Inelastic Scattering, Molecules and Other Cool Stuff to Probe sub-GeV Dark Matter

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As well as: Abir, Ashkenazi, Bloch, Budnik, Chesnovsky, Devi, Itay, Kreisel, Landsman, Sagiv, Silver, Sofer, et. al. (later in talk)

Outline

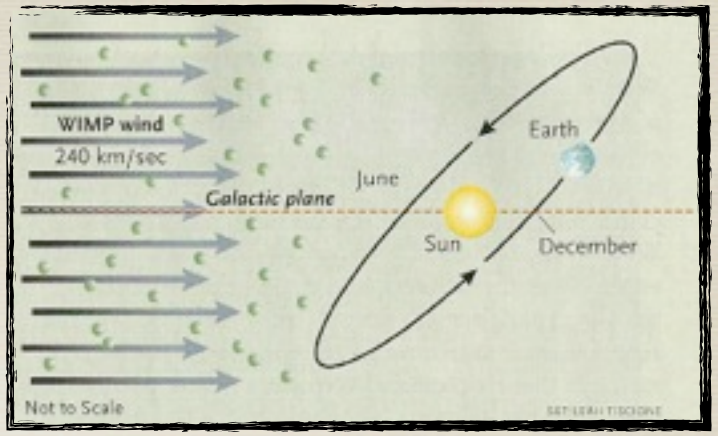
- **Motivation for Considering Low Threshold Energy, Inelastic Processes**

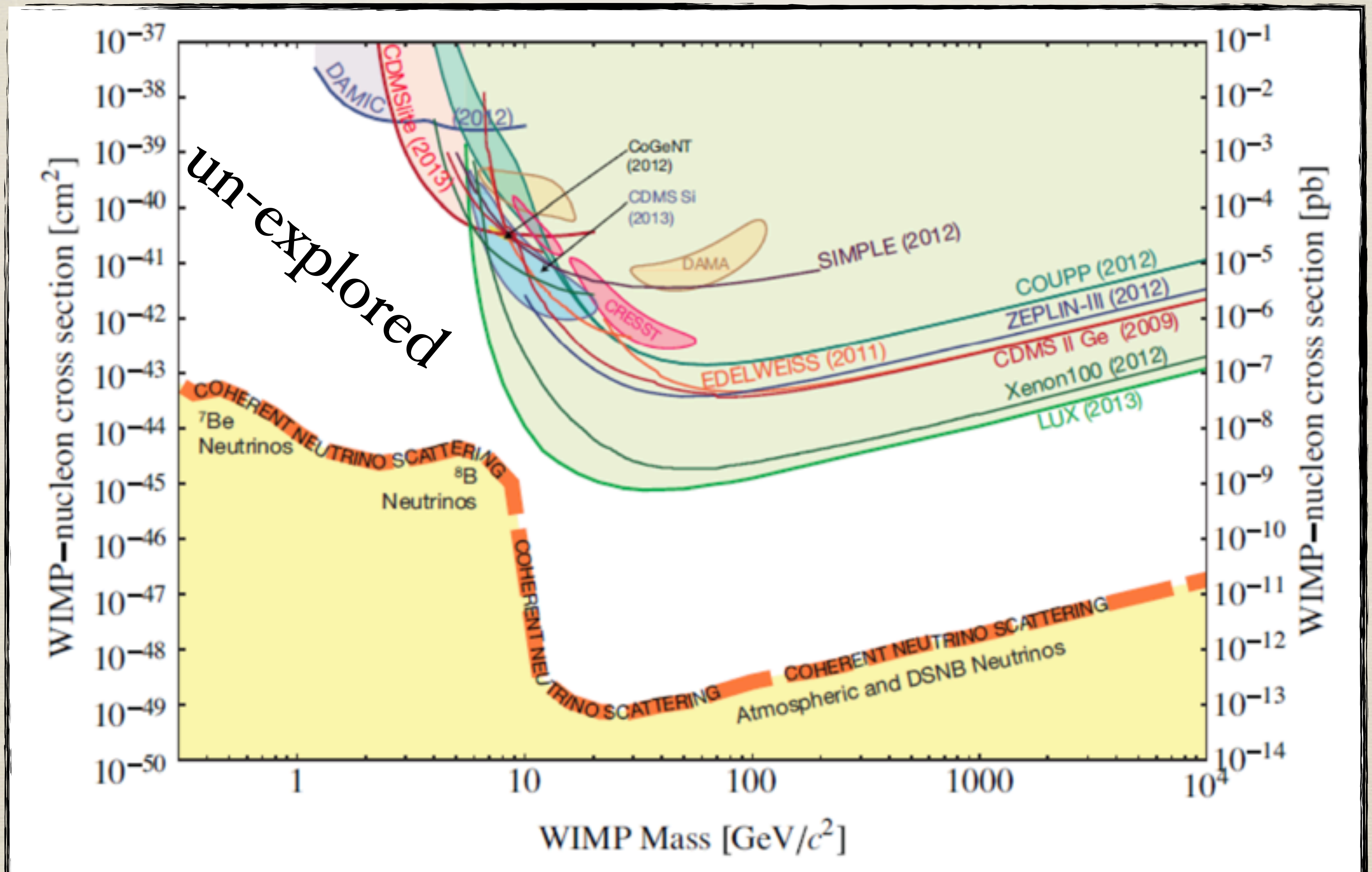
- **A Test Case - Molecules**
  - What is the physics involved?
  - What approximations can be made?
  - What do we expect to be able to measure?

- **Onward to a Realistic Experiment**
  - What are the requirements?
  - What can we do with crystals?
  - Is the physics similar to molecular dissociation?
  - What are the challenges?

Motivation

Why Light Dark Matter?





Billard,, Figueroa-Feliciano, Strigari '14

Motivation

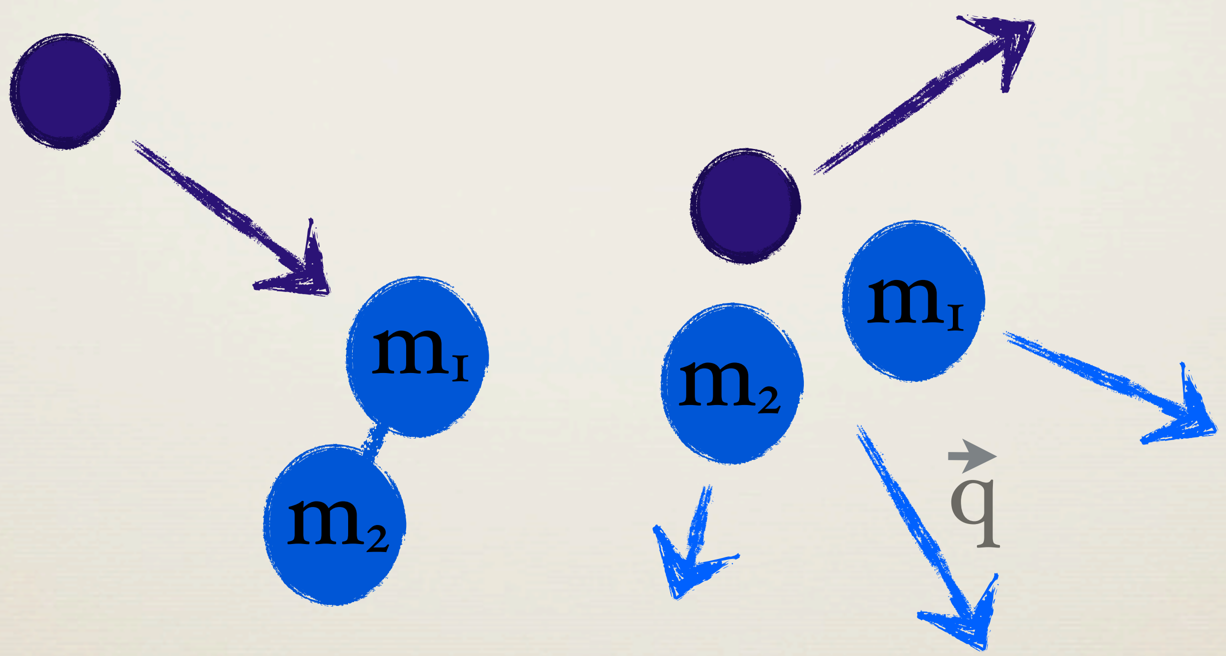
Why Inelastic Scattering?

$$E_{elastic} \sim \frac{q^2}{2M} \sim 5 \text{ eV} \left(\frac{m_\chi}{100 \text{ MeV}}\right)^2 \left(\frac{\text{GeV}}{M}\right)$$

$$E_{available} \sim \frac{1}{2} m_\chi v^2 \sim 50 \text{ eV} \cdot \left(\frac{m_\chi}{100 \text{ MeV}}\right)$$

Bond Breaking in Low Energy Threshold Systems

A Test Case:
Chemical Bond Breaking in Molecules



Threshold ~ few eV

Ingredients for Calculating the Detection Rate

$$
\begin{aligned}
R &= N_m \frac{\rho_\chi}{m_\chi} \int d^3v f(v) \int d\left\langle \sigma v \right\rangle \\
&= N_m \frac{\rho_\chi}{m_\chi} \frac{\overline{\sigma_p}(m_1 + m_\chi)^2}{4m_\chi^2 m_1^2} \int 4\pi v dv f(v) \int dln E'_{int} \int qdq |F_{DM}(\mathbf{q})|^2 |F_{dis}(q, E'_{int})|^2 \Theta\left(v - v_{min}(q, E_{int})\right)
\end{aligned}
$$

# of Targets

DM Density

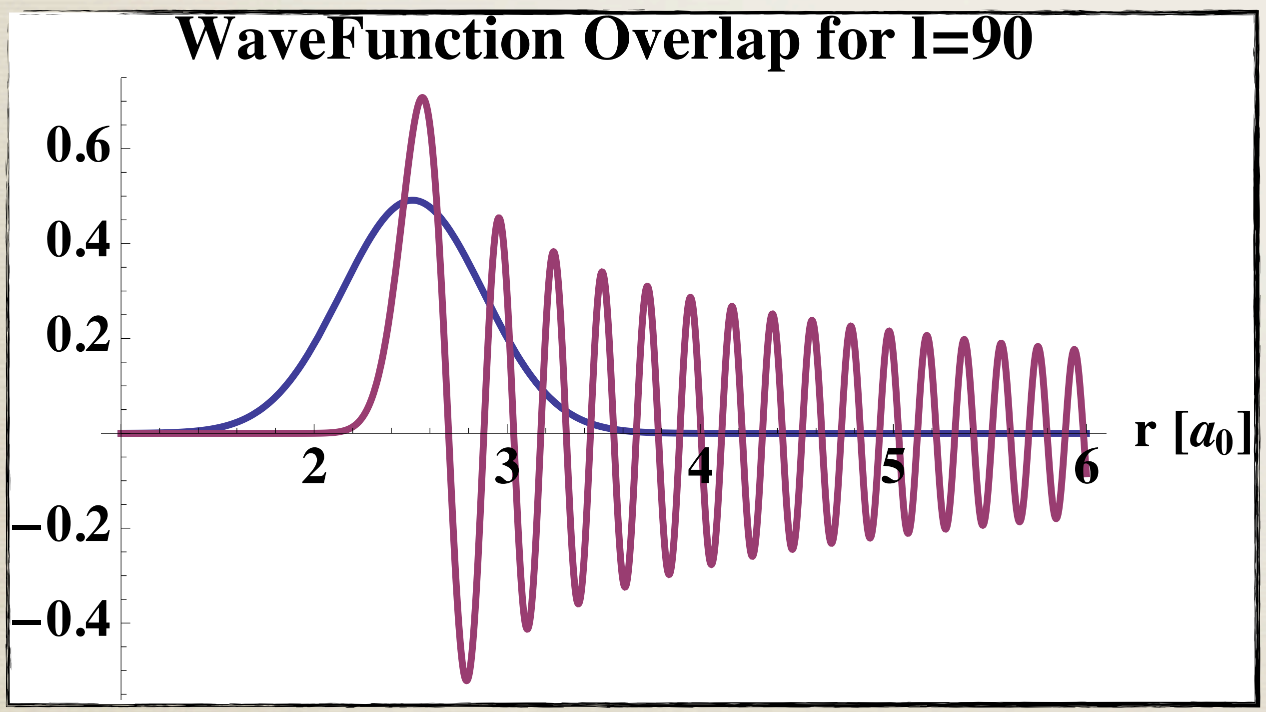
Velocity Distribution

DM Form Factor

Target Form Factor

The Molecular Form Factor

$$|\langle\Psi_f|H_{int}|\Psi_i\rangle|^2 \sim |F_{dis}(q,\tilde{q})|^2 = \frac{\tilde{q}^3}{(2\pi)^3}\int d\Omega_{\tilde{q}}|\int d^3r e^{i\frac{\mu_{12}}{m_1}\mathbf{q}\cdot\mathbf{r}}\psi_f^*(\mathbf{r})\psi_i(\mathbf{r})|^2$$



Final State Wavefunction

Initial State Wavefunction

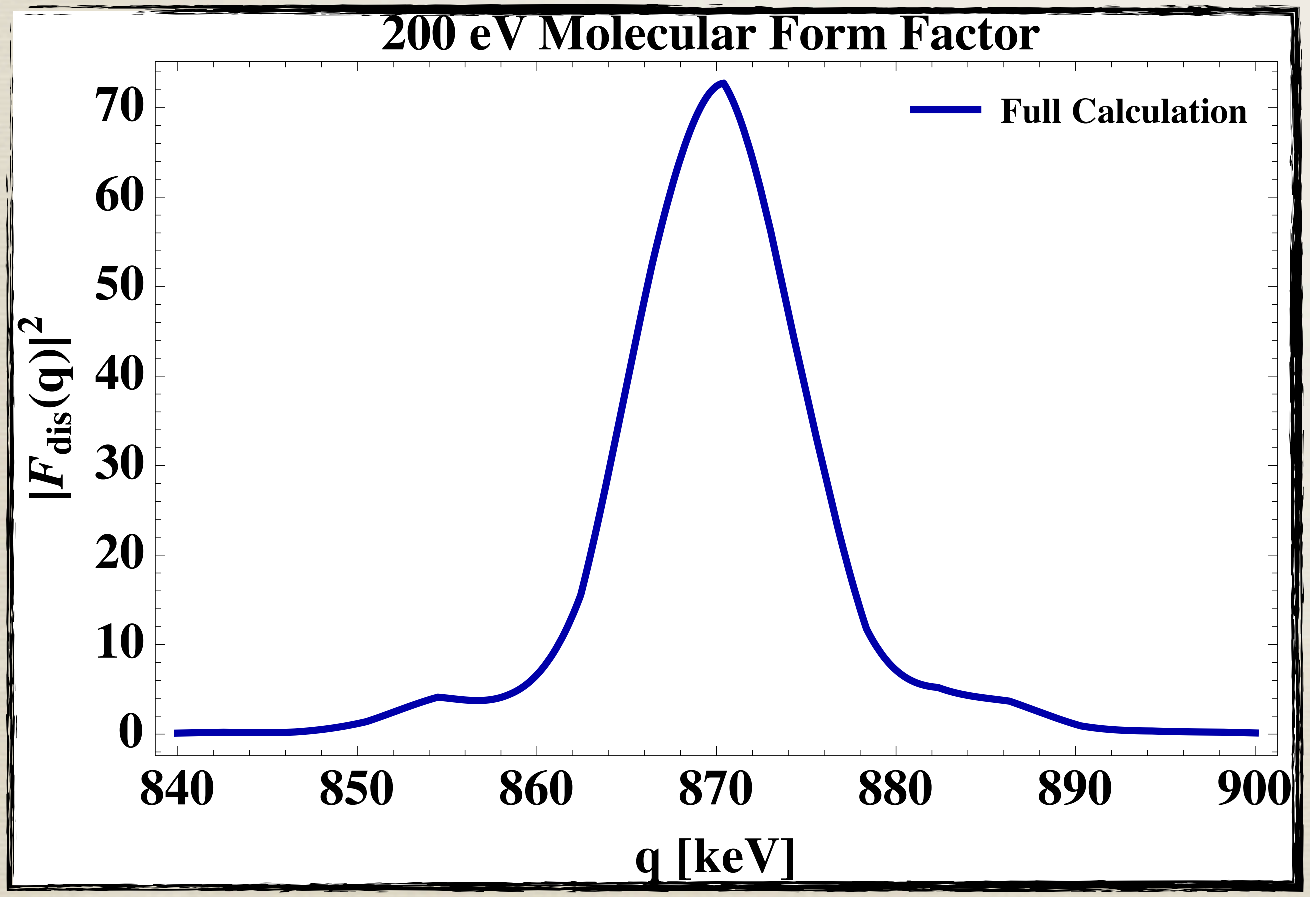
The FF - The Wavefunction Overlap - Encodes the QM effects

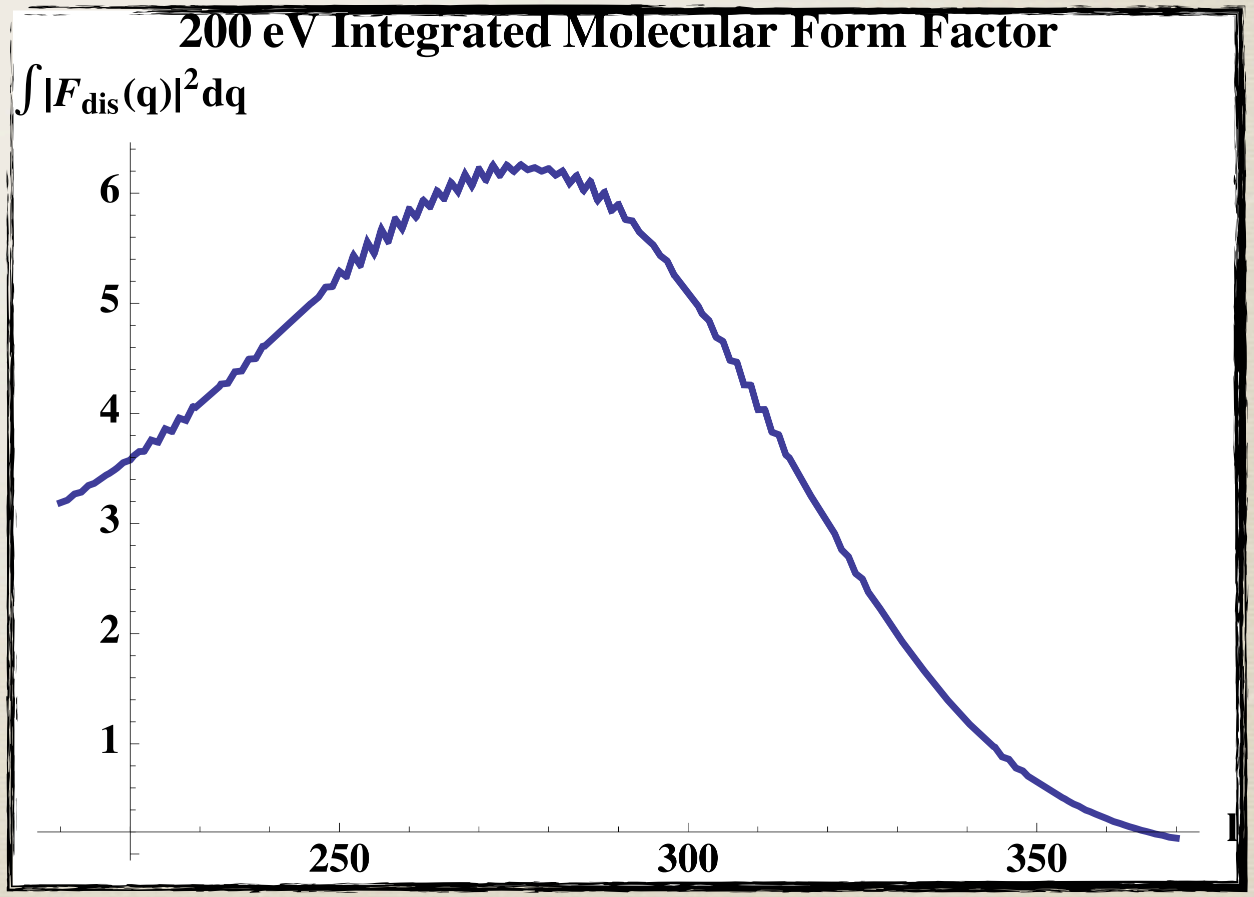
Understanding the Rate

In principle we need to calculate the initial and all final states and sum over all angular momenta (L).

The Form Factor

Integrated FF per L



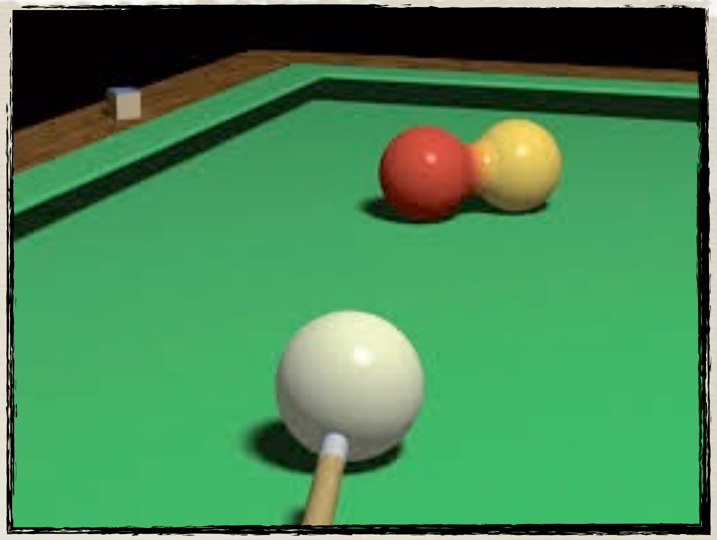


Understanding the Rate

For various DM mass regimes we can make various approximations:

- Classical Approach - no QM effects.
- The Born Approximation - no binding potential for final state.
- Improving the Born App. - Sommerfeld Enhancement

The Classical Picture



- **Good approximation for large values of angular momentum.**
  (large DM masses)

- **No QM effects.**

- **The FF is proportional to a delta function:**
  (only kinematics is involved)

$$|F_{dis}(q,\tilde{k}')|^2 \sim \frac{\tilde{k}'^3}{(2\pi)^3}\delta^{(3)}\left(\frac{\mu_{12}}{m_1}\mathbf{q} - \tilde{\mathbf{k}}'\right)$$

- **The average differential cross section:**

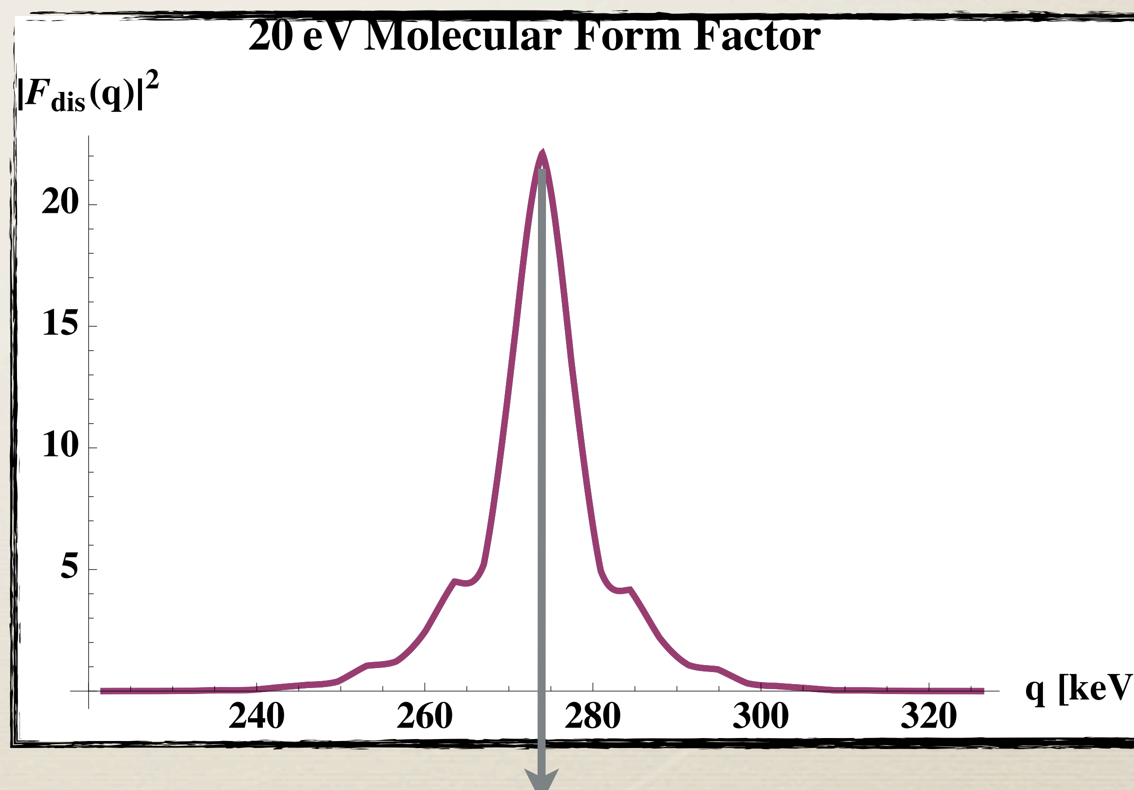
$$\left\langle \frac{d\sigma v}{dq^2} \right\rangle = A^2 \frac{\bar{\sigma}_n}{8\mu_{\chi 1}^2 v}$$

The Born Approximation

- Take the final state = free plane wave.
- Takes into account non-zero momentum for initial state.

$$|F_{dis}(q,\tilde{k}')|^2 = \frac{m_1}{\mu_{12}} \frac{\tilde{k}'^2}{(2\pi)^2} \int_{\tilde{k}'-\frac{\mu_{12}}{m_1}q}^{\tilde{k}'+\frac{\mu_{12}}{m_1}q} \frac{KdK}{q} \left|\int d^3r e^{-i\mathbf{K}\cdot\mathbf{r}}\Psi_i(\mathbf{r})\right|^2.$$

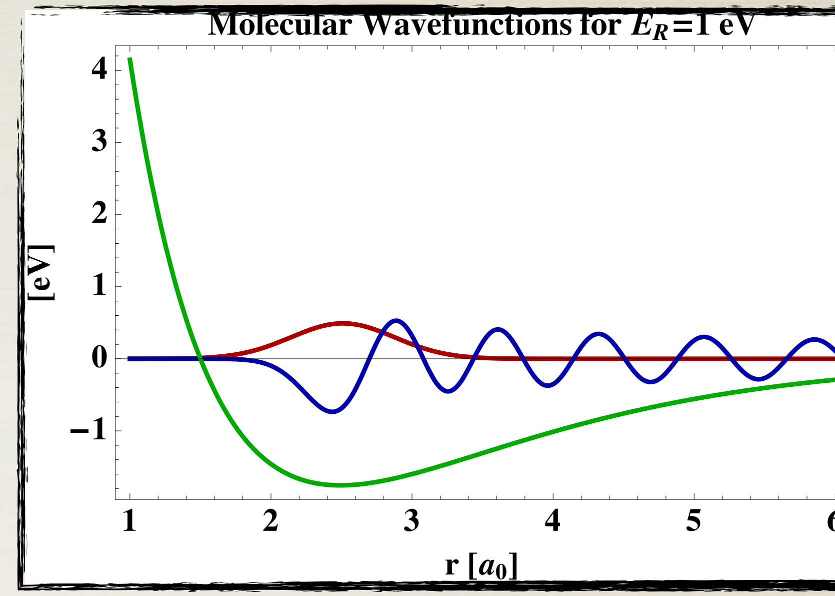
- No binding potential.
- The FF is analytical.
- The peak is at the classical momentum transfer value.



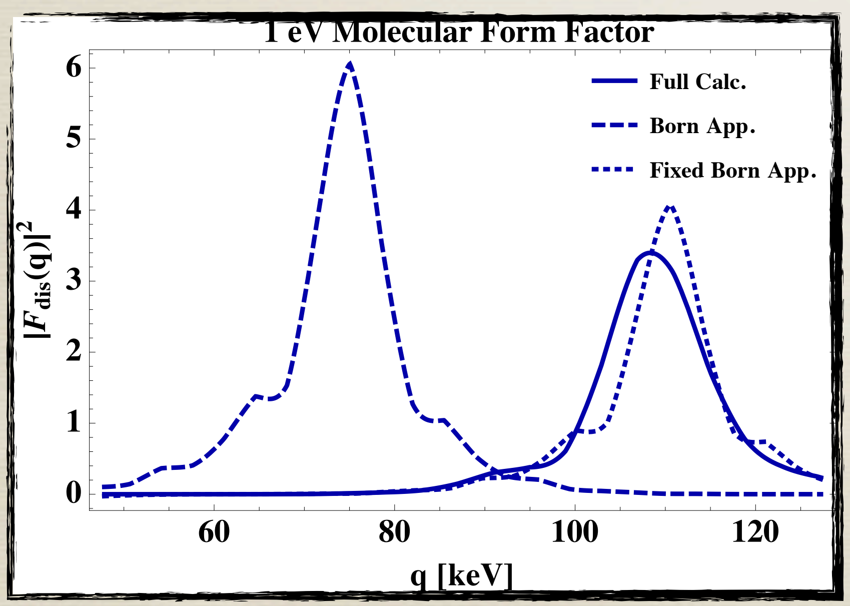
The Classical Momentum Transfer

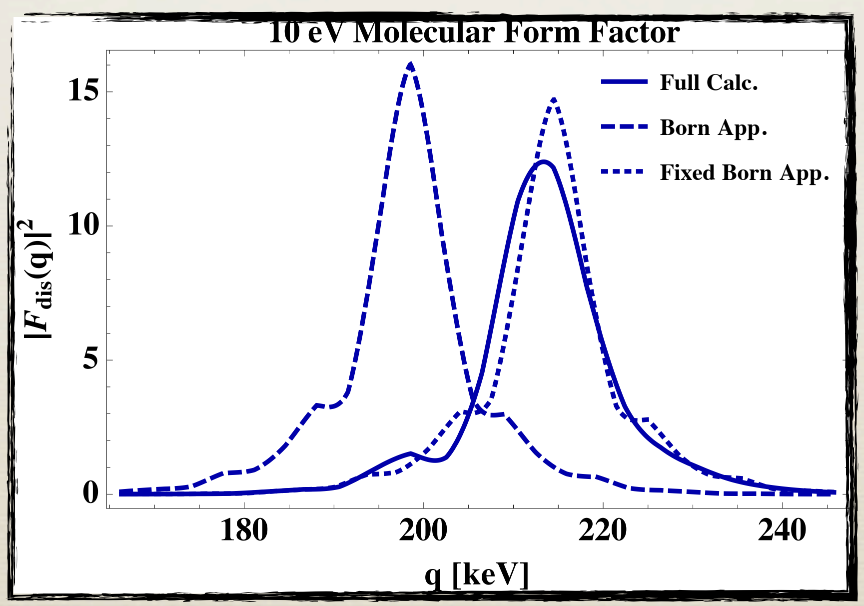
Improving the Born App.

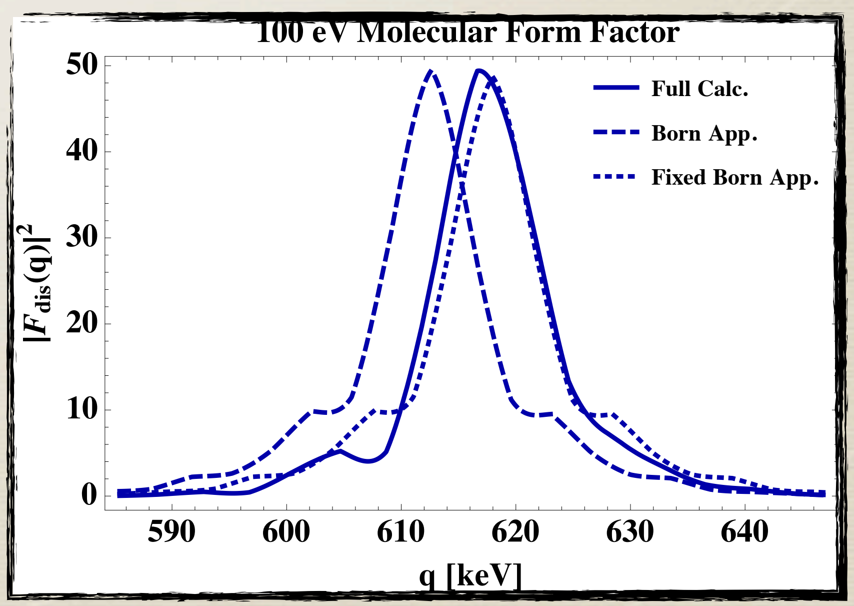
- Account for binding energy by hand.
- The FF is analytical.
- Peaks at the correct value.
- Equivalent to Sommerfeld Enhancement
- Very accurate



$$q \approx \frac{m_1}{\mu_{12}}\tilde{q}_+ = \frac{m_1}{\mu_{12}}\sqrt{2\mu_{12}(E_{int} + \Delta E_B)}.$$

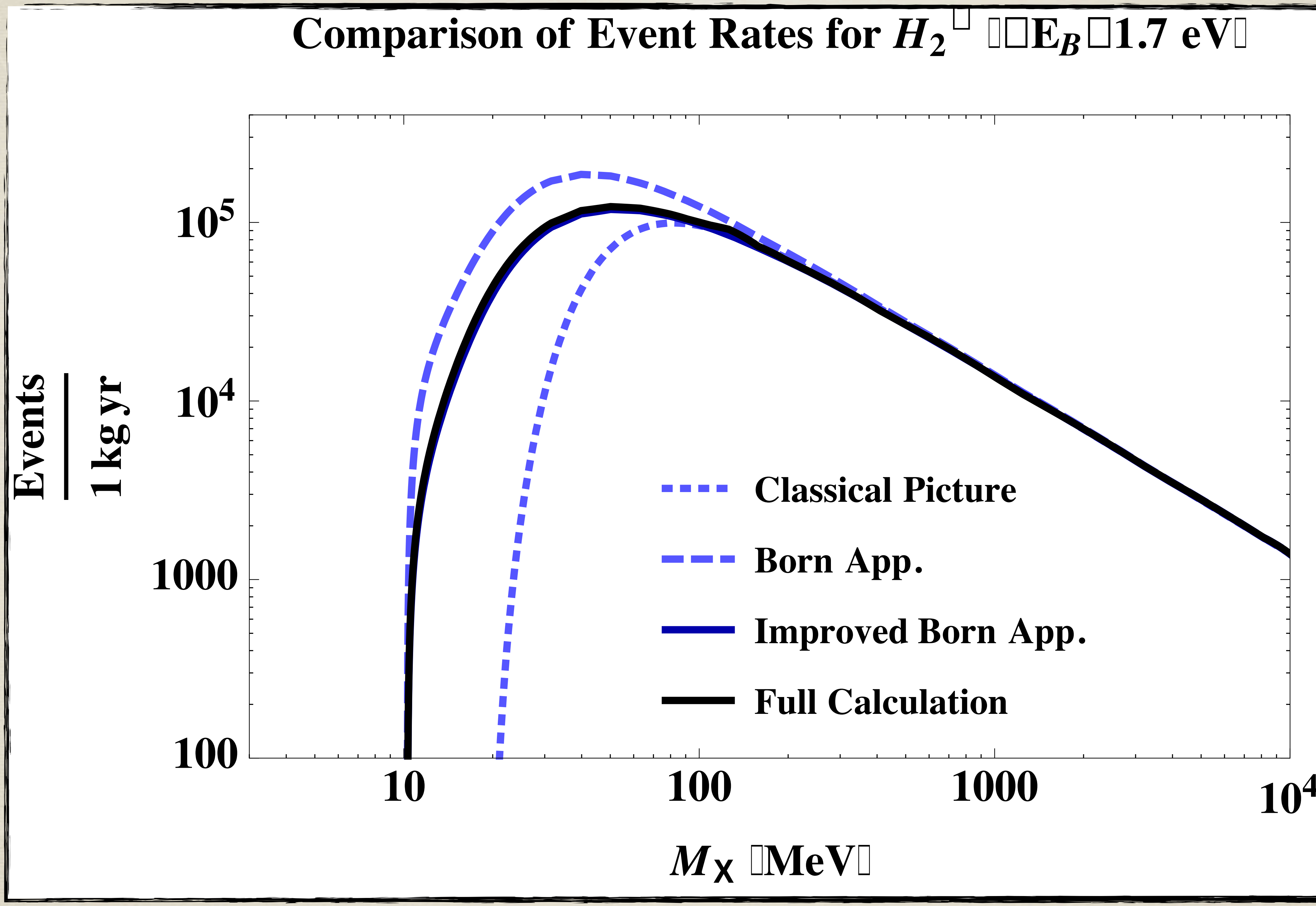






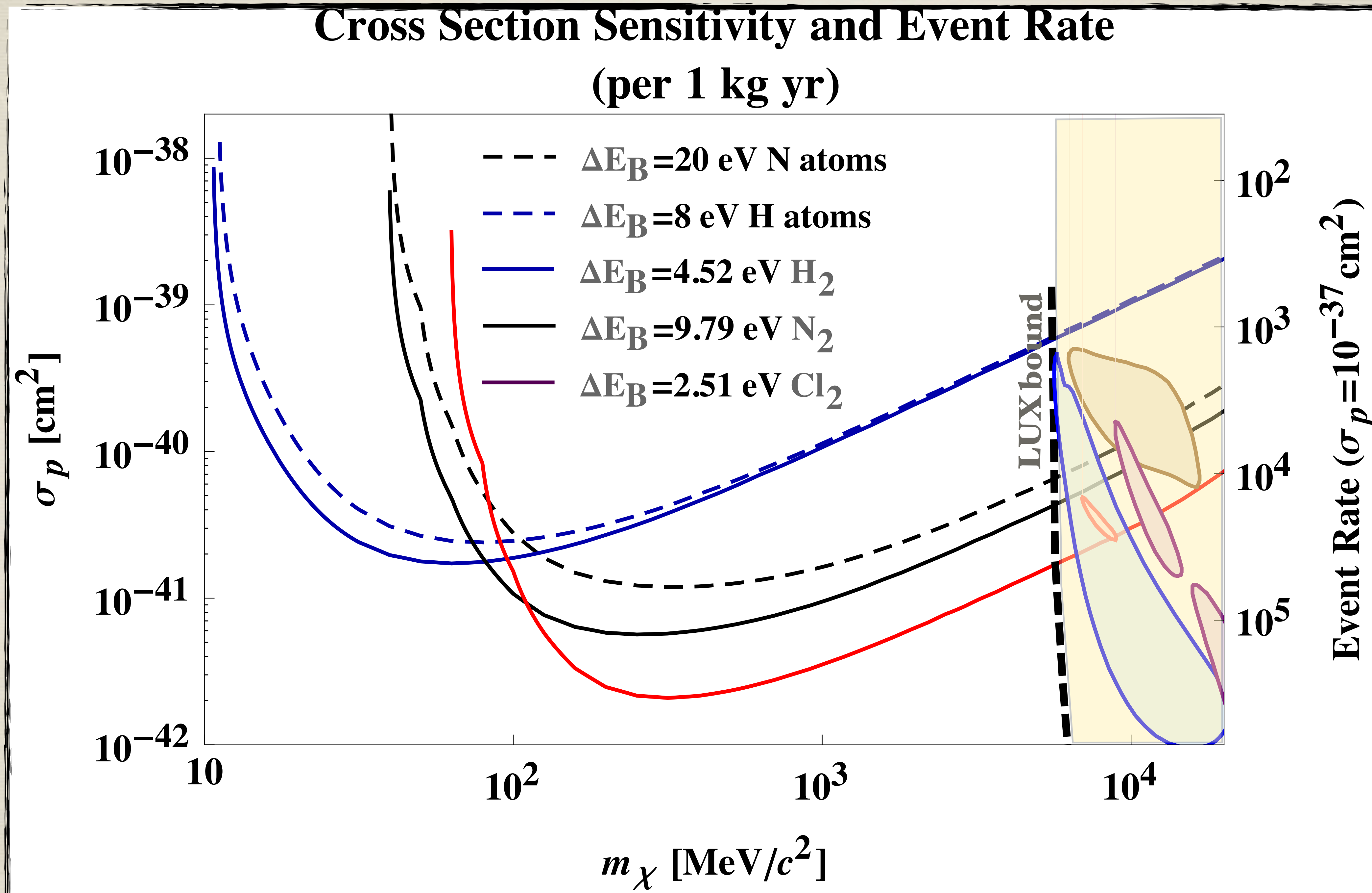
Essig, Slone, Mardon, Volansky (preliminary)

Expected Rates



Essig, Slone, Mardon, Volansky (work in progress)

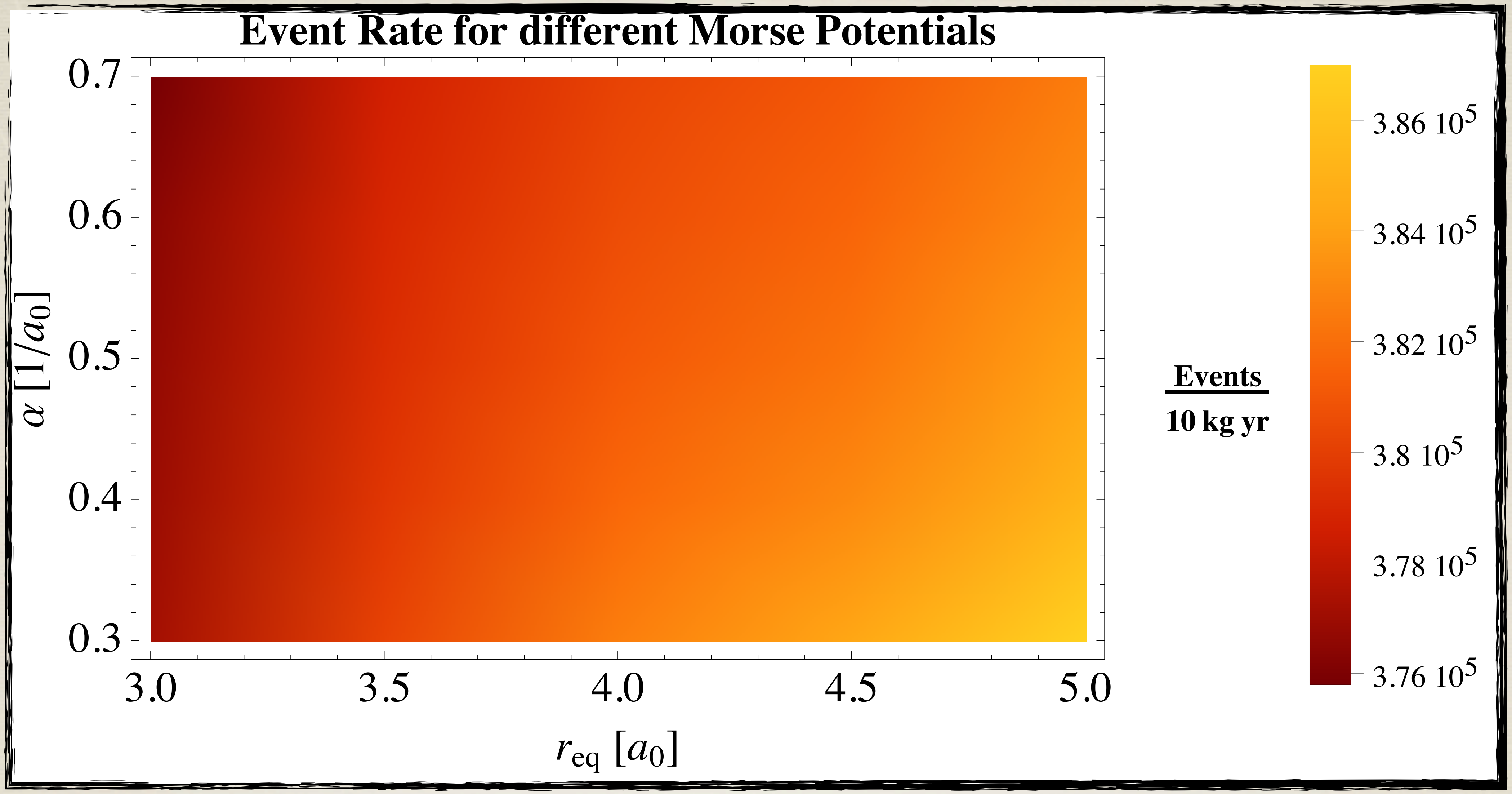
Expected Sensitivity

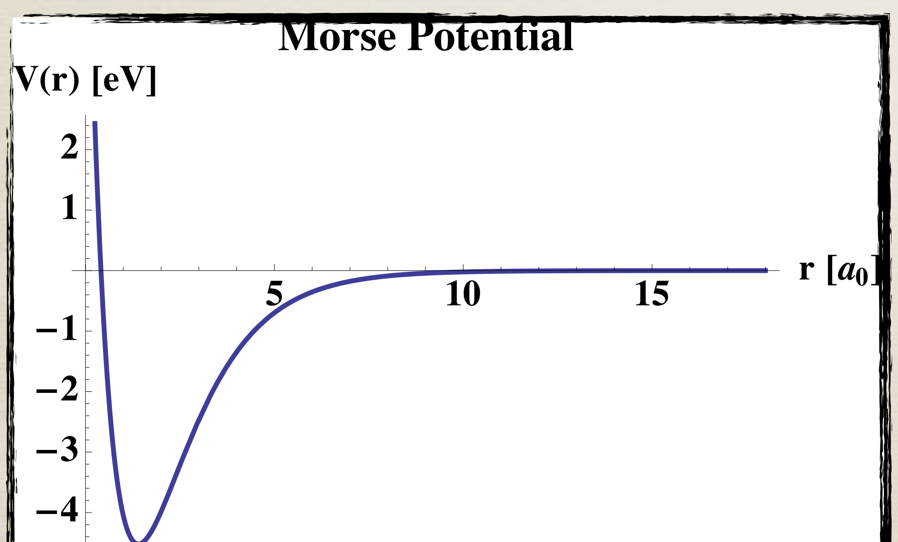


$$\frac{R_1}{R_2} \propto \sqrt{\frac{A_1}{A_2} \cdot \frac{\Delta E_{B2}}{\Delta E_{B1}}}$$

Essig, Slone, Mardon, Volansky
(work in progress)

Event Rate depends only on ΔE

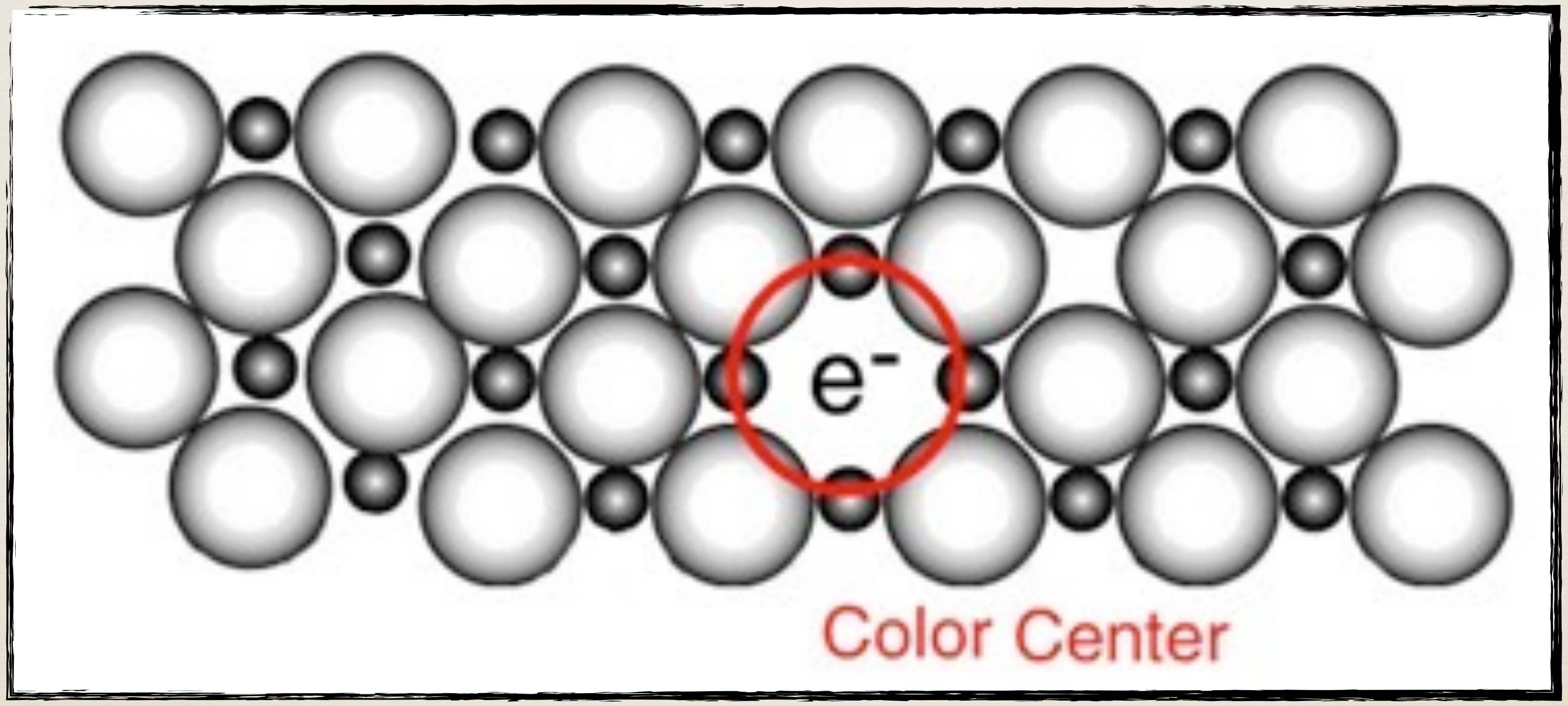




Essig, Slone, Mardon, Volansky
(work in progress)

Towards a Real Experiment

Chemical Bond Breaking in Crystals: Creation of Color Centers



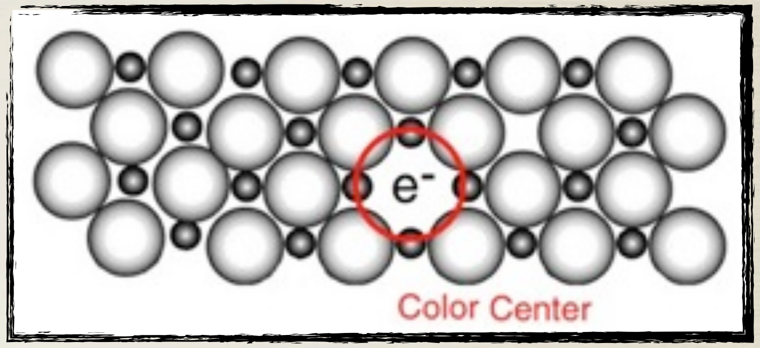
Threshold ~ few 10 eV

Towards a Real Experiment
Some Requirements

- Low Threshold Energy (realistically ~ 10 eV).
- Background Discrimination:
  - Differentiate between low / high energy events.
  - Differentiate between nuclear / electron recoils.
- Possible to detect / a signal enhancement mechanism.
- Ability to clean on short timescales.

Towards a Real Experiment
Color Centers

- Threshold Energies of ~ 10-50 eV.
- Enhancement via optical amplification.
- Detection via fluorescent properties.
- Annealing by temperature increase.

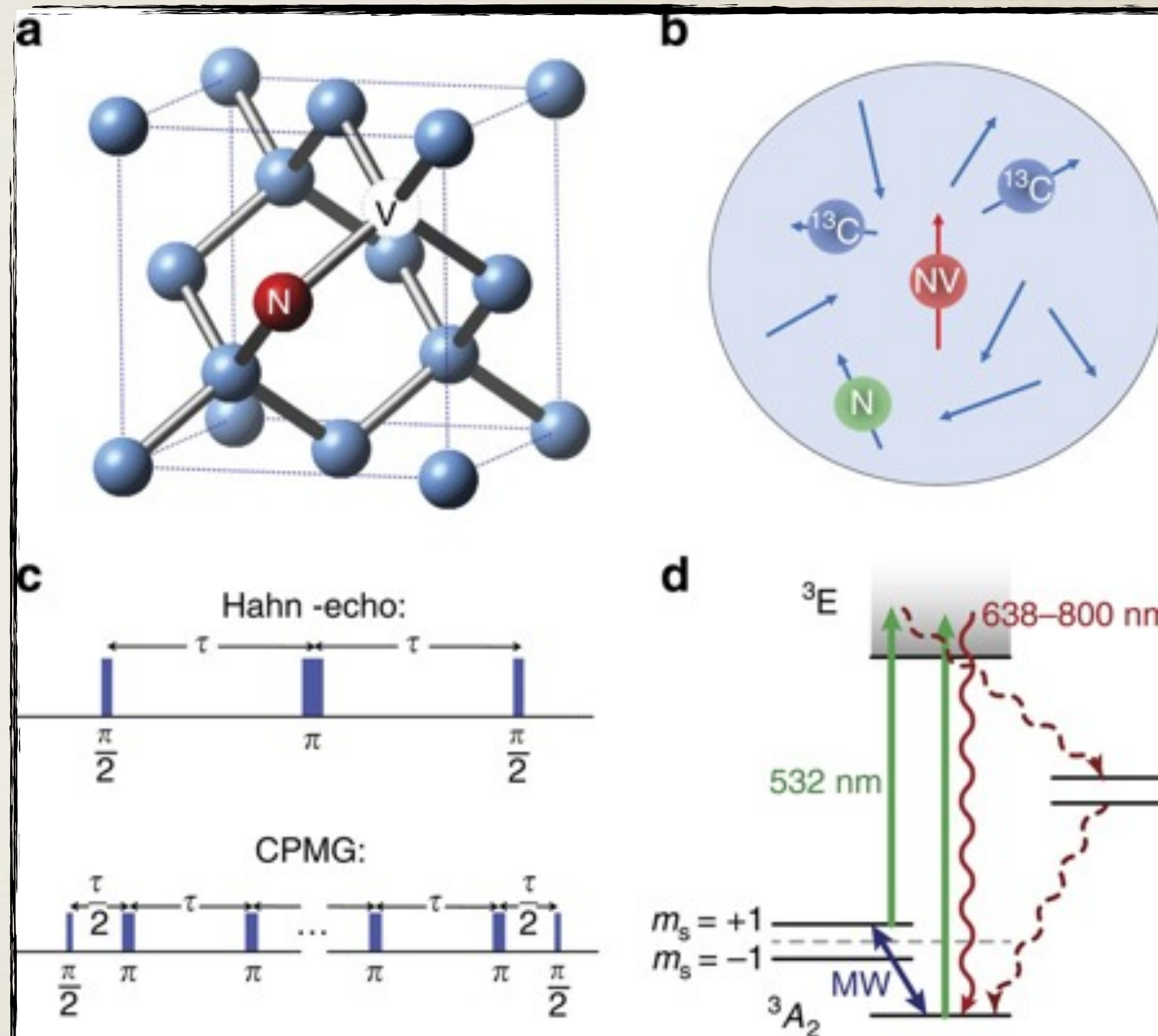


Towards a Real Experiment

What has been done: NV Centers

DIAMOND LATTICE:

- Replace a C with an N
- Create a vacancy
- Defect can have spin 0/1
- Interacts with ~50^3 sites



Single NV Defects can be measured!

Color Centers live in a far more messy environment...

Color Centers

Can we use what we've learned about molecules?

- **Calculating the FF is (in principle) the same:**
  - Solve the Schrodinger Equation for initial and final states
  - Overlap and Integrate

- **Theoretical Challenges:**
  - Time Dependent
    But are the timescales similar?
  - Not Spherical Symmetric
    But is the wavefunction very localized?
  - Are the approximations valid?
    Classical / Born / Improved Born?

Work in Progress with Amit Abir, TAU

Color Centers

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  - Are the approximations valid?
    Classical / Born / Improved Born? **MAYBE**

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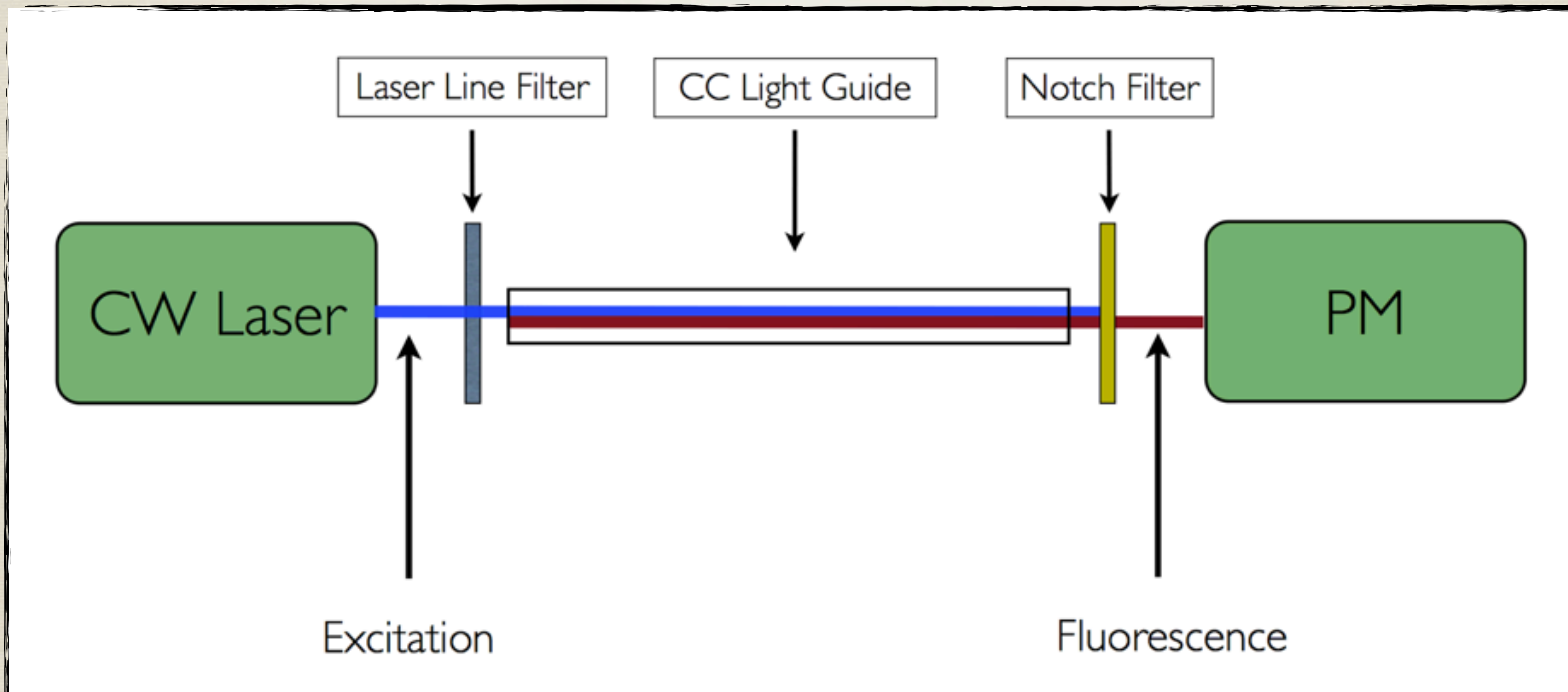
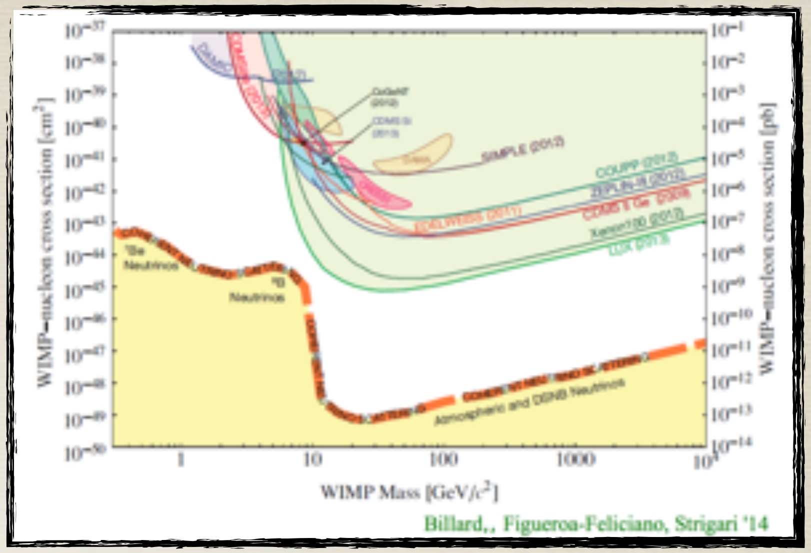
Towards a Real Experiment
Proof of Concept



Abir, Ashkenazi, Bloch, Budnik, Chesnovsky, Devi, Essig, Itay, Kreisel, Landsman, Mardon, Sagiv, Silver, Slone, Sofer, Volansky, et. al.

Future Prospects



- Understanding Color Center.
- Proof of Concept for a real experiment.
- Additional Techniques.
- Sensitivity to Solar Neutrinos.

THANK YOU