Dark Matter Direct Detection Experiments

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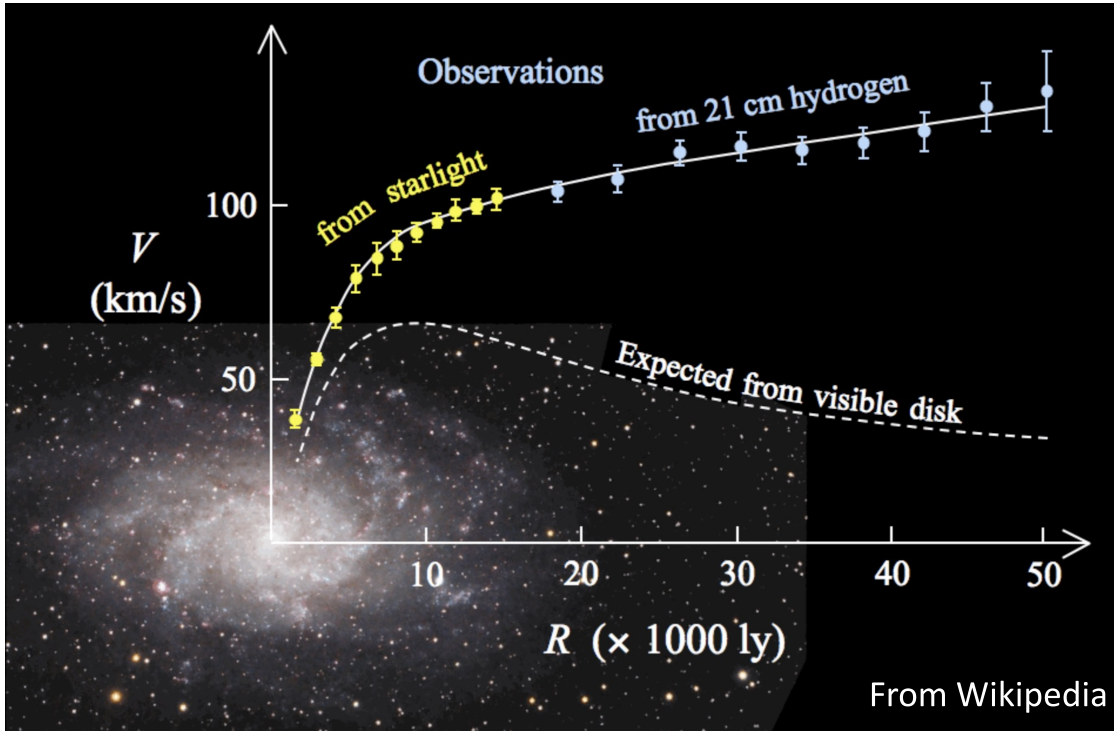
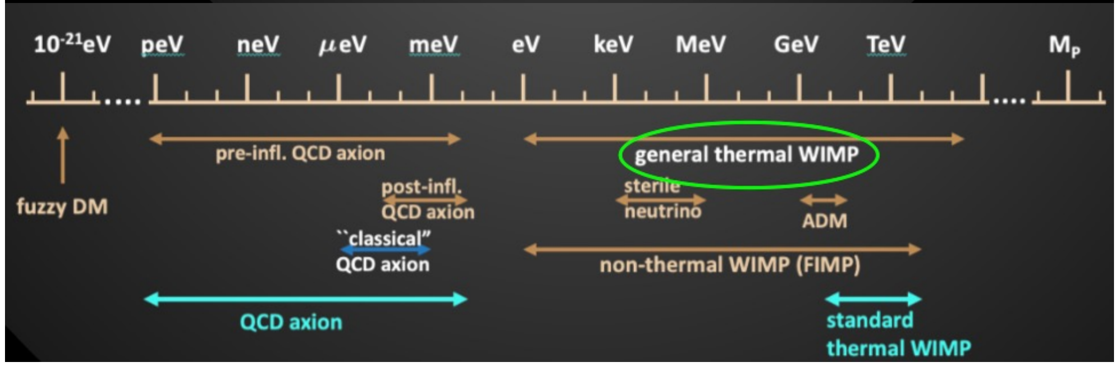
Dark matter

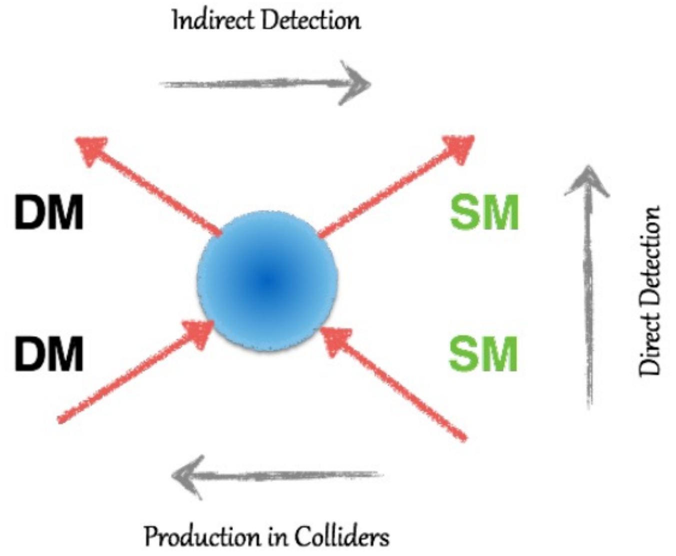
Rotation curve of spiral galaxy M33



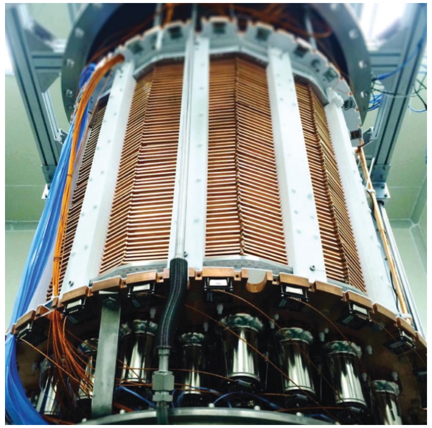
Gravitational evidences suggest dark matter is the dominant form of matter in Universe!

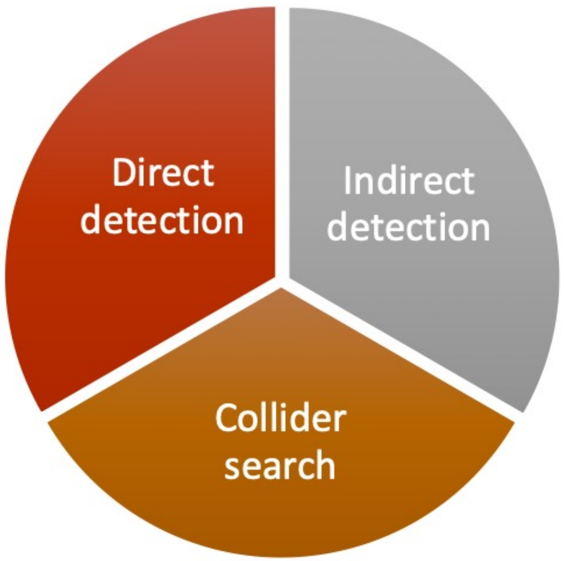


Dark matter detection



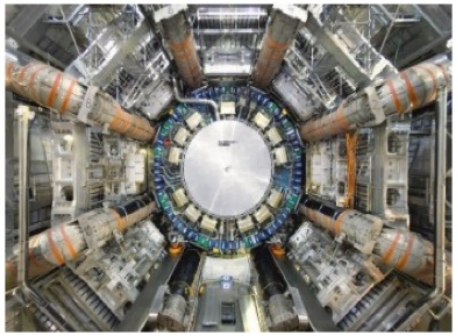
$\chi + SM \longrightarrow \chi' + SM'$





$\chi + \bar{\chi} \longrightarrow SMs$

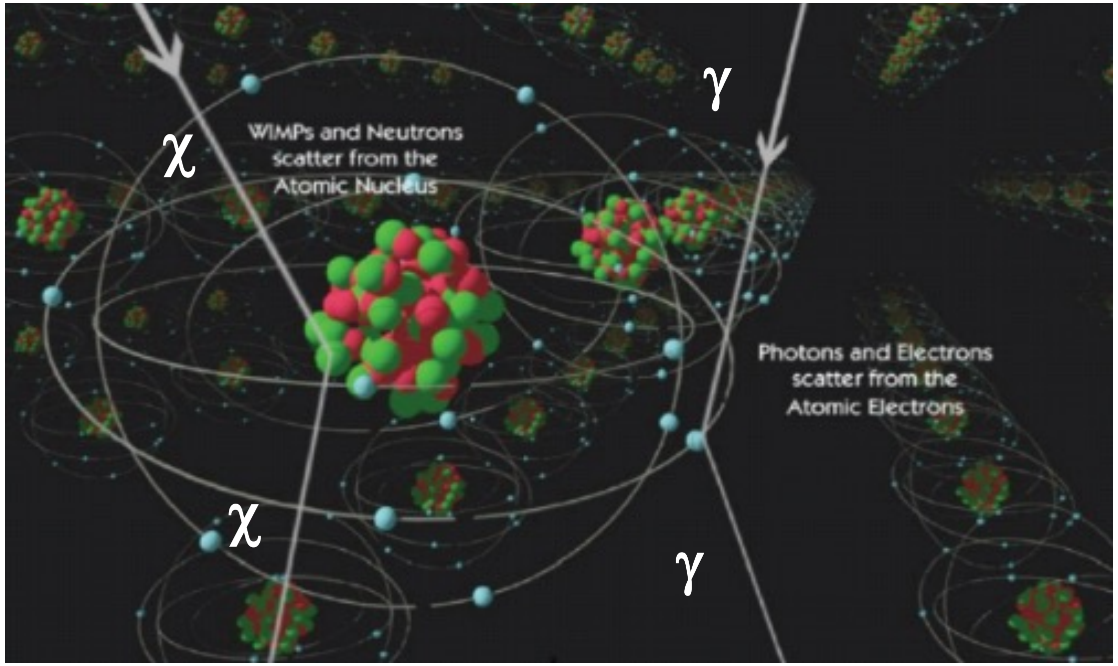
$SMs \longrightarrow \chi$(s)+(SMs)



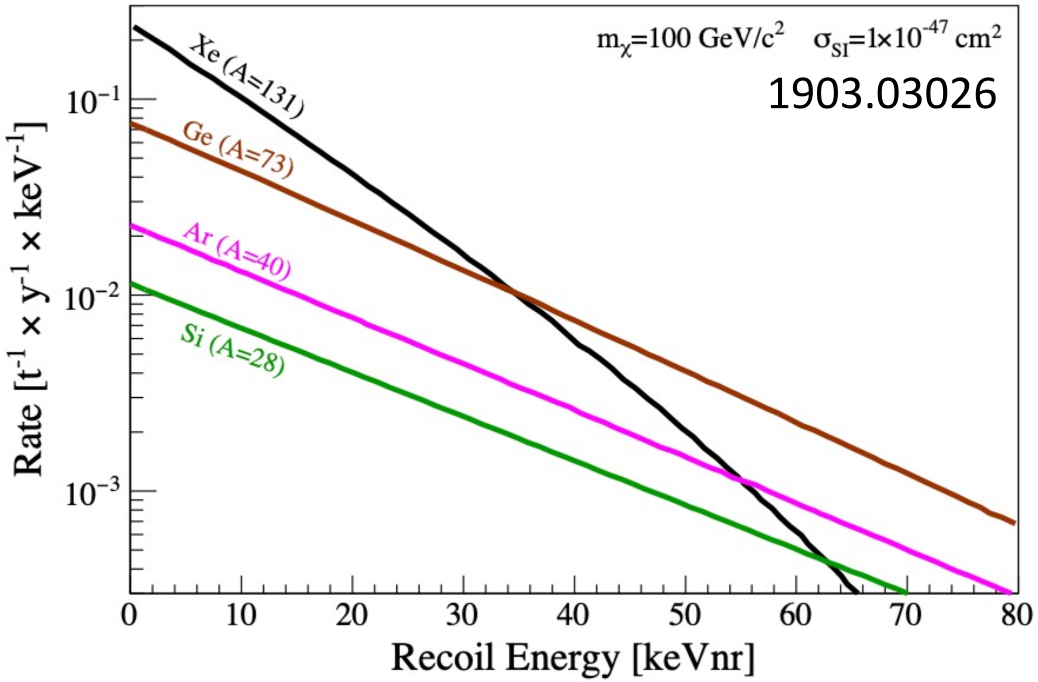
The dark matter direct detection

Nuclear recoils

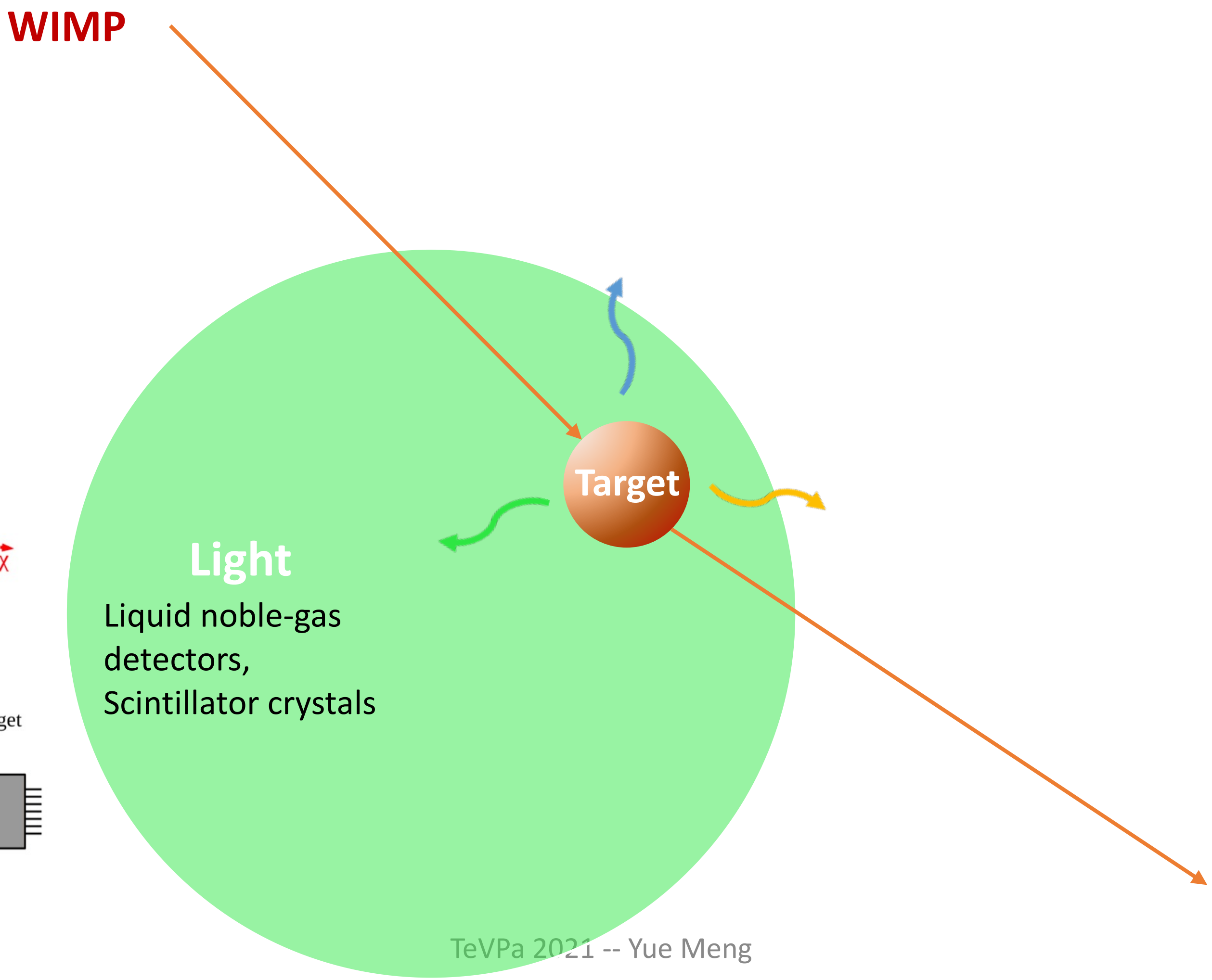
Elastic Scattering of WIMPs off target nuclei

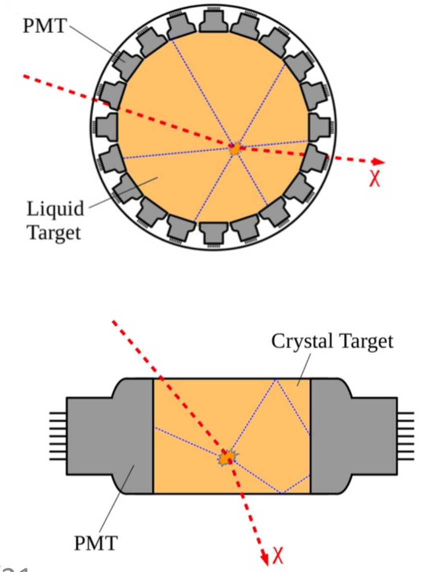


Nuclear recoil spectra

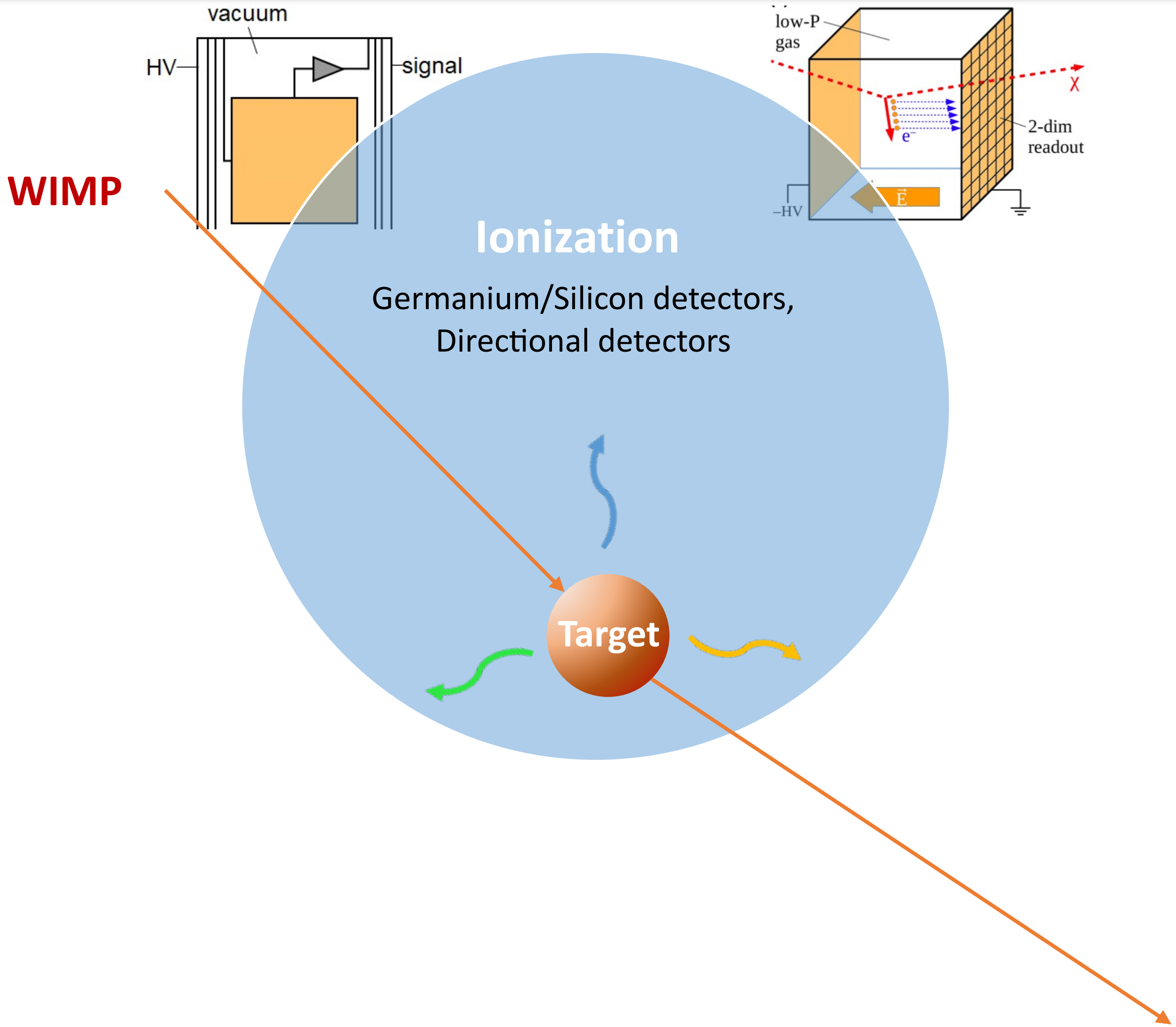


Dark matter detection technologies

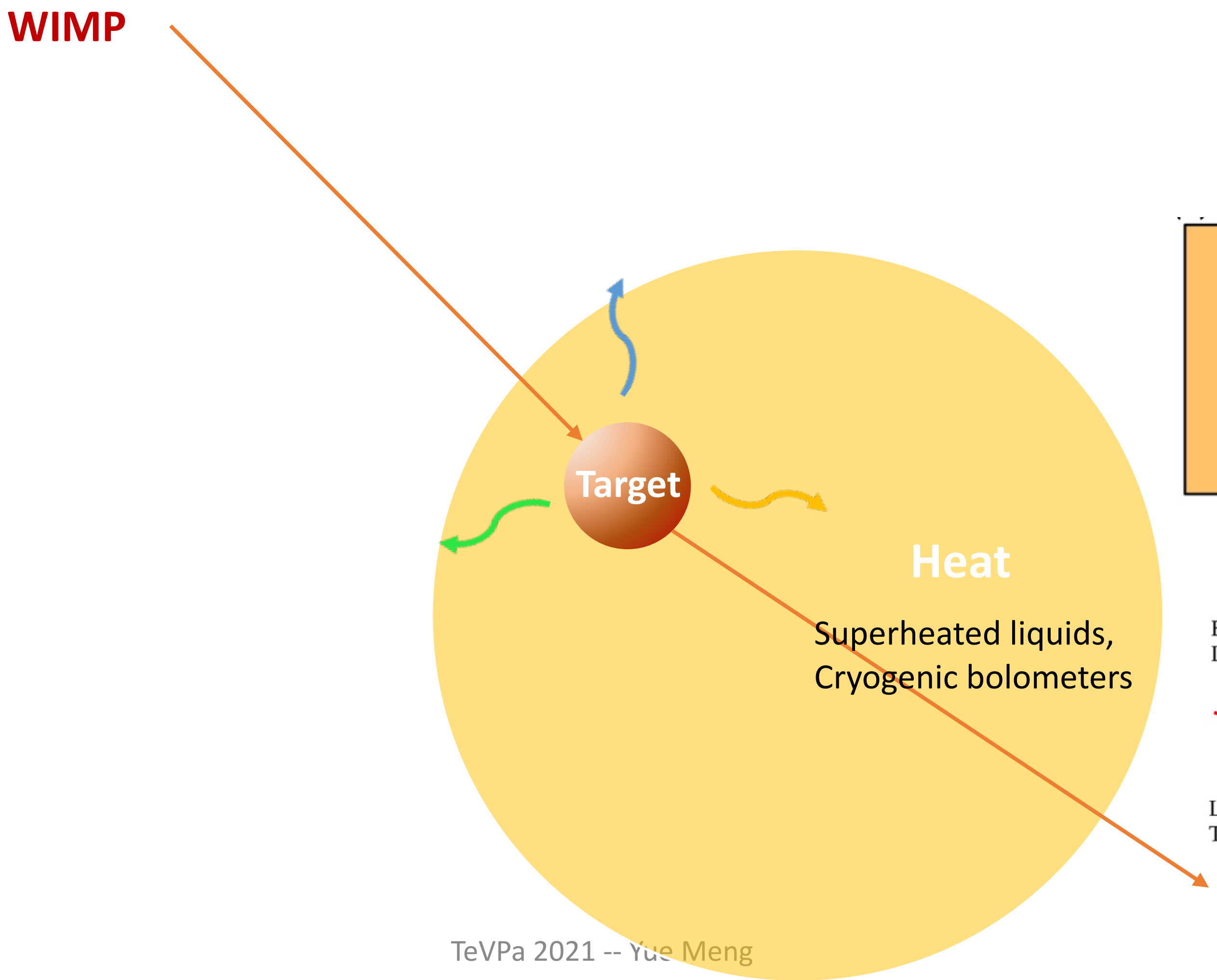


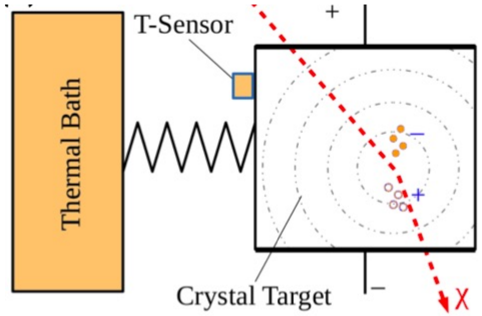


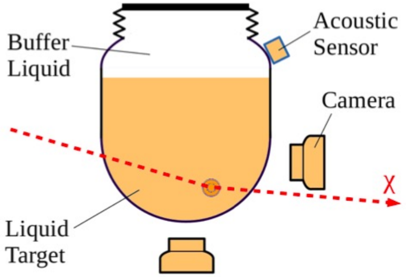
Dark matter detection technologies



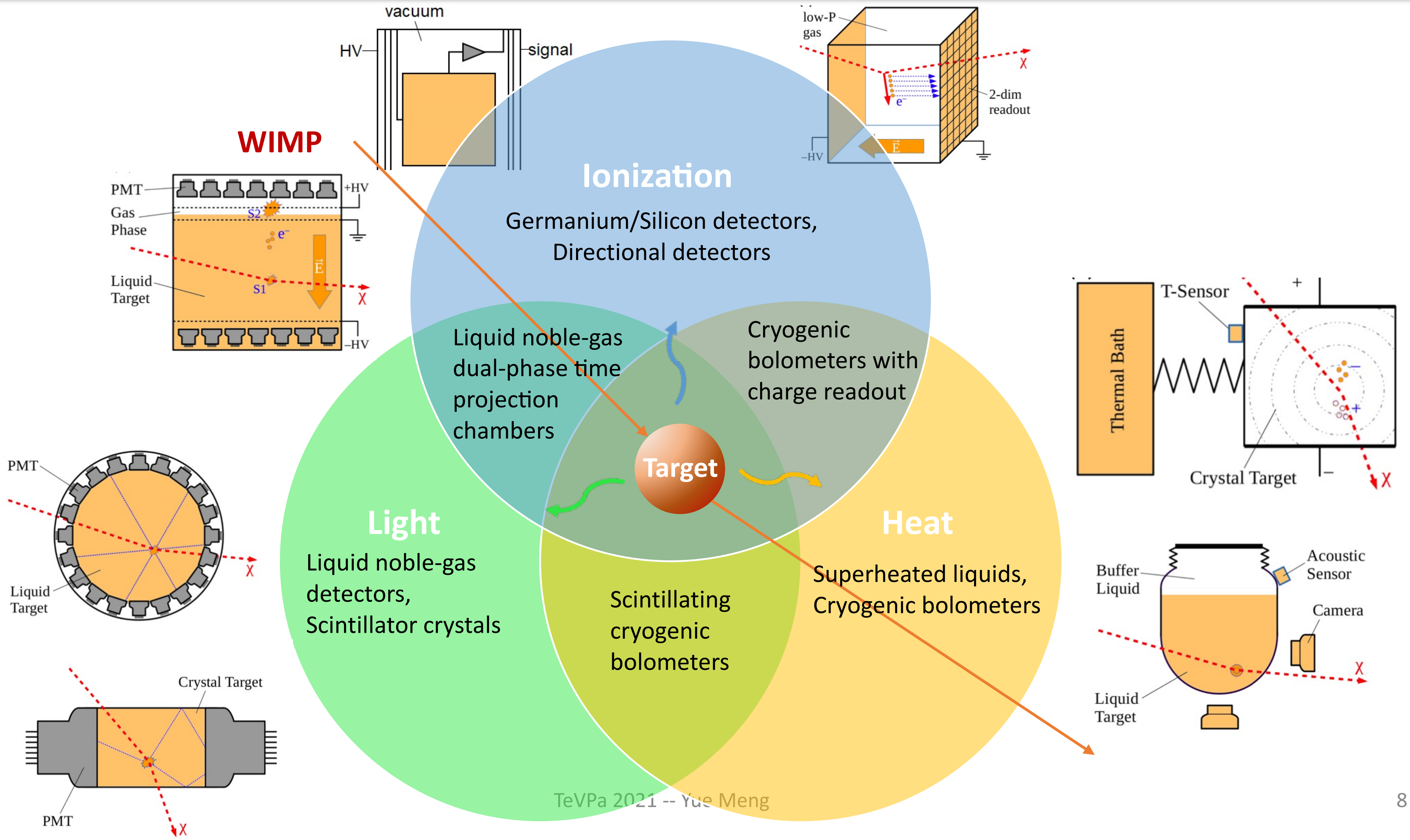
Dark matter detection technologies



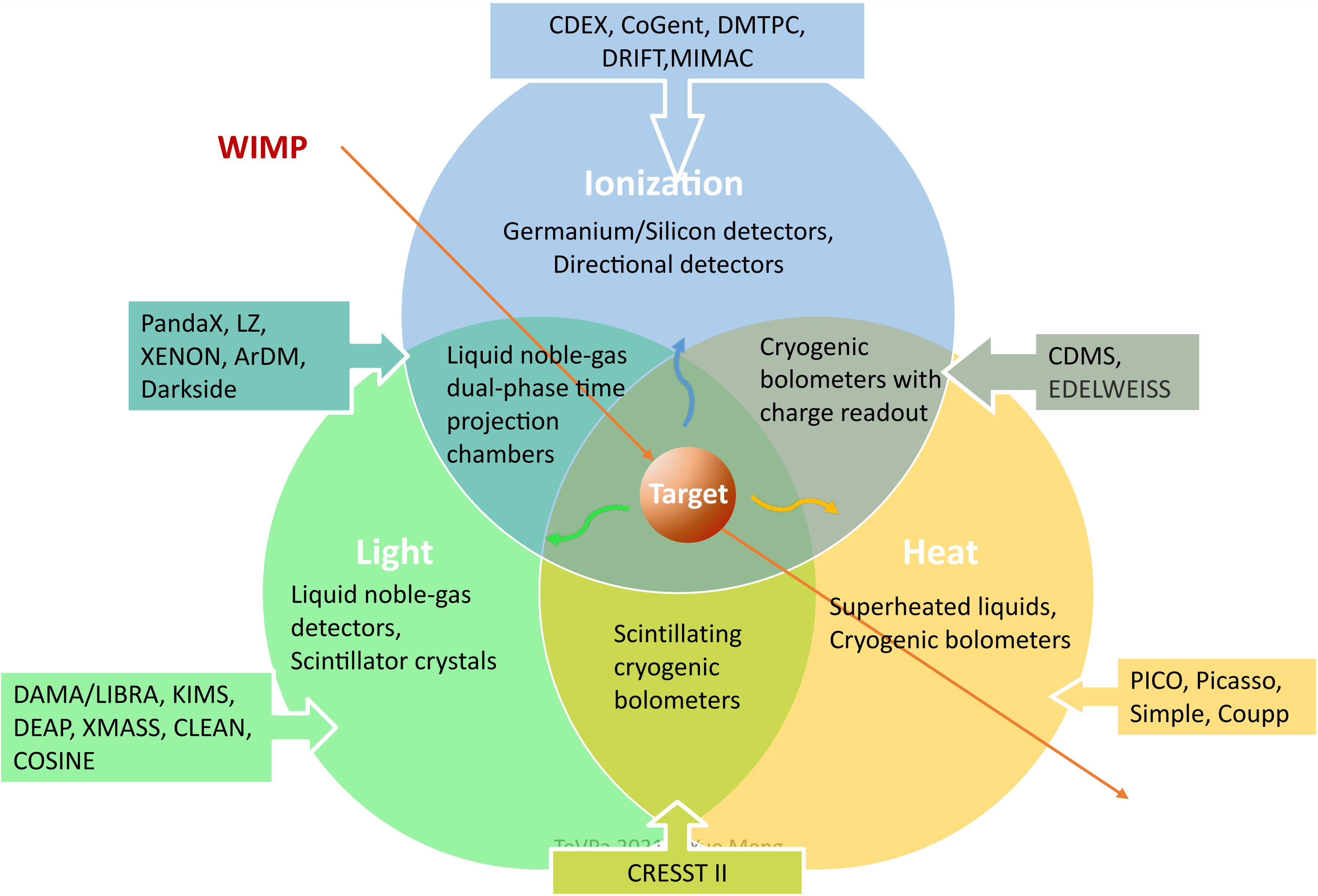




Dark matter detection technologies

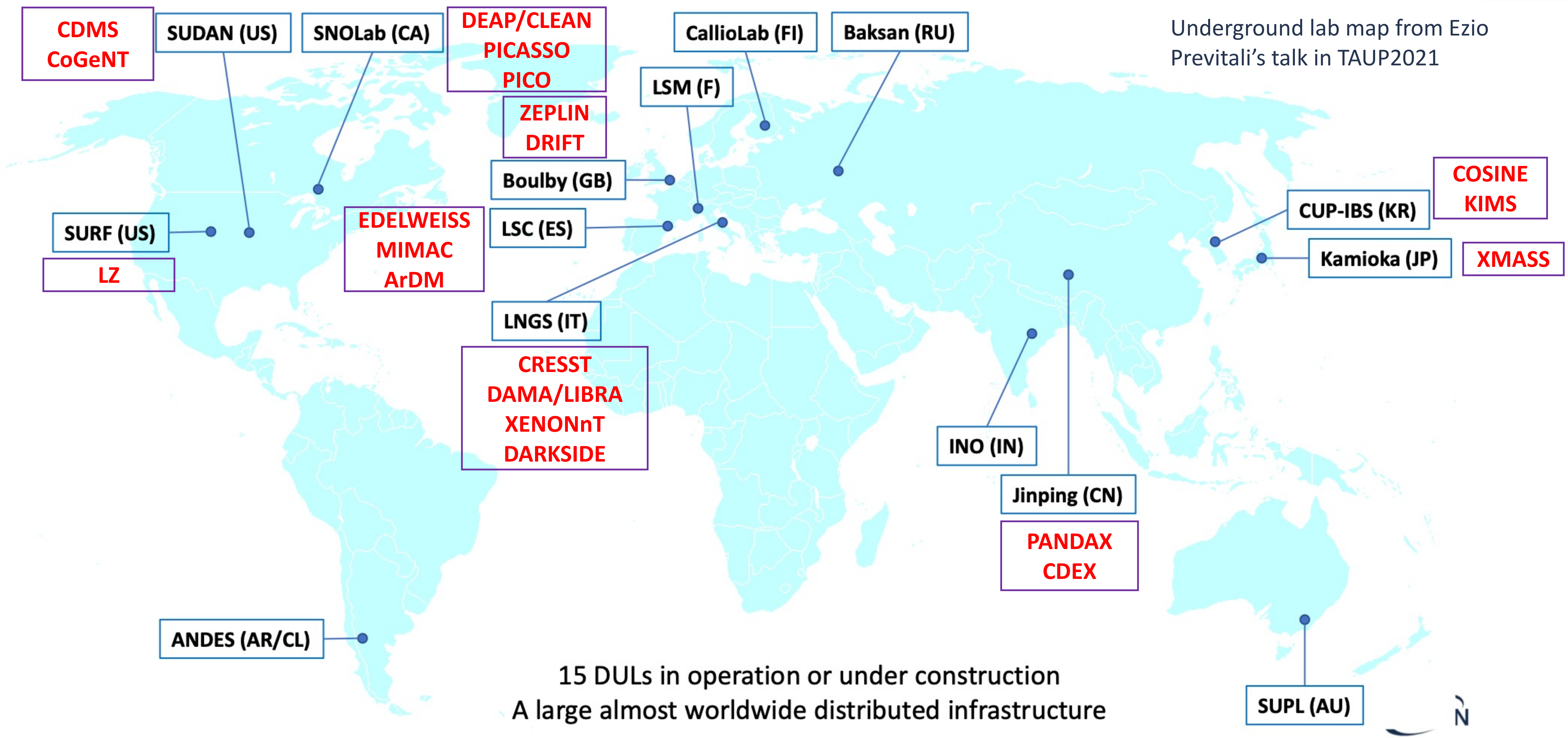


Dark matter detection technologies



Underground laboratories and DM experiments

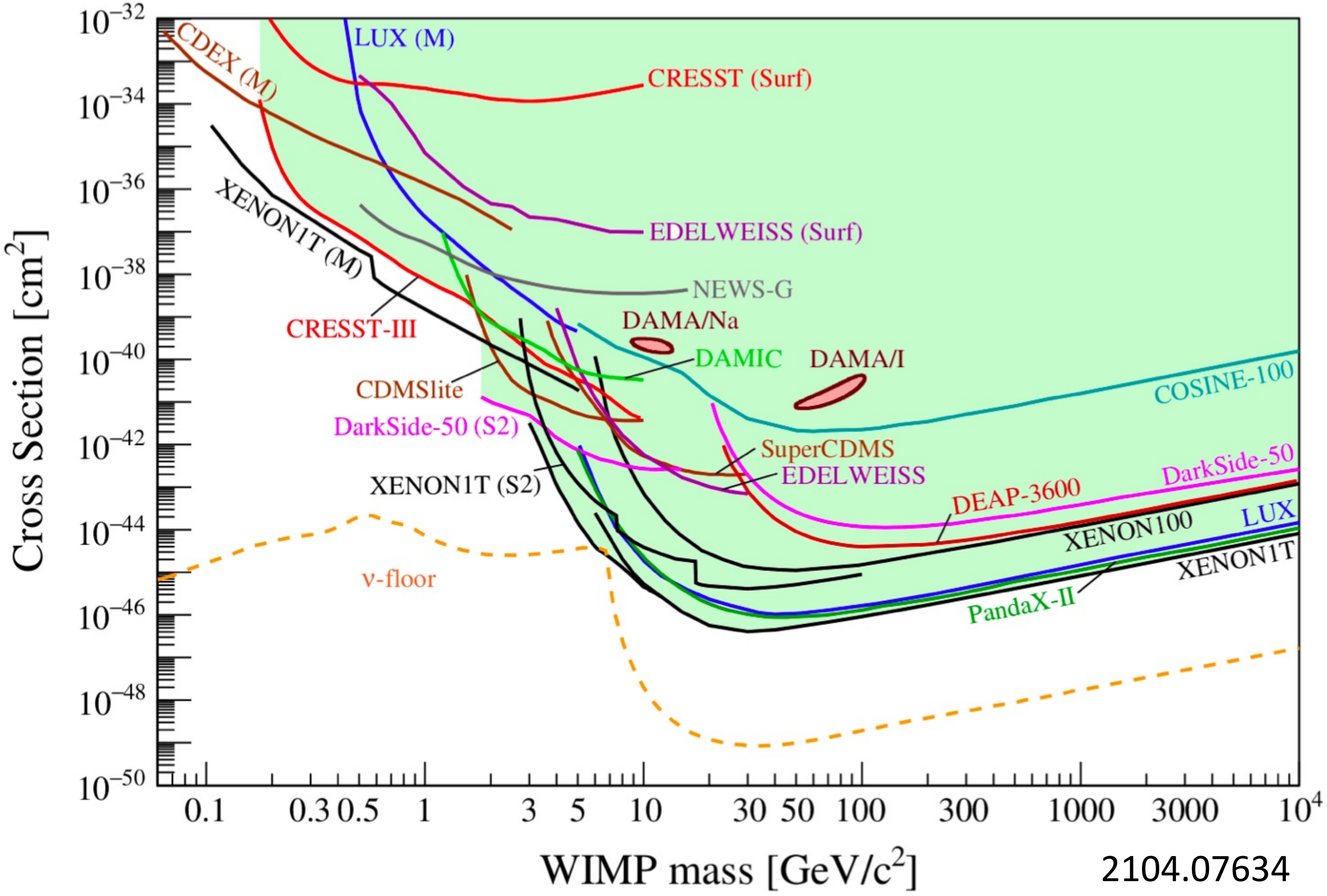
Underground lab map from Ezio Previtali's talk in TAUP2021



15 DULs in operation or under construction
A large almost worldwide distributed infrastructure

~GeV WIMP detection

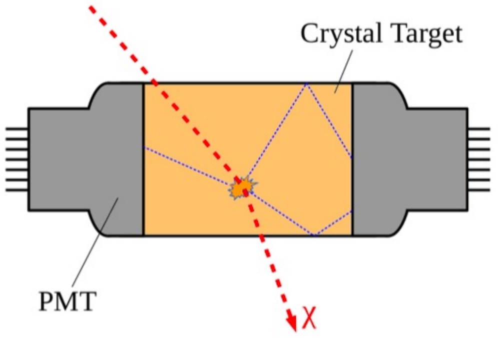
Current status (WIMP-nuclei scattering)



2104.07634

Scintillator crystals

NaI(Tl) or CsI(Tl) scintillator crystals
Search for a possible dark matter-induced annually modulating signals



Advantage:

- simple design
- at room temperature
- stable for long term operation
- a large target mass

Disadvantage:

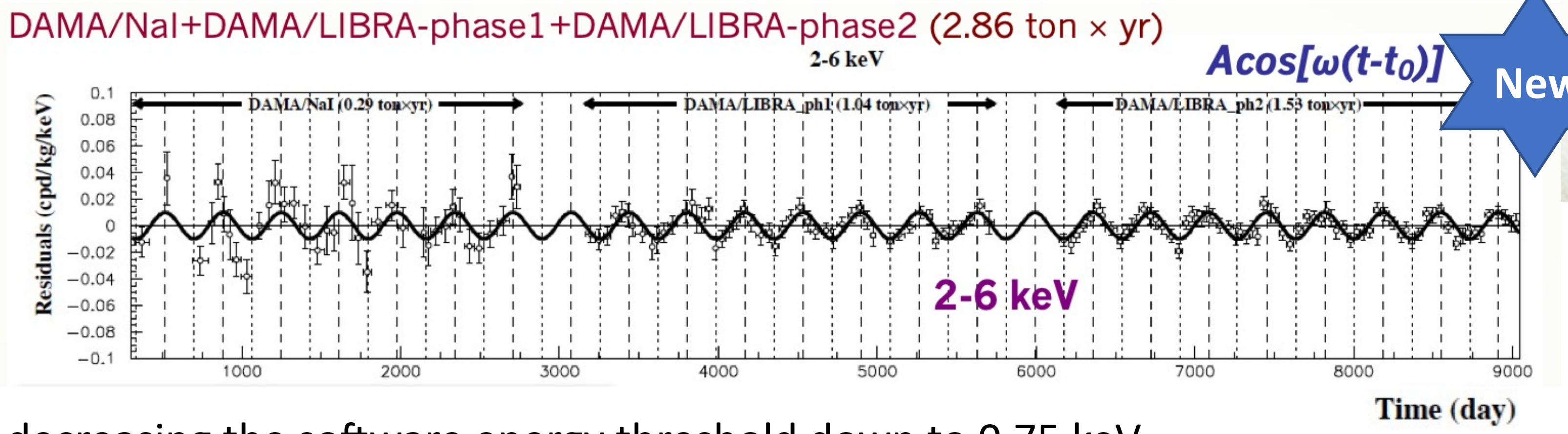
- high intrinsic background

- DAMA @LNGS underground laboratory + ultra low-radioactive NaI(Tl) crystals
- DAMA/LIBRA annual-modulated single-hit rate in the energy range (2 − 6) keVee
- SABRE @LNGS underground laboratory, highly pure NaI(Tl) crystals in an active liquid scintillator veto to tag and reduce the 40K background from the crystals and the external background.
- ANAIS @LSC laboratory, 25 kg NaI(Tl) crystals, 250 kg improving the energy threshold and the internal radioactive contamination
- DM-Ice @South pole, 17kg of NaI crystals under the ice at the South pole at a depth of 2460 m, a reverse phase to the northern hemisphere
- PICO-LON @Kamioka mine, low radioactive NaI crystals with the aim to construct 250 kg setup in the COSINE (South Korea)
- KIMs @Yangyang laboratory, an array of 103 kg CsI(Tl) crystals
- COSINE @Yangyang laboratory, low radioactive NaI crystals

Scintillator crystals

DAMA/LIBRA -- phase2

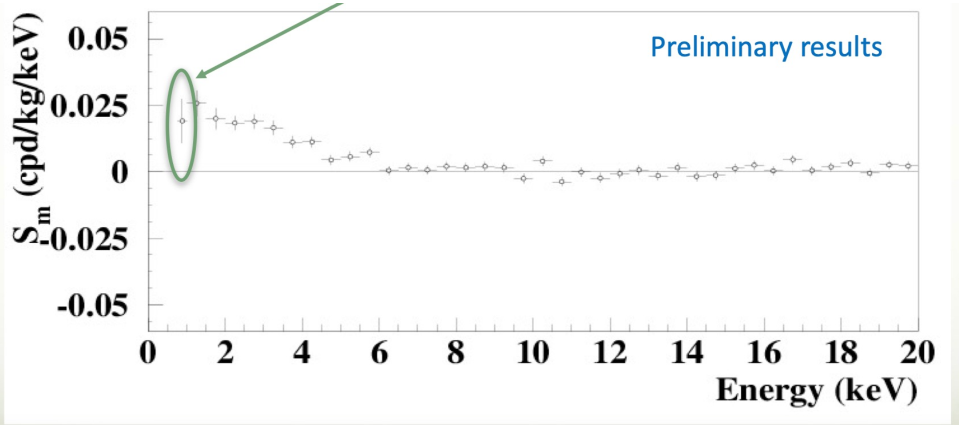
Pierluigi Belli, EPS-HEP2021



New

Favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

decreasing the software energy threshold down to 0.75 keV

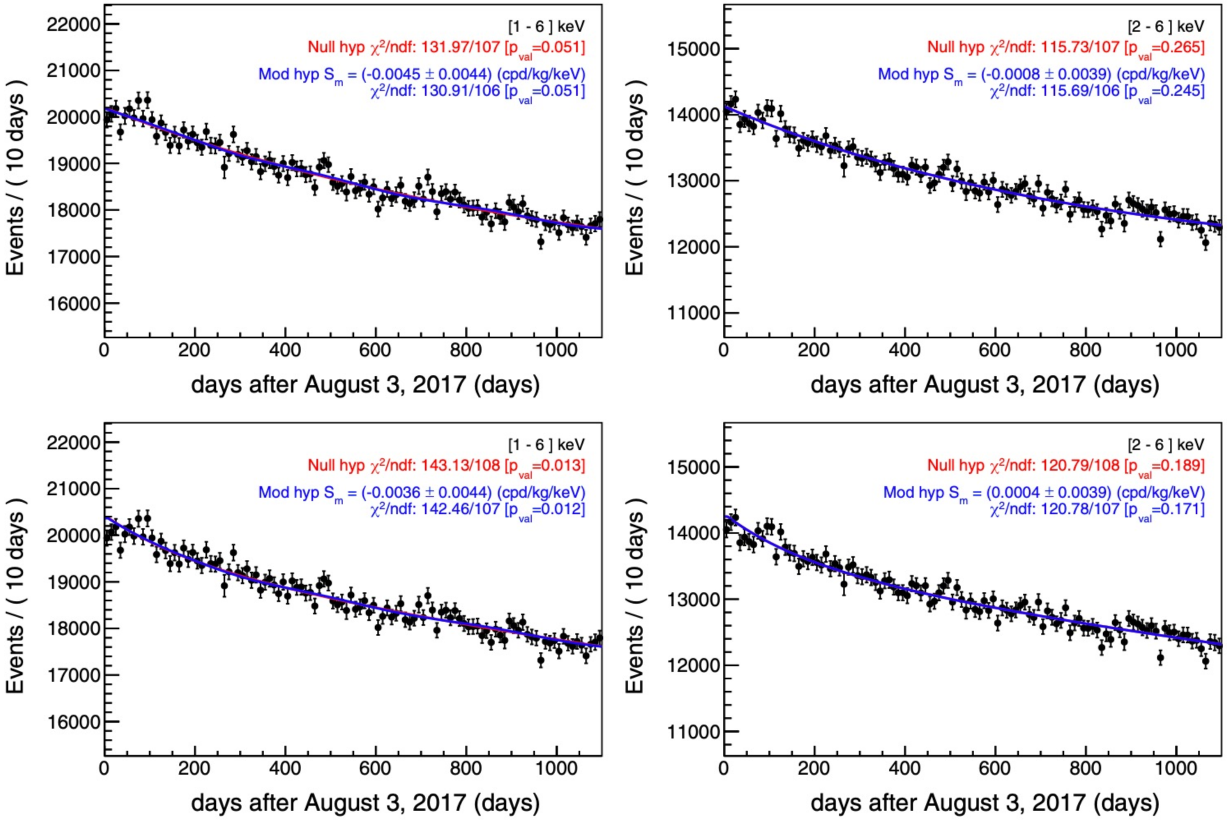


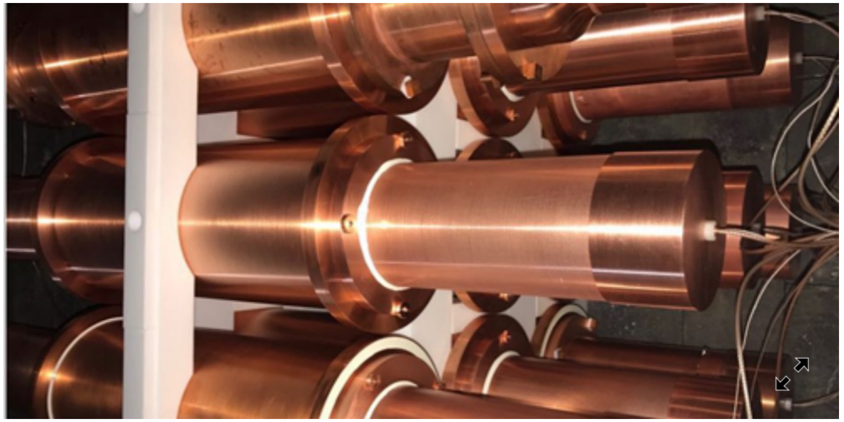
A clear modulation is also present below 1 keV, from 0.75 keV, while S_m values compatible with zero are present just above 6 keV

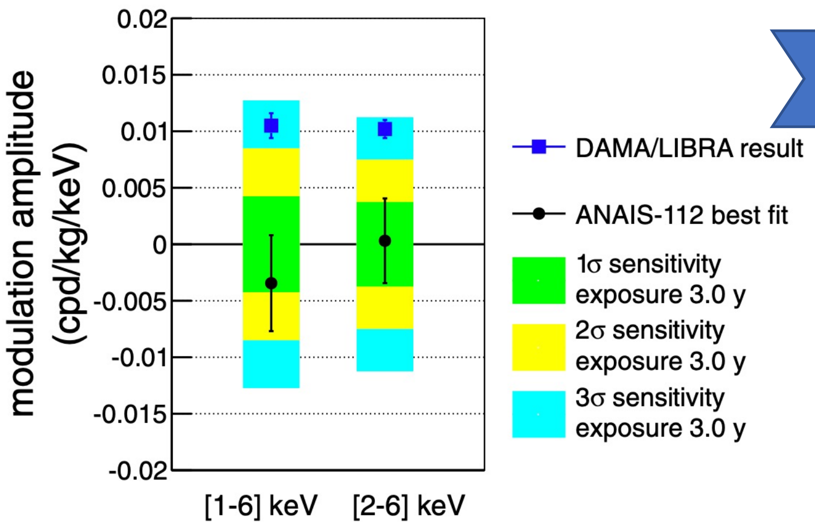
Scintillator crystals

ANAIS
Phys. Rev. D 103, 102005

- 112.5 kg of NaI(Tl) detectors
- Model independent
- three years exposure







New

incompatible with the DAMA/LIBRA result at 3.3 (2.6) σ

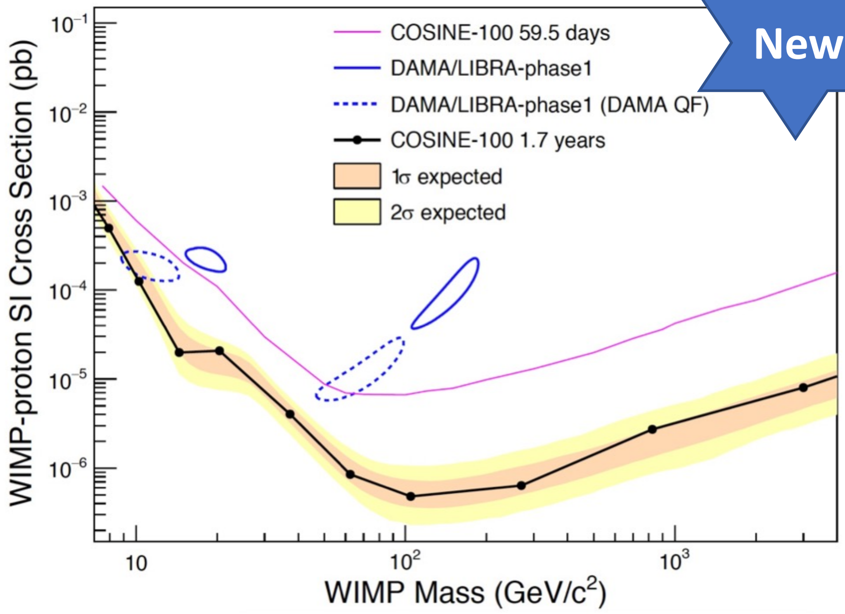
Scintillator crystals

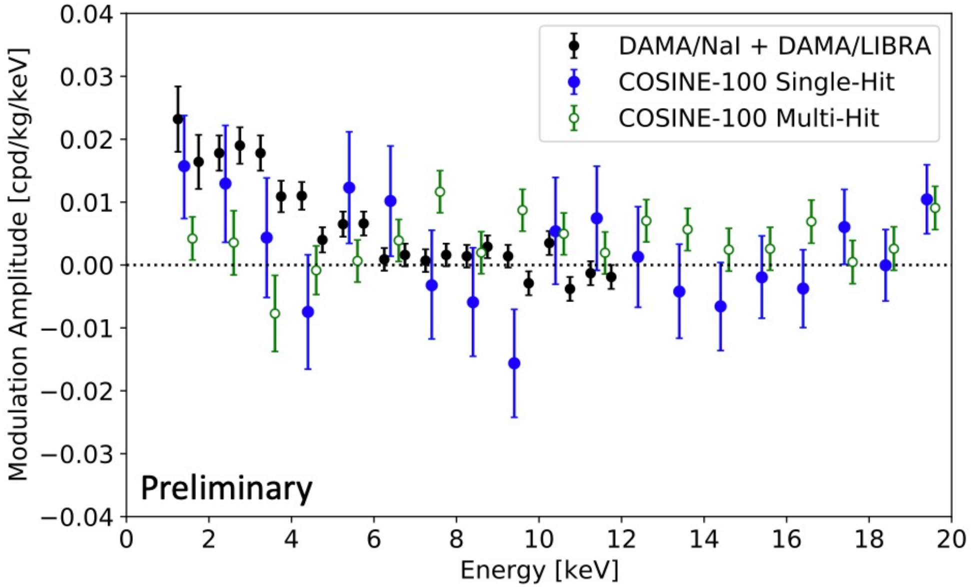
COSINE-100

Will Thompson, TAUP 2021

- 106 kg of tallium-doped sodium iodide (NaI(Tl))
- 1.7 years of COSINE-100 data

New



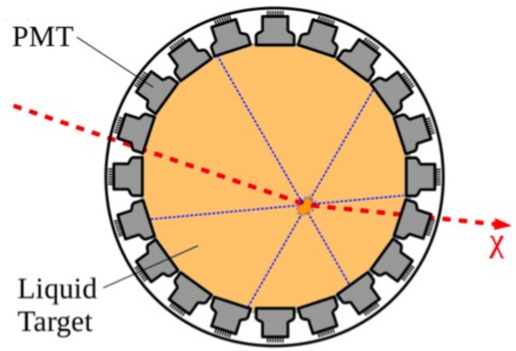


rules out model-dependent dark matter interpretations of the DAMA signals

Annual modulation search currently statistics limited

Single-phase (liquid) detectors

Argon, xenon, neon and krypton



Advantage:
- high light yield with 4π geometry
- dense target
- scale up to ton-scale easily
- pulse shape discrimination for Ar

Disadvantage:
- background discrimination
- position resolution

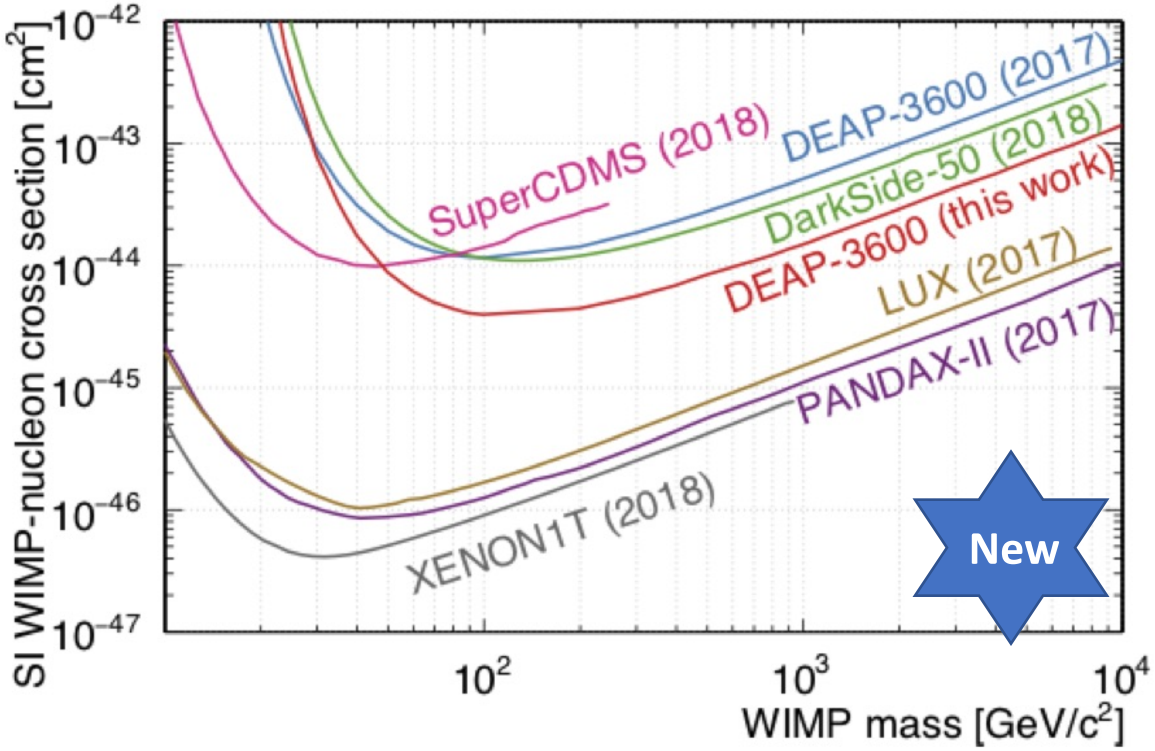
- DEAP @SNO laboratory, liquid argon in single phase, joined DarkSide
- CLEAN @SNO laboratory, liquid argon in single phase
- XMASS @Japan employs the single phase technology with about 800kg of liquid xenon, joined XENONnT collaboration
- ArDM @Canfranc underground laboratory in Spain

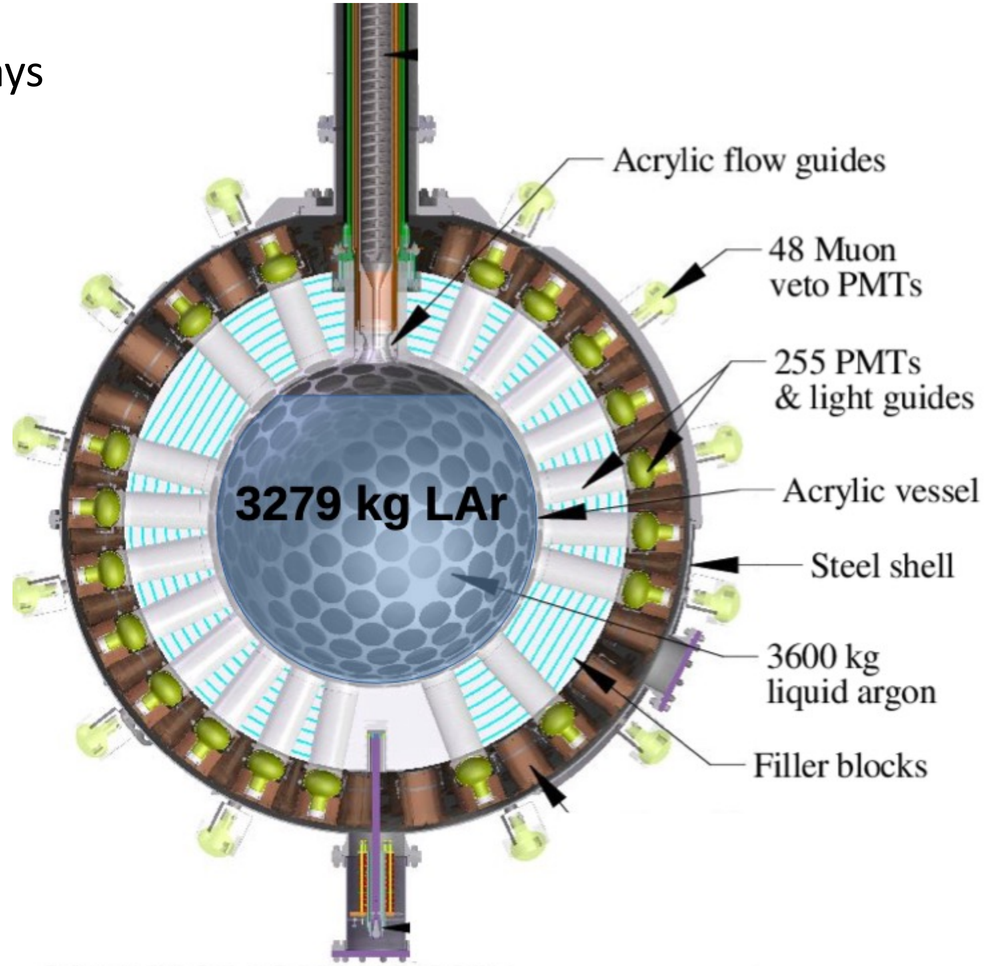
Single-phase (liquid) detectors

DEAP-3600

Simon Viel, *PoS* ICRC2021 (2021) 527

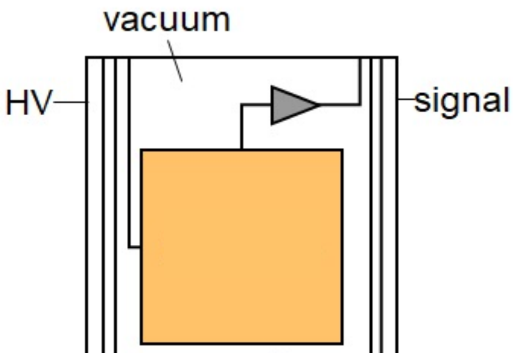
- 3.3 tonnes of liquid argon
- a total exposure of 758 tonne-days





Ionization detectors

Germanium and silicon semiconductor
ionization-mode, low threshold down to ~ 0.5keVee allowing to search for WIMPs down to masses of a few GeV/c^2



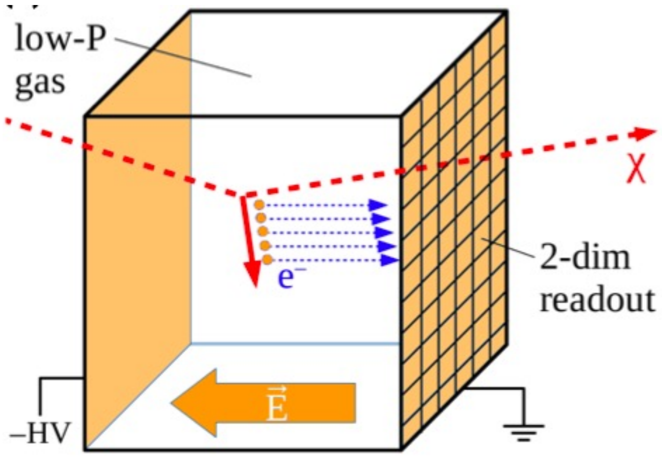
Advantage:
- excellent energy resolution
- very low thresholds, sensitivity to low-mass WIMPs
- background discrimination with rising time

Disadvantage:
- low temperature
- high purity target production

- CDEX @Jinping Underground Laboratory, Ge crystals
- CoGeNT @the Soudan Underground Laboratory, p-type point contact germanium detectors with a mass of 443g reaching an energy threshold of 500eVee.
- MAJORANA @the Kimballton underground research facility, low-background broad energy germanium detector

Directional detectors

the direction (head-tail asymmetry) of nuclear recoil events would be detected



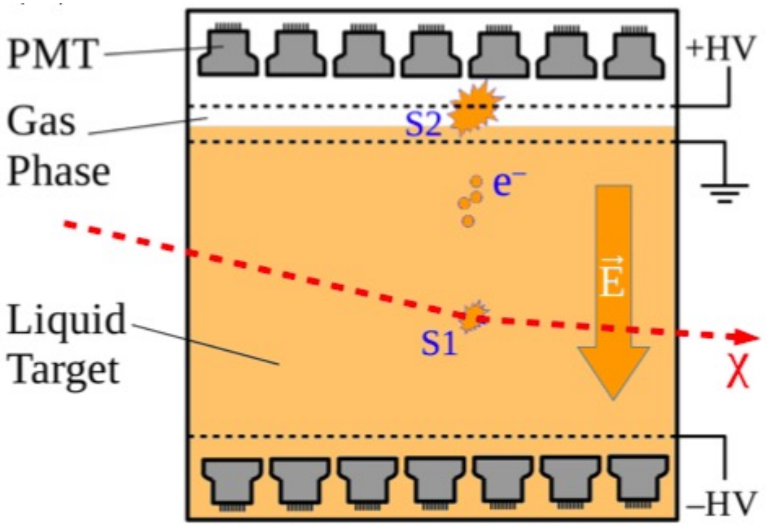
- DRIFT-II TPC @Boulby underground laboratory, 0.140 kg + 55 mbar of a CS_2 +CF_4 +O_2 mixture
- MIMAC @Modane underground laboratory (LSM) in France, 50 mbar of a mixture with CF_4, 28% CHF_3 and 2% C_4H_{10}.
- DMTPC, m3-scale TPC using CF_4 at 50 Torr
- NEWAGE @Kamioka underground laboratory

Advantage:
- statistical discrimination
- nuclear recoil’s track reconstruction

Disadvantage:
- Heavy readout

Dual-phase detectors (liquid and gas)

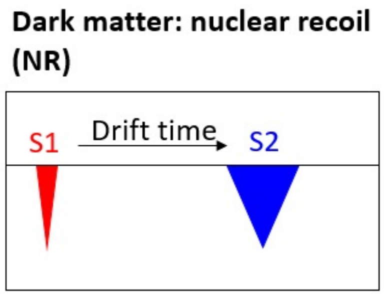
Argon, xenon and helium

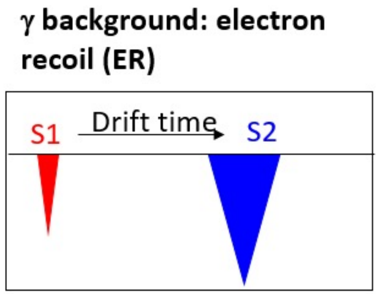


Advantage:
- self-shielding
- 3D position reconstruction
- background discrimination

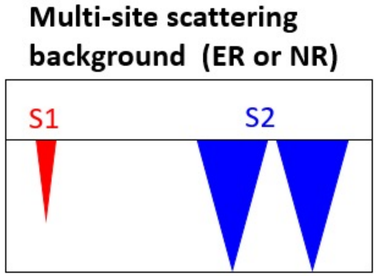
Disadvantage:
- low temperature

- PandaX-4T @Jinping underground laboratory, 4-ton Xe
- LZ @SURF underground laboratory, 7-ton Xe
- XENONnT @LNGS underground laboratory, 6.4 ton Xe
- DarkSide @LNGS underground laboratory, Ar





$(S2/S1)_{NR} << (S2/S1)_{ER}$



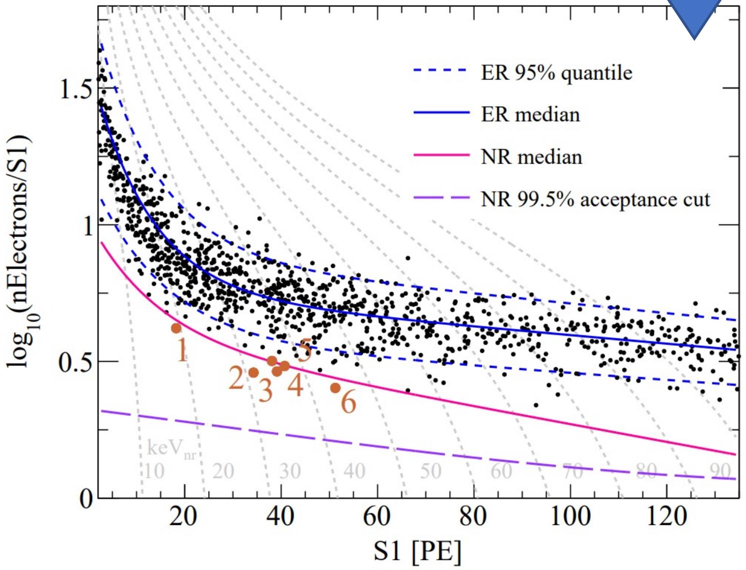
Dual-phase detectors (liquid and gas)

PandaX-4T

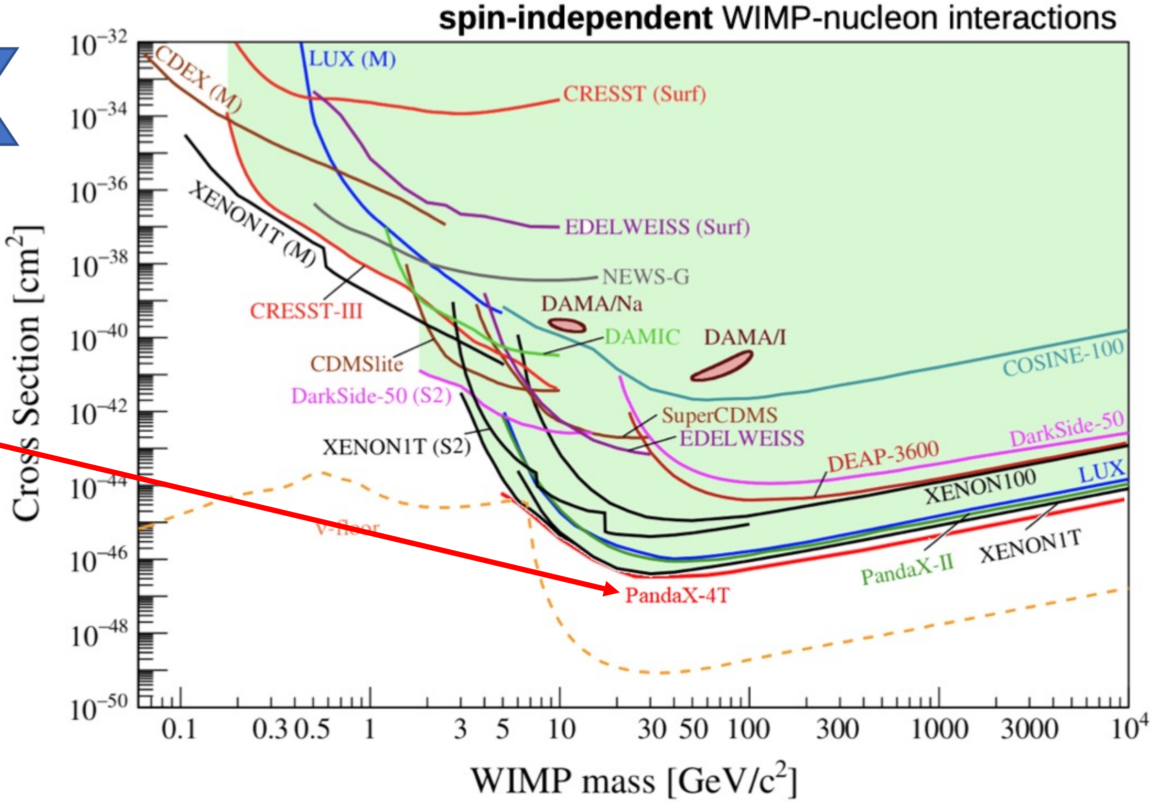
Jianglai Liu, MG-16

- 3.7-tonne of liquid xenon target
- an exposure of 0.63 tonne·year

New



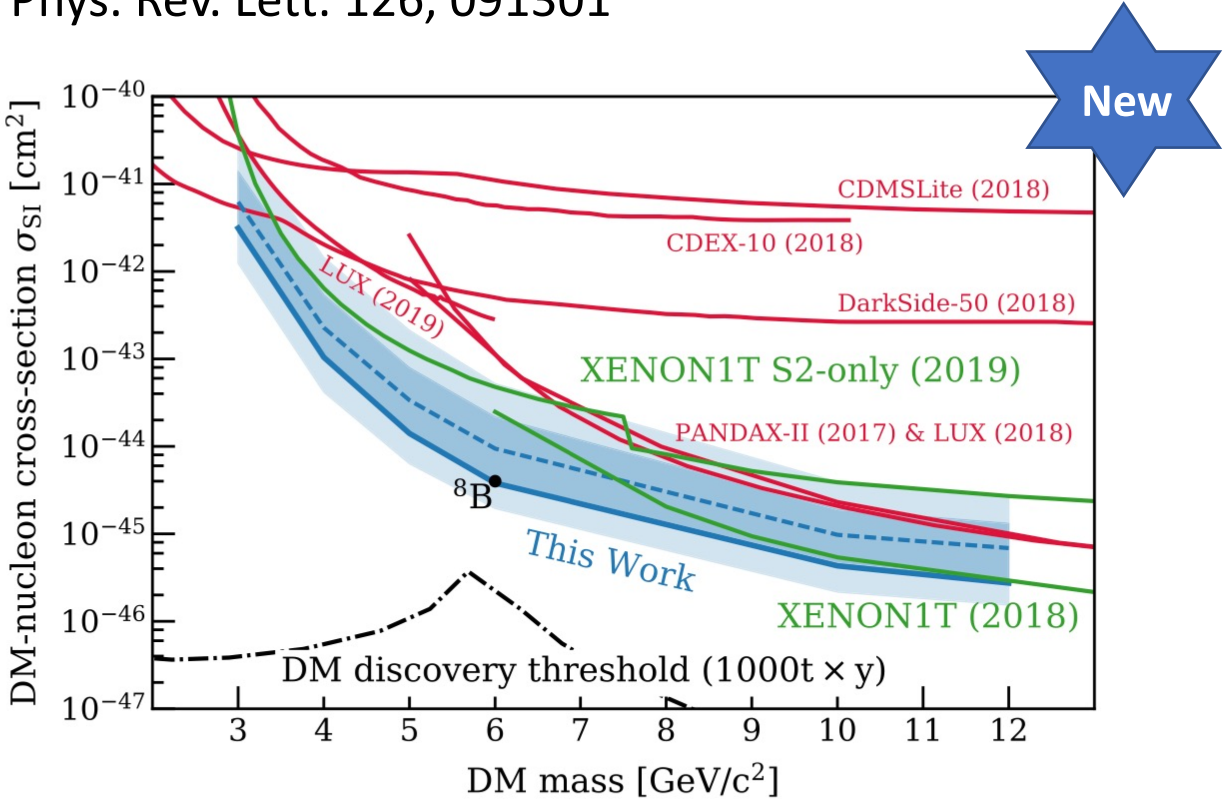
arVix: 2107.13438



Dual-phase detectors (liquid and gas)

XENON1T

Phys. Rev. Lett. 126, 091301

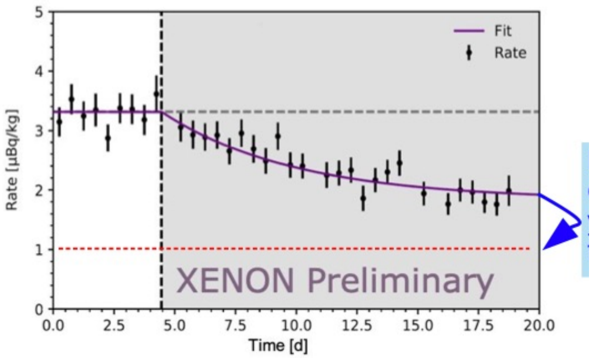


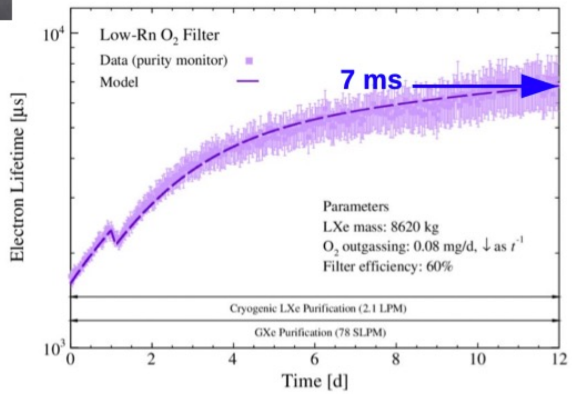
No significant ^{8}B neutrinolike excess is found in an exposure of 0.6t×y

XENONnT

A. Kopec, J. Pienaar @ TAUP 2021

- 5.9 t LXe target
- Rn activity (goal): 1 µBq/kg
- in data taking phase





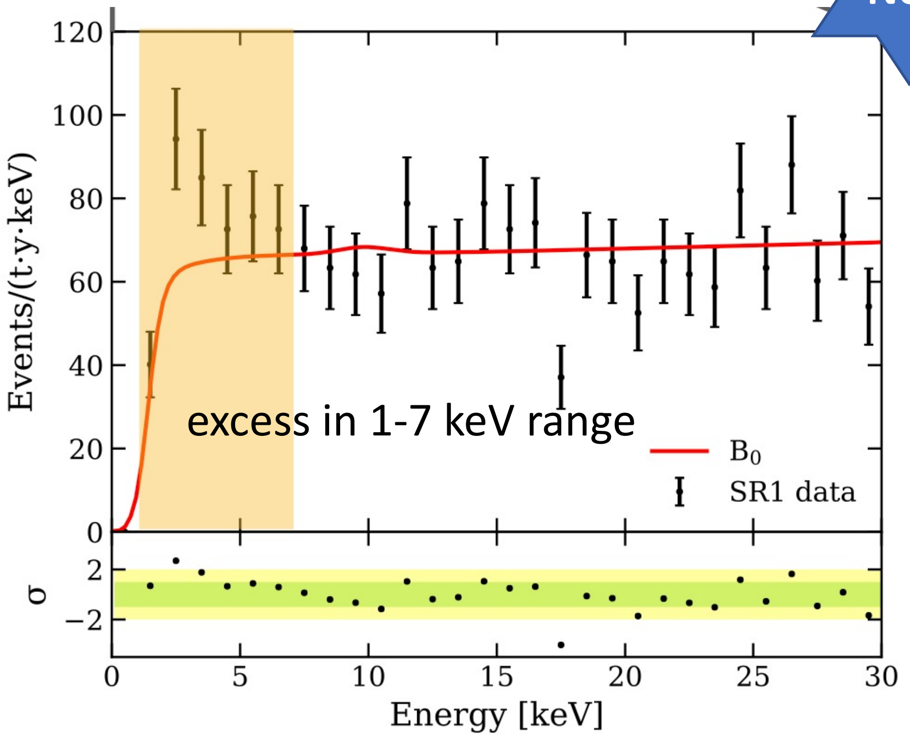
Dual-phase detectors (liquid and gas)

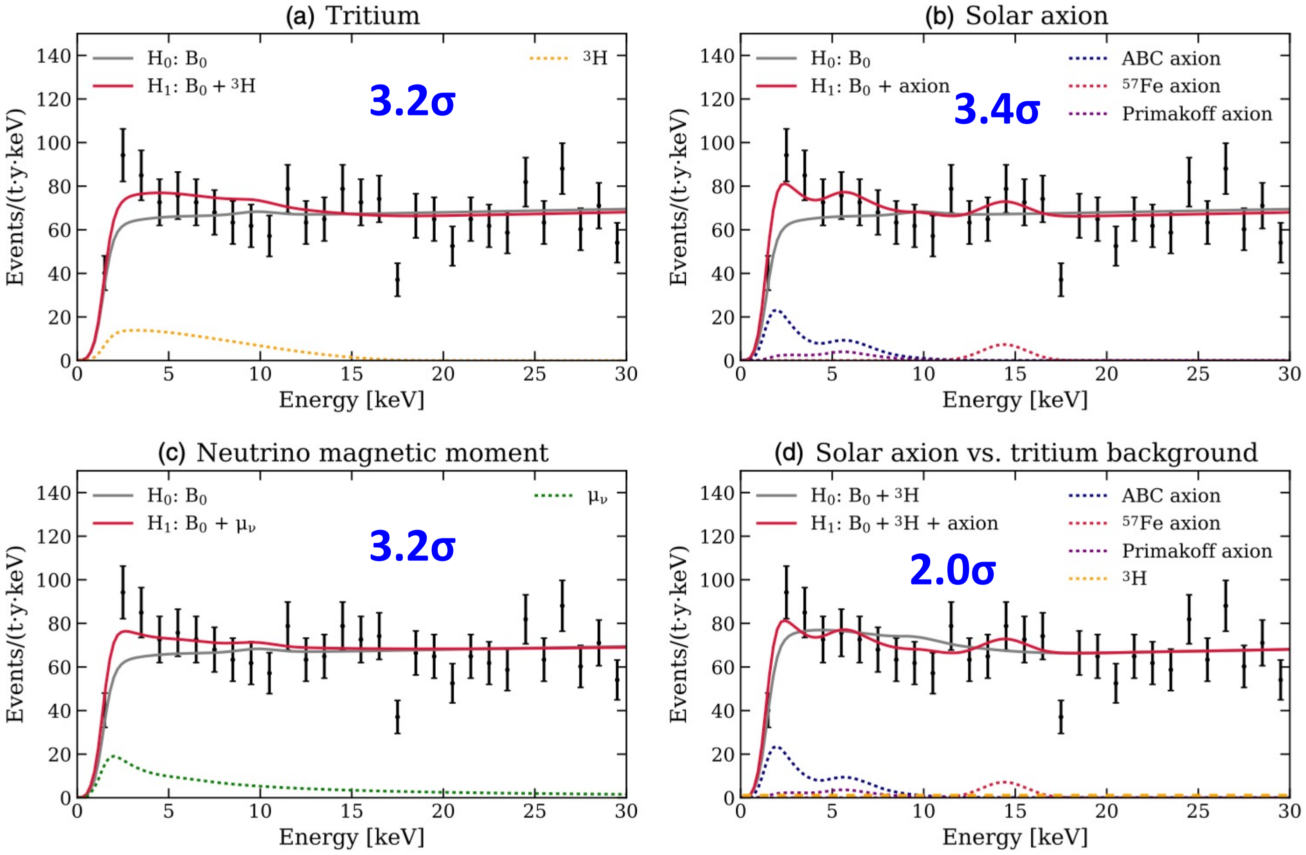
Electronic Recoil Excess in XENON1T

XENON1T

Jingqiang Ye, TAUP 2021

New





285 evts observed vs 232 ± 15 expected

→ 3.3σ fluctuation

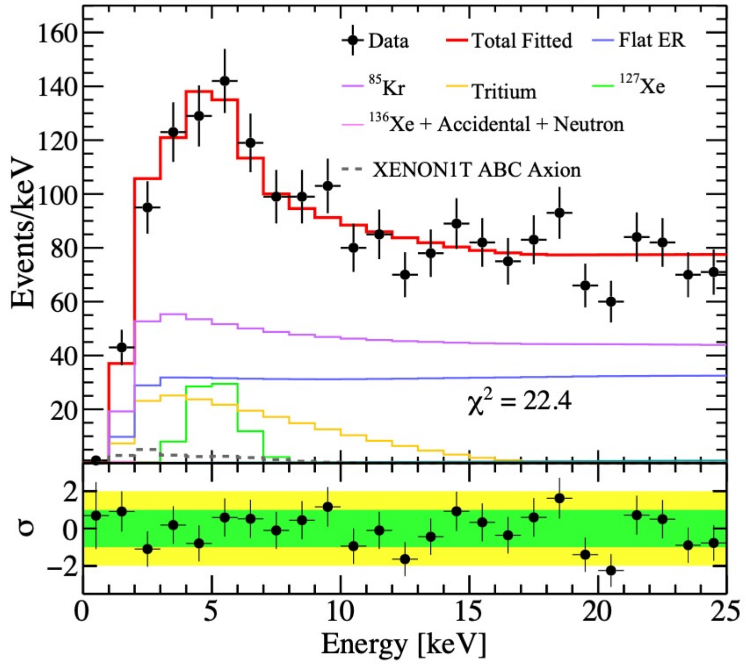
Dual-phase detectors (liquid and gas)

Electronic Recoil Excess in XENON1T

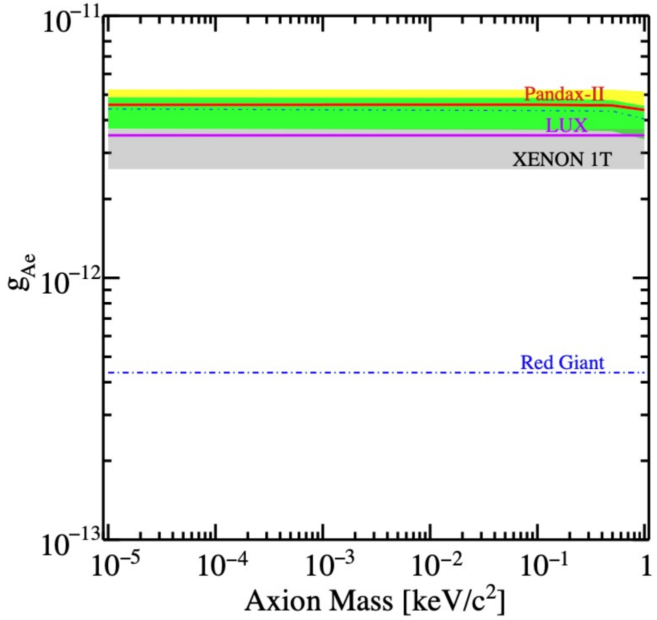
PandaX-II

Chin. Phys. Lett. 2021, Vol. 38 Issue (1): 011301

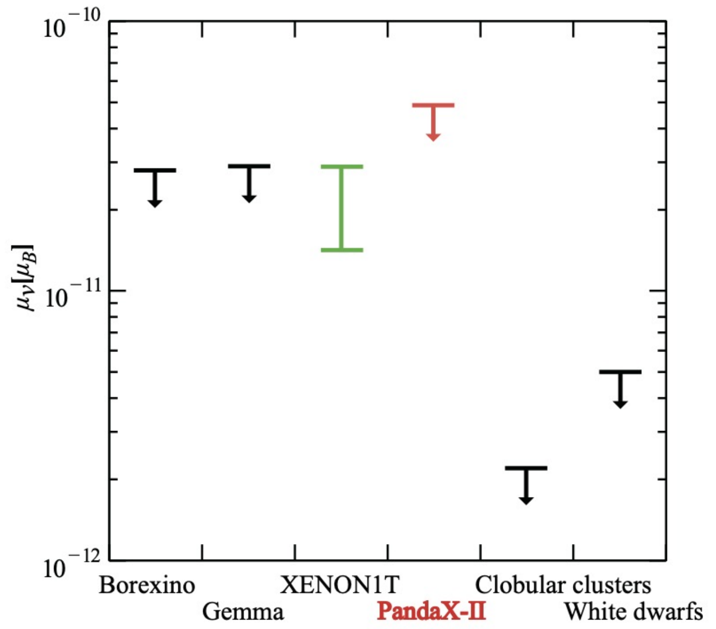
New



- the axion-electron coupling $g_{Ae} < 4.6 \times 10^{-12}$ for an axion mass less than 0.1 keV/c2



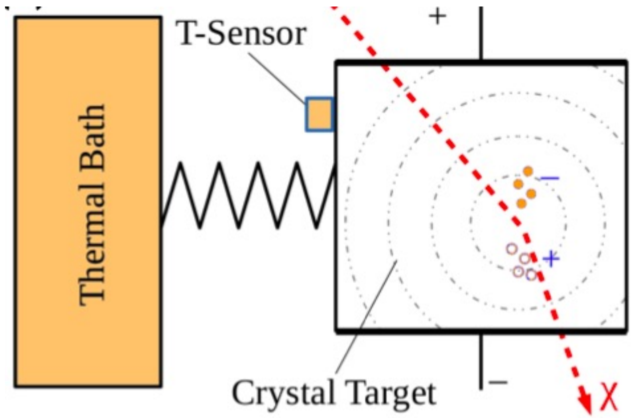
- the neutrino magnetic moment $\mu_\nu < 4.9 \times 10^{-11} \mu B$ at 90% confidence level.



The observed excess from XENON1T is within PandaX-II experimental constraints.

Cryogenic bolometers

Detectors collecting the phonon signal produced in a crystal



Advantage:

- low thresholds
- excellent energy resolution
- background discrimination
- location of the recoil

Disadvantage:

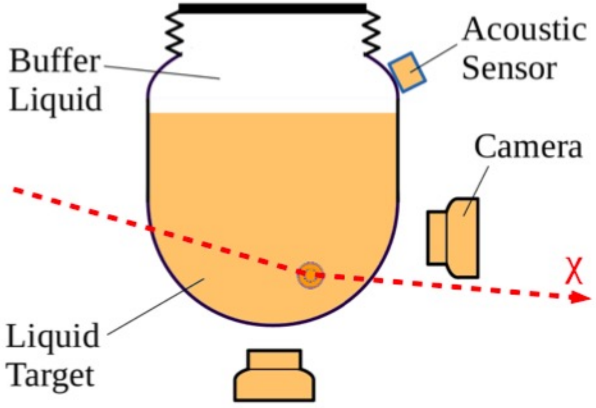
- limited size
- Complicates scale up

- CDMS/CDMS II @Soudan Underground Laboratory, 19Ge and 11Si detectors with a mass of 230g and 100g each
- SuperCDMS @SNOLAB, iZIP detector, interleaved structure of the phonon and ionisation electrodes at the top and bottom faces of the crystals, 5 Ge crystals with masses of 0.6kg
- CDMSlite, larger bias boosts phonon signals from drifting charges to lower energy threshold
- EDELWEISS @Laboratoire Souterrain de Modane (LSM), thermalized phonons with NTDs, 800g germanium bolometers
- CRESST-II @Laboratori Nazionali del Gran Sasso (LNGS), both phonon signal and the scintillation light, $CaWO_4$ crystals, 300 g x 8
- ROSEBUD @ Canfranc Underground Laboratory, sapphire crystals
- EURECA (European Underground Rare Event Calorimeter Array), aims to build a facility to operate 1000kg of cryogenic detectors, both $CaWO_4$ and Ge detectors

Bubble chambers

Superheated fluids

The liquids are kept at a temperature just above their boiling point such that a local phase transition will create a bubble



Advantage:

- low thresholds
- immune to electronic recoils

Disadvantage:

- No energy reconstruction
- complicated calibration

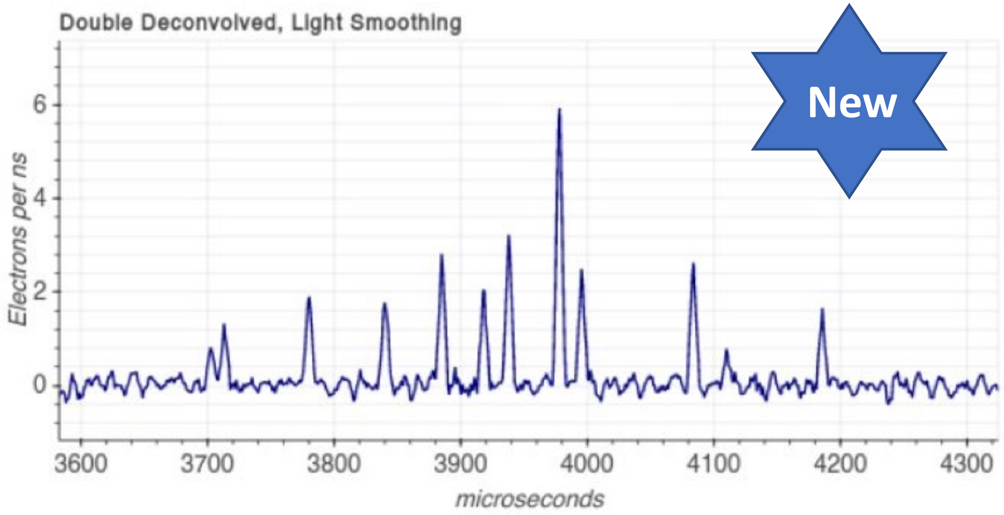
- PICO(PICASSO, COUPP), @SNOLAB 52kg C3F8
- SIMPLE, @LSBB in France, 15g of C2ClF5 as a target

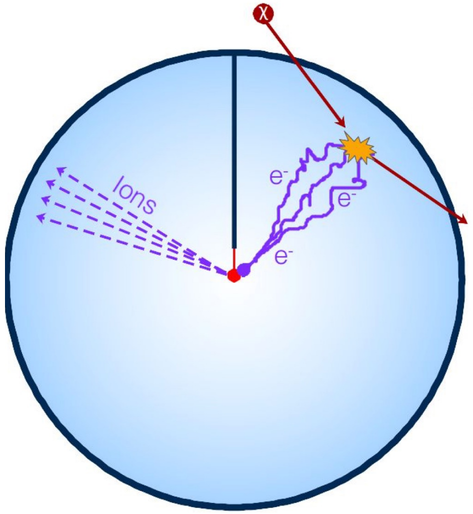
Spherical gaseous detector

NEWS-G
Marie-Cécile Piro and Daniel Durnford, TAUP 2021

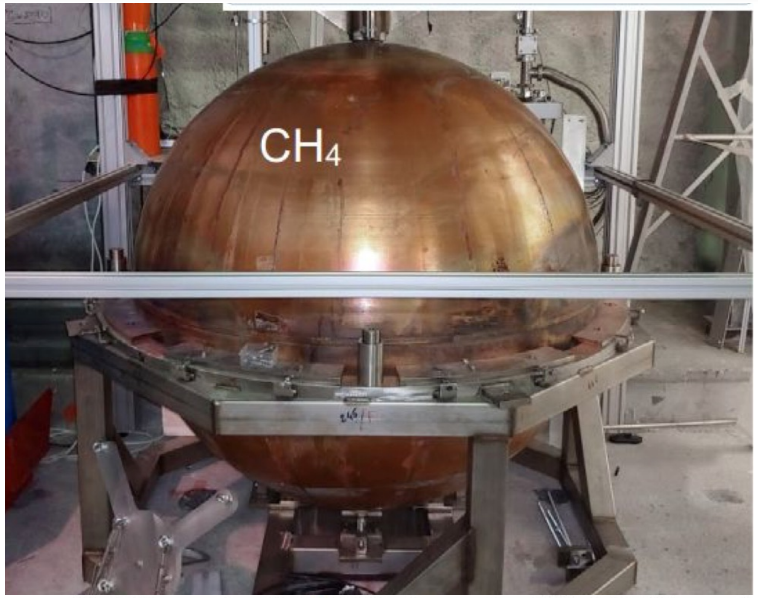
- a noble gas mixture
- Energy threshold ~10 eV

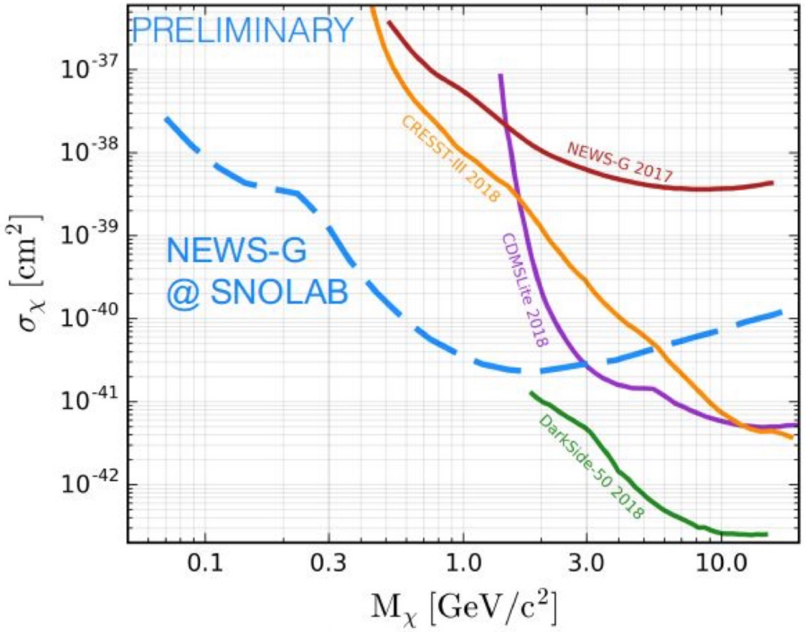
UV Laser events from new 140cm SPC:





(1) Primary Ionization
(2) Drift of charges
(3) Avalanche of secondary



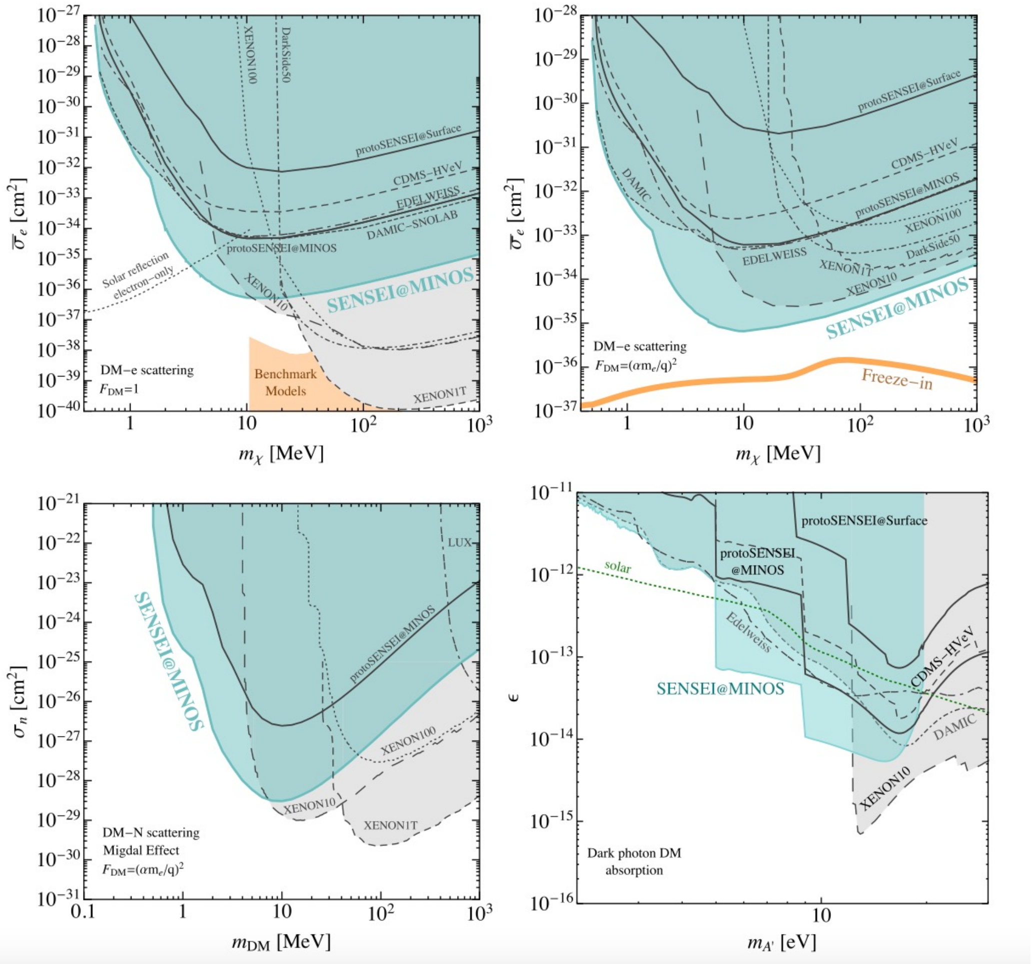


First light was observed @2021

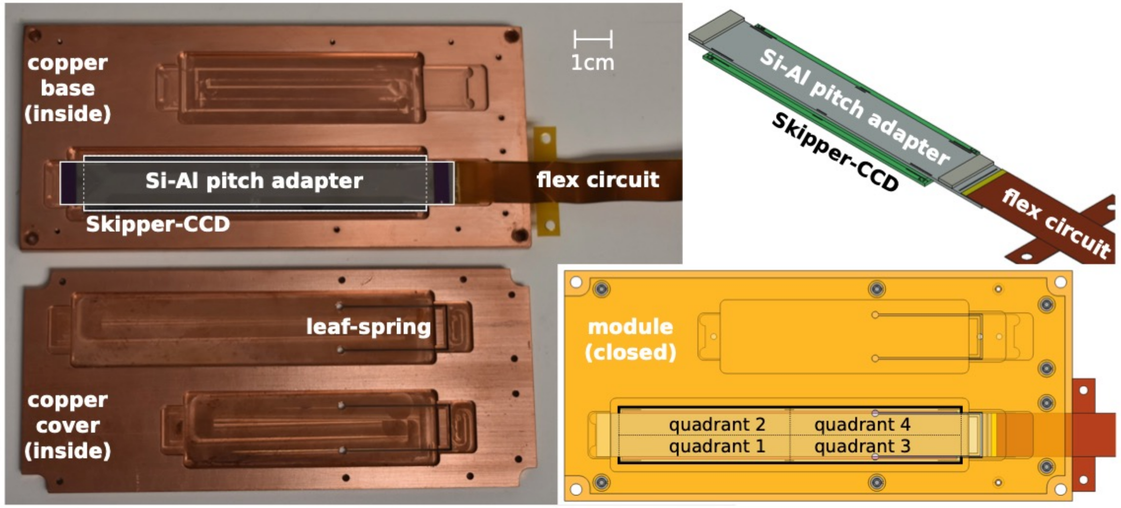
Sub-GeV WIMP detection

CCD

SENSEI
Phys. Rev. Lett. **125**, 171802



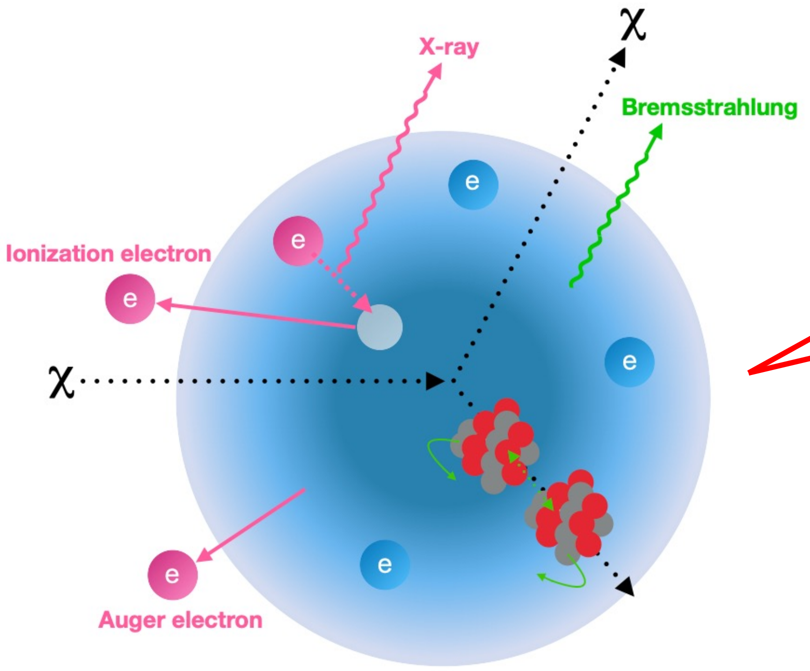
- ultralow-noise silicon Skipper charge-coupled-devices (Skipper CCDs)
- ~2g Si-CCD provides best limits >500 keV/c^2

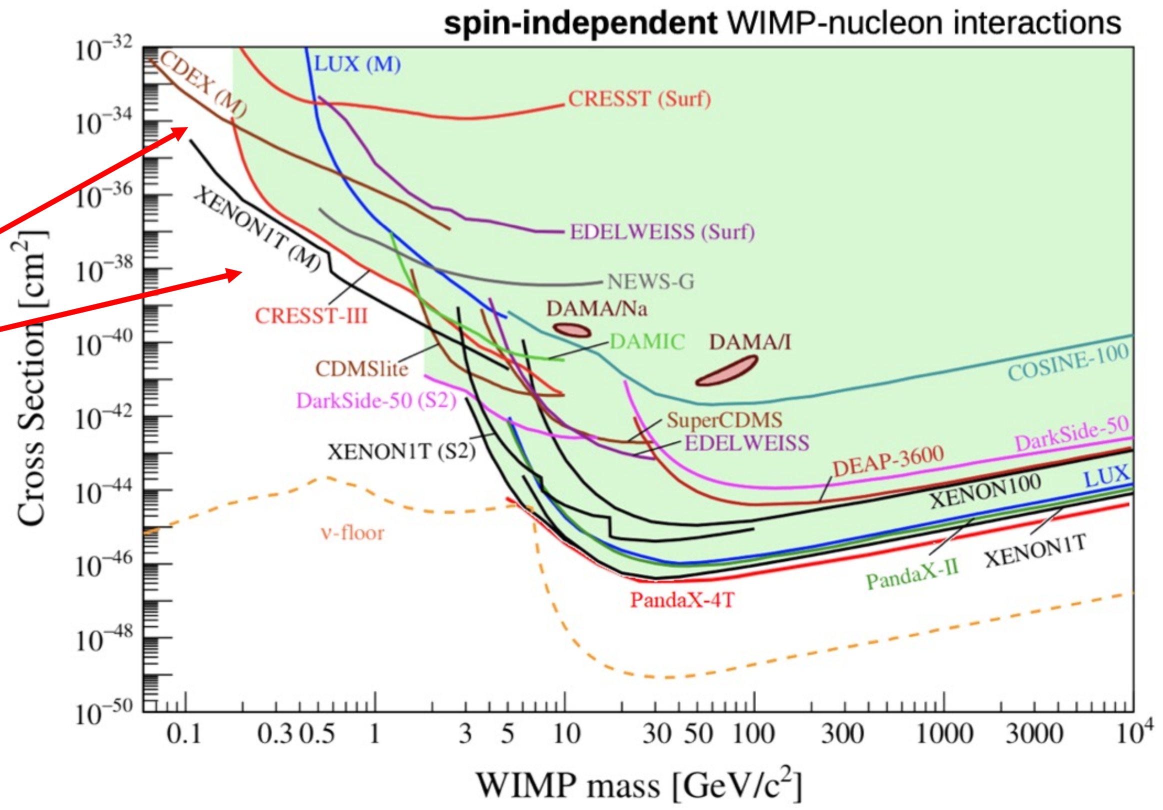


Migdal effect

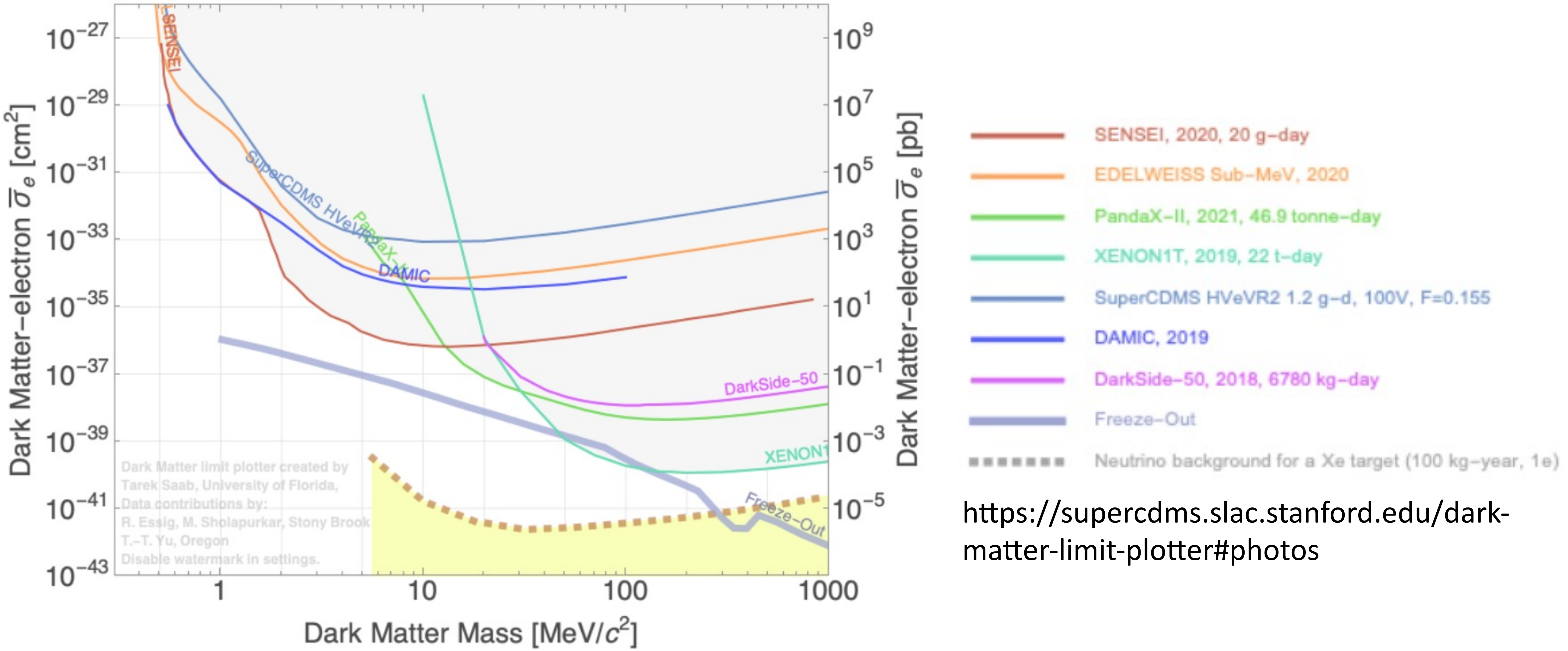
XENON1T
Phys. Rev. Lett. **125**, 171802

- searching for nuclear recoils further into the MeV/c2-regime



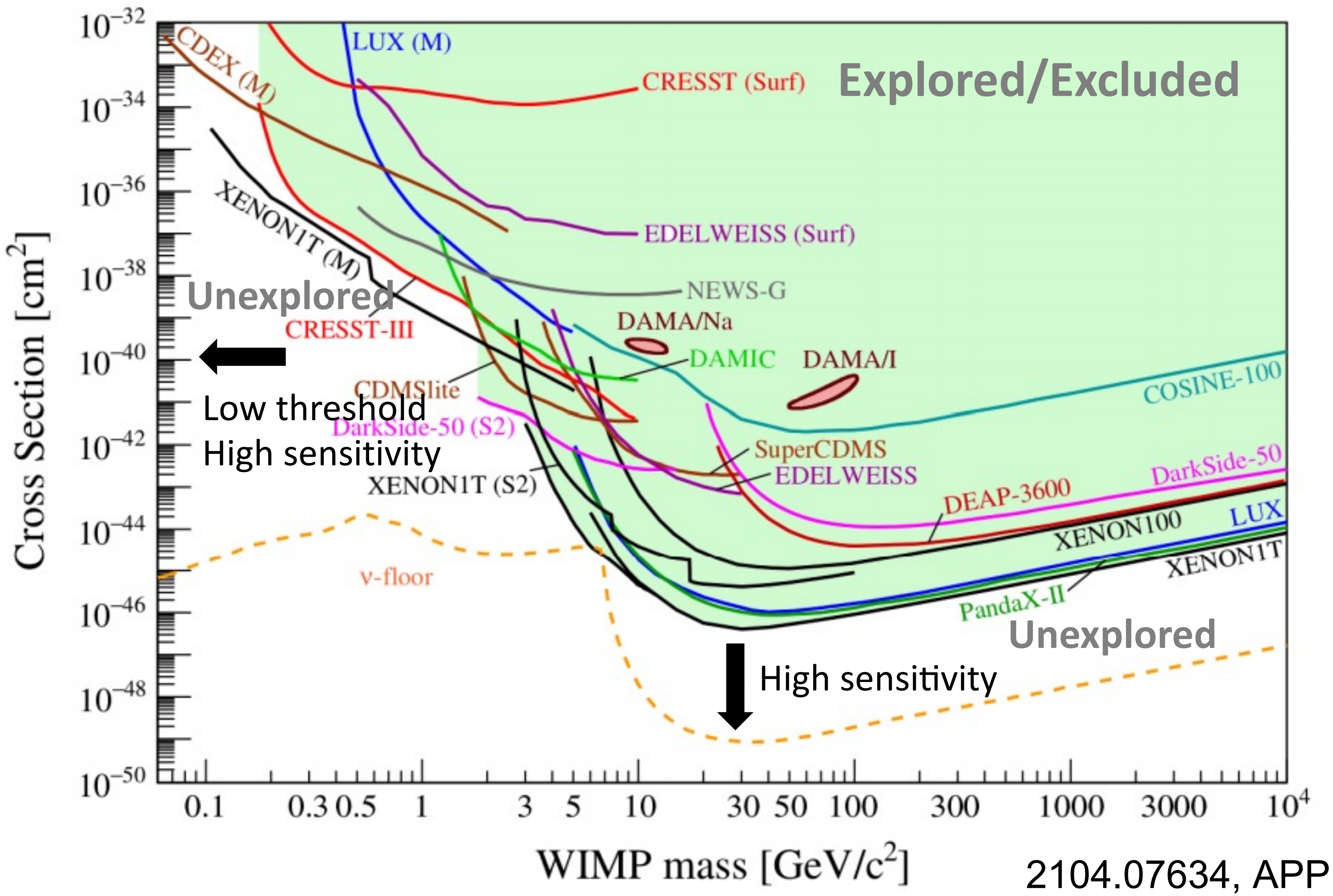


WIMP-e⁻ scattering



https://supercdms.slac.stanford.edu/dark-matter-limit-plotter#photos

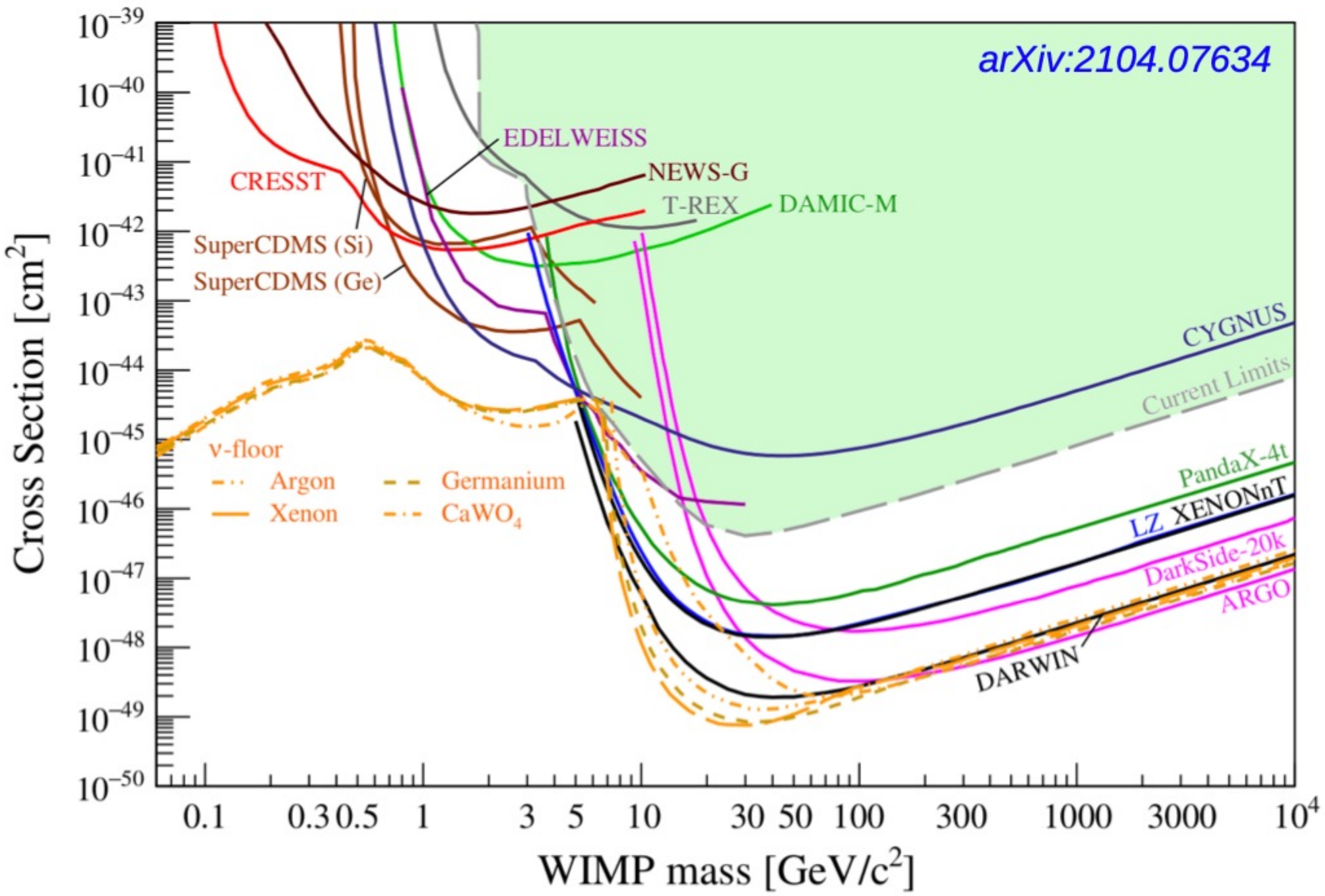
WIMP future



2104.07634, APPEC report on dark matter direct detection

Summary

- **Diverse direct detection techniques are applied to search WIMPs**
- **Unexplored parameter space will be scanned with next generation DM experiments**



Thank you for listening!

Many materials borrowed from public talks presented by individual collaborations
arXiv: 1509.08767, 1903.03026, 2104.07634