Scintillating Methods to Detect Dark Matter from Nano to Astro Scales

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MW Dark Matter Halo

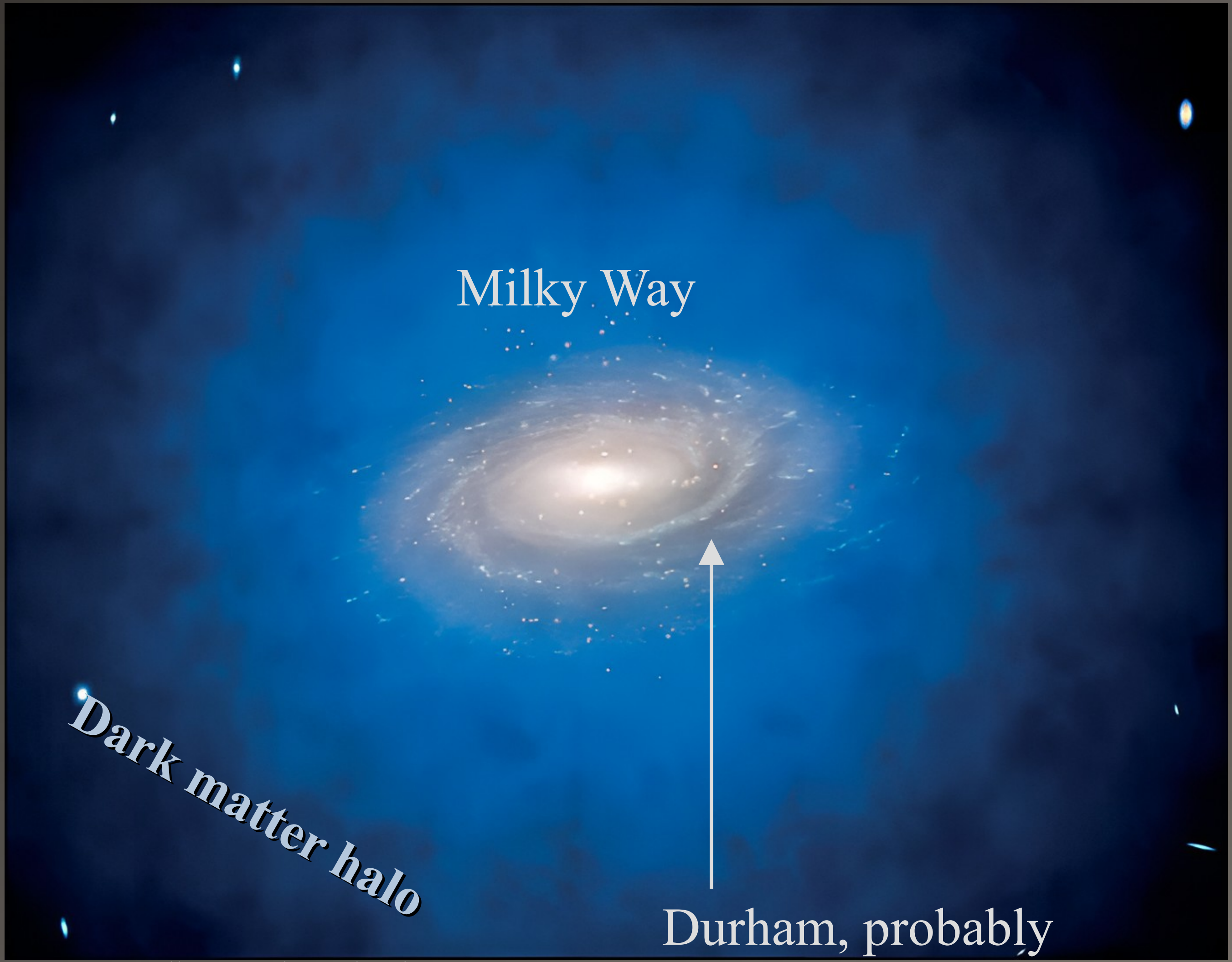


Image credit: ESO/L Calçada

Local dark matter density

$$\rho_{\rm DM} = 0.4\,{\rm GeV/cm^3}$$

Local dark matter velocity

$$\langle v_{\rm DM} \rangle \approx 300\,{\rm km/s}$$

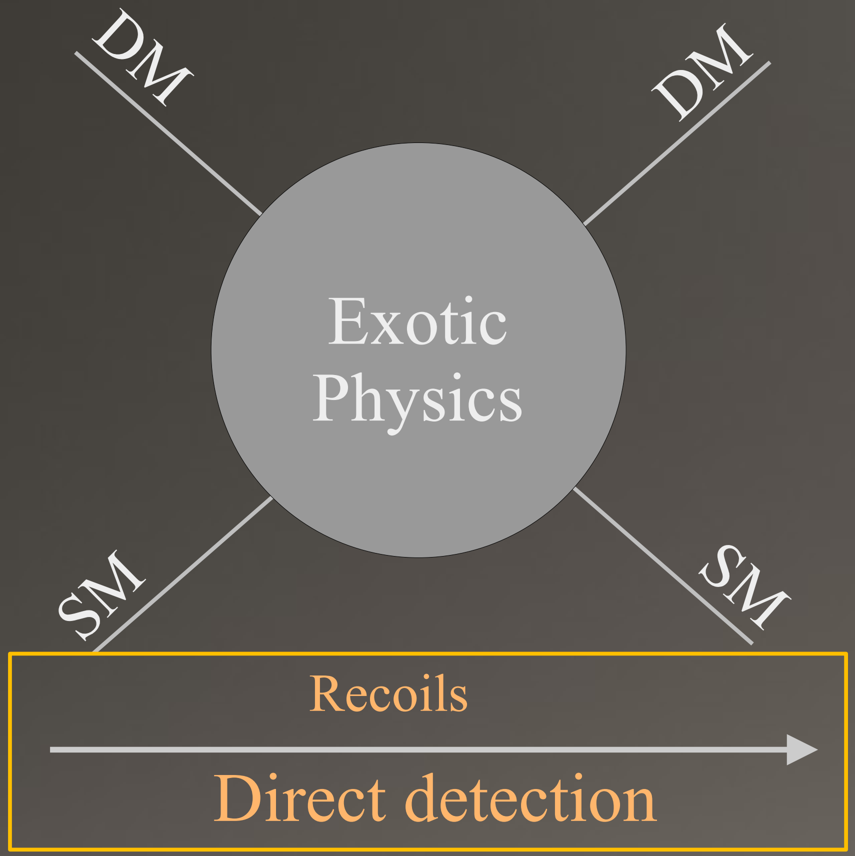
Lighter mass $\rightarrow$ more particles

$$n_{\rm DM} = \rho_{\rm DM}/m_{\rm DM}$$

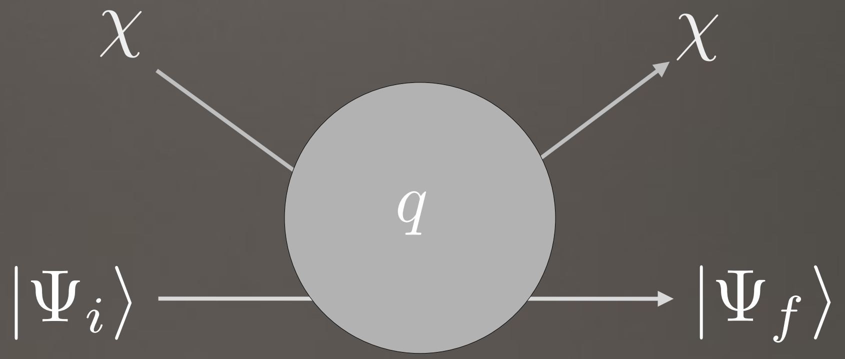
More particles $\rightarrow$ larger fluxes

$$\phi_{\rm DM} \sim v_{\rm DM}\, n_{\rm DM}$$

Dark Matter in The Lab



Direct WIMP-like *interaction*



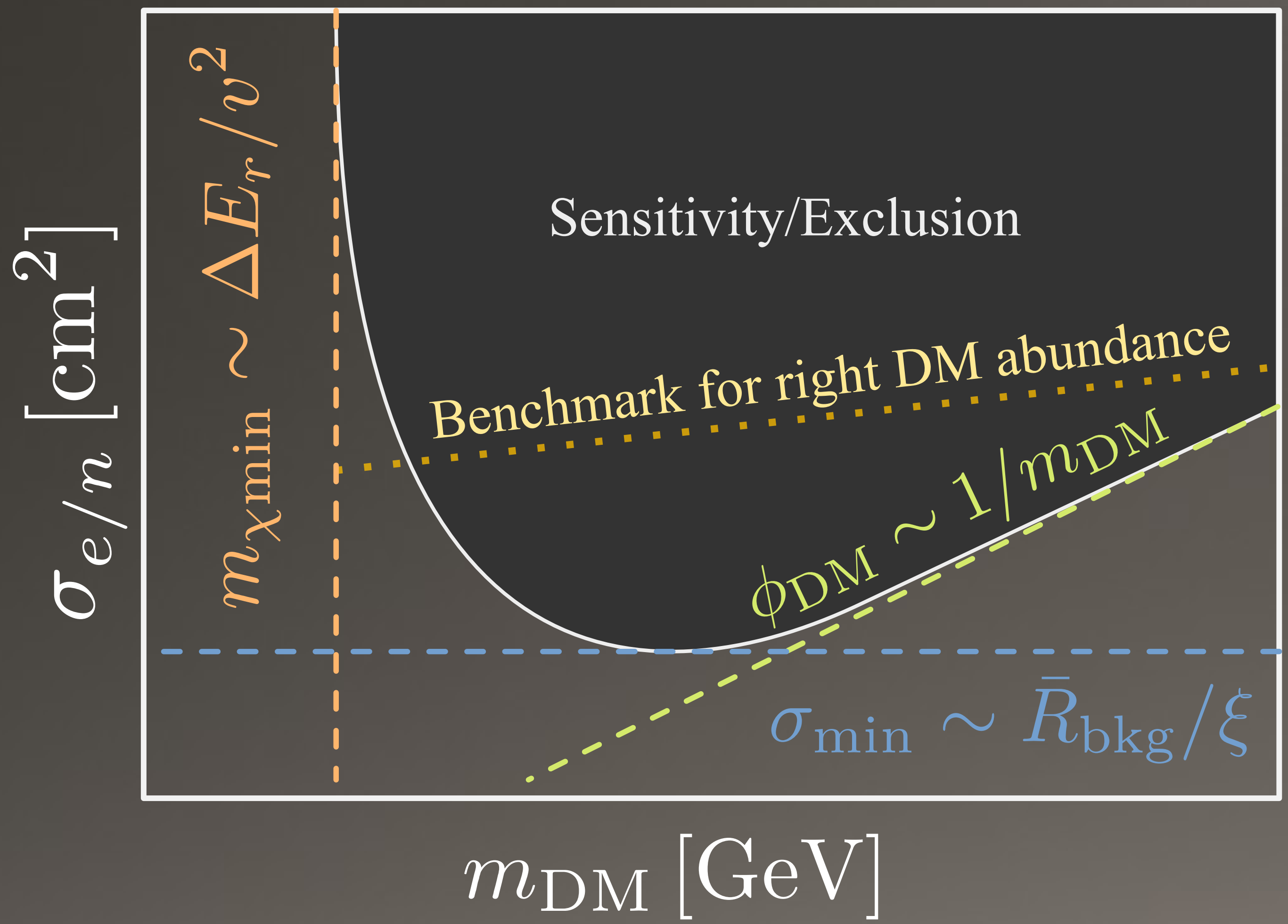
Energy Budget

$$E \sim v^2 m_\chi \approx \mathcal{O}(\mathrm{keV}) \left(\frac{\mathrm{m}_\chi}{1\,\mathrm{GeV}} \right)$$

Momentum Budget

$$q \sim v m_\chi \approx \mathcal{O}(\mathrm{MeV}) \left(\frac{\mathrm{m}_\chi}{1\,\mathrm{GeV}} \right)$$

Direct Detection



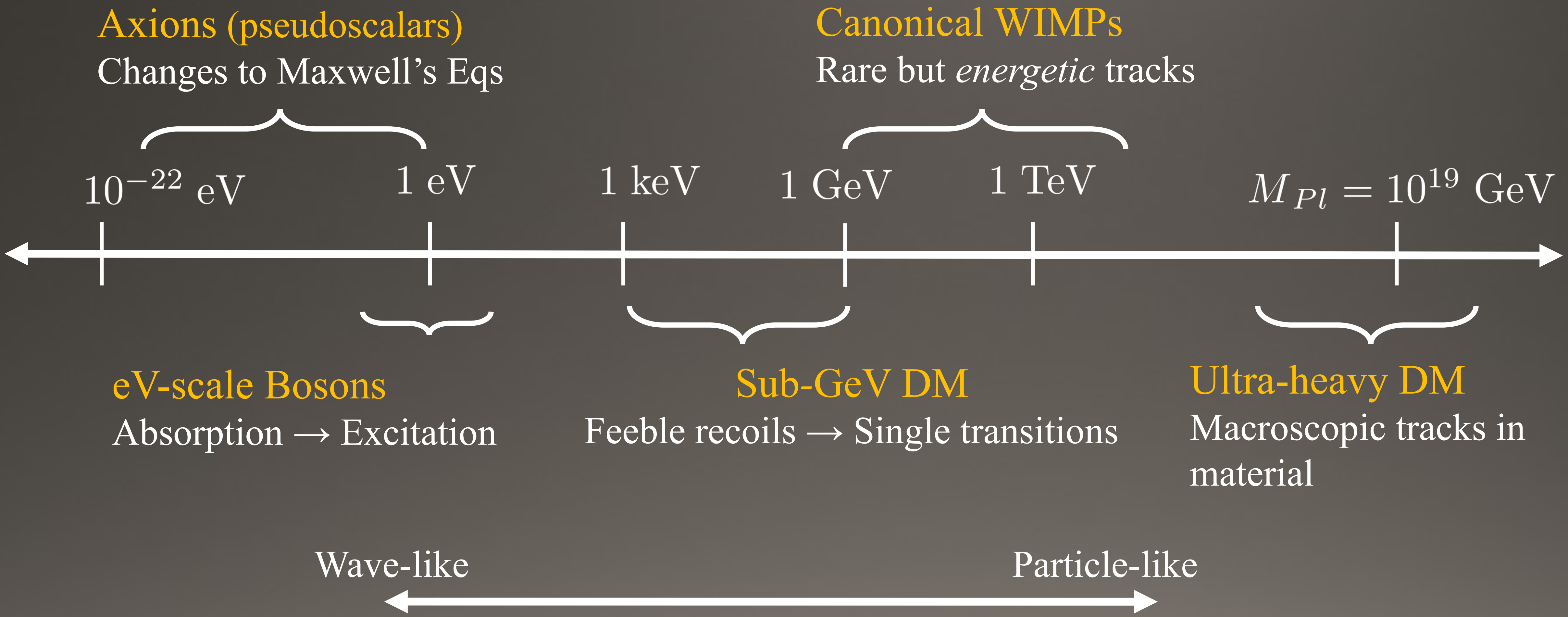
Need to *delve deep* and *search wide*

Minimize threshold energies ΔE_r

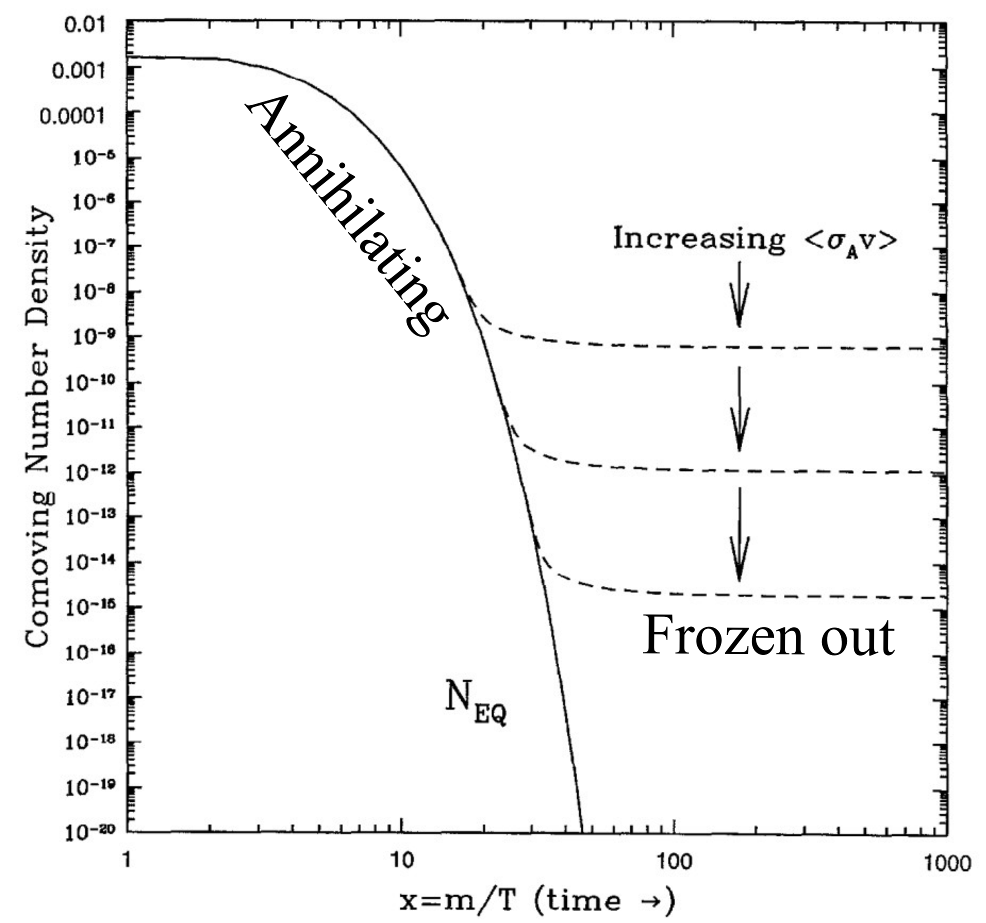
Maximize signal efficiencies ξ

Minimize backgrounds R_{bkg}

Mass Range & Detection Methods



WIMPs: The Miracle



Griest et. al: Phys Rep. 1996

Present-day abundance set by *freeze-out*

$$\Omega_c h^2 \sim \frac{1}{\langle \sigma v \rangle}$$

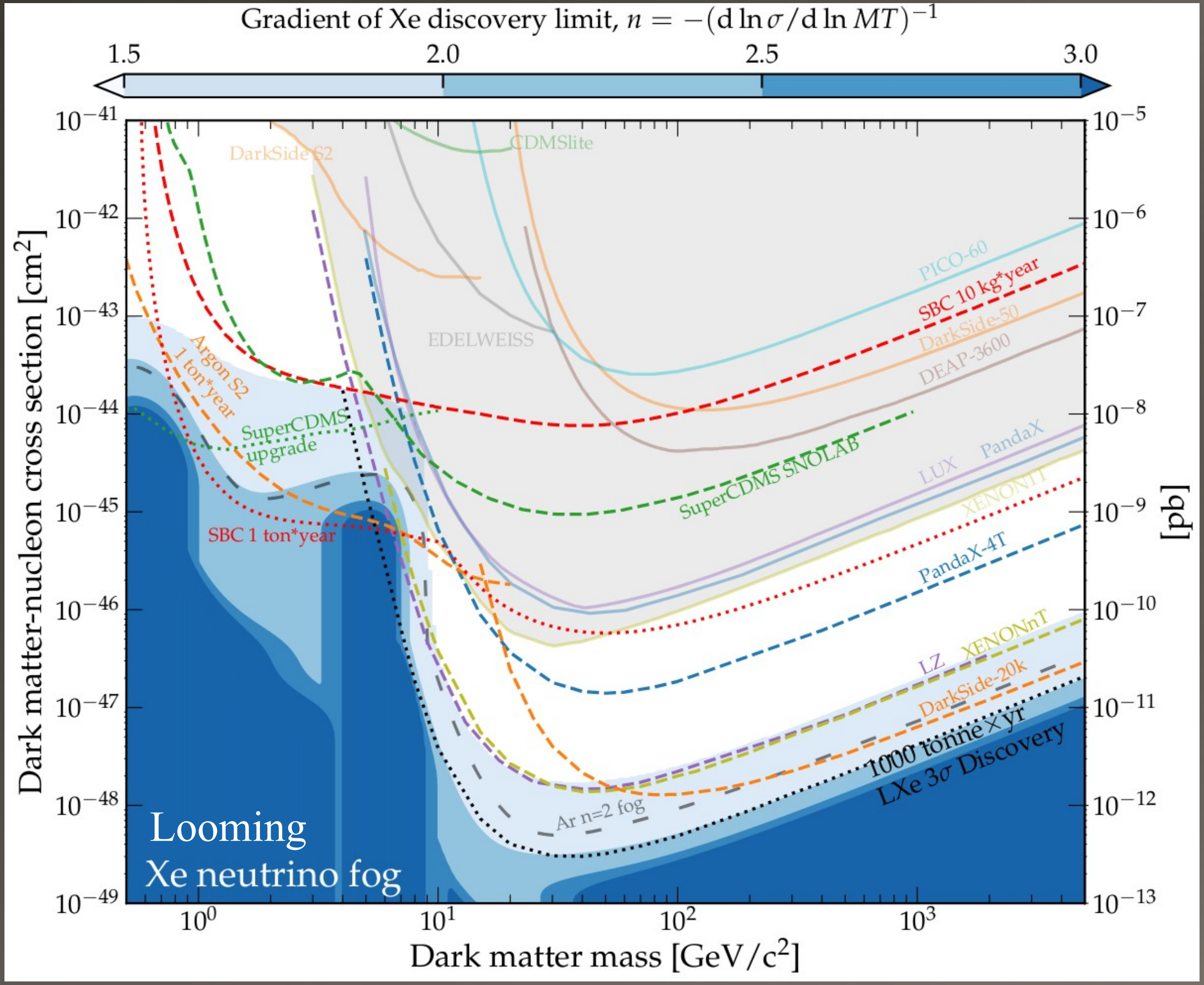
The appeal

Weak-scale masses and cross sections

$$\langle \sigma v \rangle_{\mathrm{FO}} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

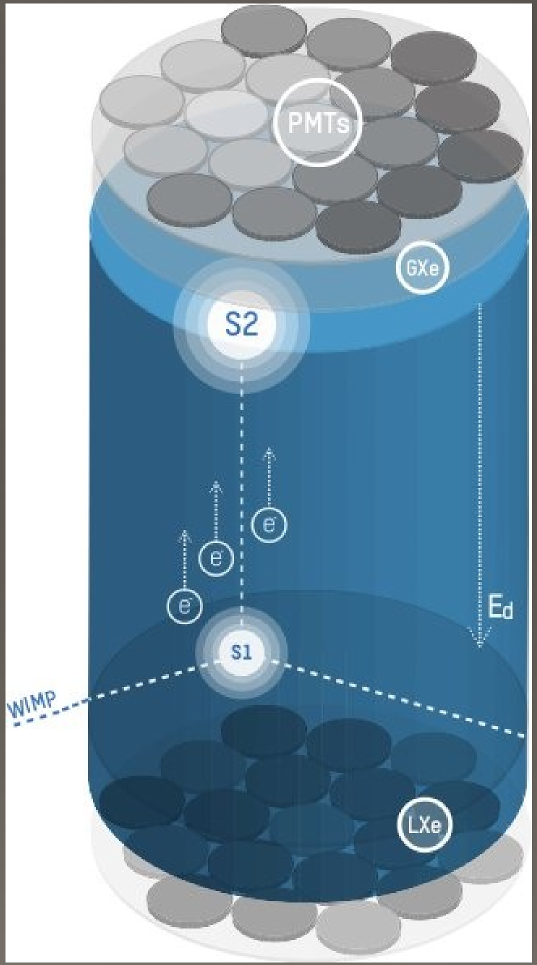
$$\approx \frac{\alpha_{\mathrm{W}}^2}{(100\,\mathrm{GeV})^2}$$

WIMPs: The Resounding Success



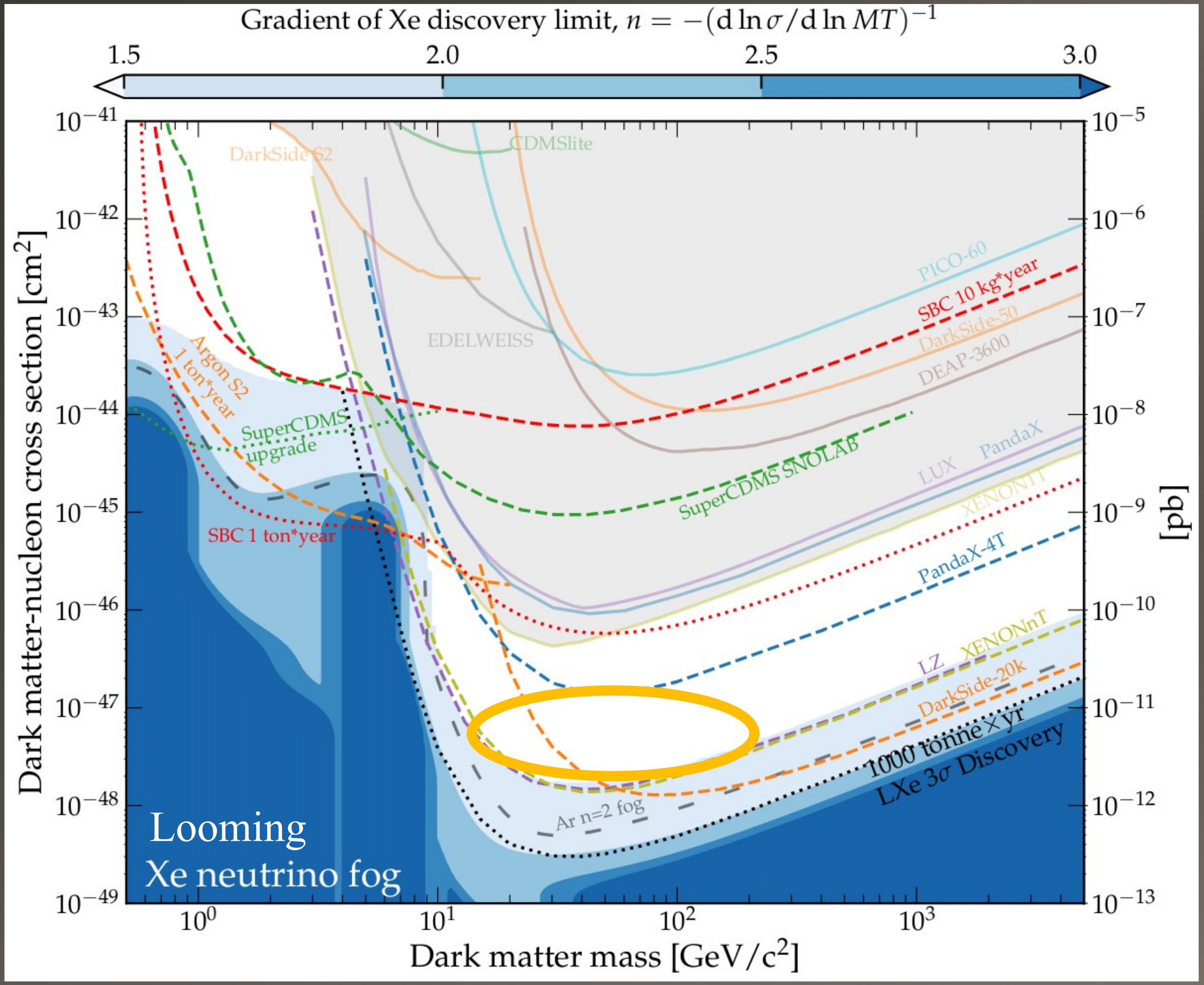
Liquid Noble Gases

Effective when $m_\chi > (O)(\mathrm{GeV})$



Akerib, D. S., et al. "*Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog.*" arXiv:2203.08084 (2022).

WIMPs: The Resounding Success



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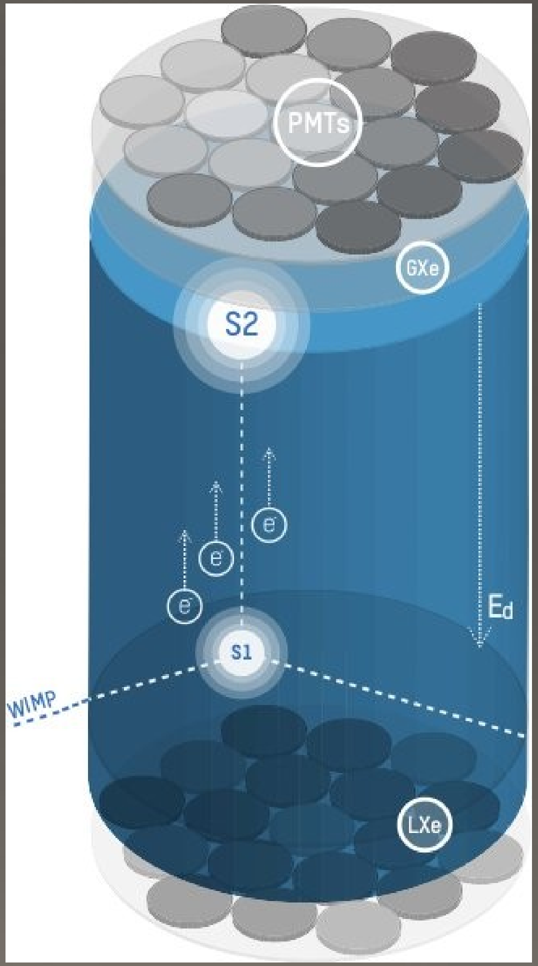
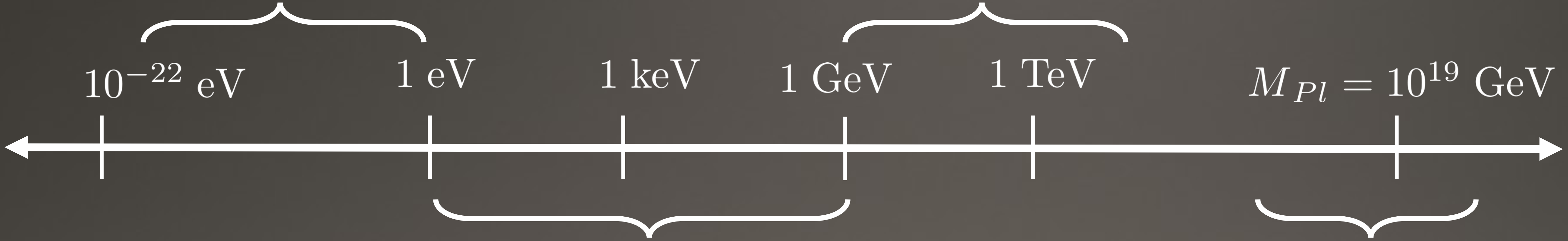


On to Non-WIMPy Dark Matter

Axions (solves strong-CP problem)
Misalignment

Canonical WIMPs
Annihilation freeze-out thermal relic



light DM
Feeble interaction→ Never in thermal contact → Freeze in abundance
Eq. *not* through annihilation → Freeze out through, e.g. scattering

Ultra-heavy DM
Composite DM
Black hole relics

Wave-like

Particle-like

Interaction Rate

Rate *spectrum* (events in detector)

$$\Gamma \sim \int \frac{d^3\vec{q}}{q} \eta(v) |F_{\mathrm{DM}}(q)|^2 |f_{i\to f}(q)|^2$$

Mean inverse velocity (Astrophysics)

$$\eta(v)$$

Transition form factor (Condensed matter / Chemistry)

$$f_{i\to f}(q) = \langle \tilde{\Psi}_f(k+q) | \tilde{\Psi}_i(k) \rangle$$

Dark matter form factor (Particle physics)

$$F_{\mathrm{DM}}(q) \propto \begin{cases} 1 & \text{, Contact interaction} \\ \left(\frac{1}{q}\right)^2 & \text{, Long-range interaction} \end{cases}$$

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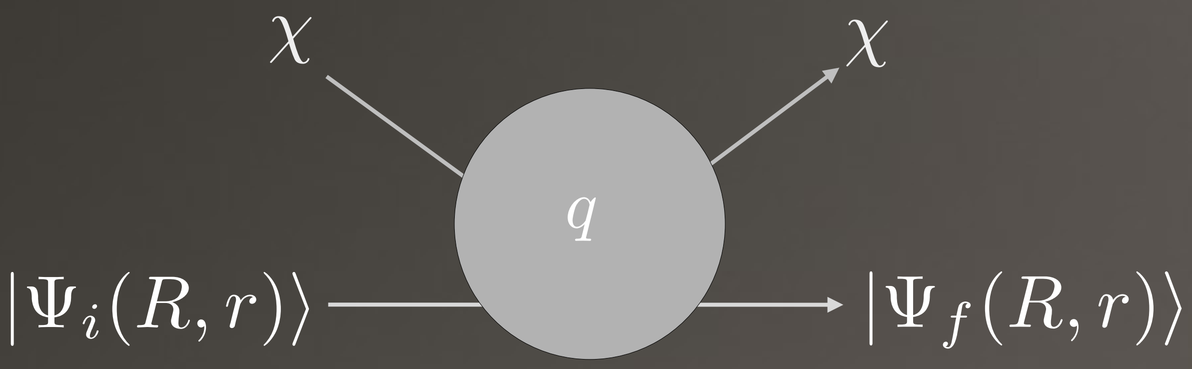
Sub-GeV Direct Detection



$R:$ Nuclei
$r:$ Electrons
$\chi:$ Dark matter

Imparted momentum in *scattering*

$$q \approx \mathcal{O}(\text{keV})\left(\frac{m_\chi}{1\,\text{MeV}}\right)$$

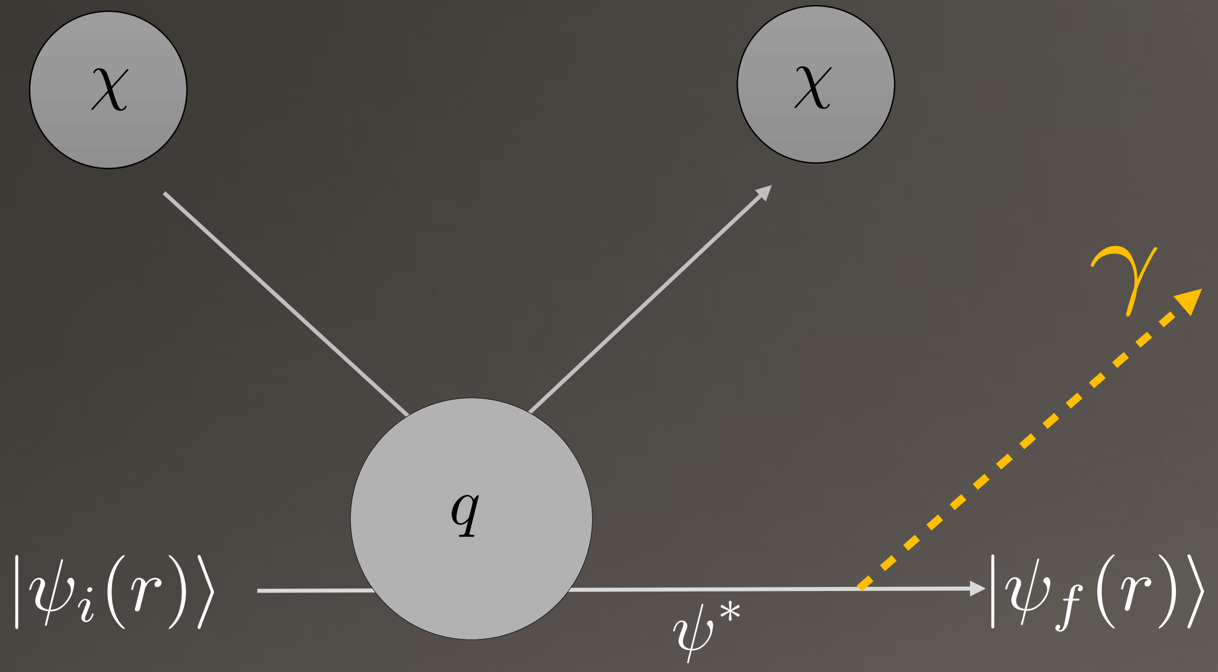
Energy Budget

$$\Delta E \approx \mathcal{O}(\text{eV})\left(\frac{\text{m}_\chi}{1\,\text{MeV}}\right)$$

Energy equals momentum in *absorption*

$$\Delta E = q = \left(\frac{m_\chi}{1\text{eV}}\right)$$

Electron Recoil → Photon Signal



Chromophores

Electronic excitation → Unstable state → Photon emission.

Molecules and Atoms (Quantized)

$$|\psi_i\rangle \sim \psi_{\text{lcao}}(r) \qquad |\psi\rangle^* \sim \psi^*_{lcao}(r)$$

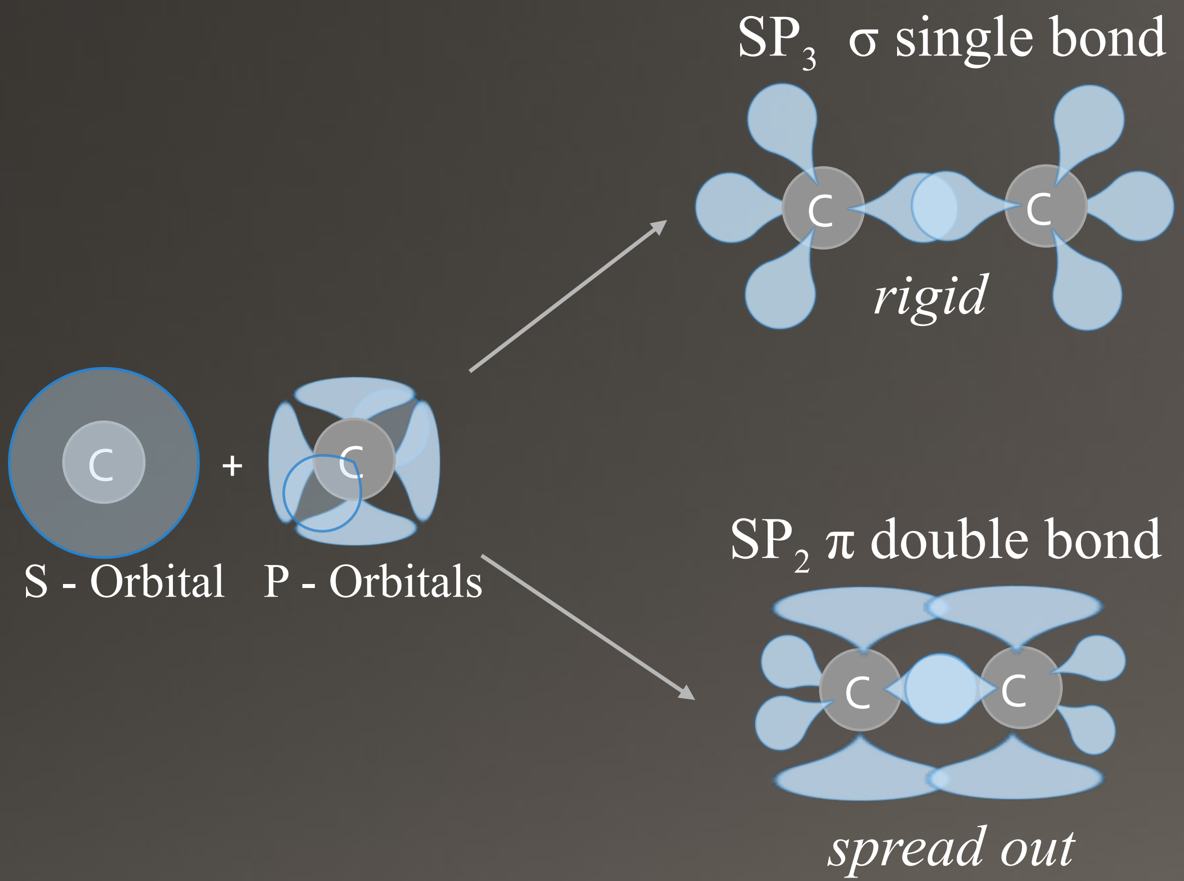
HOMO → LUMO

Crystals (Continuous)

$$|\psi_i\rangle \sim u_v(r)e^{ik\cdot r} \qquad |\psi\rangle^* \sim u_c(r)e^{ik\cdot r}$$

Valence → Conduction

Carbon: a Natural Candidate



Organic Chromophores

σ electrons form *rigid* network

π electrons *delocalized* on ring

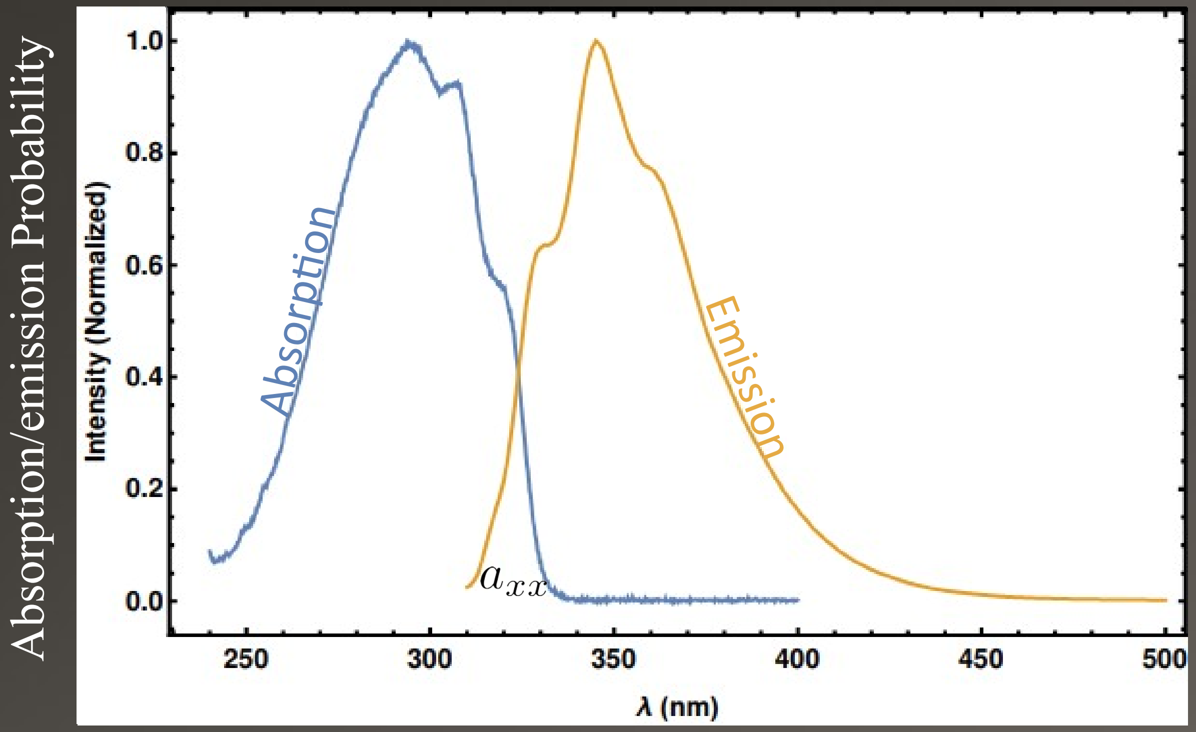
excite to produce photoemission

Delocalized π networks in molecules are natural DM detector candidates due to kinematic matching

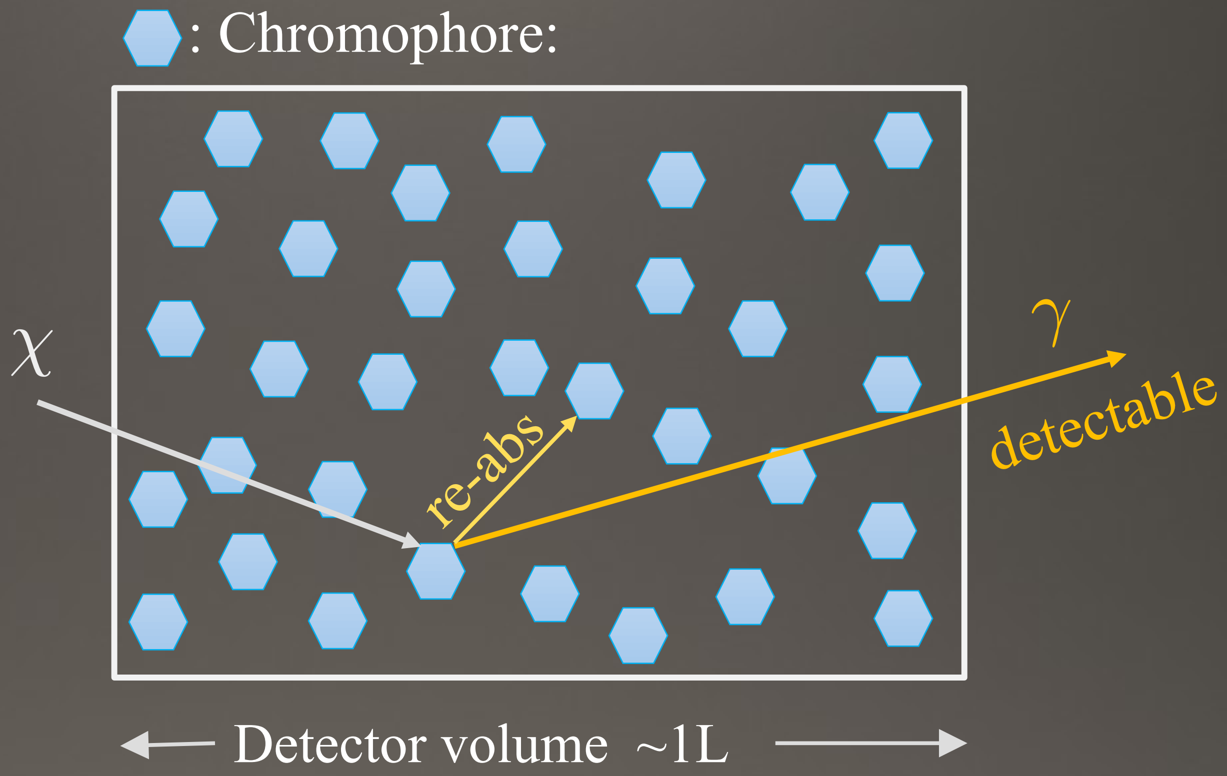
$$q_e \approx 1/a_0 \sim \mathcal{O}(\mathrm{keV}) \qquad q \sim m_\chi v_\chi \approx \mathcal{O}(\mathrm{keV}) \left(\frac{m_\chi}{1\,\mathrm{MeV}} \right)$$

Fluorescence with DM

fluorescence spectra



Decreasing energy (E) →



Probability for the photon to free stream

$\Phi_{\rm FB} \sim (1 - a_{xx})$ e.g. molecular crystals: $\Phi_{\rm FB} \approx 65\%$

Pilot Experiment

Problem

Describe the interaction between DM (BSM) with molecules (chemistry)

Many-body ground state is easy.

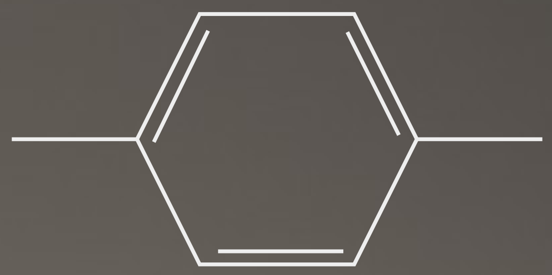
$$\Psi_G = |\psi_2\overline{\psi_2}\psi_1\overline{\psi_1}\psi_{1'}\overline{\psi_{1'}}|$$

How to compute the excited states?

The standards in the field:

FCI Hartree-Fock or *Density Functional Theory*

Molecular scintillators

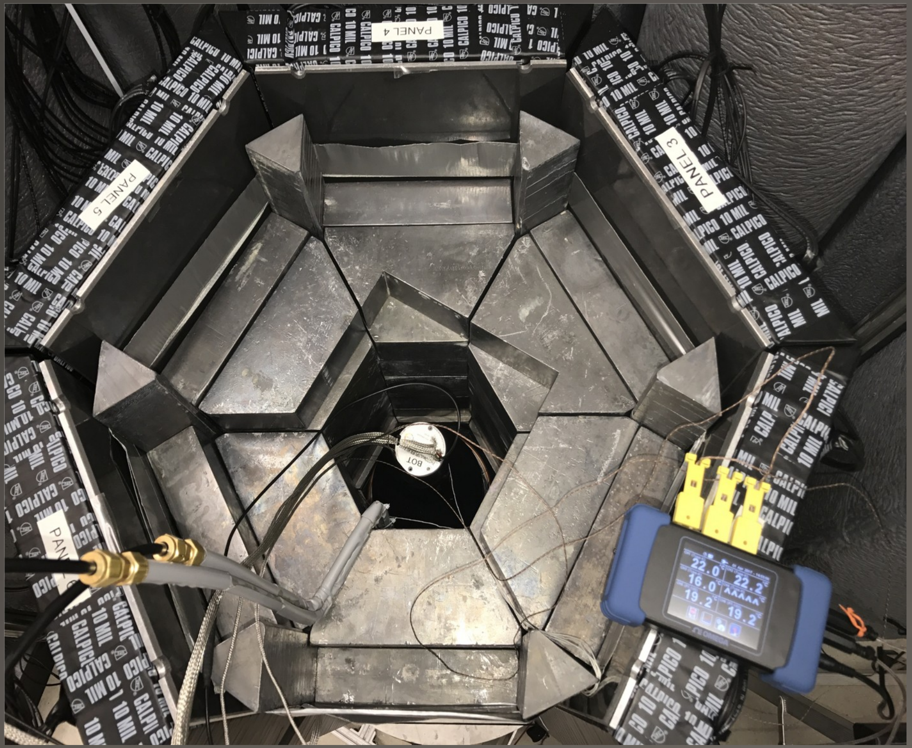


Para-xylene (EJ-301)

[CB, Collar, Kahn, Lillard '19: 1912.02822]

First Experimental Setup

1L of EJ-301



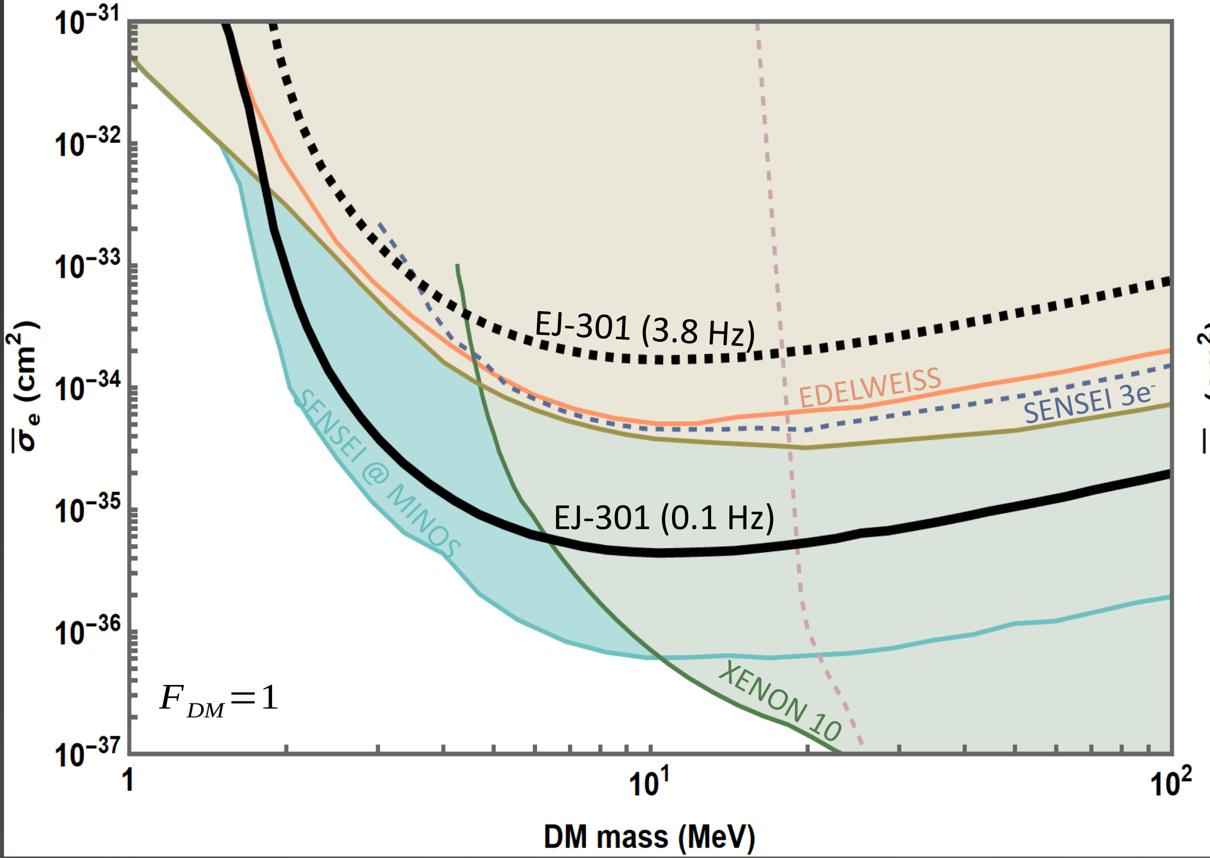
Ancient lead & Vetos

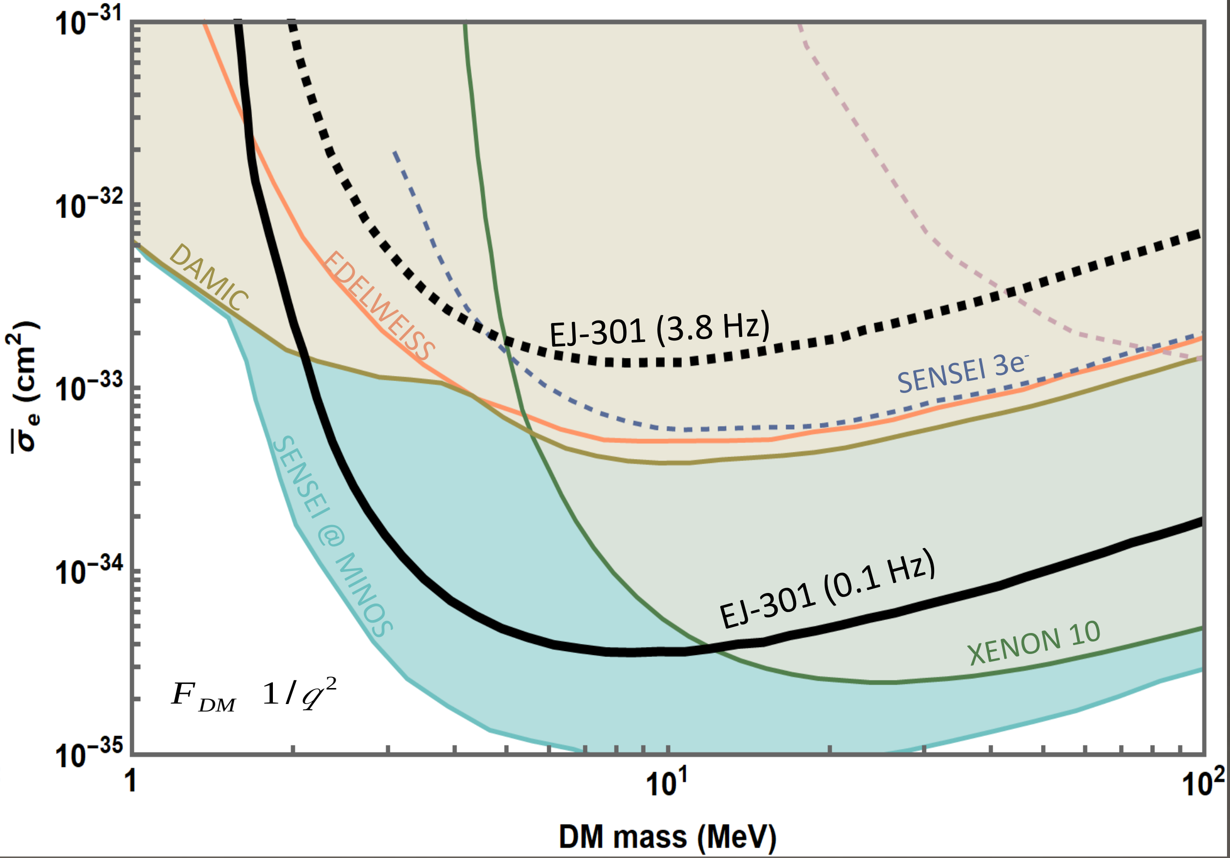
Surface run at UChicago

[**CB**, Collar, Kahn, Lillard: 1912.02822]

Results: EJ-301

(Contact interaction) (Long-range interaction)

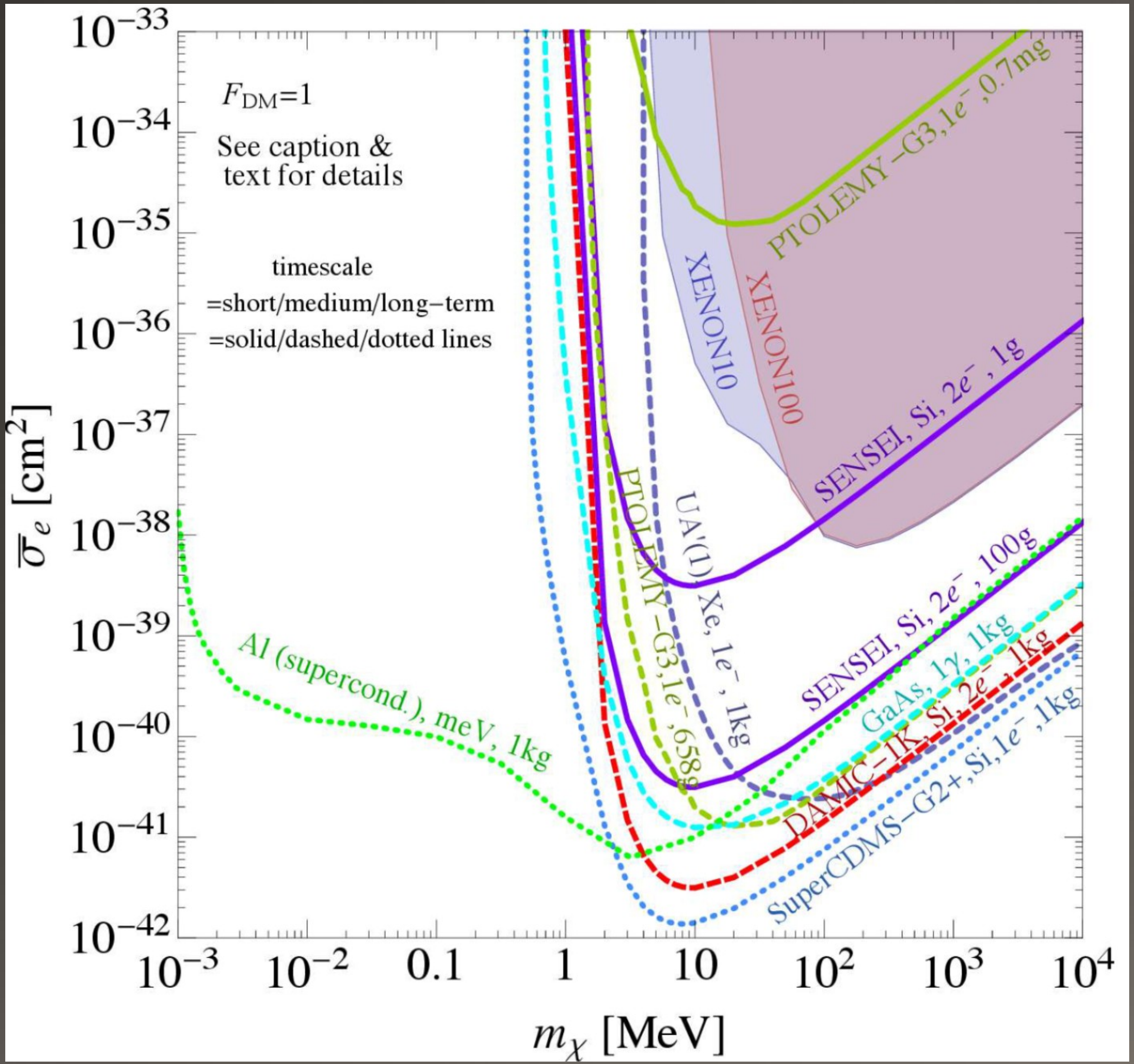




[**CB**, Collar, Kahn, Lillard: 1912.02822]

Theory → Experiment → Results in about 6 months

The Field in Context



[US Cosmic Visions: Community Report: 1707.04591]

Many materials are proposed to probe the sub-GeV Space

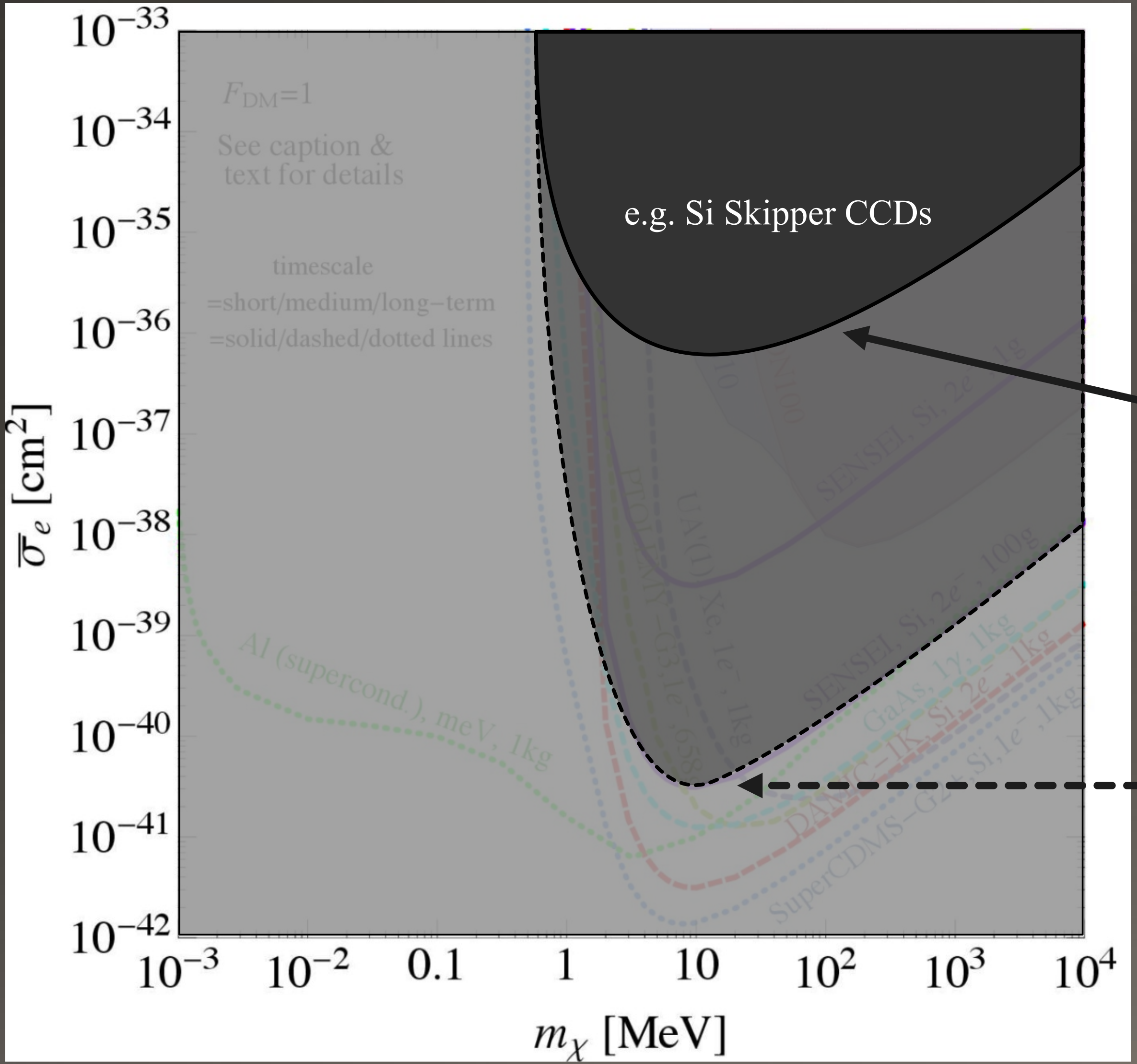
In 2017:

Short term (2 years)

Medium term (2-5 years)

Long term

Outlook and Potential Reach



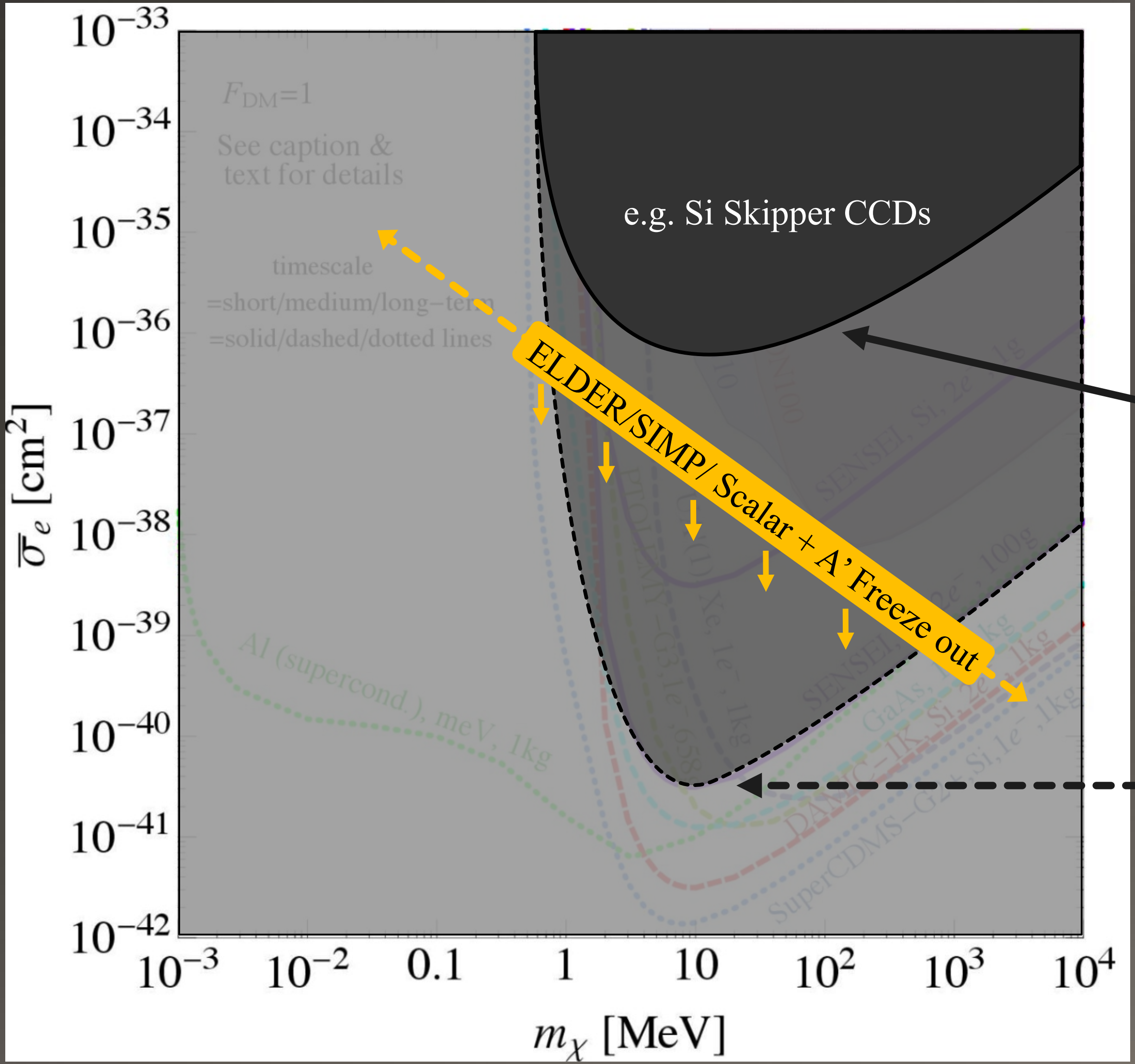
[US Cosmic Visions: Community Report: 1707.04591]

Present day:

Experimental results

Zero-background projection

Outlook and Potential Reach



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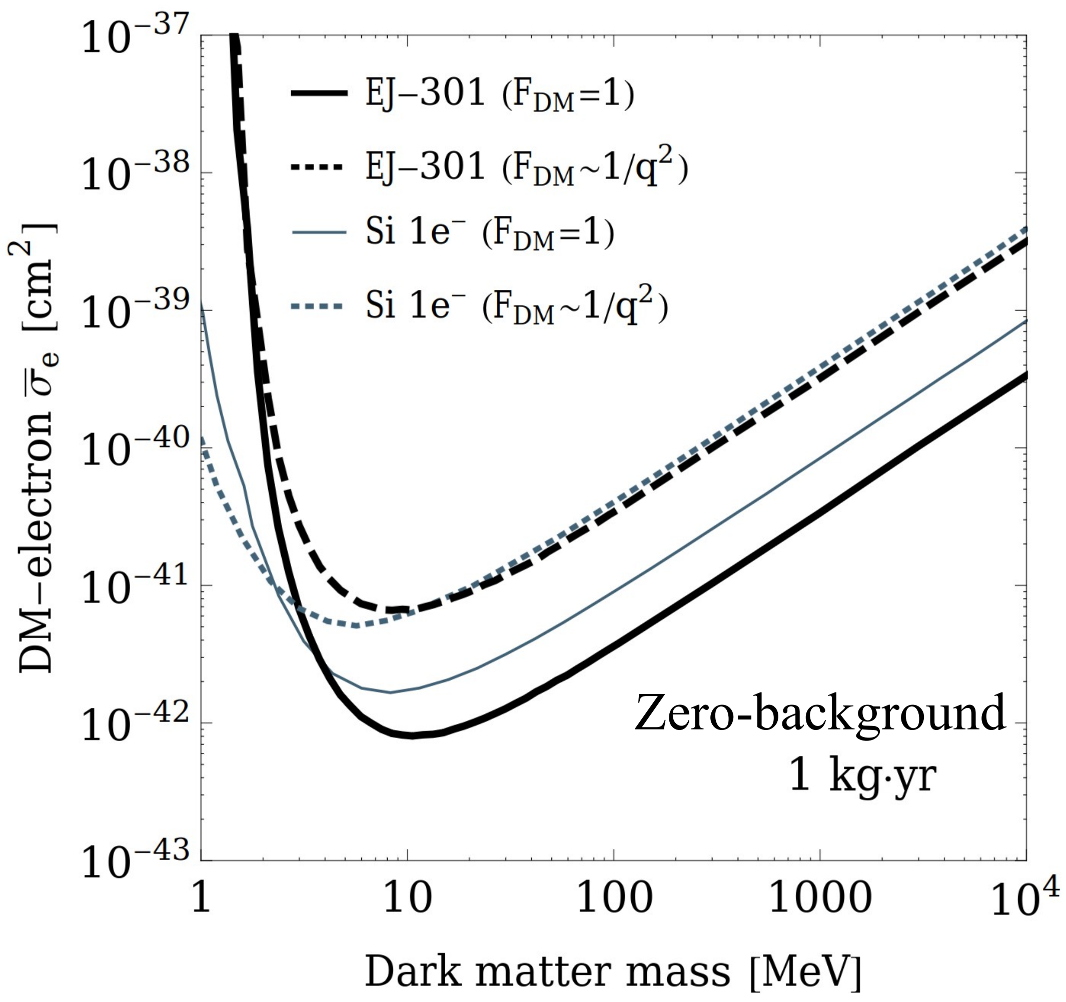


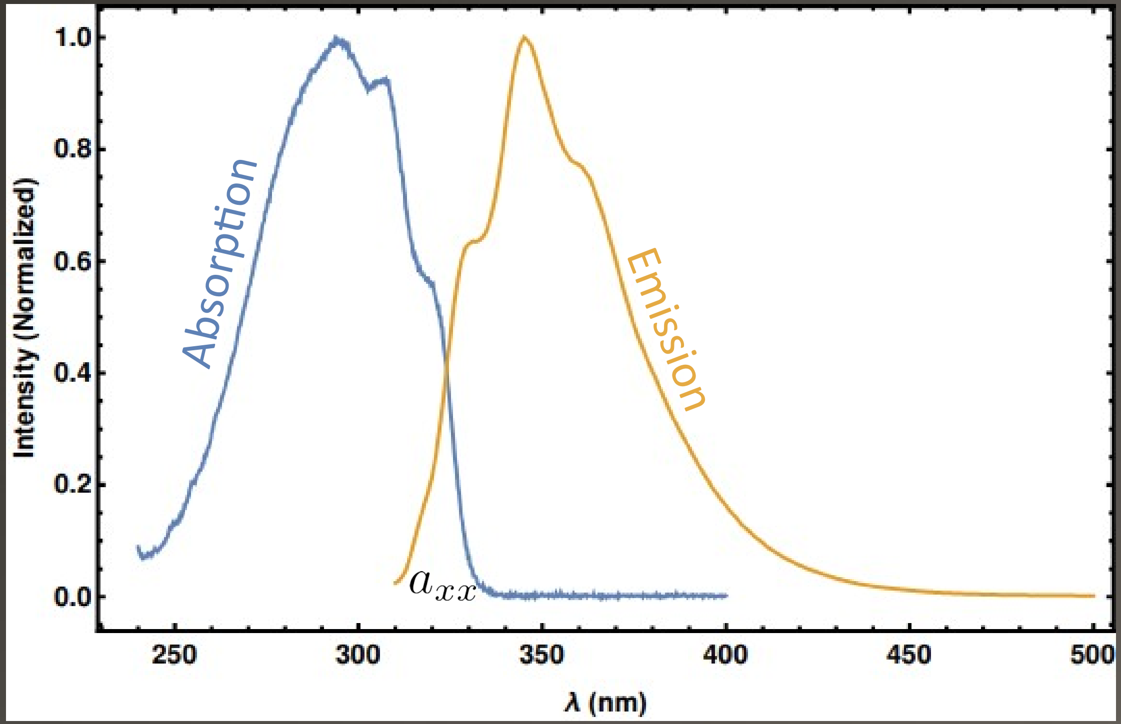
The obstacle

Backgrounds

6 orders of magnitude of potential reach awaiting

Pound (kg) for Pound (kg) molecules produce about as much signal as e.g. Si.

Fluorescence with DM Works



Next Step

Minimize background

Option 1

Reduce background in the excitation.

Molecular crystals

Anisotropic excitation → Time-varying DM signal

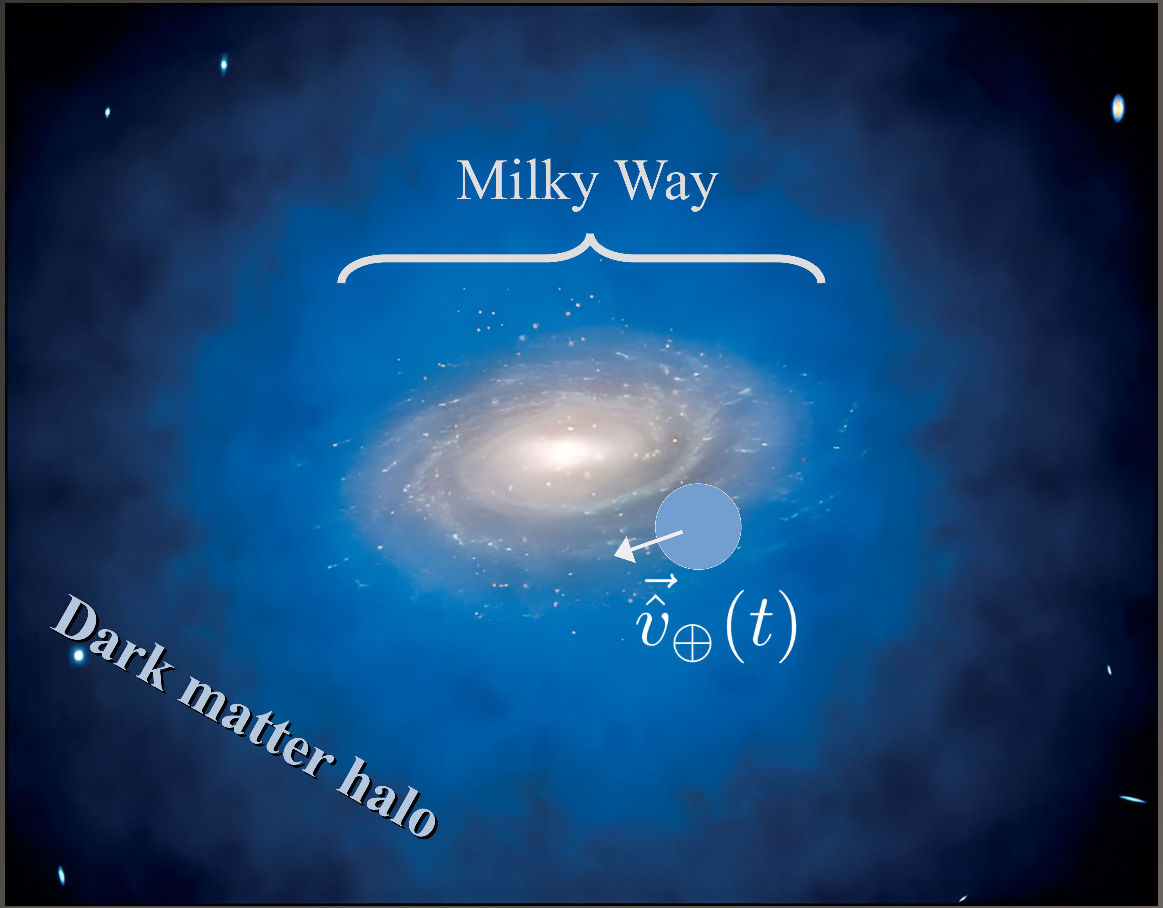
Option 2

Reduce background in the emission.

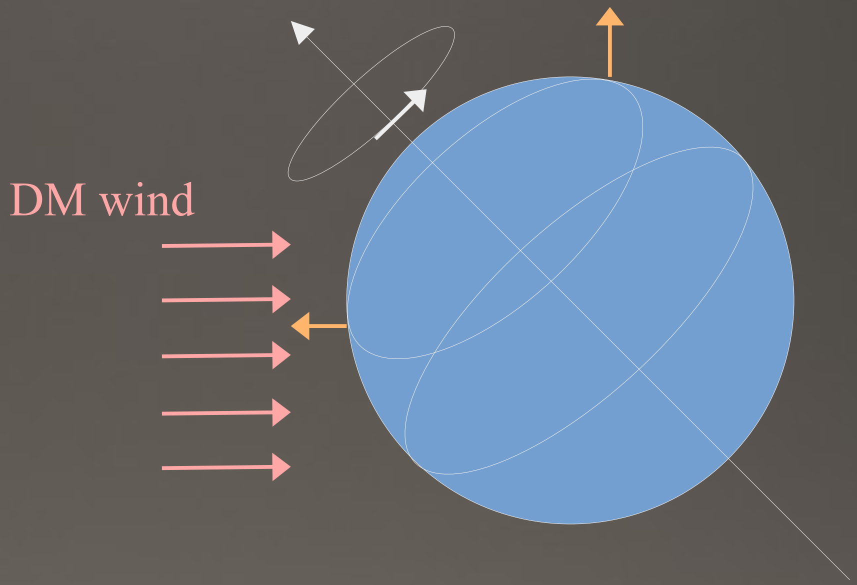
Quantum dots

Multiple excitons → Time-coincident DM signal

Directional Detection

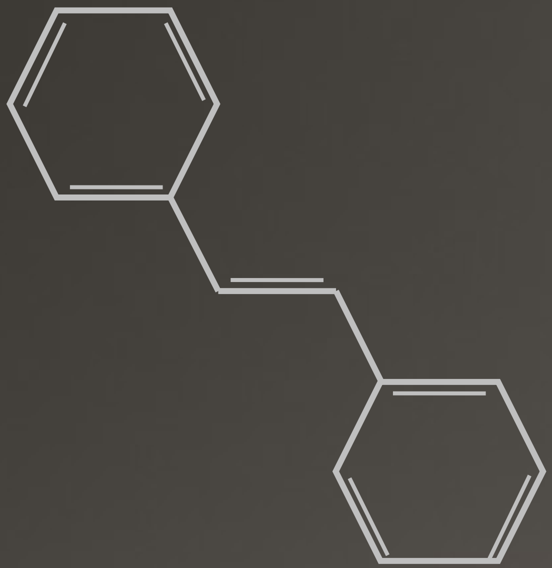


Effective dark matter "wind" from $\vec{\hat{v}}_{\oplus}(t)$

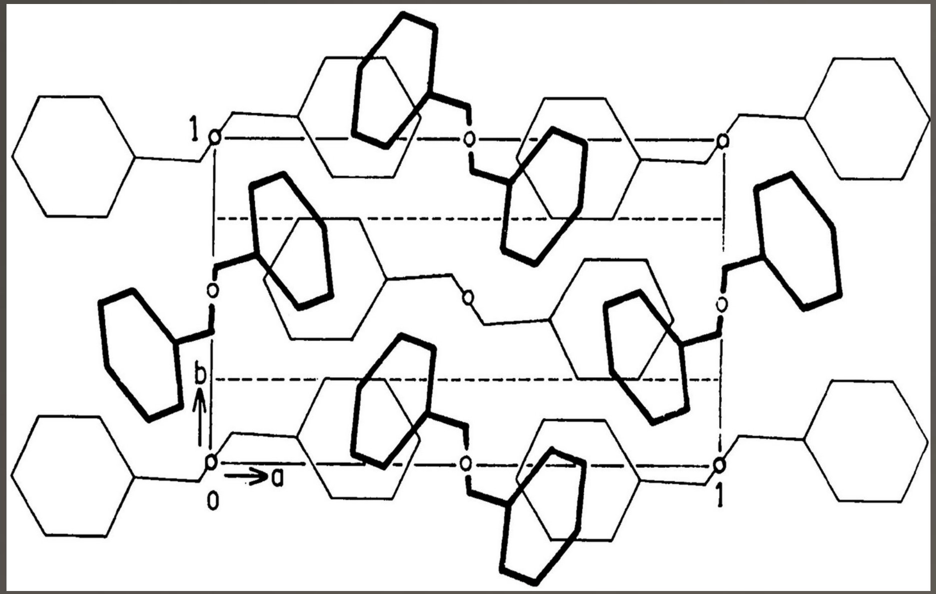


Change in relative orientation between detector and dark matter wind leads to ***daily*** modulation

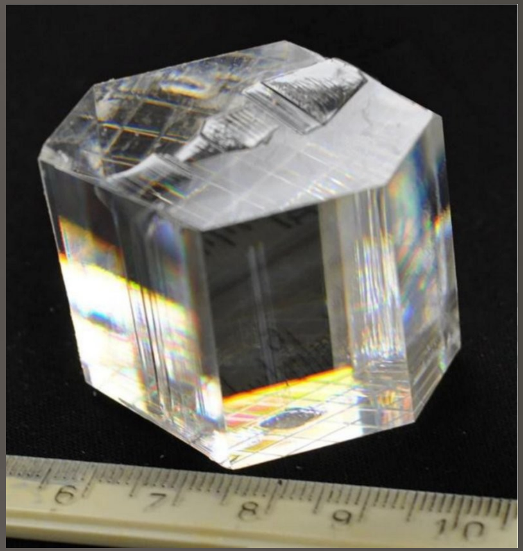
Trans-Stilbene



Delocalized and planar network of double bonds



Molecular planes oriented in crystal lattice

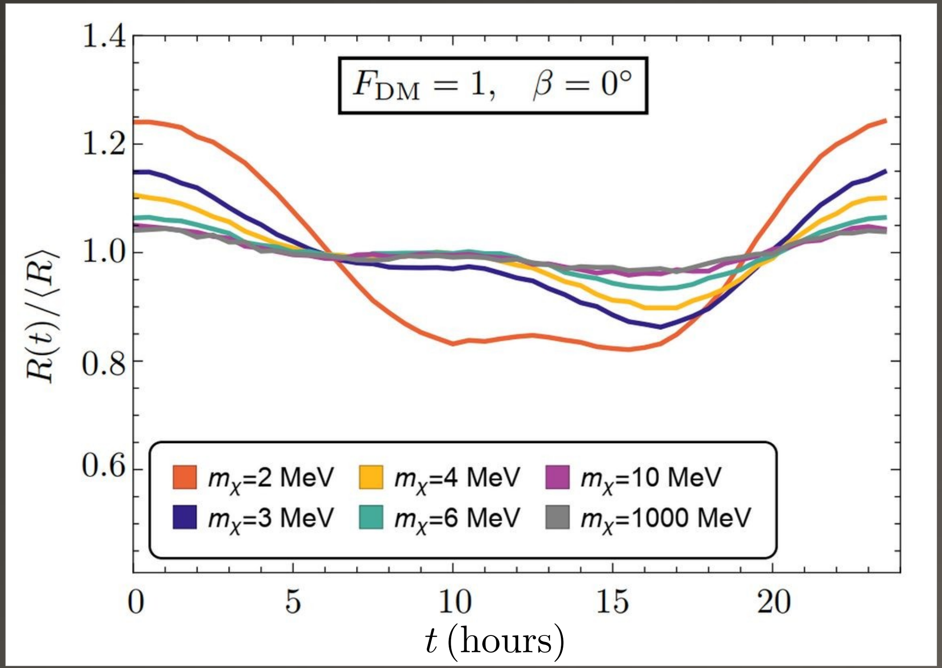


Carman, et.al. '18 (J. of Crystal Growth)

Large optical-quality crystals

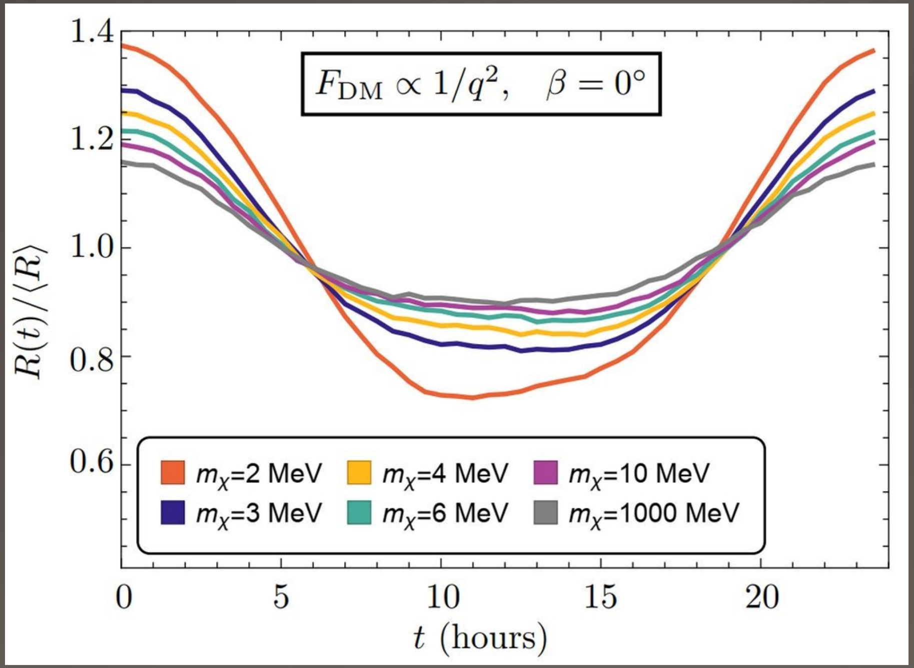
Daily Modulation

(Contact interaction)



[**CB**, Kahn, Lillard, McDermott: 2103.08601]

(Long-range interaction)

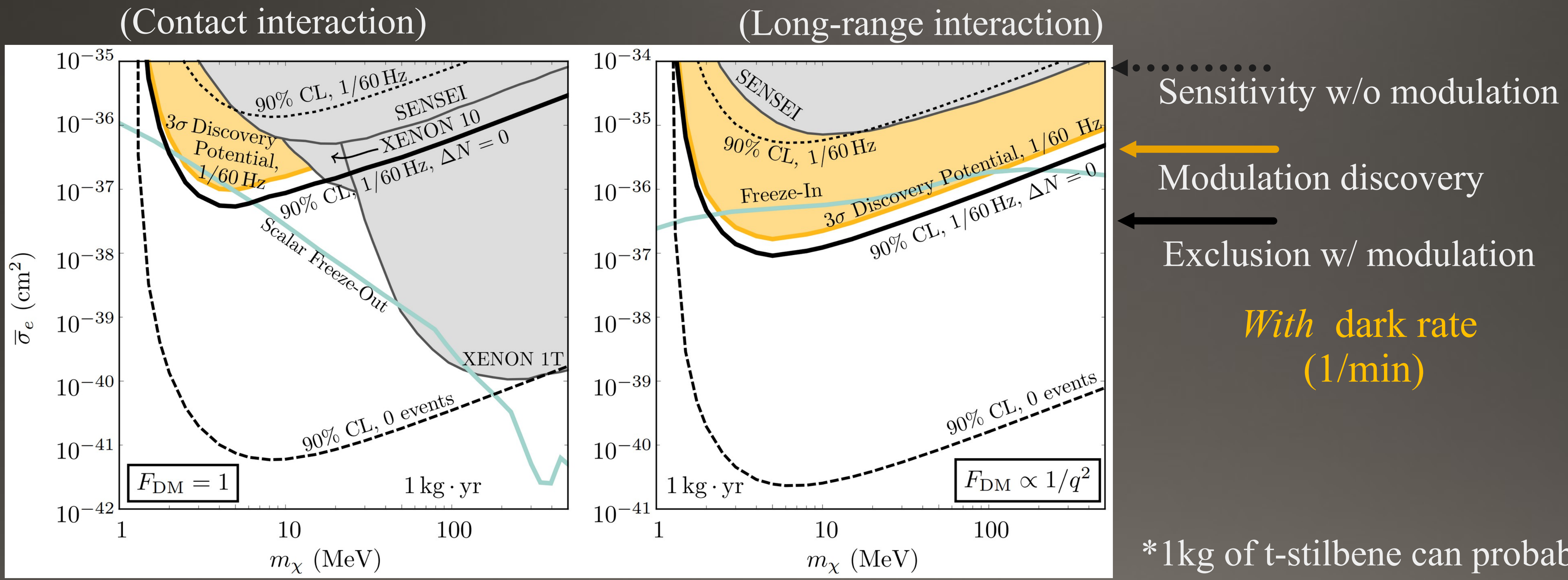


Varies up to 70%

Verifiable signal!

Modulation amplitude remains as high as 10% even at the highest masses due to the fundamental anisotropy of the molecular form factor.

Improved Sensitivity & Reach



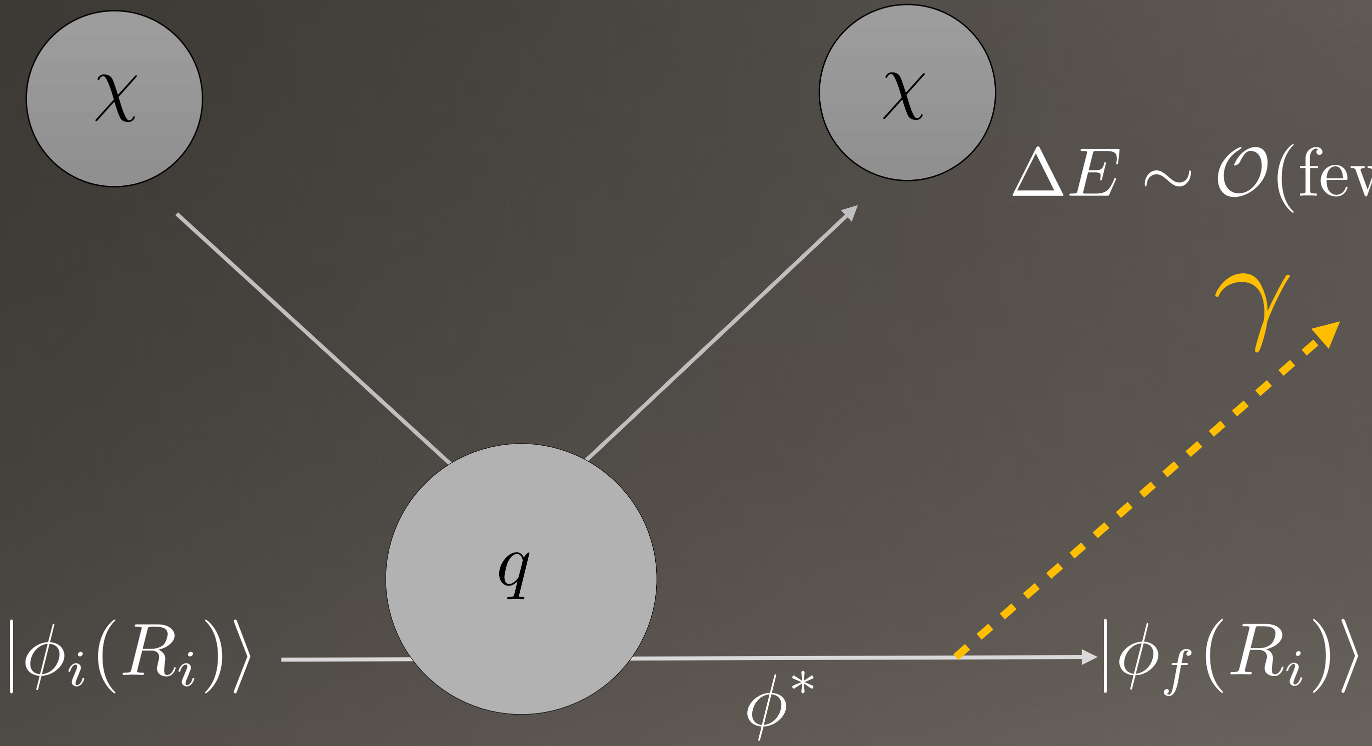
[**CB**, Kahn, Lillard, McDermott: 2103.08601]

With dark rate (1/min)

*1kg of t-stilbene can probably be found within a few blocks of this room

Improvement of *two orders of magnitude* & potential for discovery

Nuclear Recoil → Photon Signal

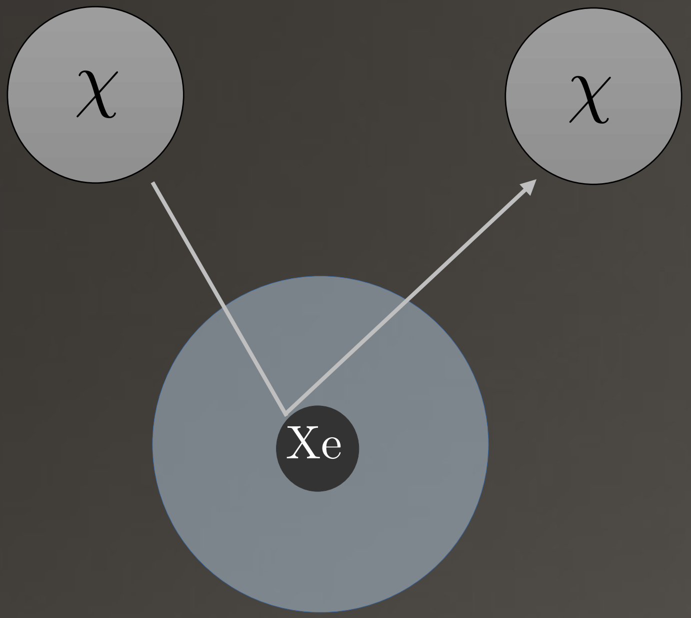


Nuclear scattering

$$\Delta E \sim \mathcal{O}(\text{few eV}) \left(\frac{m_\chi}{100\ \text{MeV}}\right)^2 \left(\frac{m_N}{130\ \text{GeV}}\right)^{-1}$$

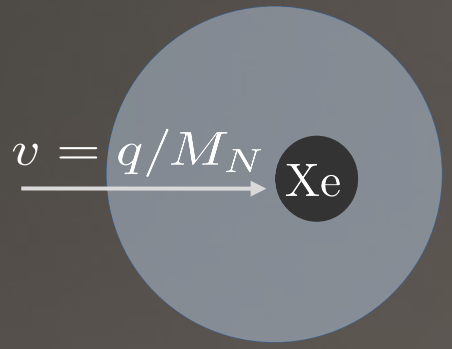
Next step in *complexity*: Nuclear recoil → ??? → Radiative emission

Ionizing Atoms Through Nuclear Recoil:

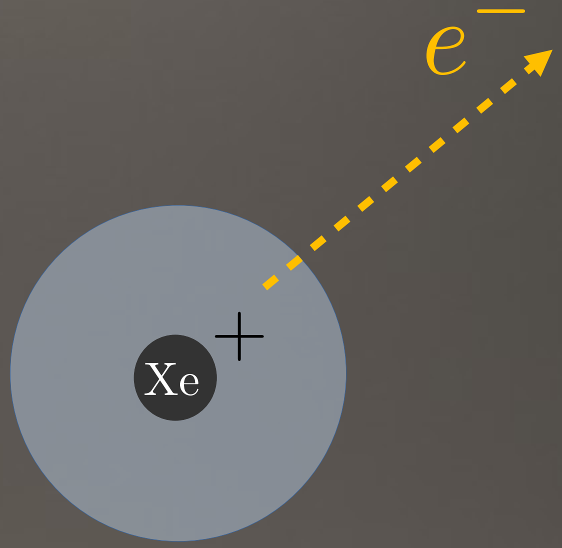


Initial nuclear recoil

$$|\psi_i\rangle \sim e^{i\frac{m_e}{M_N}\vec{q}\cdot\vec{r}}\psi_{\mathrm{AO}}(r_\beta)$$



Nucleus moves faster than electrons



Electronic transition to ionized state

The Migdal effect

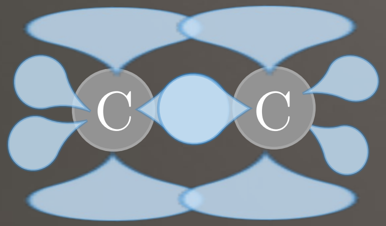
Extend the sensitivity of detectors to lower masses.

e.g. Xenon

$$f_{i\to f} \approx \frac{m_e}{M_N}\vec{q}\cdot\langle\vec{r}\rangle_{i\to f}$$

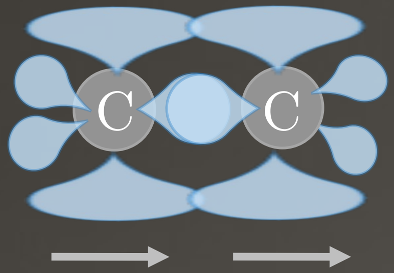
Kinematic *penalty*

The Molecular Migdal Effect(s)



Center of mass recoil (CMR)

Cause by center of mass motion



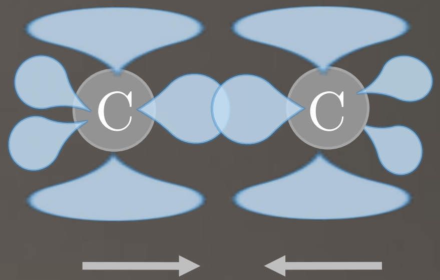
Analogous to atomic Migdal effect

$$P_{CMR} \sim \frac{m_e}{M_{mol}}$$

Moving whole molecule → BIG penalty

Non-adiabatic coupling (NAC)

Caused by relative motion



Effect beyond Born-Oppenheimer

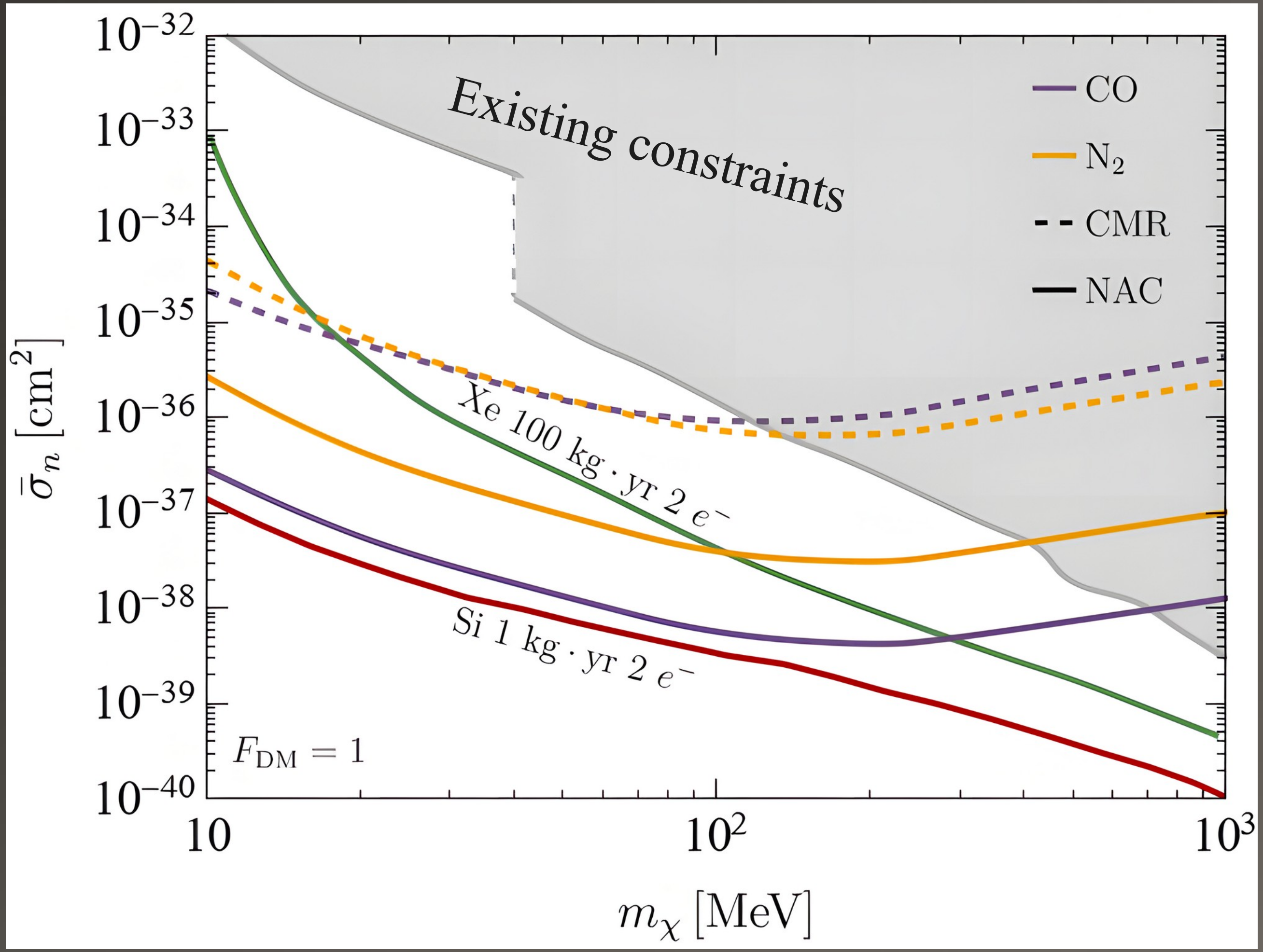
$$P_{NAC} \sim \frac{m_e}{M_N}$$

Crumpling molecule → small Penalty

Blanco '22: 2208.09002

The Molecular Migdal Effect(s)

(Contact interaction)



[**CB**, Harris*, Kahn, Lillard, Perez-Rios: 2208.09002]

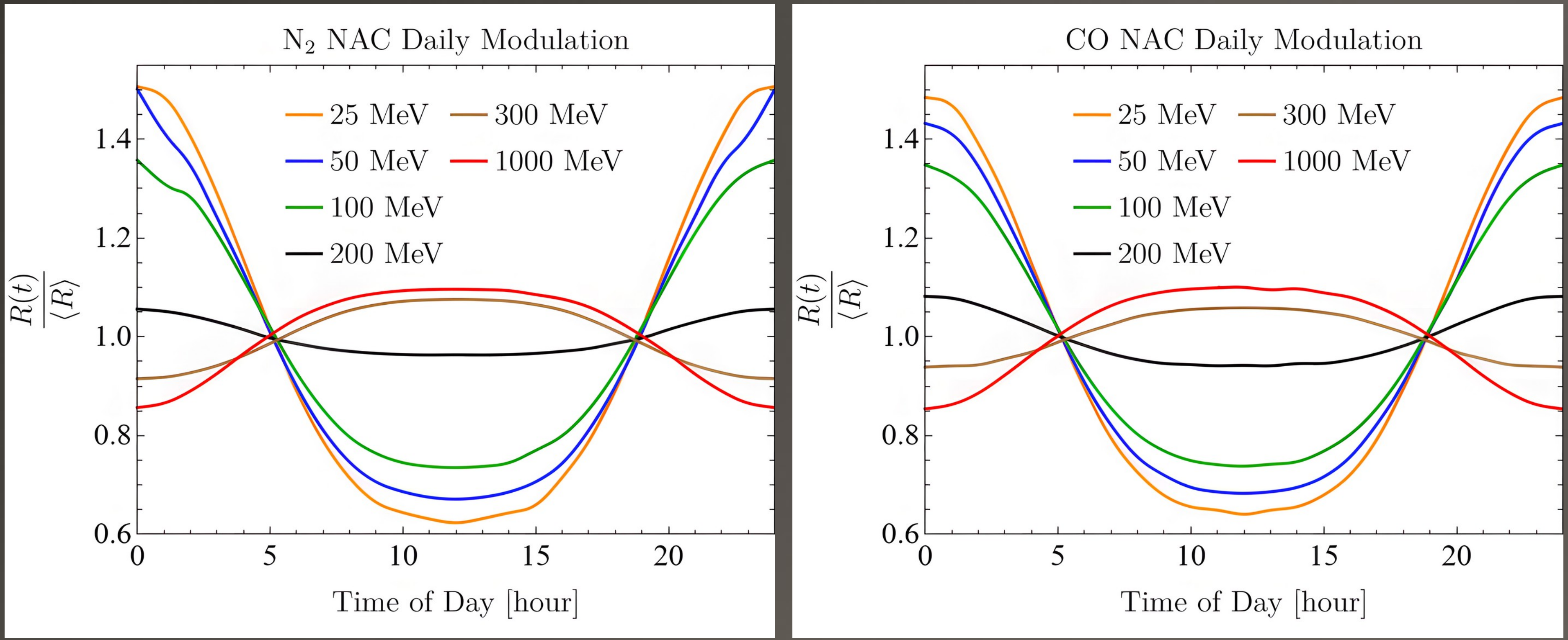
Si rate is calculated using the *CMR*-equivalent Migdal effect.
Is there an *NAC*-equivalent in Si?

Center of mass recoil
Subdominant at all masses.

Non-adiabatic coupling
Favorable kinematic factor.

Simplest molecular models already competitive.
Is there an optimal molecular target?

Directional Molecular Migdal Effect



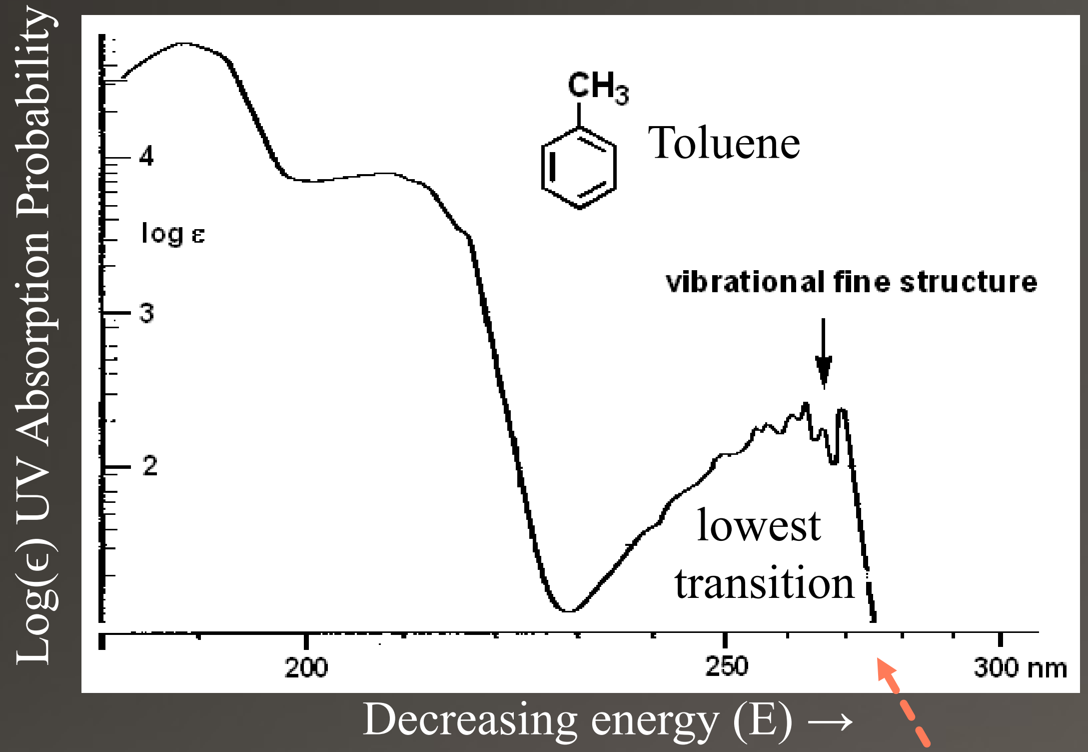
Varies up to 80%

Mass dependent phase

[**CB**, Harris*, Kahn, Lillard, Perez-Rios: 2208.09002]

Molecular alignment → Directional electronic excitation → Directional molecular Migdal effect(s)

Experimental Evidence for NAC



Classically forbidden by symmetry

No dipole moment → Classically forbidden UV absorption

Claim

NAC is visible in existing data

Photon absorption probability

$$\langle \Psi_f | \vec{r} | \Psi_i \rangle = 0 \quad \text{e.g. toluene}$$

dipole transition

[**CB**, Harris, Kahn, Lillard, Perez-Rios: 2208.09002]

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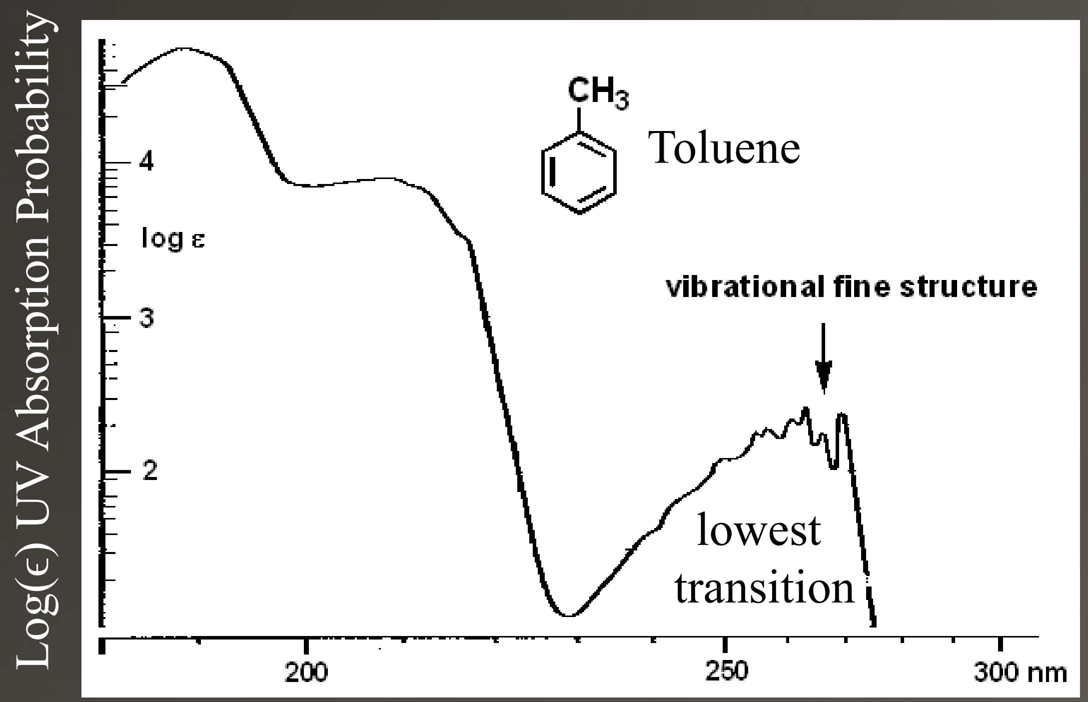


Decreasing energy (E) →

NAC form factor

How electrons respond to nuclear deformation.

$$f_{e,NAC} \sim \langle \psi_f | \nabla_R | \psi_i(r) \rangle$$

Photon absorption probability

$$\epsilon \sim \langle \Psi_f | \vec{r} | \Psi_i \rangle = 0 \quad \text{e.g. toluene}$$

dipole transition

NAC-induced UV absorption

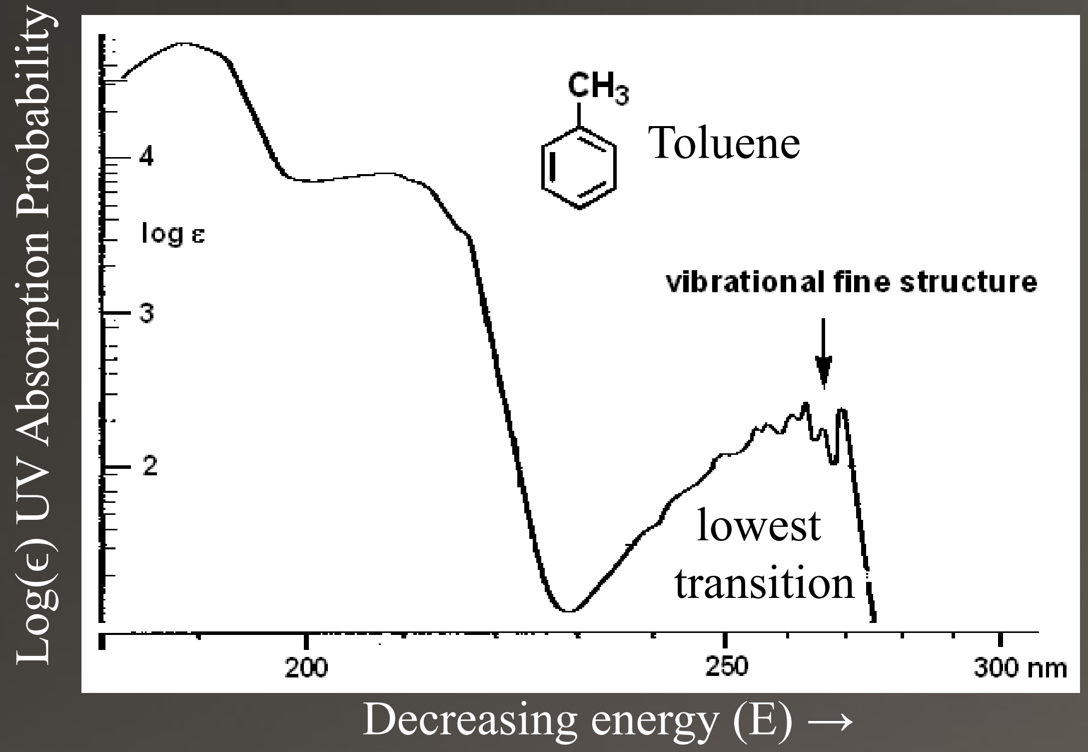
$$\epsilon \sim \langle \psi_f(r;R) | \vec{r} | \psi_i(r;R) \rangle |_{R \neq R_0} \neq 0$$

However

Nuclear deformation → Non-adiabatic dipole

[**CB**, Harris, Kahn, Lillard, Perez-Rios: 2208.09002]

Finding Optimal Targets



Find molecules with max NAC

Large NAC → Large DM interactions

Molecular symmetries → Forbidden transitions

Measured with vibrational substructure
→ Evidence of NAC

Finding Optimal Targets

Problem: Chemical space is unreasonably large

How many molecules possible with
C, O, N, F, H?

< 9 atoms: 100s of Thousands (DFT Computable)

< 30 atoms: 100s of Billions (Intractable)

...toluene has 15, xylene has 18, t-stilbene has 26

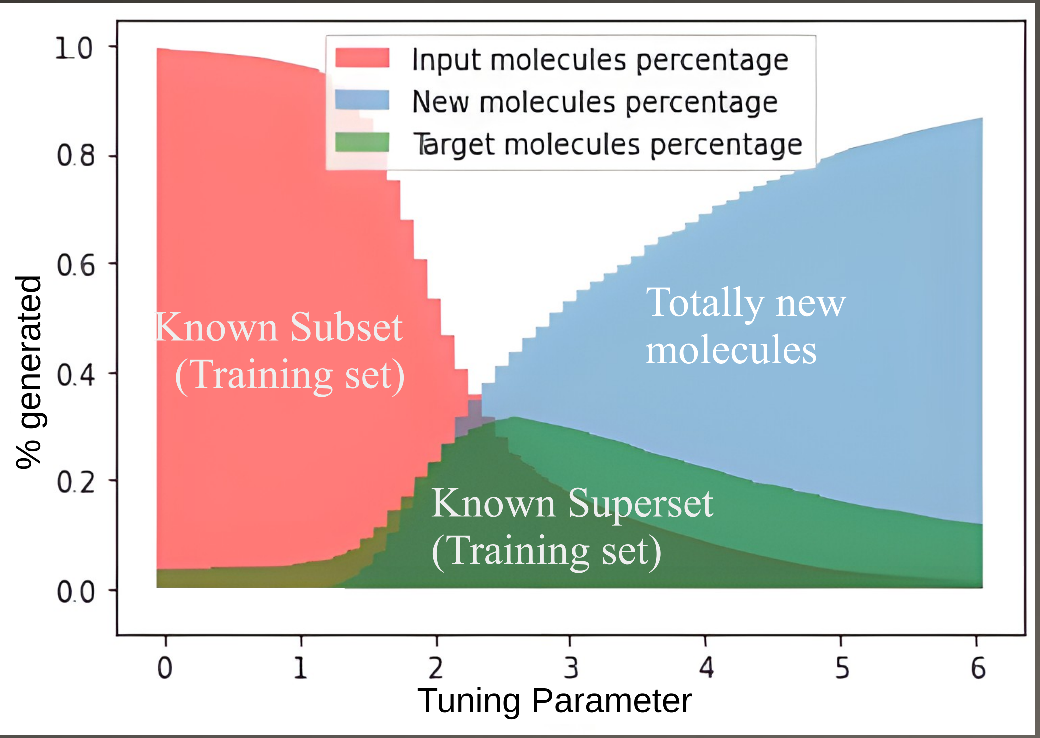
Method

1. Look for known favorable properties - *cheminformatics*
2. Extra(intra)polate onto new molecules – *machine learning*

ML for DM Direct Detection

Property prediction
Energies & Matrix elements

Molecular Generation
Sample latent space → new molecules



[**CB**, Cook*, Smirnov: 2404.xxxxx]

Using exhaustive database (< 9 atoms)
Characterize neural nets
→ Possible to learn from small subsample

Next: Large but sparse dataset up to 10s of atoms
Scale architecture
→ Generate candidate molecule *shortlist*

Future Experiment

Experimental Deployment

The DIANA experiment

Daily modulation from an **I**ntrinsically **AN**isotropic **A**rray

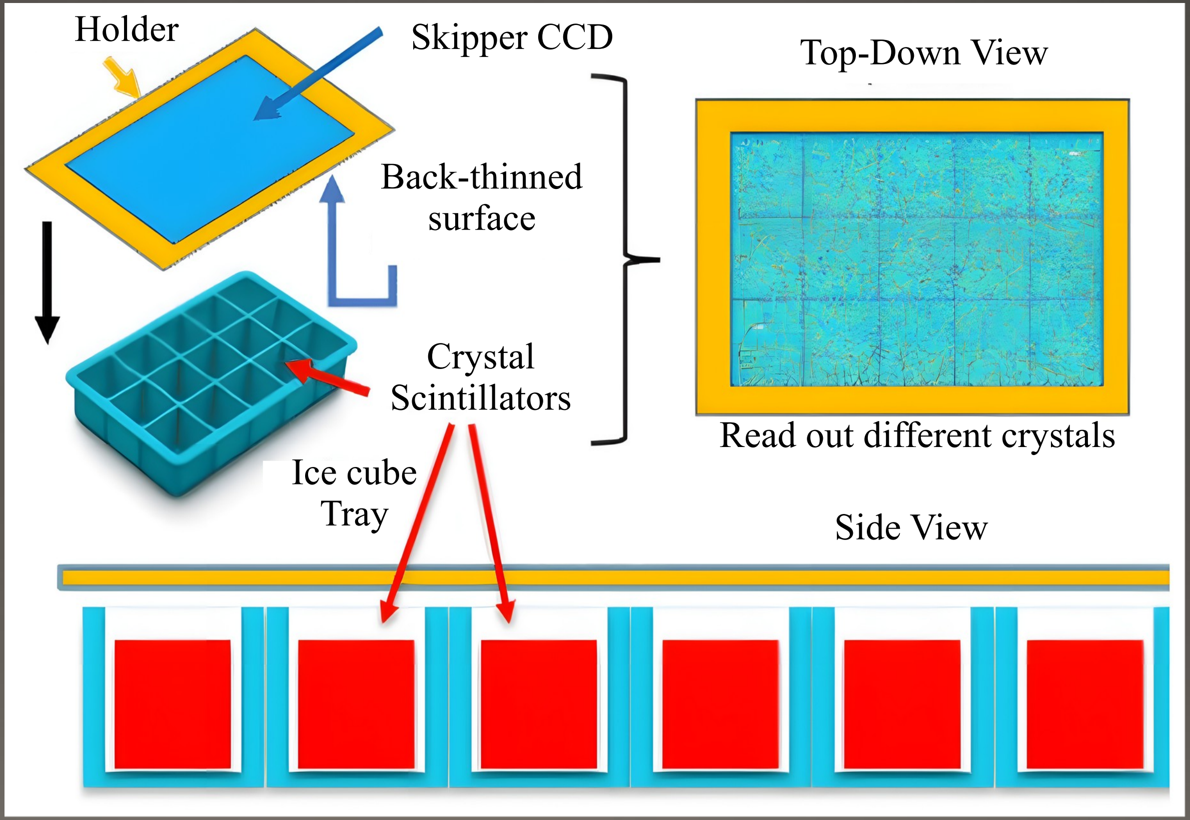
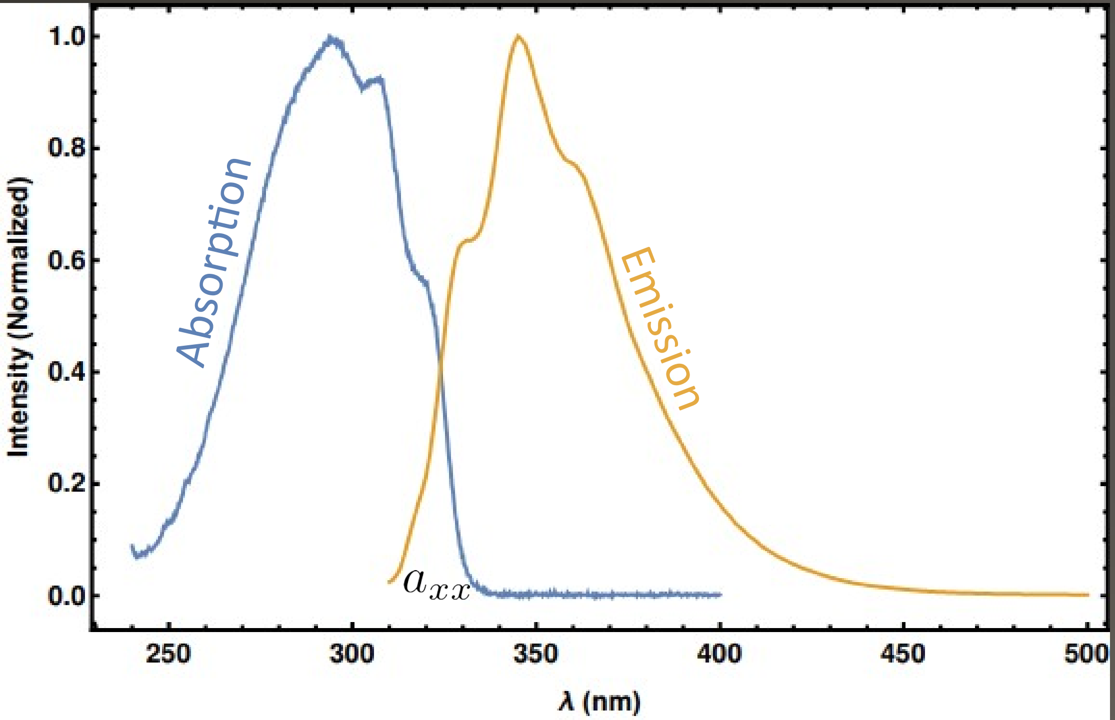


Fig: Dan Baxter
Collab: Uchicago, FermiLab, Northwestern, MIT, and UIUC

Fluorescence with DM Works



Focus

Minimize background

Option 1

Reduce background in the excitation.

Molecular crystals

Anisotropic excitation → Time-varying DM signal

Option 2

Reduce background in the emission.

Quantum dots

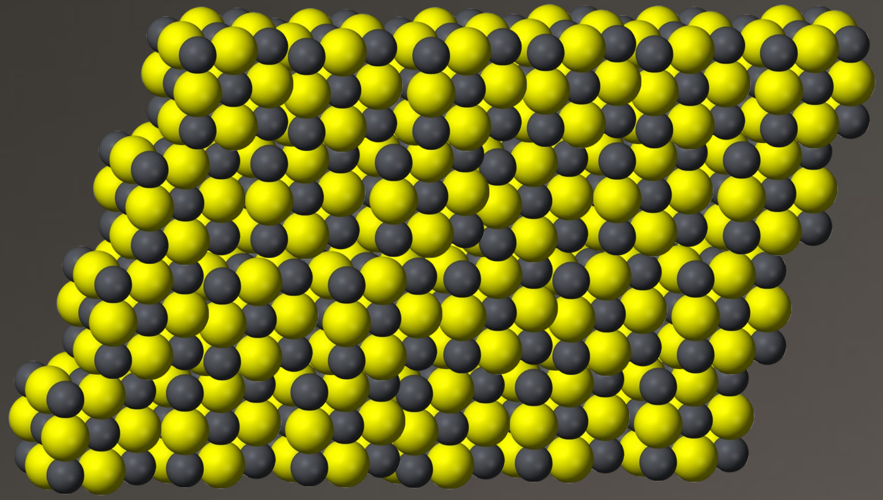
Multiple excitons → Time-coincident DM signal

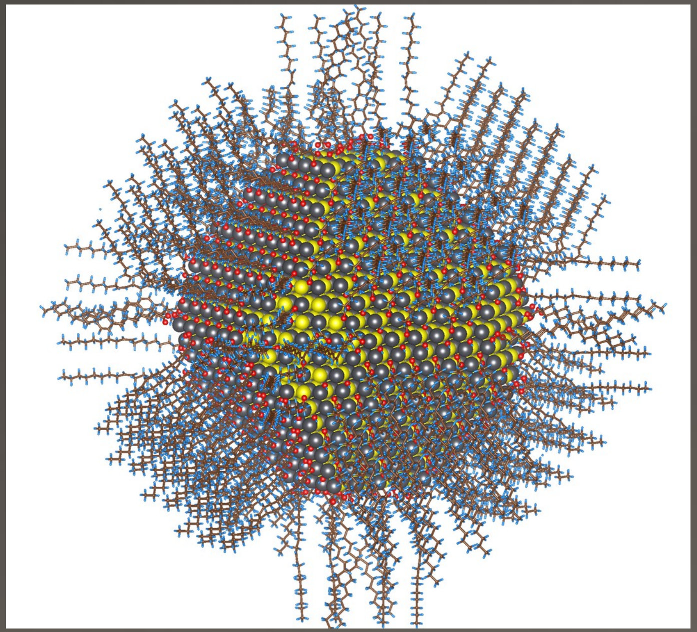
Nanocrystals: Quantum Dots

Quantum confinement affects long-wavelength physics

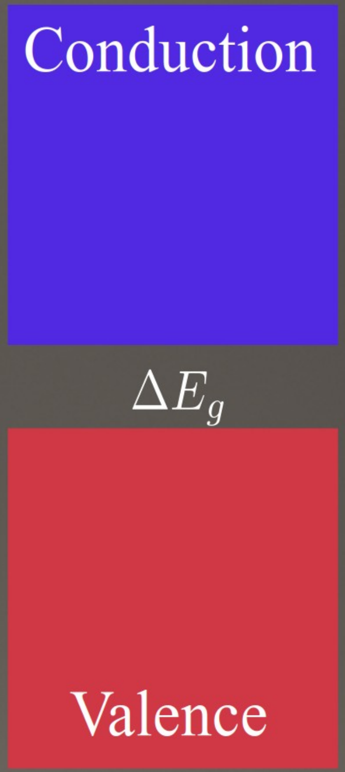
Quantum confinement

Example: PbS

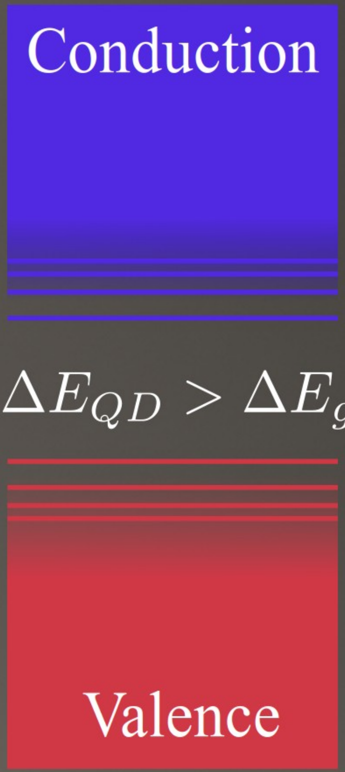




Zherebetskyy et al., Science 344, 1380 (2014)



ΔE_g



$\Delta E_{QD} > \Delta E_g$

$R \to \infty$ nm

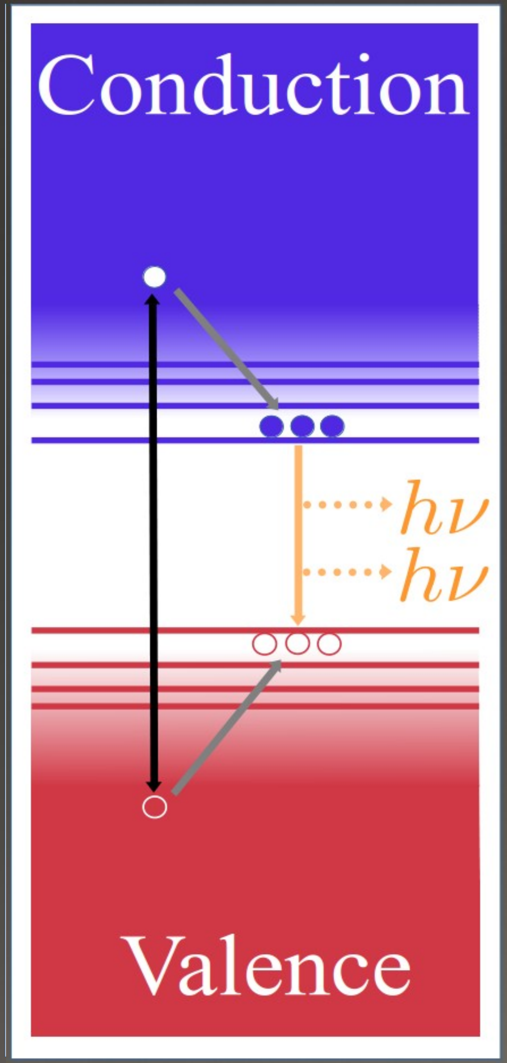
$R \sim \mathcal{O}(\text{few nm})$

$E(k)$

$|\psi_i\rangle \sim u_{\text{Bloch}}(r) e^{ik\cdot r}$

$|\psi_i\rangle \sim u_{\text{Bloch}}(r) \psi_{\text{bound}}(r)$

Quantum Dots: Coincident Signal



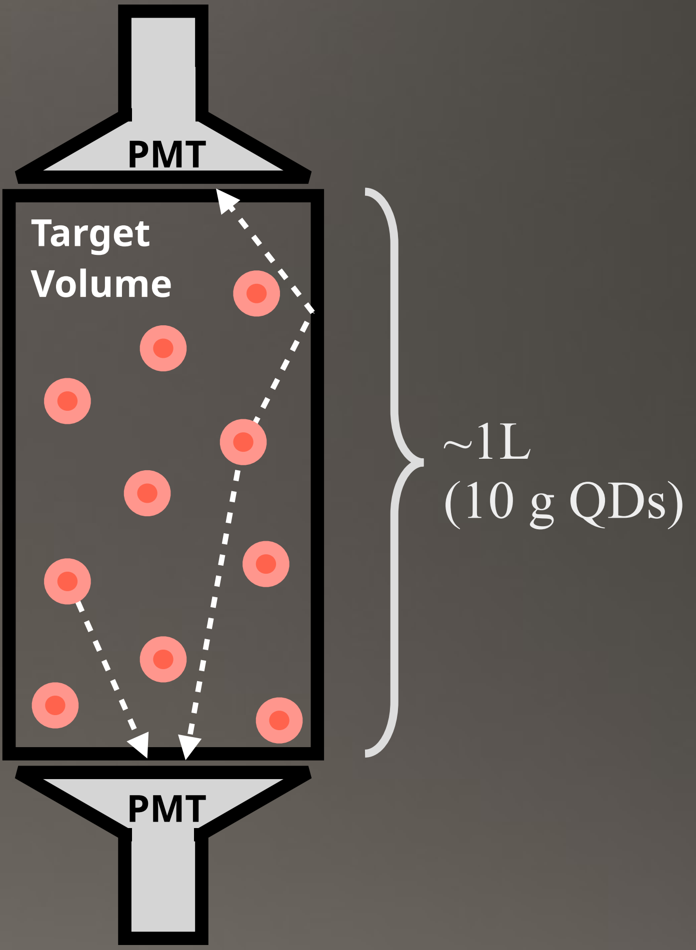
Absorption → Very *energetic* exciton

Multi-exciton generation → several excitons

If energy is greater than twice the bandgap

Radiative recombination → coincident photons

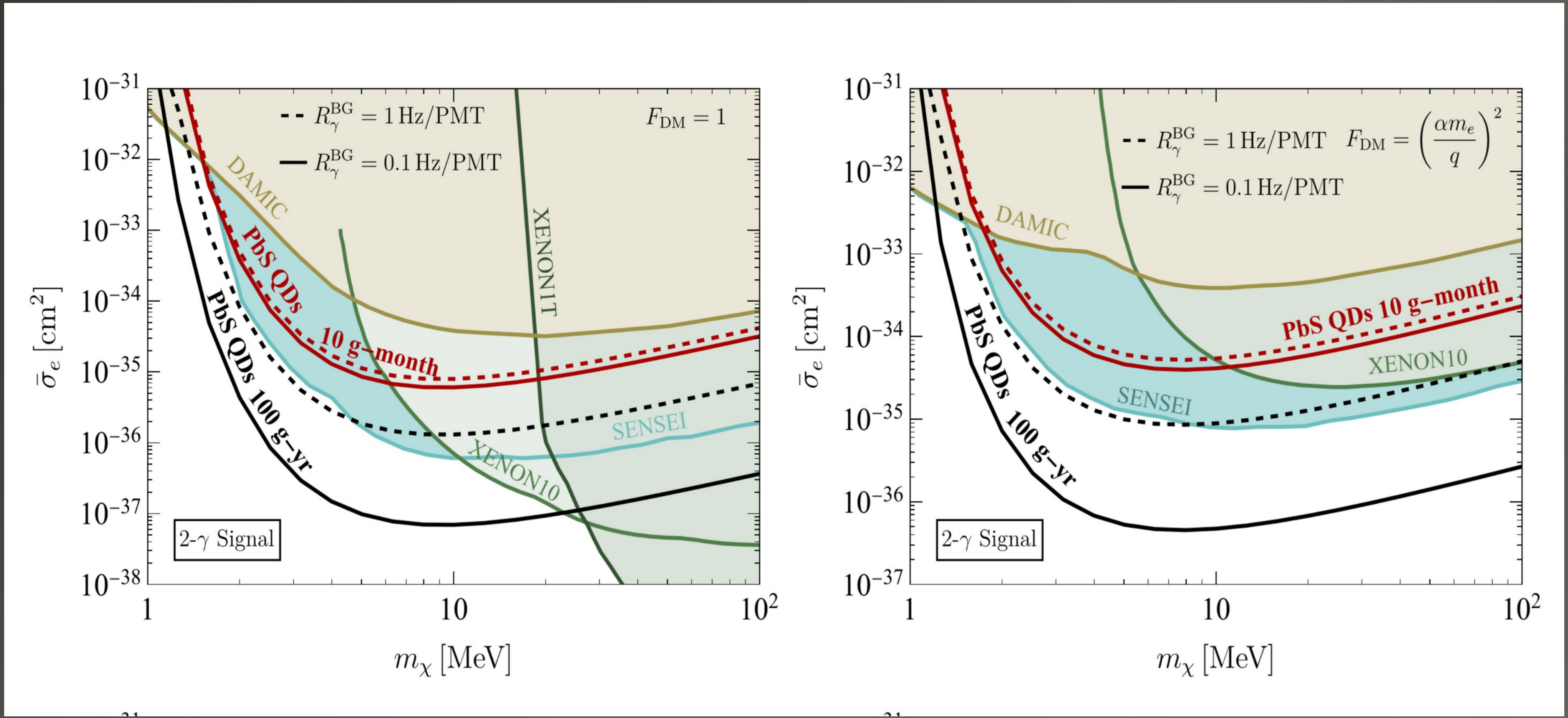
Band-edge excitons produce light



[CB, Essig, Fernandez-Serra, Ramani, Slone: 2208.05967]

PbS Quantum Dots

(Contact interaction) (Long-range interaction)



Background-free signal @ this scale

[**CB**, Essig, Fernandez-Serra, Ramani, Slone: 2208.05967]

With realistic dark rate for photodetectors.

Future Experiment

Experimental Deployment

DarkDot & The QUADRA experiment

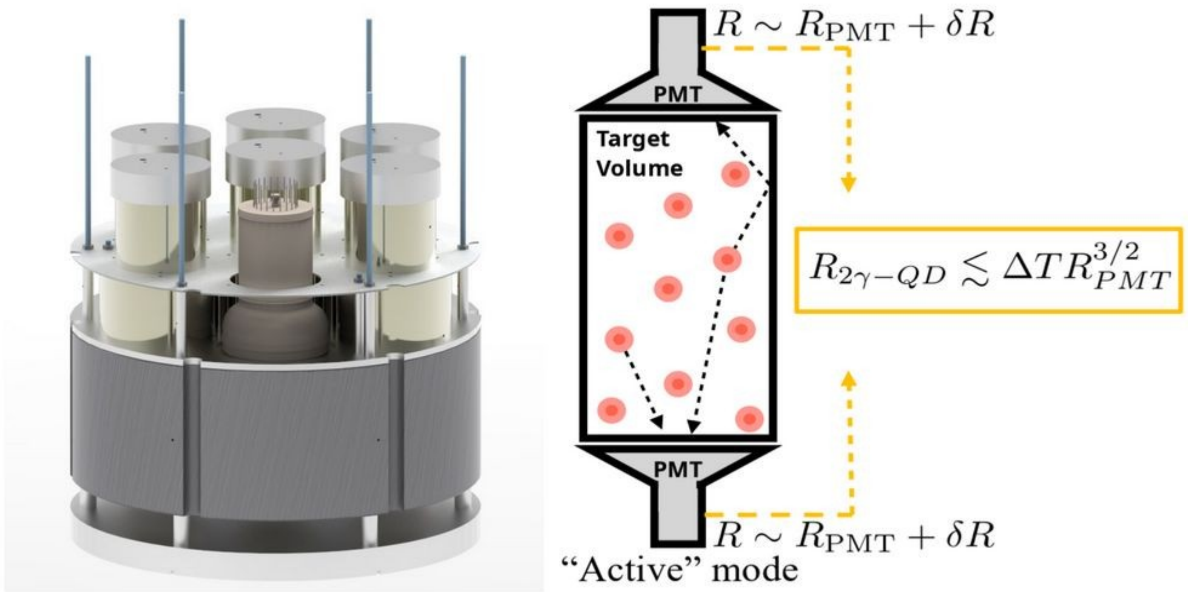
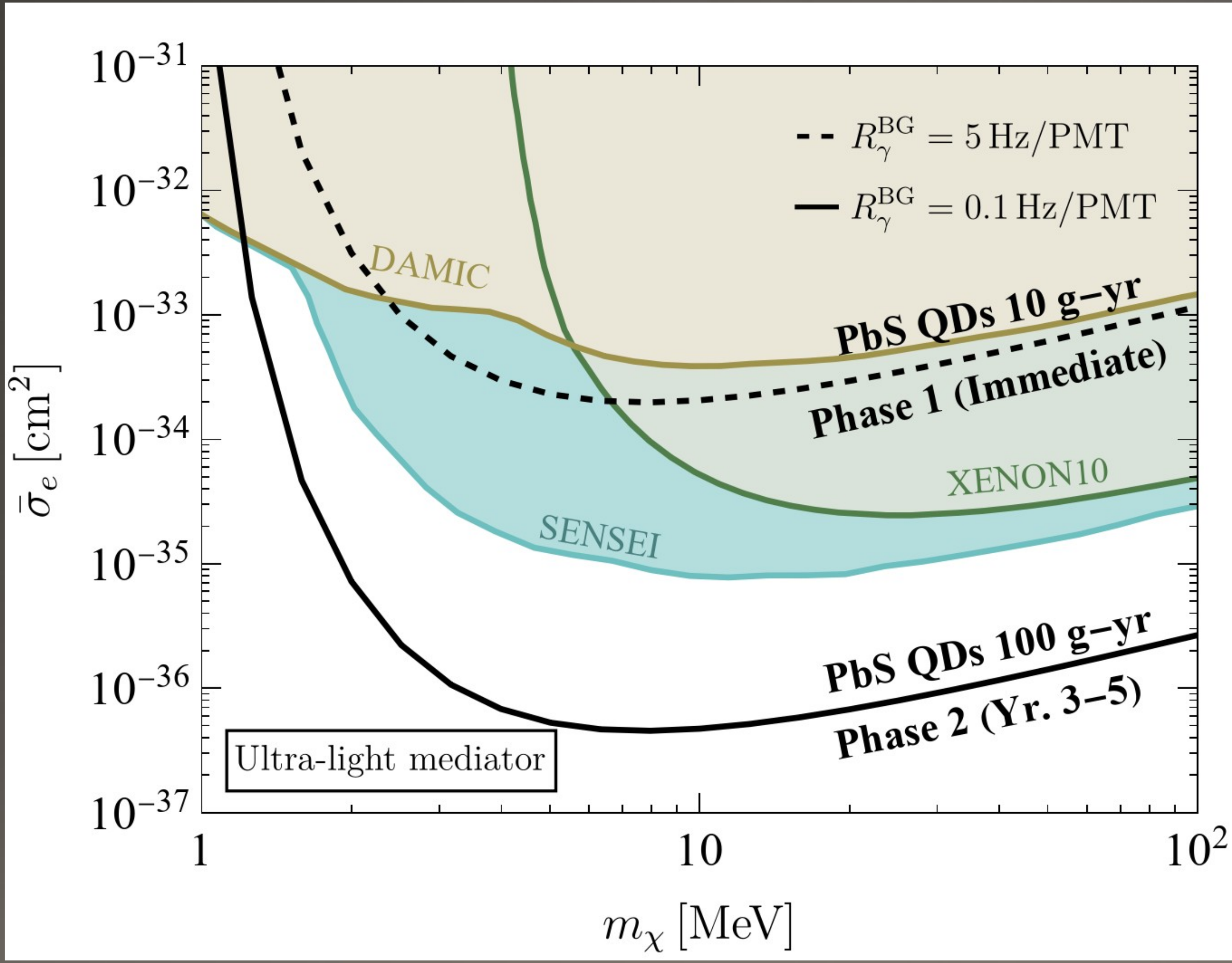


Figure 2: (Left:) Inner structure of the current SUXESs facility. (Right:) A diagram of a single module for the proposed detector.

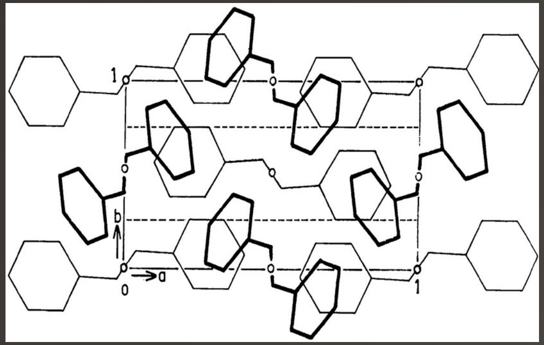
Fig: Joern Mahlstedt   Collab: Stockholm U, MIT, & Stony Brook

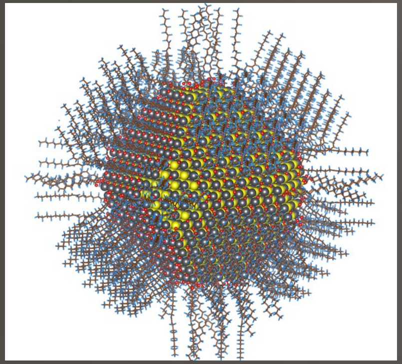
Deployment

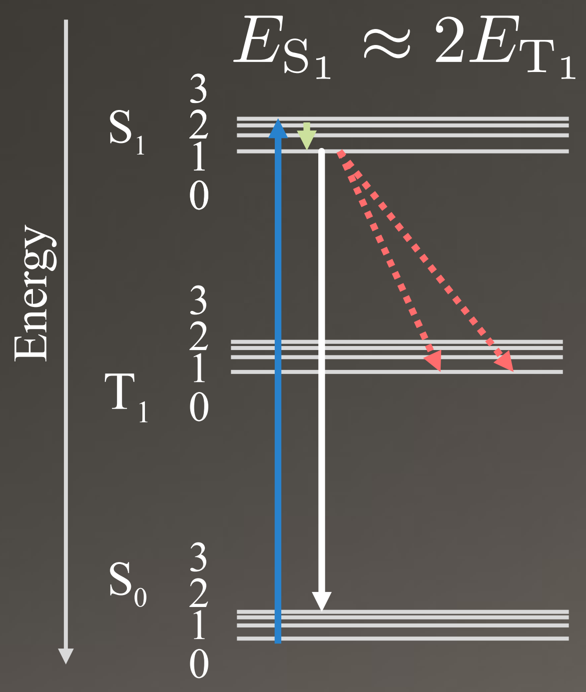


$R_\gamma^{BG} = 5\,Hz/PMT$
$R_\gamma^{BG} = 0.1\,Hz/PMT$
DAMIC
PbS QDs 10 g–yr
Phase 1 (Immediate)
XENON10
SENSEI
PbS QDs 100 g–yr
Phase 2 (Yr. 3–5)
Ultra-light mediator
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
$\bar{\sigma}_e\ [cm^2]$
1
10
10^2
m_χ [MeV]

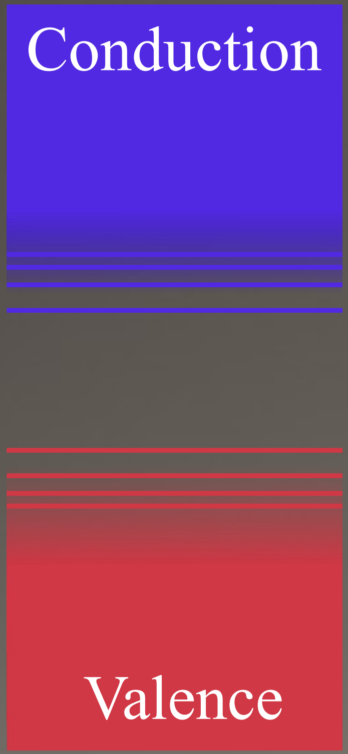
Hybrid Detectors

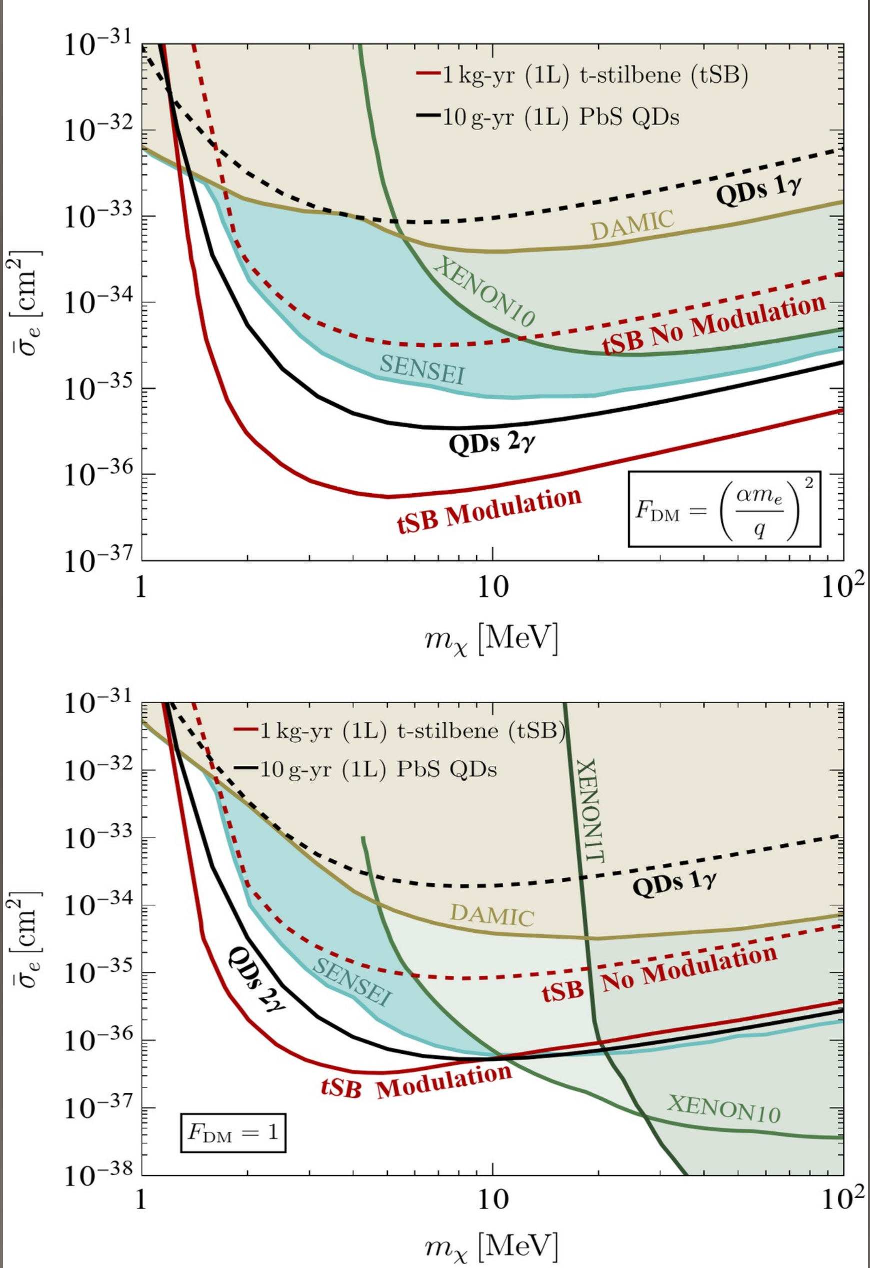




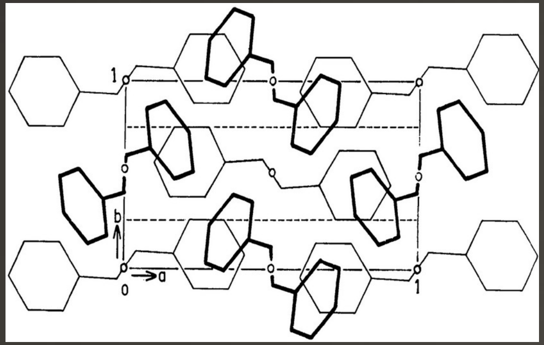


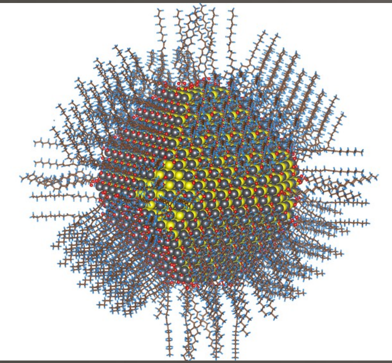
Molecular excitation
(Singlet transitions)

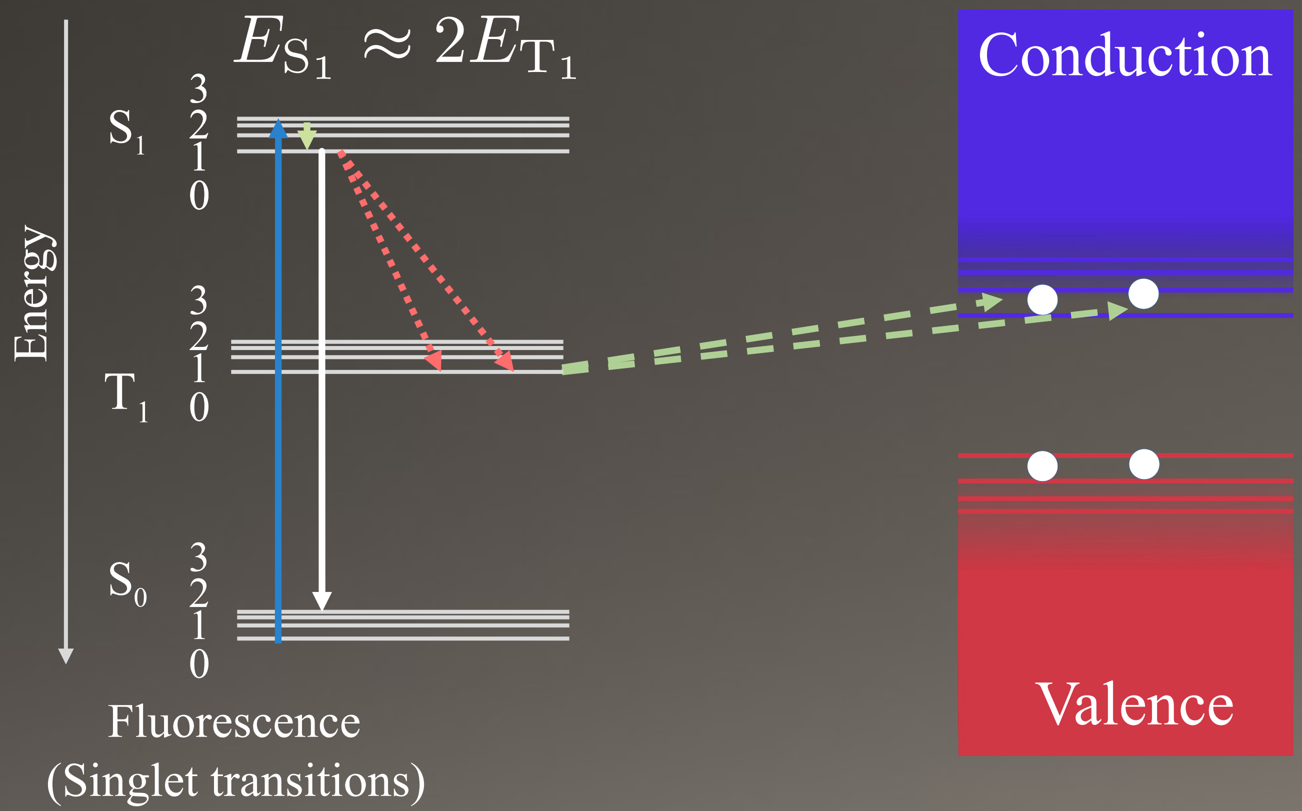


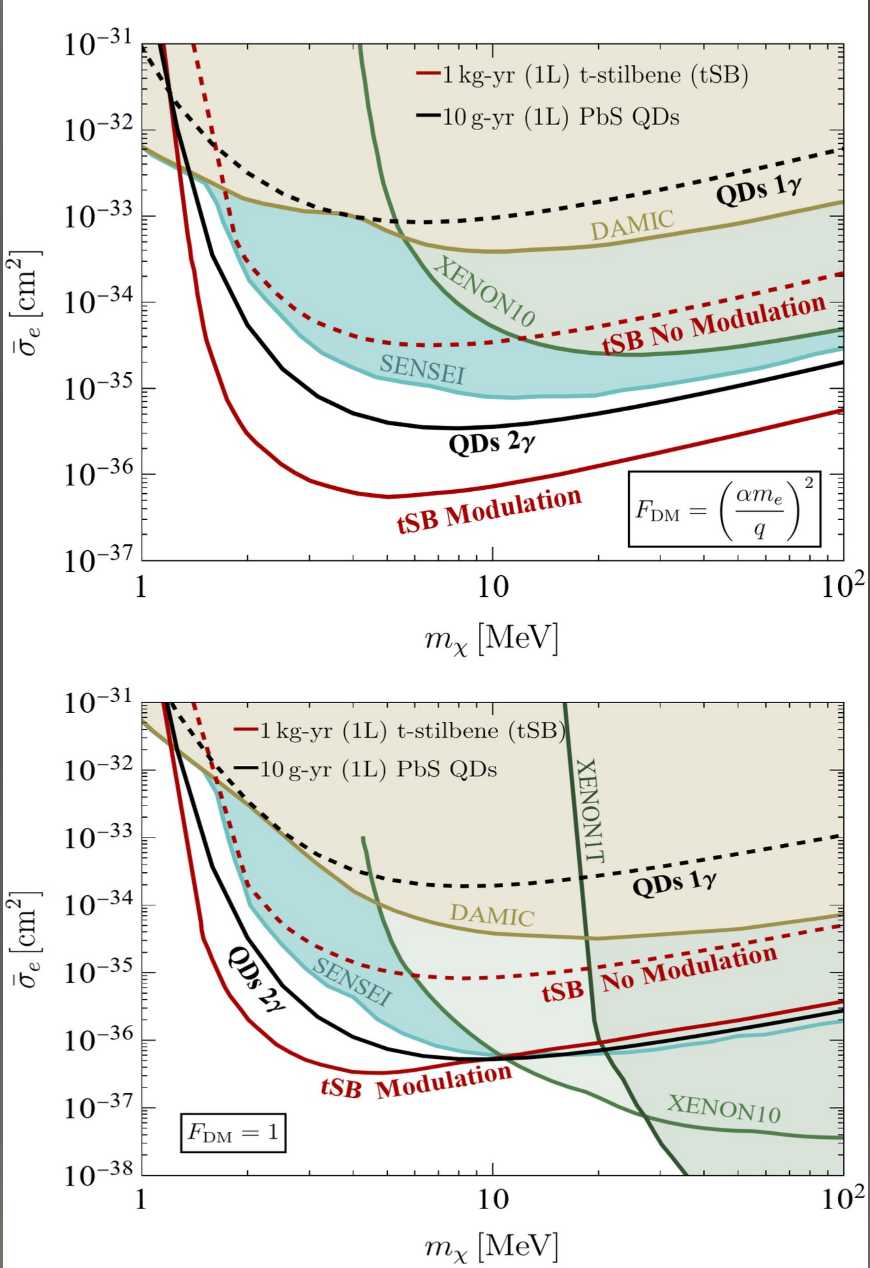


Hybrid Detectors

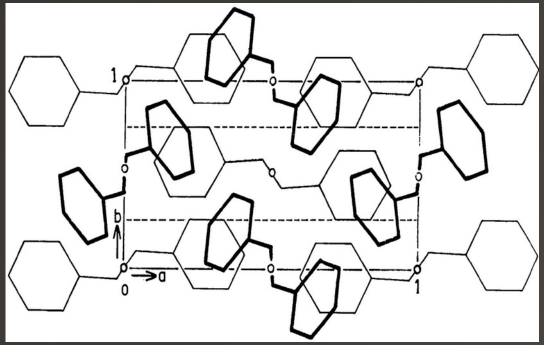




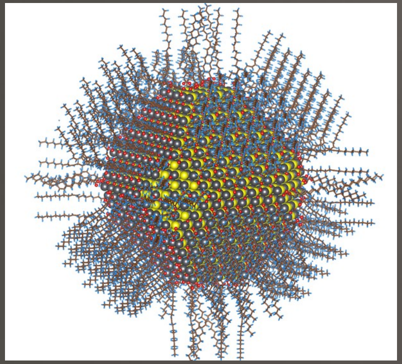


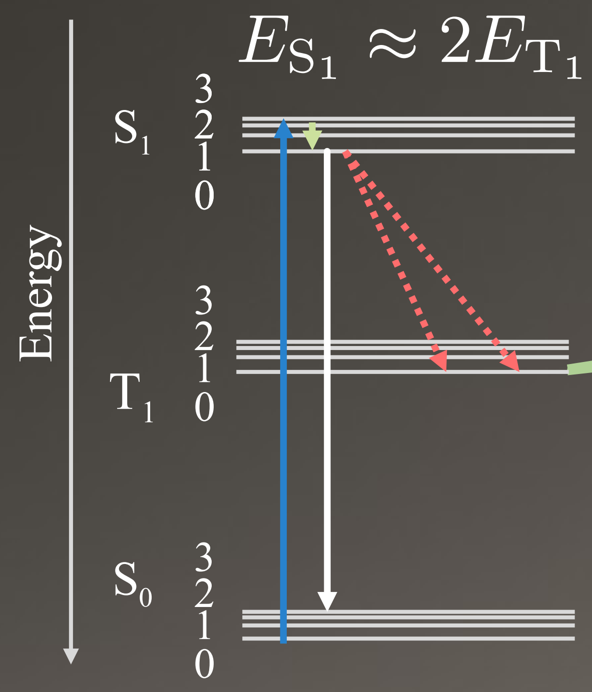


Hybrid Detectors

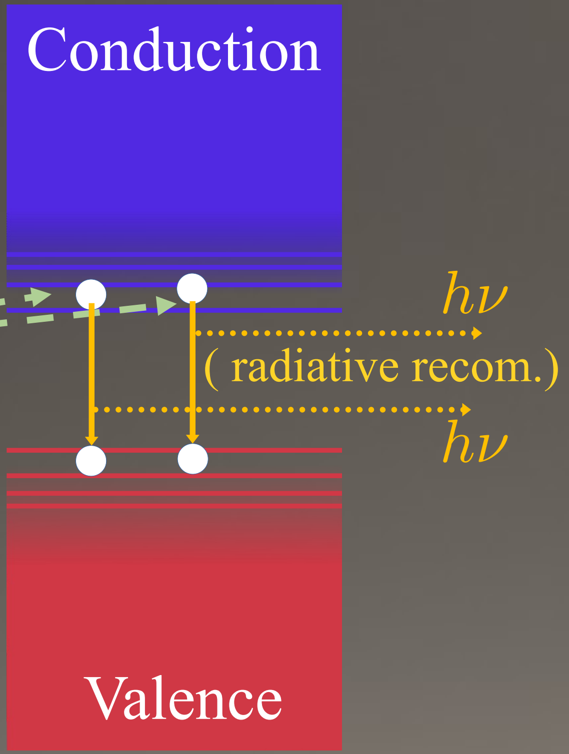


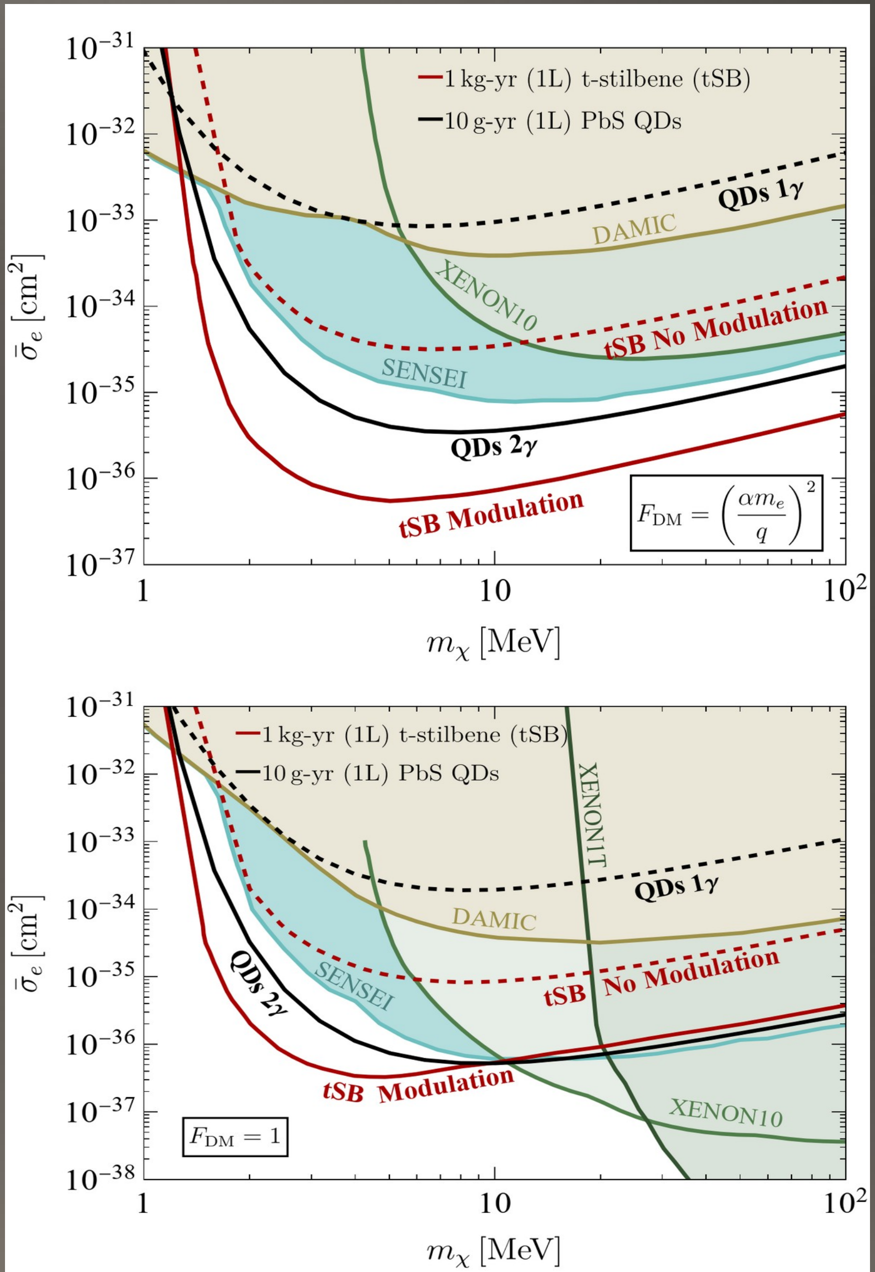
(Charge Transfer)



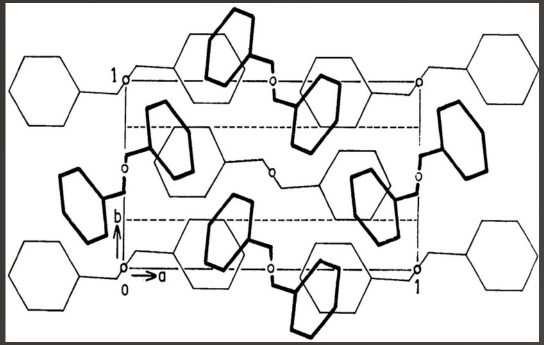


Fluorescence
(Singlet transitions)

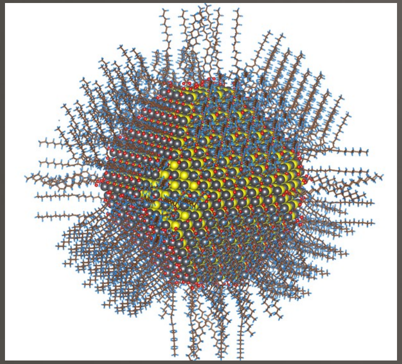


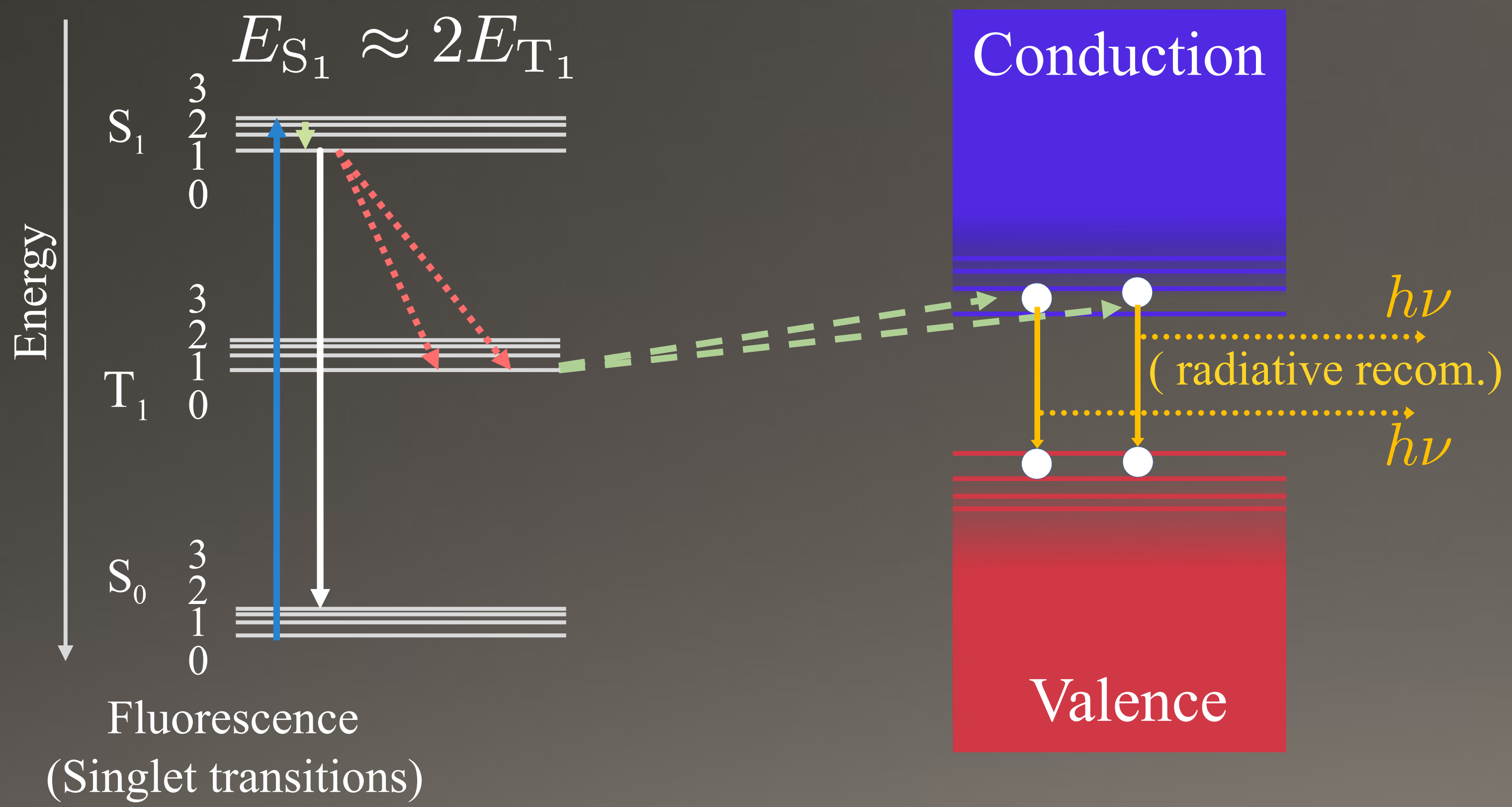


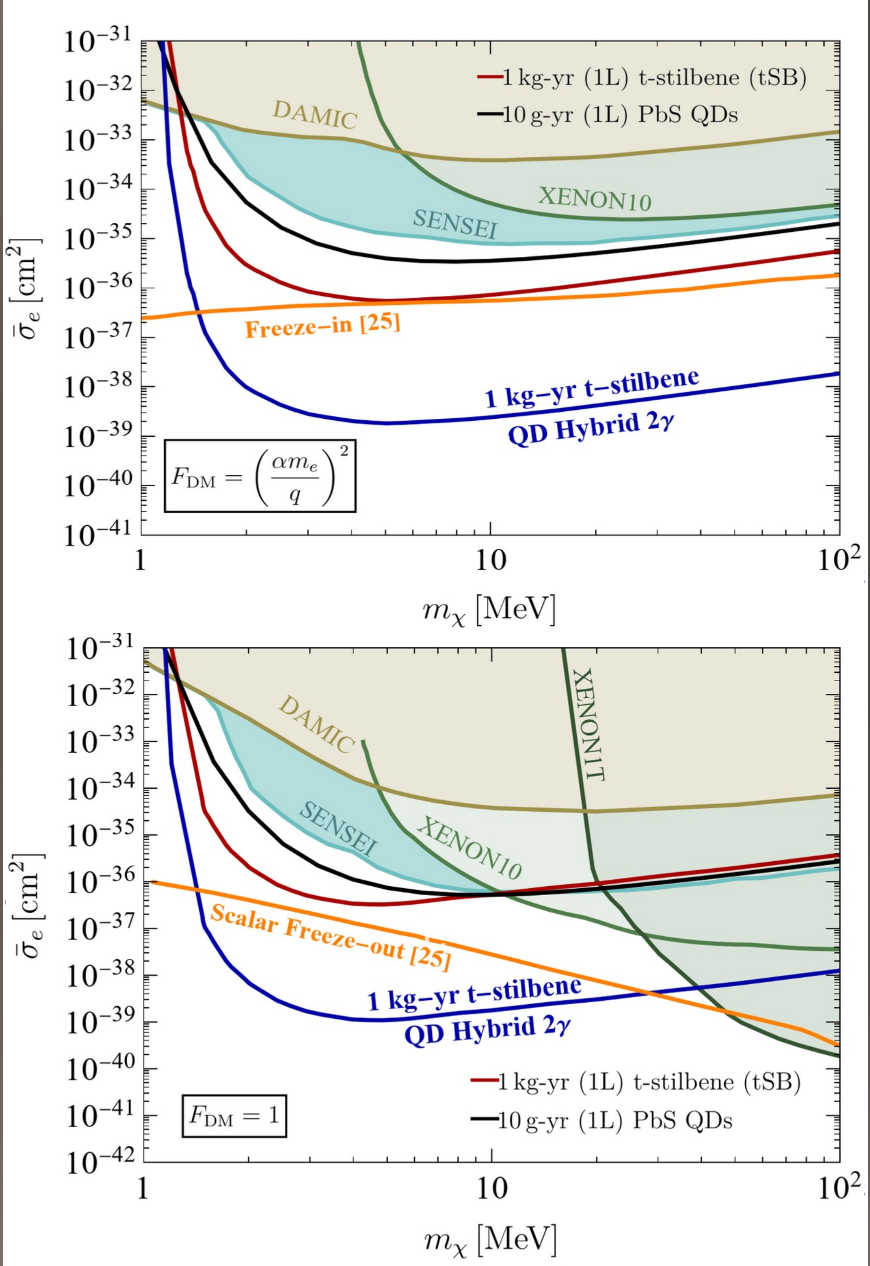
Hybrid Detectors



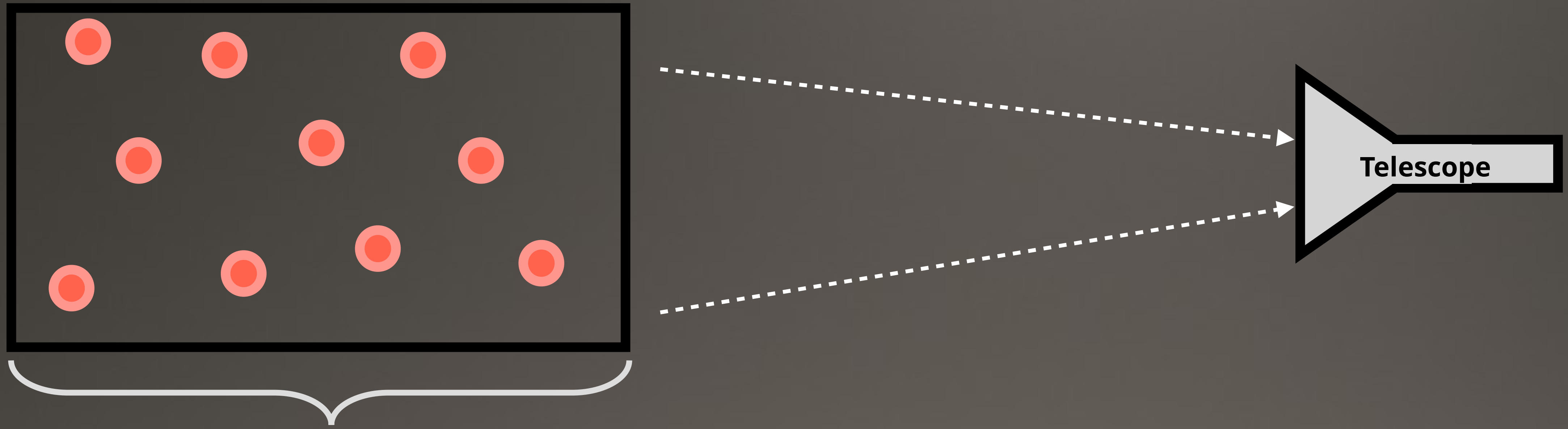
(Charge Transfer)







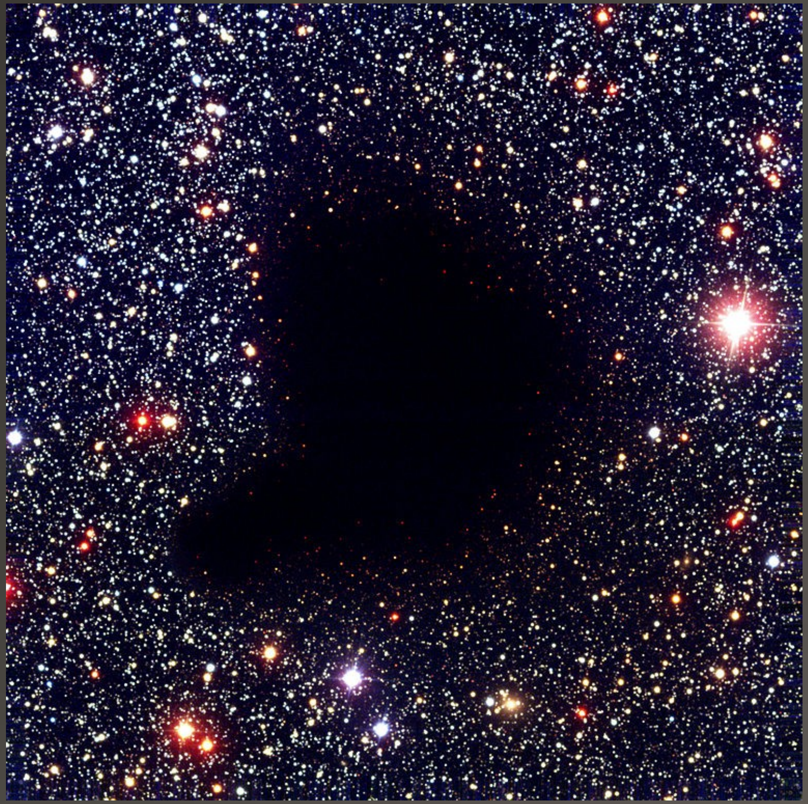
Beyond direct detection



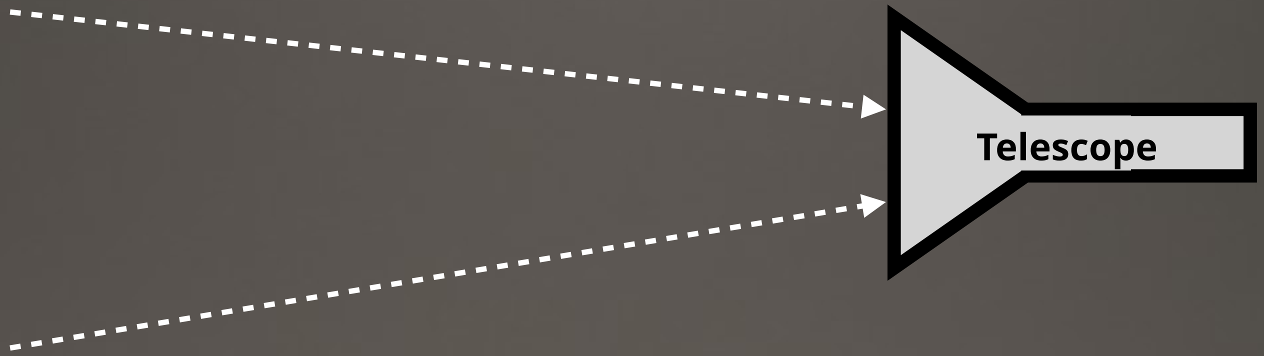
Astrophysical volume of molecules

Same theoretical techniques → Predict rates in *astrophysical* objects

Beyond direct detection

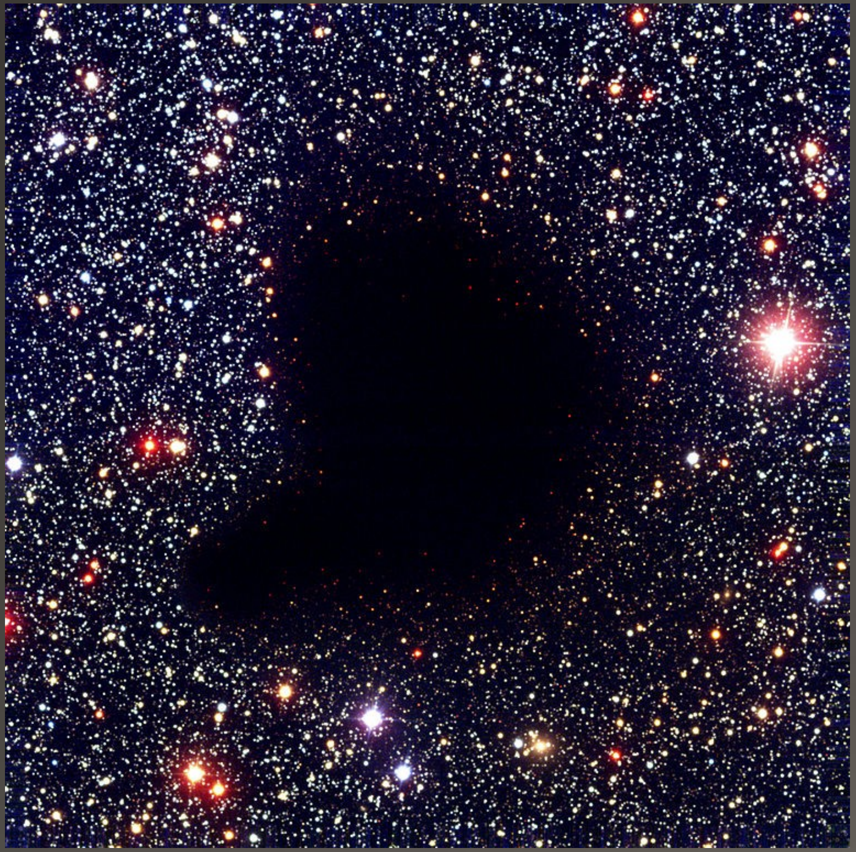


Cold molecular cloud



Same theoretical techniques → Predict rates in *astrophysical* objects

Dark matter in Molecular Clouds



~ 0.5 ly

Dense cold molecular clouds are almost entirely opaque.

$$n_{\mathrm{H}_2} \sim O(10^2)\mathrm{cm}^{-3}$$

Ionization from CR produces ionization fraction: ζ^{H_2}

$$\mathrm{CR} + \mathrm{H}_2 \rightarrow \mathrm{CR} + \mathrm{H}_2^+ + \mathrm{e}^-$$

Well measured through astro-spectroscopy of tracer molecules (line intensity measurements)

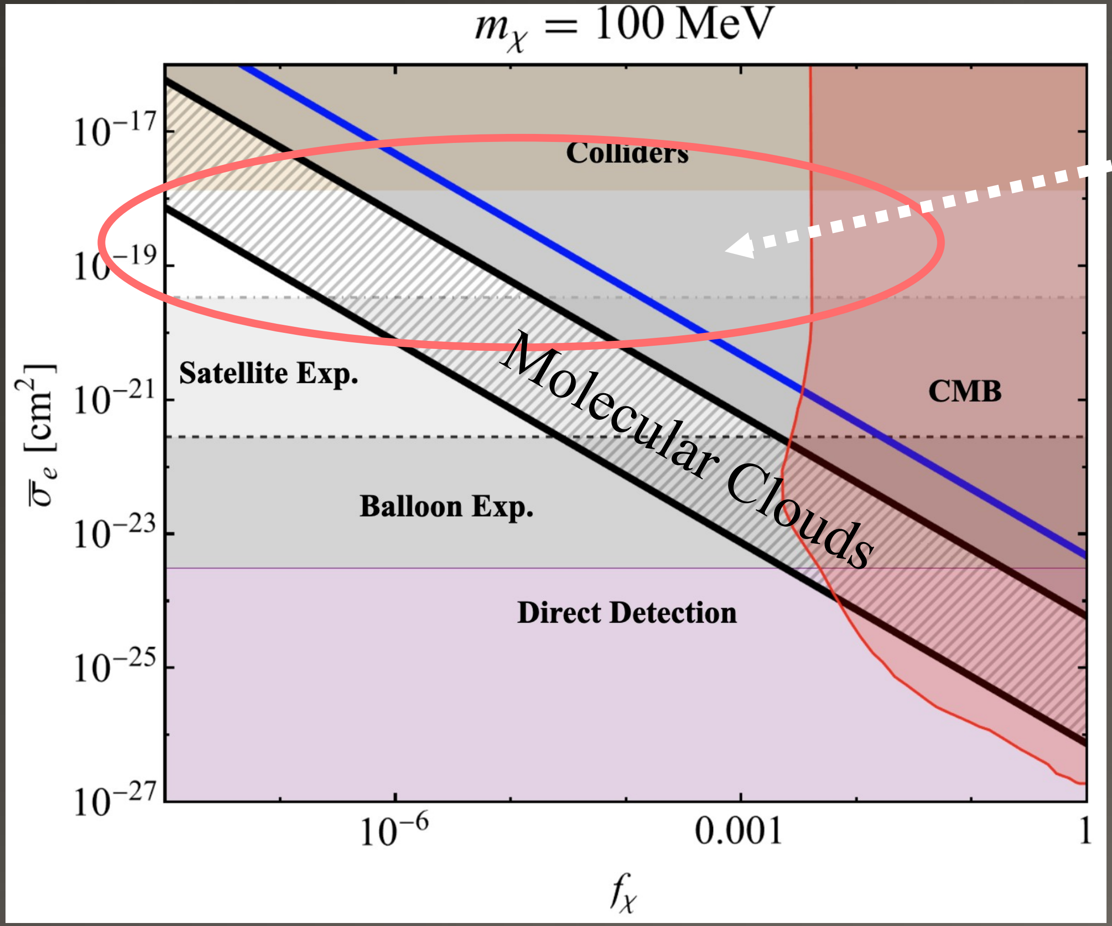
DM scattering → Add ionized SM particles

$$\zeta_i^{\mathrm{H}_2} = 2\pi \int \frac{dN_i}{dE}(E)\sigma_i(E)dE$$

[Prabhu,**CB**: 2211.05787]

Dark matter in Molecular Clouds

Constraints on DM w/ ultra-light mediator



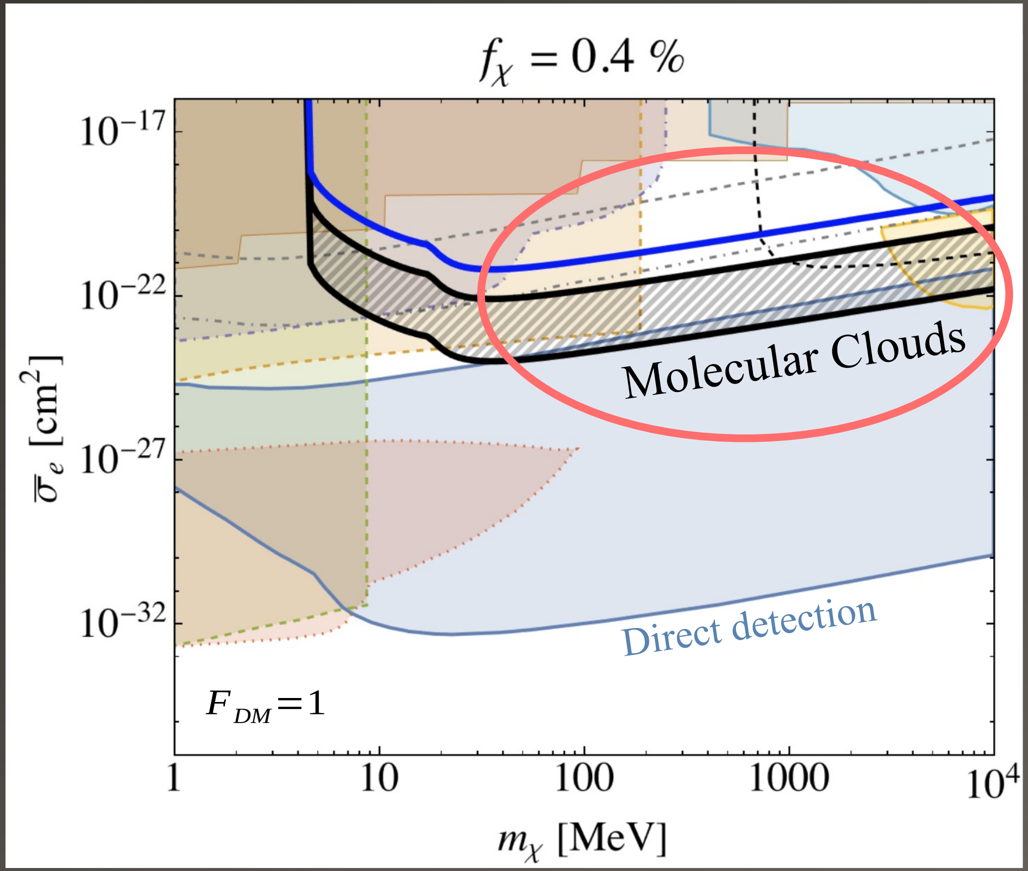
[Prabhu,**CB**: 2211.05787]

Otherwise open parameter space

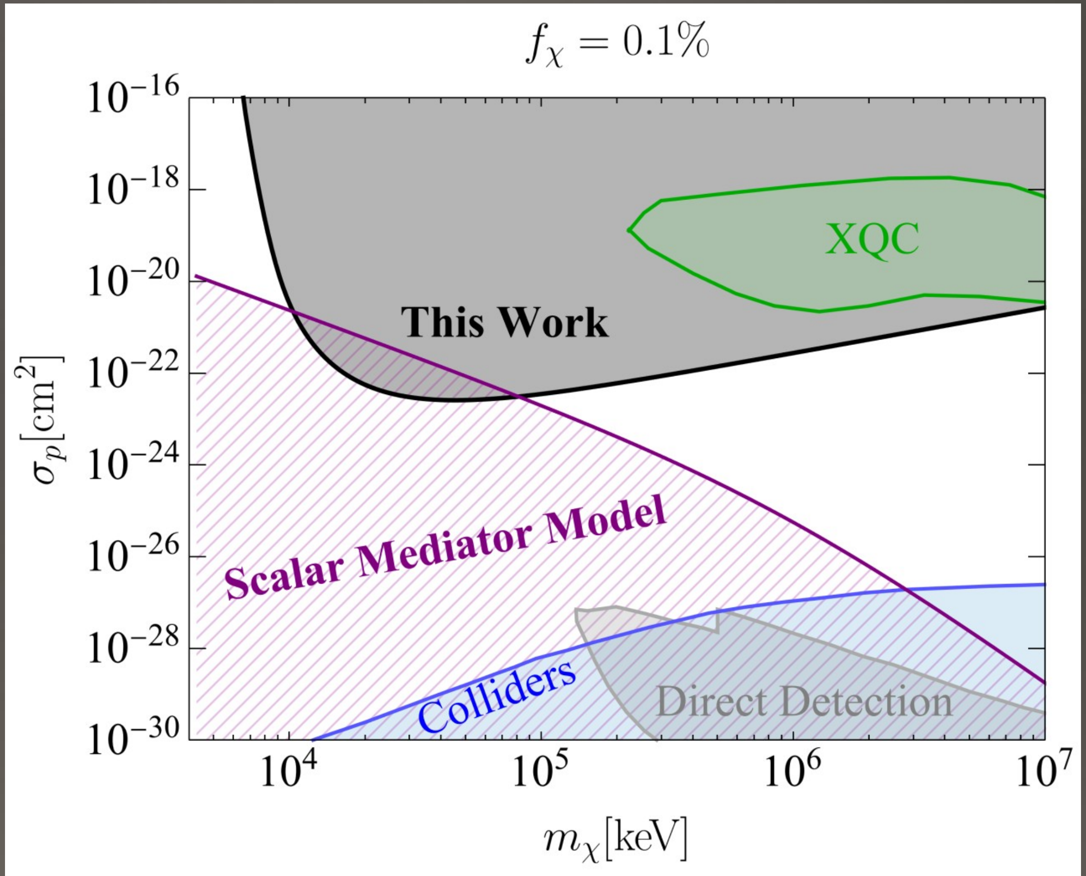
Strongly-coupled dark matter is stopped before reaching experiments.

*Uncertainty from inferred CR ionization rate due to gas depletion onto grain surfaces.

Dark matter in Molecular Clouds



[Prabhu,**CB** : 2211.05787]



[**CB**, Harris, Kahn, Prabhu: 2310.00740]

The Molecular Migdal effect(s) *in space*

Conclusions

- Successful campaign for WIMPs $\rightarrow$ Now we must look beyond.
- By developing the formalism that describes the interaction between dark matter and molecules or nano-materials, we can propose detection strategies capable of *delving deep* and *searching wide* across the dark matter parameter space.
- This remains one of the few ways to probe high-energy physics at the *bench-top* scale.
- Stay tuned for hybrid methods giving multiplicative improvements to sensitivity.

Acknowledgements

- **Grad Students**: Ian Harris (UIUC), Sandip Roy (Princeton), & Cameron Cook (Edinburgh --- soon Liverpool)
- Collaborators & colleagues: Ani Prabhu, Yoni Kahn, Ben Lillard, Juan Collar, Jesus Perez-Rios, Rouven Essig, Hari Ramani, Oren Slone, Dan Baxter, Marivi Fernandez-Serra, Sam McDermott, Ian Harris, Juri Smirnov (In no particular order)
- The work of C.B. was supported in part by NASA through the NASA Hubble Fellowship Program grant HST-HF2-51451.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555 as well as by the European Research Council under grant 742104.

NASA

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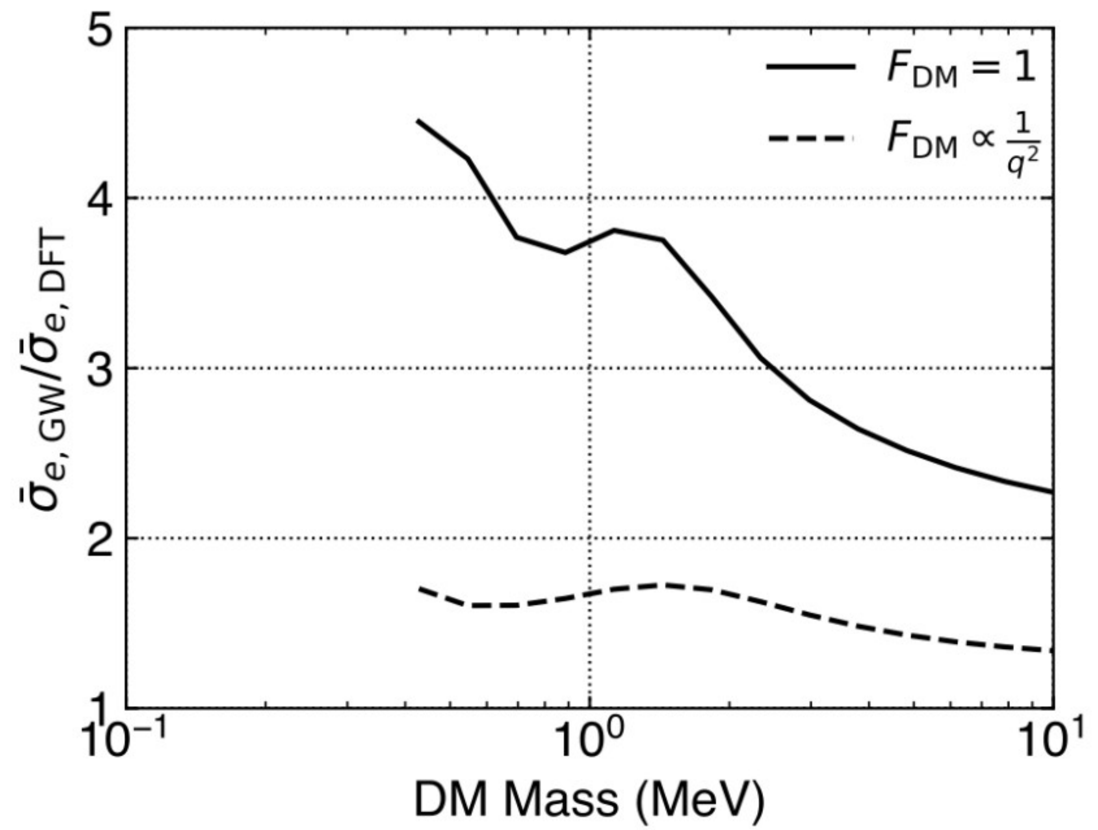
The DFT Problem



[Peterson, Watkins, Lane, Zhu ‘23: 2310.00147]

DFT is a *ground-state* theory

The systematic uncertainty from *out-of-the-box* DFT can be very large.

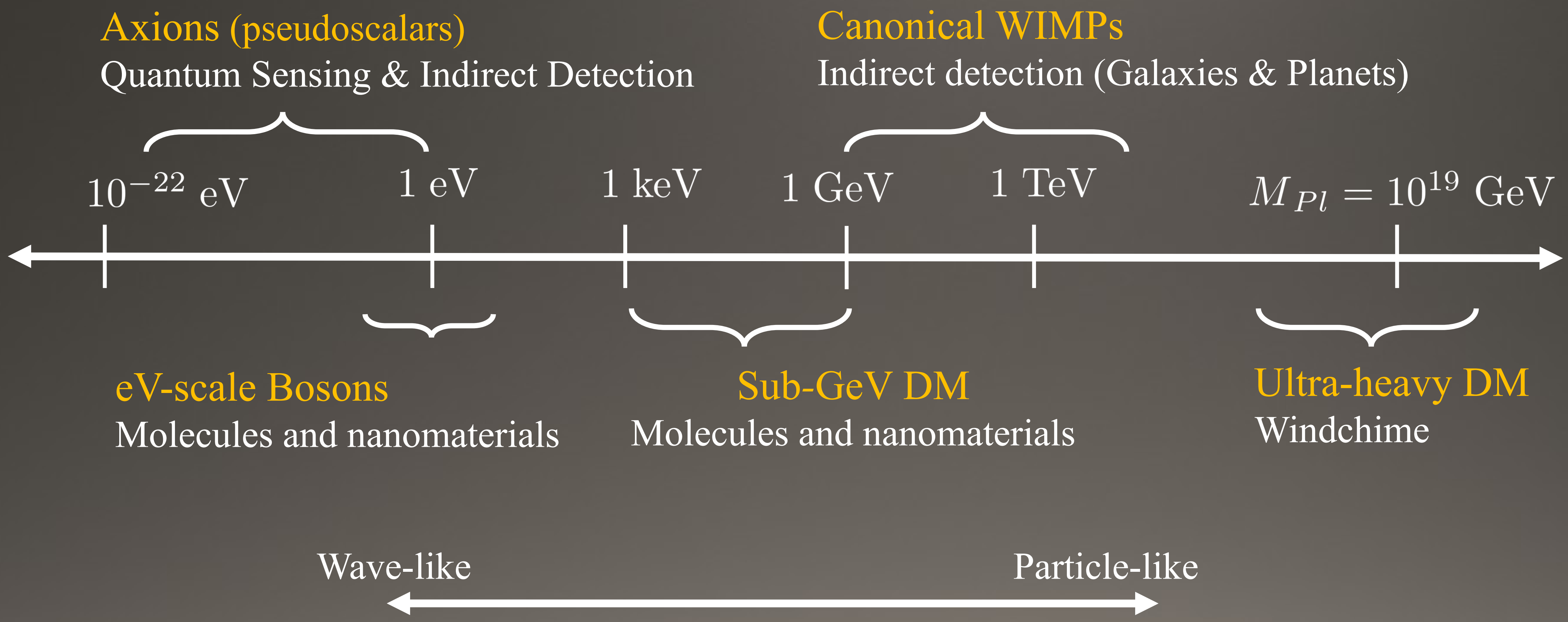
The Alternative

Self-consistent molecular orbital theory

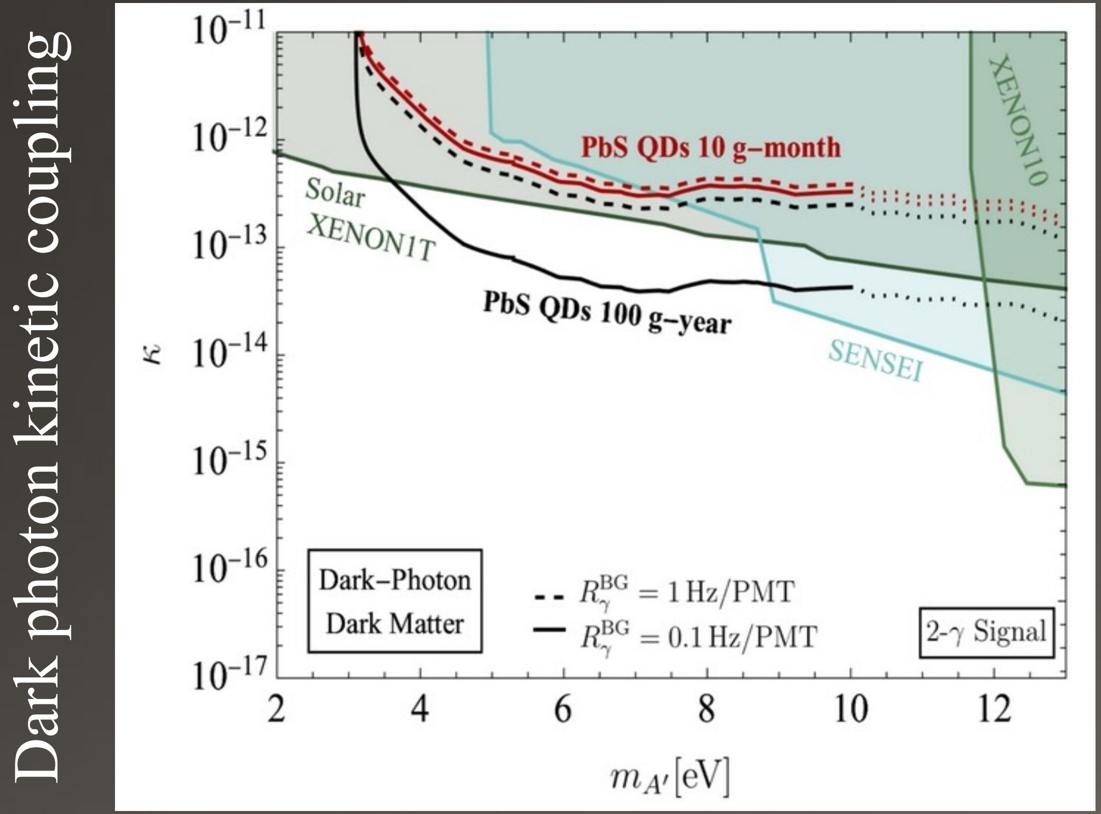
Excited states

$$\Psi_i^j = \frac{1}{\sqrt{2}}\left(|\psi_1\overline{\psi_1}\ldots\psi_i\overline{\psi_j}\ldots\psi_N\overline{\psi_N}| - |\psi_1\overline{\psi_1}\ldots\psi_j\overline{\psi_i}\ldots\psi_N\overline{\psi_N}|\right)$$

Many Methods in One Program



PbS QDs



[**CB**, Essig, Fernandez-Serra, Ramani, Slone: 2208.05967]

In the case of eV-scale dark photon absorption, we can use existing *data* to predict the sensitivity of QD-based detectors.

Key conclusions of QD analysis

1) The interaction rate in a semiconductor generated by DM is the same if the semiconductor is *monolithic* or *nanoscopically* disperse.

2) In a QD-based experiment, the readout is independent of the target.

3) The signal can be tuned through control of quantum confinement.

QDs – Cheap, tunable and scalable

QDot™ PbS Quantum Dots

$399.00 - $2,500.00

Shipping worldwide

QDot™ PbS (Lead Sulfide) Quantum Dots, oleic acid capped, absorb the light from high energy photons up to near-infrared (NIR) range and re-emit in NIR range. The absorption/emission profiles can be tuned from 800 to 2200 nm, simply by changing nanoparticle sizes from 2 to 12 nm. This material has outstanding light absorption and photoelectrical properties, and is utilised for for near-infrared (NIR) or short-wave infrared (SWIR) image sensors. For specific application convenience, two lines of QDs are available:

- With specific absorption peak in 800 – 2200 nm range
- With specific emission peak in 900 – 1600 nm range Read more

Absorption/Emission: Emission

Wavelength: 1600 nm

Quantity: 1 g

Form: Toluene 10 mg/mL

Reset

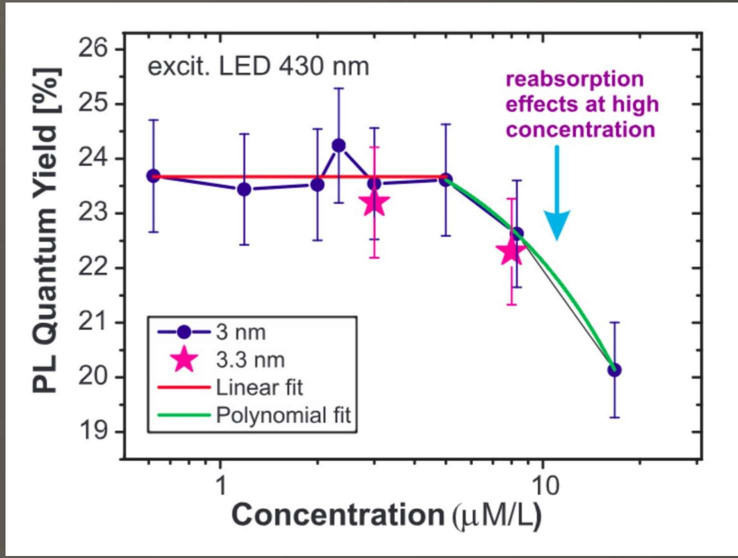
Price for choosen options

$1,700.00

1

Add to cart

Contact with our expert



Φ dependence on the solution concentration for 3nm and 3.3nm PbS QDs in toluene.

$$n_e \sim 10^{20}\ \mathrm{cm}^{-3} = 10^{23}\ \mathrm{L}^{-1}$$

Strongly Confining Quantum Dots

Semiconducting nano-spheres

$$a << a_0$$

$$E_{\text{confinement}} = \frac{\hbar^2 \pi^2}{2a^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) = \frac{\hbar^2 \pi^2}{2\mu a^2}$$

$$E = E_{\text{bandgap}} + E_{\text{confinement}}$$

$$= E_{\text{bandgap}} + \frac{\hbar^2 \pi^2}{2\mu a^2}$$

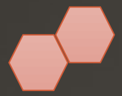
$$E_{kin} \sim \frac{1}{r^2}$$

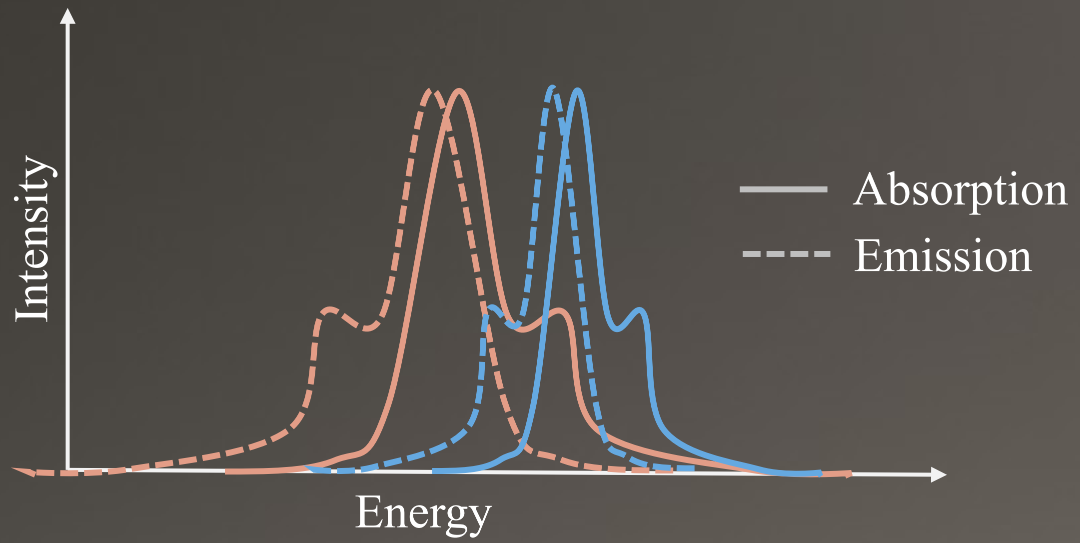
$$E_{coulomb} \sim \frac{1}{r}$$

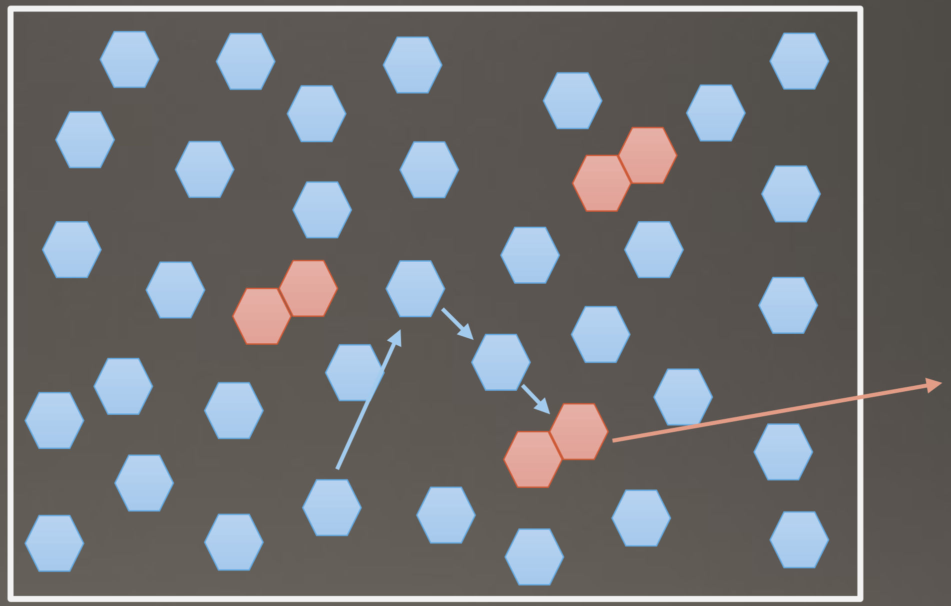
arXiv: 1912.02822

Fluorescence: Binary Scintillators

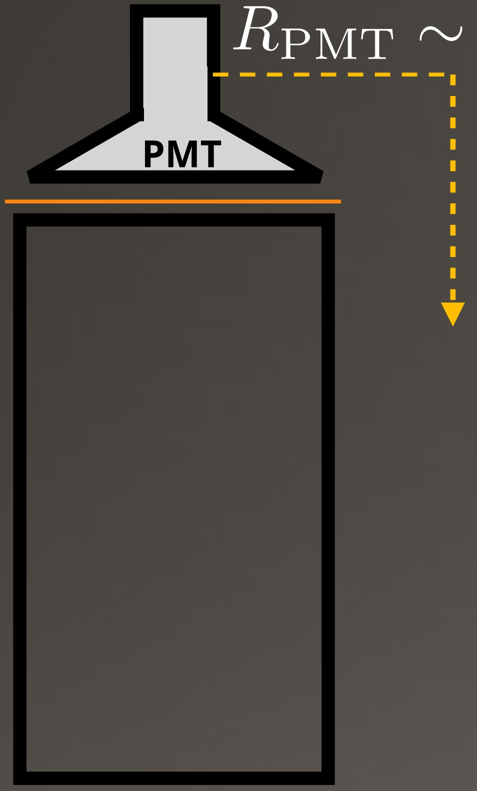
 Solvent: Primary target starts the signal

 Solute: Dilute fluor gets the signal out of the bulk



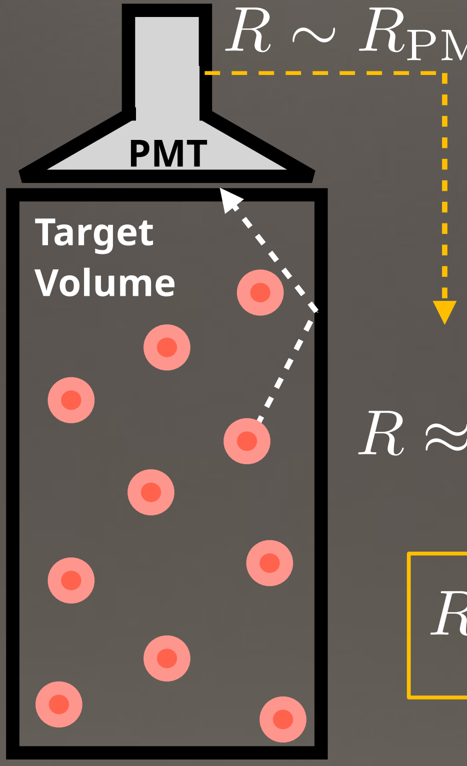


PbS QDs: Improvements



$R_{\text{PMT}} \sim 10\text{Hz}$

"Blind" mode



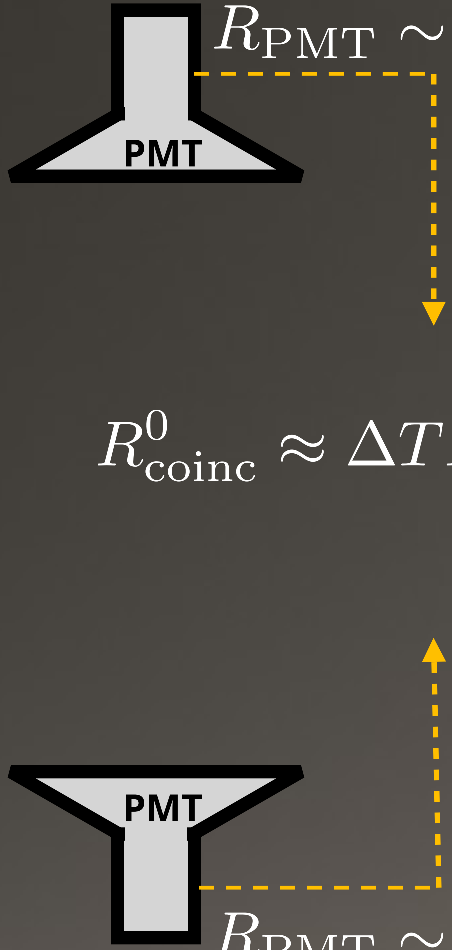
$R \sim R_{\text{PMT}} + \delta R$

$R \approx R_{PMT} + \delta R + R_{\gamma-QD}$

$R_{\gamma-QD} \lesssim \sqrt{R_{\text{PMT}}}$

"Active" mode

PbS QDs: Improvements

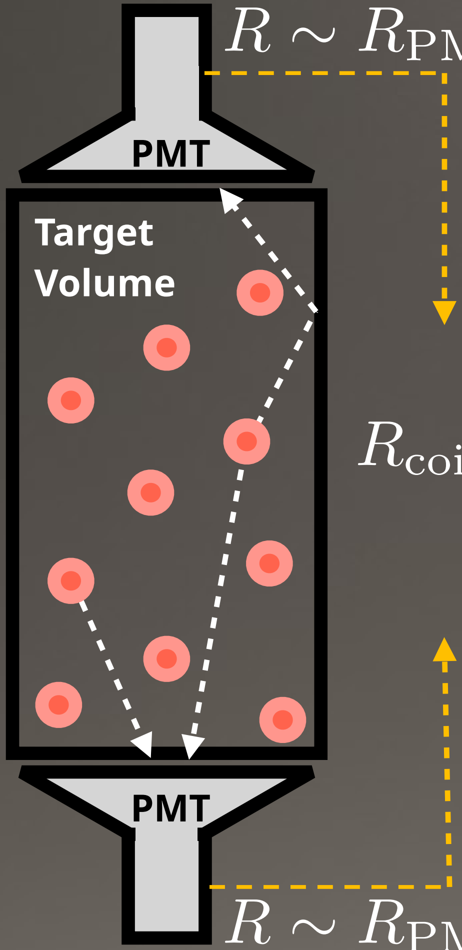


$R_{\text{PMT}} \sim 10\text{Hz}$

$$R^0_{\text{coinc}} \approx \Delta T R^2_{PMT}$$

$R_{\text{PMT}} \sim 10\text{Hz}$

"Blind" mode



$R \sim R_{\text{PMT}} + \delta R$

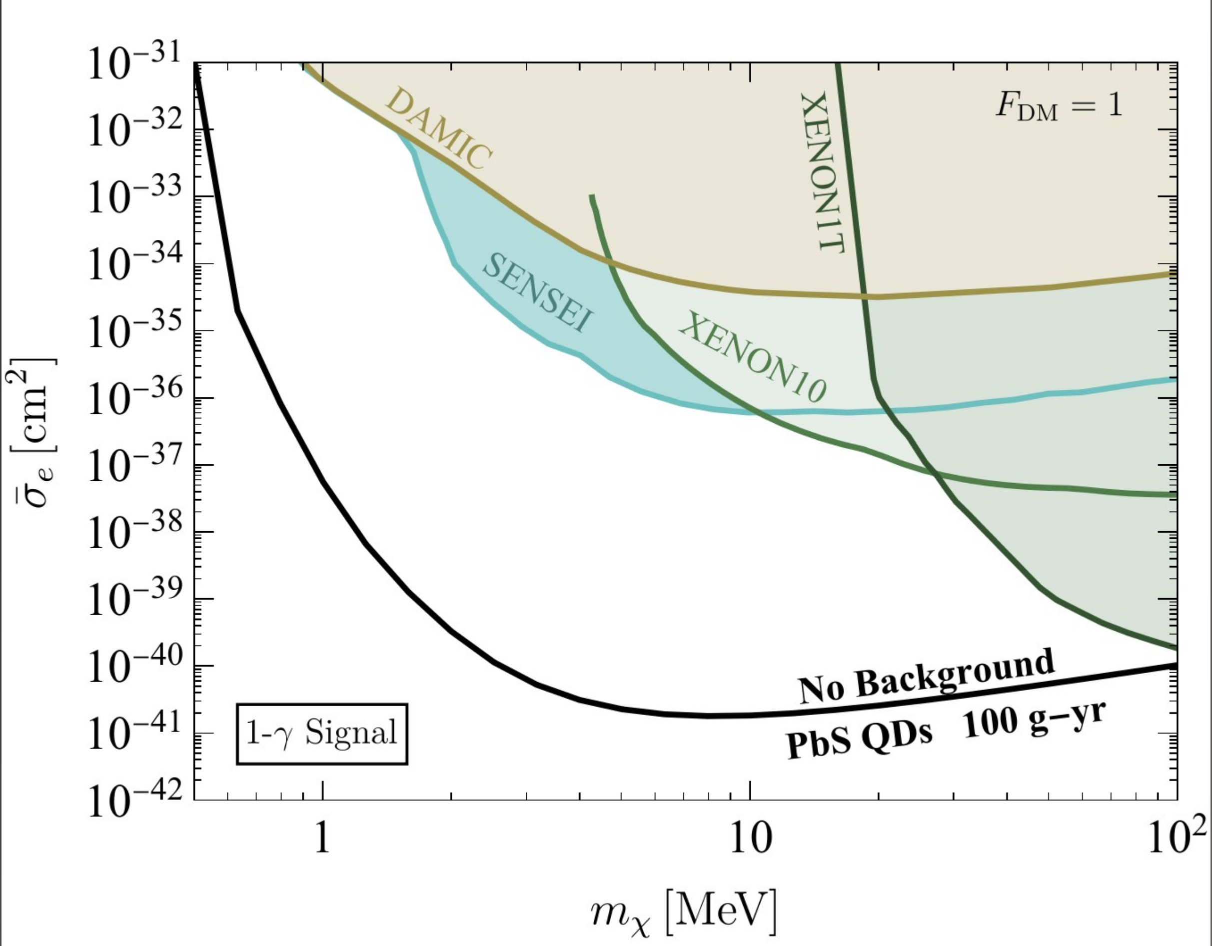
$$R_{\text{coinc}} \approx \Delta T R^2_{PMT} + 2\Delta T R_{\text{PMT}} \delta R + R_{2\gamma - QD}$$

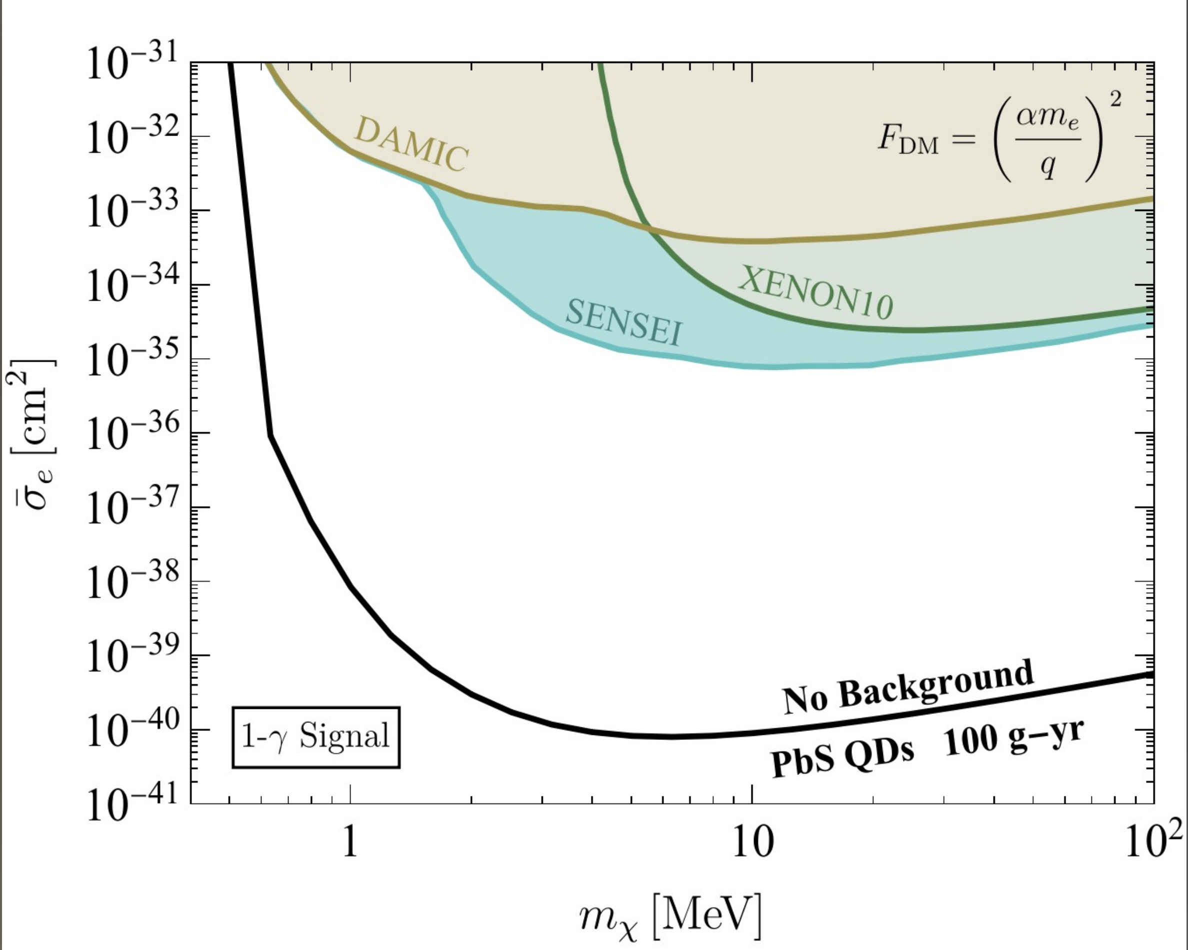
$$R_{2\gamma - QD} \lesssim \Delta T R^{3/2}_{PMT}$$

$R \sim R_{\text{PMT}} + \delta R$

"Active" mode

PbS QDs: Optimism for comparison

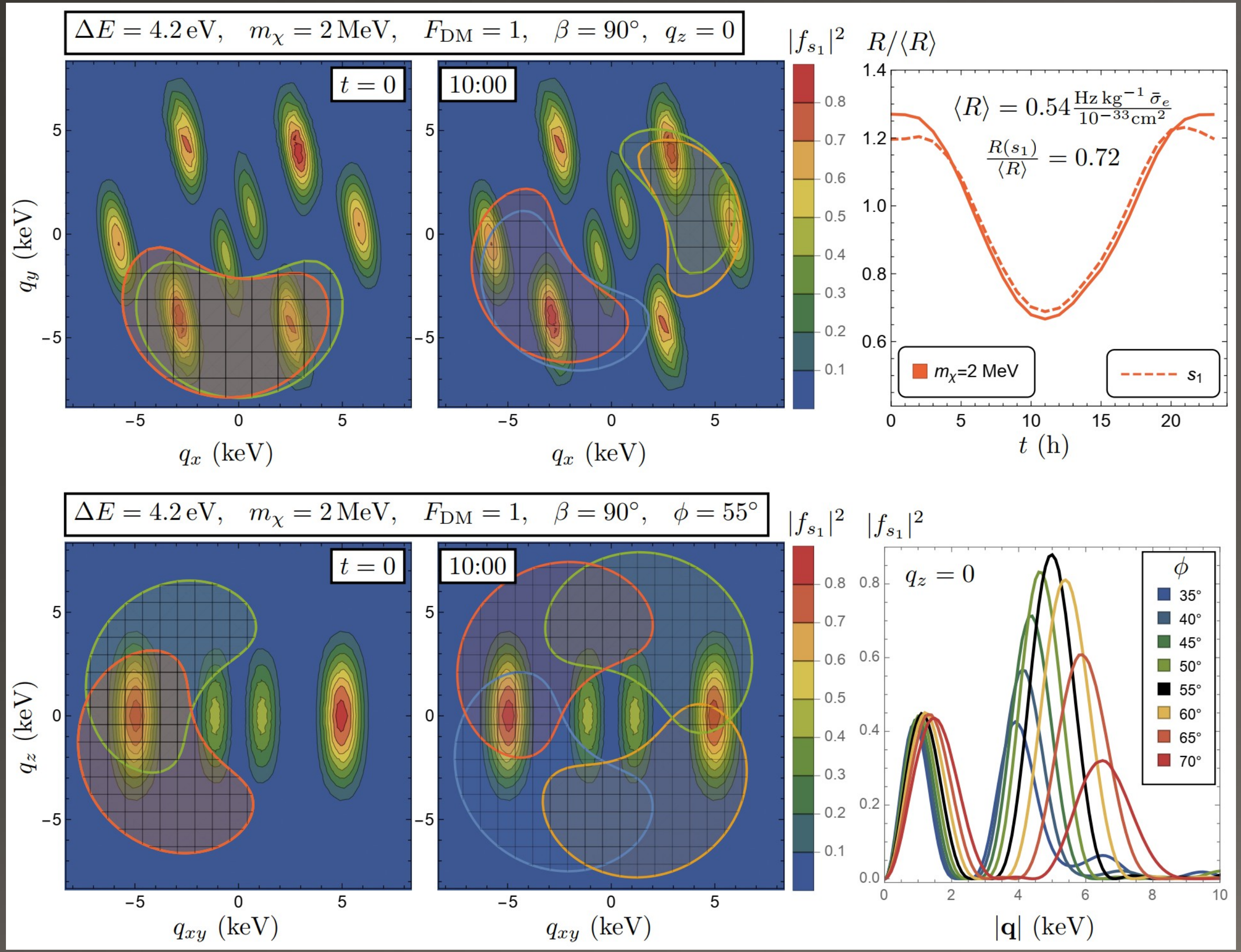




Blanco '22: 2208.05967

DM-Electron Scattering (no background 1-photon signal)

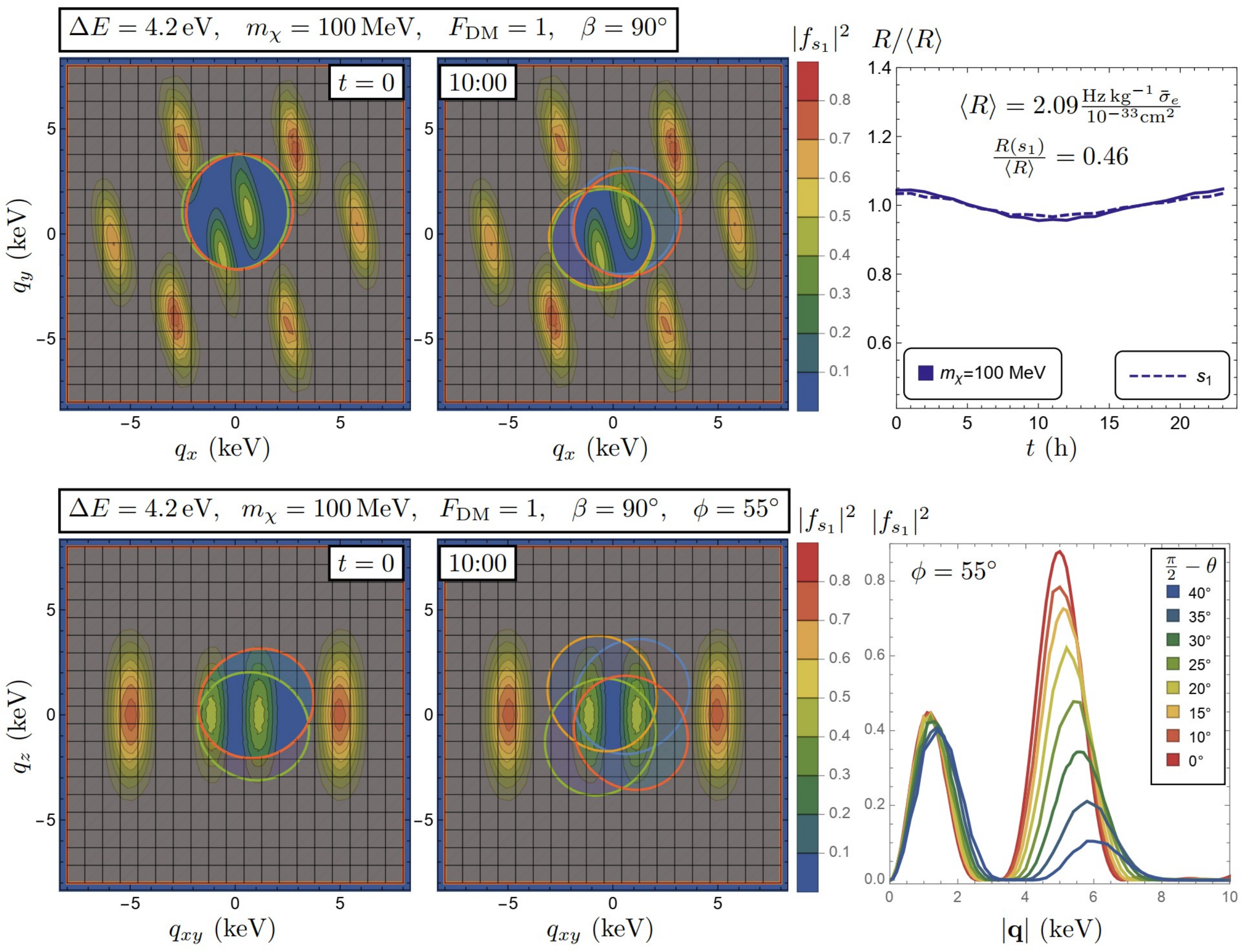
Daily Modulation: Small Mass



Molecular form factors and modulating rates for DM masses near threshold, $m_\chi = 2$ MeV. In the contour plots, the gridded shaded regions indicate the kinematically accessible momentum transfers $\vec{q}$ for the four molecules that comprise the unit cell of the crystal, shown at $t = 0$ and $t = 10\,\text{h}$. Here, $\vec{q}$ is given in the molecular basis, $q_x = \vec{q} \cdot \hat{\vec{L}}$, $q_y = \vec{q} \cdot \hat{\vec{M}}$, and the kinematically accessible region is defined by $v_-(\vec{q}) < v_{\text{esc}}$.

[**CB**, Kahn, Lillard, McDermott: 2103.08601]

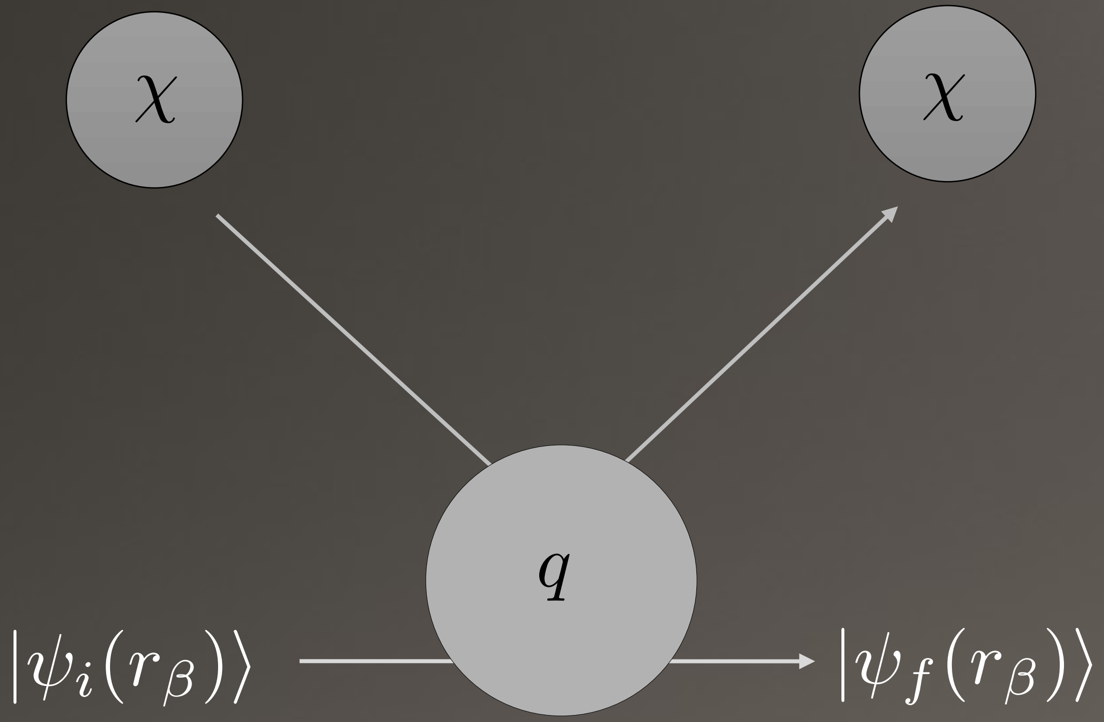
Daily Modulation: Large Mass



Same as previous figure but for large DM masses, $m_\chi = 100$ MeV. Only the nearly-spherical region near $q \sim 0$ with inner boundary $q_{\text{min}} \simeq 1.6$ keV is kinematically forbidden. As a result, the daily modulation amplitude is smaller, driven by the anisotropy of the inner secondary peaks and the tails of the primary peaks.

[**CB**, Kahn, Lillard, McDermott: 2103.08601]

Electron Recoil: Charge Signal



Electron scattering

$$\Delta E_r = (m_\chi^2/m_\mathrm{T}) \times 10^{-6}$$

$$\Delta E \sim \mathcal{O}(\text{few eV}) \left(\frac{m_\chi}{1\,\mathrm{MeV}}\right)^2$$

What has such transition energies?

- Semiconductor band gaps
- Maybe atomic ionization

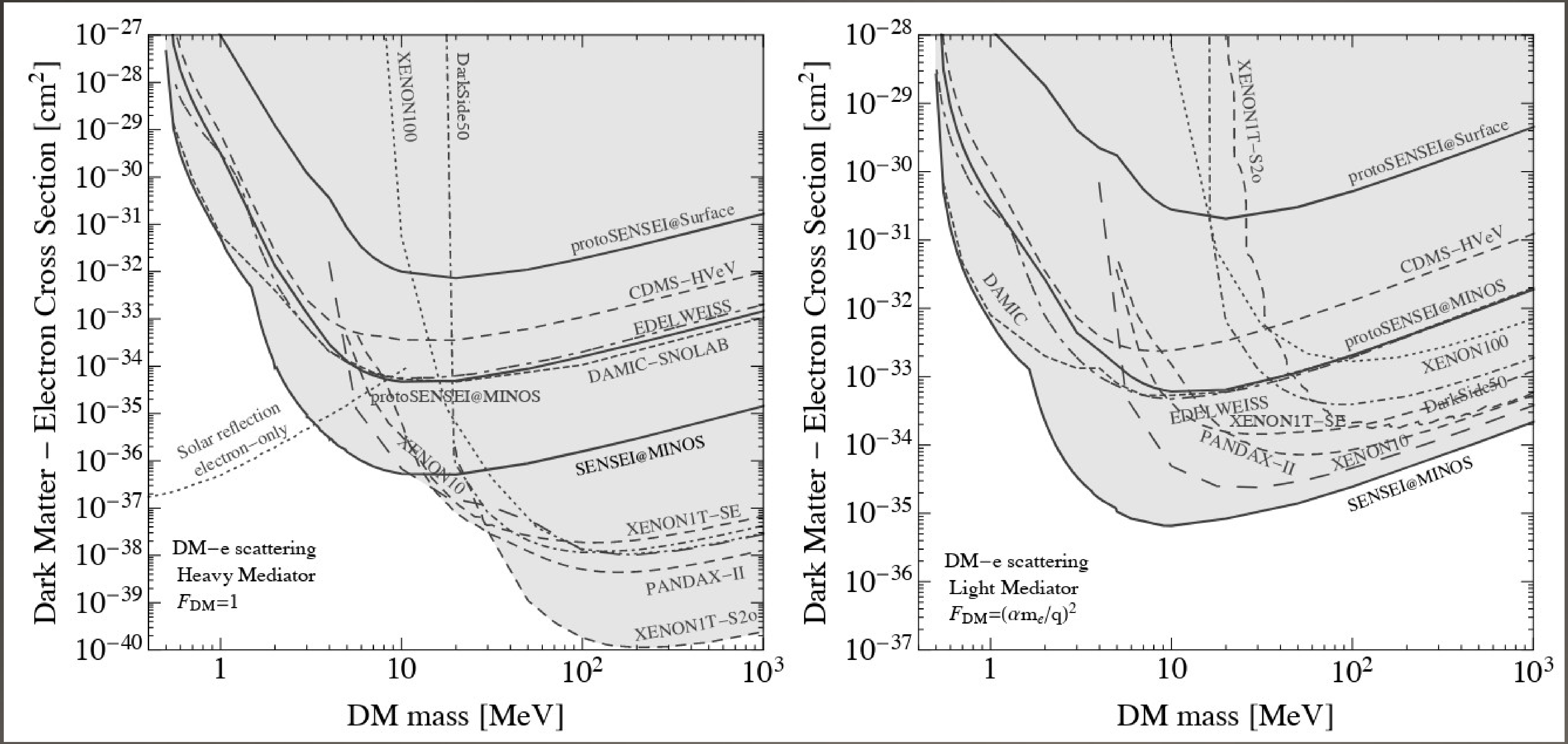
Electrons in crystals (exciton generation)

$$|\psi_i\rangle \sim u_v(r)e^{ik'\cdot r} \qquad |\psi_f\rangle \sim u_c(r)e^{ik\cdot r}$$

Electrons in atoms (ionization)

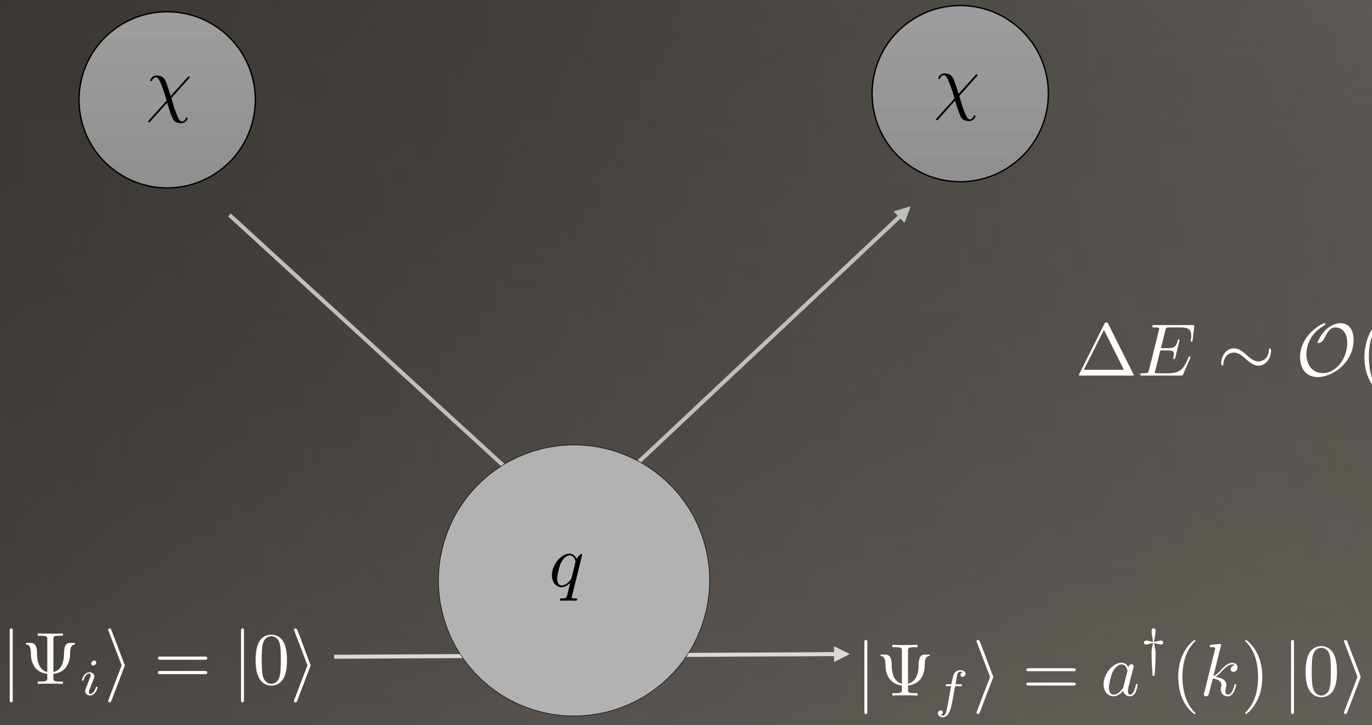
$$|\psi_i\rangle \sim \psi_\mathrm{STO}(r_\beta) \qquad |\psi_f\rangle \sim e^{ik\cdot r},\ r \gg a_0$$

Semiconductor CCDs



Essig R., et al. "*Snowmass2021 Cosmic Frontier The landscape of low-threshold dark matter direct detection in the next decade*" arXiv:2203.08297 (2022).

Nuclear Recoil: Phonon Signal

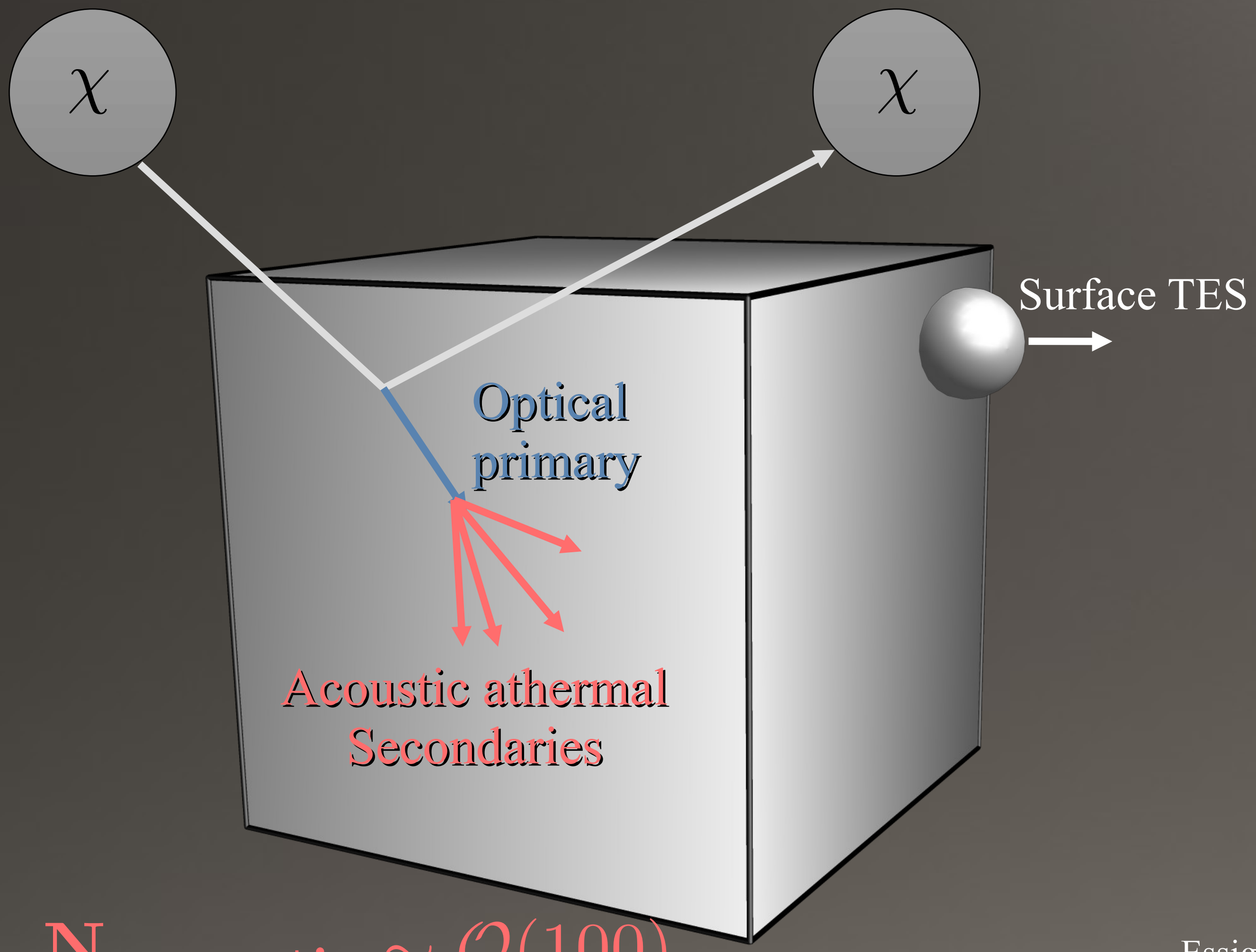


Nuclear scattering

$$\Delta E \sim \mathcal{O}(\text{few eV}) \left(\frac{m_\chi}{100\,\text{MeV}}\right)^2 \left(\frac{m_N}{130\,\text{GeV}}\right)^{-1}$$

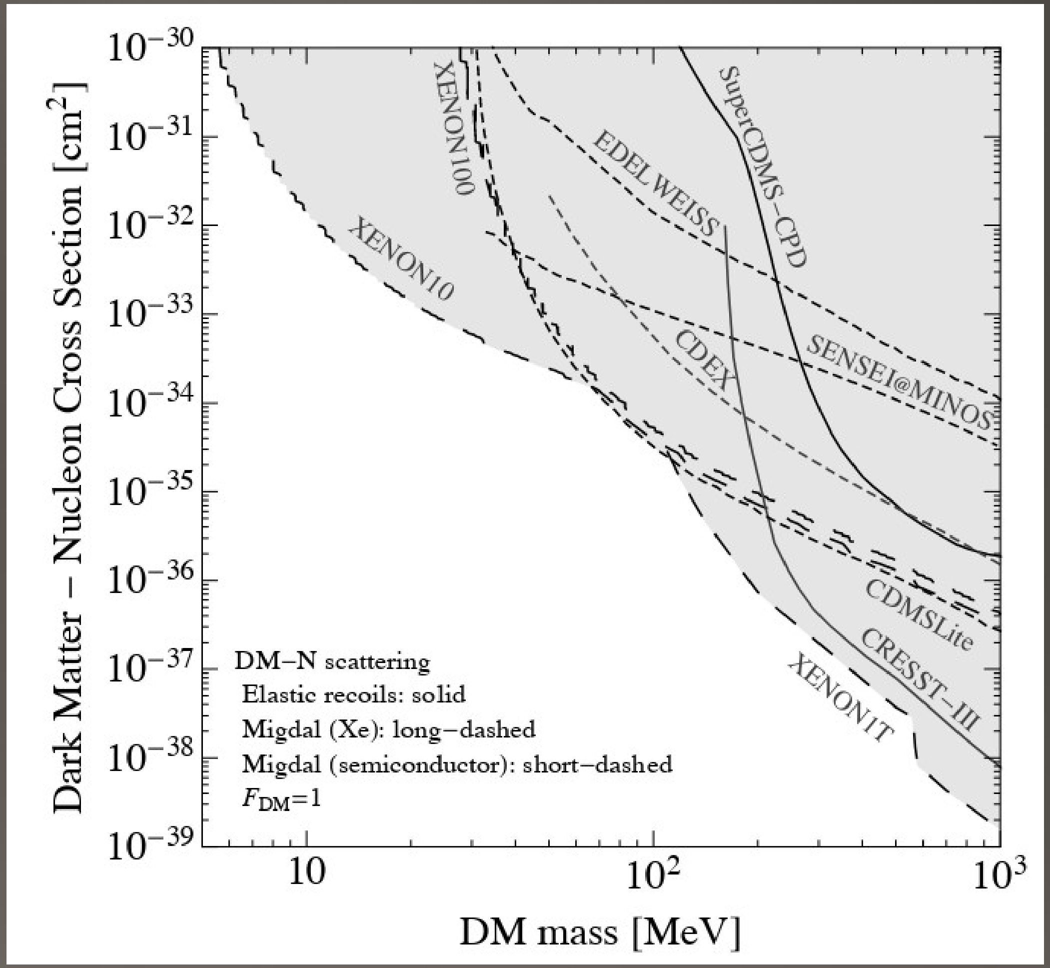
$$\omega \sim \mathcal{O}(10\text{-}100\ \text{meV})$$

Calorimeters



$N_{accoustic} \sim \mathcal{O}(100)$

$E_0 \sim 10 - 100$ meV



Essig R., et al. "*Snowmass2021 Cosmic Frontier The landscape of low-threshold dark matter direct detection in the next decade*" arXiv:2203.08297 (2022).

Trans-Stilbene

s	Platt Symbol	Symmetry	ΔE [eV]	Configuration amplitudes			
s_1	^1B	B_u	4.240	$d_{7,8} = 0.94,$	$d_{4,11} = -0.24$		
s_2	$^1G^-$	B_u	4.788	$d_{7,10} = 0.53,$	$d_{5,8} = 0.53,$	$d_{6,11} = 0.37,$	$d_{4,9} = -0.37$
s_3	$^1G^-$	A_g	4.800	$d_{7,9} = 0.53,$	$d_{6,8} = 0.53,$	$d_{5,11} = 0.37,$	$d_{4,10} = -0.37$
s_4	$^1(C,H)^+$	A_g	5.137	$d_{7,11} = 0.41,$	$d_{5,9} = -0.41,$	$d_{6,10} = -0.41,$	$d_{4,8} = -0.59$
s_5	$^1H^+$	B_u	5.791	$d_{5,10} = 0.54,$	$d_{6,9} = 0.54,$	$d_{7,12} = 0.33,$	$d_{3,8} = 0.33$
s_6	$^1G^+$	A_g	6.264	$d_{7,9} = 0.68,$	$d_{6,8} = -0.68$		
s_7	$^1C^-$	A_g	6.013	$d_{7,11} = 0.66,$	$d_{4,8} = 0.54,$		
s_8	$^1G^+$	B_u	6.439	$d_{7,10} = 0.65,$	$d_{5,8} = -0.65$		

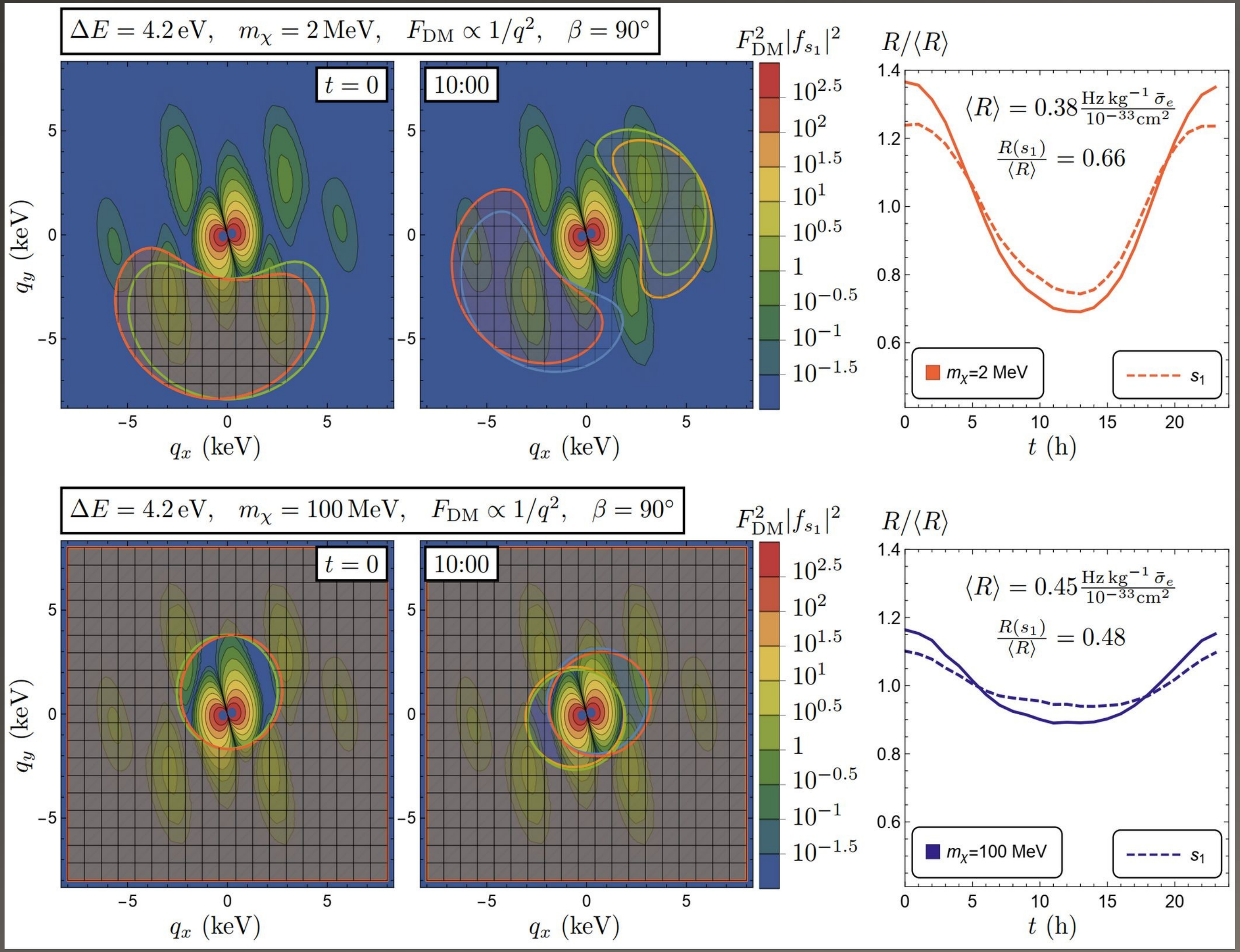
Table 1: The first eight excited states $s_{n=1\ldots8}$, with their energy eigenvalues $\Delta E(s_n)$ with respect to the ground state and coefficients $d_{ij}^{(n)}$ as calculated by Ting and McClure.

$$|s_n\rangle = \sum_{i,j>i} d_{ij}^{(n)} |\psi_i^j\rangle,$$

$$\sum_{ij} |d_{ij}^{(n)}|^2 = 1.$$

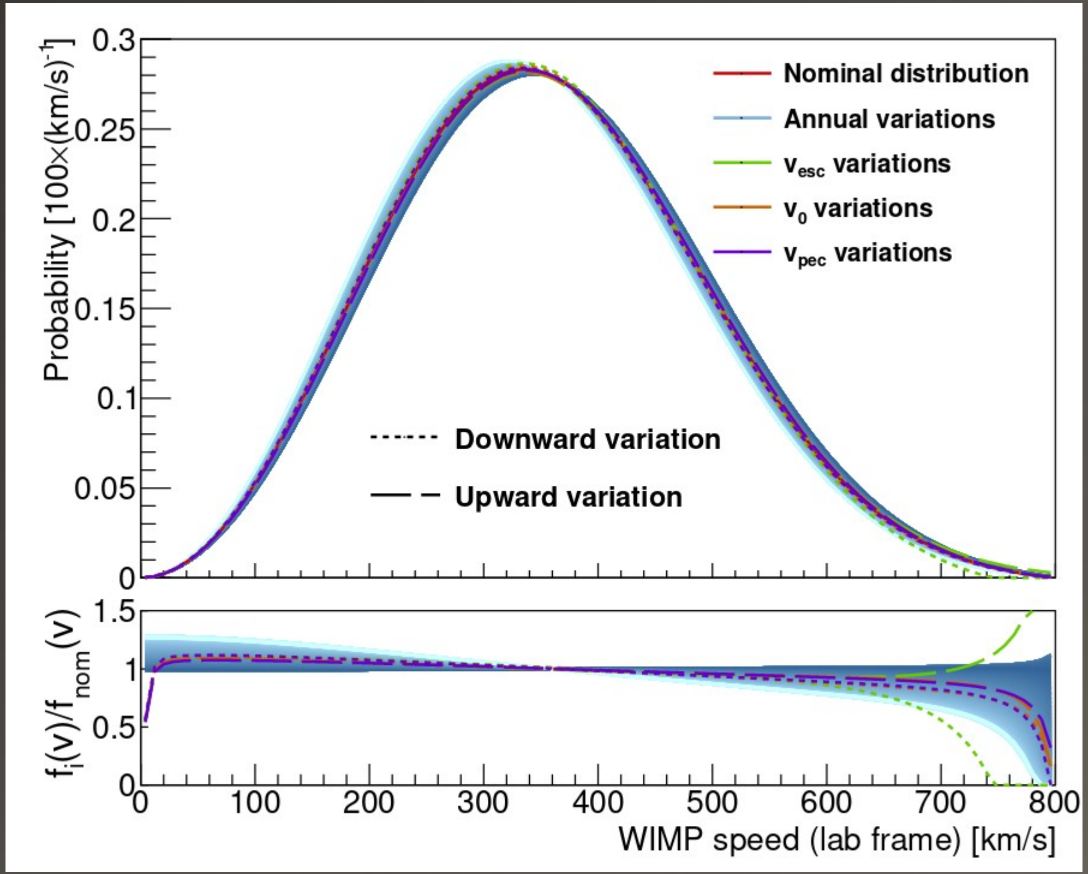
$$\begin{aligned} f_{g\to s_n}(\vec{q}) &= \left\langle \psi_{s_n}(\vec{r}_1 \ldots \vec{r}_{14}) \left| \sum_{m=1}^{14} e^{i\vec{q}\cdot\vec{r}_m} \right| \psi_G(\vec{r}_1 \ldots \vec{r}_{14}) \right\rangle \\ &= \sum_{ij} d_{ij}^{(n)} \left\langle \psi_i^j \left| e^{i\vec{q}\cdot\vec{r}} \right| \psi_G \right\rangle \\ &= \sqrt{2} \sum_{ij} d_{ij}^{(n)} \langle \Psi_j(\vec{r}) | e^{i\vec{q}\cdot\vec{r}} | \Psi_i(\vec{r}) \rangle. \end{aligned}$$

Daily Modulation: Light Mediator



Same as previous figures (top) for a light mediator DM form factor $F_{\text{DM}} = (\alpha m_e/q)^2$. Here, the contour plots show $F_{\text{DM}}^2|f(s_1)|^2$ which appears in the rate integrand; the scattering is dominated by the smallest kinematically-allowed q. **Top:** Molecular form factors with $q_z = 0$ and rate modulations for $m_\chi = 2$ MeV. **Bottom:** Molecular form factors with $q_z = 0$ and rate modulations for $m_\chi = 100$ MeV.

Local DM Phase Space



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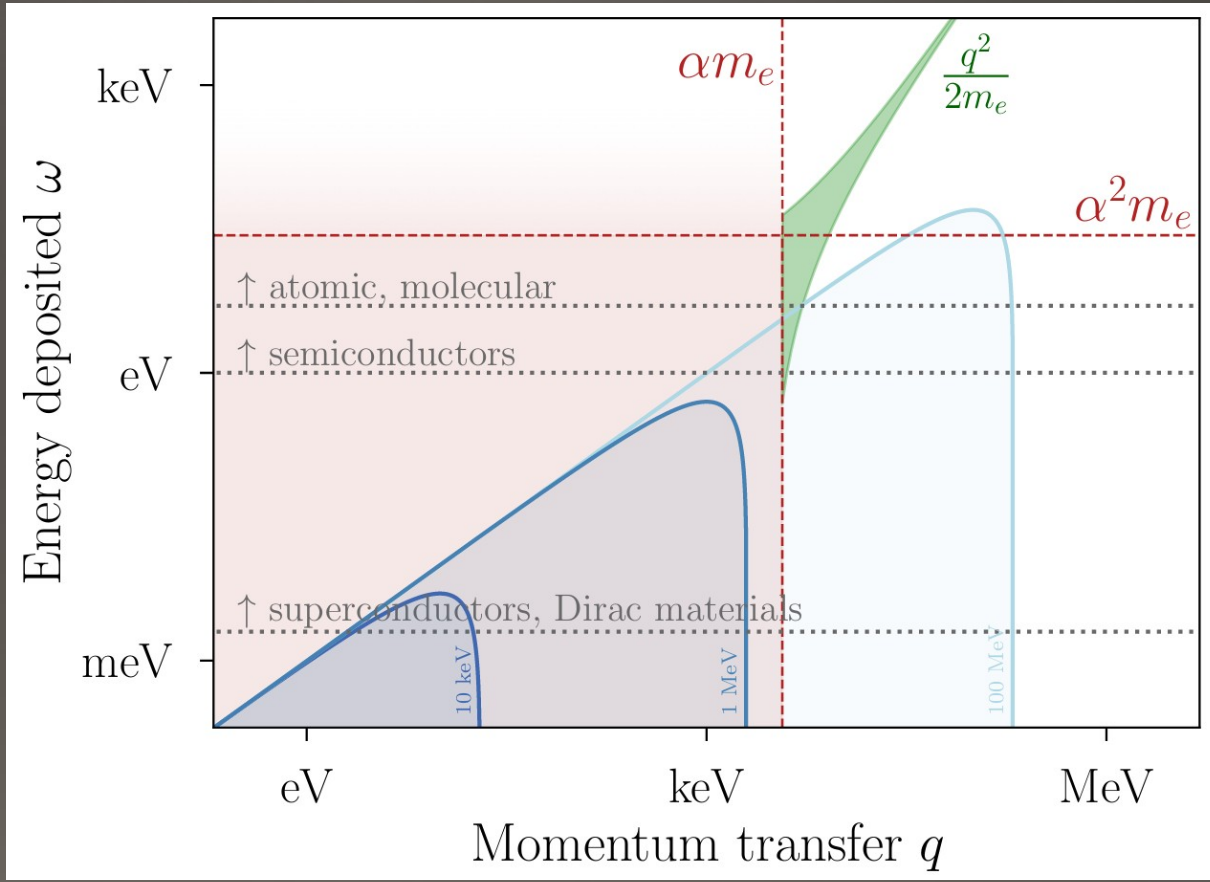

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