Detecting Light Dark Matter with Semiconductors

Peizhi Du (杜佩之)

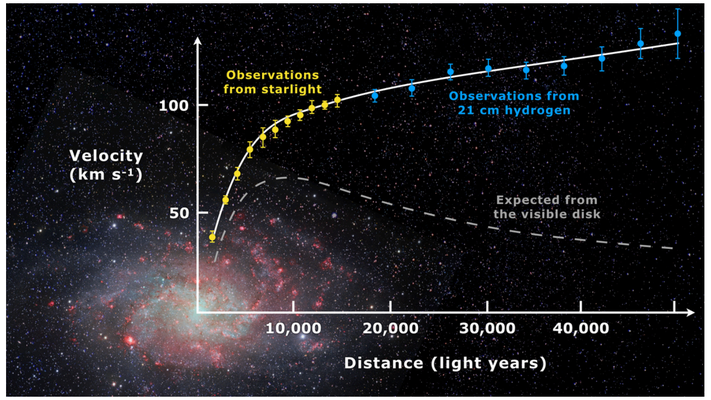
University of Science and Technology of China

Axion Dark Matter: Theory and Phenomenology, Qingdao

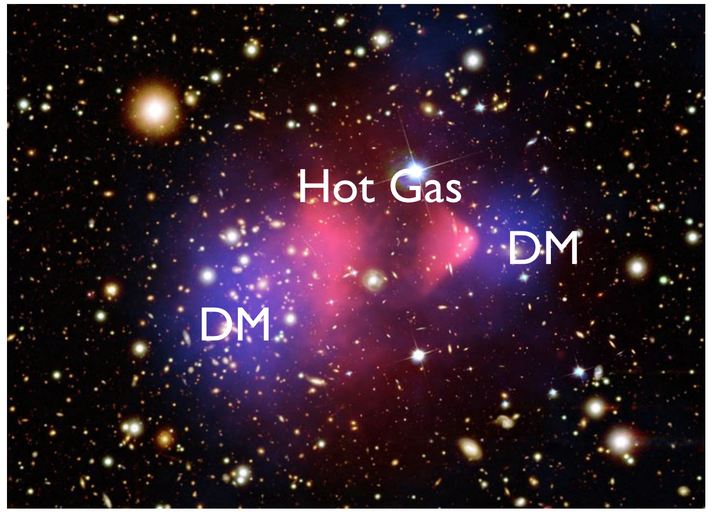
May 11, 2025

Dark Matter

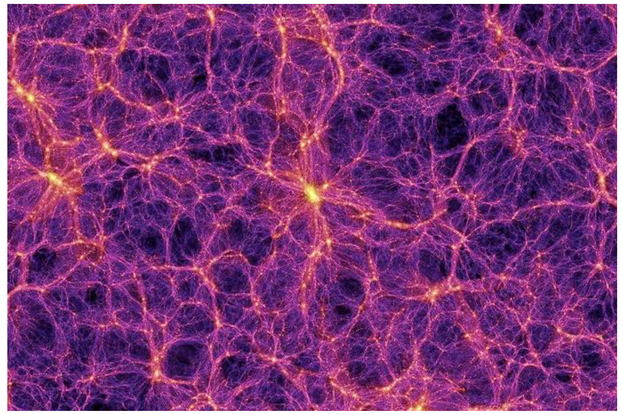
Numerous evidence for the existance of DM



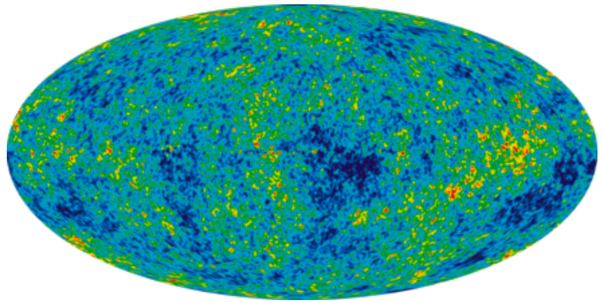
Galaxy (10^4-10^5 ly)



Galaxy Cluster (~10^6 ly)



Large Scale Structure (~10^7 ly)



Cosmic Microwave Background (~10^{10} ly)

What we know about DM

- Abundant: 85% of matter
- Massive
- Gravitational interactions
- Cold/Collisionless

What we don't know about DM

- Particle Nature
- Mass
- Interactions with visible matter?
- DM self-interactions?

…

What could Dark Matter be

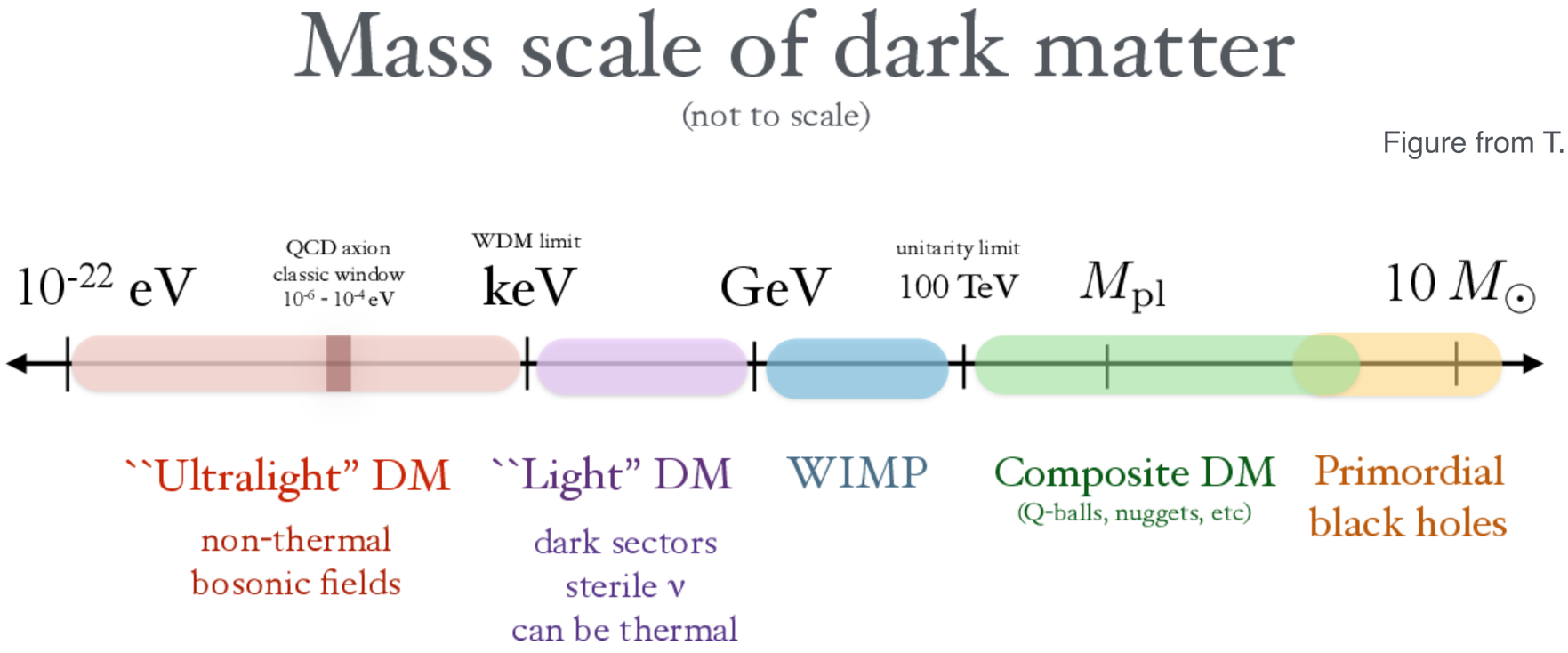


Figure from T. Lin (arXiv:1904.07915)

What could Dark Matter be

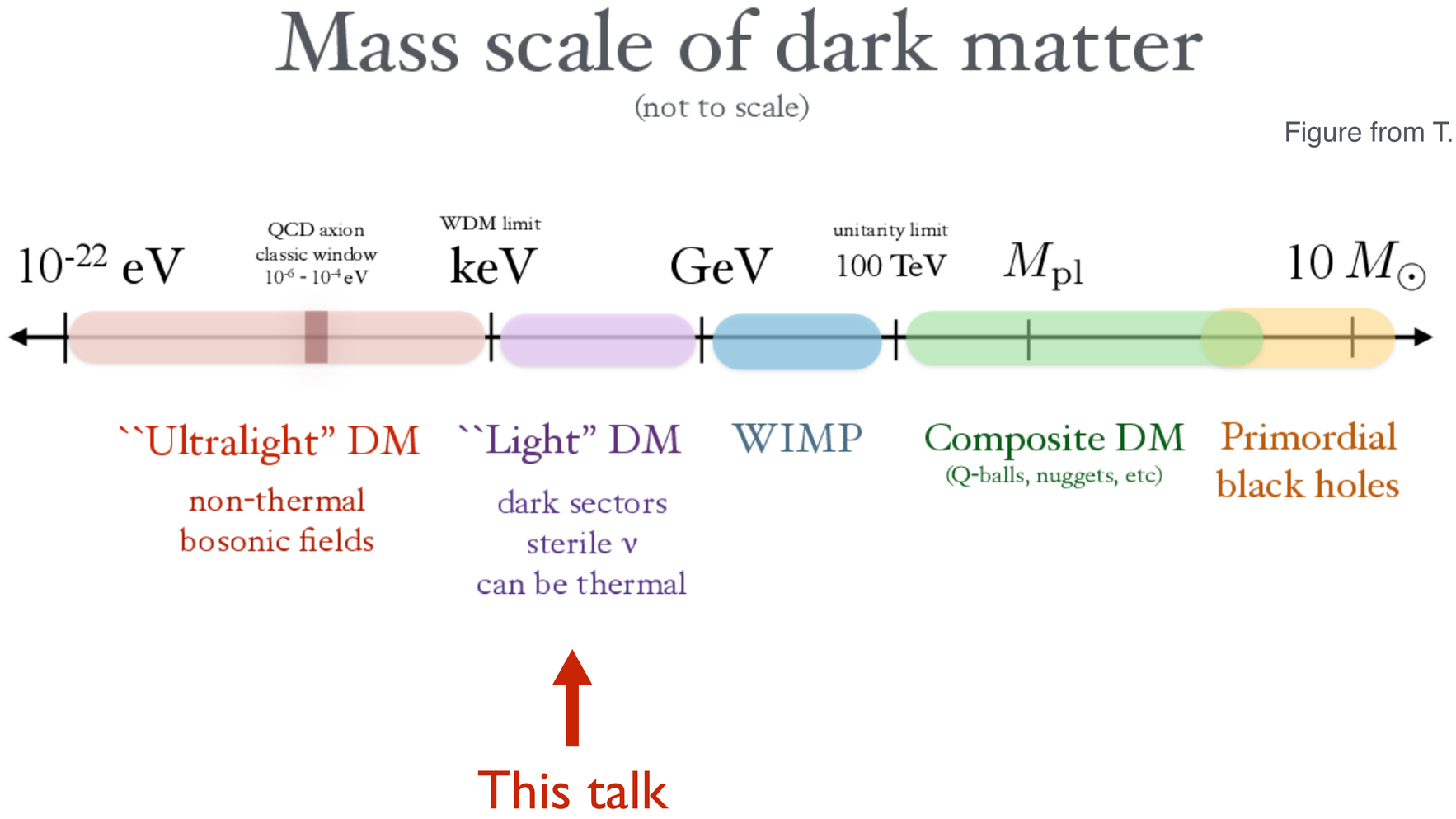
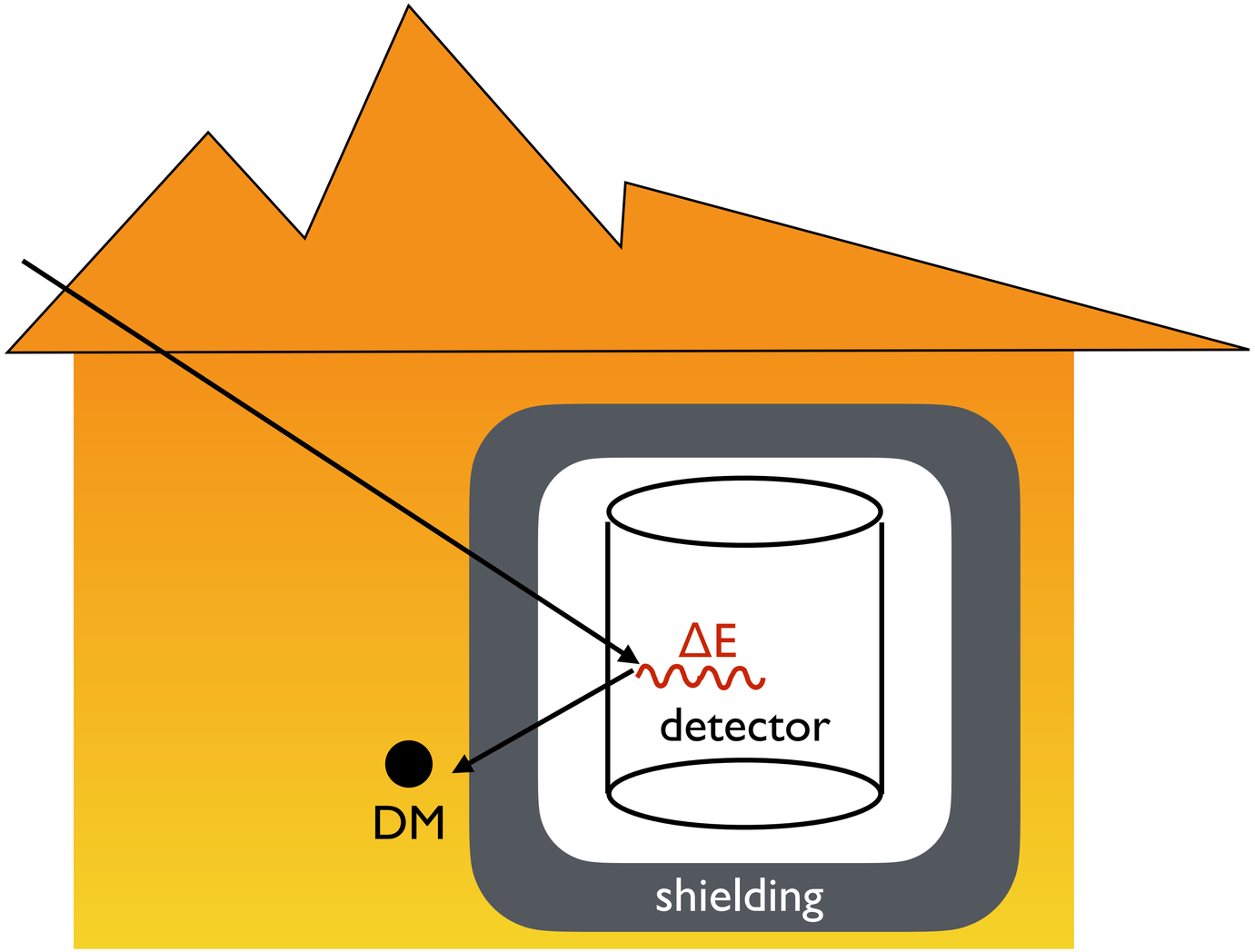


Figure from T. Lin (arXiv:1904.07915)

How to look for DM: Direct Detection of DM



WIMP

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

CDEX

LZ

XENON

Axion

ADMX
AXION DARK MATTER EXPERIMENT

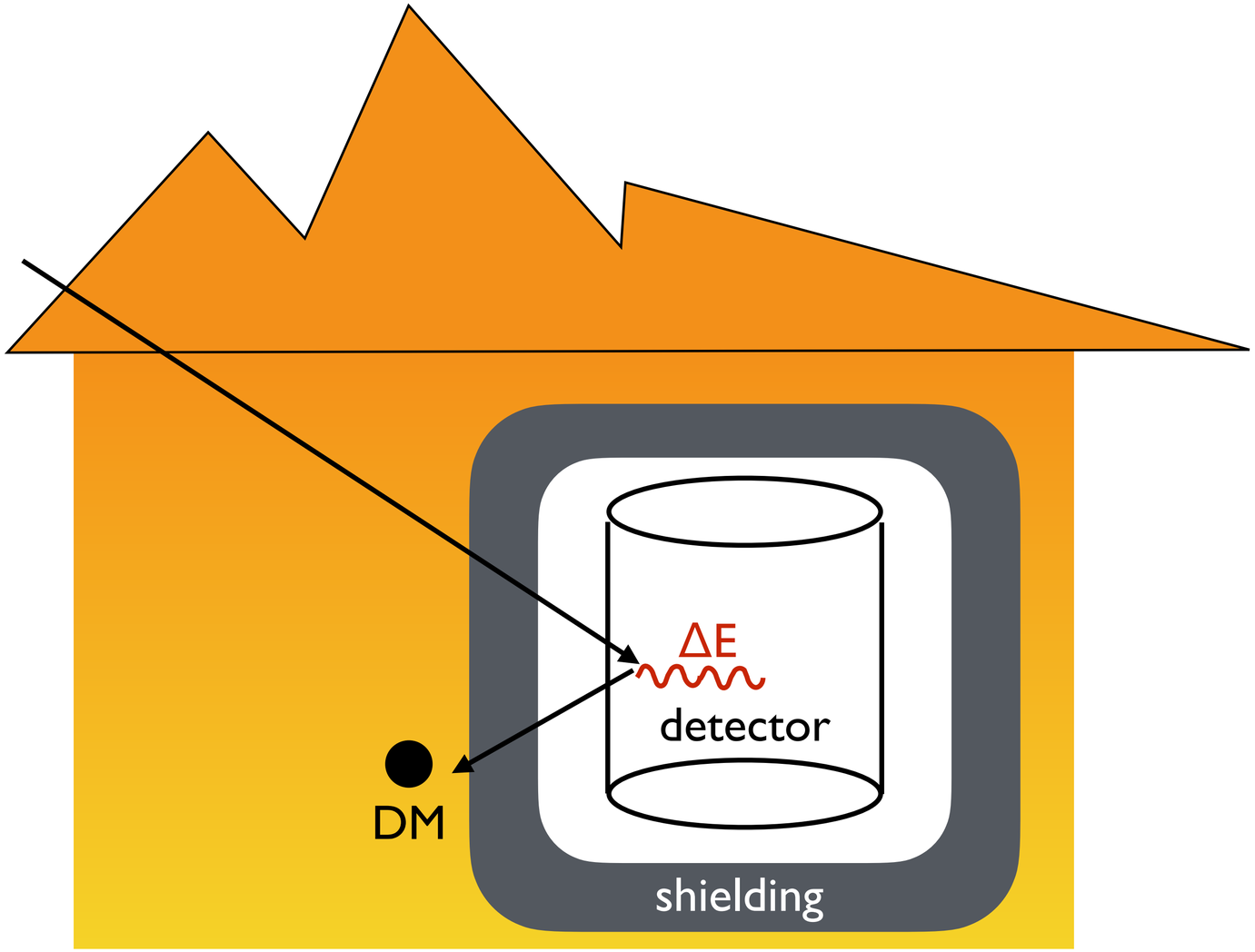
ABRACADABRA

Light DM

ensei

SUPER CDMS
Cryogenic Dark Matter Search

How to look for DM: Direct Detection of DM



WIMP

PANDA X
PARTICLE AND ASTROPHYSICAL XENON TPC

CDEX

LZ

XENON

Axion

ADMX
AXION DARK MATTER EXPERIMENT

ABRACADABRA

Light DM

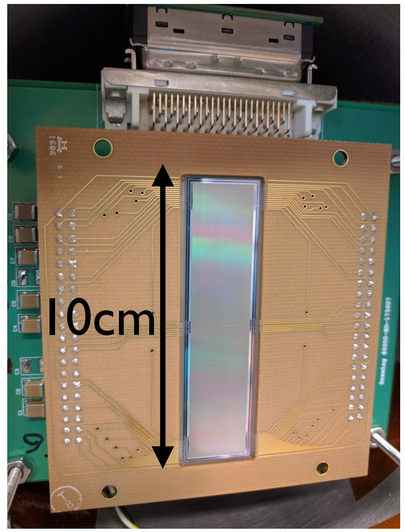
ensei

SUPER CDMS
Cryogenic Dark Matter Search

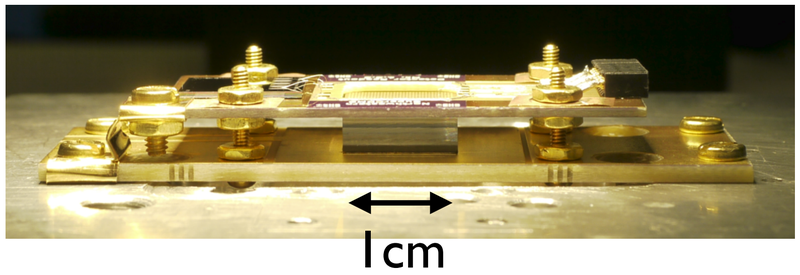
semiconductor detectors

Light DM detection: tabletop experiments

SENSEI

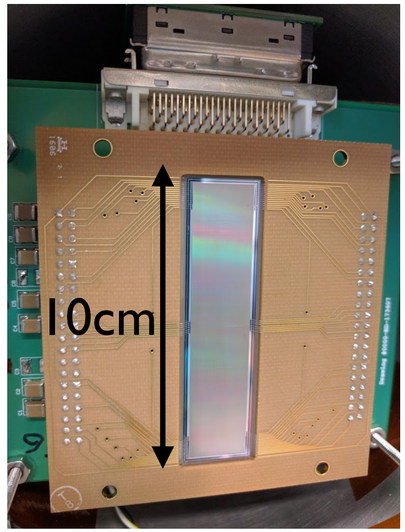


SuperCDMS HVeV

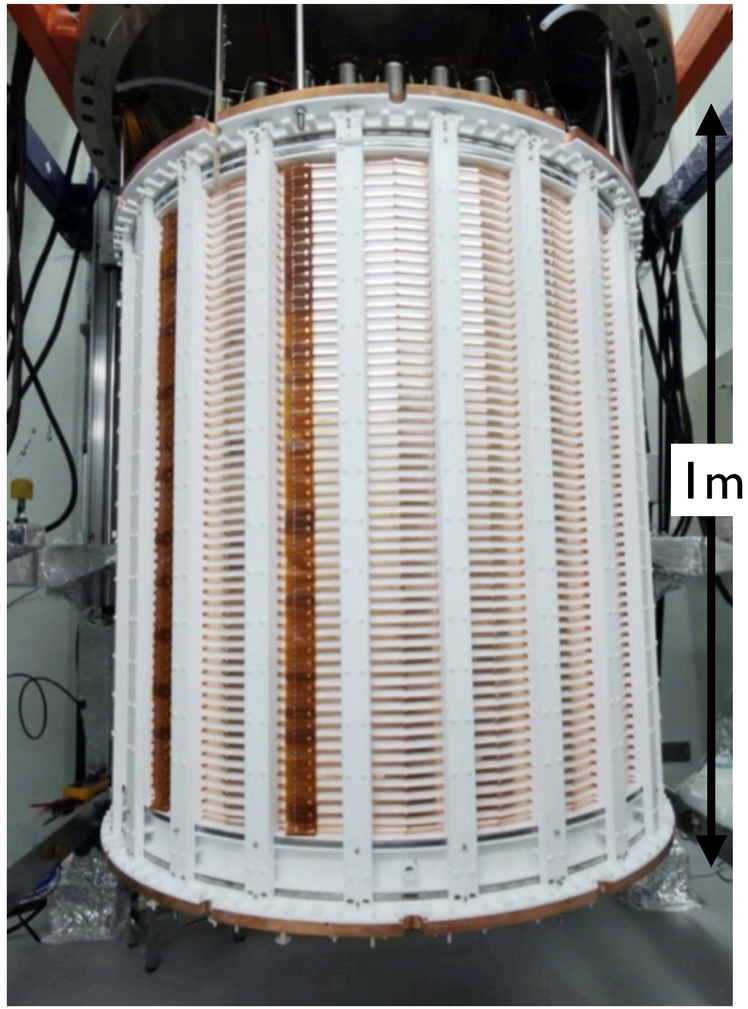


Light DM detection: tabletop experiments

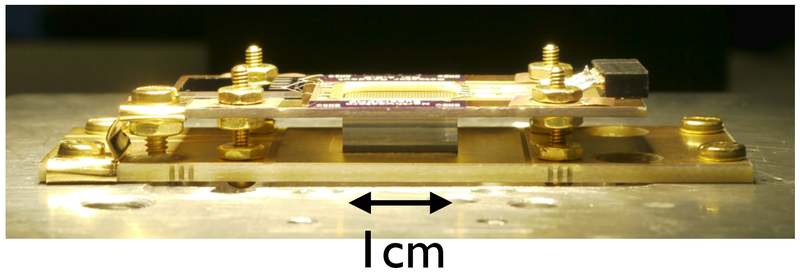
SENSEI



PandaX (WIMP)

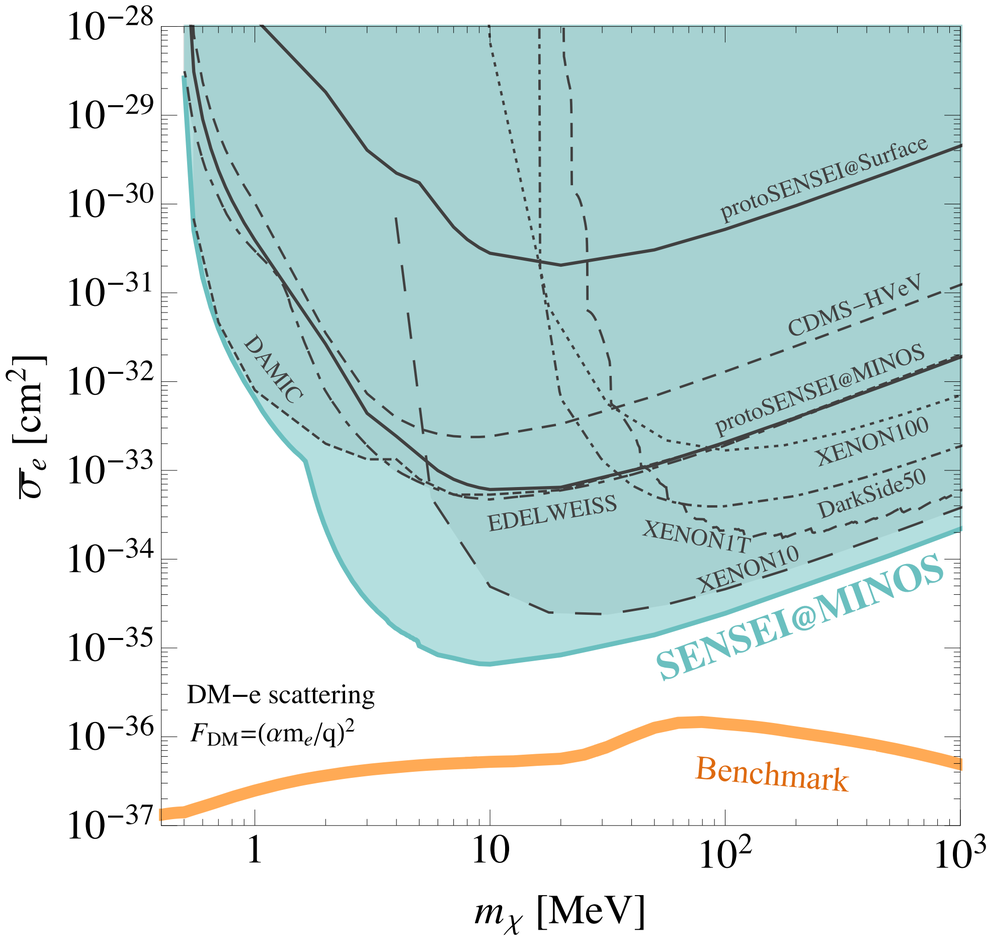


SuperCDMS HVeV



Direct Detection of Light DM

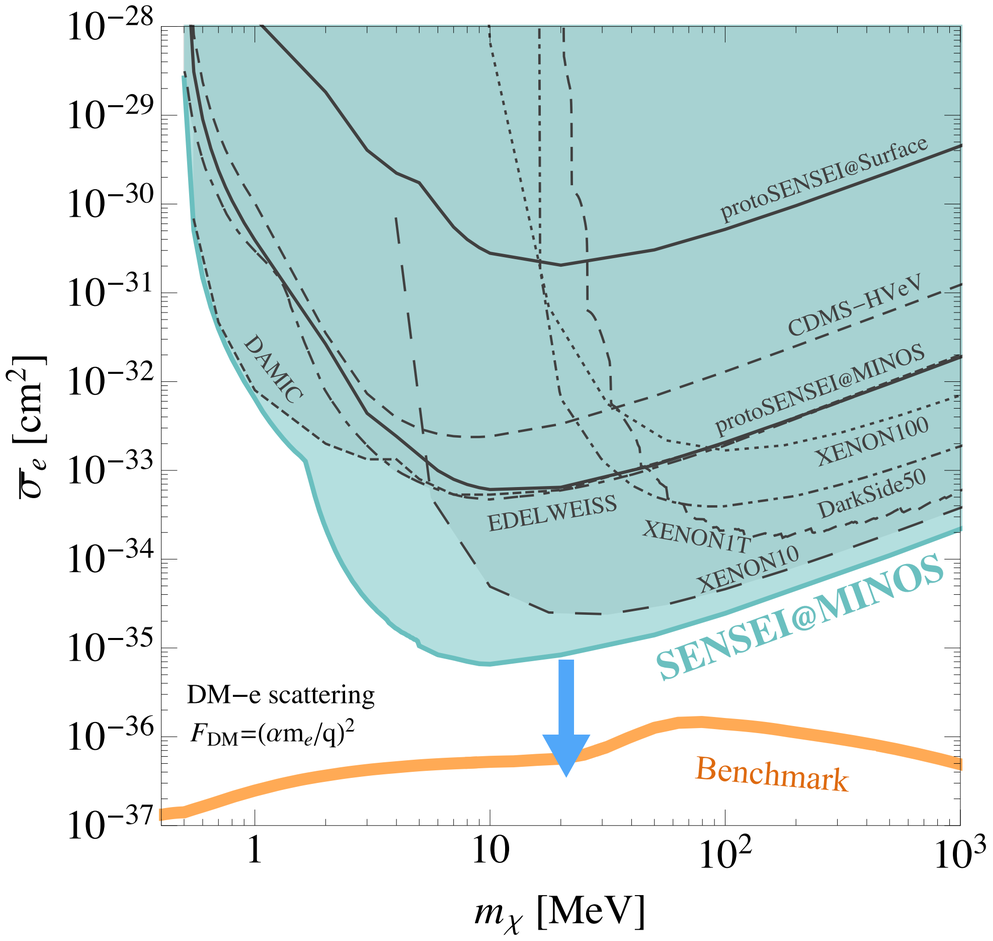
Figure from SENSEI, *PRL* 2020



$$E_{\rm ER} \lesssim \frac{1}{2} m_\chi v^2 \approx 1\,{\rm eV}\left[\frac{m_\chi}{0.5\,{\rm MeV}}\right]$$

Direct Detection of Light DM

Figure from SENSEI, *PRL* 2020

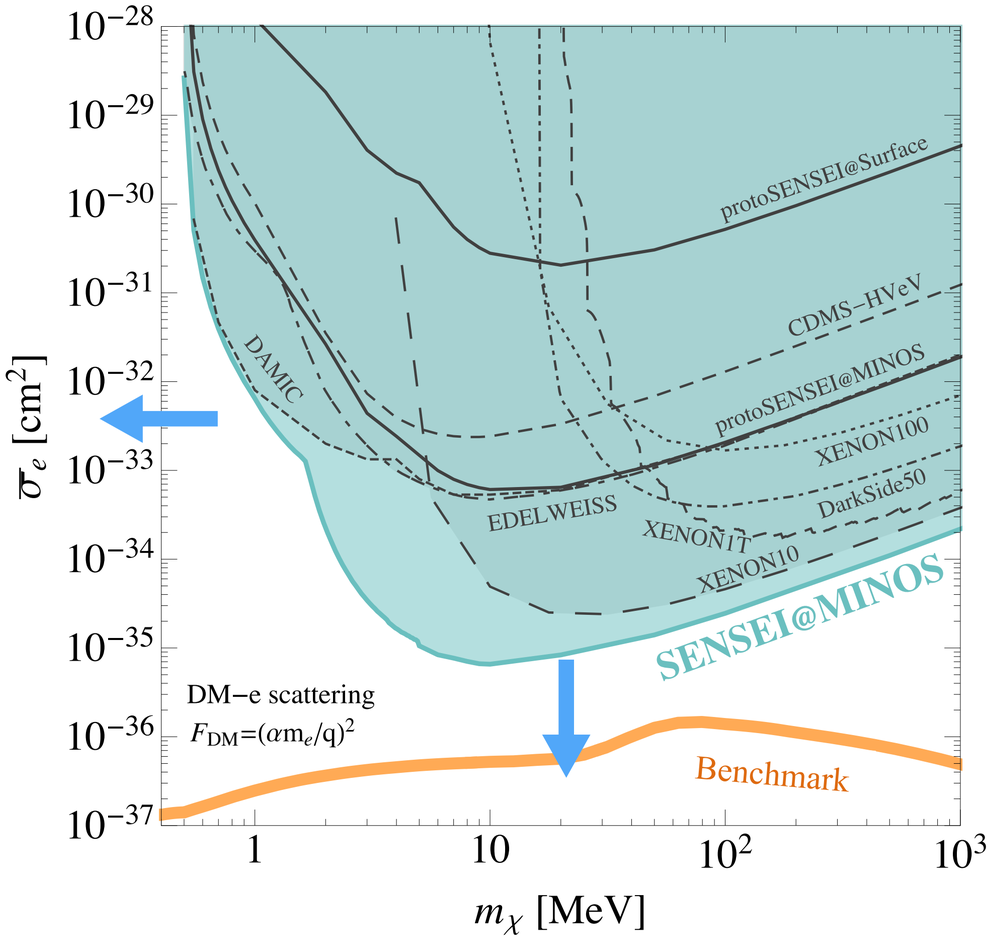


Exploring the parameter space

Probing the theory benchmark

Direct Detection of Light DM

Figure from SENSEI, *PRL* 2020



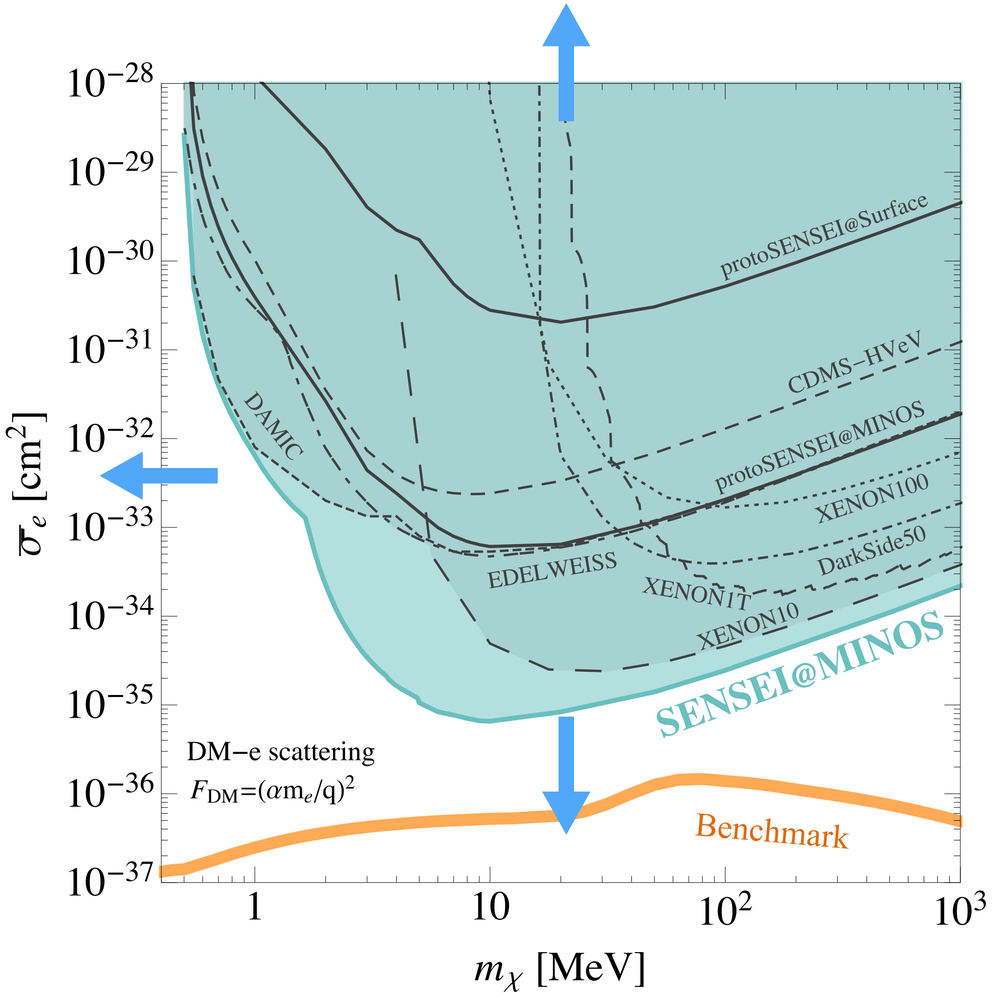
Exploring the parameter space

Probing the theory benchmark

Probing DM lighter than MeV

Direct Detection of Light DM

Figure from SENSEI, *PRL* 2020



Exploring the parameter space

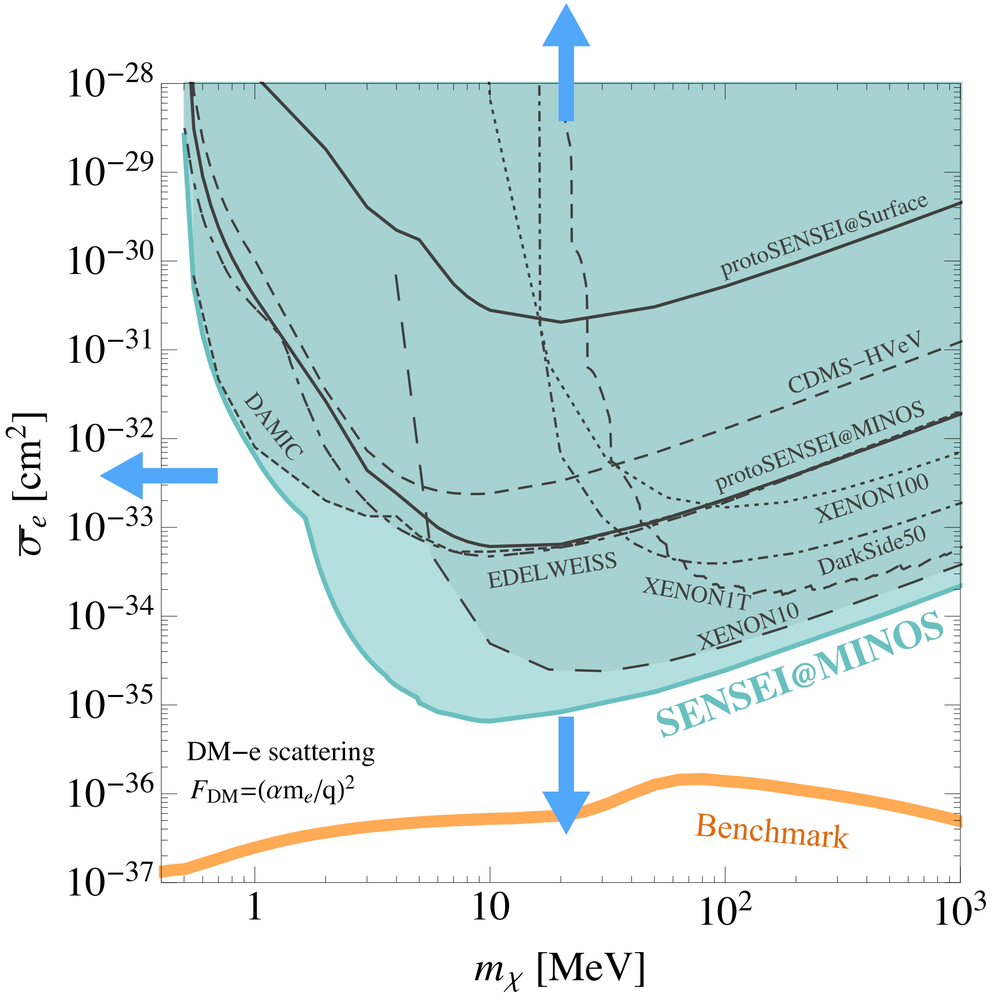
Probing the theory benchmark

Probing DM lighter than MeV

Probing strongly interacting DM

Direct Detection of Light DM

Figure from SENSEI, *PRL* 2020



Exploring the parameter space

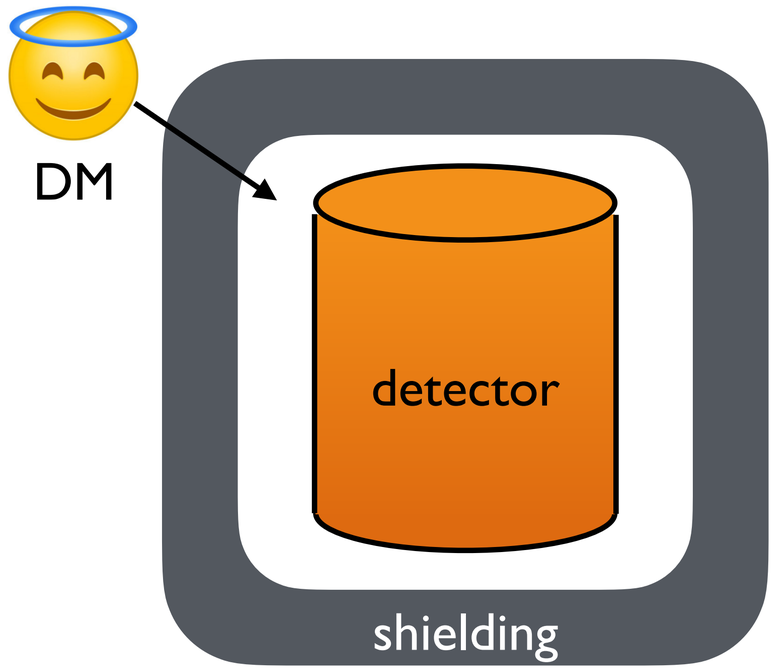
Probing the theory benchmark

Need to understand backgrounds

Probing DM lighter than MeV

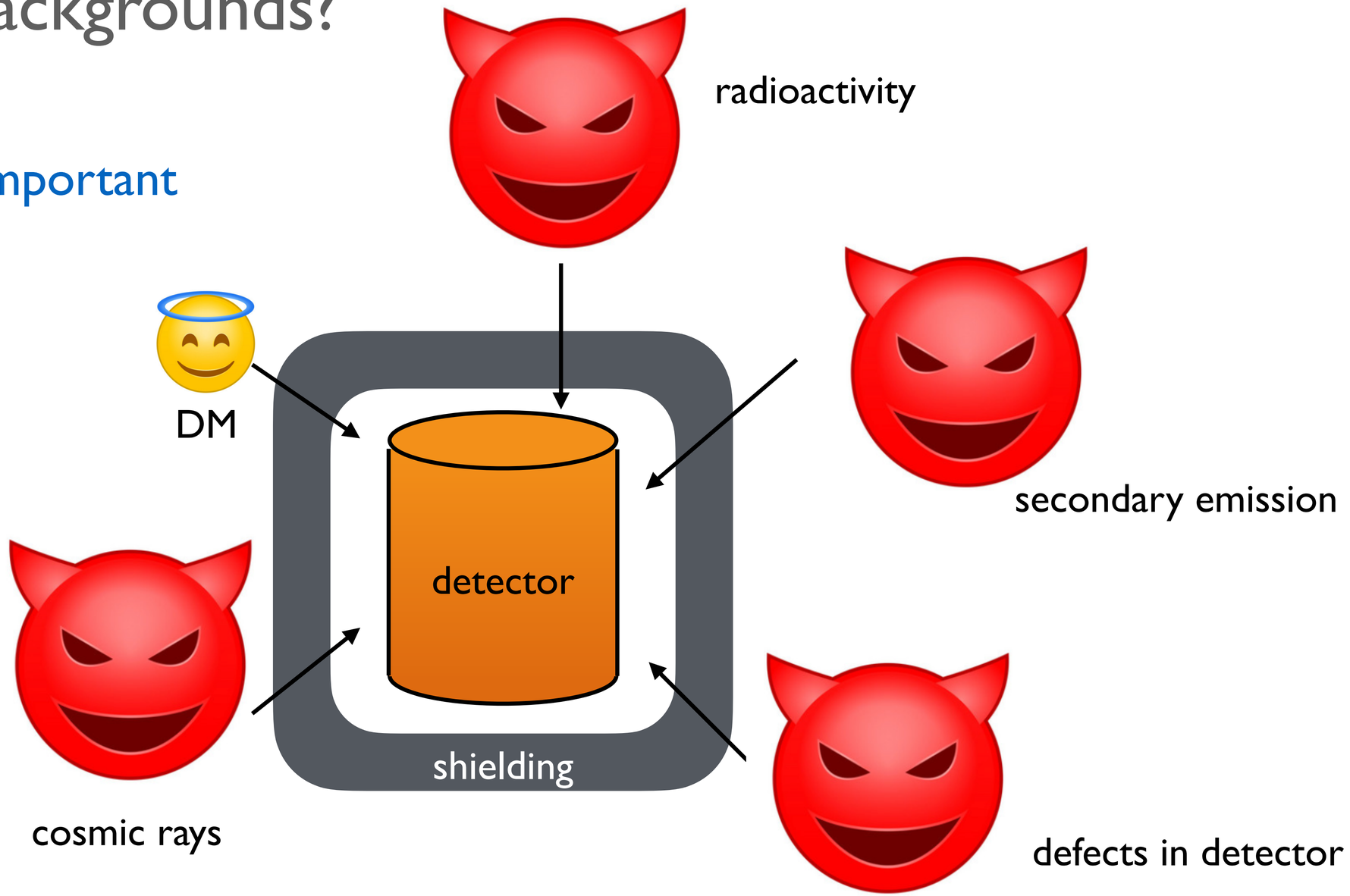
Probing strongly interacting DM

What about backgrounds?

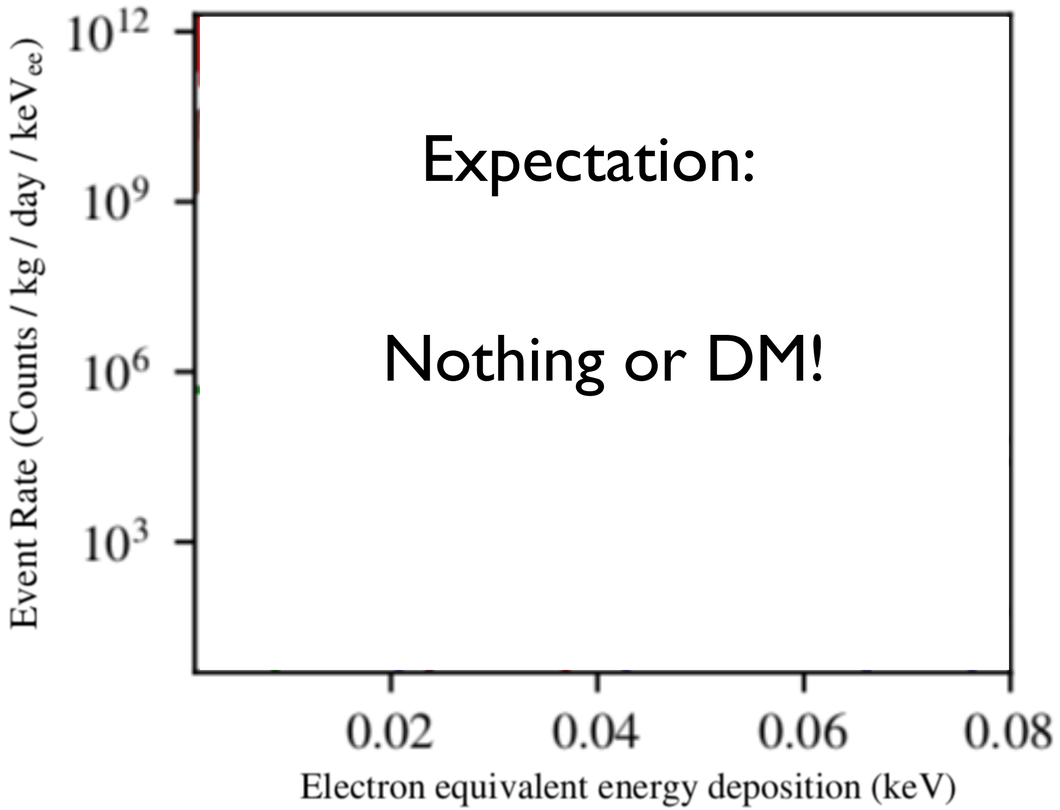


What about backgrounds?

Backgrounds are important
and interesting!

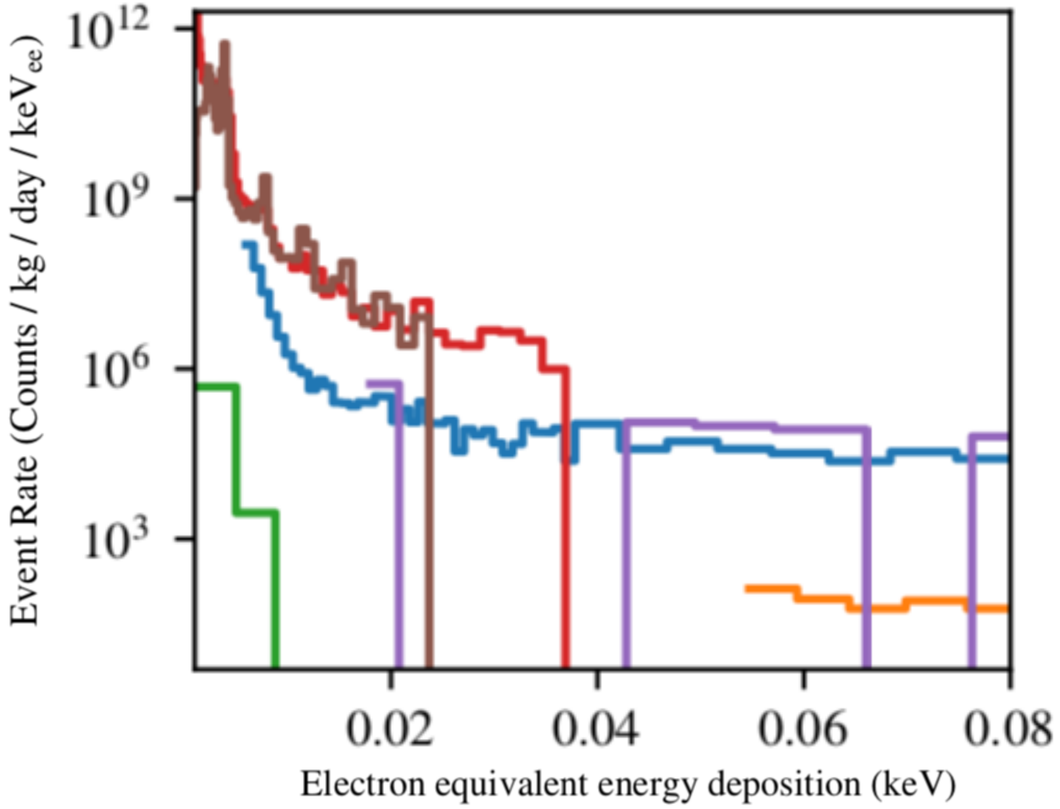


Current light dark matter detectors



- DAMIC
- EDELWEISS RED30
- SENSEI
- Skipper-CCD
- SuperCDMS HVeV Run 1
- SuperCDMS HVeV Run 2

Anomalous events in light dark matter detectors

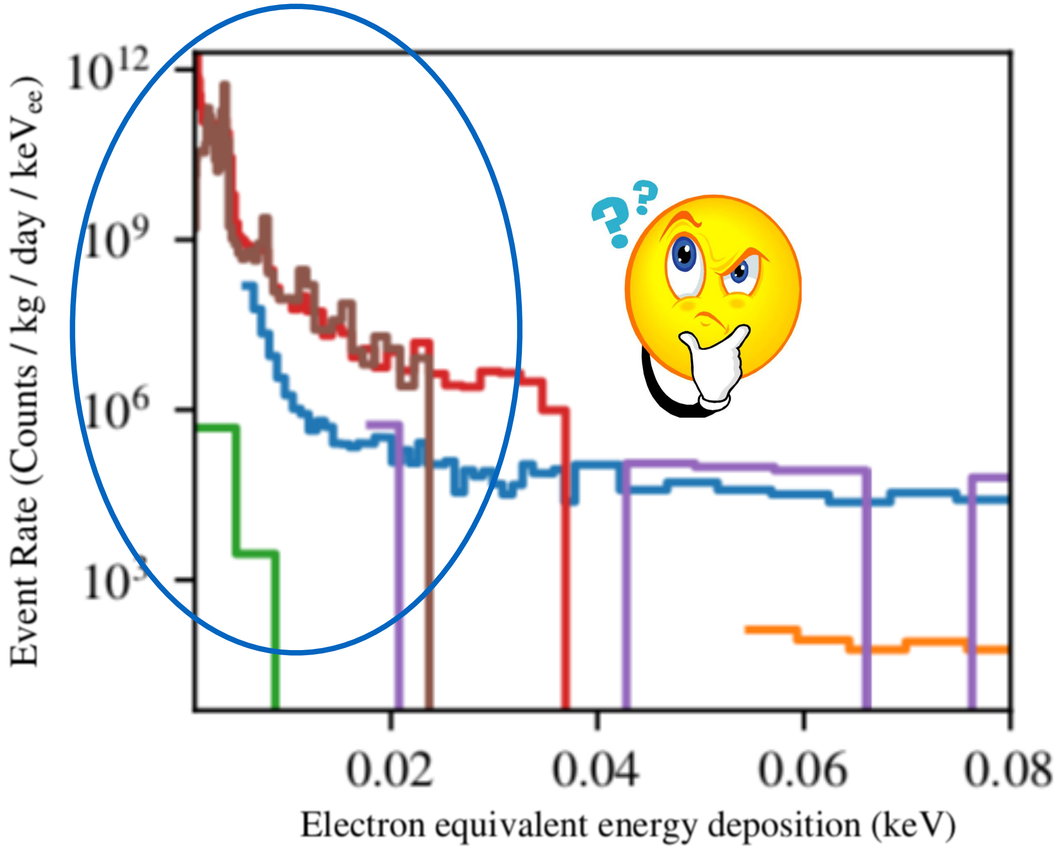


EXCESS2022 Workshop

EXCESS

- DAMIC
- EDELWEISS RED30
- SENSEI
- Skipper-CCD
- SuperCDMS HVeV Run 1
- SuperCDMS HVeV Run 2

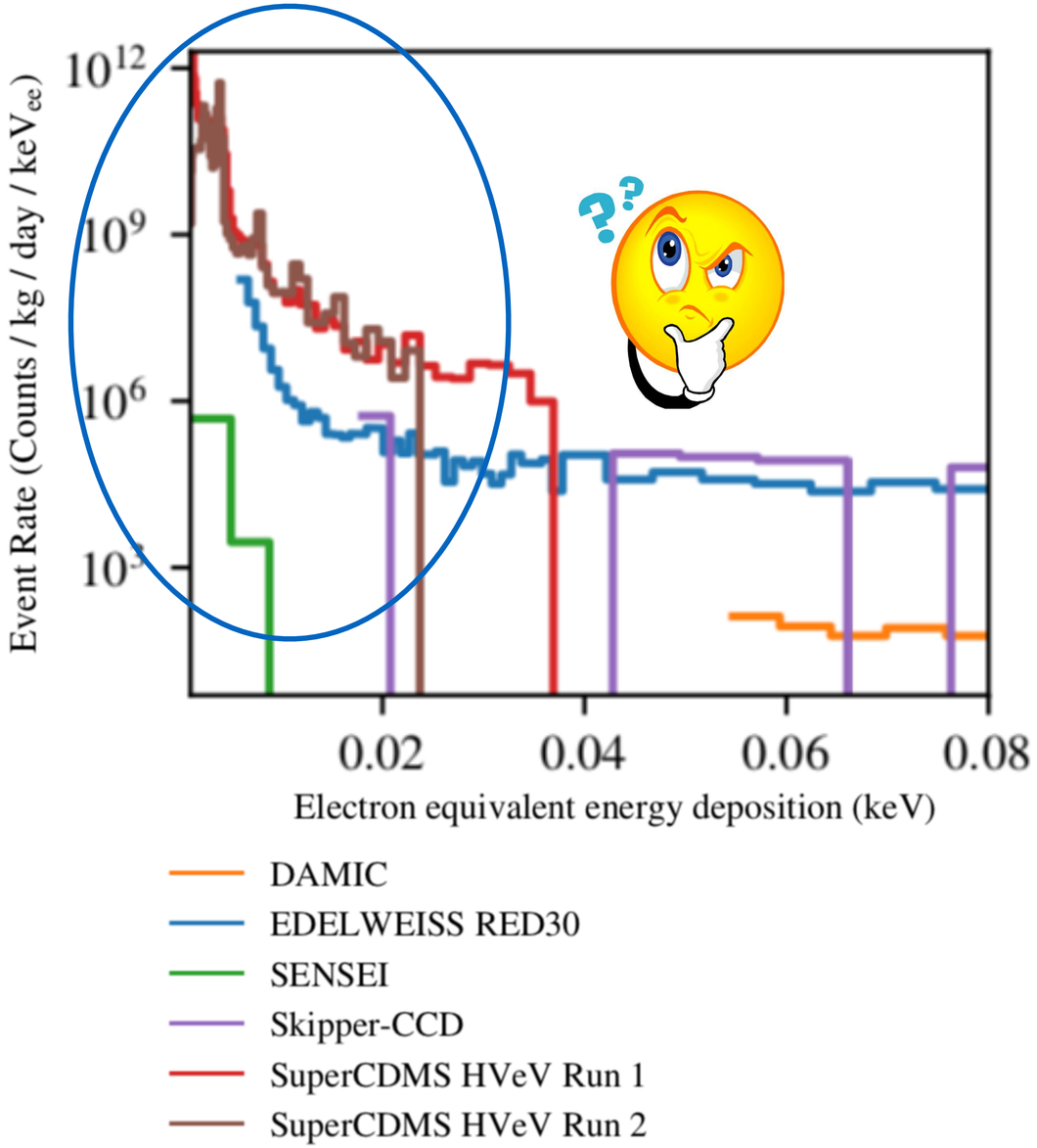
Anomalous events in light dark matter detectors



- DAMIC
- EDELWEISS RED30
- SENSEI
- Skipper-CCD
- SuperCDMS HVeV Run 1
- SuperCDMS HVeV Run 2

- Excess events are near the threshold
- Cannot be explained by known sources

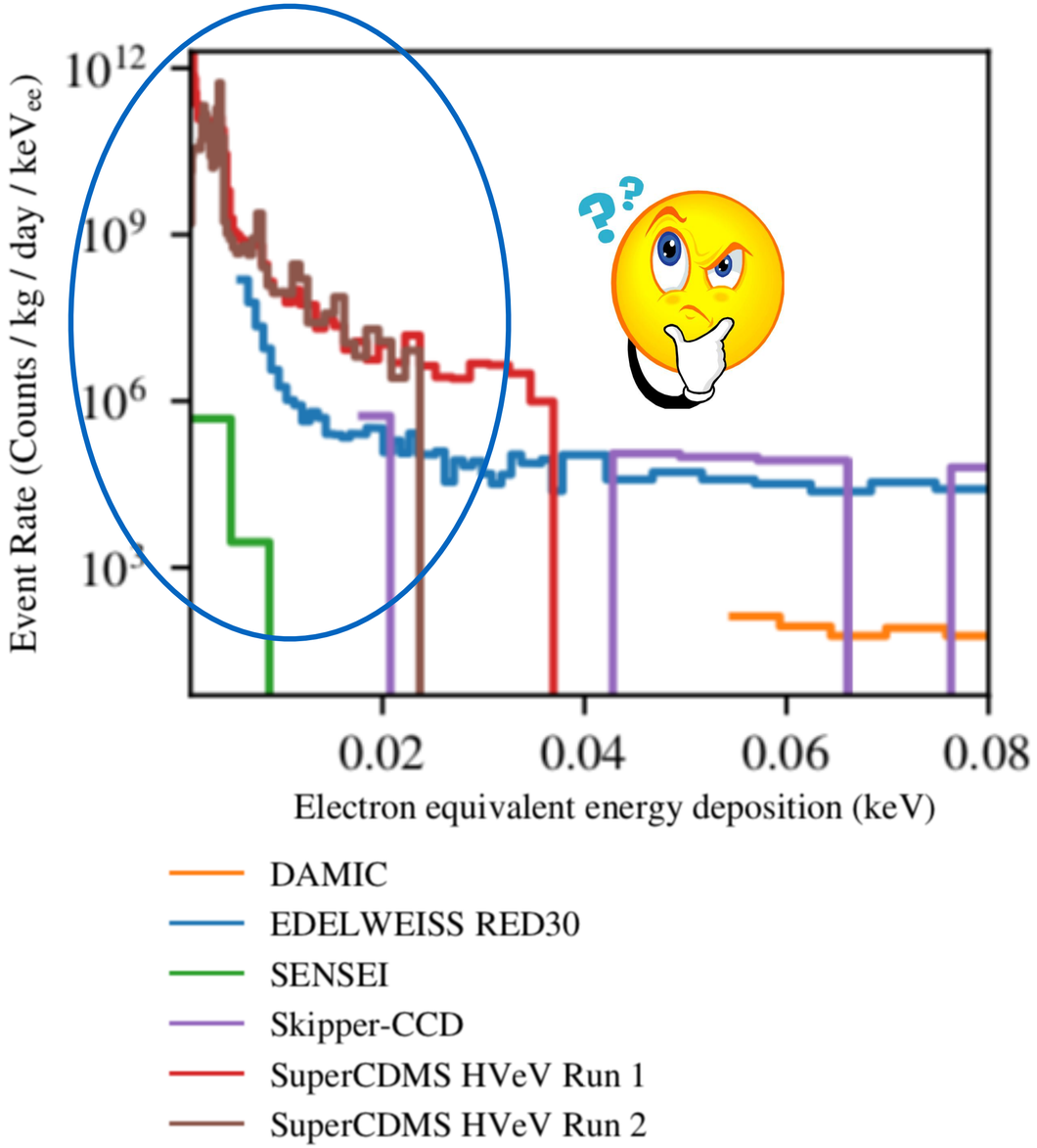
Anomalous events in light dark matter detectors



Those could come from DM !

Kurinsky, Baxter, Kahn, Krnjaic, *PRD*, 2020

Anomalous events in light dark matter detectors



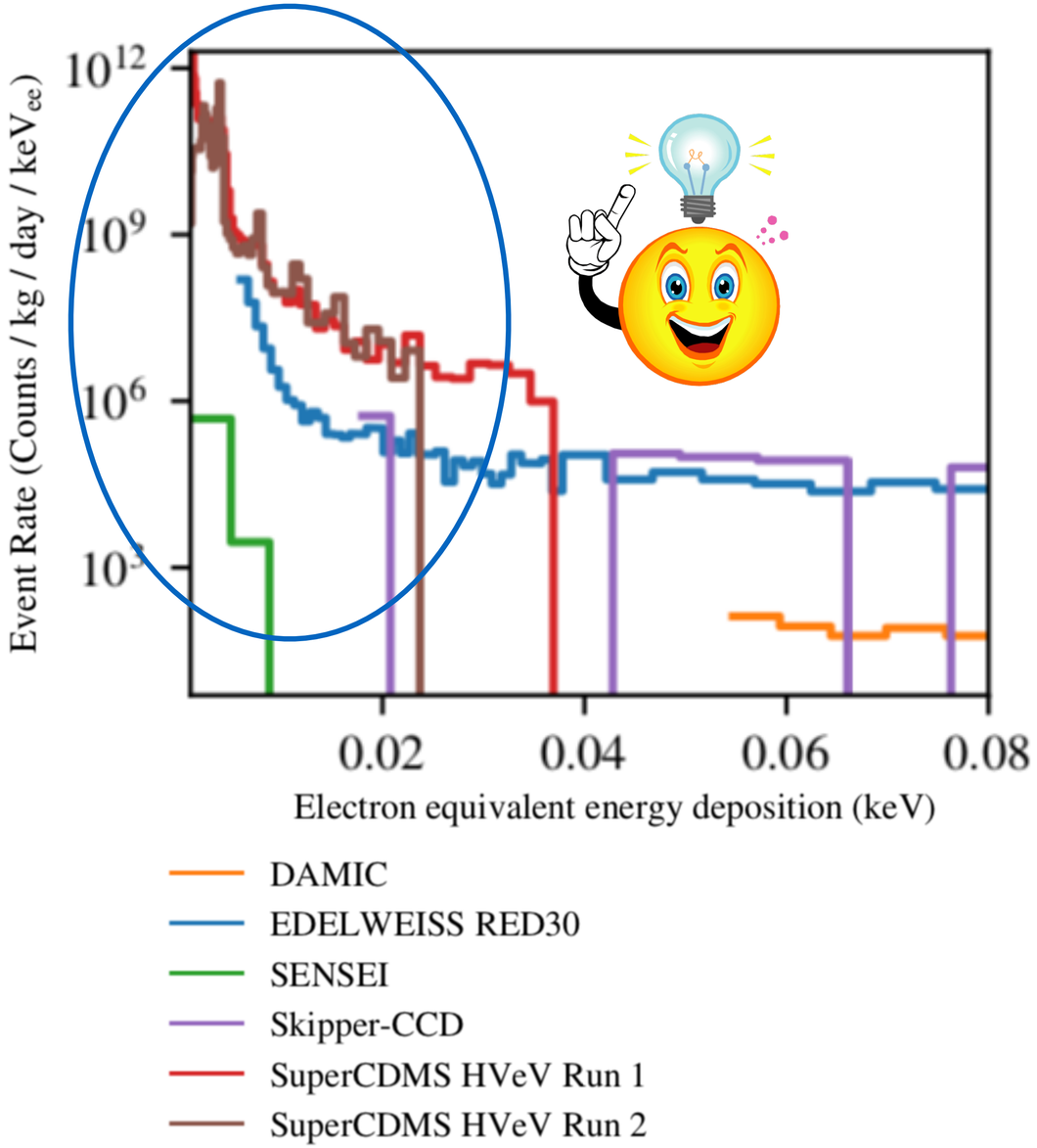
Those could come from DM !

Kurinsky, Baxter, Kahn, Krnjaic, *PRD*, 2020

Probably not DM

Kozaczuk, Lin, *PRD*, 2020

Anomalous events in light dark matter detectors



Those could come from DM !

Kurinsky, Baxter, Kahn, Krnjaic, *PRD*, 2020

Probably not DM

Kozaczuk, Lin, *PRD*, 2020

Those are likely unexplored backgrounds!

PD, Egana-Ugrinovic, Essig, Sholapurkar, *PRX*, 2022

Abbamonte, Baxter, Kahn, Krnjaic, Kurinsky, Mandava, Wagner *PRD*, 2022

SuperCDMS, *PRD* 2022

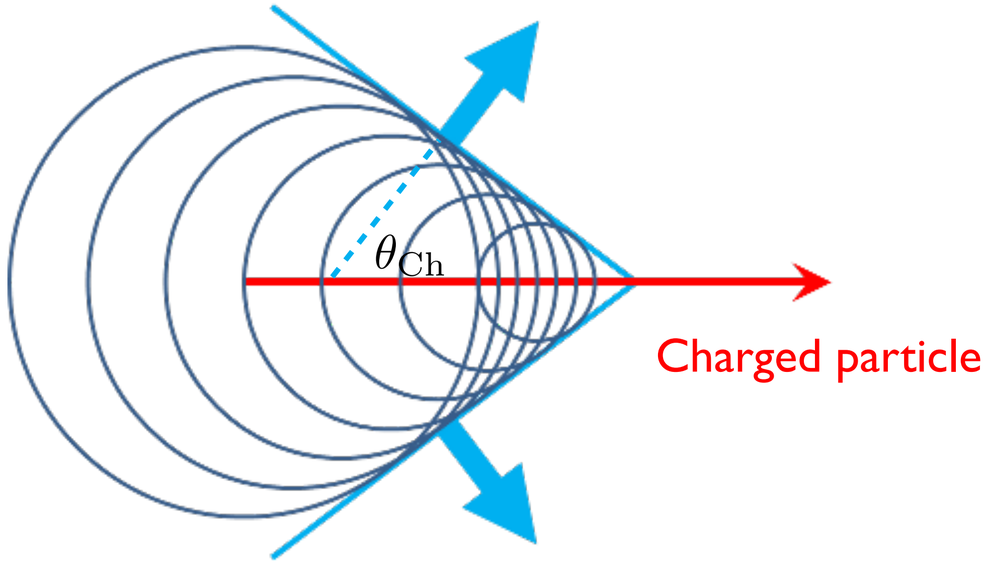
EXCESS Workshop Report, 2022

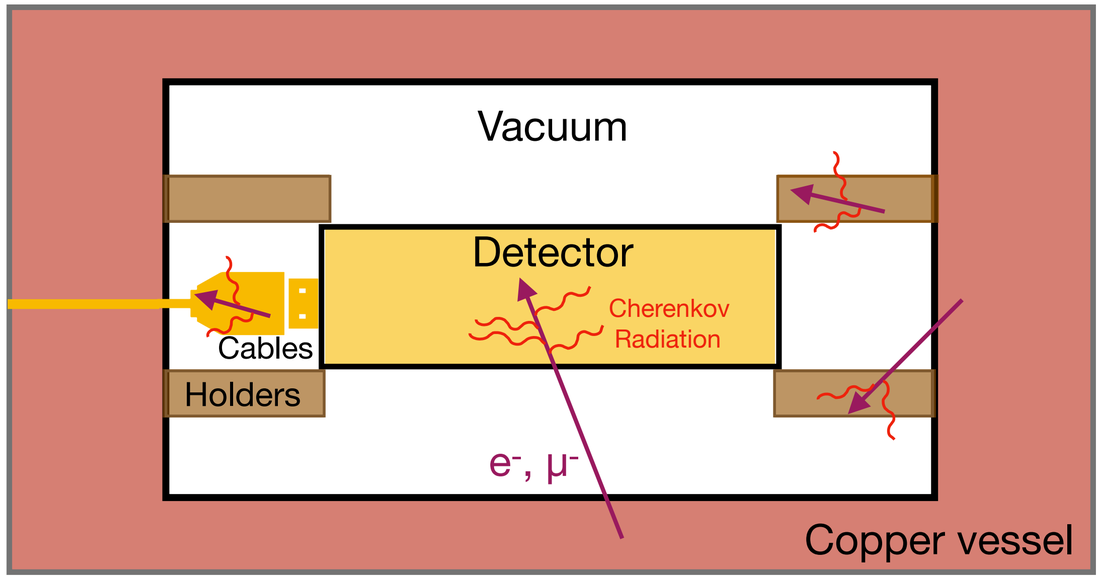
Unexplored low energy backgrounds

PD, Egana-Ugrinovic, Essig, Sholapurkar, *PRX*, 2022

Cherenkov radiation can mimic dark matter signals!

Cherenkov radiation

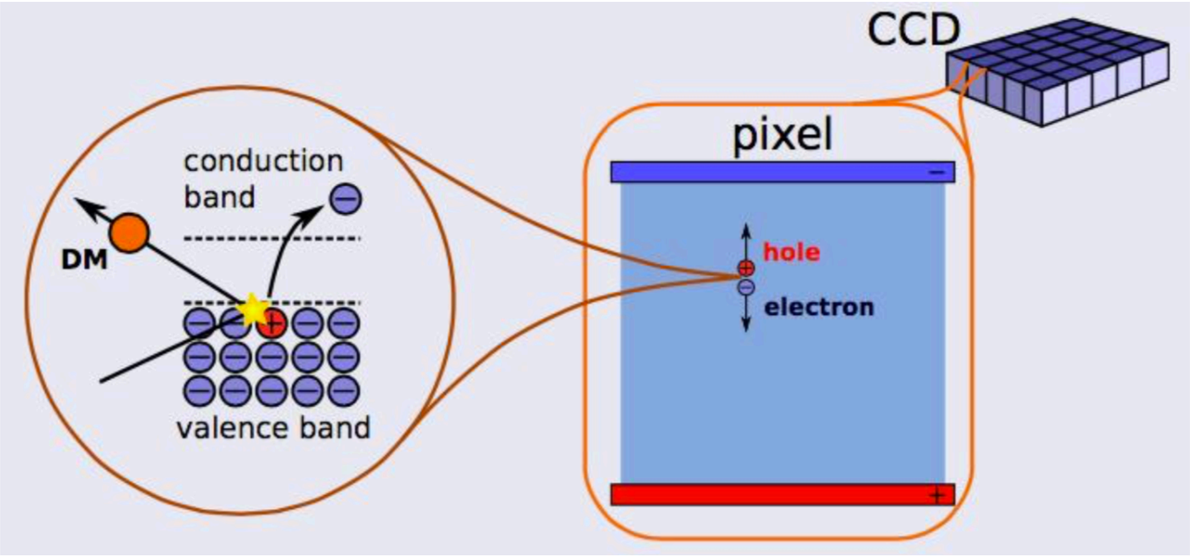




Incident charge is moving faster than
the speed of light inside the medium

SENSEI experiment

Look for electron-hole pairs in skipper CCD

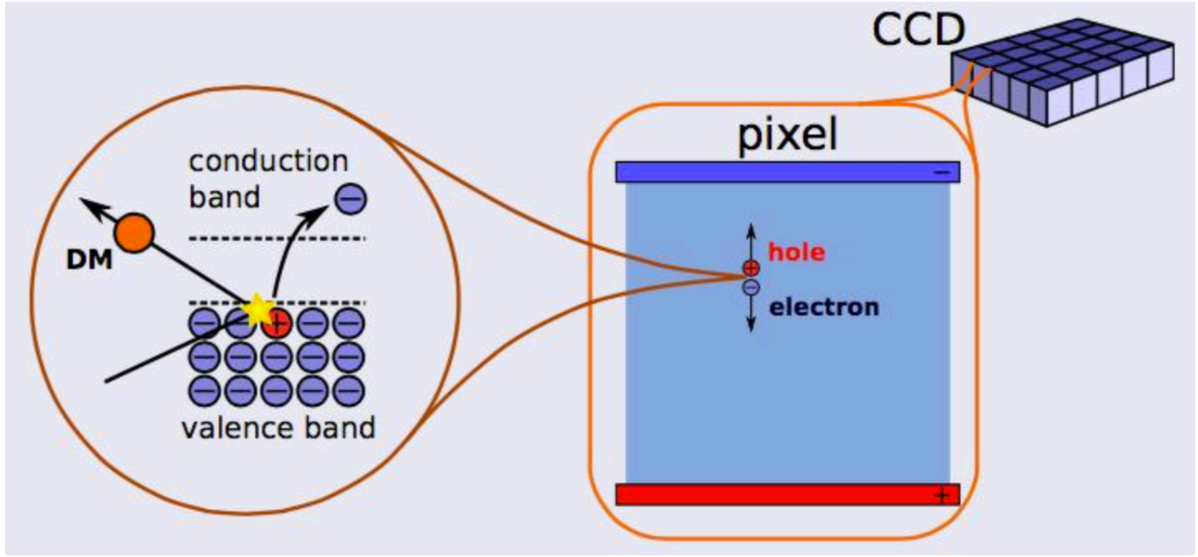


100 m underground at135 K

Expected DM signal: one or few charges per pixel

SENSEI experiment

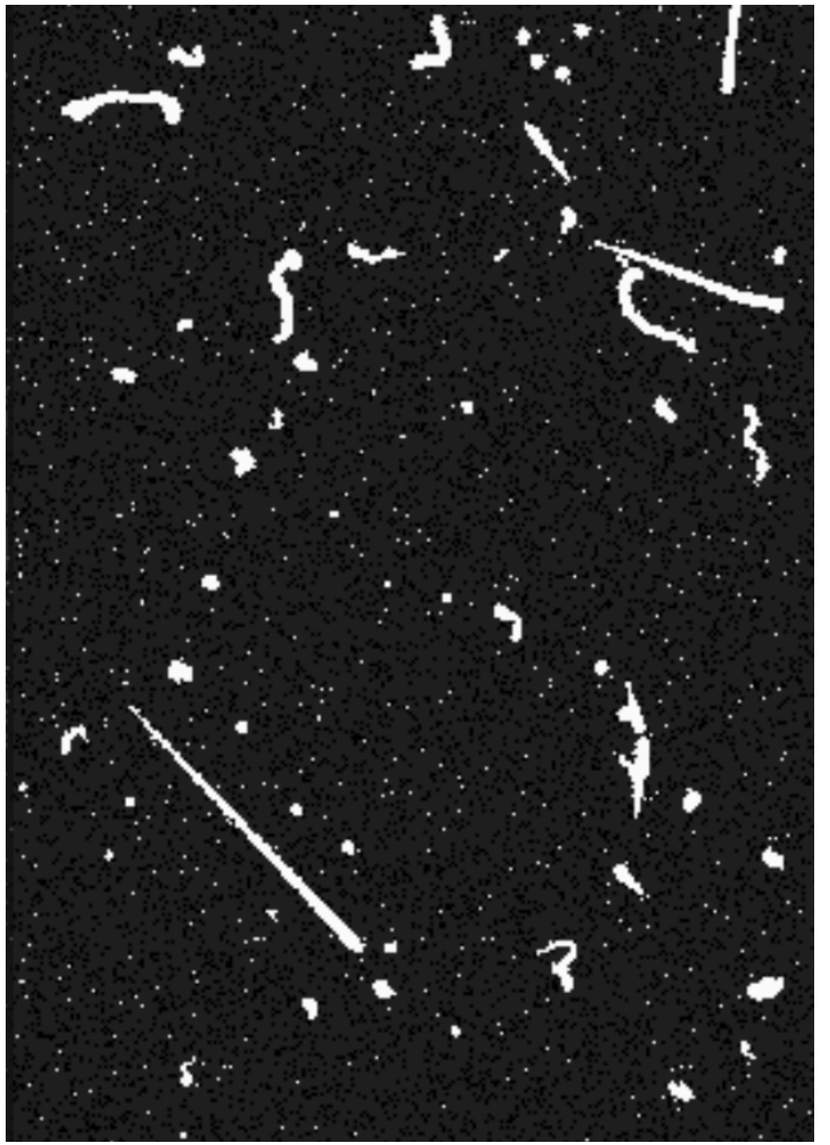
Look for electron-hole pairs in skipper CCD



100 m underground at135 K

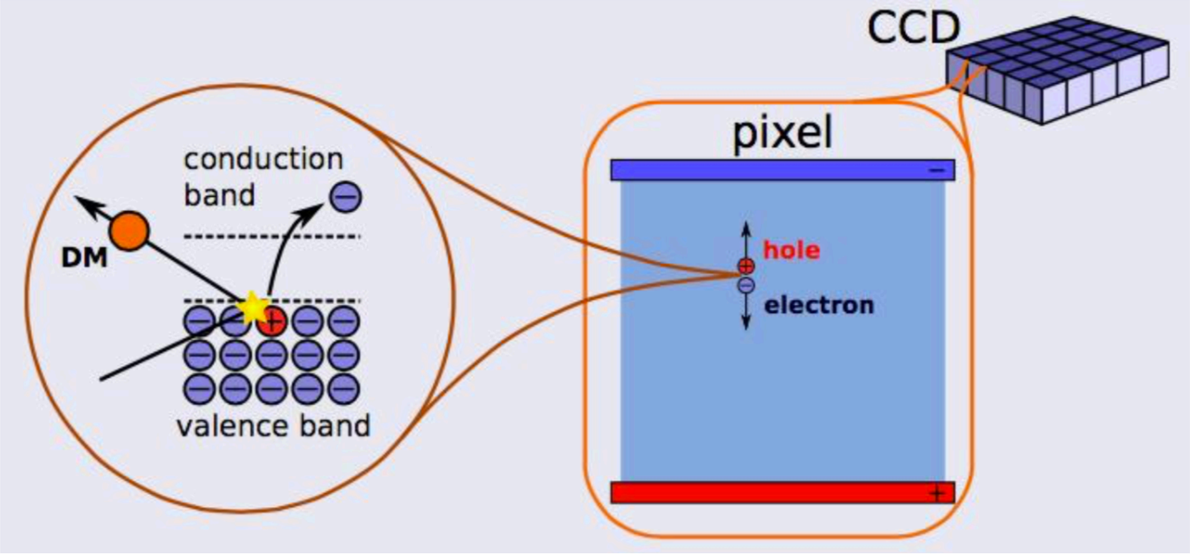
Expected DM signal: one or few charges per pixel

SENSEI image (20h exposure)



SENSEI experiment

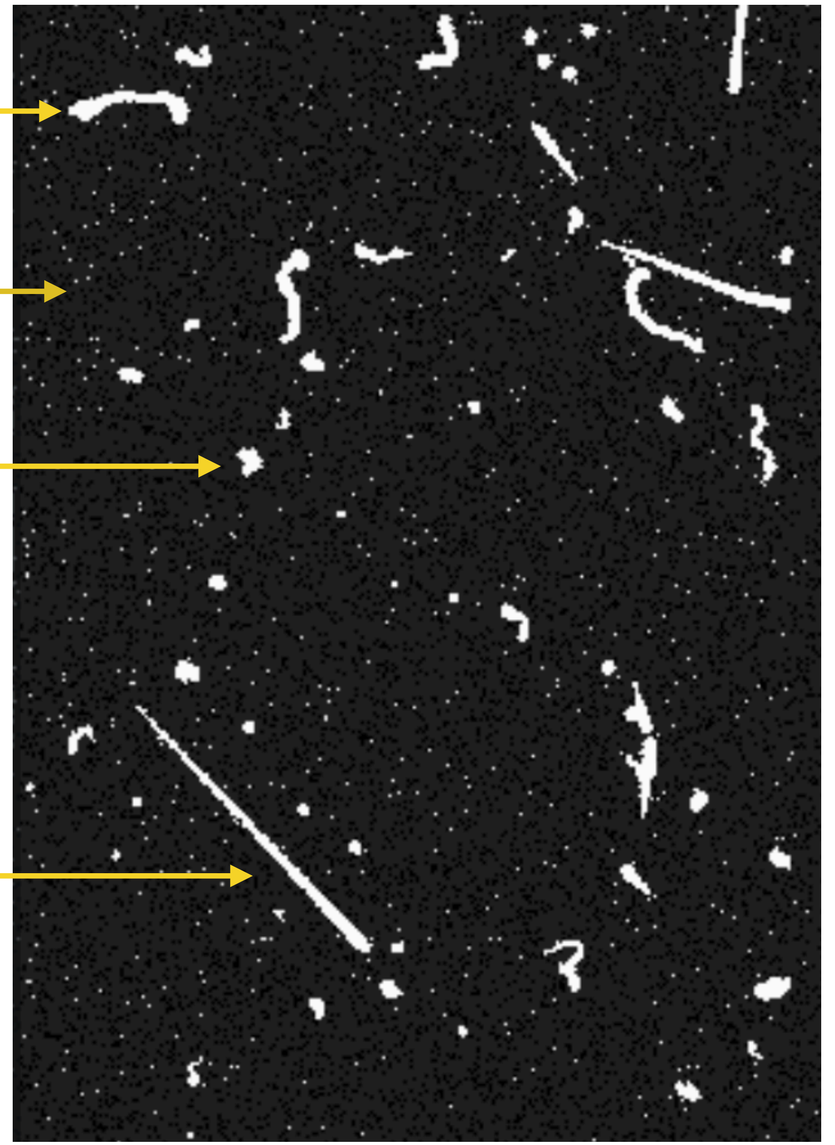
Look for electron-hole pairs in skipper CCD



100 m underground at135 K

Expected DM signal: one or few charges per pixel

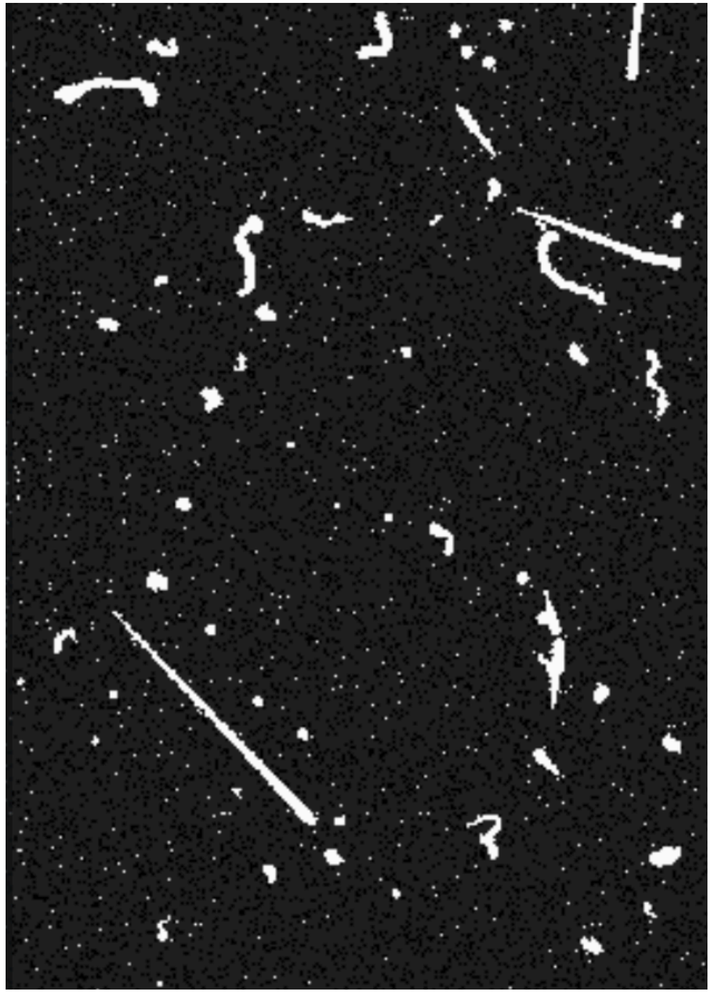
SENSEI image (20h exposure)



Simulation results

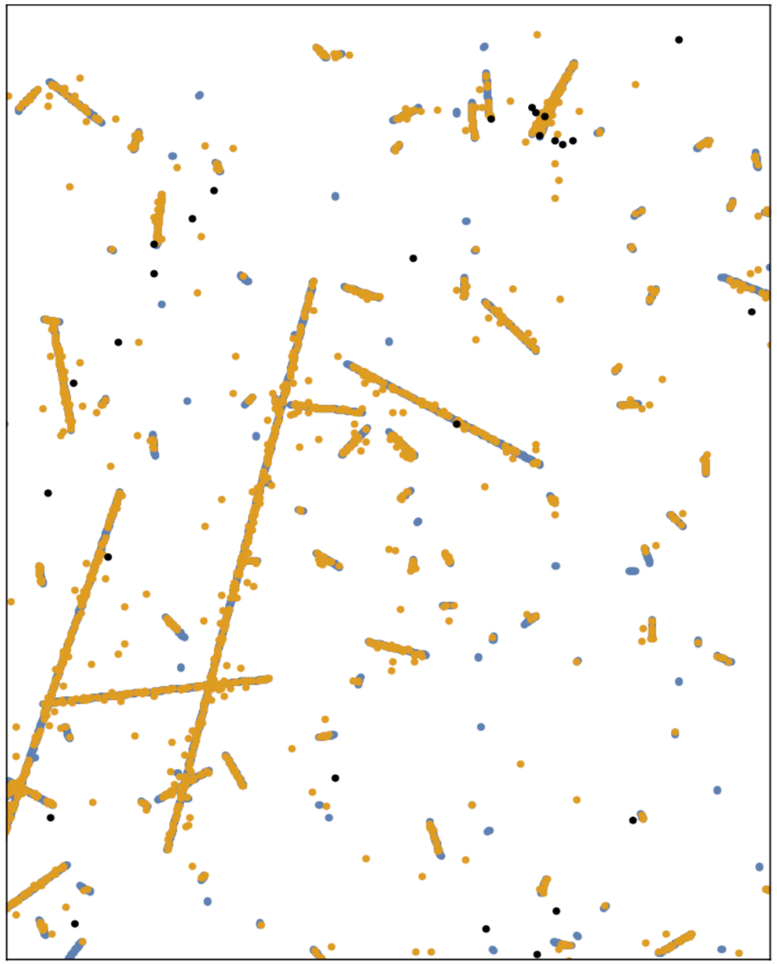
PD, Egana-Ugrinovic, Essig, Sholapurkar, *JHEP*, 2024

SENSEI image



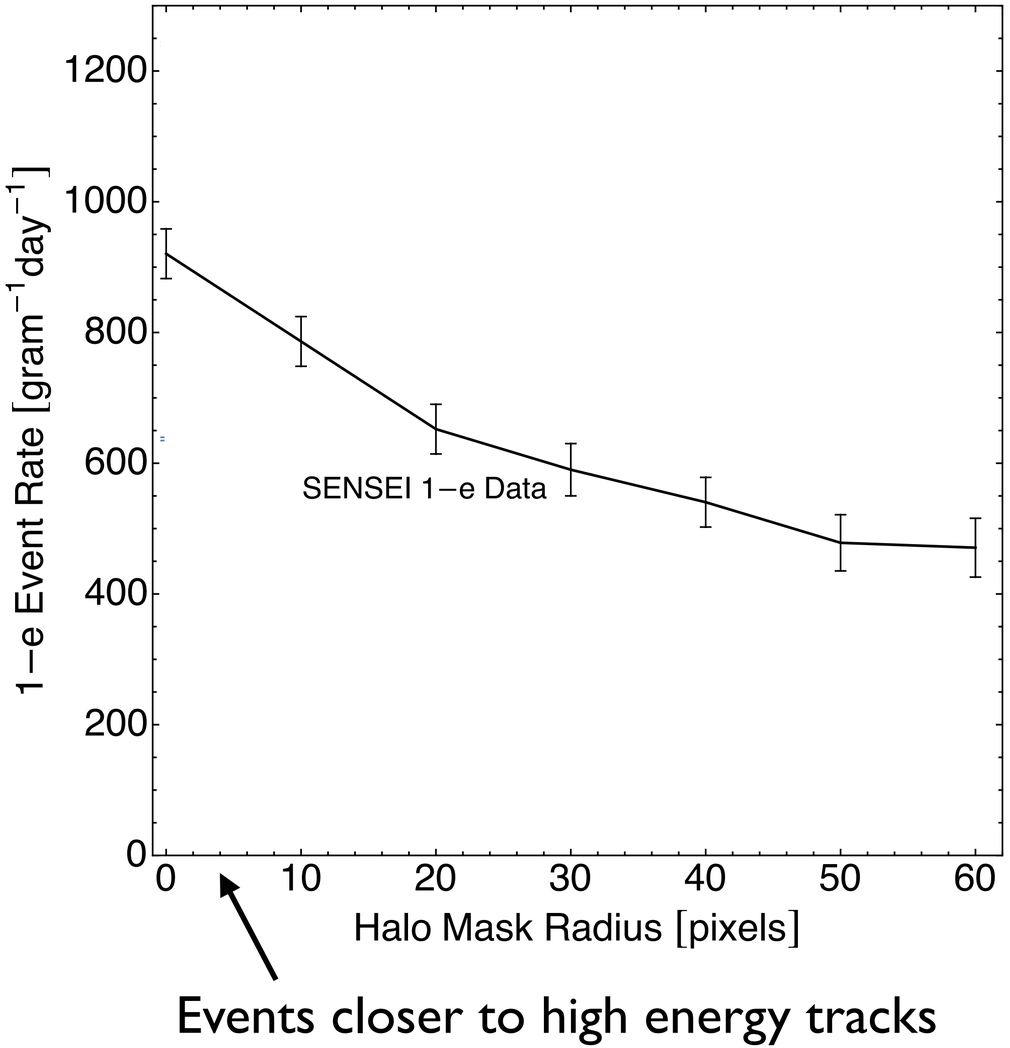
High energy tracks

High energy tracks+Cherenkov+Radiative recombination



Comparing to data

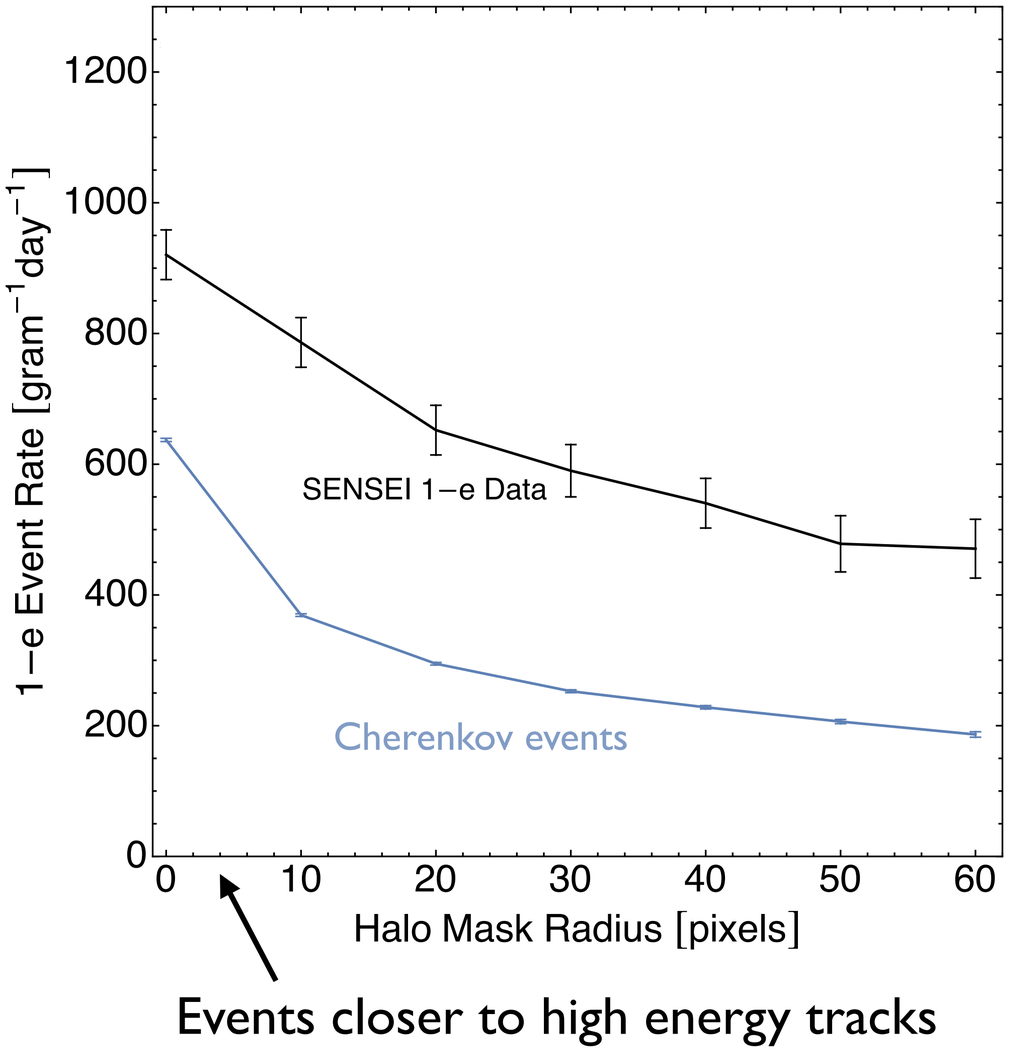
PD, Egana-Ugrinovic, Essig, Sholapurkar, *JHEP*, 2024



- 1e events spatially correlated with high energy tracks

Comparing to data

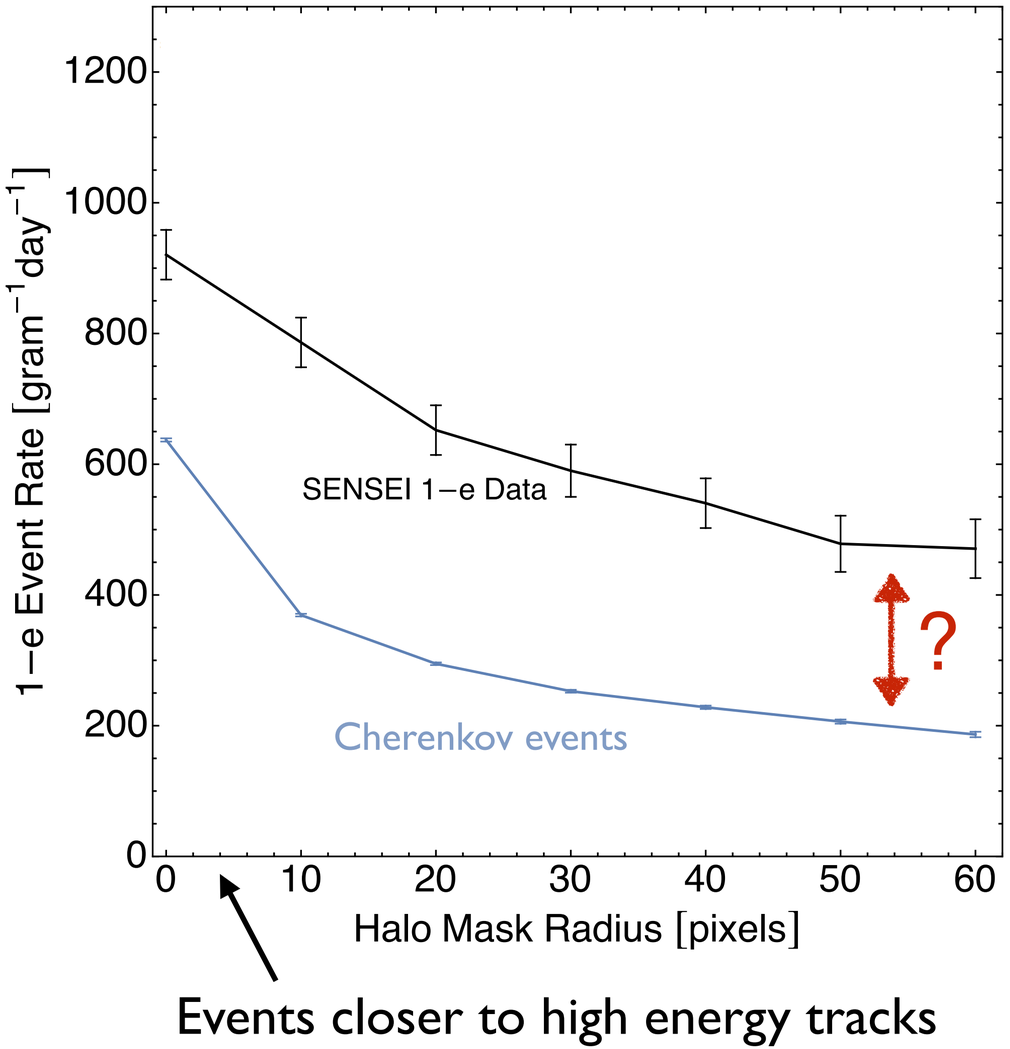
PD, Egana-Ugrinovic, Essig, Sholapurkar, *JHEP*, 2024



- 1e events spatially correlated with high energy tracks
- Cherenov explains everything? Maybe not

Comparing to data

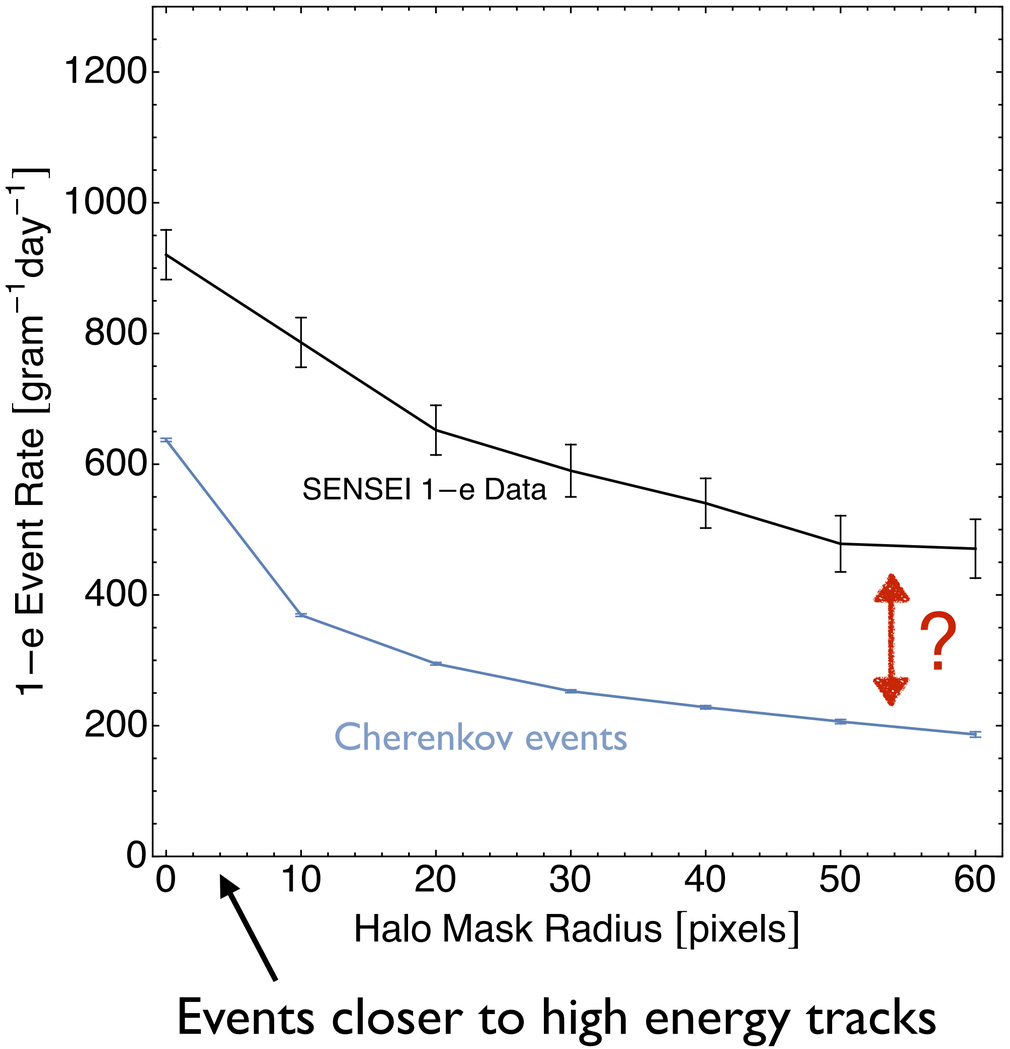
PD, Egana-Ugrinovic, Essig, Sholapurkar, *JHEP*, 2024



- 1e events spatially correlated with high energy tracks
- Cherenov explains everything? Maybe not
- Could be additional surface dark currents:
  spatially uniform; originated from surface defects…

Comparing to data

PD, Egana-Ugrinovic, Essig, Sholapurkar, *JHEP*, 2024

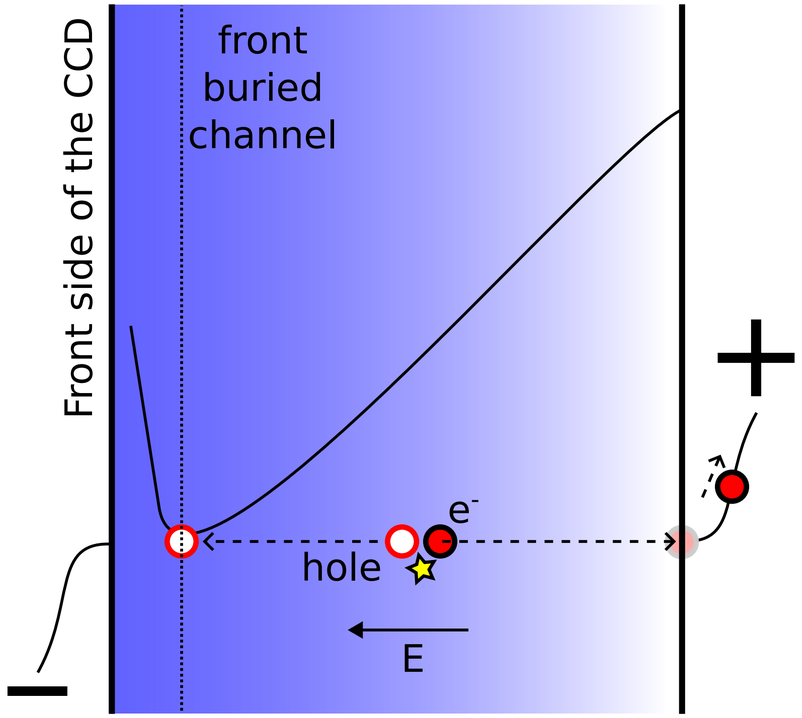


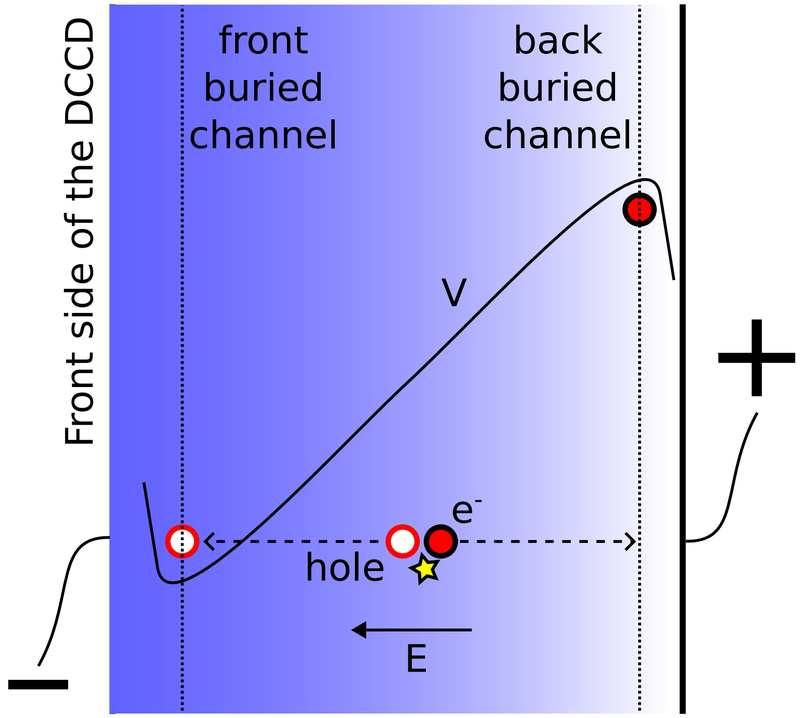
- 1e events spatially correlated with high energy tracks
- Cherenov explains everything? Maybe not
- Could be additional surface dark currents:
  spatially uniform; originated from surface defects…

How to reduce surface dark currents ?

Dual-Sided CCD

Tiffenberg, **PD**, Egana-Ugrinovic, Essig, Fernandez-Moroni, Sofo Haro, Uemura, *PR Applied*, 2024



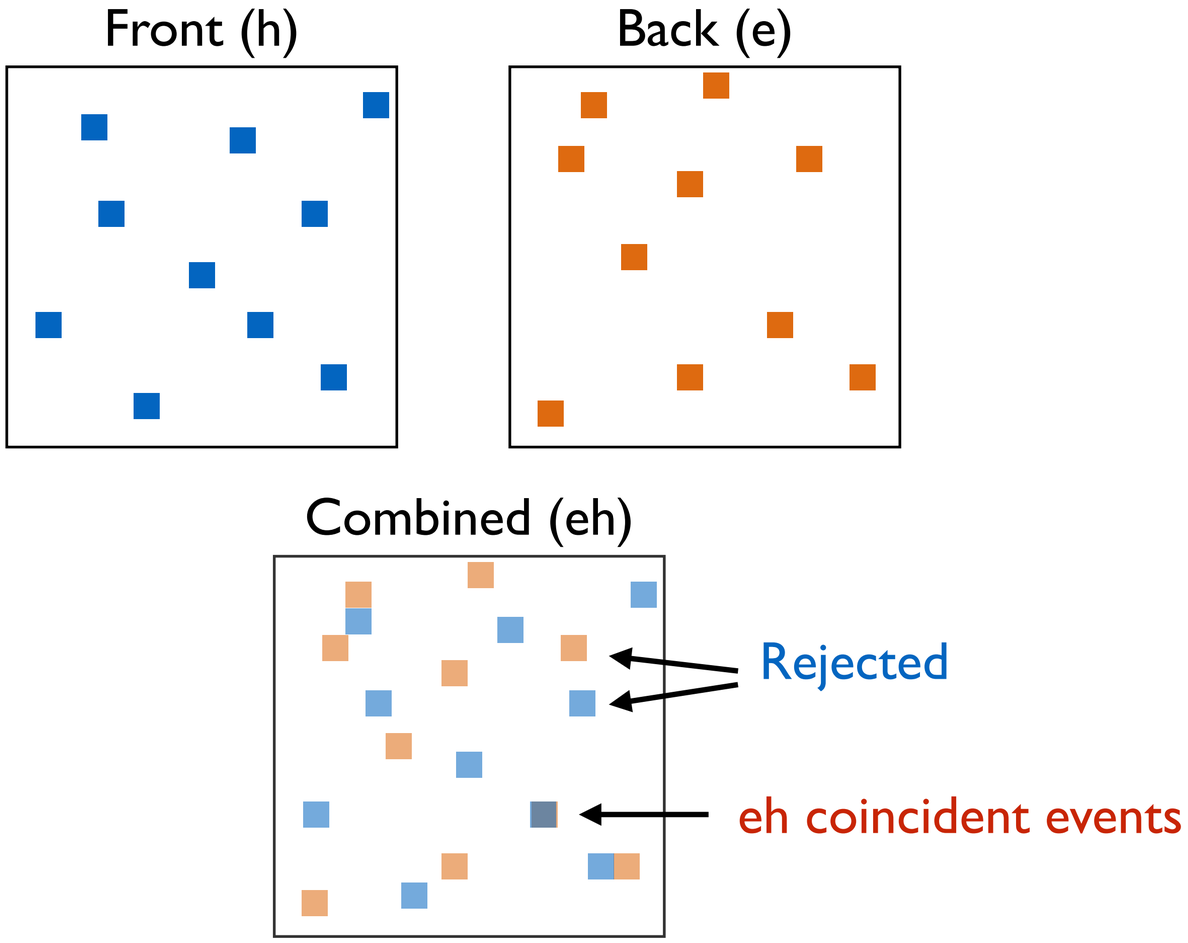


Regular CCD collects only one charge

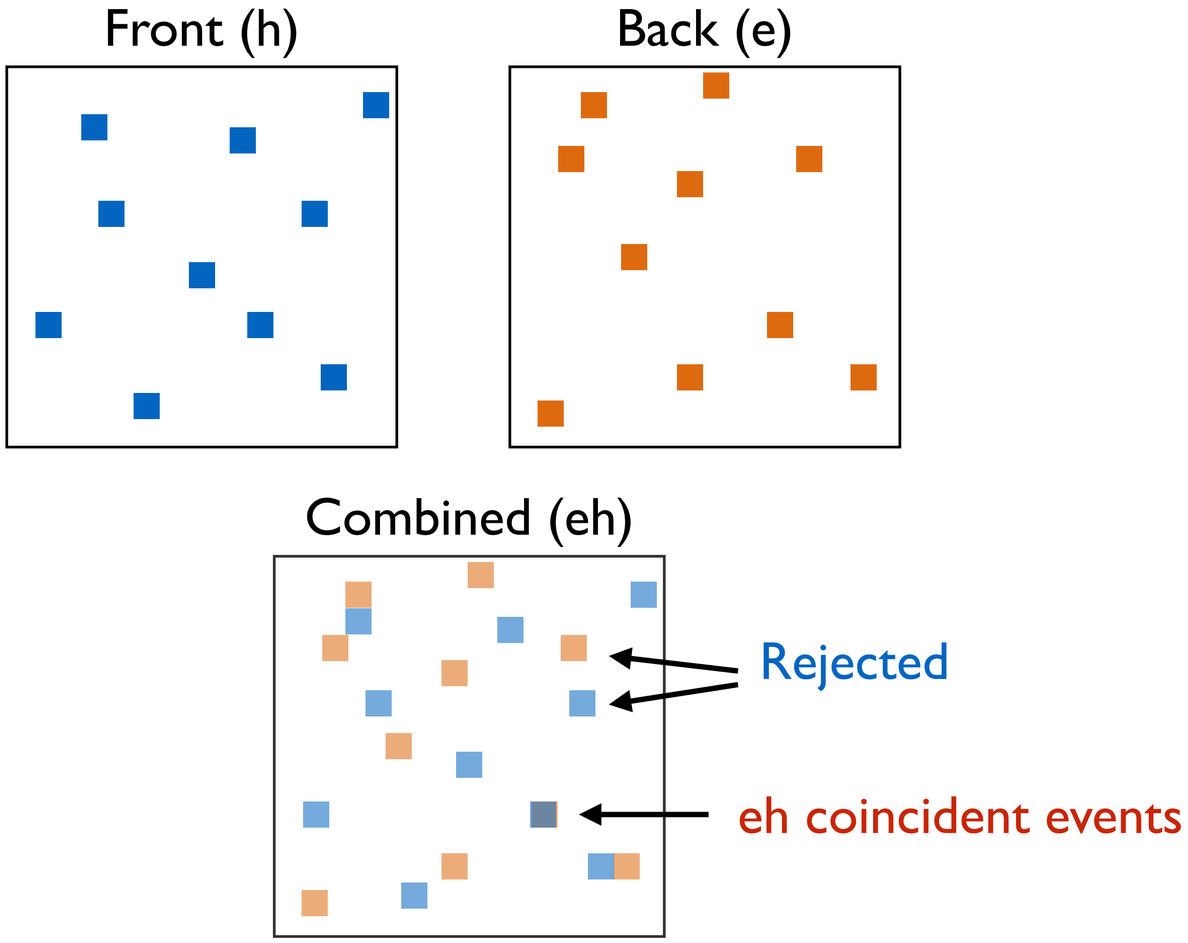
DCCD collects both charges at two sides

Surface DC are only collected in one side of the image

Surface DC rejection



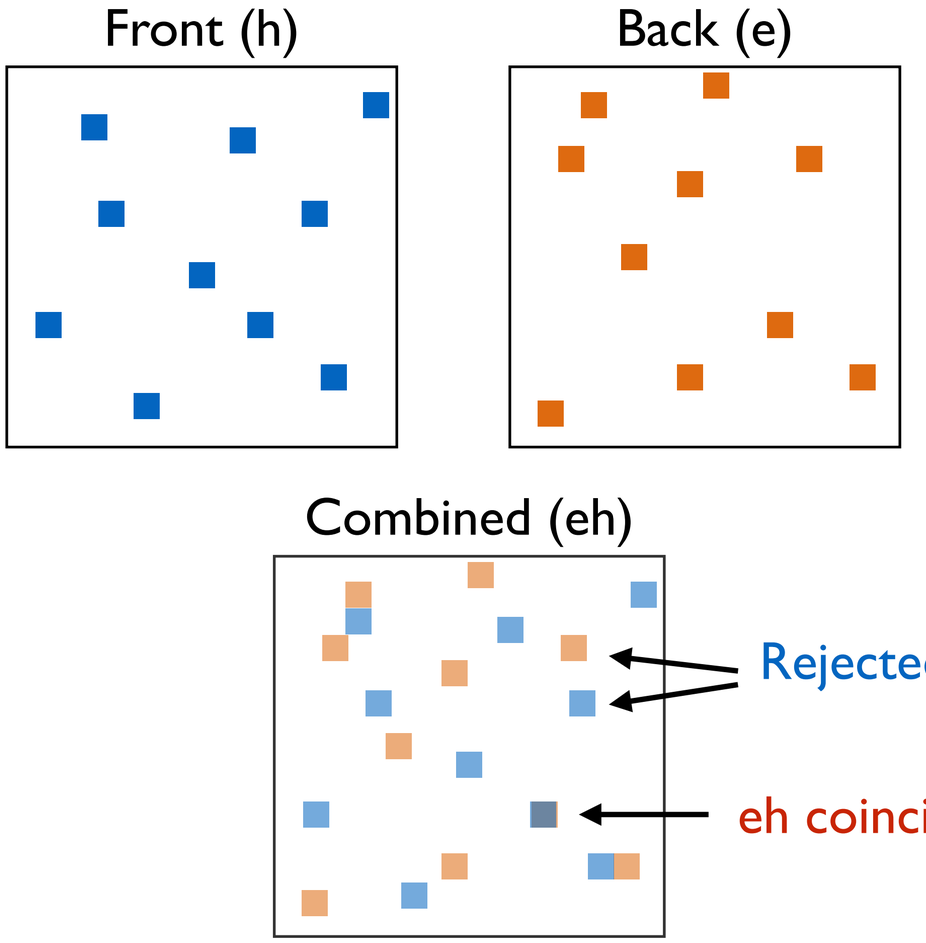
Surface DC rejection

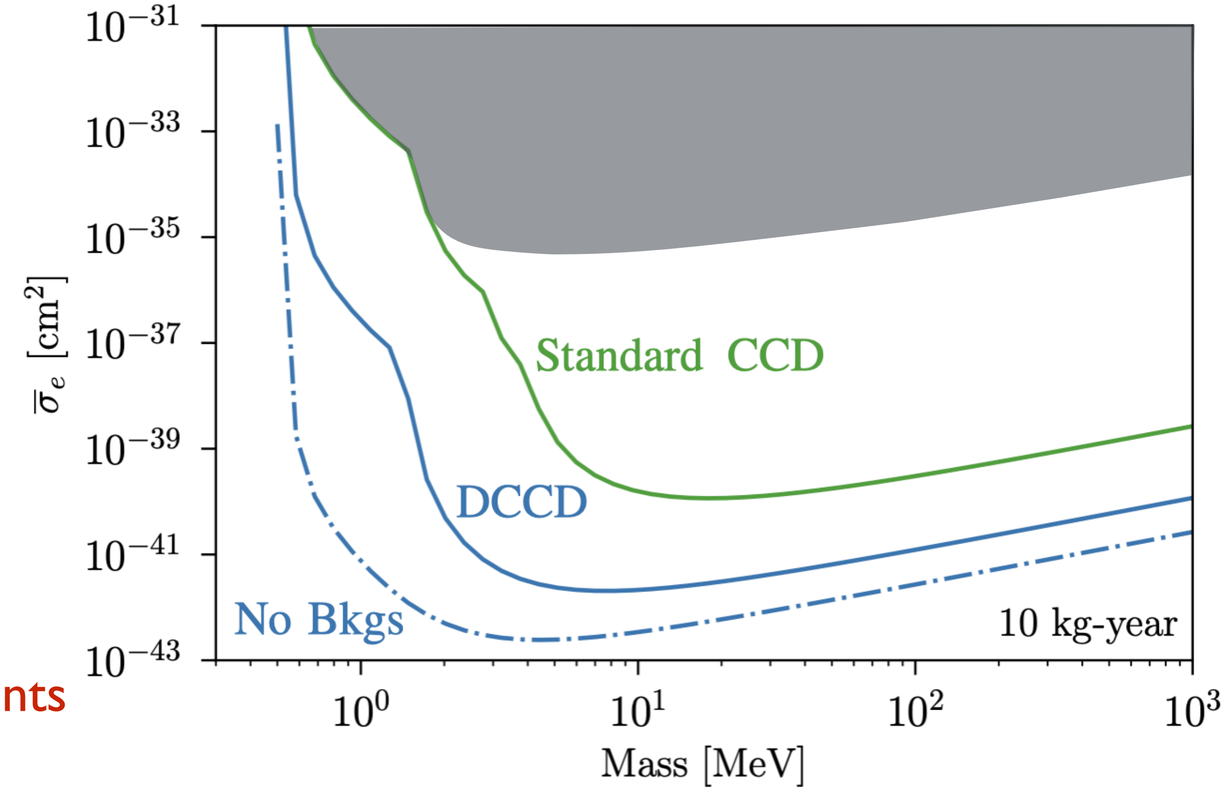


SENSEI 1e dark current: $O(10^{-4})$ e/pixel/day

dark current rejection: $O(10^{-3})$-$O(10^{-4})$

Surface DC rejection





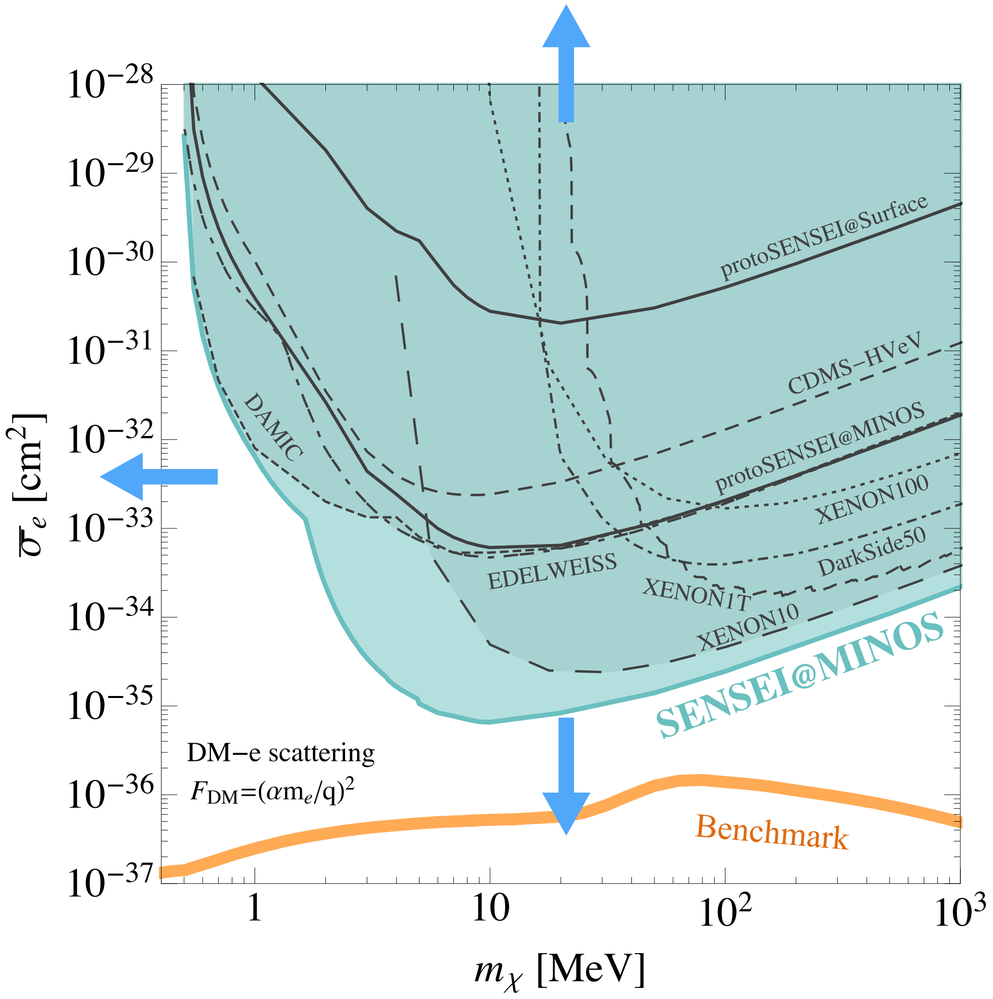
SENSEI 1e dark current: O(10^{-4}) e/pixel/day

dark current rejection: O(10^{-3})-O(10^{-4})

sensitivity improvement 10^3 or 10^4

Direct detection of light DM

Figure from SENSEI, *PRL* 2020



Exploring the parameter space

Probing the theory benchmark

Need to understand backgrounds

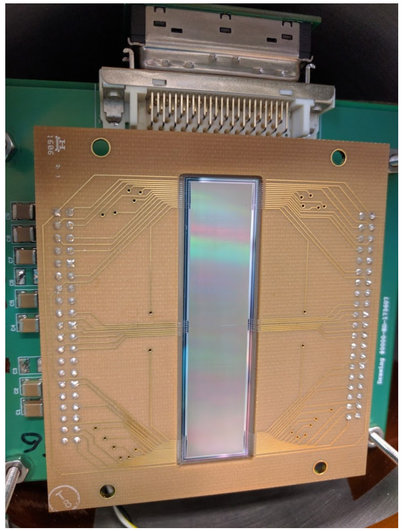
Probing DM lighter than MeV

Sub-eV threshold detectors

Probing strongly interacting DM

Probing lighter than MeV DM

Semiconductors



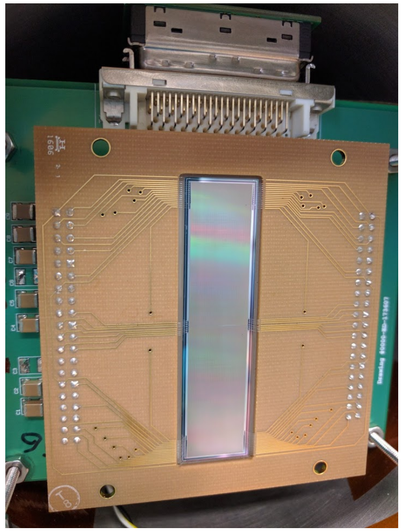
Threshold: ~1eV

DM Mass: > MeV

Low threshold detector can probe low mass DM

Probing lighter than MeV DM

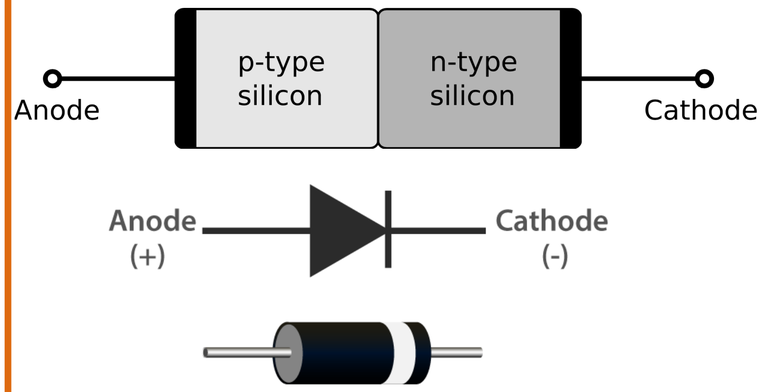
Semiconductors



Threshold: ~1eV

DM Mass: > MeV

Doped semiconductor



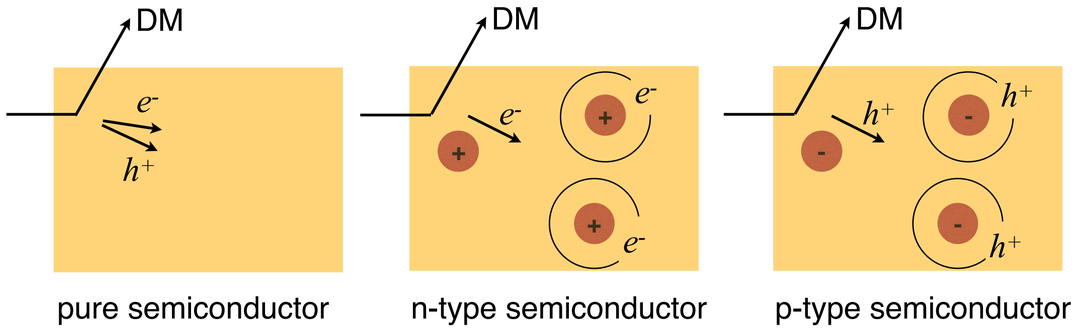
Threshold: 10-100 meV

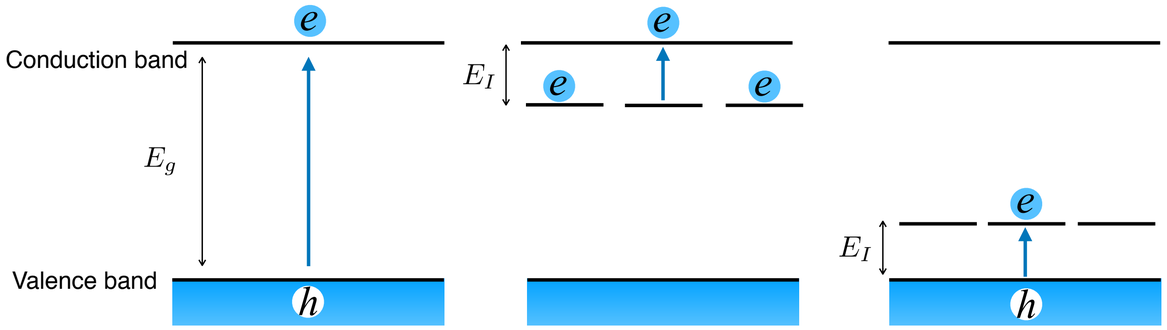
DM Mass: >10-100 keV

Low threshold detector can probe low mass DM

DM detection with doped silicon

PD, Egana-Ugrinovic, Essig, Sholapurkar, *PRD*, 2024



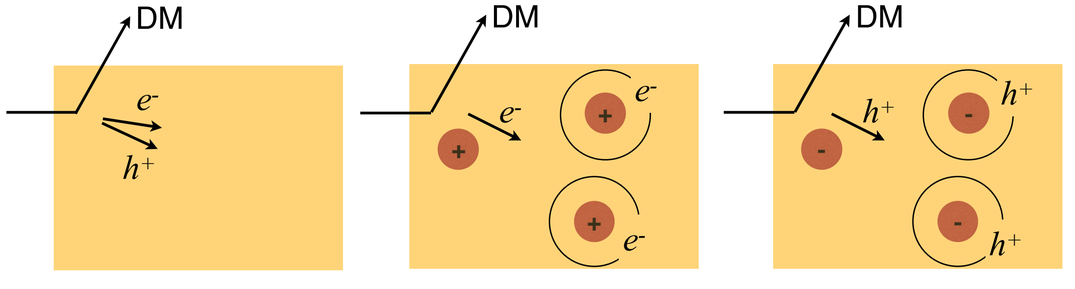


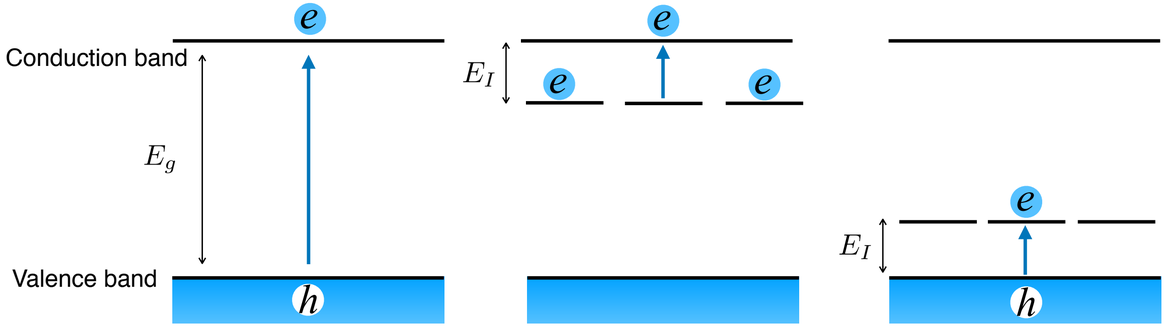
Signals: dopant ionization

Threshold: E_I~10-100 meV

DM detection with doped silicon

PD, Egana-Ugrinovic, Essig, Sholapurkar, *PRD*, 2024

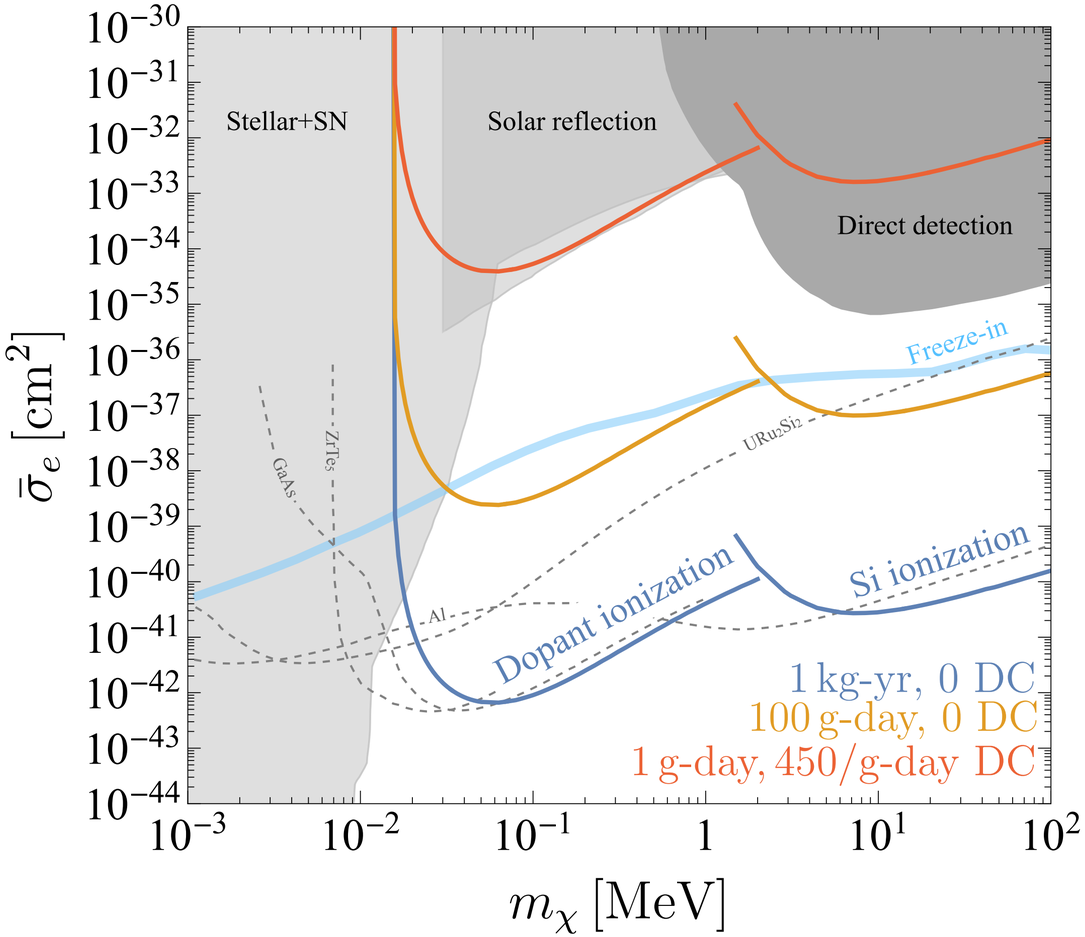




Signals: dopant ionization

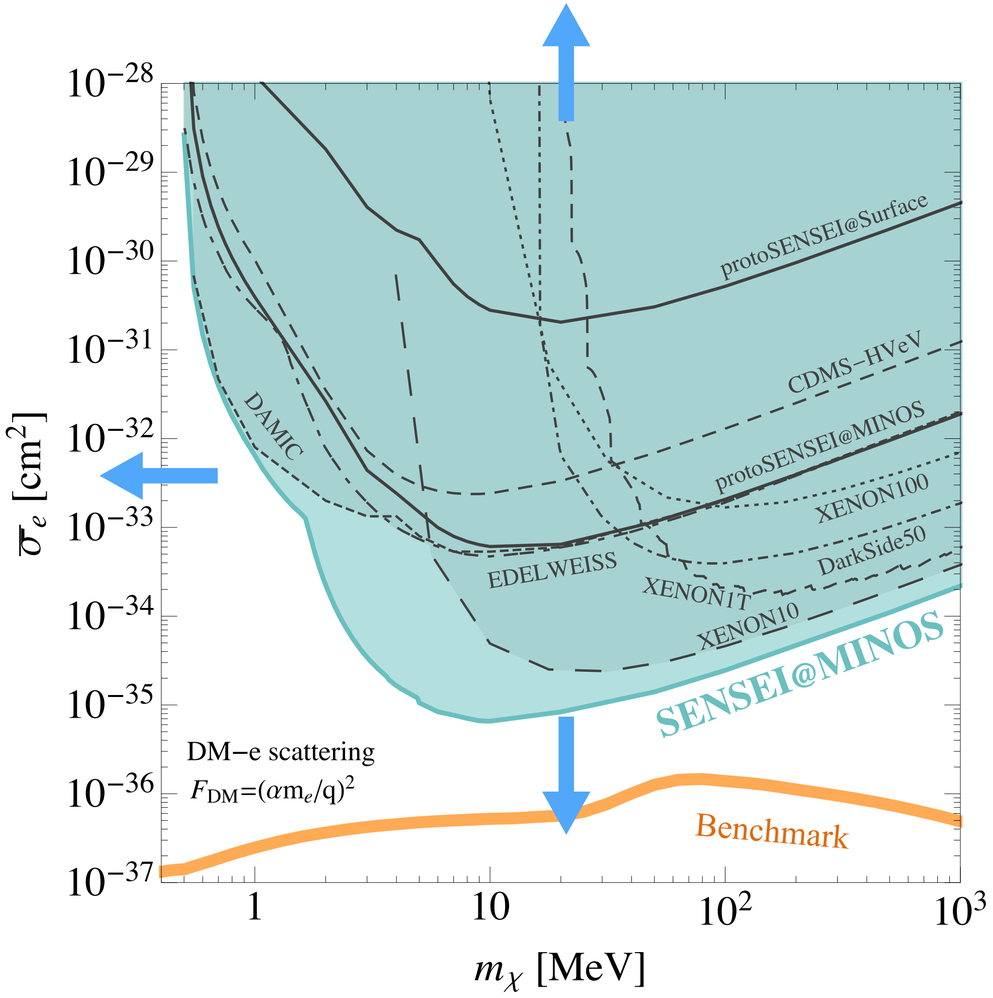
Threshold: E_I~10-100 meV

Light dark photon mediator (Si:P, n_d=1×10^{18}cm^{-3})



Direct detection of light DM

Figure from SENSEI, *PRL* 2020



Exploring the parameter space

Probing the theory benchmark

Need to understand backgrounds

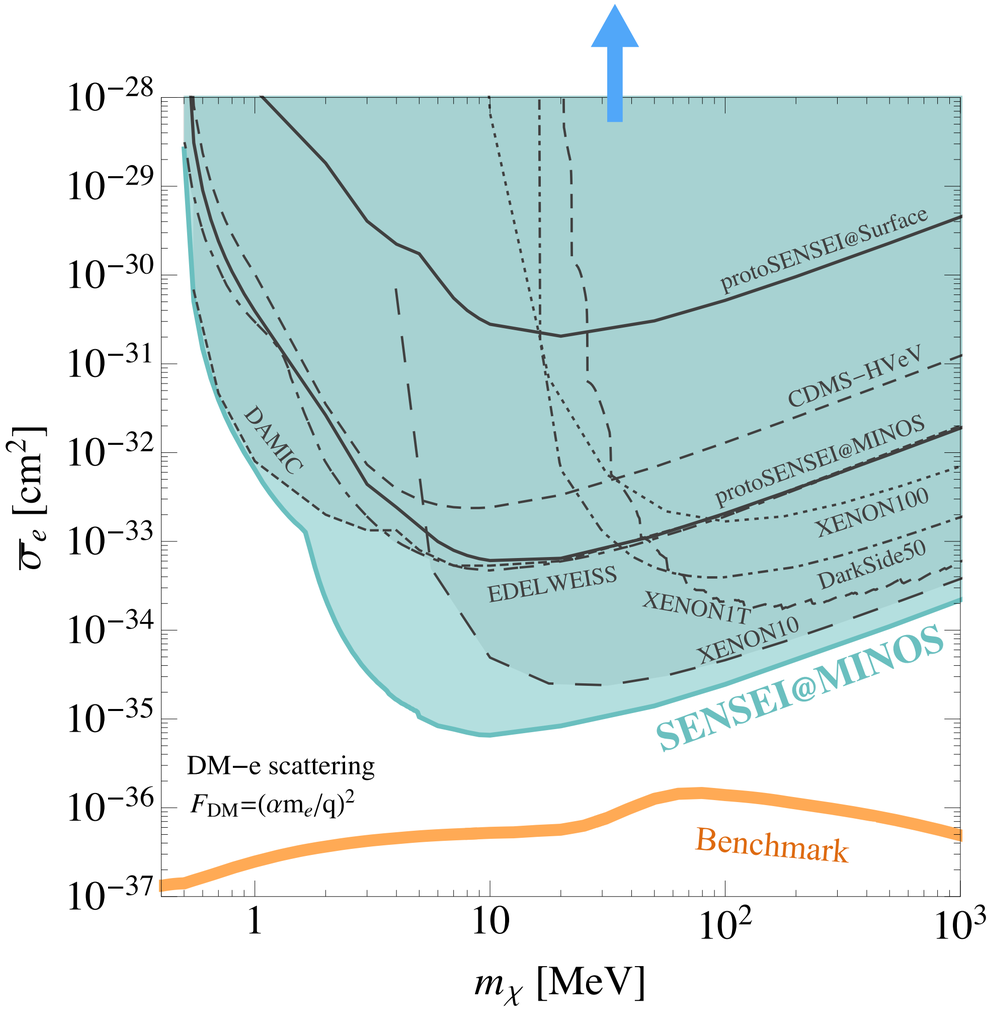
Probing DM lighter than MeV

Sub-eV threshold detectors

Probing strongly interacting DM

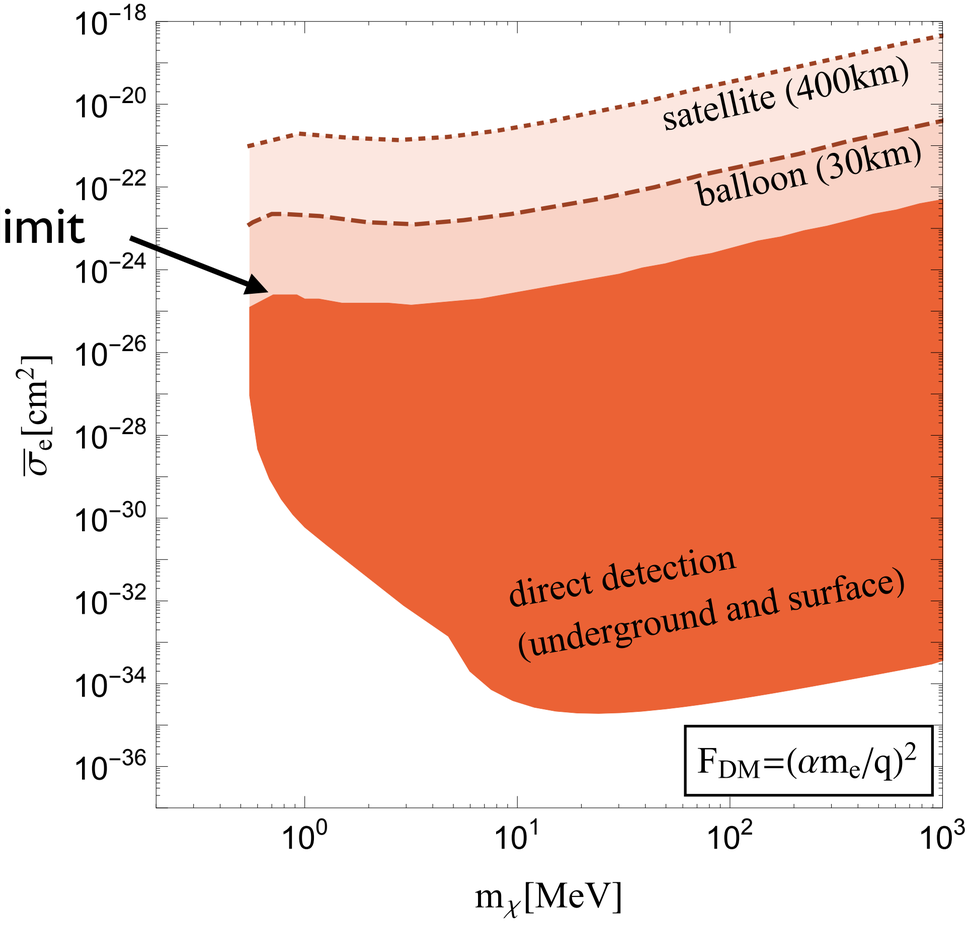
Space-based detectors

Upper limit of ground-based detectors



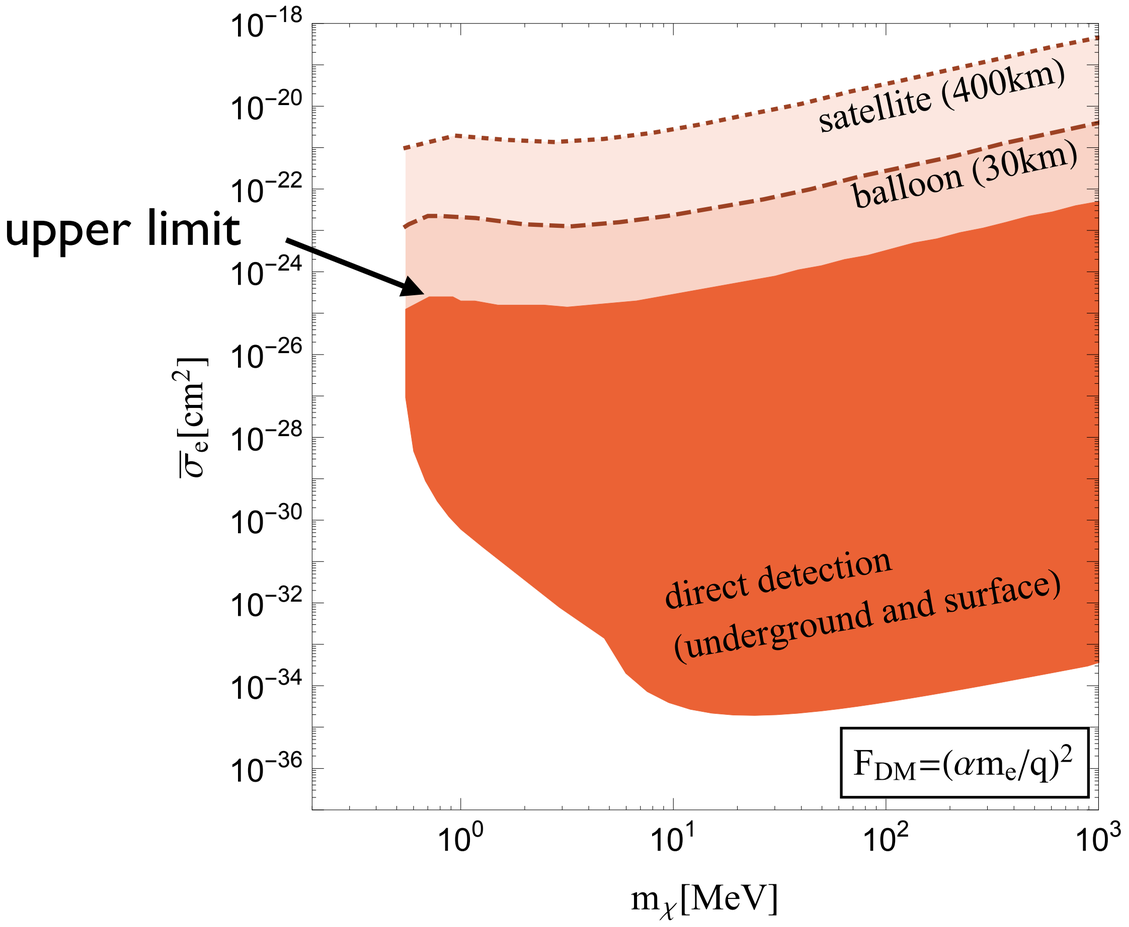
Upper limit of ground-based detectors

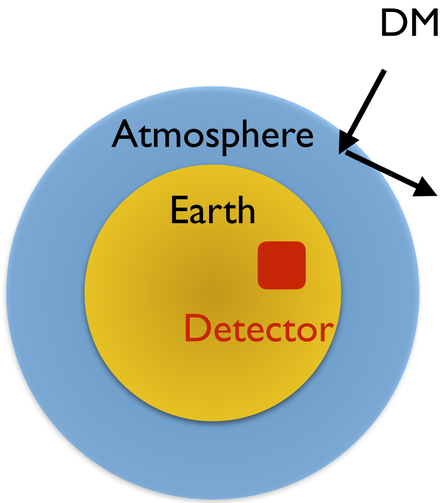
upper limit



Emken, Essig, Kouvaris, Sholapurkar, *JCAP*, 2019

Upper limit of ground-based detectors

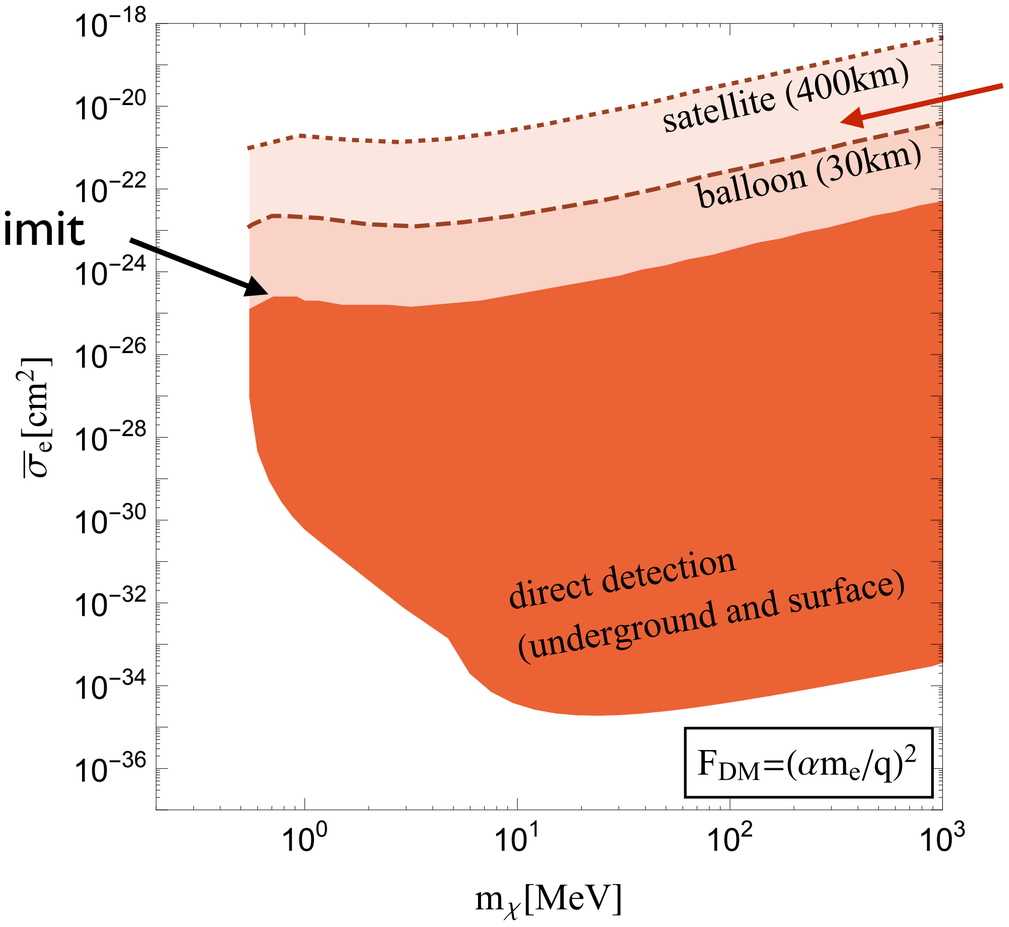




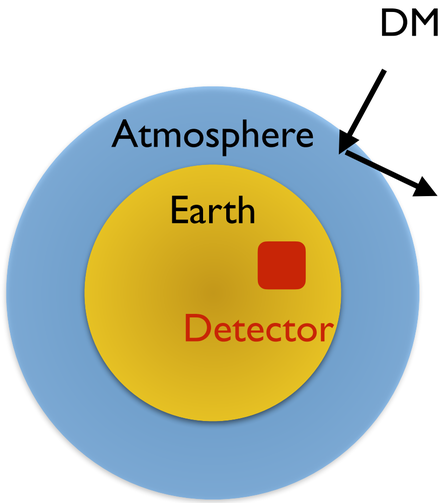
Strongly interacting DM will be scattered or slowed before reach ground based detectors

Emken, Essig, Kouvaris, Sholapurkar, *JCAP*, 2019

Upper limit of ground-based detectors



Has strongly interacting DM already been ruled out by other astro/cosmo constraints?



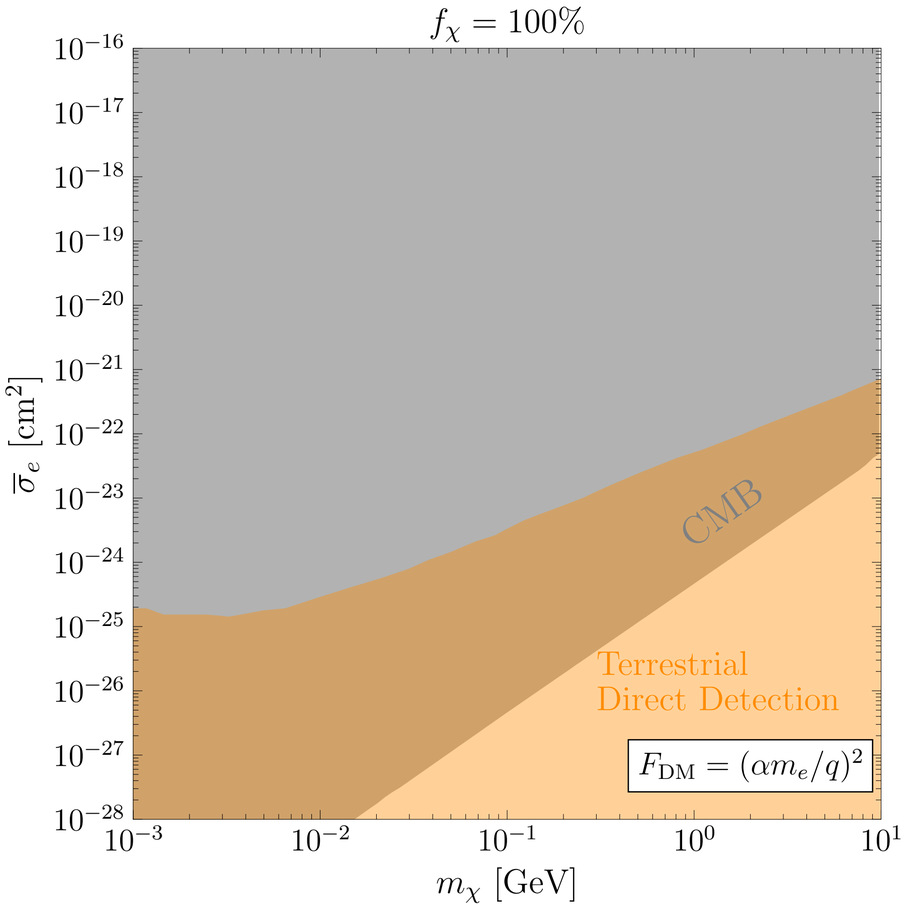
Strongly interacting DM will be scattered or slowed before reach ground based detectors

Emken, Essig, Kouvaris, Sholapurkar, *JCAP*, 2019

Parameter space for strongly interacting DM

$$f_\chi \equiv \frac{\rho_\chi}{\rho_{\rm DM}}$$

fraction of interacting DM component



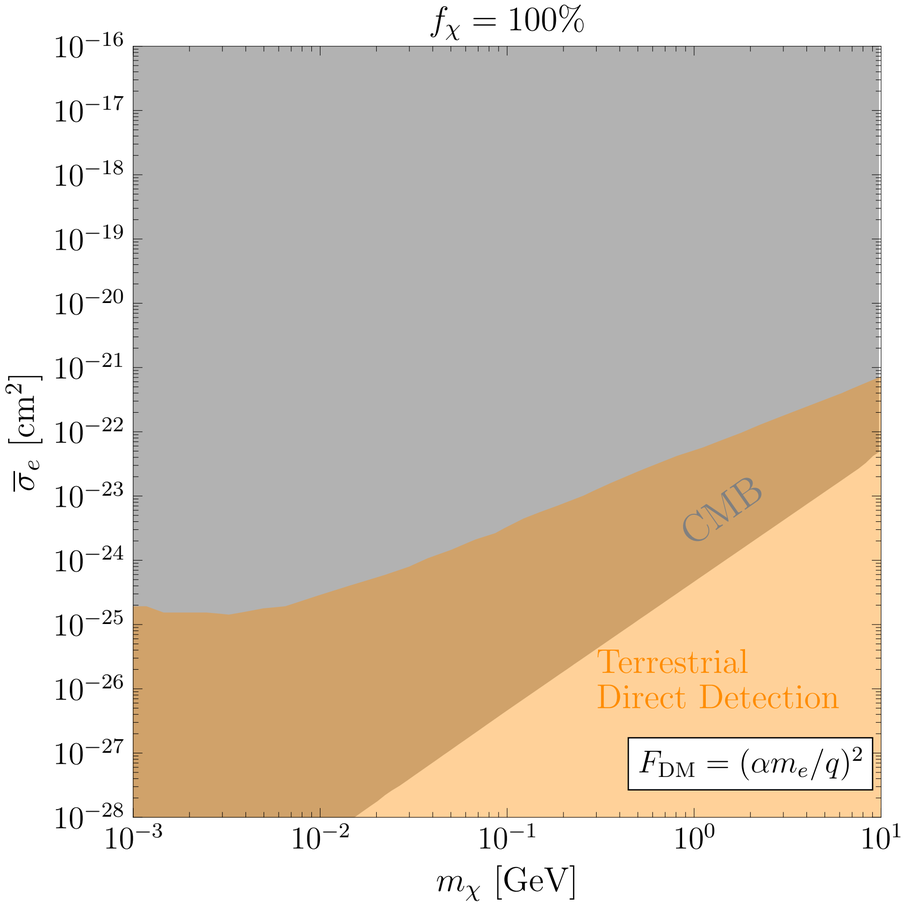
No room for strongly interacting DM if $f_\chi = 100\%$

Emken, Essig, Kouvaris, Sholapurkar, *JCAP*, 2019

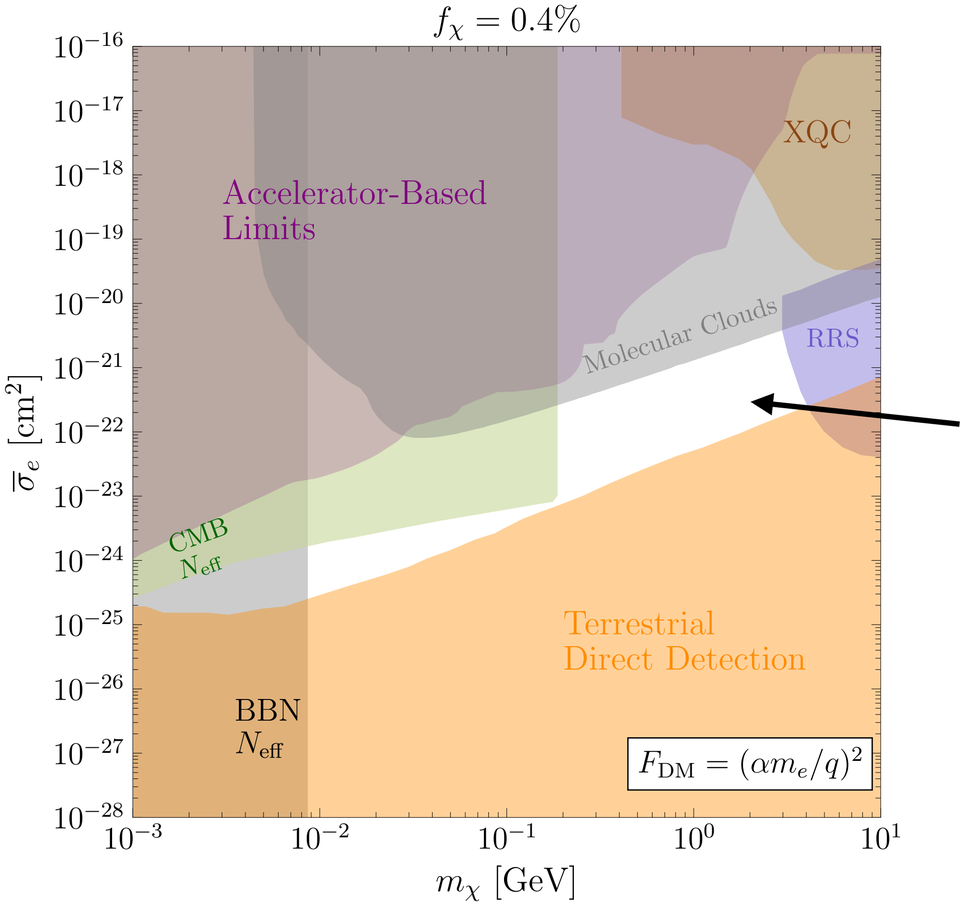
Parameter space for strongly interacting DM

$$f_\chi \equiv \frac{\rho_\chi}{\rho_{\rm DM}}$$

fraction of interacting DM component



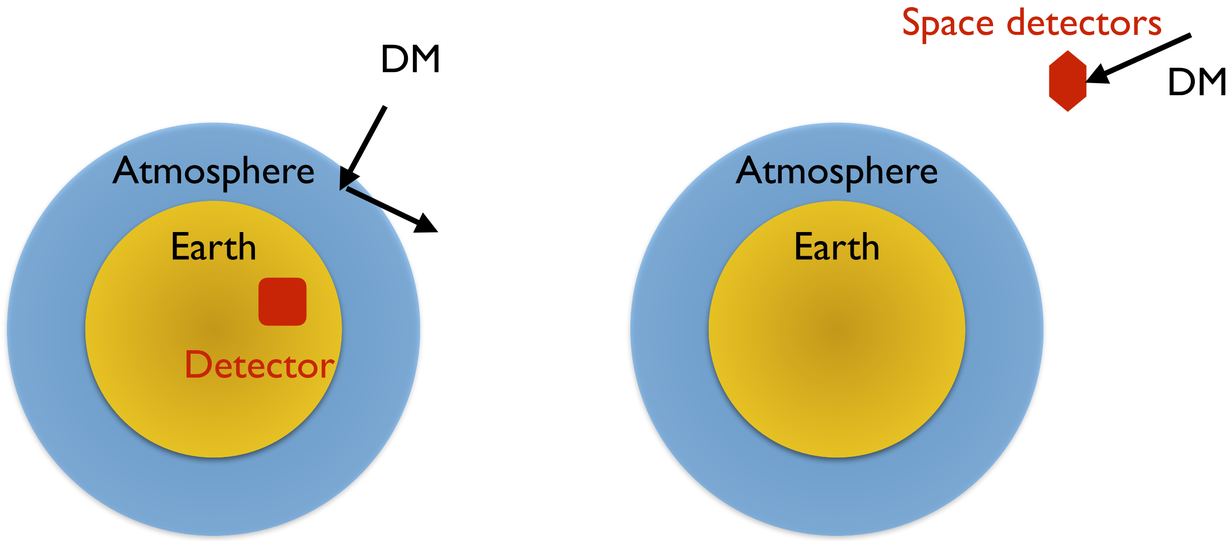
No room for strongly interacting DM if $f_\chi = 100\%$



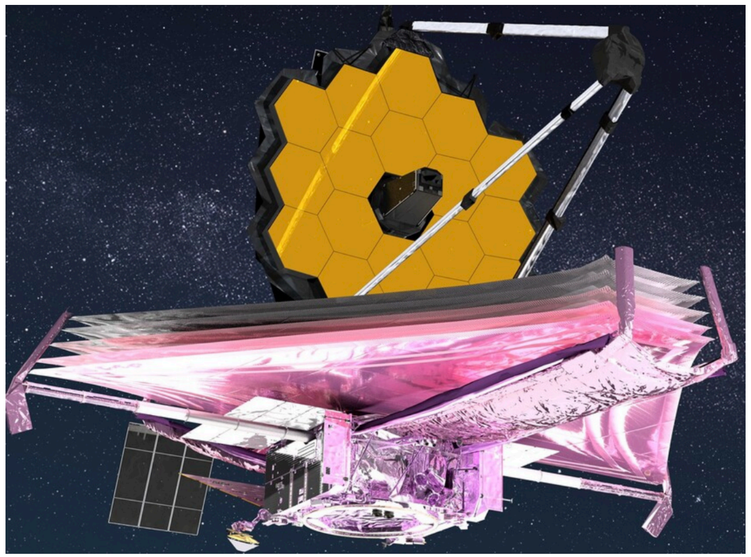
Unconstrained window for $f_\chi \lesssim 0.4\%$

Emken, Essig, Kouvaris, Sholapurkar, *JCAP*, 2019

Going to the space



JWST

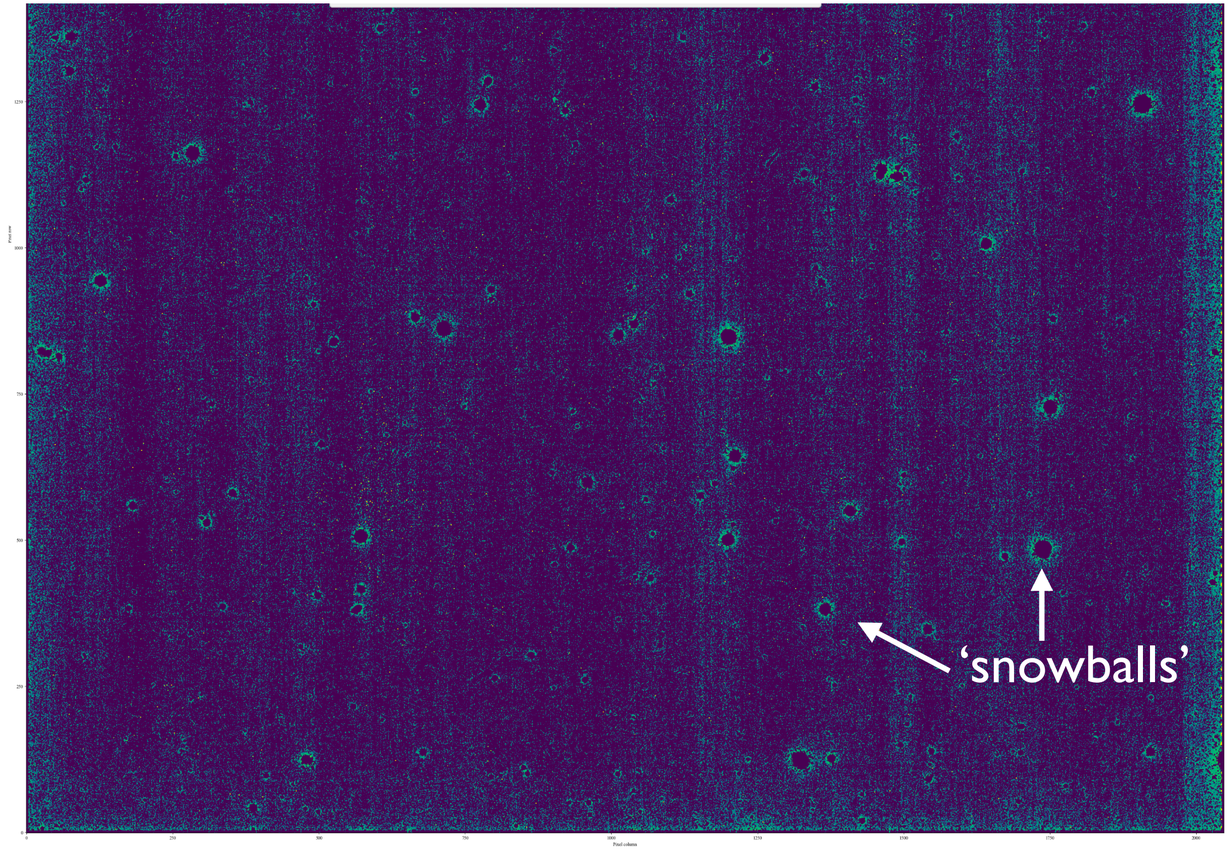


Space detectors can probe strongly interacting DM due to lack of atmospheric shielding

- IR detector: E_{th}~0.1 eV
- Low noise:
  dark current ~0.01 e/pixel/s

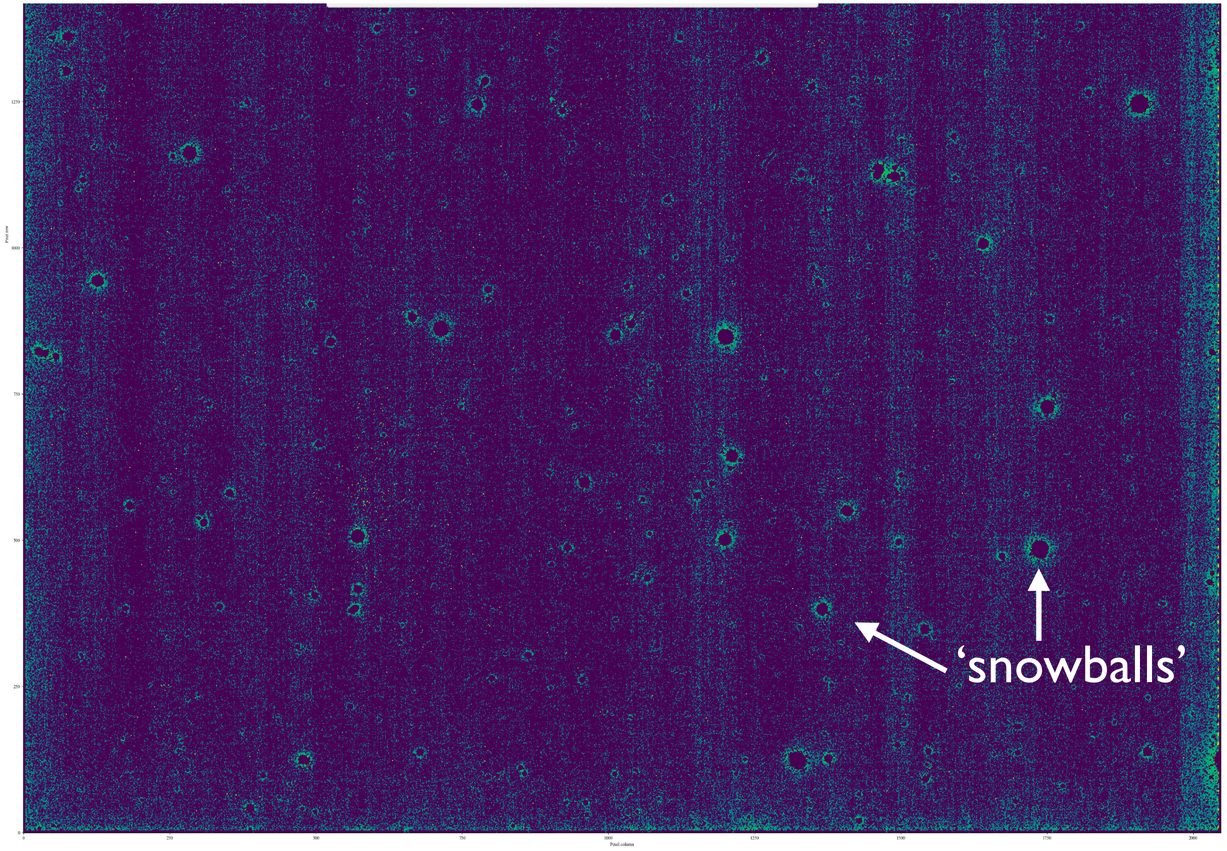
JWST dark images

Dark images from NIRSpec on JWST

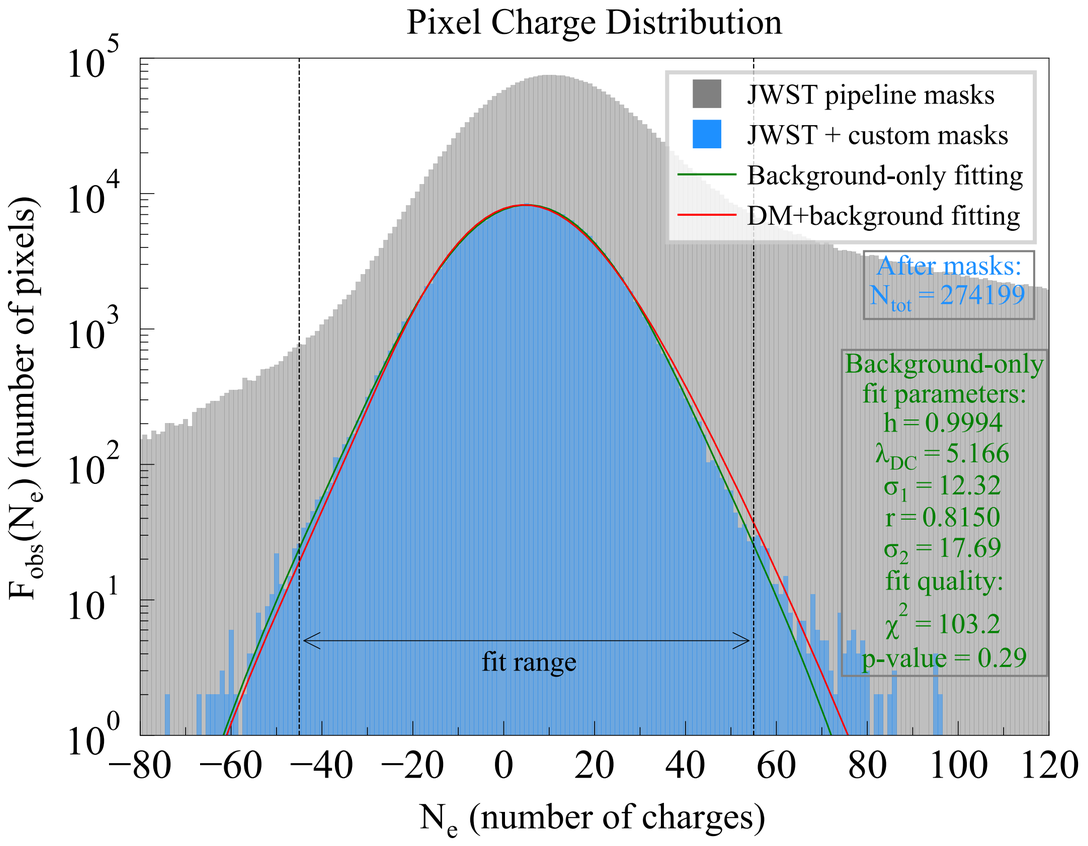


JWST dark images

Dark images from NIRSpec on JWST



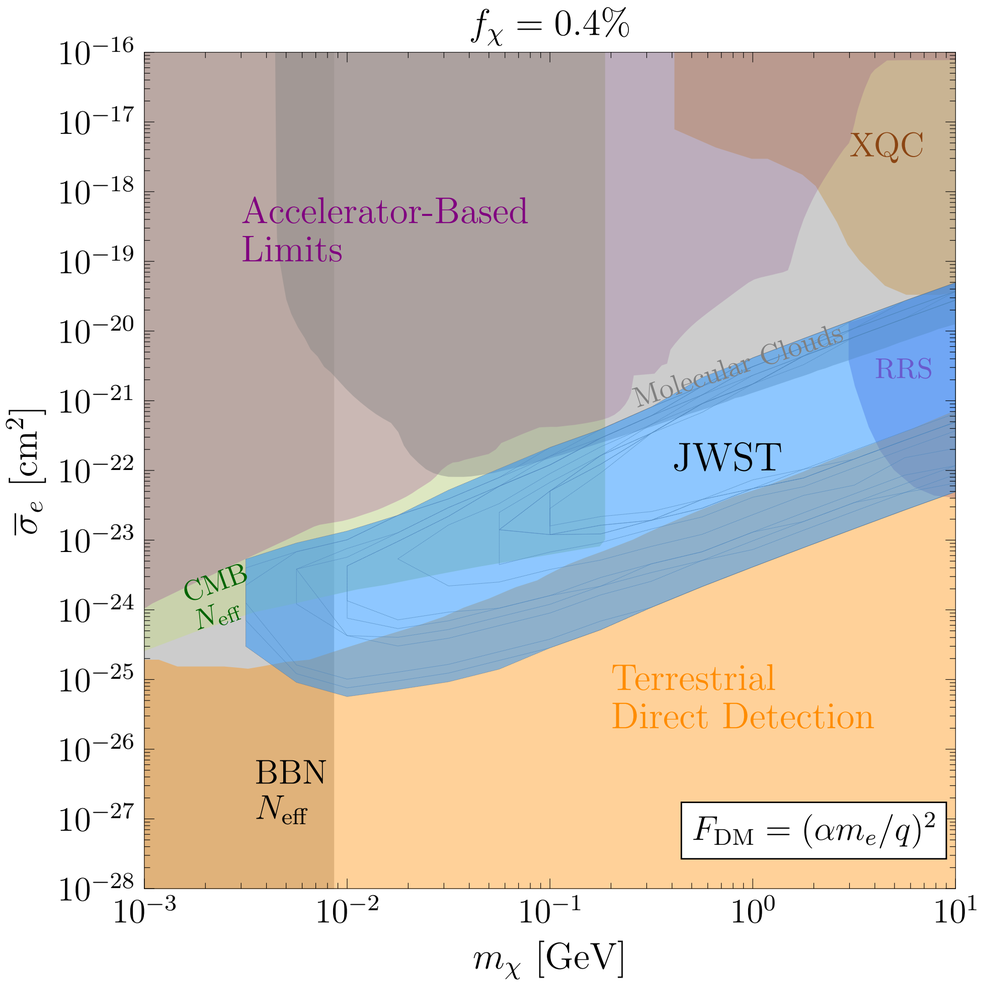
Pixel charge distribution

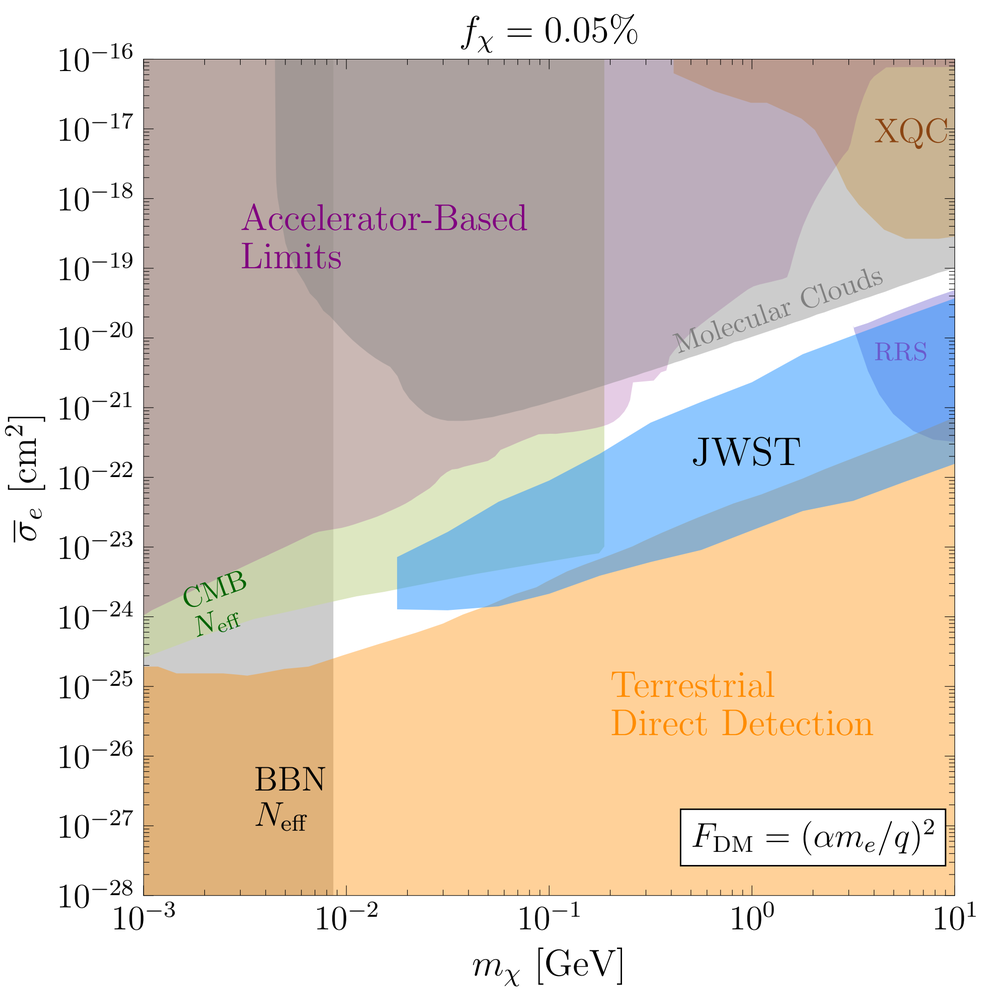


PD, Essig, Rauscher, Xu, 2024

JWST DM constraints

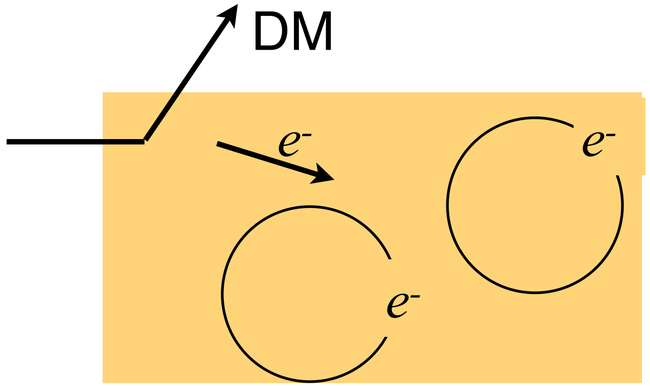
PD, Essig, Rauscher, Xu, 2024



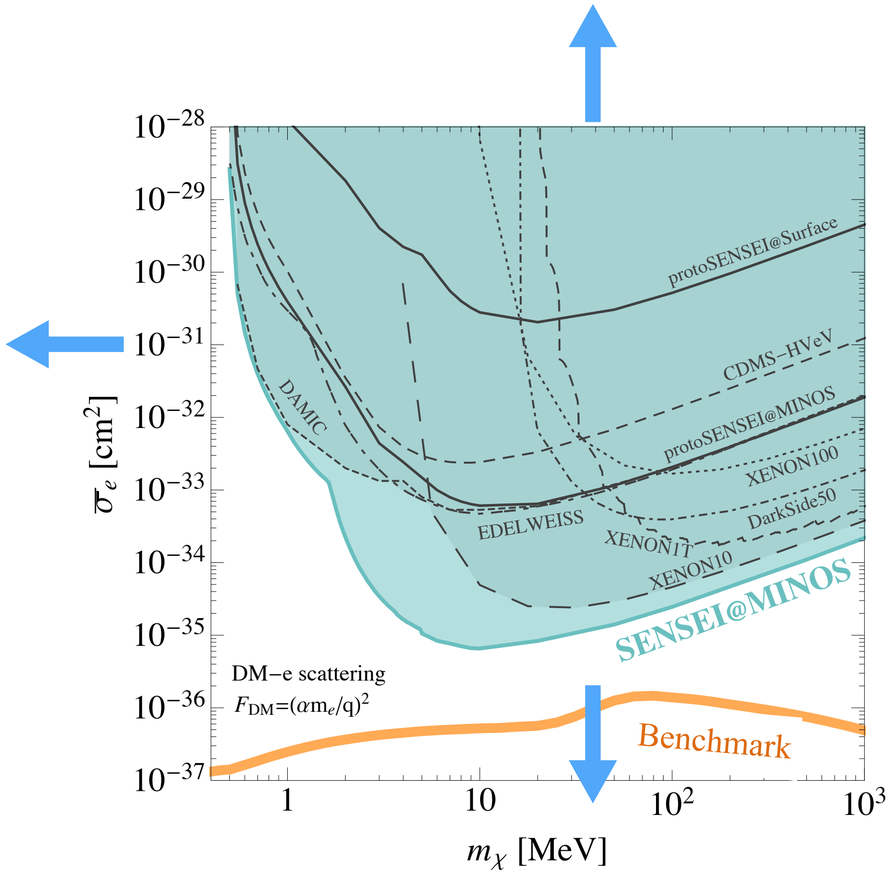


- Closing the window for 0.4% of interacting DM
- Future space detectors (e.g. DarkNESS) can further probe DM

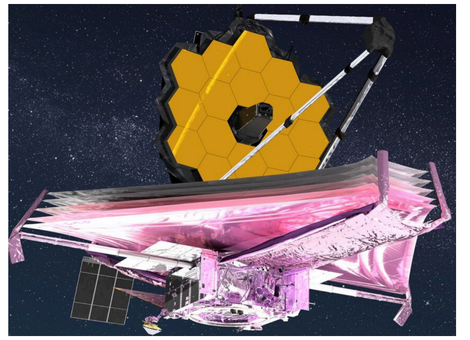
Conclusions



Low threshold detector:
Doped semiconductors

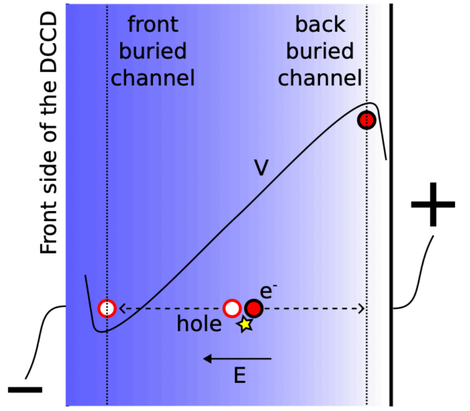


Direct Detection of Light DM



Space detectors: JWST

Need to understand backgrounds
Low-noise detector: DCCD



Thank you