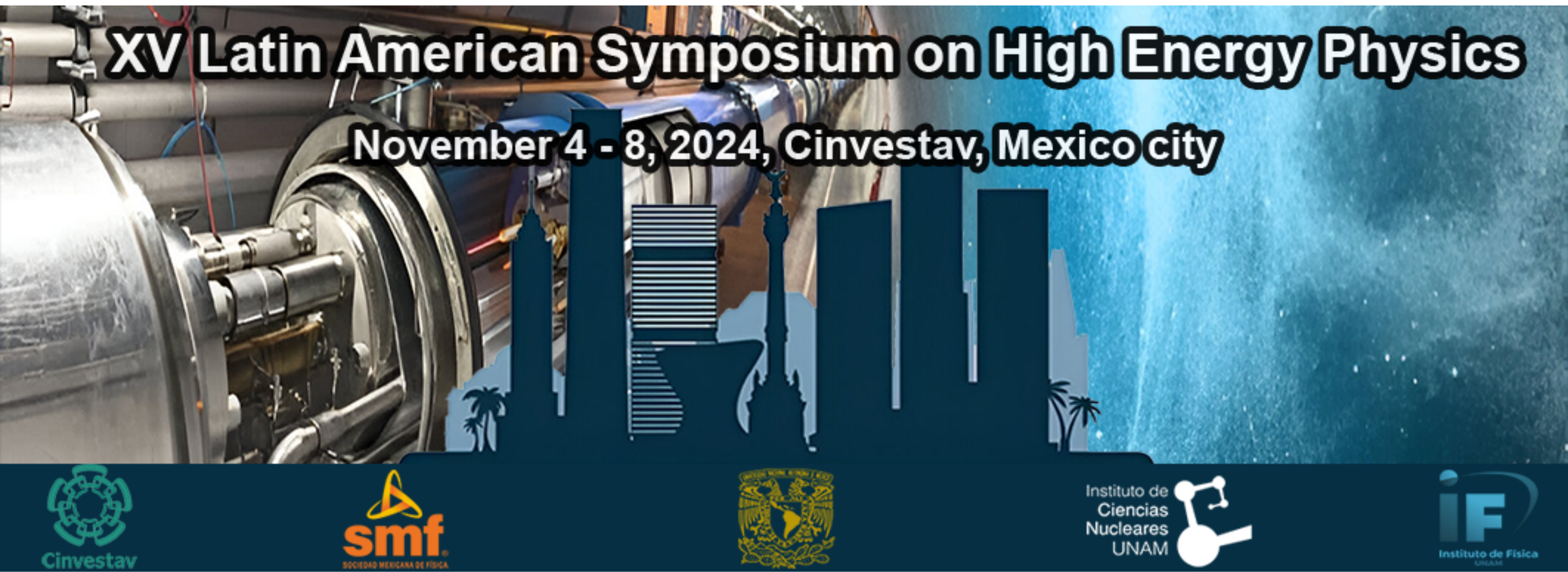
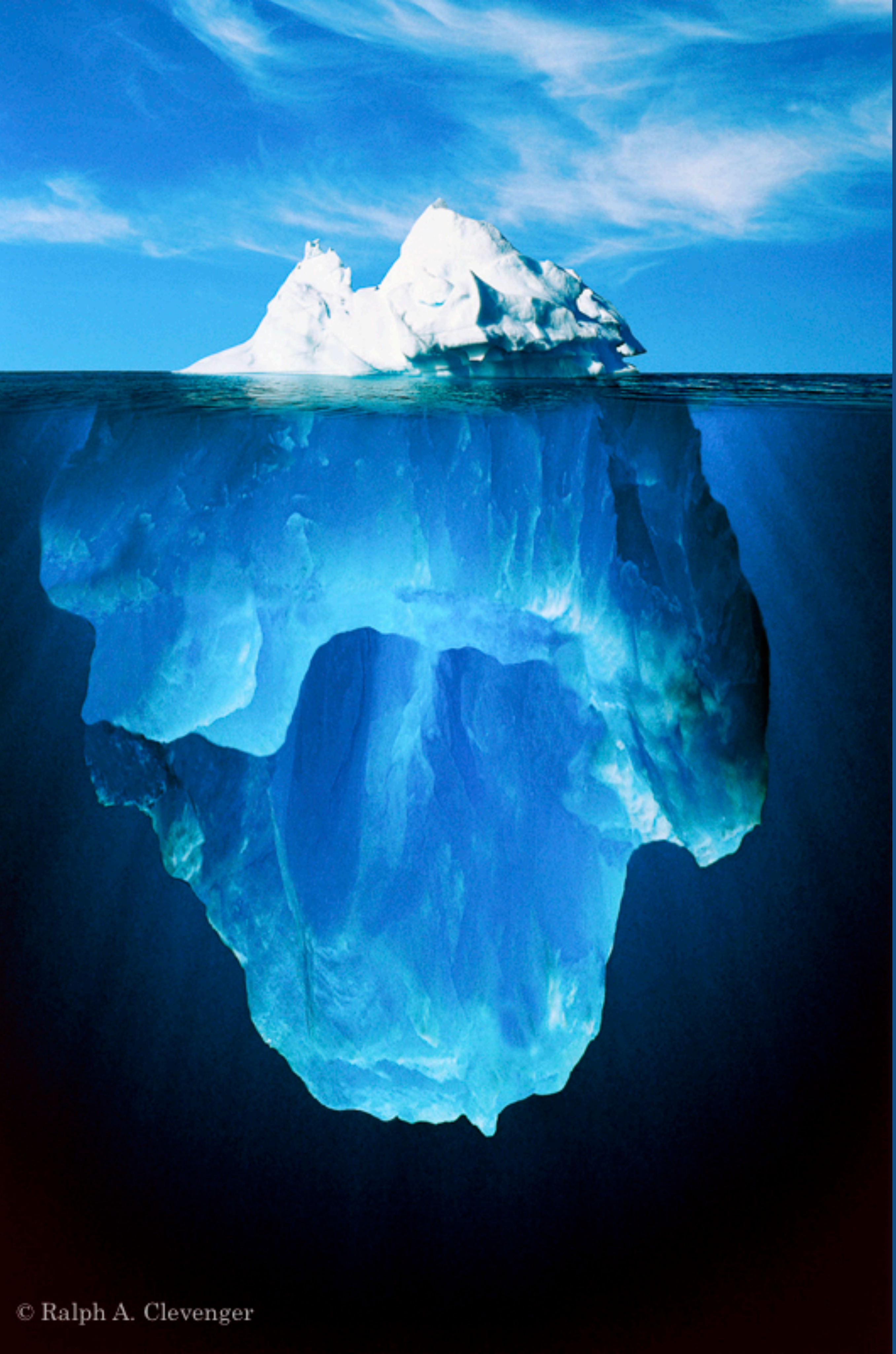
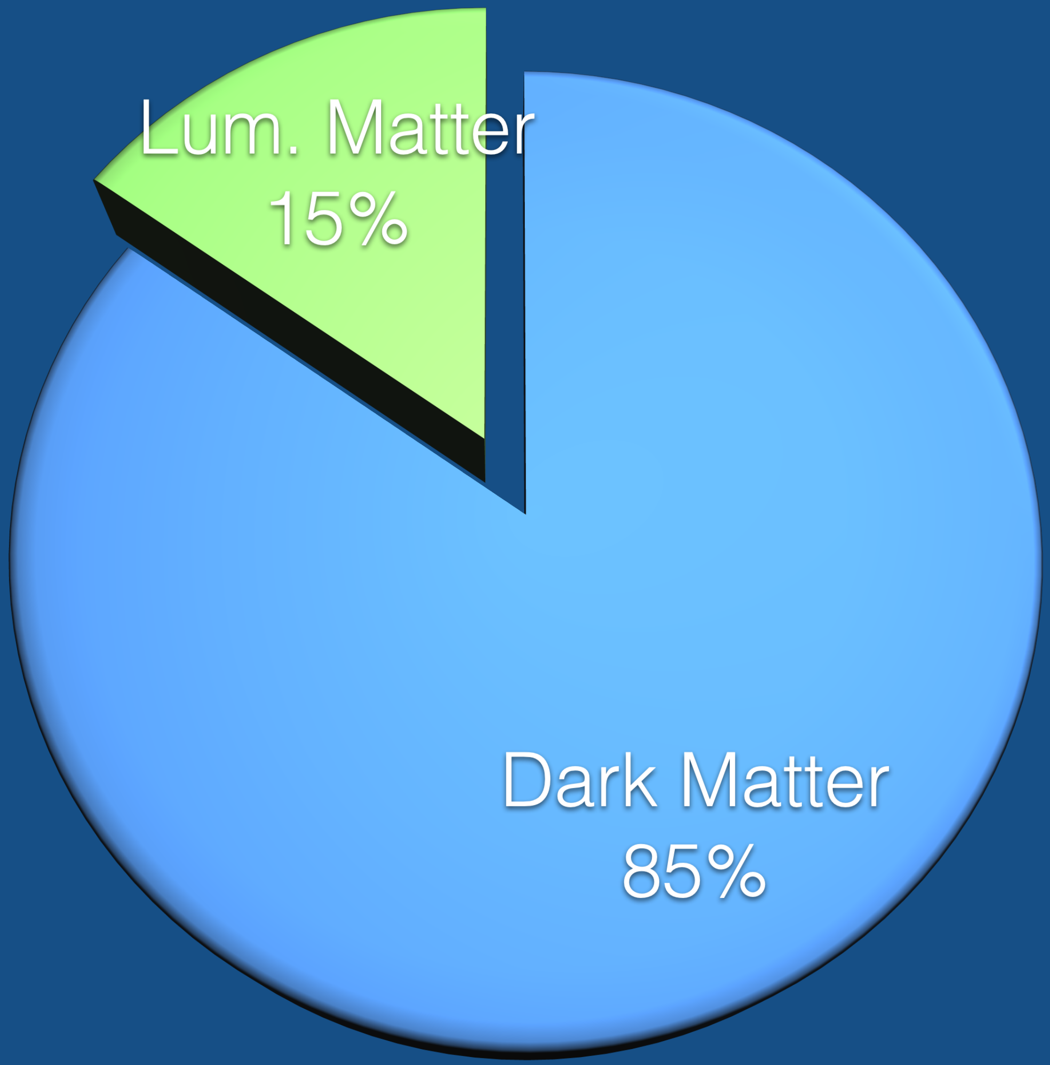
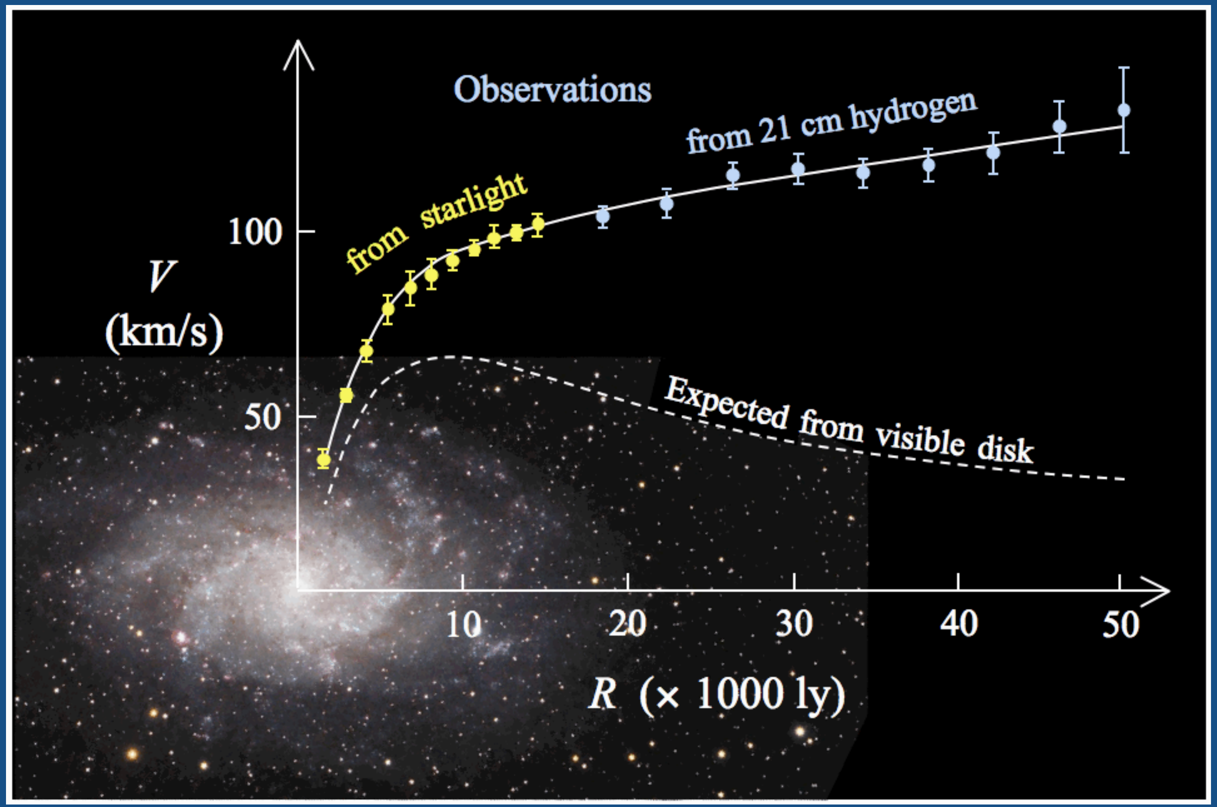
Dark Matter Experiments
Juan Estrada

Fermilab
The University of Chicago 1890




© Ralph A. Clevenger


Lum. Matter
15%
Dark Matter
85%

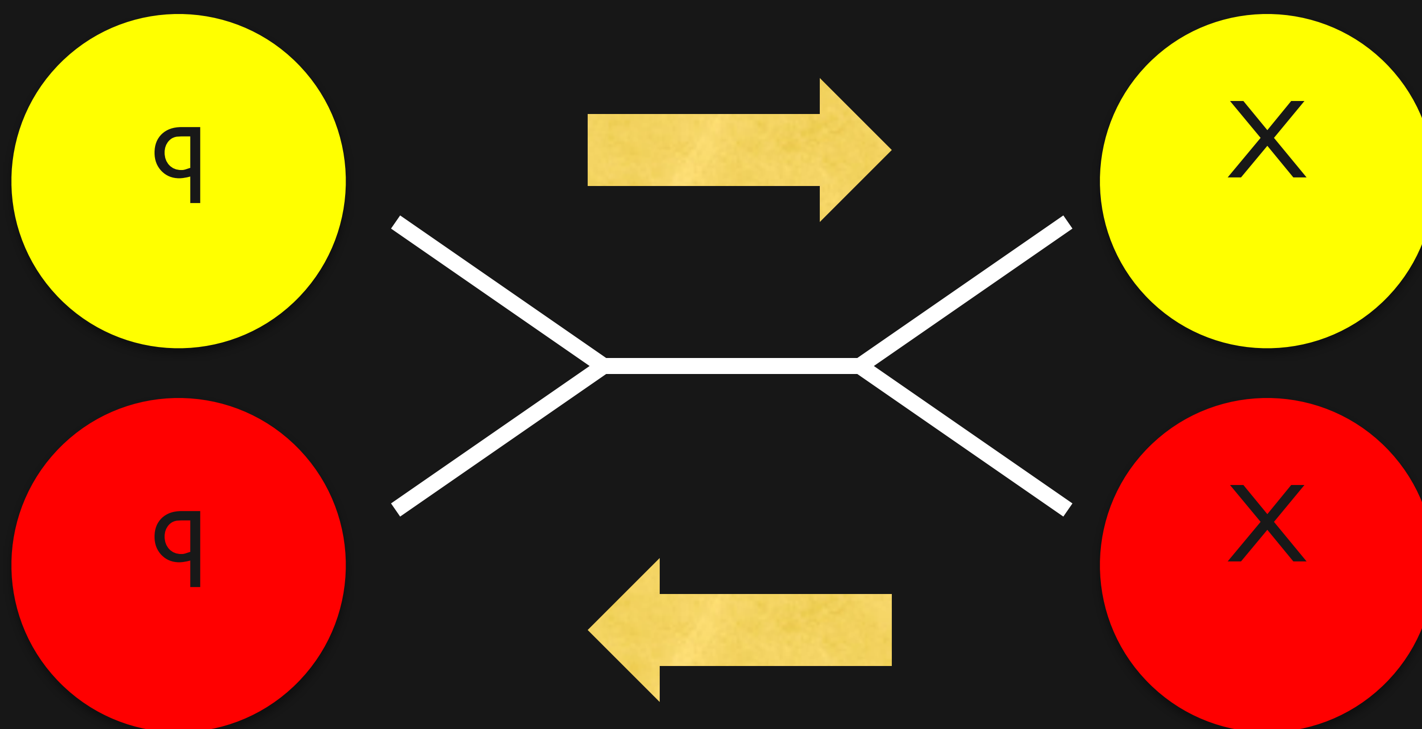

Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

Dark Matter density in solar system is approximately 1 proton-mass for every 3 cubic centimeters, roughly 6×10^{-28} kg/cm^{-3}.

proton mass ~ 1.7×10^{-27} kg

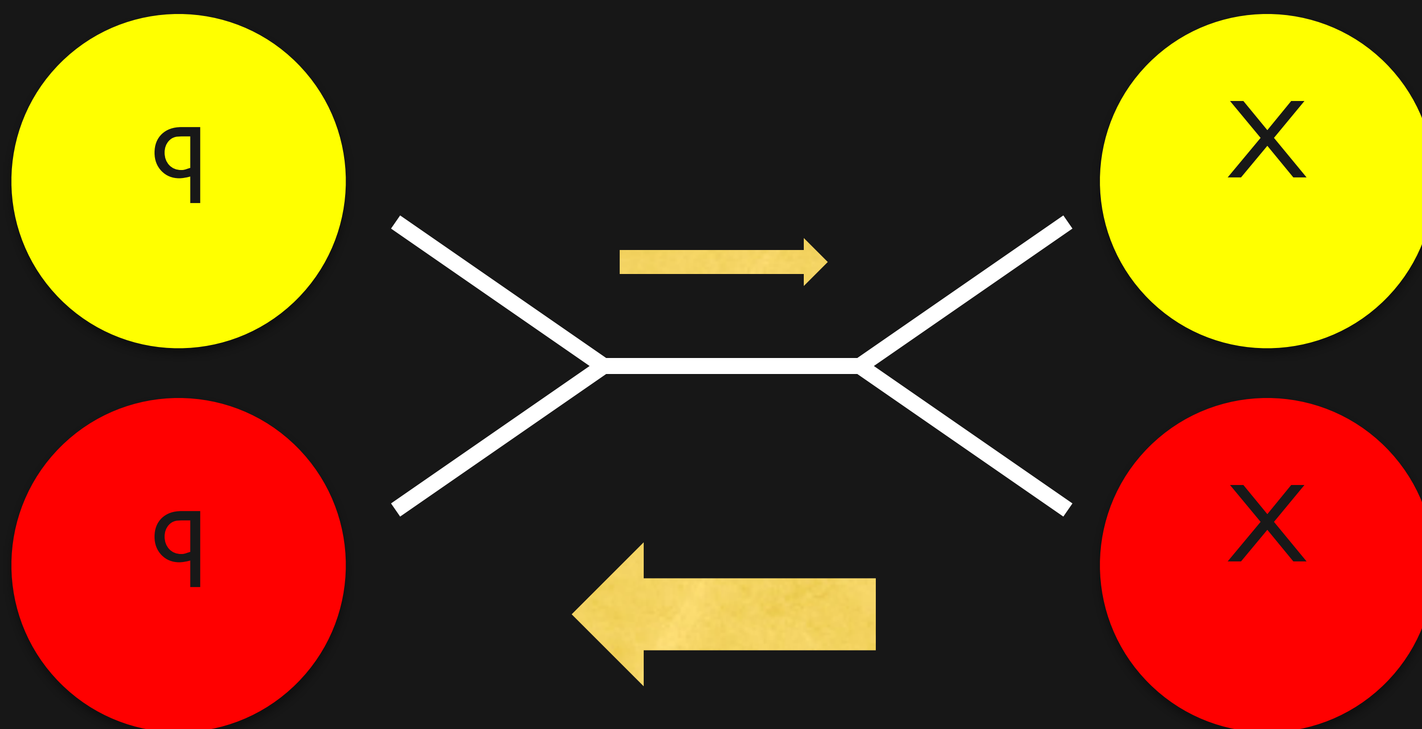
It should be everywhere…, but moving fast, velocities ~ 200 km/sec.

early Universe: hot and dense (T>>Mx)



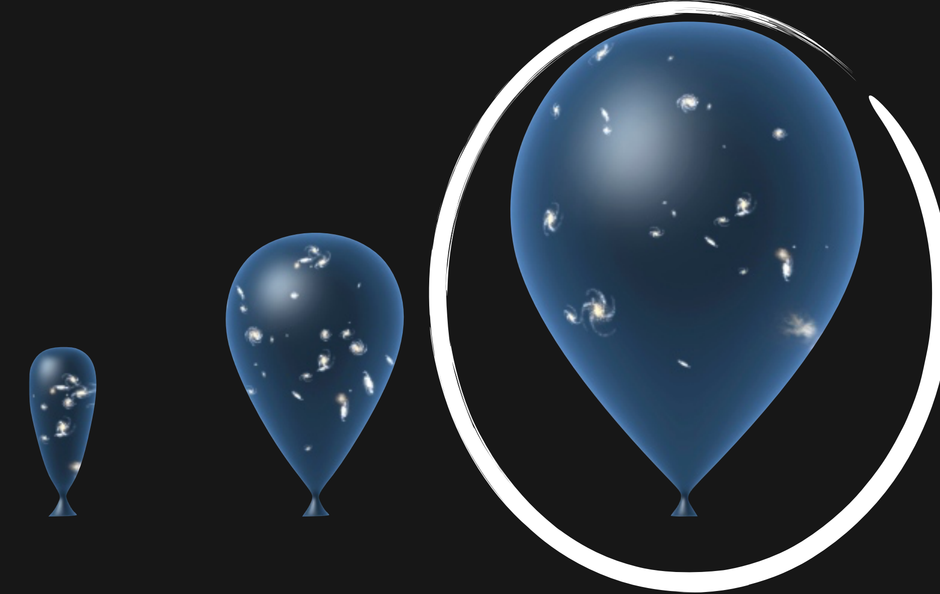
known particles (q) collide and produce dark particles (x), and vice versa.

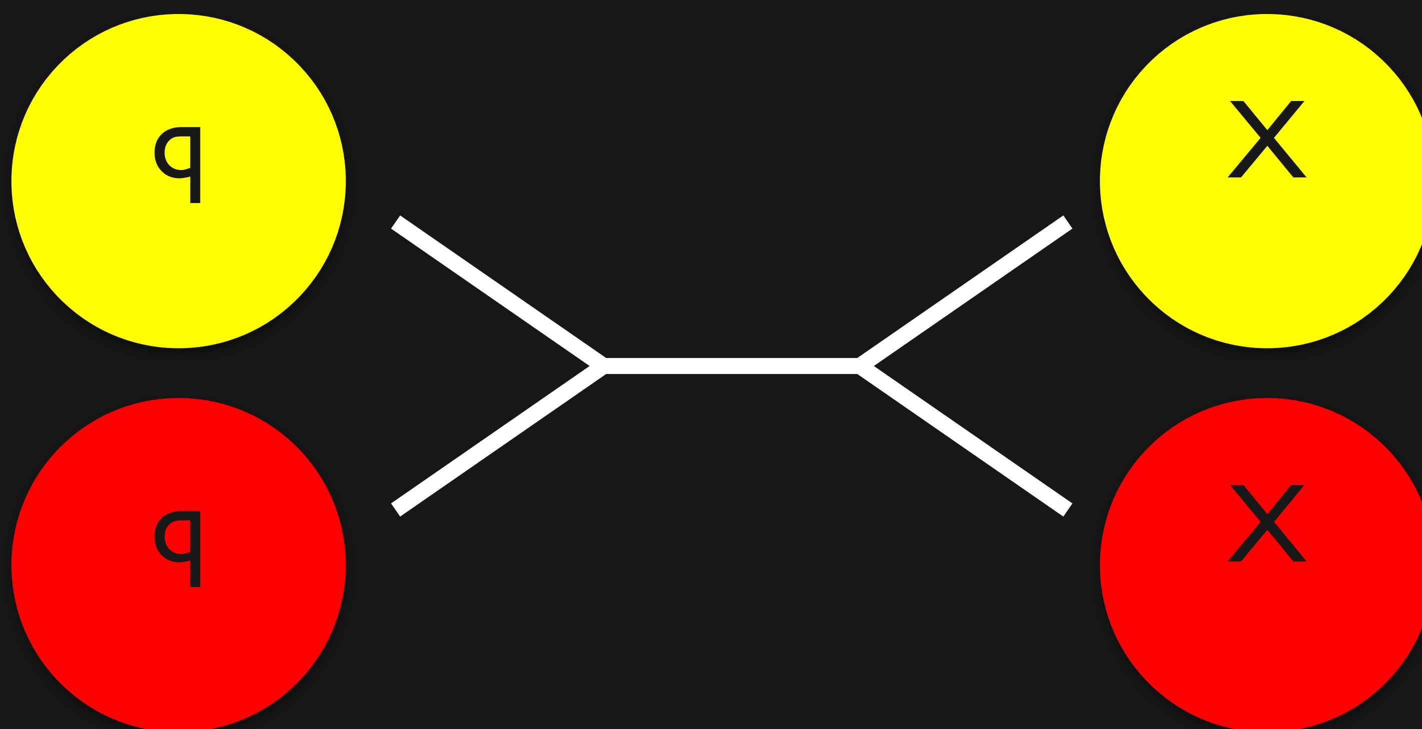
Universe: colder and dense (T < Mx)



production is now harder because of lower energy collisions, annihilation is easy because of density

Universe: cold and low density (T>>Mx)

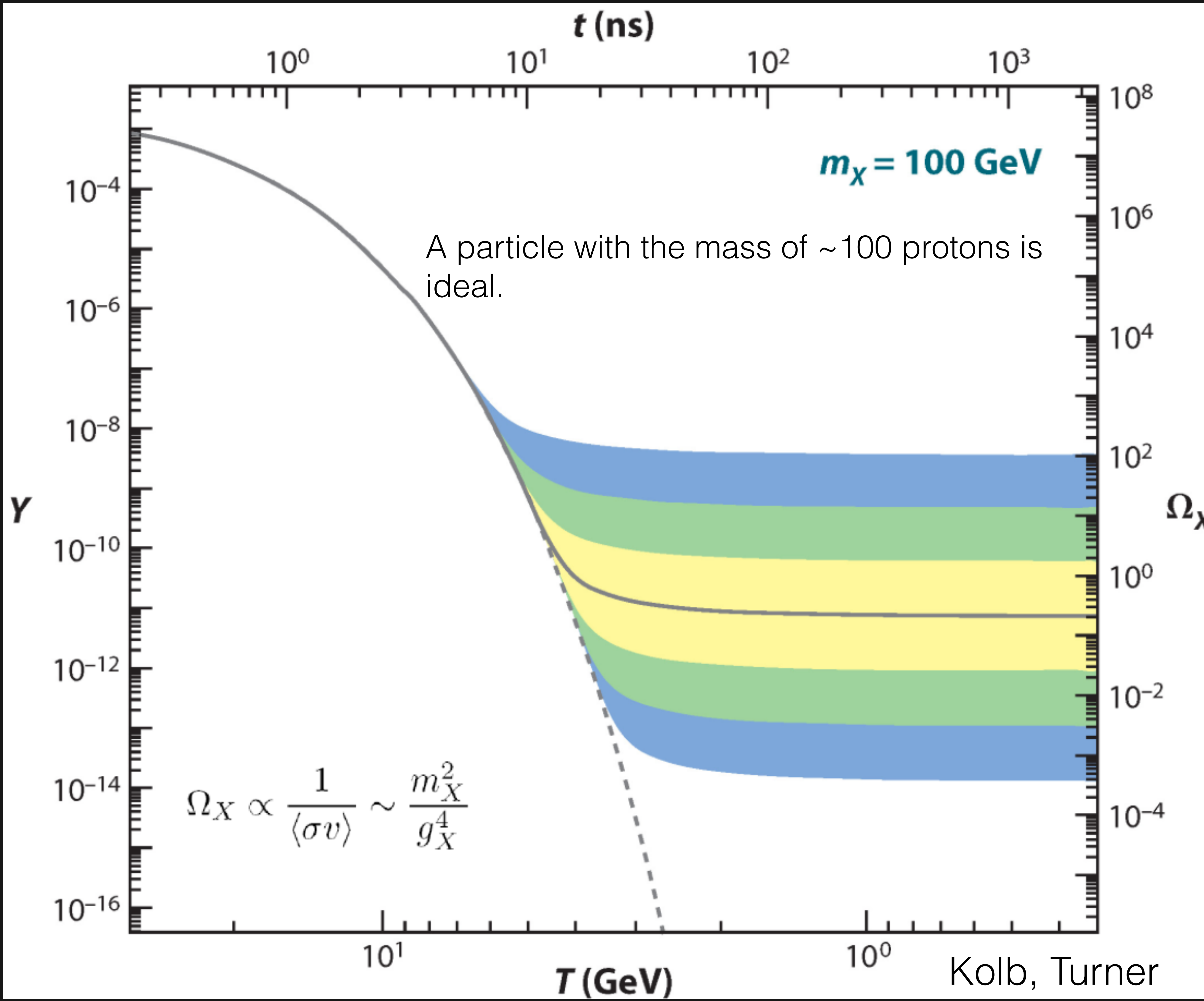




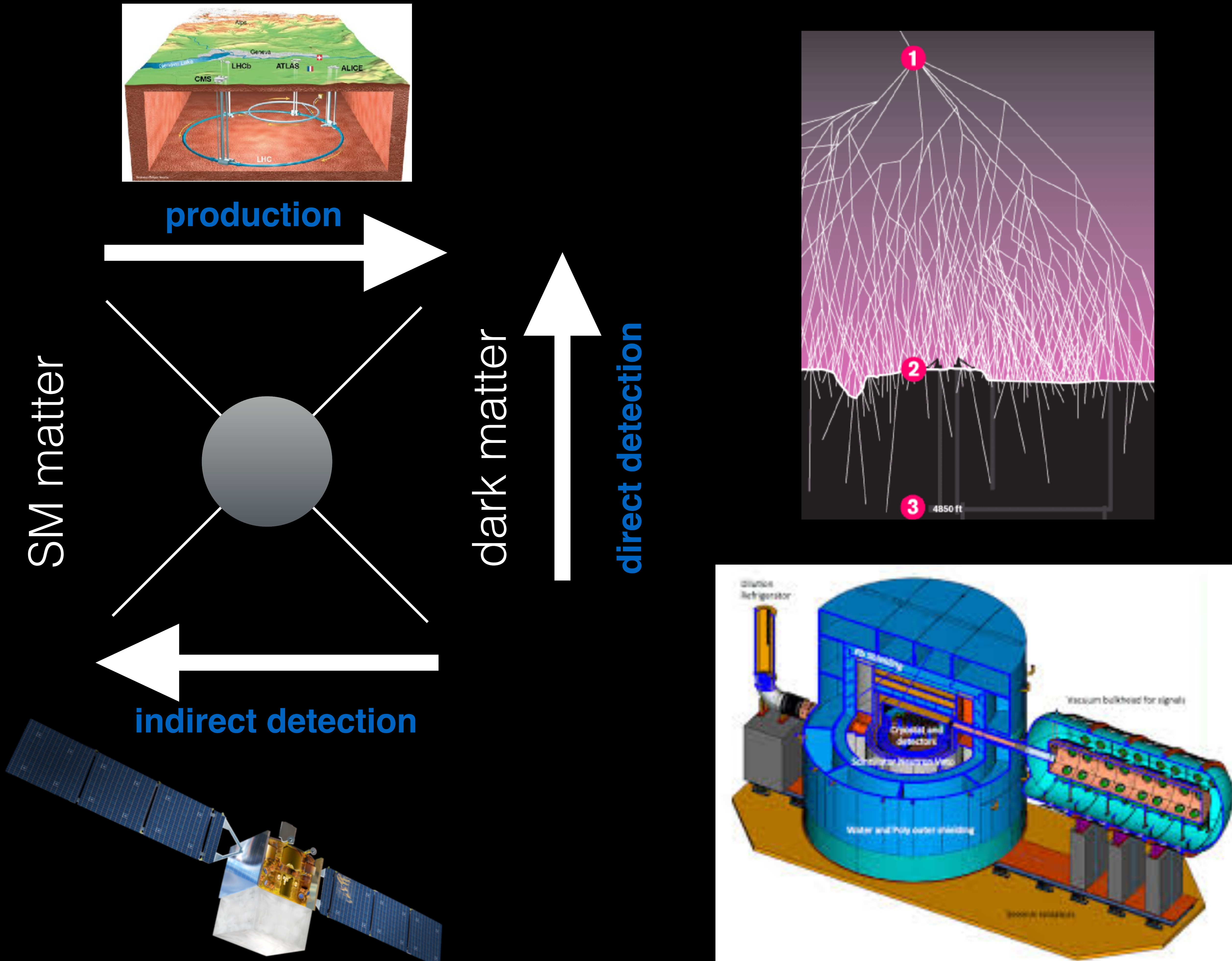
no more production

no more annihilation

“relic density”



$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$

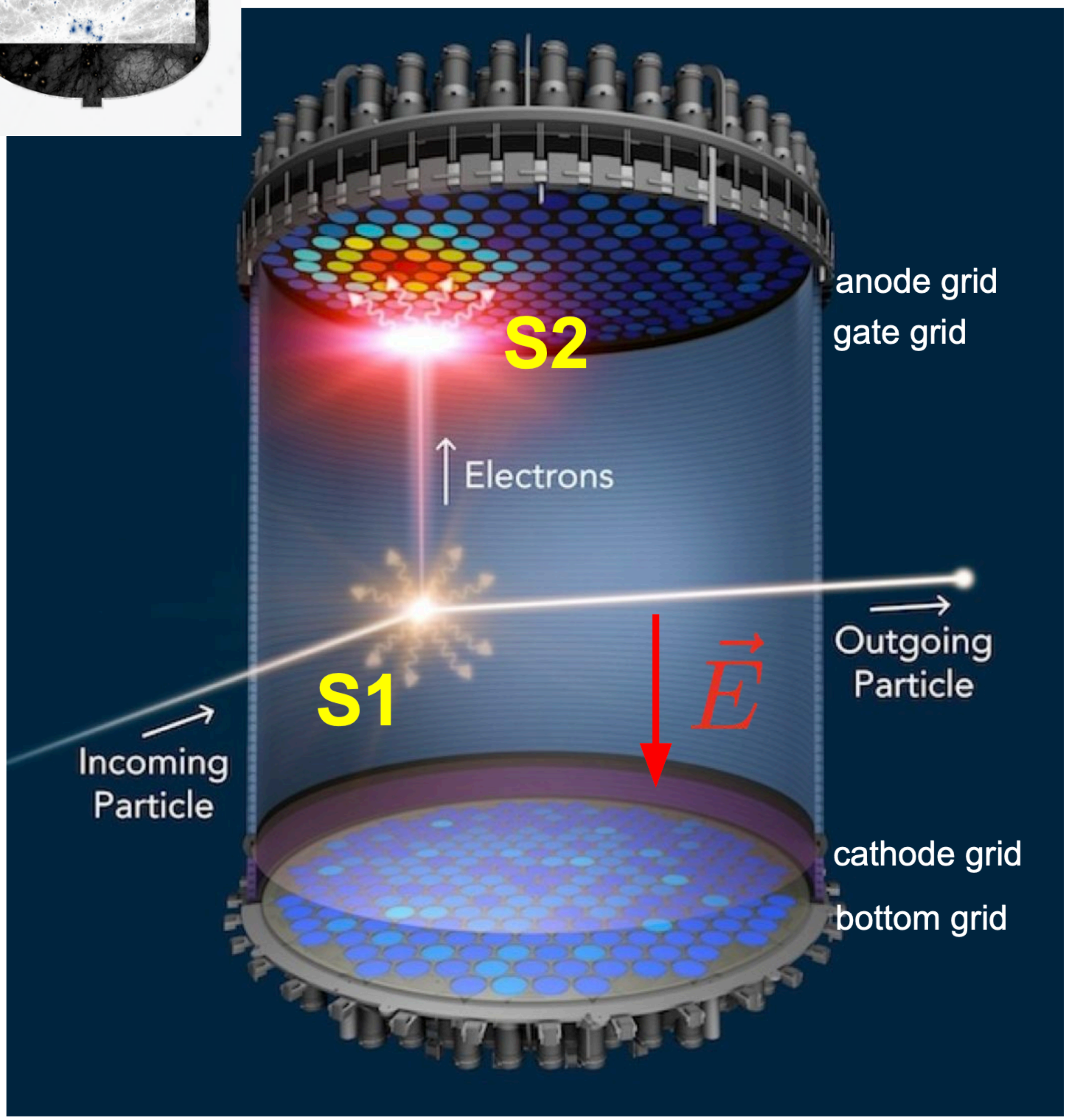


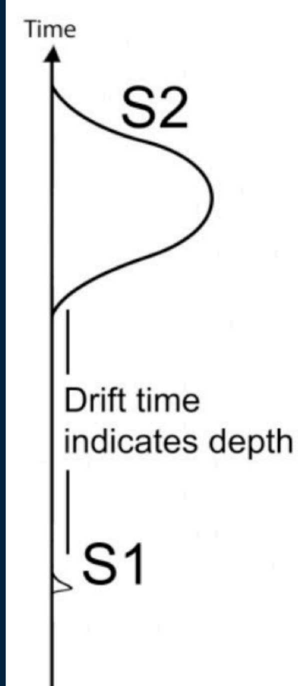
Geneva
LHCb
ATLAS
CMS
ALICE
LHC
production
SM matter
dark matter
direct detection
indirect detection
1
2
3
4850 ft

LZ experiment

Phys. Rev. Lett. 131, 041002 (2023)

Looking for wimps in a deep underground lab (SURF).





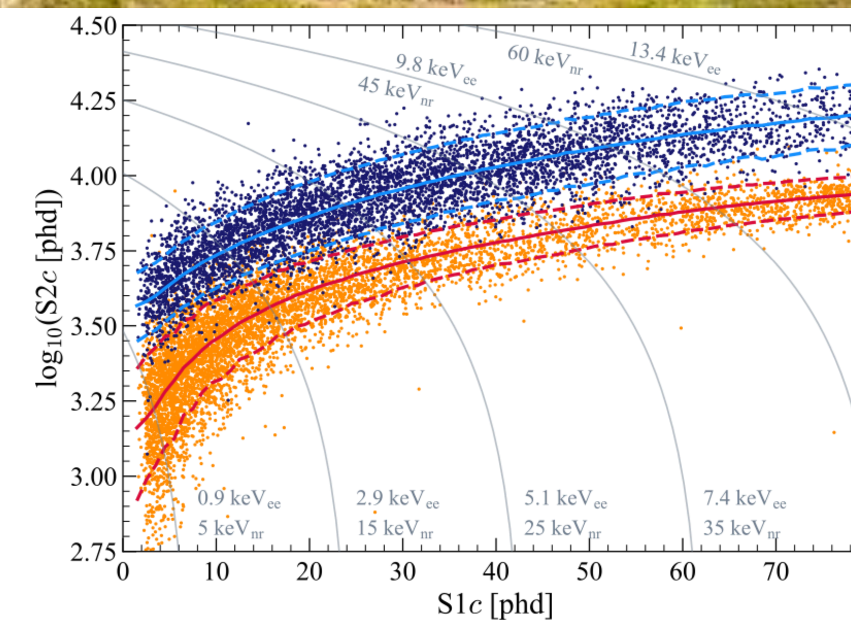
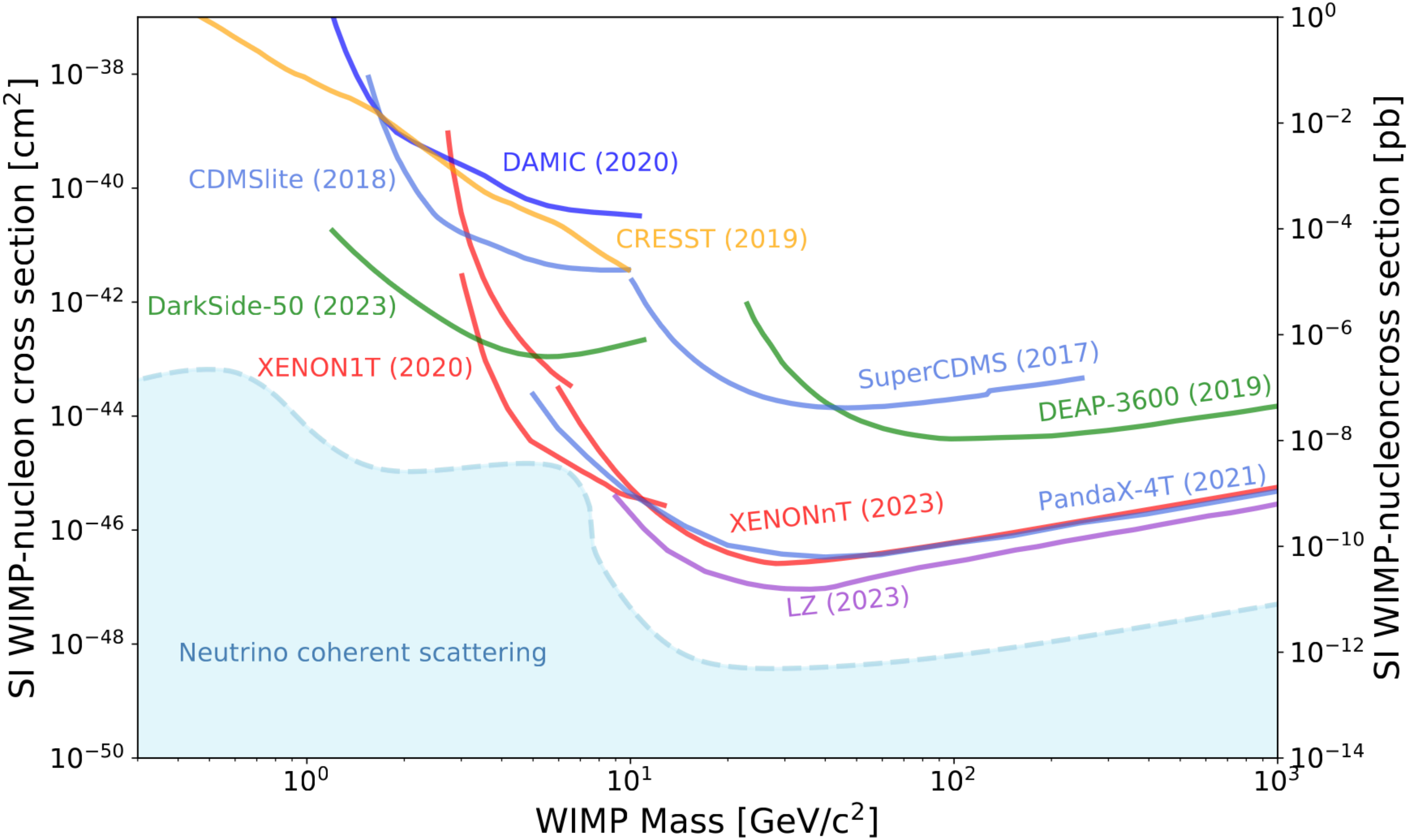


FIG. 1. Calibration events in $\log_{10}$S2c-S1c for the tritium source (dark blue points, 5343 events) and the DD neutron source (orange points, 6324 events). Solid blue (red) lines indicate the median of the ER (NR) simulated distributions, and the dotted lines indicate the 10 % and 90 % quantiles. Thin gray lines show contours of constant electron-equivalent energy (keV$_{ee}$) and nuclear recoil energy (keV$_{nr}$).

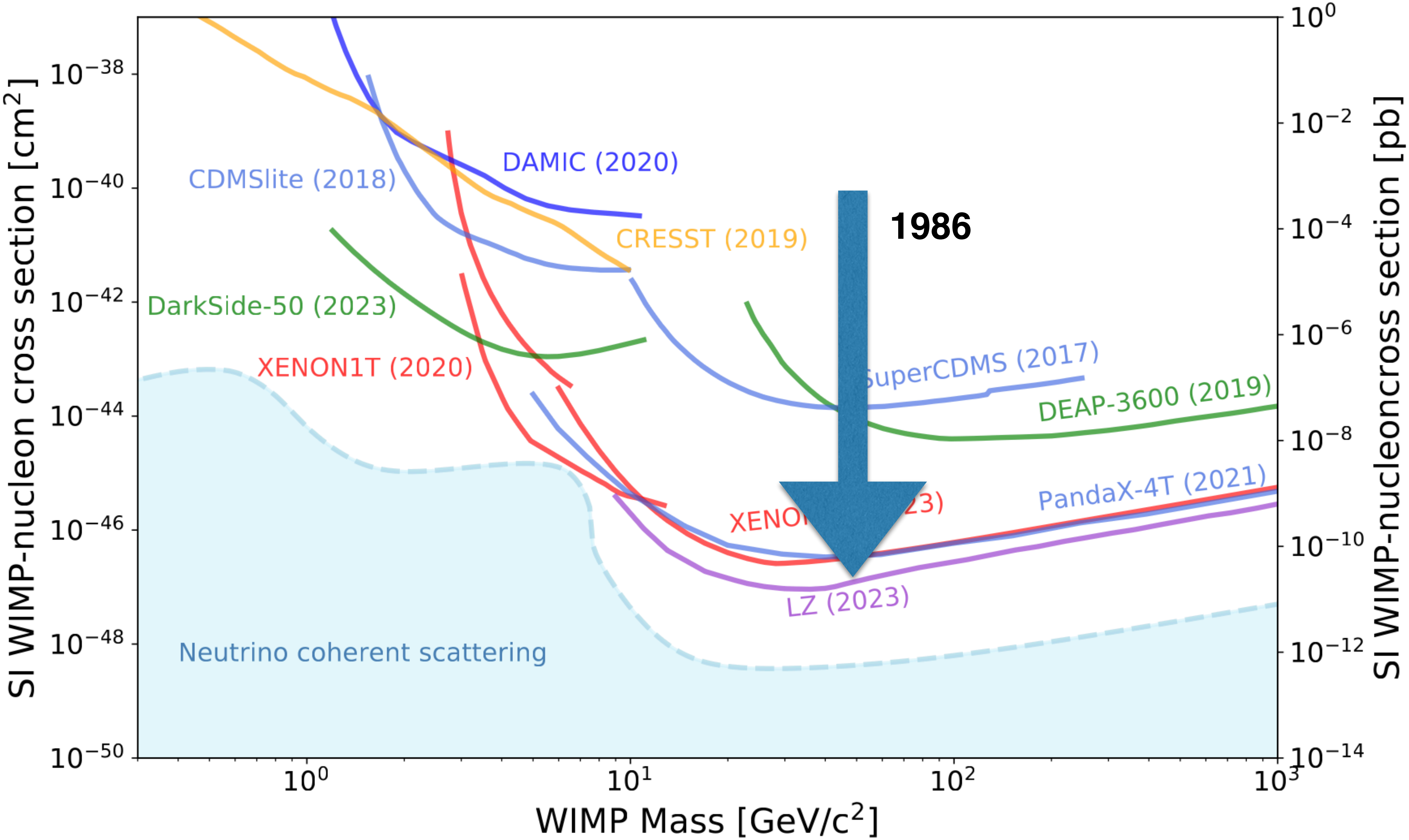
Wimp search : 7 ton active liquid xenon time projection chamber (TPC)

Current limits



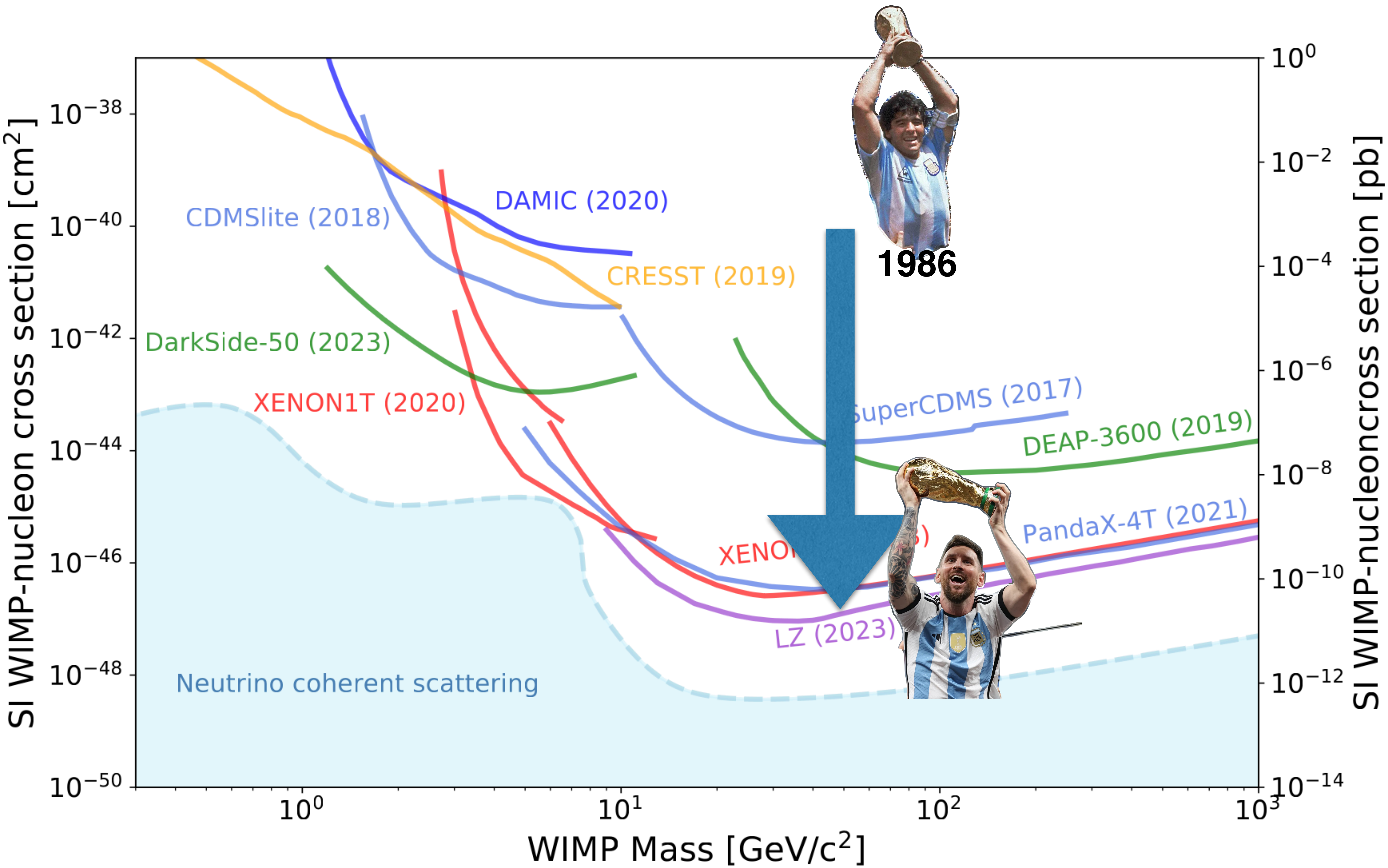
From: pdg.lbl.gov

Lots of progress no signal.



pdg.lbl.gov

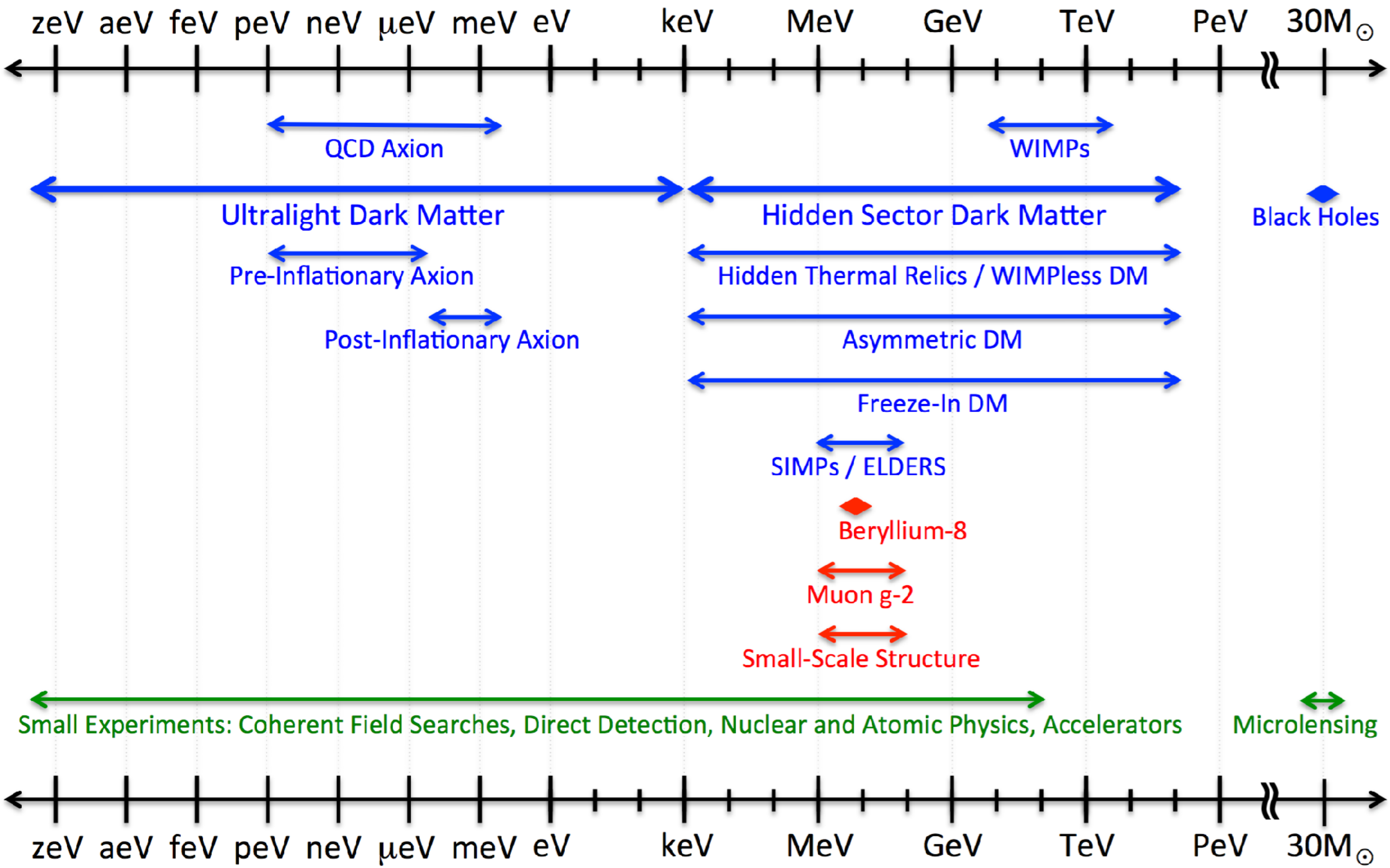
Lots of progress no signal.



pdg.lbl.gov

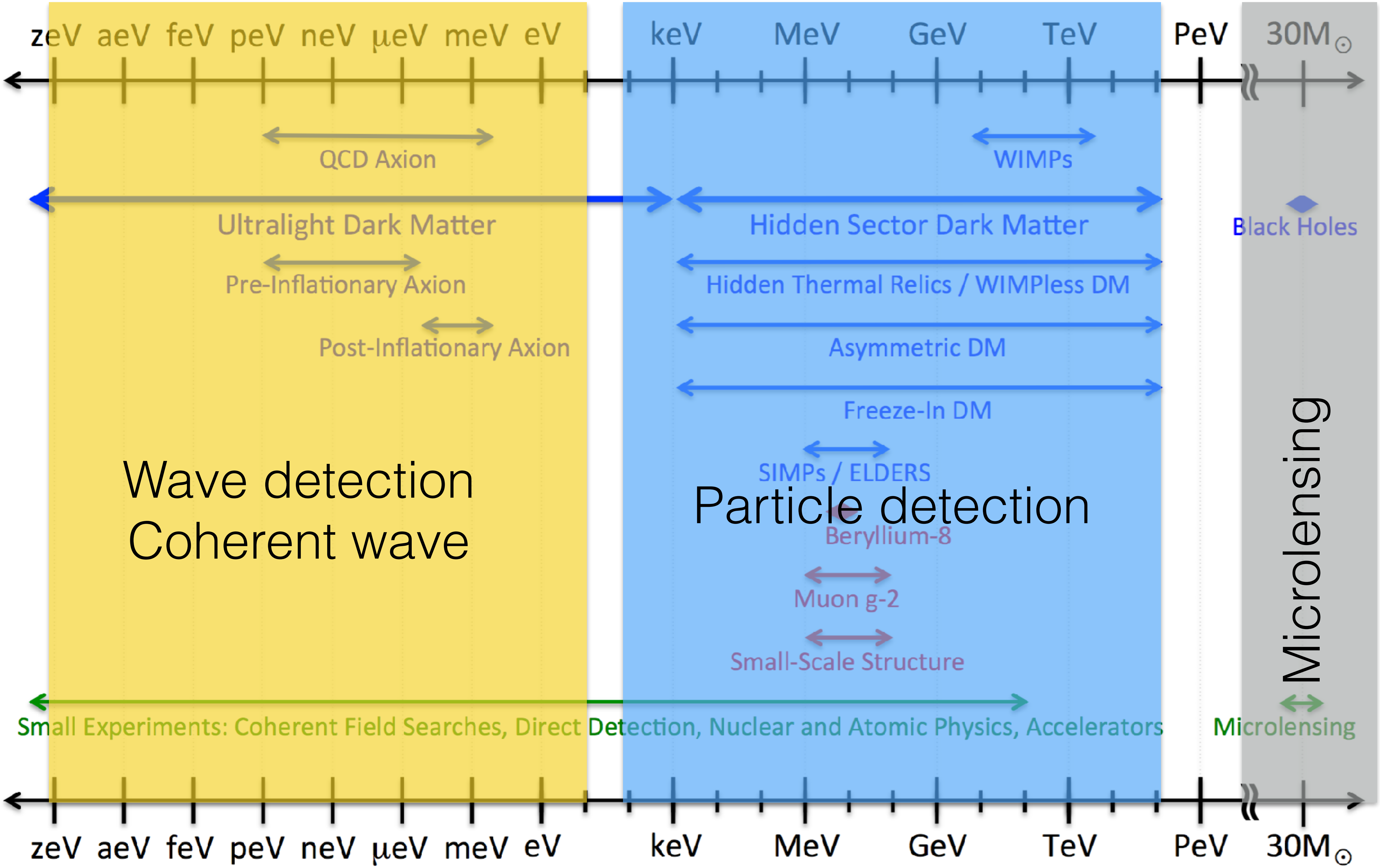
Wider net

More ideas for dark matter … beyond wimps

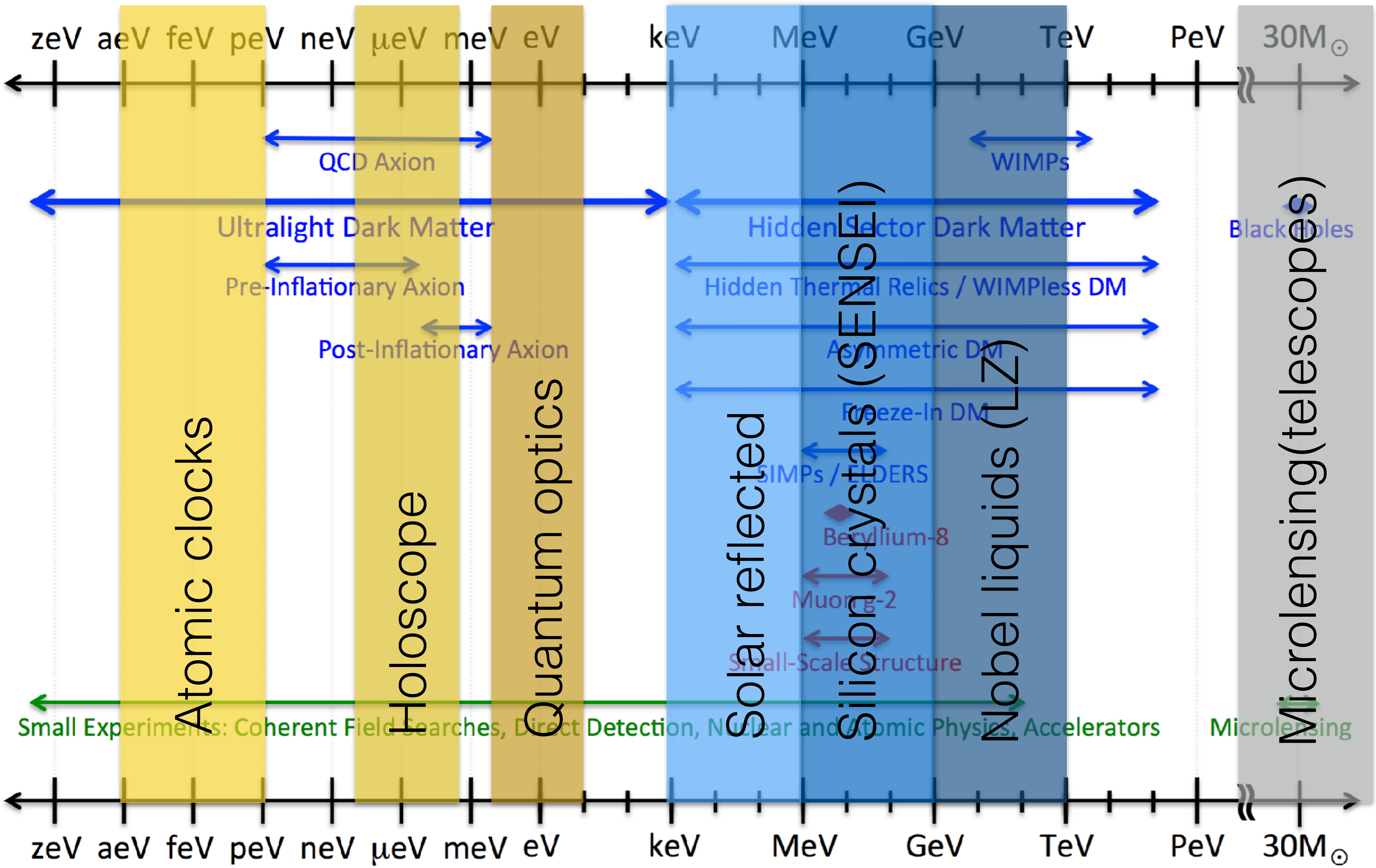


See theory talk by Carlos Yaguna.

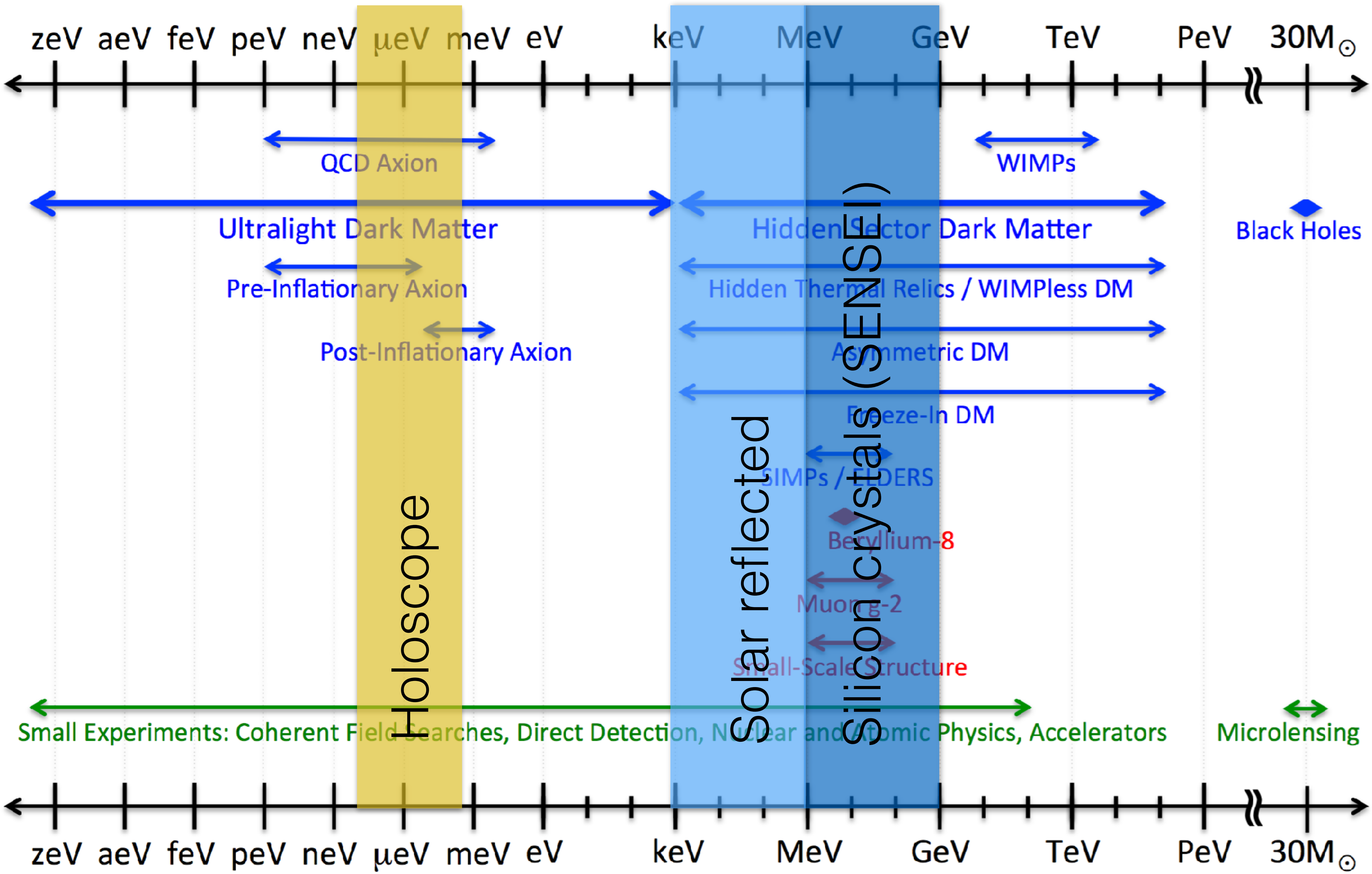
Search tools



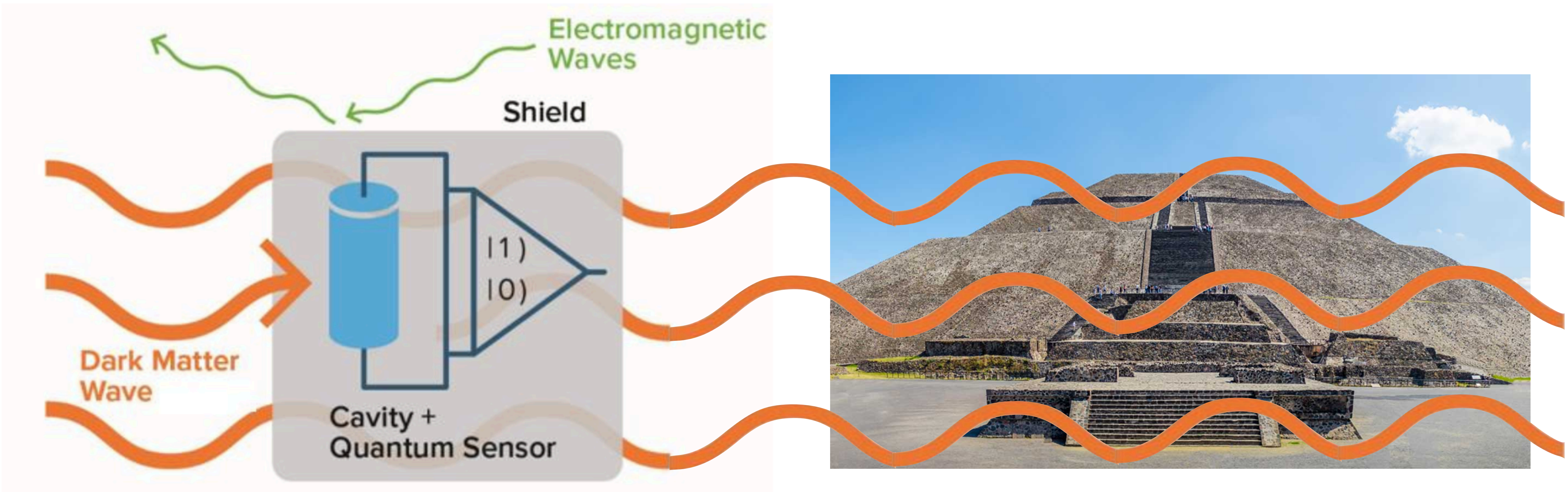
Search tools



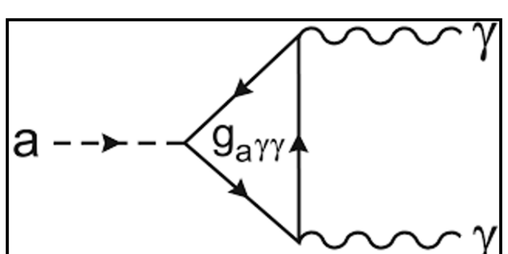
Search tools : will discuss this



Dark wave detection

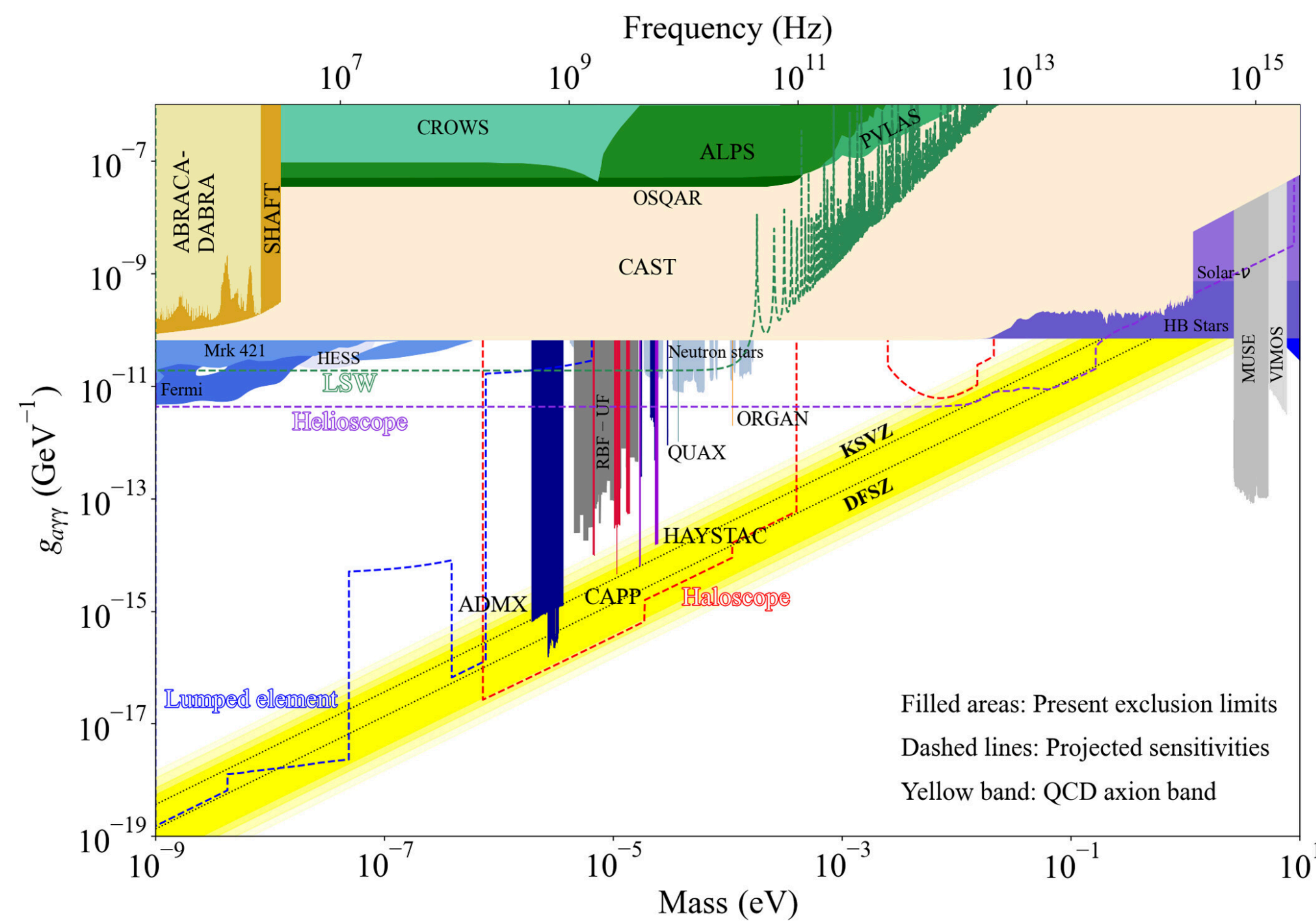


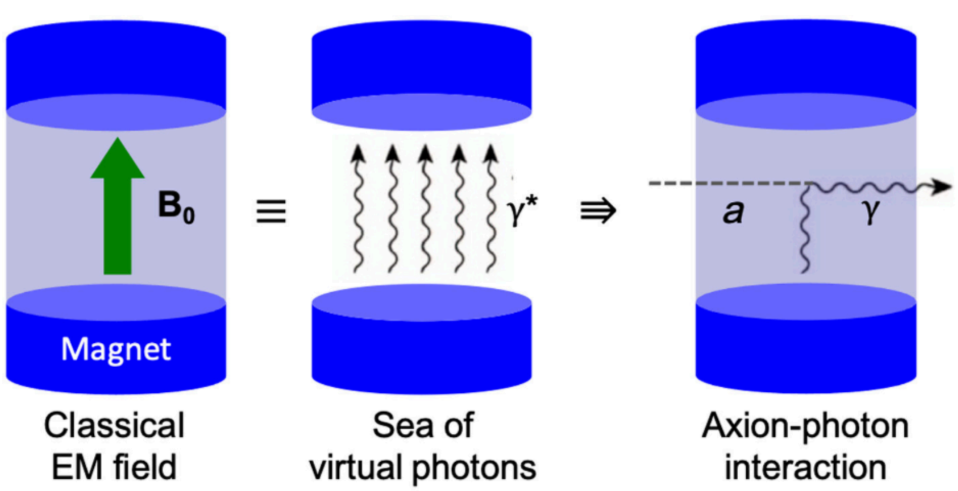
When the DM is light (~20 μeV) it becomes a coherent wave with scale ~100 m. In this case we build detectors that will resonate with this wave…

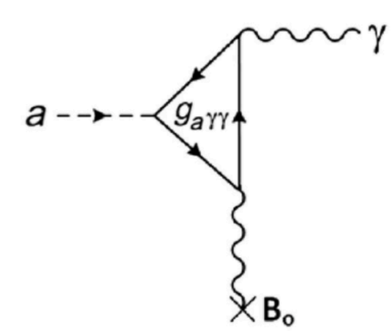


Axions particles couple to magnetic field.

Axion haloscope, uses a strong magnetic field to convert dark matter axions to detectable to microwave photons.





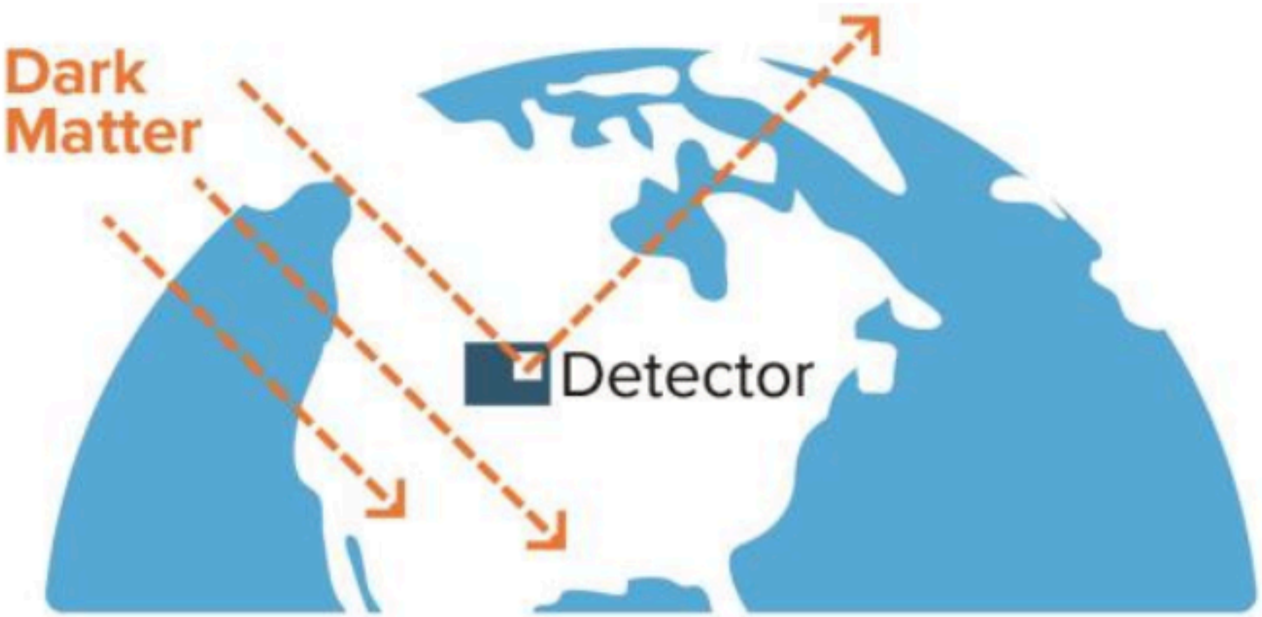


Signal power level = 10^{-23} W

Each tuning ~ 100 s.
Obtain 10^4 spectra of 100 Hz resolution spanning the 20 kHz cavity bandwidth. Tune cavity frequency slightly and repeat.

SCIENCE ADVANCES 23 Feb 2022 Vol 8, Issue 8

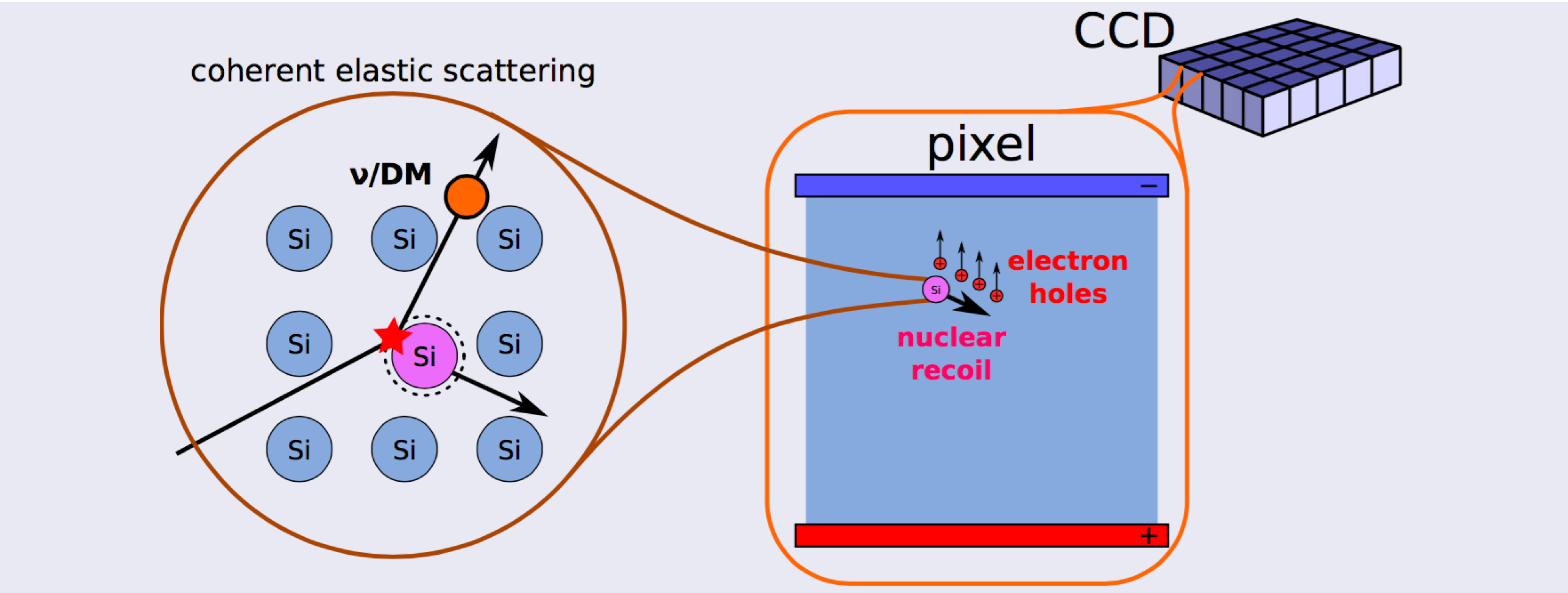
Dark particle detection



As DM becomes heavier, we look for particles hitting our detector.

LZ discussed before is an example of particle detection (WIMPS), but here will focus on lower masses (<1 GeV).

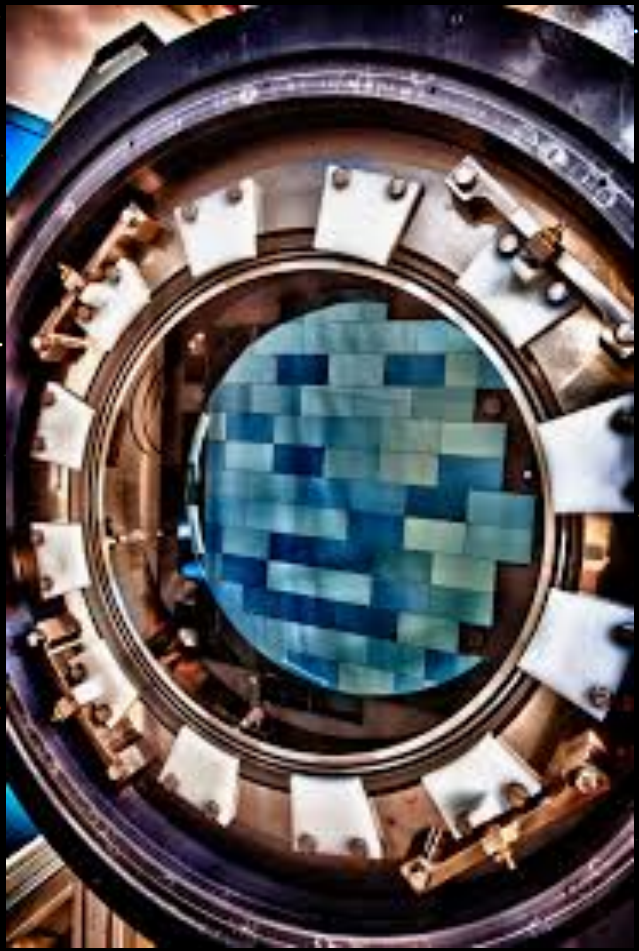
Direct Dark Matter search in CCDs (DAMIC) started with strong LA participation!



DAMIC held its first collaboration meeting at UNAM in 2013. Mexico, Paraguay, and Argentina were early supporters of this technology as a tool for dark matter.

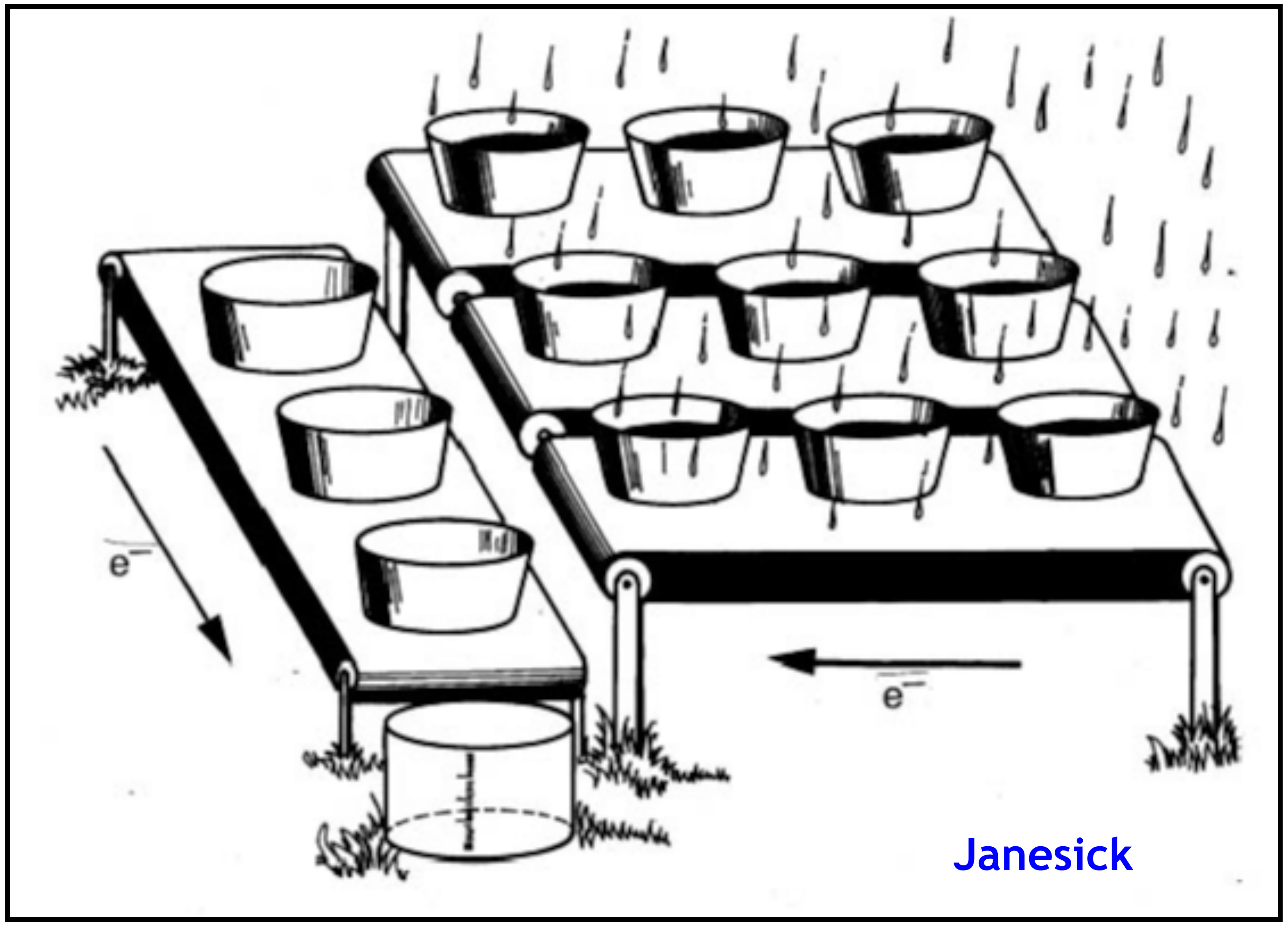
LA groups accepted risk of an unproven technology.

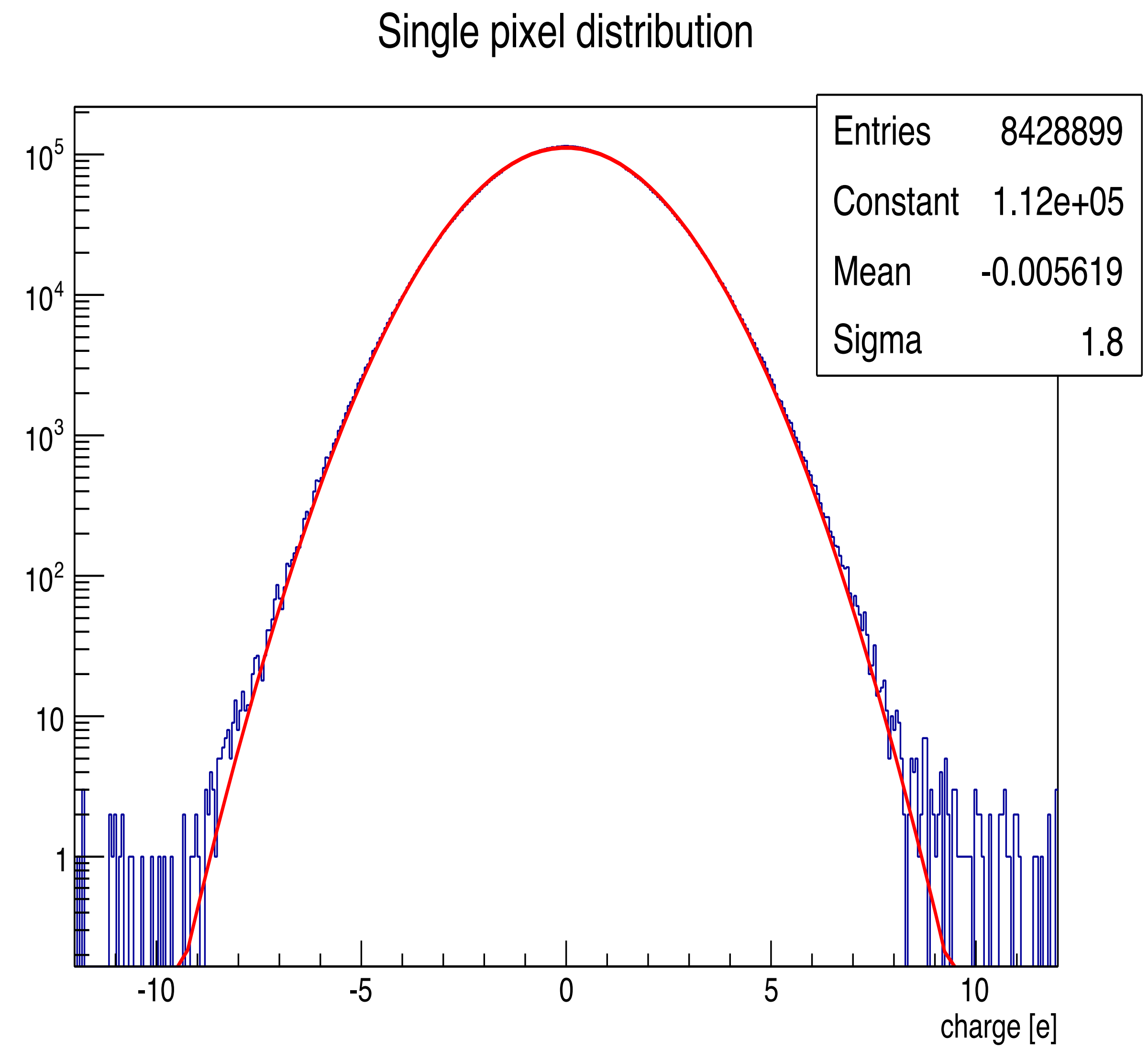
Tuesday talk on Dark Energy Survey



When building DES, we realized the sensors could be also used for direct dark matter. (Same techonology than DESI)

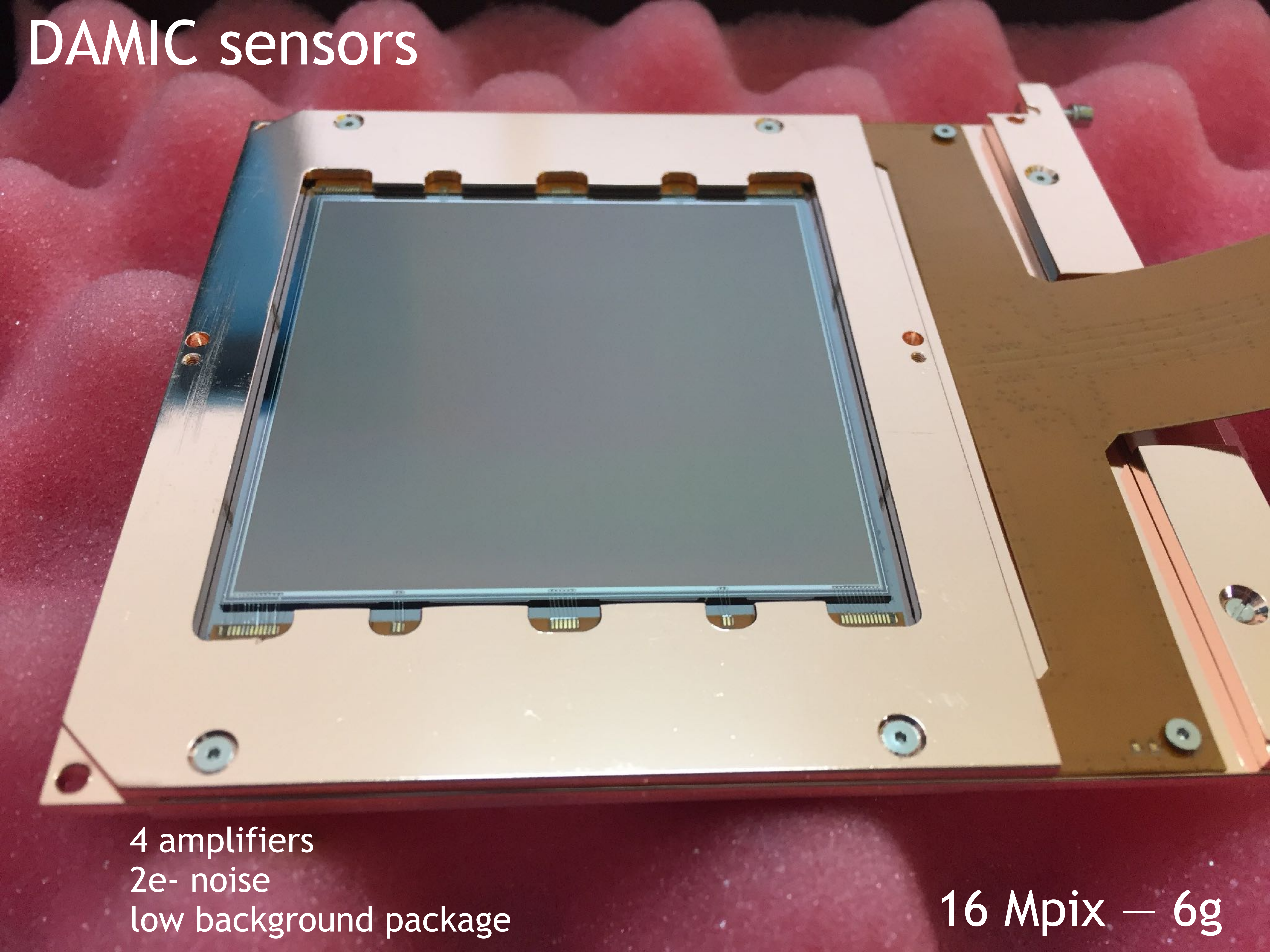
Charge-Coupled Device (CCD)





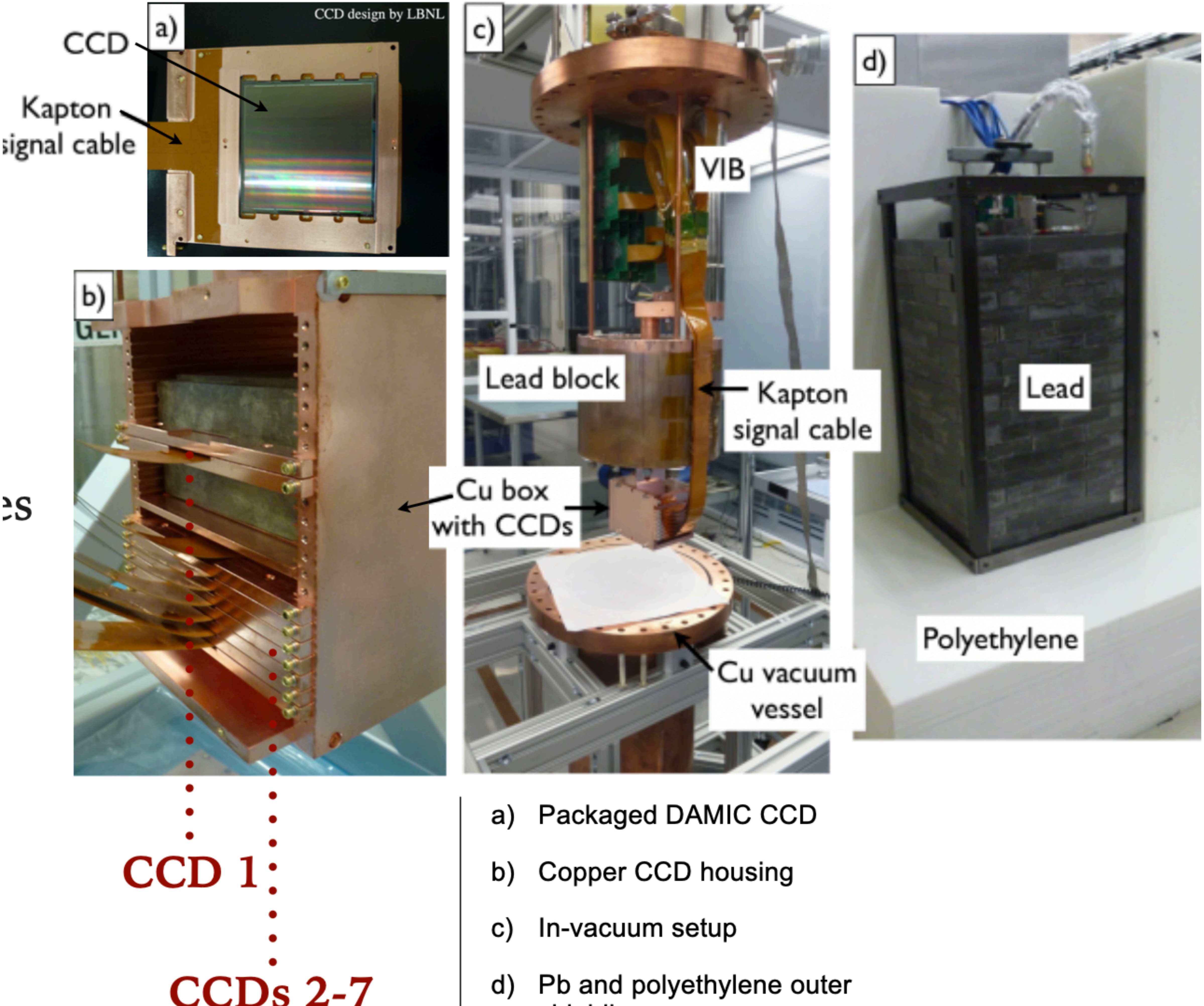
Charge coupling makes the detectors **ideal for low noise** measurements, typical noise for scientific CCDs is 2e- RMS (7.2eV). In DES, we had to make **"massive"** thick detectors to see the near IR.

DAMIC sensors



4 amplifiers
2e- noise
low background package

16 Mpix — 6g



a) Packaged DAMIC CCD

b) Copper CCD housing

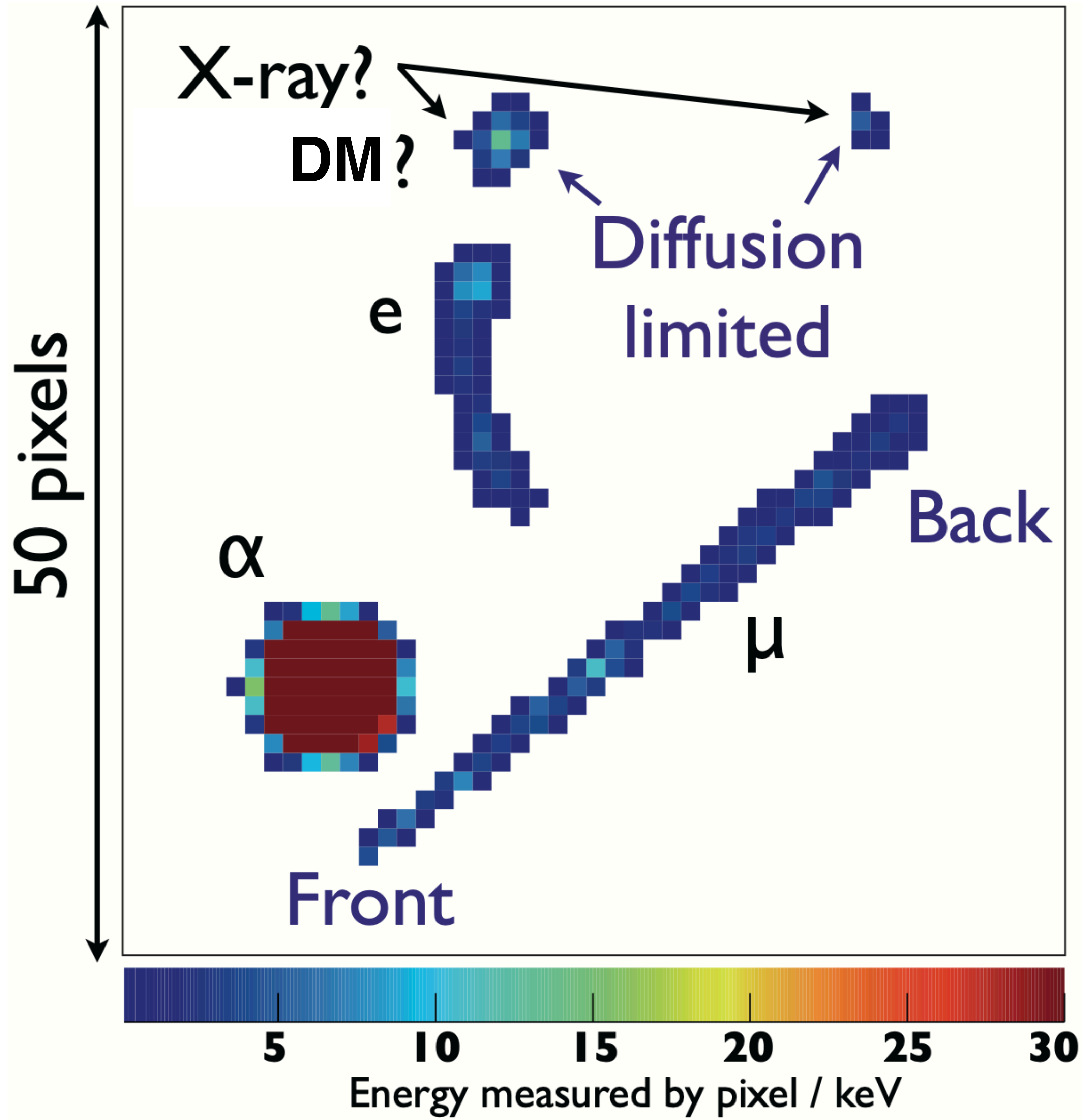
c) In-vacuum setup

d) Pb and polyethylene outer shielding

Jorge Molina (current government minister in Paraguay) working on the early deployment of DAMIC at SNOLAB.

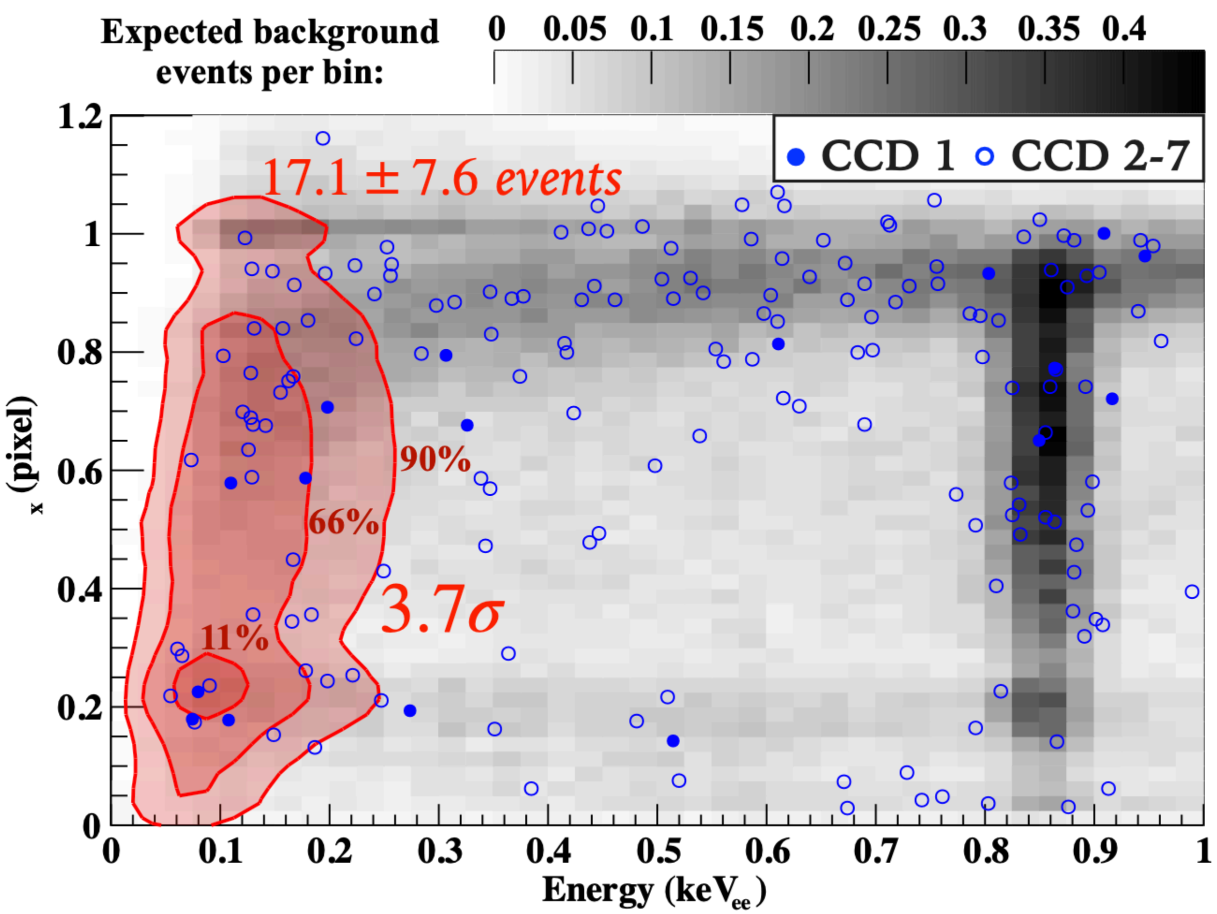
Lesson: Dark Matter gives you many job opportunities….

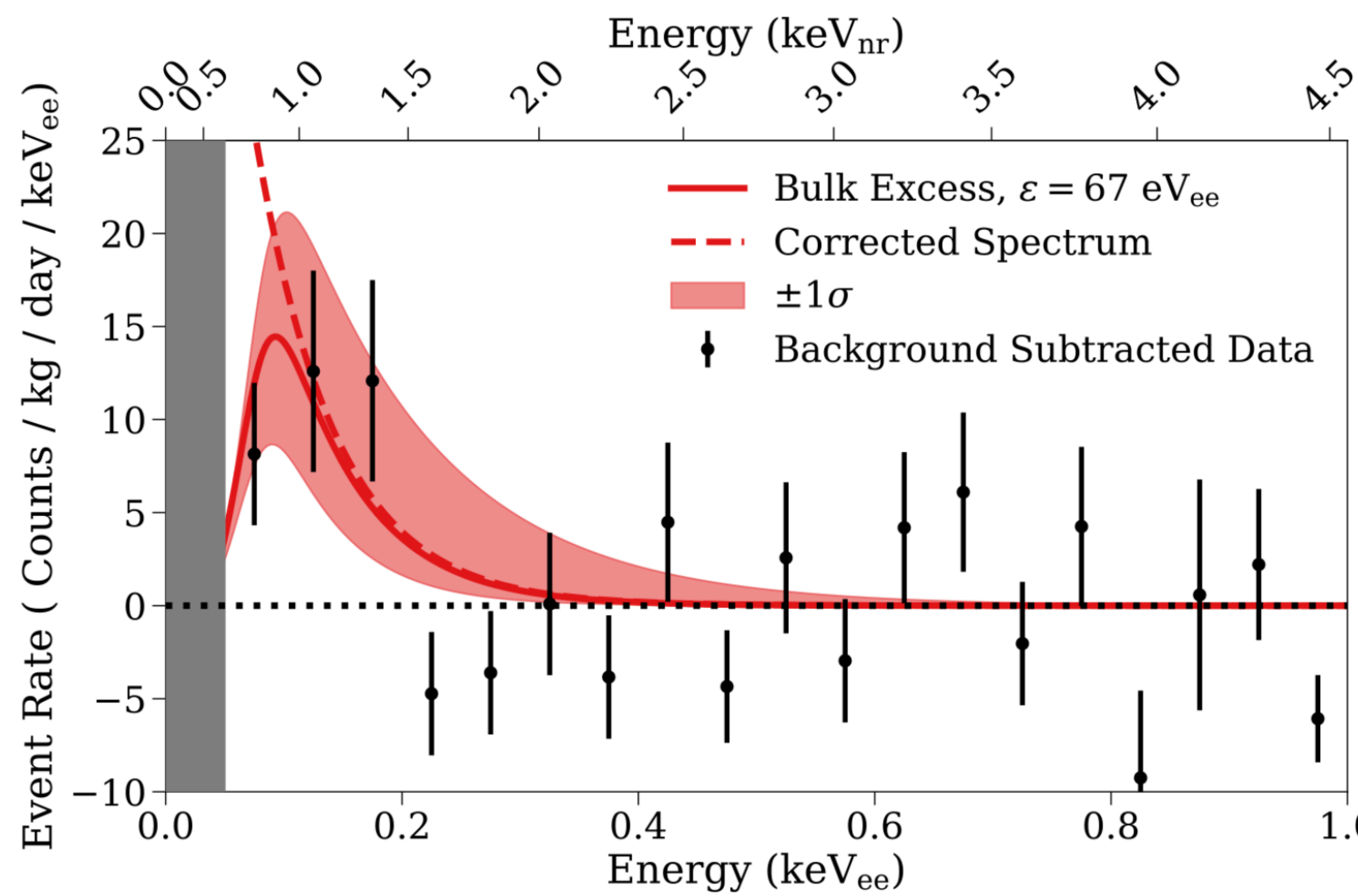
Particle ID with CCDs



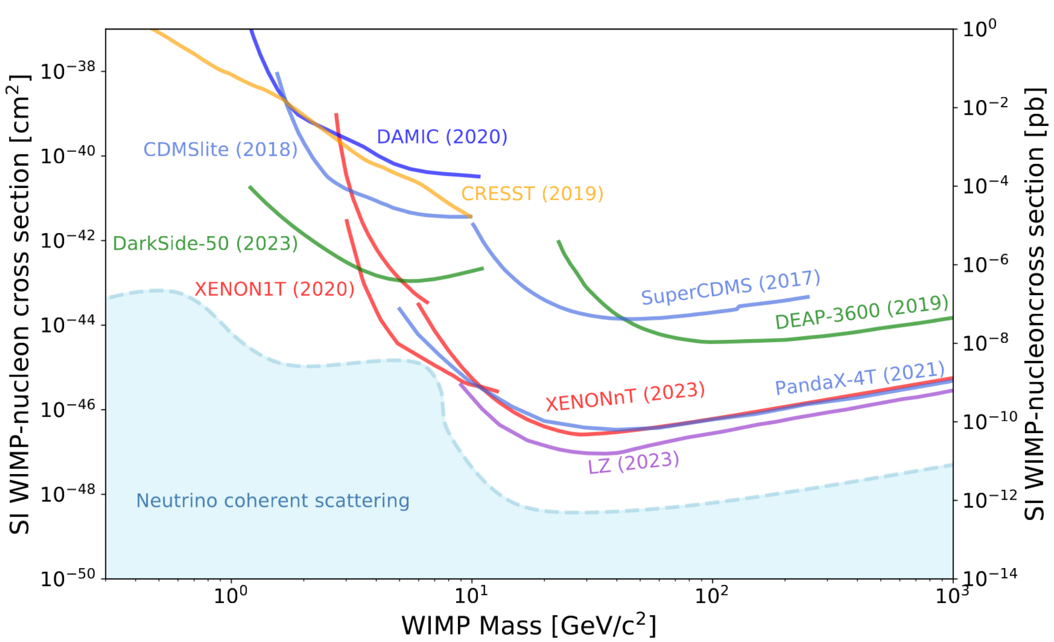
DAMIC Result
11 - kg-day

Phys. Rev. Lett. **125**, 241803 (2020)





......



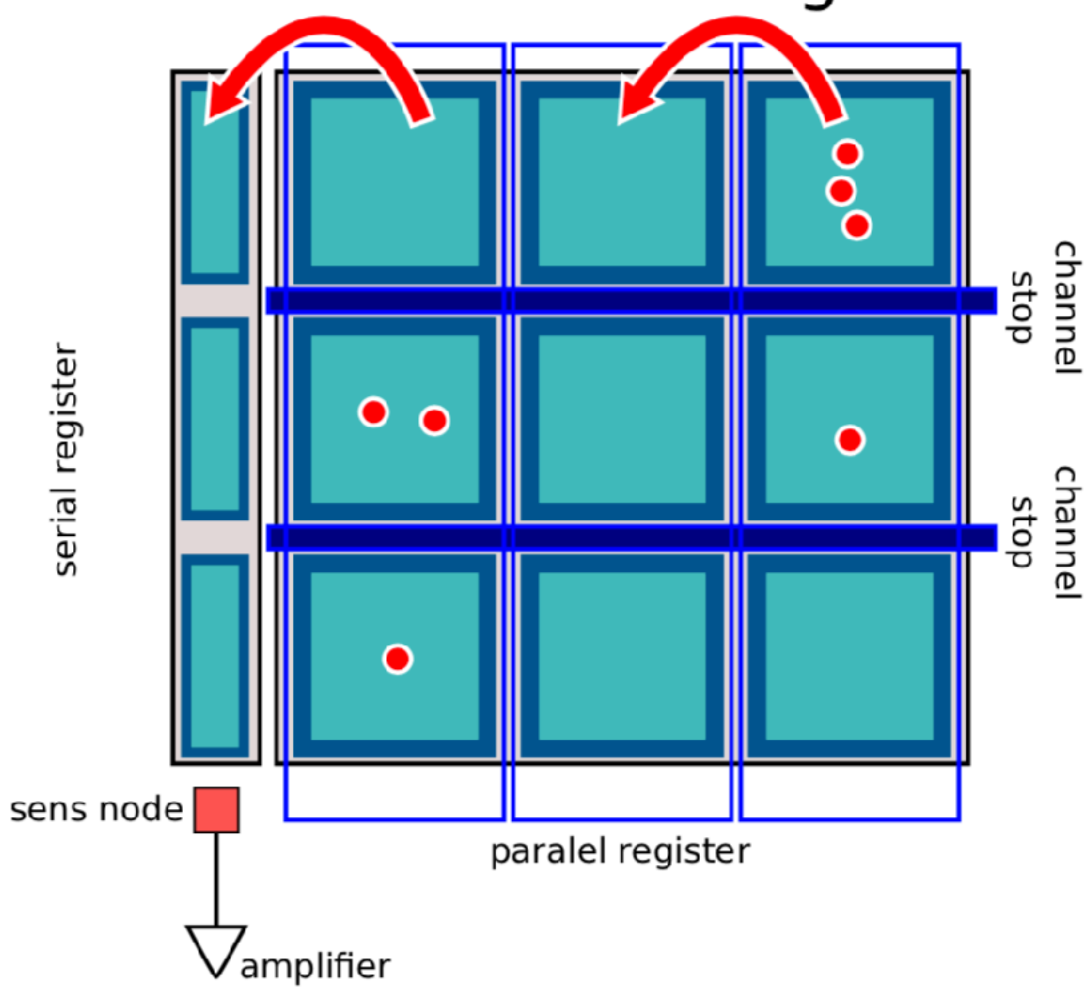
There is an excess on the bulk that we cannot explain. Need more sensitive detectors to understand (more mass + lower threshold)

skipper-CCDs

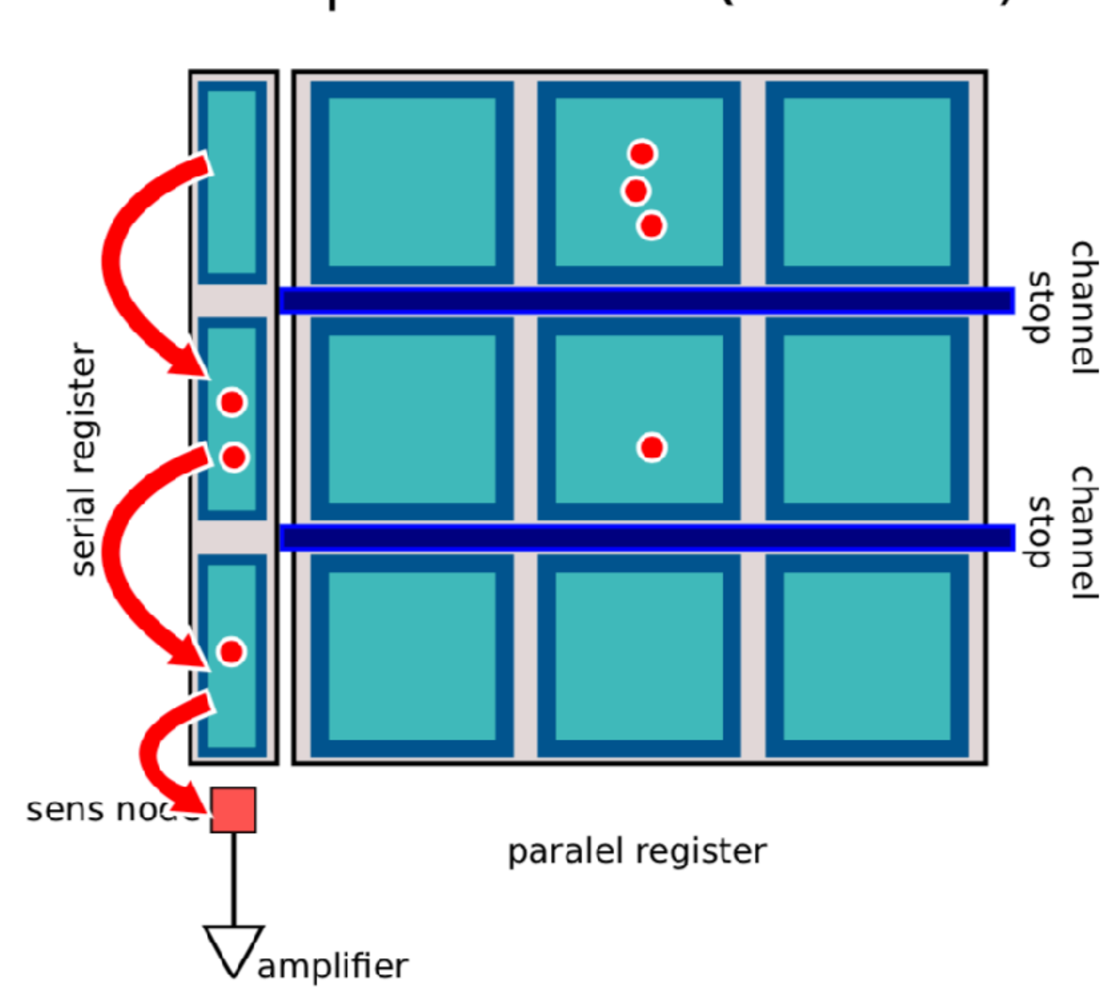
Reduction of the CCD noise by force!

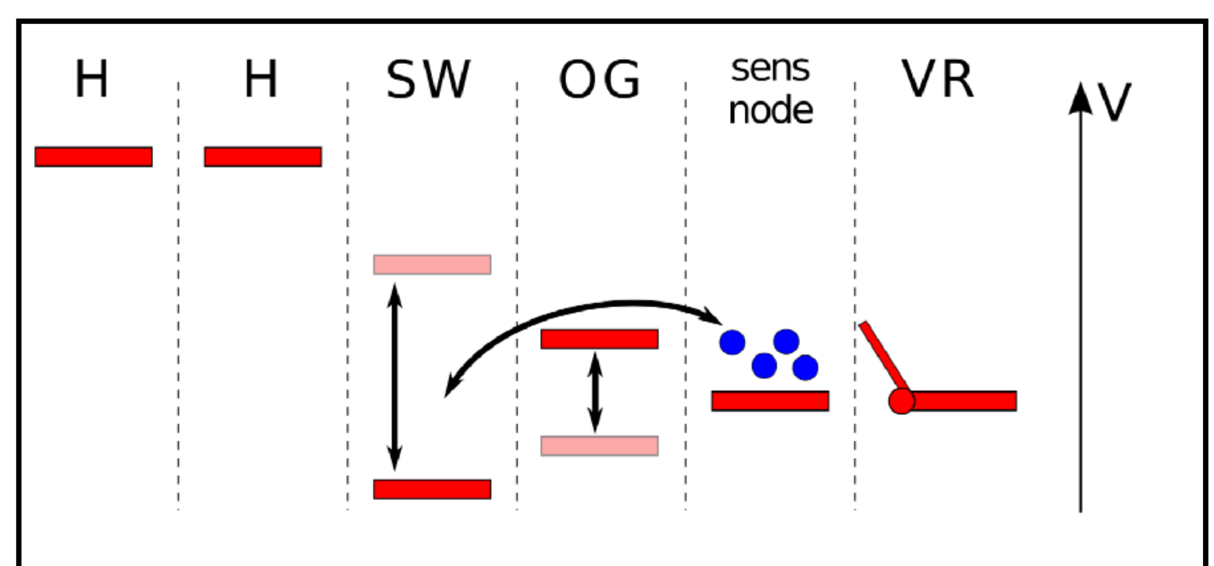
The skipper-CCD is a modification of the output stage of a CCD (Janesik et al -1990). It allows for multiple non-destructive readout of the charge in a pixel.

Shift charge one column to tha right

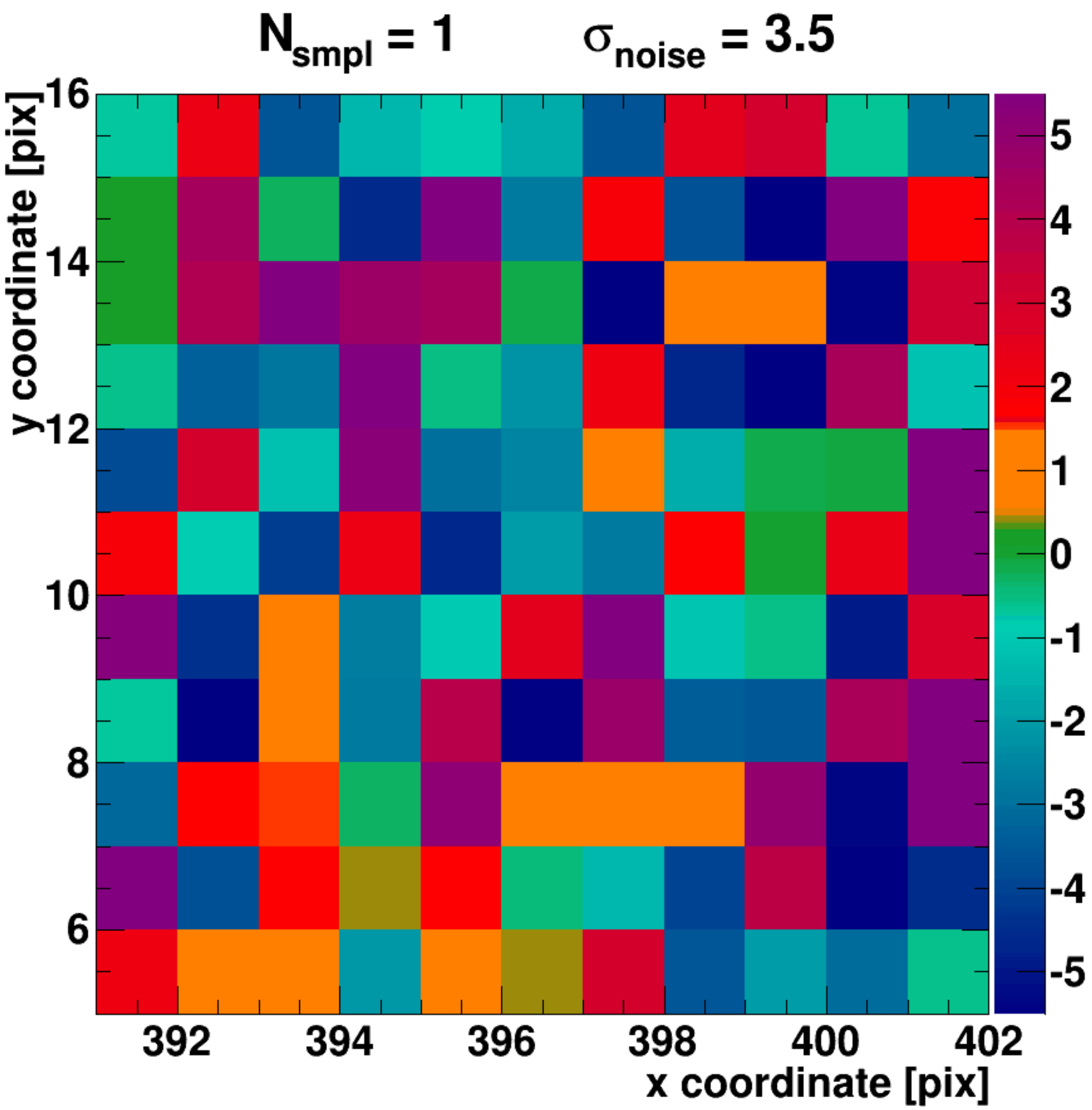


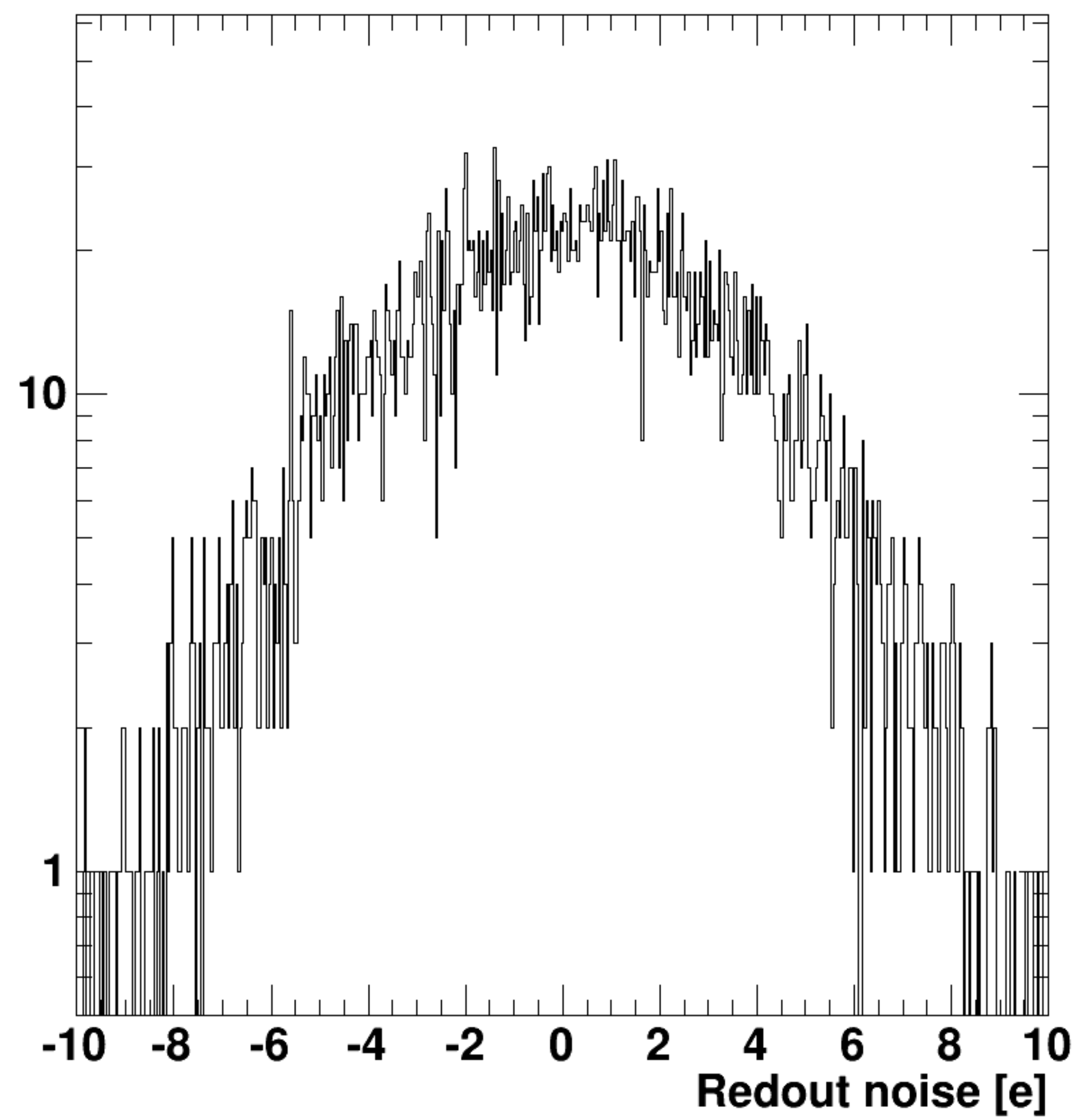
Shift charge in serial register one pixel down (3 times)



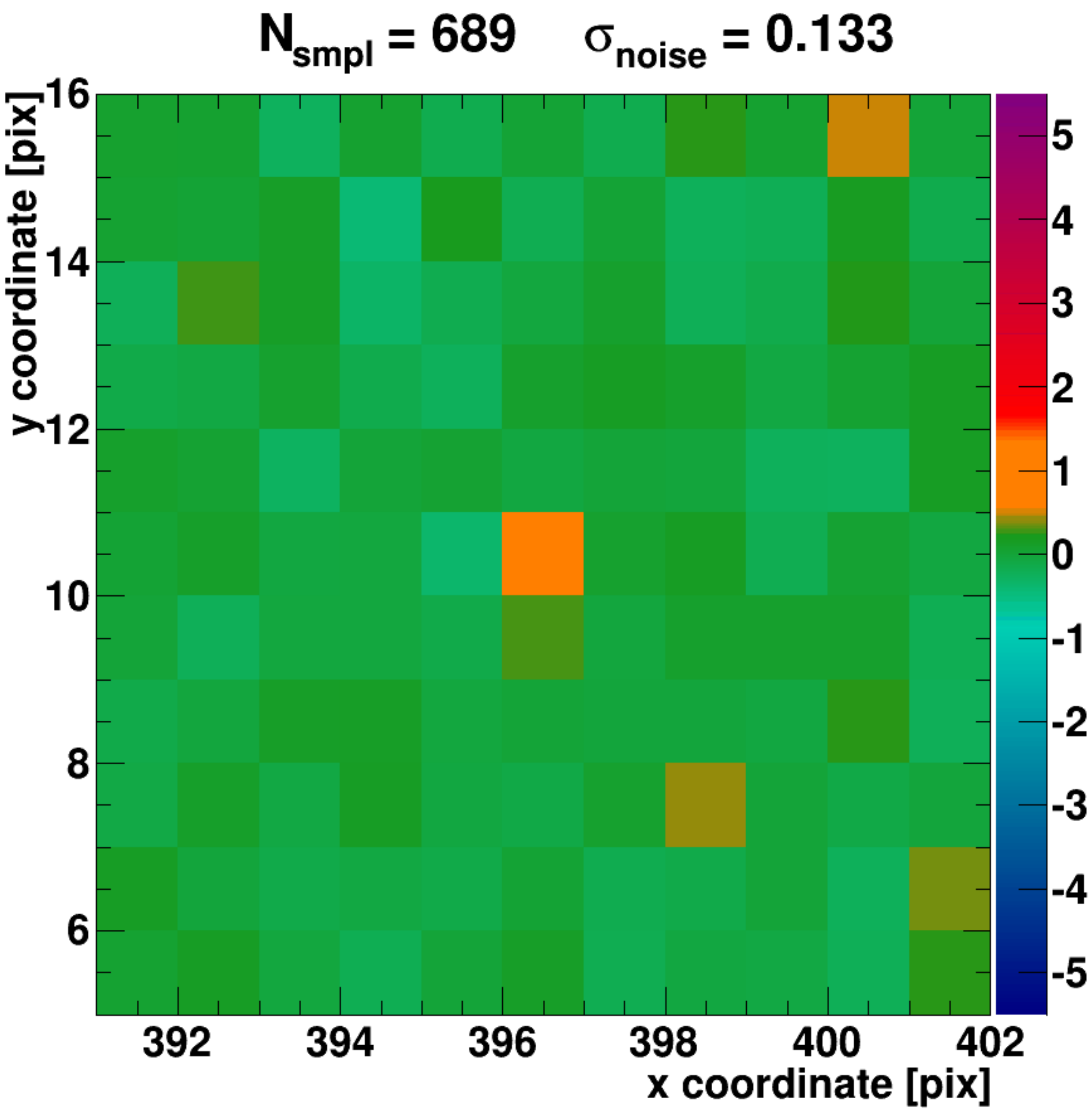


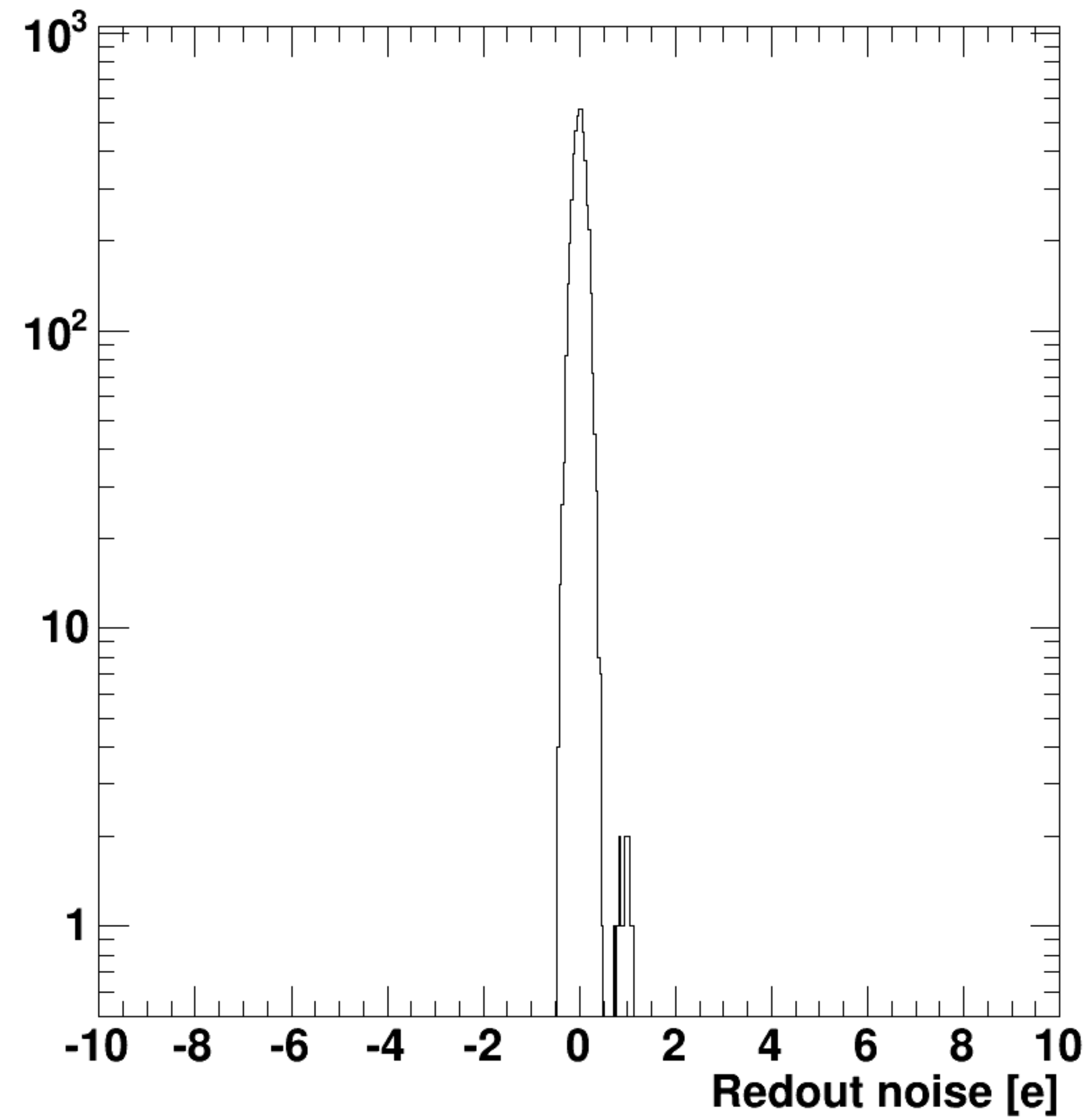
the new skippers



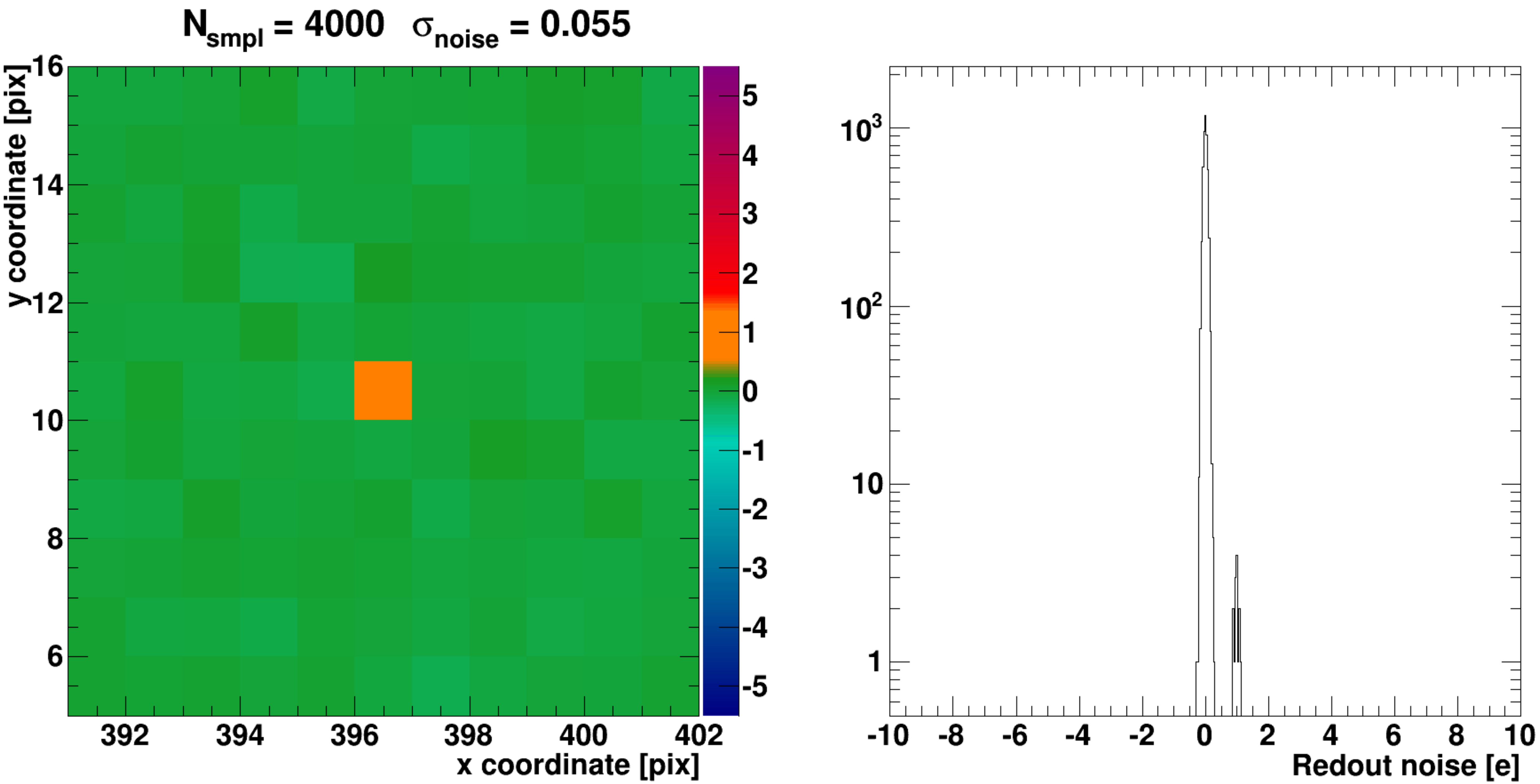


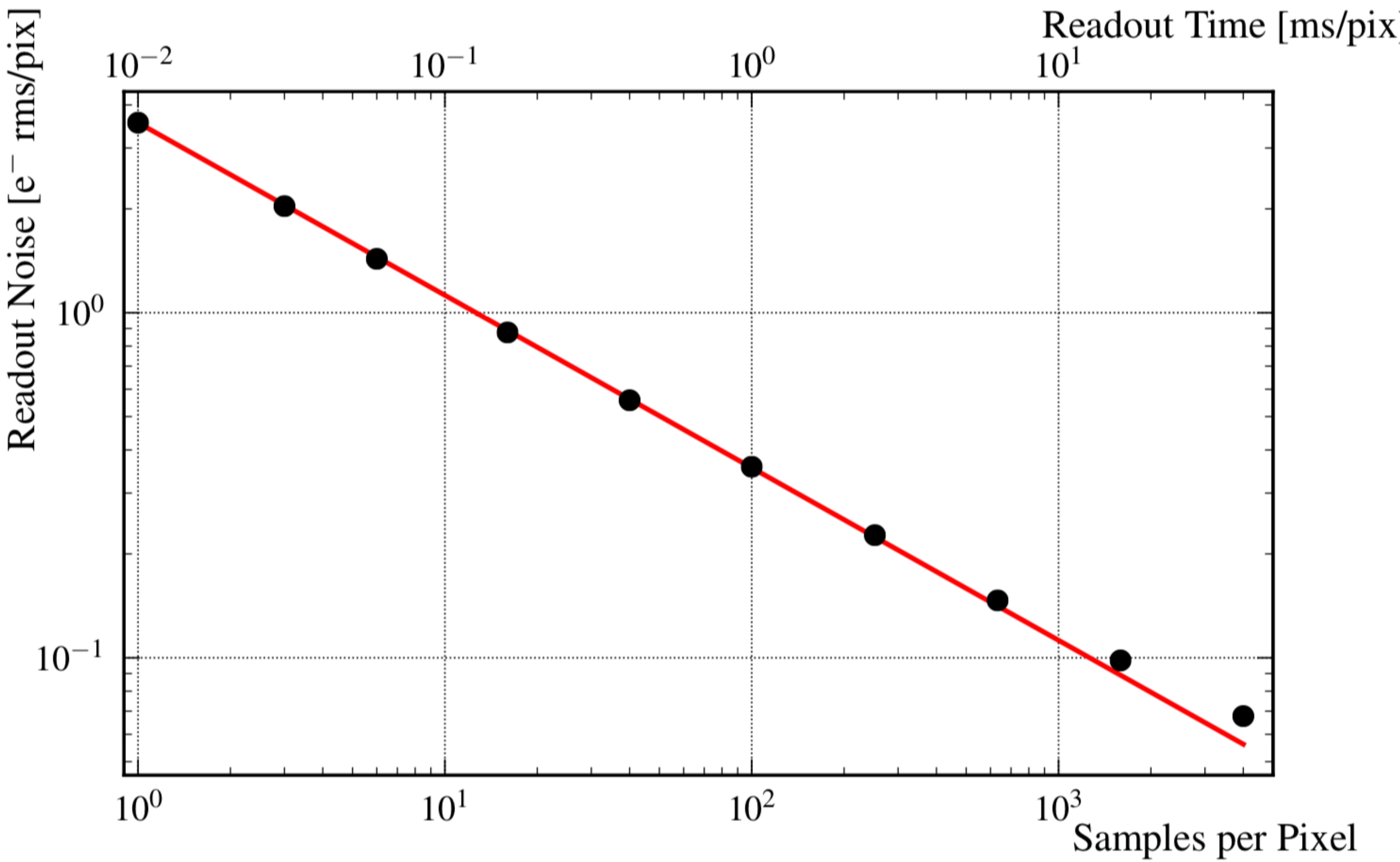
the new skippers





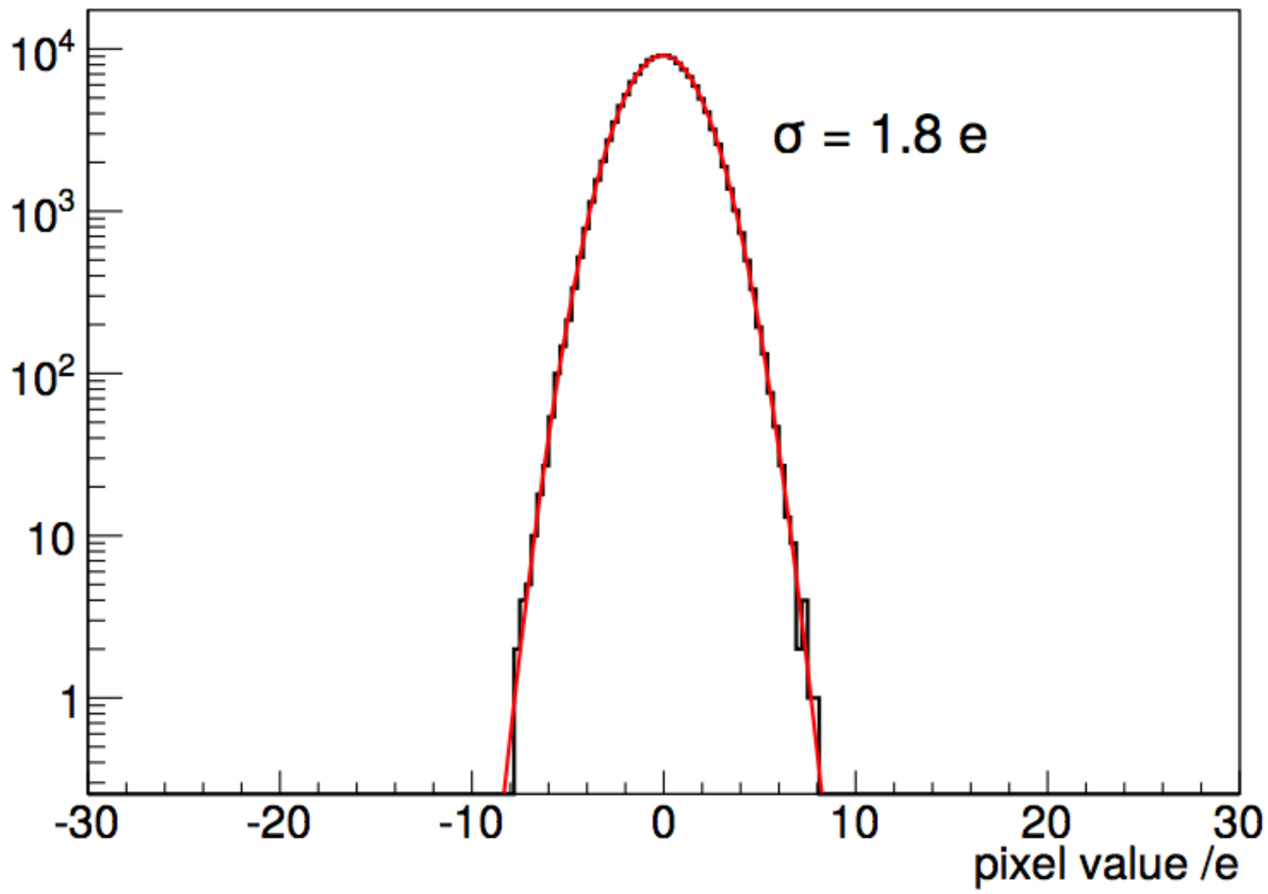
the new skippers



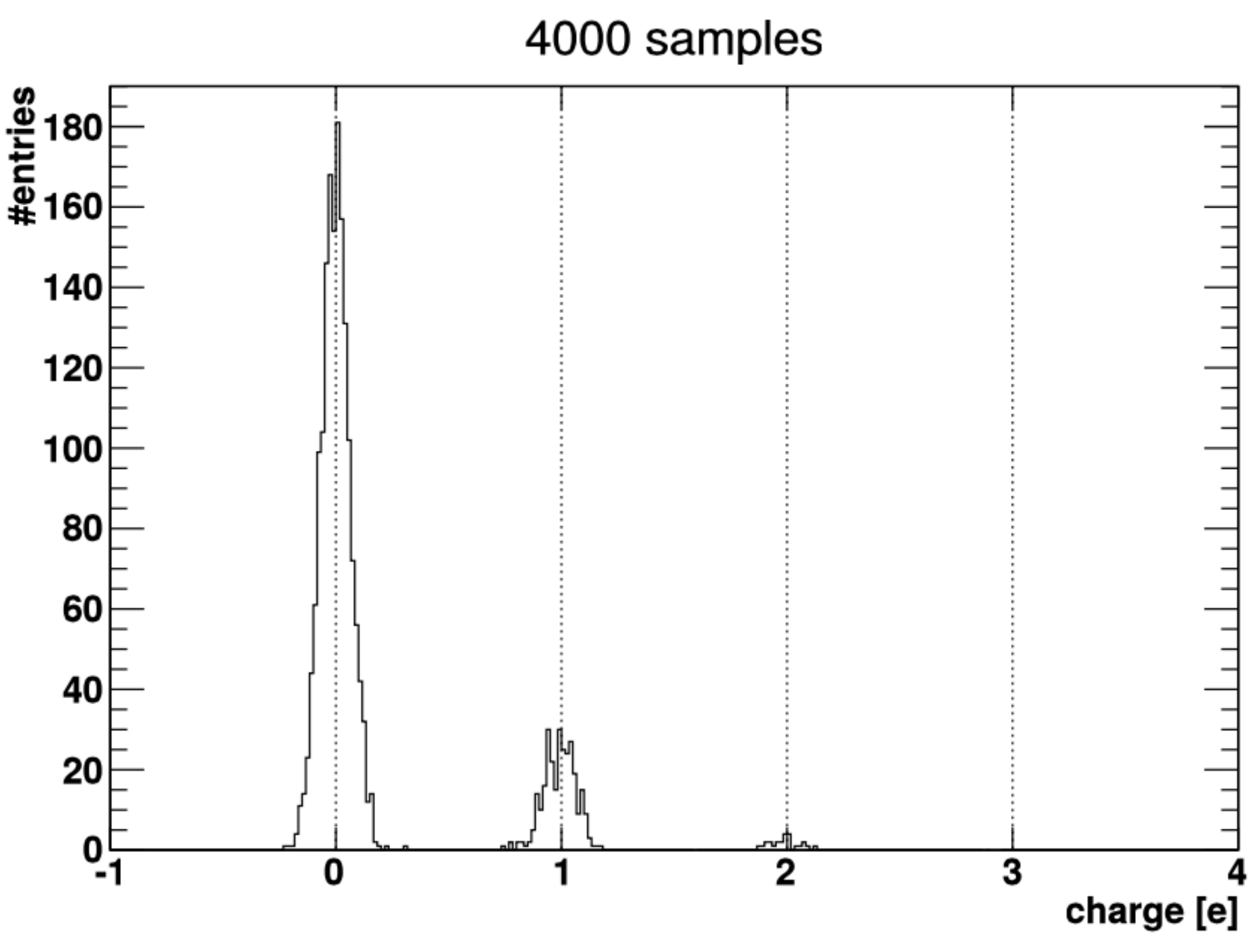


Readout Time [ms/pix]
10^{-2}
10^{-1}
10^{0}
10^{1}
Readout Noise [e^{-} rms/pix]
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Samples per Pixel

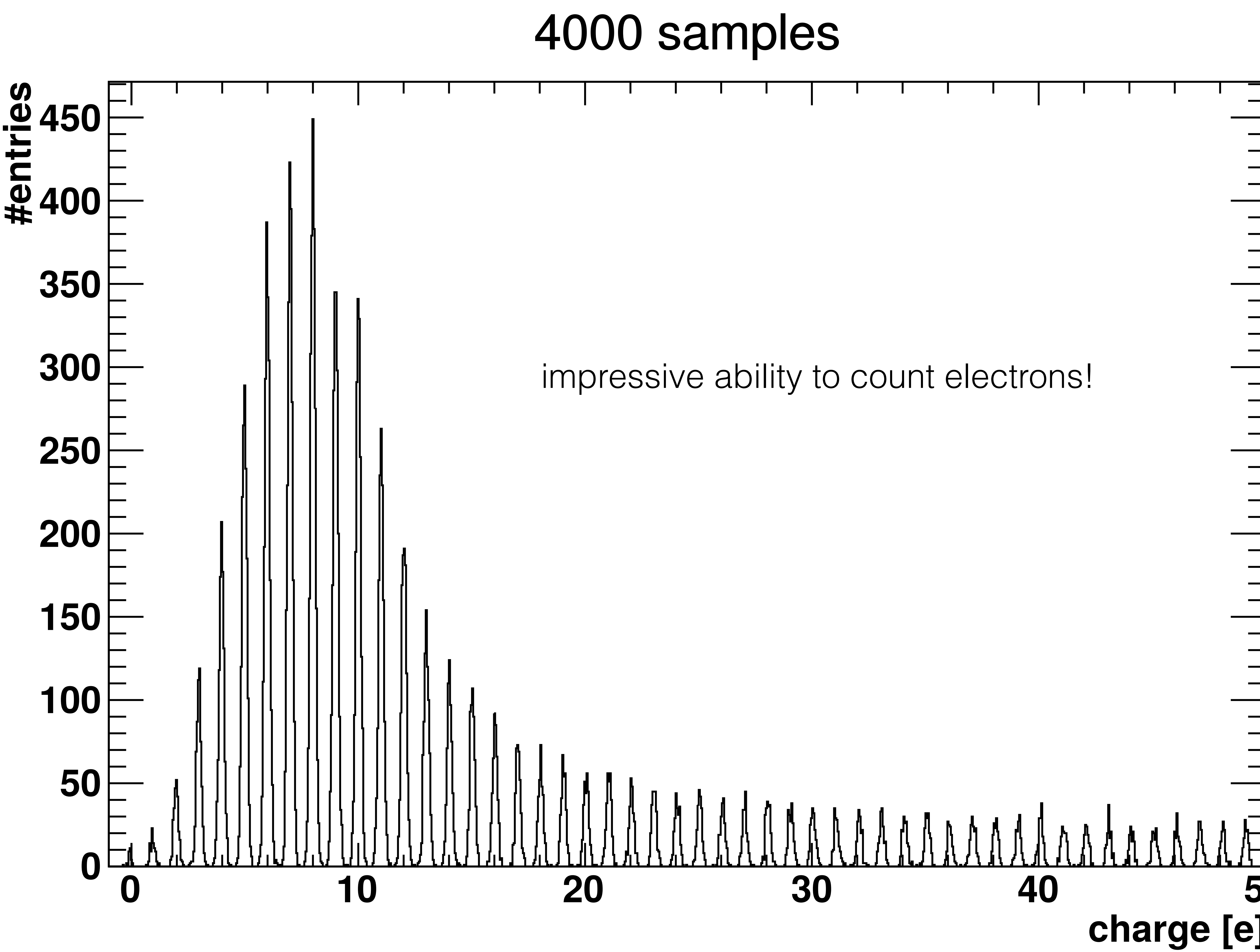
DAMIC 2014



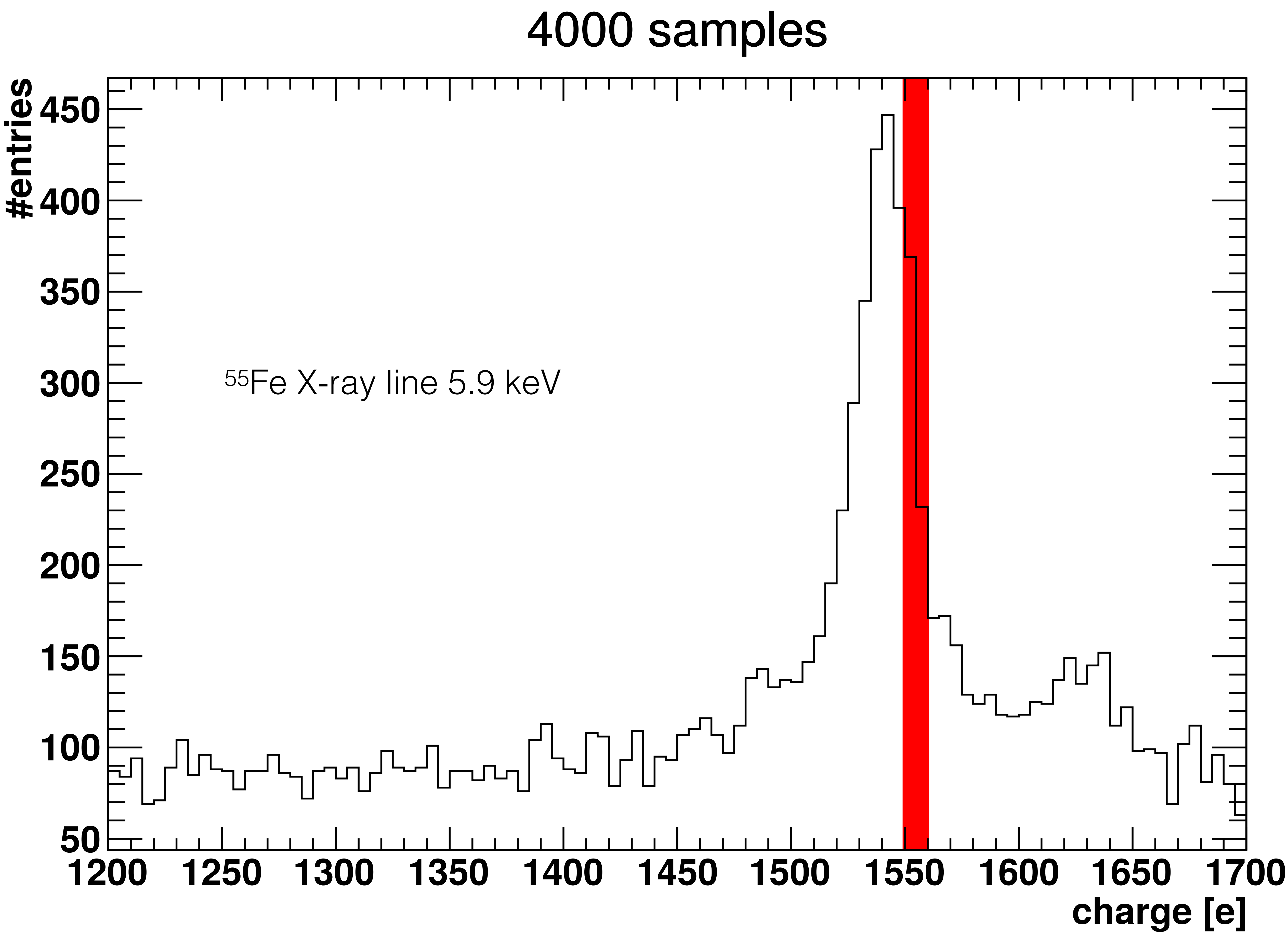
skipper CCD
SENSEI
DAMIC 2021

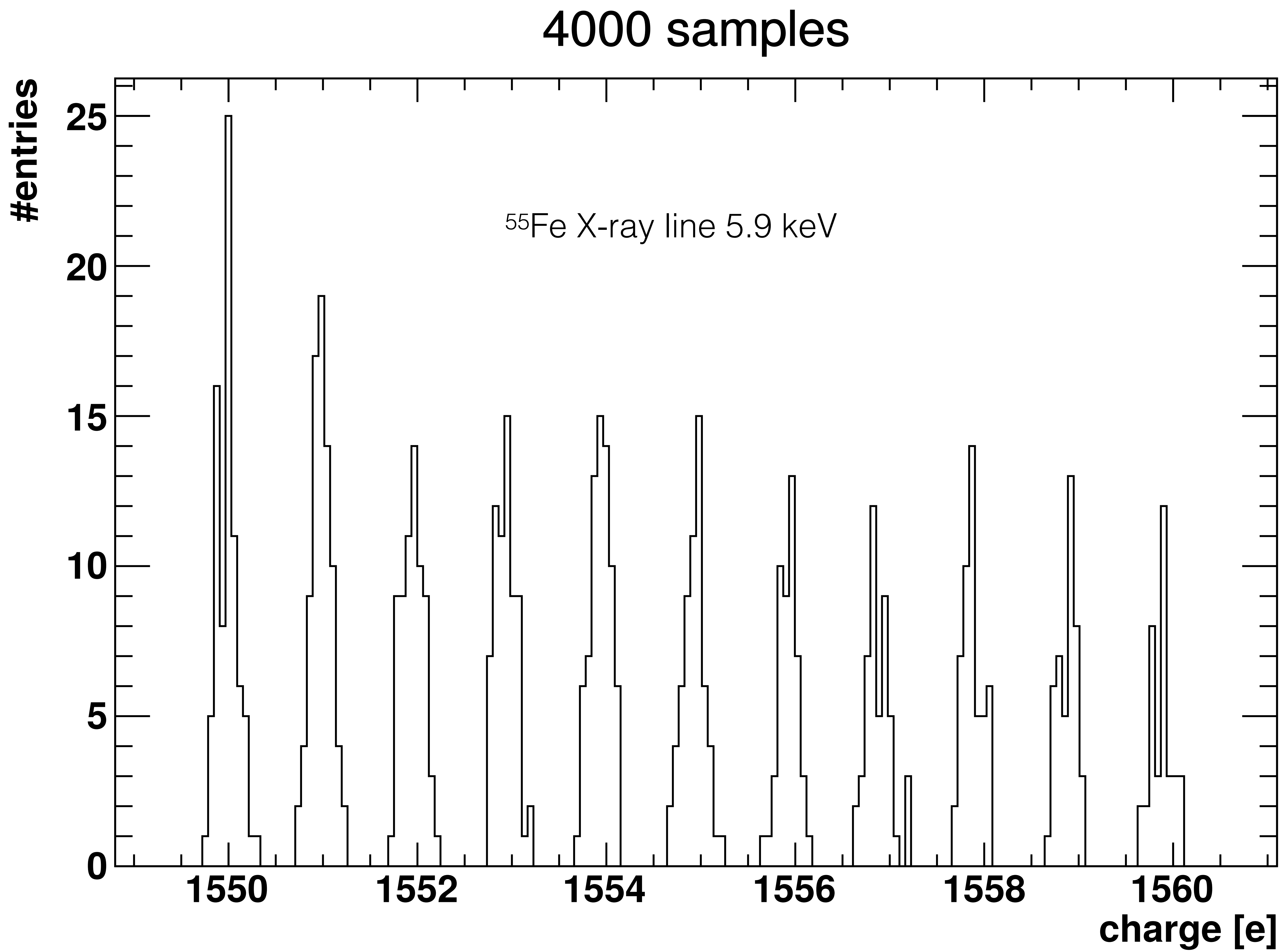


Designed ~30 years ago, and sleeping. Sensors designed by LBNL (Steve Holland),first demonstrated summer 2017 by Javier Tiffenberg et al (arXiv:1706.00028) allows reduction of the noise by 10.



4000 samples
#entries
charge [e]
impressive ability to count electrons!
0
50
100
150
200
250
300
350
400
450
0
10
20
30
40
50


4000 samples
#entries
450
400
350
300
250
200
150
100
50
55Fe X-ray line 5.9 keV
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
charge [e]


4000 samples
#entries
25
20
15
10
5
0
55Fe X-ray line 5.9 keV
1550
1552
1554
1556
1558
1560
charge [e]

skipper-CCDs for DM, is a LA development:

- 2012 paper by Guillermo Fernandez-Moroni (student from Universidad Nacional del Sur, Argentina). Fernández Moroni, G. Exp Astron 34, 43–64 (2012).

- 2017 papert by Javier Tiffenberg. The firt student who got the first result working with Javier is Miguel Sofo-Haro (Bariloche, Argentina). IEEE award for Miguel.

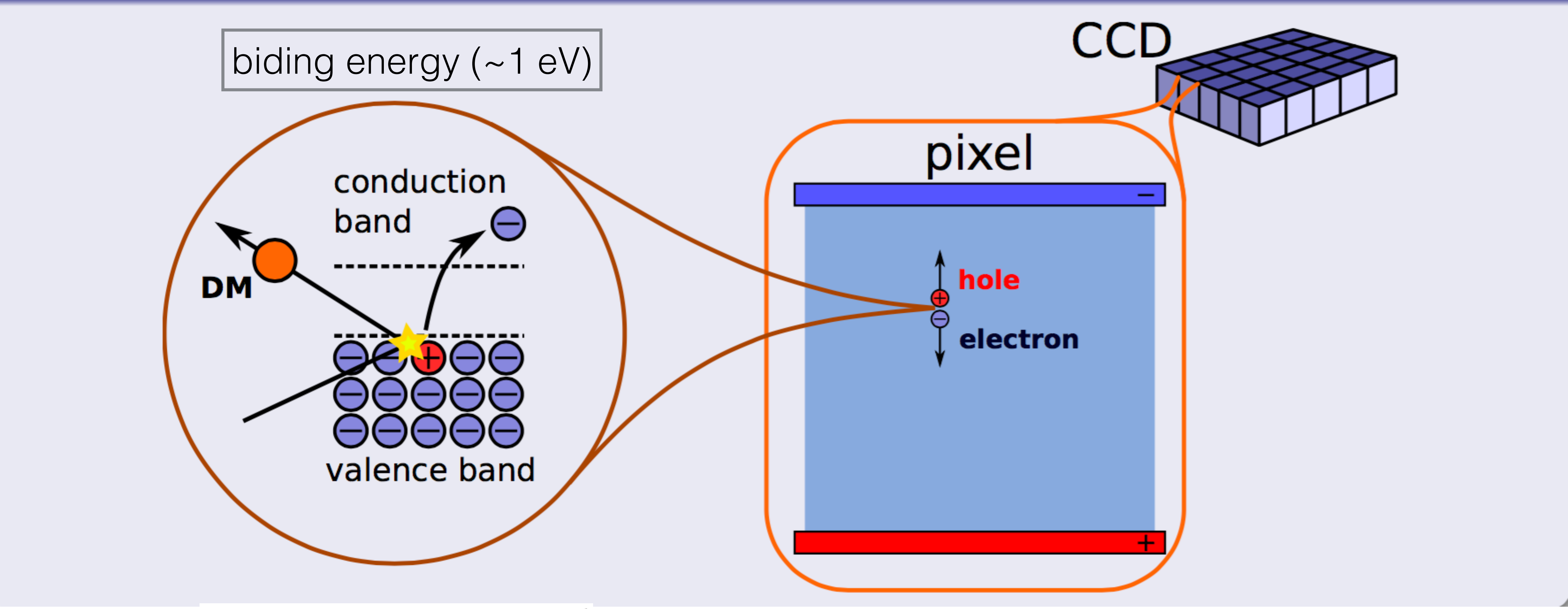
- Now 3 skipper-CCD experiments running in Argentina (DM2, Atucha reactor) and Brazil (CONNIE).

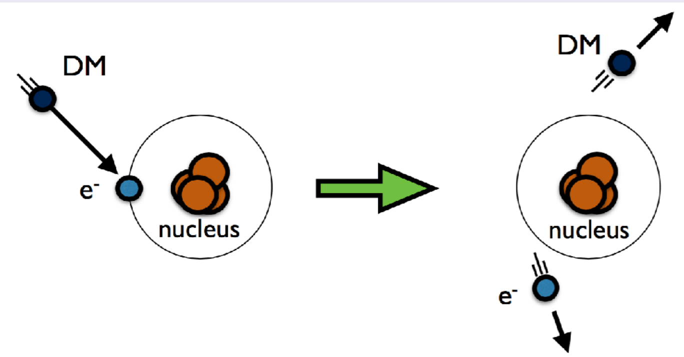
- Lambda lab in University of Buenos Aires focused in these applications (Dario Rodrigues).

Involved early in the development of the technolgy (risky) and developed expertise for a strong local program.

Dark sector search

Idea: use CCDs as target and record the ionization produced

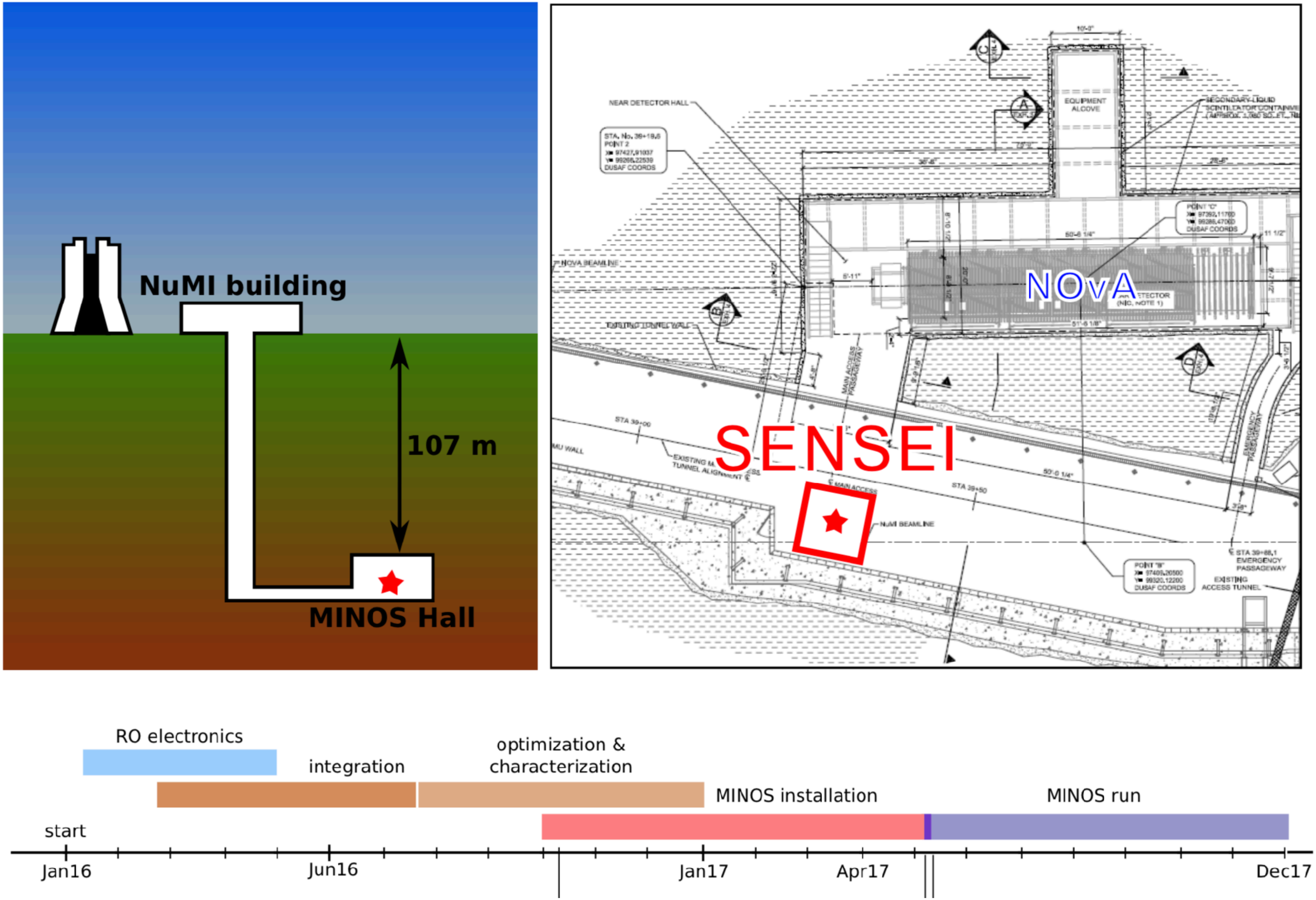




Type	Examples	E_{th}	mass threshold	Status
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~1 eV	~200 keV	E_{th} ~ 40 eV (SuperCDMS, DAMIC*) E_{th} ~ 1 eV (SENSEI) R&D ongoing
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV	R&D required

$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > \Delta E$$

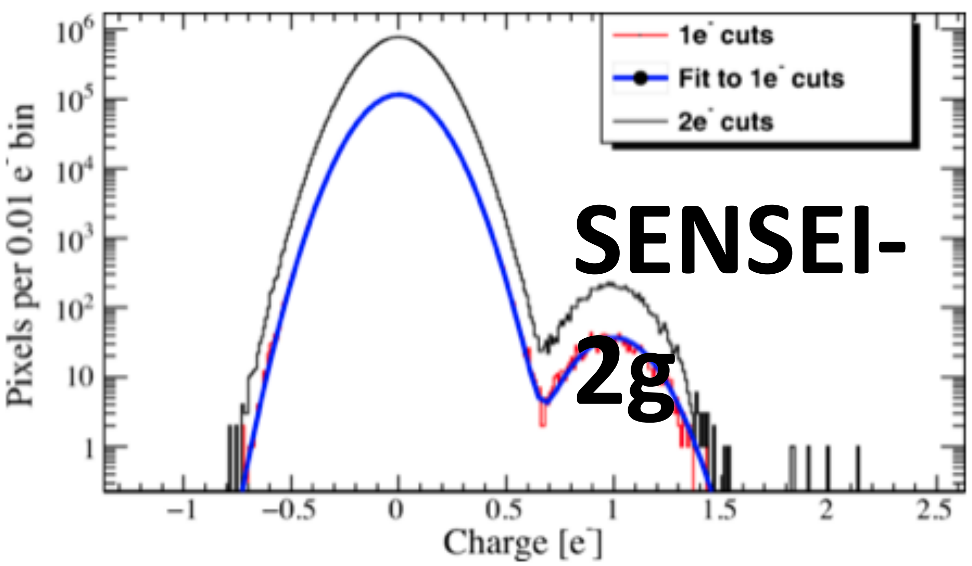
$$v_{\rm DM} \lesssim 800 \text{ km/s} \implies m_{\rm DM} \gtrsim 300 \text{ keV} \left(\frac{\Delta E}{1 \text{ eV}}\right)$$

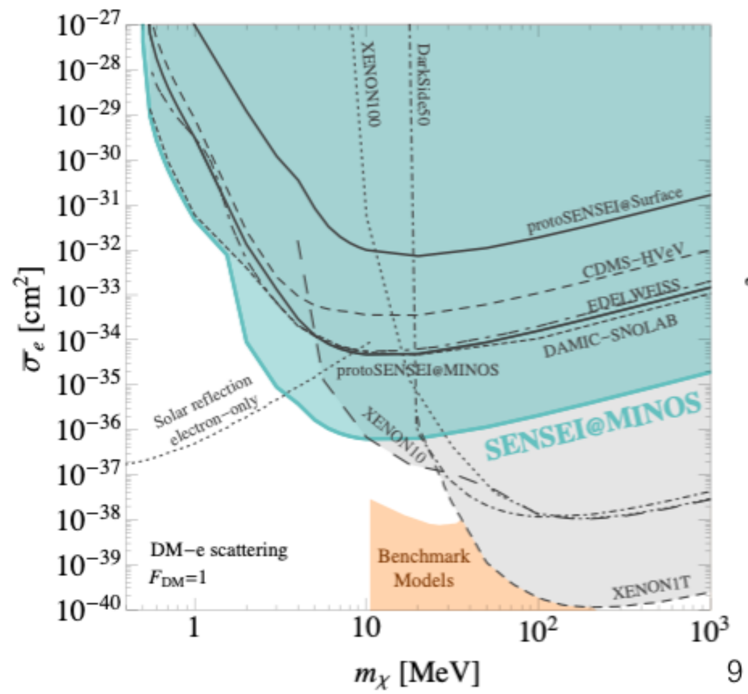

NuMI building
107 m
MINOS Hall
NOvA
SENSEI
NEAR DETECTOR HALL
EQUIPMENT ALCOVE
NUMI BEAMLINE
RO electronics
integration
optimization &
characterization
MINOS installation
MINOS run
start
Jan16
Jun16
Jan17
Apr17
Dec17

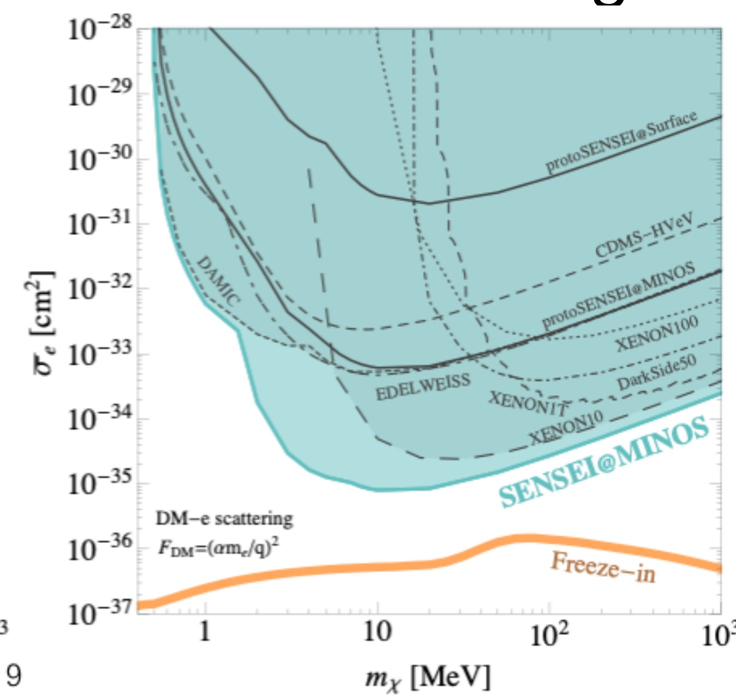
SENSEI 2020

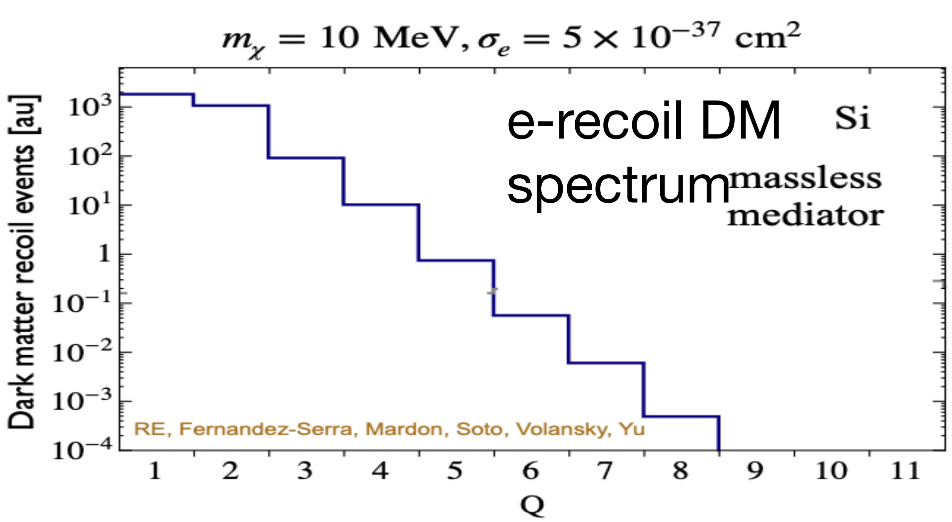
~20 g-day

Skipper-CCD is an electron counting silicon









Rates:

- 1e- = 450 ev/g-day (1.6 10^{-4} e/pix/day)
- 2e- = 2.4 ev/g-day

Phys. Rev. Lett. **125**, 171802 – Published 20 October 2020

DAMIC-M (@Modane)

~85 g-day

Phys. Rev. Lett. **130**, 171003 – Published 28 April 2023

arXiv:2302.02372

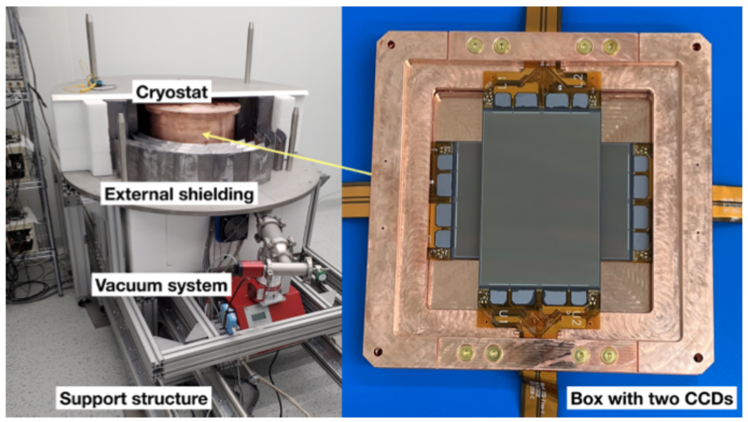
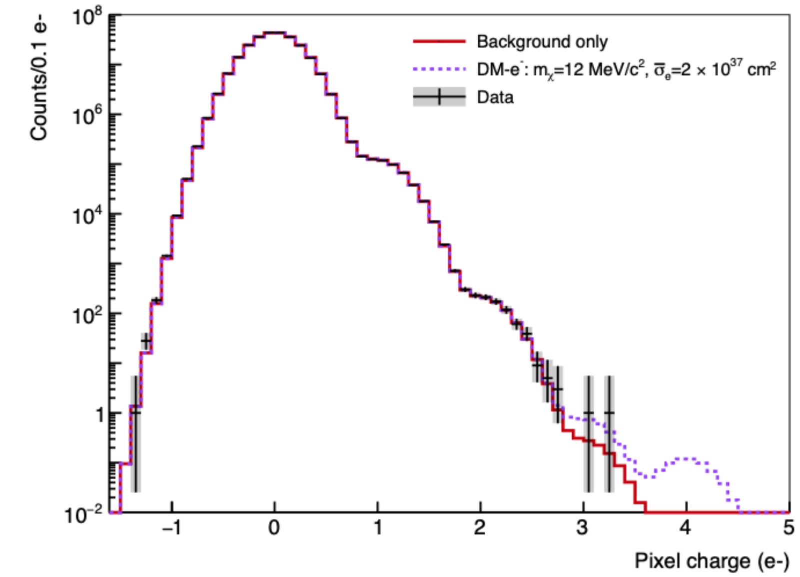
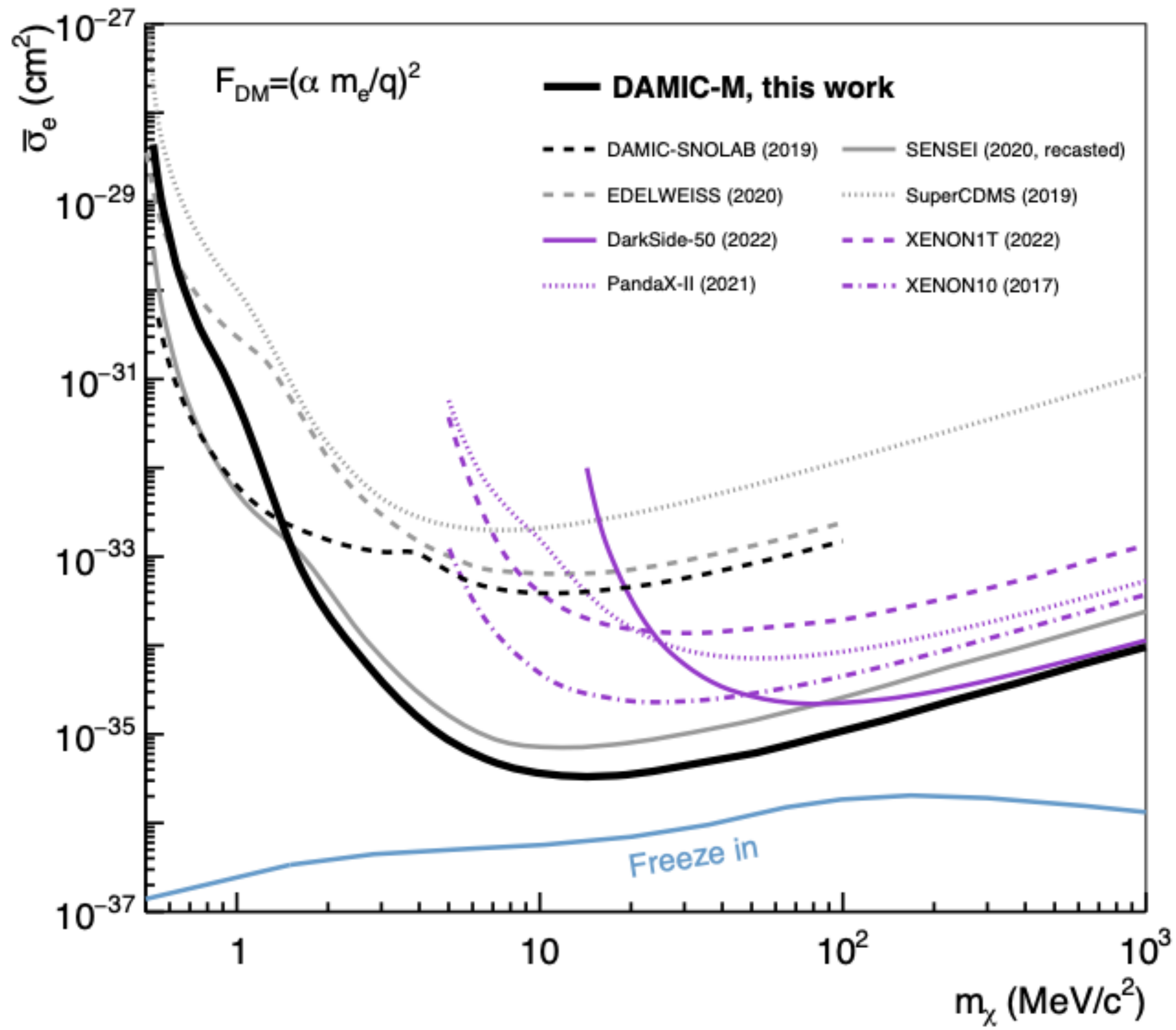


FIG. 1. The DAMIC-M Low Background Chamber installed underground at LSM: the two skipper CCDs are monted in a high-purity copper box (right); the box is placed inside the copper cryostat, visible here (left) during assembly of the external lead and polyethylene shielding.

Improvement over SENSEI 2020.

See talk by Xavier Bertou.





SENSEI-2023 (@SNOLAB)

arXiv:2312.13342

~535 g-day

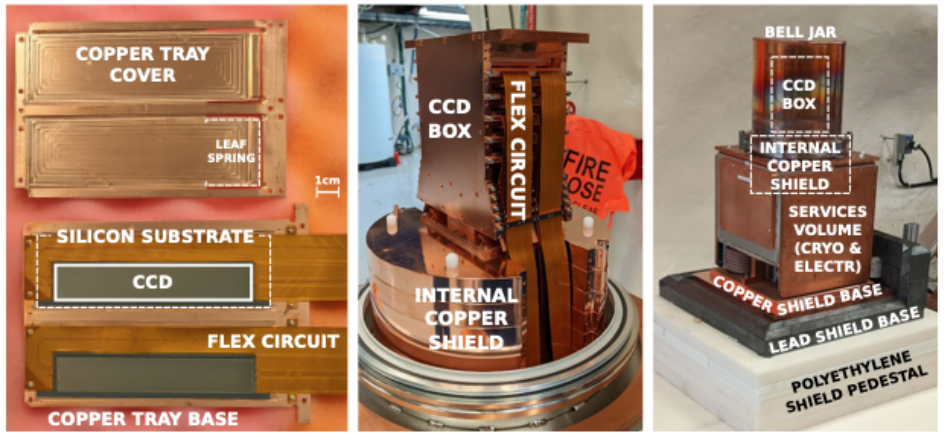
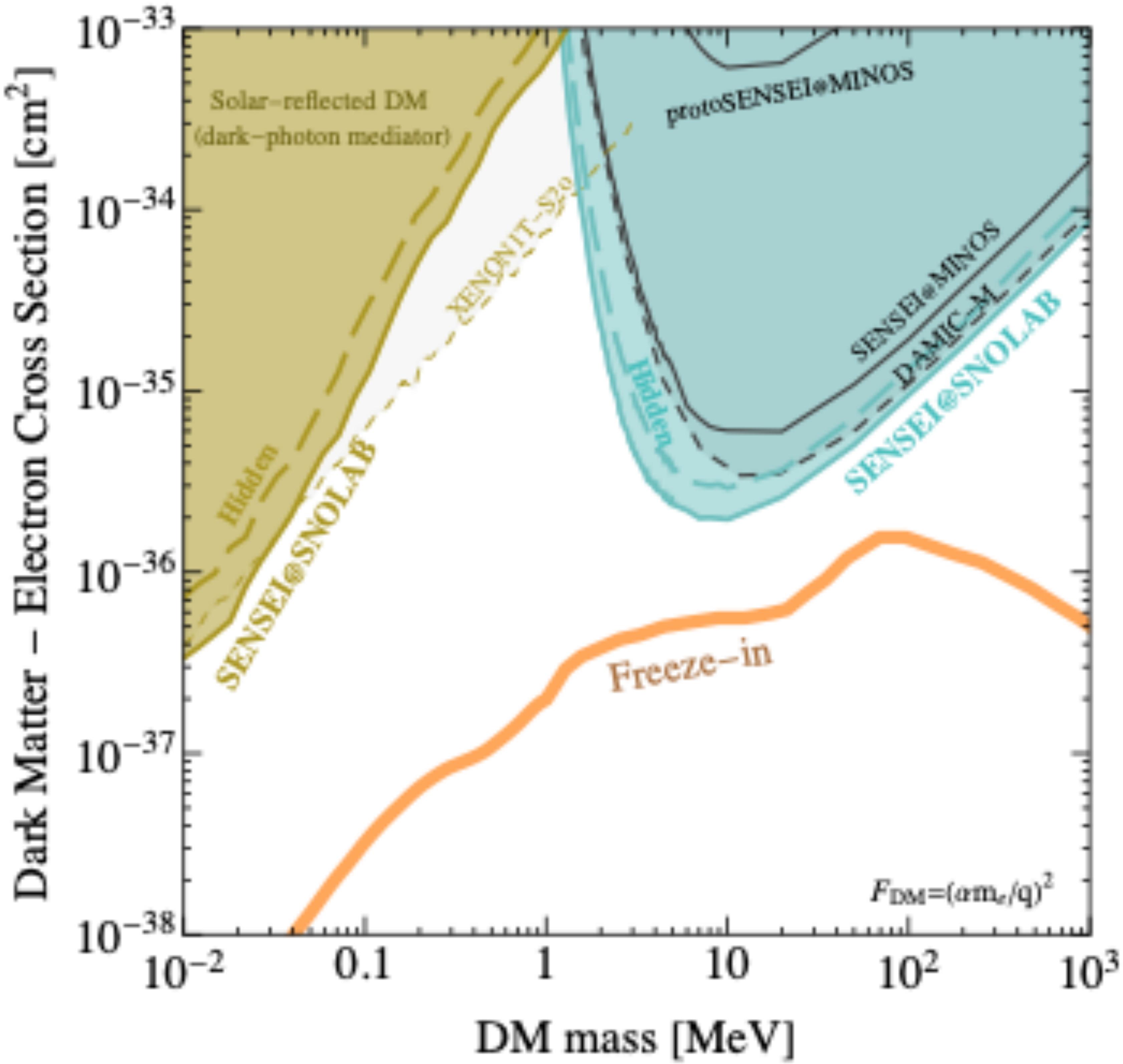


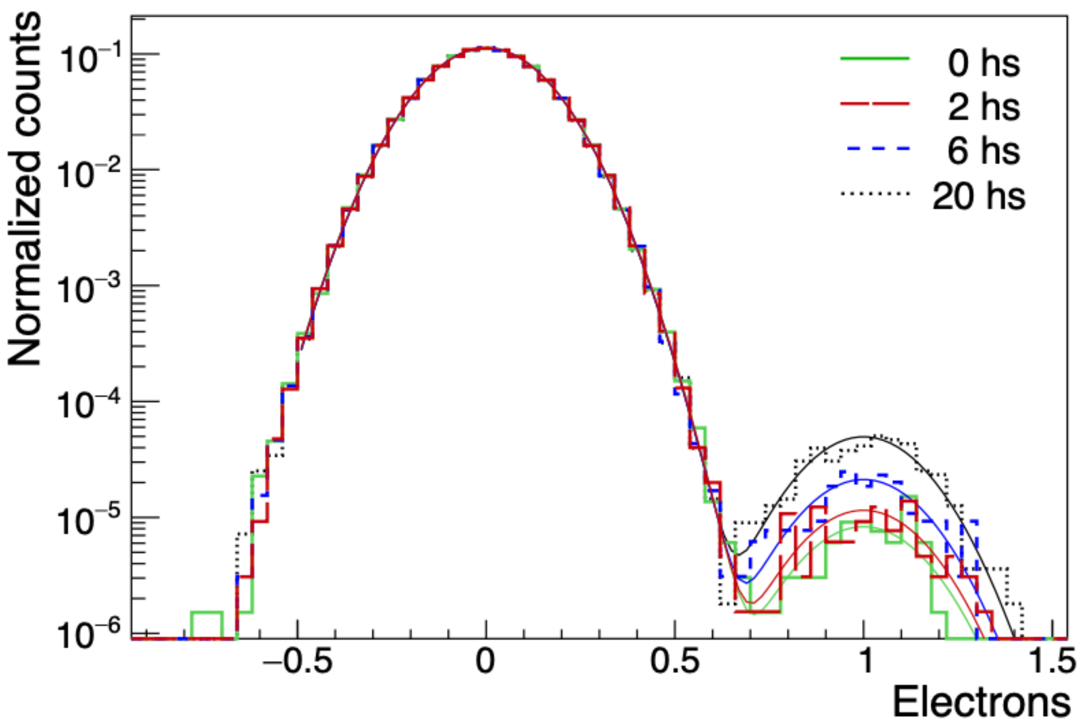
FIG. 1. The SENSEI detector at SNOLAB. **Left:** Two CCD modules in their copper tray. **Middle:** Copper CCD box and trays deployed inside the vessel. **Right:** Closed SENSEI vacuum vessel, before installing the outer copper, lead, and poly-water shields.

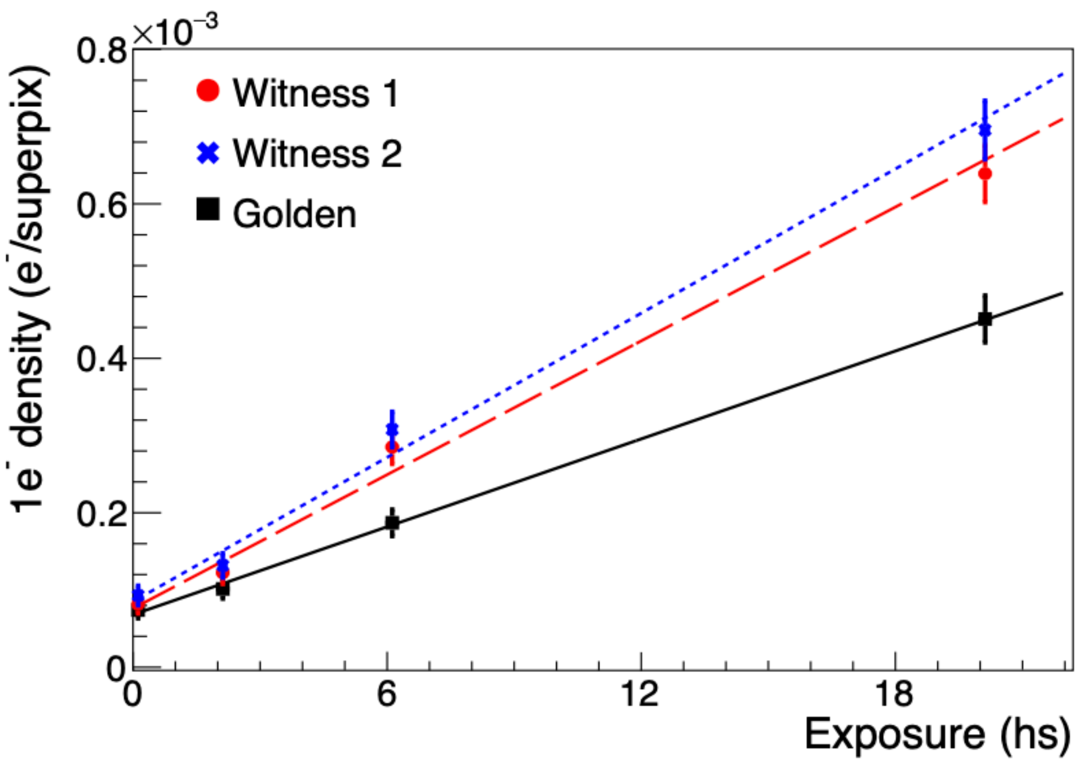
skipper-CCD technology is consistency producing the world leading results in electron-recoil dark matter since 2019.

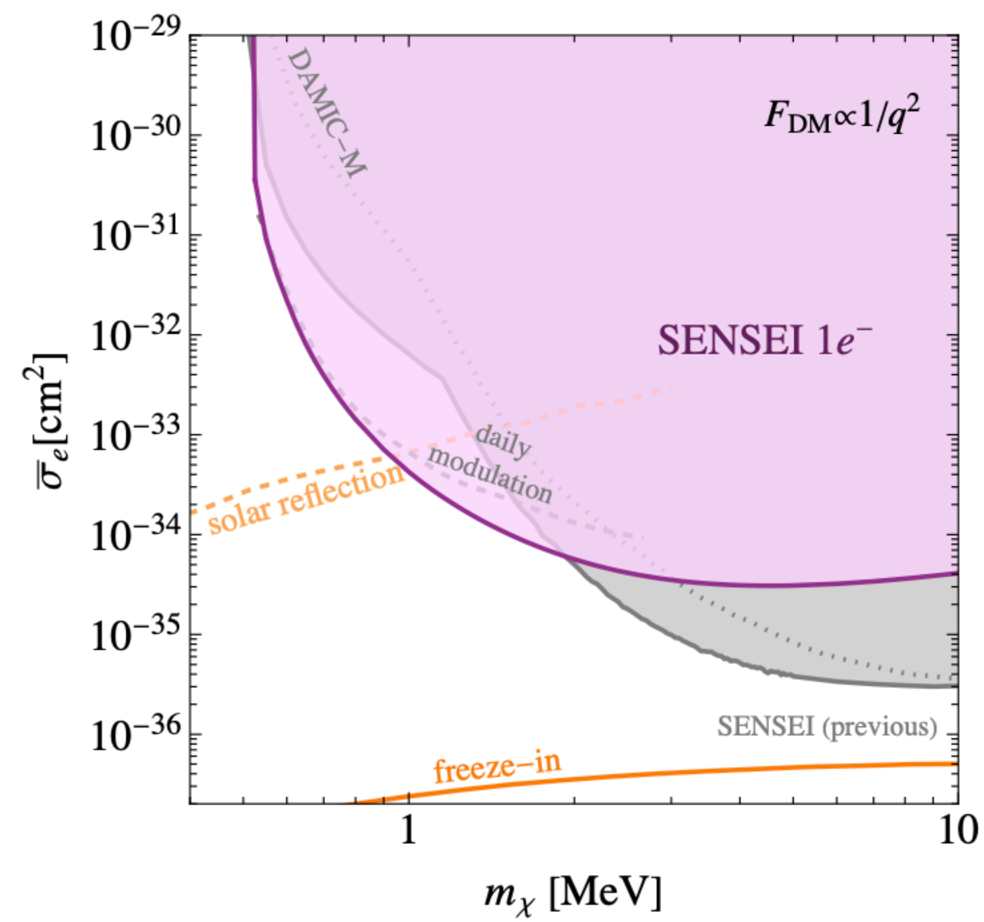


SENSEI-2024 (@SNOLAB) in arXiv: 2410.18716

Improved single electron rate (dark count rate!!!)







ϵ

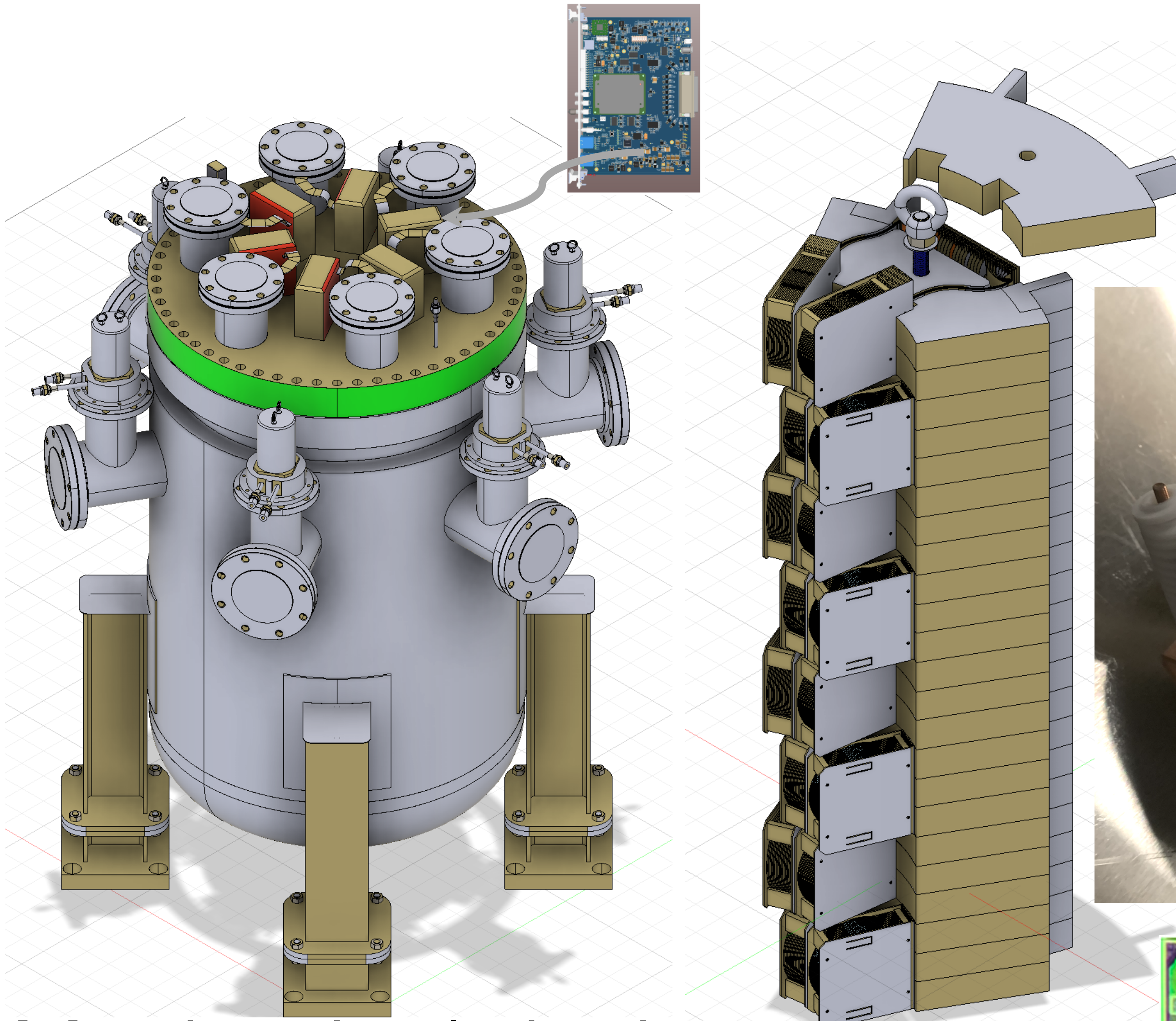
We observe a single-electron event rate of (1.39 ± 0.11) × 10⁻⁵ e−/ pix/day, corresponding to (39.8 ± 3.1) e−/gram/day. This is an order-of- magnitude improvement compared to the previous lowest single-electron rate in a silicon detector and the lowest for any photon detector in the near-infrared-ultraviolet range.

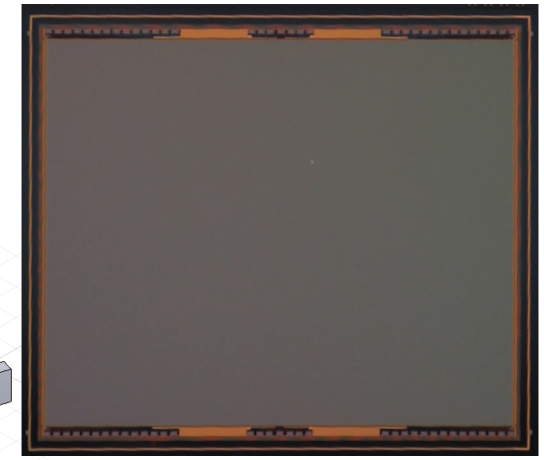
Skipper-CCD DM program : technology roadmap

Experiment	Mass [kg]	#CCDs	Radiation bkgd [dru]	Instrumental bkgd [e-/pix/day]	Commissioning
SENSEI @ MINOS	~0.002	1	3400	1.6×10^{-4}	late-2019
DAMIC @ SNOLAB	~0.02	2	~10	3×10^{-3}	late-2021
DAMIC-M LBC	~0.02	2	10	3×10^{-3}	late-2021
SENSEI-100	~0.1	50	10 (goal)		mid-2022
DAMIC-M	~1	200	0.1 (goal)		~2023
OSCURA	~10	20,000	0.025 (goal)	1×10^{-6} (goal)	~2028

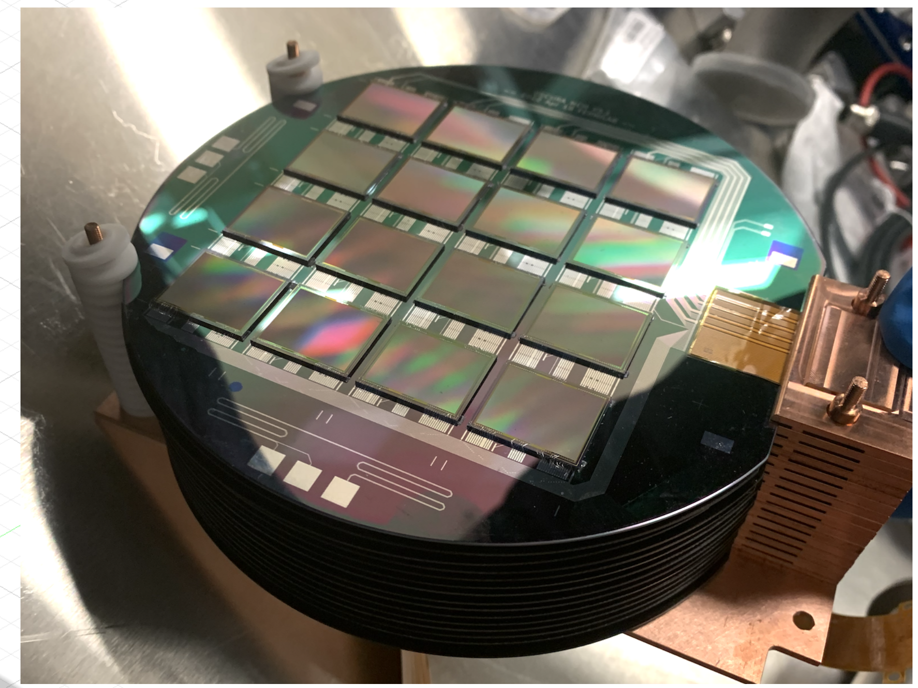
Oscura is an ambitious program that brings together the DAMIC, SENSEI and DAMIC-M teams for the development of ultimate DM experiment with skipper-CCDs. **See Brenda's talk on Oscura**

Oscura development at Latin America

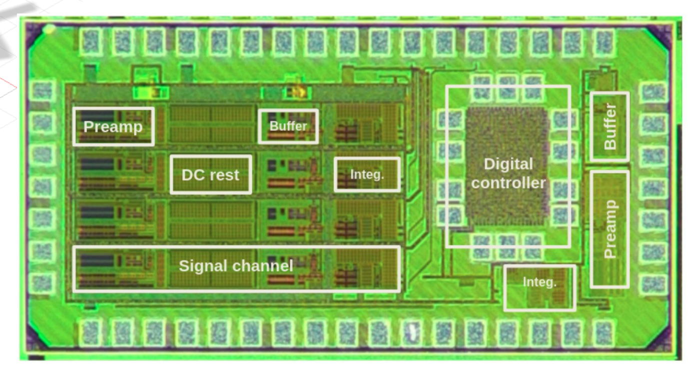




<u>Sensors:</u> characterization by students at UNAM and UBA (B.Cervantes, S.Perez).



<u>Packaging:</u> students at UNA(C. Chavez).



<u>Readout:</u> ASIC designers at Bariloche (Miguel Sofo-Haro and Fabricio Alcalde)

Mechanical design

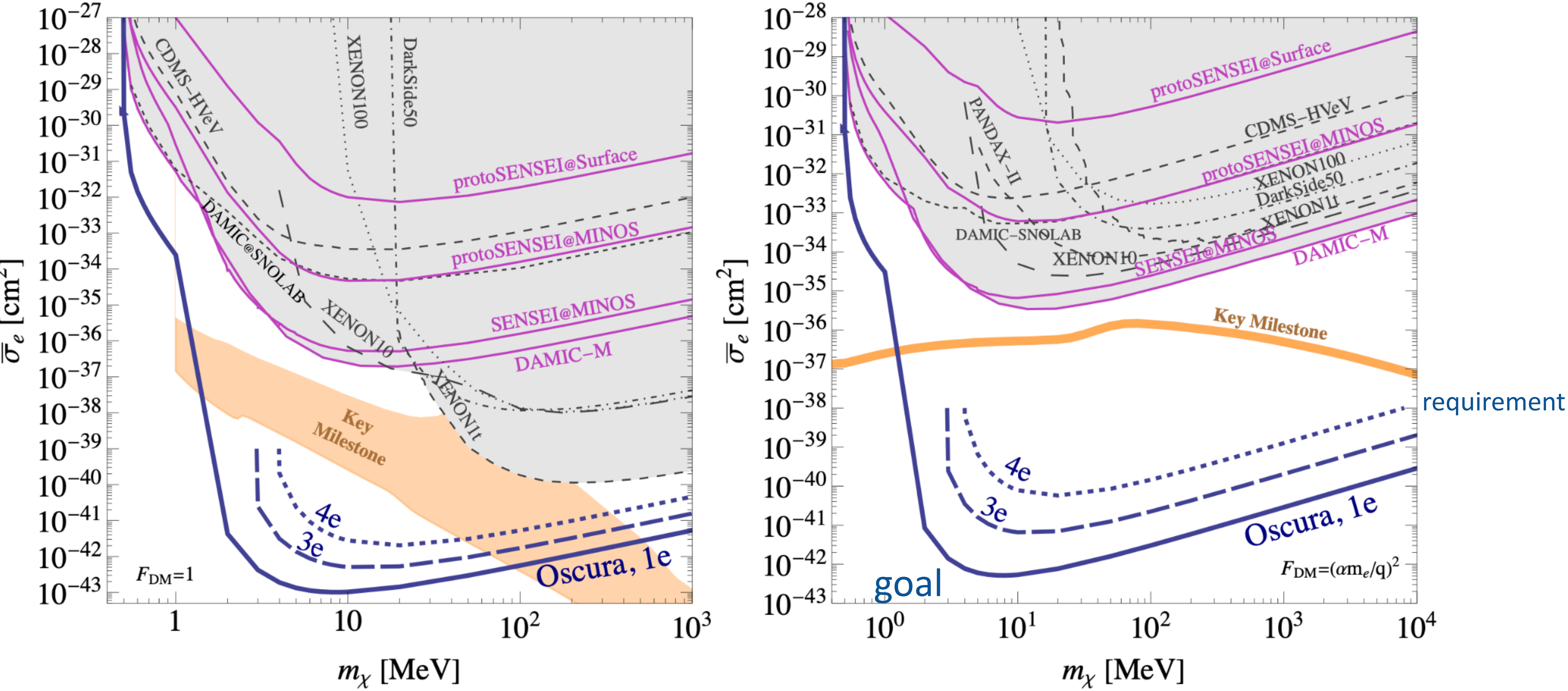
IPSUM PACIFIC Inc.

www.ipsuminc.com

<u>Tremendous expertise for this technology in LA.</u>

Oscura science forecast

arXiv:2304.0440



		goal	requirement
R1.1	total exposure	30 kg-year	27 kg-year
R1.2	analysis threshold	2e-	3e-
R1.3	backg. events at lowest elec. bin above thr.	< 1	< 5

Solar reflected Dark Matter

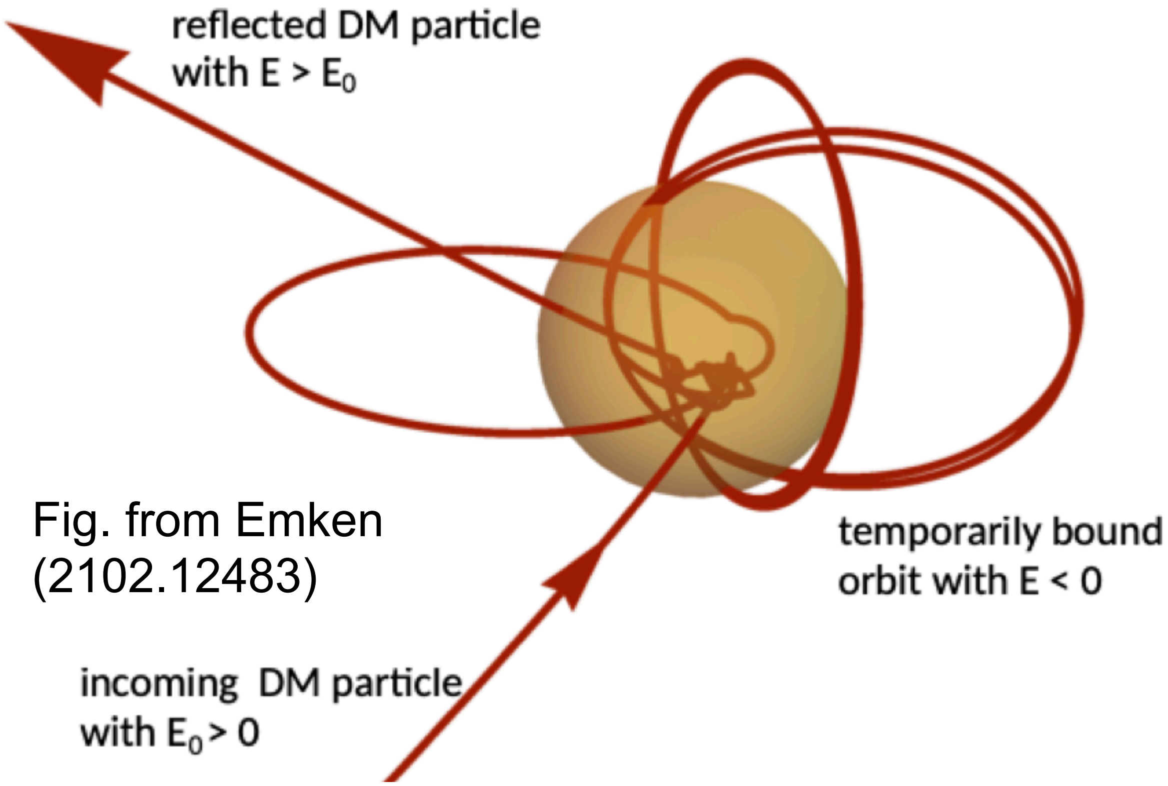
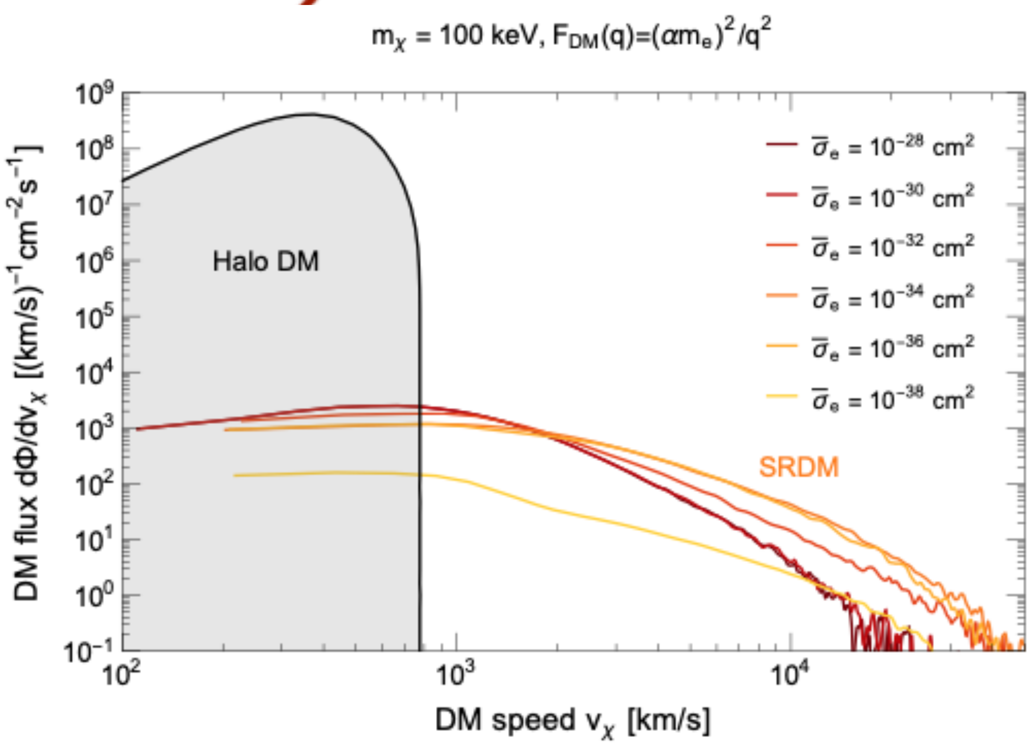
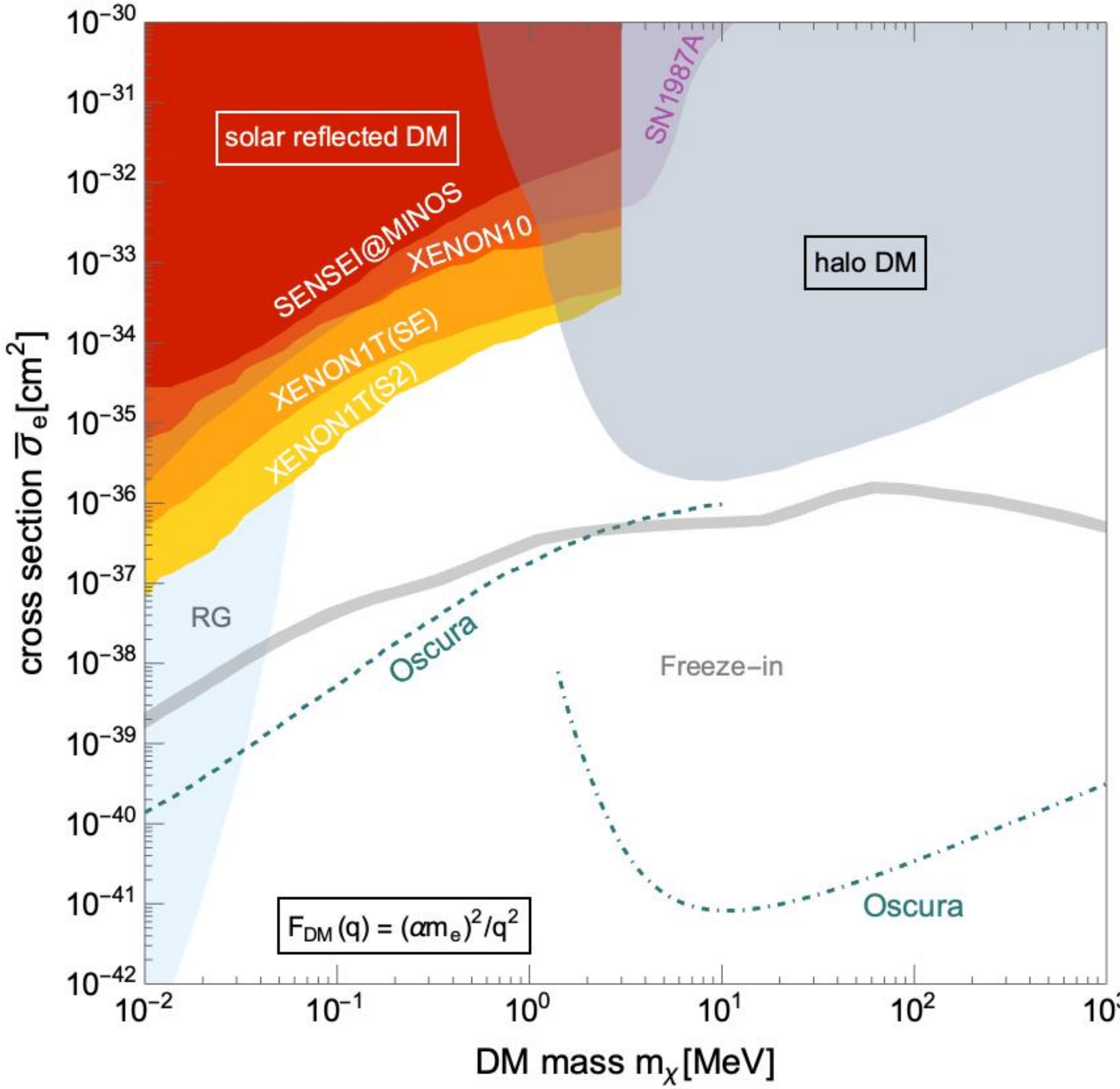


Fig. from Emken
(2102.12483)

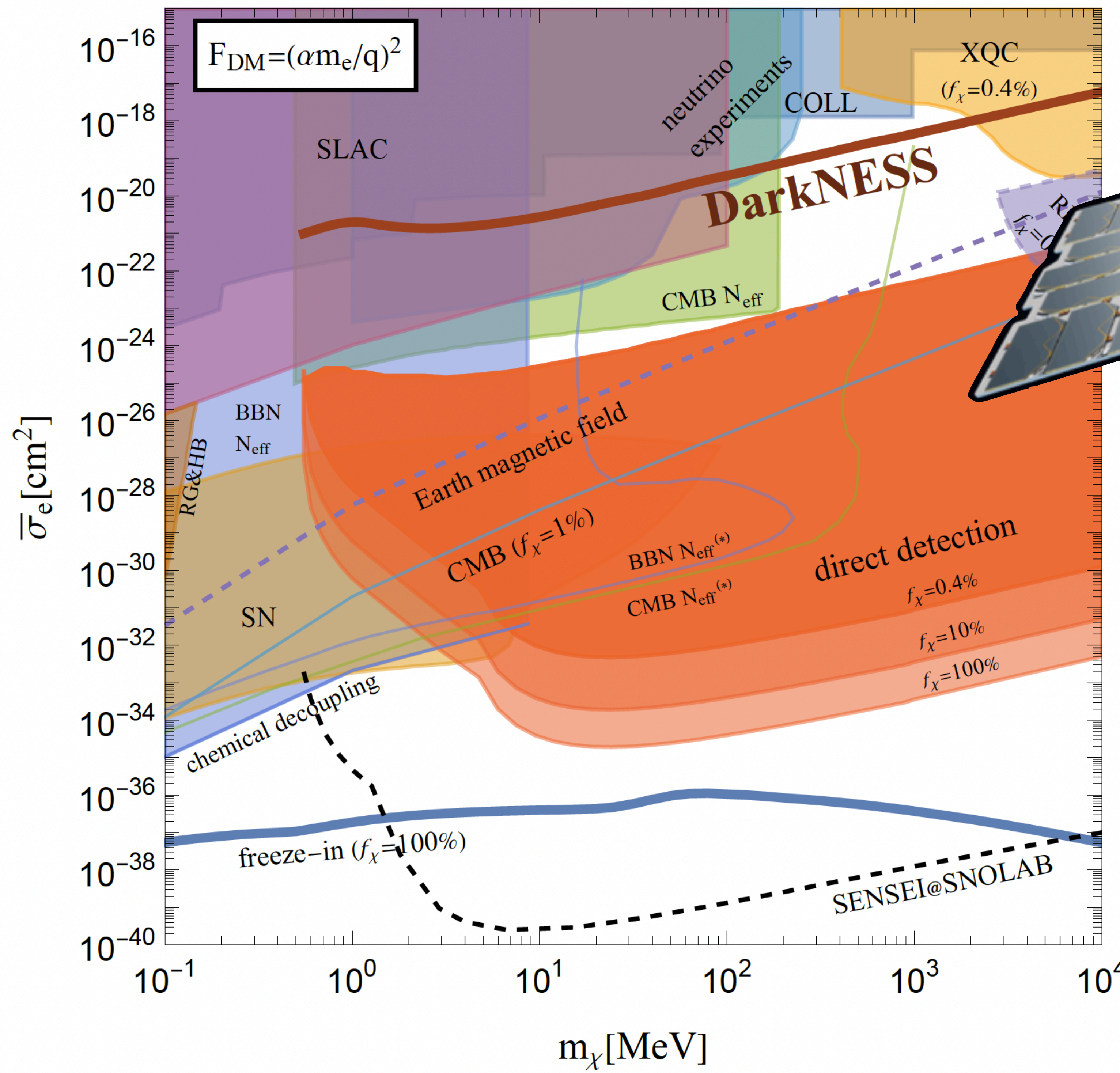


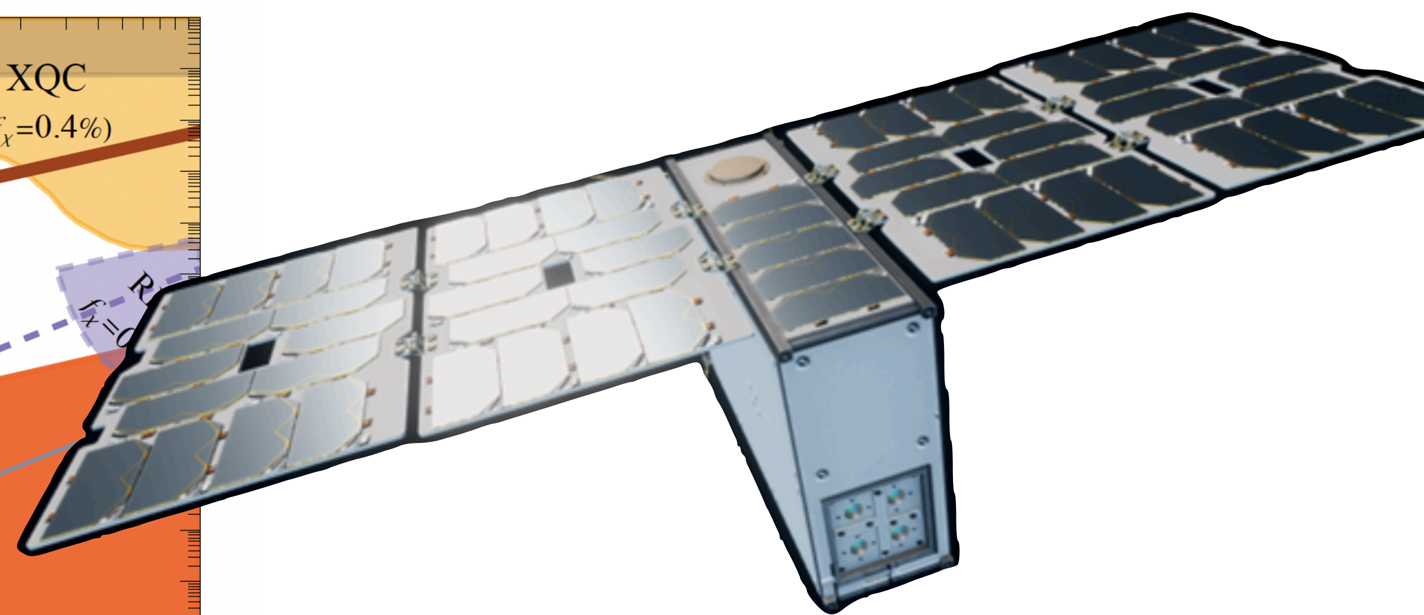


(R.Essig, Stony Brook University)

This effect allows searching for lower masses.

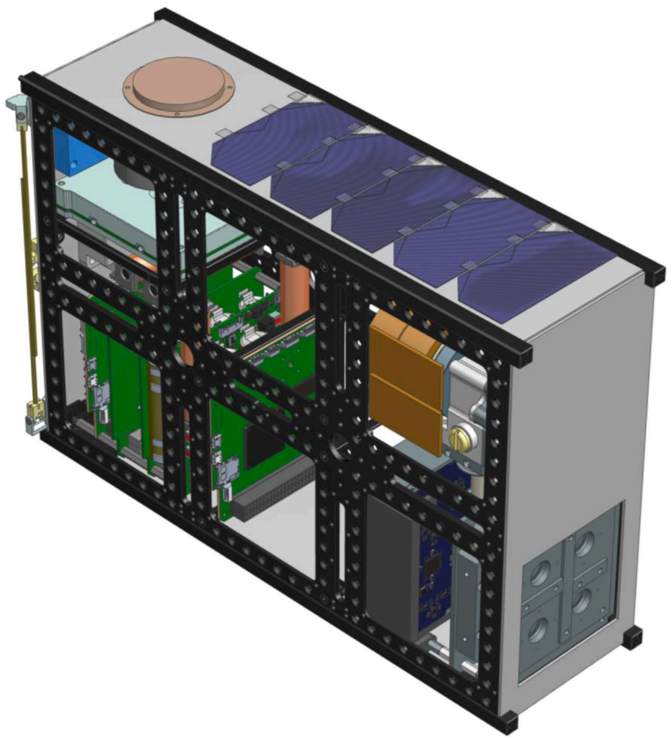
But if the cross section is too large, you do not see in underground labs.

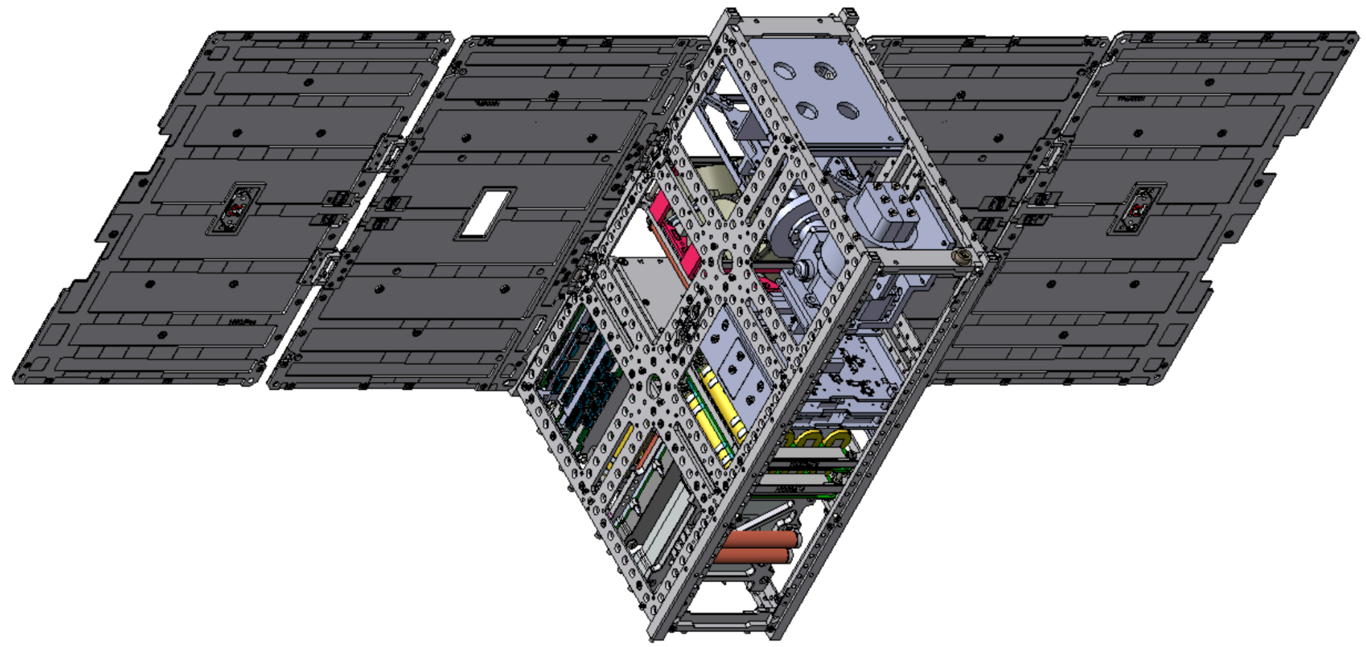


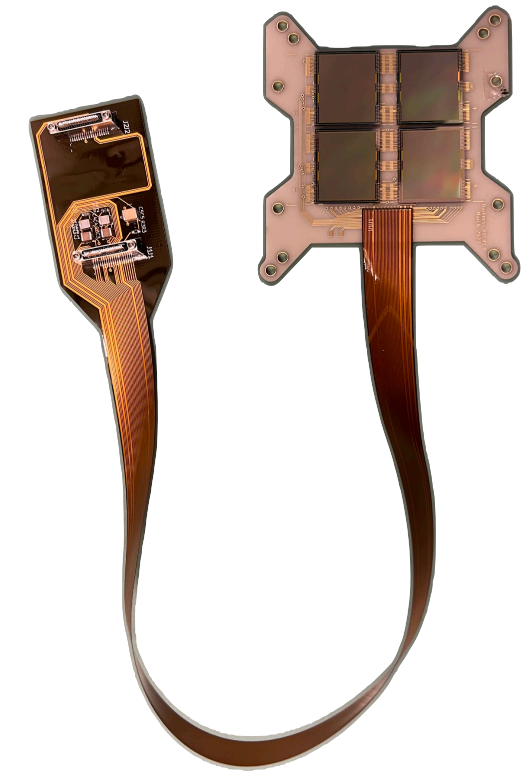


DarkNESS will have 4 skipper-CCDs to look at strongly interacting DM from Low Earth Orbit.

4 skipper-CCDs in a 6U CubeSat

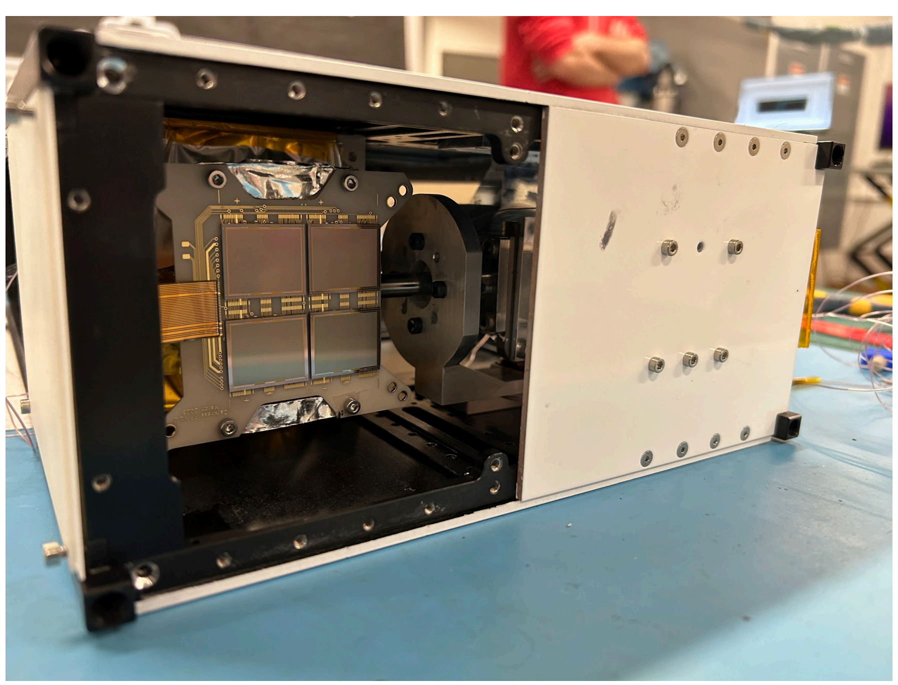




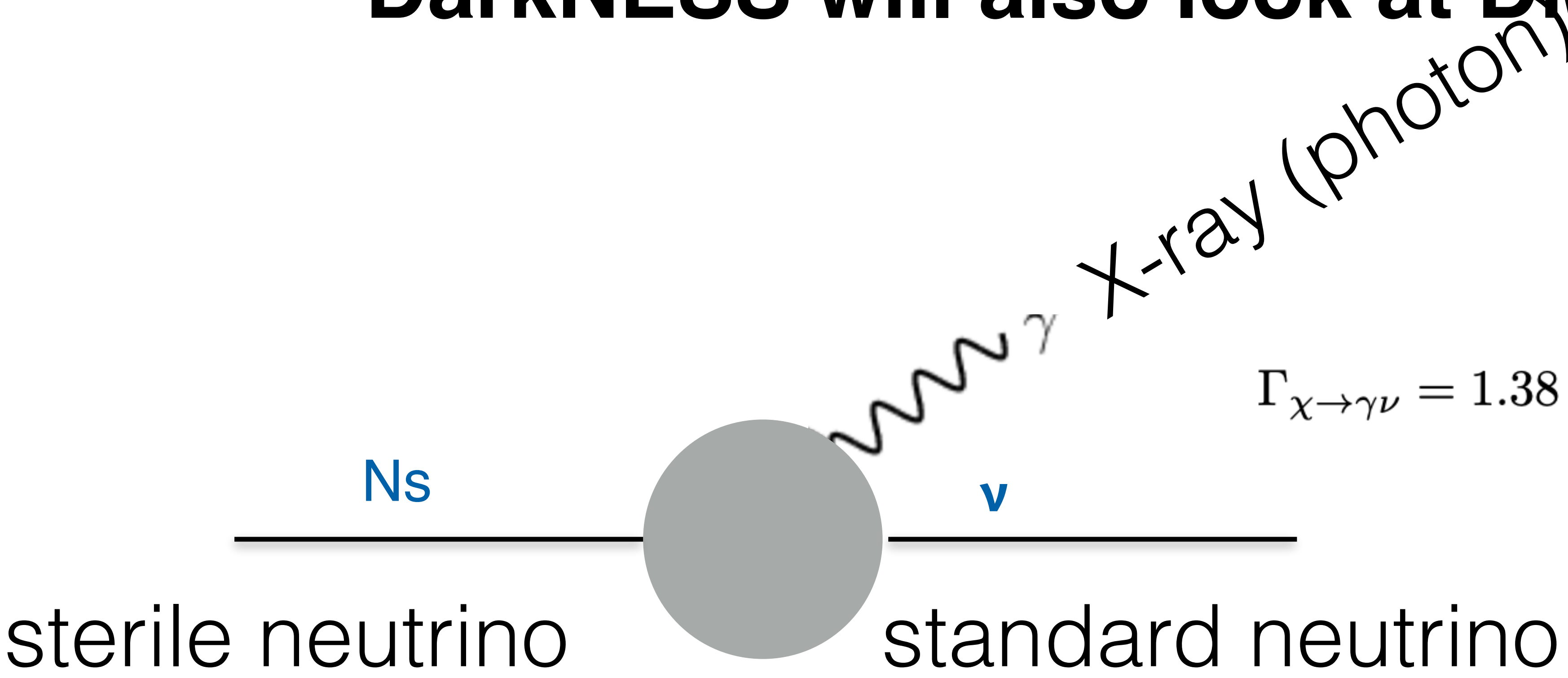


Sensor package design in UNS(Arg). Fernando Chierchie.

Current prototype



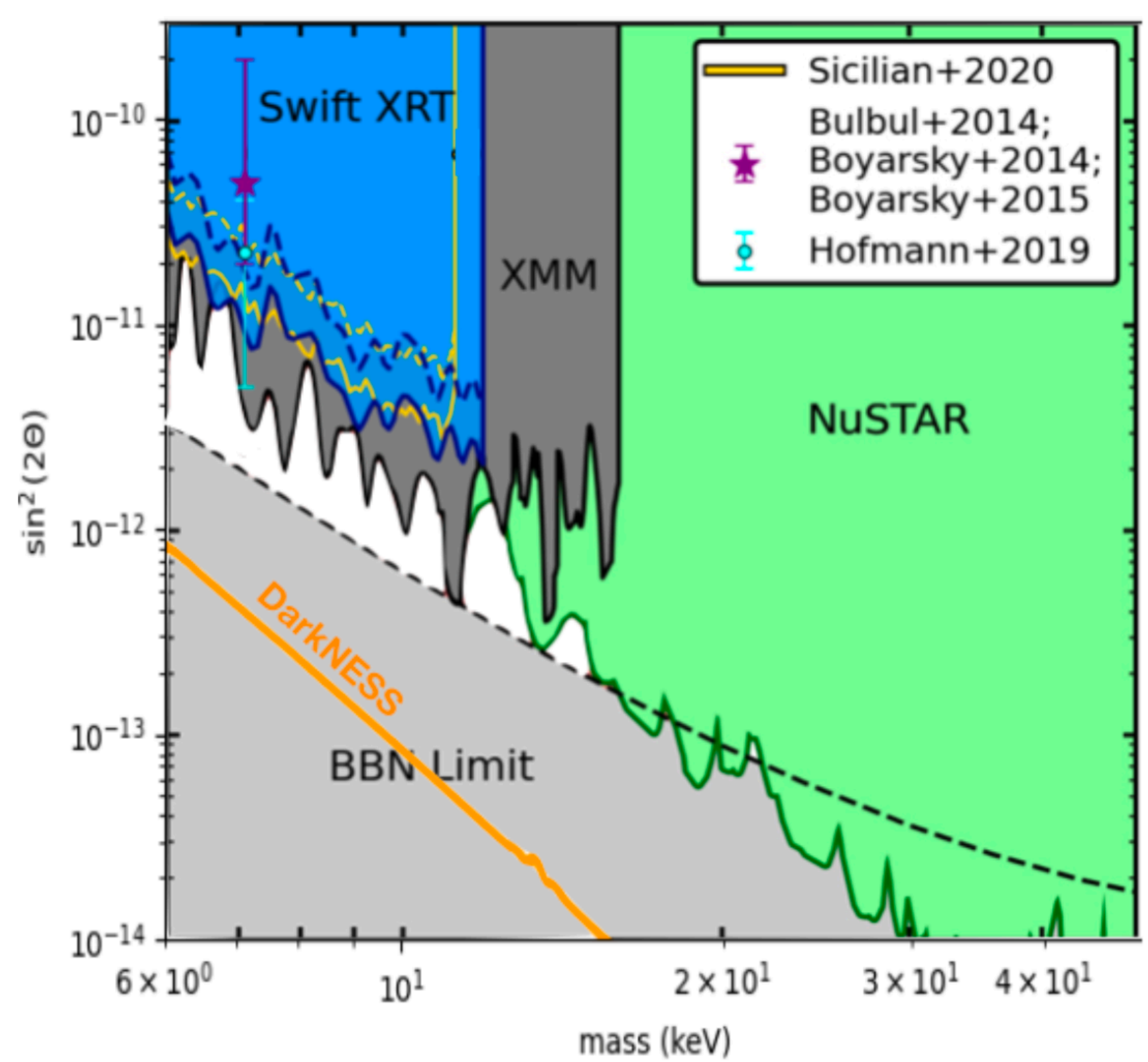
DarkNESS will also look at DM decay



$$\Gamma_{\chi\to\gamma\nu} = 1.38\times10^{-32}\,\mathrm{s}^{-1}\left[\frac{\sin^2(2\theta)}{10^{-10}}\right]\left(\frac{m_\chi}{1\,\mathrm{keV}}\right)^5$$

arXiv:2207.04572

Phys. Rev. D 107, 023009 (2023)



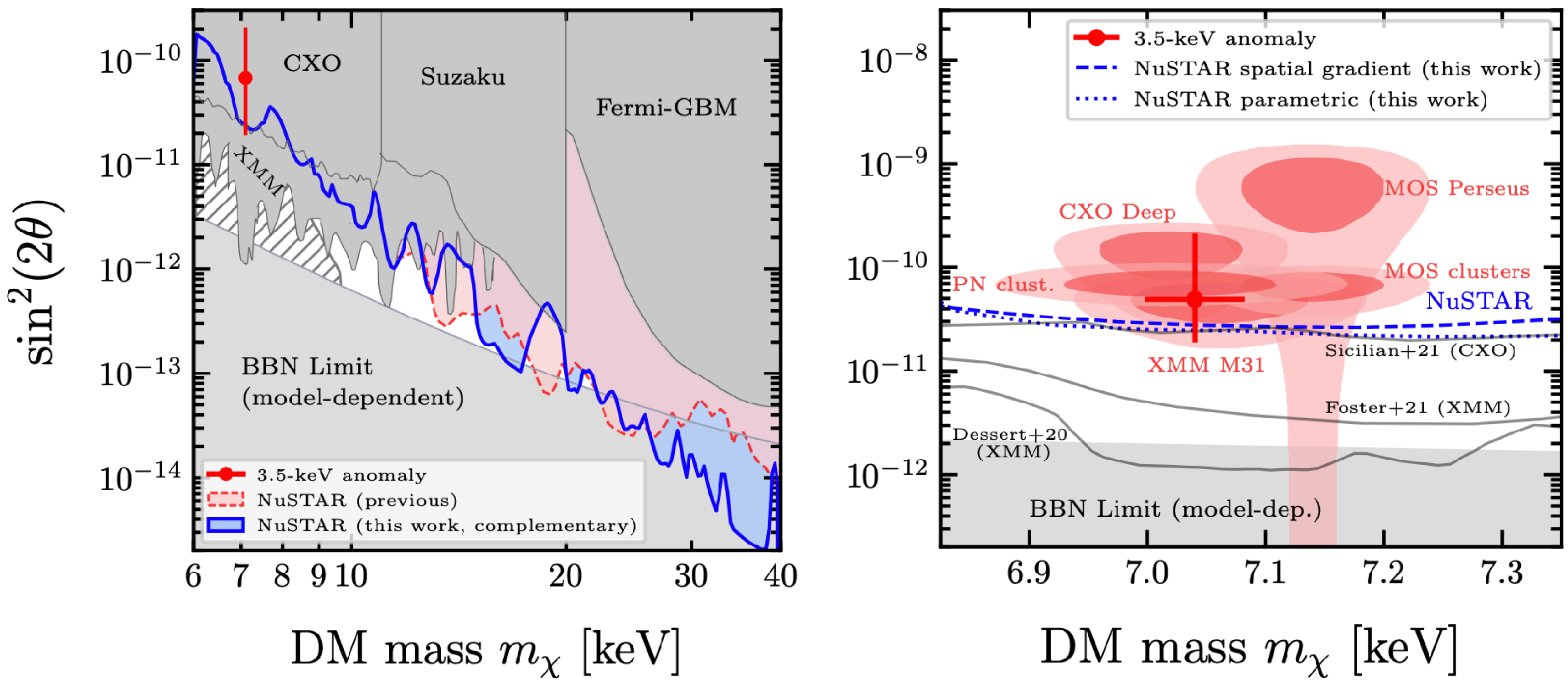
DarkNESS will be the first demonstration of skipper-CCDs for X-rays. Also the first demonstration in space. Critical for future NASA missions that require counting photons (HWO).

- Strong ongoing effort to look for WIMPs and beyond.

- Dark Matter search is a technologically diverse field, where smart ideas could have a huge impact even with small budgets.

- There is already a huge participation of the Latin America HEP community in these efforts.

Thanks!!

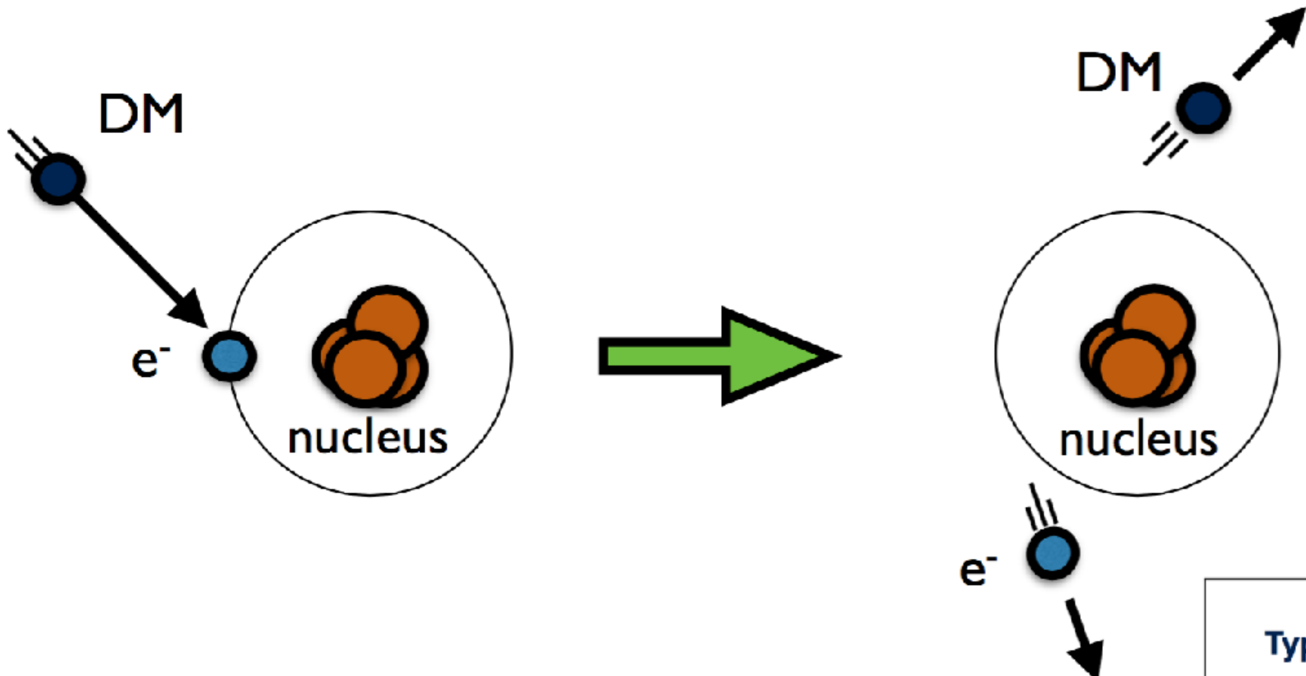


$$\Gamma_{\chi\to\gamma\nu} = 1.38\times10^{-32}\,\mathrm{s}^{-1}\left[\frac{\sin^2(2\theta)}{10^{-10}}\right]\left(\frac{m_\chi}{1\,\mathrm{keV}}\right)^5$$

Phys. Rev. D 107, 023009 (2023)

arXiv:2207.04572

the “classic” search for wimps looks for nuclear recoil, but when looking at lower mass particles the e-recoil channel is more competitive.



Type	Examples	E_{th}	mass threshold	Status
Noble liquids	Xe, Ar, He	~10 eV	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	Ge, Si	~1 eV	~200 keV	E_{th} ~ 40 eV (SuperCDMS, DAMIC*) E_{th} ~ 1 eV (SENSEI) R&D ongoing
Scintillators	GaAs, NaI, CsI, …	~1 eV	~200 keV	R&D required

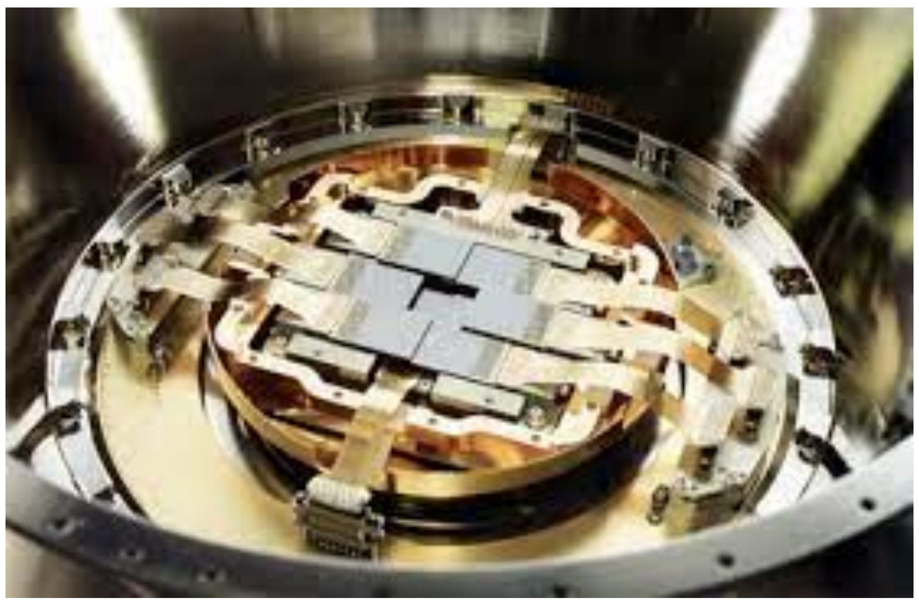
biding energy (~1 eV)

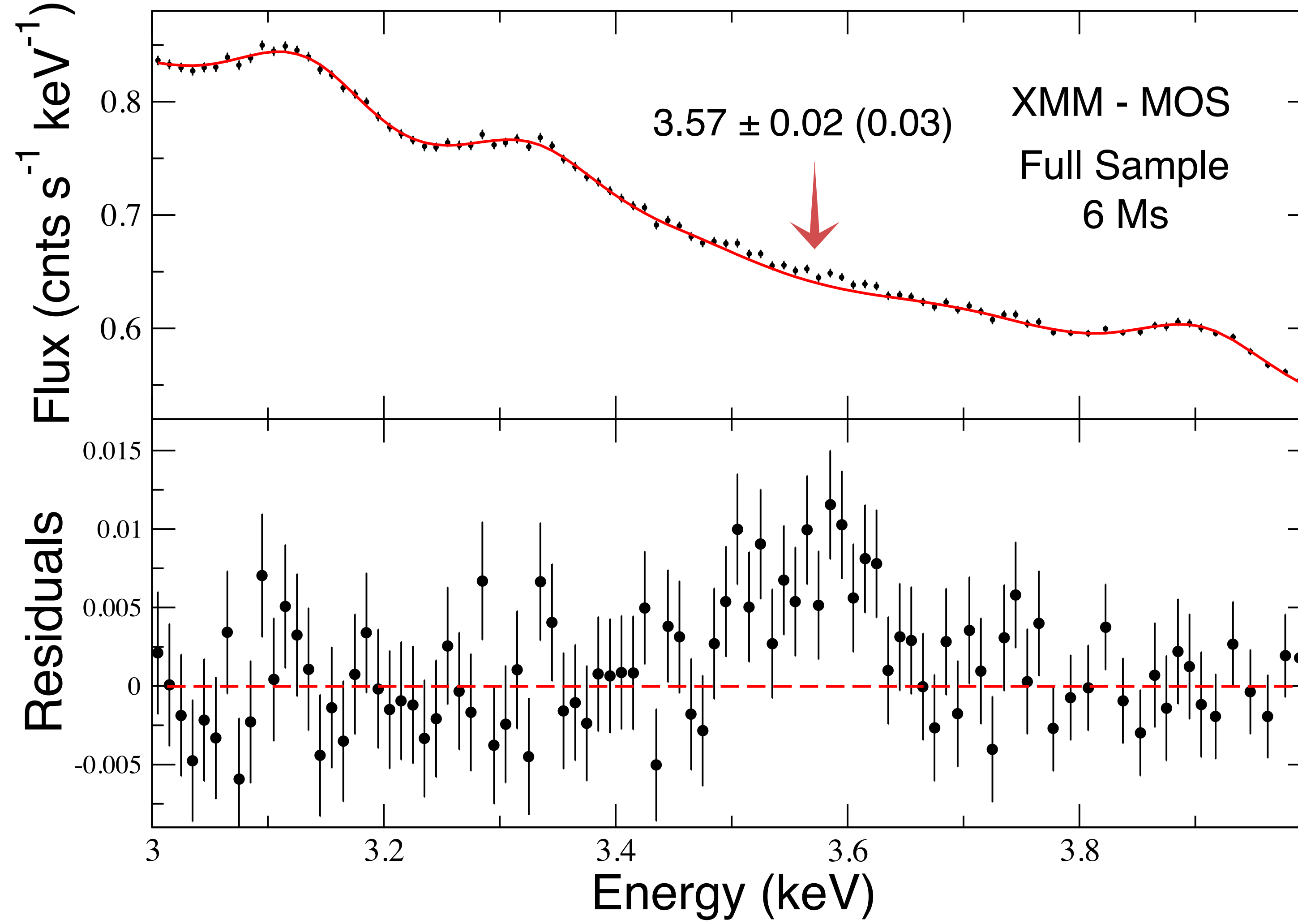
↓

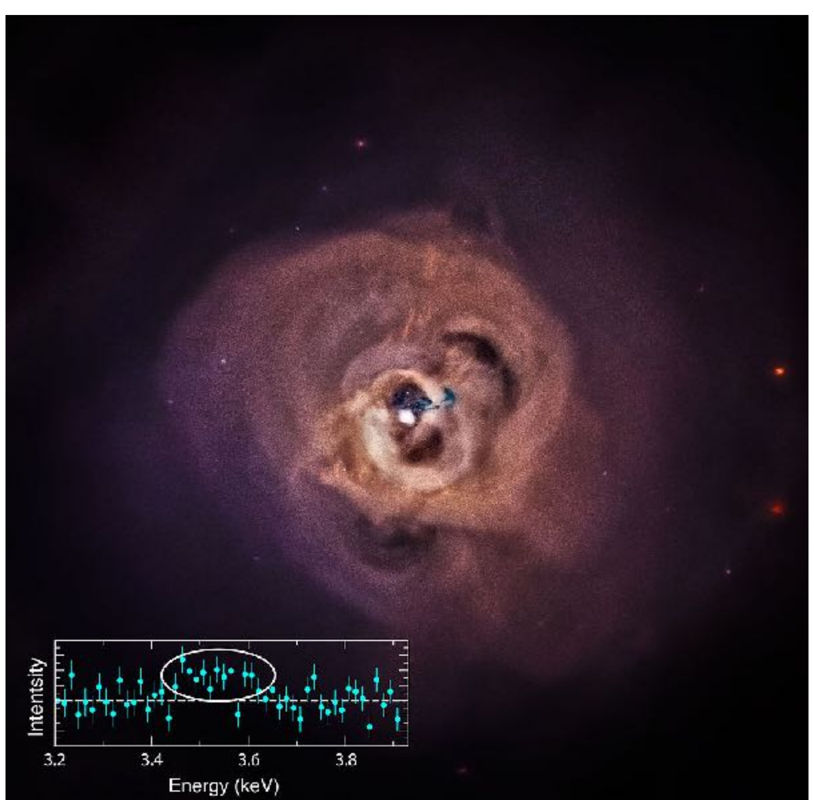
$$E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$$

$$v_{\rm DM} \lesssim 800\ {\rm km/s} \implies m_{\rm DM} \gtrsim 300\ {\rm keV} \left(\frac{\Delta E}{1\ {\rm eV}}\right)$$

XMM Newton MOS CCDs

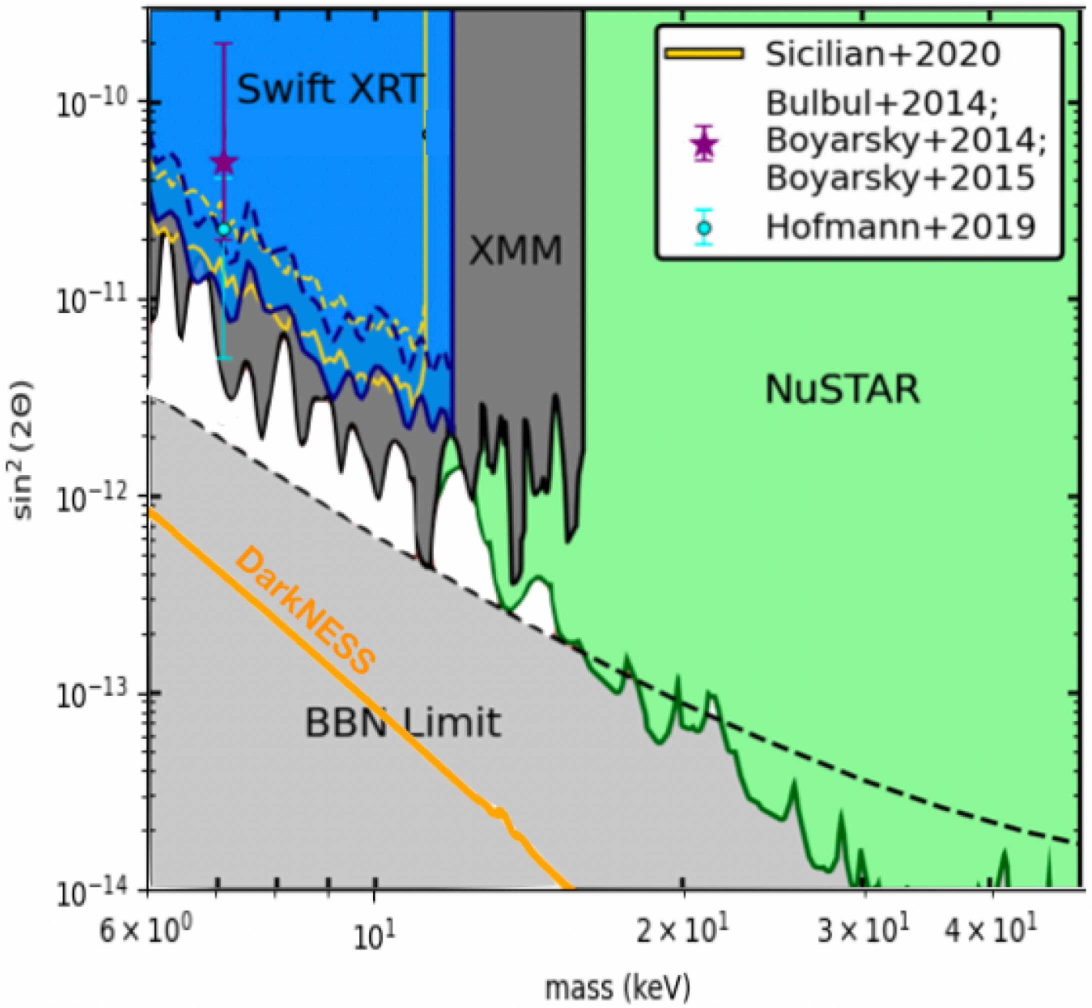




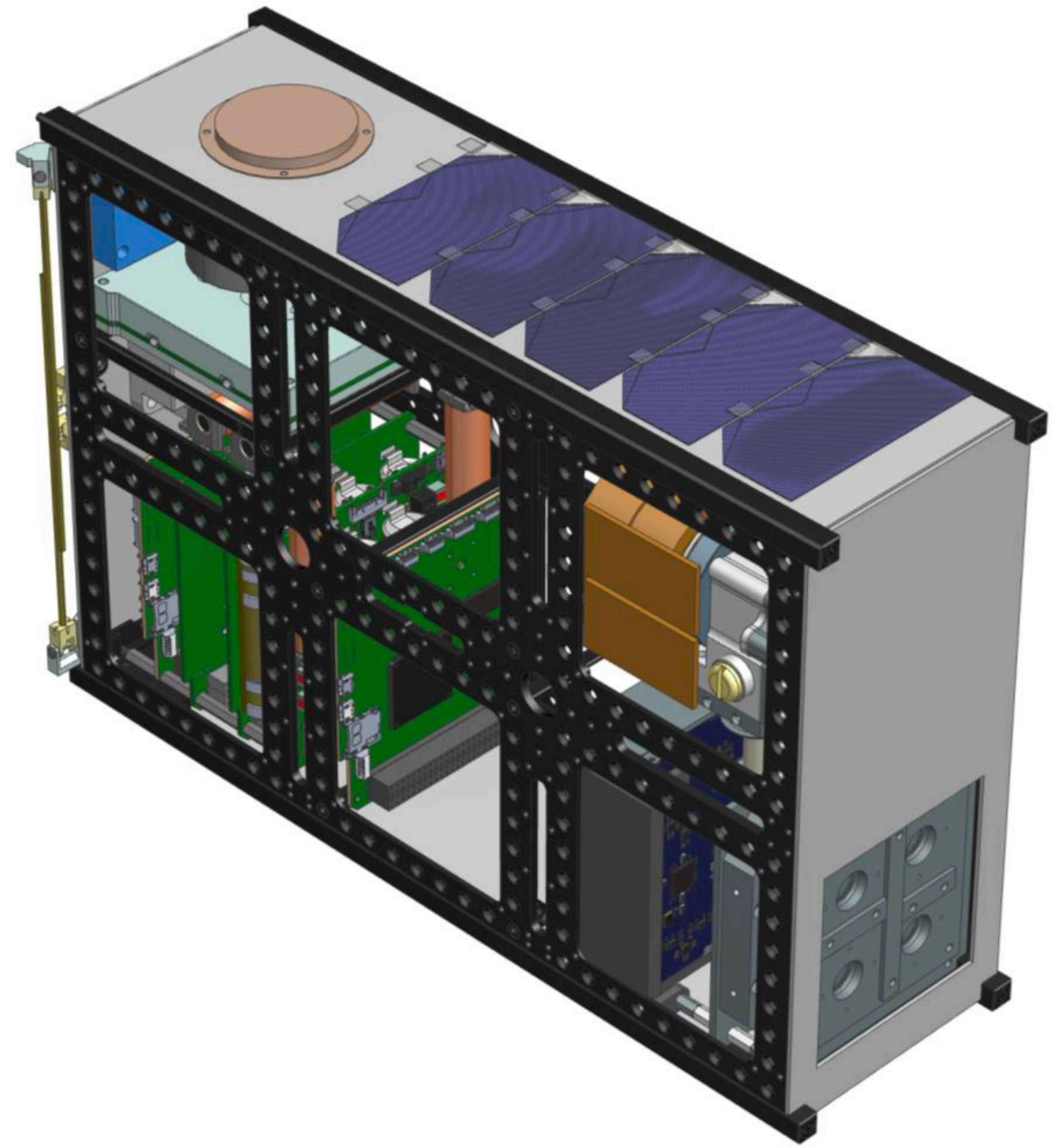


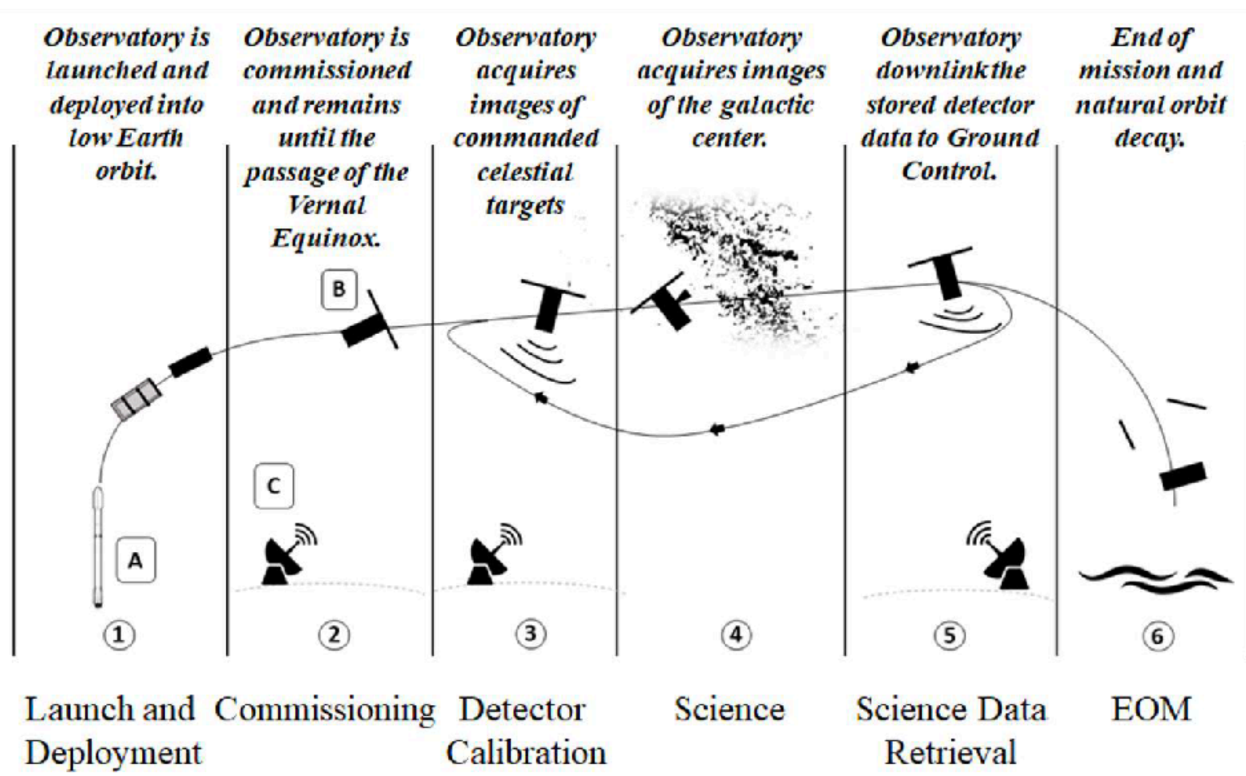
Bubul et al 2014 observed this line at 3.5 keV in galaxy clusters using X-ray telescope.

Perseus cluster in X-ray (Chandra)

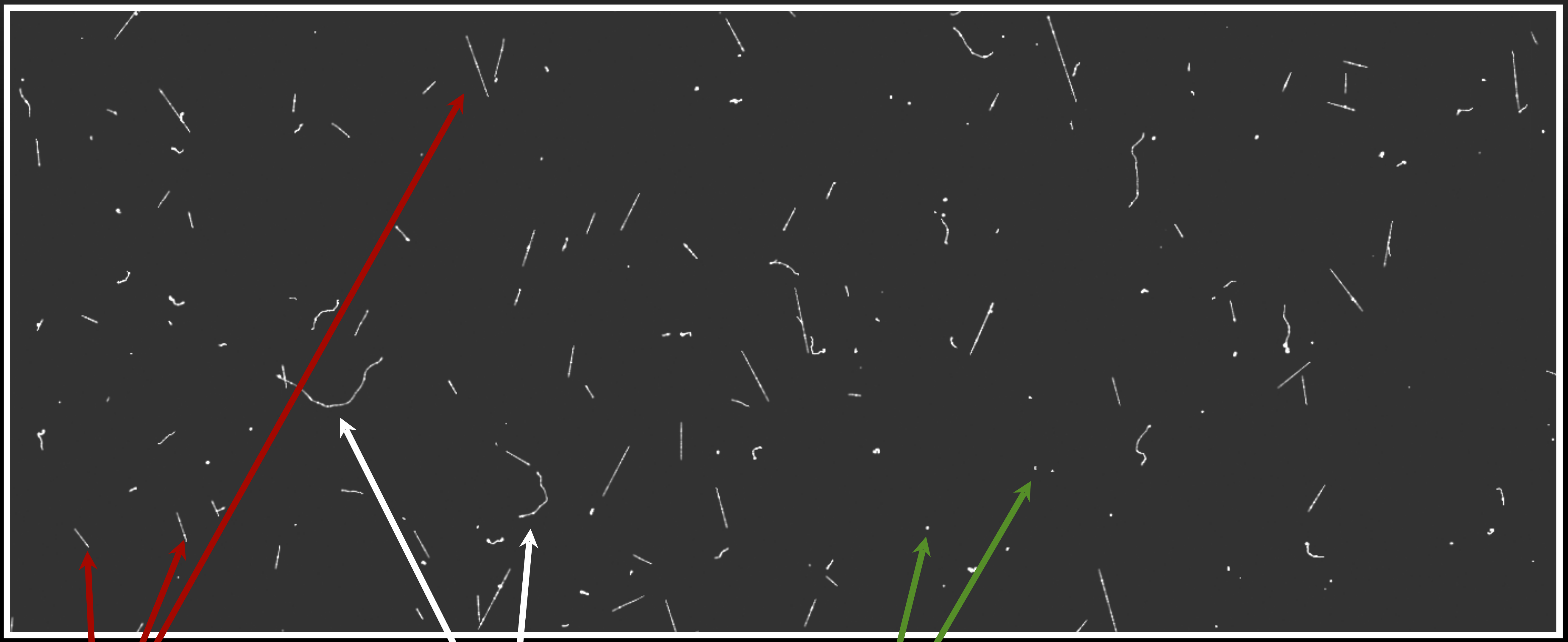


1 Mega-second exposure



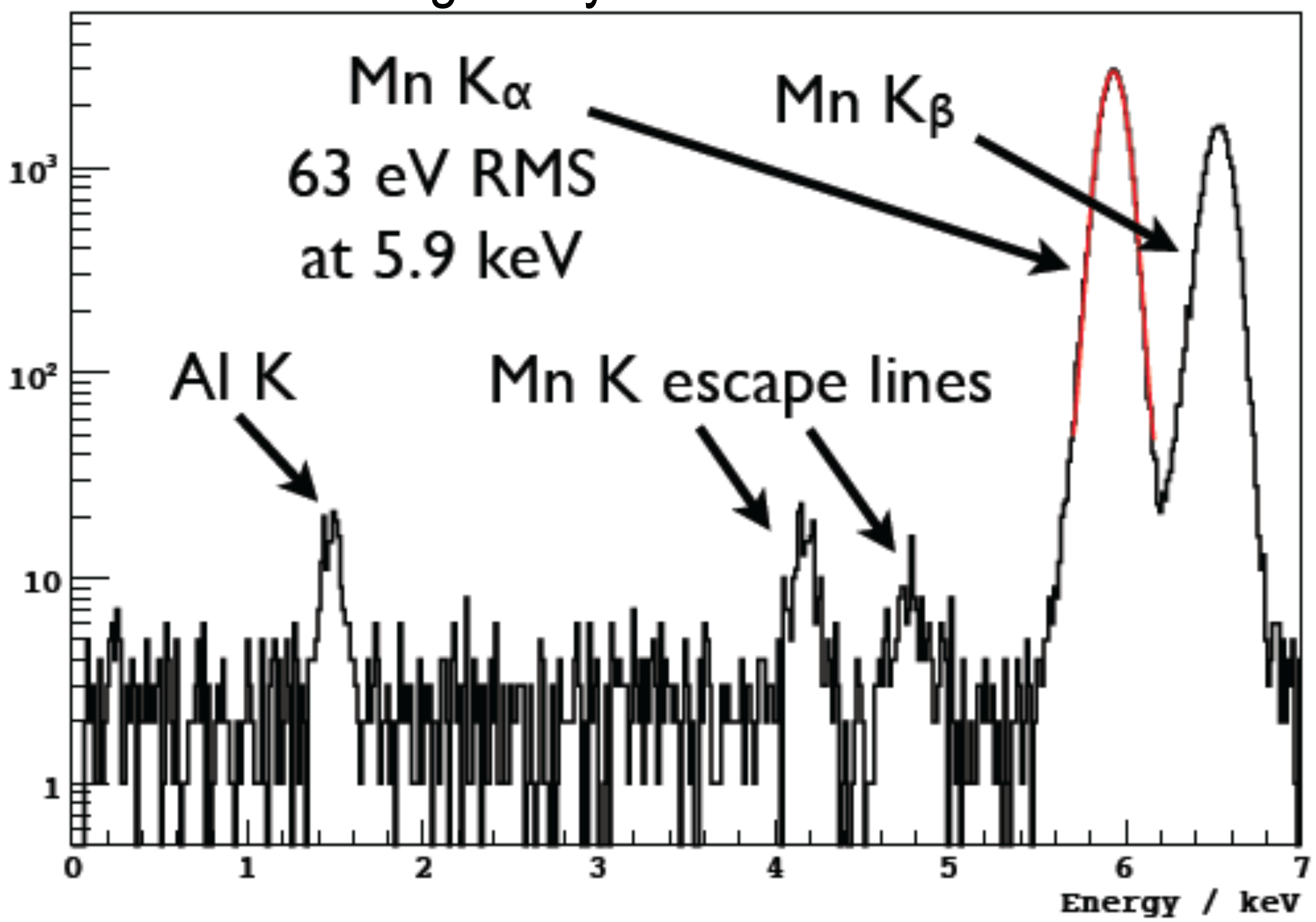


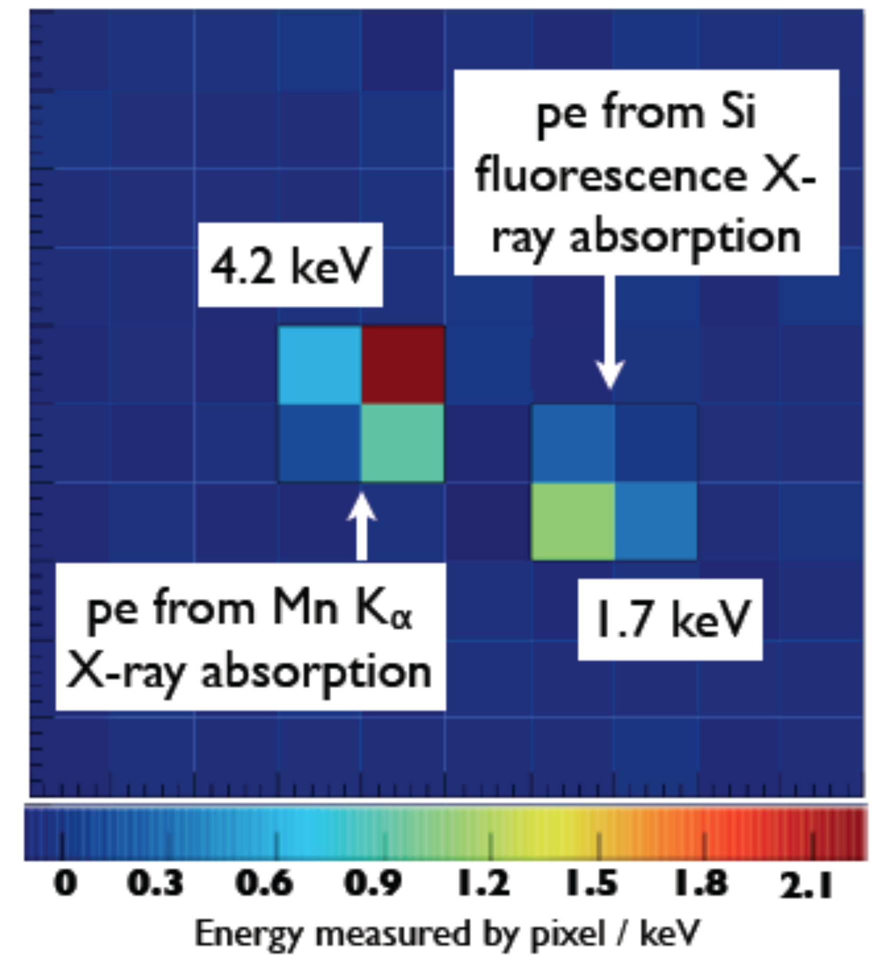
Particle identification in a CCD image

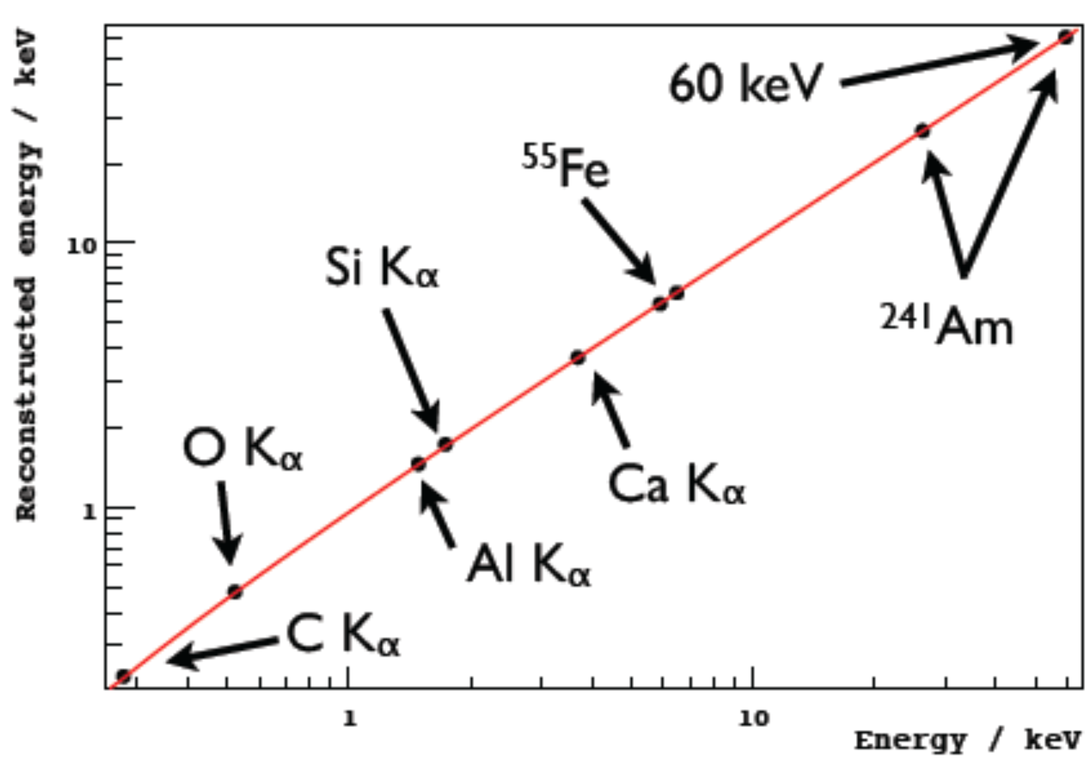


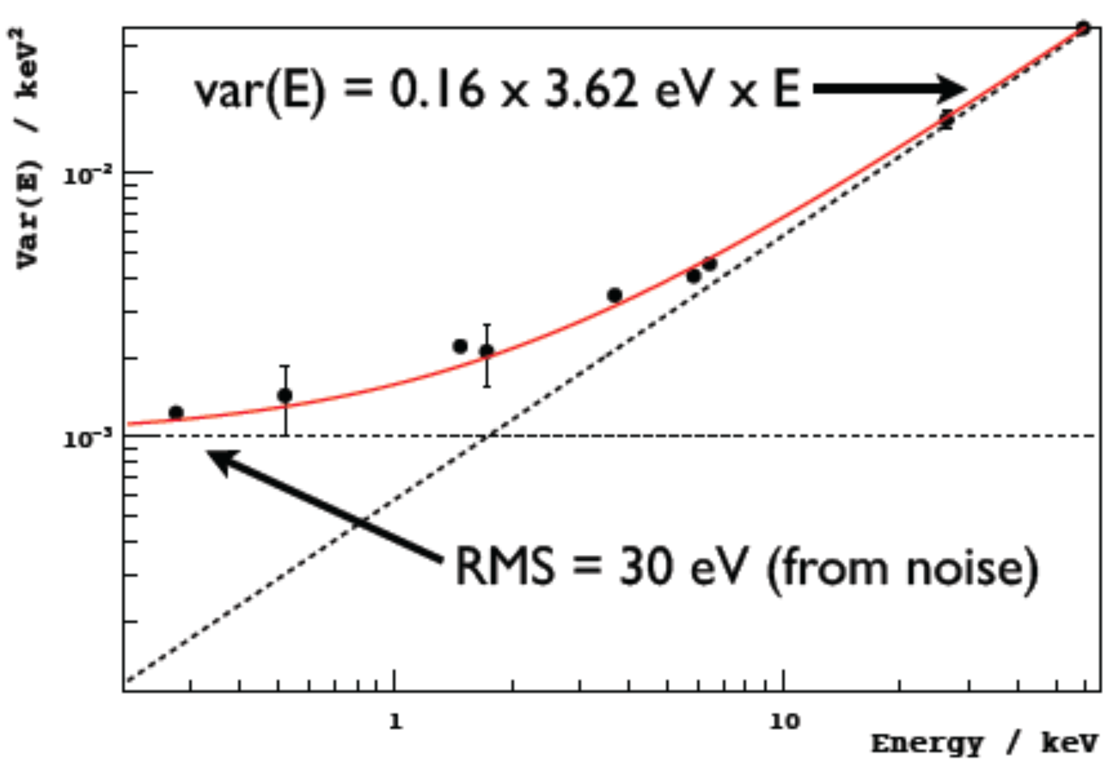
muons, electrons and diffusion limited hits.

Calibration using X-rays

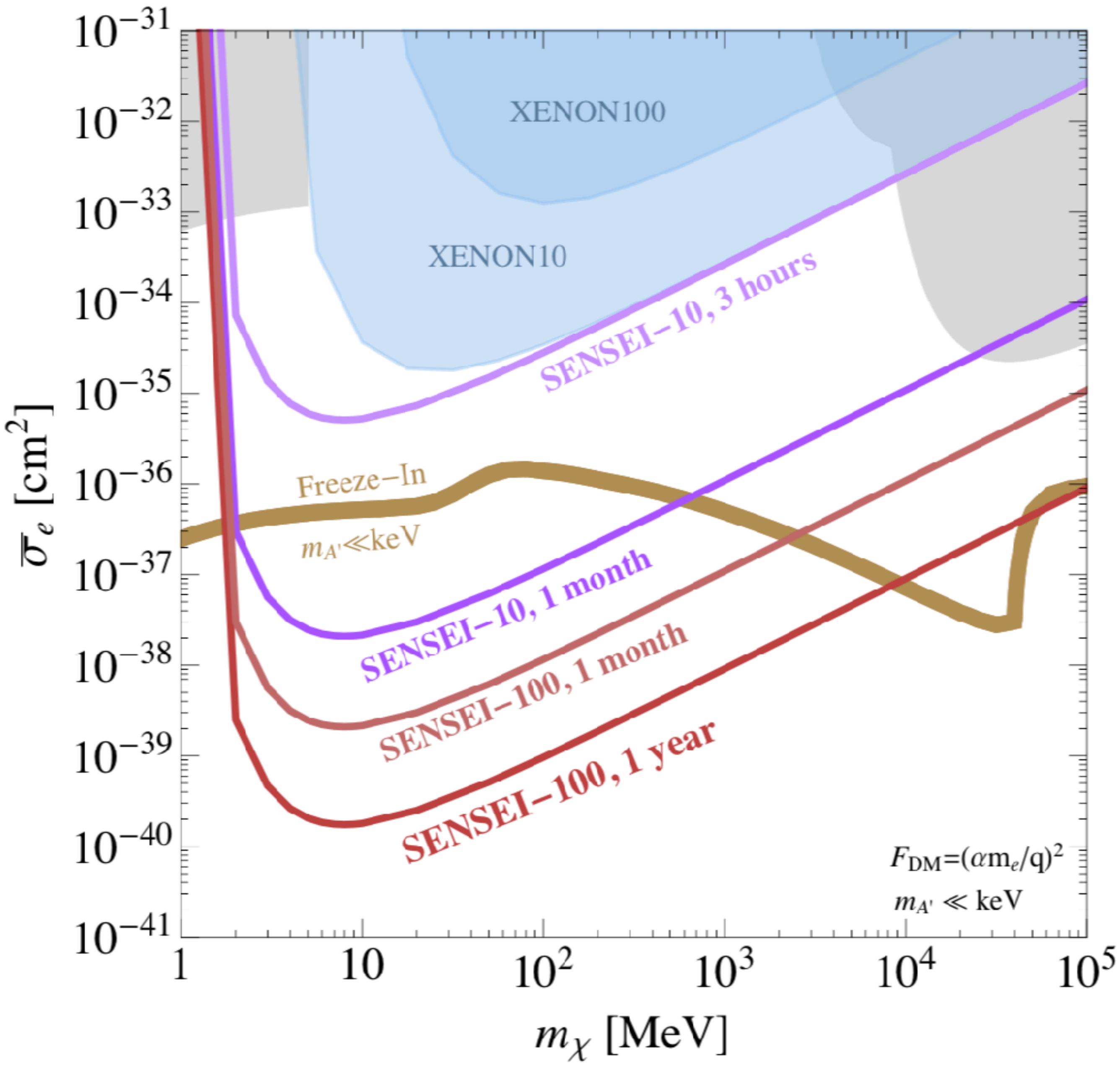


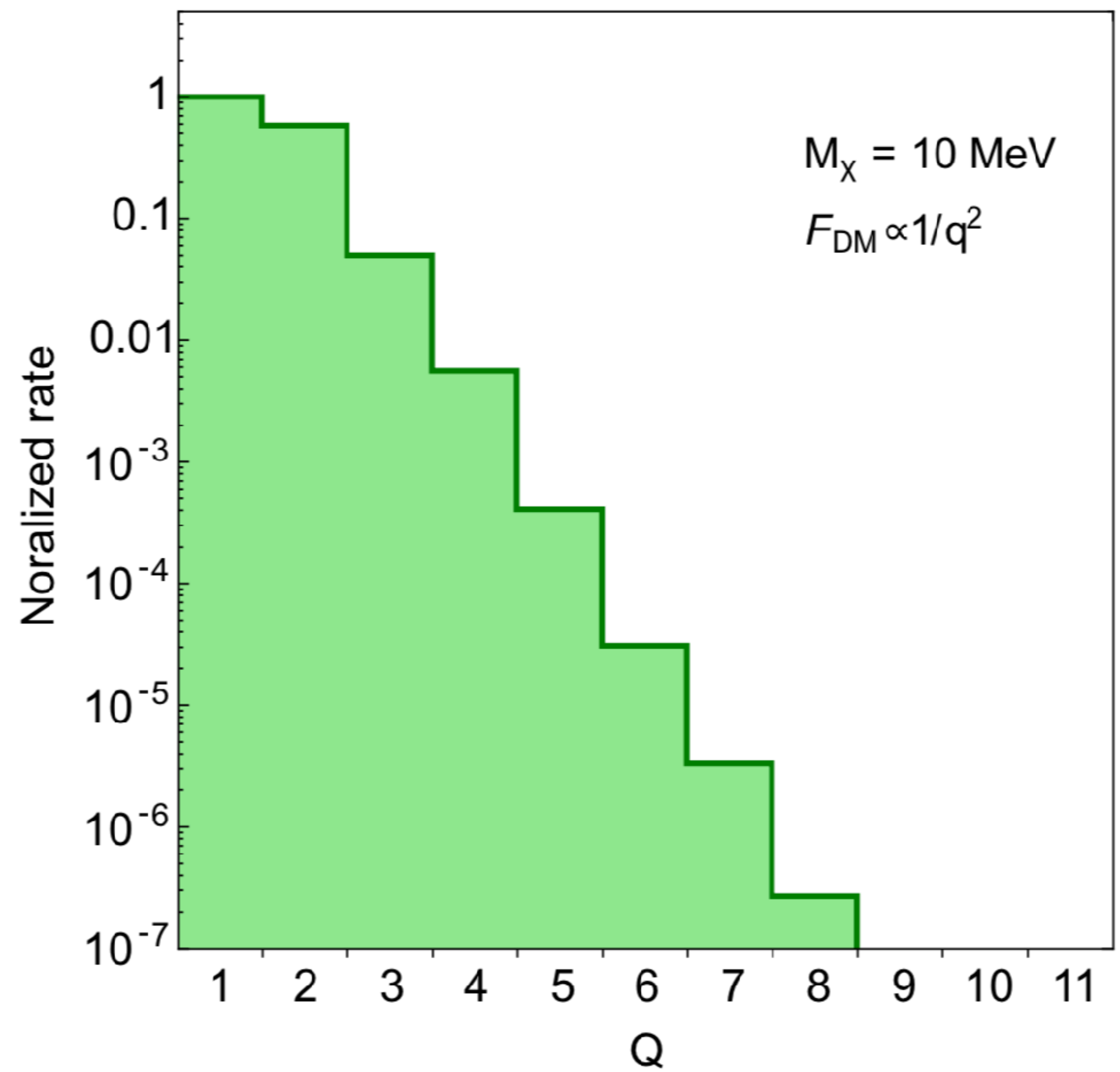


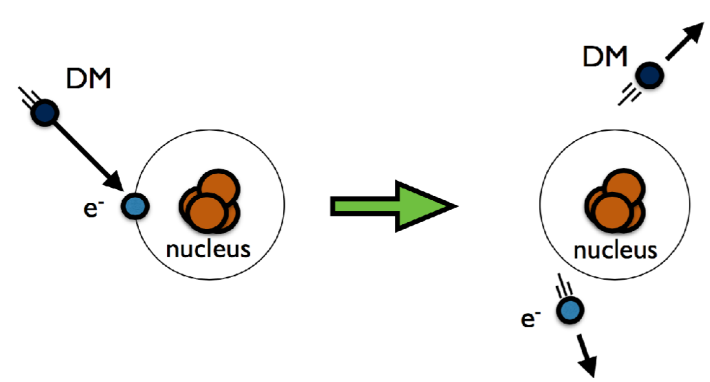




Once you can count electrons, you can search for electron recoils produced by very low mass dark matter (dark sector searches). This is what we are planning to do with the skipper-CCD in the **SENSEI experiment.**



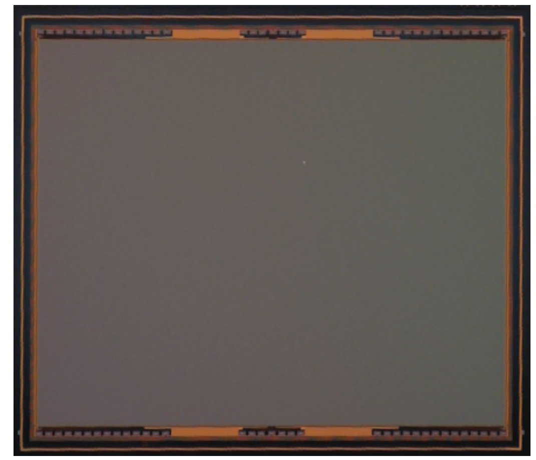




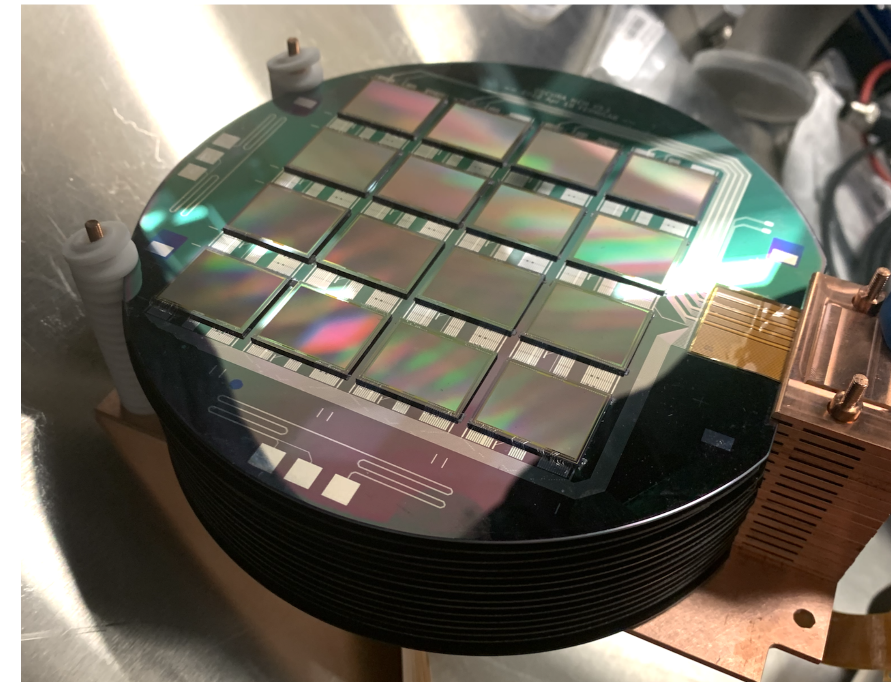
Design: Overall

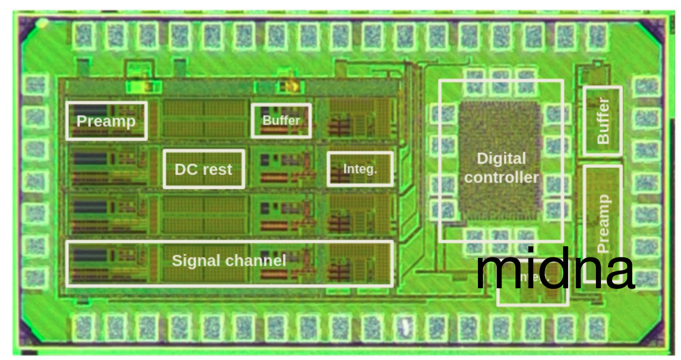
- **24,576 skipper-CCDs:**
  - 1.35 Mpix each
  - readout noise 0.15e-
  - 10 kg active mass
- **24,576 readout channels:**
  - cold front end electronics (MIDNA)
  - cold analog multiplexing
  - warm backend
- **1536 Multi Chip Modules (MCM)**
  - 16 CCDs mounted
  - Silicon substrate
  - low background flex
- **96 Super Modules (SM)**
  - 16 MCM on each
  - 130 g of active mass
- **Pressure vessel**
  - Nitrogen gas
  - internal copper and lead shield
- **Outside shield**
  - lead for gammas
  - poly/water for neutrons
- **Background**
  - Operated underground (SNOLAB)
  - 0.025 DRU

CCD

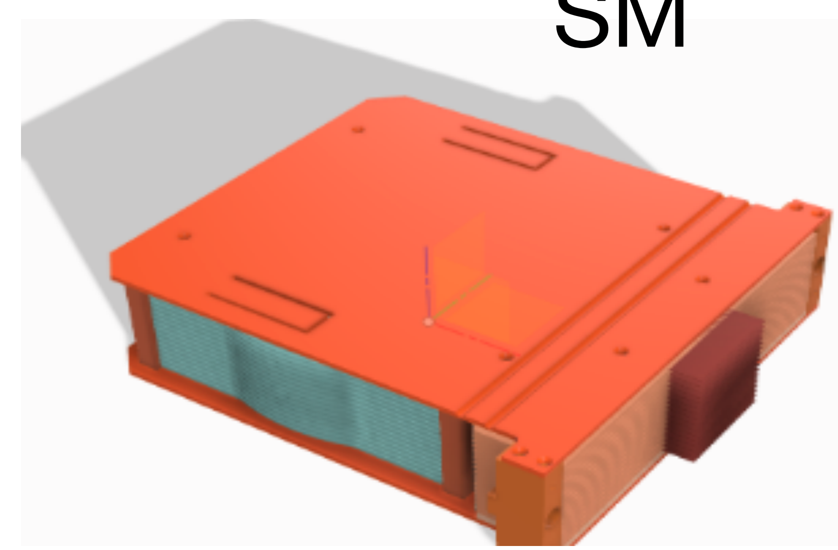


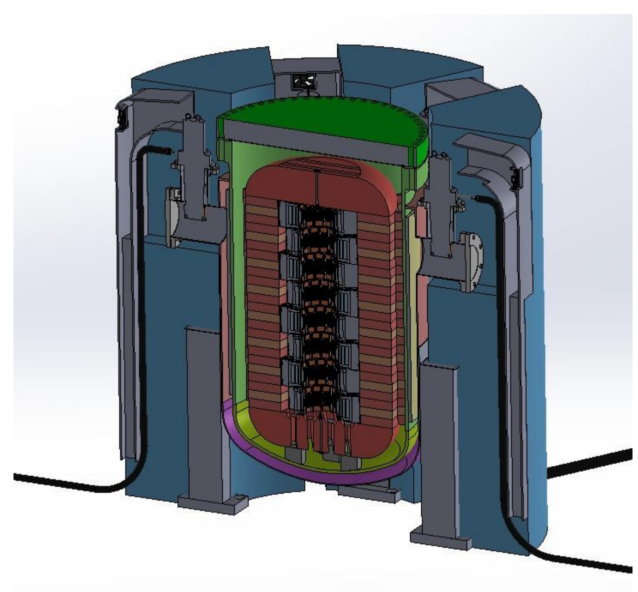
MCM





SM





pressure vessel