Hunting for light dark matter with gas-based detectors

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Together with Louis Hamaide

[and many helpful discussions with Konstantinos Nikolopoulos
& Ioannis Katsioulas at the University of Birmingham]

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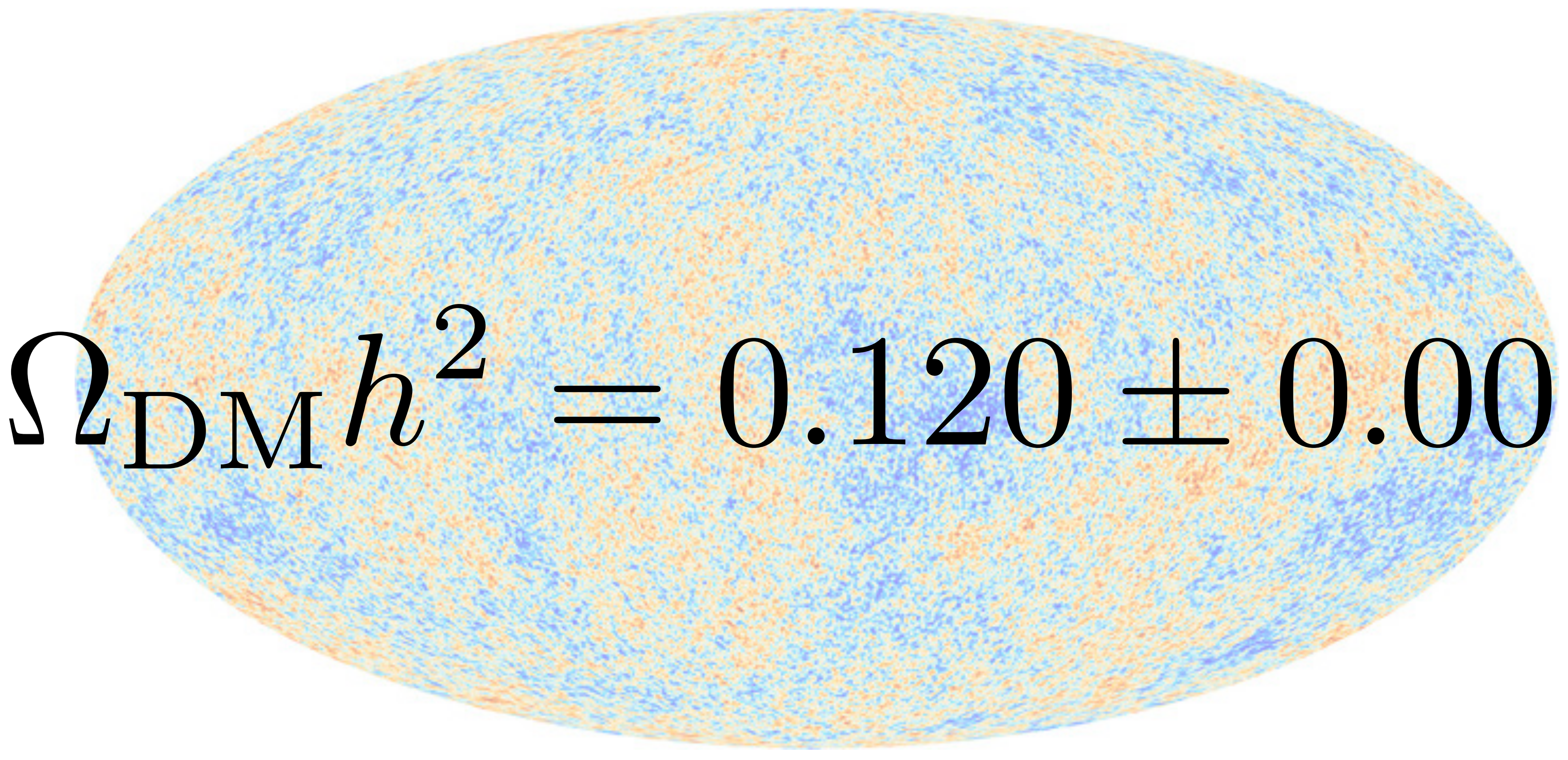
Motivation

Why should DM interact with normal matter?

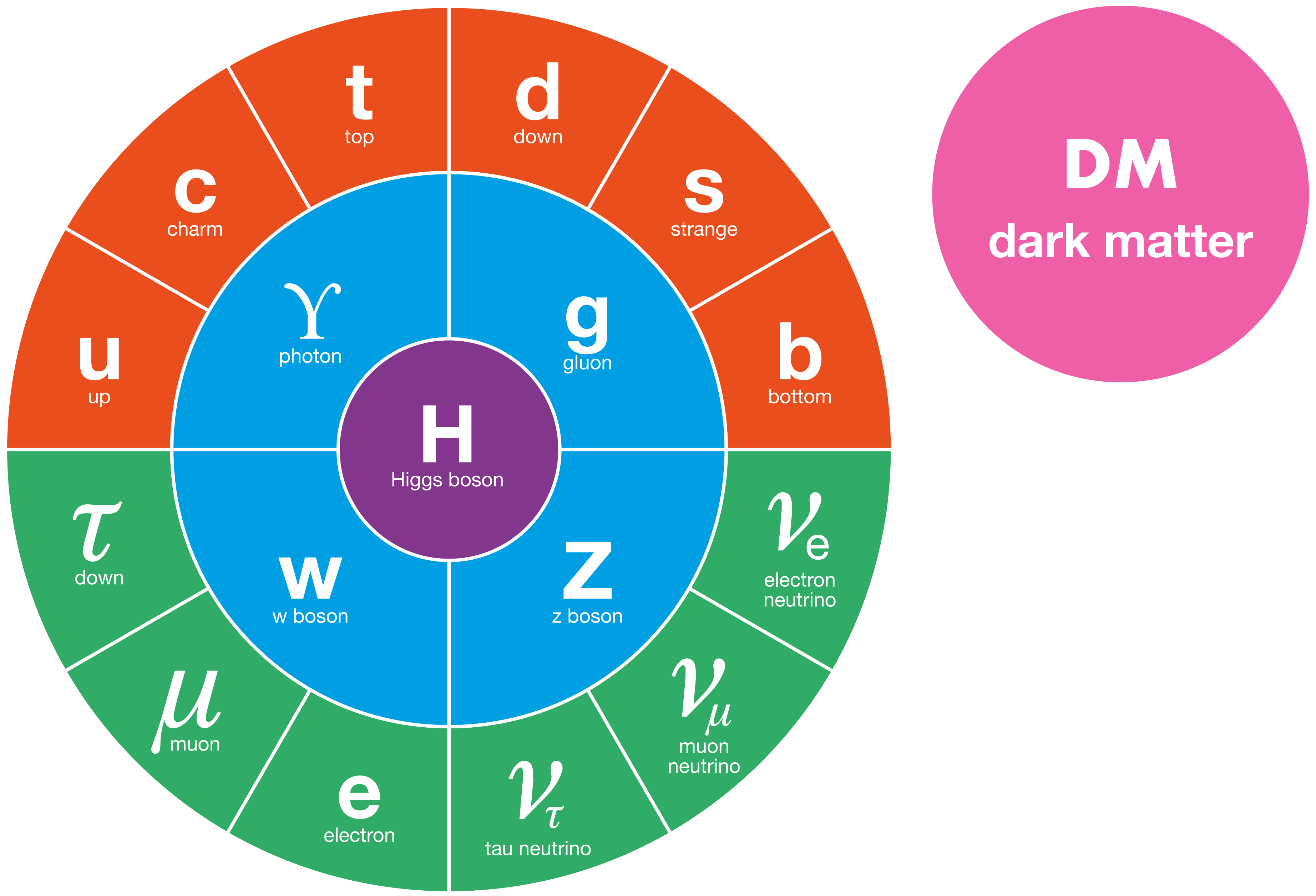
“Up to a point the stories of cosmology and particle physics can be told separately. In the end though, they will come together.” Steven Weinberg

Cosmology



$$\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$$

Particle Physics

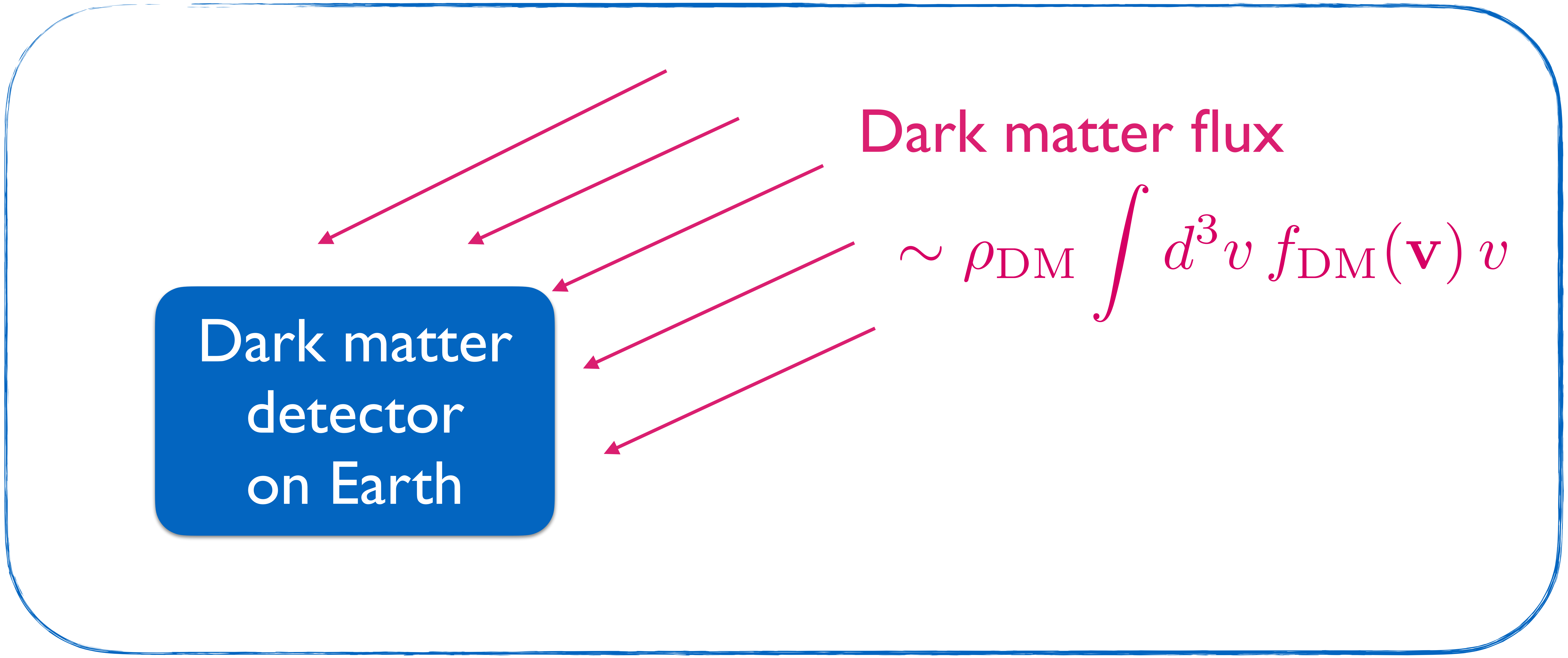


Suggests dark and visible matter interactions are generic

&

Informs and limits the possible interactions

Searching for DM-matter interactions: direct detection experiment



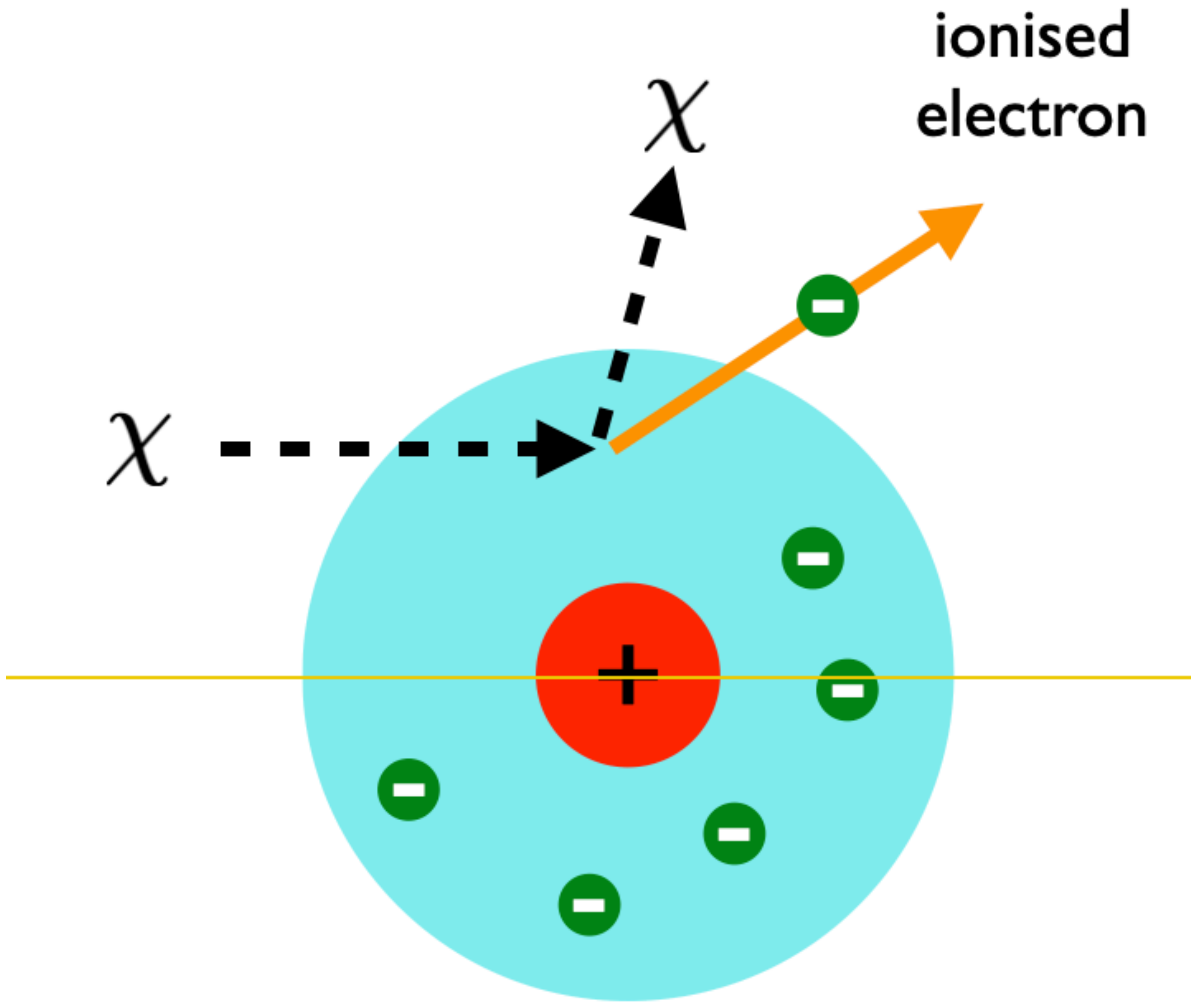
Dark matter detector on Earth

Dark matter flux

$$\sim \rho_{\rm DM} \int d^3v \, f_{\rm DM}(\mathbf{v}) \, v$$

Event rate = DM flux × particle physics × detector response

Hunting for dark matter—electron interactions



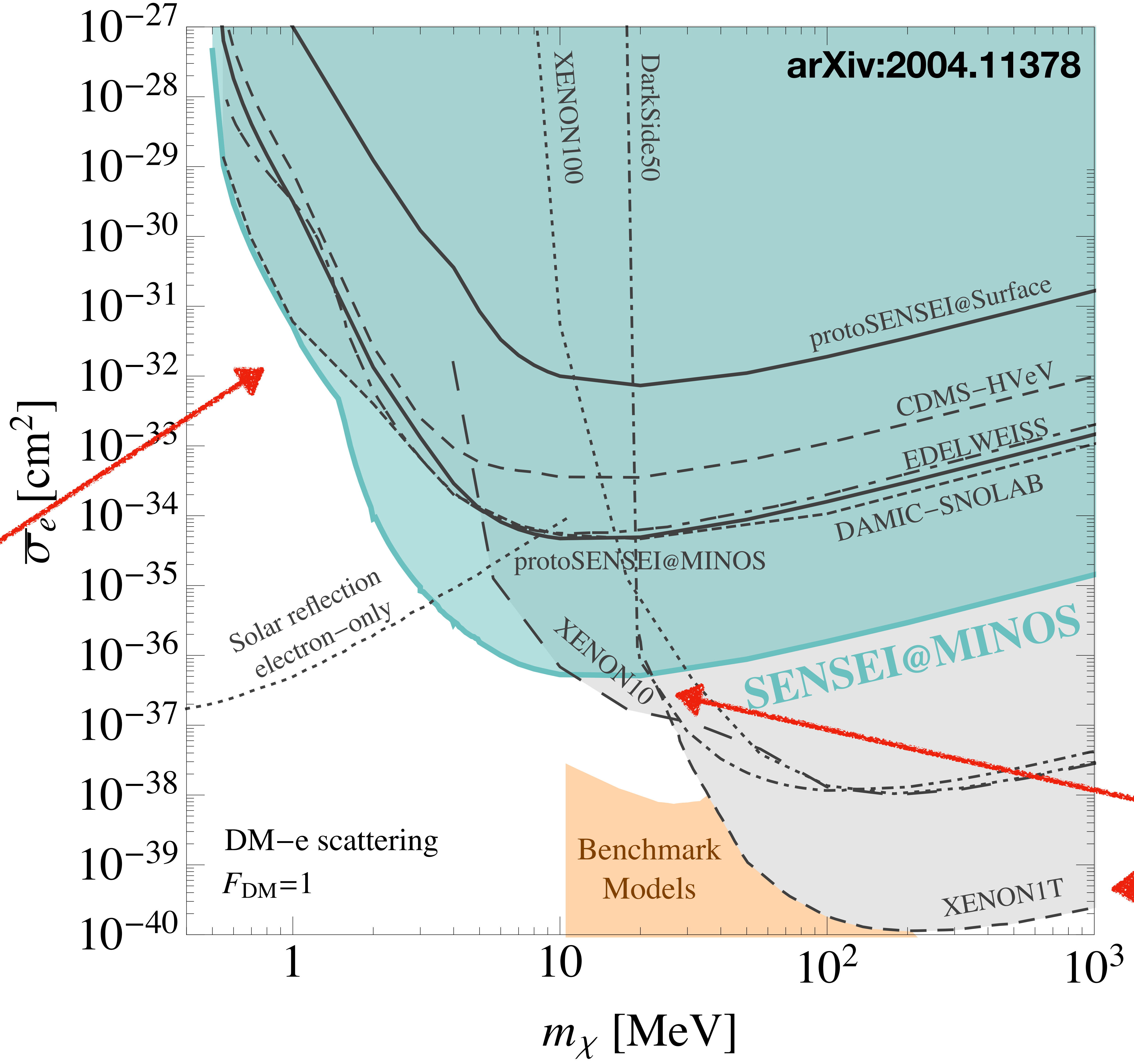
Kinematics requirement:

$$\frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \gtrsim E_{\rm binding}$$

$$m_{\rm DM} \geq 6~\text{MeV} \cdot \left(\frac{E_{\rm binding}}{15~\text{eV}} \right)$$

Constraint will be on the DM-electron scattering cross-section

The state-of-the-art

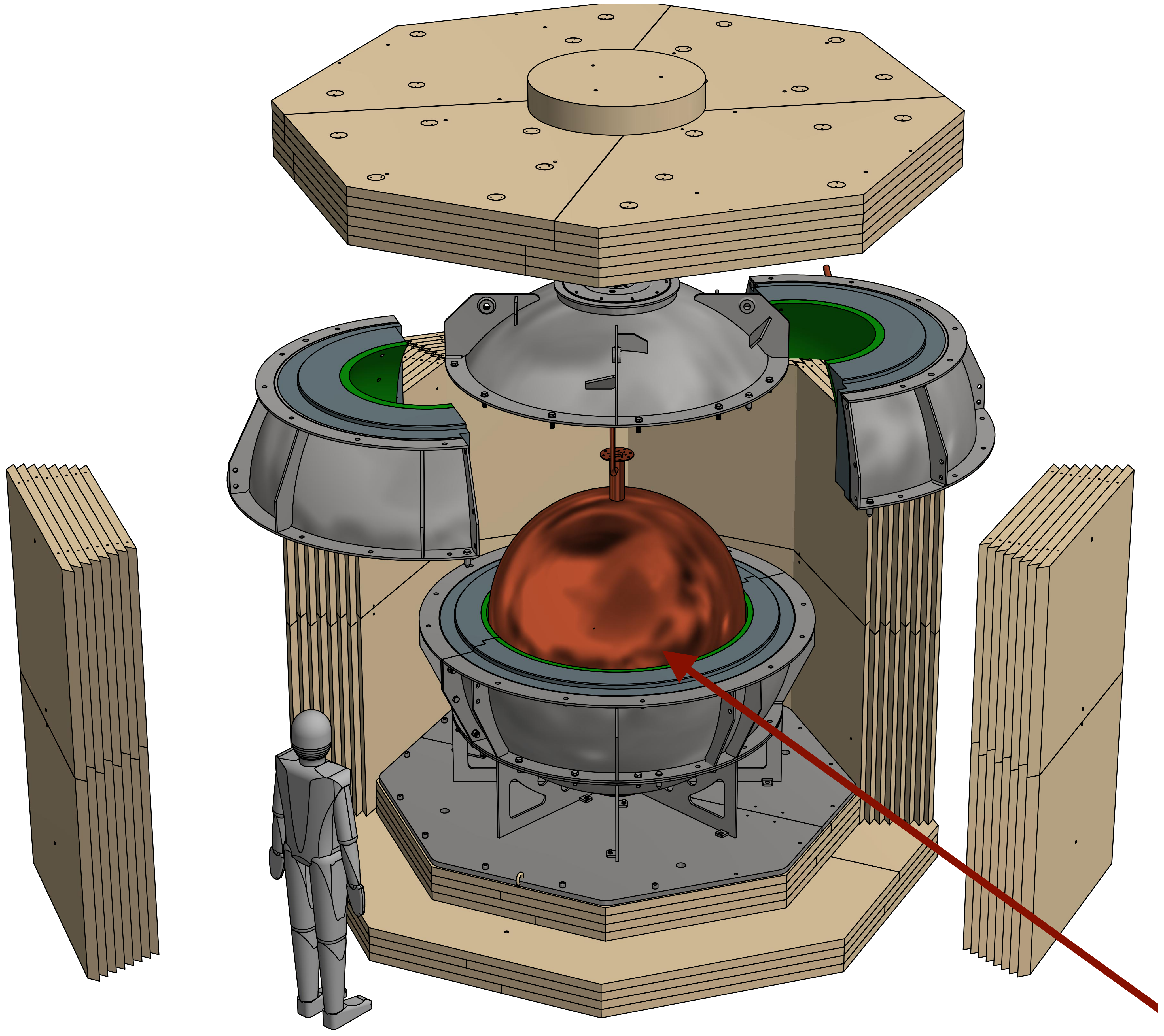


semi-conductor searches

atom searches

Gas-based detectors

A real experiment: NEWS-G



Gas filled spherical proportional counter

Advantages:

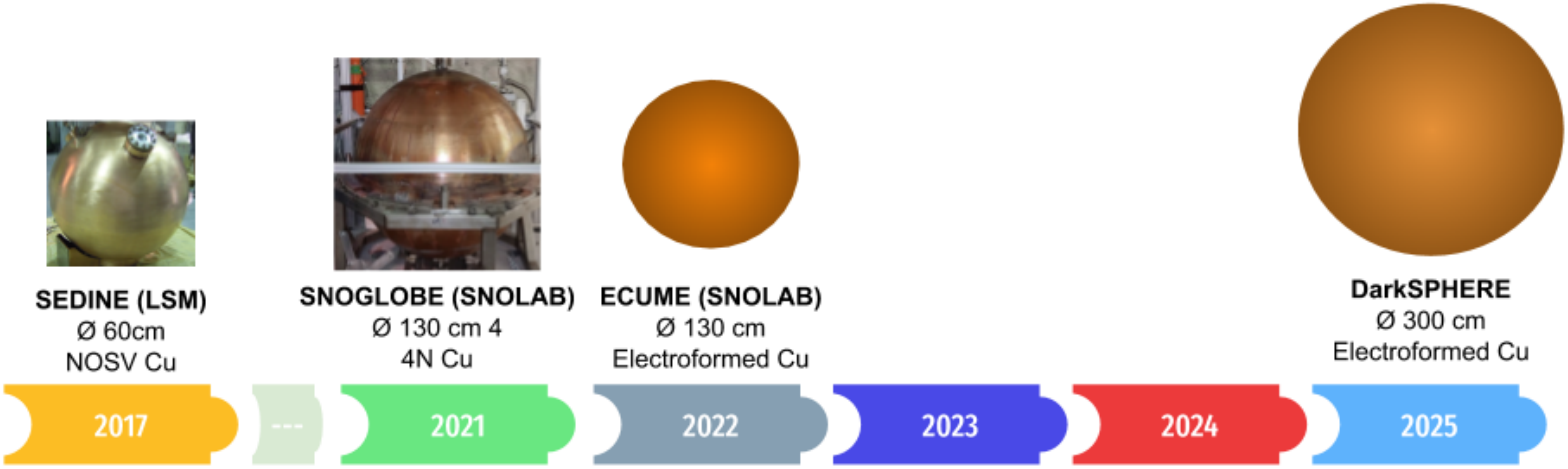
- can detect single electrons
- can be filled with different gas mixtures:

helium, neon, xenon, methane &
isobutane have all been proposed

~140cm diameter
Copper (99.99% pure) vessel

NEWS-G: towards DarkSPHERE

There is a roadmap to scale to even larger detectors



SEDINE (LSM)
Ø 60cm
NOSV Cu

SNOGLOBE (SNOLAB)
Ø 130 cm 4
4N Cu

ECUME (SNOLAB)
Ø 130 cm
Electroformed Cu

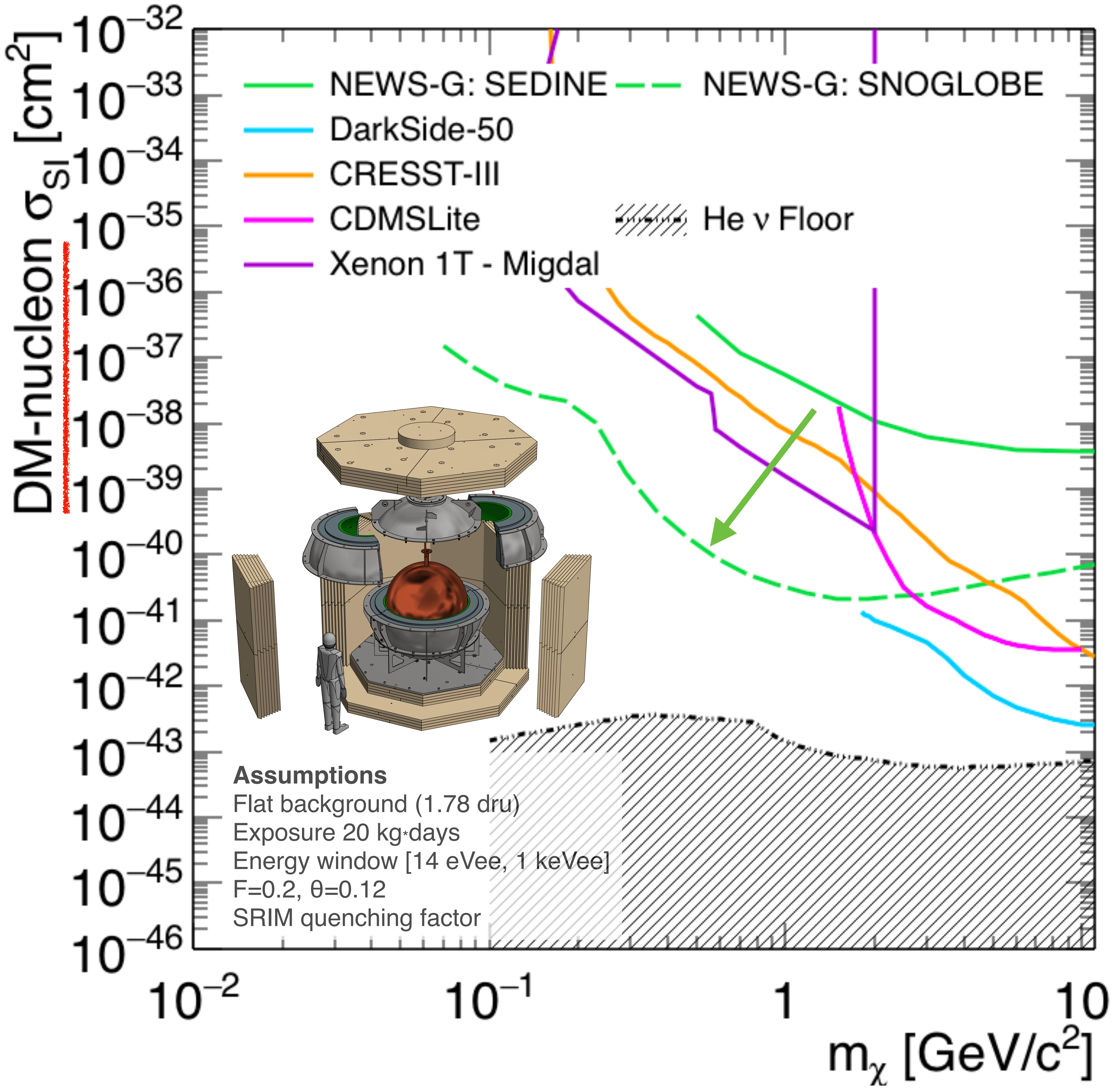
DarkSPHERE
Ø 300 cm
Electroformed Cu

in the UK?

Expected sensitivity…

Sensitivity estimates only performed for nucleon scattering

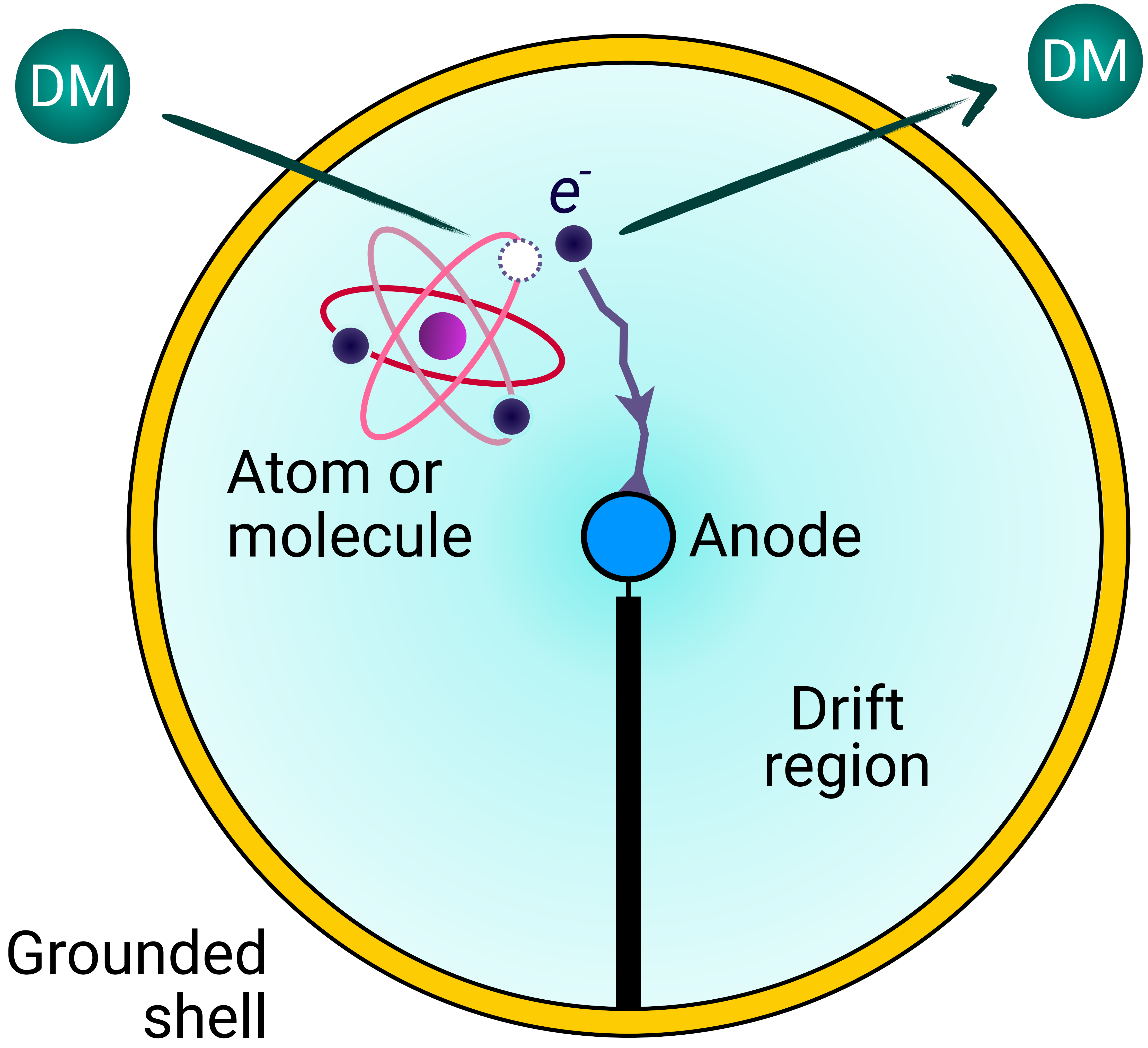
Question we asked: could this also be used to hunt for electron scattering?



Dark matter-electron scattering: proposed search

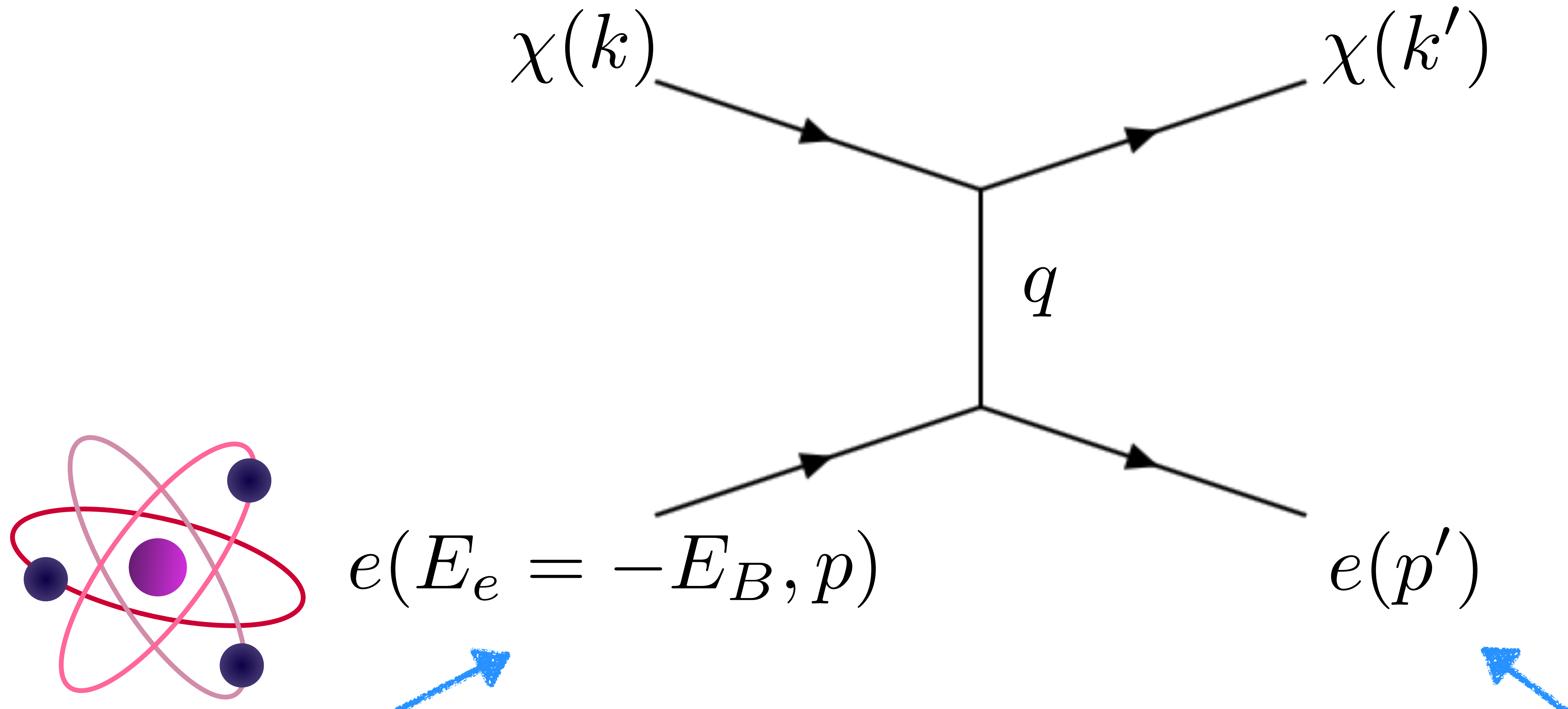
Dark matter scattering ionises an electron from an atom or molecule

Key aspect: single electrons can be detected at the anode



Developing the theory

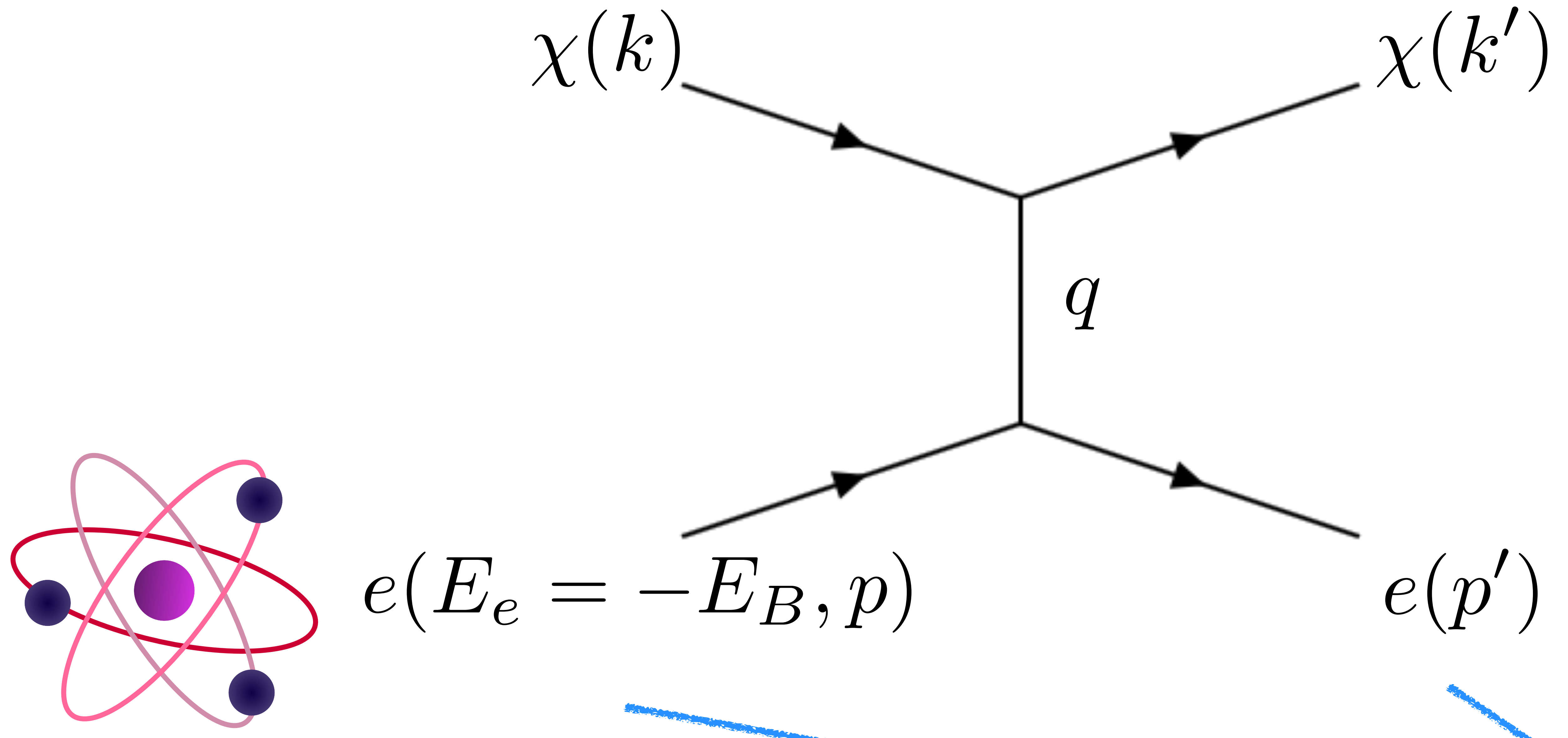
Dark matter — electron scattering



initial electron is not a momentum eigenstate (not a plane wave)

ionised electron propagates in the Coulomb field of the ionised atom (not a plane wave)

A modified scattering problem



Parameterise deviations from a plane wave in a form factor:

$$\left|f_{\text{ion}}^{i\to f}(E_e,\mathbf{q})\right|^2 = \int d\Omega_{k_e}\,\frac{2k_e^3}{8\pi^3}\,\left|\sqrt{V}\int d^3x\,\psi_f^*(\mathbf{x})\,e^{i\mathbf{q}\cdot\mathbf{x}}\,\psi_i(\mathbf{x})\right|^2$$

Challenge: we need to calculate bound/unbound states

Bound states: use ‘PySCF’

We are going to borrow from the tools of quantum chemistry for the bound states

PySCF = open-source python-based (‘Py’) quantum chemistry package that uses self-consistent field (‘SCF’) methods

Utilise Hartree-Fock methods:

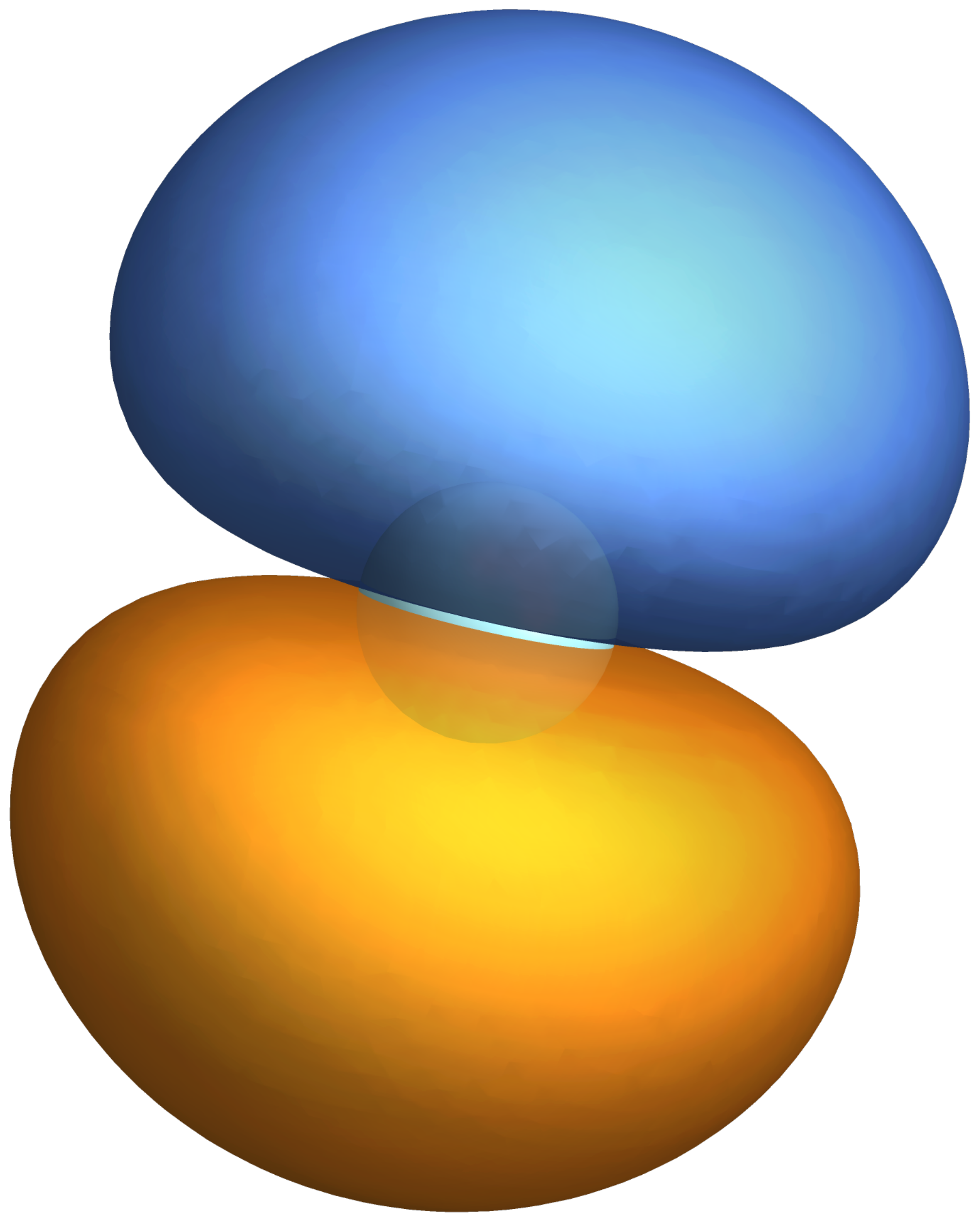
$$H = -\frac{1}{2}\sum_{i=1}^{N}\left(\nabla_i^2 + \frac{2Z}{r_i}\right) + \sum_{i>j}\frac{1}{r_{ij}}$$

Electrons move in a self-consistent field

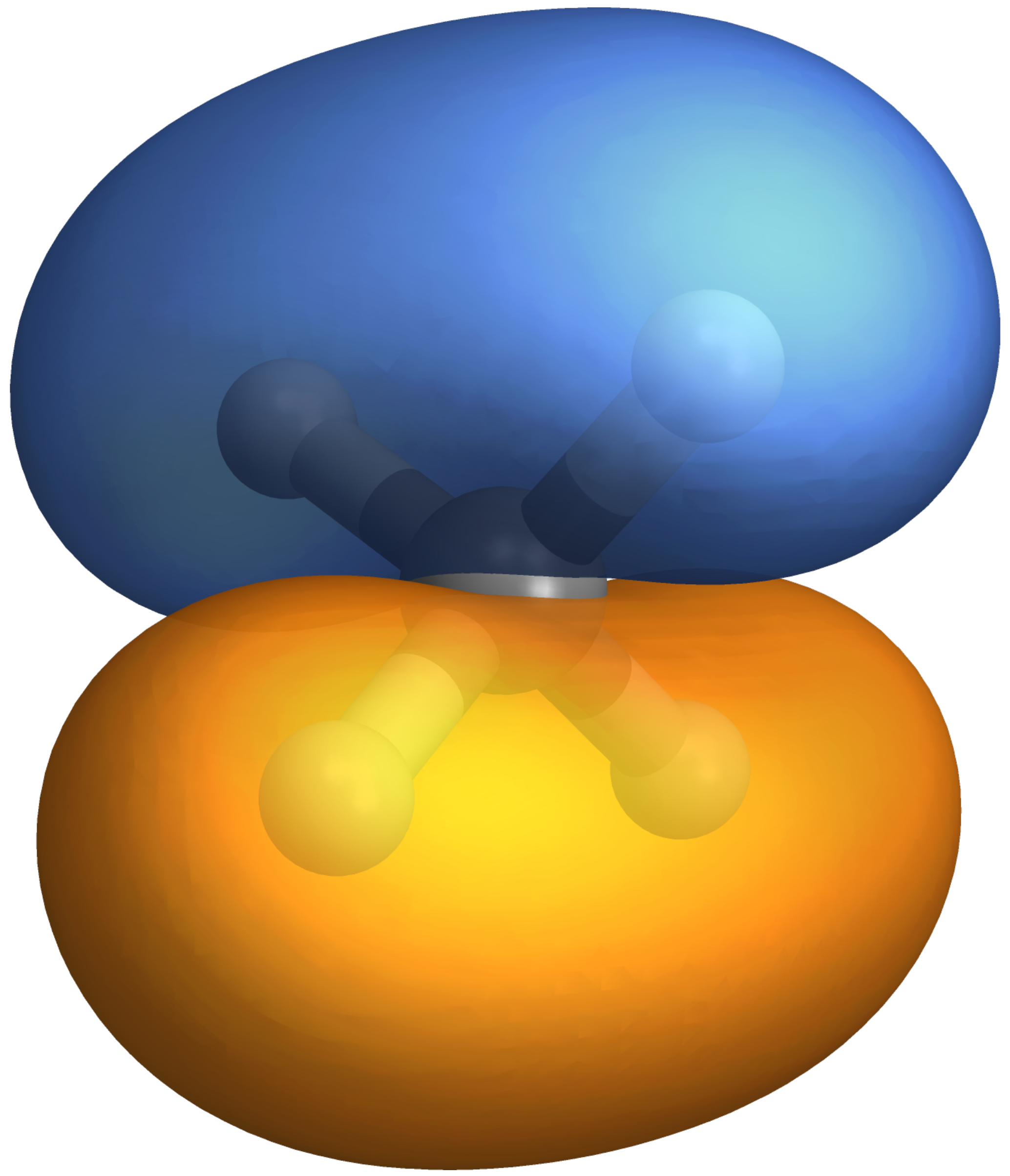
$$H \approx \hat{H} = \sum_{i=1}^{N}\left\{-\frac{1}{2}\nabla_i^2 - \frac{Z}{r_i} + V(r_i)\right\}$$

PySCF advantage: ‘easy’ to model atoms and molecules

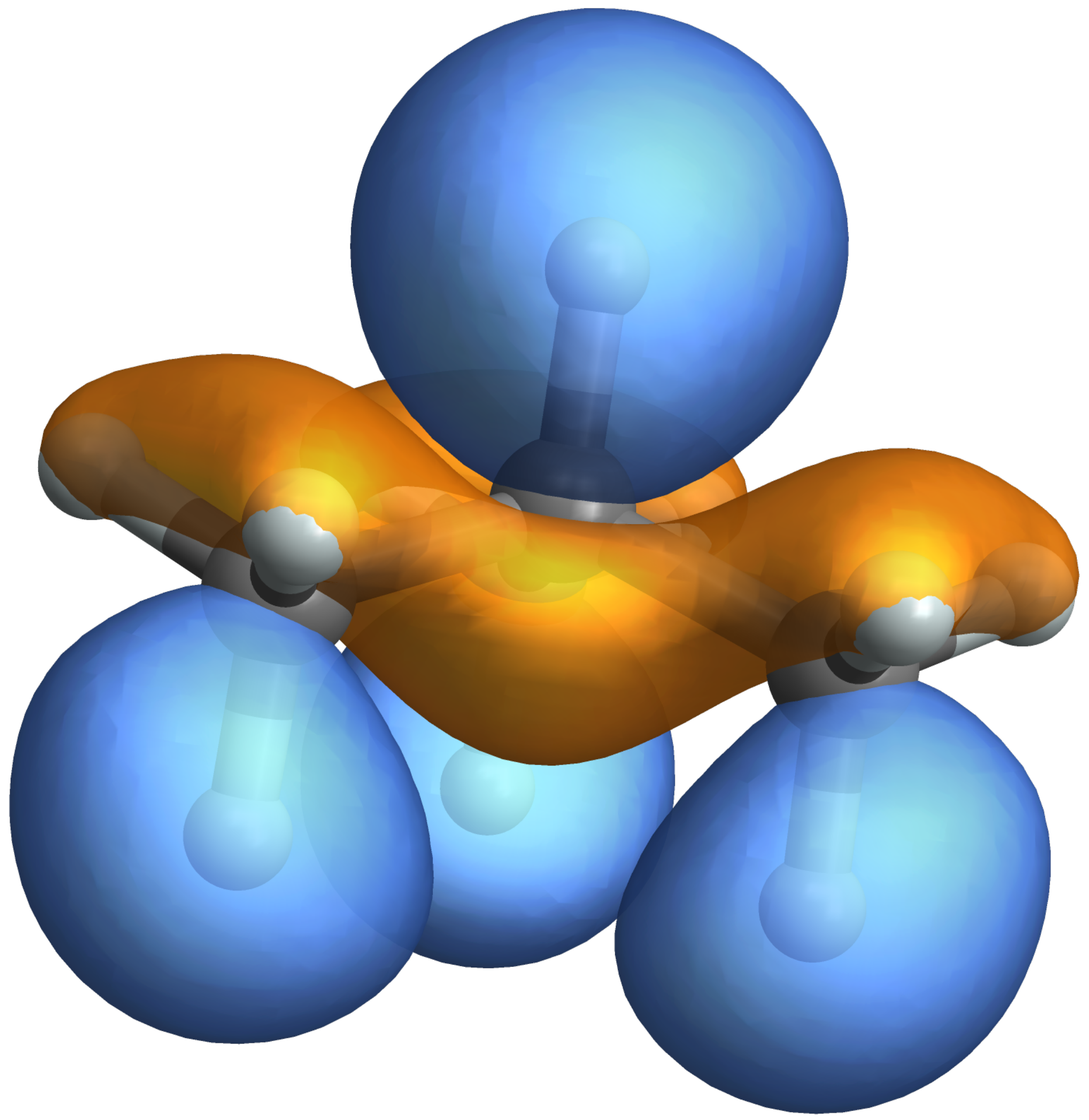
Neon: 2p and Xenon: 5p



Methane: $1t_2$



Isobutane: $6a_1$



Basics of PySCF: Atomic basis functions

The most ‘primitive’ objects are Gaussian Type Orbitals (GTO):

$$R_l^{\mathrm{GTO}}(\alpha, r) \propto r^l \exp(-\alpha r^2)$$

These functions form a basis for our solutions

$$\psi(r,\theta,\phi) = \sum_{i=1}^{N} c_i \, R_l^{\mathrm{GTO}}(\alpha_i, r) Y_{lm}(\theta,\phi)$$

Gaussian functions are used because they simply numerical integrals that are needed

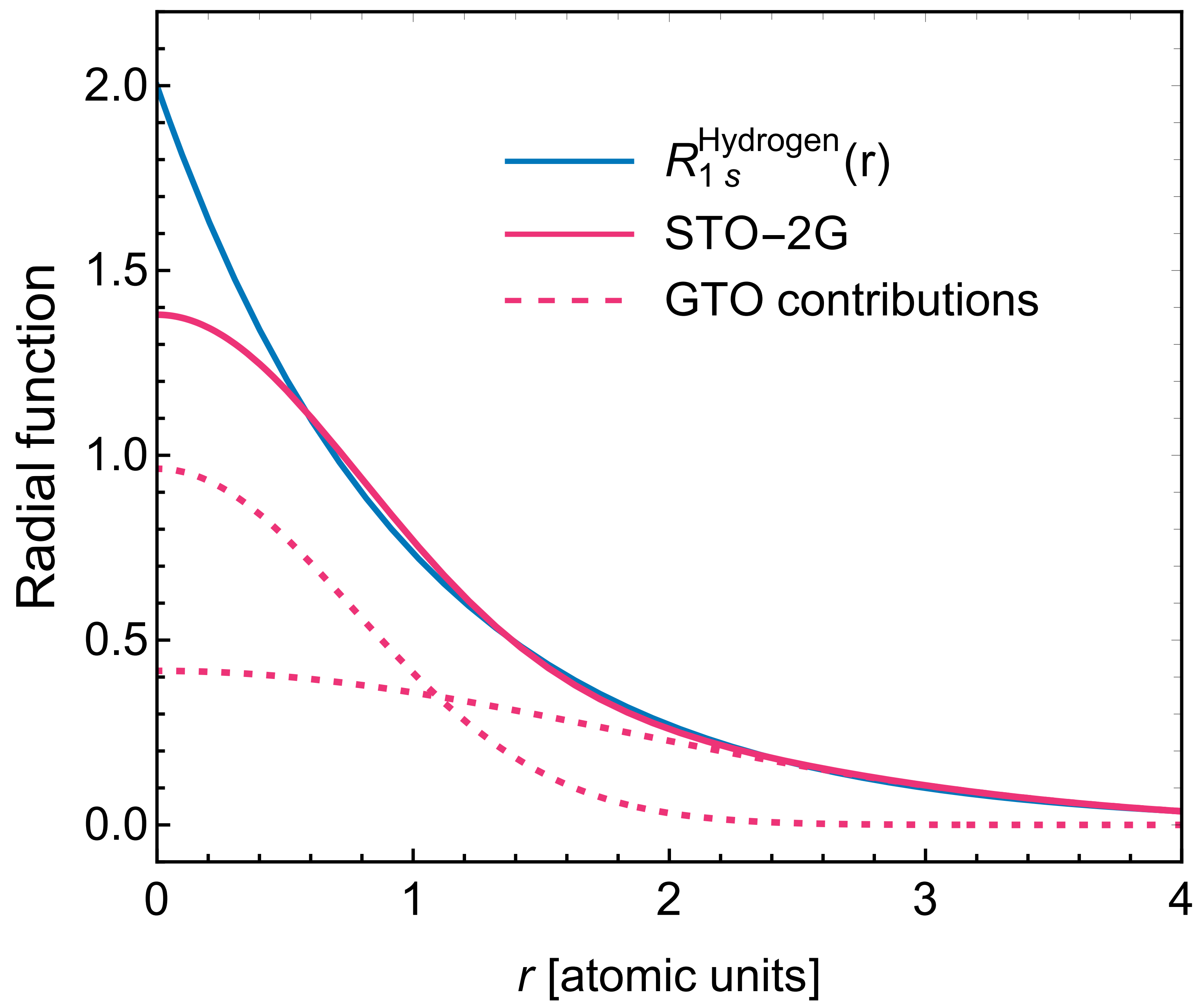
But atomic orbitals aren't Gaussian…

Atomic orbitals generally decay exponentially, not as a Gaussian

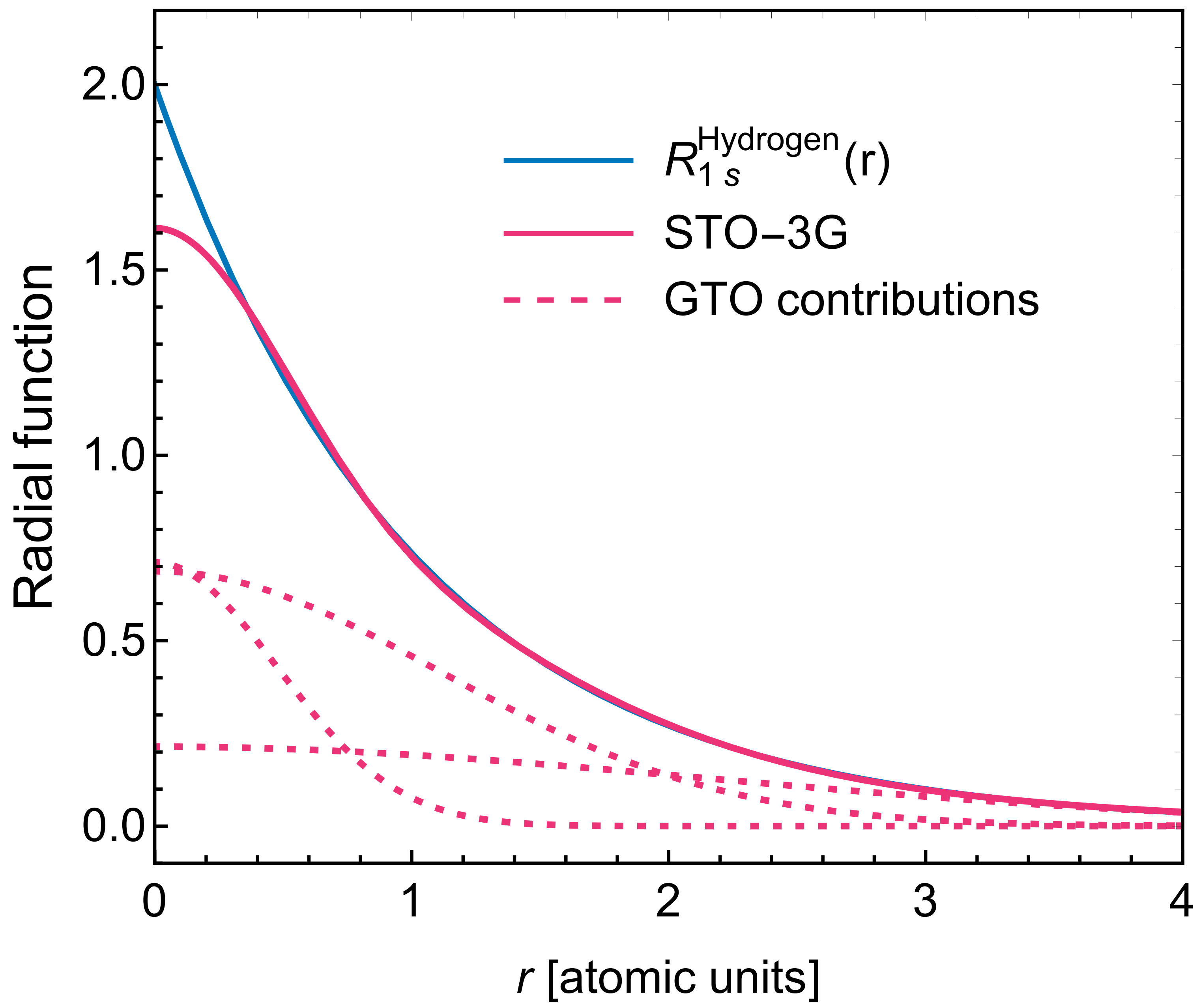
eg: $R_{1s}^{\mathrm{Hydrogen}}(r) = 2\exp(-r)$

(I'll always use atomic units)

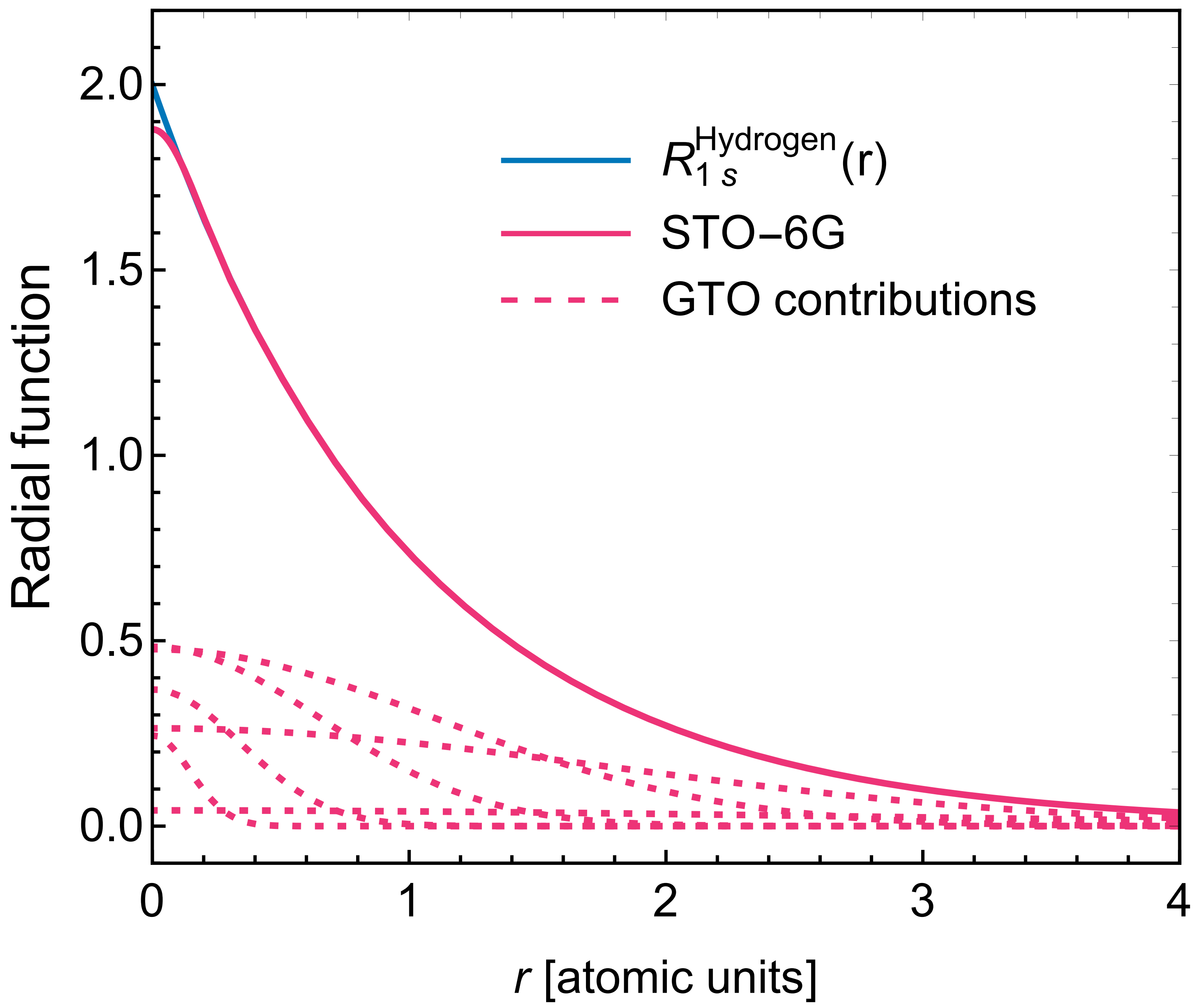
Approx with 2 Gaussians



Approx with 3 Gaussians



Approx with 6 Gaussians



More Gaussians (generally) model the true (exponential) solution more accurately

Orbitals just sums of easy to manipulate functions

```
Iso6a1[x_, y_, z_] := -0.0184365 E^(-0.8 (x^2 + y^2 + (z - 0.68975)^2)) x^2 - 0.007283 E^(-0.8 (x^2 + (y - 2.74539)^2 + (z + 0.186516)^2)) x^2 - 0.0127042 E^(-0.8 ((x - 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) x^2 - 0.0127042 E^(-0.8 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) x^2 +
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  0.0480006 E^(-2.82539 ((x + 2.43302)^2 + (y + 1.40463)^2 + (z + 2.25463)^2)) + 0.0146305 E^(-1.1 ((x + 2.43302)^2 + (y + 1.40463)^2 + (z + 2.25463)^2)) + 0.054647 E^(-0.640122 ((x + 2.43302)^2 + (y + 1.40463)^2 + (z + 2.25463)^2)) + 0.0286763 E^(-0.161278 ((x + 2.43302)^2 + (y + 1.40463)^2 + (z + 2.25463)^2)) -
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  0.000765625 E^(-1.1 ((x + 4.04817)^2 + (y + 0.386449)^2 + (z - 0.533092)^2)) y - 0.00362057 E^(-1.1 ((x - 2.35876)^2 + (y + 3.31269)^2 + (z - 0.533092)^2)) y - 0.00362057 E^(-1.1 ((x + 2.35876)^2 + (y + 3.31269)^2 + (z - 0.533092)^2)) y + 0.0877355 E^(-7.86827 (x^2 + (y - 2.74539)^2 + (z + 0.186516)^2)) y +
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  0.0343236 E^(-1.88129 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) y - 0.0388467 E^(-0.8 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) y - 0.0171299 E^(-0.544249 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) y -
  0.00281769 E^(-0.168714 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) y + 0.00067427 E^(-1.1 (x^2 + (y - 2.80946)^2 + (z + 2.25463)^2)) y - 0.000355169 E^(-1.1 ((x - 2.43302)^2 + (y + 1.40463)^2 + (z + 2.25463)^2)) y - 0.000355169 E^(-1.1 ((x + 2.43302)^2 + (y + 1.40463)^2 + (z + 2.25463)^2)) y -
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  0.169937 E^(-1.88129 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) z + 0.0320284 E^(-0.8 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) z - 0.0848103 E^(-0.544249 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) z -
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  0.0000525557 E^(-0.8 (x^2 + y^2 + (z - 0.68975)^2)) y z - 0.00879031 E^(-0.8 (x^2 + (y - 2.74539)^2 + (z + 0.186516)^2)) y z + 0.0043383 E^(-0.8 ((x - 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) y z + 0.0043383 E^(-0.8 ((x + 2.37765)^2 + (y + 1.3727)^2 + (z + 0.186516)^2)) y z
```
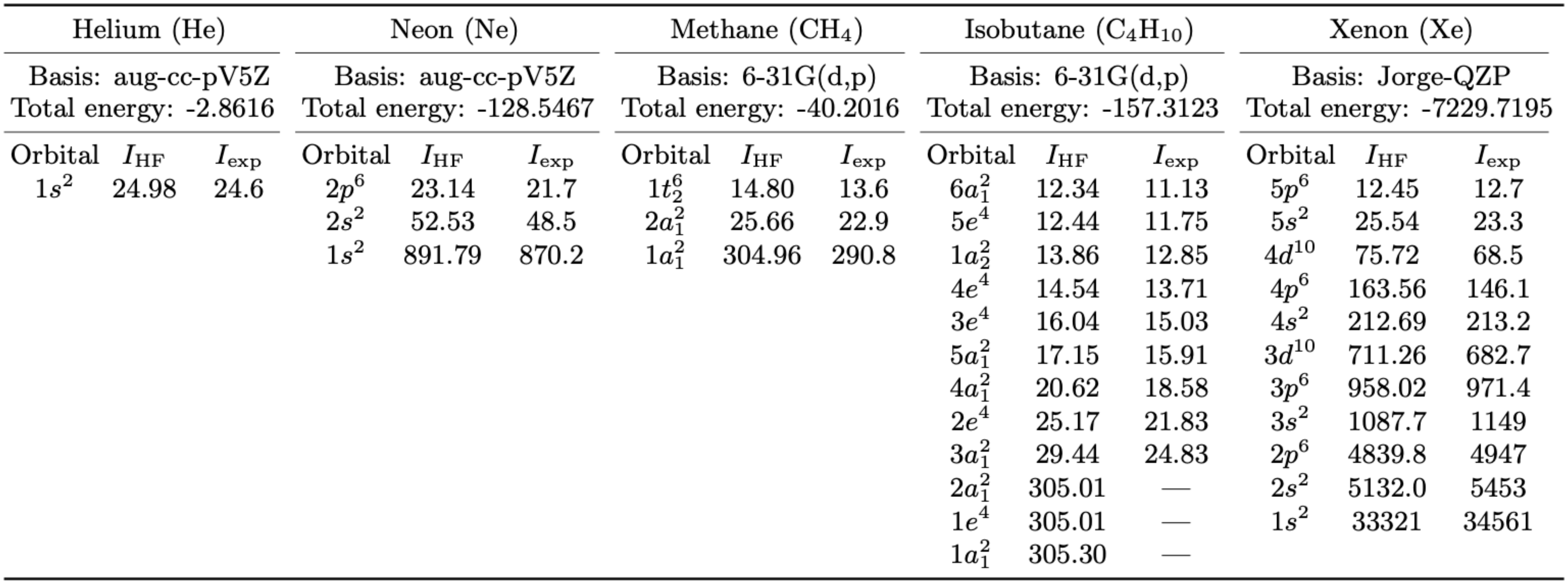

Summary of PySCF output



Helium (He)			Neon (Ne)			Methane (CH_4)			Isobutane (C_4H_{10})			Xenon (Xe)		
Basis: aug-cc-pV5Z Total energy: -2.8616			Basis: aug-cc-pV5Z Total energy: -128.5467			Basis: 6-31G(d,p) Total energy: -40.2016			Basis: 6-31G(d,p) Total energy: -157.3123			Basis: Jorge-QZP Total energy: -7229.7195		
Orbital	I_{HF}	I_{exp}	Orbital	I_{HF}	I_{exp}	Orbital	I_{HF}	I_{exp}	Orbital	I_{HF}	I_{exp}	Orbital	I_{HF}	I_{exp}
$1s^2$	24.98	24.6	$2p^6$	23.14	21.7	$1t_2^6$	14.80	13.6	$6a_1^2$	12.34	11.13	$5p^6$	12.45	12.7
			$2s^2$	52.53	48.5	$2a_1^2$	25.66	22.9	$5e^4$	12.44	11.75	$5s^2$	25.54	23.3
			$1s^2$	891.79	870.2	$1a_1^2$	304.96	290.8	$1a_2^2$	13.86	12.85	$4d^{10}$	75.72	68.5
									$4e^4$	14.54	13.71	$4p^6$	163.56	146.1
									$3e^4$	16.04	15.03	$4s^2$	212.69	213.2
									$5a_1^2$	17.15	15.91	$3d^{10}$	711.26	682.7
									$4a_1^2$	20.62	18.58	$3p^6$	958.02	971.4
									$2e^4$	25.17	21.83	$3s^2$	1087.7	1149
									$3a_1^2$	29.44	24.83	$2p^6$	4839.8	4947
									$2a_1^2$	305.01	—	$2s^2$	5132.0	5453
									$1e^4$	305.01	—	$1s^2$	33321	34561
									$1a_1^2$	305.30	—			

Methane and isobutane benefit from lower ionisation energies (compared to nobles)

Unbound states: 'straightforward' for atoms

Solve the radial Schroedinger equation:

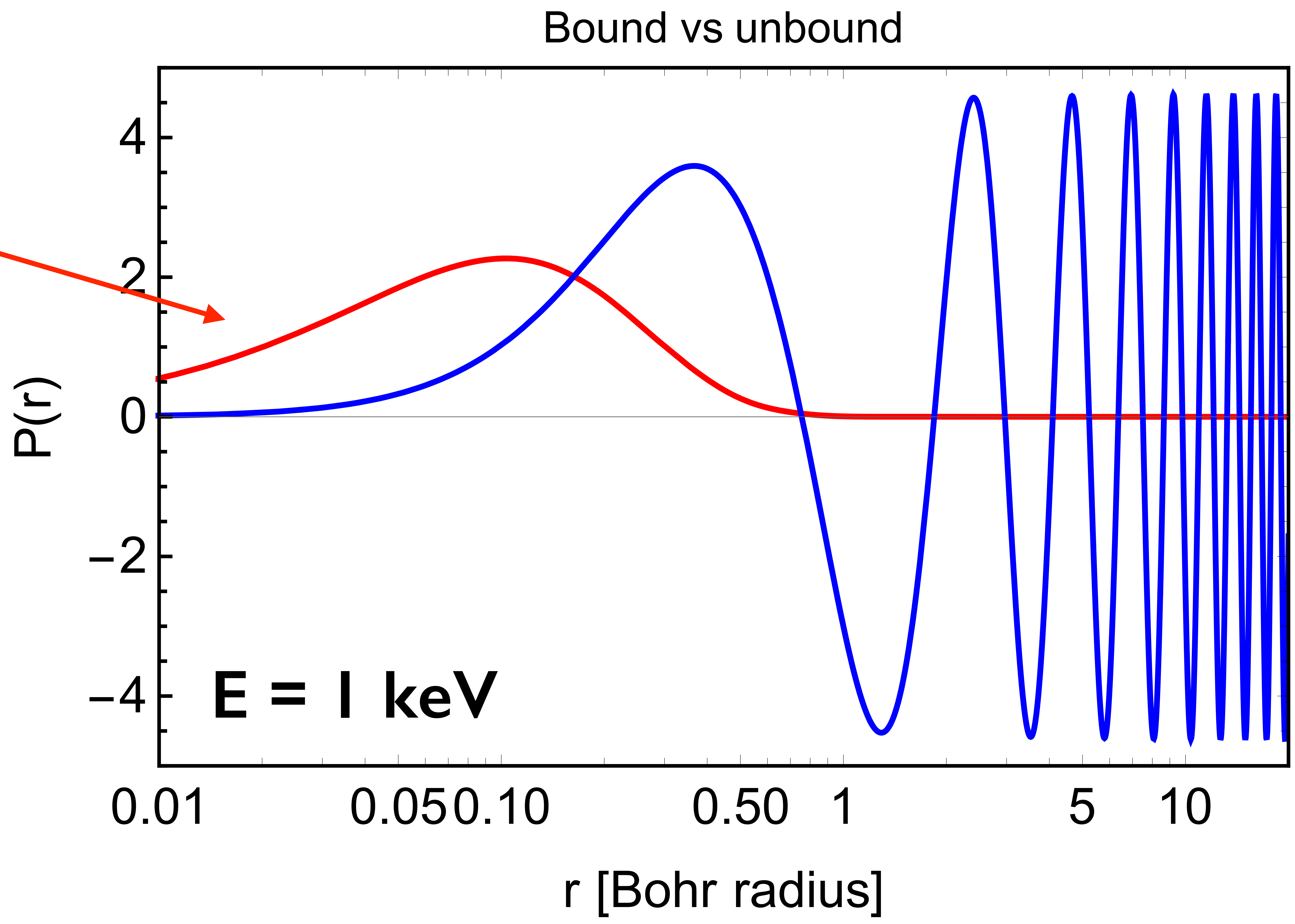
$$\left[-\frac{1}{2}\frac{d^2}{dr^2}+\frac{l_e(l_e+1)}{2r^2}+V_{nl\to k_e l_e}(r)\right]P_{nl\to k_e l_e}(r)$$
$$=E_e P_{nl\to k_e l_e}(r)+\sum_{n'l'}\delta_{l_e l'}\lambda_{k_e n'}P_{n'l'}(r)$$

Construct the potential from our bound states using Cowan's HX method to model the exchange potential

$$V_{nl\to k_e l_e}(r)=-\frac{Z}{r}+V^{\mathrm{H}}_{nl\to k_e l_e}(r)+V^{\mathrm{HX}}_{nl\to k_e l_e}(r)$$

$$V^{\mathrm{H}}_{nl\to k_e l_e}(r)=\sum_{n'l'}(w_{n'l'}-\delta_{nl,n'l'})\int_0^\infty\frac{dr'}{r_>}P^2_{n'l'}(r') \qquad V^{\mathrm{HX}}_{nl\to k_e l_e}(r)=-\frac{k_x}{2}\left(\frac{24\rho'(r)}{\pi}\right)^{1/3}$$

Example: Unbound state for Neon



$P_{1s}(r)$
Bound state

$P(l'=1)(r)$
Unbound state

Unbound states: hard for molecules!

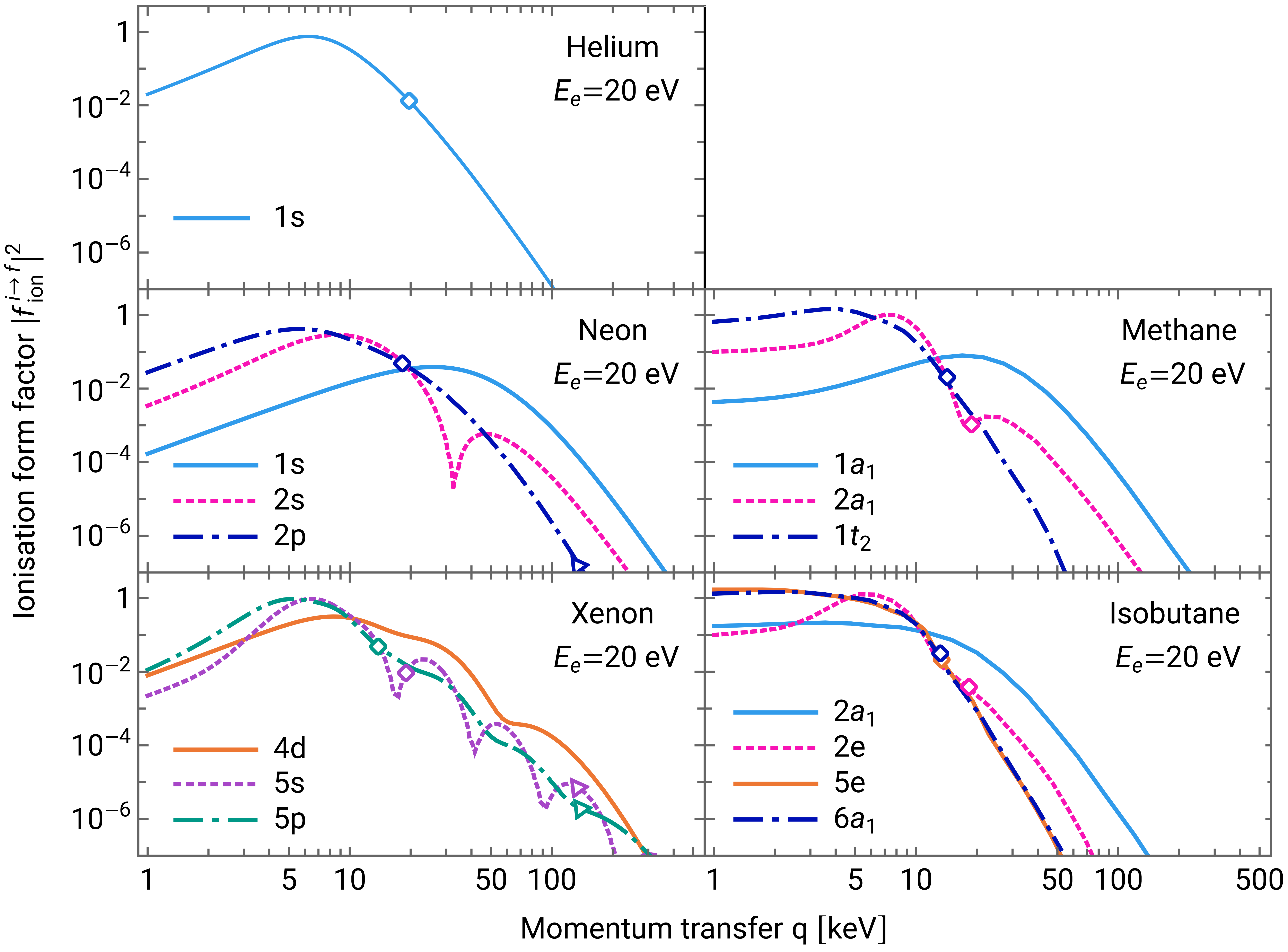
No exact spherical symmetry! But… model potential with spherical term (assume rotational averaging in gas)

$$\left[-\frac{1}{2}\frac{d^2}{dr^2}+\frac{l(l+1)}{2r^2}-\frac{Z_{\text{eff}}}{r}\right]P_{kl}(r)=EP_{kl}(r)$$

Solutions are (analytic) Coulomb functions

$$P_{kl}(r)=\frac{4\pi}{2k}\frac{\left|\Gamma\left(\ell+1-\frac{iZ_{\text{eff}}}{k}\right)\right|e^{\frac{\pi Z_{\text{eff}}}{2k}}}{(2\ell+1)!}(2kr)^{\ell+1}\times e^{-ikr}\,M\left(\ell+1+\frac{iZ_{\text{eff}}}{k},2\ell+2;2ikr\right)$$

Form factor results

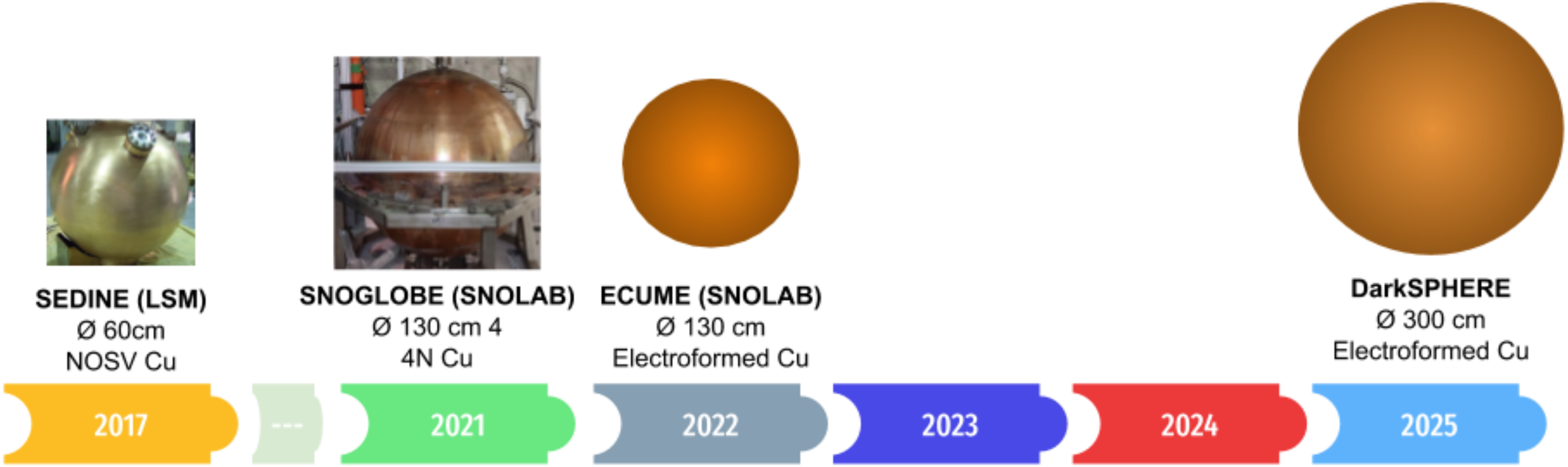


- Outer-shells similar for atoms
- Neon & methane shapes similar

Sensitivity projections

Reminder: towards DarkSPHERE

I will show projections for DarkSPHERE: the 'ultimate' detector of this type



SEDINE (LSM)
Ø 60cm
NOSV Cu

SNOGLOBE (SNOLAB)
Ø 130 cm 4
4N Cu

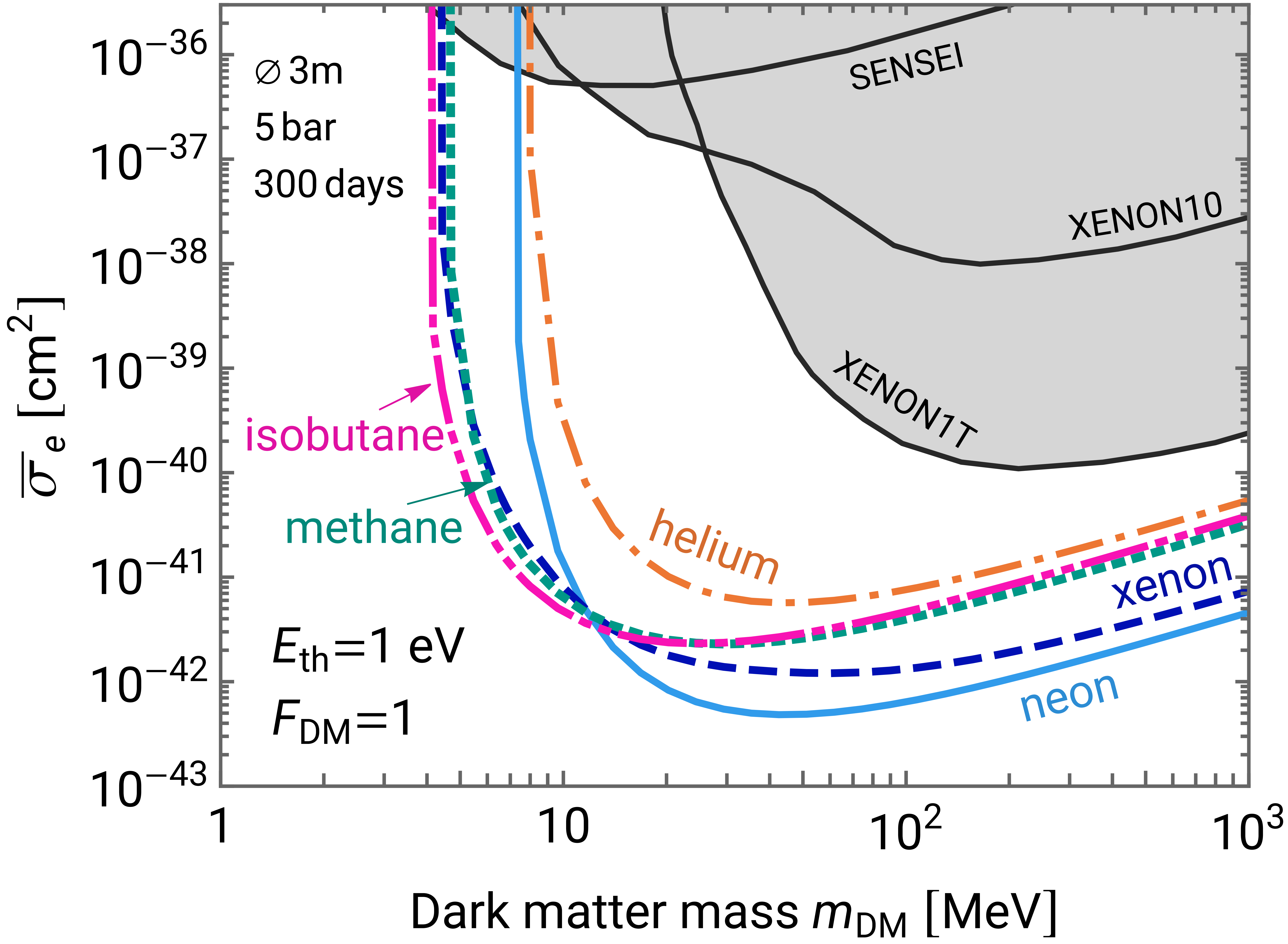
ECUME (SNOLAB)
Ø 130 cm
Electroformed Cu

DarkSPHERE
Ø 300 cm
Electroformed Cu

in the UK?

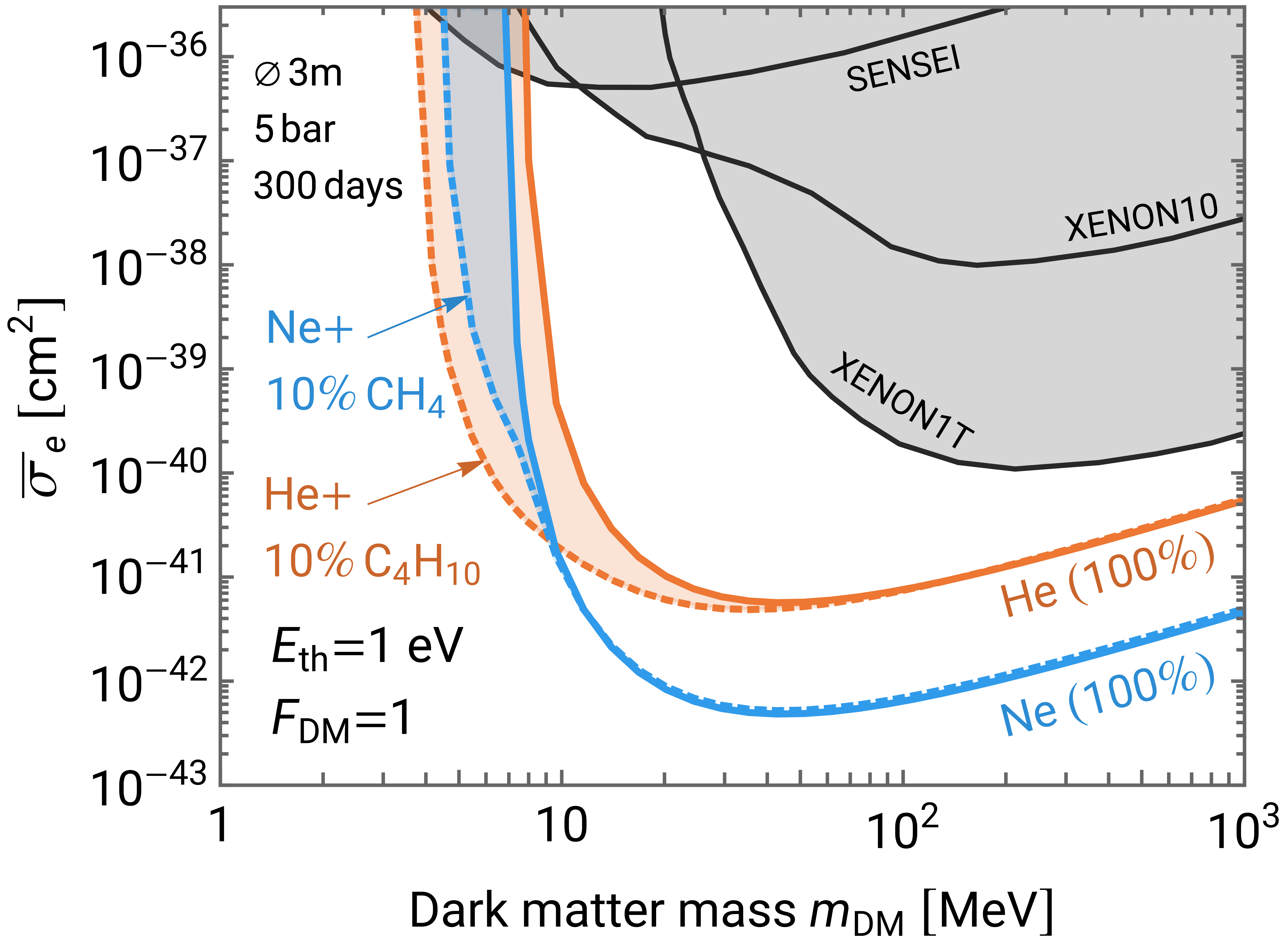
Scattering rates: pure gases

DarkSphere projected sensitivity with all five gases is significantly below current limits



Scattering rates: mixed gases

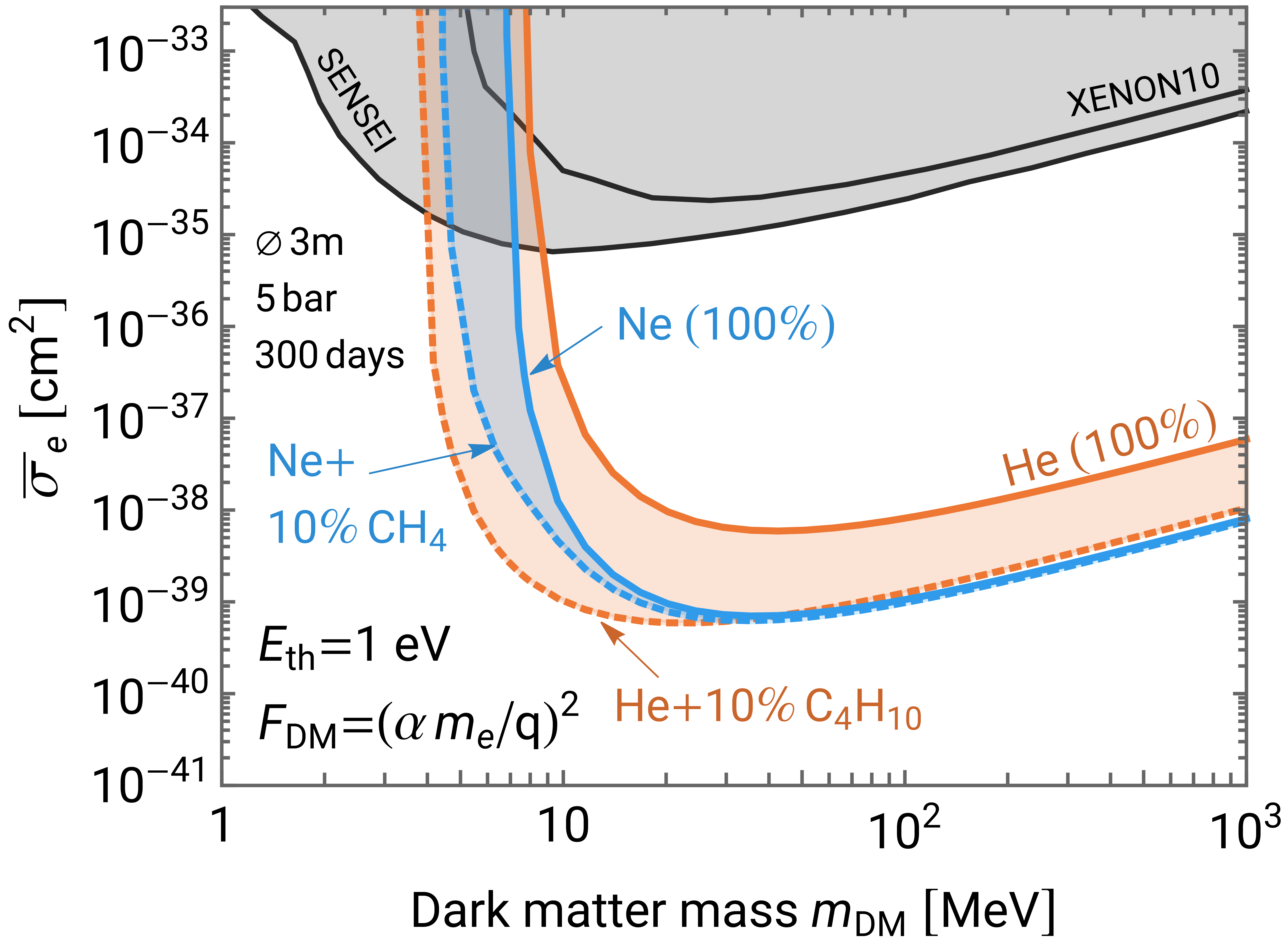
Adding molecular gases to helium or neon can improve sensitivity



Scattering rates: mixed gases

Adding molecular gases to helium or neon can improve sensitivity

…and can lead to dramatic improvements for 'light-mediator' theories



Conclusions

NEWS-G uses gas-based spherical proportional counters to hunt for dark matter

- *detectors will double in size while reducing backgrounds by factor ~100*

Until now, they only considered dark matter - nucleon interactions

- *we investigated the prospects for dark matter - electron interactions for atomic and molecular gas targets*

Calculated atomic and molecular wave functions using quantum chemistry tools

Prospects for constraining dark matter - electron interactions are excellent

- *molecular gases can improve sensitivity over noble gases alone*

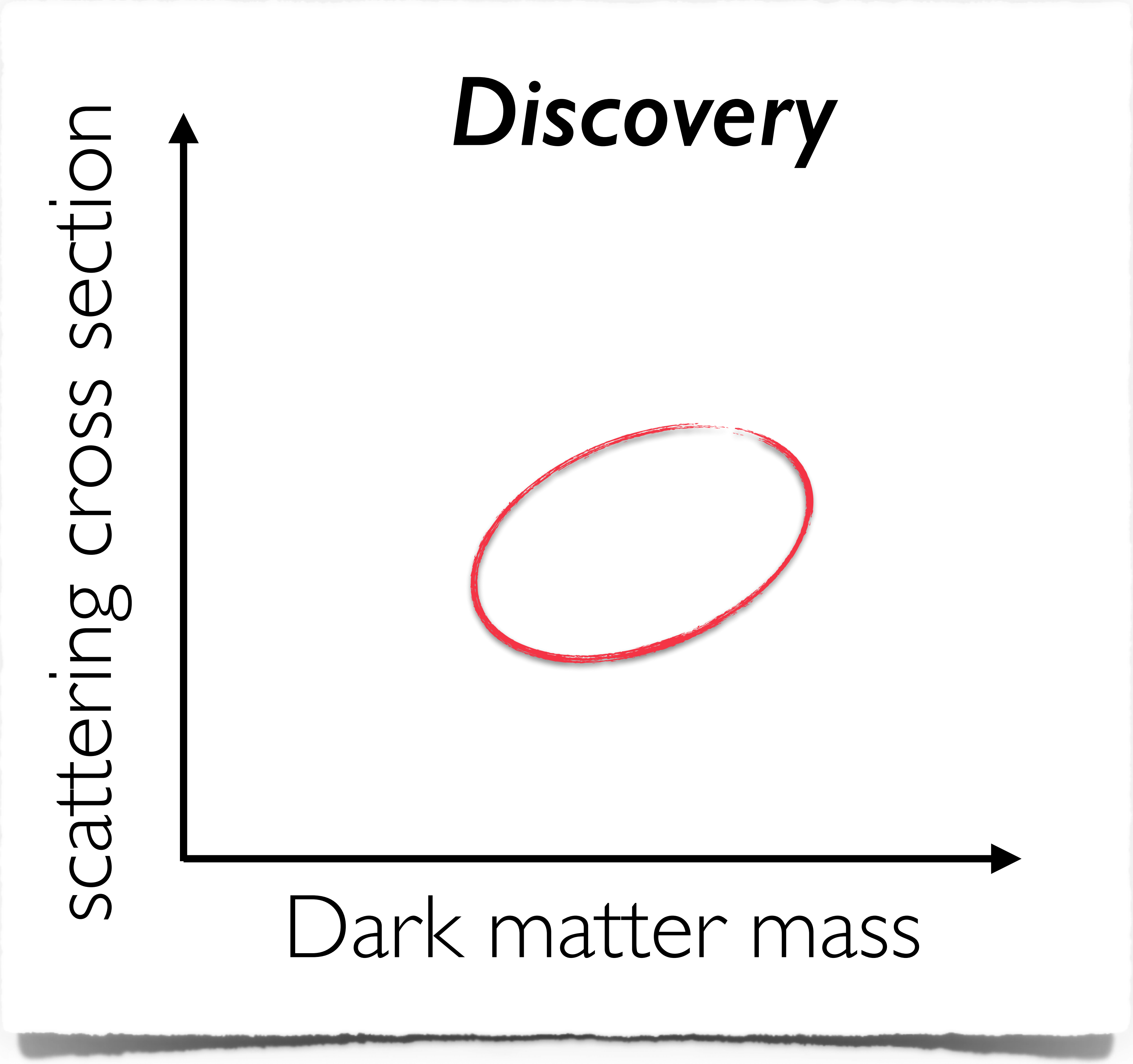
Backup

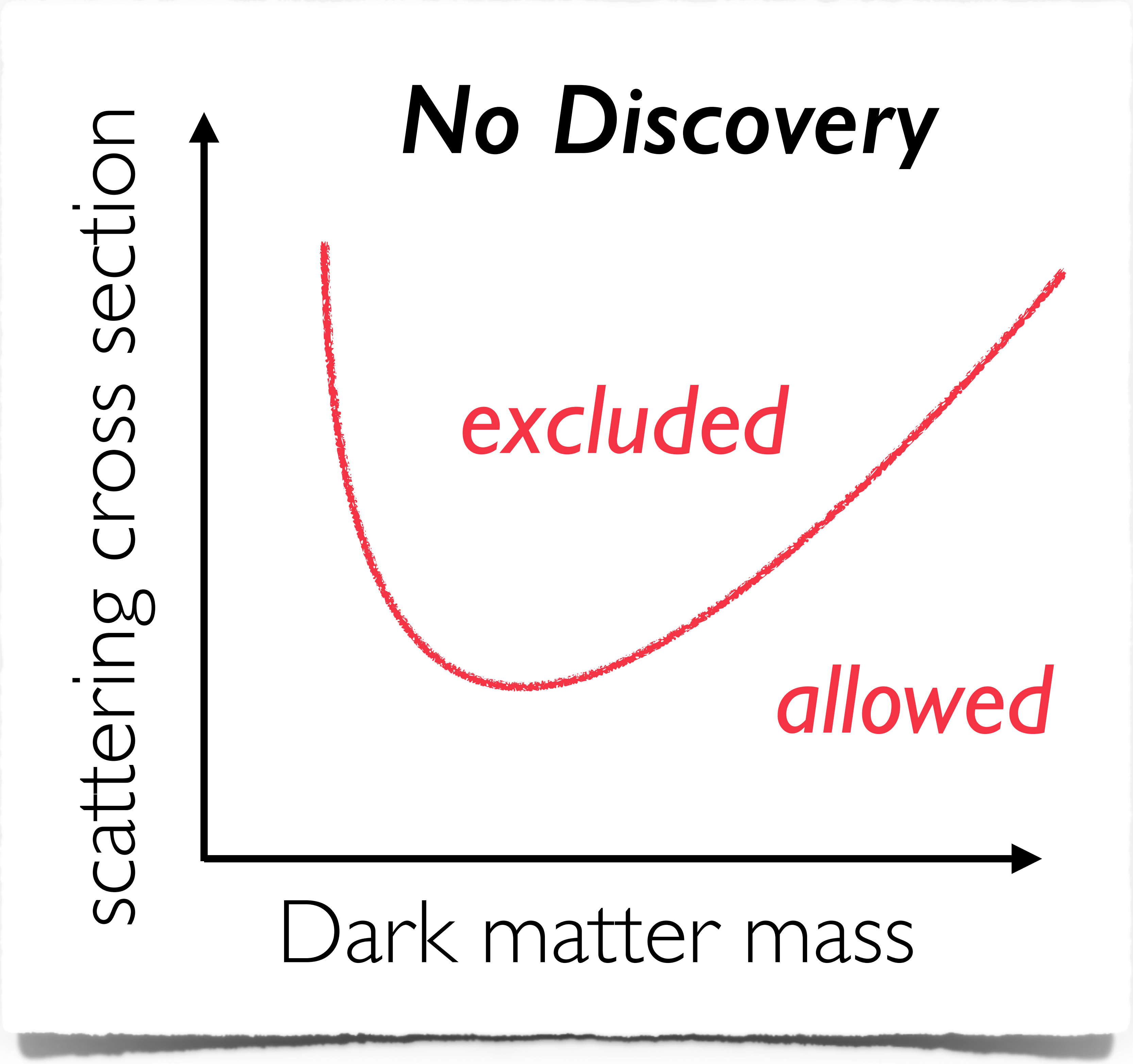
Generic direct detection result plot

Measurement/constraints on

1. Dark matter mass

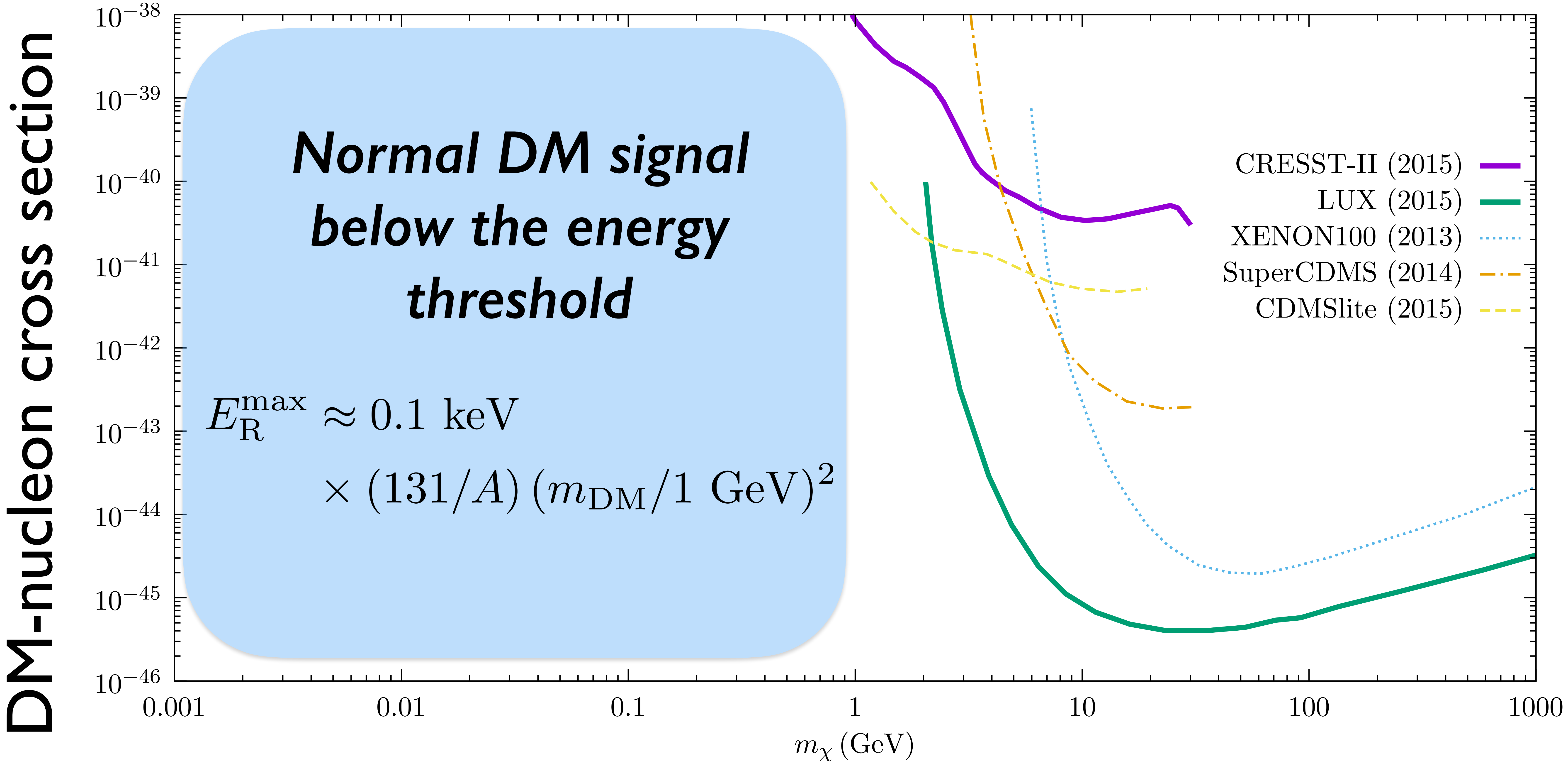
2. Scattering cross section (with nucleons, electrons, …)





Classic search: ‘nucleon scattering’

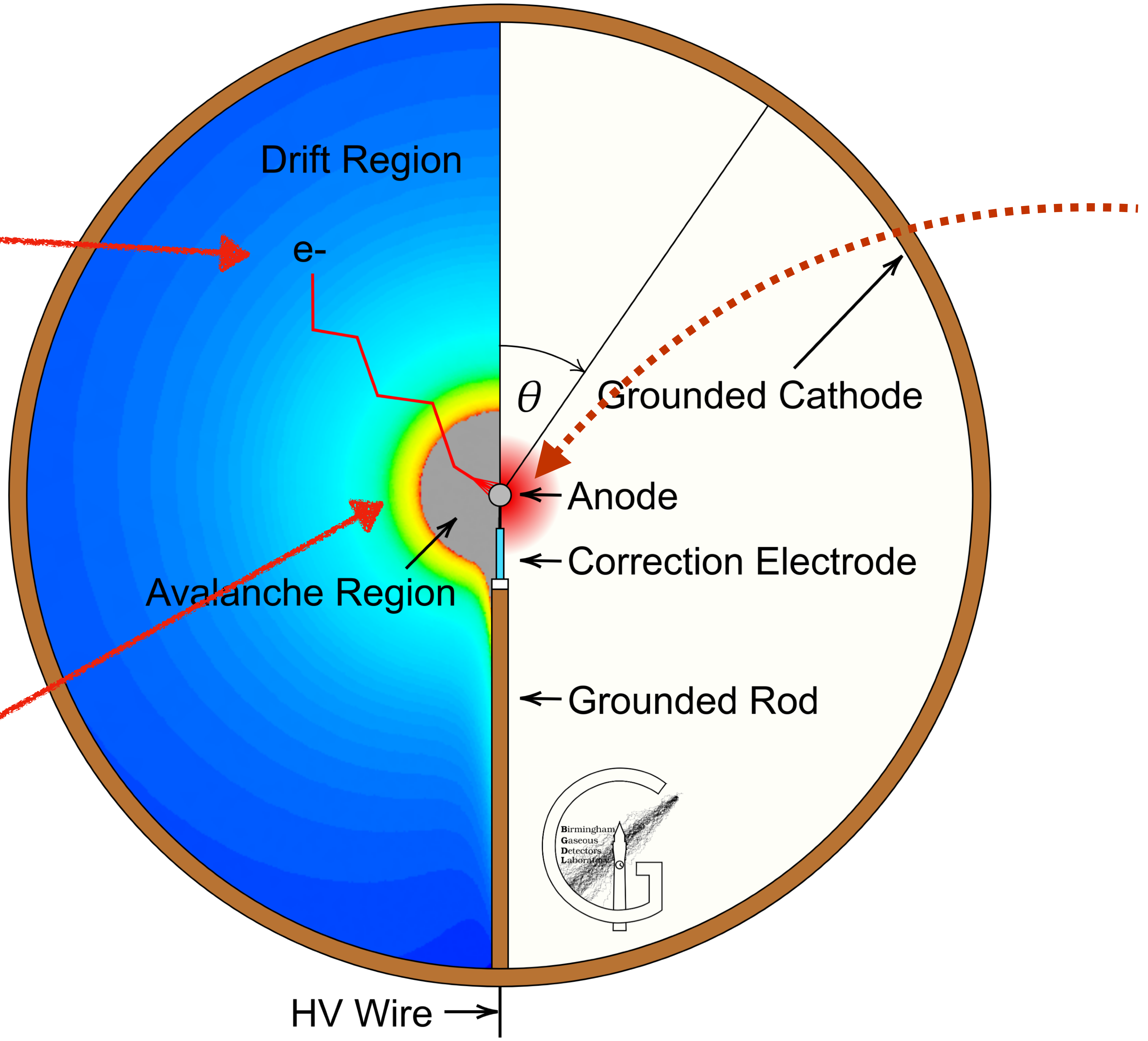
Detecting sub-GeV dark matter is hard — with nucleon scattering!



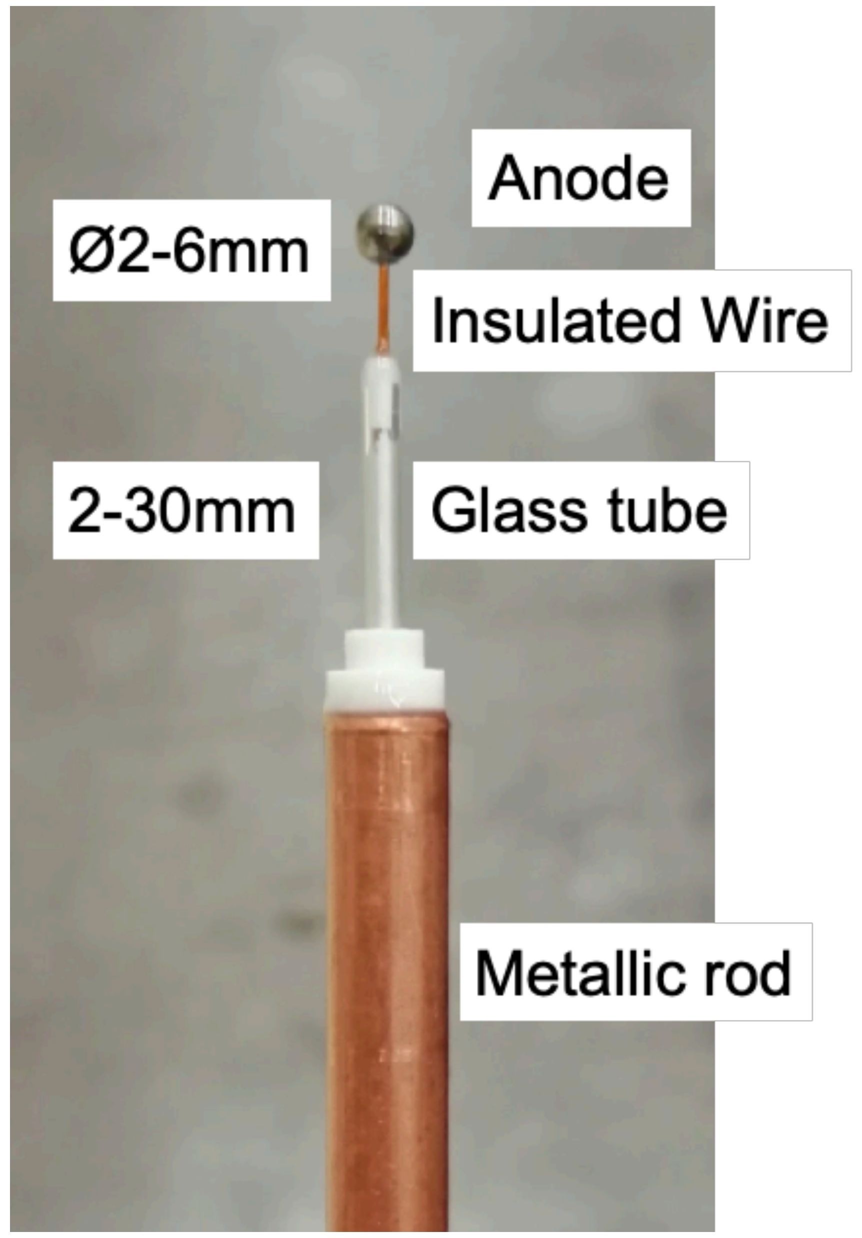
Kinematics more favourable for electron scattering: opens the window to lower DM masses

NEWS-G SPC: an alternative view

(dark matter) induces an electron through scattering



e$^-$ drifts to the anode and is detected



Scattering rates