The Glaring Problem: Dark Matter (DM)

Cosmic Microwave Background
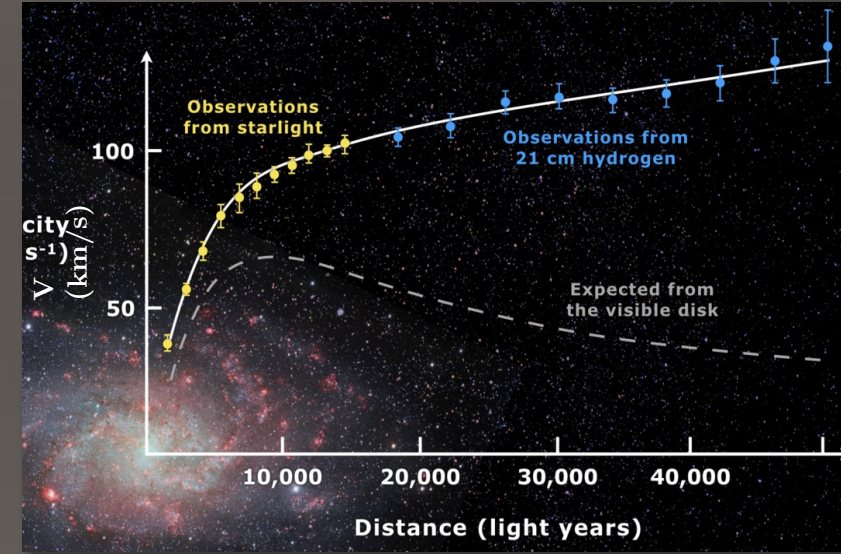### cold *non-interacting* fluid
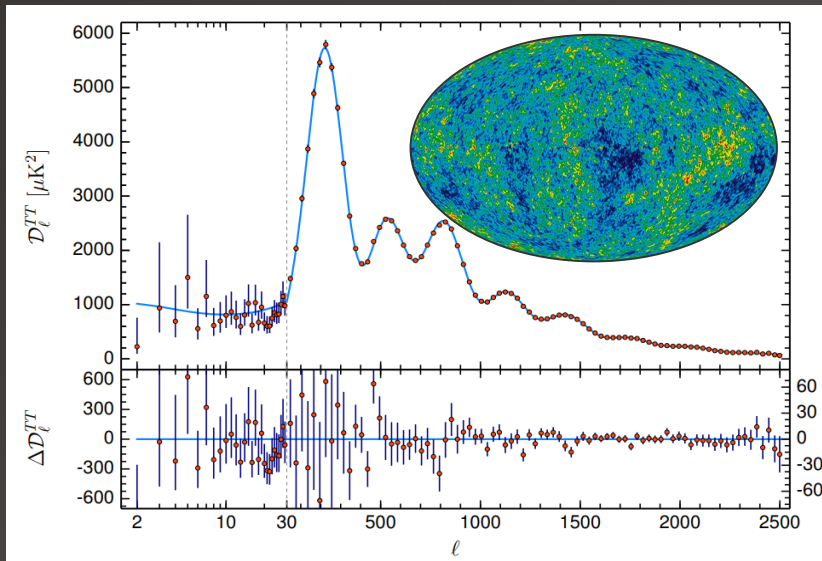
ESA and the Planck Collaboration 2020

Bullet cluster
dark and *visible* components separate

X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; D.Clowe et al.;
Lensing Map: NASA/STScI; D.Clowe et al.

Galactic rotation curves
invisible gravitating mass

Corbelli & Salucci, MNRAS 1999
Bosma, Astronomical Journal, 1989

"...we must *delve deep*... and *search wide*, to explore as much motivated DM parameter space as possible."
Report of the Topical Group on Particle Dark Matter for Snowmass, arXiv:2209.07426.

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Our dark matter halo

Milky Way

Dark matter halo

We are here.

Image credit: ESO/L Calçada

Local dark matter density

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

Local dark matter velocity

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

Lighter masses $\rightarrow$ more particles

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

More particles $\rightarrow$ larger fluxes

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

What We Don't Know

Go After the Bare Minimum

Mass: How heavy and how many?

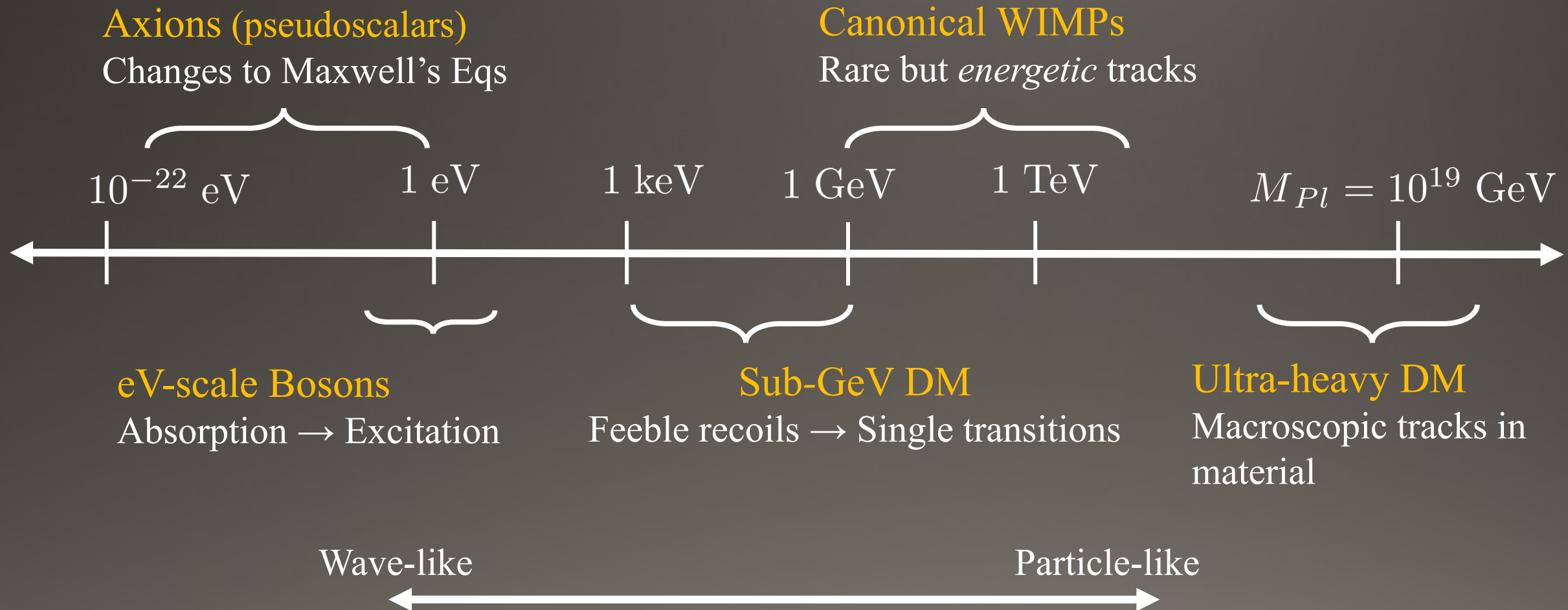Coupling: How does it interact?
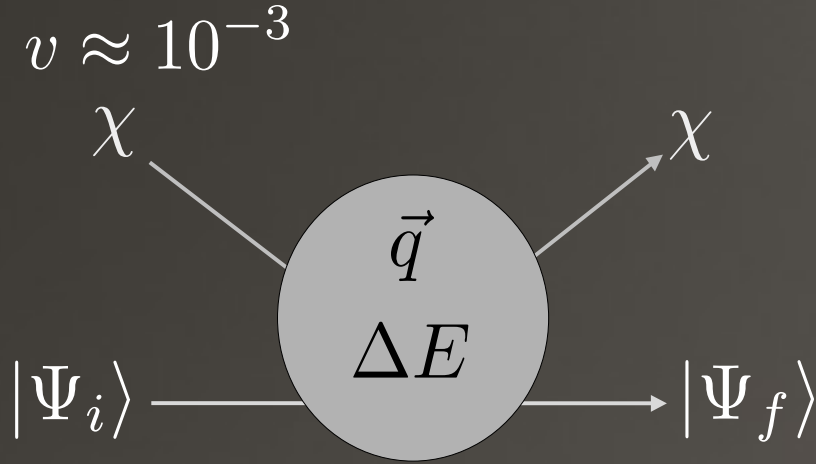
Production: How is it made?

The Method:

Bring together particle physics, condensed matter, chemistry, and astrophysics.

In brief, an *interdisciplinary* approach to the search for dark matter.
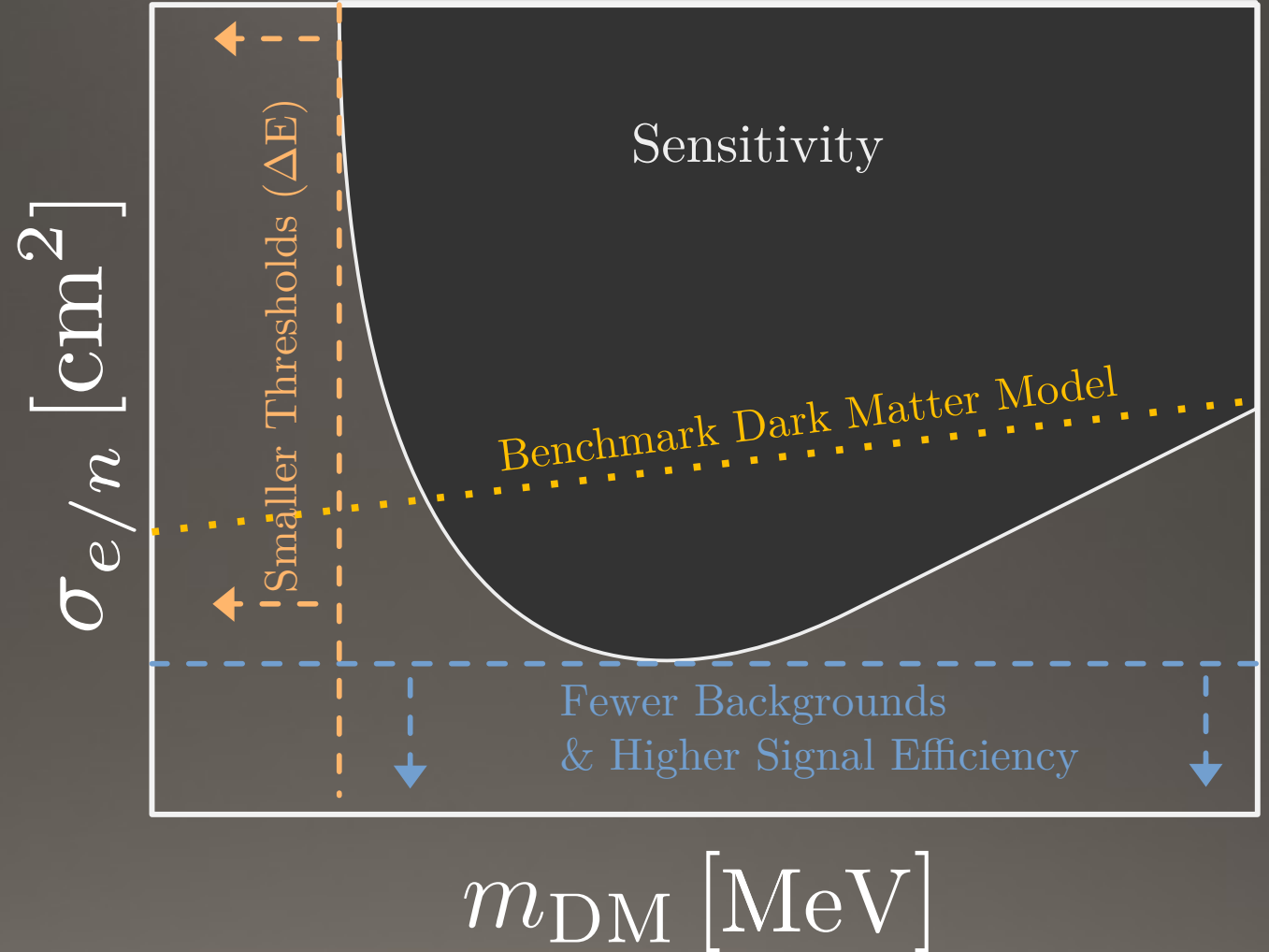
Mass Range & Detection Methods

Axions (pseudoscalars)
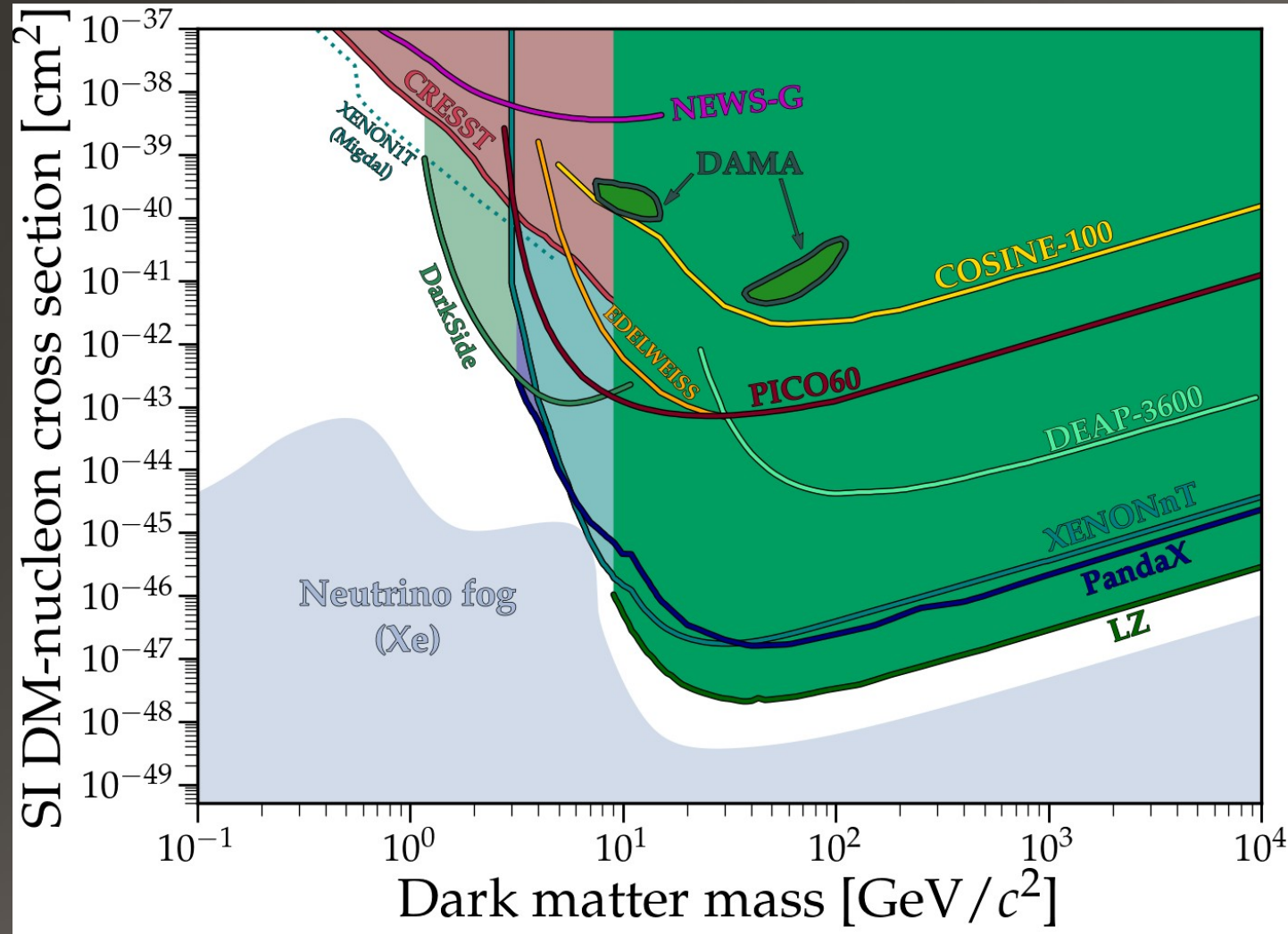Changes to Maxwell's Eqs

Canonical WIMPs
Rare but *energetic* tracks

10^{-22} eV   1 eV   1 keV   1 GeV   1 TeV $M_{Pl} = 10^{19}$ GeV

eV-scale Bosons
Absorption → Excitation

Sub-GeV DM
Feeble recoils → Single transitions

Ultra-heavy DM
Macroscopic tracks in material

Wave-like   Particle-like

How to Read These Plots

$v \approx 10^{-3}$

χ χ

$\vec{q}$

ΔE

$|\Psi_i\rangle$ $|\Psi_f\rangle$

Energy Budget

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

Momentum Budget

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

Sensitivity

Smaller Thresholds (ΔE)

Benchmark Dark Matter Model

Fewer Backgrounds
& Higher Signal Efficiency

$\sigma_{e/n}\,[\mathrm{cm}^2]$

$m_{\mathrm{DM}}\,[\mathrm{MeV}]$

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Nucleon Scattering

Plot: Ciaran O'Hare - github.com/cajohare/DirectDetectionPlots
See e.g. arXiv:2410.17036 & 2406.01705 and refs therein.

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Noble Fluid-Based

- XENON - Xe
- PandaX - Xe
- LZ - Xe
- DarkSide - Ar
- DEAP-3600 - Ar
- NEWS-G (gas) – NH_4 (H, He, Ne)

Crystal Scintillator
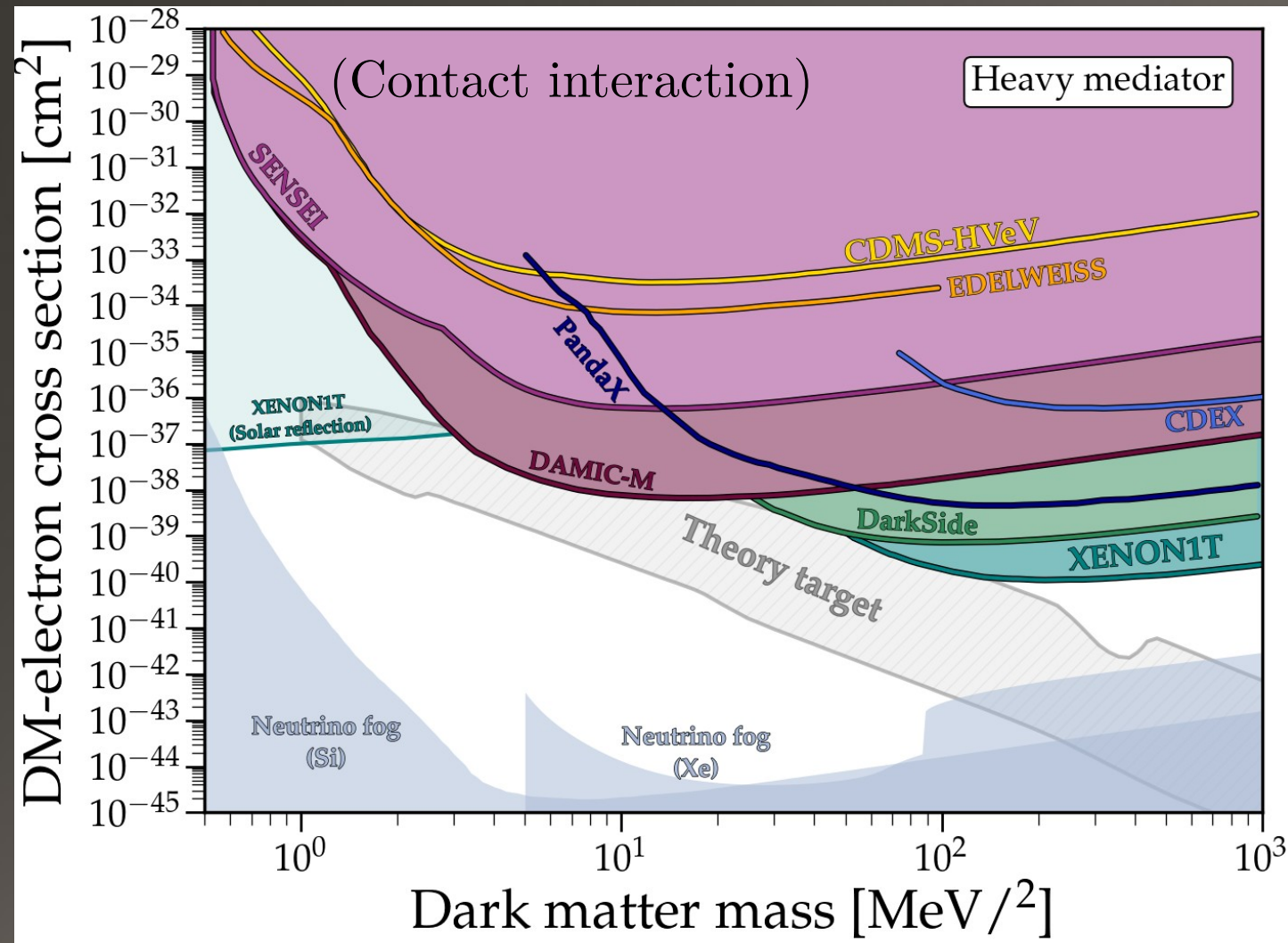
- COSINE-100 - NaI (Ti)
- CRESST – $CaWO_4$

Bubble Chamber

- PICO60 - C_3F_8

Bolometers

- CRESST – $CaWO_4$
- EDELWEISS - Ge

Electron Recoil

Plot: Ciaran O'Hare - github.com/cajohare/DirectDetectionPlots
See e.g. arXiv:2410.17036 & 2406.01705 and refs therein.

Silicon CCDs
- SENSEI
- DAMIC-M

Liquid Noble Gases
- XENON - Xe
- PandaX - Xe
- Darkside - Ar

Bolometers
- EDELWEISS - Ge
- CDMS – Ge & Si

Theory Targets
- ELDER/SIMP – Freeze out
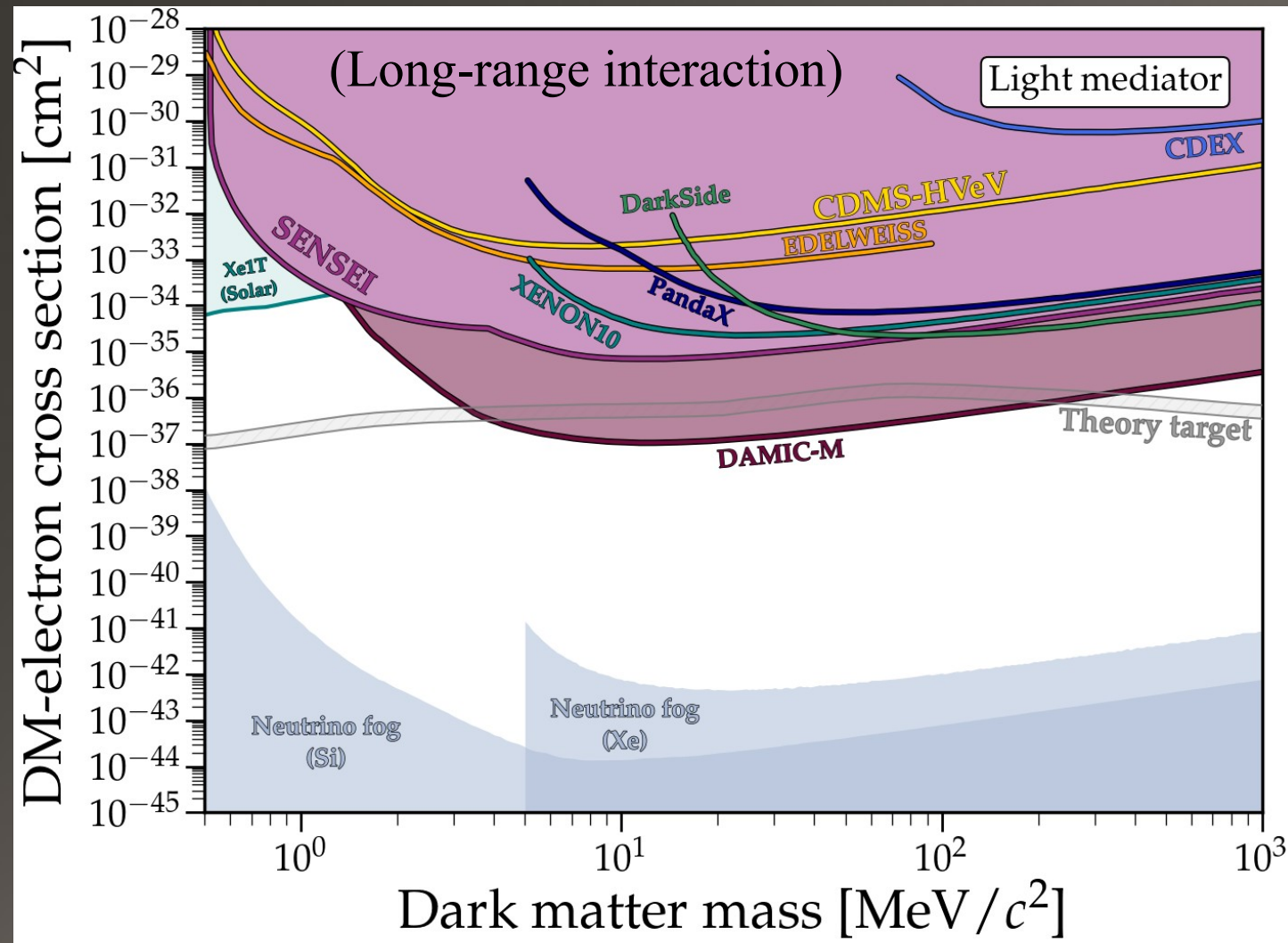
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Electron Recoil

Silicon CCDs
- SENSEI
- DAMIC-M

Liquid Noble Gases
- XENON - Xe
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- Darkside - Ar

Bolometers
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Theory Targets
- Freeze-in

Plot: Ciaran O'Hare - github.com/cajohare/DirectDetectionPlots
See e.g. arXiv:2410.17036 & 2406.01705 and refs therein.

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The Field in Context

[US Cosmic Visions: Community Report: 1707.04591]
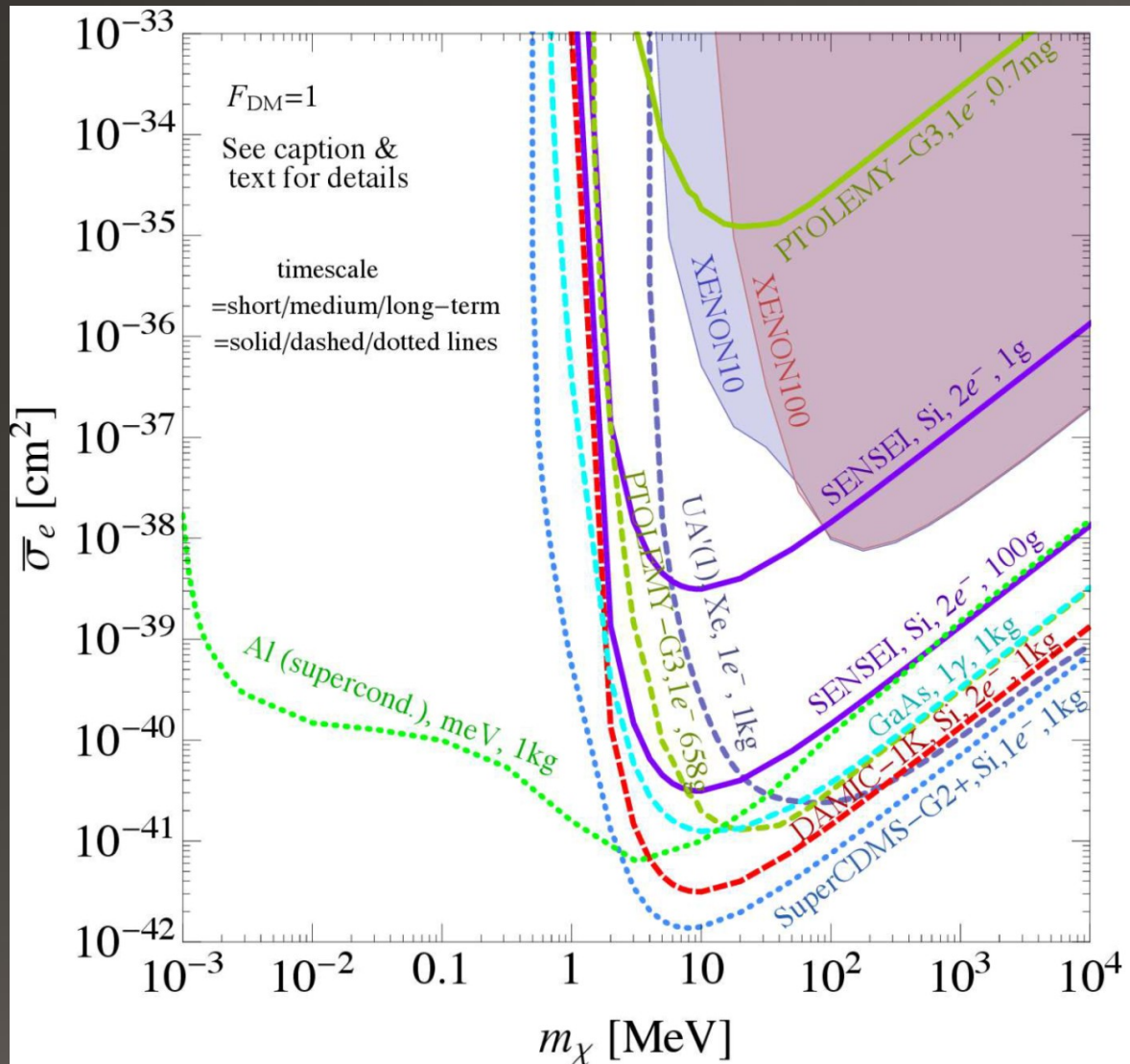
Many materials are proposed to probe the sub-GeV Space

In 2017:

Short term (2 years)

Medium term (2-5 years)

Long term

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Outlook and Potential Reach
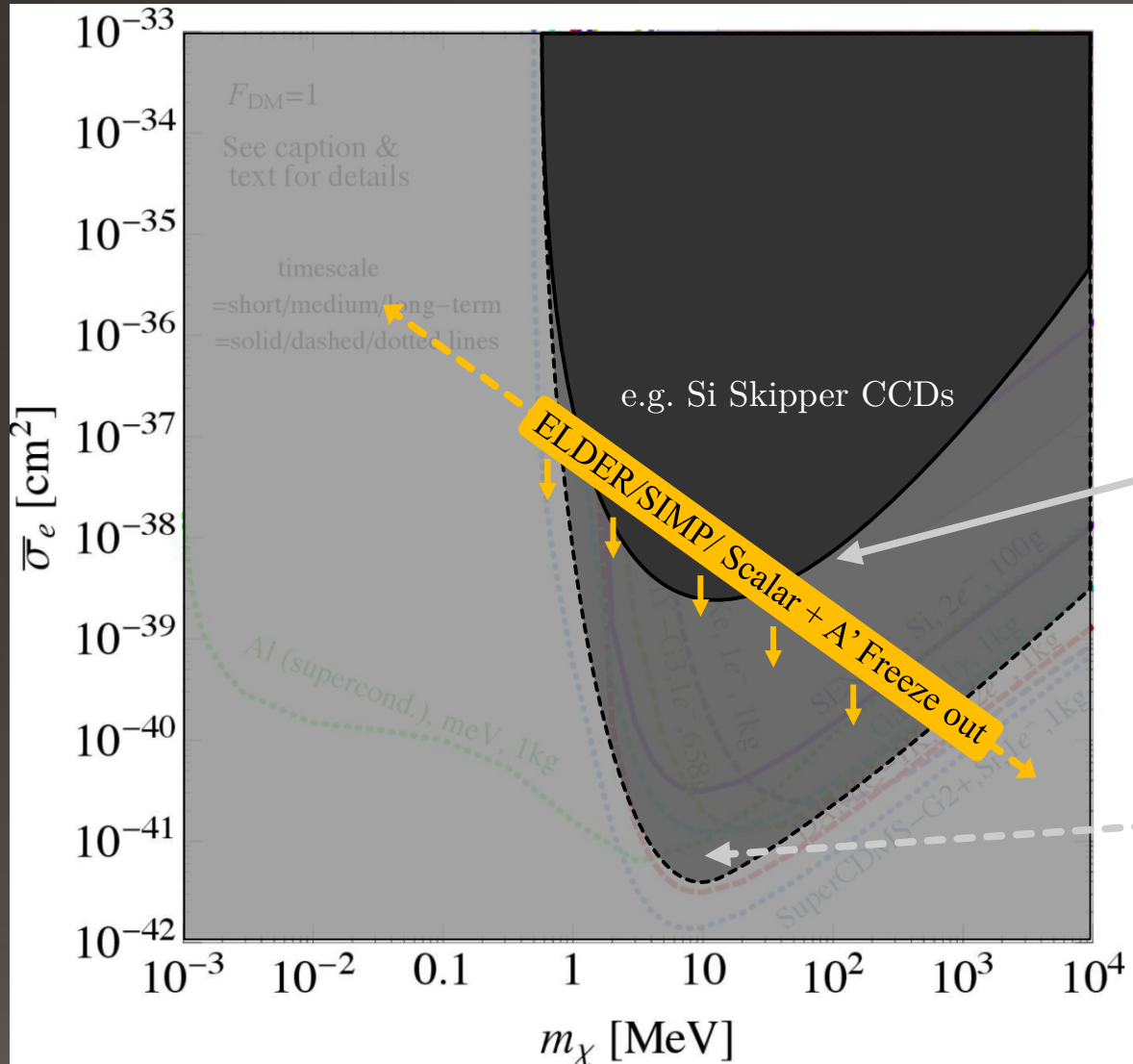
Present day:

Experimental results

Zero-background projection

e.g. Si Skipper CCDs

ELDER/SIMP/ Scalar + A' Freeze out

$F_{DM}=1$

See caption & text for details

timescale =short/medium/long−term =solid/dashed/dotted lines

[US Cosmic Visions: Community Report: 1707.04591]

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Outlook and Potential Reach

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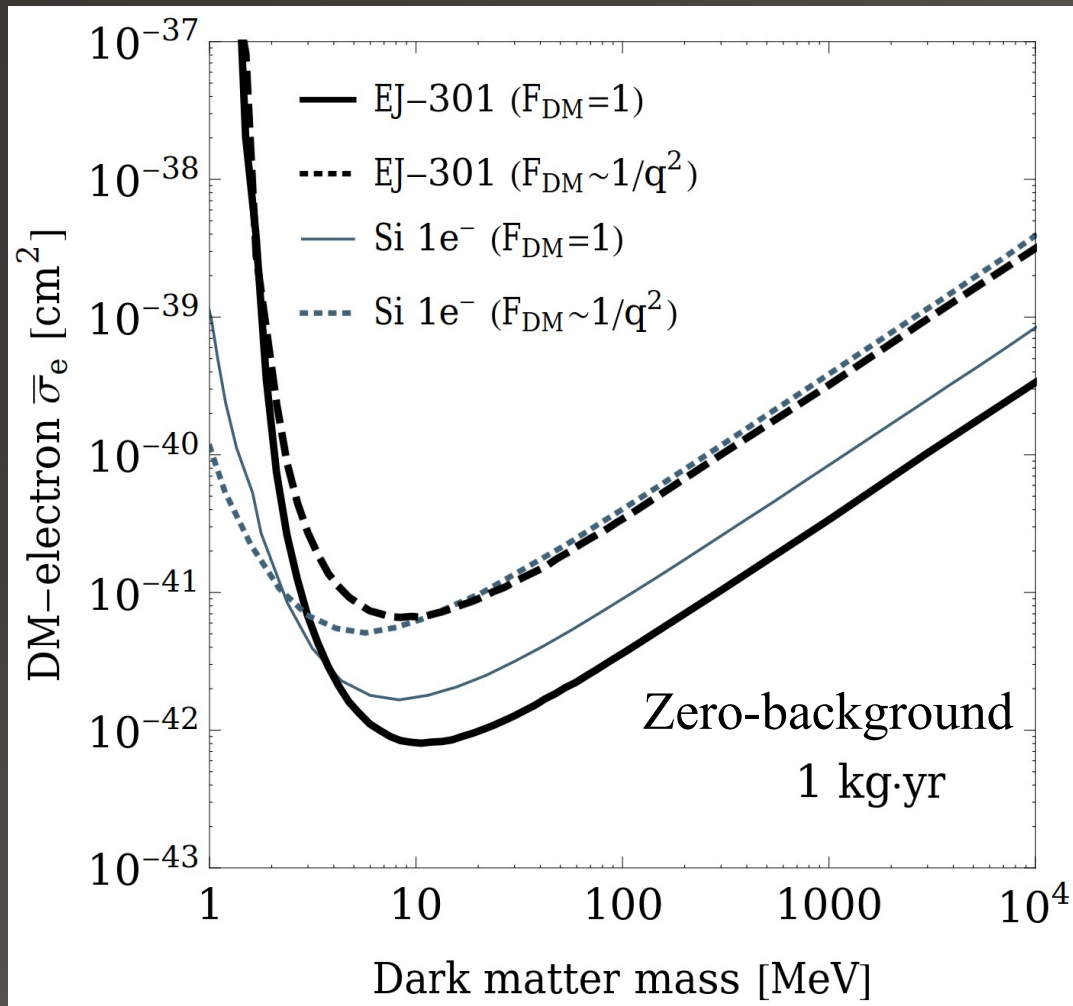
The obstacle

Backgrounds

4 orders of magnitude of potential reach awaiting

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

Directional Detection
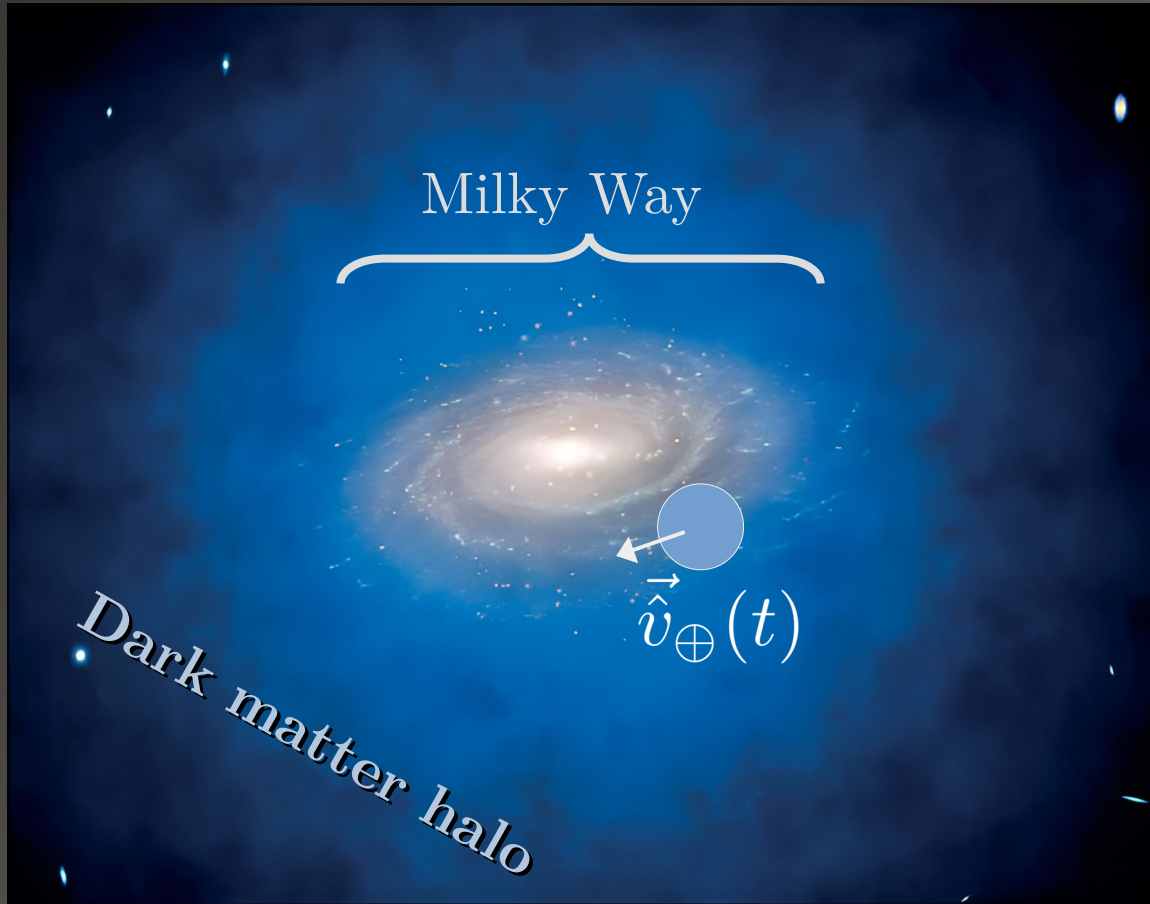
Effective dark matter "wind" from relative motion

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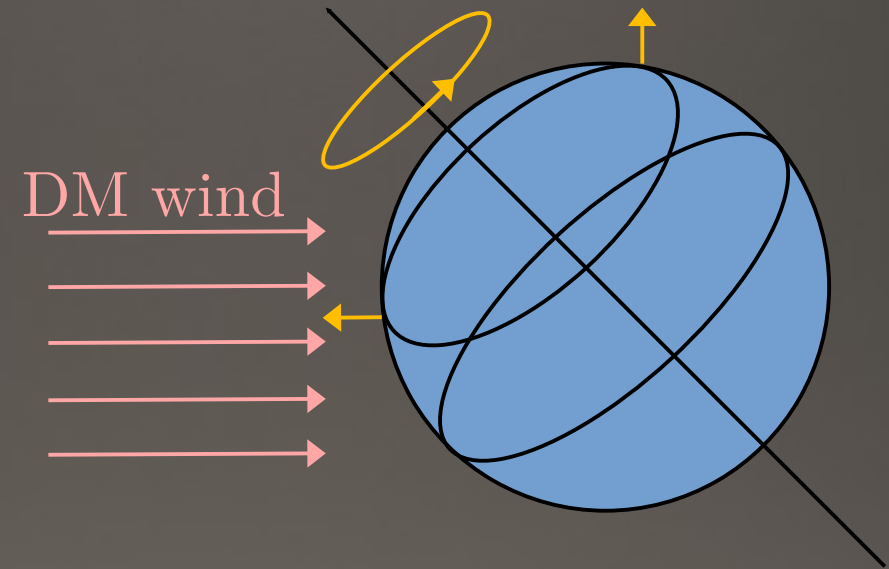
Change in relative orientation between detector and dark matter wind leads to *daily modulation*

Milky Way

$\vec{\hat{v}}_{\oplus}(t)$

Dark matter halo

Towards a Directional Detector
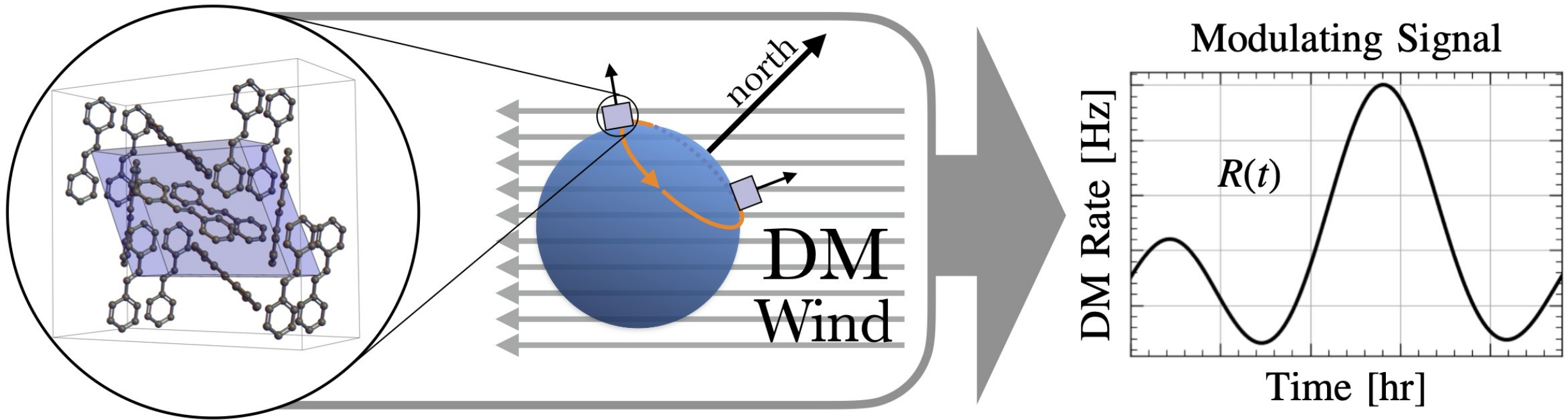
Modulating signals improve sensitivity by about two orders of magnitude and provide the potential for discovery.

Fluorescence with DM

fluorescence spectra

Absorption/emission Probability
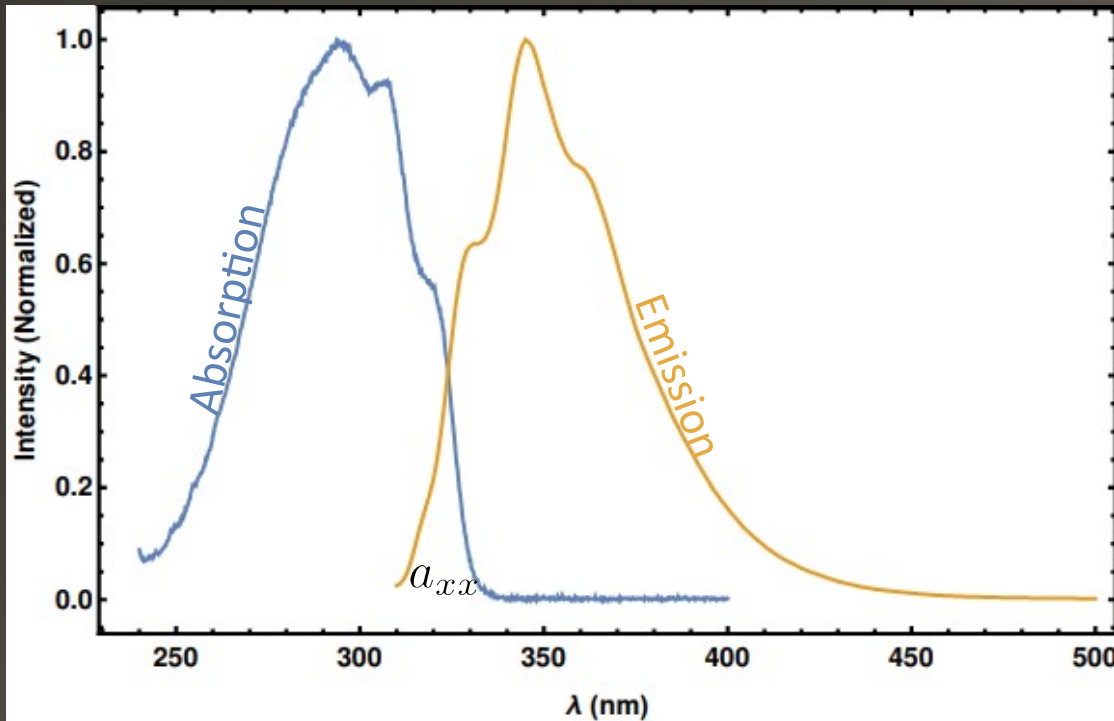
Decreasing energy (E) $\rightarrow$

: Chromophore:

χ

γ

detectable

re-abs

$\leftarrow$ Detector volume ~1L $\rightarrow$
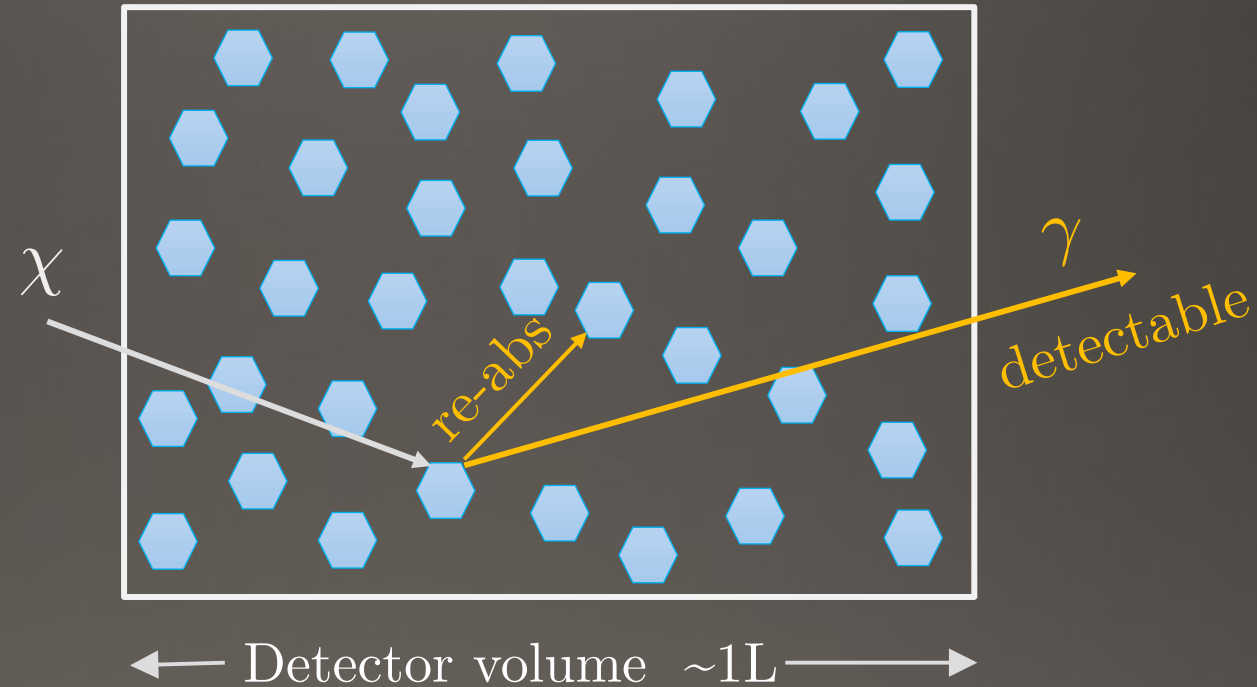
Probability for the photon to free stream

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

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Luminescent Detectors

Energy

S_1 3 2 1 0 $|\Psi_f\rangle$

$h\nu$

(radiative de-excitation)

S_0 3 2 1 0 $|\Psi_i\rangle$

Fluorescence

(Singlet transitions)
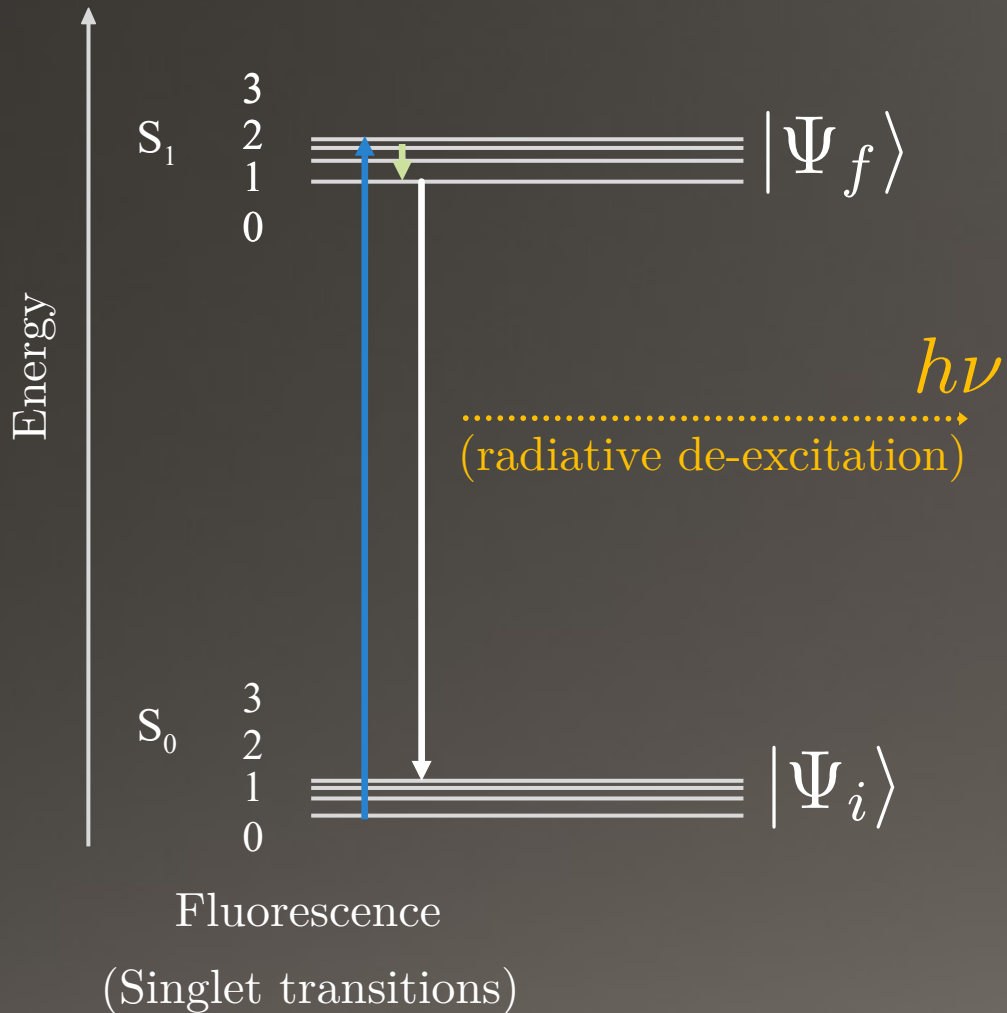
Energy Scale

$$\Delta E \approx \mathcal{O}(\text{eV})$$

Momentum Scale

$$q \sim \alpha m_e \approx \mathcal{O}(\text{keV})$$

Disambiguation*

Scintillation: Initial O(keV) recoil produces *many* ionized/excited states. These quickly deexcite, producing photons.

Fluorescence: Initial O(eV) recoil produces *single* excited state, which deexcites, producing single photon.

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First Target Candidate: Trans-Stilbene

Carman, et.al. '18 (J. of Crystal Growth)
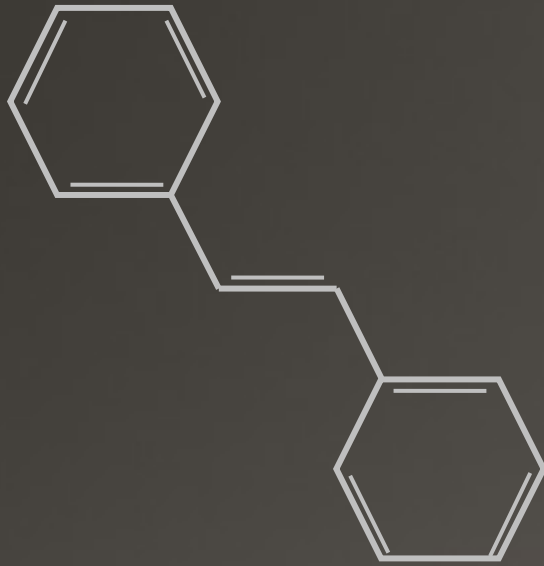
De-localized and planar network of double bonds
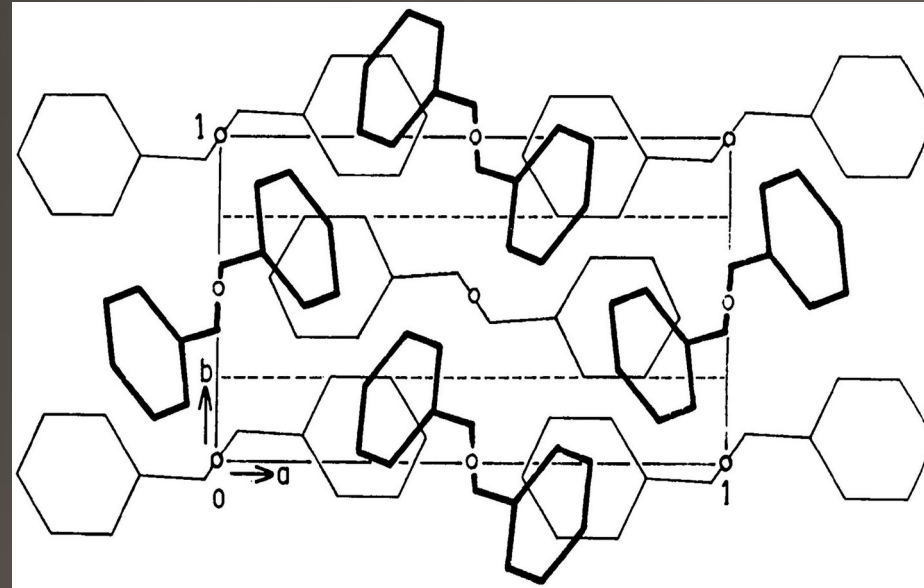
Molecular planes oriented in crystal lattice

Large optical-quality crystals

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Looking for Daily Modulation

Credit: Benjamin Lillard

https://github.com/blillard/vsdm
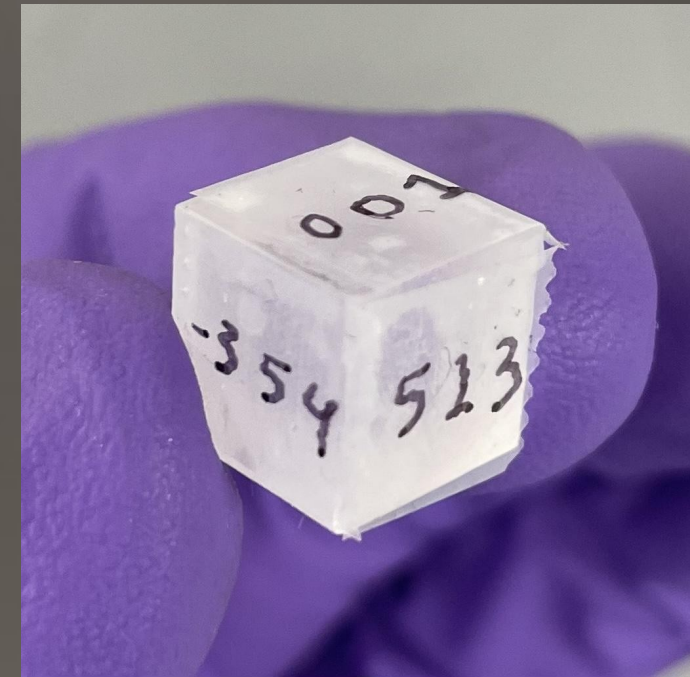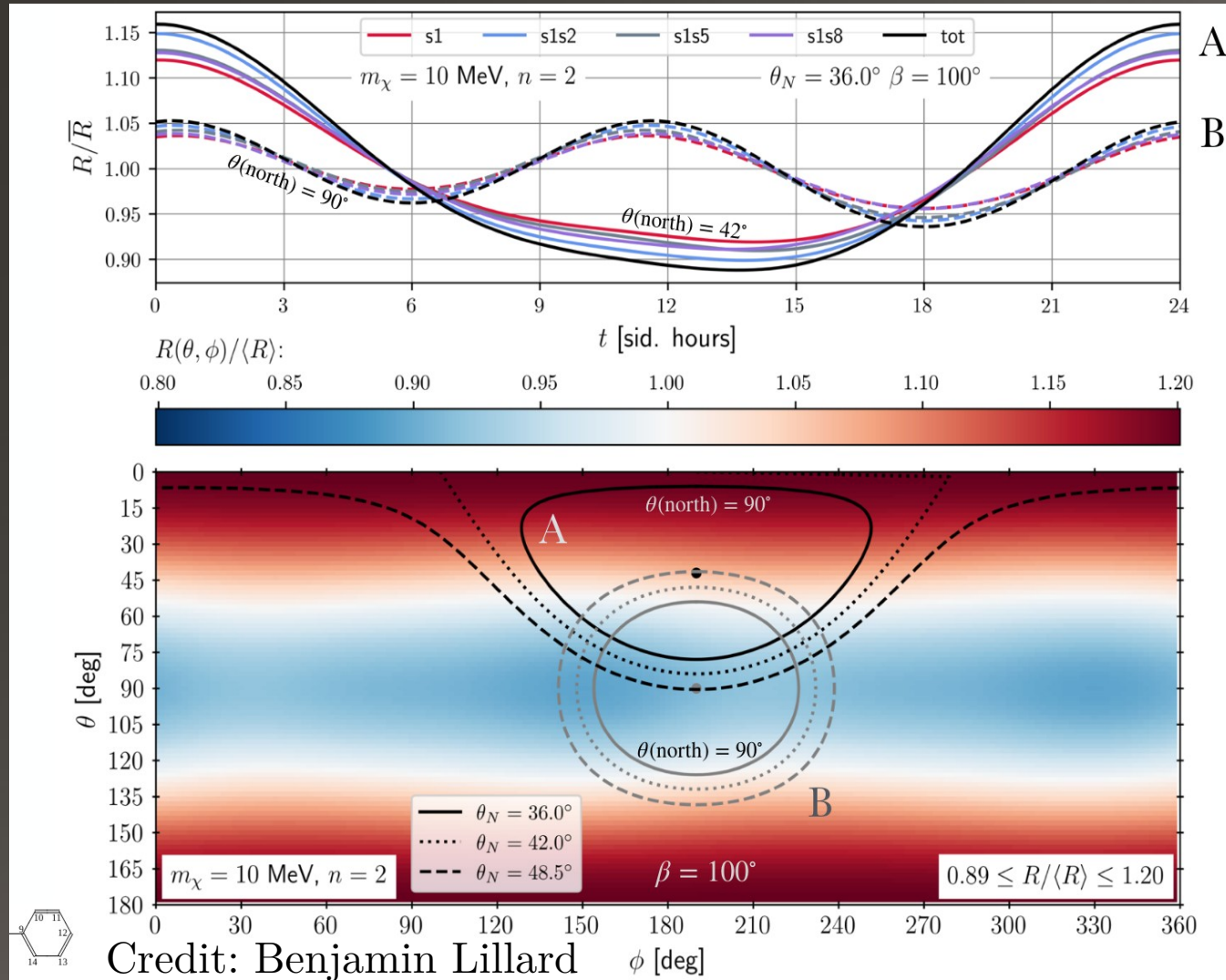
Different trajectories through rotation angles give distinct waveforms and phases. We can use the same crystal in many orientations or many different crystals.

Daily Modulation

(Contact interaction)
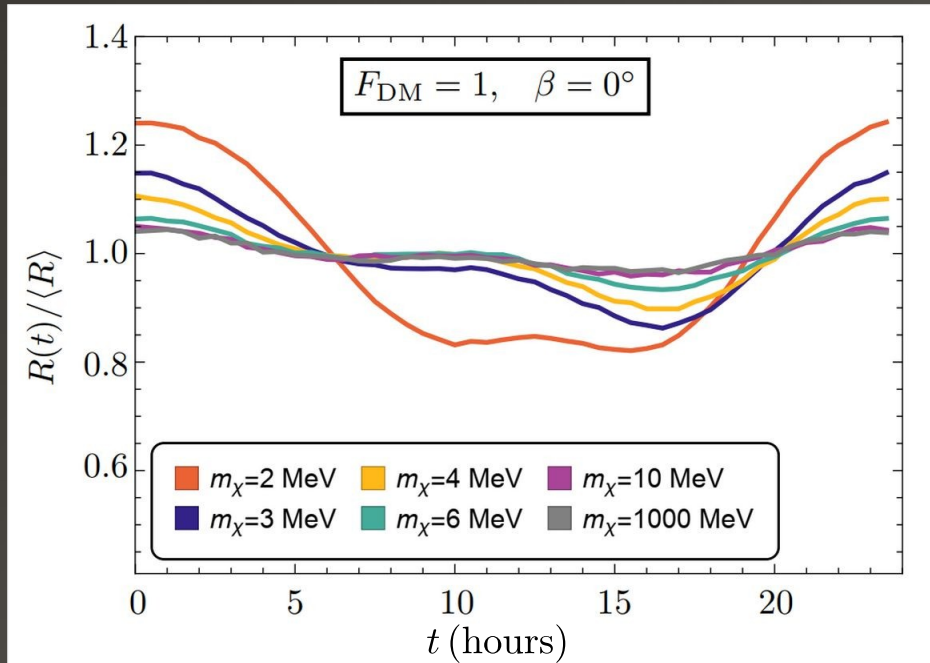
(Long-range interaction)

$F_{DM} = 1, \quad \beta = 0°$

$F_{DM} \propto 1/q^2, \quad \beta = 0°$

Legend:
- $m_\chi = 2$ MeV
- $m_\chi = 3$ MeV
- $m_\chi = 4$ MeV
- $m_\chi = 6$ MeV
- $m_\chi = 10$ MeV
- $m_\chi = 1000$ MeV

[CB, Kahn, Lillard, McDermott: 2103.08601]
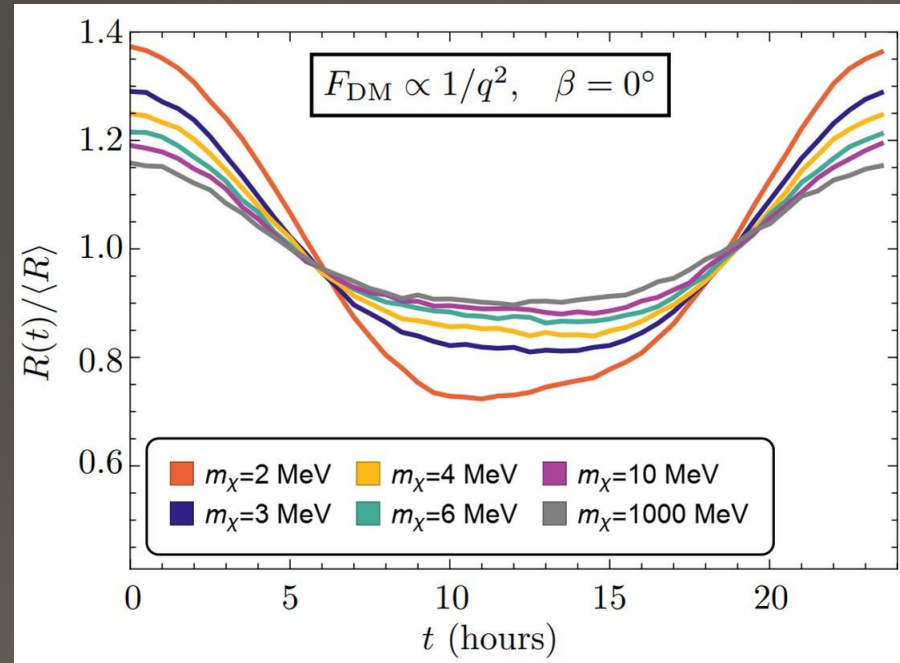
Predicted rate changes by up to 70% throughout the day.

That's a verifiable signal!

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

$$f_{RMS} = [5\% - 25\%]$$

$$N_\sigma \sim f_{RMS} \sqrt{N_{events}}$$

Sensitivity & Reach
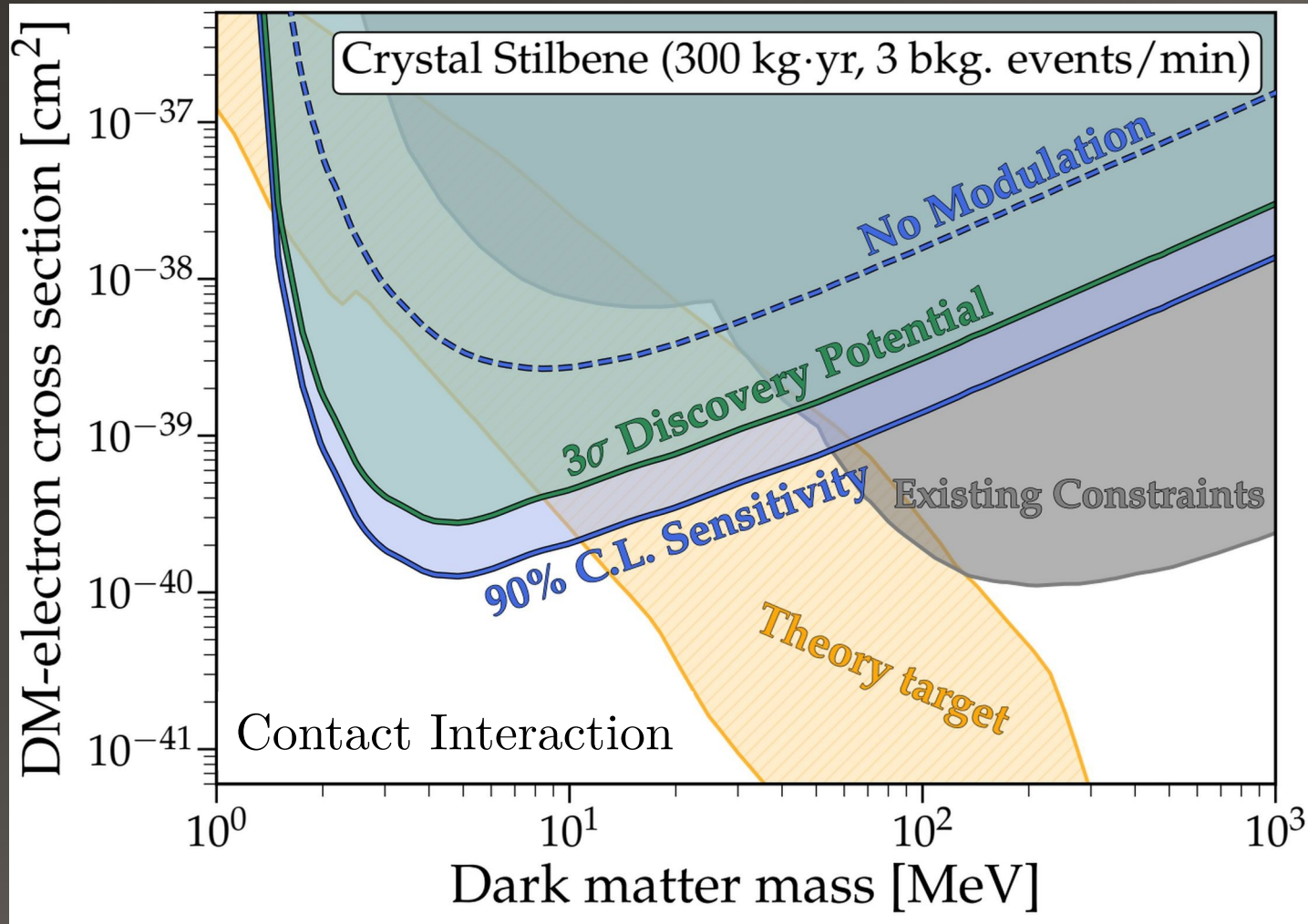
Assuming realistic backgrounds

Exclusion w/o modulation

Discovery potential w/ mod.

Exclusion w/ modulation

100 kg t-stilbene crystals exposed for 3 years w/ background rate of 3 events/min dominated by radioactivity of ^{14}C, Th, & U.

Consistent w/ Borexino ^{14}C/^{12}C ~ 10^{-18} (0.01/min/kg)

Characterizing t-stilbene

Calibrate at mg-scale
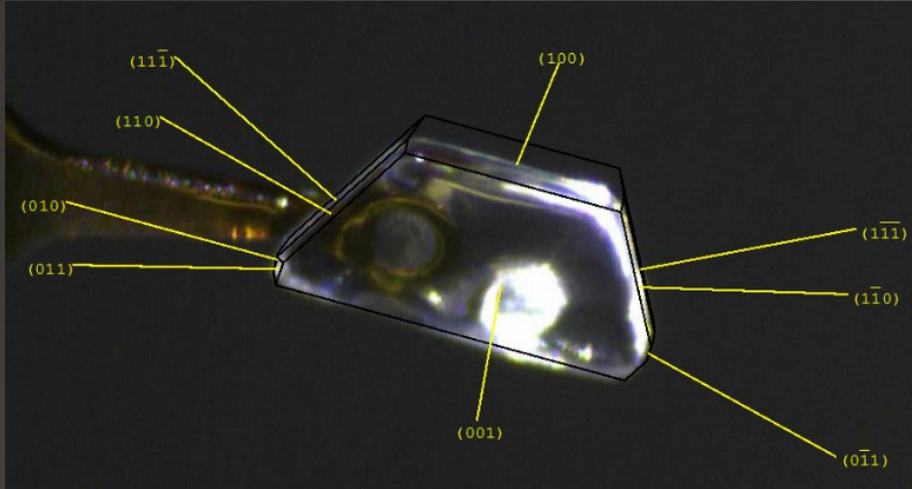
Credit: Dane Johnson
Freedman Group (MIT)

Natalia Zaitseva (LLNL)

Deploy up to kg-scale
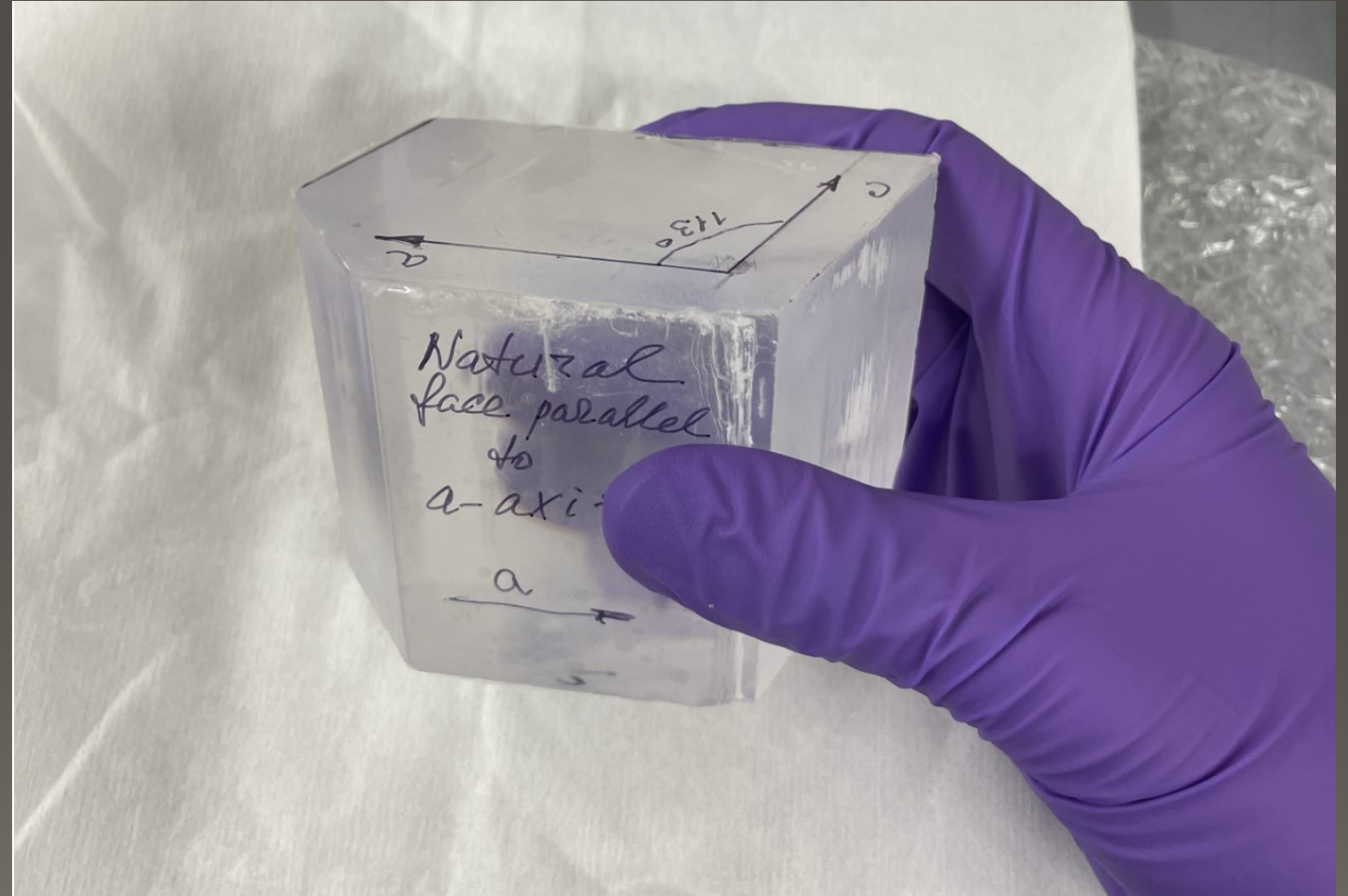
Experimental Deployment

DIANA*

Daily modulation in an Intrinsically ANisotropic Array
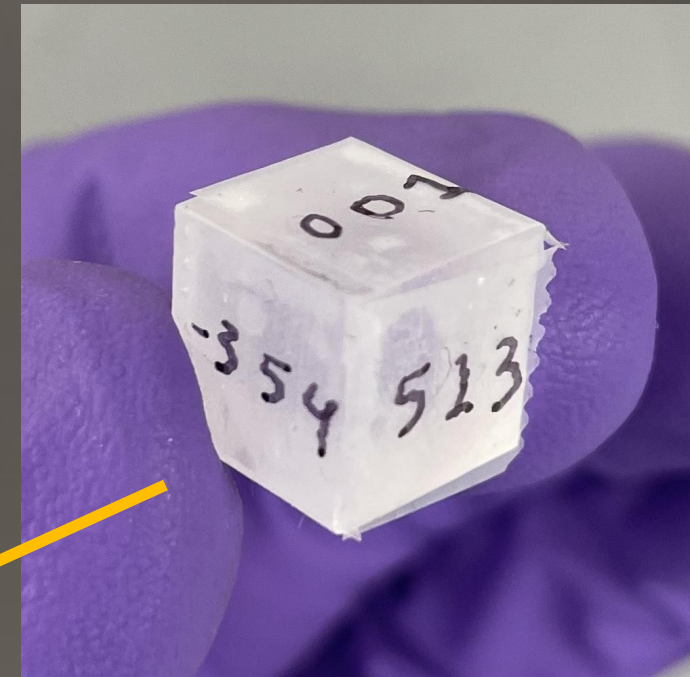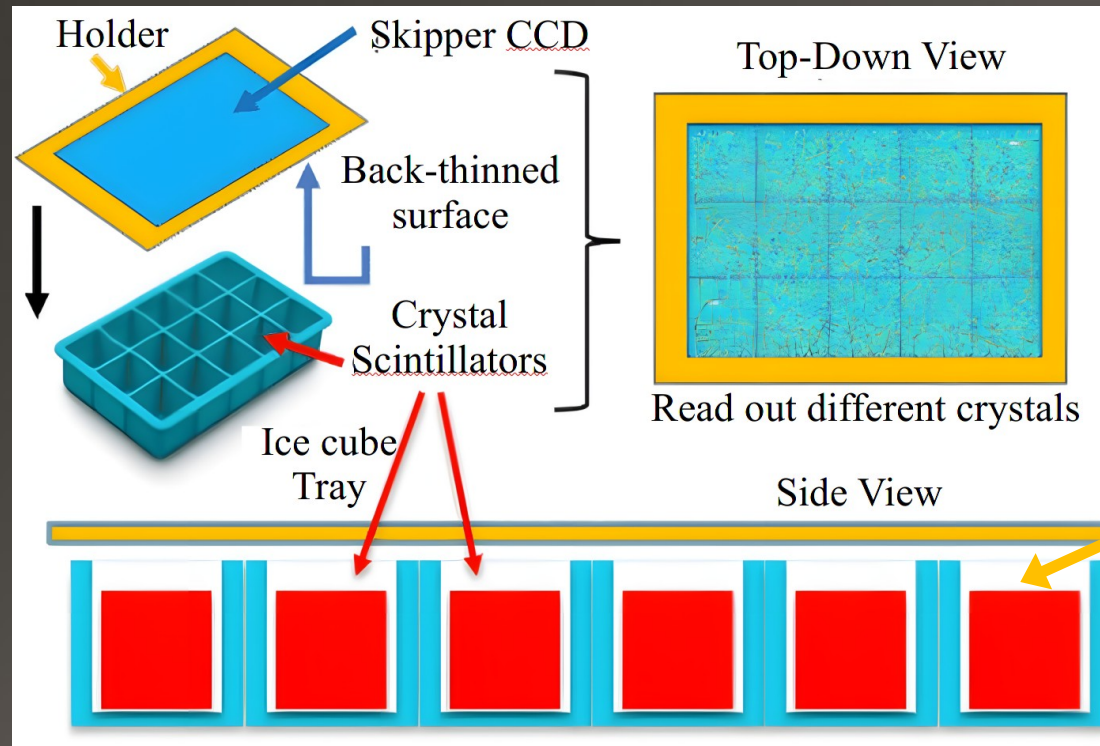
Many crystal samples can be read out by a single skipper CCD.

Collaboration: FermiLab, U. Toronto, MIT, UIUC, U. Oregon, Penn State

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Astro-Skipper CCDs as Readout

Taking pictures of crystals with a *very* sensitive CCD

Skipper CCD Measurements of trans-Stilbene
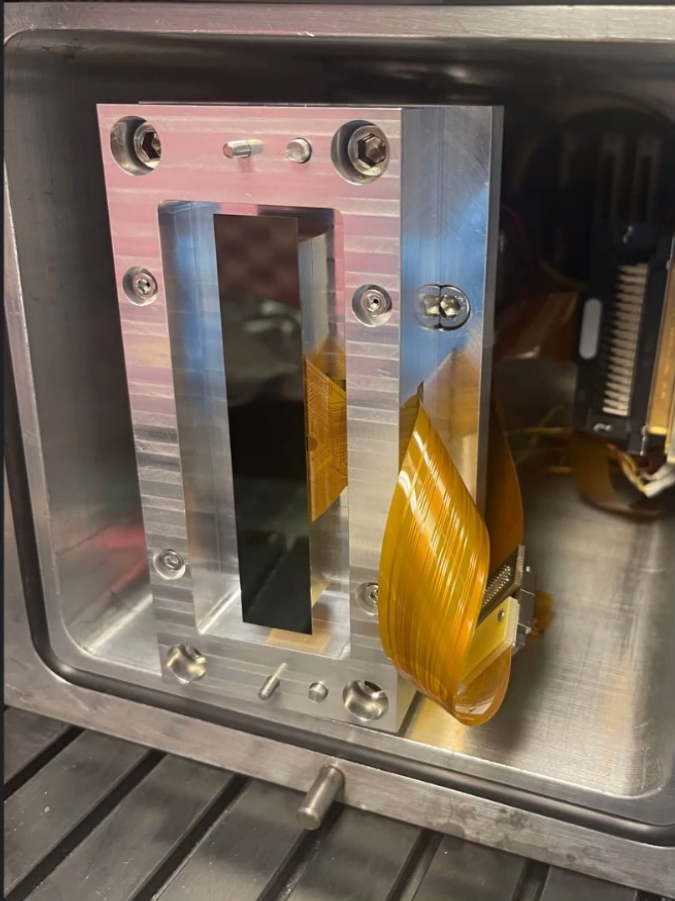
Daniel Baxter, Alex Drlica-Wagner, Edgar Marrufo, Brandon Roach

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Calibrating Anisotropic Materials

Calibration of Anisotropy via Photoabsorption

Dark Matter Scattering

$$\sigma_e \sim |f_{i \to f}(\mathbf{q})|^2 = |\langle \Psi_f | e^{i\mathbf{q}\cdot\mathbf{r}} | \Psi_i \rangle|^2$$

$$\approx |\mathbf{q} \cdot \langle \Psi_f | \mathbf{r} | \Psi_i \rangle|^2$$

UV photon absorption

$$\sigma_{\mathrm{UV}} \sim (E_f - E_i)\, |\vec{\epsilon} \cdot \langle \Psi_f | \mathbf{r} | \Psi_i \rangle|^2$$

$$A_{\mathrm{UV}} \sim n_{\mathrm{mol}} |\vec{\epsilon} \cdot \langle \Psi_f | \mathbf{r} | \Psi_i \rangle|^2$$
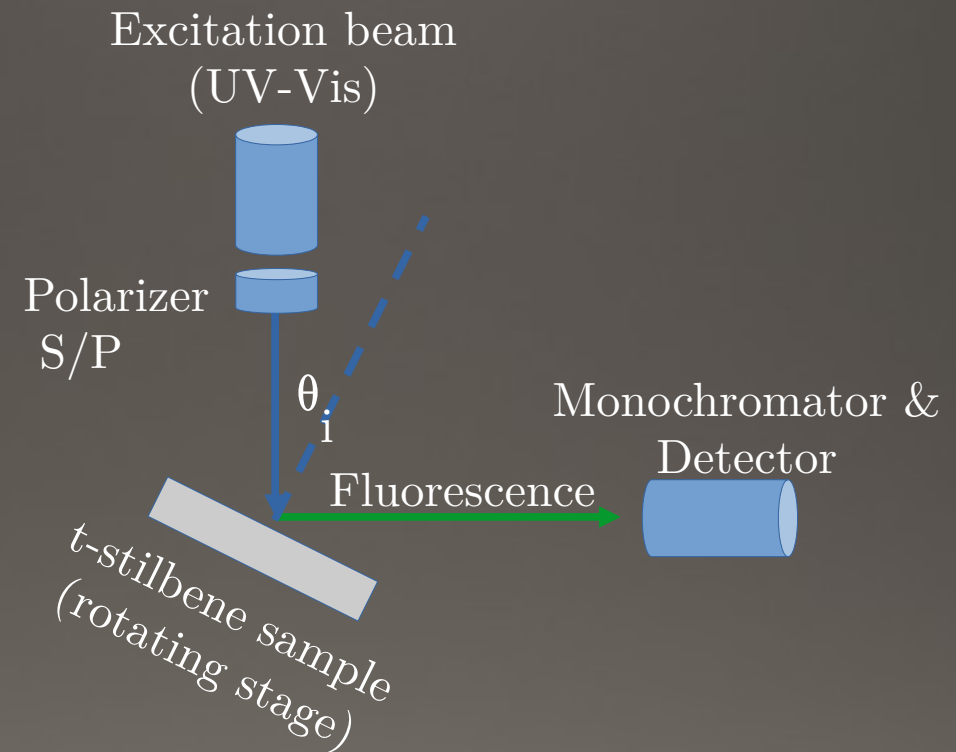
Polarization is a proxy for DM momentum

Excitation beam (UV-Vis)

Polarizer S/P

θ_i

Monochromator & Detector

Fluorescence

t-stilbene sample (rotating stage)

Calibrating Anisotropic Materials

Calibration of Anisotropy via Photoabsorption
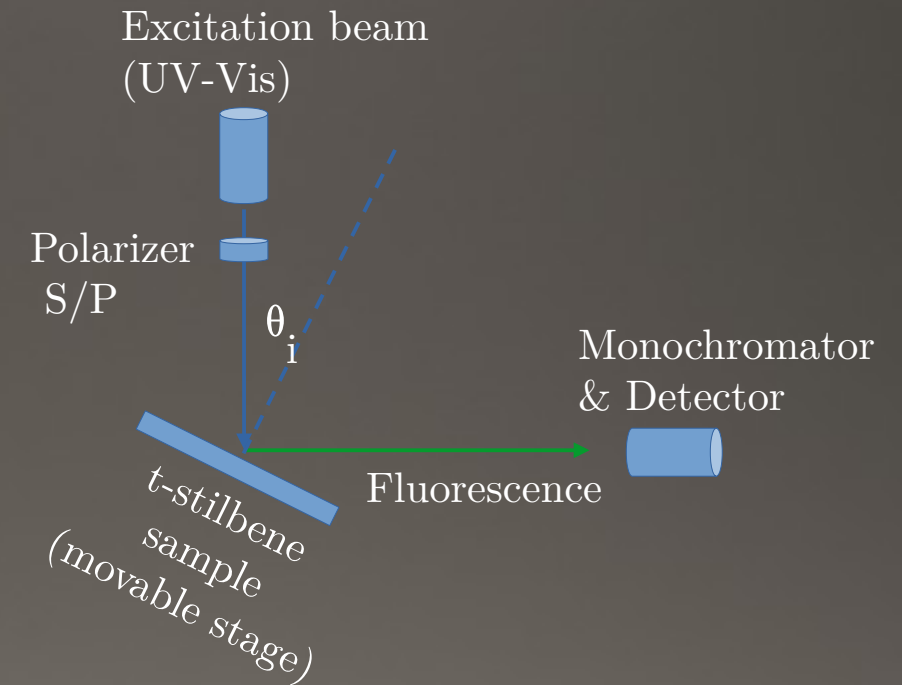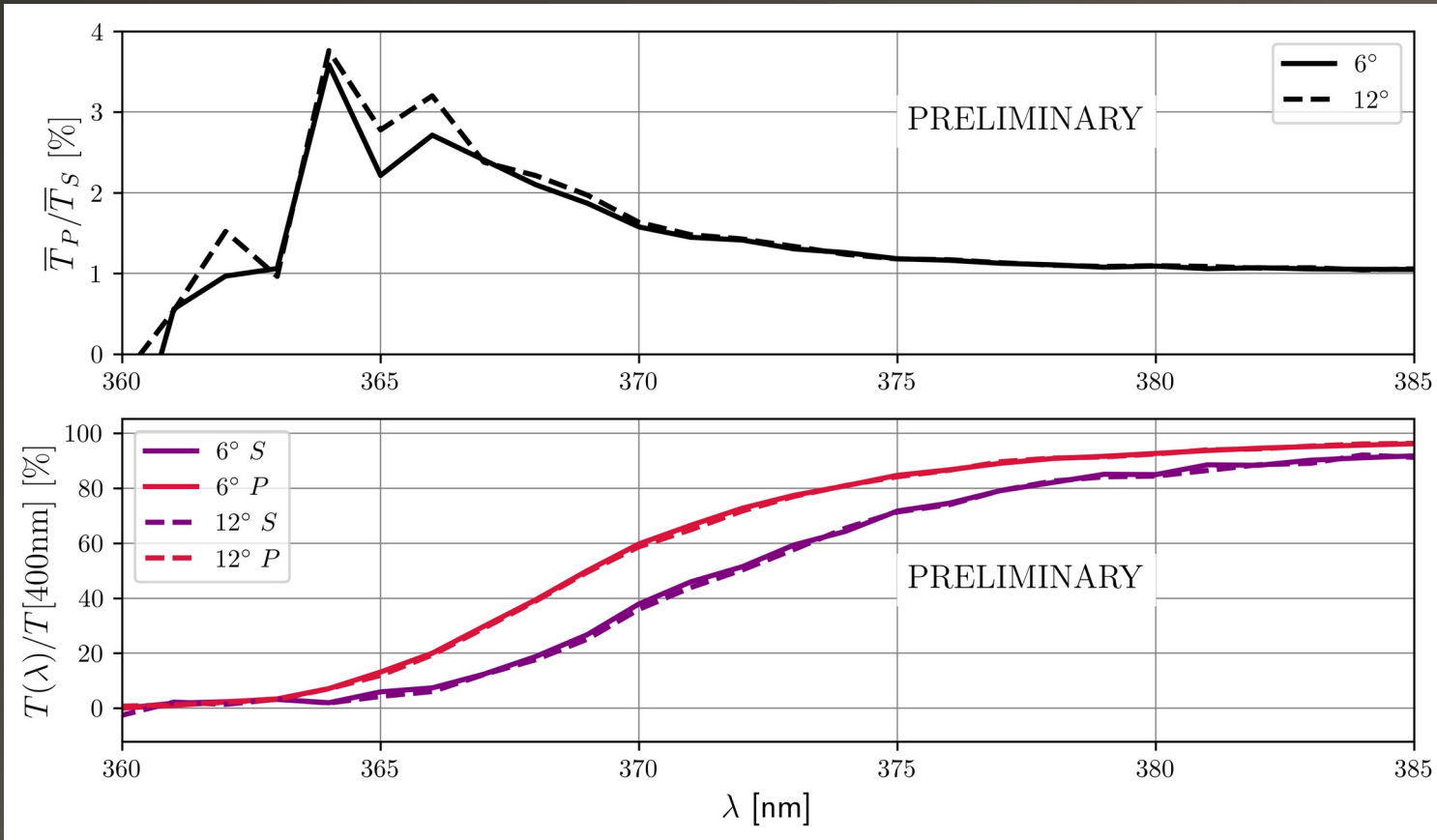
$$A_{\mathrm{UV}} \sim n_{\mathrm{mol}} |\vec{\epsilon} \cdot \langle \Psi_f | \mathbf{r} | \Psi_i \rangle|^2 \qquad A_{\mathrm{UV}} \approx \mathrm{const} - T_{\mathrm{UV}}$$

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Migdal in Liquid Noble Gas TPCs
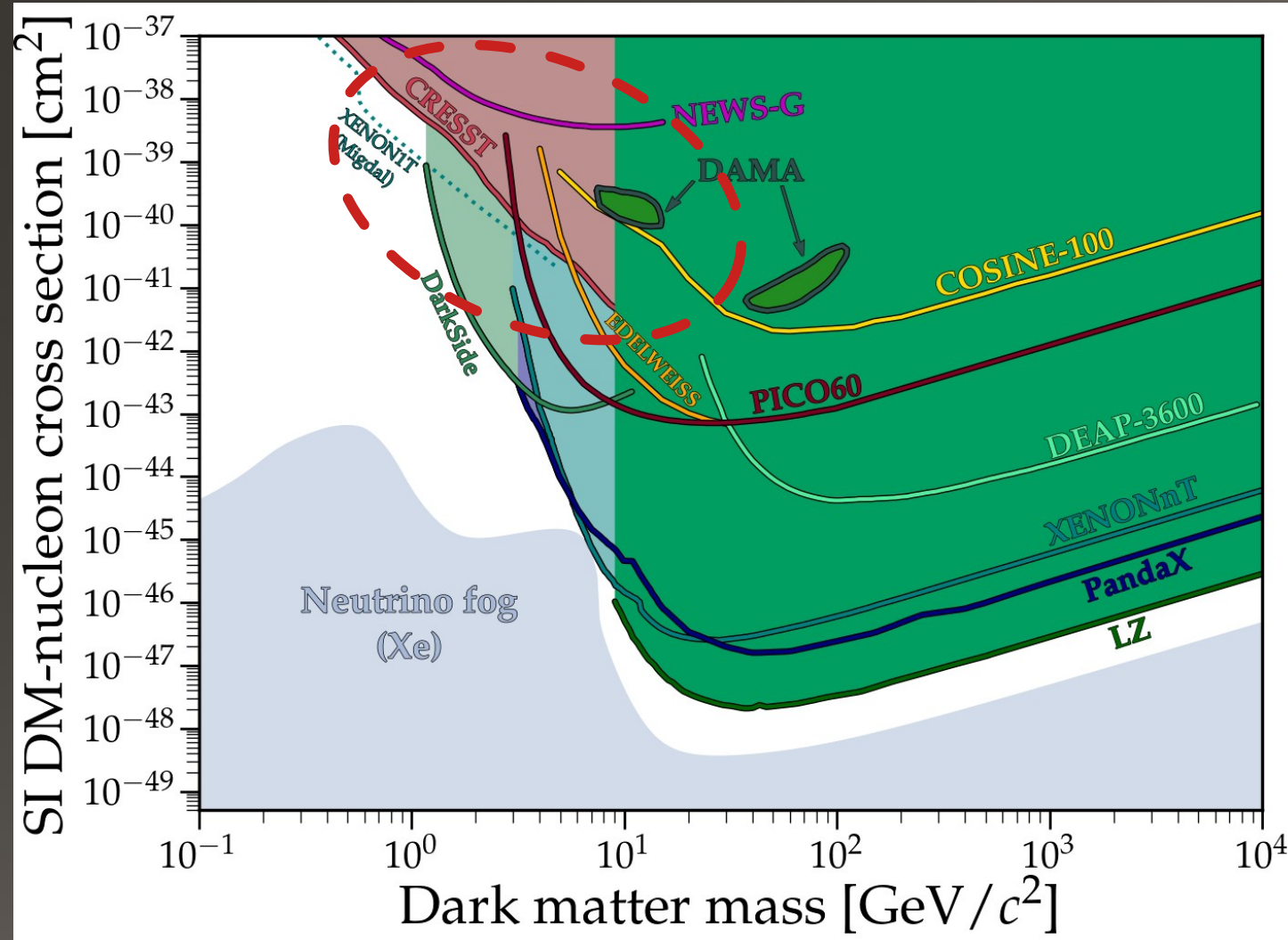
Migdal effect extends sensitivity from few GeV to 100s MeV

Plot: Ciaran O'Hare - github.com/cajohare/DirectDetectionPlots
See e.g. arXiv:2406.01705 & 1907.12771 and refs therein.

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Ionizing Atoms Through Nuclear Recoil: Migdal Effect

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

$$v = q/M_N$$
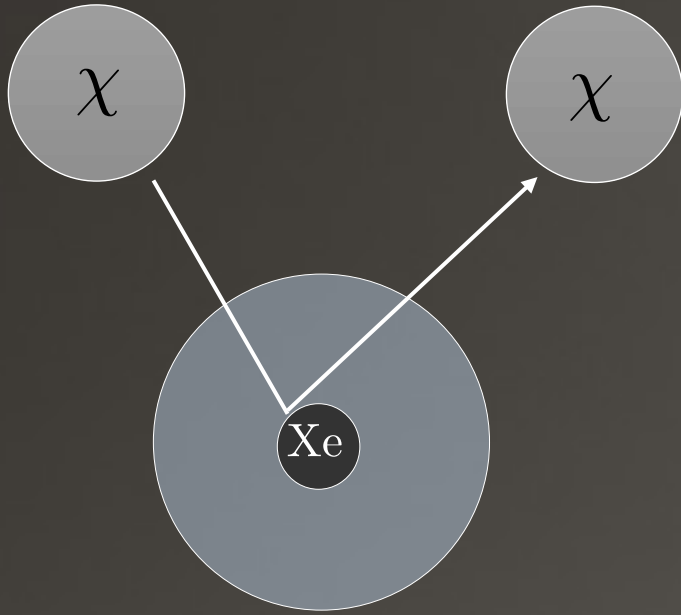
Initial nuclear recoil
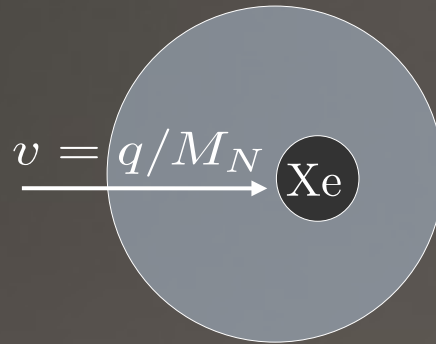
Nucleus moves faster than electrons
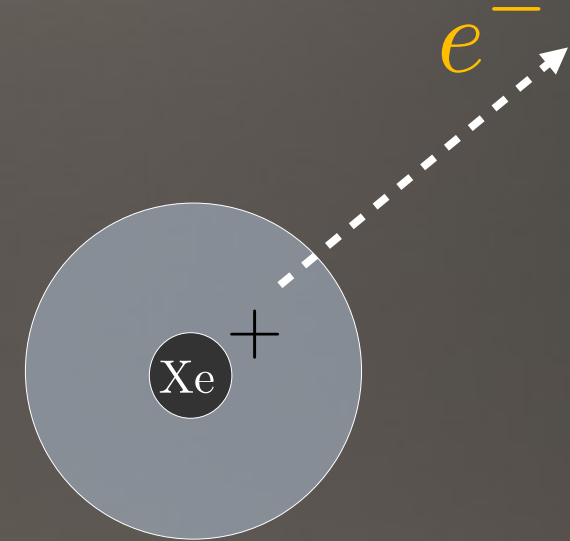
Electronic transition to ionized state

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

Kinematic *penalty*

The Migdal effect
Inelasticity extends the sensitivity of detectors to lower masses. e.g. Xenon

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The Molecular Migdal Effect(s)

Sensitivity to Nuclear Recoils

Center of mass recoil (CMR) effect

Caused by center of mass motion
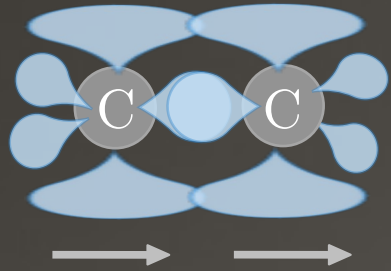
COM recoil effect is the molecular analog
of the semiclassical Migdal effect

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

Suppressed by kinematic factor due to
moving the whole molecule.

Non-adiabatic coupling (NAC) effect

Caused by relative motion
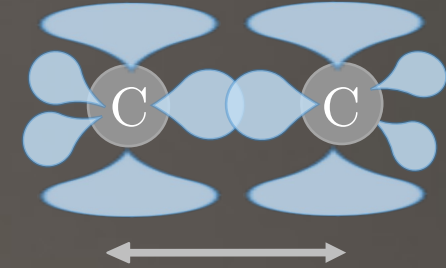
NAC caused by effects beyond
Born-Oppenheimer approximation

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

Suppressed by kinematic factor due
to moving a single atom.

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

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Directional Molecular Migdal Effect

[CB, Harris*, Kahn, Lillard, Perez-Rios: 2208.09002]
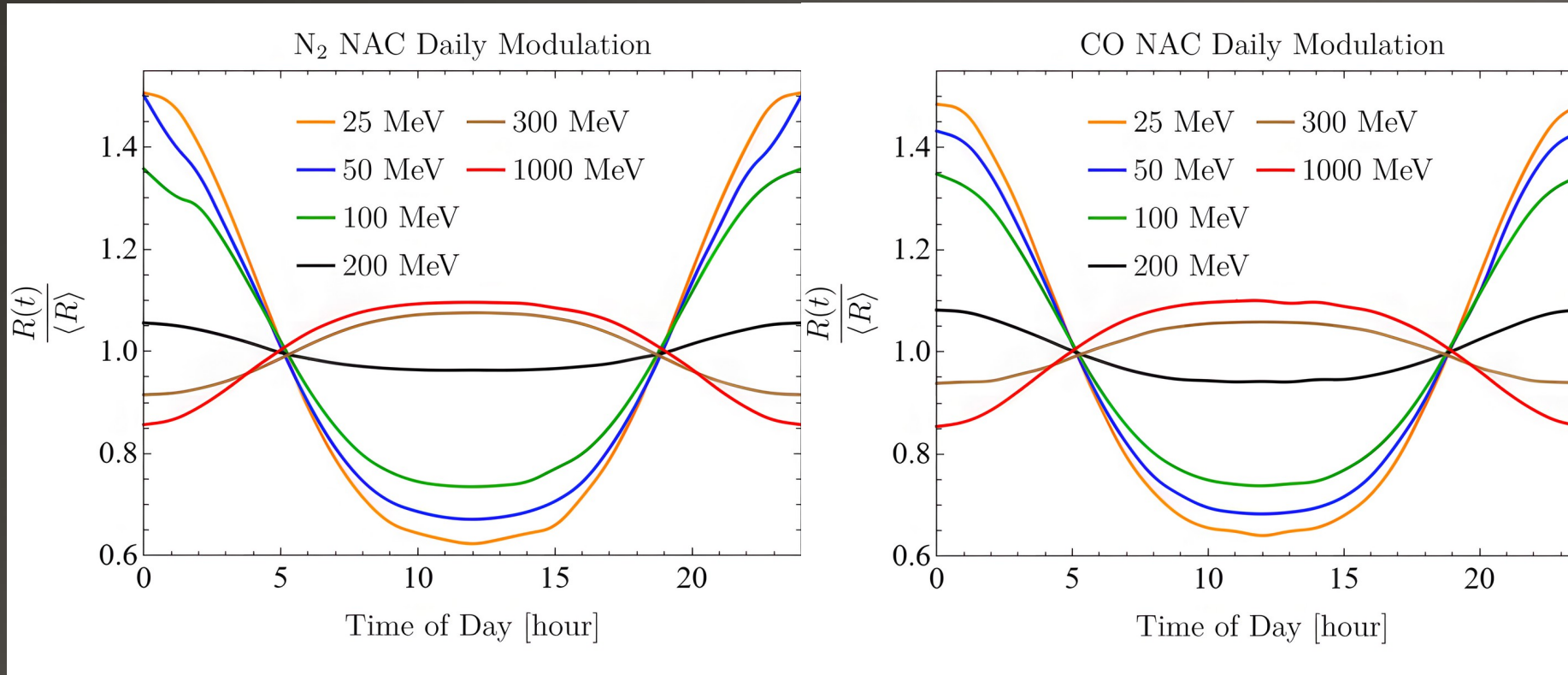
Predicted rate changes by up to 80% throughout the day.

The daily modulation phase is mass dependent.

Persistent daily modulation at large dark matter mass is generically predicted for the molecular Migdal effects. We predict that the same class of molecules that make good directional detectors for electron scattering will also be ideal for nuclear scattering because of the directional molecular Migdal effects.

The Molecular Migdal Effect(s)
Sensitivity to Nuclear Recoils

(Contact interaction)
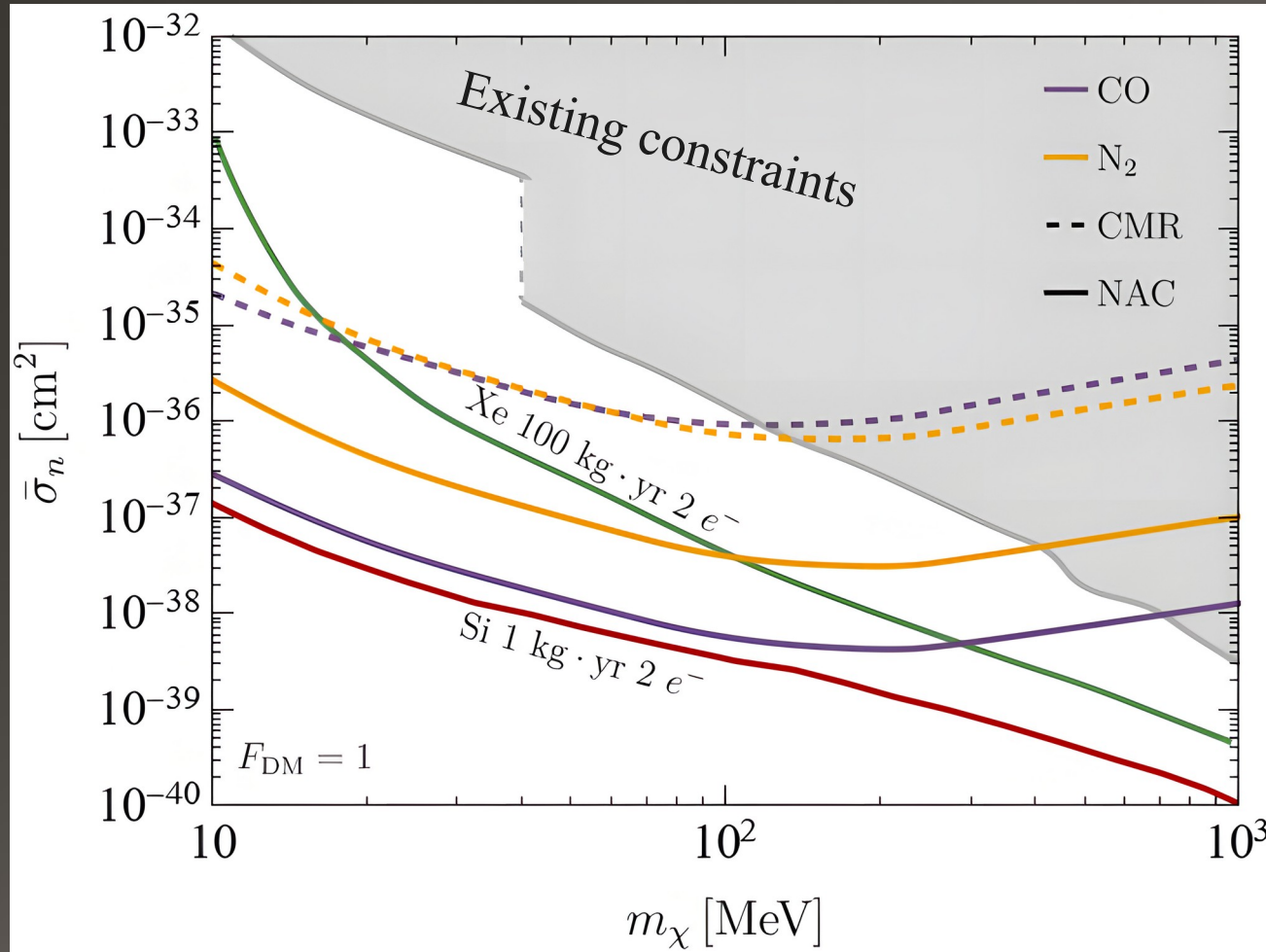
Si rate is entirely due to non-adiabatic processes. [Esposito & Rocchi 2505.08864]

Center of mass recoil effect is predicted to be subdominant at all masses.

Non-adiabatic coupling effect is predicted to dominate due to favorable kinematic factor.

Simplest molecular models already competitive.

Is there an optimal molecular target?

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

Anisotropic Materials

2D Targets: e.g. graphene, MoS_2, GaN

Polar Semiconductors: e.g. Al_2O_3, SiC, GaAs, $Eu_5In_2Sb_6$ (SPLENDOR)

Dirac materials: e.g. ZrTe5

Crystalline scintillators:
e.g. NaI, GaAs, trans-stilbene, etc...

Need
- > 10 kg low-background material
- Large anisotropy, $N_\sigma \sim f_{RMS}\,(mT_{exp})^{1/2}$

Y. Hochberg, Y. Kahn, M. Lisanti, C. G. Tully and K. M. Zurek, *Directional detection of dark matter with two-dimensional targets*, Phys. Lett. B **772**, 239 (2017), doi:10.1016/j.physletb.2017.06.051, 1606.08849.

R. Budnik, O. Chesnovsky, O. Slone and T. Volansky, *Direct Detection of Light Dark Matter and Solar Neutrinos via Color Center Production in Crystals*, Phys. Lett. B **782**, 242 (2018), doi:10.1016/j.physletb.2018.04.063, 1705.03016.

Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber and J. B. Neaton, *Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials*, Phys. Rev. D **97**(1), 015004 (2018), doi:10.1103/PhysRevD.97.015004, 1708.08929.

S. Griffin, S. Knapen, T. Lin and K. M. Zurek, *Directional Detection of Light Dark Matter with Polar Materials*, Phys. Rev. D **98**(11), 115034 (2018), doi:10.1103/PhysRevD.98.115034, 1807.10291.

A. Coskuner, A. Mitridate, A. Olivares and K. M. Zurek, *Directional Dark Matter Detection in Anisotropic Dirac Materials*, Phys. Rev. D **103**(1), 016006 (2021), doi:10.1103/PhysRevD.103.016006, 1909.09170.

R. M. Geilhufe, F. Kahlhoefer and M. W. Winkler, *Dirac Materials for Sub-MeV Dark Matter Detection: New Targets and Improved Formalism*, Phys. Rev. D **101**(5), 055005 (2020), doi:10.1103/PhysRevD.101.055005, 1910.02091.

S. M. Griffin, Y. Hochberg, K. Inzani, N. Kurinsky, T. Lin and T. Chin, *Silicon carbide detectors for sub-GeV dark matter*, Phys. Rev. D **103**(7), 075002 (2021), doi:10.1103/PhysRevD.103.075002, 2008.08560.

C. Blanco, Y. Kahn, B. Lillard and S. D. McDermott, *Dark Matter Daily Modulation With Anisotropic Organic Crystals*, Phys. Rev. D **104**, 036011 (2021), doi:10.1103/PhysRevD.104.036011, 2103.08601.

A. Coskuner, T. Trickle, Z. Zhang and K. M. Zurek, *Directional detectability of dark matter with single phonon excitations: Target comparison*, Phys. Rev. D **105**(1), 015010 (2022), doi:10.1103/PhysRevD.105.015010, 2102.09567.

C. Blanco, I. Harris, Y. Kahn, B. Lillard and J. Pérez-Ríos, *Molecular Migdal effect*, Phys. Rev. D **106**(11), 115015 (2022), doi:10.1103/PhysRevD.106.115015, 2208.09002.

C. Boyd, Y. Hochberg, Y. Kahn, E. D. Kramer, N. Kurinsky, B. V. Lehmann and T. C. Yu, *Directional detection of dark matter with anisotropic response functions* (2022), 2212.04505.

Mining for Crystals in Data
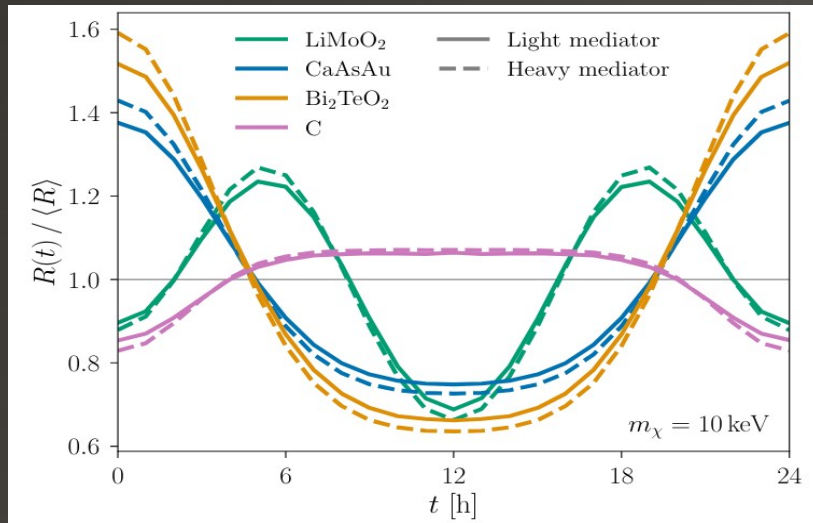
First High-throughput evaluation of Dark Matter Detector Materials
- Used the crystals in the Material Project
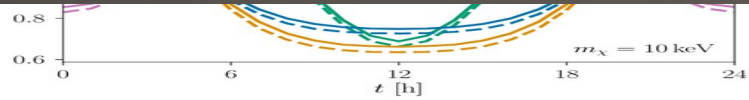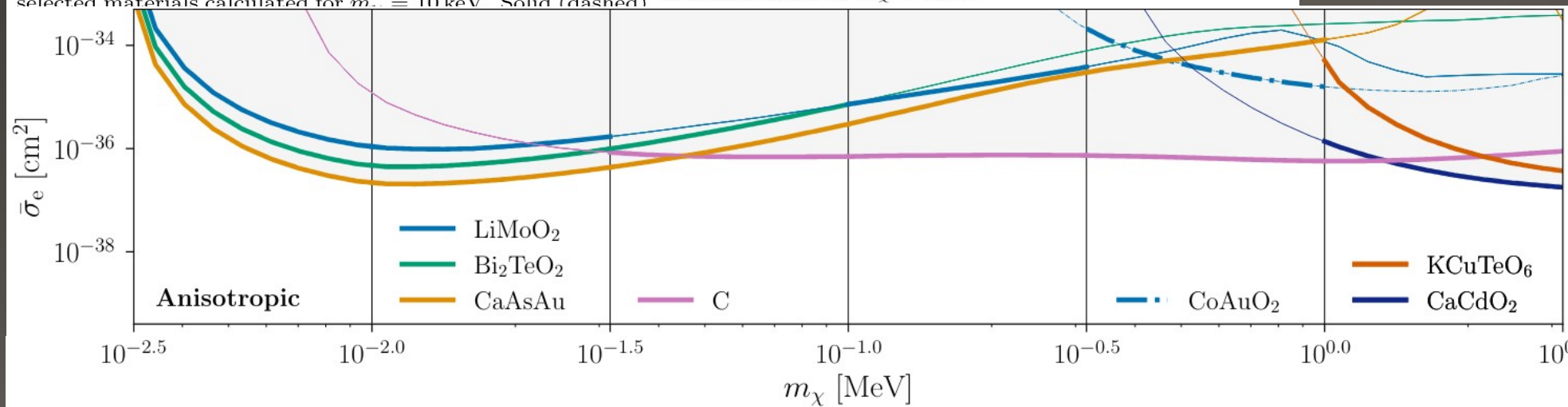- Fit anisotropic Lindhard dielectric tensor to data

[Griffin, Hochberg, Lehmann, Ovadia, Persson, Suter, Yang: 2506.19905]

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Inventing 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*

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ML for DM Direct Detection

Property prediction   Molecular Generation

Energies & Matrix elements   Sample latent space $\rightarrow$ new molecules

Small molecules : Using exhaustive database (< 9 atoms)

Characterize neural nets

$\rightarrow$ Prove it's possible to learn from small subsample

Large molecules: Sparse dataset up to 10s of atoms

Scale architecture

$\rightarrow$ Generate candidate molecule *shortlist*

Dataset of energies + oscillator strengths:

PubChemQ: a dataset of ~3M organic molecules *computed* using Density Functional Theory

[C. Cook*, CB, J. Smirnov 2501.00091]

ML for DM Direct Detection

Molecular Space: Variational Autoencoders

Energies & Matrix elements   Sample latent space → new molecules

Discrete and sparse data space

Simple MLP $C(\mu)$ $\hat{y}$ Property Prediction

$P_\phi(Z|X)$ μ Mean Z $P_\theta(\hat{X}|Z)$

$\log(\sigma)$

[Krenn et al : 1905.13741]

Input   Encoder   Variance   Decoder   Output
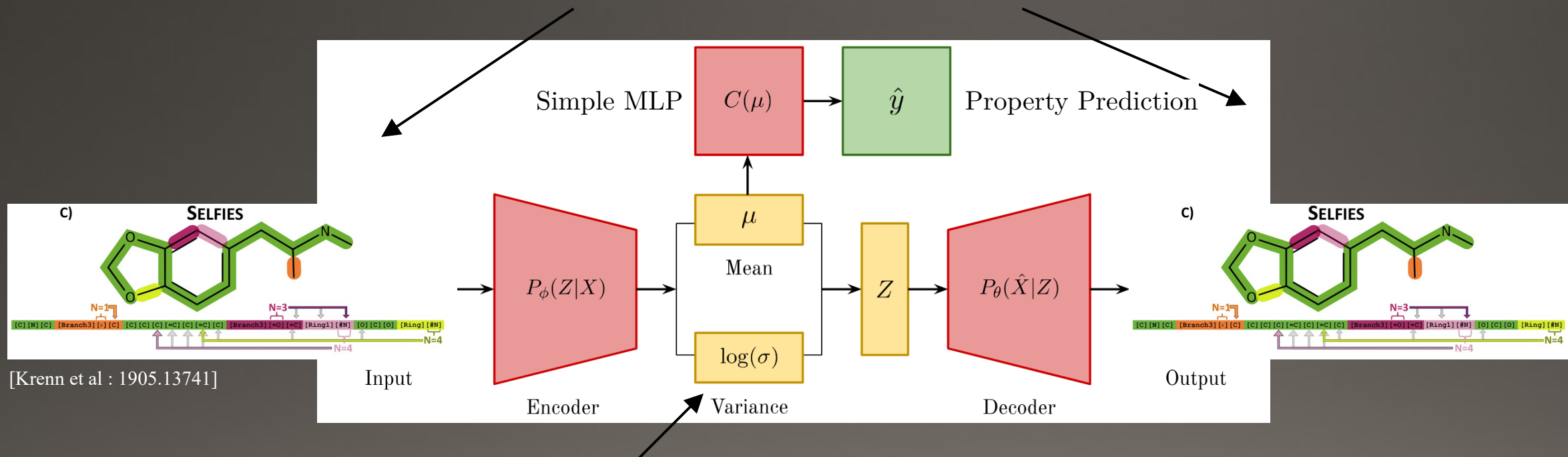
Continuous latent space

Regression Model in Action
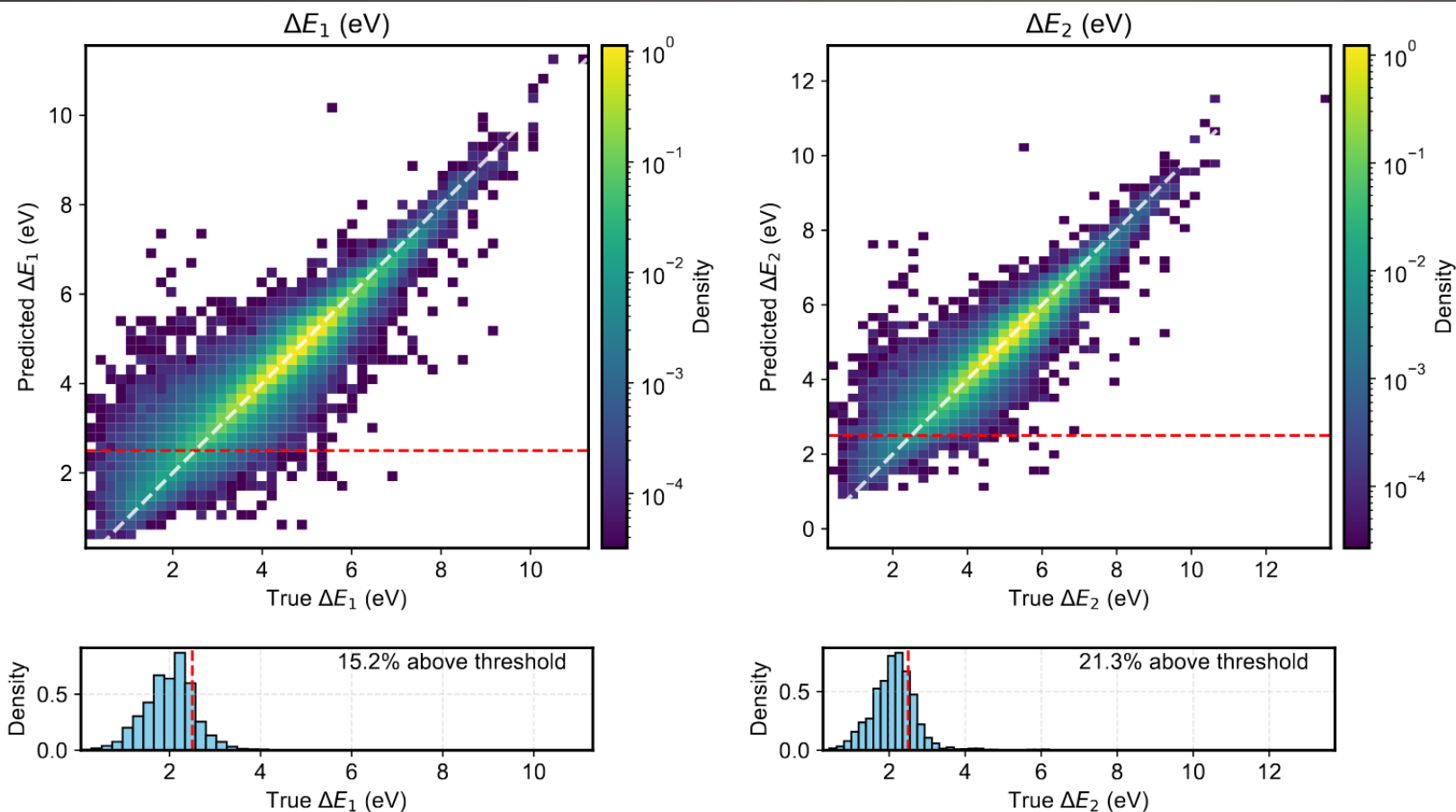
FIG. 19. We show the density of predicted values vs true values for the transition energies of our validation set, with a red line that corresponds to the threshold placed on the predicted value. The Histogram shows the distribution of true values for molecules whose predicted value is above the threshold.

Regression Model in Action
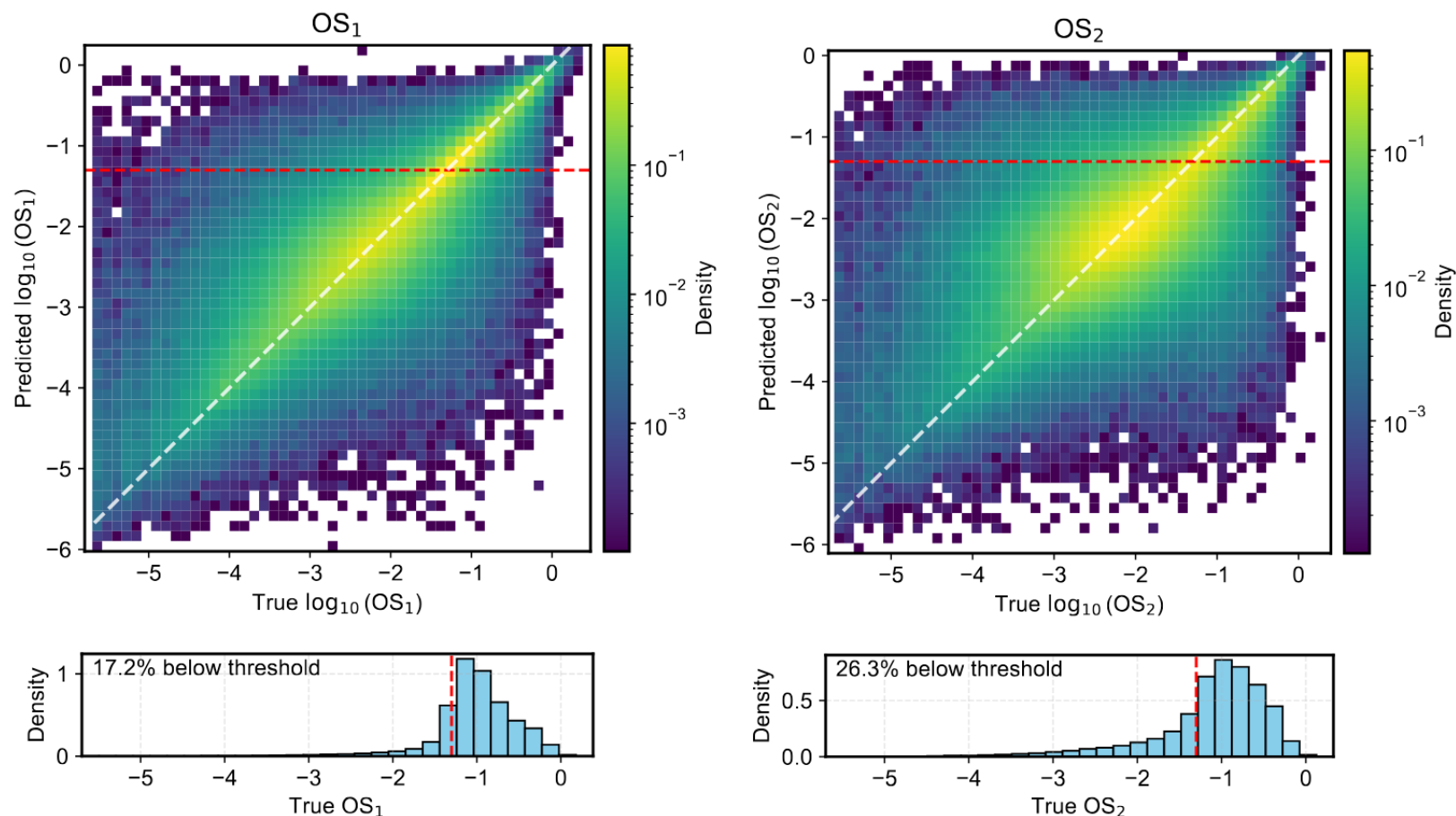
FIG. 20. We show the density of predicted values vs true values for the oscillator strength of our validation set, with a red line that corresponds to the threshold placed on the predicted value. The Histogram shows the distribution of true values for molecules whose predicted value is above the threshold.

[C. Cook*, CB, J. Smirnov 2501.00091]

ML for DM Direct Detection

Property prediction: Molecular latent space

Energies & Matrix elements   Sample latent space $\rightarrow$ new molecules

$$\Delta E \qquad\qquad \langle r_{01} \rangle \approx |f_{0,1}|/q$$

[C. Cook*, CB, J. Smirnov 2501.00091]

Clustering: Results

1. Count: 62465
2. Count: 34577
3. Count: 23404
4. Count: 20976
5. Count: 10118
6. Count: 8686
7. Count: 16948
8. Count: 23387
9. Count: 9292
10. Count: 7187
11. Count: 5760
12. Count: 4748
13. Count: 5508
14. Count: 5772
15. Count: 4468
16. Count: 5058
17. Count: 4584
18. Count: 4258
19. Count: 4383
20. Count: 3794
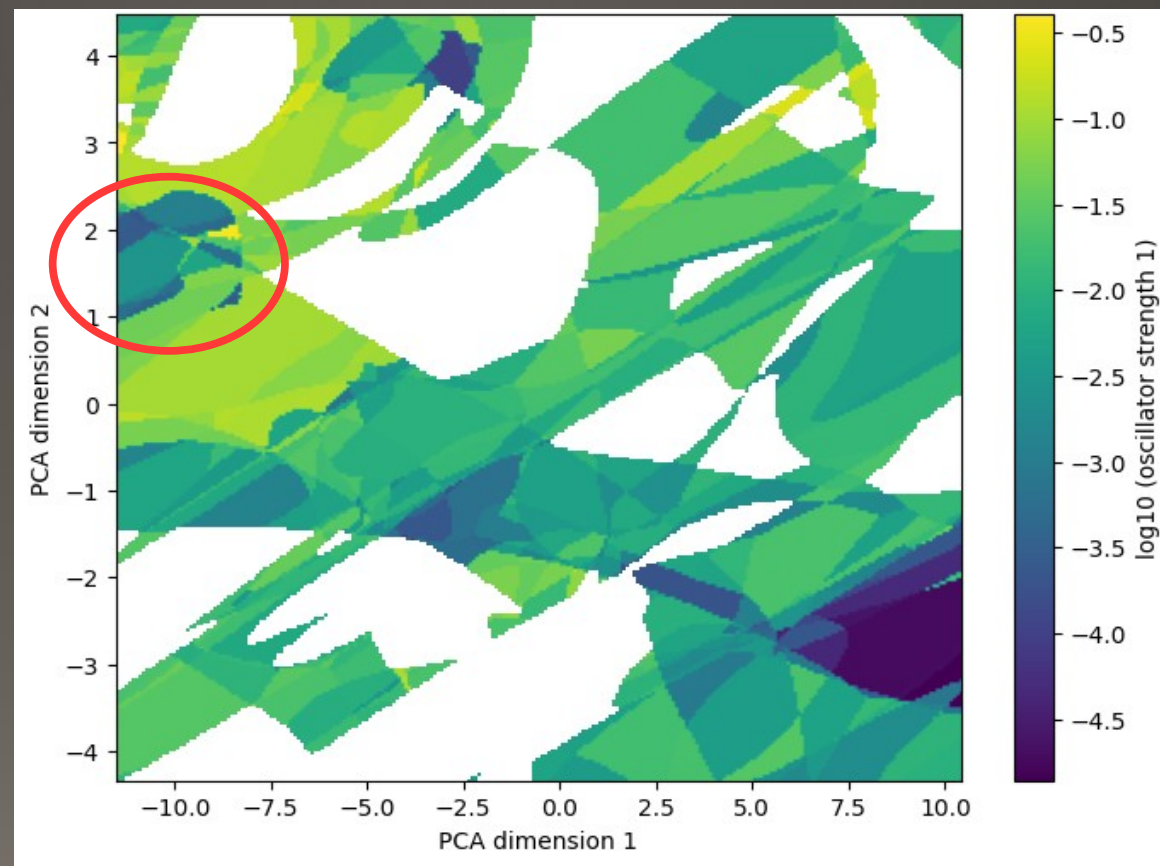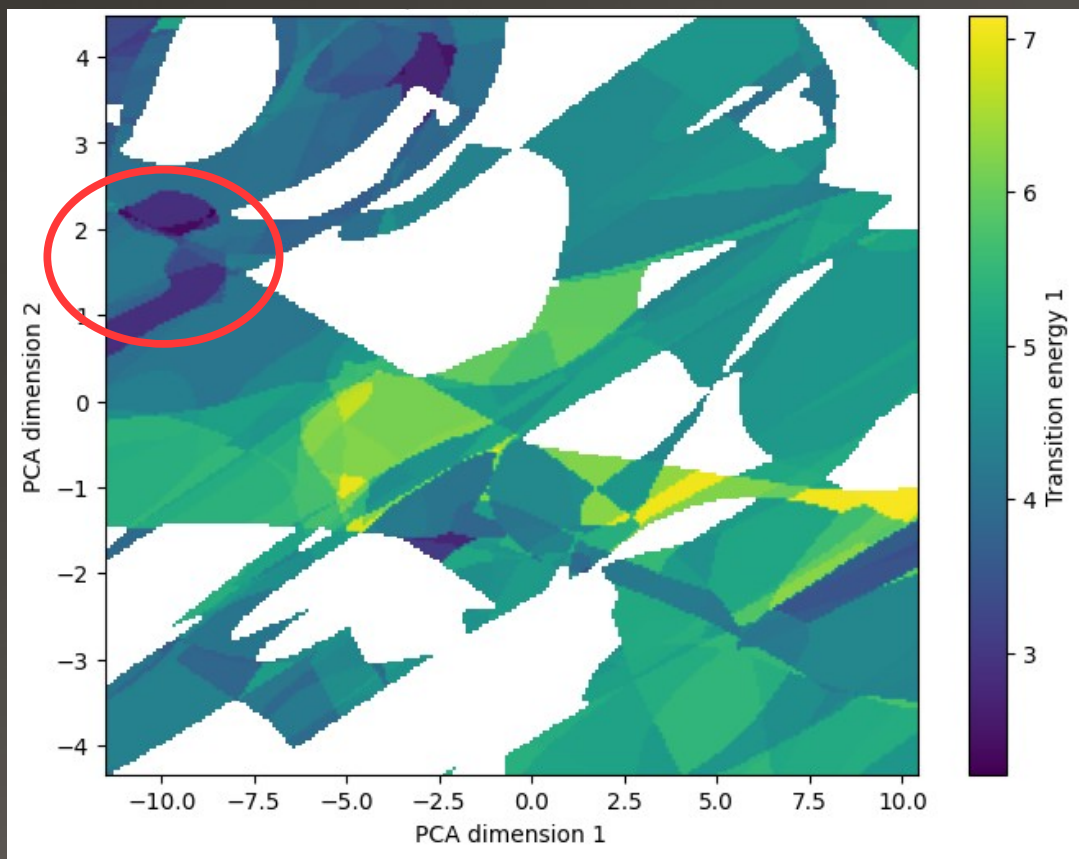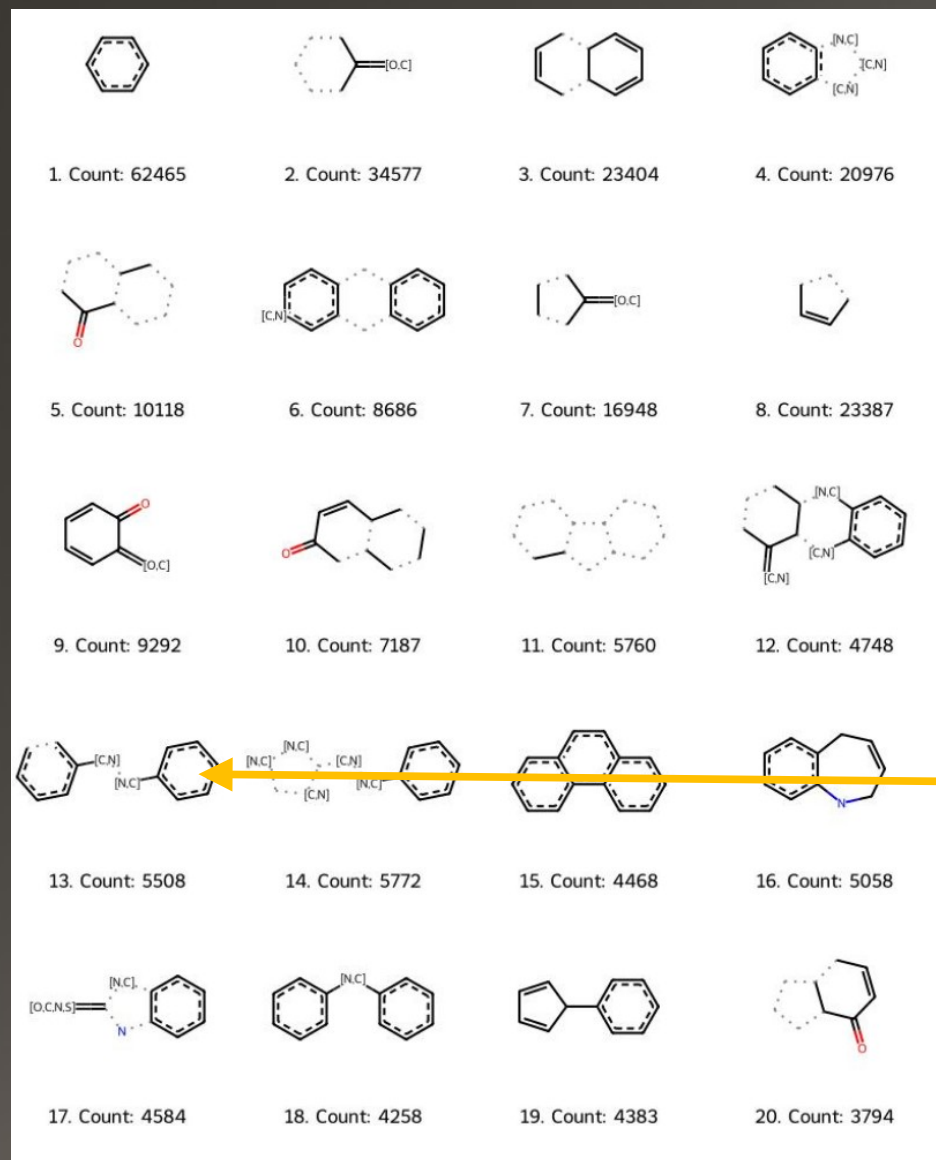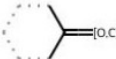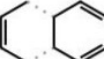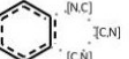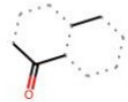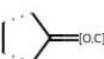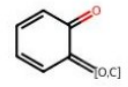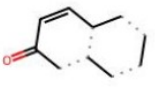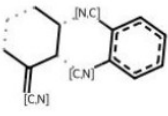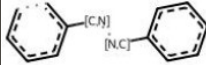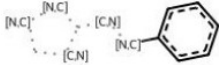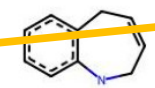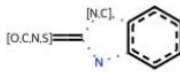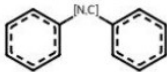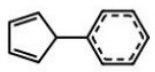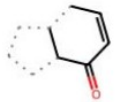
FIG. 7. Top 20 molecular motifs ranked by score. Note that certain atoms can be substituted by [C,N,O,S] as long as the structure remains isoelectronic. Dotted lines indicate that the bond could be a double or single bond.
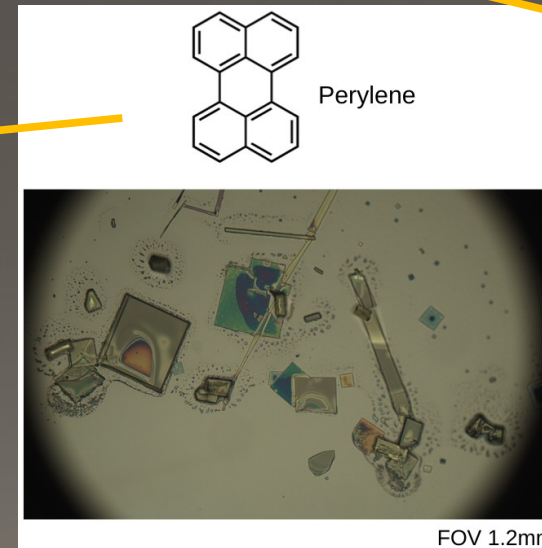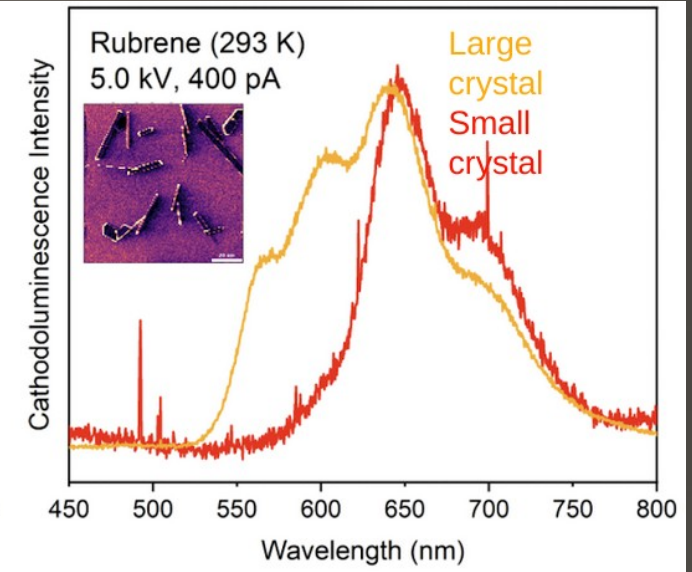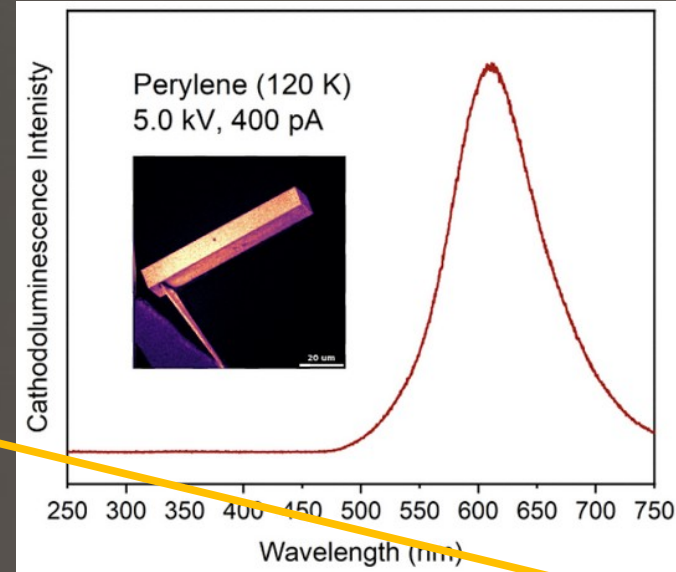
[C. Cook*, CB, J. Smirnov 2501.00091]

In hindsight, we're probably on the right track.

New Target Materials

[C. Cook*, CB, J. Smirnov 2501.00091]

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Credit: Dane Johnson (MIT)

Conclusions

1) We have done an extremely effective job looking for WIMPs above a GeV, now we must look beyond.

2) By developing the formalism that describes the interaction between dark matter and molecules, we can develop detection strategies capable of *delving deep* and *searching wide* across the dark matter parameter space.
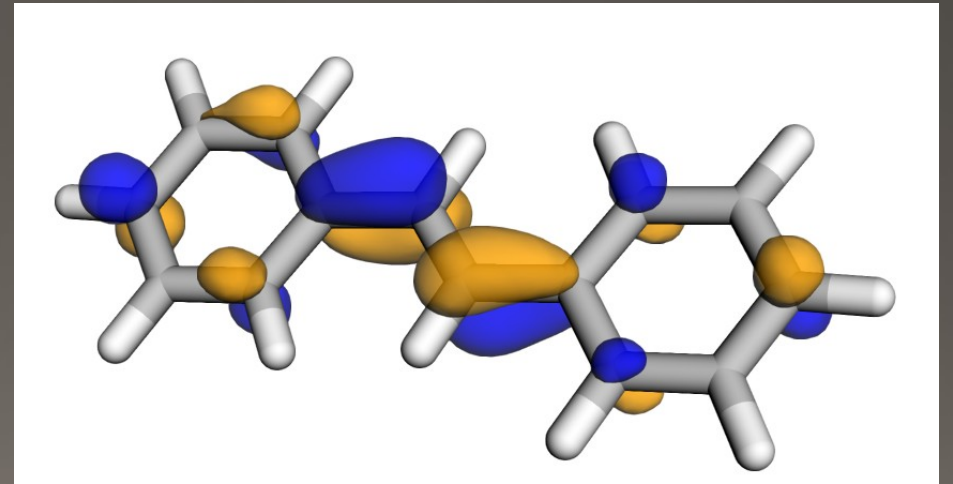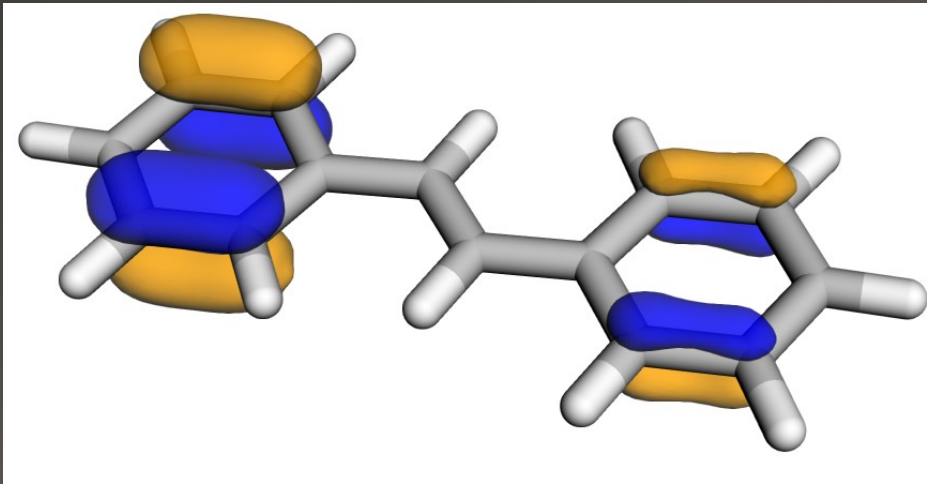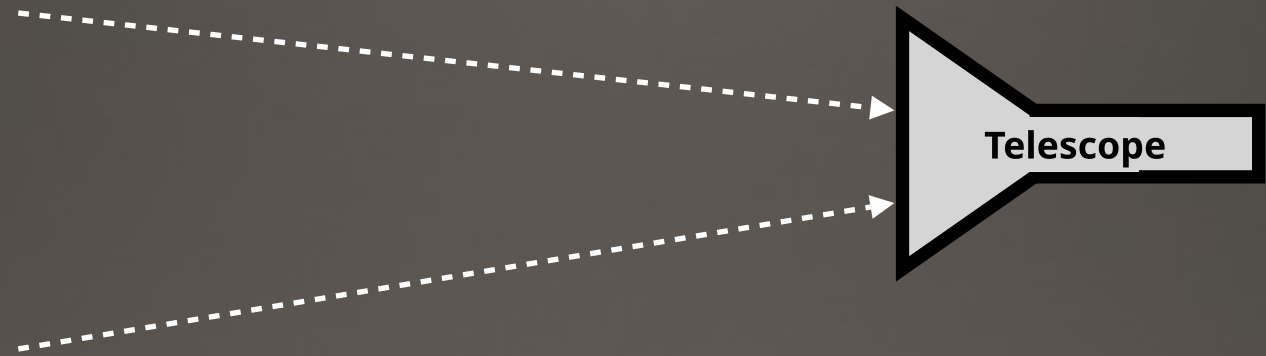
Beyond direct detection
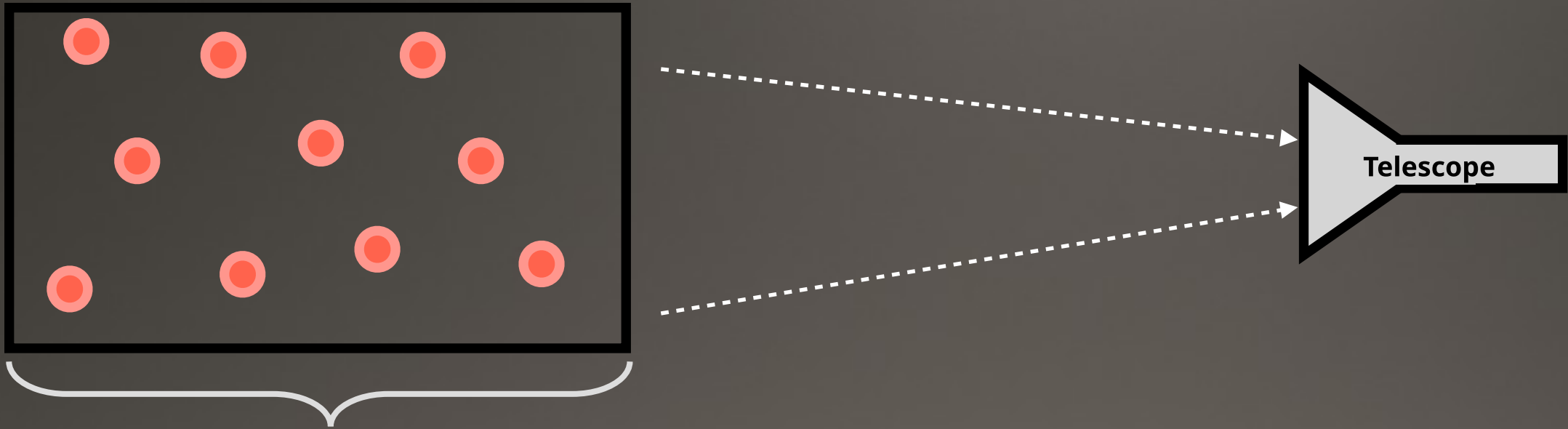
Astrophysical volume of molecules

We can use the same theoretical techniques that we've developed to predict rates in *astrophysical* objects
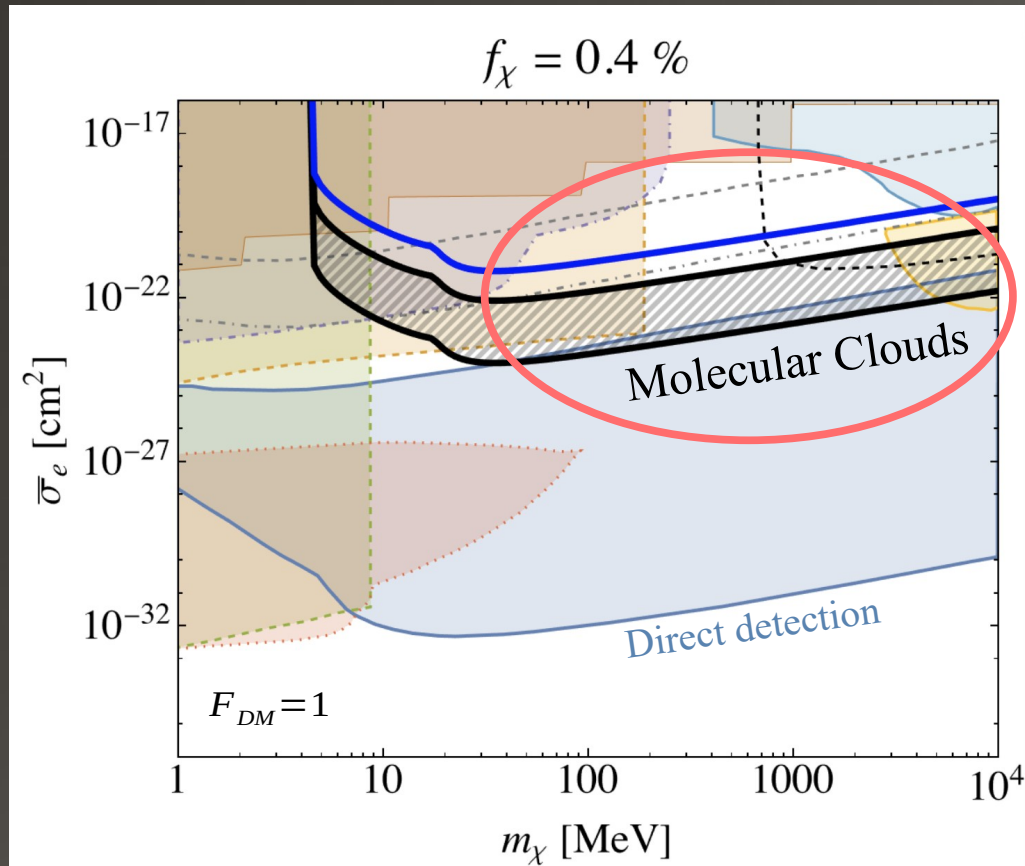
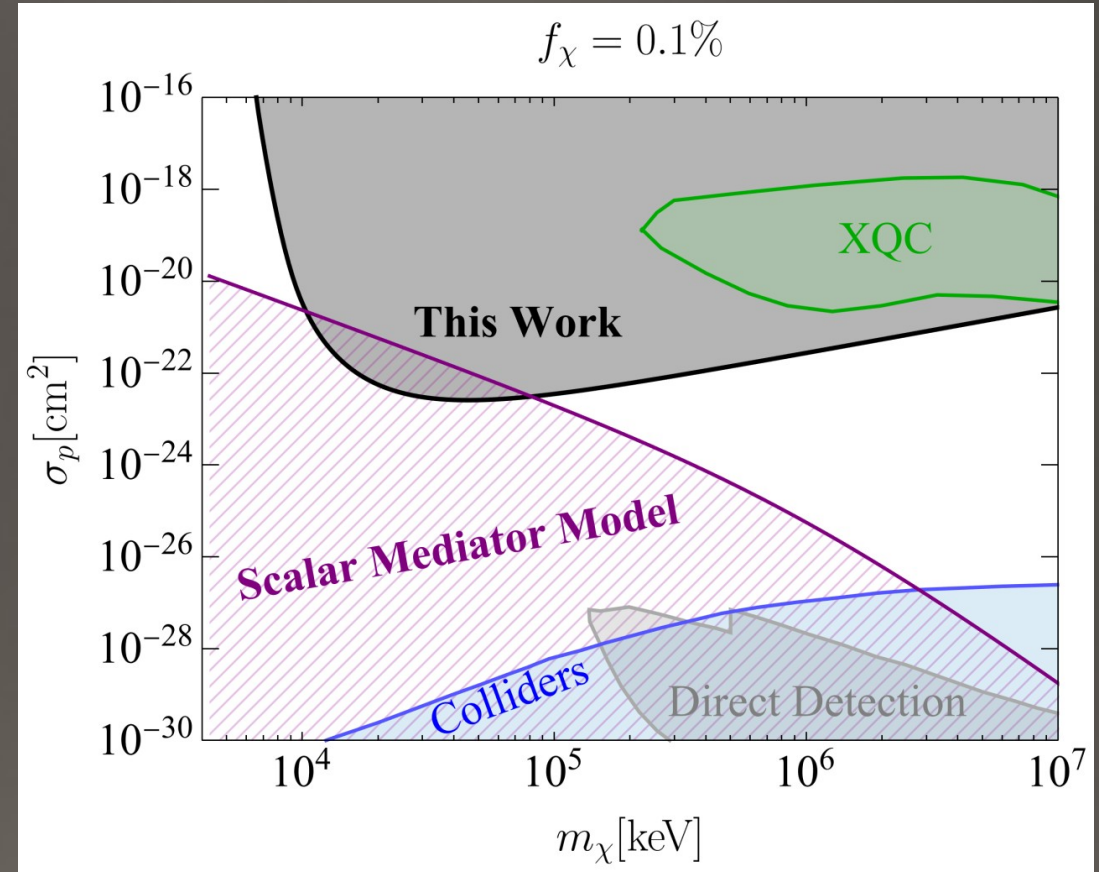# Beyond direct detection

Cold molecular cloud

We can use the same theoretical techniques that I've developed to predict rates in detectors to predict rates in *astrophysical* objects
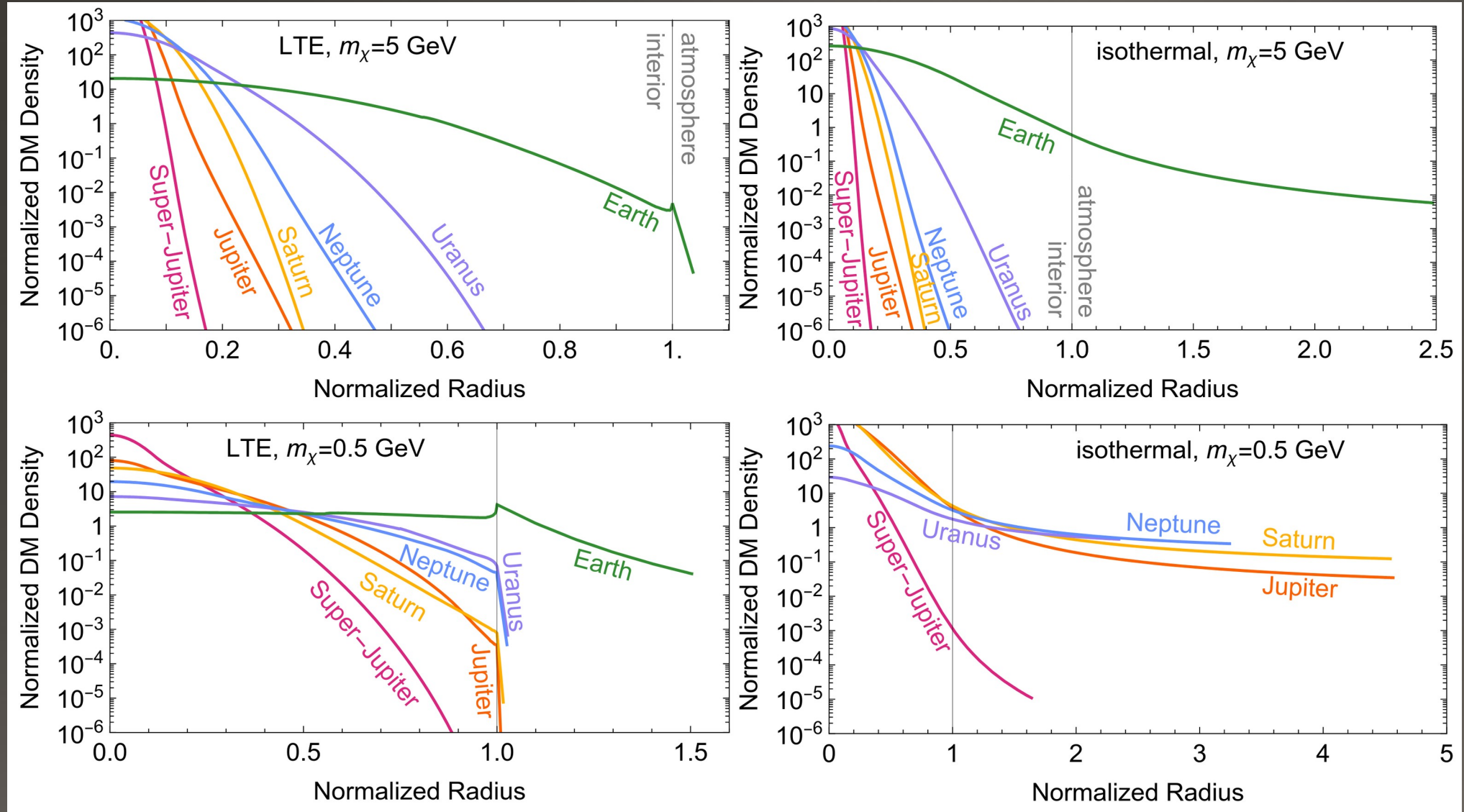
Dark matter in Molecular Clouds

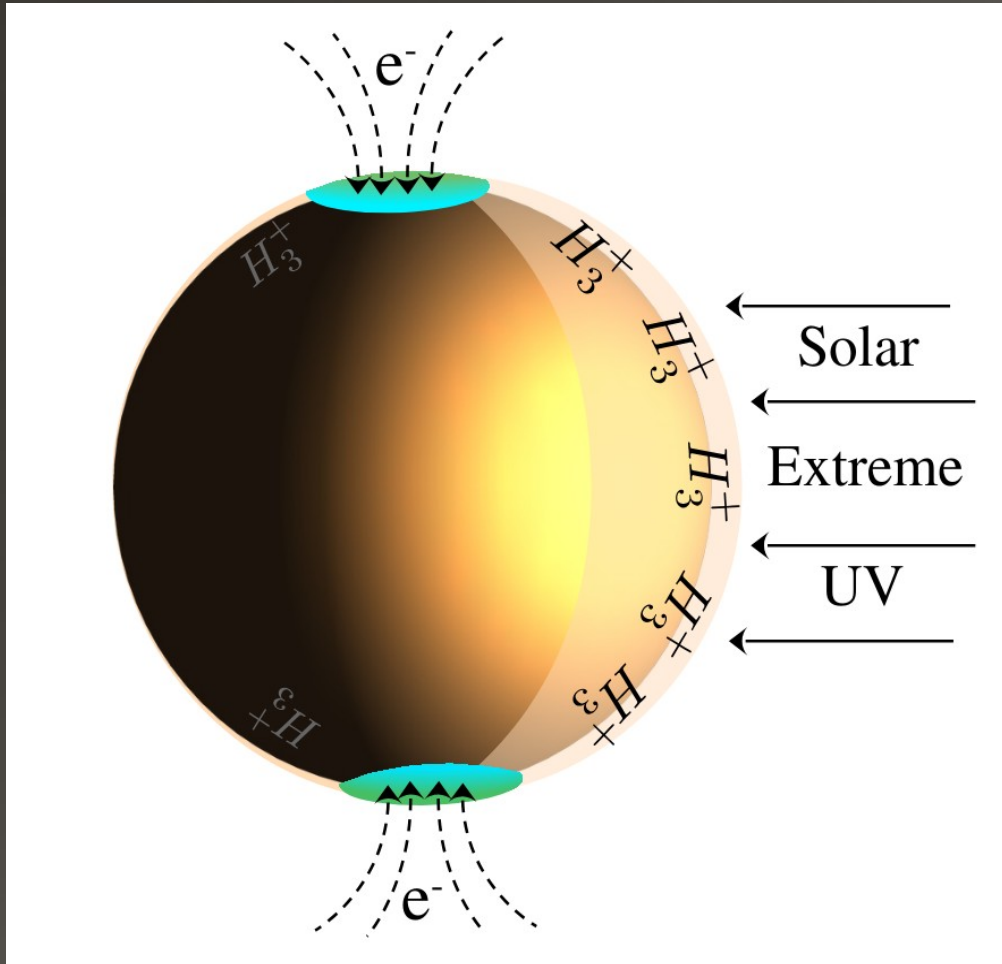[Prabhu,**CB** : 2211.05787]

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

The Molecular Migdal effect(s) *in space*

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Equilibrium Radial Distribution of Captured DM

[**CB**, Leane, Moore, Thong: 2508.00980]

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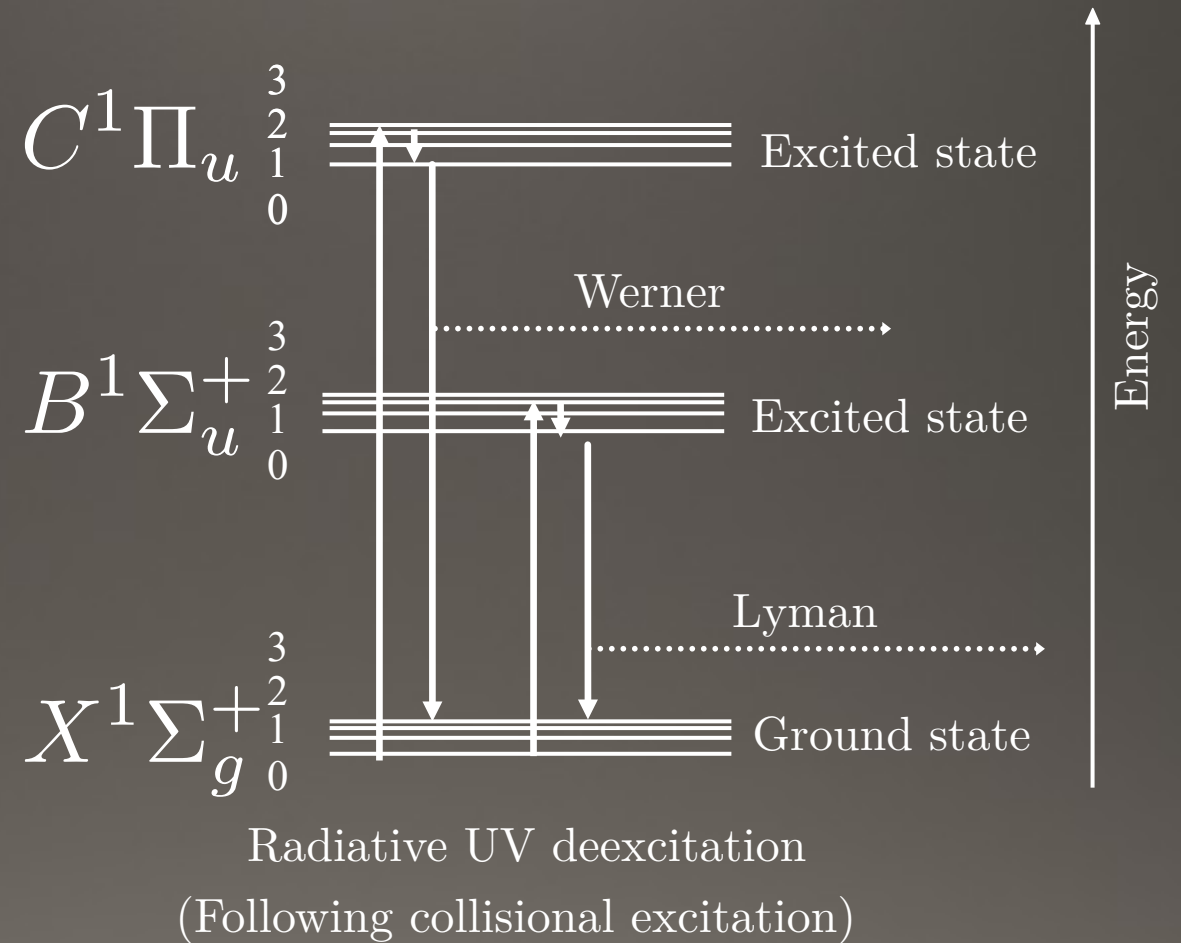
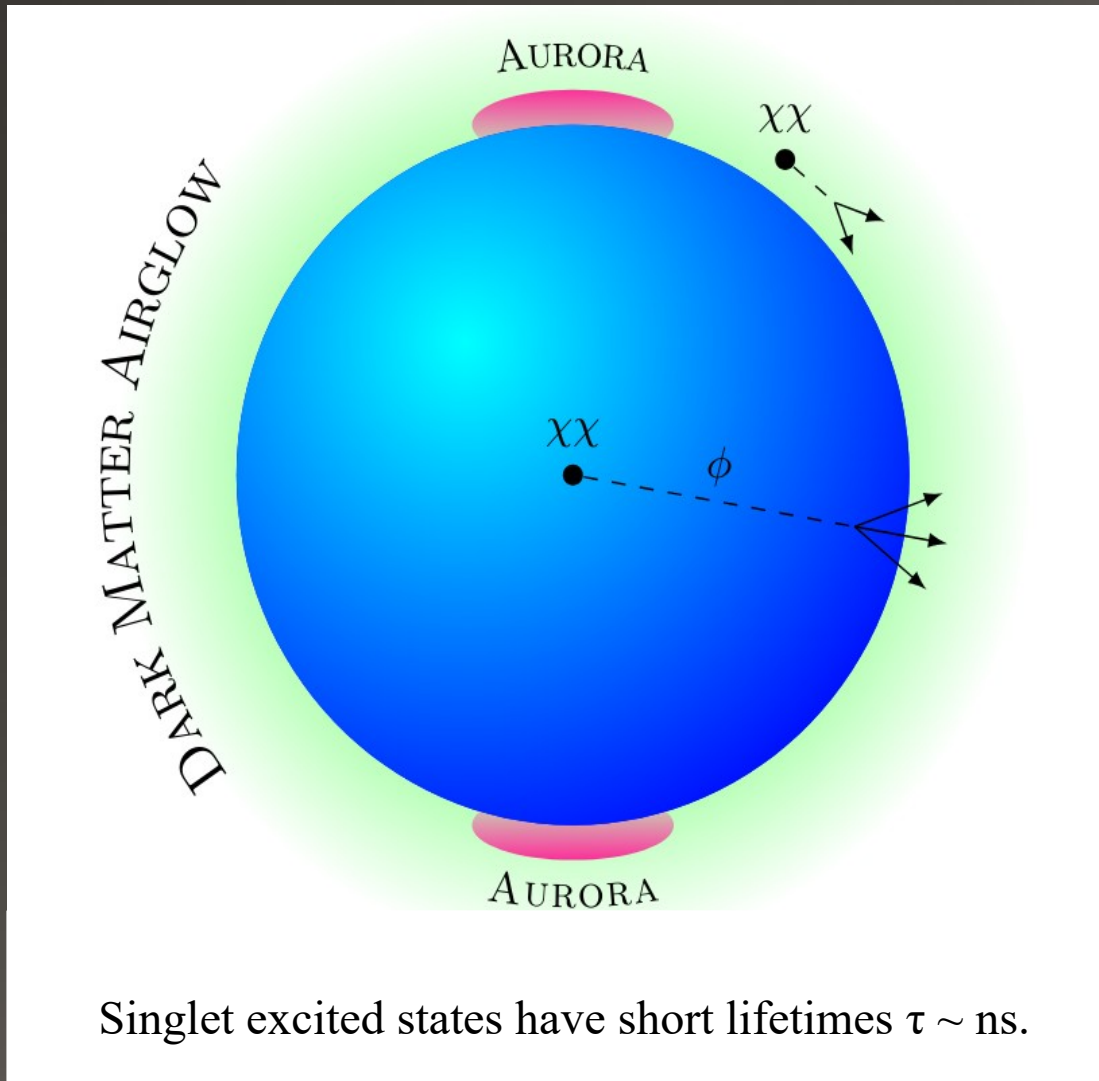# IR Signatures of DM in Jupiter

[**CB**, Leane: 2312.06758]

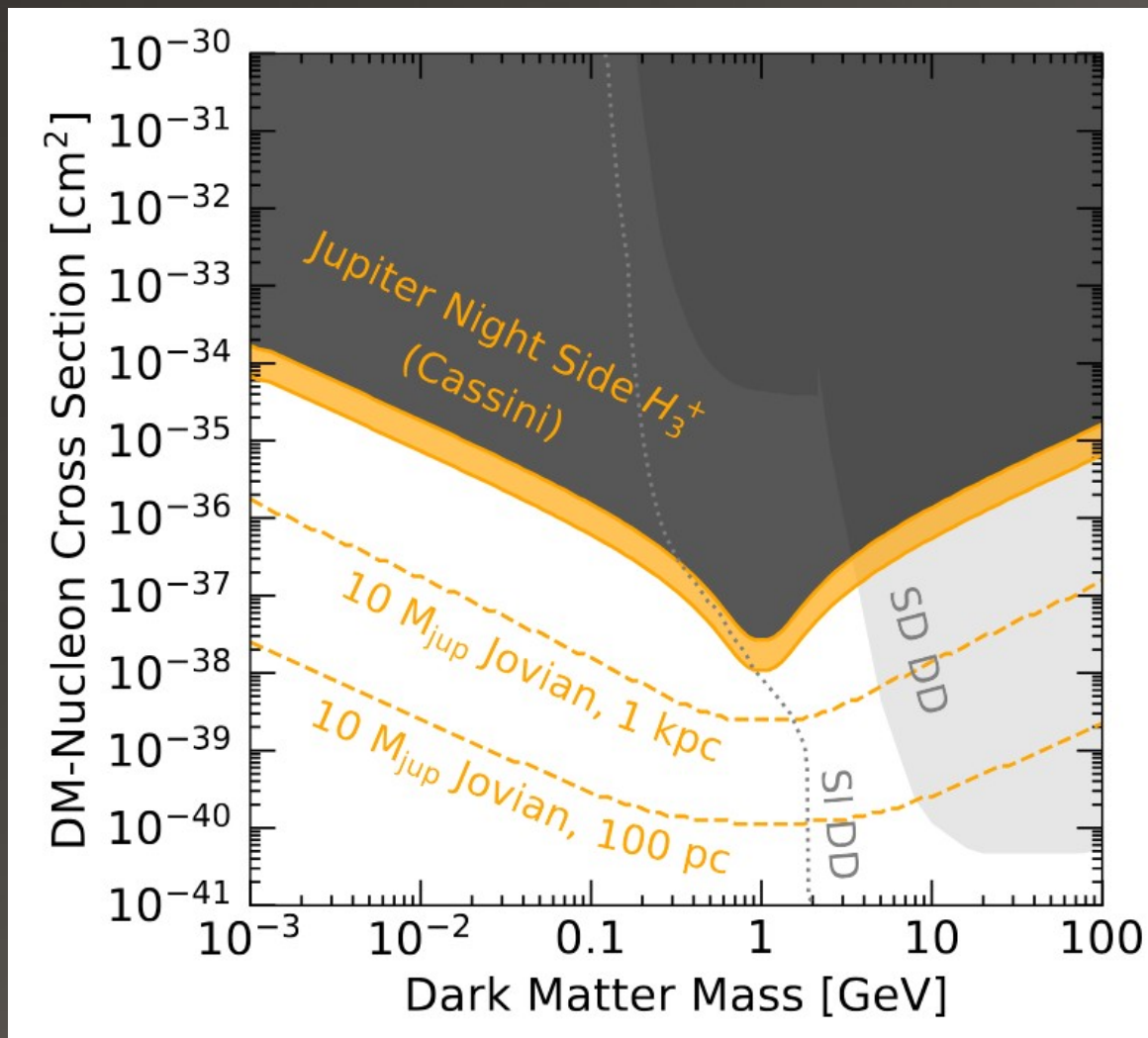Ionizing radiation generates H_3^+

H_3^+ radiates extremely efficiently in the IR. It is Jupiter's *thermostat*.

DM Annihilation $\rightarrow$ Brighter H_3^+ emission

UV Signatures of DM in Jupiter

Singlet excited states have short lifetimes $\tau \sim$ ns.

[**CB**, Leane, Moore, Thong: 2408.15318]
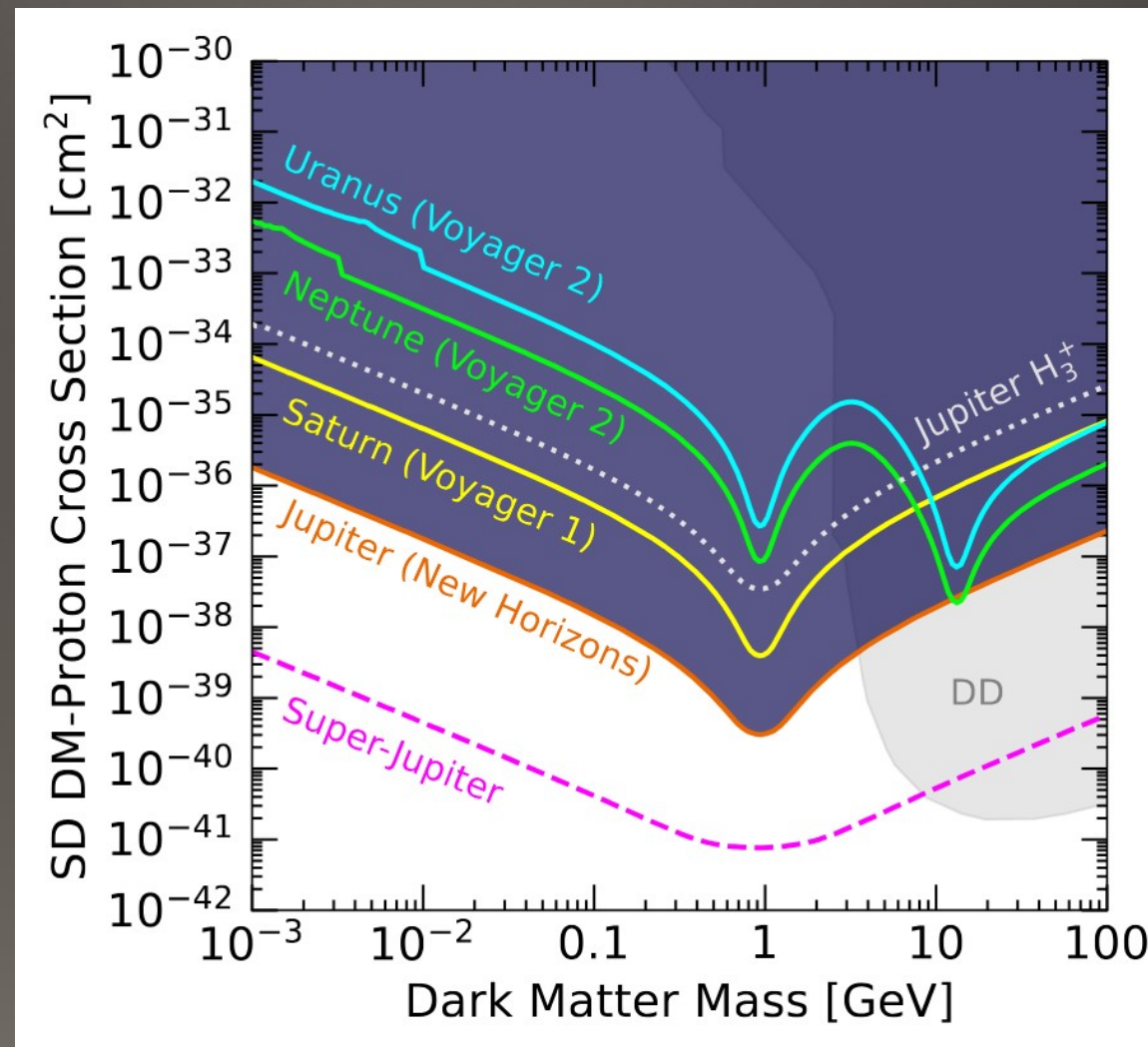
Constraints from IR and UV Molecular Emission

[**CB**, Leane: 2312.06758]

H_3^+ IR night-side emission

[**CB**, Leane, Moore, Thong: 2408.15318]

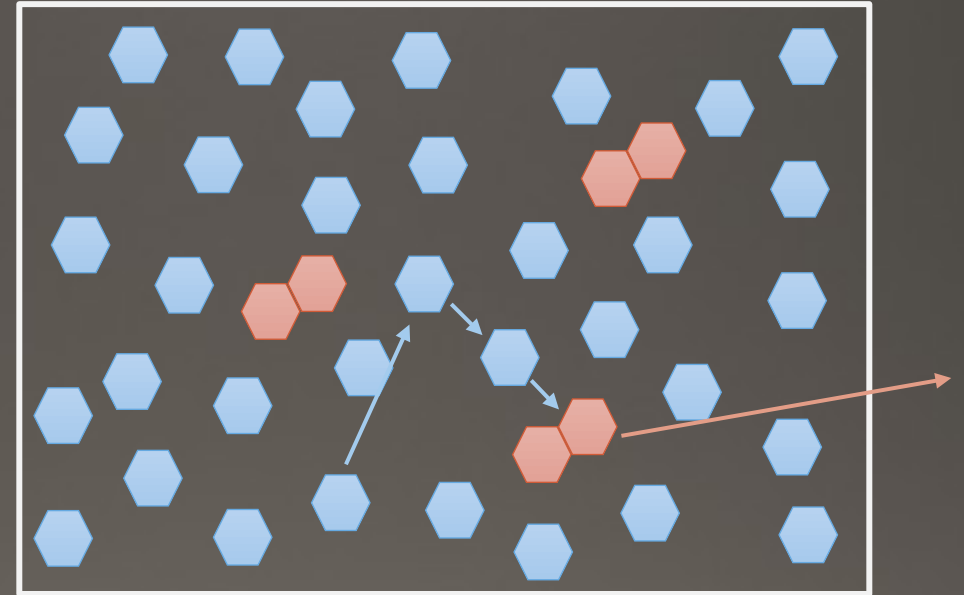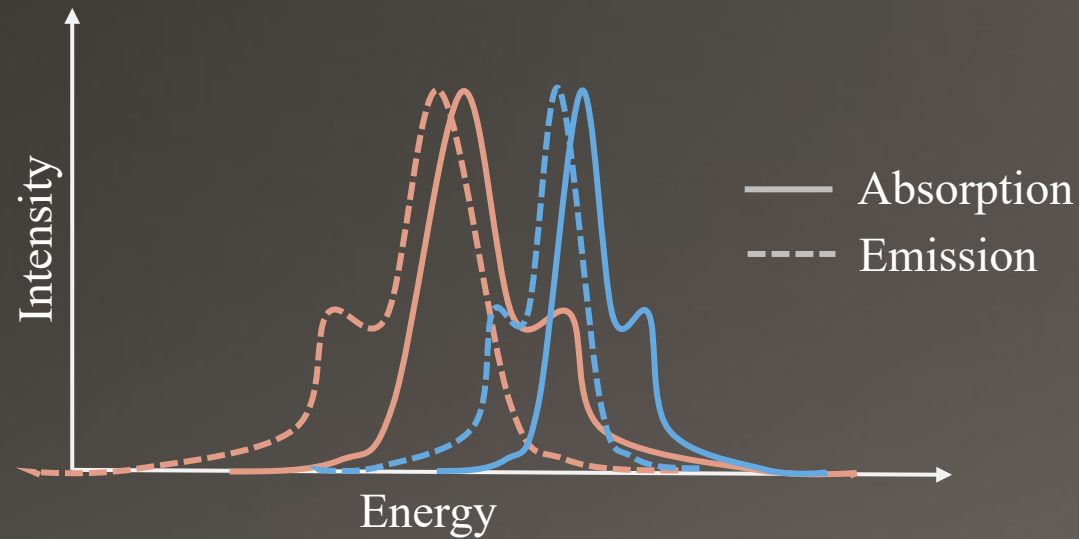UV night-side airglow

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Evaporation

UV airglow

Fluorescence: Binary Scintillators

Solvent: Primary target starts the signal

Solute: Dilute fluor gets the signal out of the bulk

Intensity

—— Absorption

- - - Emission

Energy

Electron Recoil: Charge Signal
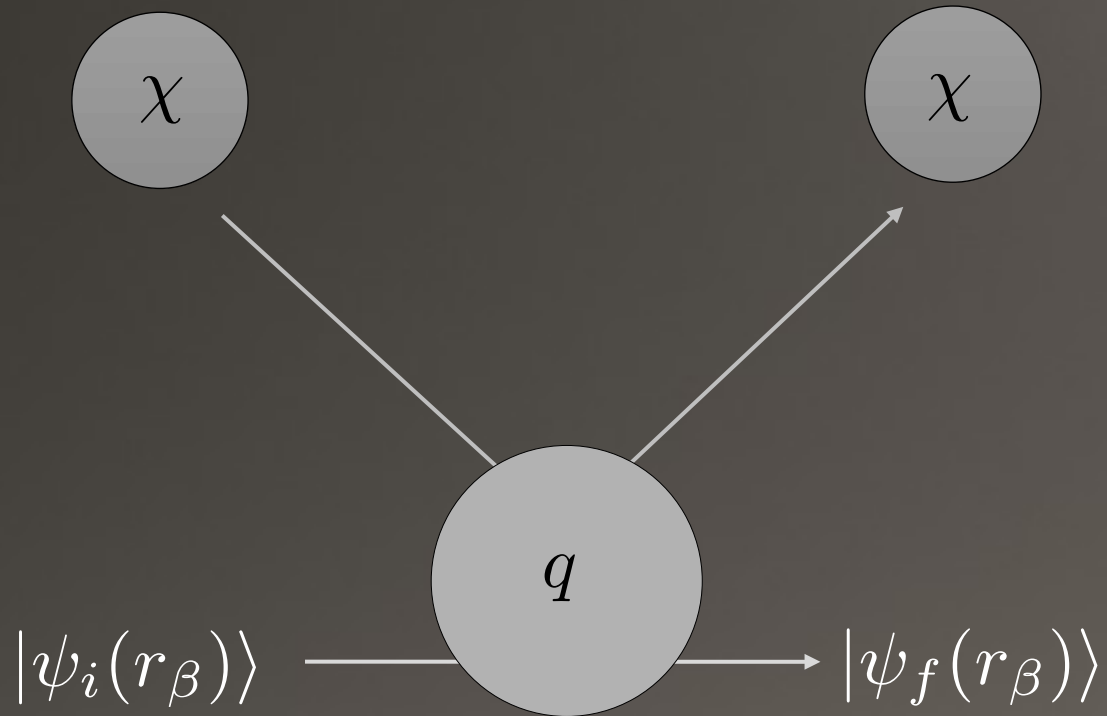
Electron scattering

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

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

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)

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

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.

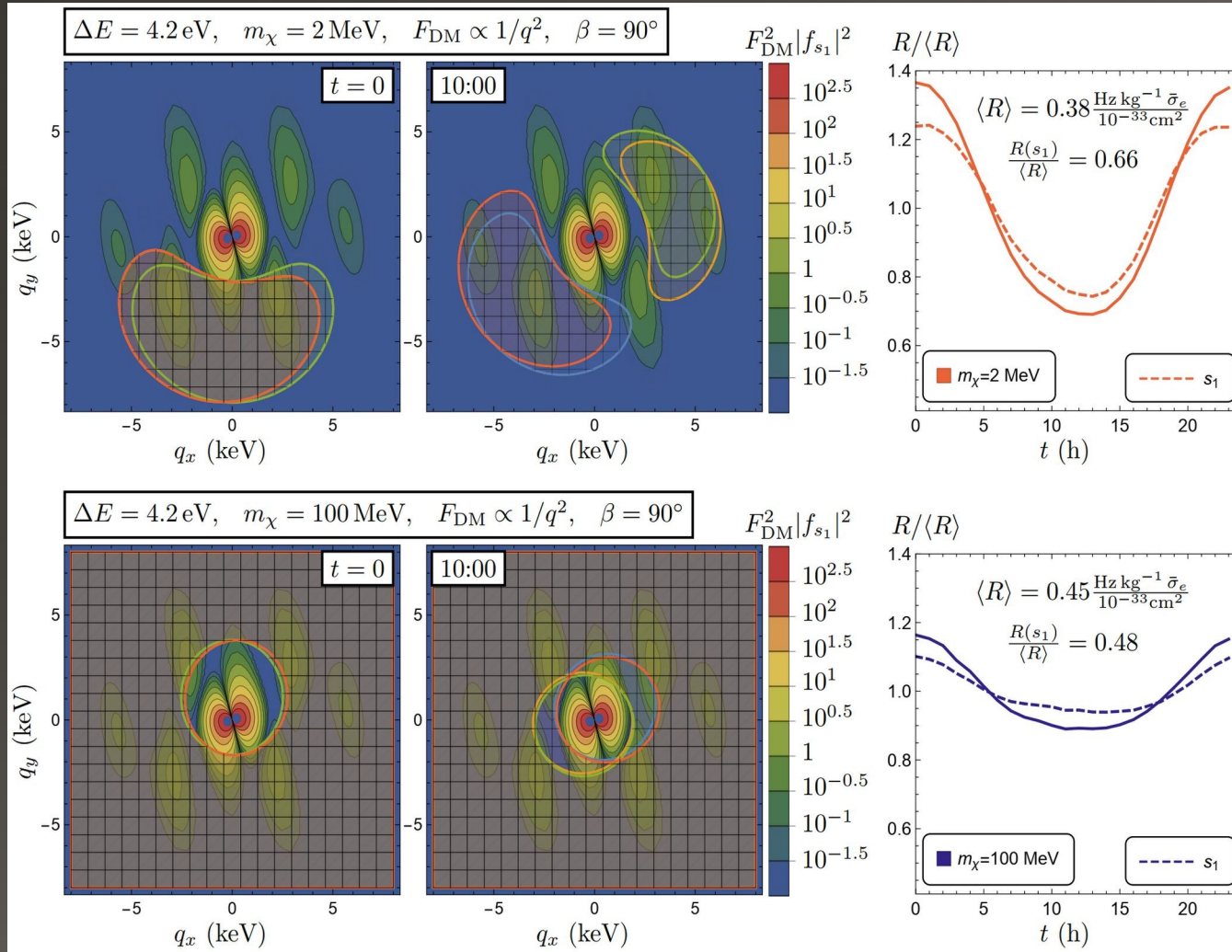$$|s_n\rangle = \sum_{i,j>i} d_{ij}^{(n)} |\psi_i^j\rangle,$$

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

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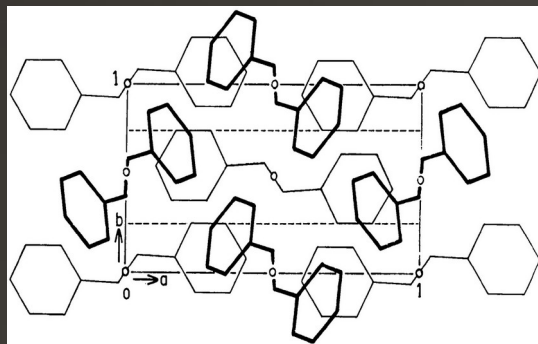&= \sum_{ij} d_{ij}^{(n)} \left\langle \psi_i^j \left| e^{i\vec{q}\cdot\vec{r}} \right| \psi_G \right\rangle \\
&= \sqrt{2} \sum_{ij} d_{ij}^{(n)} \langle \Psi_j(\vec{r})| e^{i\vec{q}\cdot\vec{r}} |\Psi_i(\vec{r})\rangle.
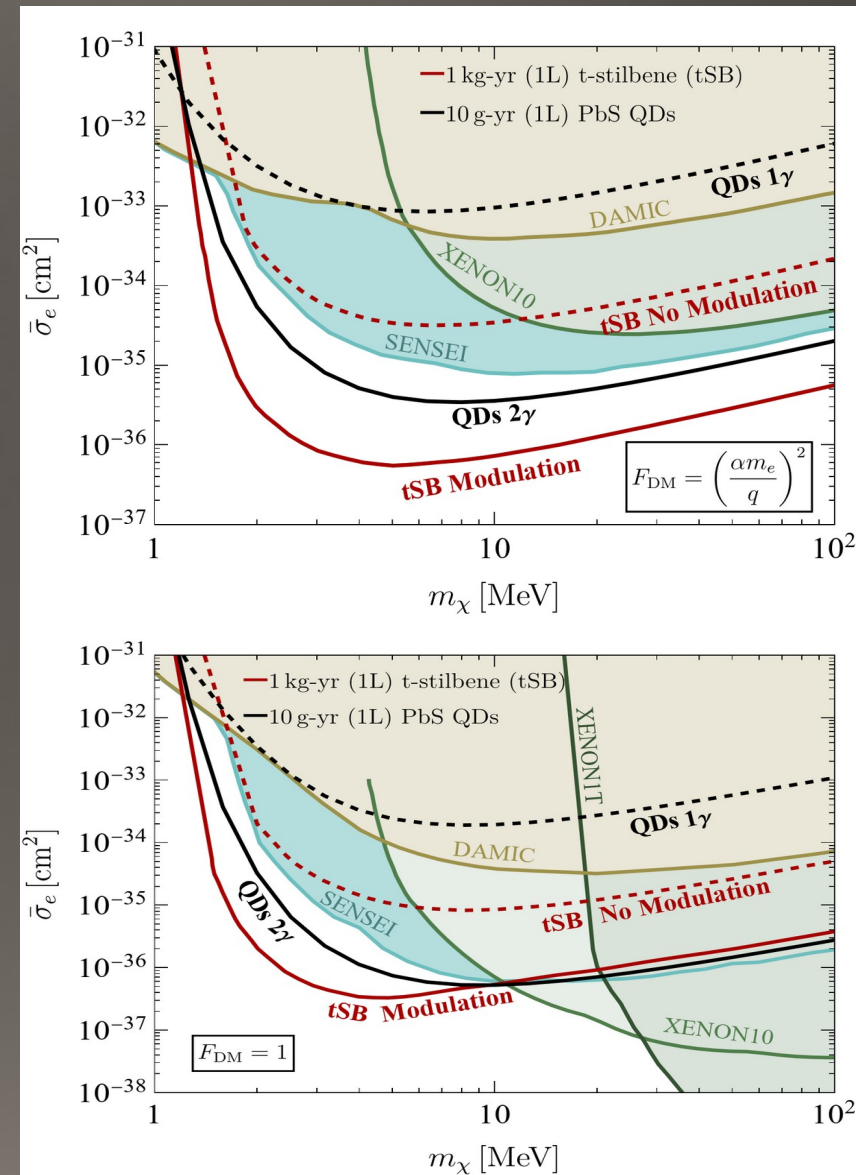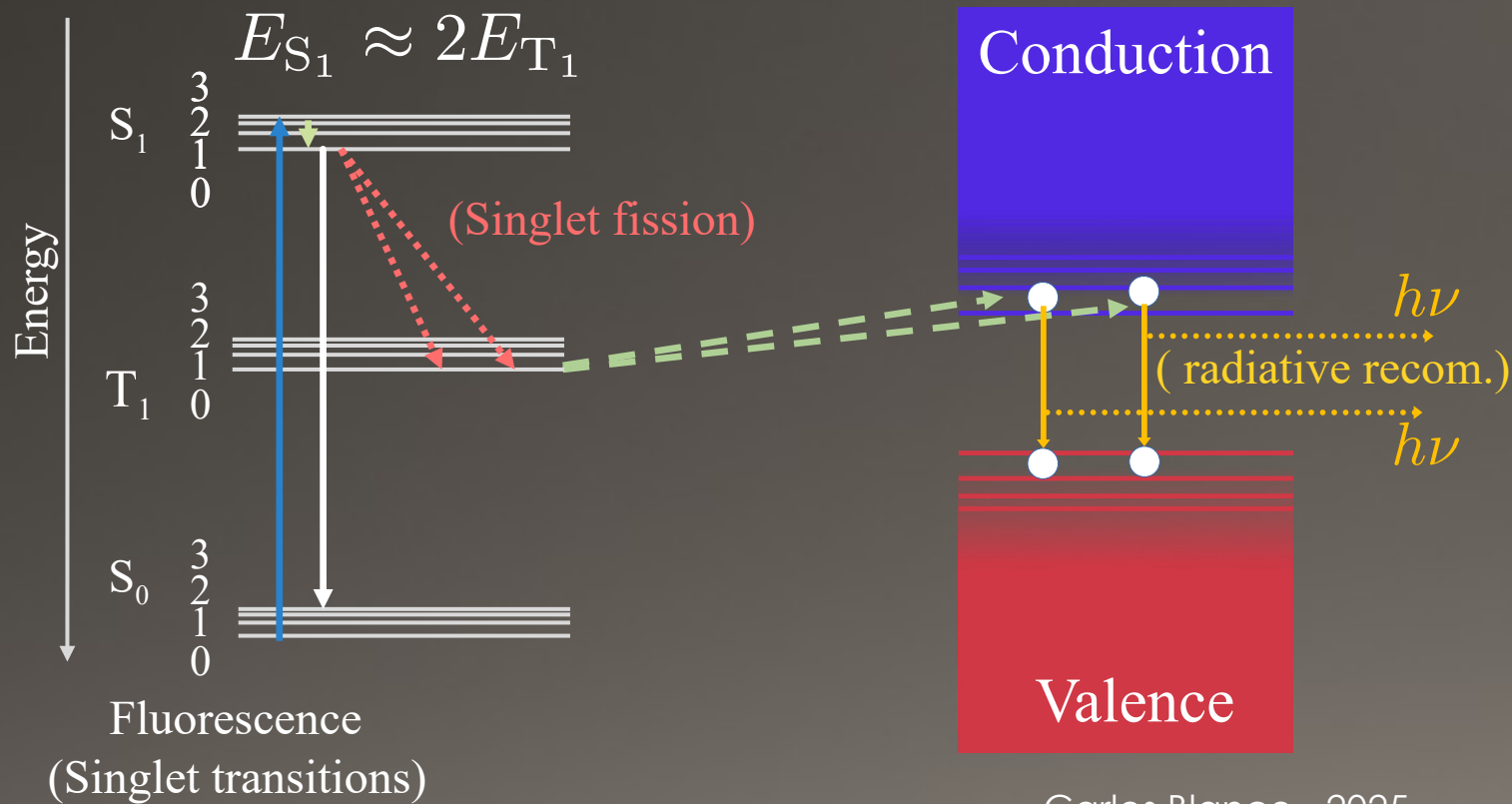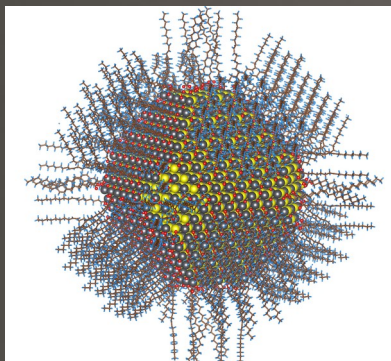\end{aligned}
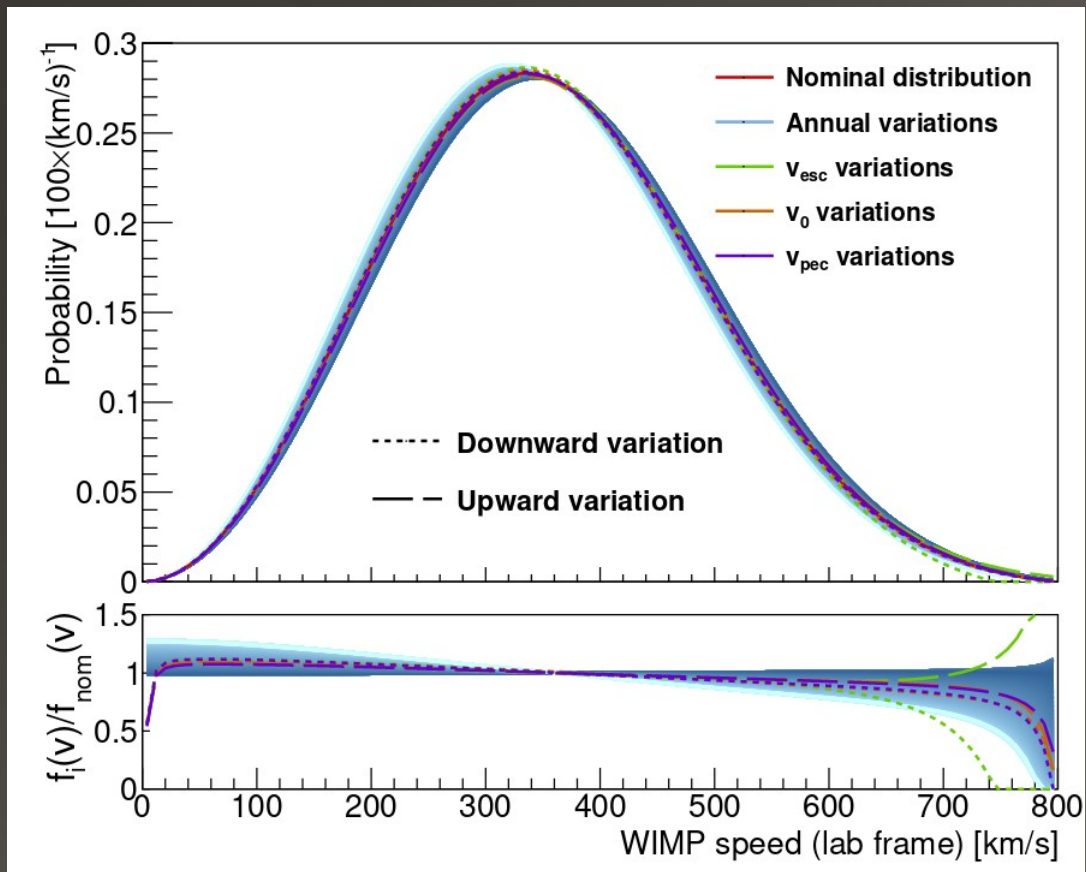$$

Daily Modulation: Light Mediator

Same as previous figures (top) for a light mediator DM form factor $F_{\mathrm{DM}} = (\alpha m_e/q)^2$. Here, the contour plots show $F_{\mathrm{DM}}^2|f(s_1)|^2$ 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.

$E_{S_1} \approx 2E_{T_1}$
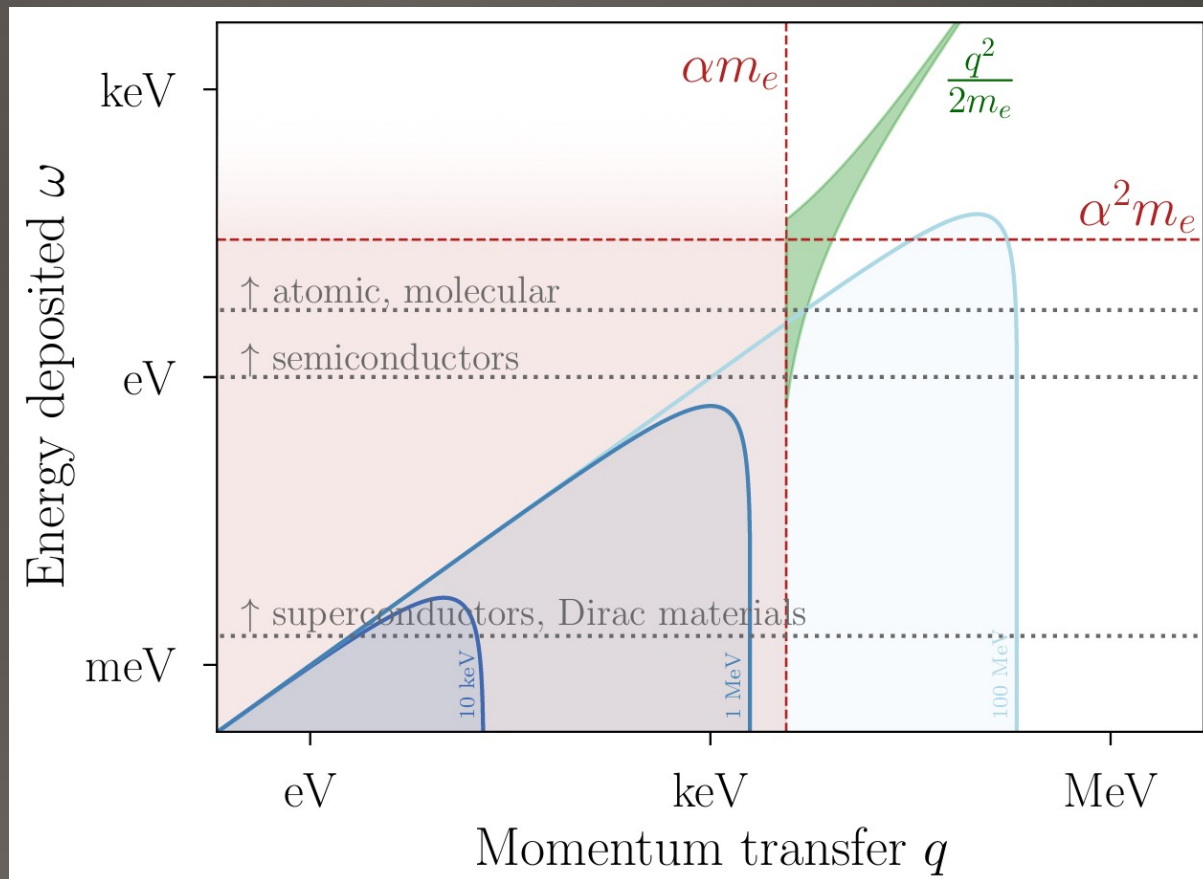
(Triplet diffusion)

(Singlet fission)

Conduction

Energy

S$_1$ 3 2 1 0

T$_1$ 3 2 1 0

S$_0$ 3 2 1 0

$h\nu$

(radiative recom.)

$h\nu$

Valence

Fluorescence
(Singlet transitions)

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Local DM Phase Space

Baxter, D., et al. "*Recommended conventions for reporting results from direct dark matter searches*." The European Physical Journal C 81.10 (2021): 1-19.

Lin, Tongyan. "*Sub-GeV dark matter models and direct detection*." SciPost Physics Lecture Notes (2022): 043.