3RD SOUTH AMERICAN DARK MATTER WORKSHOP
ICTP-SAIFR, SÃO PAULO, BRAZIL

DIRECT DETECTION: A REVIEW OF TECHNIQUES AND RESULTS

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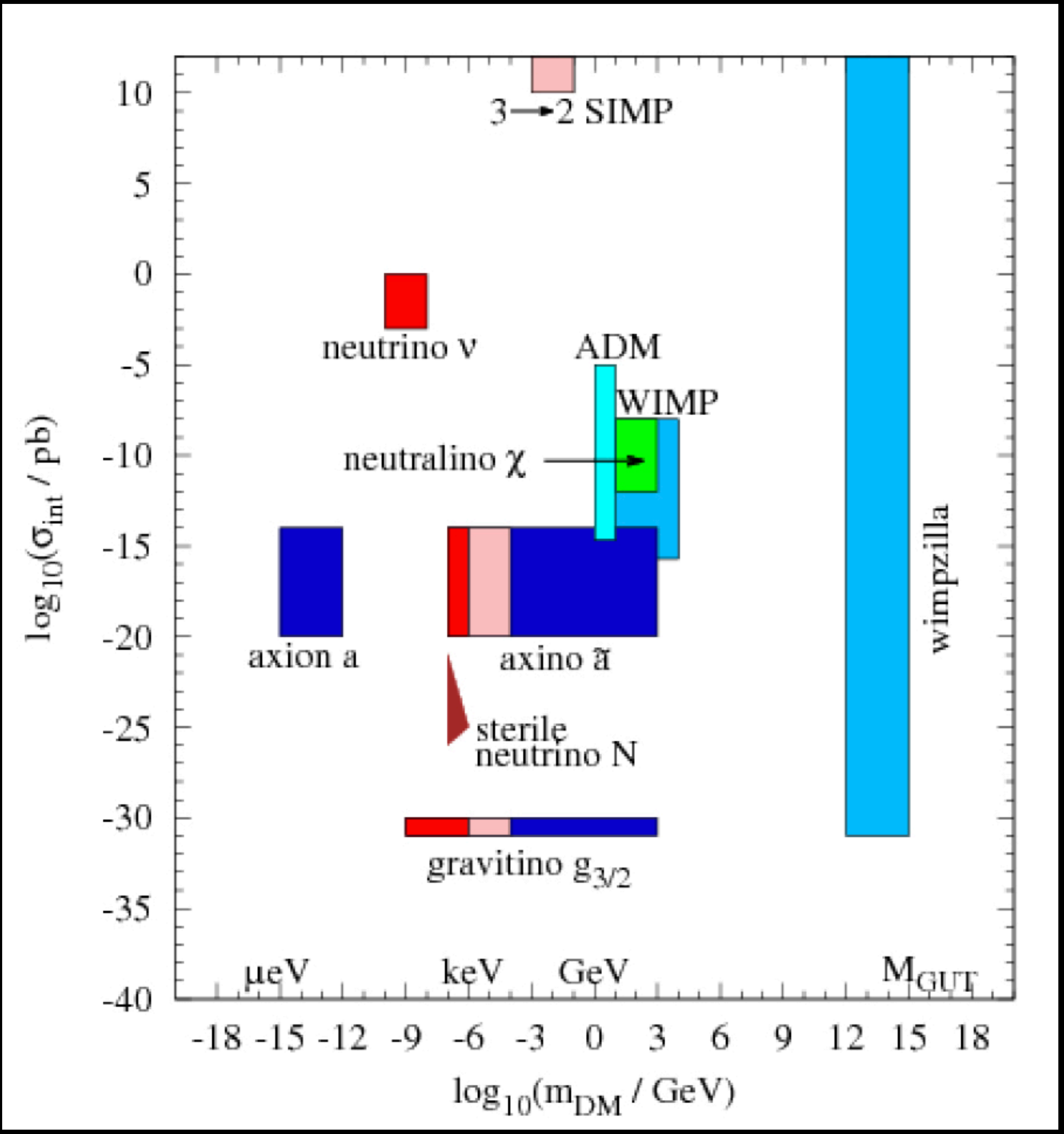
DECEMBER 2, 2020

MY TAKE-HOME MESSAGE FROM TWO PREVIOUS TALKS

- Absence of evidence IS NOT Evidence of absence
- Worth to look for DM EVERYWHERE

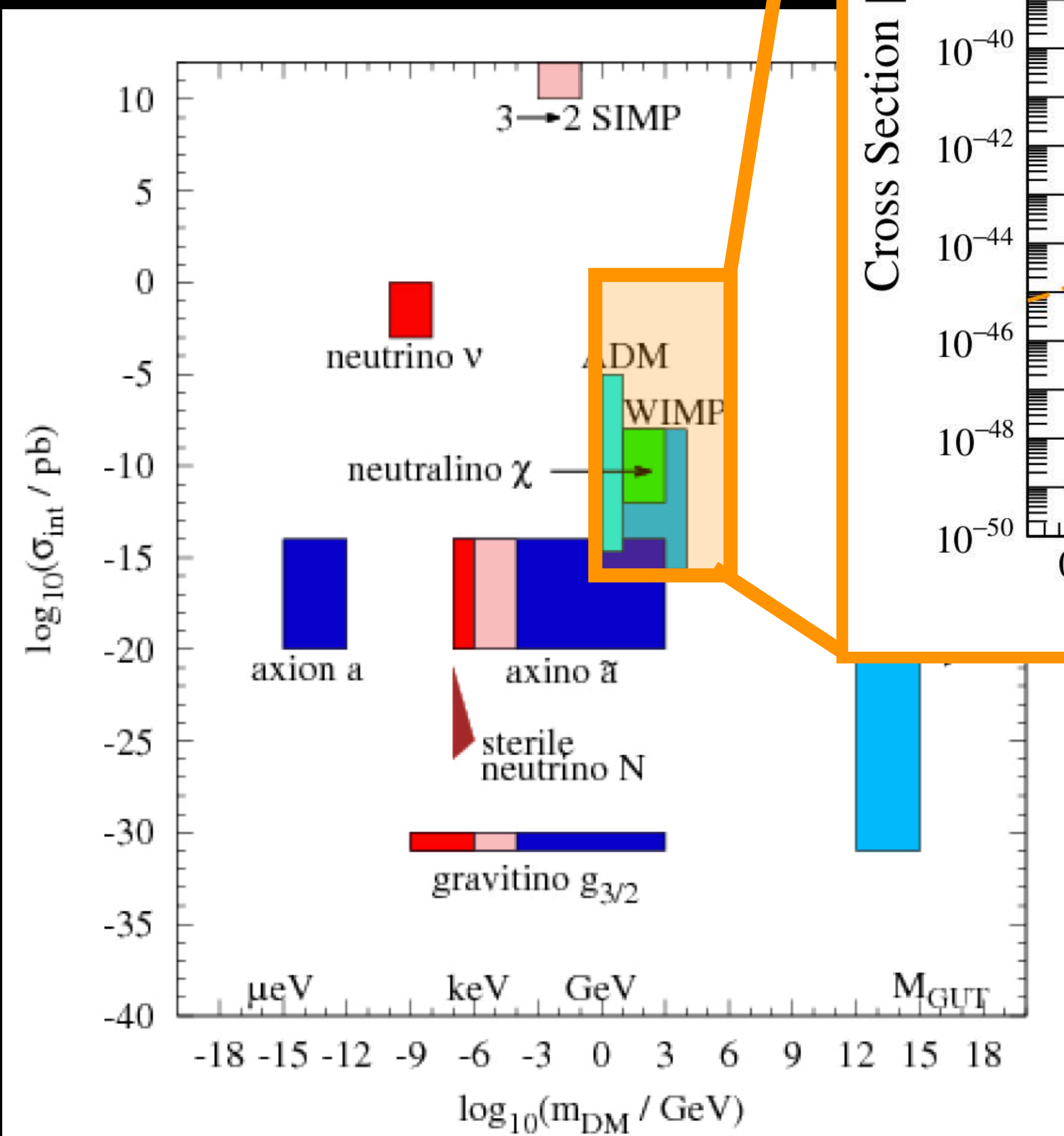
DARK MATTER CANDIDATES



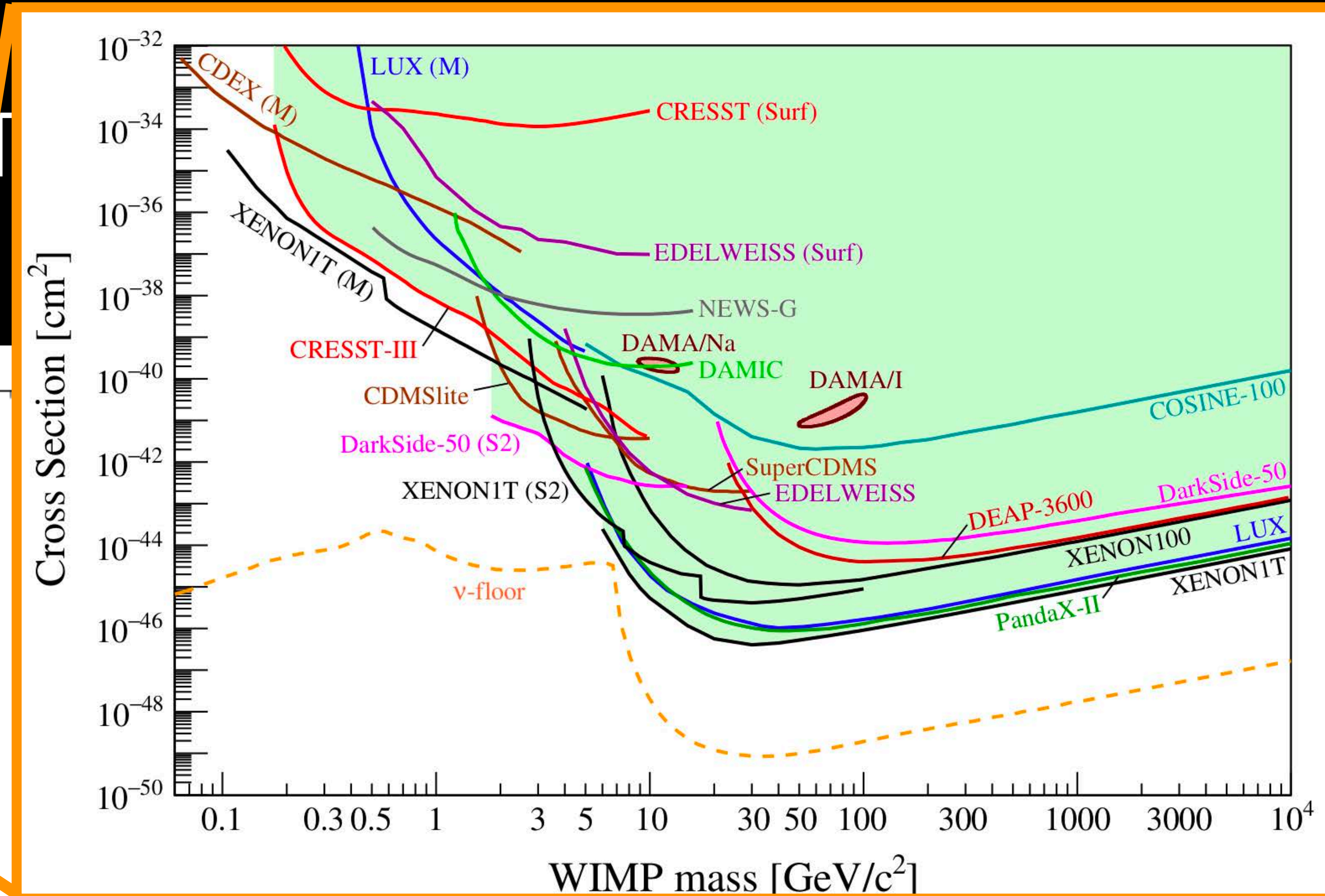
Baer et al., arXiv:1407.0017

- Thermal relics:
  - WIMP: generic weakly interacting massive particle
  - ADM: asymmetric dark matter
  - SIMP: strongly interacting massive particle
  - …
- Non- thermal relics
  - Axion: very light mass (10^{-5} eV), CDM because produced at rest in the early Universe. Its interaction strength is strongly suppressed relative to the weak strength by a factor $(m_W/f_a)^2$, where $f_a \sim 10^{11}$ GeV is the PQ breaking scale
  - … and many more

DARK MATT



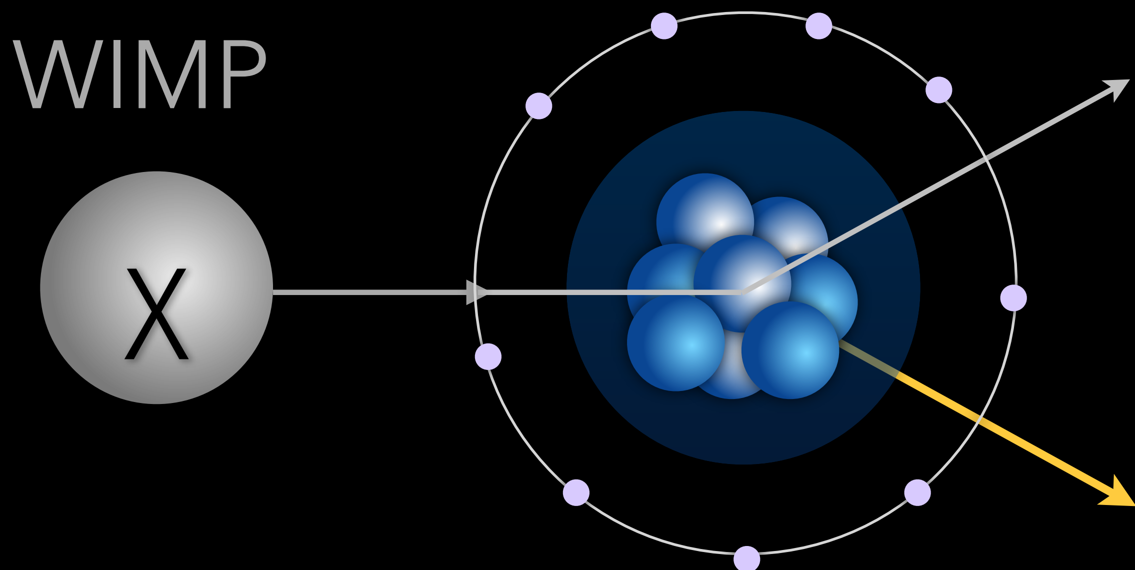
Baer et al., arXiv:1407.0017



APPEC DM Report, to be published

Direct searches generally optimised for WIMP sensitivity...

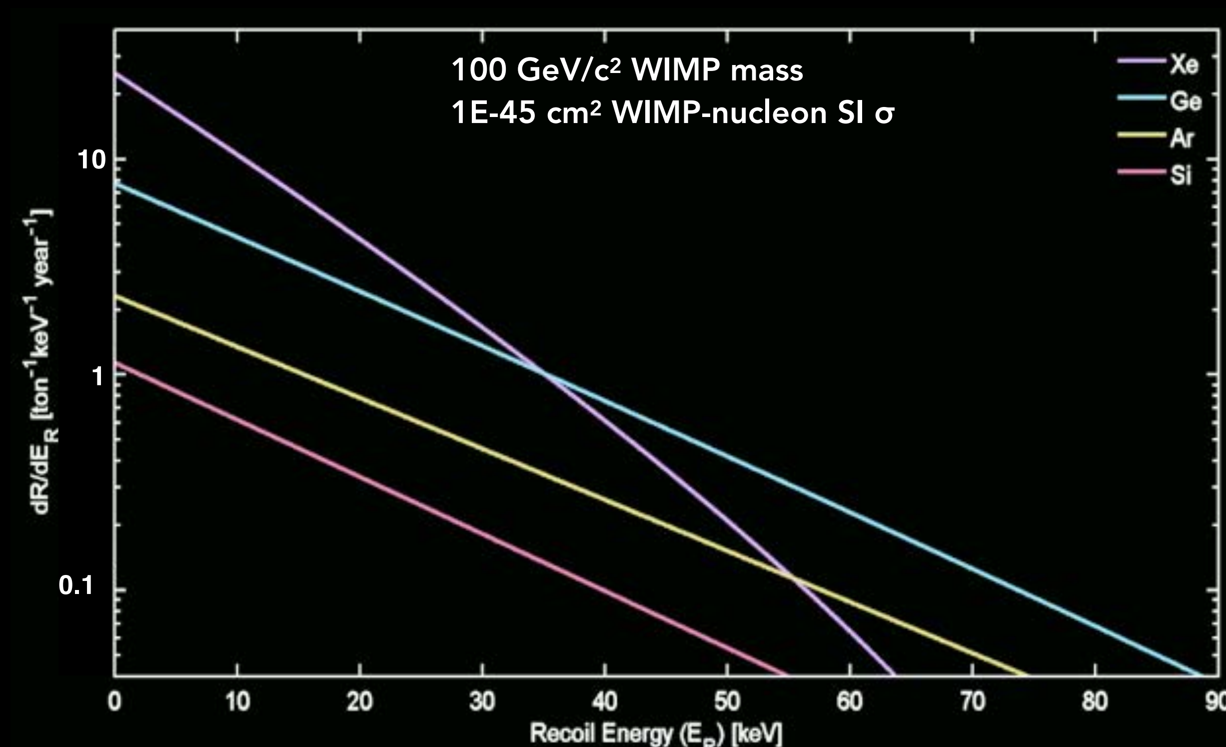
WIMP DIRECT DETECTION



$\chi N \rightarrow \chi N$

elastic scattering off nuclei

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \times \int d\mathrm{v}\, f(\mathrm{v})\, \mathrm{v} \frac{d\sigma_\chi}{dE_R}$$



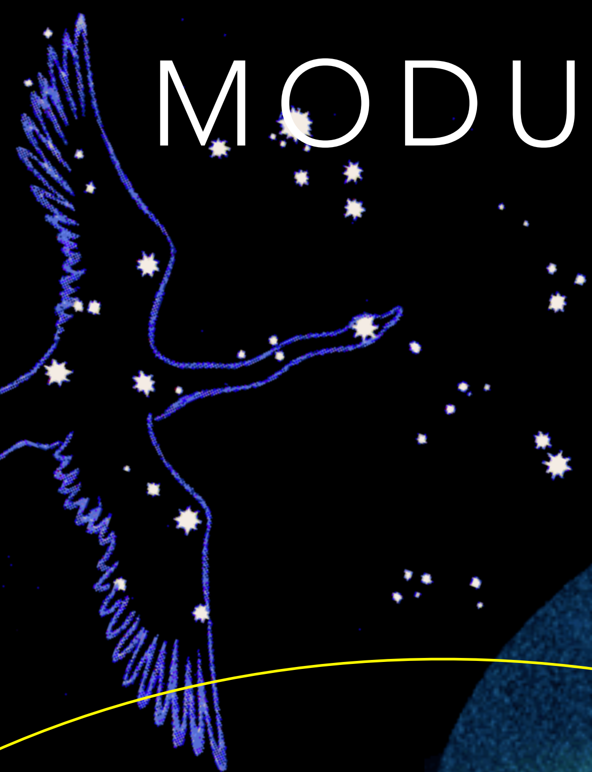
Spin Independent:
χ scatters coherently off of the entire nucleus: $\sigma \sim A^2$

Spin Dependent:
only unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

- Large detector mass, long exposure
- Low energy threshold
- Ultra-low radioactive bg
- Good bg discrimination

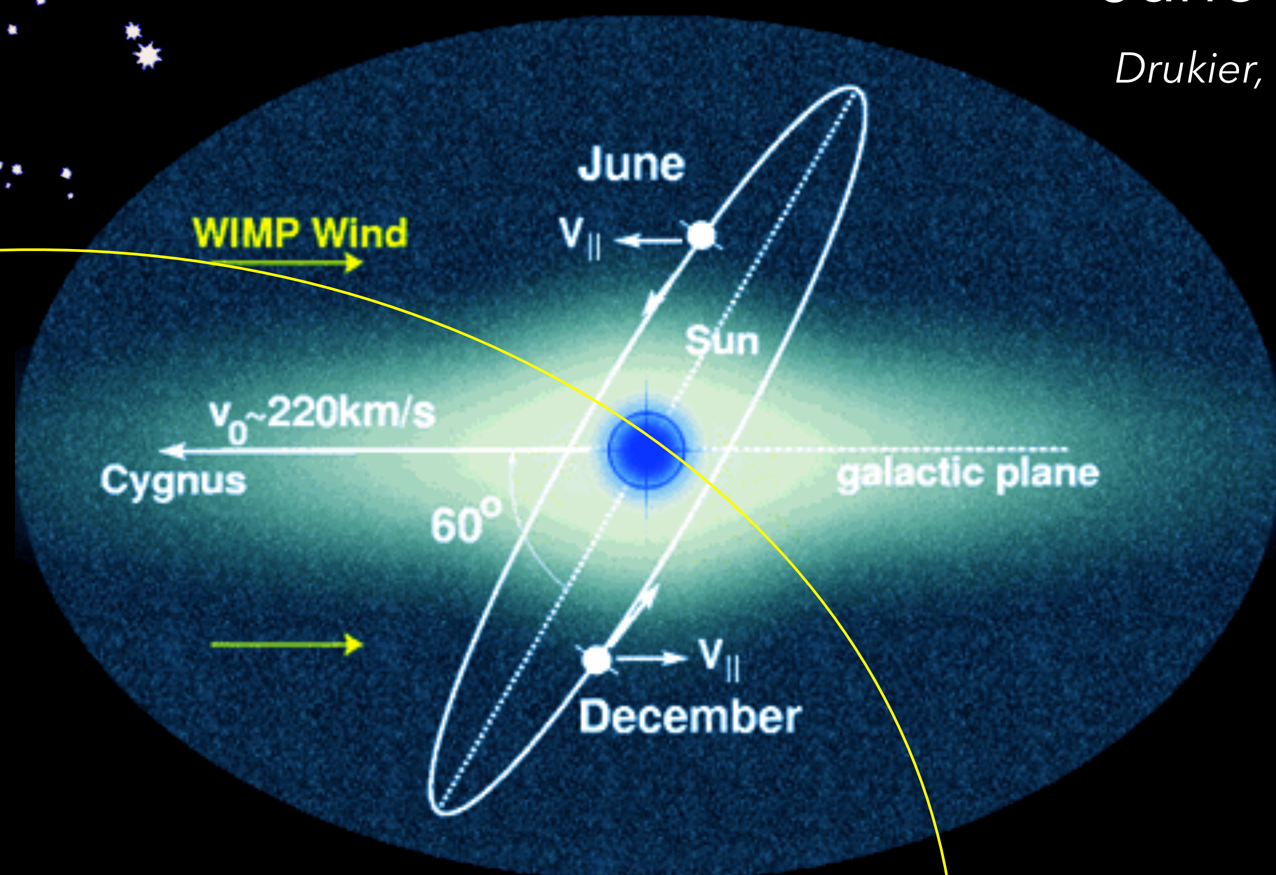
- Low rate
- Nuclear recoil energy ≈ 1÷100 keV

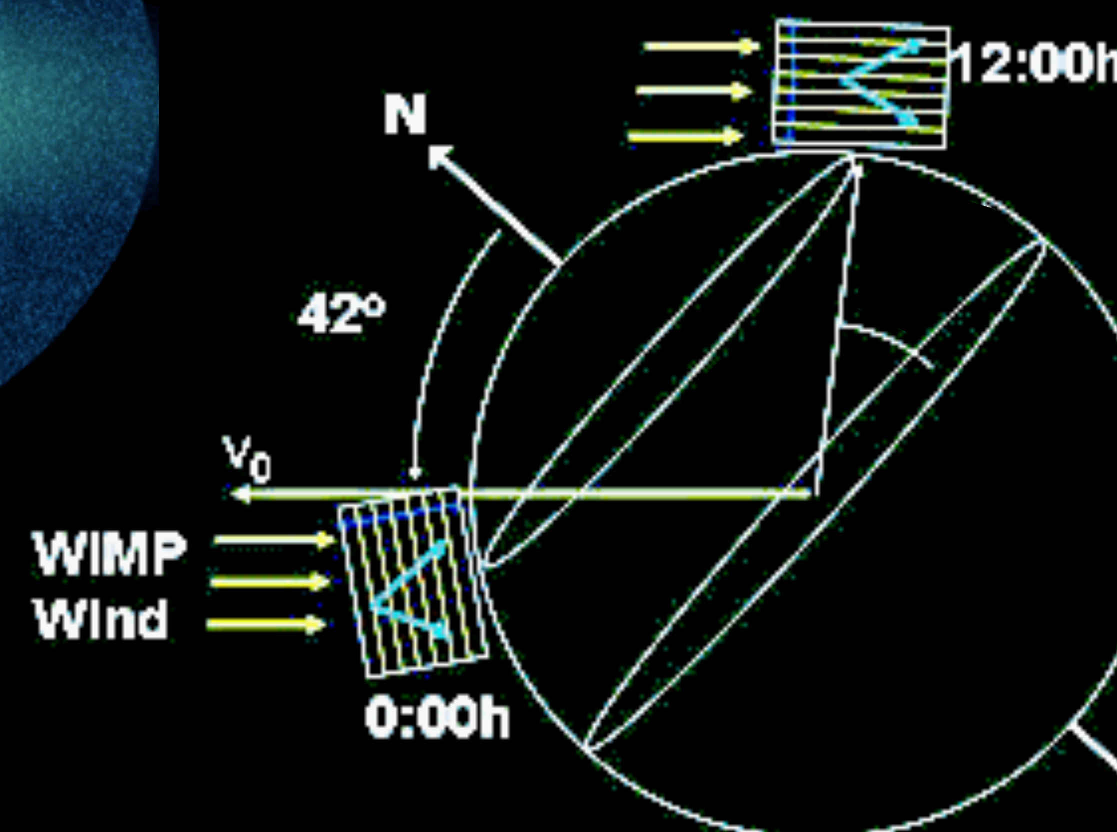
MODULATION SIGNATURES



Annual event rate modulation:
June-December asymmetry ~2-10%

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)





Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate

Spergel, Phys. Rev. D36:1353 (1988)

×3 rate variation of parallel vs perpendicular directions

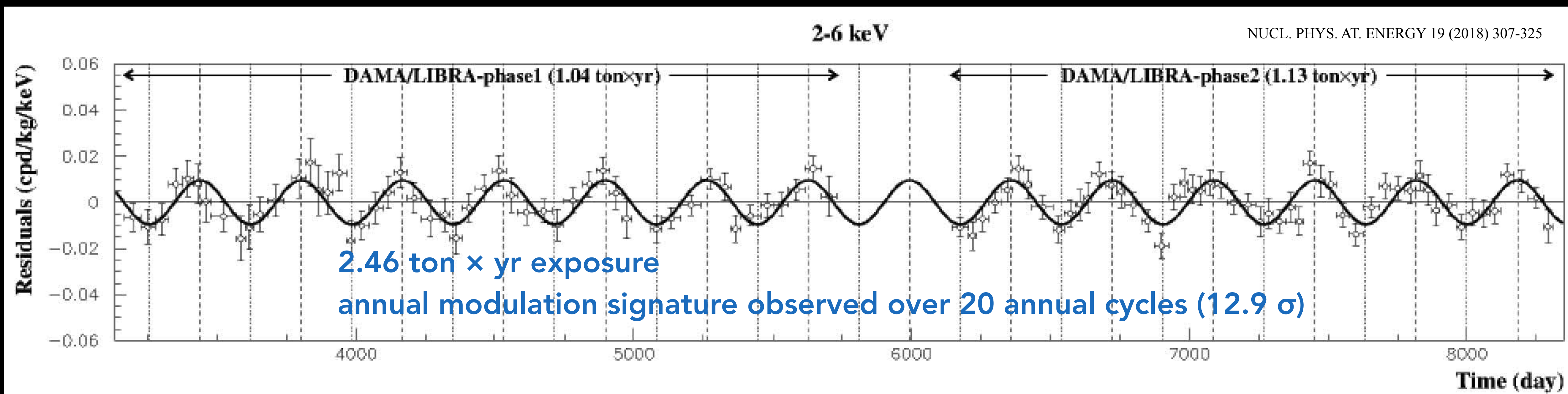
Credits Jocelyn Monroe

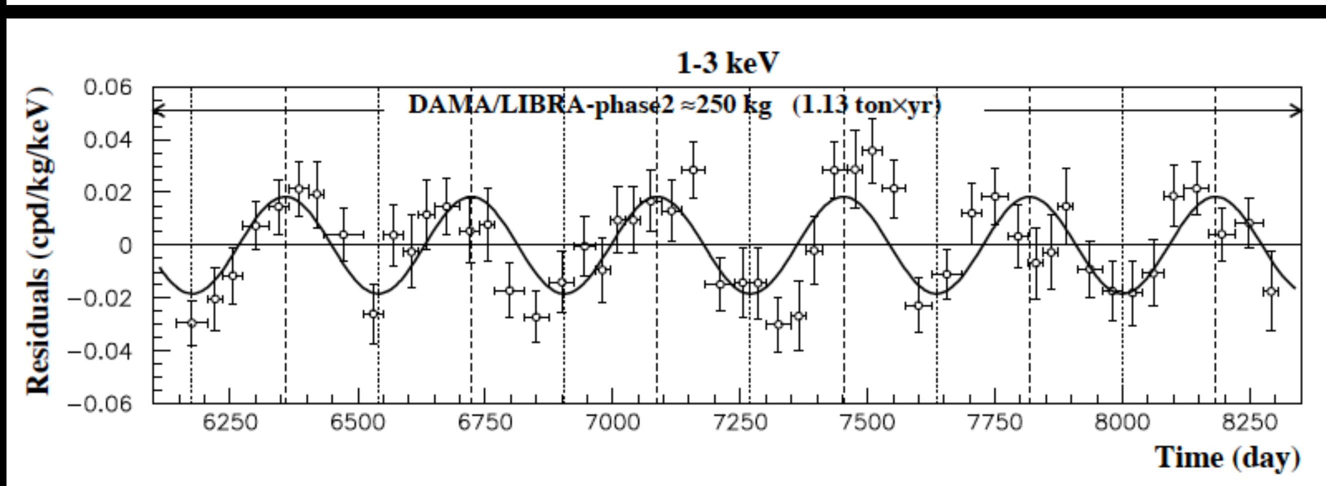
DAMA MODULATION SIGNAL

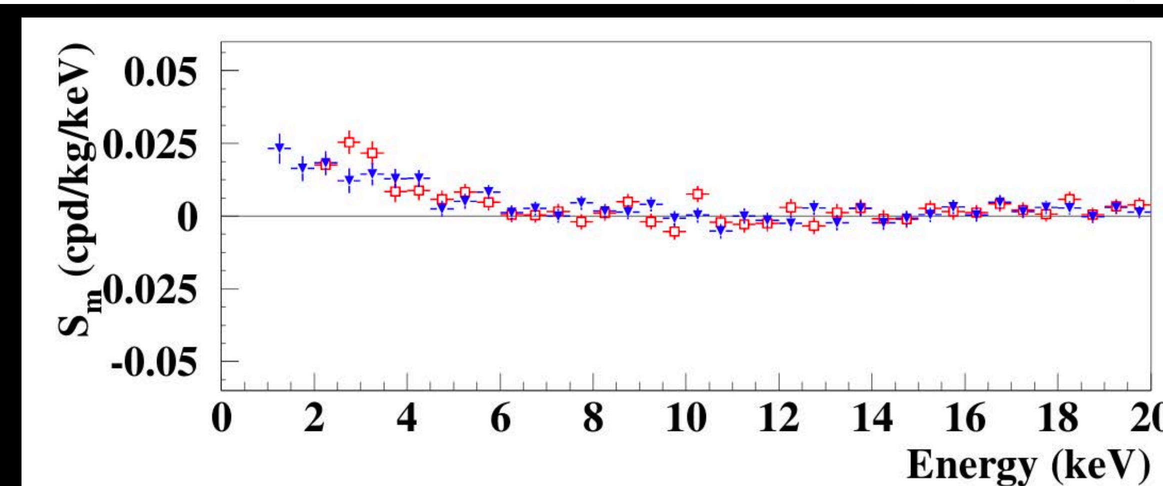
Standard Halo Model predicted modulation A~0.02-0.1, t_0=152.5 days

DAMA/NaI + DAMA/LIBRA-phase1 + phase2:

A= (0.0103 ± 0.0008) cpd/kg/keV, t_0 = (145±5) d in 2.46 t-yr (2 - 6 keV)







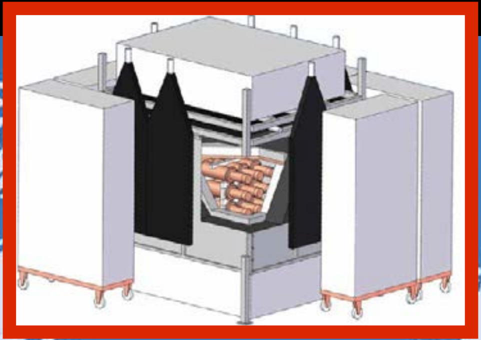
1804.01231, Baum, Freese, Kelso "Dark Matter implications of DAMA/LIBRA-phase2 results"
"the observed annual modulation signal is no longer well fitted by canonical (isospin conserving) spin-independent WIMP nucleon couplings"

Data collection expected to go on until the end of 2024, work underway for phase 3, to lower the software energy threshold below 1 keVee

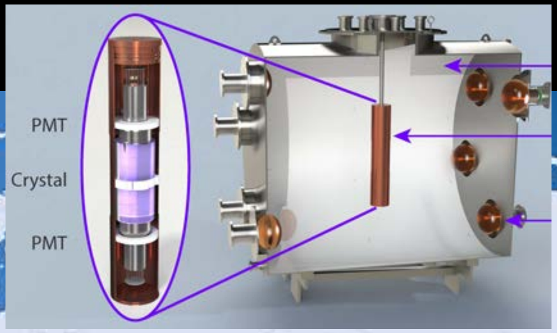
MODEL INDEPENDENT CHECK

NaI experiments

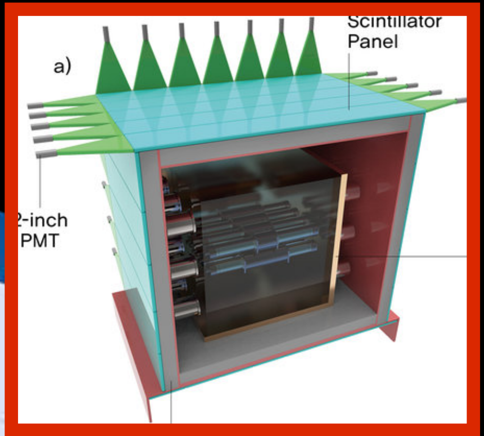
ANAIS-112



SABRE NORTH

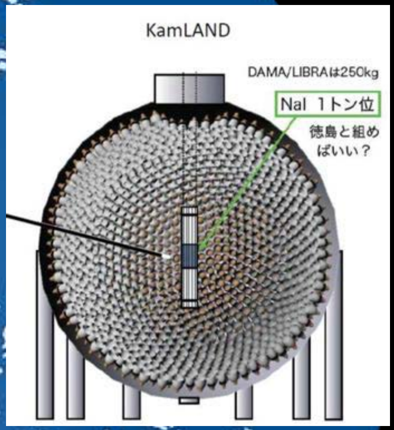


COSINE-100



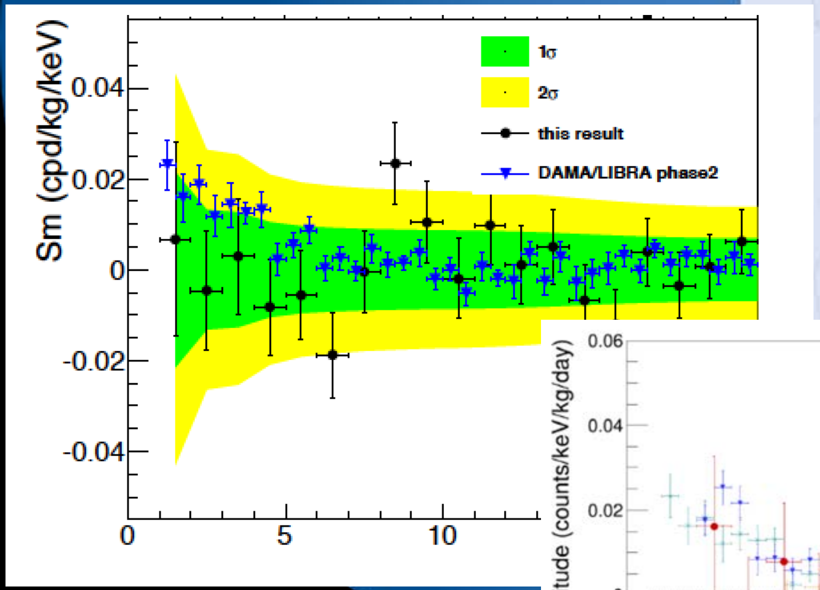
COSINUS

PICOLON

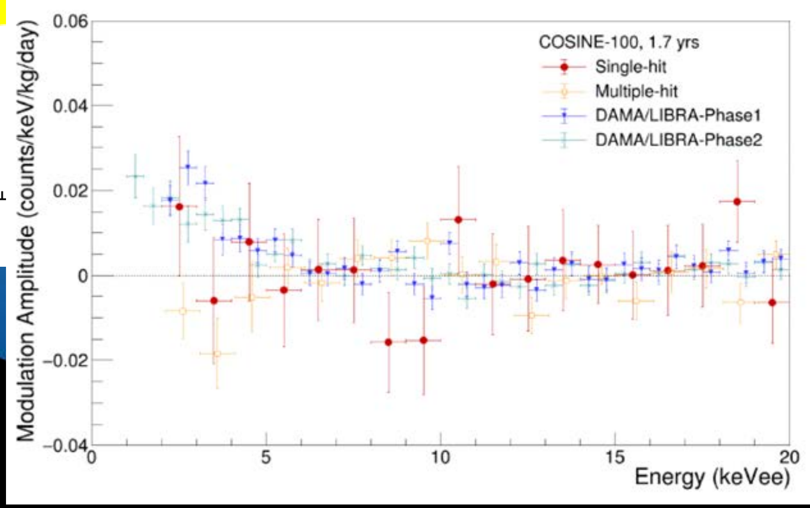


TAKING DATA

ANAIS,
Phys. Rev. Lett. 123, 031301



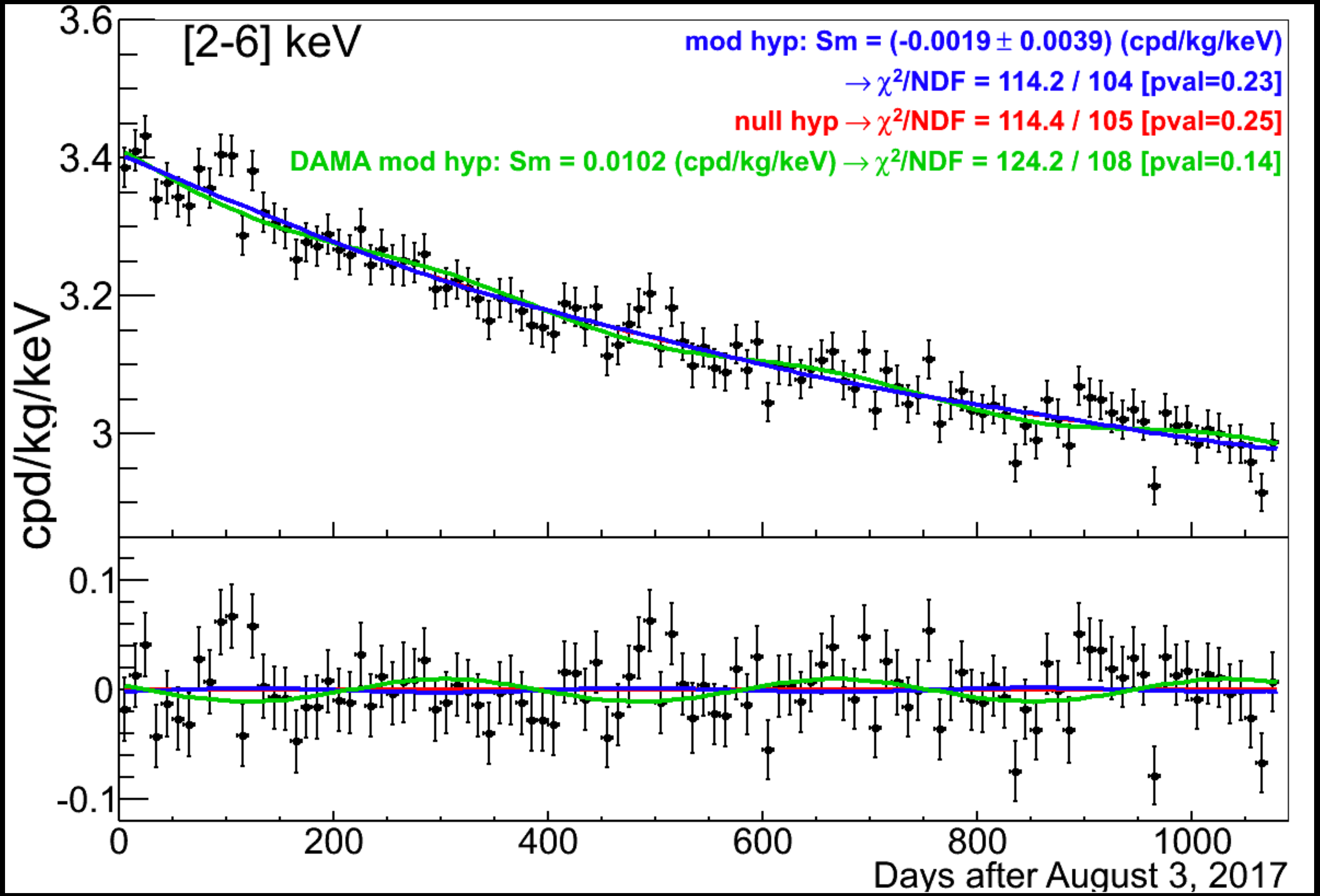
COSINE-100,
Phys. Rev. Lett. 123, 031302

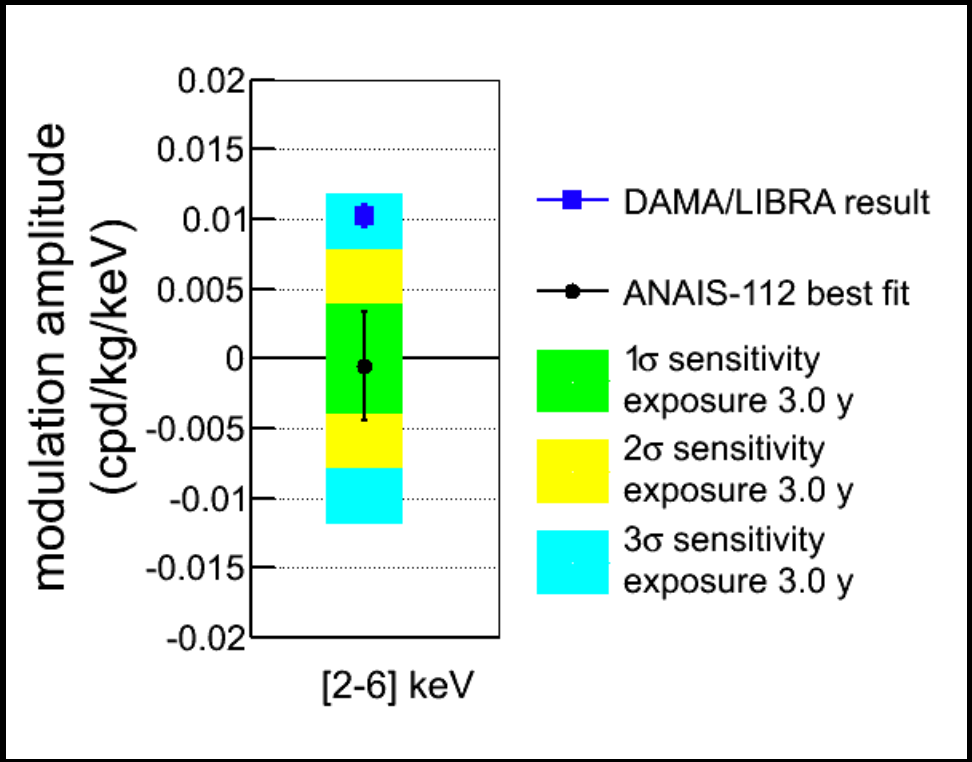


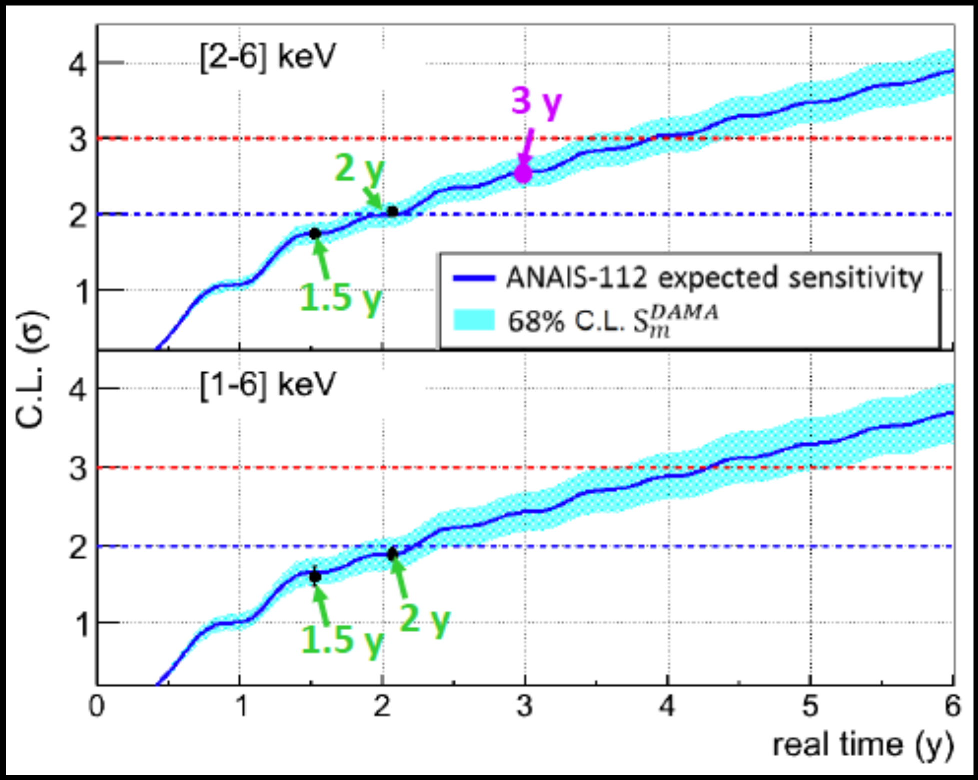
SABRE SOUTH

ANAIS-112 ANNUAL MODULATION

Preliminary results of 3 yrs data taking presented by M. Martinez @ Madrid, October 2020



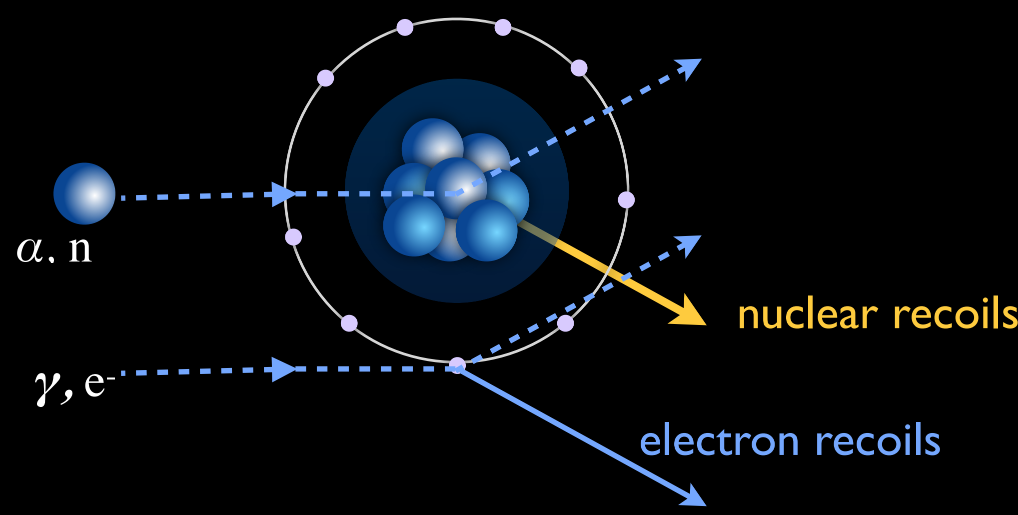




Present sensitivity @ 3 years: 2.6σ

3σ sensitivity model independent is at reach in 1 year from now

DISCRIMINATING BACKGROUNDS



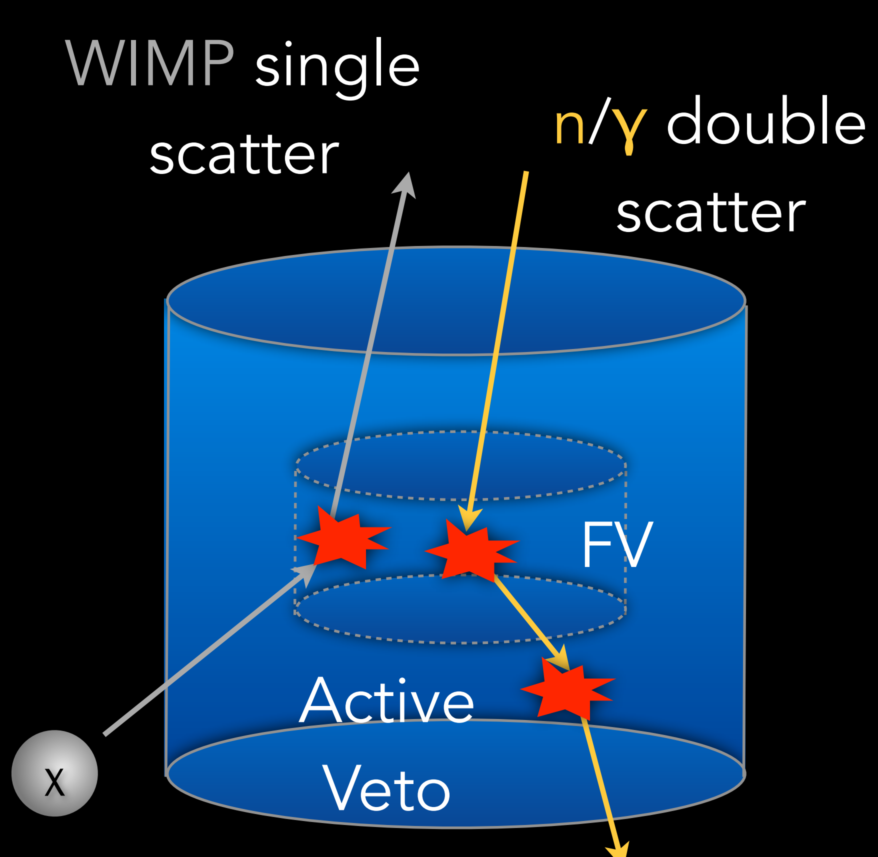
from natural radioactivity:

γ e⁻ → γ e⁻

nN → nN

N → N′ + α, β

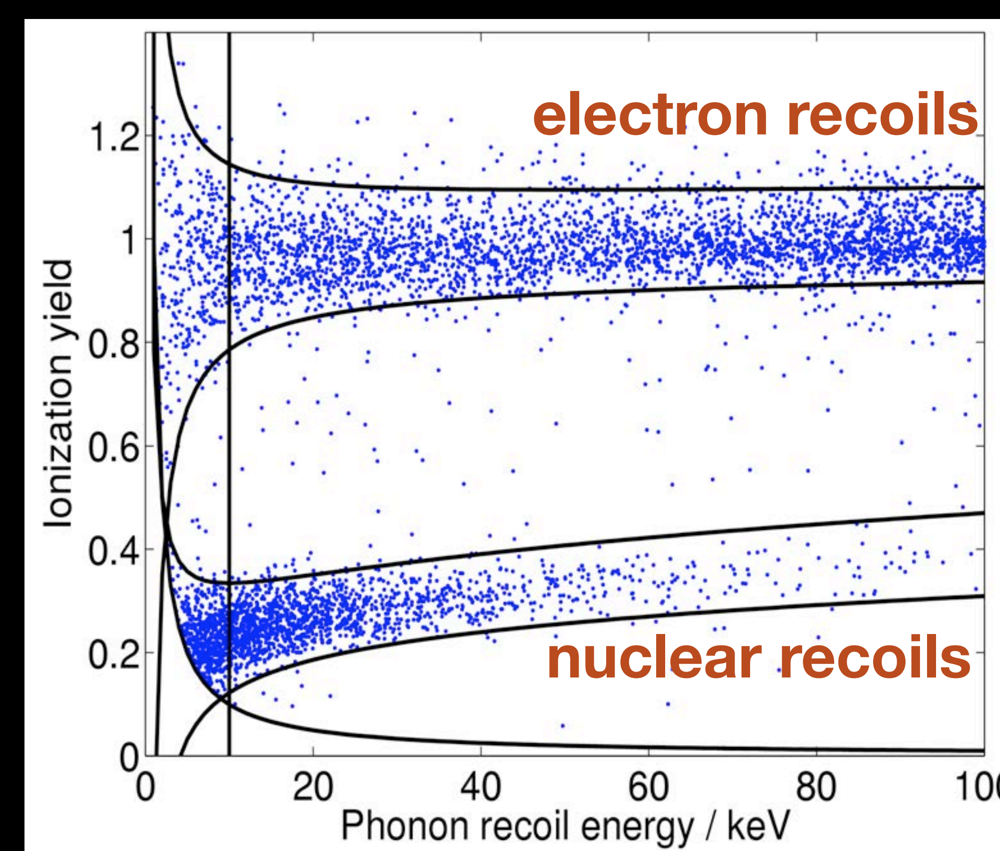
Active veto shield and fiducialization
→ identification of neutron recoils



Signal split in two components which respond differently to NR/ER
→ separation of S and B

Background region

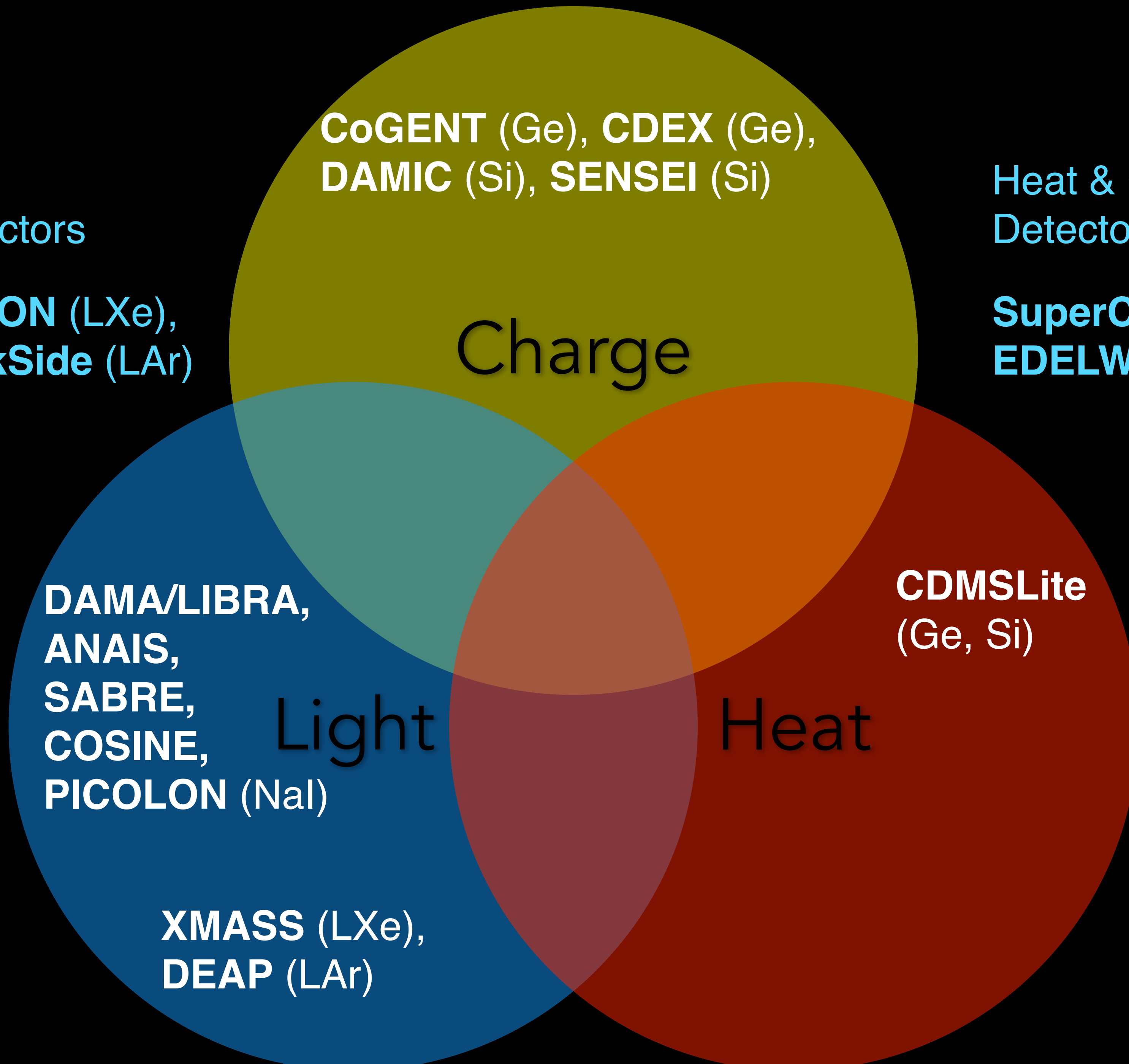
Expected signal region



DETECTOR TECHNOLOGIES

Light & Charge Detectors

PandaX (LXe), **XENON** (LXe), **LUX/LZ** (LXe), **DarkSide** (LAr)



Heat & Charge Cryogenic Detectors

SuperCDMS (Ge, Si), **EDELWEISS** (Ge)

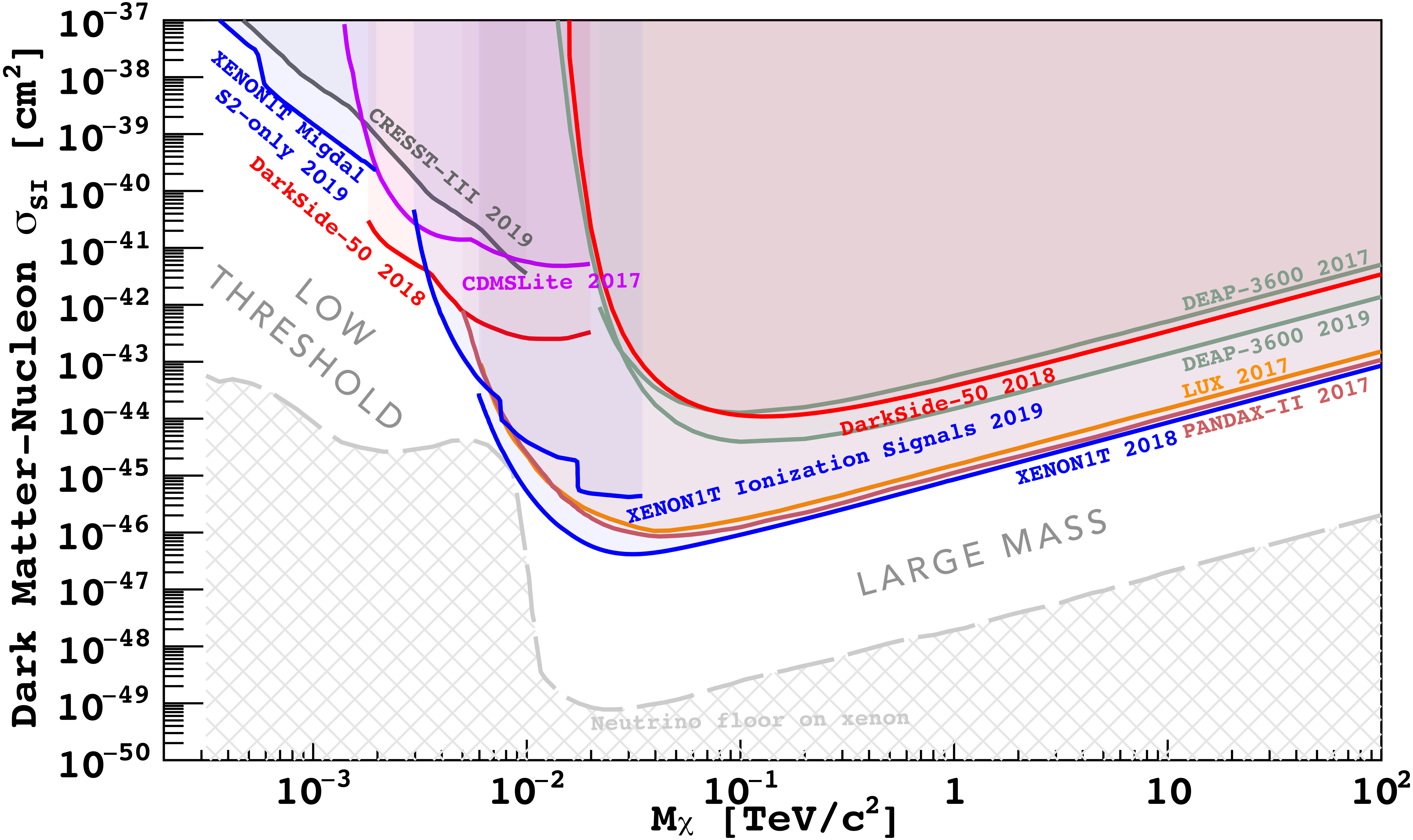
PICO (C_3F_8, CF_3I)

Light & Heat Cryogenic Detectors

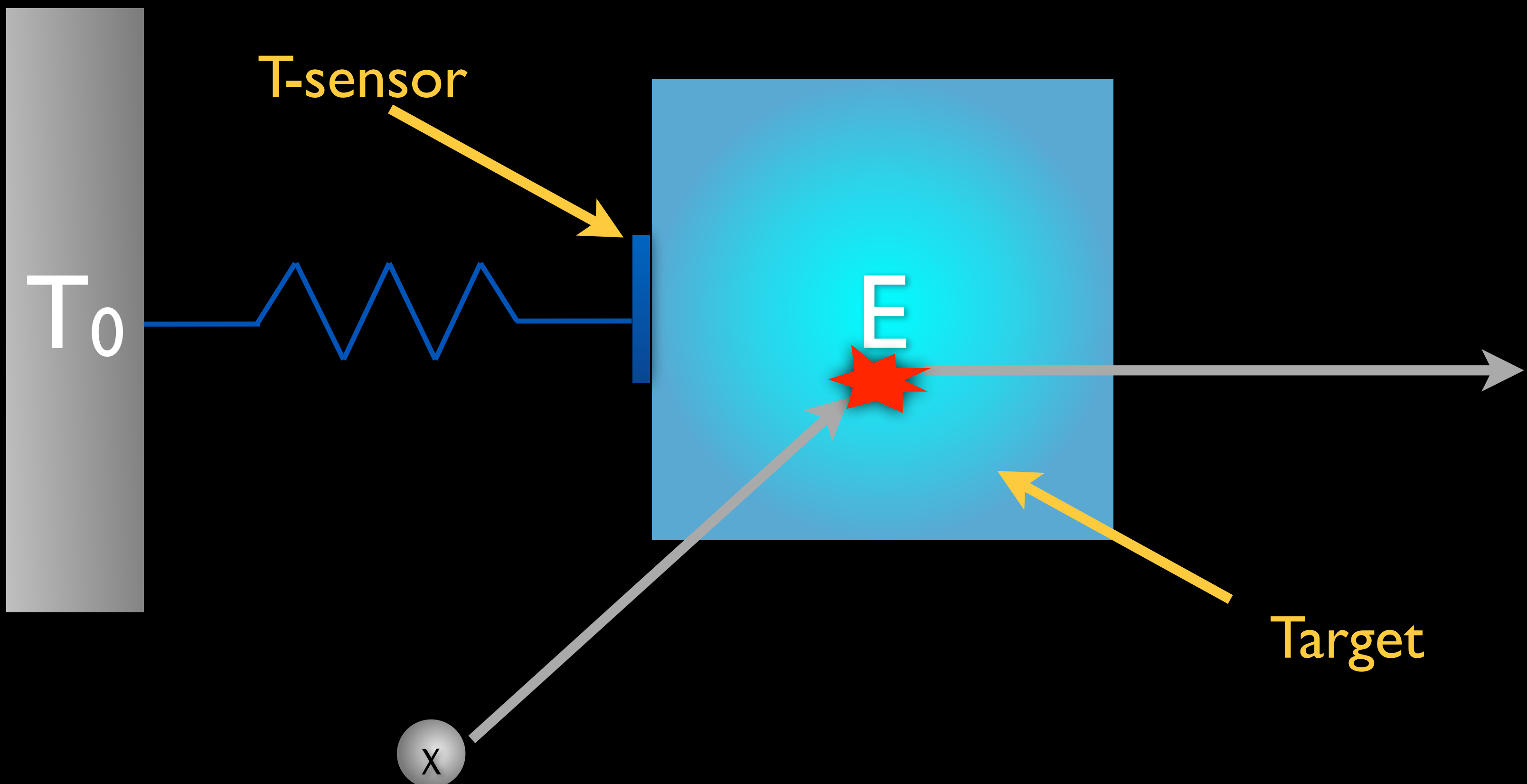
CRESST ($CaWO_4$), **COSINUS** (NaI)

Too many experiments: only a selection here

WIMP DIRECT DETECTION STATUS



LOW THRESHOLD WITH CRYOGENIC CRYSTALS

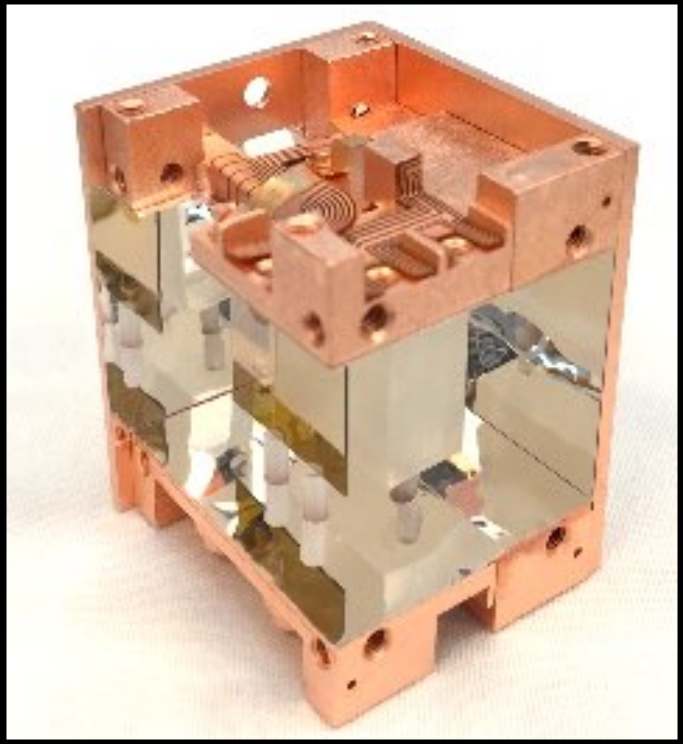


CHARGE & PHONONS:	SUPERCDMS
	CDMSLITE
	EDELWEISS
LIGHT & PHONONS:	CRESST

E deposition → temperature rise $\Delta T \sim \mu K$ → requires detectors at mK

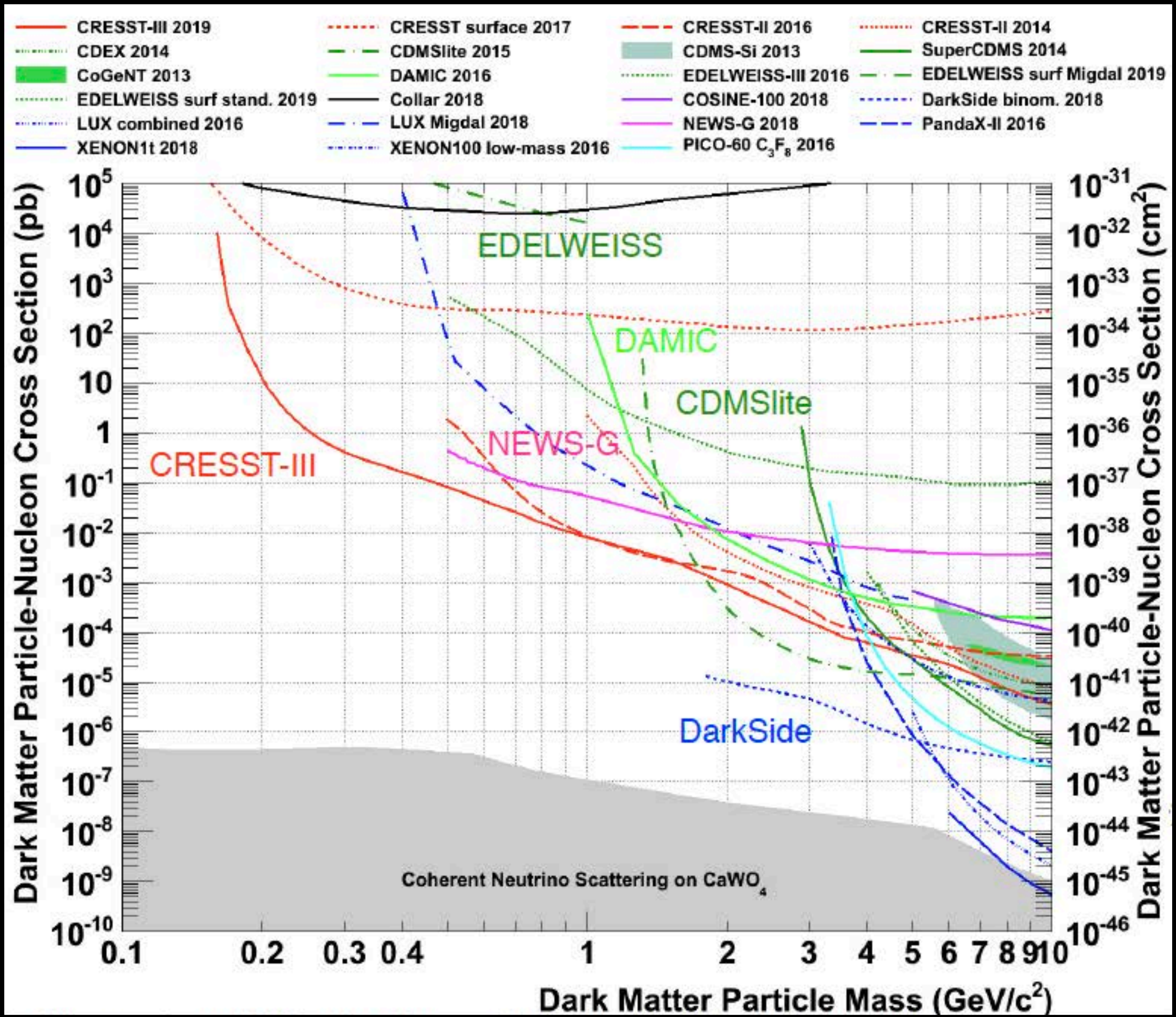
- Crystals: Ge, Si, $CaWO_4$, NaI
- T-sensors:
  - superconductor thermistors (highly doped superconductor): NTD Ge → **EDELWEISS**
  - superconducting transition sensors (thin films of SC biased near middle of normal/SC transition): TES → **CDMS, CRESST**

LOW THRESHOLD: CRESST



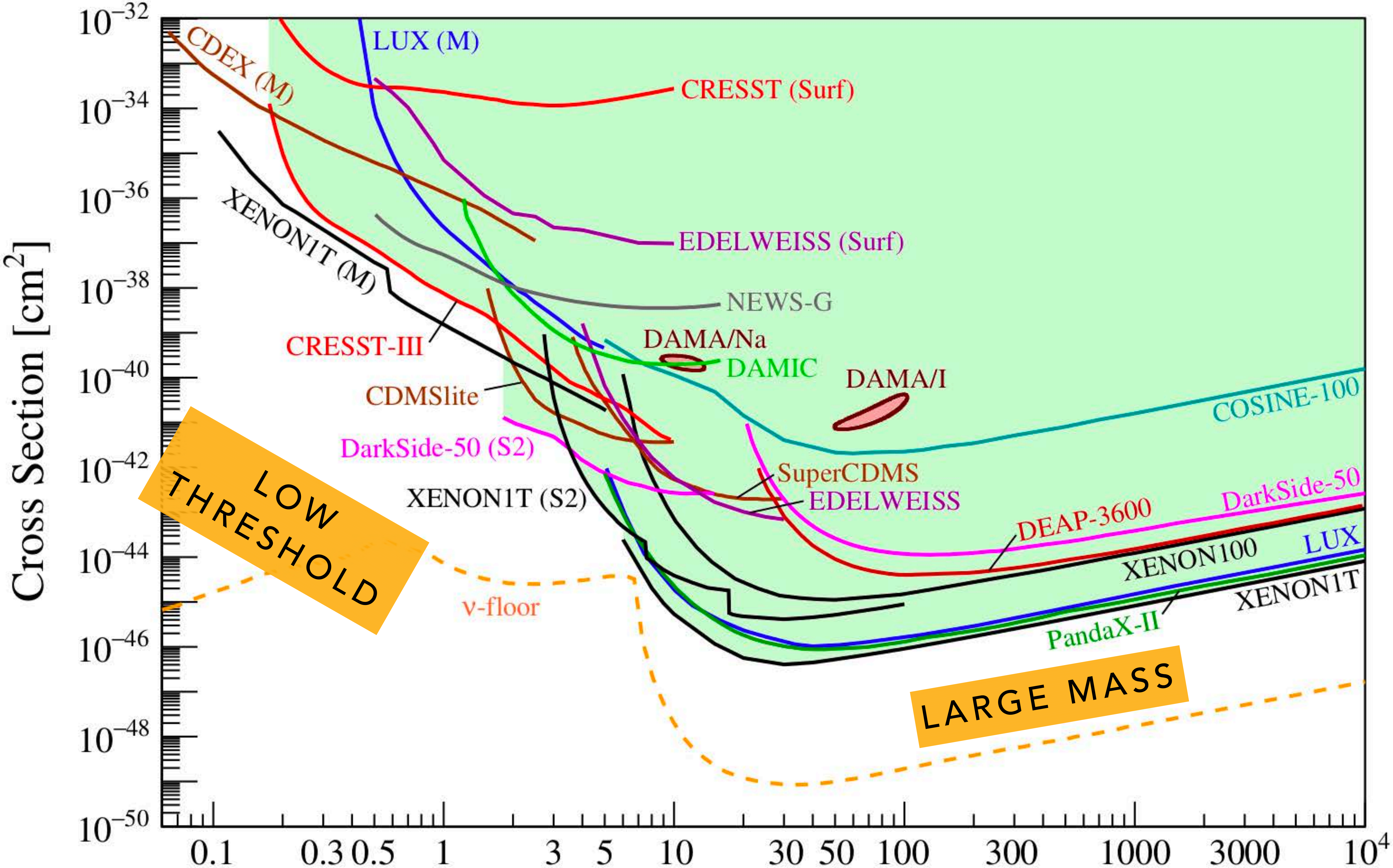
- First **CRESST-III** run 07/2016 - 02/2018
  - Target crystal mass: 23.6g
  - Gross exposure (before cuts): 5.7 kg days
  - Unprecedented low nuclear recoil thresholds of 30 eV
- Leading sensitivity over one order of magnitude:
  - 160 MeV/c^2 → 1.8 GeV/c^2
- **CRESST-III** phase 2 will push further the threshold (10 eV), upgrade to 100 modules for O(2 kg) target mass

Phys. Rev. D 100, 102002



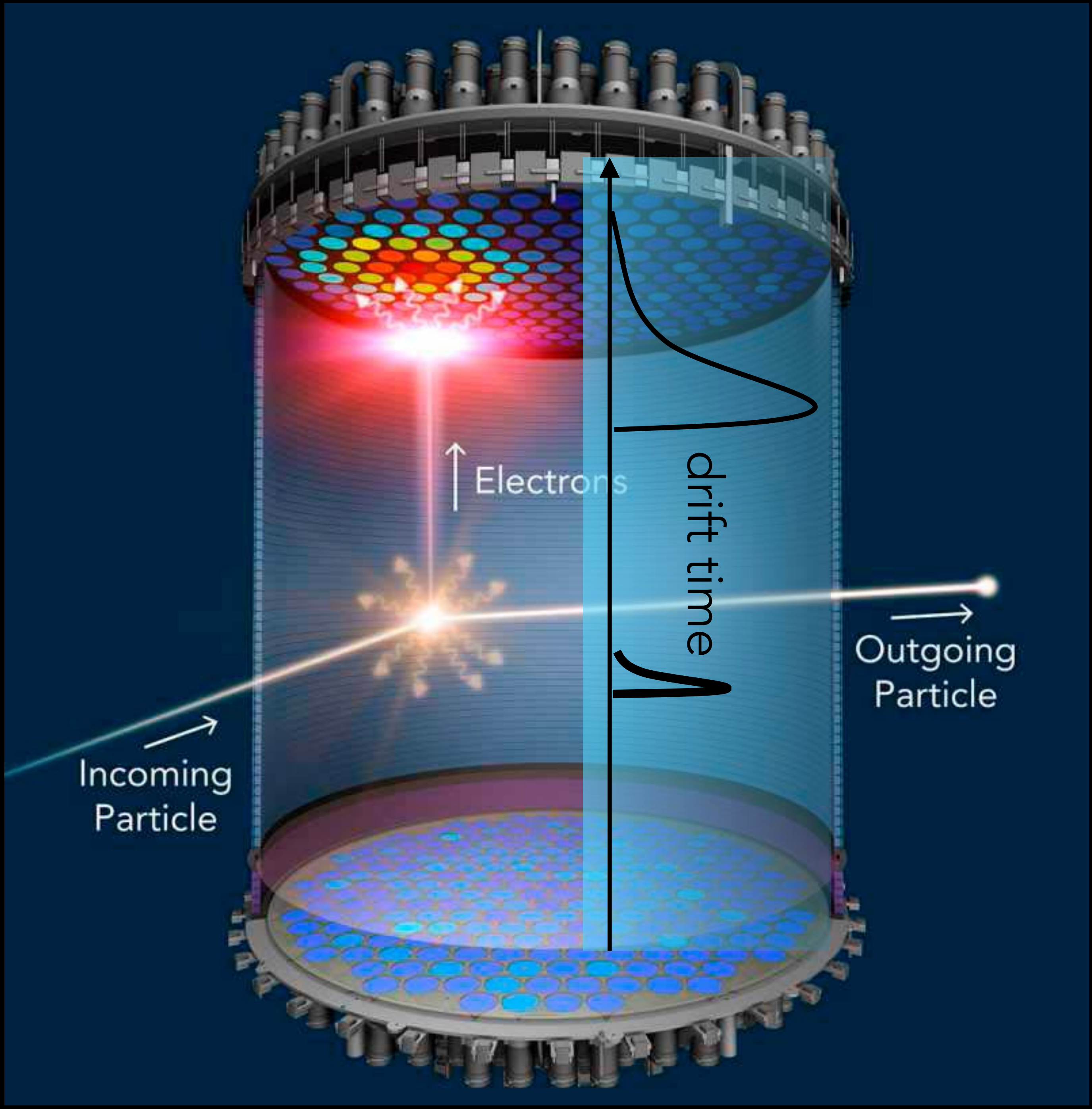
WIMP DIRECT DETECTION STATUS

APPEC DM Report, to be published



LARGE MASS: NOBLE LIQUIDS

- dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets
- read out primary scintillation: "S1" + proportional gas scintillation from drifted electrons: "S2"
- 3D position reconstruction:
  - time difference between S1 and S2 gives Z position (few mm resolution)
  - pattern of S2 light gives XY position (~1cm resolution)
- background identification + passive suppression
- zeptobarn (10^{-45} cm^2) to yoctobarn (10^{-48} cm^2) sensitivity to WIMP dark matter



XENON DETECTORS

See dedicated talks on Dec 3

XENON 10 (LNGS)
10 kg
ZEPLIN II (Boulby)
ZEPLIN III (Boulby)

2010

XENON 100 (LNGS)

100 kg

LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)

XMASS (0.8t, Kamioka)

2015

1000 kg

XENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

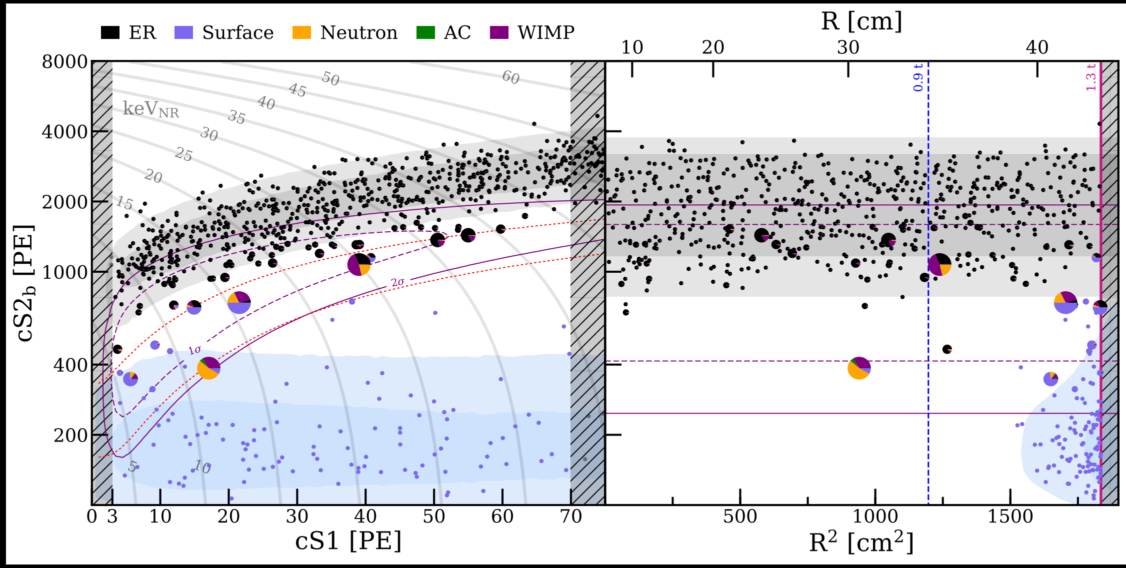
XENONnT: (6t, LNGS)
LZ: (7t, SURF)

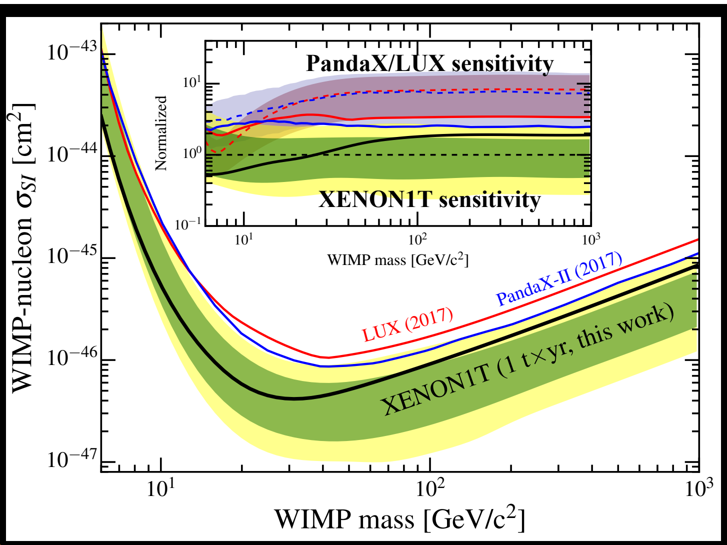
2020

10000 kg

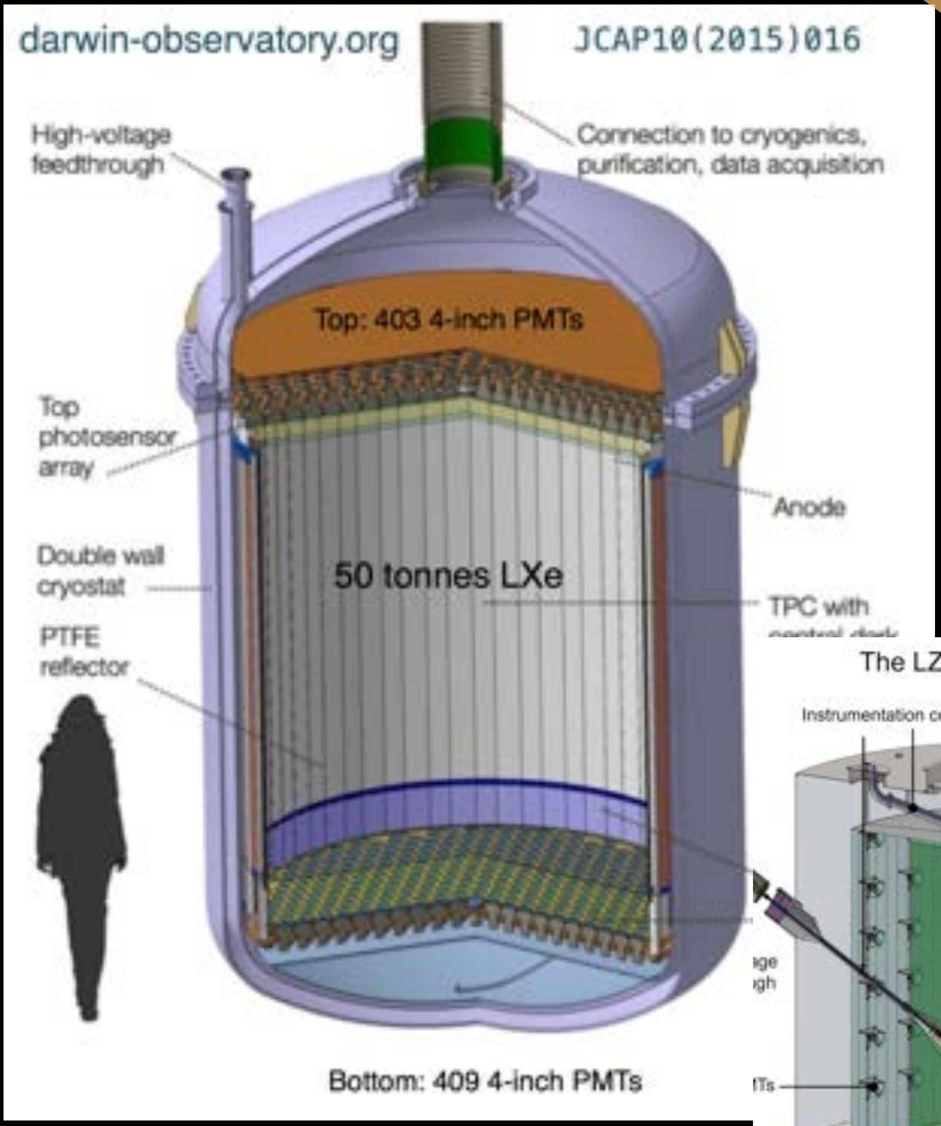
DARWIN: 50 t,
ESPPU Document #62

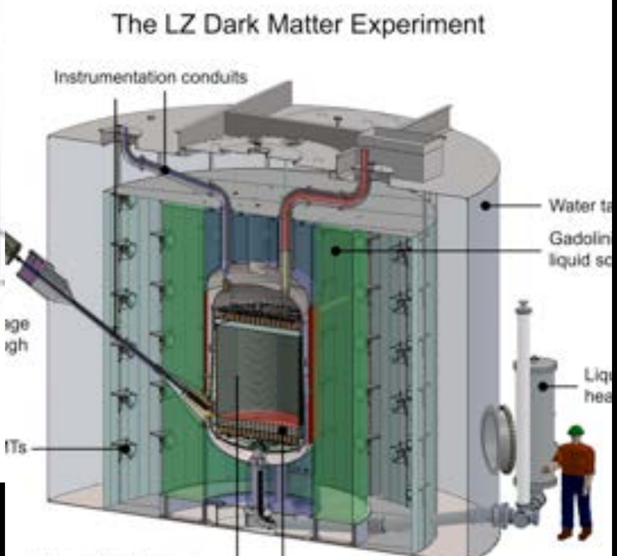
XENON1T: best limit for high WIMP masses





Aprile et al, Phys. Rev. Lett. 121, 111302 (2018)





Jocelyn Monroe, ESPP, Granada 2019

ARGON DETECTORS

See A. Kish on Dec 3

DS50 low mass: leading SI limit at 1.8-3.5 GeV/c²

DS50 high mass: background discrimination

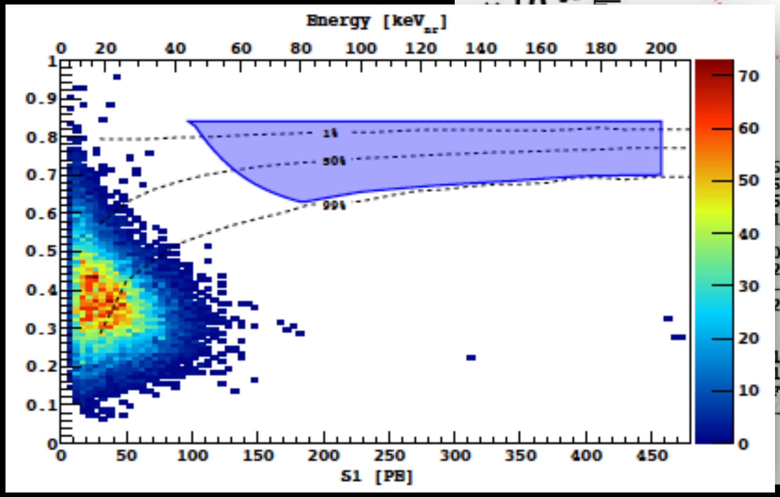
10 kg

2010

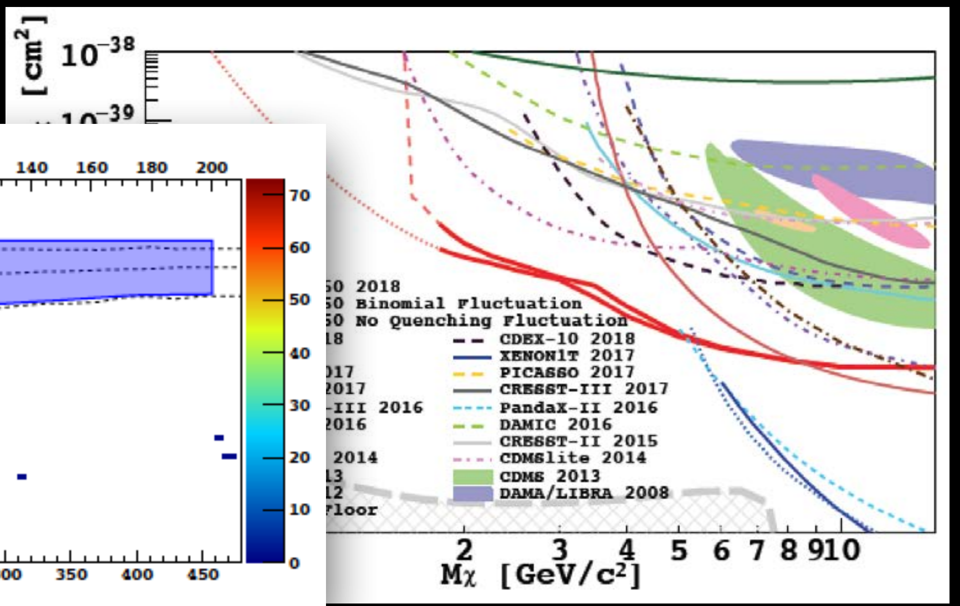
DarkSide-50 (50 kg, LNGS)

100 kg

ArDM (1t, LSC)



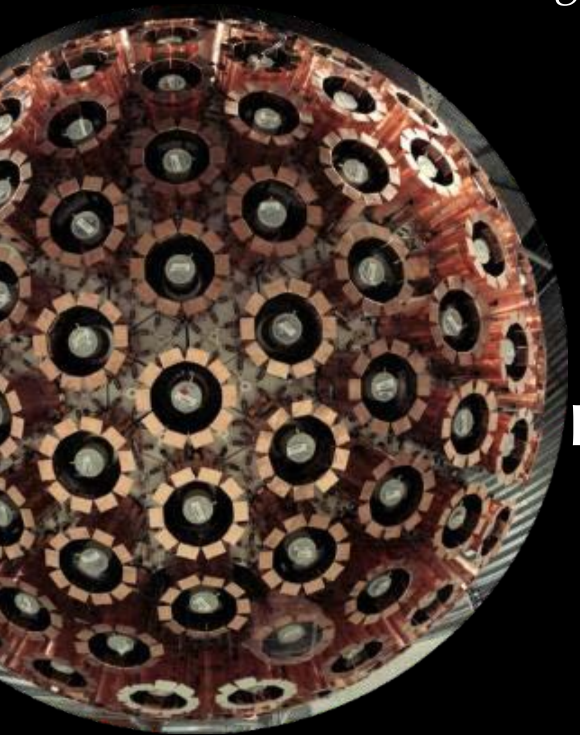
Phys. Rev. D 98, 102006 (2018)



Phys. Rev. Lett.121.081307 (2018)

1000 kg

2015



DEAP-3600 (3.6t, SNOLAB)

10000 kg

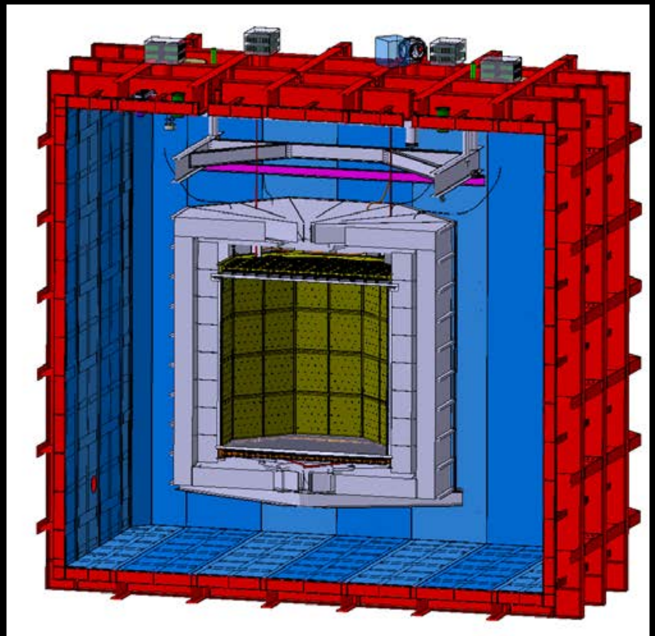
Global Argon Dark Matter Collaboration formed:

2020

DarkSide-20k (50t, LNGS)

100000 kg

ARGO: 400 t, ESPPU Document #97

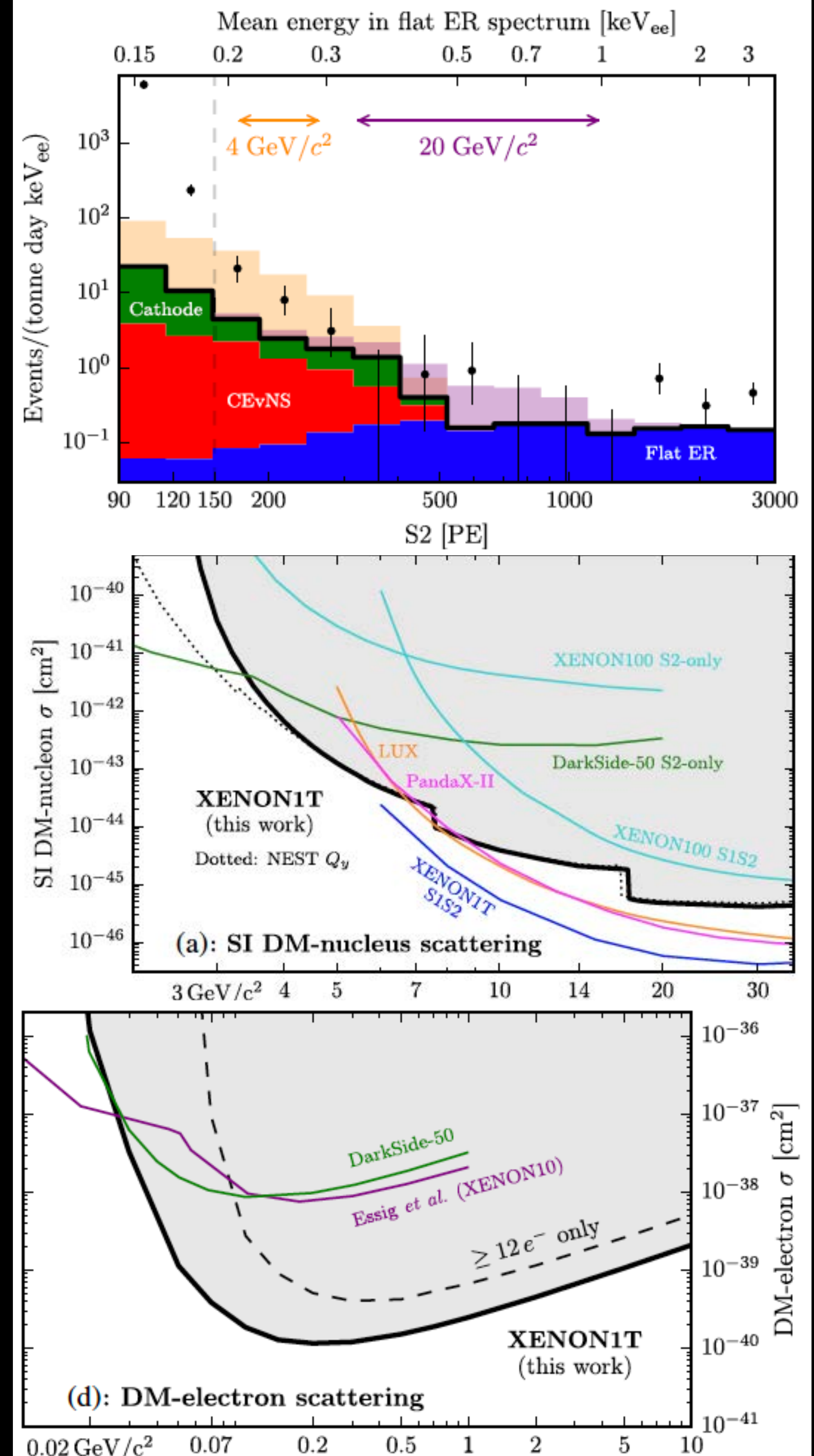


Jocelyn Monroe, ESPP, Granada 2019

LOW THRESHOLD WITH NOBLE LIQUIDS

- S2 only analysis in Xenon1T
  - effective exposure of (22 ± 3) tonne day
  - 0.7 keVnr, 0.186 keVee threshold
- Known backgrounds:
  - Beta decays from ^{214}Pb (flat ER))
  - CEvNS
  - Beta decays on the cathode wires
- Unmodeled background below 150PE
- Also probes WIMP-electron scattering

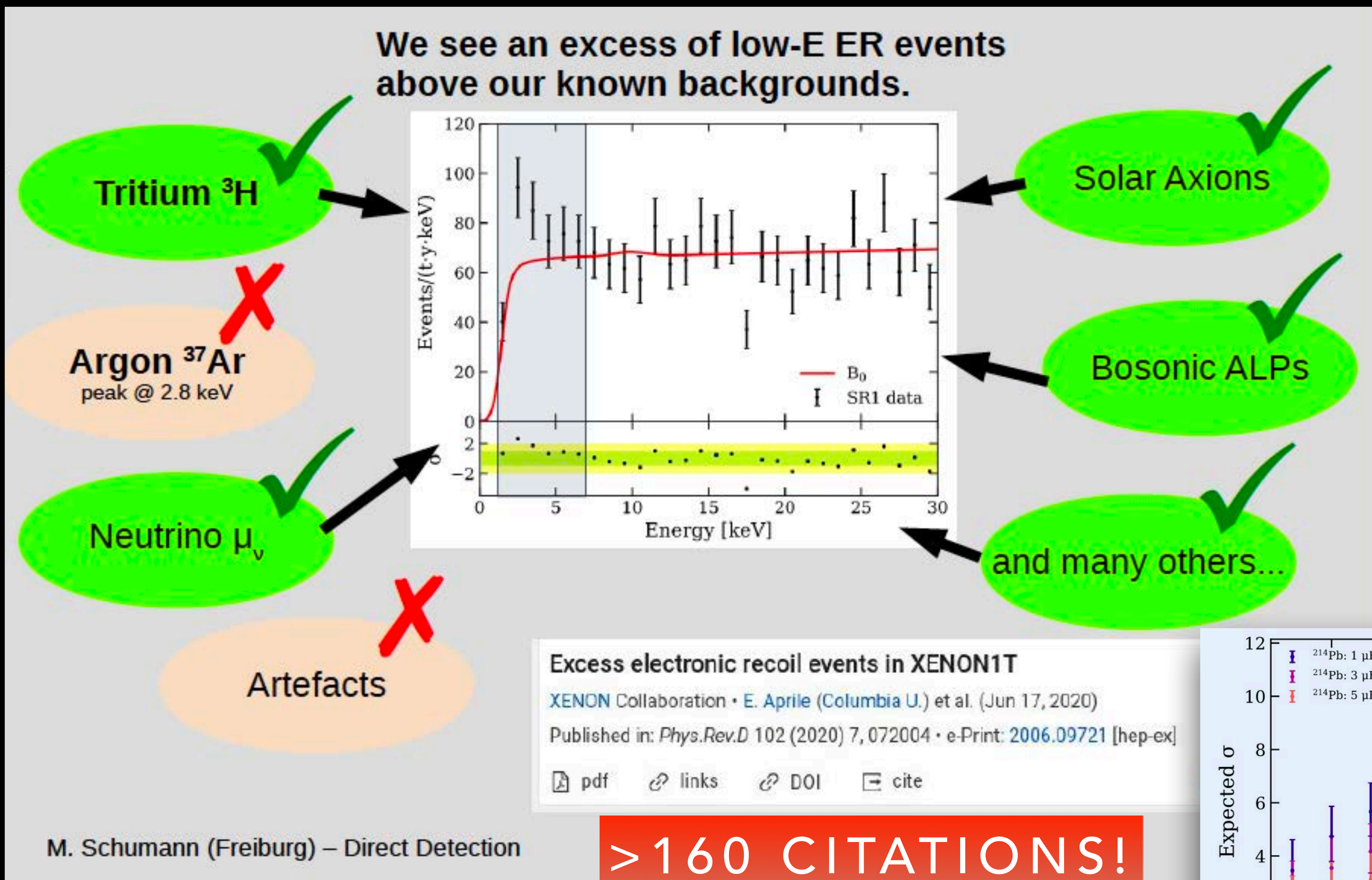
PHYSICAL REVIEW LETTERS 123,251801 (2019)



XENON1T: EXCESS ELECTRON RECOIL EVENTS

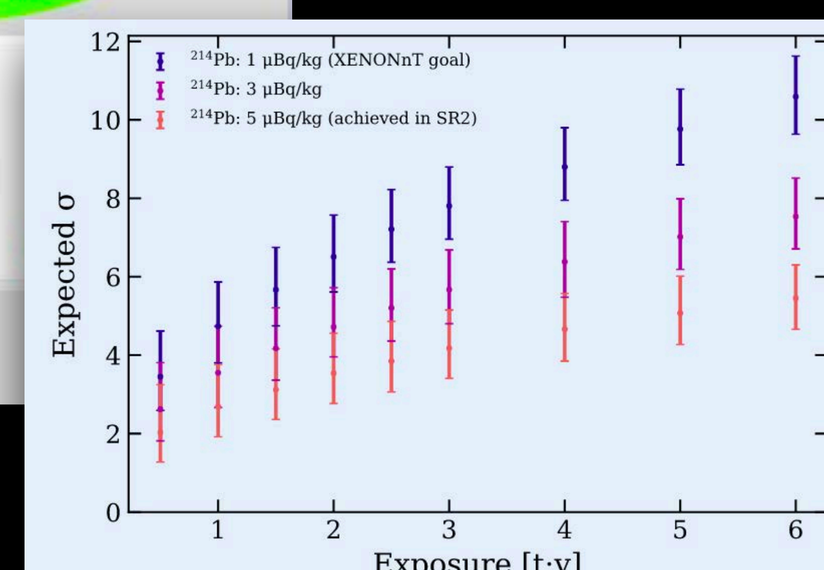
285 evts observed vs 232 ±15 expected in the range 1-7 keV

→ ~3σ fluctuation



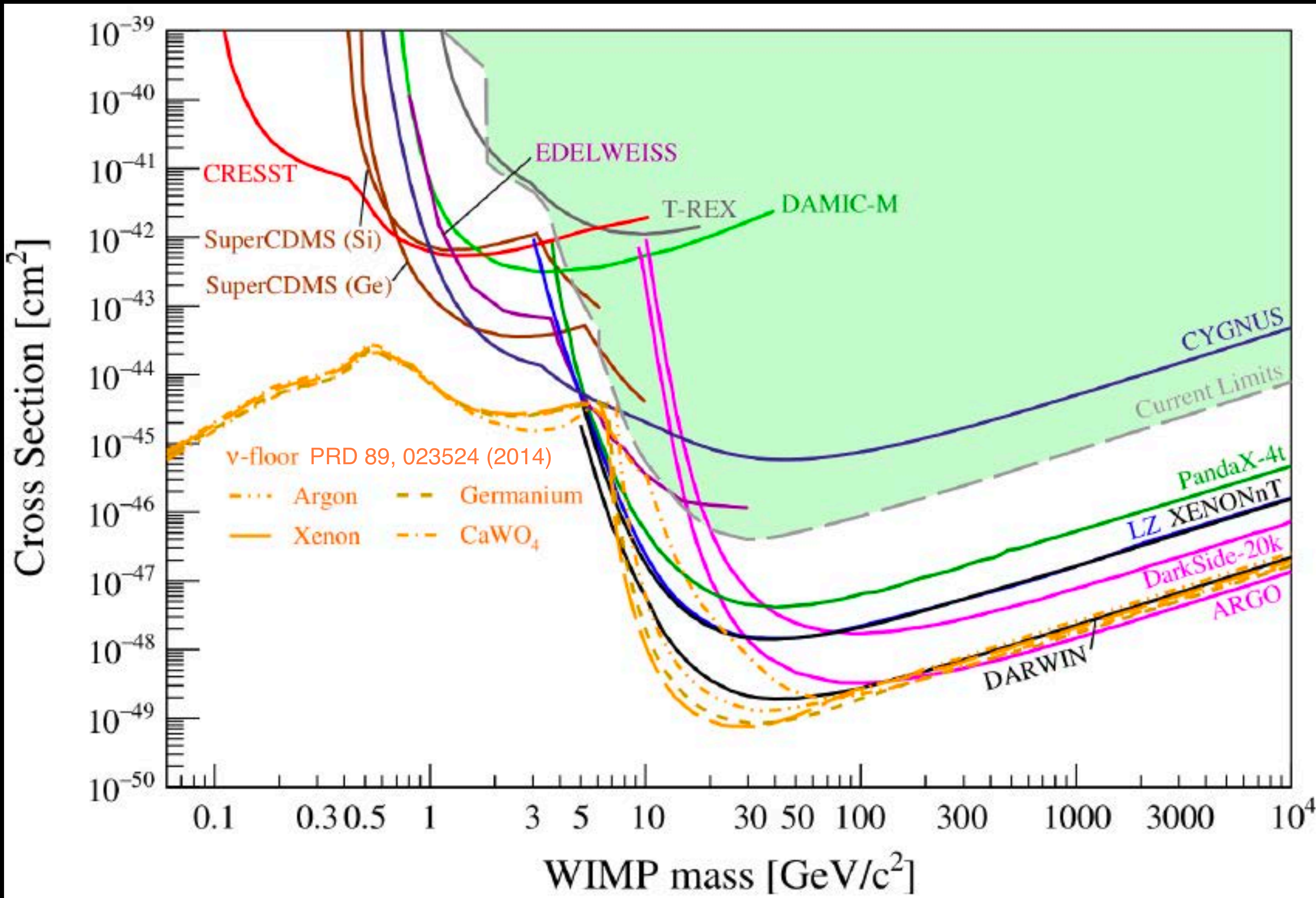
>160 CITATIONS!

Less than 1 yr data from XENONnT to distinguish axions from ^{3}H



See T. Wolf on Dec 3

WIMP DIRECT DETECTION PROSPECTS

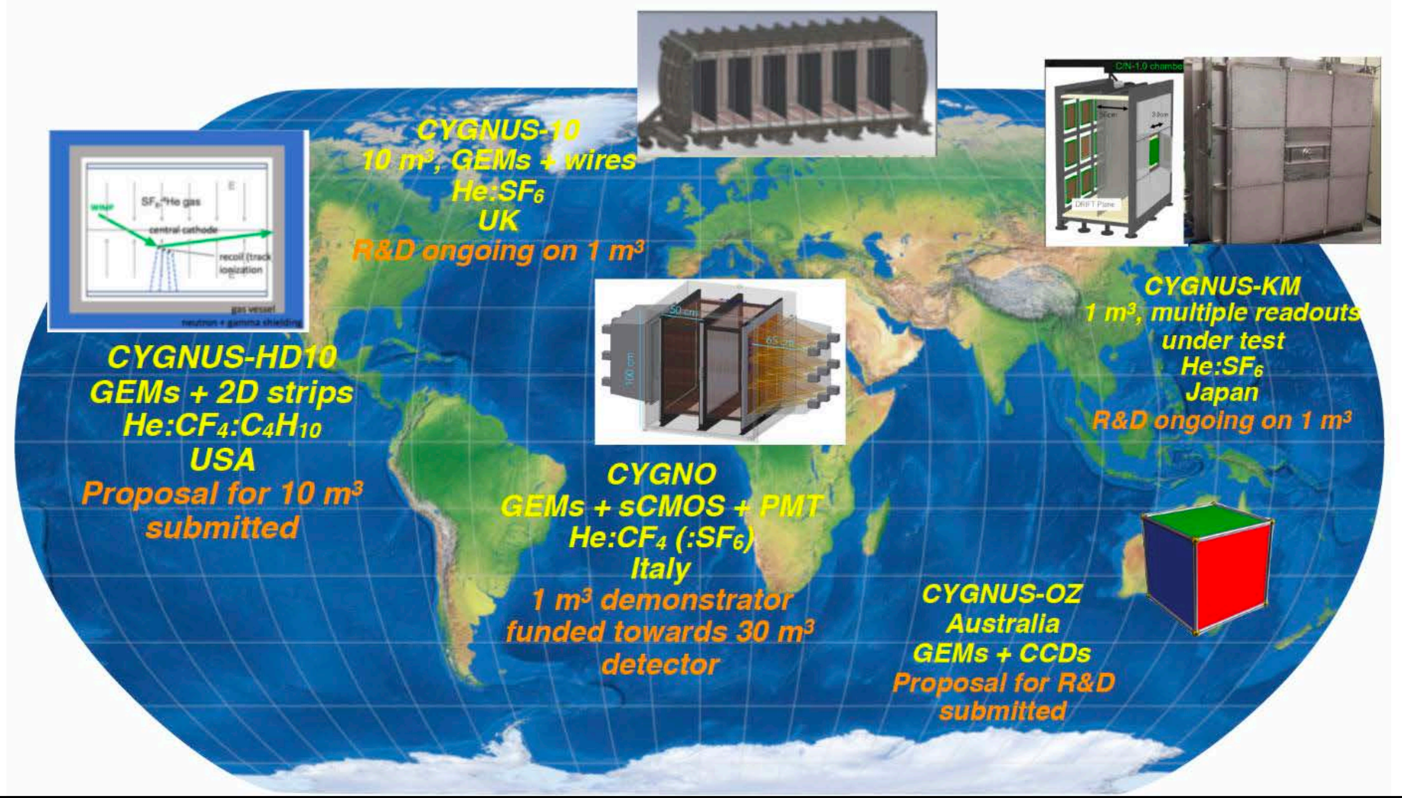


APPEC DM Report, to be published

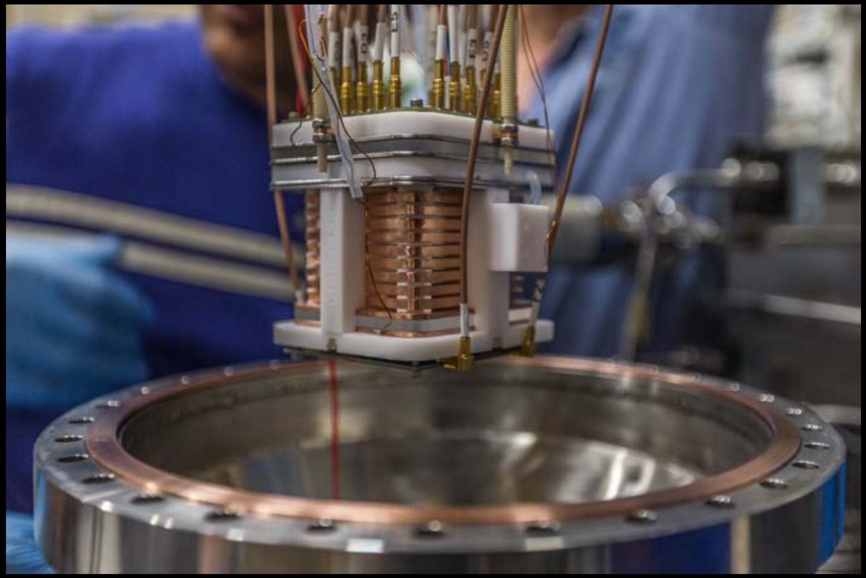
DIRECTIONAL DETECTION: BEYOND THE NEUTRINO FLOOR

- Mature technology: gaseous TPC (**DRIFT, MIMAC, DMTPC, NEWAGE, CYGNO**)
  ➟ **CYGNUS (10-1000 m³)**

- R&D on several other techniques:
  - **NEWSdm**
    - Nanometric track direction measurement in nuclear emulsions
    - Exploit resonant light scattering using polarised light
    - Measurement of track slope and length beyond the optical resolution
    - Unprecedented accuracy of 6 nm achieved on both coordinates
  - **RED**
    - Columnar Recombination in liquid argon TPC
  - **PTOLEMY**
    - Graphene target (nanoribbon or nanotubes)



See E. Baracchini on Dec 3

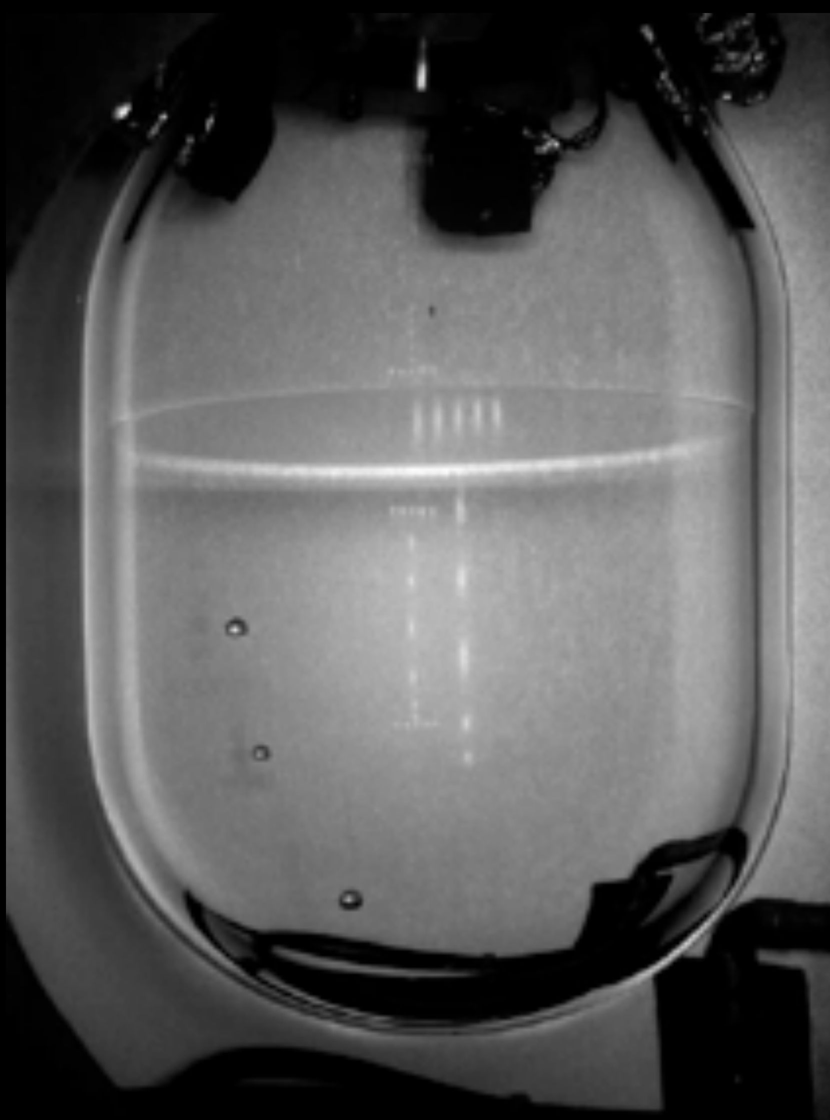


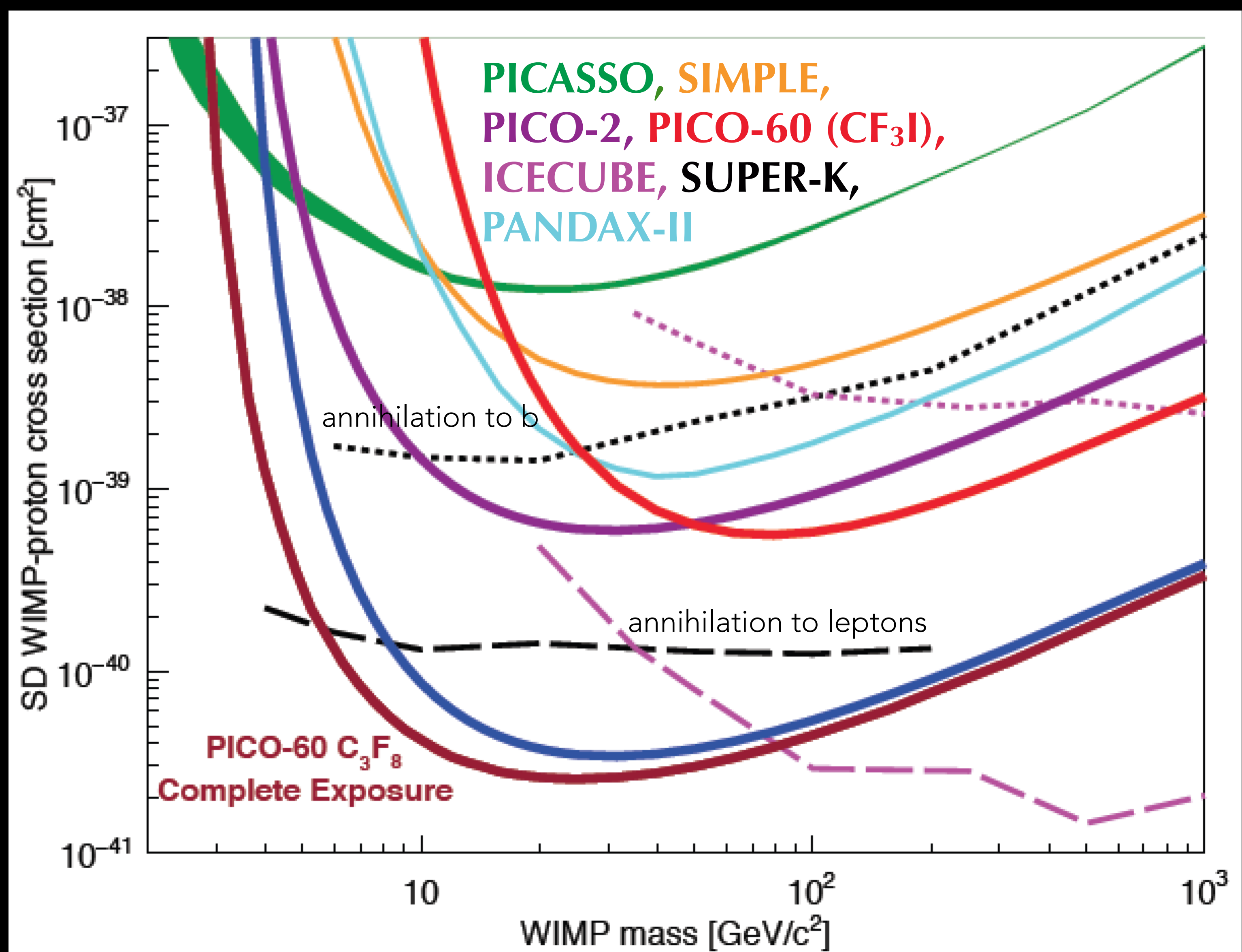
SPIN-DEPENDENT INTERACTIONS

superheated target (C_NF_M), camera + acoustic readout, background rejection based on topology $O(10^{-2})$, measure counts above threshold when dE/dx > nucleation,
SIMPLE (GESA), **PICASSO+COUPP** = **PICO** (SNOLAB)

PICO-60: leading WIMP-p limit, C_4F_8 target (60 kg), 500 kg planned
competitive limits from neutrino telescopes (IceCube, Antares, SuperK)
leading WIMP-n limits from Xe 2-phase TPCs

PHYS. REV. D100,022001 (2019)





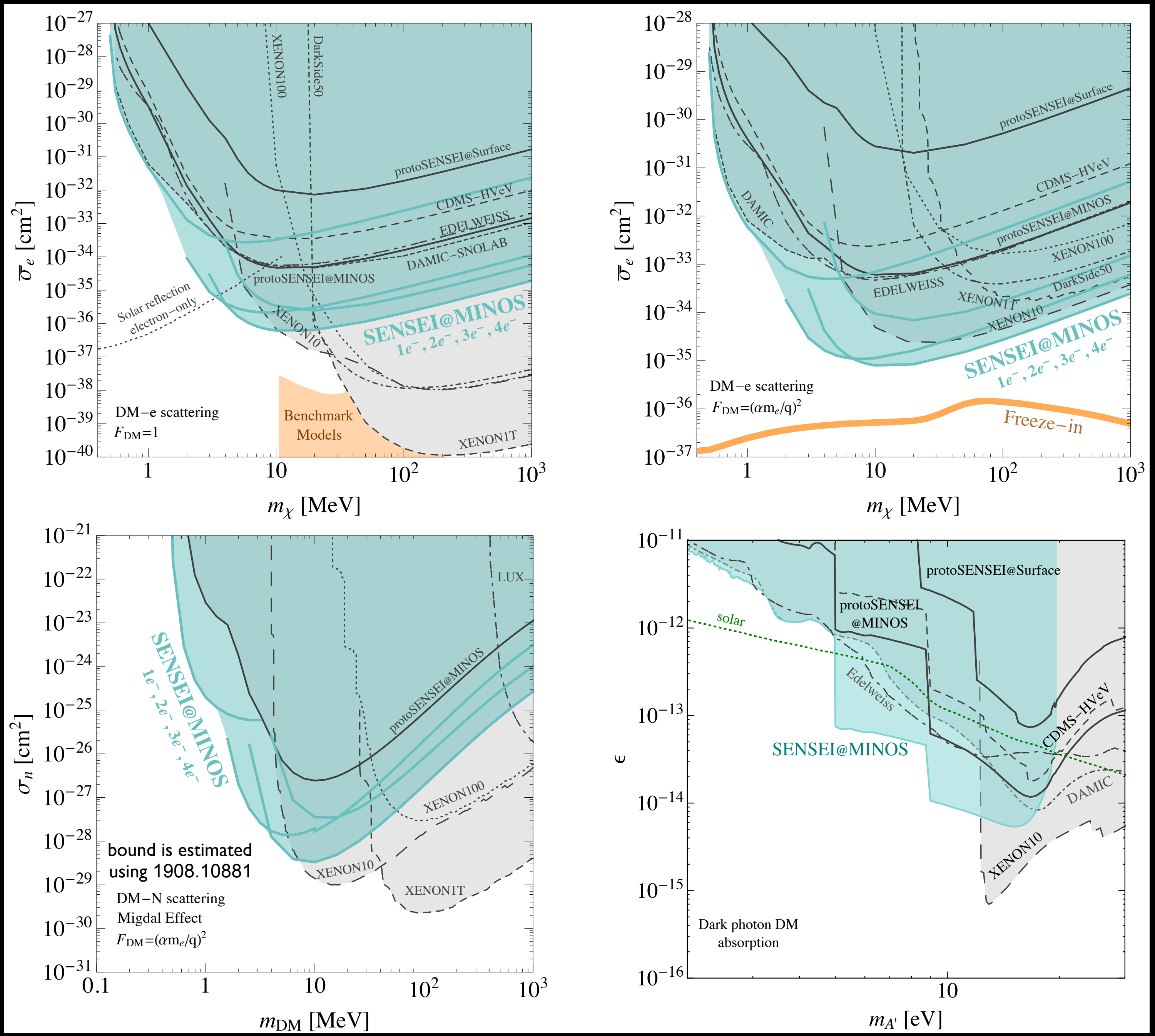
NO WIMPS YET?
PARADIGM SHIFT DRIVING SOCIAL CHANGE

Murayama @ TAUP 2019

- WIMP should be explored at least down to the neutrino floor
  - heavier? e.g., wino @ 3TeV $\Longrightarrow$ CTA
- … perhaps not necessarily heavier but rather lighter and weaker coupling?

LIGHT DARK MATTER (SUB-GEV)

- Scattering on electrons $\mathcal{O}$(MeV)
- Absorption on electrons $\mathcal{O}$(eV)
- Increasing number of dedicated experimental efforts
  - **DAMIC**
  - **SENSEI**
  - **PTOLEMY-G³**
  - Noble liquid 2-phase TPC (e.g. **UA'(1)**, **DarkSide-LM**)
  - Drift chambers
  - Superconductors
  - …



PHYSICAL REVIEW LETTERS 125, 171802 (2020)

SUMMARY & CONCLUSIONS

- A new era in the search for dark matter: need to explore DM everywhere
- WIMP still main paradigm → reach ν floor, add directional sensitivity
- Light DM probed via scattering to 1 MeV (and via absorption to ~eV), and possibly much lower
- *Ultra Light DM: a wealth of dedicated initiatives search for WISP dark matter covering > 10 orders of magnitude in mass (not covered here…)*