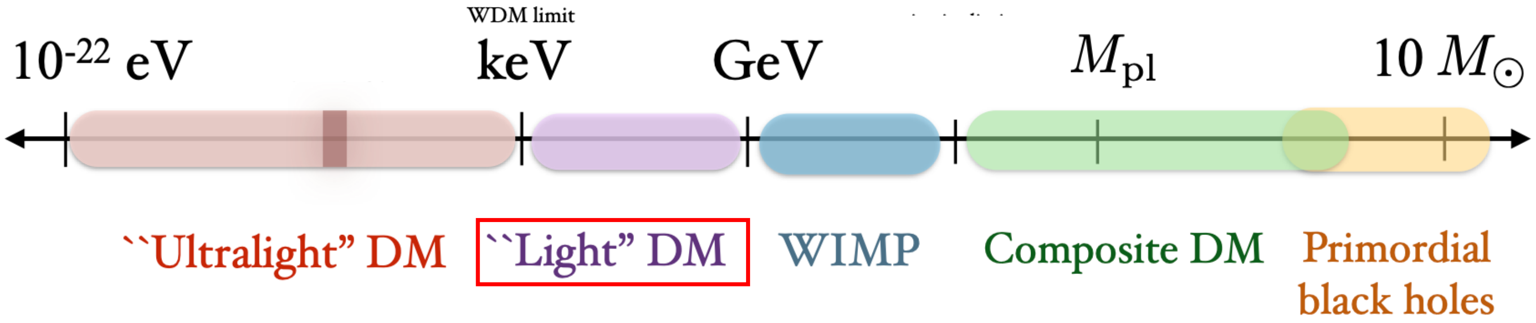
Detection of Light Dark Matter

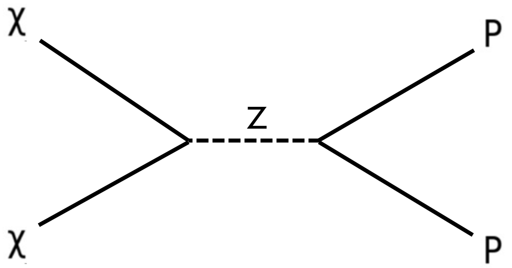
Louis Hamaide – Dark Matter Beyond The Weak Scale 03/24

Motivating Searches of Light(er) Dark Matter

- Experiments show we need to add new *dark, stable,* and relatively *collisionless* particle (dark matter) to our description of physics. Large mass range available to explore experiments and theory



- Lee & Weinberg ('77) assumed weak interaction-generated (thermal, neutrino-like) WIMPs to set ~2GeV bound on WIMP mass:



+

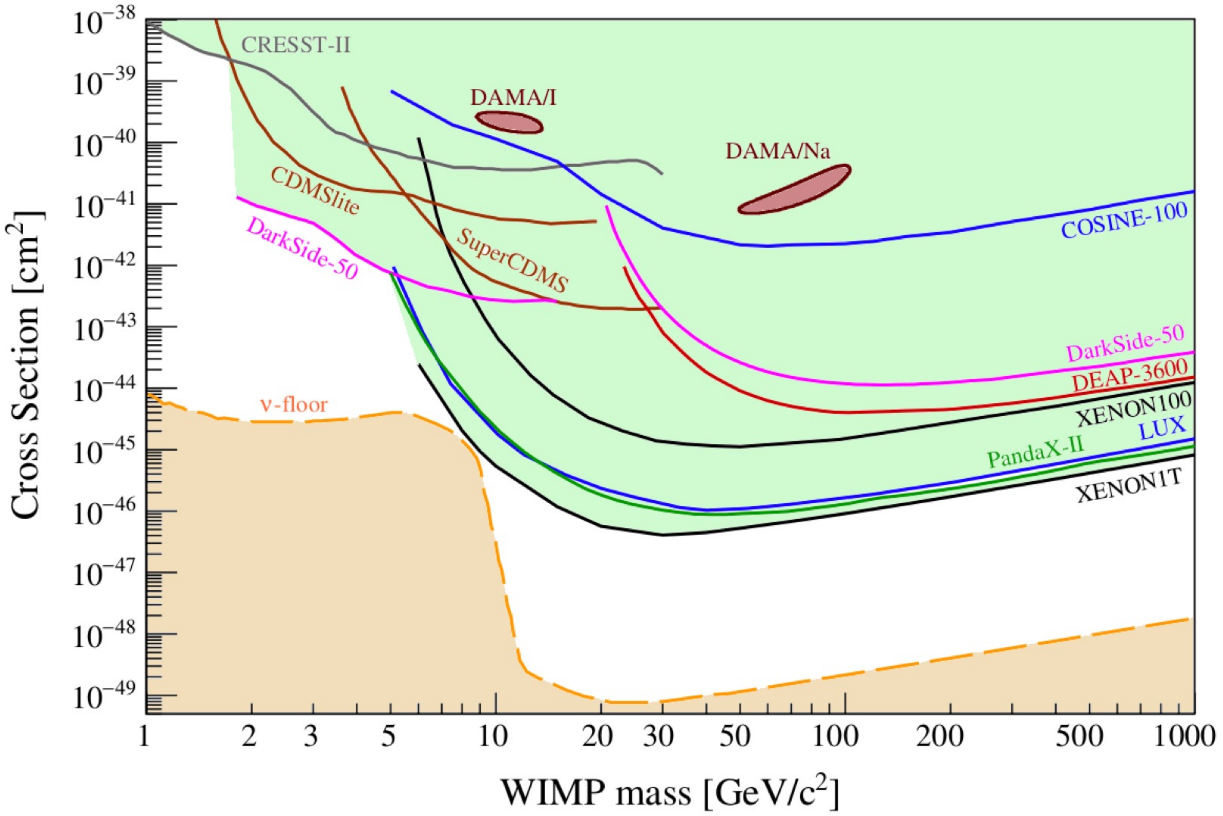
$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\,\mathrm{cm^3 s^{-1}}}{\langle \sigma_{\chi\chi} v_{rel} \rangle}$$

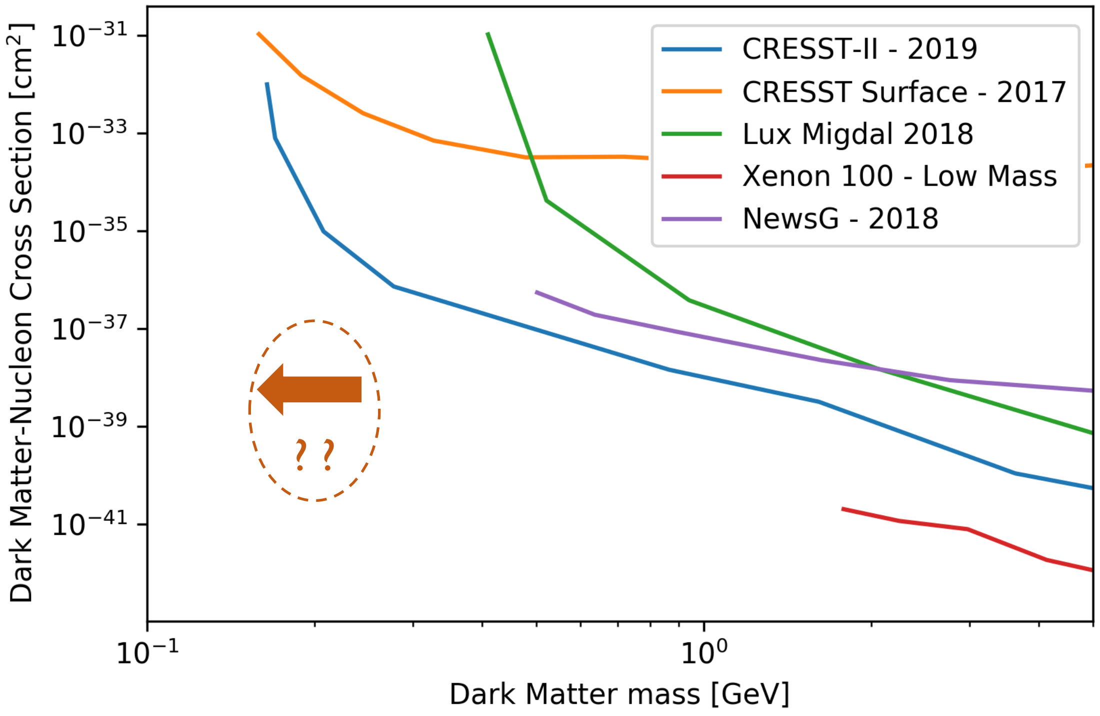
- Annihilation cross section $\sim m_\chi^2/m_Z^4$

- These assumptions can be relaxed → **search for <1 GeV DM is motivated !**

Landscape of Light DM Searches (1/2)

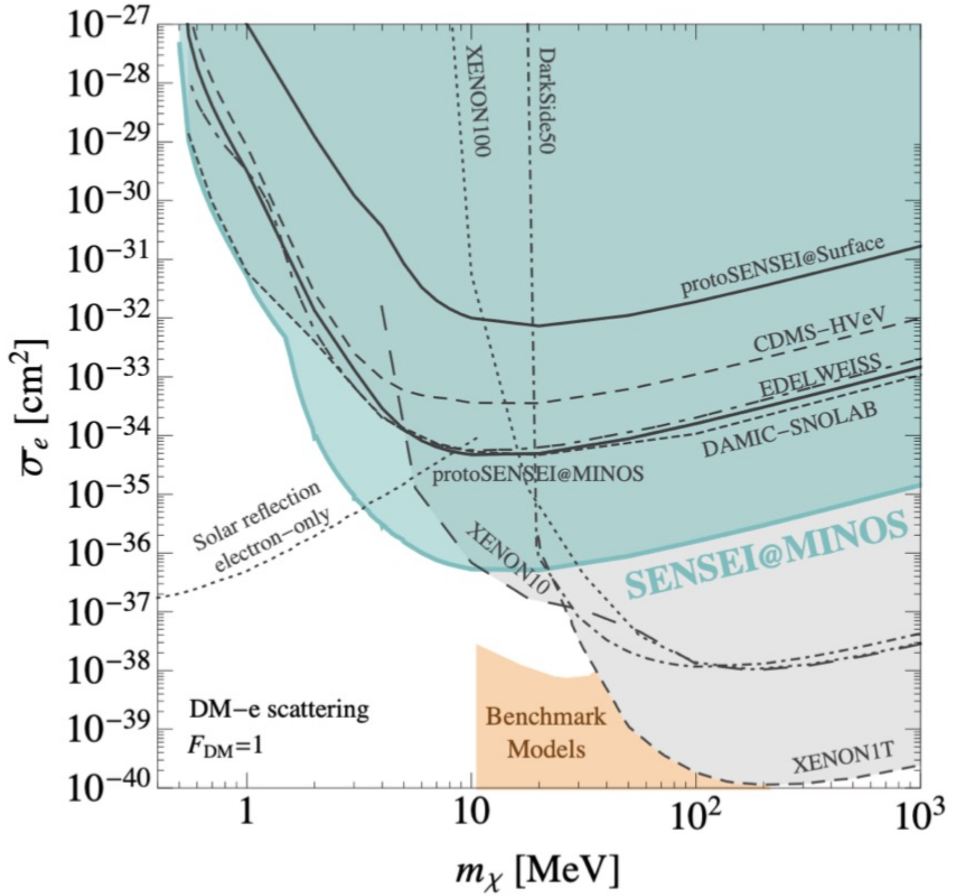
- Historically, WIMP DM detectors using Xenon (and noble gas) to search for nuclear recoils have been the most competitive





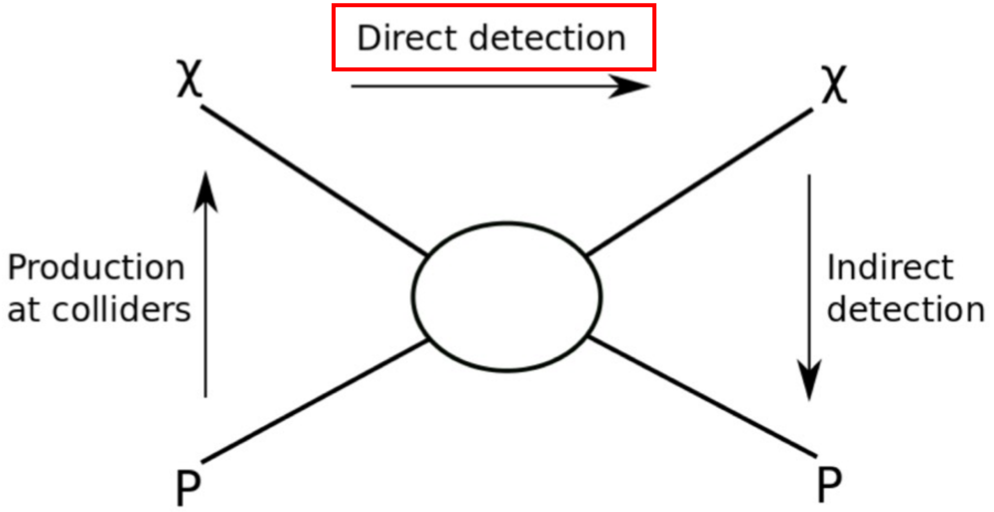
Landscape of Light DM Searches (2/2)

- The same seems to happen in electron scattering: experiments sensitive to single electron events should be competitive for lower mass electron scattering



Where To Search For Light Dark Matter

- Virtually any interaction of DM with the Standard Model can be probed using one of the following methods/signals:



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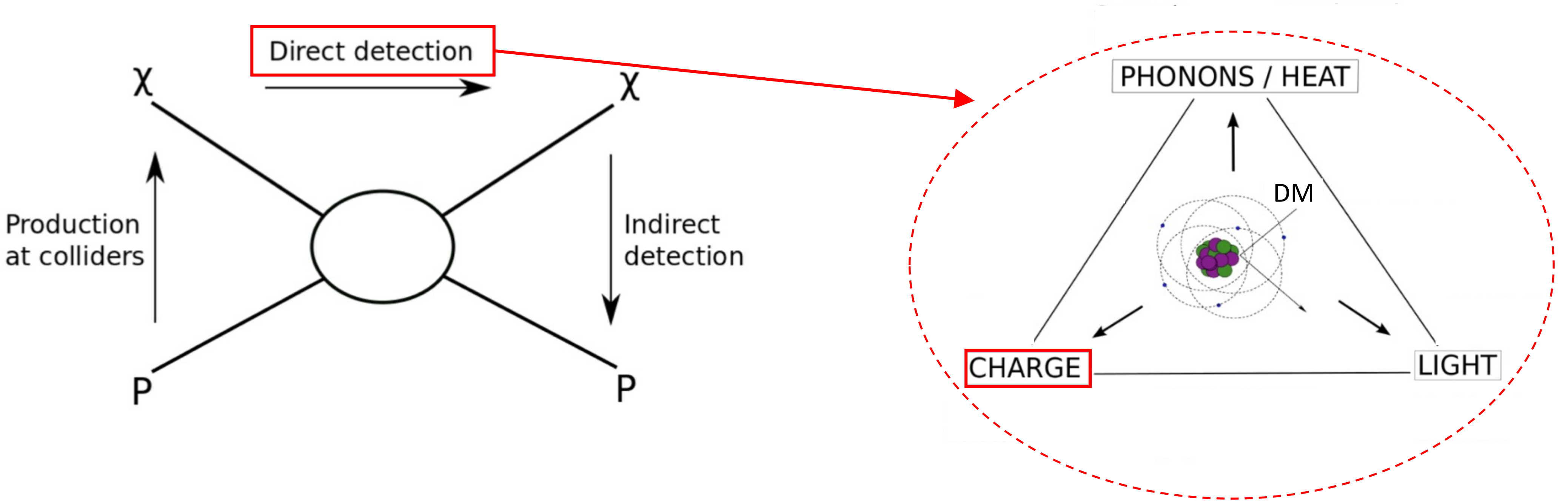
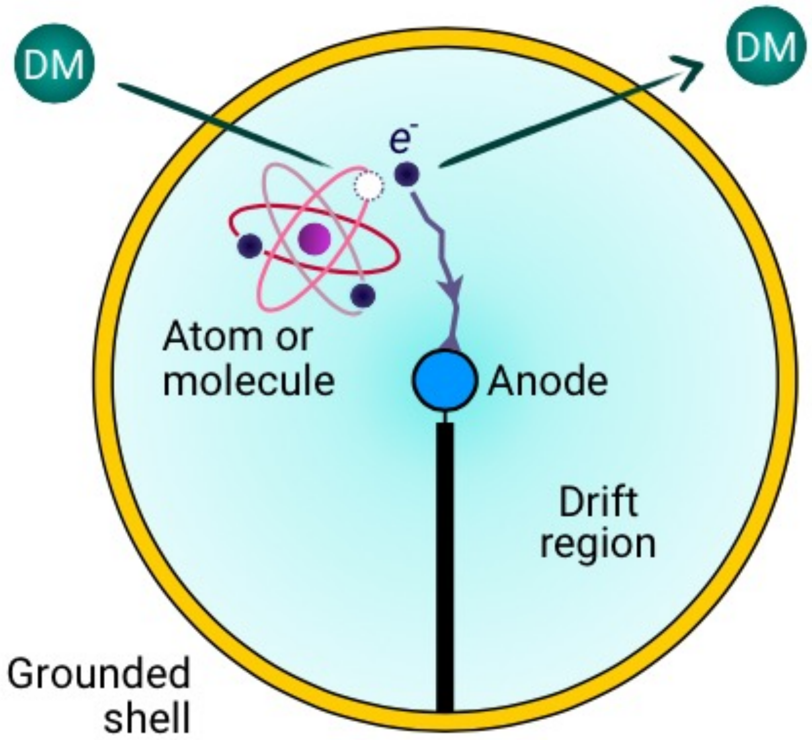
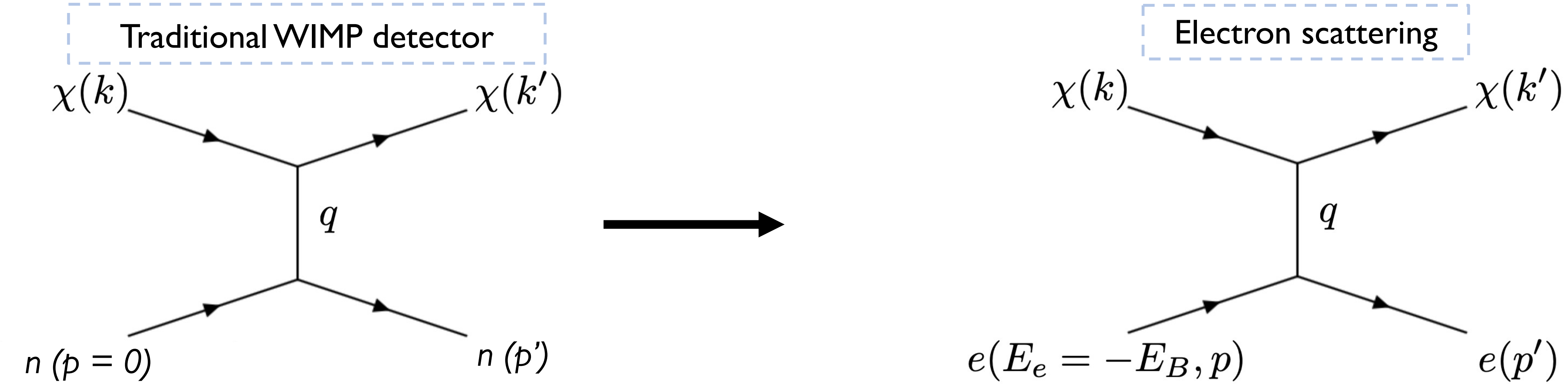


Spherical Proportional Counters For DM-e Searches

- Electron gets kicked off by DM particle and drifts down, triggering an avalanche
- Molecular "quench gas" used to stabilize detector and search for 1e events
- High voltage can be applied without spurious discharge and high signal gain



Dark Matter Electron Scattering



$$\mathcal{M} = g_x g_y \frac{1}{q^2 - m^2} \int d^3x \, e^{-i\mathbf{p}\cdot\mathbf{r}} e^{i\mathbf{q}\cdot\mathbf{r}} e^{i\mathbf{p}'\cdot\mathbf{r}} \longrightarrow \mathcal{M}(n, l \to \text{free}\, e^-) = g_x g_y \frac{1}{q^2 - m^2} \int d^3x \, \tilde{\psi}^*_{p'l'm'}(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} \psi_{nlm}(\mathbf{x})$$

$F_{DM}(q)$

where $d\sigma \;\alpha\; |\mathcal{M}|^2$

Bound electron wavefunctions (1/5)

- Hartree-Fock approximation: mean field self-consistent bound states with energies correct to first order in non-relativistic single particle time independant pertubation theory:

$$H(\mathbf{x}_1, ..., \mathbf{x}_N) = \sum_i \left(-\frac{1}{2}\nabla_i^2 - \frac{Z}{\mathbf{x}_i}\right) + \sum_{i \neq j} \frac{1}{|\mathbf{x}_i - \mathbf{x}_j|} \quad \rightarrow \quad H(\mathbf{x}) = \sum_i \left(-\frac{1}{2}\nabla_i^2 - \frac{Z}{|\mathbf{x}_i|} + U(\mathbf{x}_i) + V(\mathbf{x})\right) \; ,$$

$$H\psi(\mathbf{x}_1, ..., \mathbf{x}_N) = E\psi(\mathbf{x}_1, ..., \mathbf{x}_N) \quad \rightarrow \quad \left(\sum_i (H_i^{(0)} + H_i^{(1)})\right) \psi_1(\mathbf{x}_1)...\psi_N(\mathbf{x}_N) = (\epsilon_1^{(0)} + \epsilon_1^{(1)} + ... + \epsilon_N^{(0)} + \epsilon_N^{(1)})\psi_1(\mathbf{x}_1)...\psi_N(\mathbf{x}_N)$$

$$\text{where } H^{(0)}(\mathbf{x}_i) = -\tfrac{1}{2}\nabla^2 - \tfrac{Z}{|\mathbf{x}_i|} + U(\mathbf{x}_i) \text{ and } H_i^{(1)}(\mathbf{x}) = V_i(\mathbf{x}) = \textstyle\sum_{j \neq i} \frac{1}{|\mathbf{x_i} - \mathbf{x_j}|} - U(\mathbf{x}_i)$$

and $\epsilon_i^{(1)} = \left\langle \psi^{(0)} \middle| H_i^{(1)} \middle| \psi^{(0)} \right\rangle$

- HF wavefunctions variationally minimize energy: guarantees correct result (to first order). However does not guarantee orthogonality

Bound electron wavefunctions (2/5)

- Hartree-Fock approximation: mean field self consistent bound states:

$$-\frac{1}{2}\frac{d^2 P_{n_a l_a}}{dr^2} + \frac{l_a(l_a+1)}{2r^2}P_{n_a l_a}(r) - \frac{Z}{r}P_{n_a l_a}(r) + \sum_{n_b l_b}(4l_b+2)\left(v_0(n_b l_b, r)P_{n_a l_a}(r) - \sum_l \Lambda_{l_a l l_b} v_l(n_b l_b, n_a l_a, r)P_{n_b l_b}(r)\right)$$

$$= \epsilon_{n_a l_a}P_{n_a l_a}(r) + \sum_{n_b \neq n_a}\epsilon_{n_a l_a, n_b l_a}P_{n_b l_a}(r)$$

Self-consistent approach required

Expect accuracy of O(30%) in event rates/bounds

Bound electron wavefunctions (2/5)

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$$=\epsilon_{n_al_a}P_{n_al_a}(r)+\sum_{n_b\neq n_a}\epsilon_{n_al_a,n_bl_a}P_{n_bl_a}(r)$$

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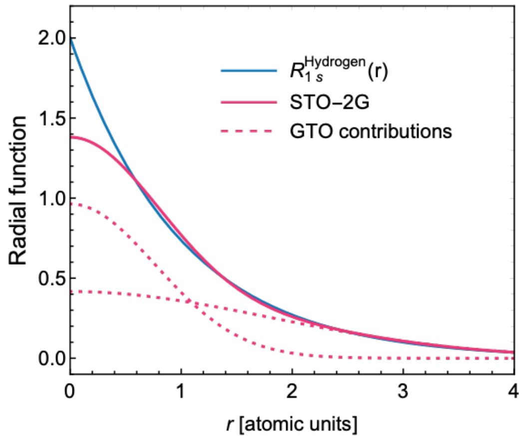

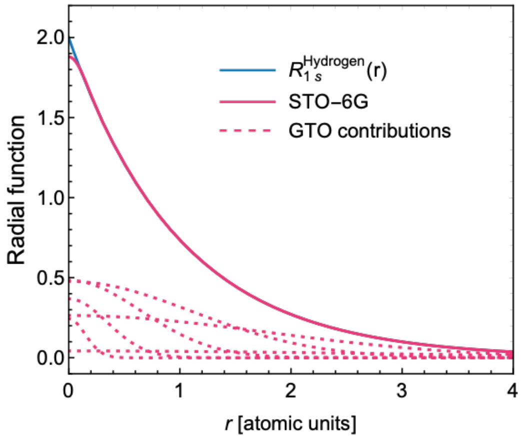

Gaussian basis choice important at small/large r

Bound electron wavefunctions (2/5)

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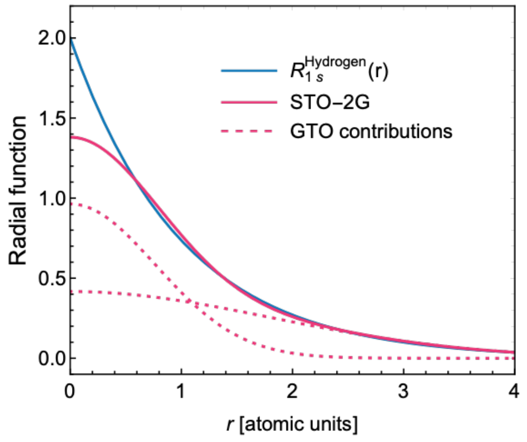
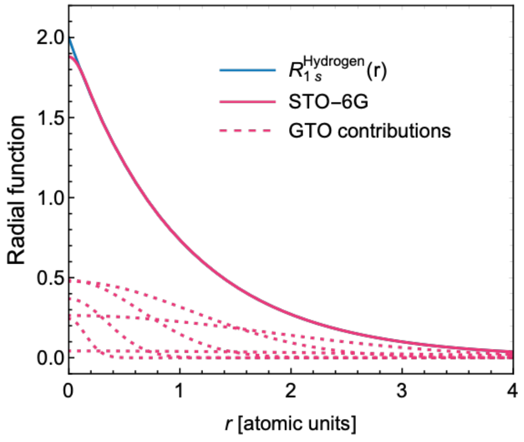
$$=\epsilon_{n_a l_a}P_{n_a l_a}(r)+\sum_{n_b\neq n_a}\epsilon_{n_a l_a,n_b l_a}P_{n_b l_a}(r)$$

Self-consistent approach required

Expect accuracy of O(30%) in event rates/bounds





Gaussian basis choice important at small/large r

pyscf

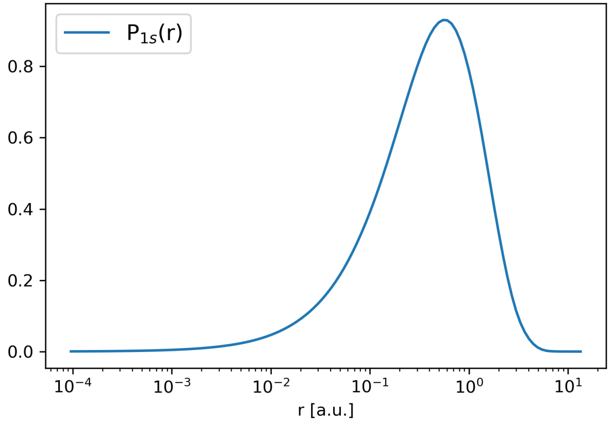
$$AO_{nlm}\propto\sum_i c_i^n\exp(-\alpha_i^n r^2)Y_{lm}(\theta,\phi)$$

$$MO_{nlm}=\bar{v}_{nlm}AO_{nlm}$$

$$H_{ij}=\int AO_i(\mathbf{r})H_j(\mathbf{r})AO_j(\mathbf{r})\,d^3\mathbf{r}\;.$$

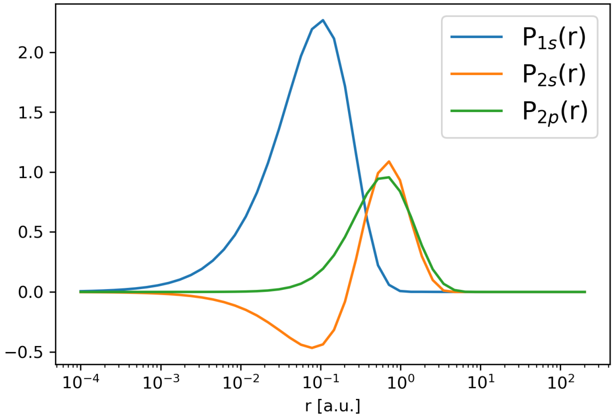
Treats atoms and molecules, relativistic treatments, molecular dipoles, and more.

Bound electron wavefunctions (3/5)



HELIUM

$E_{bound}(1s)$ =
(0.025) keV
→ 1s events!

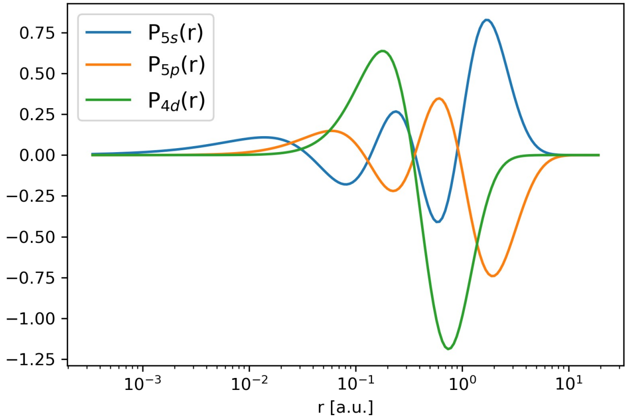


NEON

$E_{bound}(1s,2s,2p)$ =
(0.89, 0.052, 0.023)
keV
→ Only n=2 events!

Cutoff condition:

$KE_{DM} > E_B$



XENON

$E_{bound}(4s,4p,4d,5s,5p)$=
(0.21,0.16,0.075,0.025
0.012) keV
→ Only n=4, 5 events!

Bound electron wavefunctions (4/5)

- Molecular gas can **quench itself** → part of target
- Molecular orbitals are no longer eigenfunctions (spherical harmonics) of the SO(3) generators.

$$\psi(\mathbf{r}) = \frac{P(r)}{r} Y_{lm}(\theta, \phi) \quad \rightarrow \quad \psi(x, y, z)$$

- We need new classification of orbitals :

  irreducible representations of SO(3) → irreducible representation of point group

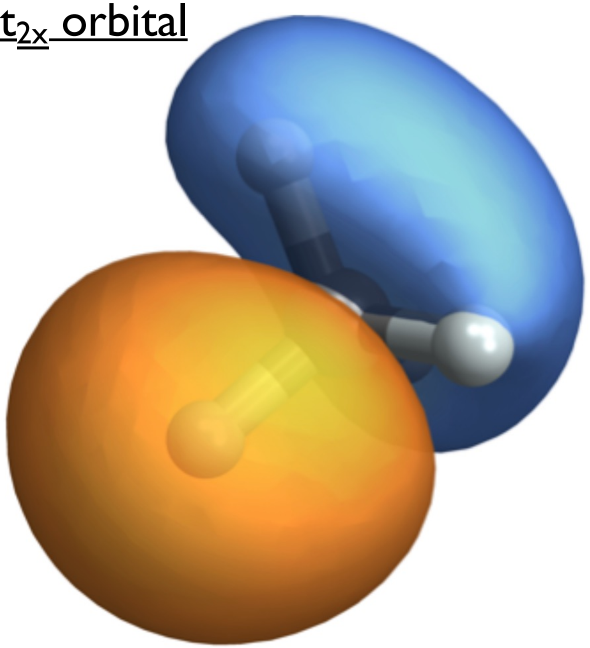
$\mathbf{T_d}$	E	$8C_3$	$3C_2$	$6S_4$	$6\sigma_d$	linear functions, rotations	quadratic functions	cubic functions
A_1	+1	+1	+1	+1	+1	-	$x^2+y^2+z^2$	xyz
A_2	+1	+1	+1	-1	-1	-	-	-
E	+2	-1	+2	0	0	-	$(2z^2-x^2-y^2, x^2-y^2)$	-
T_1	+3	0	-1	+1	-1	(R_x, R_y, R_z)	-	$[x(z^2-y^2), y(z^2-x^2), z(x^2-y^2)]$
T_2	+3	0	-1	-1	+1	(x, y, z)	(xy, xz, yz)	(x^3, y^3, z^3) $[x(z^2+y^2), y(z^2+x^2), z(x^2+y^2)]$

<u>Tetrahedral group (Methane): T_d</u>

Bound electron wavefunctions (5/5)

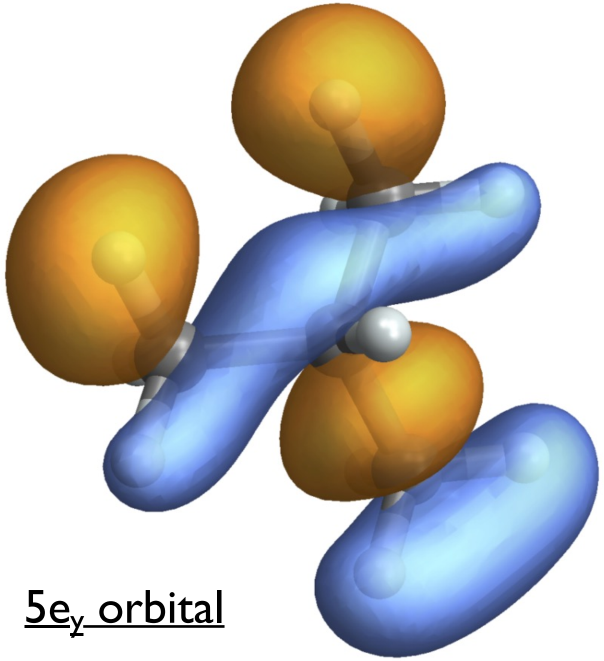
- Molecular orbitals don't enjoy the spherically symmetric Hamiltonian of noble gas. Instead the gaussian basis is multi-centered:

$2t_{2x}$ orbital



METHANE (CH_4)

E_{bound} = (-304.9 eV, -24.8 eV, -14.8 eV)
→ Only 2a and 2t events!



$5e_y$ orbital

ISOBUTHANE (C_4H_{10}))

E_{bound}= (-305.429eV, -304.941eV, … -12.4723eV, -12.318eV)
→ Only $E > E_{2a}$ events!

Unbound electron wavefunctions

- Continuum limit: Hartree-Fock integrated, approximate the self-consistent piece of the potential:

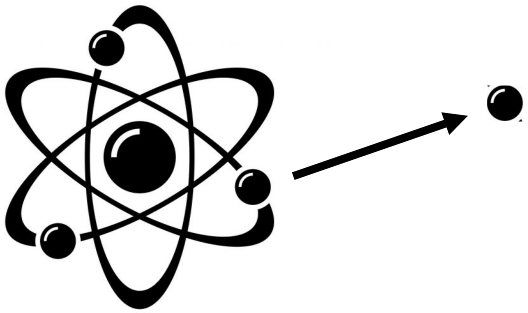
$$-\sum_{i\neq j} \frac{1}{|\mathbf{r_i}-\mathbf{r_j}|} = V_{dir}(r) + V_{exch}(r)$$

$$V_{dir}(r) = \sum_{n_b l_b} (4l_b+2) \int_0^{\infty} \left(\frac{P^2_{n_b l_b}(r_1)}{\max(r_1, r)} \right) dr_1$$

$$V_{\rm exch} = k_x \left(\frac{24\rho(r)}{\pi} \right)^{1/3}$$

→ « Hartree-Plus-Statistical-Exchange » potential (Cowan) gives accurate wavefunctions and energies (checked against bound WFs).

- Use frozen core approximation: electrons don't have time to react (ie change wavefunction) to ejected electron.

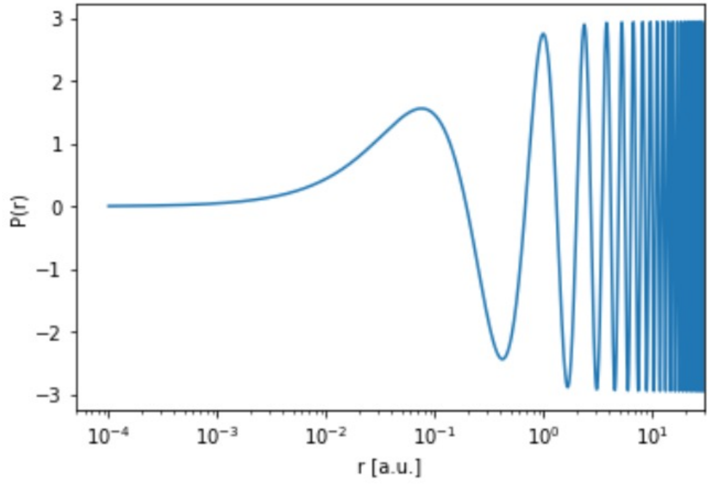


Potential:

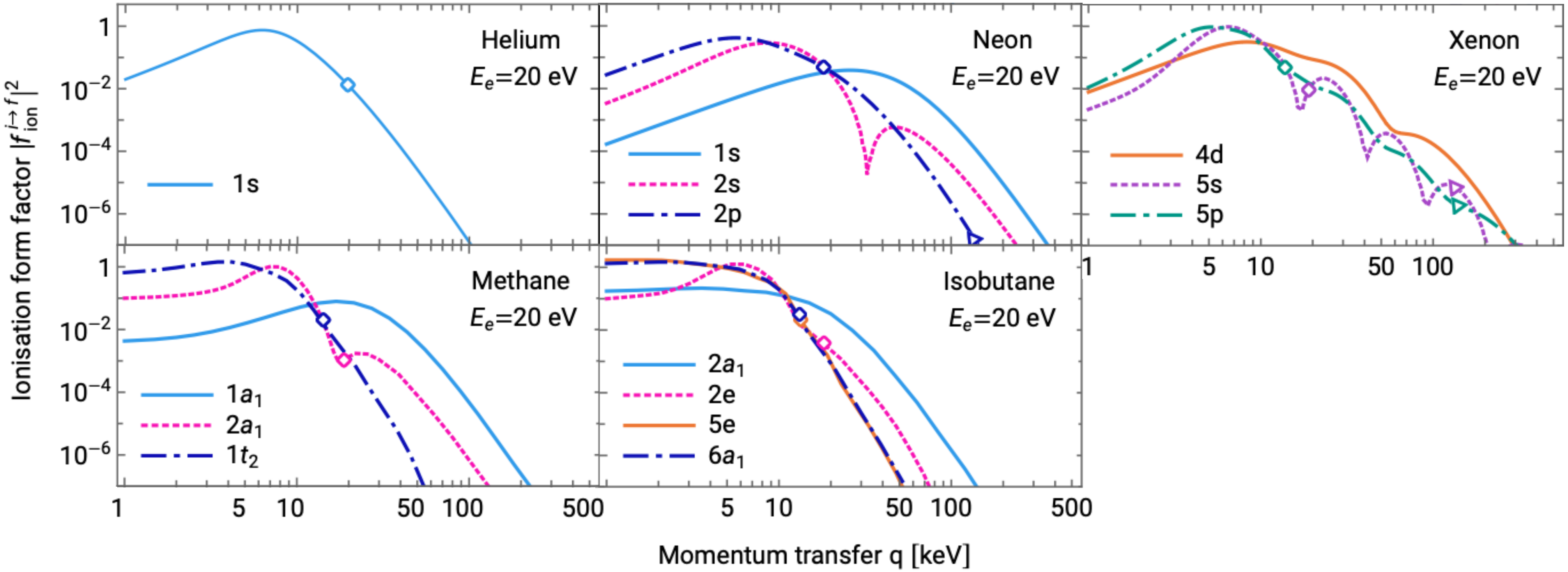
- Point nucleus : -Z/r
- Electron "cloud": $V_{dir}(r)$
- Electron "exchange": $V_{\rm exch}$

→ 1/r at large r

Neon 2p → l_R=0, E = 250eV



Form Factors

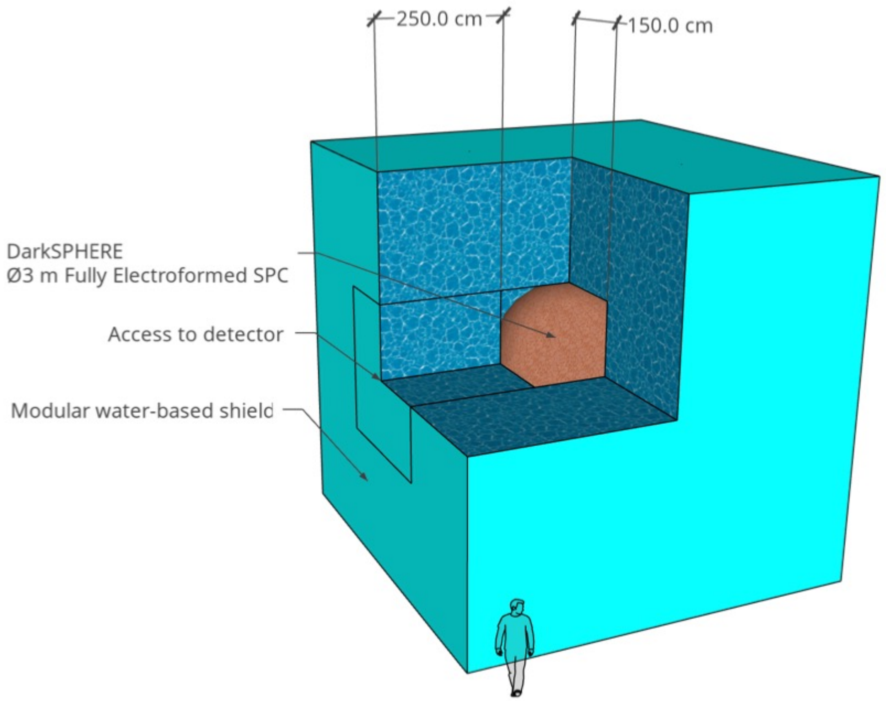


Form factor ($\boldsymbol{\alpha}|\mathcal{M}|^2$): $|f_{\text{ion}}^{nl}(q)|^2 = \frac{(2m_e E_R)^{3/2}}{\pi^2} \sum_{\text{states:i,f}} \left| \int d^3x\, \tilde{\psi}^*_{p'l'm'}(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} \psi_{nlm}(\mathbf{x}) \right|^2$

arxiv 2110.02985

DarkSPHERE at Boulby

- Boulby Underground Laboratory hosts a 4000m^3 clean room space supporting DM experiments – and is looking for new experimental proposals!
- Boulby benefits from relatively low seismic noise and radioactivity (from rock)
- We propose DarkSPHERE : a 3m SPC fully electroformed underground, similar to ECUME in Canada, and will form the next stage of the NEWS-G experiment



Shielding Configuration	Environmental background rate $\leq 1\,\mathrm{keV}$ [dru] Photon-induced	Neutron-induced		Muon-induced
	Photon	Neutron	Photon	
2.5 m water	4.2×10^{-3} (0.3)	9×10^{-5} (5)	1.3×10^{-4} (0.4)	5×10^{-3} (4)

Event rates

- The dark event rate can be calculated using:

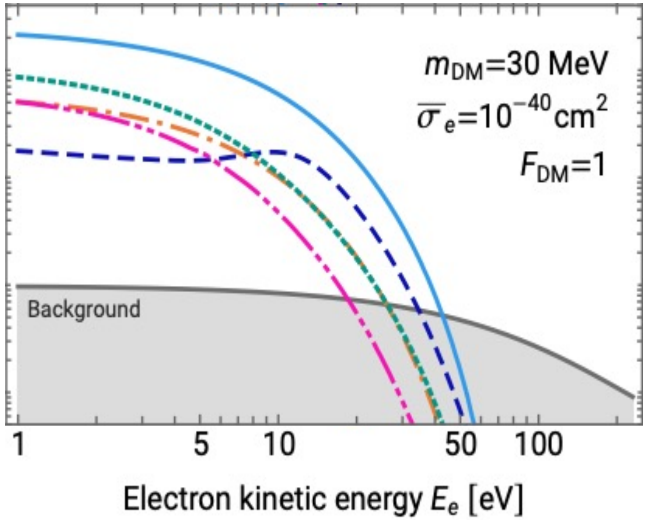
$$\frac{\mathrm{d}R}{\mathrm{d}E_e} = \frac{1}{m_A}\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}}\sum_{nl} w_{nl}\frac{\mathrm{d}\langle\sigma_{\mathrm{ion}}^{nl} v_{\mathrm{DM}}\rangle}{\mathrm{d}E_e}$$

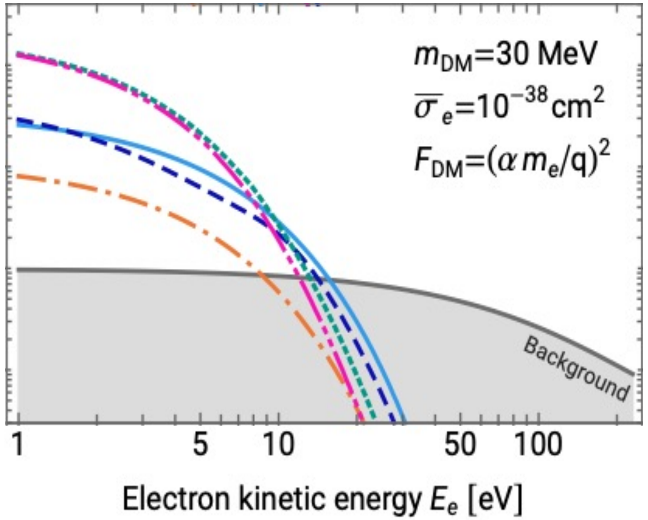
, where

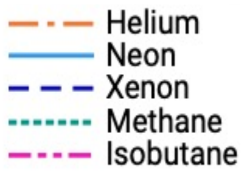
$$\frac{\mathrm{d}\langle\sigma_{\mathrm{ion}}^{nl} v\rangle}{\mathrm{d}\ln E_e} = \frac{\sigma_e}{8\mu_e^2}\int_{q_-}^{q_+} q dq \left|f_{\mathrm{ion}}^{nl}\right|^2 |F_{\mathrm{DM}}|^2 g(v_{\mathrm{min}}^{nl})$$

- Assume simulated+measured background provided by NEWS-G, $F_{DM}=1$
- 10% Methane or Isobutane (Coulomb wave) contribution

Heavy mediator ⟷ Light mediator





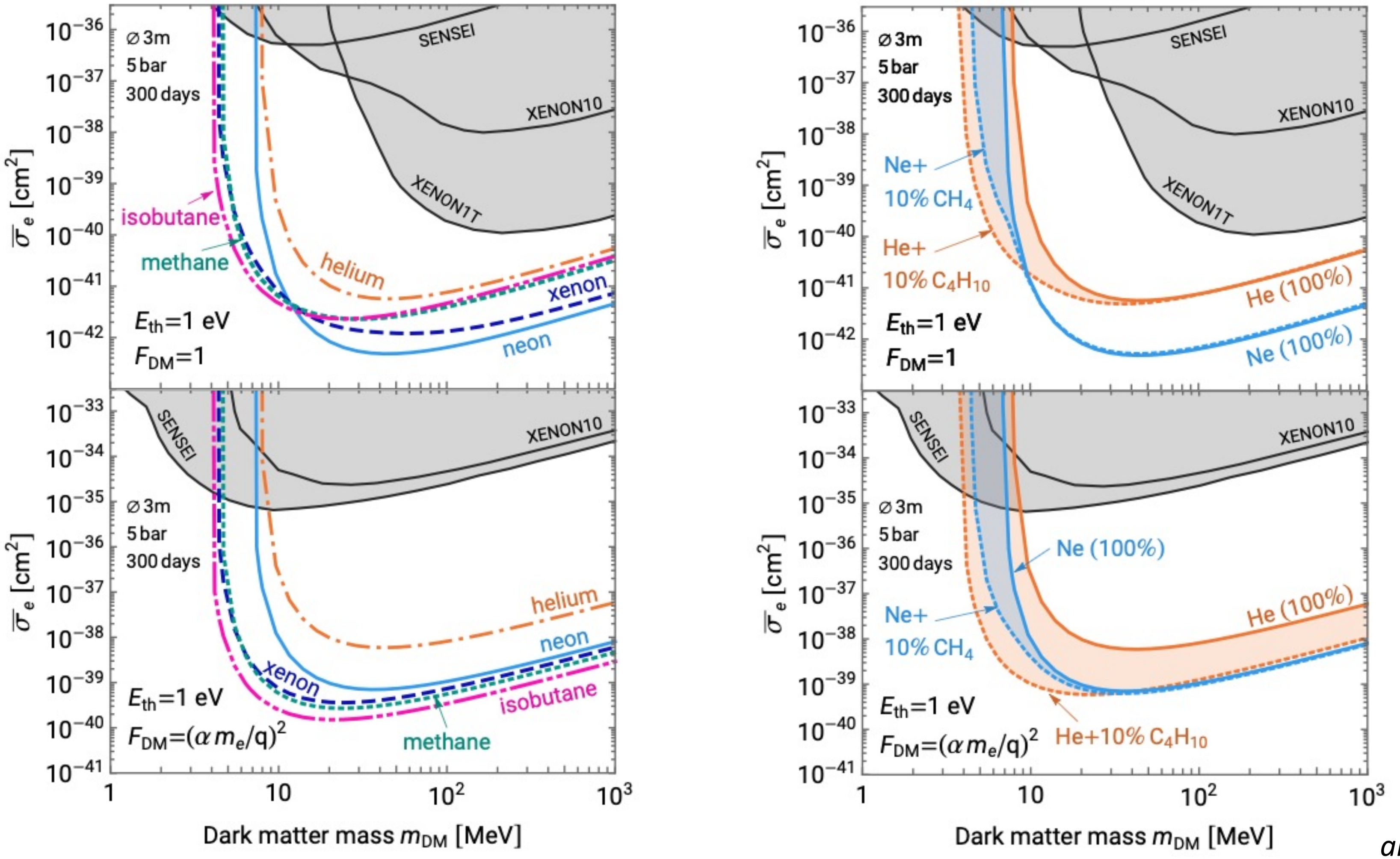


arxiv 2110.02985

Sensitivities

Heavy mediator

Light mediator

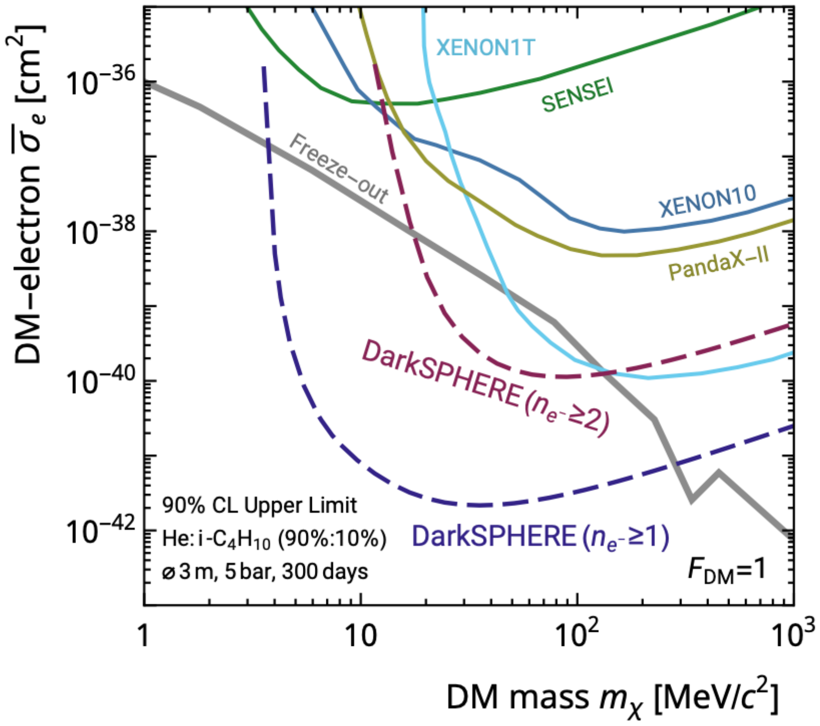


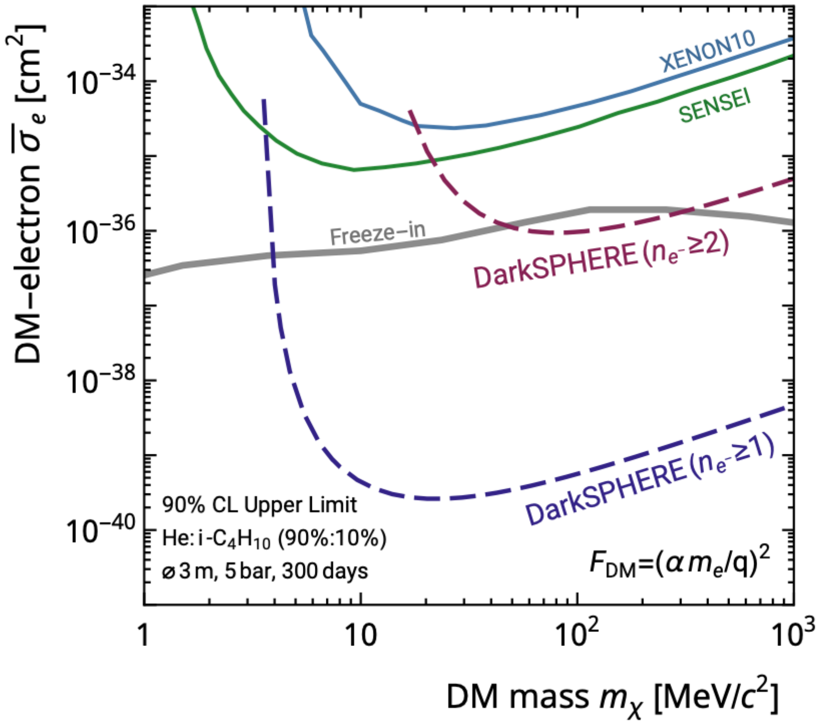
arxiv 2110.02985

Sensitivities

- Good sensitivity to freeze-in / freeze-out benchmark scenarios depends on ability to see 1e- events

Heavy mediator ⟷ Light mediator

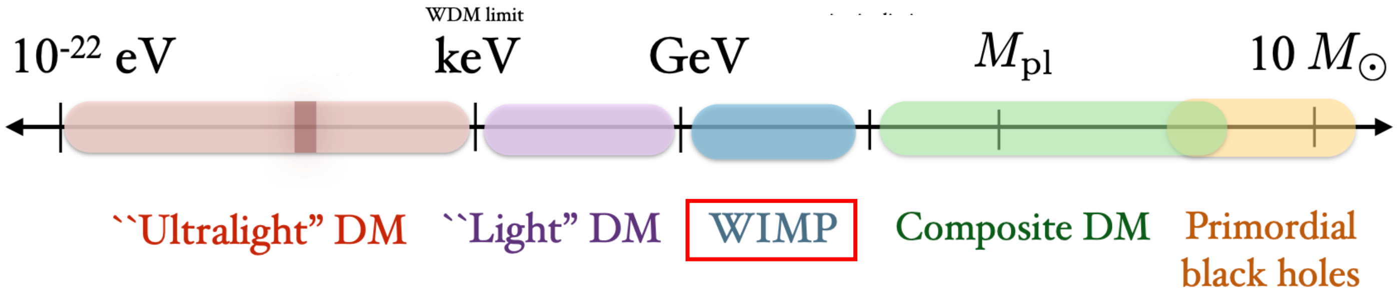


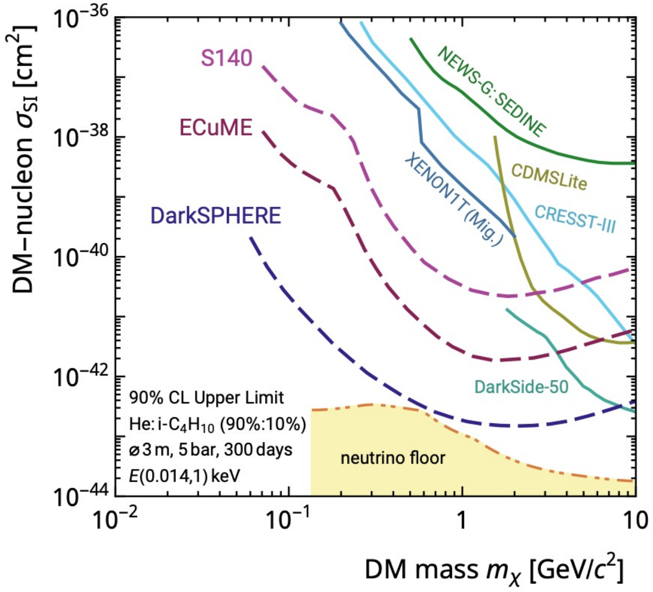


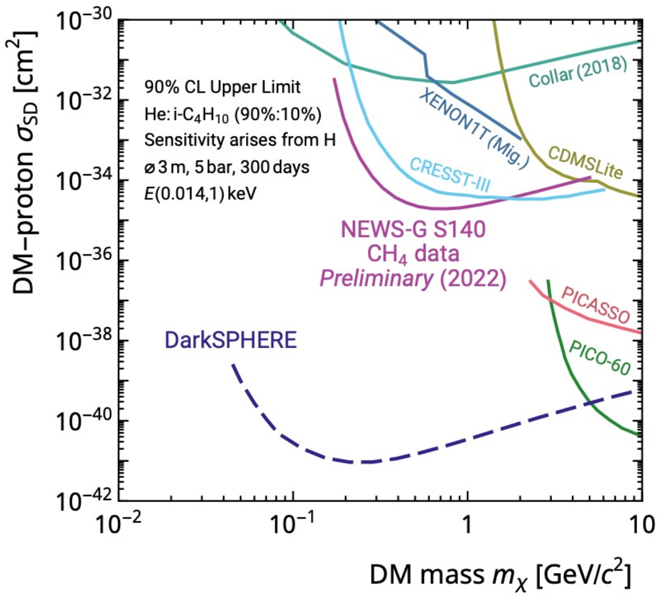
arxiv 2301.05183

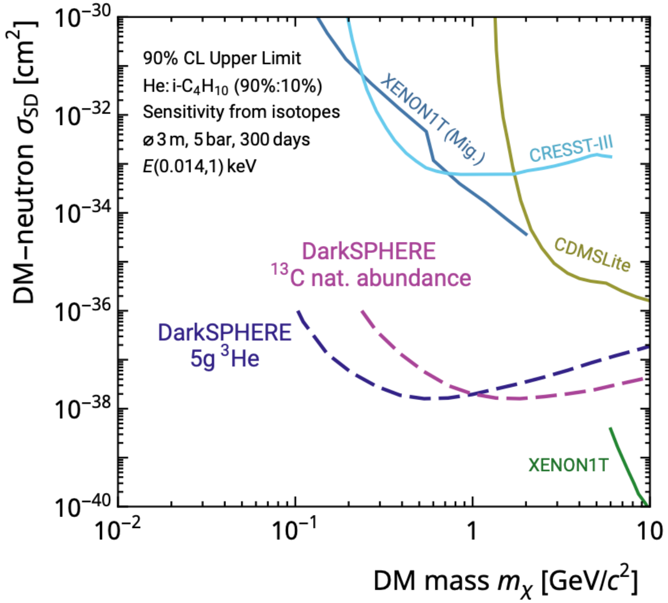
Other bounds: DM-nucleon scattering

- At higher masses DarkSPHERE is also very competitive in the 0.1-5GeV region for SI and SD interactions



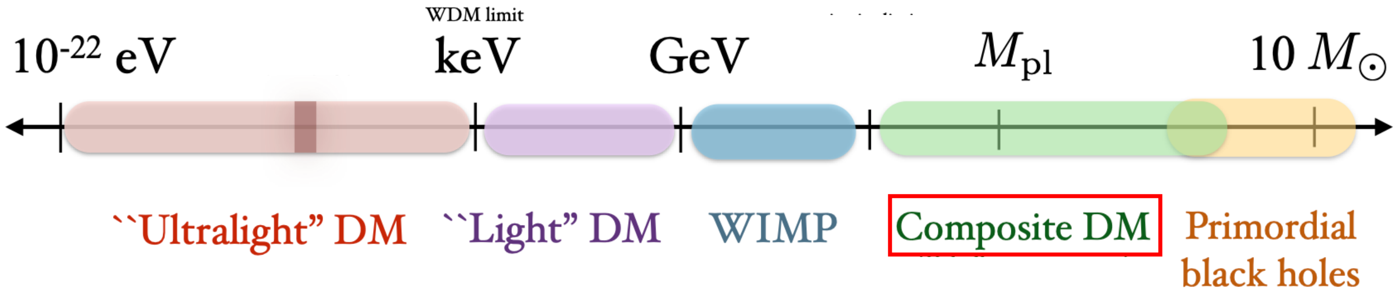


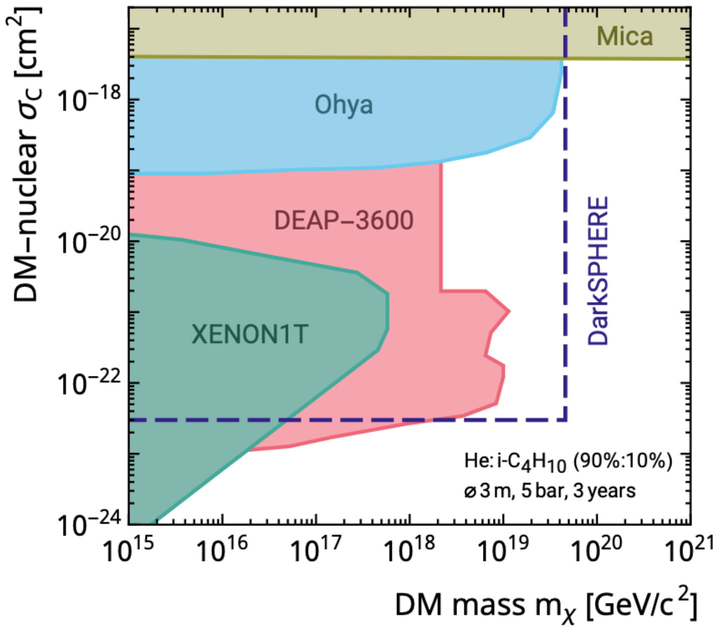




Other bounds: DM-nucleon scattering

- And at very high masses DarkSPHERE is still competitive! Sensitivity here depends on size of experiment





Summary

- Dedicated direct detection of DM-electron scattering good probe of light DM (<1GeV)
- Atomic calculation under control – good accuracy & understanding (vs. other HF & experiment). Molecular calculation more difficult (Coulomb approximation used), but can be used to set bounds (i.e. with mixing)
- More sensitive than current bounds and easier than other proposed experiments → SPC good probe of light DM-electron and scattering !
- SPCs sensitive to large range of DM masses, with more interactions to explore (e.g. dark photons, ALPs). Could also search for molecules with better form factors (i.e. looking for large q-variance)
- Boulby is ideal for a world-leading large-scale proposal (DarkSPHERE) based in the UK

Thank you!

Back up - Motivation for Light(er) Dark Matter

- Dark matter has many ways of appearing in the present day universe:

Thermal Production (e.g. freeze-out WIMP), Freeze-in (FIMP), Inflaton decay, Gravitino…

WIMPs annihilate until $T \sim m_\chi/20$, leaving relic density:

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3\text{s}^{-1}}{\langle \sigma_{\chi\chi} v_{rel} \rangle}$$

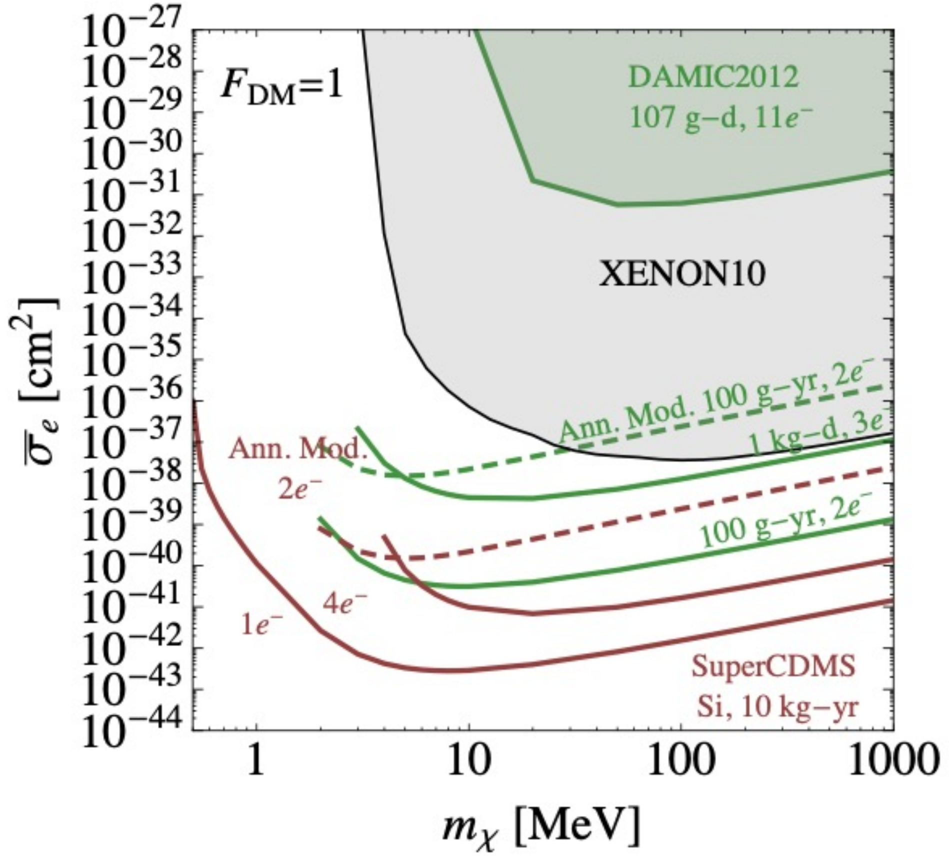
SM particles annihilate near $T \sim m_\chi$, leaving relic density:

$$\Omega_\chi h^2 \propto \langle \sigma_{\chi\chi} v_{rel} \rangle$$

- Individual models of freeze-out and or freeze-in DM can be fully tested (even for unknown details of UV cosmology).
- Without knowledge of T_R, we cannot fully test inflaton decay or gravitino

Back up – More On Constraints

Electron Recoil SuperCDMS projection (Essig et al.)



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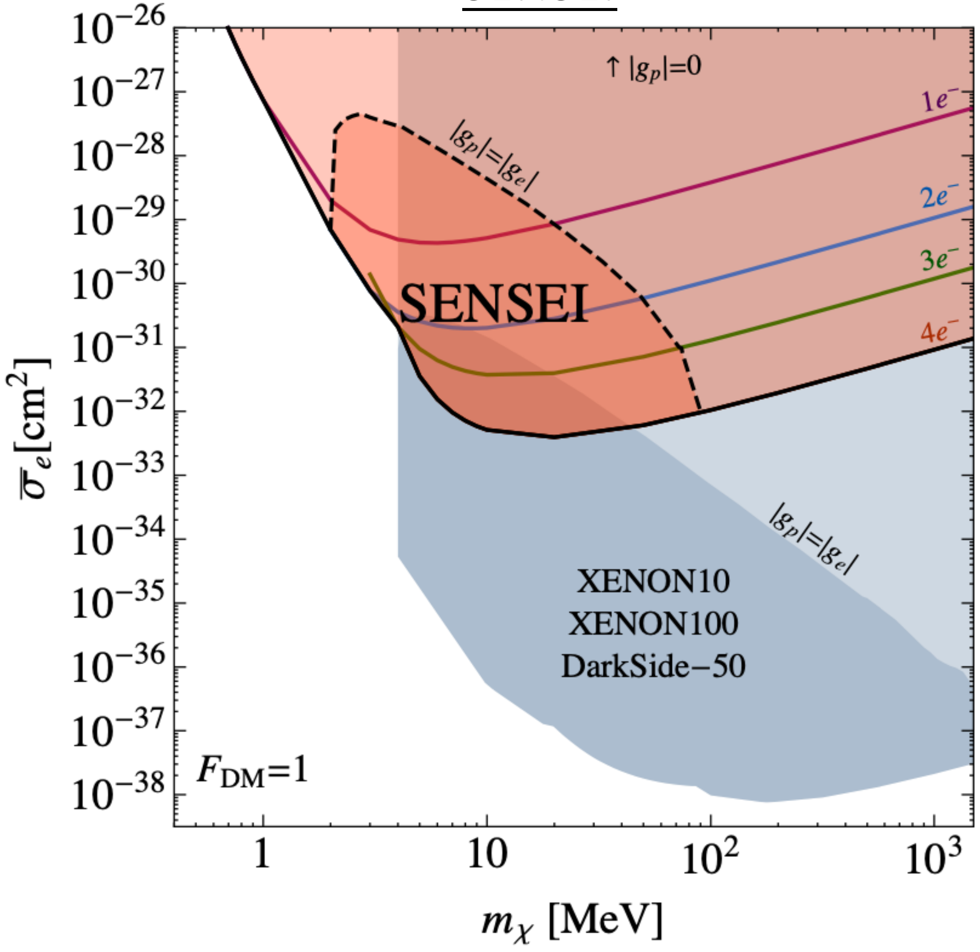


Back up – Hartree Fock choice

- Hartree-Fock approximation: self-consistent bound states with energies correct to first order:

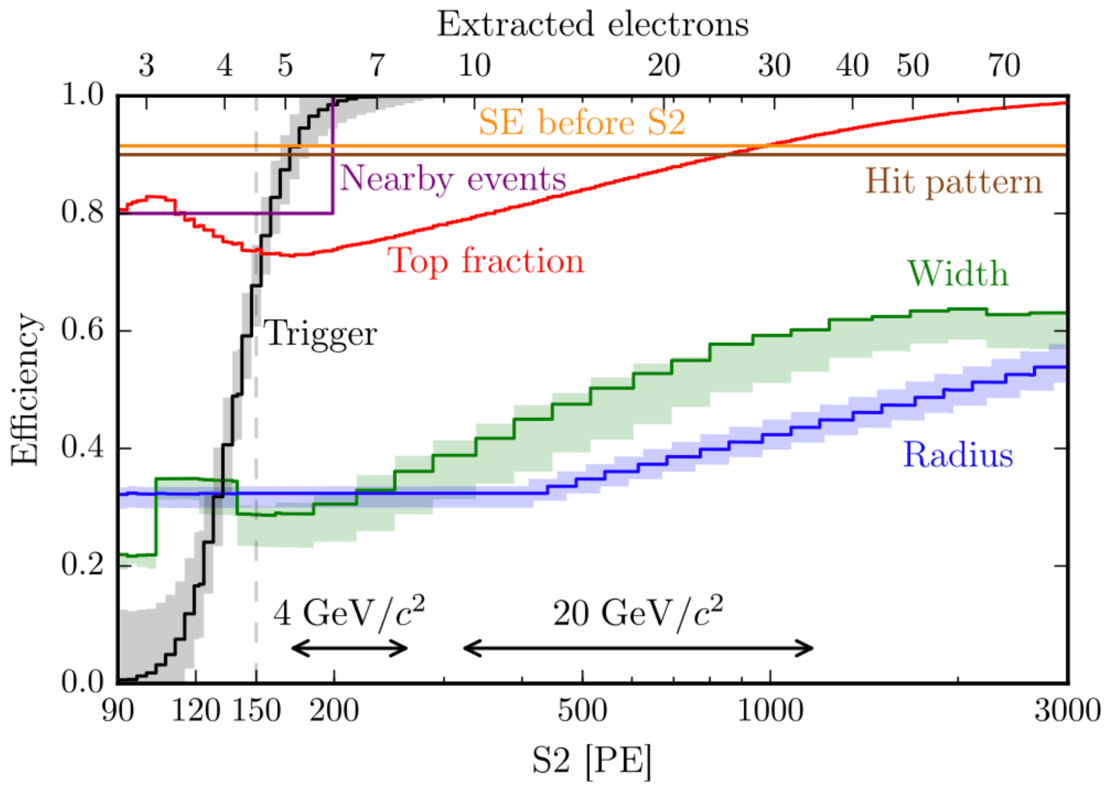
$$-\frac{1}{2}\frac{d^2P_{n_al_a}}{dr^2}+\frac{l_a(l_a+1)}{2r^2}P_{n_al_a}(r)-\frac{Z}{r}P_{n_al_a}(r)+$$
$$\sum_{n_bl_b}(4l_b+2)\left(v_0(n_bl_b,r)P_{n_al_a}(r)-\sum_l\Lambda_{l_all_b}v_l(n_bl_b,n_al_a,r)P_{n_bl_b}(r)\right)$$
$$=\epsilon_{n_al_a}P_{n_al_a}(r)+\sum_{n_b\neq n_a}\epsilon_{n_al_a,n_bl_a}P_{n_bl_a}(r),\quad (3.71)$$

Easy to solve Hamiltonians for full shell atoms	Non-Rel approx. good for q < 200keV	Accuracy of ~30% in event rates/bounds

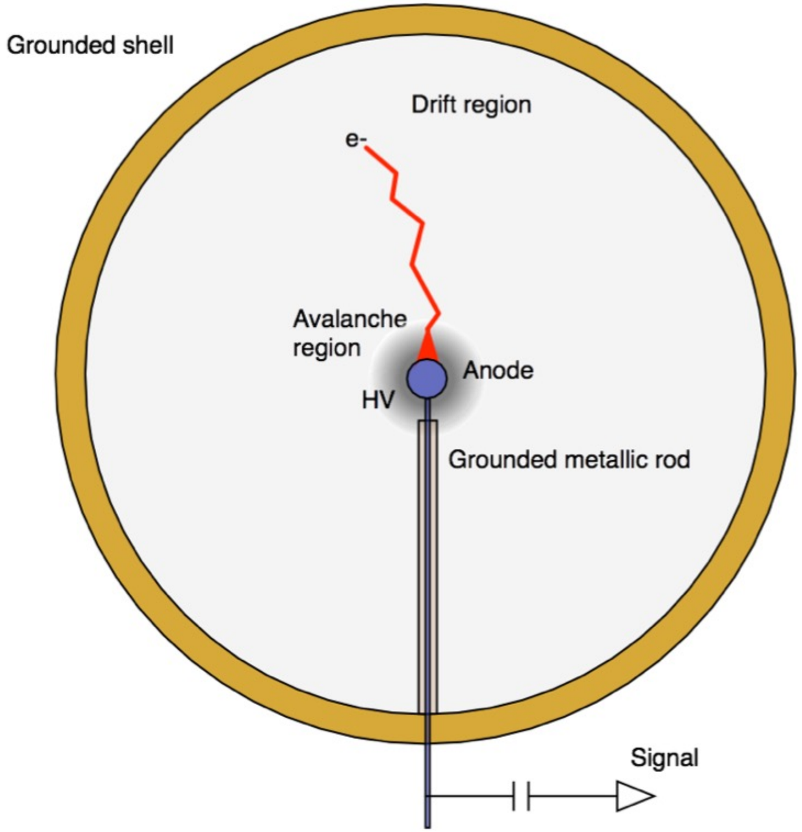
- Sensitivities of bounds to choices:
  - ➢ ~30-50% Gaussian basis choice
  - ➢ ~50-100% exchange potential choice, orthogonalization
  - ➢ ~10-20% analysis of recoil energy profile vs. deposited energies
  - ➢ ~30% astrophysical parameter choices
  - ➢ Linear with background

Back up – More On Detector

(liquid) Xenon 1T threshold (>4.5e-)

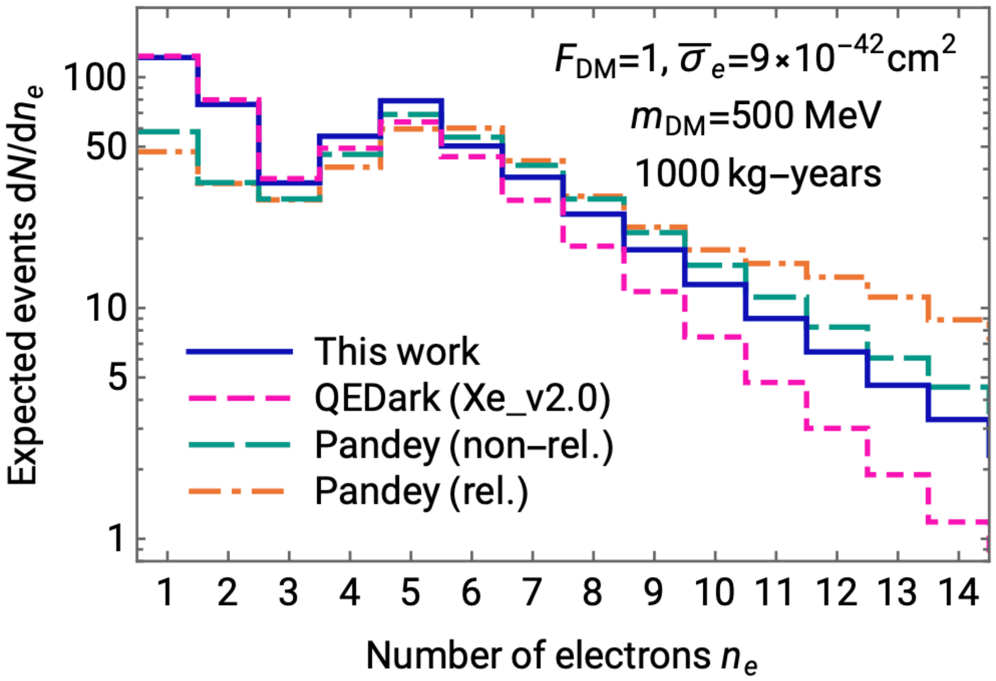


Spherical Proportional Counter (SPC, as proposed in DarkSPHERE)



Back-up

- Not all previous calculations (e.g. QEDark) exhibit modelling of atomic structure (V_{exch})



- CH_4/C_4H_{10} are quite symmetric so monocenter calculation sufficient