Searching for DM–Electron Scattering

New Constraints on Dark Matter from Liquid Scintillators

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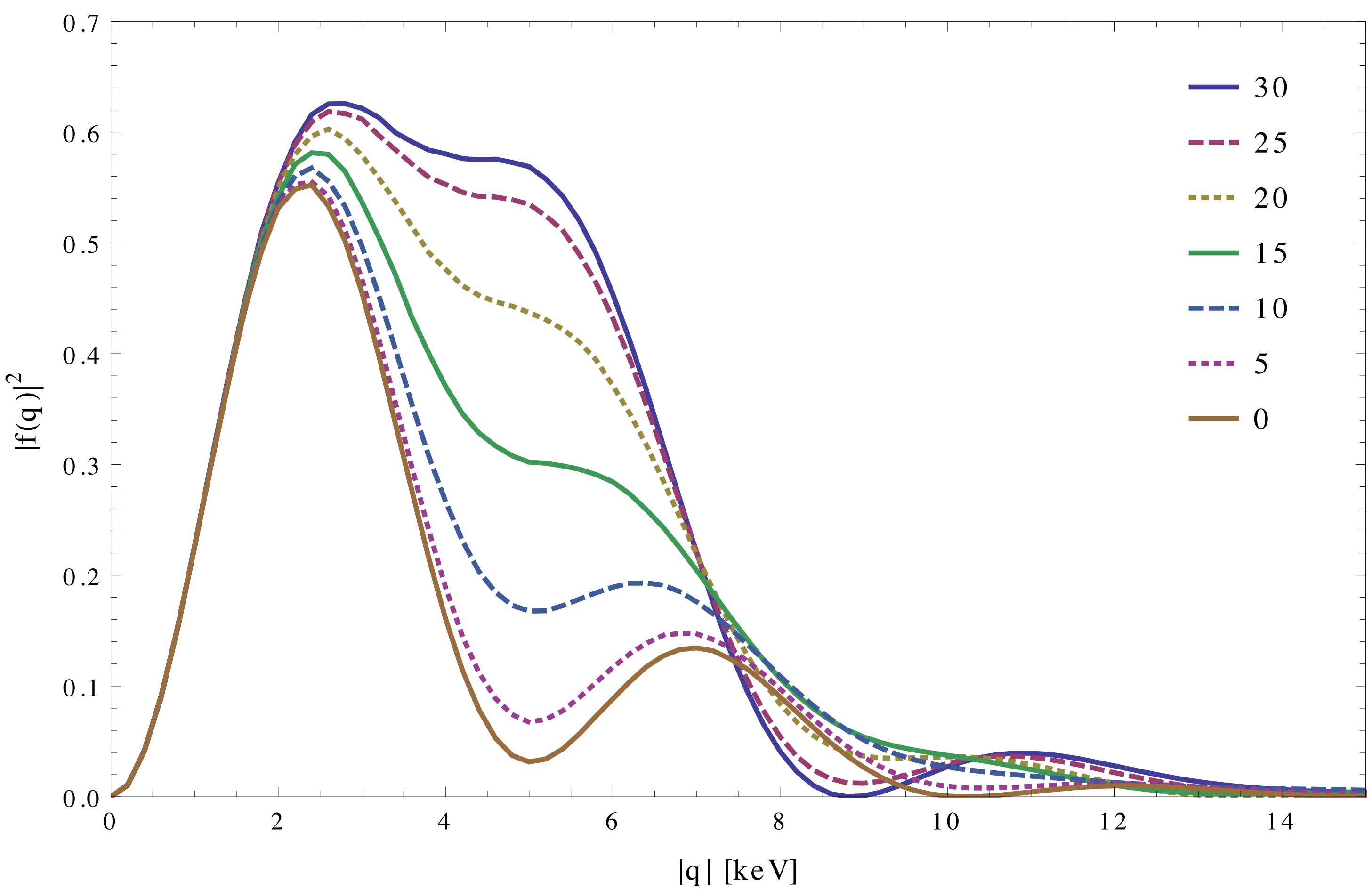
PIKIMO 2019

Based on work with **Carlos Blanco, Juan Collar,** *and* **Yonatan Kahn**



Light Dark Matter Scattering

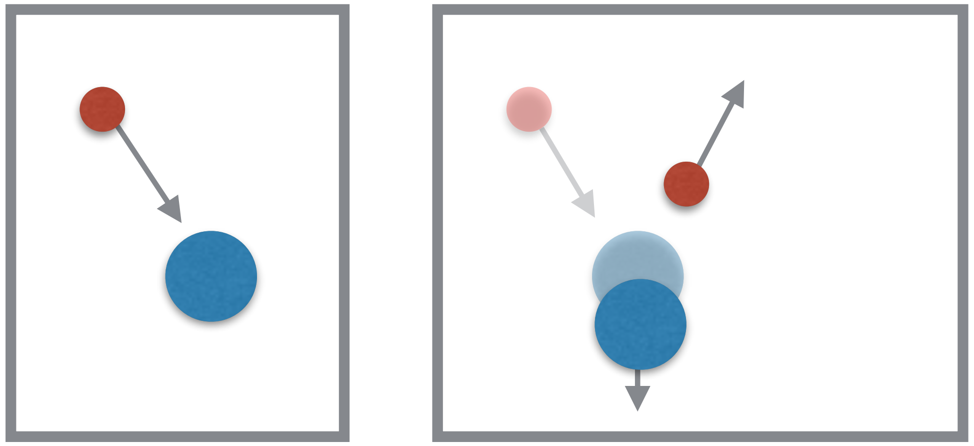
- Elastic scattering transfers some ΔE from the DM to the detector
- A realistic detector has a minimum observable ΔE
- ΔE sets the lower threshold on m_{DM}

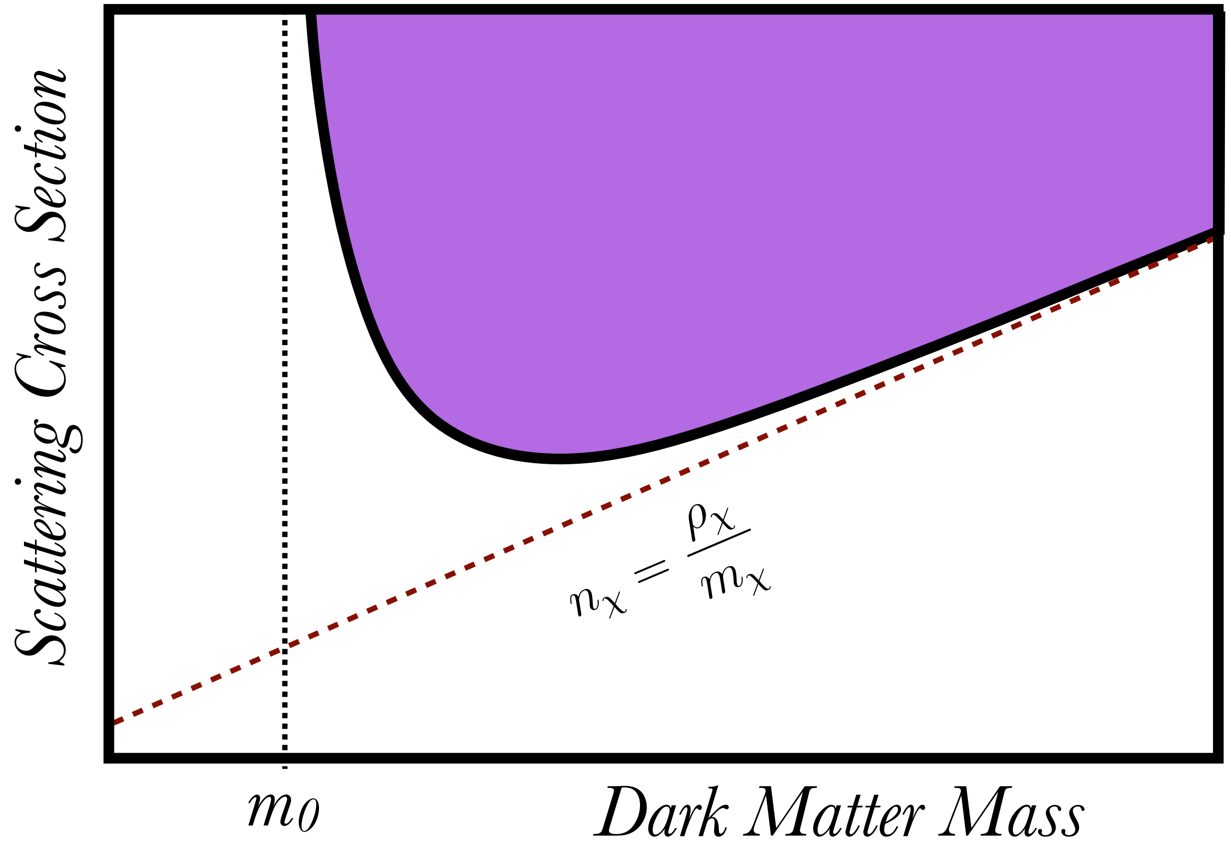
$$\frac{\Delta E}{q} + \frac{q}{2m_0} \geq v_{\mathrm{esc}} + v_E$$

- For escape velocity $v_{\mathrm{esc}} \sim 540$ km/s and $v_{\mathrm{E}} \sim 230$ km/s,

$$m_0 = 300 \text{ MeV} \times \left(\frac{\Delta E}{1 \text{ keV}}\right)$$

- **Hard to detect sub-GeV dark matter with nuclear recoil**



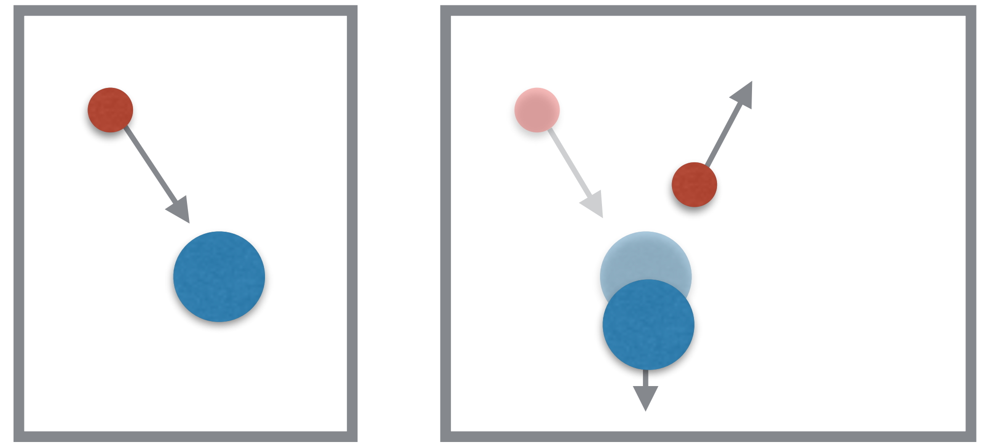


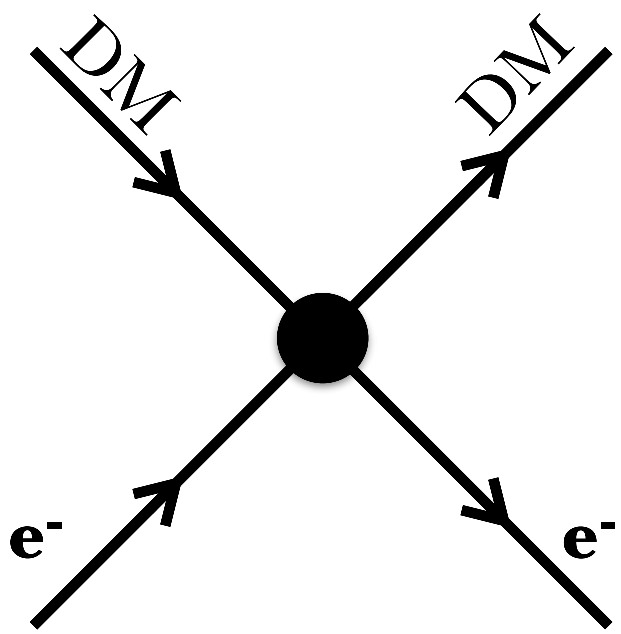
Motivation: Electron Recoil

- Typical ΔE for electrons is much lower:

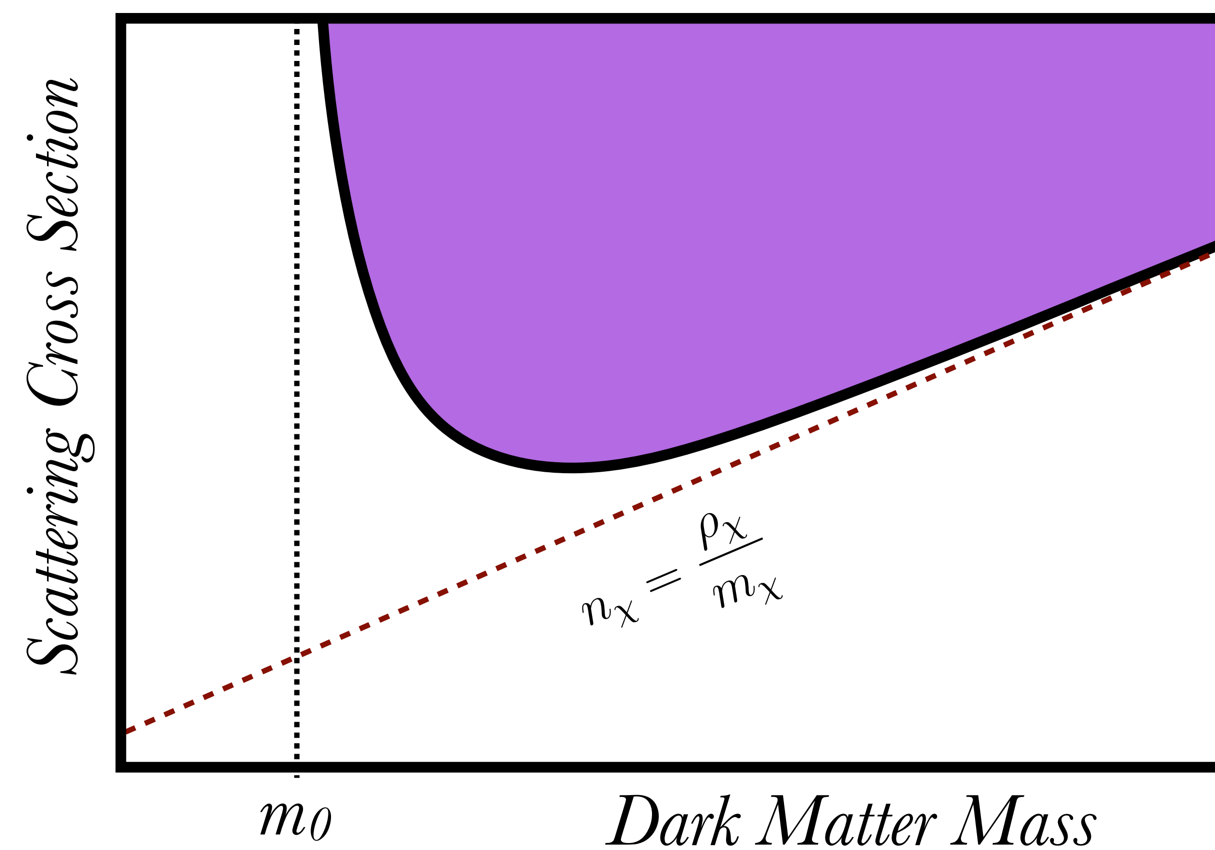
$$m_0 = 3 \text{ MeV} \times \left(\frac{\Delta E}{10 \text{ eV}}\right)$$

  - Electron recoil is sensitive to **MeV scale DM mass**



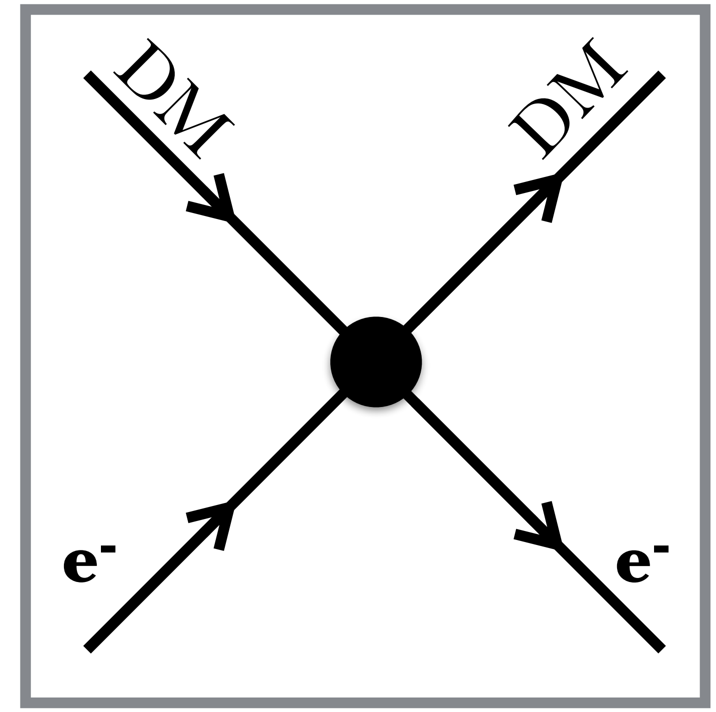


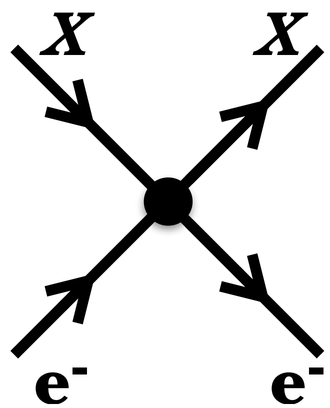
Generic DM Exclusion Plot

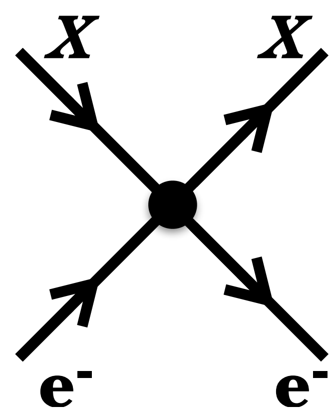


DM–Electron Scattering

- Scattering rate depends on the initial and final states of the electron: which are **not momentum eigenstates**



- $i\mathcal{M} = \Big\langle \Psi_f \Big|$  $\Big| \Psi_i \Big\rangle$

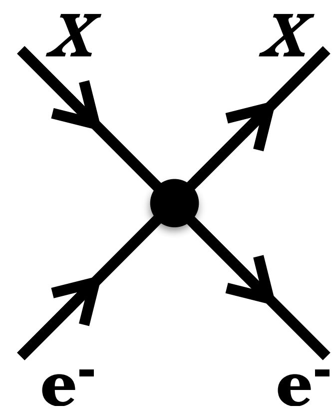
- $i\mathcal{M} = \int d^3\mathbf{p}_i \, d^3\mathbf{p}_f \, \langle \Psi_f | \, \mathbf{p}_f \rangle \Big\langle \mathbf{p}_f \Big|$  $\Big| \mathbf{p}_i \Big\rangle \langle \mathbf{p}_i | \, \Psi_i \rangle$

$i\mathcal{M}_{\text{free}}$

DM–Electron Scattering

- Need to know the **momentum space wavefunction** for the relevant electrons in the detector…

$$i\mathcal{M} = \int d^3\mathbf{p}_i\, d^3\mathbf{p}_f\, \langle \Psi_f | \mathbf{p}_f \rangle \Big\langle \mathbf{p}_f \Big|$$



$$\Big| \mathbf{p}_i \Big\rangle \langle \mathbf{p}_i | \Psi_i \rangle$$

$$(\sigma v)_{i\to f} = \int \frac{d^3\mathbf{q}}{(2\pi)^3} (2\pi)\delta(\Delta E_e - \omega) \frac{\left|\mathcal{M}_{\text{free}}\right|^2}{16 m_\chi^2 m_e^2} \left| f_{i\to f}(\mathbf{q}) \right|^2$$

- The DM–electron scattering cross section has a new component: the **molecular form factor**

$$f_{i\to f}(\mathbf{q}) = \int d^3\mathbf{r}\, \psi_i(\mathbf{r}) \psi_f^\star(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} = \int d^3\mathbf{p}\, \widetilde{\psi}_i(\mathbf{p}) \widetilde{\psi}_f^\star(\mathbf{p}+\mathbf{q})$$

Generic Scattering Rate Calculation

$$R = \frac{N_e\, \rho_\chi \bar{\sigma}_e}{8\pi m_\chi \mu_{\chi e}^2} \bar{\sigma}_e \int \frac{d^3 q}{q} \eta(v_{\min}) F_{\rm DM}^2(q) \left| f_{i\to f}(\mathbf{q}) \right|^2$$

The scattering rate is determined in three parts:

- DM velocity distribution
  (astrophysics)

$$\eta(v_{\min}) = \int \frac{4\pi v^2 dv}{v} g_\chi(v) \Theta(v - v_{\min})$$

$$v_{\min}(q) = \frac{\Delta E}{q} + \frac{q}{2m_\chi}$$

- Free DM–Electron cross section
  (particle physics)

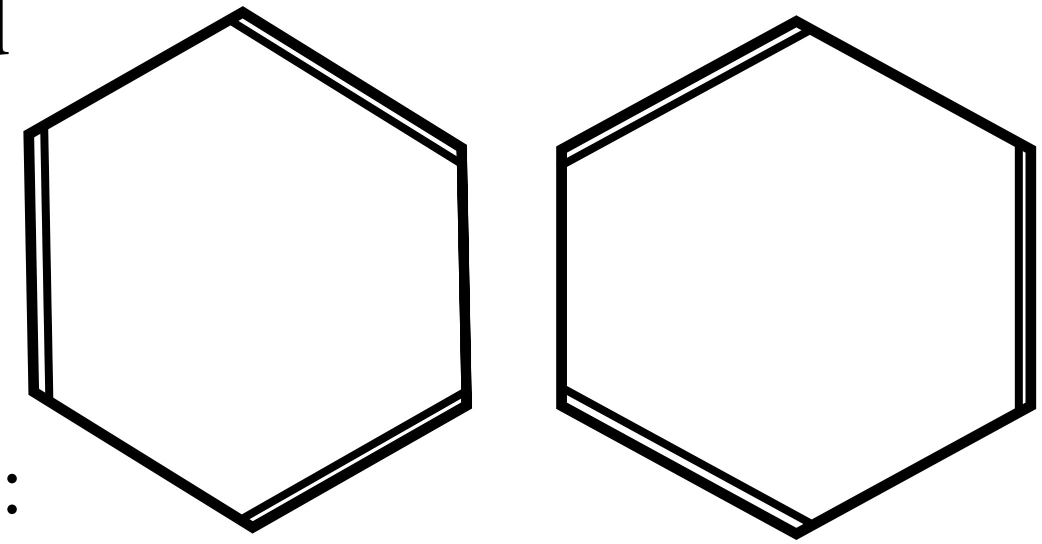
$$\frac{\left|\mathcal{M}_{\rm free}\right|^2}{16 m_\chi^2 m_e^2} = \frac{\pi \bar{\sigma}_e}{\mu_{\chi e}^2} F_{\rm DM}^2(q)$$

- **Molecular form factor**
  (chemistry)

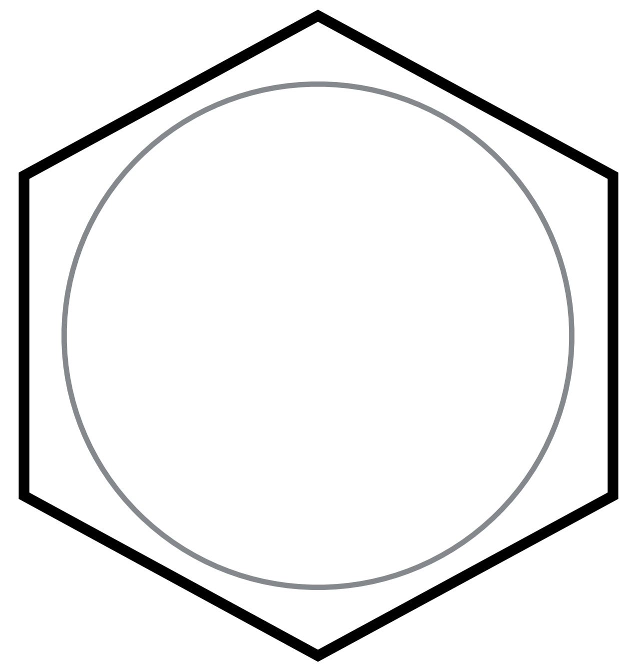
$$f_{i\to f}(\mathbf{q}) = \int d^3\mathbf{p}\, \widetilde{\psi}_i(\mathbf{p}) \widetilde{\psi}_f^\star(\mathbf{p} + \mathbf{q})$$

Organic Chemistry *for Physicists*

- *Aromatic Organic Compounds* are a good candidate for a DM experiment:
  ΔE ~ 5 eV for the first transitions

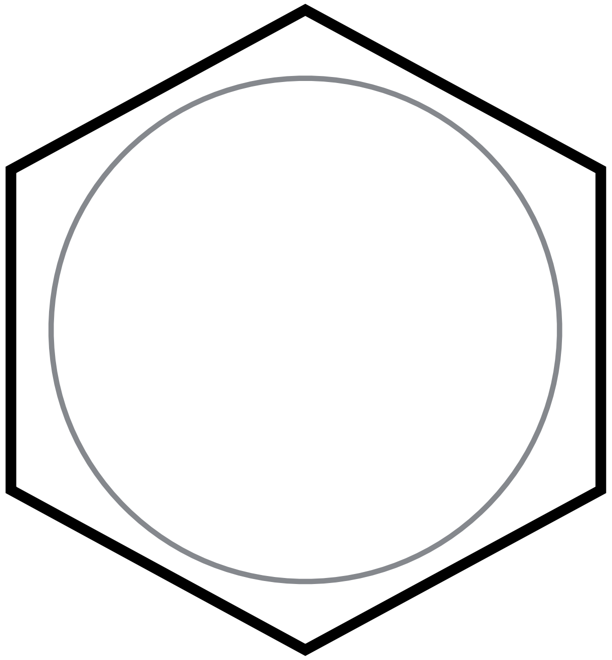


- Benzene (C_6H_6) as a simple example: 6 carbon nuclei form a ring



- The six electrons expected to be in the double bonds **delocalize** along the ring

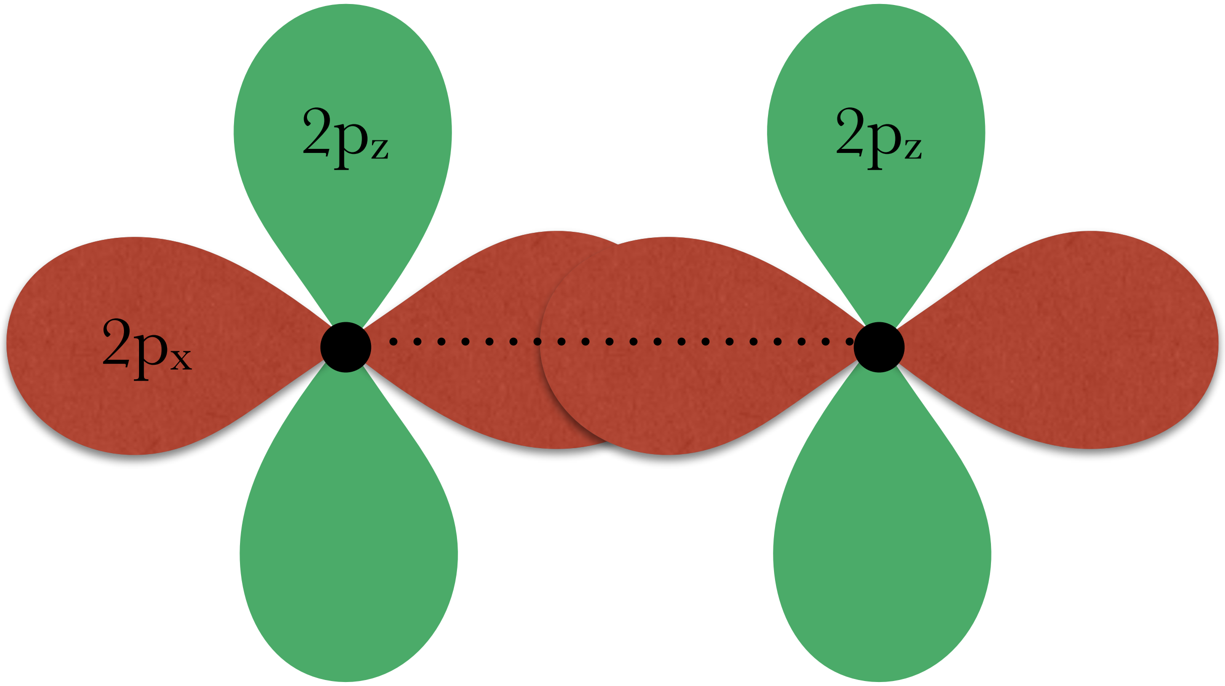
Organic Chemistry *for Physicists*

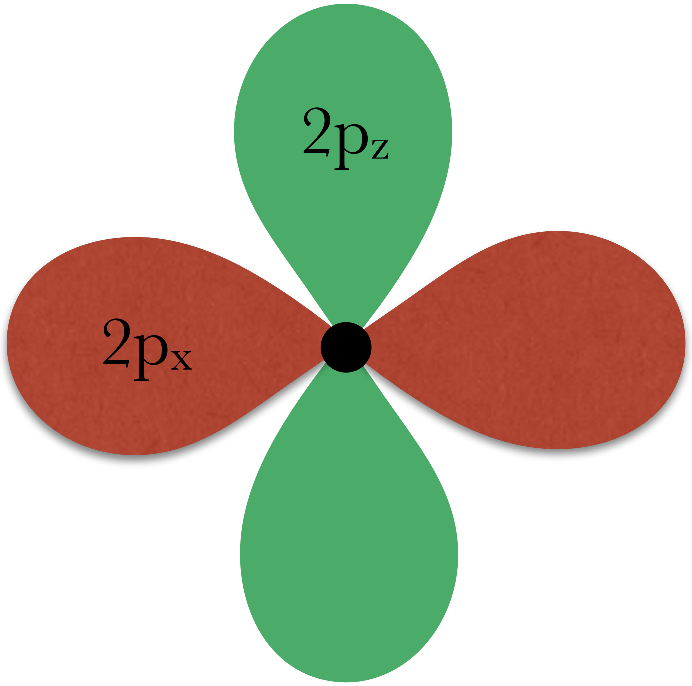


- How to calculate the electron wavefunctions for such a complicated system?

Linear Combination of Atomic Orbitals
(LCAO Approximation)

- Single and double bonds can be approximated by splicing together individual 2p orbitals





Organic Chemistry *for Physicists*

Linear Combination of Atomic Orbitals

- Benzene (and related molecules) are planar: only the $\mathbf{2p_z}$ orbitals are relevant for the lowest-energy transitions
- Diagonalize **H** to find six linear combinations:

$$c_i^{(2)} = \frac{(1,1,1,1,1,1)}{\sqrt{6}}$$

$$c_i^{(1)} = \frac{(1,0,-1,-1,0,1)}{2}$$

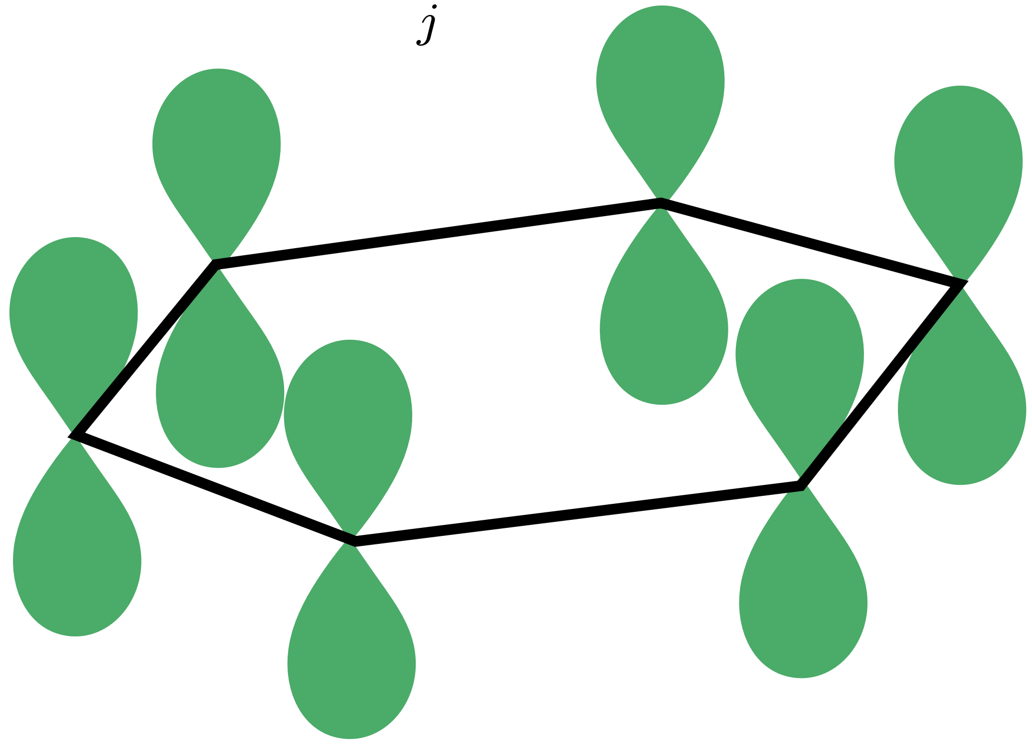
$$c_i^{(1')} = \frac{(1,2,1,-1,-2,-1)}{\sqrt{12}}$$

$$c_i^{(-1)} = \frac{(-1,0,1,-1,0,1)}{2}$$

$$c_i^{(-1')} = \frac{(-1,2,-1,-1,2,-1)}{\sqrt{12}}$$

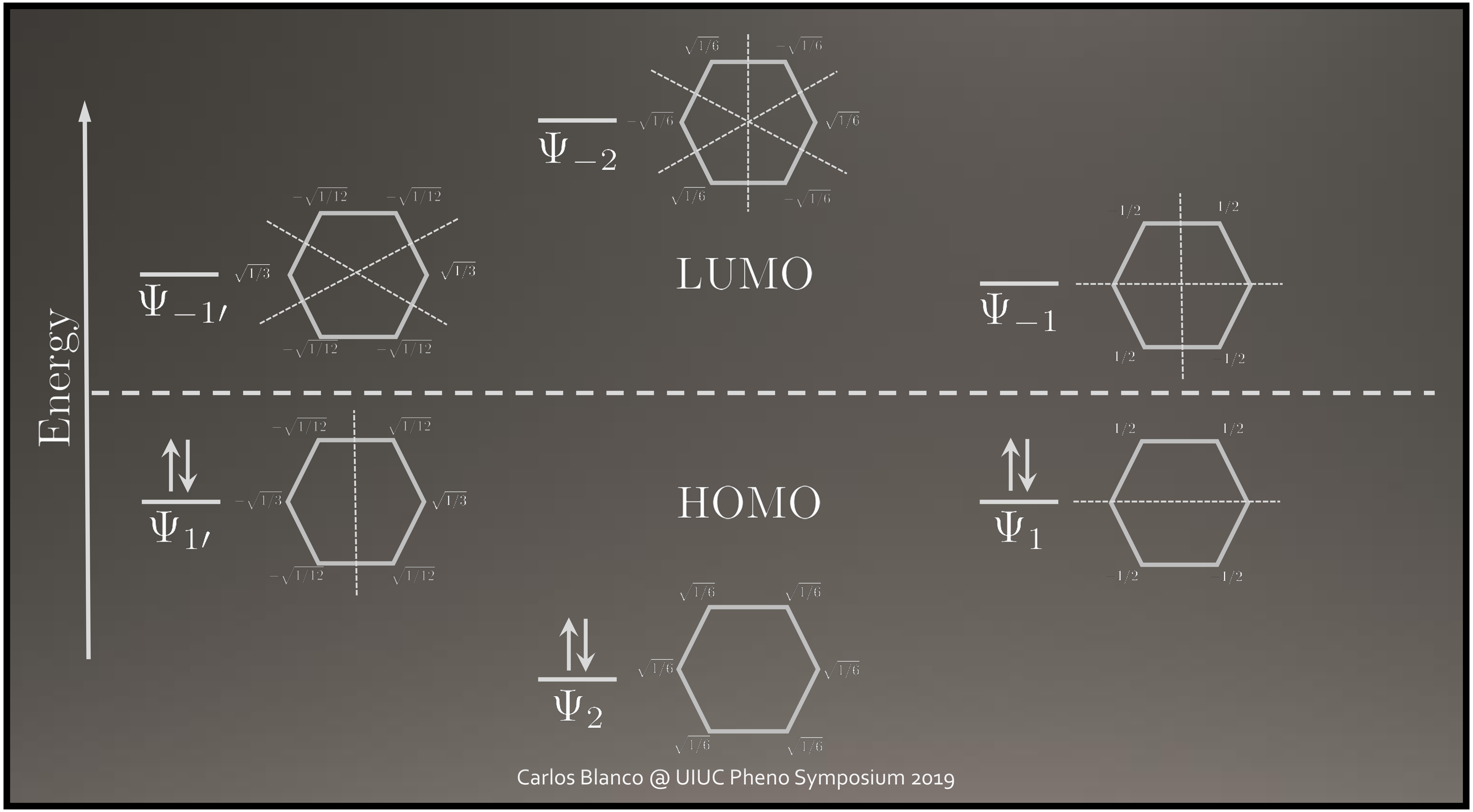
$$c_i^{(-2)} = \frac{(-1,1,-1,1,-1,1)}{\sqrt{6}}$$

$$\Psi_i(\mathbf{r}) = \sum_j c_j^{(i)} \phi(\mathbf{r} - \mathbf{R}_j)$$



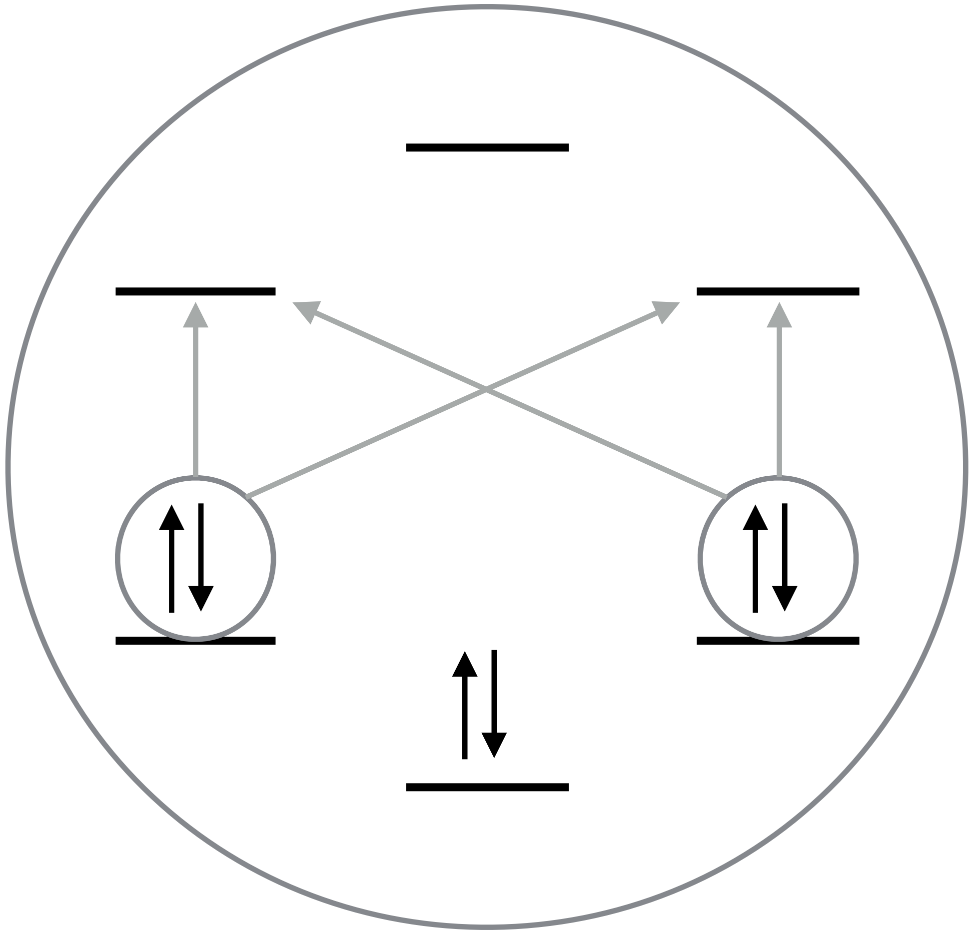
Organic Chemistry *for Physicists*

- 6 electrons occupy the lowest 3 energy levels:



Organic Chemistry *for Physicists*

- 6 electrons occupy the lowest 3 energy levels:
- First four transitions at **4.9 eV**, **6.2 eV**, and two at **7.0 eV**
- Linear Combinations of Atomic Orbitals: "Easy" to find momentum space wavefunctions for molecular orbitals



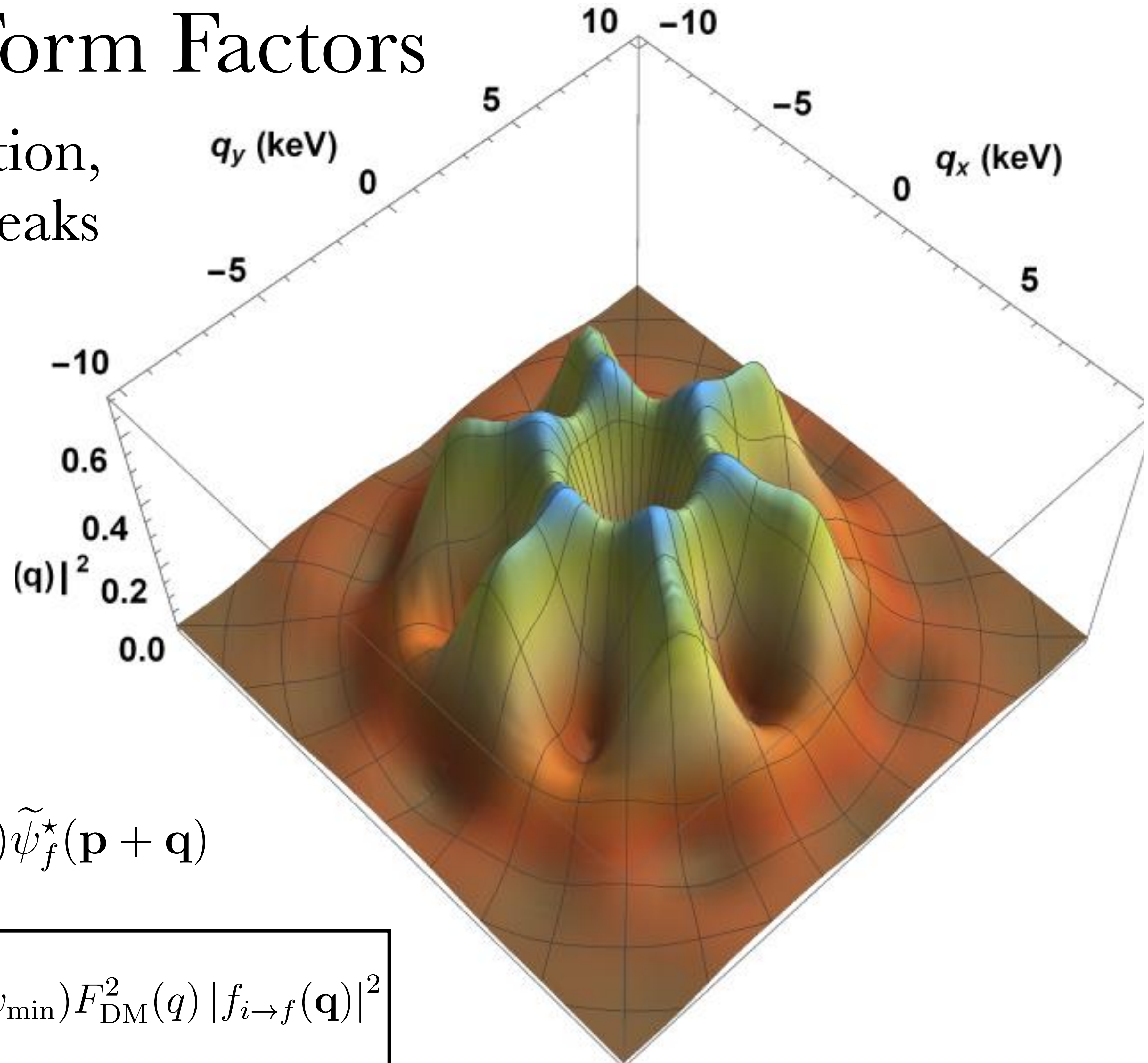
$$\phi_{2p_z}(\mathbf{r}) = \mathcal{N} a_0^{-3/2} \frac{r\cos\theta}{a_0} \exp\left(\frac{-Z_{\text{eff}} r}{2a_0}\right)$$

$$\widetilde{\phi}_{2p_z}(\mathbf{k}) = \widetilde{\mathcal{N}} a_0^{3/2} \frac{a_0\, k_z}{\left(a_0^2 k^2 + (Z_{\text{eff}}/2)^2\right)^3}$$

$$\boxed{\widetilde{\Psi}(\mathbf{k}) = \left(\sum_{i=1}^{6} c_i e^{-i\mathbf{k}\cdot\mathbf{R}_i}\right) \widetilde{\phi}(\mathbf{k})}$$

Molecular Form Factors

- For 4.9 eV transition, the form factor peaks at **small values** of $\mathbf{q_x}$ and $\mathbf{q_y}$

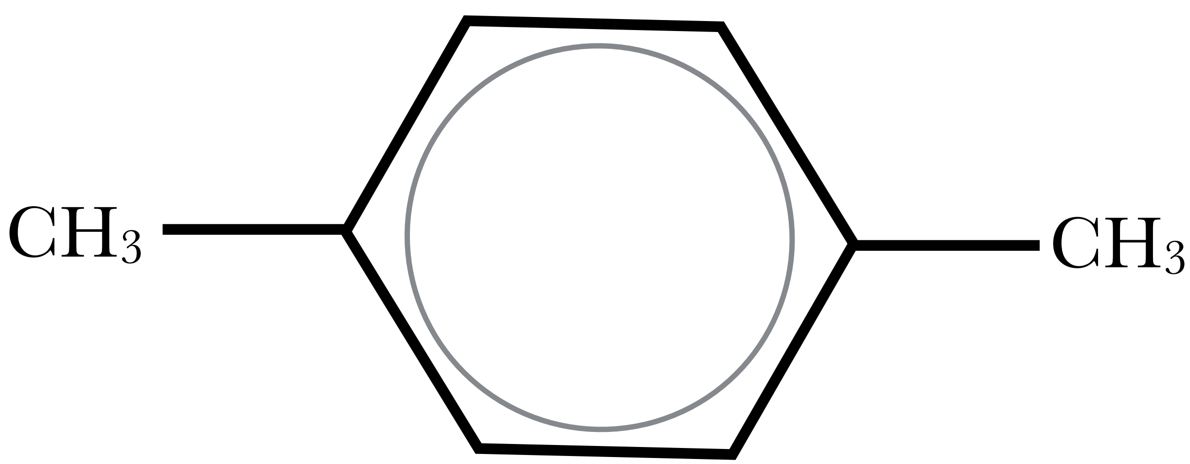


$$f_{i\to f}(\mathbf{q}) = \int d^3\mathbf{p}\, \widetilde{\psi}_i(\mathbf{p}) \widetilde{\psi}^\star_f(\mathbf{p}+\mathbf{q})$$

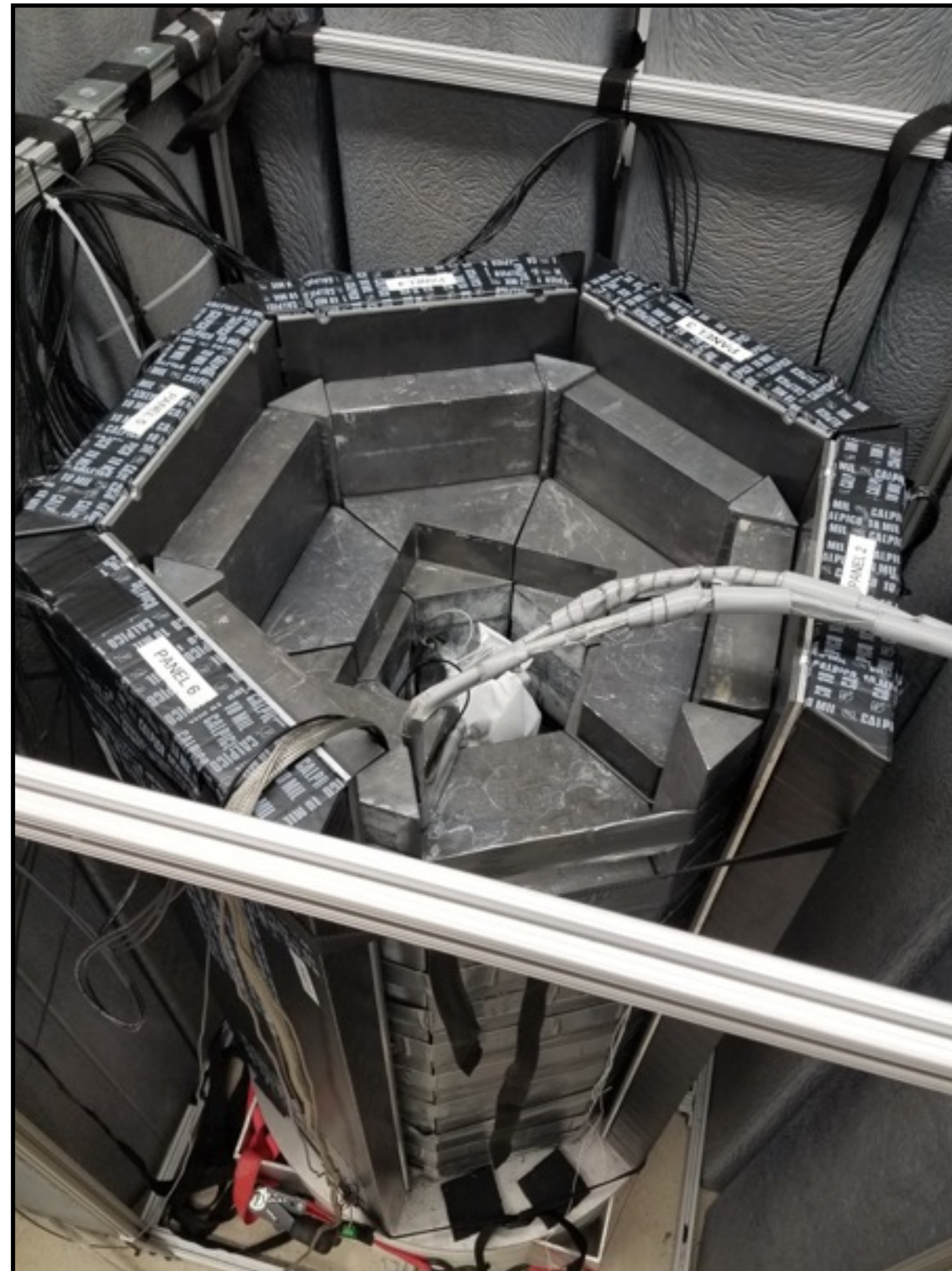
$$R = \frac{N_e\, \rho_\chi \bar{\sigma}_e}{8\pi m_\chi \mu^2_{\chi e}} \bar{\sigma}_e \int \frac{d^3q}{q} \eta(v_{\min}) F^2_{\rm DM}(q)\, |f_{i\to f}(\mathbf{q})|^2$$

Experimental Design

- 1.5 kg of EJ-301 scintillator with 0.1 C temperature control
- PMT manufacturer claims a dark rate as low as 0.1 Hz.
- Solvent in EJ-301 is para-xylene:



- Same bond length as benzene ring; nearly identical excitation energy (4.7 eV)



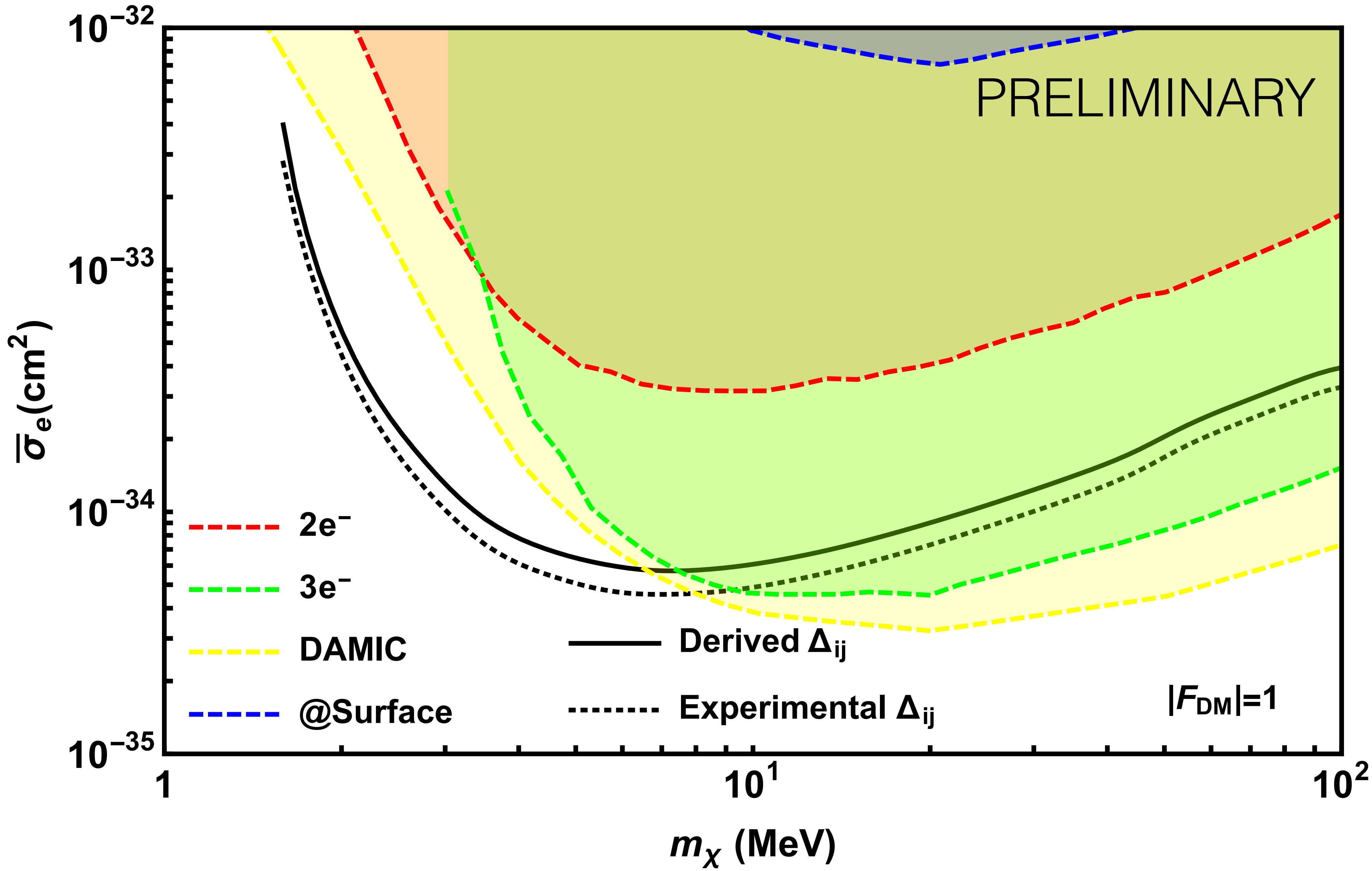
Experimental Design

- Cooling system
- Photomultiplier Tube

- 1.5 kg of EJ-301
- Muon Veto
- Shielding

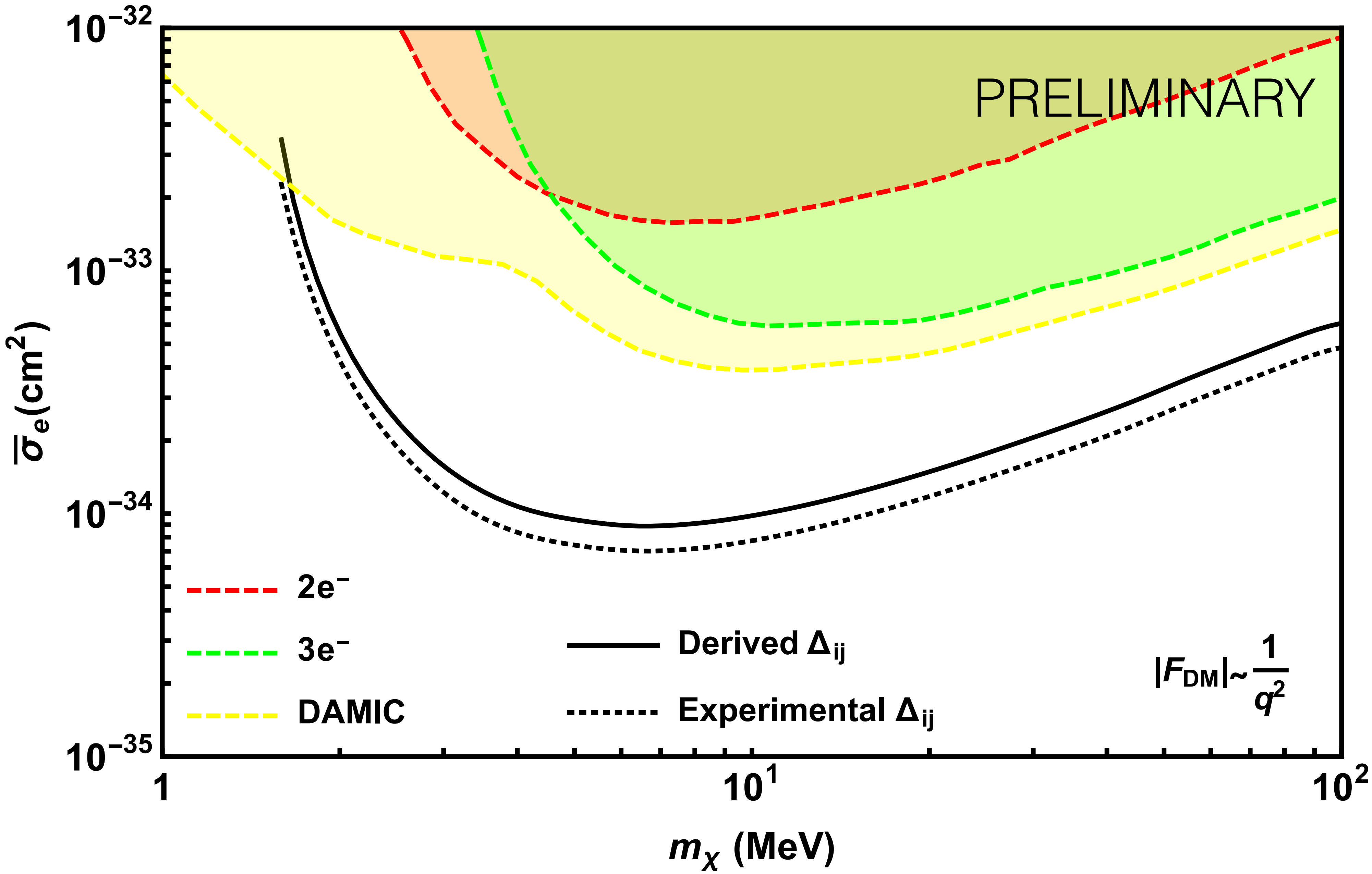
Measuring a dark rate of ***O(1 Hz)*** or lower can set **new limits on dark matter** in the few-MeV range

Predicted Sensitivity: $F_{DM} = 1$



- Example for **F_{DM} = 1** model, supposing R = 0.25 Hz

Predicted Sensitivity: $F_{DM} = 1/(q\, a_0)^2$

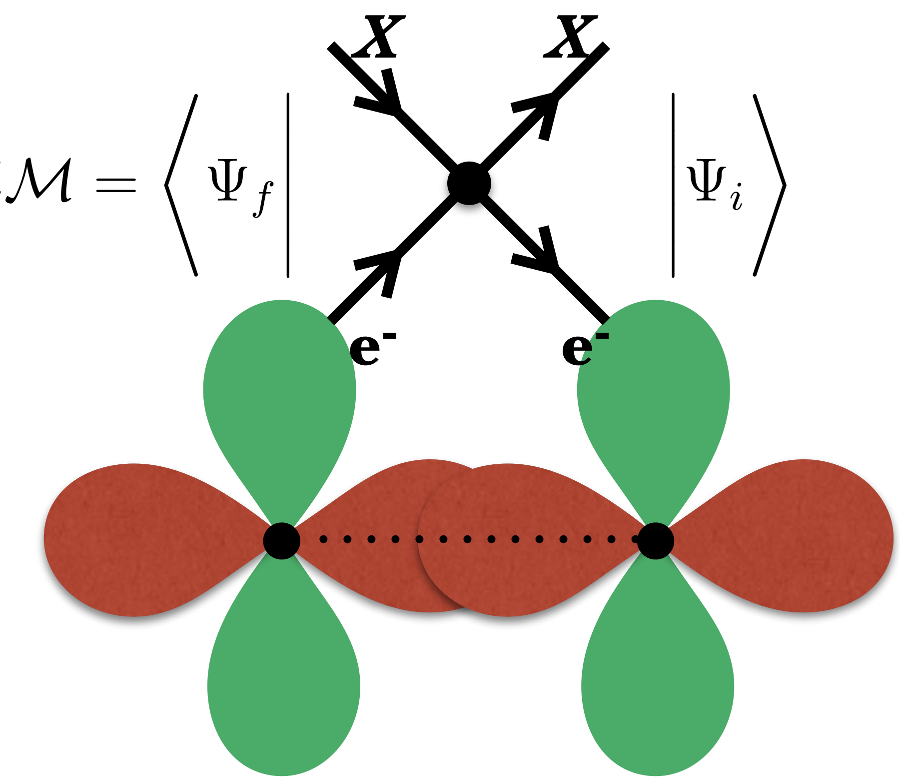


- Example for light mediator model, supposing R = 0.25 Hz

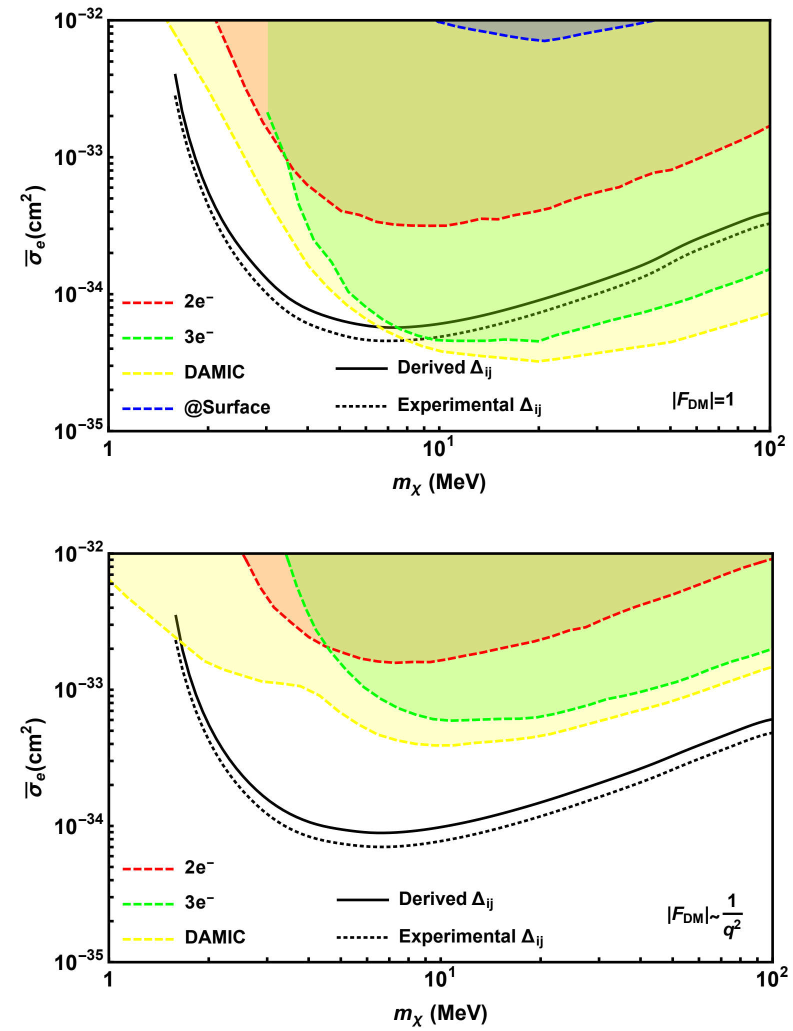
Conclusion

- We expect results **within a few weeks**!

$+$



$$i\mathcal{M} = \left\langle \Psi_f \right| \cdots \left| \Psi_i \right\rangle \stackrel{?}{=}$$



Special thanks to my collaborators Carlos Blanco, Juan Collar, *and* Yoni Kahn