Discovering Composite Dark Matter with the Migdal Effect

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based on:
JA, Bramante & Goodman, 2108.10889

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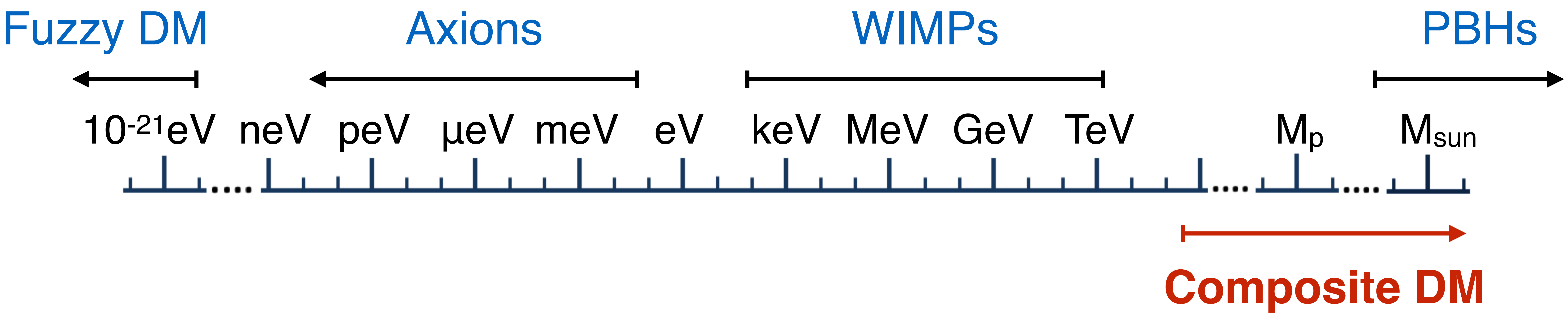
Dark Matter

~ 26% energy content, but only gravitational interactions known

Plenty of candidates:



→ few events at DM exp.

→ need large couplings to SM for detection?

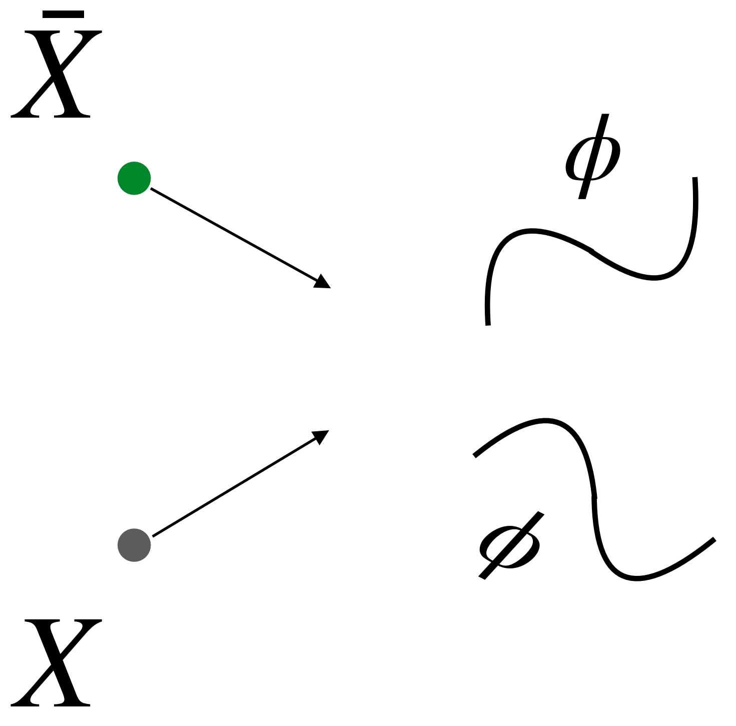
Wise & Zhang, 1411.1772
Gresham et. al., 1707.02316
JA, Bramante & Goodman, 2012.10998

A Simple Composite Model

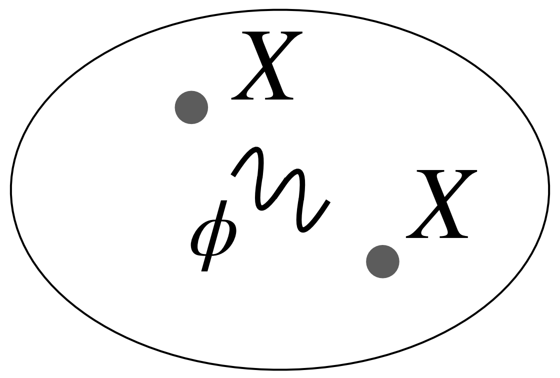
$$\mathscr{L}_{\mathrm{DM}} = \frac{1}{2}\partial^2\phi + \frac{1}{2}m_\phi^2\phi^2 + \bar{X}\left(i\gamma^\mu\partial_\mu - m_X\right)X + g_X\bar{X}X\phi$$

For concreteness: $m_\phi \sim 1\ \mathrm{MeV} - 100\ \mathrm{MeV}$ $\quad m_X \sim 1\ \mathrm{GeV} - 100\ \mathrm{TeV}$

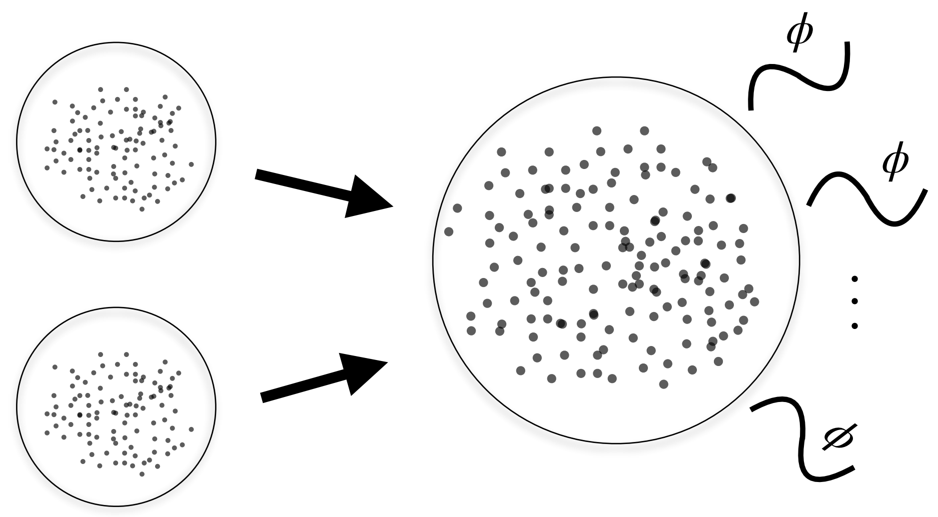
This model allows for composite synthesis:



$X\bar{X}$ annihilation



${}^2X$ formation



${}^NX$ fusion

“Saturated” Composite States

After assembly is complete:

$$10^{10}\ \text{GeV} \lesssim M_X \lesssim 10^{45}\ \text{GeV}$$

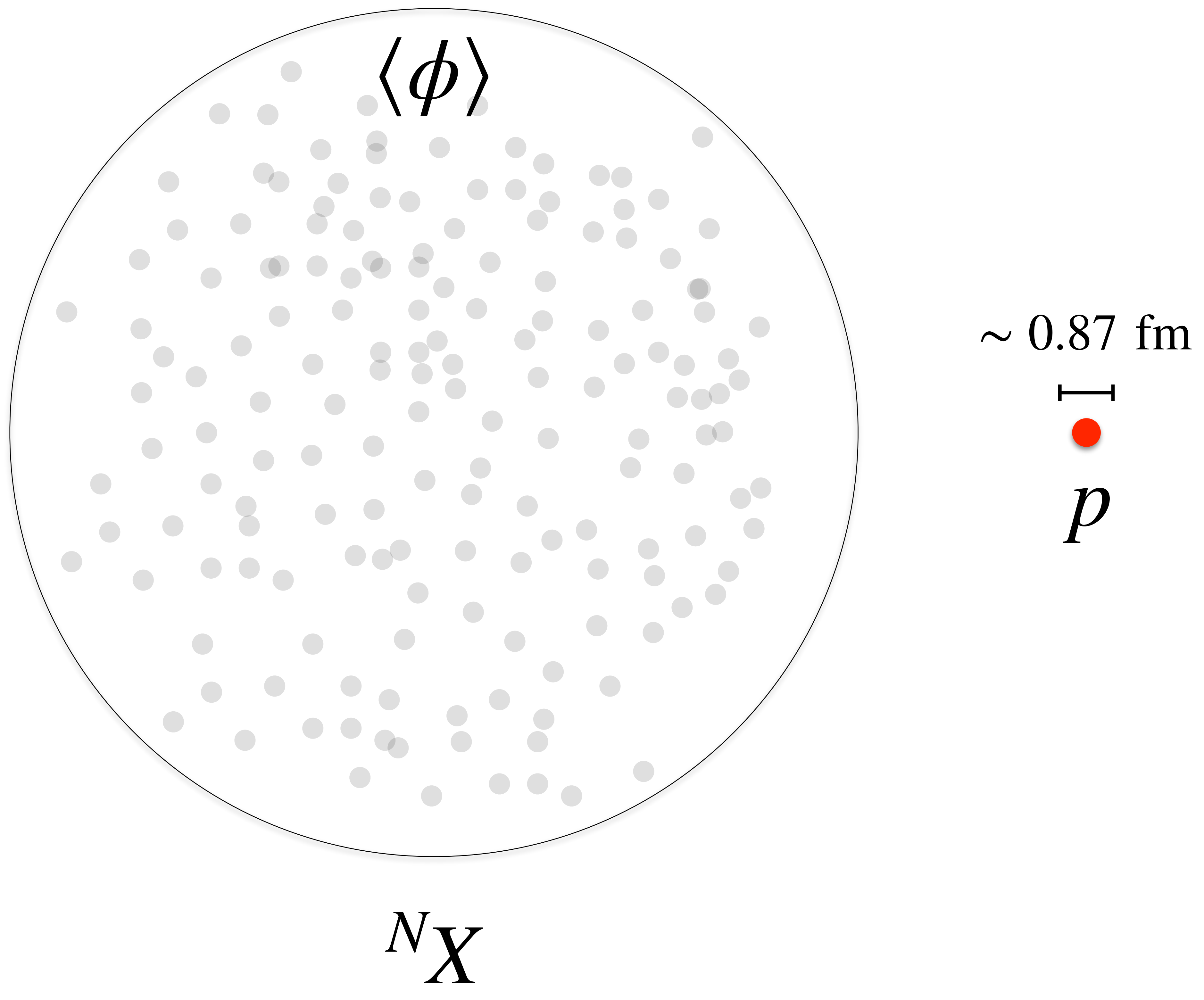
$$100\ \text{fm} \lesssim R_X \lesssim 10\ \mu\text{m}$$

⟶ Highly degenerate constituents:

$$p_F \gtrsim \text{GeV}$$

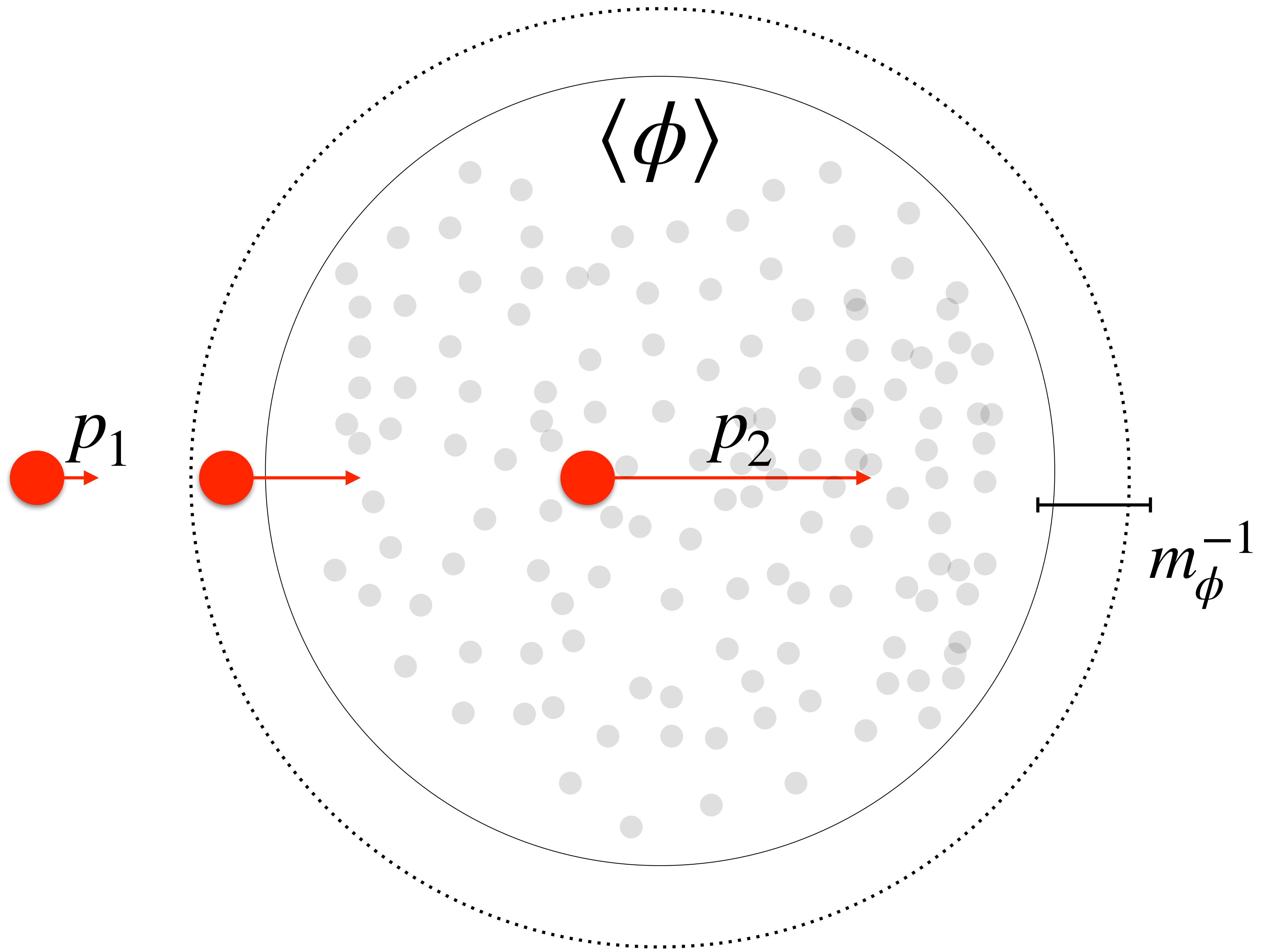
⟶ Very intense, uniform binding field:

$$\langle\phi\rangle \propto m_X \sim 1\ \text{GeV} - 100\ \text{TeV}$$



Adding a Nuclear Coupling

Add attractive Yukawa interaction: $\mathscr{L} = \mathscr{L}_{\rm DM} + g_n \bar{n} \phi n$

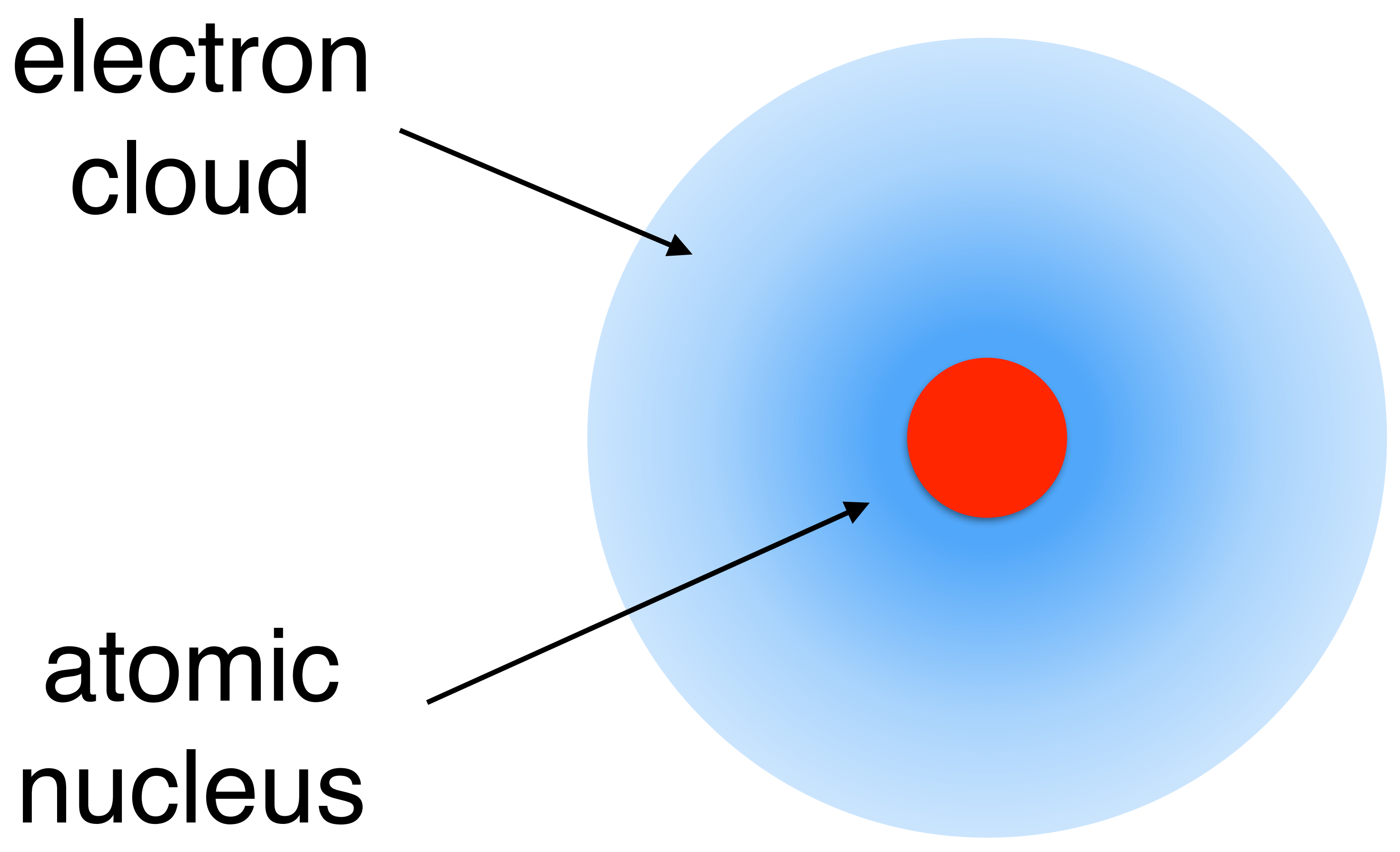


$$p_1^2 + m_N^2 = p_2^2 + (m_N - A g_n \langle \phi \rangle)^2$$

↓ NR limit

$$\frac{p_2^2 - p_1^2}{2m_N} \propto g_n \langle \phi \rangle \propto g_n m_X$$

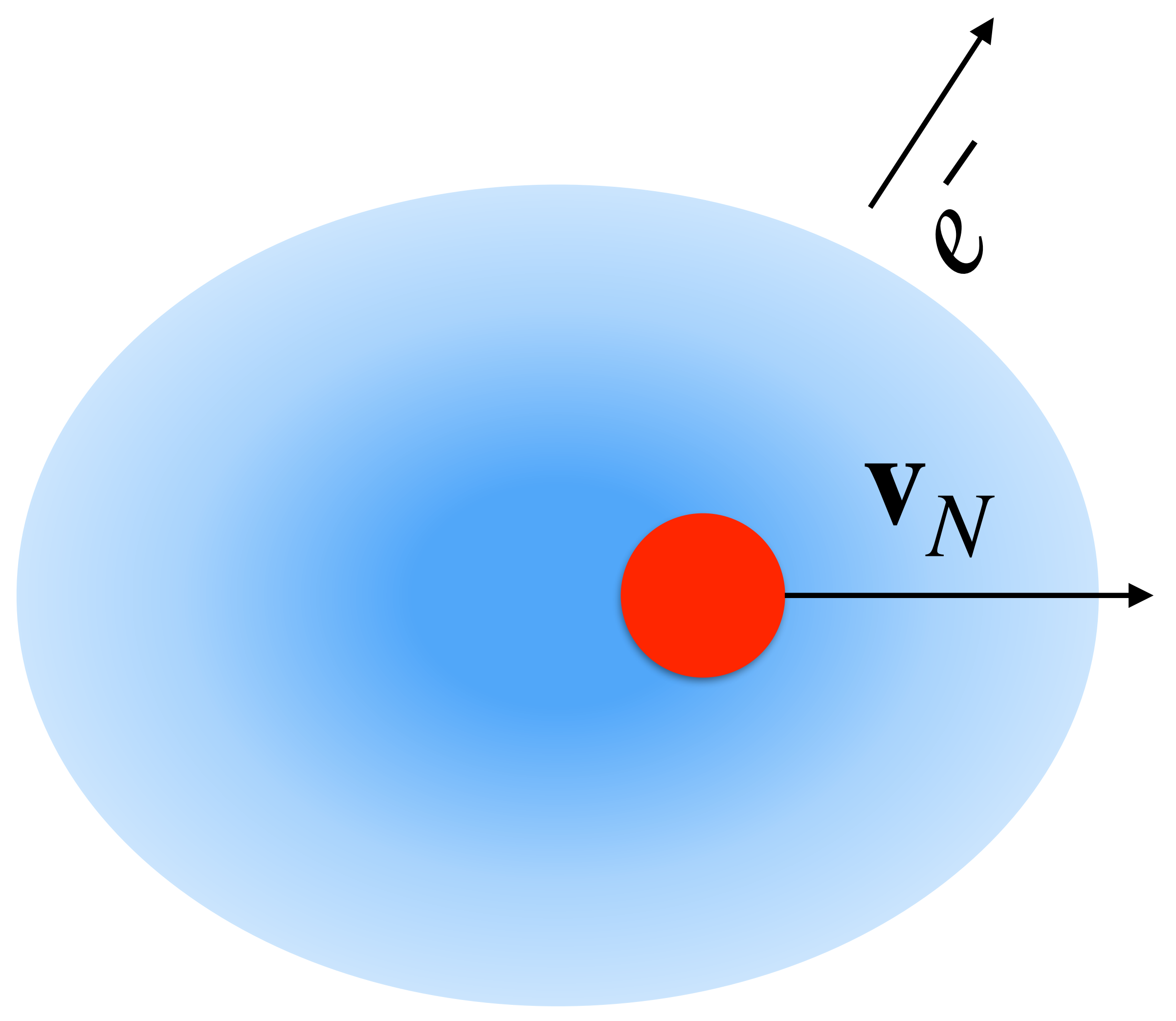
The Migdal Effect



sudden nuclear recoil

e.g. $\alpha, \beta^{\pm}$ decay

DM scattering?



$$|\psi_0\rangle$$

$$\langle \psi_k | \psi_0 \rangle = 0$$

$$|\psi\rangle \simeq e^{\left(-i m_e \sum_j \mathbf{v_N} \cdot \hat{\mathbf{x}}_j\right)} |\psi_0\rangle$$

$$\langle \psi_k | \psi \rangle \neq 0$$

How sudden? $\Delta t_{\mathrm{recoil}} \ll 10^{-17}$ s Migdal approximation

(e.g. Xe, Ar)

Excitation & Ionization Probabilities

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

initial level →

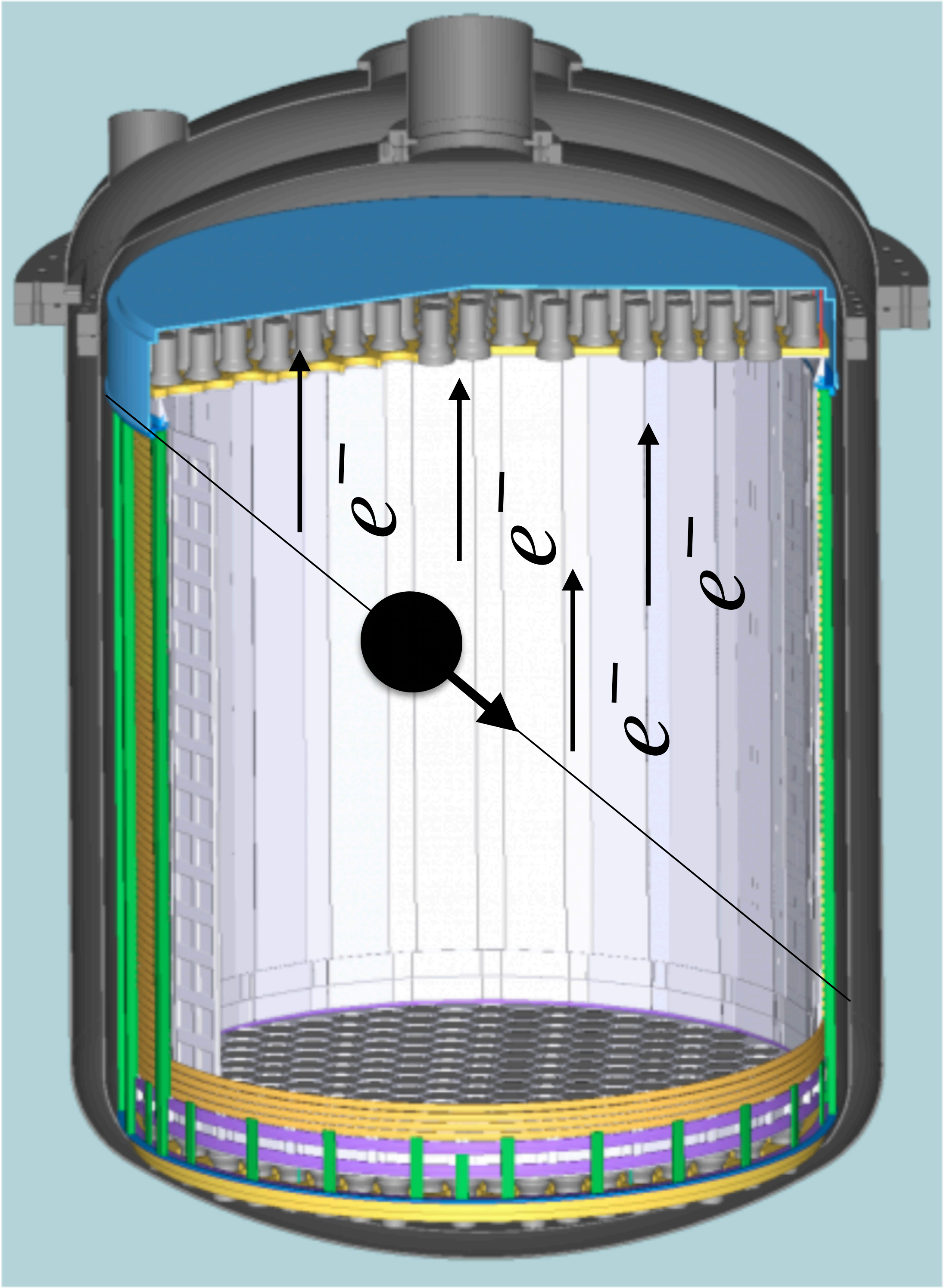
(n,ℓ)	$\mathcal{P}_{\to 4f}$	$\mathcal{P}_{\to 5d}$	$\mathcal{P}_{\to 6s}$	$\mathcal{P}_{\to 6p}$	$E_{n\ell}$ [eV]	$\frac{1}{2\pi}\int dE_e \frac{dp^c}{dE_e}$
1s	–	–	–	7.3×10^{-10}	3.5×10^{4}	4.9×10^{-6}
2s	–	–	–	1.8×10^{-8}	5.4×10^{3}	3.0×10^{-5}
2p	–	3.0×10^{-8}	6.5×10^{-9}	–	4.9×10^{3}	1.3×10^{-4}
3s	–	–	–	2.7×10^{-7}	1.1×10^{3}	1.1×10^{-4}
3p	–	3.4×10^{-7}	4.0×10^{-7}	–	9.3×10^{2}	6.0×10^{-4}
3d	2.3×10^{-9}	–	–	4.3×10^{-7}	6.6×10^{2}	3.6×10^{-3}
4s	–	–	–	3.1×10^{-6}	2.0×10^{2}	3.6×10^{-4}
4p	–	4.1×10^{-8}	3.0×10^{-5}	–	1.4×10^{2}	1.5×10^{-3}
4d	7.0×10^{-7}	–	–	1.5×10^{-4}	6.1×10	3.6×10^{-2}
5s	–	–	–	1.2×10^{-4}	2.1×10	4.7×10^{-4}
5p	–	3.6×10^{-2}	2.1×10^{-2}	–	9.8	7.8×10^{-2}

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

← ionization prob.

Ionization Signal

Xenon-1T



Computed event rate:

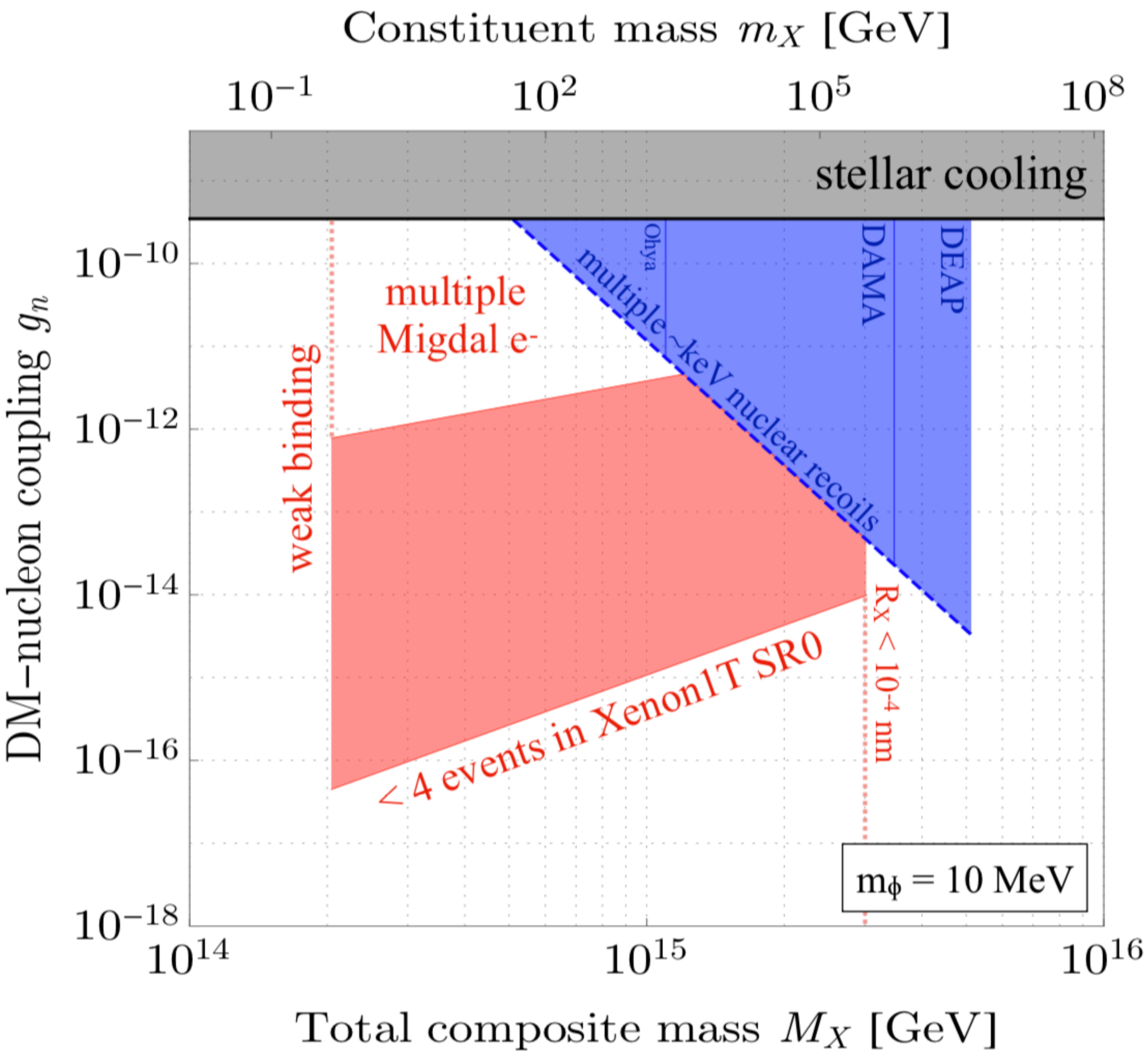
$$R_{ion} = \left(\frac{4\pi R_X^2 n_X}{m_N}\right) \times \left(\int_{v>v^{(\min)}} dv\ v\ g(v)\right) \times \left(\frac{1}{2\pi}\sum_{n,l}\int dE_e\ \varepsilon(E_{em})\frac{dp_q}{dE_e}(n,l\to E_e)\right)$$

Xenon-1t's 1st DM search exposure:

$$N_{ion} \simeq (98\ \text{kg yr})\ R_{ion} \simeq 10\ \left(\frac{m_X}{\text{TeV}}\right)^{-\frac{2}{5}}\left(\frac{m_\phi}{\text{MeV}}\right)^{-\frac{4}{5}}\left(\frac{g_n}{10^{-17}}\right)\left(\frac{\alpha_X}{0.3}\right)^{-\frac{1}{10}}$$

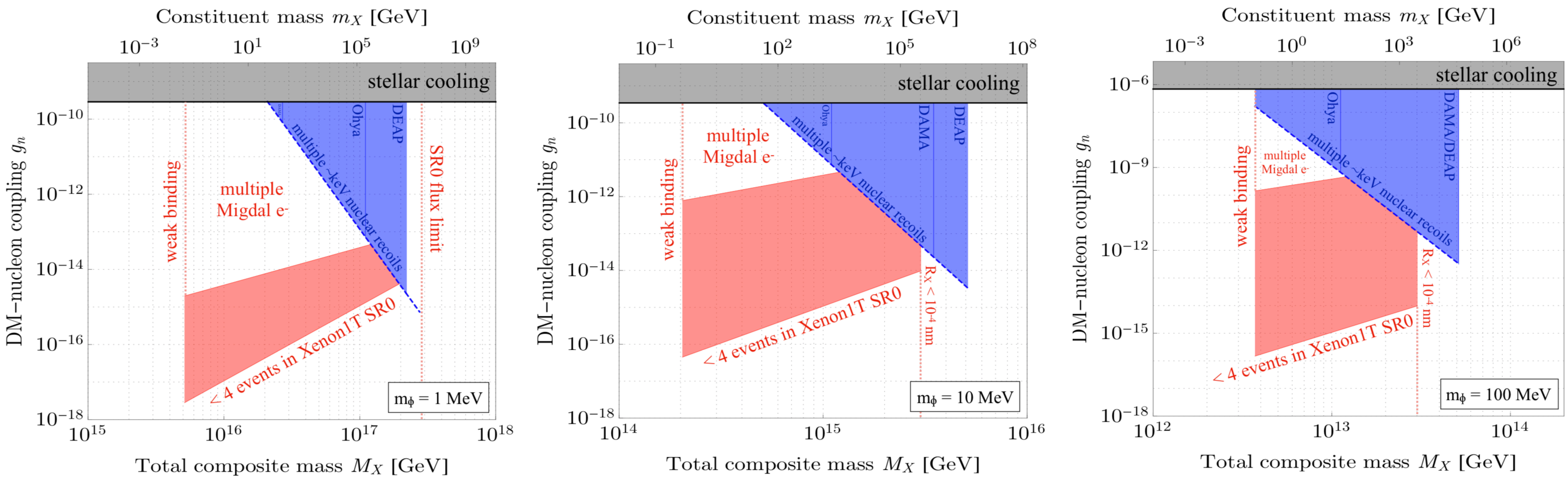
lots of ionization events even for $g_n \sim 10^{-17}$!

Xenon-1T Constraints



JA, Bramante & Goodman, 2012.10998

Xenon-1T Constraints



Migdal effect covers wide range of masses & couplings!

Some Final Remarks

- The Migdal effect is a promising venue to search for weakly-coupled composite dark matter in experiments like Xenon-1T, DEAP-3600, LZ.

- Several composite dark matter models are candidates for a similar study.

- Other nuclear recoil signatures can be investigated, such as atomic collisions or even induced nuclear reactions.

(ask me later!)

Thank you!

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