

Through the Dark Mirror: New Paths to Dark Matter Detection

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International Institute of Physics 21.07.26

Many thanks to my collaborators: T. Kozynets, R. K.
Leane, C. Blanco, C. Cook, J. Shergold, A. Bodas



UNIVERSITY OF
LIVERPOOL

Dark Matter Research in Liverpool

Quantum Materials and Astroparticle Physics

Post-Doctoral Researchers



Tetiana Kozynets
Post-Doctoral Researcher



Jack Shergold
Post-Doctoral Researcher



Juri Smirnov
Principal Investigator

PhD Students



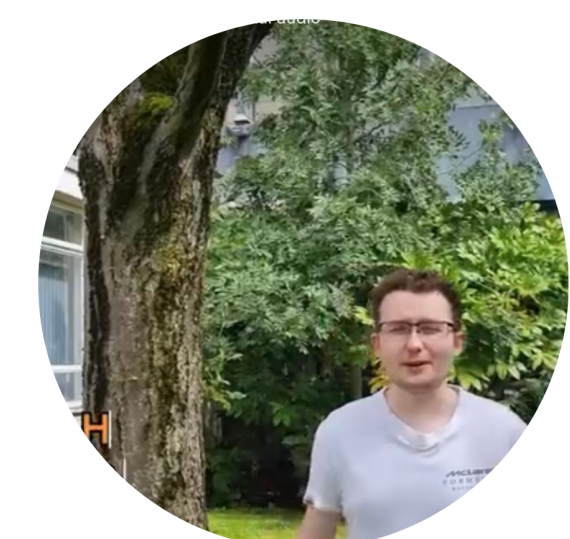
Cameron Cook
PhD Student



Jacinto Paulo Neto
PhD Student
Visitor



Erin Charnley
PhD Student



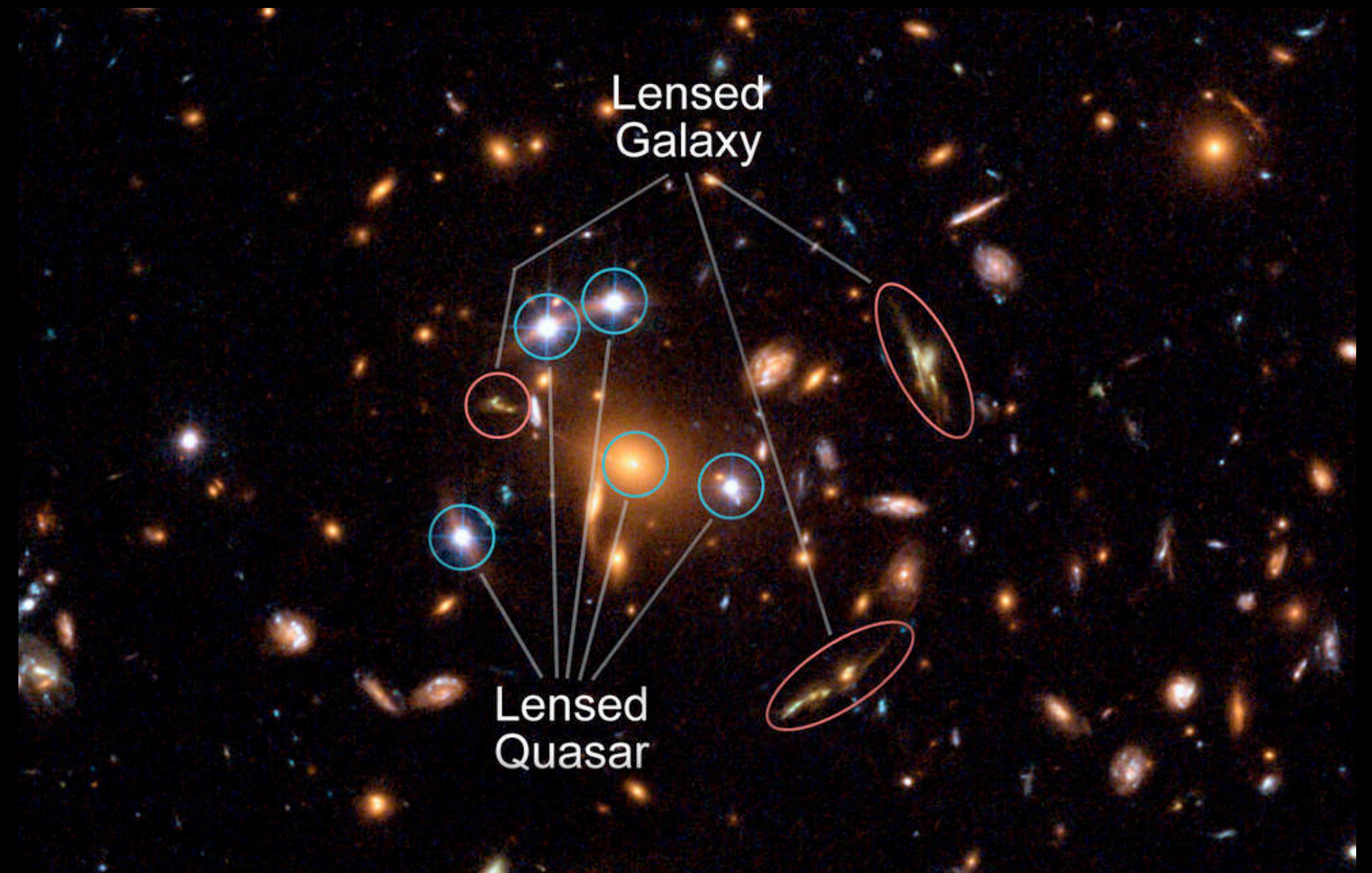
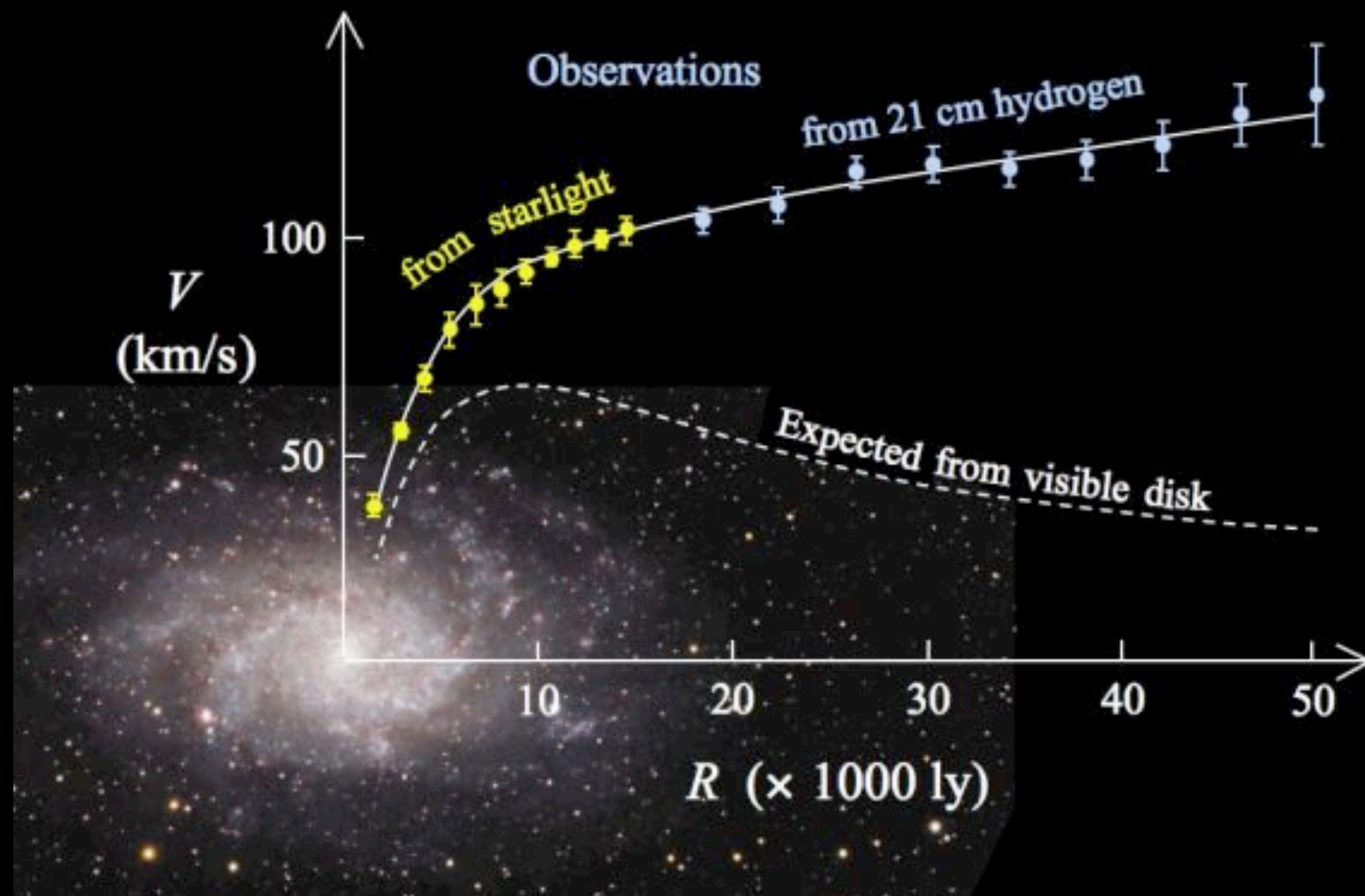
Henry McKeena
PhD Student



Insta: @qu.map

Observational Evidence

Evidence in Different Systems



Don't Mess wit the Force

Observed:

$$R_c \sim M^{1/3}$$

Expected from a matter system of given density

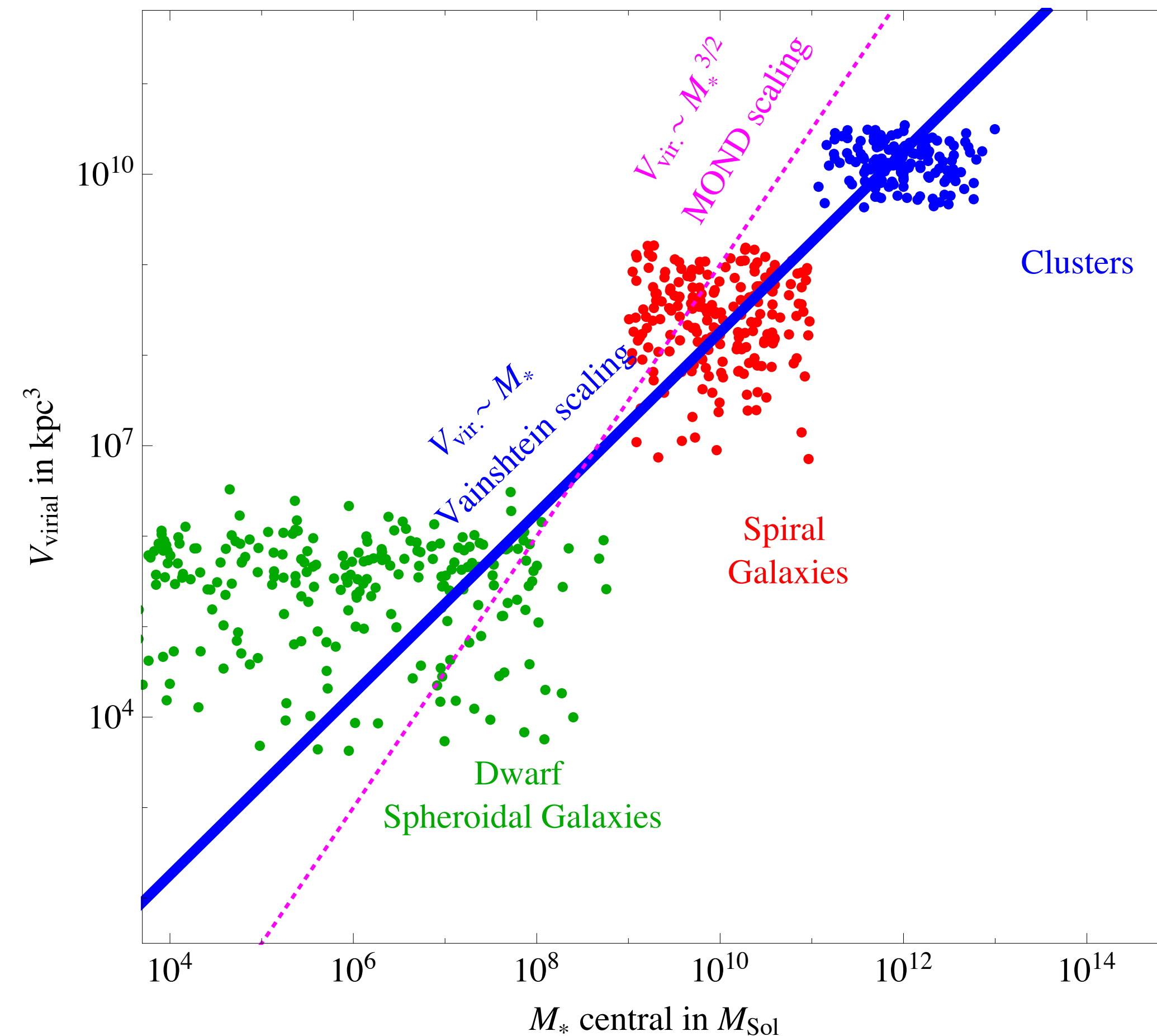
Modified Newtonian Dynamics (MOND):

$$a_c = \text{constant} \sim M/R_c^2$$

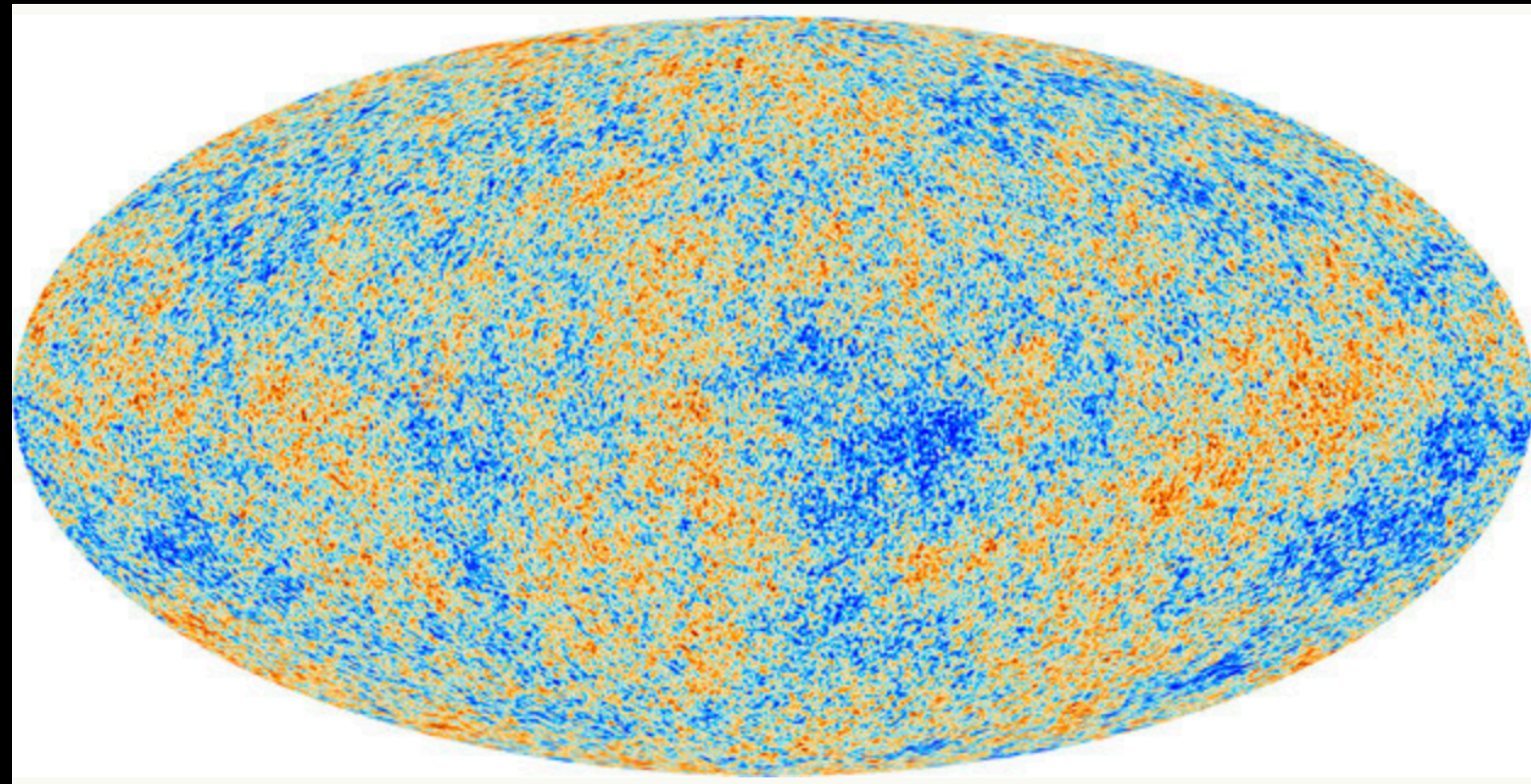
Implies:

$$R_c \sim M^{1/2}$$

Difficult to reconcile across systems.



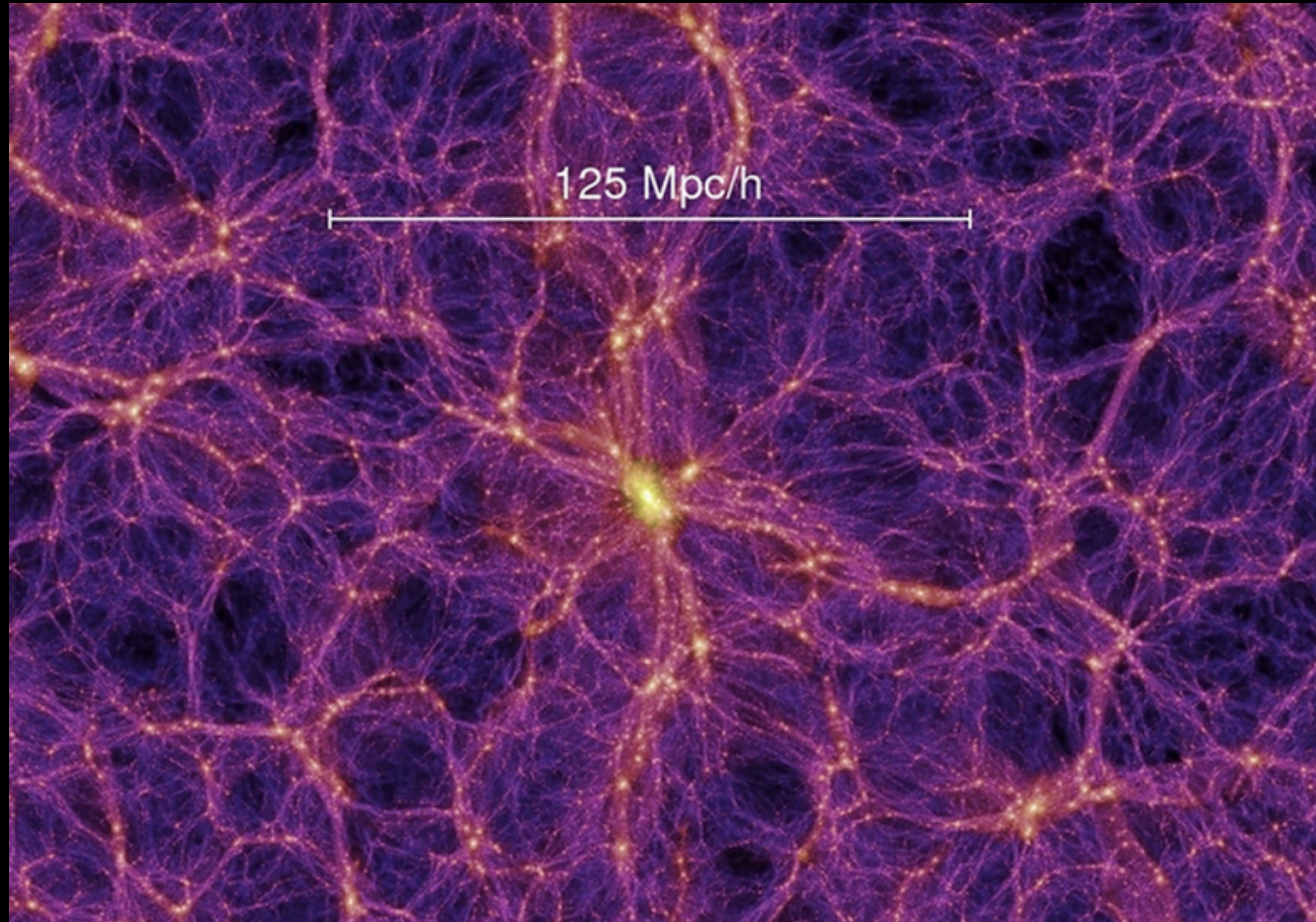
The Matter Budget



We need about 25 % of our
Universal budget to be matter
(Zero pressure fluid)

A large fraction of that matter
has to interact
weakly with radiation

Seeded Structure Formation



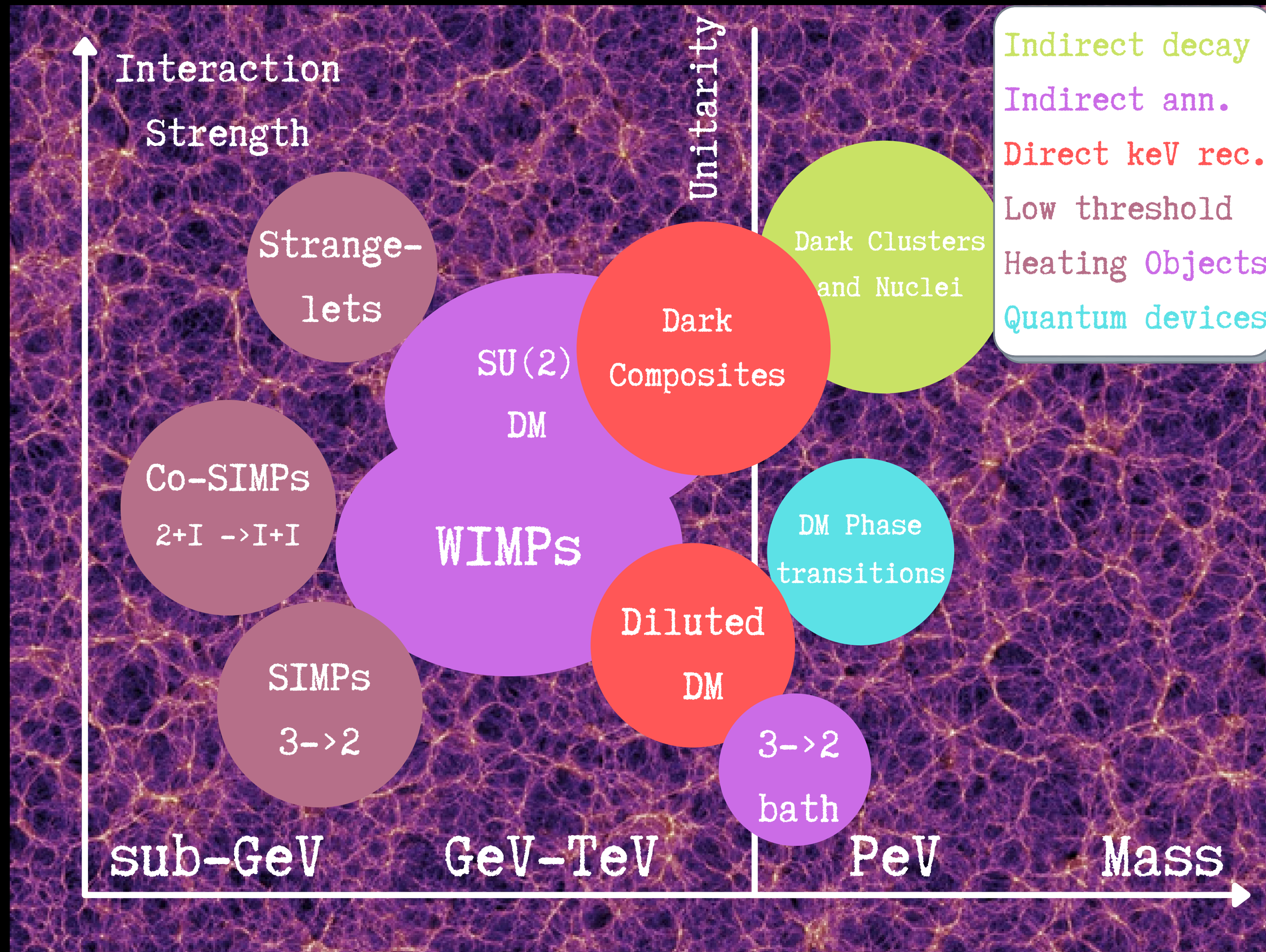
Structure
forms from
local seeds

Again we
find that
about 90% of
the matter
needs to
form diffuse
halos

To form seeds we can't have neutrinos as DM either ...

Origin of Dark Matter

Dark Matter Scenario Space



Motivated by UV and Quantum Gravity

$$E_8 \times E_8$$

↓
Reheating
GUT

↓
SM + Dark Sector

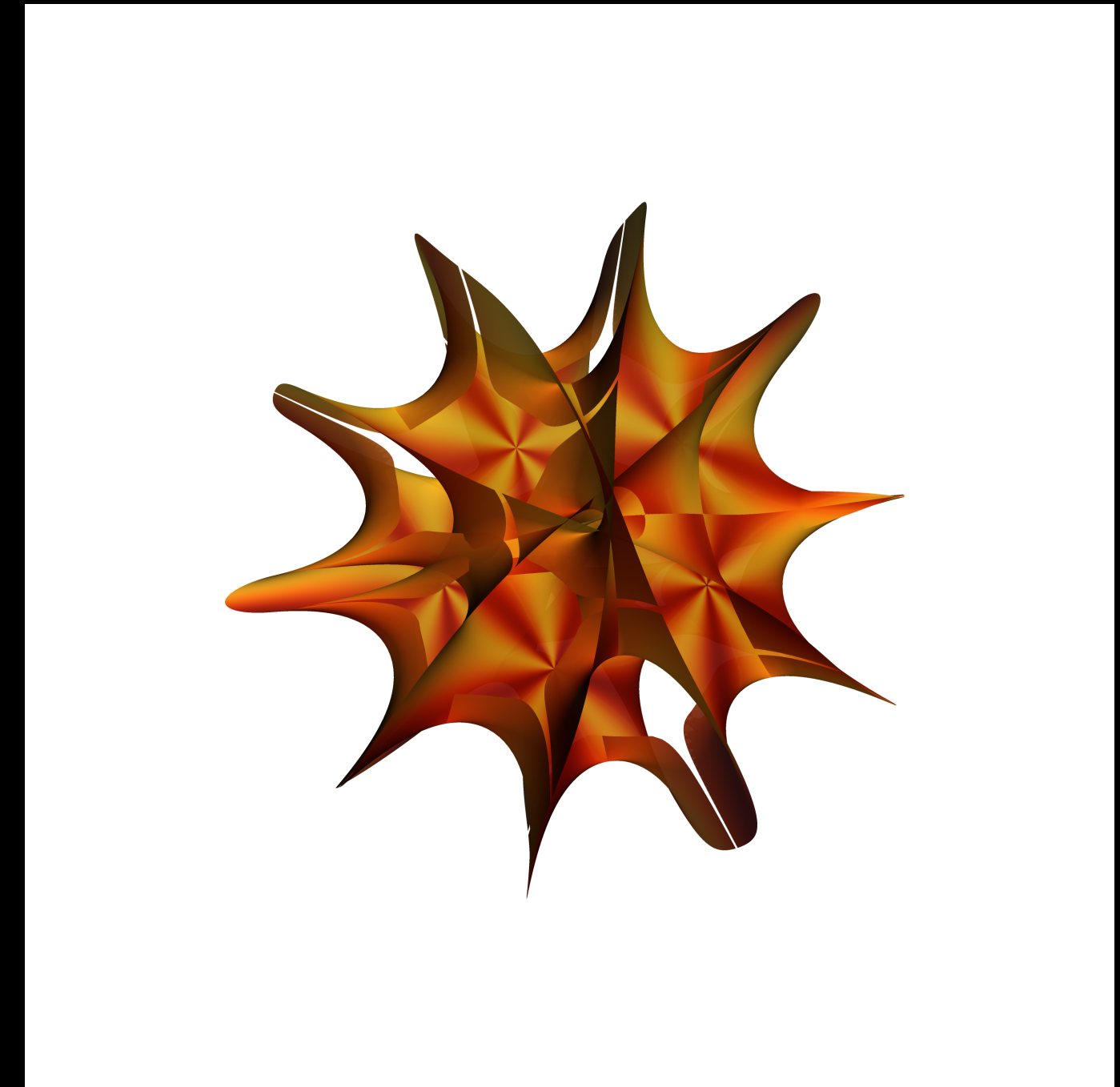
$$E_8 \times E_8$$

Reheating

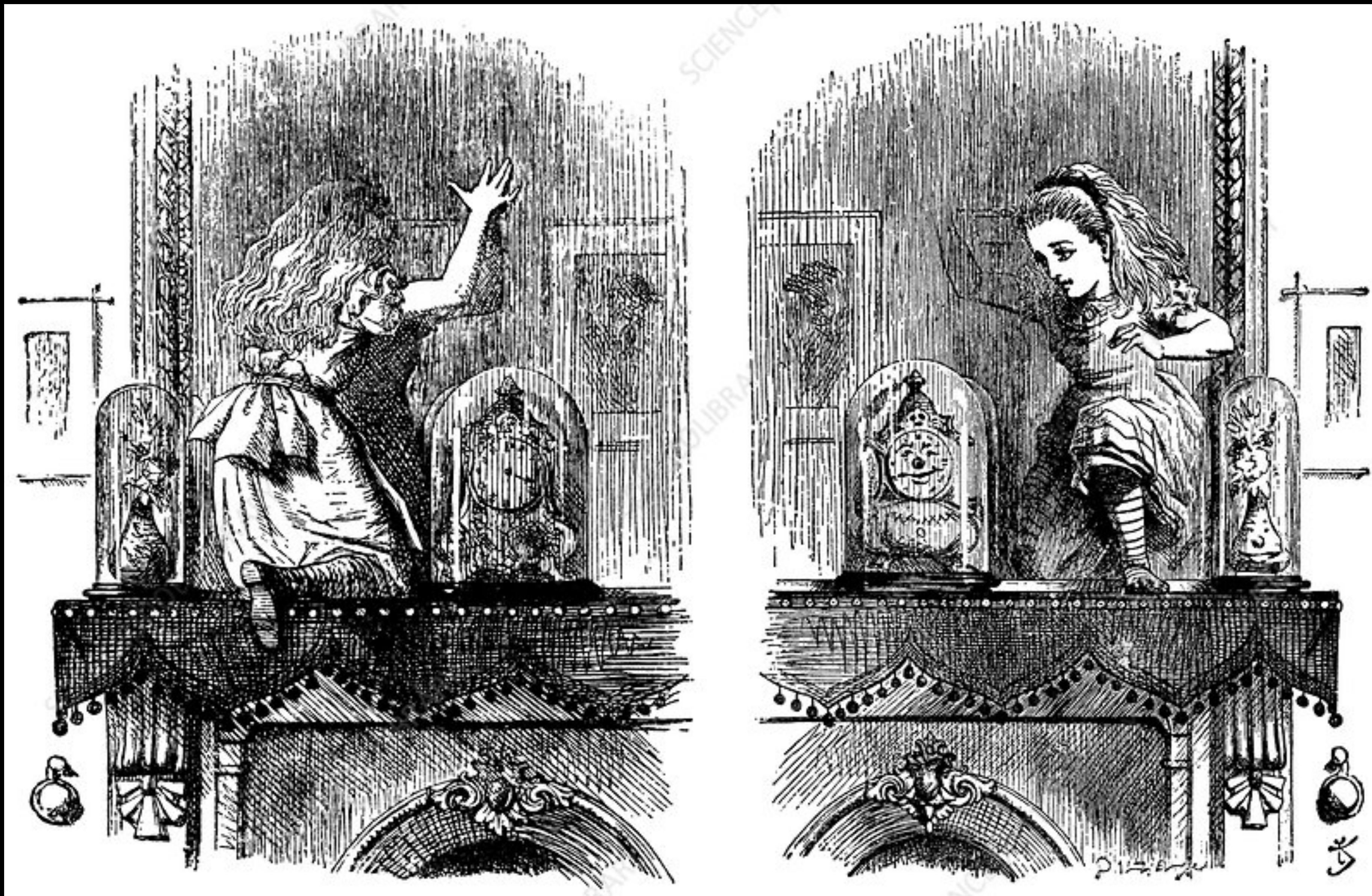
↓ ↓
GUT GUT'

↓ ↓
SM Shadow SM

$\sim Z_2$



Schematic of a CY



Through the looking glass, Lewis Carroll

A Slightly Broken Mirror

- + Shadow version of the SM
- + Approximate Z_2 , softly broken
- + Asymmetric Inflaton Coupling
- + Reheating $T' < T$ is compatible with CMB
- + Higgs vev and Yukawas such that proton slightly heavier than neutron
- + Interaction weak: gravity, $U(1)$ mixing, axions

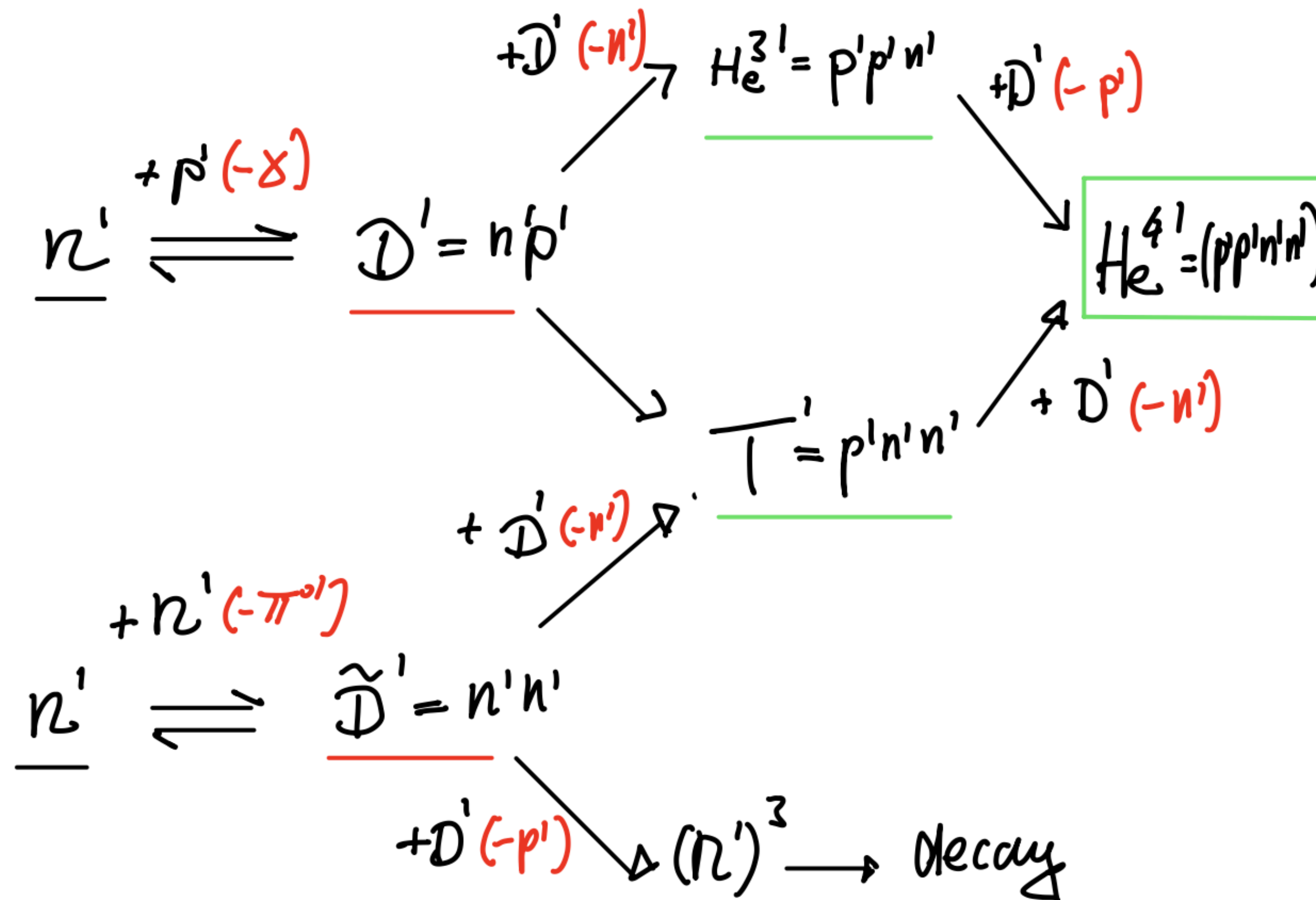
Shadow protons decay

$$p' \rightarrow n' + e'^+ + \nu'_e$$

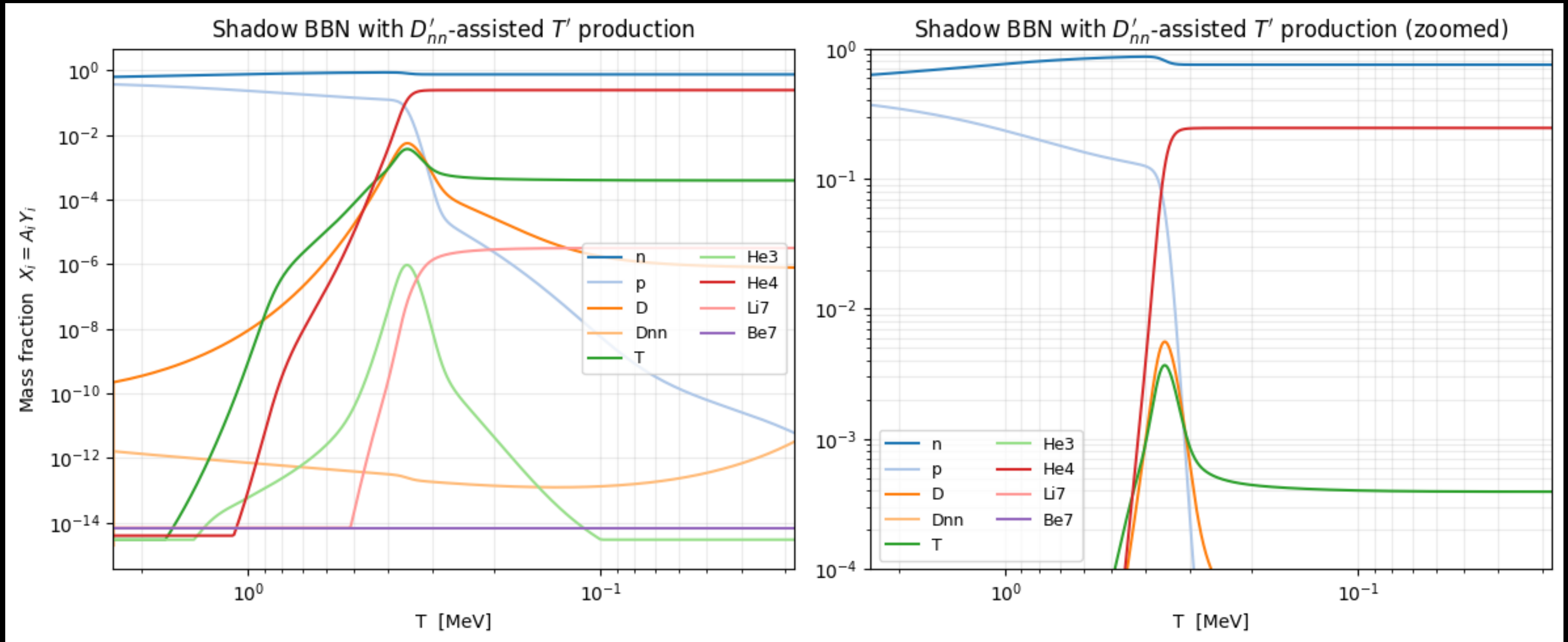
But shadow nucleons can be stable

$$p' + n' \rightarrow D' + \gamma$$

Shadow BBN Network



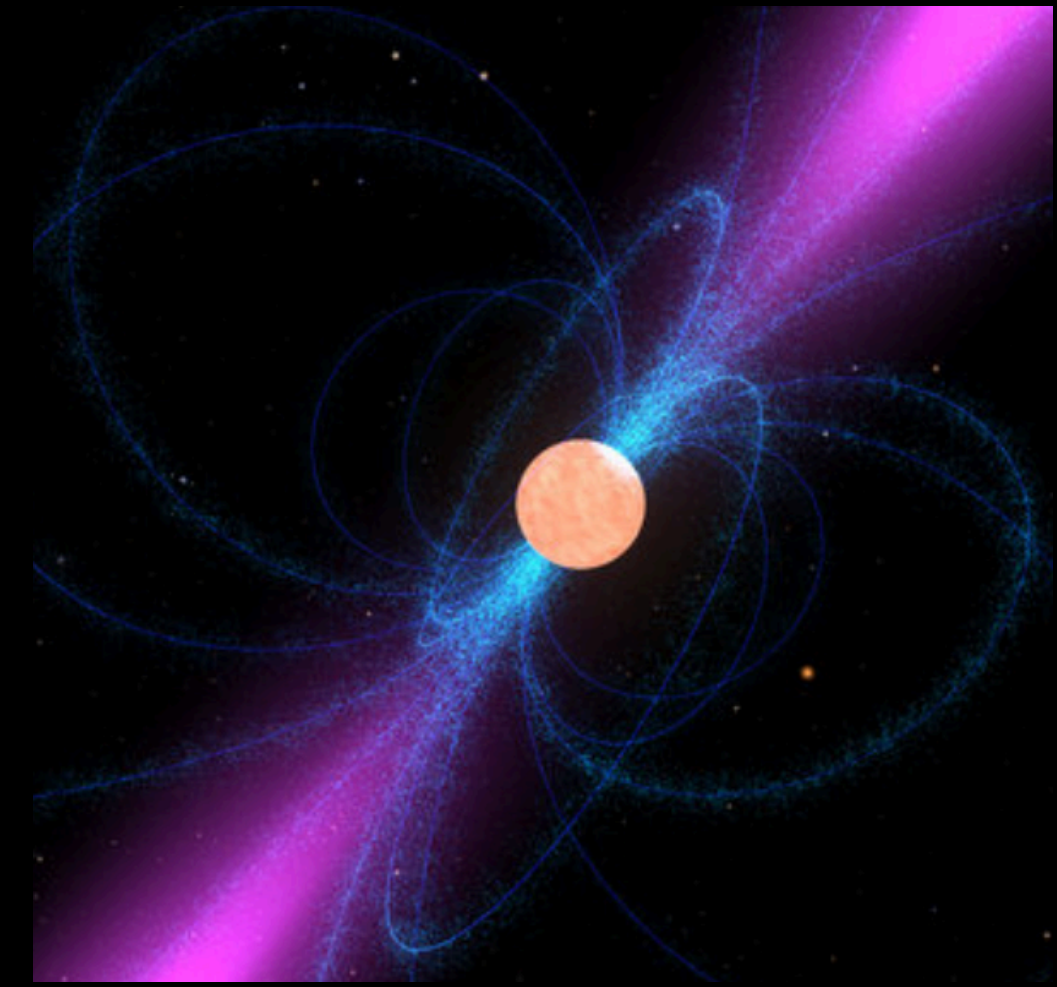
Shadow Nucleosynthesis



$$T' \sim 0.3 T_{\text{SM}}$$

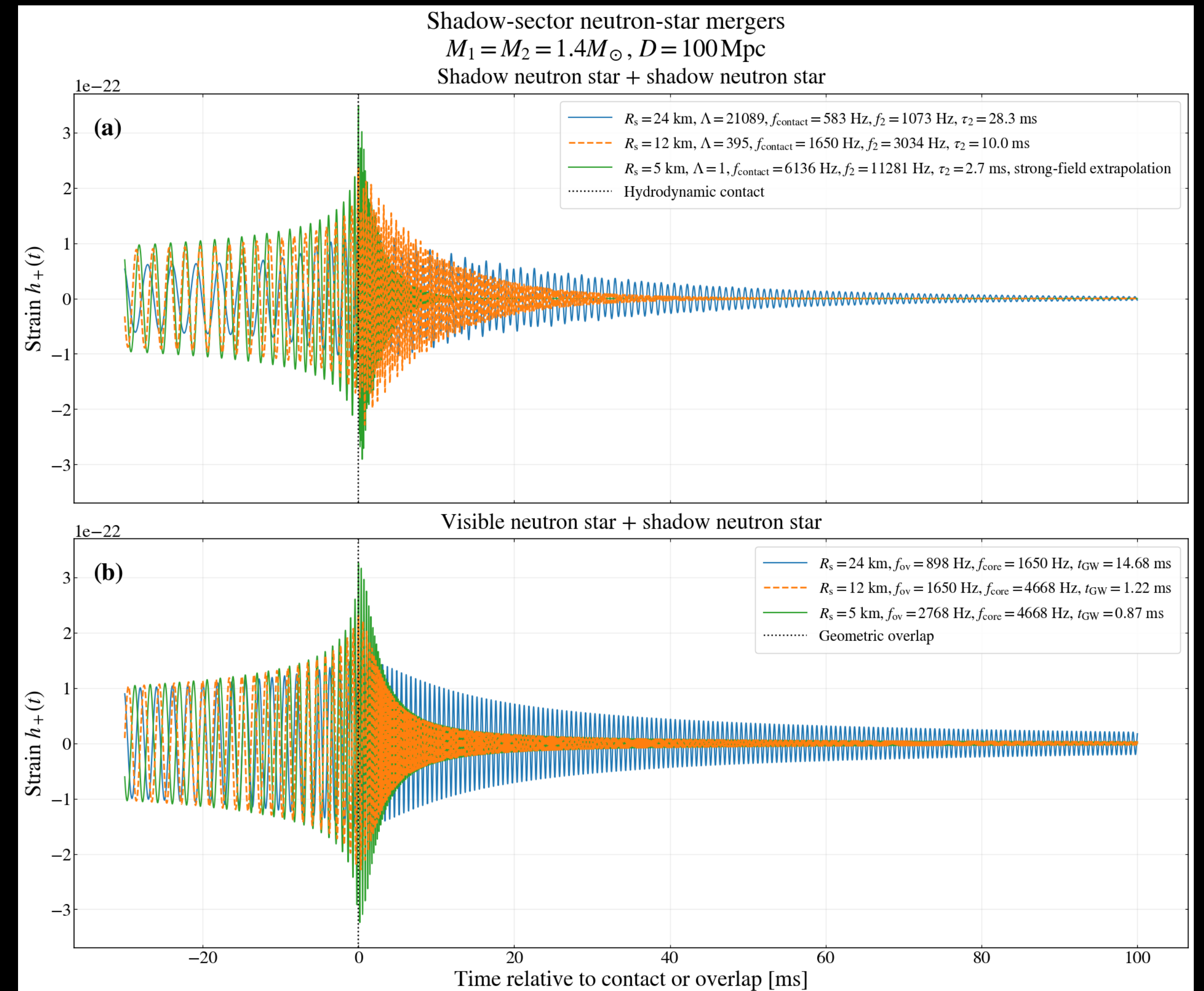
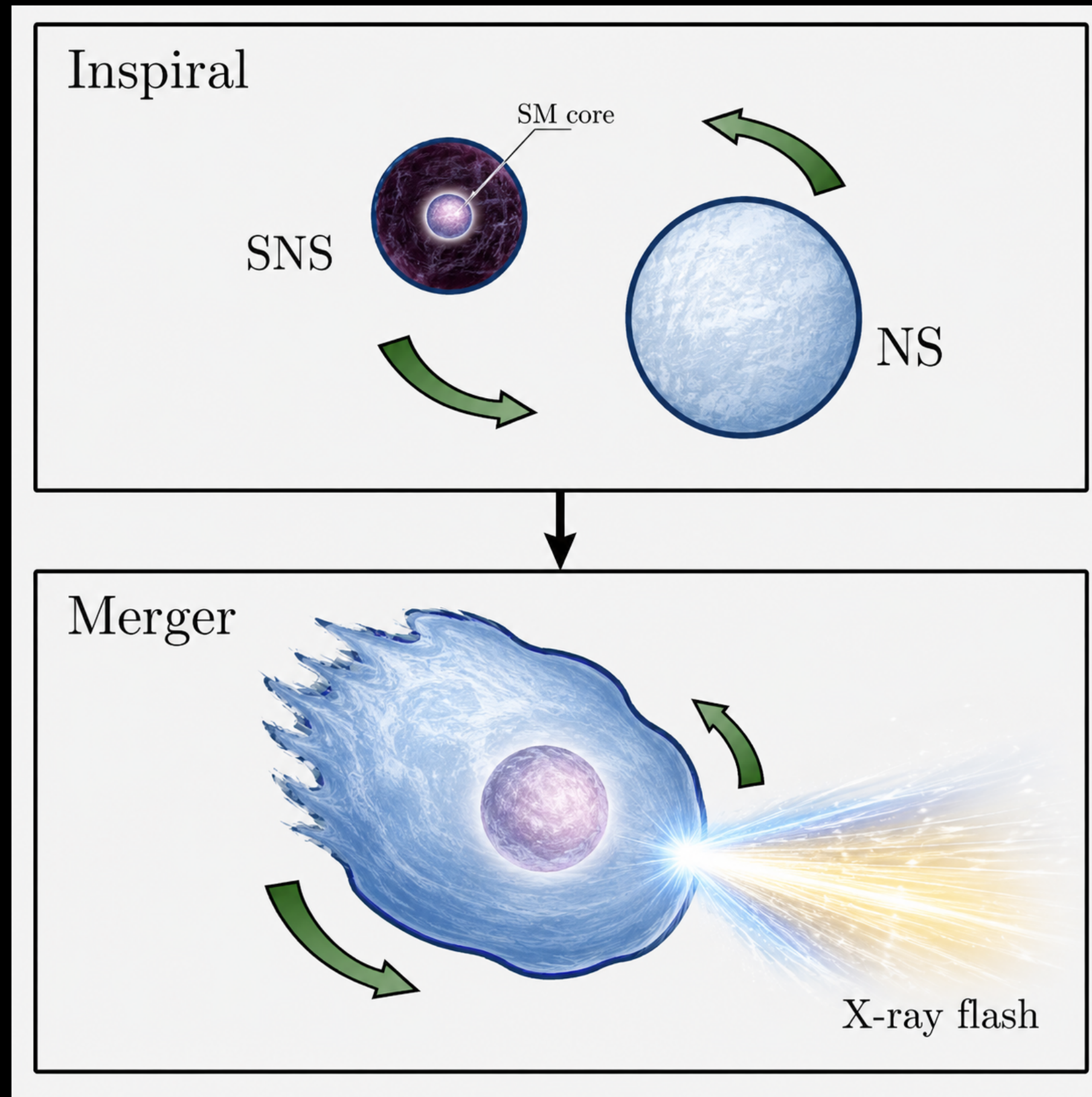
Shadow Sector forms Halos and Structures!

- + In addition to shadow neutron halo dissipative plasma:
(99% $4\text{He}'$), (1% T')
- + ($4\text{He}'$) drives high-temperature cooling; (T'/T^2') enables lower-temperature cooling
- + Dissipation forms a dark disk, clouds and shadow stars
- + High cooling floor $\rightarrow$ large Jeans masses and rapid accretion
- + Shadow-star IMF is top-heavy, roughly Population-III-like: Typical masses: 10 - 100 MSun with efficient (D/T^2') cooling, and direct BH collapse without it
- + Short-lived massive stars end mainly as shadow neutron stars or black holes



Astrophysical Searches for Shadow Worlds

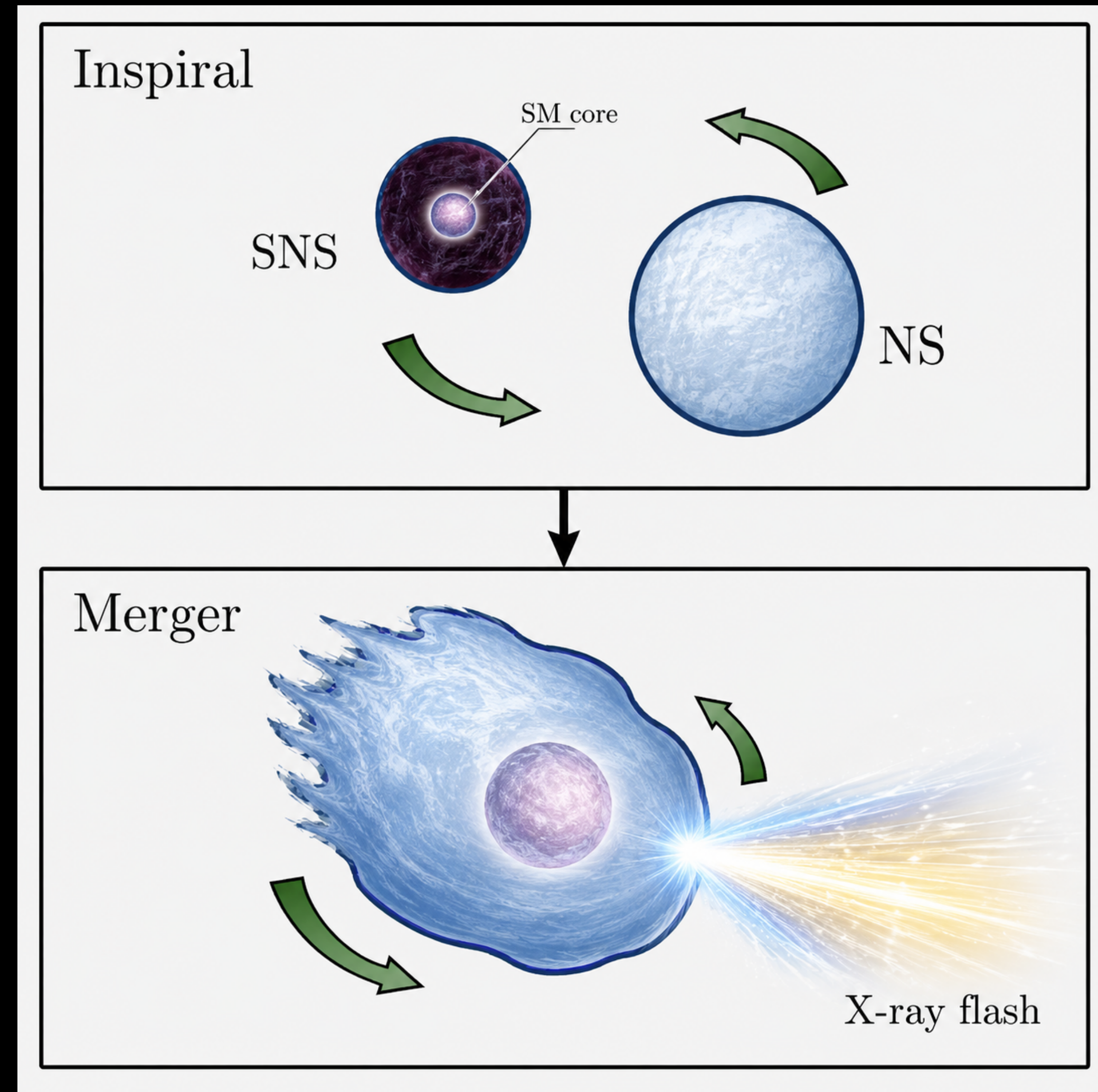
GW and Multi messenger Signals



X-rays from captured SM Matter

- + SM matter in a compact core inside the shadow neutron star.
- + During merger, this SM core is shock-heated producing a hot thermal photon bath.
- + The characteristic temperature reaches the keV regime, so the prompt emission peaks in X-rays.
- + Unlike an ordinary NS mergers, there is much less surrounding SM material.
- + X-rays therefore encounter a smaller SM optical depth and escape more easily
- + Visibility reaches the Mpc scale

$$E_{\gamma,\text{prompt}}^{\text{vs}} = \eta_{\text{bo}} E_{\text{dep}}^{\text{vs}} \simeq 10^{40} \text{ erg} \left(\frac{\eta_{\text{bo}}}{10^{-3}} \right) \left(\frac{M_{\text{cap}}}{10^{23} \text{ g}} \right).$$



Direct Detection of Shadow Matter

Expected Interactions and Cross Sections

$$\epsilon F_{\mu\nu} F'^{\mu\nu} \text{ and } m'_x \approx 0$$

$\Rightarrow$ millicharged states $q = \epsilon e$

Shadow bound states:

$n' = (u' d' d')$ neutral state

$$n' \text{ residual int.} \Rightarrow \underline{\sigma_{n'p} \sim 10^{-51} \left(\frac{\epsilon}{10^{10}}\right)^2 \text{ cm}^2}$$

a) Atoms:

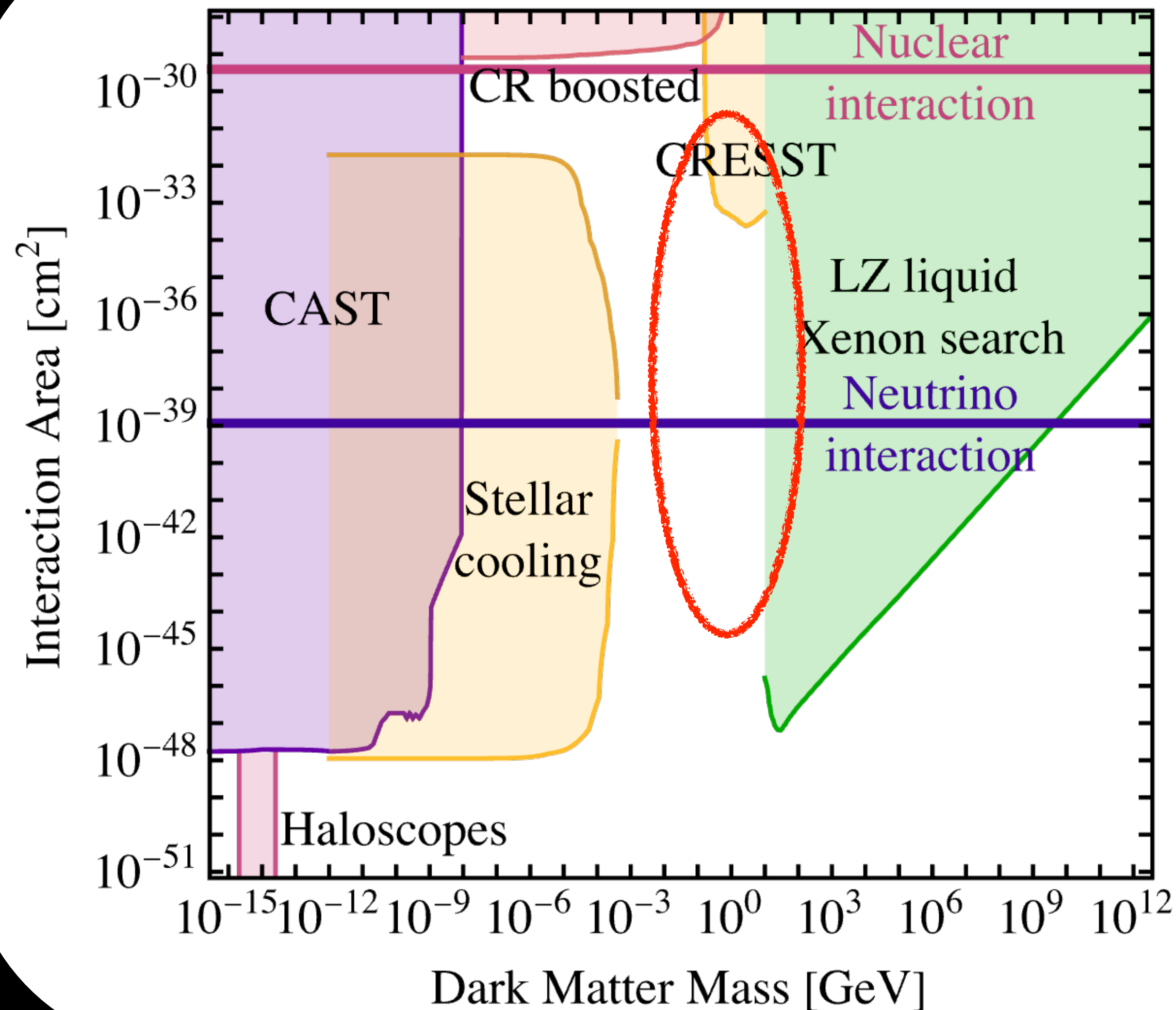
$$e' \left(\begin{array}{c} n' n' \\ p' p' \end{array} \right) e' \int \sim \frac{1}{\alpha' m_{e'}} \left\{ \begin{array}{l} v \sim v_0 \rightarrow \underline{\sigma_{Ap} \sim 10^{-37} \left(\frac{\epsilon}{10^{10}}\right)^2 \left(\frac{10^{-3}}{v}\right)^4 \text{ cm}^2} \\ v \ll v_0 \rightarrow \underline{\sigma'_{Ap} \sim 10^{-30} \left(\frac{\epsilon}{10^{10}}\right)^2 \left(\frac{a'_0}{a_0}\right)^4 \text{ cm}^2} \end{array} \right.$$

nuclear int.

b)

$$\begin{array}{c} \text{---} \bigcirc \text{---} \\ e^- \rightarrow \text{---} \leftarrow e^- \end{array} \quad \begin{array}{l} v \sim v_0 \\ \Rightarrow \underline{\sigma_{Ae} \sim 10^{-36} \left(\frac{\epsilon}{10^{10}}\right)^2 \left(\frac{a'_0}{a_0}\right)^4 \text{ cm}^2} \end{array}$$

Direct Detection Range Cartoon



We need lower Energy Thresholds

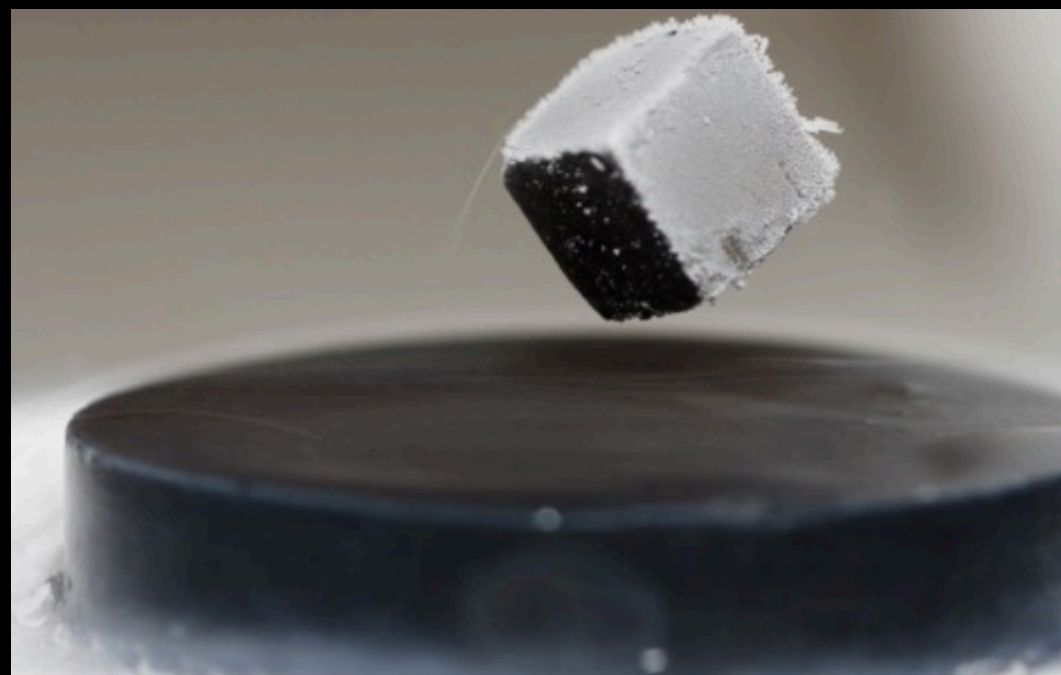


Superfluid He

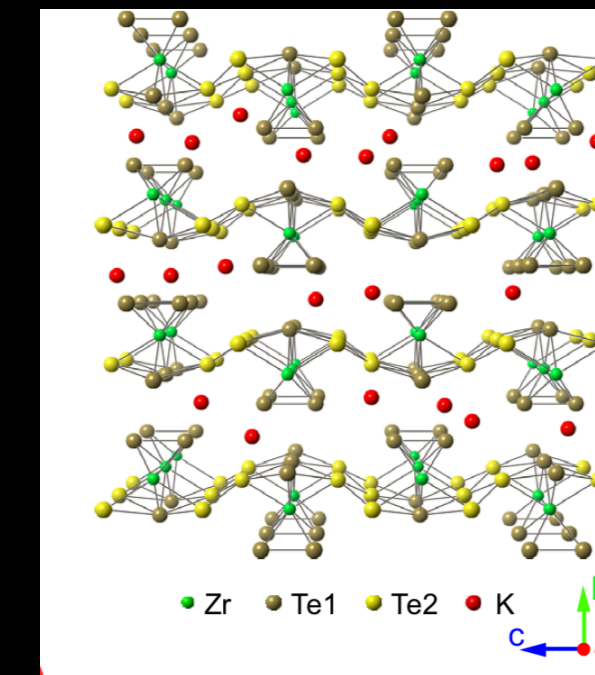


Materials with Lattice Defects

Small ΔE



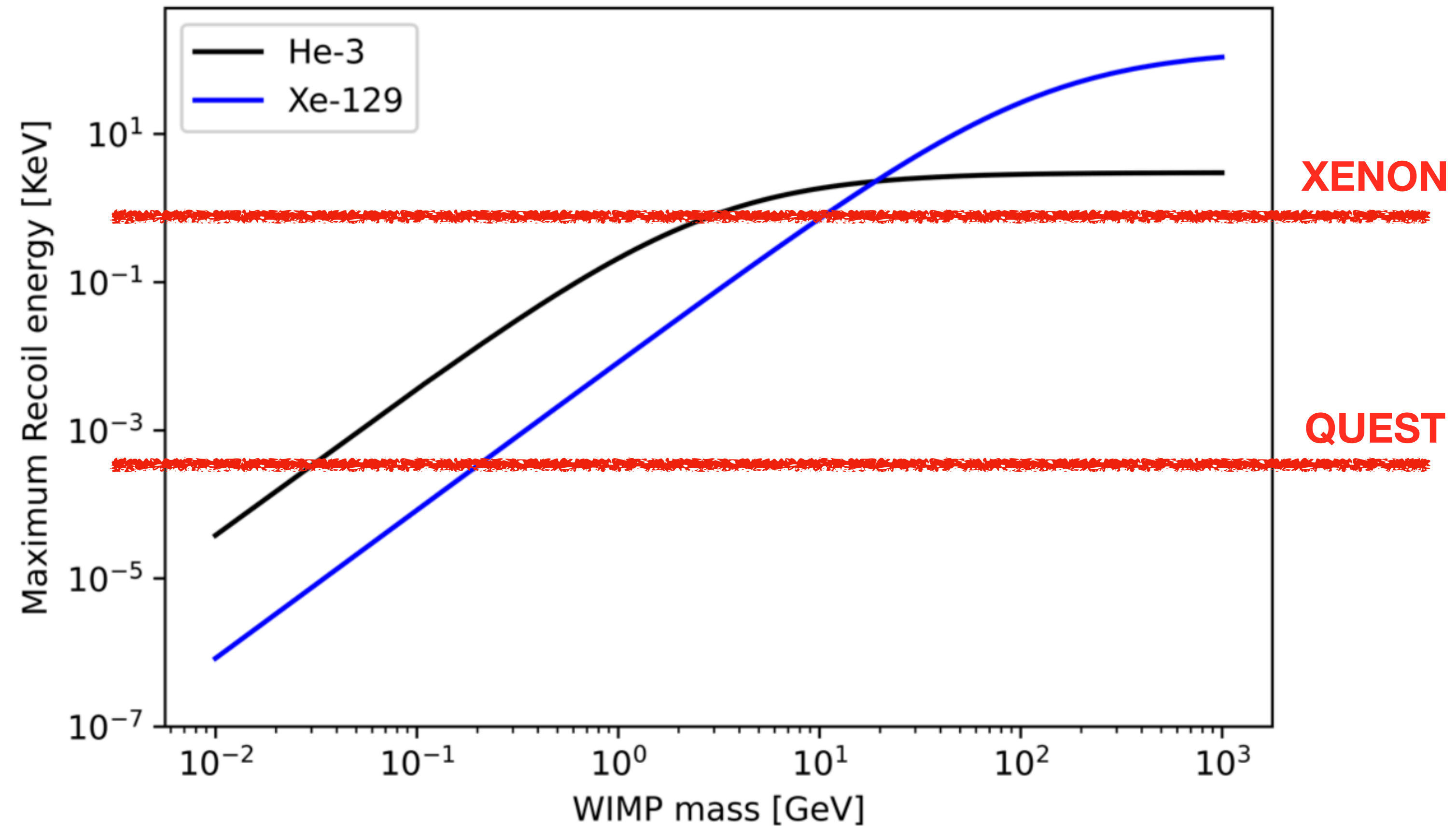
Superconductors



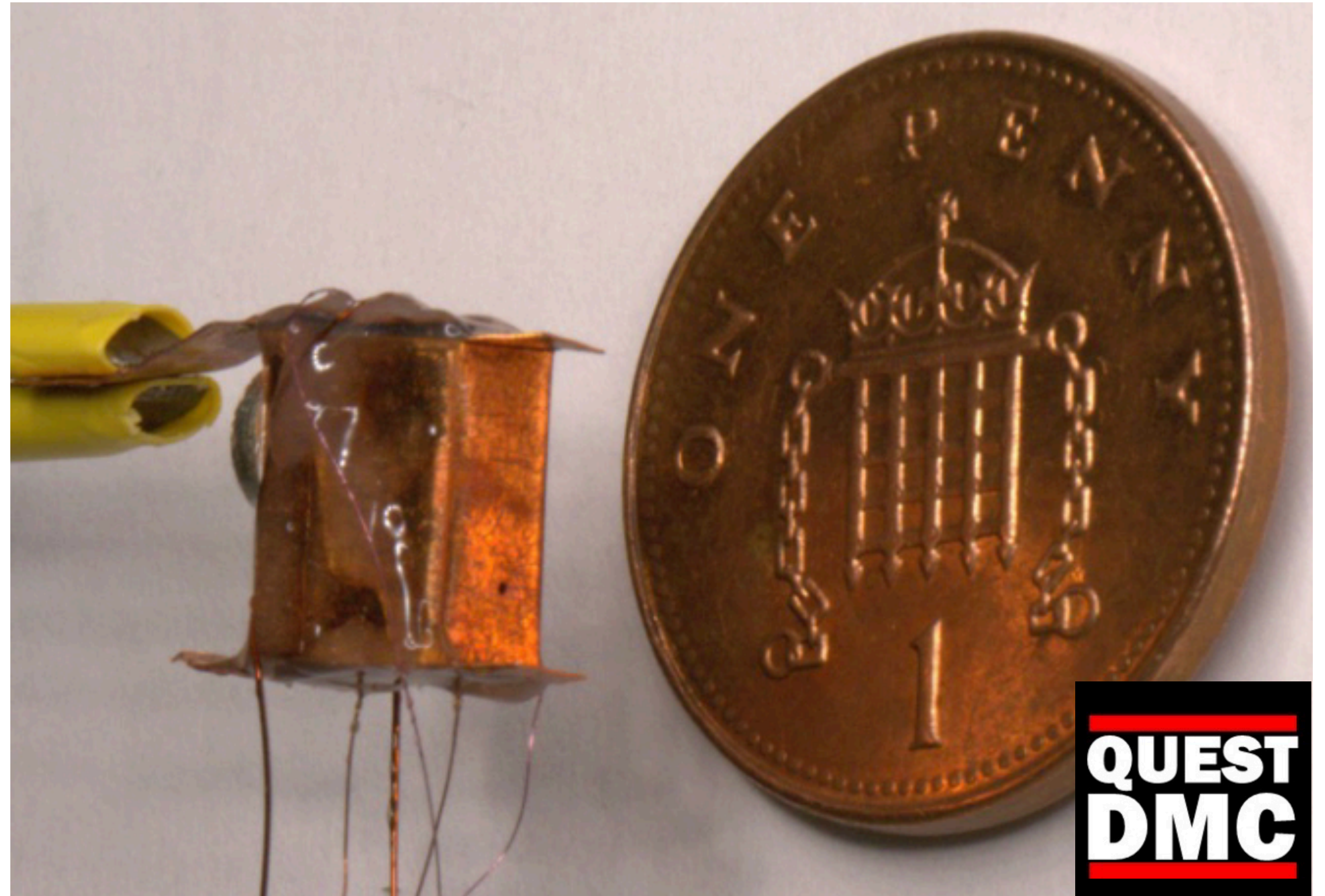
3D Dirac Materials

1) Quantum Sensing and Superfluid He3

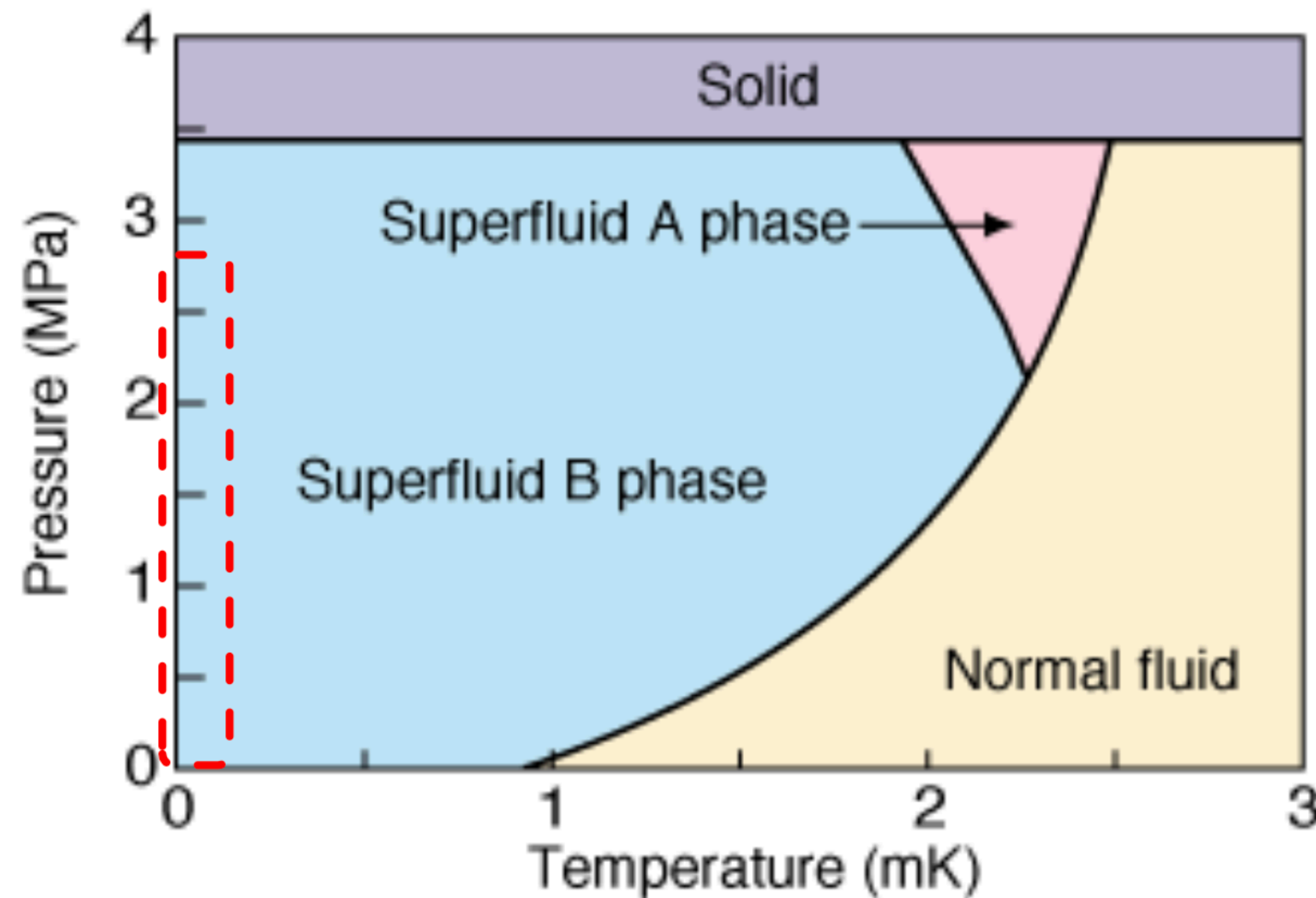
QUEST-DMC Superfluid He3



QUEST-DMC Superfluid He3



Phases of He3

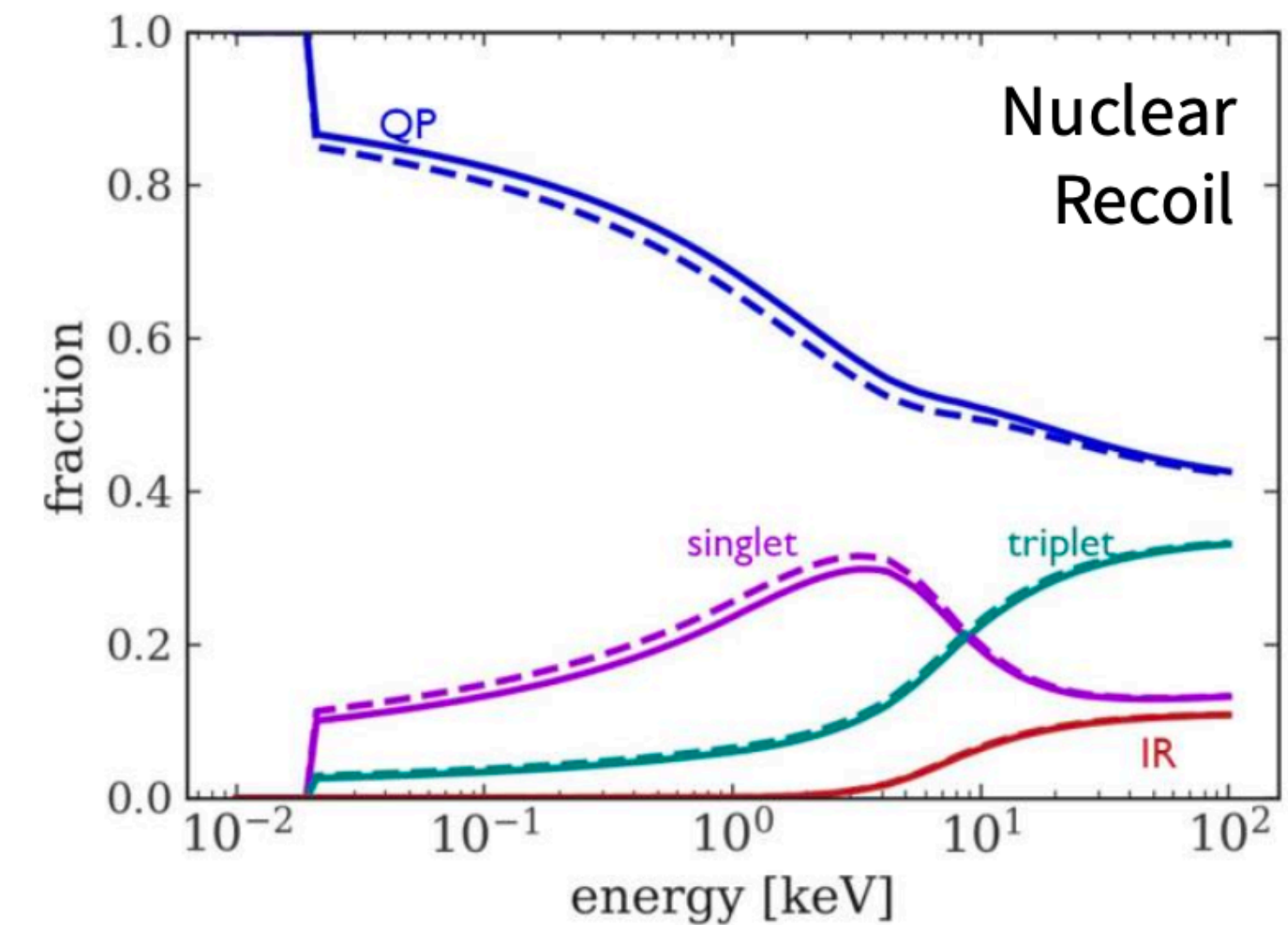
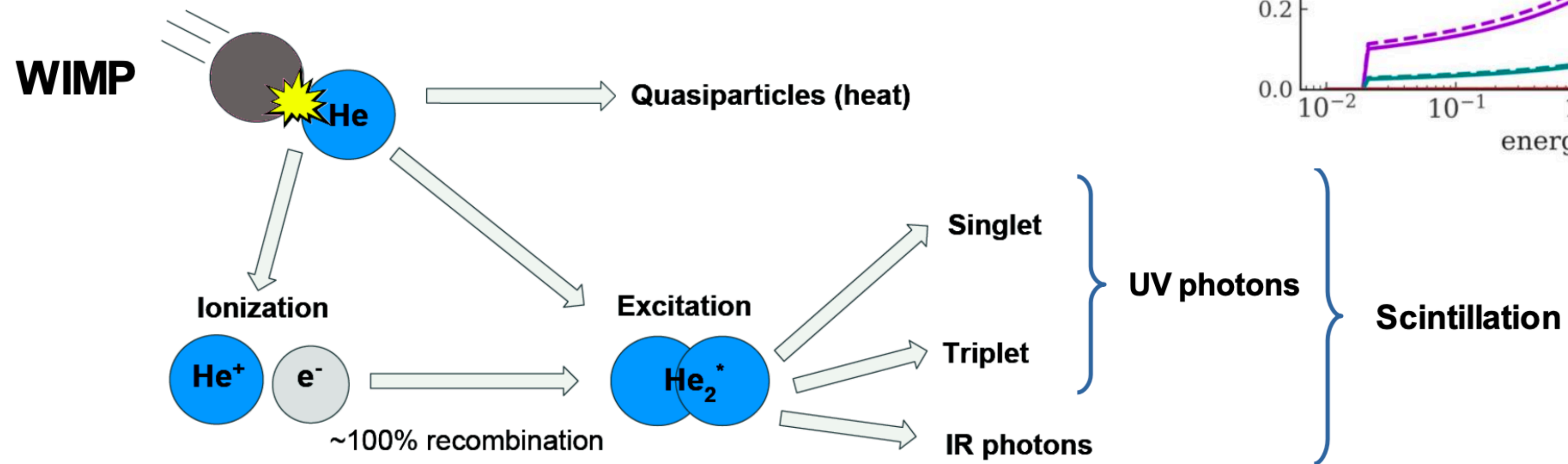


$$\Psi_A = \Delta_{\parallel}(z) \left(\begin{array}{c} L_z = -1, S_z = -1 \\ L_z = 1, S_z = 1 \end{array} \right)$$

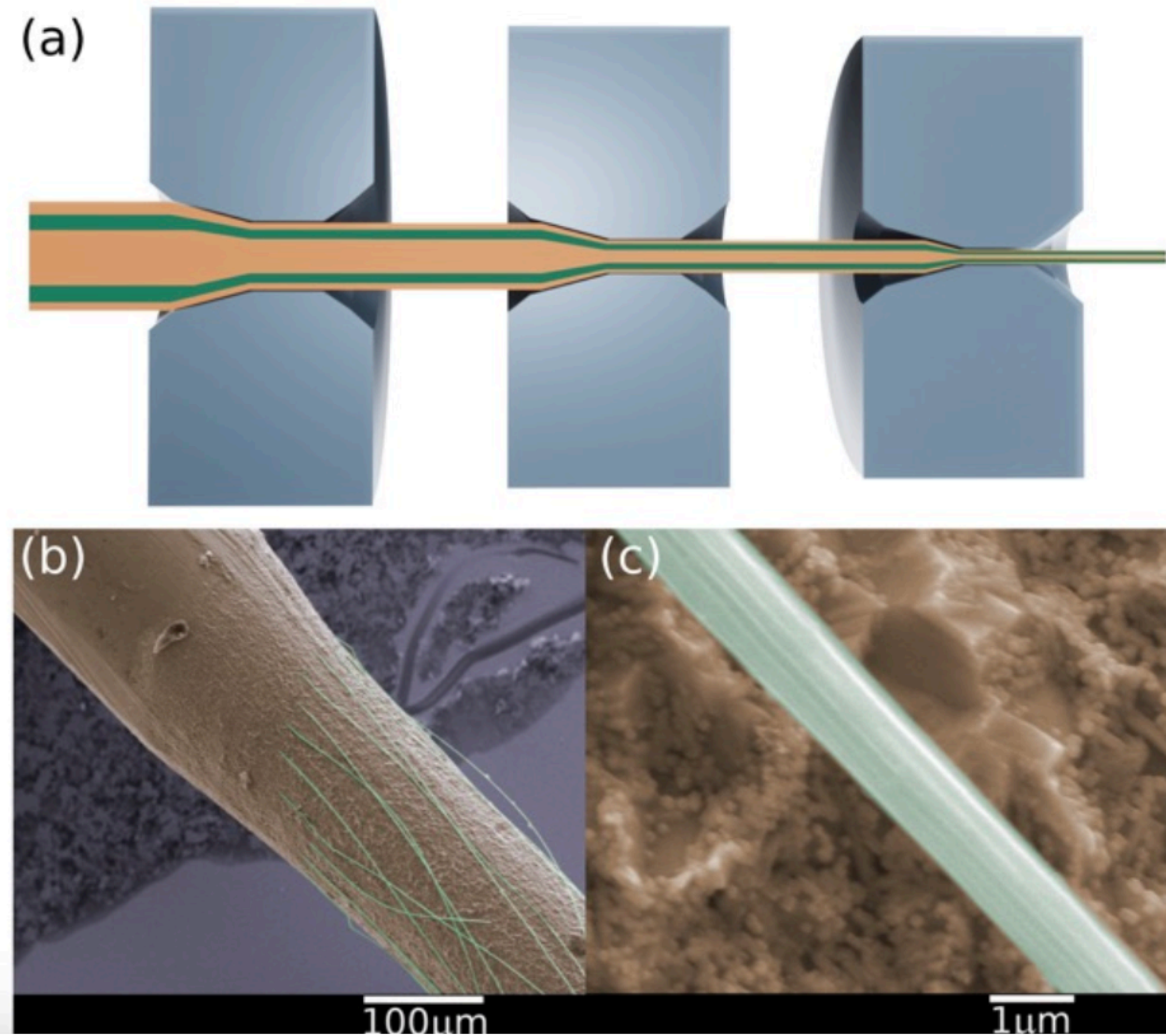
$$\Psi_B = e^{i\phi} \left(\Delta_{\parallel}(z) \begin{array}{c} L_z = 1, S_z = -1 \\ L_z = 0, S_z = 0 \\ L_z = -1, S_z = 1 \end{array} + \Delta_{\perp}(z) \begin{array}{c} L_z = 0, S_z = 0 \\ L_z = -1, S_z = 1 \end{array} \right)$$

Energy Deposition

- Collision WIMP-He³ atom
 - Heat as **quasiparticle** excitations
 - **Light** from de-excitation



Nano-wire Signal Readout



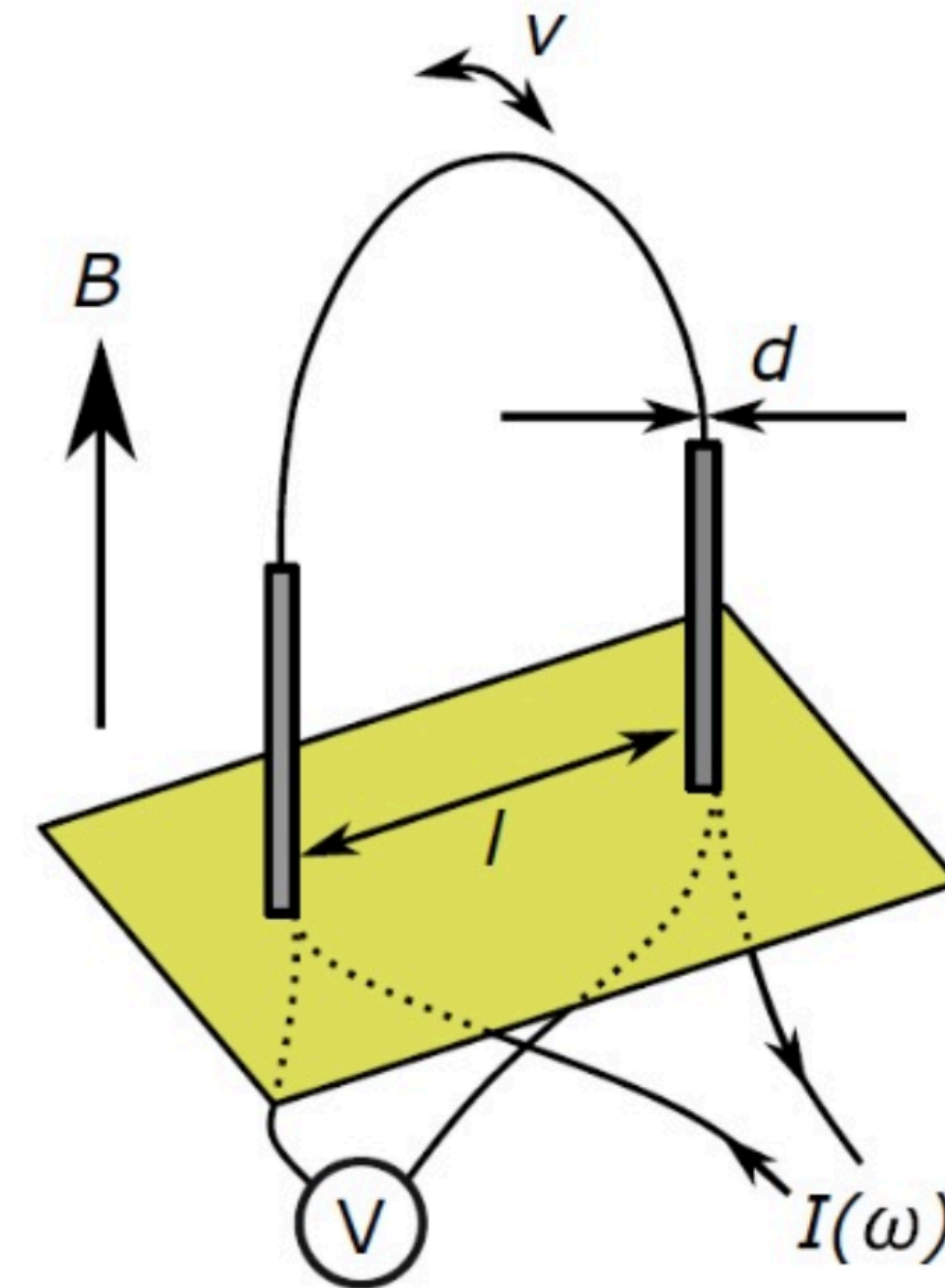
Quasi Particle Dampening

- Vibrating nanowire resonator in a vertical magnetic field

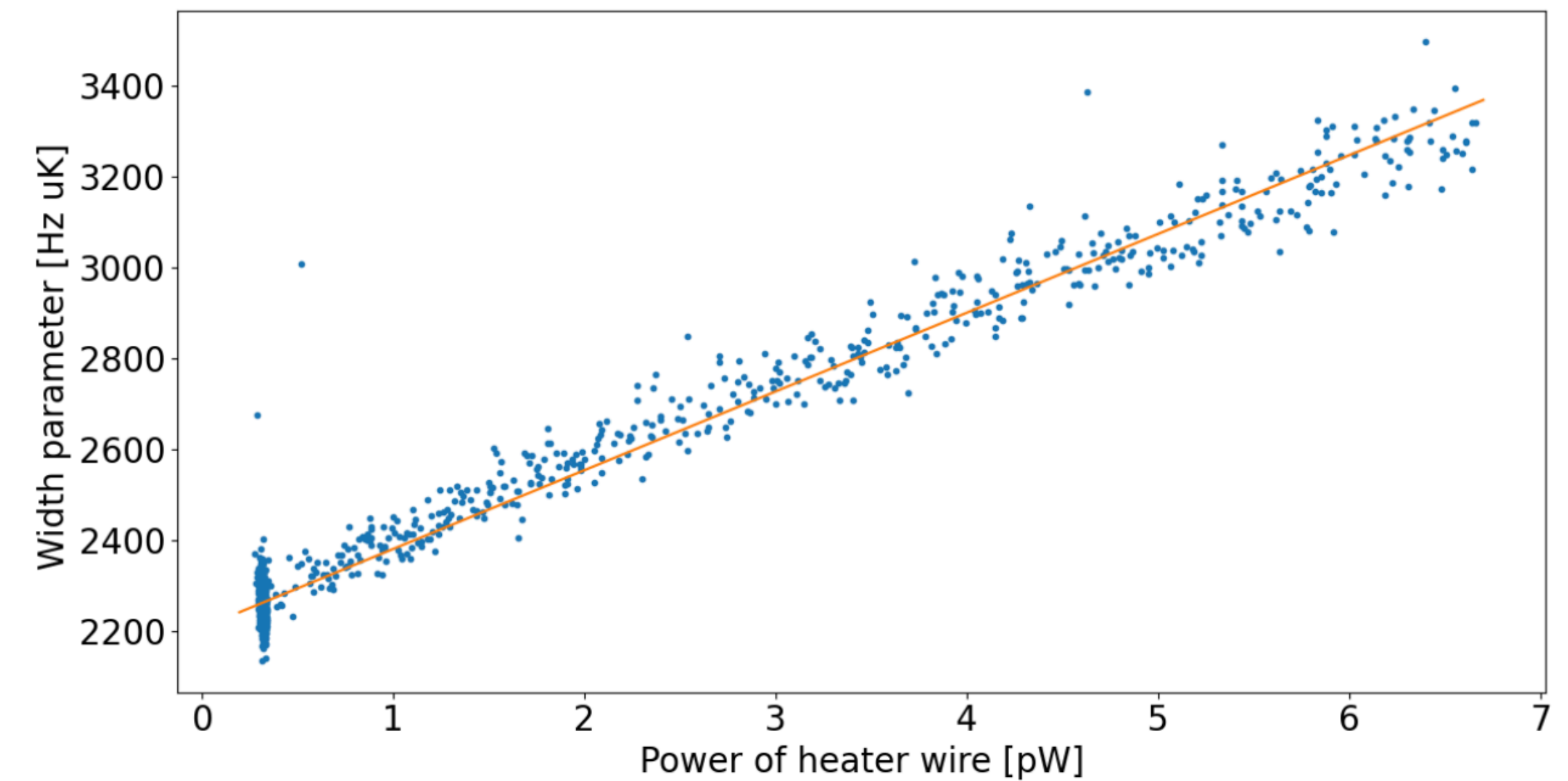
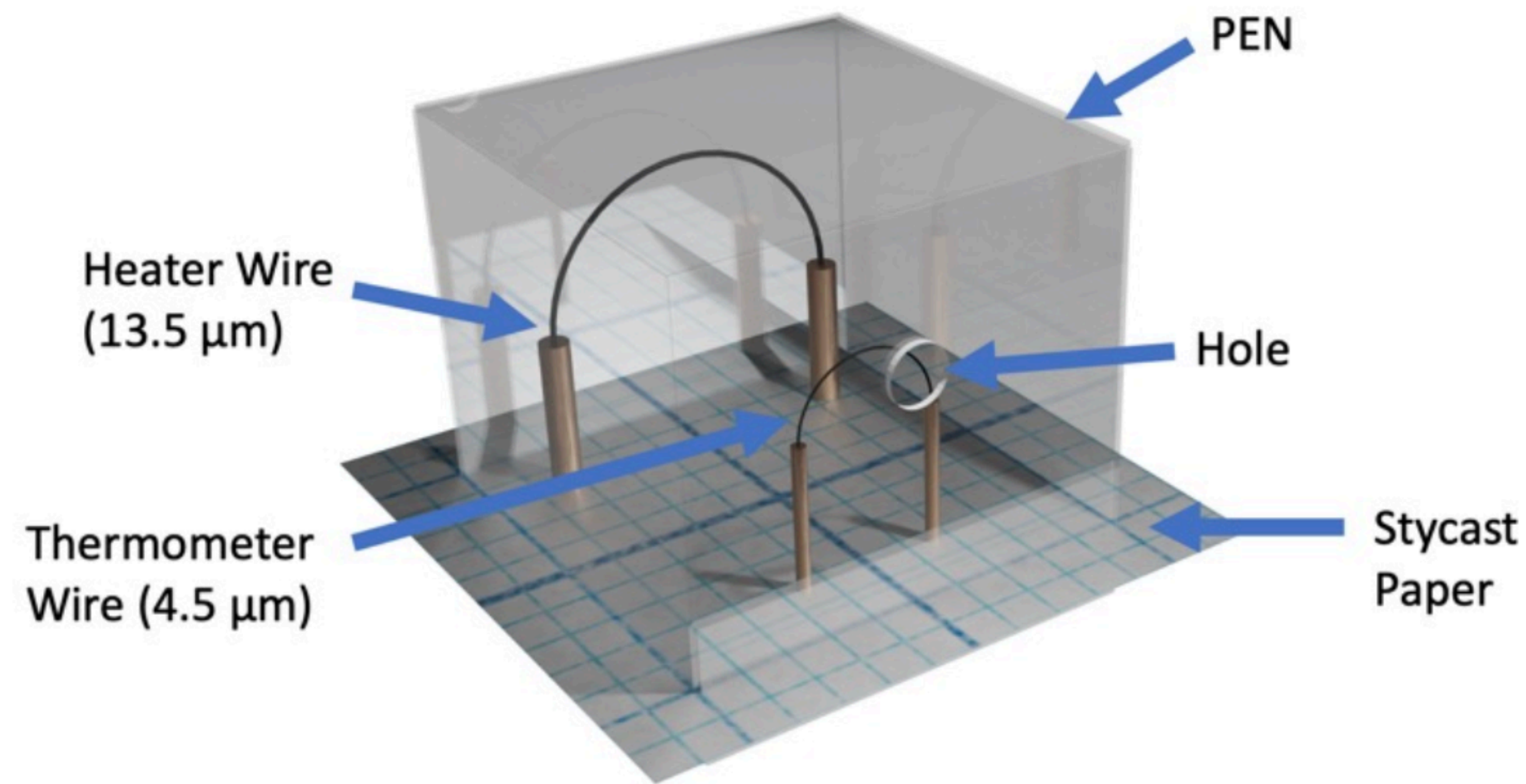
- Damping force from QP collisions:

$$F = \frac{\pi}{4} \underset{\text{wire}}{v} \underset{3\text{He}}{d} p_F^2 v_F N_0 \exp\left(\frac{-\Delta}{k_B T}\right)$$

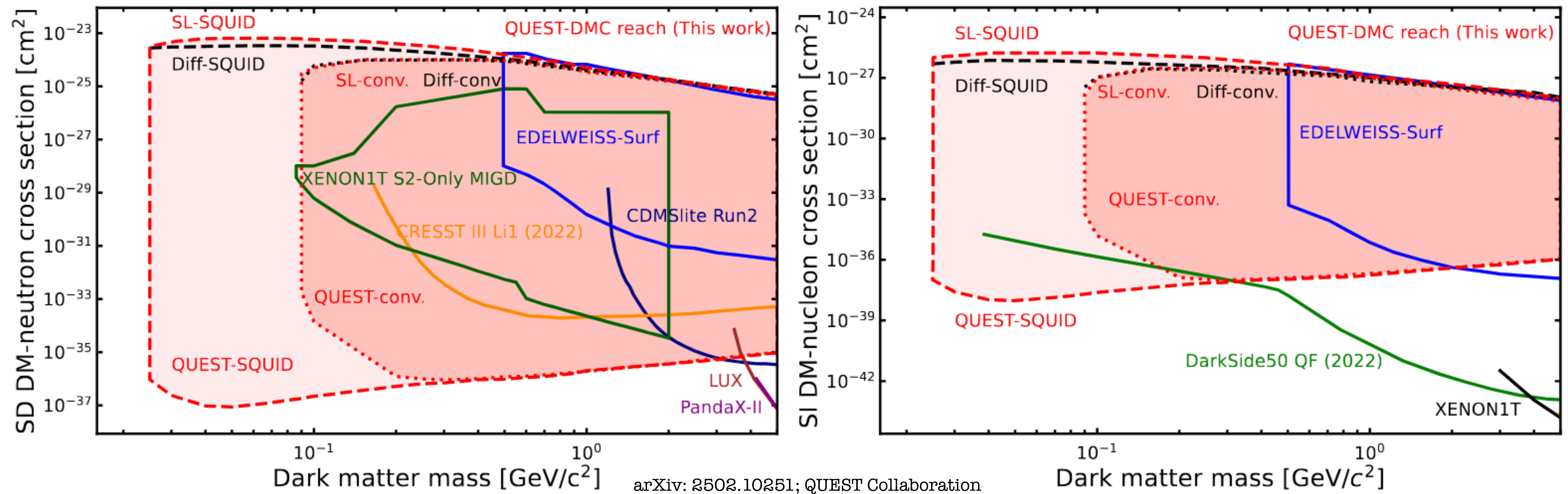
- Andreev scattering amplifies force



Readout Calibration



Overall Sensitivity and effect

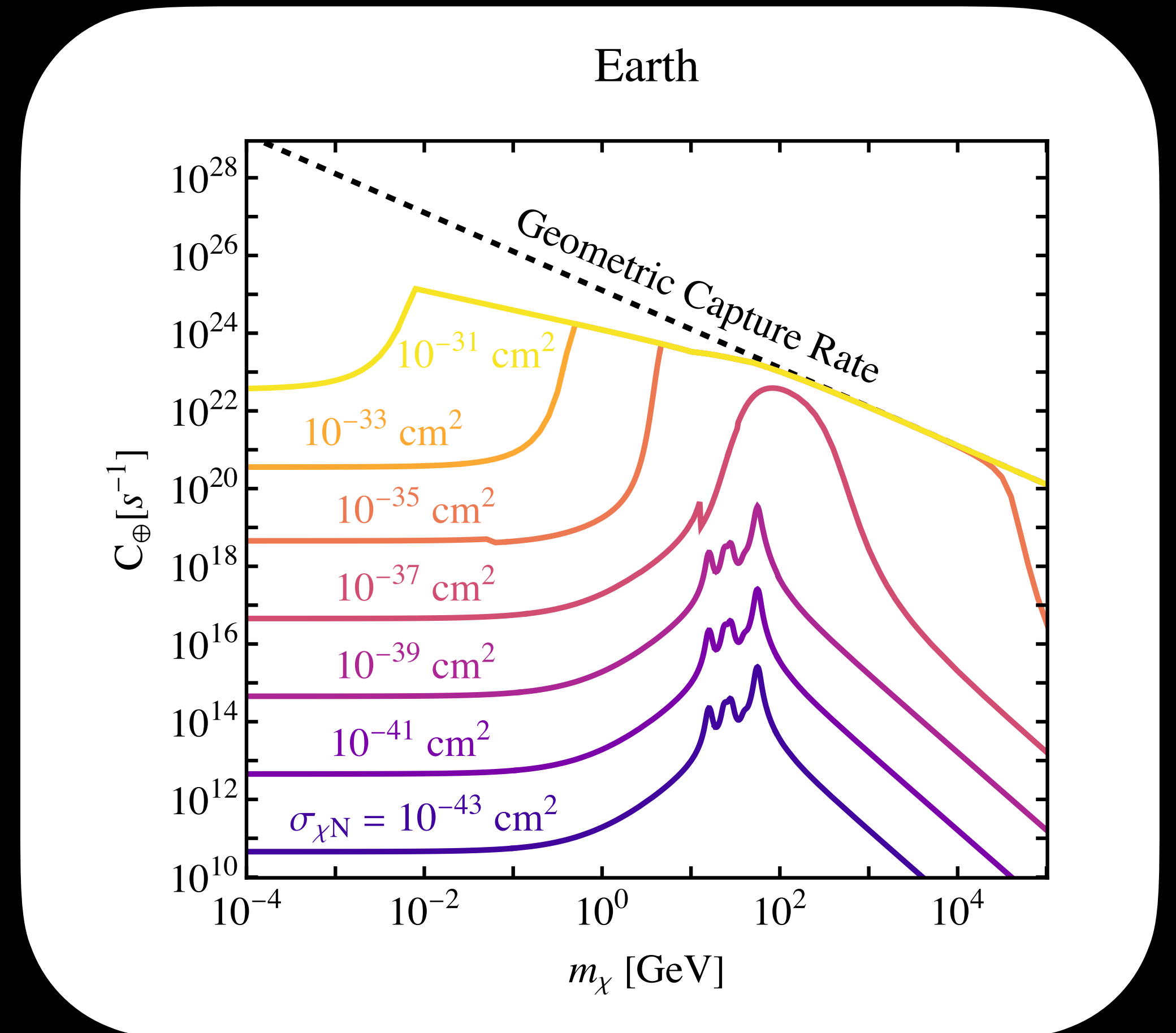


Even lower Thresholds...

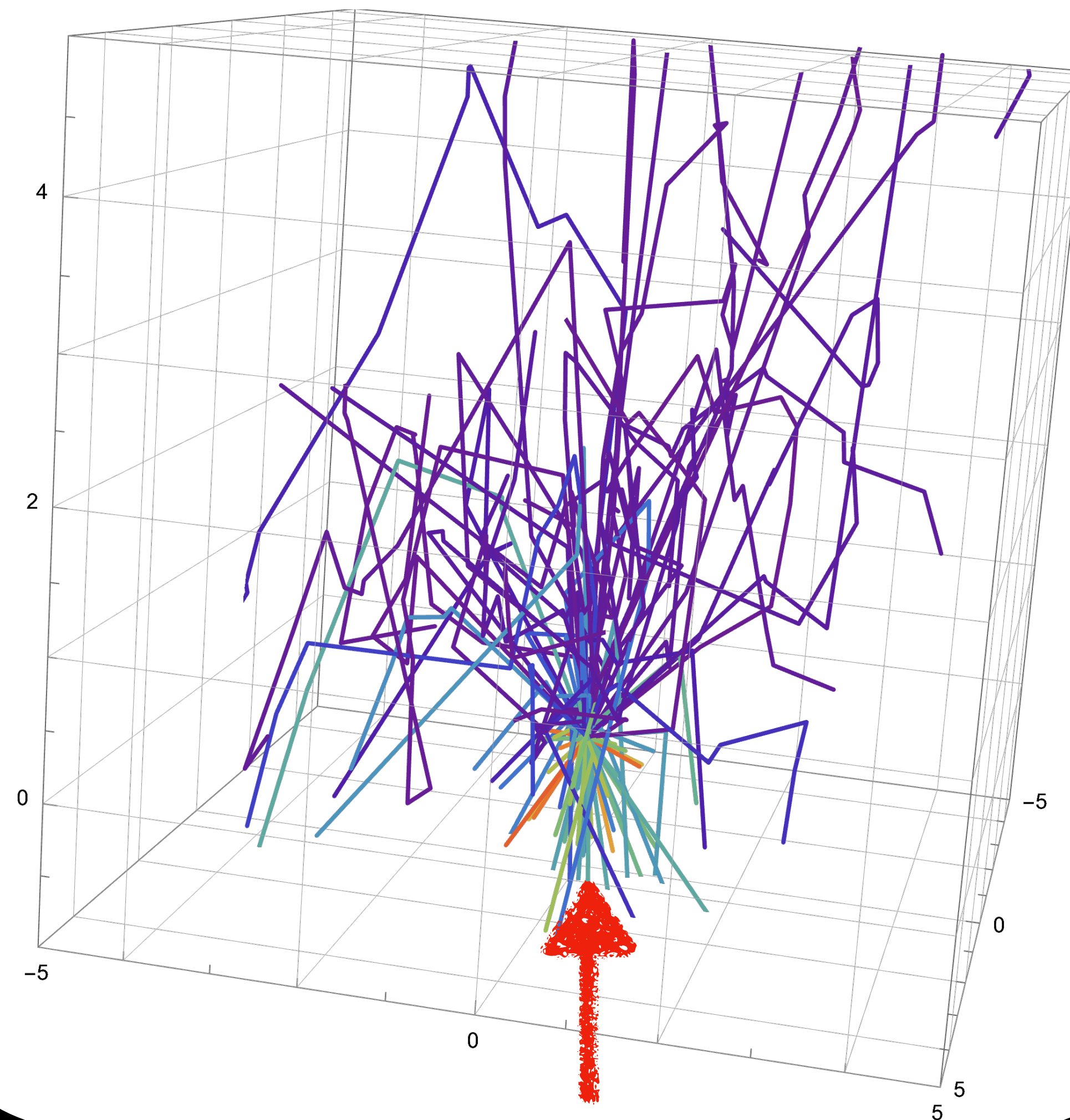
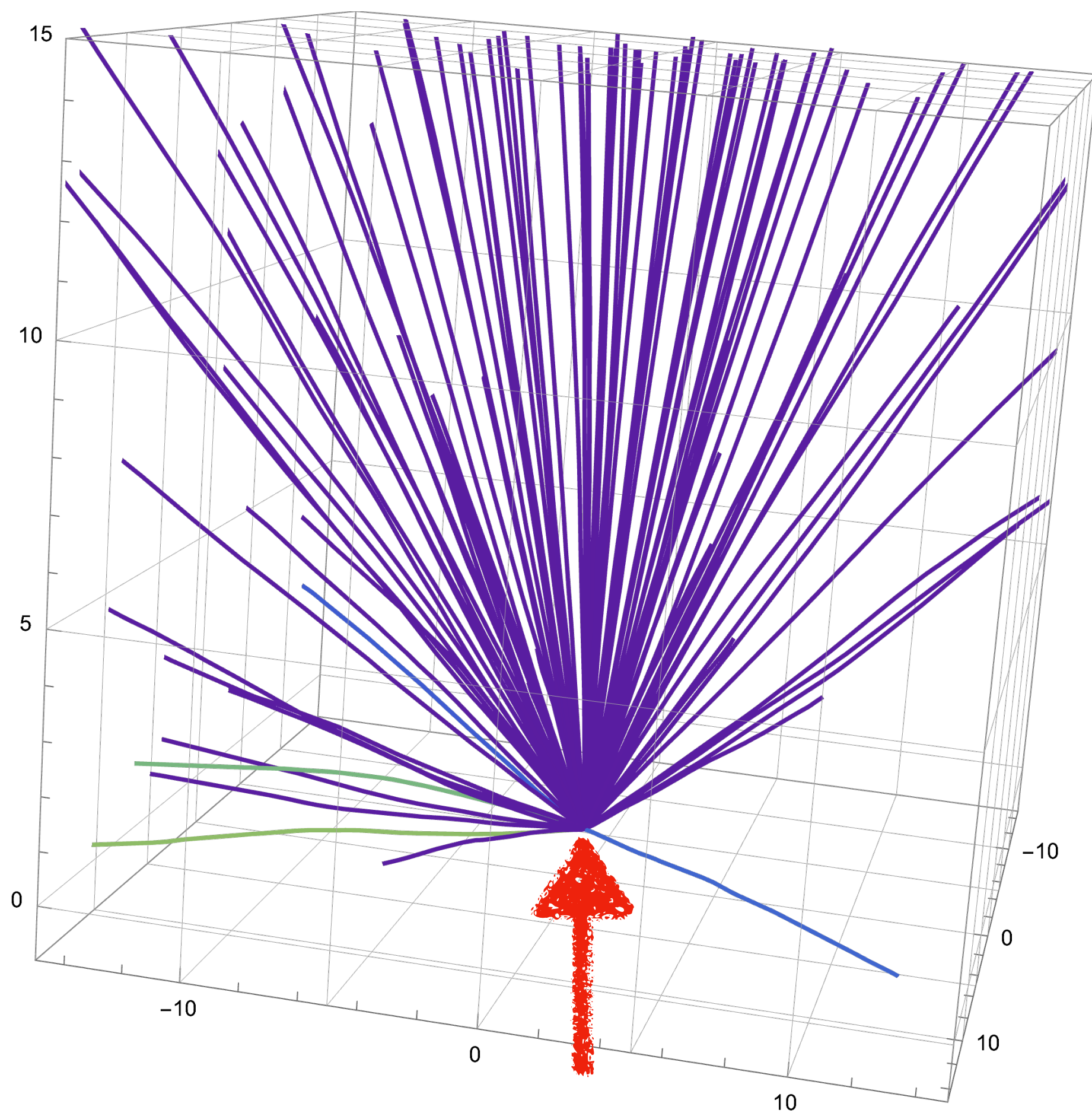
Dark Matter Capture Rates

$$C_{\text{cap}} \approx v_{\text{DM}} \pi R^2 \left(1 + \frac{3}{2} \frac{v_{\text{esc}}^2}{v_{\text{DM}}^2} \right) \times \sum_{N=1}^{\infty} f_N(\tau) g_N(v_{\text{DM}}, v_{\text{esc}}) = \phi_{\text{DM}} f_{\text{cap}}$$

Asteria Code by:
R. K. Leane (SLAC),
J. Smirnov



Reflection Correction Possible



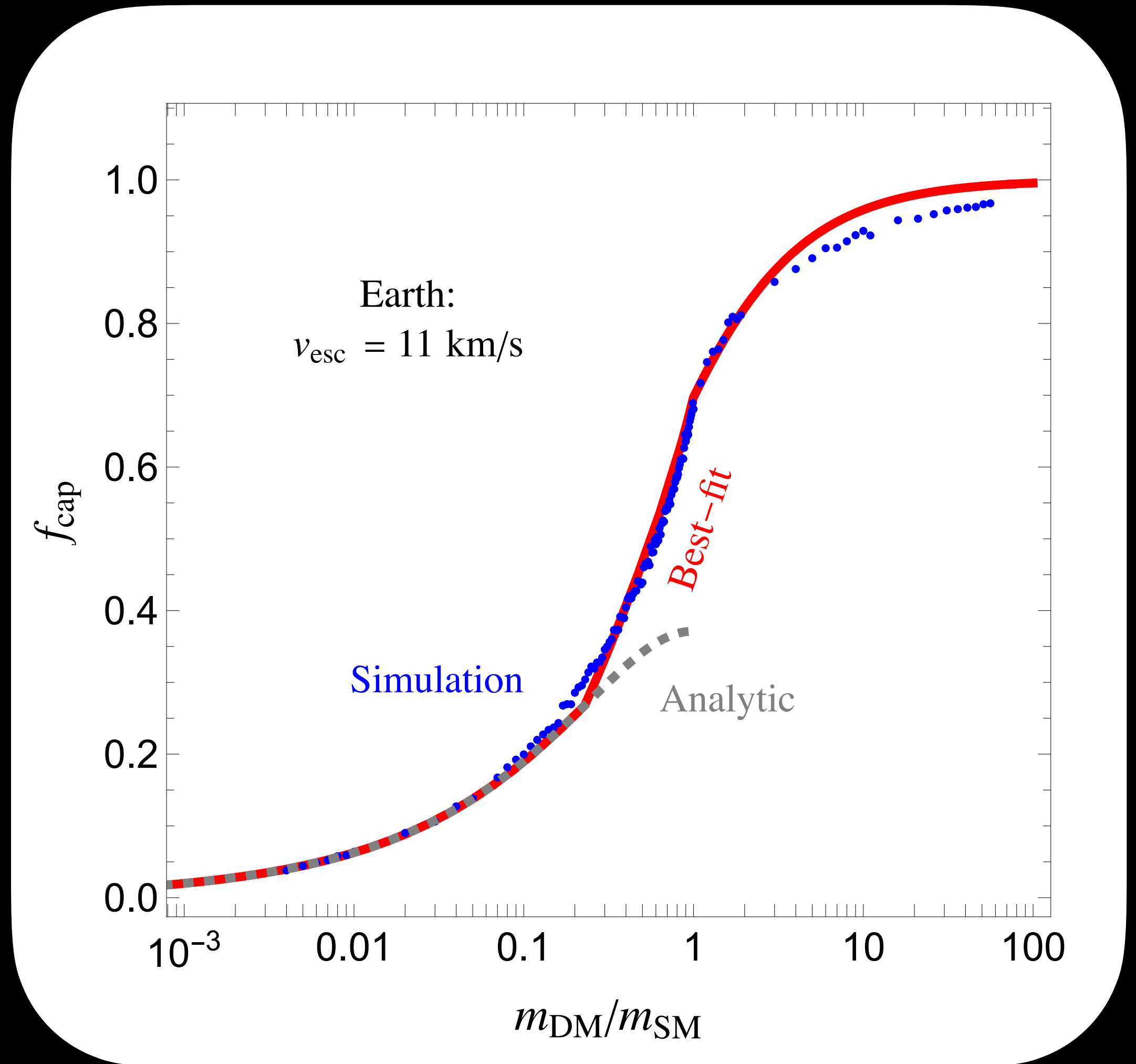
Simulation and Analytic Result

$$f_{\text{ref}} \approx 1 - \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{N_{\text{cap}}}}$$

$$N_{\text{cap}} \approx \frac{\log \left(\frac{v_{\text{DM}}^2}{v_{\text{esc}}^2} \right)}{\log (1 - \langle z \rangle \beta)}$$

$$\langle z \rangle \sim \frac{1}{2} \text{ and } \beta = \frac{4m_{\text{DM}}m_{\text{SM}}}{(m_{\text{DM}} + m_{\text{SM}})^2}$$

Asteria Code by:
R. K. Leane (SLAC),
J. Smirnov



Captured Dark Matter Profile

$$\frac{\nabla(n_\chi T)}{n_\chi T} + \frac{f_{\text{grav}}(r)}{T} + \kappa \frac{\nabla T}{T} - \frac{n_\chi^0 v_\chi^0}{n_\chi D_{12}} \left(\frac{R}{r} \right)^2 = 0$$

Hydrostatic equilibrium:
Isothermal DM

Thermal diffusion:
Local thermal eq.

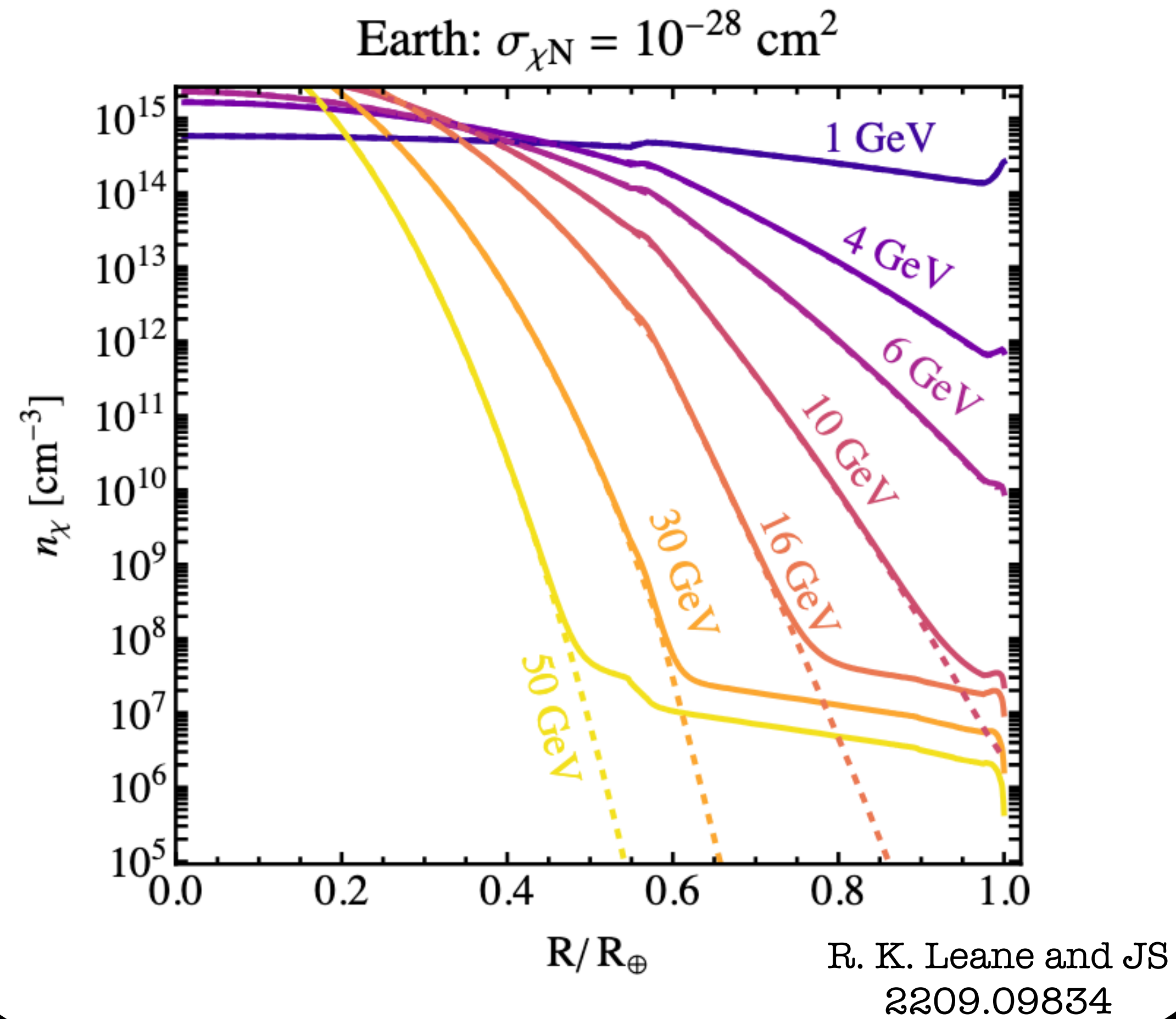
DM influx & diffusion:
Dynamical equilibrium

Ref: Effect of hypothetical, weakly
interacting, massive particles on energy
transport in the solar interior
D.N. Spergel and W.H. Press in 1984

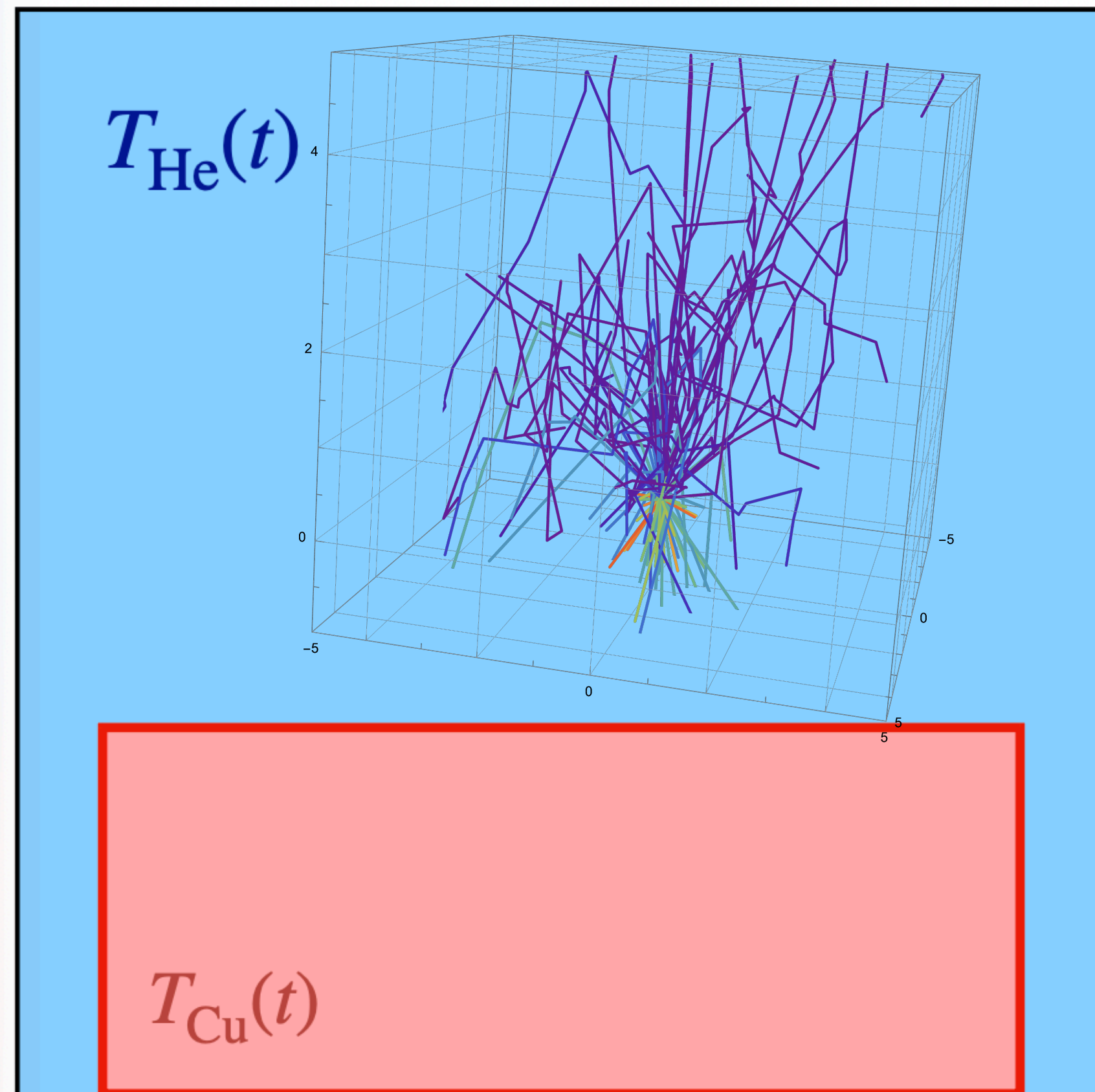
Ref: Big bang archeology:
WIMP capture by the earth
at finite optical depth
A. Gould in 1991

Ref: Floating Dark Matter in
Celestial Bodies: 2209.09834
R.K. Leane and J. Smirnov

DM Diffusion in the Earth



Heating of Components and Heat Transport



Tetiana Kozynets
Post-Doctoral Researcher



Erin Charnley
PhD Student

Technique has
potential to
get rid of readout
thresholds

Sensitive to even
slow drifting DM

Heating Through Particle Scattering

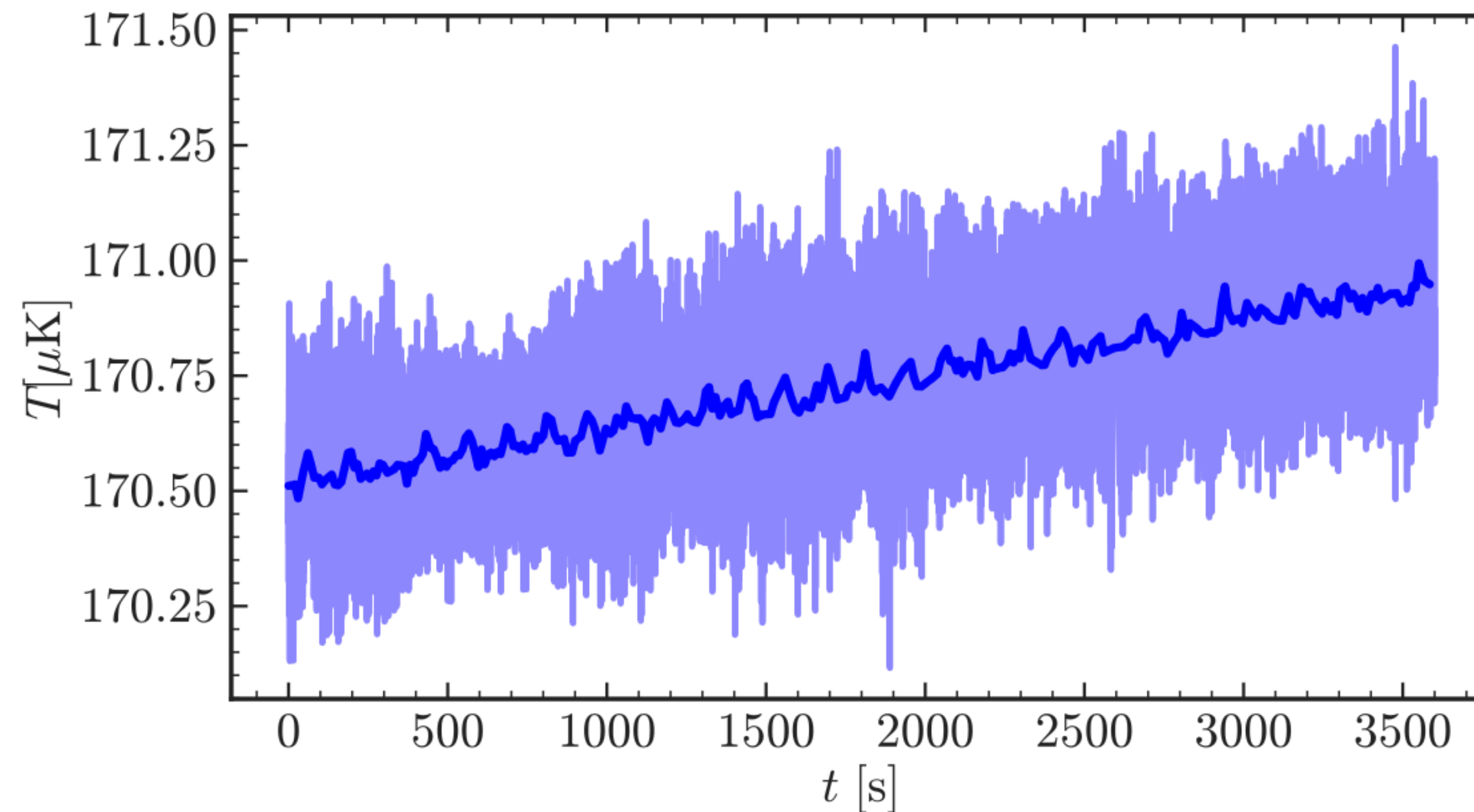
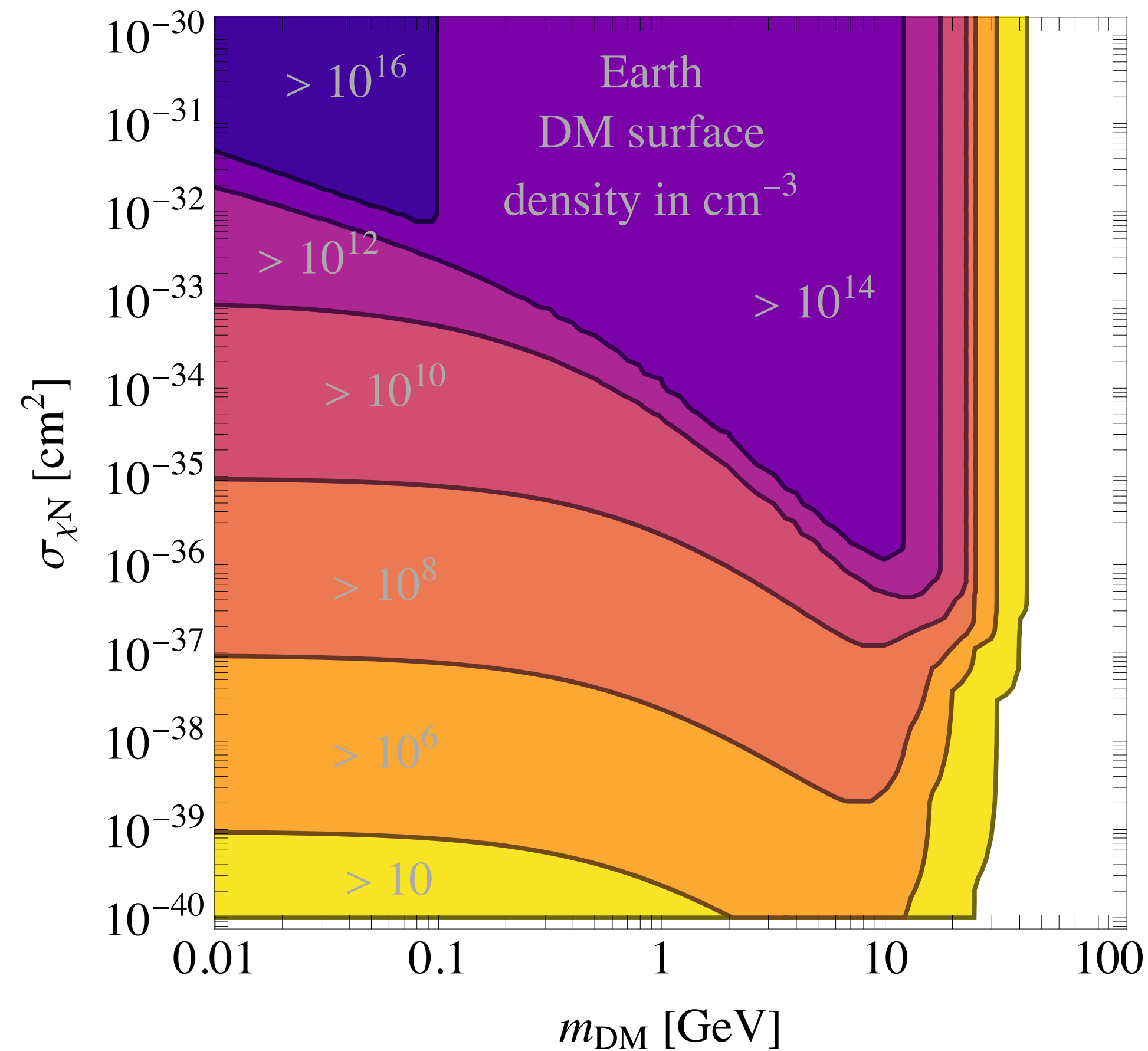


Figure 2: Example evolution of the ^3He temperature in QUEST-DMC over 1 hour, measured at 0 bar pressure. Data courtesy of Robert Smith and the QUEST-DMC Collaboration (February 2023).

Surface Overdensity for Yukawa Force DM

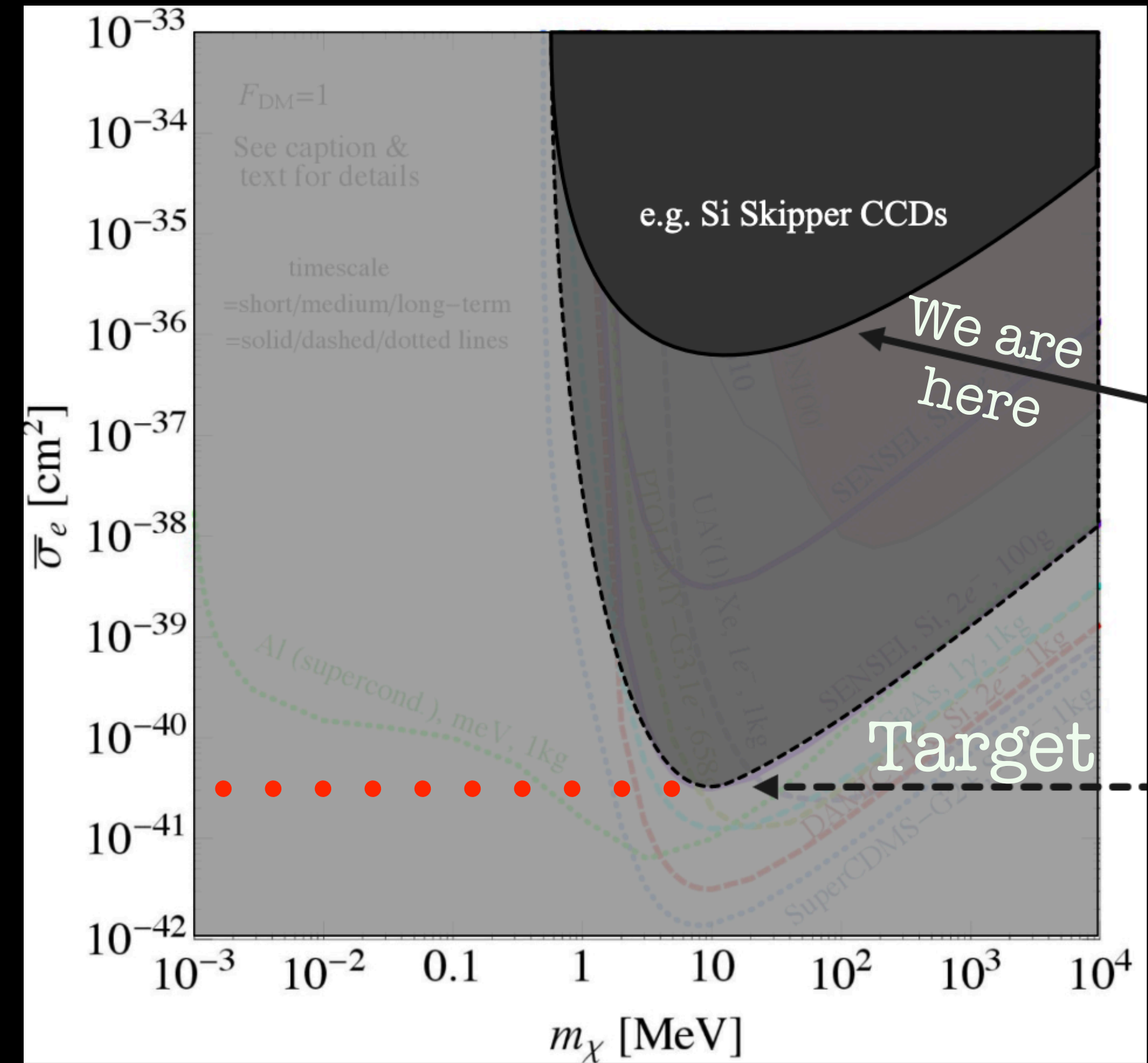
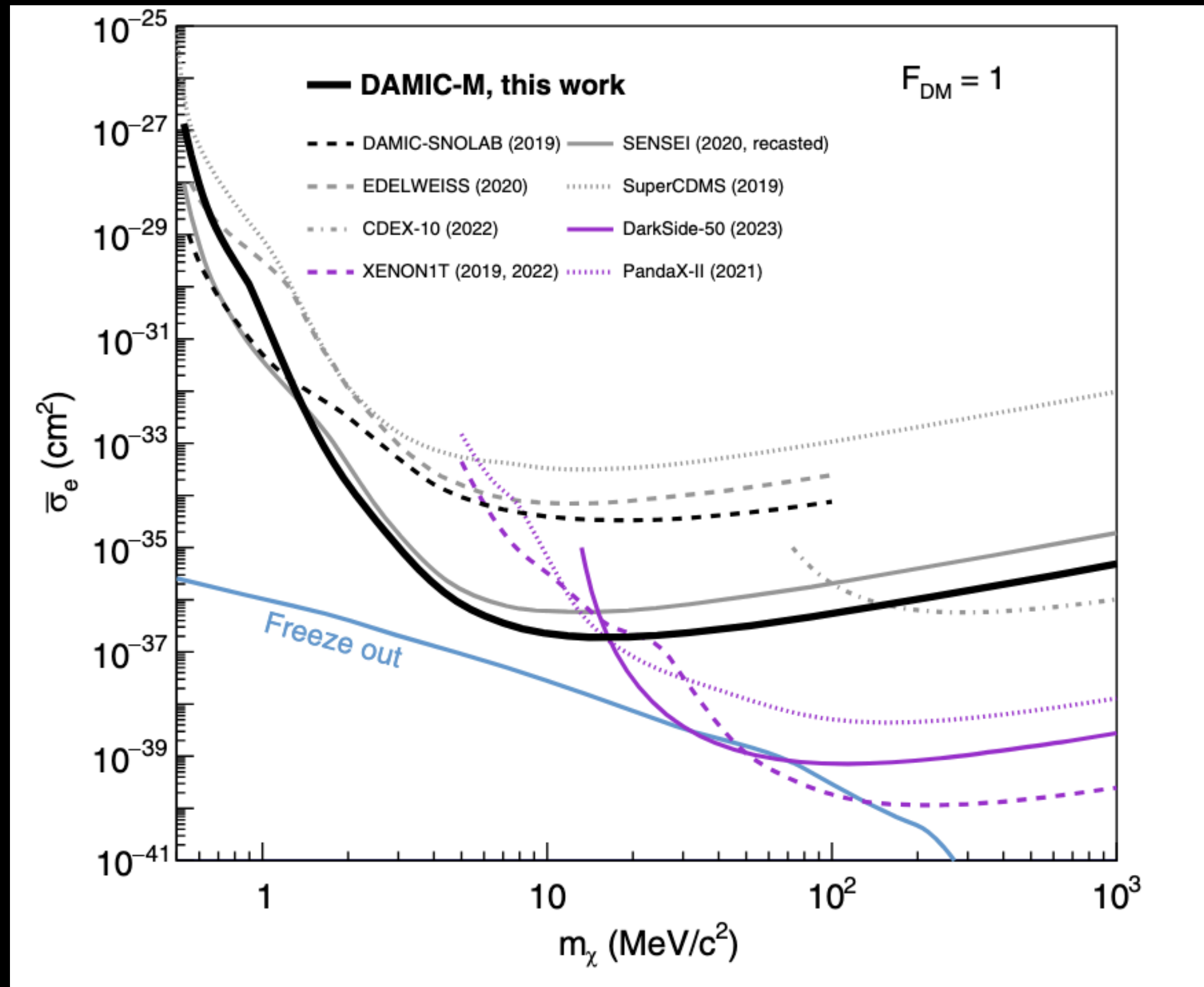
Preliminary



2) Design of New Materials

Matching DM Mass with Electron Targets

Electron Scattering



For example: DAMIC 2025

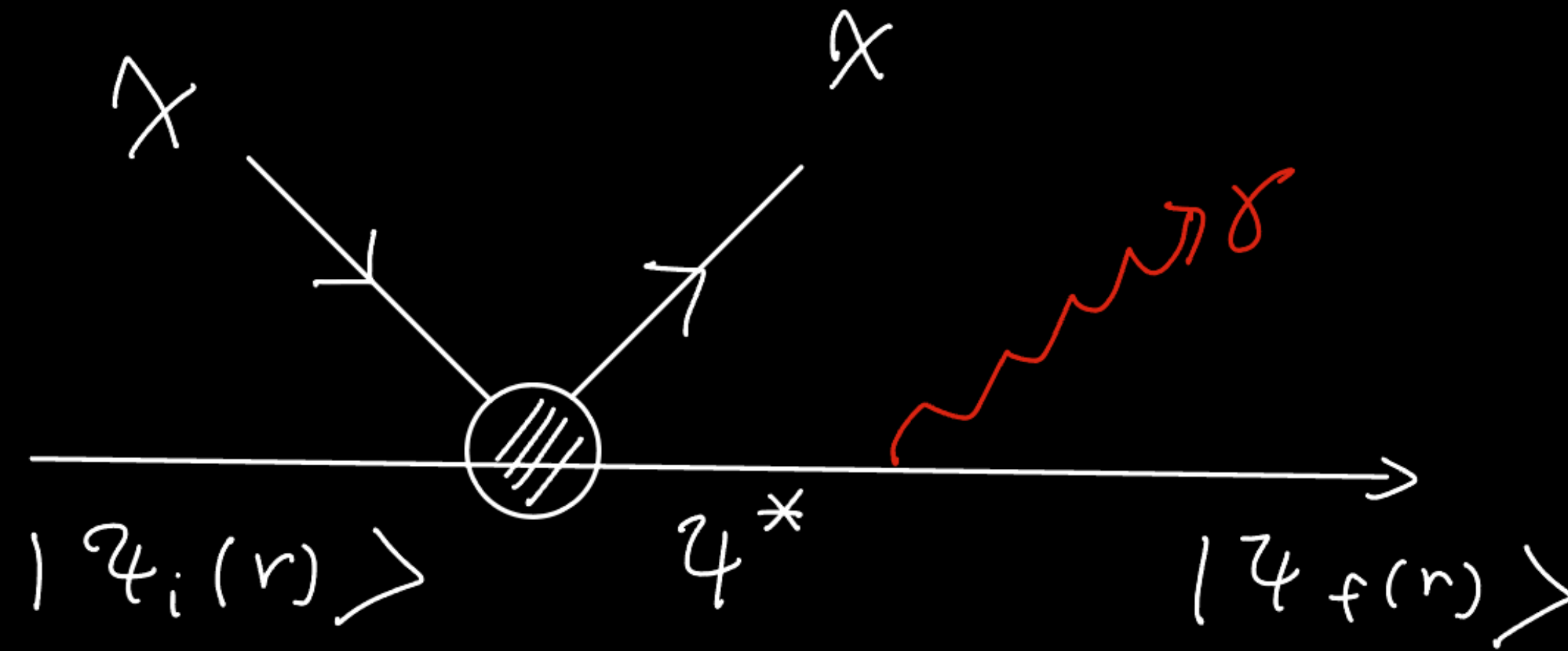
Dark Matter Event Rate in the Detector

DM
rate @ detector

$$\frac{dR}{d\epsilon_n(E_r)} \sim \int \frac{d^3q}{q} \underbrace{\gamma(\sigma)}_{\text{mean inv. velocity astro}} |F_{DM}(q)|^2 \underbrace{|f_{i \rightarrow f}(q)|^2}_{\text{Transition form factor Cond. mat./Chemistry}}$$

DM form factor
model dependent

Low Excitation Energy & Large Oscillator St.

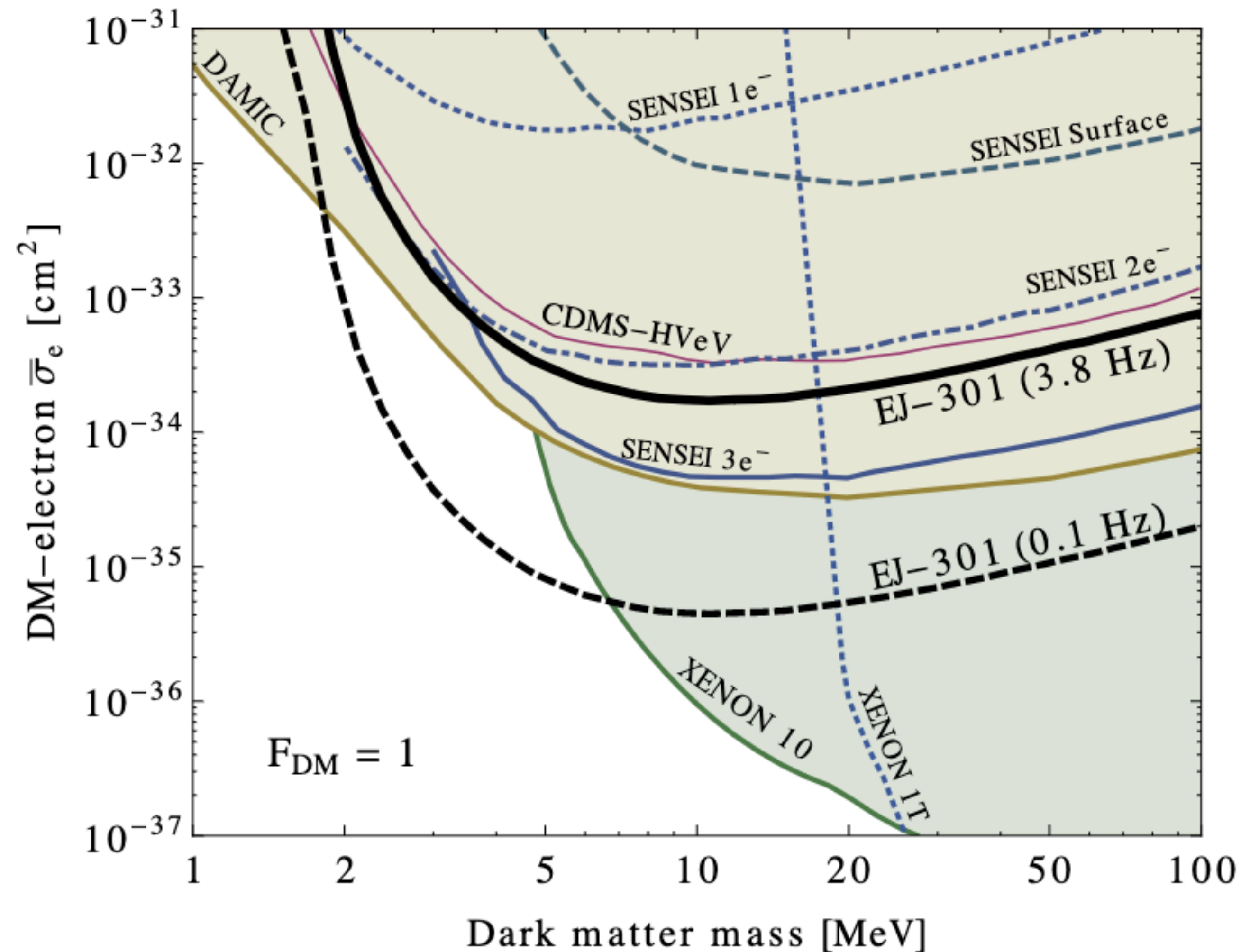
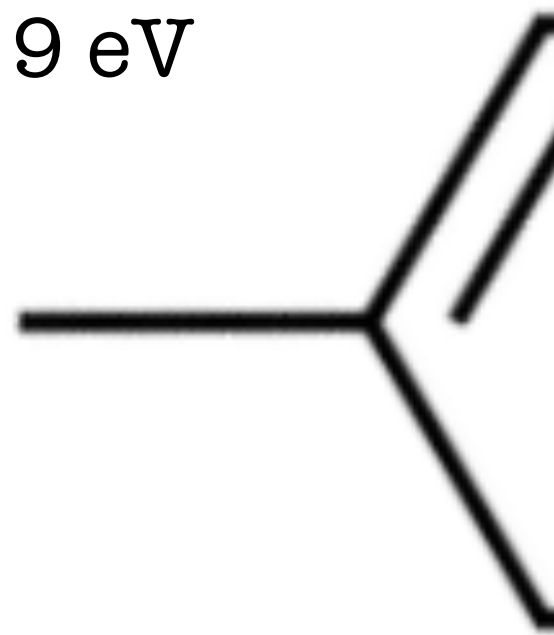


$$\begin{aligned}
 f_{i \rightarrow f}(q) &= \langle \psi_f | e^{i \vec{q} \cdot \vec{r}} | \psi_i \rangle \\
 &= \langle \psi_f(k+q) | \psi_i(k) \rangle \\
 &\sim \langle \psi_f | \vec{r} | \psi_i \rangle : \text{estimate}
 \end{aligned}$$

A Proof of Concept Setup

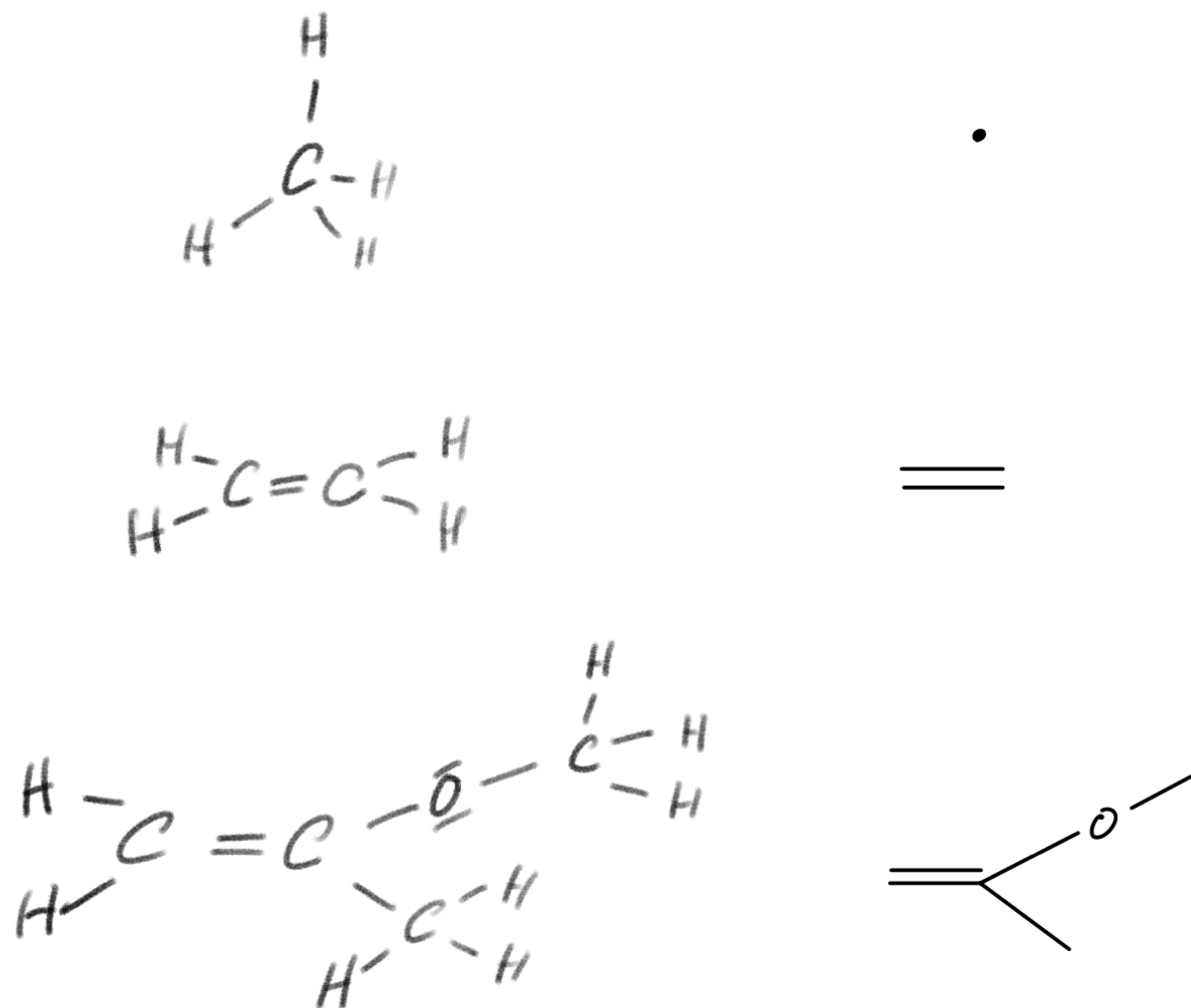
Direct Detection with Organic Molecules

8 - 9 eV

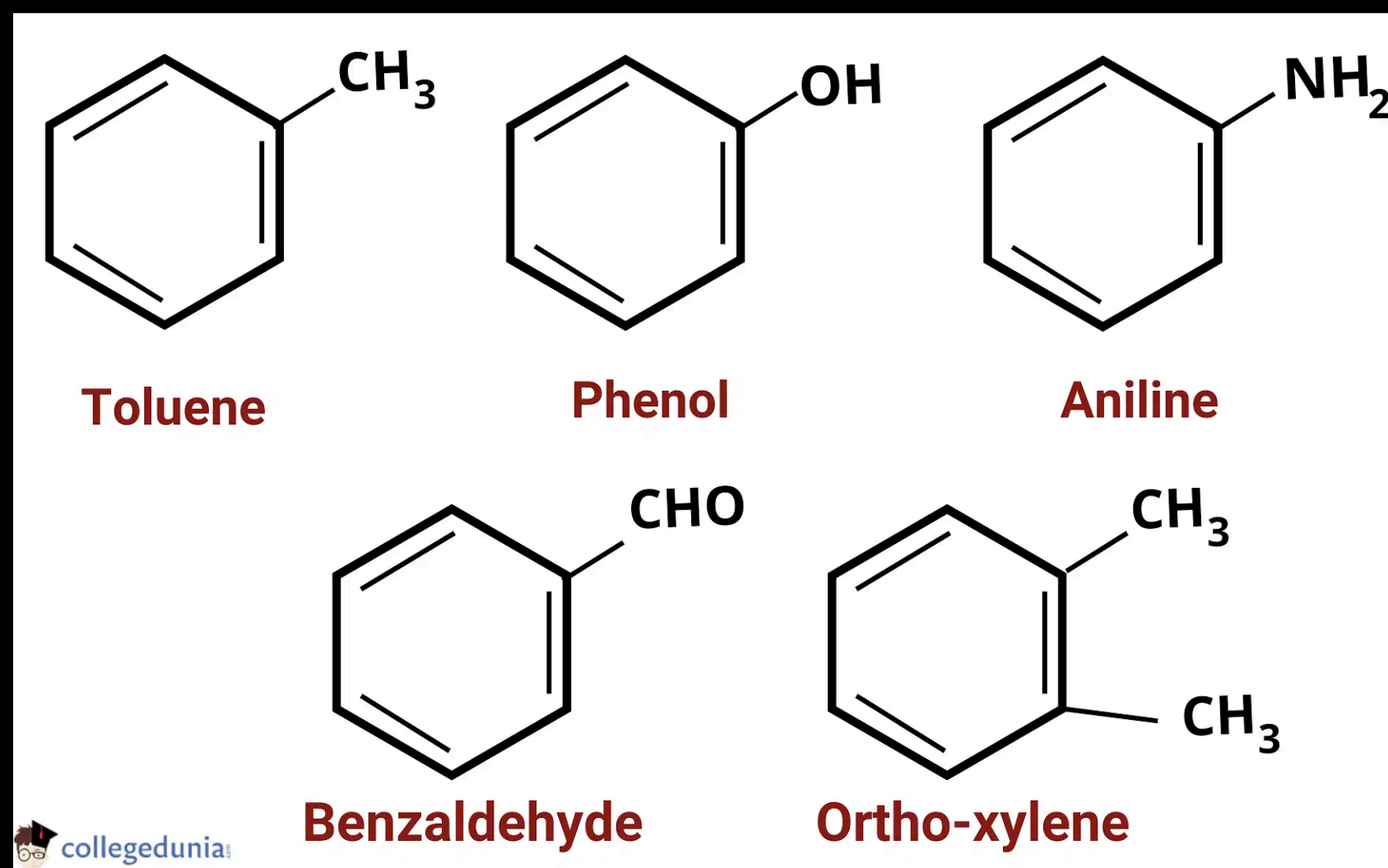


What is the optimal Target ?

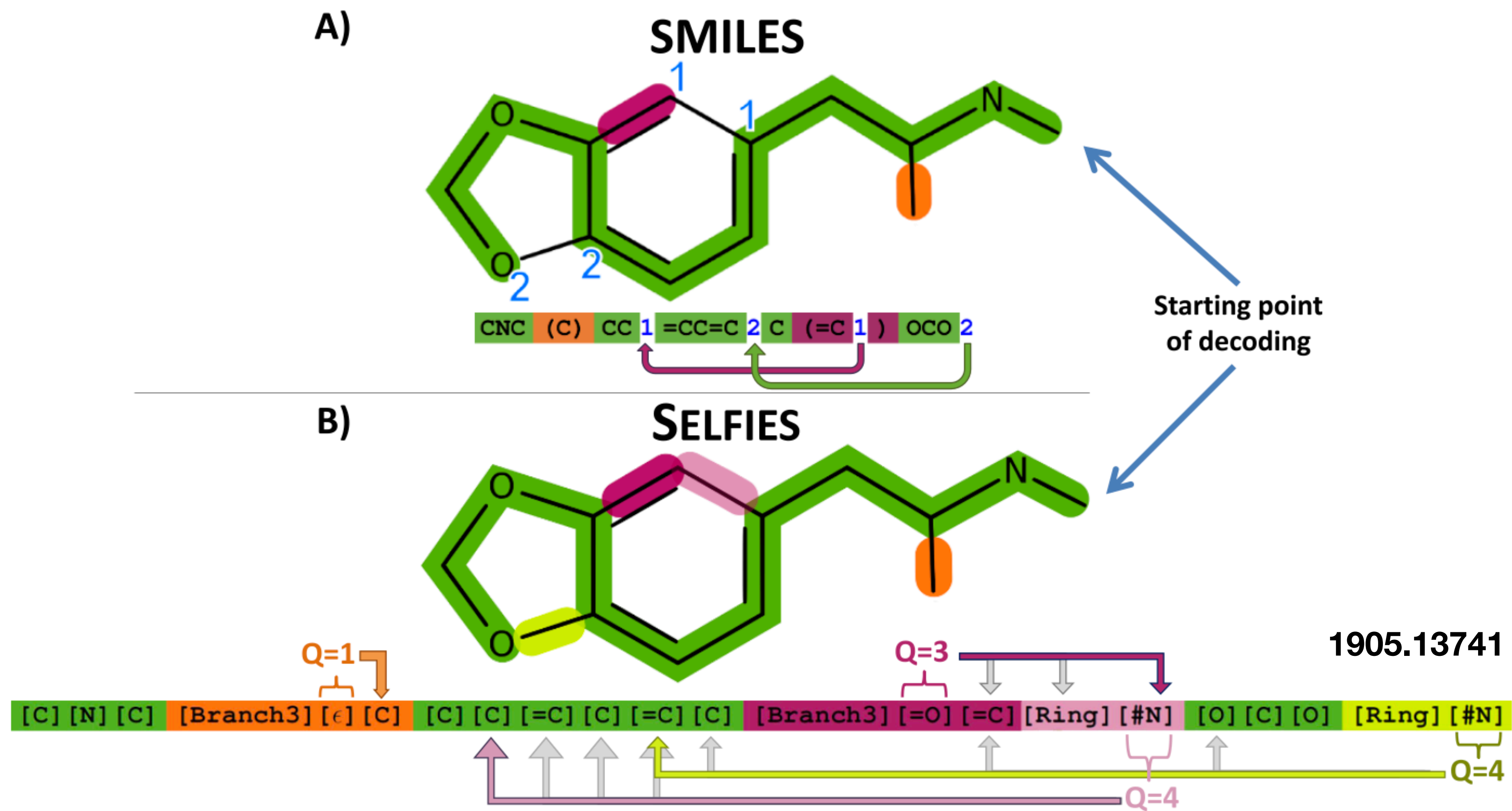
Organic Chemistry Notation



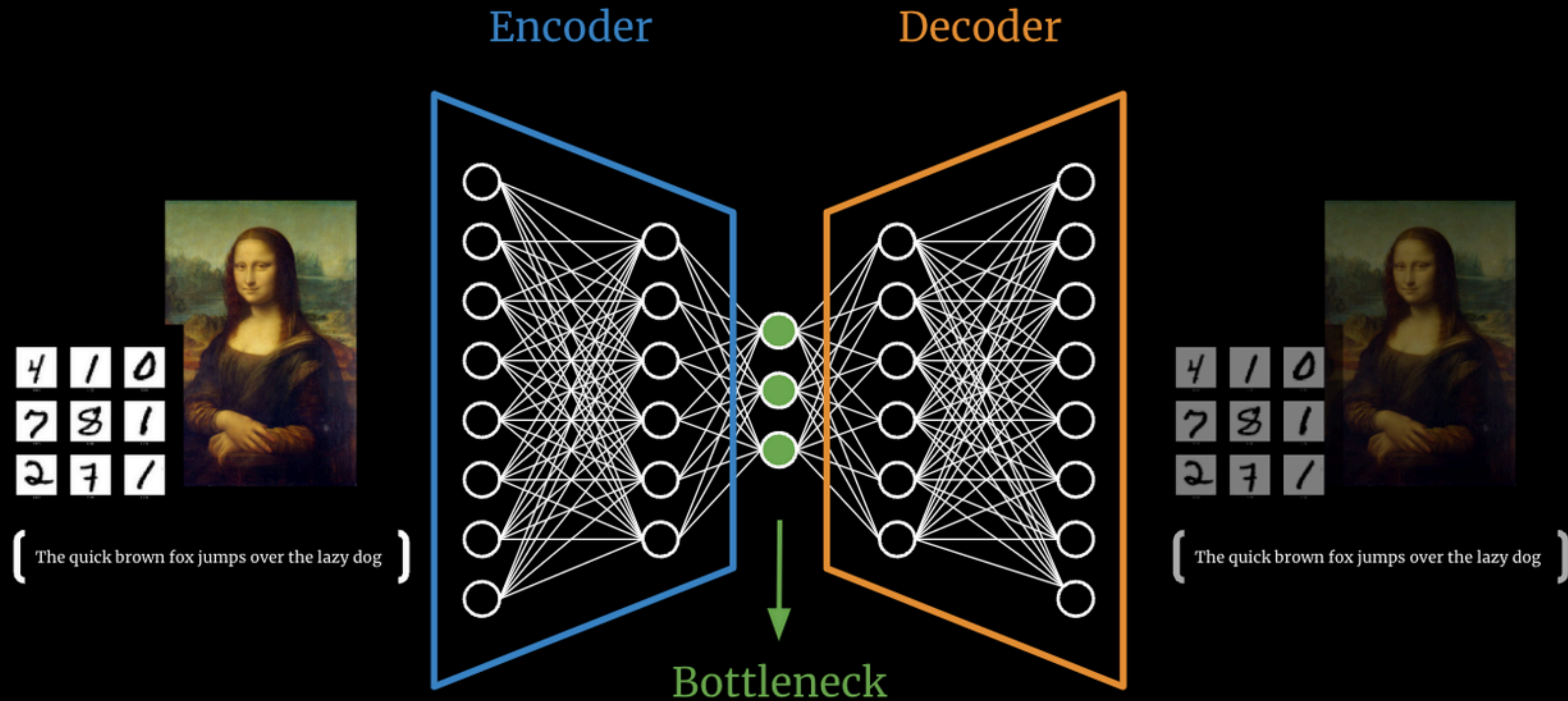
For example:
Aromatic molecules



Language: SMILES and SELFIES

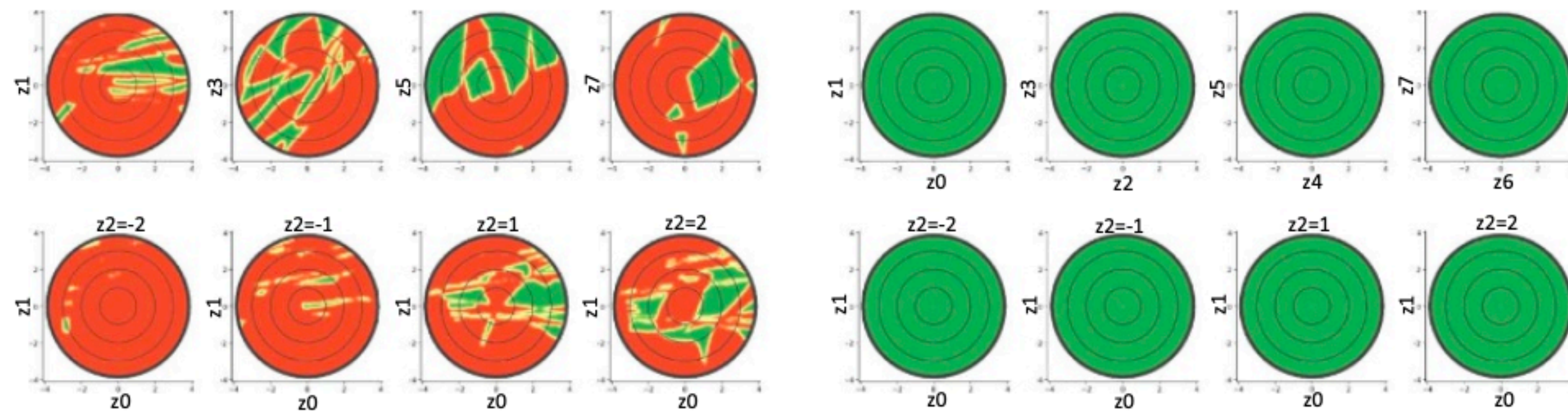


Generative Neural Networks



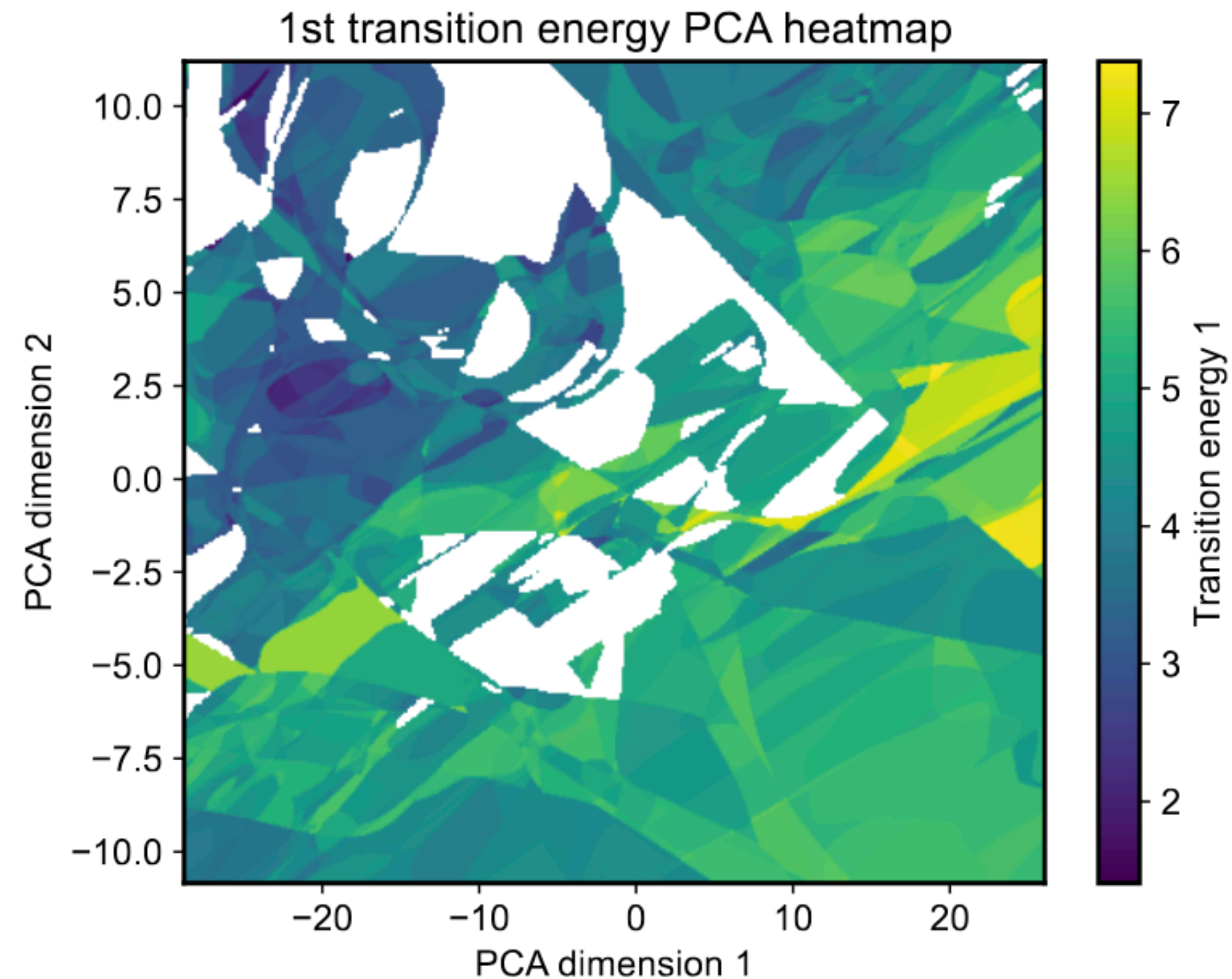
Latent Space Quality

Validity of Latent Space in VAE SMILES SELFIES



Datasets: PubChemQC3M

Latent Space Projection



Cameron Cook

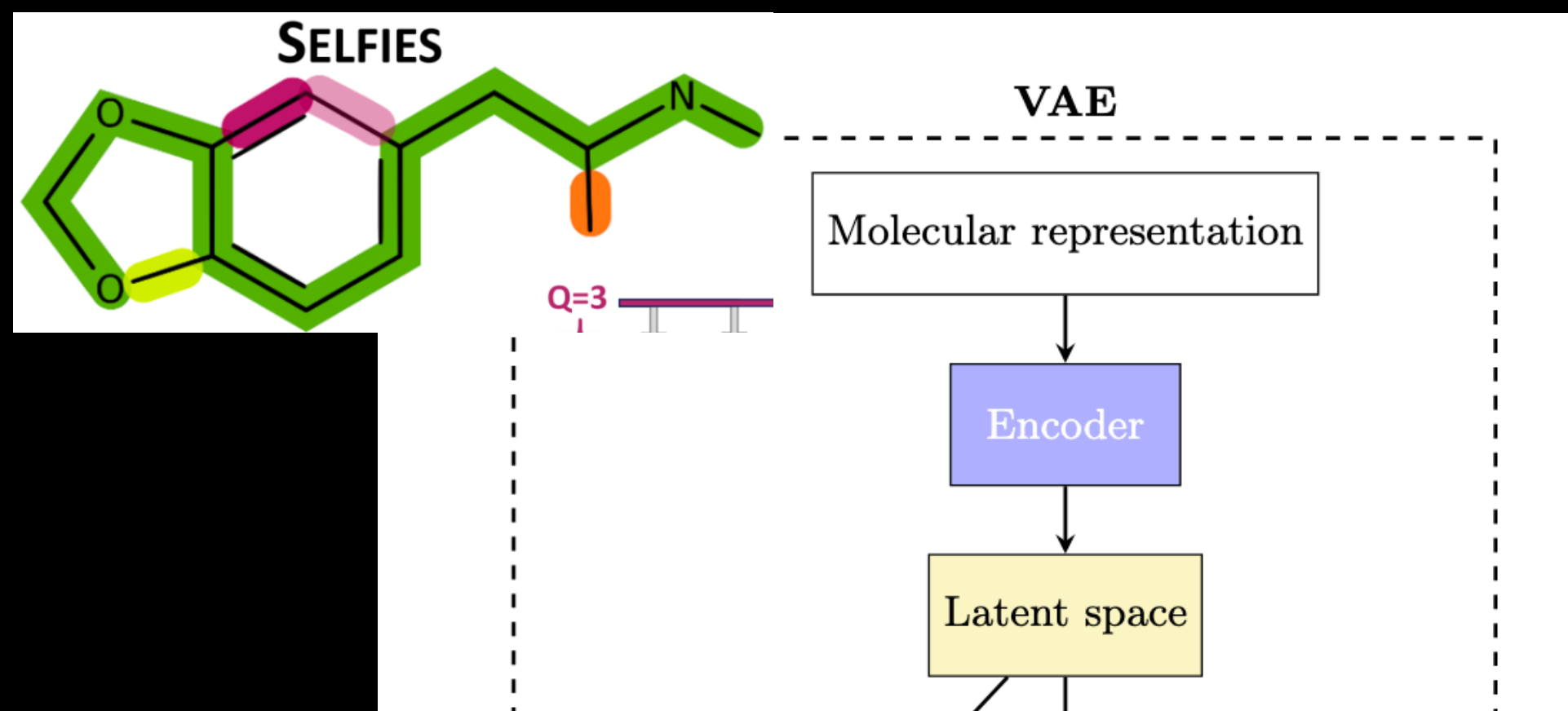
PhD Student

Cook, Blanco,
Smirnov
2501.00091

The Architecture

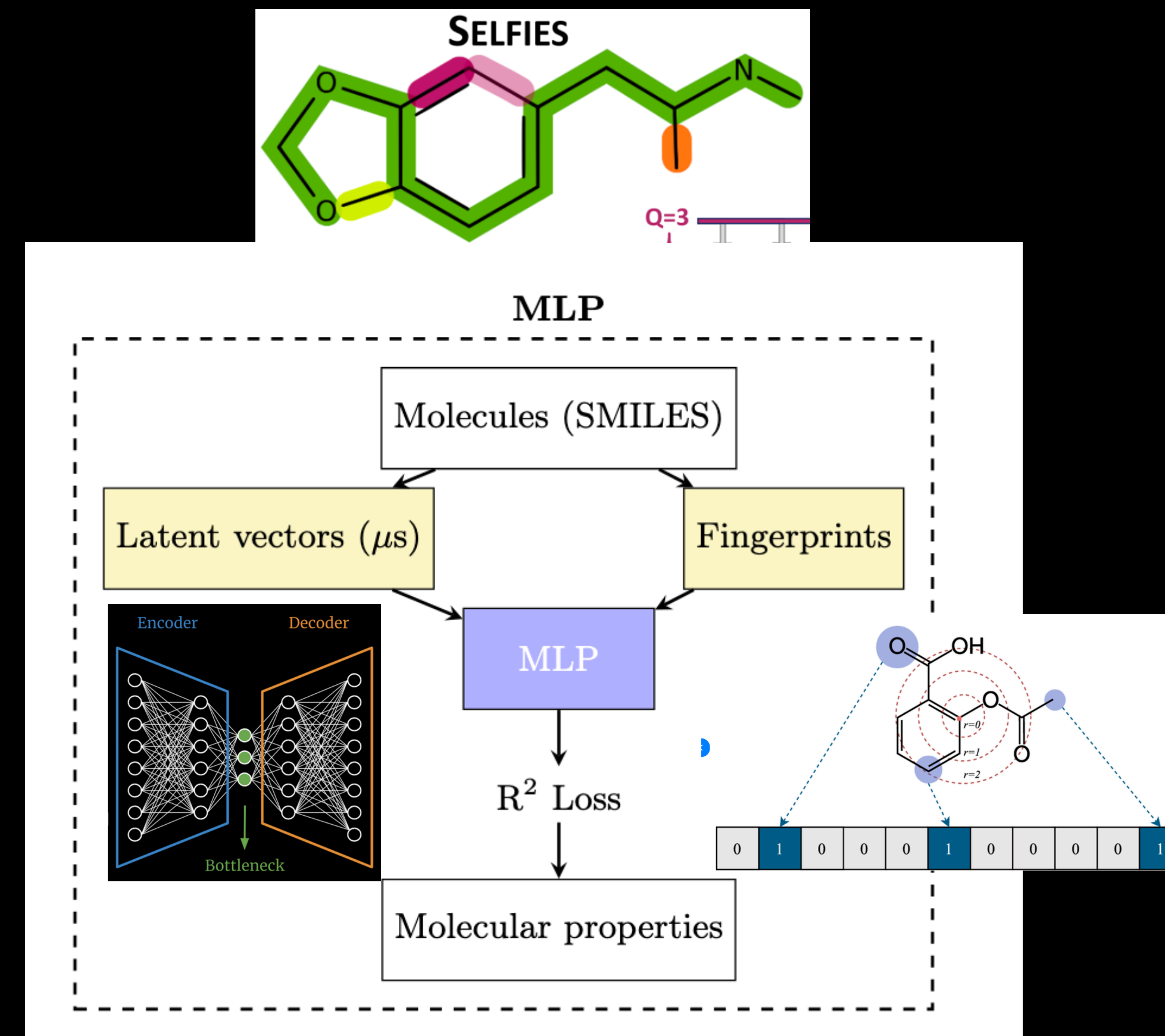
Combining:

A) Generative Task

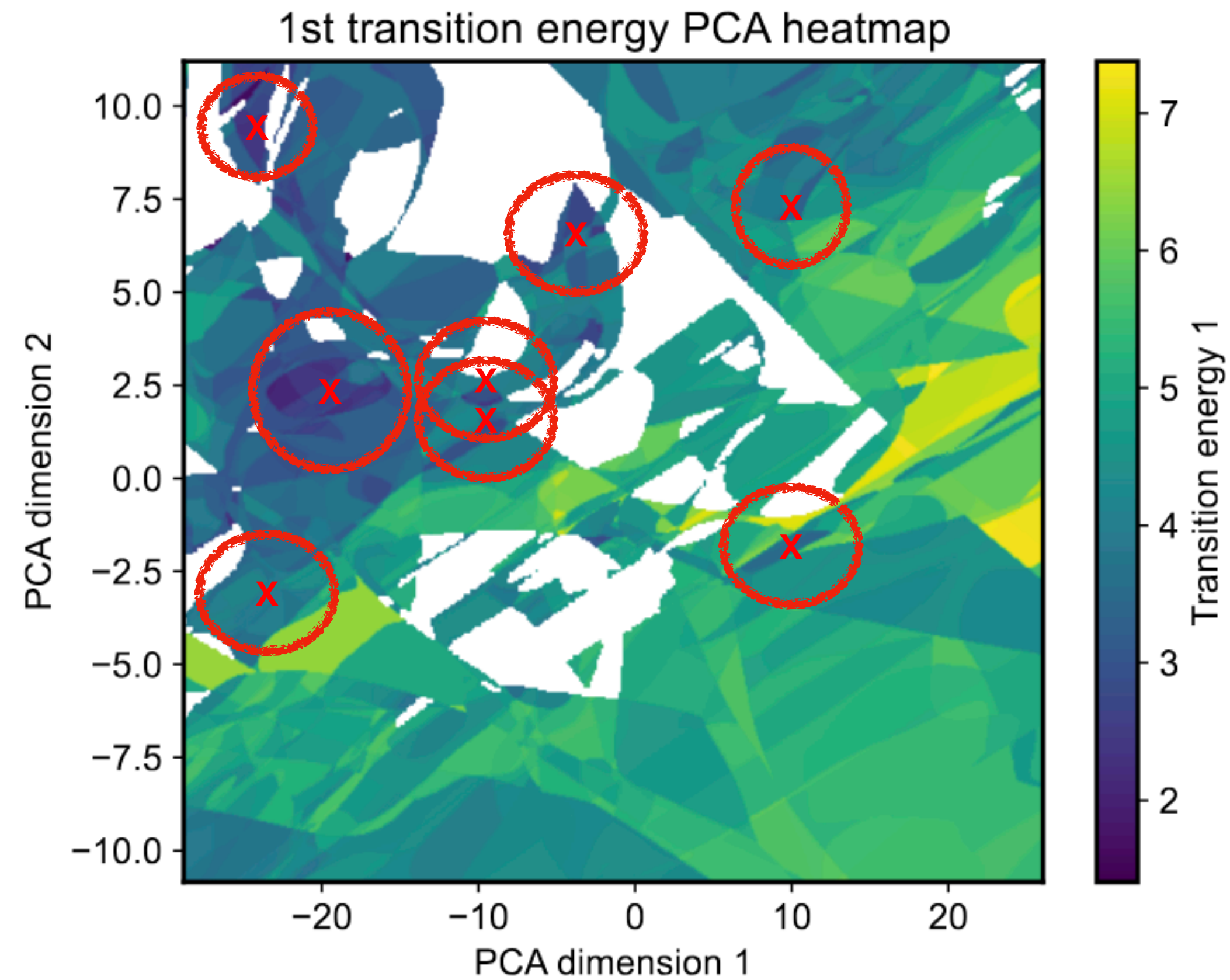


Molecular property	Training R^2	Validation R^2
$\Delta E1$	0.9788	0.9438
$\Delta E2$	0.9765	0.9392
OS1	0.7880	0.7478
OS2	0.7603	0.5619

B) Regression Task



Seeded Sampling Algorithm

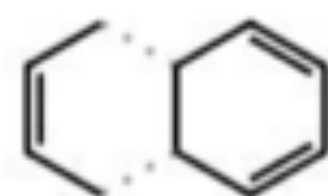


Cook, Blanco,
Smirnov
2501.00091

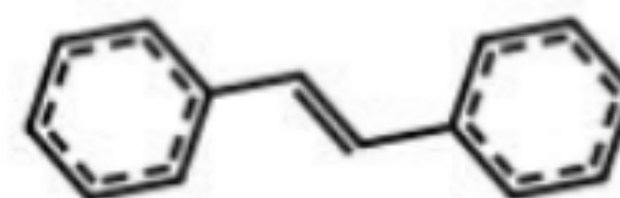
Patterns & Observations



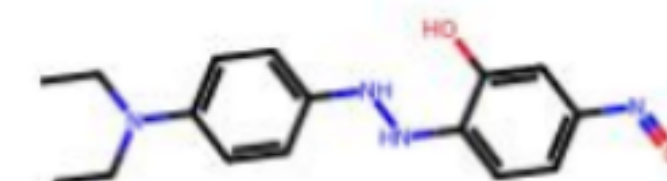
1. Count: 62465



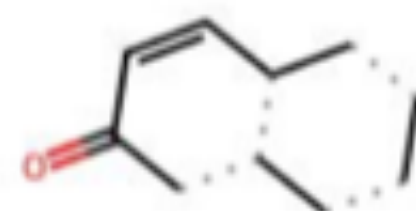
3. Count: 23404



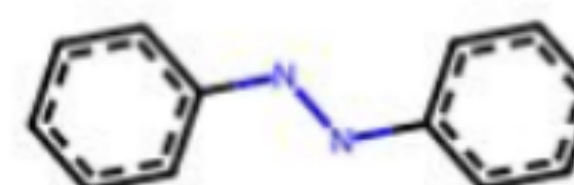
2. Count: 1052



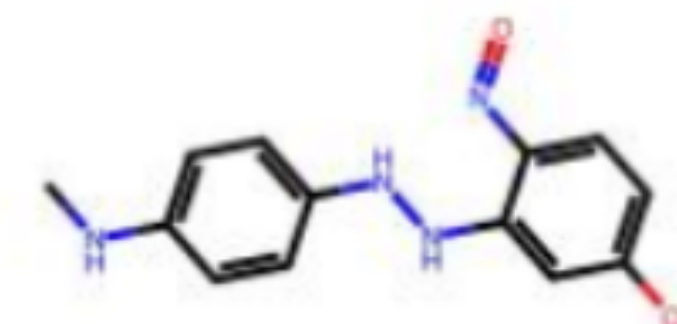
8. Count: 24



10. Count: 7187



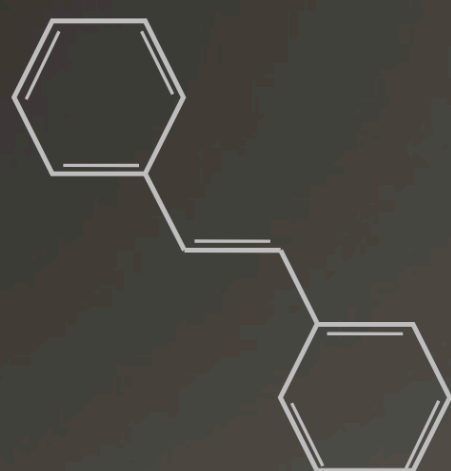
6. Count: 370



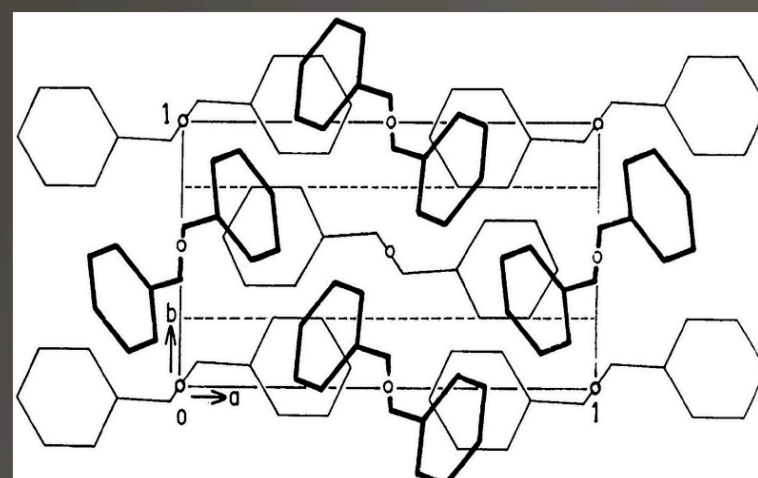
9. Count: 34

Variations on a Scheme

Trans-Stilbene

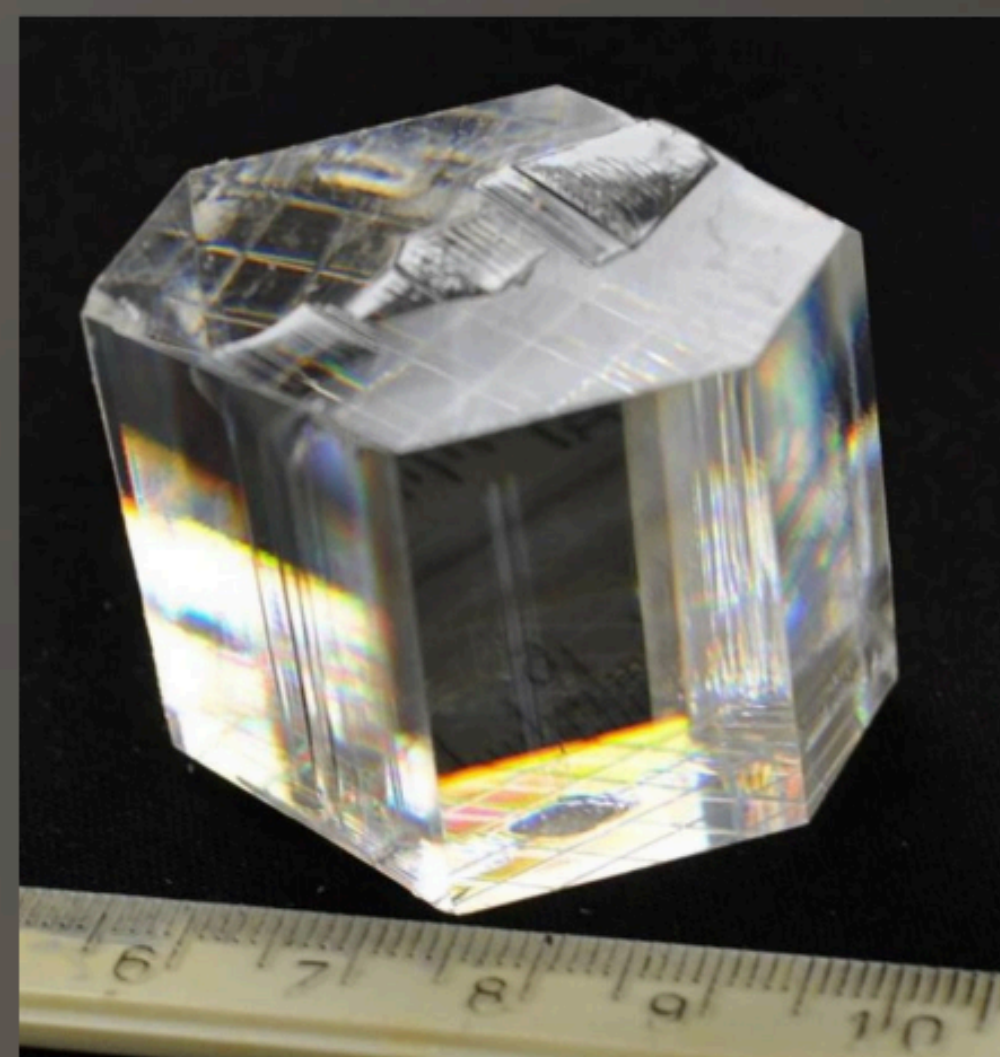
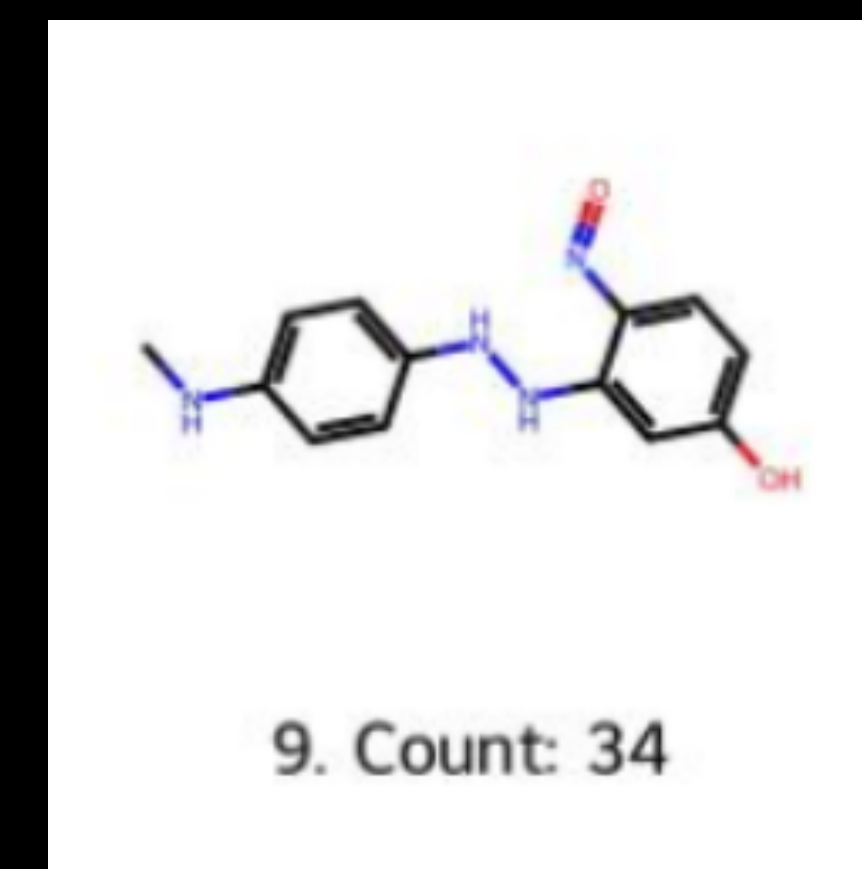
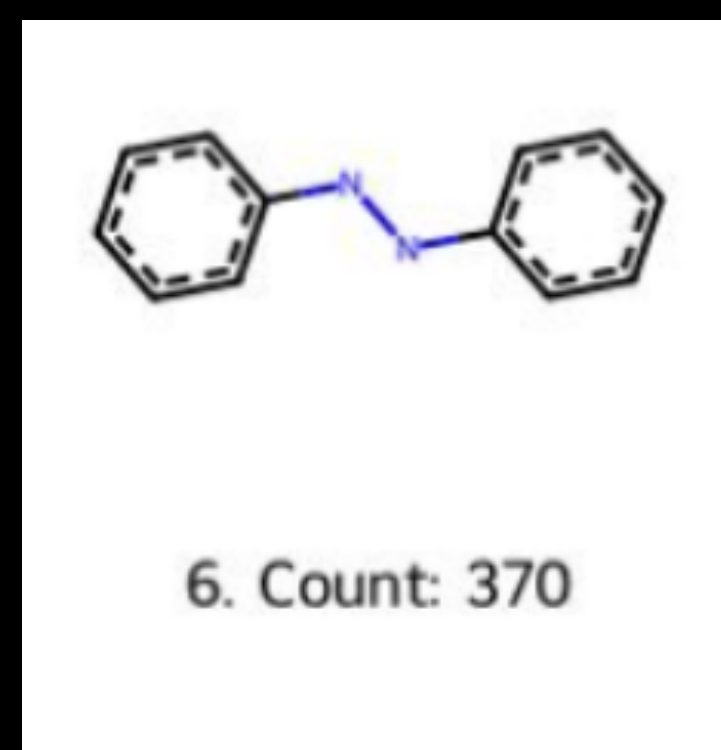
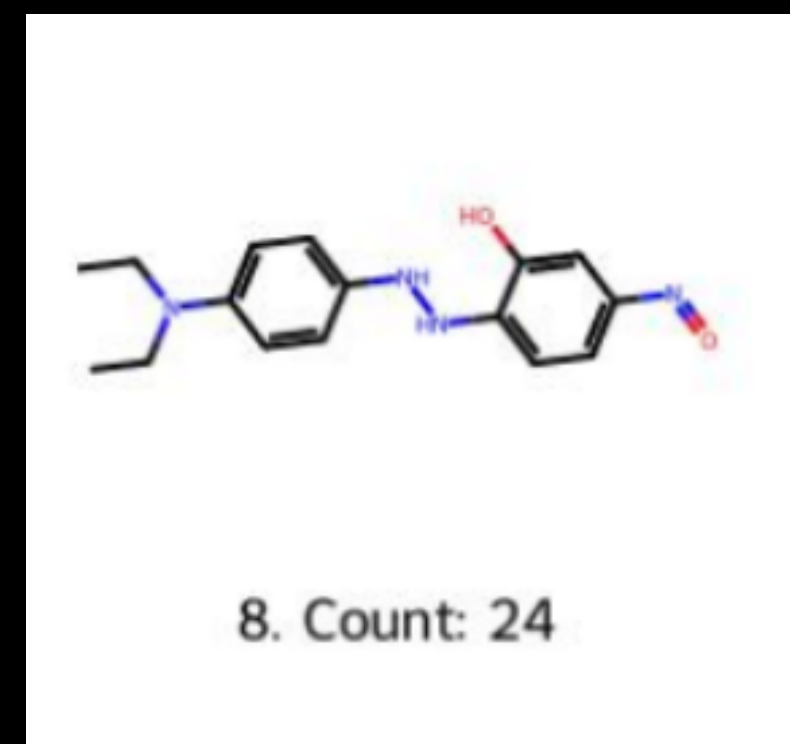


De-localized and planar network of double bonds



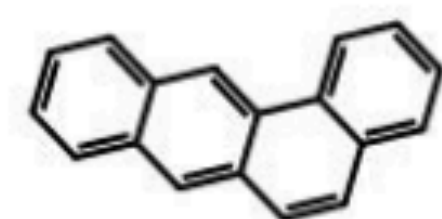
Molecular planes oriented in crystal lattice

Blanco et al.
2103.08601



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

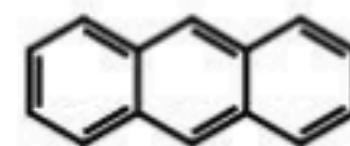
Correlation with Crystals



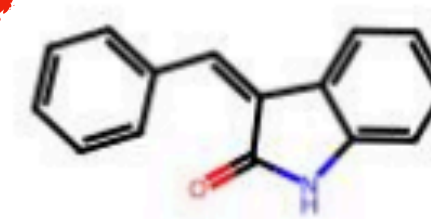
1



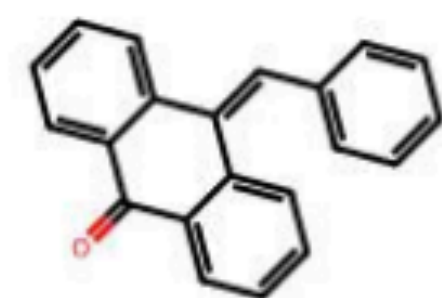
2



3



4



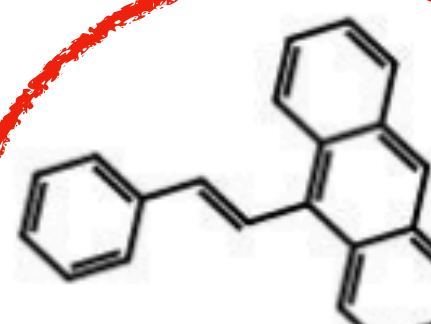
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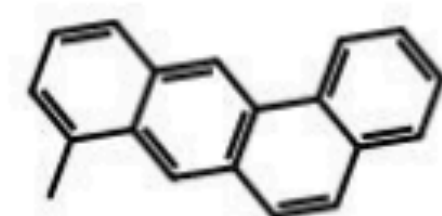
6



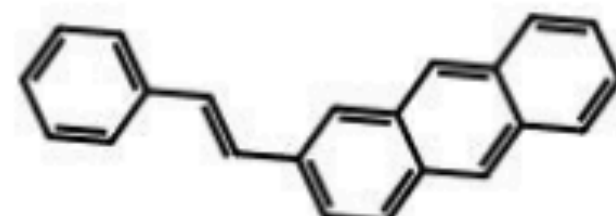
7



8



9



10

Danna
Freedmann @



Iterative ML Expansion

Numerical Validation

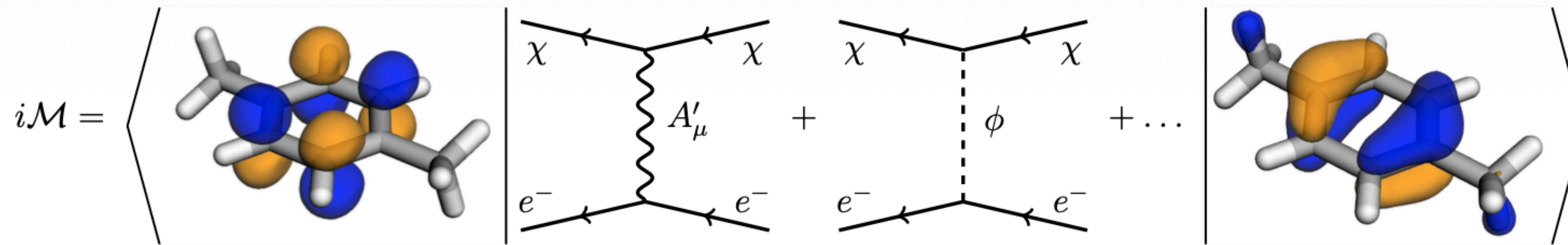
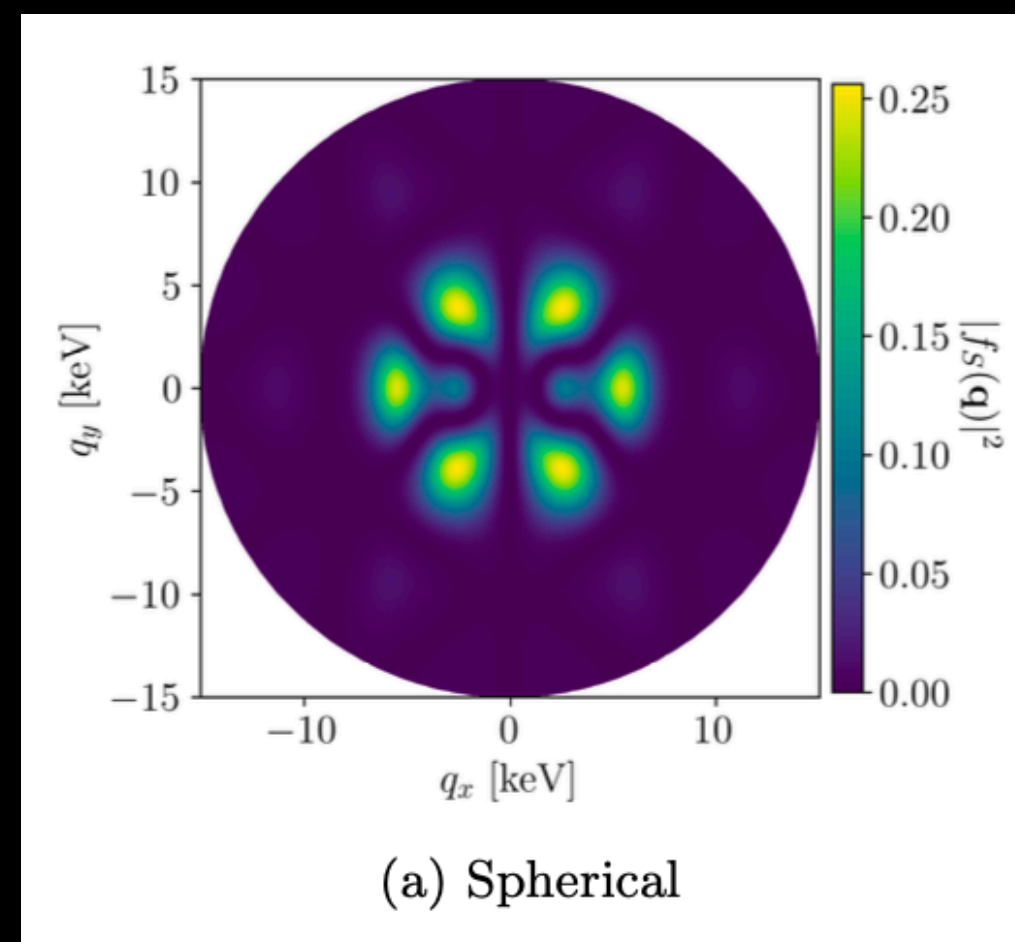


Figure 1: A weakly interacting particle χ scatters with an electron in a multiparticle ground state, transferring to it some momentum and energy, and leaving it in a higher energy eigenstate.



SCarFFF

Computation of form factors for scattering on molecules.

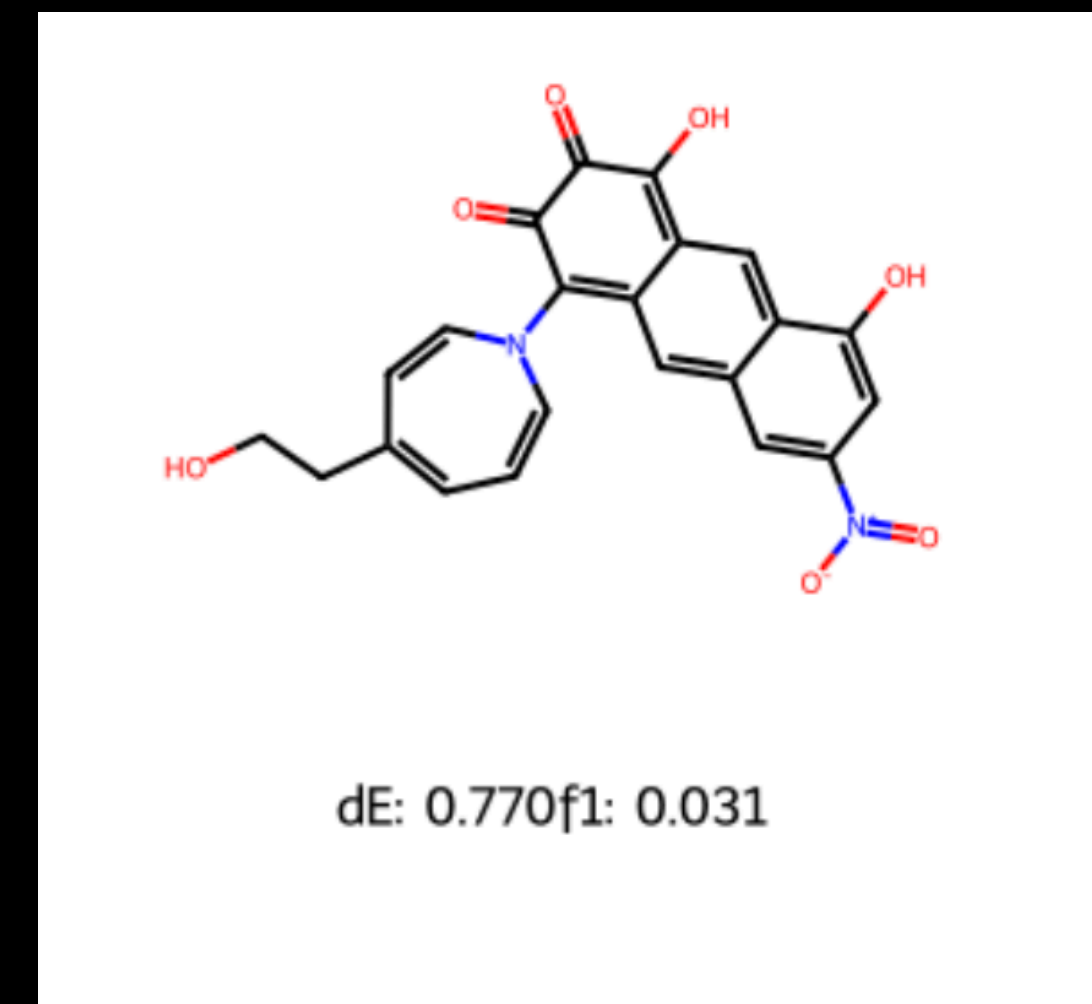
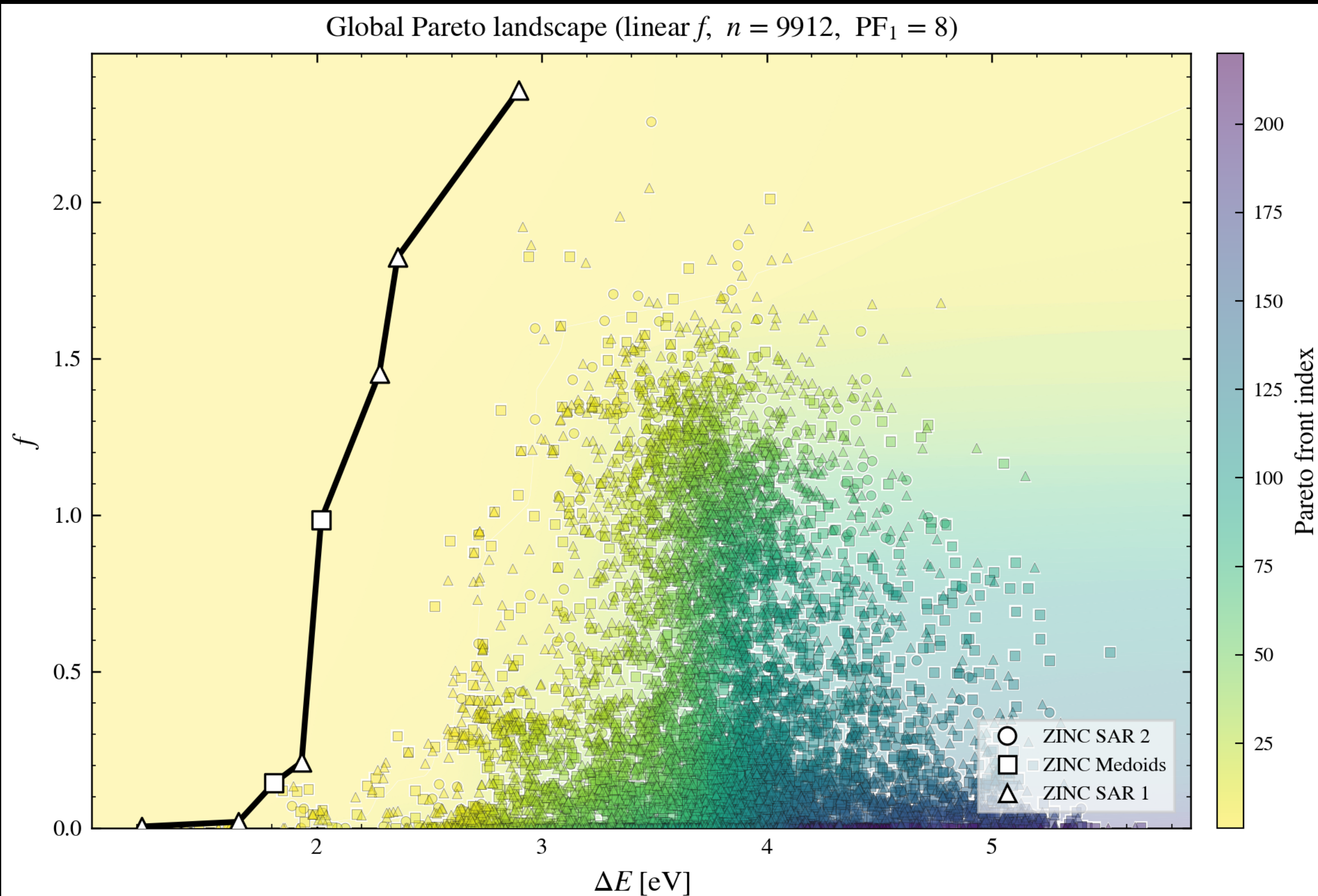
<https://github.com/jdshergold/SCarFFF/>



Jack Shergold

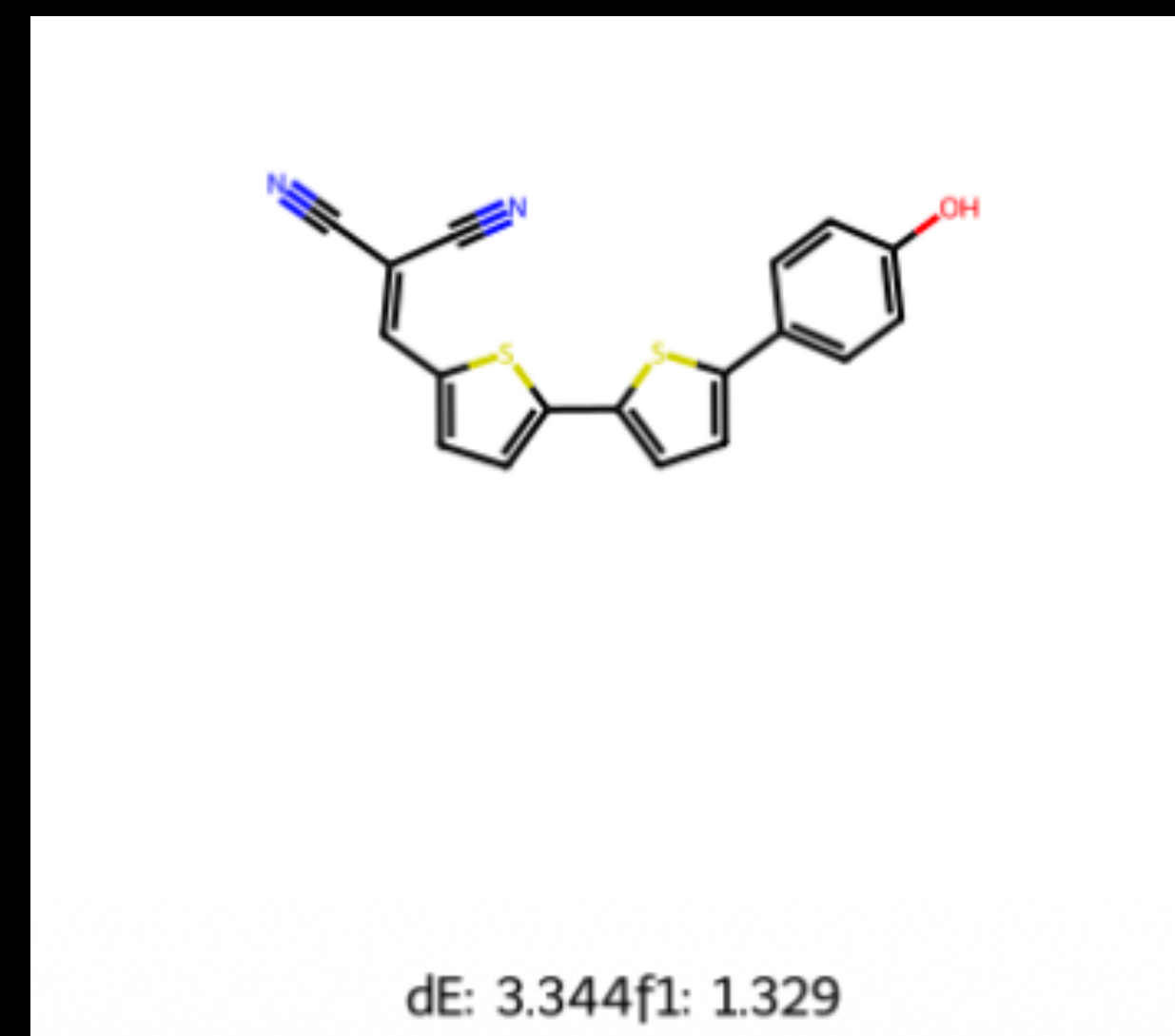
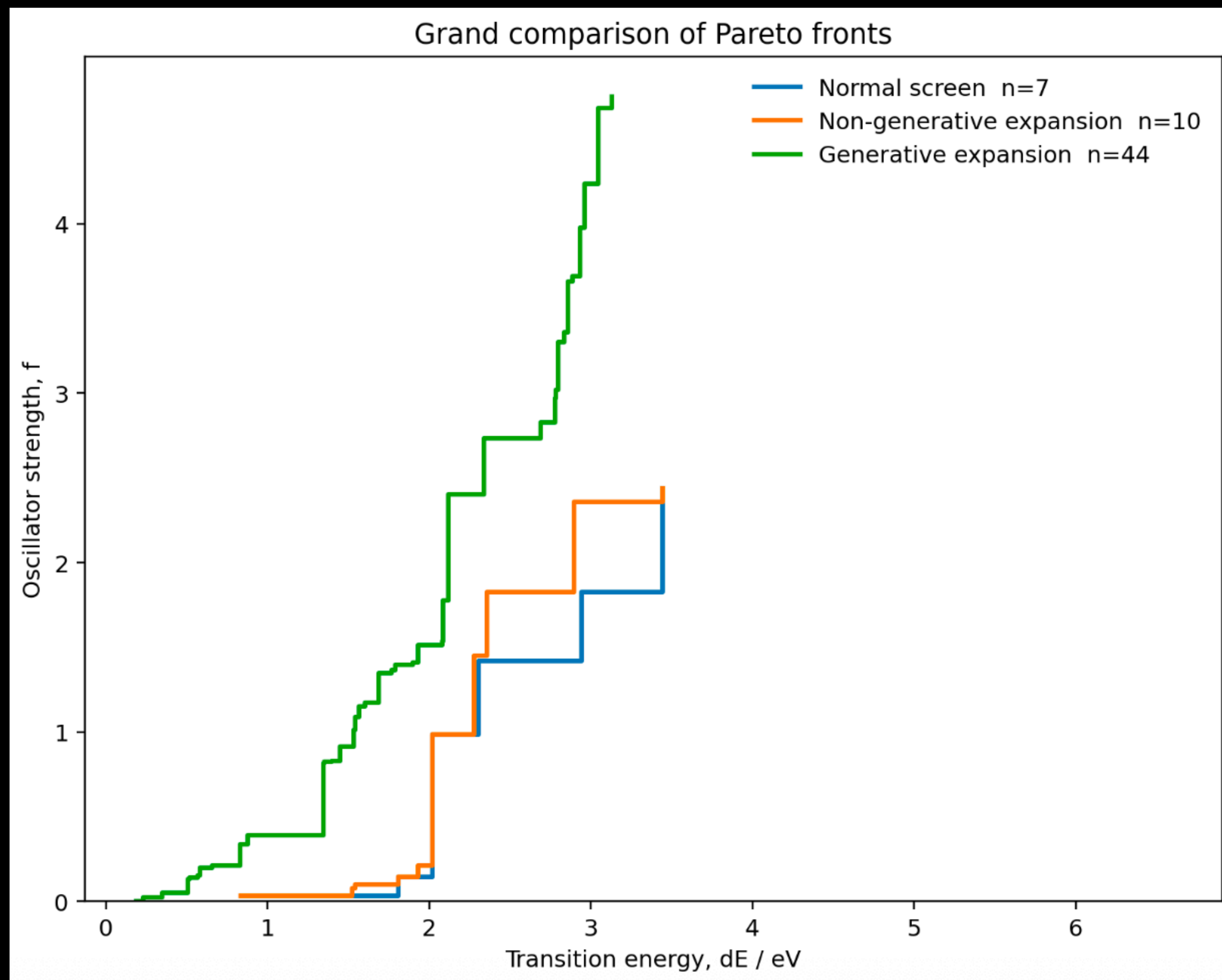
Post-Doctoral Researcher

Pareto Front Expansion



Example of new low
Delta E backbone

Pareto Front Expansion (ML boosted)



- + Purchasable molecules are being tested now
- + Next we need to combine with synthesis predictor networks

3) Time Varying Signals

Dark Matter Wind

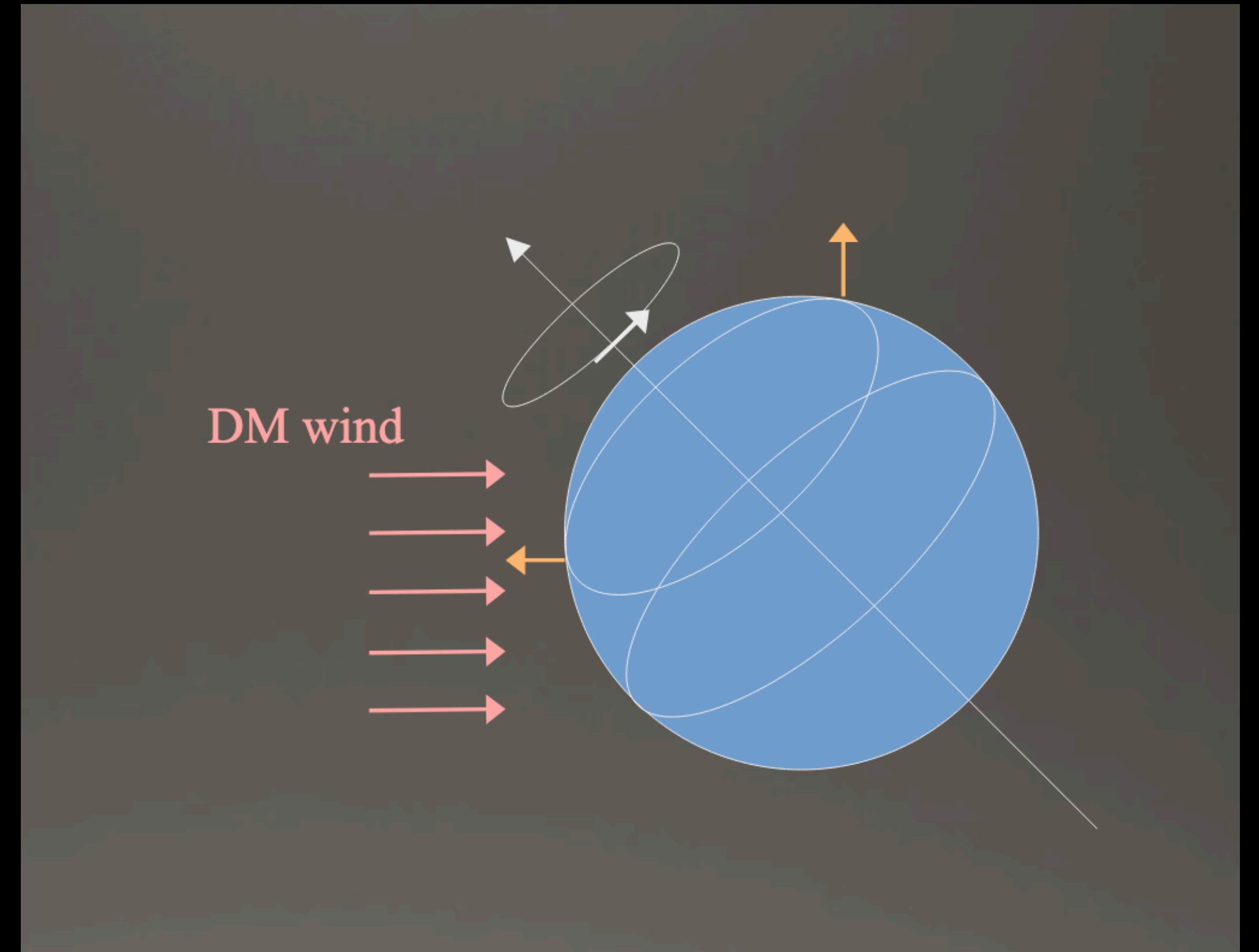
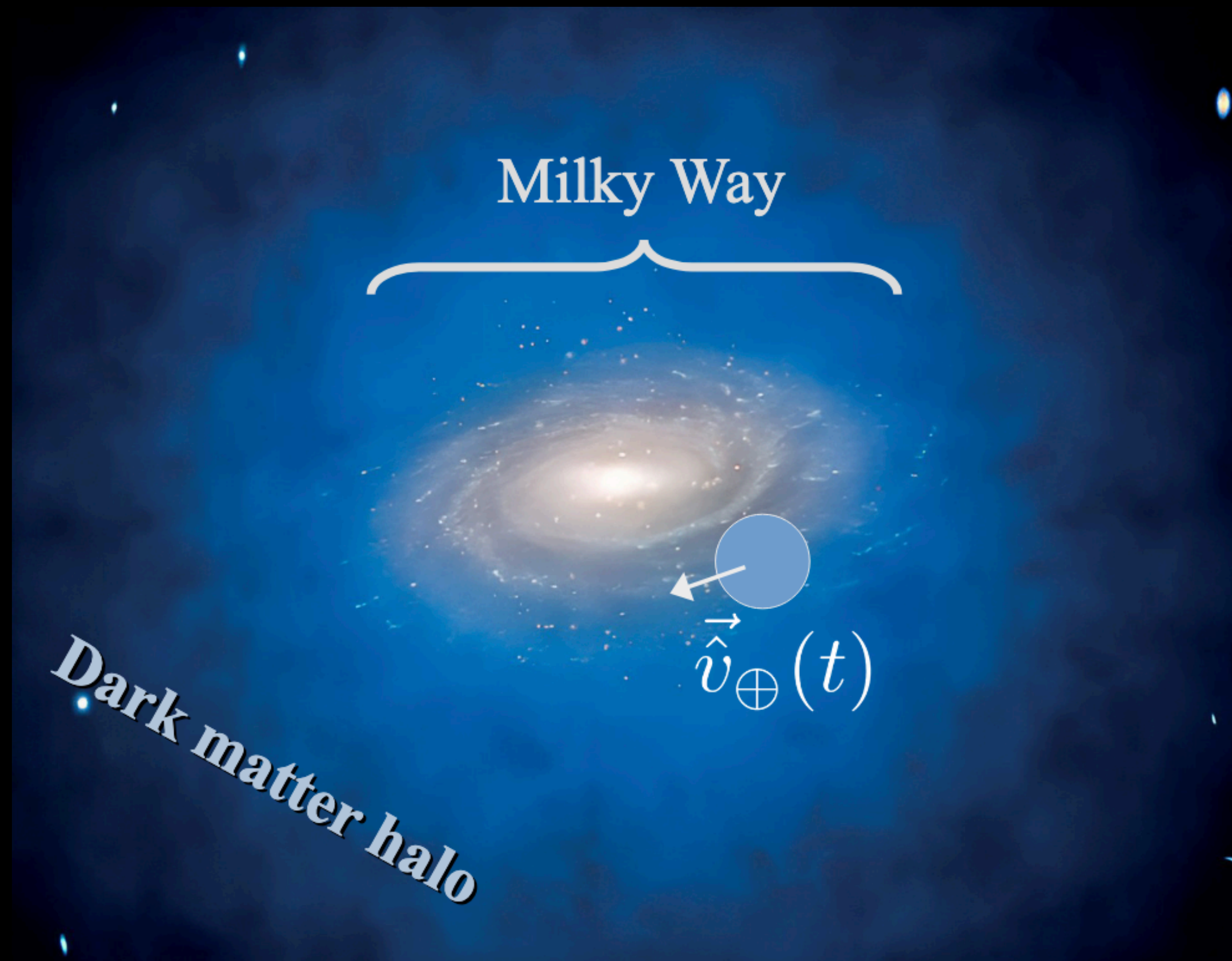
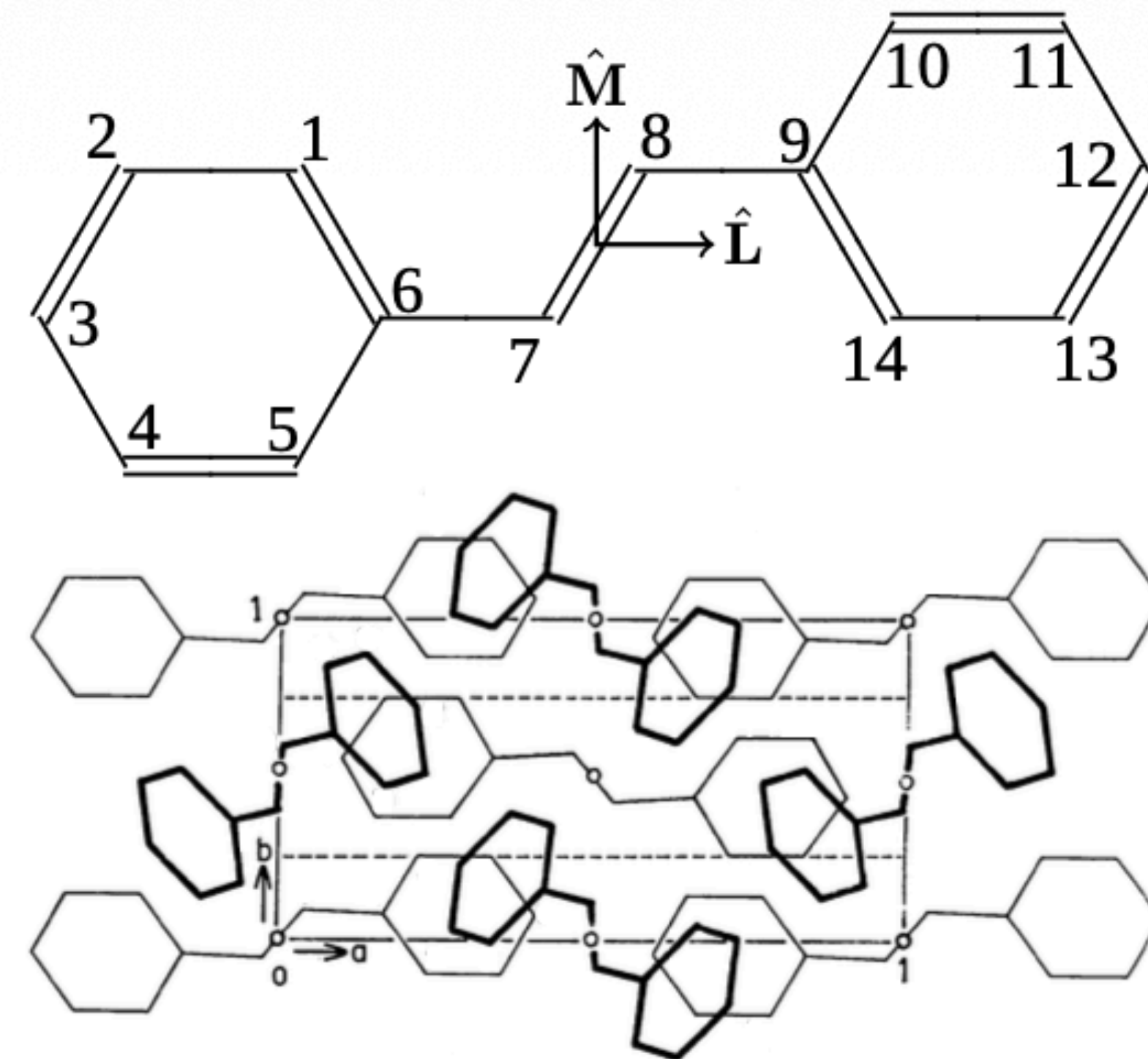
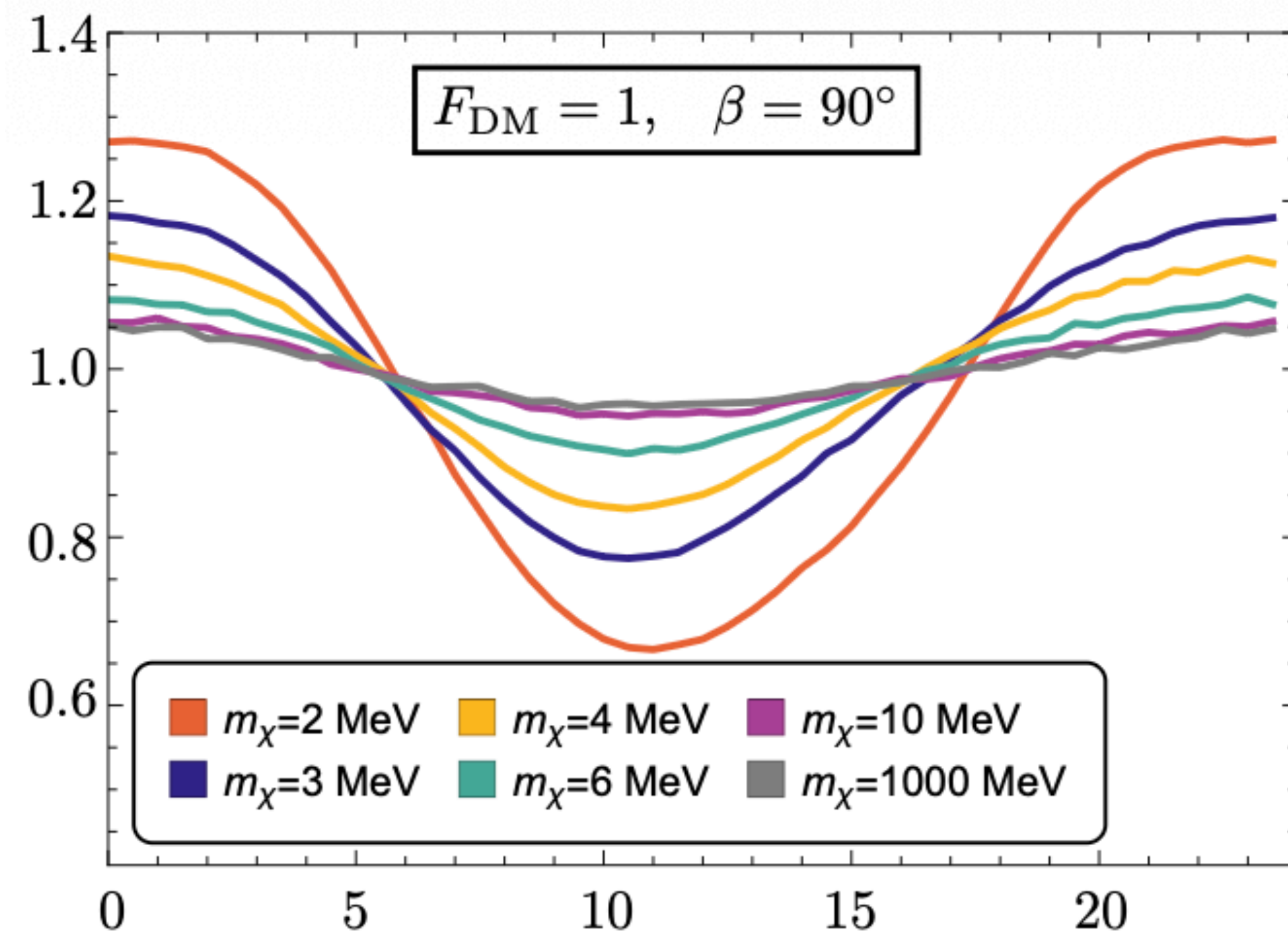


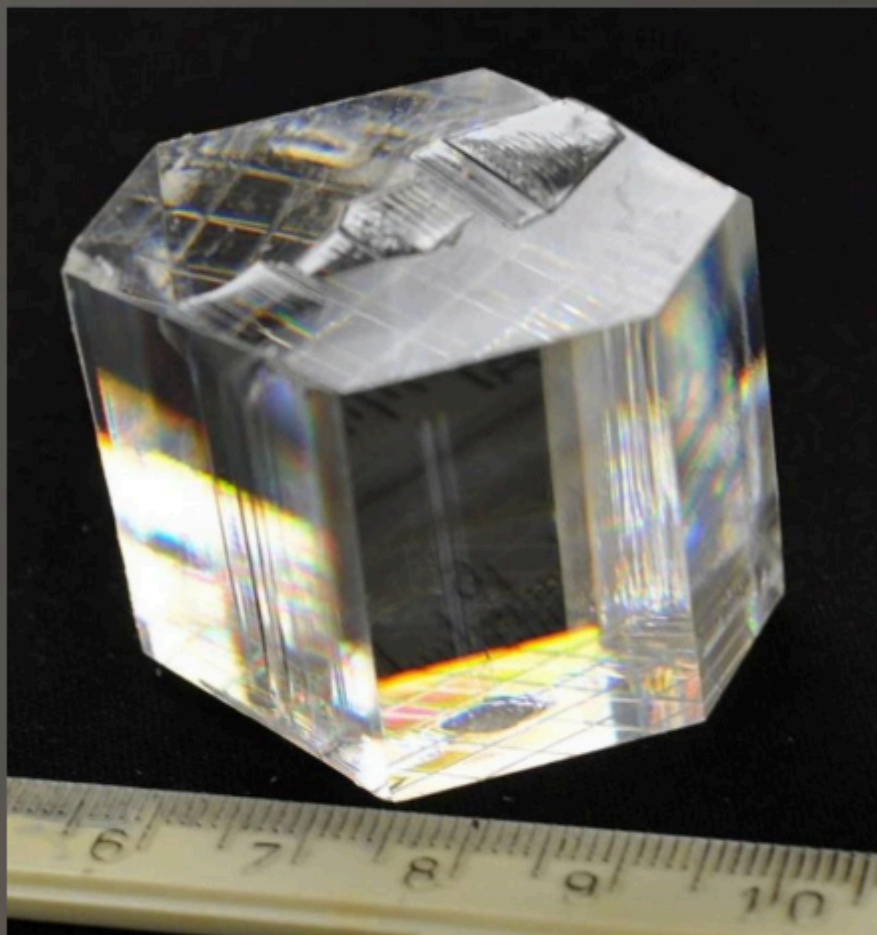
Image credit: C. Blanco

Direct Detection with Organic Molecules

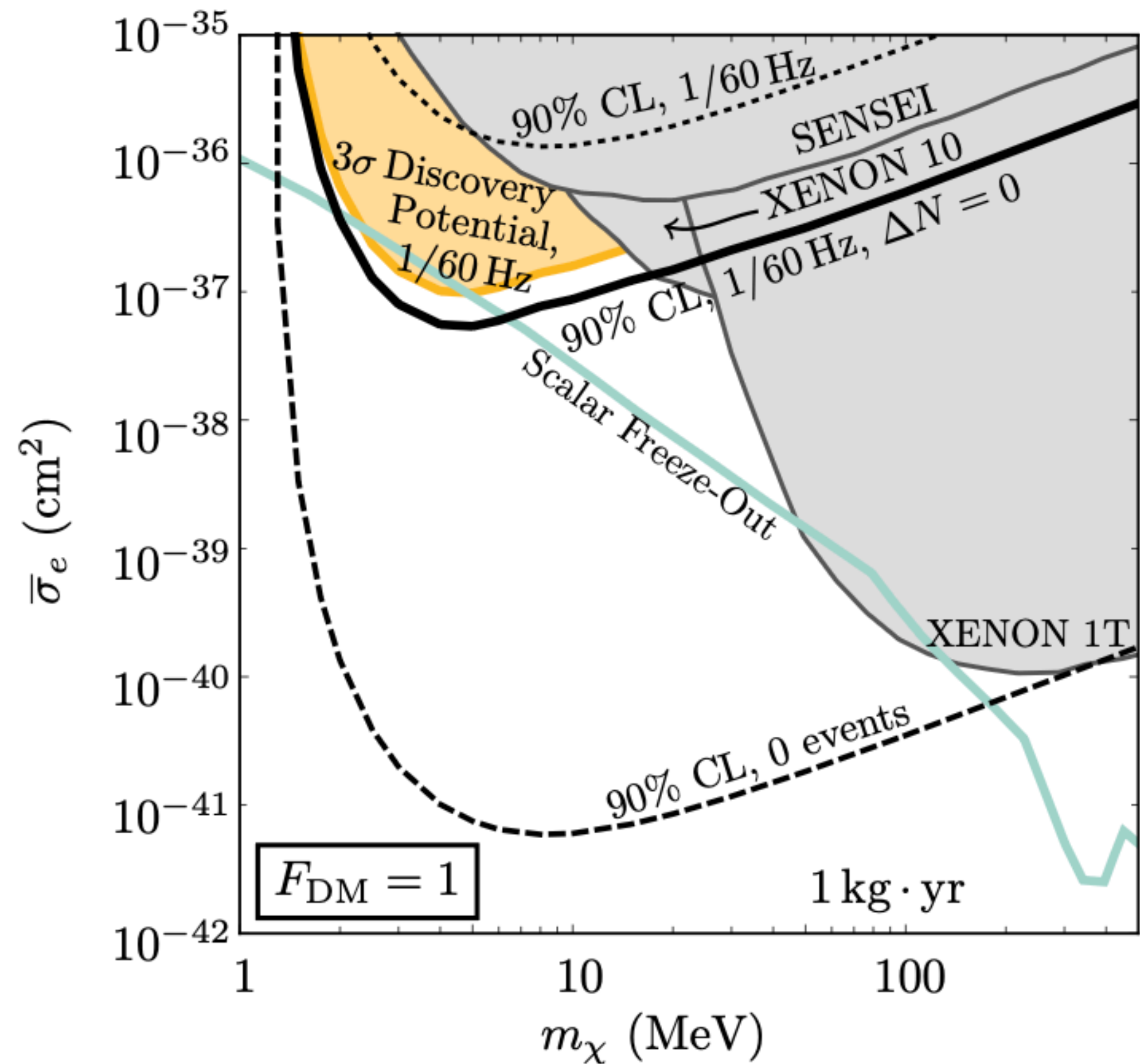


Potential Sensitivity Boost

Crystalline Trans-Stilbene

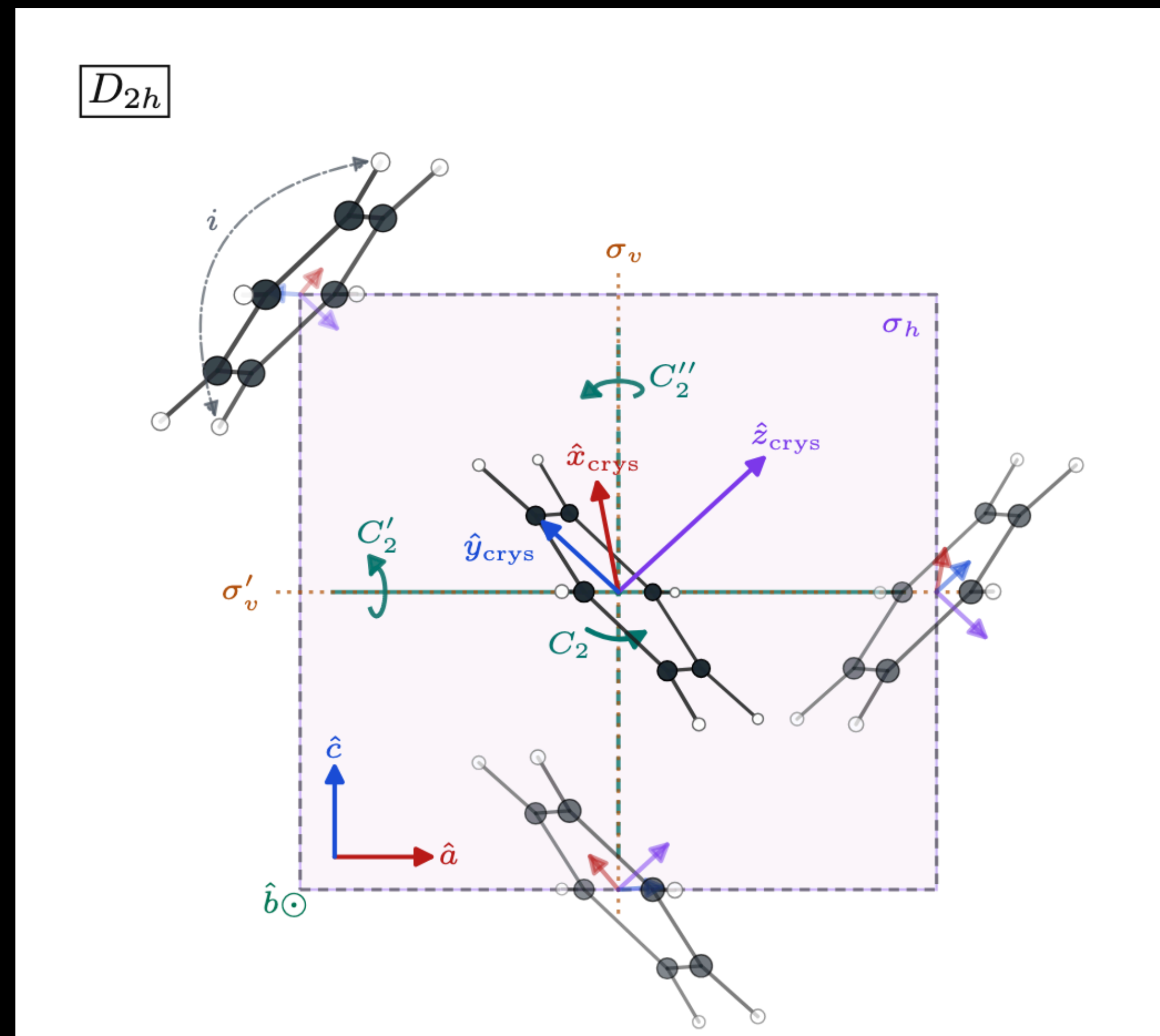
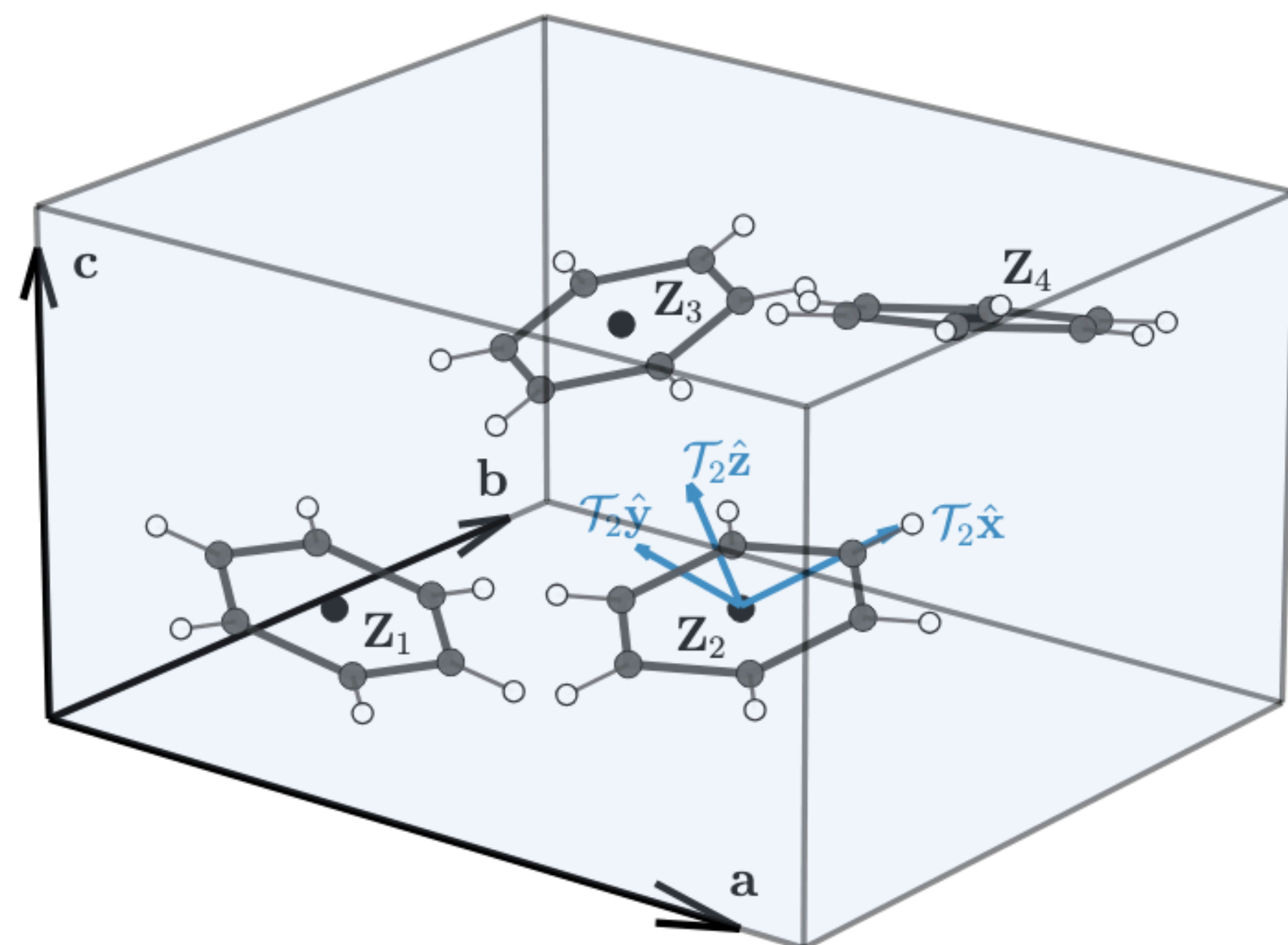


Carman, et.al. '18 (J. of Crystal Growth)



Efficient Detector Design

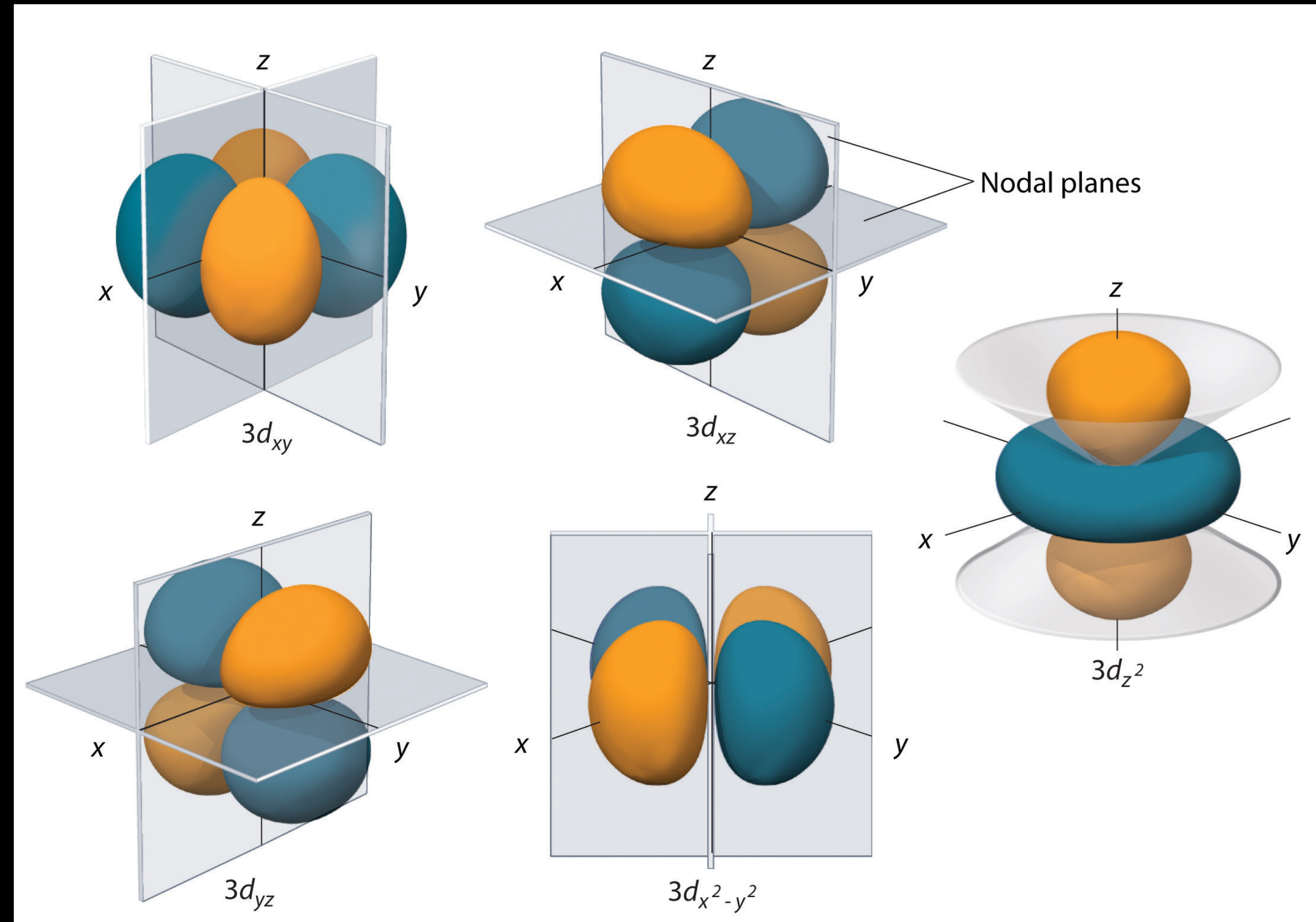
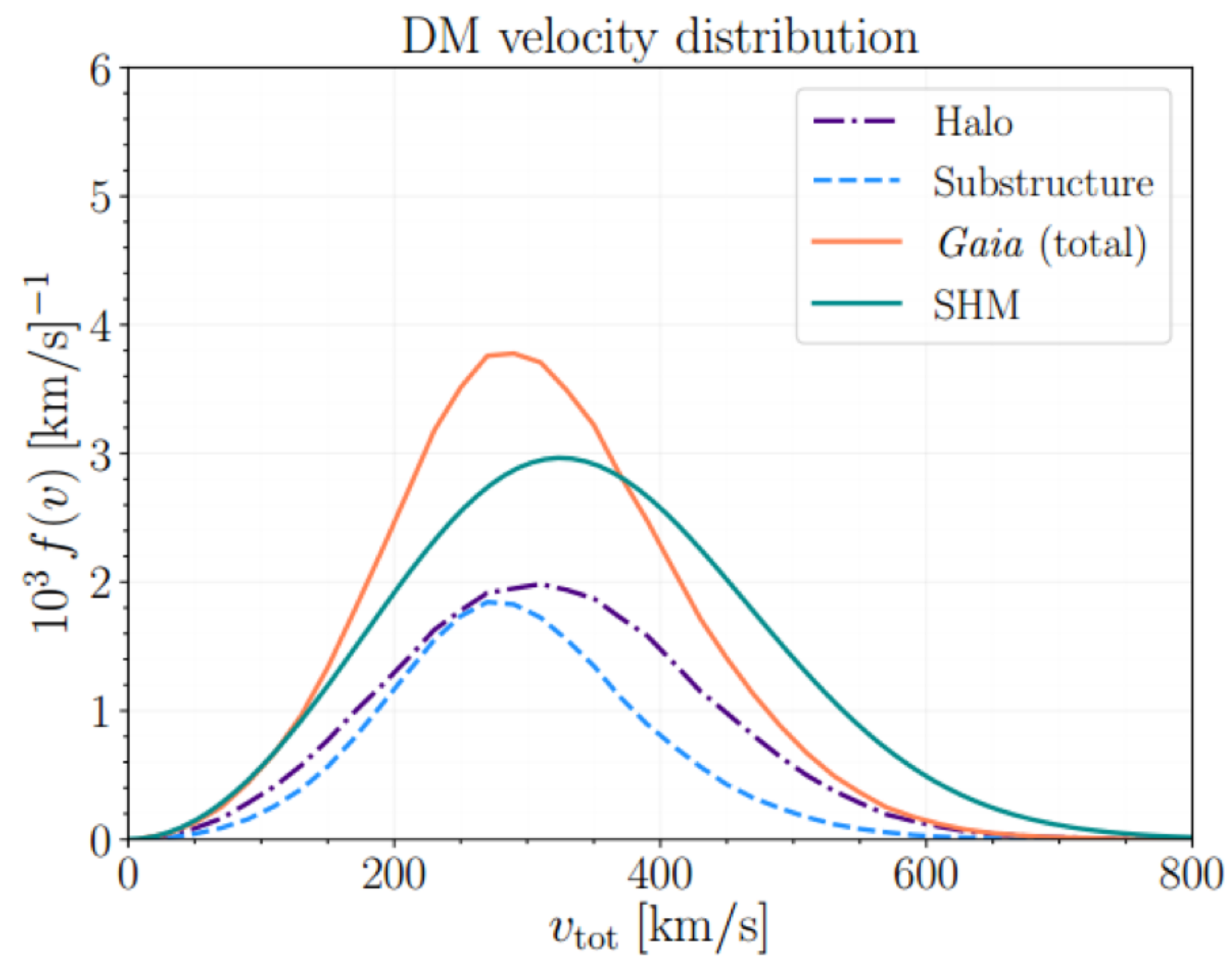
Molecules in Crystals



A Convenient Basis Set

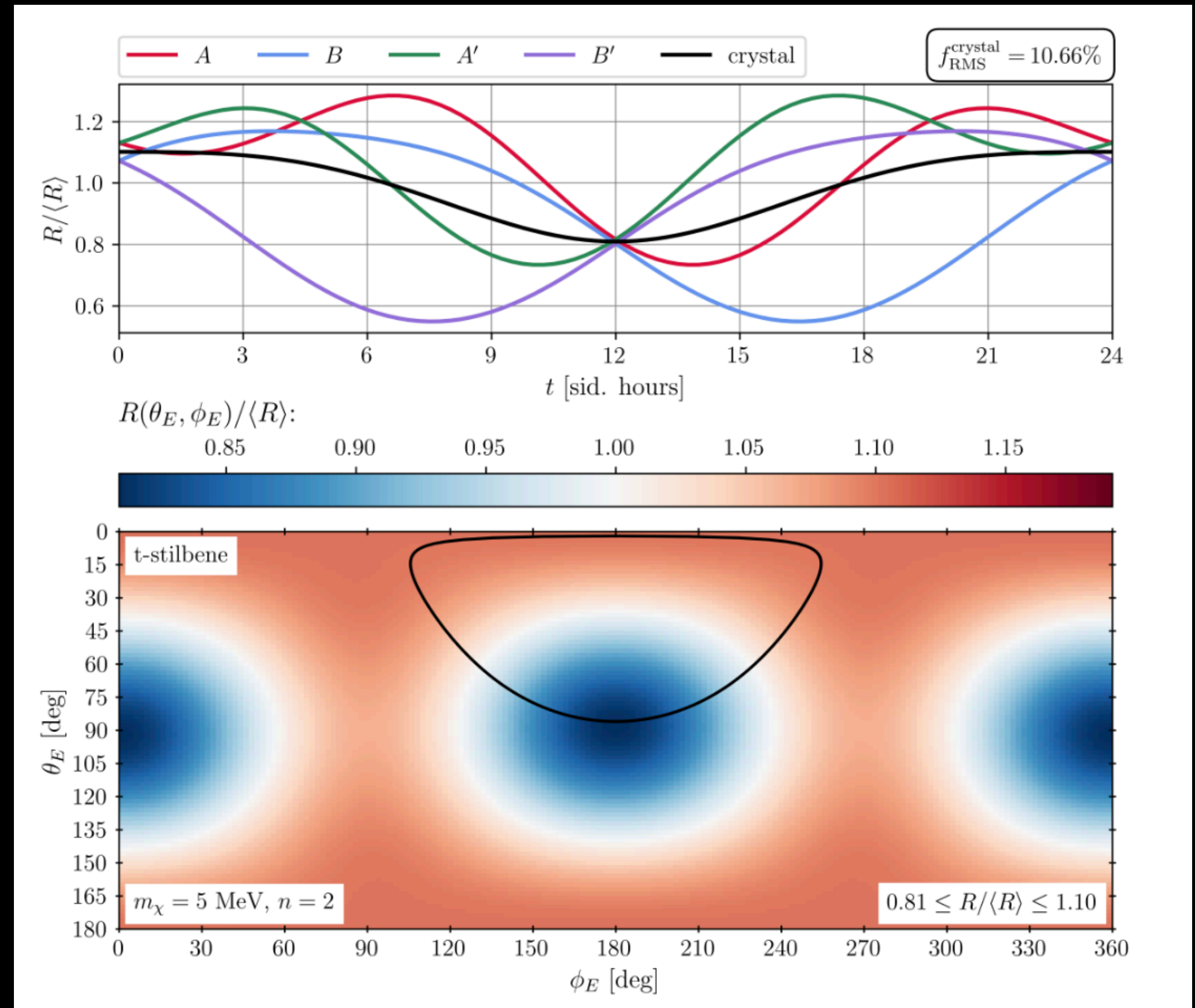
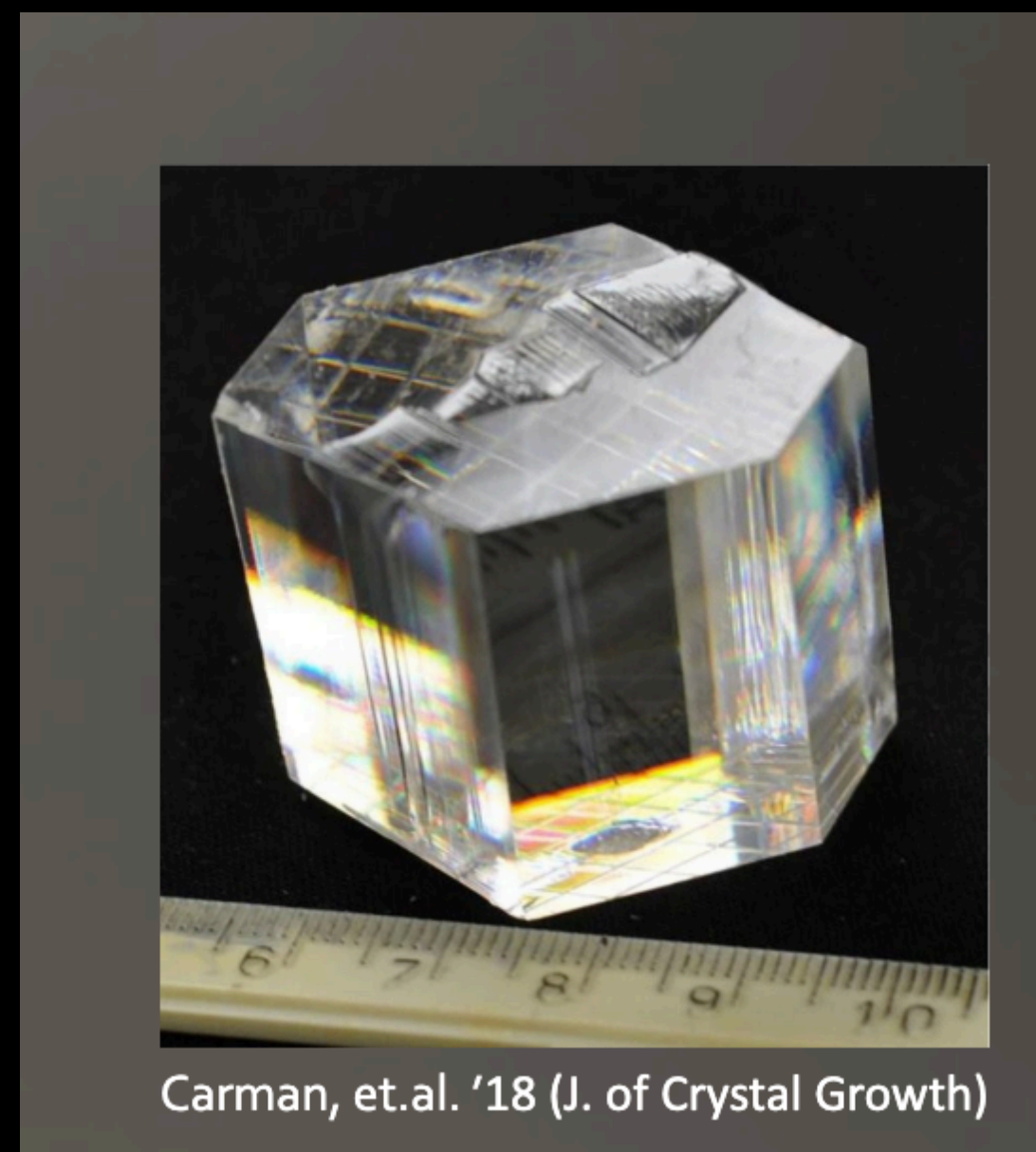
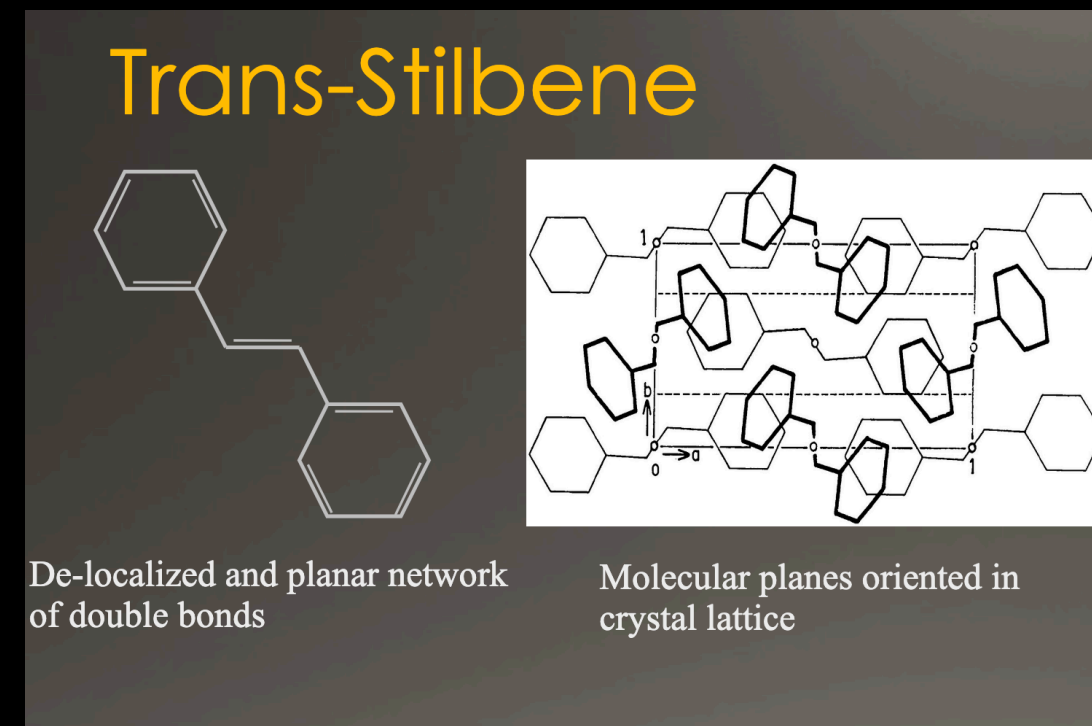
$$|f_s(\mathbf{q})|^2 = \sum_{\ell,m} f_{s,\ell m}^2(q) Y_{\ell m}(\hat{q}),$$

$$g_\chi(\mathbf{v}) = \sum_{\ell,m} g_{\ell m}(v) Y_{\ell m}(\hat{v}),$$



$l=1$ dipole modes cancel in squared form factor, $l=2$ quadrupole dominate modulation

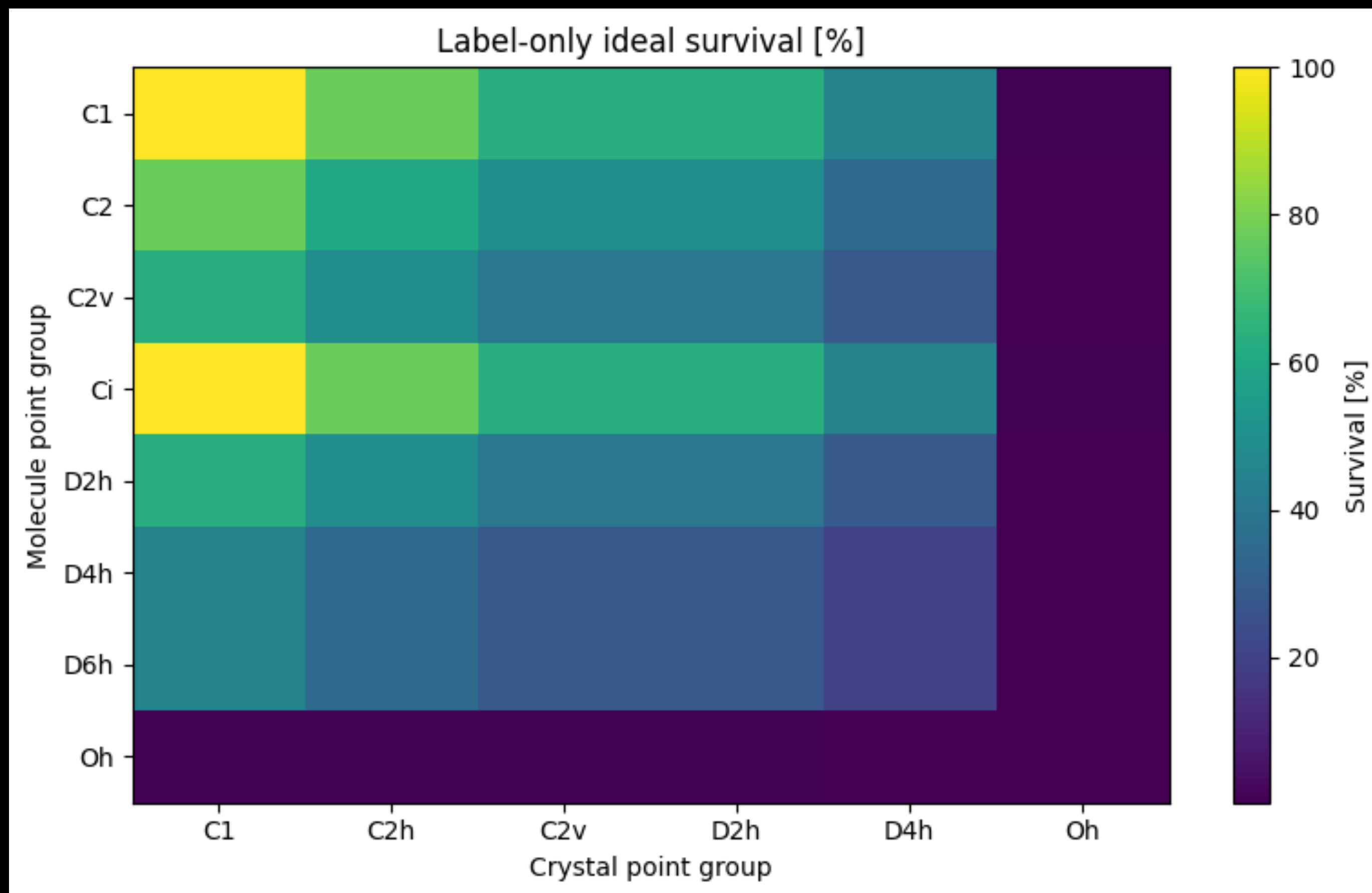
Example of Trans-Stilbene



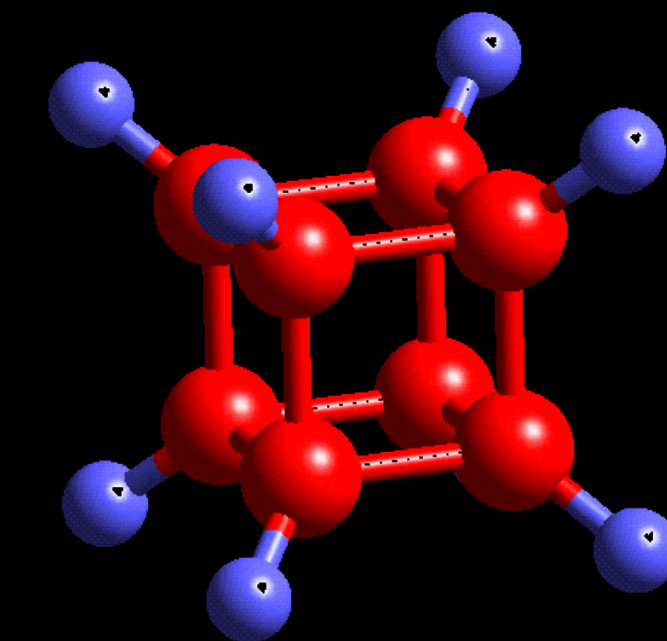
Fast Tool for DM Detector Design

The Role of Symmetries in Dark Matter Detector Design

Benjamin Lillard (Penn State U., University Park, IGC), Jack D. Shergold (Liverpool U., Dept. Math.), Juri Smirnov (Liverpool U., Dept. Math.)



Dangerous: cubic groups,
like octahedral
symmetry Oh



Rare in molecular
crystals, common in
atomic crystals

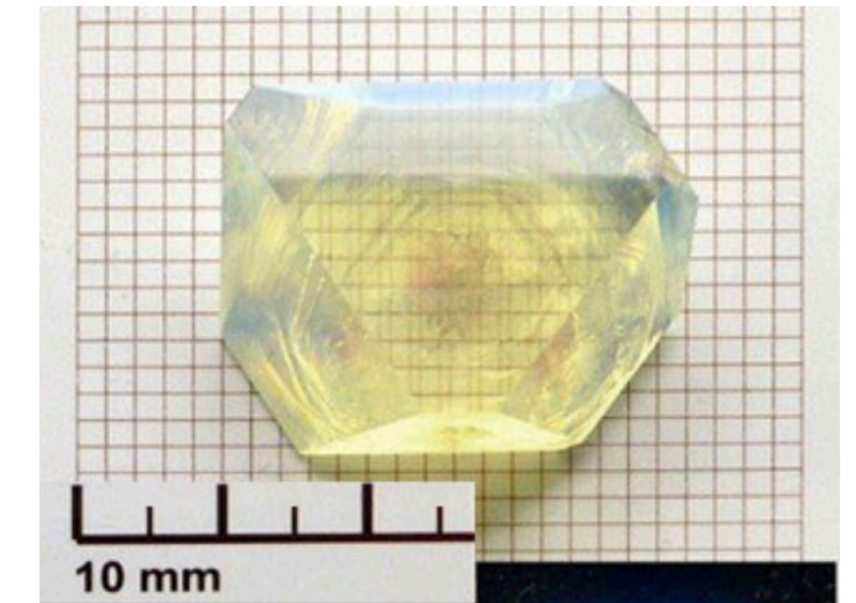
Get the Symmscreen Python
package: [https://github.com/
jdshergold/symmscreen](https://github.com/jdshergold/symmscreen)

Next Steps towards Molecular Detectors

- + Combining the Pareto Front Expansion with Synthesis Pathway NNs
- + Experimental Validation
- + Testing readout, low T SiPMs as a demonstrator
- + Prototype in collaboration with University of Oxford
- + Explore Scalability and Crystal Combinations with Fermi Lab and Penn State

9,10-Diphenylanthracene (DPA)

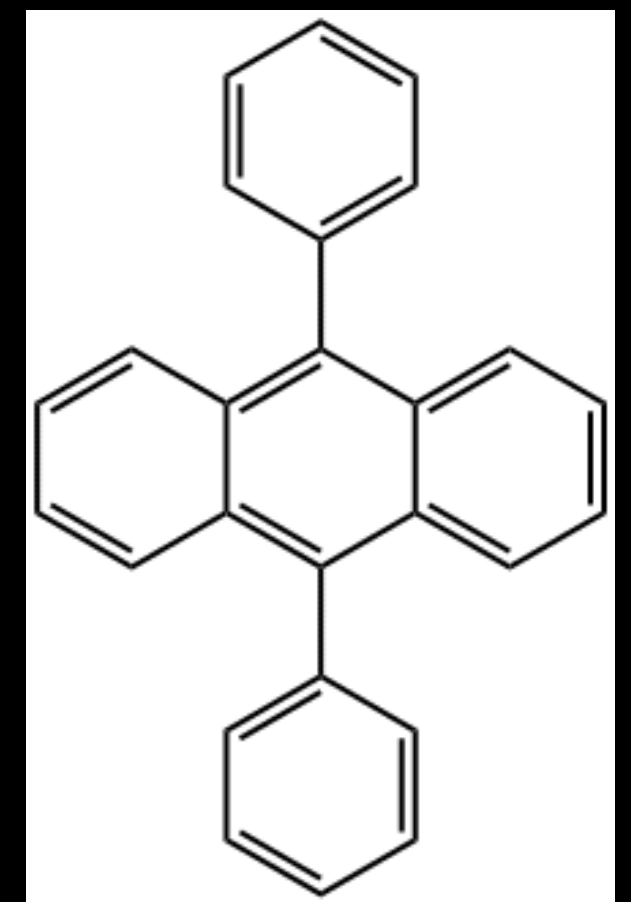
- Size: Available in sizes up to 5 in³
- Chemical formula: C₂₆H₁₈
- Density: 1.22 g/cm³
- Emission wavelength: 468 nm with a light yield of 14,000 ph/MeV
- Figure of Merit for neutron/gamma PSD: > 2.0 at 1 MeVee
- Operating temperature: Not to exceed 120°C
- Care: Crystals are very brittle and need to be handled with care



9,10-Diphenylanthracene (DPA) Organic Scintillation Crystal

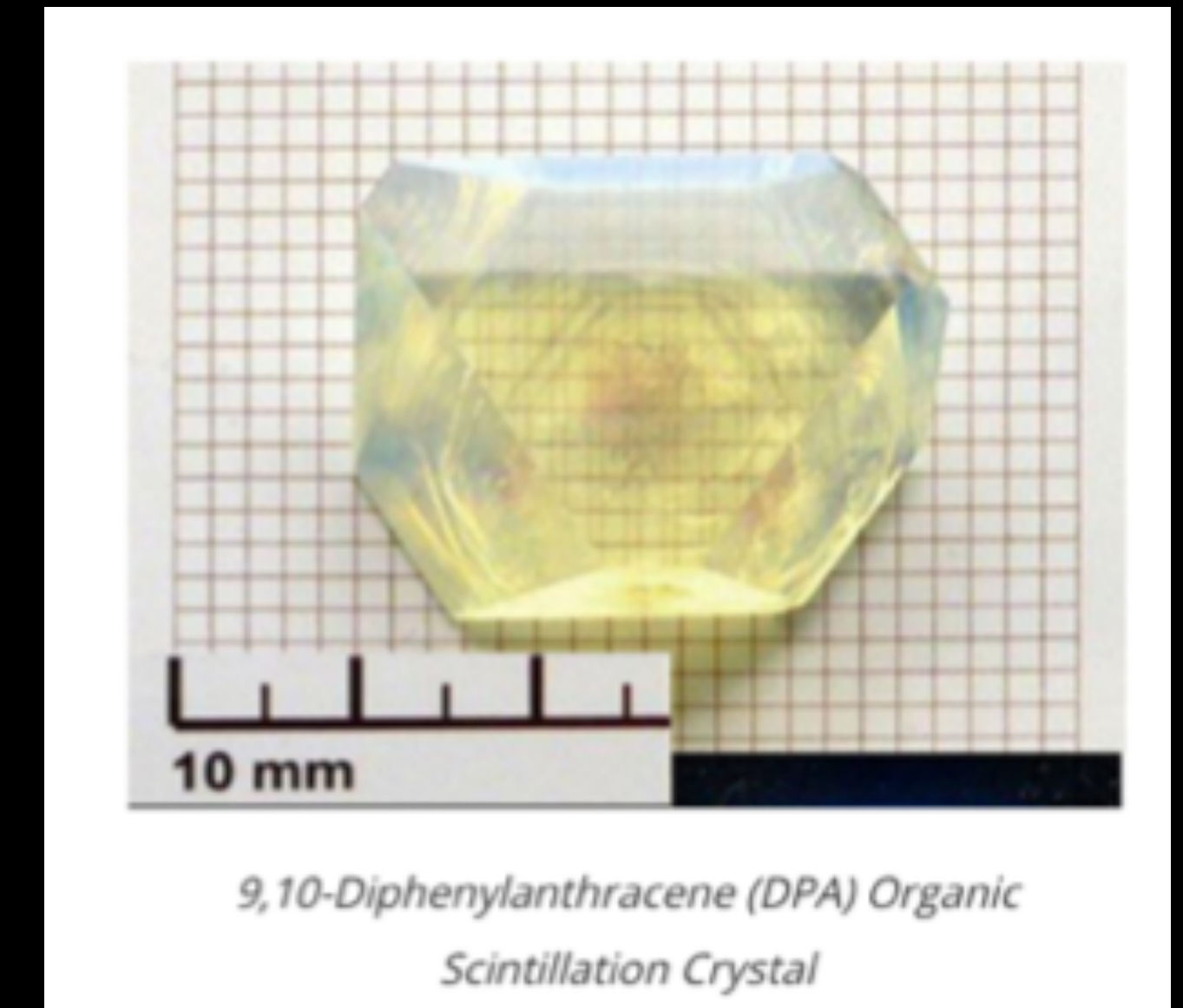
+ 4eV -> 3 eV
Delta E

+ Boost in
brightness



Summary

- Shadow Sectors with broken Z_2 symmetry lead to a whole new realm of unseen universes
- Motivation to explore the MeV- GeV DM mass scales
- 1) Low Threshold Detectors and Quantum Sensors at the limit of our sensitivity
- 2) Molecular Crystals for low Energy and Daily Modulation
- ML and Chemistry a new and exciting playground



Bonus Material

Expanding the ML Chemistry Pipeline

Bonus Episode: Initial Results in 2026

Target validation with partner lab in Hamburg: Hanse Scientific GmbH

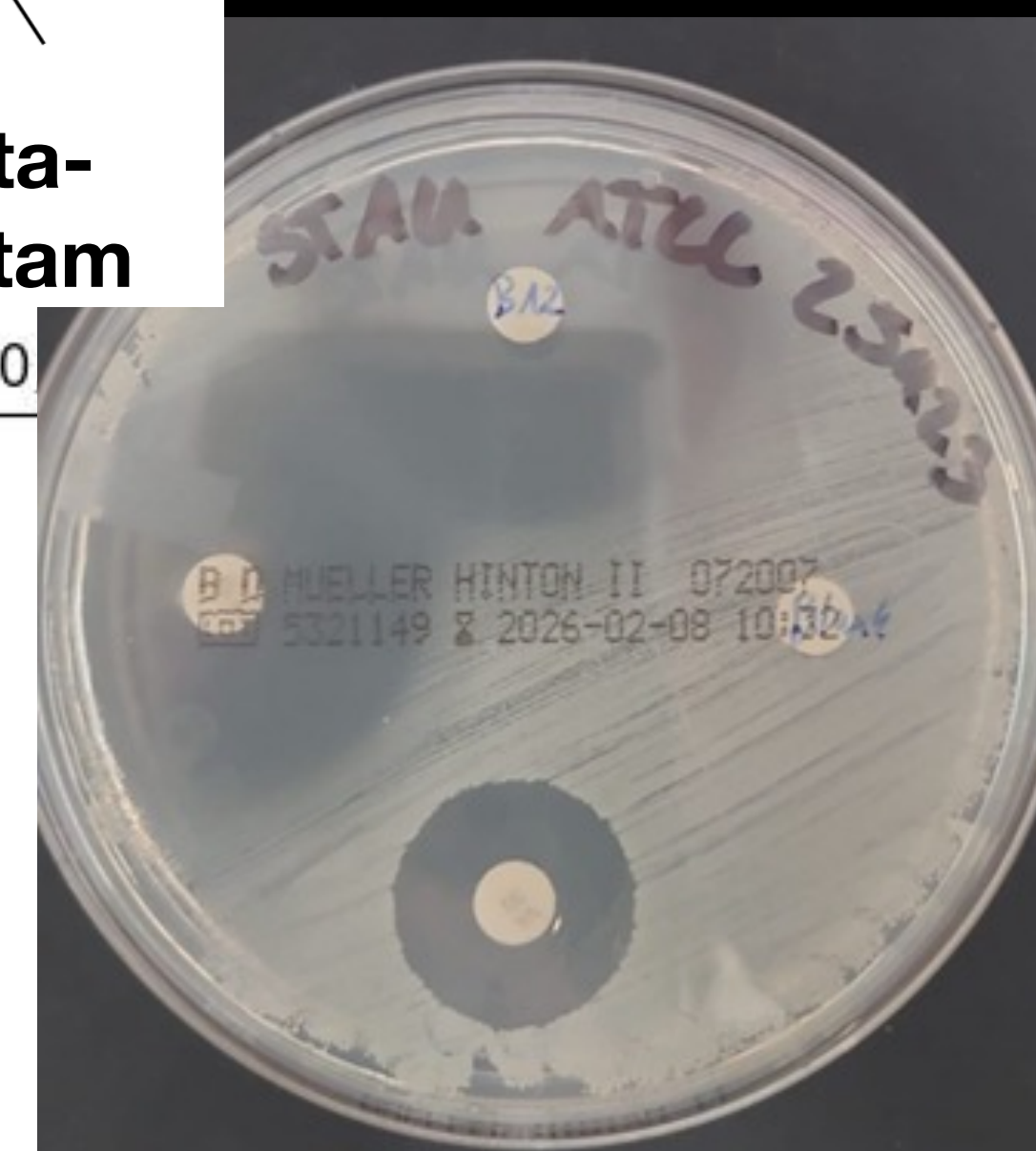
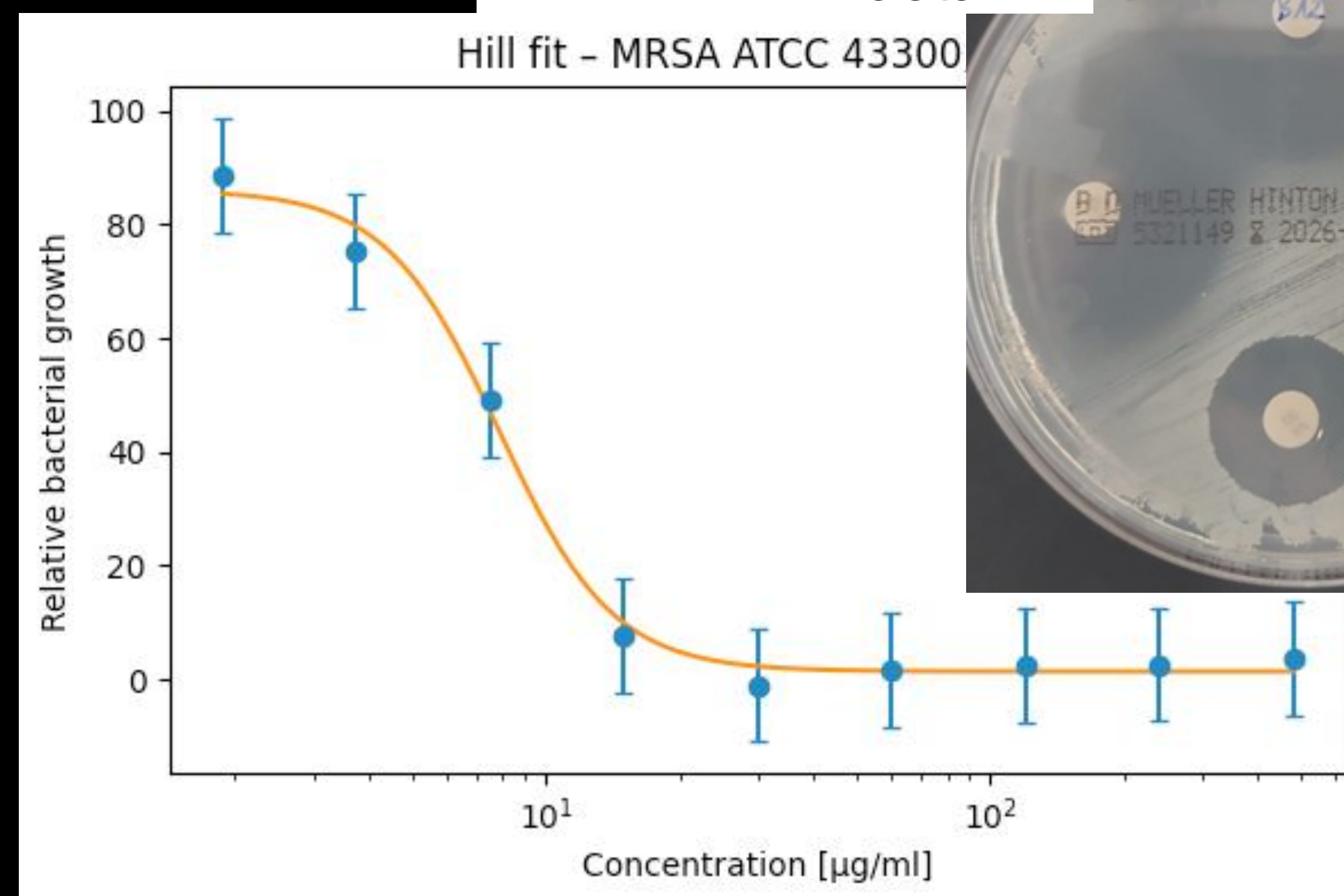
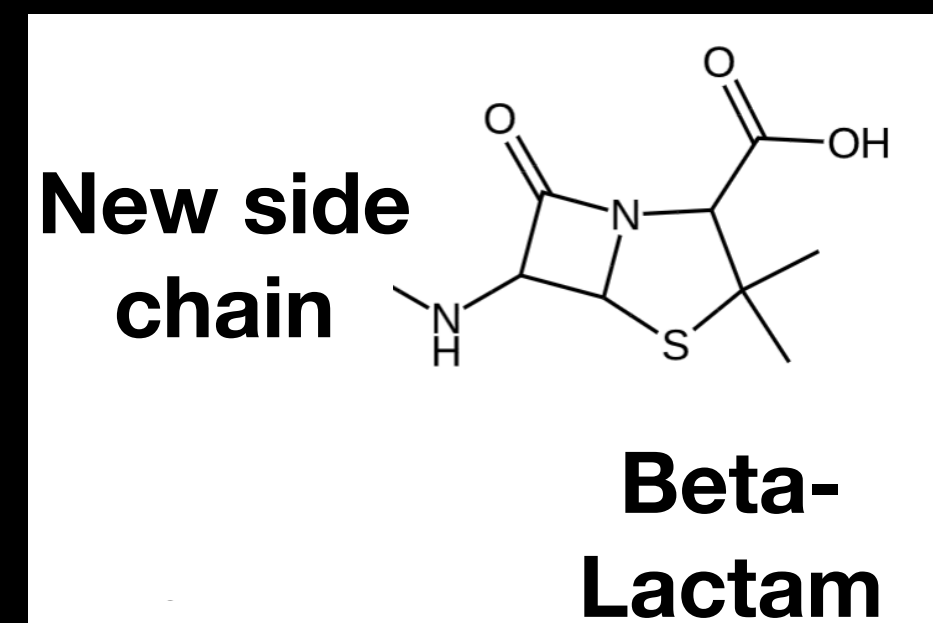
Proof of principle run:

Initial costs \$2k.

40 molecular candidates shortlisted.

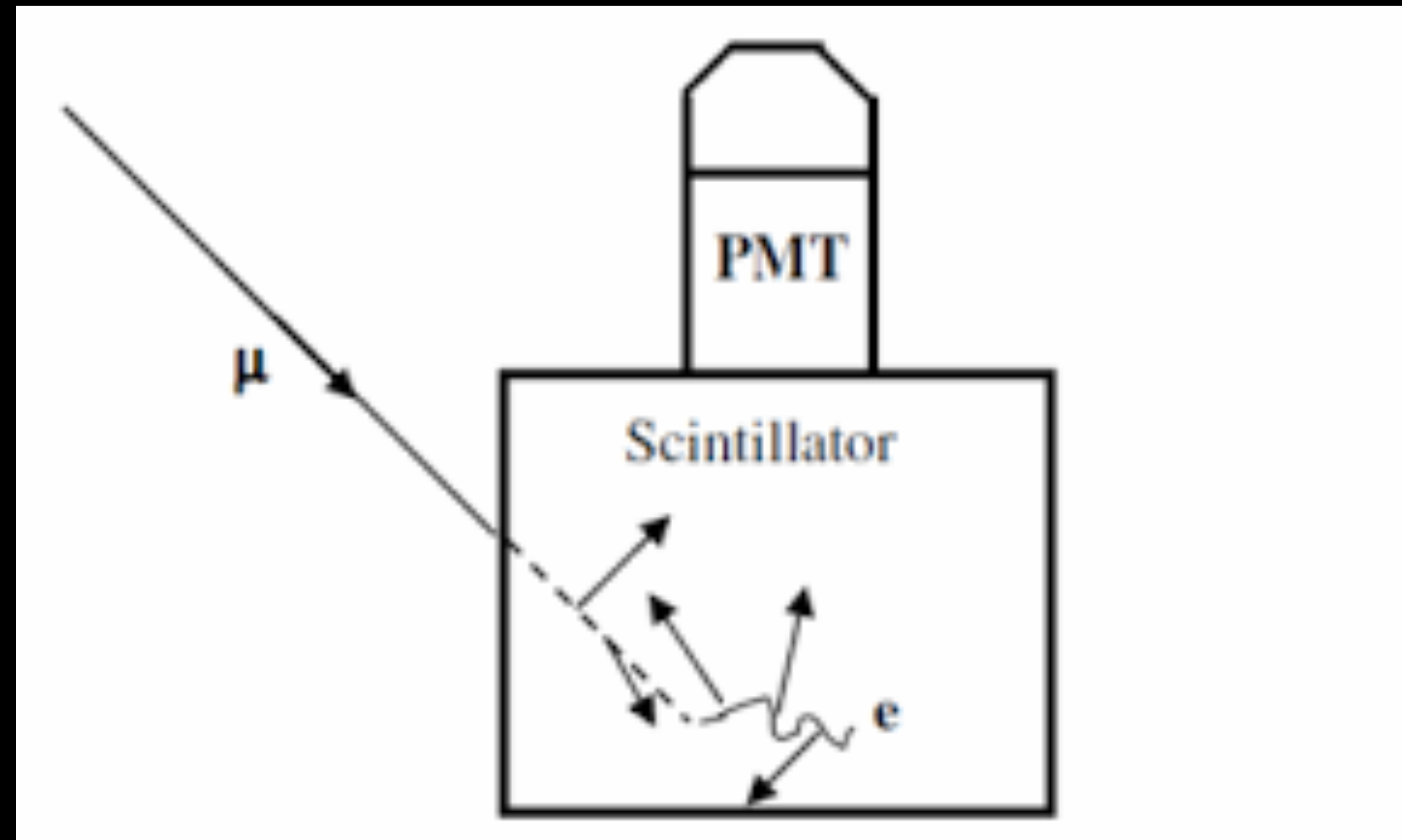
3 experimentally validated inhibitory hits.

One strong MRSA-active compound (new beta-lactam substructure).



ML Assisted Scintillator and Veto Detector Design

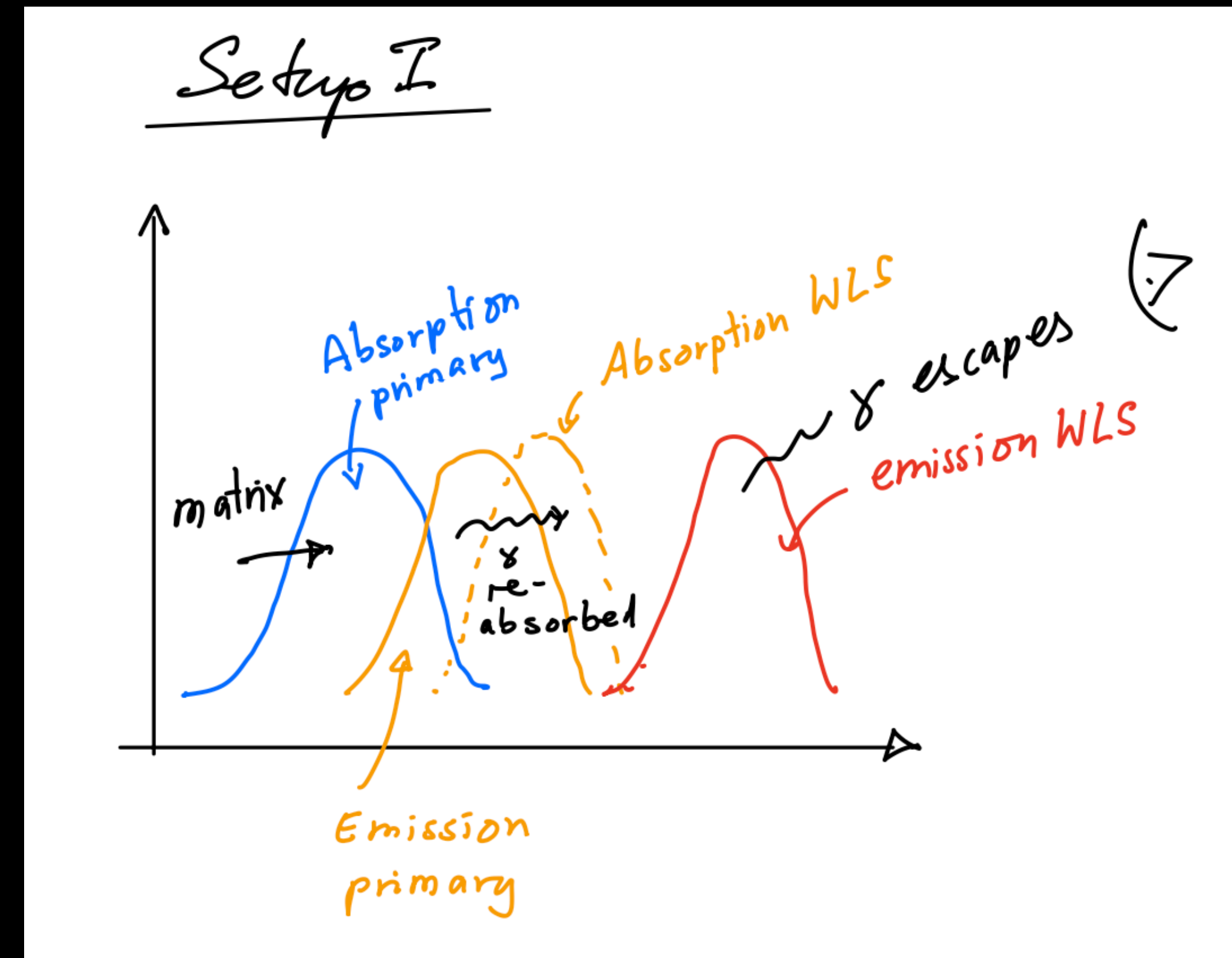
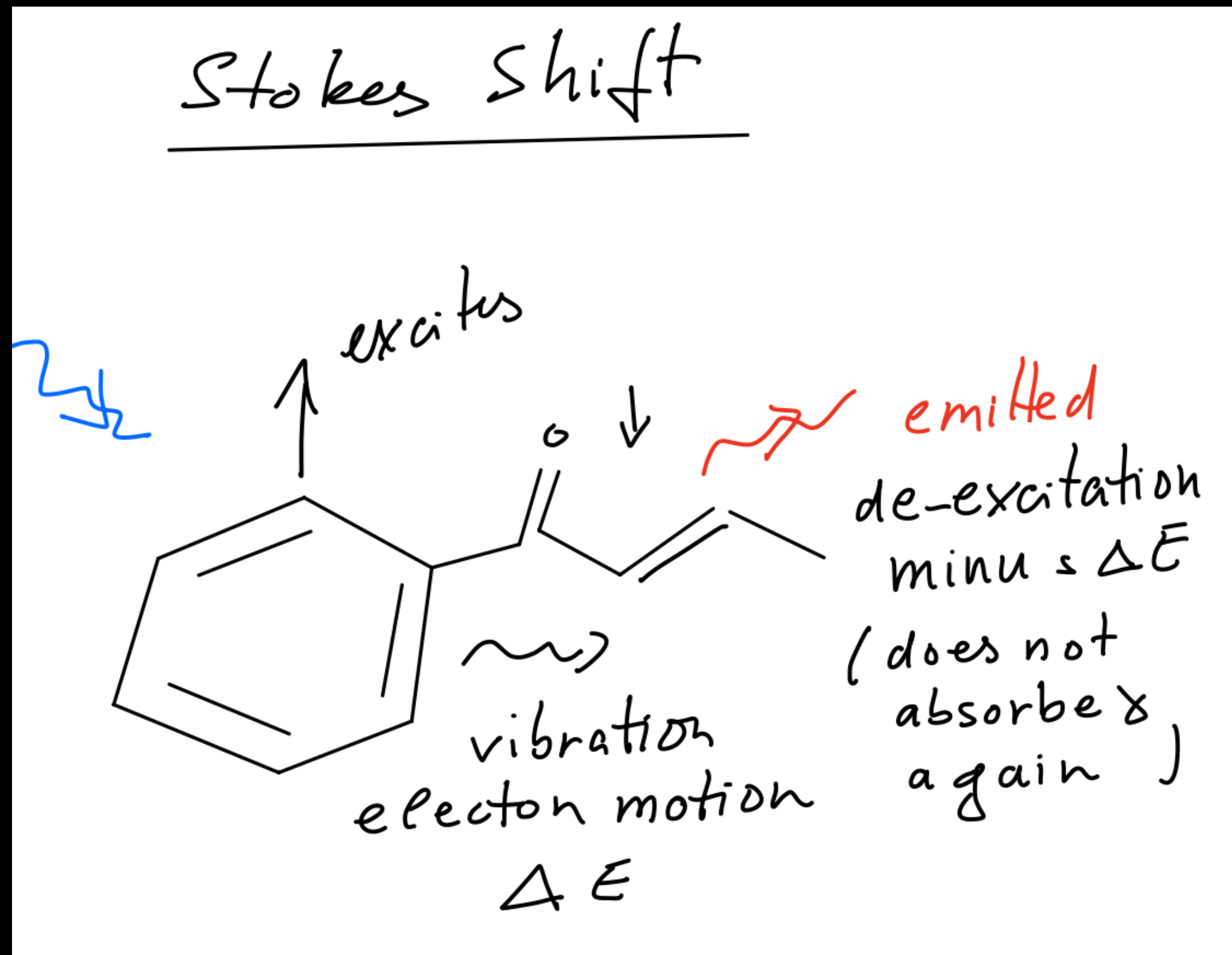
Design low T Scintillator for SiPM readout



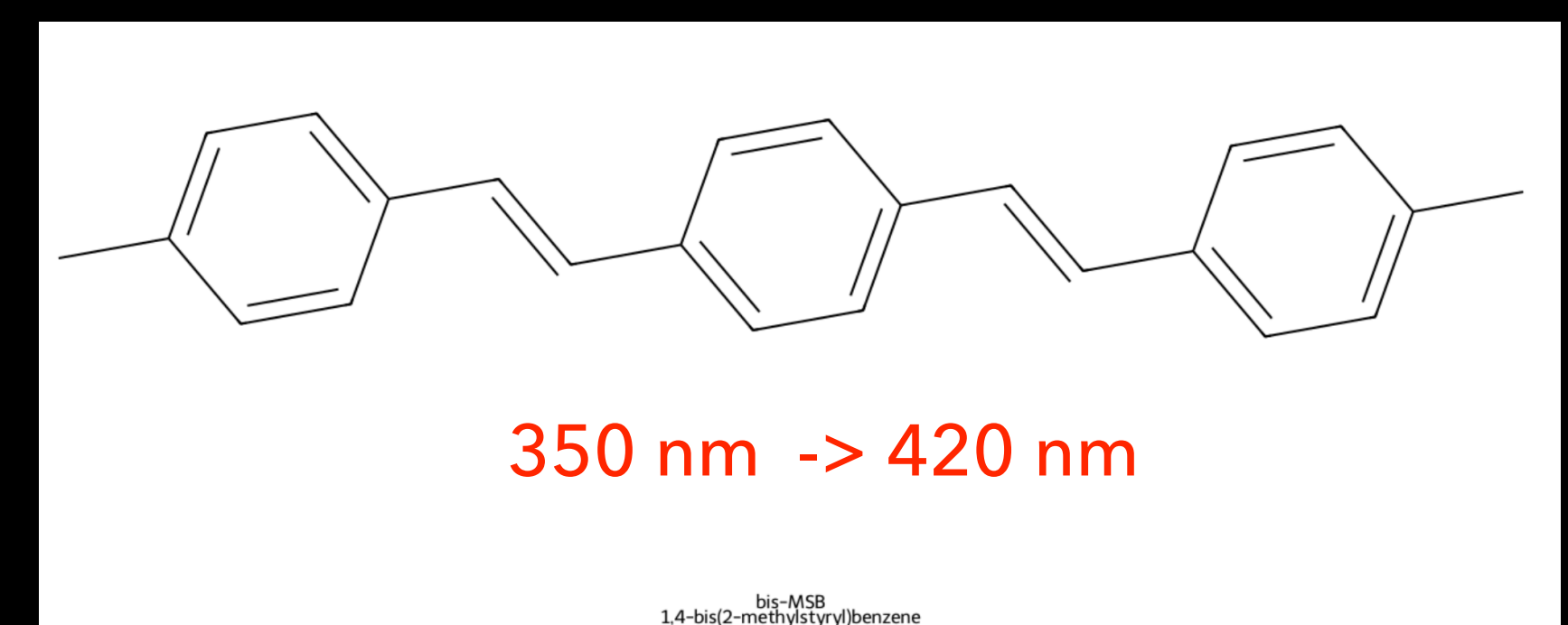
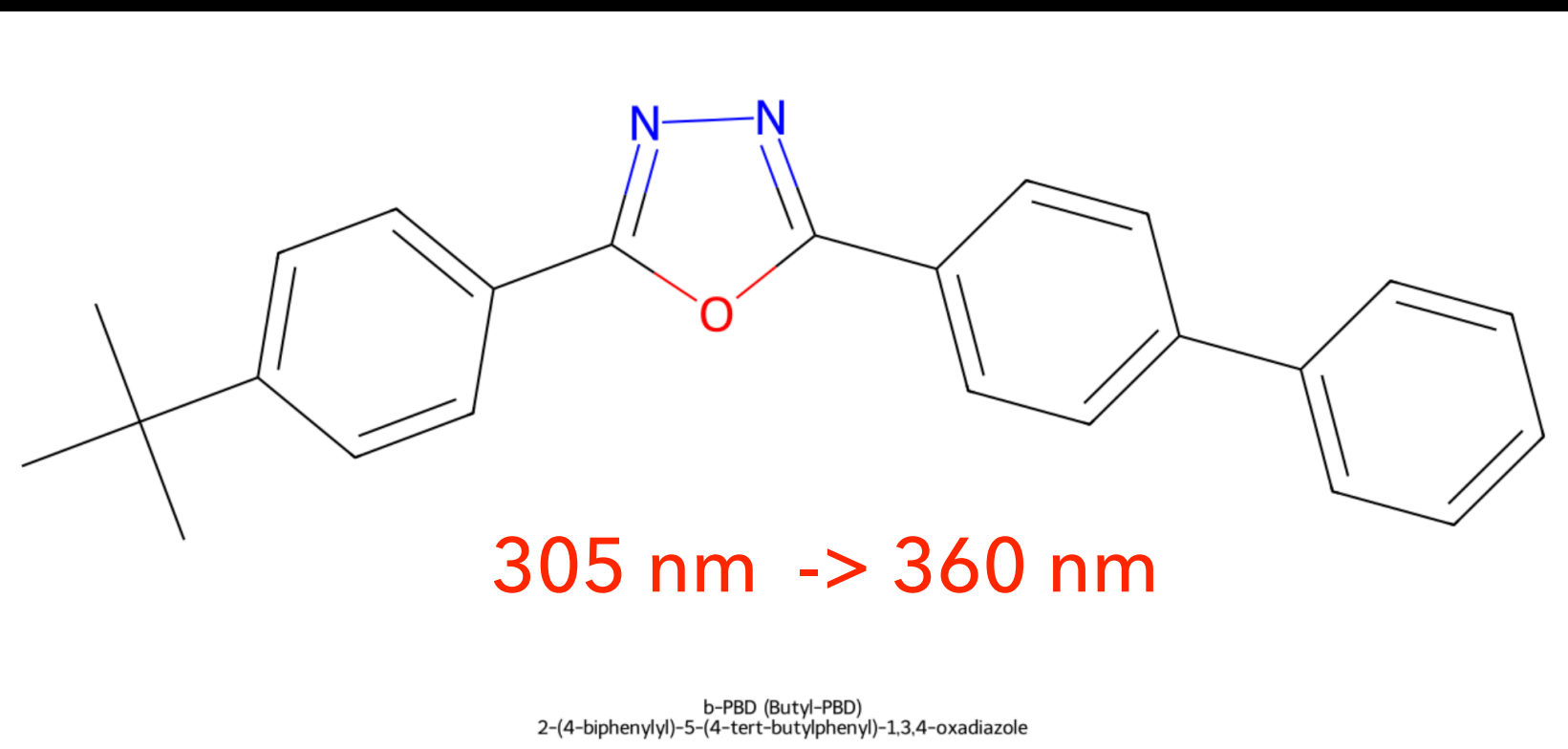
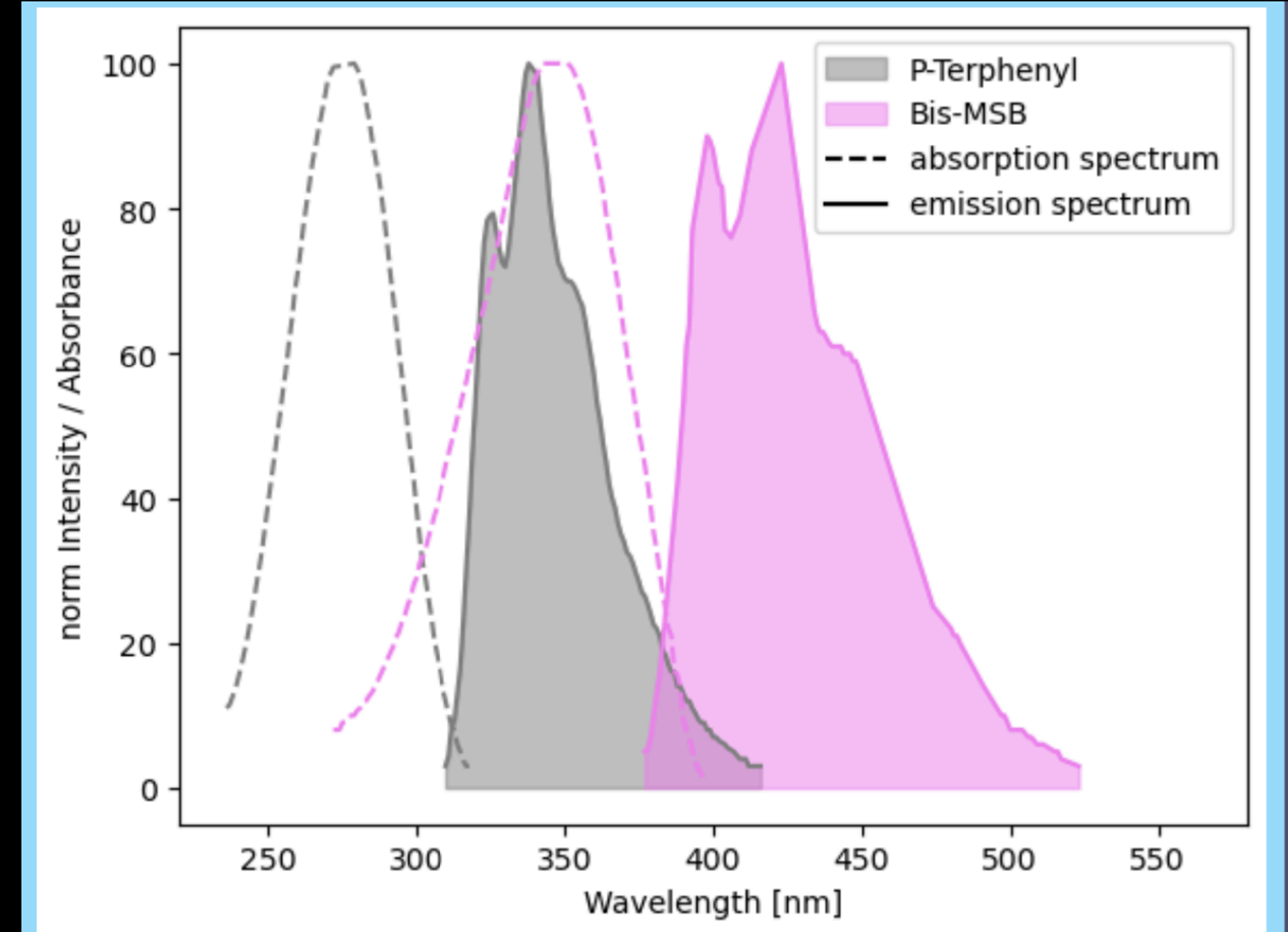
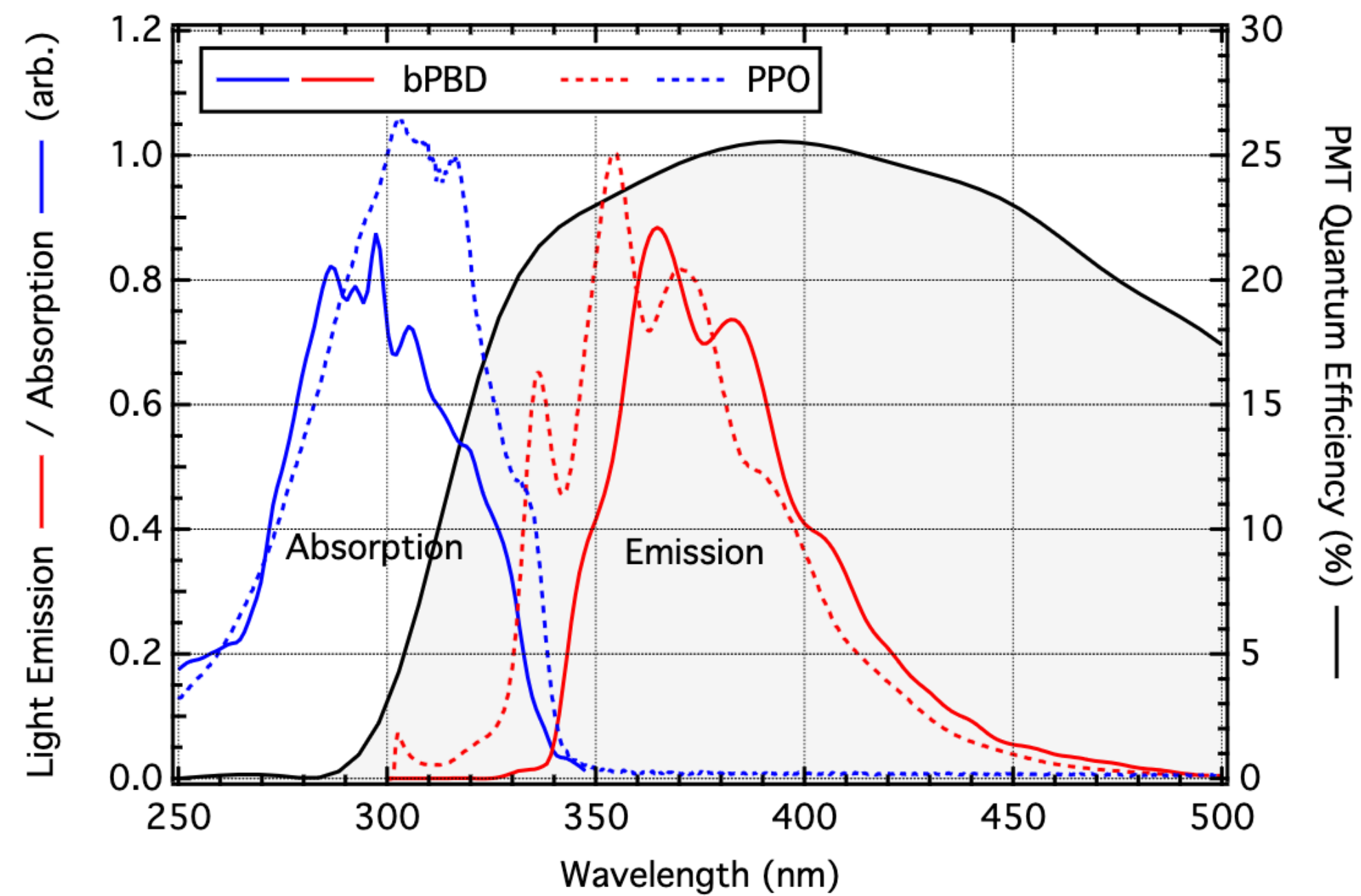
- 1) Scintillator Design: Matrix + Flour system (typically primary flour + wavelength-shifter)

Based on Stokes Shift

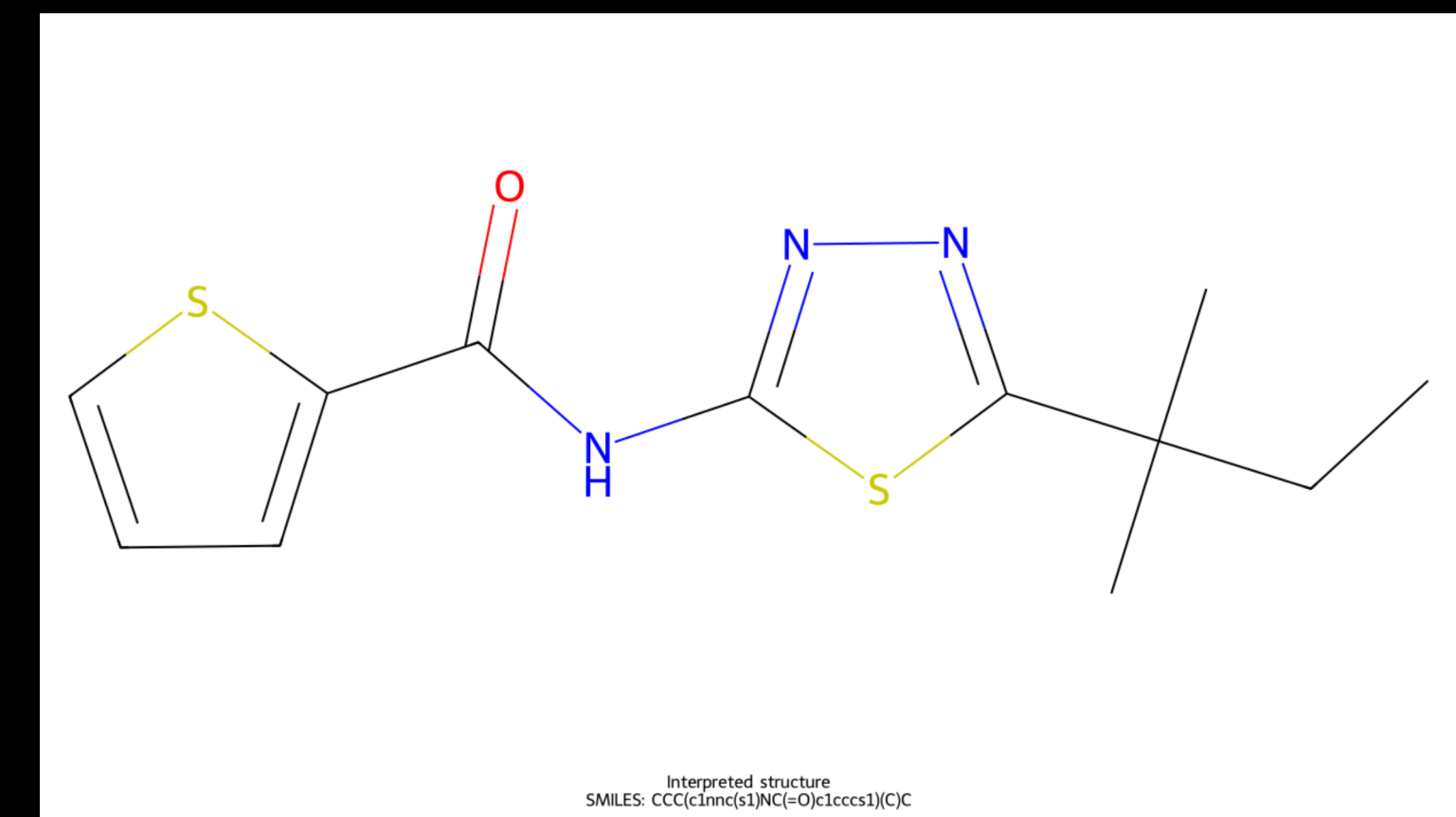
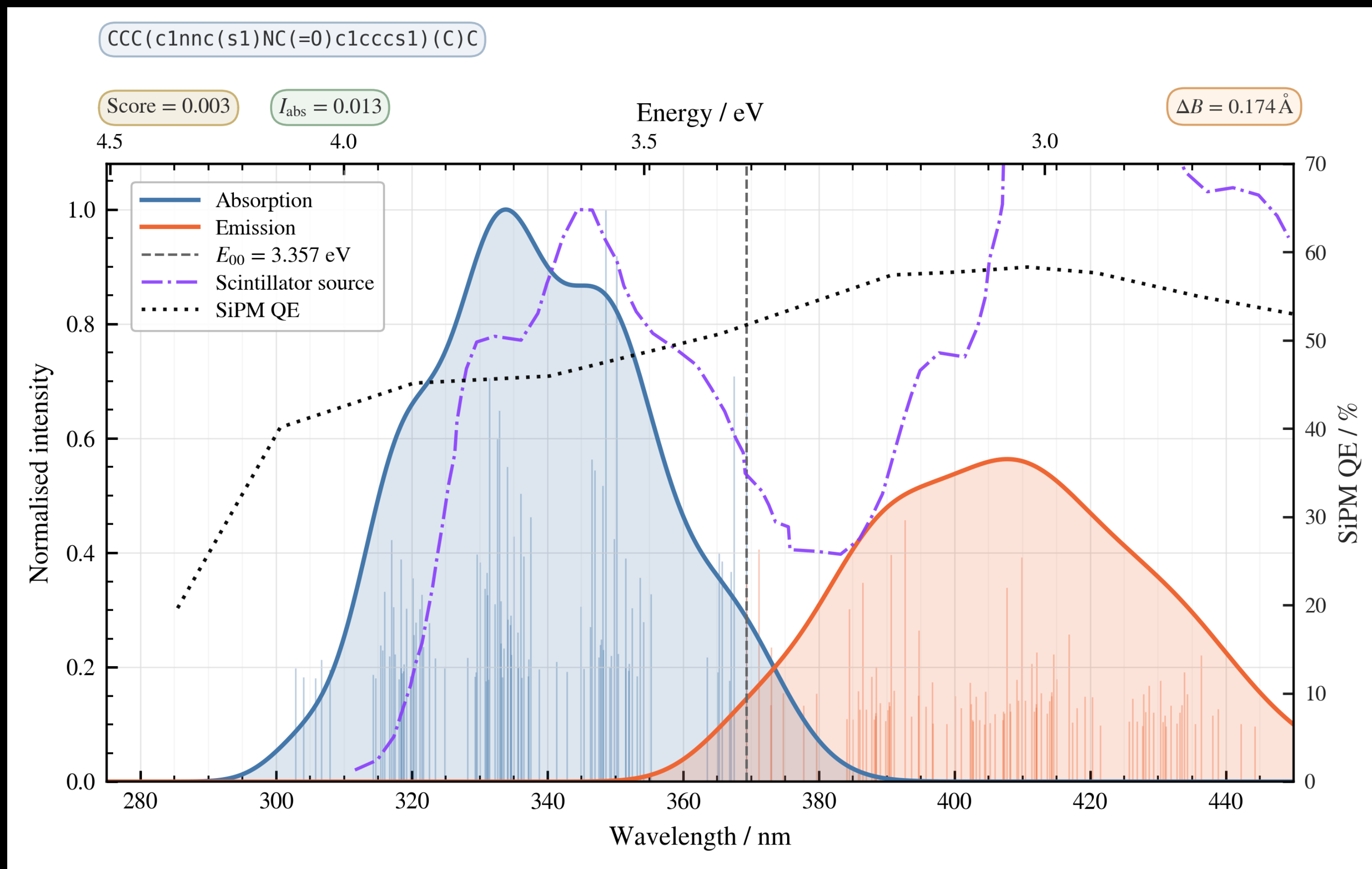
1) EJ200 Polyvinyl Toluene (PVT) Matrix + primary @320-370 nm + shifter @ 425 nm



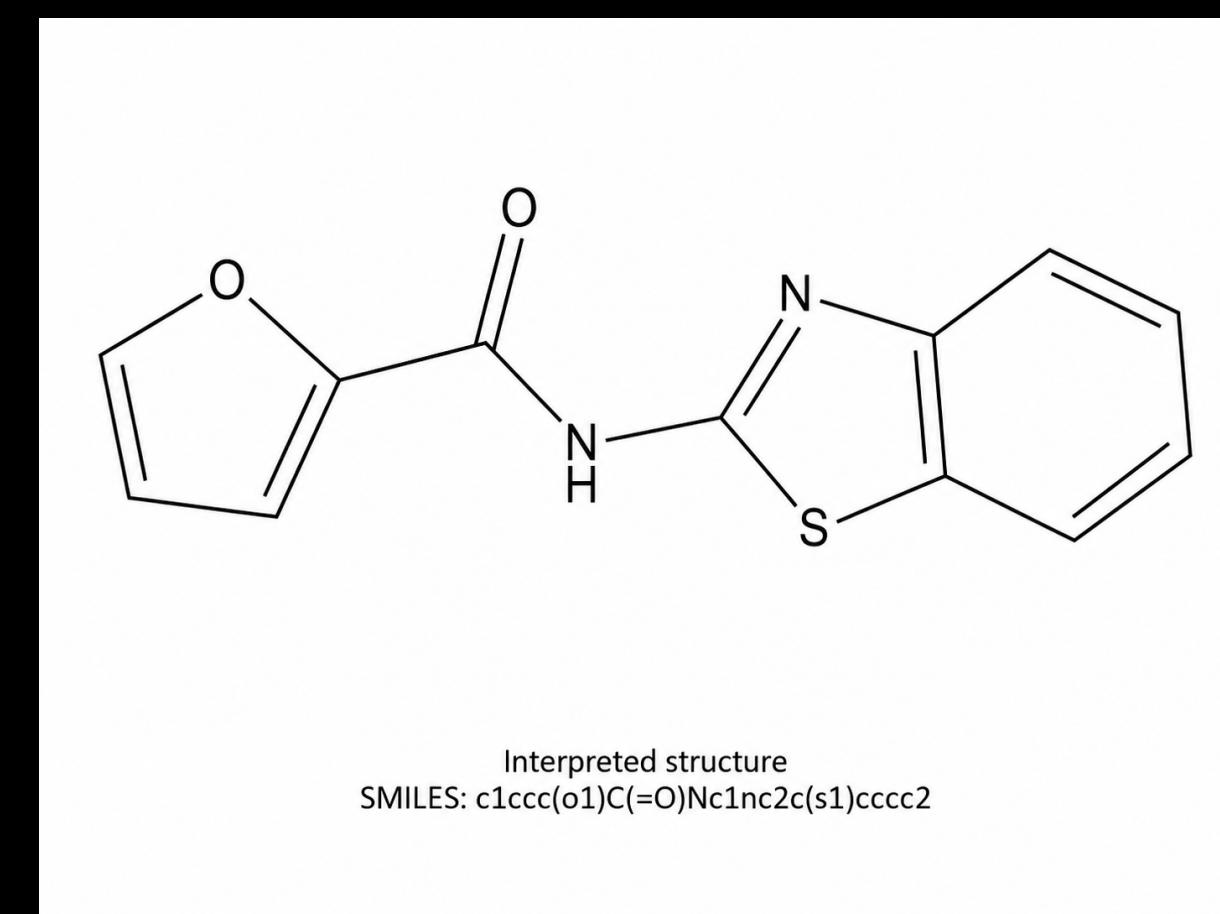
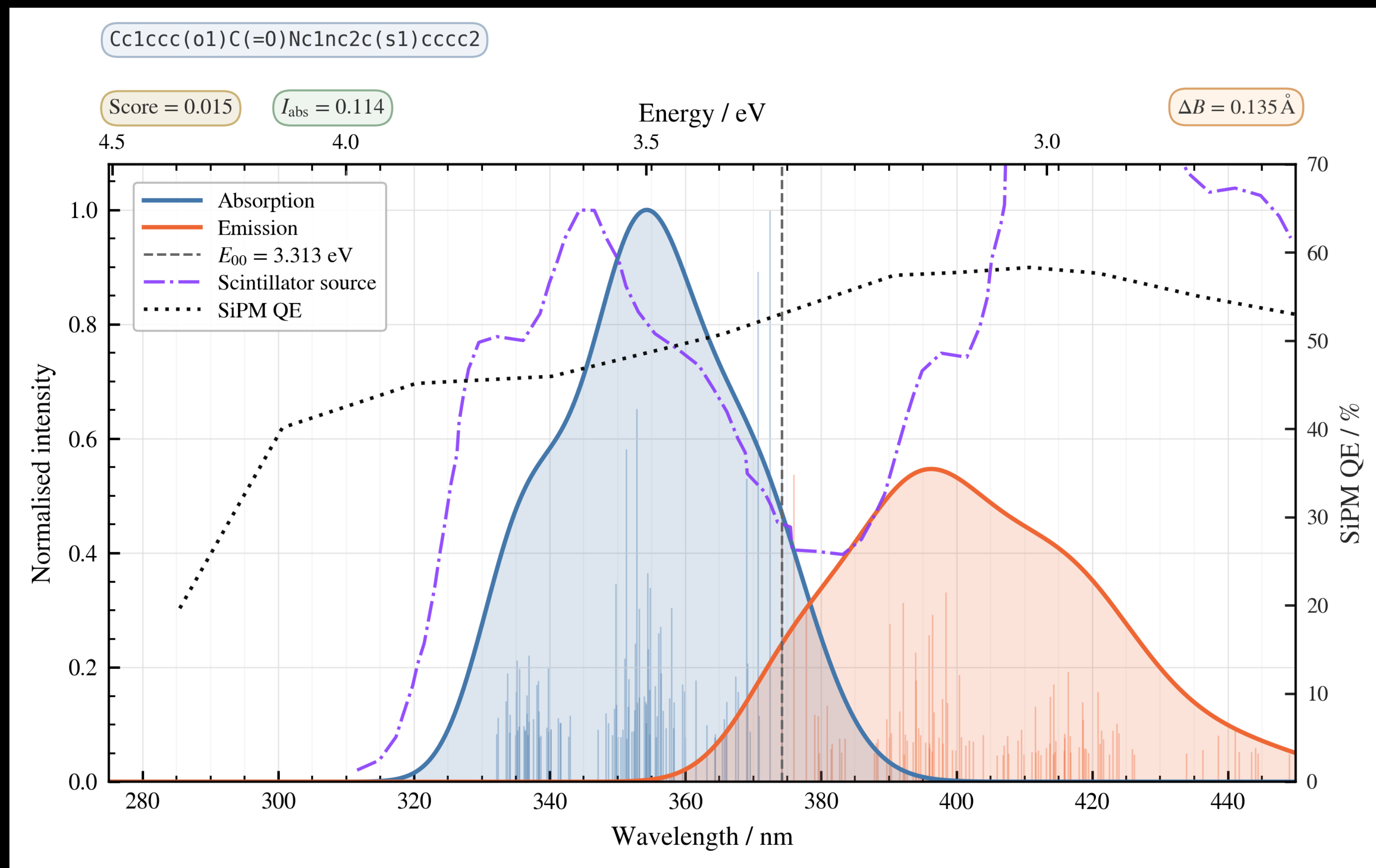
Spectra for the two fluor system



Spectra from tDFT 1



Spectra from tDFT 2

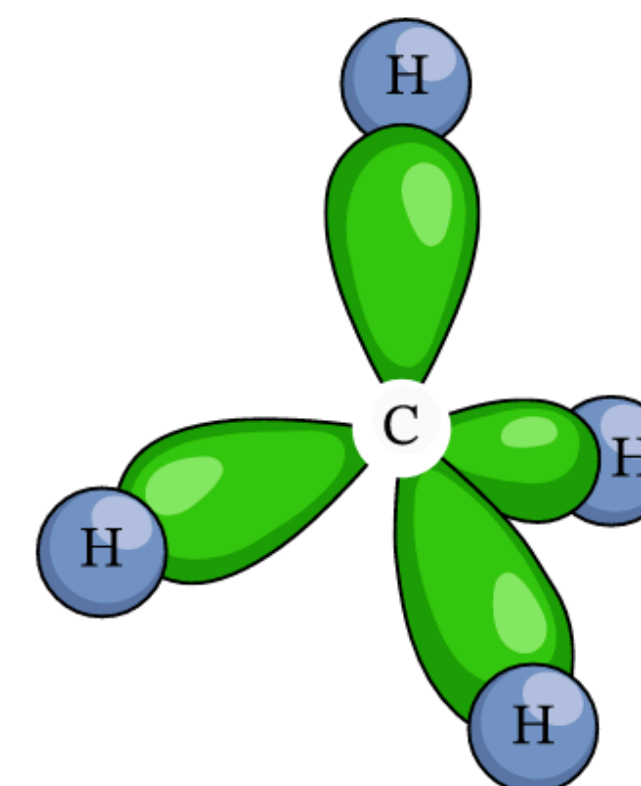
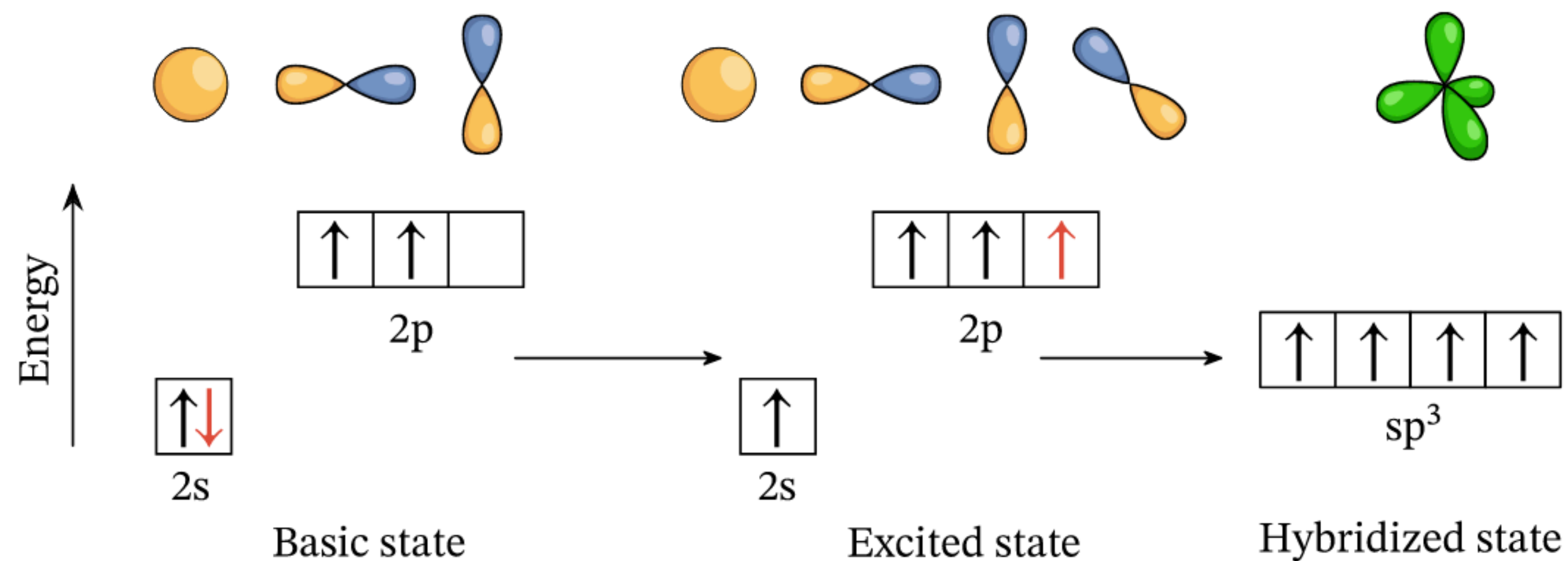


Cured Epoxy Resin + Additives

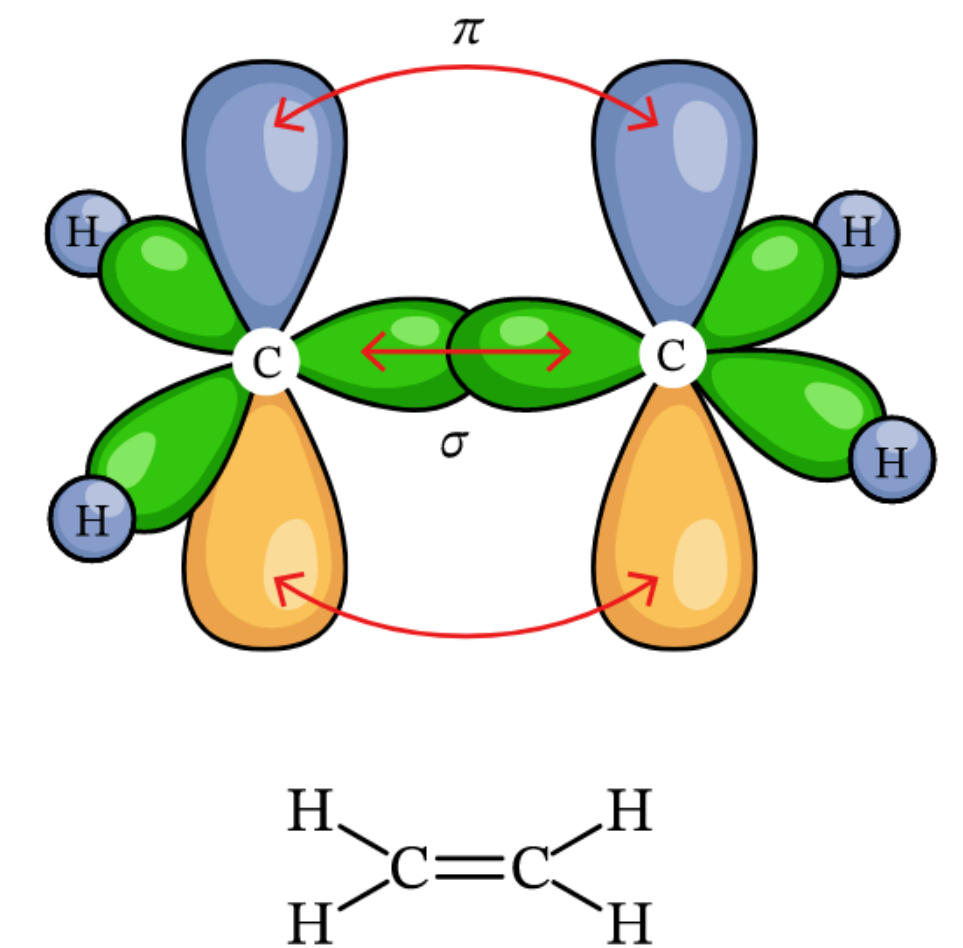
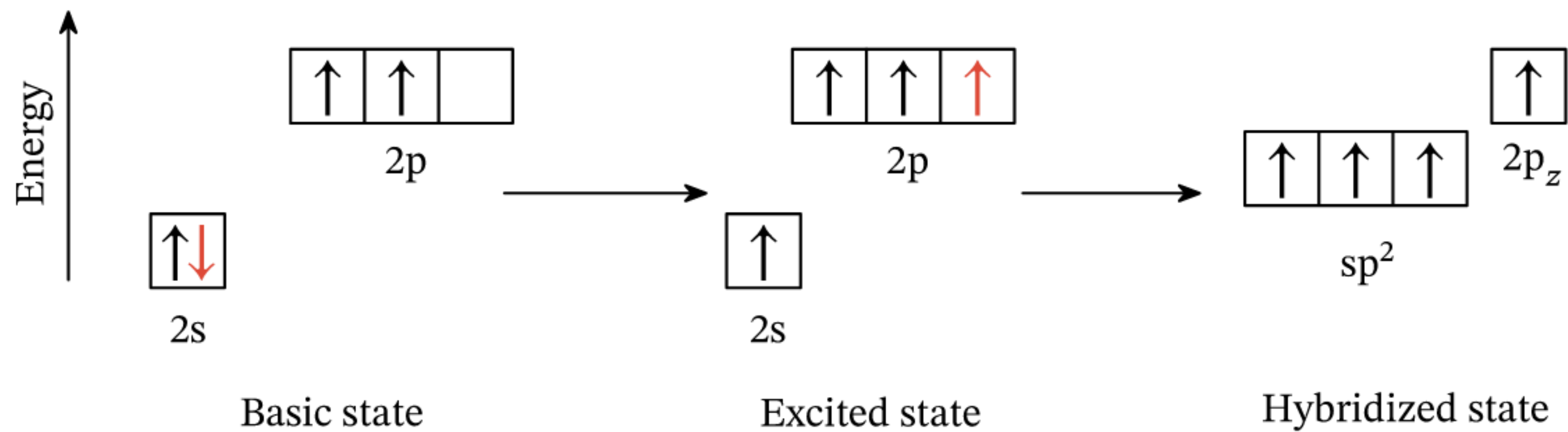


Basics of Organic Chemistry

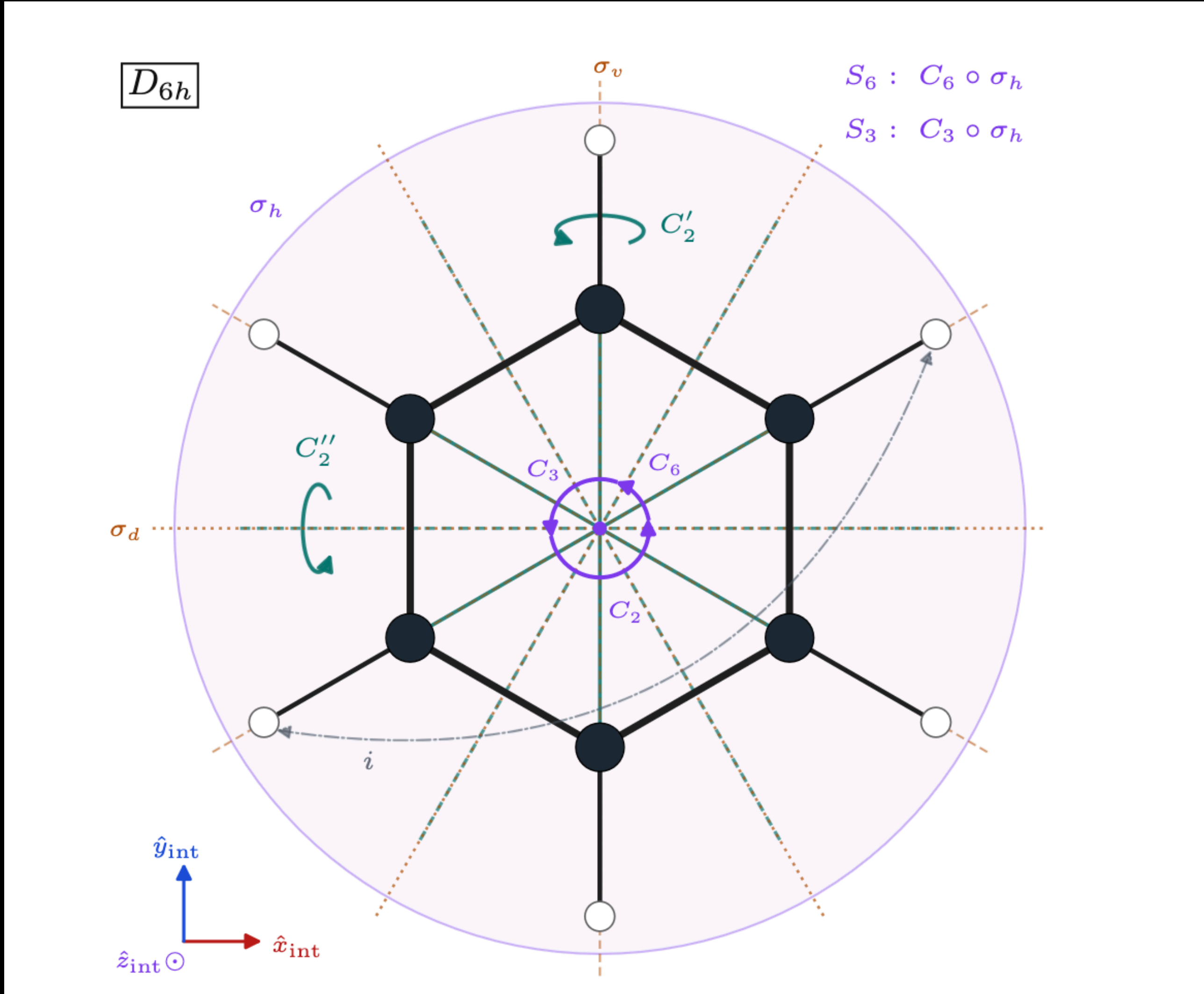
Carbon Hybridisation sp^3



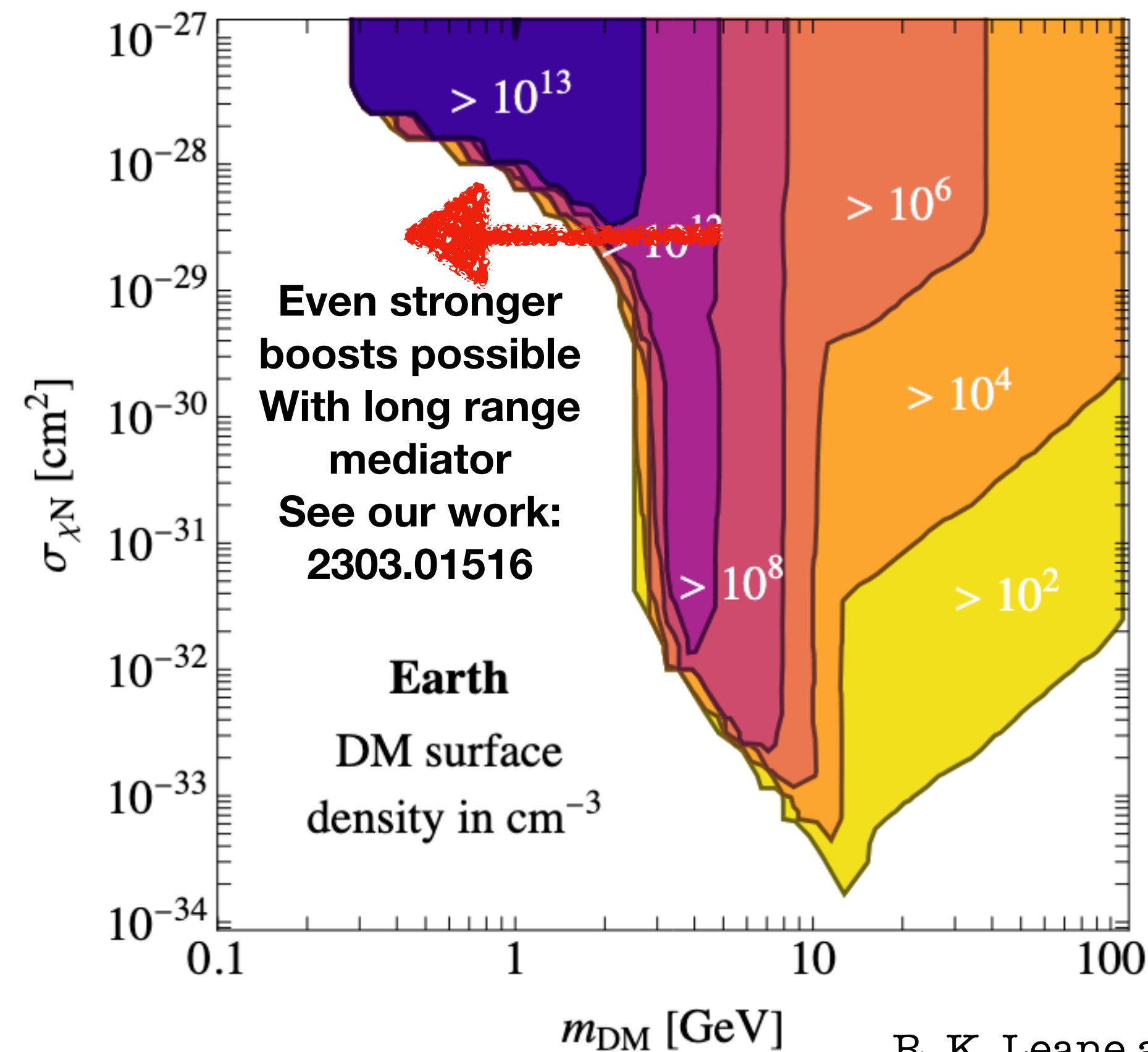
Carbon Hybridisation sp²



Molecular Symmetry (Points Groups)



Evaporation Effects for Short Range Int.



R. K. Leane and JS
2209.09834