Dark matter detection with atomic spectroscopy

Jack Shergold

& Martin Bauer, Javier Pérez-Soler; 2407.12913

JHEP 10 (2024), 176
and 2507.14287

Contents

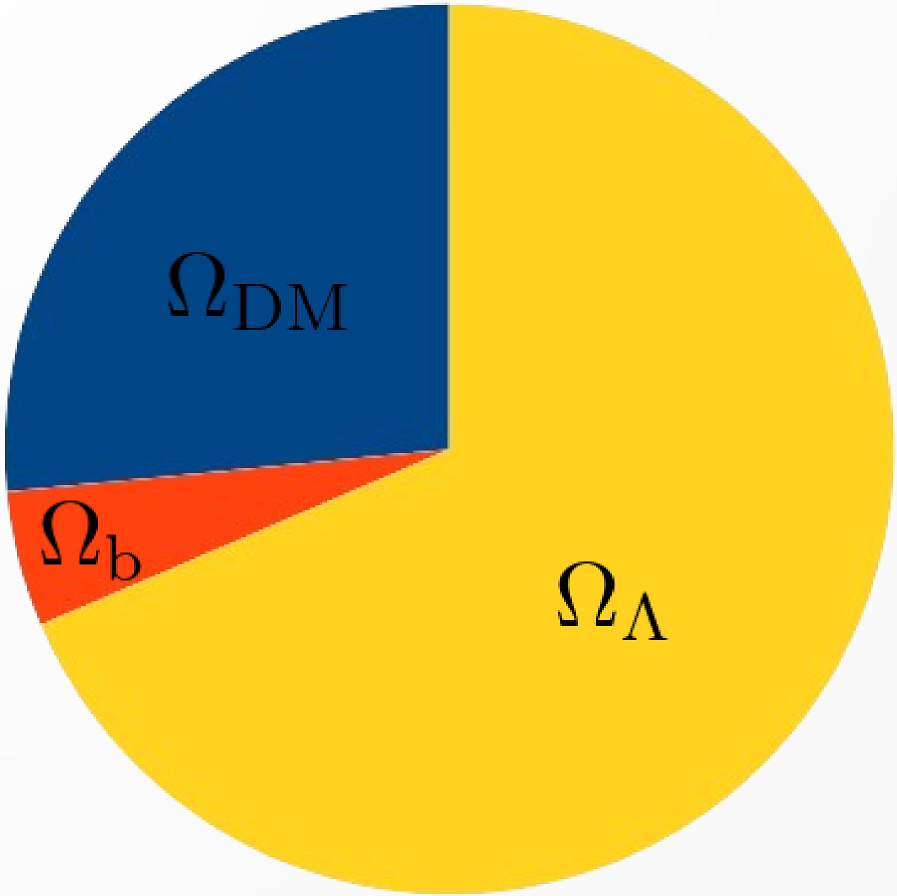
- Generalised hydrogen interactions
- Pair absorption

Contents

- Generalised hydrogen interactions ⇐
- Pair absorption

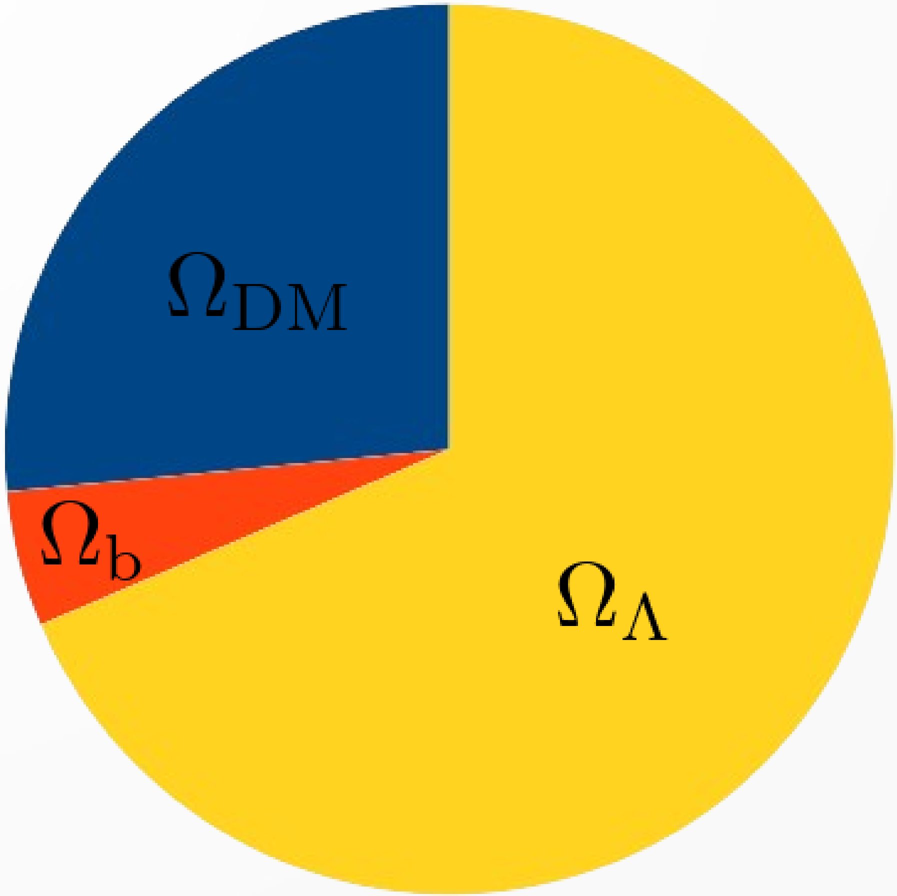
Generalised hydrogen interactions

- Gravitional evidence for dark matter on many scales



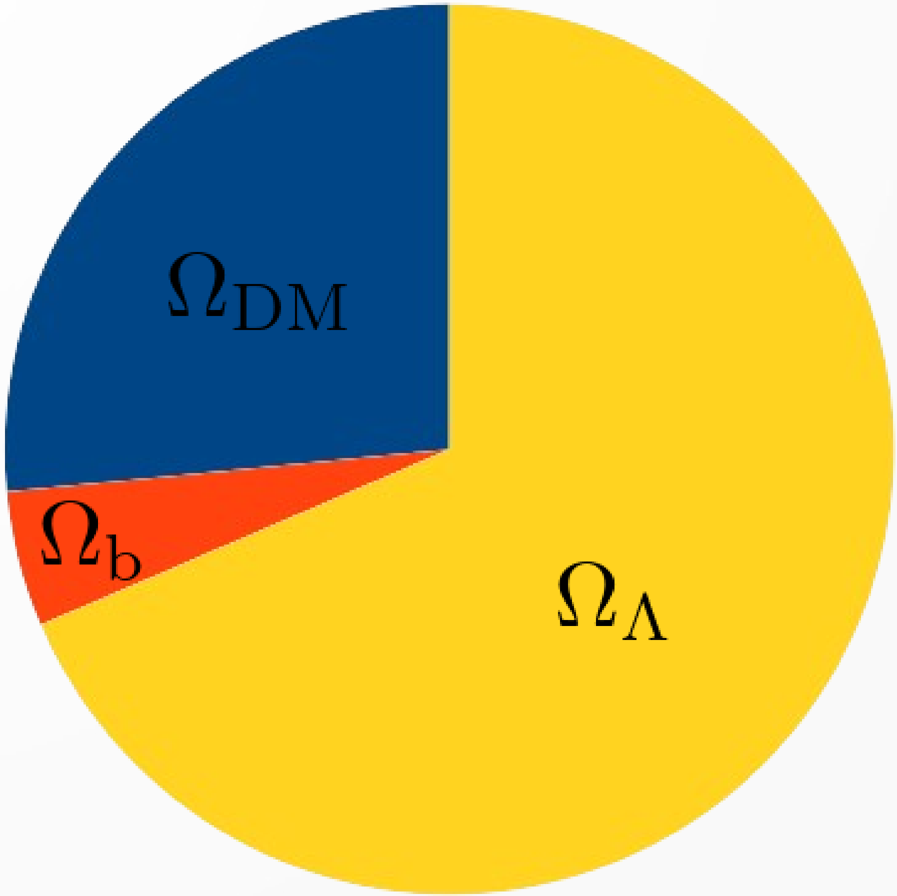
Generalised hydrogen interactions

- Gravitional evidence for dark matter on many scales
- Estimated to make up ~27% of the universe



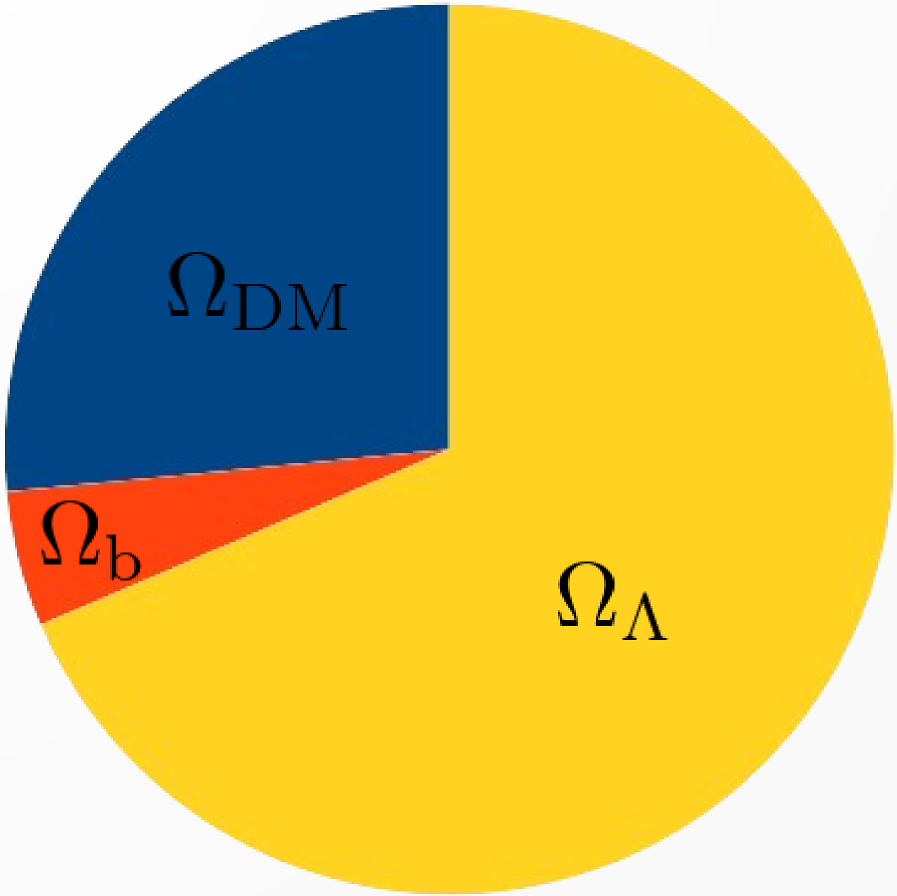
Generalised hydrogen interactions

- Gravitional evidence for dark matter on many scales
- Estimated to make up ~27% of the universe
- Microscopic nature completely unknown



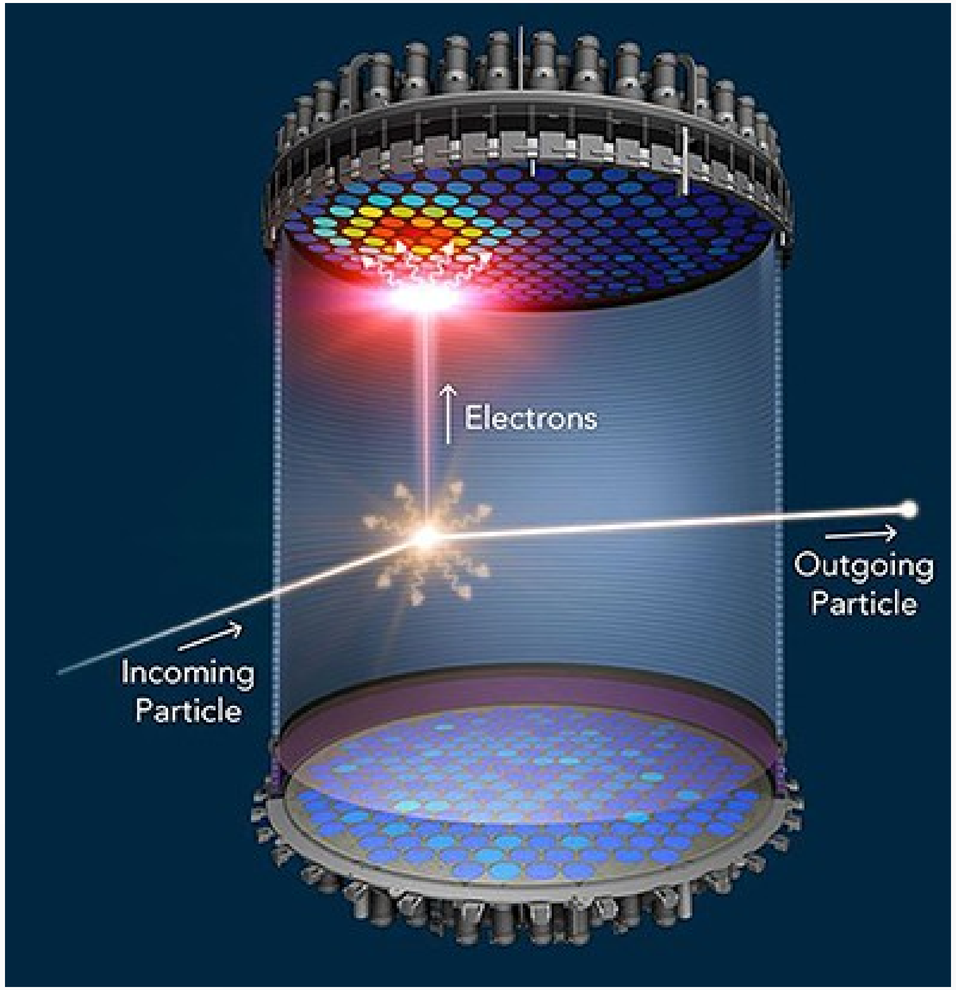
Generalised hydrogen interactions

- Gravitional evidence for dark matter on many scales
- Estimated to make up ~27% of the universe
- Microscopic nature completely unknown
- How do we search for it?



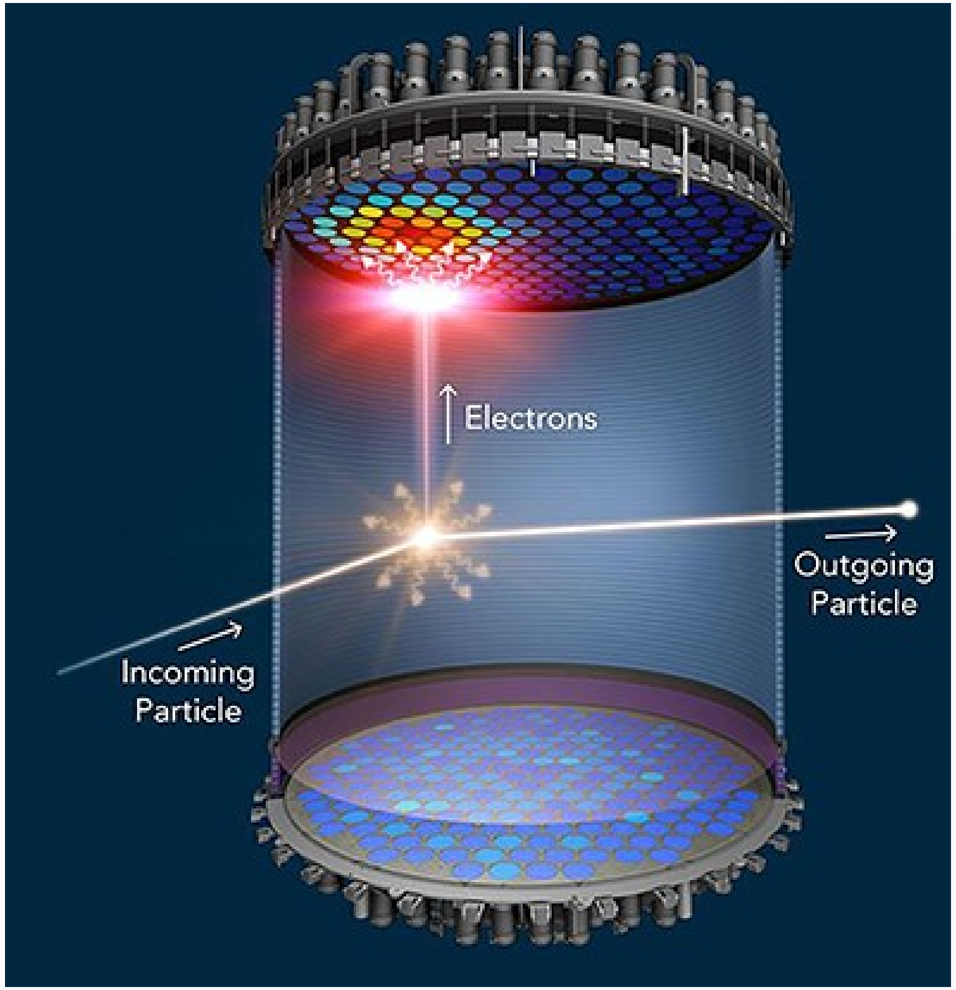
Generalised hydrogen interactions

- Cryogenic detectors



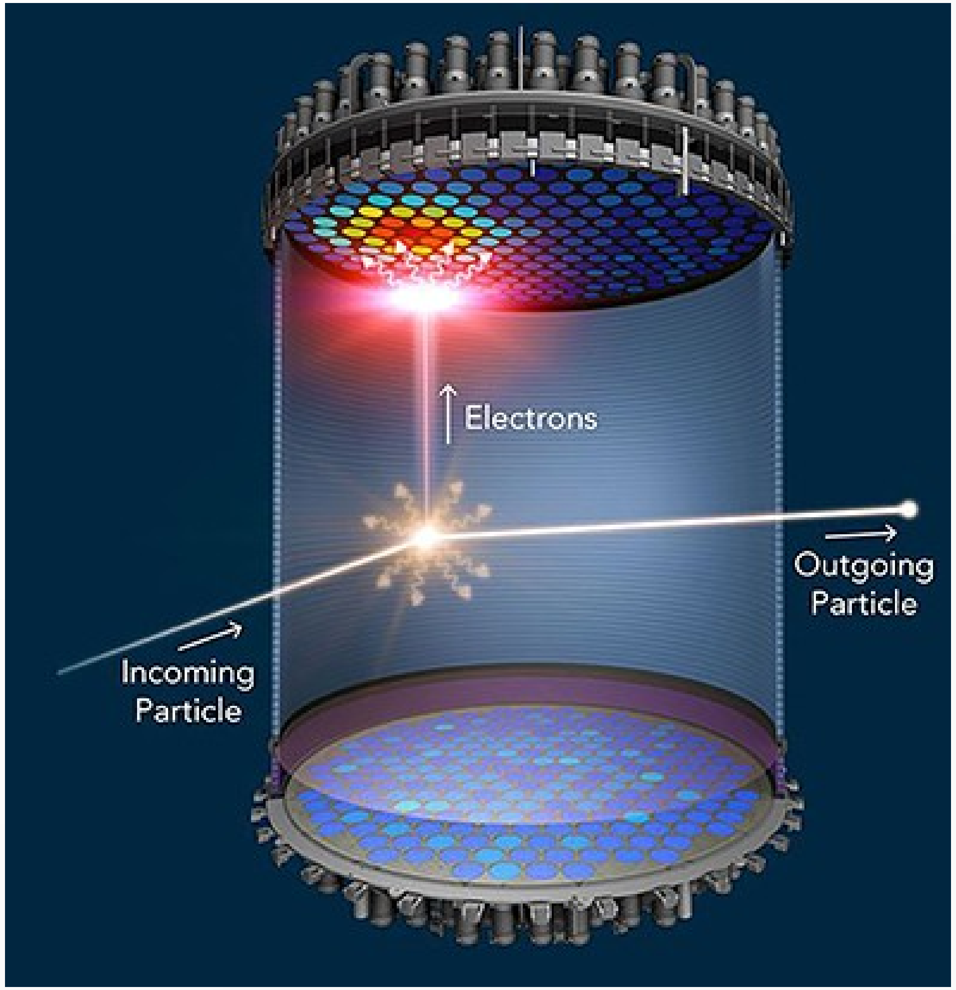
Generalised hydrogen interactions

- Cryogenic detectors
- Spin precession experiments



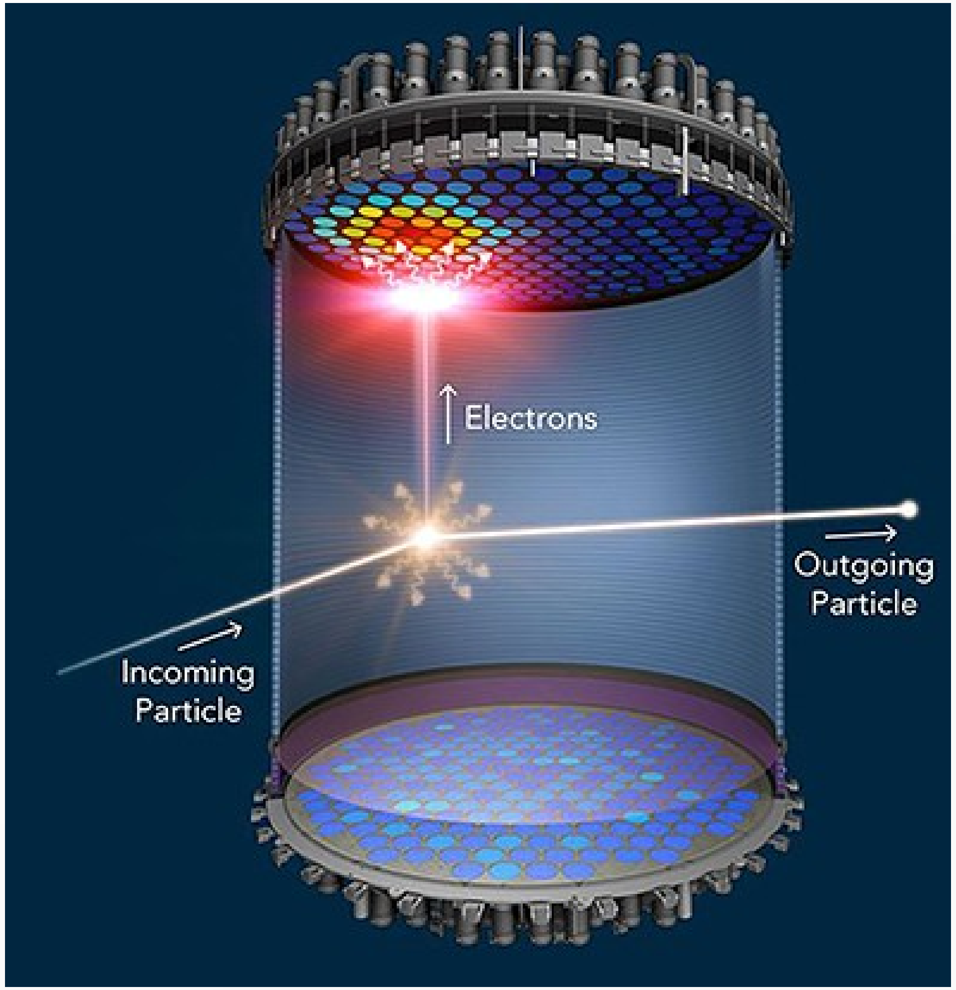
Generalised hydrogen interactions

- Cryogenic detectors
- Spin precession experiments
- Atom interometers



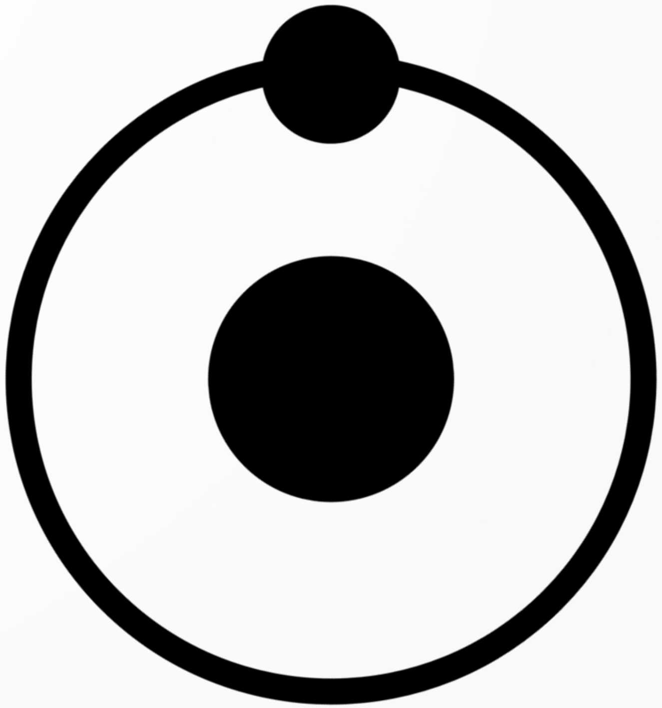
Generalised hydrogen interactions

- Cryogenic detectors
- Spin precession experiments
- Atom interometers
- …



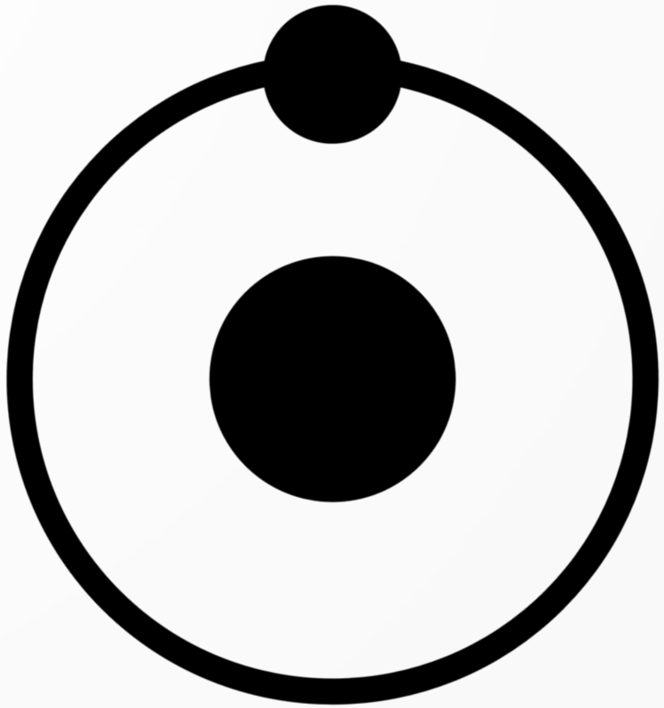
Generalised hydrogen interactions

- Hydrogen is one of the best studied QM systems



Generalised hydrogen interactions

- Hydrogen is one of the best studied QM systems
- Hydrogen is a very *clean* laboratory

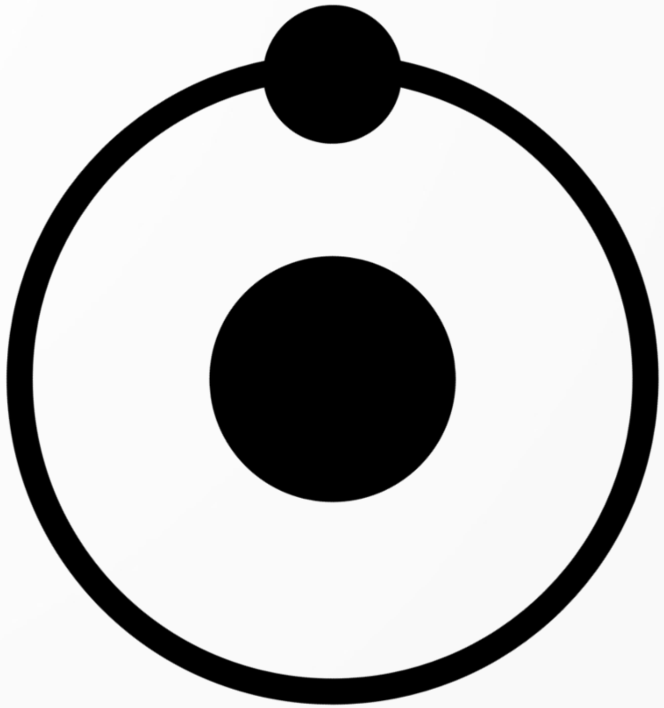


Generalised hydrogen interactions

- Hydrogen is one of the best studied QM systems

- Hydrogen is a very *clean* laboratory

- Sensitive to new physics!



Generalised hydrogen interactions

- Where is the dark matter?

Generalised hydrogen interactions

- Where is the dark matter?

- Long range forces:

$$U(r) = \frac{Z\alpha_{\mathrm{EM}}}{r}$$

Generalised hydrogen interactions

- Where is the dark matter?

- Long range forces:

$$U(r) = \frac{Z\alpha_{\mathrm{EM}}}{r} \longrightarrow U_{\mathrm{NP}}(r) = \frac{Z\alpha_{\mathrm{EM}}}{r} + \beta\mathcal{R}(r)$$

Generalised hydrogen interactions

- Where is the dark matter?

- Long range forces:

$$U(r) = \frac{Z\alpha_{\mathrm{EM}}}{r} \longrightarrow U_{\mathrm{NP}}(r) = \frac{Z\alpha_{\mathrm{EM}}}{r} + \beta\mathcal{R}(r)$$

- In general:

$$\mathcal{R}(r) = \frac{1}{r^n}e^{-mr}$$

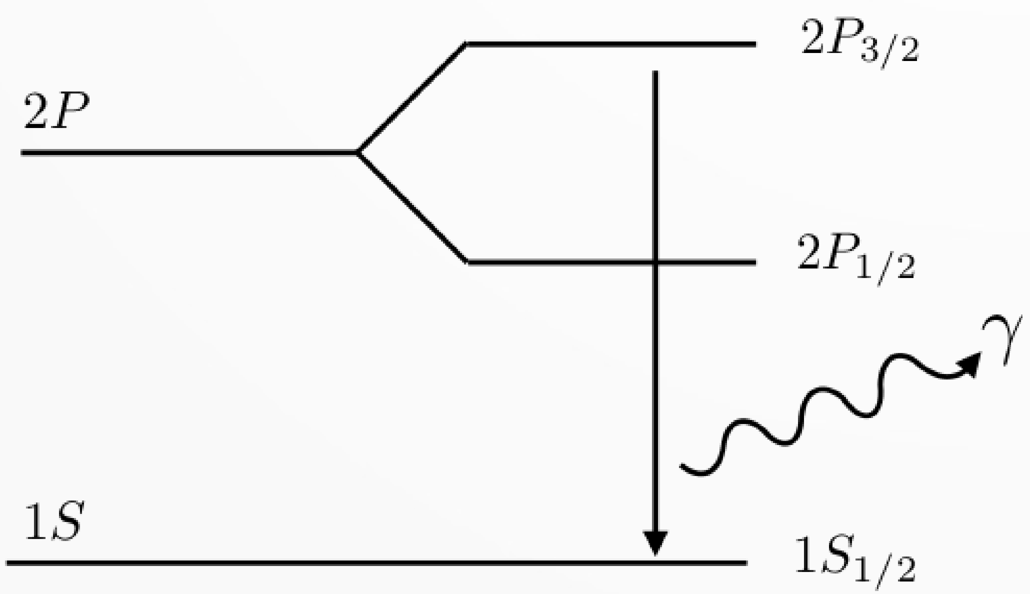
Generalised hydrogen interactions

- Where is the dark matter?
- New transitions:

Generalised hydrogen interactions

- Where is the dark matter?

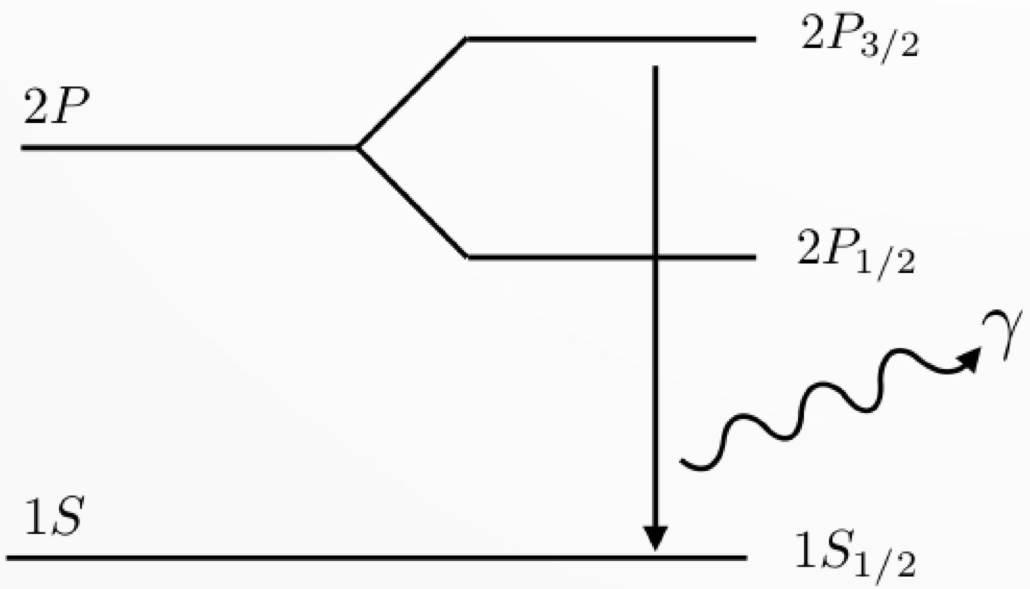
- New transitions:

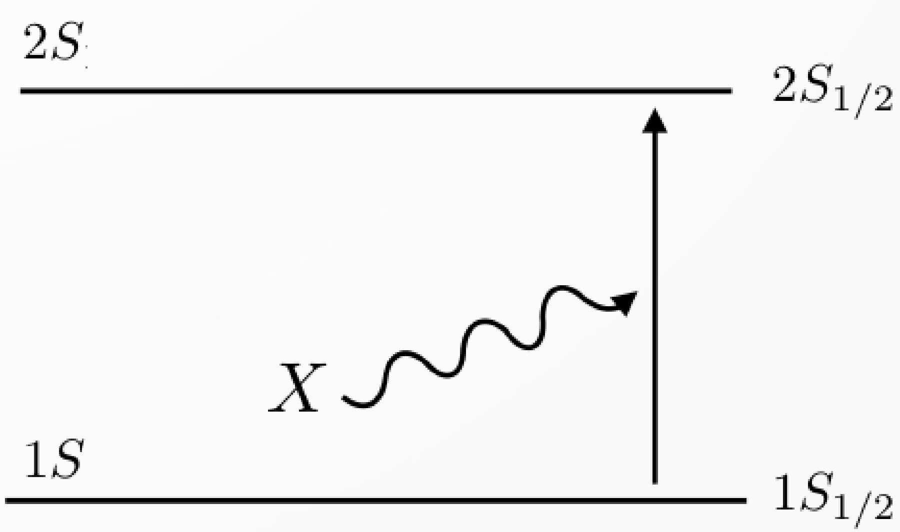


Generalised hydrogen interactions

- Where is the dark matter?

- New transitions:





Generalised hydrogen interactions

- Fermi's golden rule:

$$d\Gamma = 2\pi|\mathcal{M}_{fi}|^2\delta\left(\sum_i E_i - \sum_f E_f\right)d\rho$$

Generalised hydrogen interactions

- Fermi's golden rule:

$$d\Gamma = 2\pi|\mathcal{M}_{fi}|^2\delta\left(\sum_i E_i - \sum_f E_f\right) d\rho$$

- In general:

$$\mathcal{M}_{fi} = \langle f| \int d^3x\, \mathcal{H}_{\text{int}} |i\rangle$$

Generalised hydrogen interactions

- Fermi's golden rule:

$$d\Gamma = 2\pi |\mathcal{M}_{fi}|^2 \delta\left(\sum_i E_i - \sum_f E_f\right) d\rho$$

- In general:

$$\mathcal{M}_{fi} = \langle f| \int d^3x \, \mathcal{H}_{\text{int}} |i\rangle$$

$$\mathcal{H}_{\text{int}} = \mathcal{H}_{\text{int}}(\psi_e, A_\mu, \phi, \dots)$$

Transition rates

- A huge mess!

Transition rates

- A huge mess!
- Up to 16 Lorentz indices per Lorentz structure, interference terms...

Transition rates

- A huge mess!
- Up to 16 Lorentz indices per Lorentz structure, interference terms…
- Radial integrals are non-trivial to compute

Transition rates

- A huge mess!
- Up to 16 Lorentz indices per Lorentz structure, interference terms...
- Radial integrals are non-trivial to compute
- What if we want to sum over polarisations?

CINCO

Available: https://gitlab.com/JShergold/cinco

CINCO

$$(n, j, \ell, m)$$

CINCO

Available: https://gitlab.com/JShergold/cinco

CINCO

(n, j, ℓ, m)

(n', j', ℓ', m')

CINCO

Available: https://gitlab.com/JShergold/cinco

CINCO

$$(n, j, \ell, m)$$

$$(n', j', \ell', m')$$

$$\gamma^\mu, \gamma^\mu\gamma^5$$

Available: https://gitlab.com/JShergold/cinco

CINCO

(n, j, ℓ, m)

(n', j', ℓ', m')

$\gamma^\mu, \gamma^\mu\gamma^5$

CINCO

$\langle |\mathcal{M}_{fi}|^2 \rangle_{m,m'}$

Available: https://gitlab.com/JShergold/cinco

CINCO

$$\left.\begin{array}{r}(n, j, \ell, m) \\ (n', j', \ell', m') \\ \gamma^{\mu}, \gamma^{\mu}\gamma^{5}\end{array}\right\} \longrightarrow \textbf{CINCO} \longrightarrow \left\{\begin{array}{l}\langle |\mathcal{M}_{fi}|^2 \rangle_{m,m'} \\ \mathcal{I}_r\end{array}\right.$$

Available: https://gitlab.com/JShergold/cinco

CINCO

$$(n, j, \ell, m) \longrightarrow \quad \longrightarrow \langle |\mathcal{M}_{fi}|^2 \rangle_{m,m'}$$

$$(n', j', \ell', m') \longrightarrow \text{CINCO} \longrightarrow \mathcal{I}_r$$

$$\gamma^\mu, \gamma^\mu\gamma^5 \longrightarrow \quad \longrightarrow \Delta E_{fi}$$

Available: https://gitlab.com/JShergold/cinco

Contents

- Generalised hydrogen interactions

- Pair absorption ⇦

Pair absorption

- Scattering deposits only a small amount of energy:

Pair absorption

- Scattering deposits only a small amount of energy:

$$\Delta E_{fi} \sim m_{\rm DM}\, v_{\rm DM}^2$$

Pair absorption

- Scattering deposits only a small amount of energy:

$$\Delta E_{fi} \sim m_{\rm DM}\, v_{\rm DM}^2$$

- Only sensitive to heavier DM

Pair absorption

- Scattering deposits only a small amount of energy:

$$\Delta E_{fi} \sim m_{\mathrm{DM}}\, v_{\mathrm{DM}}^2$$

- Only sensitive to heavier DM

- But, scattering possible for any quantum numbers:

Pair absorption

- Scattering deposits only a small amount of energy:

$$\Delta E_{fi} \sim m_{\rm DM}\, v_{\rm DM}^2$$

- Only sensitive to heavier DM

- But, scattering possible for any quantum numbers:

$$\mathcal{L}_{\rm scat} \sim S^\dagger S\, \bar{\psi}_{\rm SM}\, \psi_{\rm SM}$$

Pair absorption

- Absorption deposits the entire mass-energy of the DM:

Pair absorption

- Absorption deposits the entire mass-energy of the DM:

$$\Delta E_{fi} \sim m_{\mathrm{DM}}$$

Pair absorption

- Absorption deposits the entire mass-energy of the DM:

$$\Delta E_{fi} \sim m_{\mathrm{DM}}$$

- Sensitive to far lighter DM

Pair absorption

- Absorption deposits the entire mass-energy of the DM:

$$\Delta E_{fi} \sim m_{\mathrm{DM}}$$

- Sensitive to far lighter DM

- But, linear operators lead to unstable DM:

Pair absorption

- Absorption deposits the entire mass-energy of the DM:

$$\Delta E_{fi} \sim m_{\rm DM}$$

- Sensitive to far lighter DM

- But, linear operators lead to unstable DM:

$$\mathcal{L}_{\rm absorb} \sim S\, \bar{\psi}_{\rm SM}\, \psi_{\rm SM}$$

Pair absorption

- Pair absorption, best of both worlds?

Pair absorption

- Pair absorption, best of both worlds?

$$\Delta E_{fi} \sim m_{\mathrm{DM}}$$

Pair absorption

- Pair absorption, best of both worlds?

$$\Delta E_{fi} \sim m_{\rm DM} \qquad\qquad \mathcal{L}_{\rm scat} \sim S^\dagger S\, \bar{\psi}_{\rm SM}\, \psi_{\rm SM}$$

Pair absorption

- Pair absorption, best of both worlds?

$$\Delta E_{fi} \sim m_{\rm DM} \qquad\qquad \mathcal{L}_{\rm scat} \sim S^\dagger S\, \bar{\psi}_{\rm SM}\, \psi_{\rm SM}$$

- Added bonus, scales with the square of the density:

Pair absorption

- Pair absorption, best of both worlds?

$$\Delta E_{fi} \sim m_{\rm DM} \qquad\qquad \mathcal{L}_{\rm scat} \sim S^\dagger S\, \bar{\psi}_{\rm SM}\, \psi_{\rm SM}$$

- Added bonus, scales with the square of the density:

$$\Gamma_{\rm pair} \sim \rho_{\rm DM}^2 \sim 1/m_{\rm DM}^2$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Spin-flip transitions (μeV - meV):

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Spin-flip transitions (μeV - meV):

$$\Delta n = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Spin-flip transitions (μeV - meV):

$$\Delta n = 0, \qquad \Delta j = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Spin-flip transitions (μeV - meV):

$$\Delta n = 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Spin-flip transitions (μeV - meV):

$$\Delta n = 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0, \qquad \Delta m \neq 0$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  – Spin-flip transitions (μeV - meV):

$$\Delta n = 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0, \qquad \Delta m \neq 0$$

  – Sensitive to axial-vector couplings only

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Spin-flip transitions (μeV - meV):

$$\Delta n = 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0, \qquad \Delta m \neq 0$$

  - Sensitive to axial-vector couplings only

  - Transition energy tunable with $\vec{B}_{\mathrm{ext}}$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Fine structure transitions (μeV, meV - eV):

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Fine structure transitions (μeV, meV - eV):

$$\Delta n = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Fine structure transitions (μeV, meV - eV):

$$\Delta n = 0, \qquad \Delta j \neq 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Fine structure transitions (μeV, meV - eV):

$$\Delta n = 0, \qquad \Delta j \neq 0, \qquad \Delta \ell = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Fine structure transitions (μeV, meV - eV):

$$\Delta n = 0, \qquad \Delta j \neq 0, \qquad \Delta \ell = 0, \qquad \Delta m = 0$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Fine structure transitions (μeV, meV - eV):

$$\Delta n = 0, \qquad \Delta j \neq 0, \qquad \Delta \ell = 0, \qquad \Delta m = 0$$

  - Sensitive to axial-vector couplings only

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Fine structure transitions (μeV, meV - eV):

$$\Delta n = 0, \qquad \Delta j \neq 0, \qquad \Delta \ell = 0, \qquad \Delta m = 0$$

  - Sensitive to axial-vector couplings only

  - Example: $2p_{1/2} \rightarrow 2p_{3/2}$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Principal quantum number transitions (eV):

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Principal quantum number transitions (eV):

$$\Delta n \neq 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:

  - Principal quantum number transitions (eV):

$$\Delta n \neq 0, \qquad \Delta j = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Principal quantum number transitions (eV):

$$\Delta n \neq 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0,$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Principal quantum number transitions (eV):

$$\Delta n \neq 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0, \qquad \Delta m = 0$$

Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Principal quantum number transitions (eV):

$$\Delta n \neq 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0, \qquad \Delta m = 0$$

  - Sensitive to both scalar and axial-vector couplings

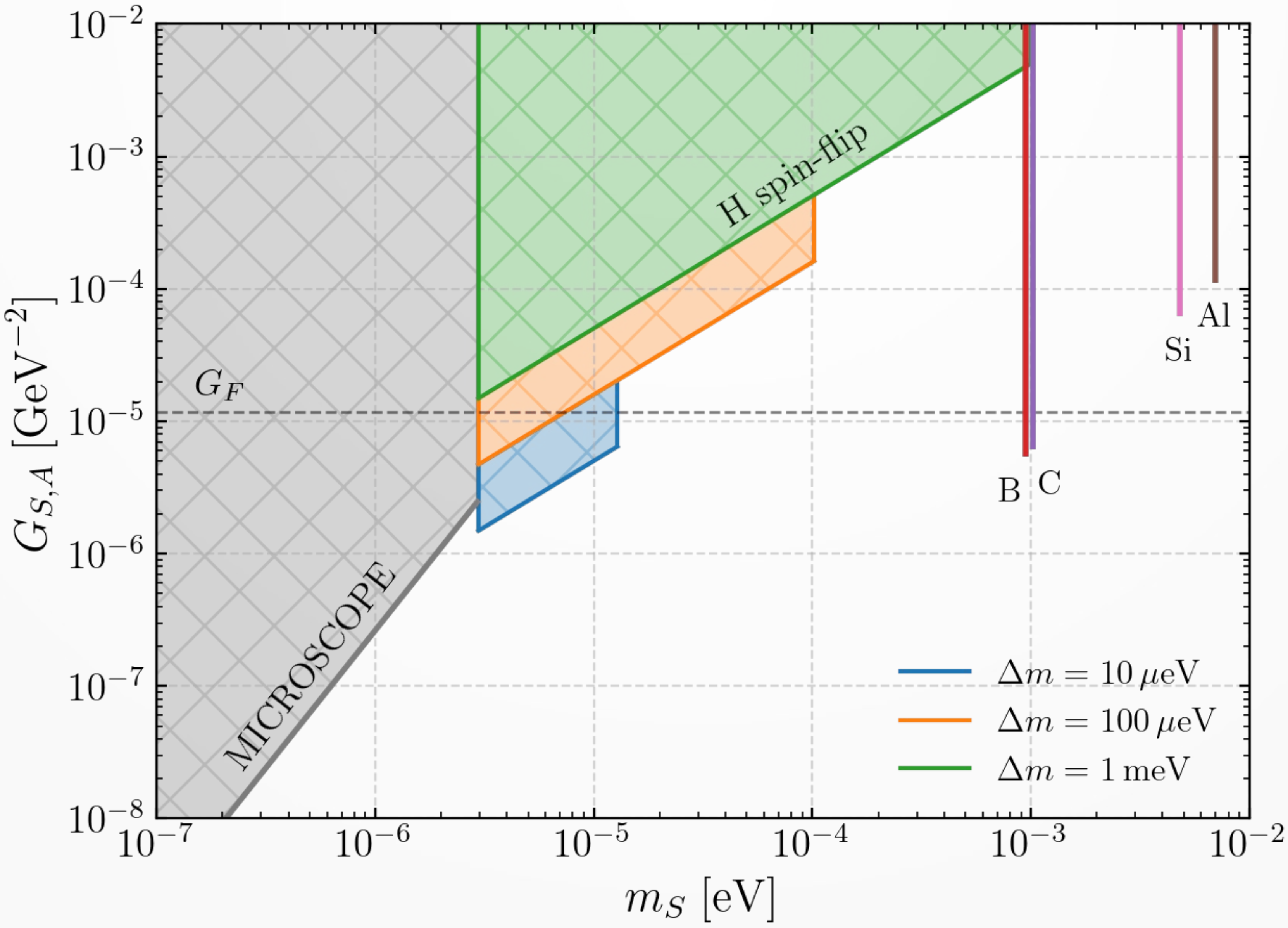
Pair absorption

- Consider three kinds of transitions, all forbidden to photons:
  - Principal quantum number transitions (eV):

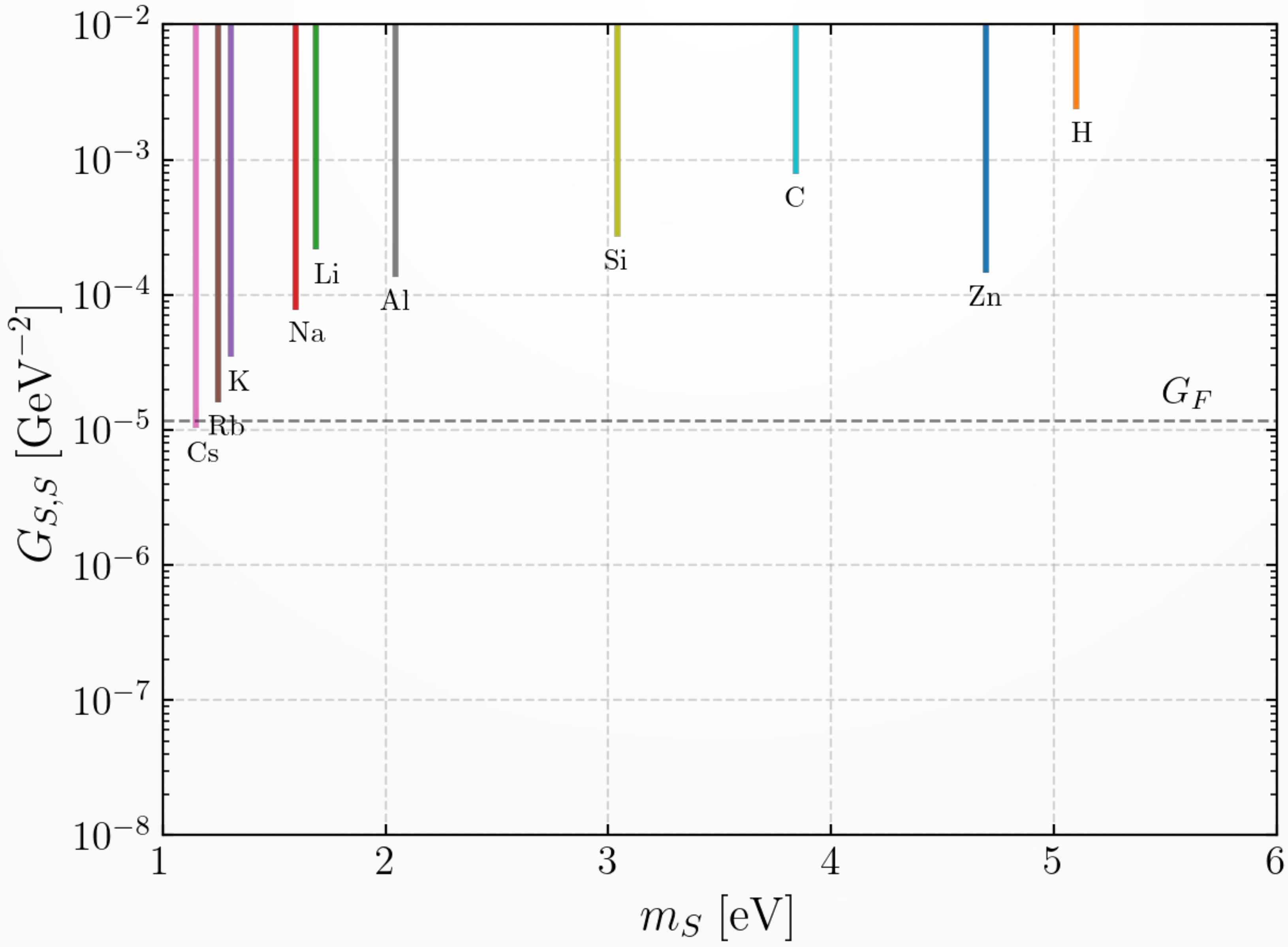
$$\Delta n \neq 0, \qquad \Delta j = 0, \qquad \Delta \ell = 0, \qquad \Delta m = 0$$

  - Sensitive to both scalar and axial-vector couplings
  - Example: $1s_{1/2} \to 2s_{1/2}$

Pair absorption



Pair absorption



Cosmic neutrino background?

- *"Dark fermion with electroweak axial-vector couplings"*

Cosmic neutrino background?

- *"Dark fermion with electroweak axial-vector couplings"*

- Able to constrain the neutrino overdensity:

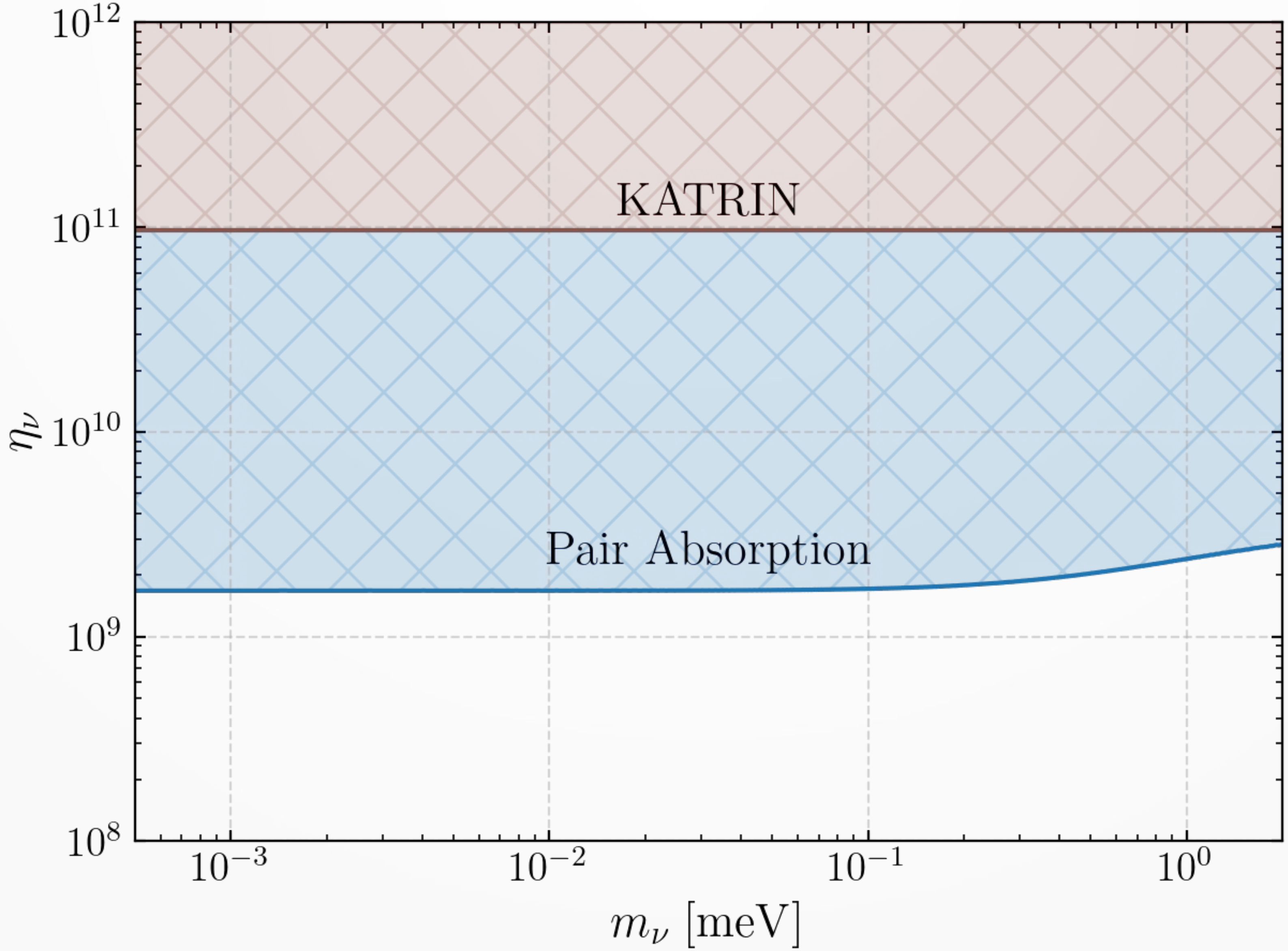
Cosmic neutrino background?

- *"Dark fermion with electroweak axial-vector couplings"*

- Able to constrain the neutrino overdensity:

$$\eta_\nu = \frac{n_\nu}{n_{\nu,0}}$$

Cosmic neutrino background?



Summary

- Atomic transitions are incredibly sensitive to sub-eV DM

Summary

- Atomic transitions are incredibly sensitive to sub-eV DM
- Pair absorption particularly sensitive at small masses

Summary

- Atomic transitions are incredibly sensitive to sub-eV DM
- Pair absorption particularly sensitive at small masses
- Able to constrain electroweak axial and scalar couplings

Summary

- Atomic transitions are incredibly sensitive to sub-eV DM
- Pair absorption particularly sensitive at small masses
- Able to constrain electroweak axial and scalar couplings
- Also capable of constraining the CνB

Thank you!
Questions?