Probing the Landscape of Heavy, Strongly Interacting, and Composite Dark Matter

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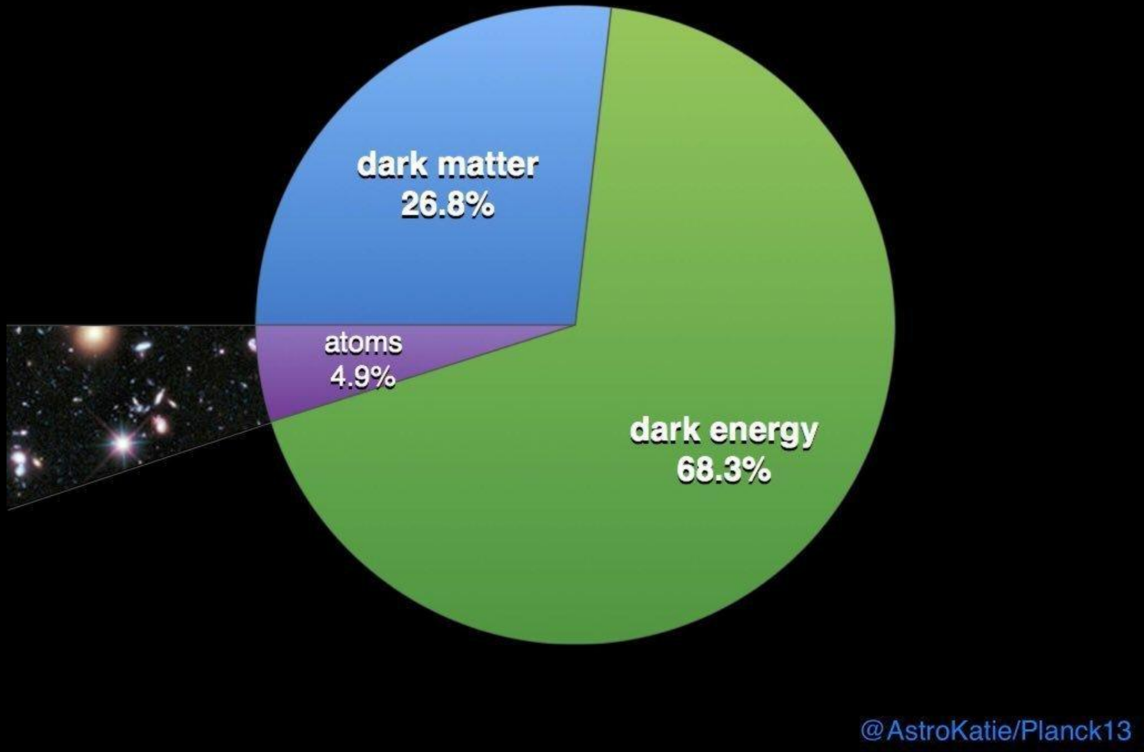
Searching for Dark Matter



Tests of dark matter: collider searches, direct detection experiments, indirect detection, cosmological probes, and much more…

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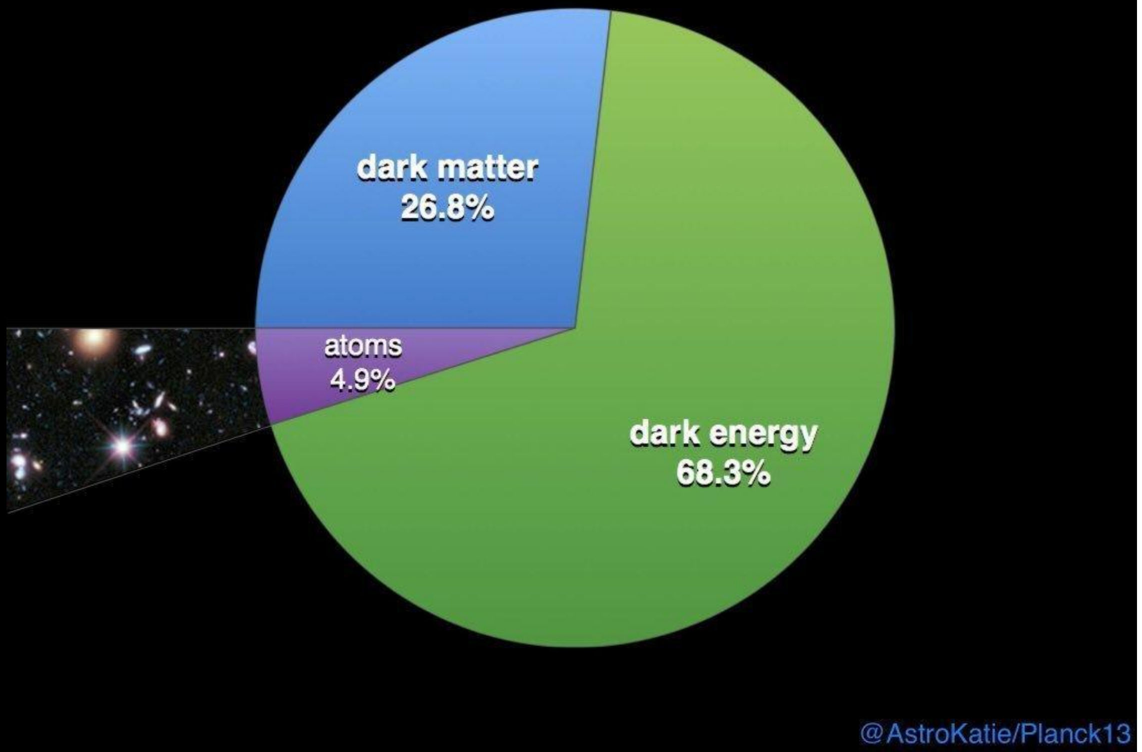

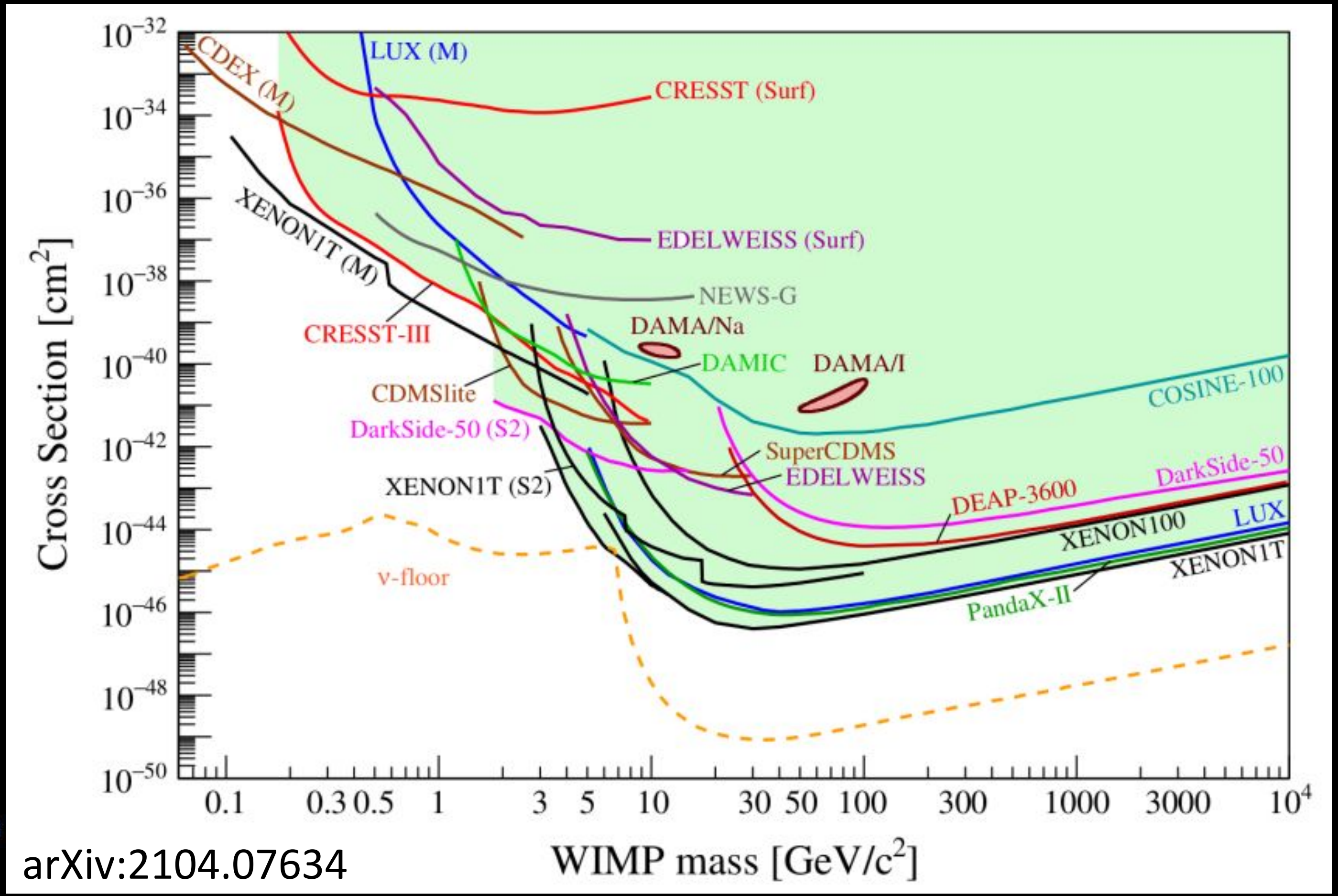

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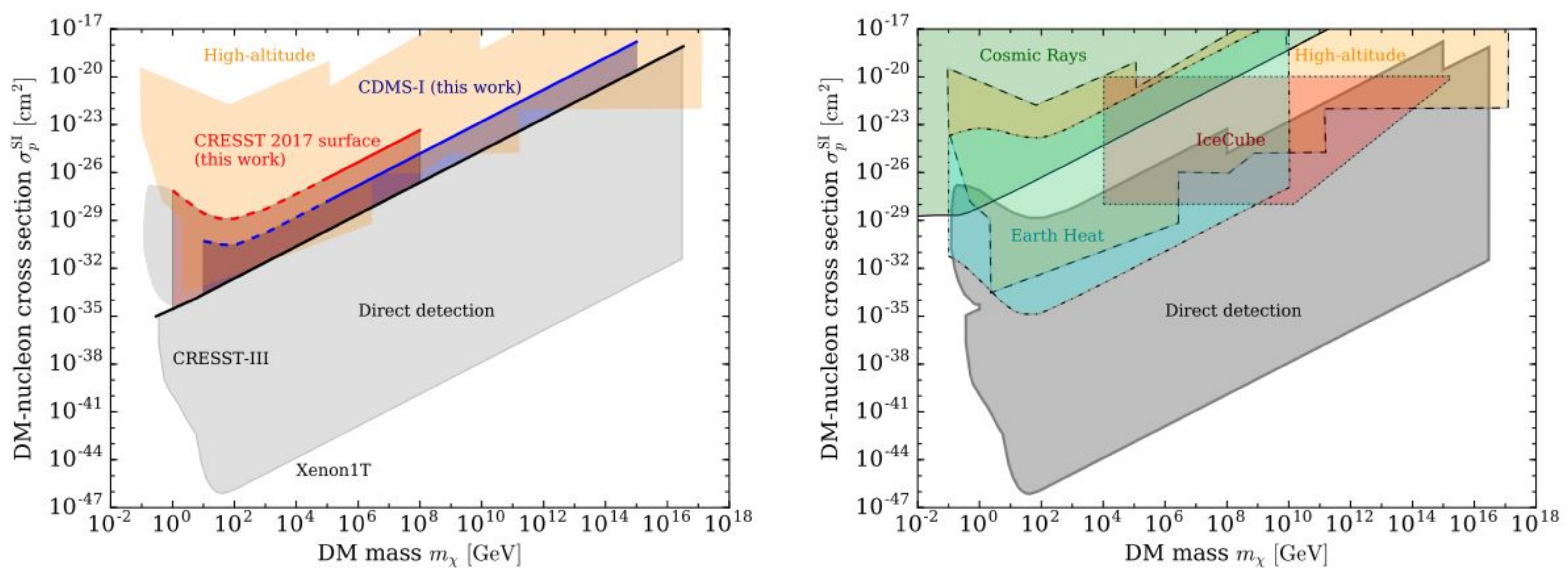
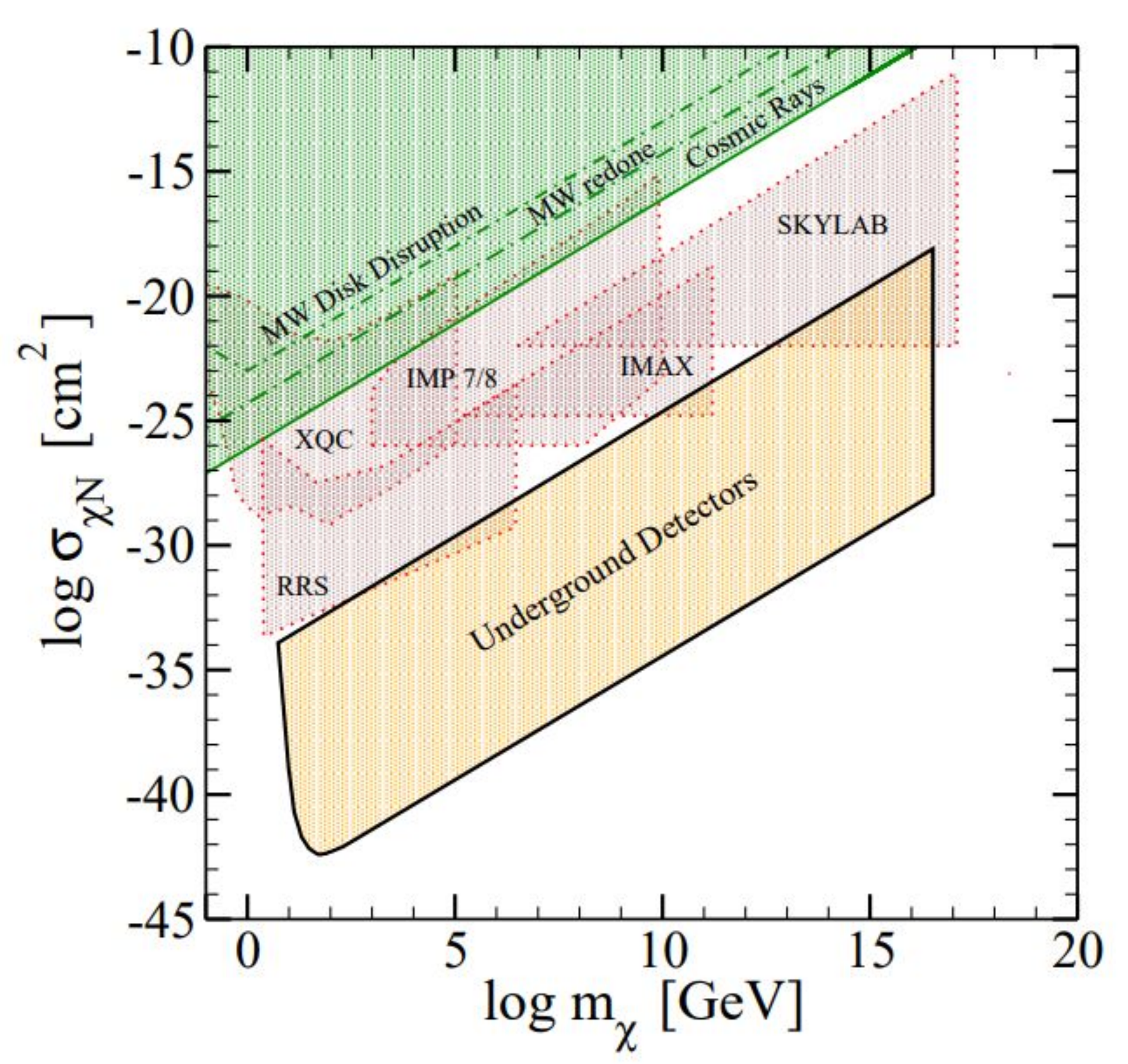
Attenuation in the Earth's Crust



arXiv:1712.04901 (Kavanagh)

Direct detection ceilings due to attenuation in the Earth (Starkman et al. 1990, Baudis & Albuquerque 2004, Mahdawi & Farrar 2017, Emken & Kouvaris 2017, Kavanagh 2018, others)

Above the Direct Detection Ceiling



arXiv:0705.4298 (Mack, Beacom, Bertone)

High Altitude Detectors
RRS (Rich et al. 1987)
Skylab (Starkman et al. 1990)
IMP/IMAX (Wandelt et al. 2000)
XQC (Erickcek et al. 2007)

Astrophysical/cosmological constraints
Interstellar Gas (Chivukula et al. 1990, Bhoonah et al. 2018 , Wadekar & Farrar 2019)
Cosmic Rays (Cyburt et al. 2007)
CMB (Chen et al. 2002, Slatyer & Wu 2018 , Xu et al. 2018)
Milky Way Satellites (Nadler et al. 2020)

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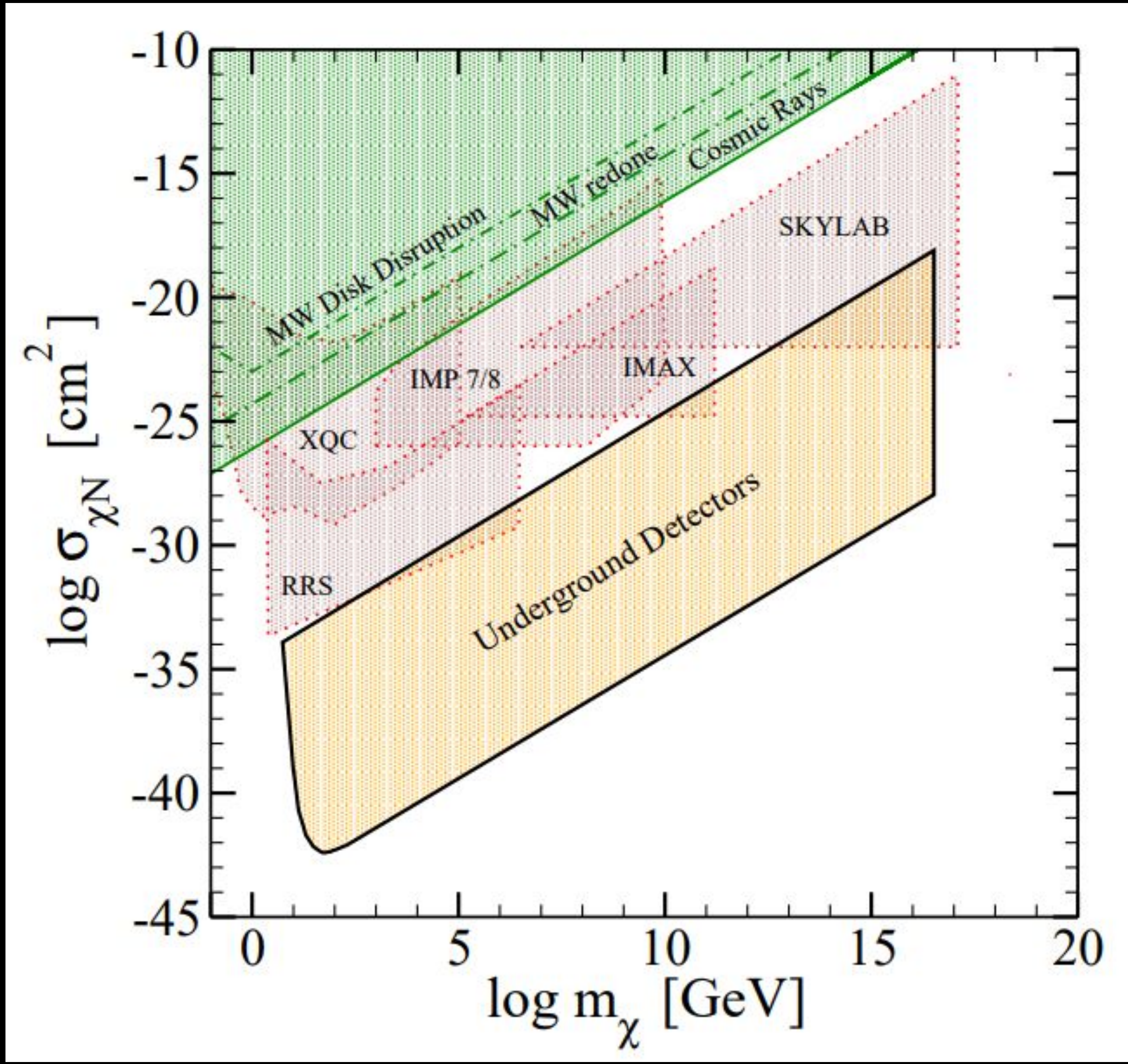

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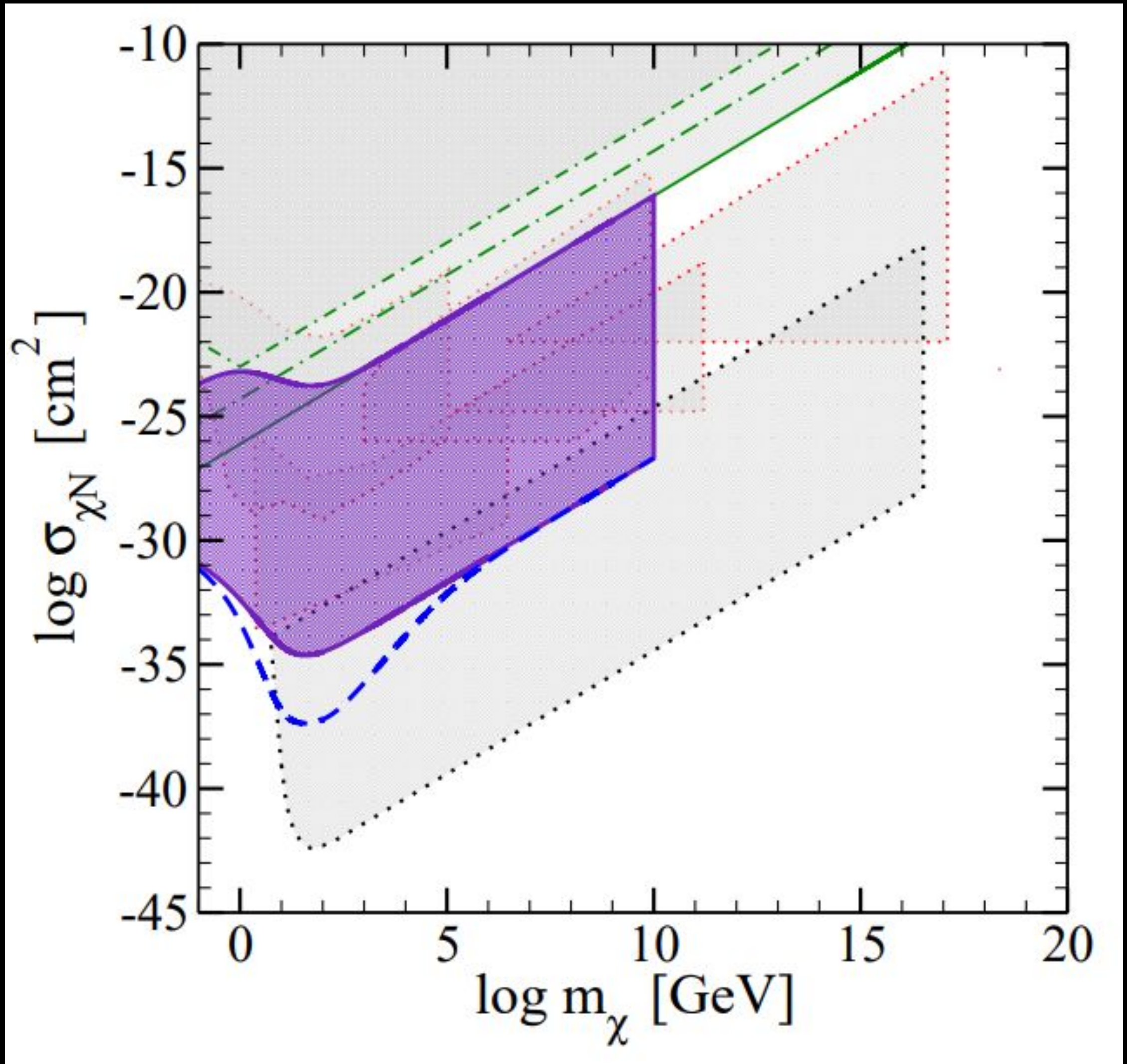


See also Bramante et al. (2019), Leanne & Smirnov (2020)

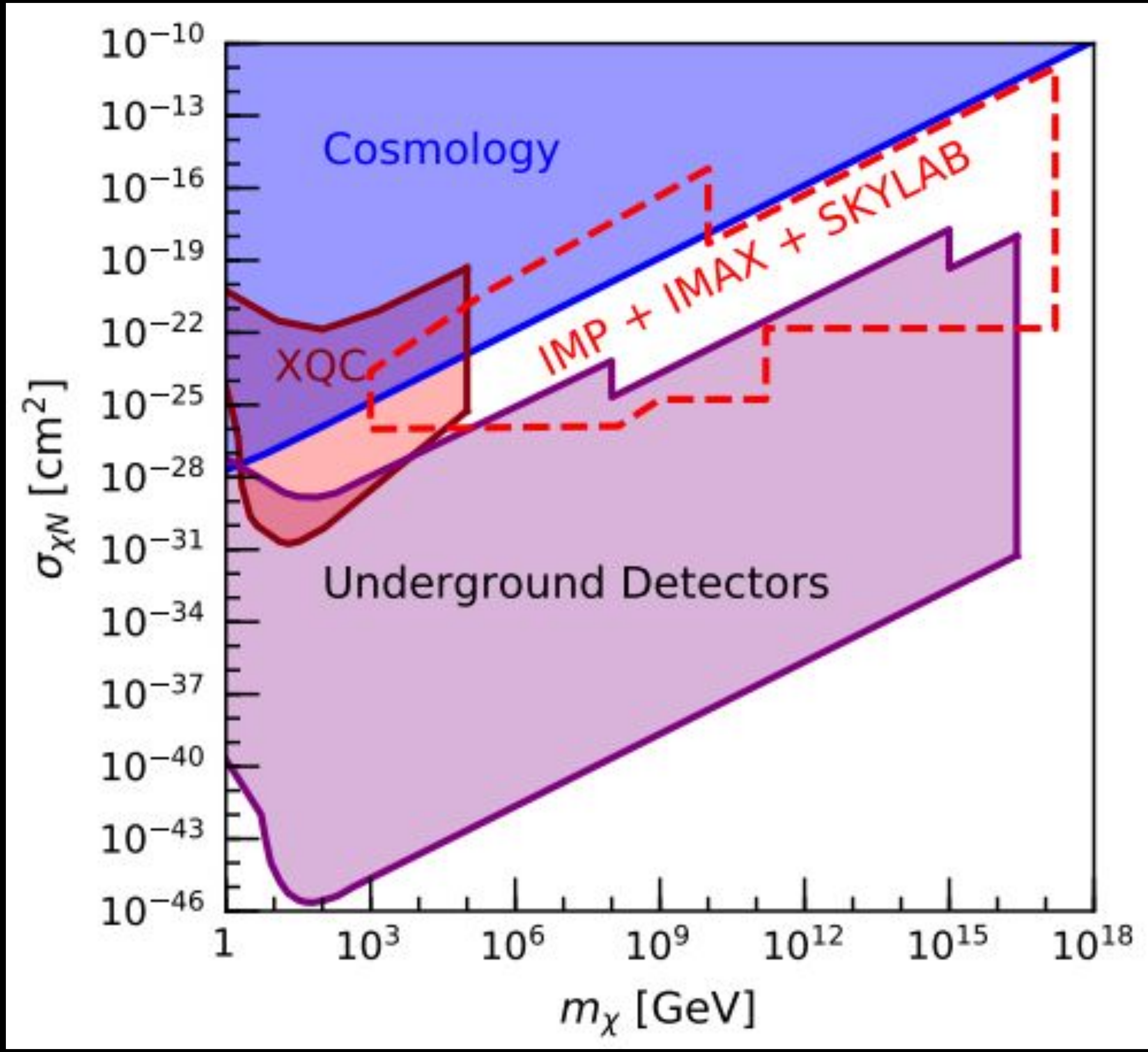
Part 1: High Cross Section Dark Matter is Dead*

Digman, Cappiello, Beacom, Hirata, and Peter, arXiv:1907.10618
(PRD 100 063013)

Spin-Independent Scattering Scaling Relation

- Typical assumptions: pointlike DM, contact interaction with nuclei
- Maximum DM cross section based on energy loss in shielding
- For spin-independent WIMP scattering, standard relation between cross sections:

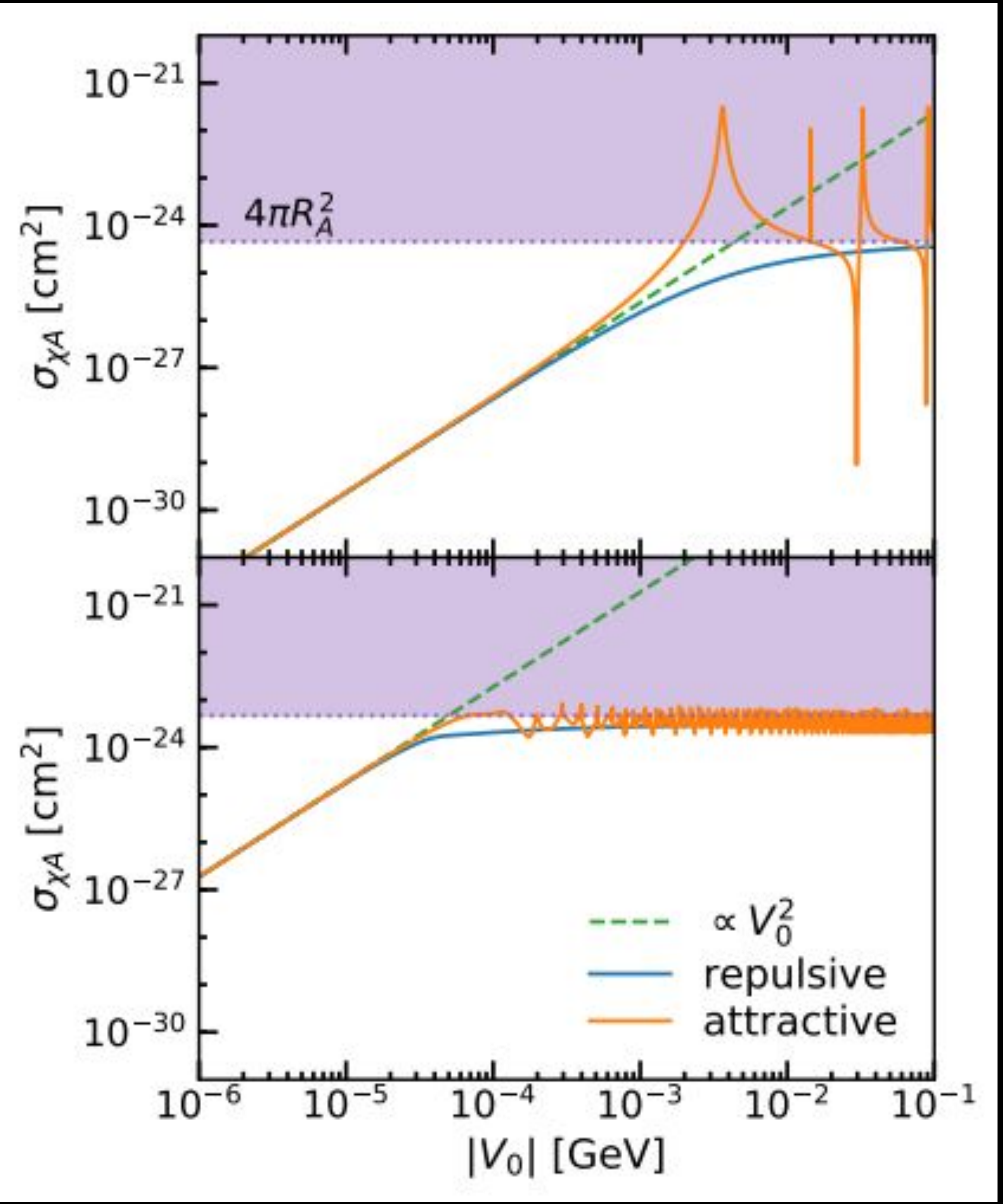
$$\sigma_{XA} = (\mu_{XA}/\mu_{XN})^2 A^2 \sigma_{XN} \approx A^4 \sigma_{XN}$$



arXiv:1907.10618 (Digman, **Cappiello** et al.)

Breakdown of Traditional Scaling

- Green dashed line: cross section assuming A^4 scaling
- Maximum cross section for repulsive potential: $4\pi R^2$
- Attractive potential: only narrow resonances reach higher cross section
- Top: ^{4}He; Bottom: ^{131}Xe



arXiv:1907.10618
(Digman, **Cappiello** et al.)

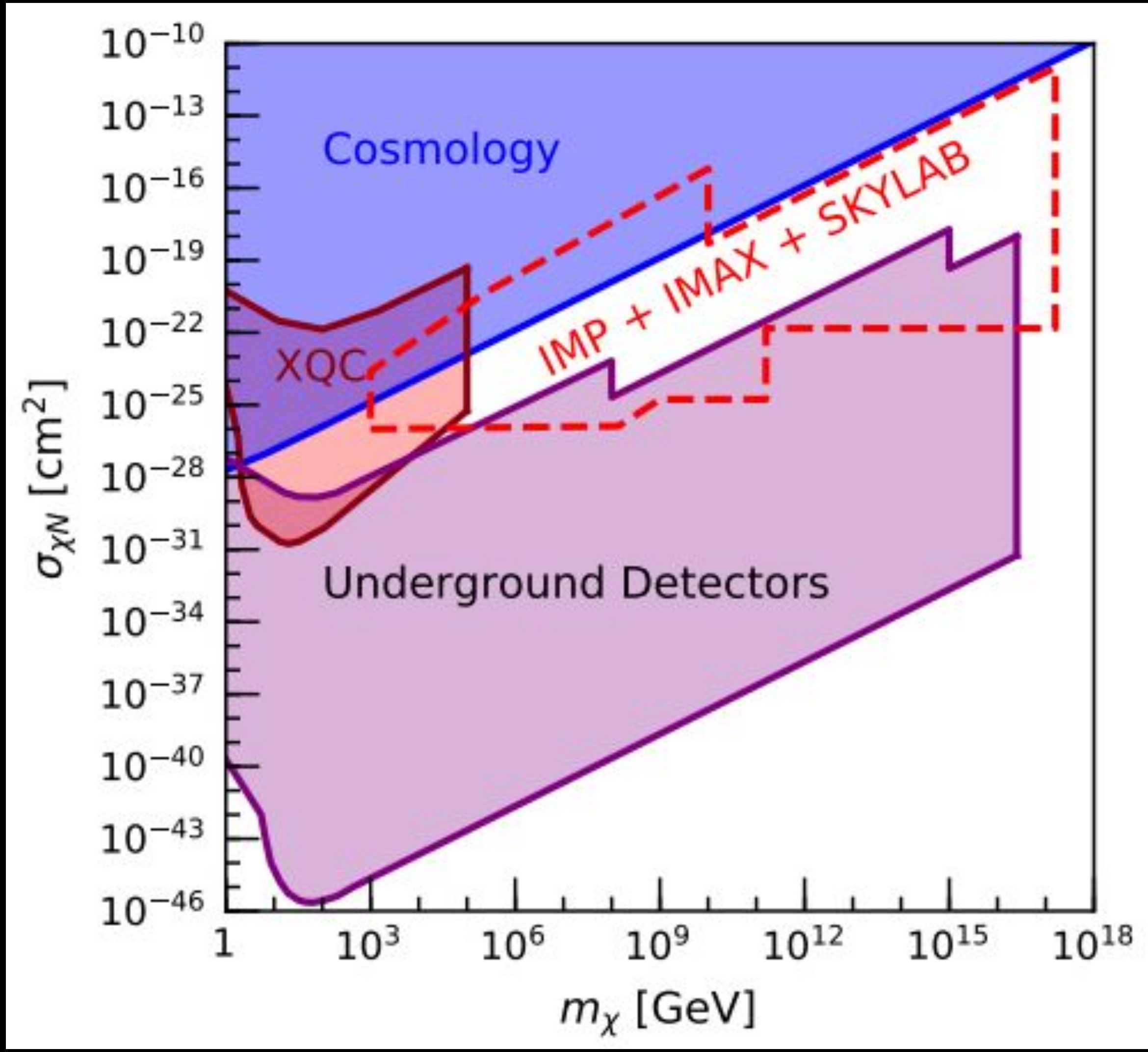
Direct Detection Ceiling

- Maximum DM mass determined by exposure

- Maximum DM cross section based on energy loss in shielding

- For spin-independent WIMP scattering, standard relation between cross sections:

$$\sigma_{\chi A} = (\mu_{\chi A}/\mu_{\chi N})^2 A^2 \sigma_{\chi N} \approx A^4 \sigma_{\chi N}$$



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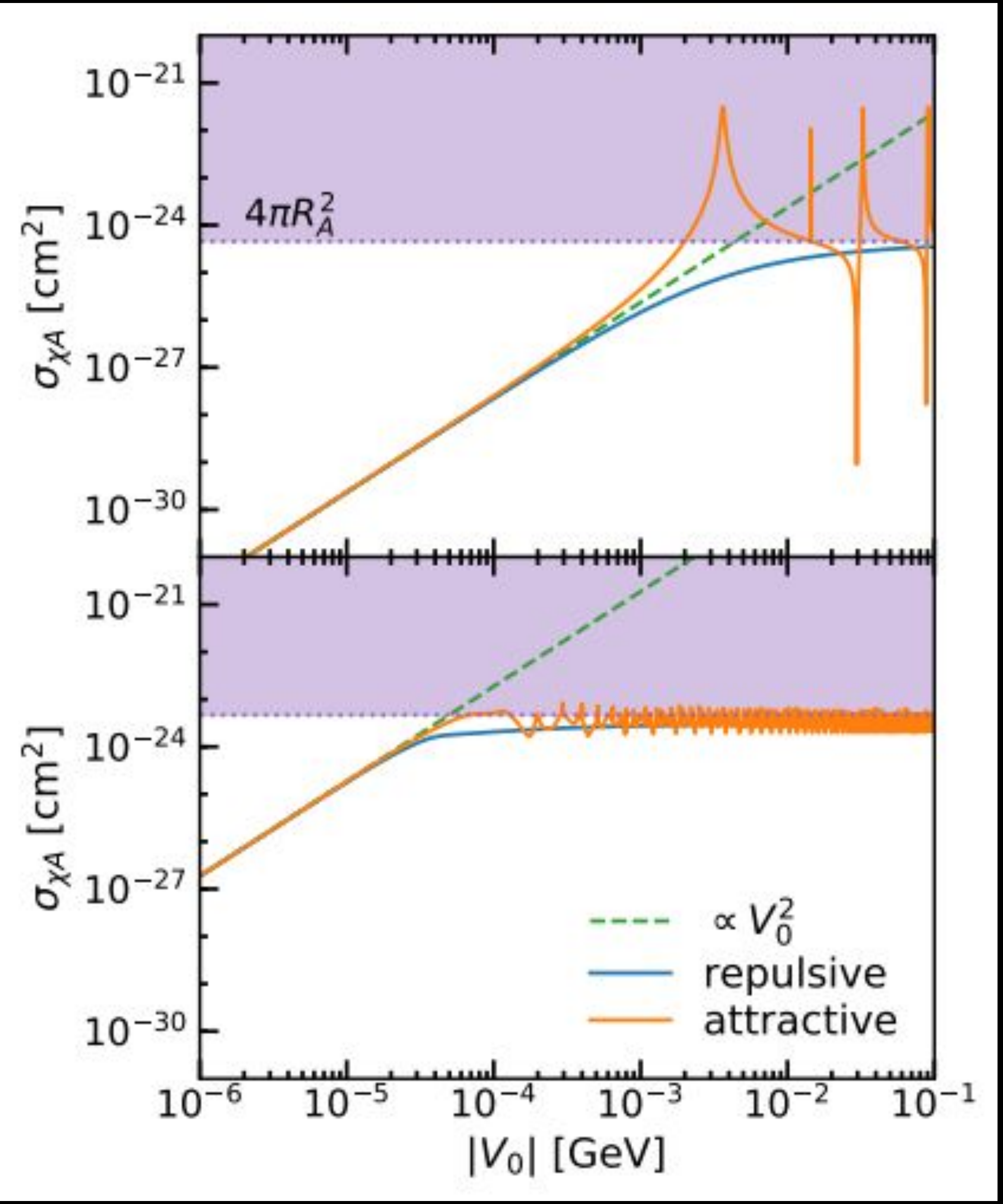

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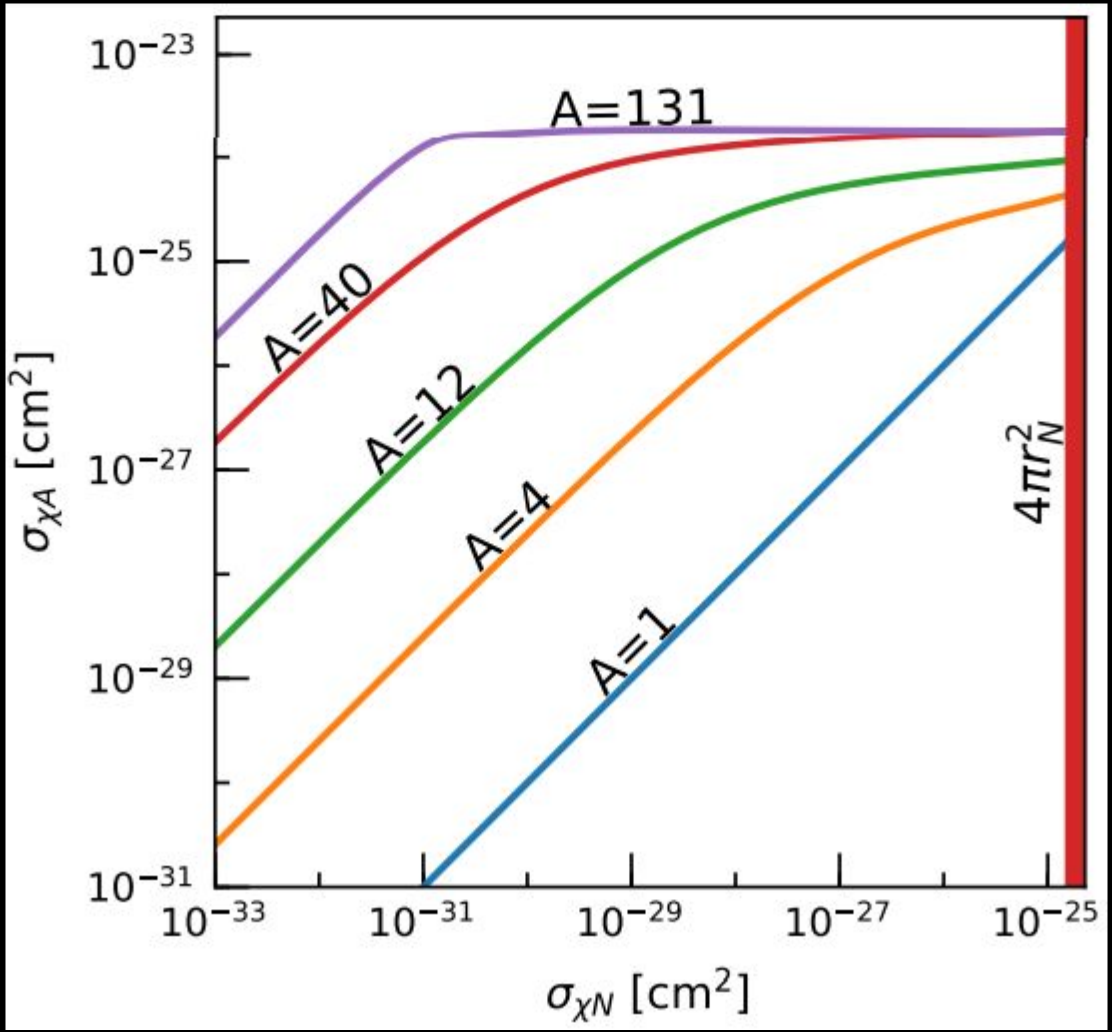
Nucleus vs Nucleon Cross Section

- DM-nucleus cross section saturates at $4\pi R^2$
- A^4 scaling breaks down far below computed ceilings
- Maximum nucleon cross section: $\sim 10^{-25}$ cm^2



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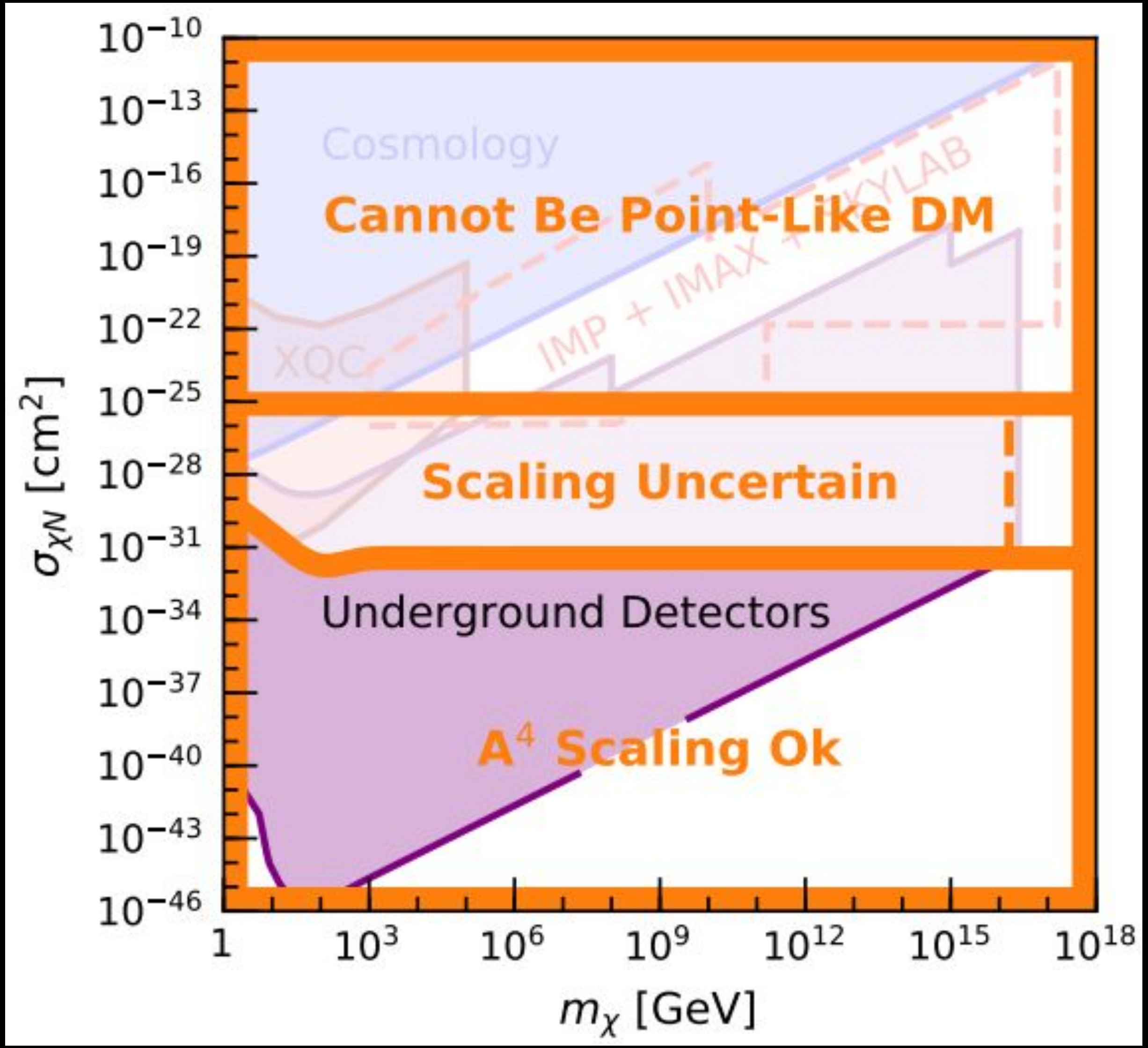
Maximum Cross Section for Pointlike DM

- Low cross section: scaling works fine
- Intermediate cross section: typical scaling breaks down depending on nucleus
- High cross section: not possible for point-like dark matter
- <u>Large cross sections are impossible</u> (maybe…)



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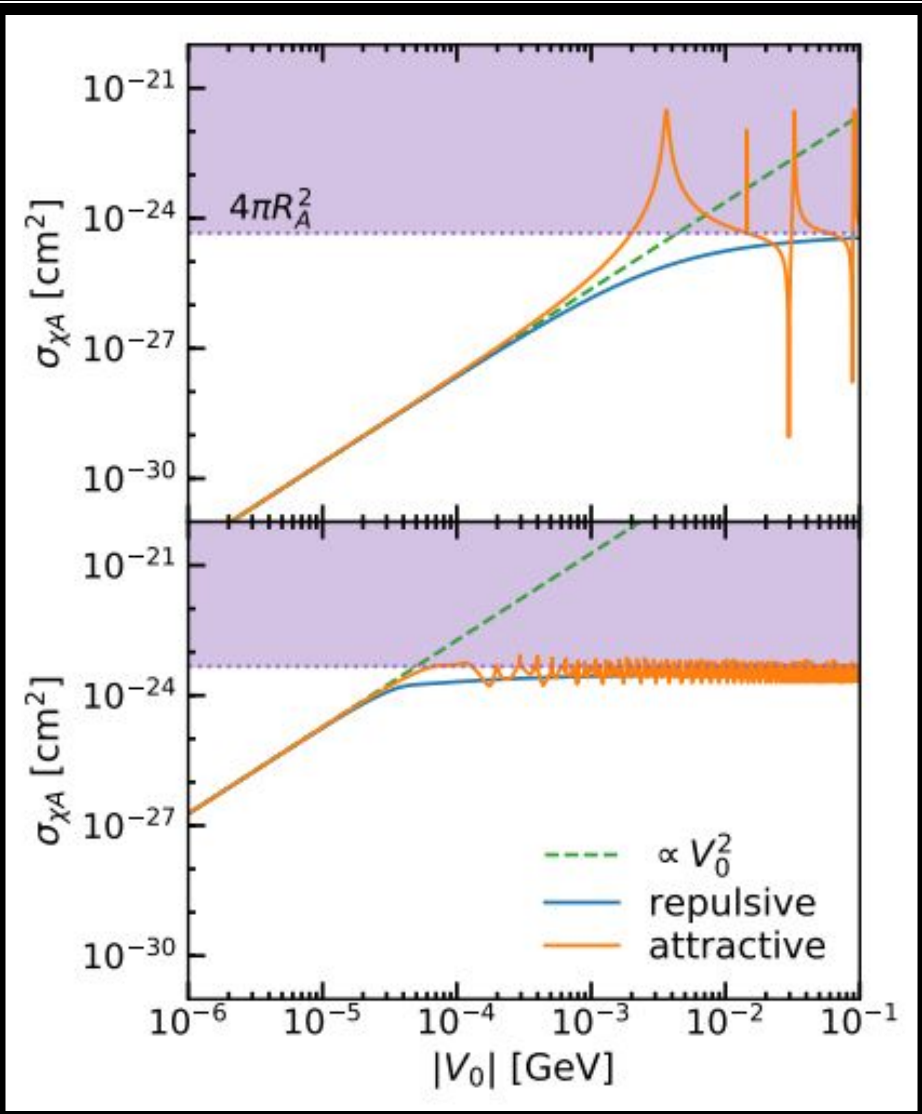
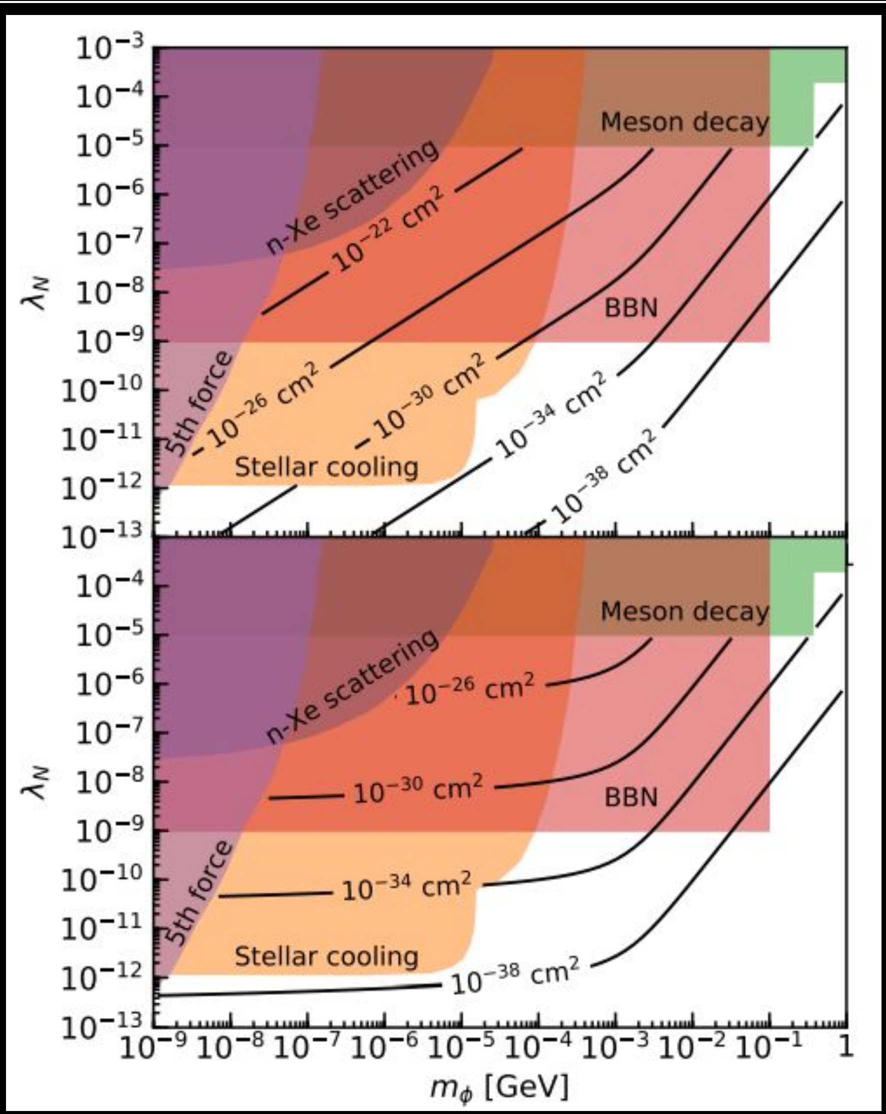
Attractive Resonances and Light Mediators





Resonances: see e.g. arXiv:2101.00142 (Xu & Farrar 2021)

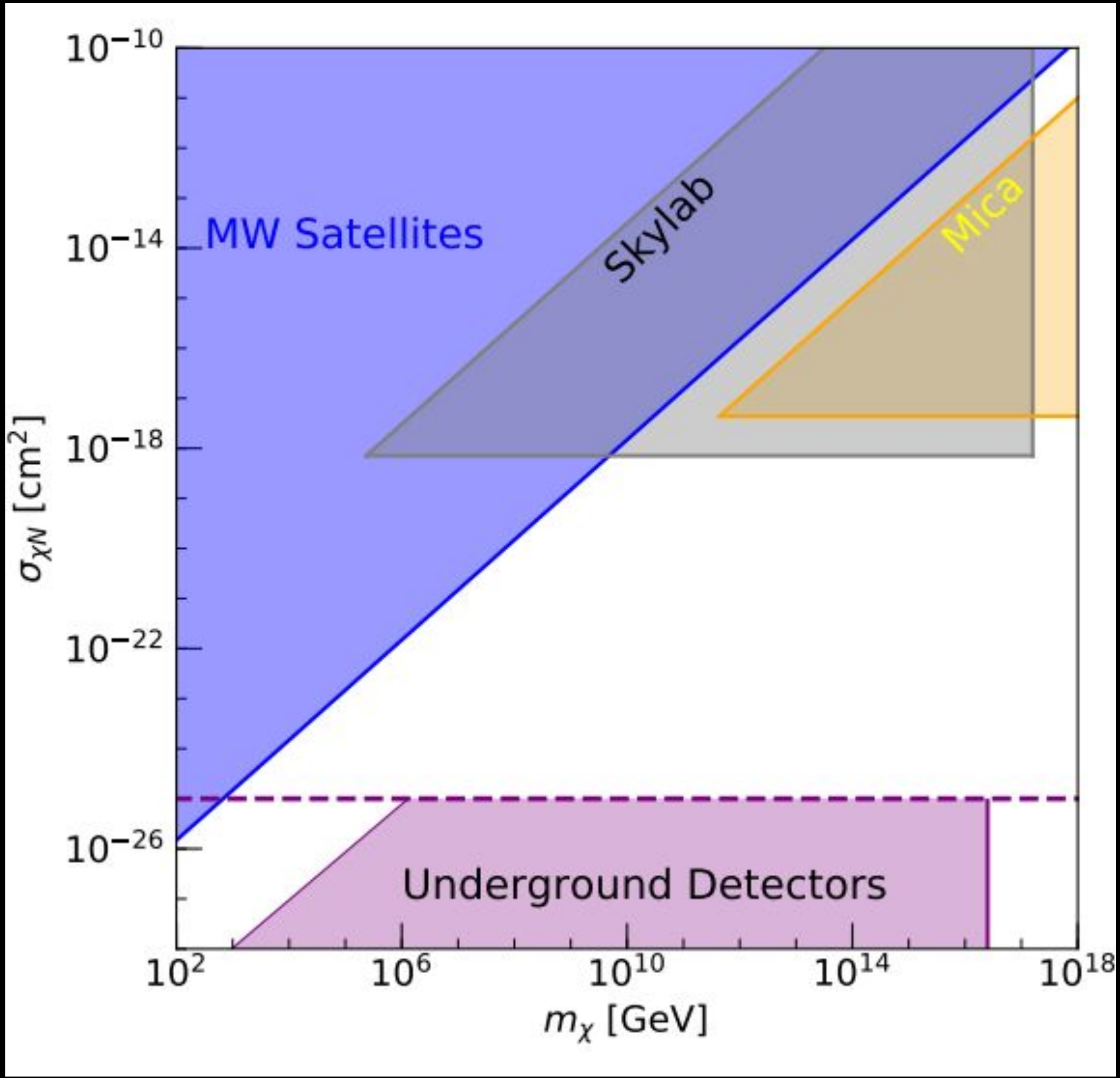
Light Mediators: see e.g. arXiv:1709.07882 (Knapen, Lin & Zurek 2017)

Part 2: Long Live High Cross Section Dark Matter

Cappiello, Collar, and Beacom, arXiv:2008.10646 (PRD 103 023019)

An Alternative: Composite Dark Matter

- Composite dark matter: can achieve large cross sections if $R_X > R_N$
- Simple model: $\sigma_{\chi N} = \sigma_{\chi A} = \pi R_X^{\,2}$
- Dashed purple line: largest cross section for pointlike dark matter
- Gap in limits between maximum point cross section and structure formation bounds



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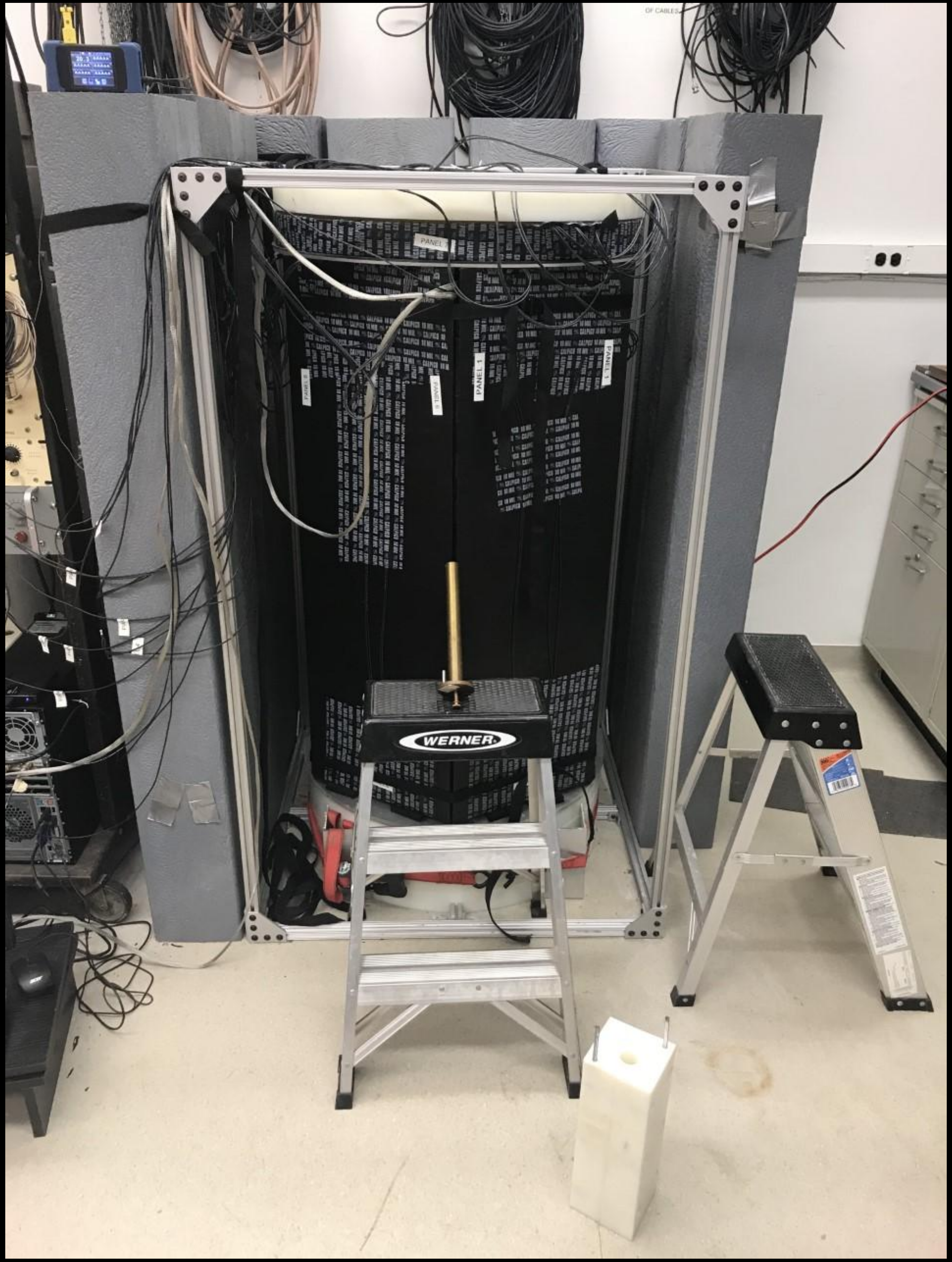

WERNER
PANEL 1

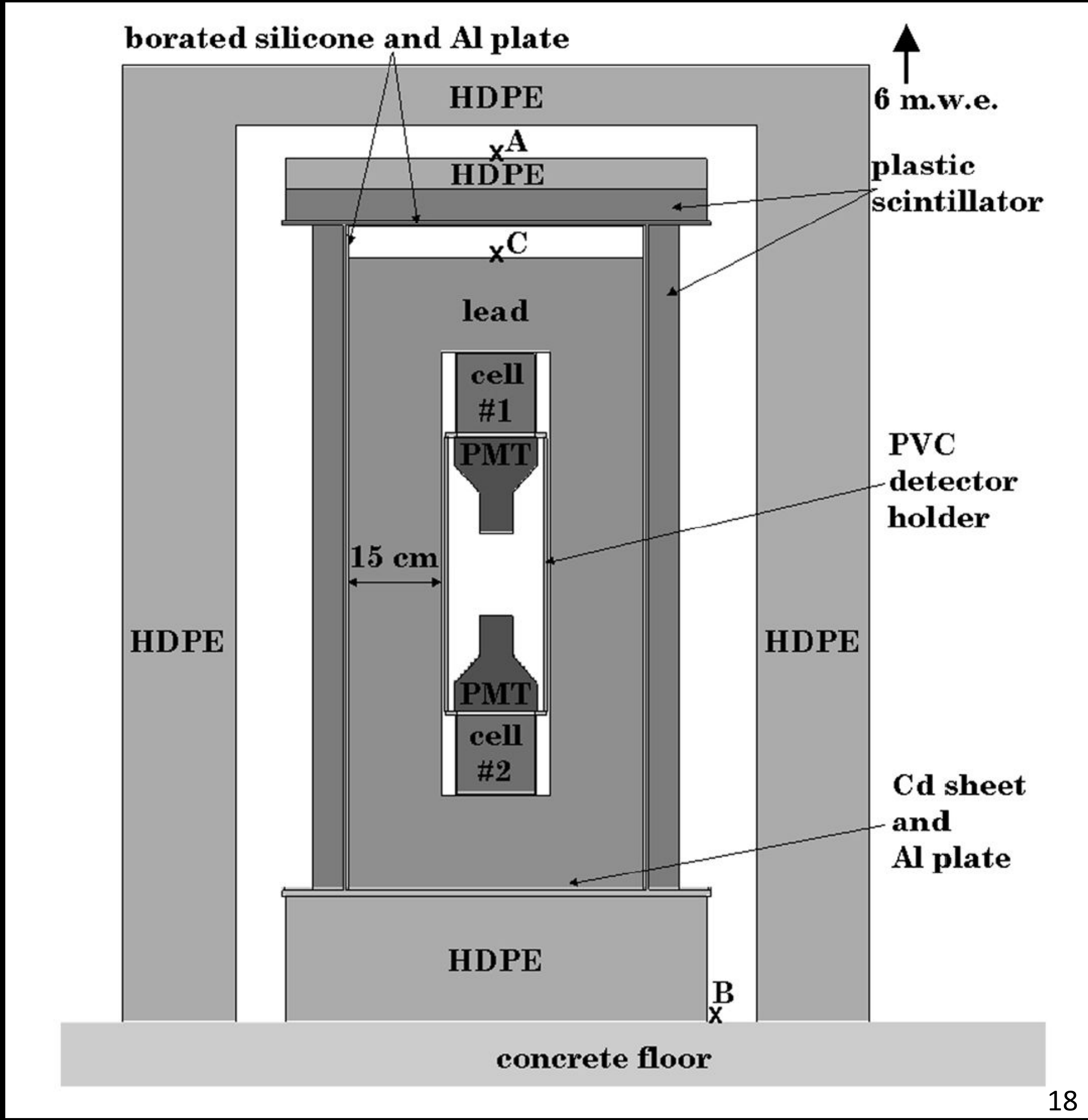
PANEL 4
PANEL 3
PANEL 6
CALPICO 10 MIL

Detector Setup

- Experimental setup and data from Juan Collar at University of Chicago's shallow depth lab

- Detector uses two EJ-301 cells containing hydrogen-rich liquid scintillator, able to distinguish NR from ER

- Two-cell design: time-of-flight used to discriminate between dark matter and relativistic backgrounds



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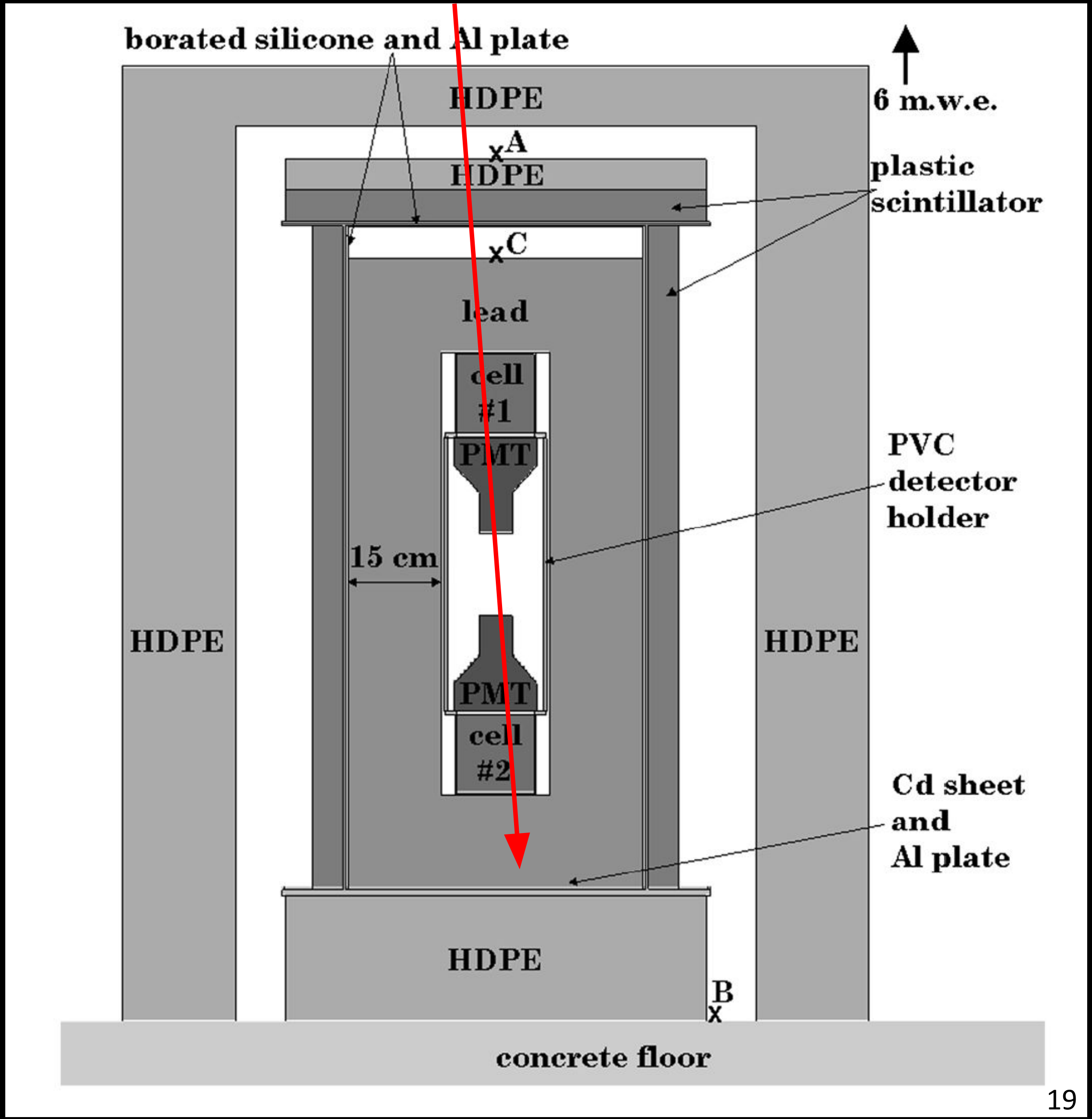
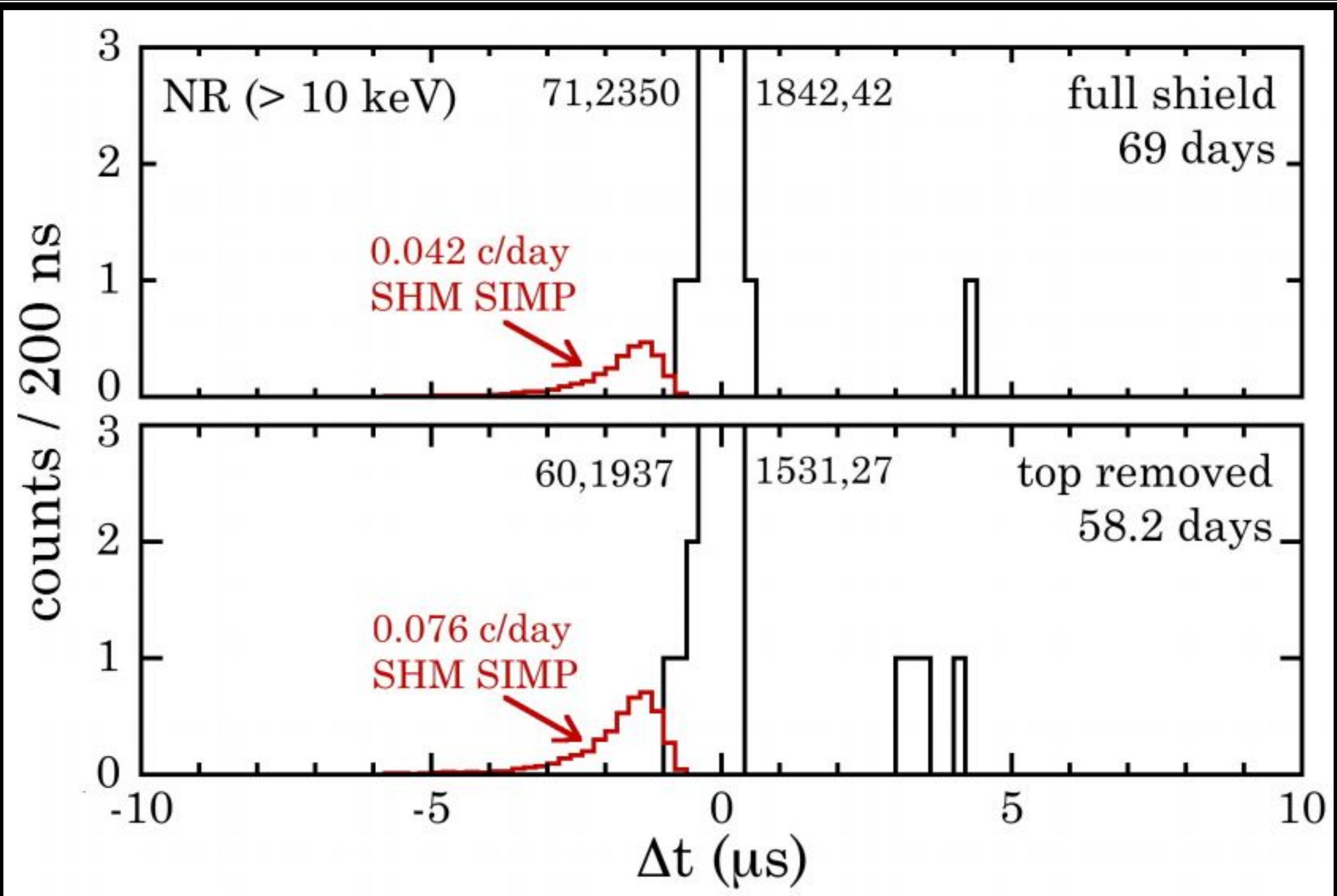


Time Delay Distribution



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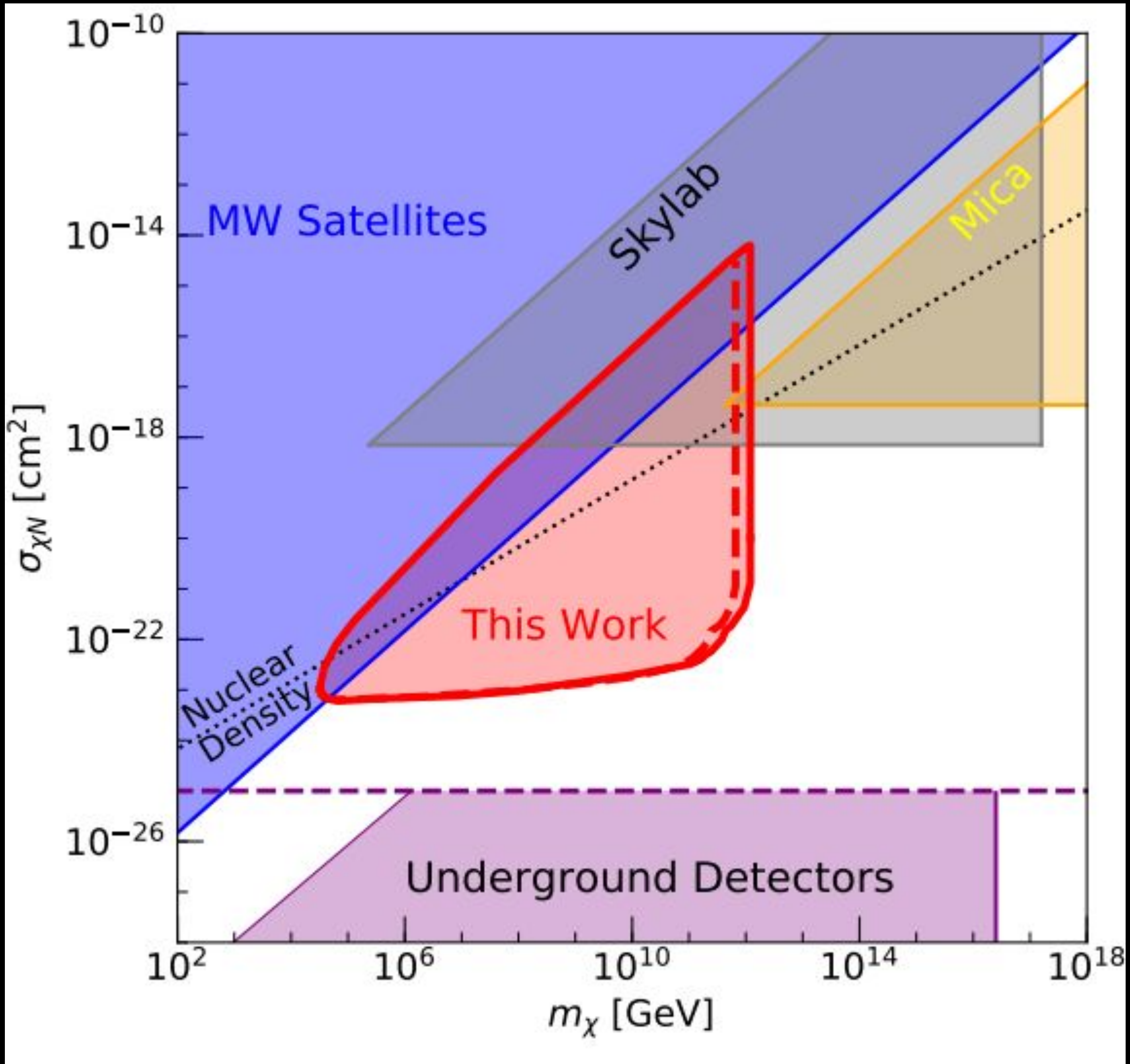
New Constraints on Composite Dark Matter

- Ceiling determined by attenuation in atmosphere and shielding
- Bottom of region set by energy threshold
- High mass edge determined by exposure (time and acceptance angle)



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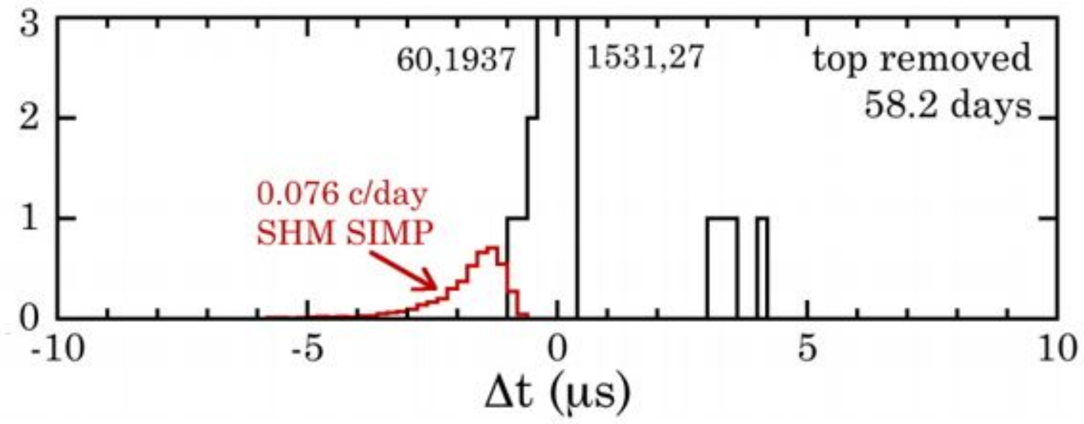

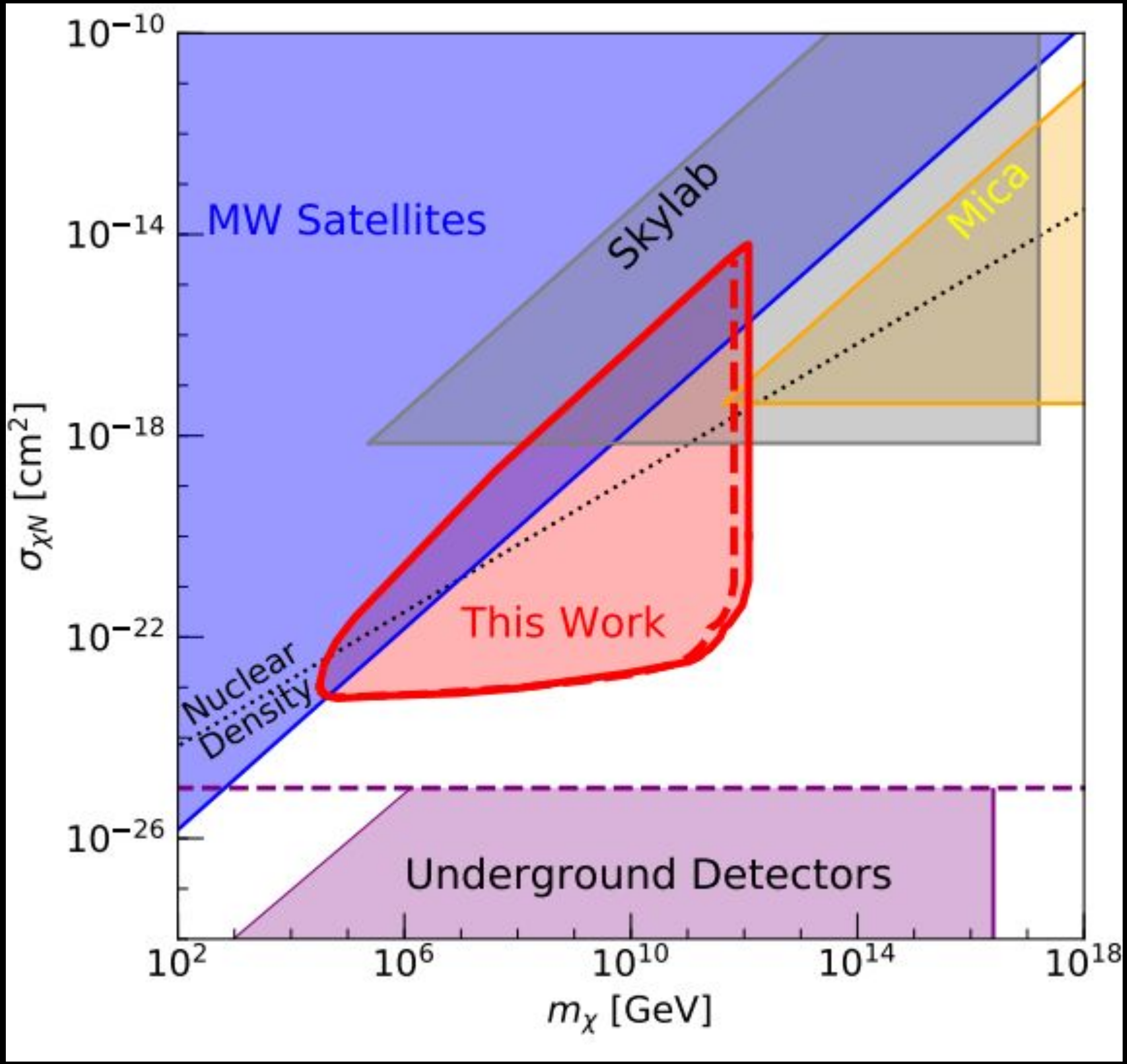

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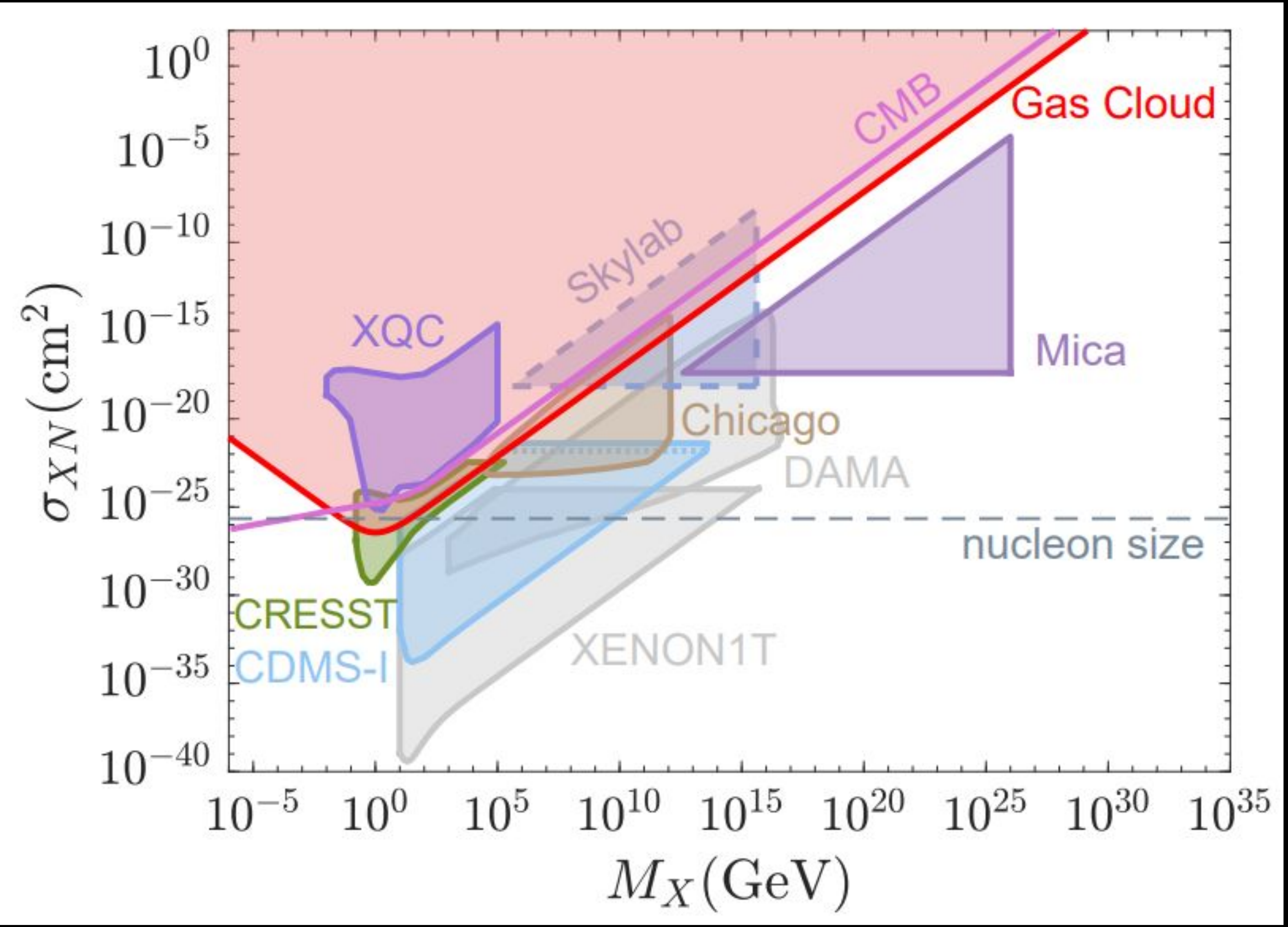
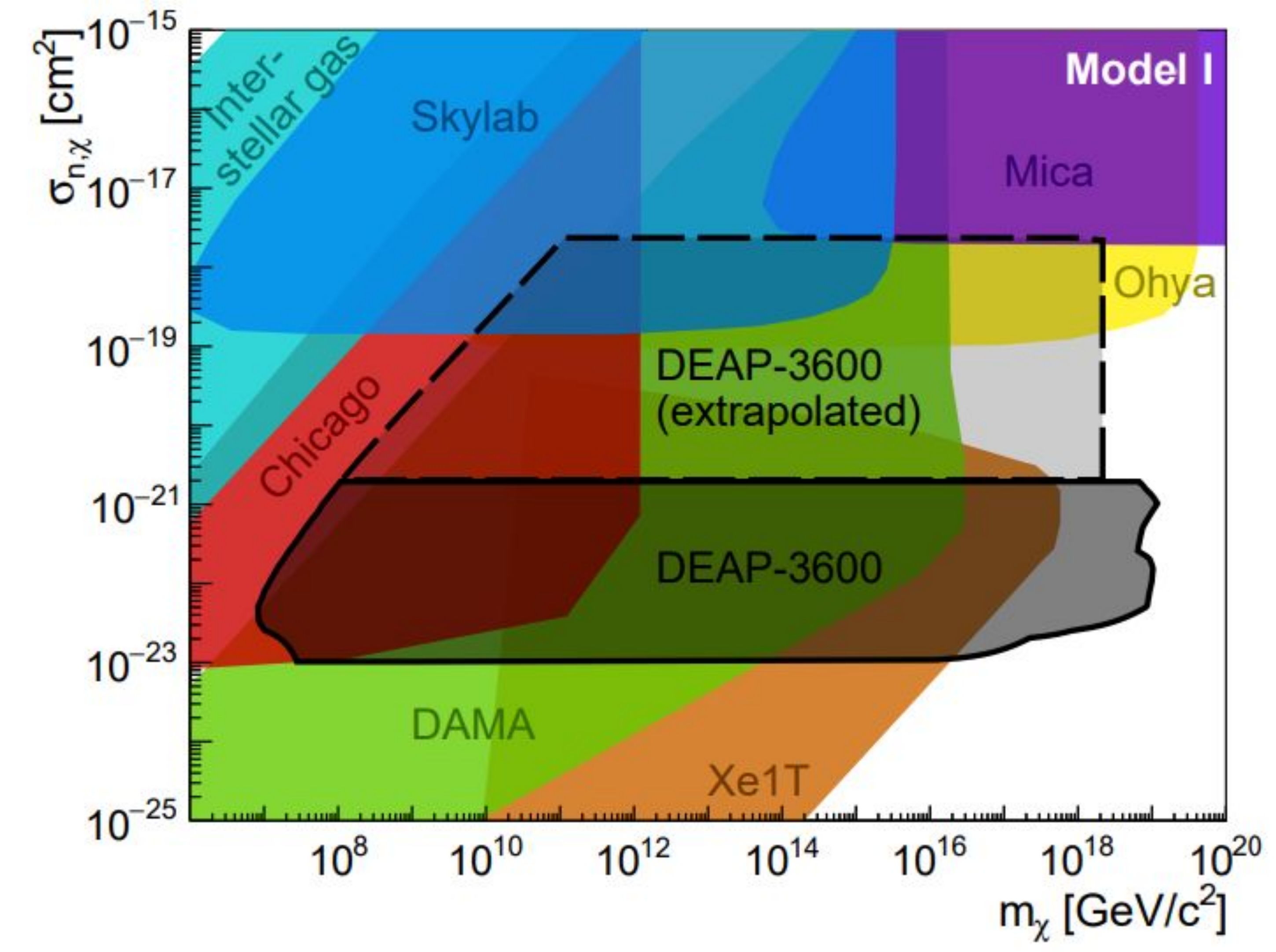
Direct Detection and Composite Dark Matter



arXiv:2010.07240 (Bhoonah et al.)

Additional Constraints

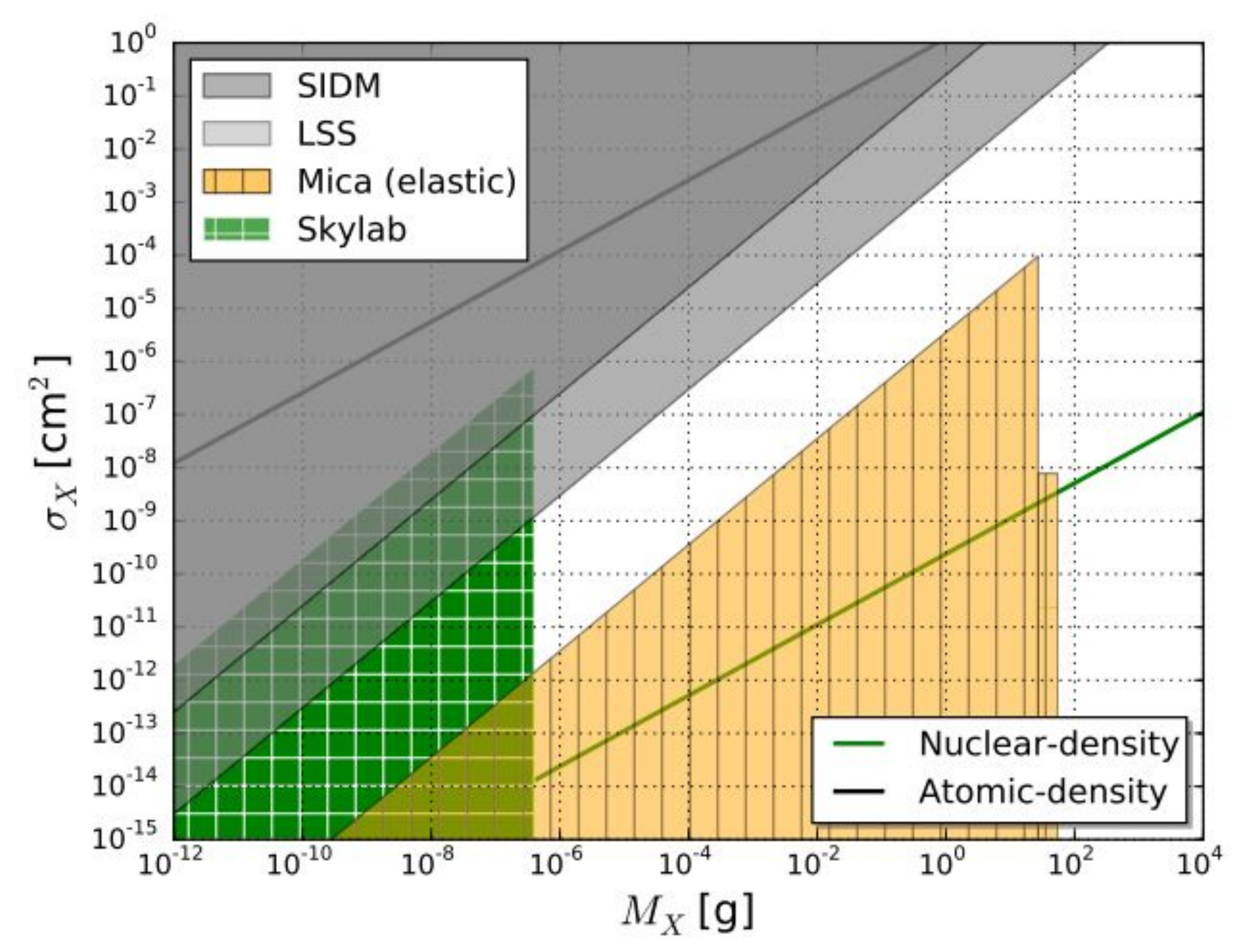


arXiv:2108.09405 (Adhikari et al.)

Part 3: Mica, Meteors, and Dark Matter Beyond the Planck Mass

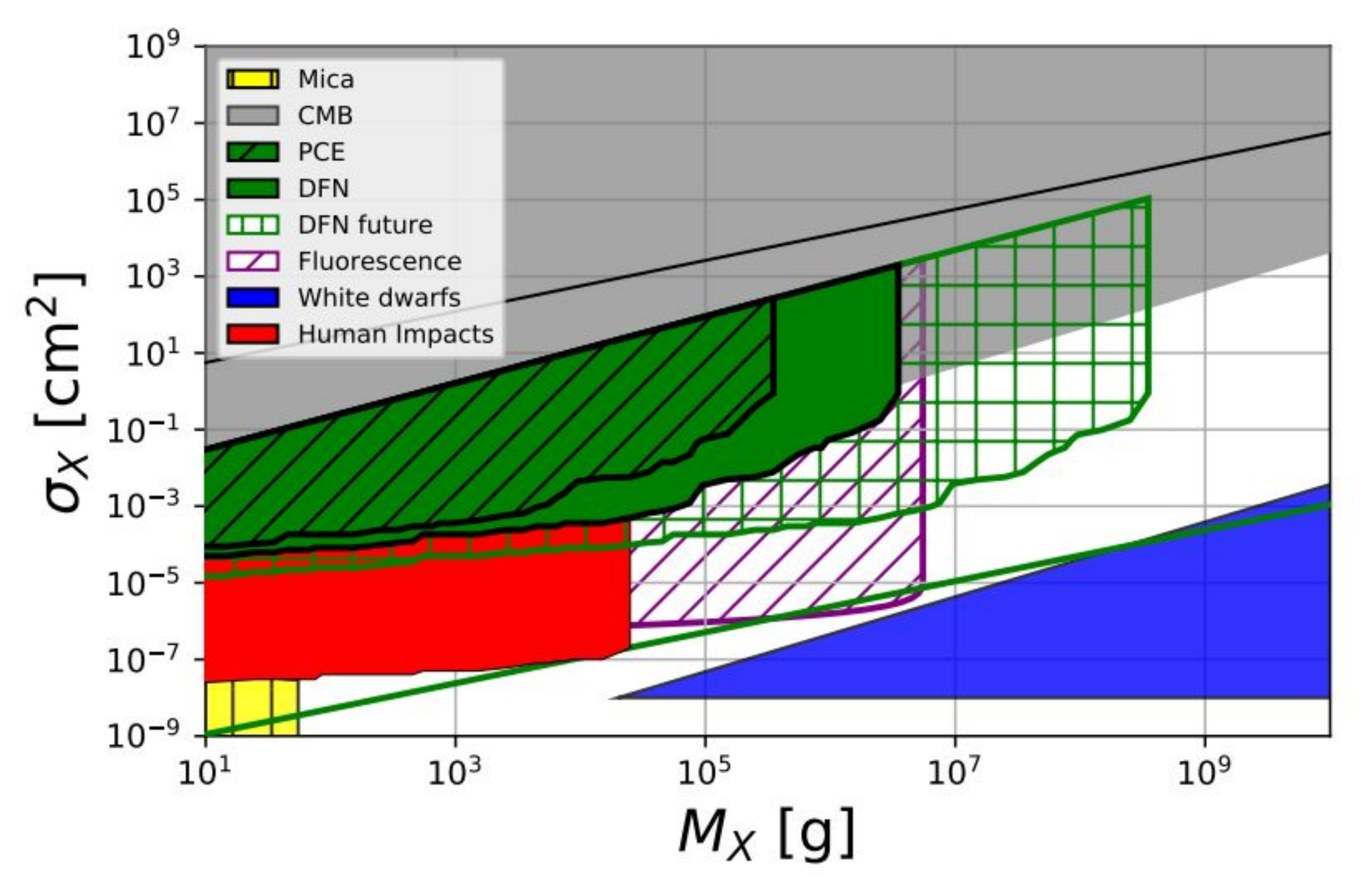
Dhakal, Prohira, Cappiello, Beacom, Palo, and Marino (in prep)

Limits from Ancient Mica



arXiv:1410.2236 (Jacobs et al., from Price and Salamon 1985)

Limits from Bolide Cameras



arXiv:1908.00557 (Sidhu et al.)

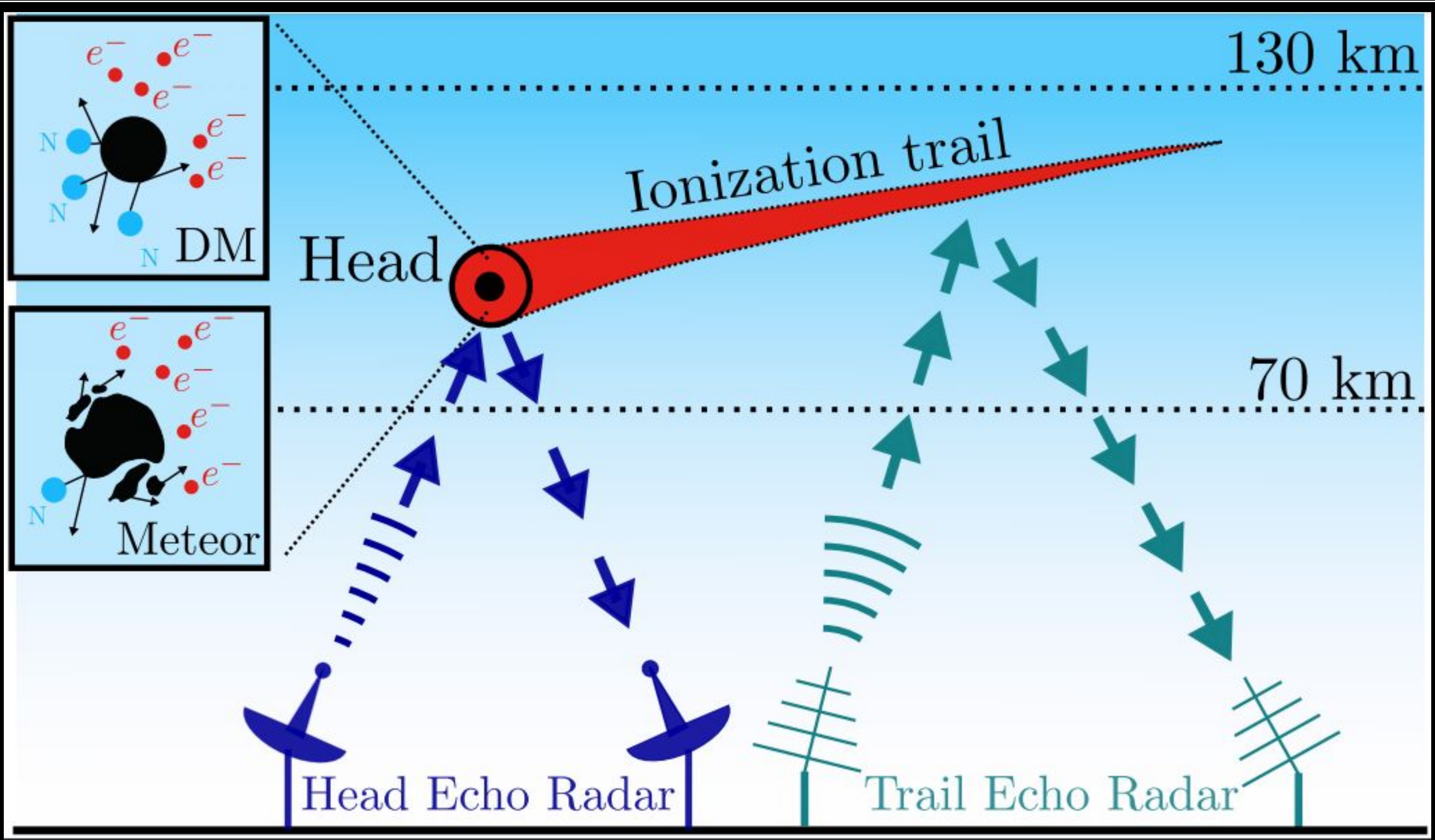
Radar Meteor Detection

Space.com

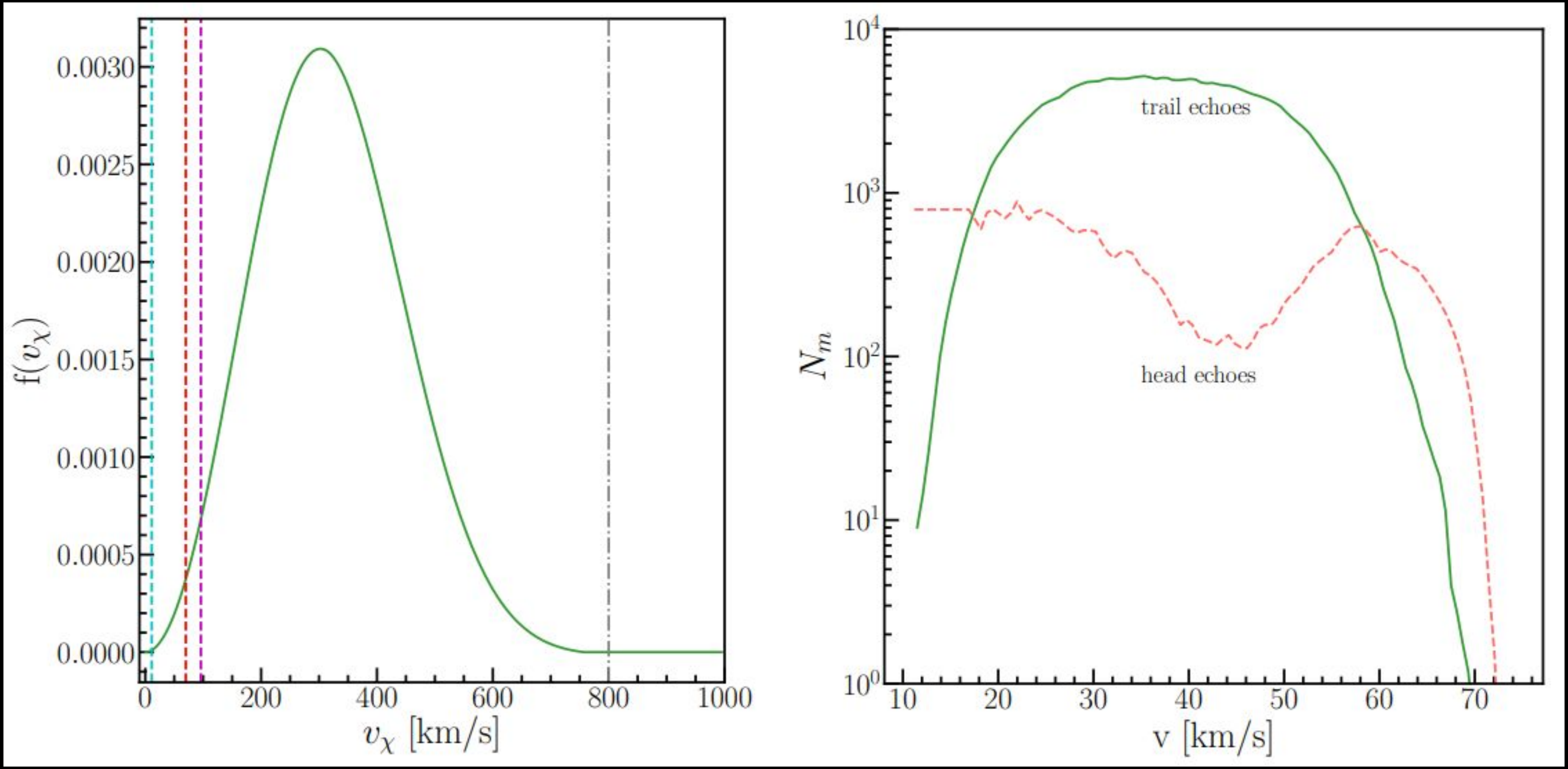
Shigaraki Middle and Upper Atmosphere Radar Observatory

http://www.rish.kyoto-u.ac.jp/organization_e/collaborative_research/mur/

Head Echoes and Trail Echoes

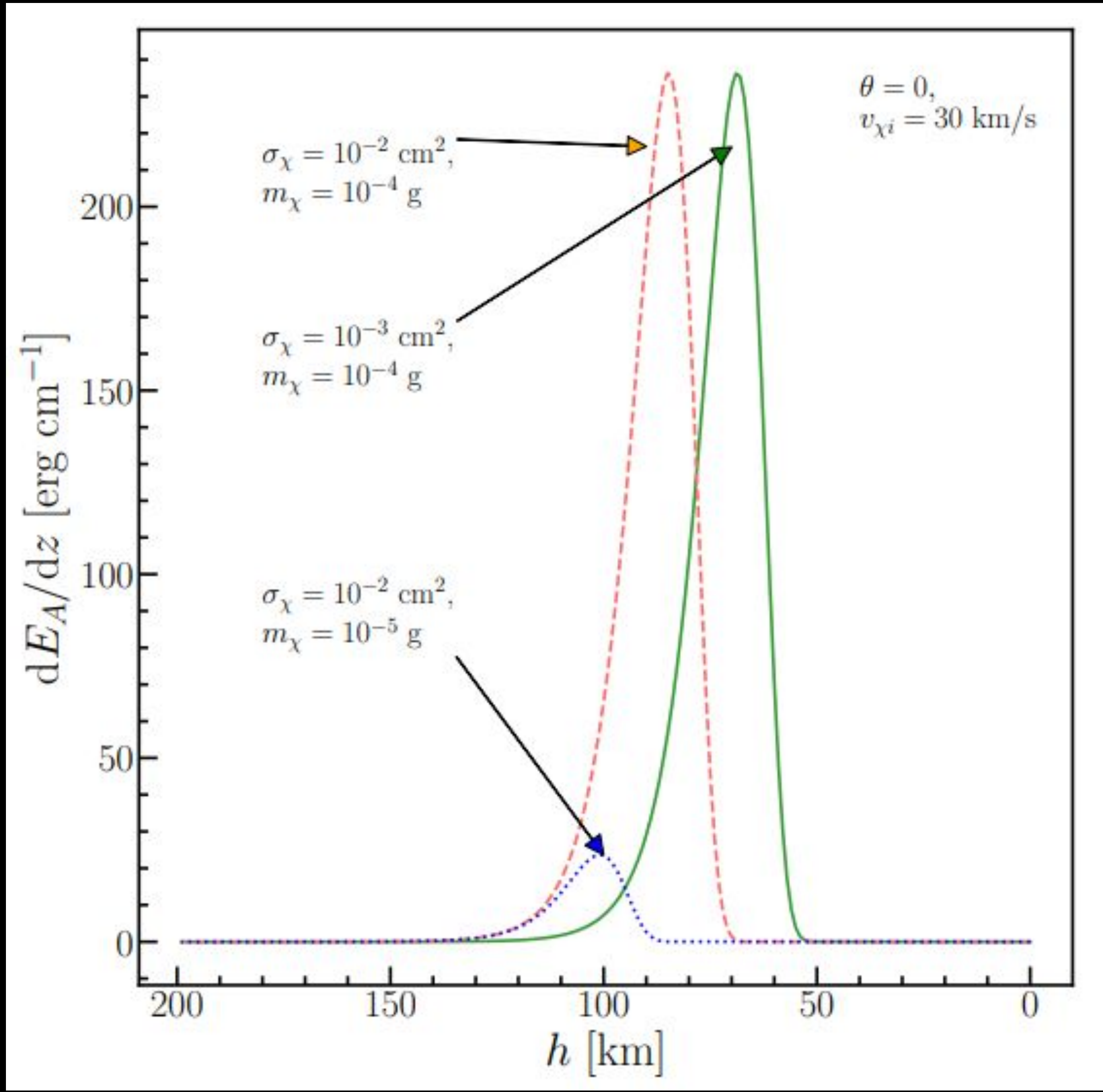


DM and Meteor Velocities



Dhakal et al. in prep.

DM Energy Deposition in the Atmosphere



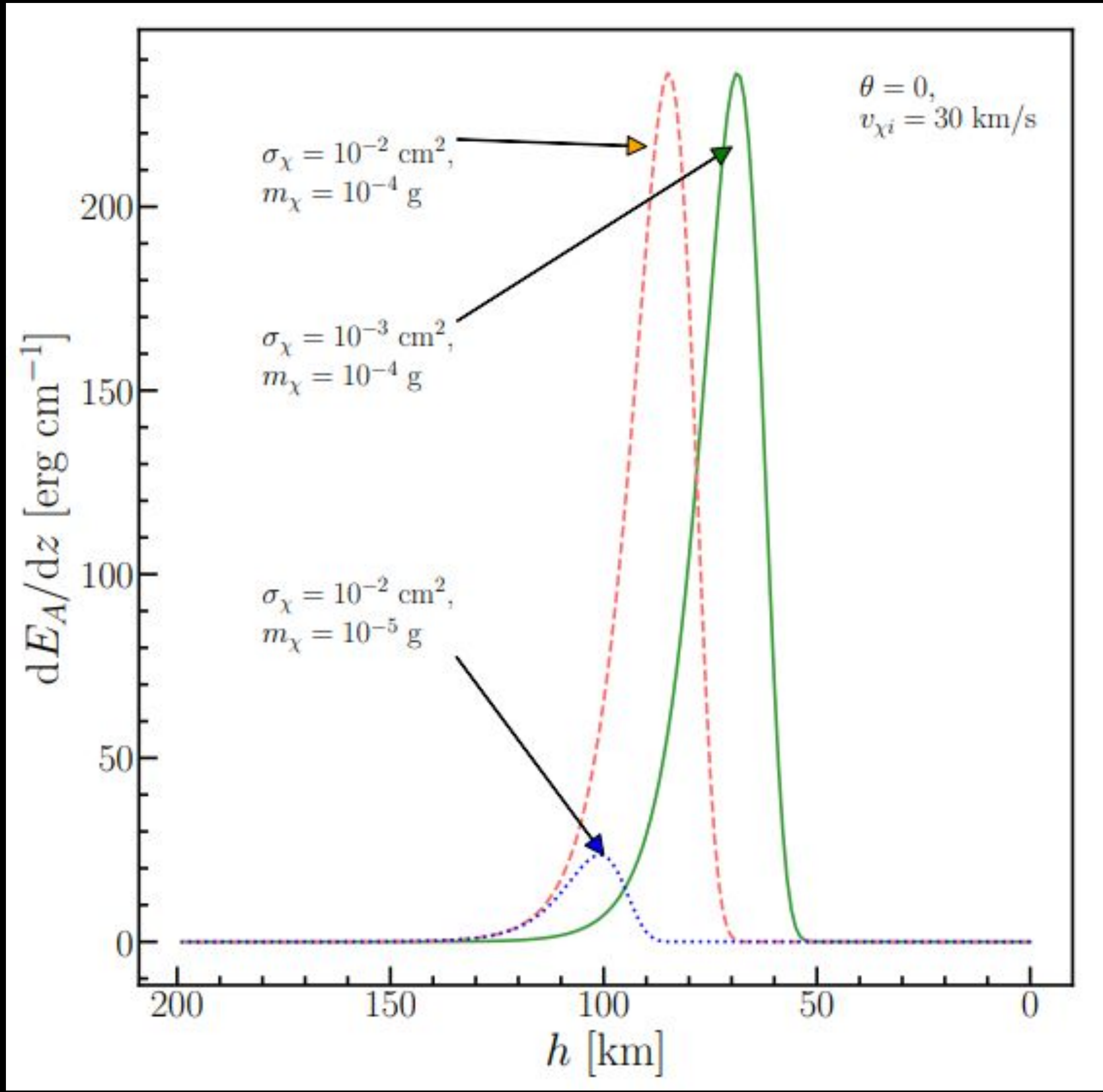
Dhakal et al. in prep.

Higher energy deposition leads to higher electron line density:

$$q_e = \frac{\mathrm{d}E_A \,/\, \mathrm{d}z}{\langle I \rangle}$$

$\langle I \rangle$ is average energy to produce an electron-ion pair in air

DM Energy Deposition in the Atmosphere



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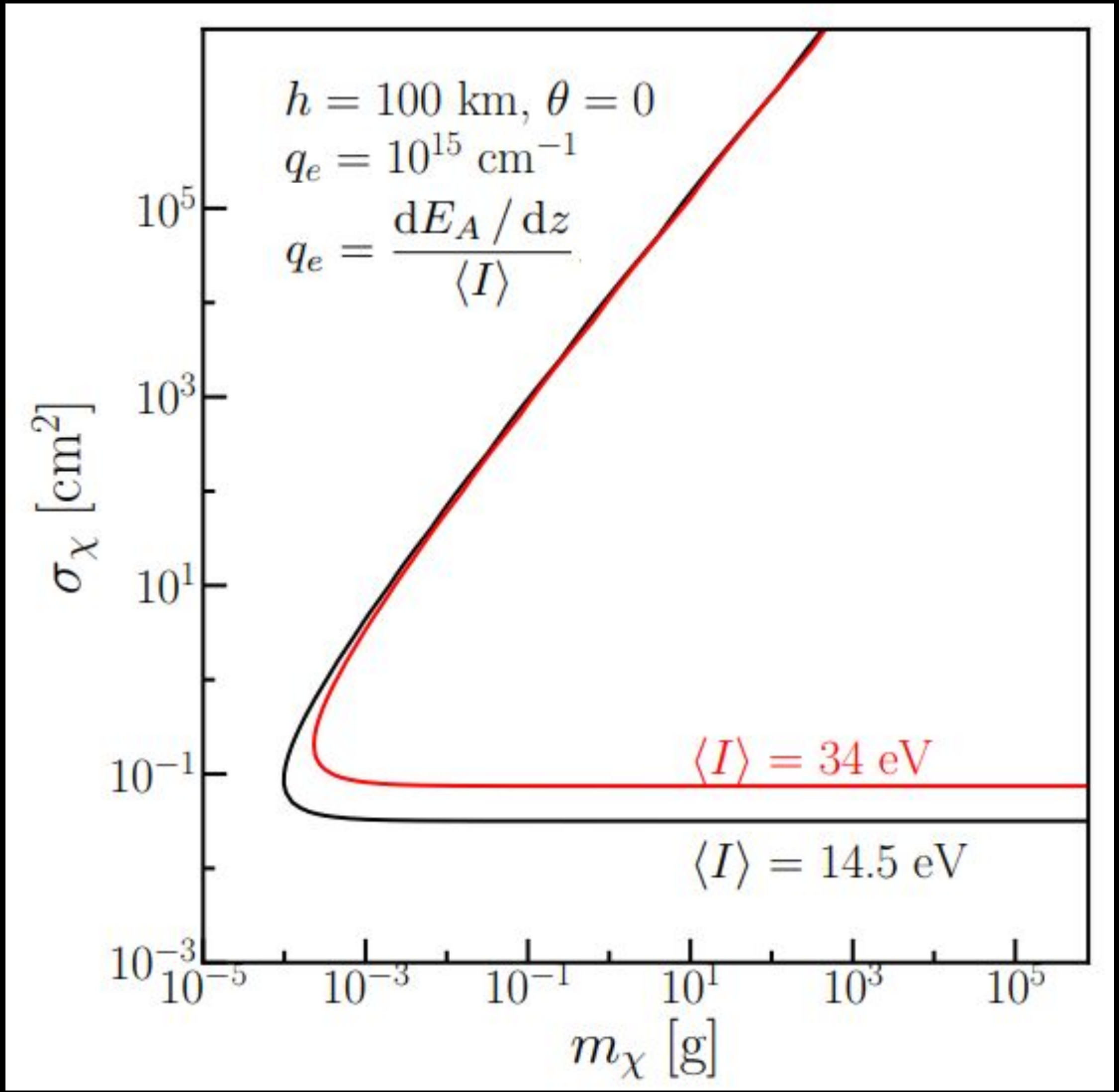
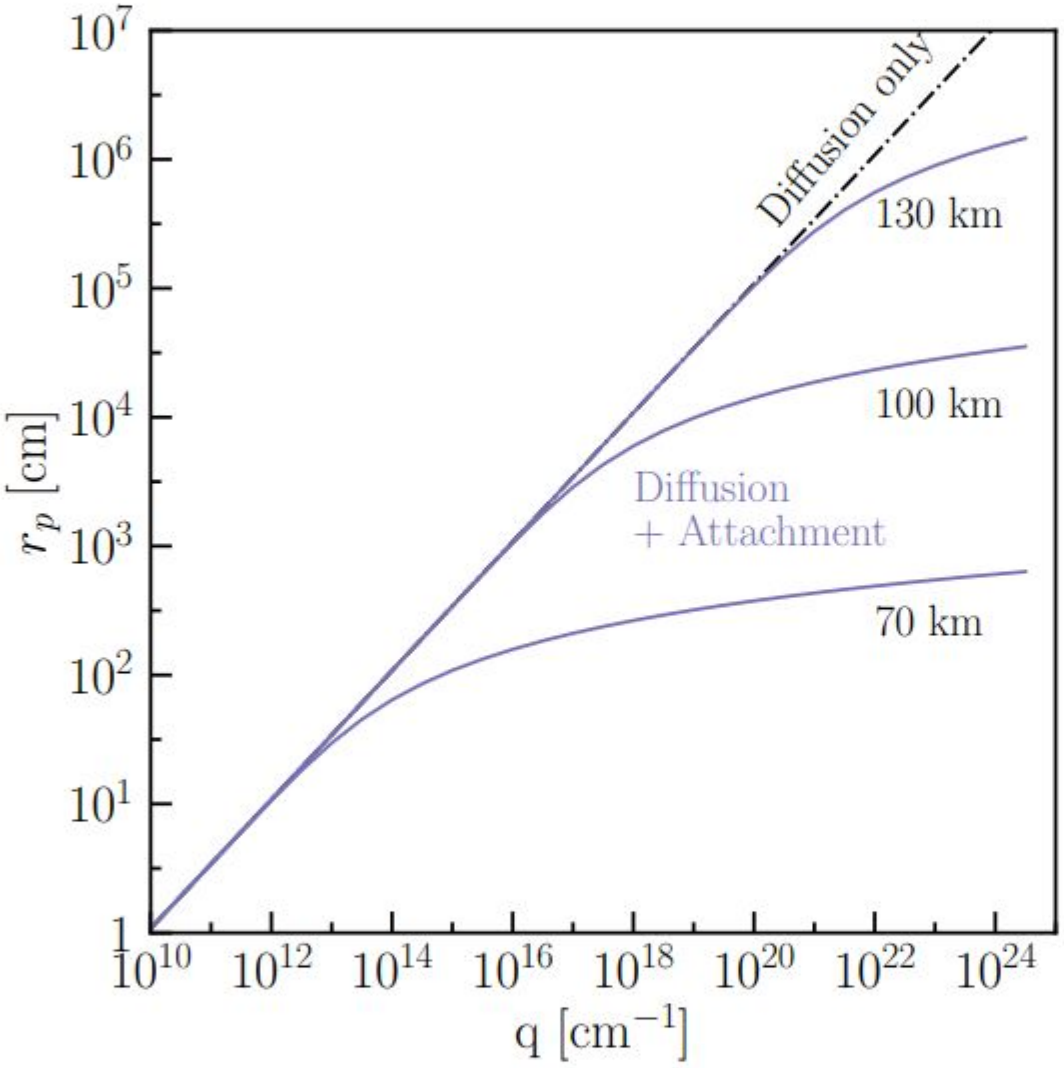
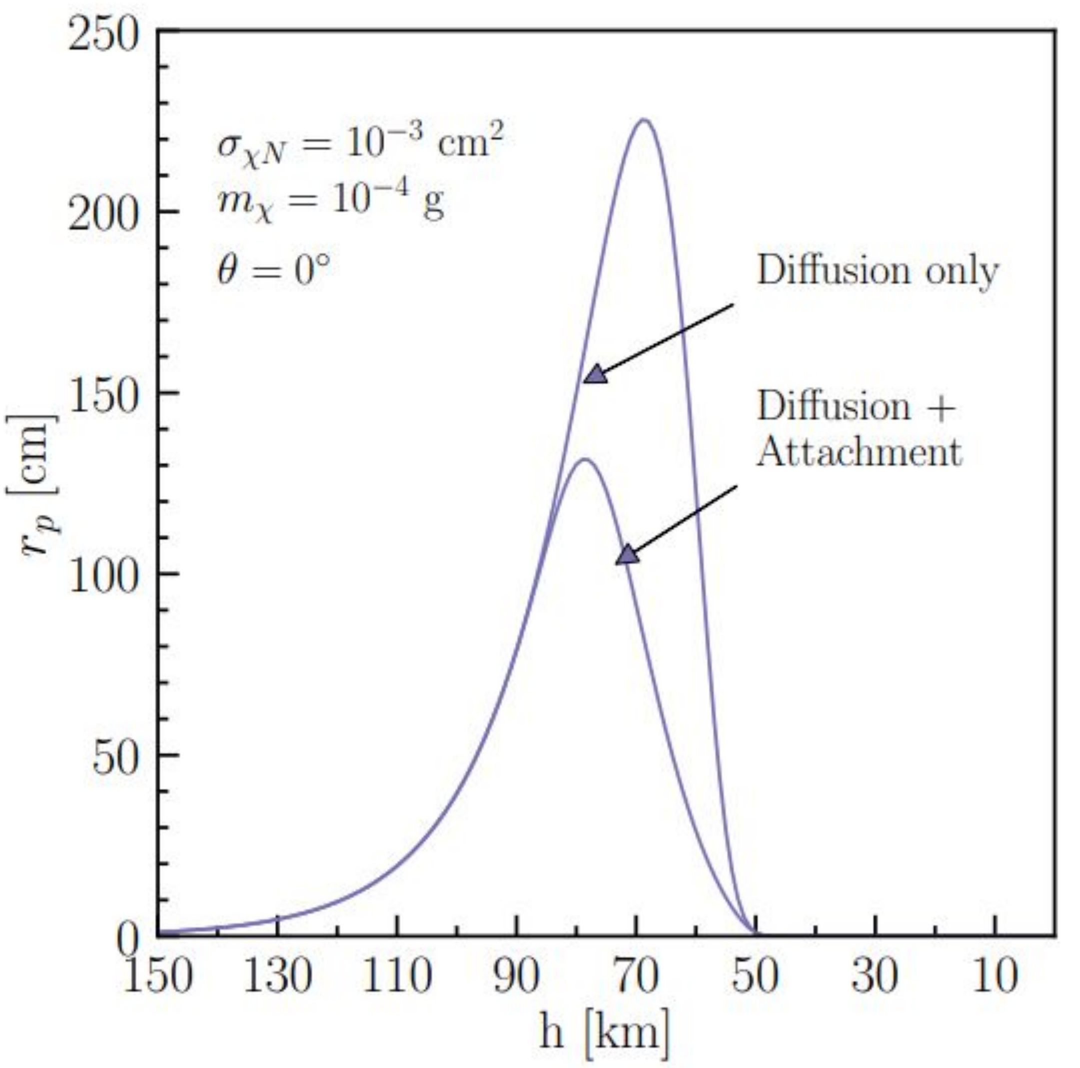


Dhakal et al. in prep.

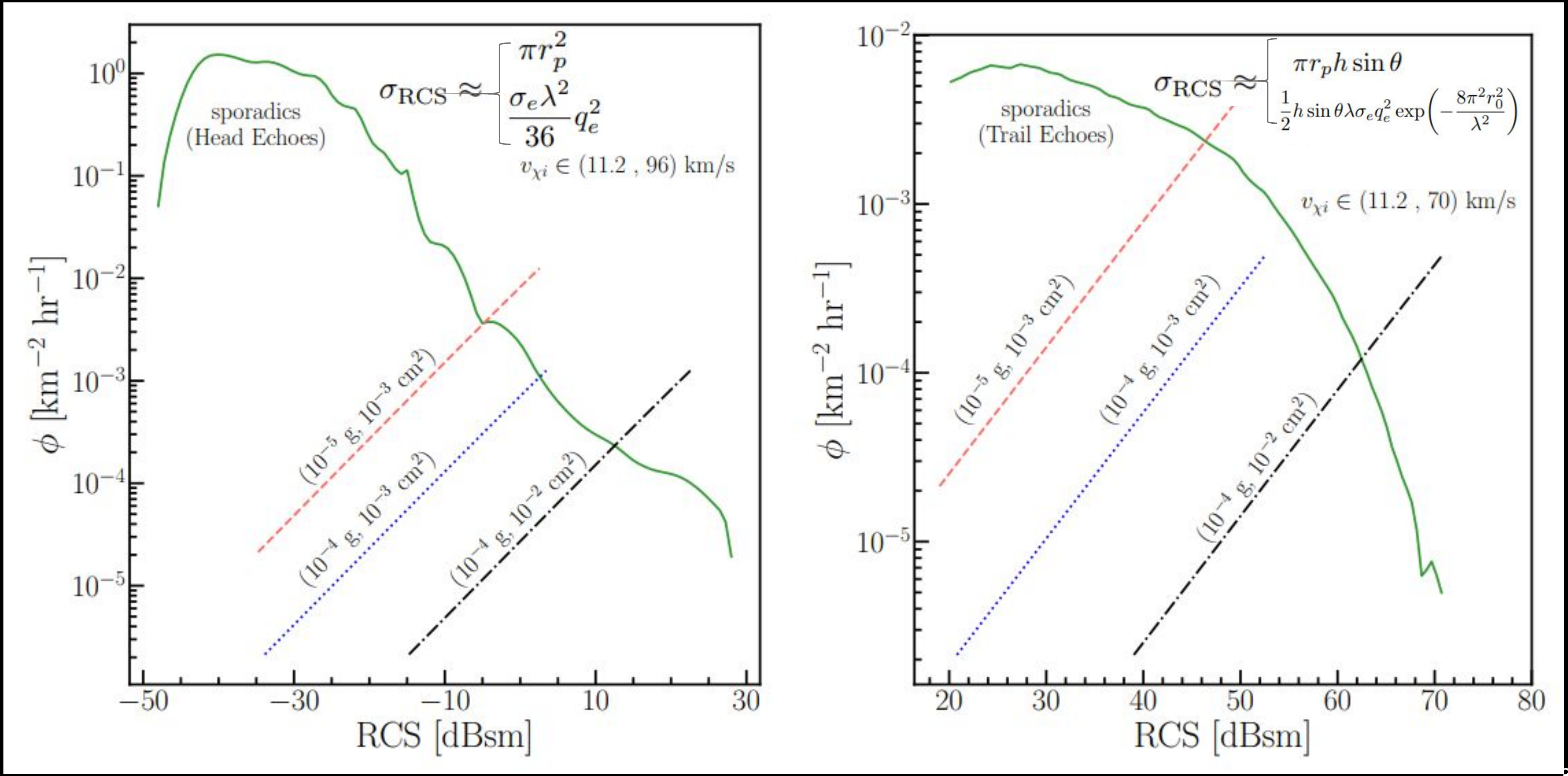
Diffusion and Plasma Radius





Dhakal et al. in prep.

DM vs Meteor Flux



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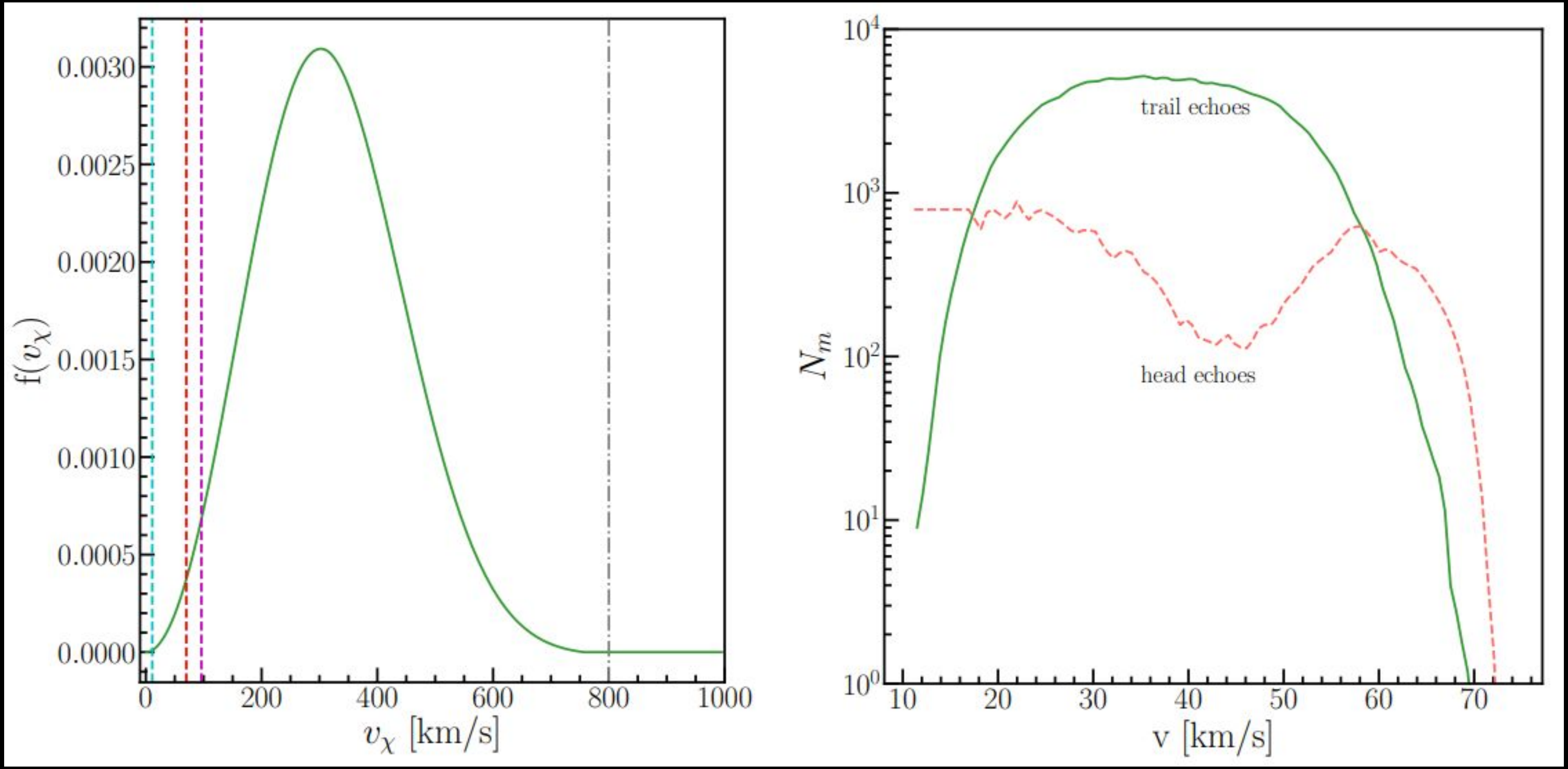

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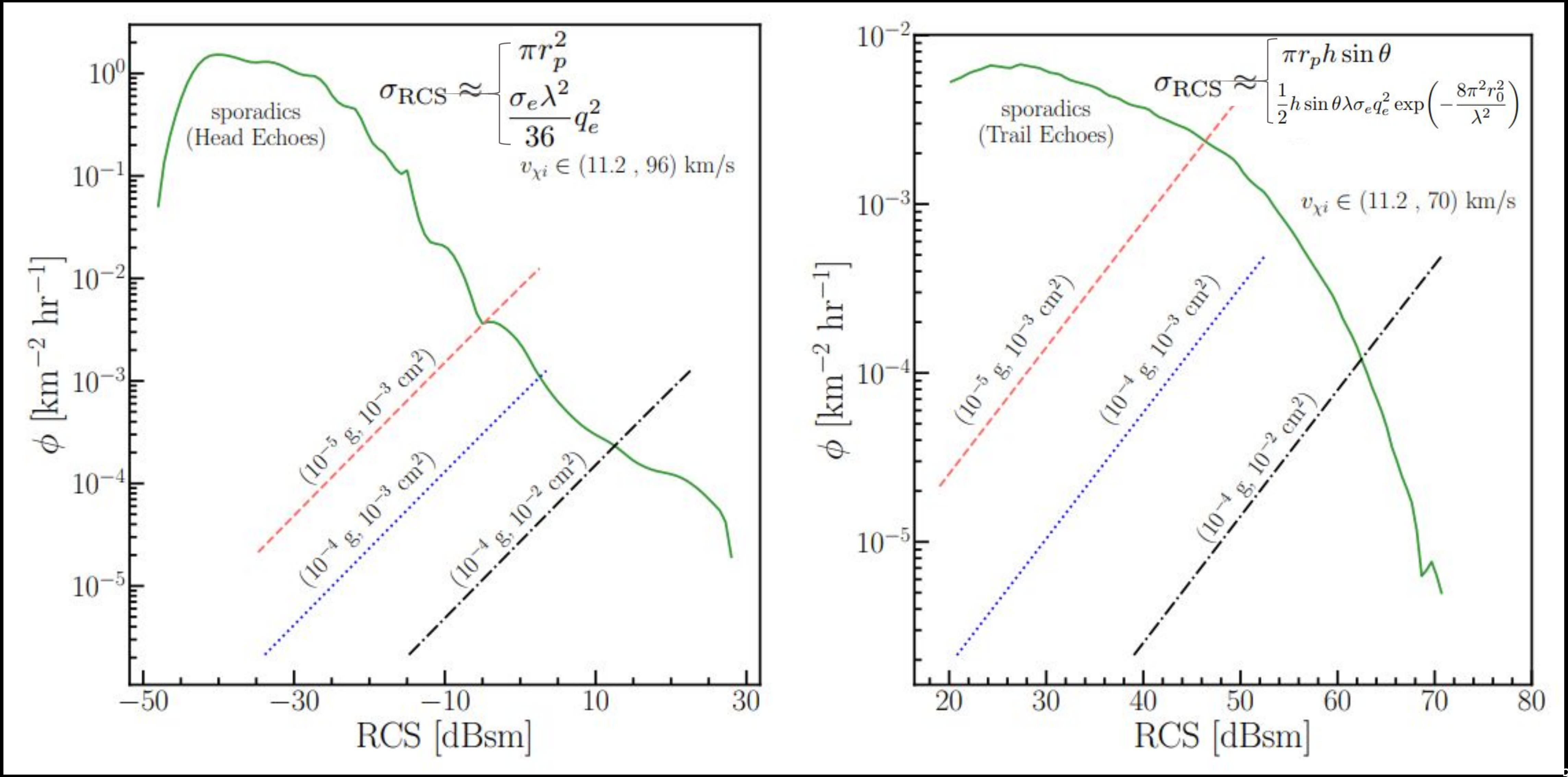
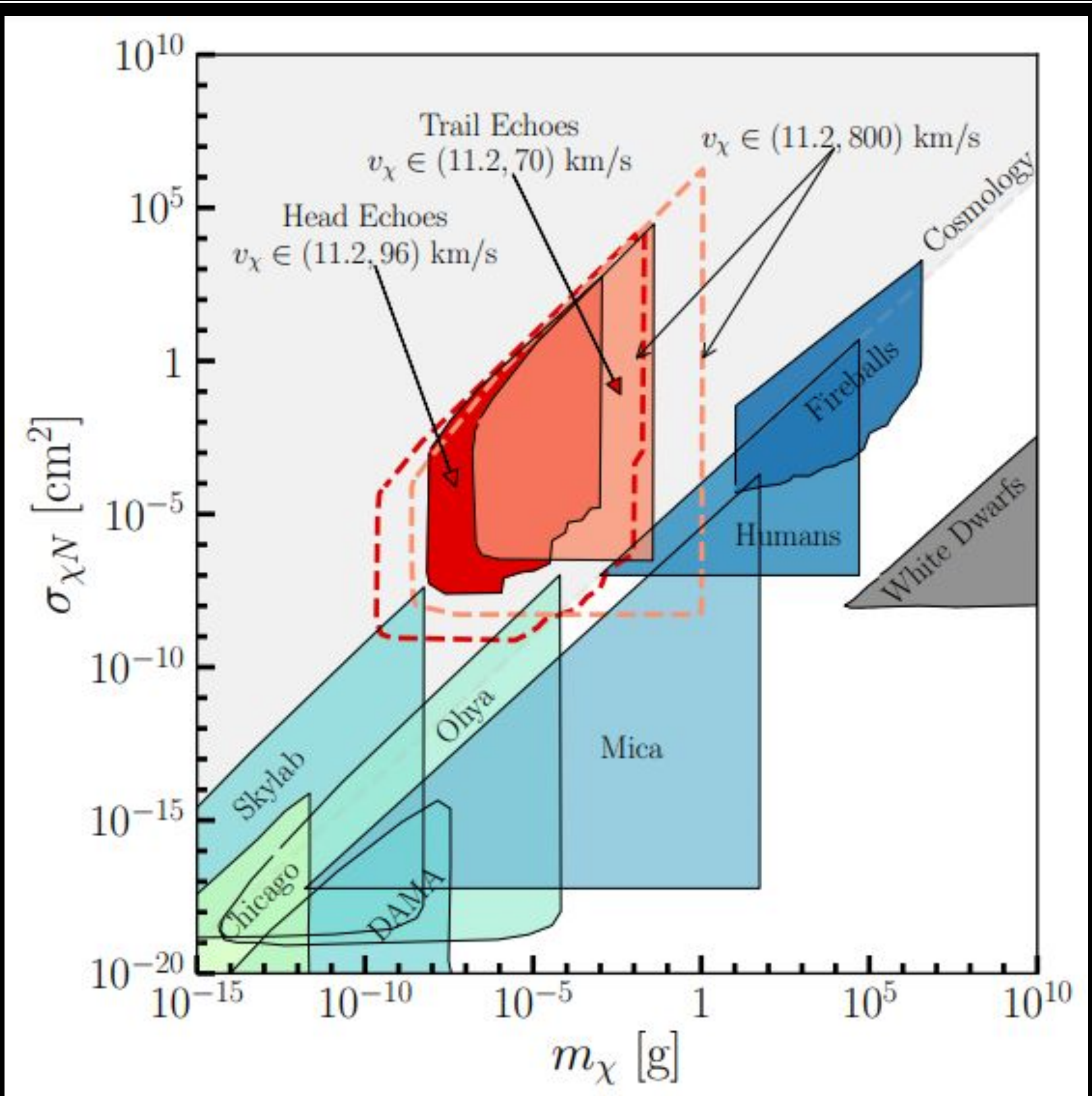


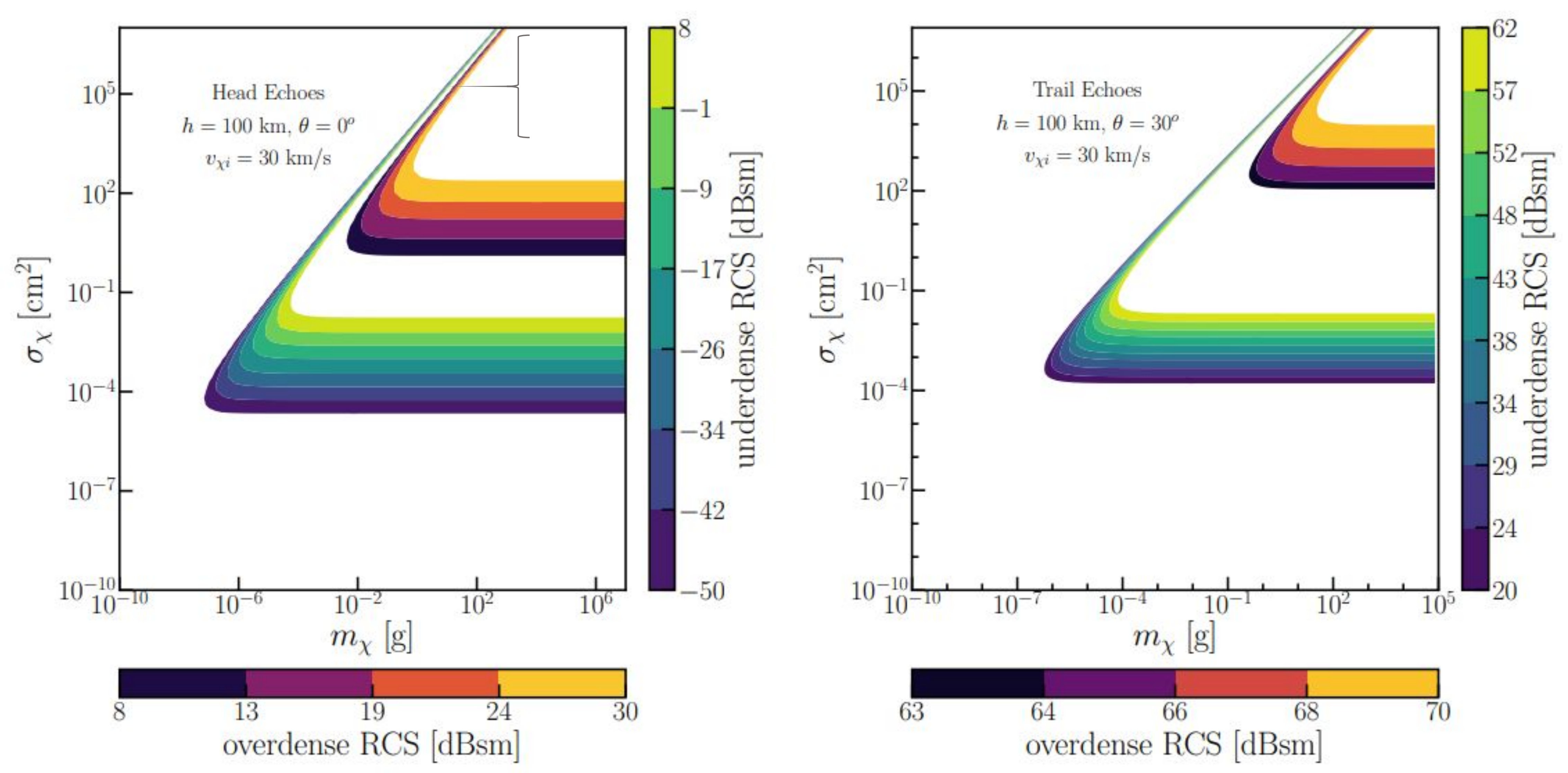
Dhakal et al. in prep.

Meteor Exclusion Region



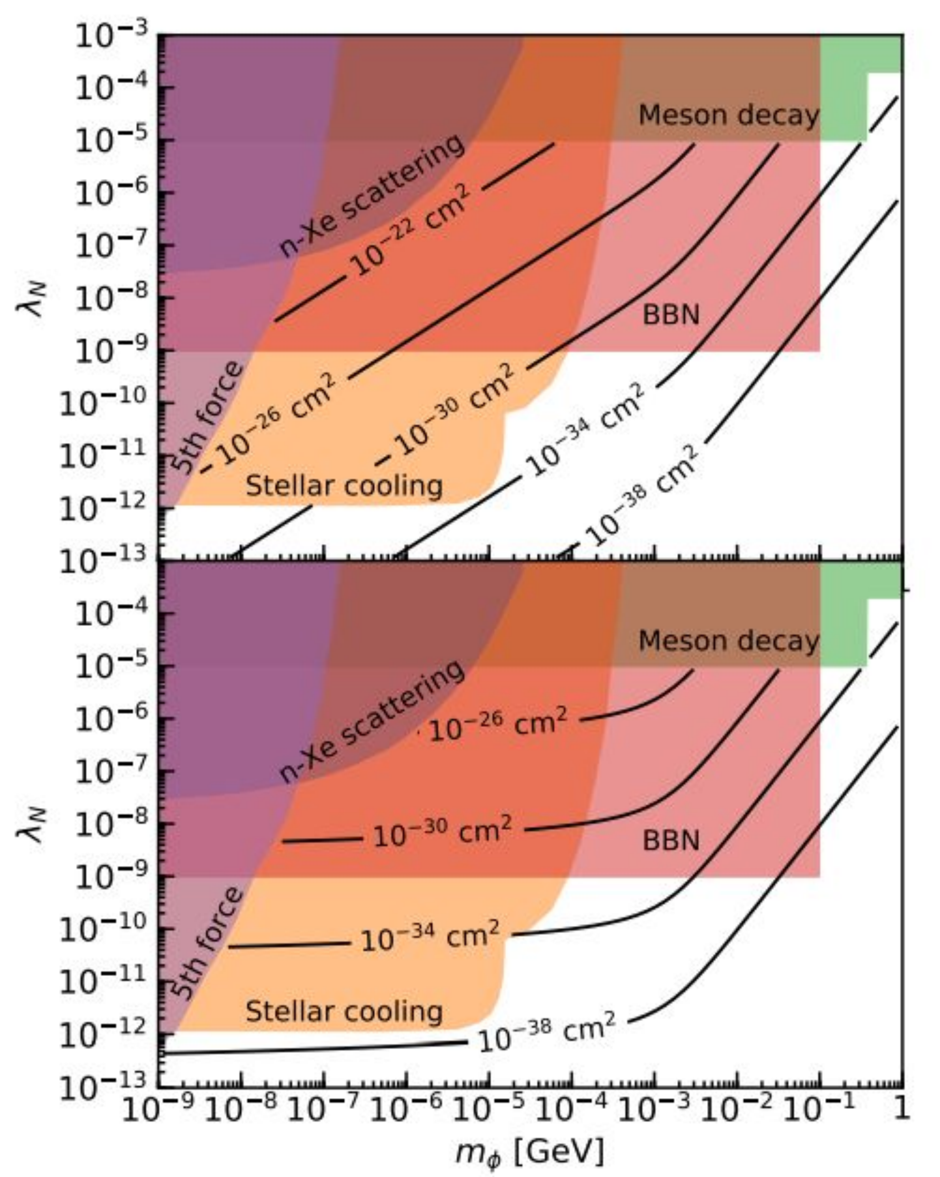
Dhakal et al. in prep.

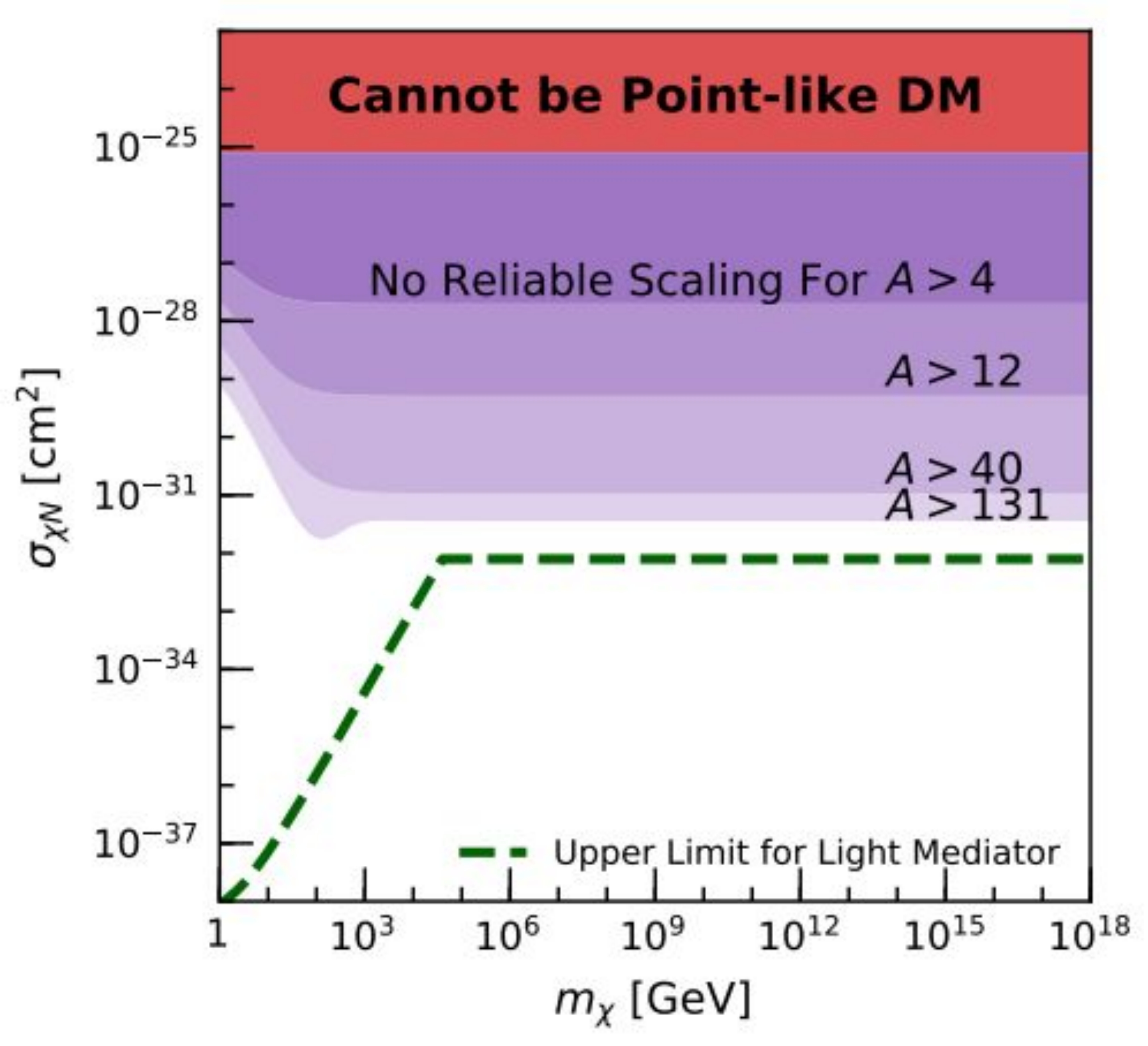
Overdense and Underdense Echoes



Dhakal et al. in prep.

Light Mediators





arXiv:2008.10646 (Digman, Cappiello et al.)

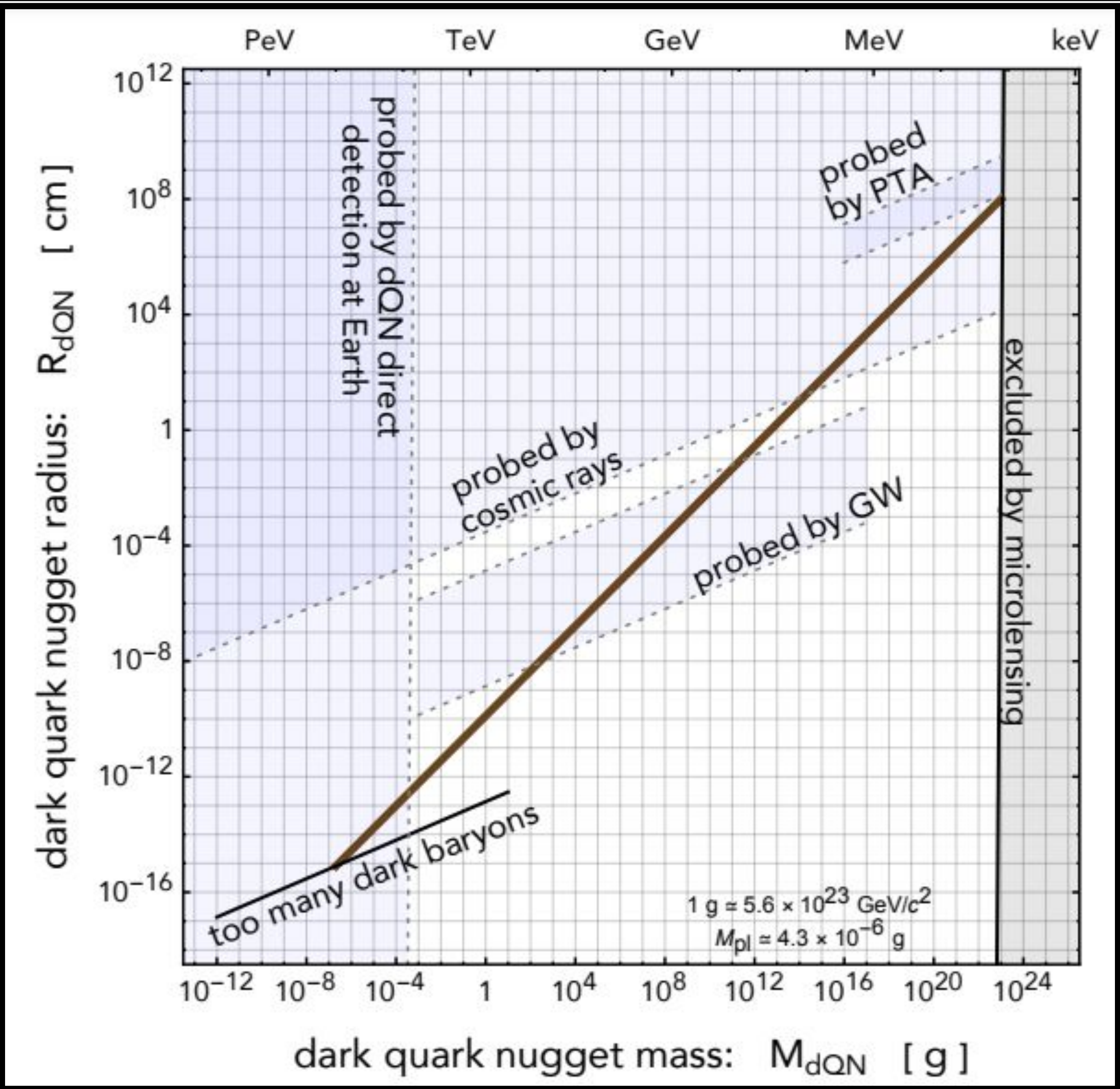
Superheavy DM Models

Dark Quark Nuggets: arXiv:1810.04360 (Bai, Long & Lu 2018)

Fermi balls created via first order phase transition: arXiv:2008/04430 (Hong, Jung & Xie 2020)

Supermassive DM from reheating/inflaton decay/gravitational production: arXiv:hep-ph/9805473, arXiv:hep-ph/9809453 (Chung, Kolb & Riotto 1998/1999)

Scalar asymmetric composite DM: arXiv:1407.4121 (Wise & Zhang 2014), arXiv:1707.02316 (Gresham, Lou & Zurek)



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