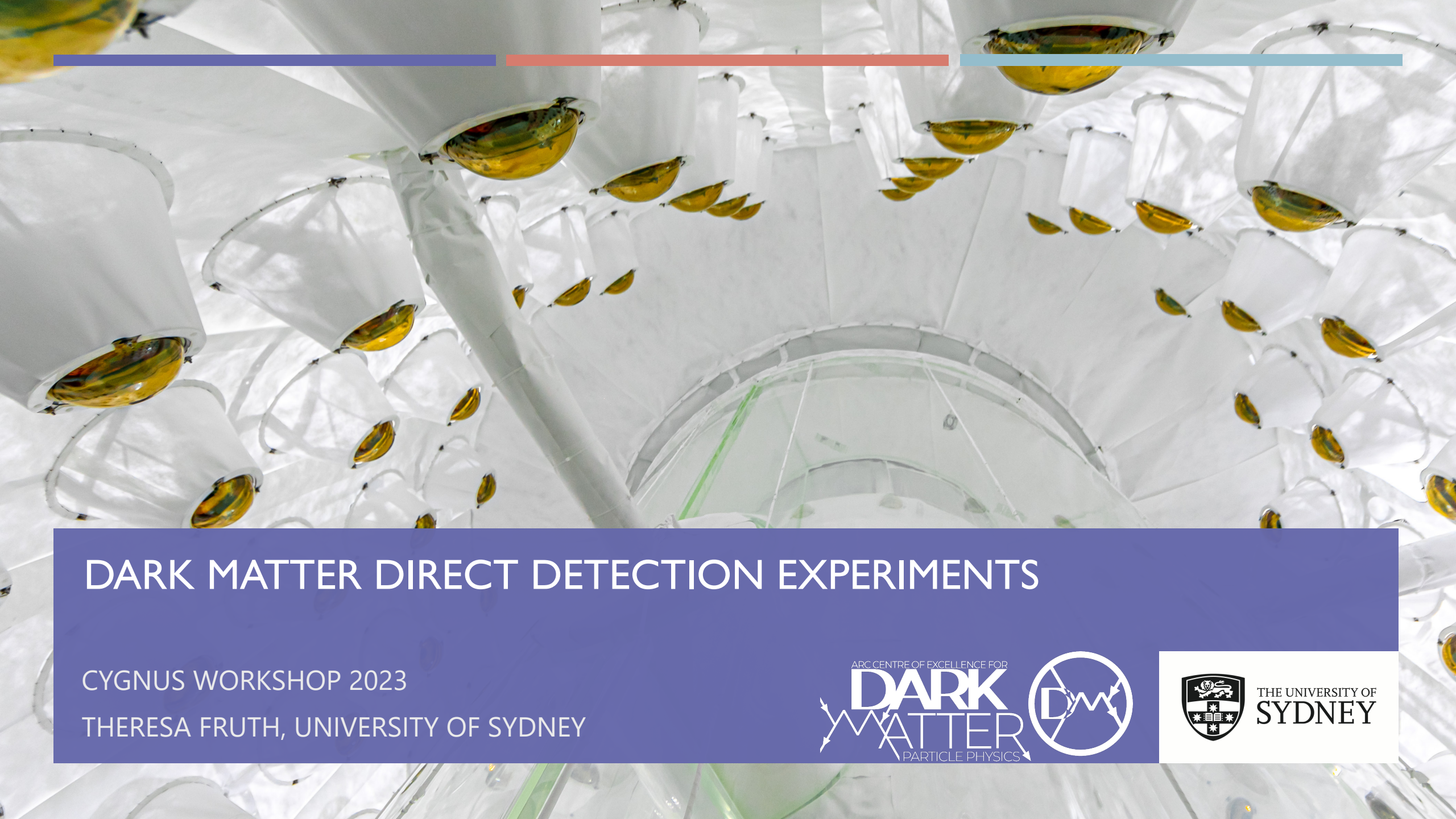


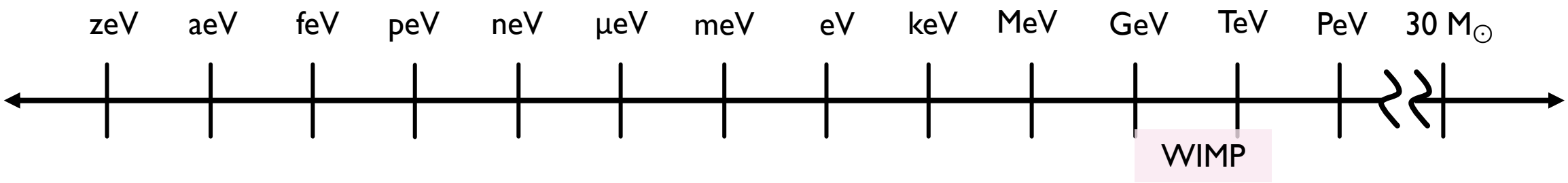
DARK MATTER DIRECT DETECTION EXPERIMENTS

CYGNUS WORKSHOP 2023

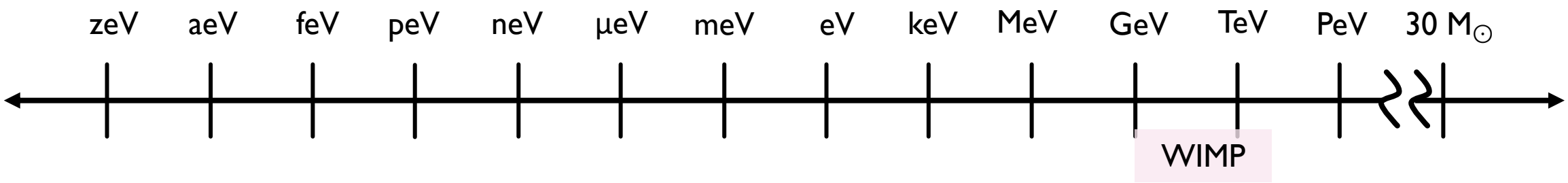
THERESA FRUTH, UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

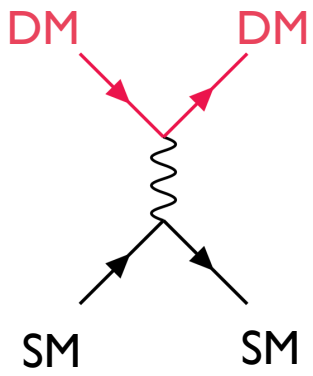
THE UNIVERSITY OF SYDNEY



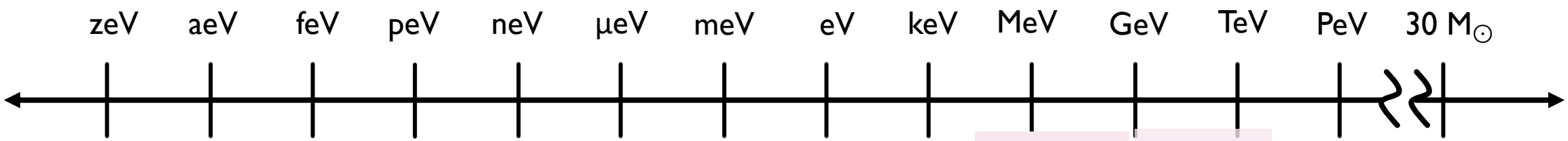
Particle-like dark matter



Particle-like dark matter



DM scattering

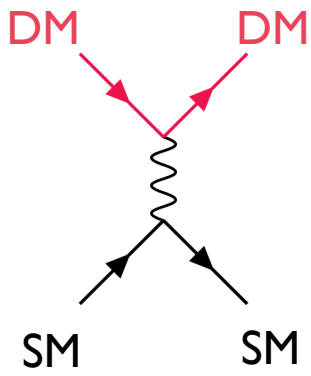


Light DM

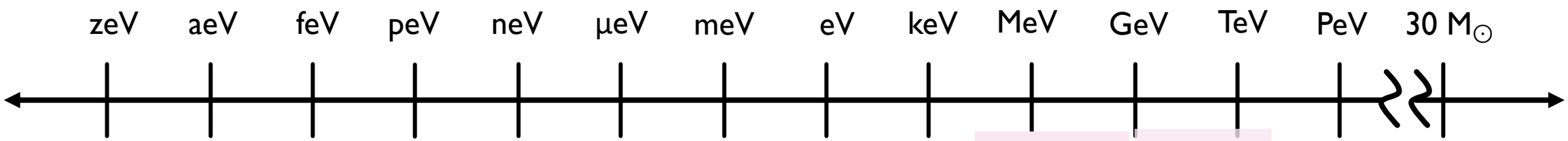
WIMP

Hidden sector DM

Particle-like dark matter



DM scattering



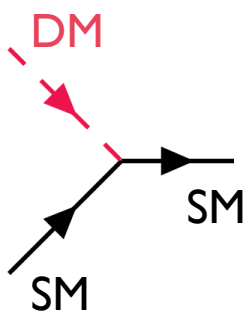
Light DM

WIMP

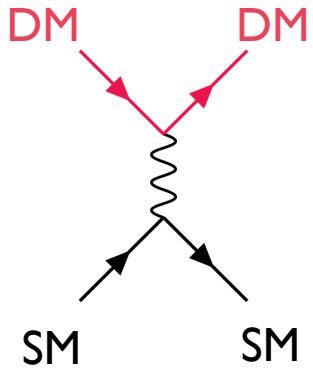
Hidden sector DM

Wave-like dark matter

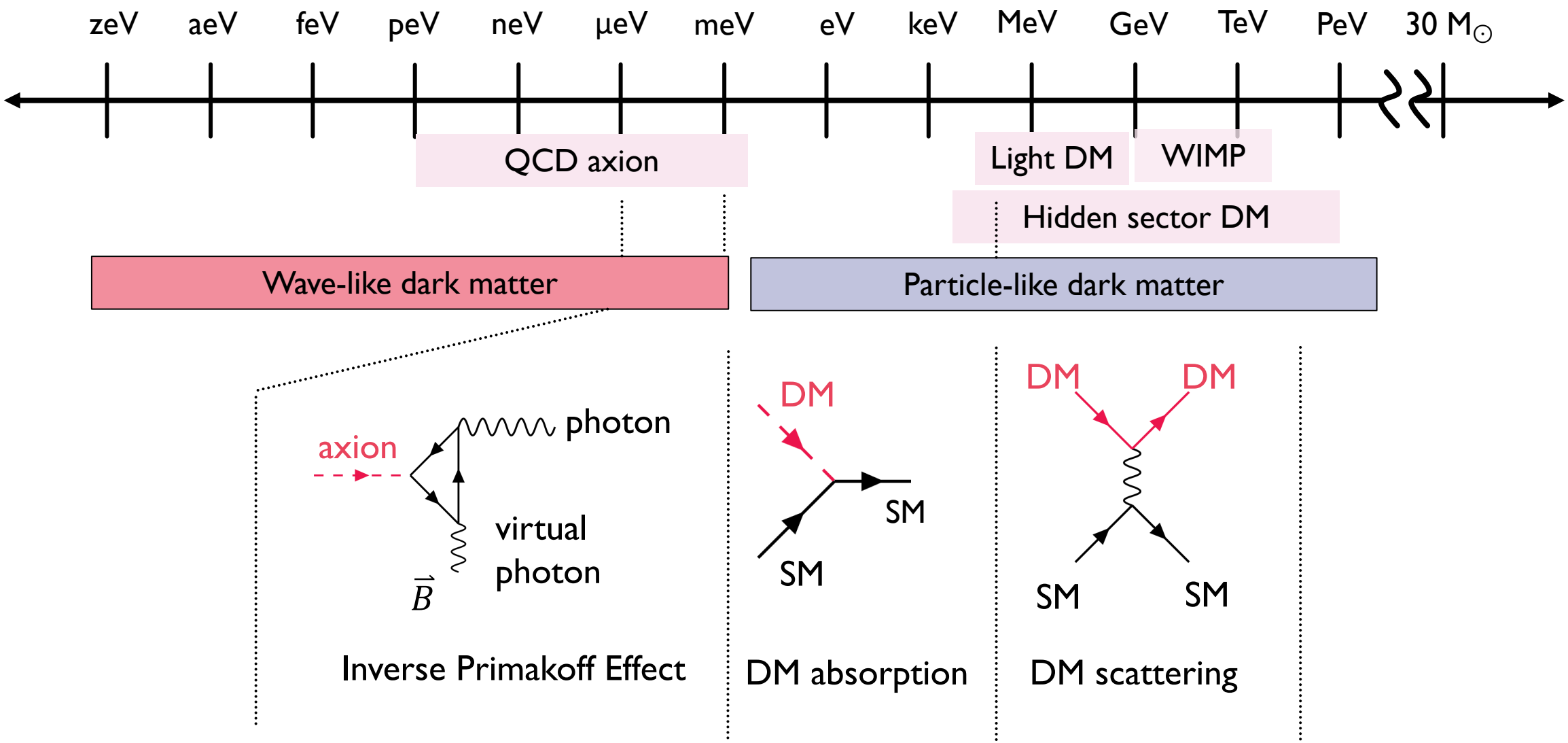
Particle-like dark matter

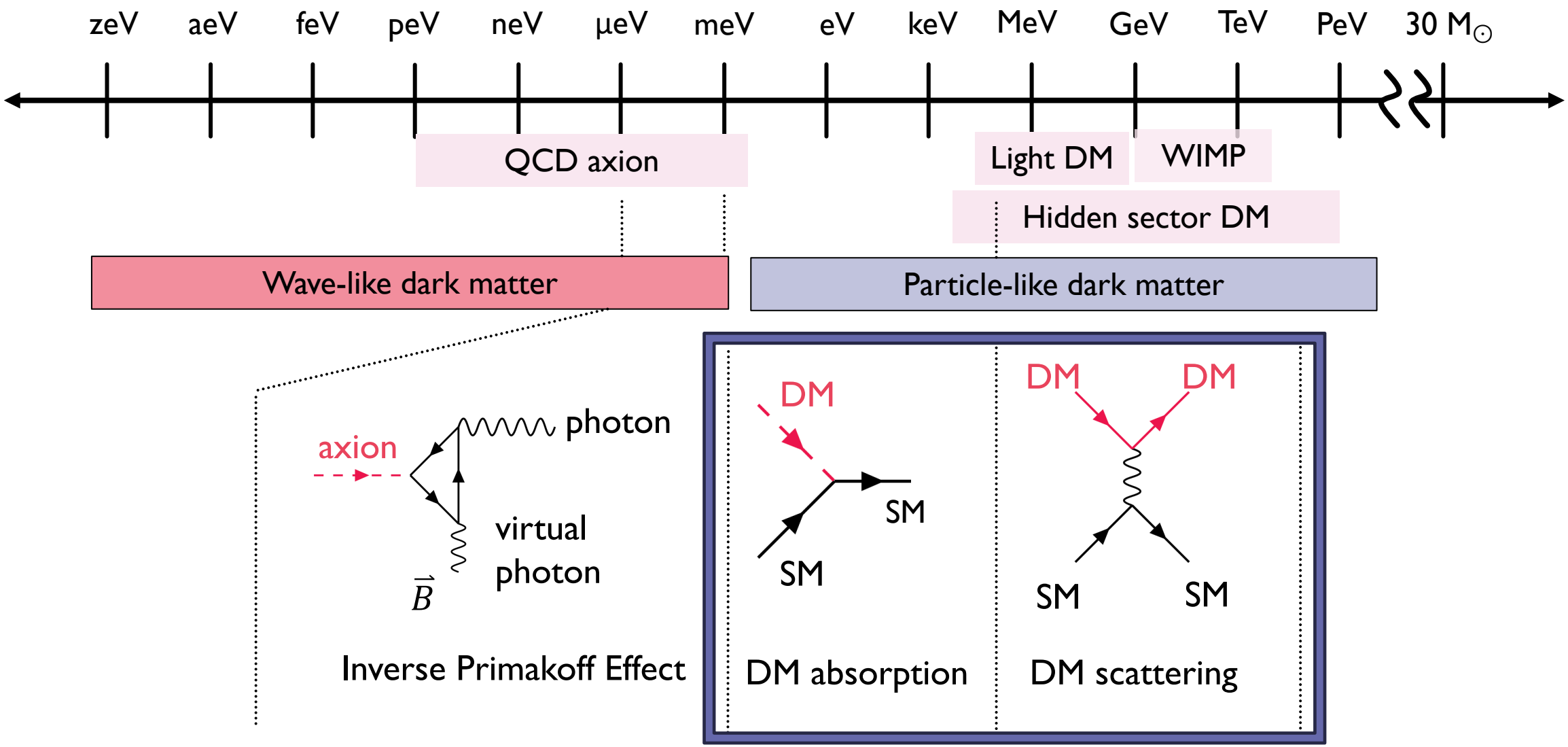


DM absorption

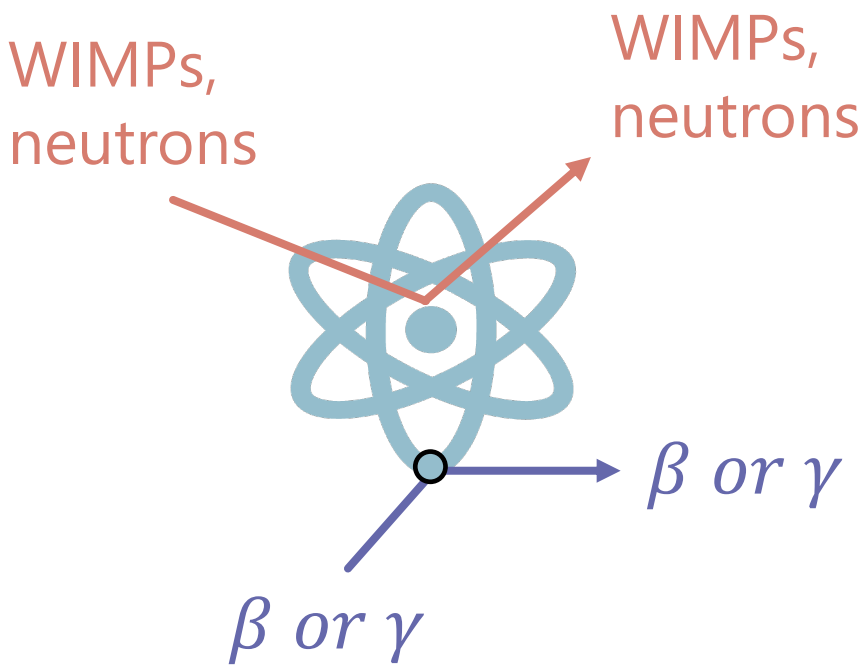


DM scattering





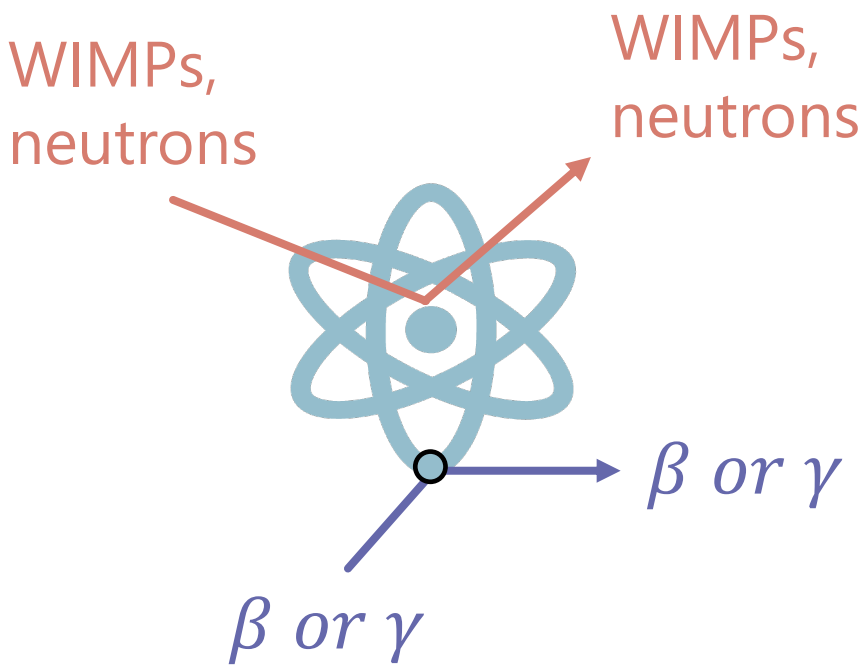
DARK MATTER – NUCLEUS SCATTERING



DM particle (mass: GeV-TeV) scatters elastically of nucleus causing a nuclear recoil

- Rare events (< 0.0001 evt/kg/day)
- Low energy (~ keV scattering)

DARK MATTER – NUCLEUS SCATTERING



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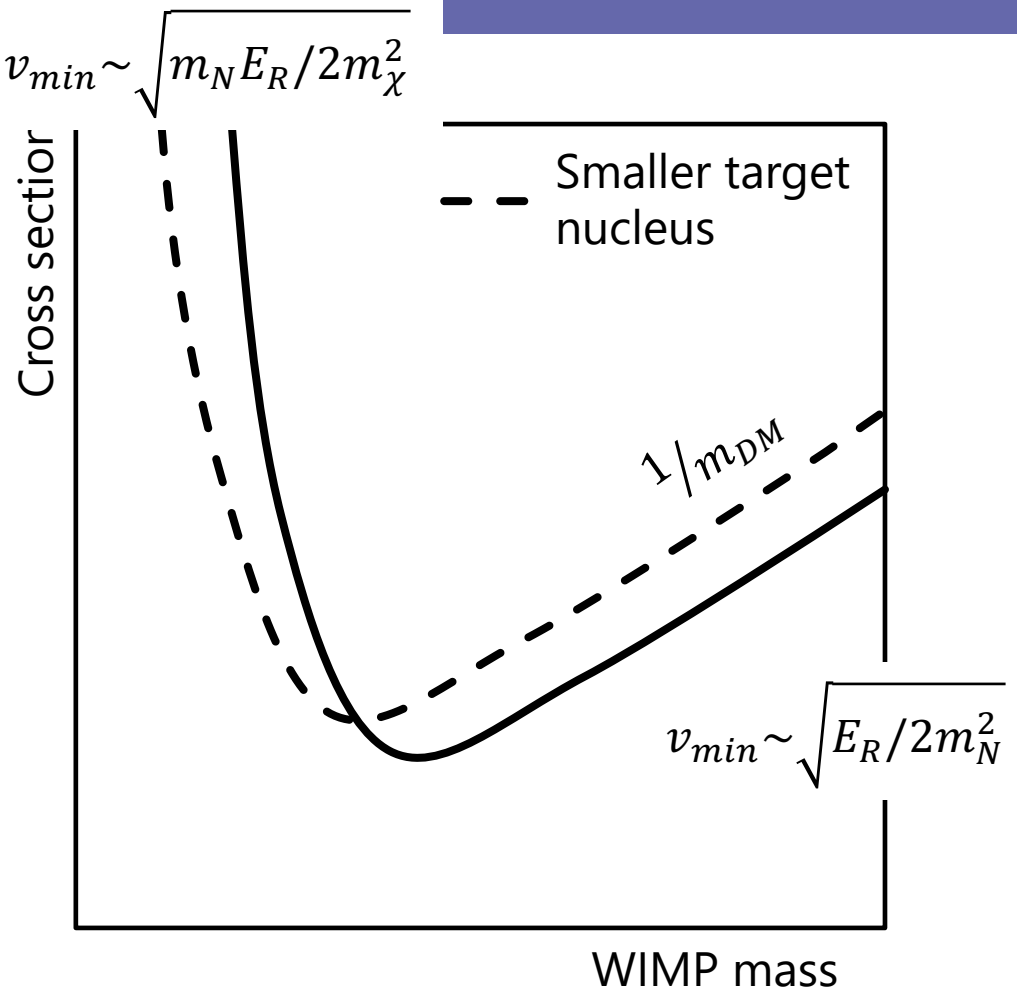
We need to:

- Reduce backgrounds
- Achieve low energy thresholds
- Maximise exposure

DARK MATTER – NUCLEUS SCATTERING



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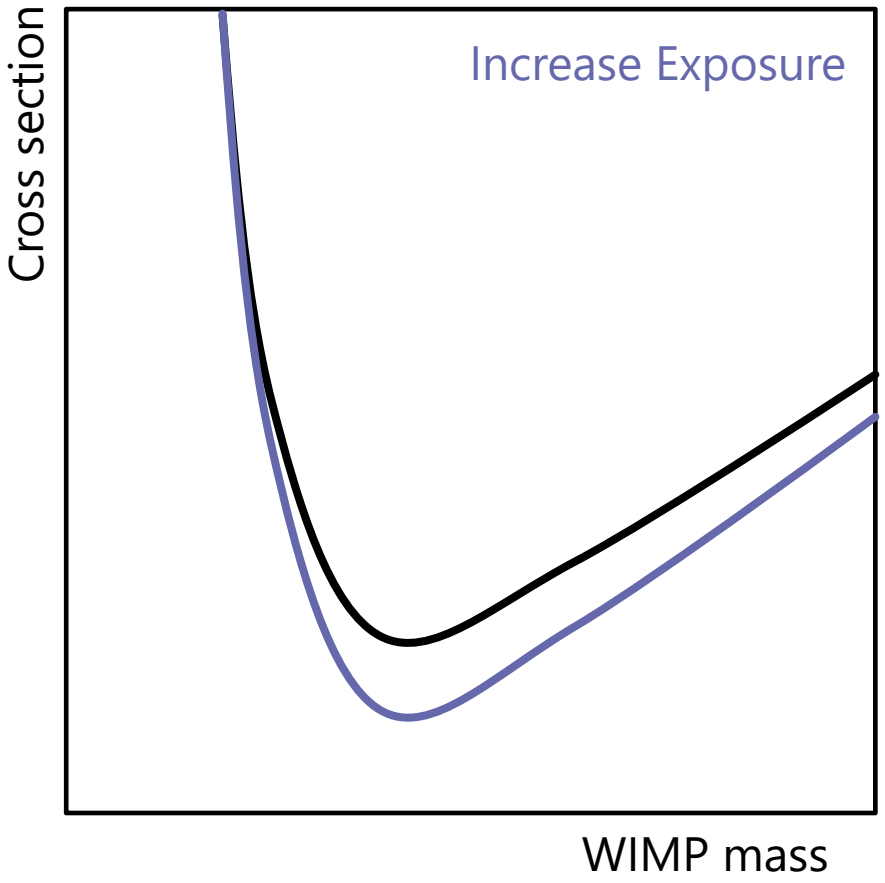

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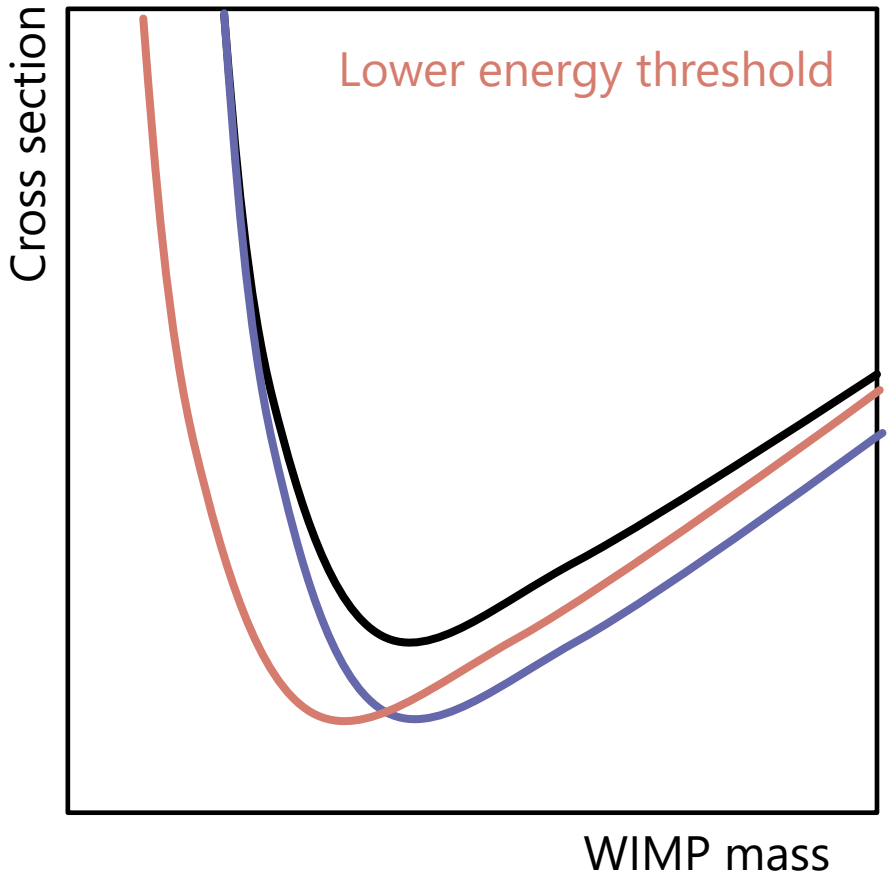

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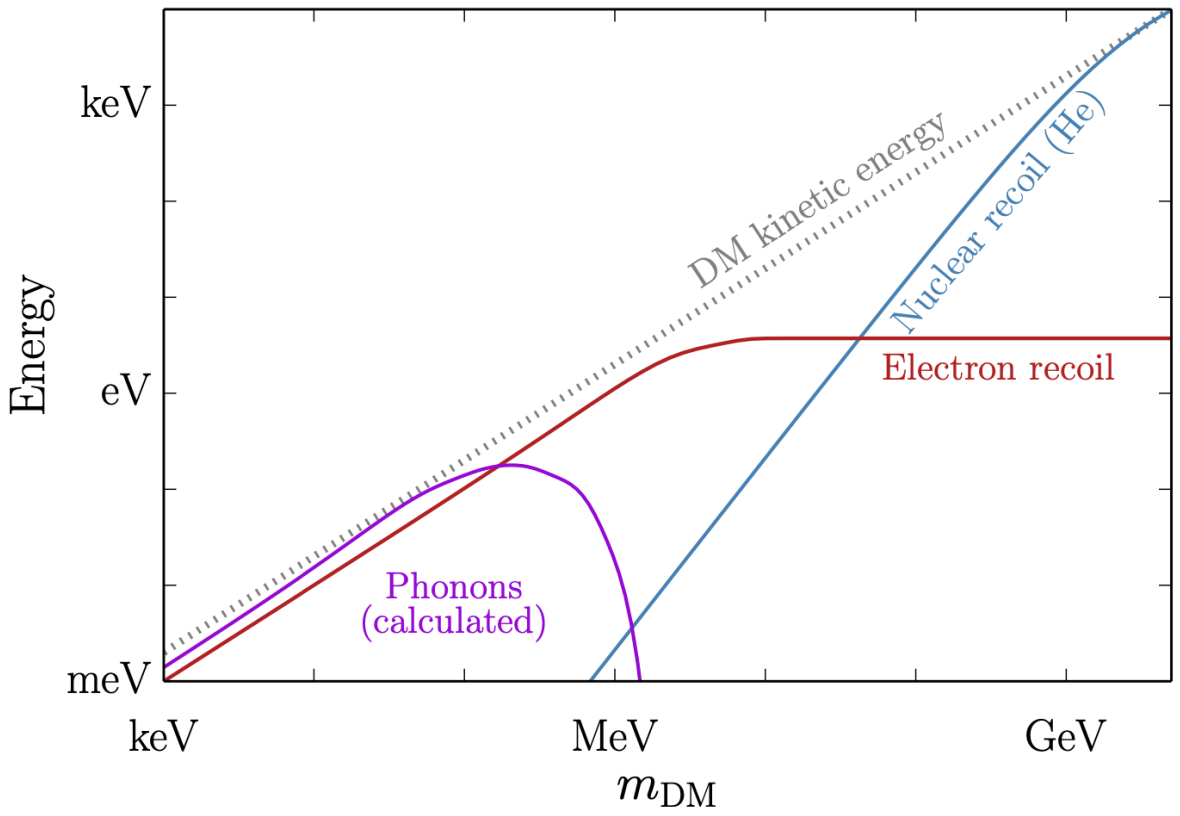
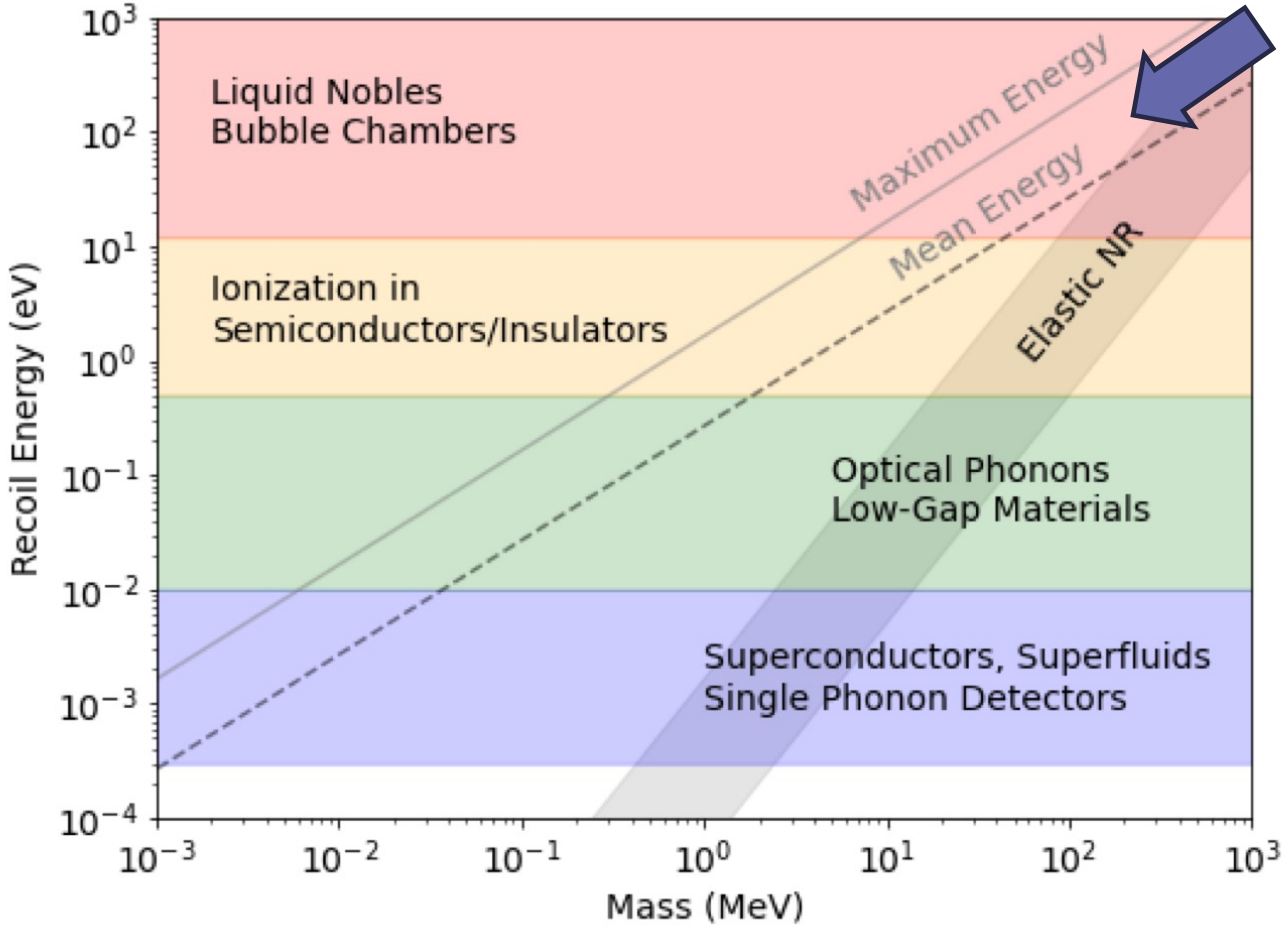
PUSHING TO LOWER ENERGIES



$$DM\ kinetic\ energy = \frac{1}{2} m_\chi v$$

TASI lectures on DM (Tongyan Lin) https://arxiv.org/pdf/1904.07915.pdf

PUSHING TO LOWER ENERGIES



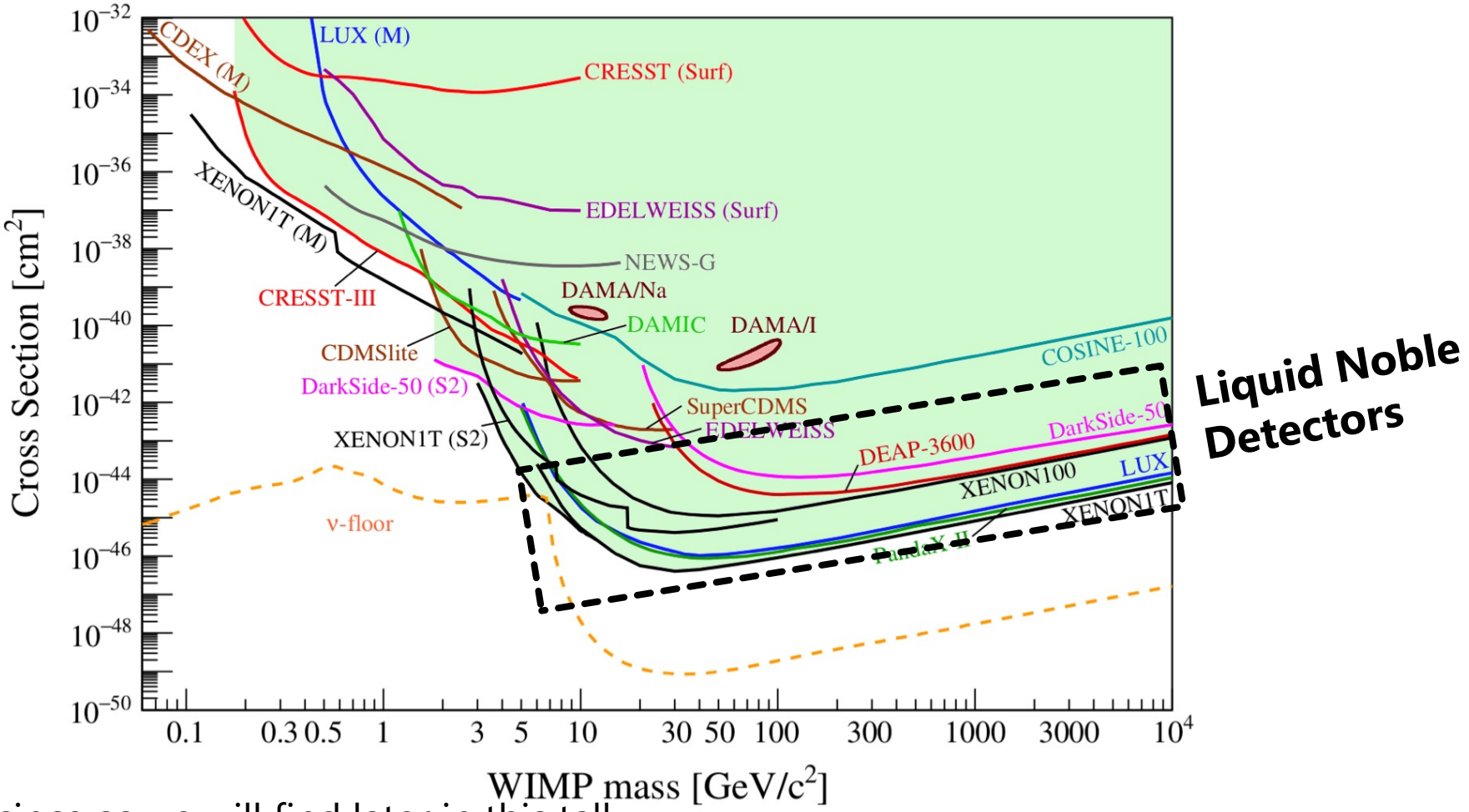
https://arxiv.org/pdf/2203.08297.pdf

Inelastic interactions:

- DM – electron scattering
- DM – nucleus scattering with Migdal
- DM scattering with collective modes

APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf

WHERE ARE WE AT?



*almost – a few updates since as we will find later in this talk

APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf

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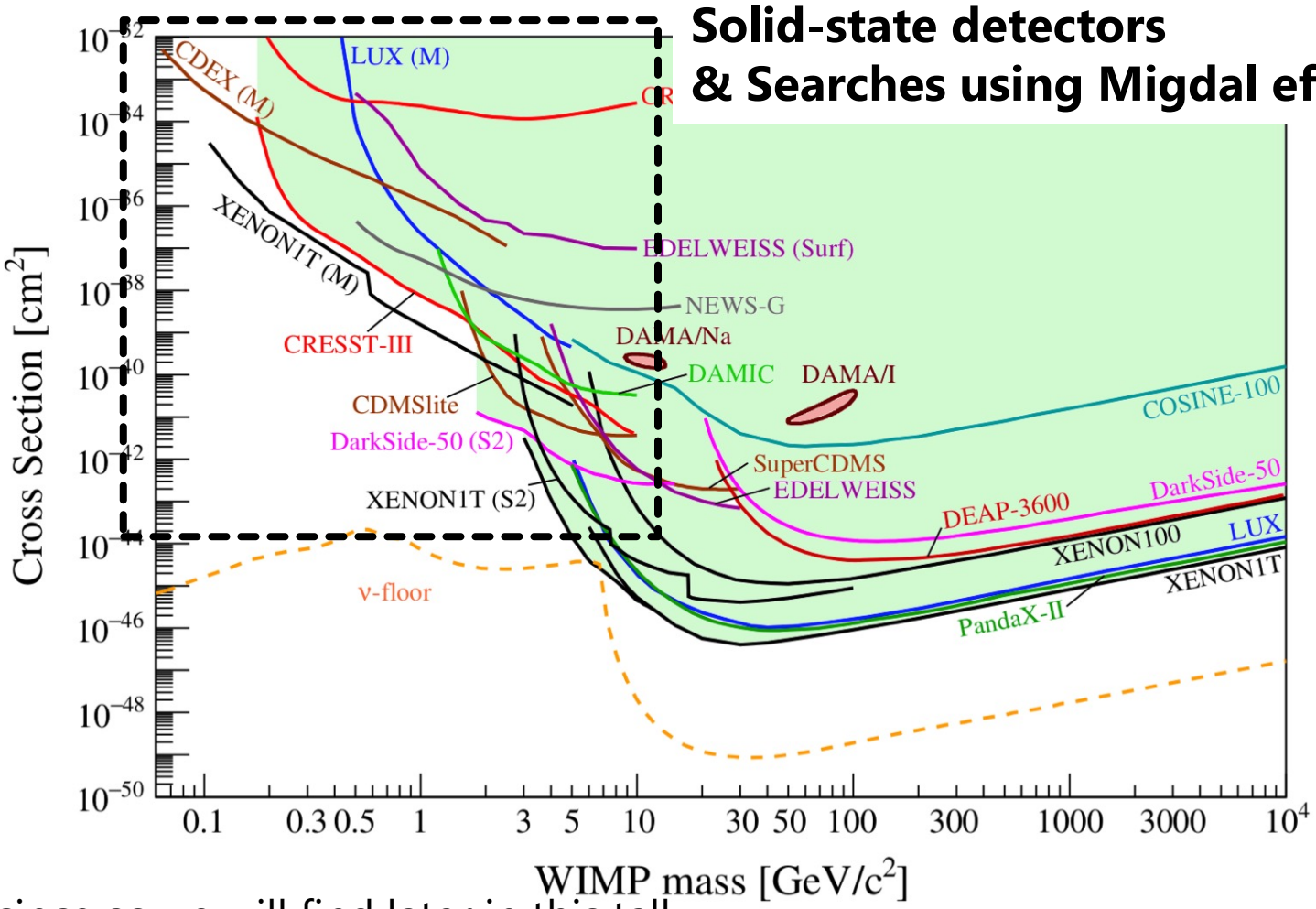

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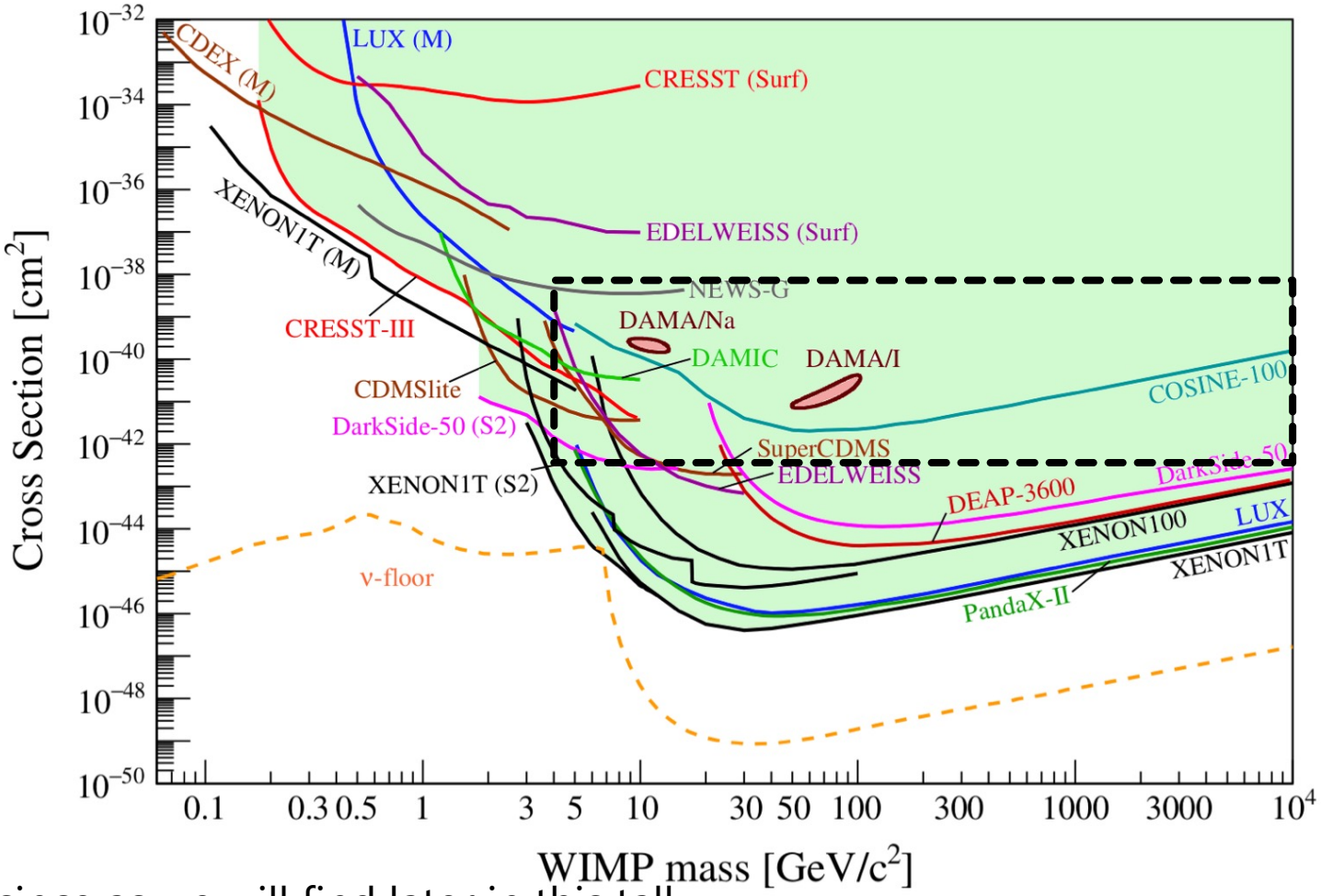
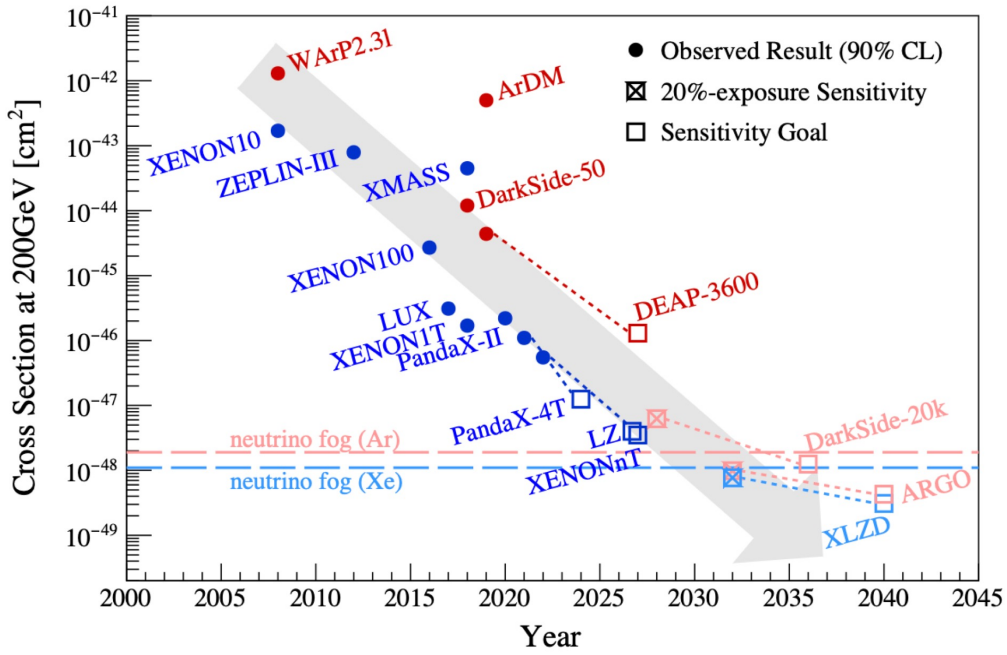


NaI efforts

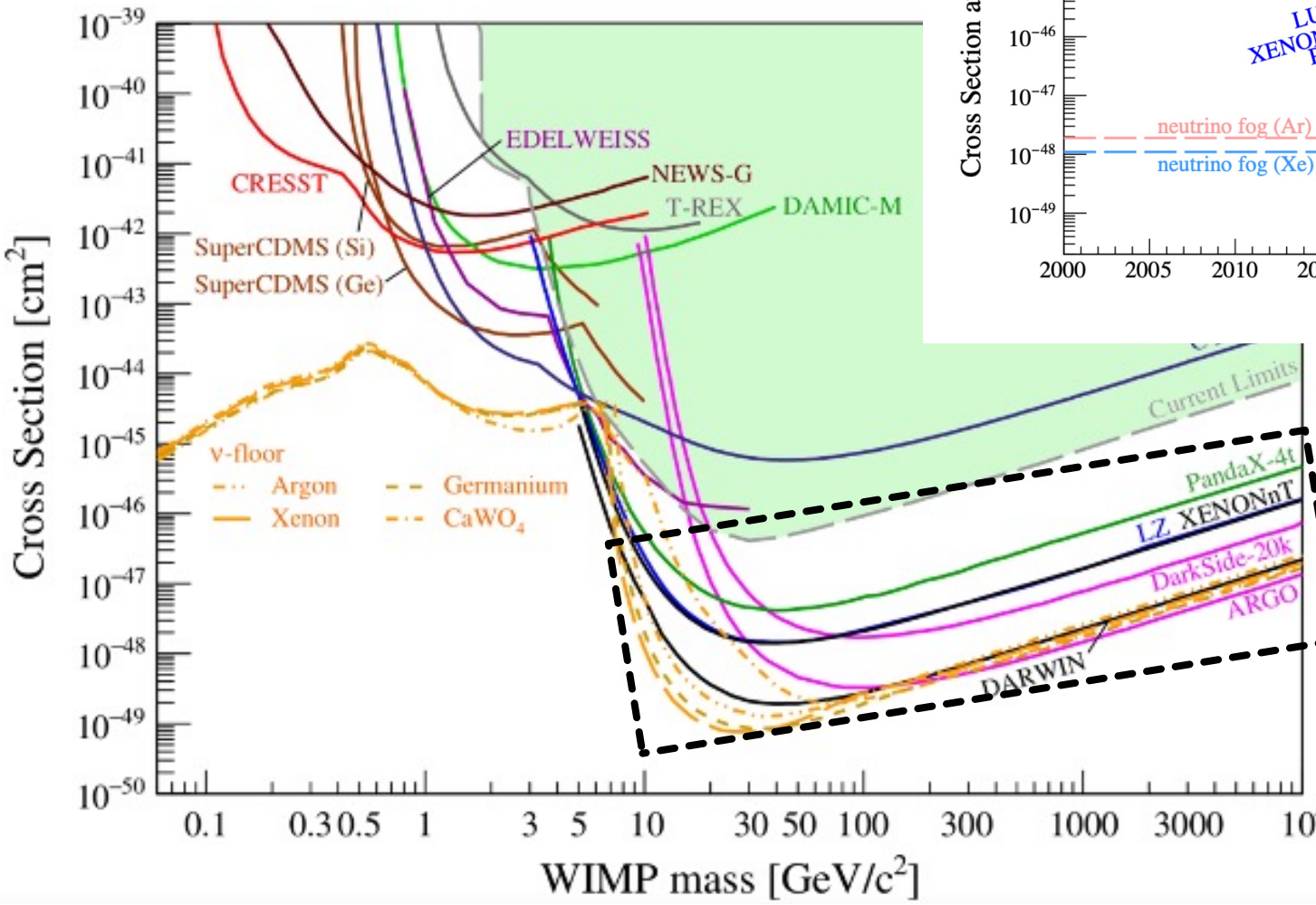
*almost – a few updates since as we will find later in this talk

APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf

WHERE ARE WE GOING?



Shengchao Li, SNOWMASS CF1 Convener's Report



Liquid Noble Detectors

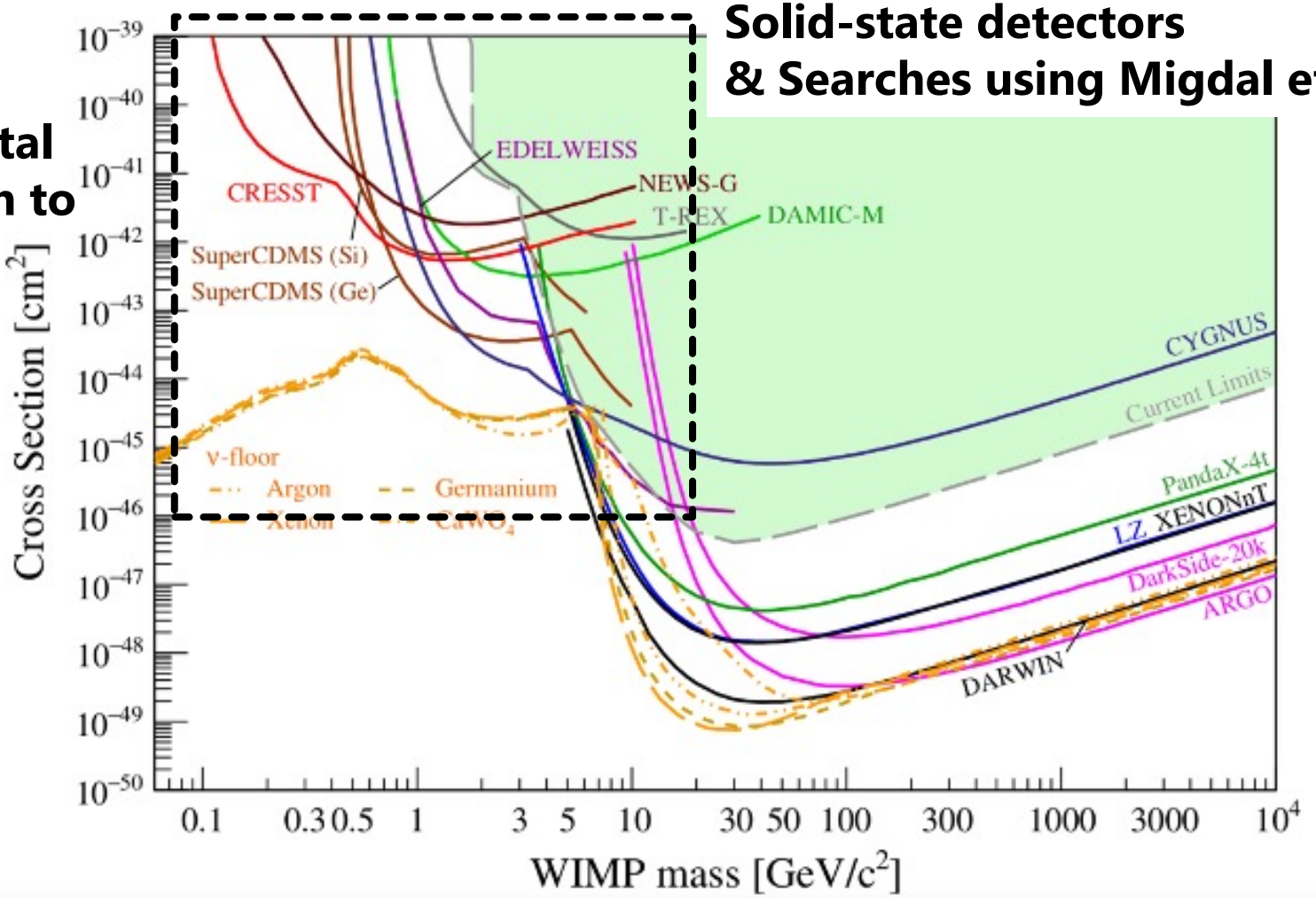
Roadmap towards the neutrino fog

APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf

WHERE ARE WE GOING?

Diverse experimental approaches to push to lower energies

Solid-state detectors & Searches using Migdal effect

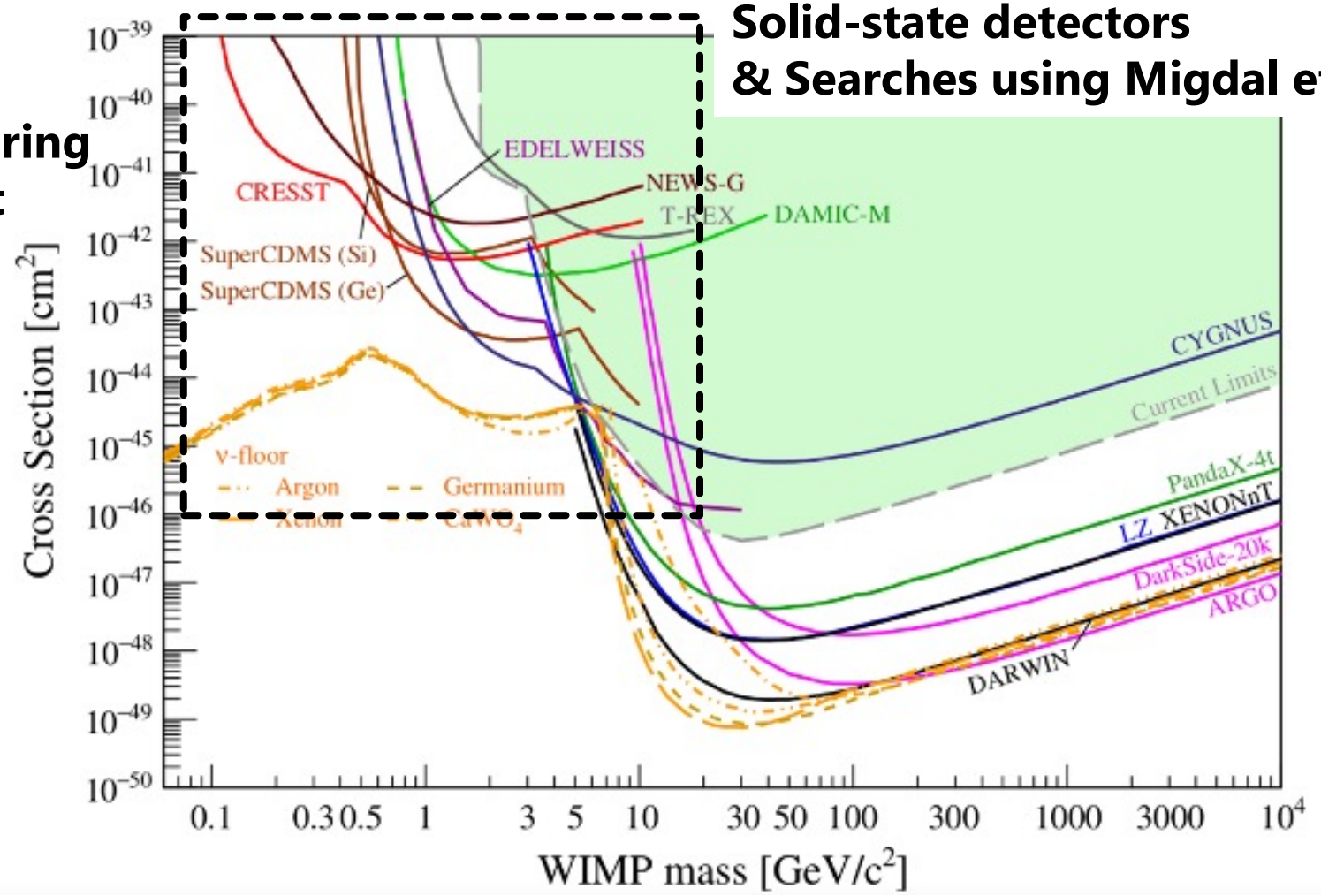


APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf

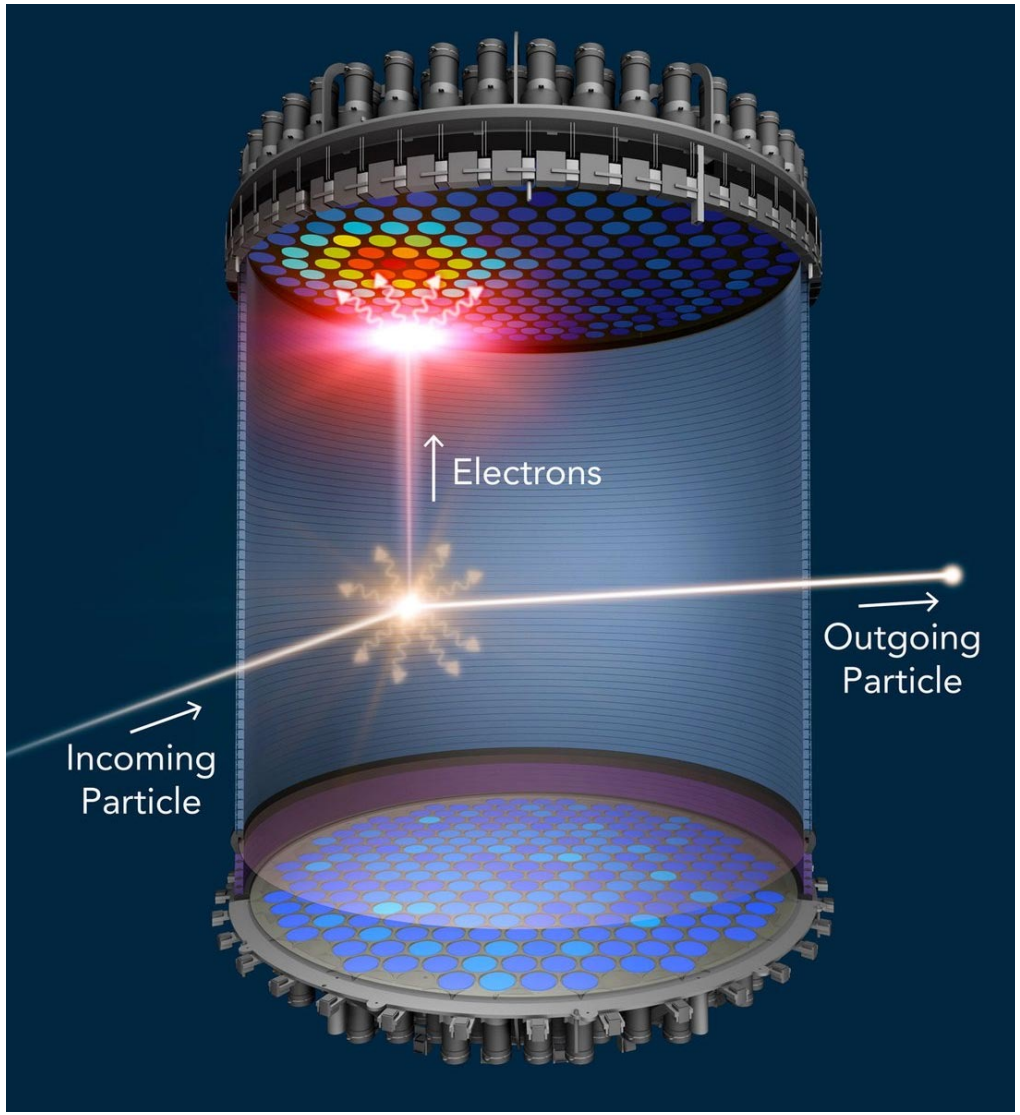
WHERE ARE WE GOING?

Calibrating/measuring the MIGDAL effect

Solid-state detectors & Searches using Migdal effect



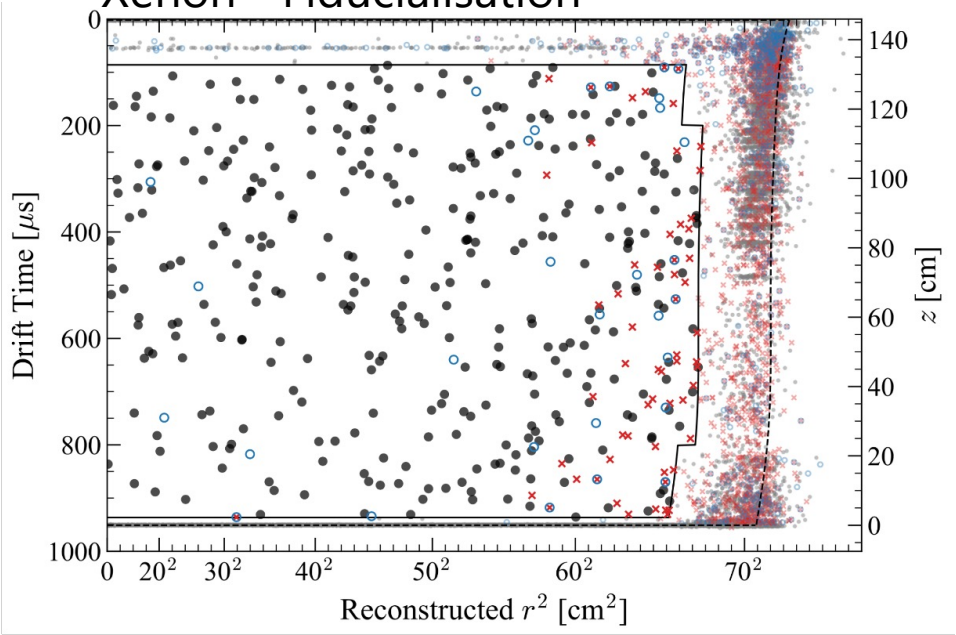
LIQUID NOBLE DETECTORS



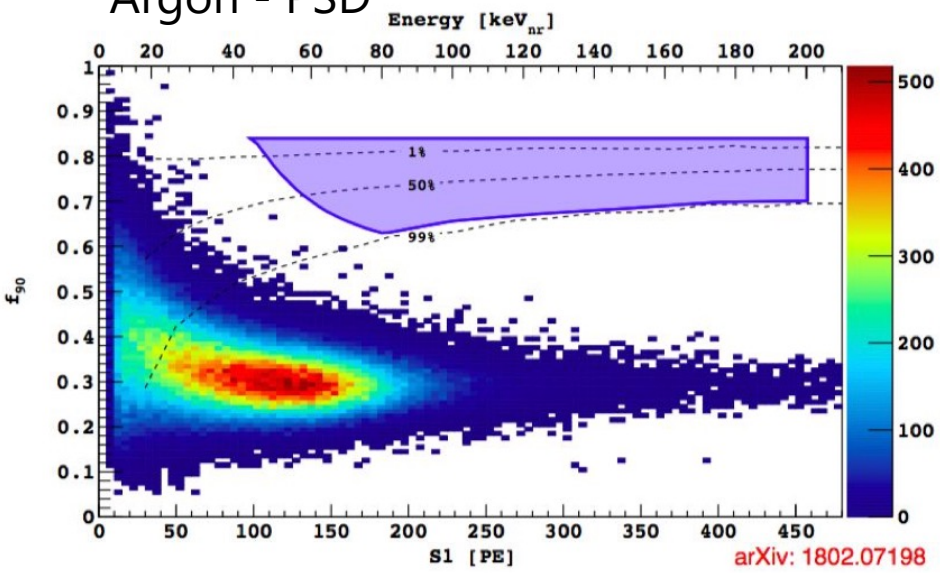
- Noble Liquids: Xe, Ar
- Good scintillators and easily ionized
- Scintillation signal & electroluminescence from ionization charge (in TPC configuration)
- Large target volume, fiducialisation possible
- Event-by-event discrimination by S2/S1 ratio (Xe) or pulse-shape (Ar)

LIQUID NOBLE DETECTORS

Xenon - Fiducialisation



Argon - PSD



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Xenon detectors

PandaX-4t

- 3.7 tonnes of Xe (active volume)
- 368 PMTs
- Status: running

XENONnT

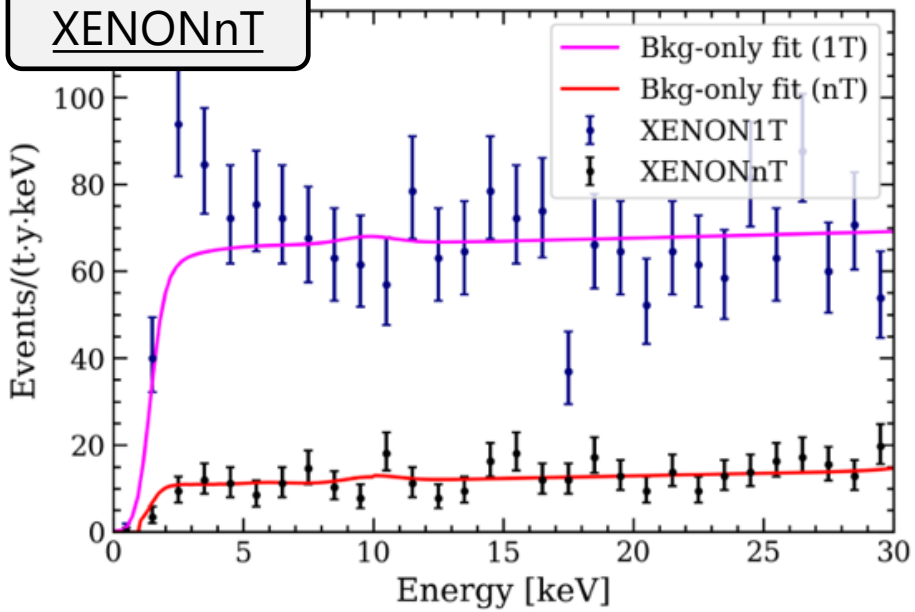
- 5.9 tonnes of Xe (active volume)
- 494 PMTs
- Status: running

LZ

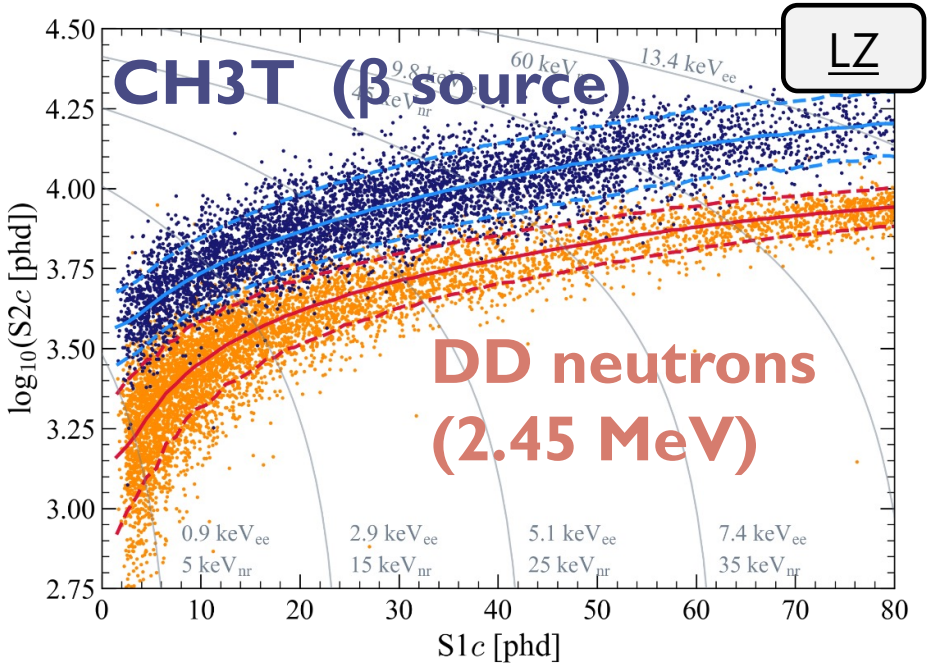
- 7 tonnes of Xe (active volume)
- 494 PMTs
- Status: running

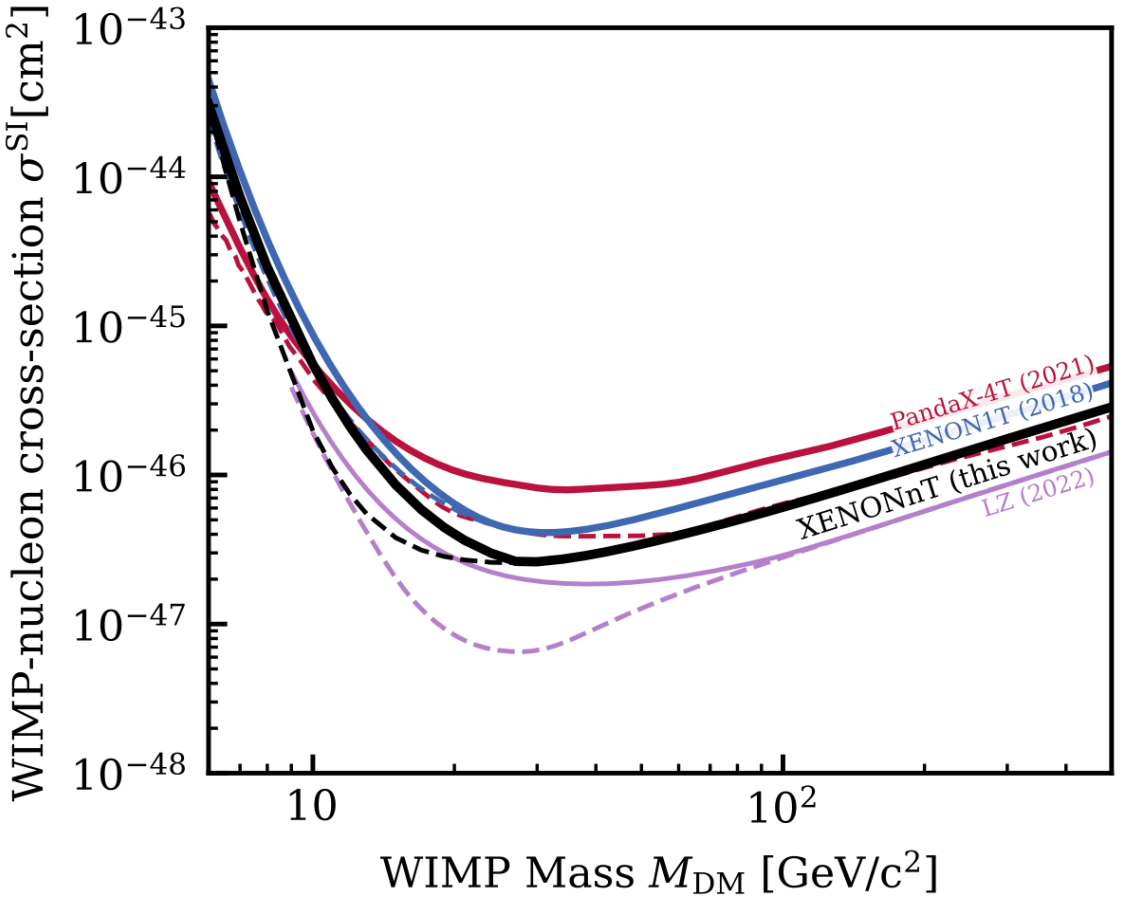
Xenon detectors

XENONnT



LZ





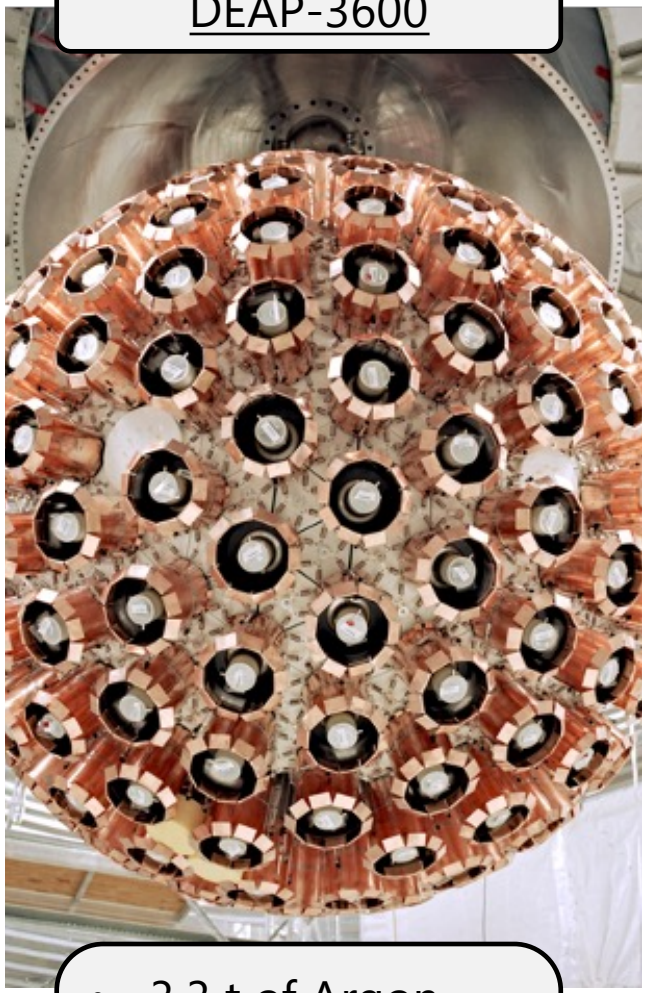
PandaX-4T: Phys. Rev. Lett. **127**, 261802
LZ: Phys. Rev. Lett. **131**, 041002 (2023)
XENONnT: Phys. Rev. Lett. **131**, 041003 (2023)

NEXT GENERATION

- Consortium formed by **X**ENONnT, **L**UX-**Z**EPLIN and **D**ARWIN
- MoU signed in 2021
- 350+ members, 60+ institutions
- 60-80t detector
- Search for WIMP dark matter down to the neutrino fog
- Definitive search in accessible parameter space

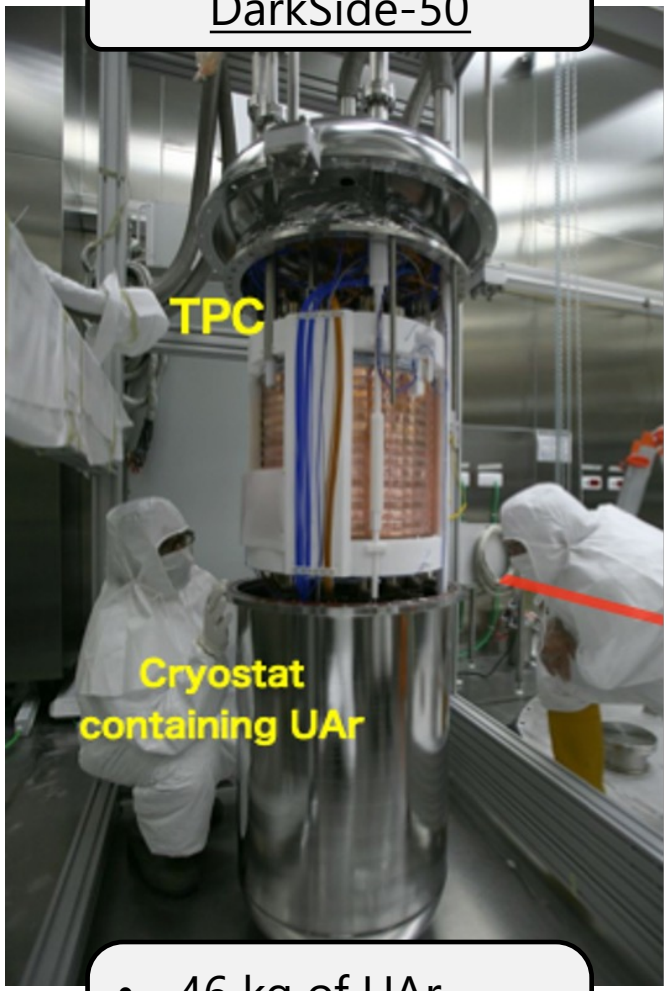
Argon detectors

DEAP-3600



- 3.3 t of Argon
- 255 PMTs & light guides
- Status: running

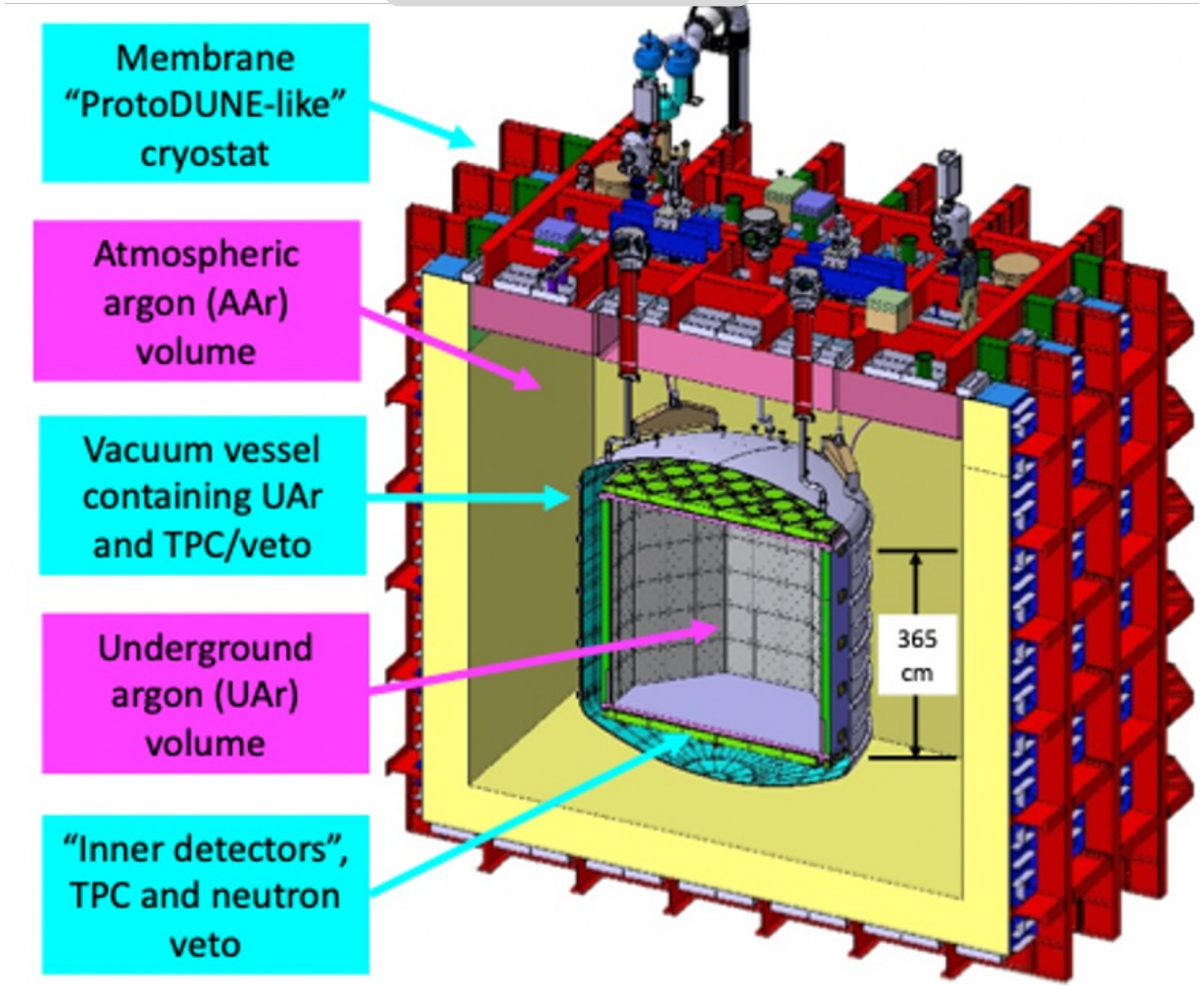
DarkSide-50



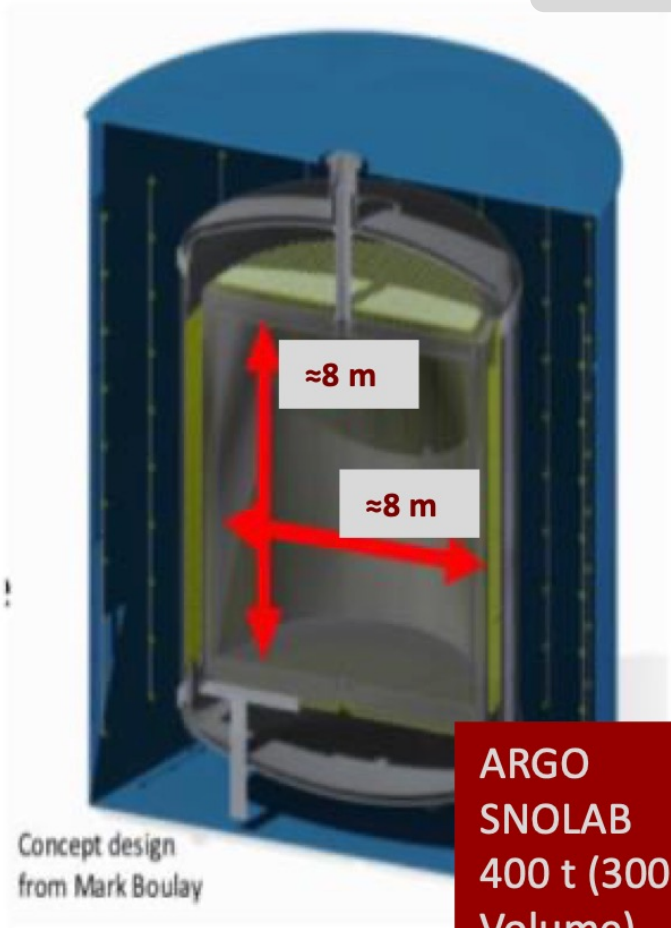
- 46 kg of UAr
- 38 PMTs
- Status: ended

NEXT GENERATION

DarkSide – 20k



ARGO

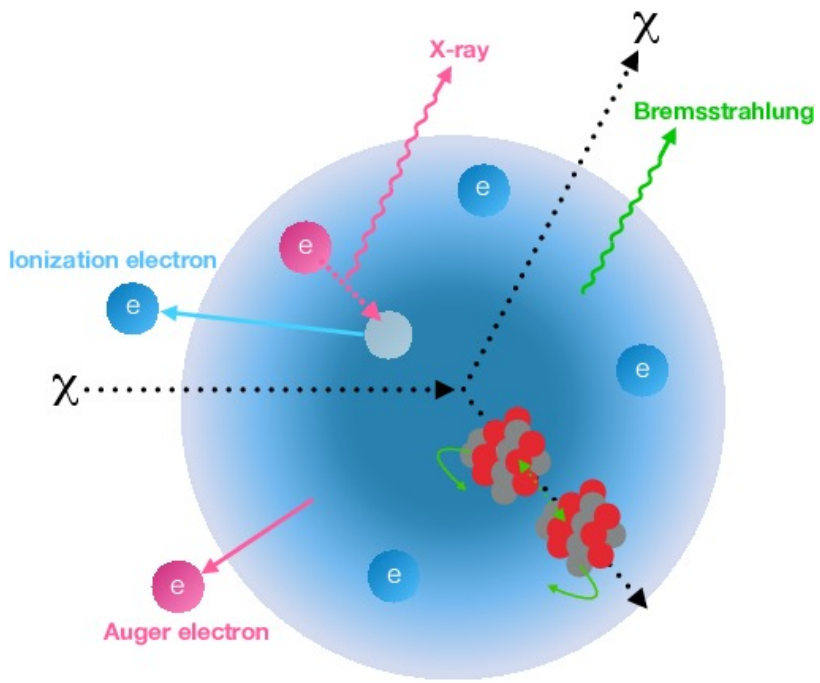


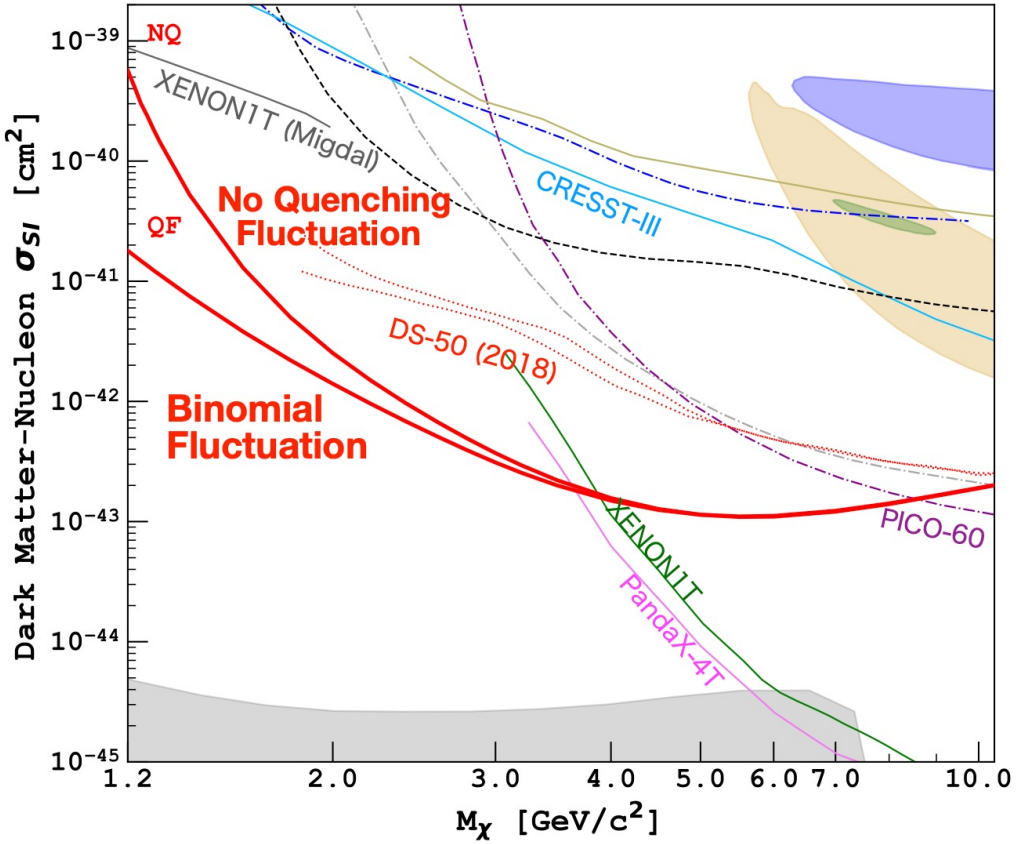
ARGO
SNOLAB
400 t (300 t Fiducial Volume)

Global Argon Dark Matter Community

PUSHING TO LOWER DM MASSES

Migdal effect & Bremsstrahlung[1]



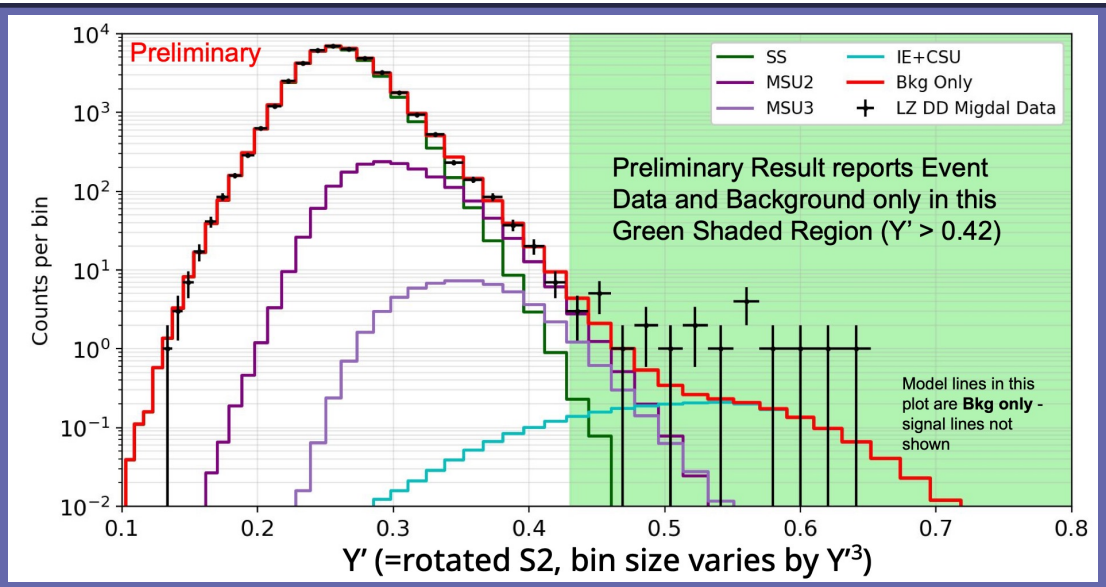


DarkSide 50 (PRL, 130, 101001 2023)

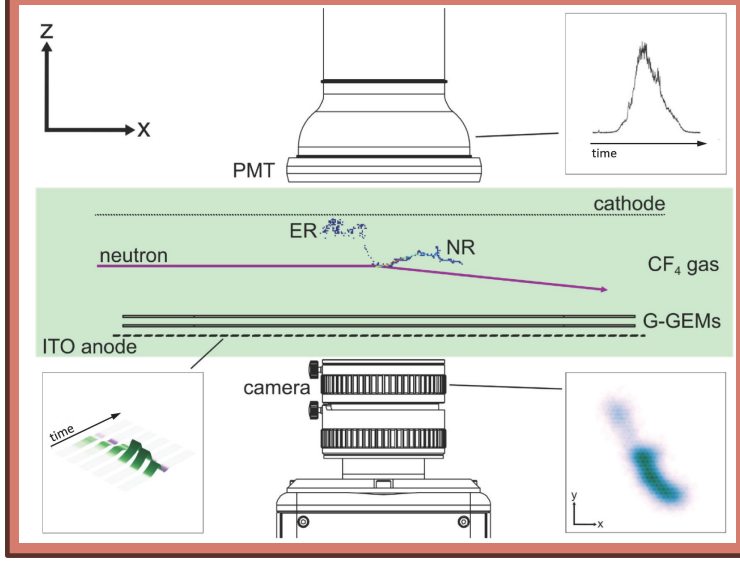
DarkSide-LowMass proposal, PRD 107 112006 (2023):
1 tonne scale optimised for low threshold

[1]XENON1T, https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.123.241803

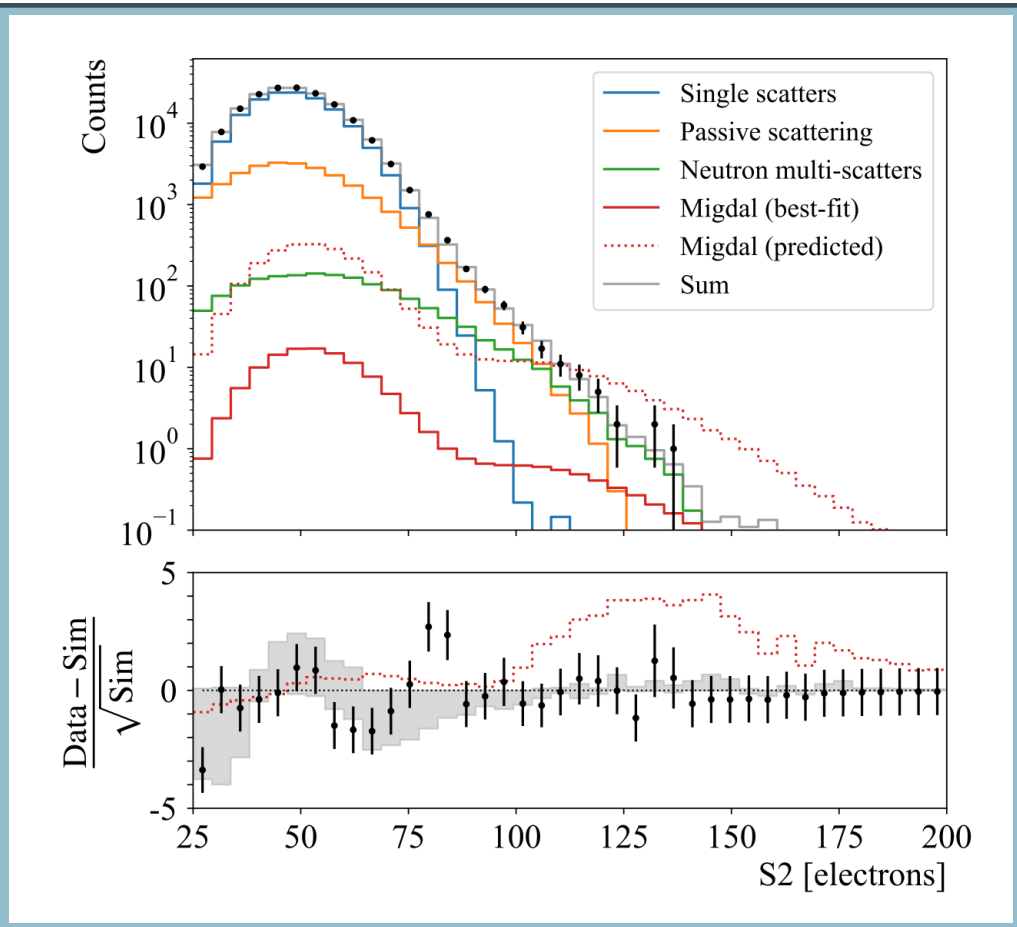
EFFORTS TOWARDS MEASURING THE MIGDAL EFFECT



Preliminary LZ study presented by Jeanne Bang, UCLA DM 2023



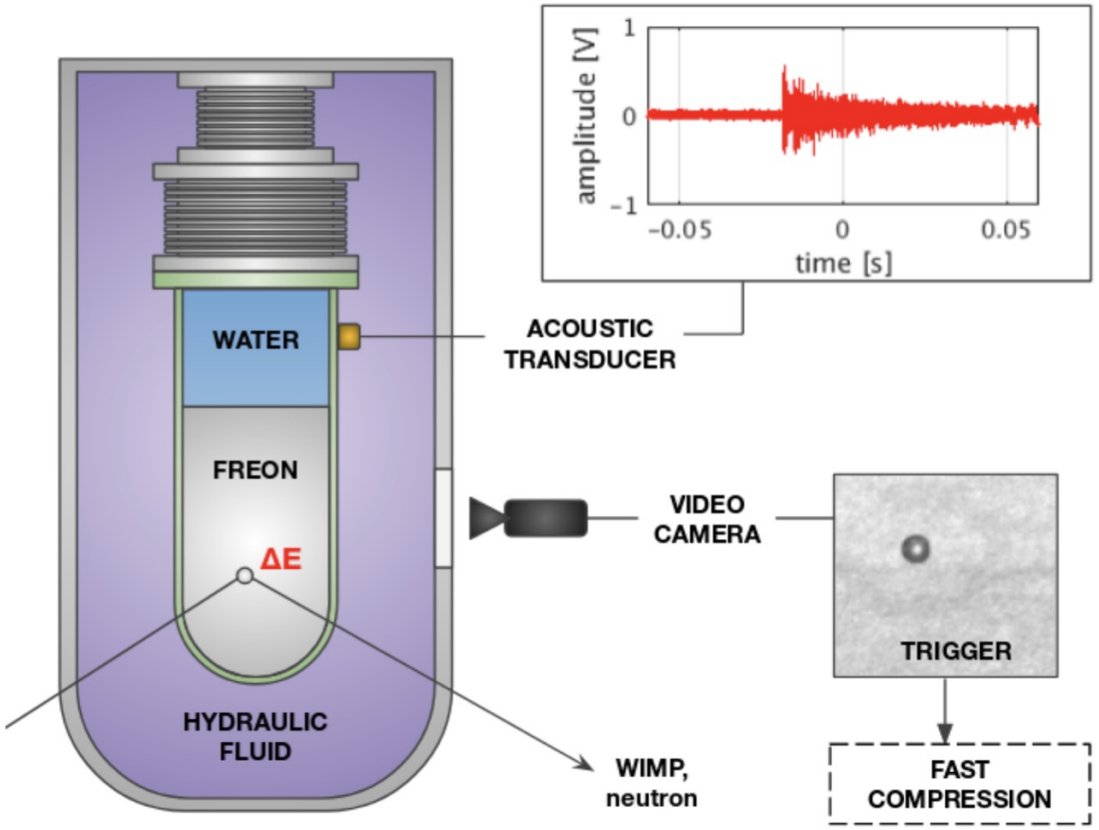
MIGDAL collaboration
H.M.Araújo et al. 2023 Astroparticle Physics, Volume 151,102853



Liquid Xenon with tagged neutron scatters (7keV)

Jingke Xu et al. 2023 arXiv:2307.12952

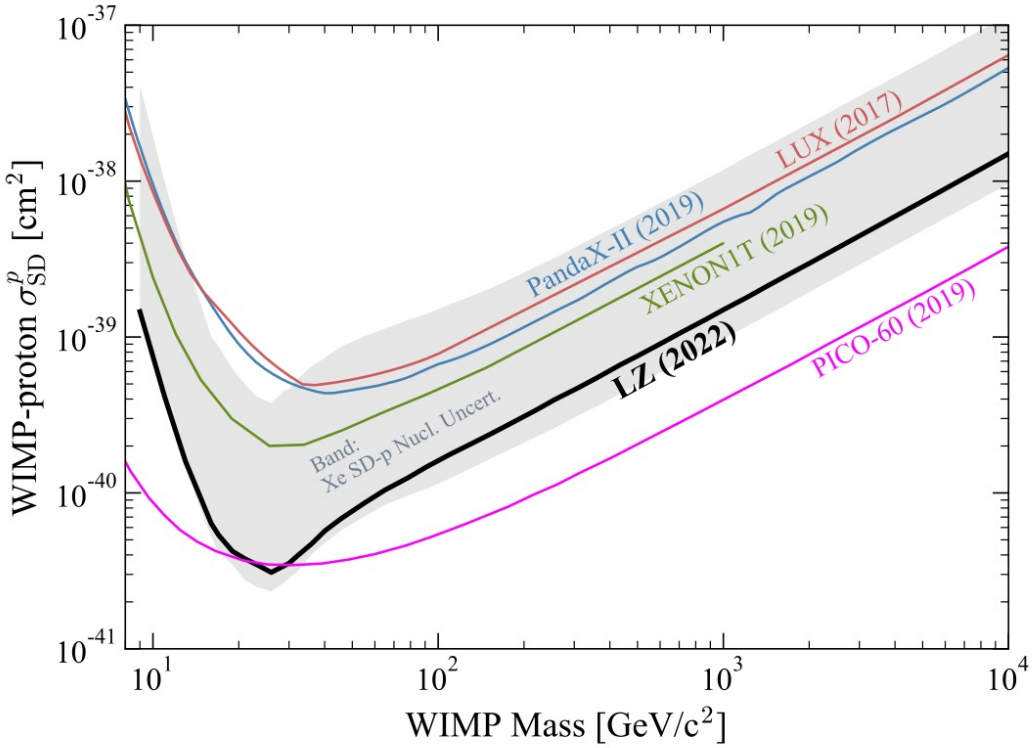
BUBBLE CHAMBERS



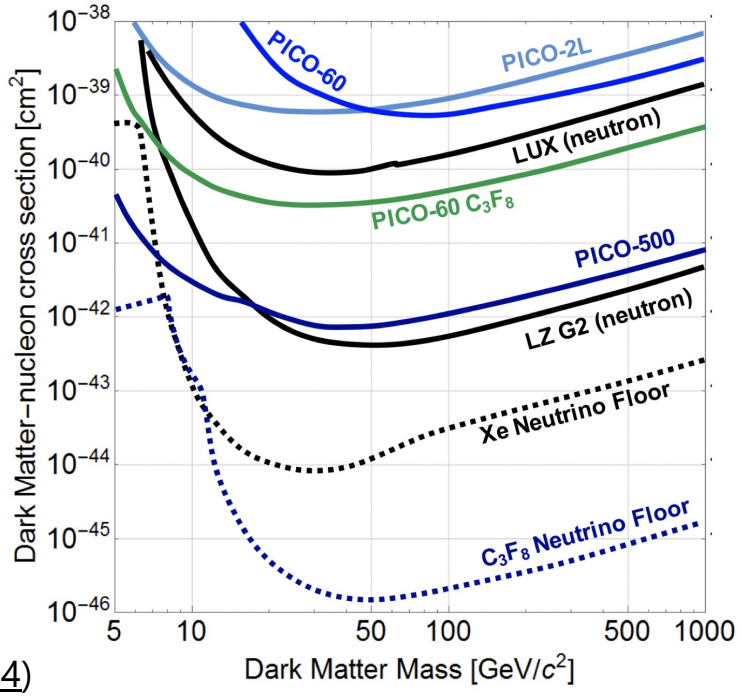
- Bubble chambers using superheated liquids (Freon-based).
- Threshold detector, ER background suppression by energy tuning
- 3D event reconstruction

Guillaume Giroux 2021 J. Phys.: Conf. Ser. 2156 012068

BUBBLE CHAMBERS



- Leading WIMP-proton spin-dependent limits with PICO-60
- Next generation: PICO-500

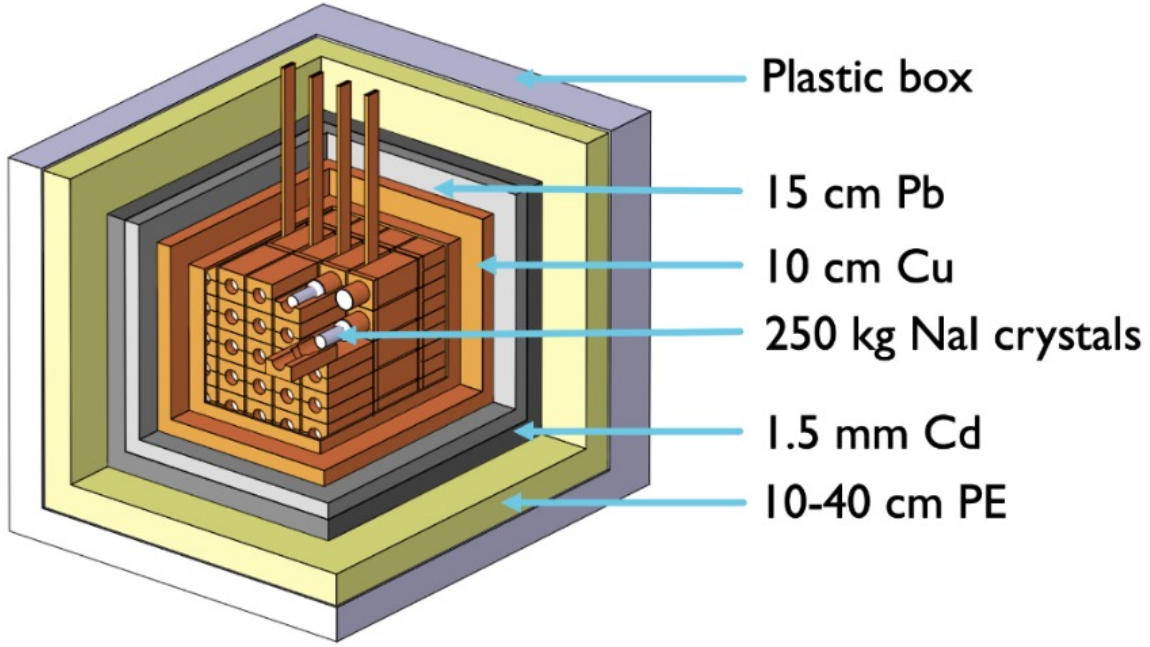


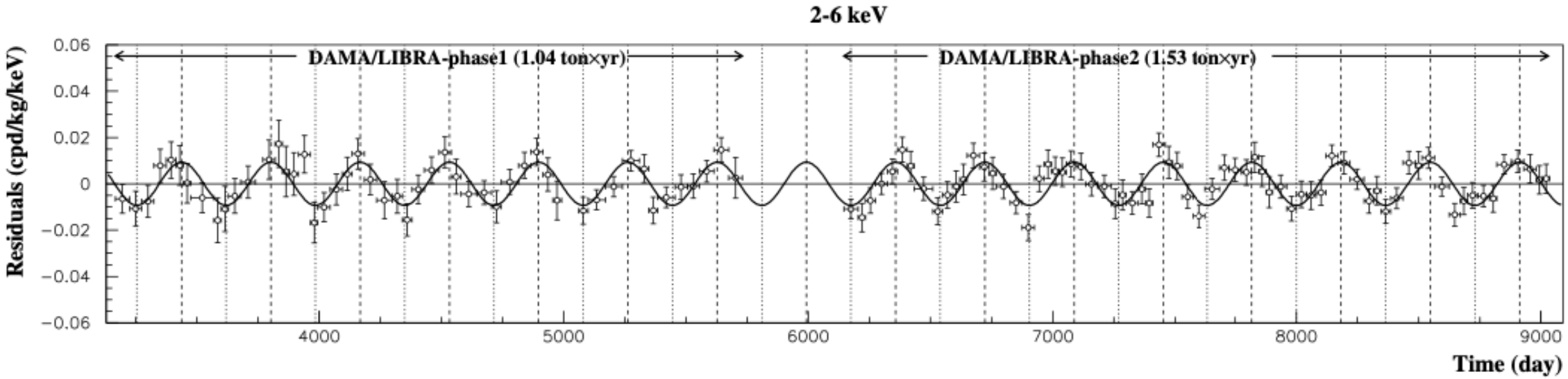
[1] First dark matter search result from the LZ Experiment (https://arxiv.org/abs/2207.03764)
[2] Guillaume Giroux 2021 J. Phys.: Conf. Ser. 2156 012068

DAMA/LIBRA

https://scipost.org/SciPostPhysProc.12.025

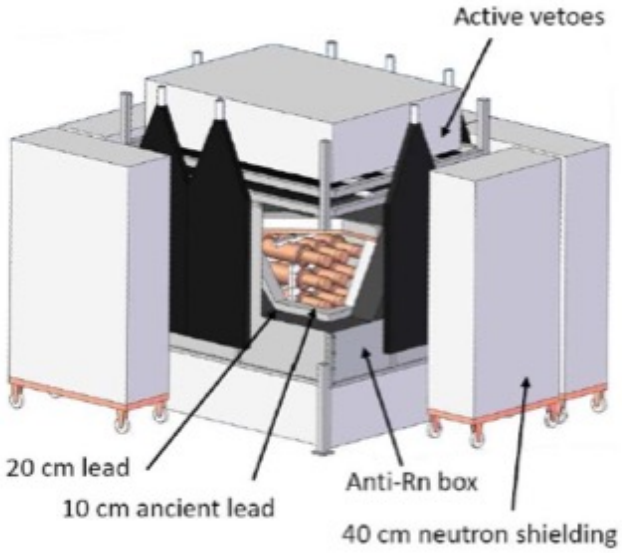
- Phase 2 setup (since 2011):
  - 250 kg high-purity NaI(Tl) crystals
- Total exposure: 2.86 ton x yr over 22 annual cycles
- Claiming 13.7 sigma





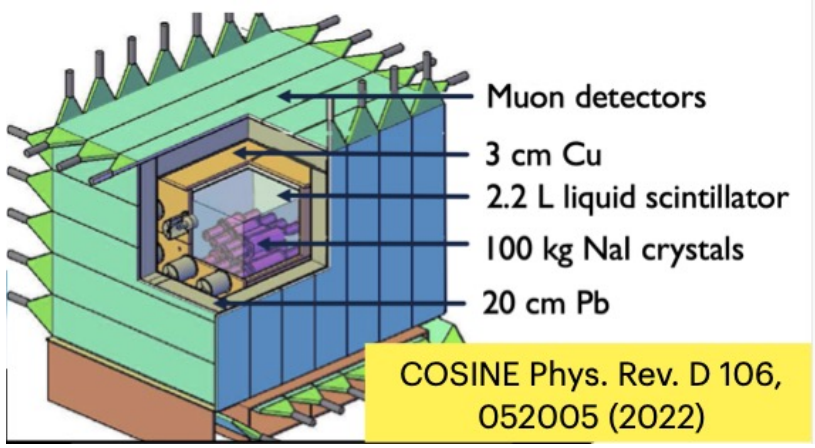
NaI experiments

ANAIS



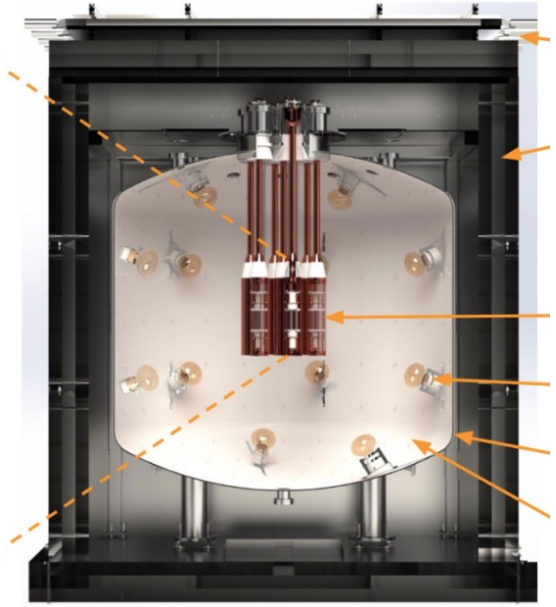
- 112.5 kg total
- Status: data taking since 2017, 3 years analysed
- Incompatible with DAMA at 2.5 σ

COSINE



- 106 kg total
- Liquid scintillator & muon veto
- Status: Upgrade & moving labs
- First results are consistent with DAMA and no modulation

SABRE

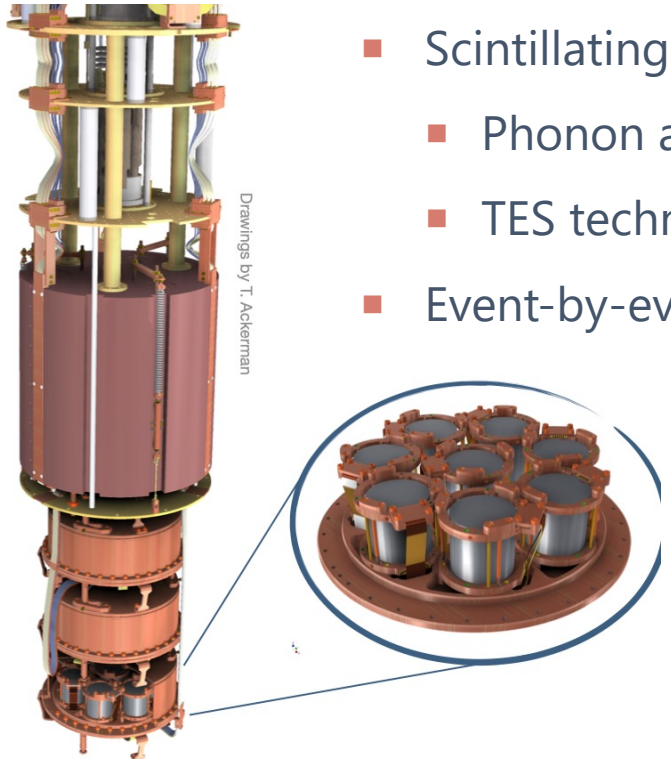


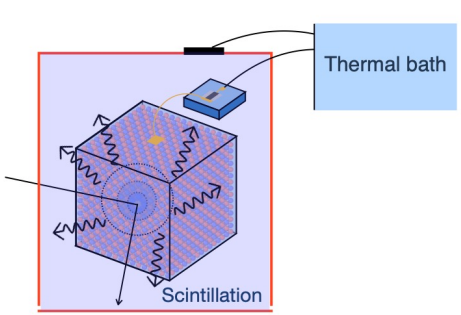
- North & South detectors with 35-50kg each
- Focus on ultra radio-pure crystals
- Status: In preparation

NaI experiments

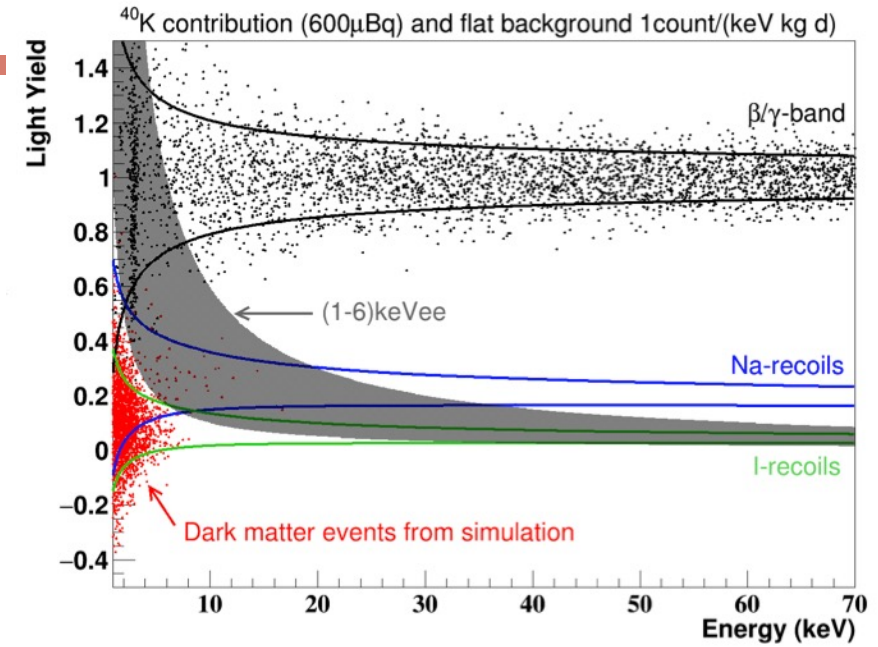
COSINUS

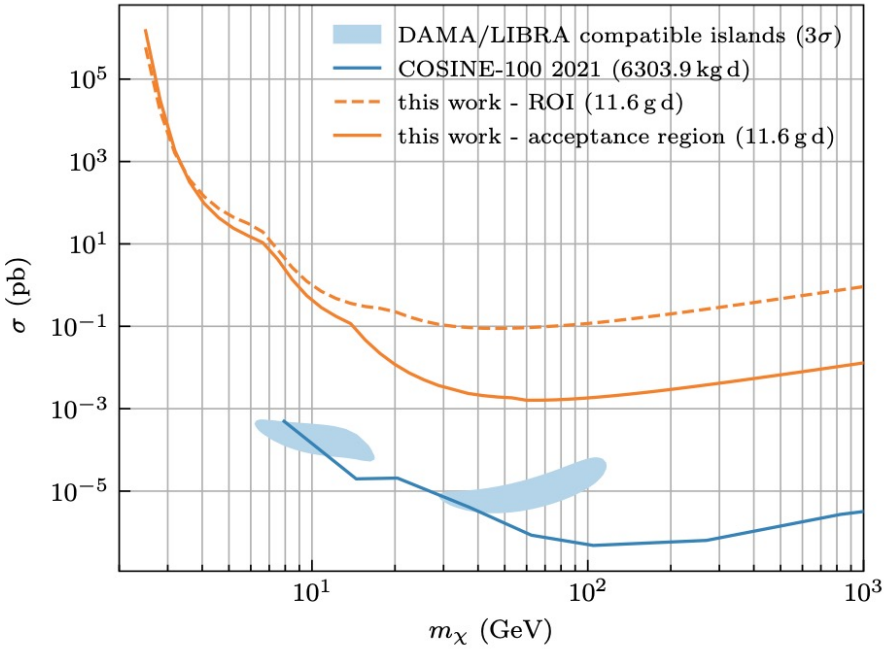
- Detector:
  - Scintillating cryogenic calorimeter:
    - Phonon and scintillation signal
    - TES technology from CESST
  - Event-by-event background discrimination





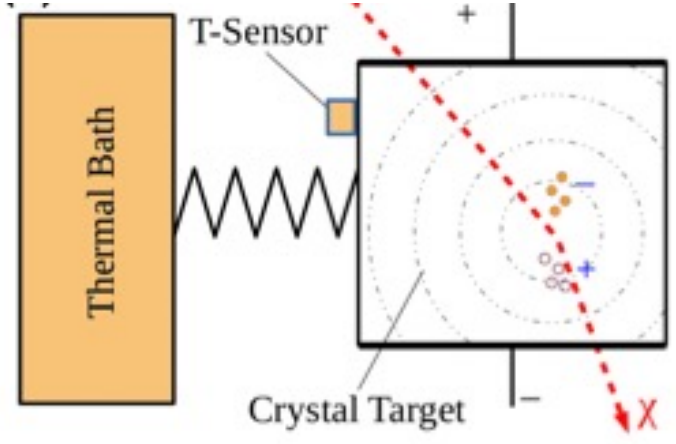
- Plan:
  - Data taking to start in 2024
  - 100 kg days in 2025

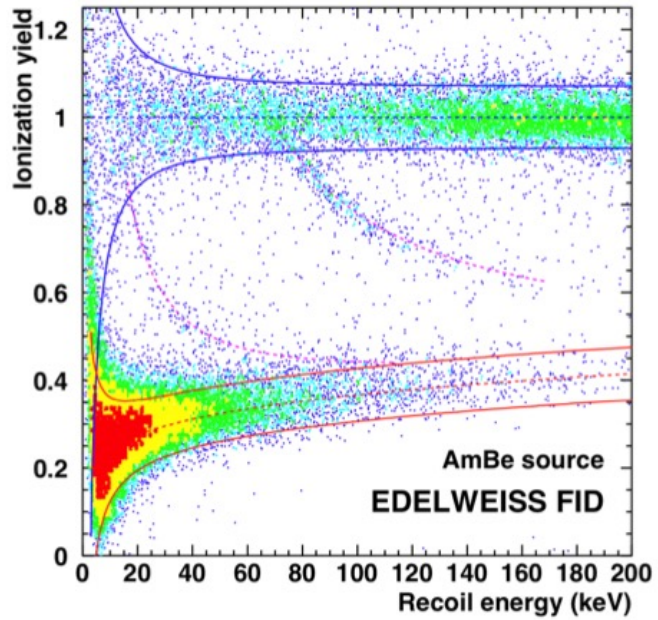




https://indico.cern.ch/event/1199289/contributions/5449514/attachments/2705060/4695810/COSINUS_TAUP23.pdf

CRYOGENIC BOLOMETERS

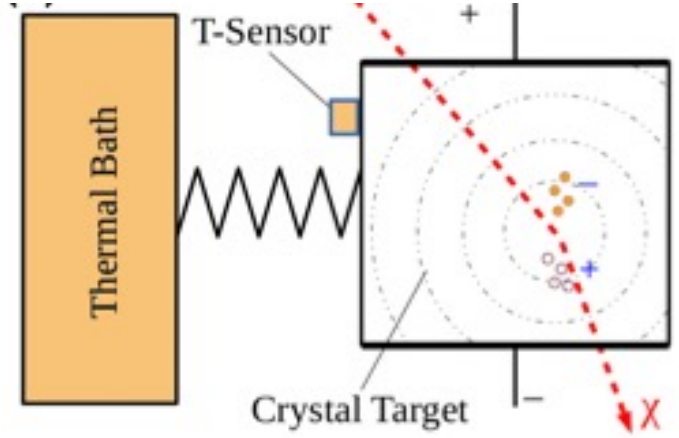


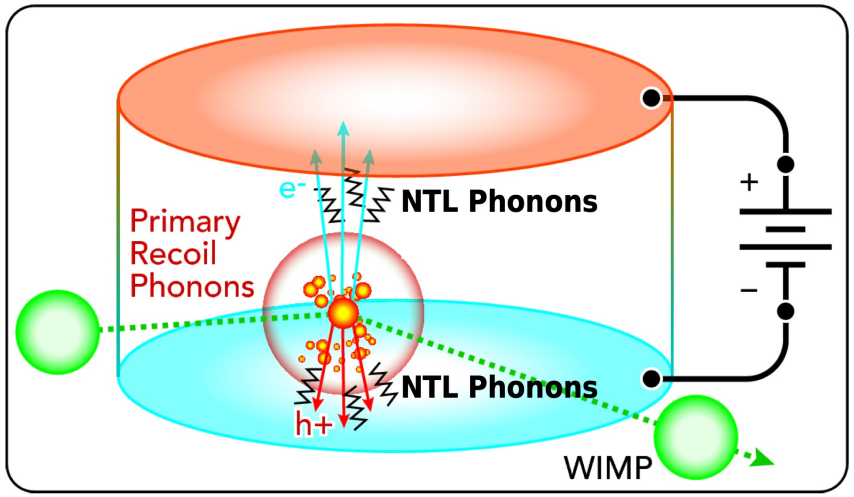


- Crystal targets (Ge, $CaWO_4$) operated < 50mK
- Phonon readout via NTD or transition edge sensors
- Simultaneous readout of ionization or scintillation signal allows background discrimination
- Excellent energy resolution

[1] APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf
[2] E. Armengaud *et al* 2017 *JINST* **12** P08010, https://arxiv.org/pdf/1706.01070.pdf

CRYOGENIC BOLOMETERS





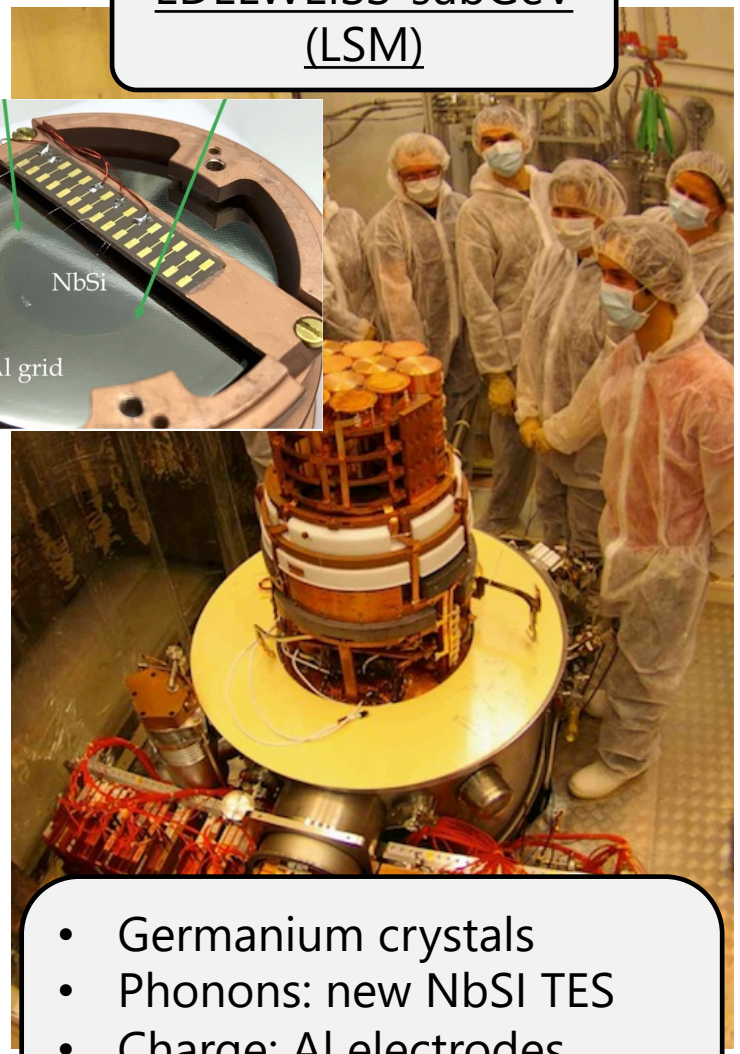
V_{bias} ~ 100 V

- Crystal targets (Ge, $CaWO_4$) operated < 50mK
- Phonon readout via NTD or transition edge sensors
- Simultaneous readout of ionization or scintillation signal allows background discrimination
- Excellent energy resolution
- Neganov-Trofimov-Luke effect allows lower thresholds

[1] APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf
[2] B Krosigk IDM 2018

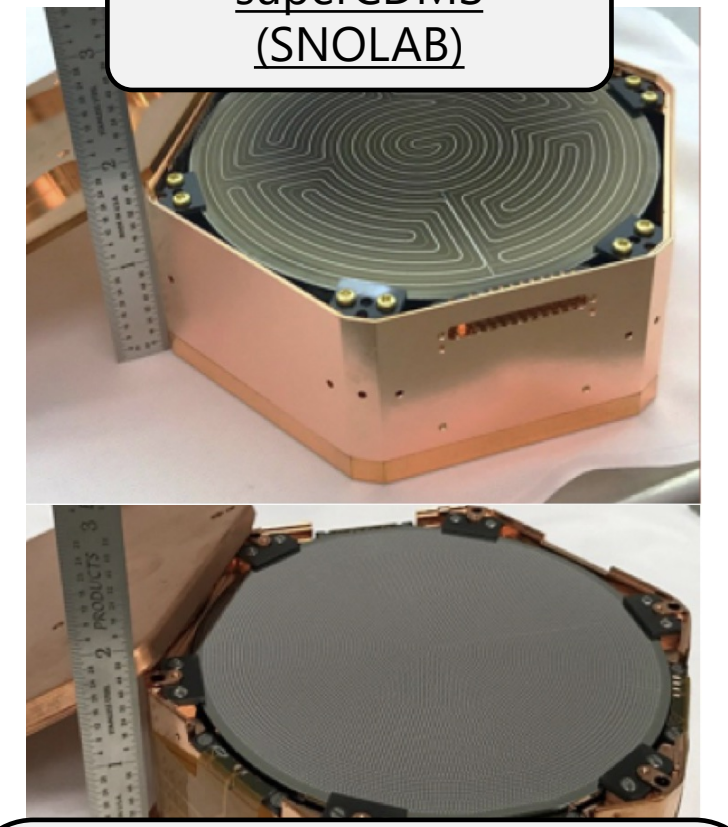
CRYOGENIC BOLOMETERS

EDELWEISS-subGeV (LSM)



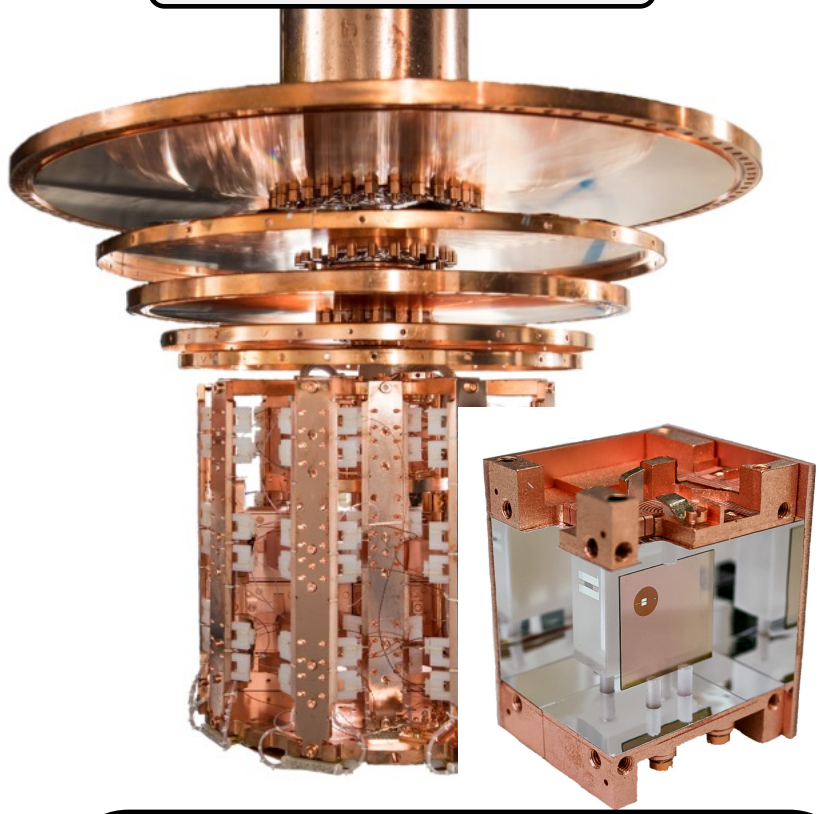
- Germanium crystals
- Phonons: new NbSI TES
- Charge: Al electrodes
- Status: running, R&D for CRYOSEL module

superCDMS (SNOLAB)



- Si and Ge crystals
- Phonons: QETES, Charge: interleaved electrodes
- Optimisation: low threshold or background discrimination
- Status: Construction ongoing

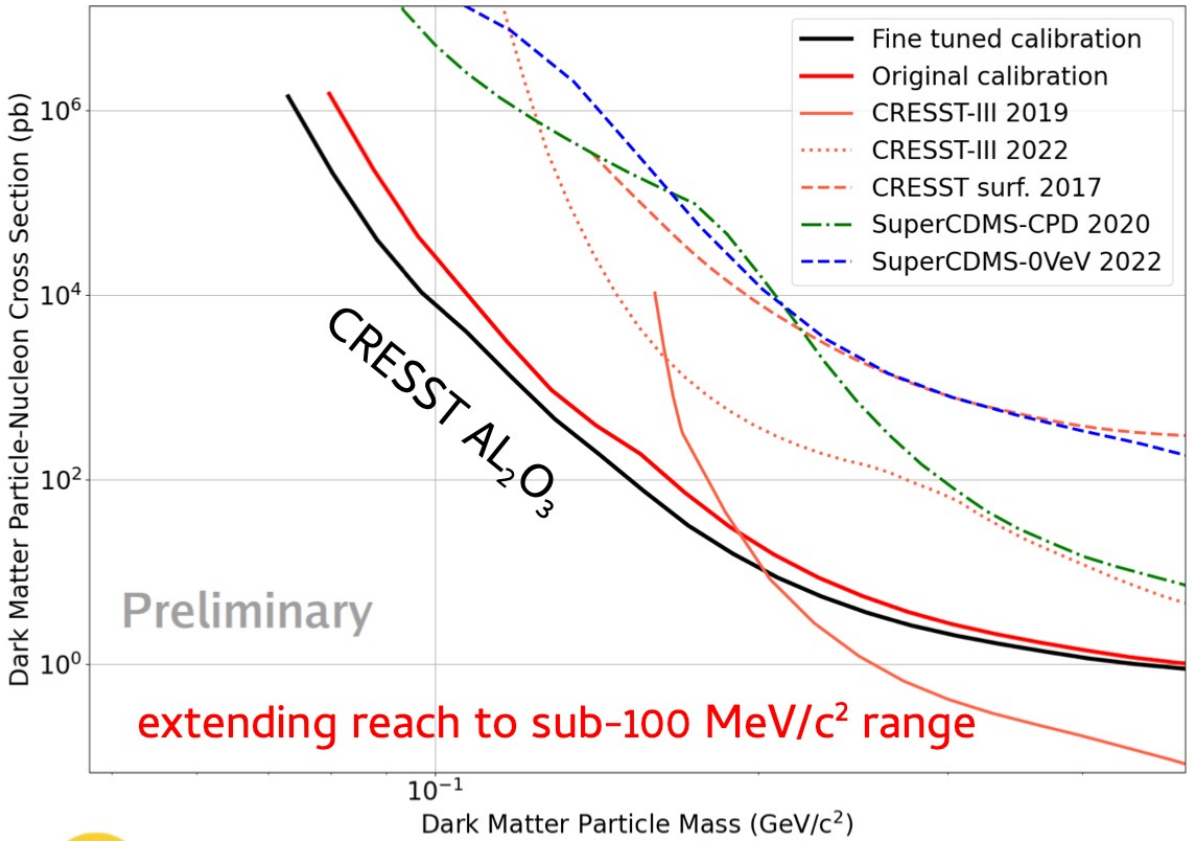
CRESST-III (LNGS)



- $CaWO_4$, Al_2O_3 LiAlO2, Si
- Phonons: W-TES
- Light: Silicon-on-Sapphire wafer
- Status: Upgrade work ongoing
- New: diamond crystal above ground tests

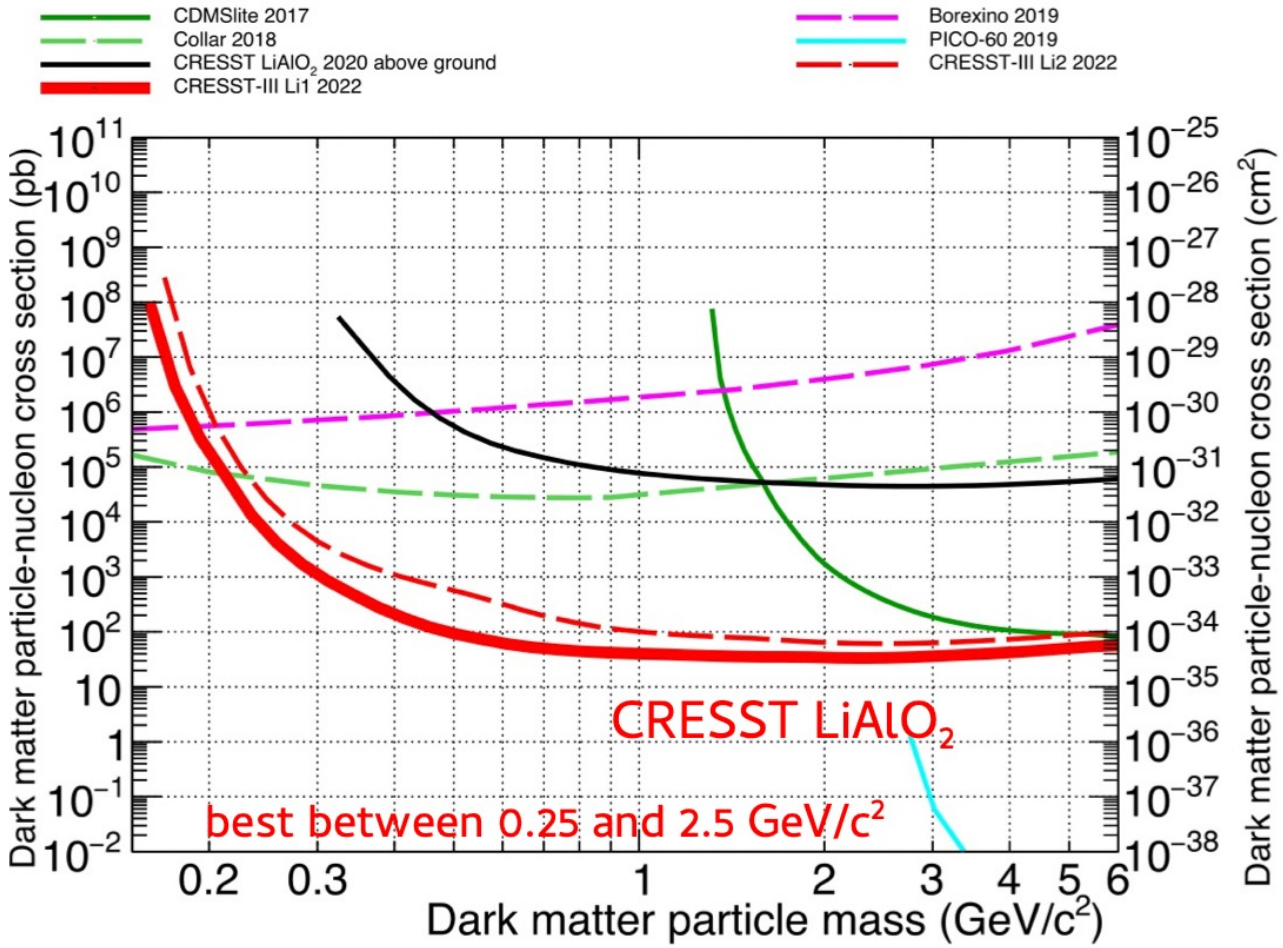
CRESST recent results

Low energy



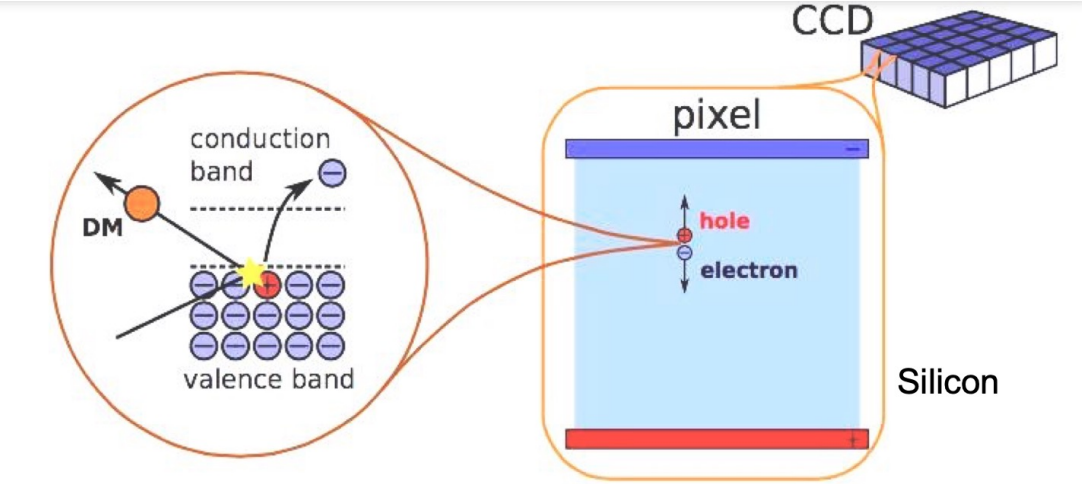
Proton

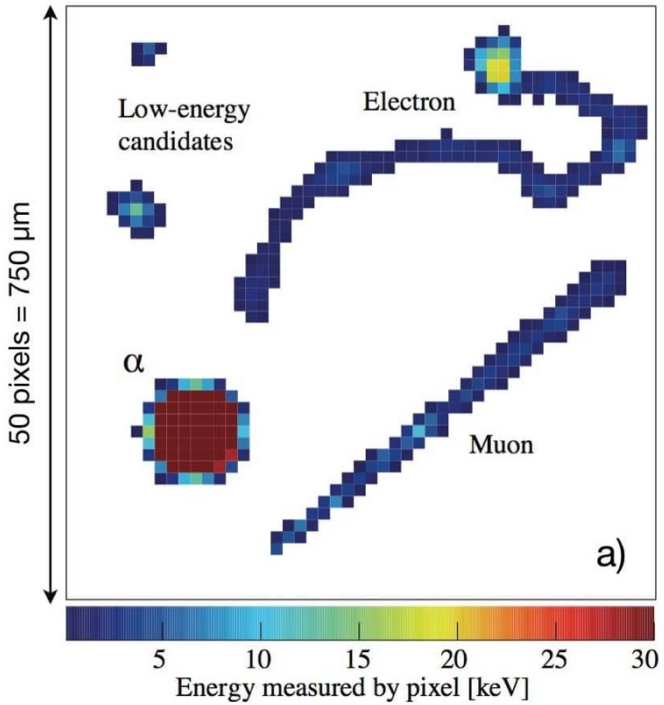
Spin-dependent



From TAUP: https://indico.cern.ch/event/1199289/contributions/5449631/

SILICON CCDs



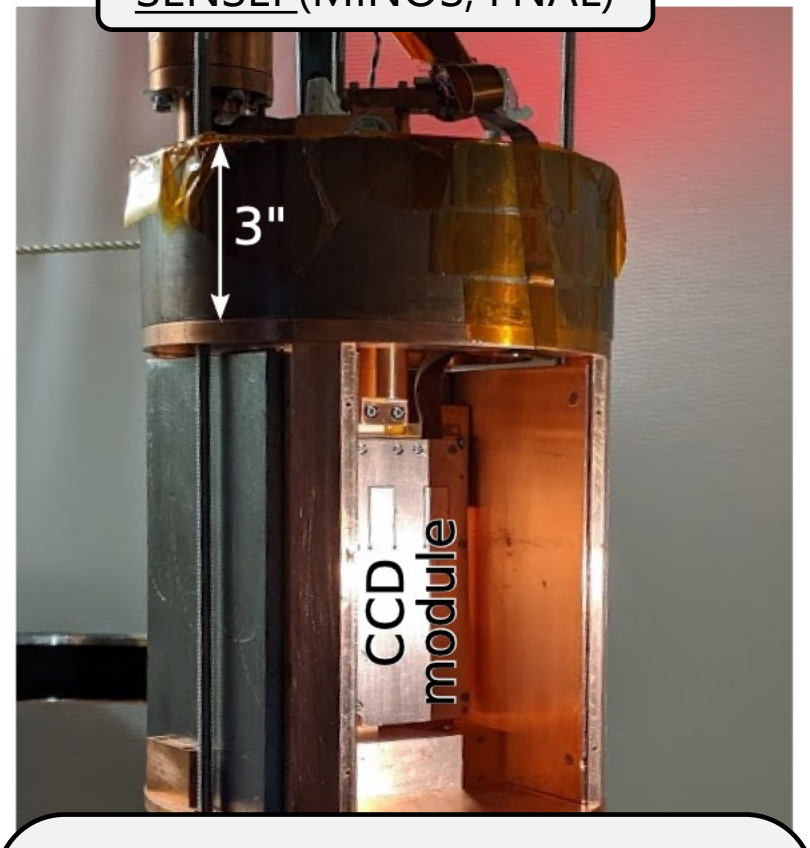


- DM-electron scattering in silicon CCDs (Charge coupled devices)
- Charge is drifted to pixel gates (readout)
- Position reconstruction form diffusion
- Spatial resolution allows particle ID

https://damic.uchicago.edu/detector.php

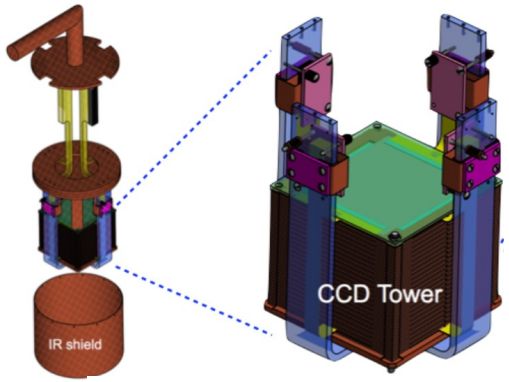
SILICON CCDs

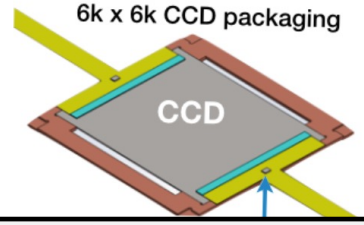
SENSEI (MINOS, FNAL)



- 2-gram
- high-resistivity Skipper-CCD (charge readout)
- Status: second science run of 100-gram version at SNOLAB starting soon

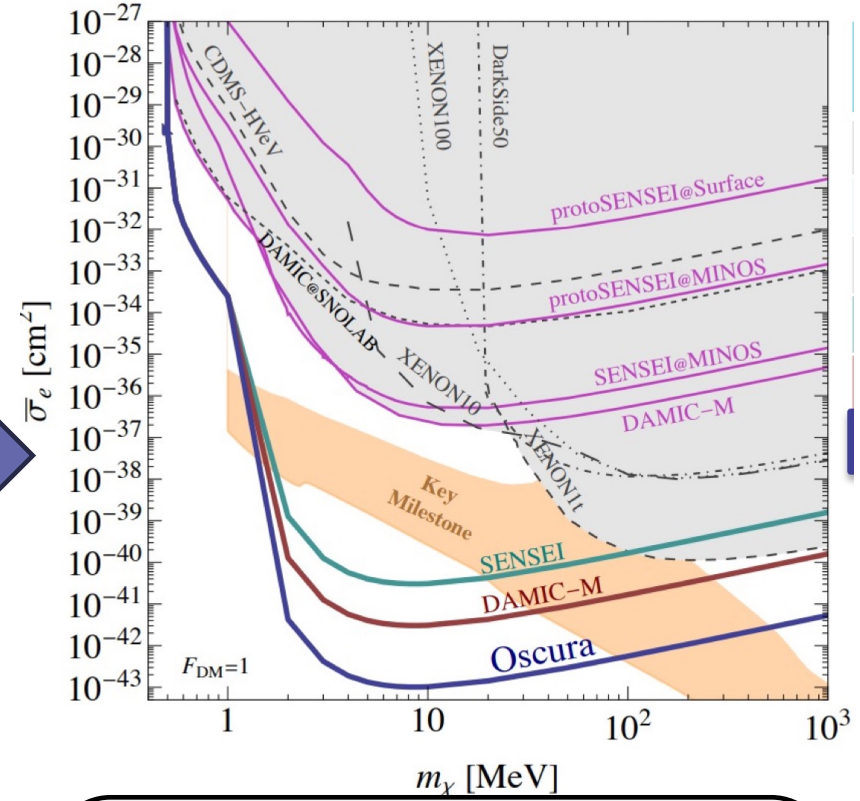
DAMIC-M (Modane)





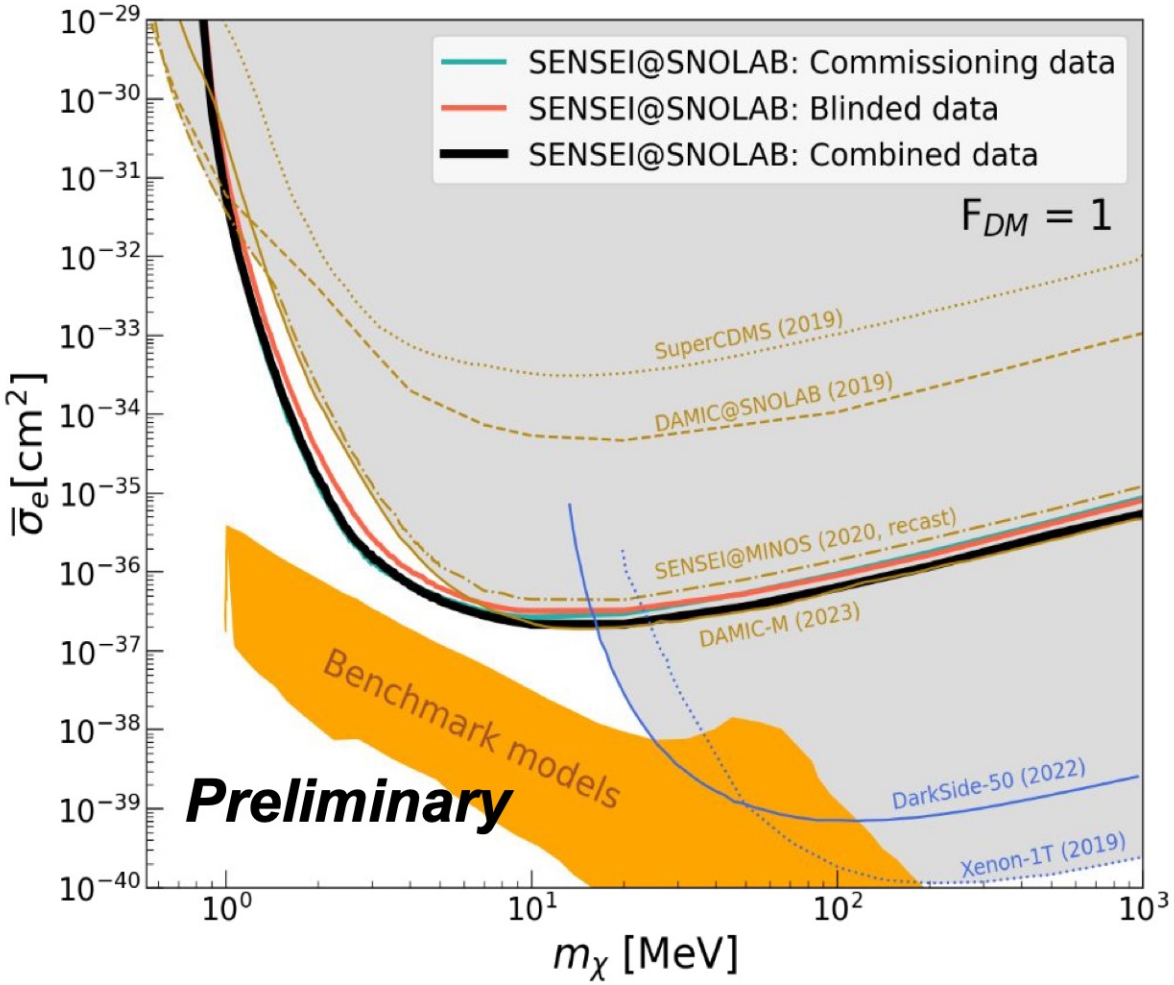
- 1kg Si
- High resistivity CCD-Skipper (charge readout)
- Status: construction

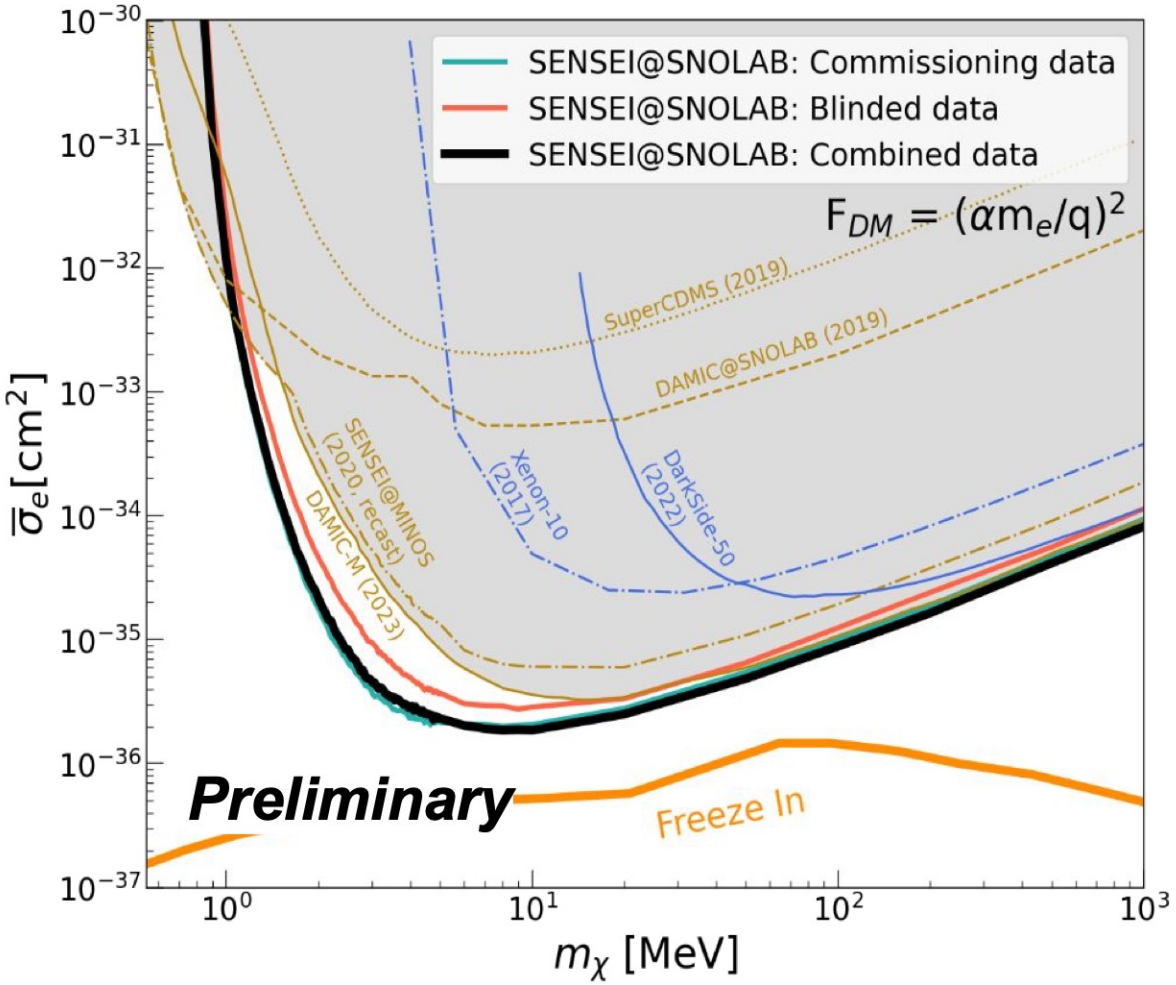
Oscura



- 10 kg
- R&D needed to increase mass and reduce backgrounds (2 orders of magnitude)
- Status: R&D/Design

SILICON CCDs



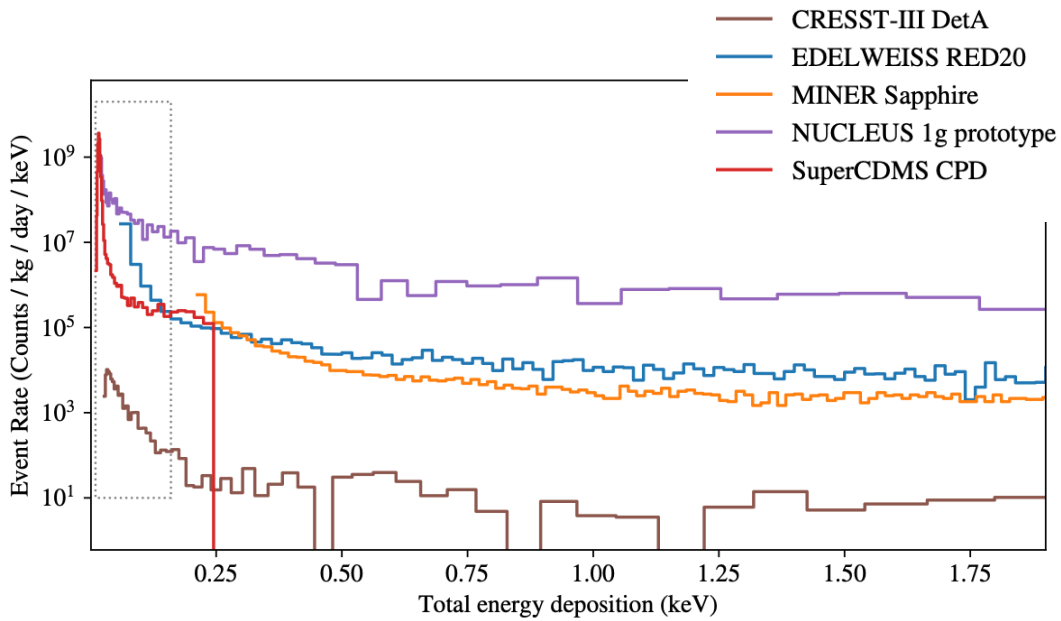


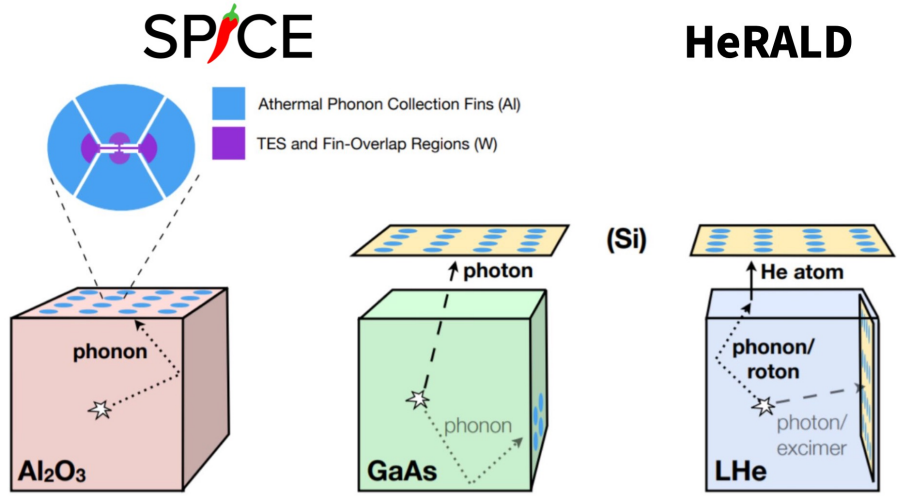
DAMIC 2023: PRL 130, 171003 (2023)

https://indico.cern.ch/event/1199289/contributions/5449602/attachments/2705775/4697202/SENSEI@TAUP.pdf

UNIFYING R&D EFFORTS ACROSS EXPERIMENTS

- Understand and minimize Low-energy excess
  - EXCESS workshop series
  - long-lived metastable states releasing energy into systems
- Pushing TES to meV thresholds
  - Reduce heat capacity and lower temperature
- Resulting sensors can be used for different target materials:
  - SPICE, HeRALD





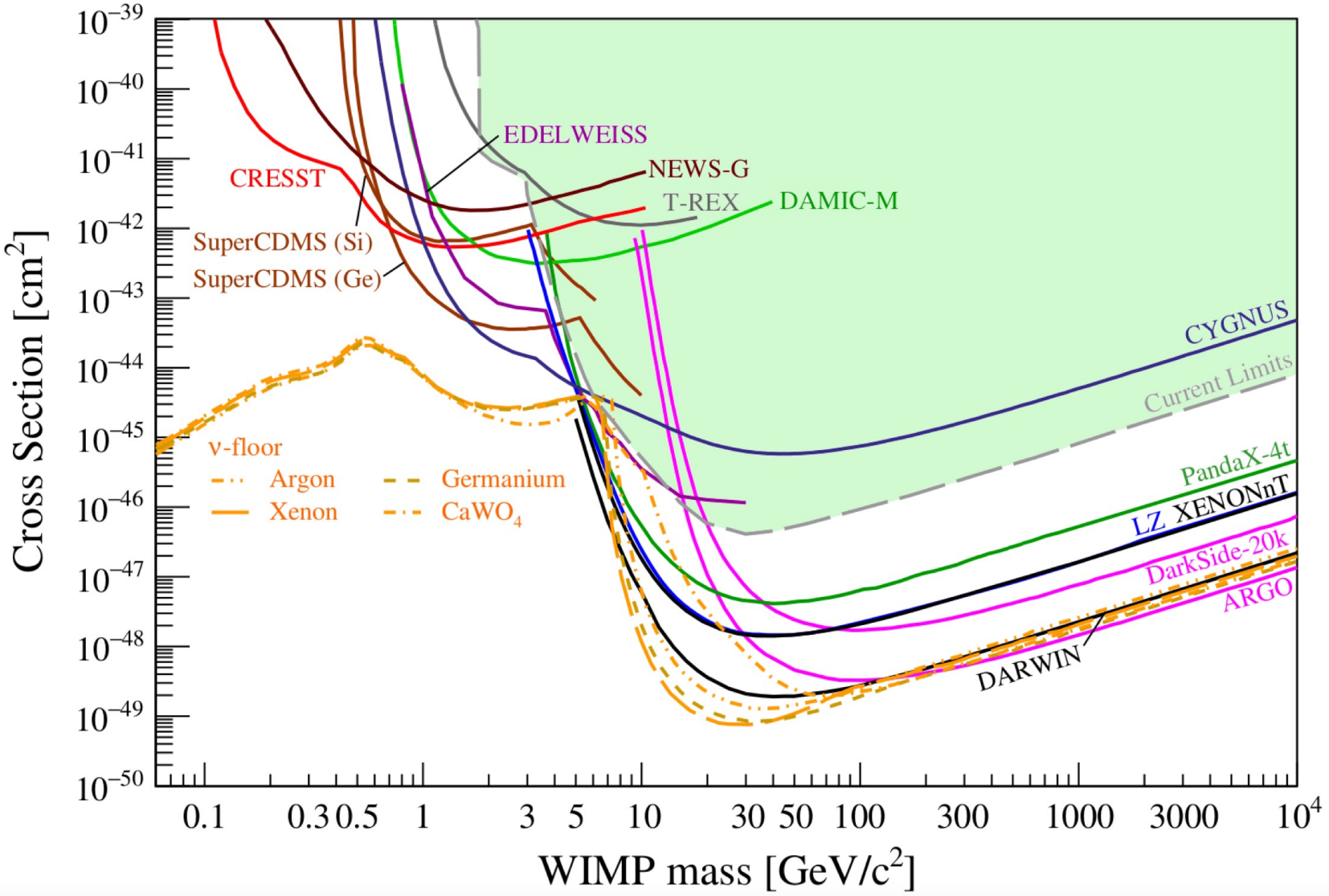
*also called TESSERACT

TESSERACT

PROSPECTS

Lowering thresholds & better E resolution

Understanding & reducing backgrounds



APPEC Committee Report 2021, https://arxiv.org/pdf/2104.07634.pdf

Exciting time for dark matter direct detection with many more results expected in the coming years and promising R&D ongoing!

Name	Detector	Target	Active Mass	Location of Experiment	Status	Start_Ops	End_Ops
XMASS	Scintillator	LXe	832 kg	Kamioke	Ended	2010	2019
XENON10	TPC	LXe	62 kg	LNGS	Ended	2006	2008
XENON100	TPC	LXe	62 kg	LNGS	Ended	2012	2016
XENON1T	TPC	LXe	”1,995 kg”	LNGS	Ended	2017	2019
XENON1T (Ionization)	TPC Ioniz.-only	LXe	”1,995 kg”	LNGS	Ended	2017	2019
XENONnT	TPC	LXe	”7,000 kg”	LNGS	Construction/Run	2021	2025
LUX	TPC	LXe	250 kg	SURF	Ended	2013	2016
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg	SURF	Ended	2017	2019
LZ	TPC	LXe	”8,000 kg”	SURF	Construction/Run	2021	2025
PandaX-II	TPC	LXe	580 kg	CJPL	Ended	2016	2018
PandaX-4T	TPC	LXe	”4,000 kg”	CJPL	Running	2021	2025
LZ HydroX	TPC	LXe+H2	”8,000 kg”	SURF	R&D	2026	
Darwin / US G3	TPC	LXe	”50,000 kg”	LNGS/SURF/Boulby	Planning	2028	2033
DEAP-1	Scintilator	LAr			Ended	2007	2011
DEAP-3600	Scintillator	LAr	”3,300 kg”	SNOLAB	Running	2016	202X
DarkSide-50	TPC	LAr	46 kg	LNGS	Ended	2013	2019
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg	LNGS	Ended	2018	2019
Darkside-20k	TPC	LAr	30 t	LNGS	Planning/Construct	2025	2030
ARGO	TPC or Scintillator	LAr	300 t	SNOLAB	Planning	2030	2035
GADMC	TPC	LAr			Planning	2030	
DAMA/LIBRA	Scintillator	NaI	250 kg	LNGS	Running	2003	
ANAIS-112	Scintillator	NaI	112 kg	Canfranc	Running	2017	2022
COSINE-100	Scintillator	NaI	106 kg	YangYang	Running	2016	2021
COSINE-200	Scintillator	NaI	200 kg	YangYang	Construction	2022	2025
COSINE-200 South Pole	Scintillator	NaI	200 kg	South Pole	Planning	2023	?
COSINUS	Bolometer Scintillator	NaI	?	LNGS	Planning	2023	?
SABRE PoP	Scintillator	NaI	5 kg	LNGS	Construction	2021	2022
SABRE (North)	Scintillator	NaI	50 kg	LNGS	Planning	2022	2027
SABRE (South)	Scintillator	NaI	50 kg	SUPL	Planning	2022	2027
CDEX-10	Ionization (77K)	Ge	10 kg	CJPL	Running	2016	?
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg	CJPL	Planning	202X	

SuperCDMS	Cryo Ionization	Ge	9 kg	Soudan	Ended	2011	2015
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	Soudan	Ended	2012	2015
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	Soudan	Ended	2012	2015
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	Surface Lab	Ended	2018	2018
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg	SNOLAB	Running	2020	2022
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg	SNOLAB	Construction	2023	2028
EDELWEISS III	Cryo Ionization	Ge	20 kg	LSM	Ended	2015	2018
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g	LSM	Running	2019	
CRESST-II	Bolometer Scintillation	CaWO4	5 kg	LNGS	Ended	2012	2015
CRESST-III	Bolometer Scintillation	CaWO4	240 g	LNGS	Ended	2016	2018
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4		LNGS	Running	2020	
COUPP	Bubble Chamber	CF3I	4 kg	SNOLAB / Fermilab	Ended	2011	2012
PICASSO	Superheated Droplet	C4F10	3 kg	SNOLAB	Ended		2017
PICO-2	Bubble Chamber	C3F8	2 kg	SNOLAB	Ended	2013	2015
PICO-40	Bubble Chamber	C3F8	35 kg	SNOLAB	Running	2020	
PICO-60	Bubble Chamber	”CF3I,C3F8”	52 kg	SNOLAB	Ended	2013	2017
PICO-500	Bubble Chamber	C3F8	430 kg	SNOLAB	Construction/Run	2021	
DRIFT-II	Gas Directional	CF_4	0.14 kg	Boulby	Ended		
NEWAGE-03b’	Gas Directional	CF4	14 g	Kamioka	Running	2013	2023
MIMAC	Gas Directional	$CF_4+CHF_3+C_4H_{10}$		LSM (Modane)	Running	2012	
CYGNO	Gas Directional	He + CF_4	0.5 - 1 kg	LNGS	Planning	2024	
CYGNUS	Gas Directional	He + SF_6/CF_4		Multiple sites	Planning		
NEWS-G	Gas Drift	CH4		LSM	Ended	2017	2019
NEWS-G	Gas Drift	CH4		SNOLAB	Construction/Run	2020	2025
DAMIC	CCD	Si	2.9 g	SNOLAB	Ended	2015	2015
DAMIC	CCD	Si	40 g Si	SNOLAB	Ended	2017	2019
DAMIC100	CCD	Si	100 g Si	SNOLAB	Not Built		
DAMIC-M	CCD Skipper	Si	1 kg Si	LSM	Construction/Run	2021	2024
SENSEI	CCD Skipper	Si	2 g Si	Fermilab u/g	Running	2019	2020
SENSEI	CCD Skipper	Si	100 g Si	SNOLAB	Construction/Run	2021	2023
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	Planning	2024	2028
SNOWBALL	Supercooled Liquid	H2O			Planning		
ALETHEIA	TPC	He		China Inst. At. Energy	R&D		
TESSERACT	Cryo TES	He		LBNL	R&D		