

Dark Matter from a Slightly broken Mirror

Associate Prof./ Future Leaders Fellow
University of Liverpool

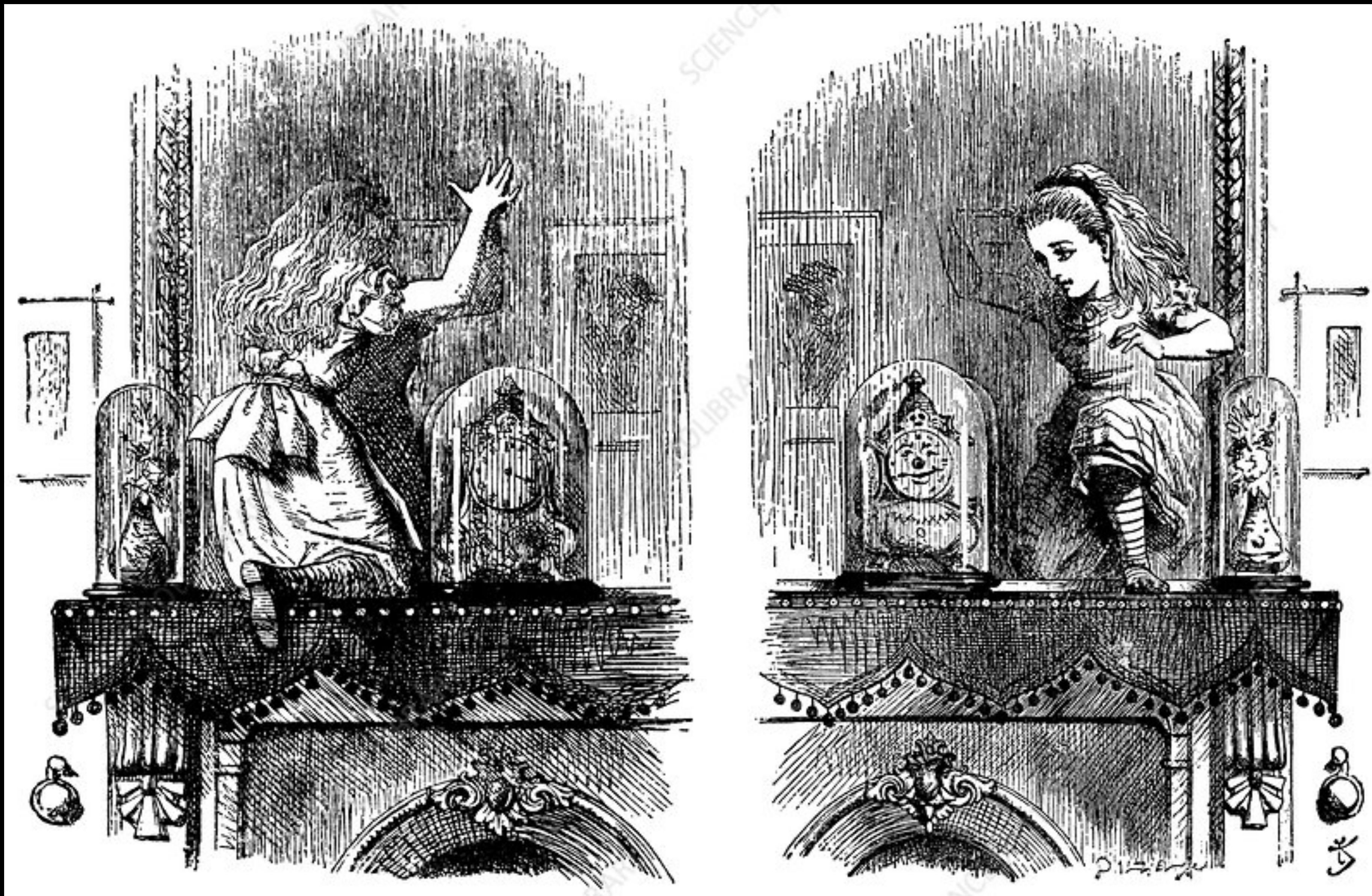


Particle Physics in the Early Universe 14.09.26

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



UNIVERSITY OF
LIVERPOOL



Through the looking glass, Lewis Carroll

A Slightly Broken Mirror

Ongoing work with
Arushi Bodas,
PostDoc NYU



- + 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

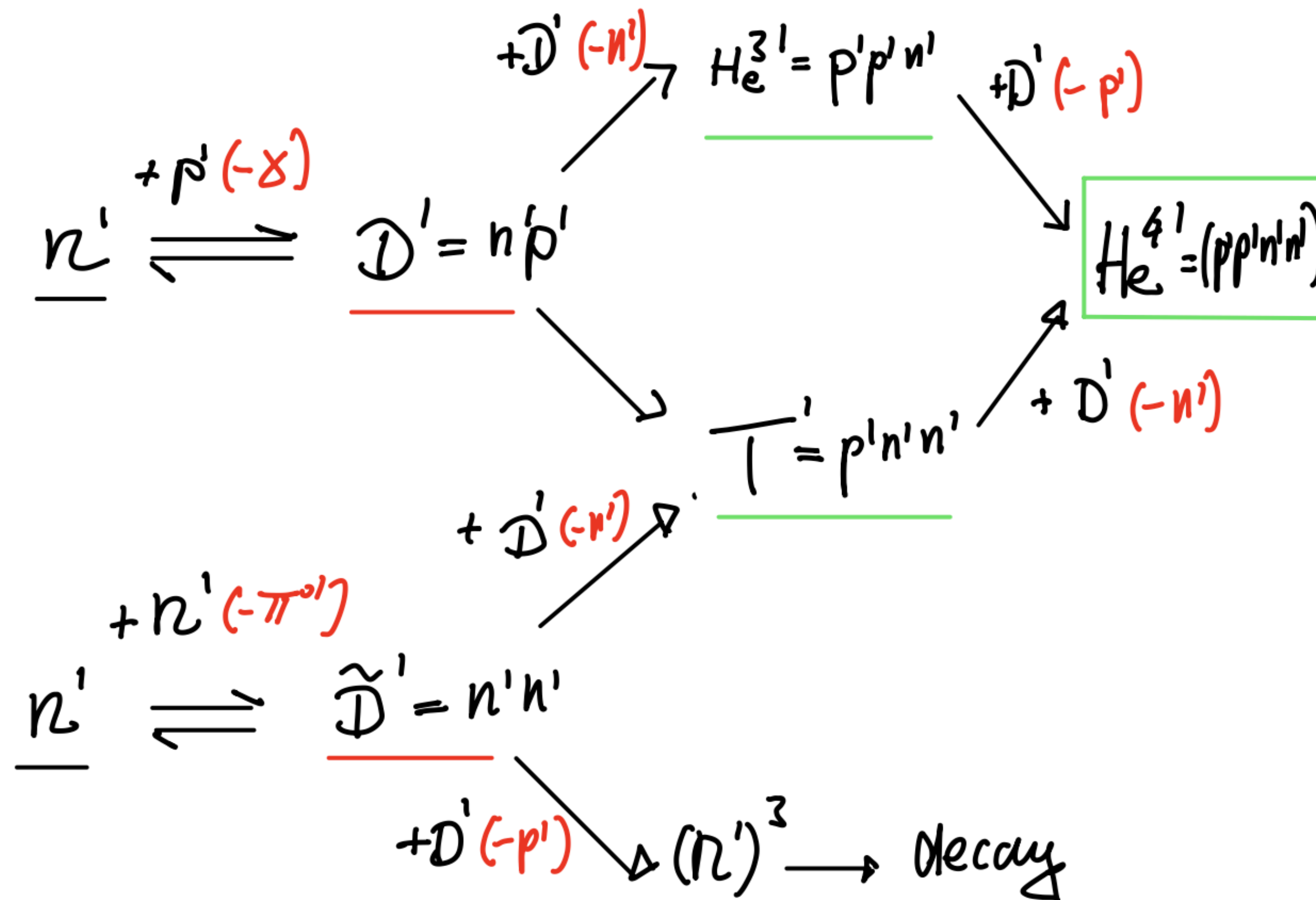
Shadow protons decay

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

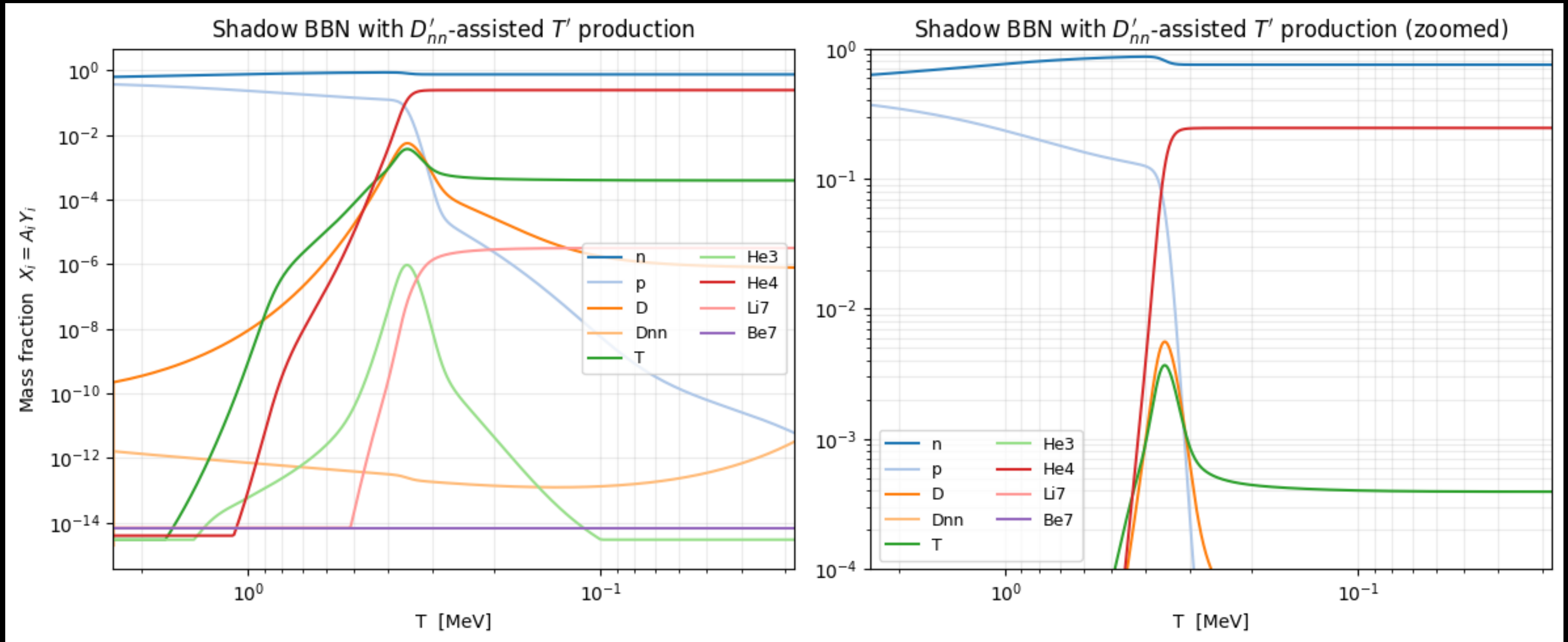
But shadow
nucleons can be
stable

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

Shadow BBN Network



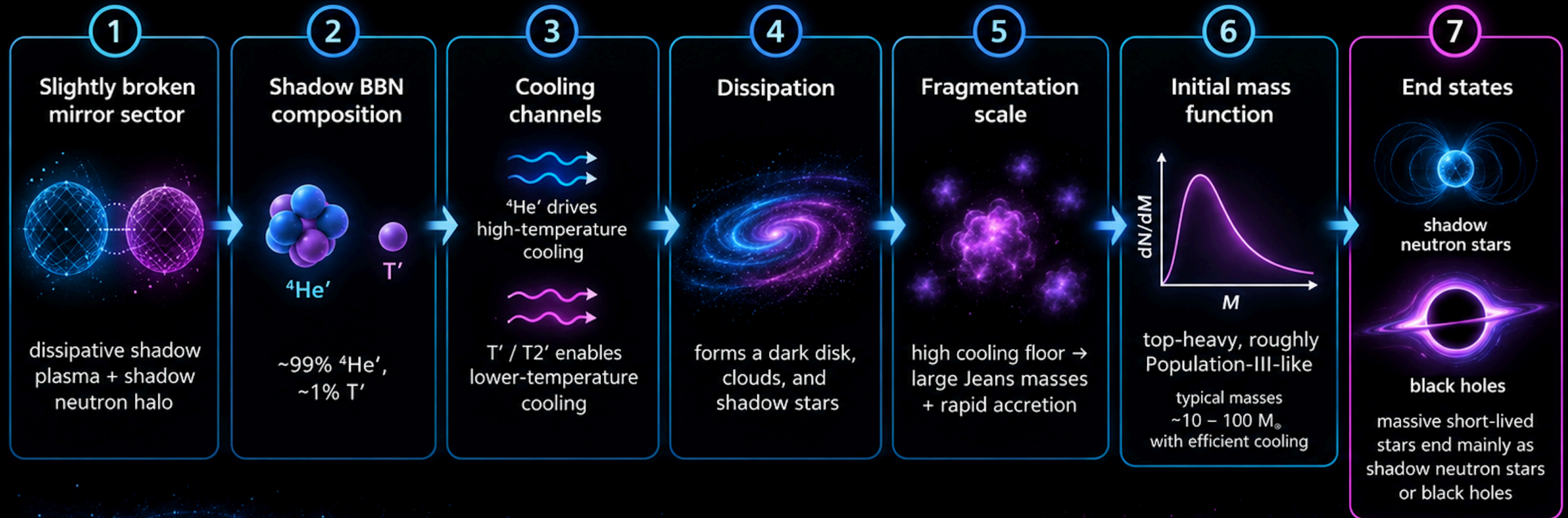
Shadow Nucleosynthesis



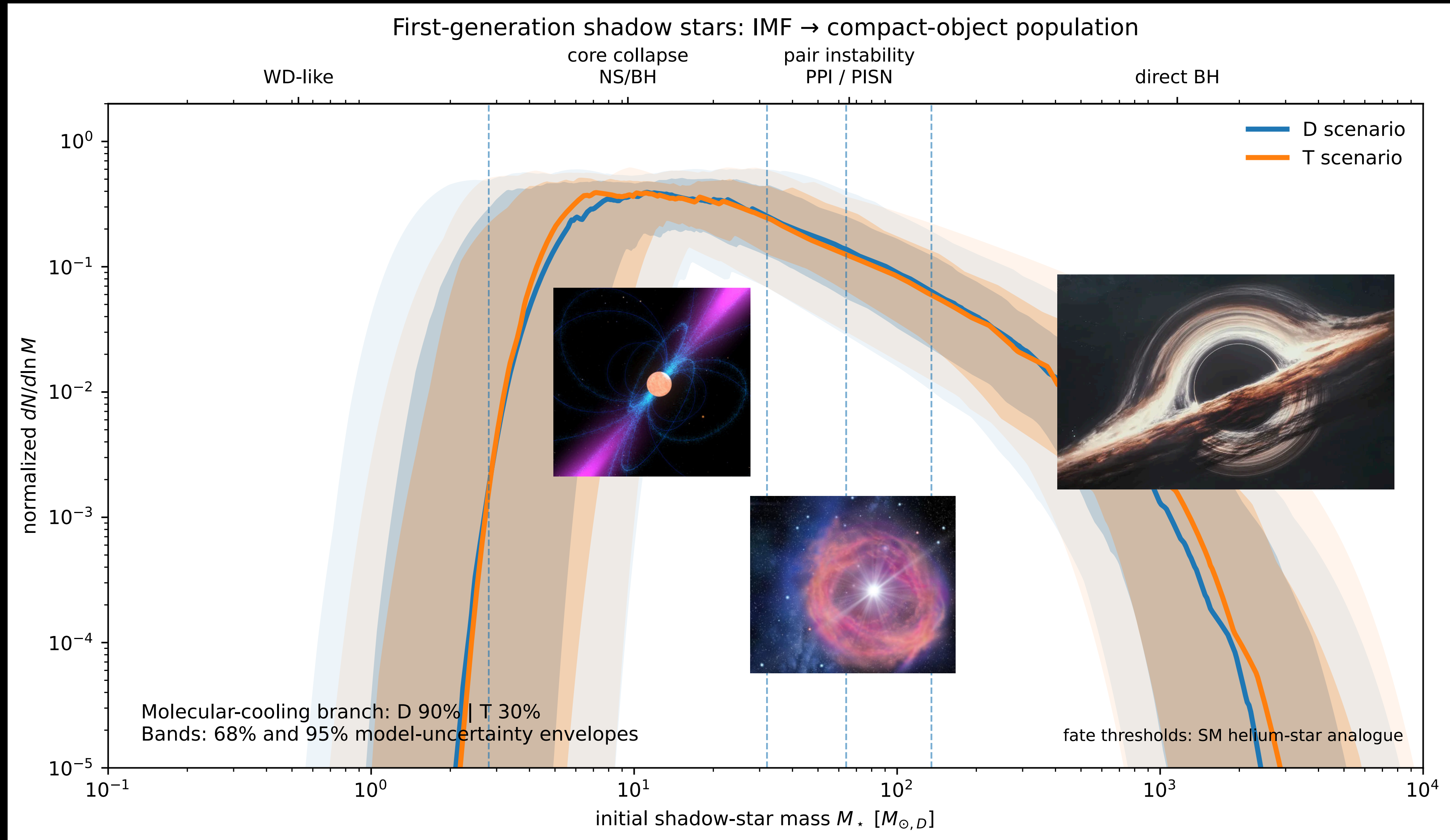
$$T' \sim 0.3 T_{\text{SM}}$$

Compact Shadow Structures

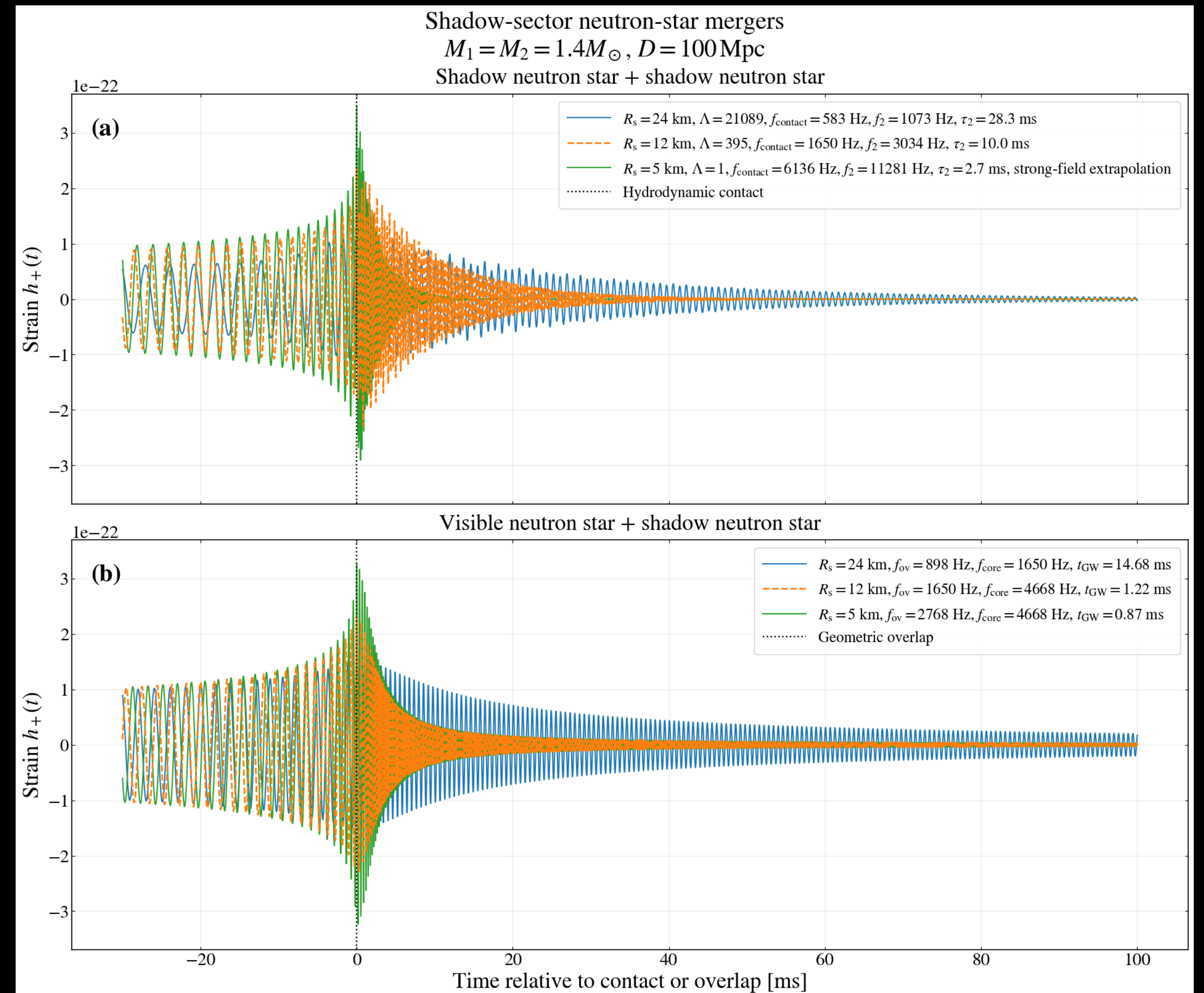
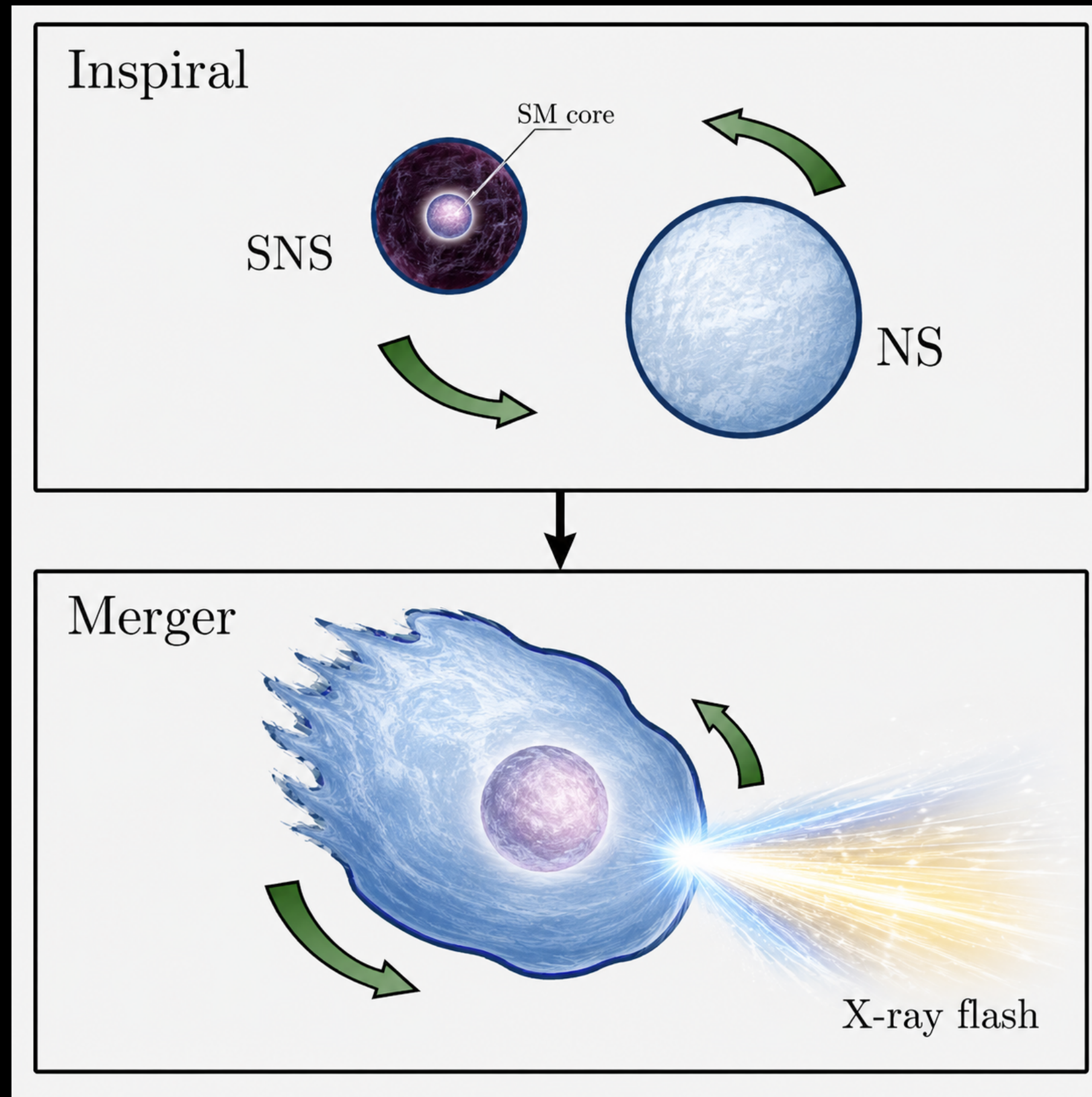
Shadow Sector forms Halos and Structures!



Expected Shadow Object Population



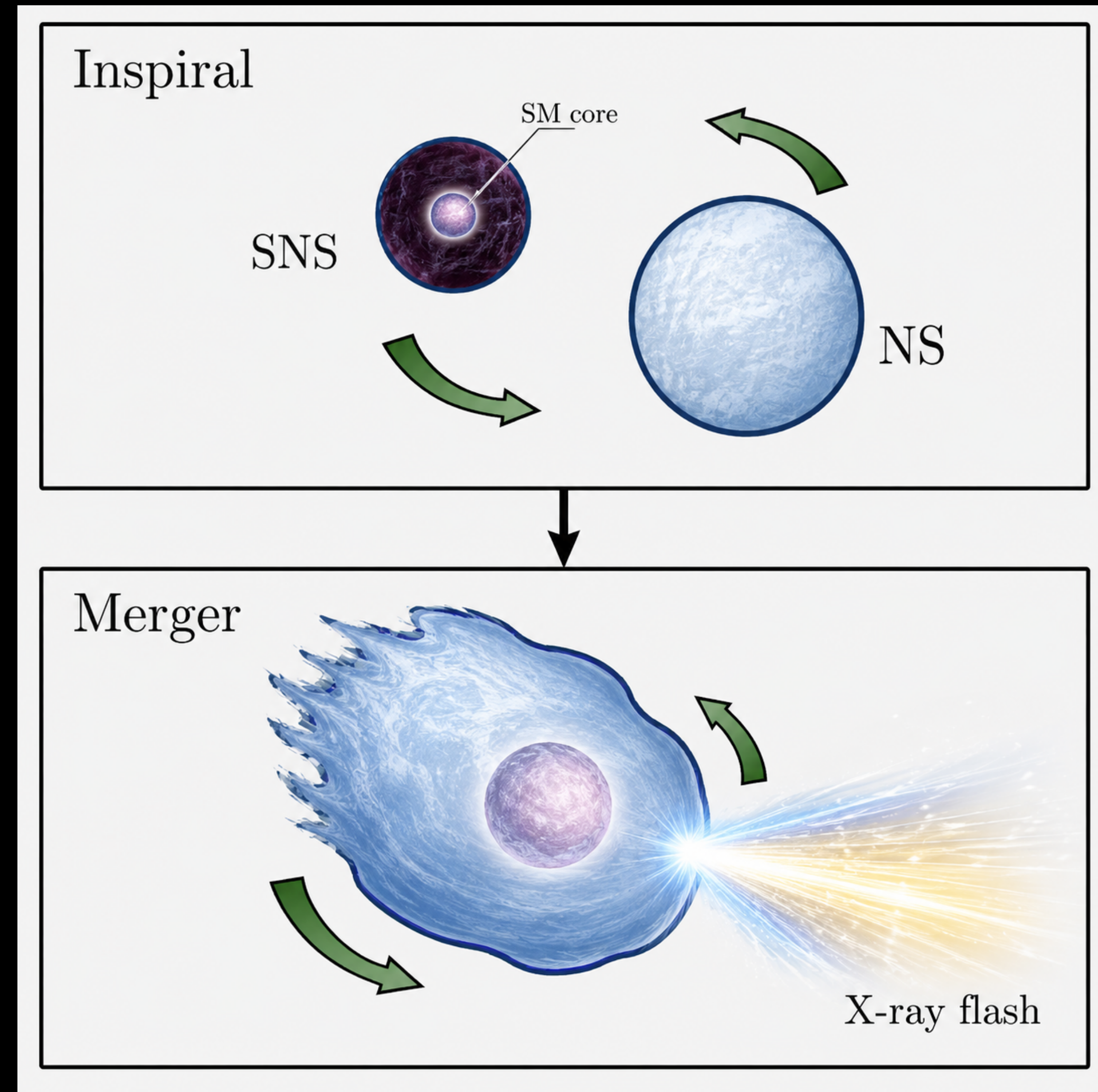
GW and Multi messenger Signals



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

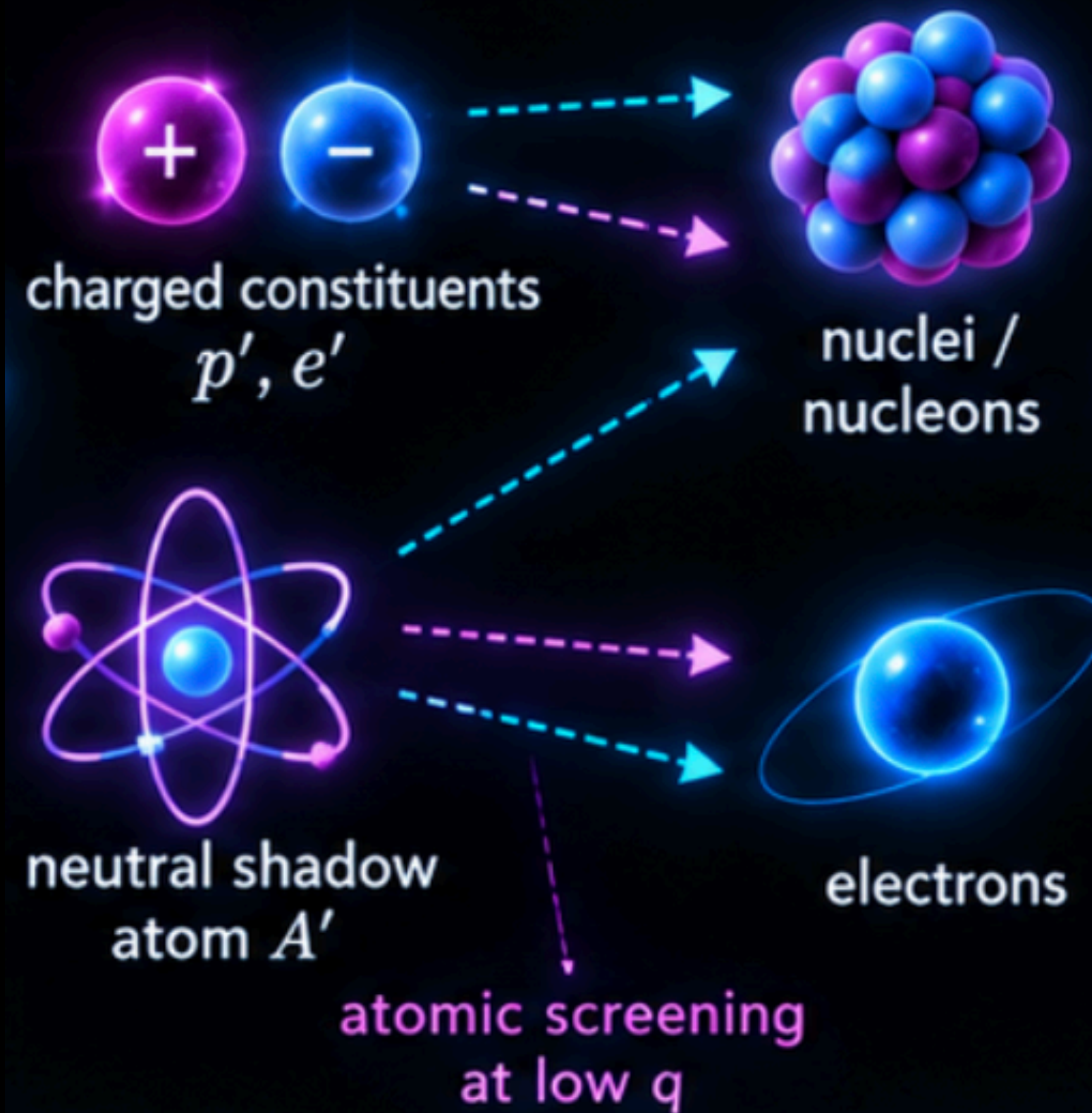
$$E_{\gamma, \text{prompt}}^{\text{vs}} = \eta_{\text{bo}} E_{\text{dep}}^{\text{vs}} \simeq 10^{40} \text{ erg} \left(\frac{\eta_{\text{bo}}}{10^{-3}} \right) \left(\frac{M_{\text{cap}}}{10^{23} \text{ g}} \right).$$



Shadow Matter in the Lab

Expected Interactions and Cross Sections

Couplings to visible matter



Parametric scaling

Charged constituent scattering:

$$\sigma \propto \frac{\epsilon^2 \alpha^2}{\mu^2 v^4}$$

Neutral shadow atom:

$$\sigma_{\text{eff}} \sim F_{\text{scr}}(q)^2 \sigma$$
$$F_{\text{scr}}(q) \ll 1 \quad \text{for} \quad qa'_0 \ll 1$$

Shadow neutron:

residual interaction only
→ strongly suppressed

**Low- q scattering is controlled
by atomic screening and the
internal shadow structure.**

Cross Section Scaling

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

$\Rightarrow$ 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:

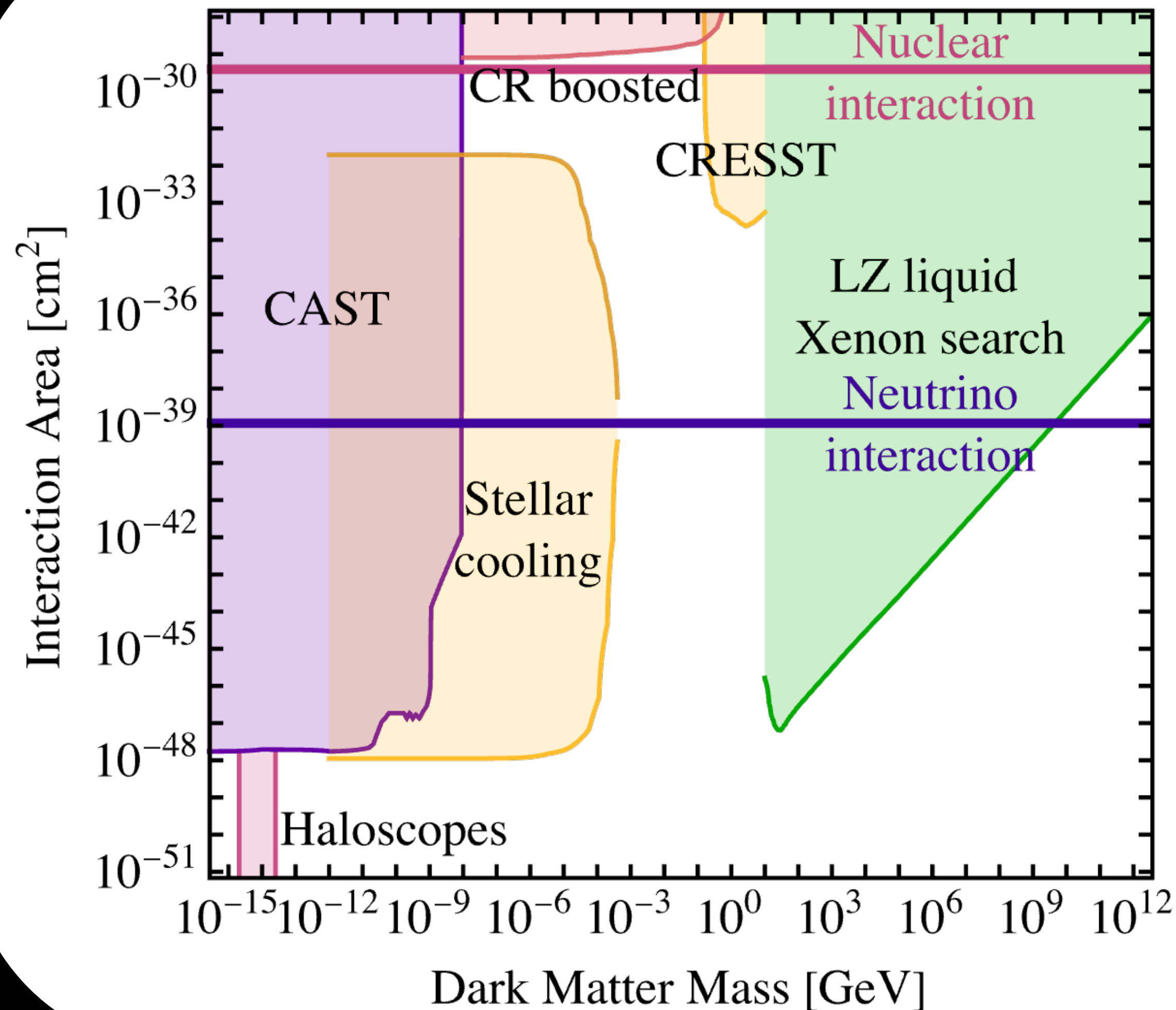
$$e' \left(\begin{smallmatrix} n' n' \\ p' p' \end{smallmatrix} \right) e' \int \sim \frac{1}{\alpha' m_{e'}} \begin{cases} v \sim v_0 \rightarrow \underline{\sigma_{Ap} \sim 10^{-37} \left(\frac{\epsilon}{10^{10}}\right)^2 \left(\frac{10^{-3}}{v}\right)^4 \text{ cm}^2} \\ v \ll v_0 \rightarrow \underline{\sigma'_{Ap}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

nuclear int.

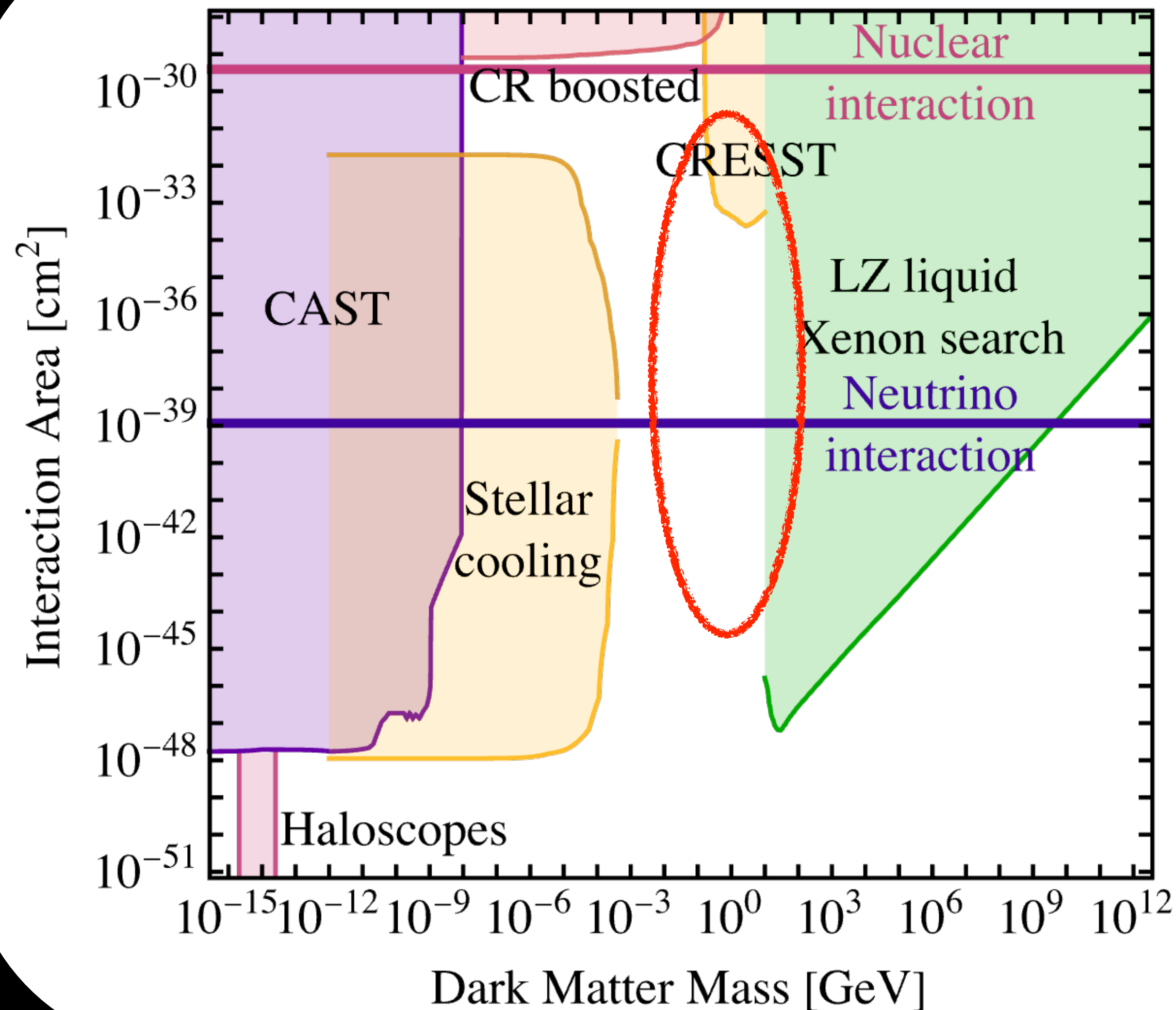
b)

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

Direct Detection Range Cartoon



Direct Detection Range Cartoon

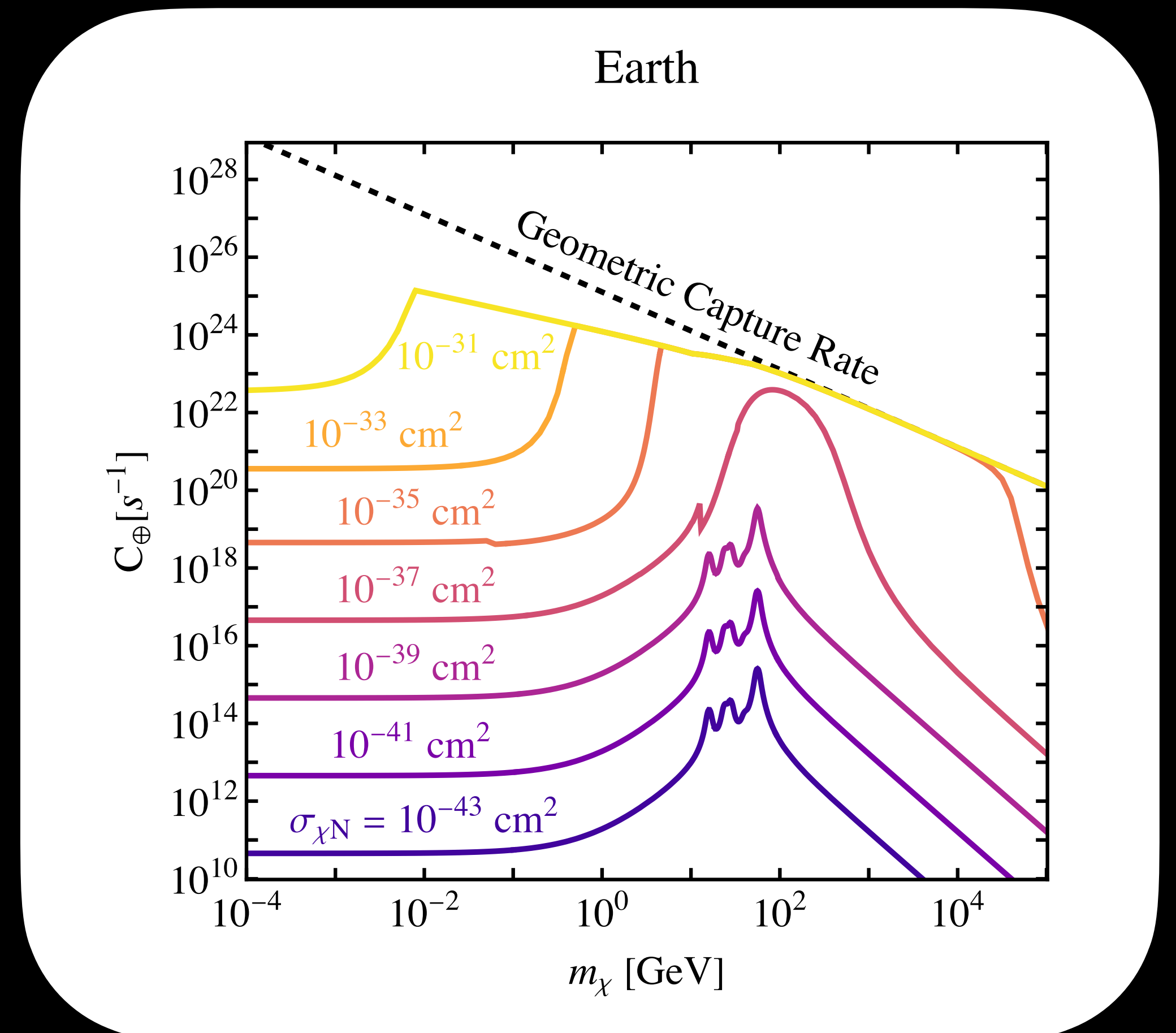


The Earth as a Dark Matter Accumulator

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



Captured Dark Matter Profile

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

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

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

Captured Dark Matter Profile

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Hydrostatic equilibrium:
Isothermal DM

Thermal diffusion:
Local thermal eq.

Ref: Effect of hypothetical, weakly
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Ref: Big bang archeology:
WIMP capture by the earth
at finite optical depth
A. Gould in 1991

Captured Dark Matter Profile

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Hydrostatic equilibrium:
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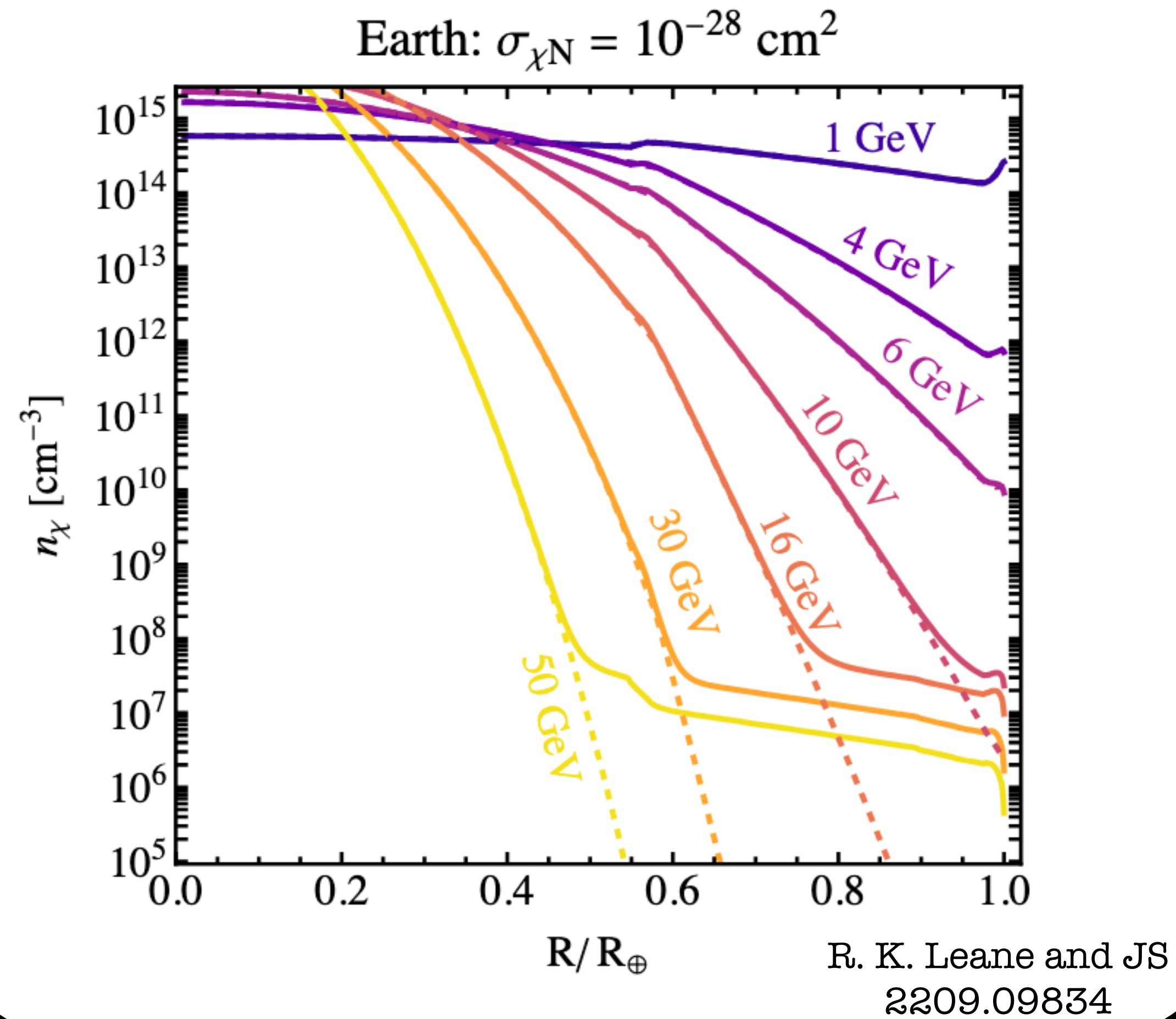
DM influx & diffusion:
Dynamical equilibrium

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

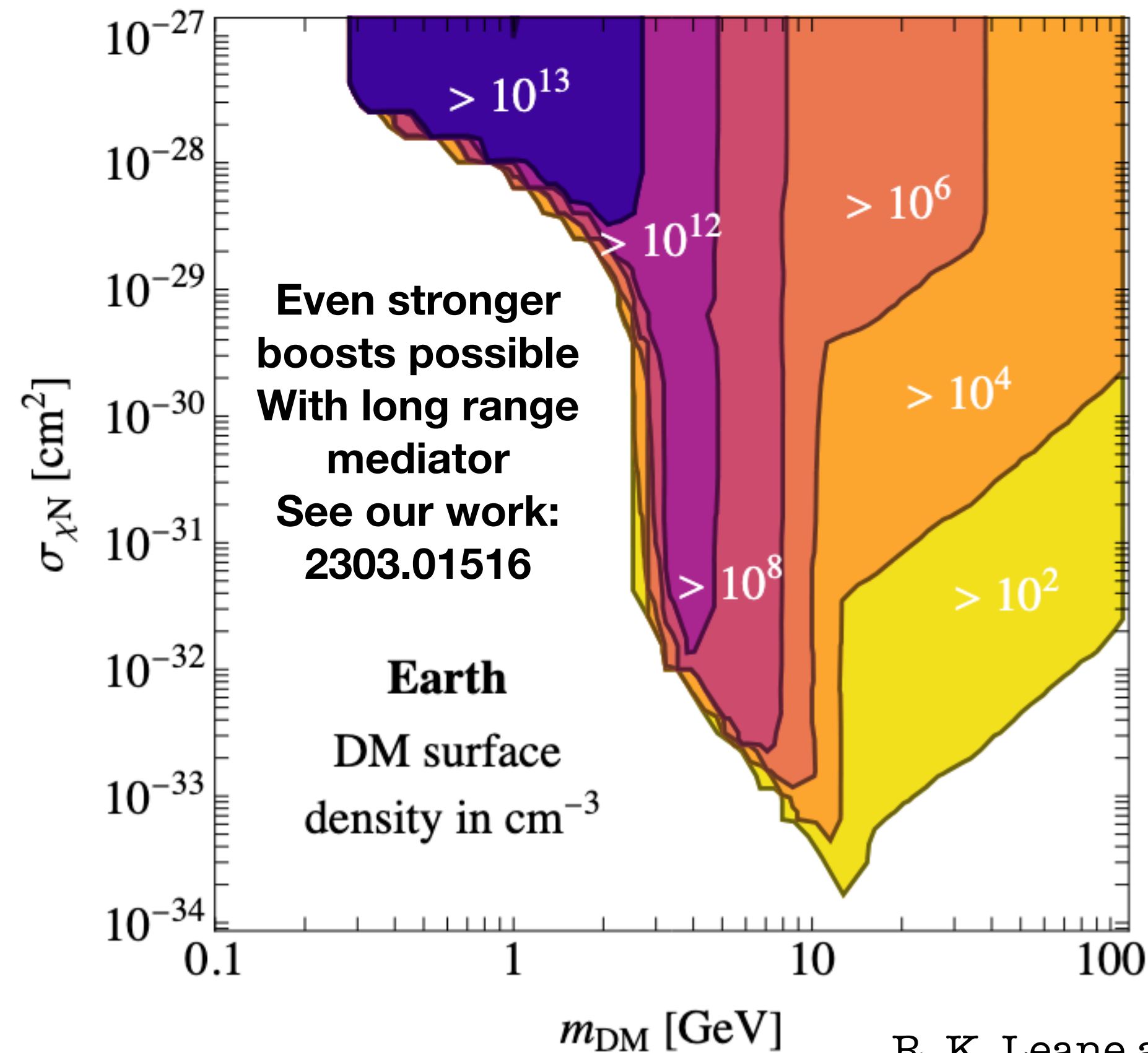
Ref: Big bang archeology:
WIMP capture by the earth
at finite optical depth
A. Gould in 1991

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

DM Diffusion in the Earth

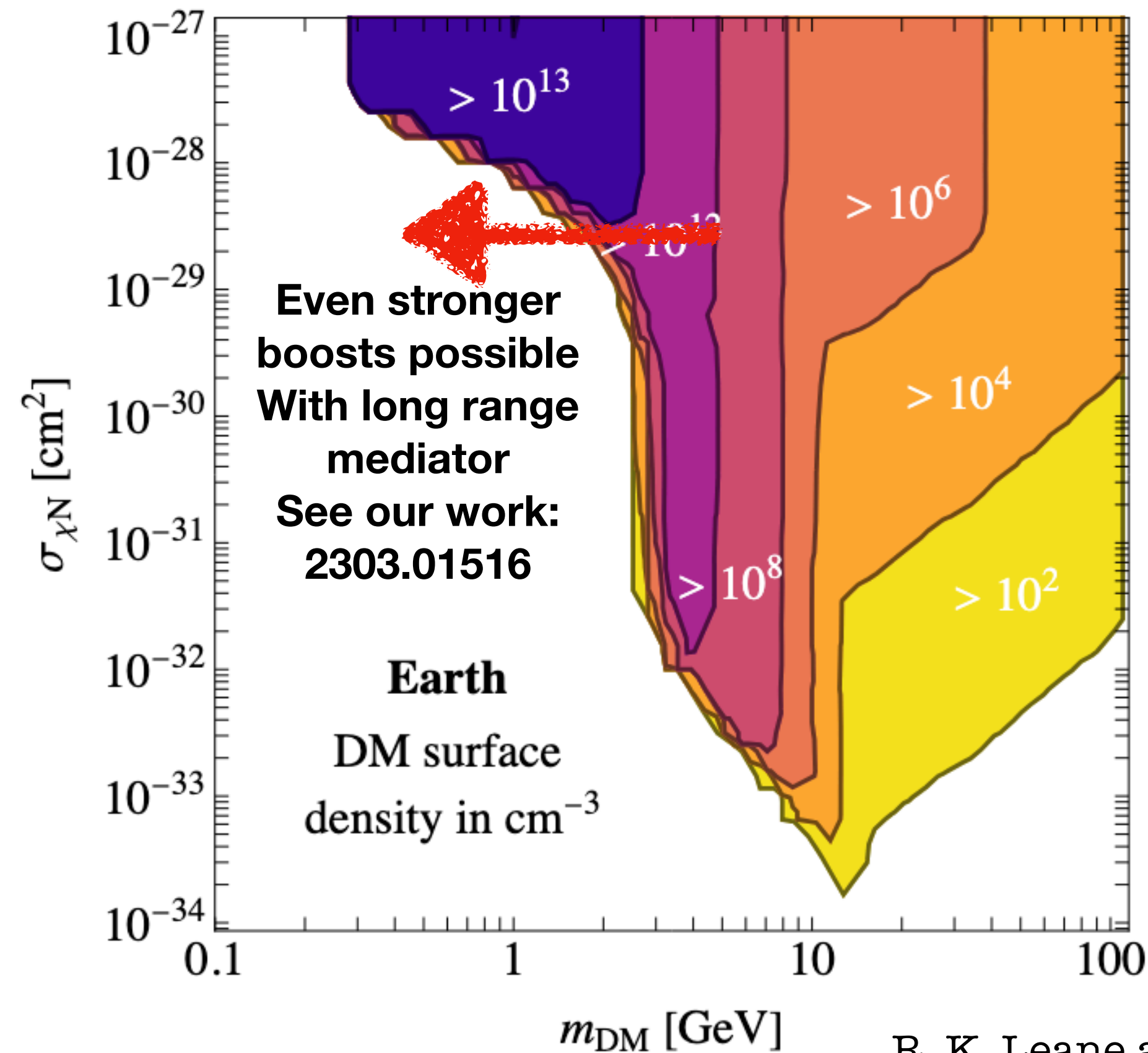


Locally Enhanced Dark Matter Density



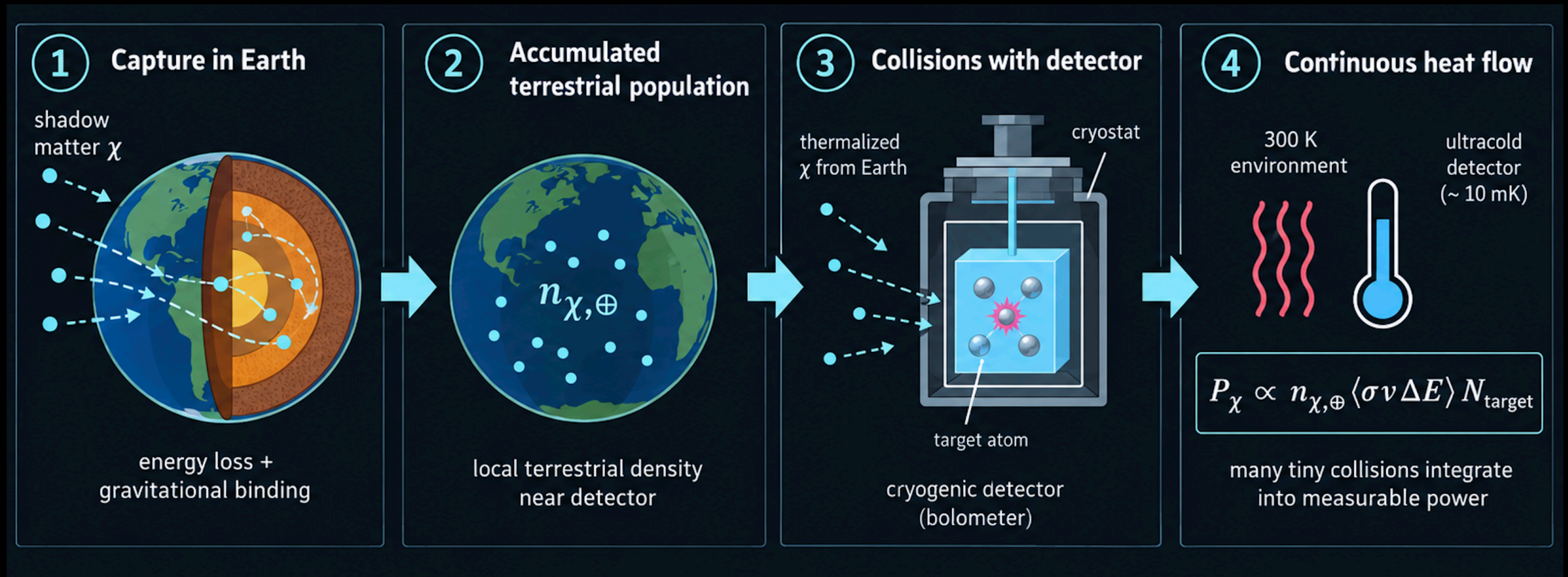
R. K. Leane and JS
2209.09834

Locally Enhanced Dark Matter Density



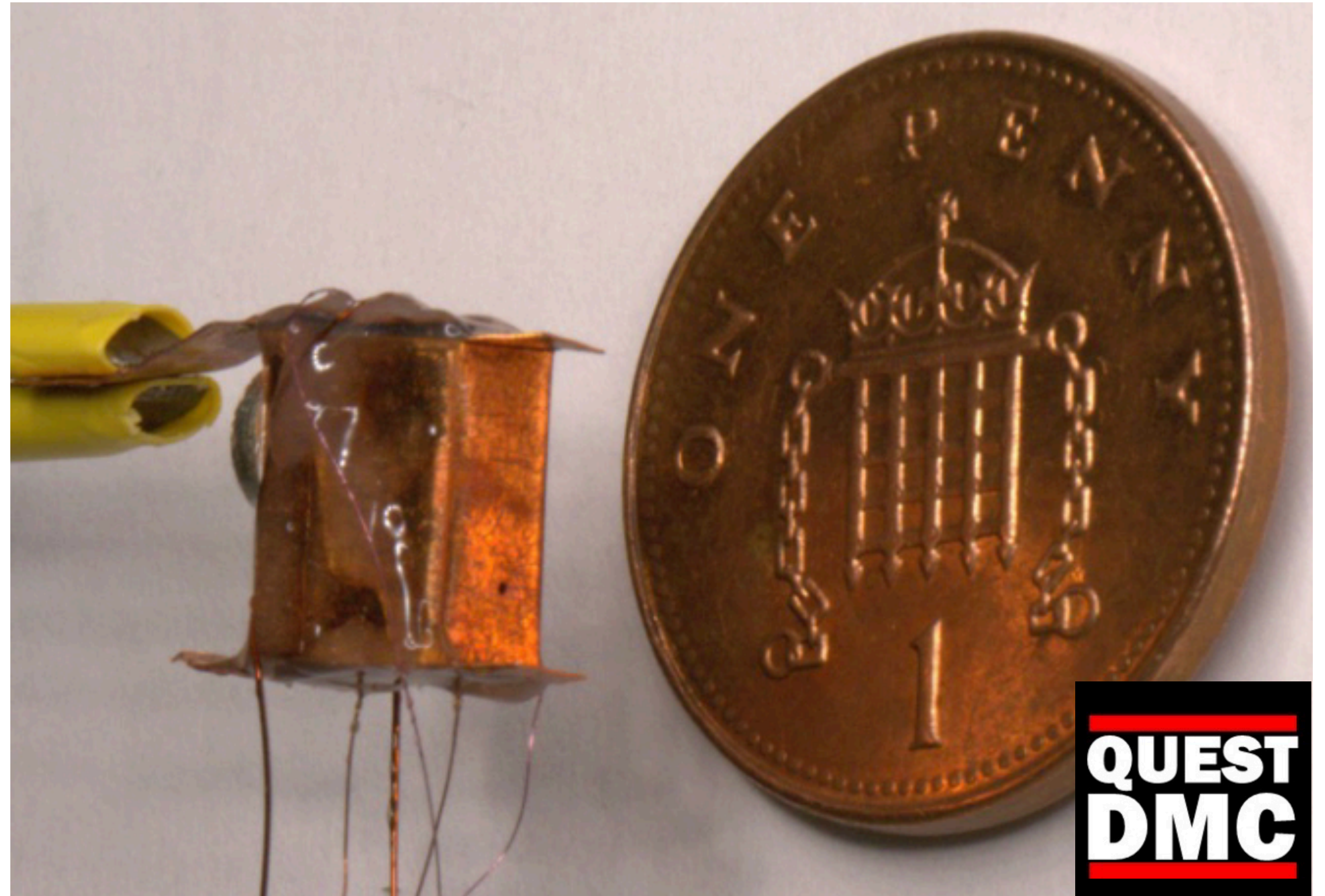
R. K. Leane and JS
2209.09834

New Detection Concept without a Threshold

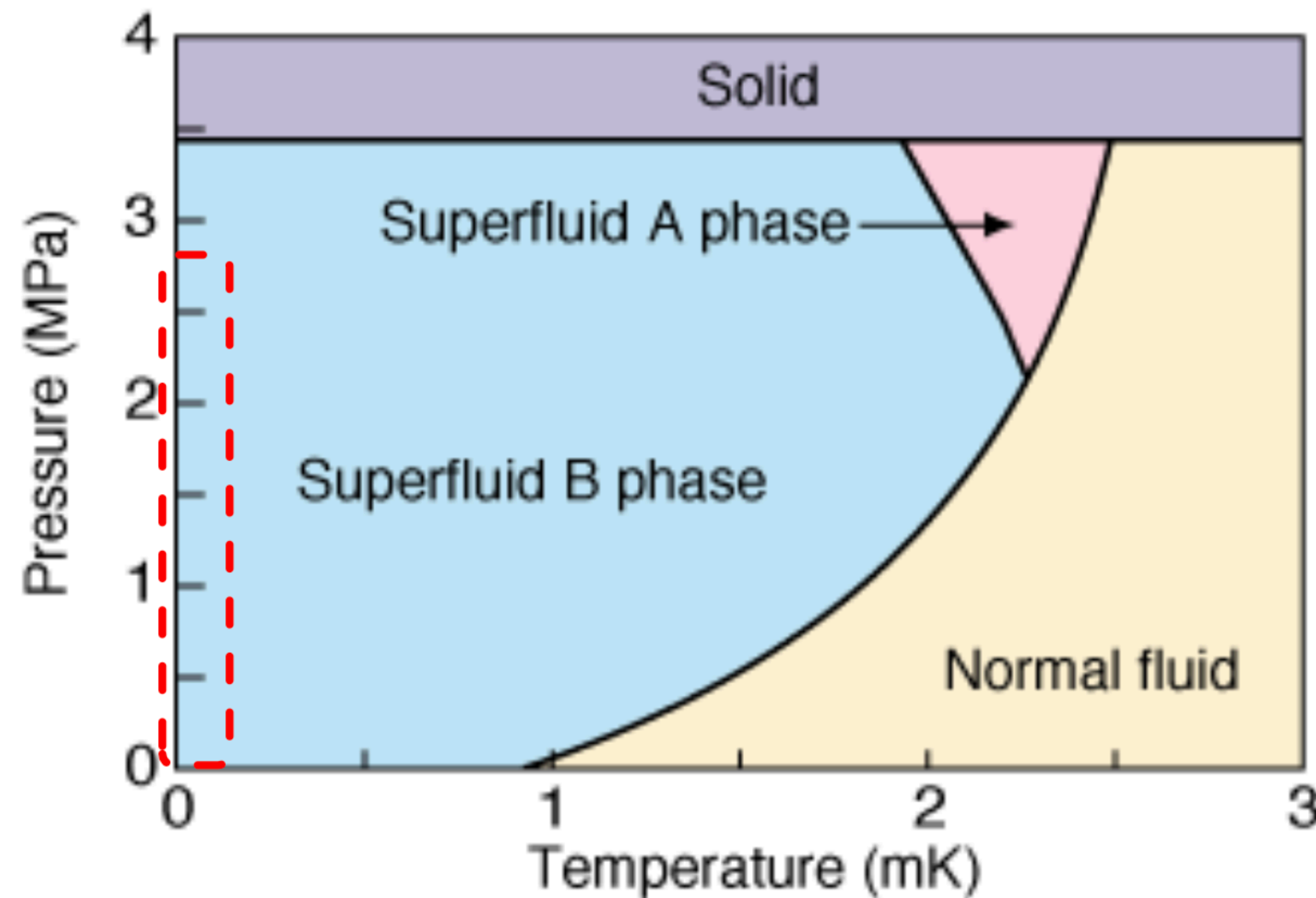


Quantum Sensing and Superfluid He3

QUEST-DMC Superfluid He3



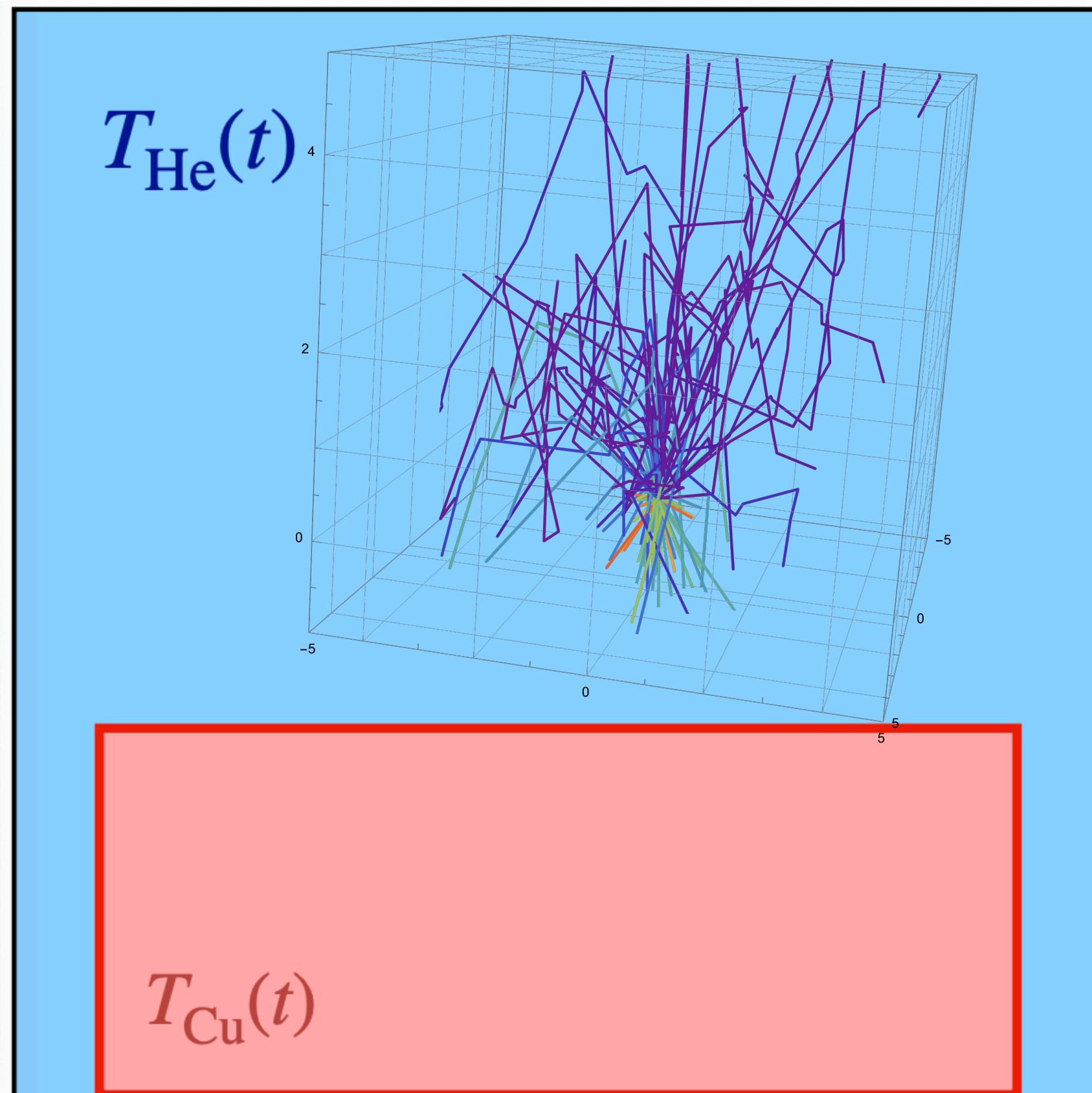
Phases of He3



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

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

Measure Power not Recoils!



Tetiana Kozynets
Post-Doctoral Researcher

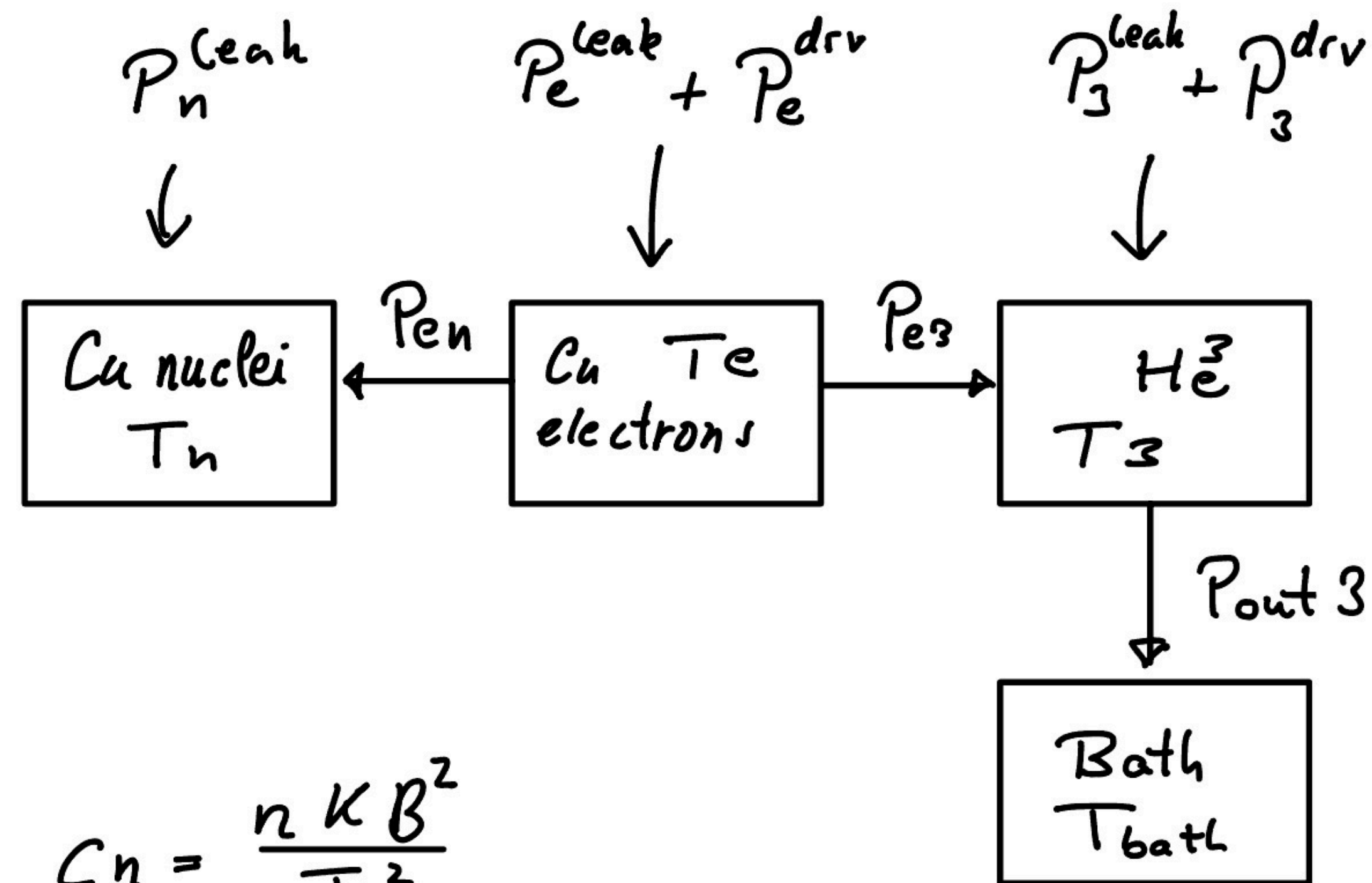


Erin Charnley
PhD Student

Technique has
potential to
get rid of readout
thresholds

Sensitive to even
slow drifting DM

Heat Exchange and Heat Leaks

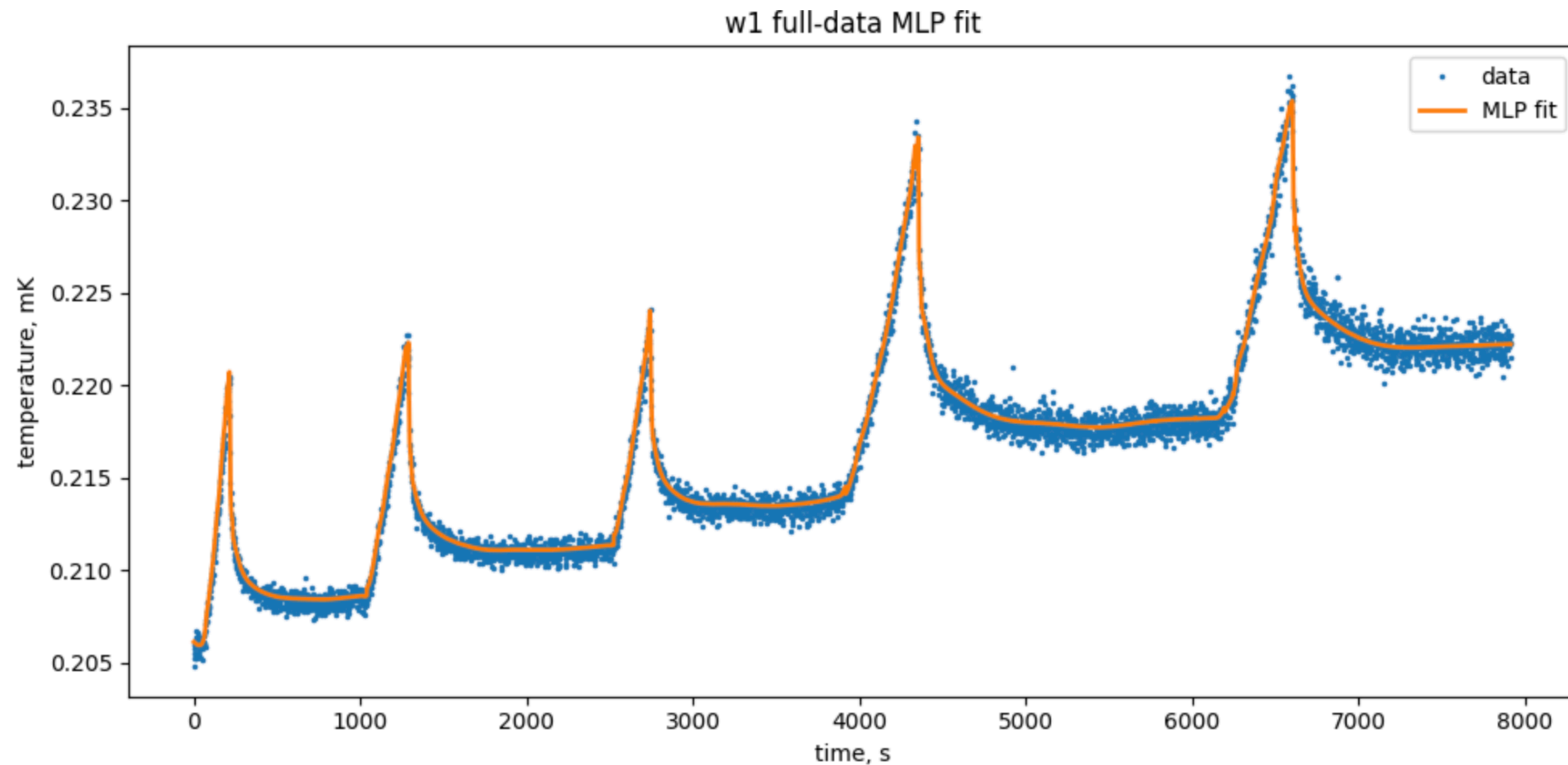


$$C_n = \frac{n K B^2}{T_n^2}$$

$$C_e = \gamma n T_e$$

$$C_3 \text{ (mode of He}^3\text{)}$$

Calibration Run and Parameter Extraction



Temperature Drift in the Bolometer

$$P_{\text{leak}} < \text{pW}$$

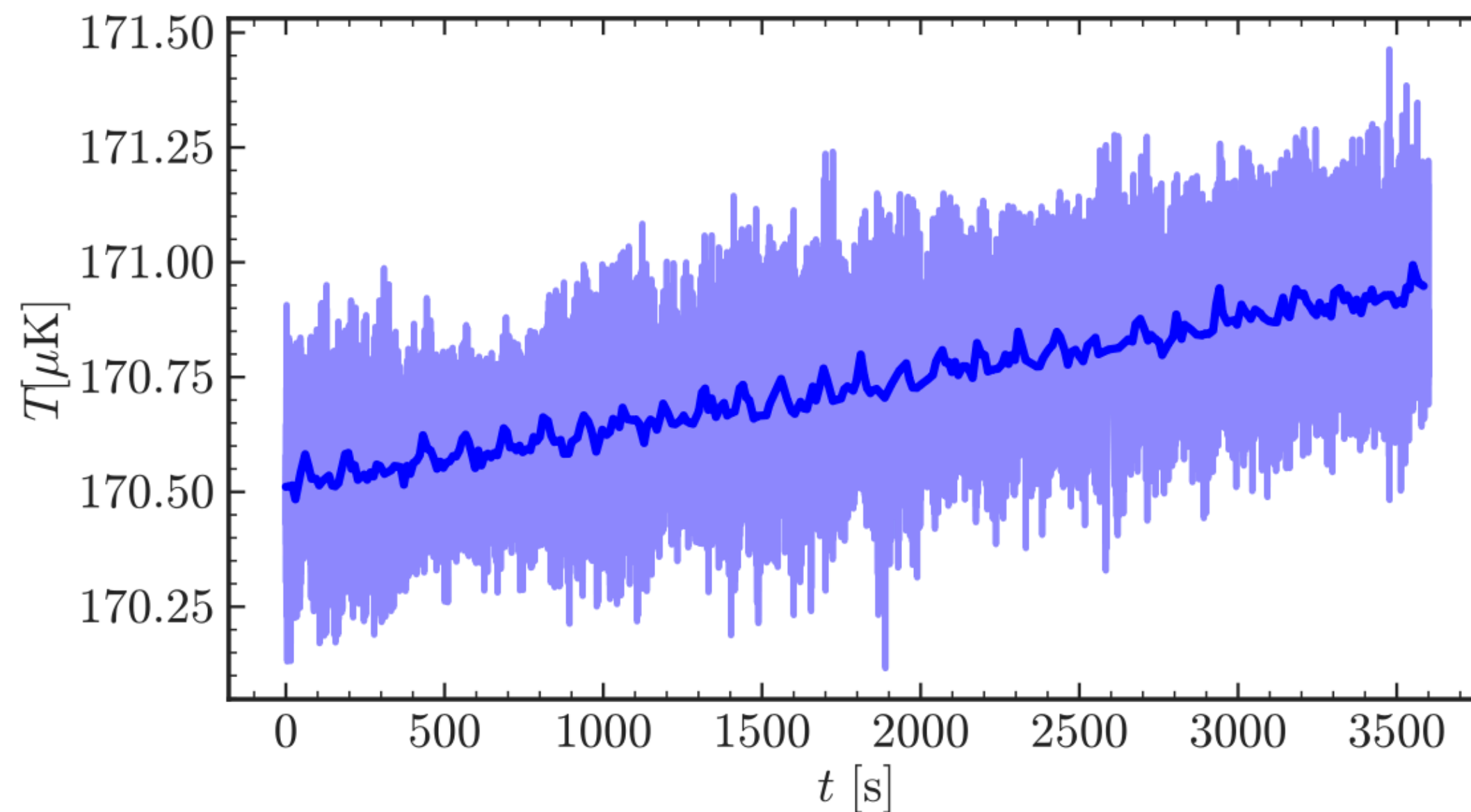


Figure 2: Example evolution of the ^3He temperature in QUEST-DMC over 1 hour, measured at 0 bar pressure. Data courtesy of Robert Smith and the QUEST-DMC Collaboration (February 2023).

Estimated from
simulations

$$P_{\text{radiogenic}} \sim 1.2 \times 10^{-4} \text{ pW},$$

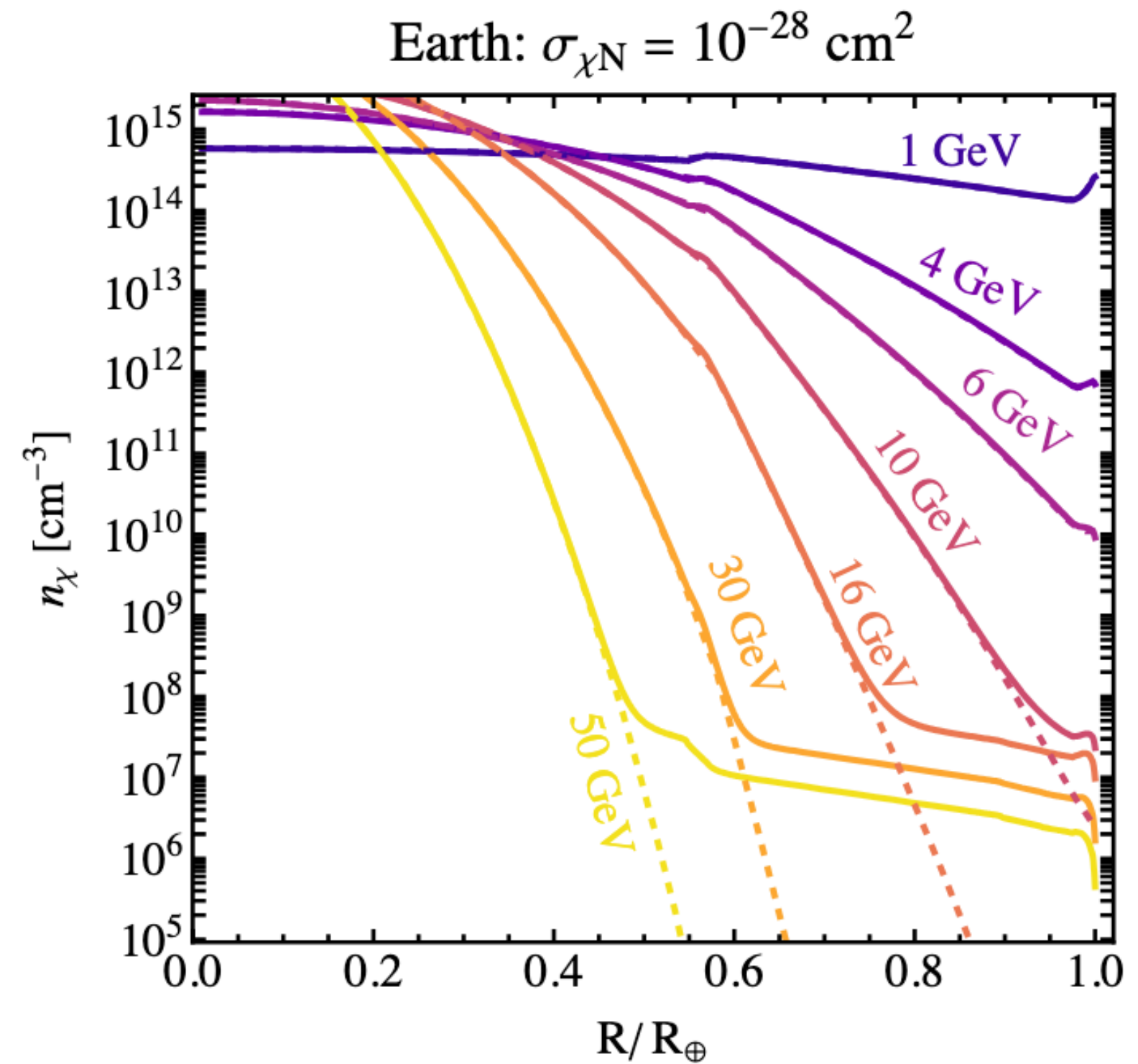
$$P_{\text{cosmic,surface}} \sim 6.3 \times 10^{-4} \text{ pW},$$

$$P_{\text{cosmic,underground}} \sim 1.5 \times 10^{-9} \text{ pW}.$$

Signals with Varying Depth

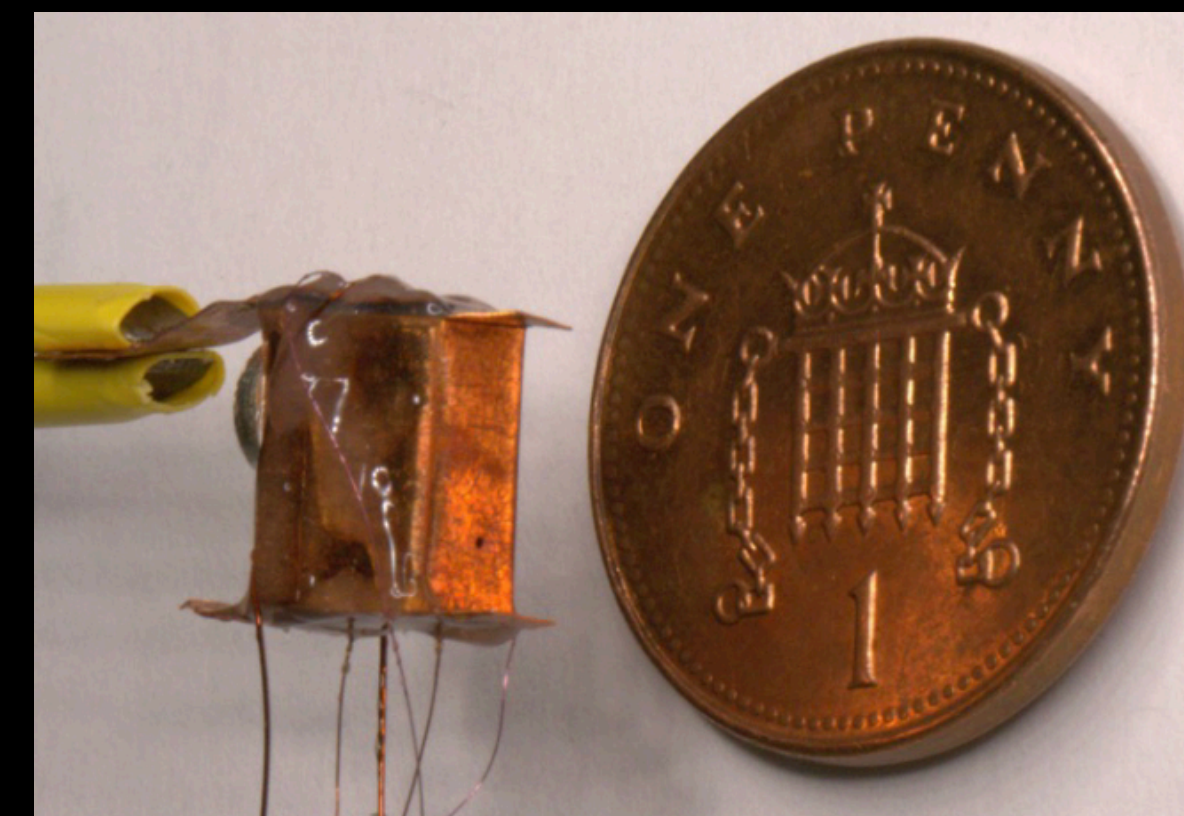
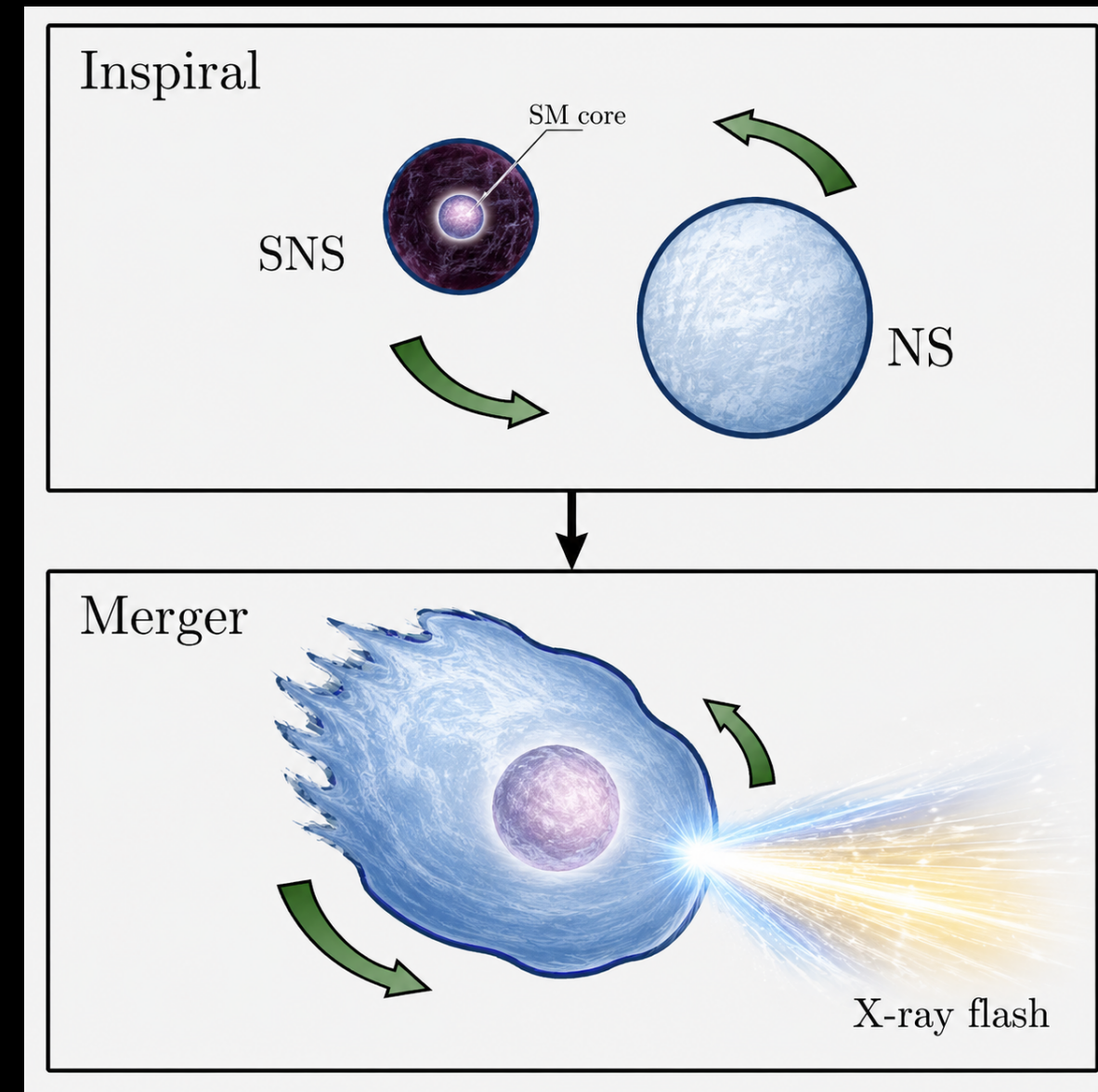
$$P_\chi(r) \propto n_\chi(r) \langle \sigma v \Delta E \rangle.$$

- Already push below pW sensitivity
- Heat leak depth dependent
- Cosmics are as well
- Effects calculable
- Differential measurement



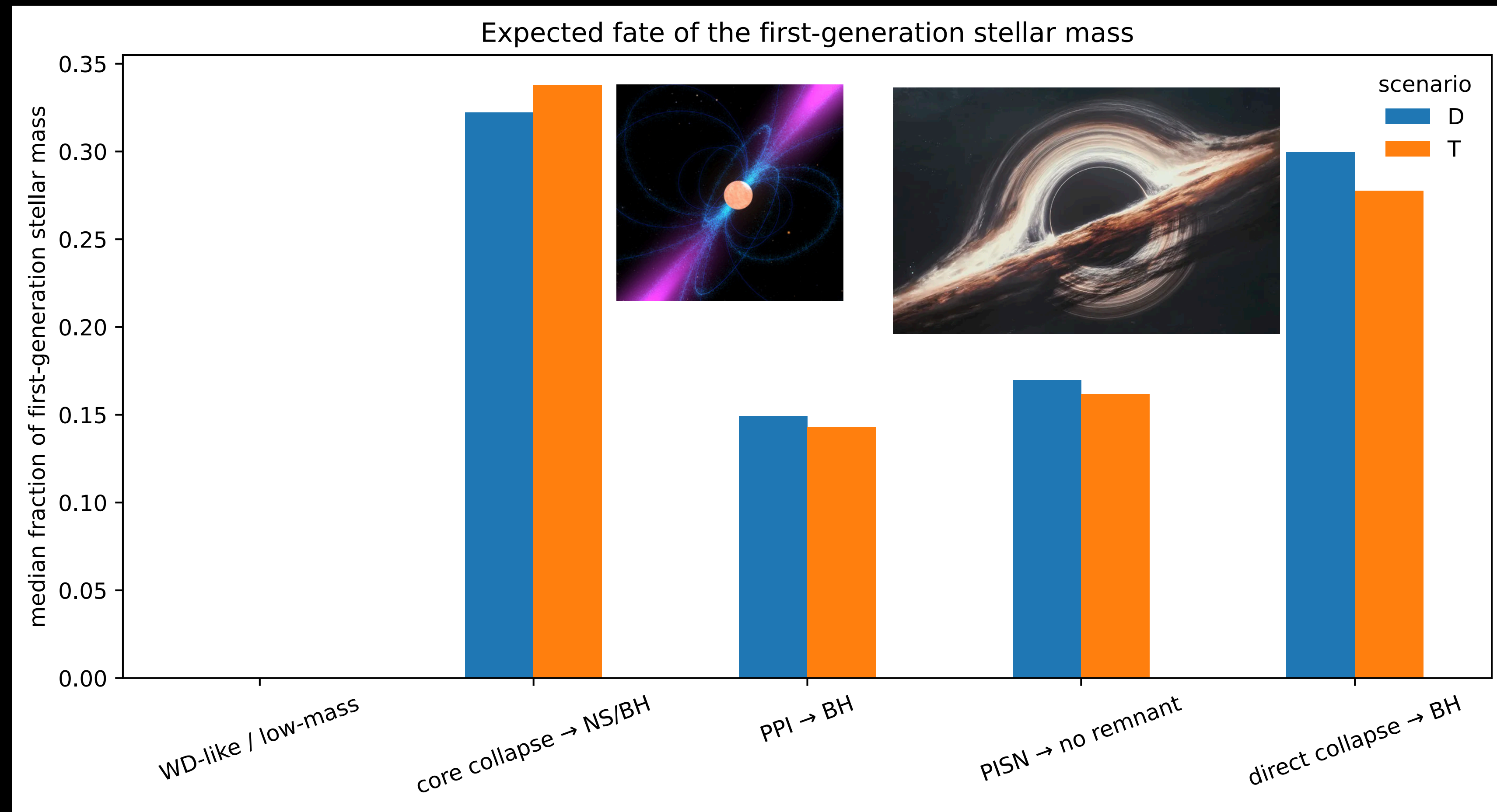
Summary

- Shadow sector with dissipative Dark Matter
- Astrophysical multi messenger signals
- New signatures in ultra-low temperature experiments
- Earth bound slow dark matter population contributes to a thermal link/ anomalous heat leak
- Signal strength varies with detector depth



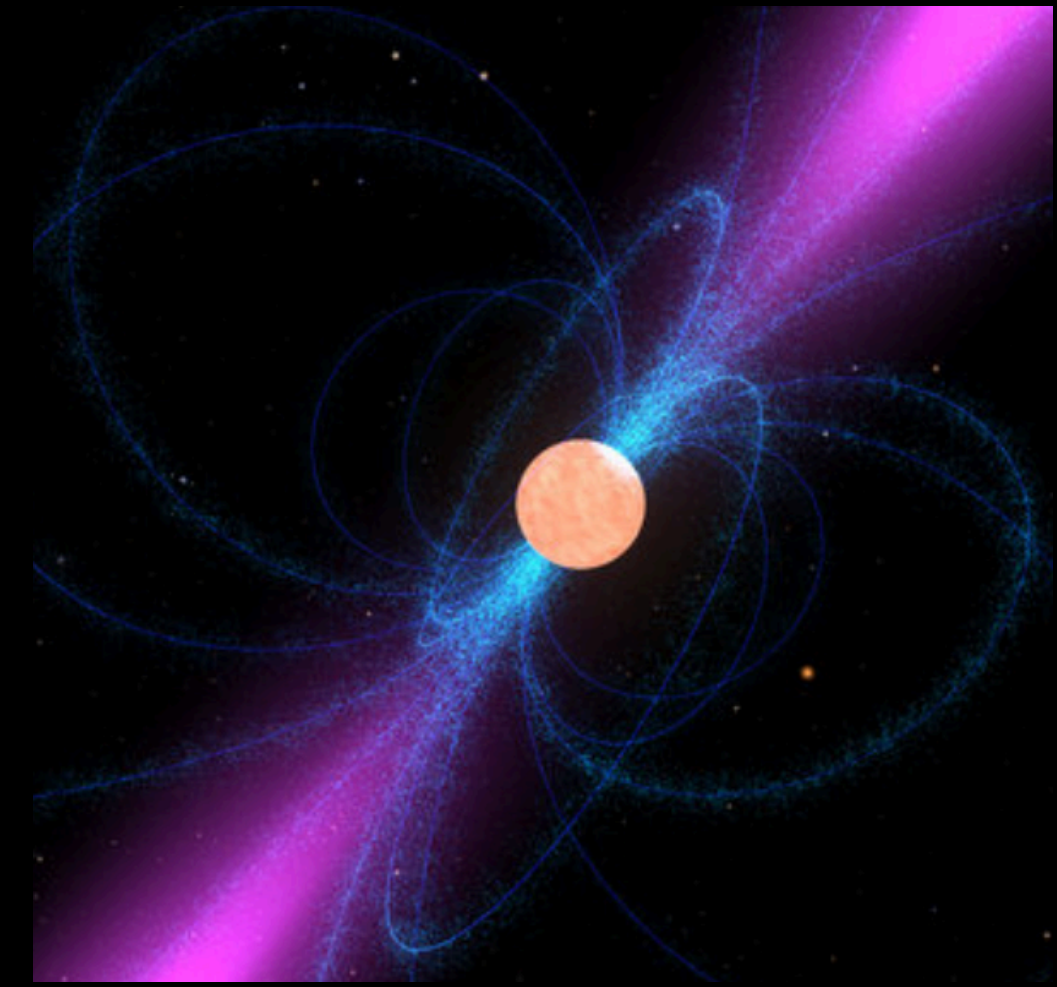
Backup

Expected Shadow Object Population

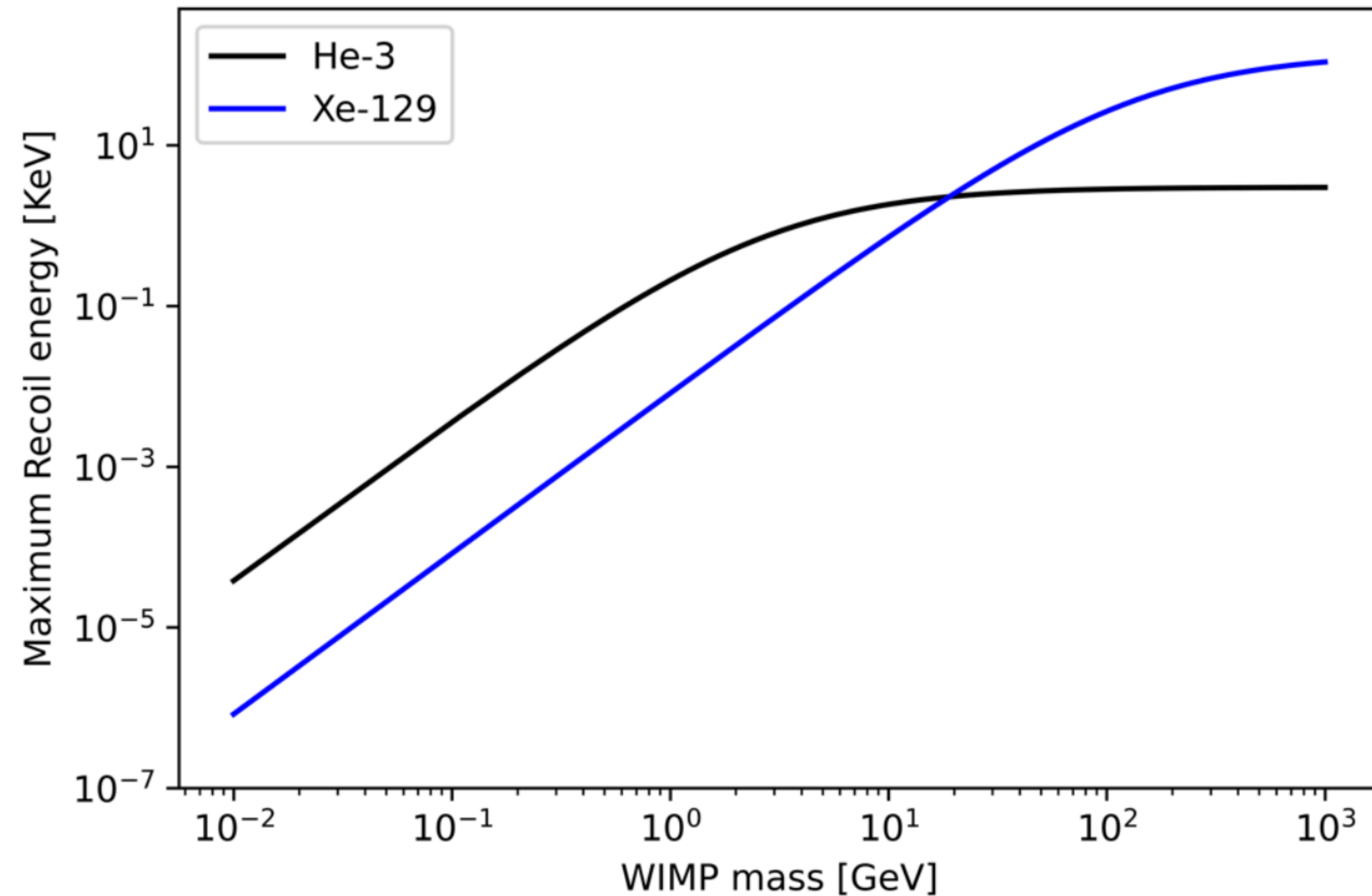


Shadow Sector forms Halos and Structures!

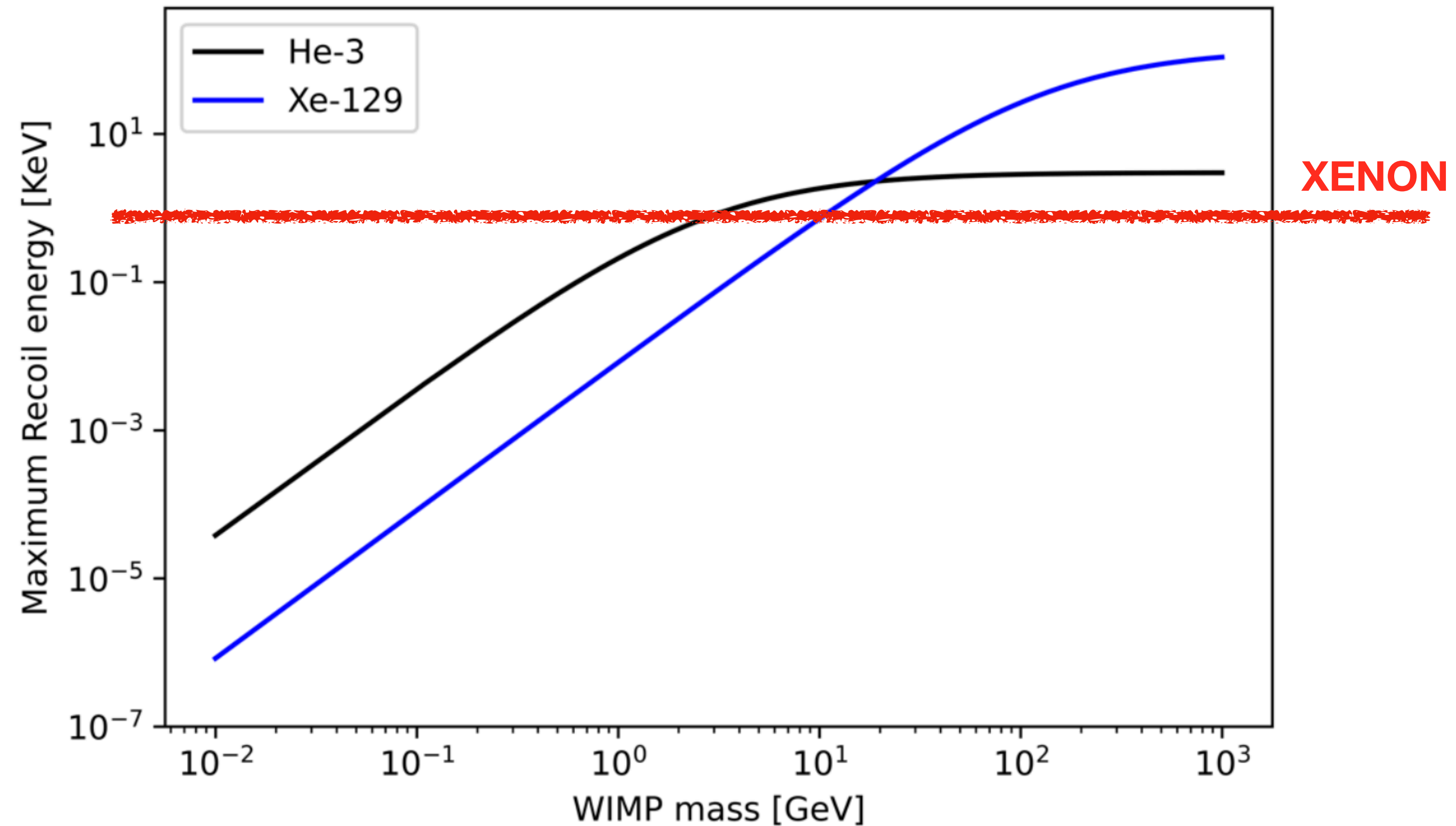
- + In addition to shadow neutron halo dissipative plasma:
(99% $4\text{He}'$), (1% T')
- + ($4\text{He}'$) drives high-temperature cooling; (T'/T_2') enables lower-temperature cooling
- + Dissipation forms a dark disk, clouds and shadow stars
- + High cooling floor $\rightarrow$ large Jeans masses and 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



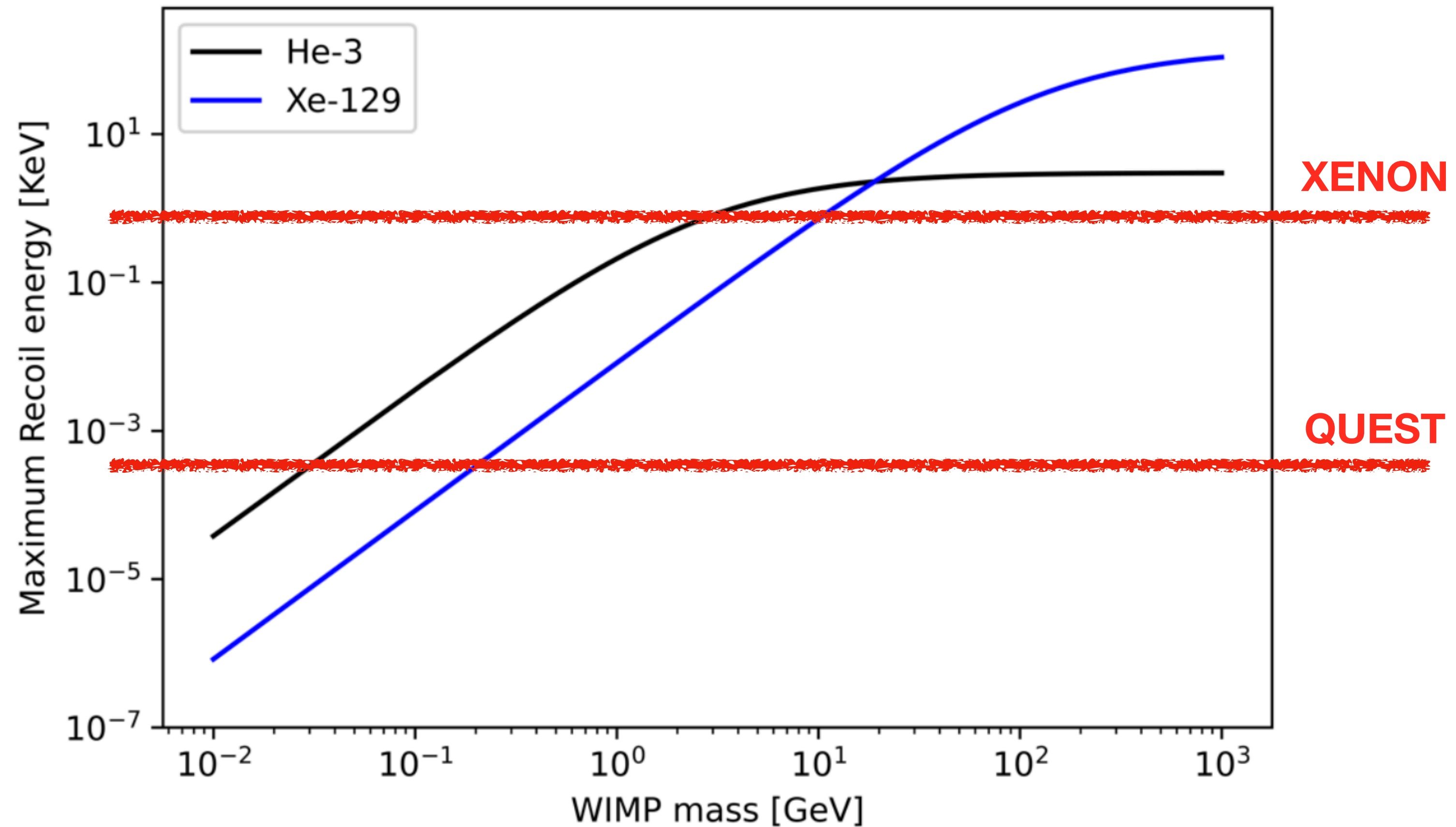
QUEST-DMC Superfluid He3



QUEST-DMC Superfluid He3

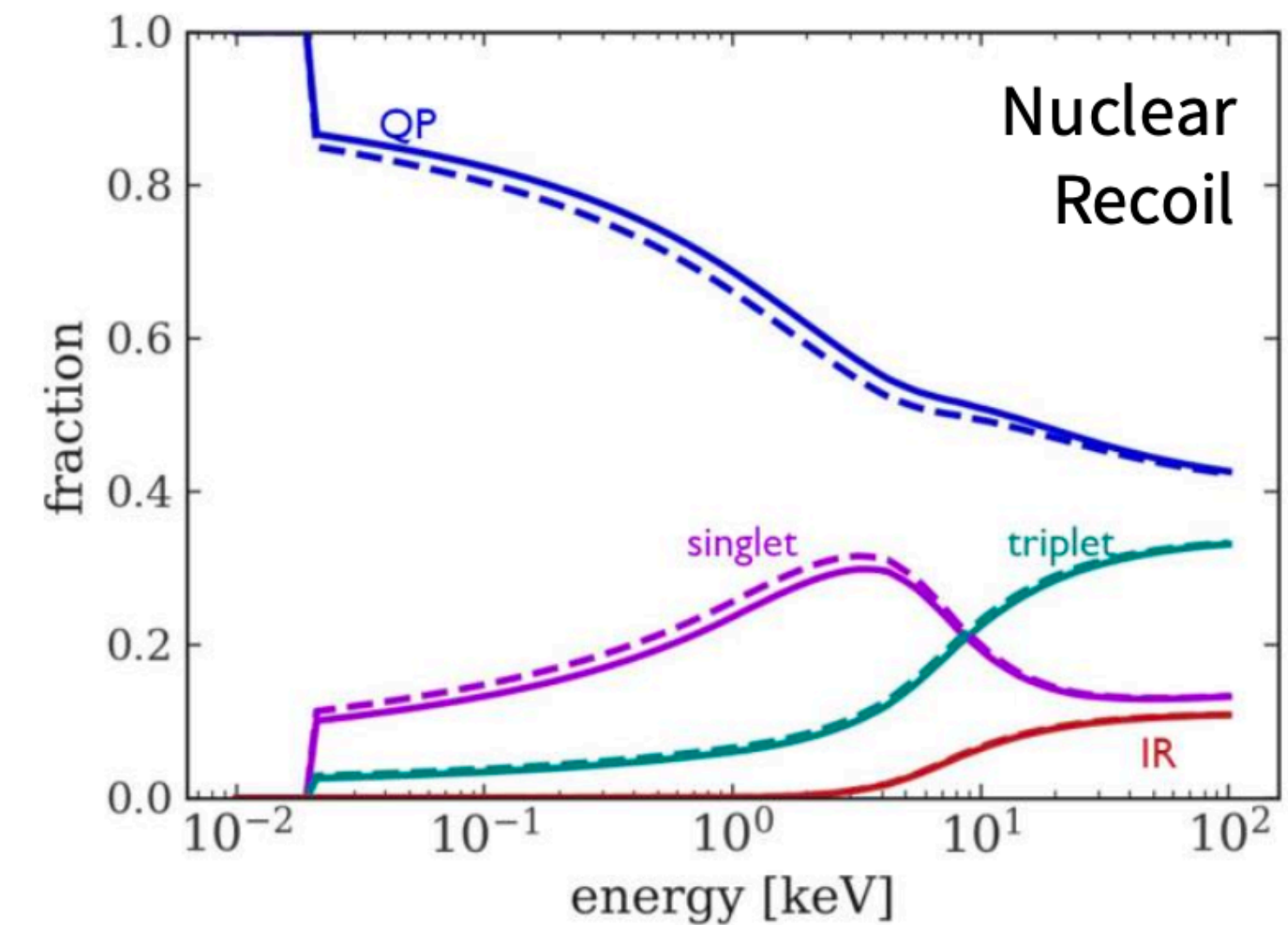
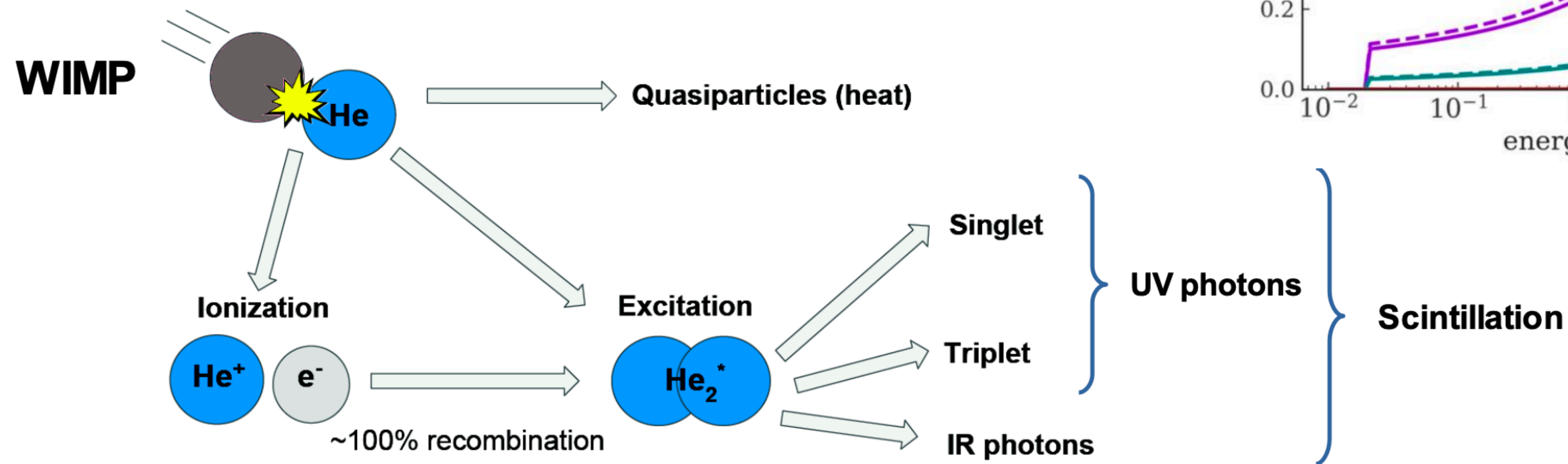


QUEST-DMC Superfluid He3

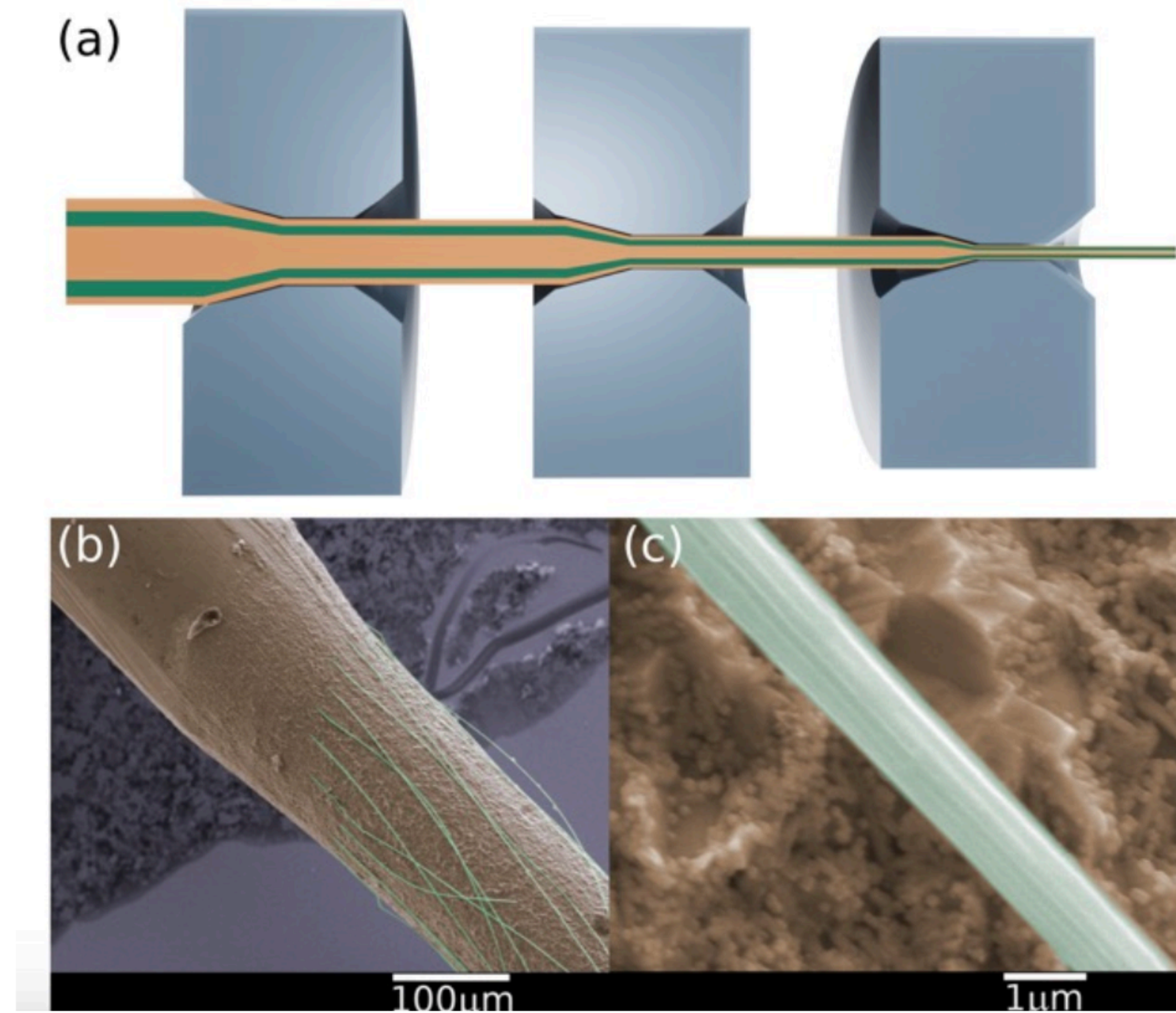


Energy Deposition

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



Nano-wire Signal Readout



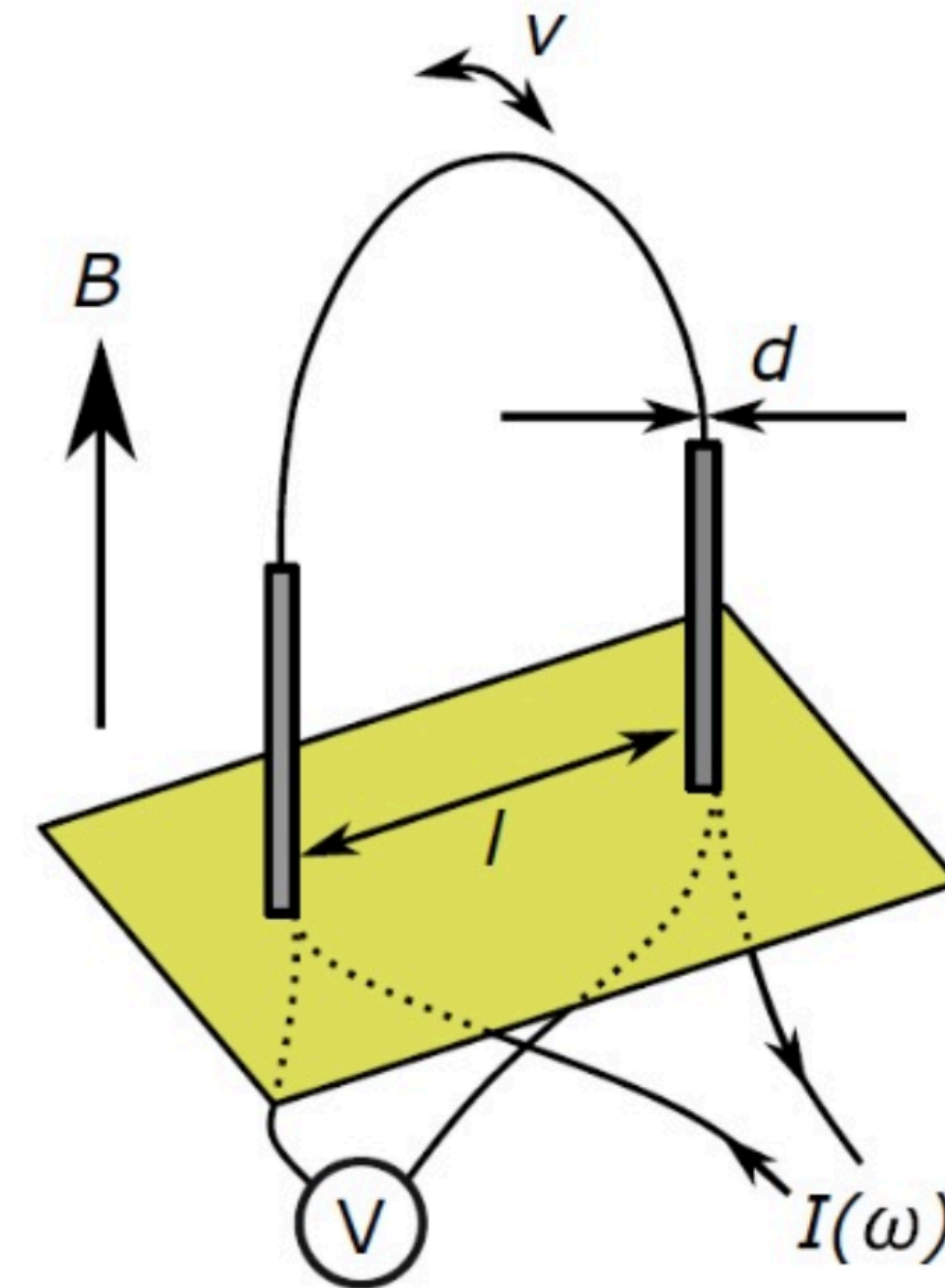
Quasi Particle Dampening

- Vibrating nanowire resonator in a vertical magnetic field

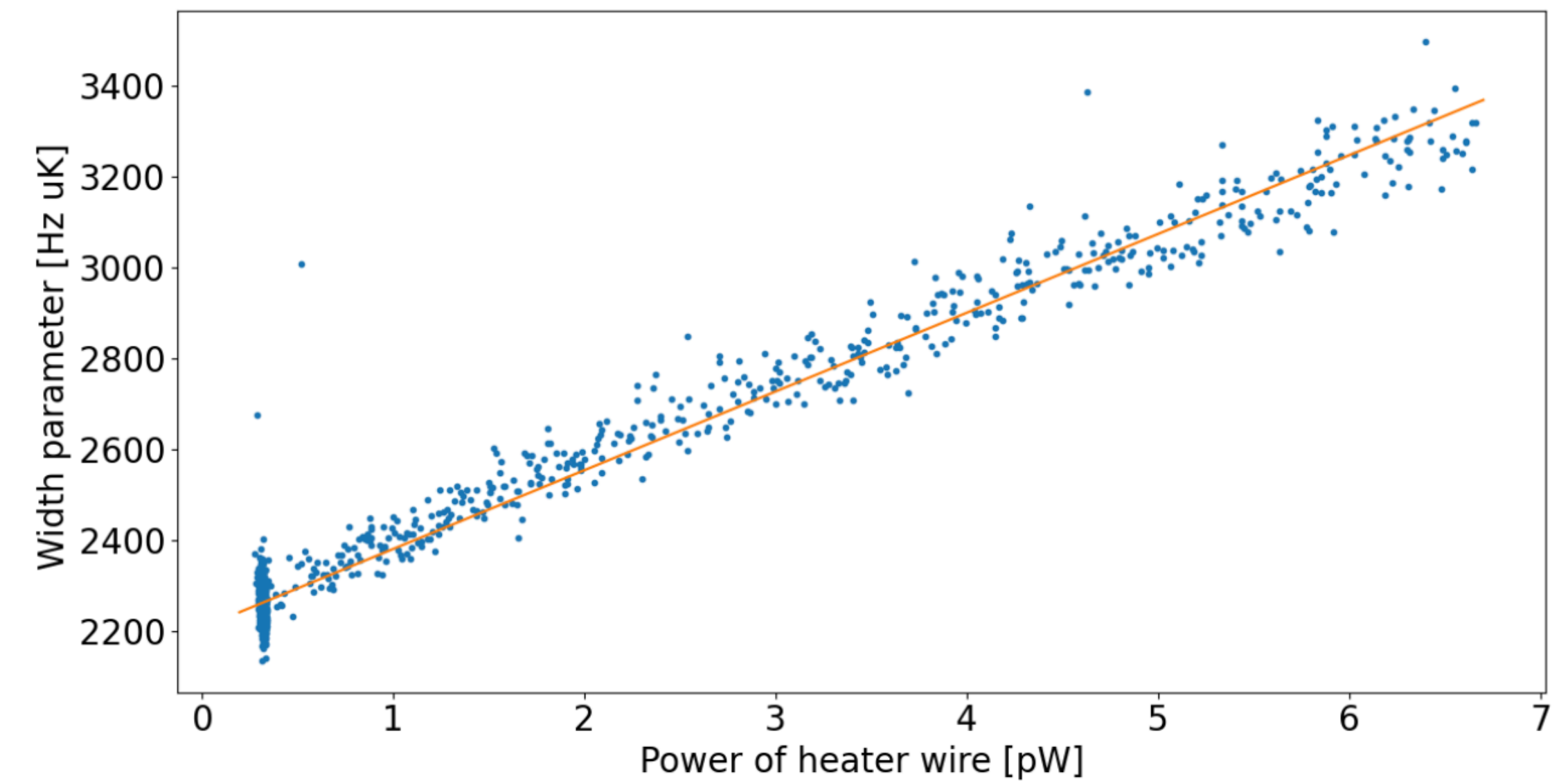
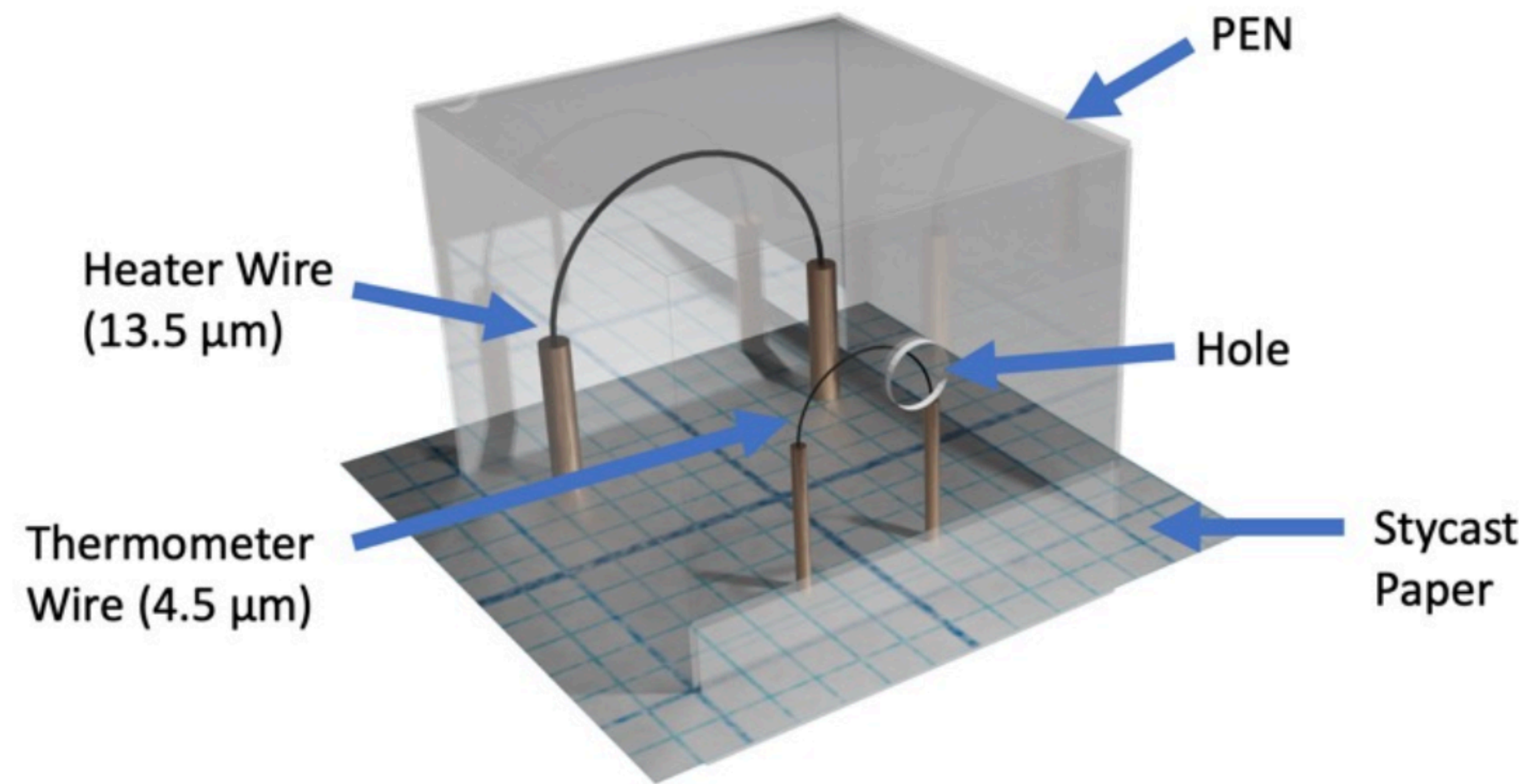
- Damping force from QP collisions:

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

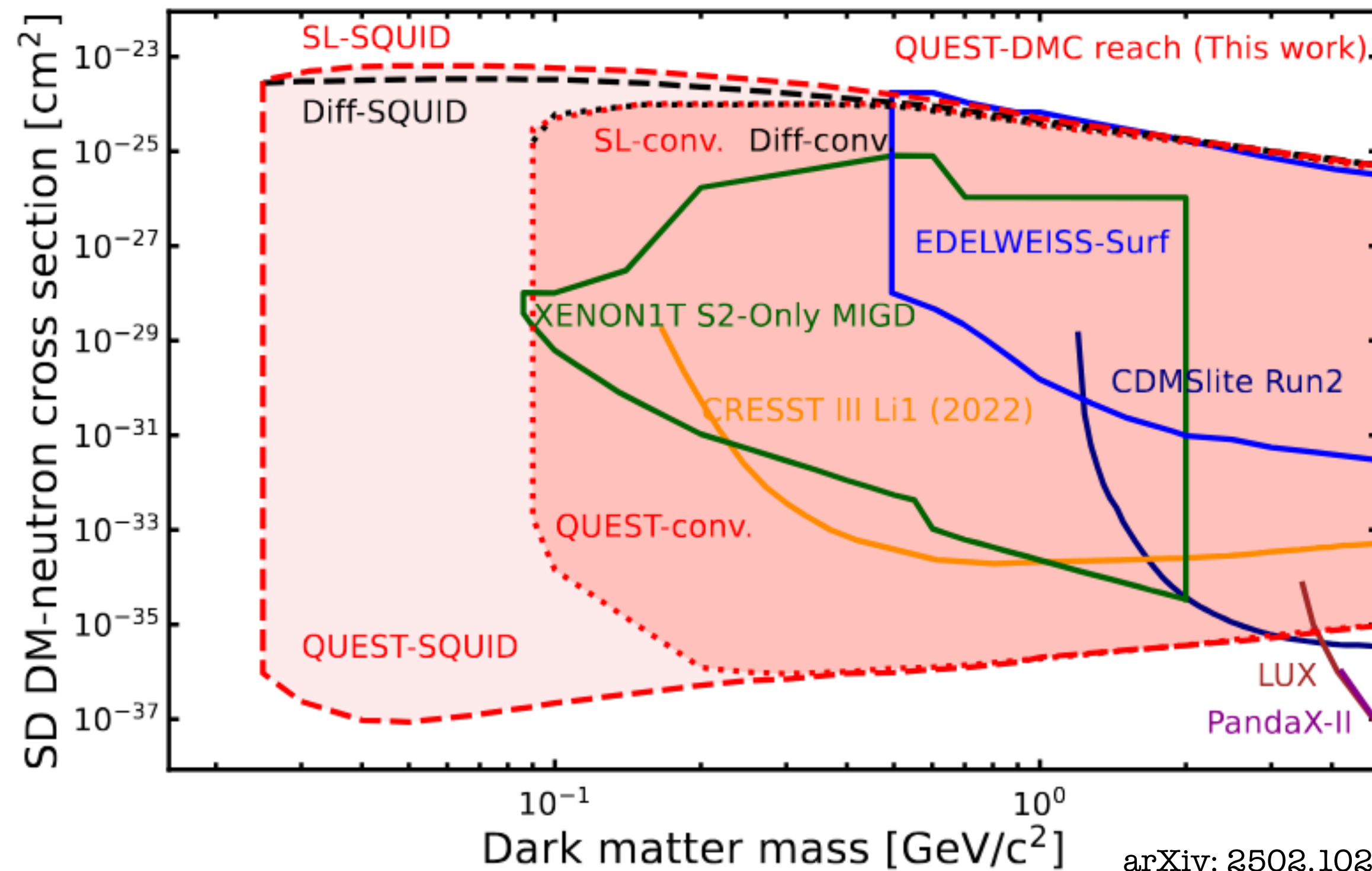
- Andreev scattering amplifies force



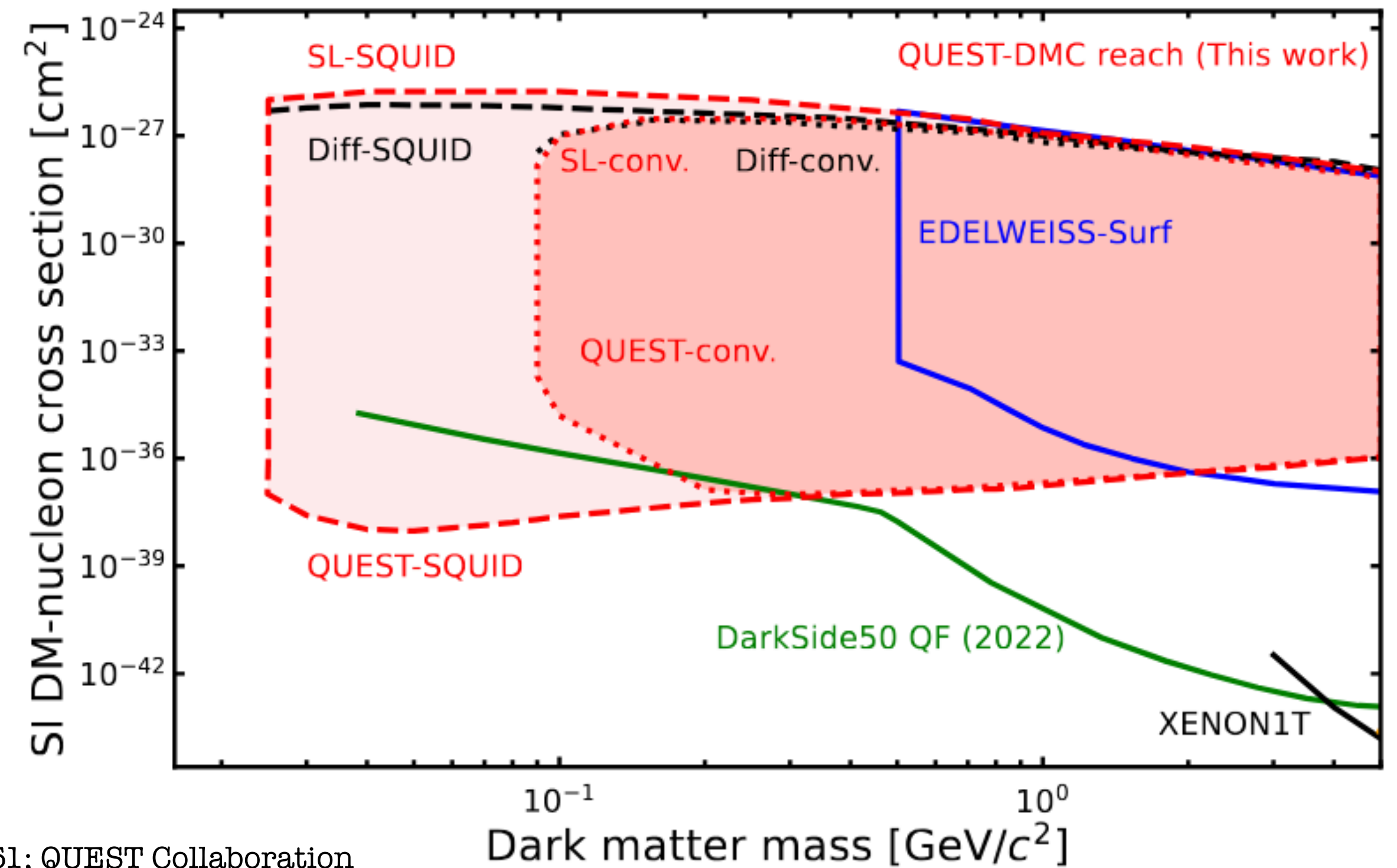
Readout Calibration



Overall Sensitivity and effect

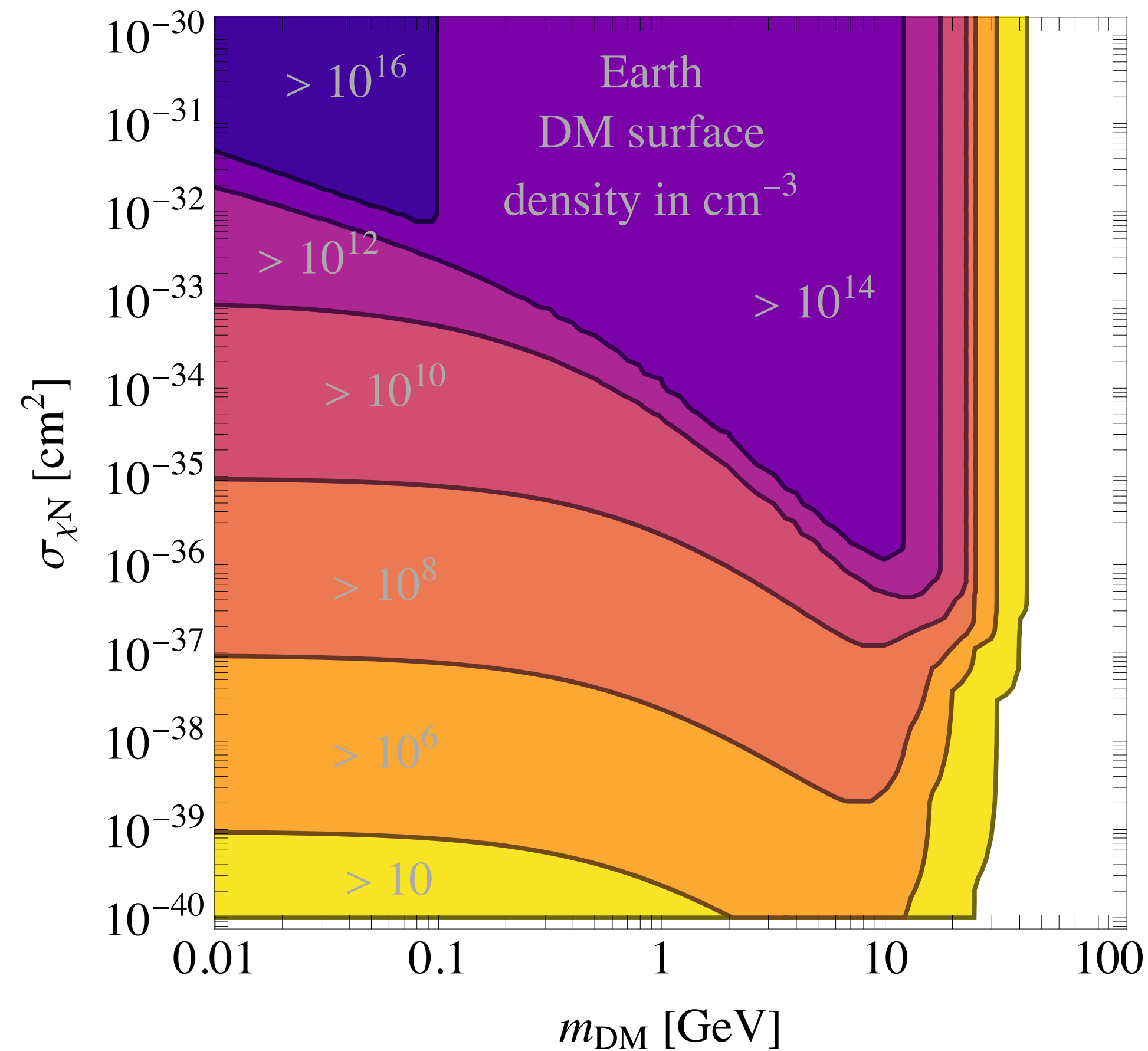


arXiv: 2502.10251; QUEST Collaboration



Surface Overdensity: DM w. long range force

Preliminary



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

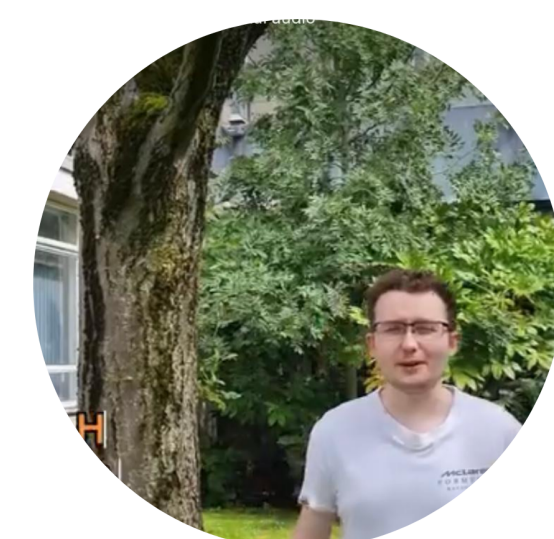
PhD Student

Visitor



Erin Charnley

PhD Student



Henry McKeena

PhD Student



Insta: @qu.map