

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

Speakers: Christopher Cappiello

Series: Particle Physics

Date: April 19, 2022 - 1:00 PM

URL: <https://pirsa.org/22040120>

Abstract: Direct detection searches for dark matter are typically optimized to search for weakly interacting particles with masses on the ~GeV scale. But these experiments are, in principle, sensitive to masses as large as approximately the Planck mass, for cross sections much larger than typical Weak-scale cross sections. However, certain assumptions typically made in direct detection analyses break down at such large cross sections, and must be reexamined. In my talk, I will discuss the theoretical considerations that become important for heavy, strongly interacting dark matter, as well as new types of dark matter search that become possible at such high masses and cross sections.

Zoom Link: <https://pitp.zoom.us/j/98807962972?pwd=UXFWLzA0N2dPQ3JrVUo4TStmSGtWUT09>

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

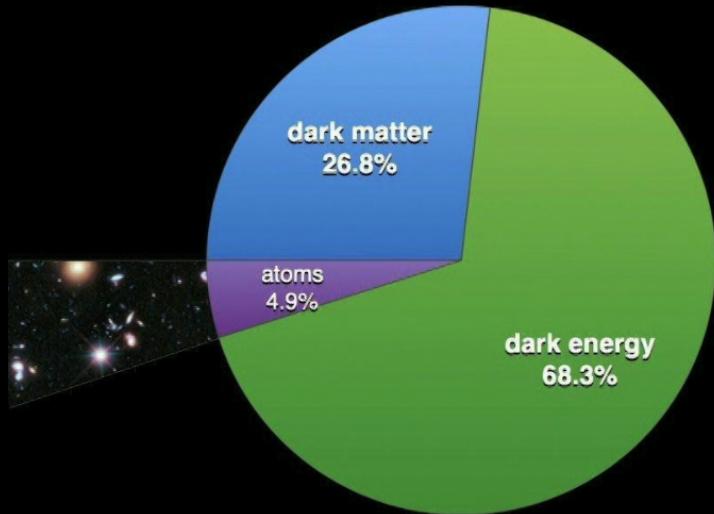
Christopher Cappiello



Arthur B. McDonald
Canadian Astroparticle Physics Research Institute



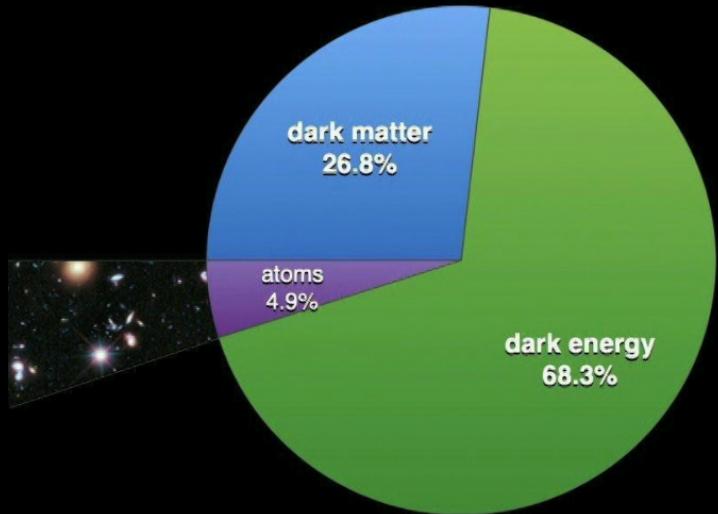
Searching for Dark Matter



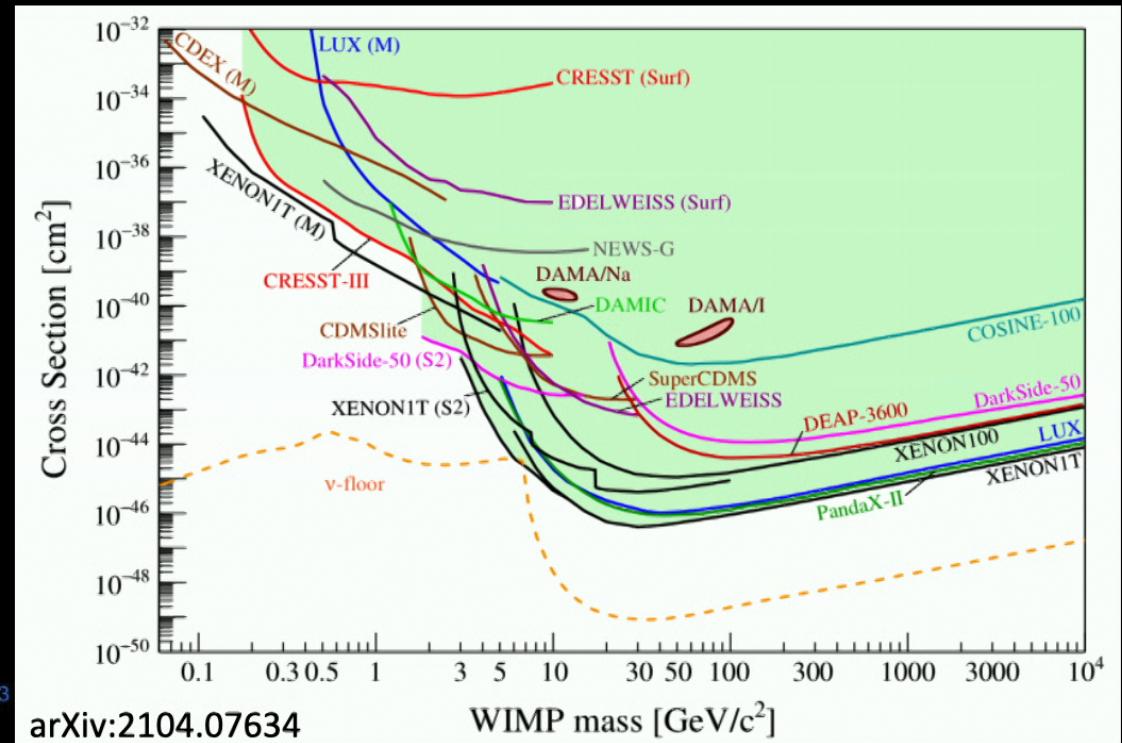
@AstroKatie/Planck13

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

Searching for Dark Matter

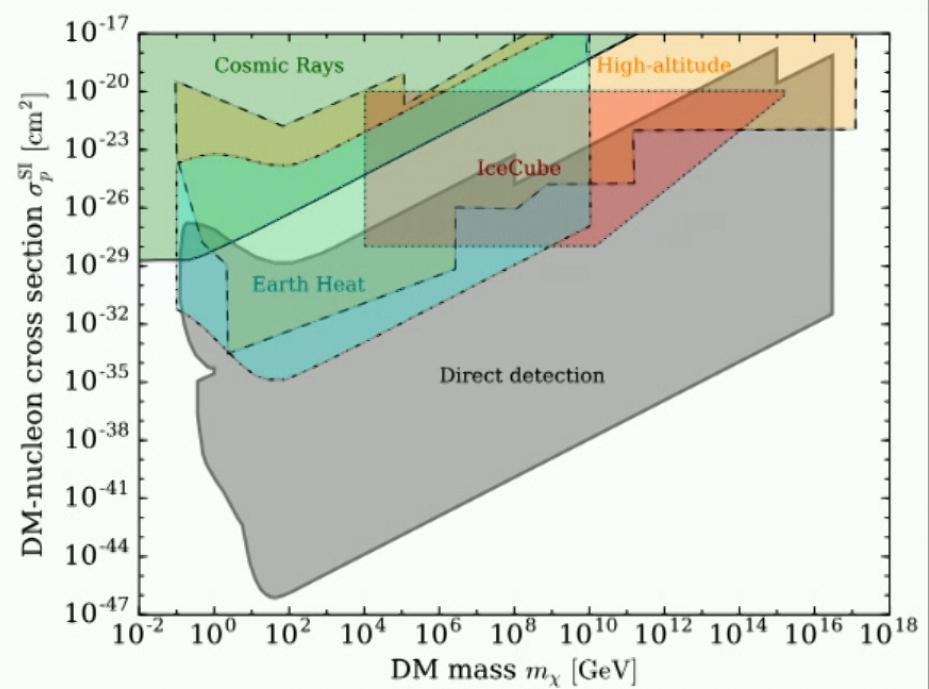
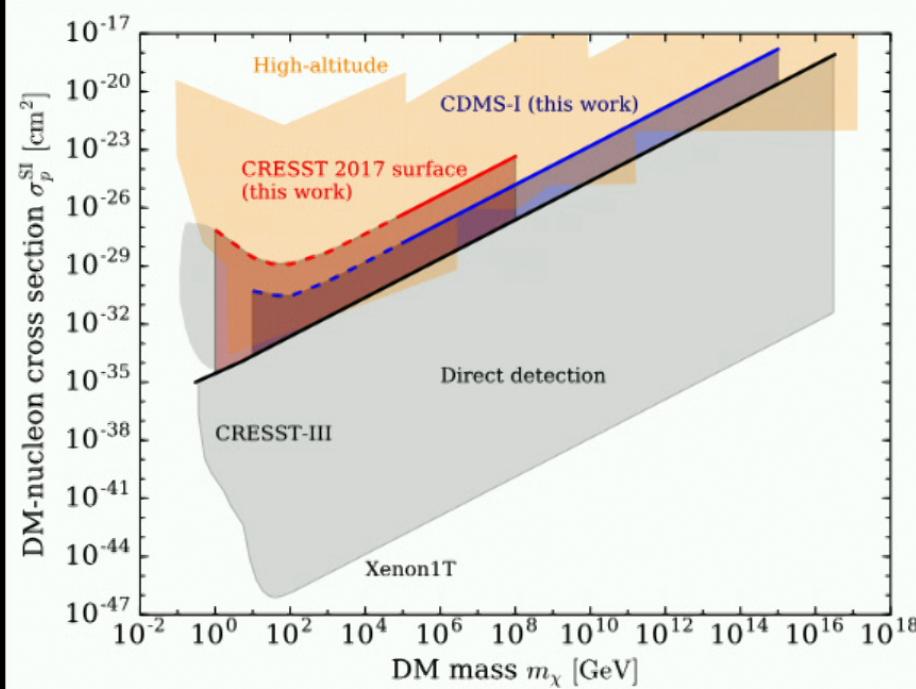


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Tests of dark matter: collider searches, direct detection experiments, indirect detection, cosmological probes, and much more...

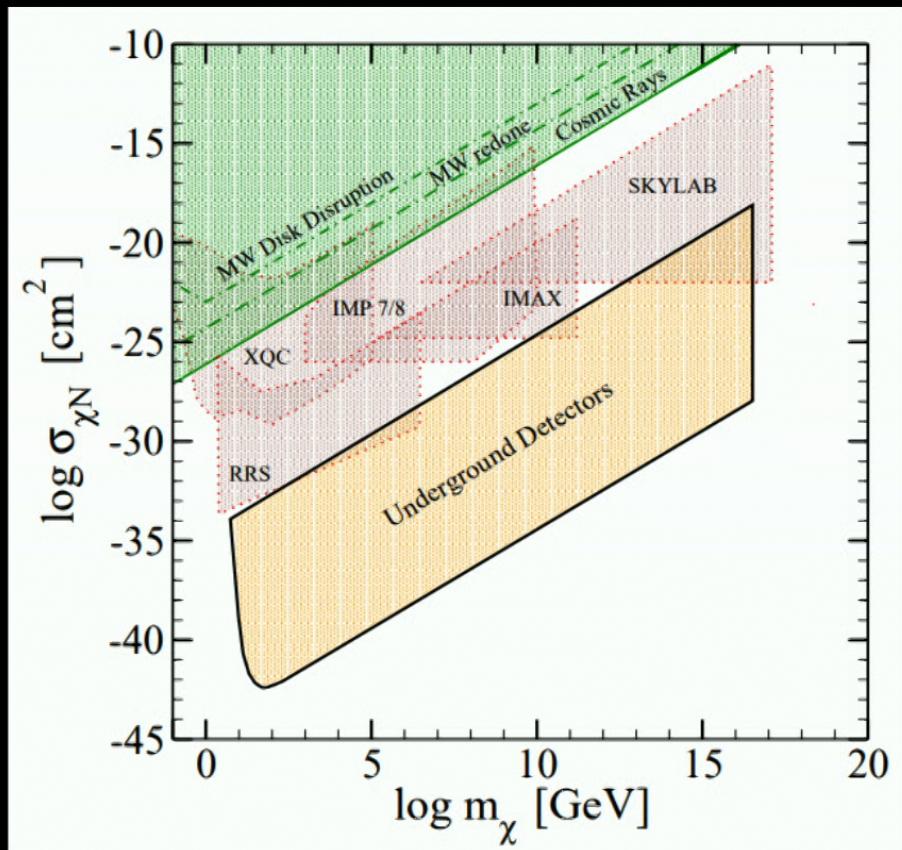
Attenuation in the Earth's Crust



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



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

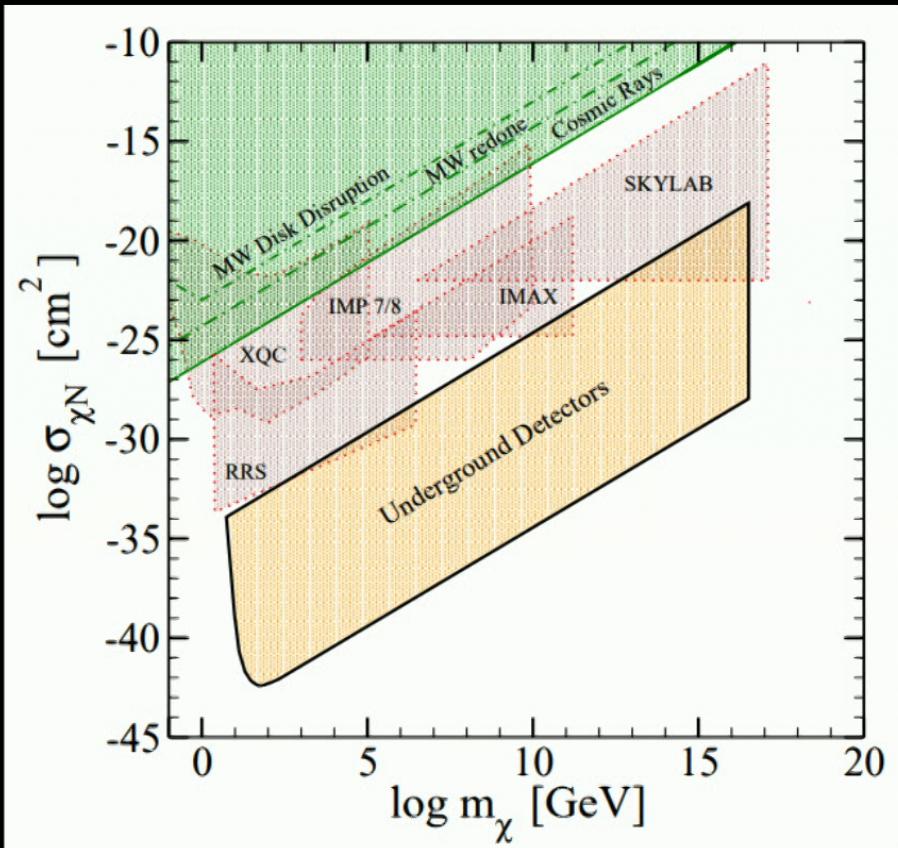
Interstellar Gas (Chivukula et al. 1990, Bhoonah et al. 2018, Wadekar & Farrar 2019)

Cosmic Rays (Cyburt et al. 2007)

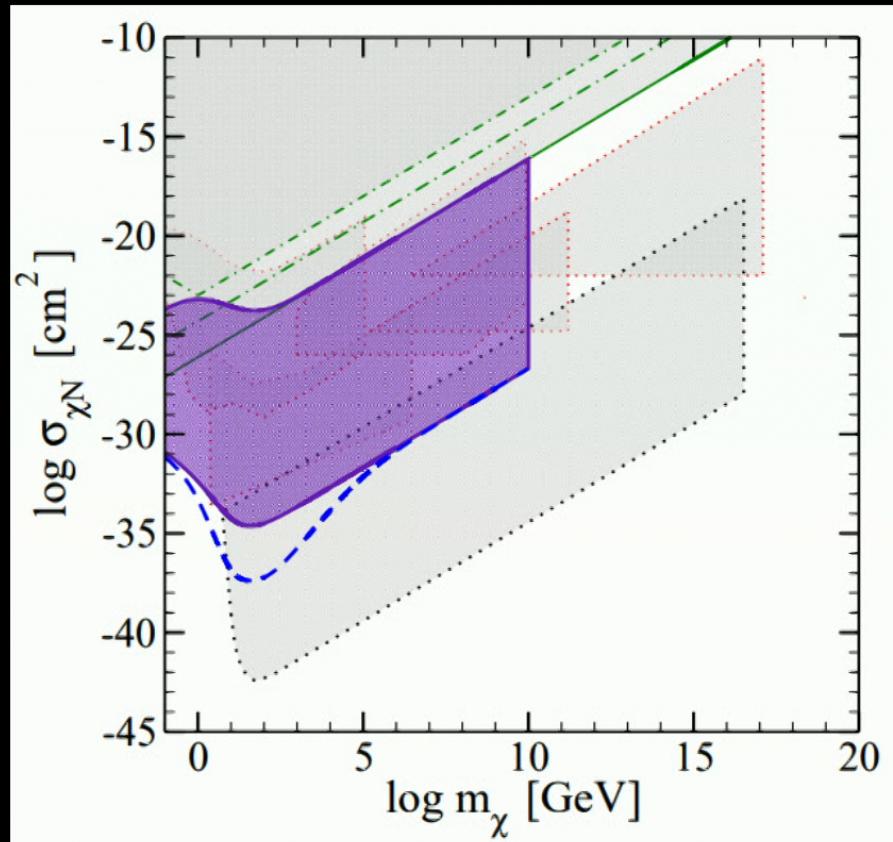
CMB (Chen et al. 2002, Slatyer & Wu 2018, Xu et al. 2018)

Milky Way Satellites (Nadler et al. 2020)

Above the Direct Detection Ceiling



arXiv:0705.4298 (Mack, Beacom, Bertone)

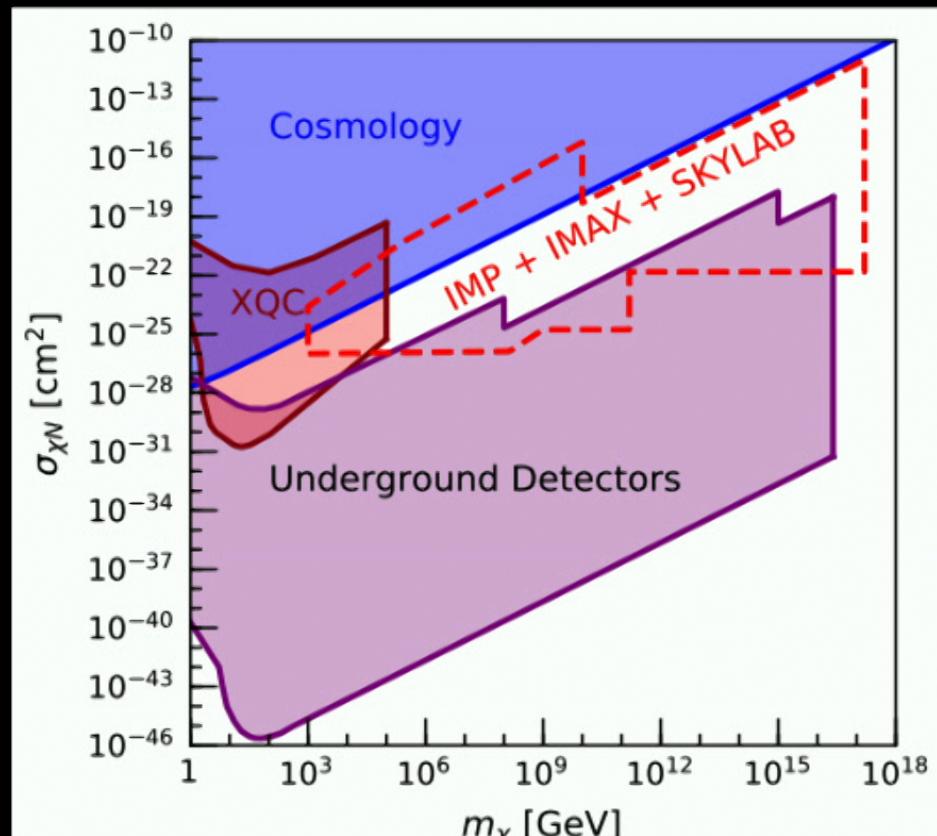


See also Bramante et al. (2019), Leanne & Smirnov (2020) ⁶

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:

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



arXiv:1907.10618 (Digman, Cappiello et al.)

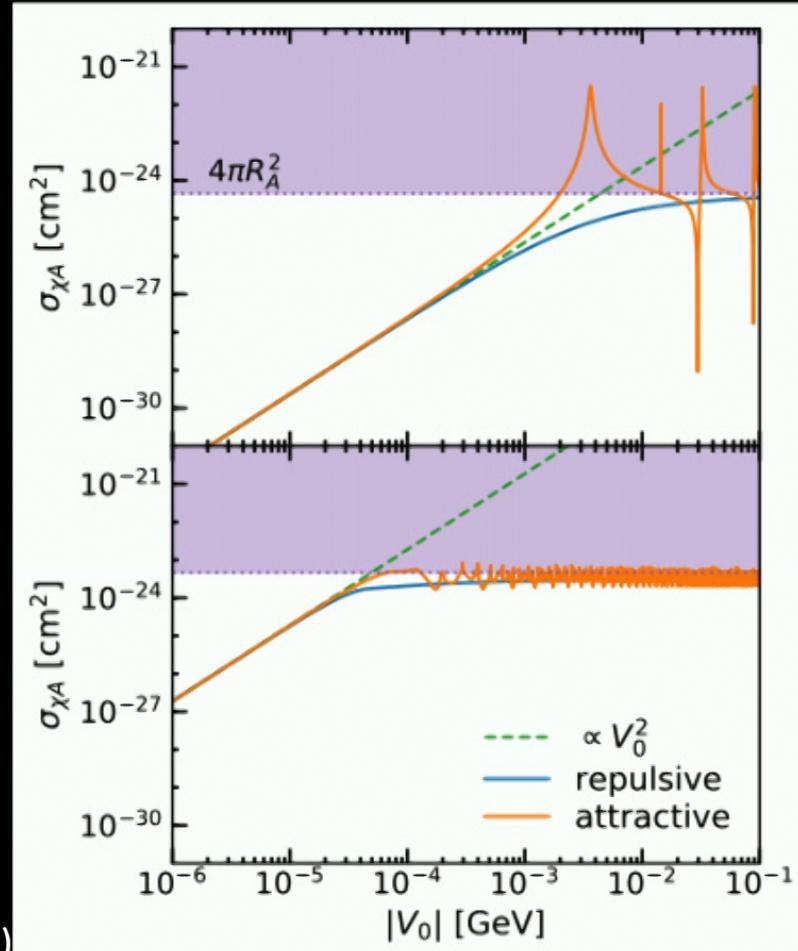
Part 1: High Cross Section Dark Matter is Dead*

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

Breakdown of Traditional Scaling

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

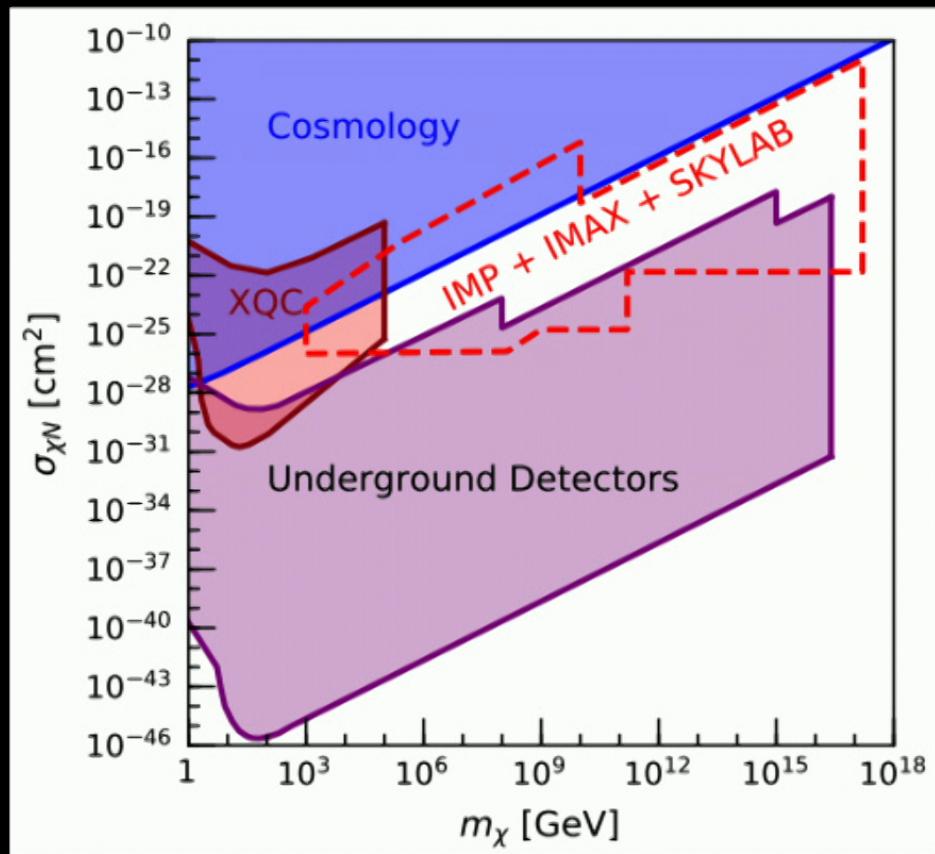
arXiv:1907.10618
(Digman, Cappiello et al.)



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:

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

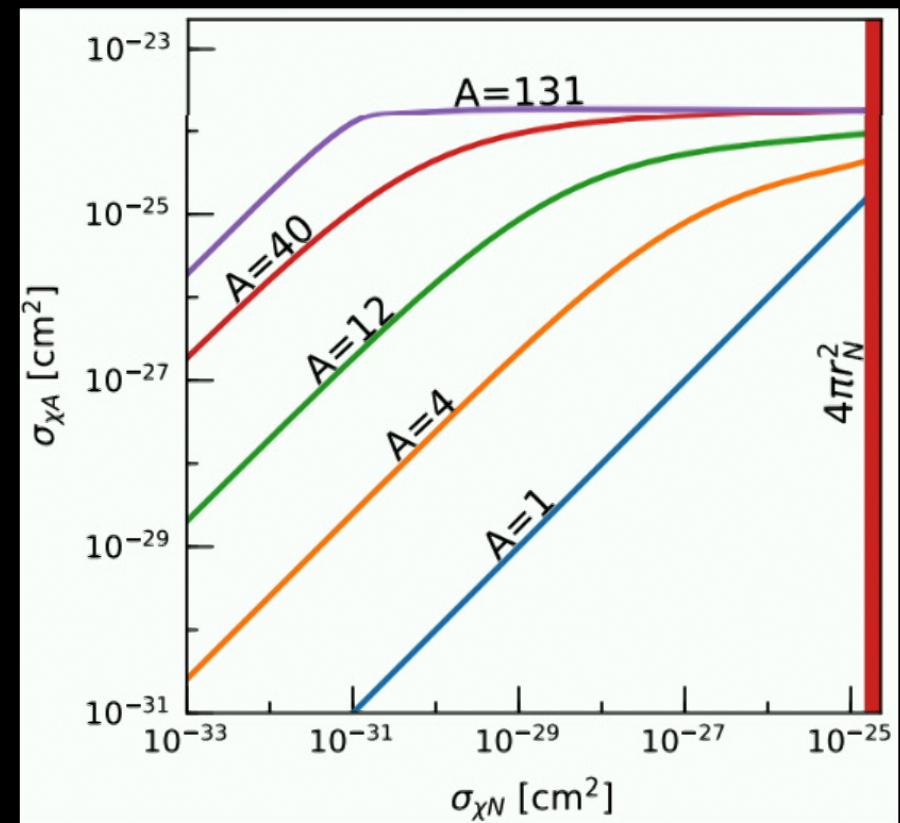


arXiv:1907.10618 (Digman, Cappiello et al.)

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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: $\sim 10^{-25} \text{ cm}^2$

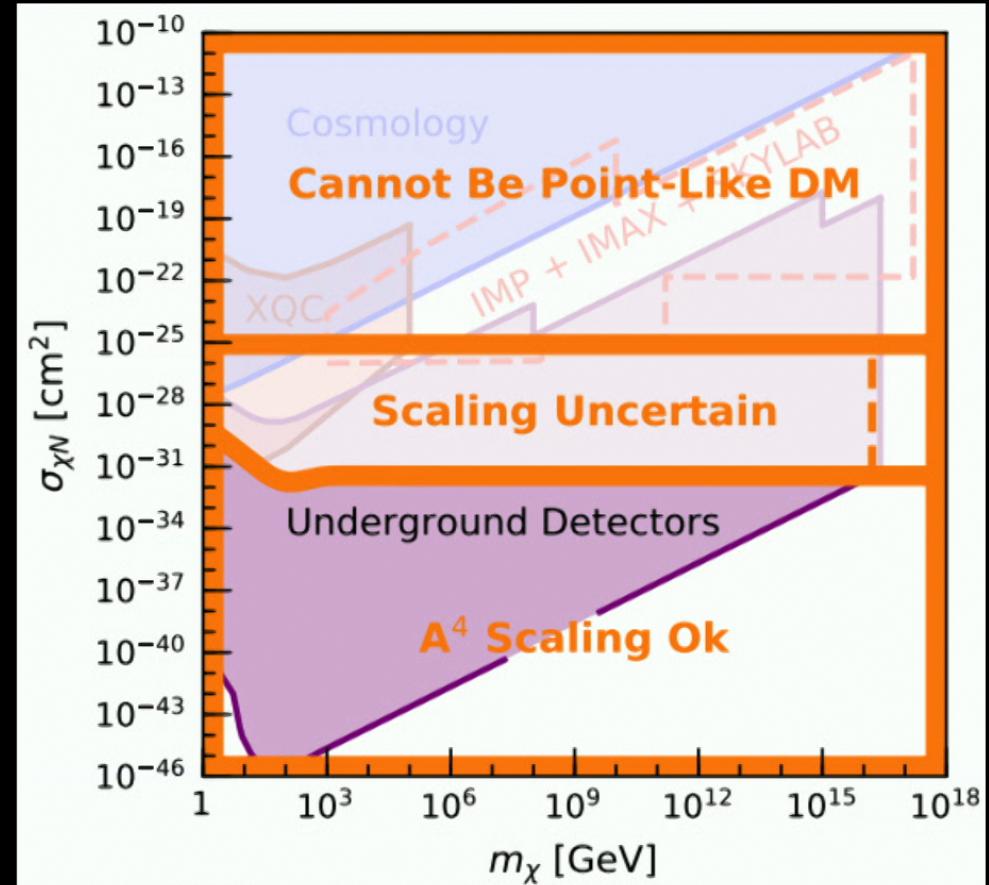


arXiv:1907.10618 (Digman, Cappiello et al.)

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Maximum Cross Section for Pointlike DM

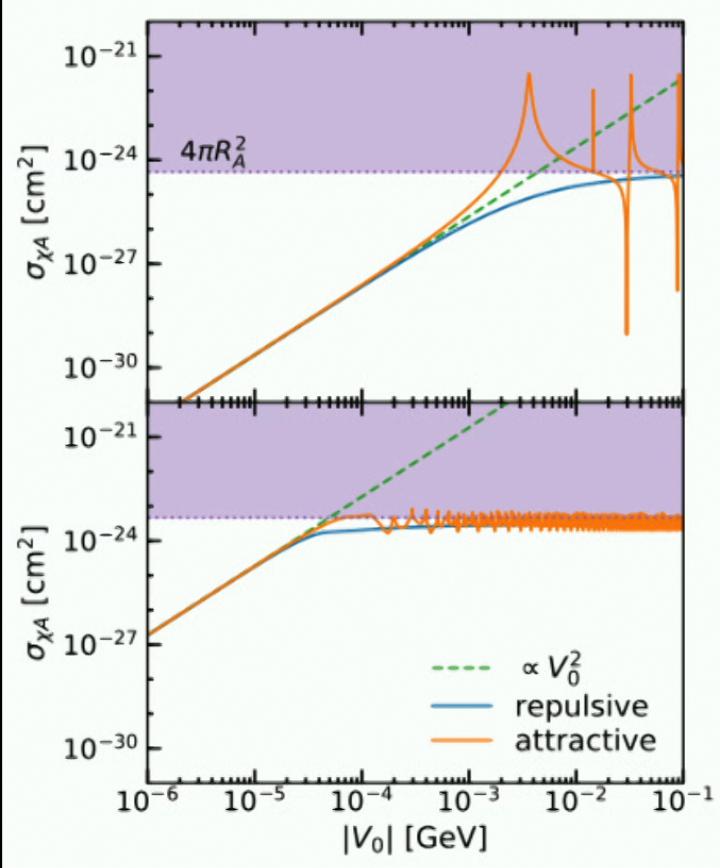
- Low cross section: scaling works fine
- Intermediate cross section: typical scaling breaks down depending on nucleus
- High cross section: not possible for point-like dark matter
- Large cross sections are impossible (maybe...)



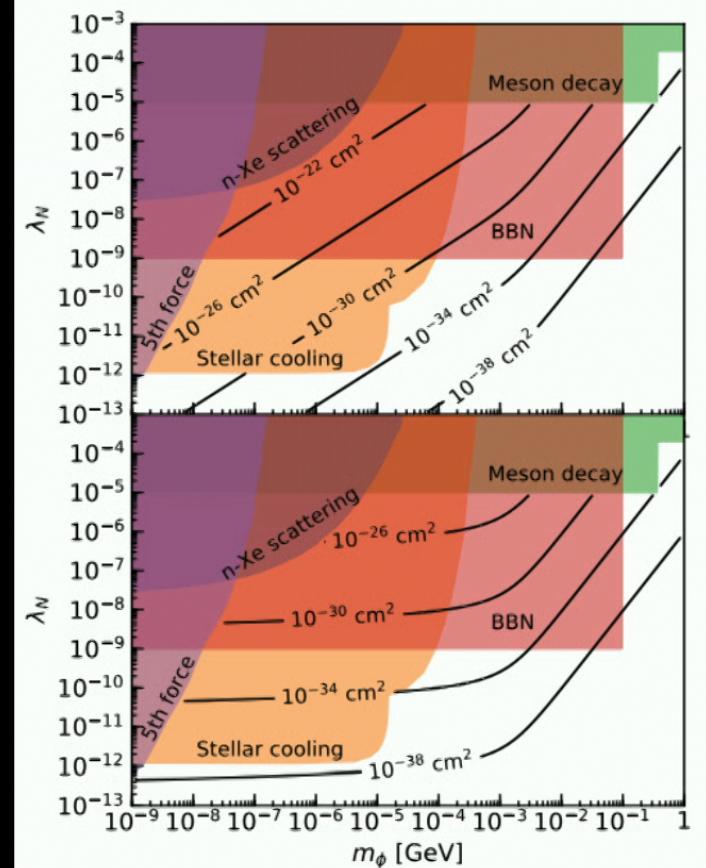
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Attractive Resonances and Light Mediators



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



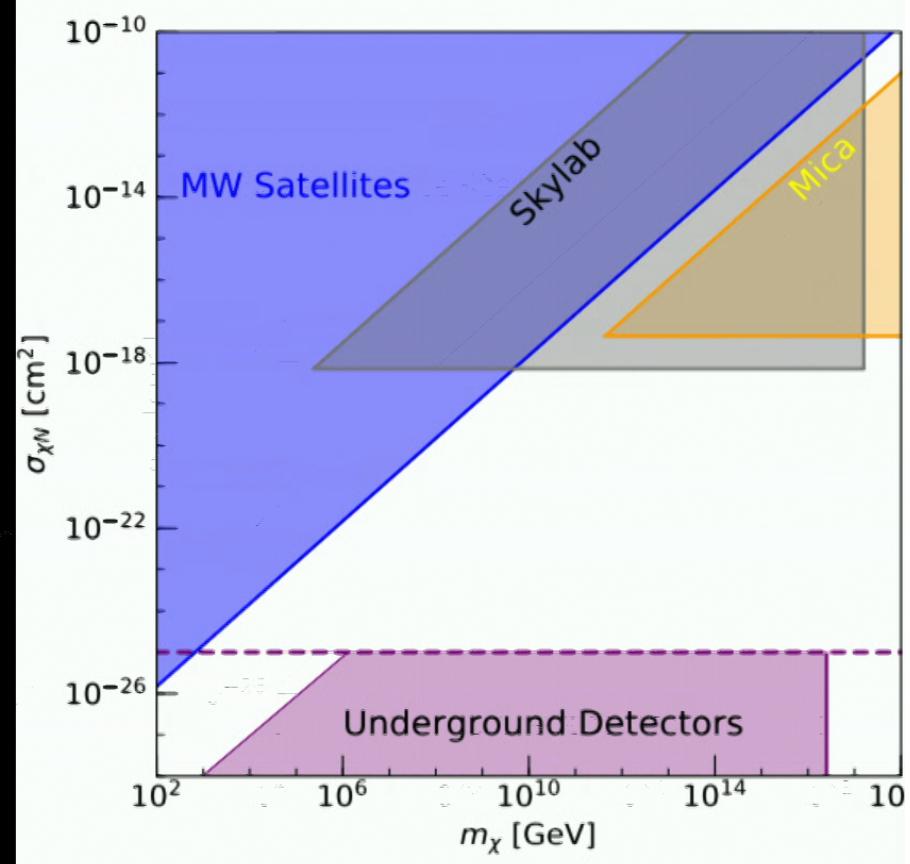
Light Mediators: see e.g. arXiv:1709.07882 (Knapen, Lin & Zurek 2017) 14

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: $\sigma_{xN} = \sigma_{xA} = \pi R_x^2$
- Dashed purple line: largest cross section for pointlike dark matter
- Gap in limits between maximum point cross section and structure formation bounds



arXiv:2008.10646 (Cappiello, Collar, Beacom)



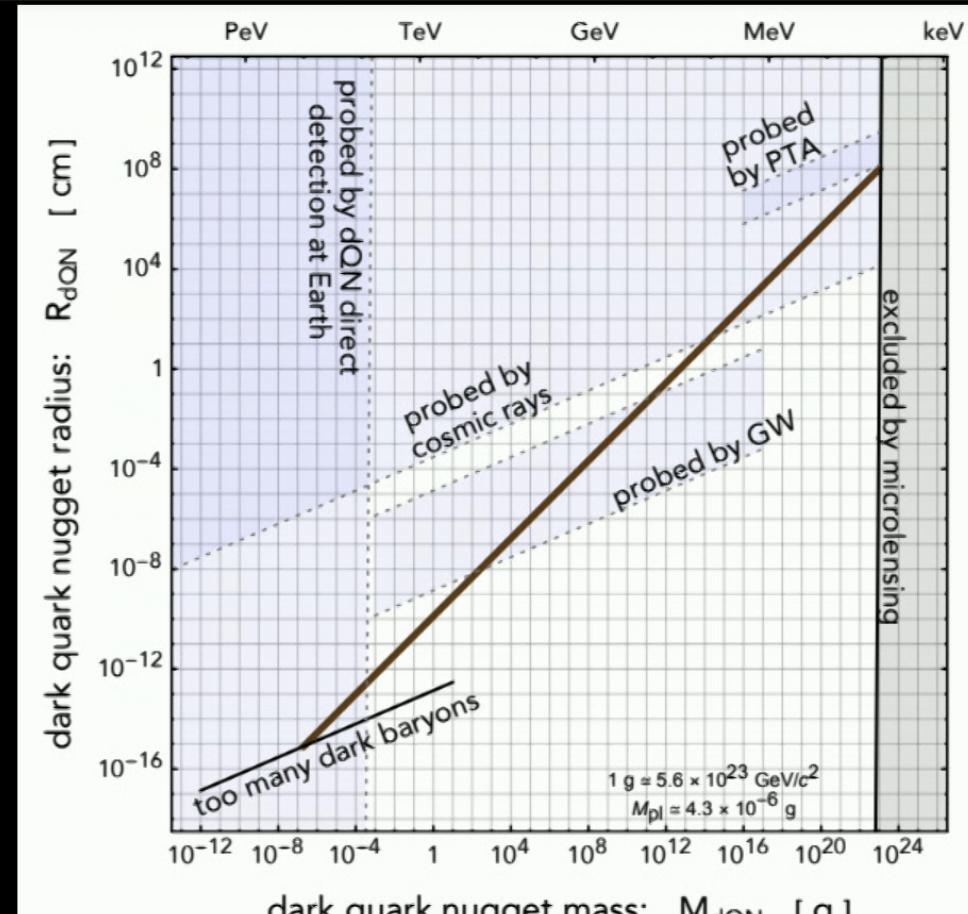
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Superheavy DM Models

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)

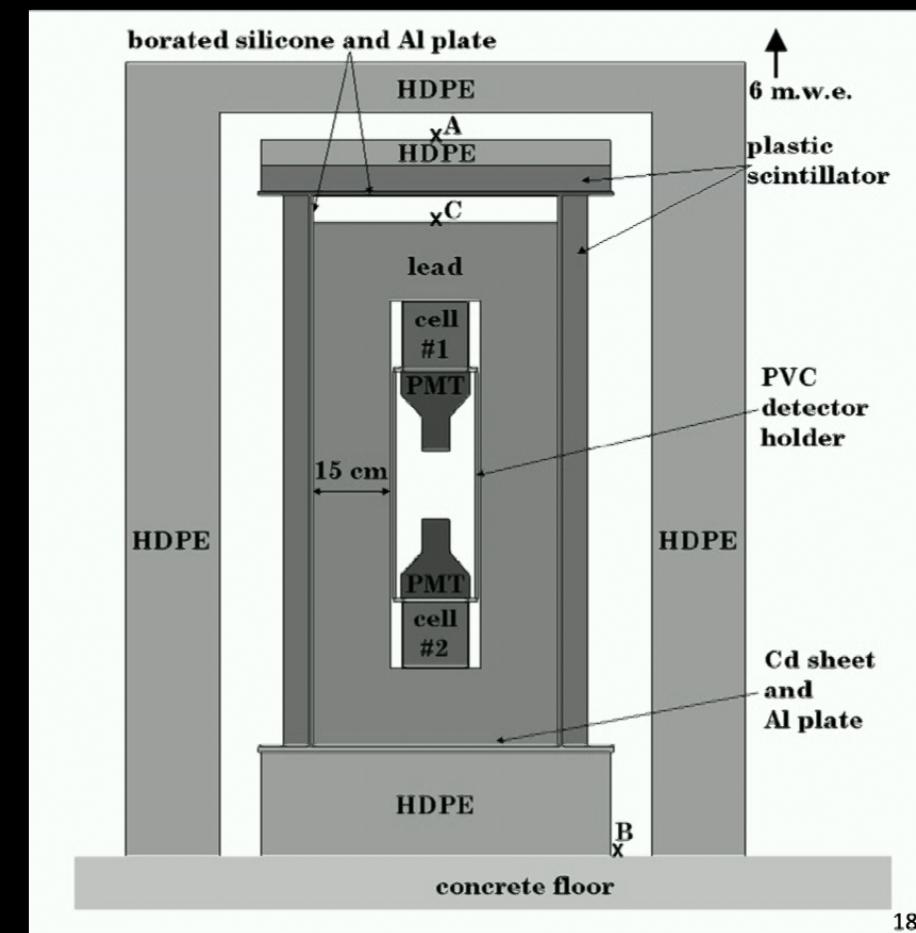


arXiv:1810.04360 (Bai, Long & Lu 2018)

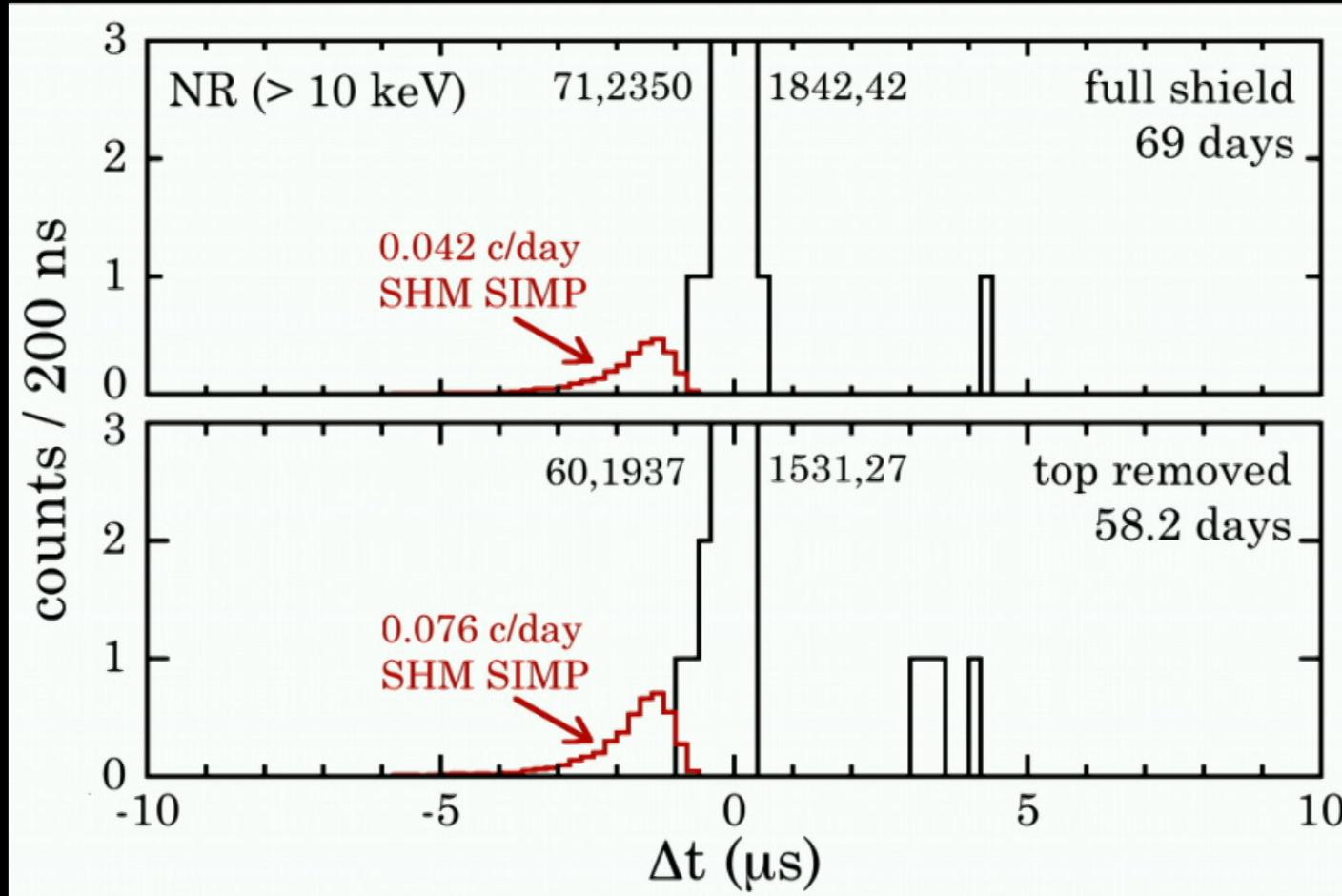
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Detector Setup

- 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



Time Delay Distribution

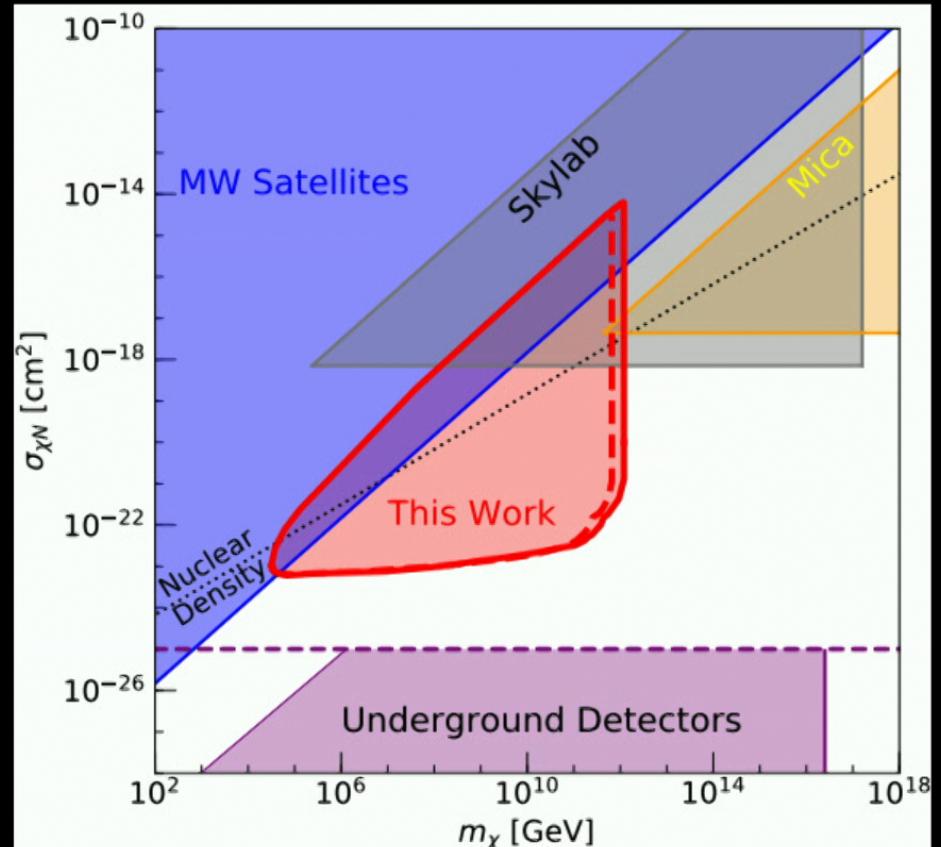
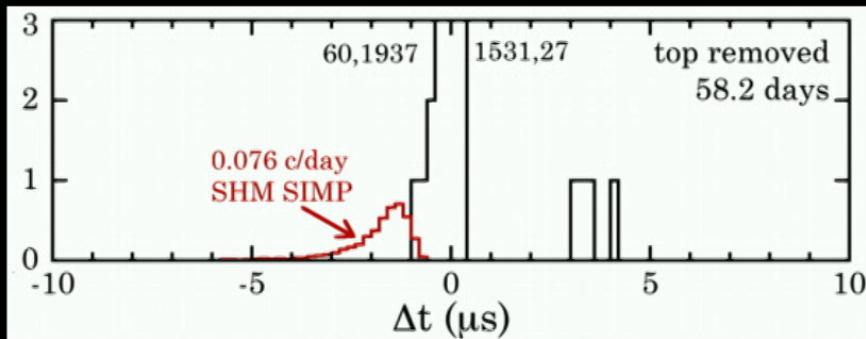


arXiv:2008.10646 (Cappiello, Collar, Beacom)

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New Constraints on Composite Dark Matter

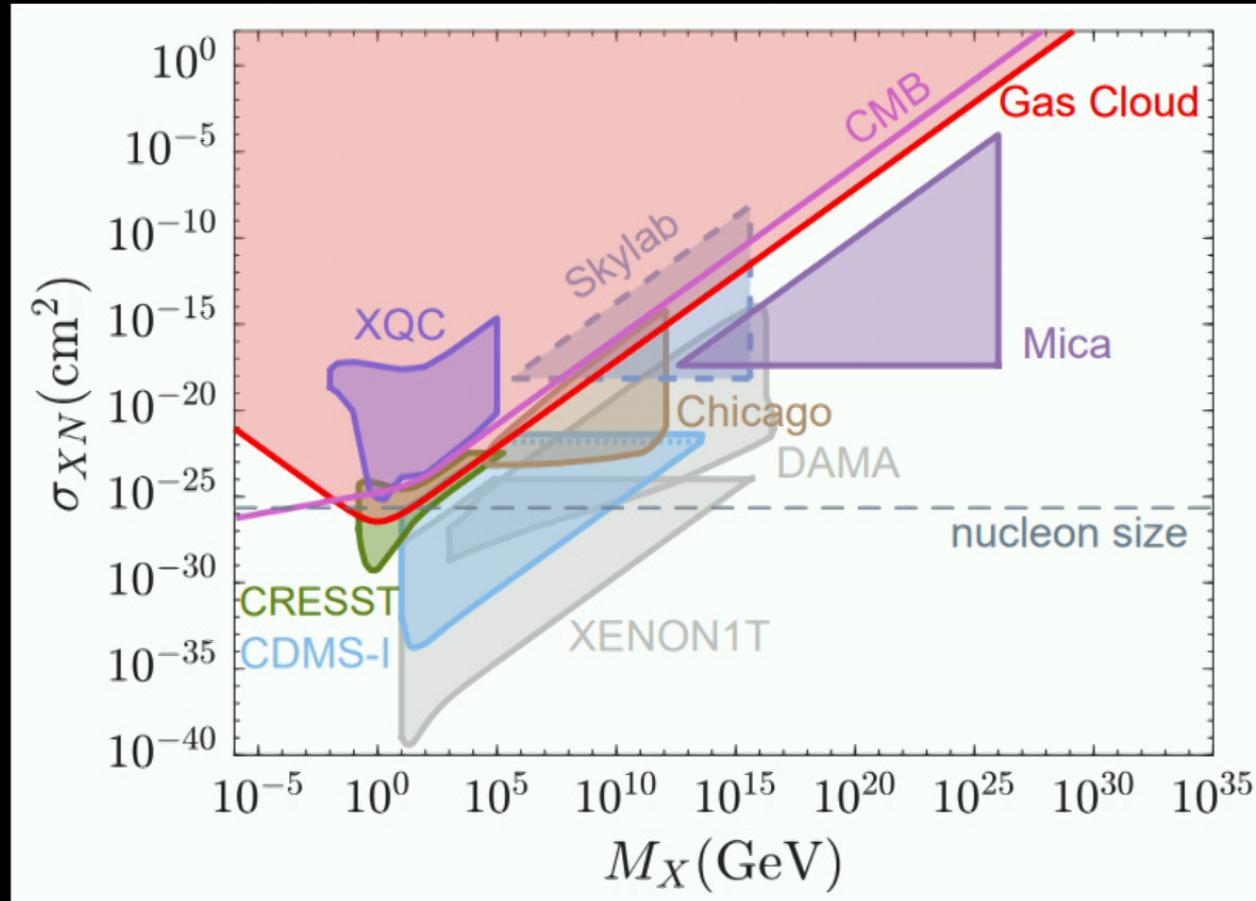
- Ceiling determined by attenuation in atmosphere and shielding
- Bottom of region set by energy threshold
- High mass edge determined by exposure (time and acceptance angle)



arXiv:2008.10646 (Cappiello, Collar, Beacom)

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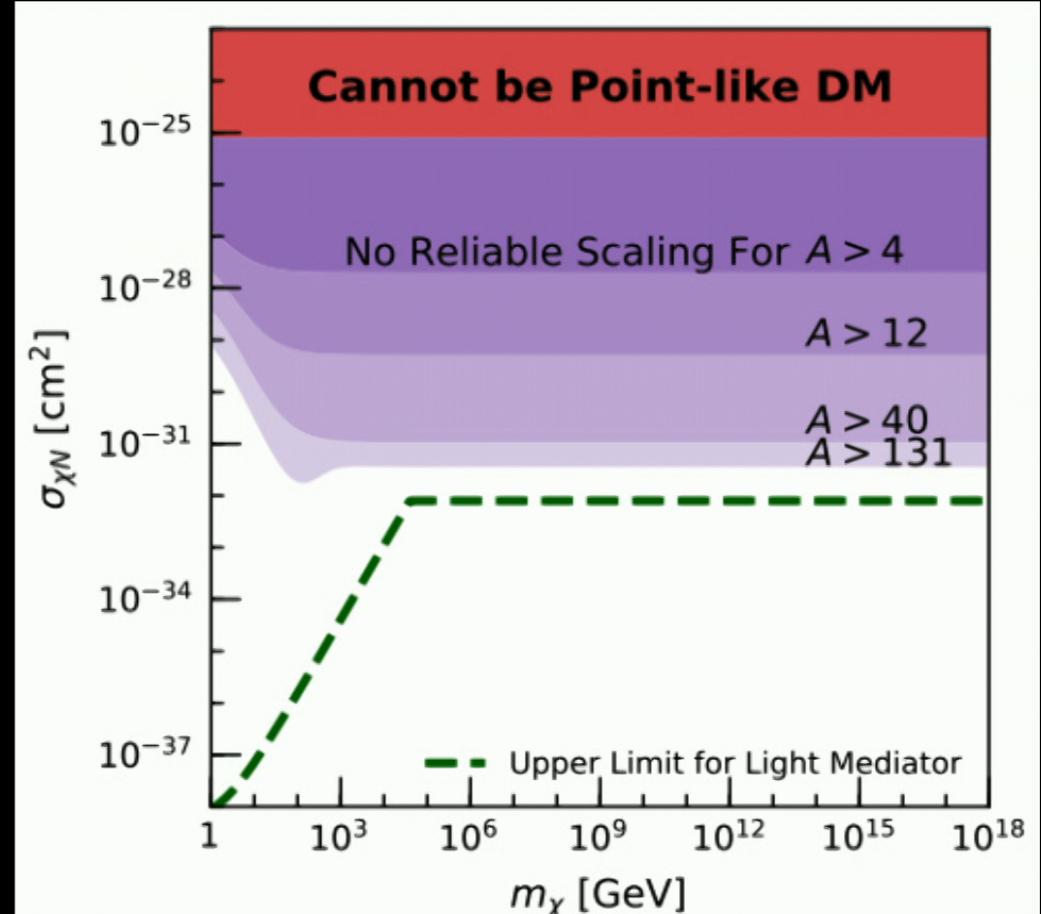
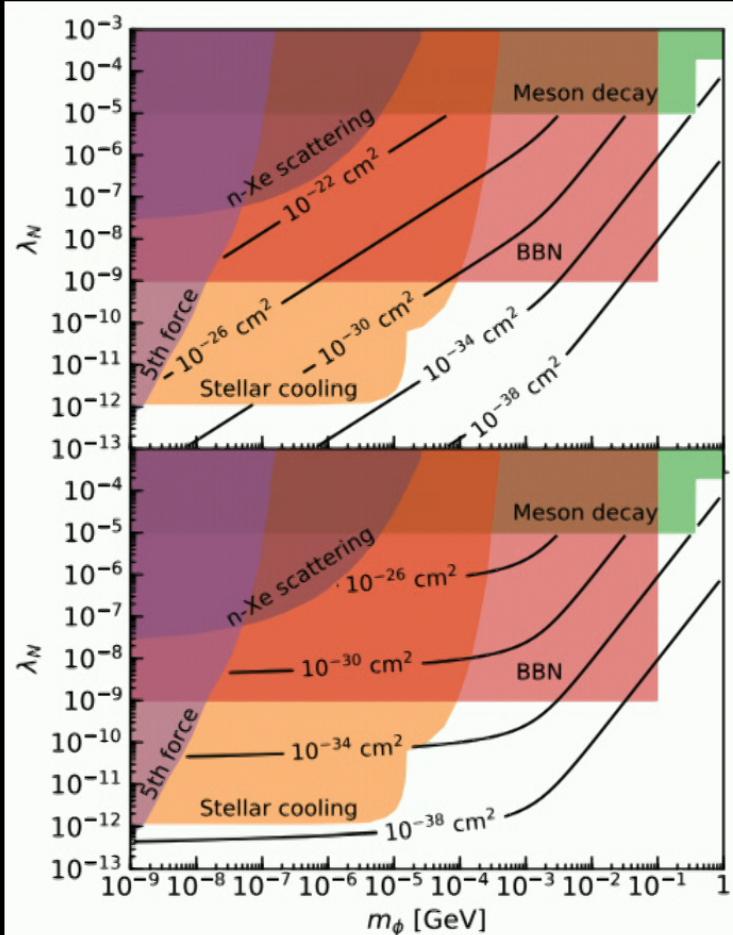
Direct Detection and Composite Dark Matter



arXiv:2010.07240 (Bhoonah et al.)

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Light Mediators



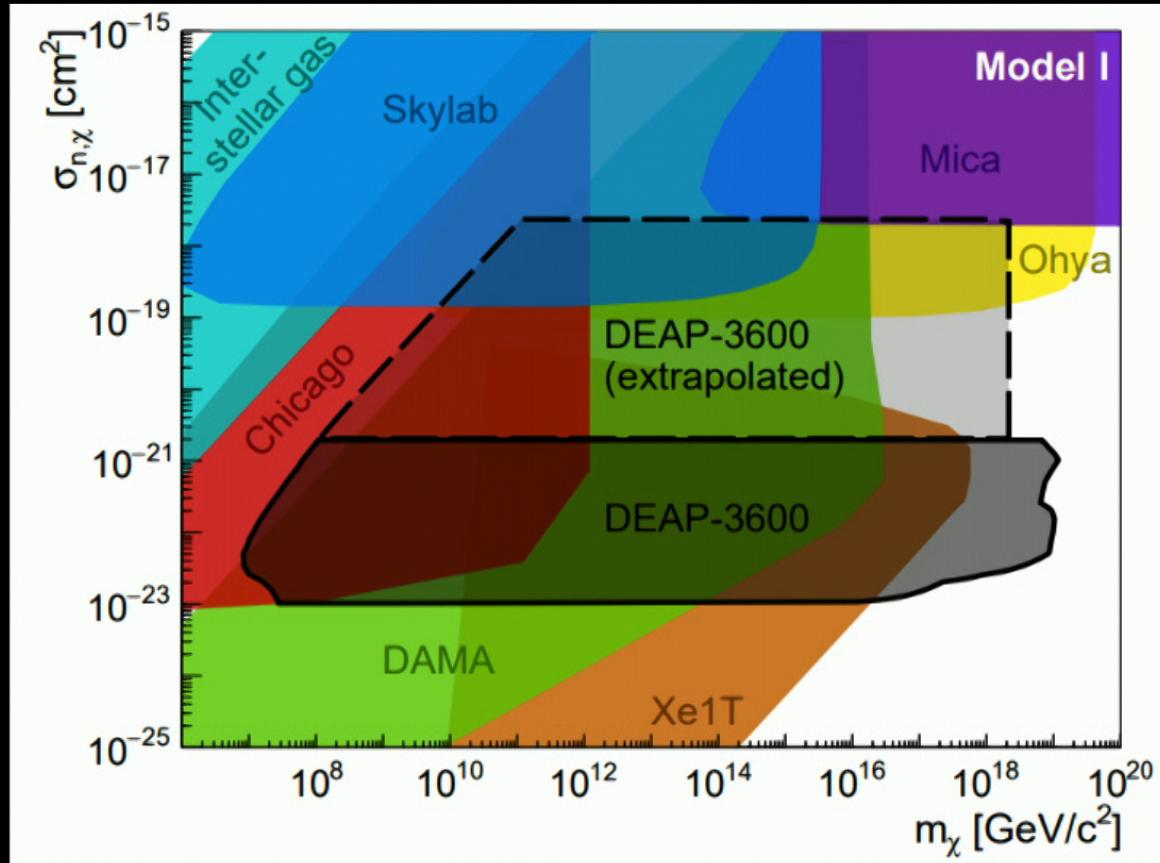
arXiv:2008.10646 (Digman, Cappiello et al.)

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

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

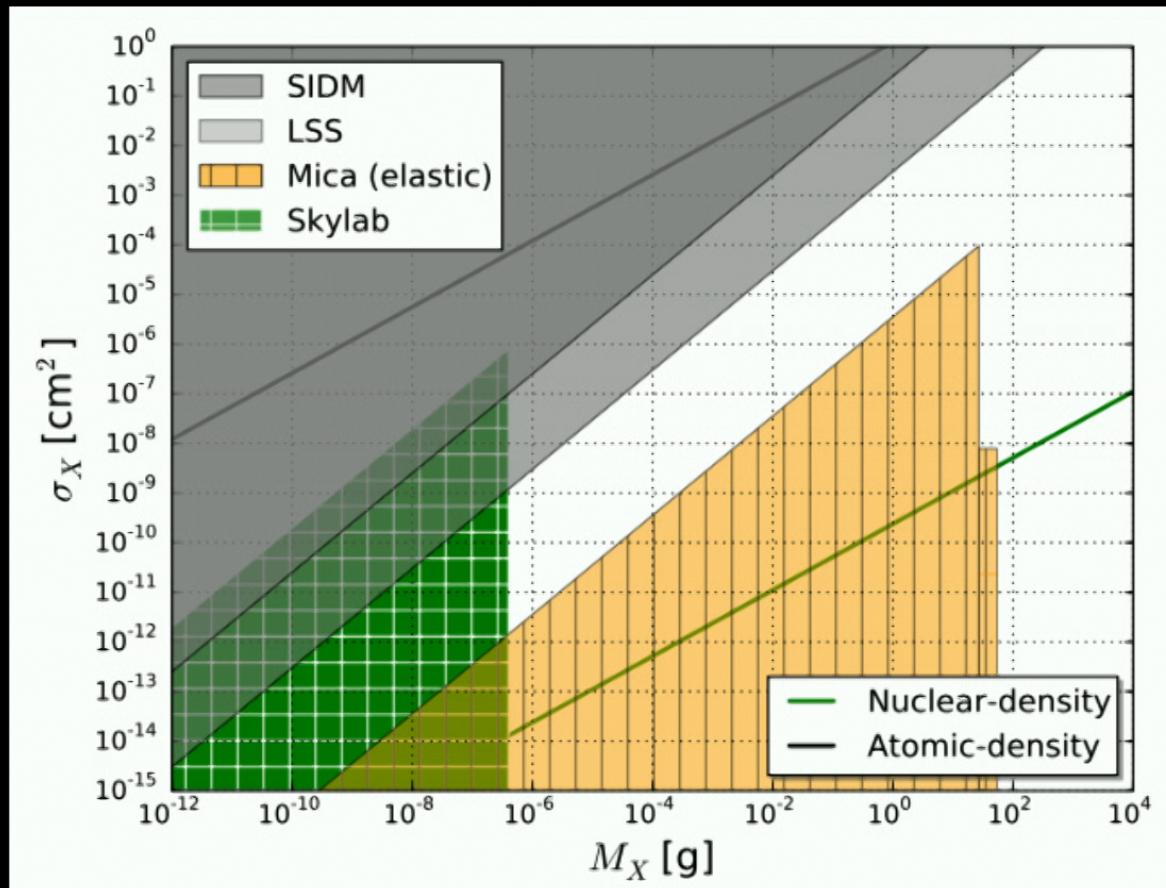
Additional Constraints



arXiv:2108.09405 (Adhikari et al.)

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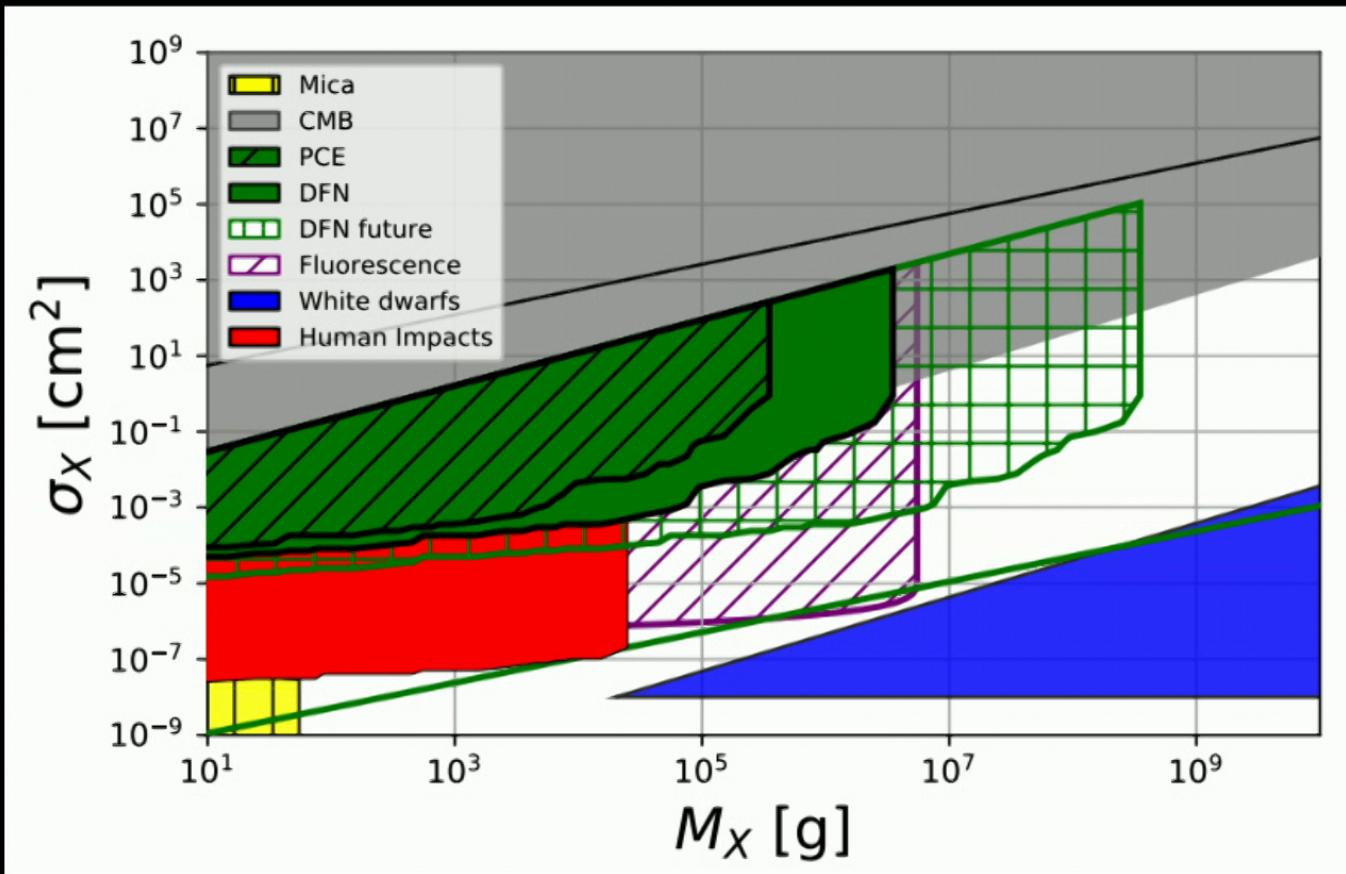
Limits from Ancient Mica



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

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Limits from Bolide Cameras



arXiv:1908.00557 (Sidhu et al.)

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Radar Meteor Detection



Space.com

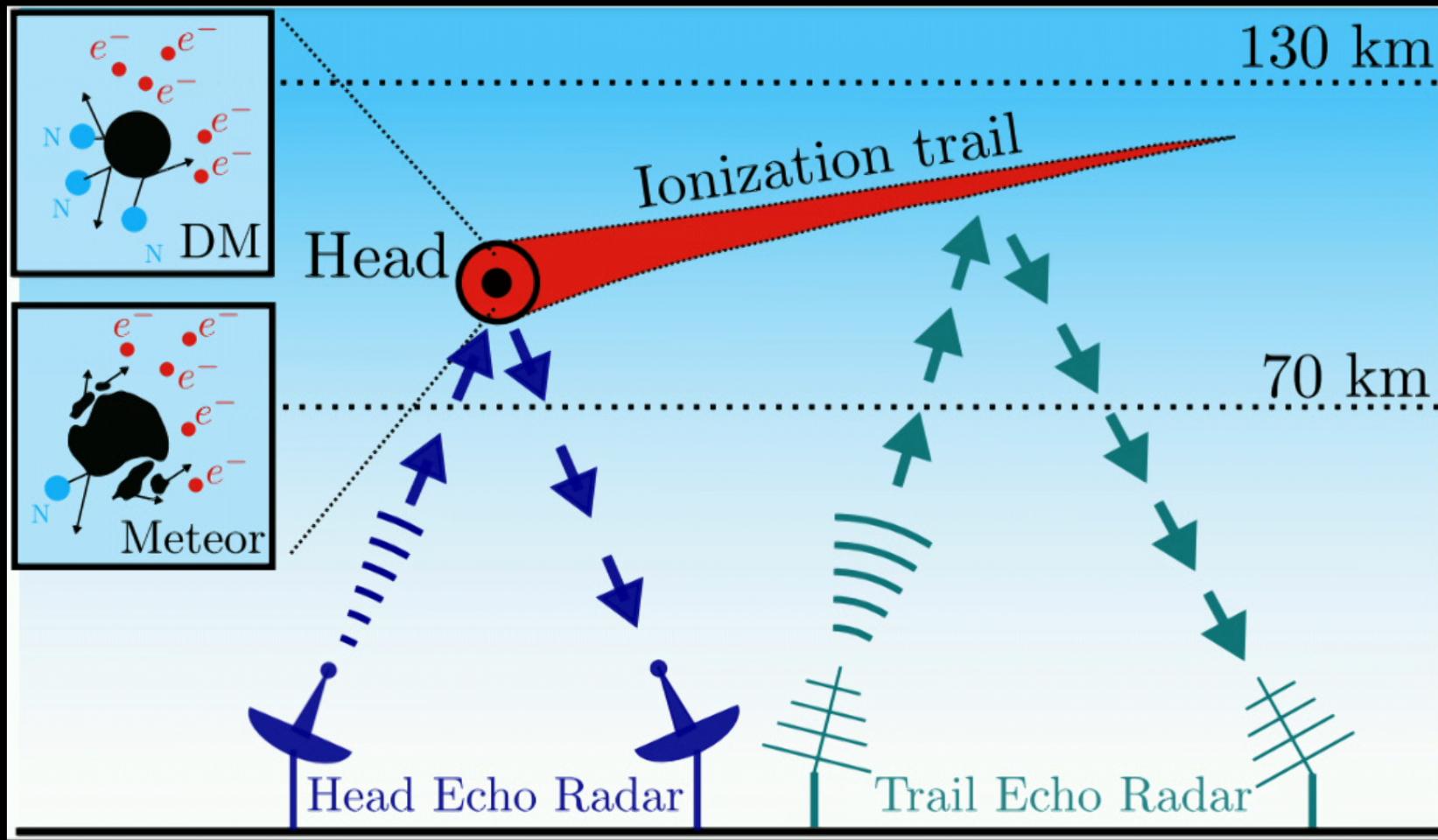
Shigaraki Middle and Upper Atmosphere Radar Observatory



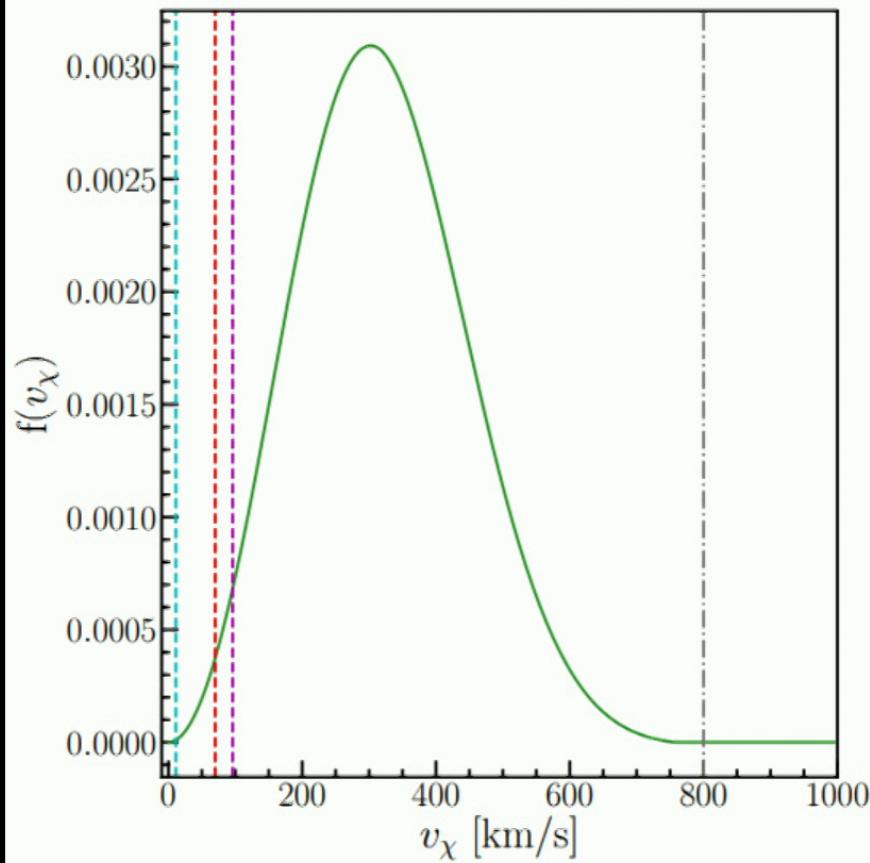
http://www.rish.kyoto-u.ac.jp/organization_e/collaborative_research/mur/

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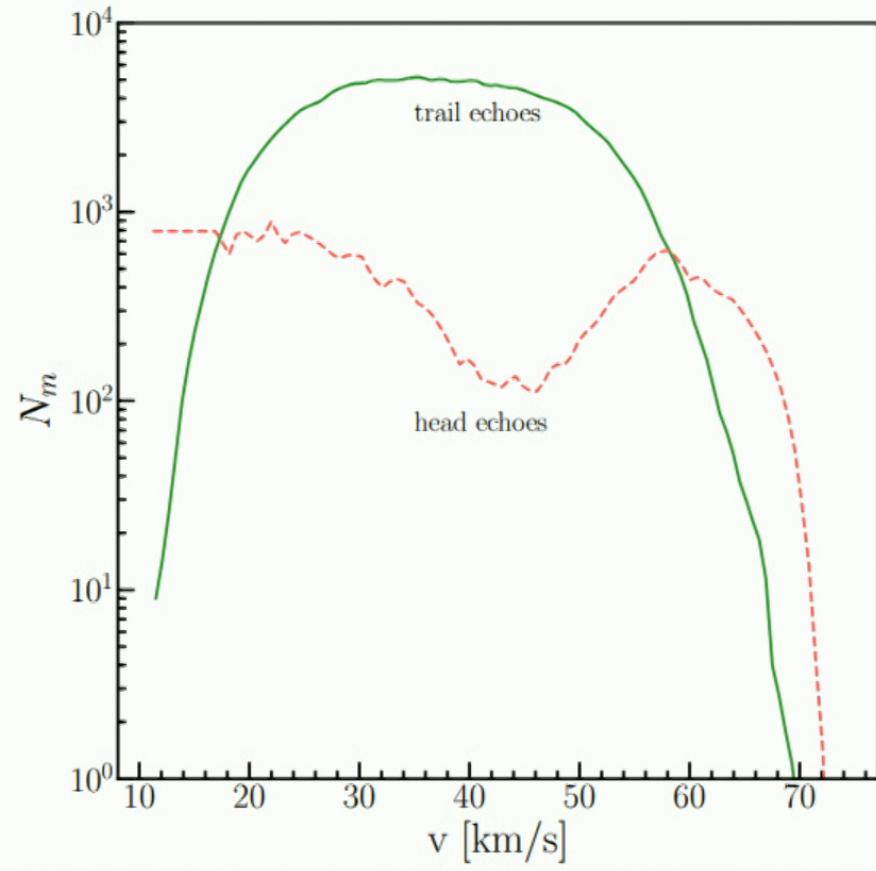
Head Echoes and Trail Echoes



DM and Meteor Velocities

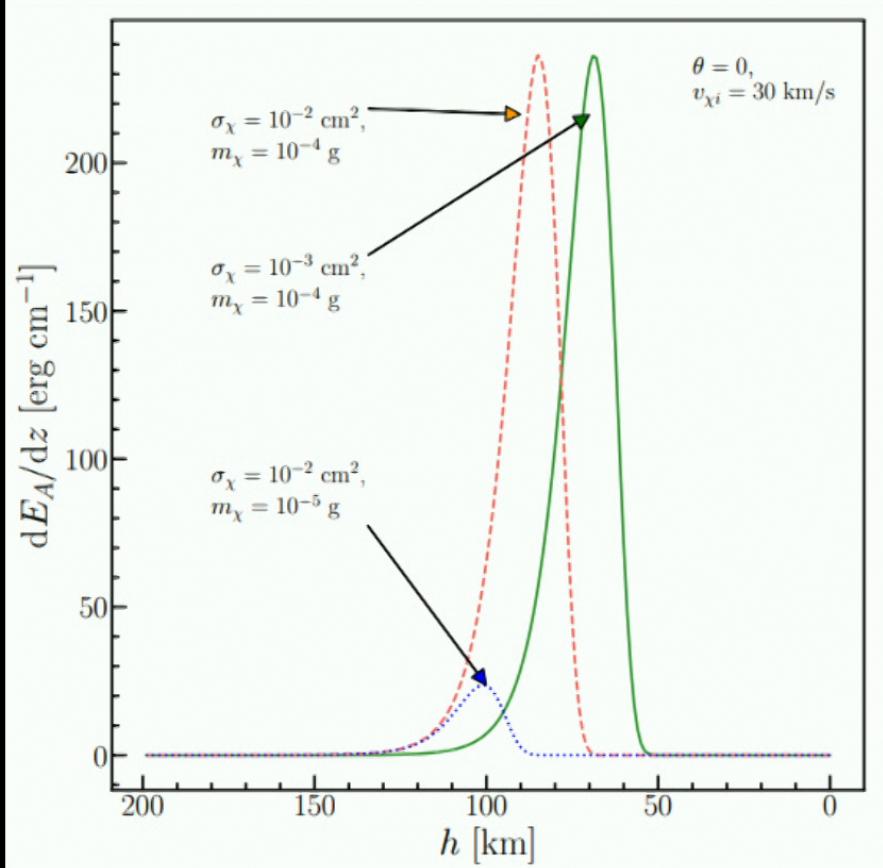


Dhakal et al. in prep.



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DM Energy Deposition in the Atmosphere



Higher energy deposition leads to higher electron line density:

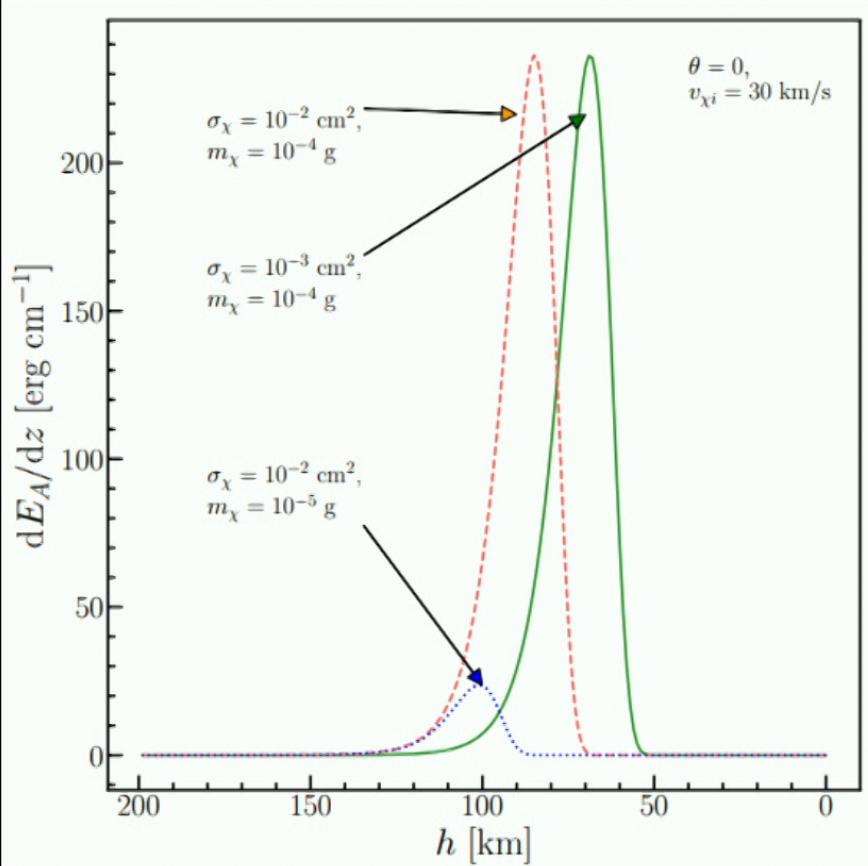
$$q_e = \frac{dE_A / dz}{\langle I \rangle}$$

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

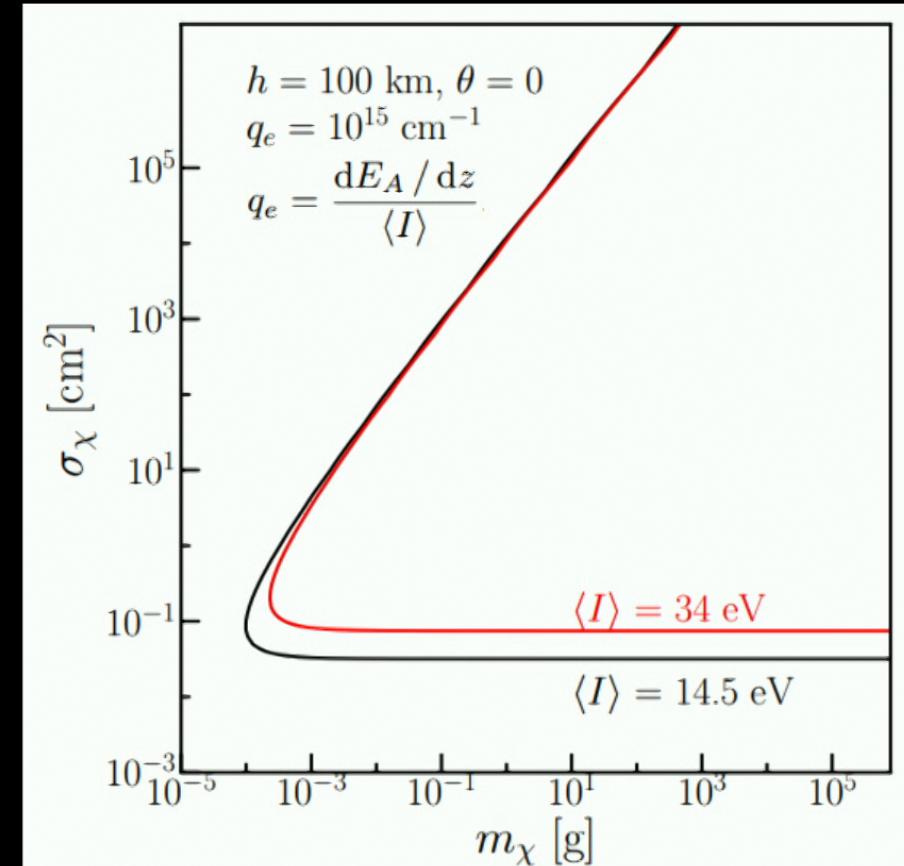
Dhakal et al. in prep.

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DM Energy Deposition in the Atmosphere

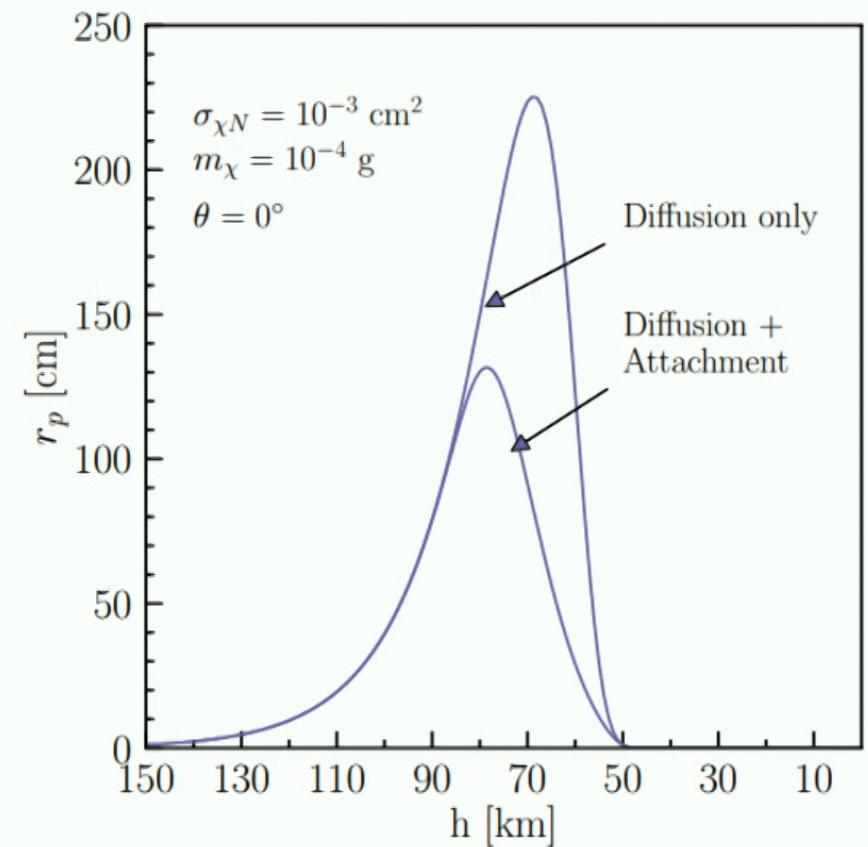
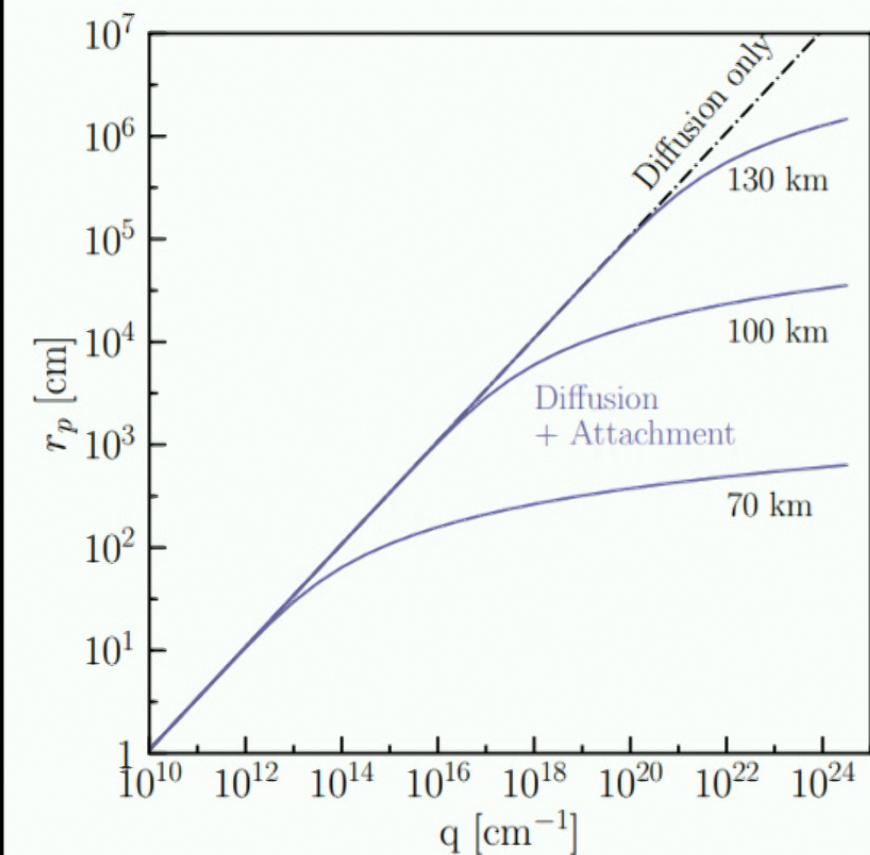


Dhakal et al. in prep.



Dhakal et al. in prep.

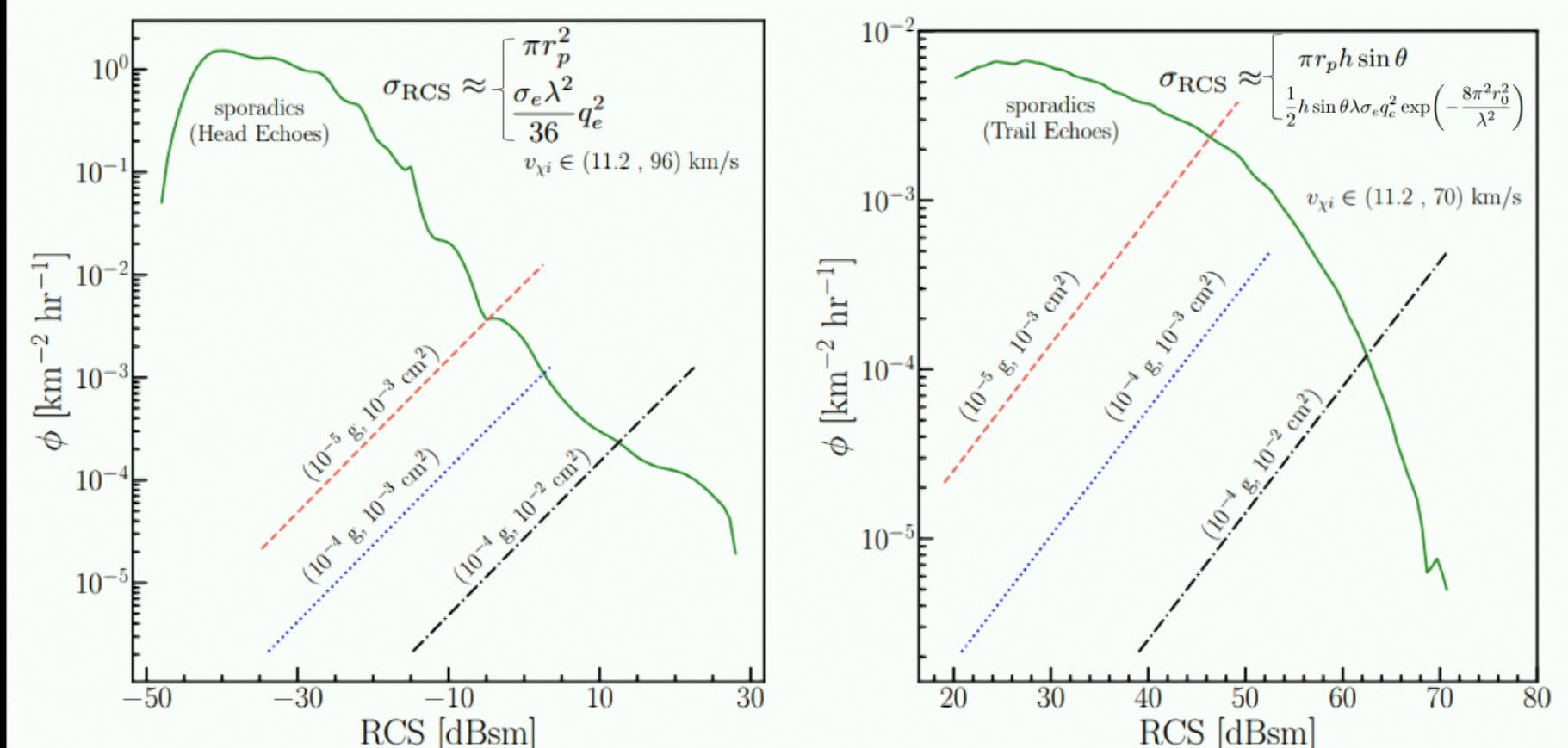
Diffusion and Plasma Radius



Dhakal et al. in prep.

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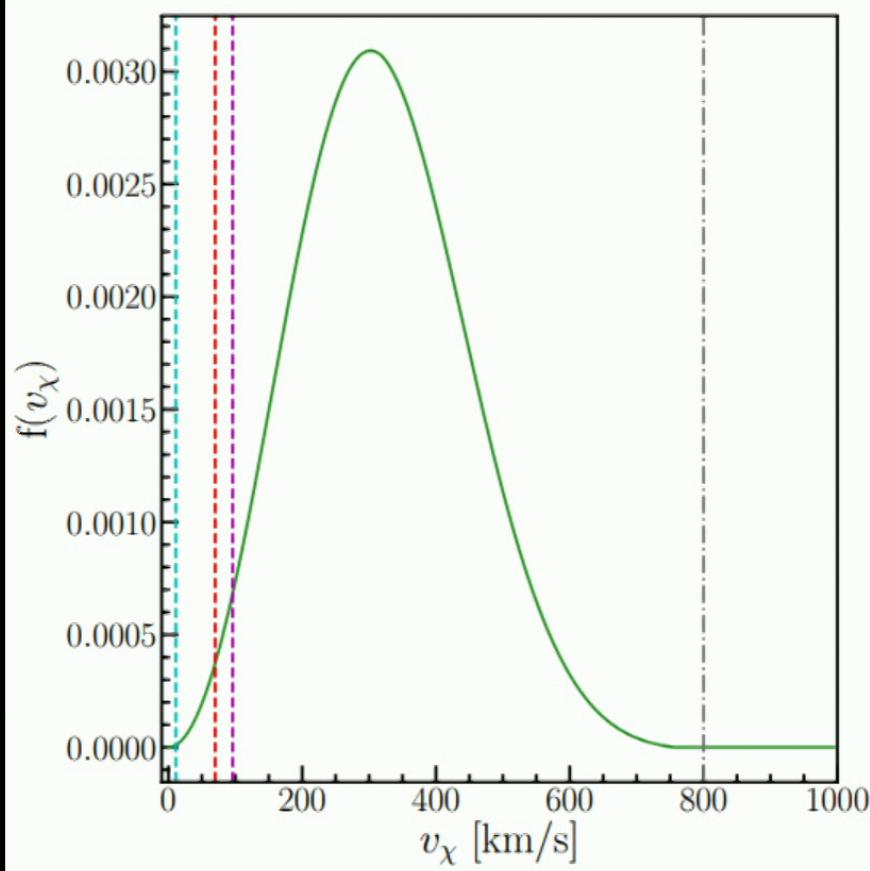
DM vs Meteor Flux



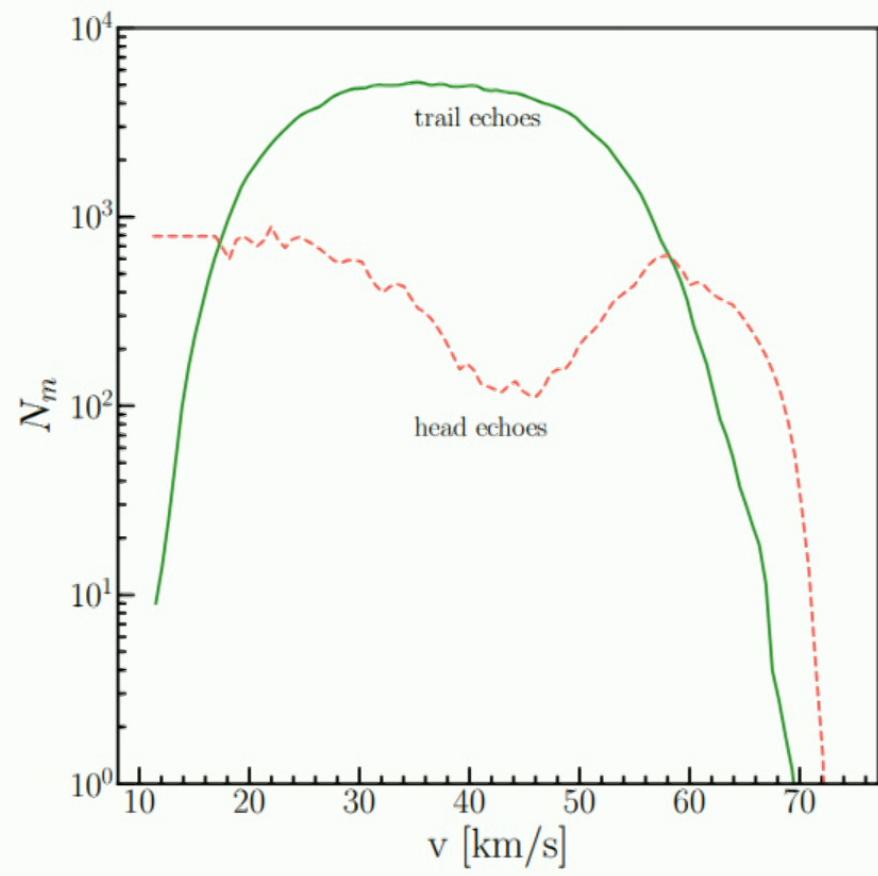
Dhakal et al. in prep.

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DM Energy Deposition in the Atmosphere

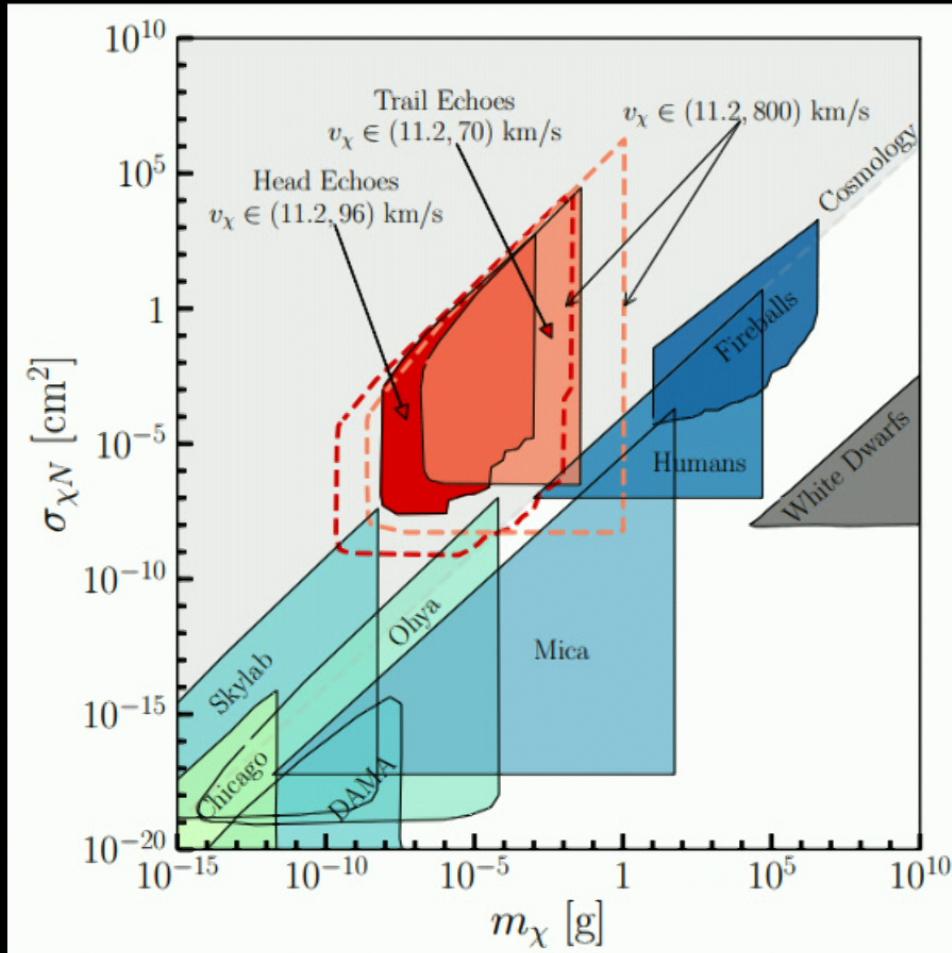


Dhakal et al. in prep.



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Meteor Exclusion Region



Dhakal et al. in prep.

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