

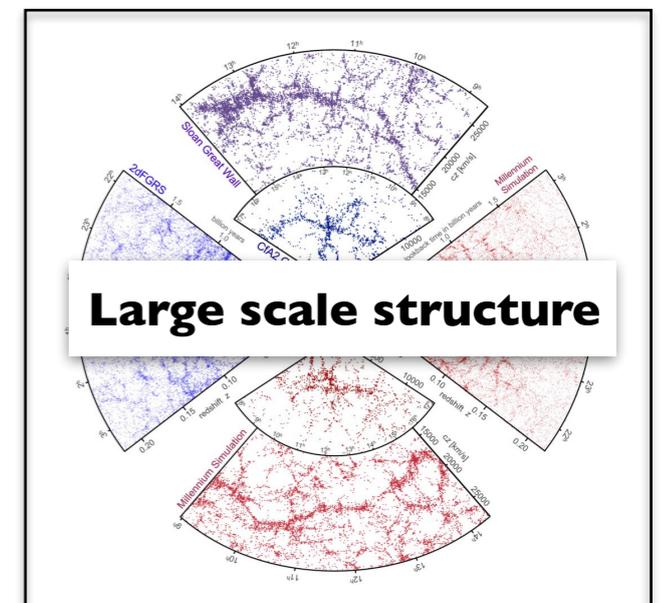
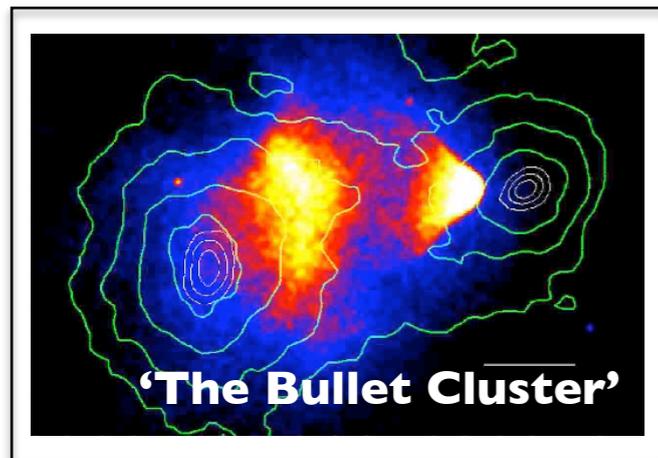
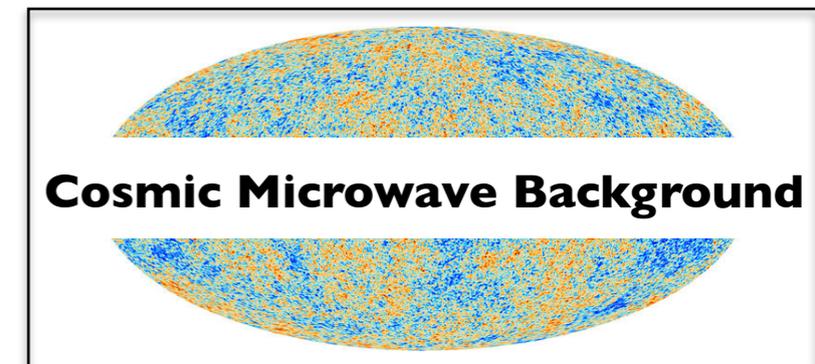
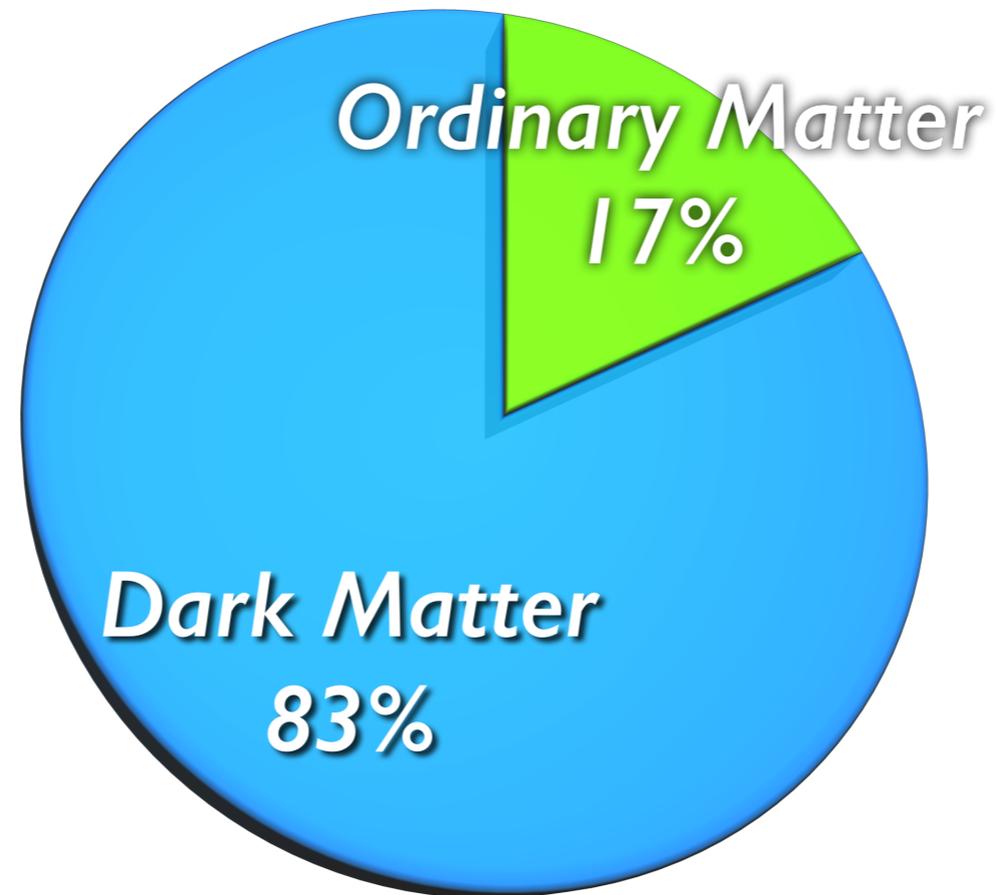
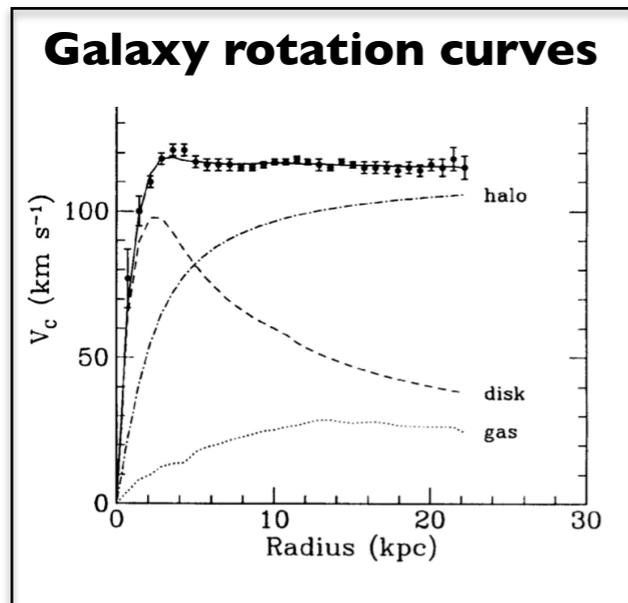
# Searching for galactic dark matter

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**Christopher McCabe**

# We have detected dark matter!

## Matter in the Universe



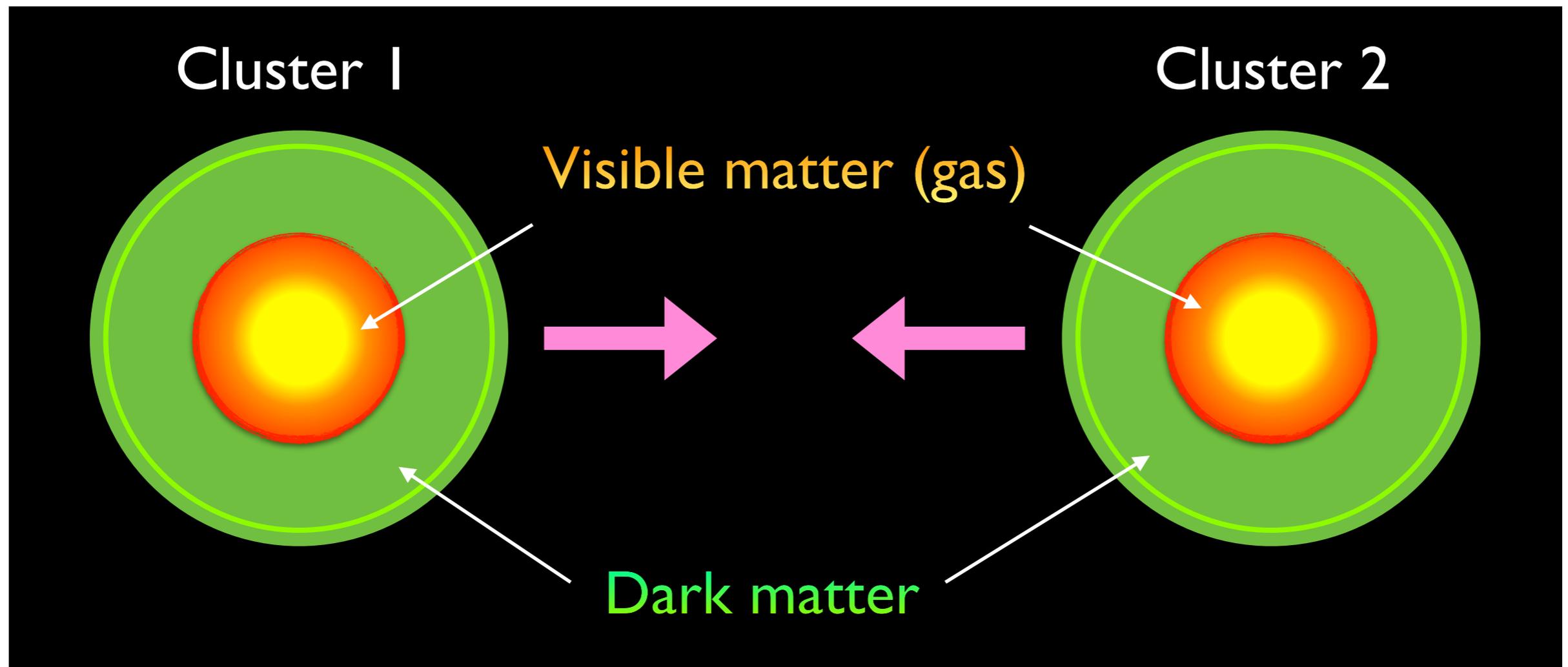
Evidence from gravitational interactions...

...over many distance scales

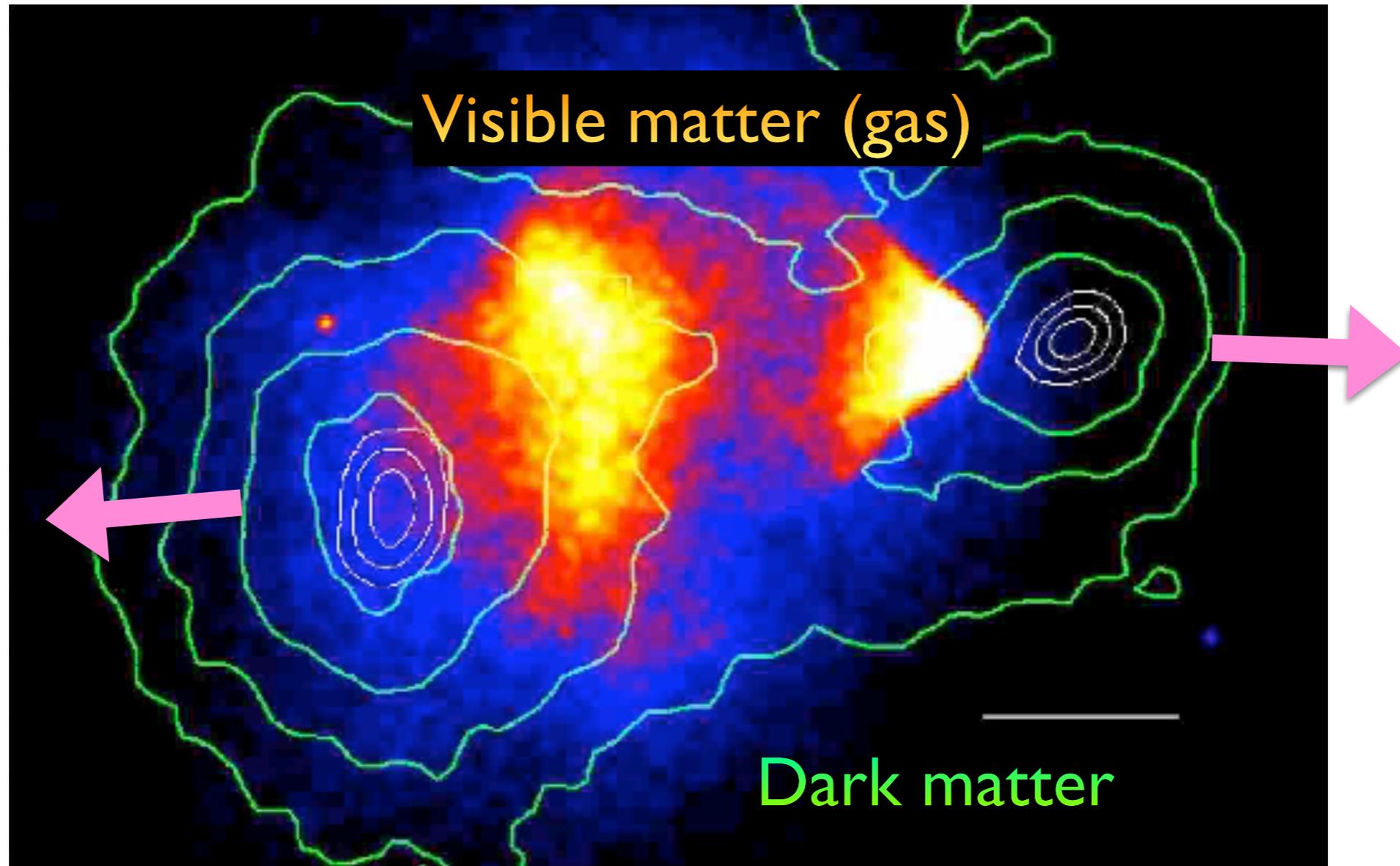
# One piece of evidence

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*Consider the collision of galaxy clusters:*



# One piece of evidence



Gas collided and formed a shock front  
Dark matter passed straight through

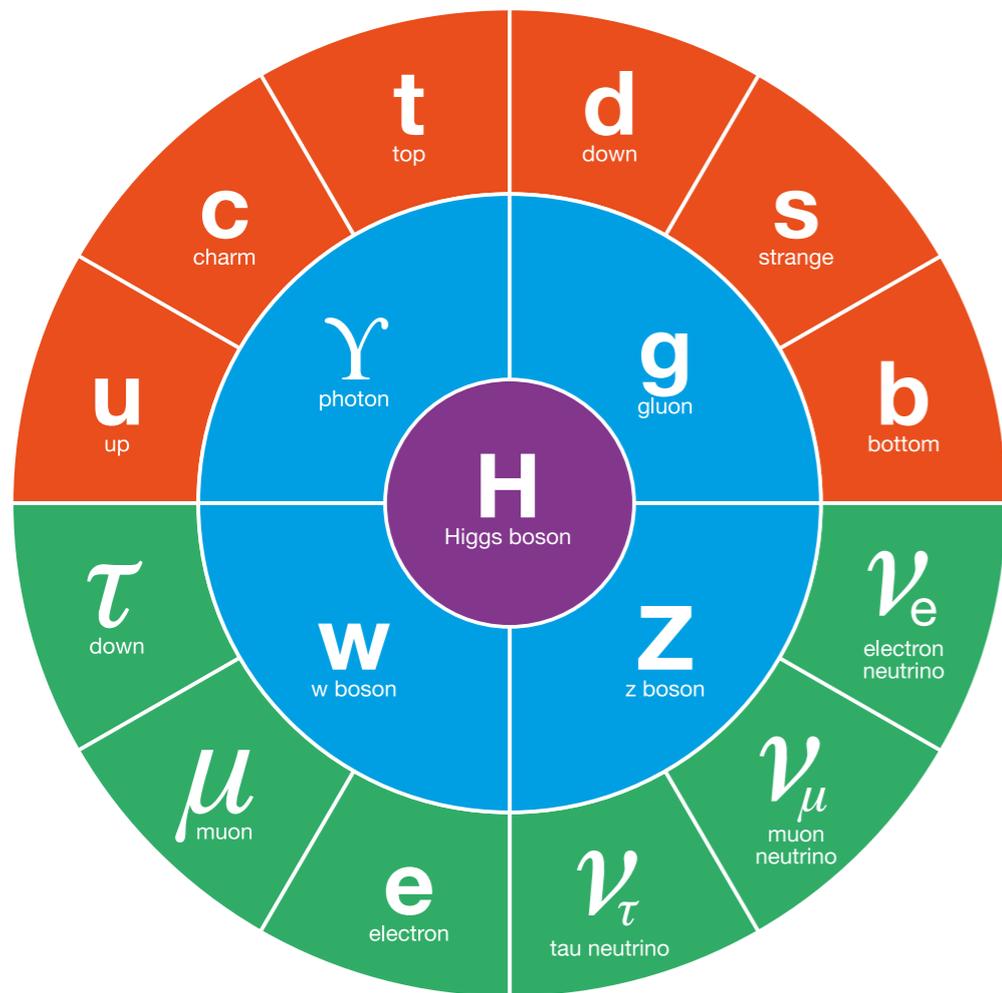
# Dark matter in our galaxy

***Visible stars embedded in a much larger invisible 'dark matter halo'***



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

# We have detected dark matter! Job done?



## 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: ?

# How can we find out more?

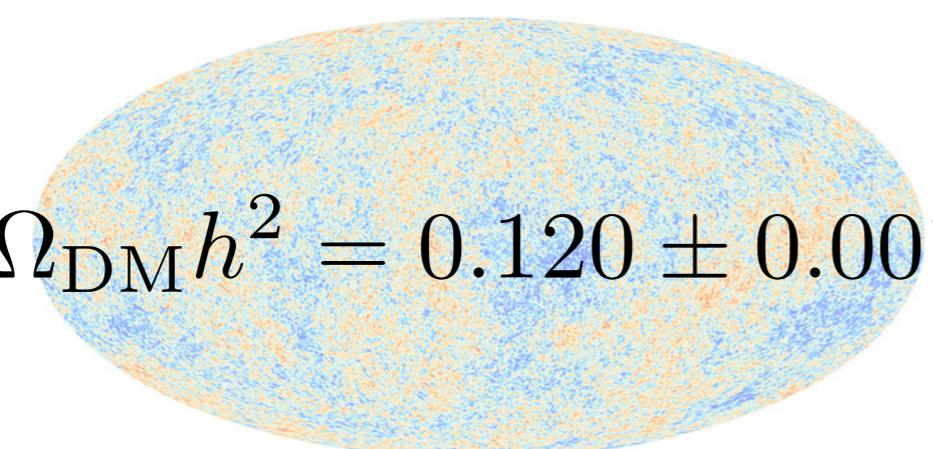
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*“Up to a point the stories of **cosmology** and **particle physics** can be told separately. **In the end though, they will come together.**”*

Steven Weinberg

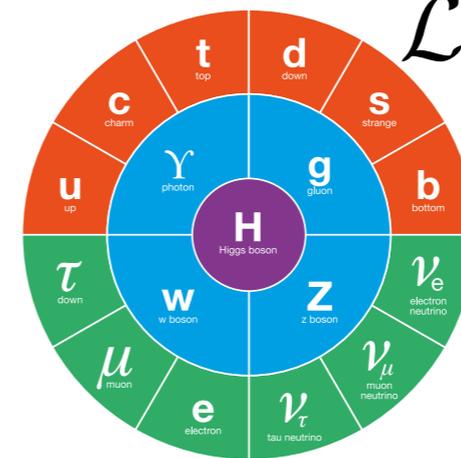
# How can we find out more?

## Cosmology


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

+

## Particle Physics



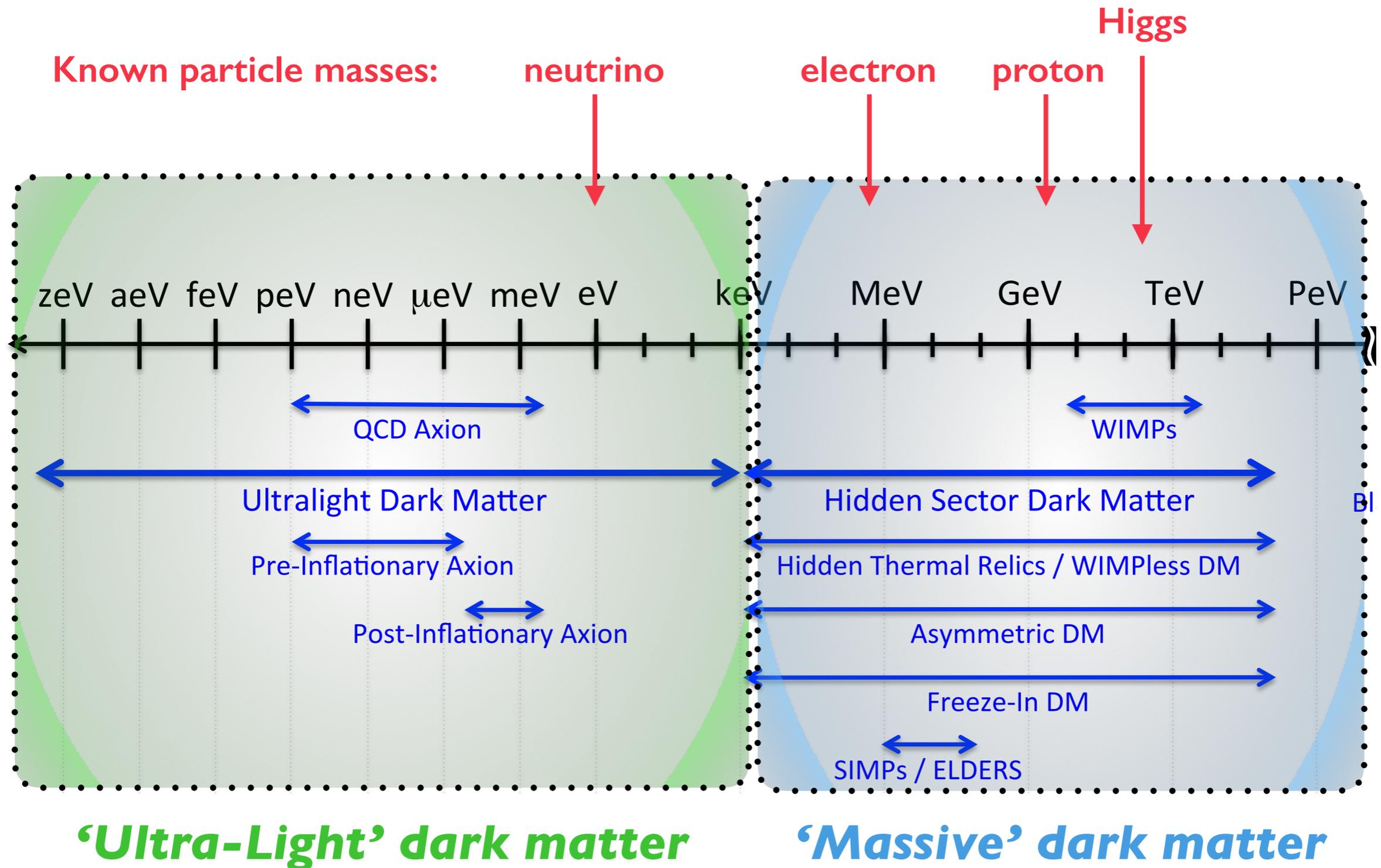
$$\mathcal{L} = \mathcal{L}_{\text{SM}}$$

$$+ \frac{m_q}{\Lambda^3} \bar{\chi} \chi \bar{q} q$$

+ ...

== Suggests dark and visible matter interactions are generic

# Many dark matter candidates



**How do you search for something you can't see?**

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How do you search for something you can't see?

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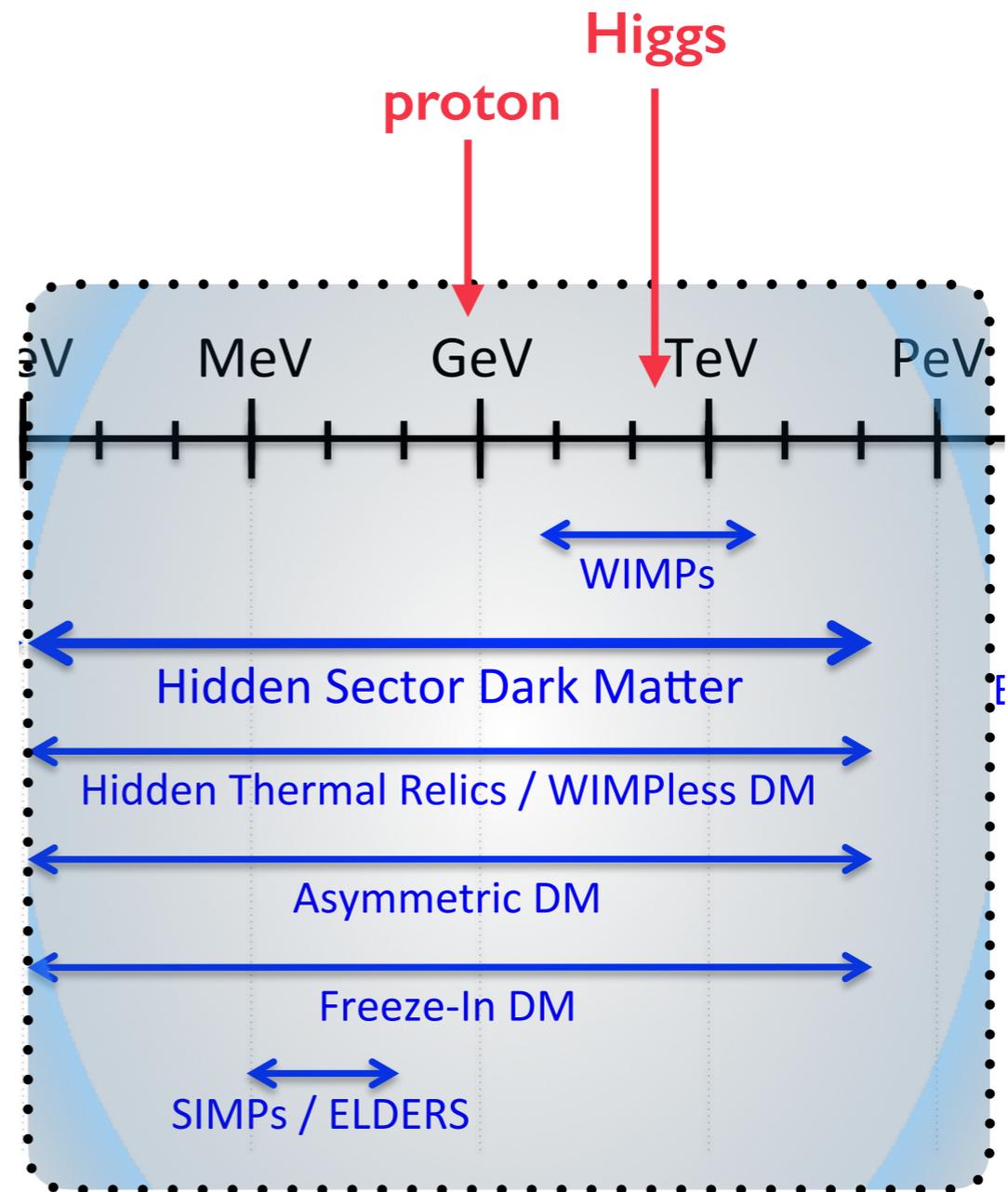
***Listen***

***Feel***

# Direct detection

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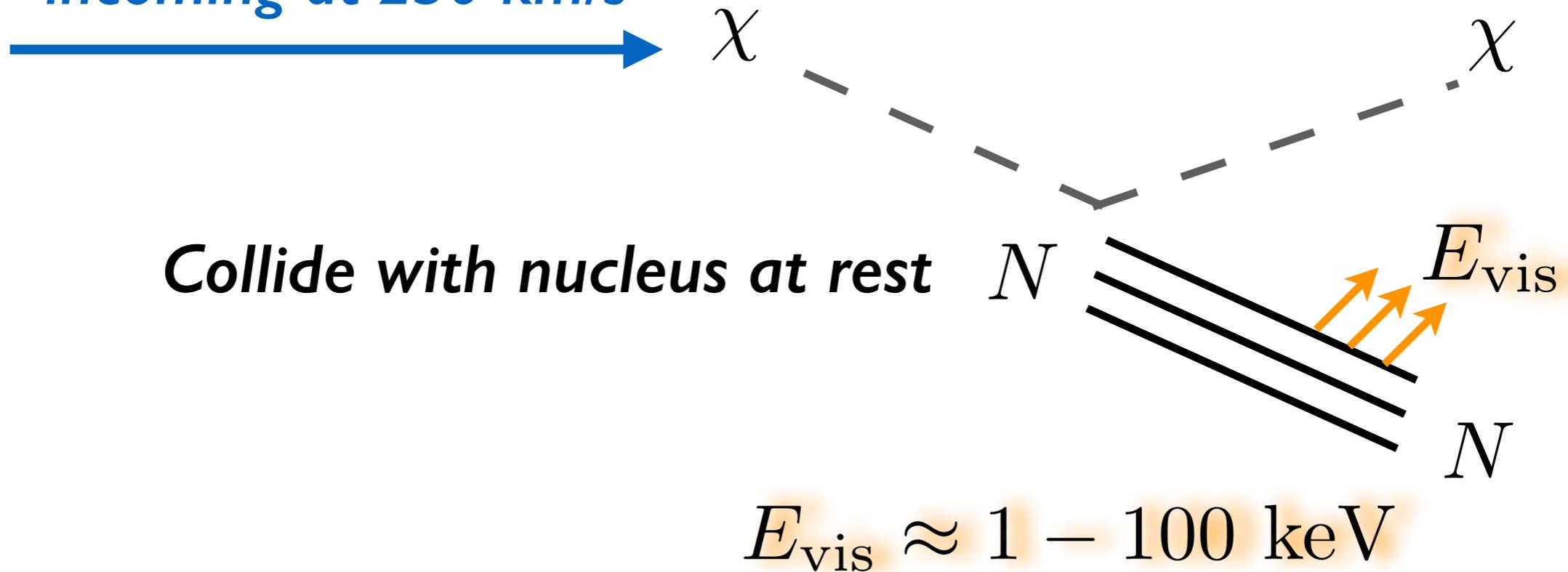
*Feel*



*'Massive' dark matter*

# Basics of direct detection

Wind of dark matter  
incoming at 250 km/s



Event rate: few events / year

World's most sensitive keV energy detectors

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



THE UNIVERSITY  
of EDINBURGH

Imperial College  
London



**UCL**



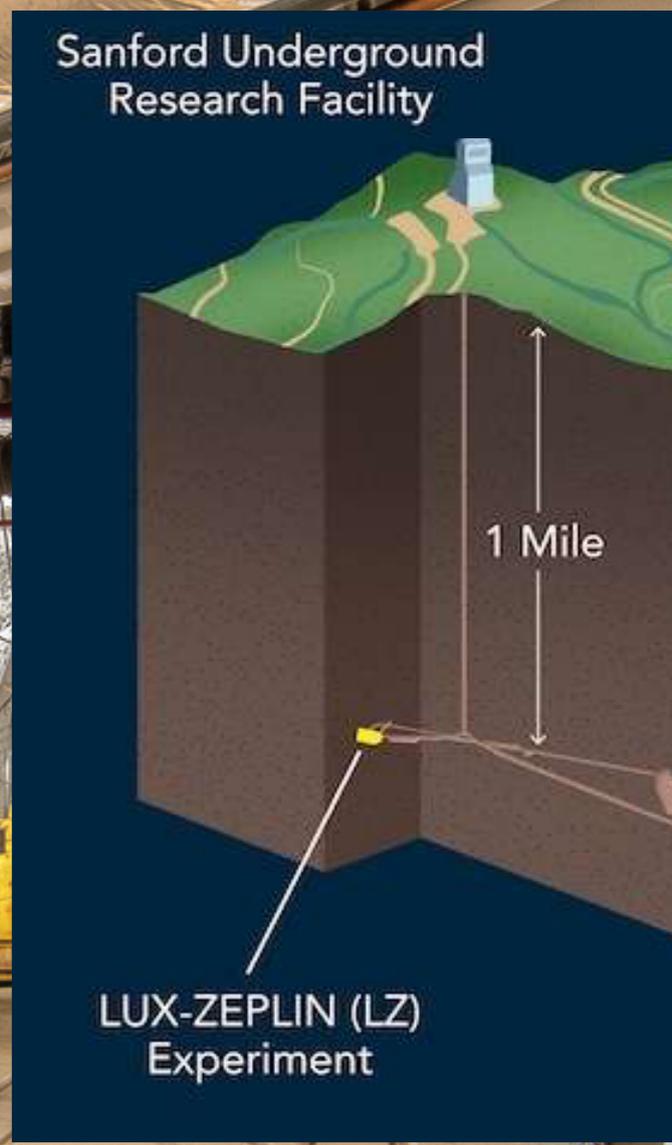
+ 30 institutes  
in US, Portugal,  
South Korea &  
Russia



Surface facilities at SURF  
where LZ is based  
Image credit Sanford Underground Research Facility

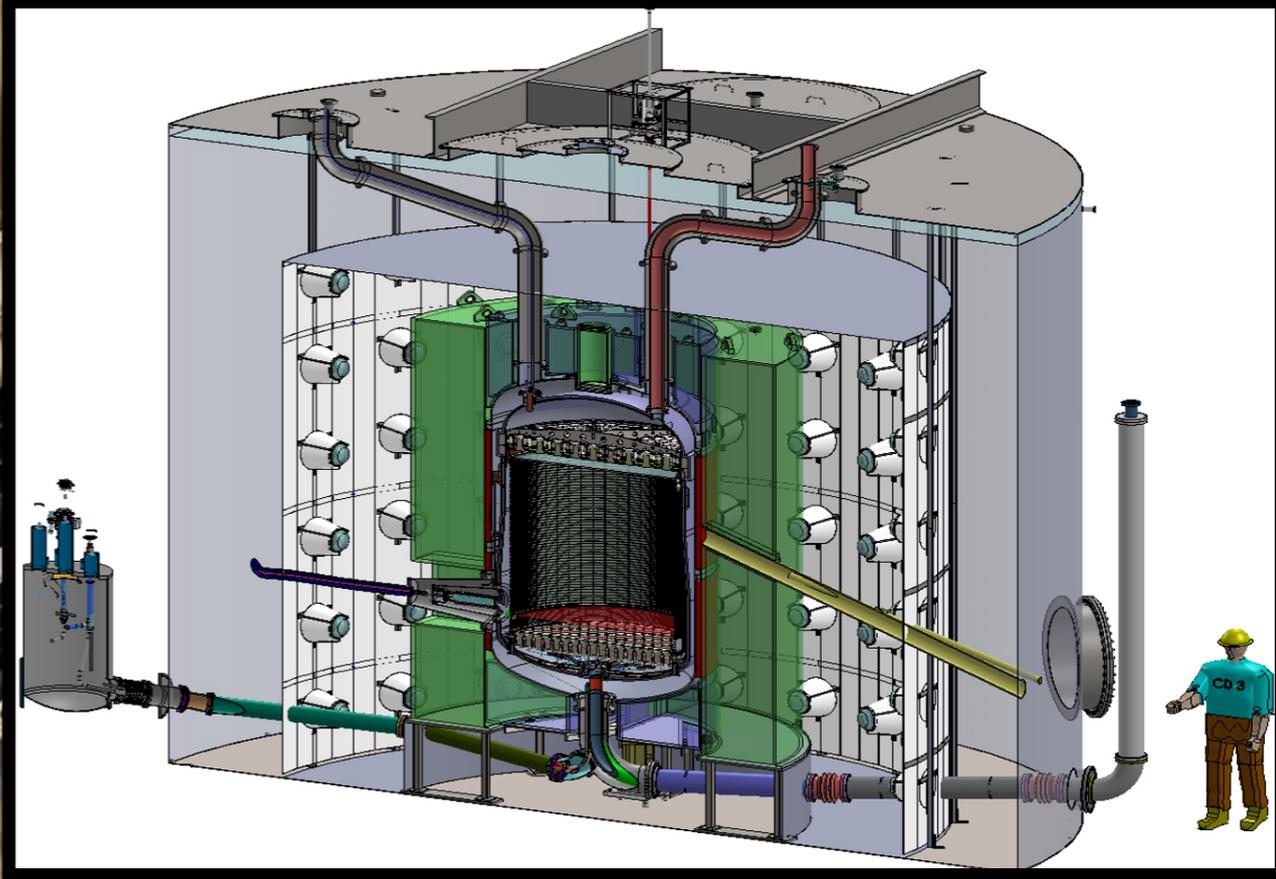
**Access to Davis Lab to left and  
Yates shaft cage to right.**

Image credit Sanford Underground Research Facility



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





View of the water tank -  
provides even more shielding.  
LZ is installed inside  
Image credit Carlos Faham

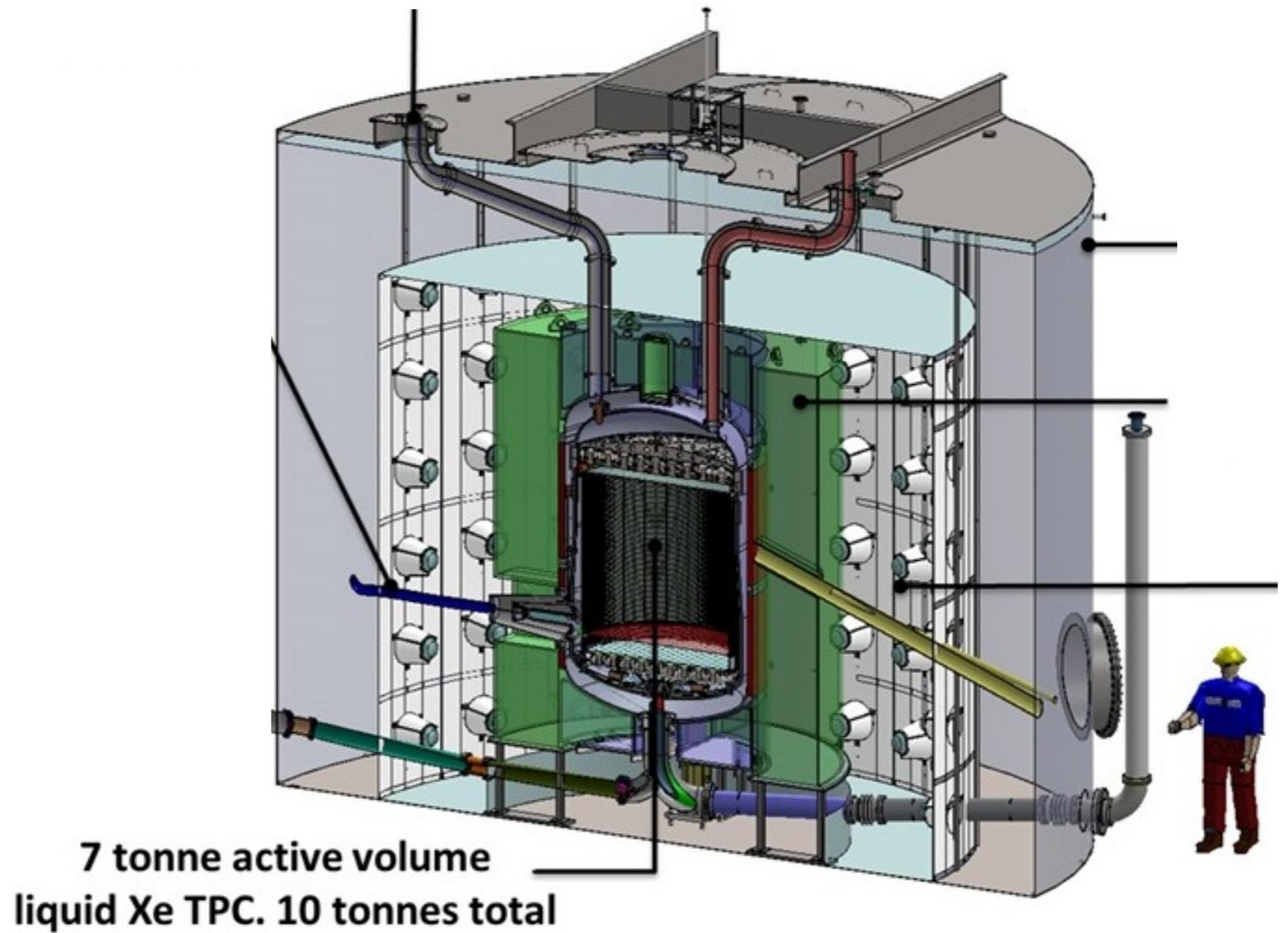
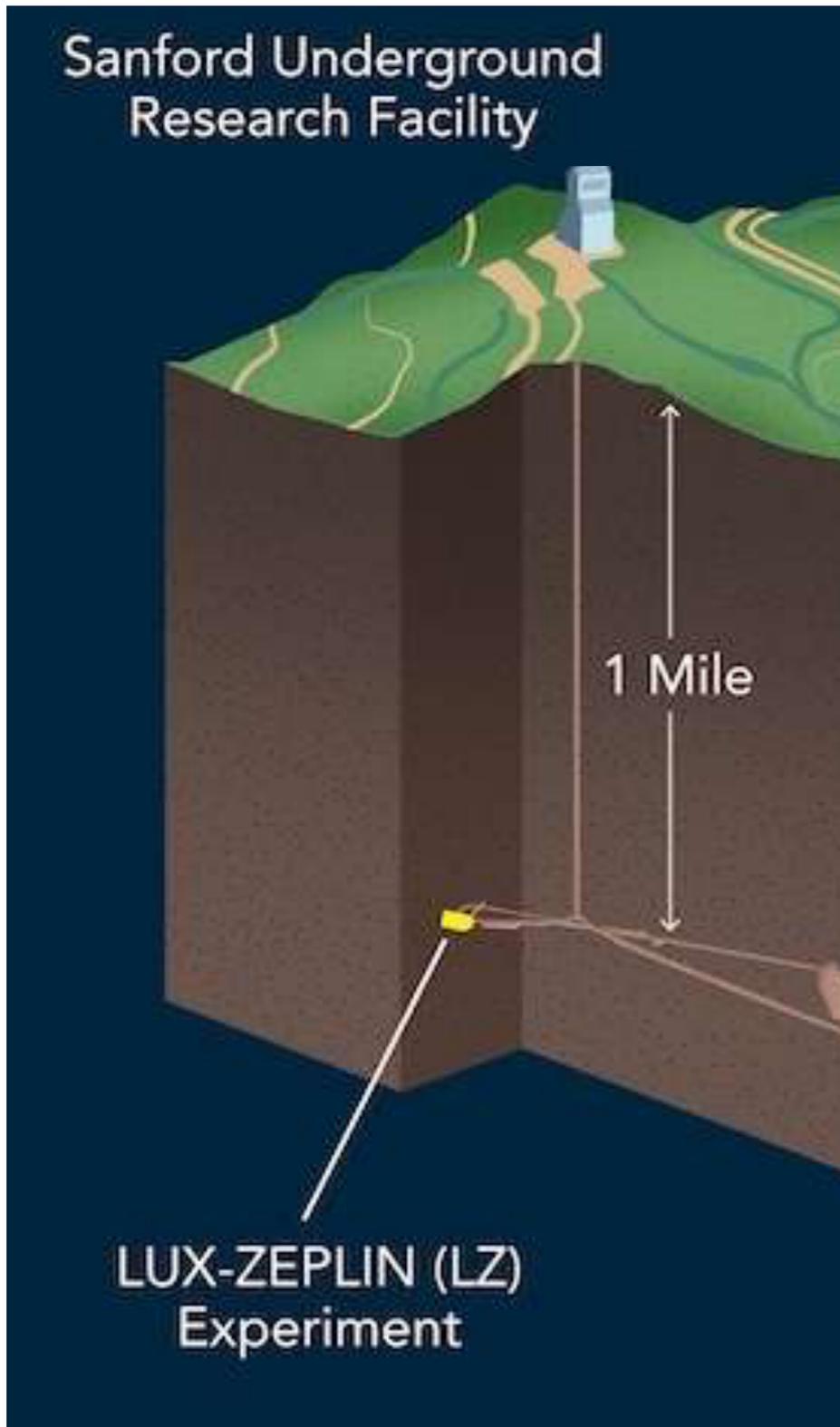




# Experiment inside the water tank

Image credit Sanford Underground Research Facility

# LZ detector

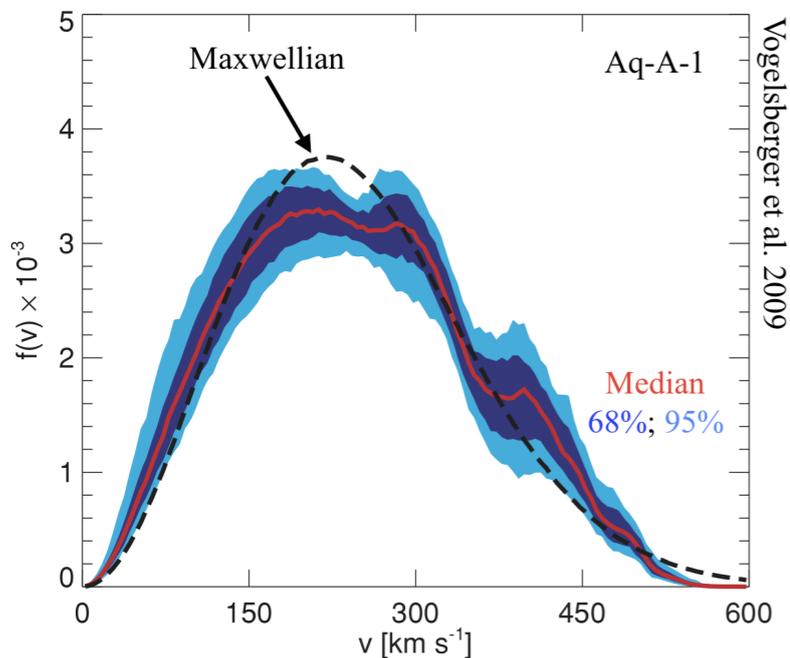


# The theorist's job

$$\text{signal} = \text{Flux} \times \text{cross section} \times \text{detector response}$$

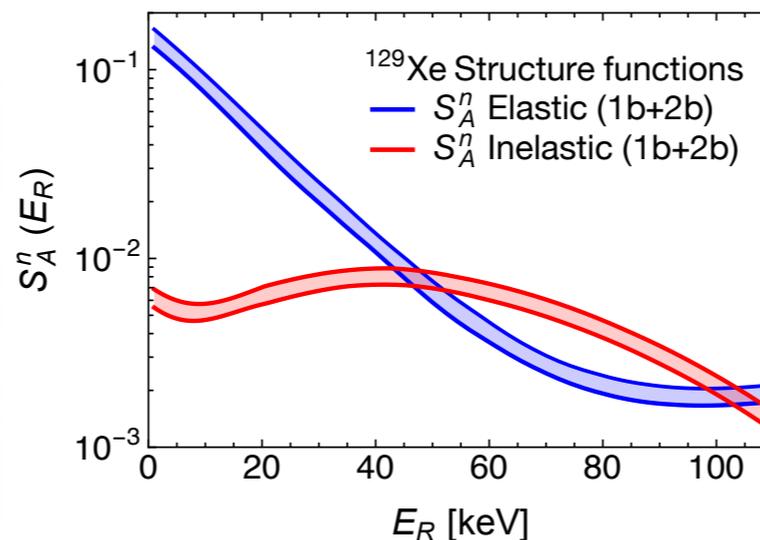
$$\text{signal} = \text{astrophysics} \times \text{particle/nuclear physics} \times \text{low-energy/atomic physics}$$

## DM velocity distribution

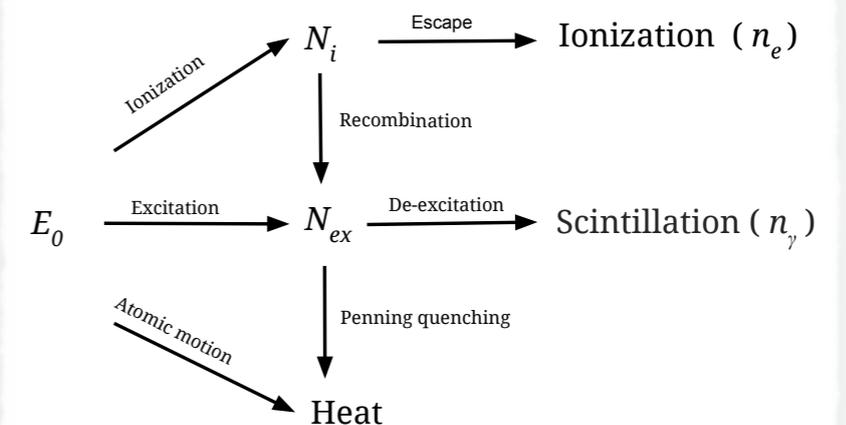


## Favourite DM theory

$$\mathcal{L} = \frac{1}{\Lambda^2} \bar{\chi} \chi \bar{q} q + \dots ?$$

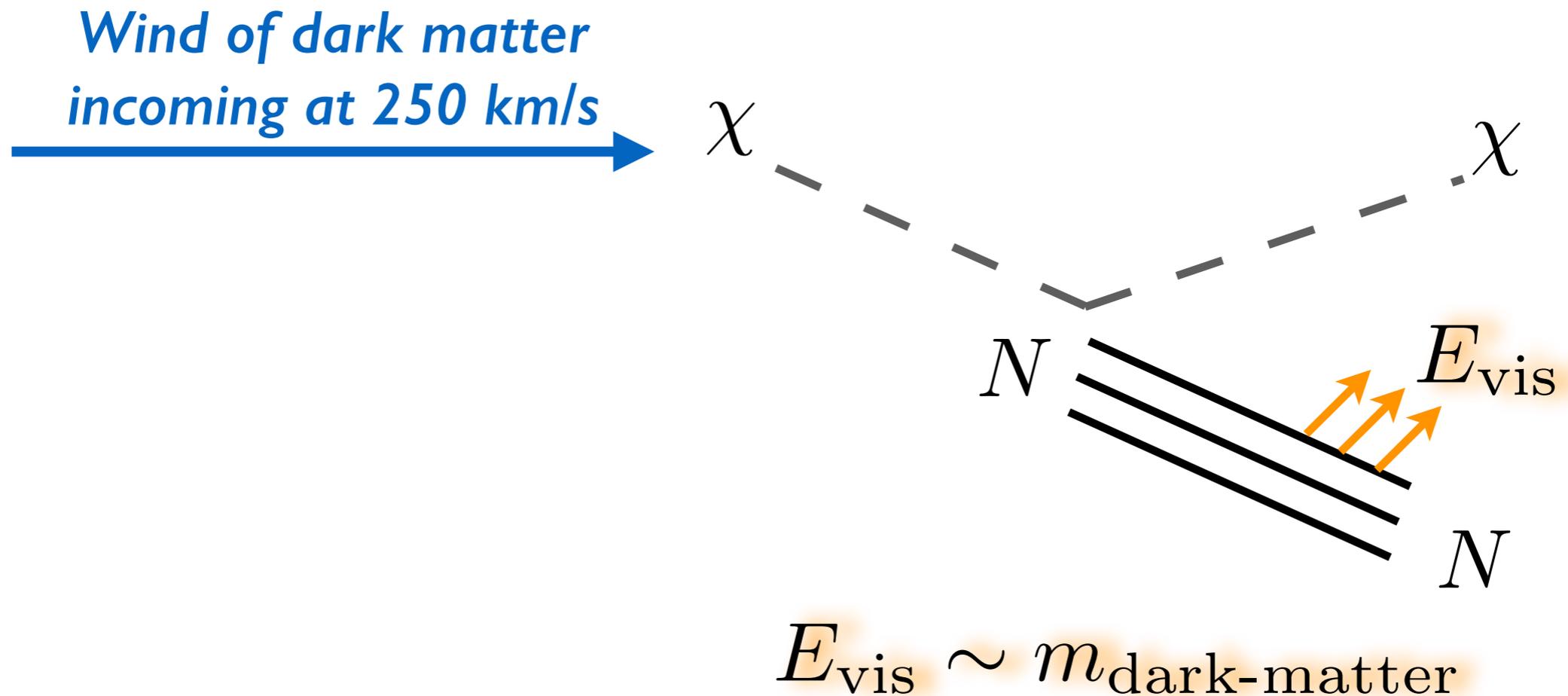


## Recoil energy transferred to photons, electrons or heat



# Theory in simple terms

## I. Nucleus recoil energy tells you about the dark matter mass

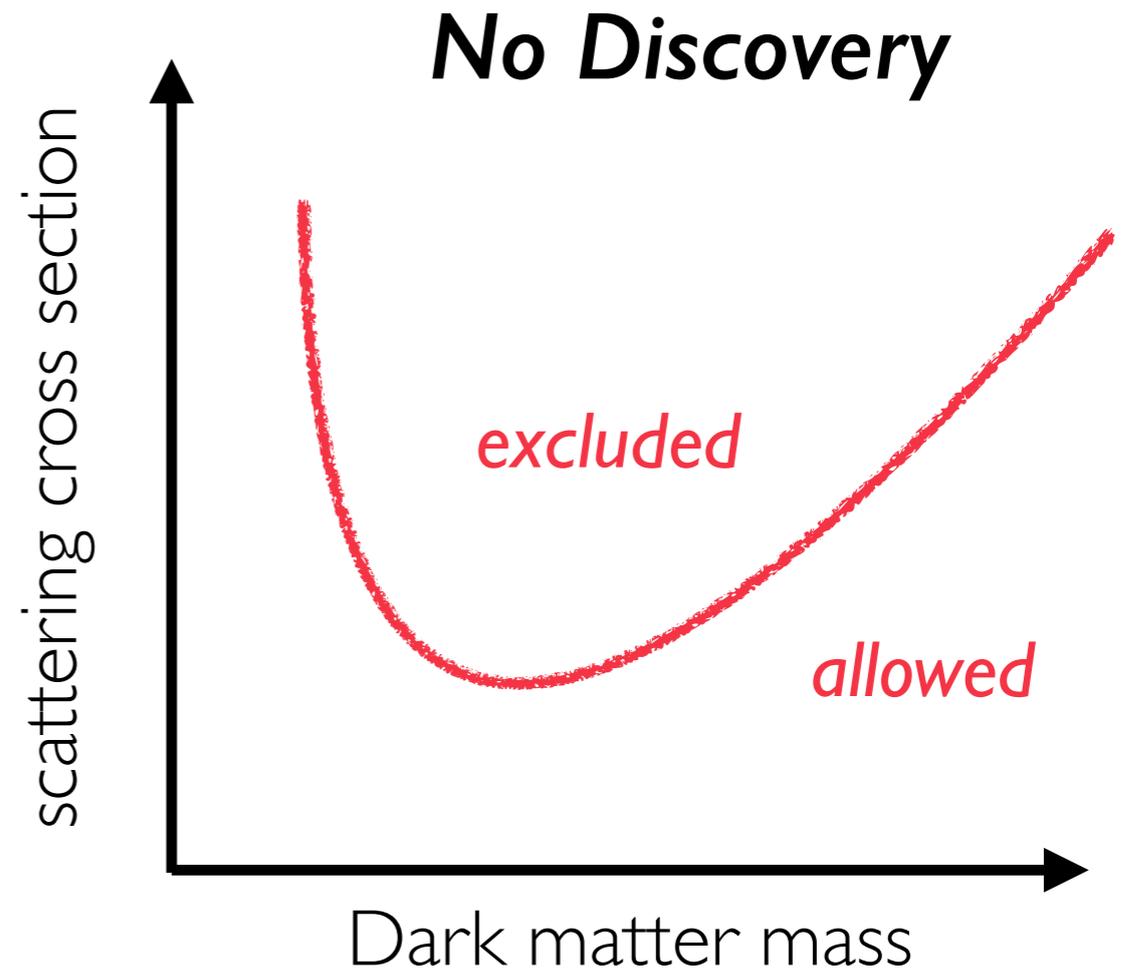
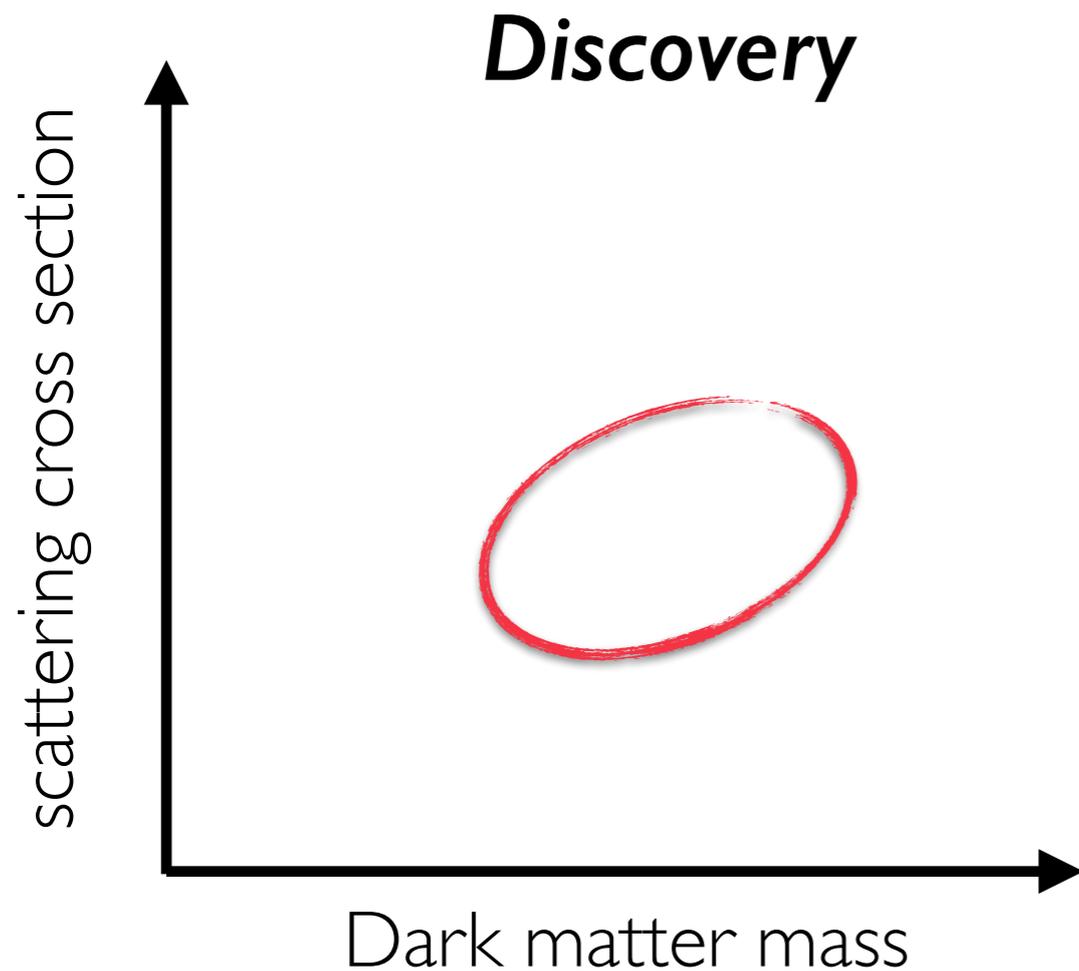


## 2. Rate of collisions tells you about the force between dark matter and visible matter

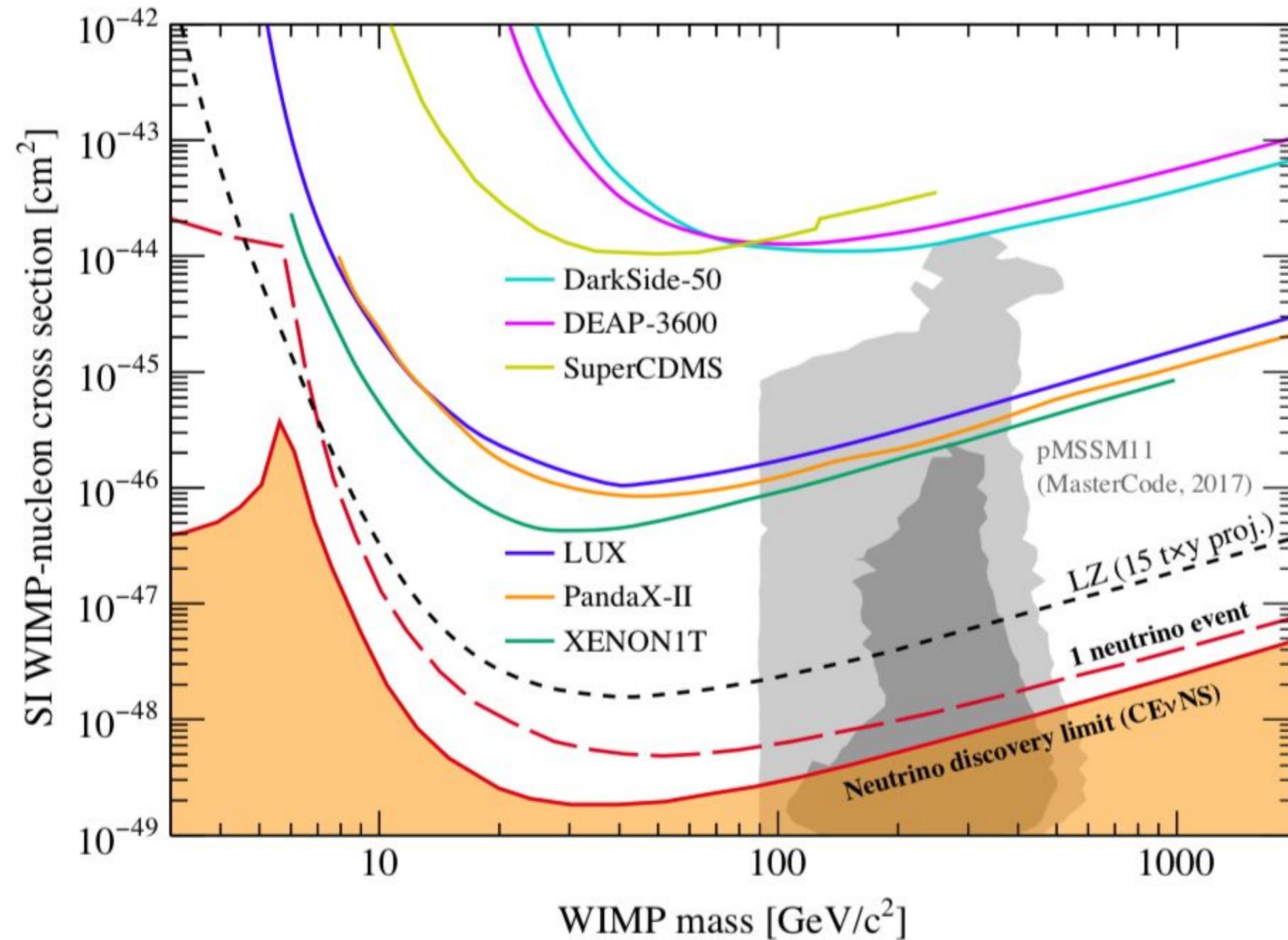
# In simple terms

These experiments can tell us about:

1. *Dark matter mass*
2. *Force between dark and visible matter (cross section)*



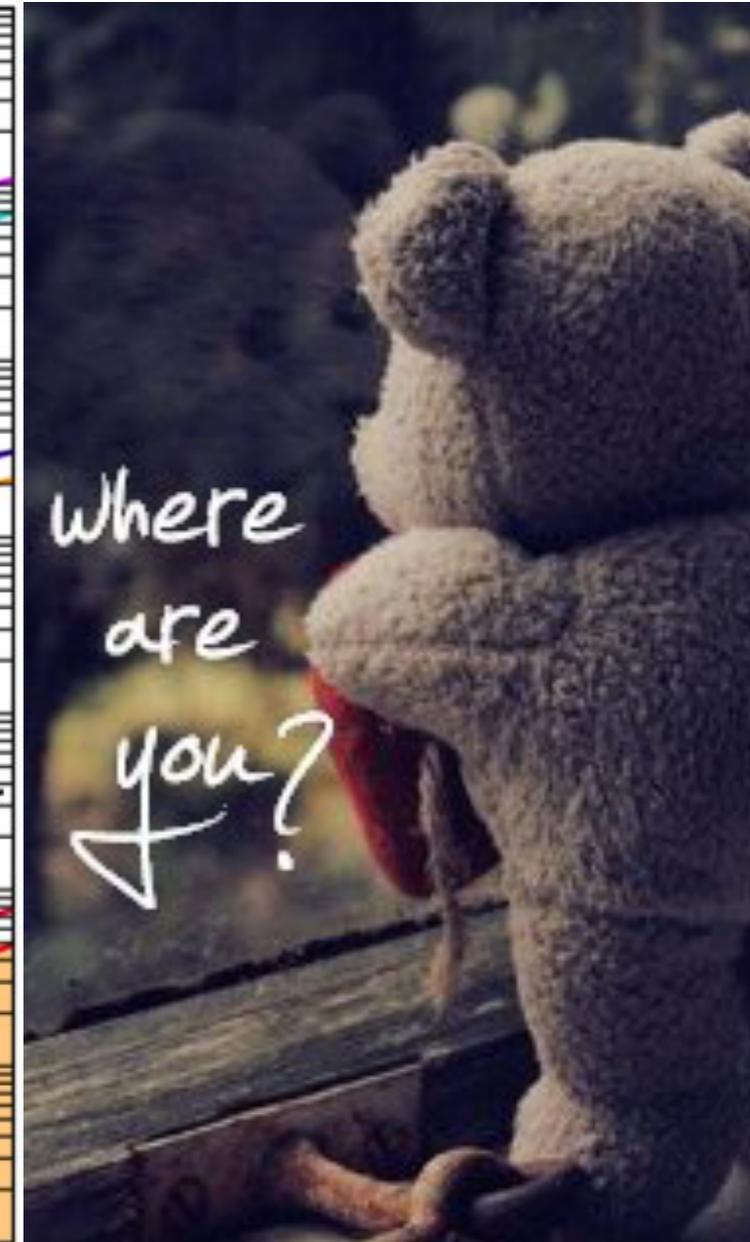
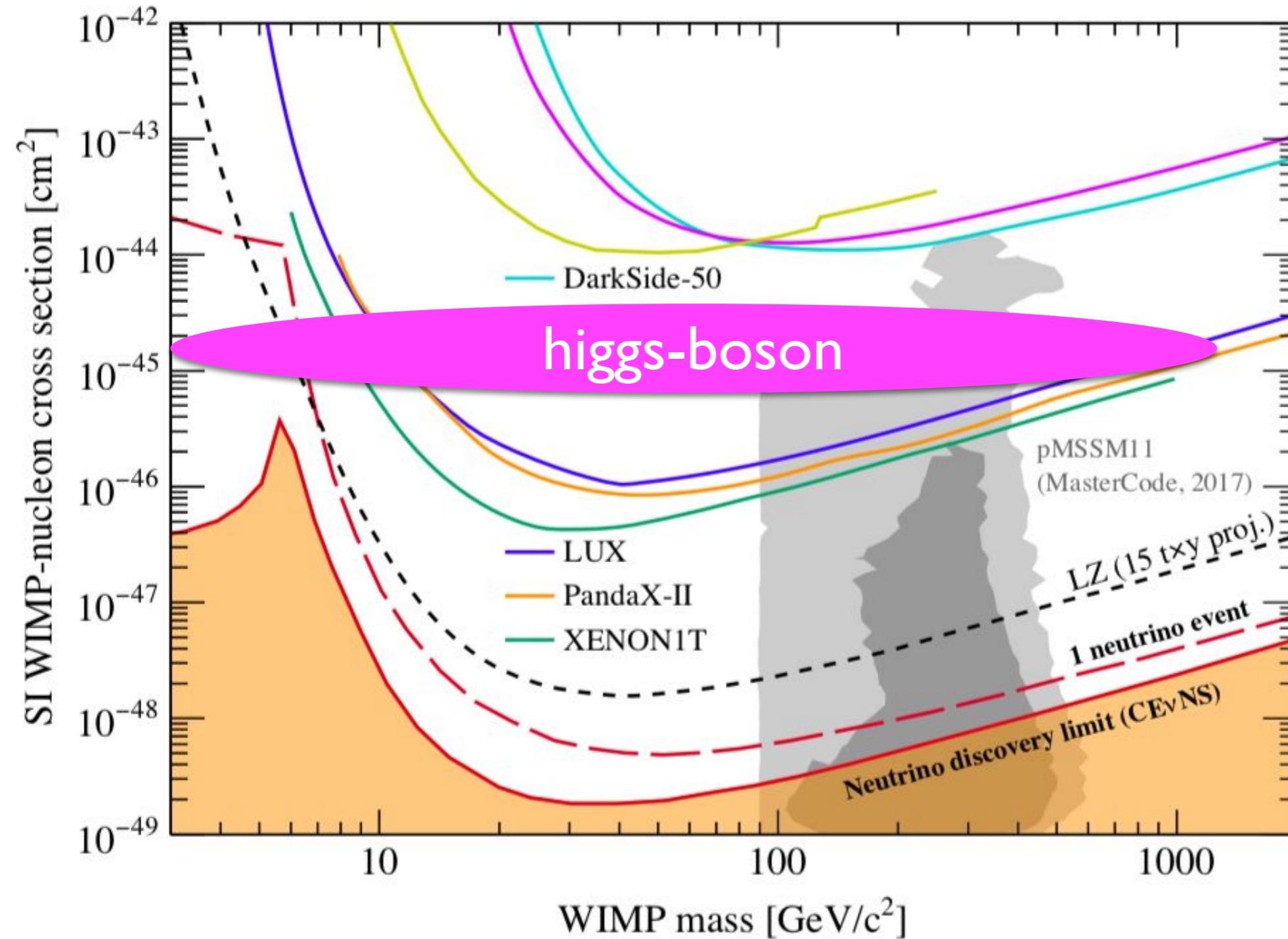
# No discovery yet...



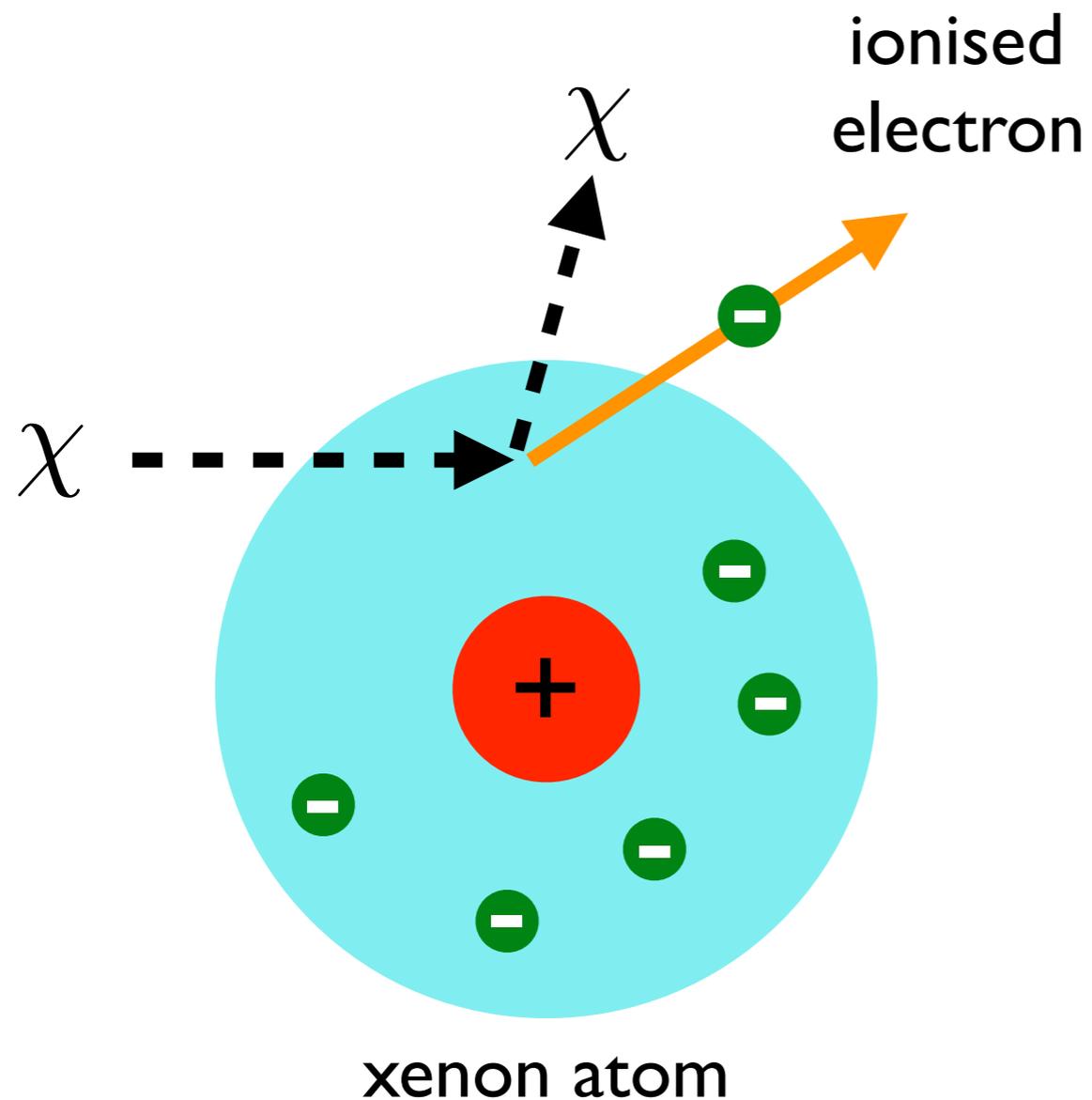
# No discovery yet...

$10^{-39}$

$Z^0$ -boson



# Can also ionise atoms



For ionisation, require:

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

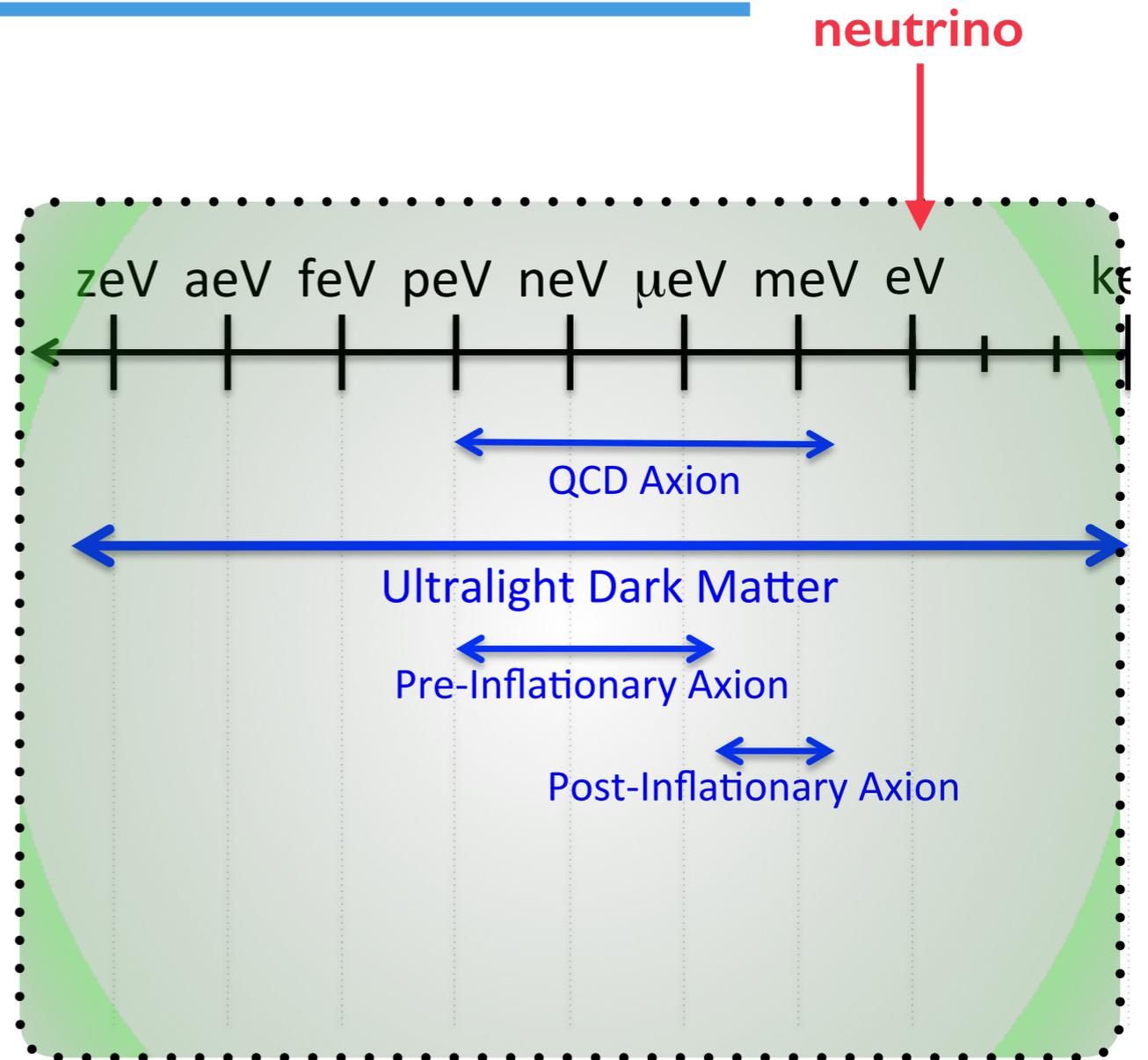
$$m_{\text{DM}} \gtrsim 5 \text{ MeV}$$

# No discovery yet...

---

# Haloscopes and quantum sensors

***Listen***

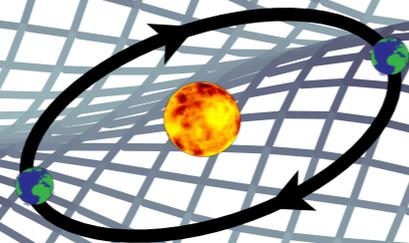


***'Ultra-Light' dark matter***

# Ultra-light dark matter

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

*Better modelled as a wave rather than individual particles*



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

# ADMX: Axion Dark Matter eXperiment

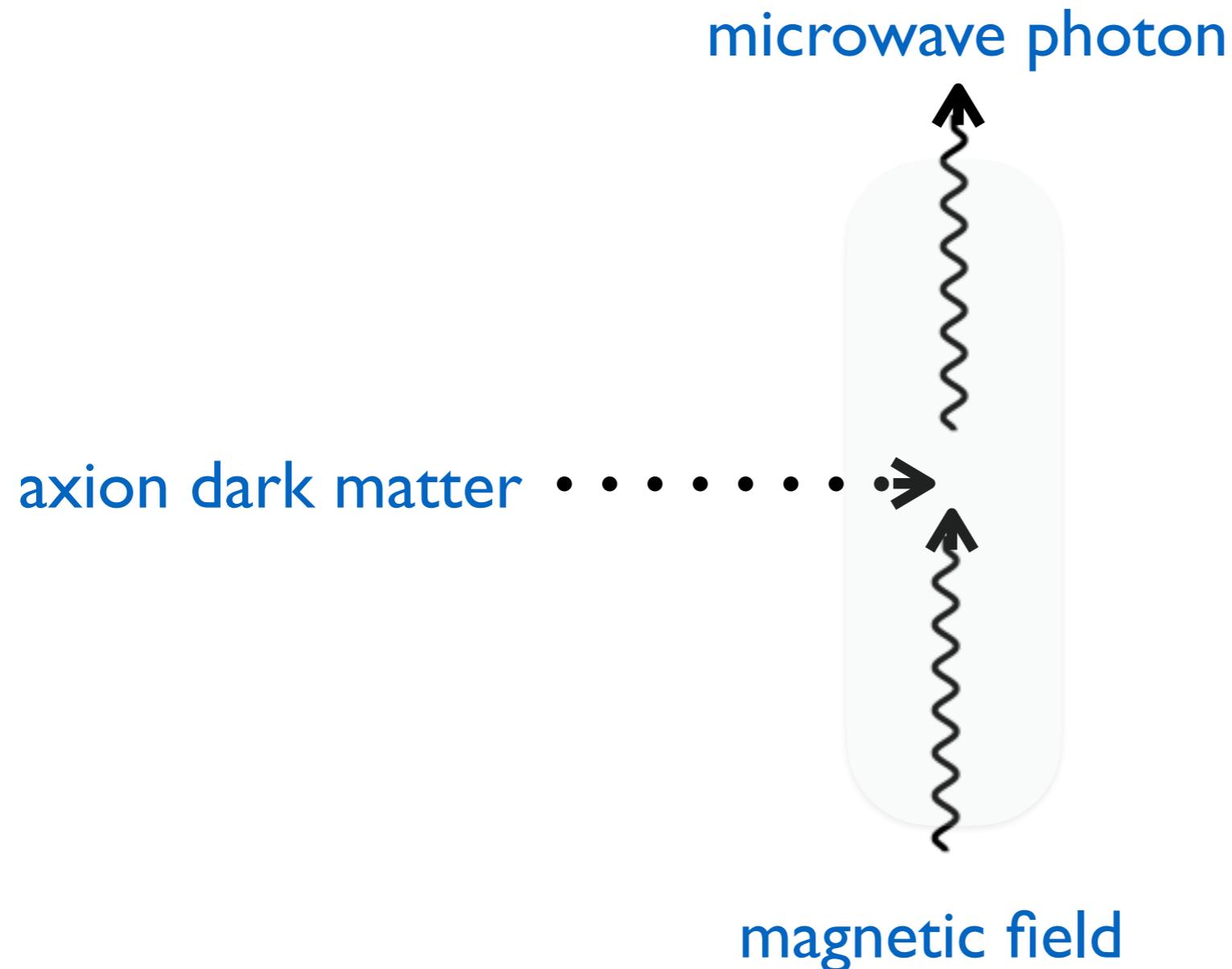
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*University of Sheffield + 8 USA institutions*

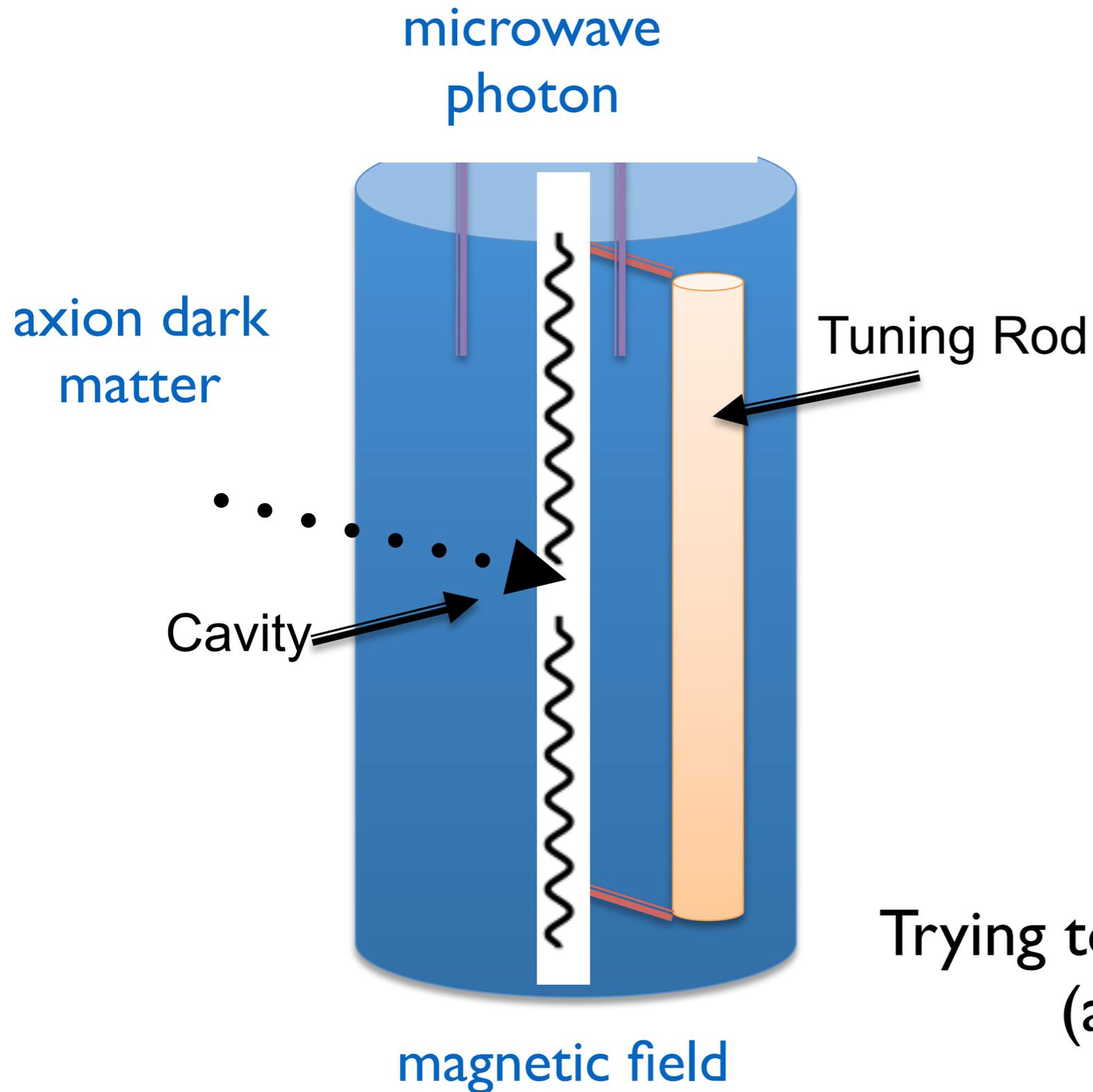
# ADMX: Axion Dark Matter eXperiment

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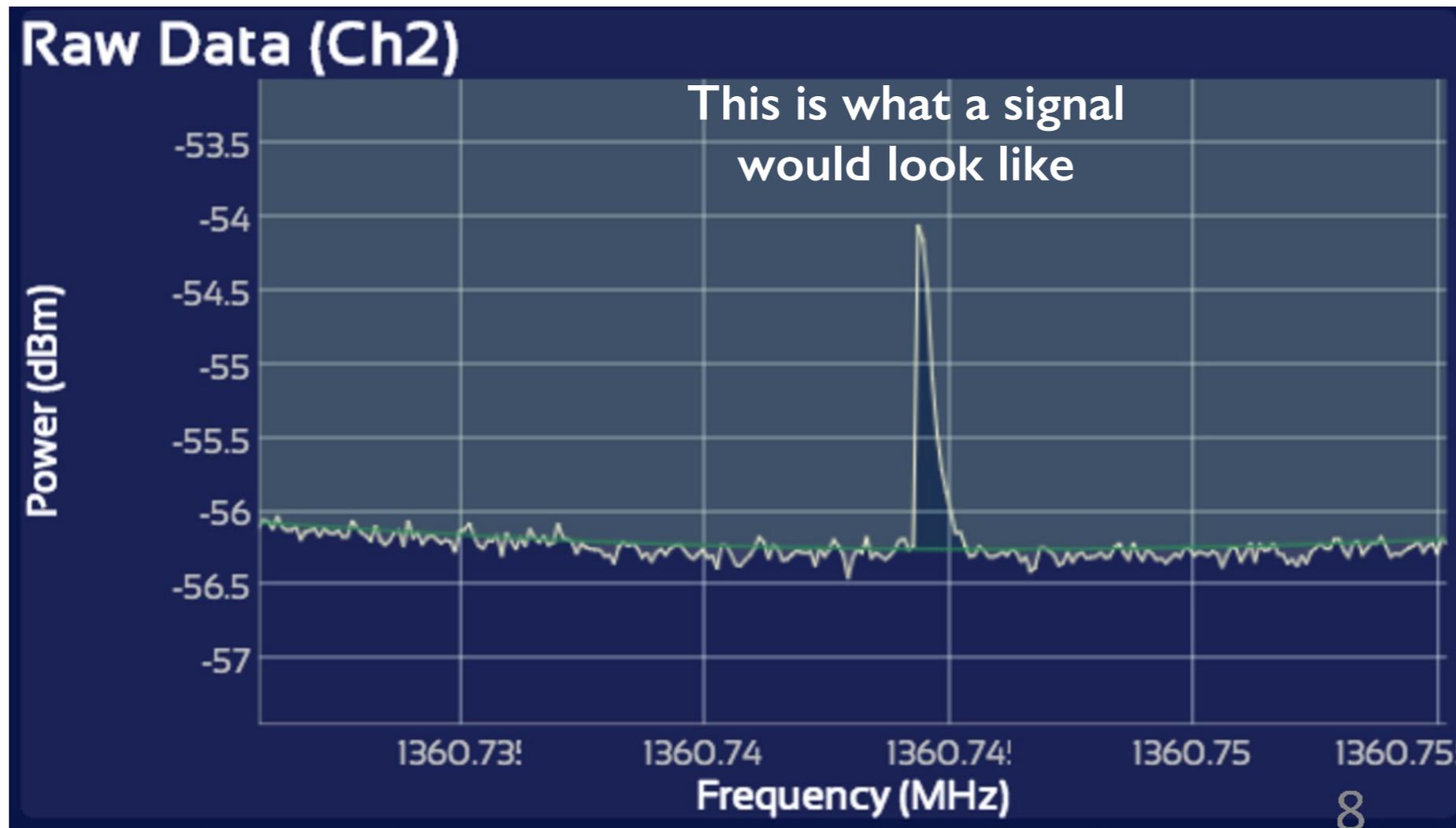
**Axions in magnetic fields convert to microwave photons**

# ADMX: Axion Dark Matter eXperiment



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

# ADMX: Axion Dark Matter eXperiment

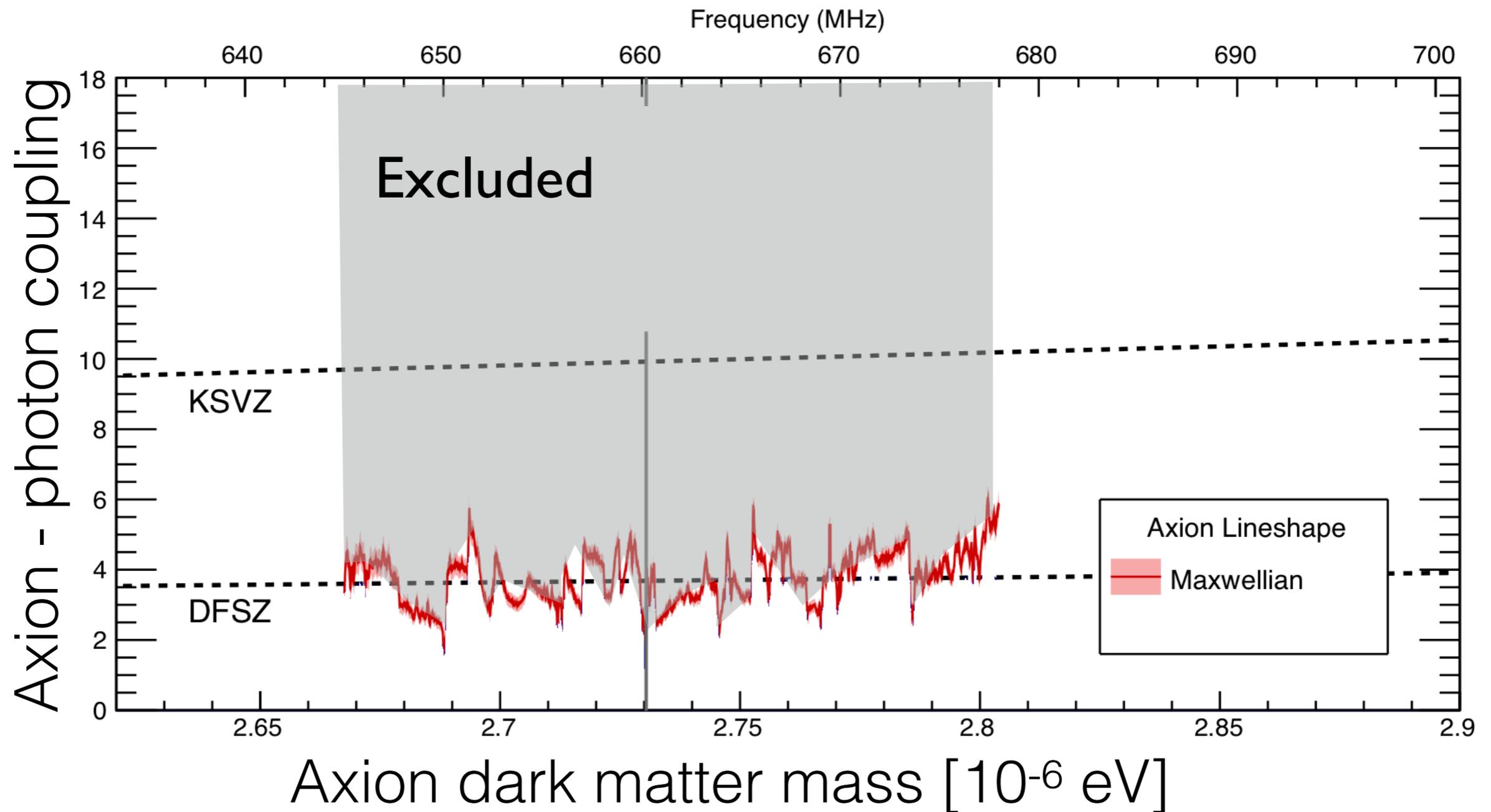


*Tuneable cavity:*

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

# No discovery yet...

*Experiments could tell us:  
the axion dark matter mass & axion-photon coupling*



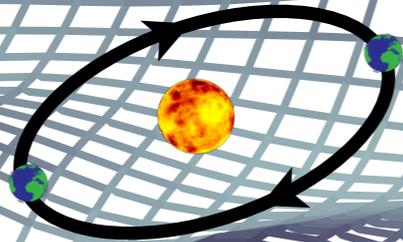
# Quantum sensors

*Oscillating dark matter can induce changes in fundamental constants*

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

*Induces tiny changes in atoms: a new field opening up*

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



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

# Summary

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- We know dark matter exists...  
... but we have yet to measure the particle properties
- Many ideas for what dark matter could be...  
...and many experiments searching for them
- A truly global effort with the UK at the forefront