The status of light dark matter

Jia Liu (刘佳)
Peking University

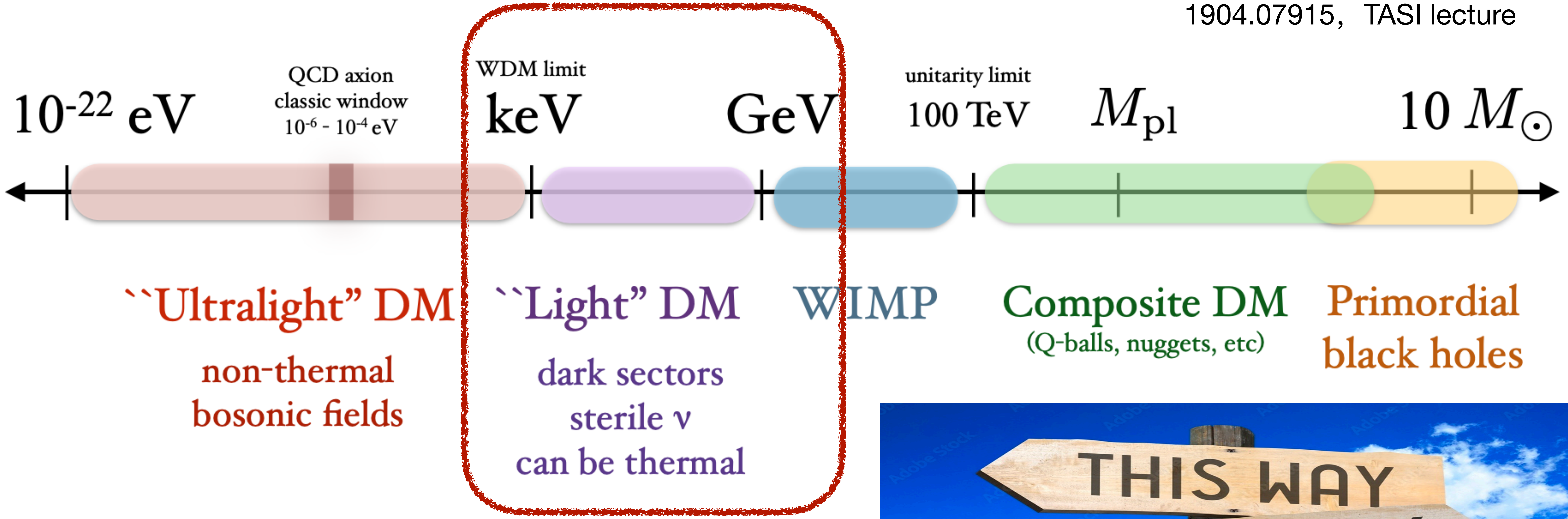
第二届地下和空间粒子物理与宇宙物理前沿问题讨论会
2023-05-10

Outline

- Models
  - Production
  - Interactions
- Detection
  - Direct Detection
  - Intensity Frontier detection
  - Astrophysics detection

The dark matter candidate models

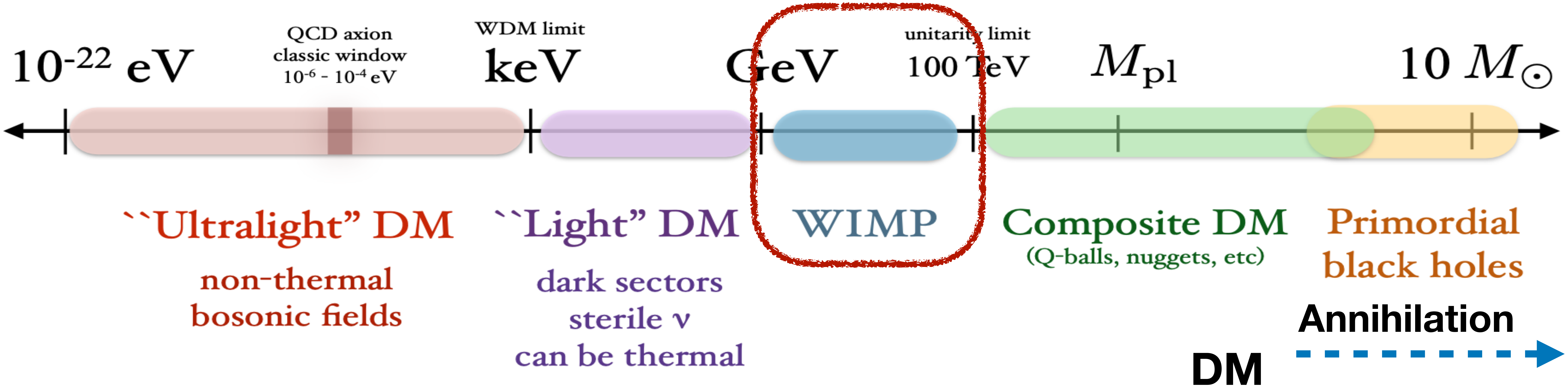
1904.07915，TASI lecture



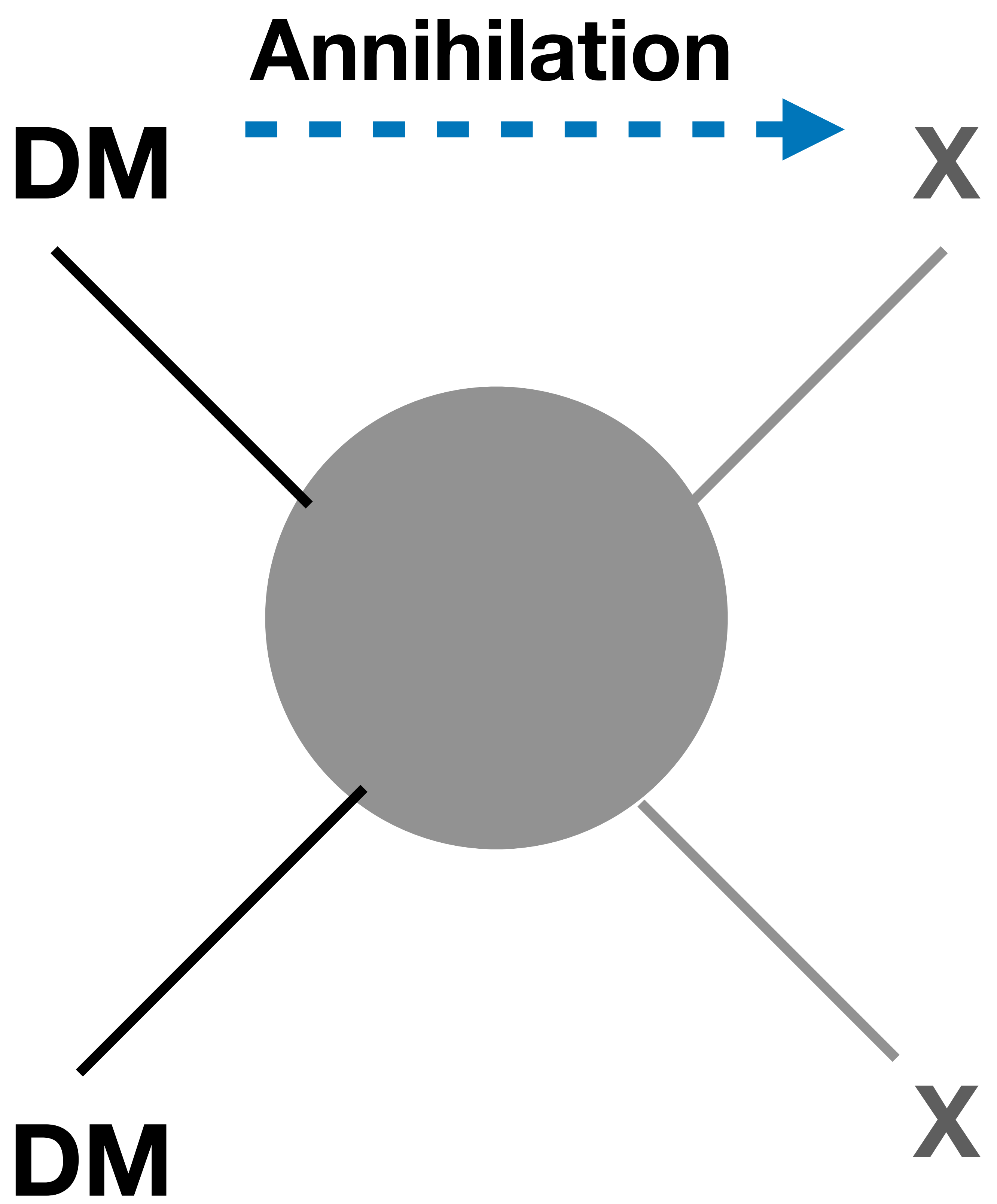
- In this talk:
  - We focus on the light DM

HEP at a cross-road: explore all directions!

Start with Weakly Interacting Massive Particles



- WIMP DM is a massive elementary particle
- WIMP has an electroweak-scale coupling
  - WIMP starts with thermal distribution
  - Relic abundance is determined by freeze-out mechanism



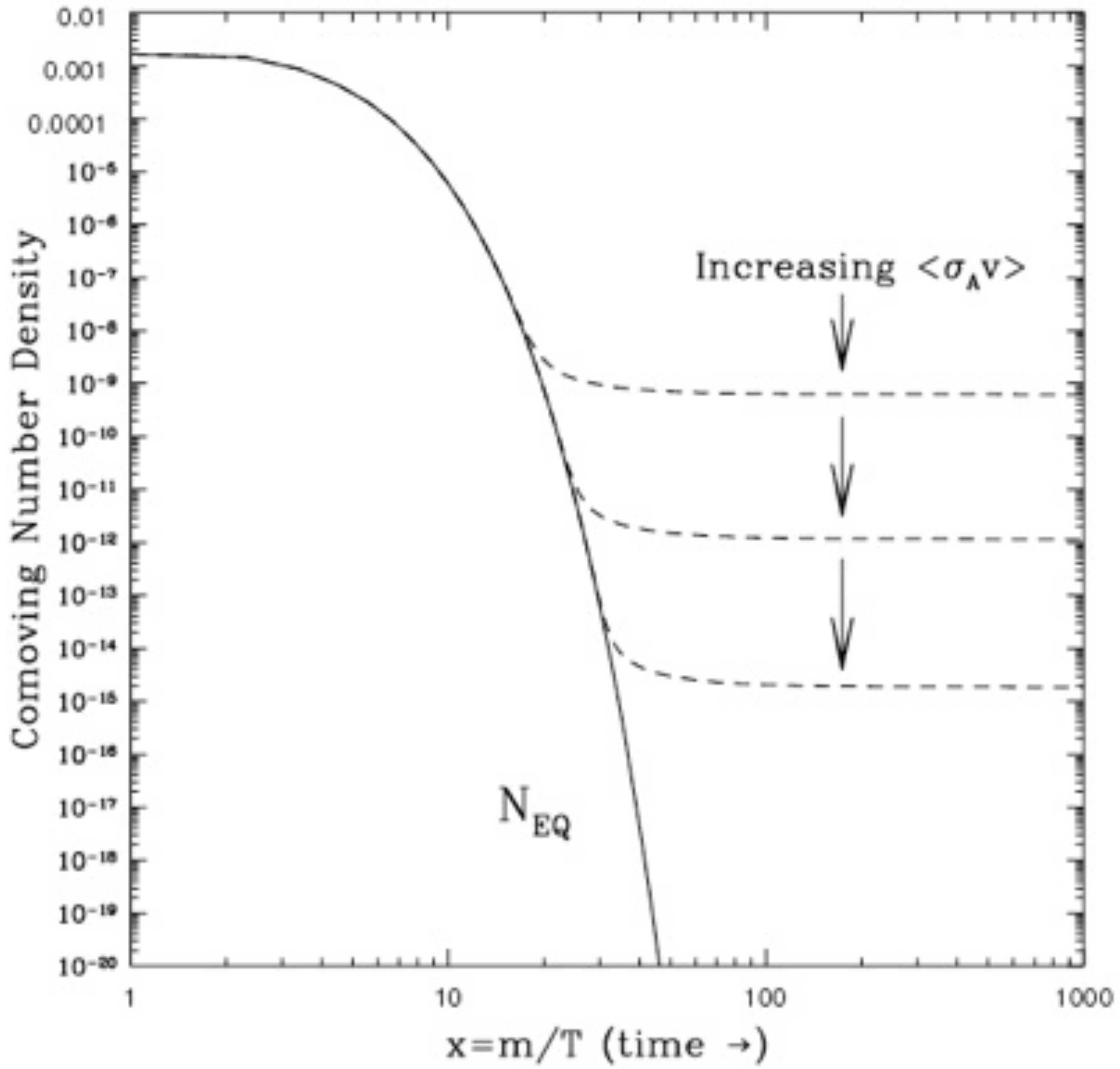
The freeze-out of WIMP DM

- Thermal cross-section

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- DM Annihilation cross-section

$$\langle \sigma v \rangle \sim \frac{g^4}{m_{\mathrm{DM}}^2} \Rightarrow g \sim \sqrt{\frac{m_{\mathrm{DM}}}{10\mathrm{TeV}}}$$



Jungman *et al* hep-ph/9506380

This is called WIMP miracle!

The freeze-out of WIMP DM

- Thermal cross-section

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- DM Annihilation cross-section

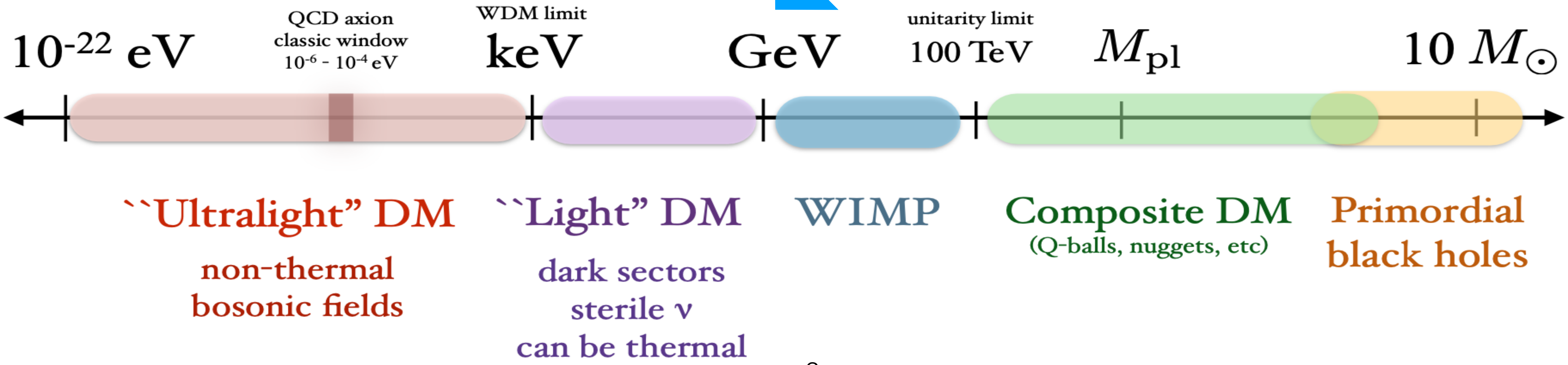
$$\langle \sigma v \rangle \sim \frac{g^4}{m_{\mathrm{DM}}^2} \Rightarrow g \sim \sqrt{\frac{m_{\mathrm{DM}}}{10\mathrm{TeV}}}$$

- WIMP lower mass bound at GeV

- Heavy neutral lepton L_0, annihilate through Z/W mediation

$$\langle \sigma v \rangle \sim \mathcal{O}(1) \times G_F^2 m_{\mathrm{DM}}^2$$

B. W. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977)



Light dark matter models

- Needs light mediator/portal particles: X
- X: dark photon, dark scalar,

Boehm and Fayet [hep-ph/0305261]

Pospelov et al [0711.4866]

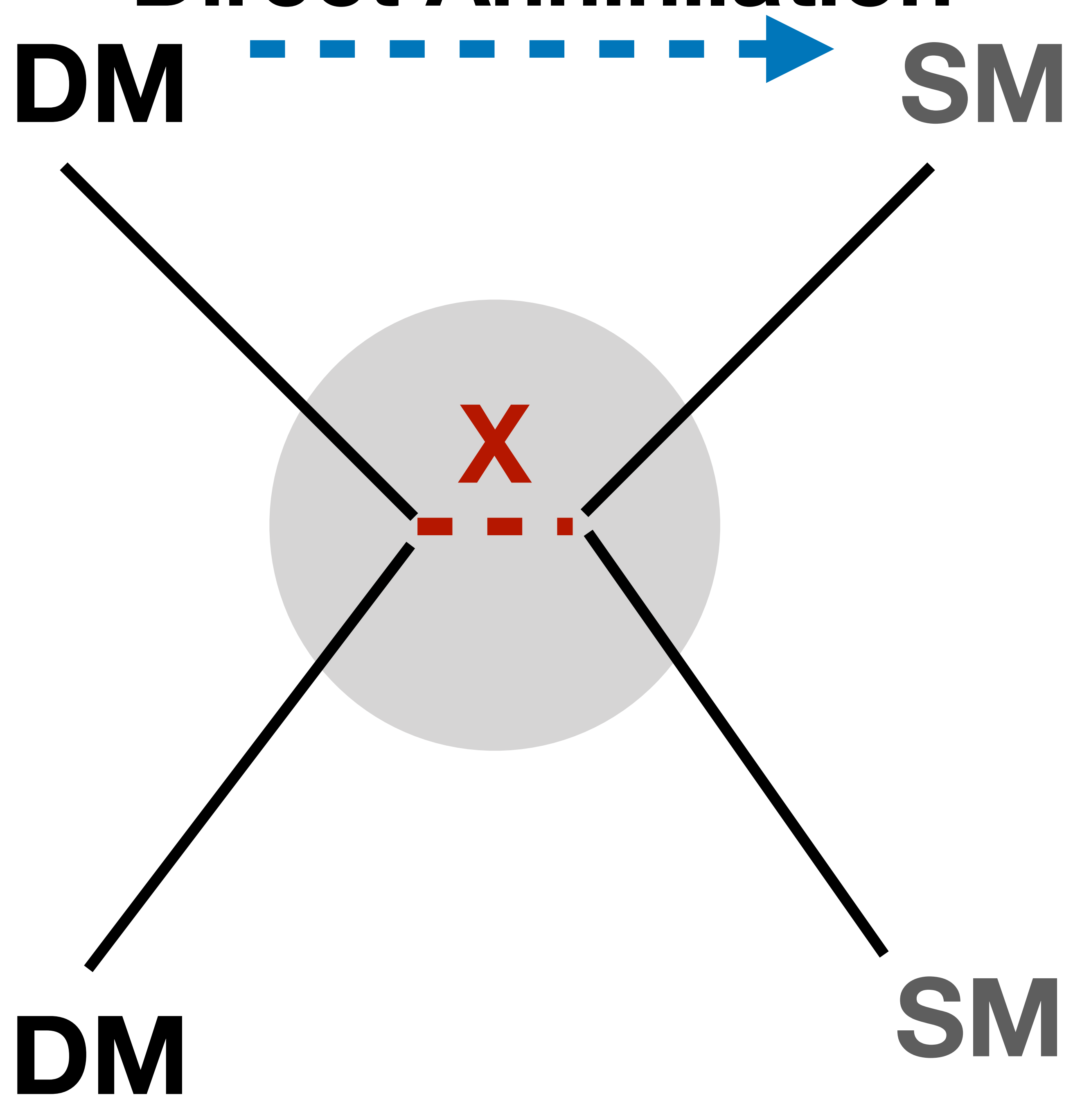
$$\langle \sigma v \rangle_L \sim \frac{g_{DM}^2 g_{SM}^2}{4\pi} \frac{1}{m_{\rm DM}^2}$$

$$\langle \sigma v \rangle_H \sim \frac{g_{DM}^2 g_{SM}^2}{4\pi} \frac{m_{DM}^2}{m_{\rm X}^4}$$

$g_{DM} g_{SM}$

can not be too small

Direct Annihilation



Light dark matter models

- Needs light mediator/portal particles: X

Boehm and Fayet [hep-ph/0305261]

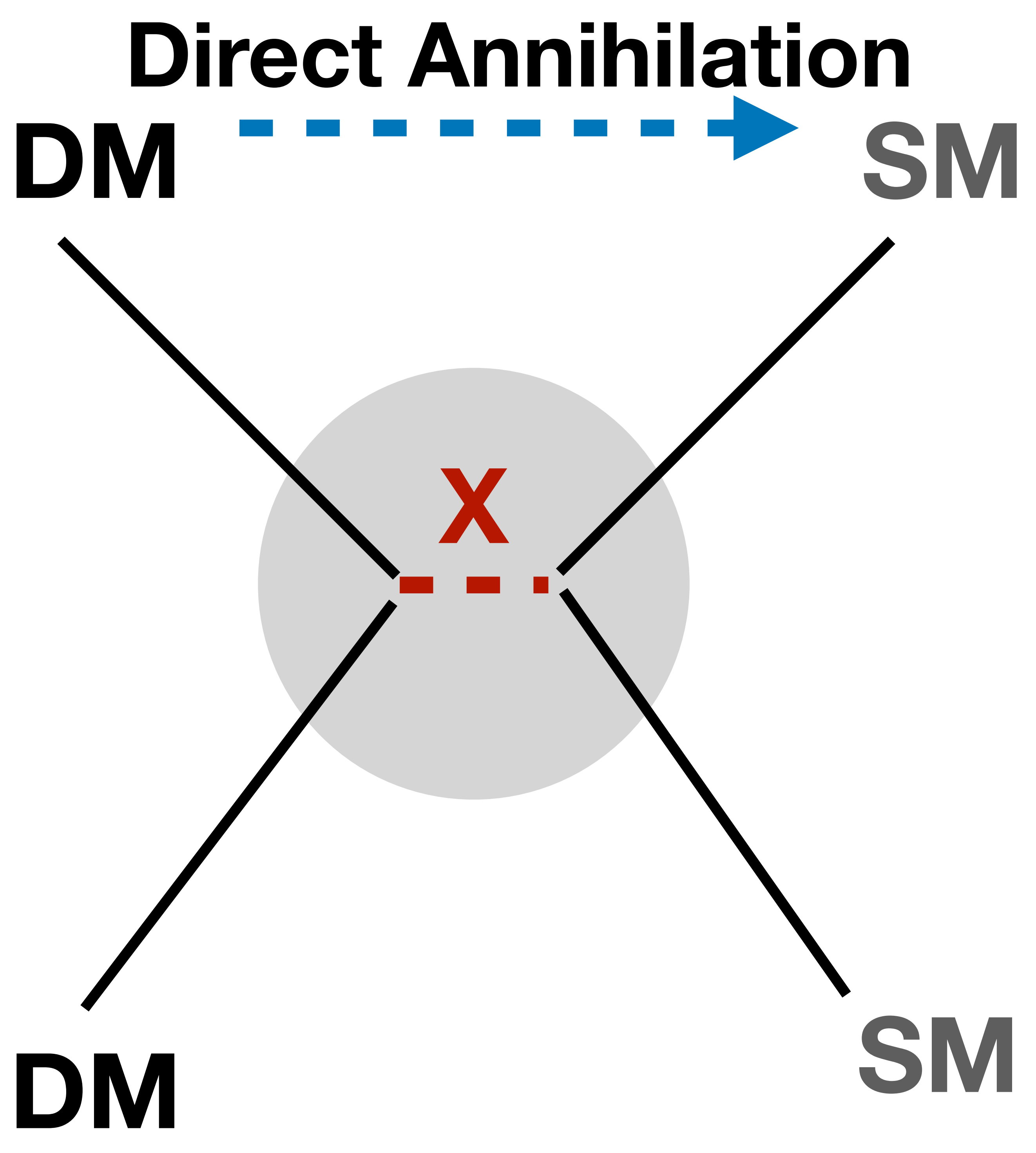
Pospelov et al [0711.4866]

- X: dark photon, dark scalar,

$$\langle \sigma v \rangle_L \sim \frac{g_{DM}^2 g_{SM}^2}{4\pi} \frac{1}{m_{\rm DM}^2}$$

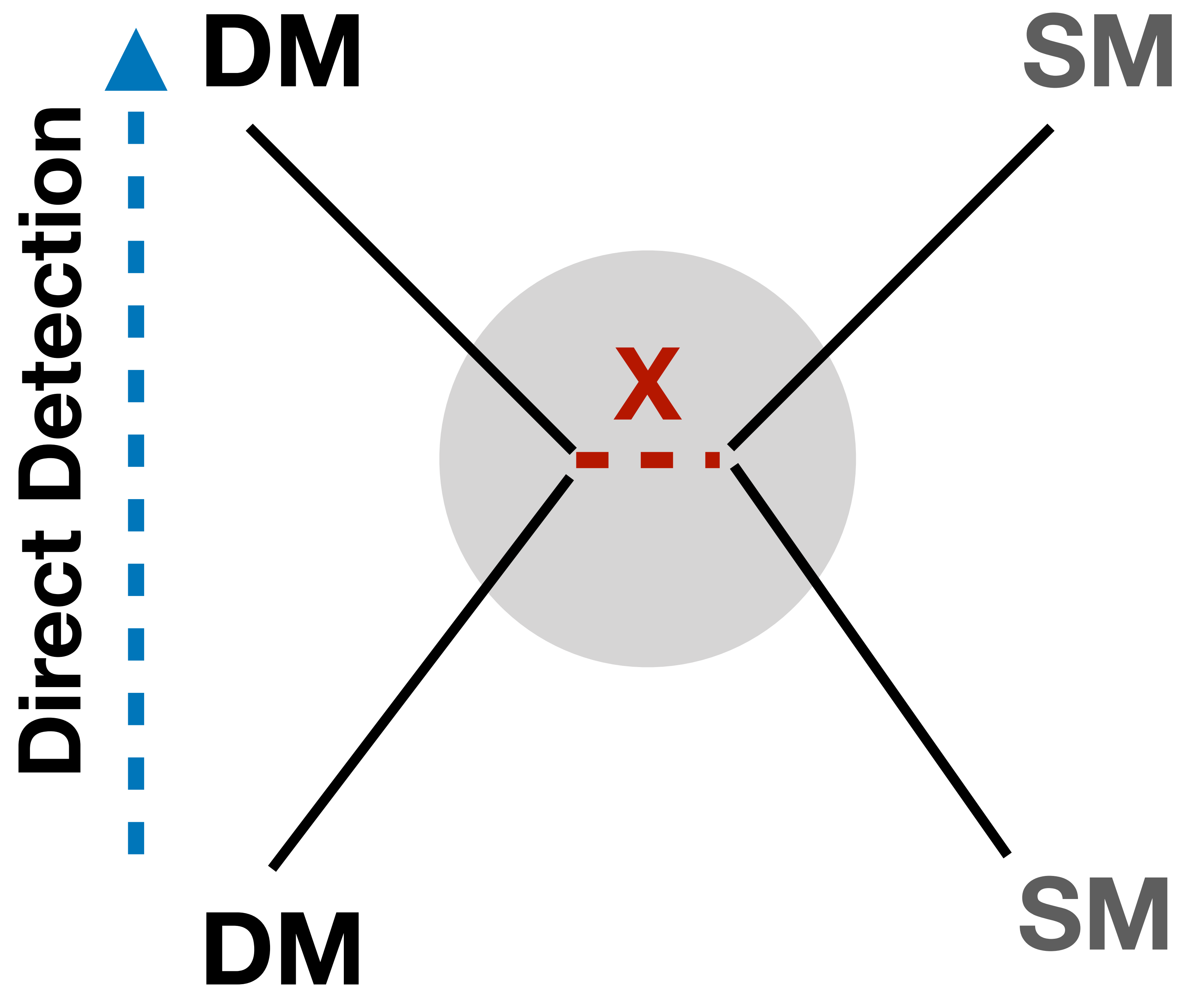
$$\langle \sigma v \rangle_H \sim \frac{g_{DM}^2 g_{SM}^2}{4\pi} \frac{m_{DM}^2}{m_{\rm X}^4}$$

$g_{DM} g_{SM}$
can not be too small



$$F_L \sim \frac{1}{q^2}$$

$$F_H \sim 1$$



Light dark matter models

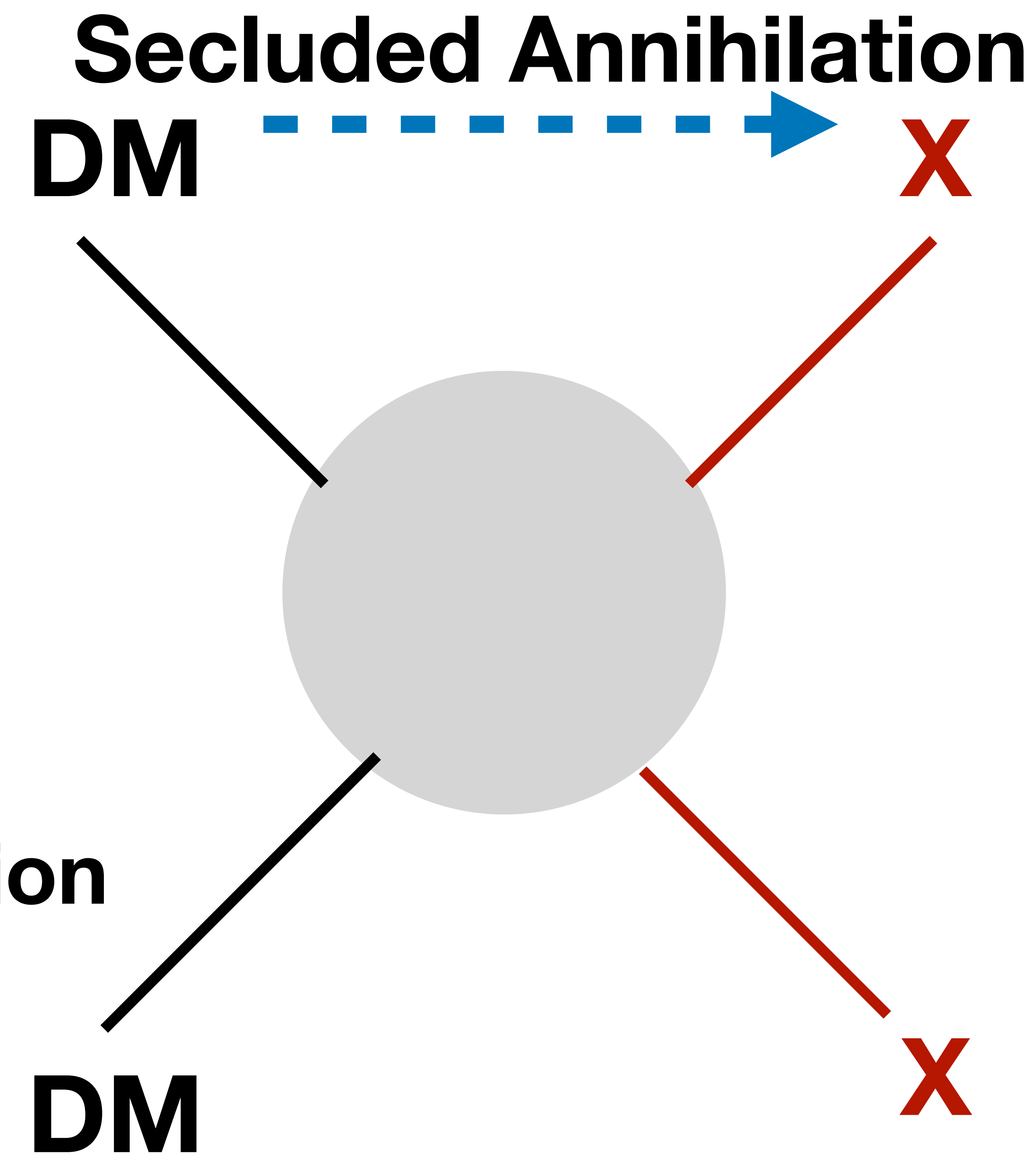
- Needs light mediator/portal particles: X
- X: dark photon, dark scalar,

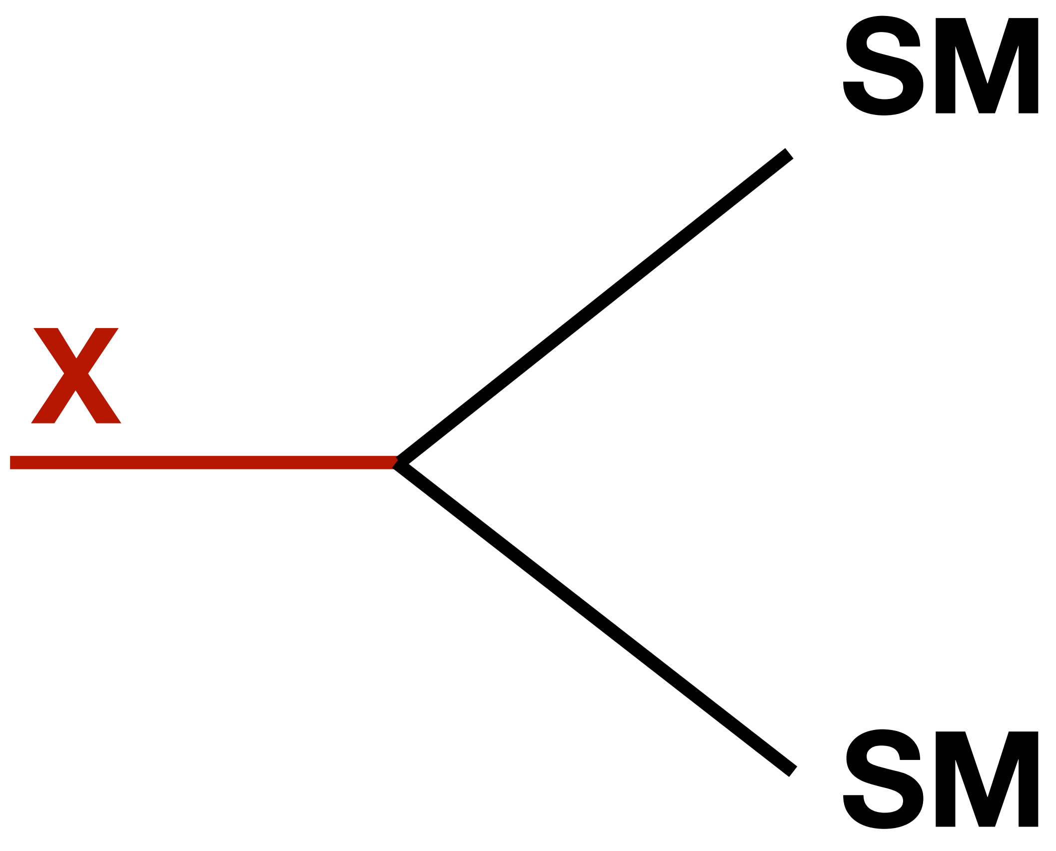
Boehm and Fayet [hep-ph/0305261]
Pospelov et al [0711.4866]

$$\langle \sigma v \rangle \sim \frac{g_{DM}^4}{4\pi} \frac{1}{m_{\rm DM}^2}$$

$$g_{SM} \gtrsim 10^{-10}$$

to ensure thermalization





Search for X mediator directly
Long-lived particle X searches

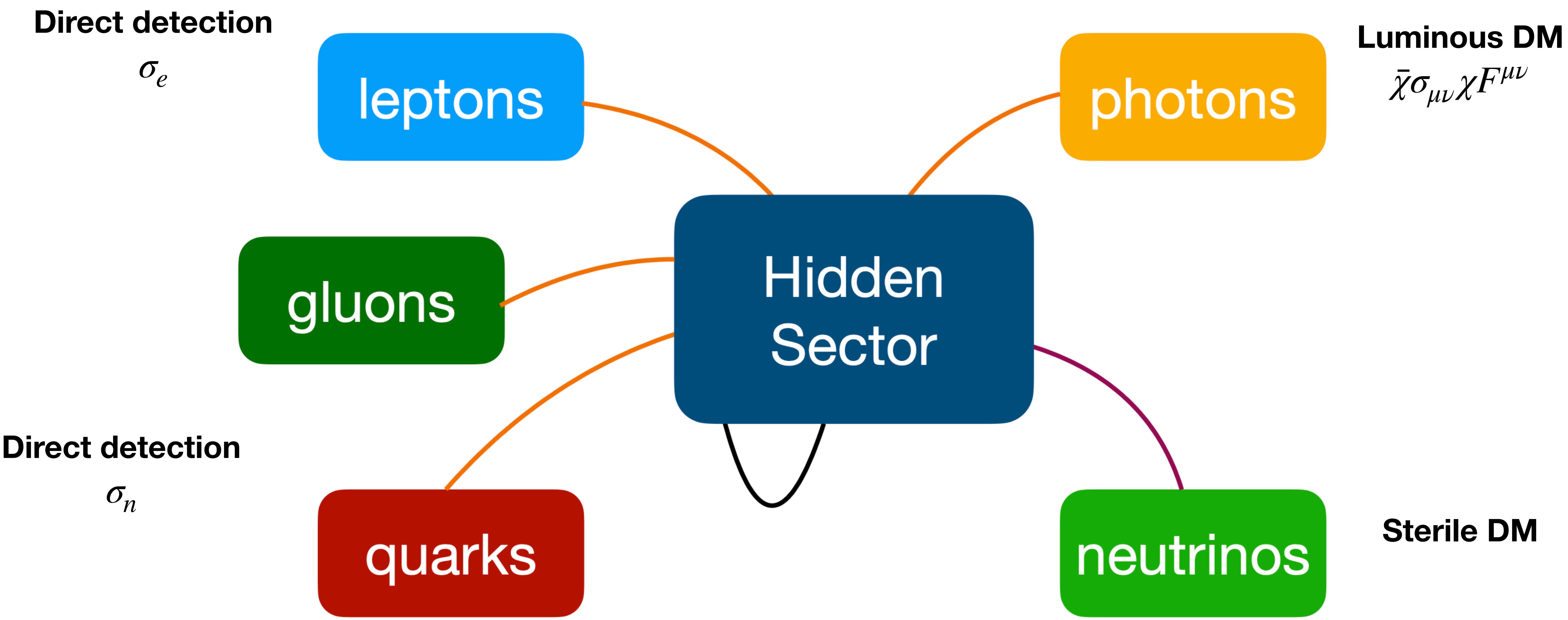
Light dark matter models

- Other cosmic production: non-minimal misalignment, cosmic strings, inflationary fluctuations

  - dark scalar, dark photon dark matter

  - Direct detection of DM absorption

Light dark matter interactions

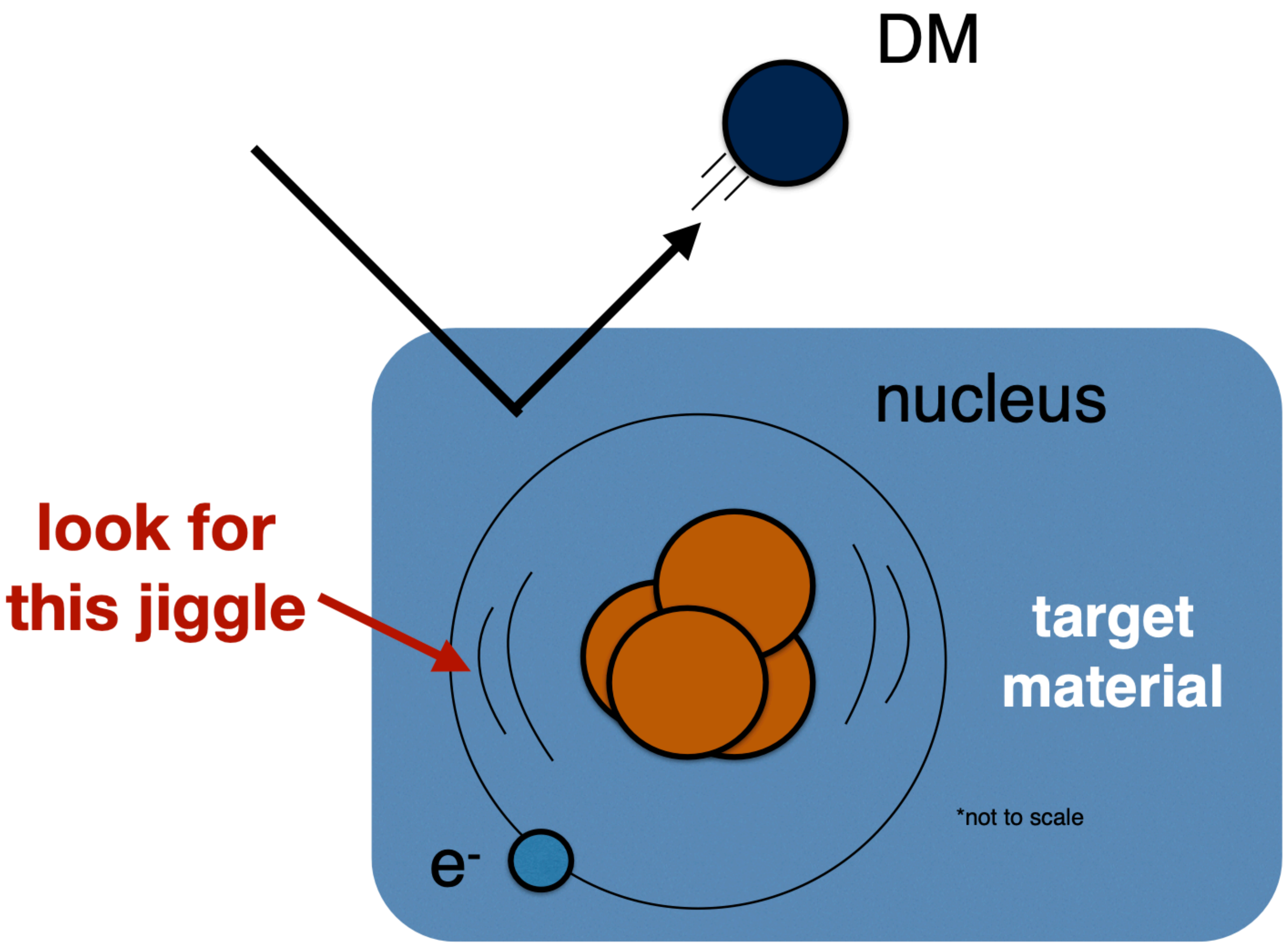


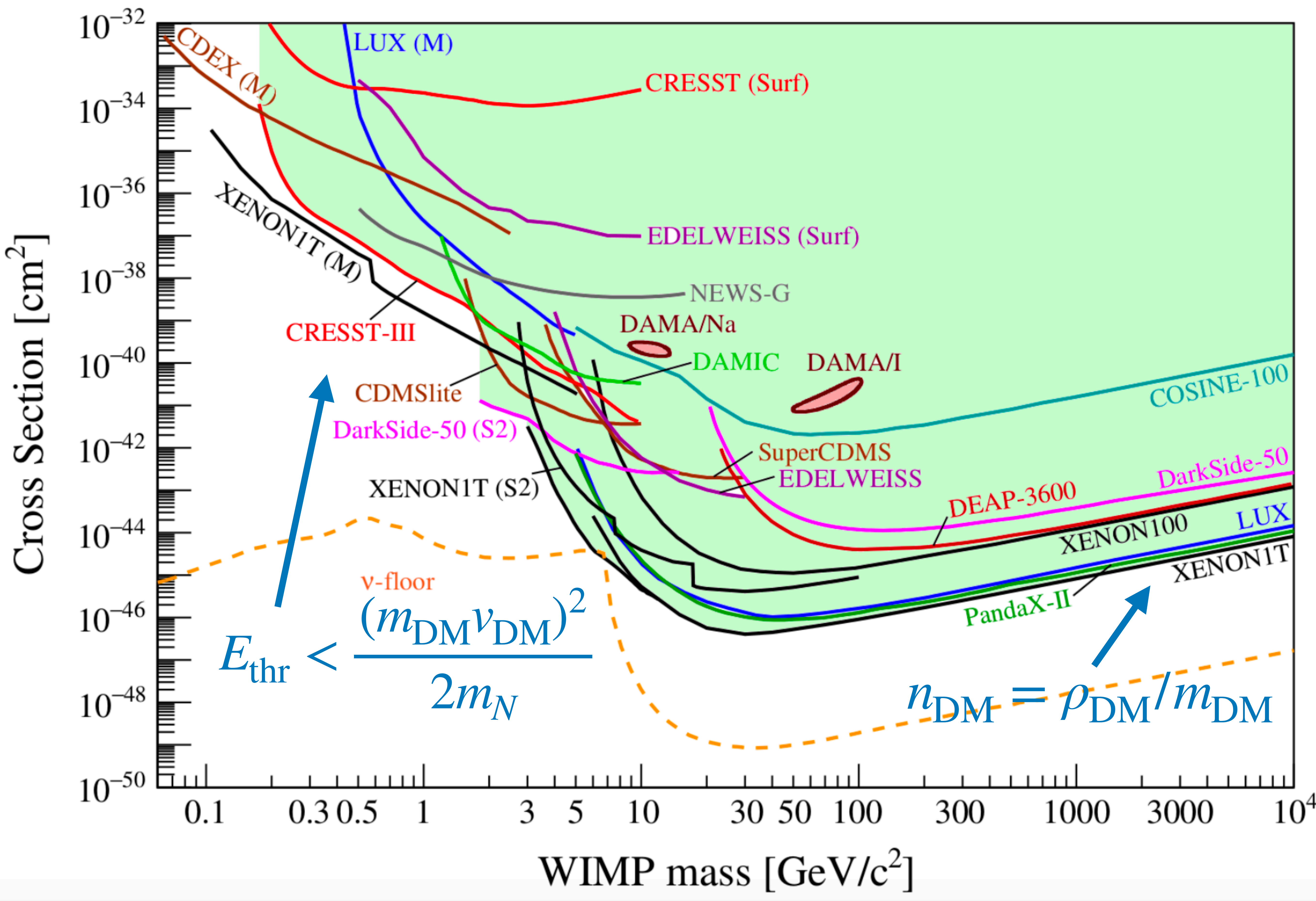
The detection of light dark matter

- Direct Detection: lowering the EXP energy threshold
  - Deep underground particle physics experiments
  - Condensed Matter quasi-particle related experiments
  - AMO experiments
- Intensity frontier: enough energy
  - collider/beam-dump experiments
- Astrophysics: increase the DM energy
  - indirect constraints

Direct Detection with Nuclear elastic Scattering

Elastic nuclear scattering

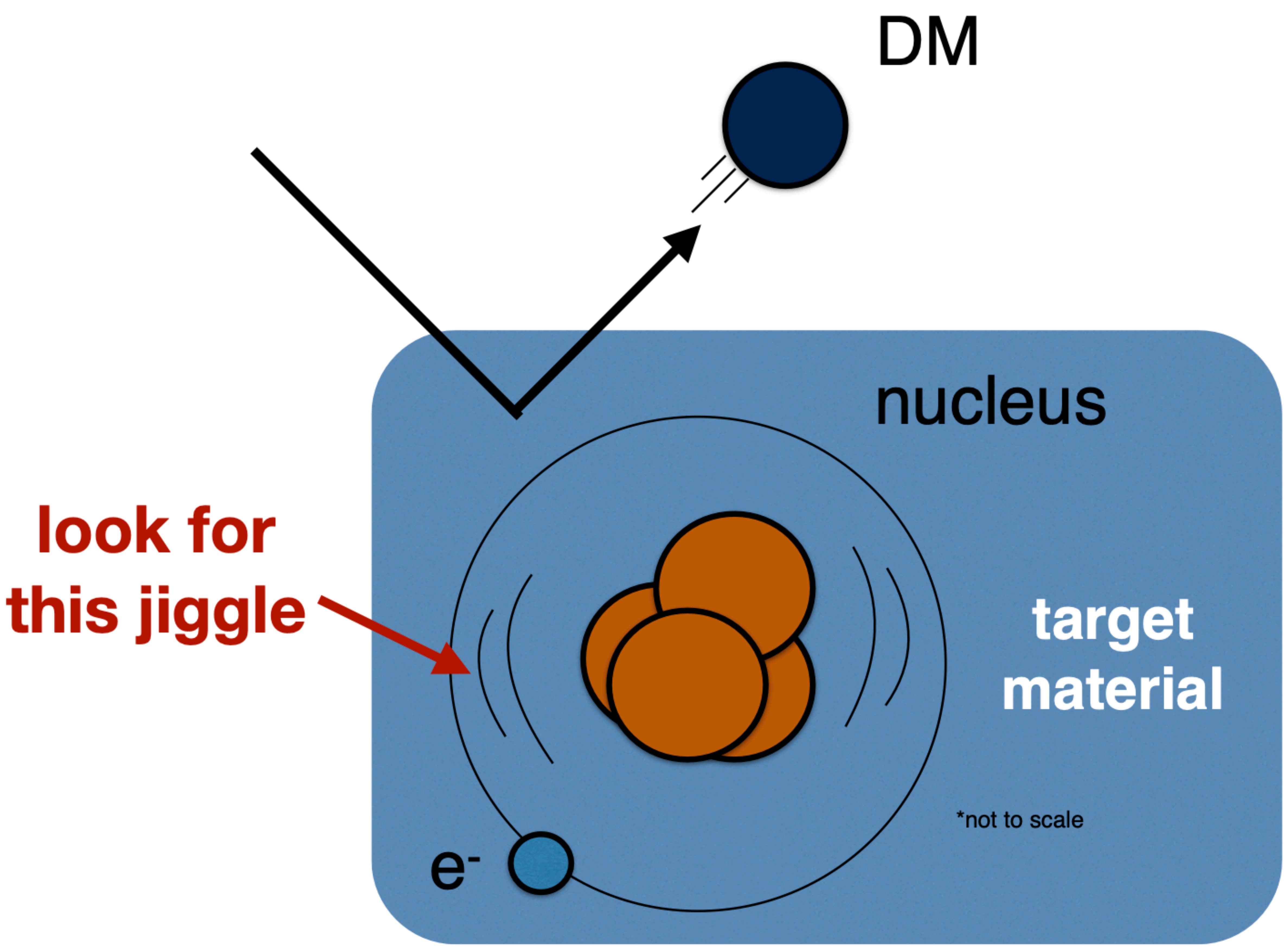




APPEC Committee Report: 2104.07634

Direct Detection with Nuclear elastic Scattering

Elastic nuclear scattering



- DM energy:

$$E_k = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim {\rm keV} \frac{m_{\rm DM}}{1{\rm GeV}}$$

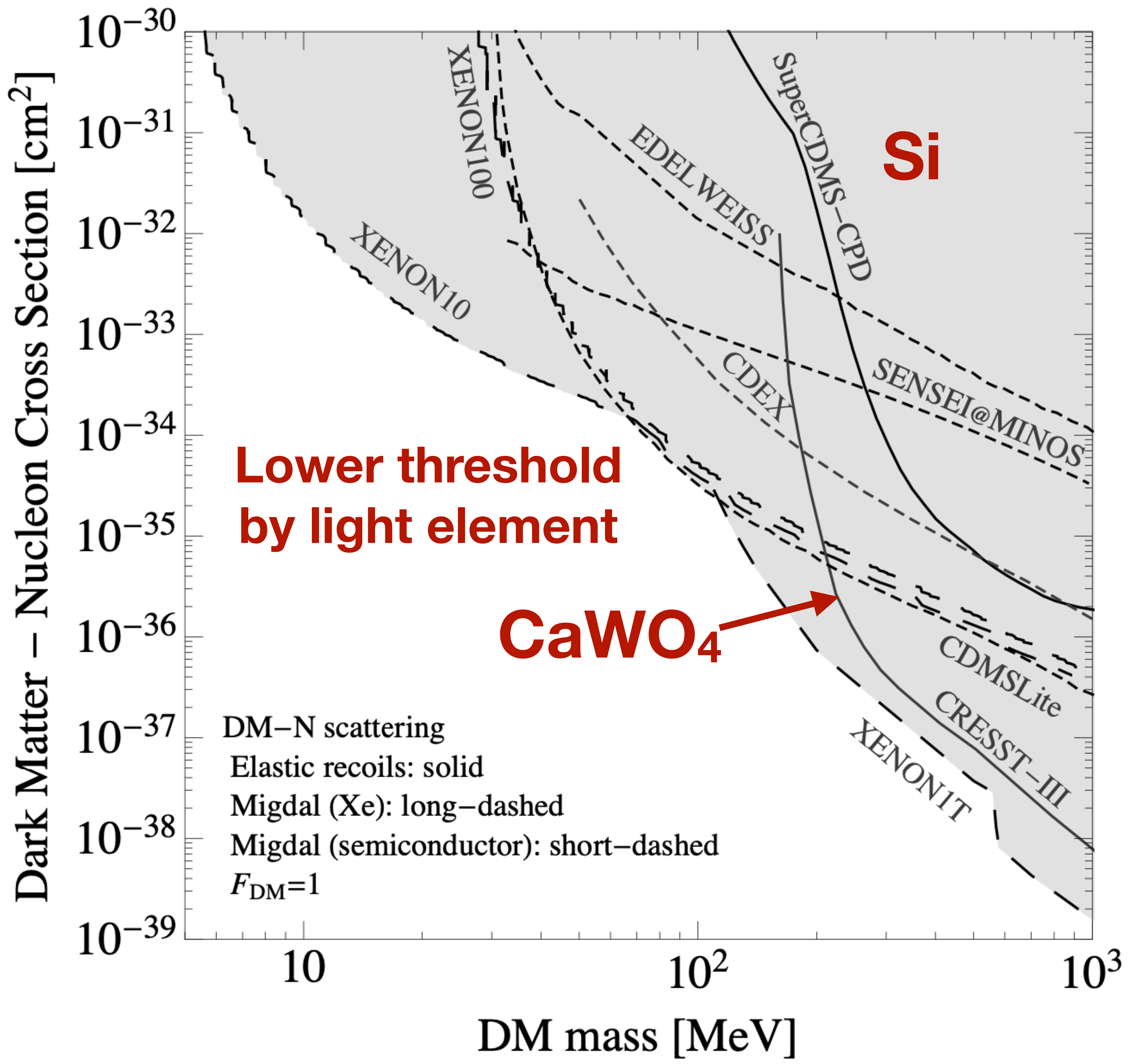
- Energy transfer to nucleus

$$E_r \approx \frac{(m_{\rm DM} v_{\rm DM})^2}{2 m_N} \approx \frac{({\rm MeV})^2}{2 m_N} \frac{m_{\rm DM}^2}{{\rm GeV}^2}$$

- Lighter element is better
He, O, Si, Ge, Ar

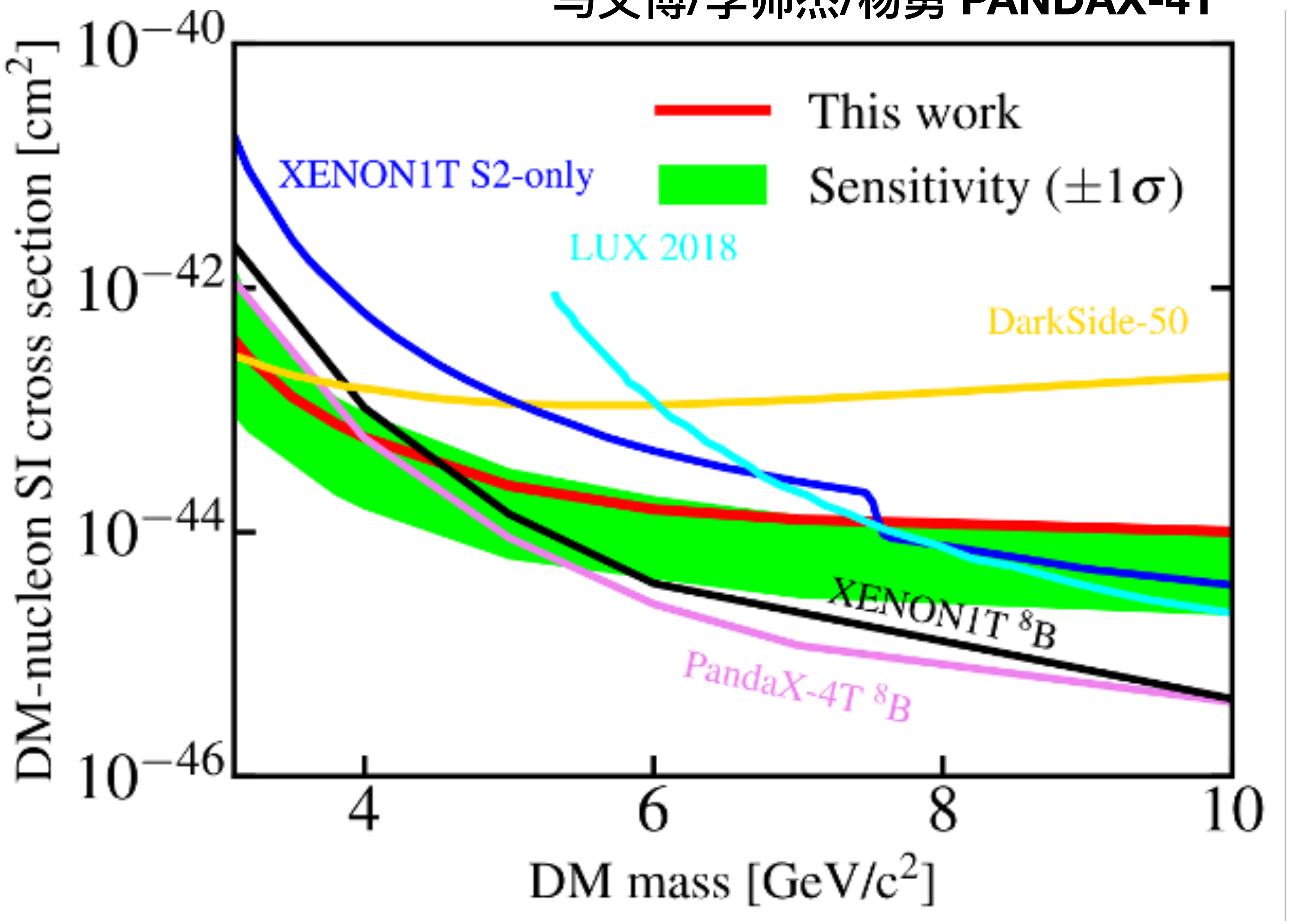
- Lower experiment threshold S2

Direct Detection with Nuclear elastic Scattering



Snowmass 2021: 2203.08297

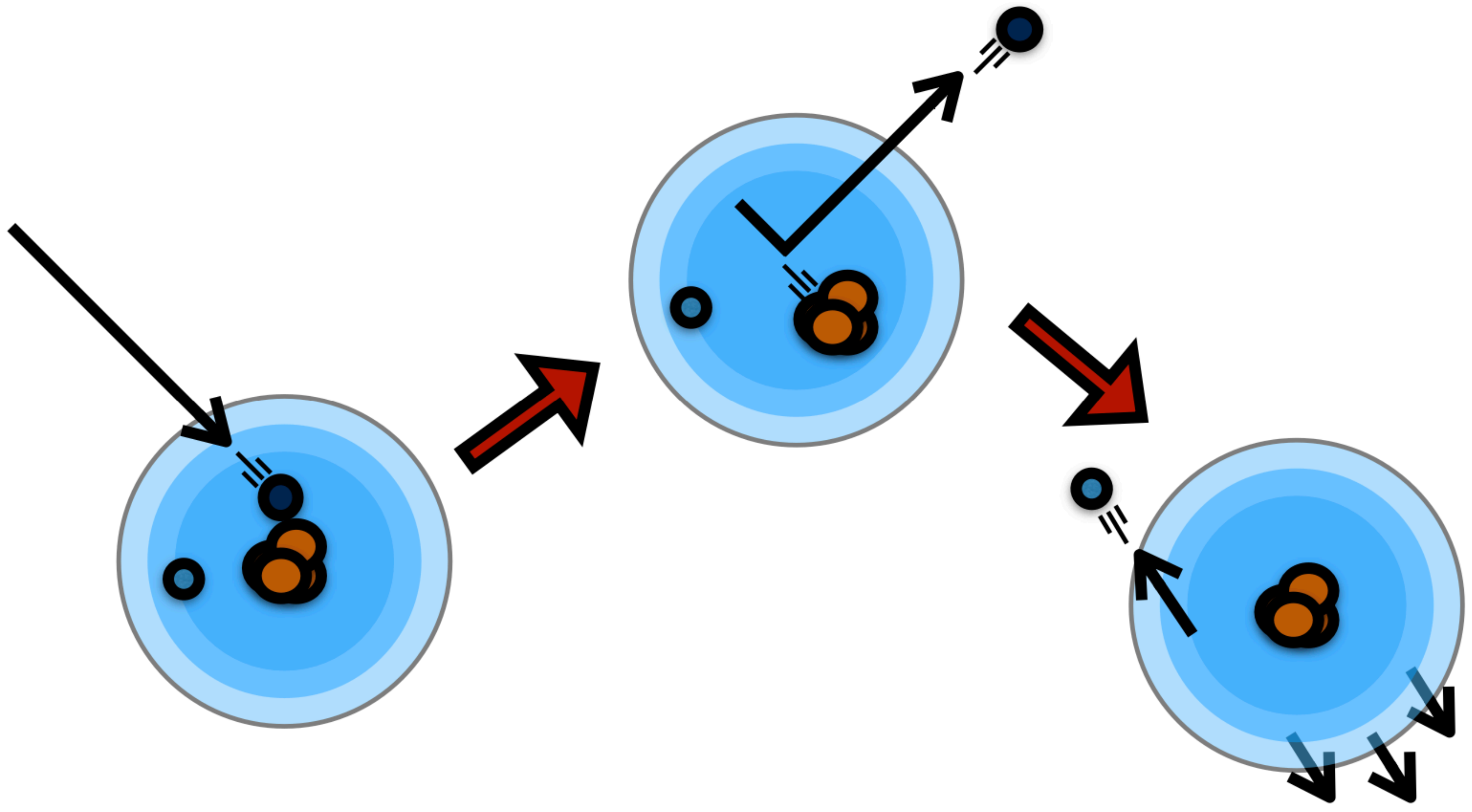
马文博/李帅杰/杨勇 PANDAX-4T



For liquid xenon TPC, use S2-only channel to reduce the energy threshold

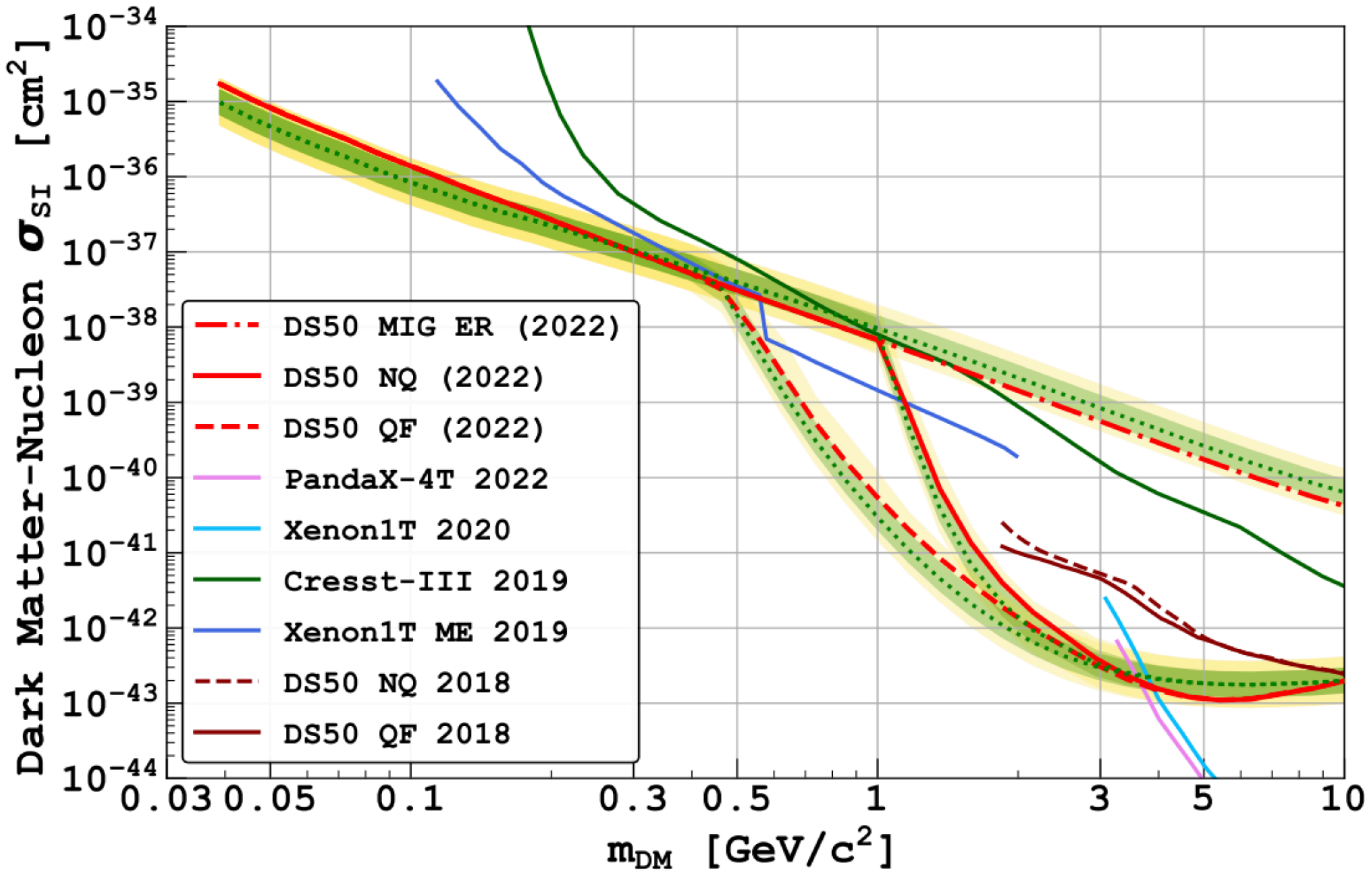
Direct Detection with Nuclear elastic Scattering

Migdal effect



dark matter-nucleus scattering (Migdal)

Lower threshold via transferring to electronic events



王毅 DarkSide-50
With Migdal effect

Tientien Yu, IAS-HEP 2023

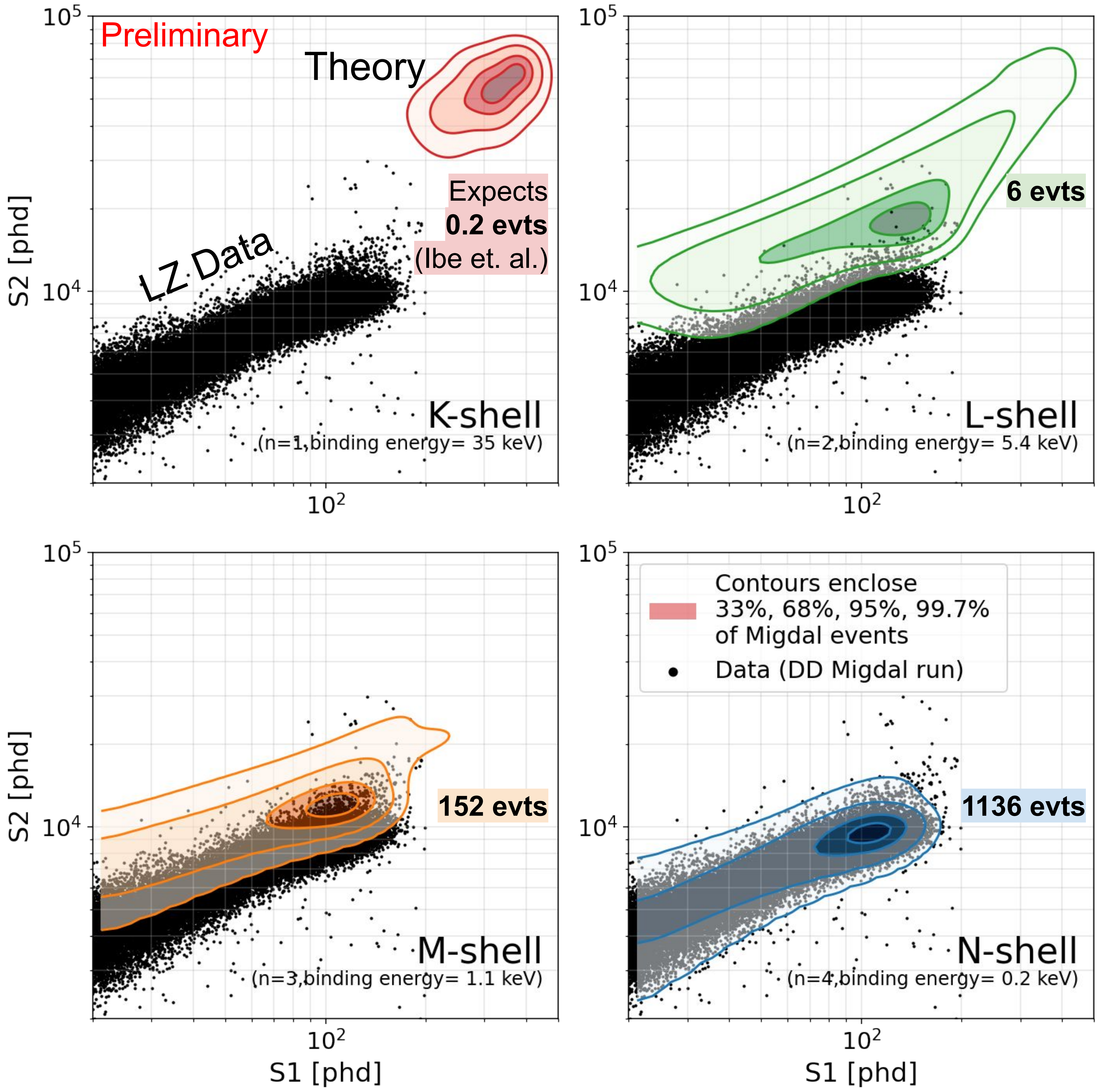
Direct Detection with Nuclear elastic Scattering

Migdal Signal Calculation

- Migdal rate and deposited energy are predicted based on Ibe et al.
  - Calculated Number of Migdal Events for 36k SS above threshold (E_{Recoil}>20 keVnr) is shown in the plots (JHEP03(2018)194)
  - Cox et al. (Phys. Rev. D 107, 035032) reported 1.2x higher rate due to multiple ionization in Xe

Our analysis focuses on:

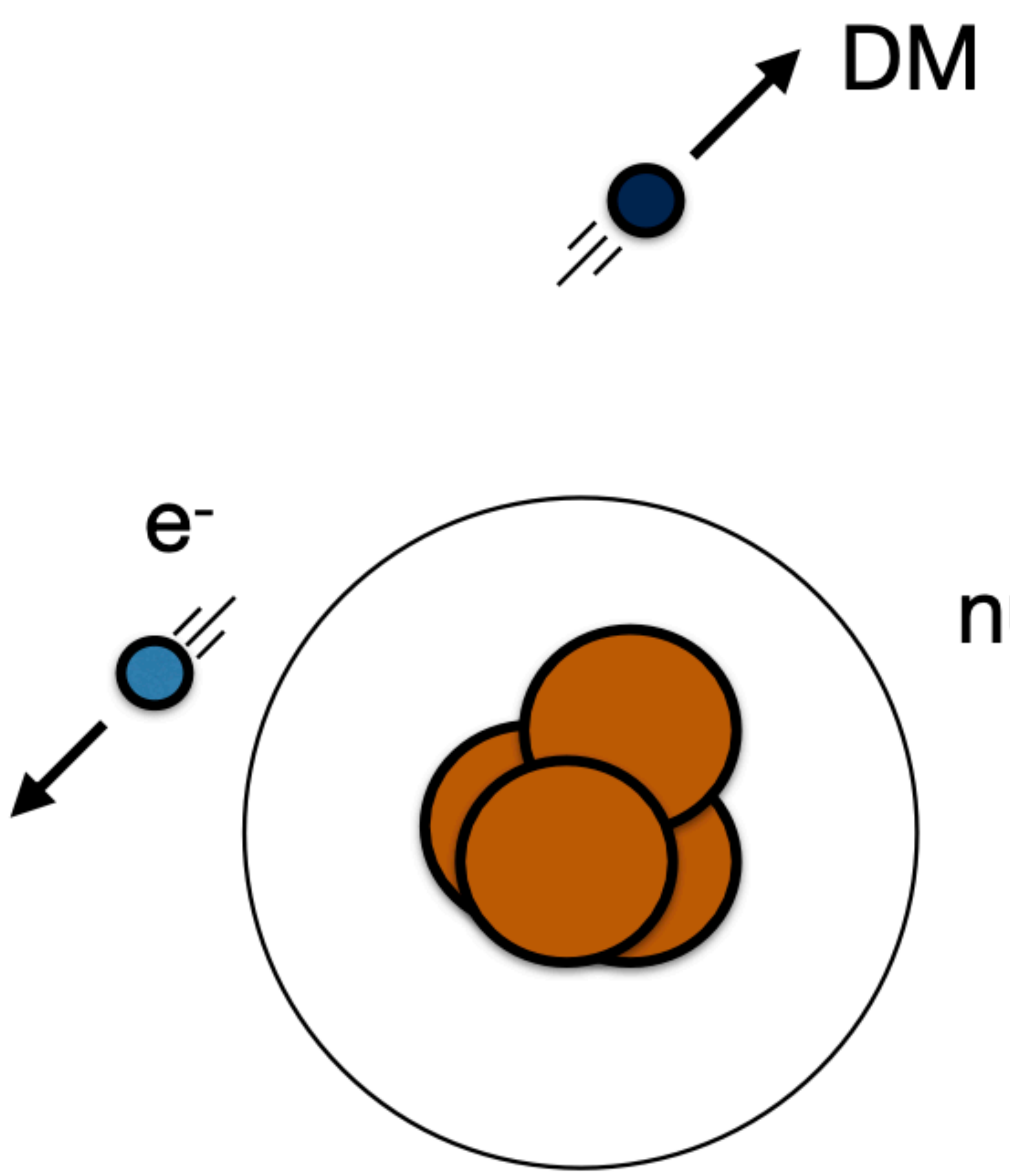
- L-shell Migdal
  - Expect 6 events, with +5 keVee
- M-shell Migdal
  - Expect 152 events, with +1 keVee
- Other shells are …
  - K shell Migdal is too few
  - N shell Migdal is too similar to NR



LZ results
UCLA DM 2023
3.4σ excess

Direct Detection with Electron Scattering

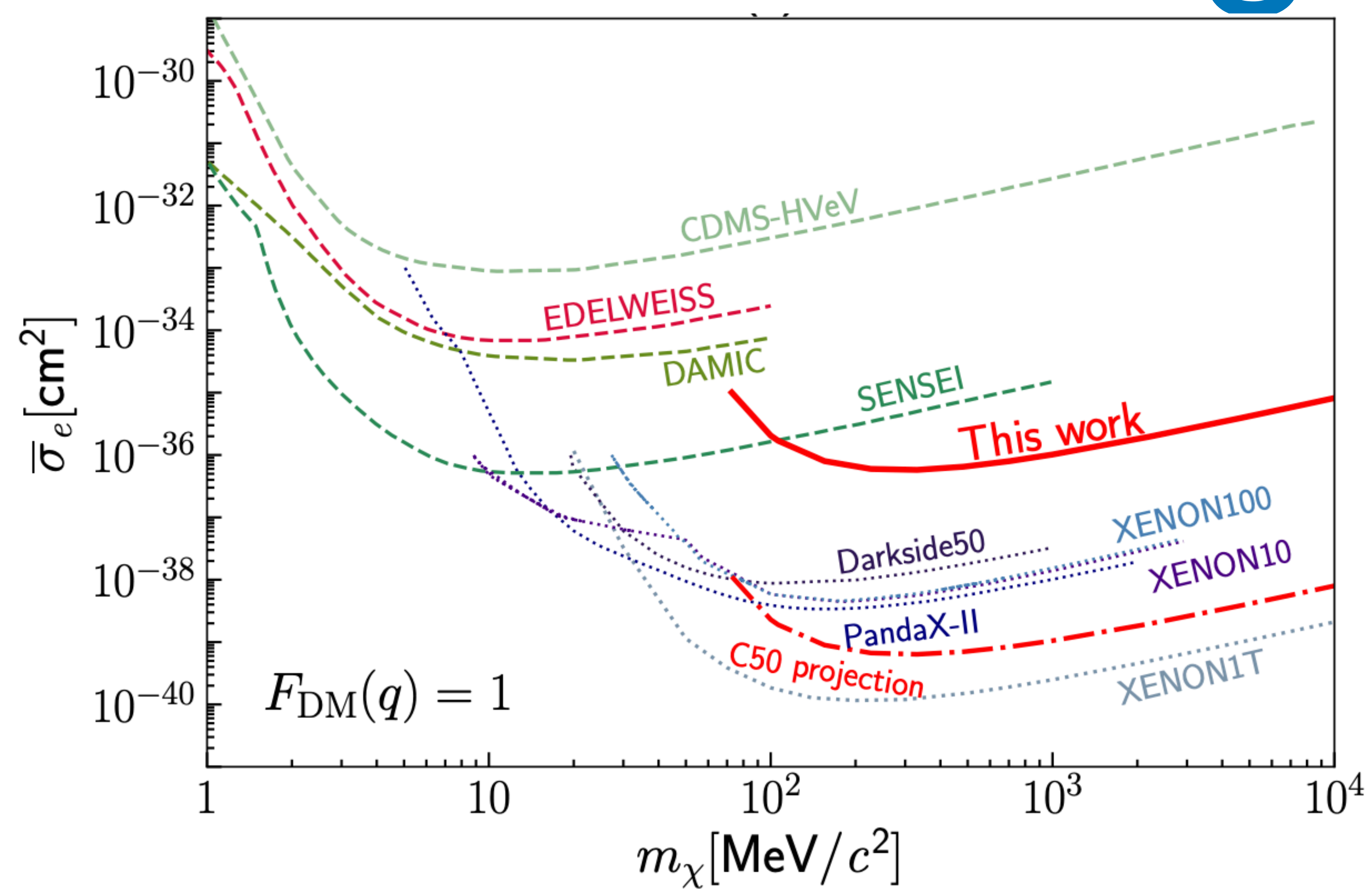
Electron scattering: excitation/ionization



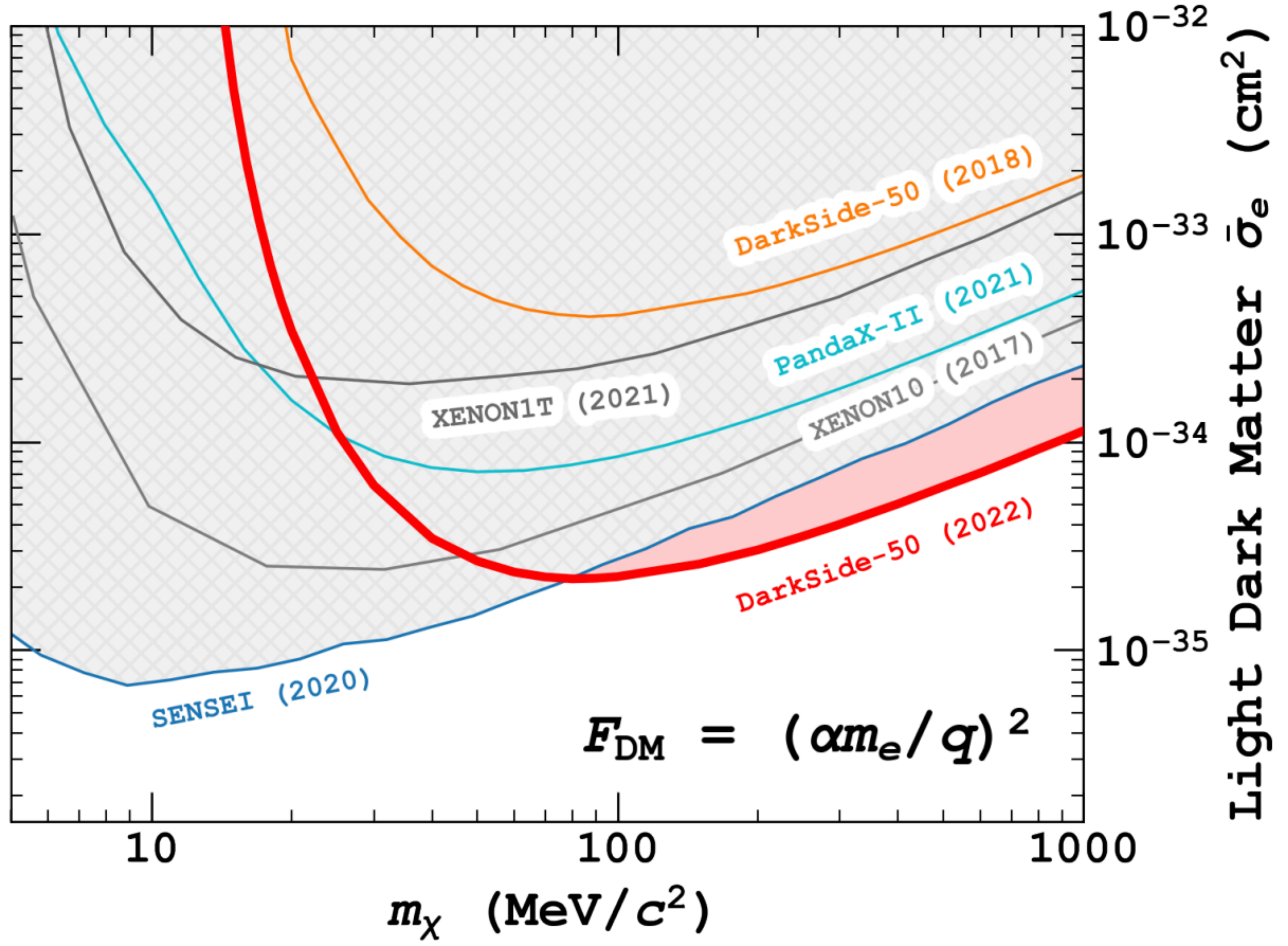
DM-electron scattering

$$\overline{\sigma}_e \sim 4\pi\alpha_D\epsilon^2\alpha\frac{\mu^2_{\chi,e}}{q^4}$$

杨丽桃 CDEX-10
2206.04128 [PRL]

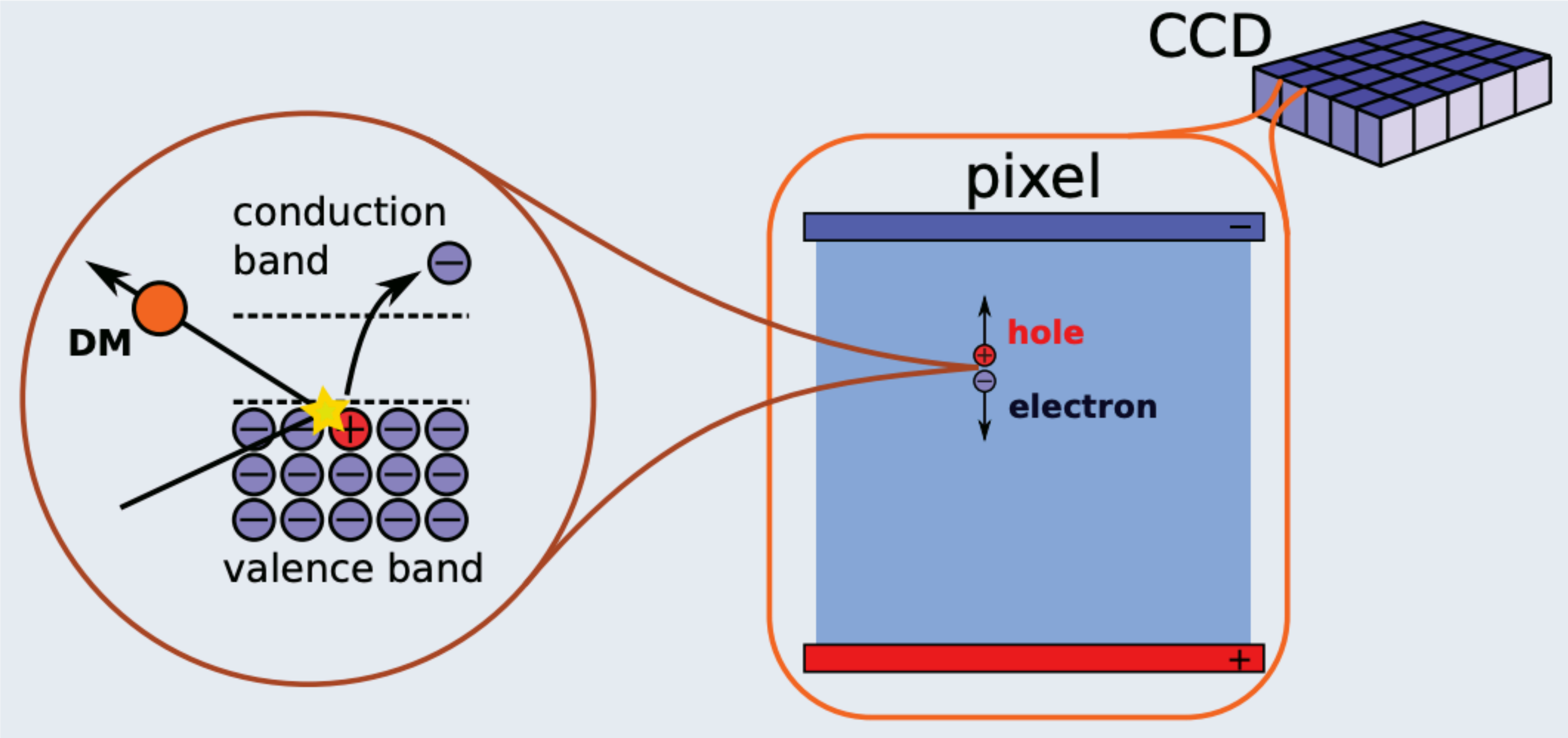


李毅 DarkSide-50
2207.11968 [PRL]



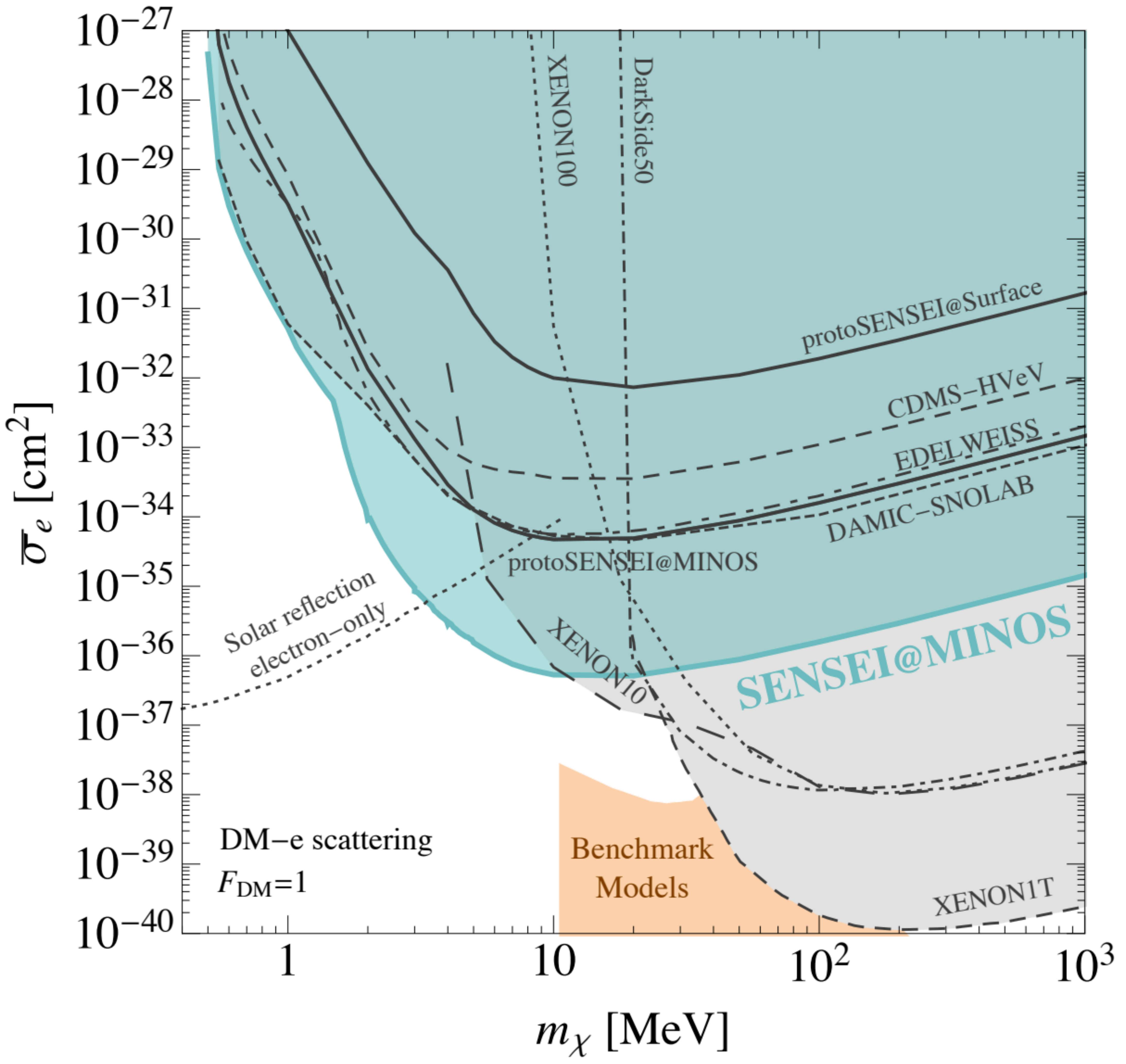
Direct Detection with Electron Scattering

- Skipper CCD:
  - single electron detection
  - Detection threshold 28 eV
  - Multiple measurements trade resolution with speed
  - N = 300 (13 ms/pixel), noise 0.14 e^-



Direct Detection with electron scattering

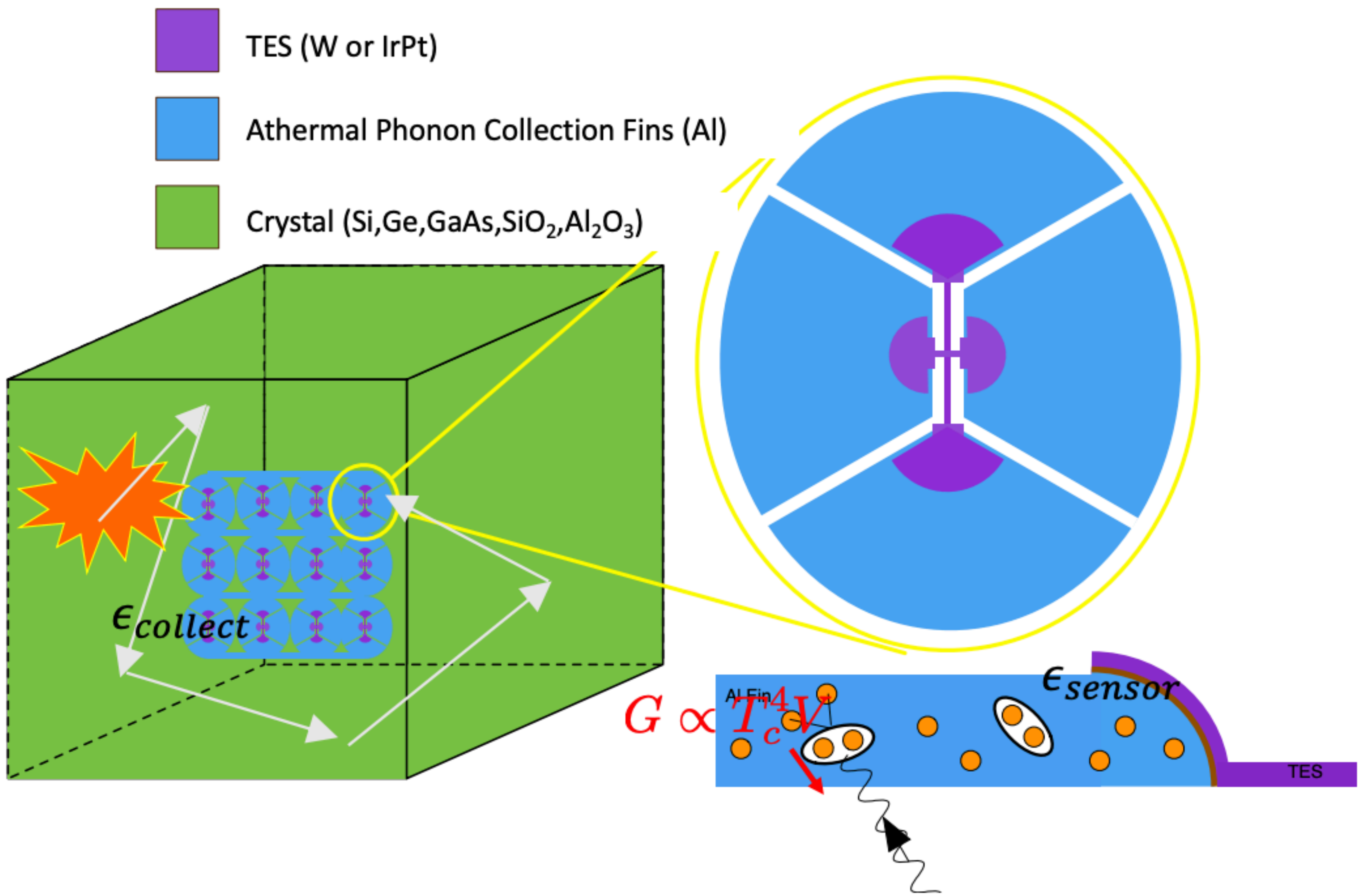
- Skipper CCD:
  - single electron detection
  - Detection threshold 28 eV
  - Multiple measurements trade resolution with speed
  - N = 300 (13 ms/pixel), noise 0.14 e^-



SENSEI 2004.11378 [PRL]

Direct Detection with quasi-particle excitation

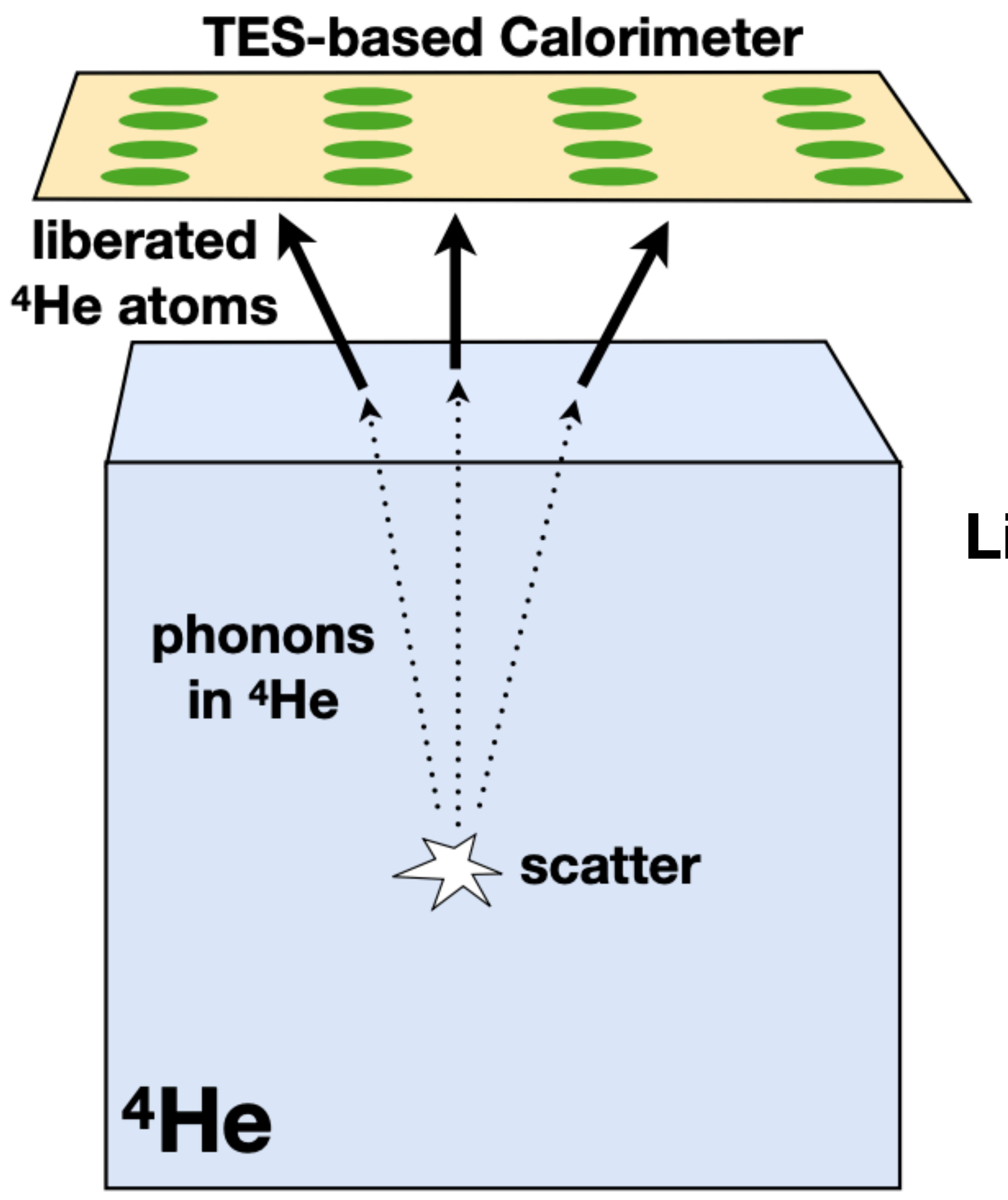
- Condensed matter quasi-particle related
  - Photon and roton excitations has low energy threshold sub-eV
  - K. Zurek, Z.K Zhang, W. Xue …
  - Experiment status TESSERACT Dark Matter Project
  - Al_2O_3, GaAs, LHe



Snowmass2021 Letter of Interest
TESSERACT Dark Matter

Direct Detection with quasi-particle excitation

- Condensed matter quasi-particle related
  - Photon and roton excitations has low energy threshold sub-eV
  - K. Zurek, Z.K Zhang, W. Xue …
  - Experiment status TESSERACT Dark Matter Project
  - Al_2O_3, GaAs, LHe

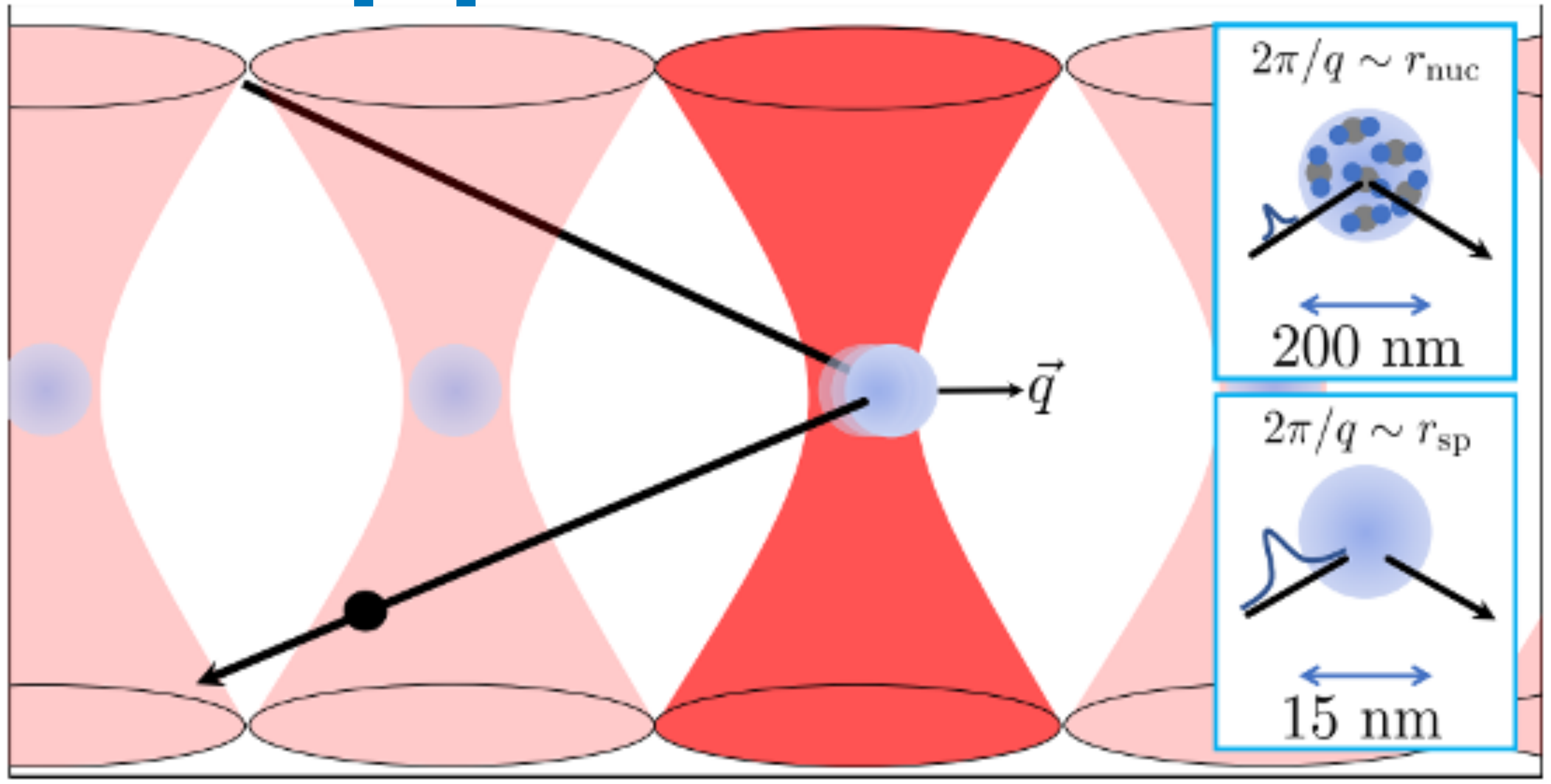


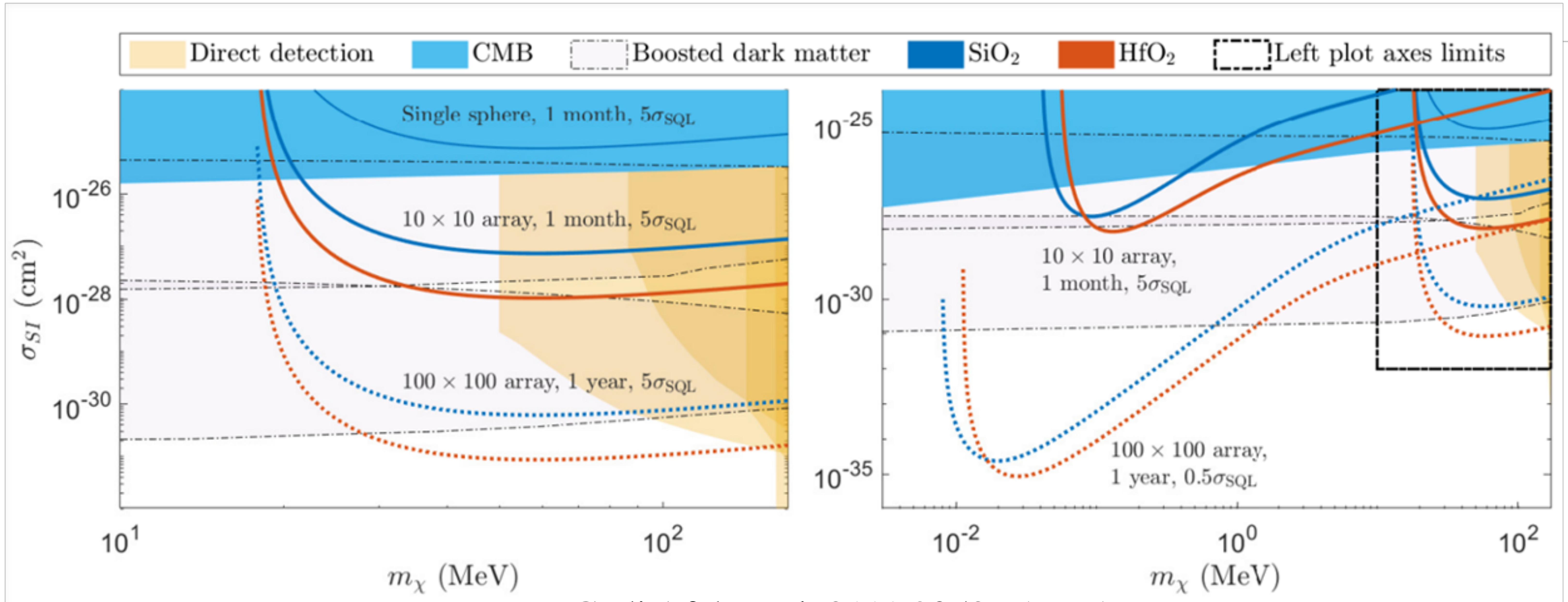
Liberate He atom to surface ~ 0.62 meV

HeRALD superfluid He4
TESSERACT Dark Matter

Direct Detection with AMO trapped sensors

- Nanosphere in optical trap sensors
- Low mass DM coherent scattering with macroscopic nanosphere
    - "Large", 200 nm-diameter spheres, DM interacts coherently with individual.
    - "Small", 15 nm-diameter spheres, where the interaction is coherent over the entire sensor.

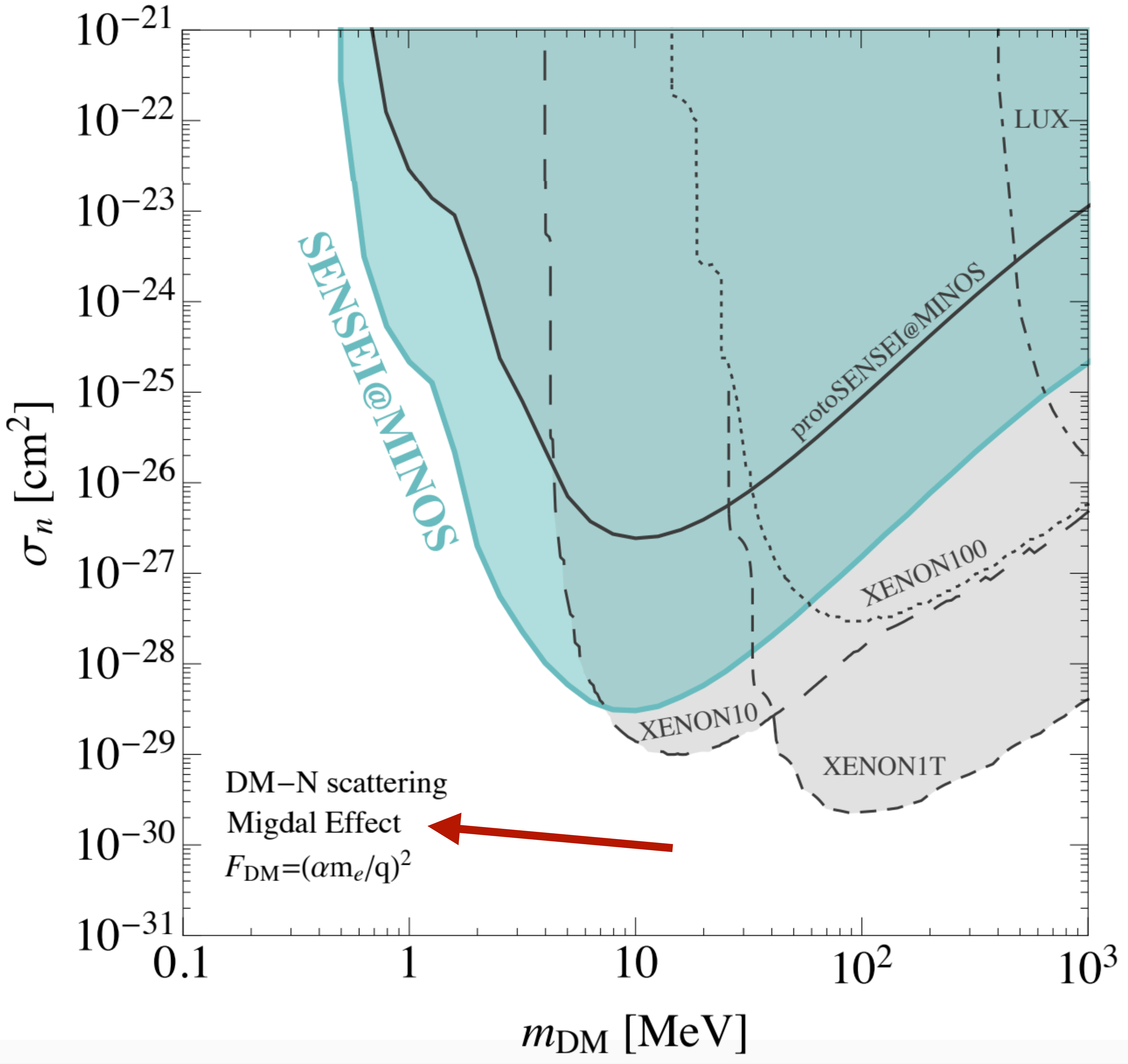


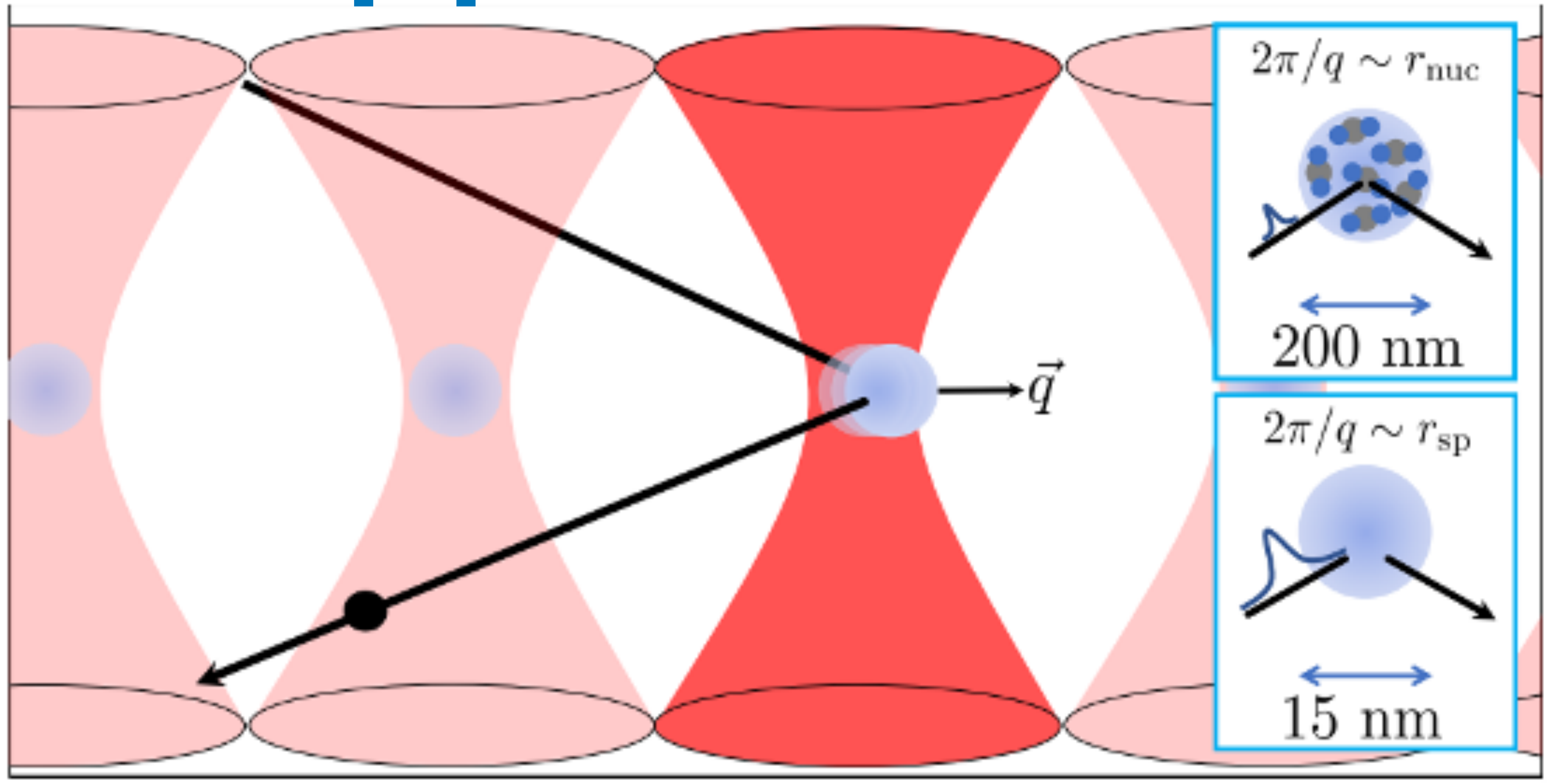


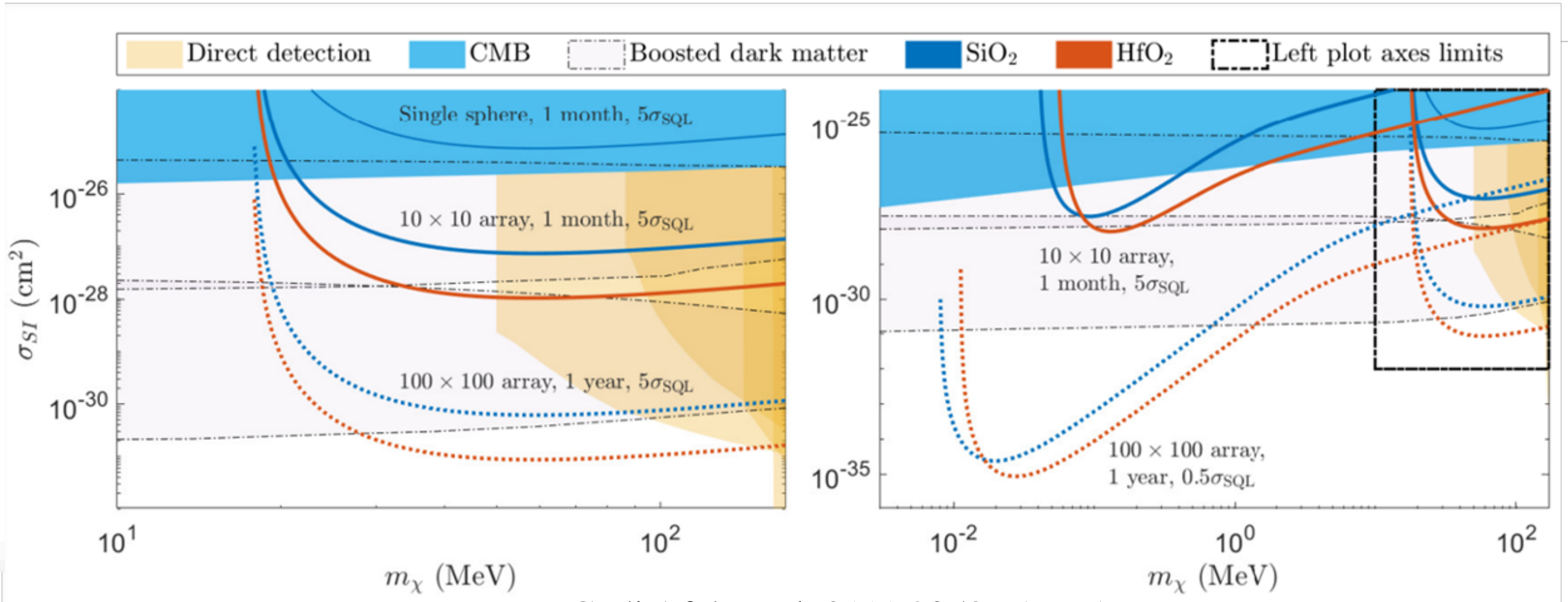
Gadi Afek et al, 2111.03597 (PRL)

Direct Detection with AMO trapped sensors

- Direct measuring σ_n



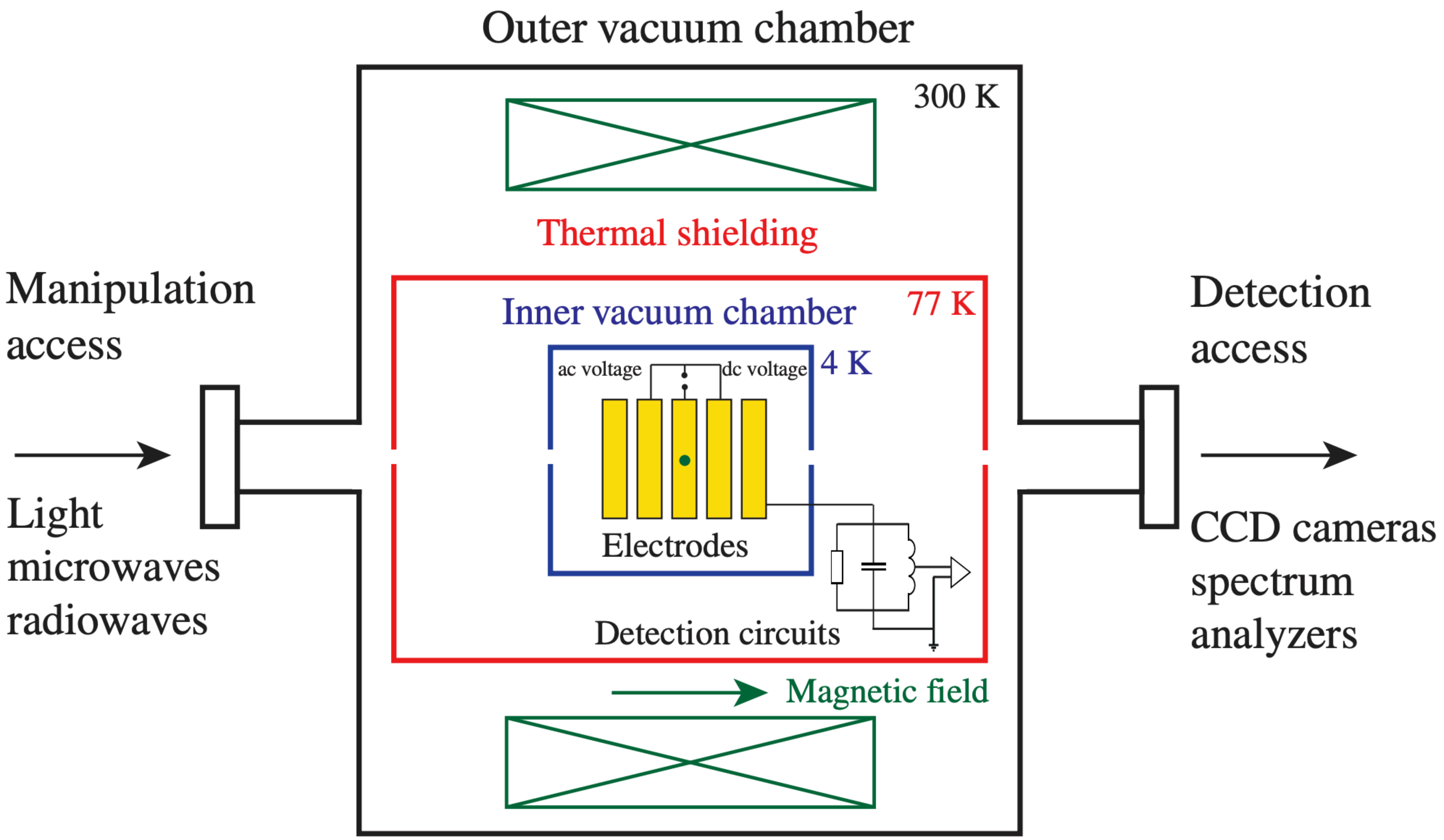




Gadi Afek et al, 2111.03597 (PRL)

Direct Detection with AMO trapped sensors

- Ion trap sensors
- Millicharged DM with thermalization with surface
  - Large n_{DM} and small v_{DM}
  - Energy threshold neV

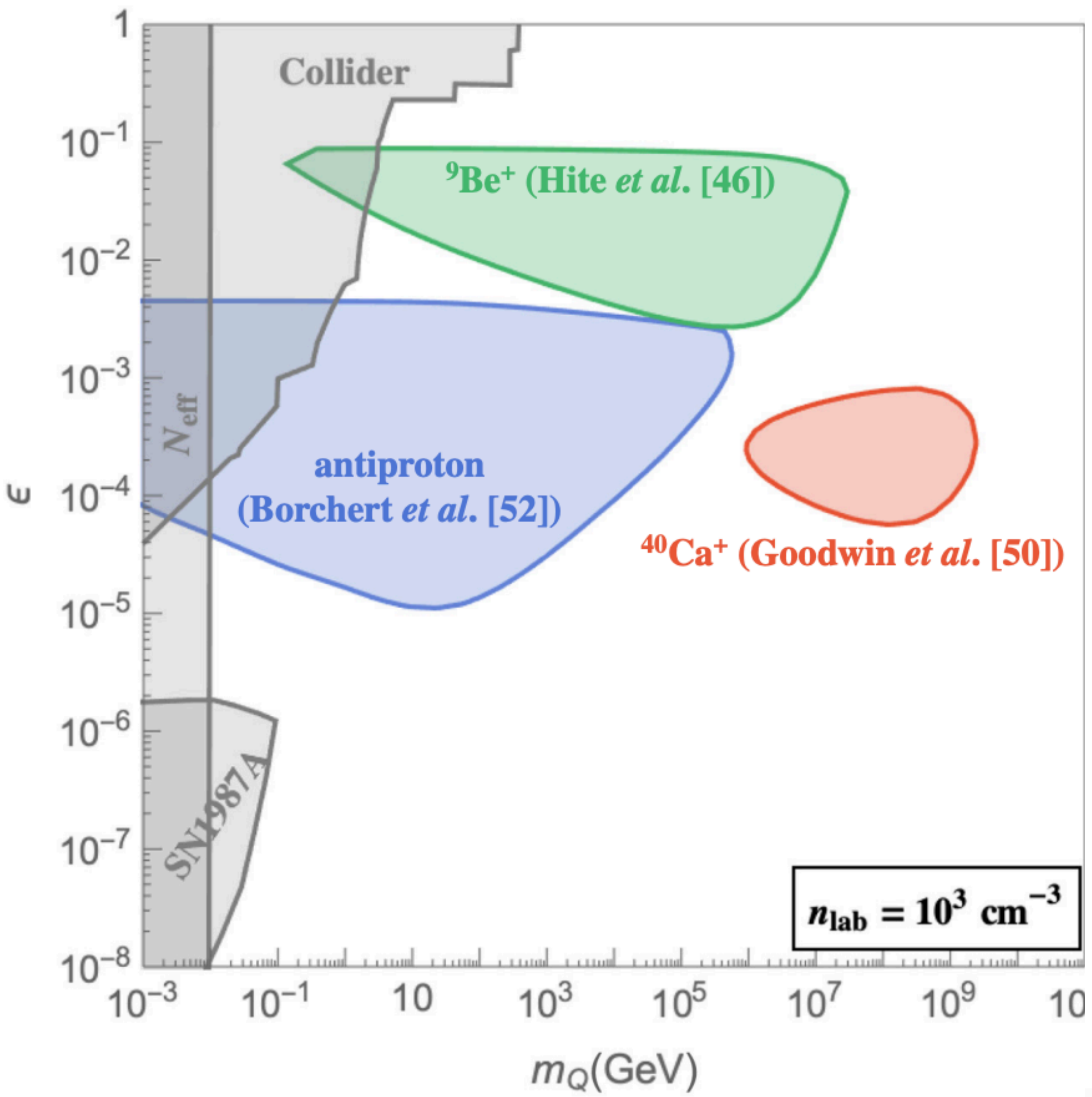


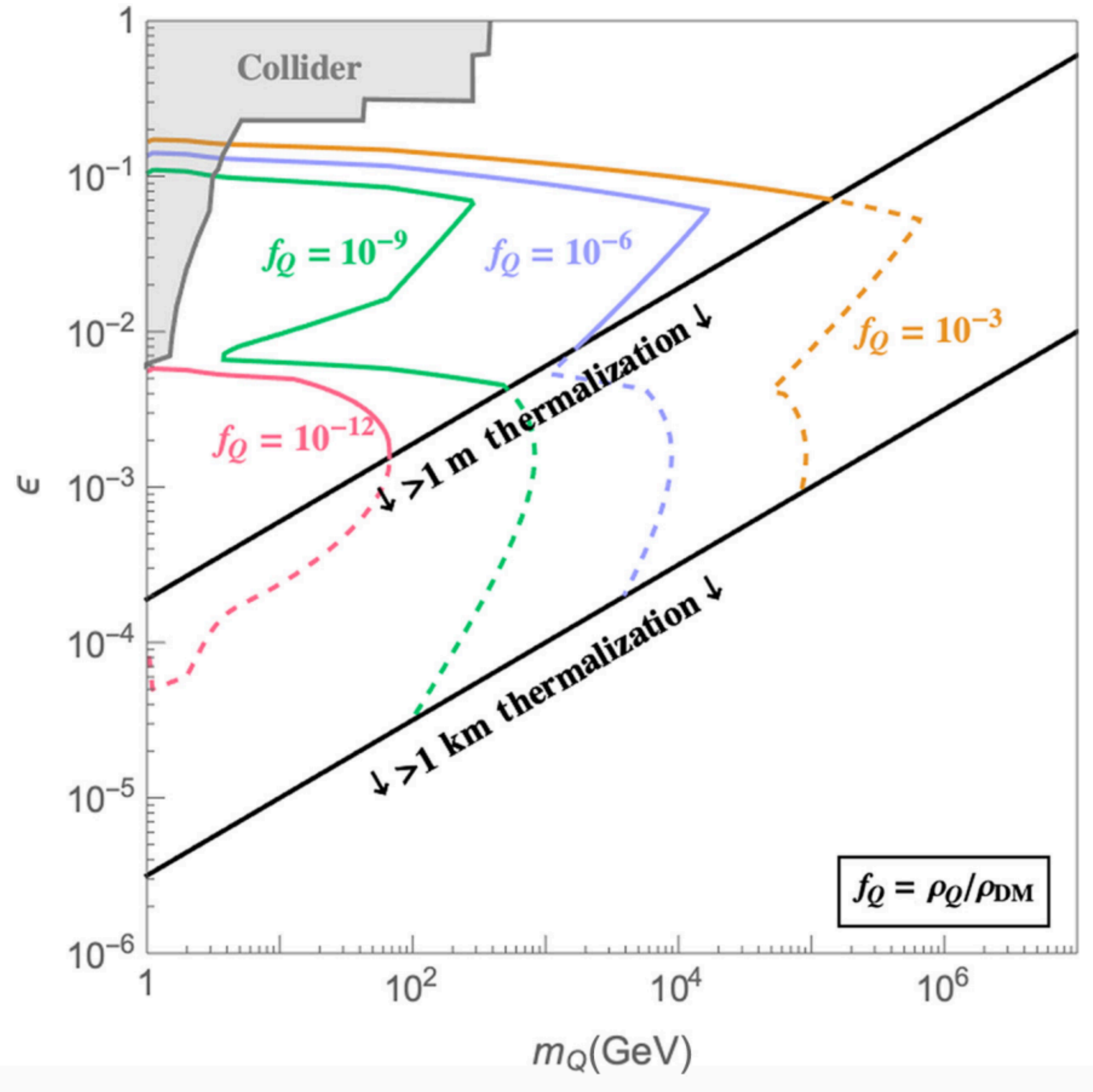
Experiment	Type	Ion	V_z	$T_{\rm wall}$	ω_p (neV)	$T_{\rm ion}$ (neV)	Heating rate (neV/s)
Hite *et al.* [46]	Paul	^{9}Be$^+$	0.1 V	300 K	$\omega_z = 14.8$	14.8	640 ± 30
Goodwin *et al.* [50]	Penning	^{40}Ca$^+$	175 V	300 K	$\omega_z = 1.24$	1.24	0.37 ± 0.25
Borchert *et al.* [52]	Penning	$\bar{p}$	0.633 V	5.6 K	$\omega_+ = 77.4$ $\omega_- = 0.050$	7240	0.012 ± 0.019

Budcker et al, 2108.05283 (PRX)

Direct Detection with AMO trapped sensors

- Ion trap sensors
- Millicharged DM with thermalization with surface
  - Large n_{DM} and small v_{DM}
  - Energy threshold neV



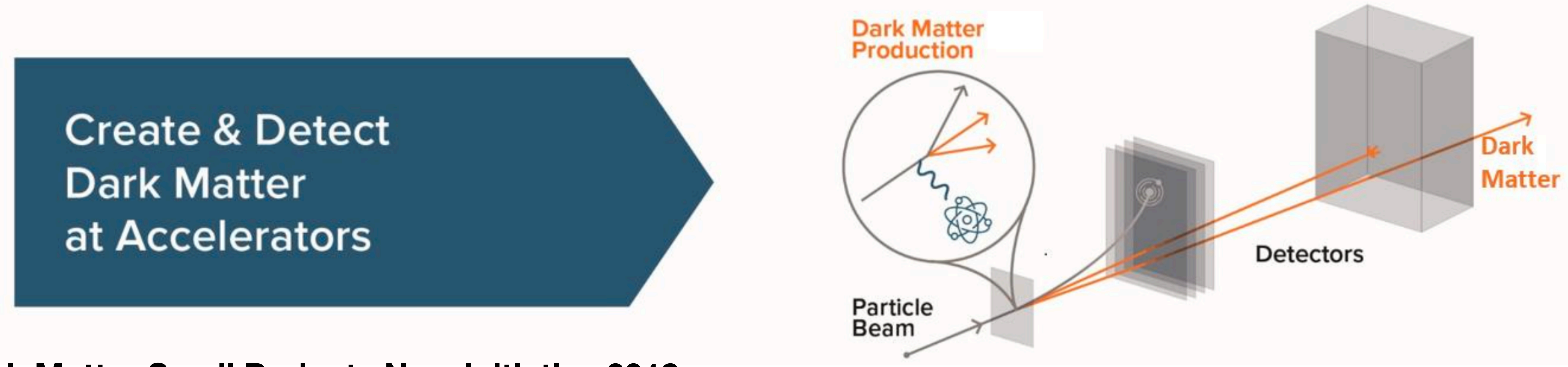


Budcker et al, 2108.05283 (PRX)

The detection of light dark matter

- Direct Detection: lowering the EXP energy threshold
  - Deep underground particle physics experiments
  - Condensed Matter quasi-particle related experiments
  - AMO experiments
- Intensity frontier: enough energy
  - collider/beam-dump experiments
- Astrophysics: increase the DM energy
  - indirect constraints

Intensity frontier: collider/beam-dump experiment



Dark Matter Small Projects New Initiative 2018

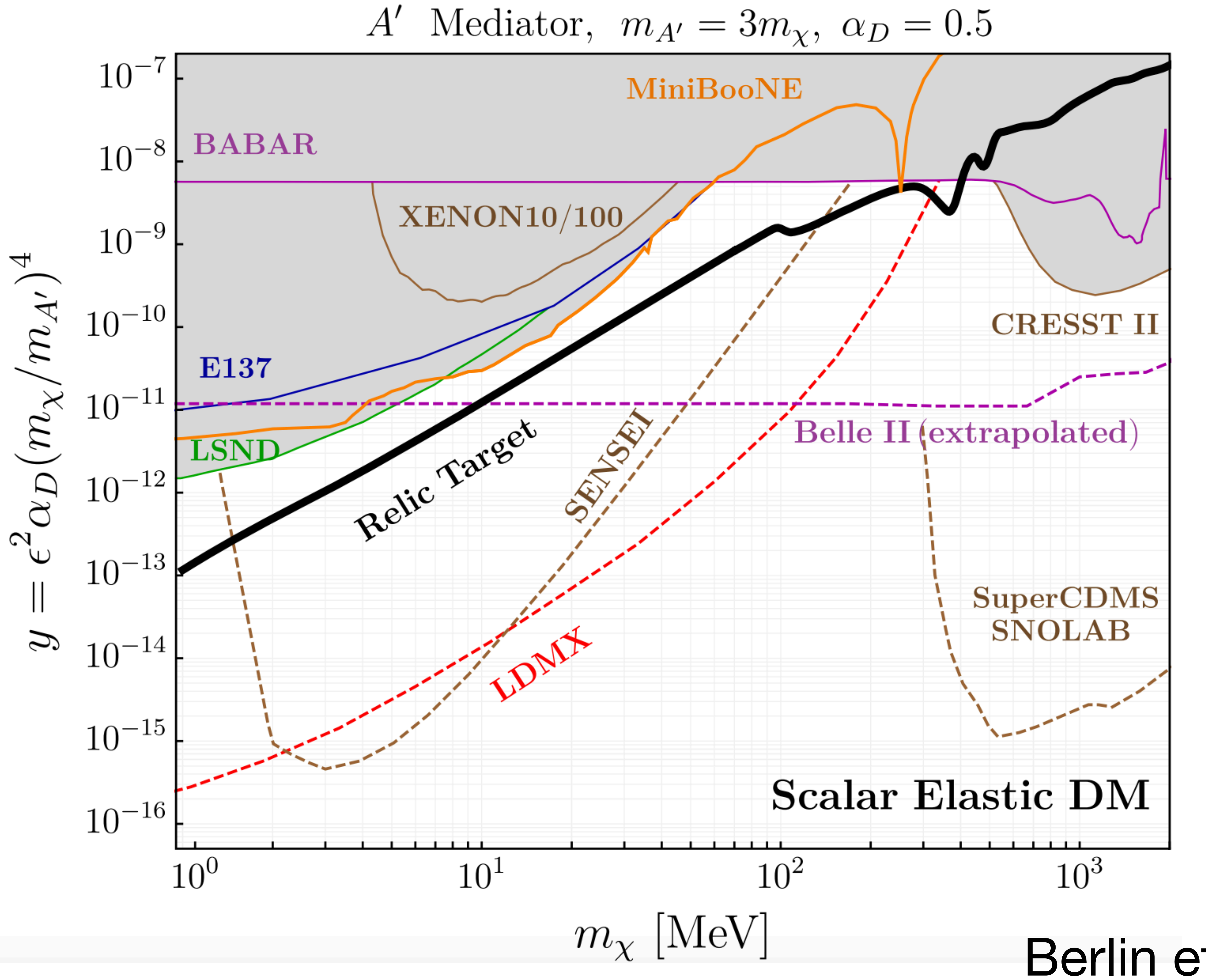
- Using energetic beam to produce DM and detect DM via missing energy or secondary particles

$$\mathcal{L} \supset \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

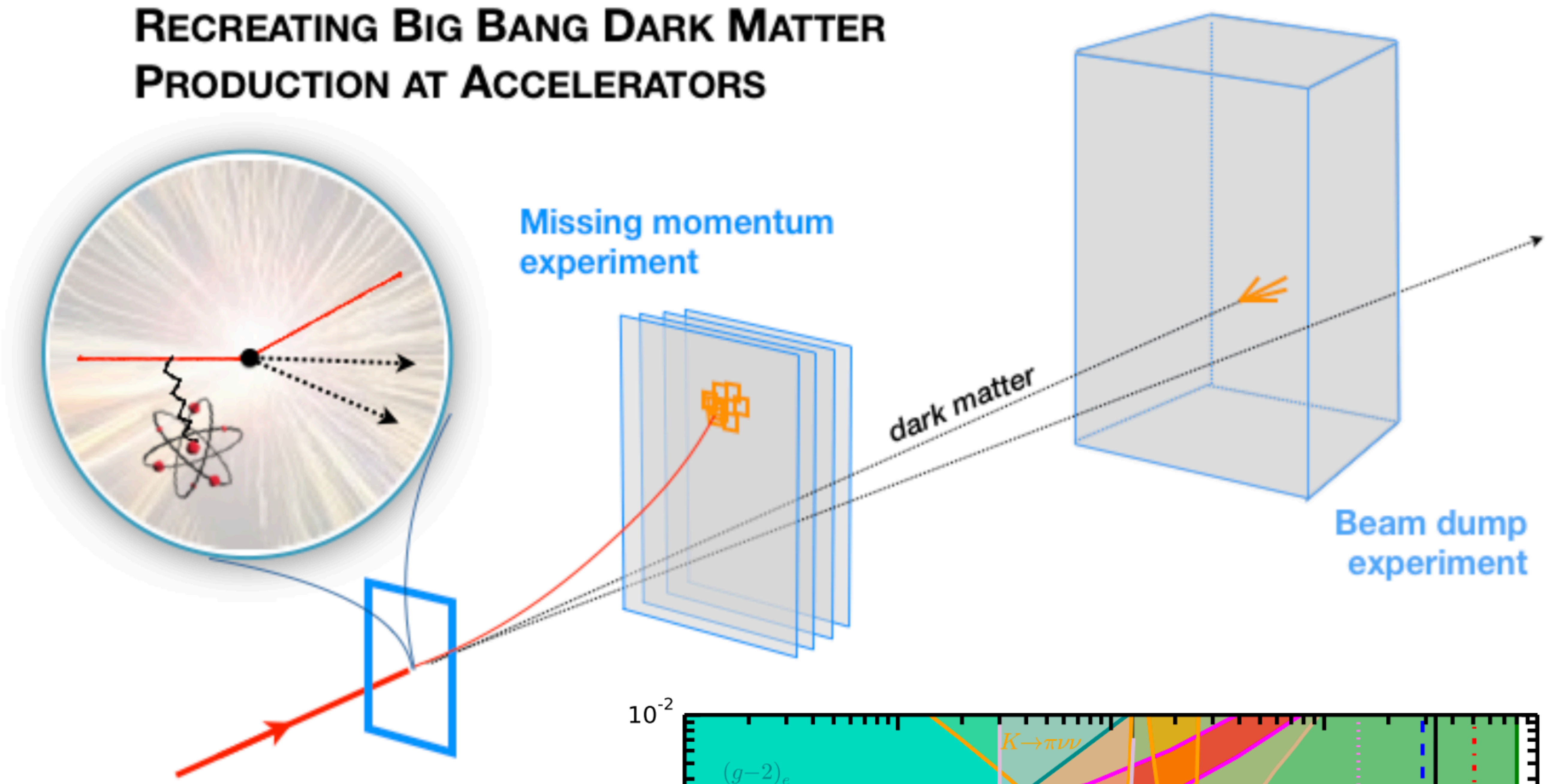
- Kinetic mixing dark photon/dark scalar mediator

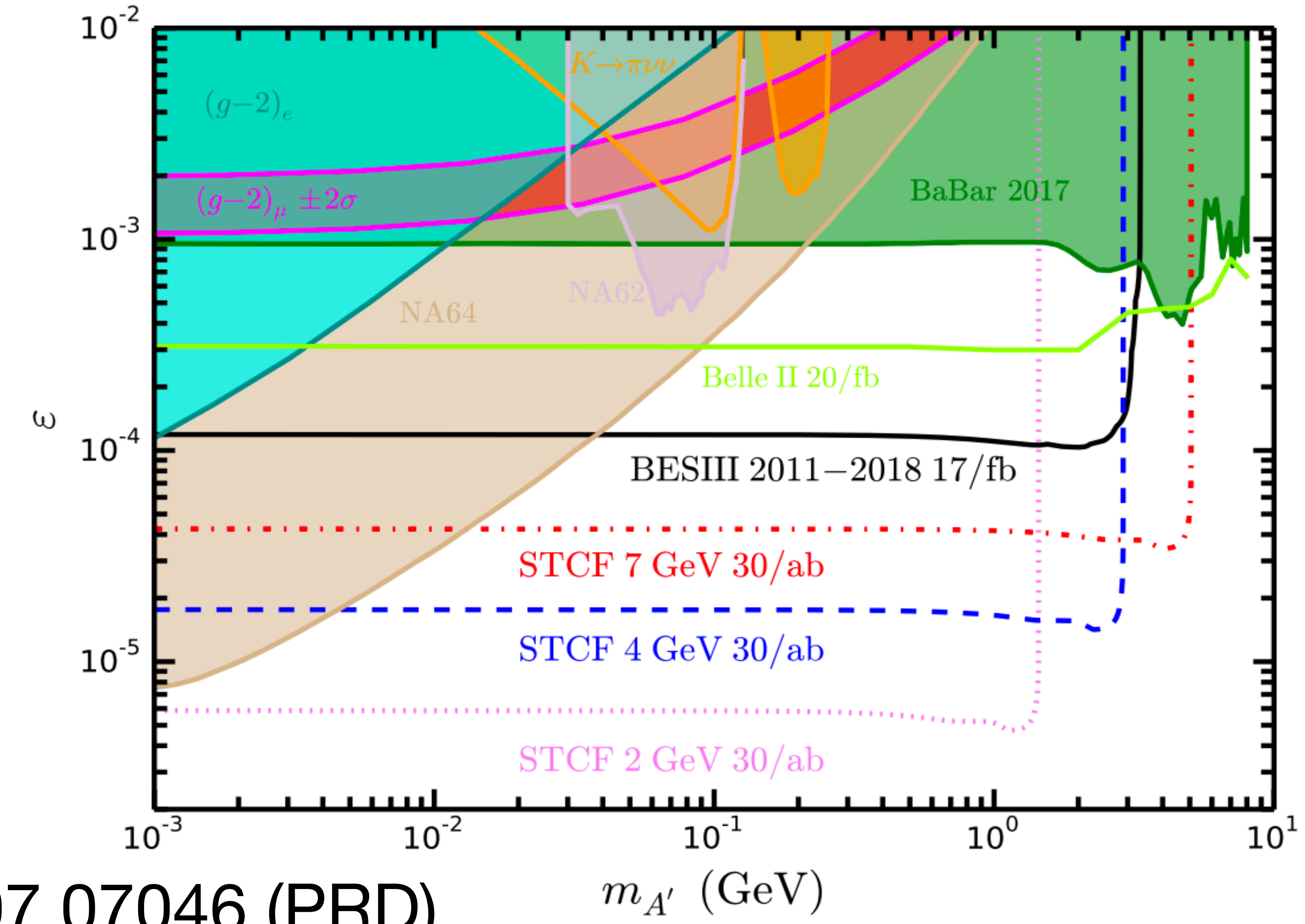
- Elastic or inelastic dark matter $-\mathcal{L} \supset A'_\mu (\epsilon e J^\mu_{\rm EM} + g_D J^\mu_D)$

Intensity frontier: collider/beam-dump experiment



Berlin et al, 1807.01730 (PRD)

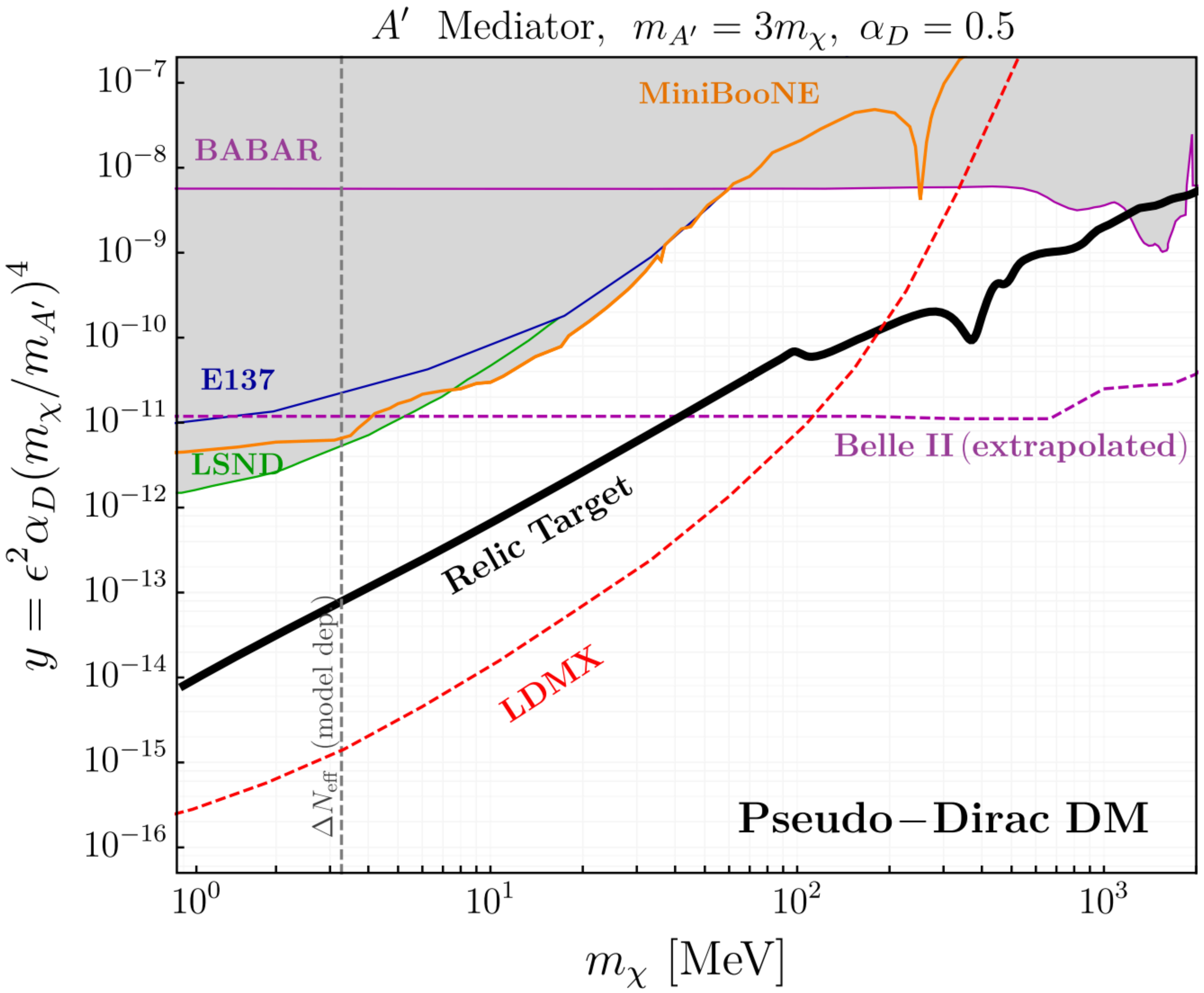




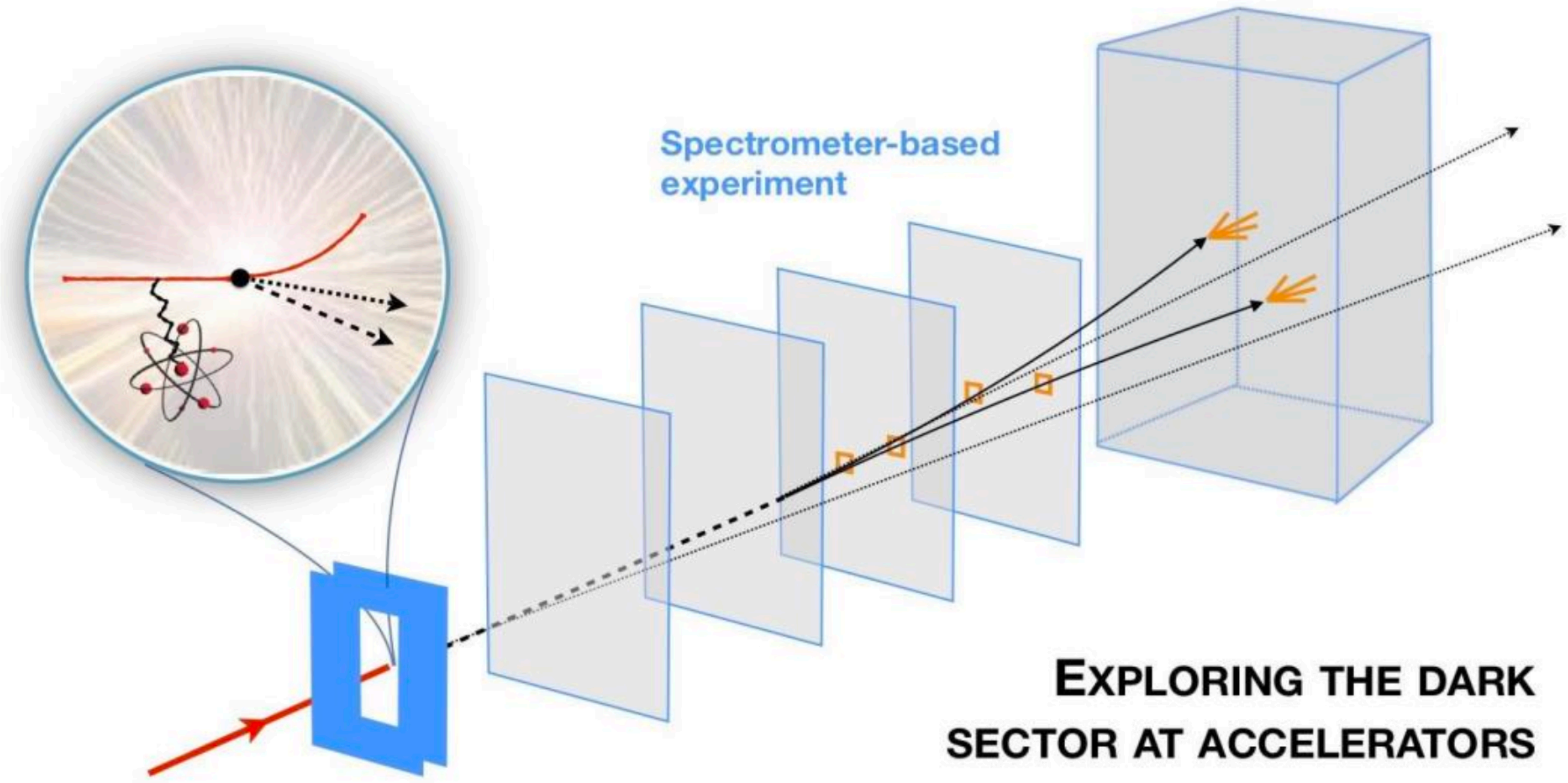
BESIII: 1907.07046 (PRD)

- Searching for missing energy
  - ee Collider: BESIII/Belle II
  - Beam-dump: NA64

Intensity frontier: collider/beam-dump experiment



Berlin et al, 1807.01730 (PRD)



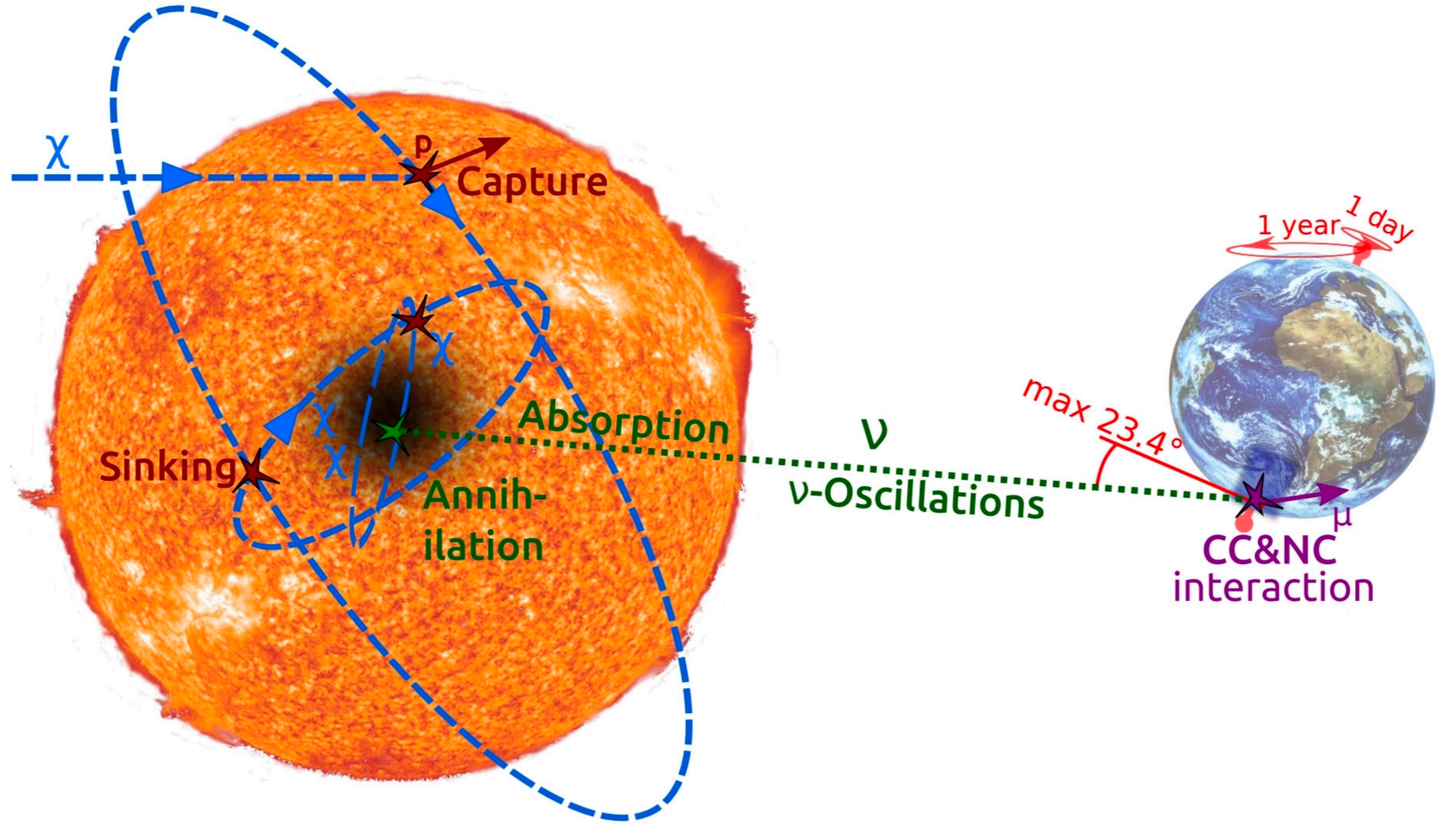
- Searching for secondary particles
    - Light dark sector particle decays: long-lived signature
    - Inelastic DM searches
    - Unique to intensity frontier study

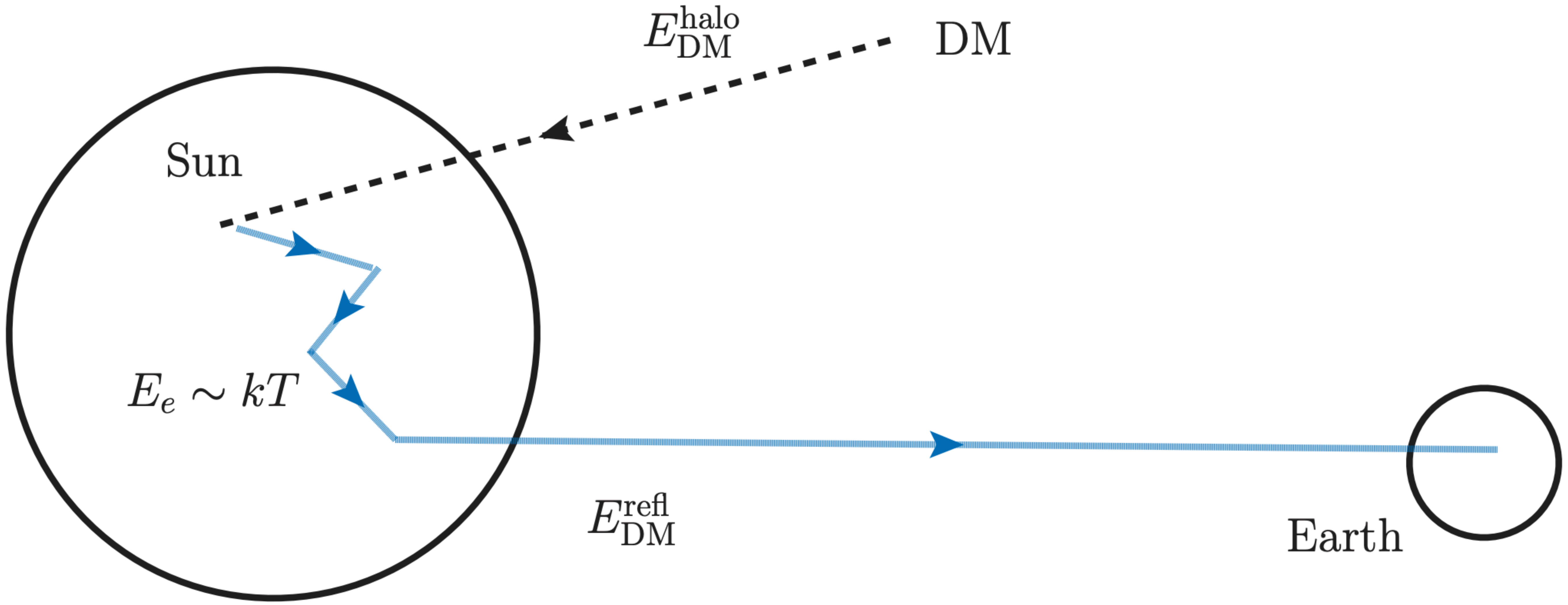
The detection of light dark matter

- Direct Detection: lowering the EXP energy threshold
  - Deep underground particle physics experiments
  - Condensed Matter quasi-particle related experiments
  - AMO experiments
- Intensity frontier: enough energy
  - collider/beam-dump experiments
- Astrophysics: increase the DM energy
  - indirect constraints

Astrophysics: increase the DM energy

- Solar reflected DM
  - DM evaporation when < GeV for DM annihilation in Sun, looking for high energy neutrino from Sun
  - Reflected light DM obtain extra energy via scattering with Sun

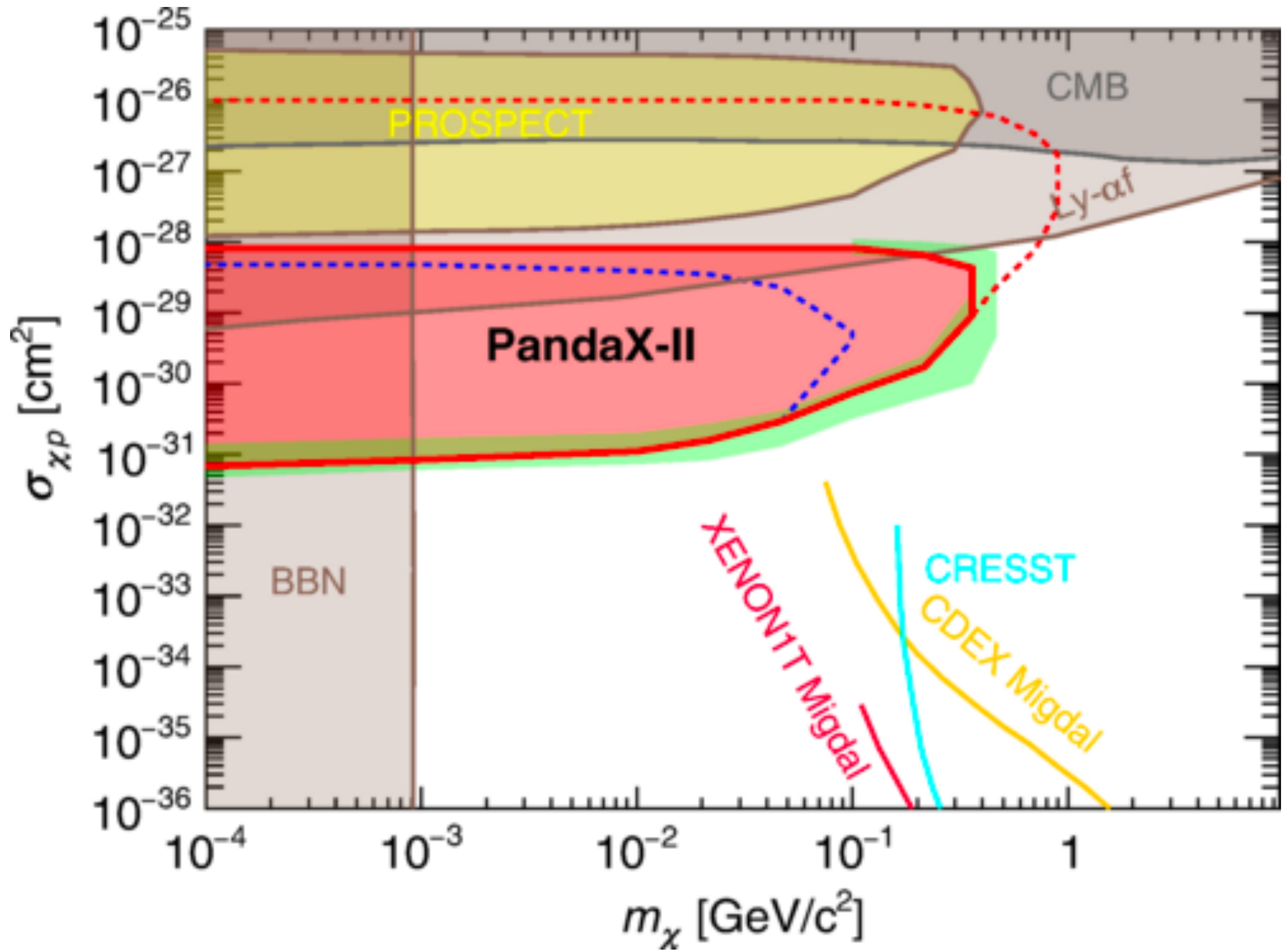


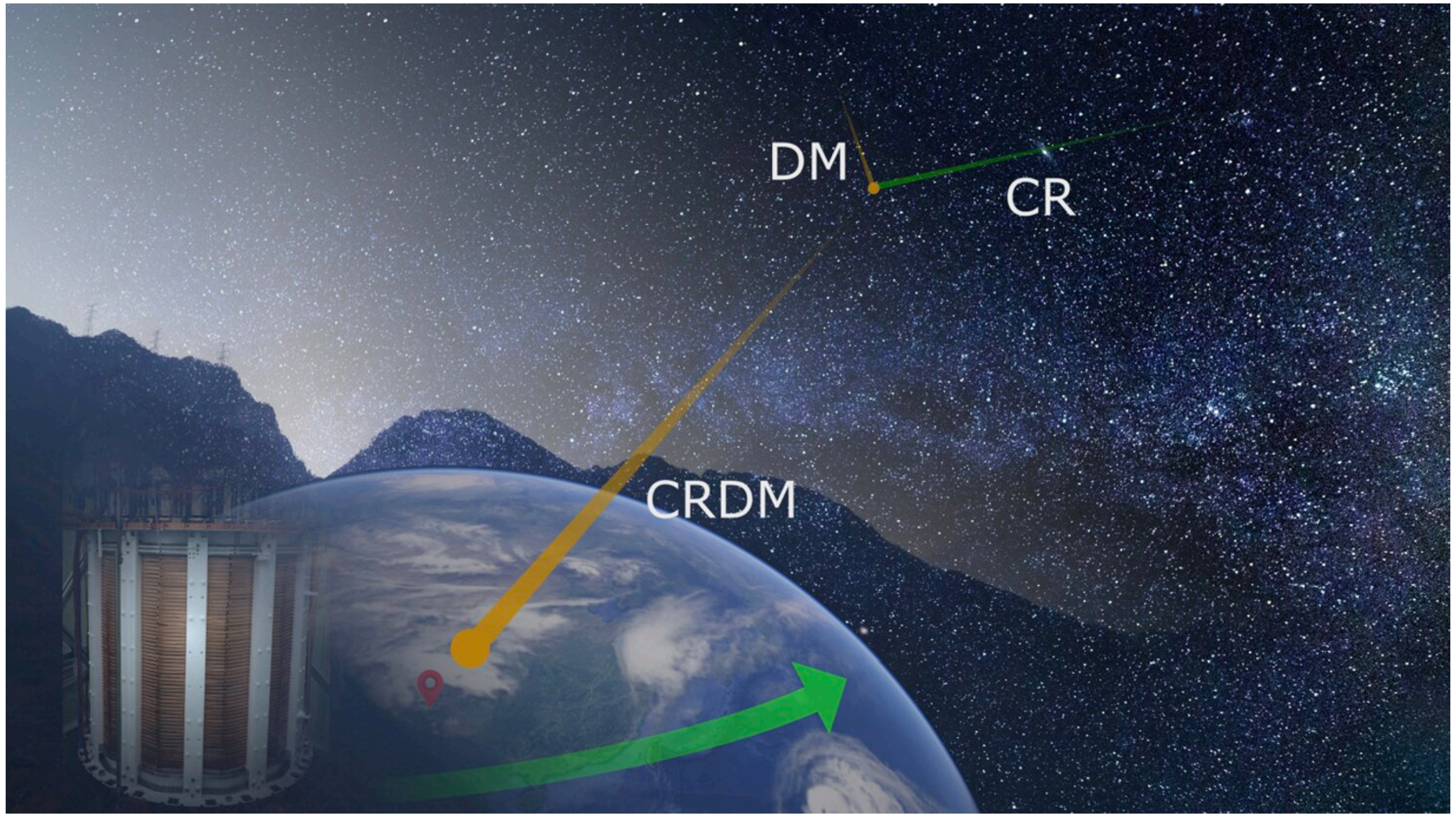


Haipeng An et al, 1708.03642 (PRL); 2108.10332 (PRD)

Astrophysics: increase the DM energy

- Cosmic-ray boosted DM
  - Light DM particles get boosted via cosmic ray collision
  - Collision and detection via nucleon scattering σ_n



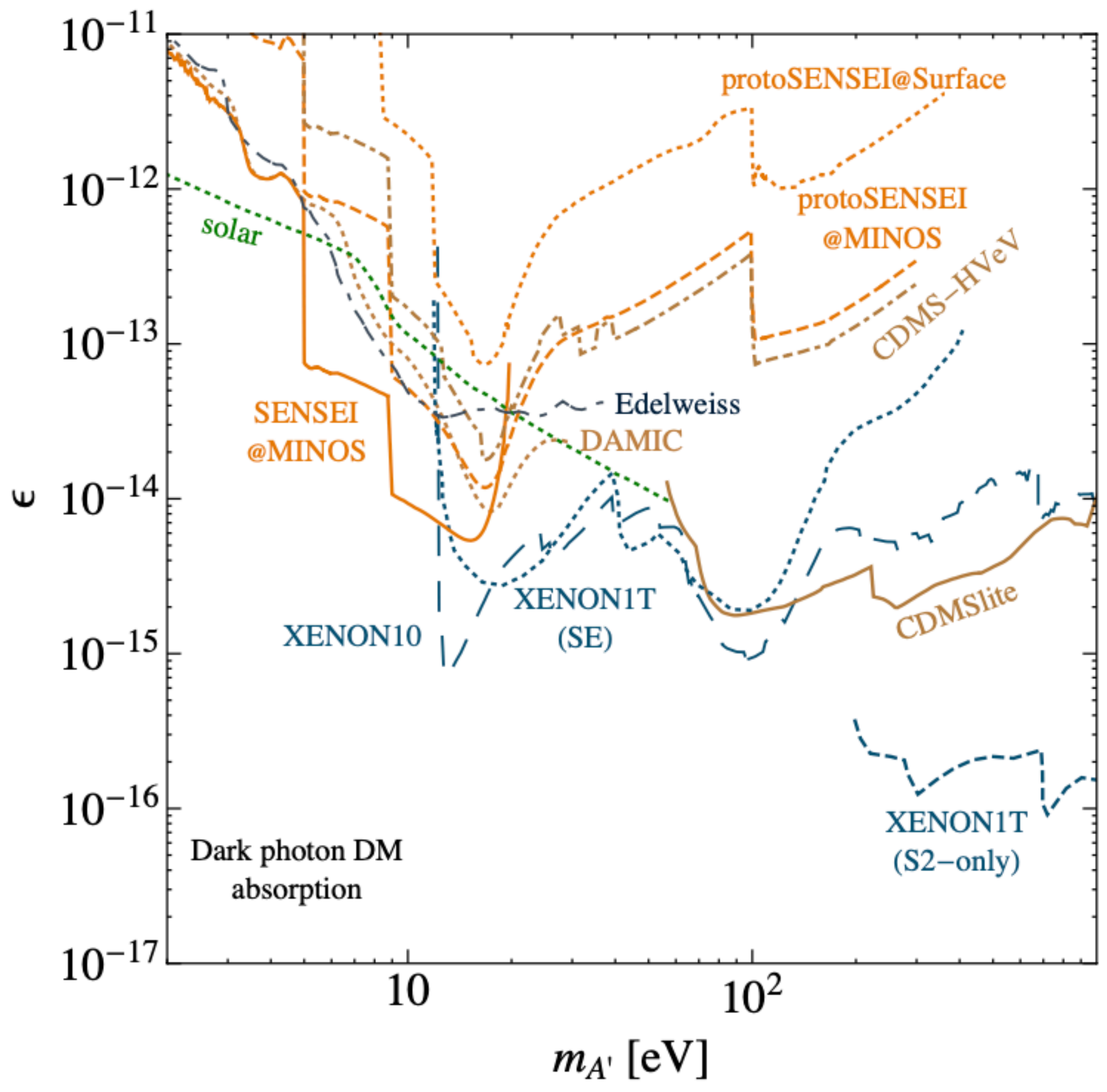


phys.org report on PANDAX results

Pospelov 1810.10543 (PRL)
Yanhao Xu, Xianwei Kang, Yufeng Zhou, Lei Wu, Shaofeng Ge, Qiang Yuan, Ning Zhou, Jianglai Liu, CDEX, PANDAX

Astrophysics: increase the translated energy

- Dark matter absorption/transition
  - Bosonic DM as dark photon (scalar) can be absorbed in Direct Detection

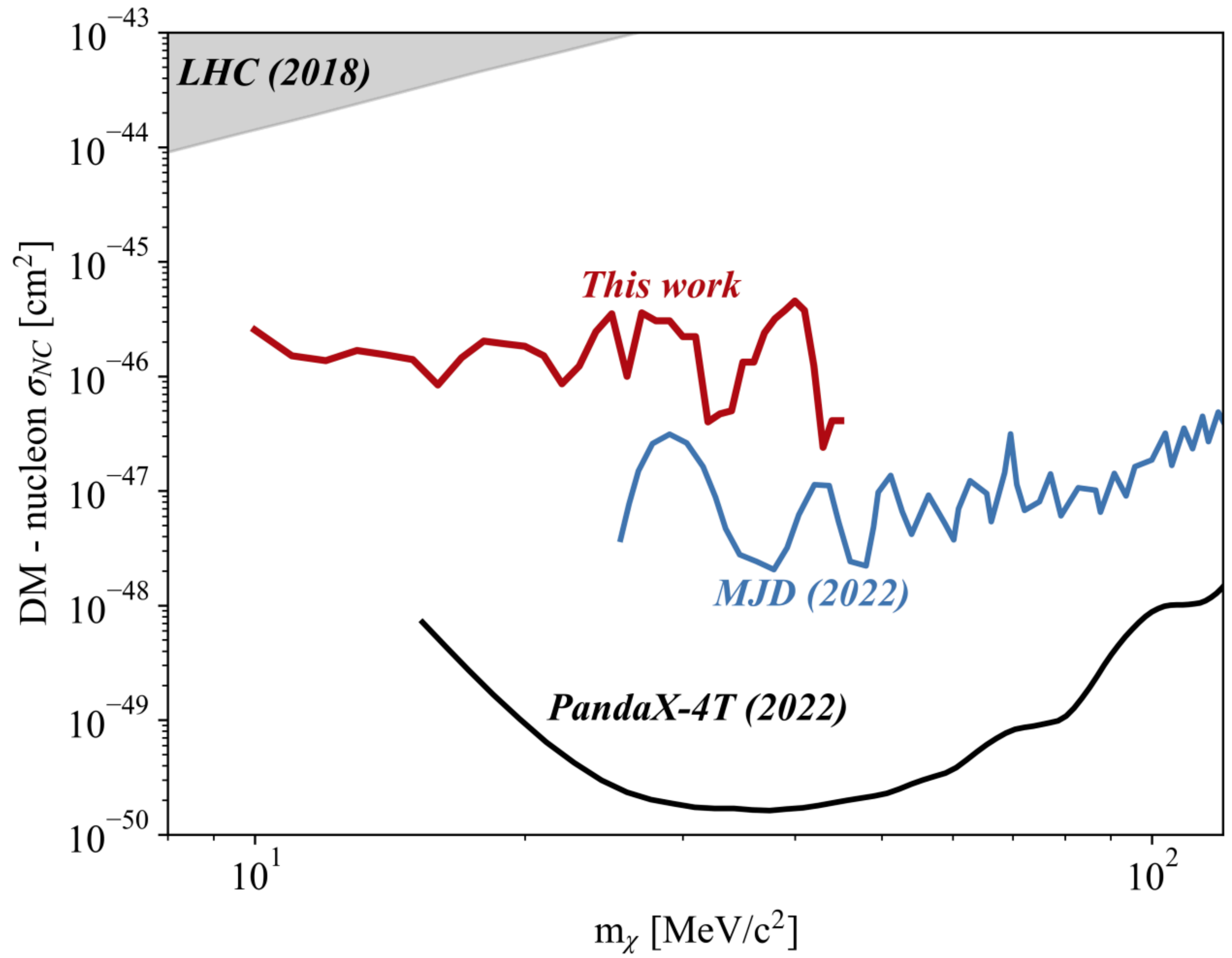


Snowmass 2021: 2203.08297

- (Fermionic) DM translate into low mass state in inelastic down-scattering

$\chi_2 q \to \chi_1 q$, long-lived $\chi_2 \to \chi_1 \gamma$

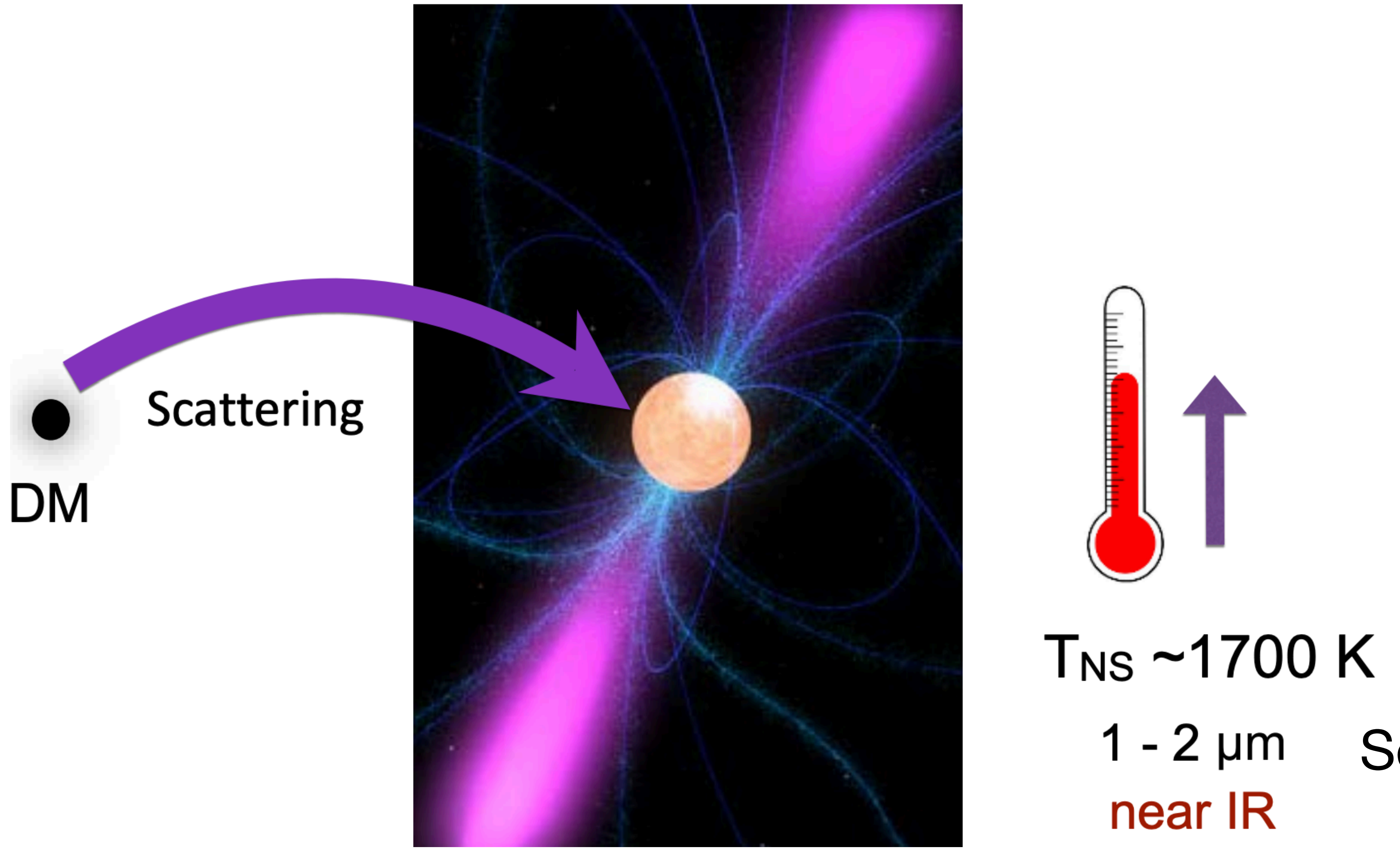
$\chi e \to \nu e$



Shaofeng Ge et al, 2201.11497 (JHEP)
PANDAX 2206.02339 (PRL)
代文翰 CDEX 2209.00861(PRL)

Astrophysics: DM heating celestial body

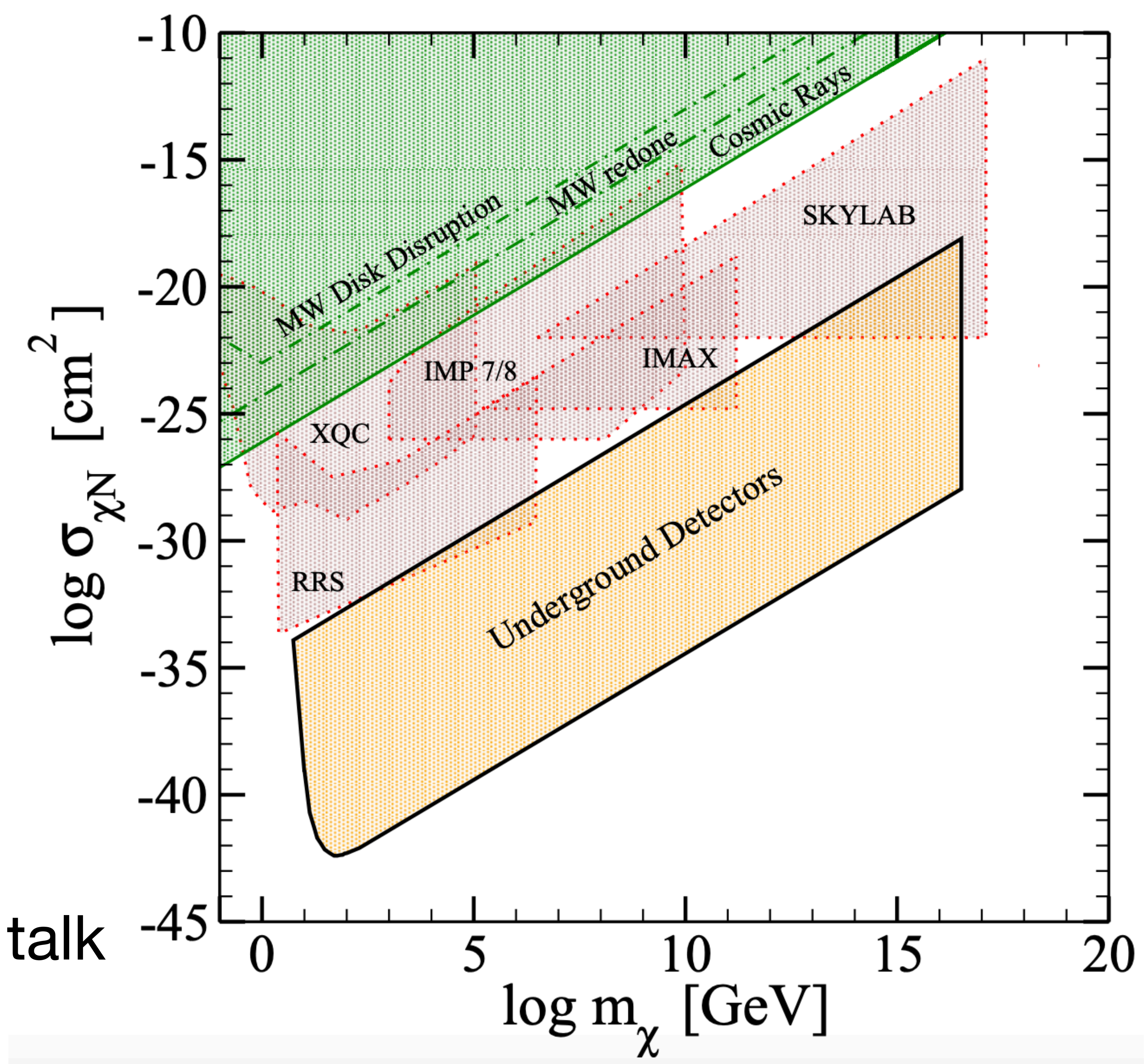
- Dark matter collides with stars and increases its temperature
  - Heating the neutron star M. Baryakhtar et al. 1704.01577 (PRL)
    - Light dark matter/DD suppressed with velocity/q
    - Detection with infrared telescopes, James Webb Space Telescope etc



See Ningqiang Song's talk

- Captured DM annihilation in the celestial body
  - Heating the Earth
  - Detect with high-altitude balloons, rockets, or satellites

J. Beacom et al. 0705.4298 (PRD)



Summary

- Light dark matter arises from null result of WIMP DD searches
- Dark sector motivated light dark matter model
- Various detection methods/ideas:
  - Direct Detection: lowering threshold with different materials
  - Intensity frontier: enough energy, important and complementary
  - Astrophysics: increasing DM energy or energy transfer, many new ideas

Thank you!