for solid state targets via the EELS)

2. The detector response to a Migdal event

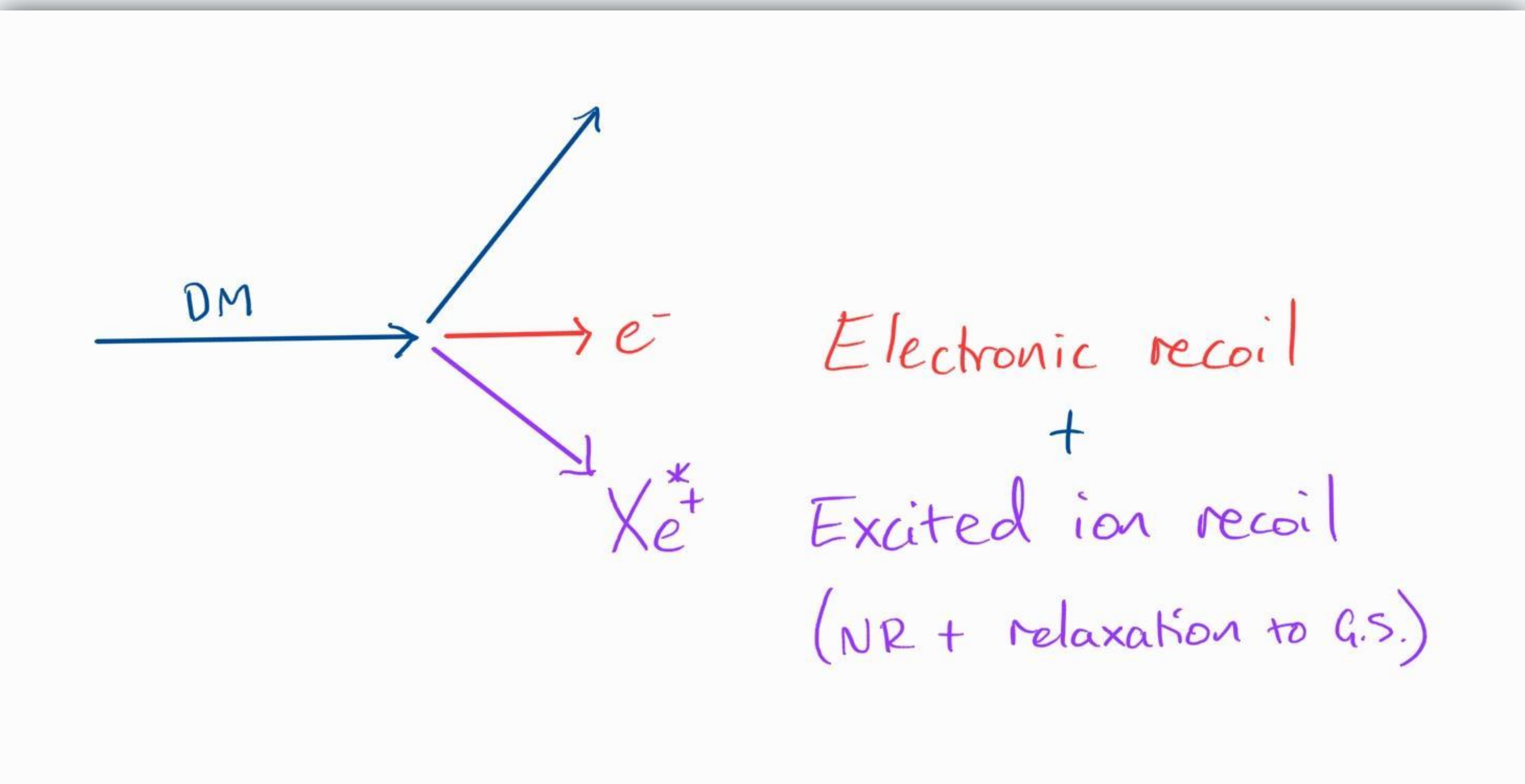
$$E_{\mathrm{det}} = \mathcal{L}E_R + E_e + E_{nl}$$



M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, arXiv:1707.07258

Quanta production for a Migdal event

How does a Migdal event change the signal production process?



→ A calibration is needed

Calibrating the Migdal effect

- Use nuclear recoils from neutral particles:

neutrons:

$$E_{\mathrm{R,max}} = \frac{4\mu_T^2 E_n}{m_n m_T}$$

$$E_{\mathrm{EM,max}} = \frac{\mu_{\mathrm{T}} E_n}{m_n}$$

neutrinos:

$$E_{R,\mathrm{max}} = \frac{2E_\nu^2}{m_T + 2E_\nu^2}.$$

$$\mathrm{E}_{\mathrm{EM,max}} = E_\nu - E_R$$

Two proposals (that I’m aware of):

- The MIGDAL experiment will attempt to observe Migdal events with neutrons from a DD generator (2.5 MeV) in a gaseous CF_4 optical TPC
- Kentaro Miuchi et al. who suggest using a LiBe reaction at AIST, producing 565 keV neutrons, and gaseous xenon and argon targets

Calibrating the Migdal effect

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neutrinos:

$$E_{R,\max} = \frac{2E_\nu^2}{m_T + 2E_\nu^2}.$$

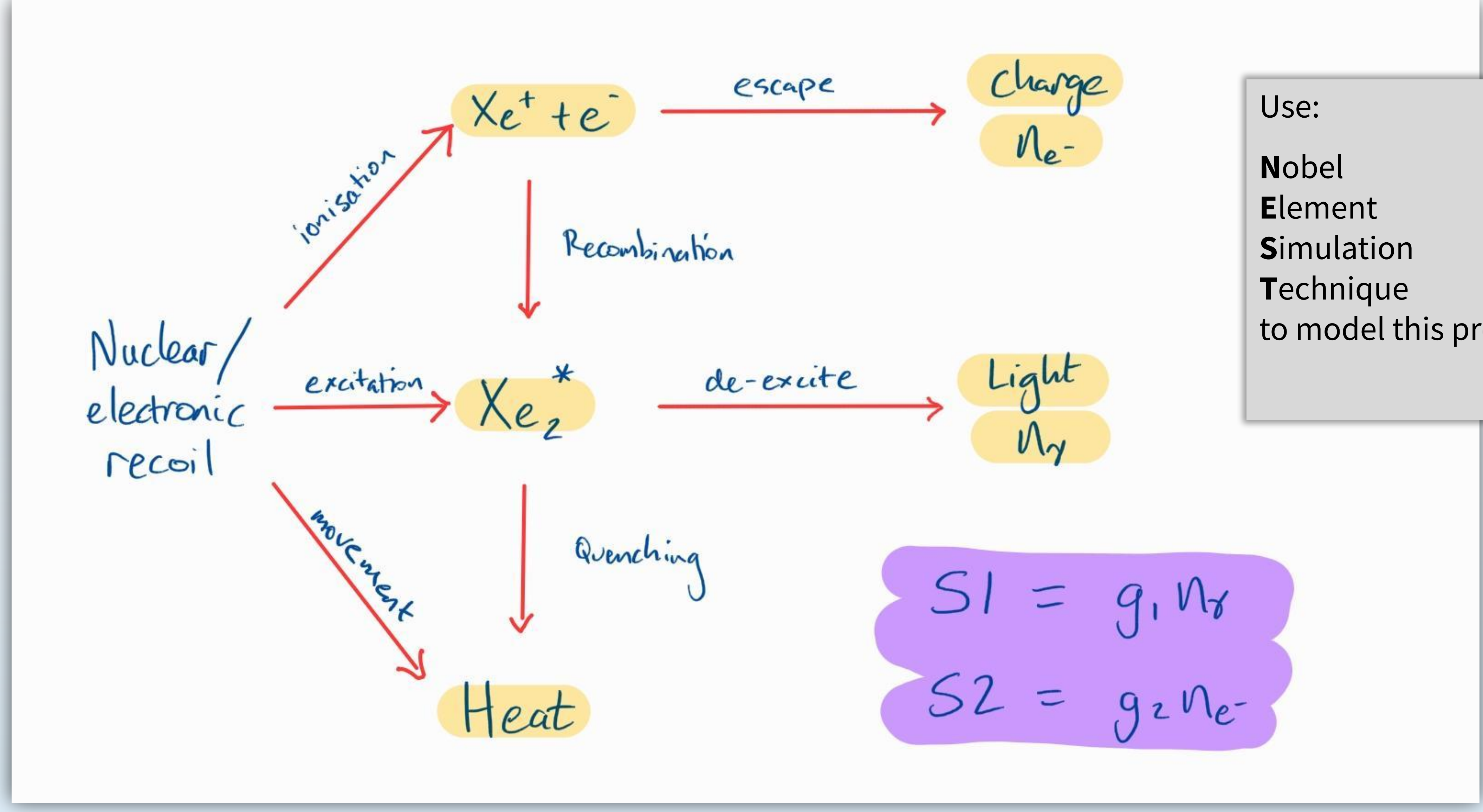
These proposals could provide a validation of theoretical calculation of the atomic ionization probabilities, **however**:

- It is *higher energy recoils* than a low mass DM would induce
- Theoretical calculations of a *'molecular' Migdal effect* have not been performed (and would be difficult)
- Does not calibrate the *detector response of* Migdal event in a dark matter detector

Two pro

- The M ons from a DD
- Kent g 565 keV neutrons, and gaseous xenon and argon targets

Signal production



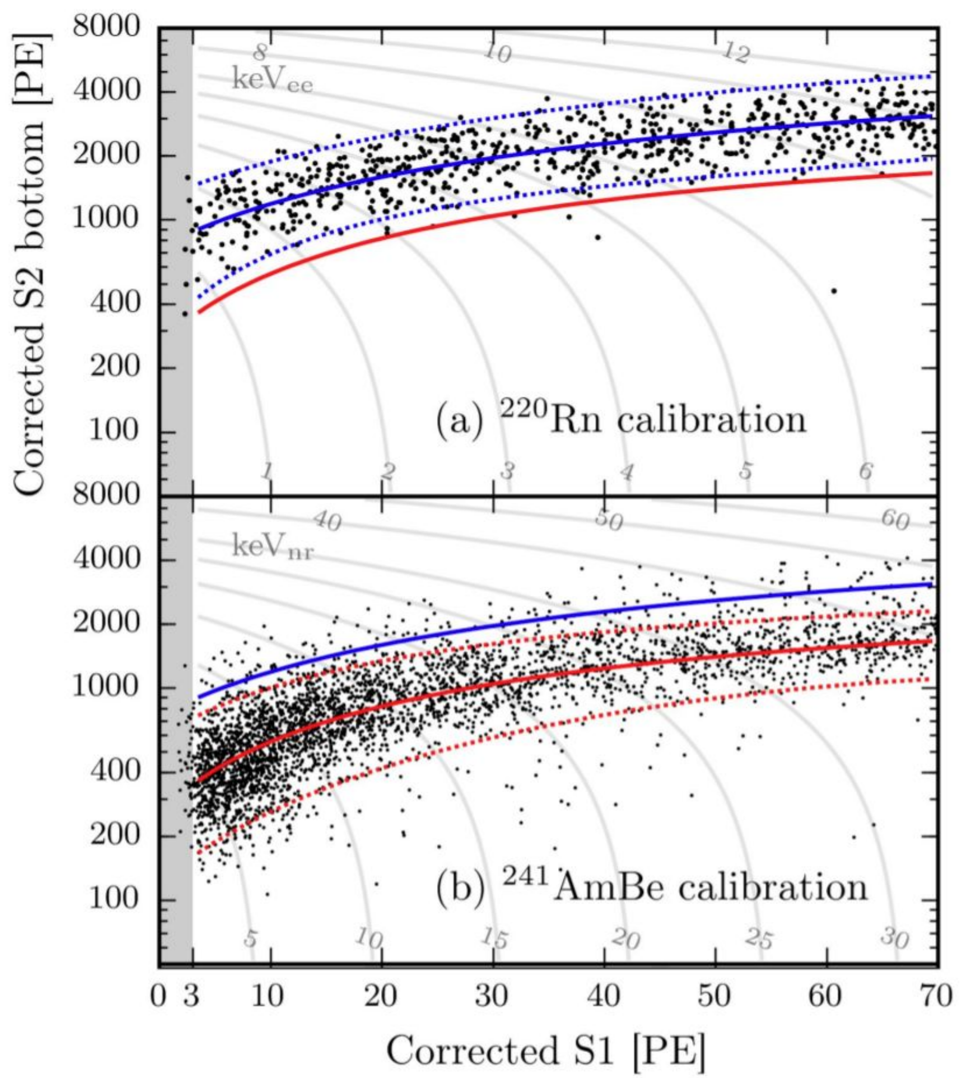
$$S1 = g_1 n_\gamma$$

$$S2 = g_2 n_{e^-}$$

Use:

Nobel
Element
Simulation
Technique
to model this process

Anatomy of a dual-phase xenon detector



arXiv:1705.06655

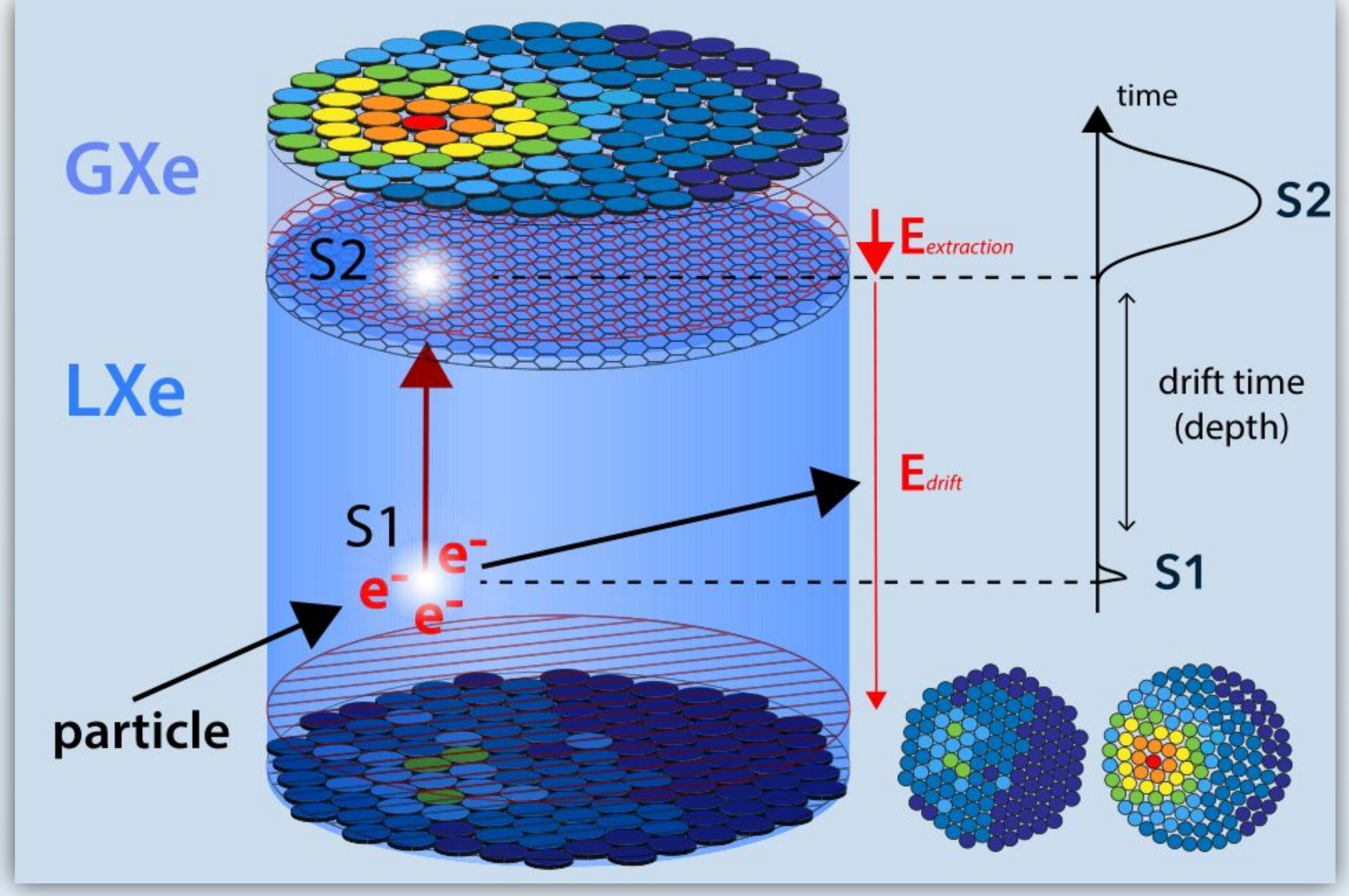
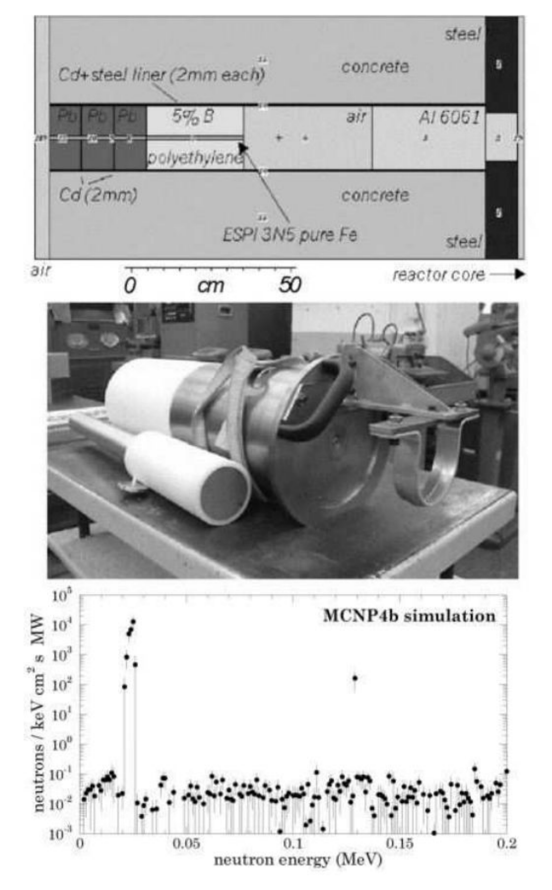


Image: XENON1t collaboration

Potential low-energy neutron sources

Nuclear reactor + filter

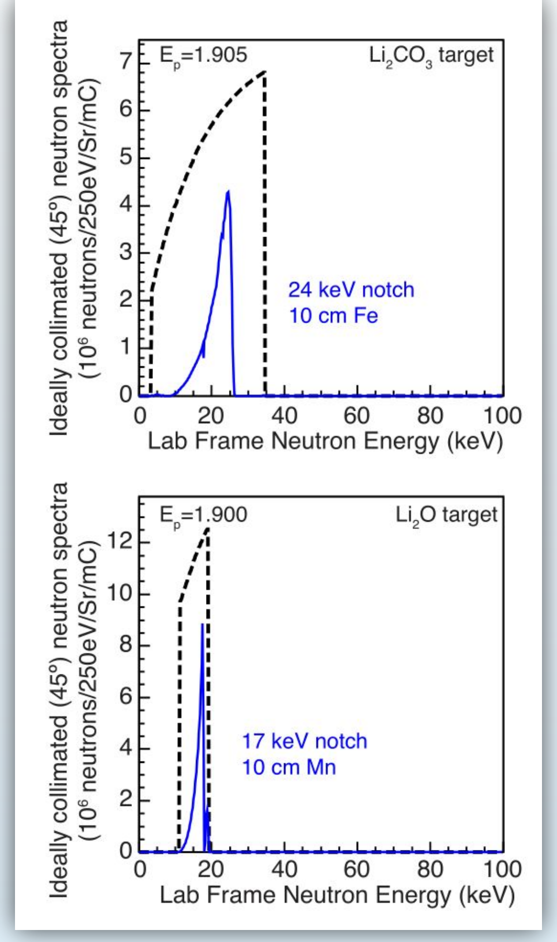


arXiv:nucl-ex/0701011

Pros:
-Large flux
-Continuous operation

Cons:
-Gamma backgrounds

Li + p near threshold + filter

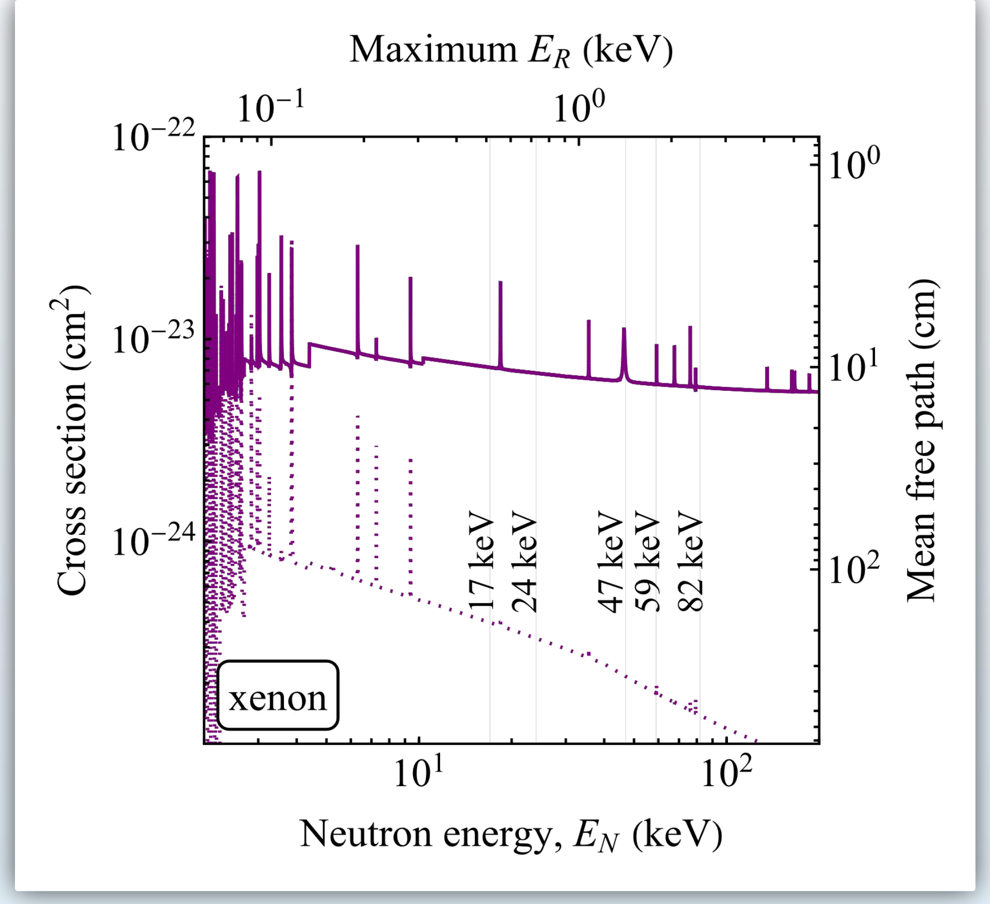


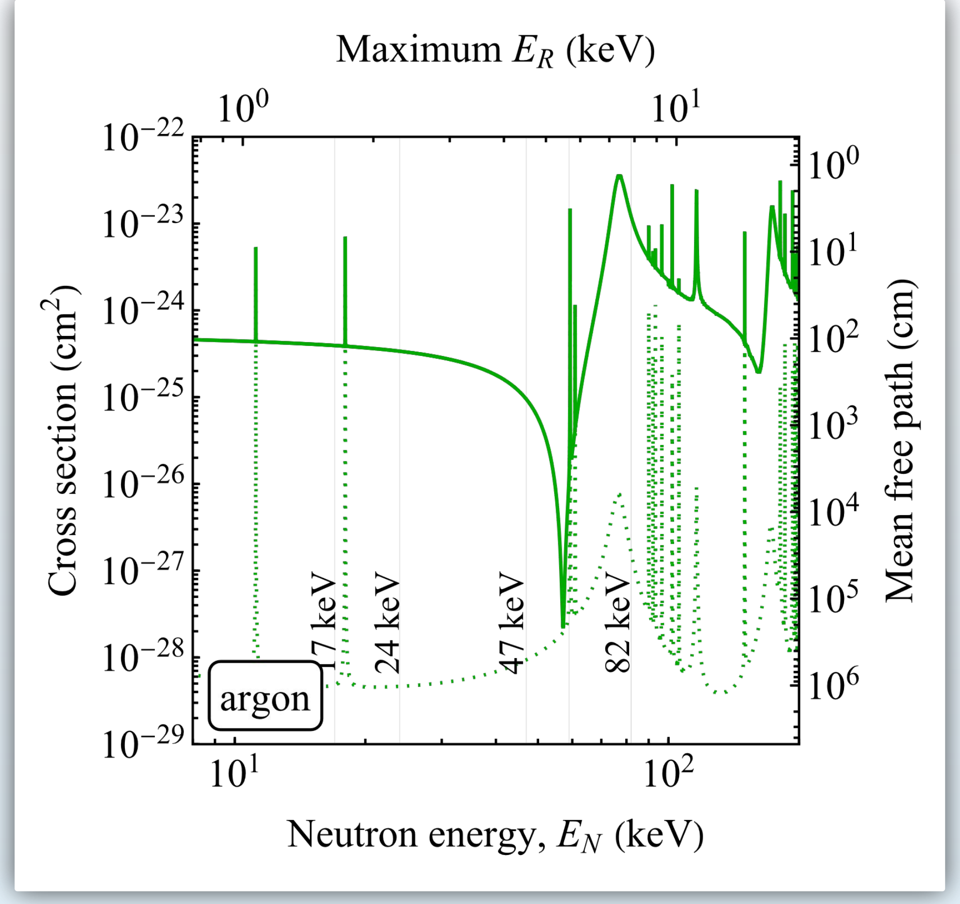
arXiv:1403.1285

Pros:
-Pulsed operation

Cons:
-Larger fluxes may require large/cooled targets

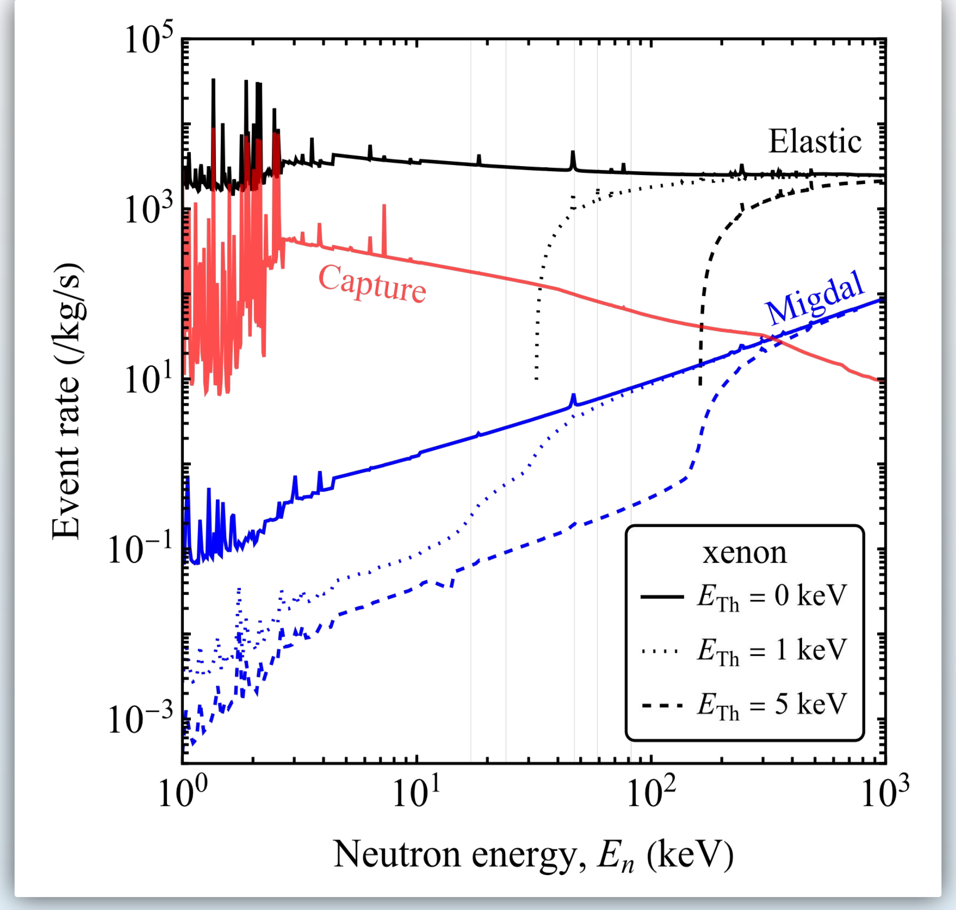
The neutron scattering landscape

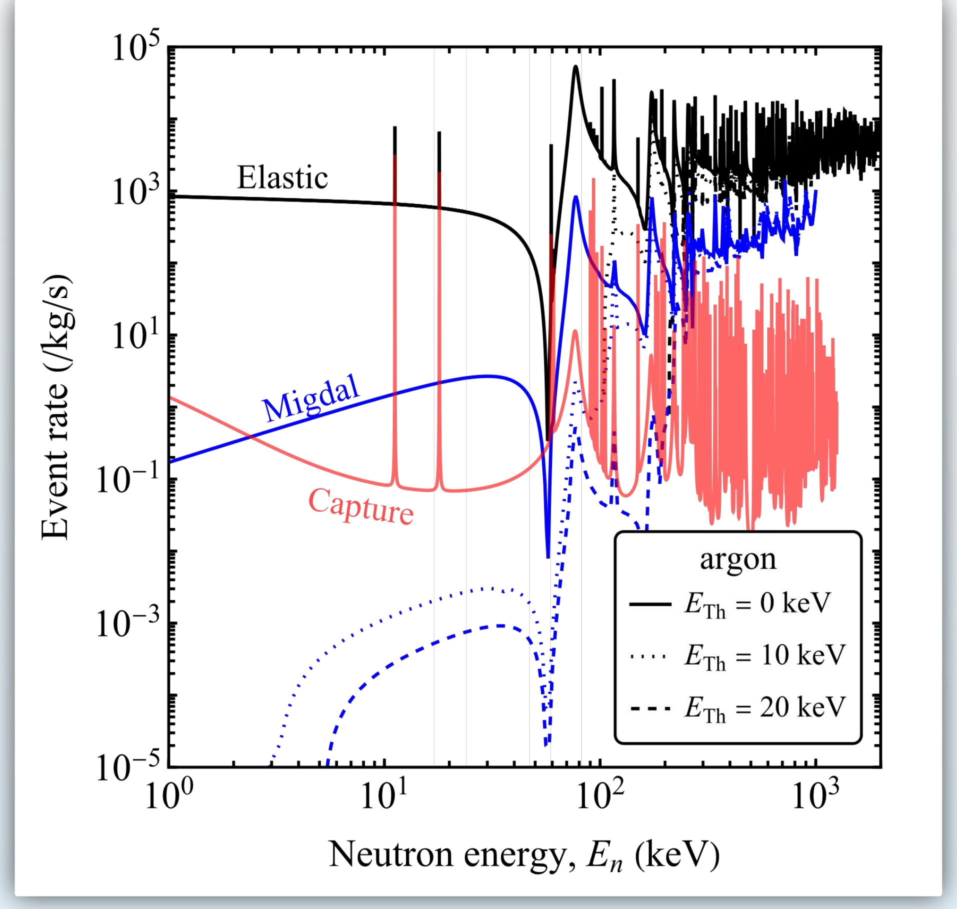




- Radiative capture of neutrons will be a significant background
- Inelastic scattering is >100 keV threshold for all but xenon-129

The neutron scattering landscape





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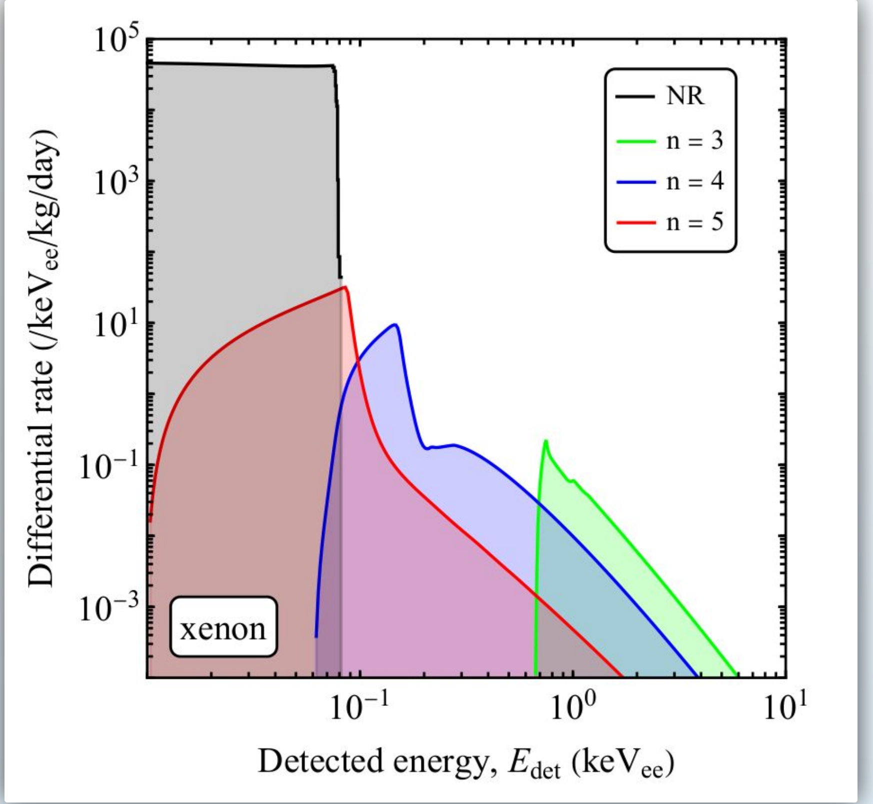
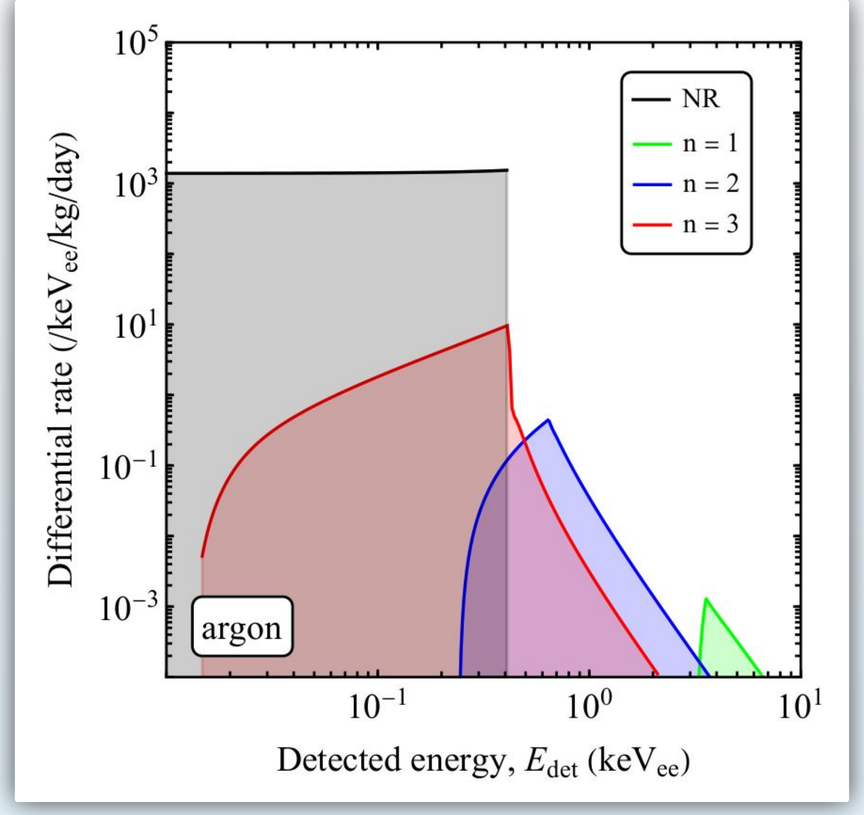
- Inelastic scattering is >100 keV threshold for all but xenon-129

Low-energy neutron Migdal rates

E = 17 keV neutrons, flux = 100 n/cm^2/s





Total rates (raw):

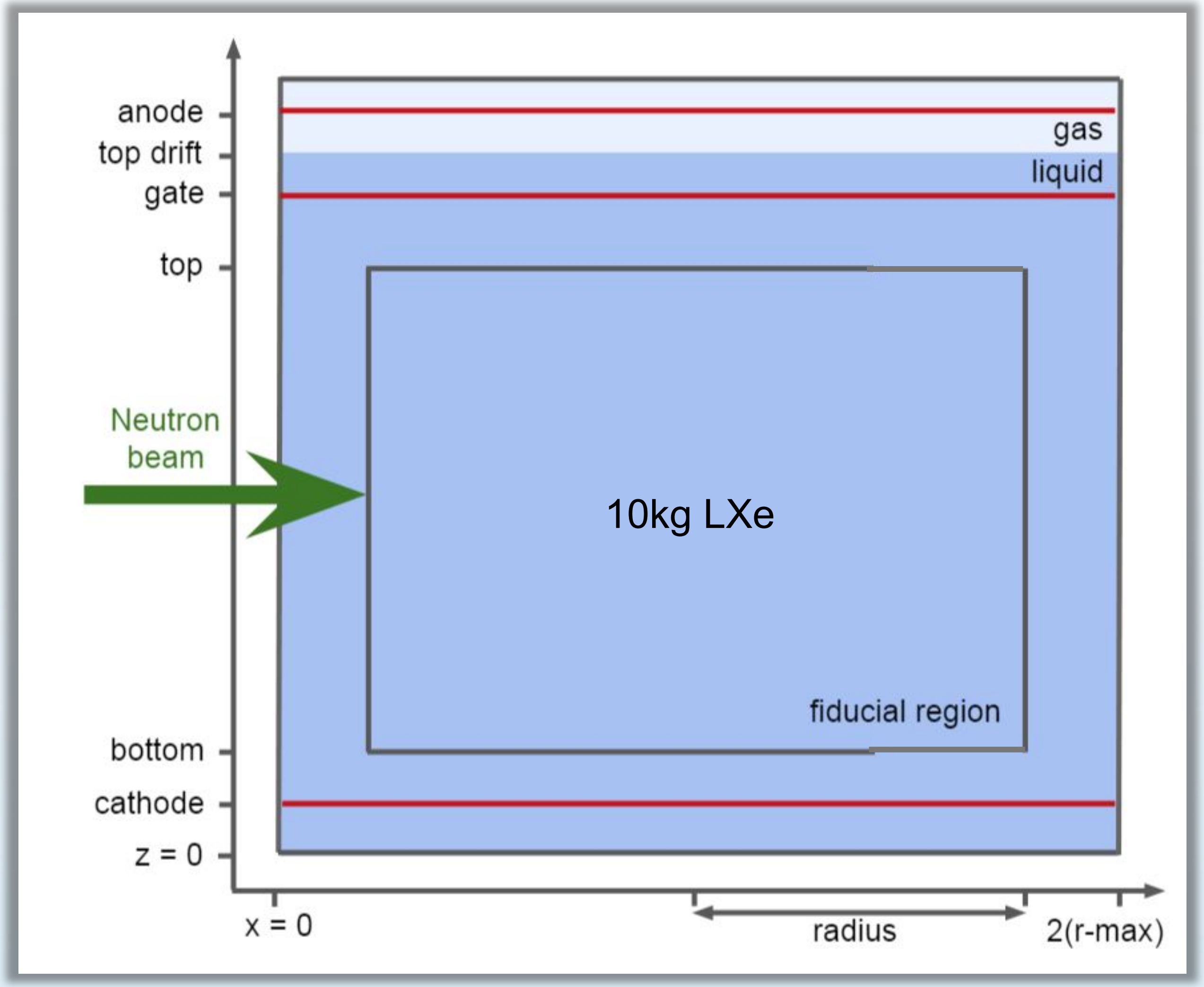
Nuclear:	3,300 events/kg/s	600 events/kg/s
Migdal:	2 events/kg/s	2 events/kg/s

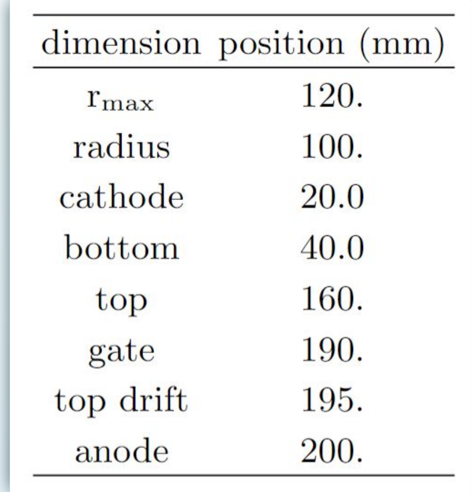
Simulation of a neutron beam source

Gaussian neutron beam:

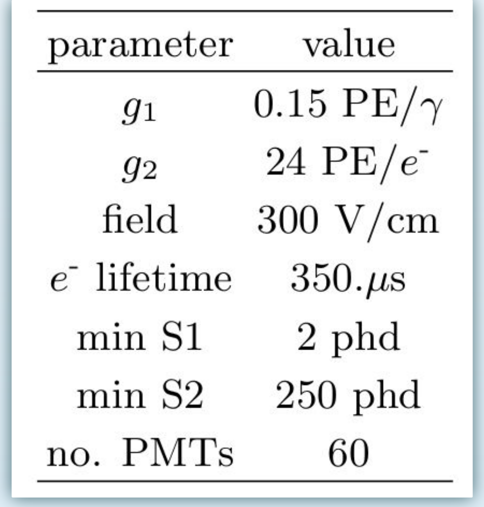
FWHM = 6cm
Peak flux = 10^8n/hr
(avg 100n/cm^2/s)

Modelled on Barbeau et al.



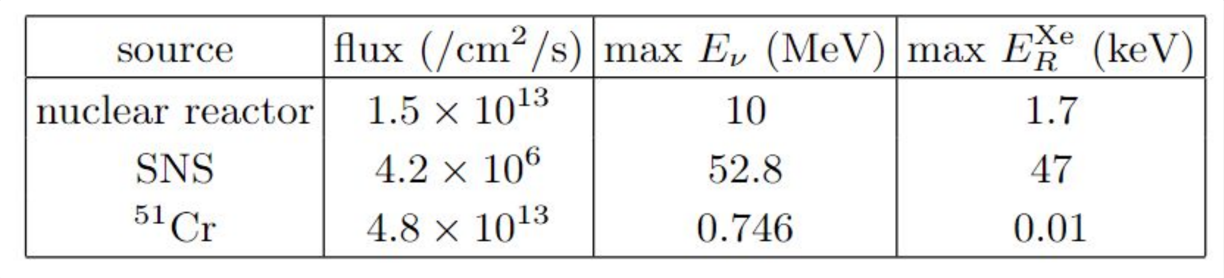


dimension	position (mm)
r_{max}	120.
radius	100.
cathode	20.0
bottom	40.0
top	160.
gate	190.
top drift	195.
anode	200.

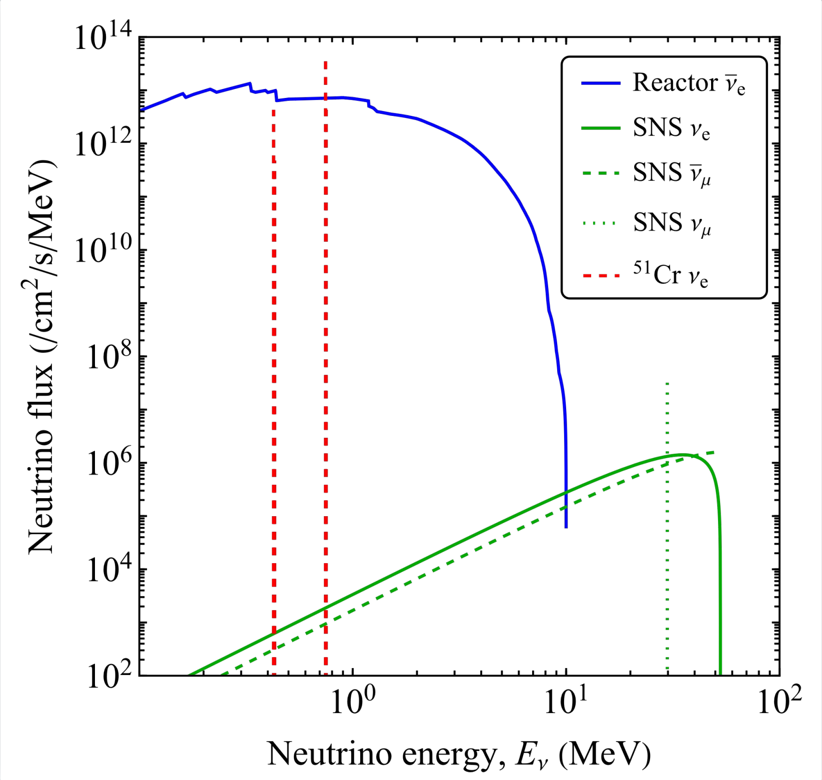


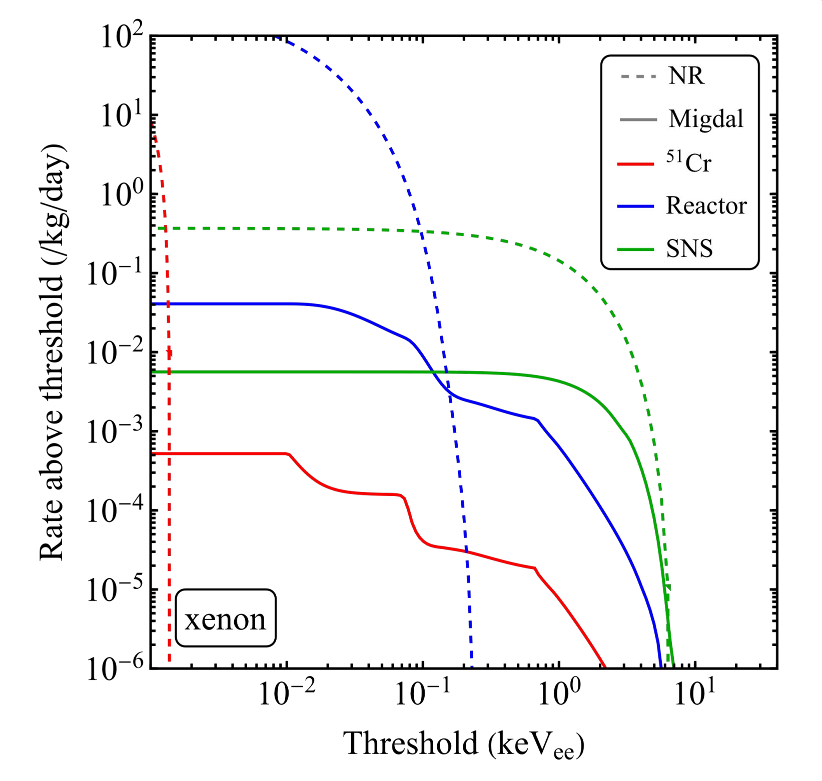
parameter	value
g_1	0.15 PE/γ
g_2	24 PE/e^-
field	300 V/cm
e^- lifetime	350.μs
min S1	2 phd
min S2	250 phd
no. PMTs	60

Low-energy neutrino sources



source	flux (/cm^2/s)	max E_ν (MeV)	max E_R^{Xe} (keV)
nuclear reactor	1.5×10^{13}	10	1.7
SNS	4.2×10^{6}	52.8	47
^{51}Cr	4.8×10^{13}	0.746	0.01



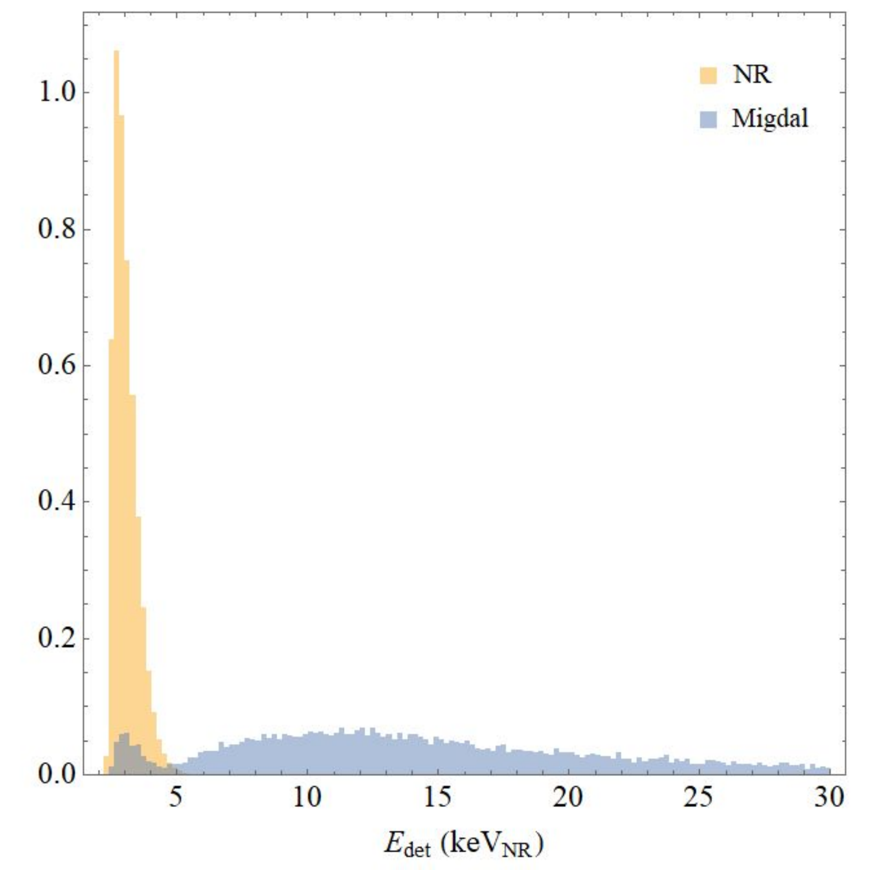


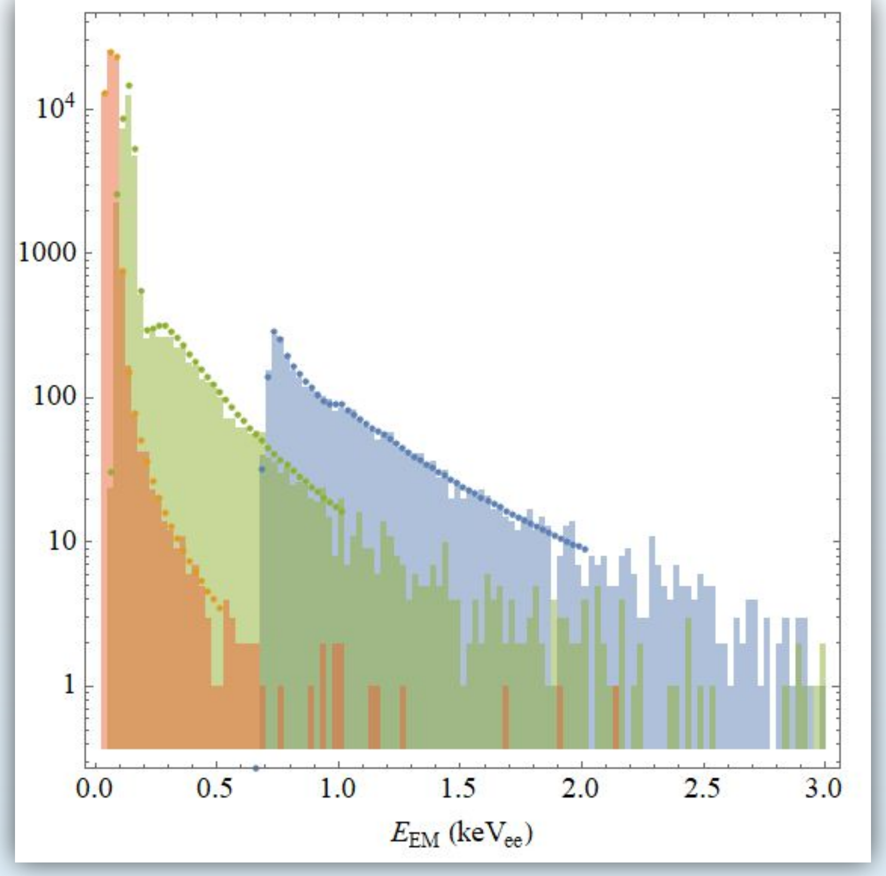
Simulating NR + Migdal events with NEST

1. Select NR energy from distribution, E_R calculate max. allowed E_{EM}
2. Loop over atomic shells, E_{nl}, and randomly (MC) ionize an electron with E_e distributed as shown earlier (with prob. scaled by the atomic recoil velocity)
3. Calculate the yields of ions and excitons produced by E_R, E_e and $E_{nl,}$ using NEST models for NR, β and β respectively
4. Calculate the quanta from the summed yields and the subsequent S1 & S2

Simulation with NEST

Event by event simulation:
NR + electron + de-excitation





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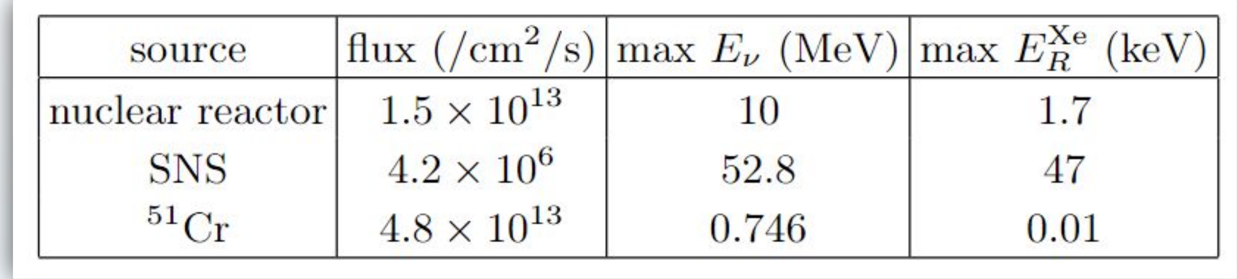

source	flux ($/\mathrm{cm}^2/\mathrm{s}$)	max E_ν (MeV)	max E_R^{Xe} (keV)
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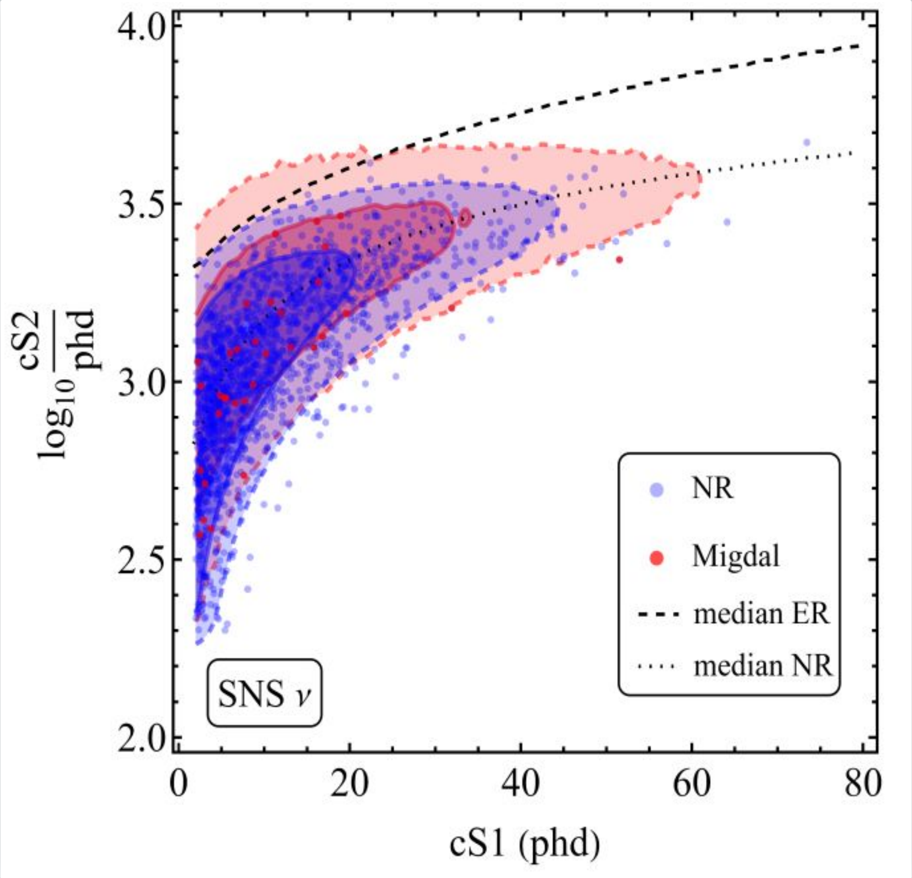
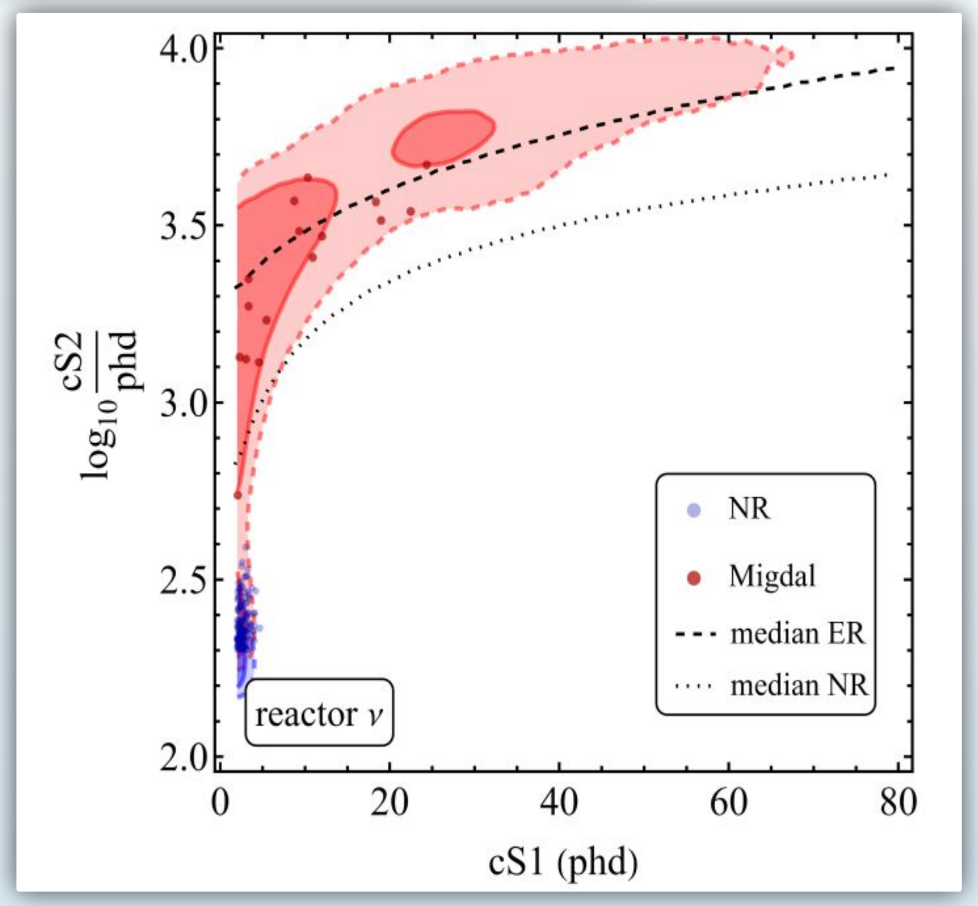
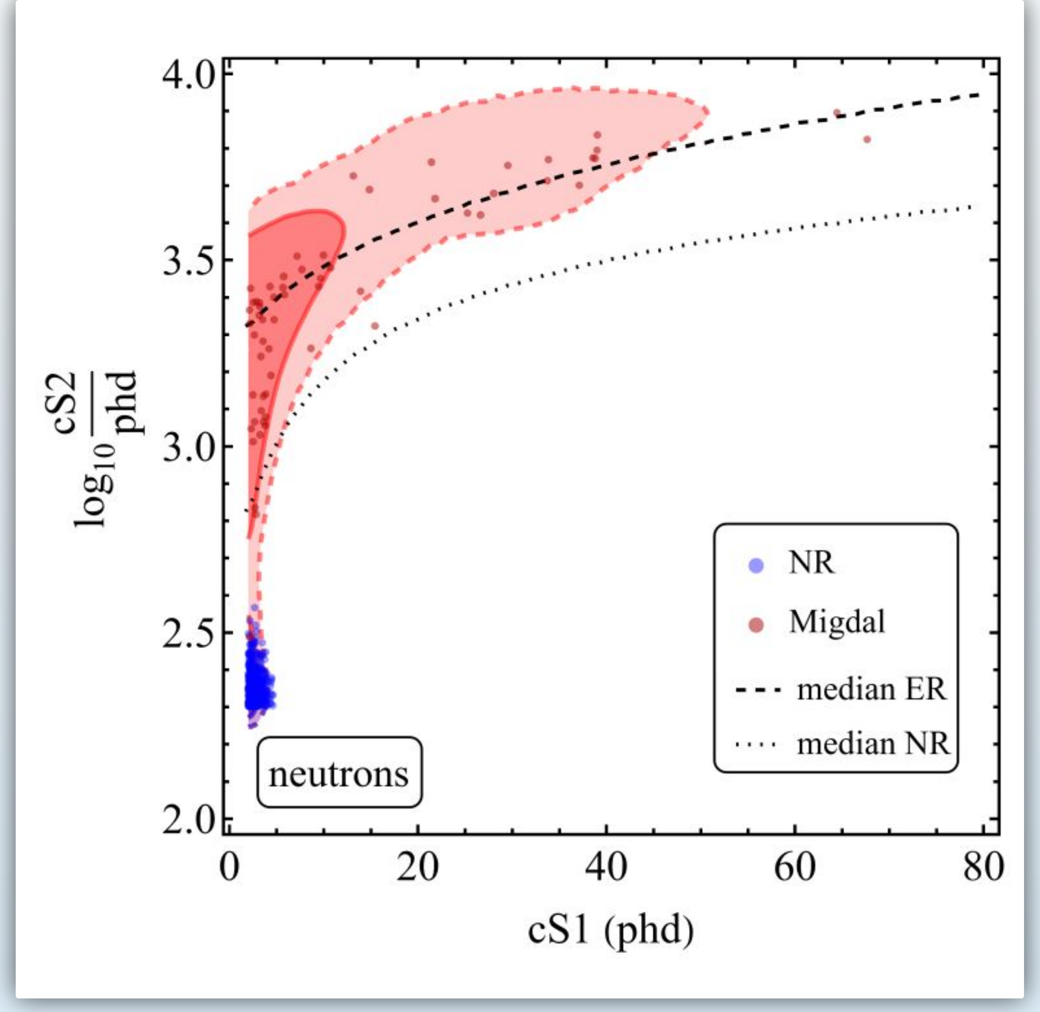
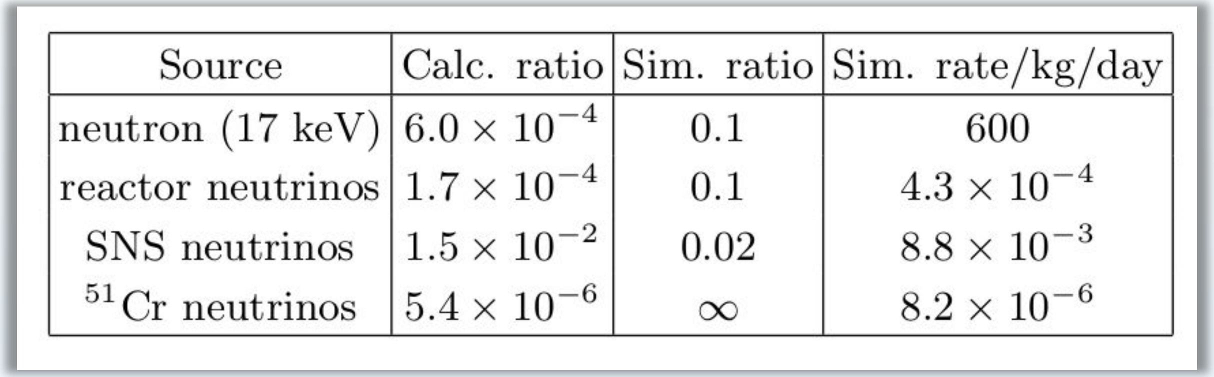




Simulation with NEST (xenon)

S1 vs S2 signal (17 keV neutrons):





Source	Calc. ratio	Sim. ratio	Sim. rate/kg/day
neutron (17 keV)	6.0×10^{-4}	0.1	600
reactor neutrinos	1.7×10^{-4}	0.1	4.3×10^{-4}
SNS neutrinos	1.5×10^{-2}	0.02	8.8×10^{-3}
^{51}Cr neutrinos	5.4×10^{-6}	∞	8.2×10^{-6}

- Neutrons are the only viable candidate

Summary and open questions:

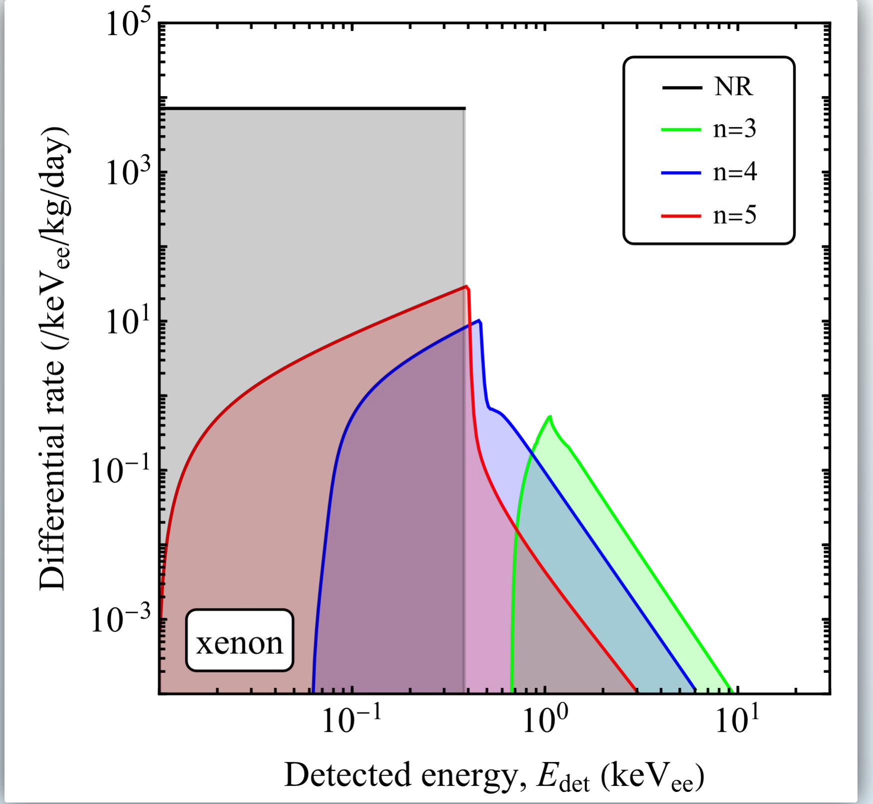
- The Migdal effect is a powerful tool to extend the reach of xenon DM experiments
- A calibration of the Migdal effect directly in a liquid xenon target is desirable
- How do we model the quanta production? (is it necessary?)
- Low-energy beams of neutrons appear to be a viable option
- Background mitigation will be key

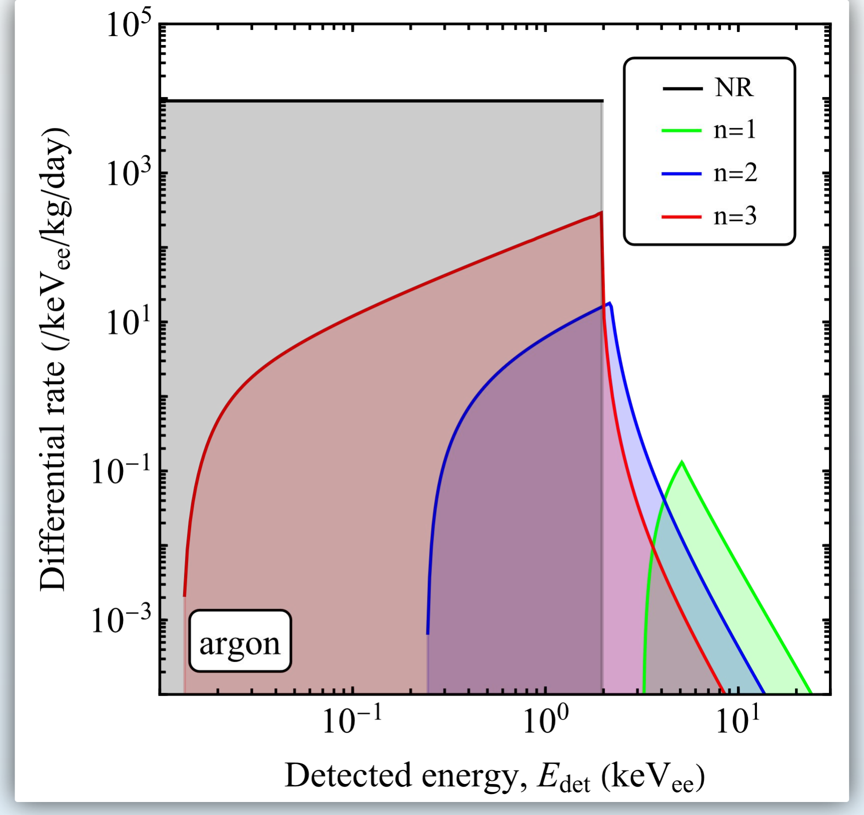
~/code$

https://zenodo.org/record/5587760
https://github.com/jaydenn/nuMigdalCalc
https://github.com/jaydenn/thinNEST
https://github.com/jaydenn/MigdalMC

Low-energy neutron Migdal rates

E = 82 keV neutrons, flux = 100 n/cm^2/s



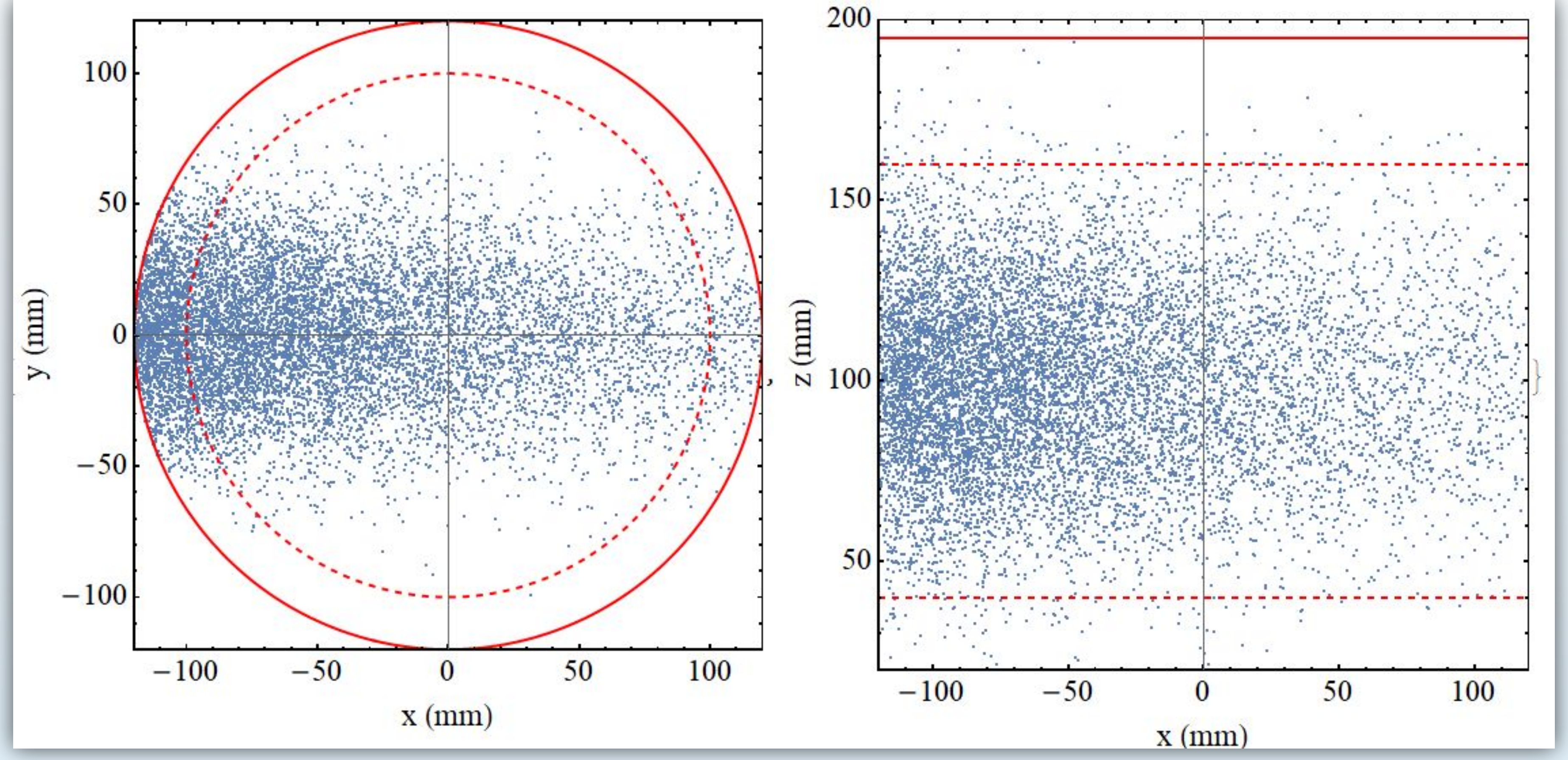


Total rates:

Nuclear:	2,700 events/kg/s	12,300 events/kg/s
Migdal:	8 events/kg/s	320 events/kg/s

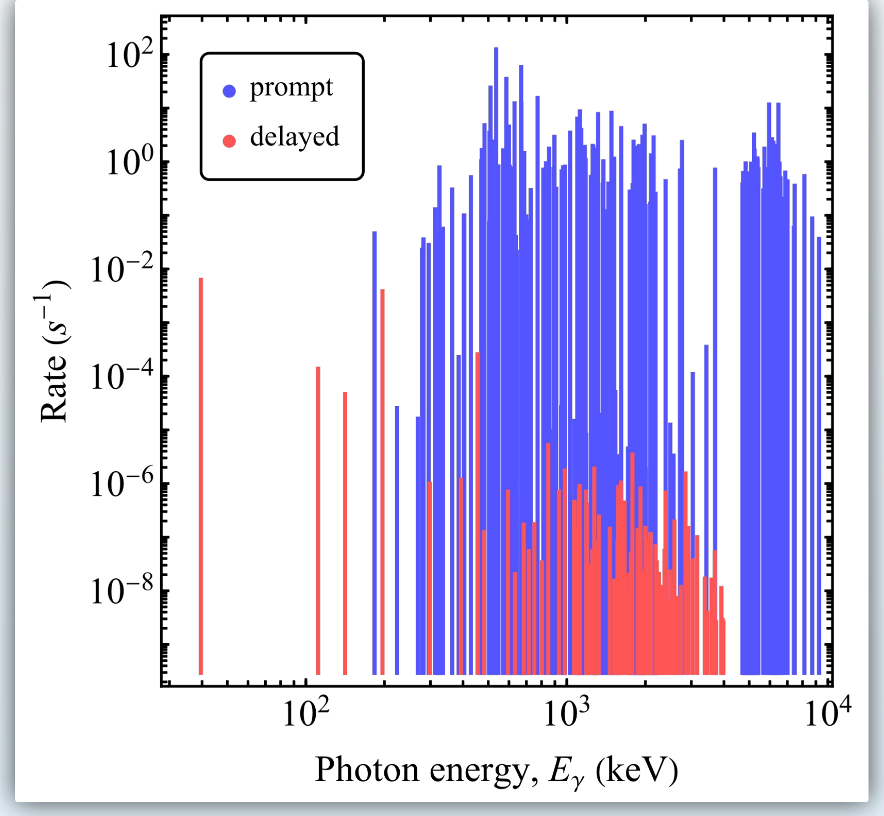
Simulation of a neutron beam source

- Mean free path of 17 keV neutrons in xenon is ~10cm

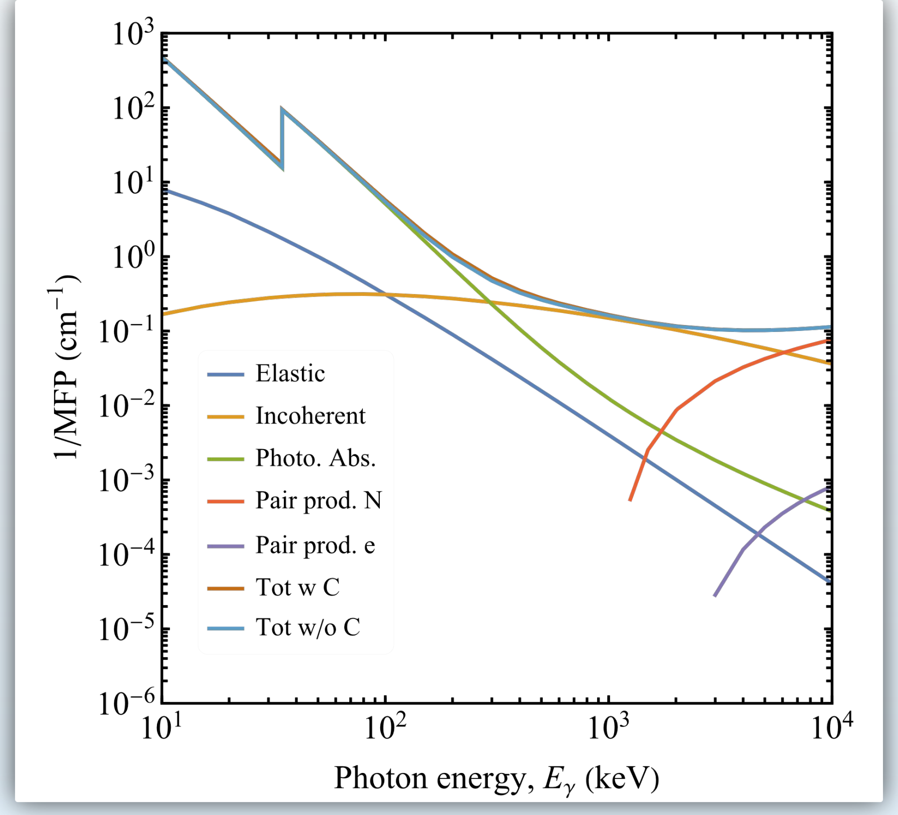


Neutron capture backgrounds

Radiative capture



Photon mean free path

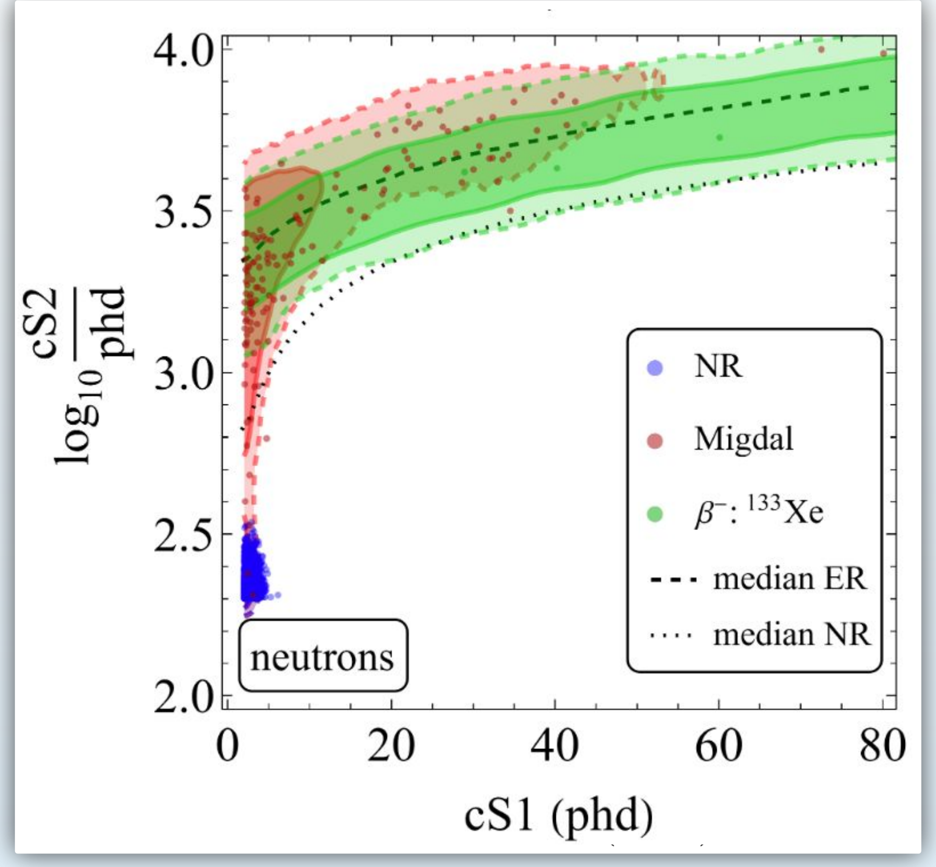


Neutron capture backgrounds

Subsequent decays:

xenon-125 → EC + iodine-125 (t~17 hrs)
xenon-127 → EC + iodine-127 (t~36 days)

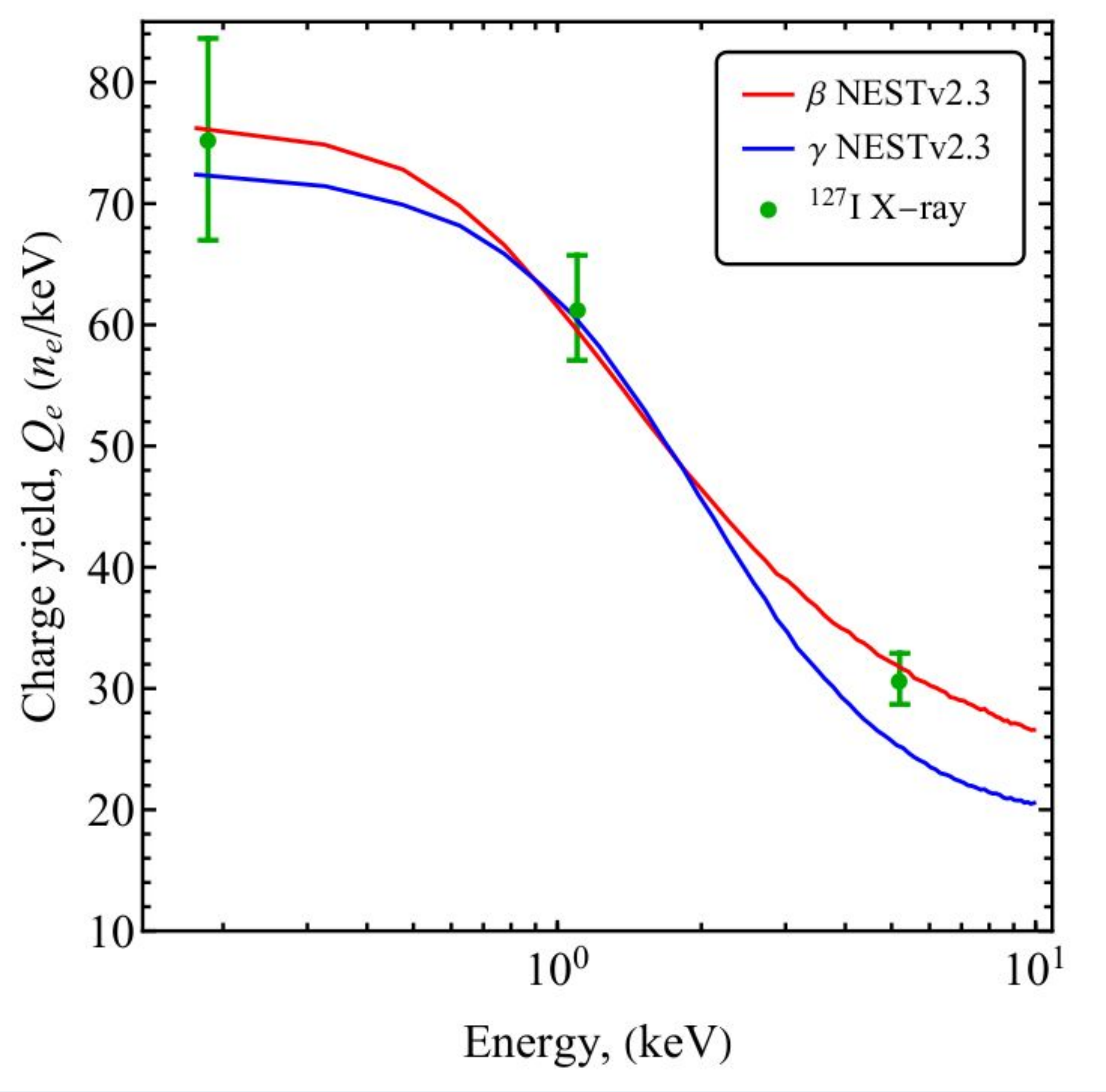
xenon-133 → β^- + cesium-133 (t~5 days)
xenon-135 → β^- + cesium-135 (t~9 hrs)
xenon-137 → β^- + cesium-137 (t~4 min)



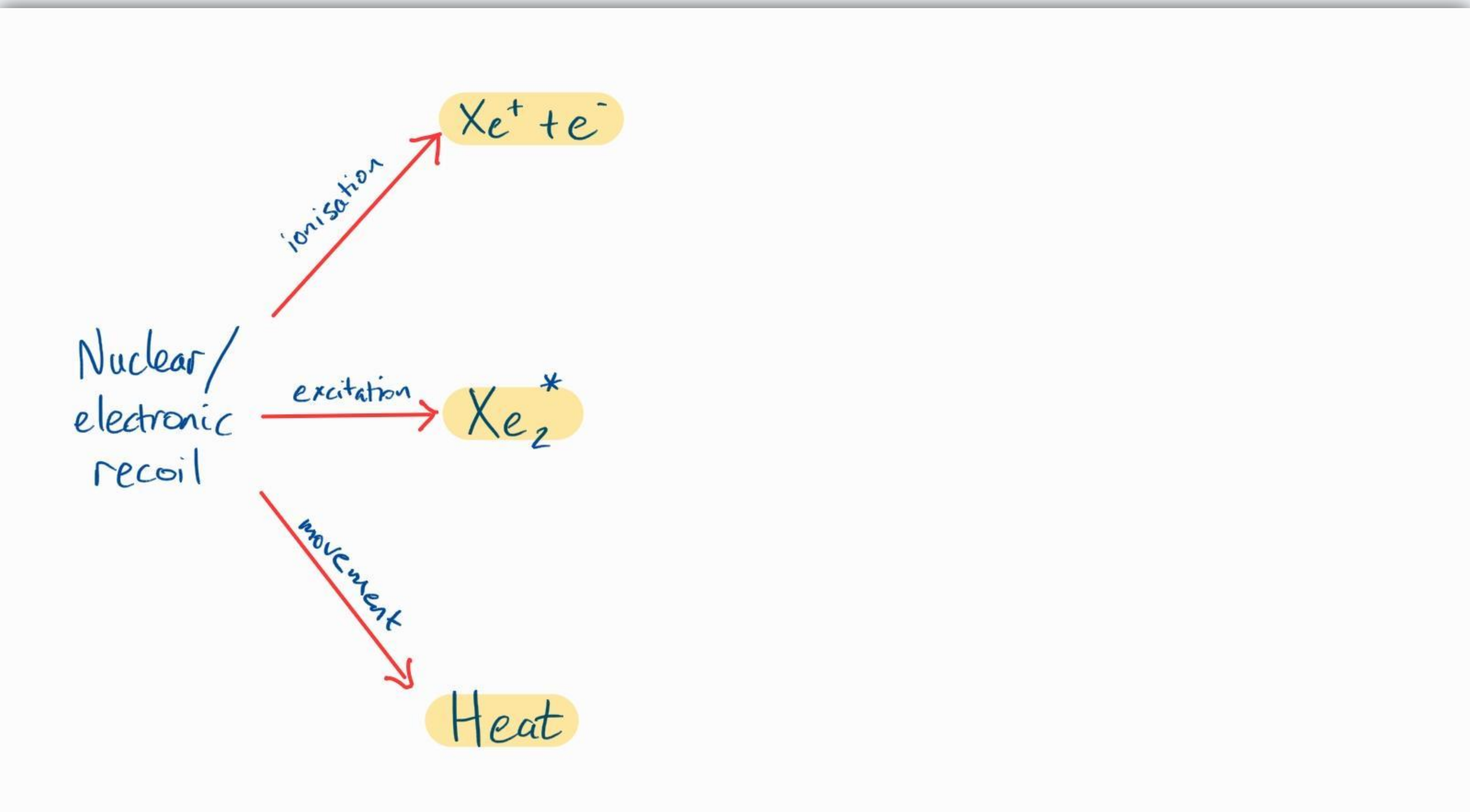
Background mitigation

	Radiative decay	Subsequent decays	External backgrounds
Multi-scatter	✓	✓	✓
Pulsed beam trigger		✓	✓
‘Fiducial’ cut on beam		✓	✓
Cycle det on/off		✓	
Extra xenon flow		✓	

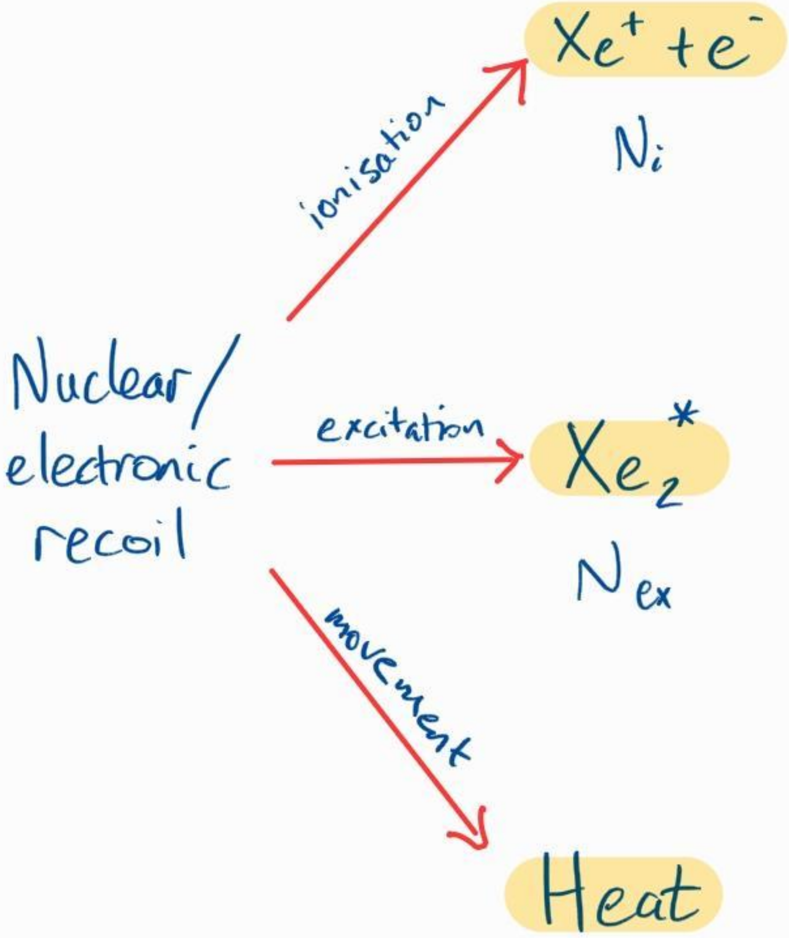
Charge yields



Signal production

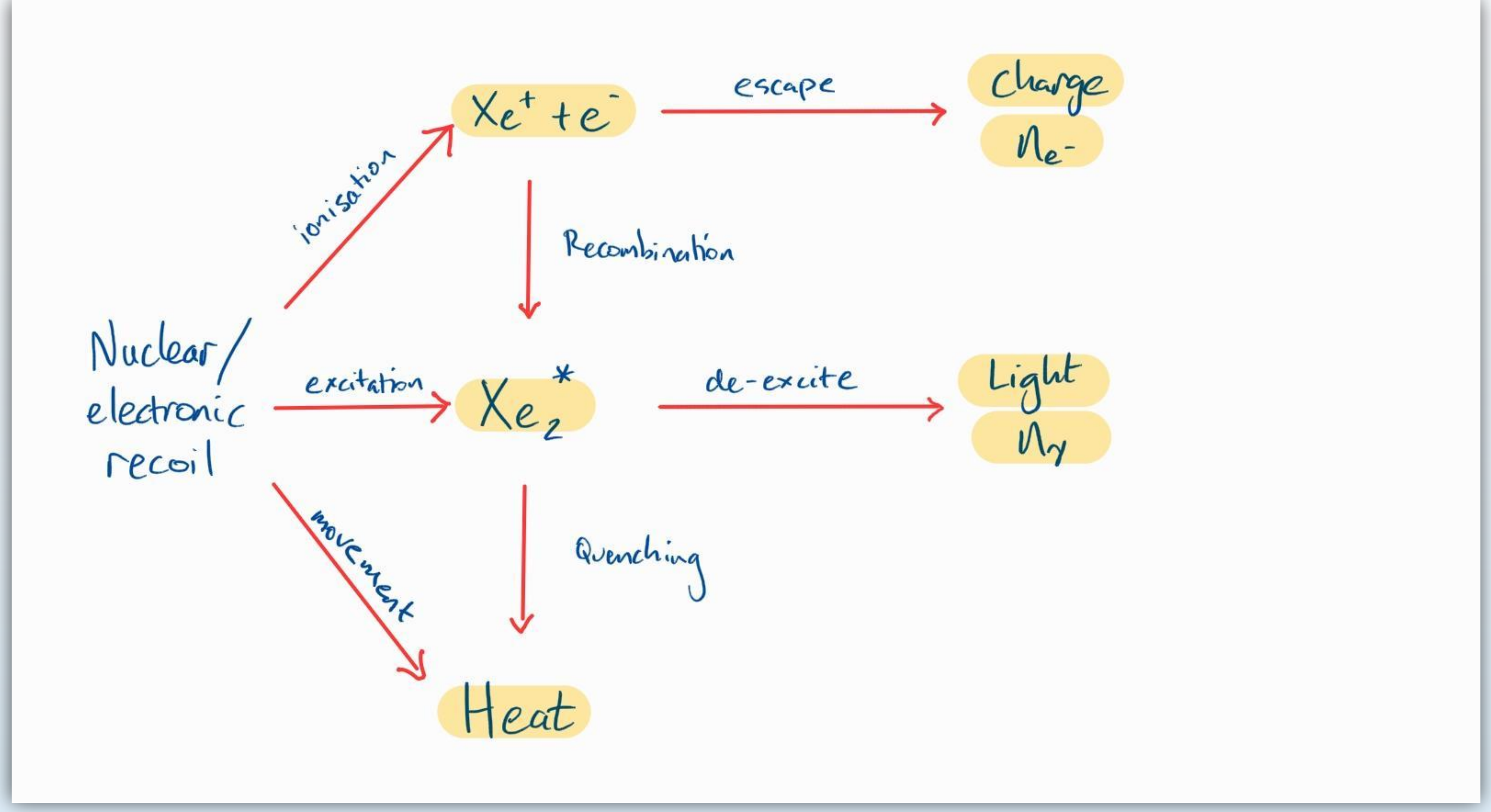


Signal production

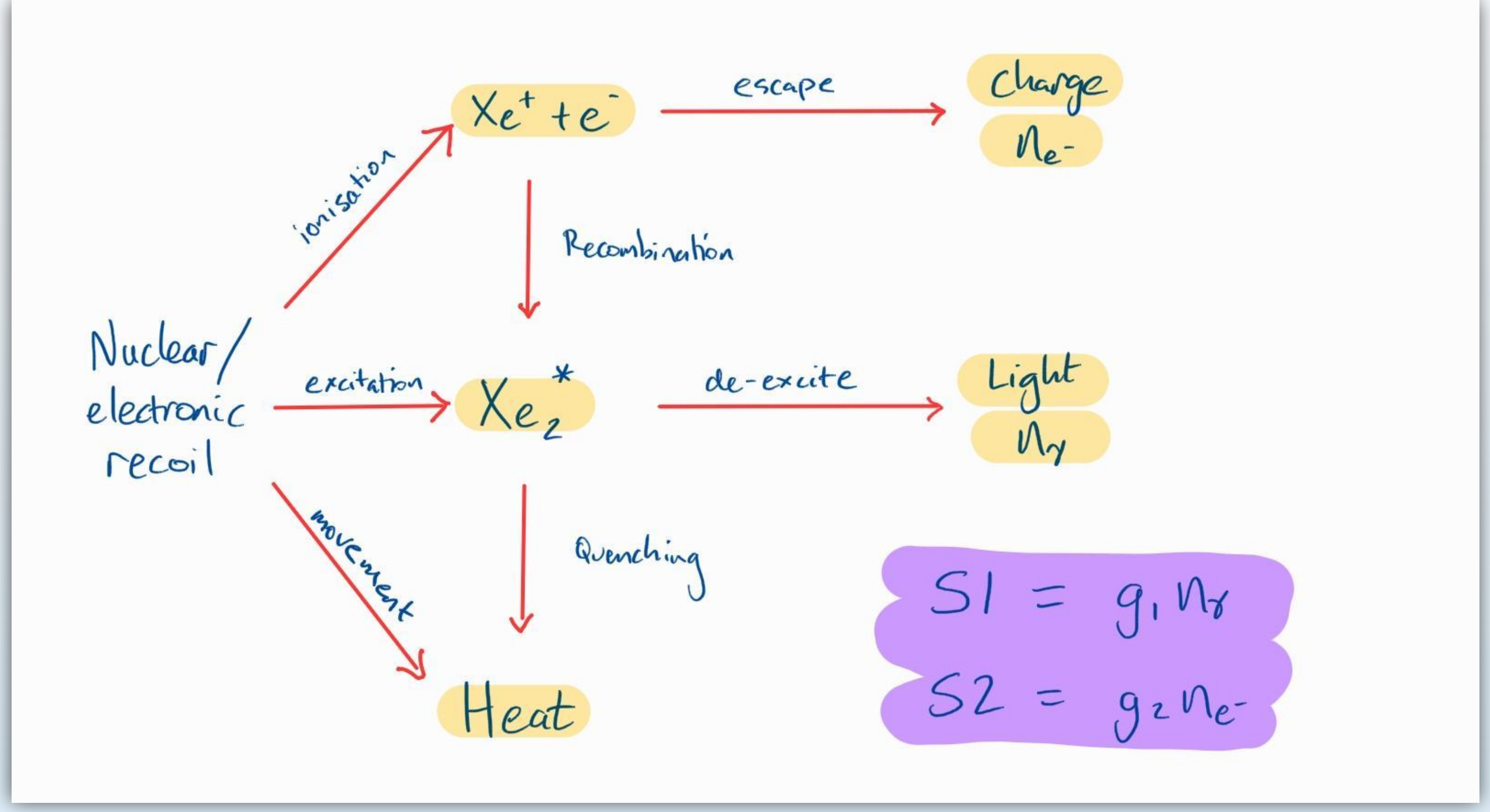


$$\text{ratio} \left(\frac{N_{ex}}{N_i}\right)_{NR} \sim 0.1 > \left(\frac{N_{ex}}{N_i}\right)_{ER}$$

Signal production



Signal production



$$S1 = g_1 n_\gamma$$

$$S2 = g_2 n_{e^-}$$