DIRECT DETECTION OF DARK MATTER WITH SUPERCONDUCTING NANOWIRES

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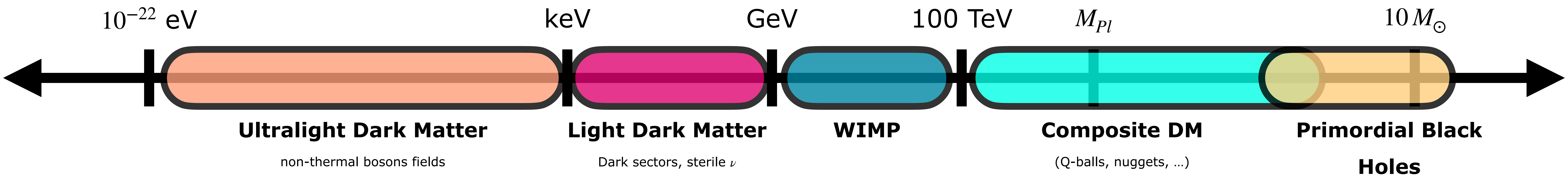
LOOKING FOR DARK MATTER

WHAT IS DARK MATTER ?



WIMP = main paradigm in the last 40 years

However, extensive searches have yielded no definitive WIMP detections, raising the need to consider alternatives

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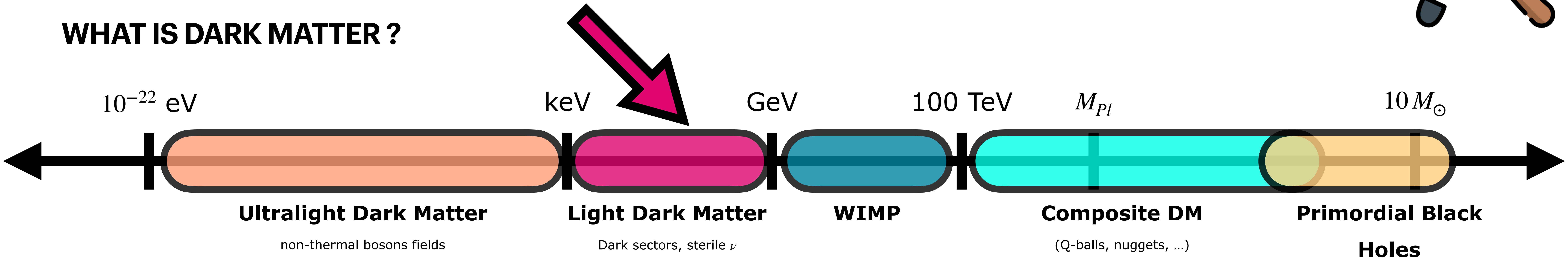

WIMP = main paradigm in the last 40 years

However, extensive searches have yielded no definitive WIMP detections, raising the need to consider alternatives

Several theories suggest Dark Matter could be **much lighter** than previously assumed, possibly even down to eV scales.

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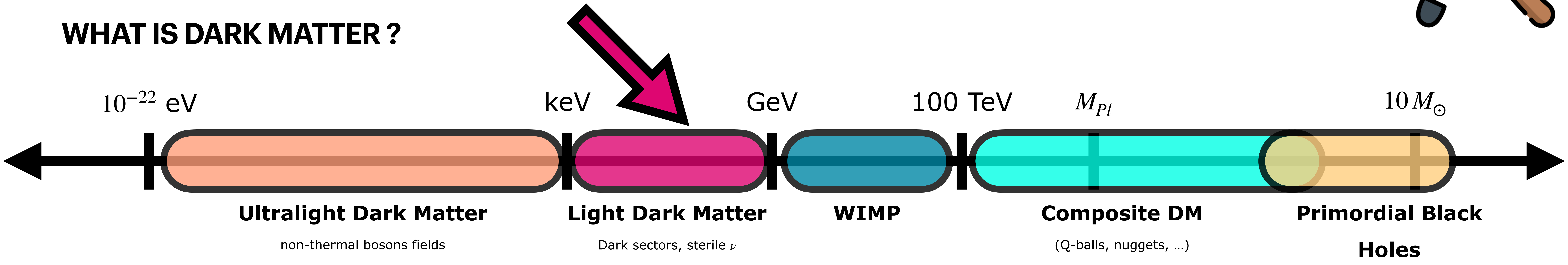


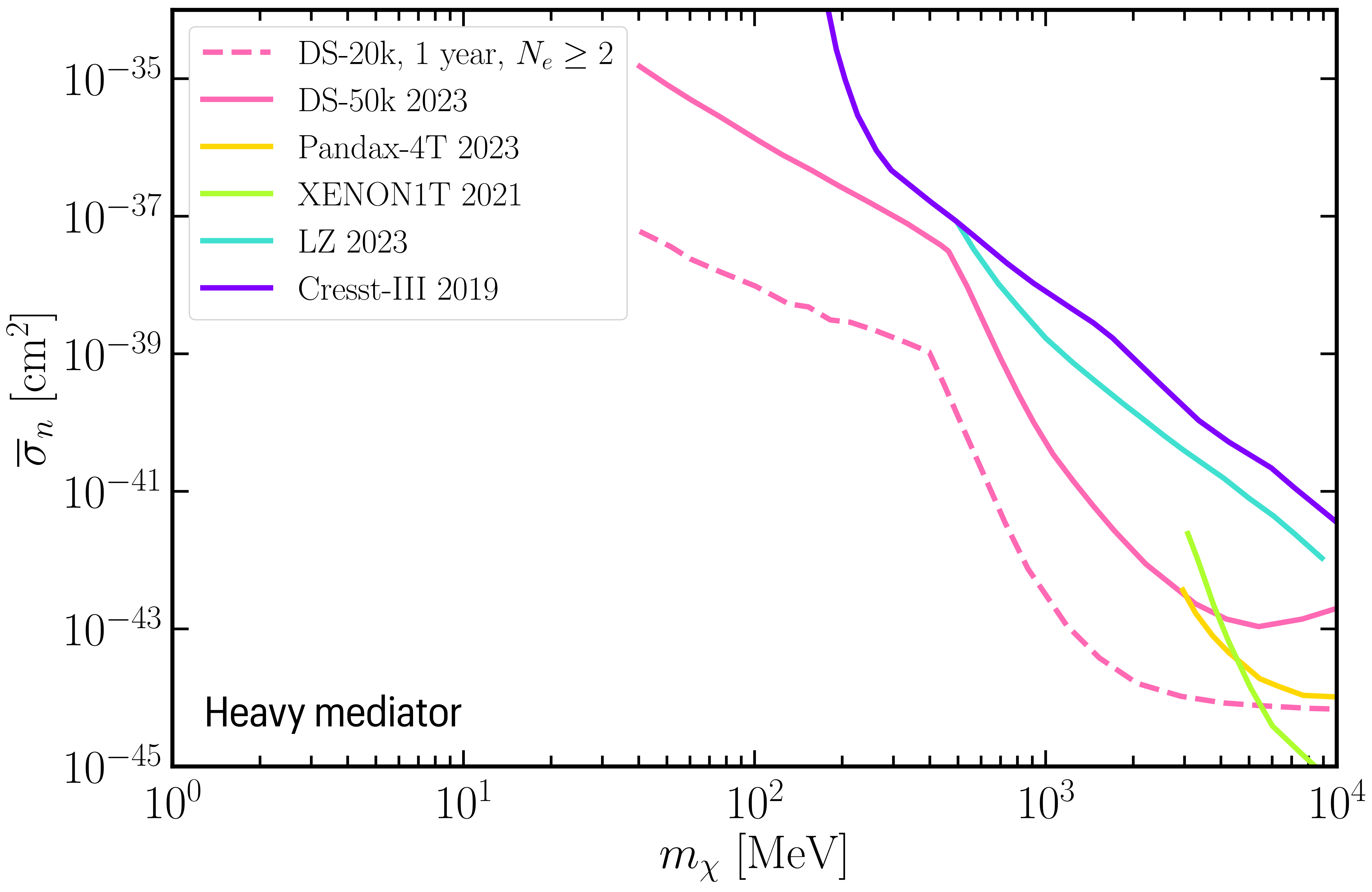
How can we reveal light Dark Matter ?

- Dark Matter - nucleon scattering
- Dark Matter - electron scattering
- Dark Photon absorption
- …

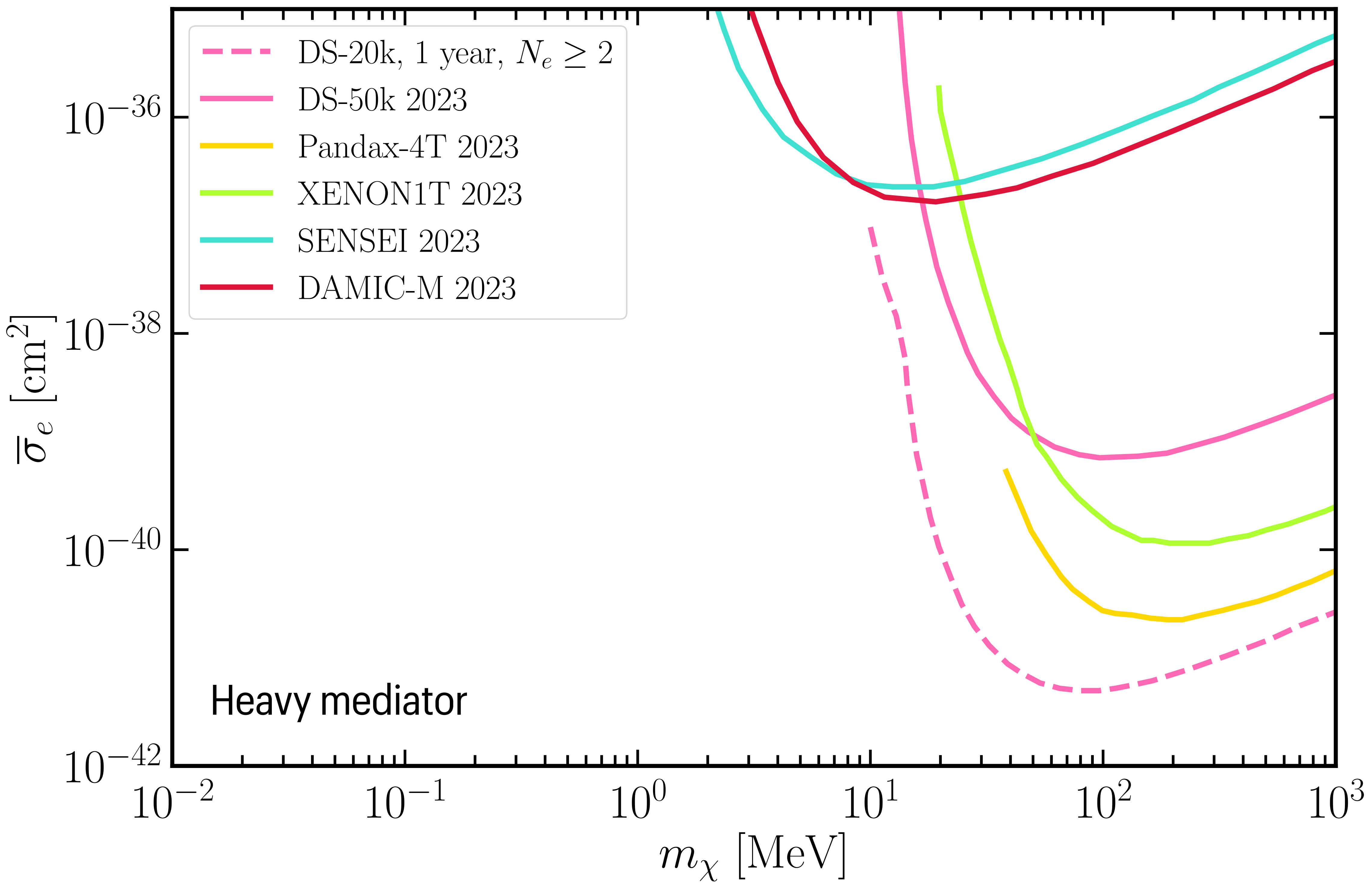
LOOKING FOR DARK MATTER

PUSHING THE BOUNDARIES: HOW LOW IN MASS CAN CURRENT EXPERIMENTS GO?

DARK MATTER - NUCLEON SCATTERING



DARK MATTER - ELECTRON SCATTERING



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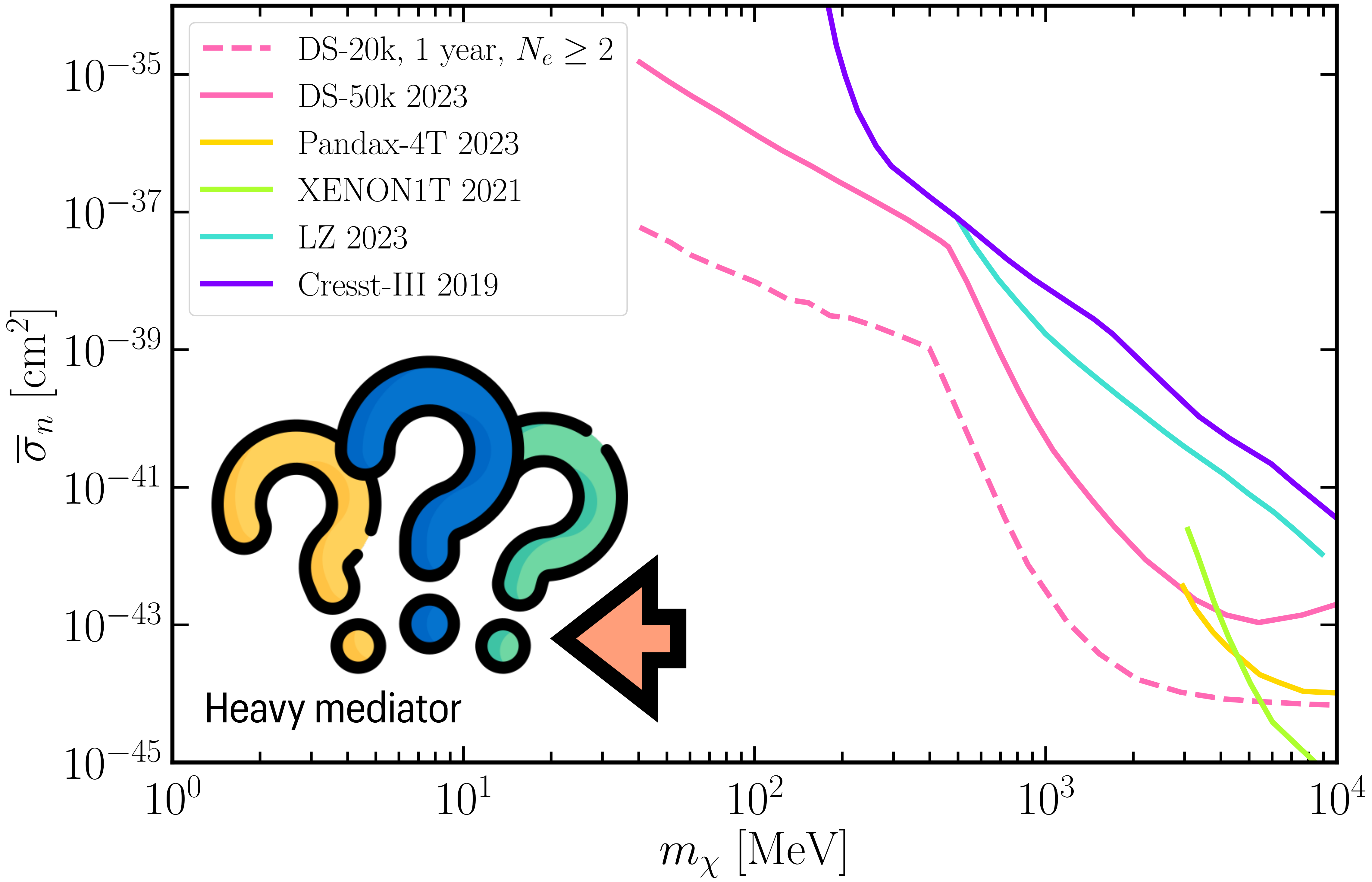

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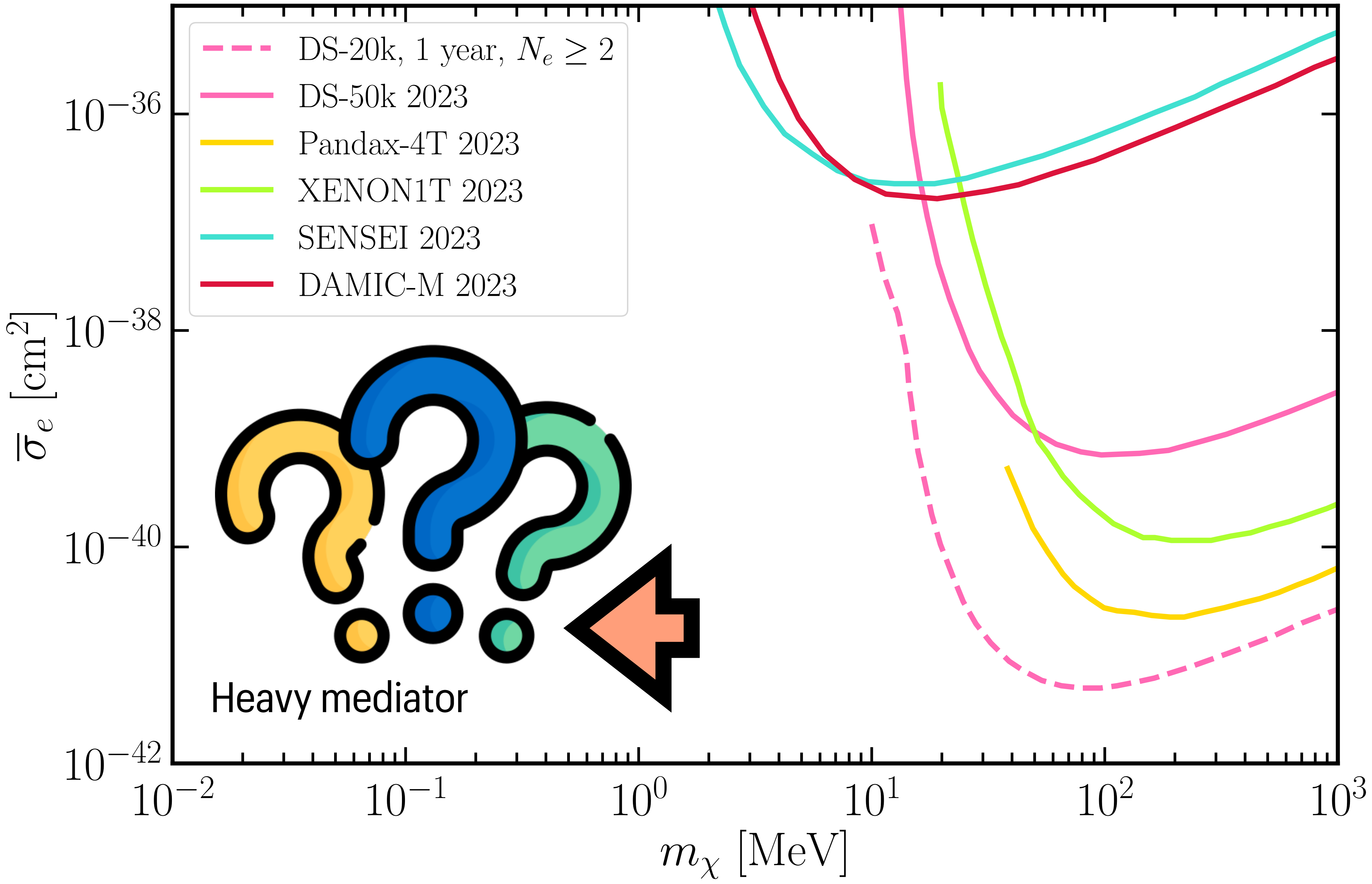

LOOKING FOR DARK MATTER

BEYOND THE LIMITS: PUSHING THE SEARCH TO EVEN LOWER MASSES

In the last few years, several ideas have emerged to explore the sub-MeV region

- Atomic excitations (R. Essig, J. Mardon, and T. Volansky, Phys. Rev. D 85, 076007 (2012))
- Electron recoils in semiconductors (R. Essig, J. Mardon, and T. Volansky, PRD 85, 076007 (2012); R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, PRL 109, 021301 (2012); P. W. Graham, D. E. Kaplan, S. Rajendran, and M. T. Walters, PDU 1, 32 (2012); N. Kurinsky, T. C. Yu, Y. Hochberg, and B. Cabrera,PRD 99, 123005 (2019).)
- Superfluid Helium (QUEST-DMC collaboration Eur.Phys.J.C 84 (2024) 3, 248, HeRALD collaboration PRD 110 (2024) 7, 072006)
- Superconductors (Y. Hochberg, et al, PRL 116, 011301 (2016), JHEP 08 (2016) 057, Phys Rev. Lett. 123, 151802 (2019), Phys. Rev. D 107, 076015 (2023), Phys. Rev. D 106, 112005 (2022), QROCODILE collaboration Arxiv: 2412.16279)
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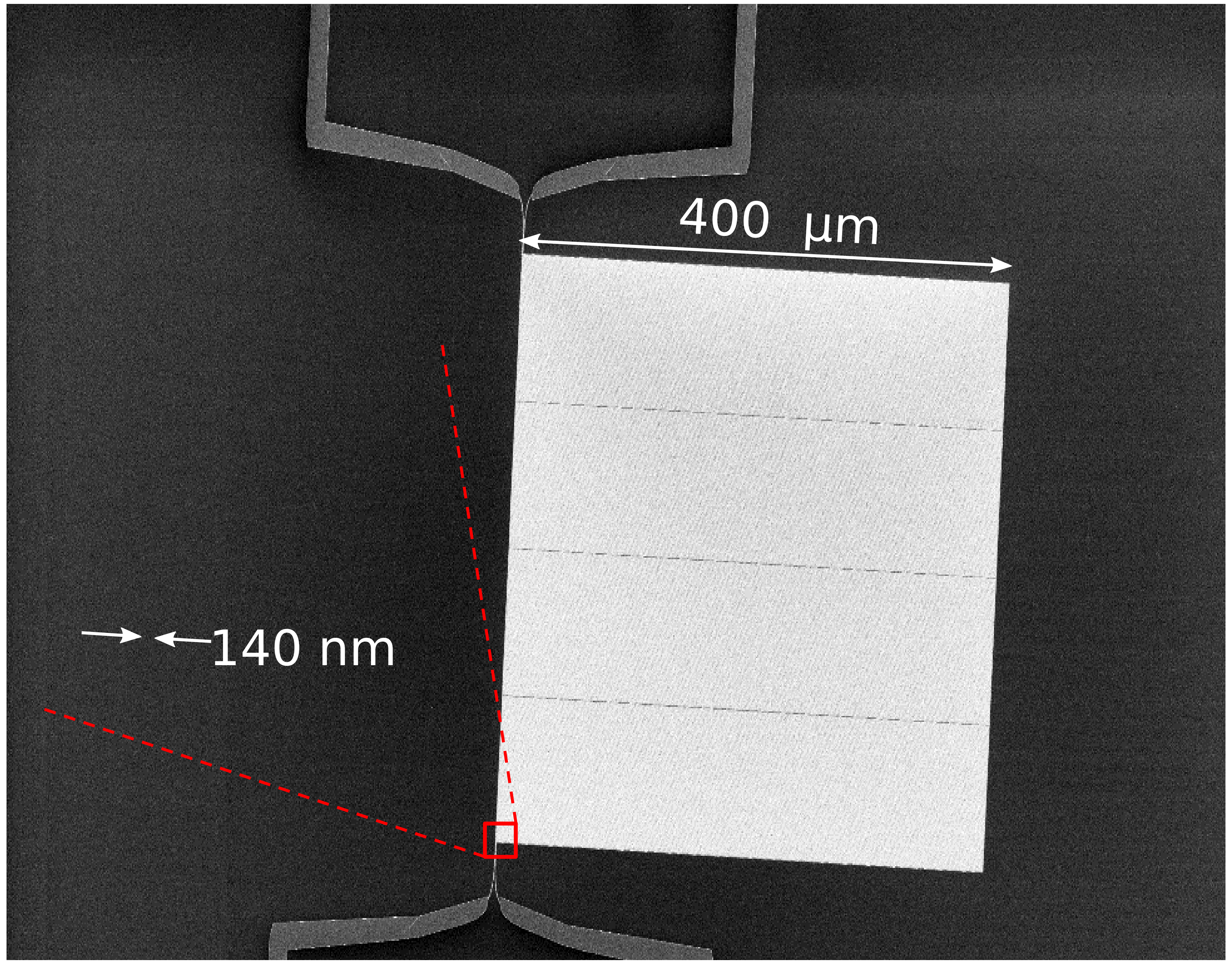
SUPERCONDUCTORS AS TARGET

SNSPDS: A NEW FRONTIER FOR DARK MATTER DETECTION

Superconducting nanowire single photon detectors (**SNSPDs**) are a rapidly developing technology with applications in

- Space communications
- Lidar
- Quantum Information science
- ...



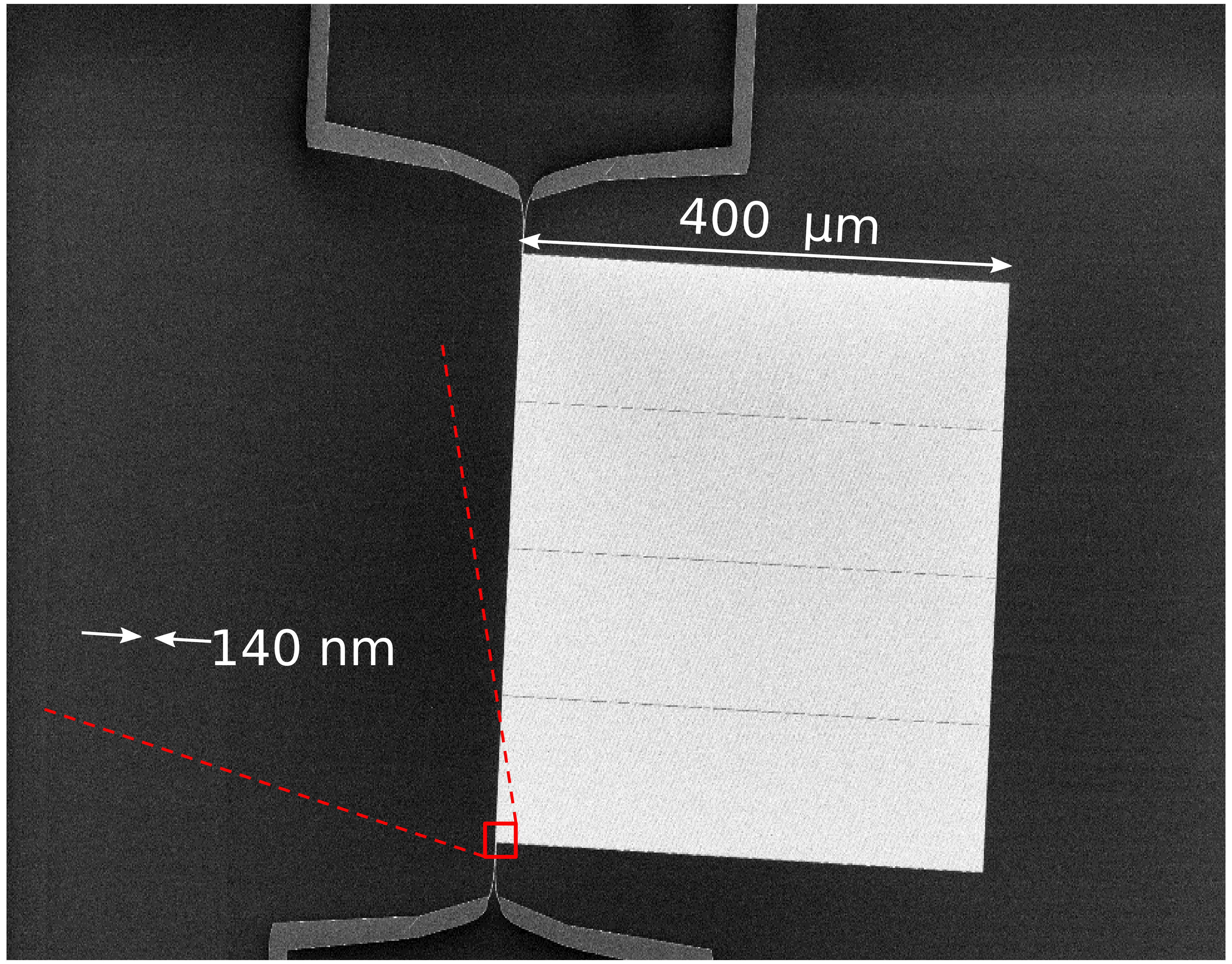
Hochberg et al, *Phys.Rev.Lett.* 123 (2019) 15, 151802

SUPERCONDUCTORS AS TARGET

SNSPDS: A NEW FRONTIER FOR DARK MATTER DETECTION

Why SNSPDs?

- Sub-eV energy threshold
- High efficiency (Reddy, D. V.,et al, Optica 7, 1649–1653 (2020))
- Fewer than 10 dark counts/day in optimal conditions (E. Wollman et al., Opt. Express 25, 26792 (2017).)
- **High Scalability:** Prototypes with 1k SNPDs already demonstrated (E. E. Wollman et al., Opt. Express 27, 35279–35289 (2019). And A. N. McCaughan et al., Appl. Phys. Lett. 121, 102602 (2022).), with 400k planned in the near future (B.G. Oripov et al., Nature 622, 730-734 (2024))



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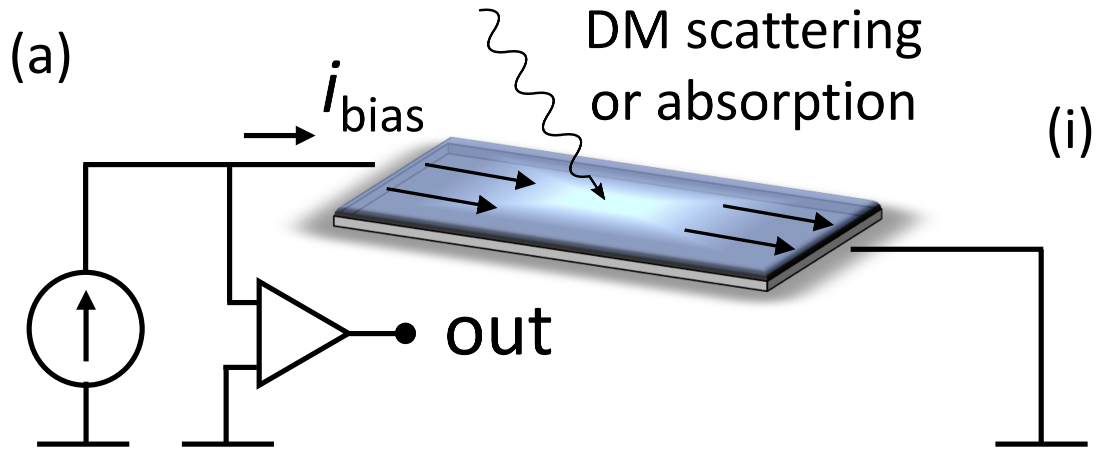
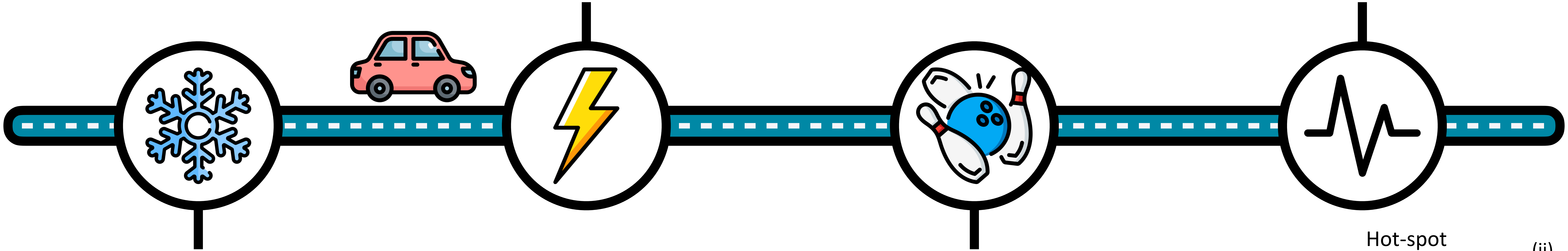
SUPERCONDUCTORS AS TARGET

SNSPDS: ACTIVE TARGETS



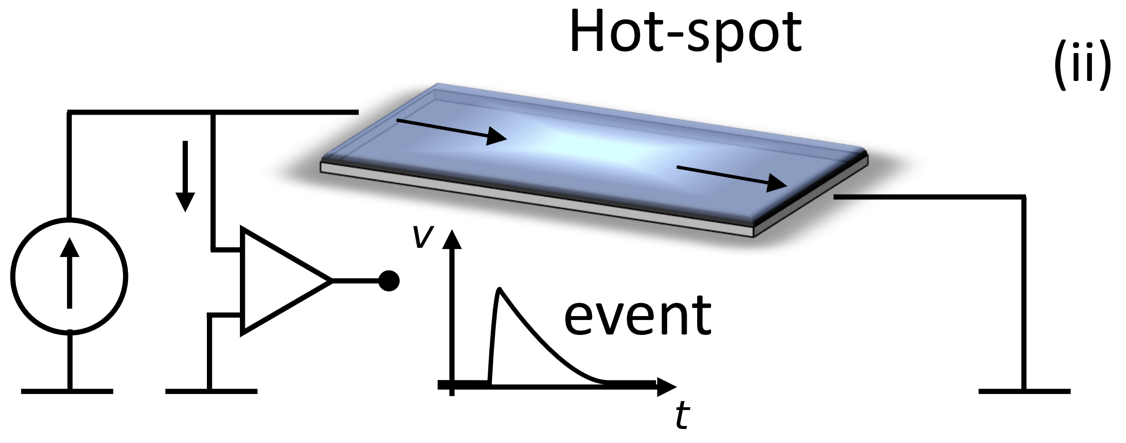
Biased close to the their critical current ($\sim \mu A$)

This restive region results in voltage pulses of amplitudes of $\sim$ mV and duration of $\sim 1 - 10$ ns



Cooled down below the superconducting transition temperature

The energy deposited by incident particles can cause the transition of a portion of the nanowire into the normal state



Hochberg et al, *Phys.Rev.Lett.* 123 (2019) 15, 151802

SUPERCONDUCTORS AS TARGET

SNSPDS: HOW LOW IN MASS CAN THEY GO?

SCATTERING

Dark Matter interacts with electrons or nucleons, imparting kinetic energy.

$$E_{\rm max} \approx v_{\rm max}^2 m_\chi \rightarrow E_{\rm th} \sim 10^{-6} m_\chi.$$

Sub-eV threshold → down to sub-MeV masses.

ABSORPTION

Dark Photons can be absorbed by the SNSPDs electron, transferring their entire mass-energy into the detector.

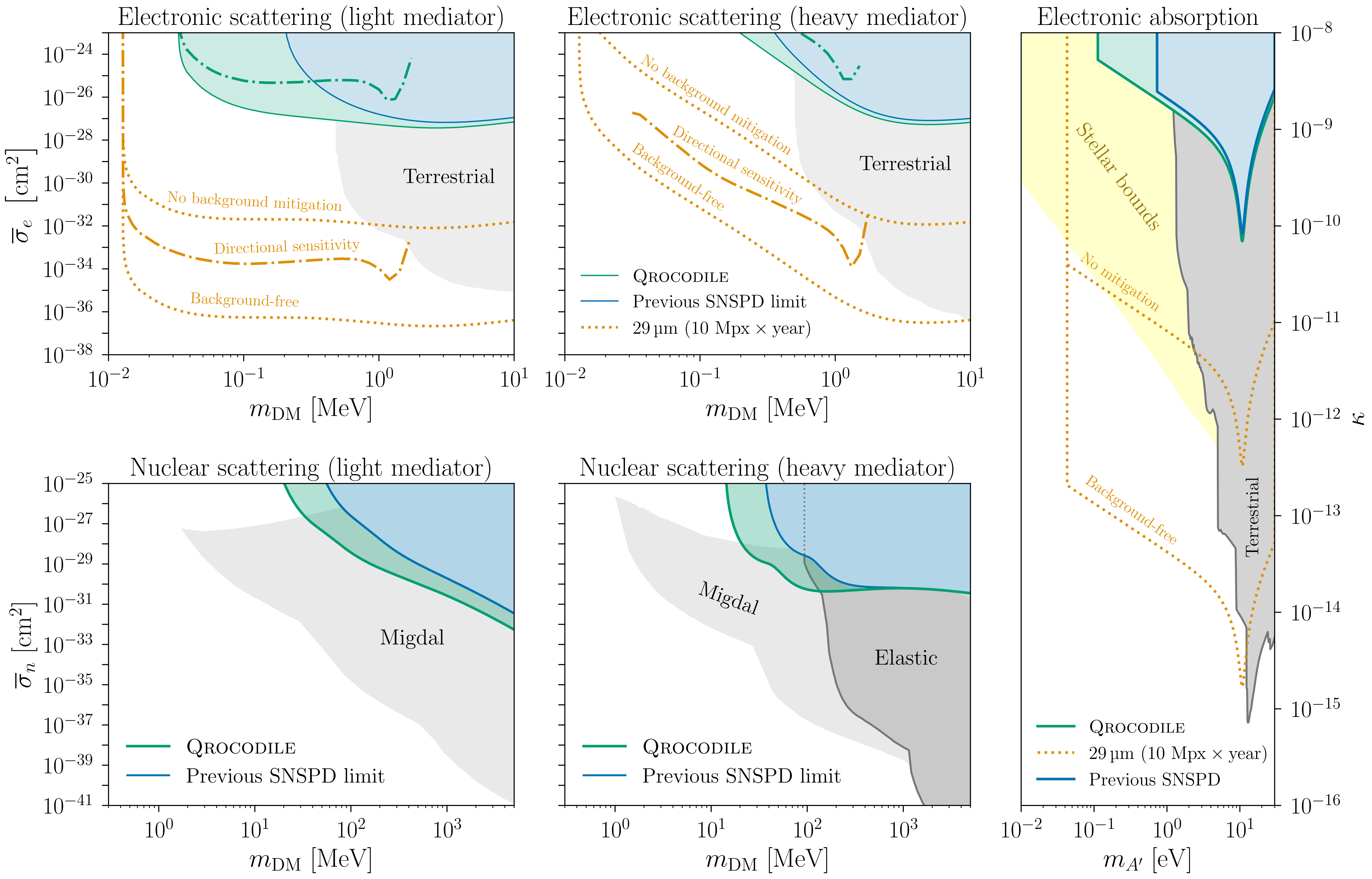
Sub-eV threshold → down to sub-eV masses.

SUPERCONDUCTORS AS TARGET

SNSPDS: ALREADY USED IN PROOF-OF-CONCEPTS EXPERIMENTS

Most recent results!

QROCODILE collaboration

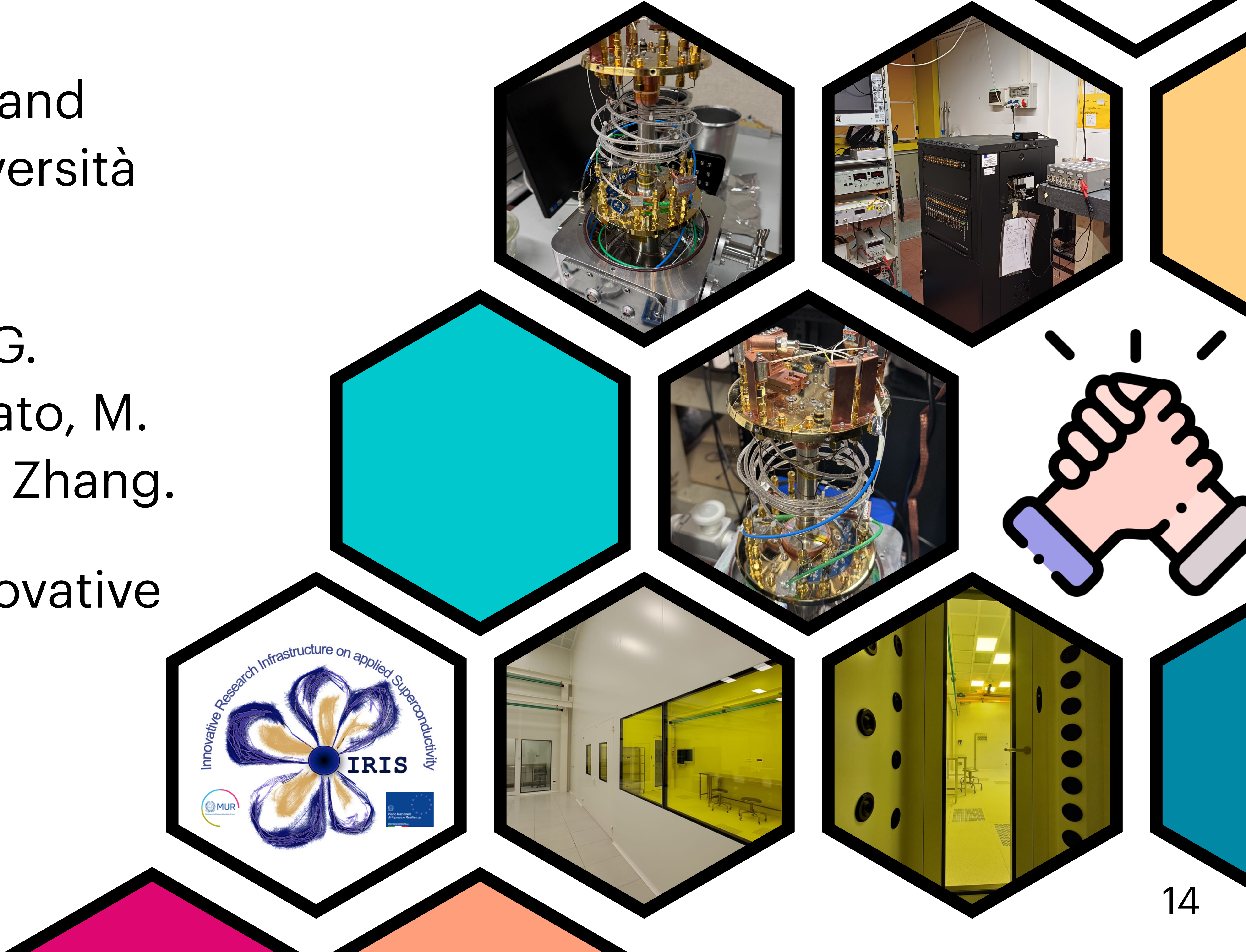


(Y. Hochberg,et al. Phys Rev. Lett. 123, 151802 (2019), Phys. Rev. D 107, 076015 (2023), Phys. Rev. D 106, 112005 (2022), QROCODILE collaboration Arxiv: 2412.16279)

SUPERCONDUCTORS AS TARGET

WHAT ARE WE DOING?

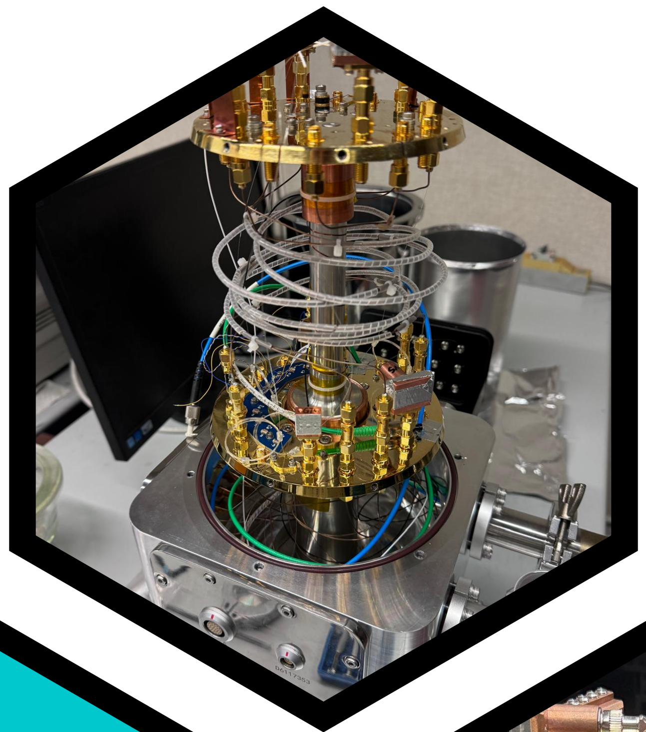
- Born from the **synergy** of the Dark Matter and superconducting Quantum groups @ Università degli studi di Napoli “Federico II”
  - C. Bruscino, R. Calabrese, P. Ercolano, G. Fiorillo, G. Grauso, G. Matteucci, L. Parlato, M. Peluso, G. Pepe, D. Rudik, D. Salvoni, CJ Zhang.
- The **final setup** will be housed in **IRIS** (Innovative Research Infrastructure for Applied Superconductivity) laboratory in Naples
  (L. Rossi et al., IEEE Transactions on Applied Superconductivity no. 9500309)

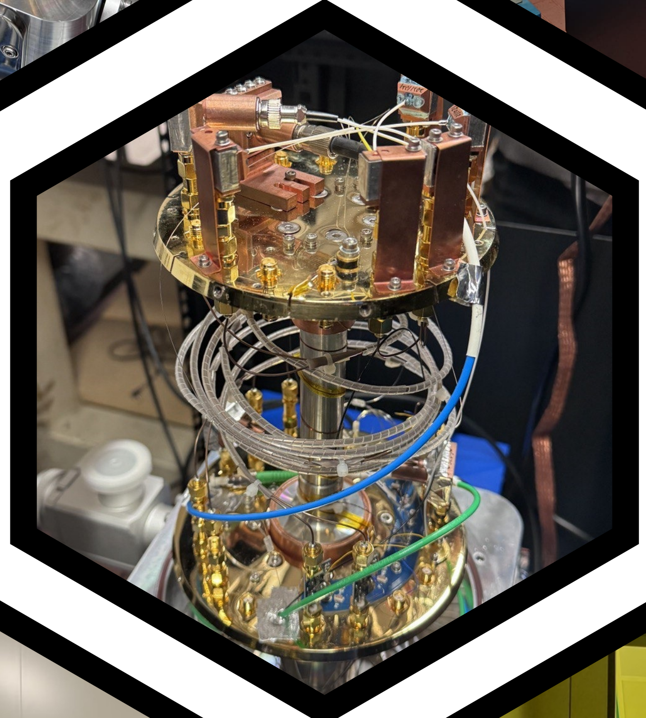


SUPERCONDUCTORS AS TARGET

WHAT ARE WE DOING?

- NbN nanowire from Photec with a mass of 4.9 ng
- 2000 s exposure
- 5×10^{-4} Hz dark count rate
- 0.8 eV energy threshold
- Efficiency: $\sim 90\,\%$

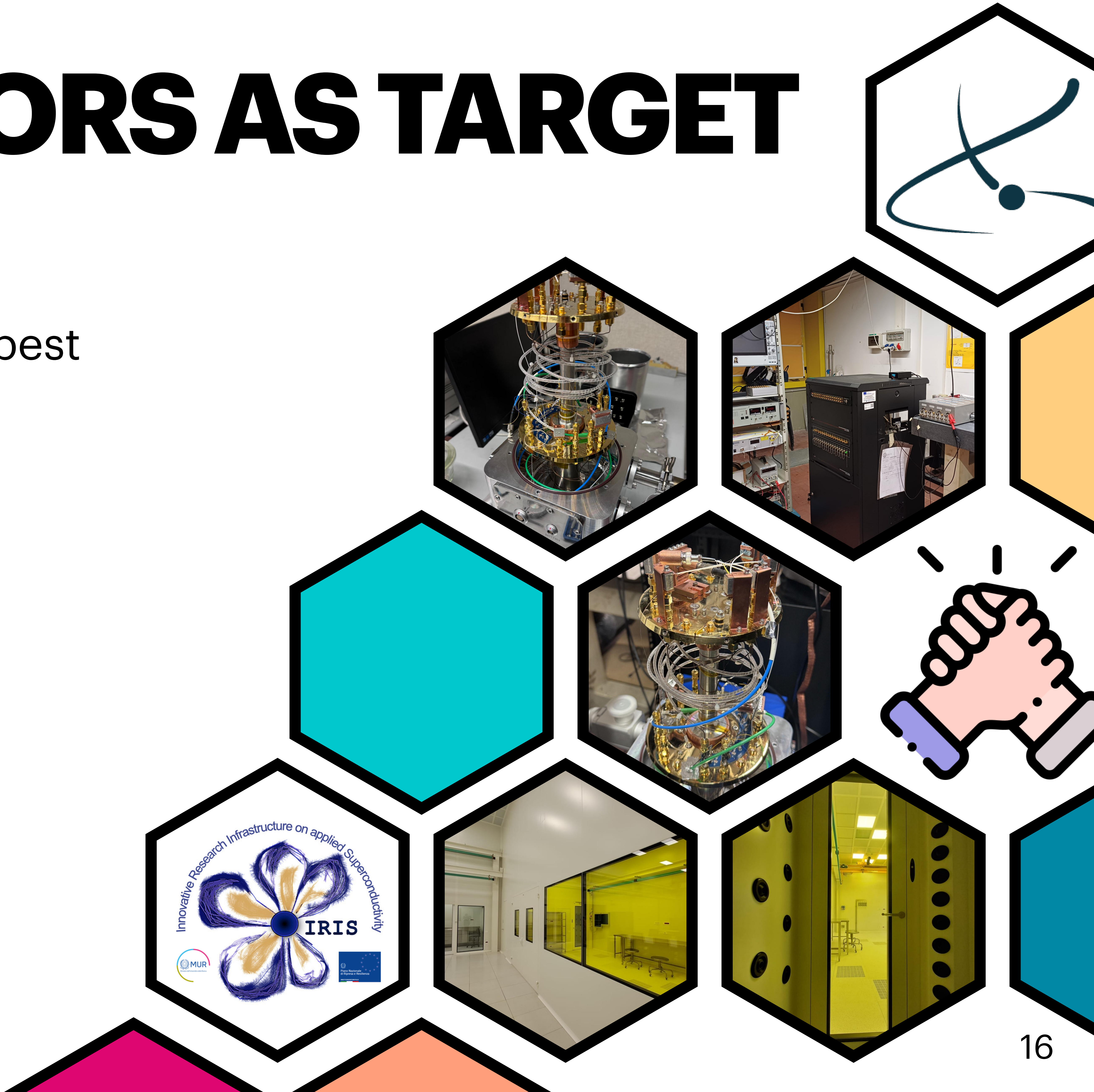




SUPERCONDUCTORS AS TARGET

WHAT ARE WE PLANNING?

- Test several alloy and select that with the best performances
- Test several working conditions
- Implement shield and veto system
- Scale up the system
- Perform a run with a high exposure



EXPECTED EVENT RATE

DARK MATTER SCATTERING: MEDIATORS

Assumption: χ interacts with Standard Model particles via the exchange of a mediator ϕ

We can write the cross-section as

$$\sigma_t = \bar{\sigma}_t \times \mathscr{F}_{med.}(q)^2$$

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We can write the cross-section as

$$\sigma_t = \overline{\sigma}_t \times \mathcal{F}_{med.}(q)^2$$

- σ_t: Cross-section of the process
- $\overline{\sigma}_t$: cross-section for $q = q_{ref}$
- $\mathcal{F}_{med.}(q)^2$: **Form factor:** It the dependence on q, the momentum transfer

$$\mathcal{F}_{med.}(q) = \frac{m_\phi^2 + q_{\rm ref}^2}{m_\phi^2 + q^2}$$

EXPECTED EVENT RATE

DARK MATTER - ELECTRON SCATTERING

Electrons are not free: they are bound in Cooper's pairs.

$$\overline{\sigma}_e^{bound} = \overline{\sigma}_e \times S(\vec{q}, \omega)$$

Where $\vec{q}$ is the momentum transfer, ω the energy deposit.

T. Trickle et al, JHEP 03, 036

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DARK MATTER - ELECTRON SCATTERING

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$$\overline{\sigma}_e^{bound} = \overline{\sigma}_e \times S(\vec{q}, \omega)$$

- $\overline{\sigma}_e^{bound}$: Cross-section of the process
- $\overline{\sigma}_e$: Free electron cross-section
- $S(\vec{q}, \omega)$: Dynamical structure function: Describes the response of the system to external perturbation

Where $\vec{q}$ is the momentum transfer, ω the energy deposit.

T. Trickle et al, JHEP 03, 036

EXPECTED EVENT RATE

DARK MATTER - ELECTRON SCATTERING

The Dynamical structure function is determined by the available final states of the target system

$$S(\vec{q},\omega) = \frac{2\pi}{V}\sum_f \left| \langle f | \hat{n}(-\vec{q}) | 0 \rangle \right|^2 \delta(\omega - E_f + E_0) = 2\,\mathrm{Im}\left[-\frac{q^2}{e^2}\frac{1}{\varepsilon(\vec{q},\omega)} \right]$$

Where $\varepsilon(\vec{q},\omega)$ is the dielectric function, defined as the linear response of the system.

T. Trickle et al, JHEP 03, 036

EXPECTED EVENT RATE

DARK MATTER - ELECTRON SCATTERING

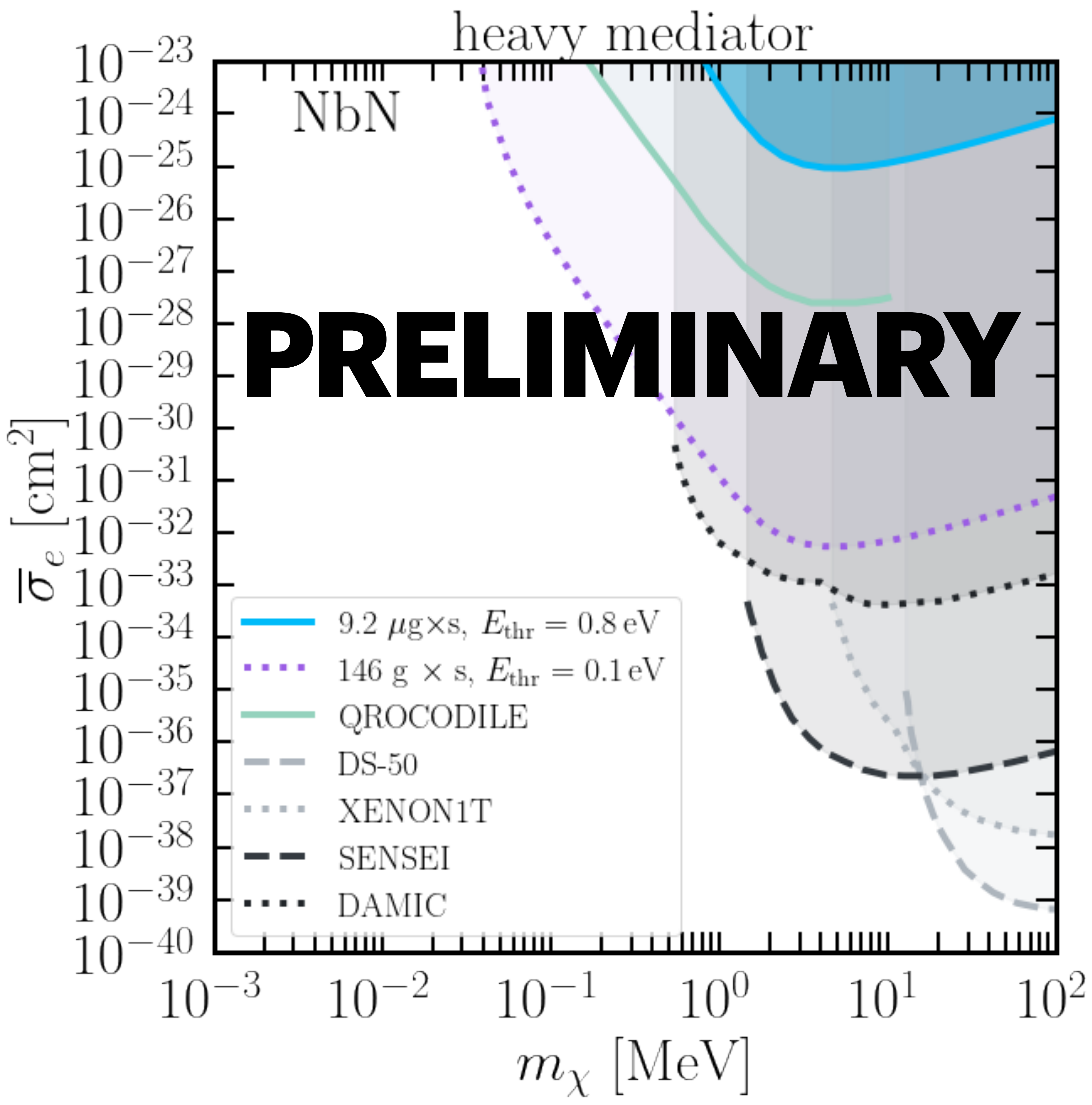
The event rate per unit detector mass is

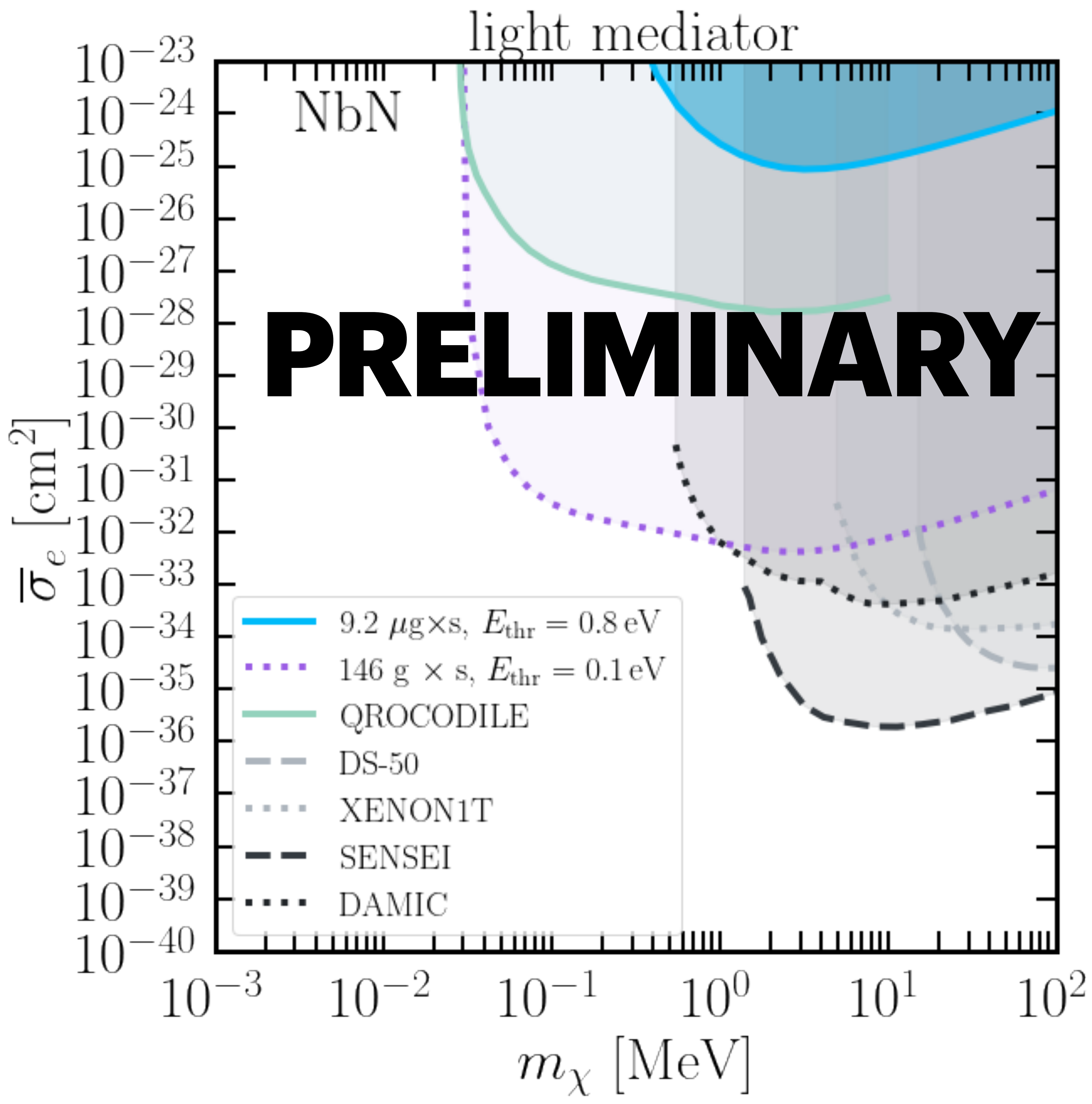
$$R = \frac{\pi n_\chi \overline{\sigma}_e}{\mu^2_{e-\chi}\rho_t (2\pi)^3} \times \int d\vec{v}_\chi \, d\vec{q} \, d\omega \, f_{MB}(\vec{v}_\chi) \, \mathcal{F}^2_{med.}(|\vec{q}|) \, S(\vec{q}, \omega) \, \delta(\omega - \omega_{\vec{q}})$$

- f_{MB} is the Dark Matter velocity distribution
- $\omega_q = \vec{q} \cdot \vec{v}_\chi - q^2/2m_{DM}$
- $q_{ref} = \alpha m_e$

EXPECTED EVENT RATE

DARK MATTER - ELECTRON SCATTERING





95% C.L. with Feldman Cousins method

EXPECTED EVENT RATE

DARK MATTER - NUCLEON SCATTERING

- **Cooper pair dissociation:** Nuclear scattering in the SNSPDs or its substrate produce phonon that can disrupt Cooper pairs
- **Small kinetic energies:** we can treat the interaction as Coherent
- **Assumption:** χ couple the same to neutron and proton
- **Reference cross-section:** $q_{\text{ref}} = m_\chi < v_\chi >$

EXPECTED EVENT RATE

DARK MATTER - NUCLEON SCATTERING

The event rate per unit detector mass is

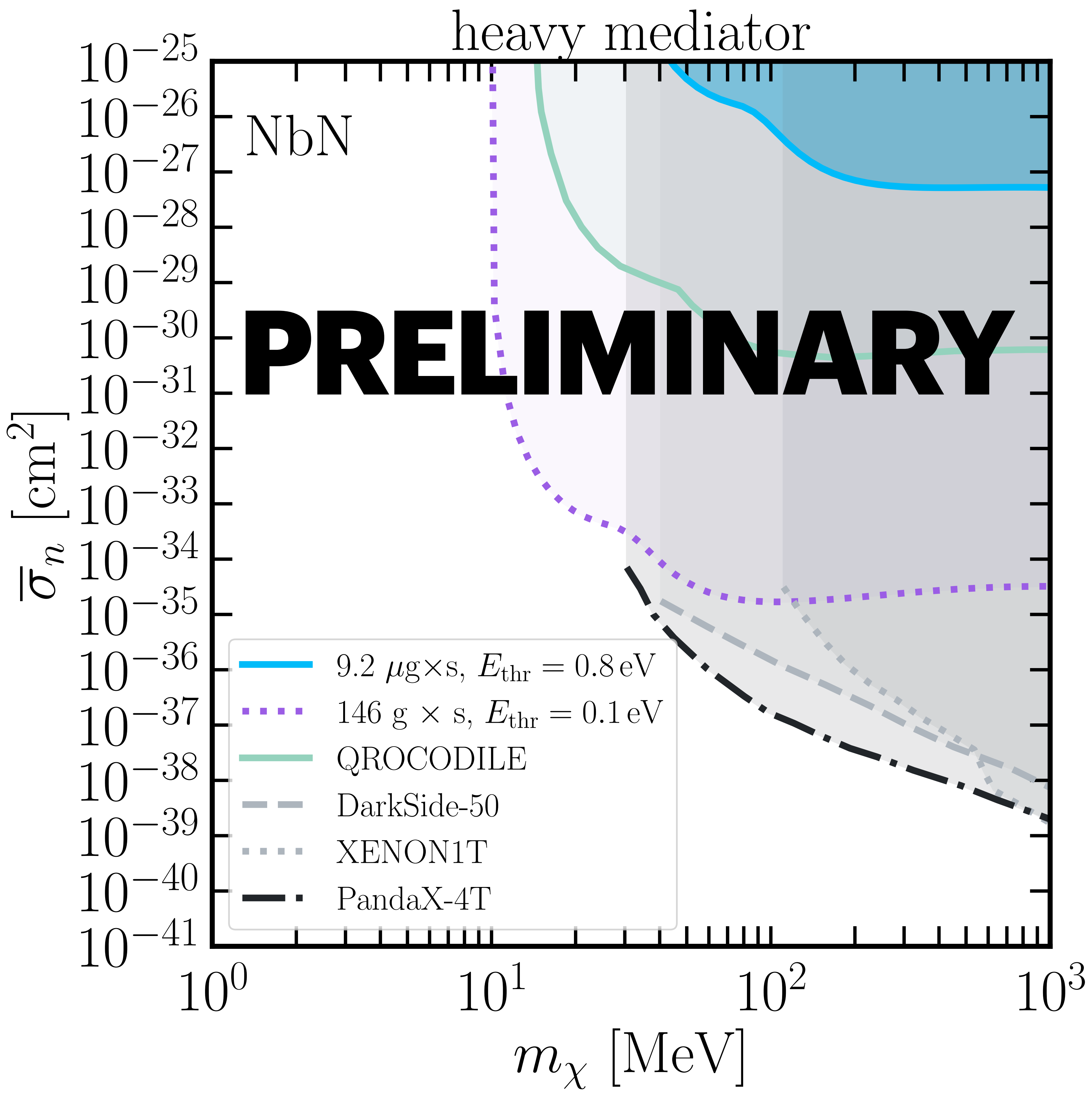
$$R = \frac{n_{DM}\bar{\sigma}_n}{2\mu_{DM,n}^2 \sum_i A_i} \sum_i \int d\omega A_i^3 \mathcal{F}_{med}^2(\vec{q})\, \mathcal{F}_i^2(\vec{q})\, \eta(v_{min}) \Big|_{q=\sqrt{2m_i\omega}}$$

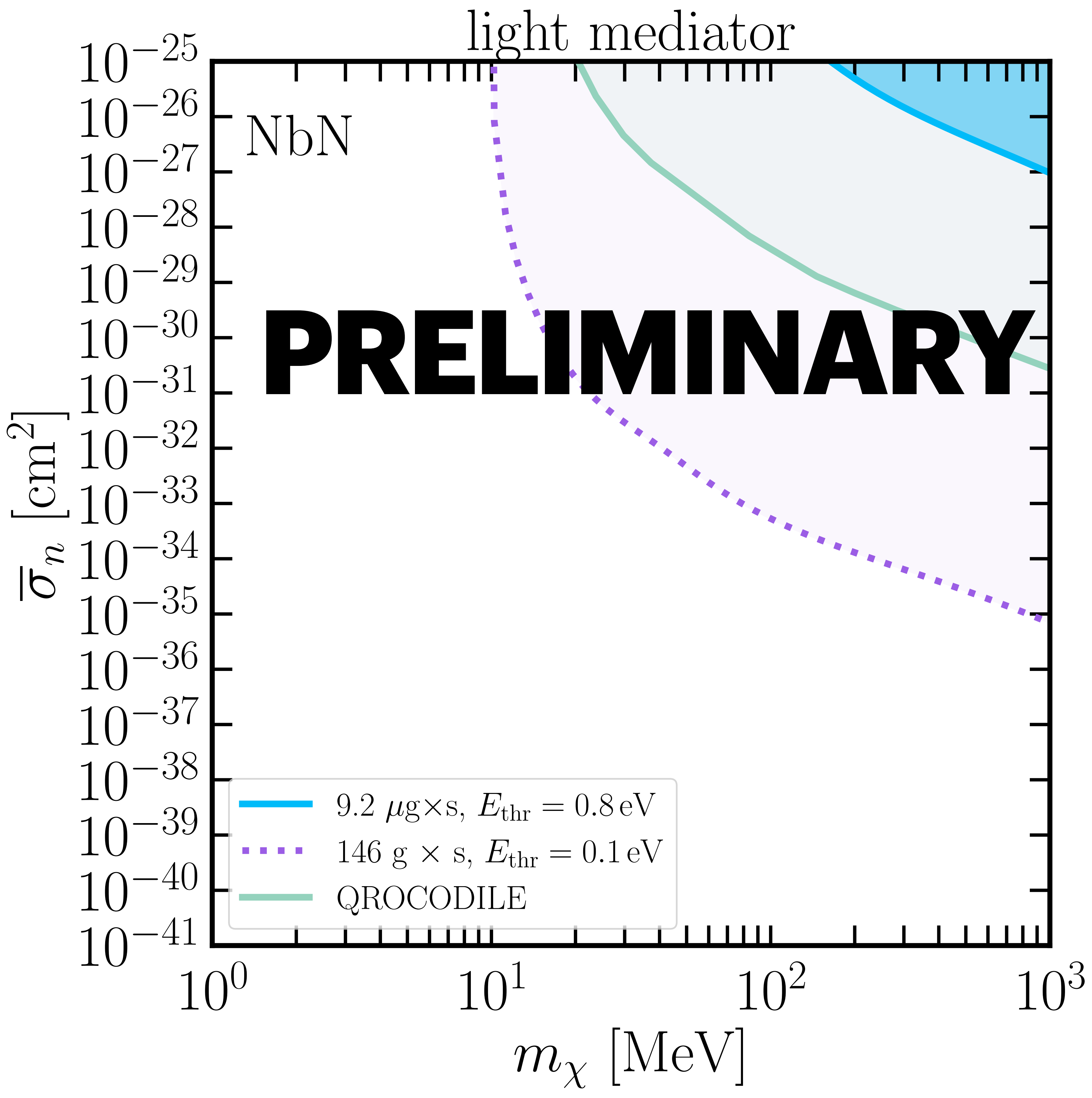
- A_i is the atomic mass number
- $\mathcal{F}_i^2(\vec{q})$ is the Helm nuclear form factor
- $\eta(v_{min}) = \int d\vec{v}\, v\, f_{MB}(\vec{v})\, \Theta(v - v_{min})$

T. Trickle et al, JHEP 03 (2020) 036

EXPECTED EVENT RATE

DARK MATTER - NUCLEON SCATTERING





95% C.L. with Feldman Cousins method

EXPECTED EVENT RATE

DARK PHOTON ABSORPTION

Minimal Dark Sector model: introduce an additional $U(1)_V$

Kinetic mixing (κ) of the hypercharge field strength $F_{\mu\nu}$ with the field strength $V_{\mu\nu}$ of $U(1)_V$ links the Standard Model to the new physics sector.

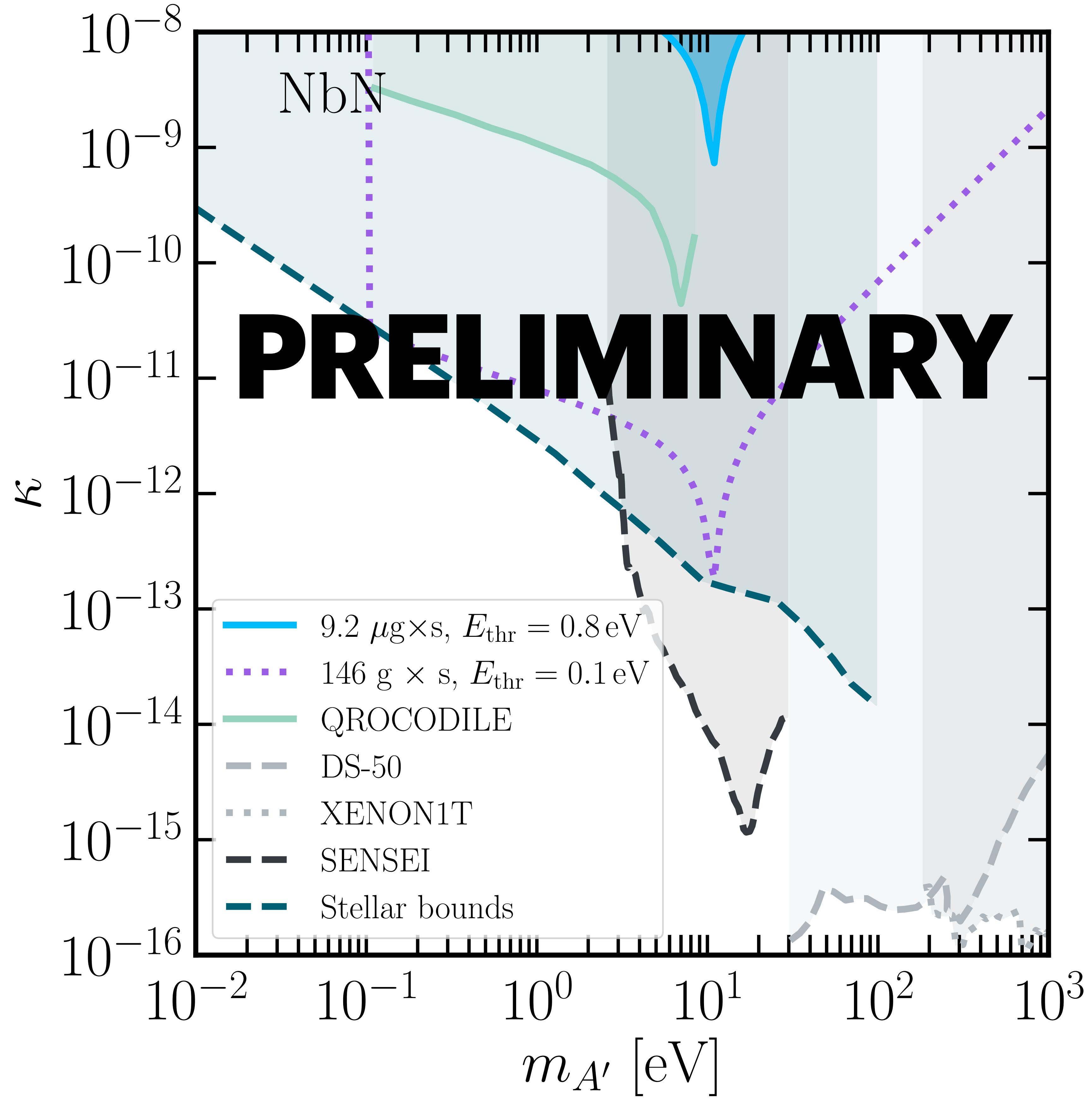
$$\mathscr{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}$$

In this case, the absorption rate is

$$R = \frac{n_\chi}{\rho_t}\int d\vec{v}_\chi f_\chi^A(\vec{v}_\chi, \kappa)\Gamma_A \qquad \text{where } \Gamma_A = m_{\gamma'}\kappa^2 e^2 p_{\gamma'}^{-2}\frac{S(\vec{p}_{\gamma'}, m_{\gamma'})}{2}$$

EXPECTED EVENT RATE

DARK PHOTON ABSORPTION



95% C.L. with Feldman Cousins method

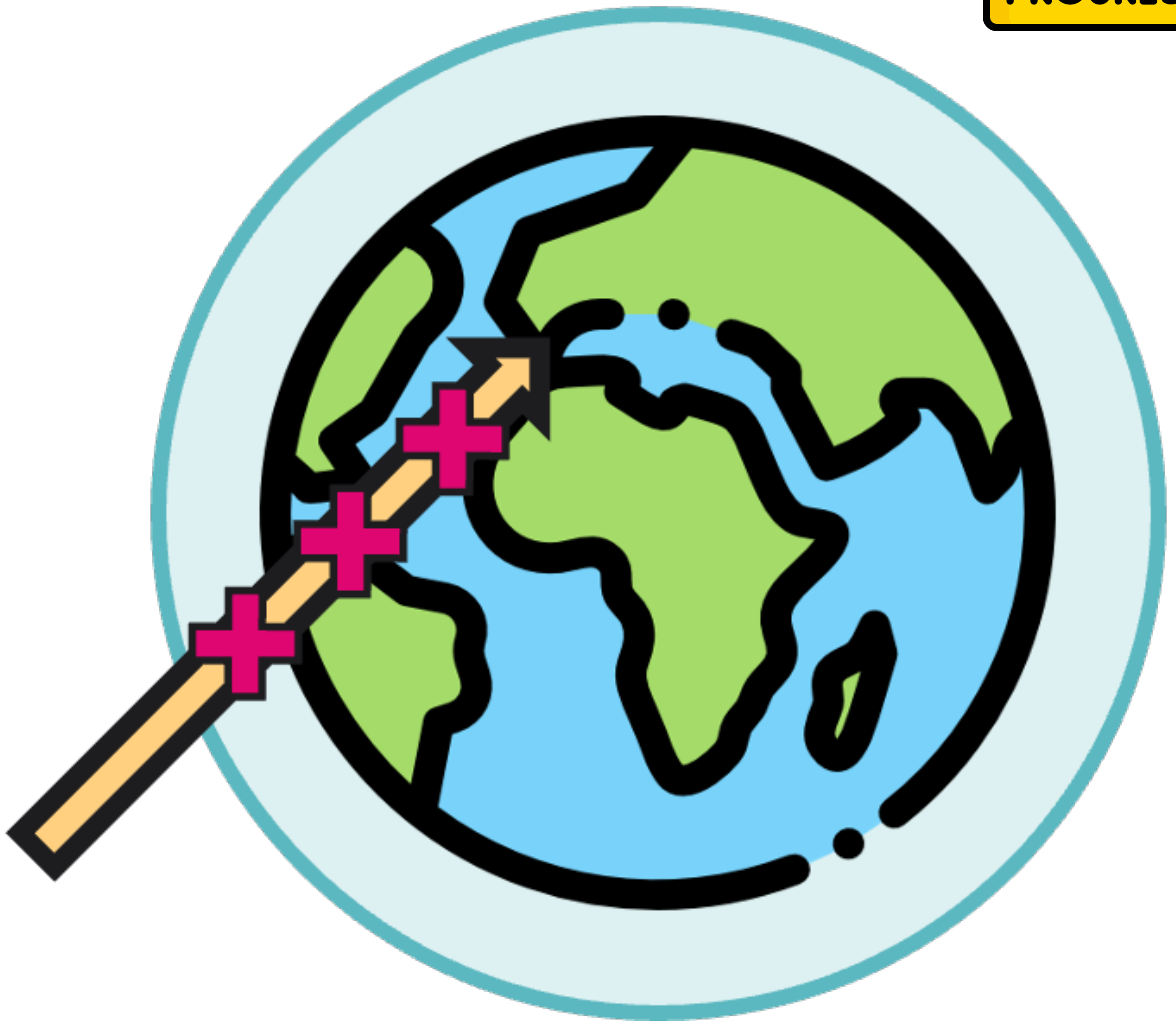
WORK IN PROGRESS

STAY TUNED!

We are finalizing the results of the run!

Many improvements will be show in the paper.

For instance, we will include the effects of **Earth and atmosphere attenuation** on the flux!

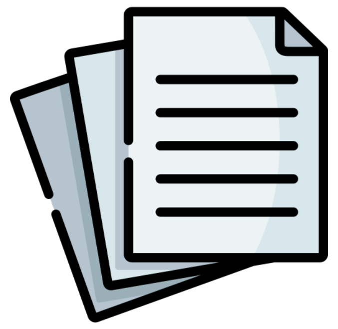


CONCLUSIONS

EXPANDING THE SEARCH

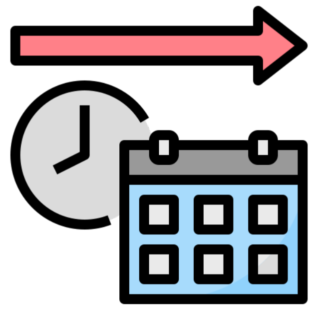
Why superconductors ?

- **Superconducting band gap: e**xceptionally sensitive to small energy depositions
  - Access to unexplored Dark Matter masses



Stay tuned!

- Finalizing our paper



Future plans

- Add shielding and veto systems
- Study of different alloys and configurations
- Final expansion to a large array of SNSPDs.