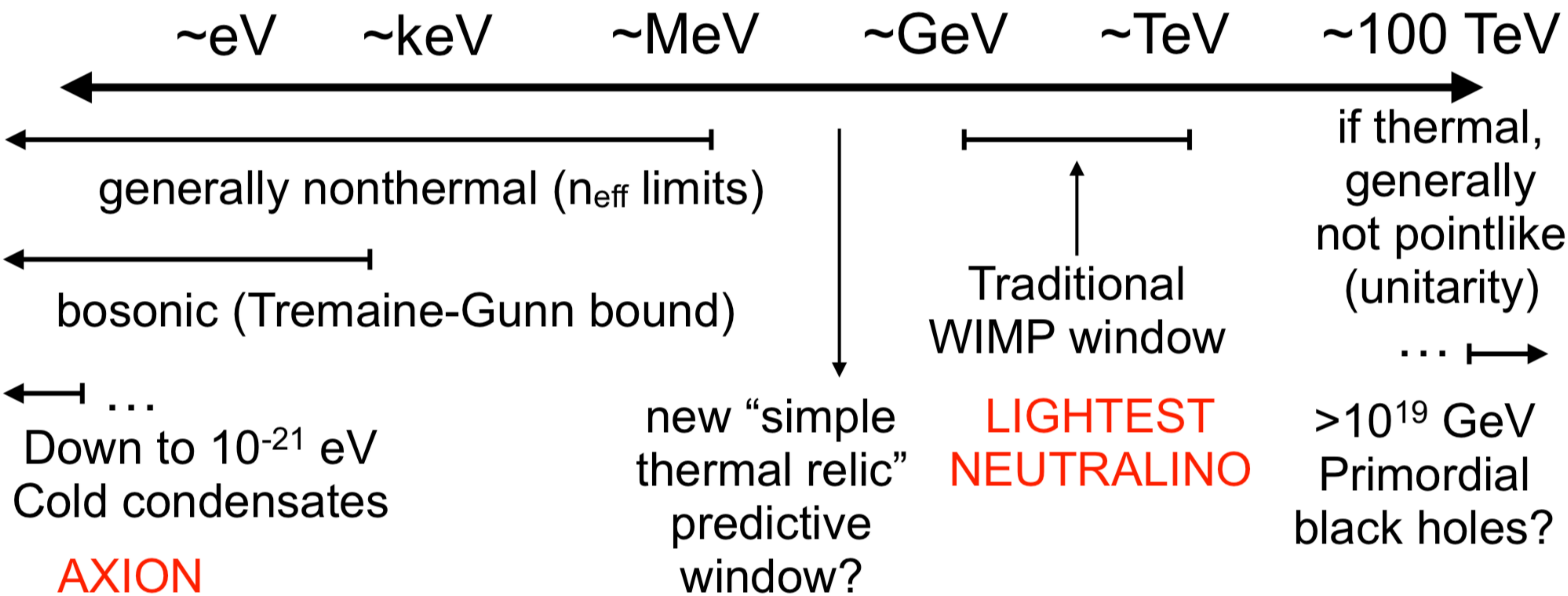
To the neutrino floor…
…and beyond…

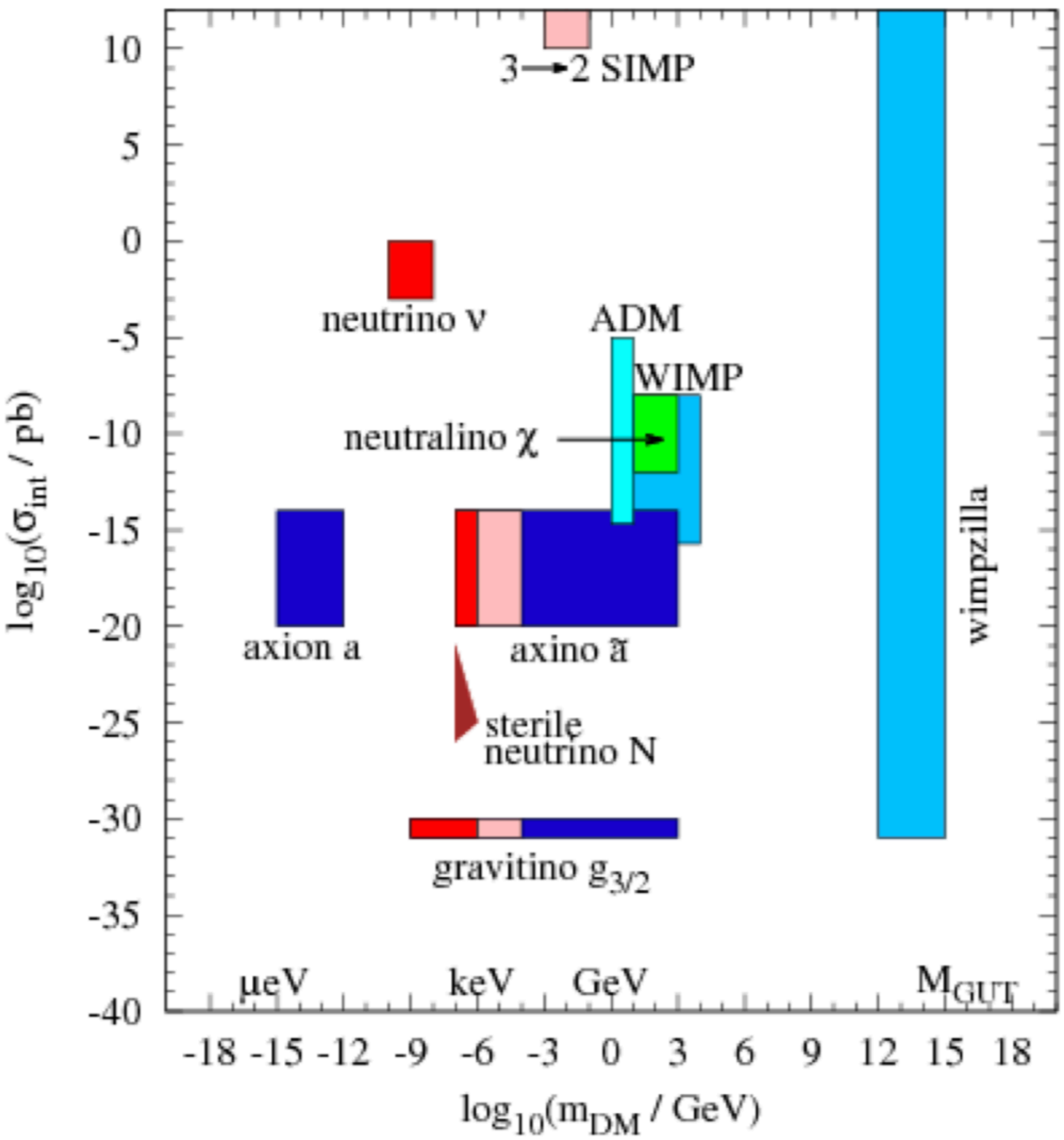
Walter M. Bonivento, INFN Cagliari, Italy

Low Mass DM searches in underground labs

Dark matter mass scales

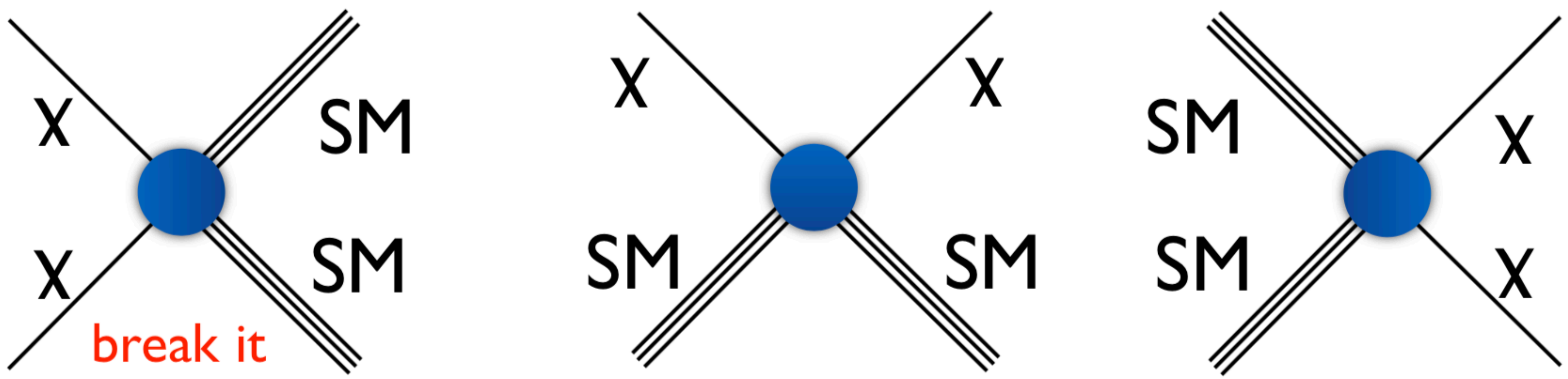


Baer et al. 2014



you are free to choose your preferred one…

WIMP searches

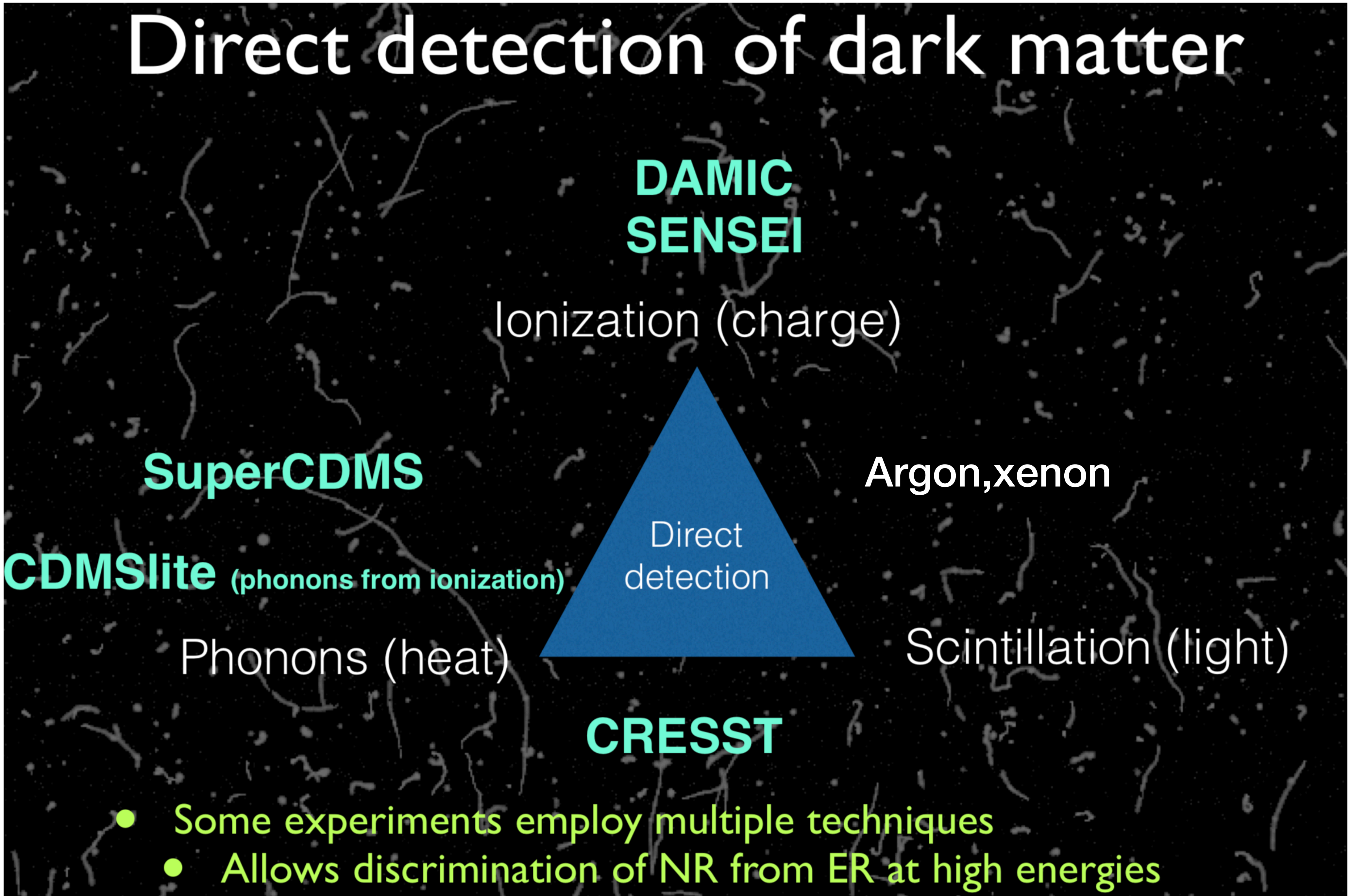


Indirect detection

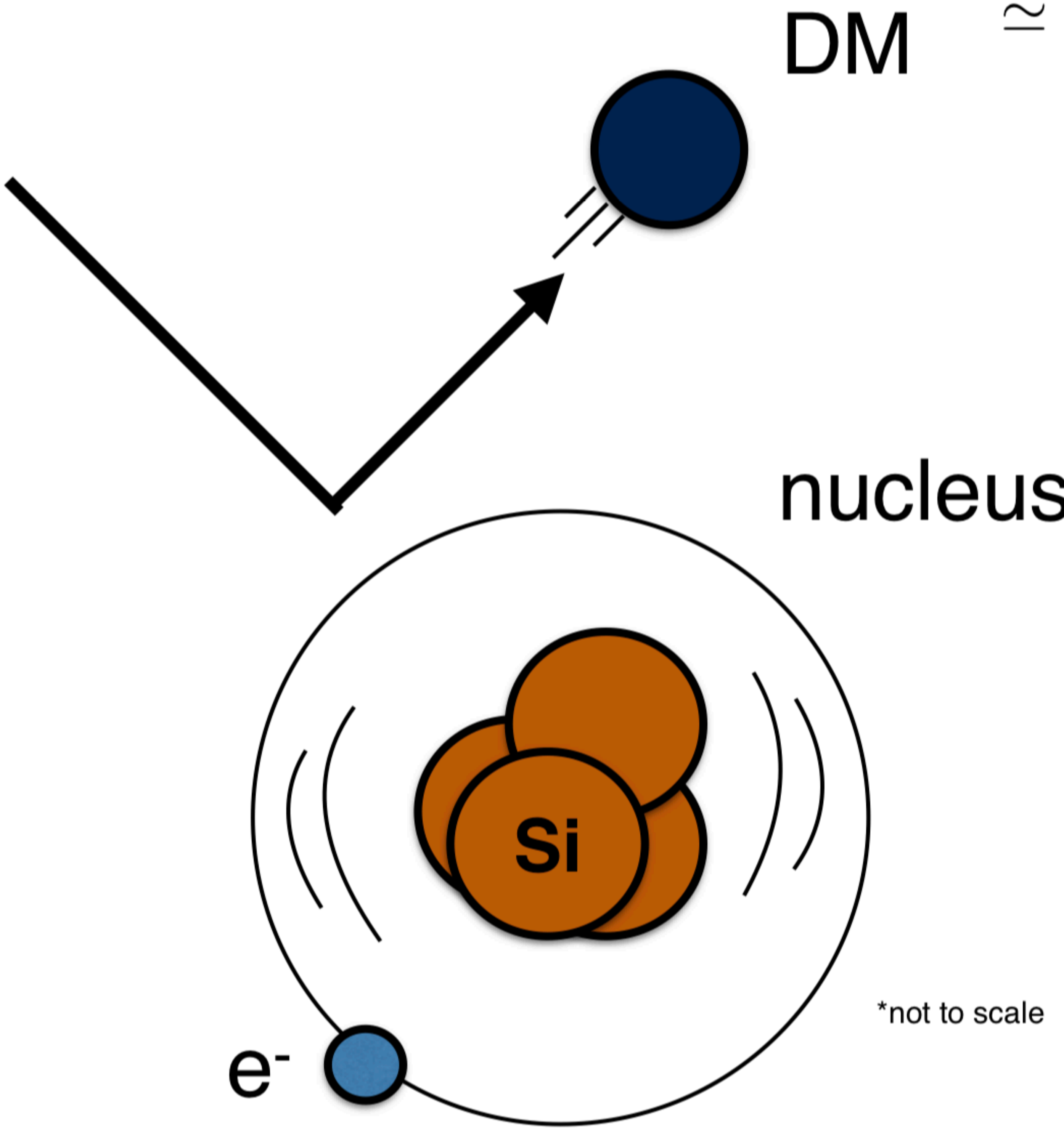
Direct detection

Collider

The triangle of WIMP detection



The high mass searches



$$E_R = \frac{q^2}{2m_N}$$

momentum transfer

$$\simeq 50\ \text{keV} \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)$$

nucleus mass

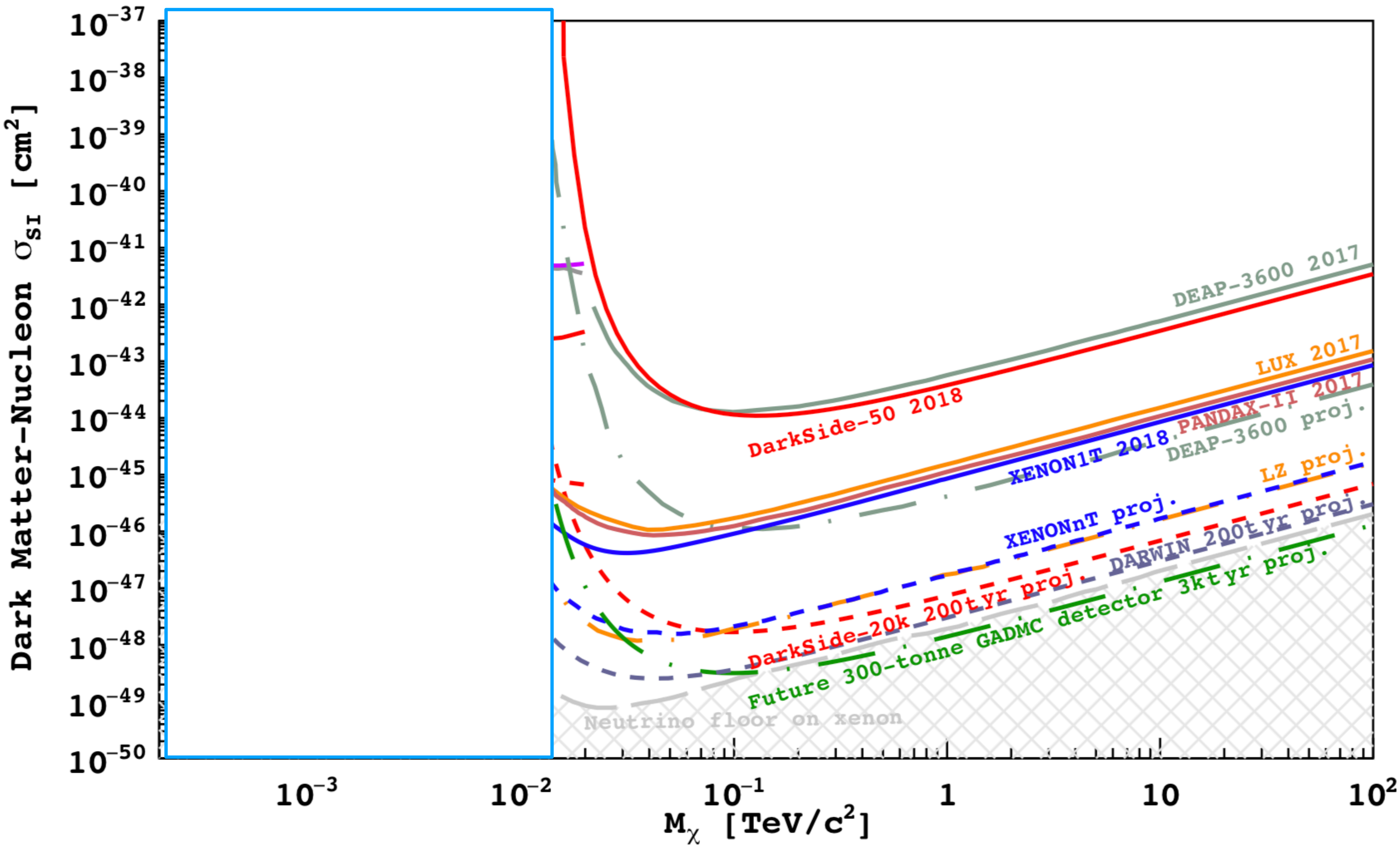
$$m_N = 28\ \text{GeV}$$

$$m_\chi = 100\ \text{GeV}$$

$$E_R \sim 100\ \text{keV}$$

available for detection

High mass status and prospects



The neutrino floor

A "real" bottom level for DM searches, since CENNS is really indistinguishable from WIMP scattering.
"Real" after the discovery of CENNS by COHERENT at ORNLL

At low masses it is dominated by solar neutrinos (^{8}B). The floor comes from the uncertainty on fluxes and CENNS cross sections. At best it will be a few %.

Could go lower by directional techniques, but those developed so far (mostly at low DM mass) have little mass (gas detectors, emulsions, carbon nano-tubes), while to go beyond the neutrino floor one needs large detector mass (exposures).

At present it is not something to worry about. It will be in the future. Some techniques may overcome the others since the floor depends on the material.

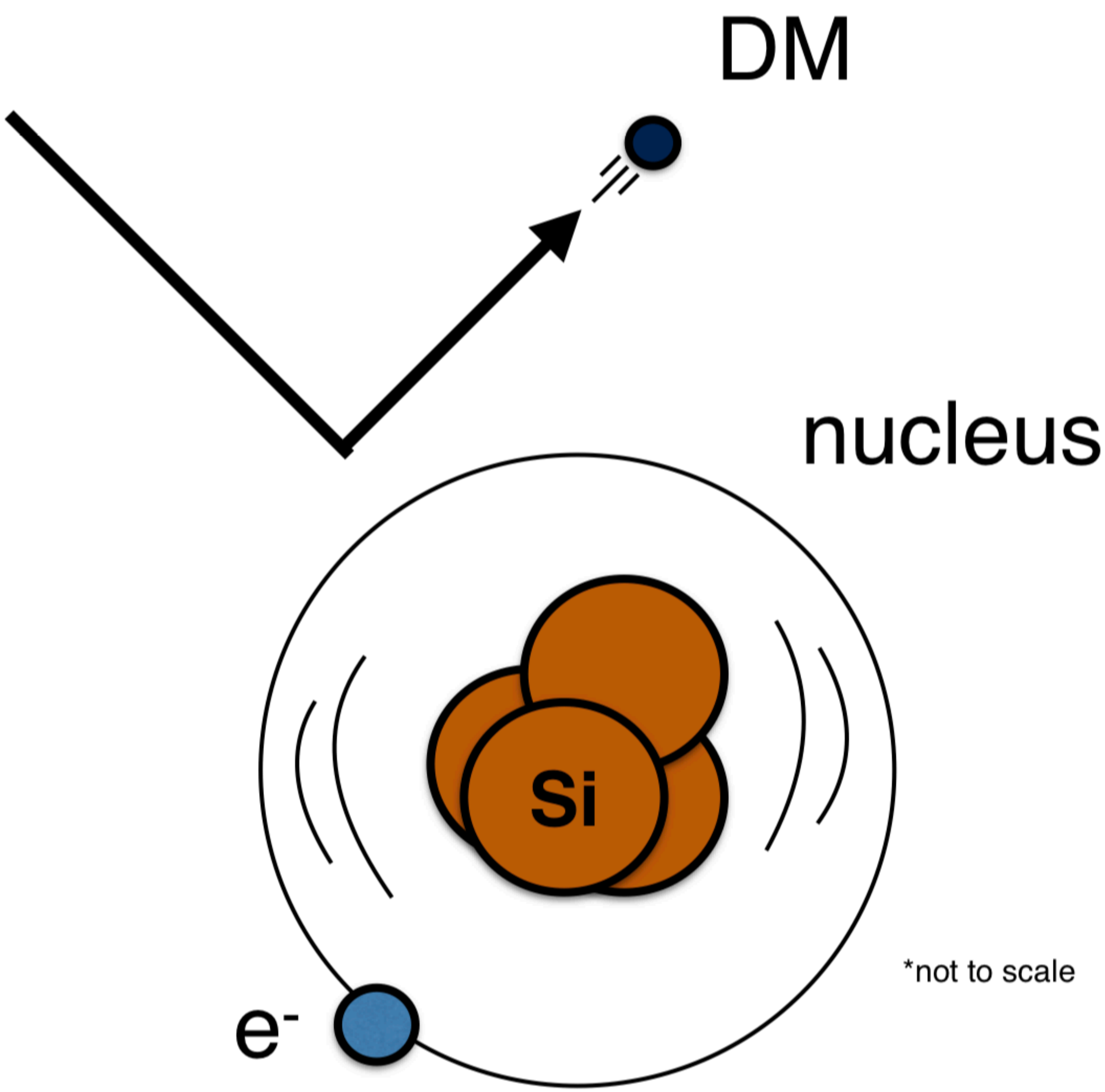
The low mass searches

$$E_R = \frac{q^2}{2m_N}$$

momentum transfer

$$\simeq 50 \text{ keV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

nucleus mass



$$m_N = 28 \text{ GeV}$$

$$m_\chi = 100 \text{ MeV}$$

$$E_R \sim 0.1 \text{ eV}$$

available for detection

detecting sub-GeV DM in 2 easy steps

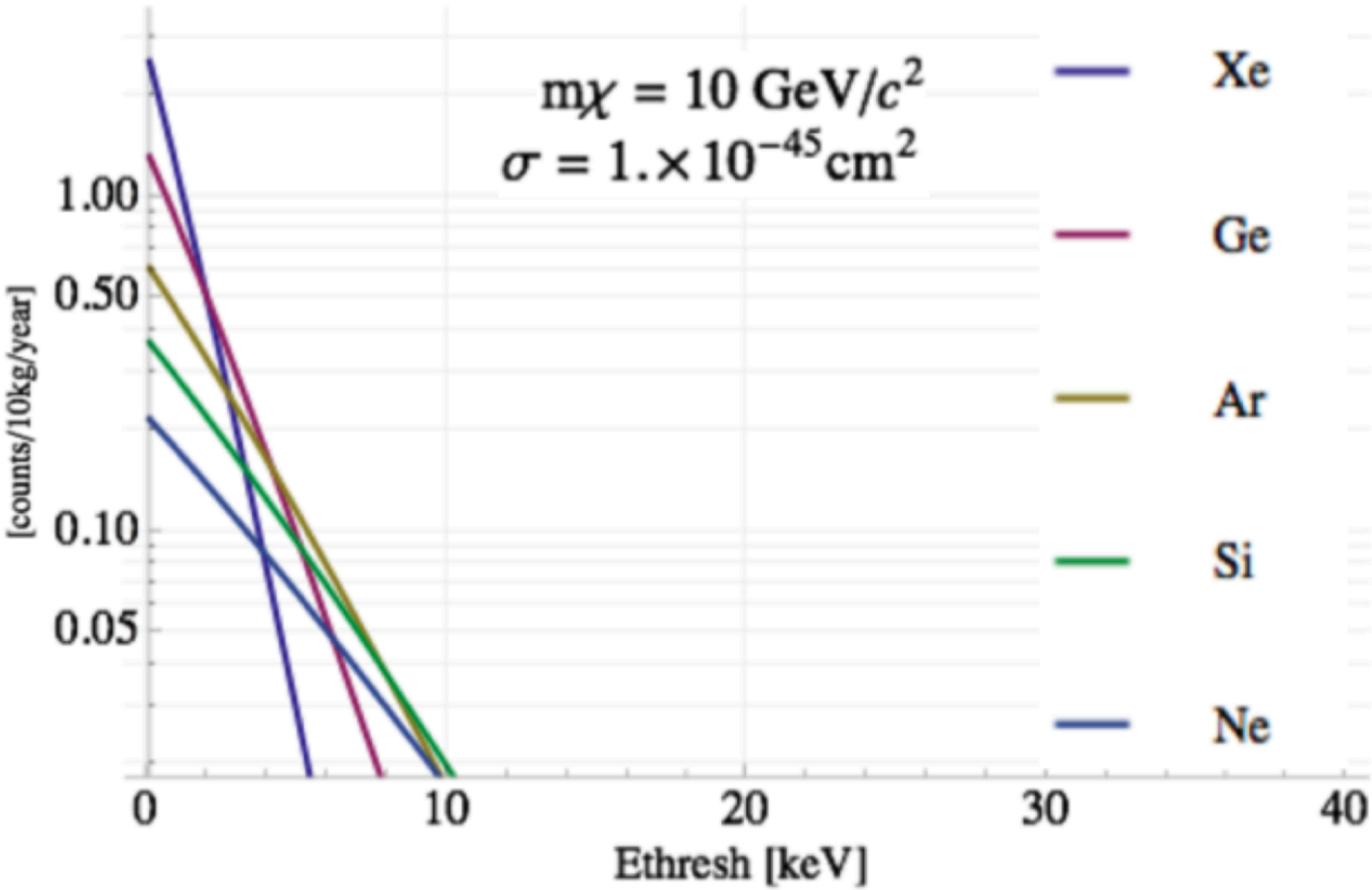
1. decrease energy threshold or increase sensitivity

consider a variety of materials

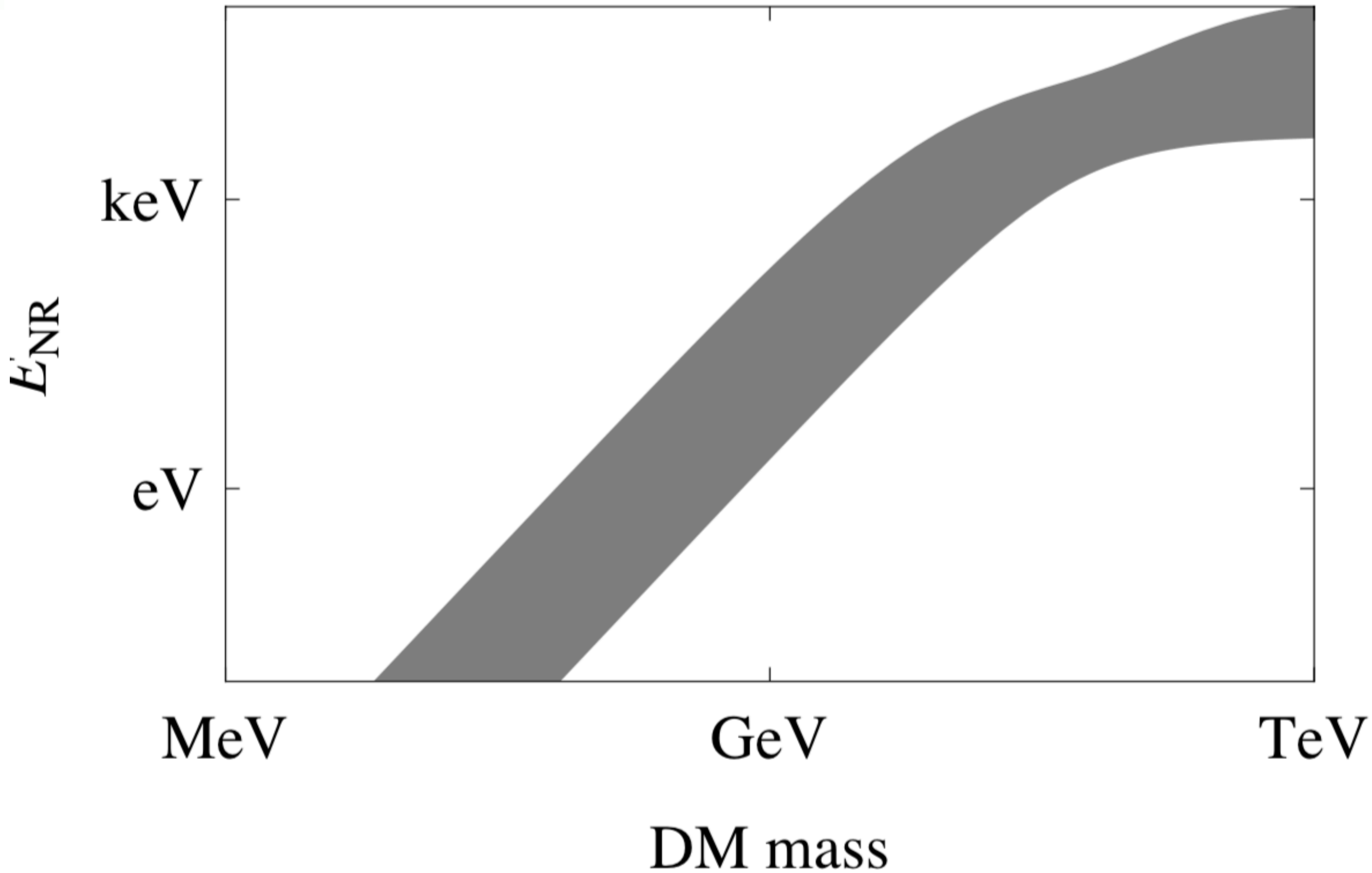
2. increase amount of detectable energy

consider different physical processes

Recoil spectra



[a] Mirabolfathi - arXiv:1308.0044



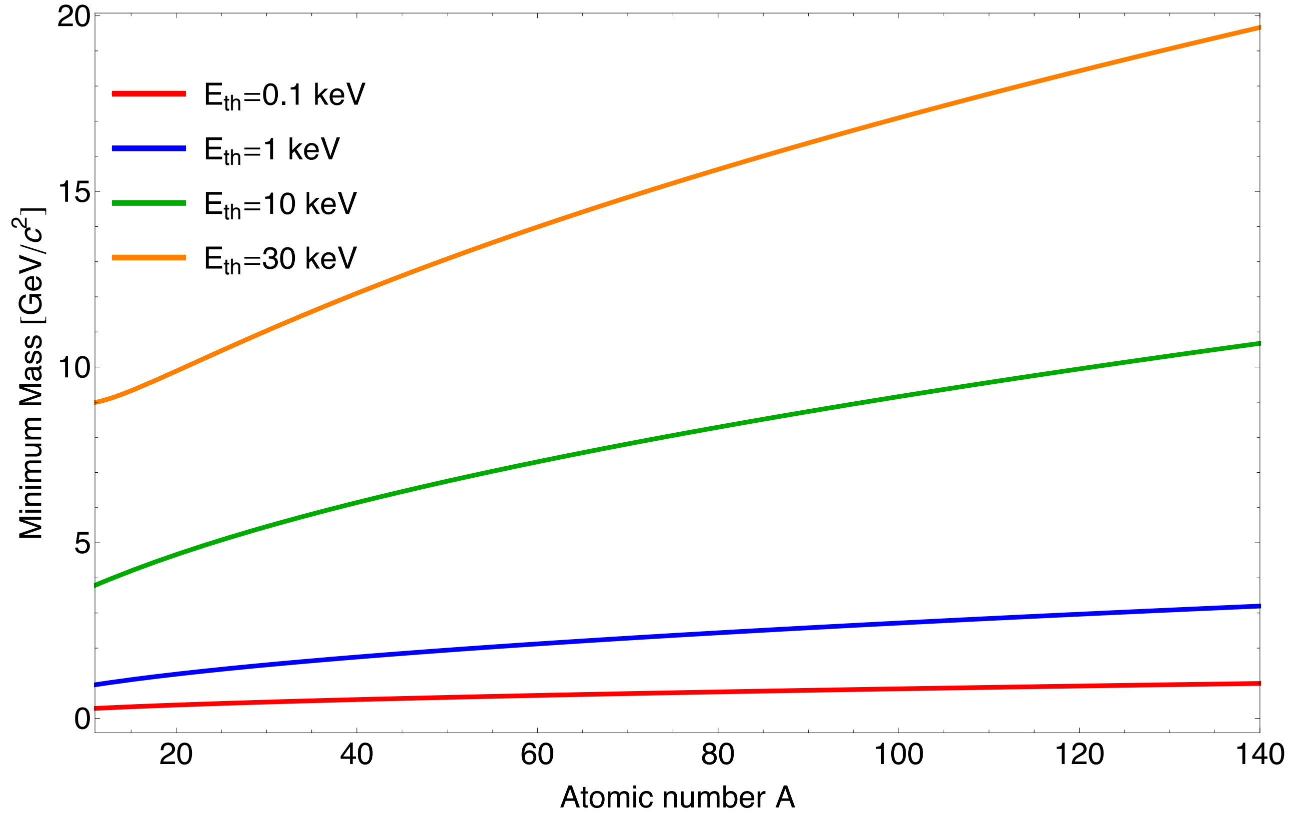
Exp	E_{th} (keV_{NR})	Ref
LUX	~3	1512.03506
DAMIC	~0.5	1510.00044
CDMSlite	~0.3	1509.02448
CRESST-II	~0.3	1509.01515

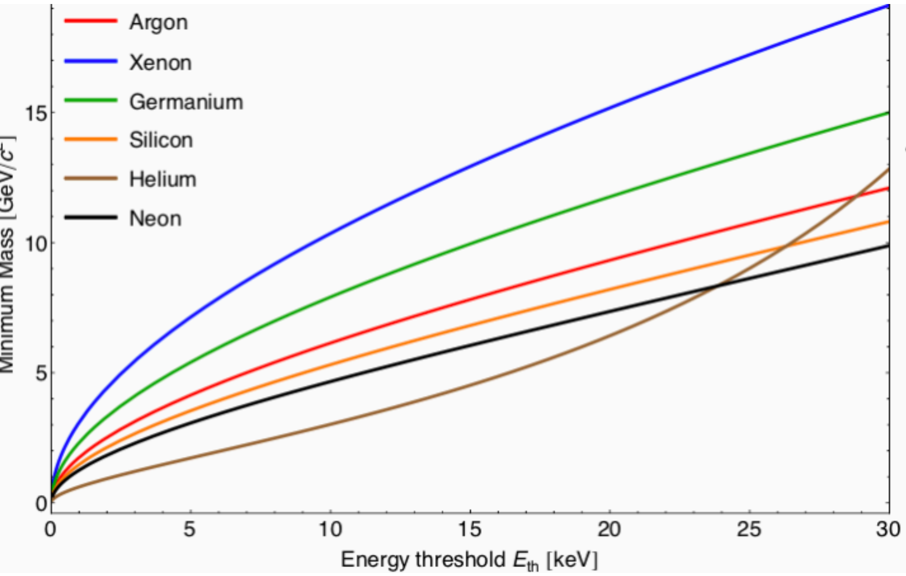
DARKSIDE 50 0.6

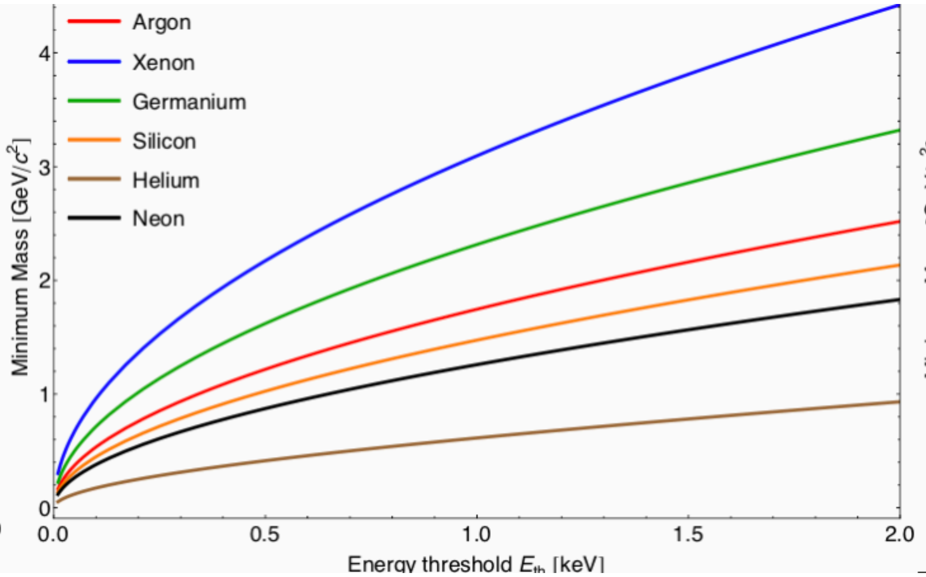
SuperCDMS —>40eV in prospect

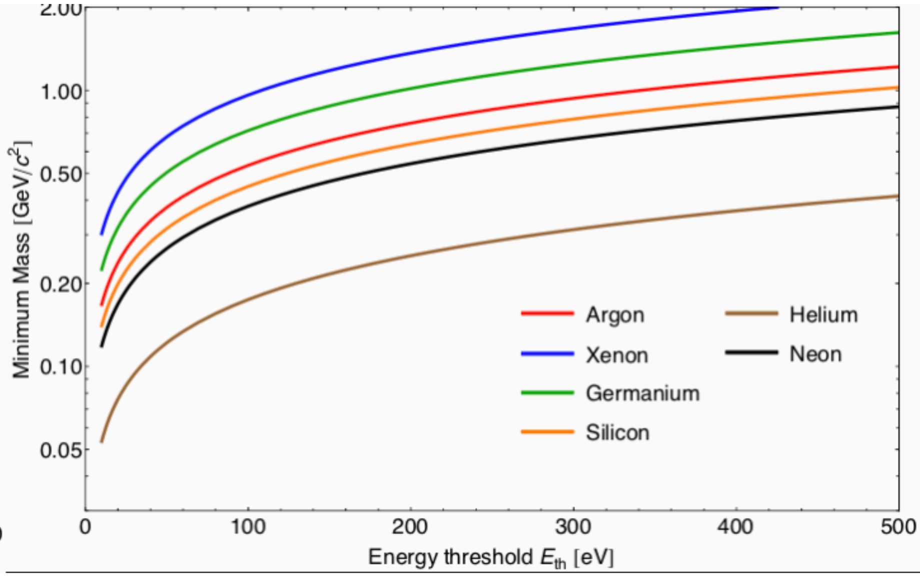
CRESST-III 30eV—>10eV in prospect

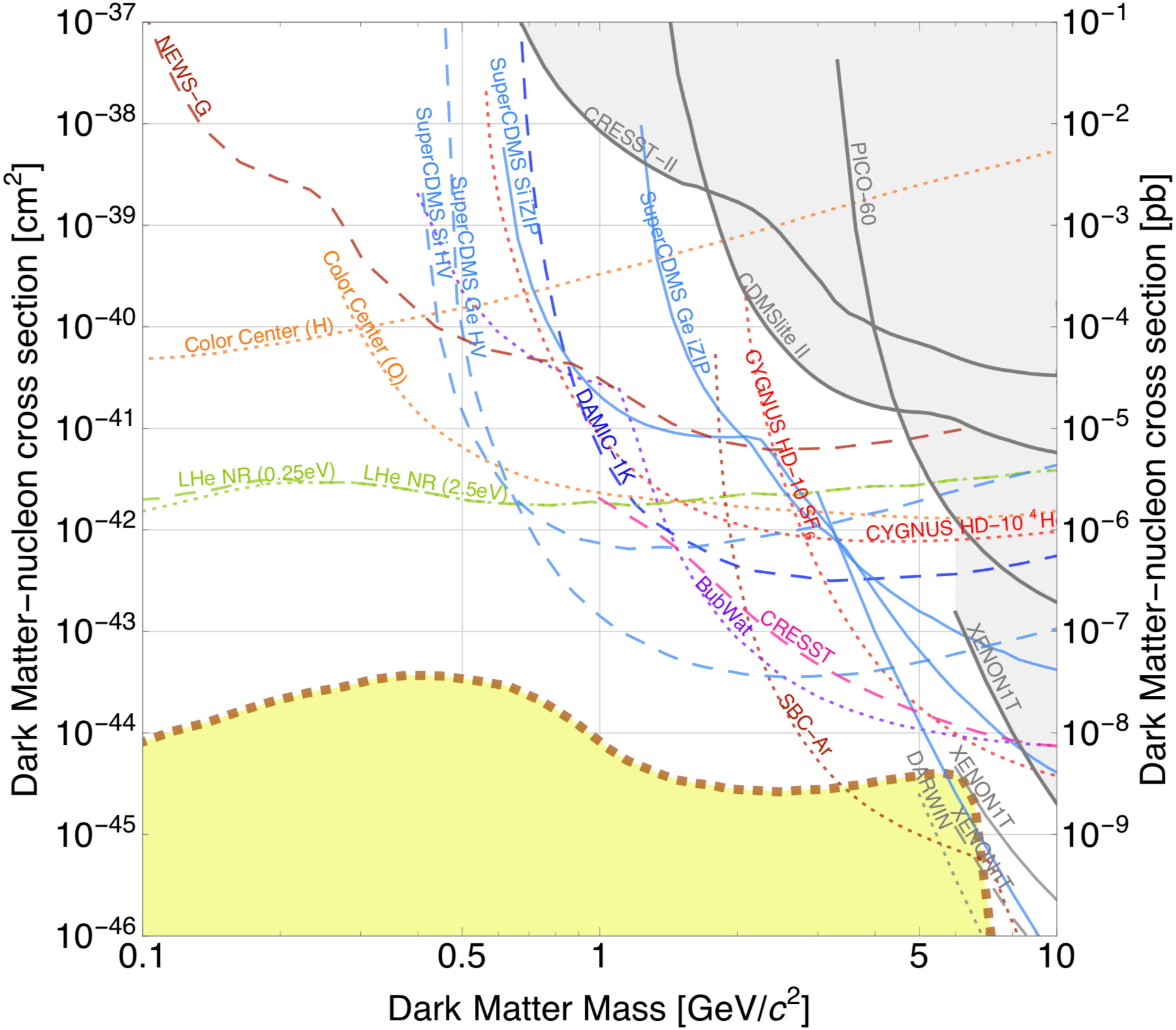
Thresholds vs minimum DM mass



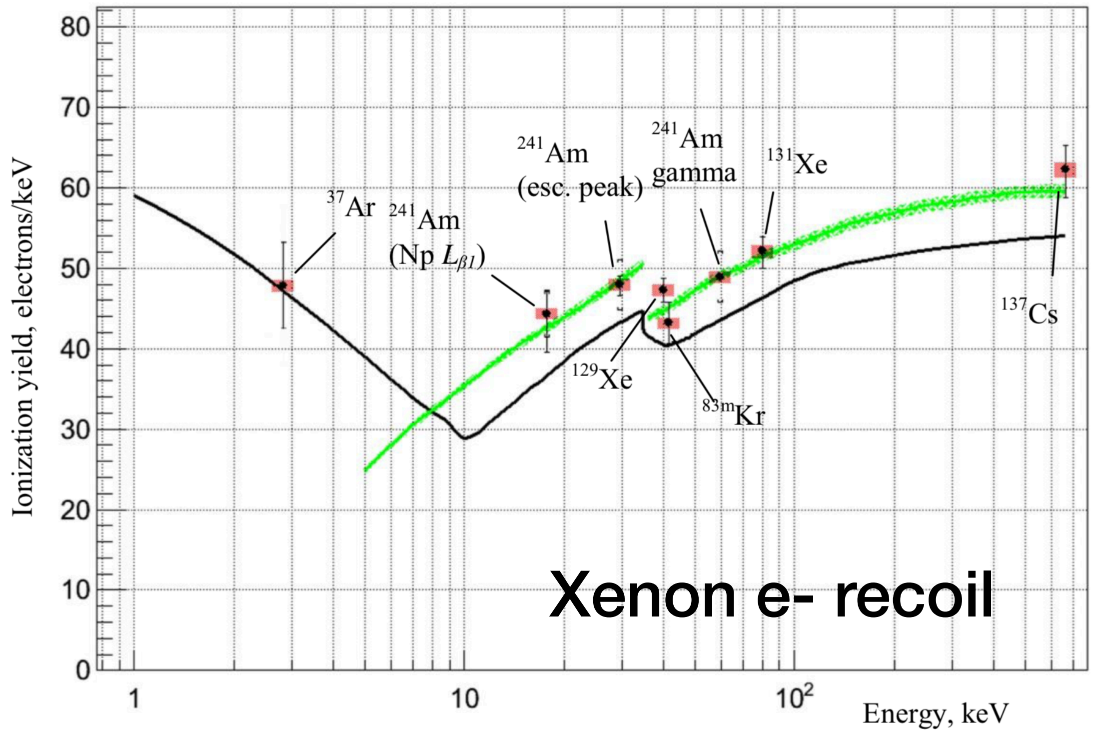


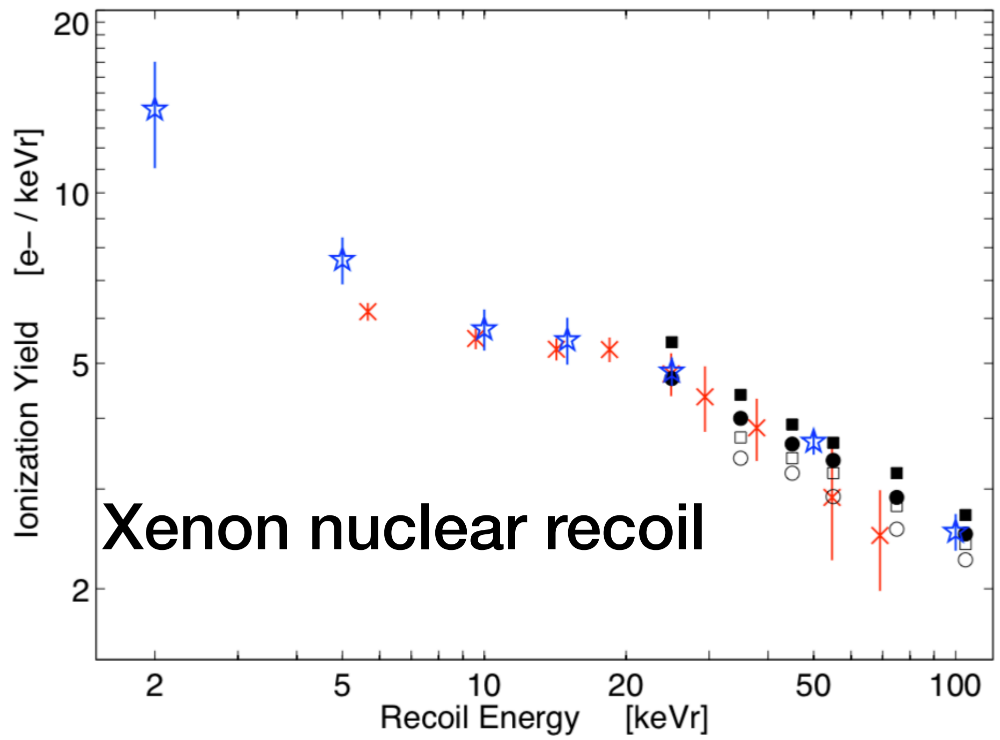





Dark Matter–nucleon cross section [cm^2]
Dark Matter–nucleon cross section [pb]
Dark Matter Mass [GeV/c^2]
NEWS-G
Color Center (H)
Color Center (O)
LHe NR (0.25eV)
LHe NR (2.5eV)
SuperCDMS Si HV
SuperCDMS Ge HV
SuperCDMS Si iZIP
SuperCDMS Ge iZIP
DAMIC-1K
CRESST-II
CDMSlite II
PICO-60
CYGNUS HD-10 SF$_6$
CYGNUS HD-10 ^{4}He
BubWat
CRESST
SBC-Ar
XENON1T
DARWIN

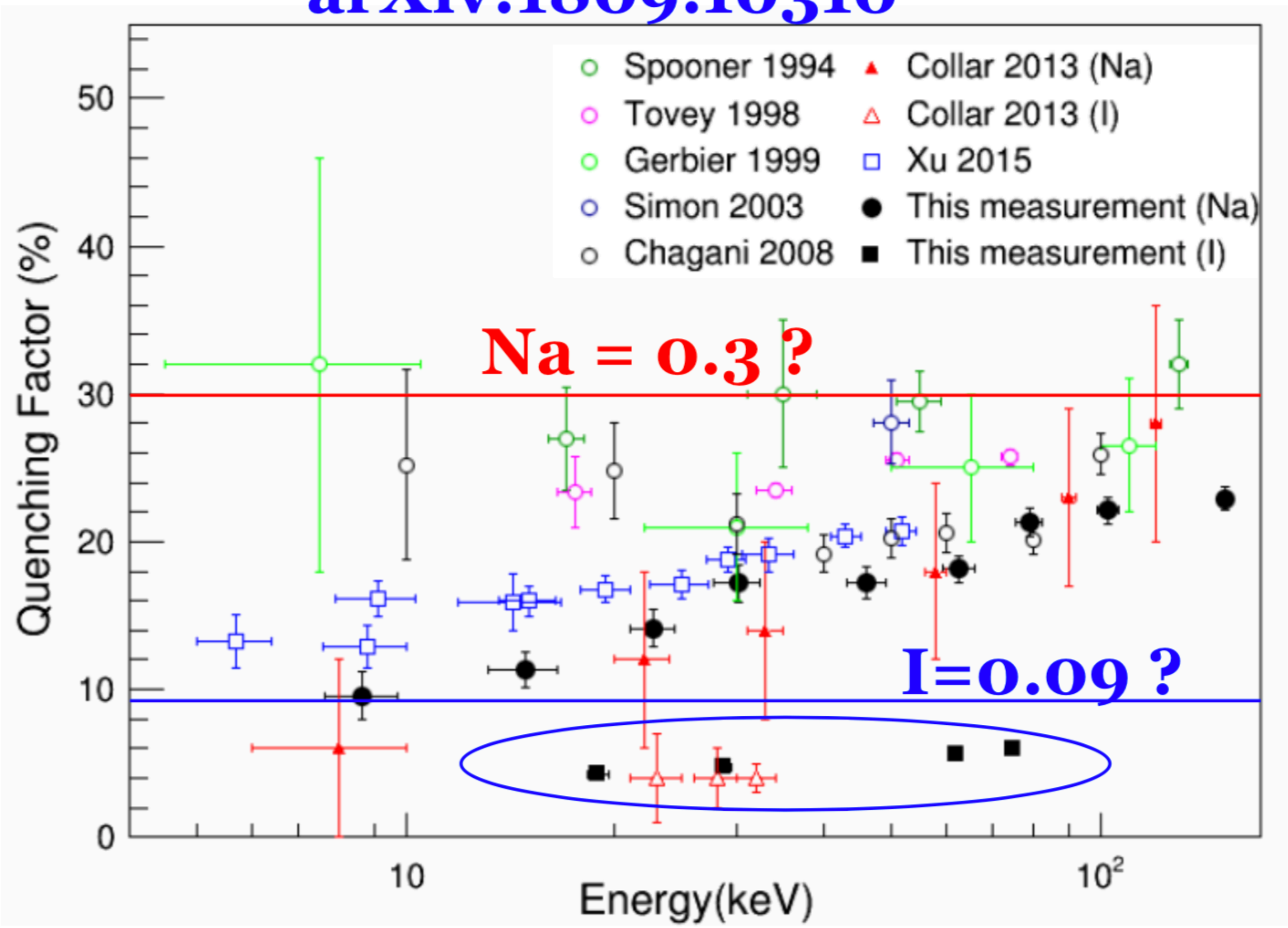
Issues a): ionisation response calibration





Issues a): scintillation response calibration; nuclear quenching!

arXiv:1809.10310



Very difficult measurements, in particular at low energies, that require real side experiments that last for years!

Issues b): background suppression

Backgrounds to DM searches are:

- cosmogenic activation or n-induced (not really direct cosmic rays)—> going underground
- radiogenic (material radioactivity)
  - shielding
  - material screening (experiments in the experiments)

For the low mass DM searches the particle id capabilities are generally lost (due to the low recoil energy)

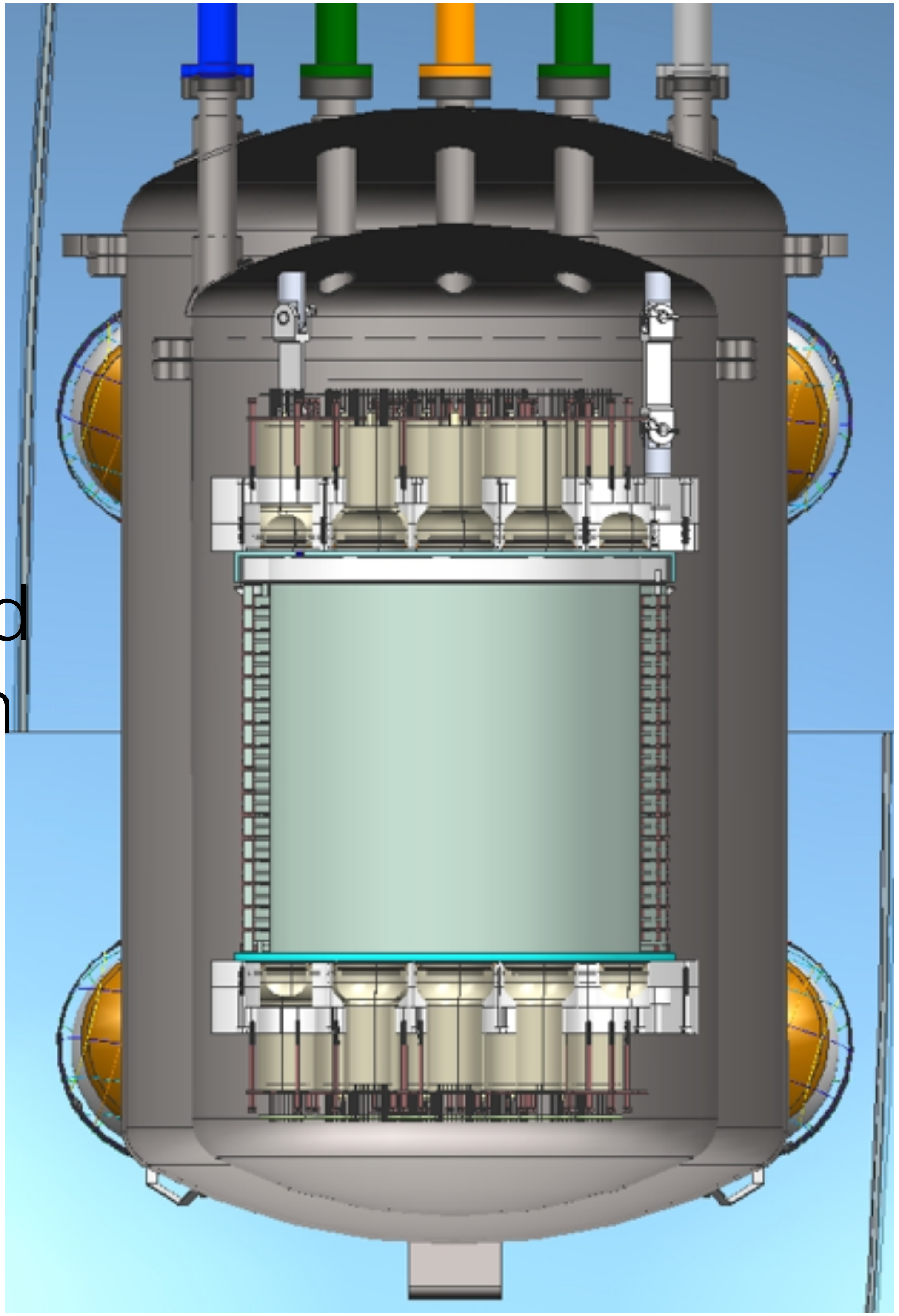
Therefore the dominant backgrounds are by far the electron recoils (e.g. ^{40}K in NaI crystals)

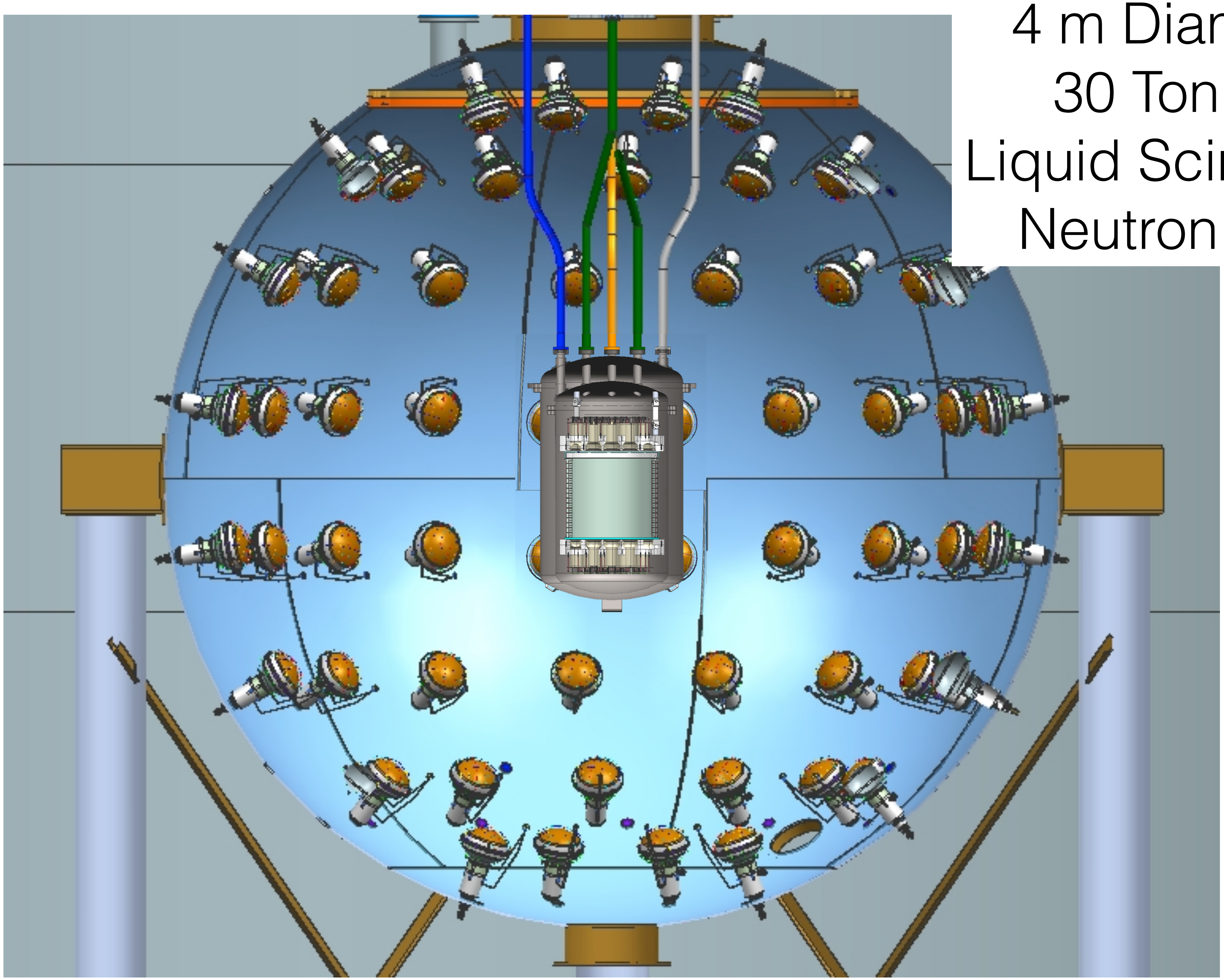
New backgrounds appear that are not present at high masses:

- single electrons trapped (noble liquids)
- unknown stuff (e.g. CRESST-III)

Setting the stage: DarkSide-50 results

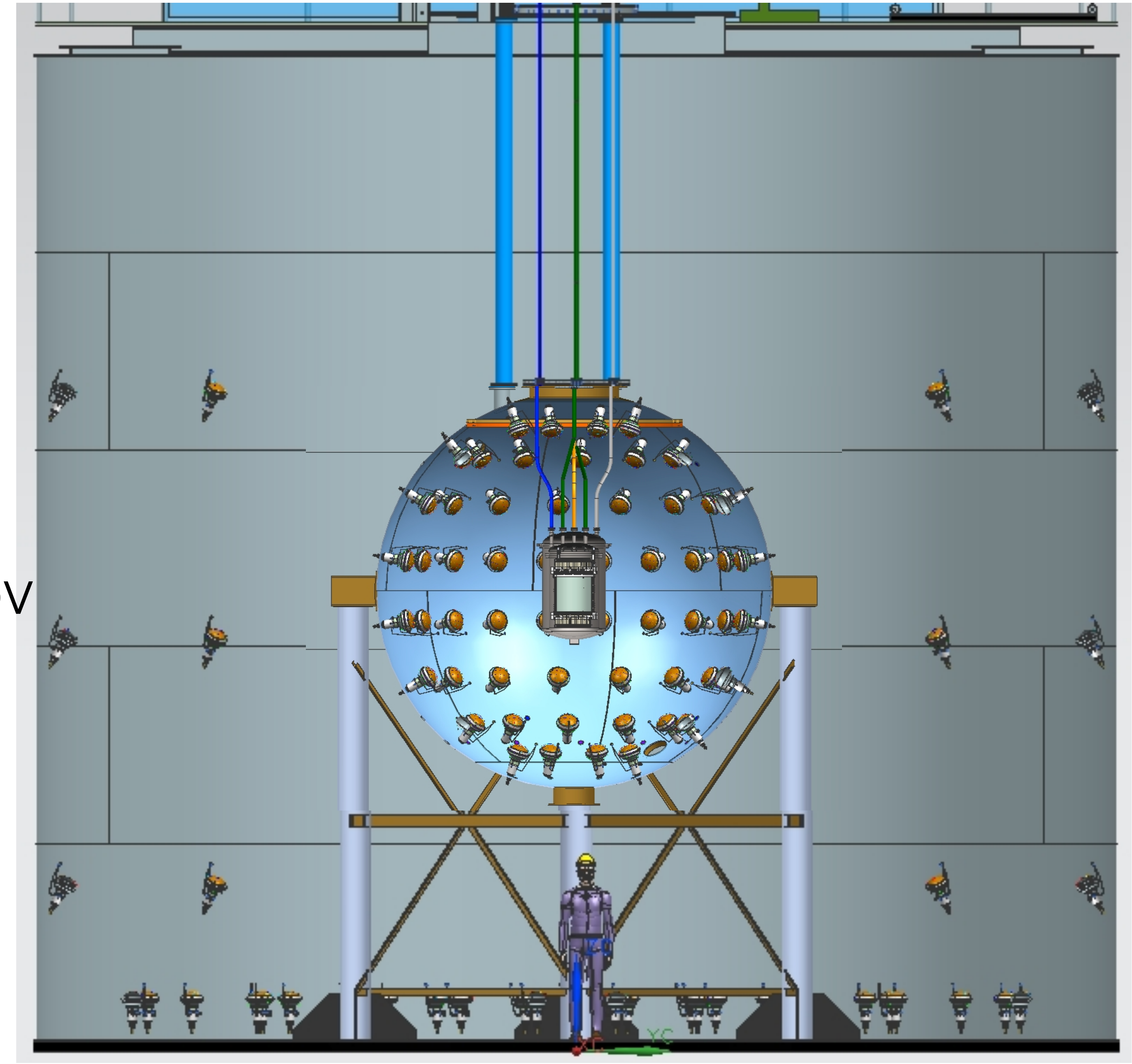
Liquid Argon TPC
153 kg ^{39}Ar-Depleted
Underground Argon
Target



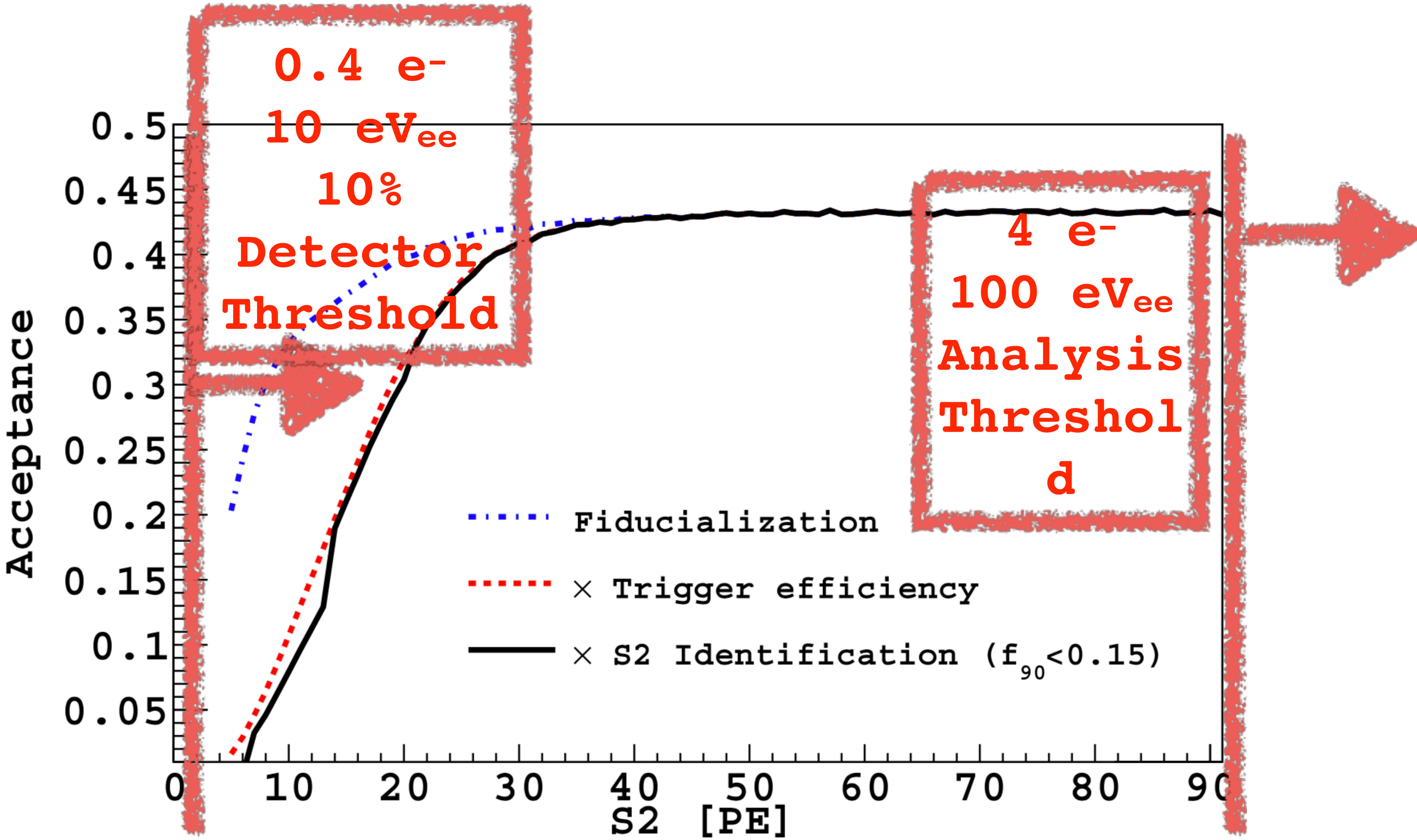


4 m Diameter
30 Tonnes
Liquid Scintillator
Neutron Veto

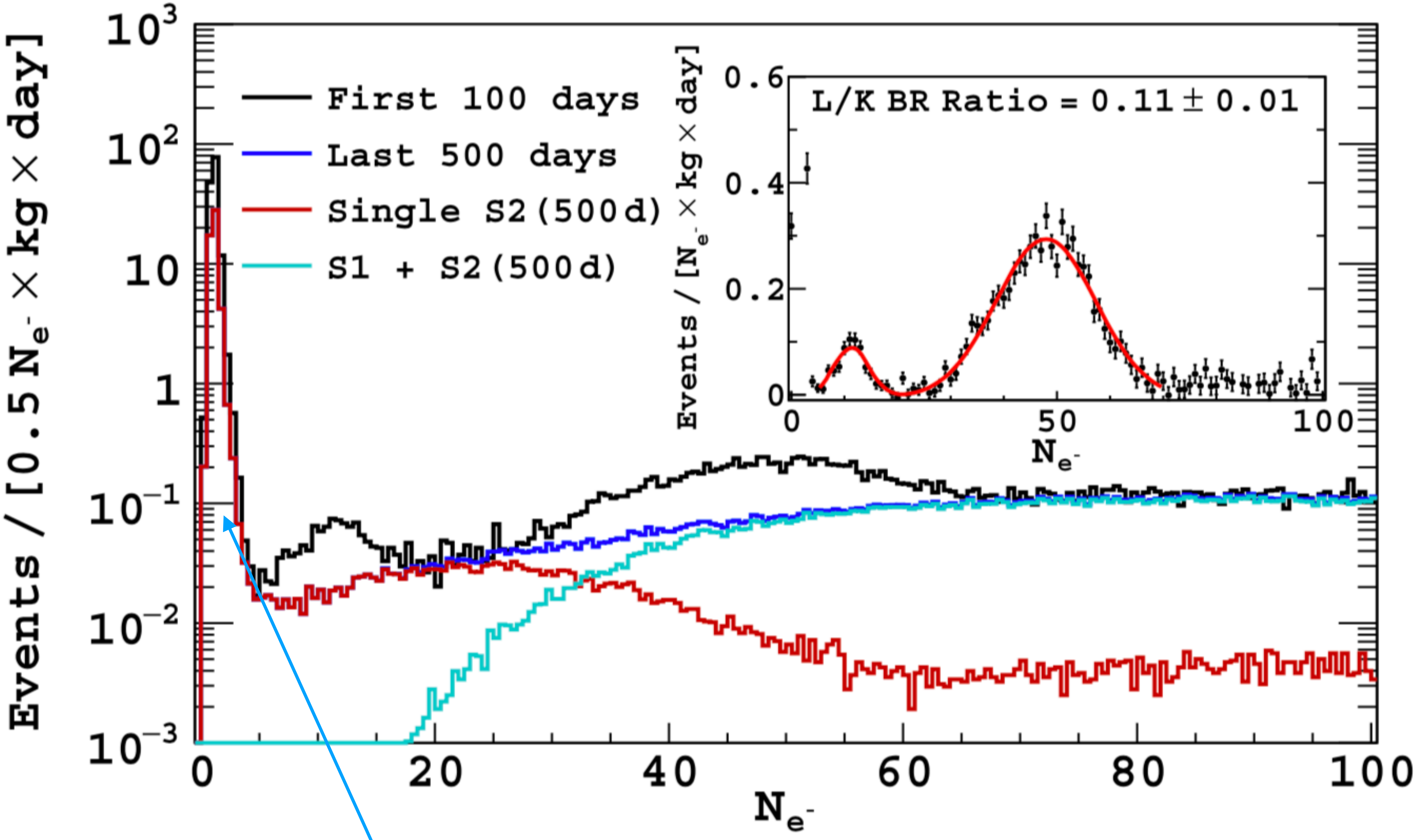
10 m Height
11 m Diameter
1,000 Tonnes
Water Cherenkov
Muon Veto



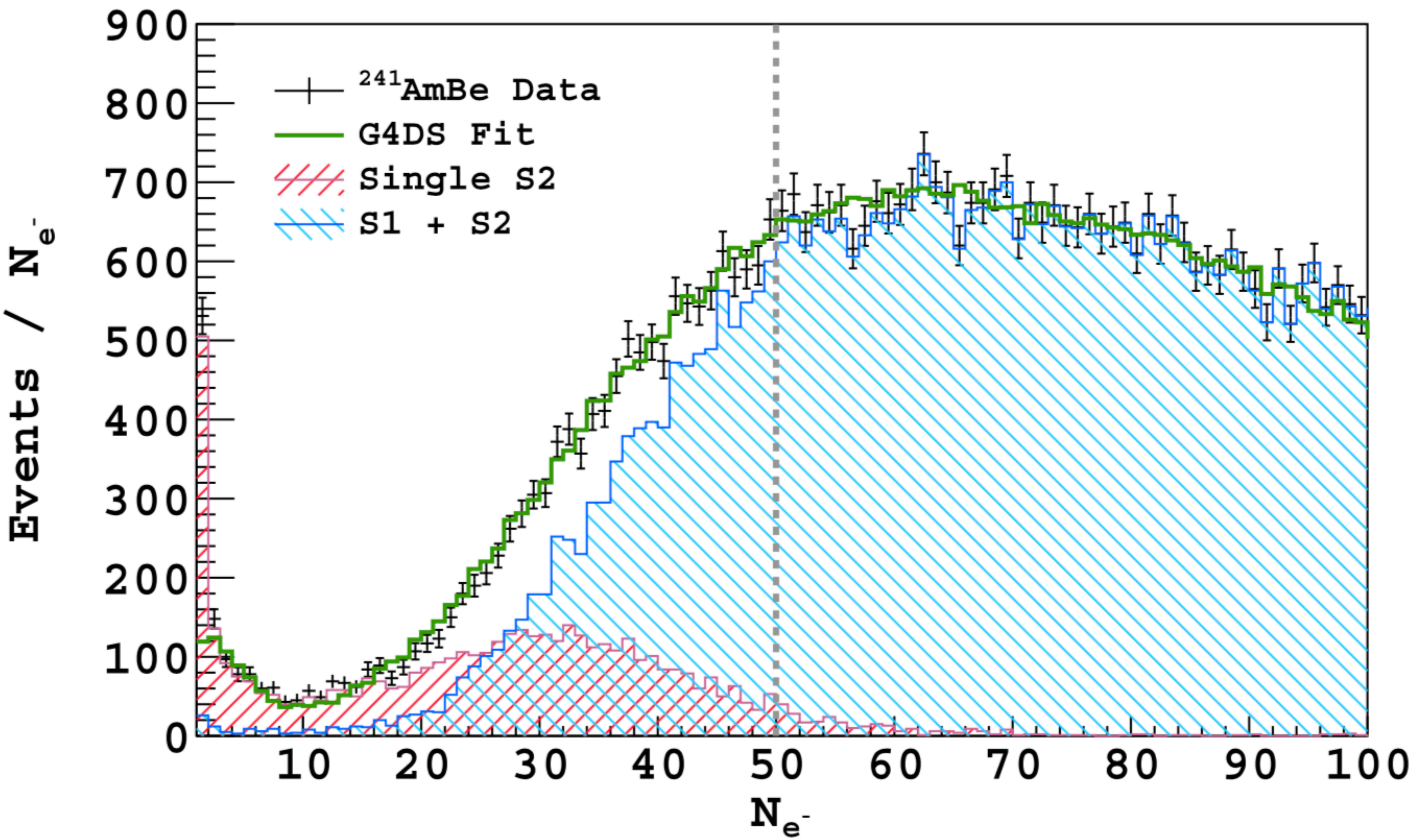
DM-nucleon low-mass



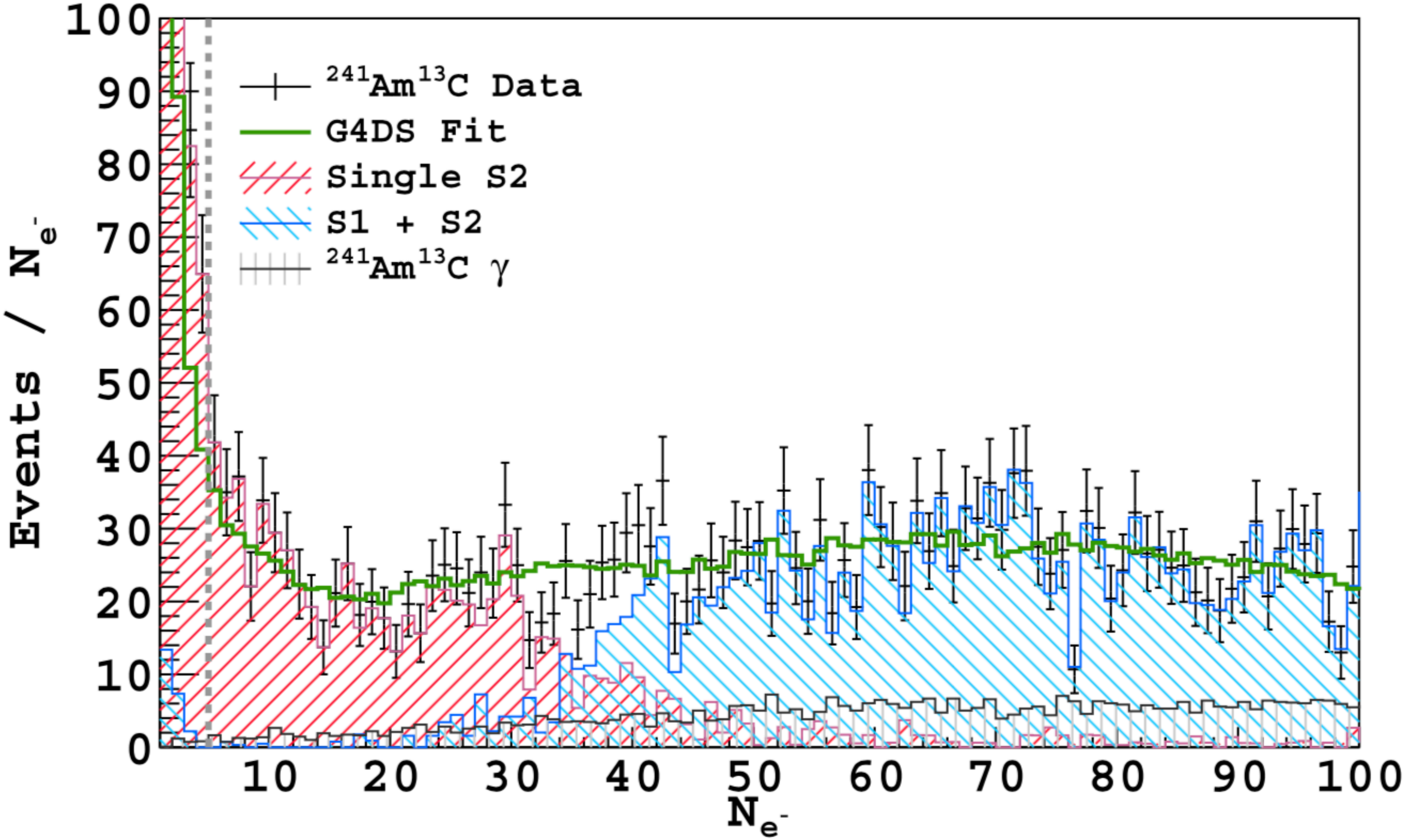
0.4 e-
10 eVee
10%
Detector
Threshold
4 e-
100 eVee
Analysis
Threshol
d
Acceptance
S2 [PE]
Fiducialization
× Trigger efficiency
× S2 Identification (f_{90}<0.15)

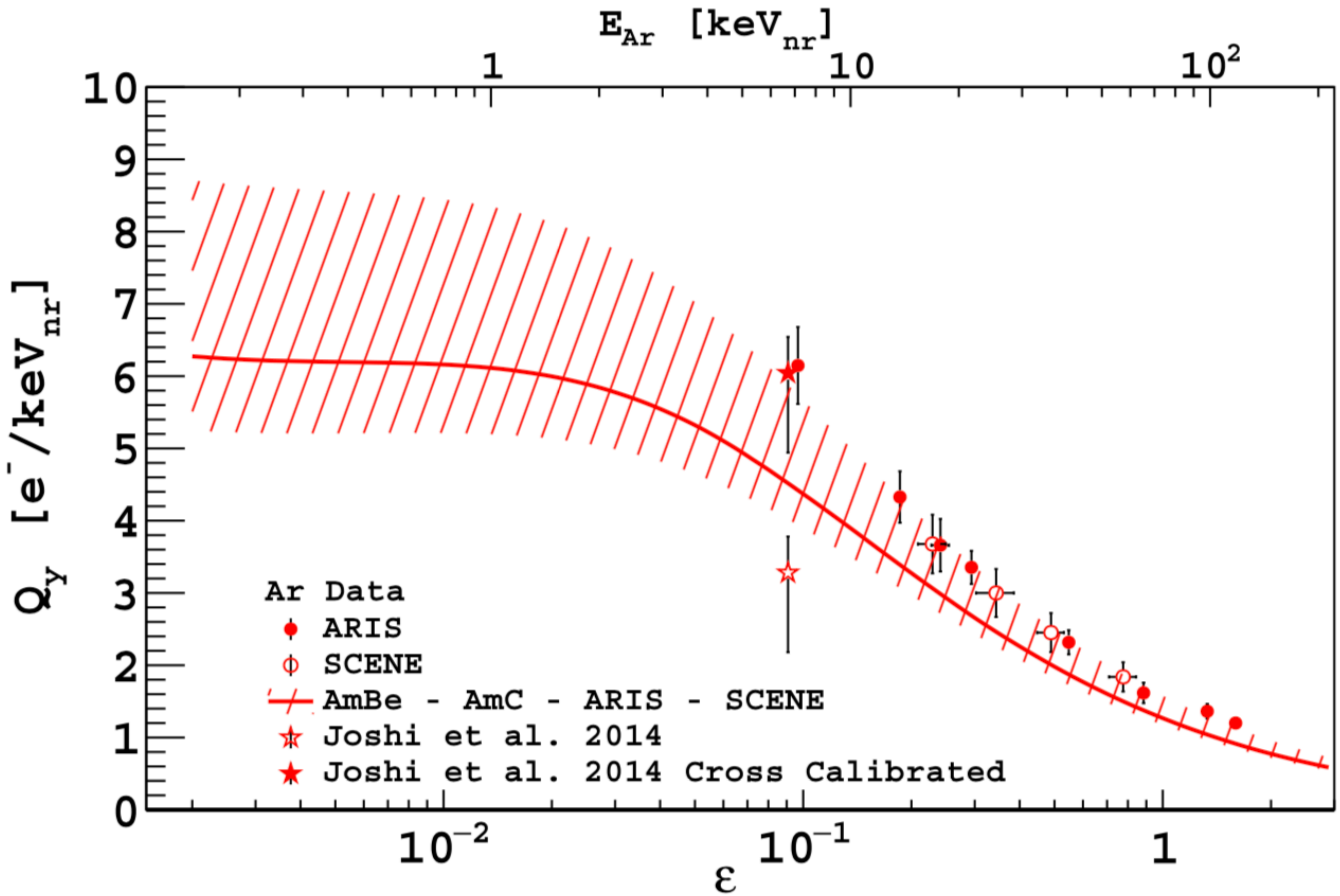


electrons trapped by impurities and late-released

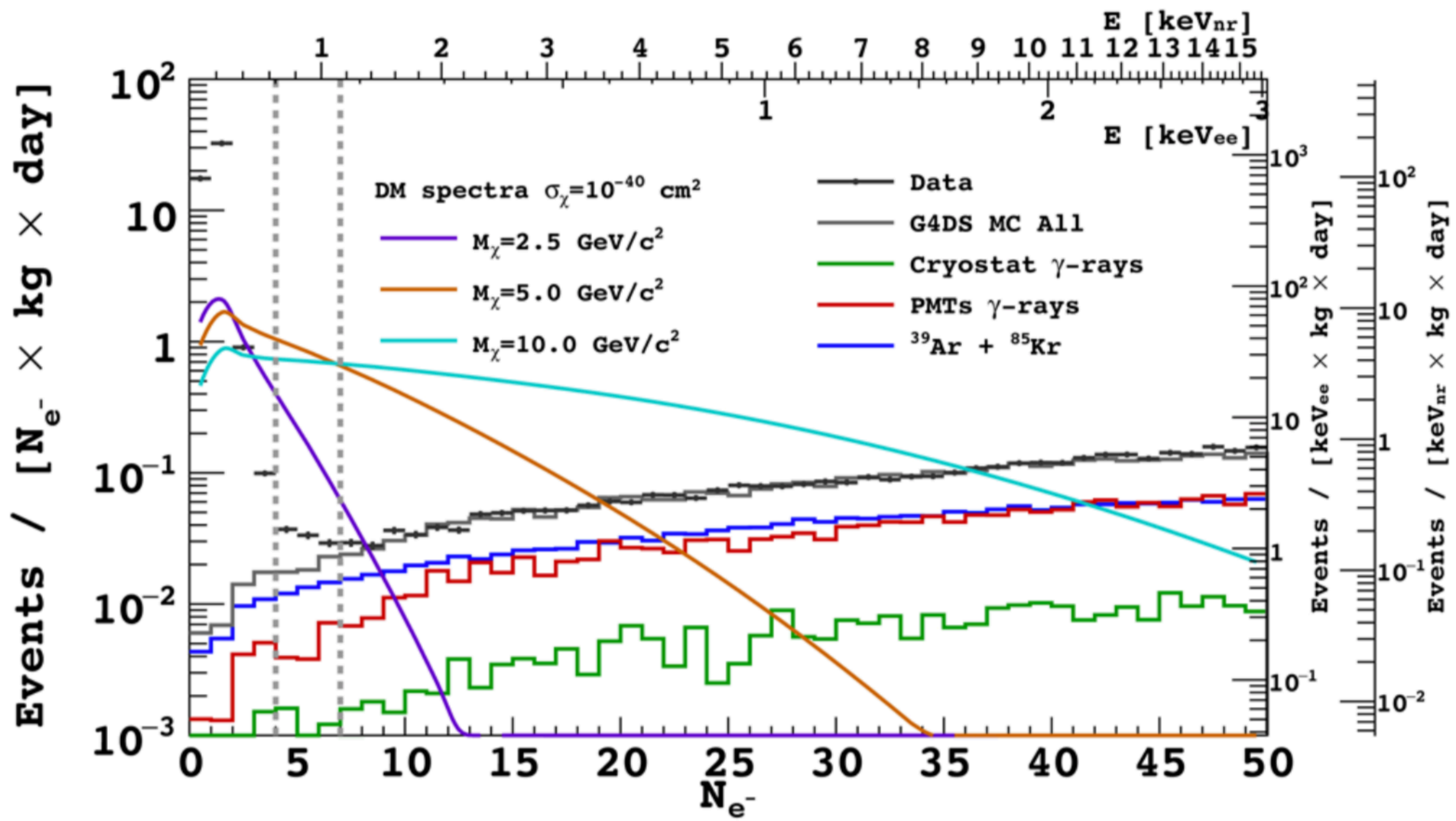


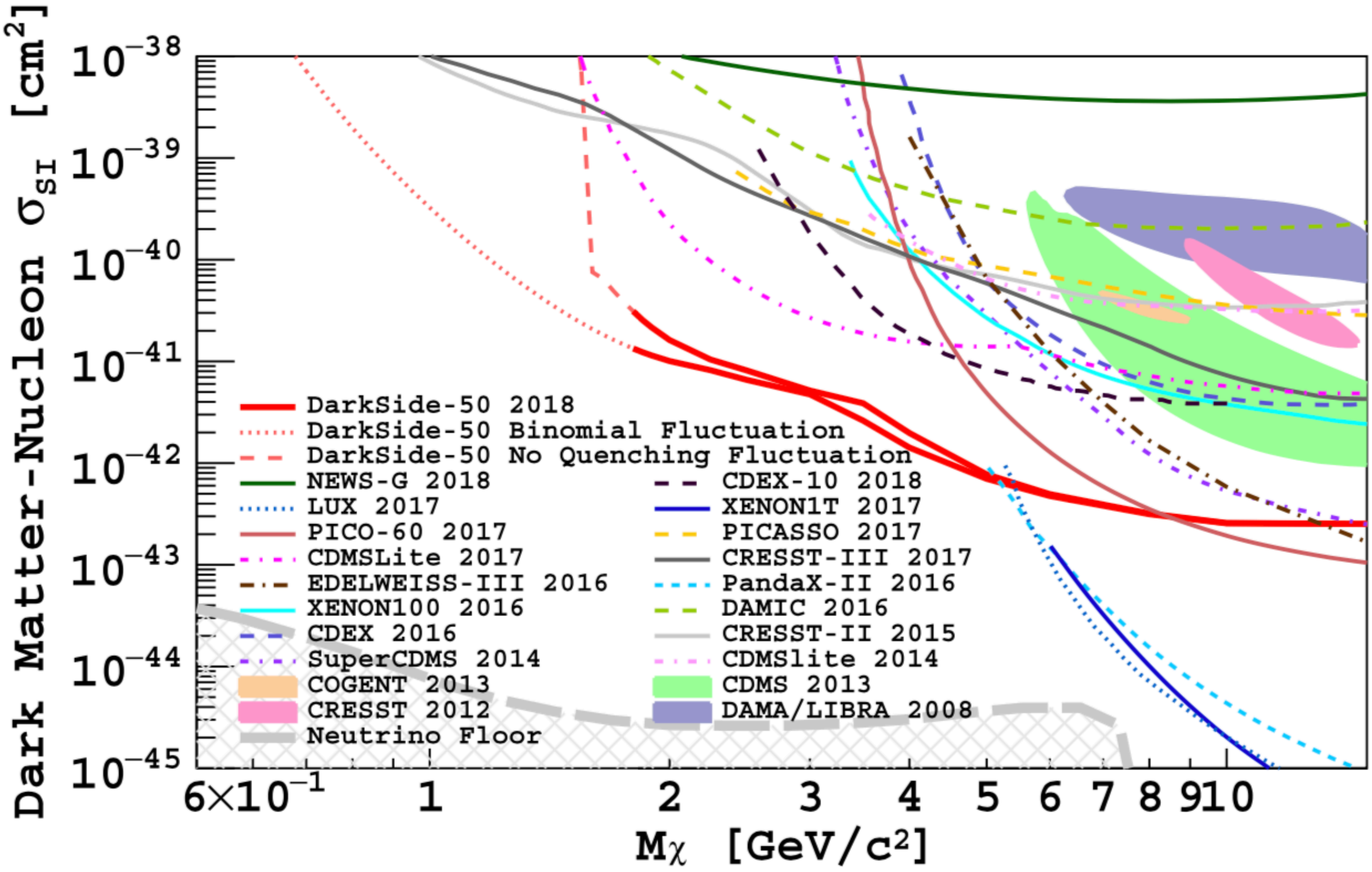
^{241}AmBe Data
G4DS Fit
Single S2
S1 + S2
Events / N_{e^-}
N_{e^-}


100
90
80
70
60
50
40
30
20
10
0
Events / N_{e^-}
^{241}Am^{13}C Data
G4DS Fit
Single S2
S1 + S2
^{241}Am^{13}C γ
10
20
30
40
50
60
70
80
90
100
N_{e^-}



E_Ar [keV_nr]
1
10
10^2
Q_y [e^-/keV_nr]
Ar Data
ARIS
SCENE
AmBe - AmC - ARIS - SCENE
Joshi et al. 2014
Joshi et al. 2014 Cross Calibrated
10^-2
10^-1
1
ε

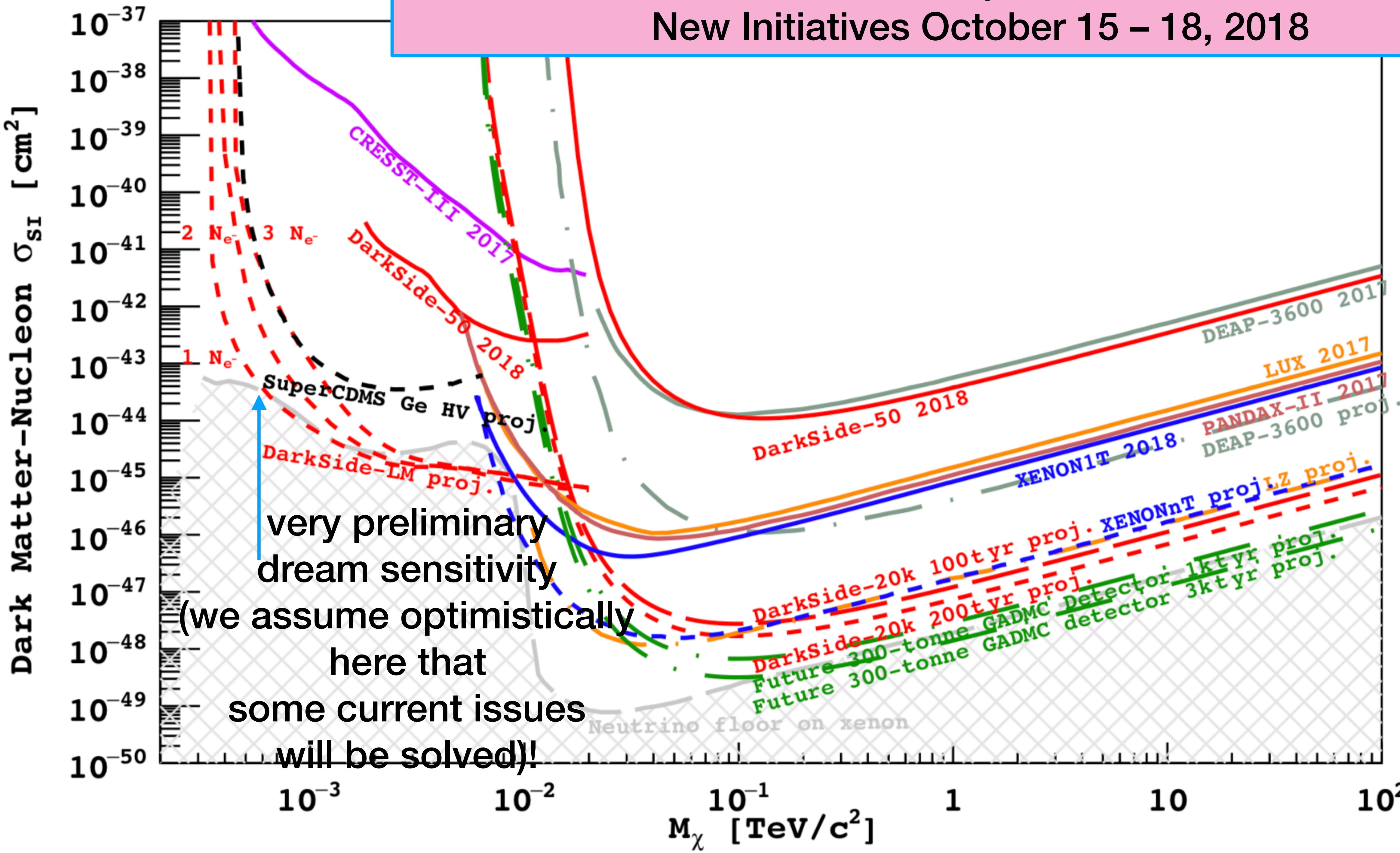

E [keVnr]
E [keVee]
DM spectra σχ=10^-40 cm²
Mχ=2.5 GeV/c²
Mχ=5.0 GeV/c²
Mχ=10.0 GeV/c²
Data
G4DS MC All
Cryostat γ-rays
PMTs γ-rays
39Ar + 85Kr
Events / [Ne- × kg × day]
Events / [keVee × kg × day]
Events / [keVnr × kg × day]
Ne-

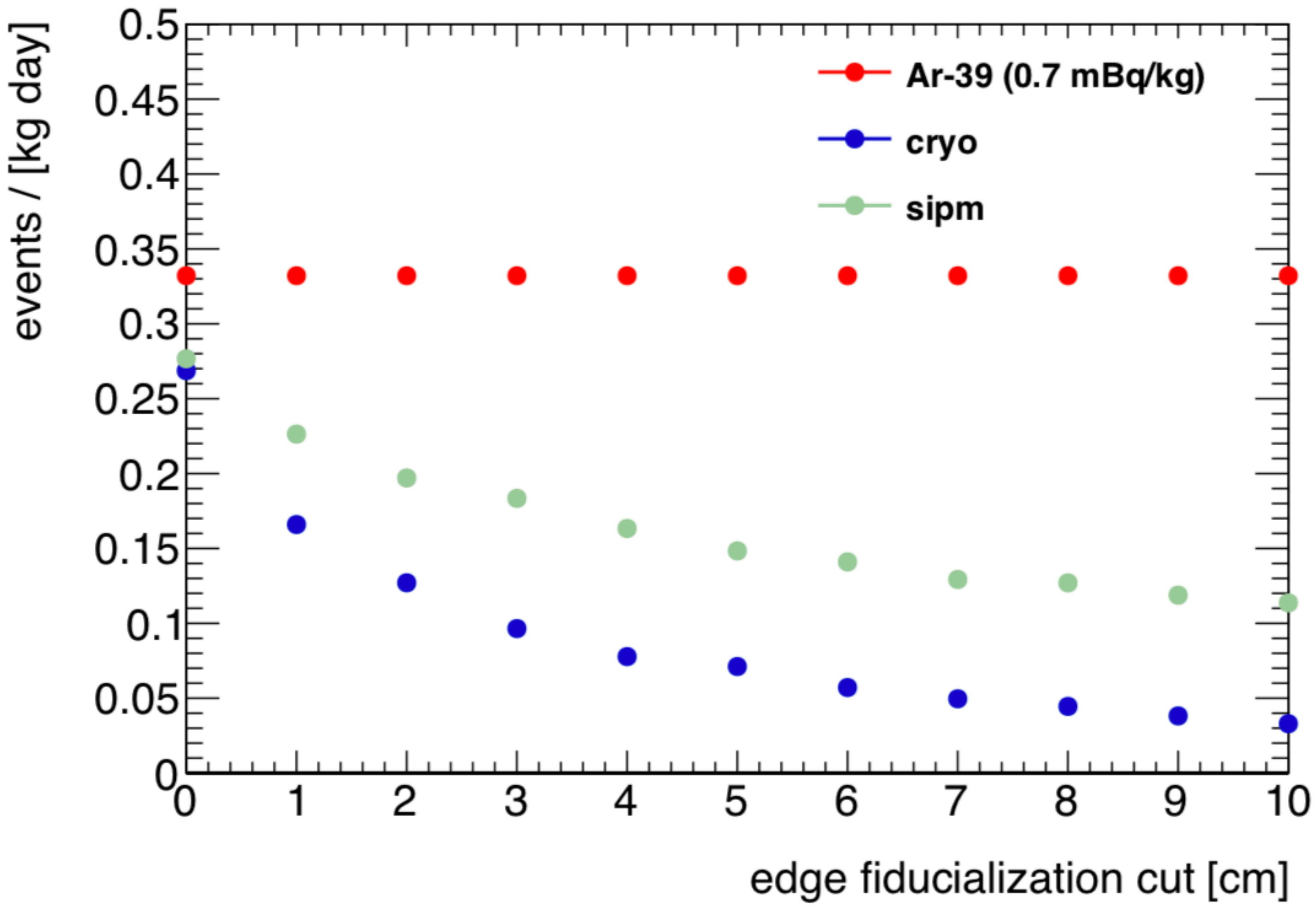


Dark Matter-Nucleon σ_SI [cm²]
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
6×10⁻¹
1
2
3
4
5
6
7
8
9
10
Mχ [GeV/c²]
DarkSide-50 2018
DarkSide-50 Binomial Fluctuation
DarkSide-50 No Quenching Fluctuation
NEWS-G 2018
LUX 2017
PICO-60 2017
CDMSLite 2017
EDELWEISS-III 2016
XENON100 2016
CDEX 2016
SuperCDMS 2014
COGENT 2013
CRESST 2012
Neutrino Floor
CDEX-10 2018
XENON1T 2017
PICASSO 2017
CRESST-III 2017
PandaX-II 2016
DAMIC 2016
CRESST-II 2015
CDMSlite 2014
CDMS 2013
DAMA/LIBRA 2008

DarkSide-LM

Basic Research Needs Workshop on Dark Matter Small Projects
New Initiatives October 15 – 18, 2018





To be compared to DS50

^{39}Ar+^{85}Kr: 1.75 ev/kg/day

cryo: 0.27 ev/kg/day

PMT: 1.57 ev/kg/day

Two crucial technologies

Liquid argon target depleted in the radioactive ^{39}Ar , with respect to the 1Bq/Kg of the atmospheric argon (AAr)

Cryogenic SiPMs replacing PMTs

—> higher light yield (#PE/KeV), low cost for large areas, very low dark noise, very low radioactivity background (with radio-pure substrates), long term stability

(New) Argon Collaboration

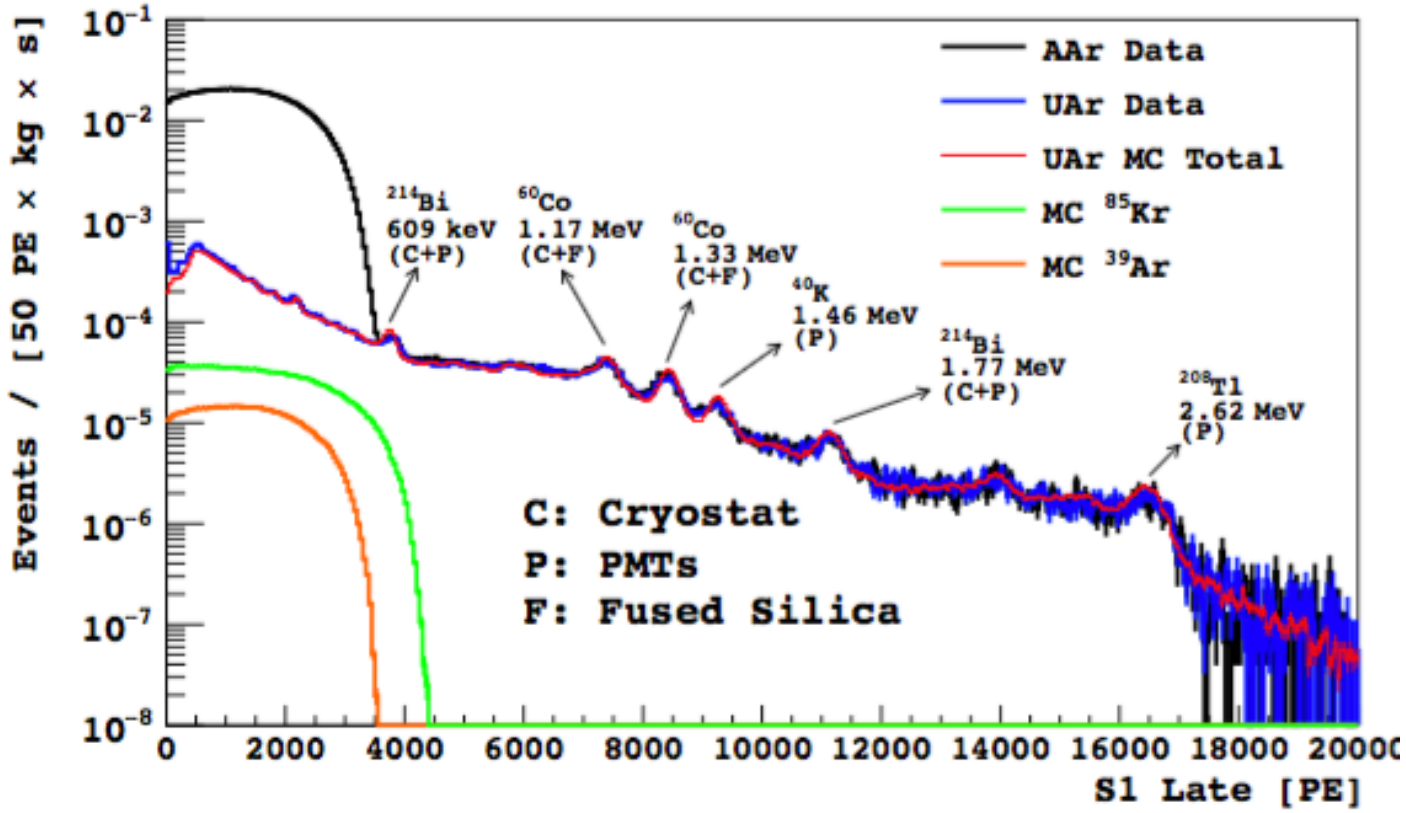
Researchers from

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

→ DS-20K → multi-100-T

planning to collaborate on future program:

- Completion of current science and R&D programs by each collaboration (DS-50, DEAP-3600, MiniCLEAN, ArDM)
- Joint collaboration on DS-20K at LNGS, including Low Radioactivity Argon (operation starting 2021) and SiPM photodetectors
- Joint collaboration on future multi-hundred-tonne LAr detector, site TBD (mid-2020's)



For DarkSide-50, about 70Kg of underground argon (UAr) were extracted with a pilot plant

UAr vs AAr in DS-50: (0.73±0.11)x10^{-3}Bq/Kg vs 1Bq/Kg

The argon path

The Urania project@Kinder Morgan Doe Canyon Facility, CORTEZ,CO (USA)

extraction of 50t of UAr from CO_2 deep wells where cosmic rays hardly make any ^{39}Ar

Starting from 95% CO2 and 440ppm of UAr!

New plant, funded, under tendering

The Aria project: includes regional funds from Sardinia, Italy

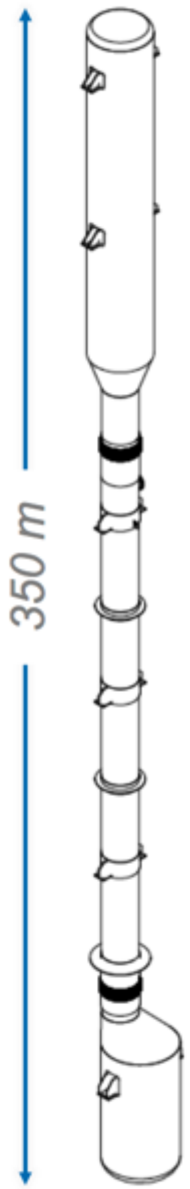
^{39}Ar isotopic separation with cryogenic distillation —> factor 10 suppression per pass (from UAr to DAr)

CarboSulcis mine in

Nuraxi-Figus

The Seruci-I column:

350m height, 30cm diameter



CERN : leak tests

first step : installation and test of a 28m tall test column Seruci-0 in a surface building at the mine


Genie ZX-135/70
TECNOALT
Genie
CTE


Polaris

For DarkSide-20k:

Seruci I —>removal of chemical impurities to make the UAr detector grade with 2 passes at 1t/day with 85% recovery—> inlet purity required by DS20k getters of order 0.25-1ppm

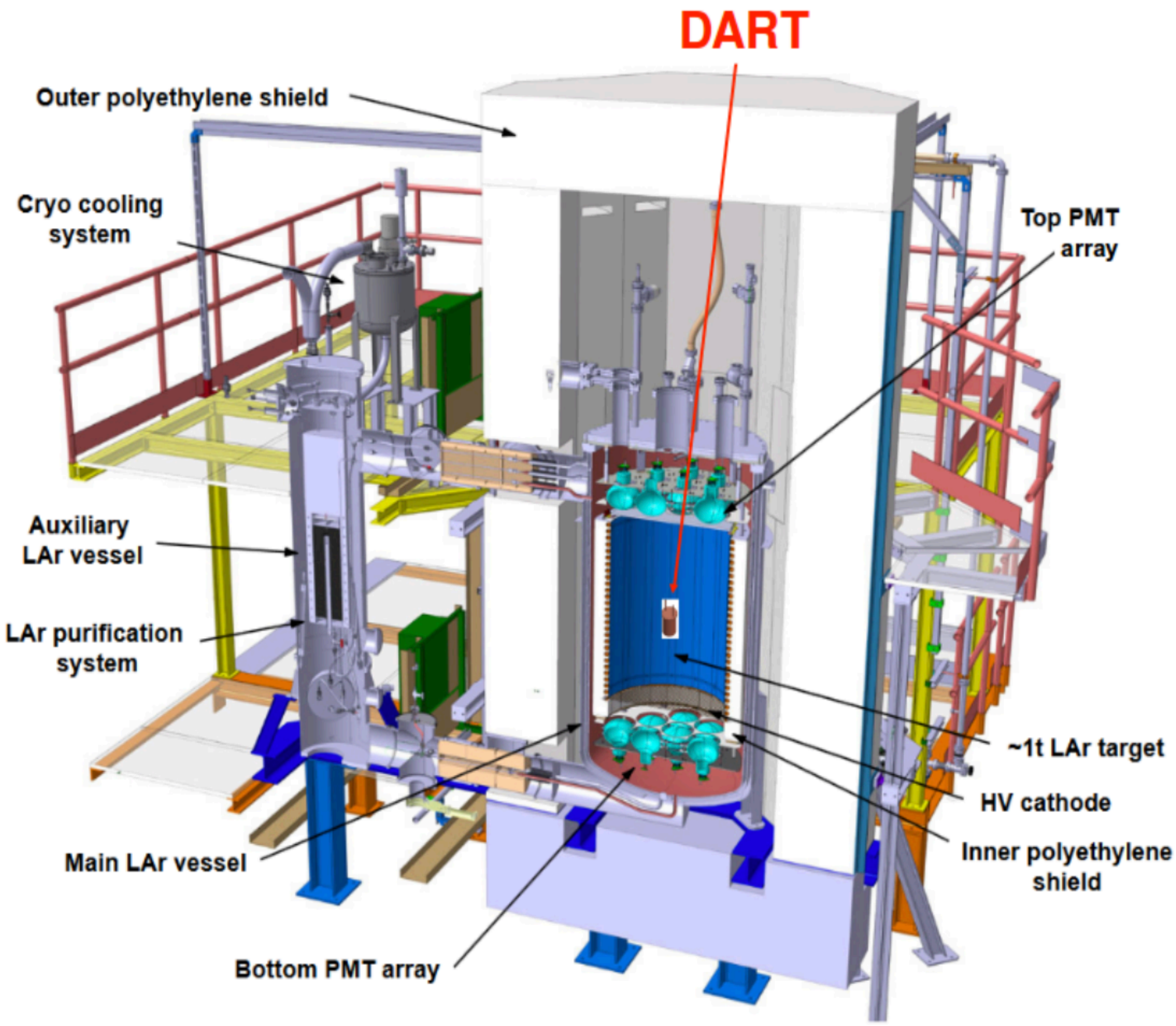
For DarkSide low-mass:

10Kg/day isotopic distillation of ^{39}Ar and chemical purification

A measuring device:

The measurement of ^{39}Ar content in the argon coming from Urania and Aria is planned with a specific innovative device named DART based on LAr active vetoing approach

Experimental set-up using the ArDM facility



Insertion of active small chamber in ArDM. Use ArDM as veto(single phase).

Dissipated power and condensation heat to be absorbed by ArDM cryogenic system.

At LSC Spain

3

A new SiPM production chain

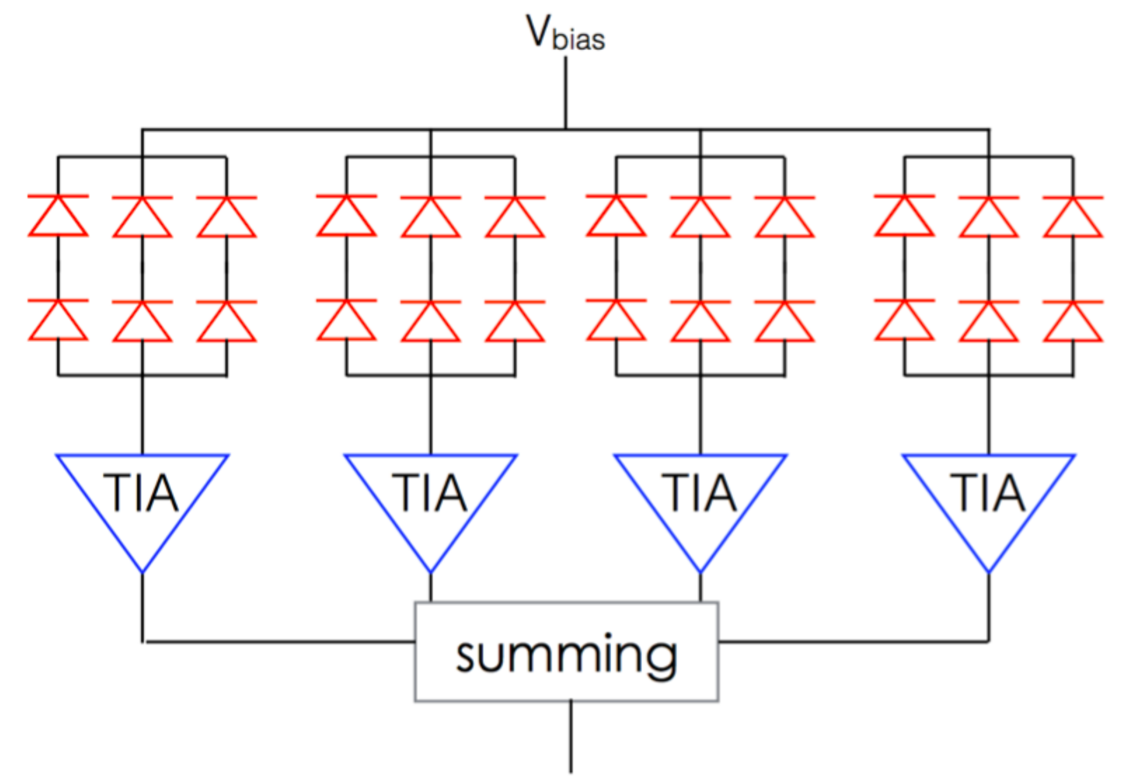
NUV-HD-LF working at cryogenic temperatures

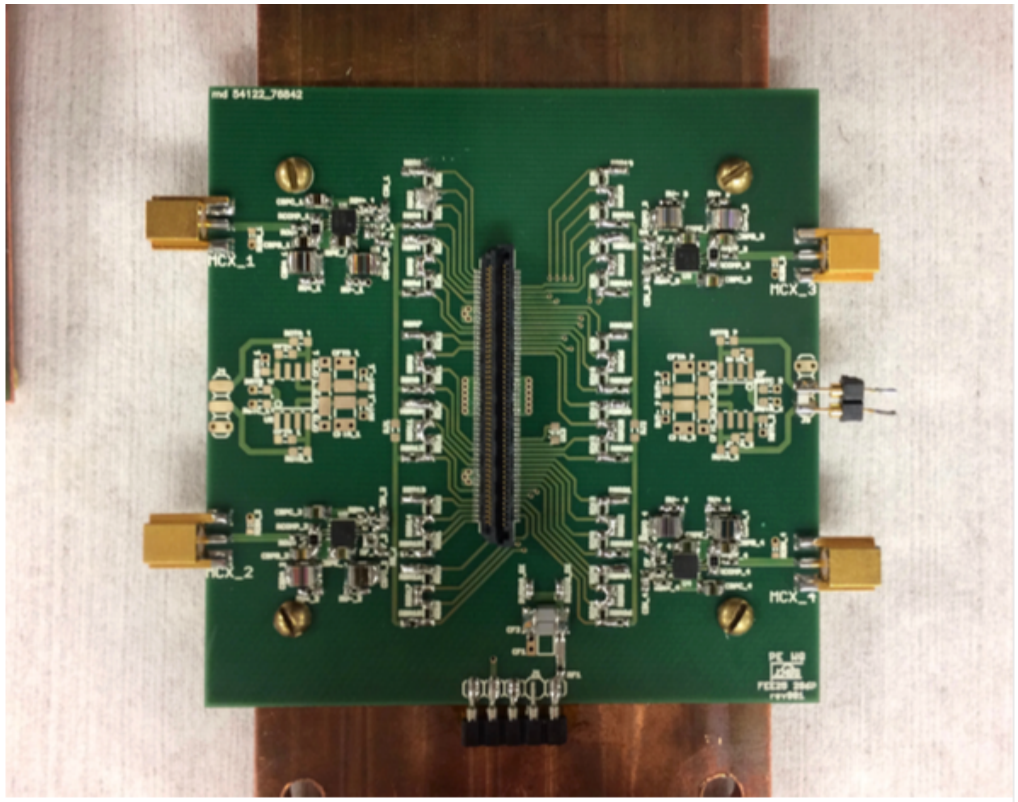
Low field SPADs, near UV (410nm) peak efficiency, 25μm cell size

Regional funds from Abruzzo, Italy—>

— SiPM large scale production at LFoundry, Avezzano (AQ) after successful R&D and design by FBK, Trento (TN)

— NuovaOfficinaAssergi at l'Aquila Tecnopolo for packaging and module assembly

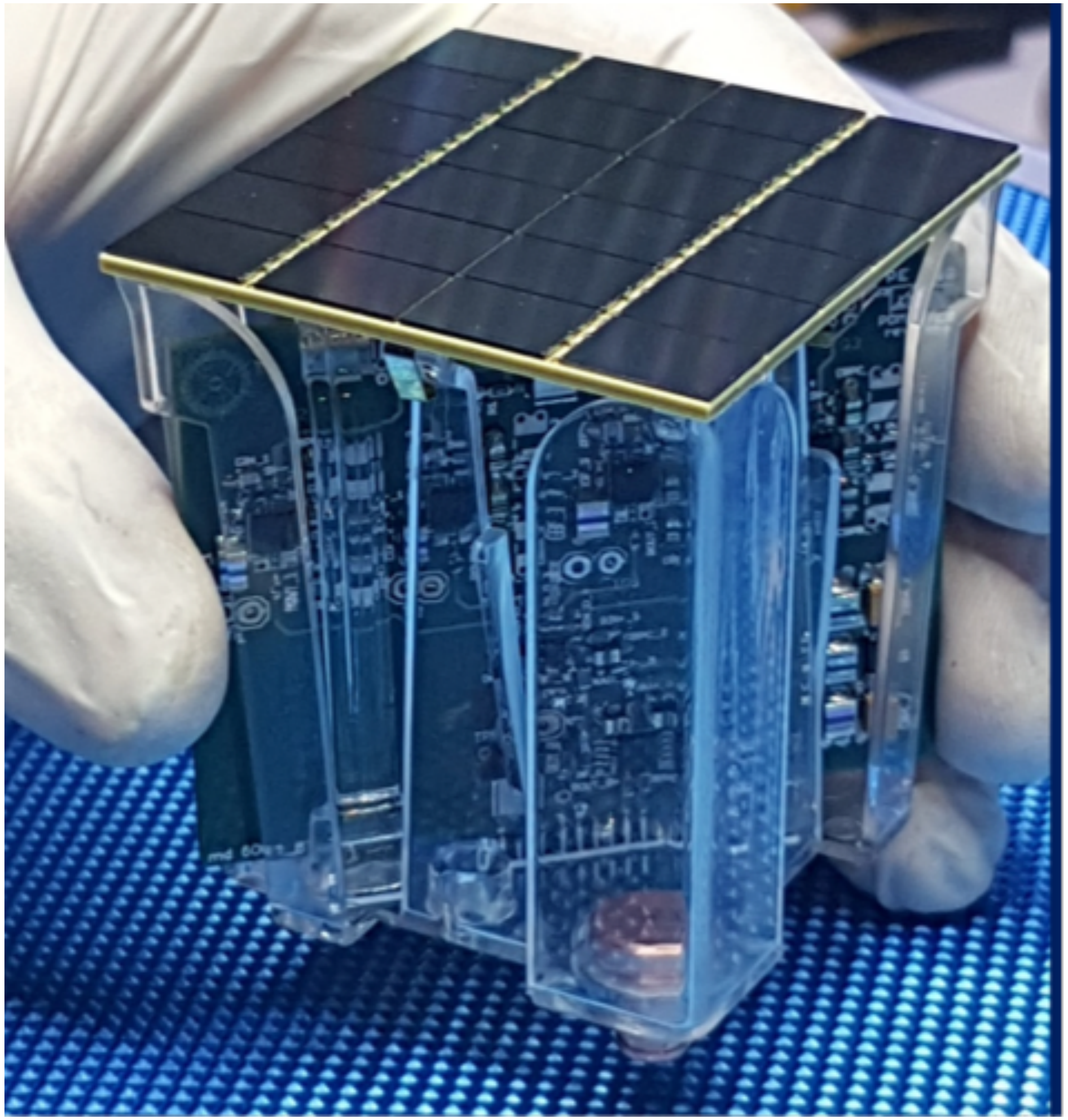




The tile is readout by 4 TransImpedanceAmplifiers (large detector C of 50 pF/mm²) with discrete components

mounted on radio-pure substrates

24 cm^2 tiles equipped with 1x1cm^2 SiPMs fully working



Need 8280

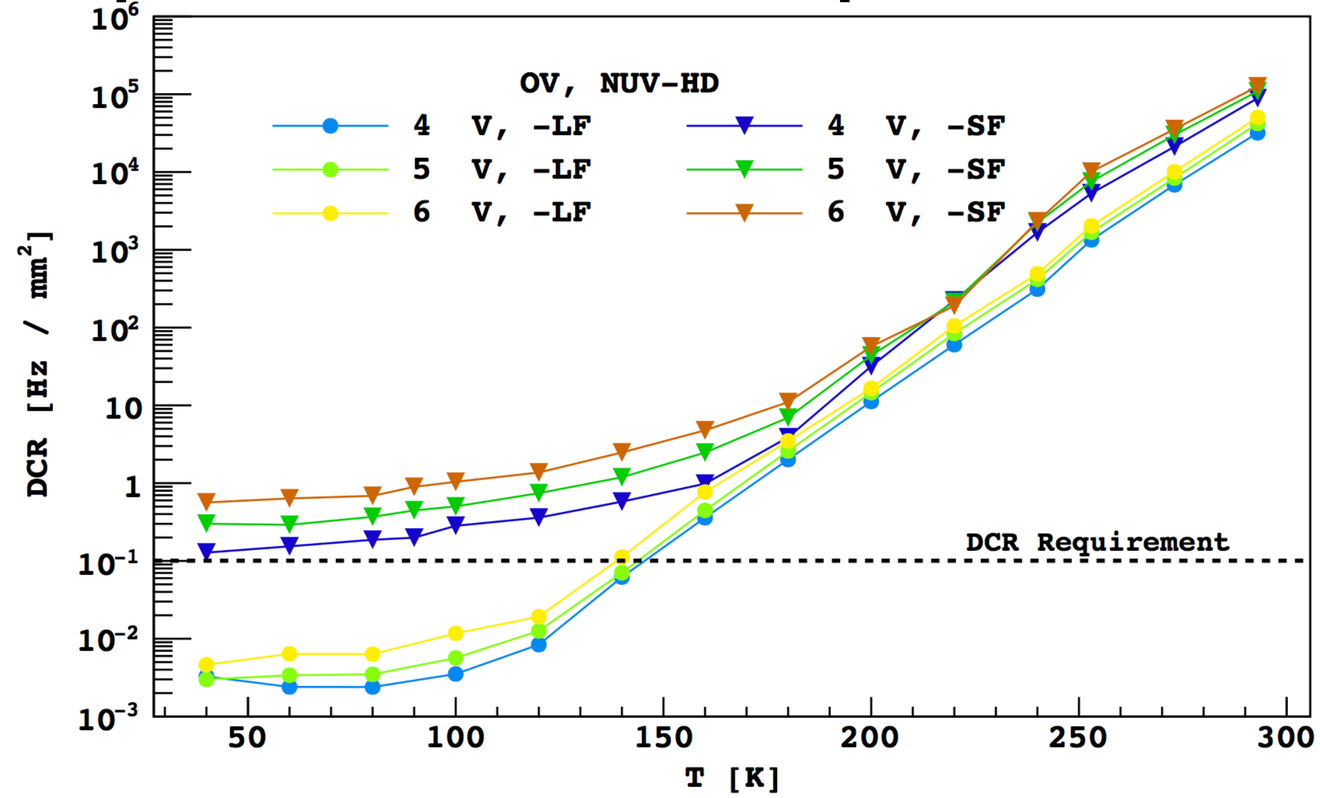
… assembled as self-consistent one-channel units PhotonDetectorModules, replacing 3” PMTs

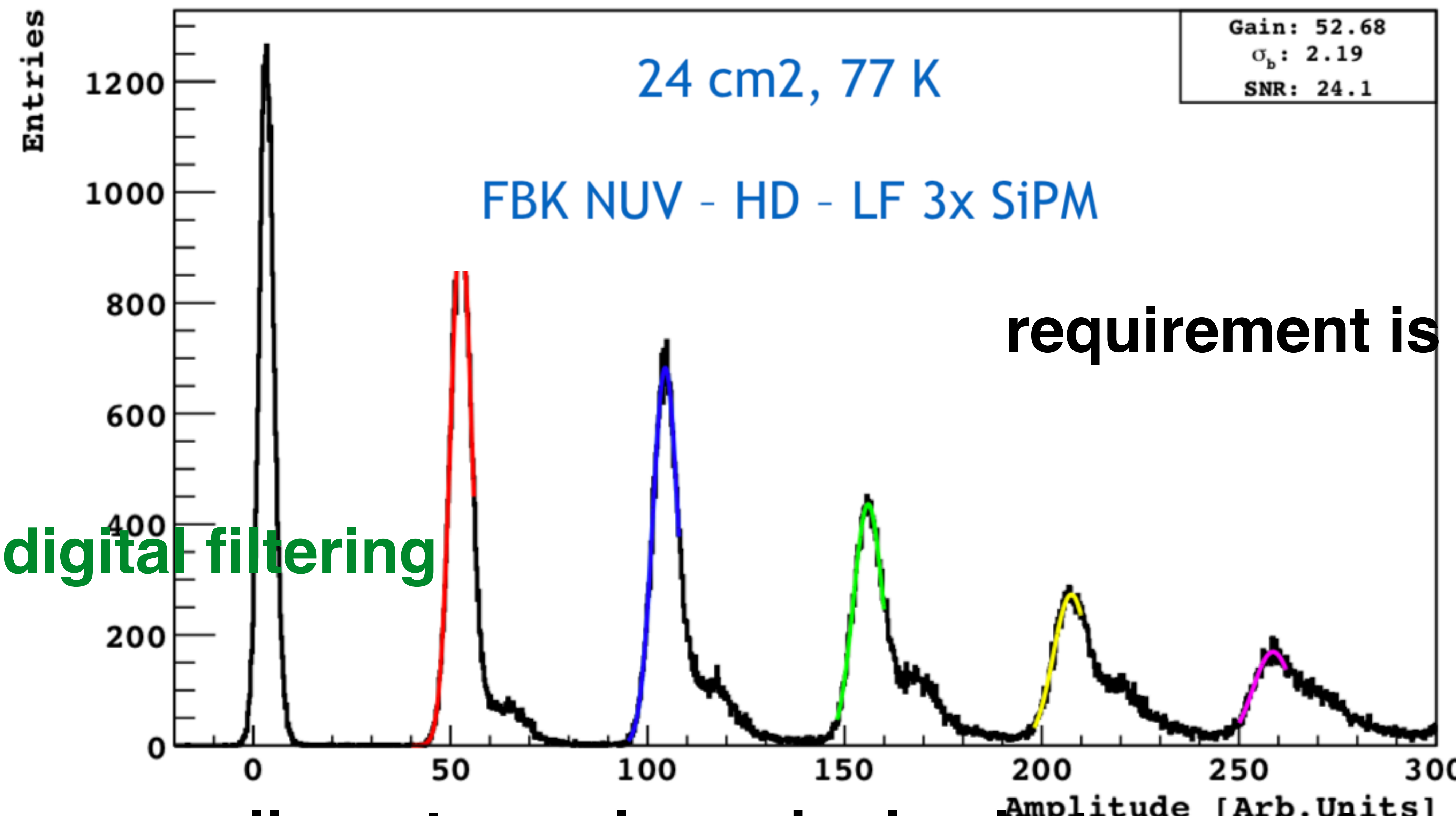
Photon Detection Efficiency (PDE): 45% requirement met and surpassed

Dark Count Rate (DCR): 0.1 Hz/mm² requirement met and surpassed

250mW power/consumption/PDM

20ns time resolution

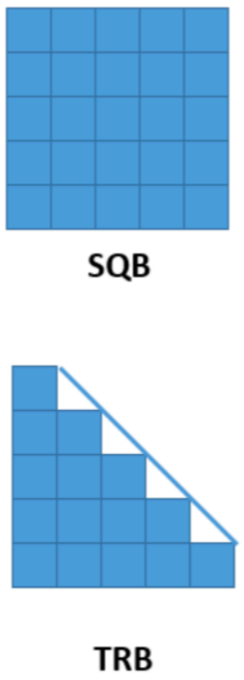


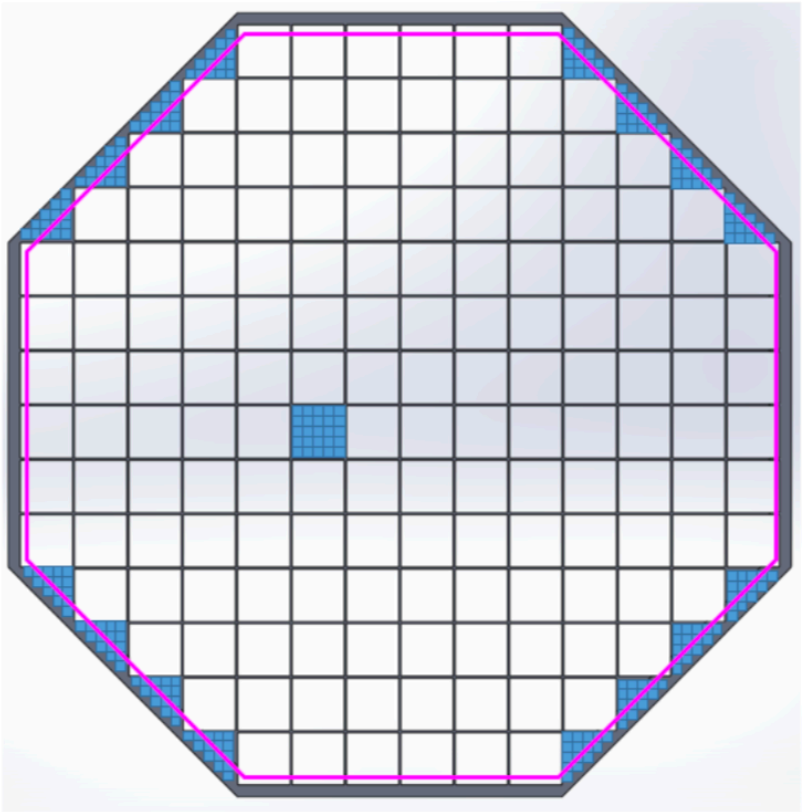


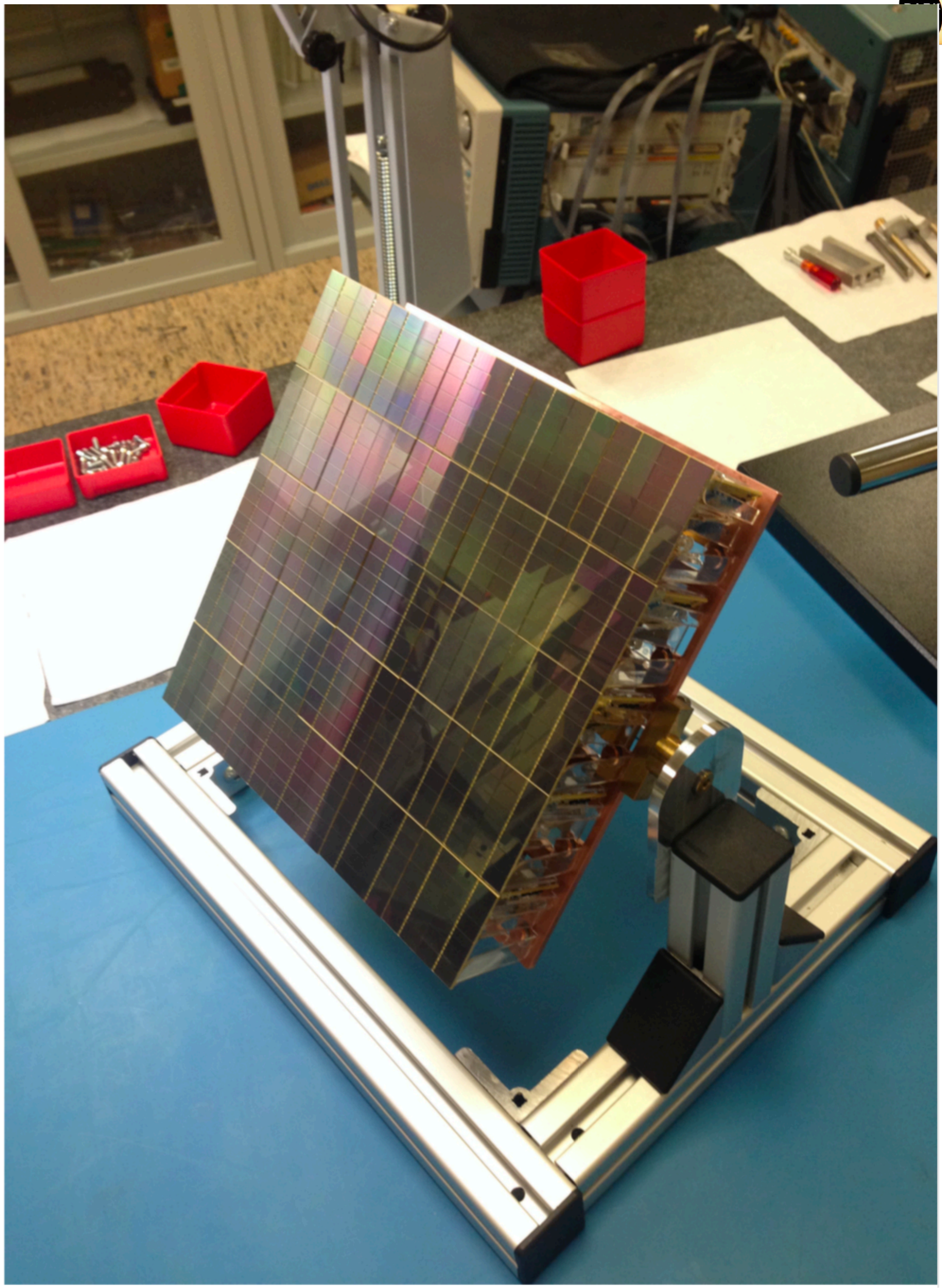
requirement is SNR>8

after digital filtering

allows to work as single photon counter

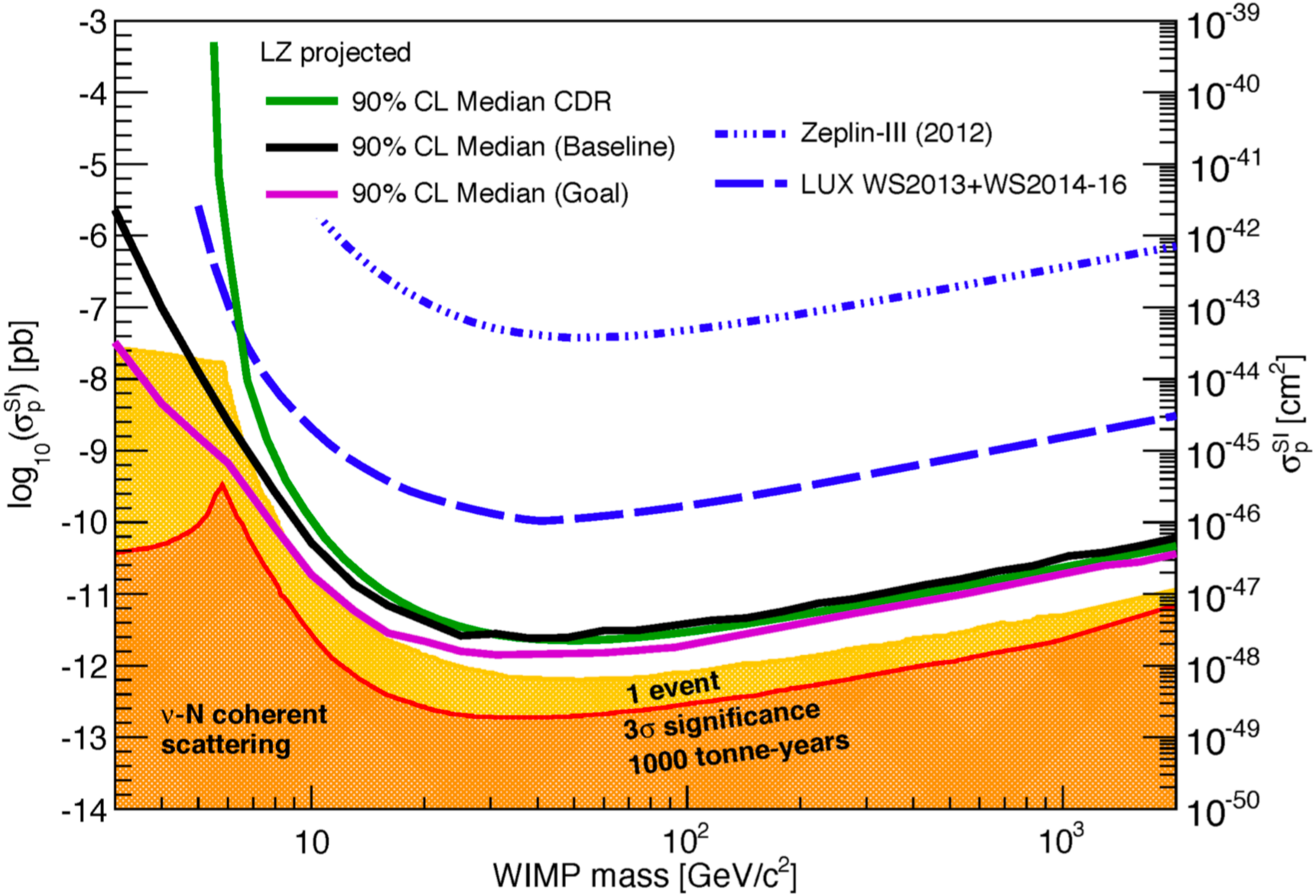

SQB
TRB



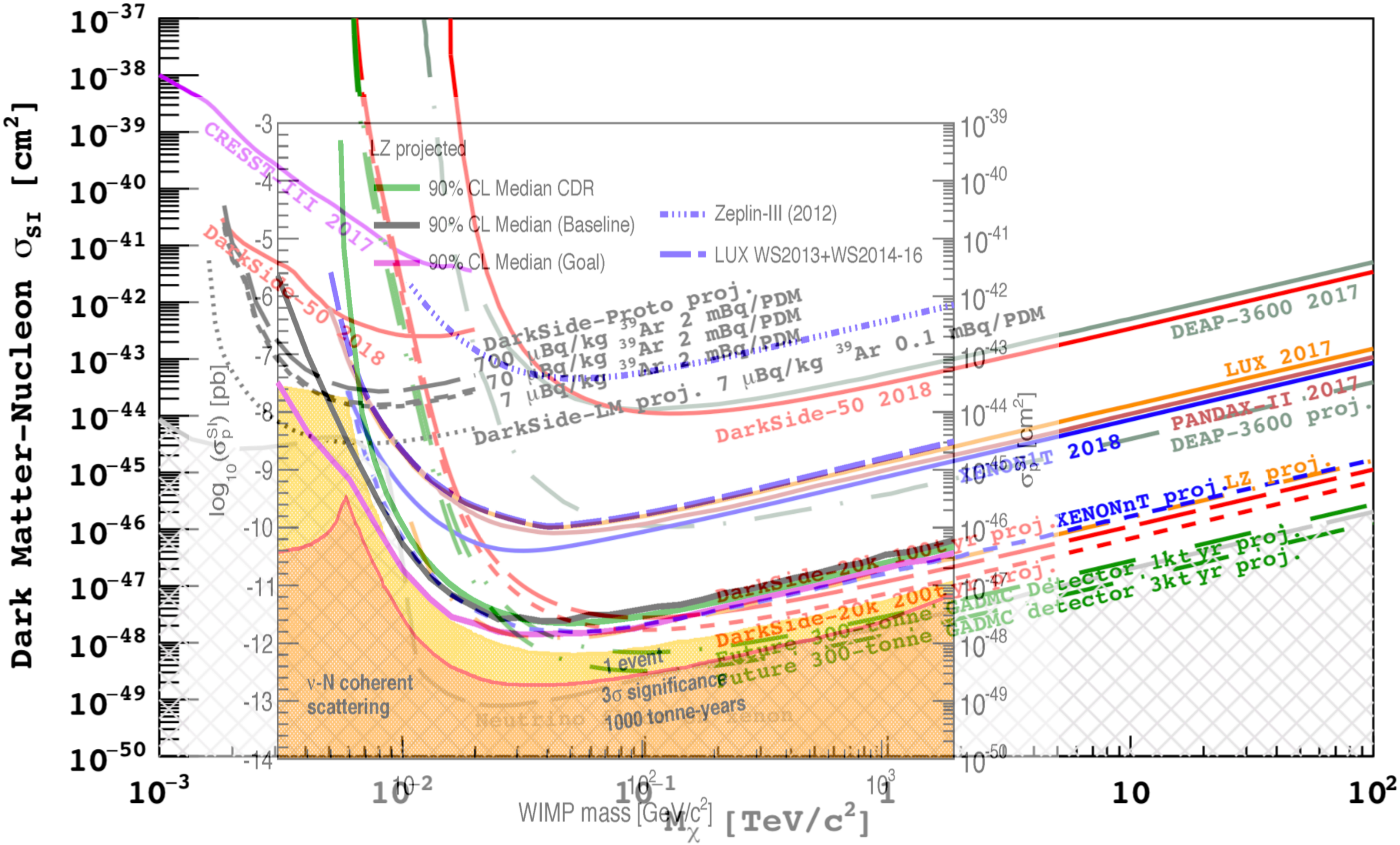


Competing technologies?

LZ xenon TPC



LZ projected
90% CL Median CDR
90% CL Median (Baseline)
90% CL Median (Goal)
Zeplin-III (2012)
LUX WS2013+WS2014-16
ν-N coherent scattering
1 event
3σ significance
1000 tonne-years
$\log_{10}(\sigma_p^{SI})$ [pb]
σ_p^{SI} [cm^2]
WIMP mass [GeV/c^2]
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10
10^2
10^3



Dark Matter-Nucleon σSI [cm²]
Mχ [TeV/c²]
WIMP mass [GeV/c²]
LZ projected
90% CL Median CDR
90% CL Median (Baseline)
90% CL Median (Goal)
Zeplin-III (2012)
LUX WS2013+WS2014-16
CRESST-III 2017
DarkSide-50 2018
DarkSide-Proto proj.
DarkSide-LM proj.
DEAP-3600 2017
LUX 2017
PANDAX-II 2017
DEAP-3600 proj.
XENON1T 2018
XENONnT proj.
LZ proj.
DarkSide-20k 100t yr proj.
DarkSide-20k 200t yr proj.
Future 300-tonne GADMC Detector 1kt yr proj.
Future 300-tonne GADMC detector 3kt yr proj.
ν-N coherent scattering
1 event
3σ significance
1000 tonne-years

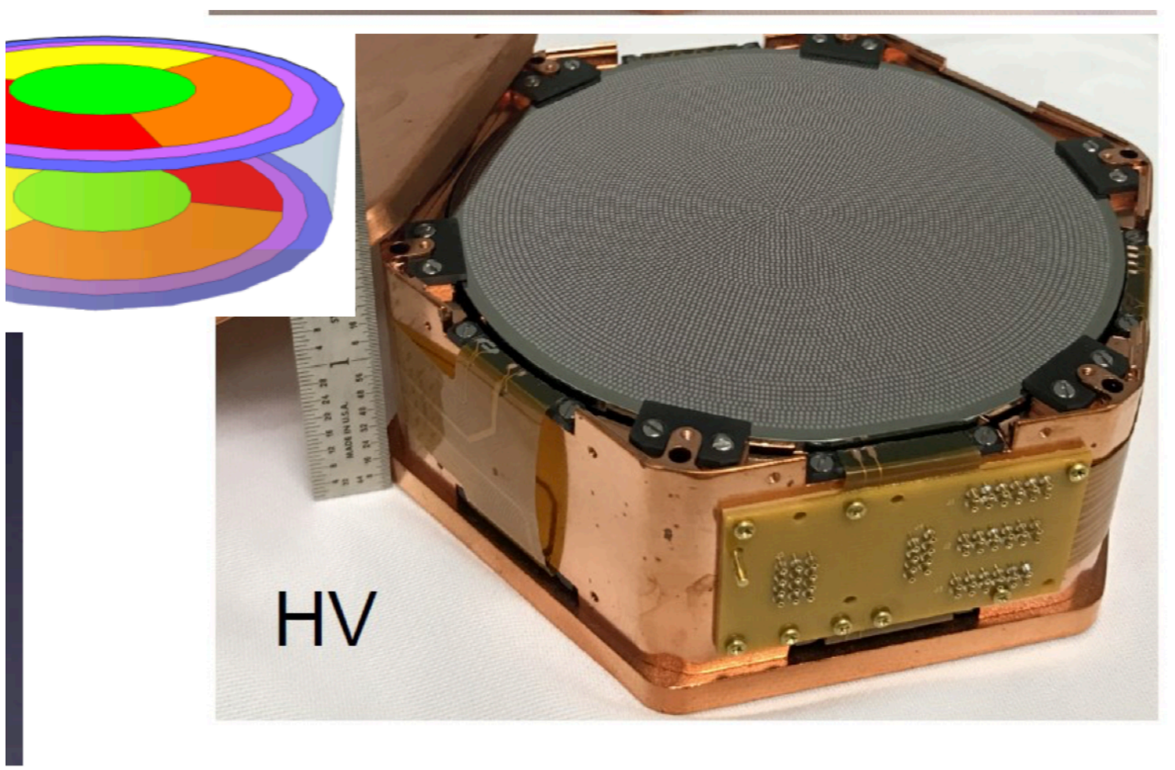
Detector Parameter	Reduced	Baseline	Goal
Light collection (PDE)	0.05	0.075	0.12
Drift field (V/cm)	160	310	650
Electron lifetime (μs)	850	850	2800
PMT phe detection	0.8	0.9	1.0
N-fold trigger coincidence	4	3	2
^{222}Rn (mBq in active region)	13.4	13.4	0.67
Live days	1000	1000	1000

THE ULTIMATE GOAL, VERY CHALLENGING

Going to lower thresholds
(sure you already heard of them)

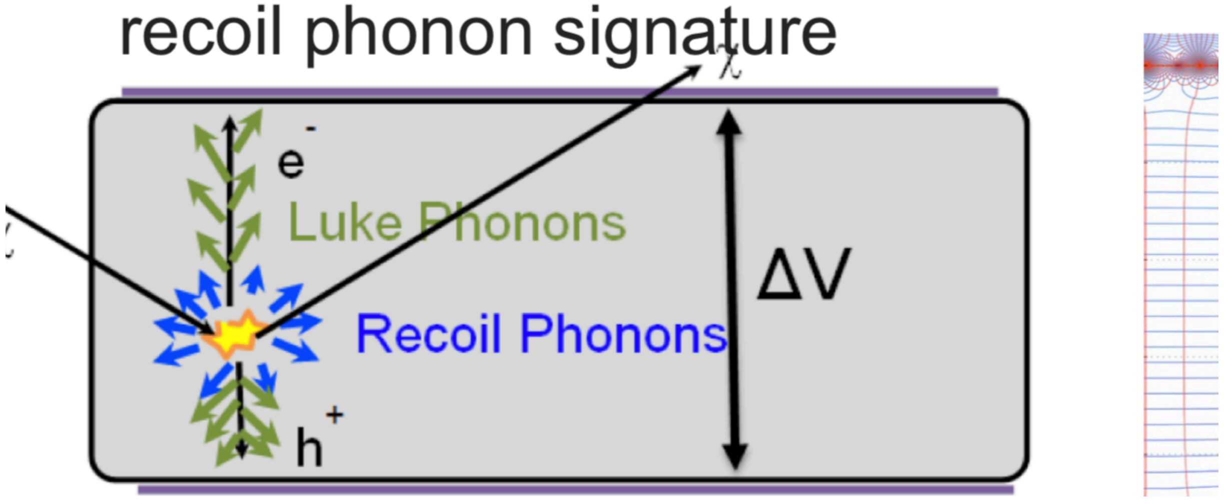
SuperCDMS (SNOLAB)

- Ultra-pure ~kg Ge and Si crystals
- Operate at 10's of mK
- Measure athermal phonon signal via transition edge sensor

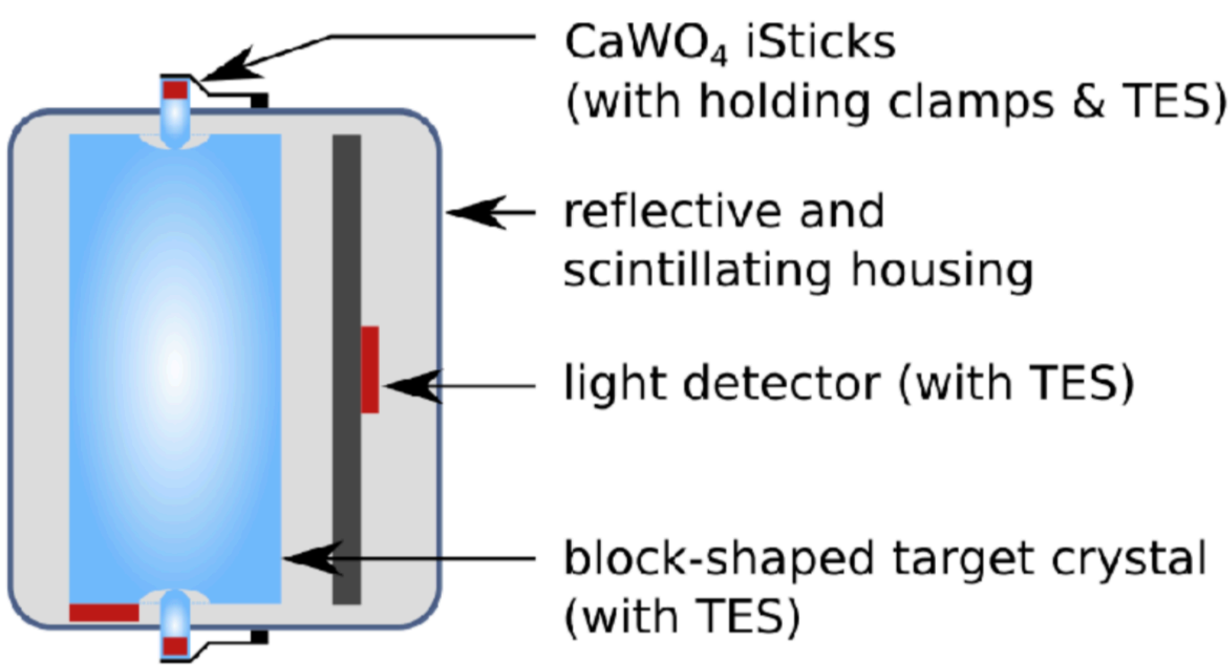


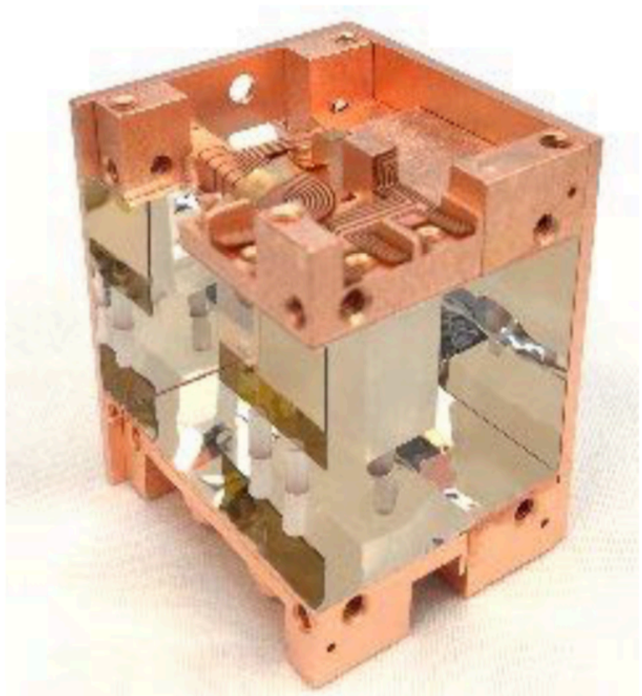
High Voltage (CDMSlite)

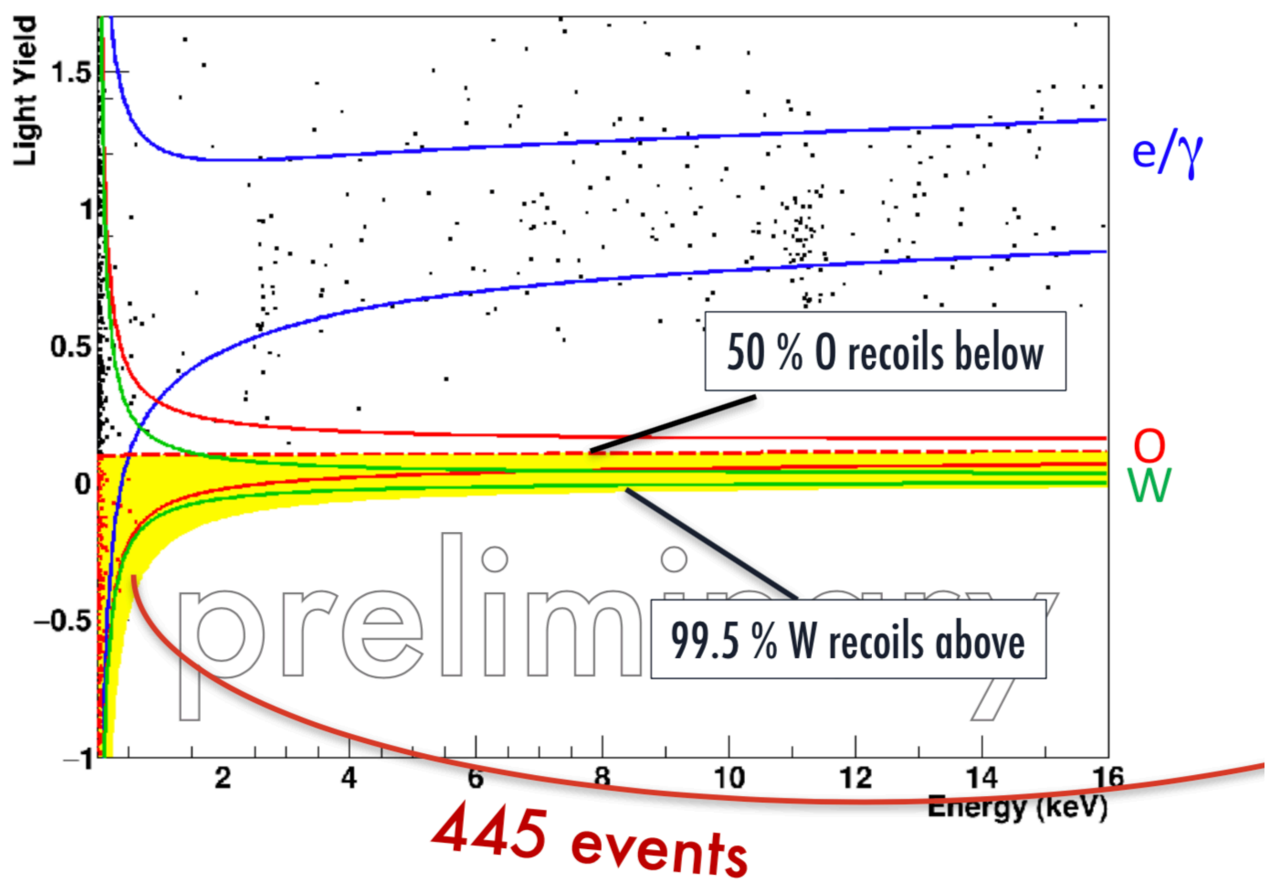
- Free e/h ionization from interaction gains energy from large potential (~100 V)
- Emits Luke-Neganov phonons from scattering on lattice
- Analogous to electroluminescence gain (S2 production) in TPC
- Luke phonons drown out intrinsic recoil phonon signature



CRESST-III scintillating bolometer

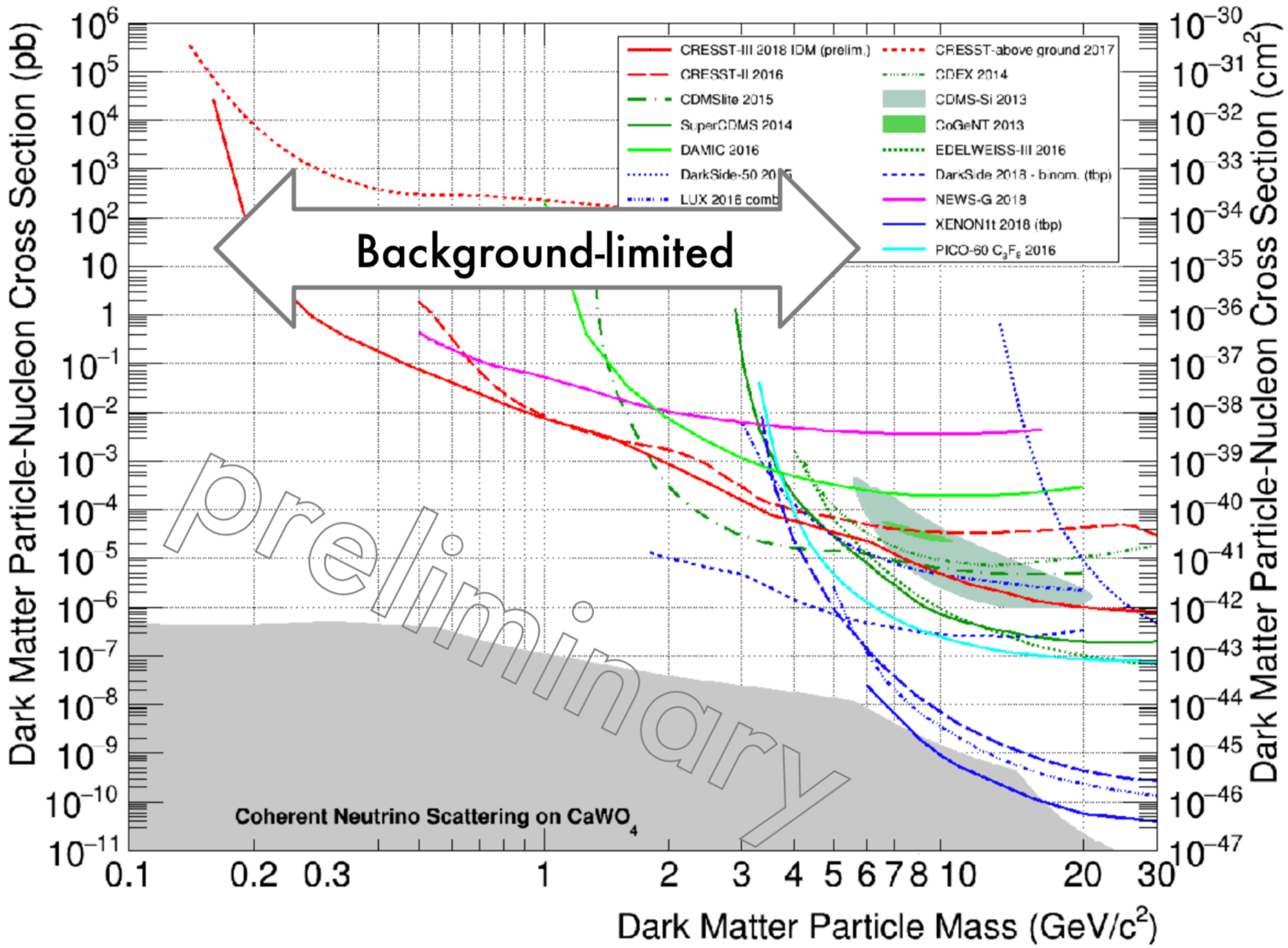


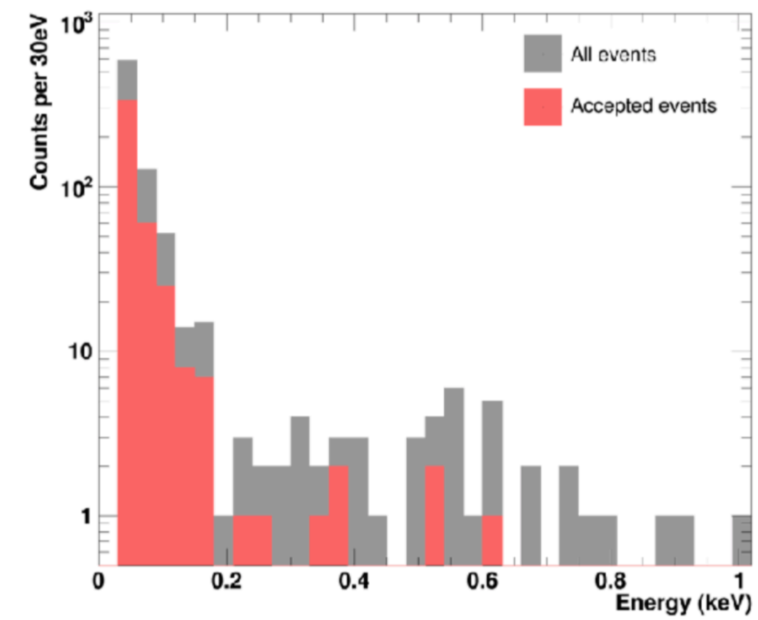




CRESST-III scintillating bolometer

(Preliminary) Result



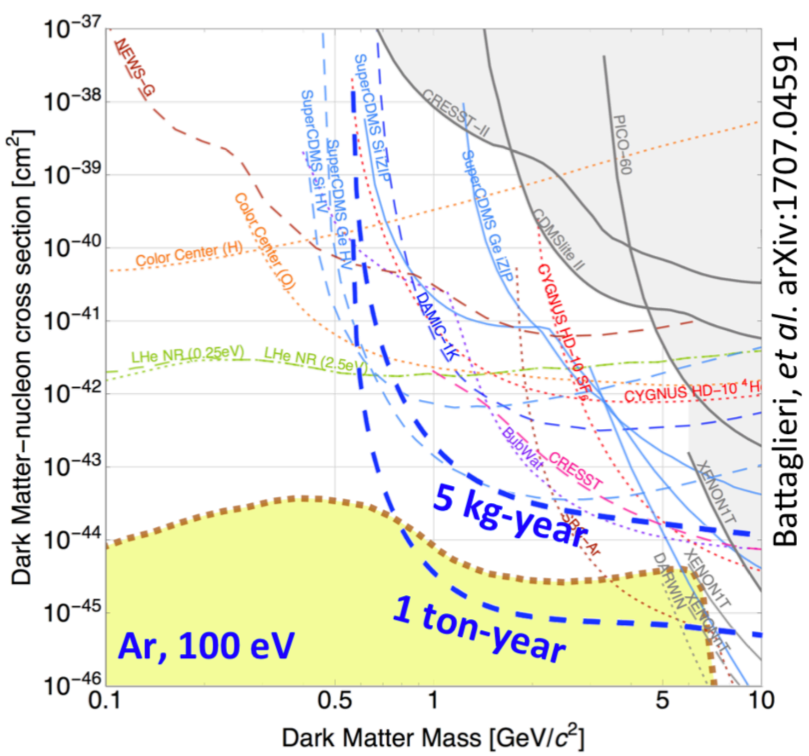


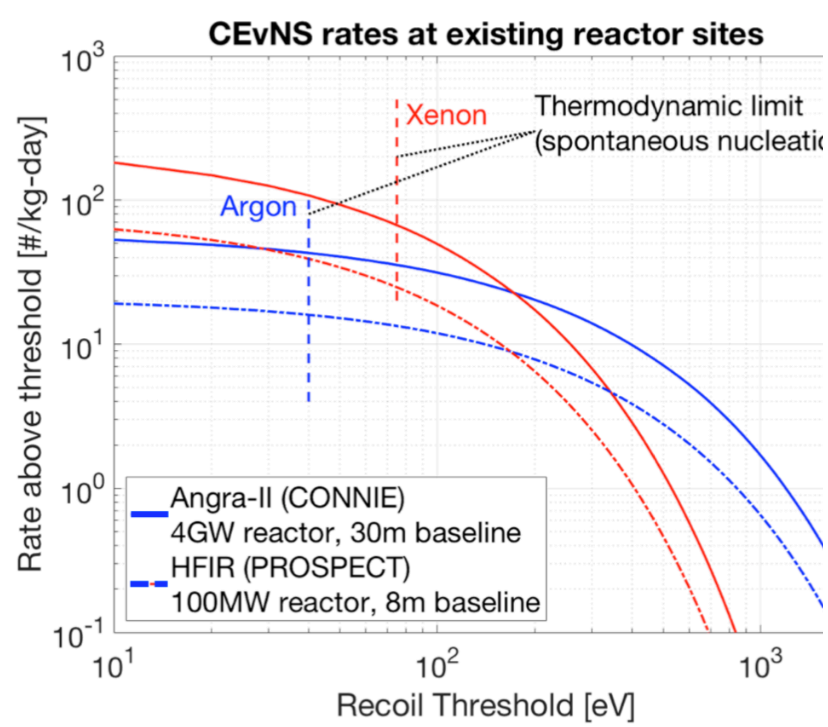
Unexpected rise of event rate < 200eV

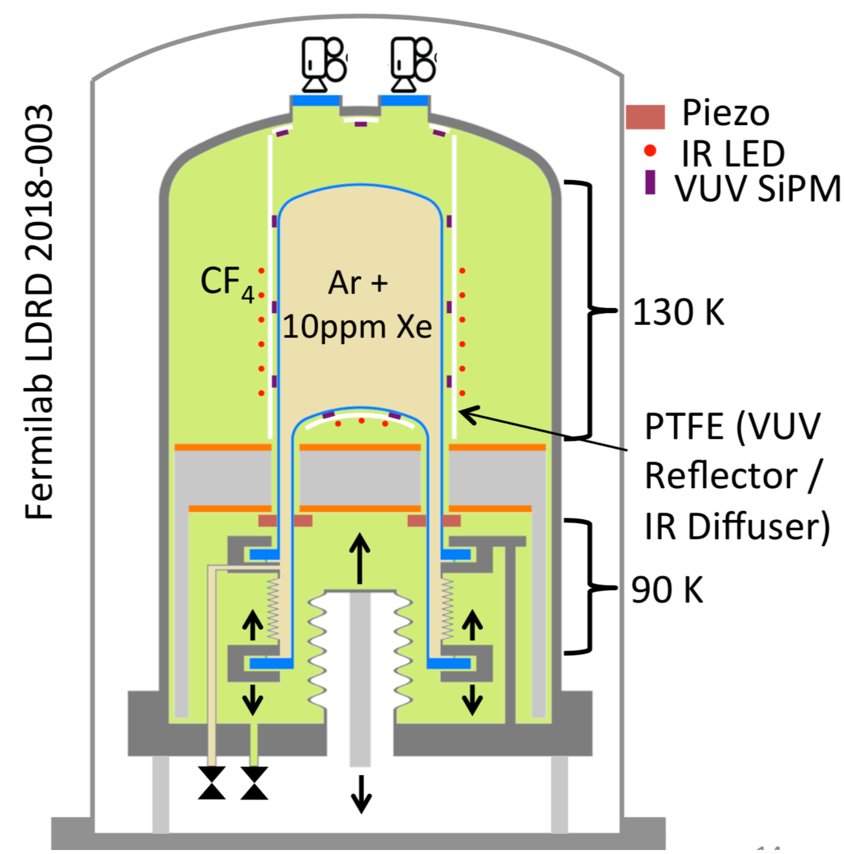
Some new stuff

40eV threshold for bubble formation
no e- recoil background

Physics with an Argon Bubble Chamber

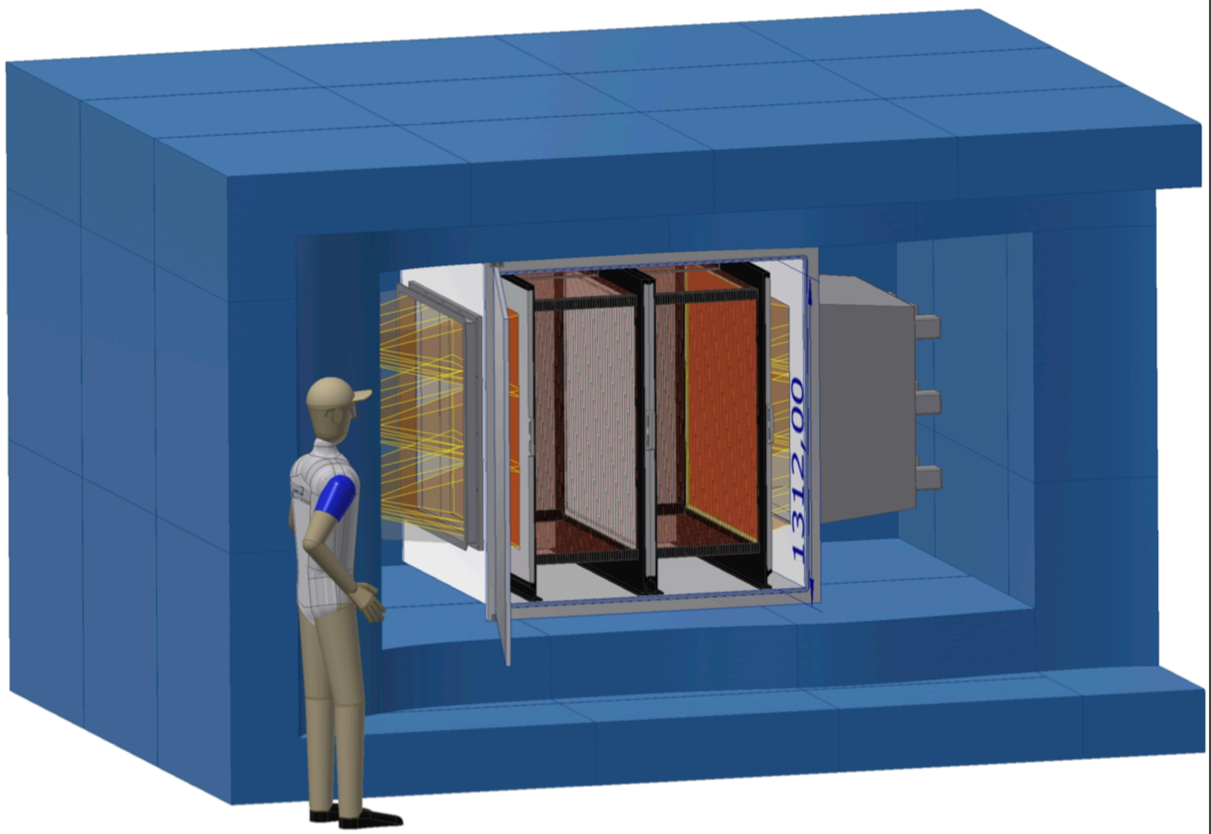




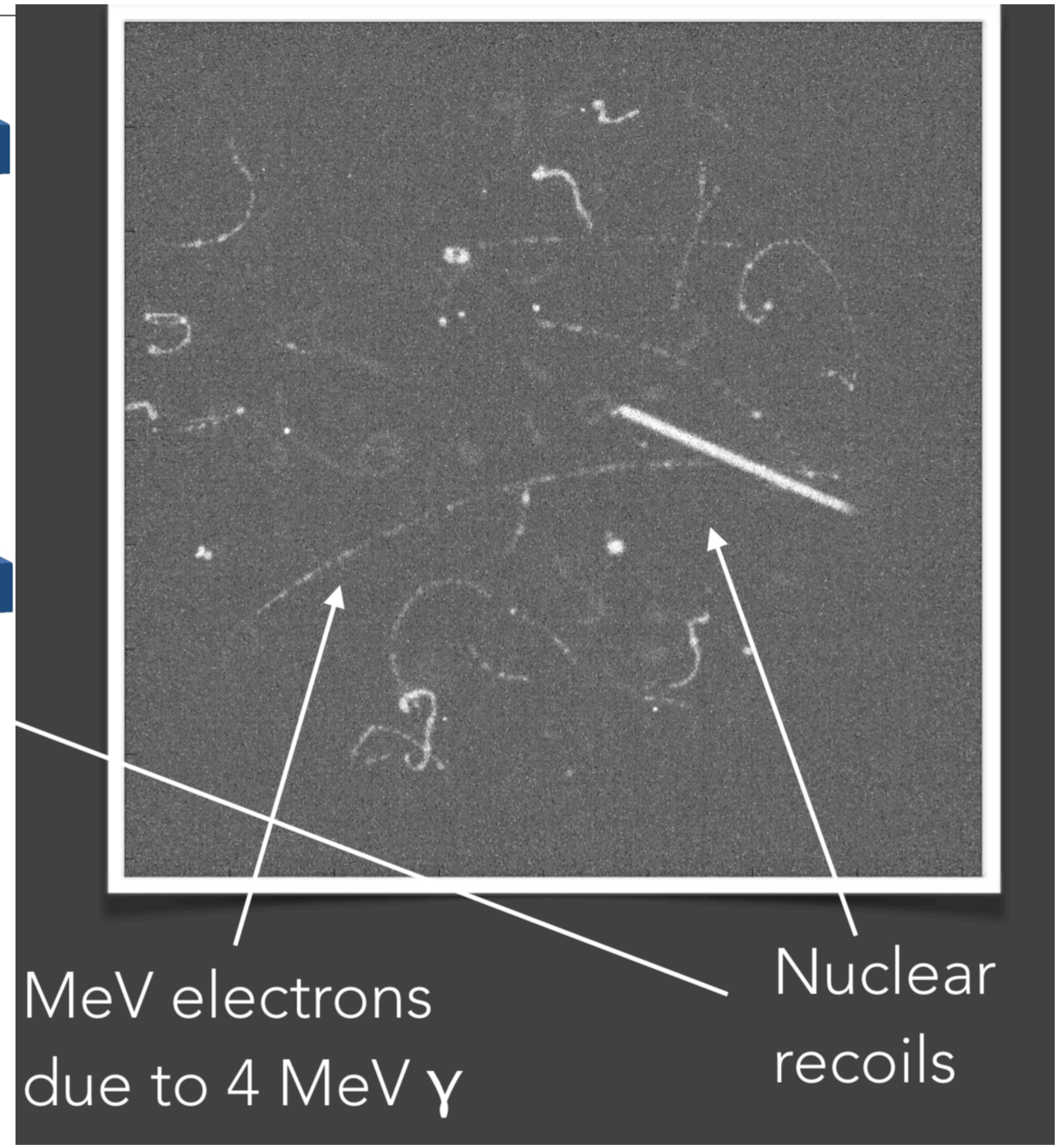


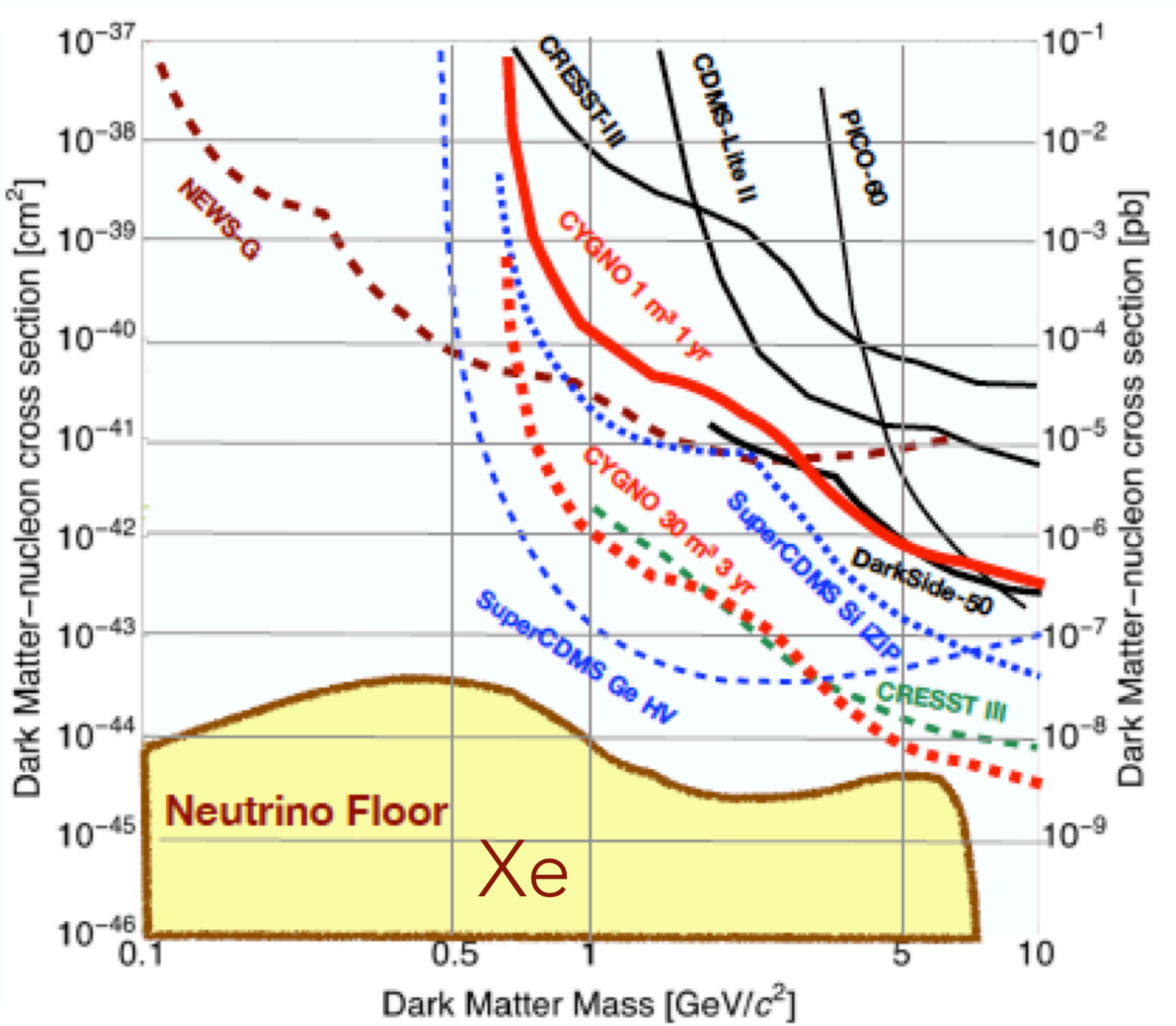
- WIMP searches to solar ν-floor (1 – 7 GeV)
- *O*(10) CEvNS events / kg-day @ reactor ← **Follows Calibration @ FNAL**

CYGNUS



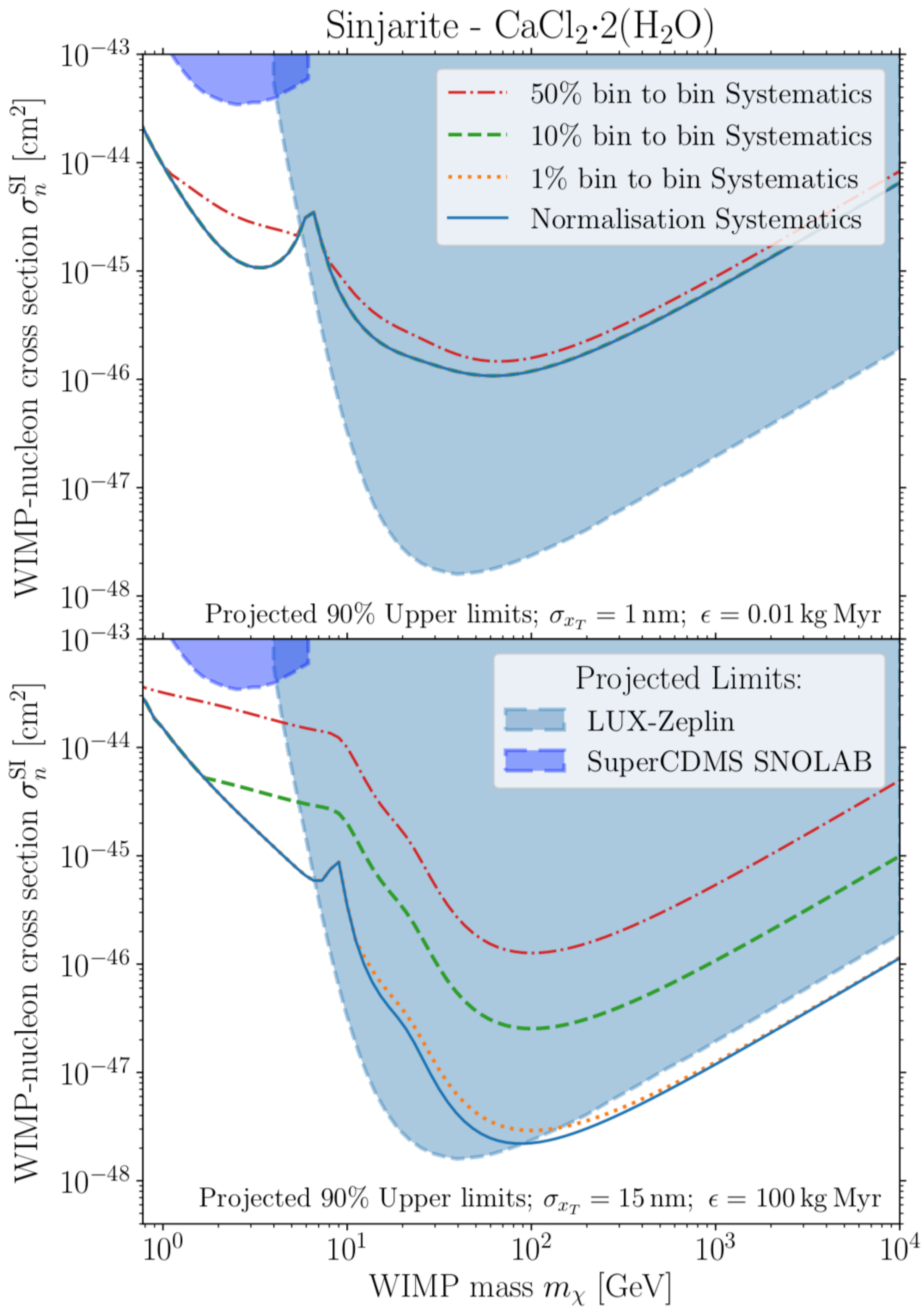
Roma1-GSSI…
He gas TPC
optical readout





Dark Matter–nucleon cross section [cm^2]
Dark Matter–nucleon cross section [pb]
Dark Matter Mass [GeV/c^2]
NEWS-G
CRESST-III
CDMS-Lite II
PICO-60
CYGNO 1 m³ 1 yr
CYGNO 30 m³ 3 yr
SuperCDMS Si iZIP
DarkSide-50
SuperCDMS Ge HV
CRESST III
Neutrino Floor
Xe

Paleo-detectors



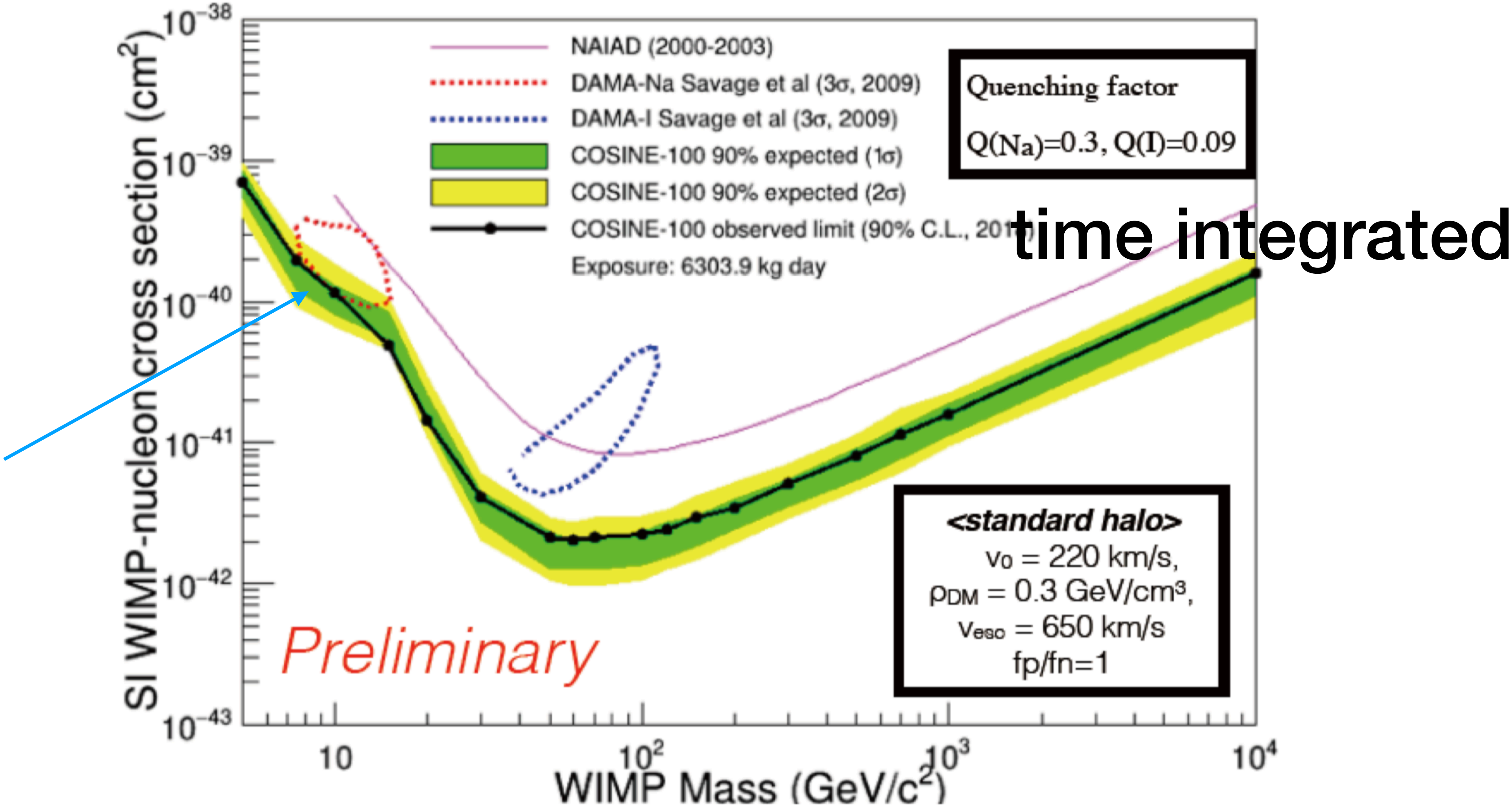
Can I say anything new about DAMA?

COSINE-100 NaI(Tl) crystals

New result from the COSINE Collaboration

8 crystals, 106 kg in total

Limit on WIMP-nucleon cross section

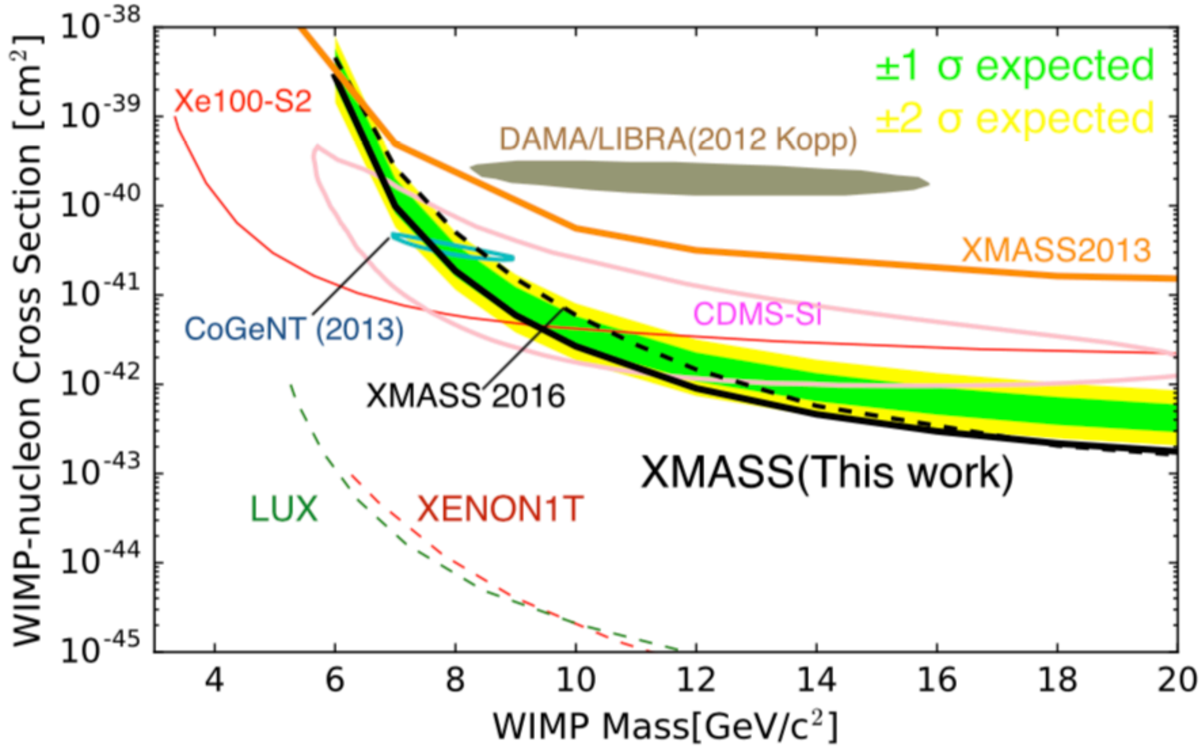


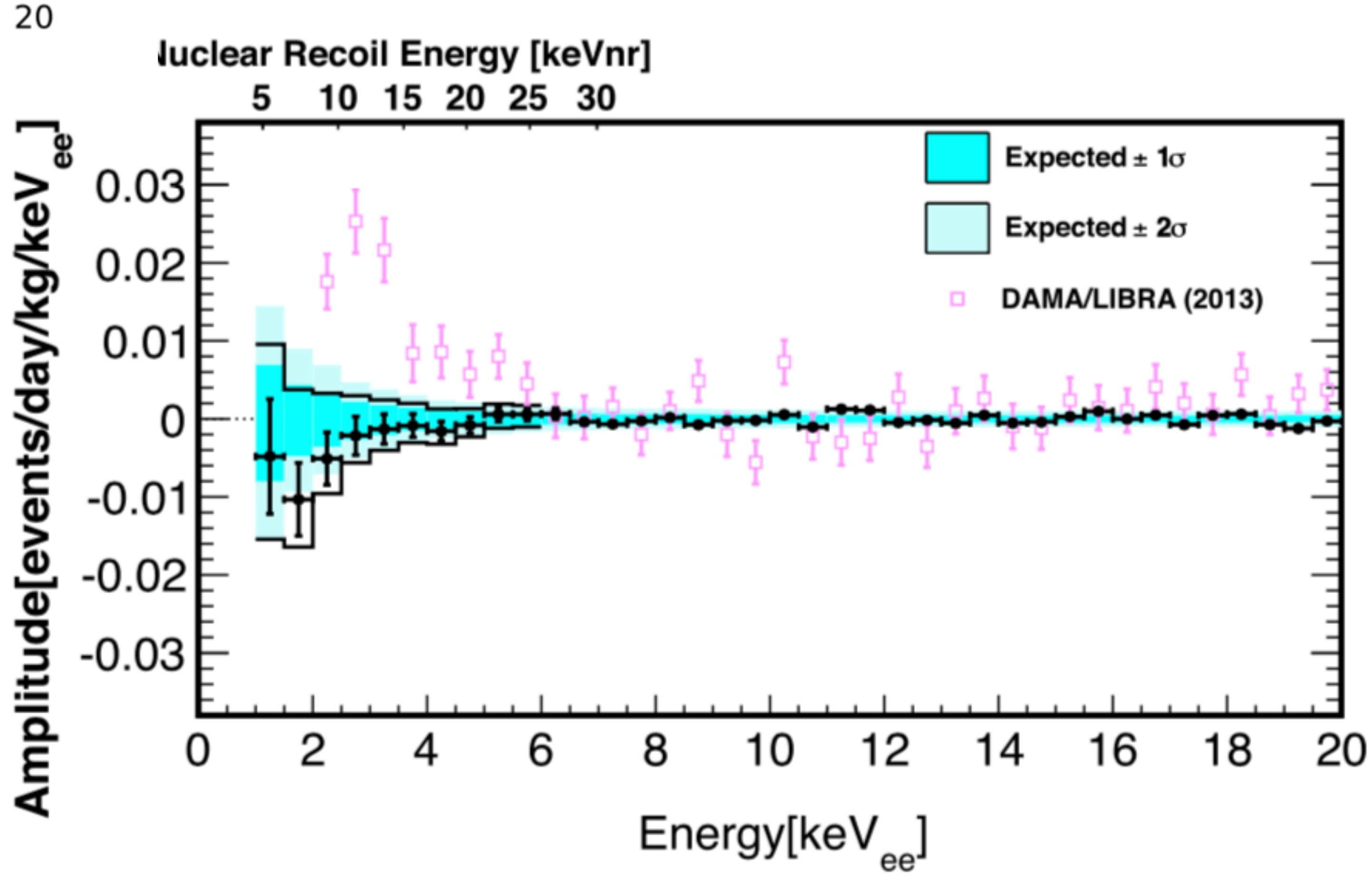
COSINE-100 excludes DAMA/LIBRA-phase1's interpretation with the spin-independent WIMP interaction in Standard Halo Model

First time with same NaI(Tl) target

Consistent with other null experiments

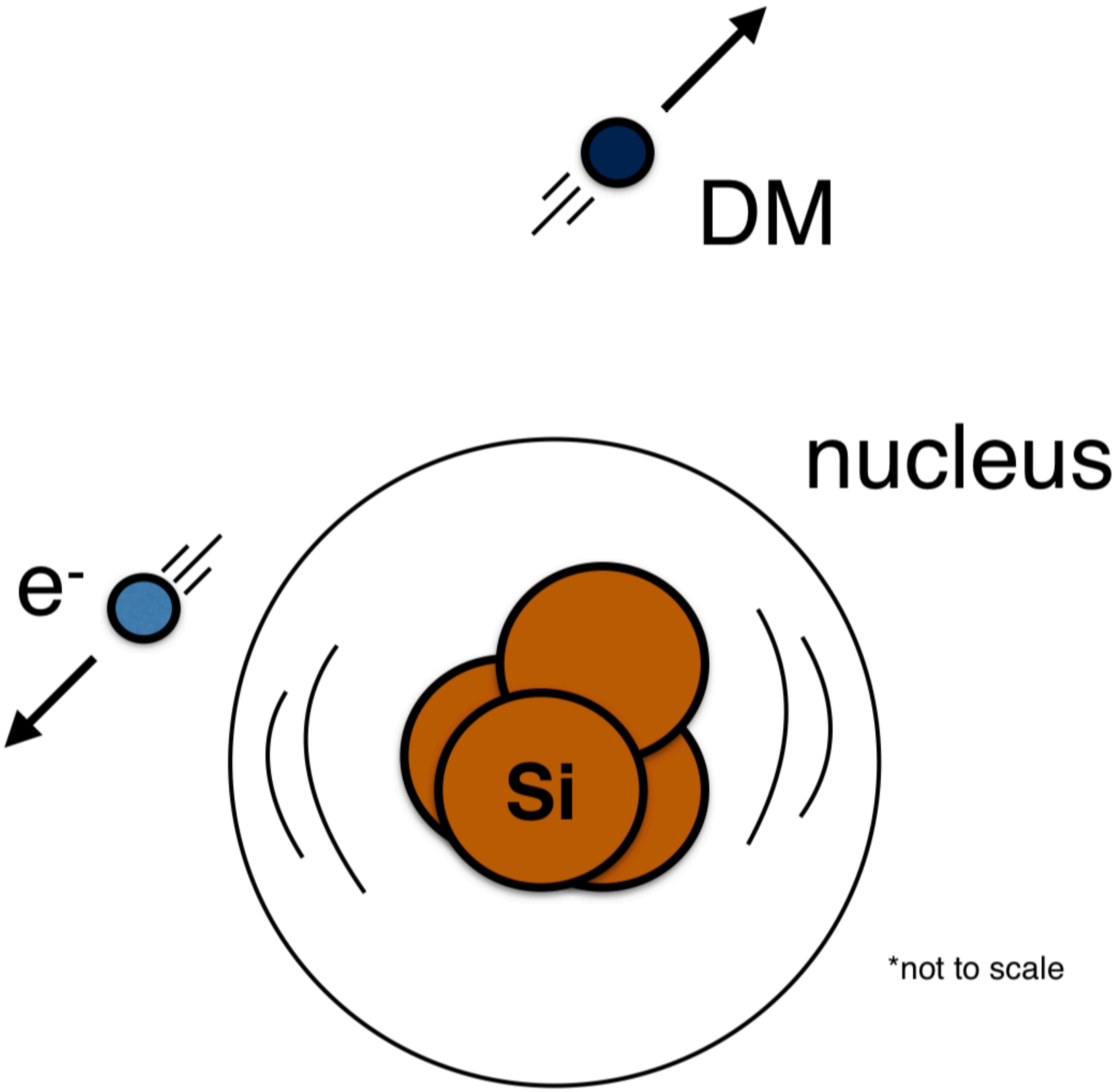
XMASS (xenon) 2018 annual modulation analysis





DM-electron scattering

$$E_R = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$
$$\sim \frac{1}{2}\text{eV} \times \left(\frac{m_\chi}{\text{MeV}}\right)$$



$$m_N = 28 \text{ GeV}$$

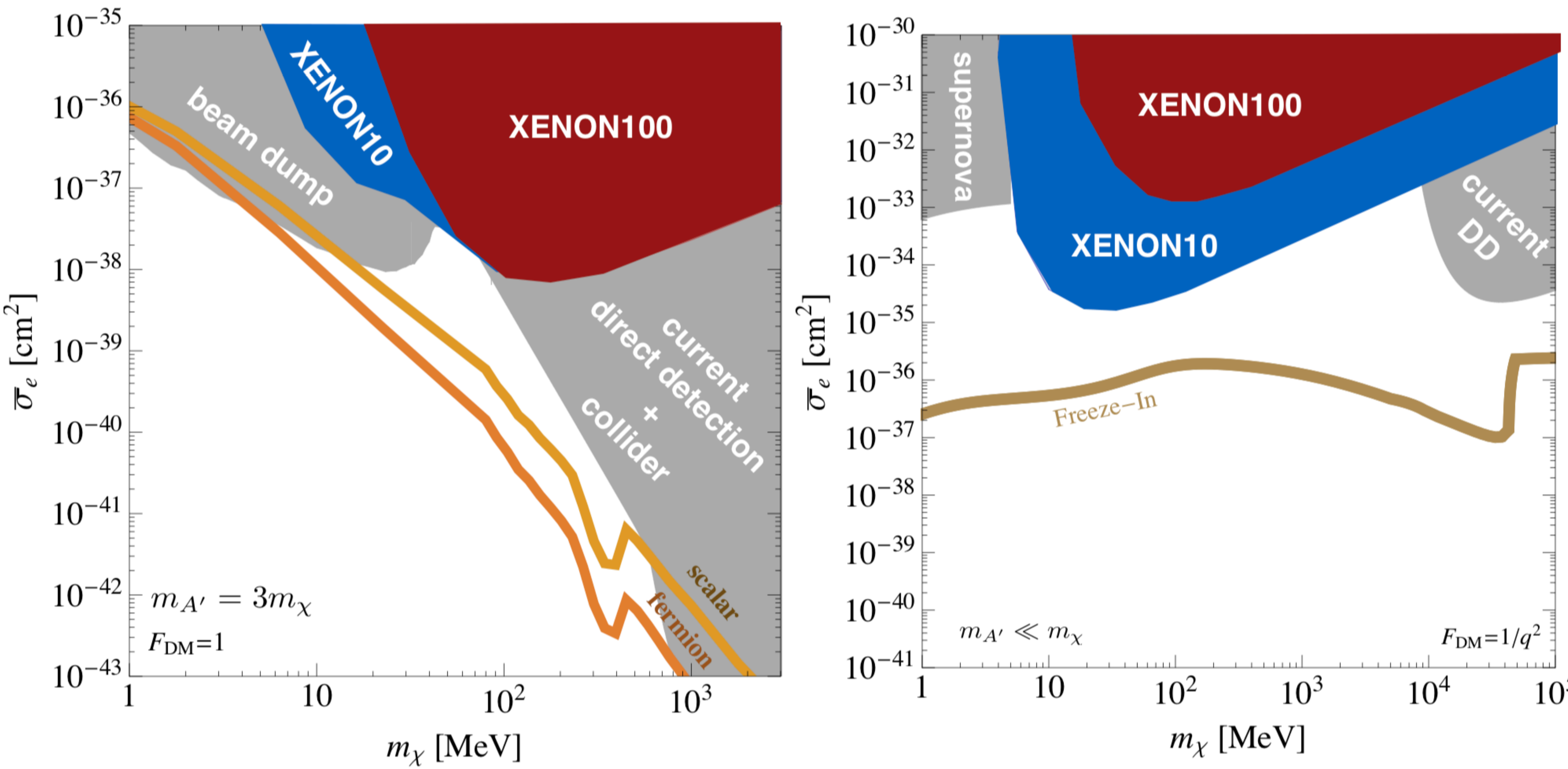
$$m_\chi = 100 \text{ MeV}$$

$$E_R \sim 50 \text{ eV}$$

available for detection

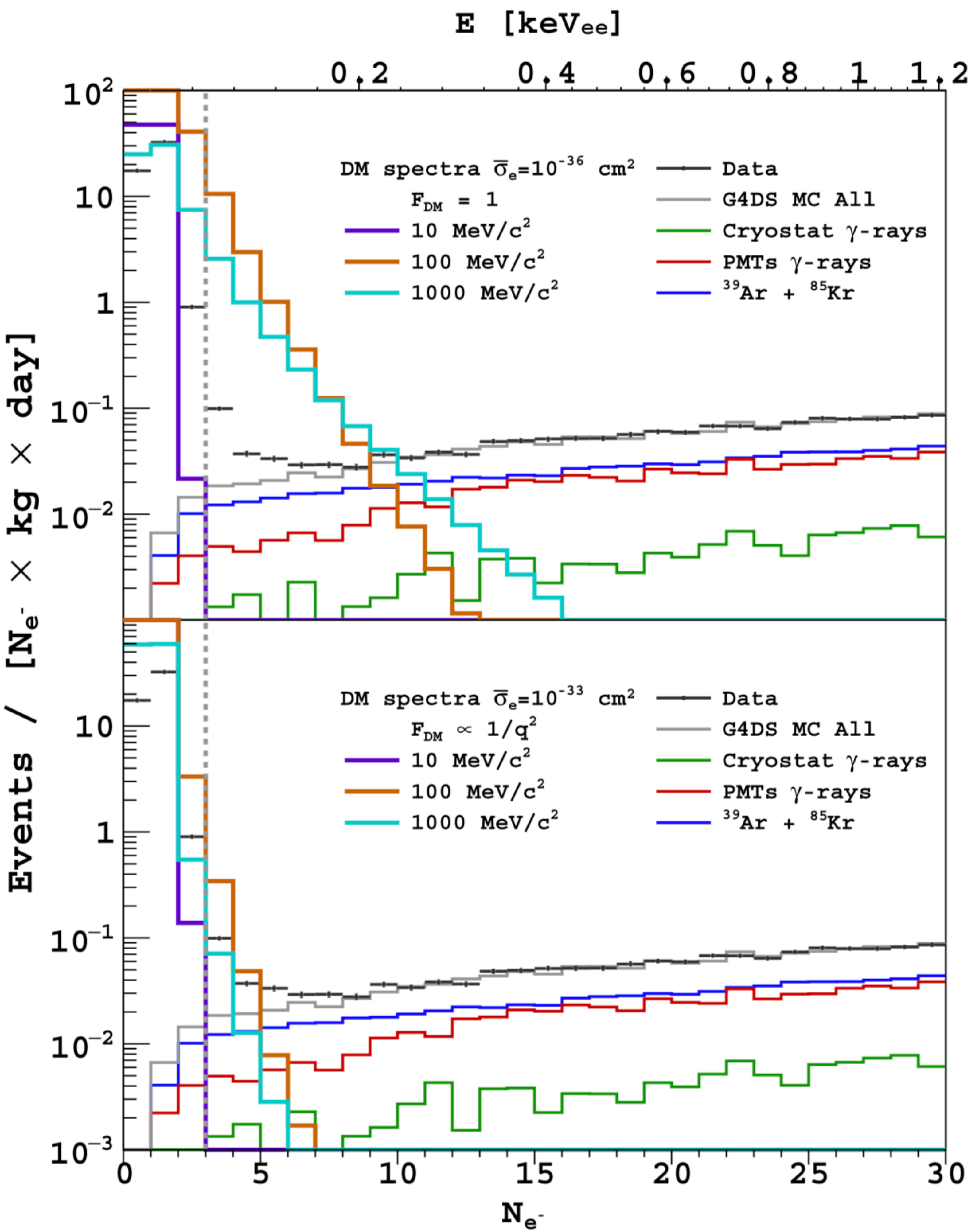
Type	Examples	E_{th} (eV)	$m_{DM,\,th}$ (MeV)	Status
Noble liquids	xenon argon helium	~10 eV (atom)	~5 MeV	Done w/ XENON10+100 data; improvements possible
Semi-conductors	germanium silicon	~1 eV (bandgap)	~200 keV	~40-50 eV (SuperCDMS, DAMIC); improvements need further R&D
Scintillators	GaAs, NaI, CsI, …	~1 eV (bandgap)	~200 keV	Requires R&D, but probably feasible soon
Super-conductors	aluminum	~1 meV	~1 keV	Requires R&D

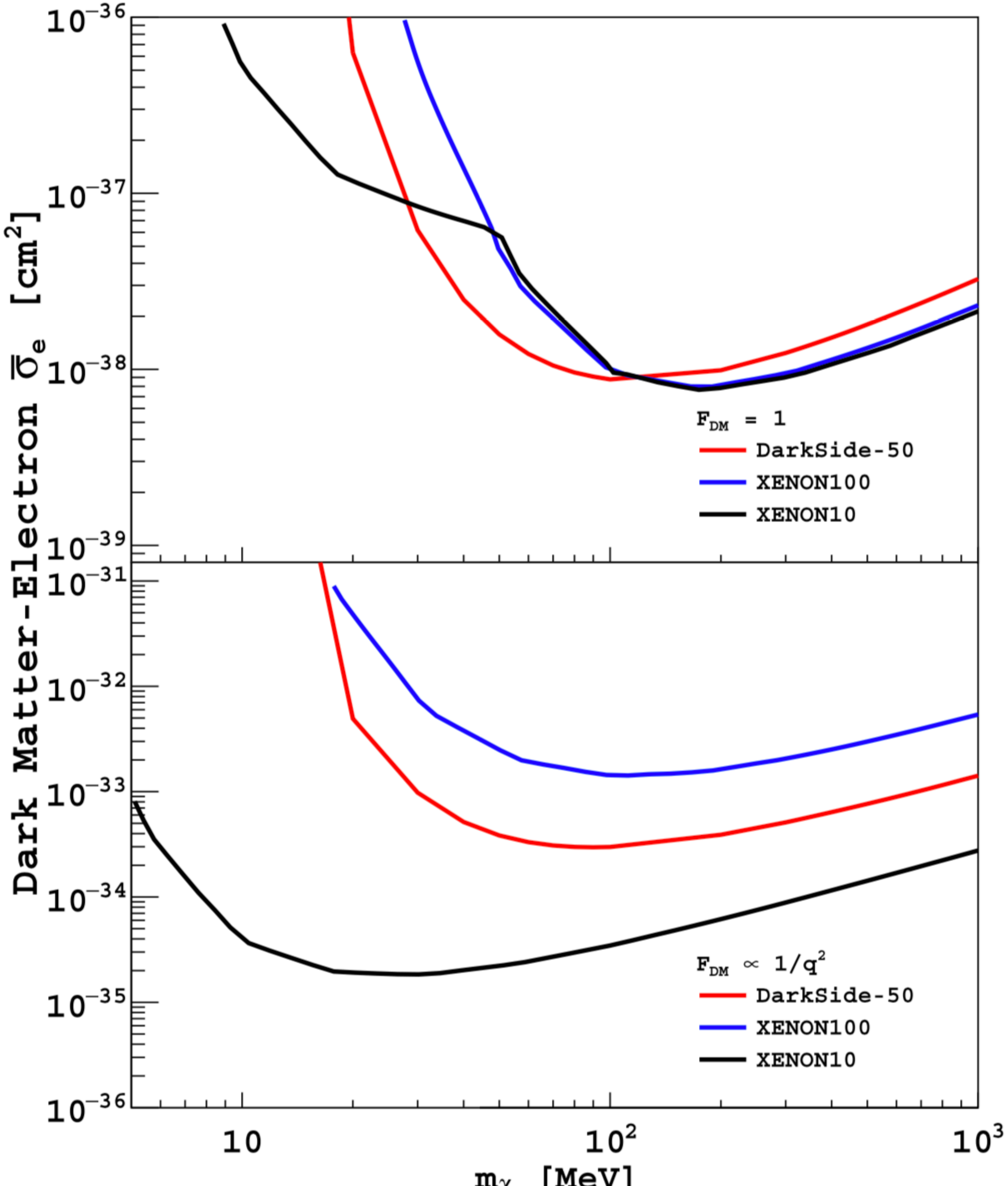
DM-electron scattering



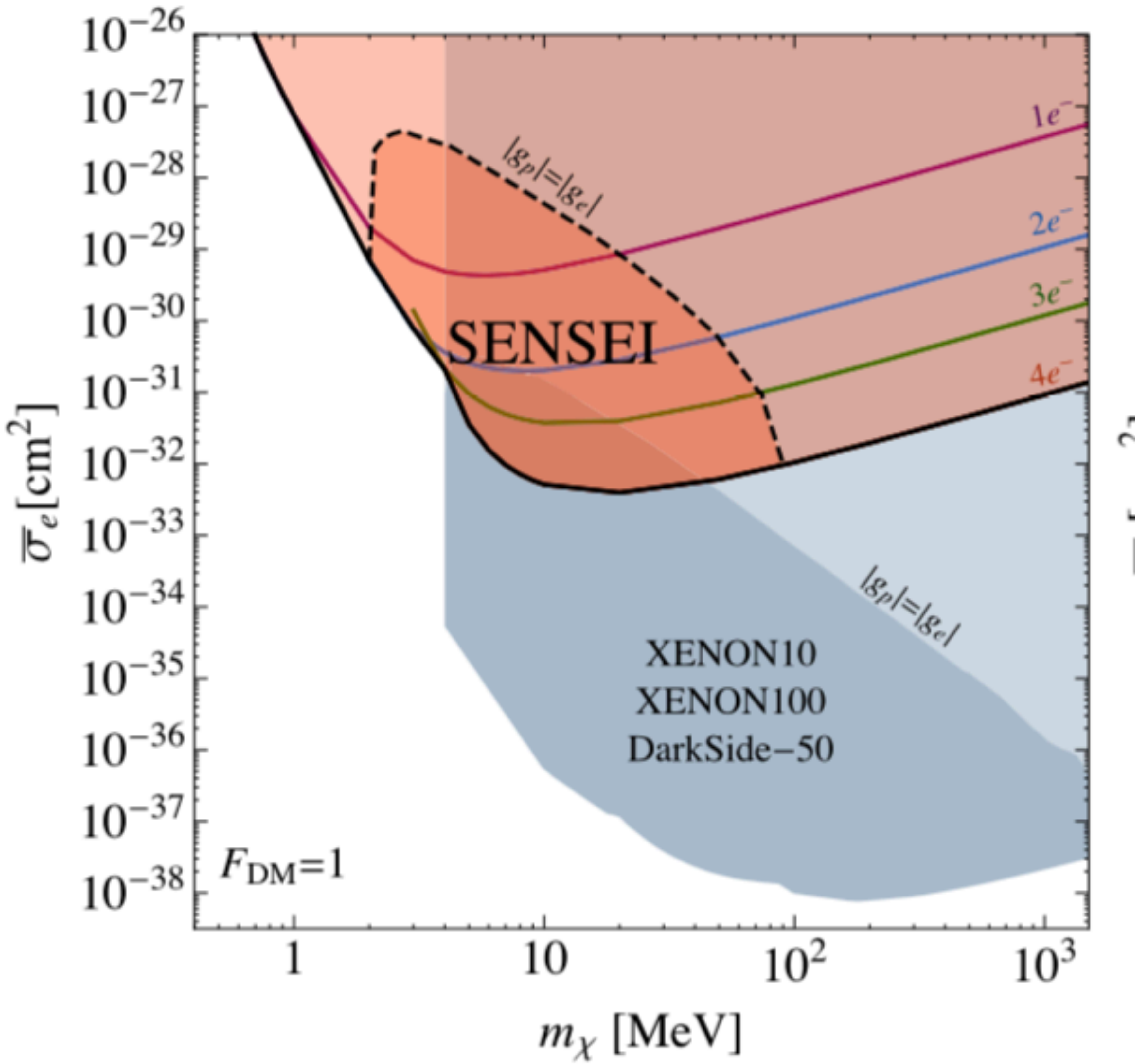
Essig, Volansky, TTY [1703.00910]

DARKSIDE50

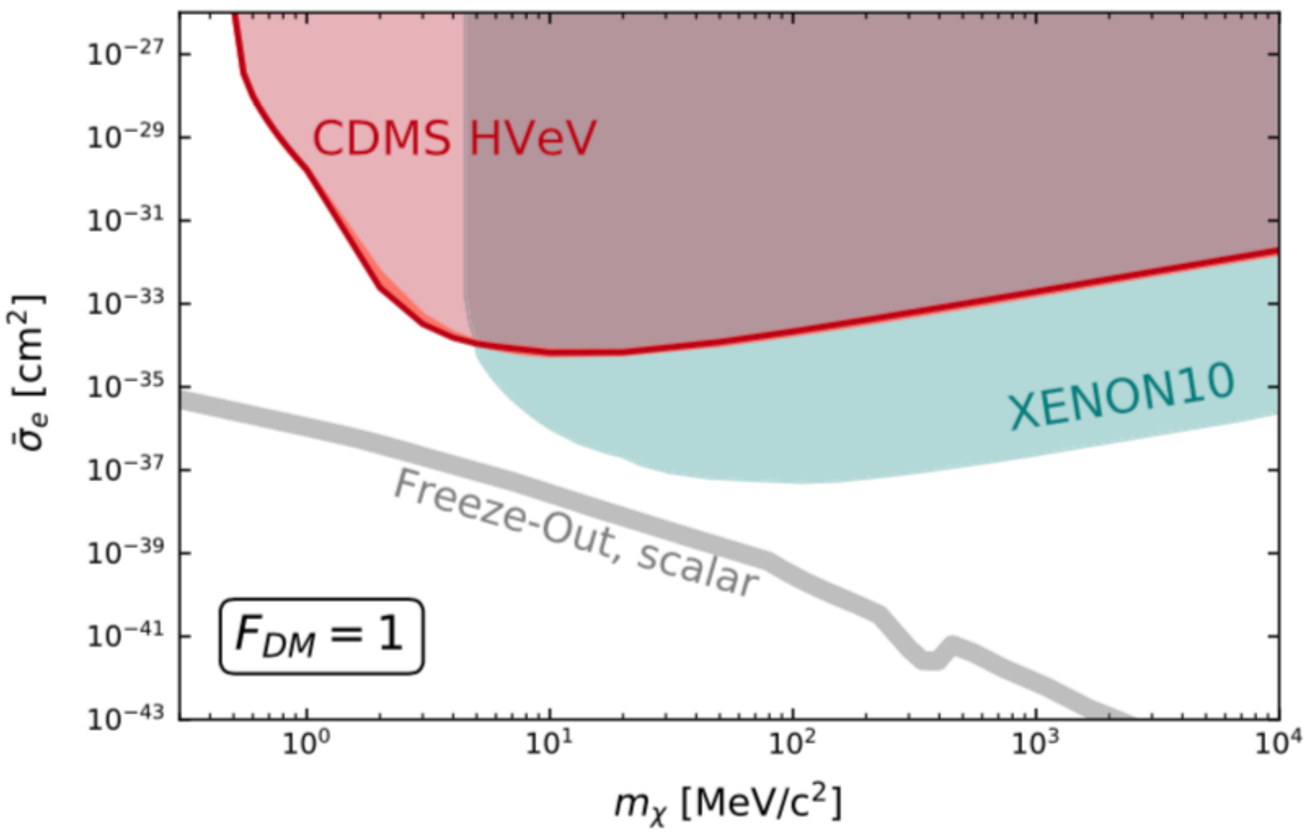

E [keVee]
0.2
0.4
0.6
0.8
1
1.2
Events / [Ne- × kg × day]
DM spectra σe=10^-36 cm²
FDM = 1
10 MeV/c²
100 MeV/c²
1000 MeV/c²
Data
G4DS MC All
Cryostat γ-rays
PMTs γ-rays
39Ar + 85Kr
DM spectra σe=10^-33 cm²
FDM ∝ 1/q²
10 MeV/c²
100 MeV/c²
1000 MeV/c²
Data
G4DS MC All
Cryostat γ-rays
PMTs γ-rays
39Ar + 85Kr
0
5
10
15
20
25
30
Ne-

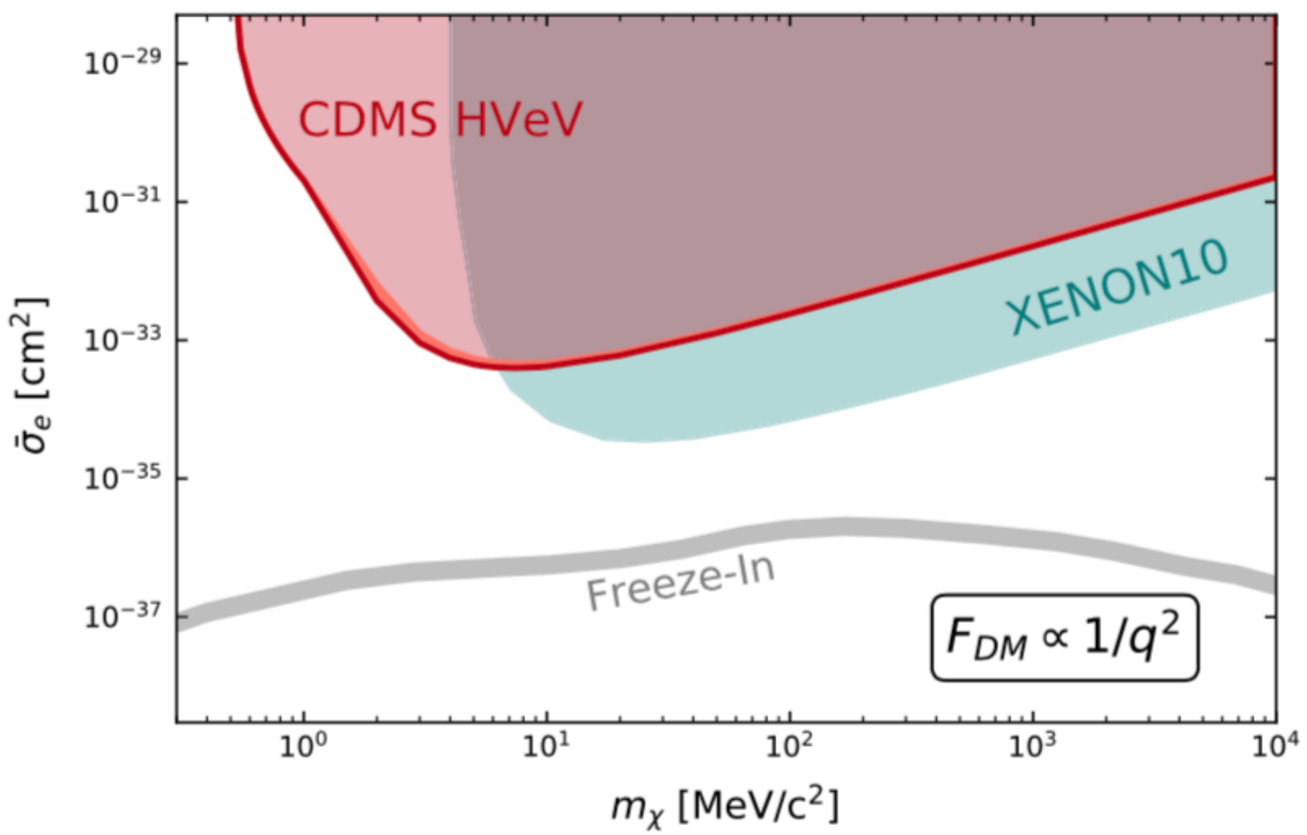


Dark Matter-Electron $\bar{\sigma}_e$ [cm^2]
10^{-36}
10^{-37}
10^{-38}
10^{-39}
$F_{DM} = 1$
DarkSide-50
XENON100
XENON10
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
$F_{DM} \propto 1/q^2$
DarkSide-50
XENON100
XENON10
10
10^2
10^3
m_χ [MeV]

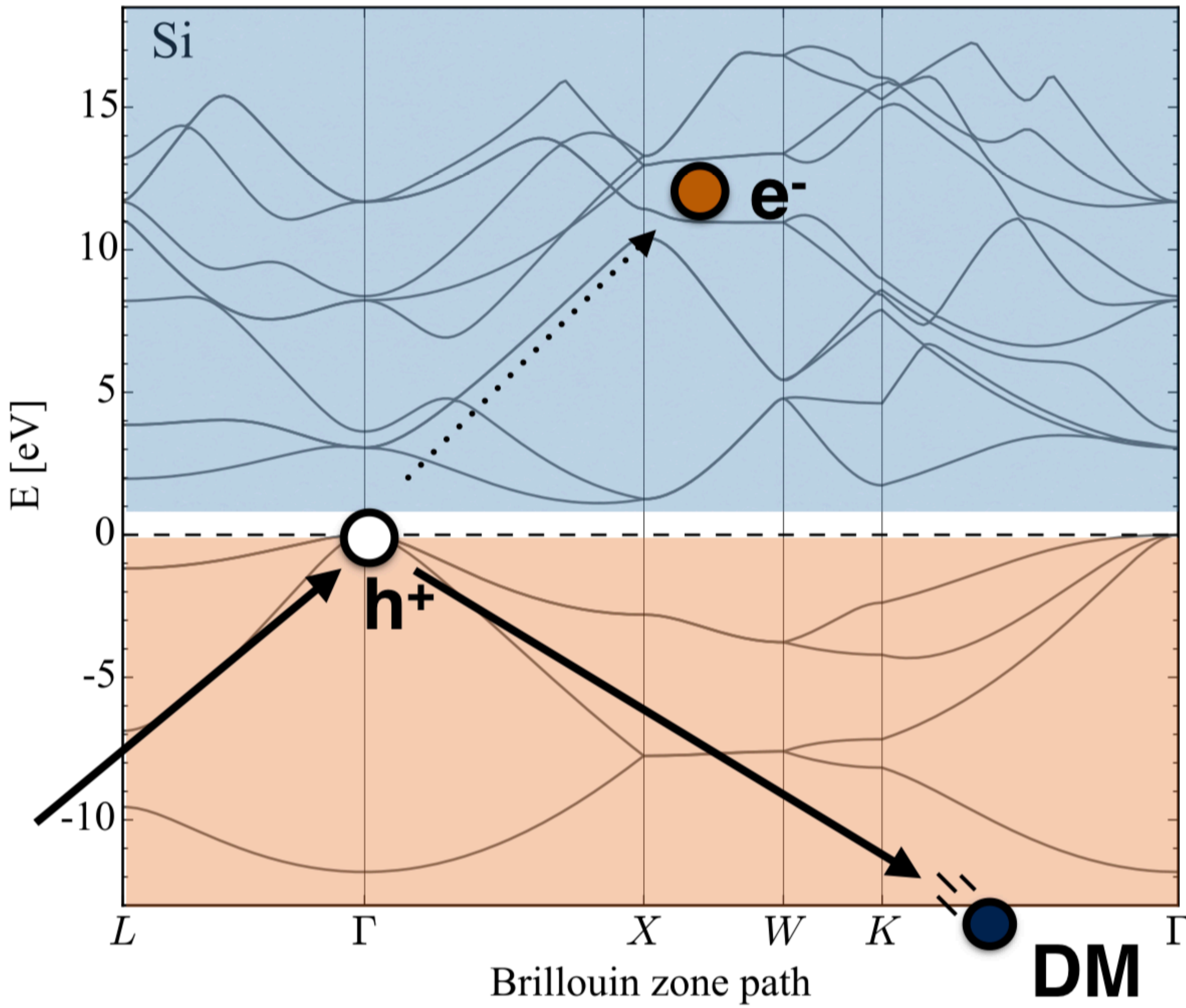


SENSEI
$1e^-$
$2e^-$
$3e^-$
$4e^-$
$|g_p|=|g_e|$
$|g_p|=|g_e|$
XENON10
XENON100
DarkSide−50
$F_{DM}=1$
$\overline{\sigma}_e[\text{cm}^2]$
m_χ [MeV]


CDMS HVeV
XENON10
Freeze-Out, scalar
$F_{DM} = 1$
$\bar{\sigma}_e$ [cm²]
m_χ [MeV/c²]


CDMS HVeV
XENON10
Freeze-In
$F_{DM} \propto 1/q^2$
$\bar{\sigma}_e$ [cm²]
m_χ [MeV/c²]

semiconductor targets



detect the electron(s)

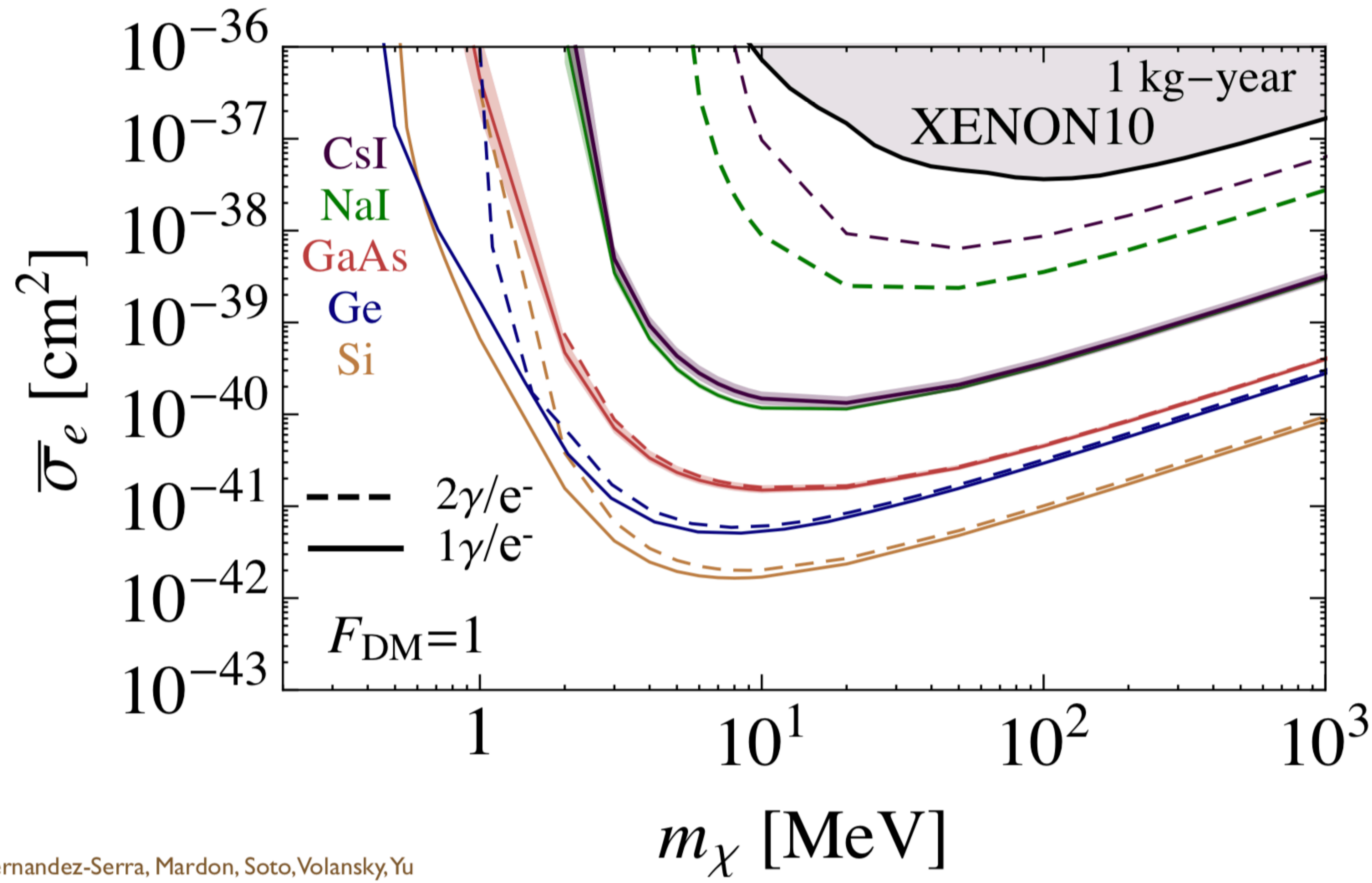
sensitive to ~eV energy depositions

i.e. silicon, germanium

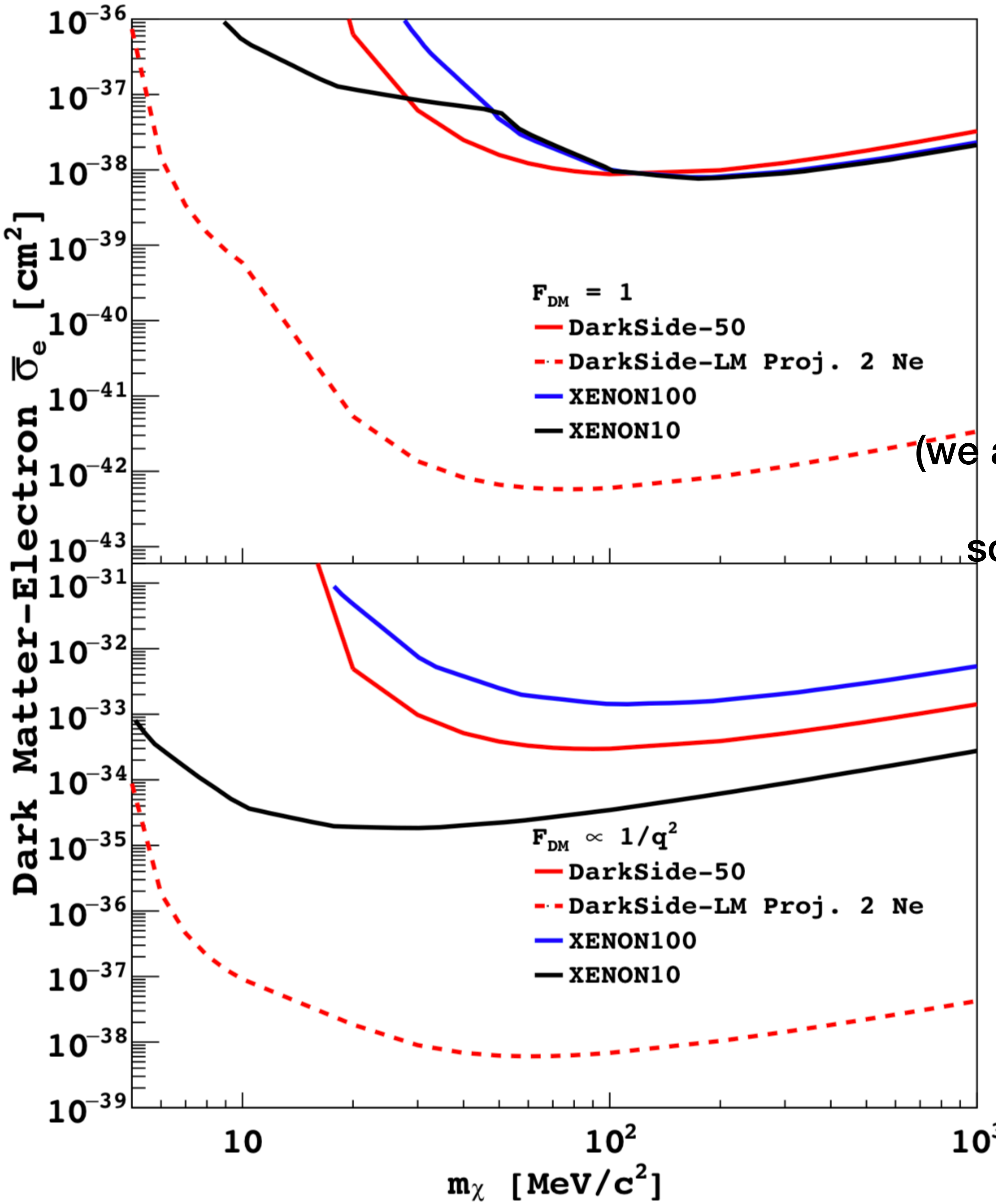
Essig, Mardon, Volansky [1108.5383]
Graham, Kaplan, Rajendran, Walters [1203.2531]
Lee, Lisanti, Mishra-Sharma, Safdi [1508.07361]
Essig, Fernandez-Serra, Mardon, Soto, Volansky, TTY [1509.01598]

Prospects?

95% c.l. for zero background (i.e. 3.6 DM events)

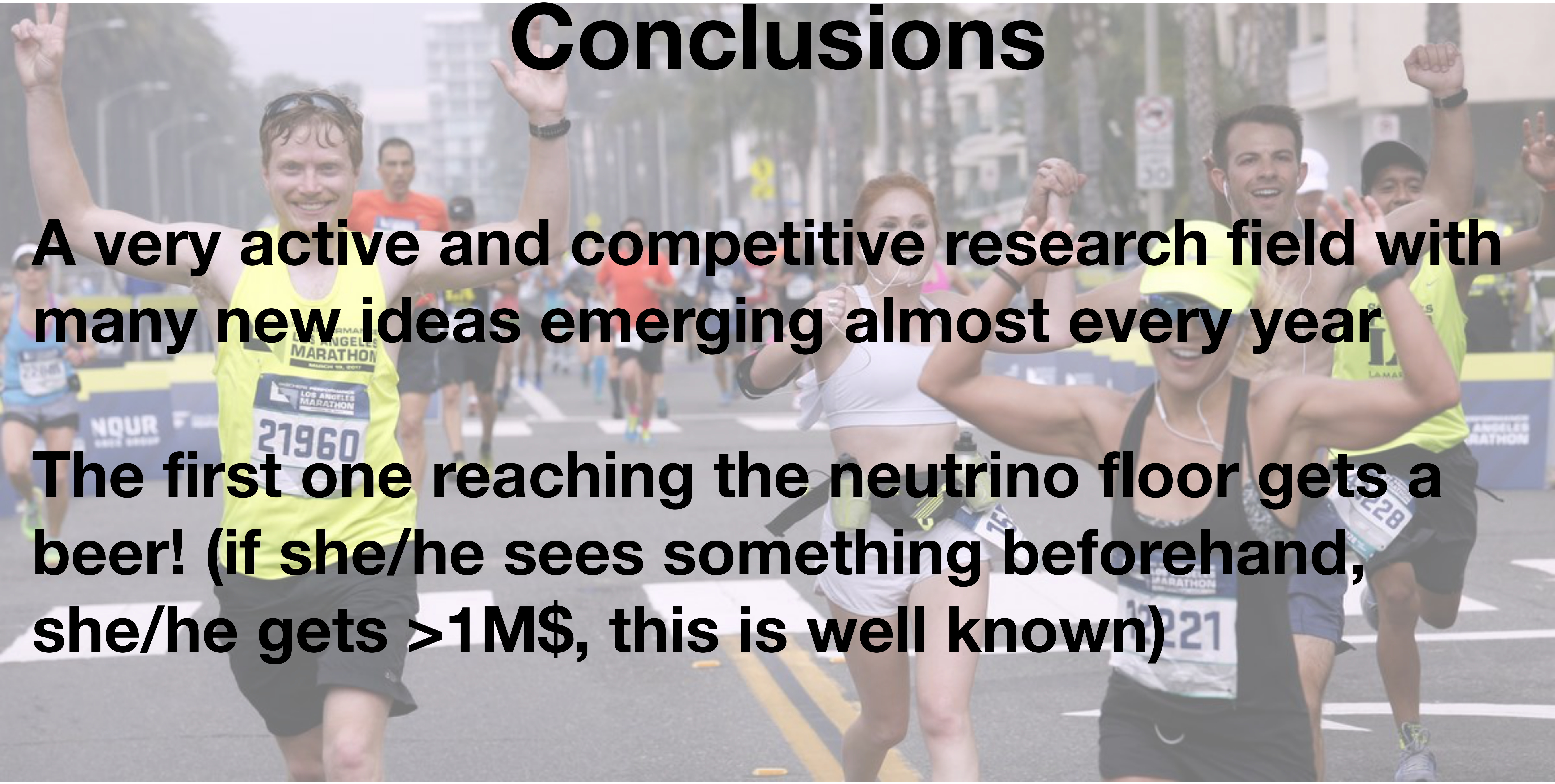


RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu



very preliminary
dream sensitivity
(we assume optimistically
here that
some current issues
will be solved)!

Conclusions



A very active and competitive research field with many new ideas emerging almost every year

The first one reaching the neutrino floor gets a beer! (if she/he sees something beforehand, she/he gets >1M$, this is well known)