Direct search for dark matter with DarkSide-20k experiment

Marie van Uffelen - 3rd year PhD student

PhD supervisors: Fabrice Hubaut (CPPM), Emmanuel Nezri (LAM)

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DARKSIDE

Institut Physique de l'Univers
Aix*Marseille Université

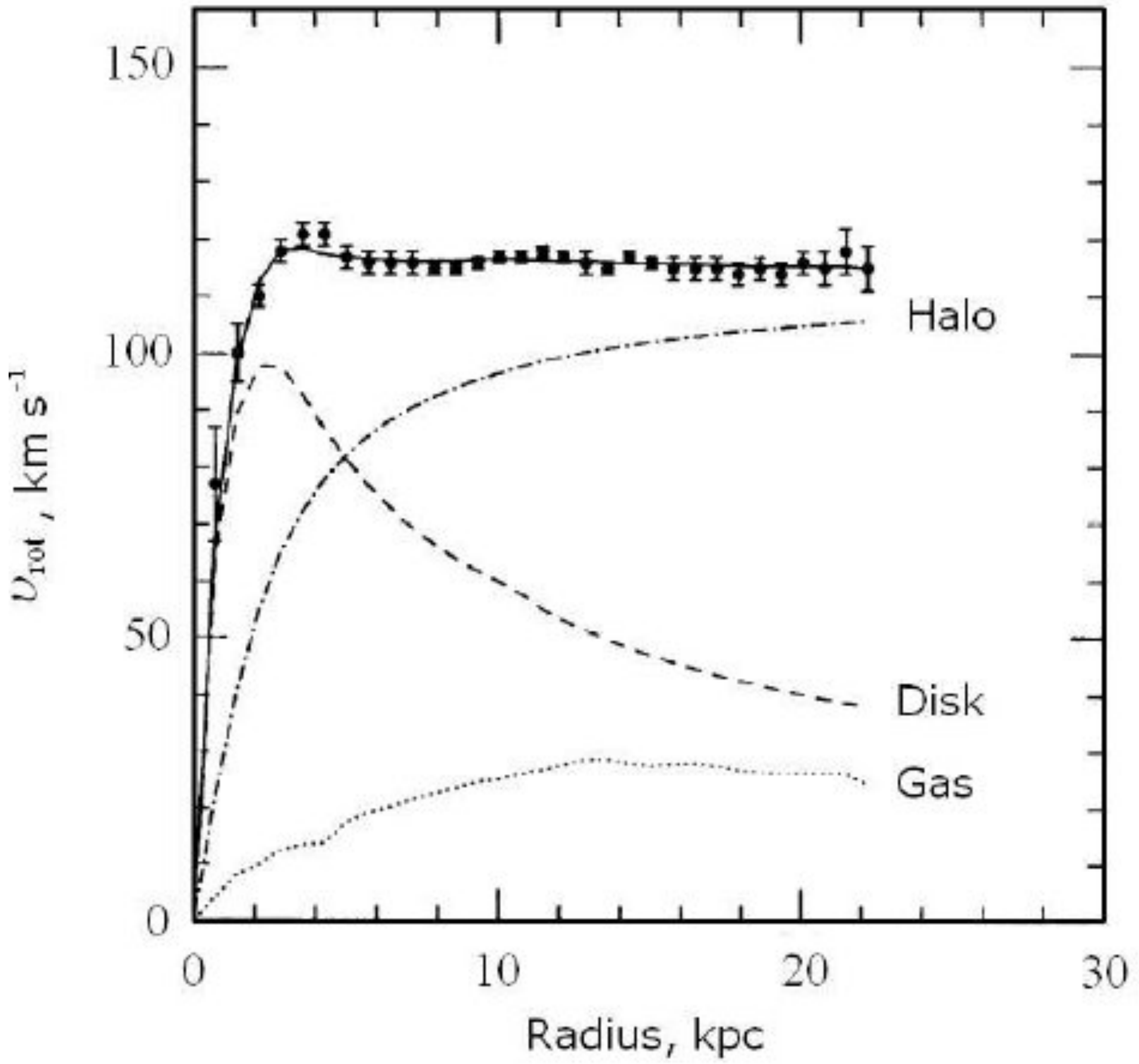
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

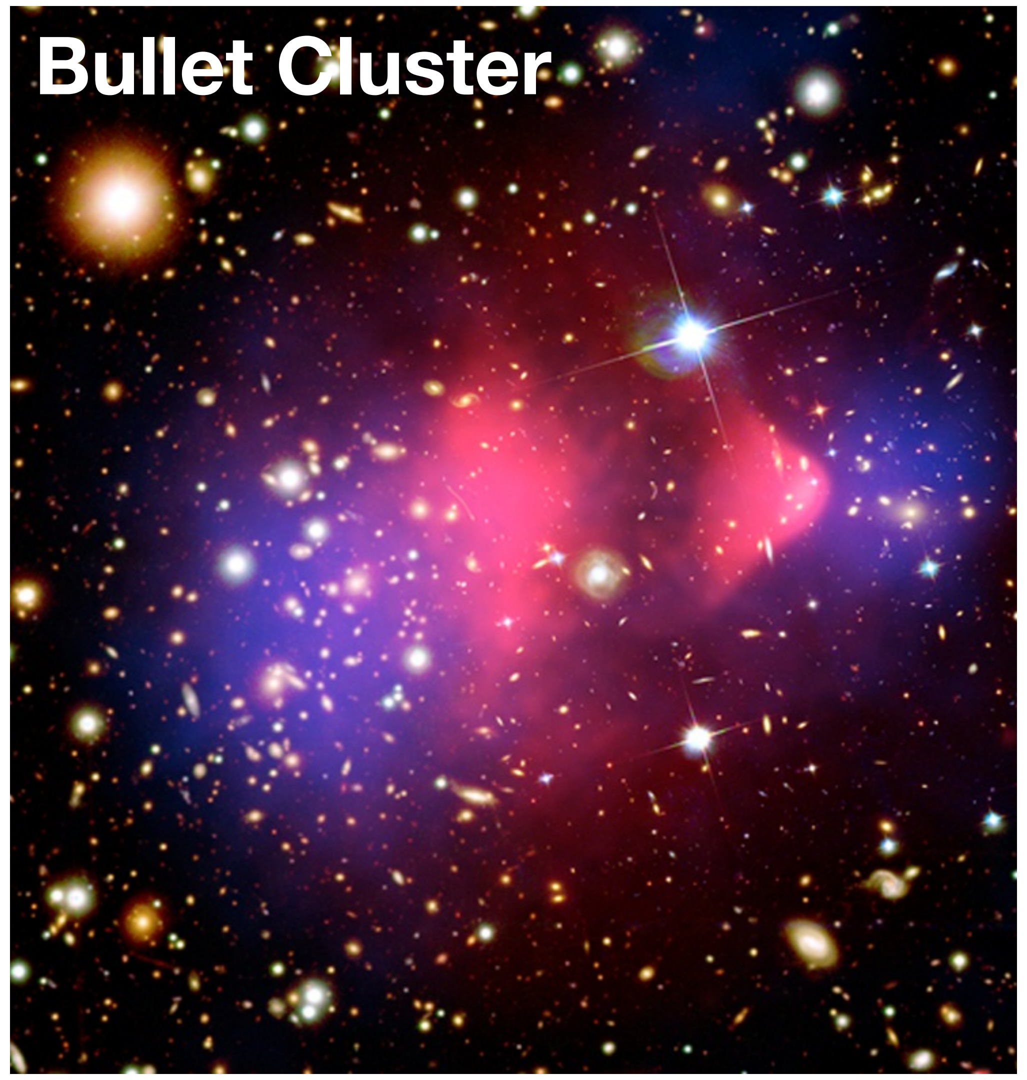
Dark matter ?

Rich evidence for Dark Matter (DM) from gravitational effects at all scales

Galaxy rotation curves

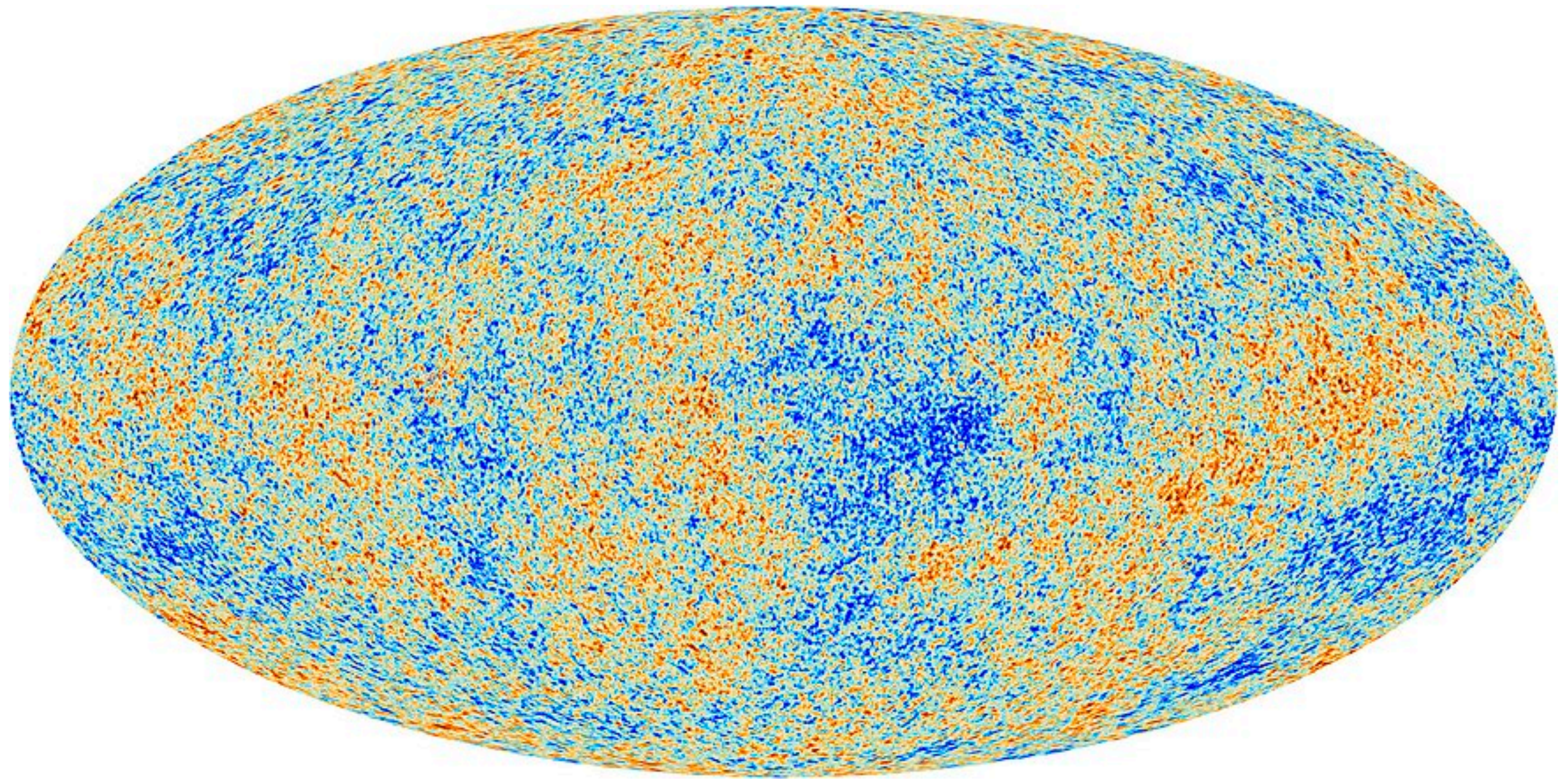


Collision of galaxy clusters



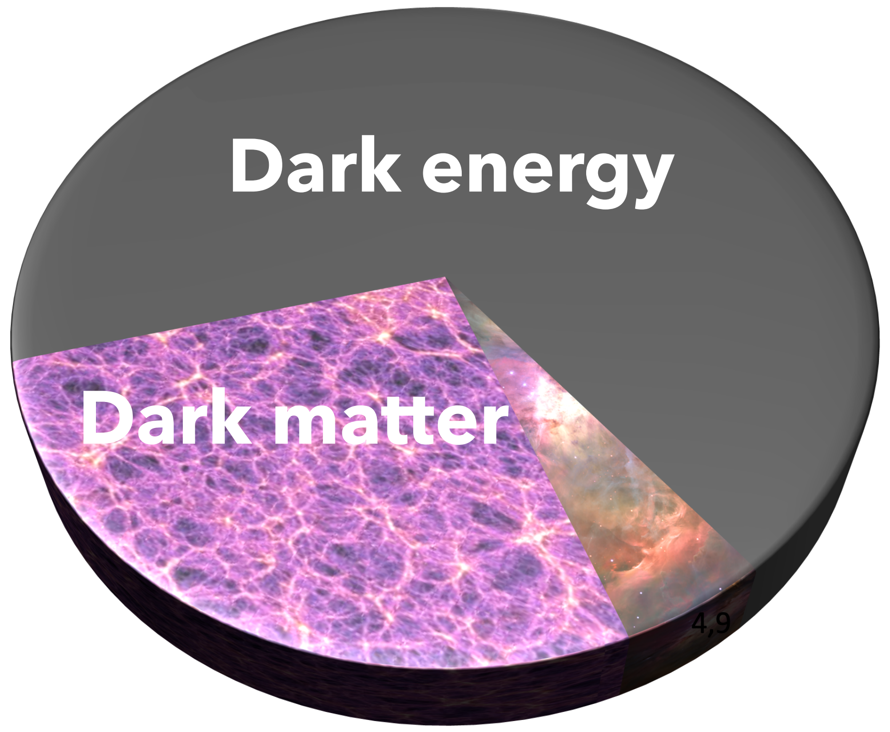
Gravitational lensing

CMB



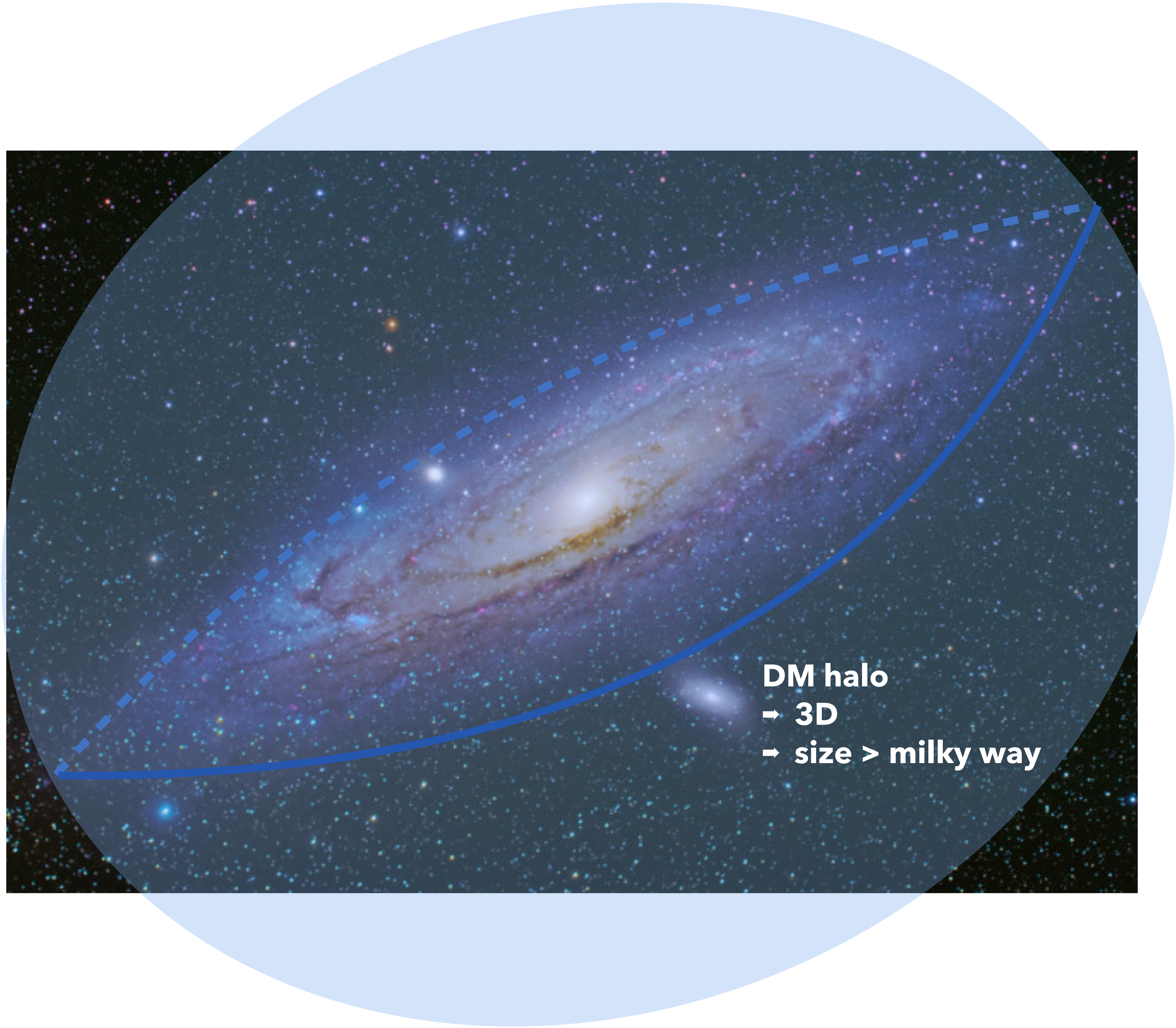
➡ **Missing mass in the Universe**
Standard model does not provide particle candidate for dark matter

Λ_{CDM}



Direct search for WIMP dark matter

Direct search for WIMP dark matter



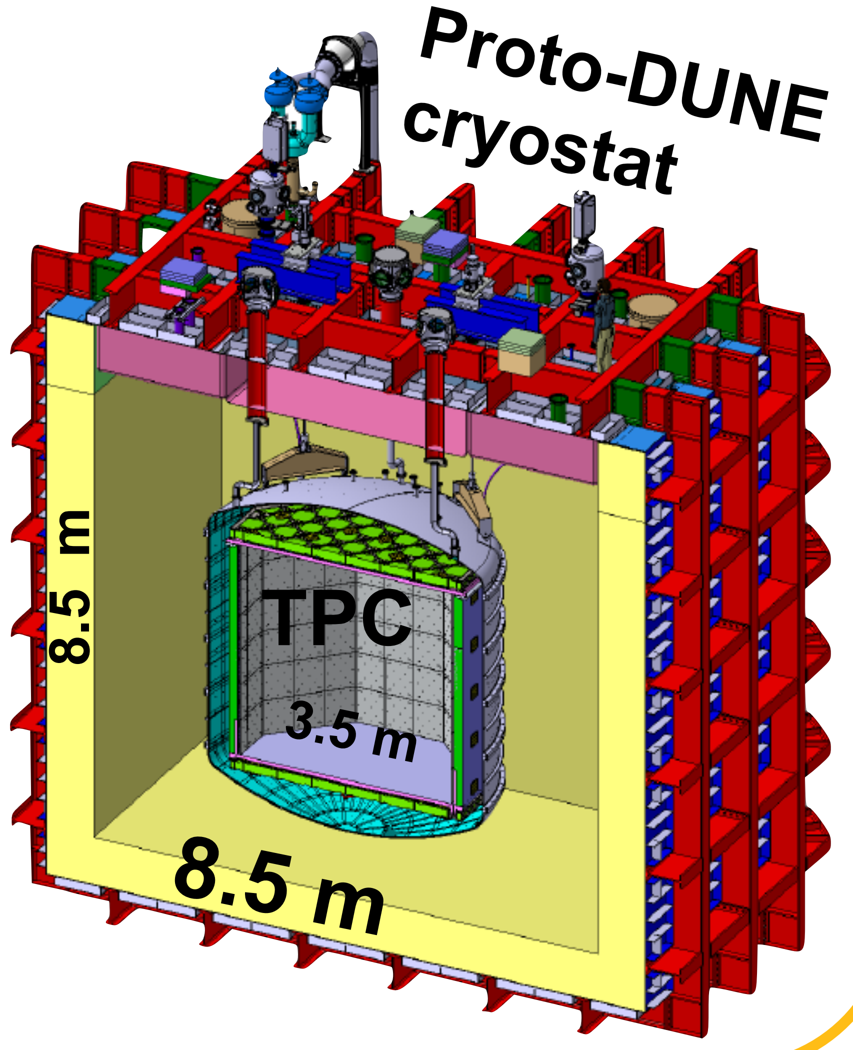
Direct search for WIMP dark matter

How to search for WIMPs ?

Create scalable detectors

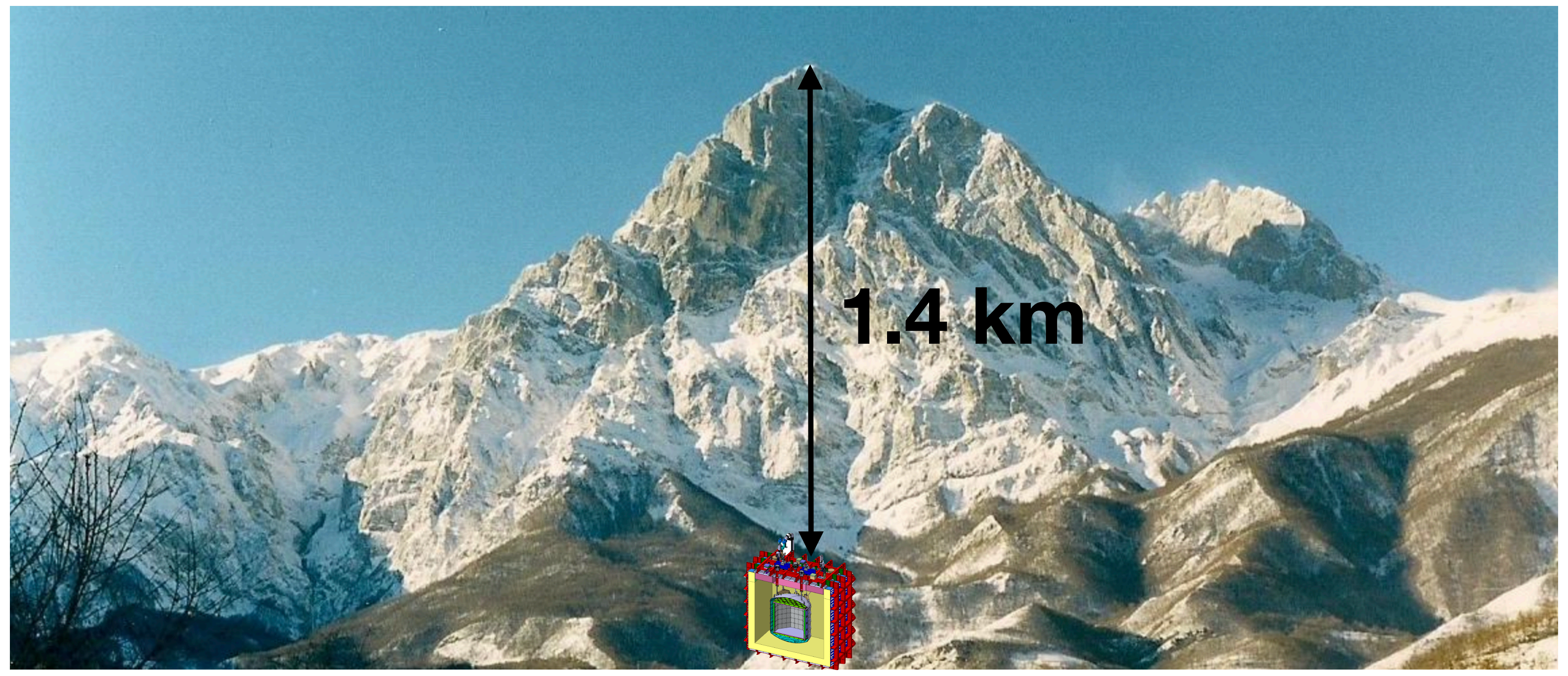
DarkSide-20k : 20t of argon at liquid phase in fiducial volume (700t in total)

Largest TPC ever built for DM search purposes



Shield the detector from background

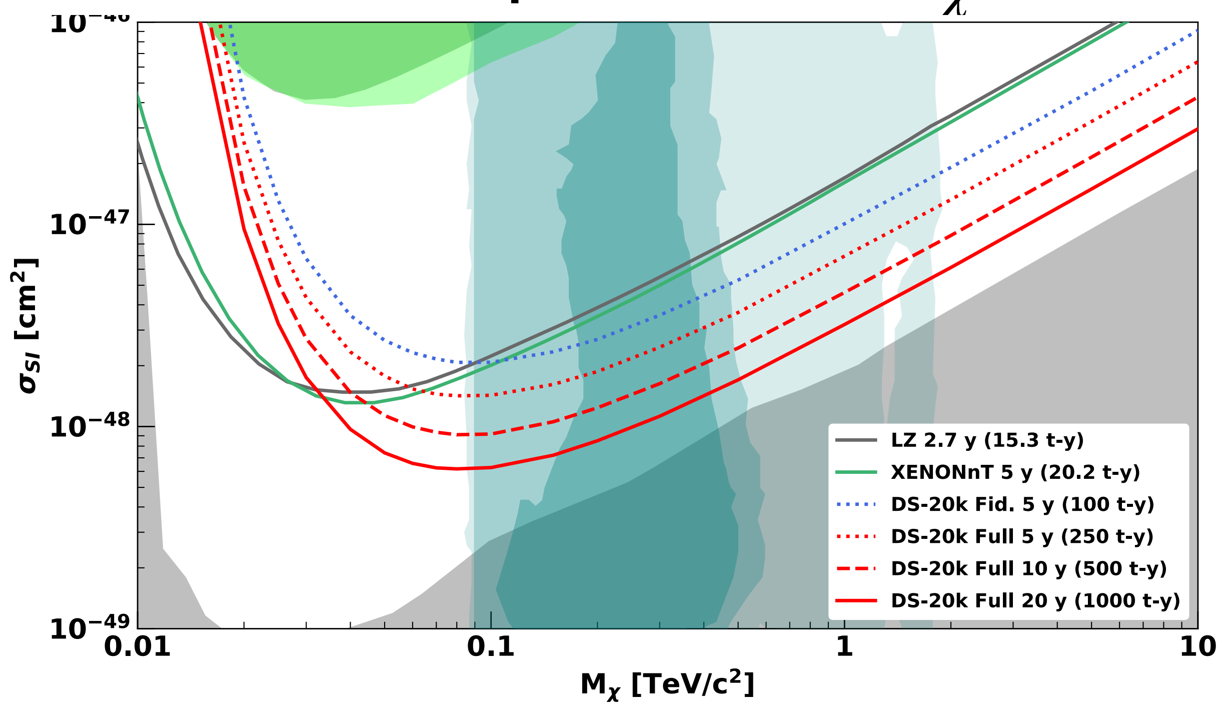
DarkSide-20k : located at LNGS under 1.4km of roc in Italy to shield from cosmic rays



Searching for WIMPs

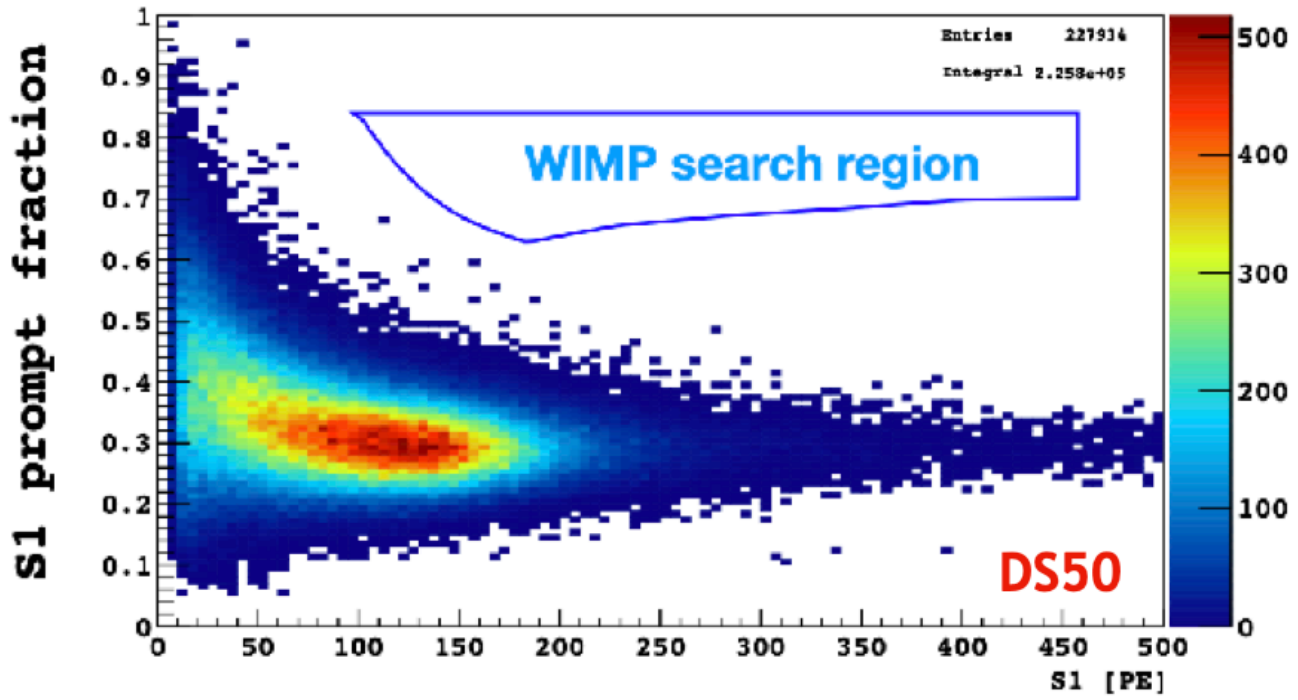
Compute the sensitivity of the experiment

DarkSide-20k : competitive at M_χ > 100 GeV



Understand and discriminate backgrounds and signal

Argon: extremely powerful discrimination between backgrounds and signal



Background budget (after cuts): 0.1 event / 10y

How to search for WIMPs ?

Create scalable detectors

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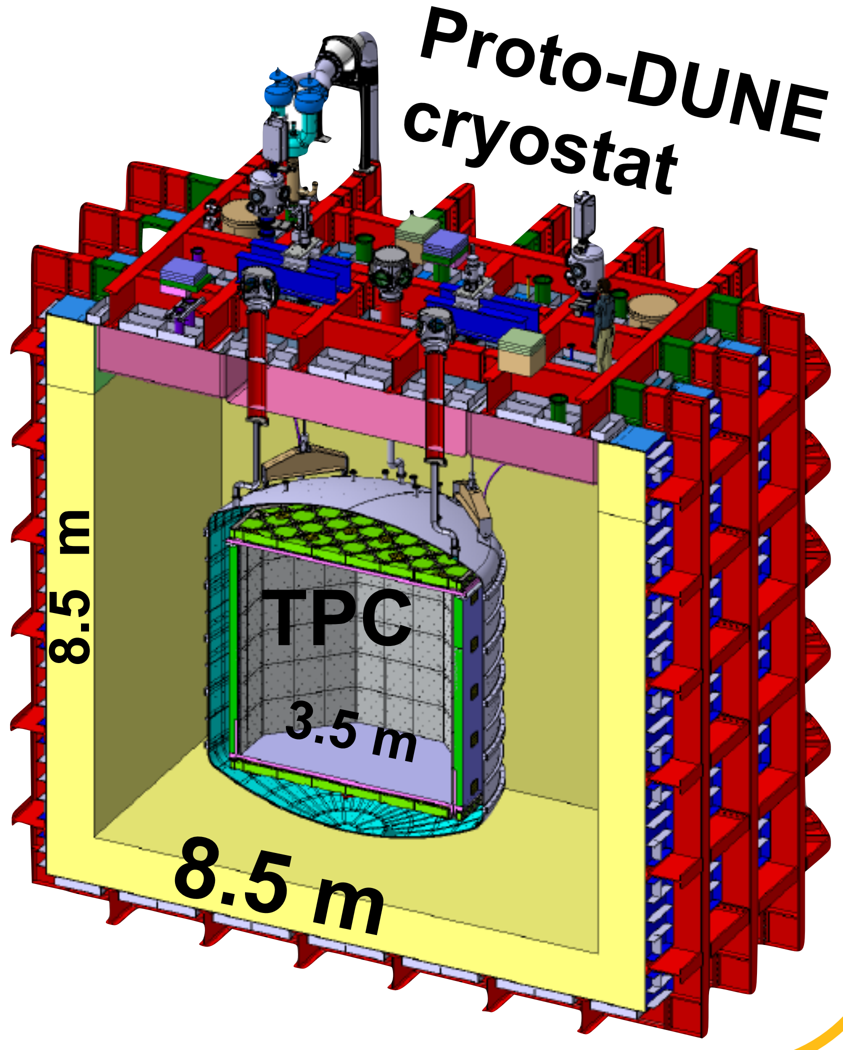

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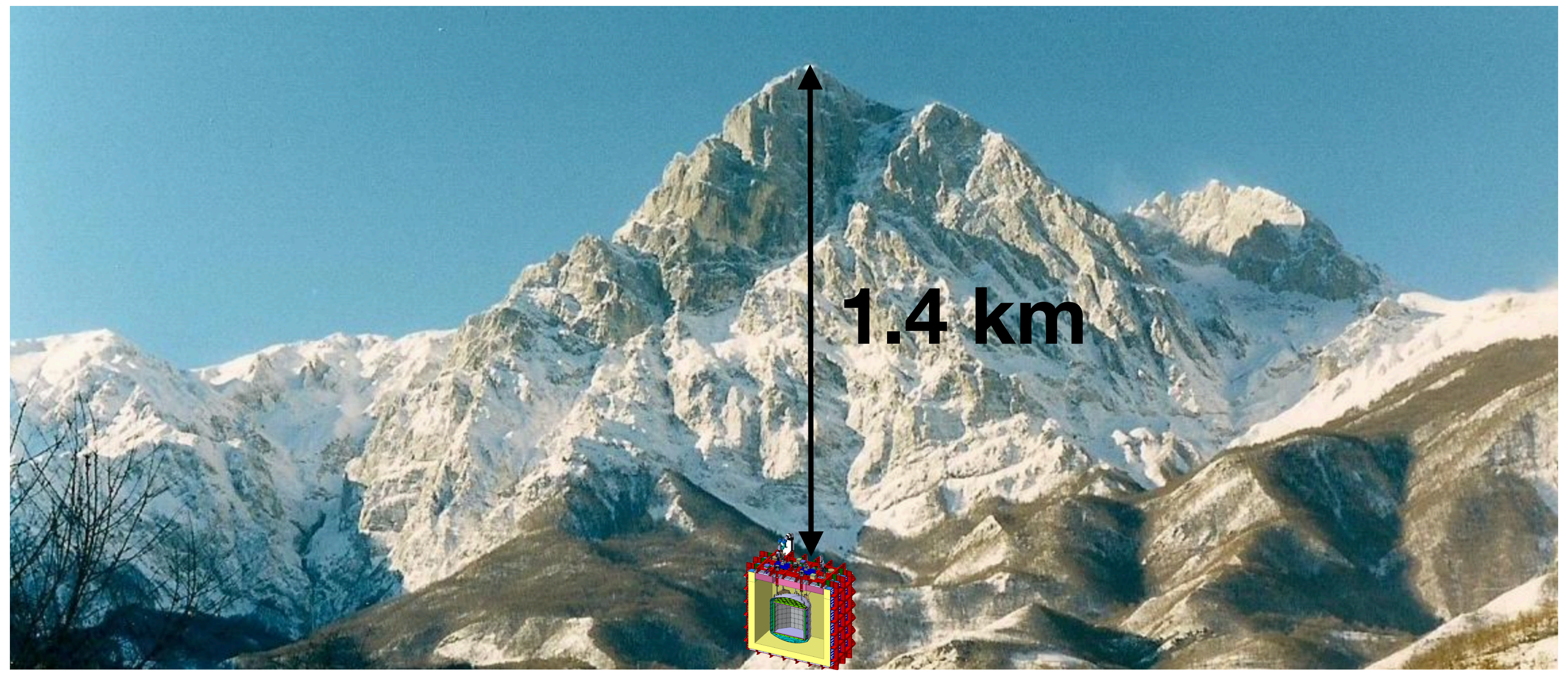
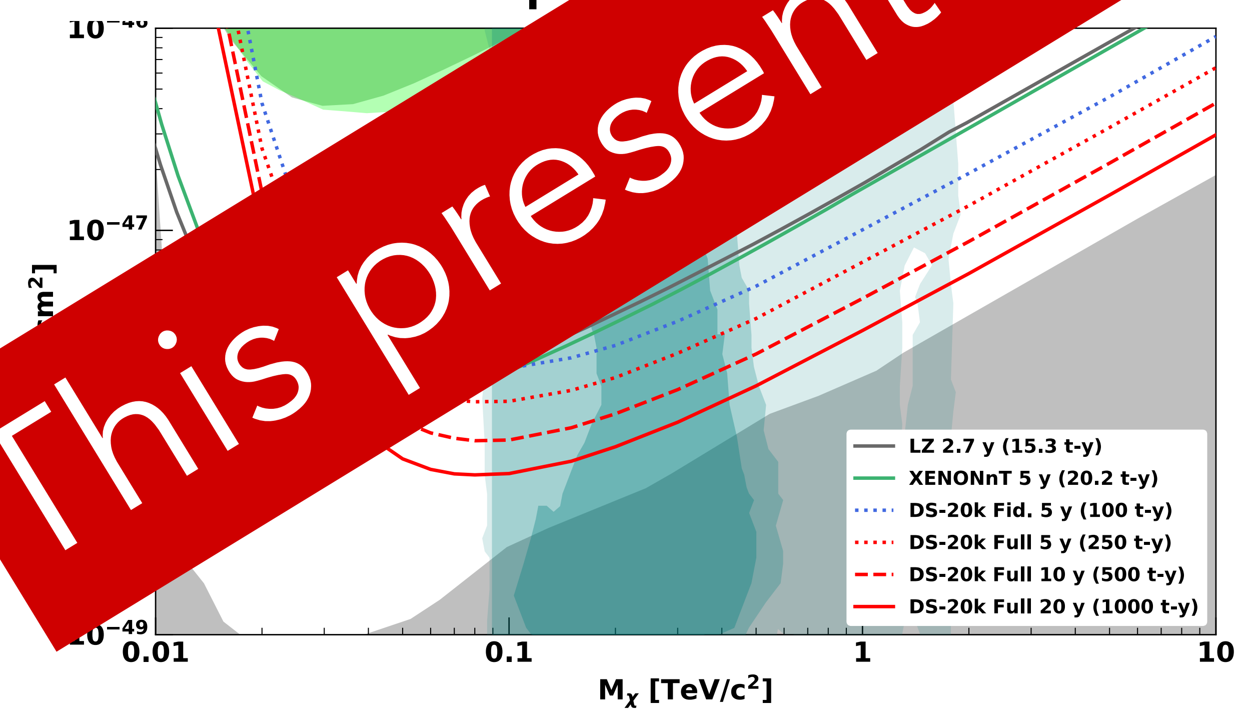


Searching for WIMPs

Compute the sensitivity … the experime…

DarkSide-20k : compet… 00 GeV



This presentation

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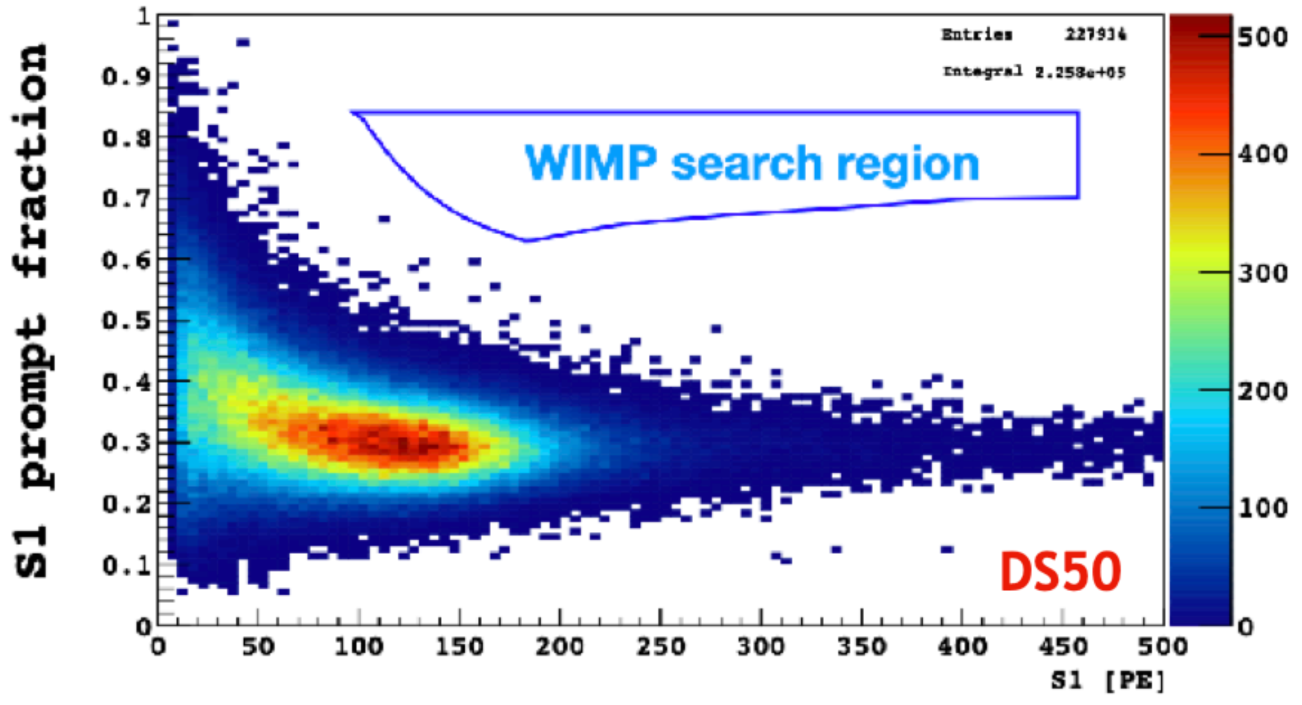

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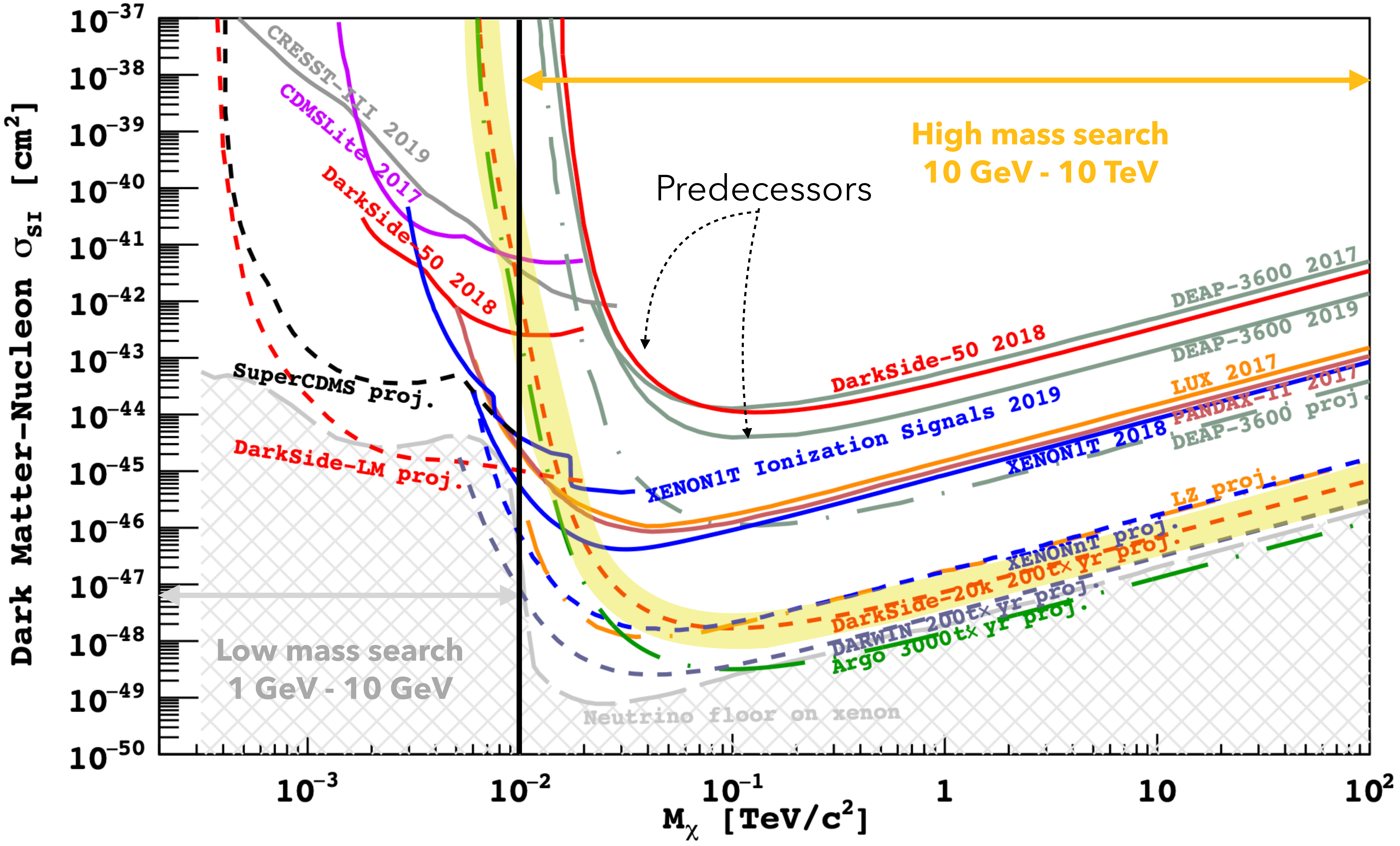
State of the art of WIMP direct detection



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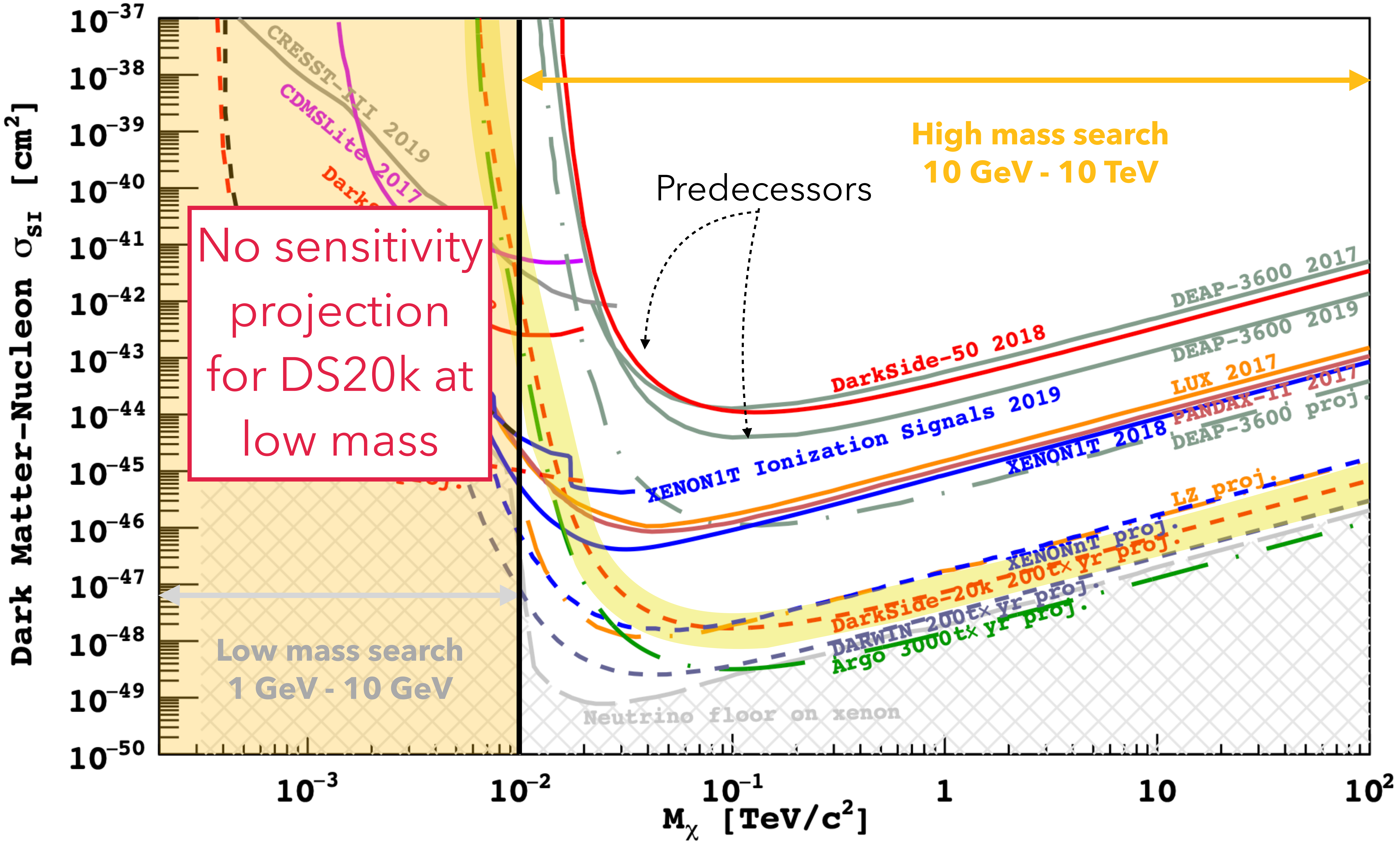
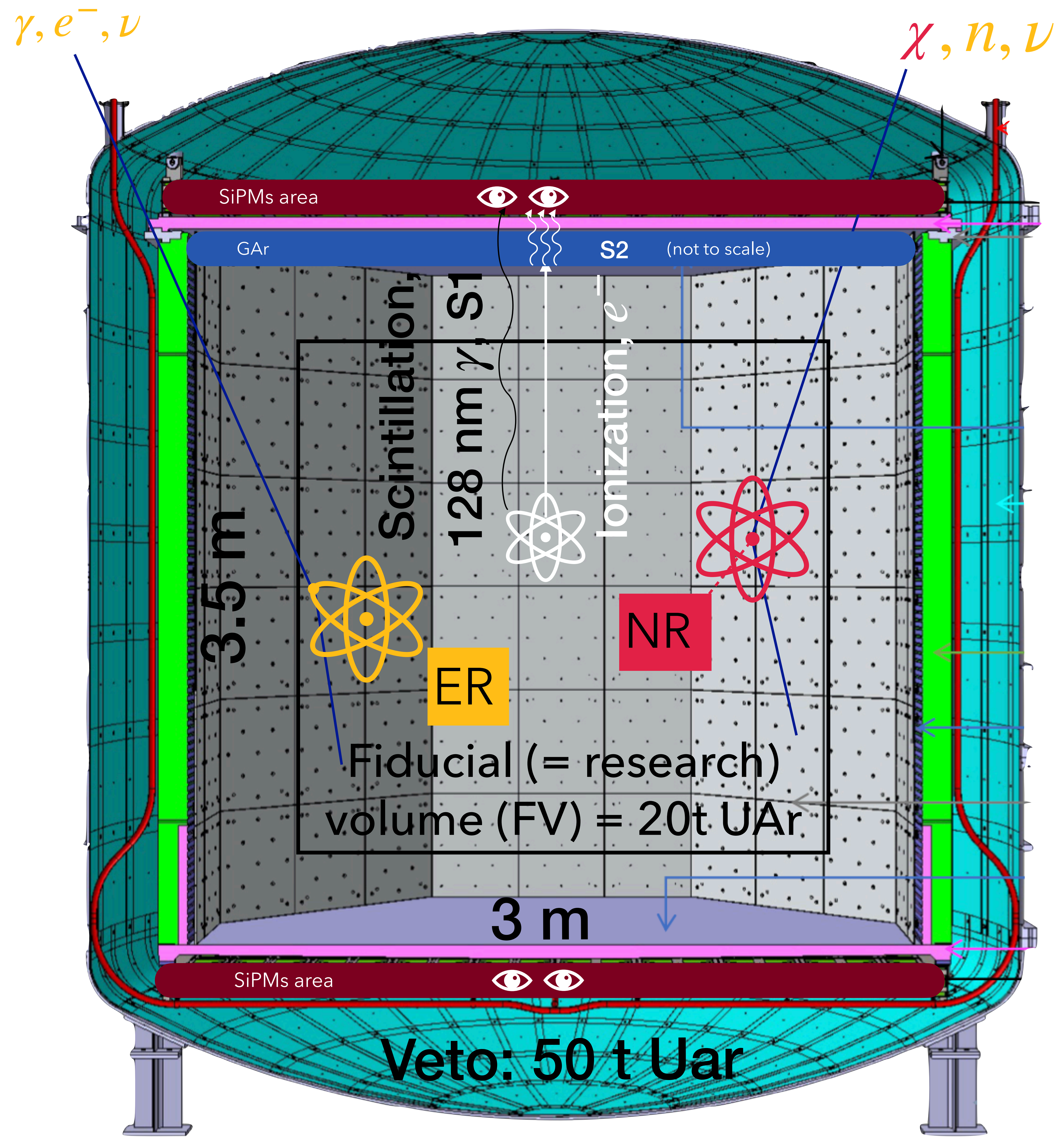


DarkSide-20k



Signal characteristics

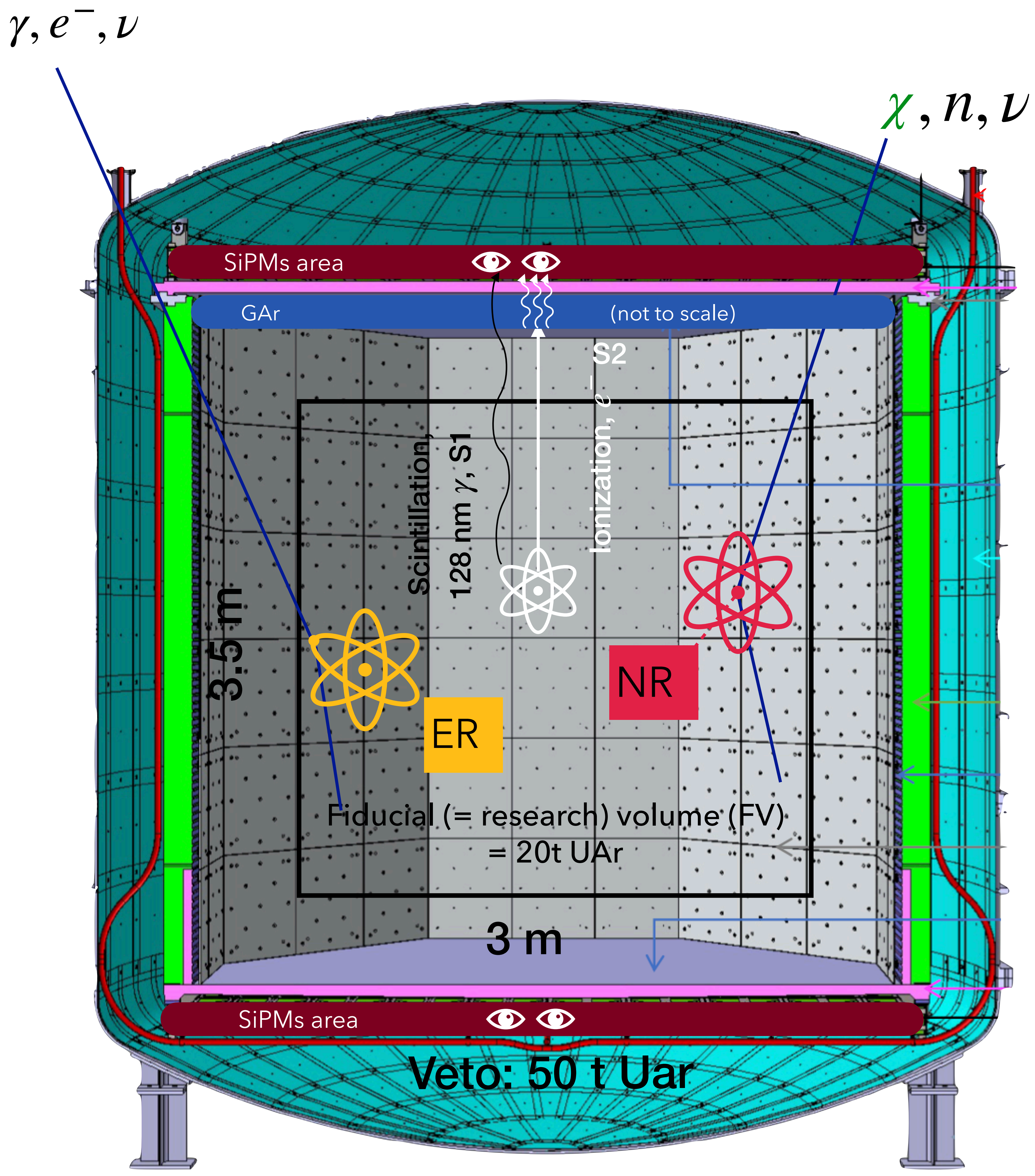
- Nuclear Recoil (NR)
- Single scatter (SS)
- Energy Region of Interest (RoI) at low mass: $E \in [0 - 35]$ keV_{nr}

S1/S2 very different for ER and NR + argon: **Pulse Shape Discrimination** (PSD) => very good separation NR/ER

Background characteristics

- Photons & electrons (ER), neutrons (NR) from residual radioactivity
- Neutrinos (ER/NR)

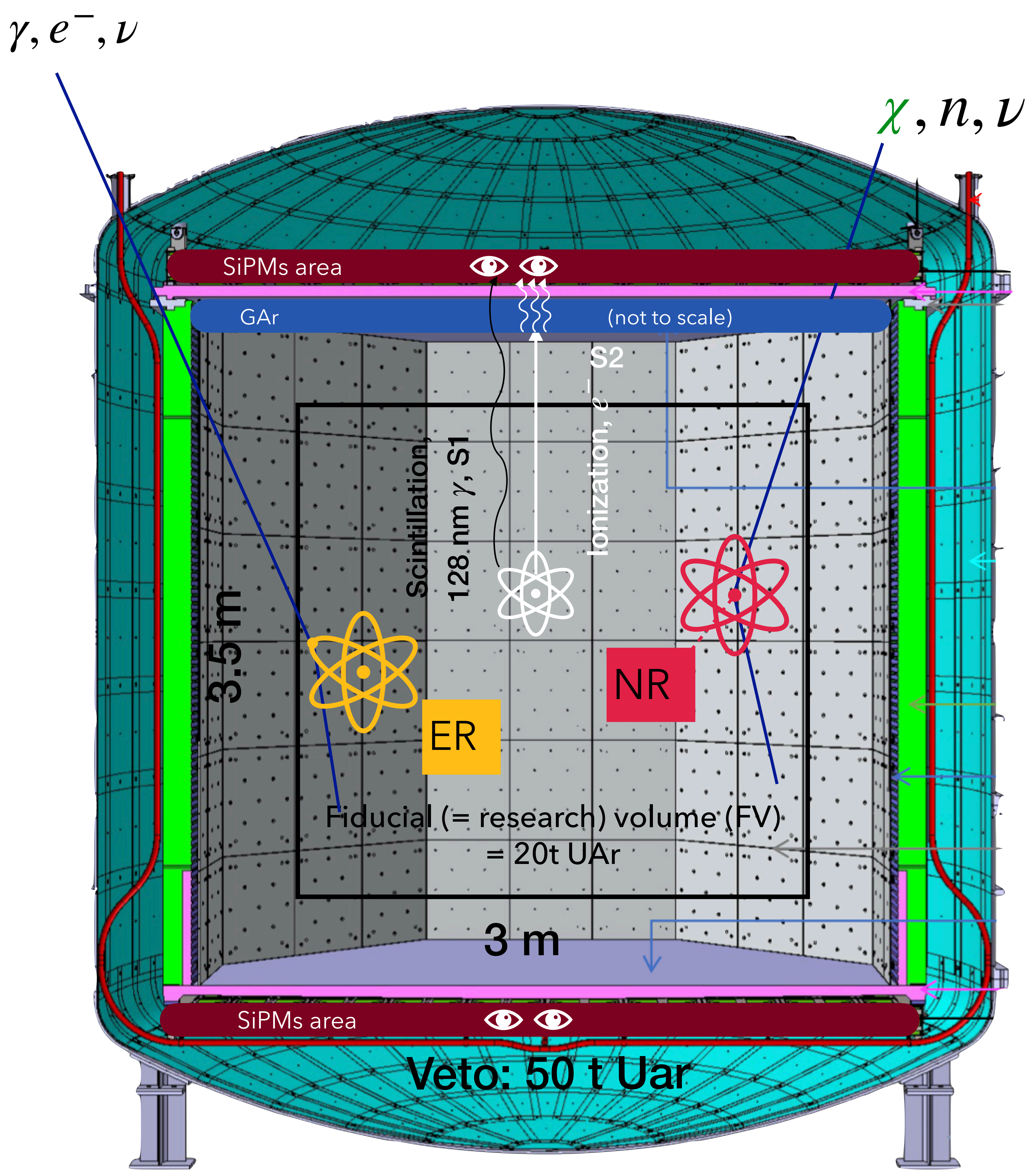
The detection principle below M_χ=10 GeV



- **sub-keV threshold to extract S2 signal** (without producing S1) -> possibility to compute the sensitivity of DS20k at masses below 10 GeV **if able to understand a S2 - only analysis** (no separation ER/NR → **not a background free** analysis anymore)

- DS50 proved to be able to perform such analysis (2207.11966 (WIMP NR), 2207.11967 (WIMP NR with Migdal effect), 2207.11968 (other light DM signals with electron final state))

The detection principle below M_χ=10 GeV



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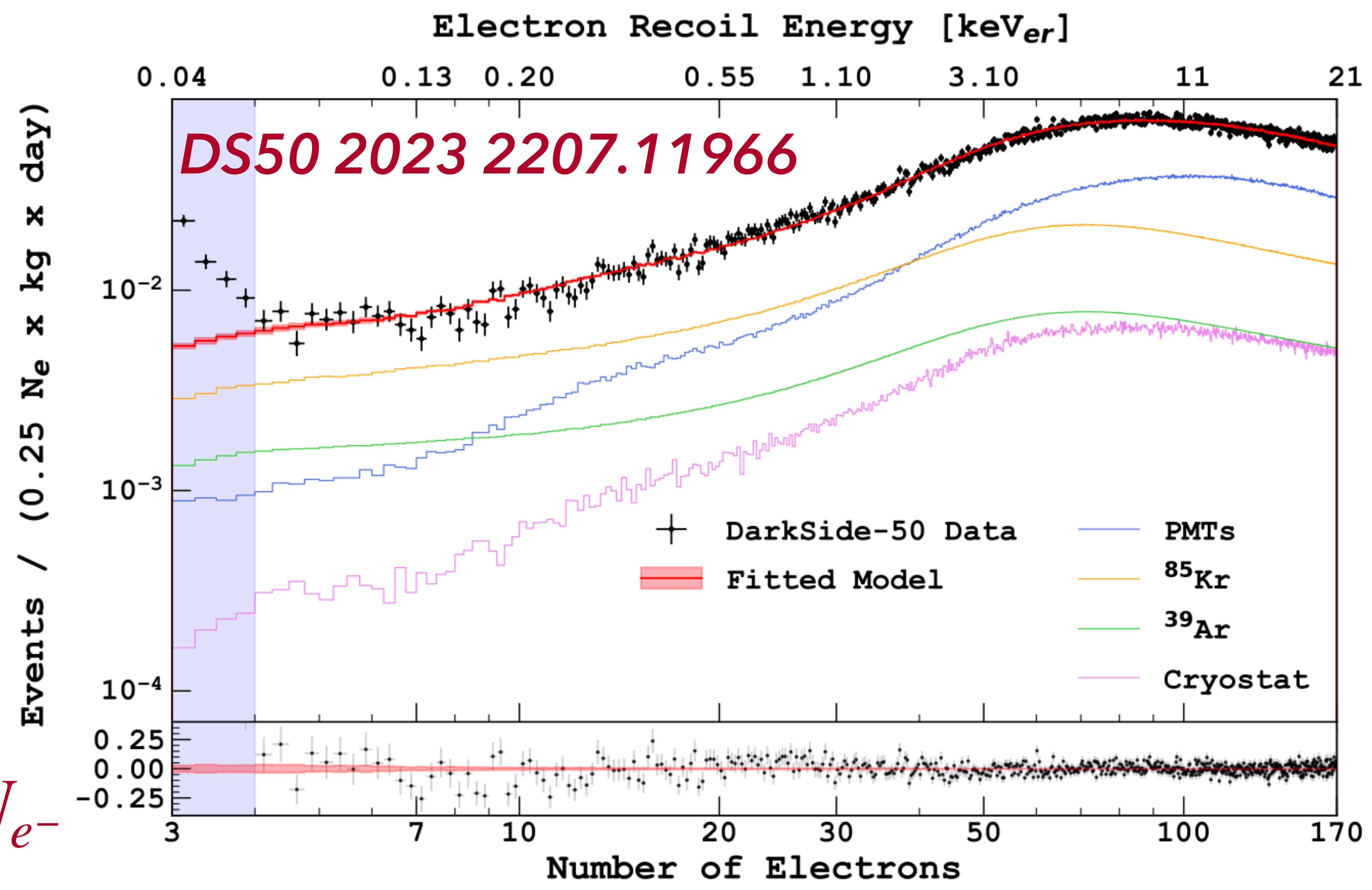
- DS50 prove
  ([2207.1196](#)
  with Migdal
  signals with



Excellent bkg description above 4 N_{e^-}

DarkSide-20k : background model

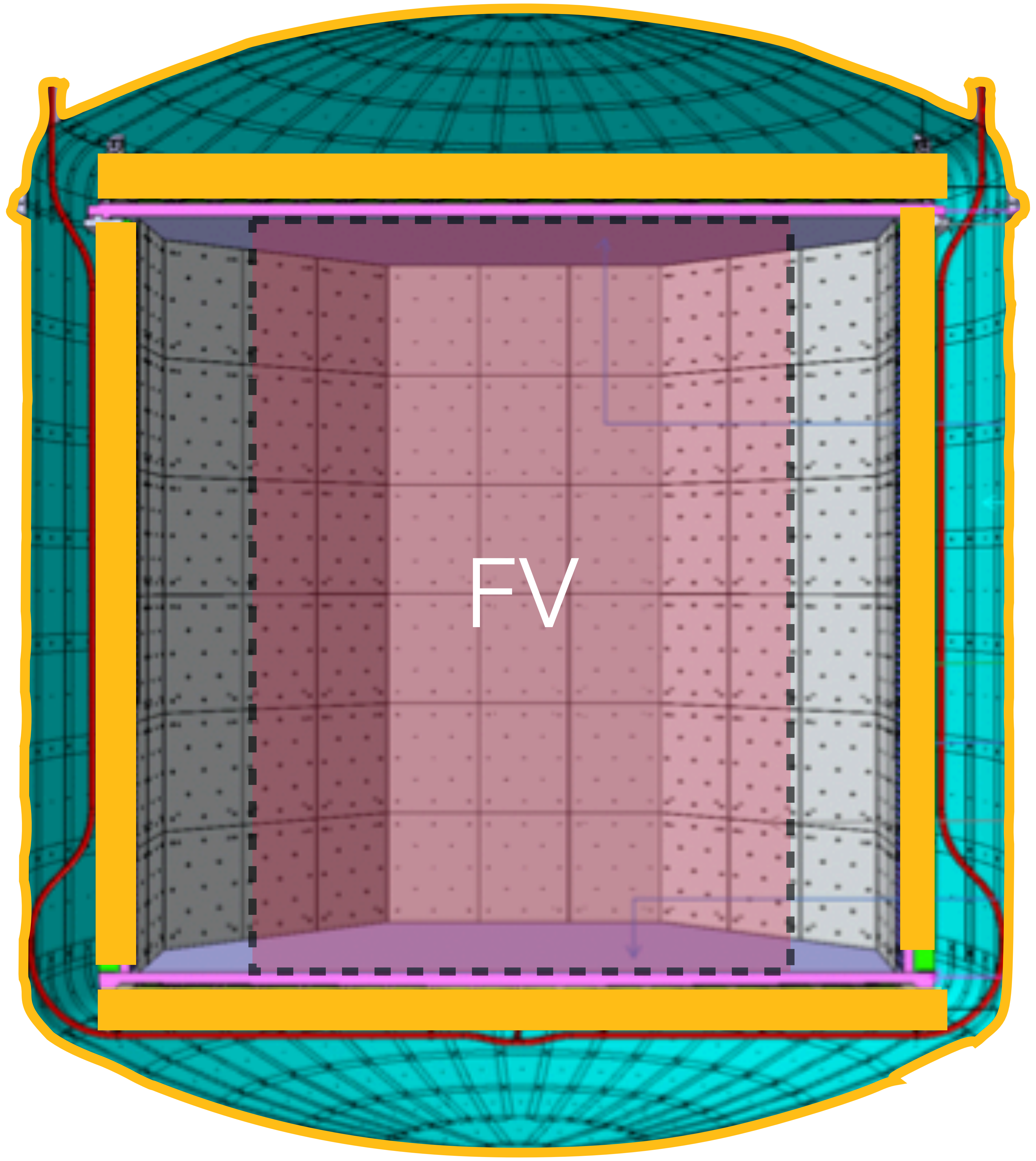
Internal backgrounds

➡ Cosmogenic ^{39}Ar → bulk background ∝ FV size

➡Assumption: activity of DS50 = 0.73 mBq/kg

➡DS50 : ^{85}Kr in data, here not taken into account thanks to cryogenic distillation

We estimated the **proportion of background** WIMP candidate events that we will **keep in the real data analysis** (events without pile up) : **72%**



External backgrounds

➡Radio-contamination of the materials

➡SiPMs from the TPC, Gd - loaded acrylic walls, Stainless steel vessel

➡Precise material assays to determine their contamination

ν background

➡Consider atmospheric and solar neutrinos

➡CEνNS and ν - ES interactions

DarkSide-20k : signal

Signal : WIMP NR

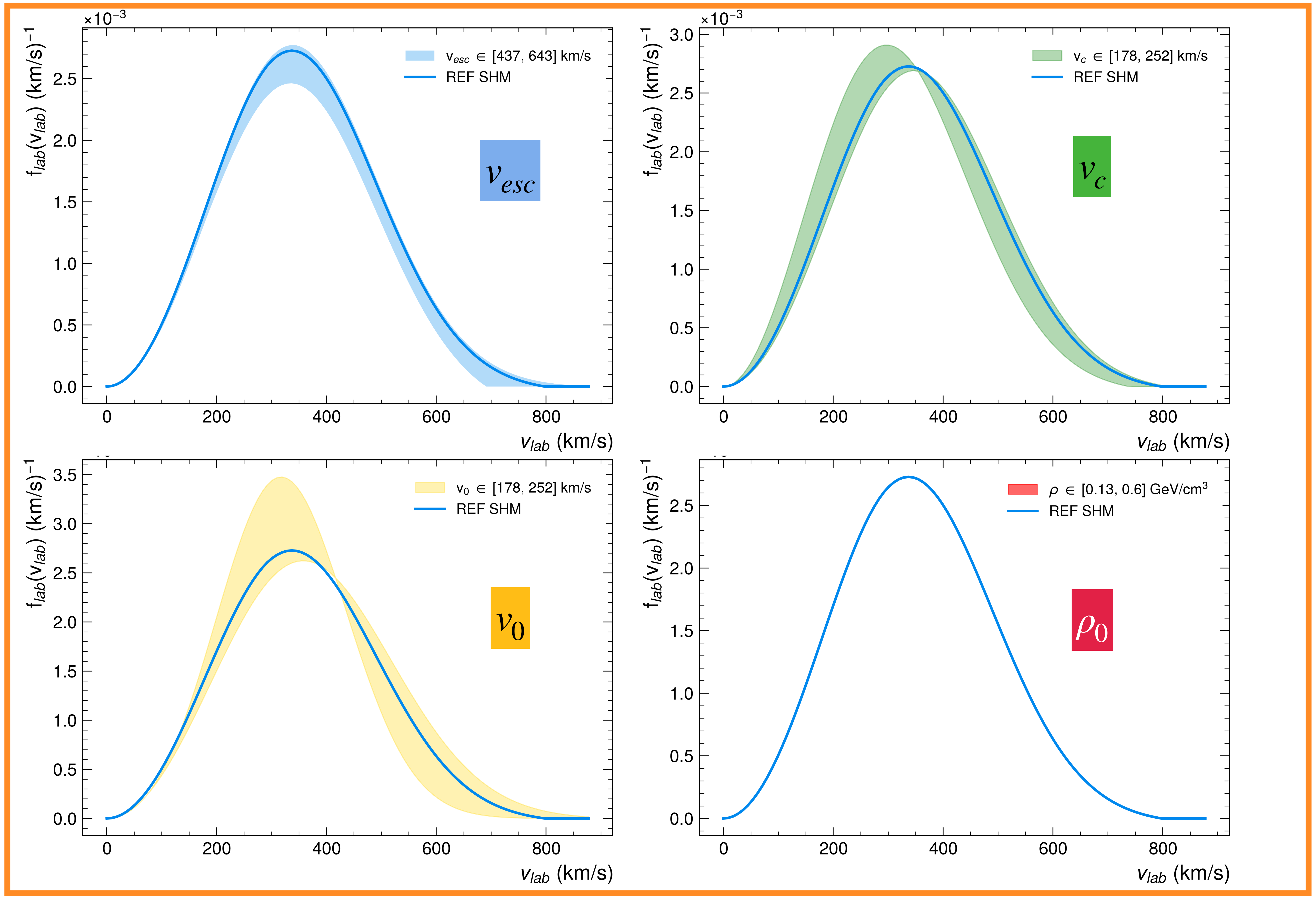
➡ Rate of interaction computed with Standard Halo Model (SHM) & Recommended conventions *Baxter et al. Eur.Phys.J.C 81 (2021) 10, 907*

➡ Signal rate ∝ FV size

➡ Event rate :

$$\frac{dR}{dE} = \frac{\rho_0}{m_\chi m_A} \int_{v>v_{min}}^{v_{max}} \frac{d\sigma}{dE} v \, f(\vec{v}) \, d^3\vec{v}$$

WIMP velocity distribution on Earth with kinetic uncertainties



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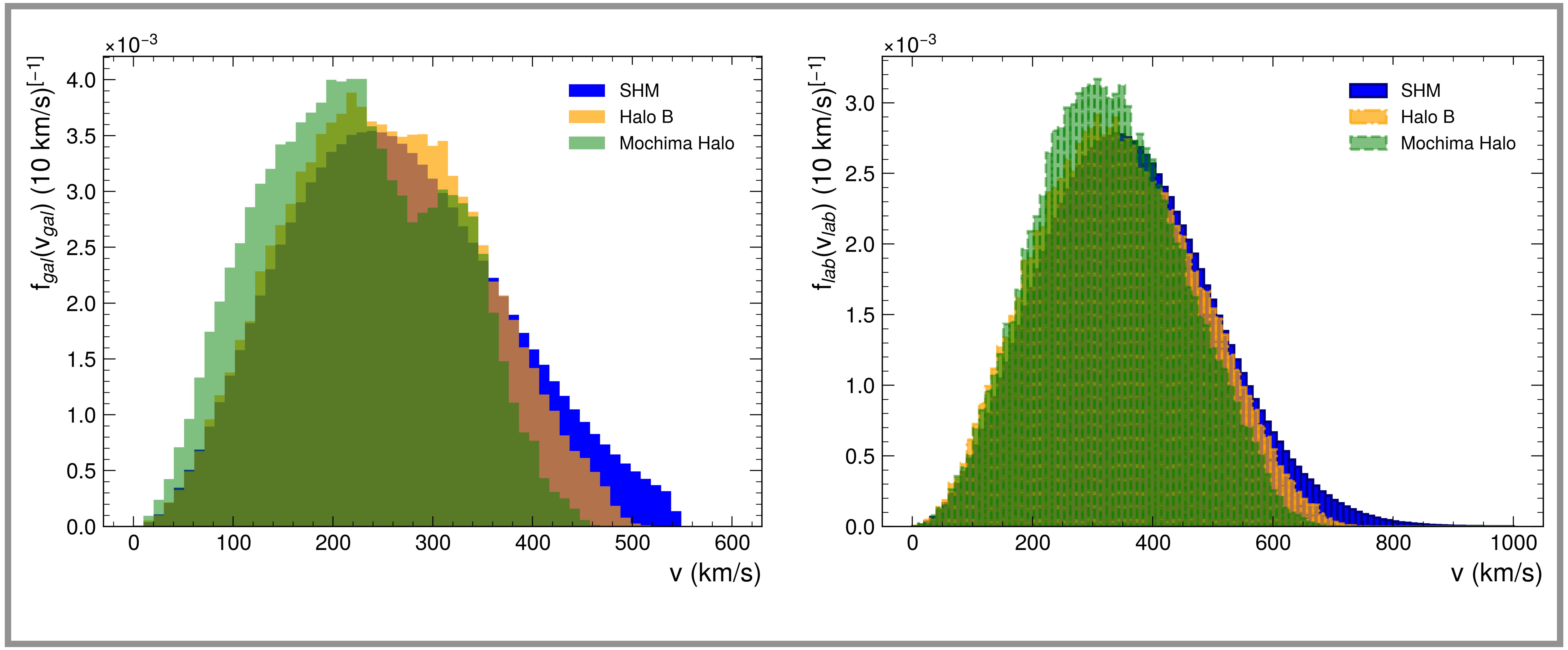
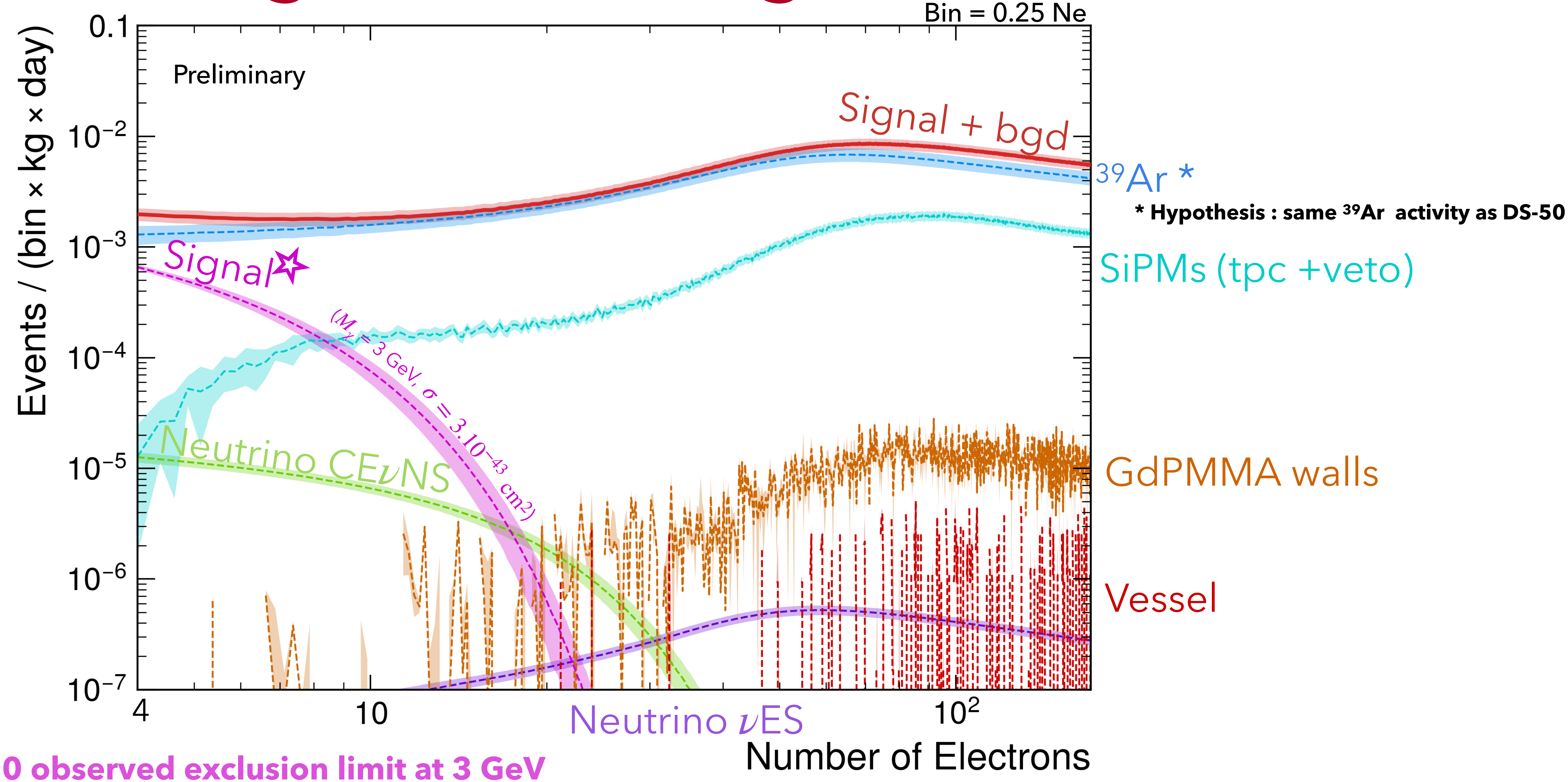
WIMP velocity distribution from DM + baryon cosmological simulations



Signal and background model

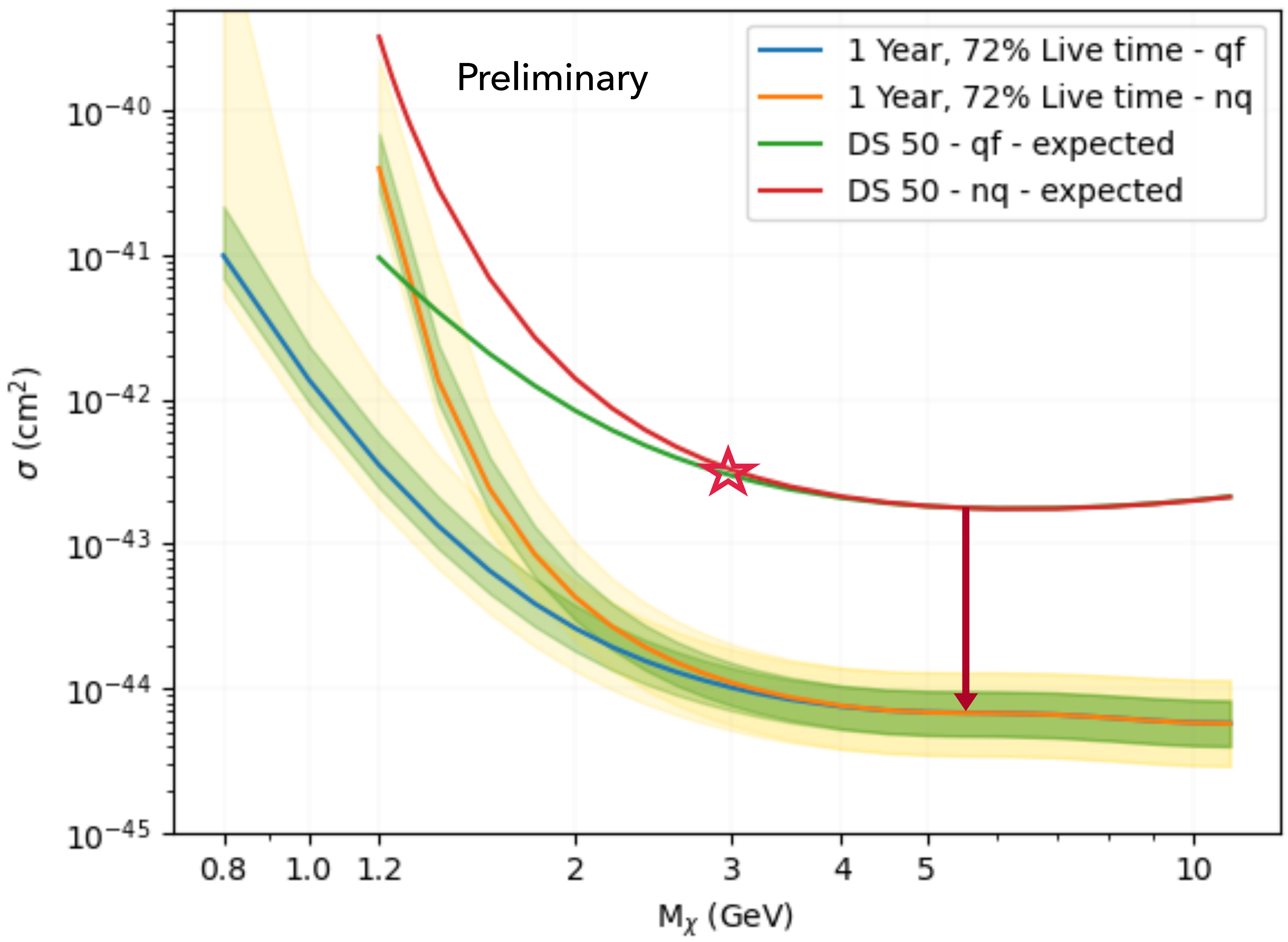


☆ DS50 observed exclusion limit at 3 GeV

DS-20k low mass sensitivity

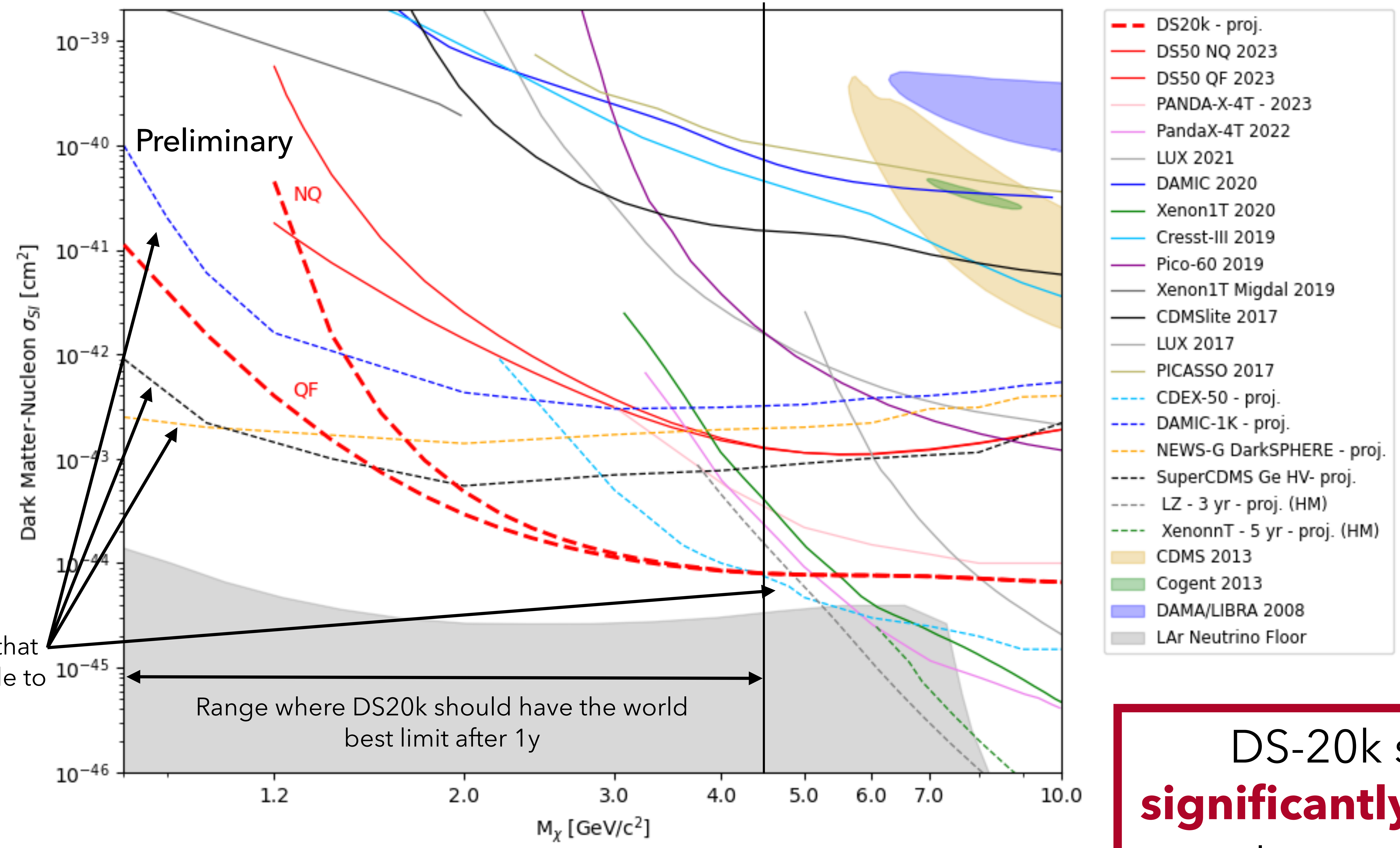
1 year

*** Hypothesis : same ^{39}Ar activity as DS-50**



DS20k: 25x more sensitive than DS50

Comparison with other experiments



Prospective experiments that need to be able to scale up their technology

DS-20k should quickly **significantly improve** existing limits at M_χ **< 4 GeV**

Tests of impacts from the models and other DM candidates

Impact of experimental assumptions

1. Tests of different internal backgrounds
2. Tests of different detector models
   - XY resolution (nominal = 1cm, change to 2 cm and 5 cm)
   - Electron lifetime (nominal = 15.8 ms, change to 8 ms)
   - FV definition (nominal radial cut = 30 cm, change to 20 cm and 10 cm)
   - Single electron resolution (nominal = 0.27, chante to 0.15 and 0.50)
3. Sensitivity increase with exposure
4. Analysis impact (N_{e^-} cut, systematics, multi-variate analysis)
5. External background simulations with more recent version of simulation software

➡ Sensitivity robust against detector model assumptions
➡ Main sensitivity change would come from wrong internal backgrounds level assumption
➡ Sensitivity increases with $\sqrt{\text{exposure}}$
➡ Multi-variate analysis won't improve much the result

Impact of theoretical assumptions

6. Signal systematics from astrophysical uncertainties

Other signal models

7. Sensitivity to other signals (ER) (LDM with F~1, LDM with F~1/q², Dark Photon, ALPs, WIMP ER with Migdal, Sterile neutrino)

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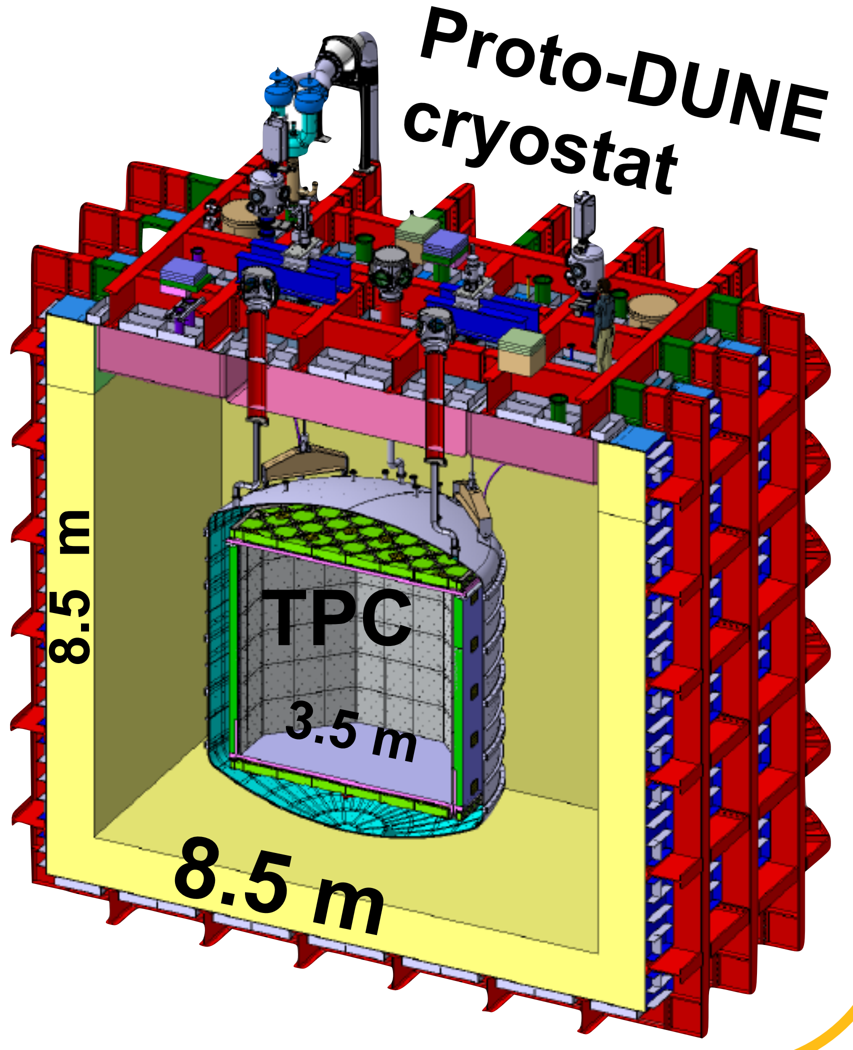

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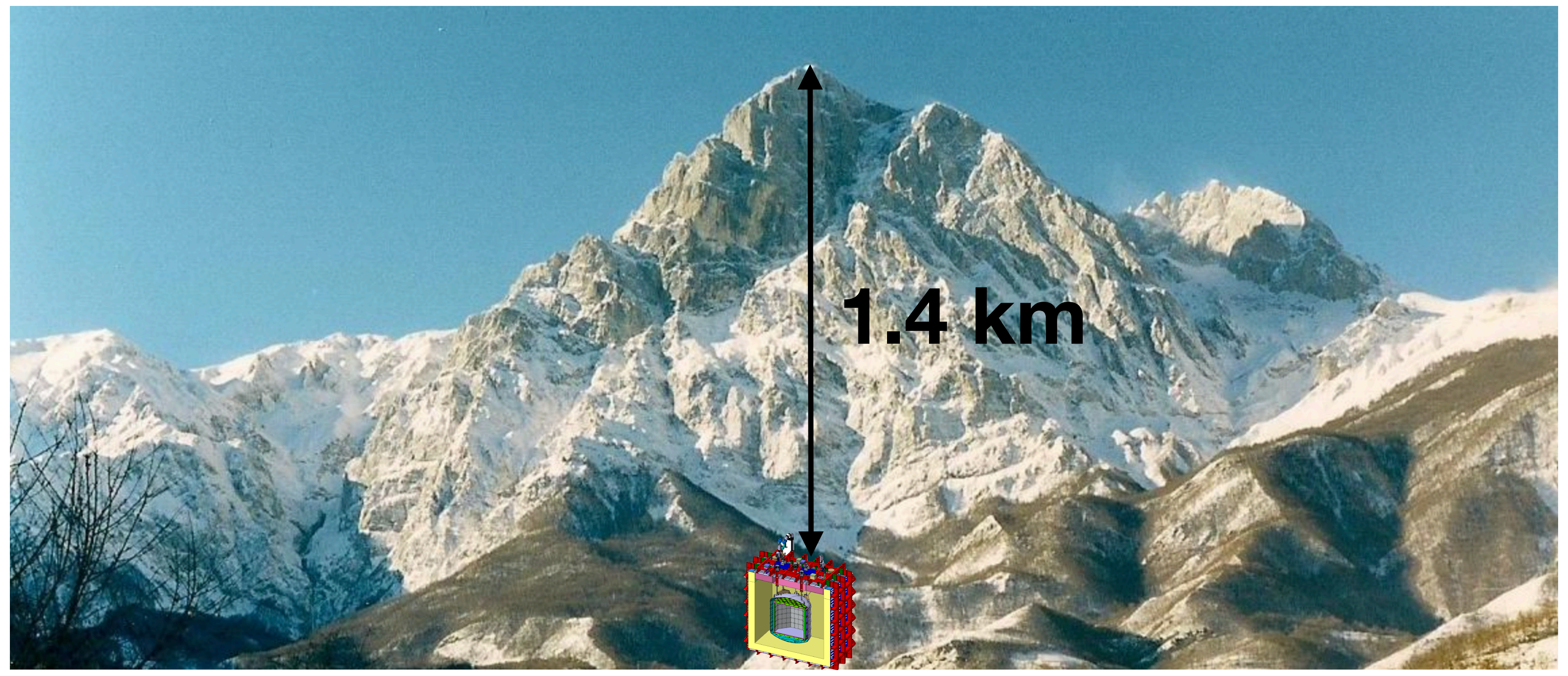
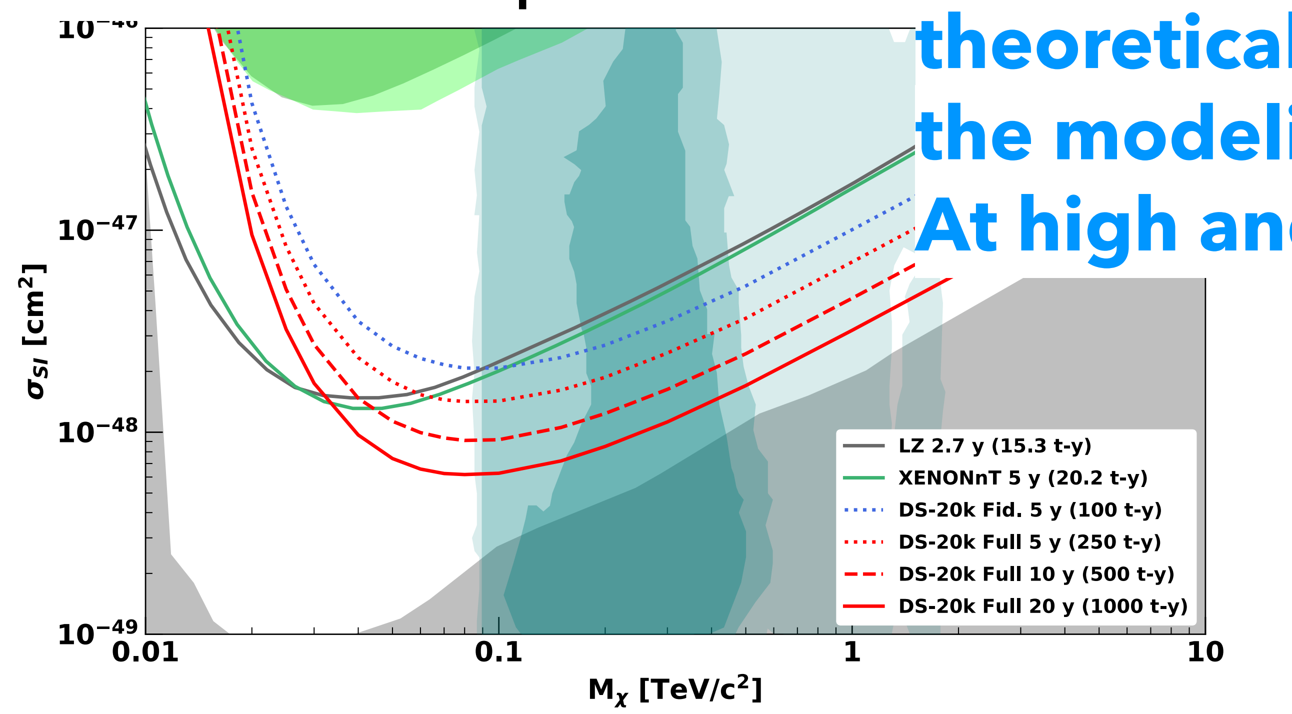


Compute the sensitivity of the experiment

DarkSide-20k : competitive at M



Sensitivity uncertainty: theoretical uncertainties from the modeling of the DM halo At high and low mass

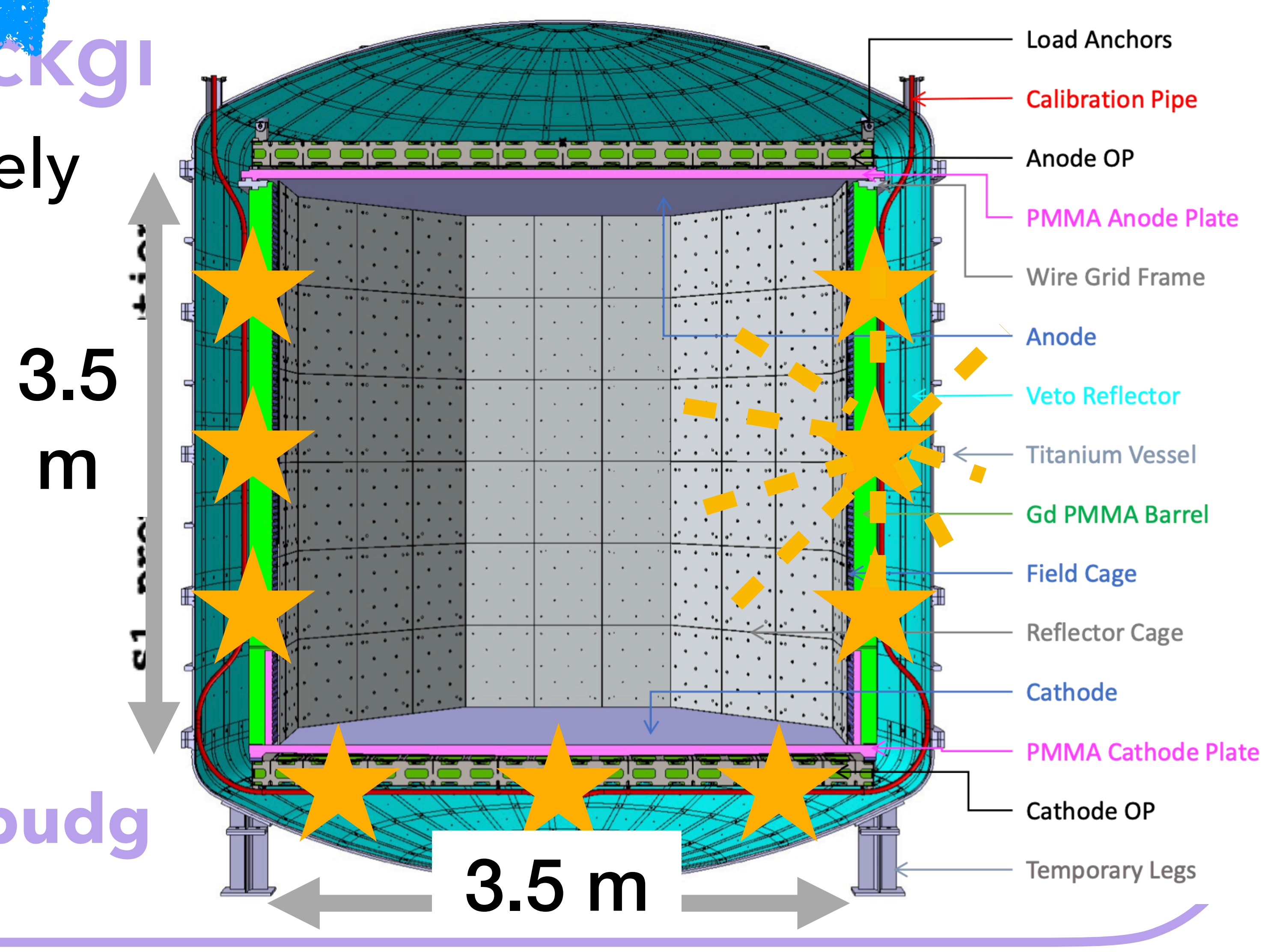
Searching for WIMPs

Other commitments during PhD

Understand and discriminate backgr

Argon: extremely powerful discrimination between backgrounds and signal

Calibration of DS20k



Background budg

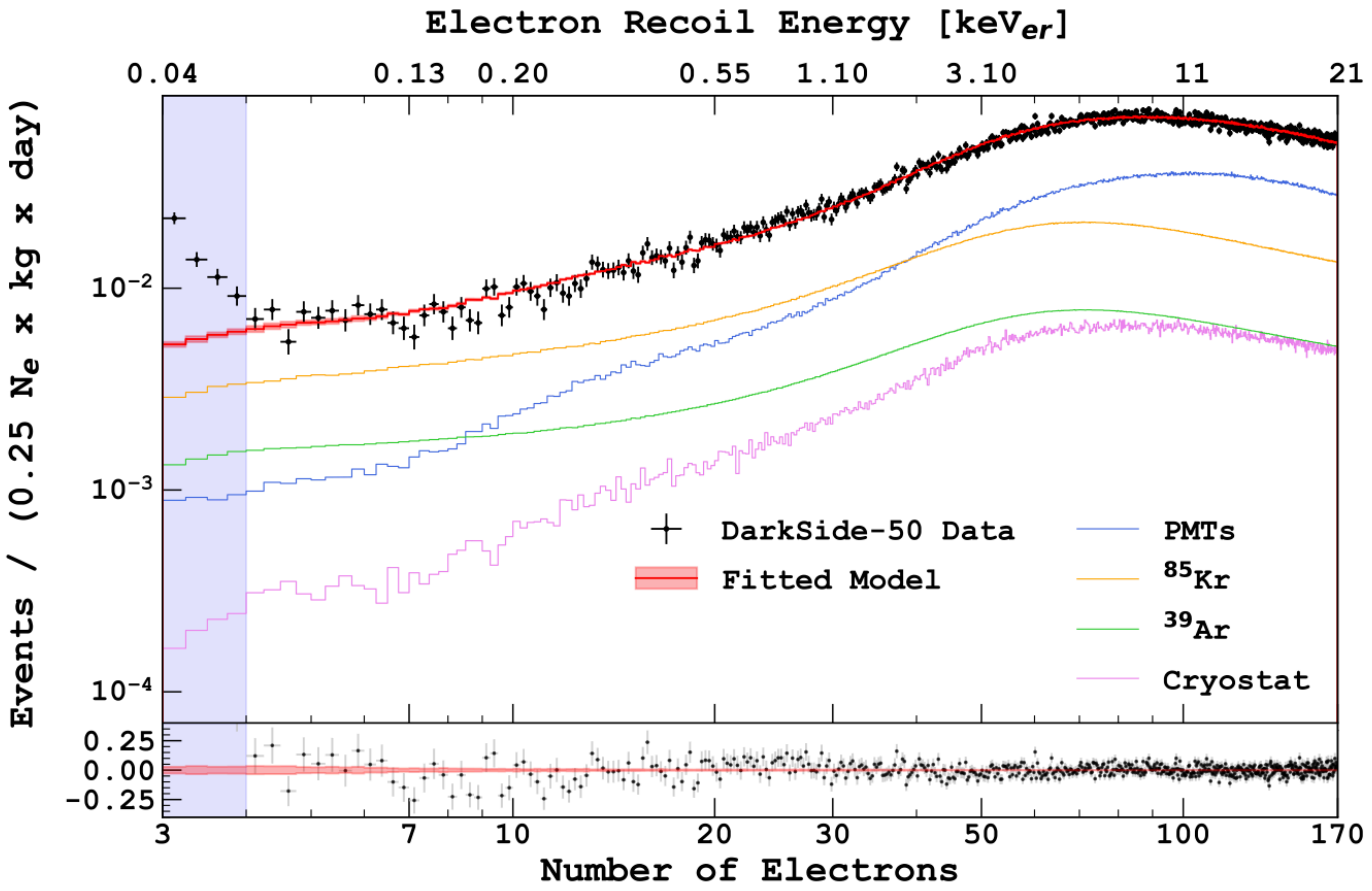
Back up

Results of DarkSide-50

3 papers in 2022/2023

DS50 low mass analysis

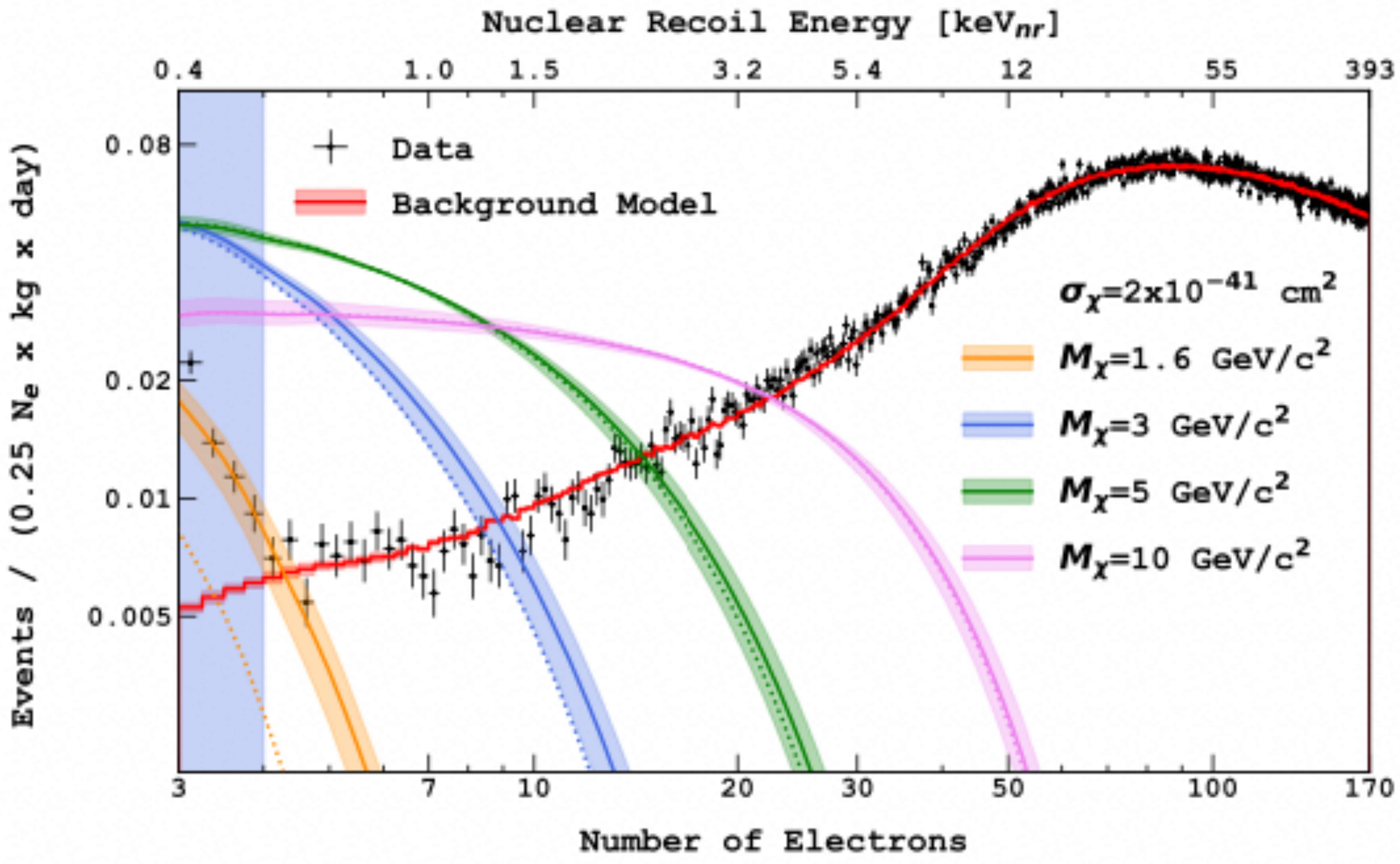
Background model

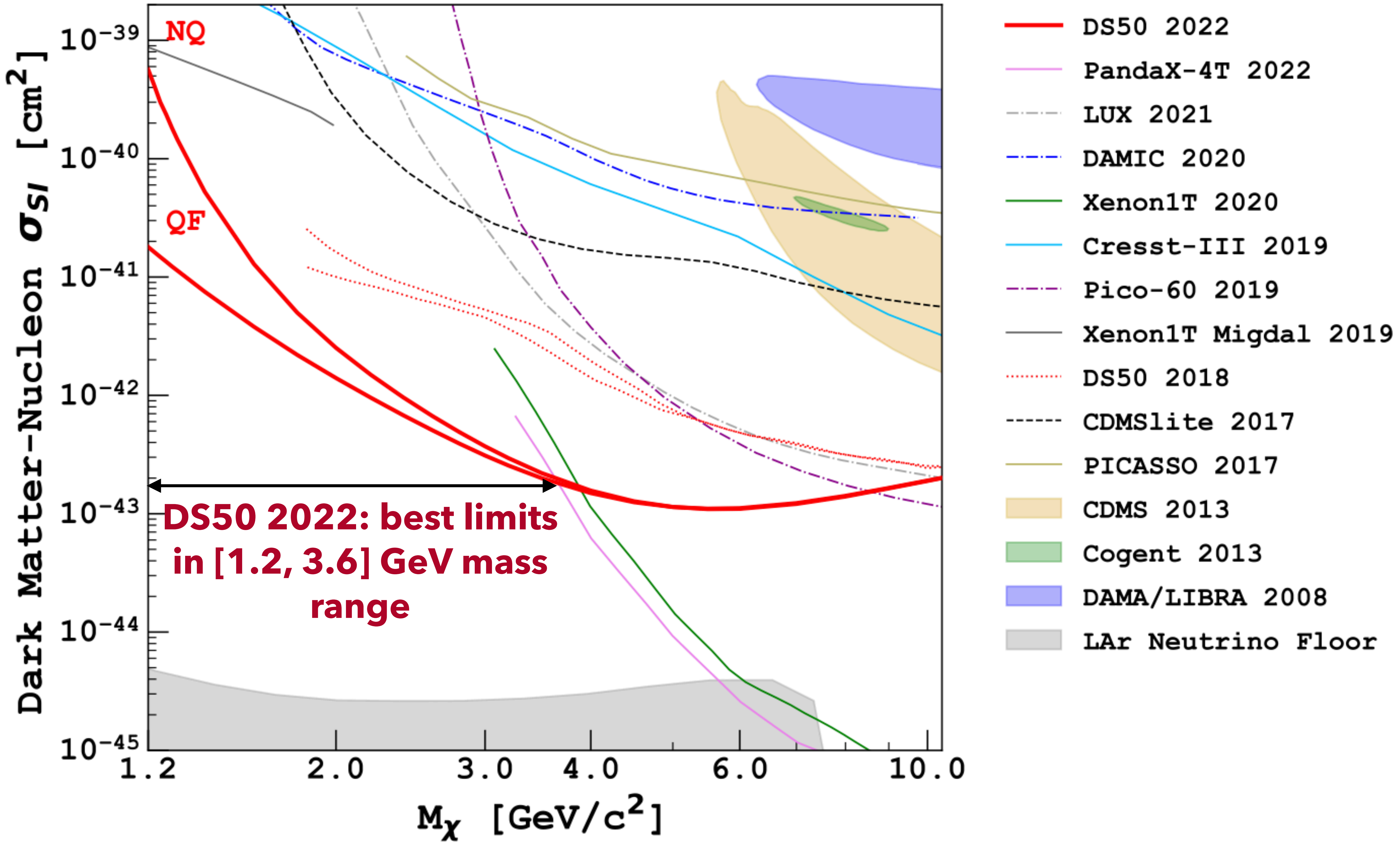


Excellent bkg description above 4 N_{e^-}

DS50 low mass analysis

WIMP NR





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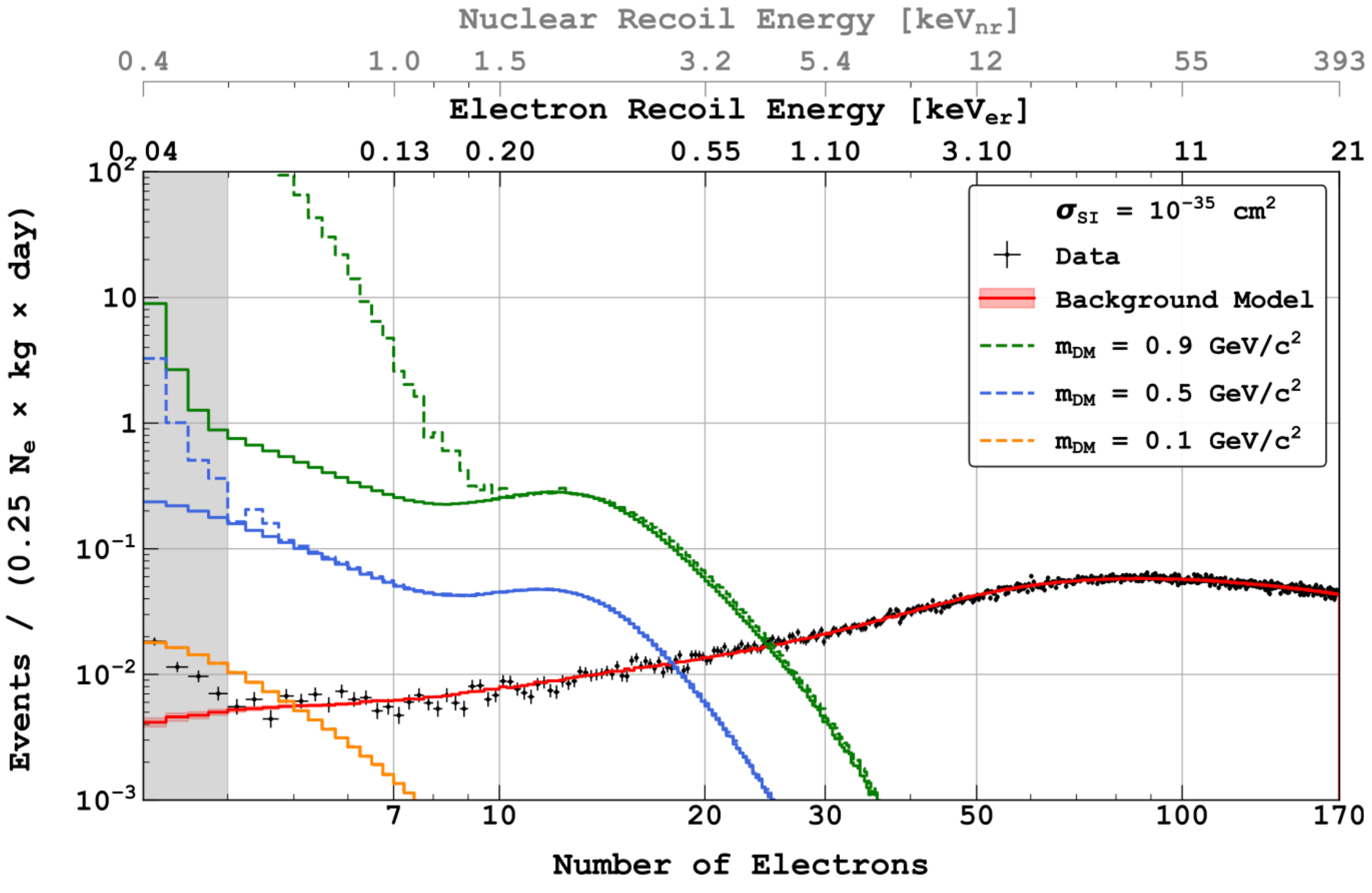
DS50 low mass analysis

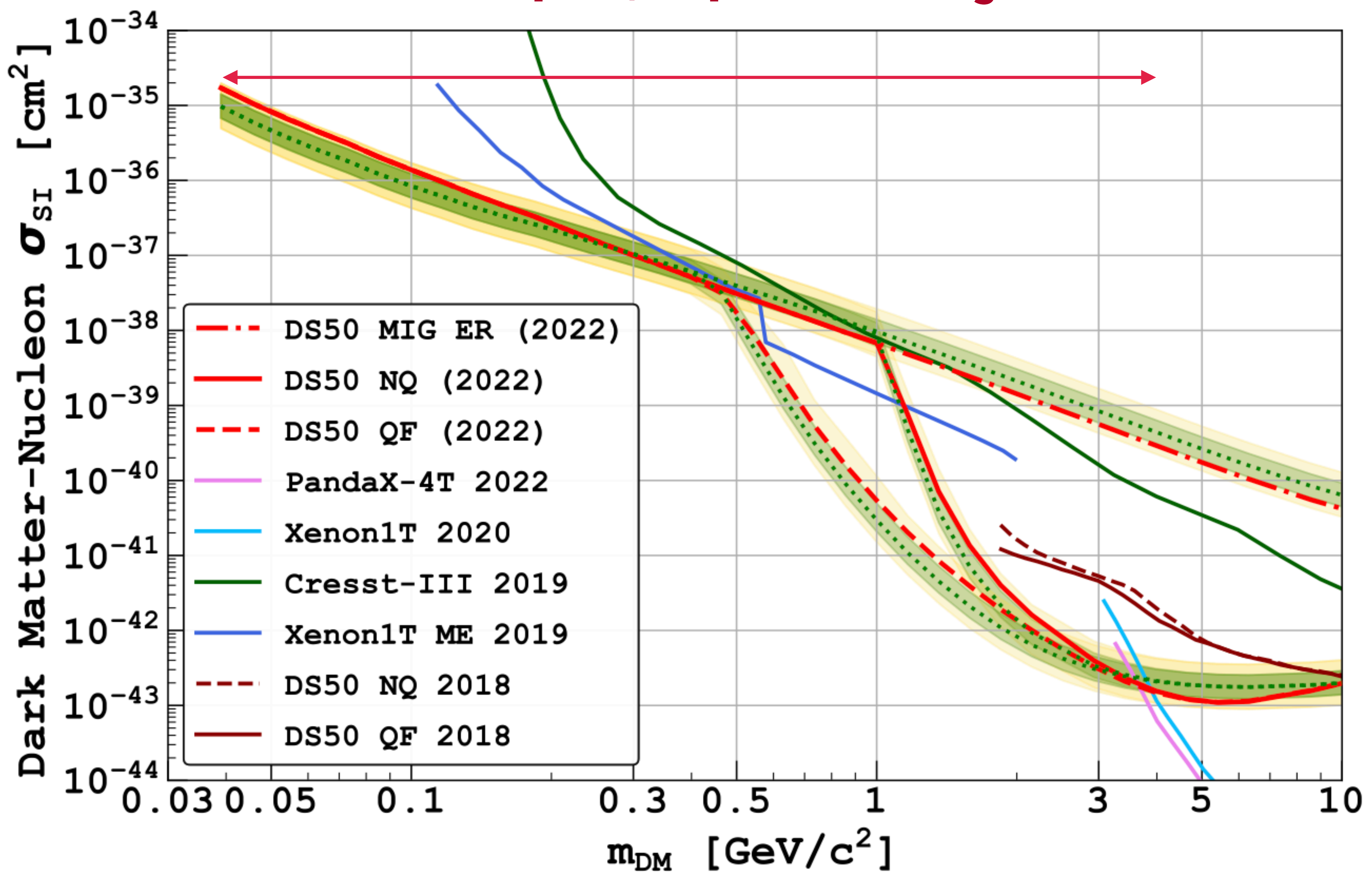
WIMP NR + Migdal

Migdal effect = possible additional effect of emitted electrons in NR

With NR + additional ER component, higher probability to exceed detection threshold → scan lower WIMP masses



DS50 2022 NR with Migdal: world best limits in [0.04, 3.6] GeV mass range



Other DM signals (ER)

Light Dark Matter (LDM)

20MeV - 1GeV

Elastic scatter of LDM off bound electrons

LDM = Sub GeV fermion or scalar boson

Mediator can be heavy (→ F~1) or light (→ F~1/q²)

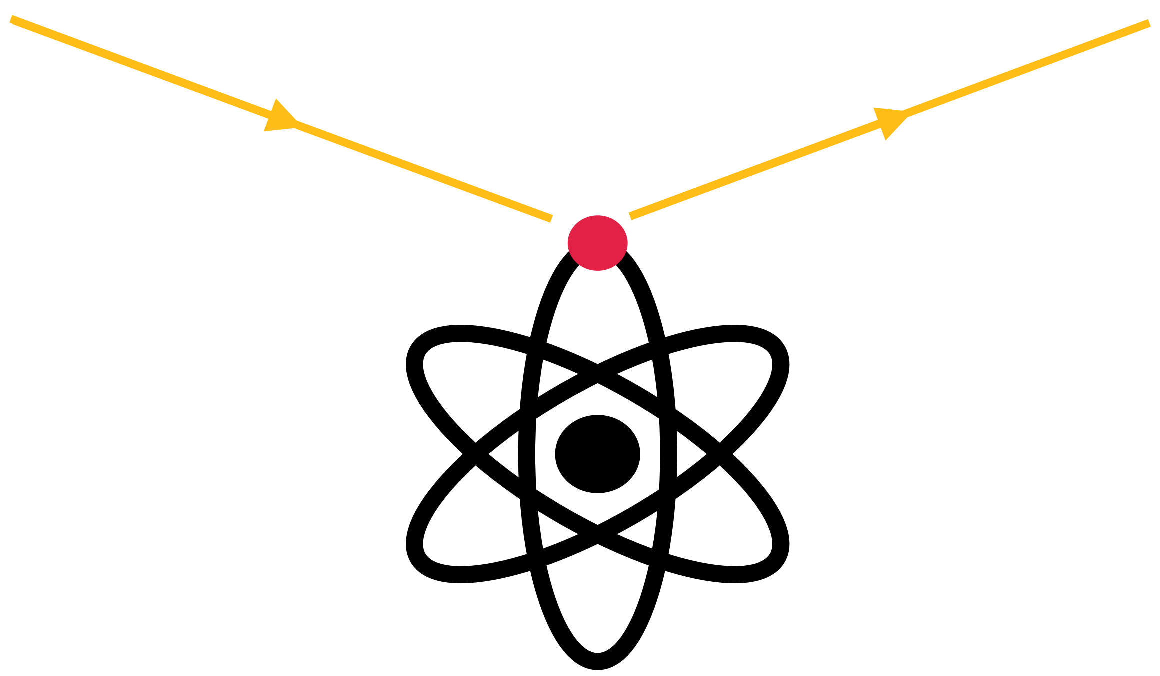
Axion Like Particles (ALPs)

30eV - 20keV

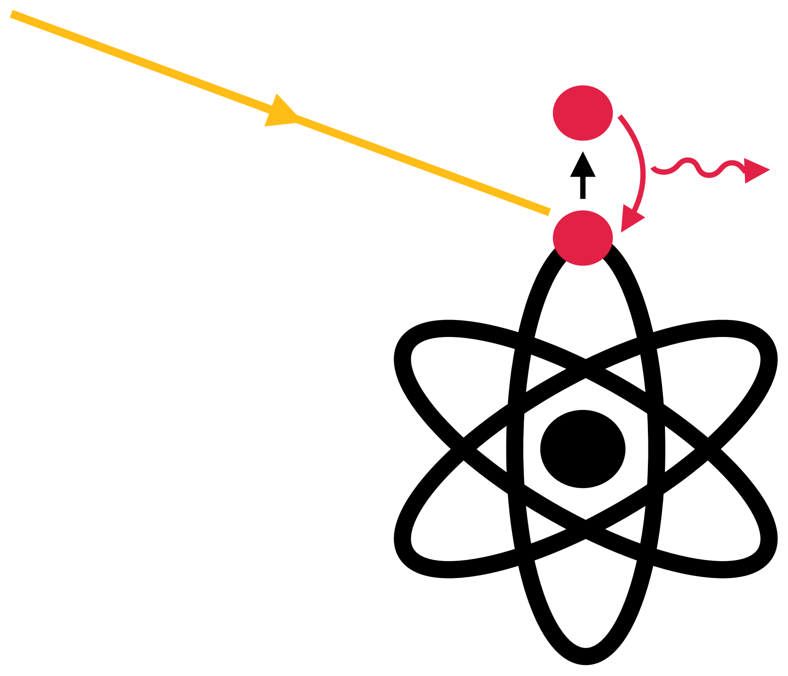
Absorption of ALP by bound electrons → monoenergetic signal

ALP = pseudo scalar particle

Coupling ALP - electrons → g_{Ae}



ER signals



Sterile neutrino

7keV - 35keV

Inelastic scatter of sterile ν off bound electrons

Possible mixing with active neutrinos → PMNS-like matrix element $|U_{e4}|^2$

Dark Photon (DP)

30eV - 20keV

Absorption of DP by bound electrons → monoenergetic signal

DP = vector boson particle, mediator of a new dark force with new local U(1) symmetry

Kinetic mixing between DP and SM photons → strength κ

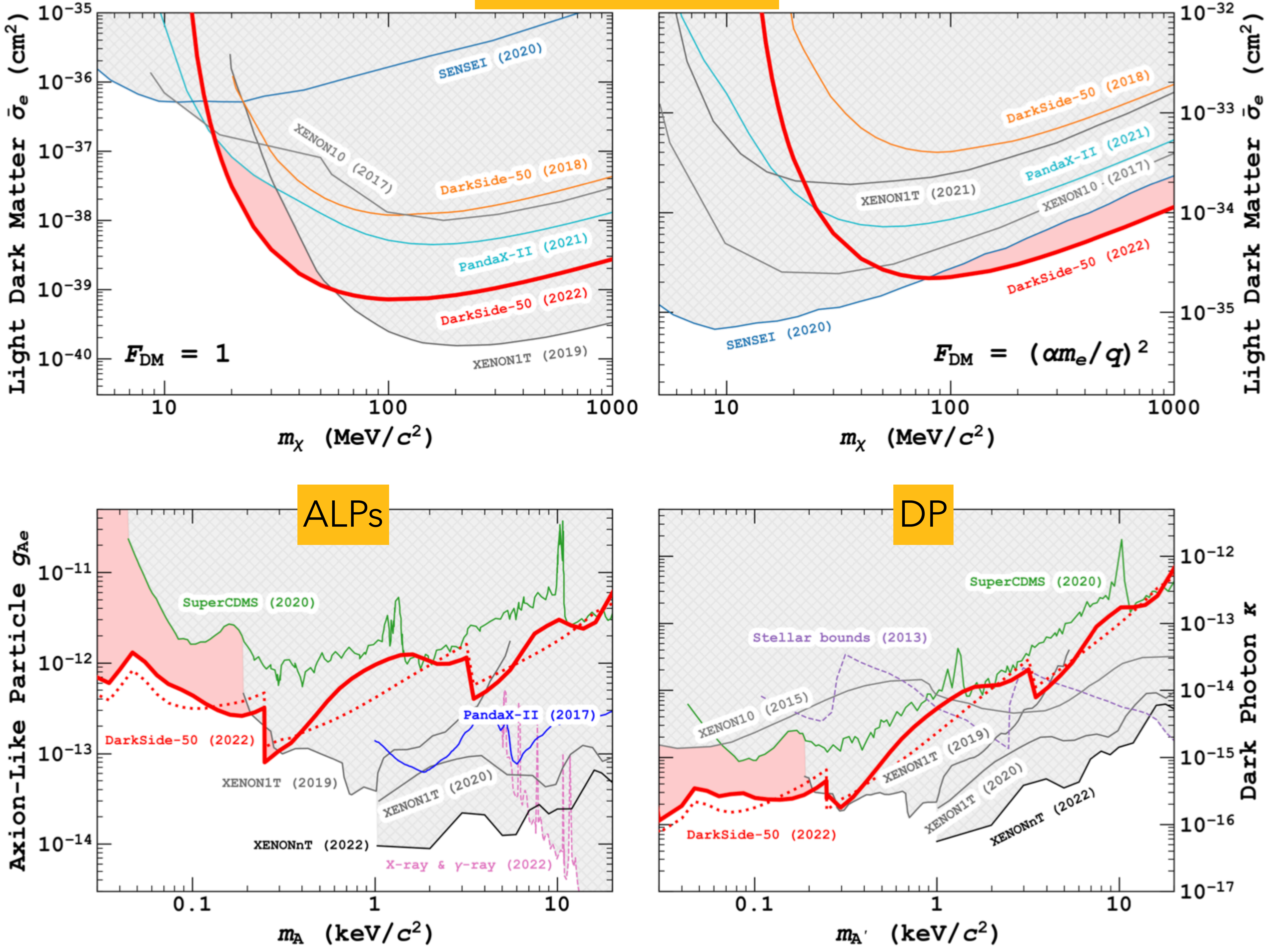
DS50 low mass analysis

Light Dark Matter

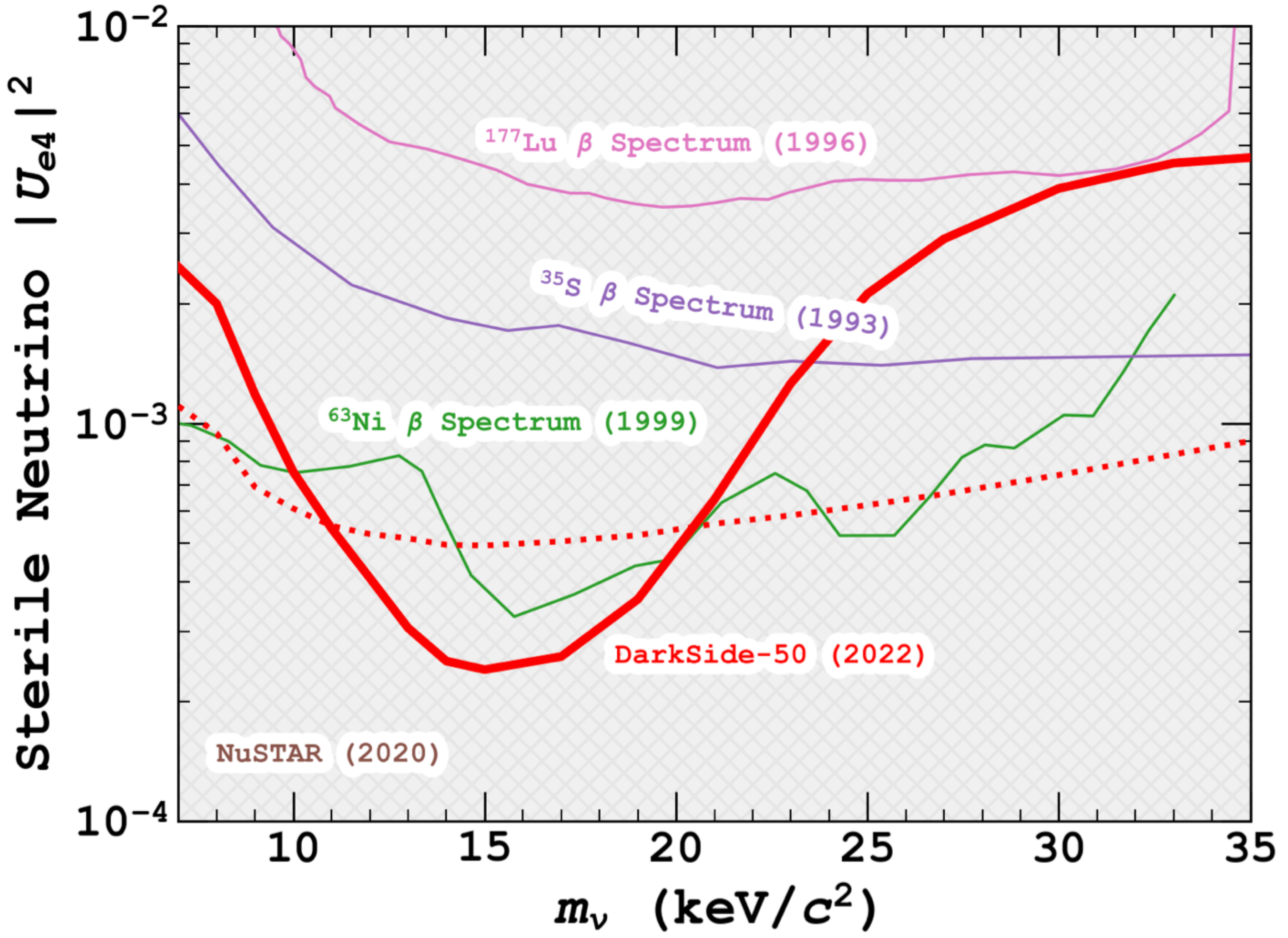
Other DM signals

ALPs

DP



Sterile ν



Theoretical sys. uncertainties from the DM halo modeling

Signal systematics from DM halo (astro) uncertainty

- Theoretical event rate :

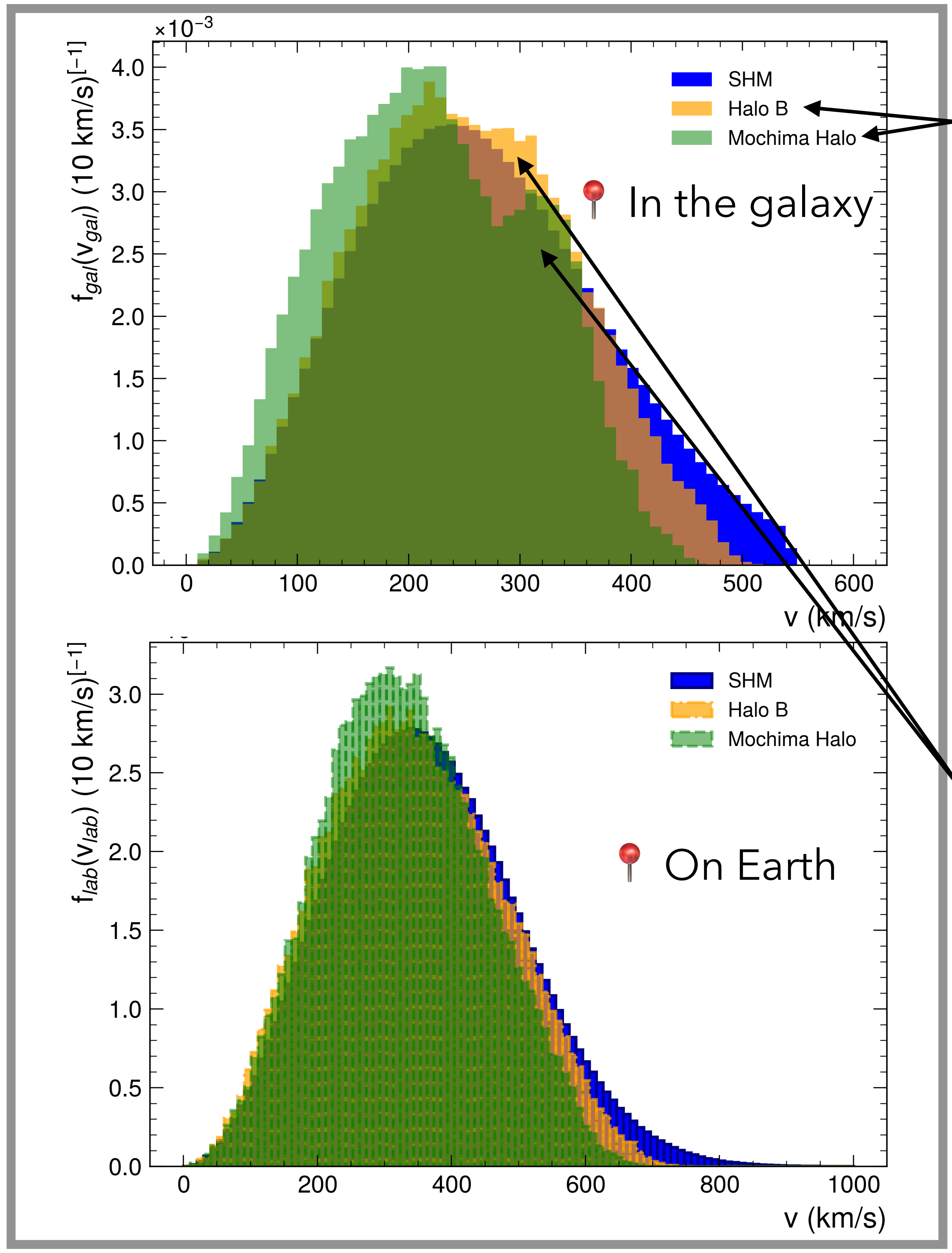
$$\frac{dR}{dE} = \frac{\rho_0}{m_\chi m_A} \int_{v>v_{min}}^{v_{max}} \frac{d\sigma}{dE} v \, f(\vec{v}) \, d^3\vec{v}$$

SHM → Maxwellian velocity distribution

- SHM includes divergences → cannot be physically correct → test velocity distributions derived from motivated cosmological simulations

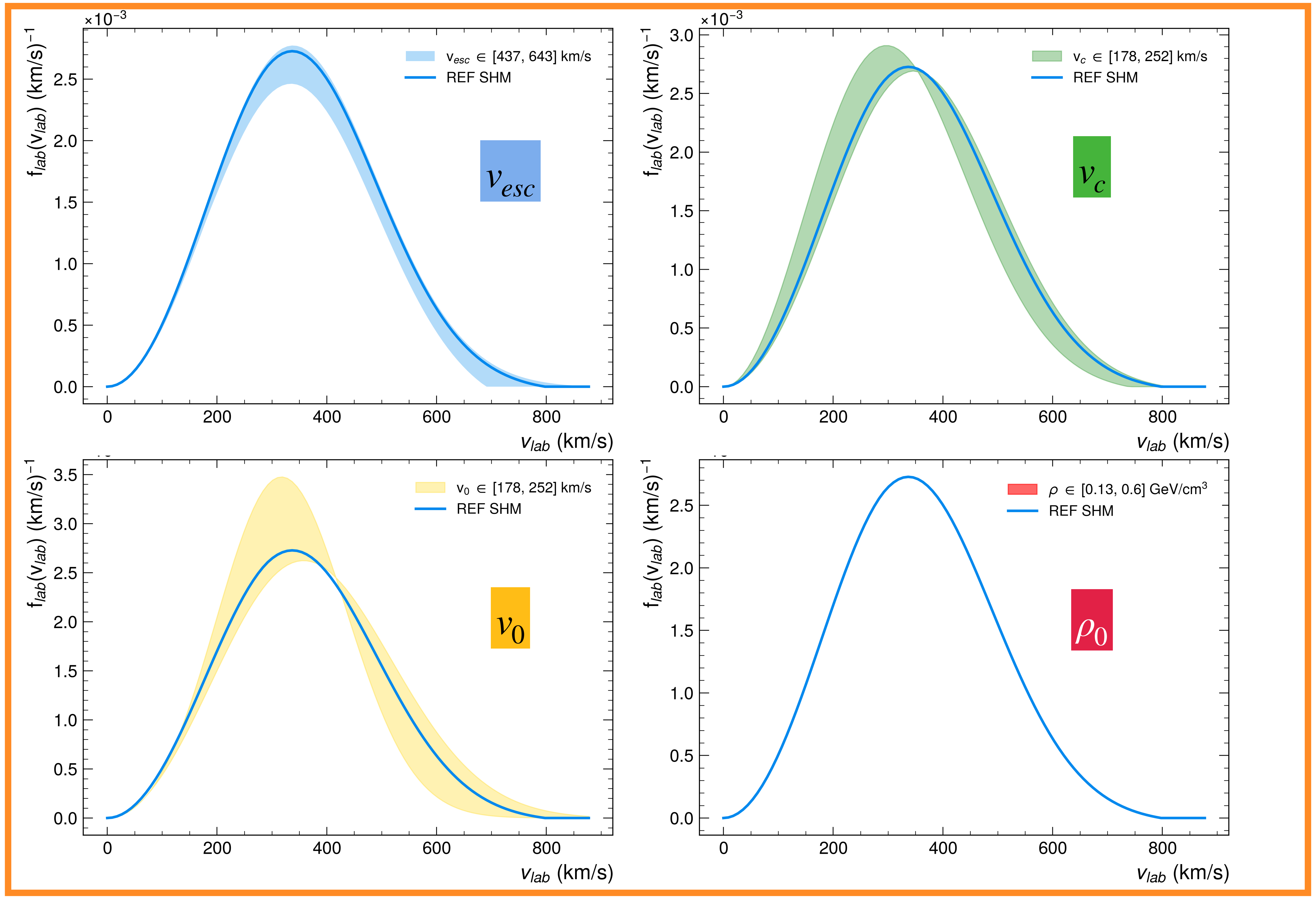
Astrophysical parameters

- $v_{max} = v_{esc} + v_{Earth}$, v_{esc}=544 km/s
- $v_c = v_0 = 238$ km/s
- ρ_0 = 0.3 GeV/cm³



DM haloes of Milky-Way-like galaxies derived from **DM+baryon cosmological simulations**

Bumps resulting from non - linearities in the history of the halo formation

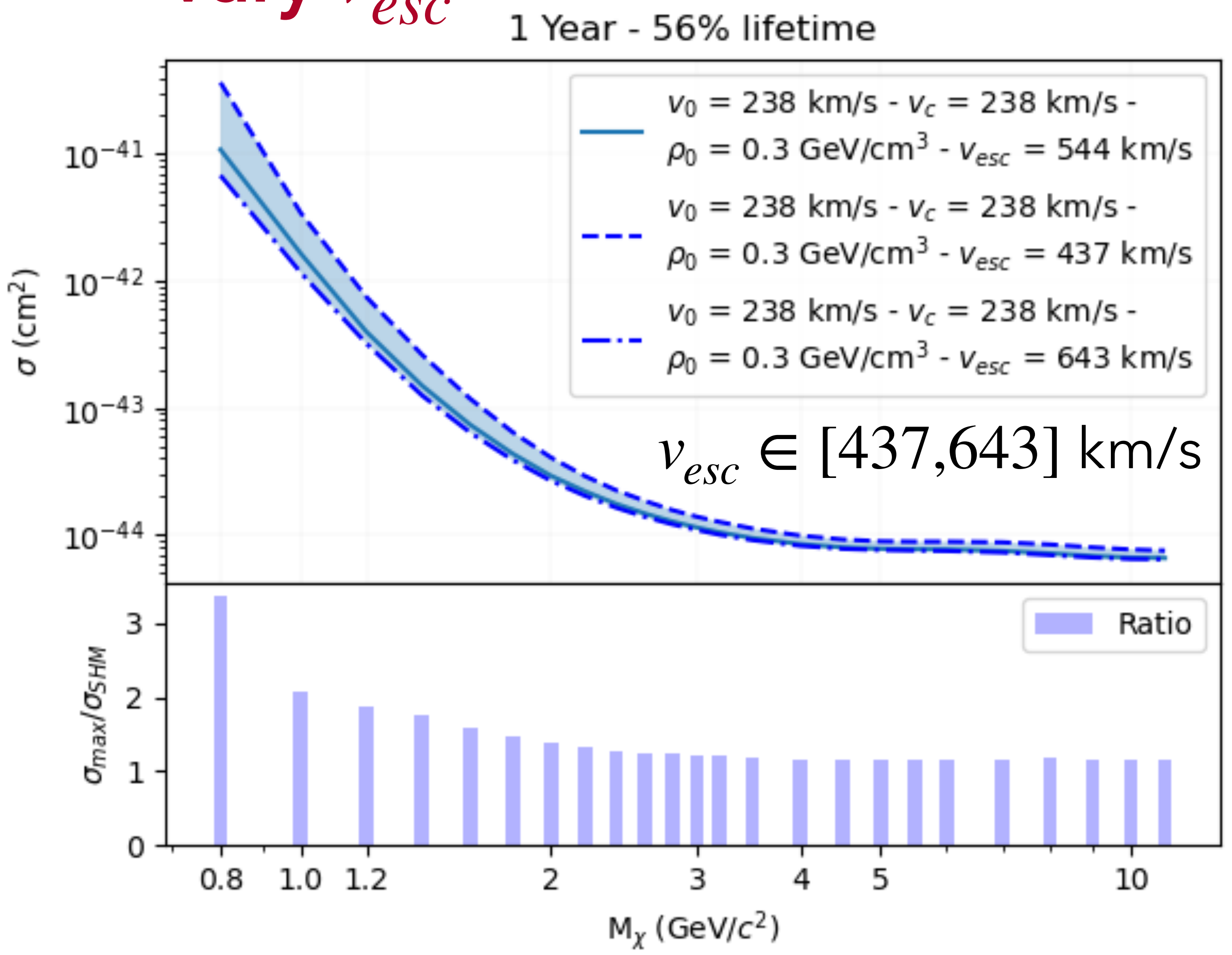


On Earth

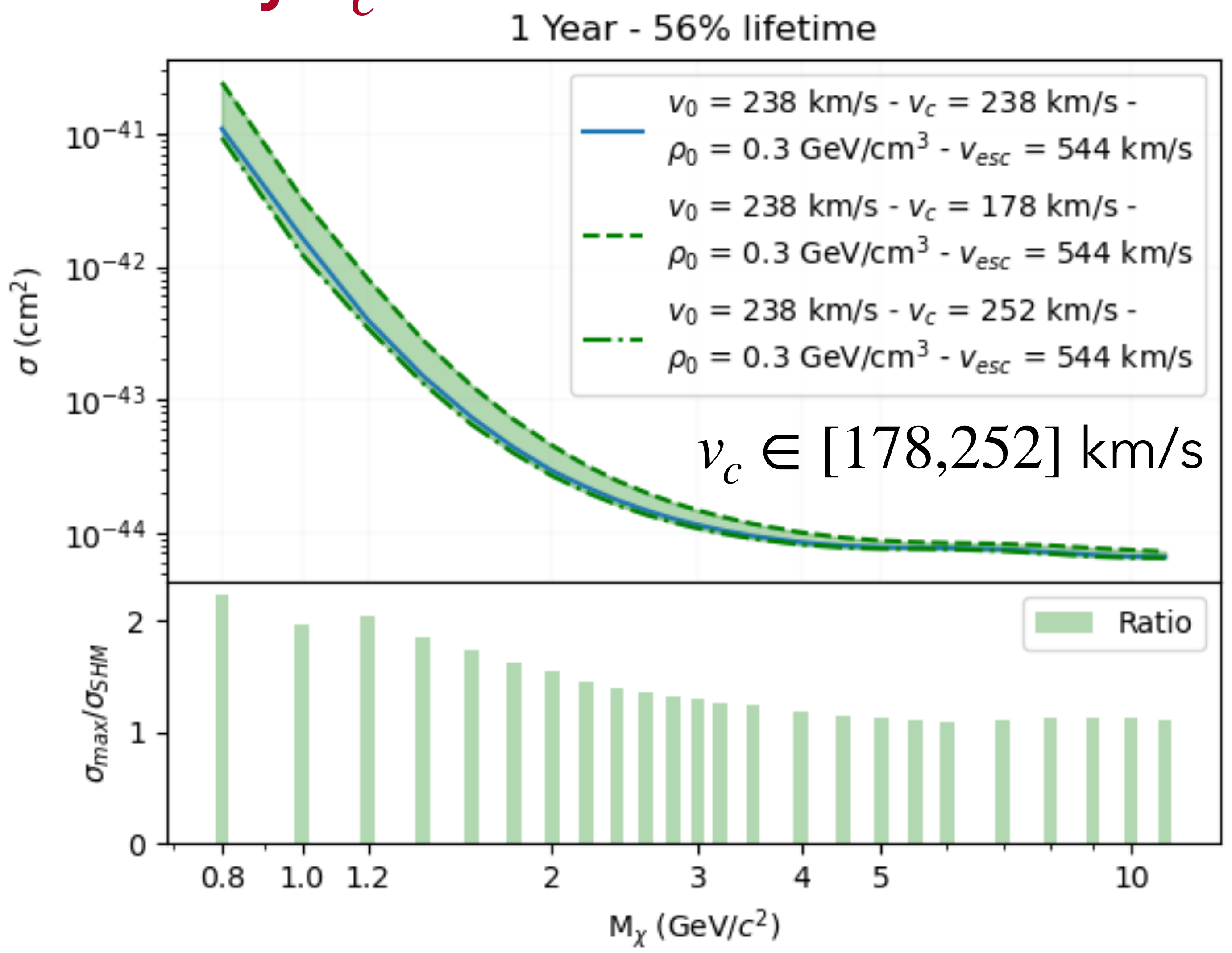
Signal systematics from DM halo (astro) uncertainty

Event rate in WIMP search = $\frac{dR}{dE} = \frac{\rho_0}{m_\chi m_A} \int_{v>v_{min}}^{v_{max}} \frac{d\sigma}{dE} v \, f(\vec{v}) \, d^3\vec{v}$

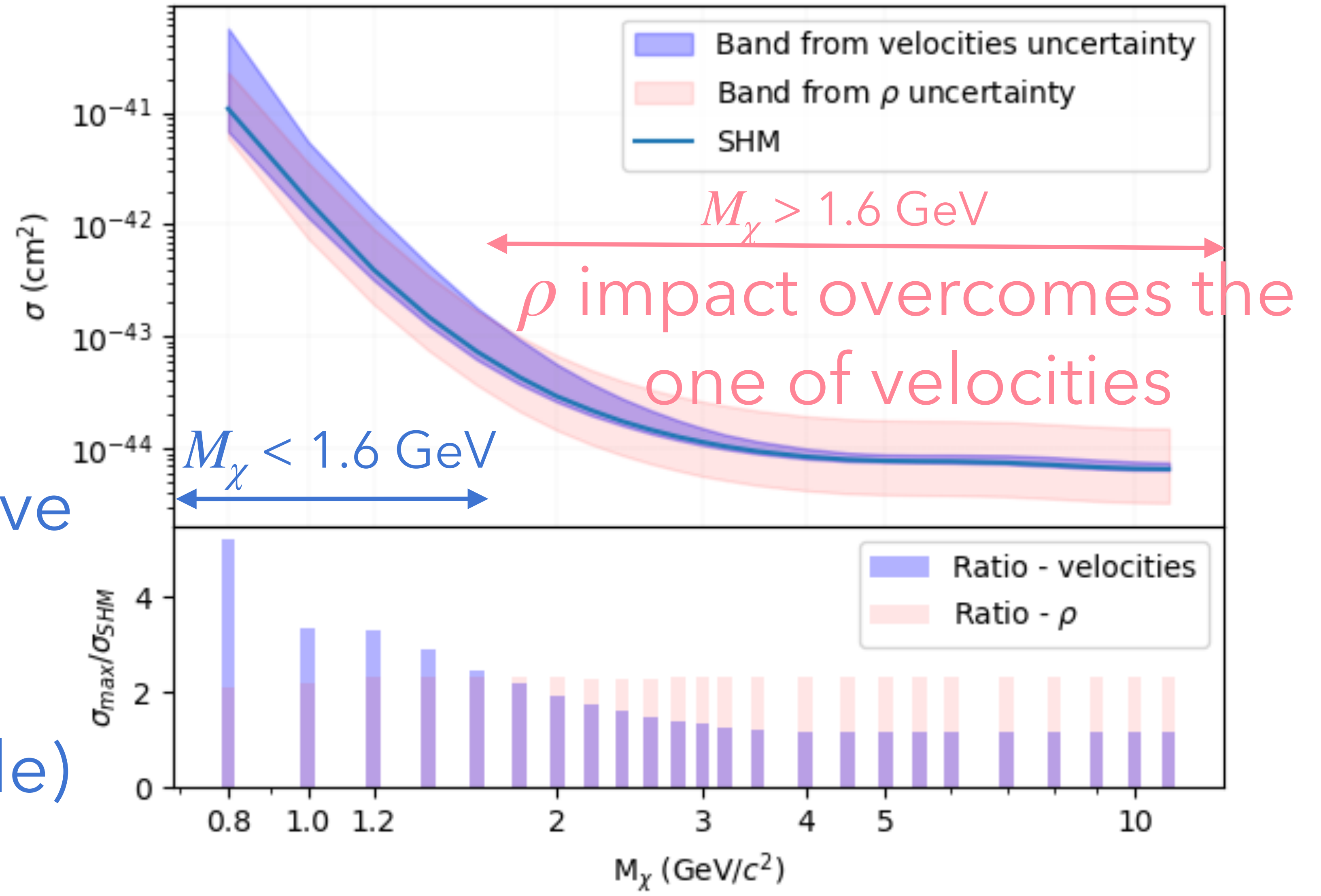
Vary v_{esc}



Vary v_c

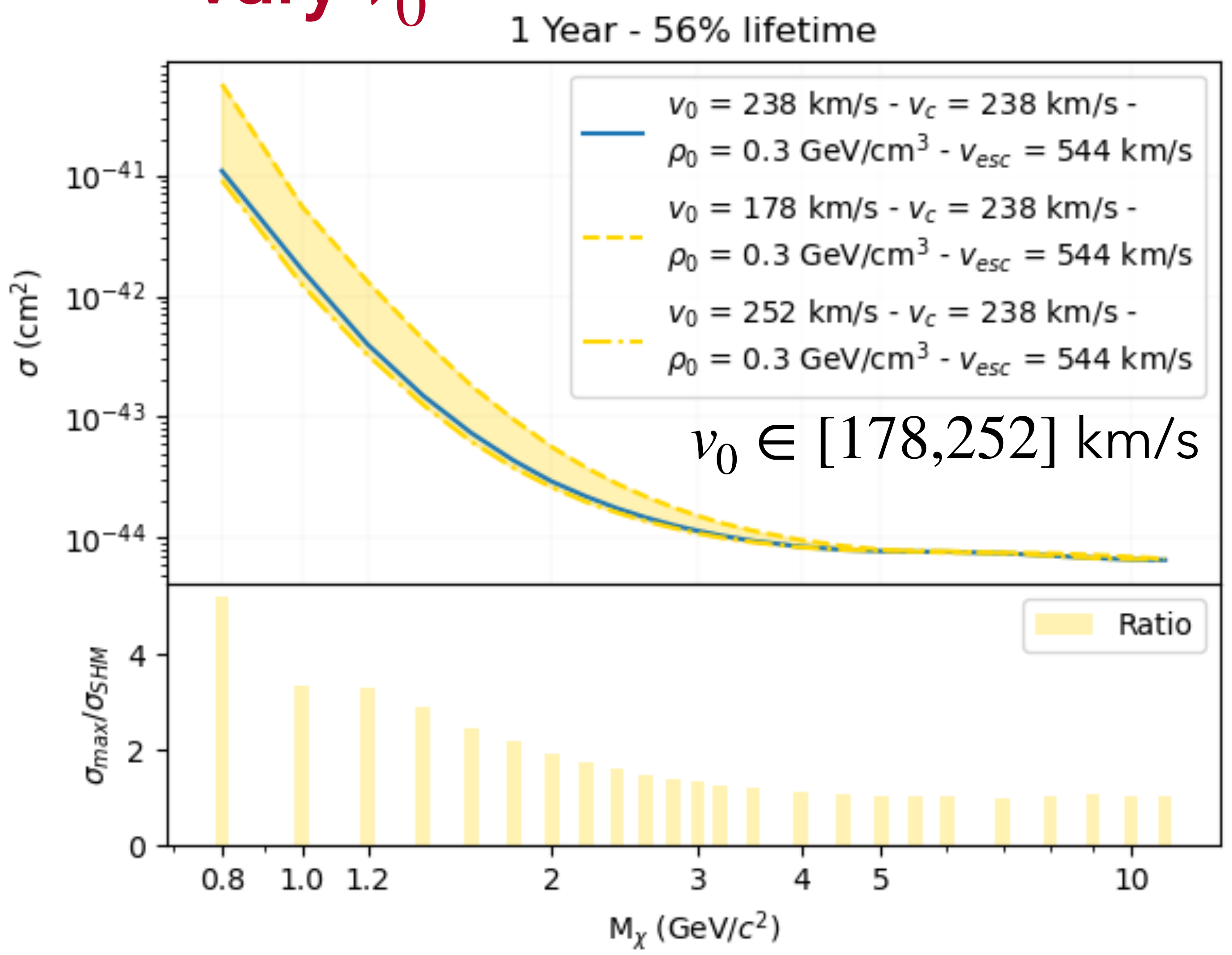


Summary astro. param.

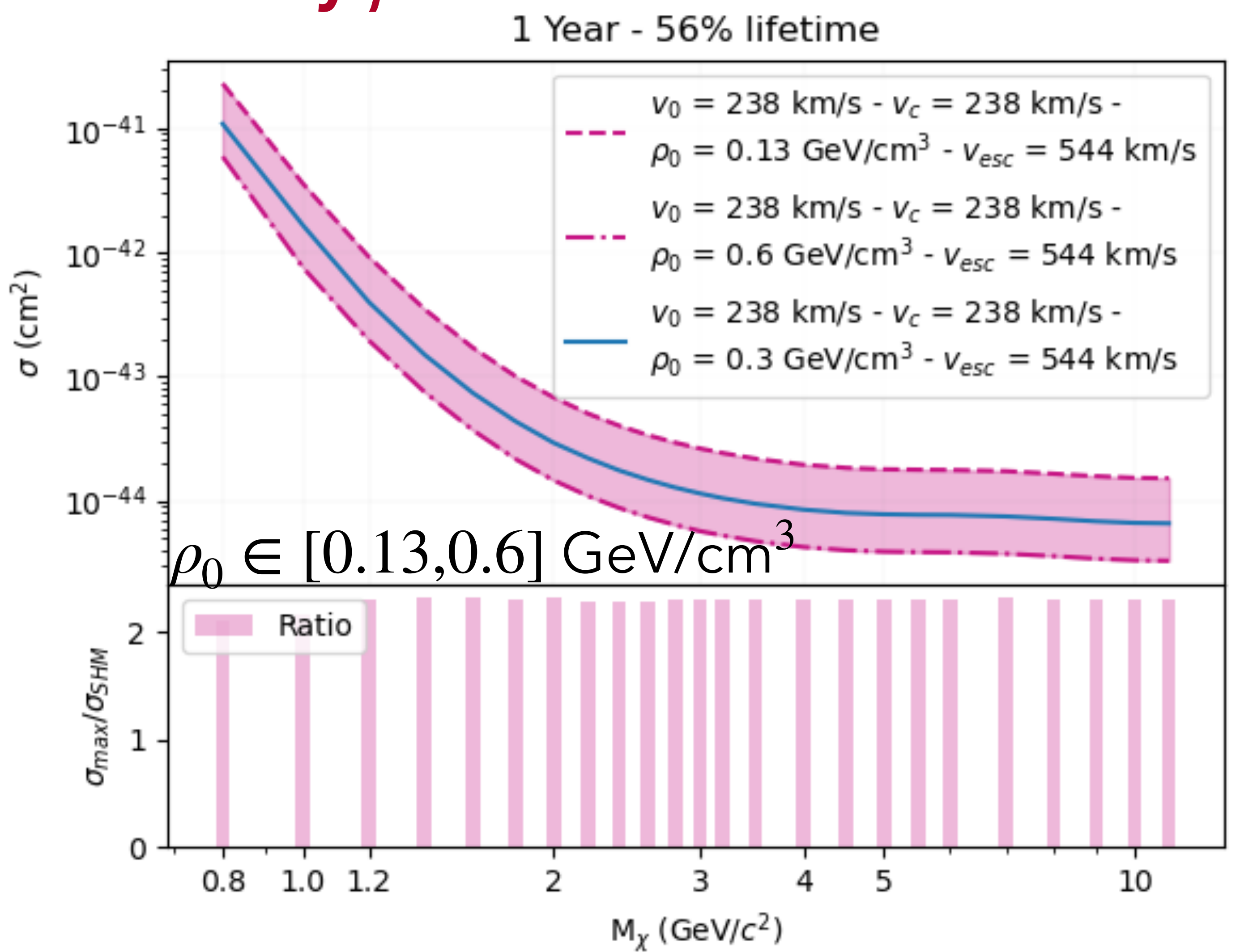


Most conservative sensitivity from velocities (up to 5.2x less sensible)

Vary v_0

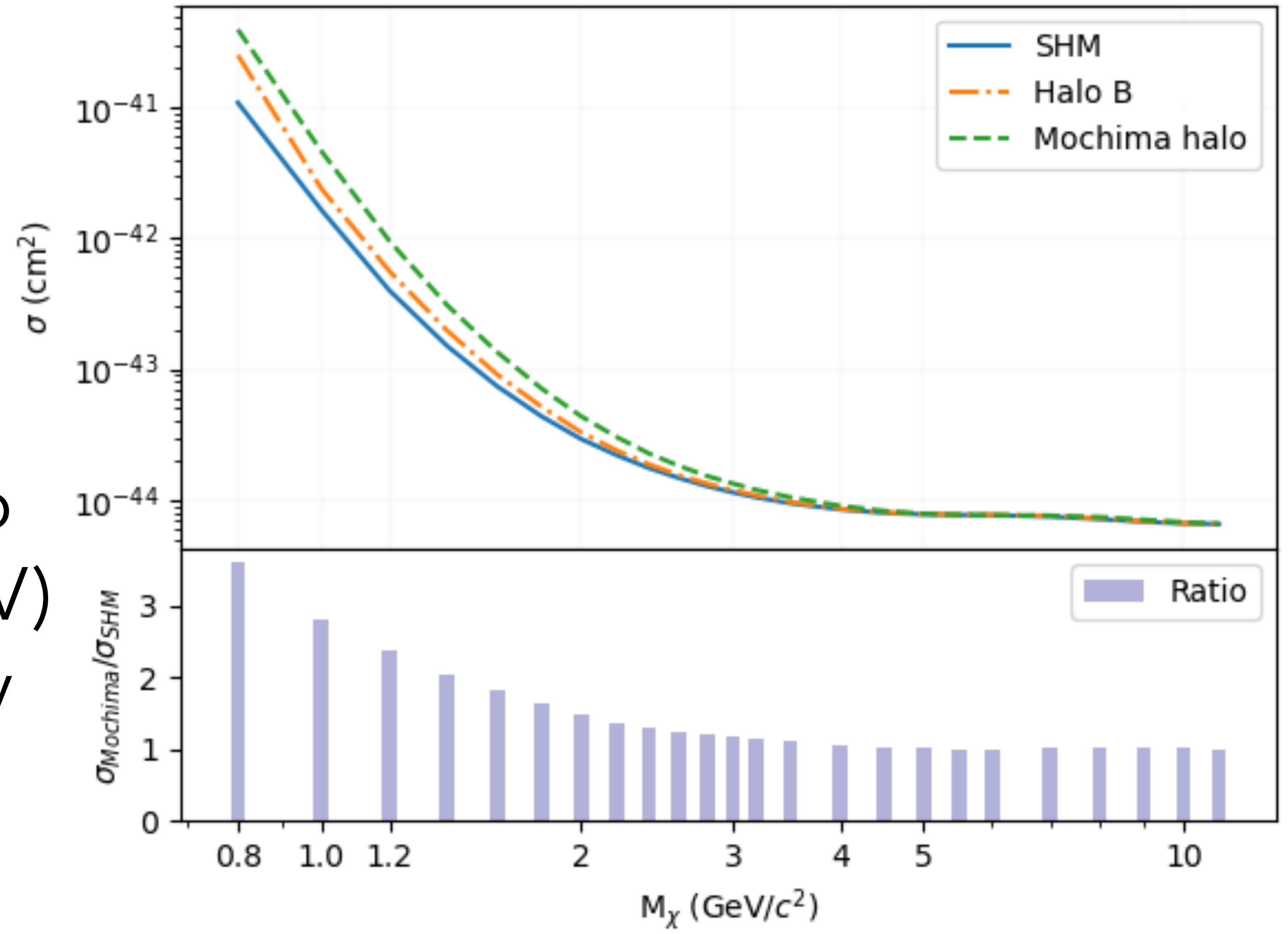


Vary ρ



SHM = least conservative model
With SHM, up to 3.6x (at 800 MeV) better sensitivity

Simulated halo models



TPC calibration

The calibration of DarkSide-20k

Design and stakes

Goals of the calibration

- Calibrate energy deposits of NR signal and ER background
- Study the linearity of the detector response
- Study its spatial uniformity
- Study its time stability

Diffuse sources
ER uniform calibration

^{83m}Kr | ^{220}Rn | ^{39}Ar

Only background characterization

External sources
ER + NR calibration

^{57}Co | ^{133}Ba | ^{22}Na | ^{137}Cs | ^{60}Co

AmLi | AmC | AmBe

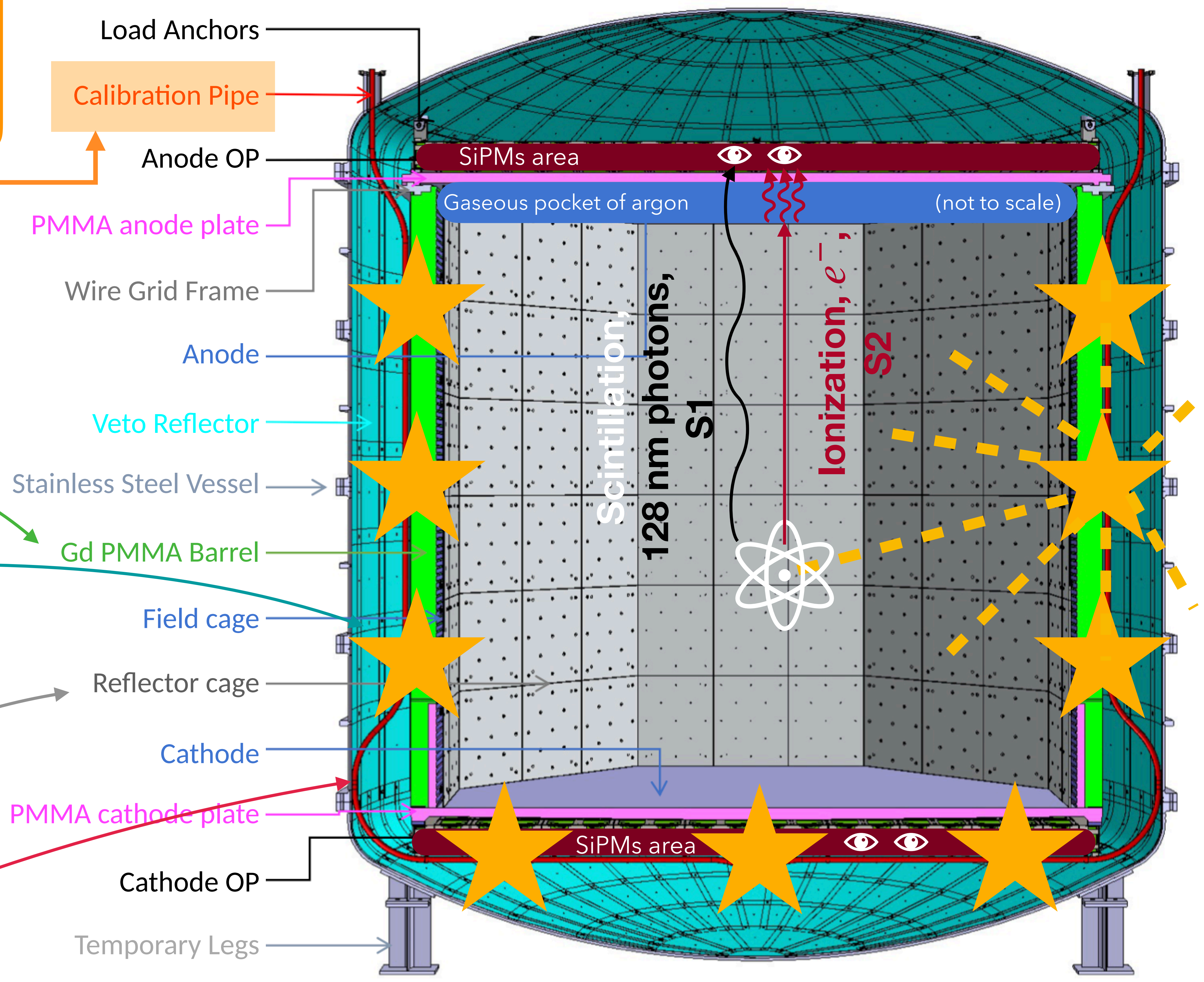
Circulated in calibration pipes

Simulations, with GEANT4-based software (g4ds)

Mock up tests

Potential issues

- The calibration is not efficient
- The pipes lower too much the Light Collection Efficiency in the veto buffer
- The material of the pipes induce too much background in the Inner detector
- The source circulation is difficult due to geometry or cold

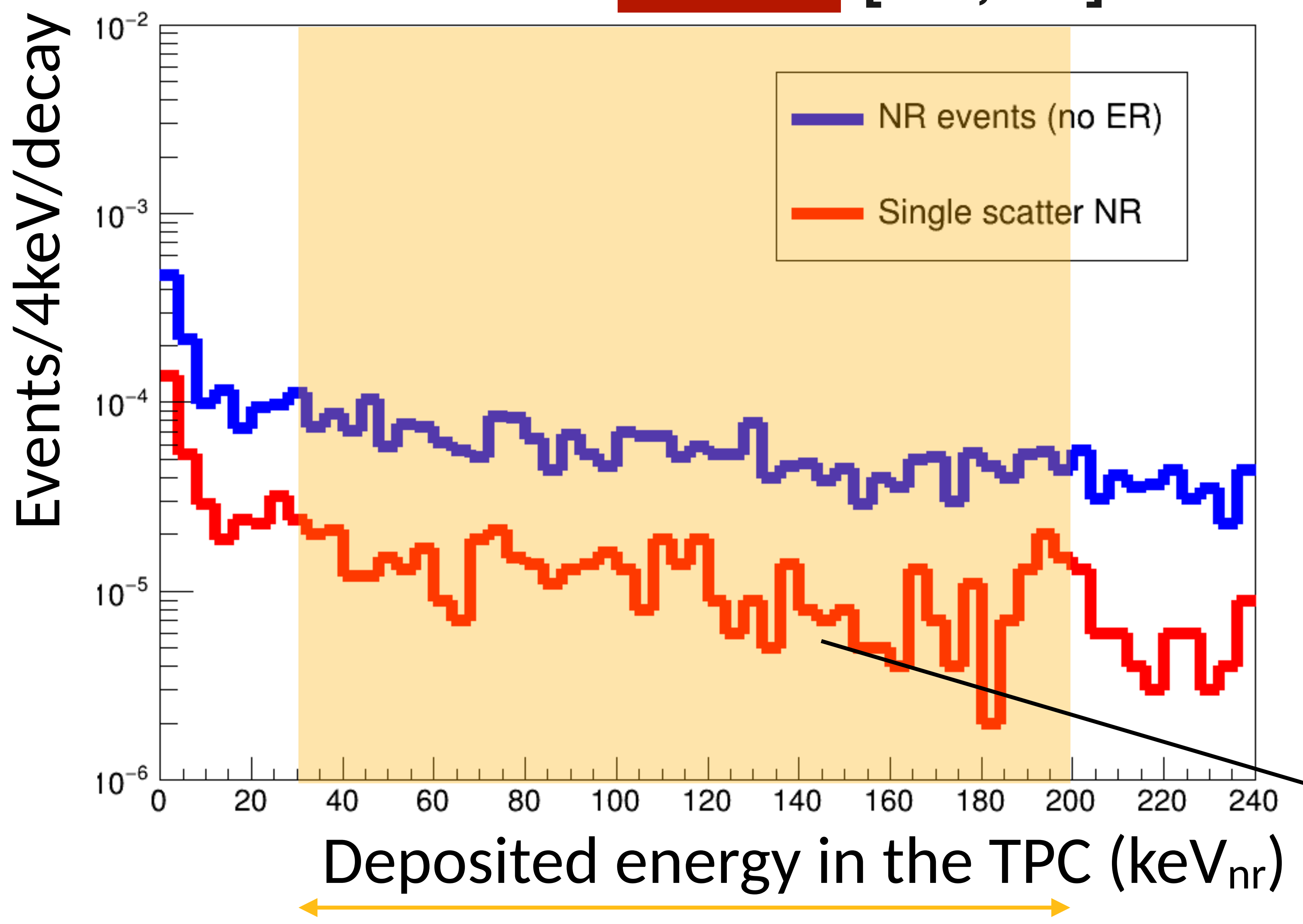


Simulation of the calibration - software = GEANT4-based

NR calibration

	AmBe	AmC
E (MeV)	[0.2, 12]	[2, 7]

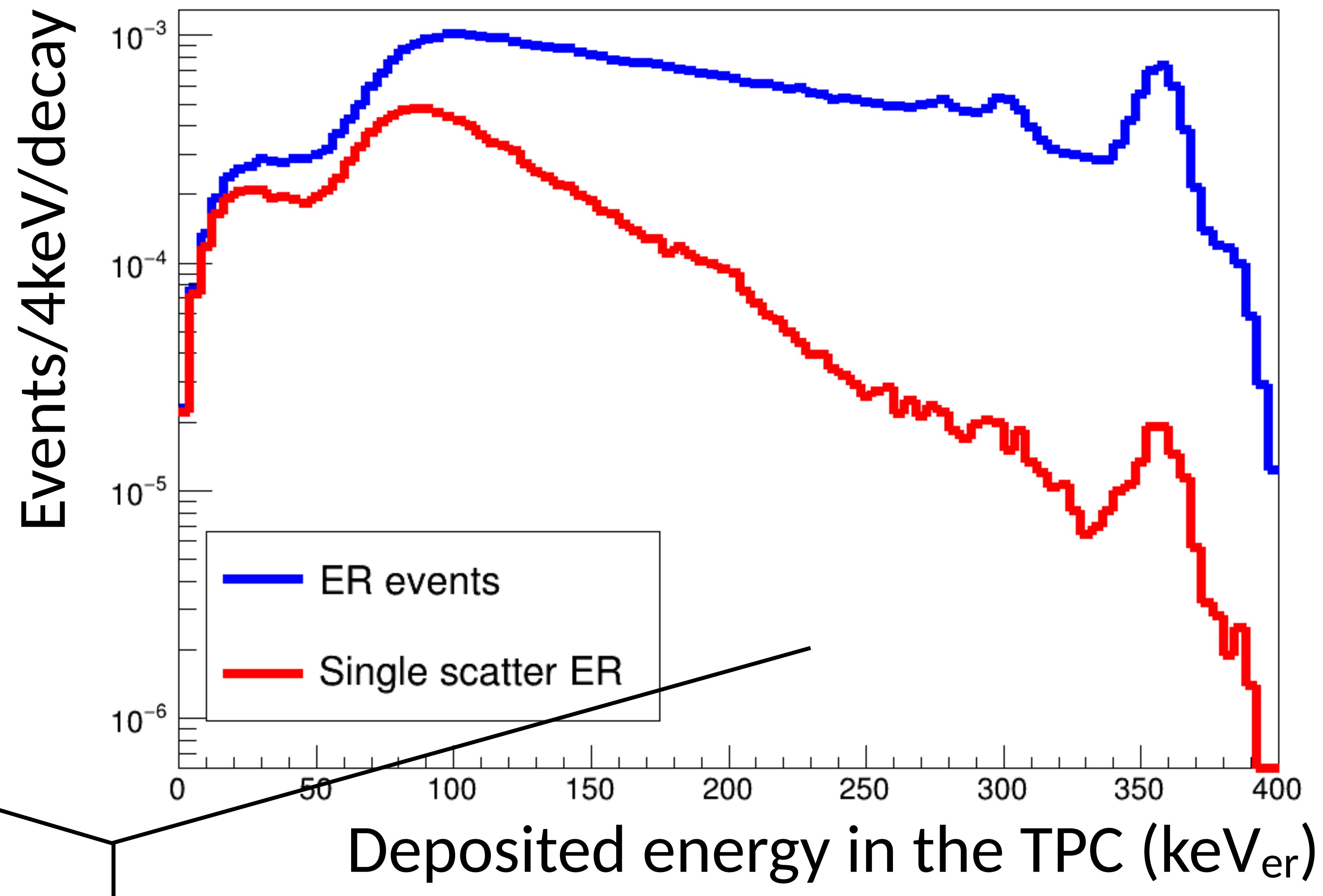
AmBe [0.2, 12] MeV

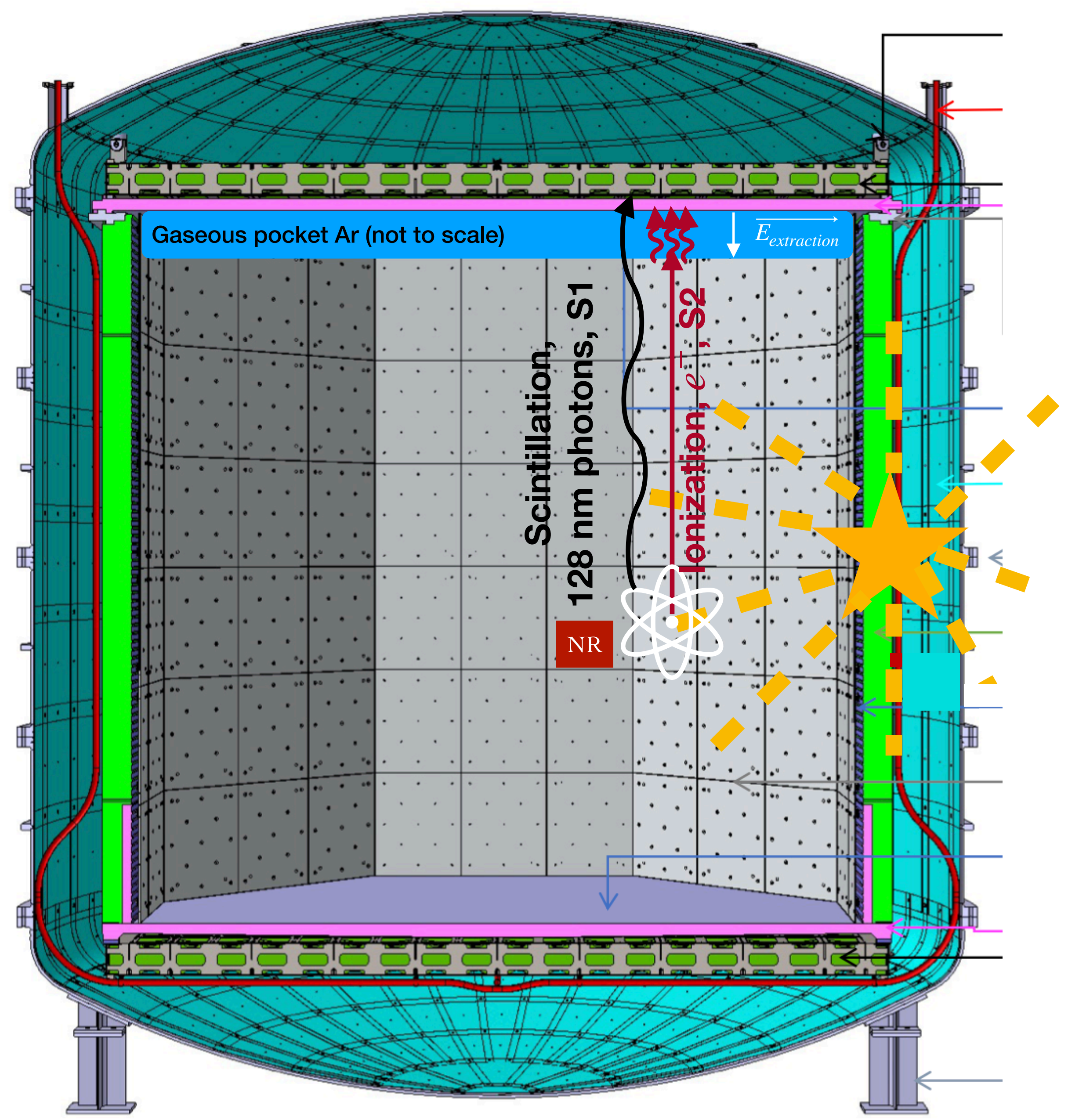


ER calibration

	^{57}Co	^{133}Ba	^{22}Na	^{22}Na	^{137}Cs	^{60}Co	^{60}Co
E (keV)	122	356	511	1274	662	1173	1322

^{133}Ba 356 keV





Computation of rates of events/decay
+
Assumptions on the calibration runs (verified in the future with the mock up at CPPM)

Estimate of the time needed to perform the calibration program

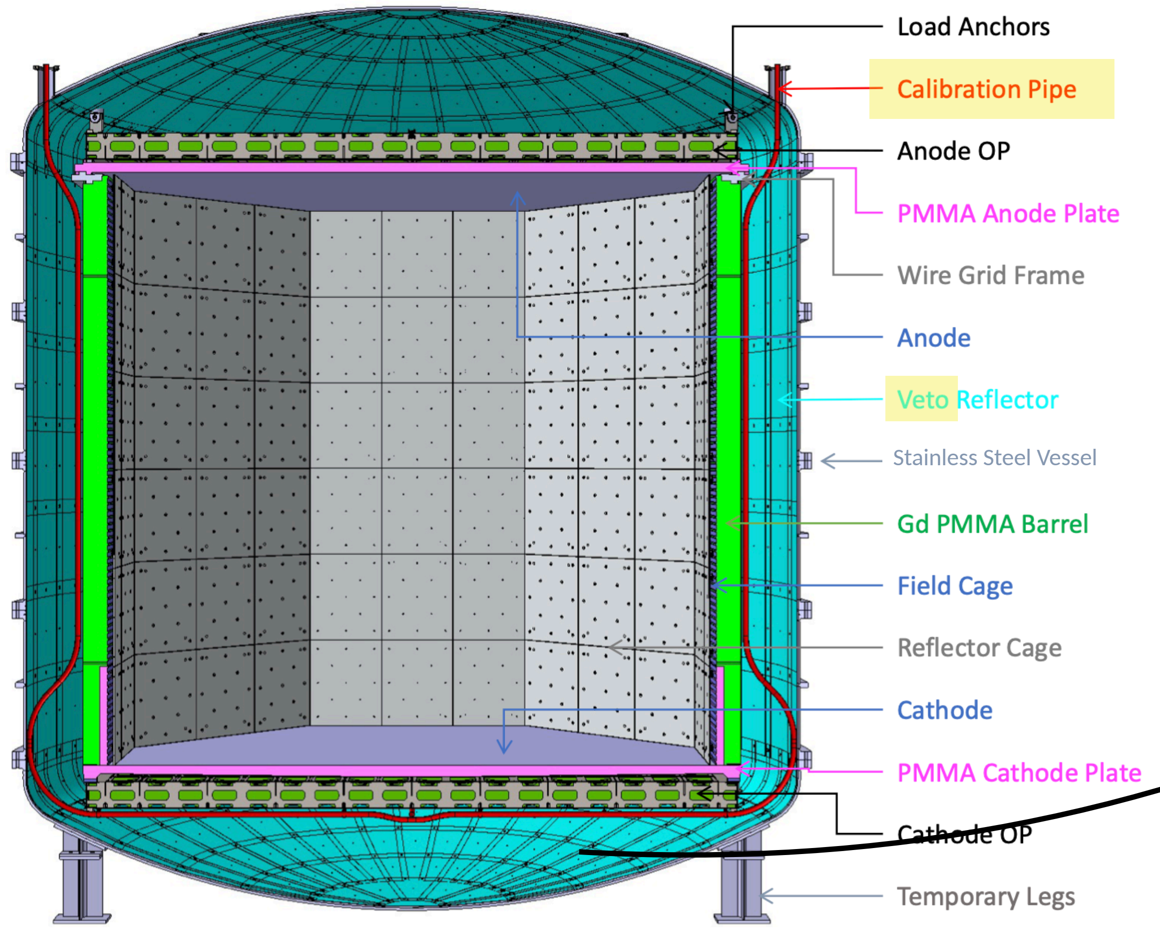
With 9 positions of calibration

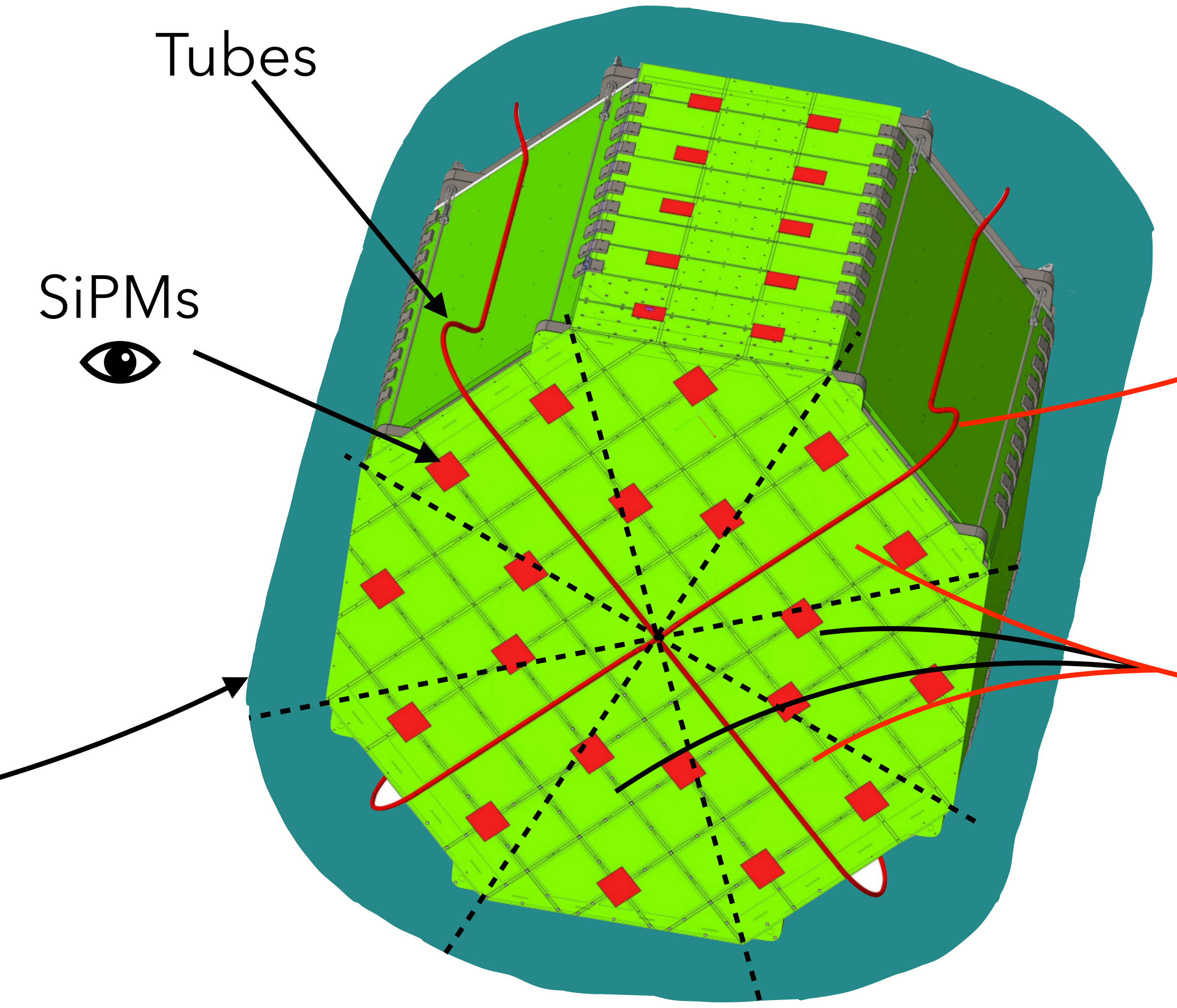
NR calibration (with neutrons) : 15 days

ER calibration (with photons) : 1 day to 1 week

Impact of the tubes on the detector

Veto's Light Collection Efficiency (LCE)





Tubes can absorb the light emitted by the argon when scintillating: this could lower the veto LCE

Asymmetry between octants up to 0.3 %

LCE	Relative loss of LCE (%)
Full veto buffer (3D)	0.9
Octants with pipes	1.1

Errors on these numbers are < 1e-2
(Gaussian statistical errors)

$$\frac{LCE^{Full}_{without-pipes} - LCE^{Full}_{ESR}}{LCE^{Full}_{without-pipes}}$$

$$\frac{LCE^{Pipes-octants}_{without-pipes} - LCE^{Pipes-octants}_{ESR}}{LCE^{Pipes-octants}_{without-pipes}}$$

With **reflector-wrapped** stainless steel tubes

= Best solution after different **tests of optical boundaries**

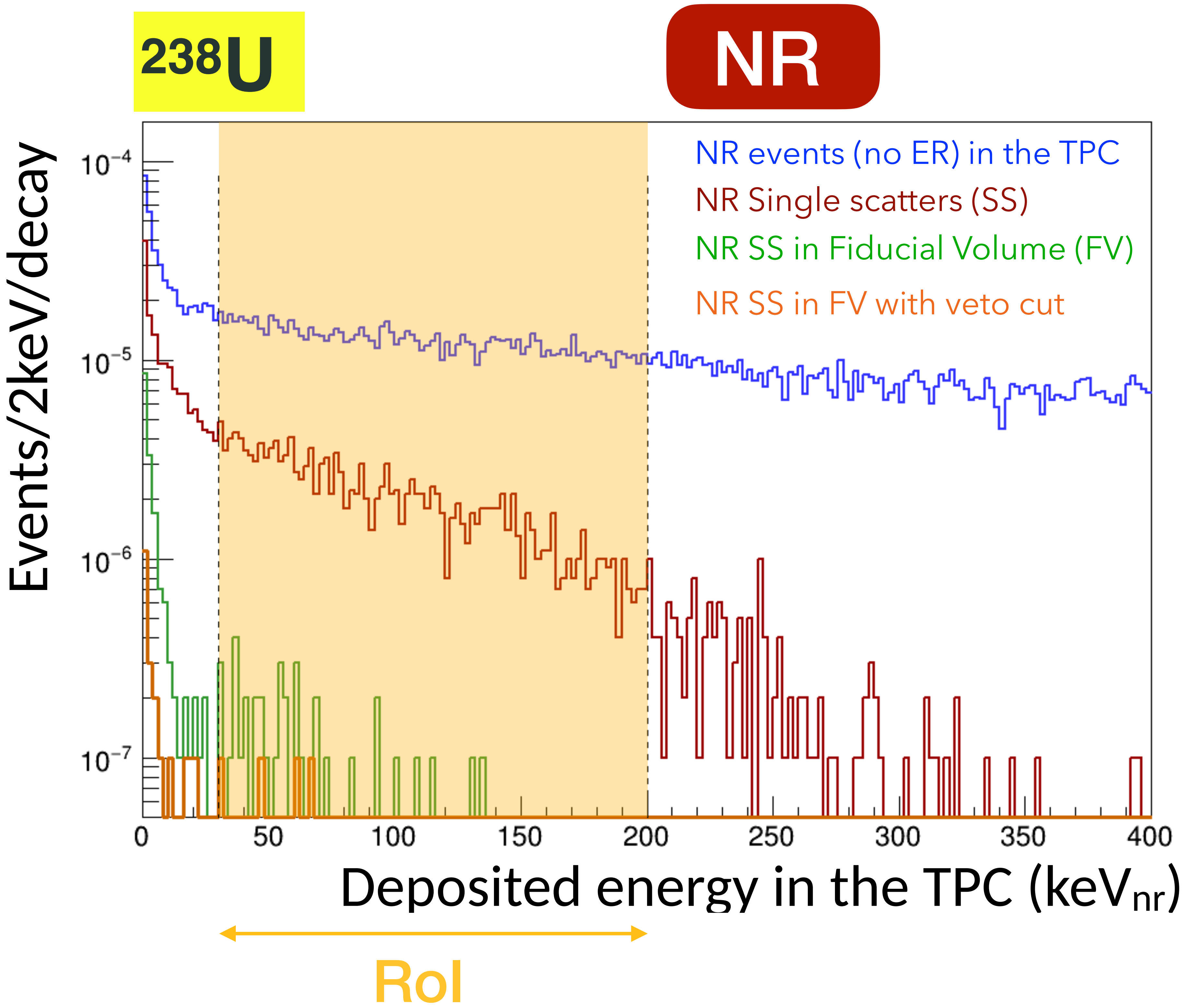
Impact of the tubes on the detector

Background induced in the veto and in the TPC

Very low background experiment & stainless steel tubes => control radio-purity

	^{238}U up	^{238}U mid	^{238}U low	^{232}Th	^{235}U	^{40}K	^{60}Co	^{137}Cs
Activity (mBq/kg)	1	0.72	1	0.83	0.046	0.49	3.1	0.86
Neutron yield (n/decay)	1.1e-9	4.8e-7	1.1e-9	1.8e-6	3.7e-7			

From (α, n) reactions due to natural contamination in ^{232}Th and ^{238}U and spontaneous fission of ^{238}U



	^{238}U up	^{238}U mid	^{238}U low	^{232}Th	^{235}U
NR bknd / 10 years (200 t.y.)	4.0e-9	1.3e-6	4.0e-9	5.7e-6	6.0e-8

- NR background from pipes represents < 0.01% of DS20k budget: **fully negligible**
- Same study for ER : **ER background also negligible + S1/S2 ratio and PSD (= argon asset)**

Tests at CPPM and CERN with mock ups

Sept. 2022 — Cold tests at LN2 temperature — March 2023 — Room temp tests with scale-1 mock up — May 2023 — Cold tests at LAr temperature →