Identifying dark matter

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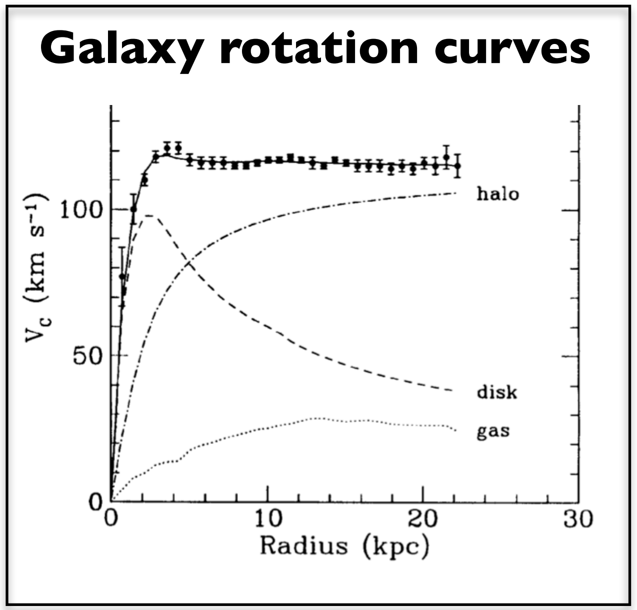
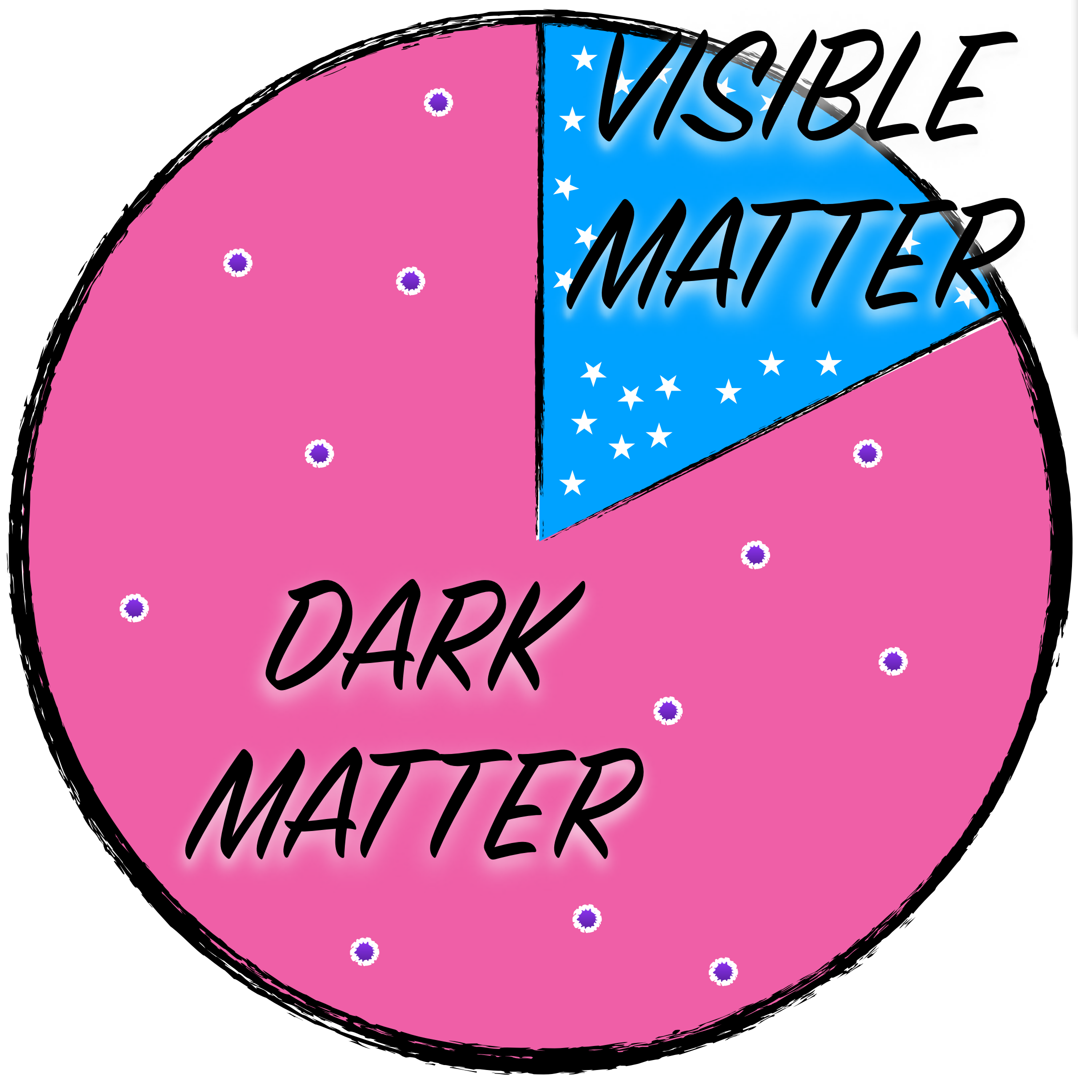
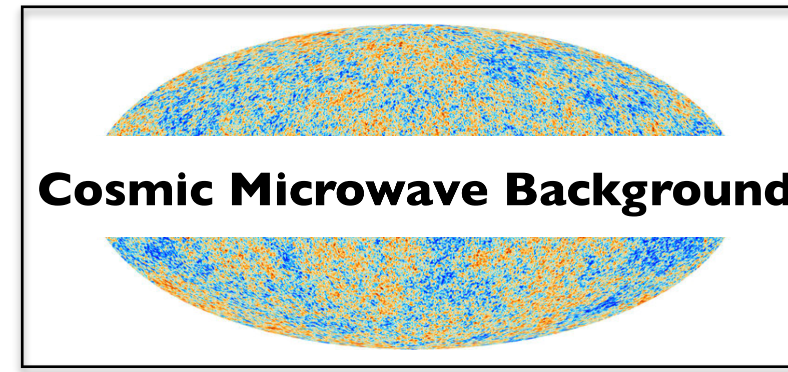
STFC Introductory Course for new Astronomy Research Students - 16th January 2021

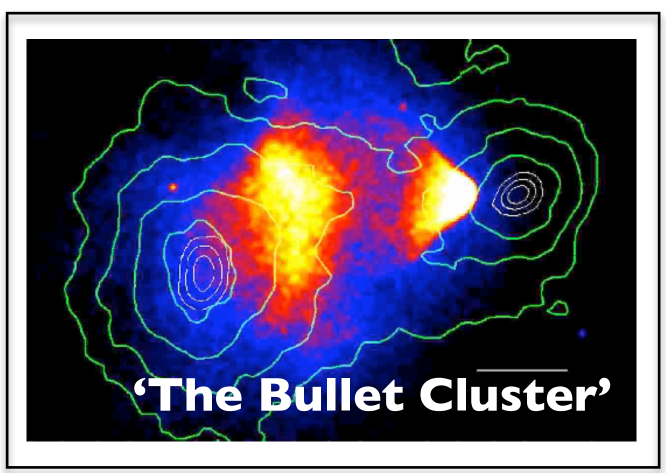
Preamble

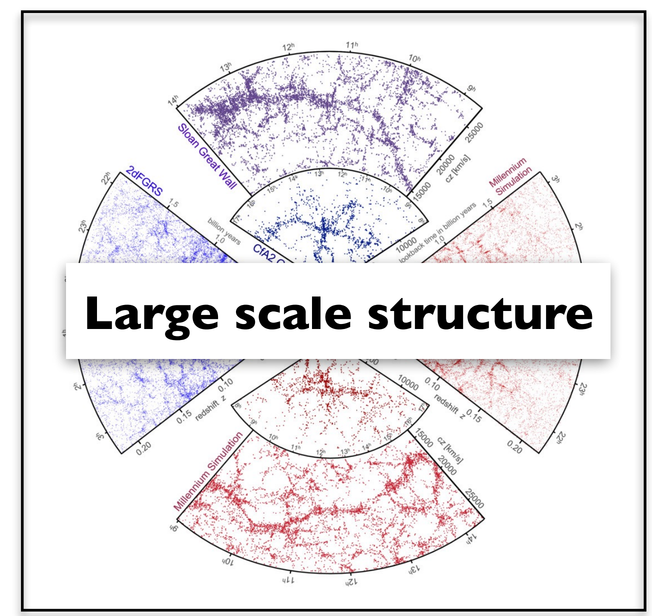
We have detected dark matter







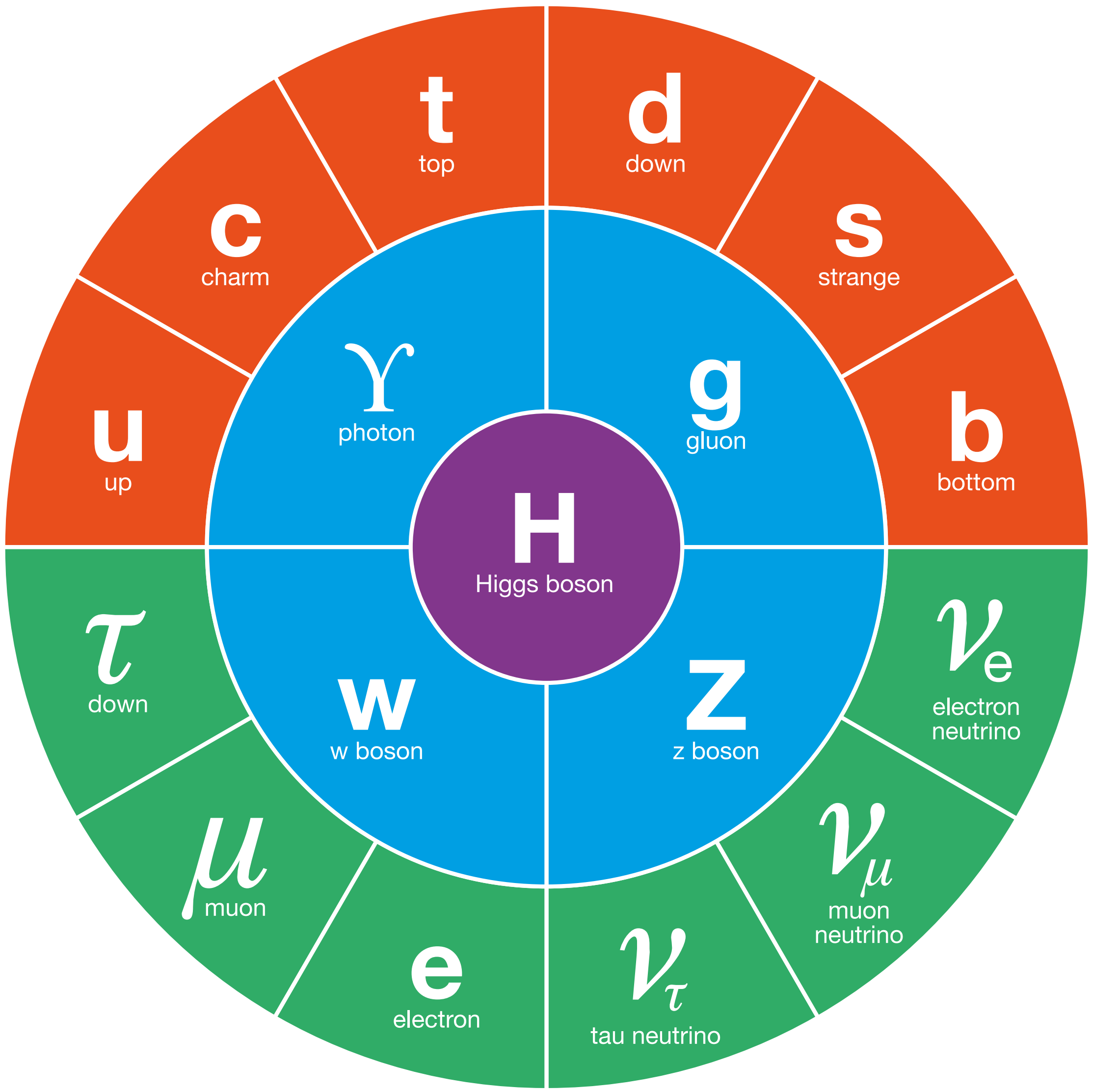




Evidence from gravitational interactions…

…over many distance scales

The challenge is to identify its properties



Dark Matter Particle (X^0)

X^0 mass: $m = ?$
X^0 spin: $J = ?$
X^0 parity: $P = ?$
X^0 lifetime: $\tau = ?$
X^0 scattering cross-section on nucleons: $?$
X^0 production cross-section in hadron colliders: $?$
X^0 self-annihilation cross-section: $?$

$\vdots$

In principle, straightforward…?

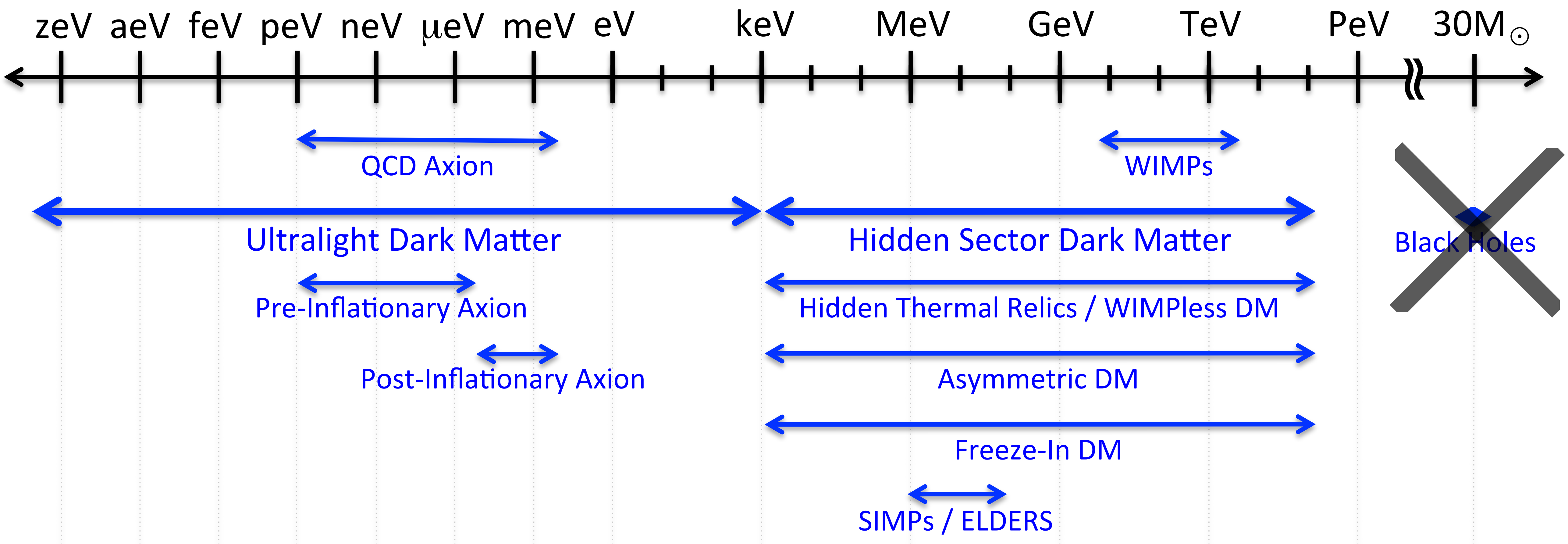
experimental signal

signal model

dark matter properties

Particle Physics Models

A wide landscape

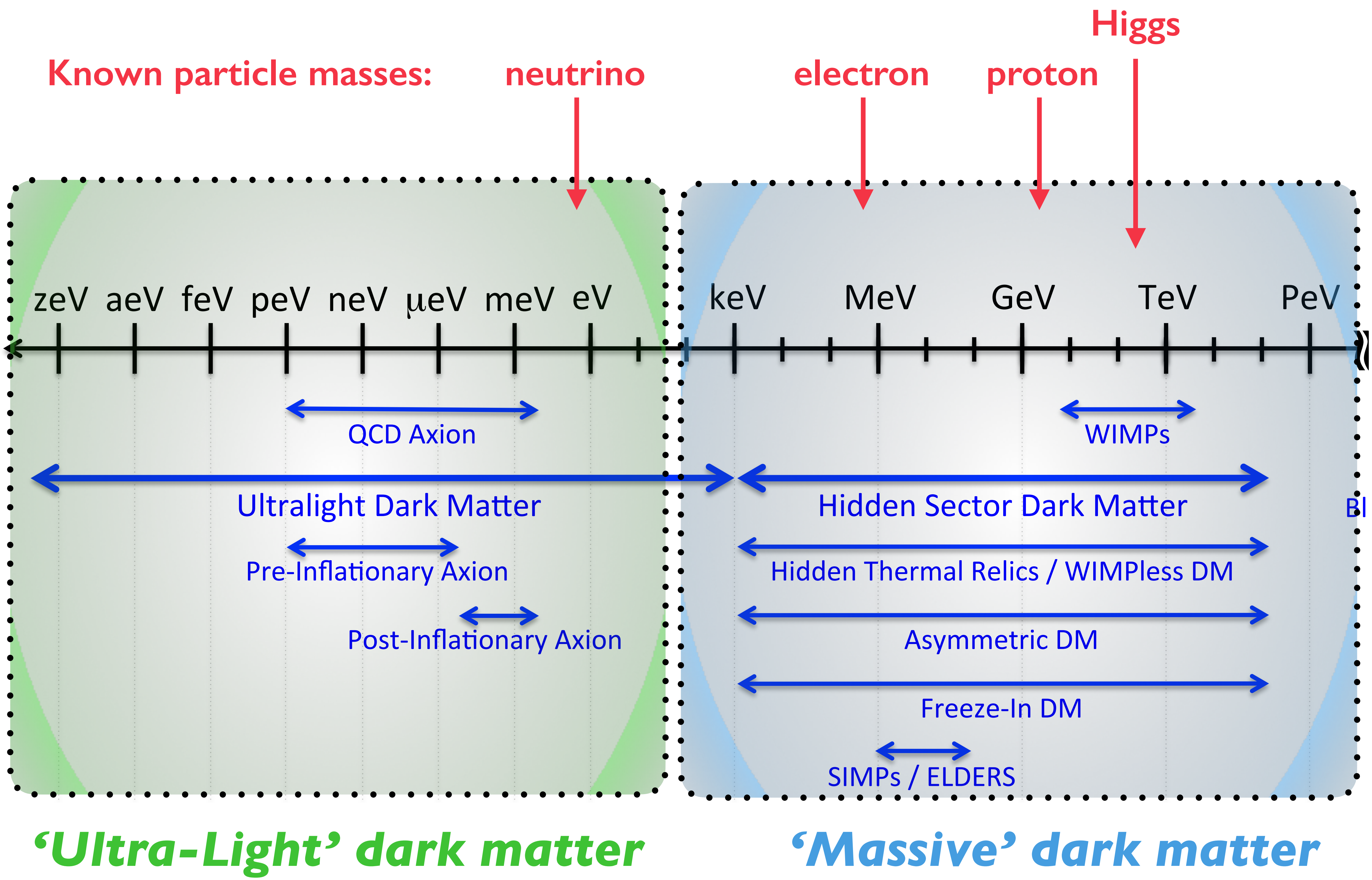


US Cosmic Visions

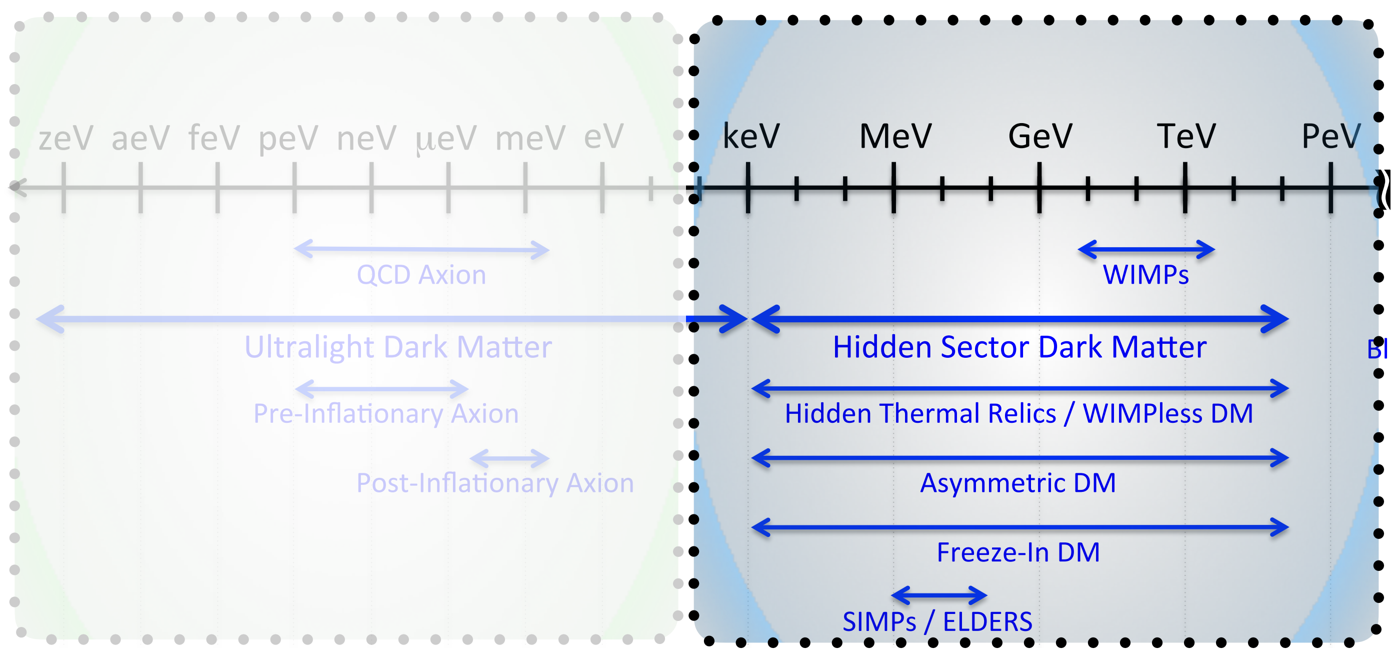
Many candidates…

…all with SM interactions

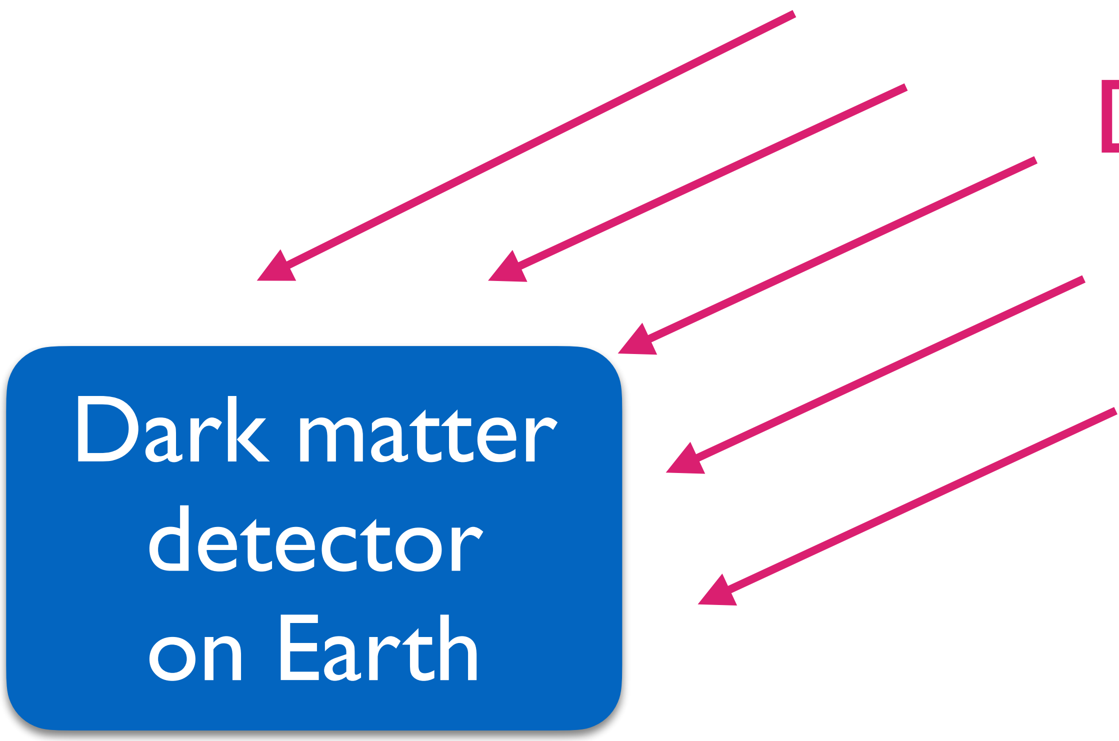
Broadly two separate categories



Searching for ‘massive’ DM candidates: *‘Direct detection experiments’*



Generic direct detection experiment



Dark matter flux

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

Event rate = DM flux $\times$ *particle physics*

Model the DM flux to extract the particle physics

Approaches to modelling the DM flux

Standard Halo Model: DM speeds

Simple spherical model with flat rotation curve

$$f(\mathbf{v}) = \frac{1}{N v_0^3} \, e^{-\mathbf{v}^2/v_0^2} \quad : |\mathbf{v}| < v_{\rm esc}$$

Assumptions:

- *Round halo*
- *Gaussian (Maxwellian)*
- *Isotropic*
- *No substructure*

Standard Halo Model: DM speeds

Simple spherical model with flat rotation curve

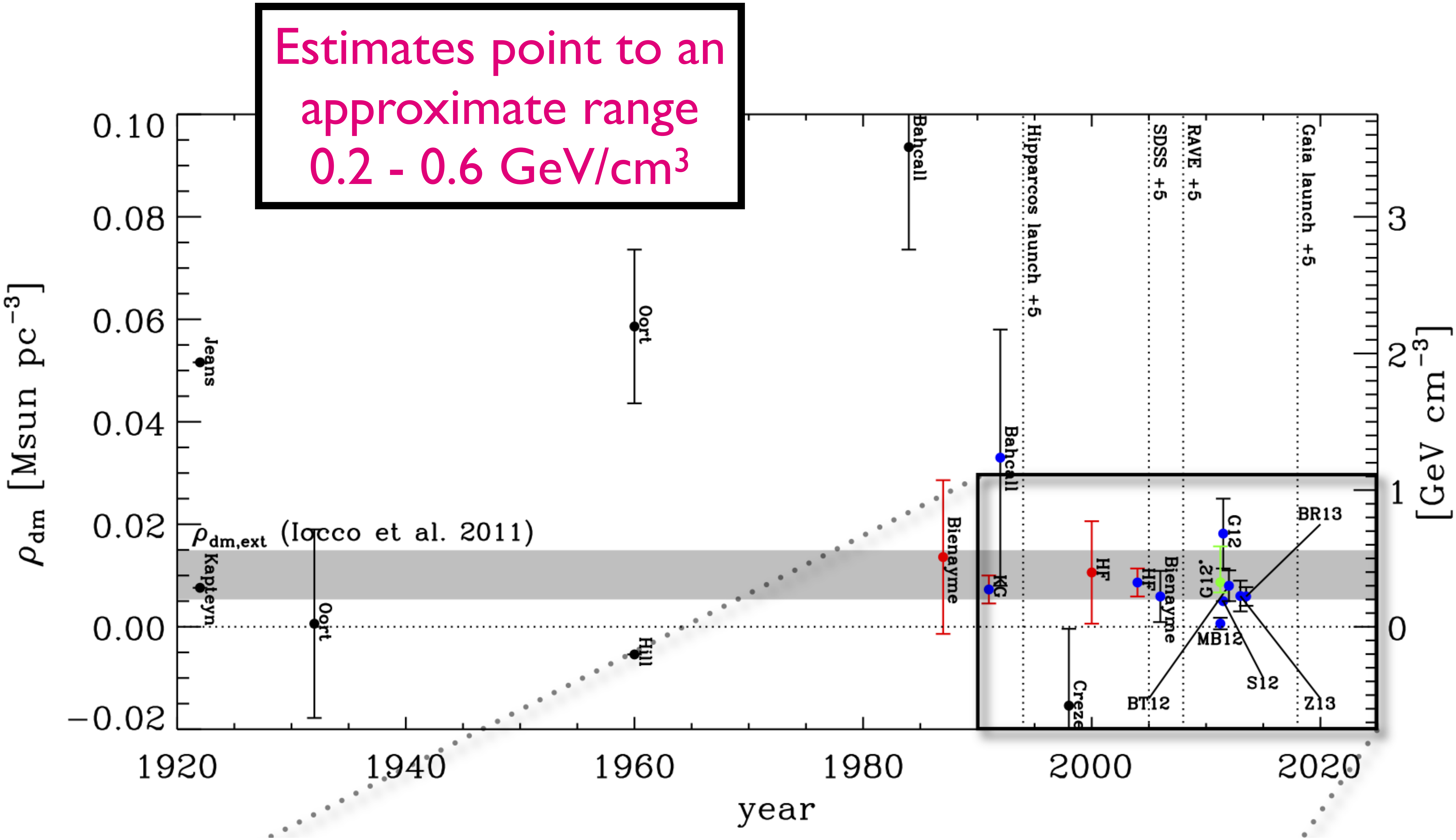
$$f(\mathbf{v}) = \frac{1}{N v_0^3} e^{-\mathbf{v}^2/v_0^2} \quad : |\mathbf{v}| < v_{\rm esc}$$

Advantages:

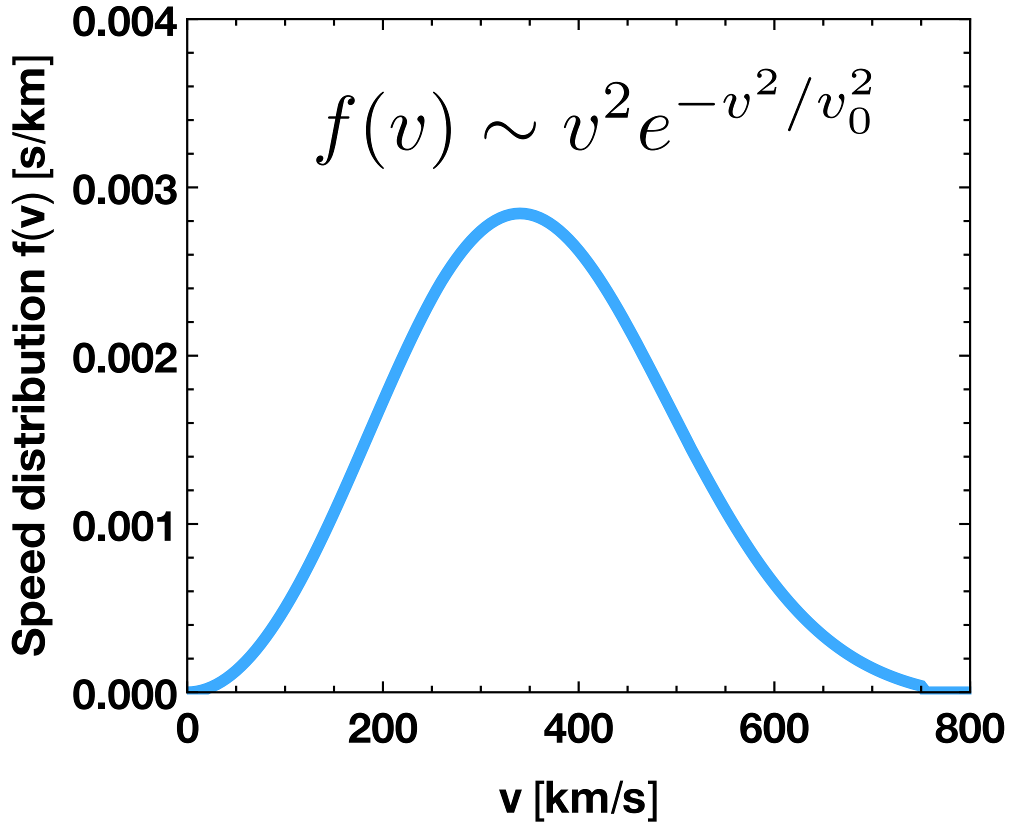
- *Simple*
- *Only 2 parameters*
- *Accurate (?)*

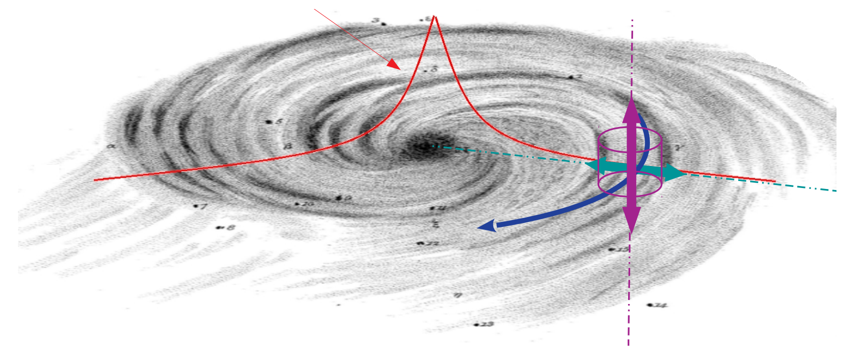
Standard Halo Model: Local DM density

Excellent resource is the review by Justin Read (arXiv:1404.1938)



We have the ingredients to find the flux

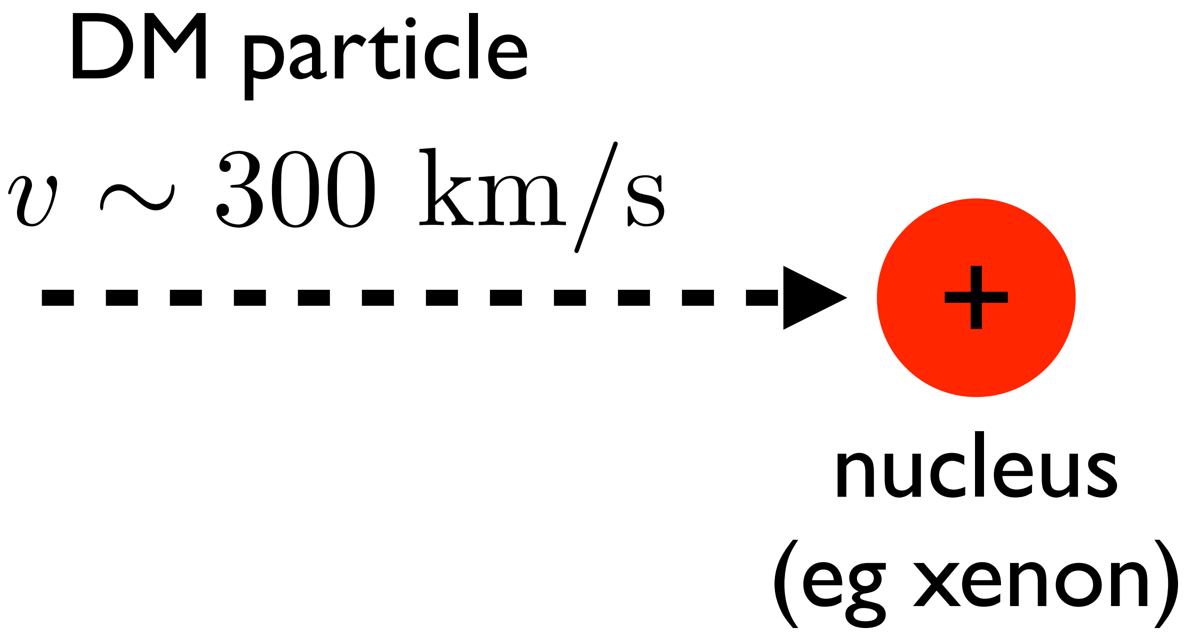




$$\rho_{\mathrm{DM}}(\text{@Sun}) \sim 0.3\ \mathrm{GeV/cm^3}$$

$$\phi_{\mathrm{thumb}} \sim 10^7 \left(\frac{m_{\mathrm{proton}}}{m_{\mathrm{DM}}}\right)\ \text{particles/s}$$

Basics of direct detection experiments



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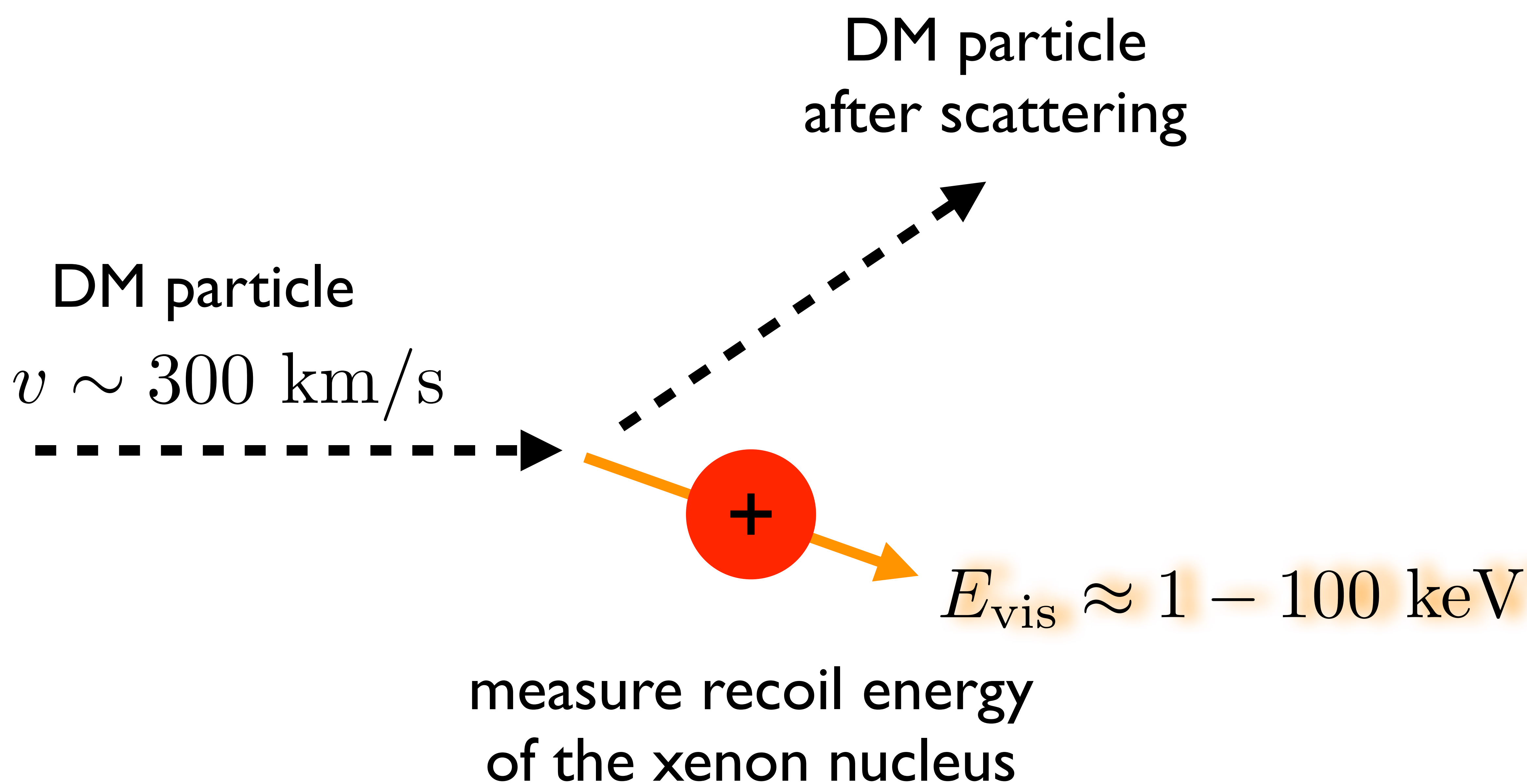

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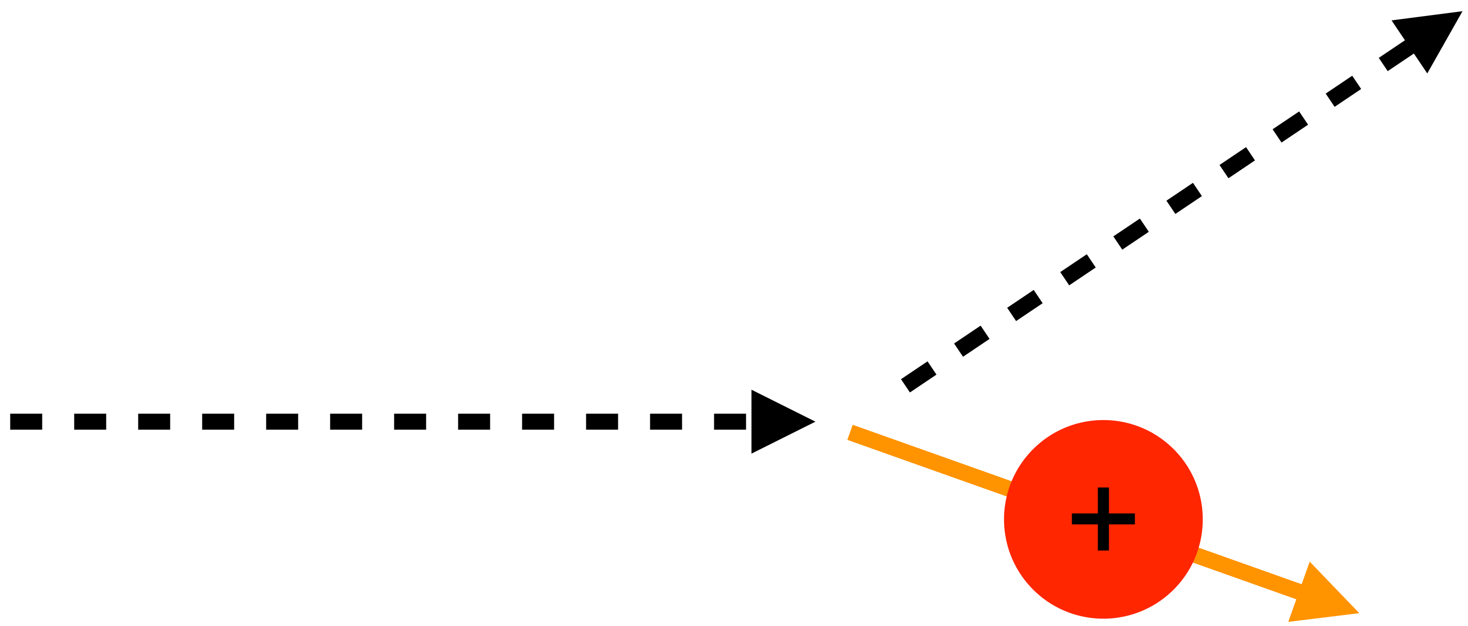


Experimental wish-list:

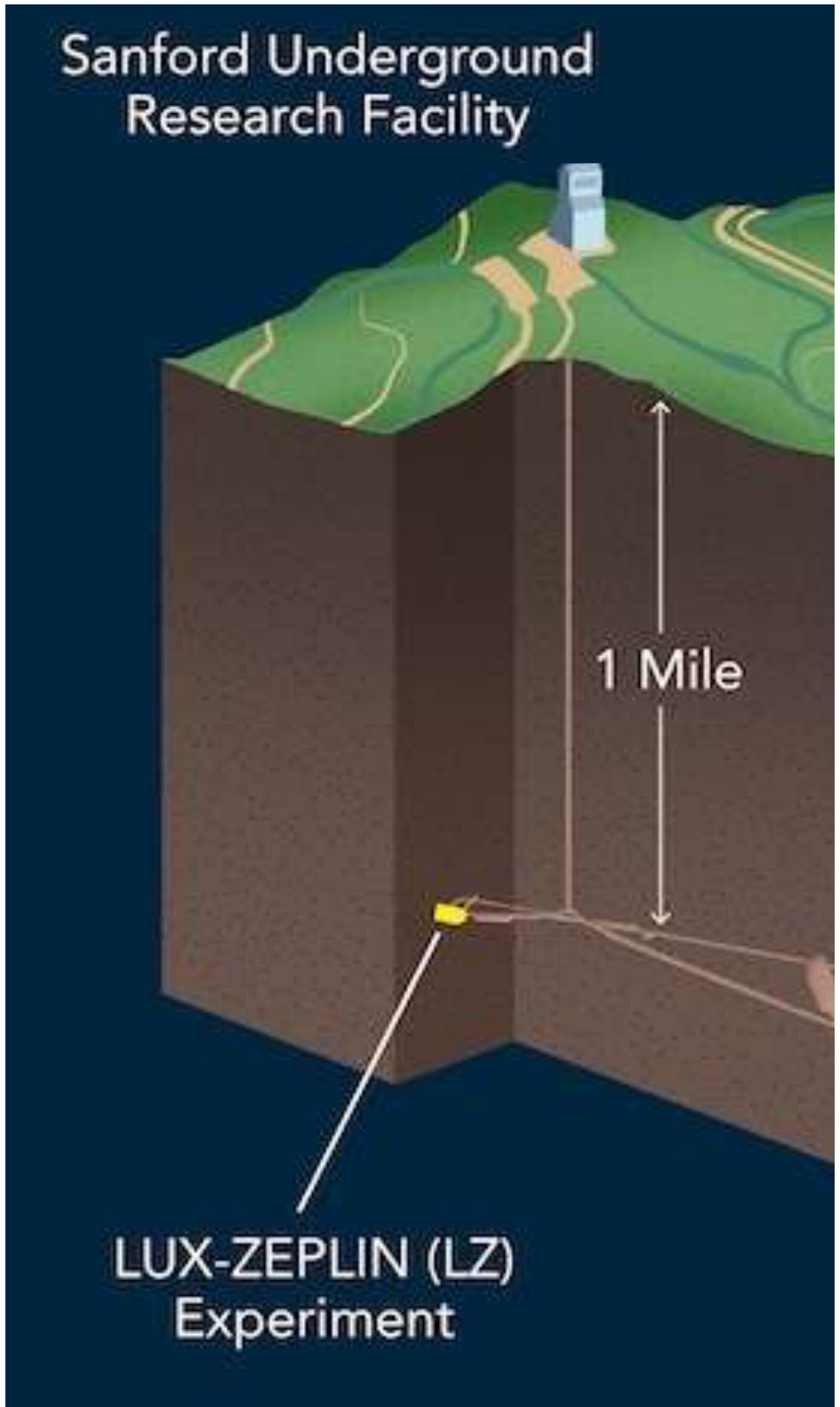
keV-energy detectors

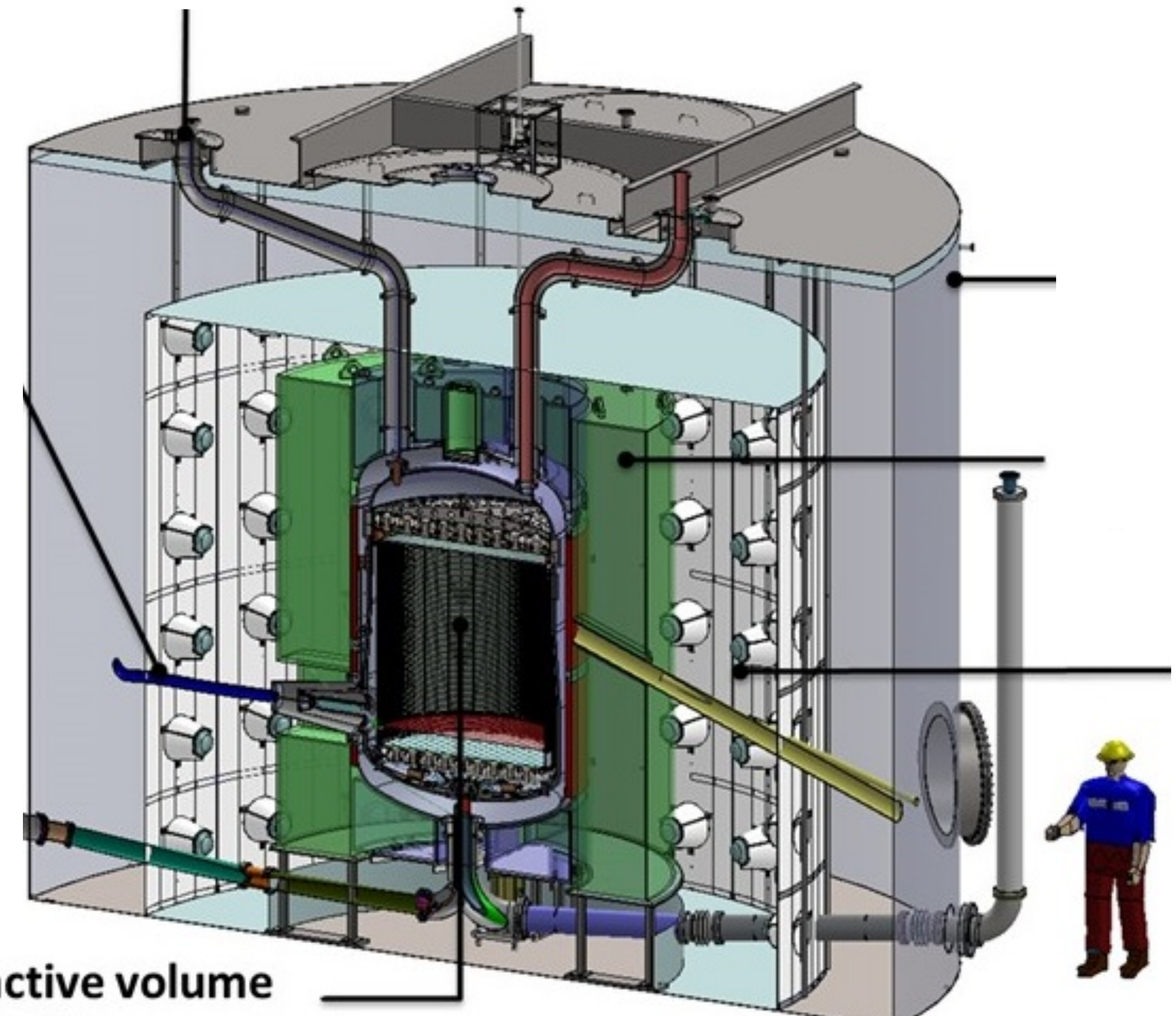
Ultra-sensitive (low background rates)

Large: lots of target nuclei to improve probability of scattering

There are many experiments using different technologies

UK principal involvement: the LUX-ZEPLIN (LZ) detector





UK principal involvement: the LUX-ZEPLIN (LZ) detector

BOULBY UNDERGROUND LABORATORY

University of BRISTOL

THE UNIVERSITY of EDINBURGH

Imperial College London

UNIVERSITY OF LIVERPOOL

The University Of Sheffield.

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UCL

UNIVERSITY OF OXFORD

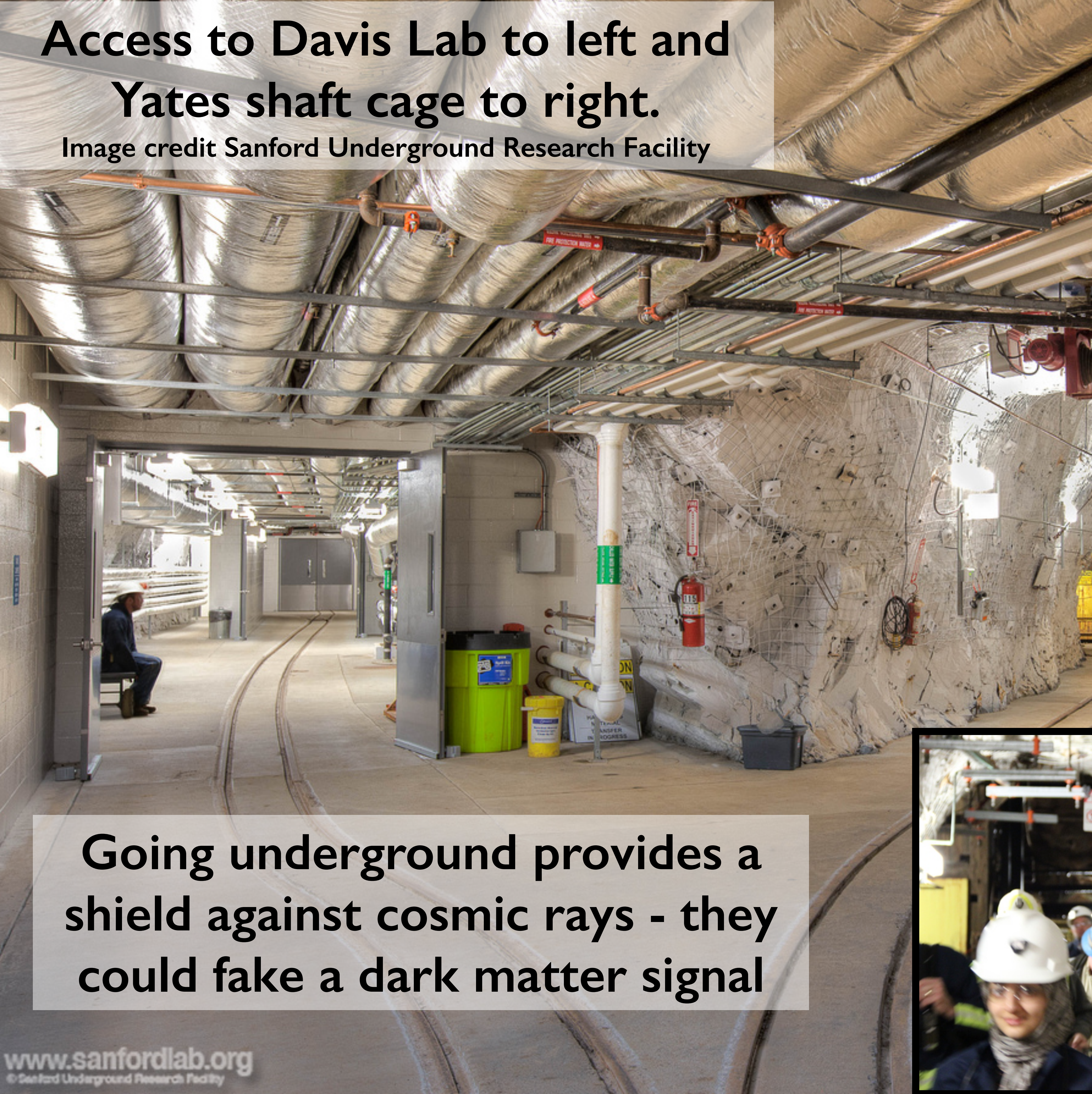
+ 30 institutes in US, Portugal, South Korea & Russia

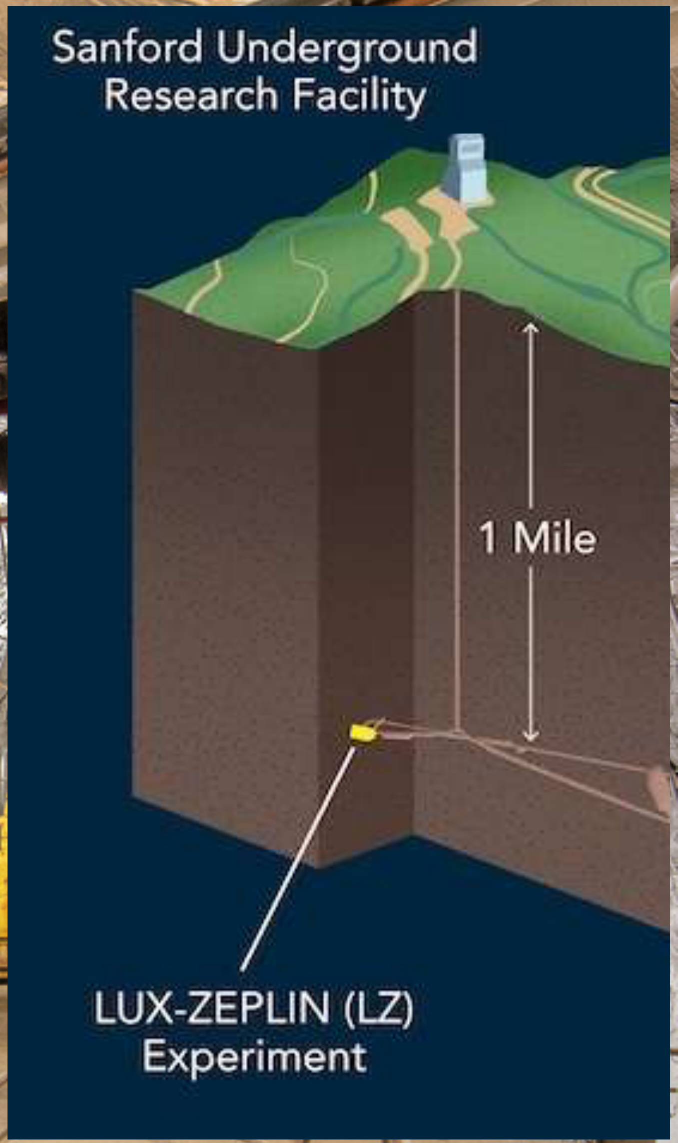
Surface facilities at SURF where LZ is based

Image credit Sanford Underground Research Facility

Access to Davis Lab to left and Yates shaft cage to right.

Image credit Sanford Underground Research Facility

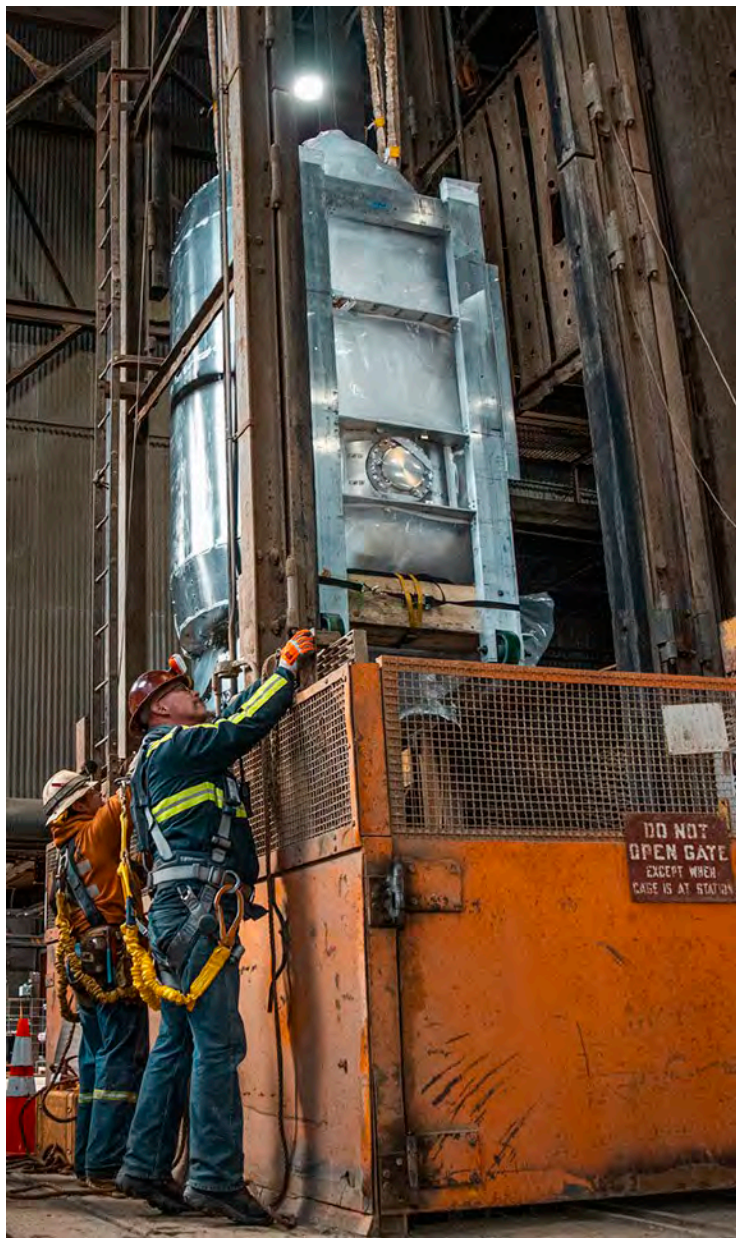




Going underground provides a shield against cosmic rays - they could fake a dark matter signal

Installing the experiment underground

October 2019



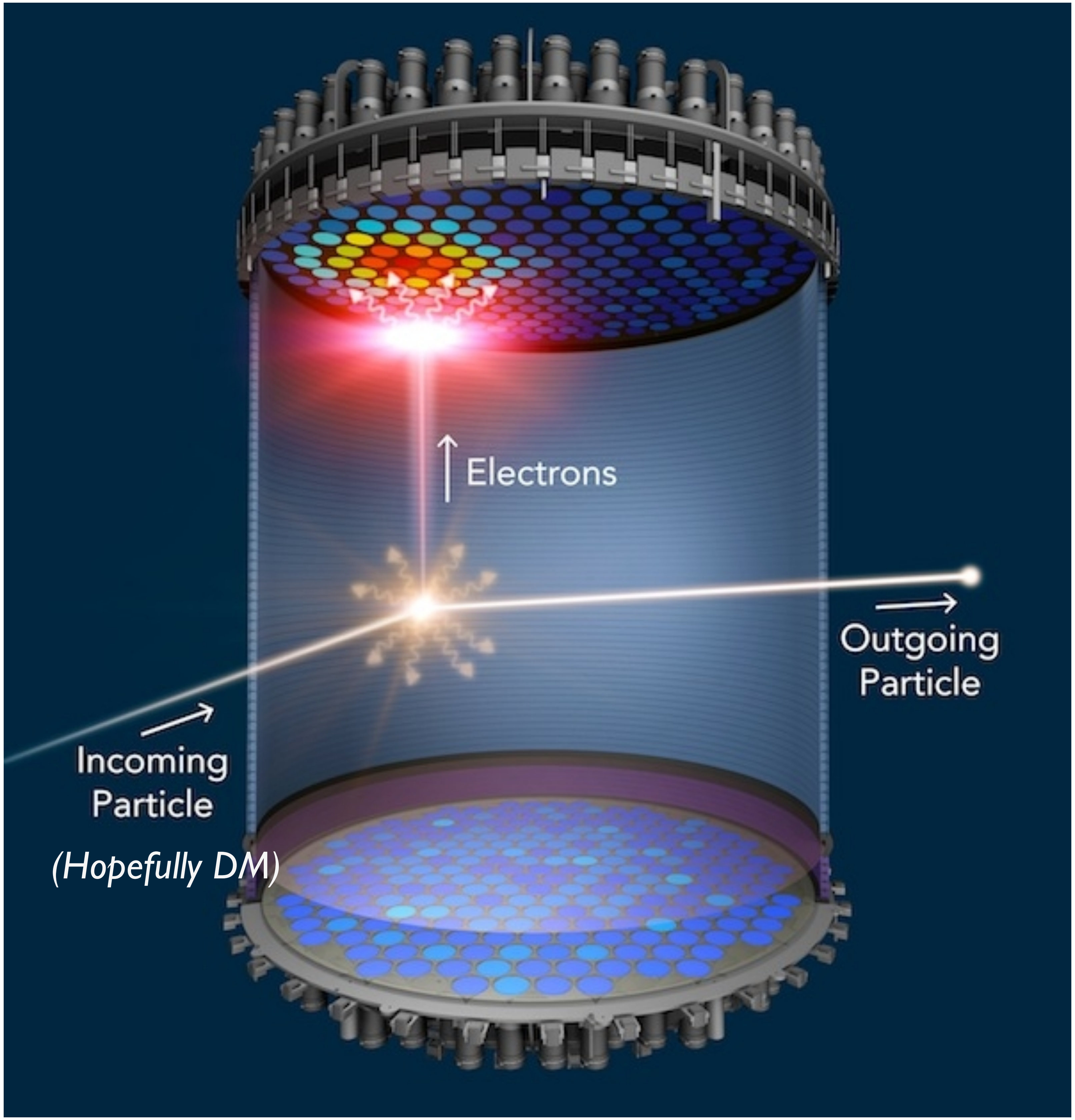
View of the water tank - provides even more shielding. LZ is installed inside

Image credit Carlos Faham

Experiment inside the water tank

Image credit Sanford Underground Research Facility

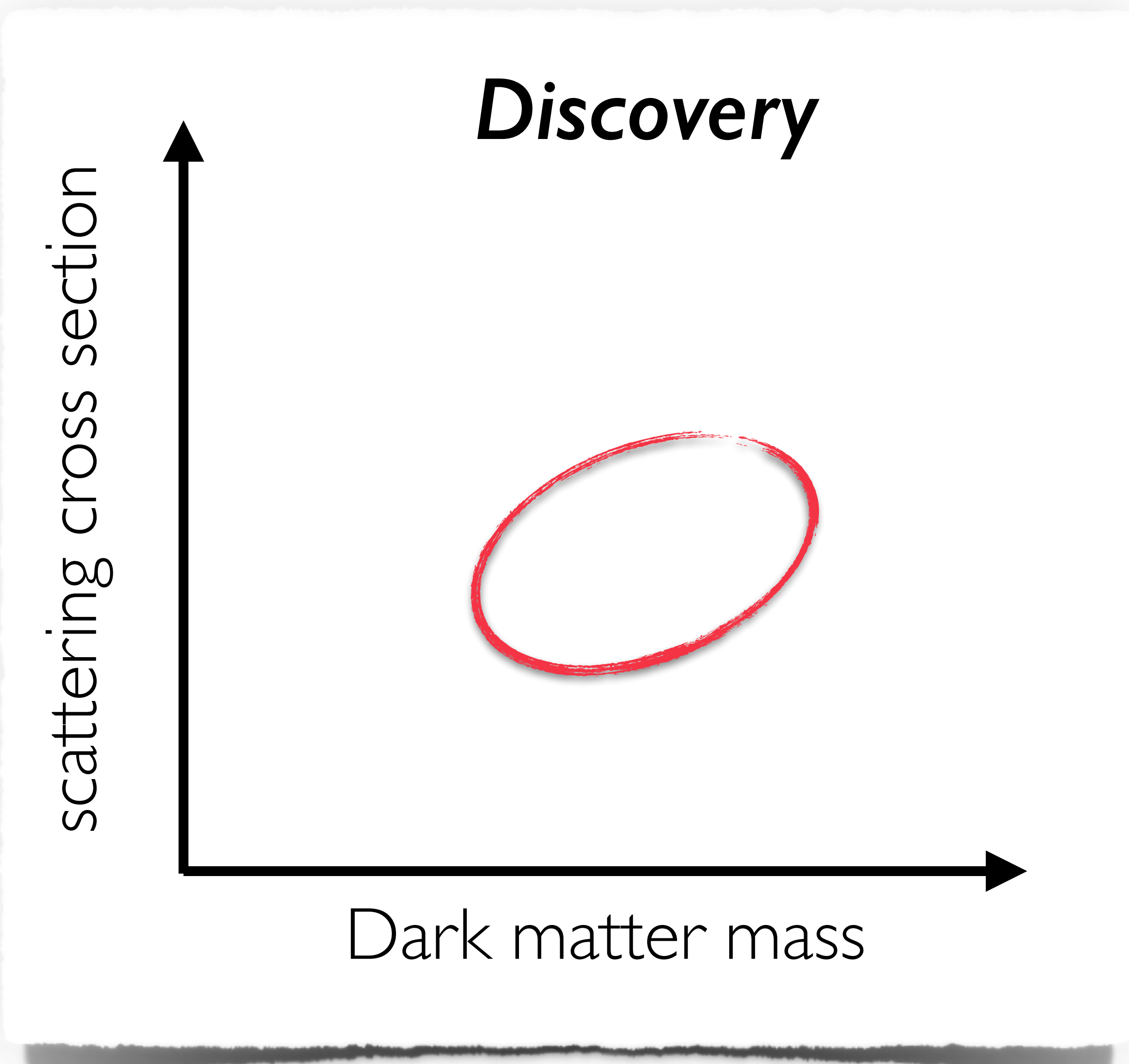
Energy is reconstructed from light and electron signals

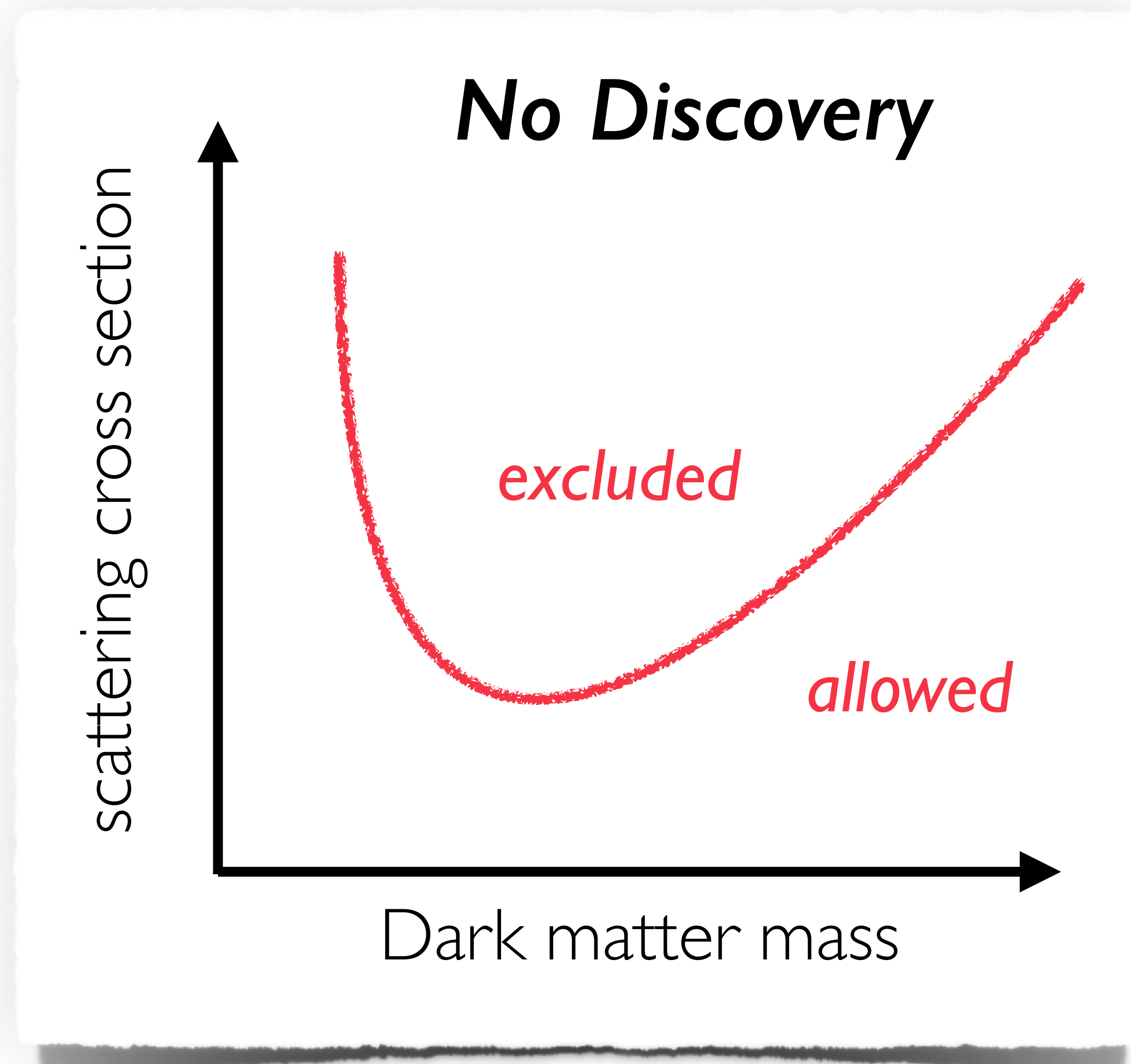


Results: in terms of Particle Physics parameters

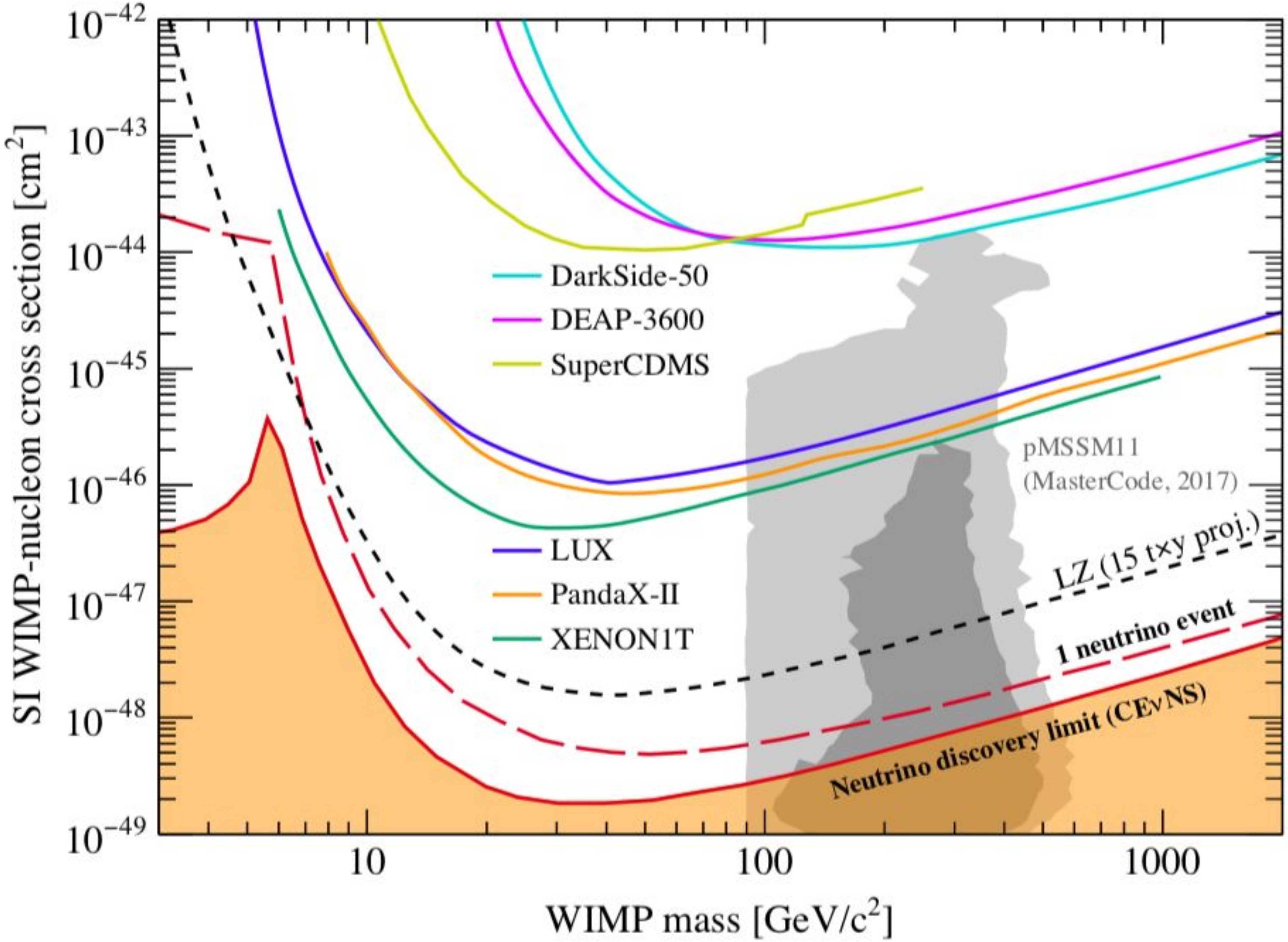
Measurement/constraints on

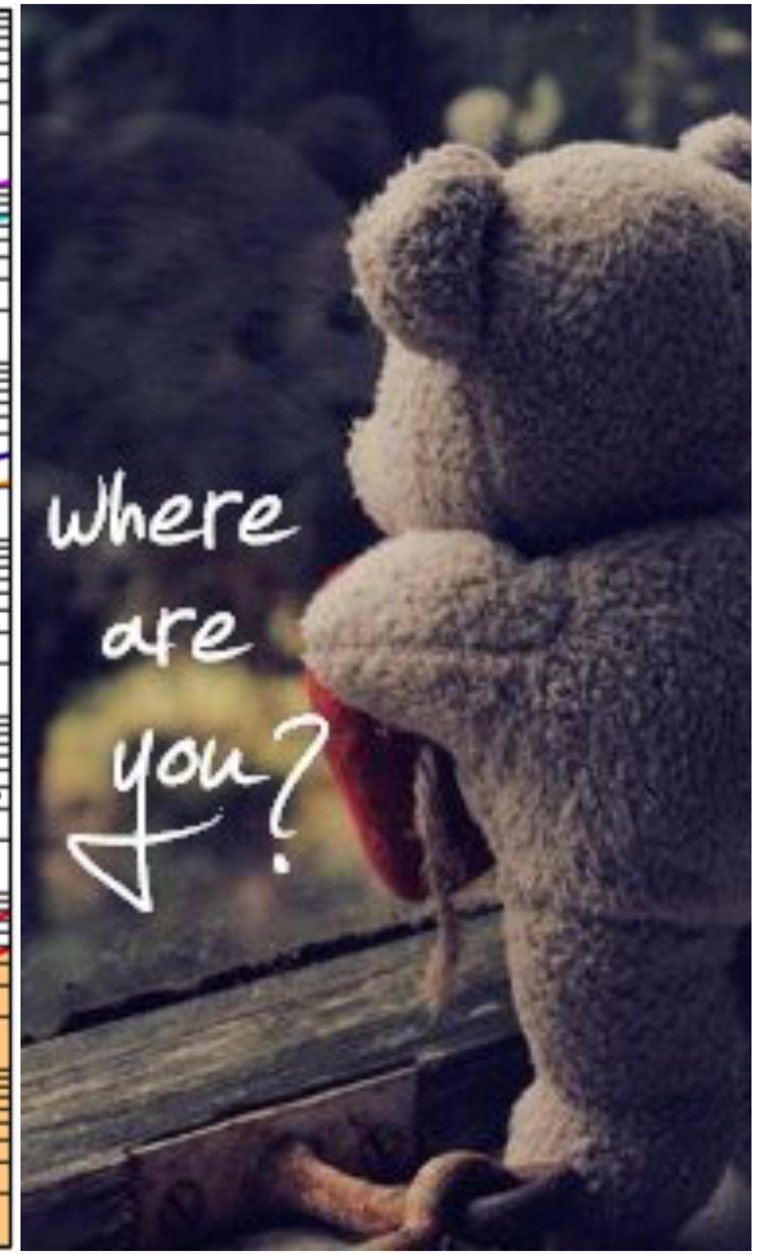
1. *Dark matter mass*
2. *Scattering cross section with nucleons*





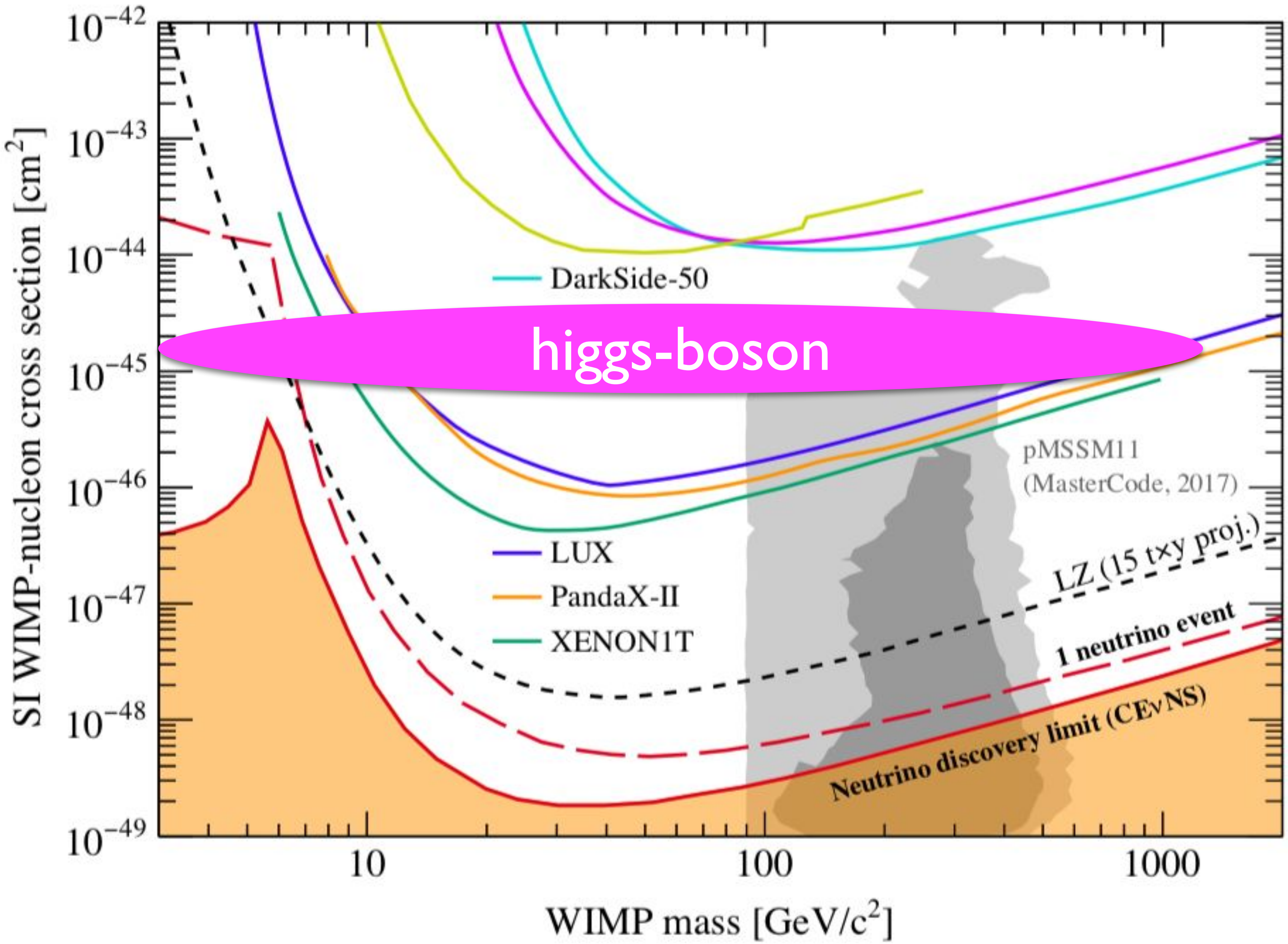
No discovery yet…



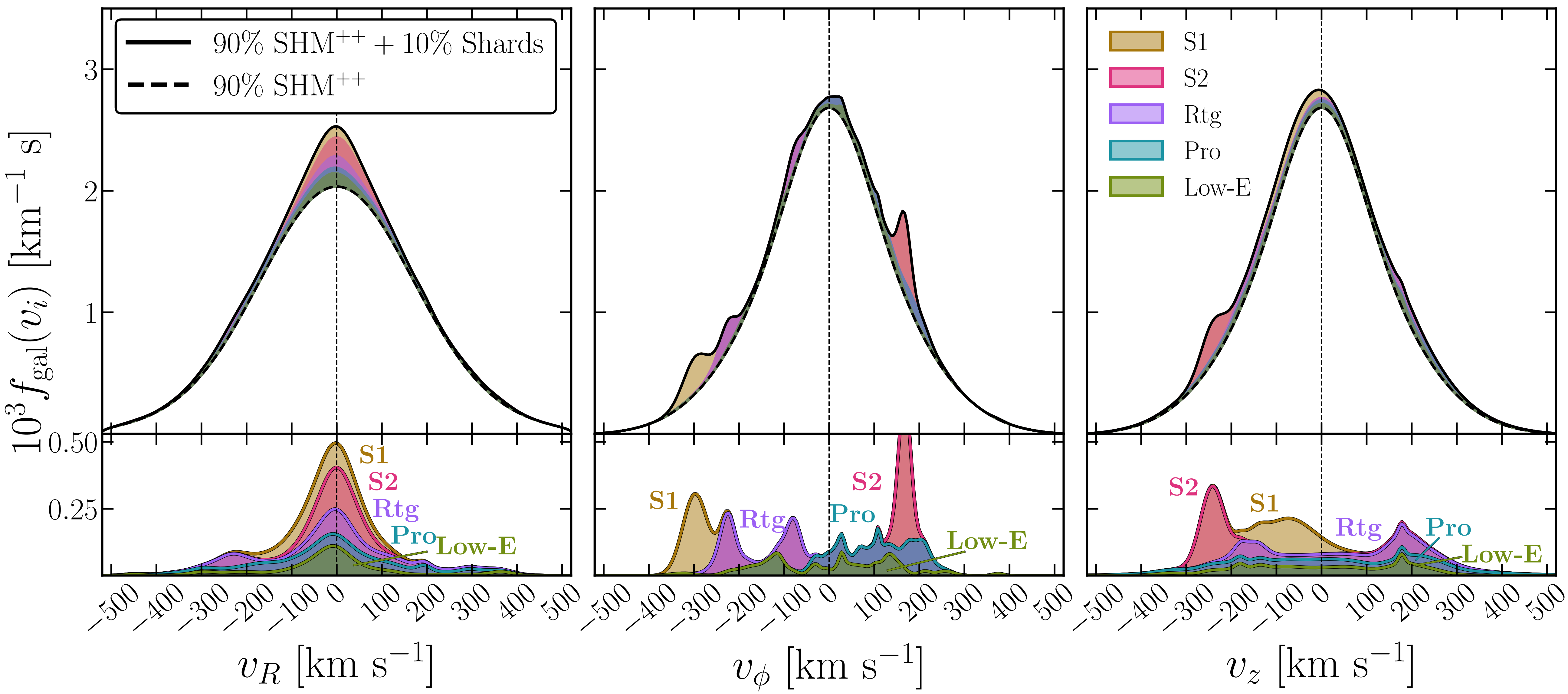


No discovery yet… but we still learn something

10^{-39} Z0-boson

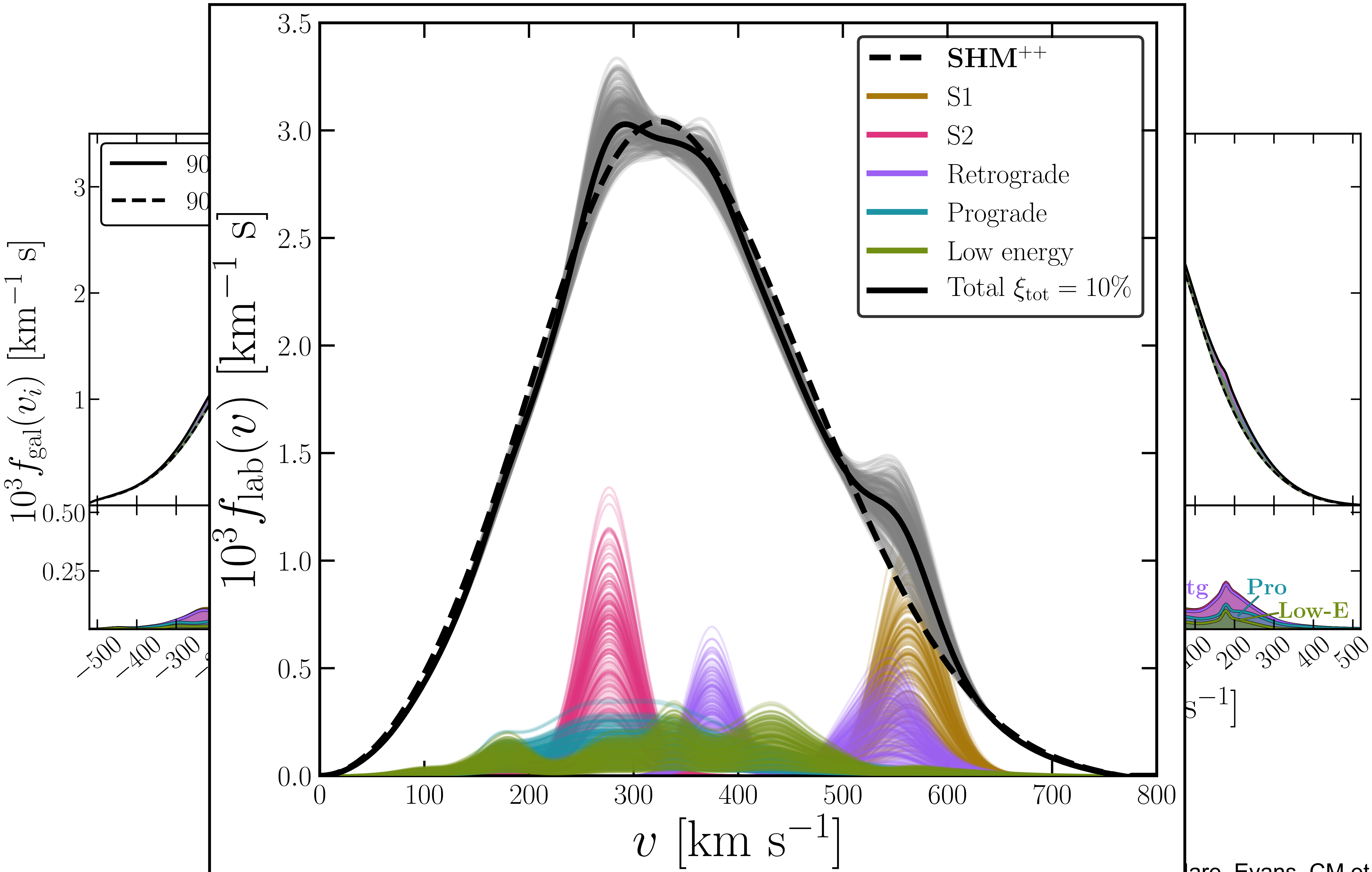


Going beyond the simple Standard Halo Model



O'Hare, Evans, CM et al
arXiv:1909.04684

Going beyond the simple Standard Halo Model



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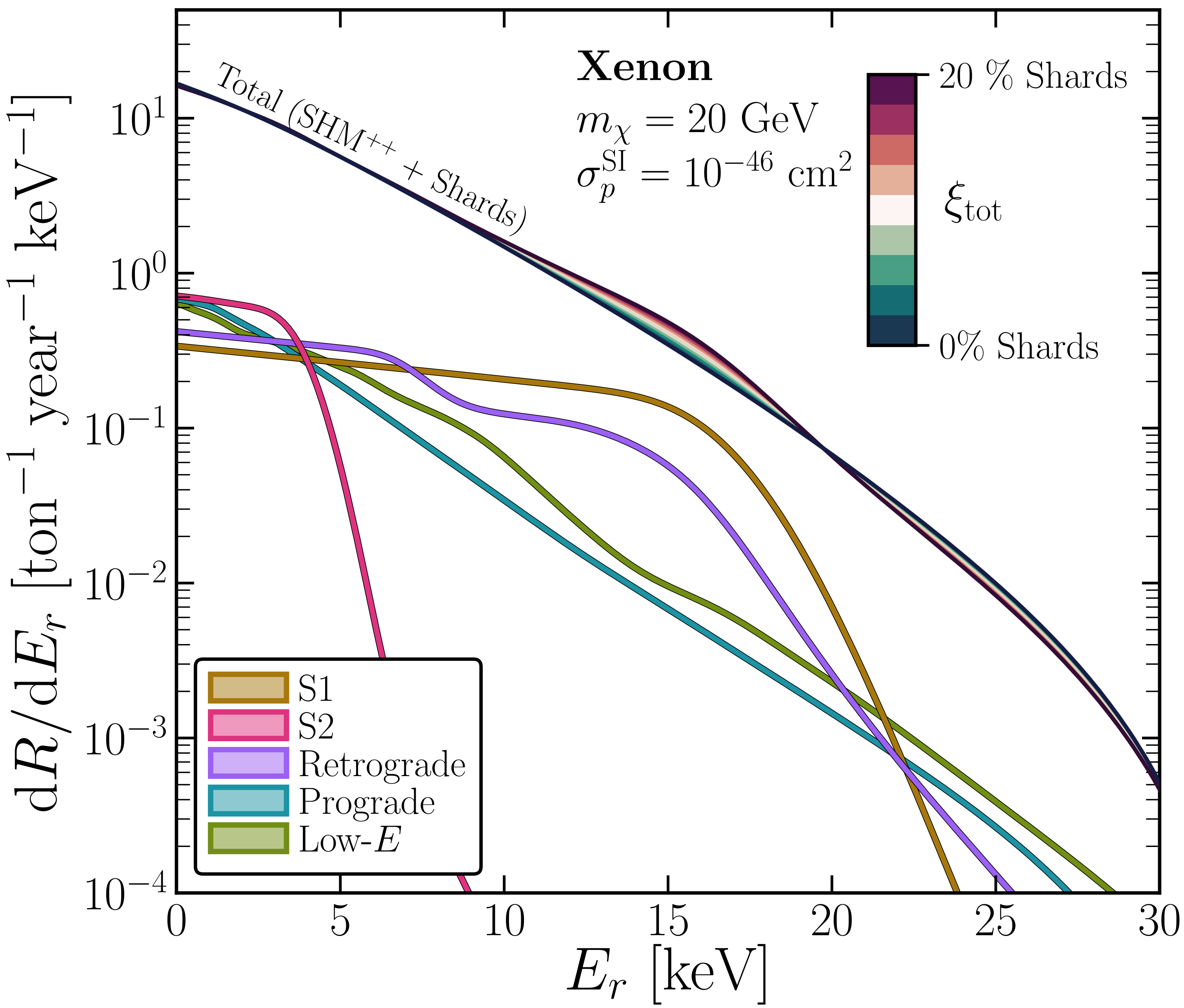
arXiv:1909.04684

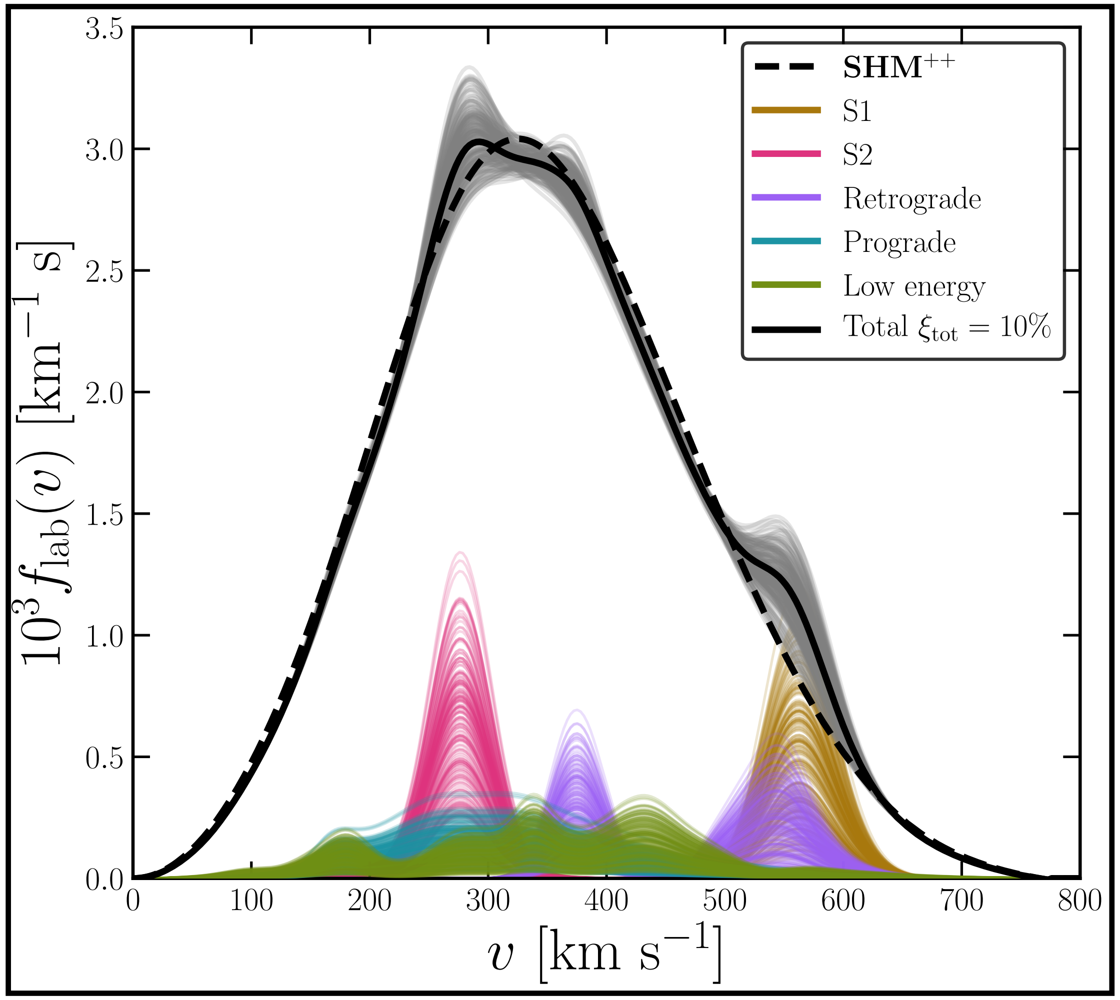
Beyond the Standard Halo Model: effects are small



This is a log-plot to emphasise differences… yet impact on the total rate is always small (for nuclear recoil signals)

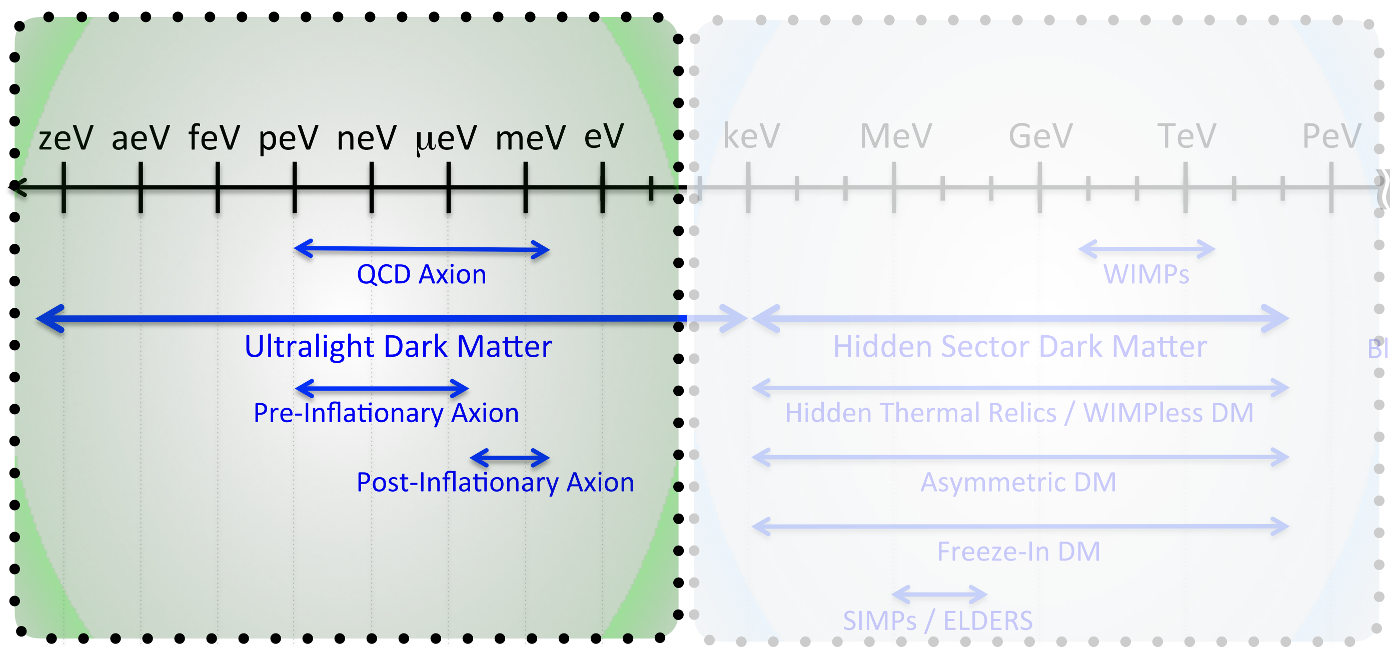
Beyond the Standard Halo Model: effects are small

Experimental signals depend on the integrated flux: structure is 'integrated away'



$$\frac{dR}{dE_r} = N_{\rm Xe}\frac{\rho_{\rm DM}}{m_{\rm DM}}\int_{v_{\rm min}(E_r)} v f_{\rm lab}(v)\frac{d\sigma}{dE_r}d^3v$$

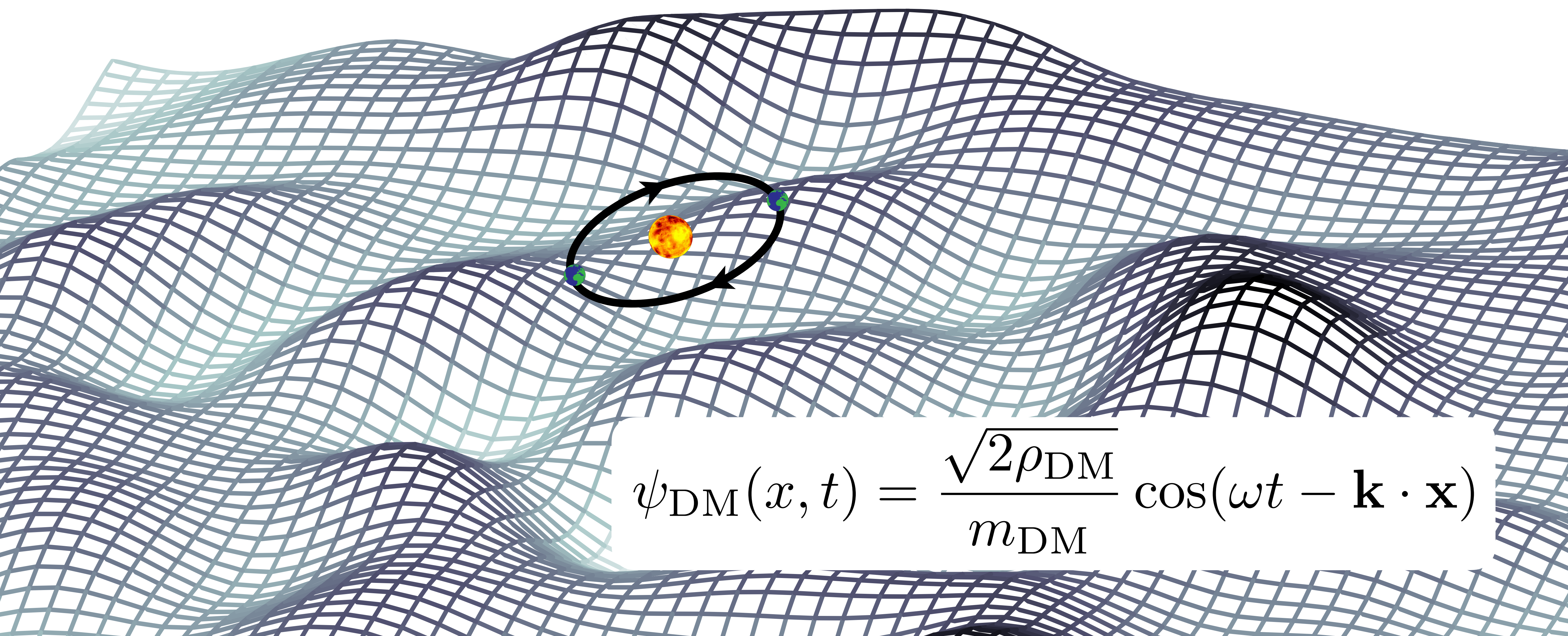
Searching for ‘ultra-light’ DM candidates



Ultra-light dark matter

Flux is huge: $\phi_{\rm thumb} \sim 10^{22} \left(\frac{10^{-6} m_{\rm neutrino}}{m_{\rm DM}} \right)$ particles/s

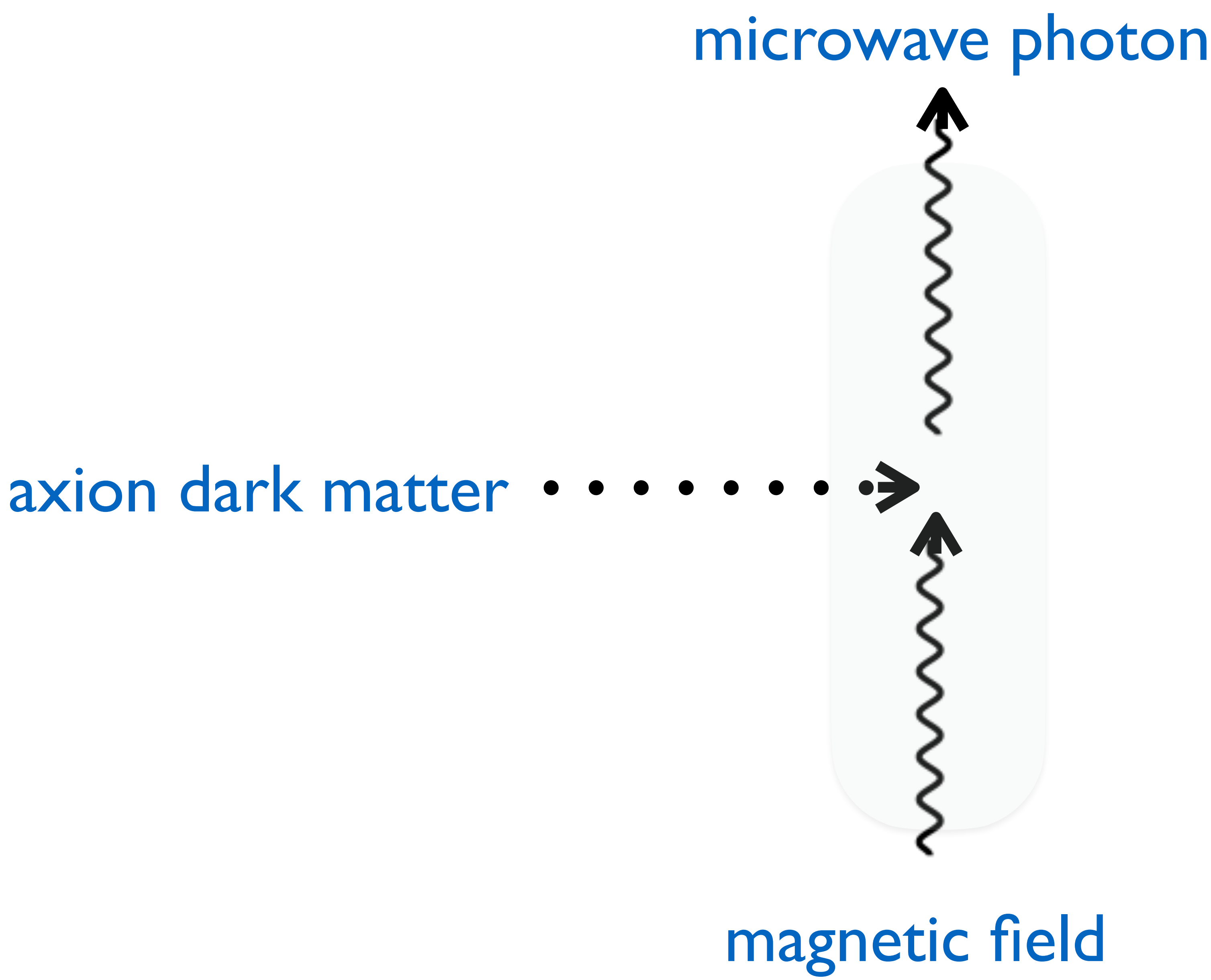
Better modelled as a wave rather than individual particles



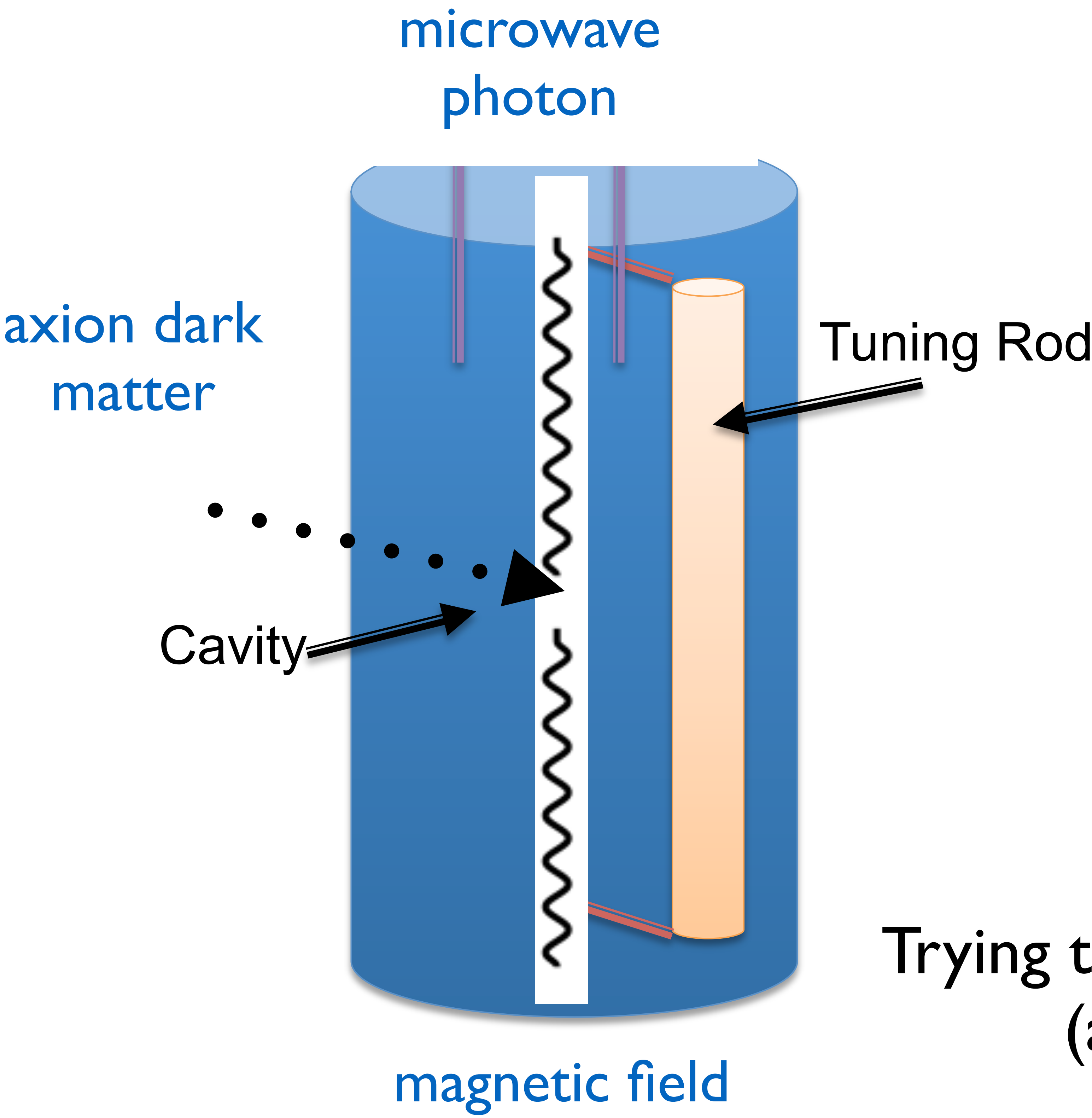
$$\psi_{\rm DM}(x,t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}} \cos(\omega t - \mathbf{k}\cdot\mathbf{x})$$

ADMX: Axion Dark Matter eXperiment

Basic idea:
Axions in magnetic fields convert to microwave photons

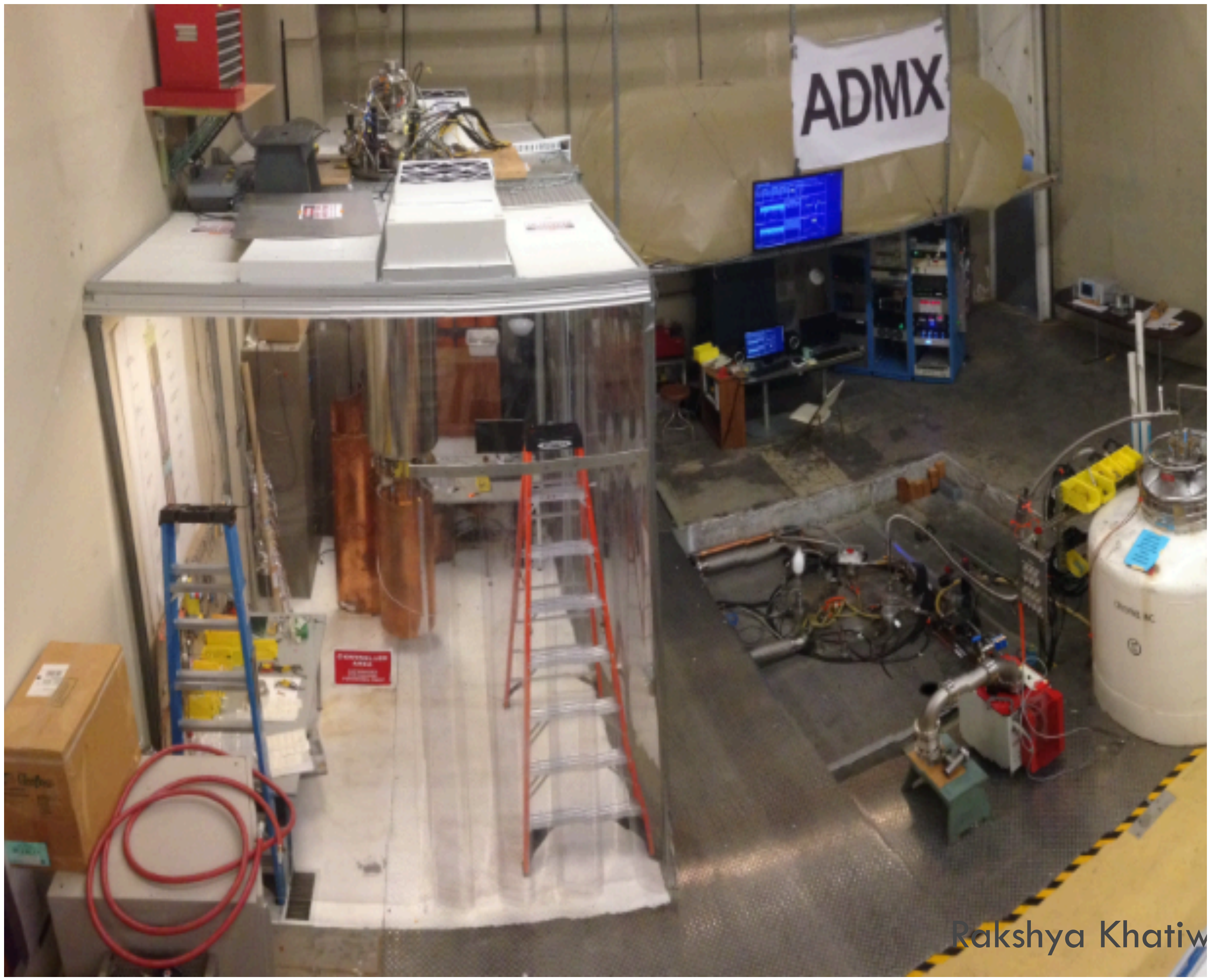


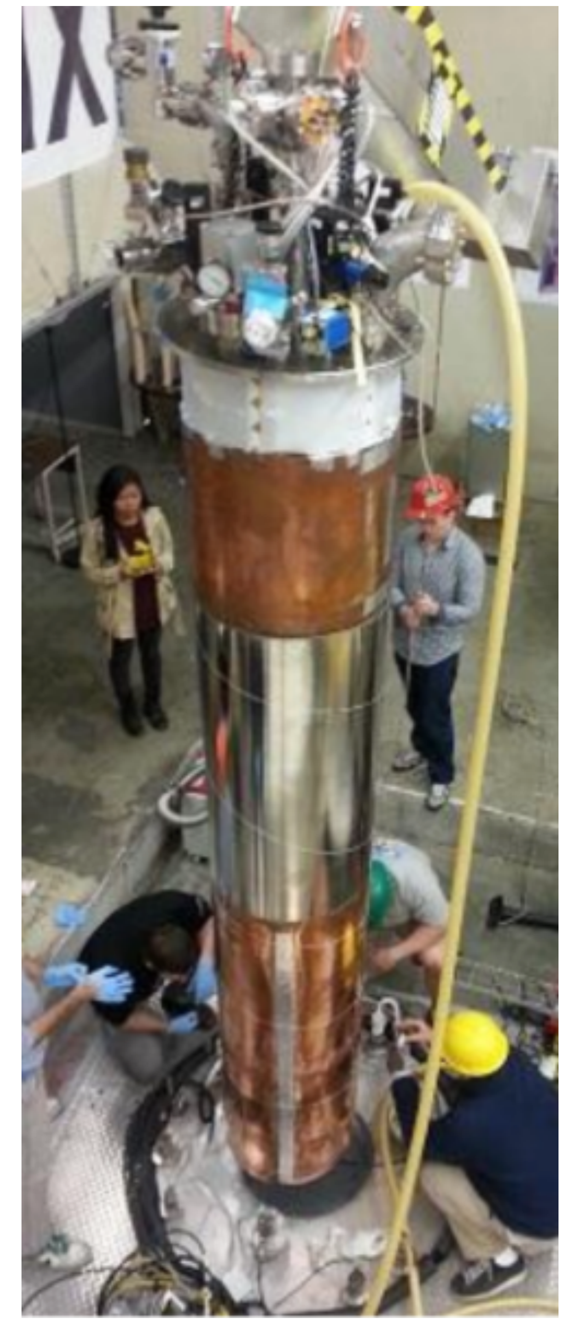
ADMX: Axion Dark Matter eXperiment



Tuneable cavity:
Trying to tune onto the axion mass
(a dark matter radio?)

ADMX: Axion Dark Matter eXperiment



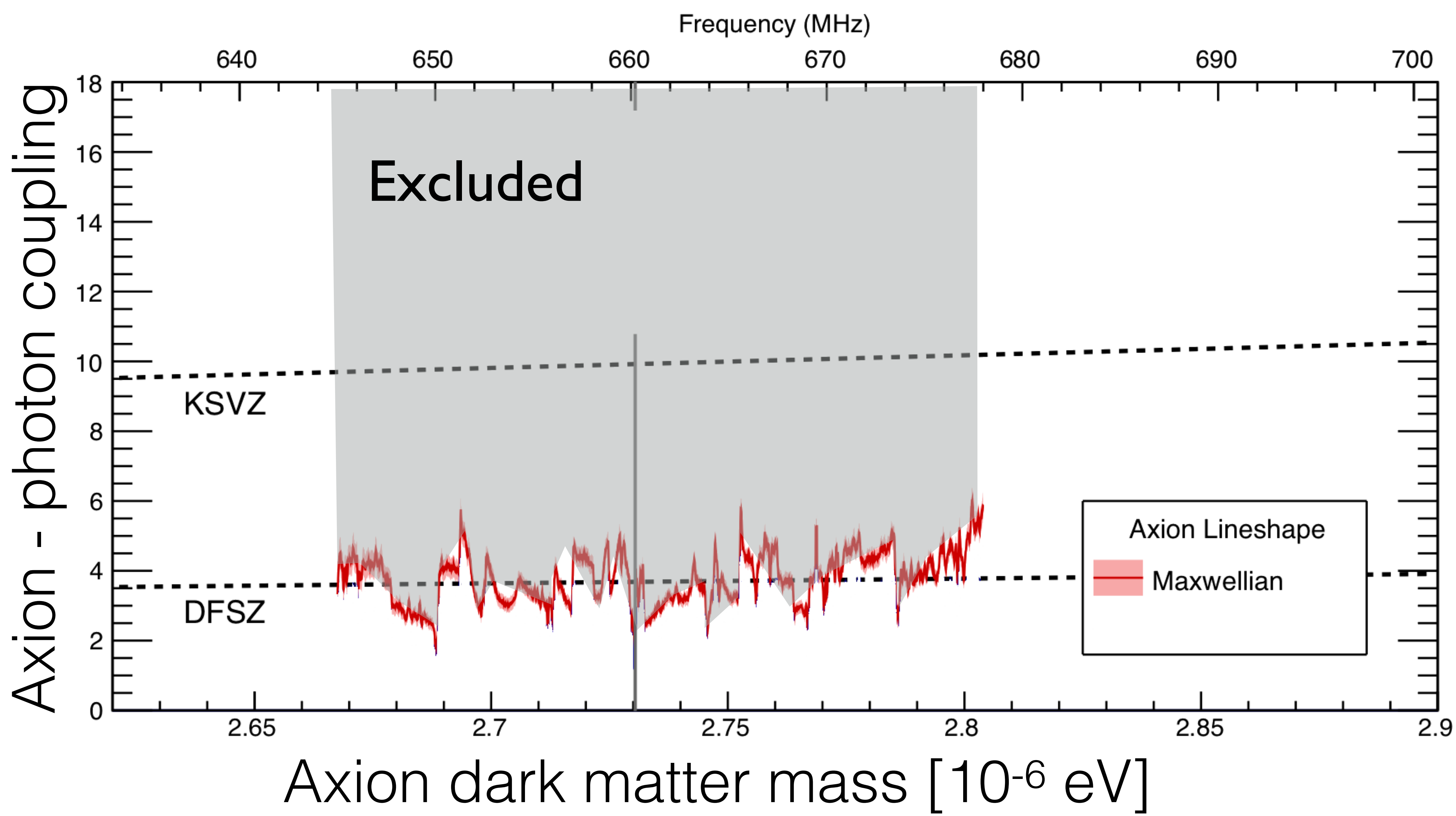


University of Sheffield + 8 USA institutions

ADMX: No discovery yet…

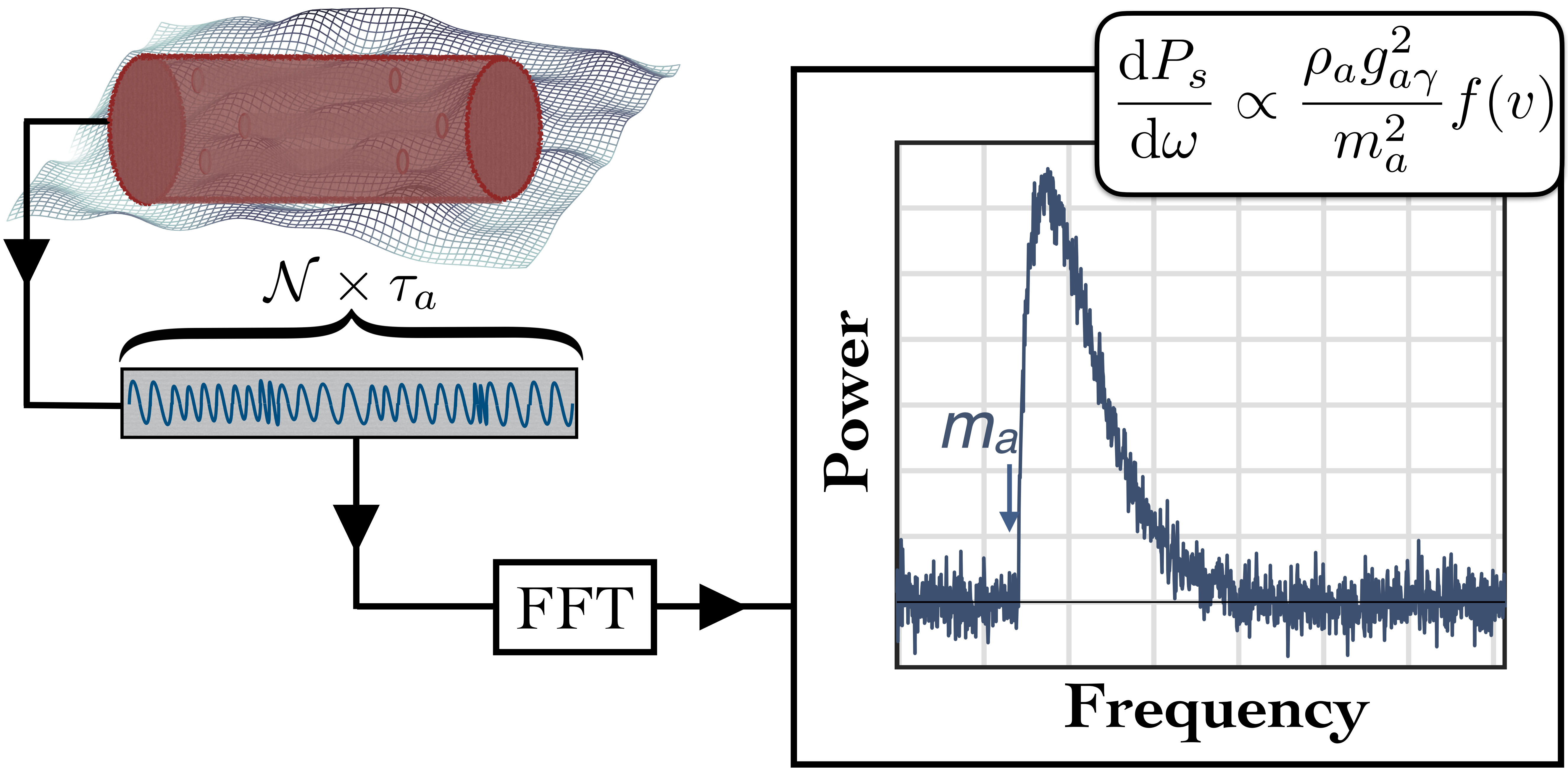
Experiments could tell us:

the axion dark matter mass & axion-photon coupling



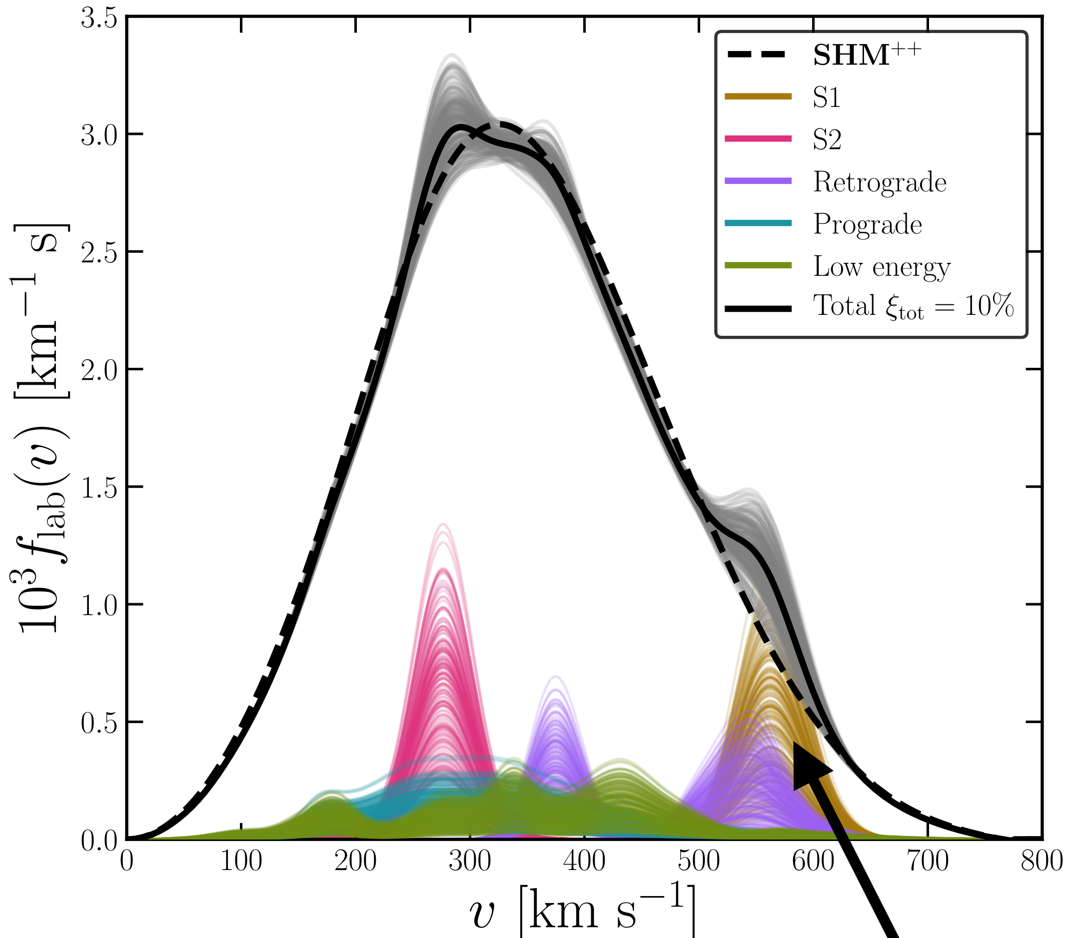
Post-discovery: measuring the DM distribution

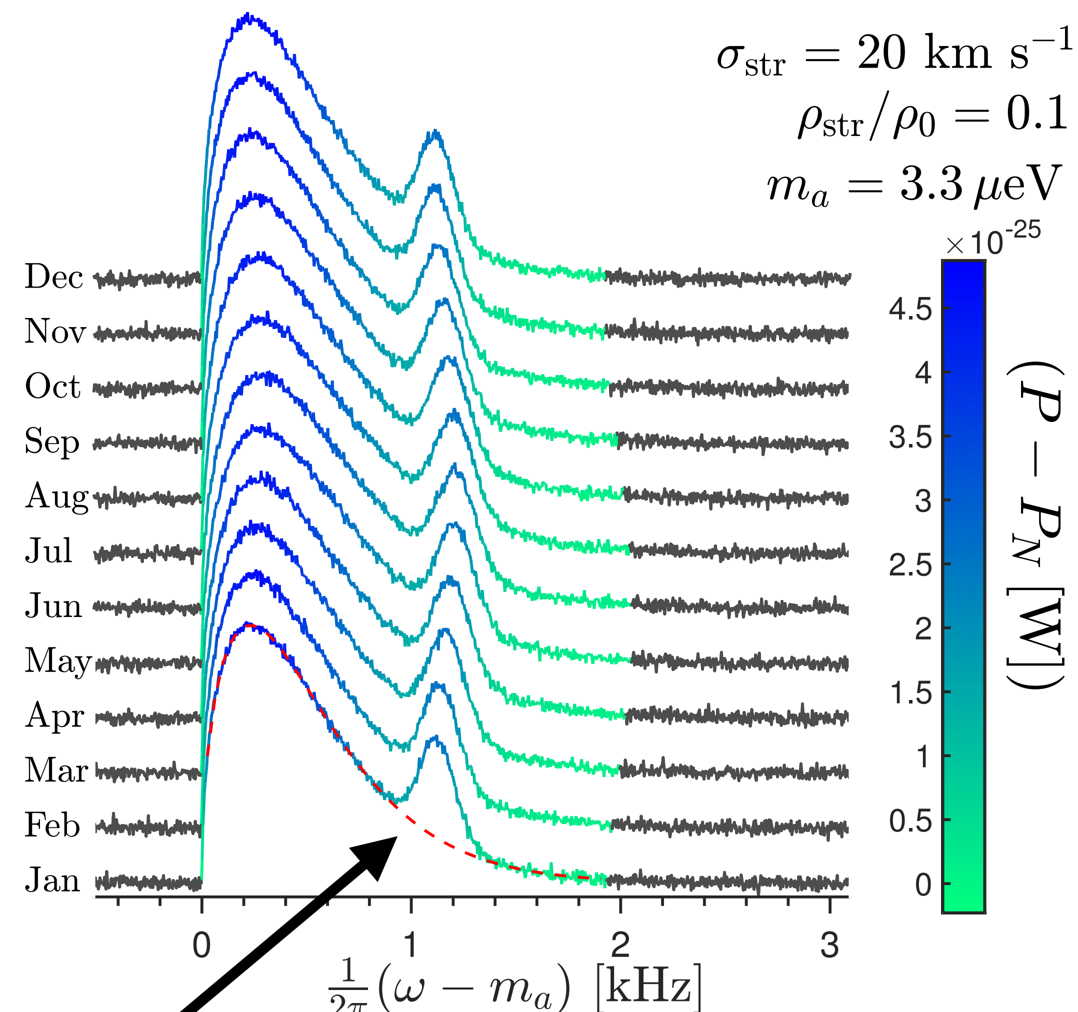
Sample axion field over many coherence times:
gives the Power spectrum, proportional to speed distribution



Ciaran O'Hare

ADMX: precision astronomy?



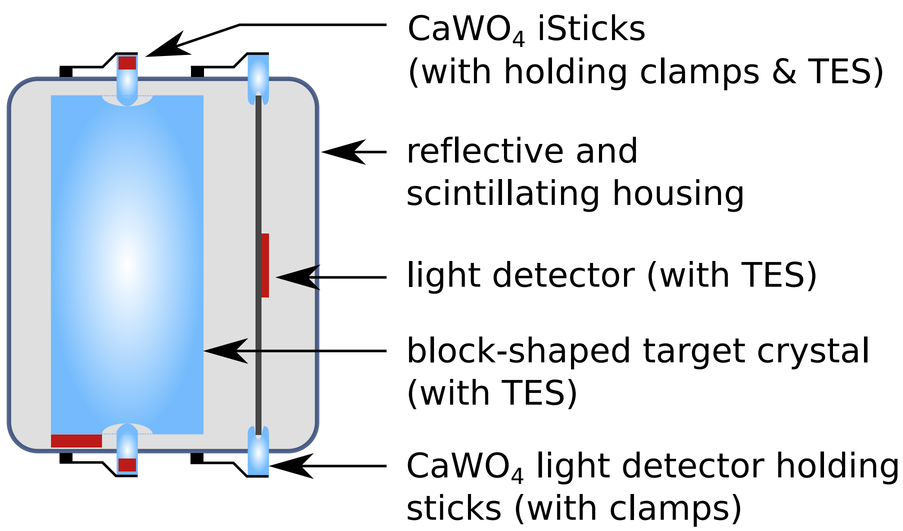


Features in the speed distribution would show up in the measured signal

What I didn't cover…

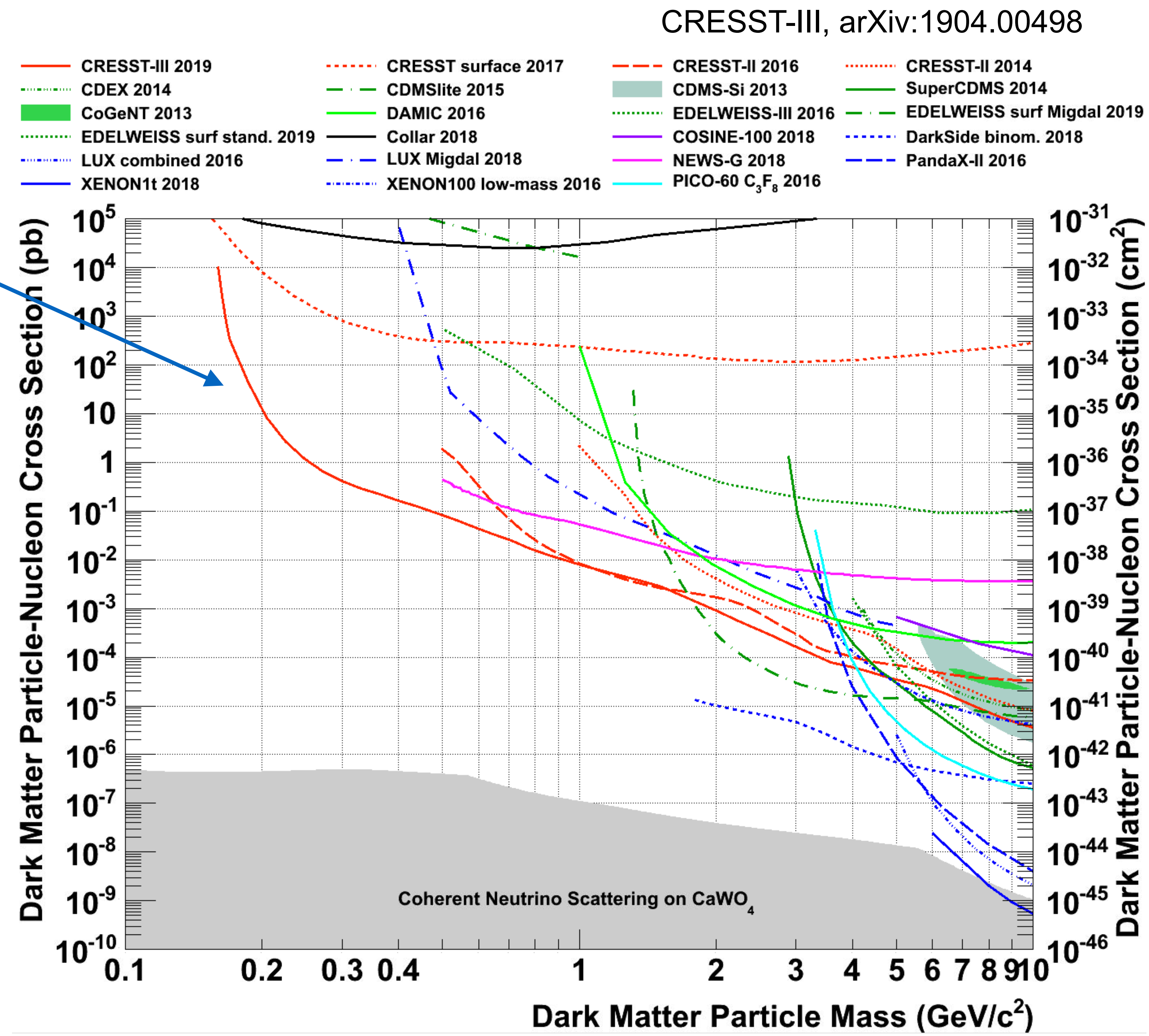
Nuclear recoils: below the normal WIMP range

CRESST-III

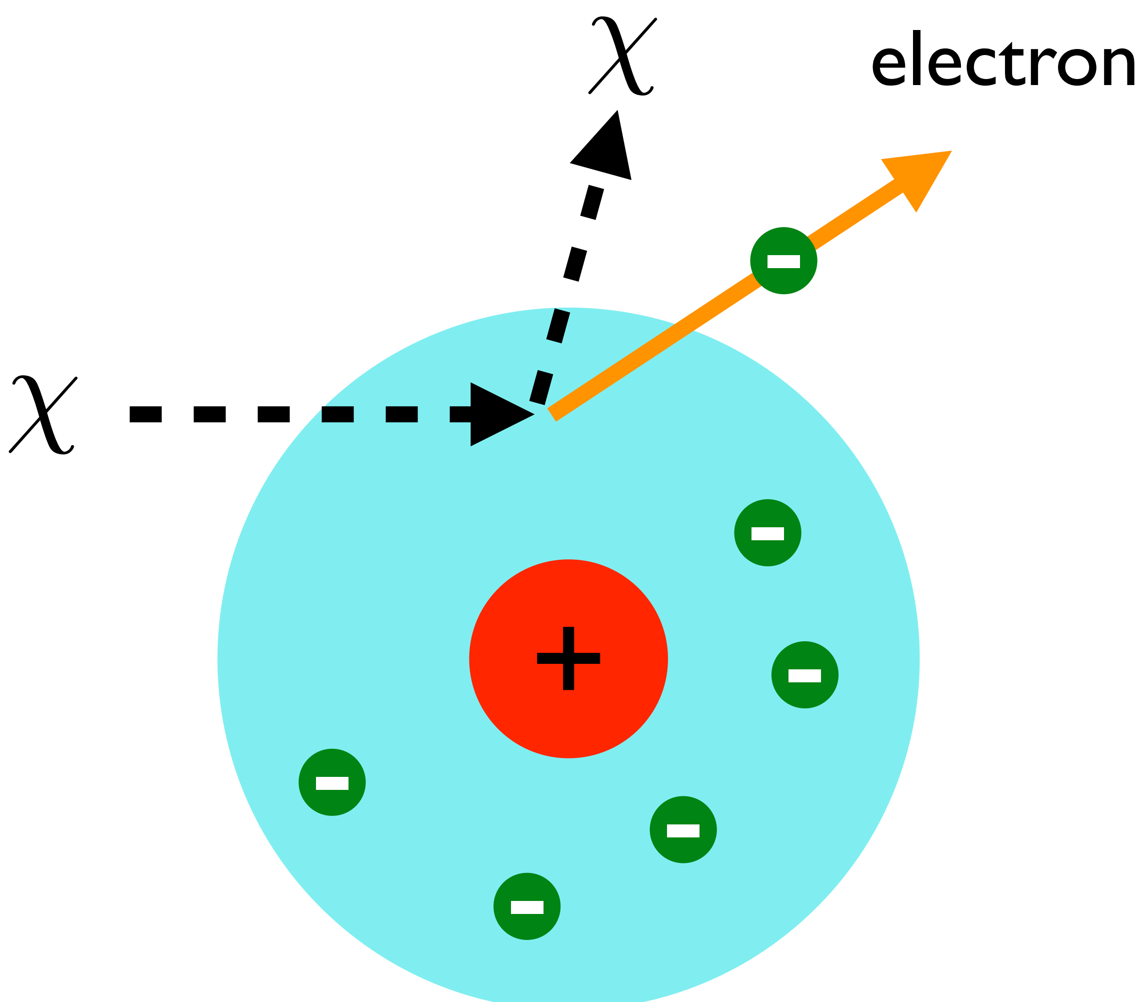


Detector mass: 24 grams

Detector threshold: 30 eV



Electron-ionisation in atoms



For ionisation, require:

$$\frac{1}{2} m_{\mathrm{DM}} v_{\mathrm{DM}}^2 \gtrsim E_{\mathrm{binding}} (\sim 12 \text{ eV})$$

$$\boxed{m_{\mathrm{DM}} \gtrsim 5 \text{ MeV}}$$

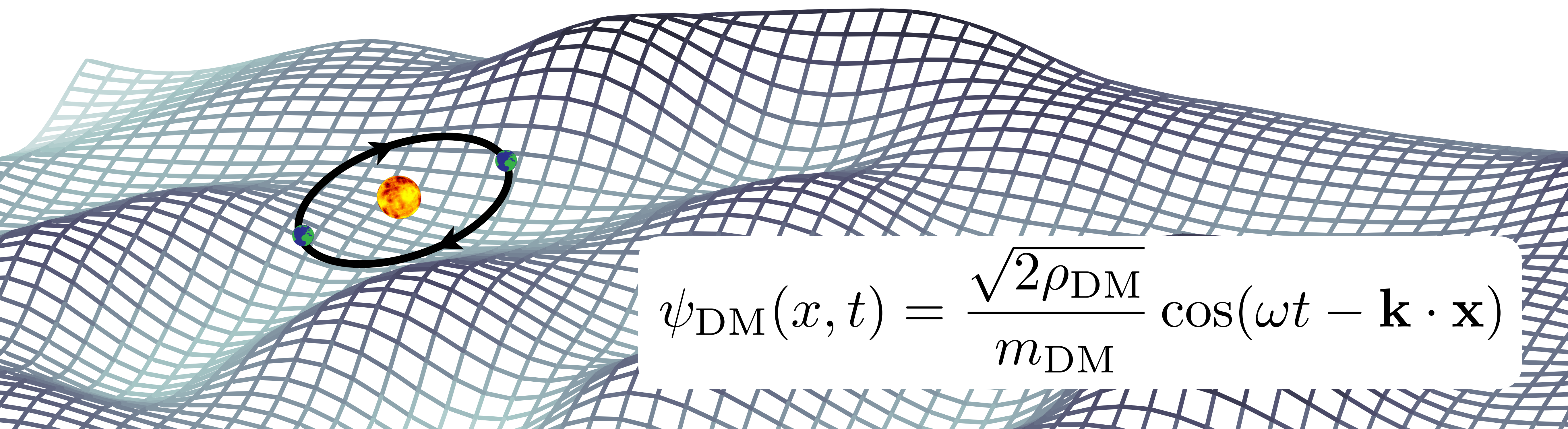
Exciting developments using quantum sensors

Oscillating dark matter can induce changes in fundamental constants

$$m_e(x,t) \approx m_e \left[1 + 10^{-22}\psi_{\rm DM}(x,t)\right]$$

Induces tiny changes in atoms: a new field opening up

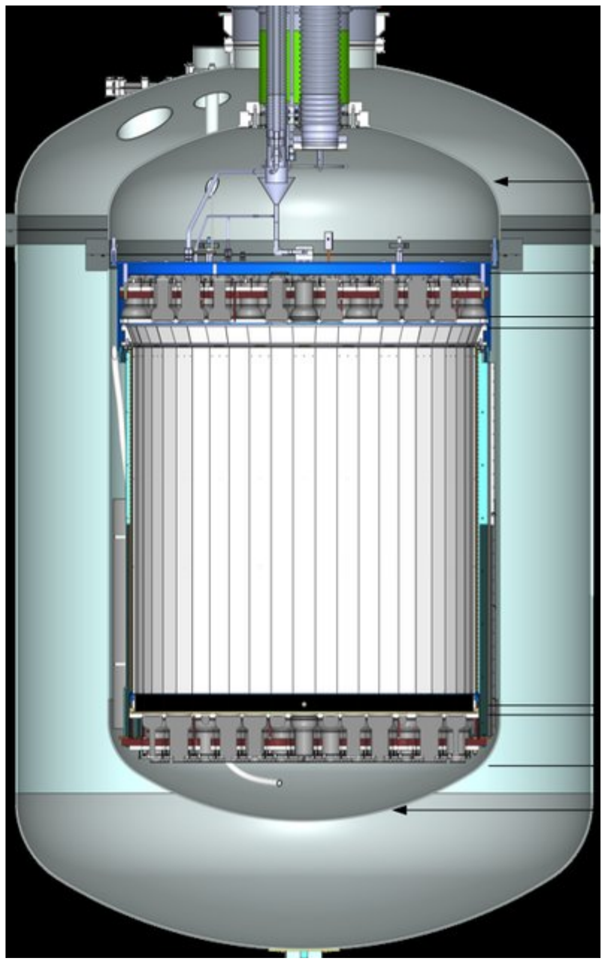
Groups beginning to search for tiny changes with:
atomic clocks, magnetometers, accelerometers, interferometers…



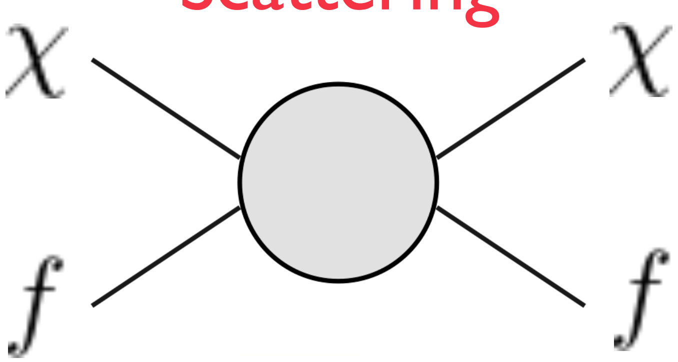
$$\psi_{\rm DM}(x,t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}} \cos(\omega t - \mathbf{k}\cdot\mathbf{x})$$

Other types of searches

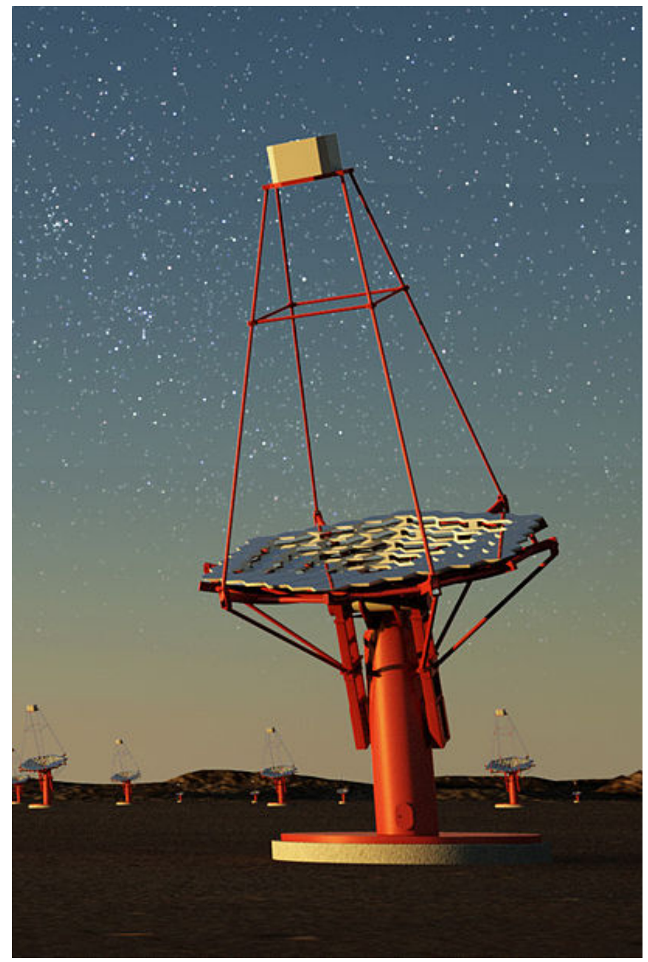
Direct detection



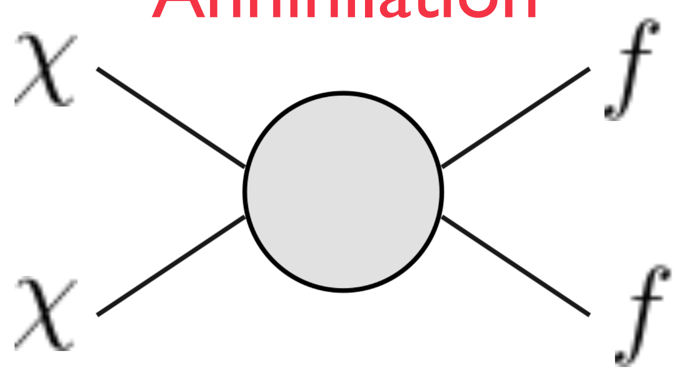
Scattering



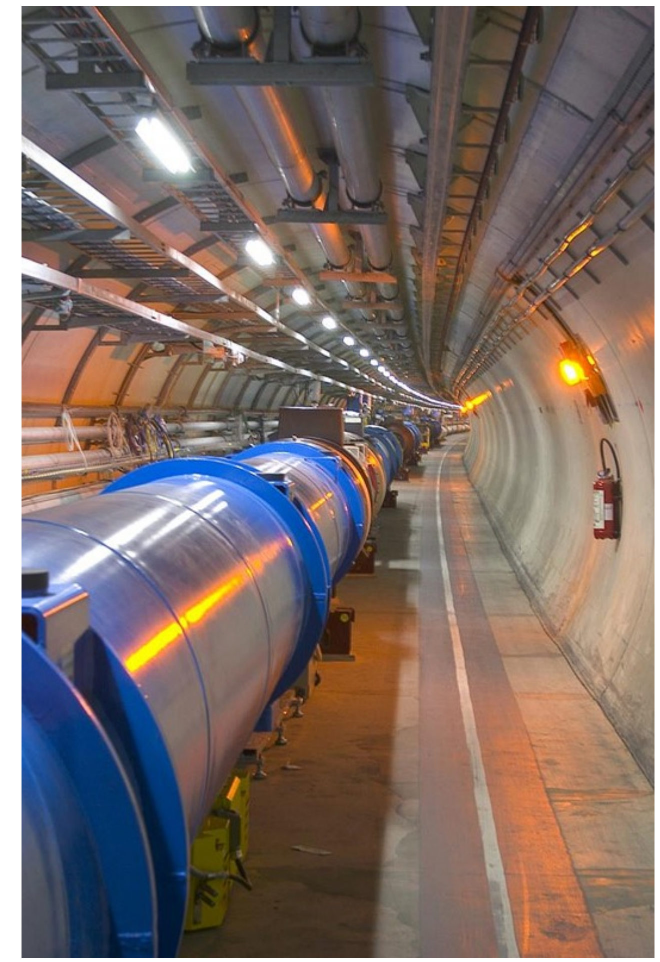
Indirect detection



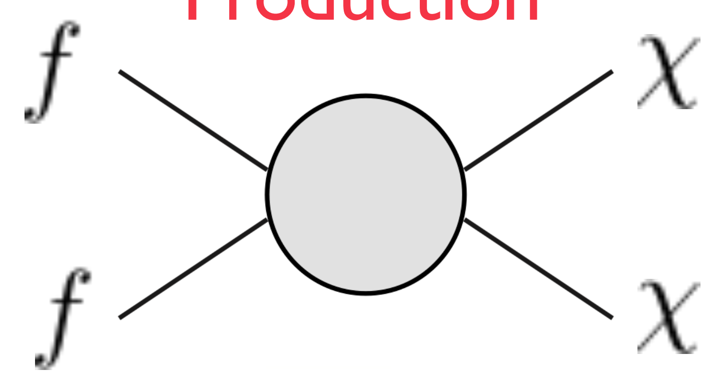
Annihilation



Collider



Production



Summary

- Theory and experimental community are very actively trying to identify the properties of dark matter
- I have tried to summarise some of the attempts to learn more about DM with experiments on Earth
- No single experiment can search for all dark matter candidates
- Robust particle physics constraints/measurements requires a good model of the dark matter halo