

Dark Matter Direct Detection Review

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INFN Bologna

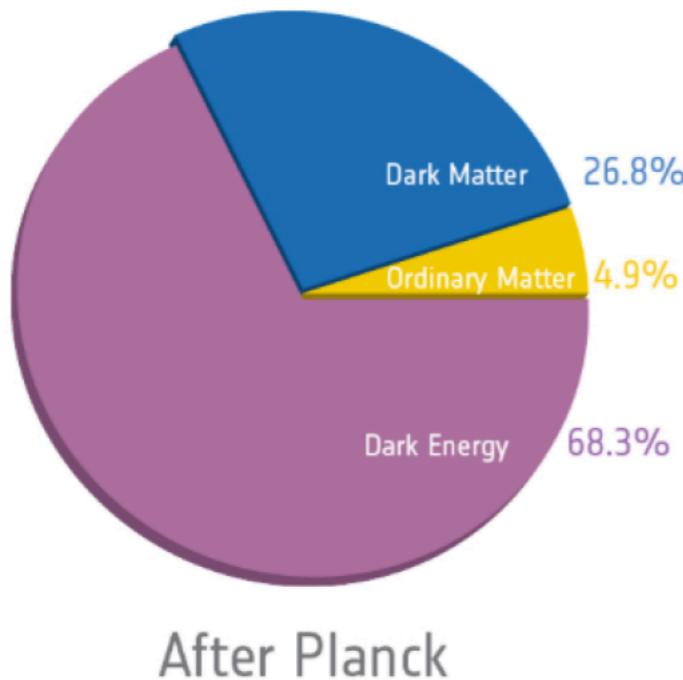
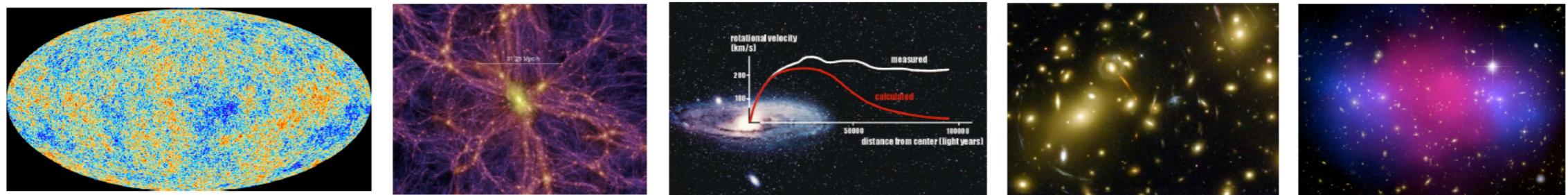
Outline

- Quick review of WIMP model (no Axions/others in this talk)
- Generalities on signal and backgrounds
- Most effective detection techniques
- Selection of recent results from direct DM detection experiments

Usual, but correct, disclaimers of these kinds of review talks:
not complete, biased, personal view, etc

* many thanks to
E. Aprile, L. Baudis, P. Belli, R. Bernabei, G. De Lellis, G. Fiorillo, P. Gorla,
T. Marrodan, K. Palladino, D. Pinci, K. Ni, M. Schumann, K. Schaeffner, C. Vignoli
for useful materials used in this review

Particle Dark Matter



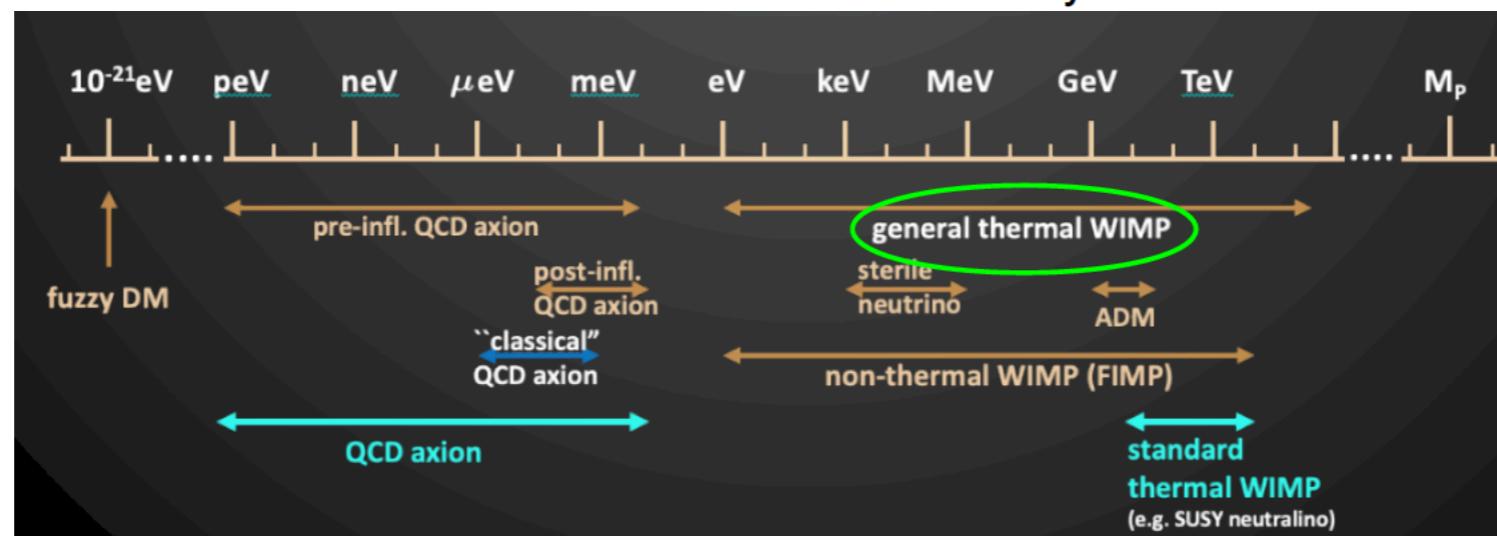
Well motivated theoretical approach:

WIMP

(Weakly Interacting Massive Particle)

But dark matter could be non
weakly-interacting or a completely different
type of particle

→ This talk is mainly focus on searches for WIMPs

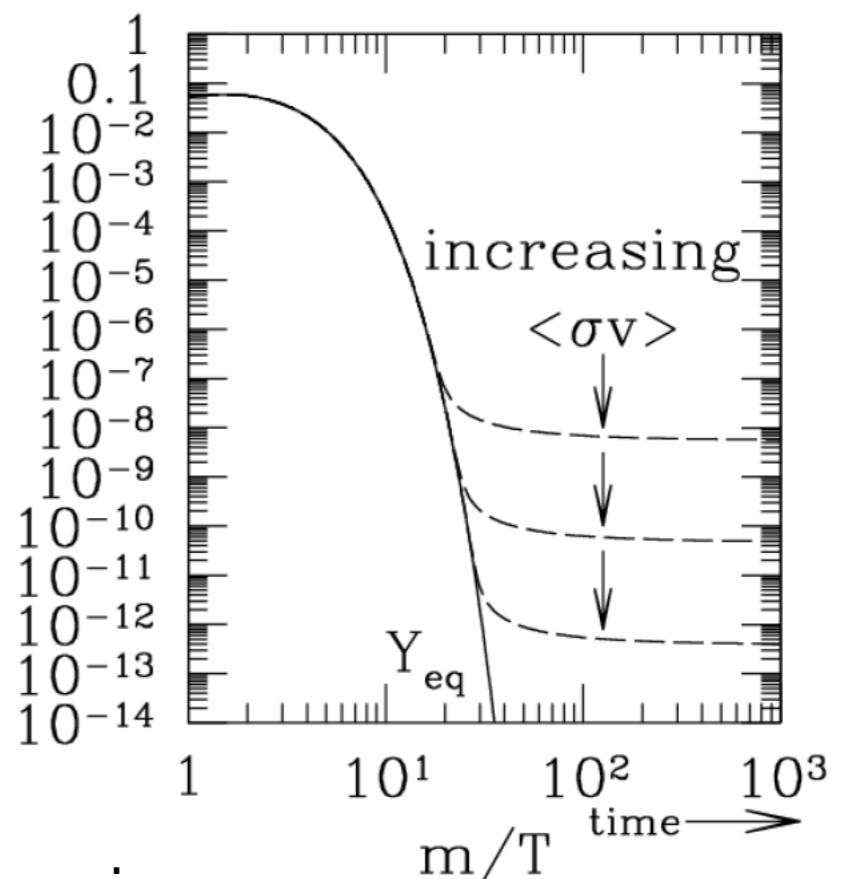


WIMPs

Well motivated theoretical approach:

WIMP
(Weakly Interacting Massive Particle)

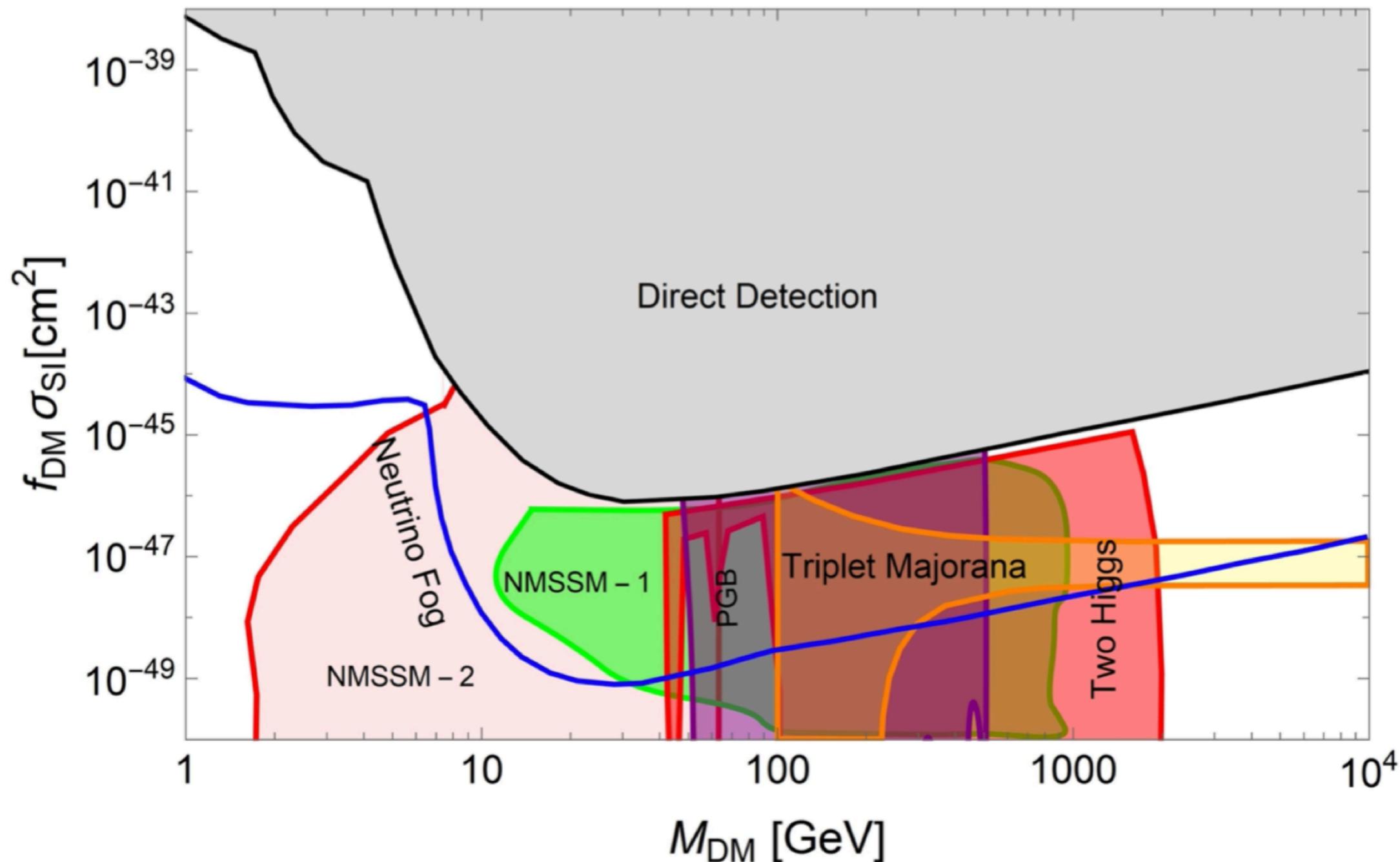
- In the early Universe particles are in thermal equilibrium:
creation \leftrightarrow annihilation
 $\chi\bar{\chi} \leftrightarrow e^+e^-, \mu^+\mu^-, q\bar{q}, W^+W^-, ZZ\dots$
- When annihilation rate \ll Universe expansion rate \rightarrow 'freeze out'
- Correct relic density for an annihilation rate \sim weak scale
- WIMPs are independently predicted in many BSM theories



In this talk I will focus mostly on WIMP direct detection

WIMP hypothesis is still alive

CF1 WP1 arXiv:2203.08084
Thanks to Ben Loer, PNNL +
Graciela B. Gelmini, UCLA



Dark Matter searches

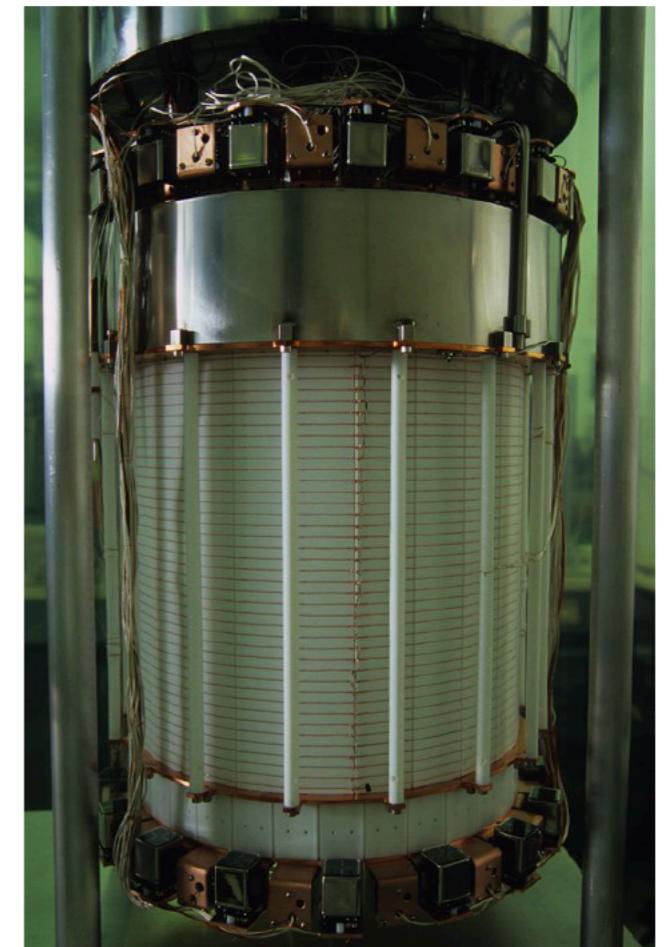
- Production at LHC



- Indirect detection



- Direct detection

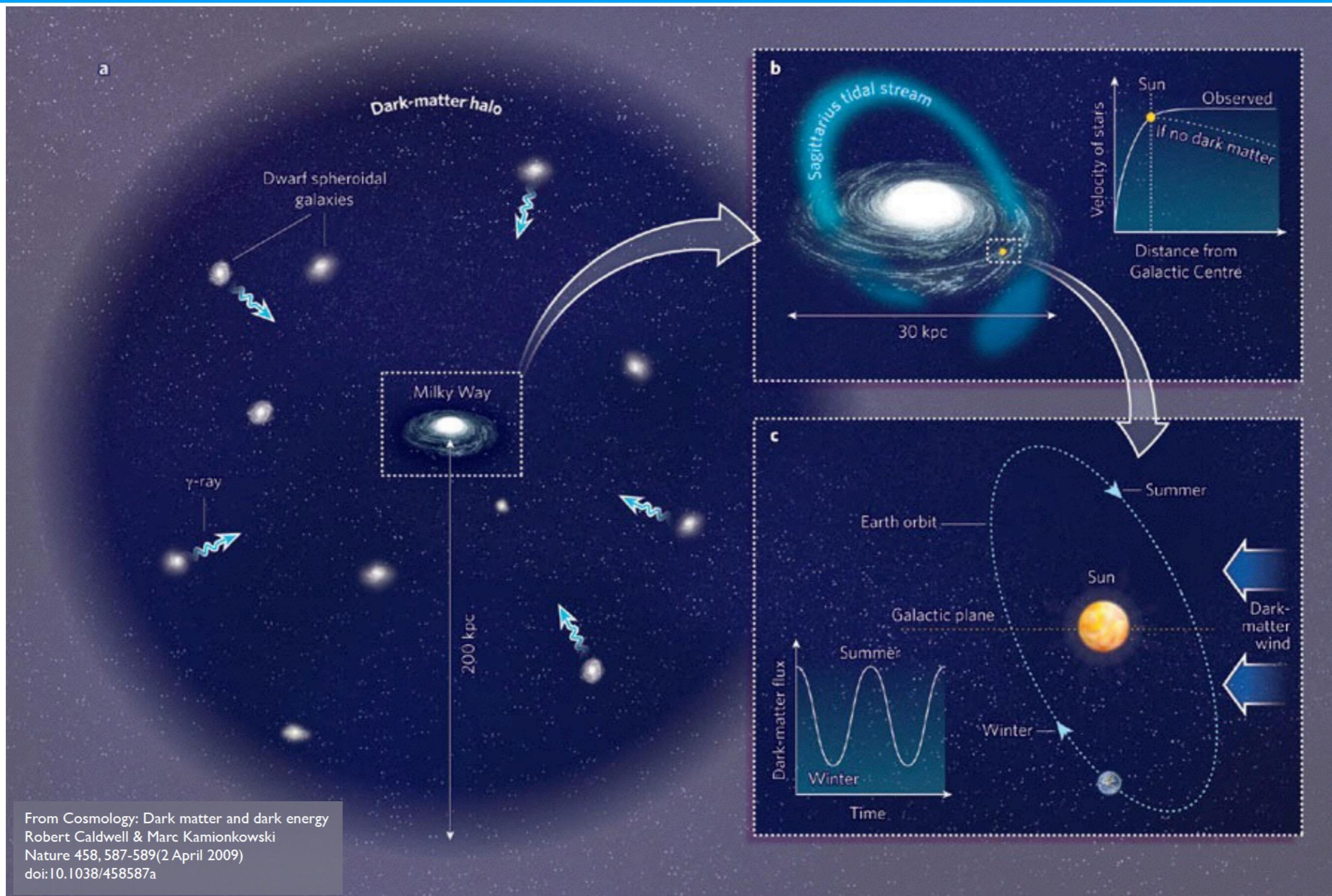


$p + p \rightarrow \chi\bar{\chi} + \text{a lot}$

$\chi\chi \rightarrow \gamma\gamma, q\bar{q}, \dots$

$\chi N \rightarrow \chi N$

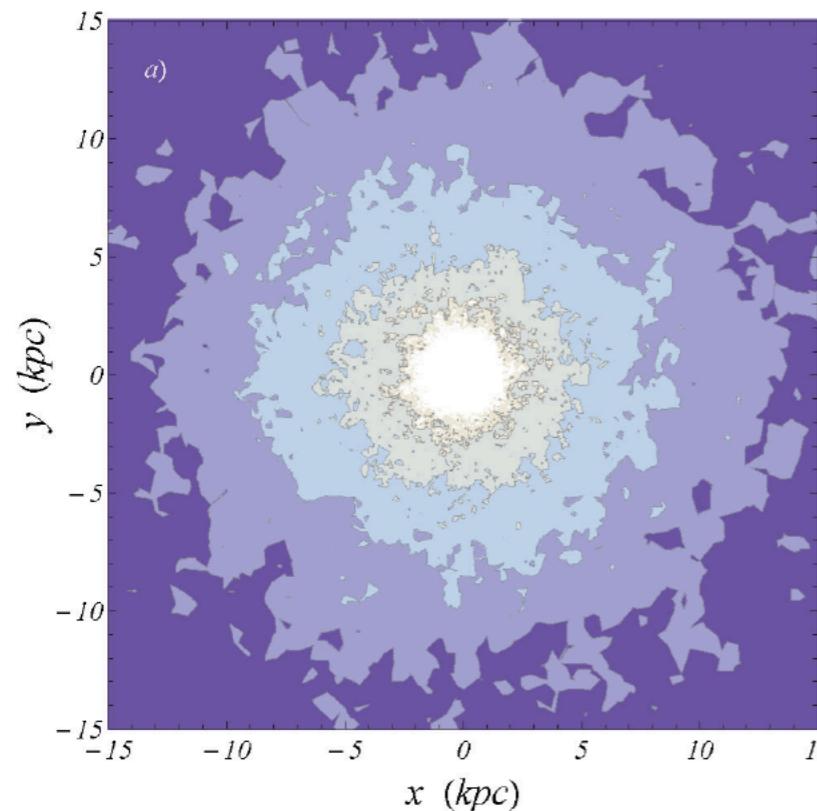
We live in a dark matter halo



WIMP density and velocity distribution

WIMPs in the galactic halo

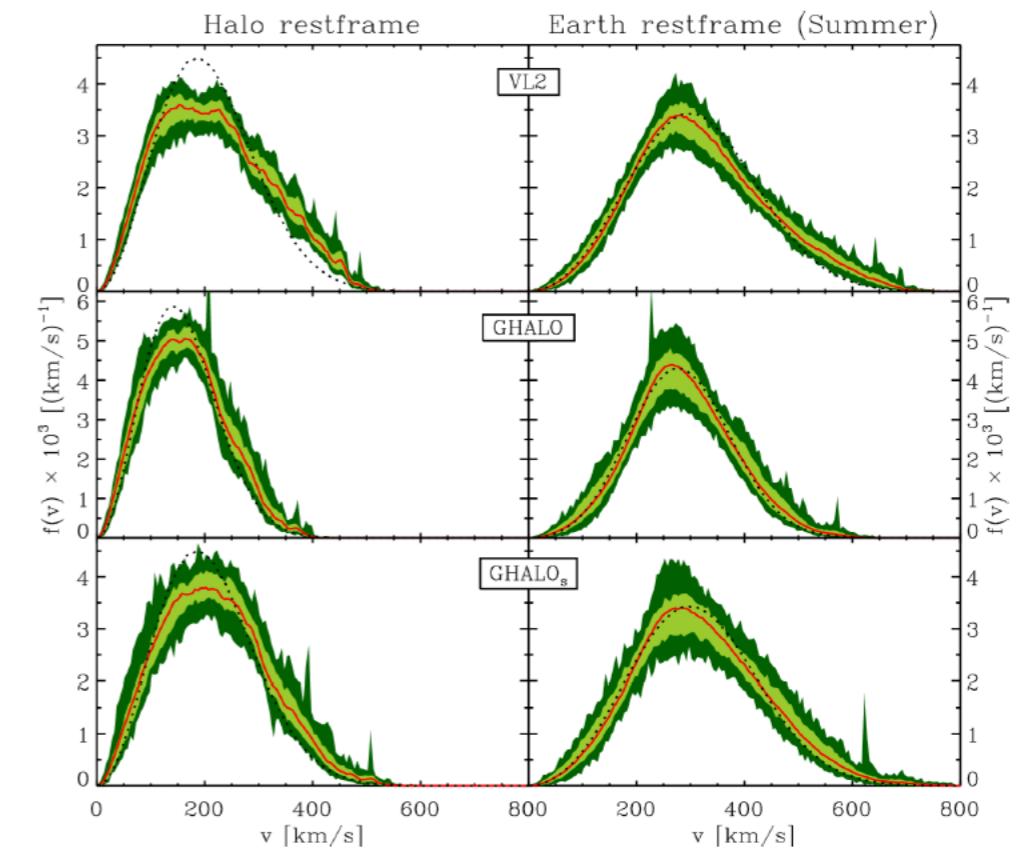
Density map of the dark matter halo
 $\rho = [0.1, 0.3, 1.0, 3.0] \text{ GeV cm}^{-3}$



High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

$$\rho_{\text{local}} \sim 0.3 \text{ GeV} \cdot \text{cm}^{-3}$$

Velocity distribution of WIMPs in the galaxy

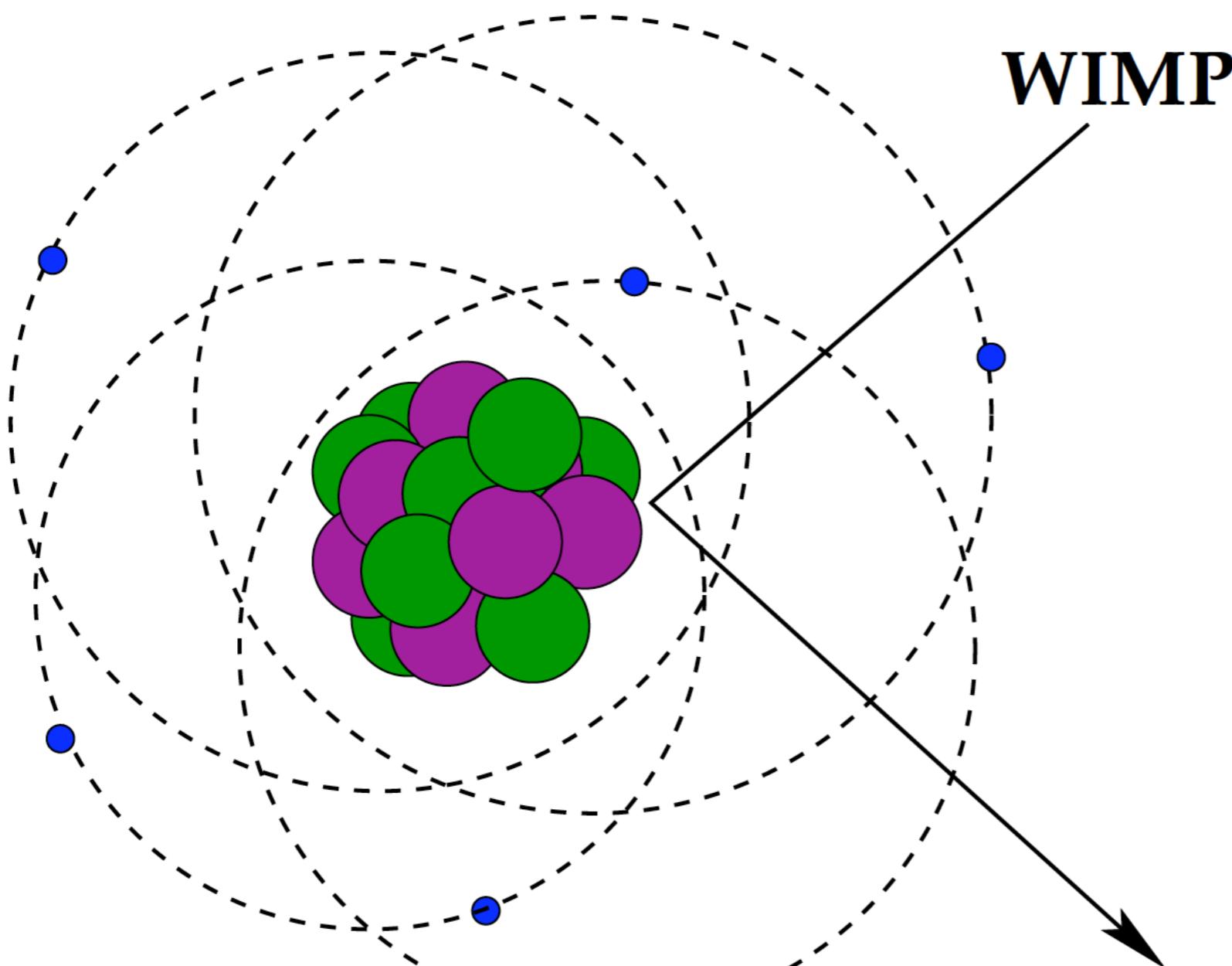


M. Kuhlen et al, JCAP02 (2010) 030

From cosmological simulations of galaxy formation: departures from the simplest case of a Maxwell-Boltzmann distribution

In direct detection experiments, mostly a simple MB distribution, truncated at v_{esc} , is used in the sensitivity calculation

Direct Dark Matter Detection



$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

$E_R \sim \mathcal{O}(10 \text{ keV})$

also:

Electron recoils ? !

Dark Matter in the Milky Way

Expected interaction rates in a detector:

$$\frac{dR}{dE}(E, t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int \mathbf{v} \cdot f(\mathbf{v}, t) \cdot \frac{d\sigma}{dE}(E, \mathbf{v}) d^3 v$$

Credit: ESO/L. Calçada



Astrophysical parameters:

- ρ_0 = local density of the dark matter in the Milky Way
'Standard' value: $\rho_\chi \simeq 0.3 \text{ GeV/cm}^3$
- $f(\mathbf{v}, t)$ = WIMP velocity distribution,
 $\langle v \rangle \sim 220 \text{ km/s}$

Parameters of interest:

- m_χ = WIMP mass ($\sim 100 \text{ GeV}$)
- σ = WIMP-nucleus elastic scattering cross section (SD or SI)

Scattering Cross Section

- In general, interactions leading to WIMP-nucleus scattering are parameterized as:
 - **scalar interactions** (coupling to WIMP mass, from scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2} [Zf_p + (A - Z)f_n]^2$$

f_p, f_n : scalar 4-fermion couplings to p and n

=> nuclei with large A favourable (but nuclear form factor corrections)

- **spin-spin interactions** (coupling to the nuclear spin J_N , from axial-vector part of L)

$$\sigma_{SD} \sim \mu^2 \frac{J_N + 1}{J_N} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

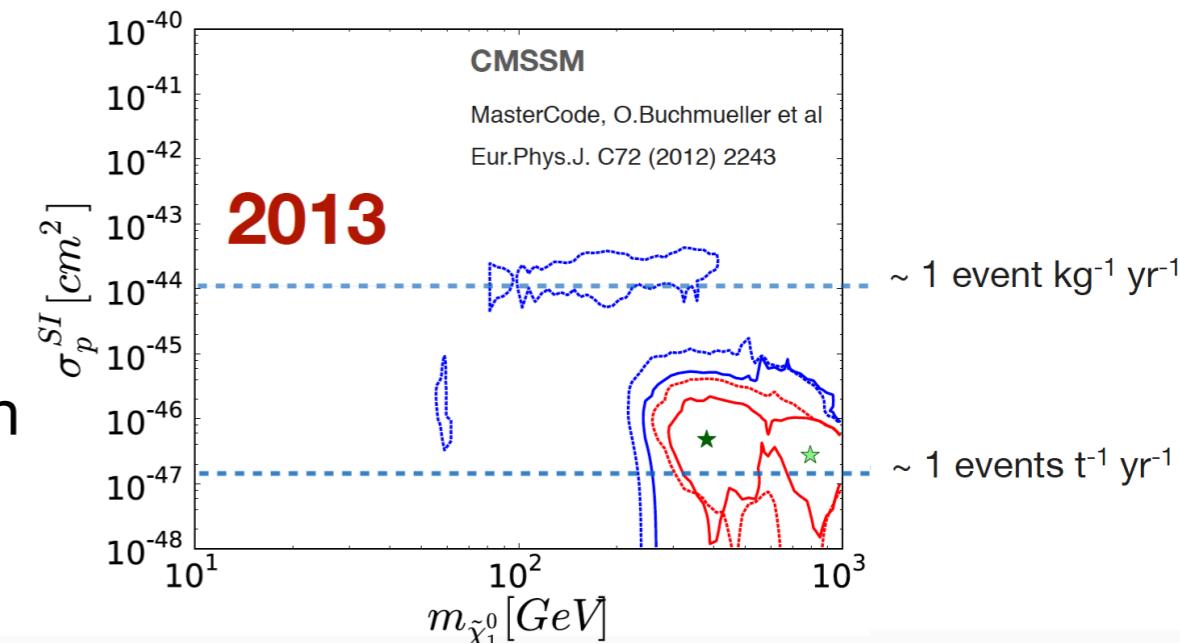
a_p, a_n : effective couplings to p and n; $\langle S_p \rangle$ and $\langle S_n \rangle$ expectation values of the p and n spins within the nucleus

=> nuclei with non-zero angular momentum (corrections due to spin structure functions)

Detector requirements and signatures

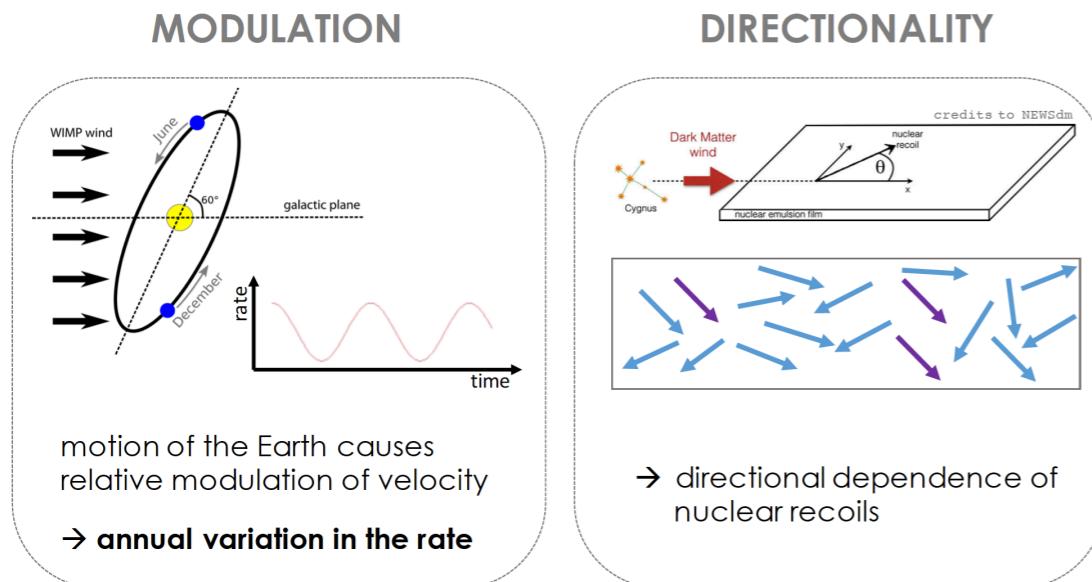
- Requirements for a dark matter detector

- Large detector mass
- Low **energy threshold** ~ sub-keV to few keV's
- Very **low background** and/or background discrimination
- Long term stability



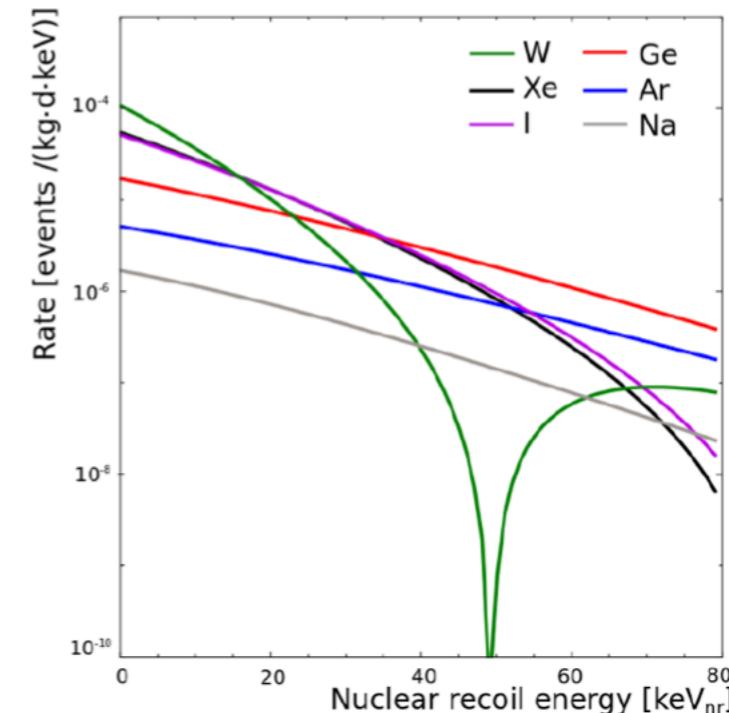
- Possible signatures of dark matter

- Spectral shape of the recoil spectrum
- Annual modulated rate
- Directional dependance



Spectral Shape

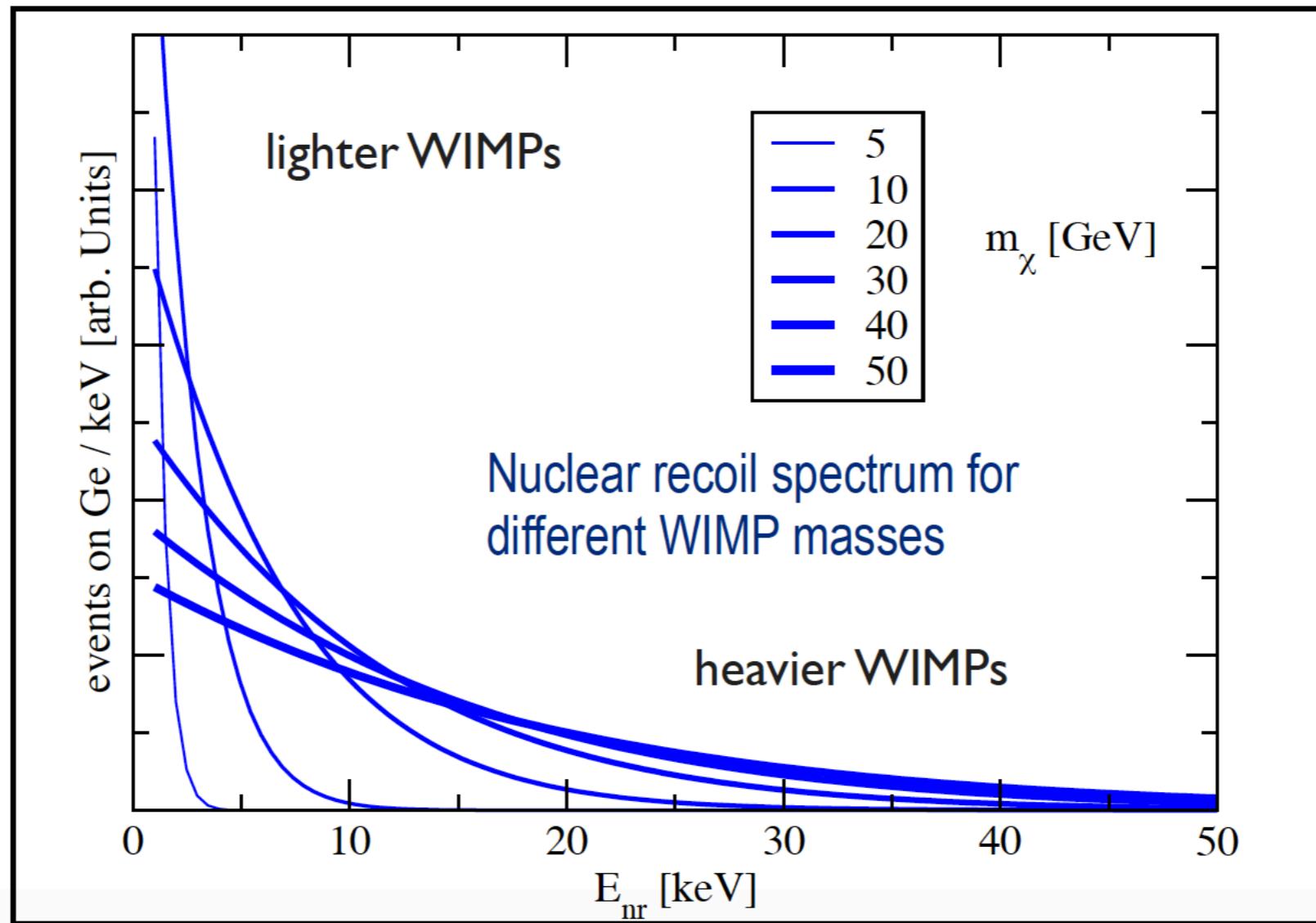
J. Phys. G: 43 (2016) 1, arXiv:1509.08767



Nuclear Recoil Energy Spectrum

Rate after integration over WIMP velocity distribution

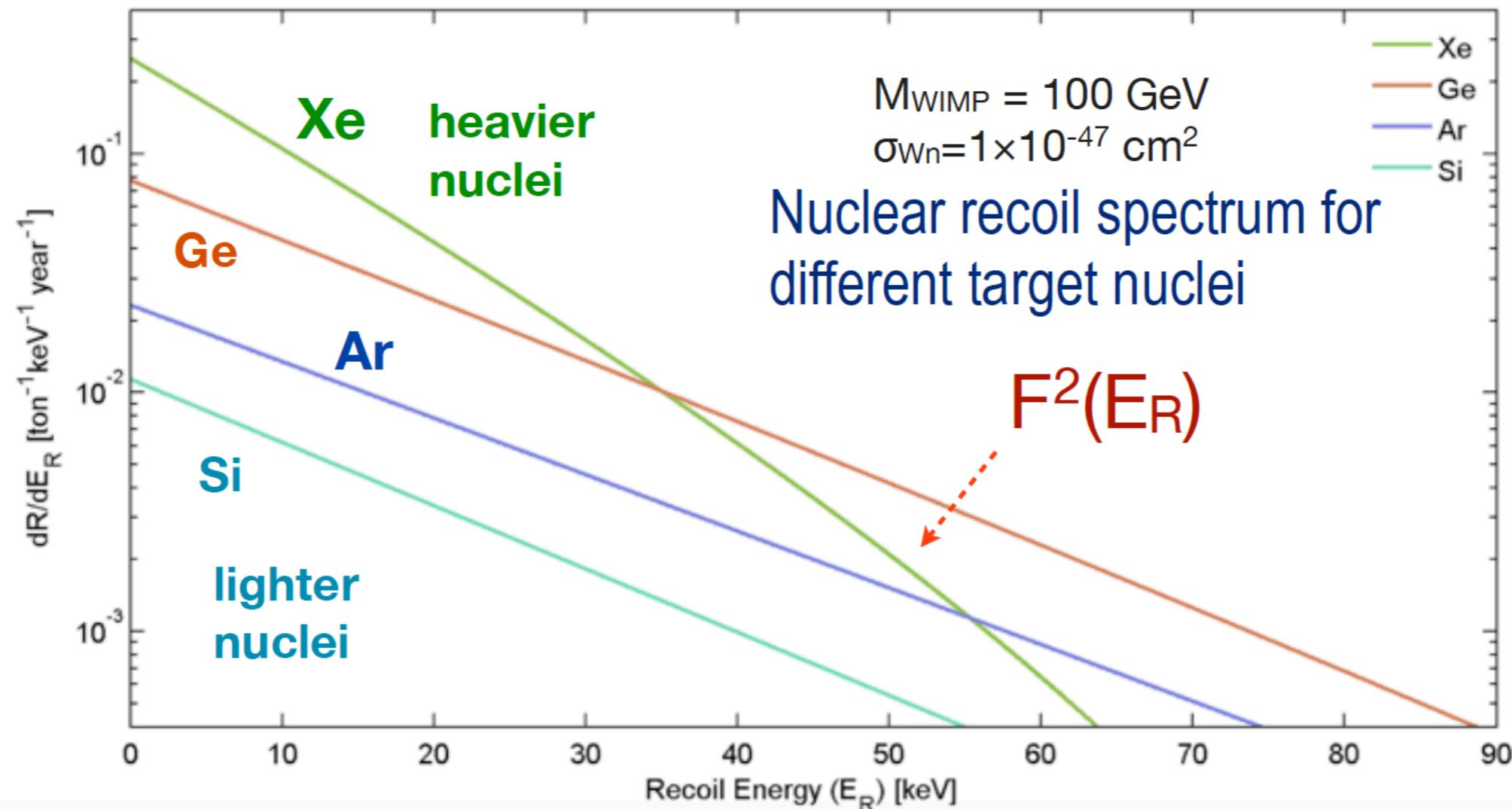
$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38} \text{ cm}^2} \times \frac{\langle v \rangle}{220 \text{ km s}^{-1}} \times \frac{\rho_0}{0.3 \text{ GeV cm}^{-3}} \right]$$



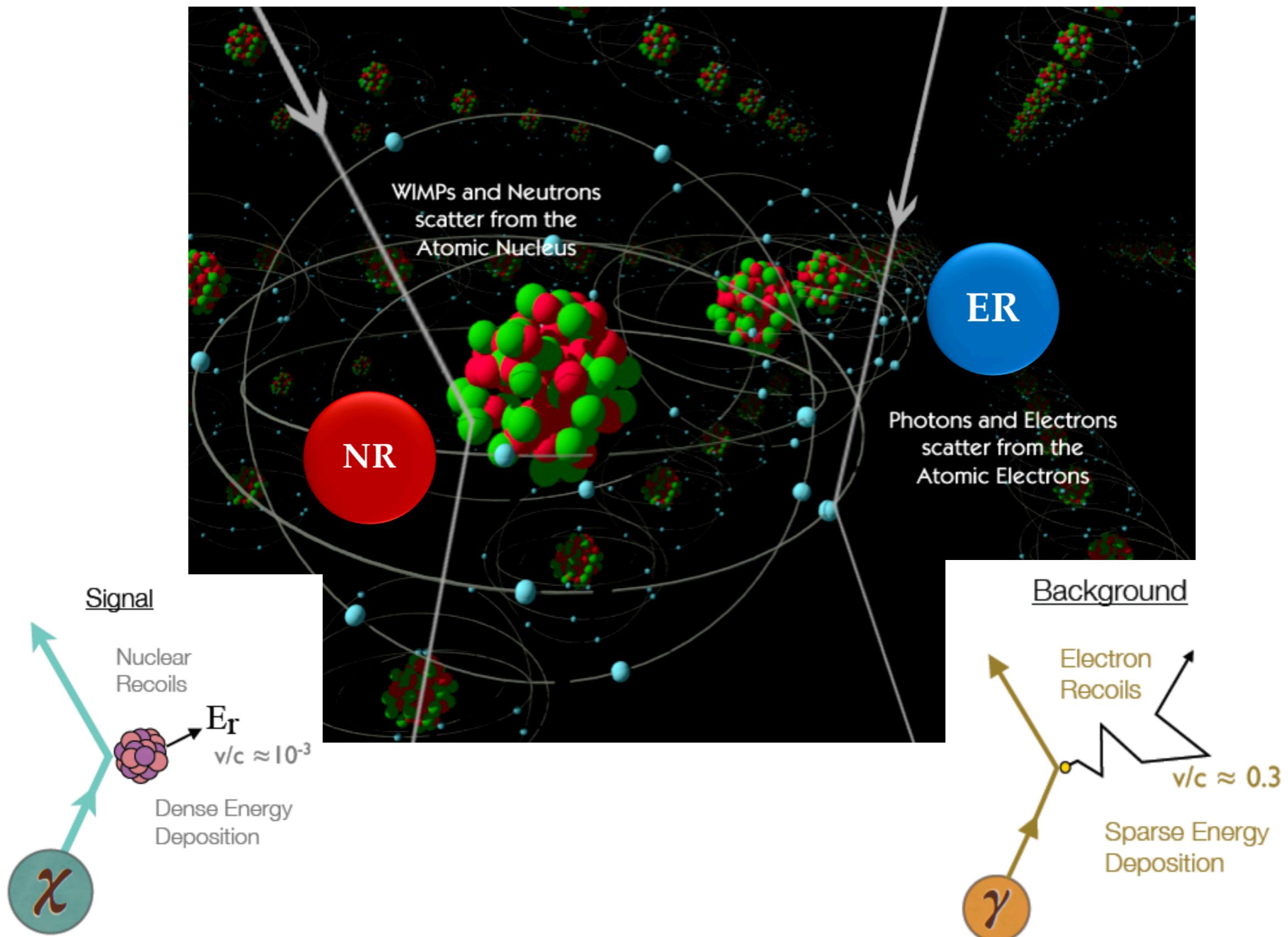
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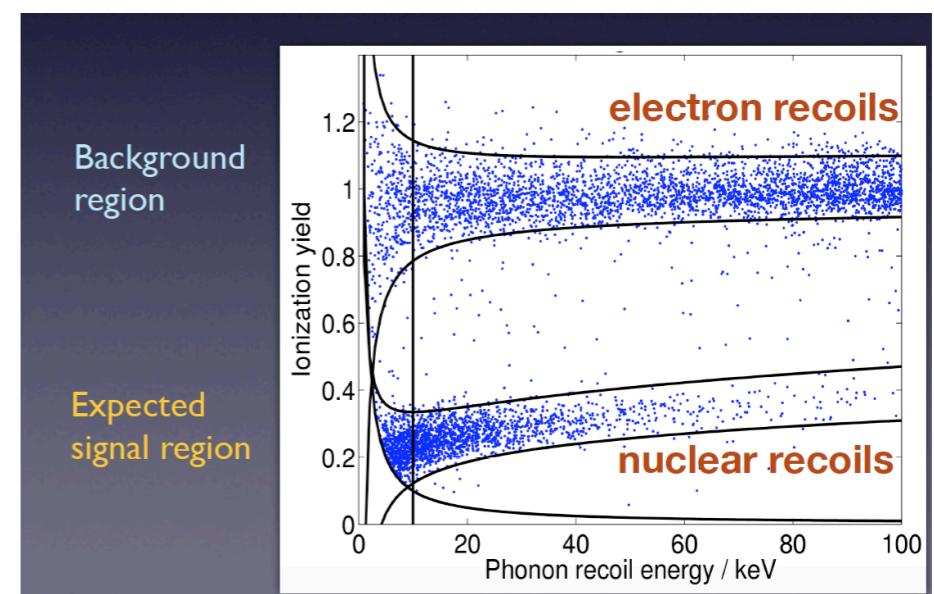
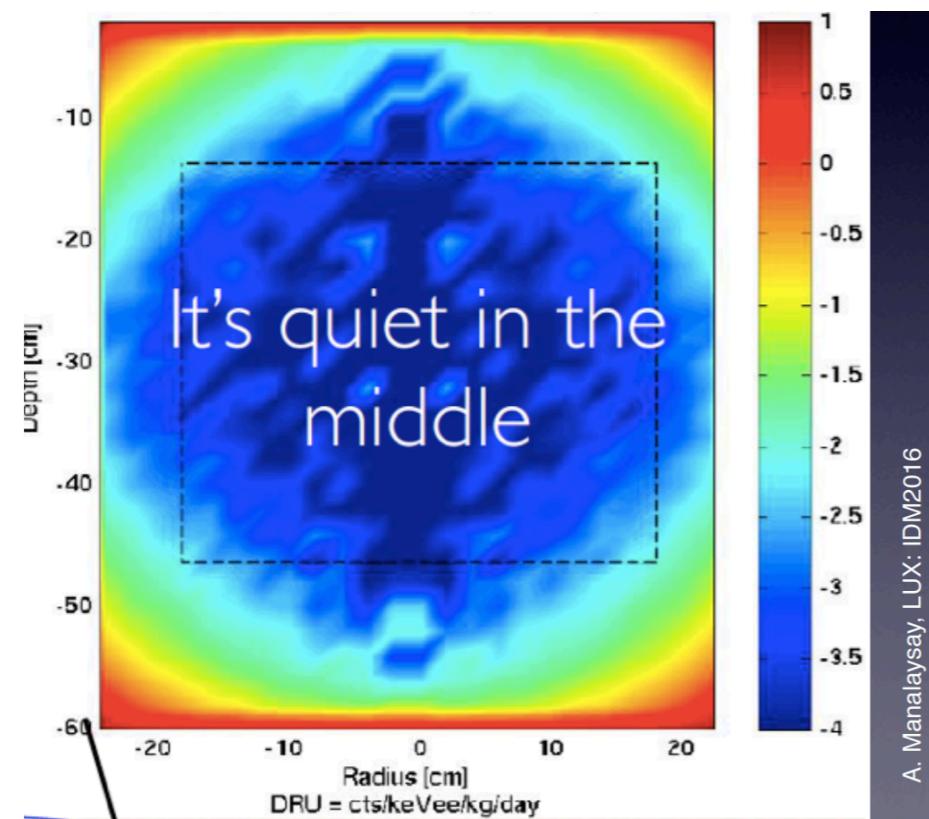
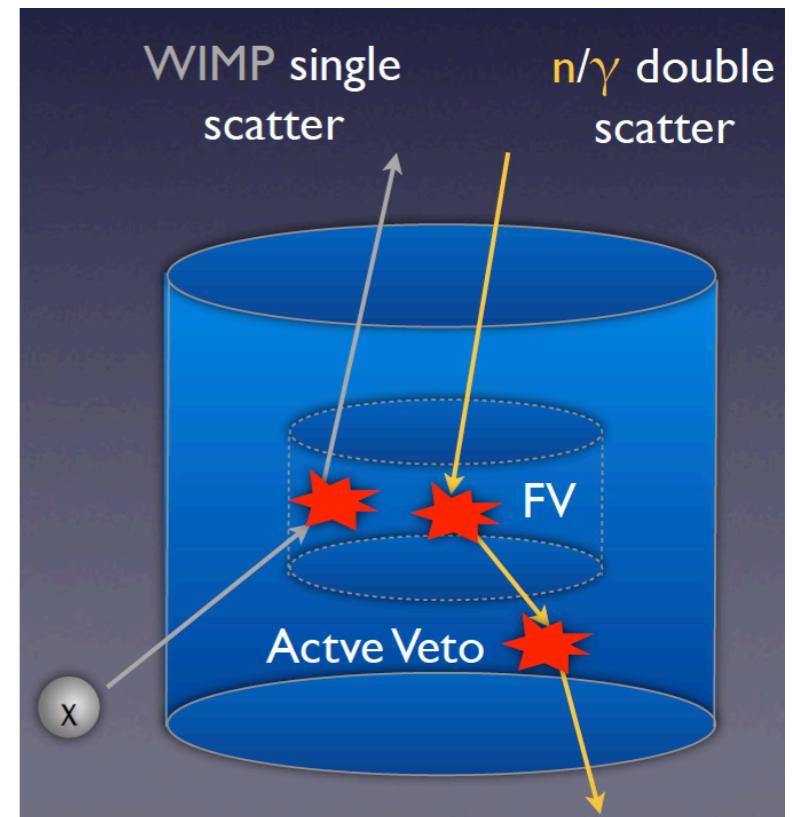


Backgrounds: Electron & Nuclear Recoils

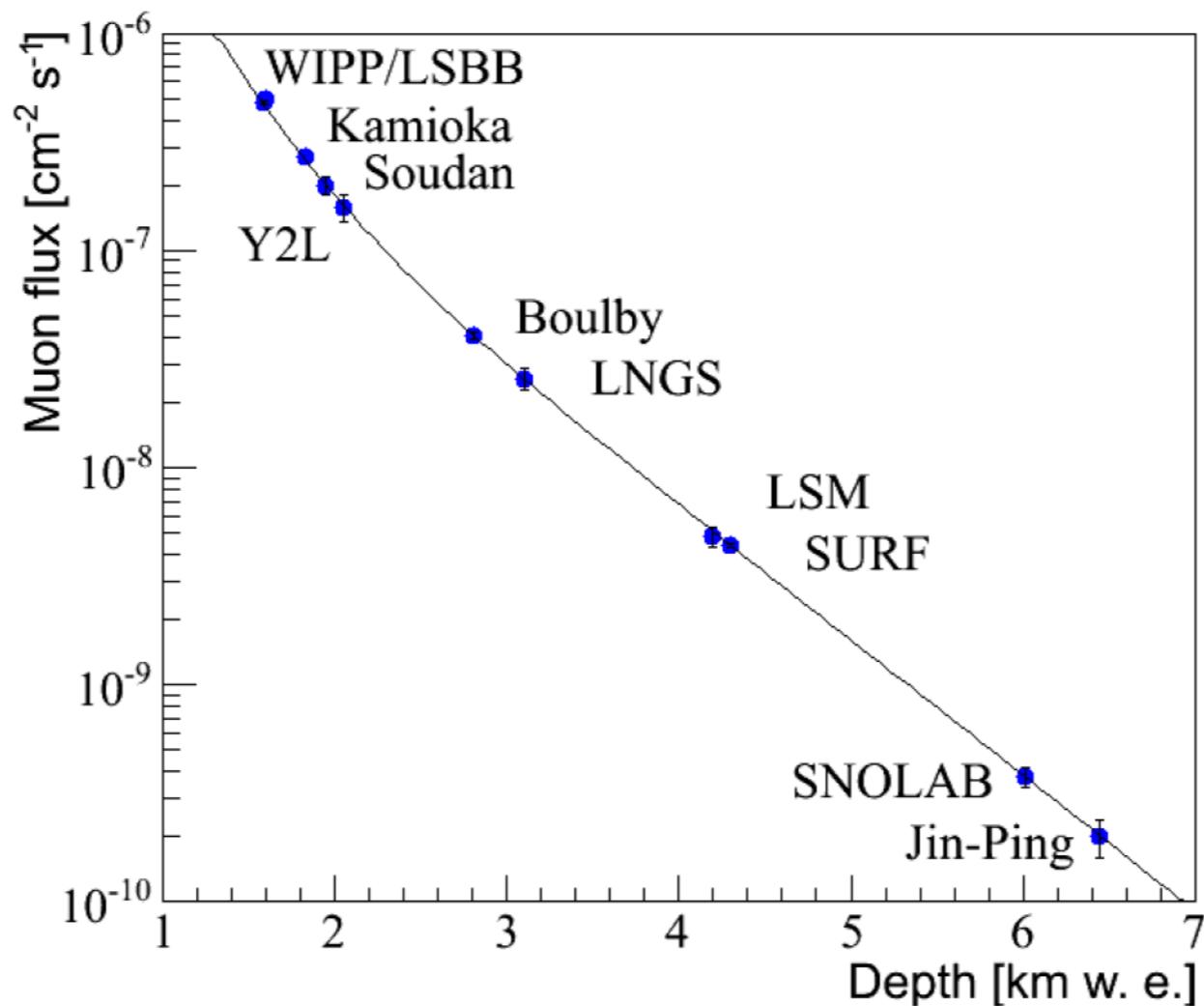


Backgrounds: external sources

- External γ 's from natural radioactivity:
 - Suppression via self-shielding of the target
 - Material screening and selection
 - Rejection of multiple scatters & discrimination
- External neutrons:
muon-induced, (α, n) and from fission reactions
 - Go underground!
 - Shield: passive (polyethylene) or active (water/scintillator vetoes)
 - material selection for low U and Th contaminations



Underground laboratories



- WIPP in USA (DMTPC)
- LSBB in France (SIMPLE)
- Kamioka in Japan (XMASS, NEWAGE)
- Soudan in USA (SuperCDMS, GoGeNT)
- Y2L in Corea (KIMS)
- Boulby in UK (DRIFT, ZEPLIN)
- LNGS in Italy (XENON, DAMA, Cresst, DarkSide)
- LSM in France (Edelweiss, MIMAC)
- SURF in USA (LUX)
- SNOLAB in Canada (DEAP/CLEAN, PICASSO, COUPP)
- Jin-Ping in China (PandaX, CDEX)

Underground laboratories



Backgrounds: internal and surface sources

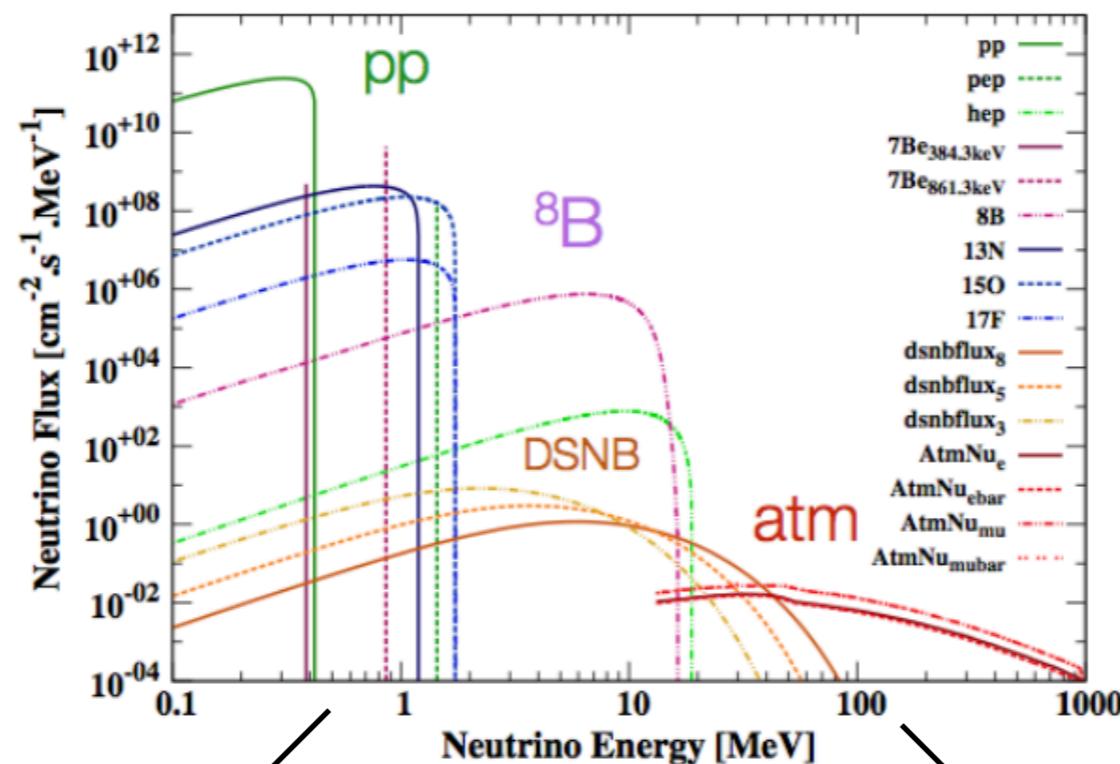
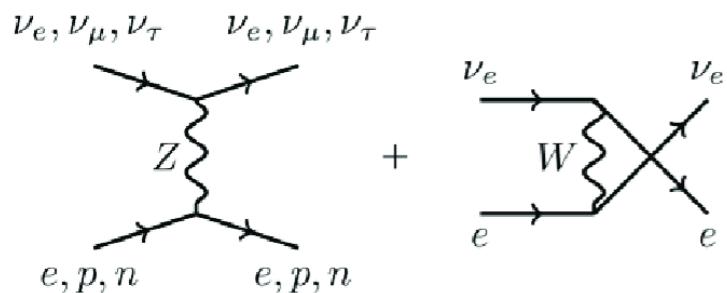
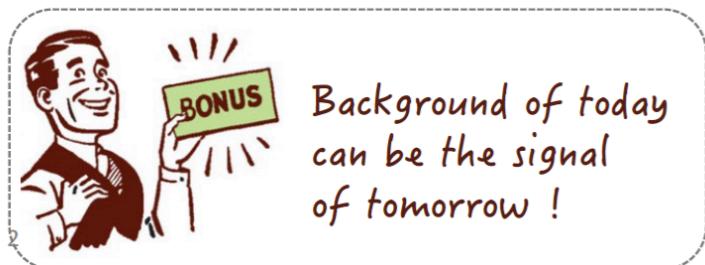
- Internal contamination in liquids:

- ^{85}Kr : removal by cryogenic distillation/chromatography/centrifuges
- Rn: removal using activated carbon, distillation, dust removal
- Argon: ^{39}Ar (565 keV endpoint, 1 Bq/kg), ^{42}Ar
- Xenon: ^{136}Xe $\beta\beta$ decay ($T_{1/2} = 2.2 \times 10^{21}$ y) *long lifetime!*

- Surface background in solids:

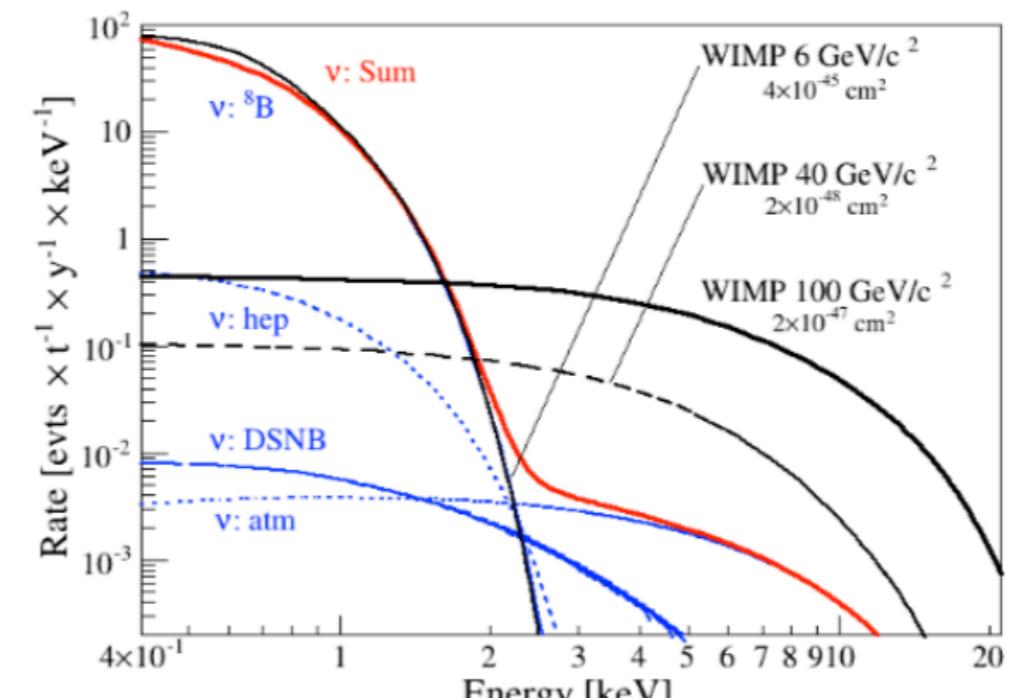
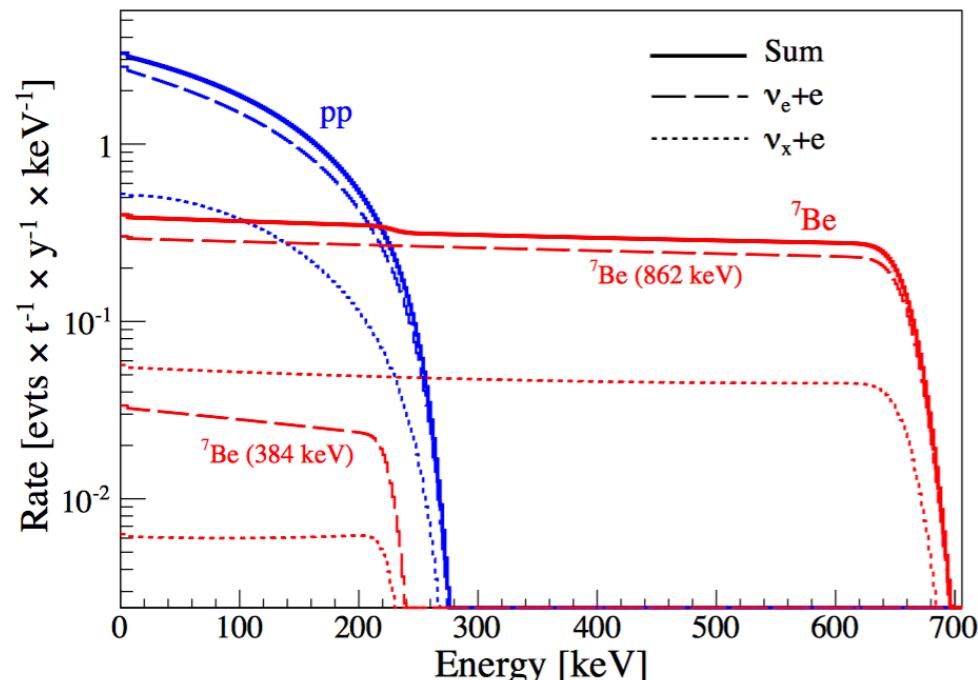
- Germanium detectors or solid scintillators grown out of high purity powders or melts → low intrinsic background
- Cosmic activation
- Surface events from α or β -decays

The ultimate background from neutrinos

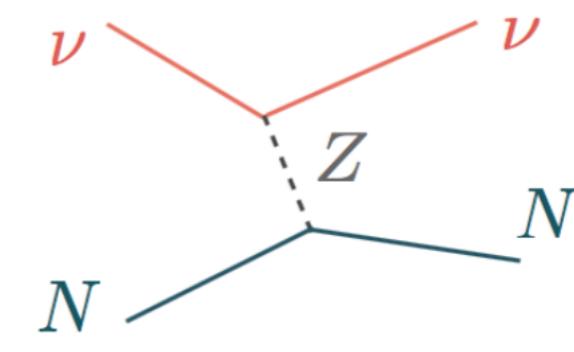
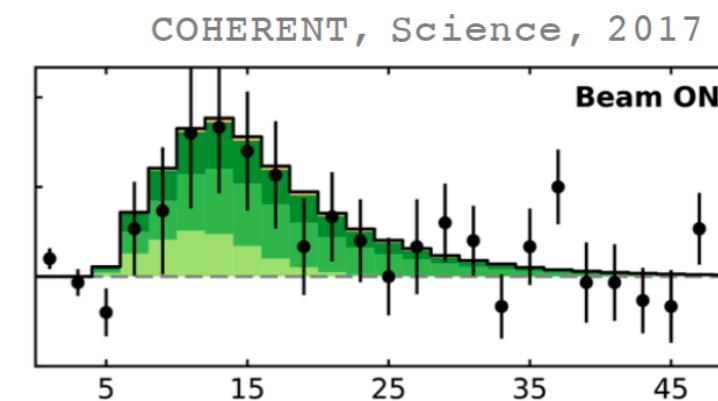


F. Ruppin et al., 1408.

ER



LB et al., JCAP01 (2014) 044

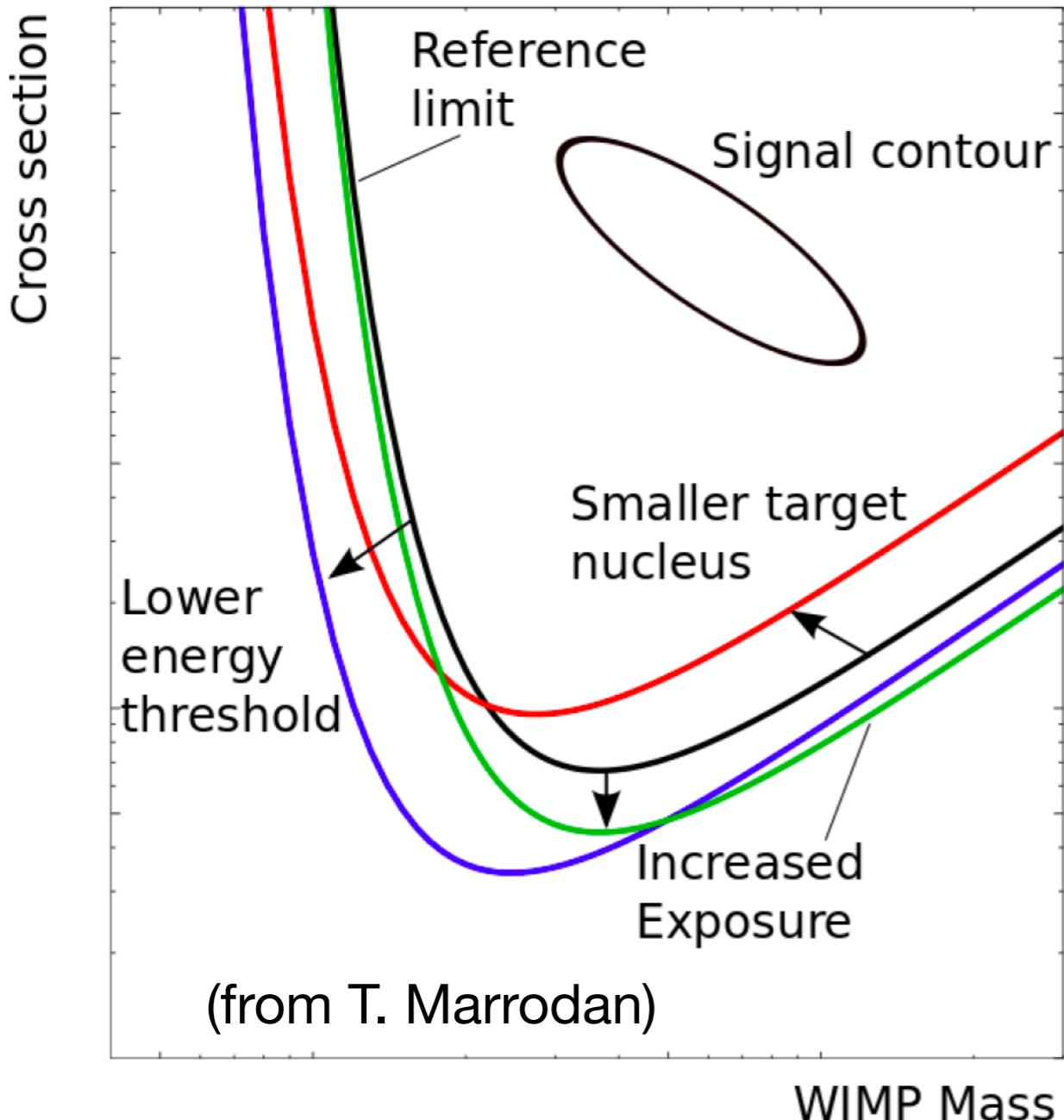


Sensitivity plot in direct DM experiments

→ Statistical significance of signal over expected background?

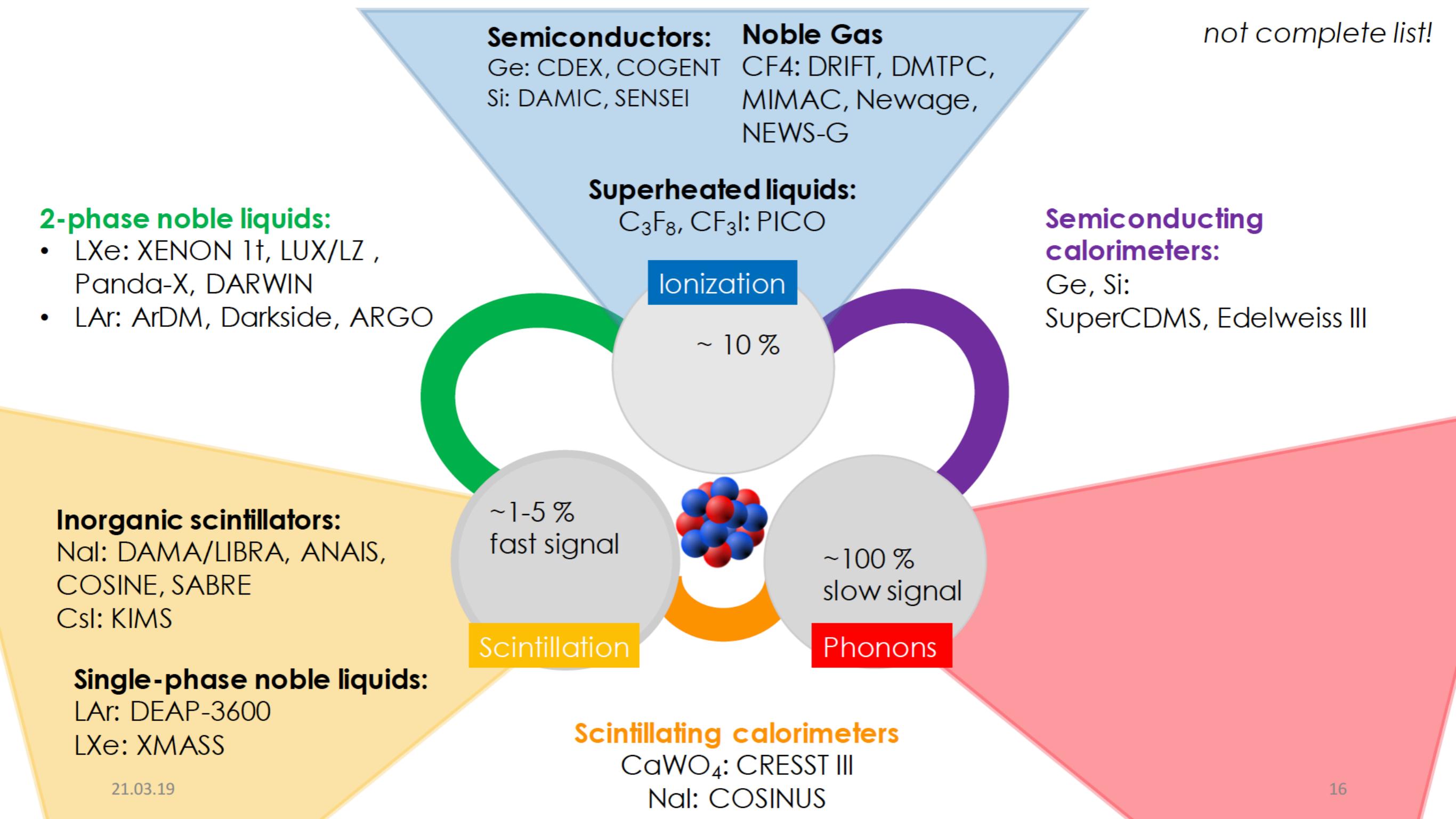
J. Phys. G43 (2016) 1, 013001 & arXiv:1509.08767

$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$

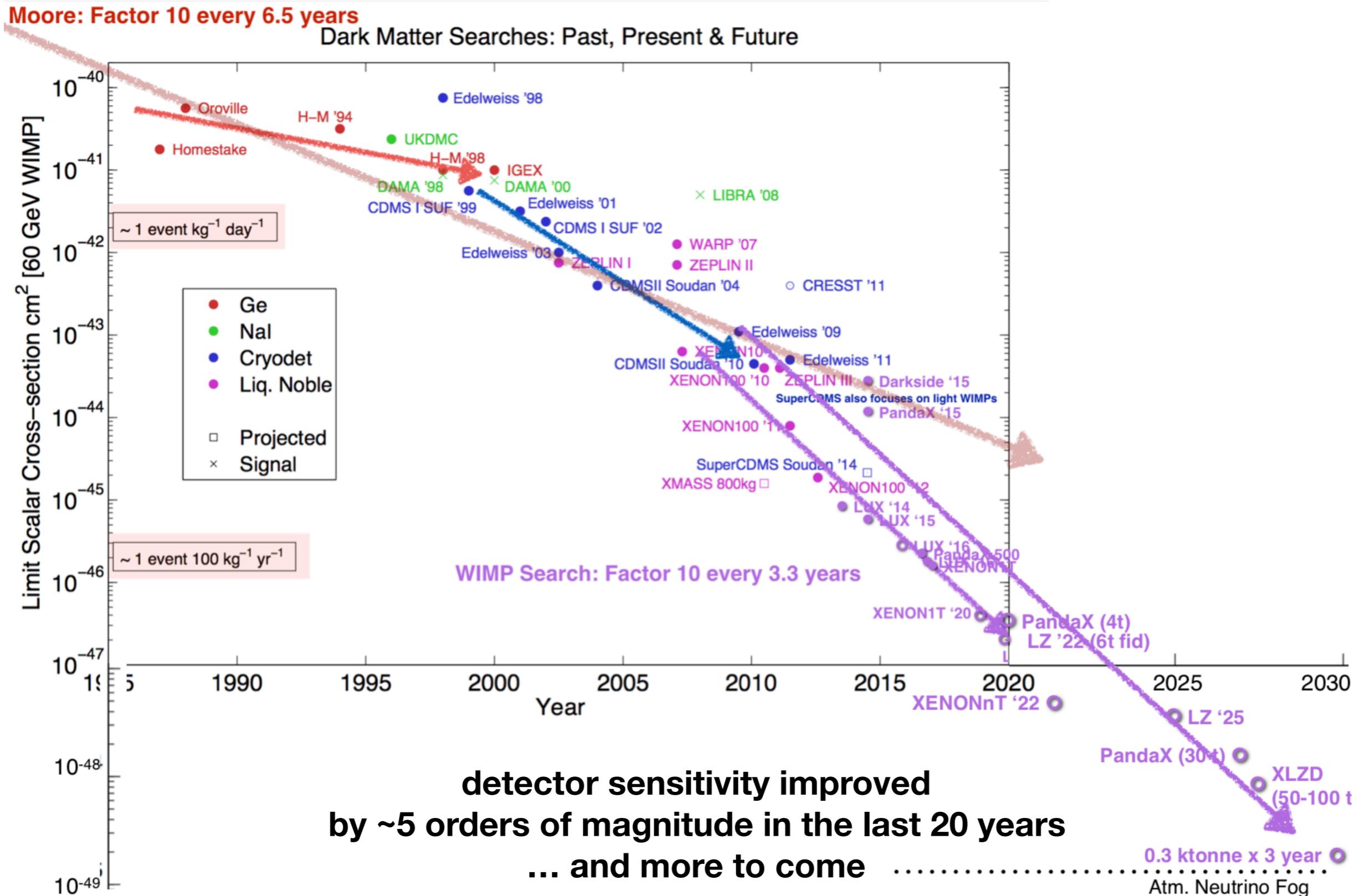


- Positive signal
 - Region in σ_χ versus m_χ
- Zero signal
 - Exclusion of a parameter region
- Low WIMP masses:
detector threshold matters
- Minimum of the curve:
depends on target nuclei
- High WIMP masses:
exposure matters $\epsilon = m \times t$

Direct detection Techniques

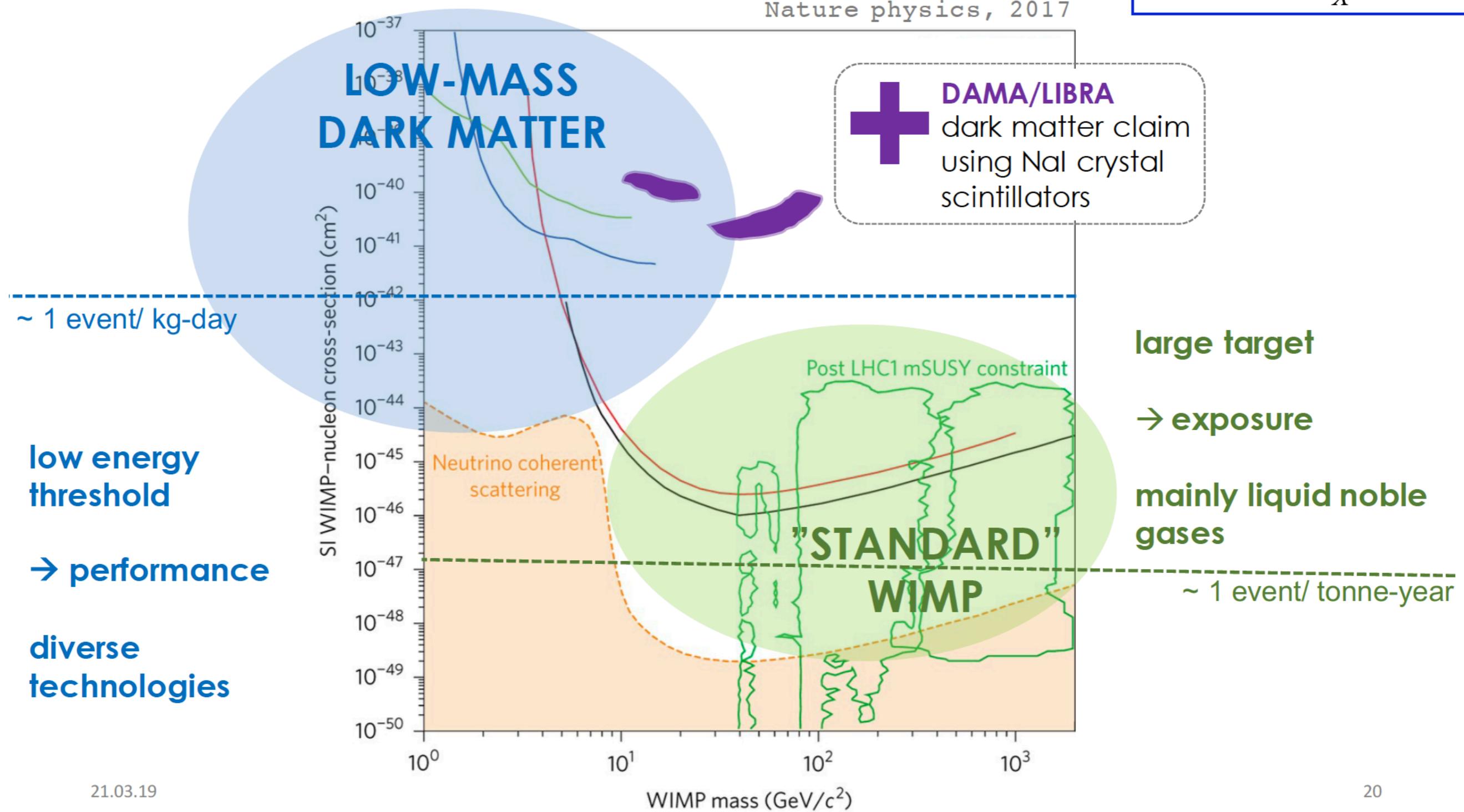


Competitive field, rapid progress



Two main lines of improvements (+ others)

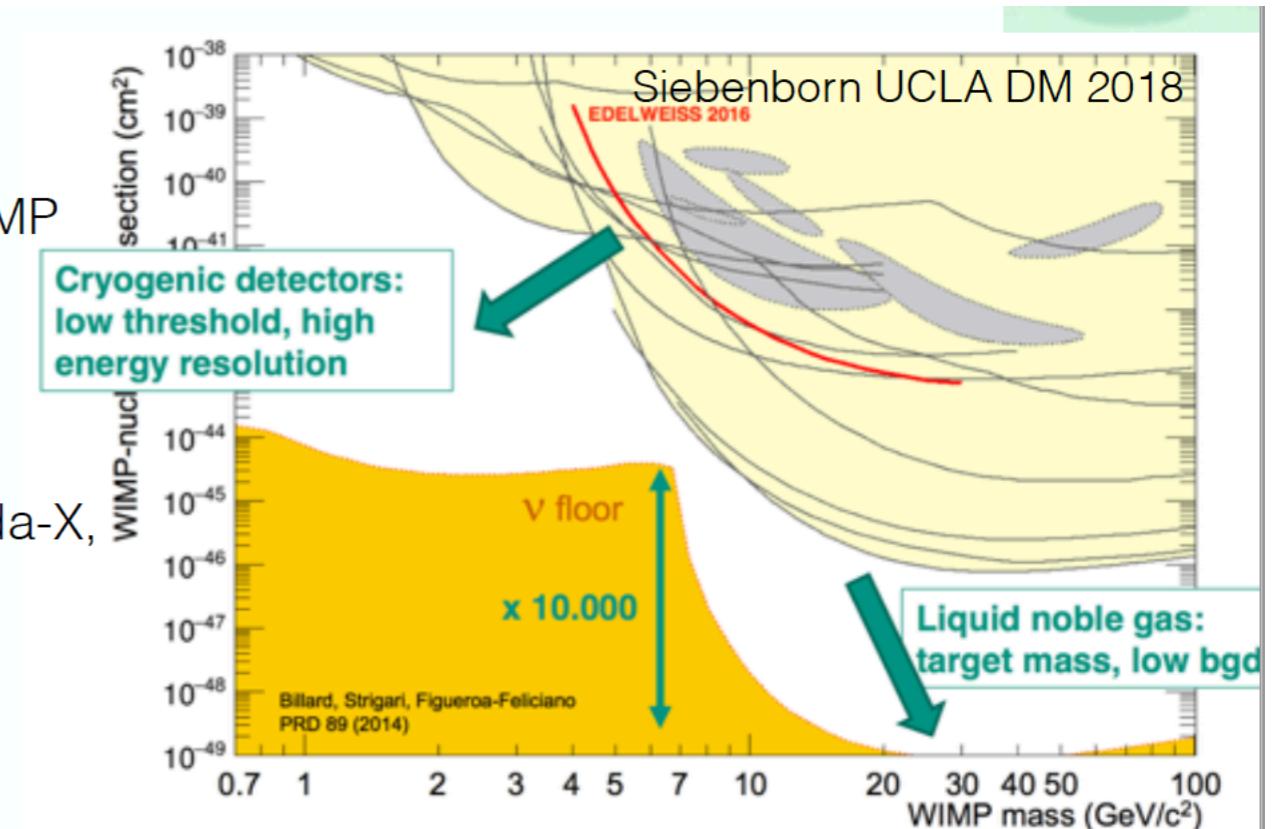
$$R \propto N_T \frac{\rho_0}{m_X} \sigma \langle v \rangle$$



Two main lines of improvements (+ others)

- **Liquid Noble targets**

- Largest and most sensitive over the widest WIMP range
- 5 GeV-1 TeV WIMP masses probed
- Darkside, DARWIN, DEAP3600, LUX, LZ, Panda-X, XENON1T, XENONnT

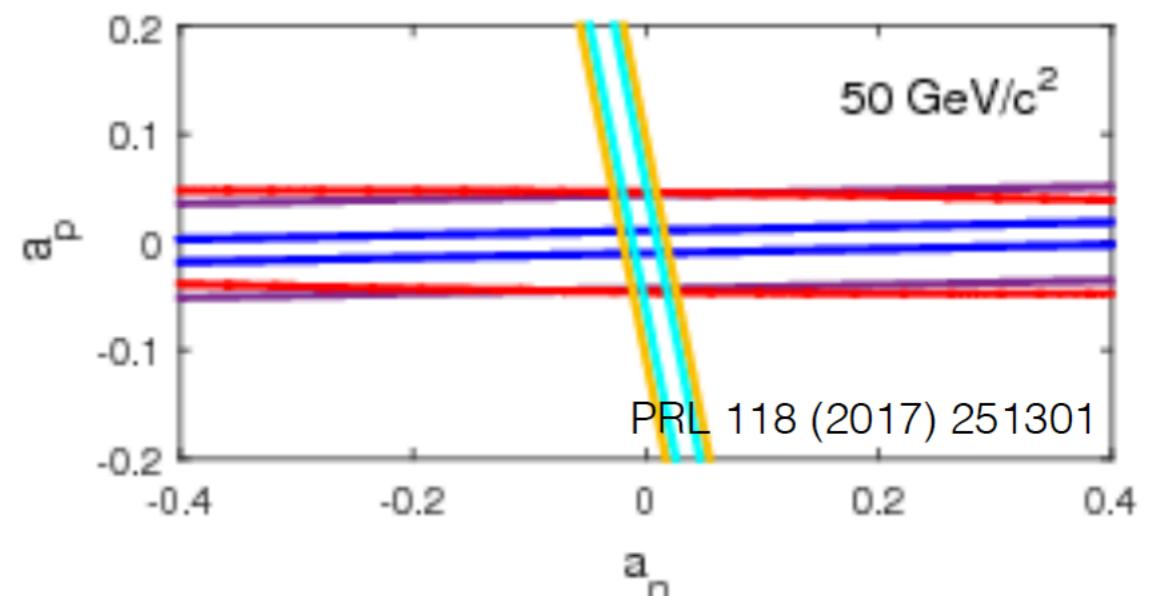


- **Cryogenic crystal targets**

- Oldest technology, with new innovations
- 1-10 GeV WIMP masses probed
- CRESST, EDELWEISS, SuperCDMS,

- **Alternate targets with unique properties**

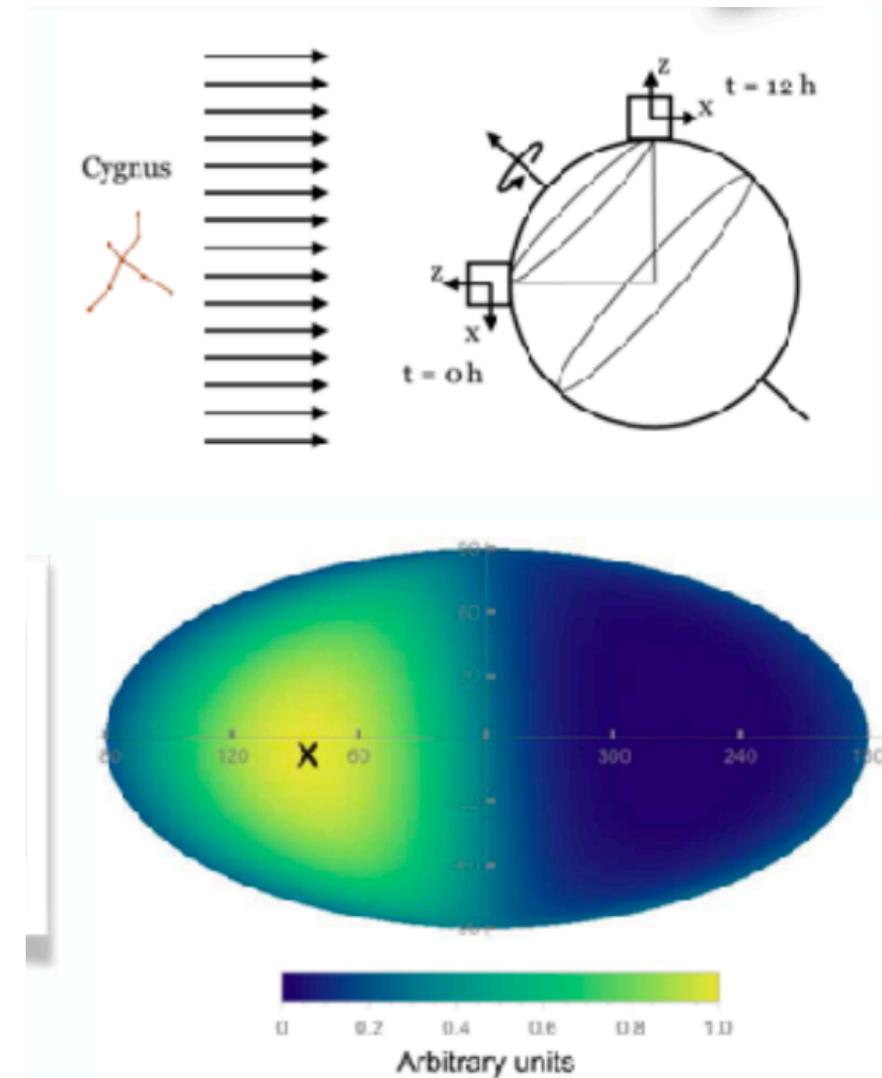
- NaI crystals, bubble chambers
- ANAIS, COSINE, DAMA/LIBRA, SABRE, PICO
- Directional detectors



Directional detectors

Various techniques:

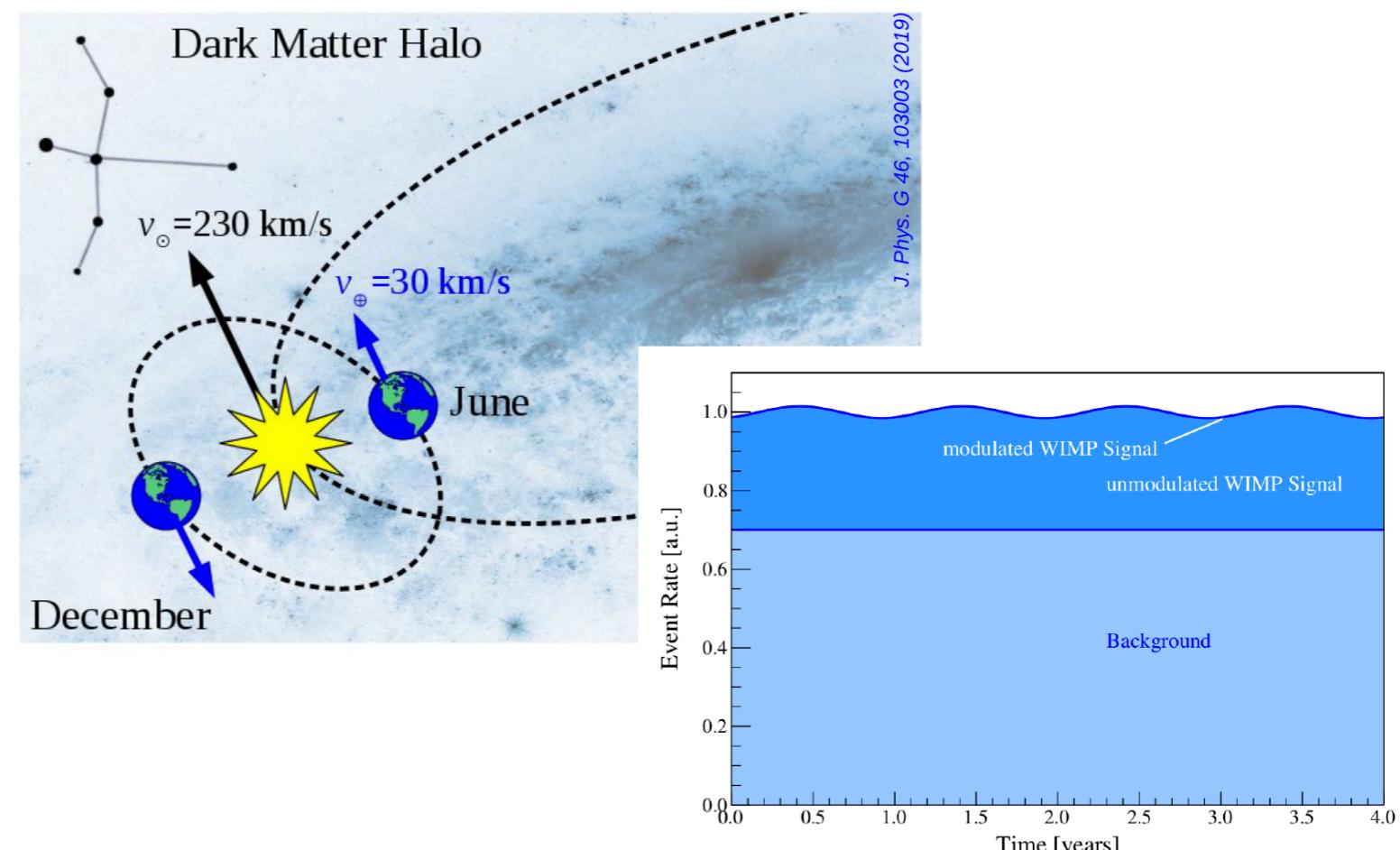
- Low pressure Gas TPC (Cygno, DRIFT, NEWAGE, D3, DMTPC, ...)
- Nuclear Emulsion (NEWSdm)
- Columnar recombination in noble gas (RED: LAr)
- Crystals with Anisotropic Response (ADAMO: ZnWO₄)
- Carbon NanoTubes
- ...



**Directional dependence:
an O(100) forward/backward
asymmetry that no background
whatsoever can mimic**

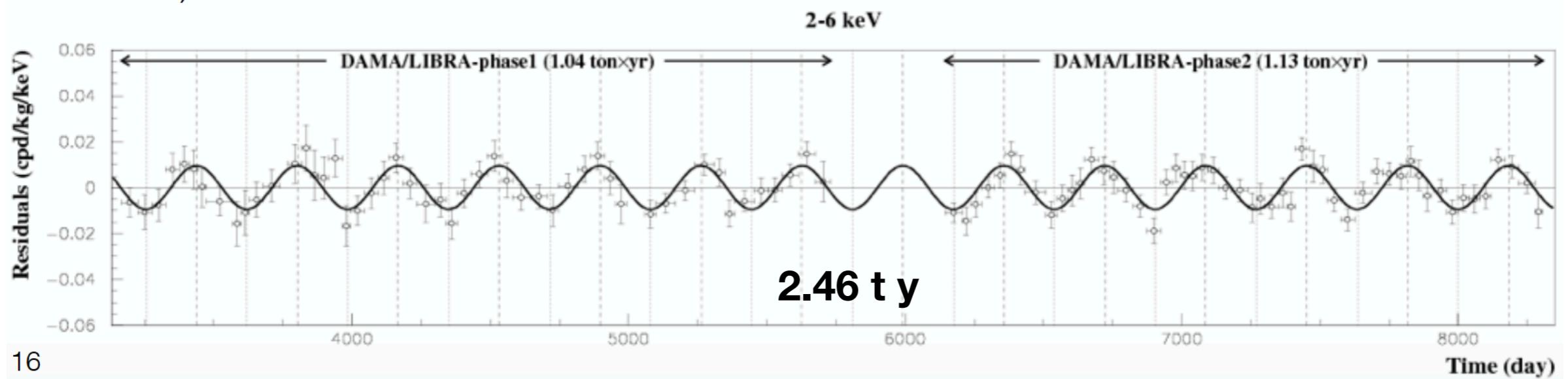
Scintillating crystals and annual modulation

- Mostly NaI (TI) and CsI (TI) used in dark matter searches
- Arrays of several crystals at room temperature
→ simple operation, important for long-term stability
- No particle discrimination
 - Low radioactivity of the target material
 - Rejection of multiple scatters in different crystals



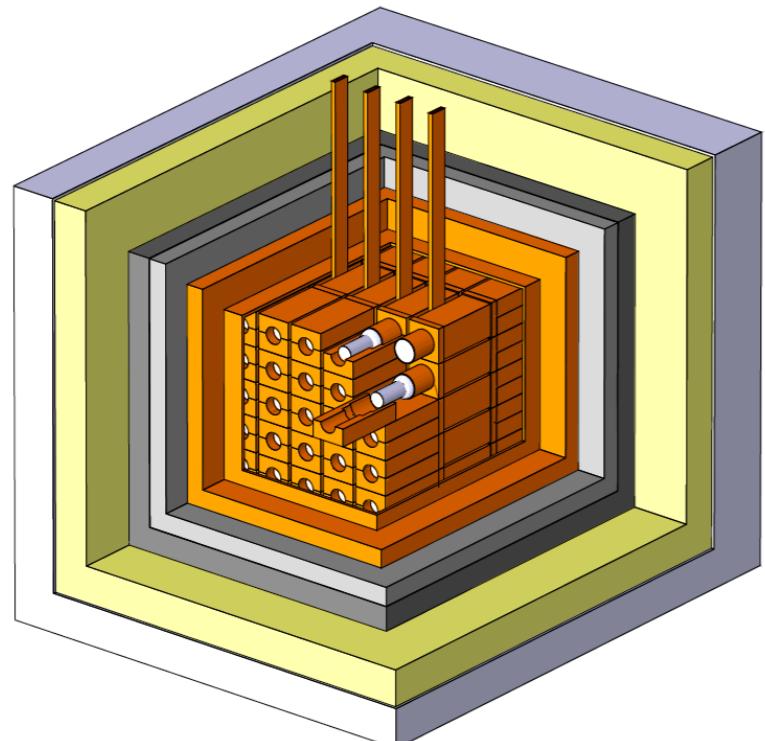
DAMA-LIBRA

- DAMA and DAMA/LIBRA phase 1
 - 250-kg high-purity NaI(Tl) array collected data for 14 solar cycles
 - observed ~ 0.01 cpd/kg/keV modulation in 2 - 6 keV energy range
 - over 9σ stat. significant; WIMP signal interpretation in tension with other experiments
- DAMA/LIBRA phase 2 arXiv:1805.10486
 - 250-kg high-purity NaI(Tl) array collected data for 6 solar cycles
 - 2-6 keV range combined now gives 12.9σ stat. significant
 - Modulation clearly evident in lowest energy bins now too (1-3 keV)



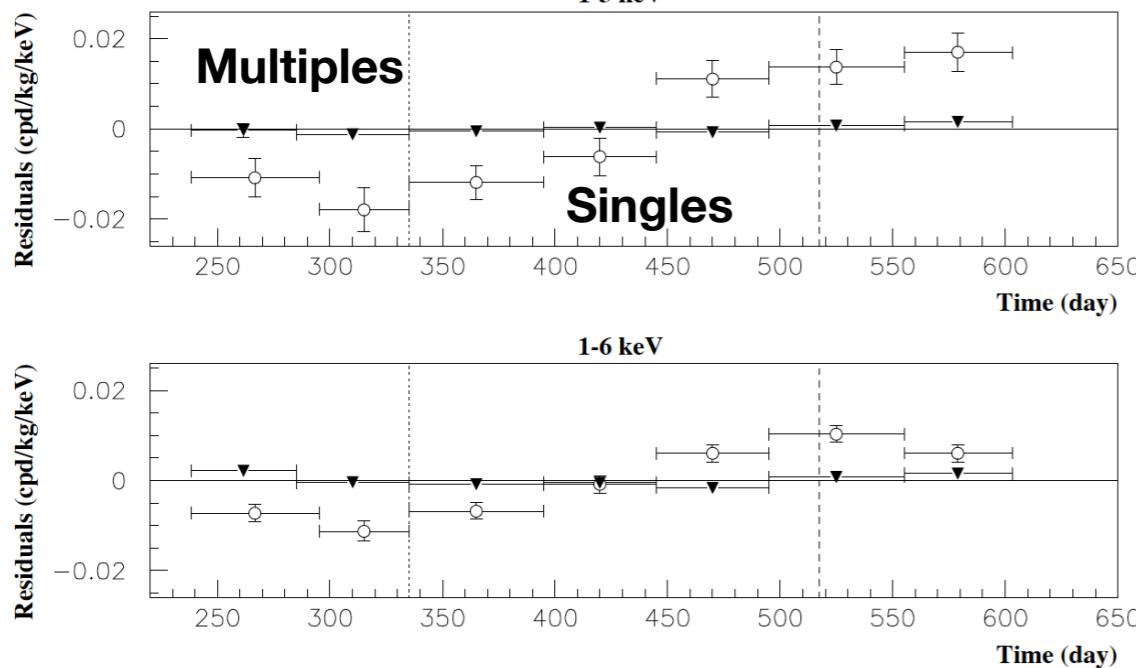
DAMA-LIBRA results

R. Bernabei et al., Nucl. Phys. At. Energy 19, 307 (2018)

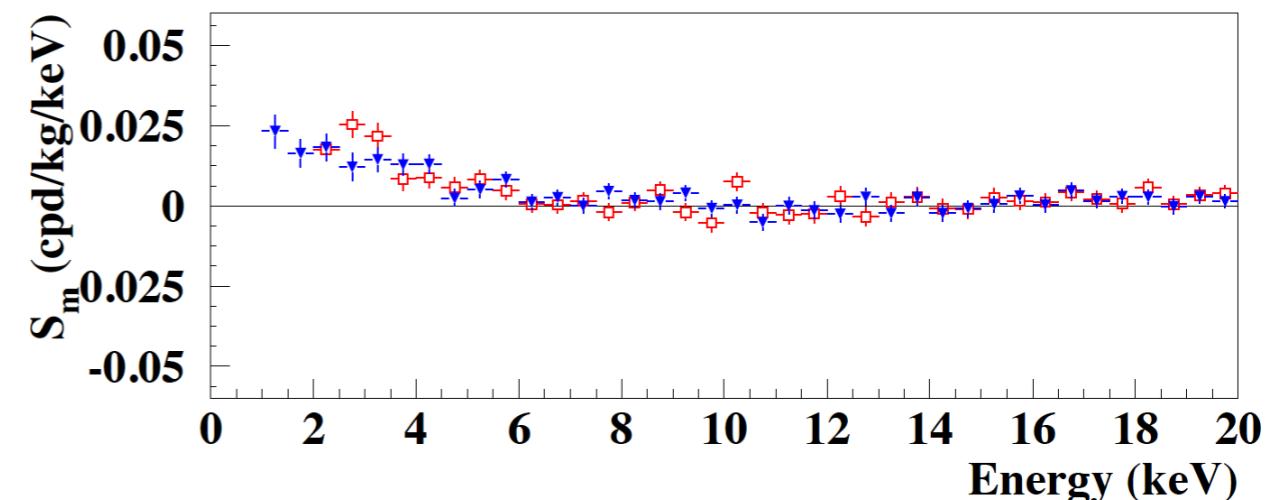
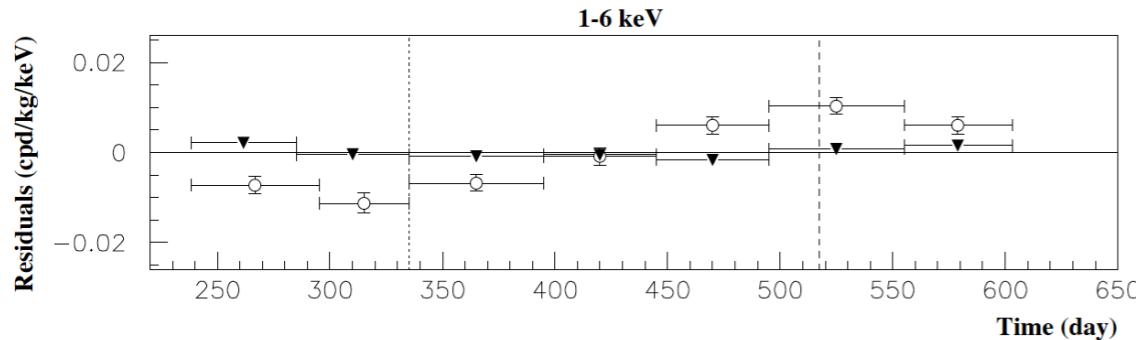
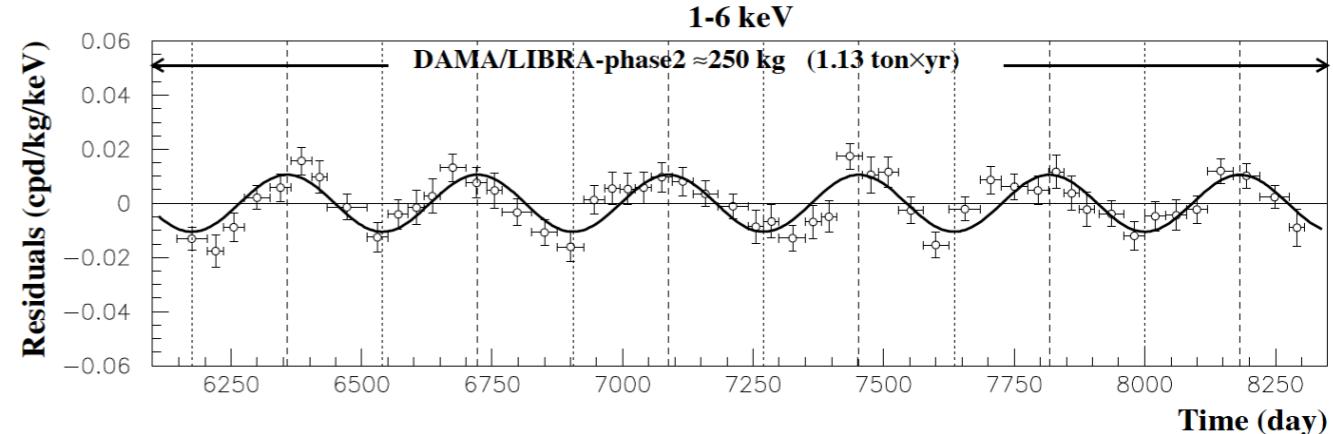
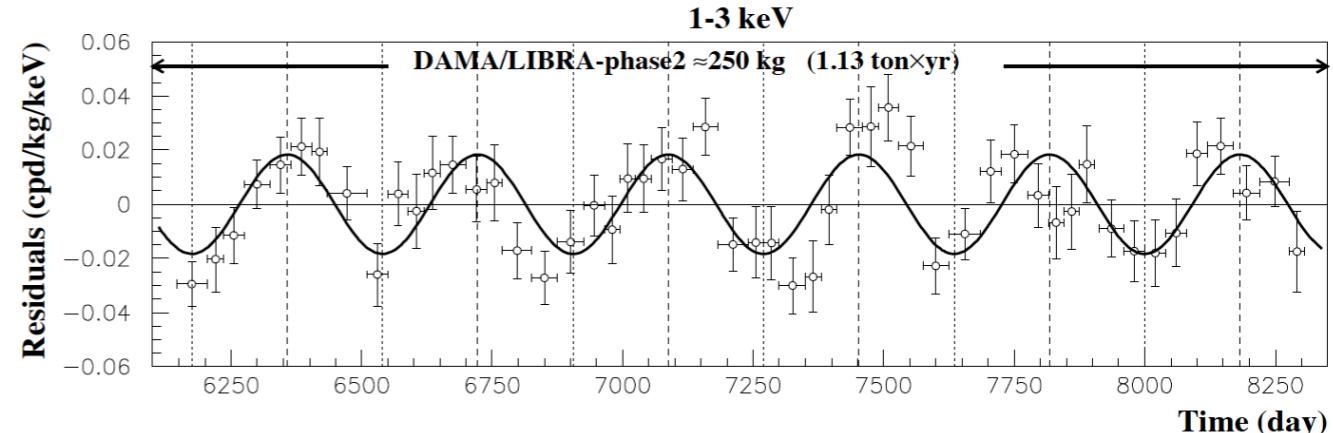


a)

b)



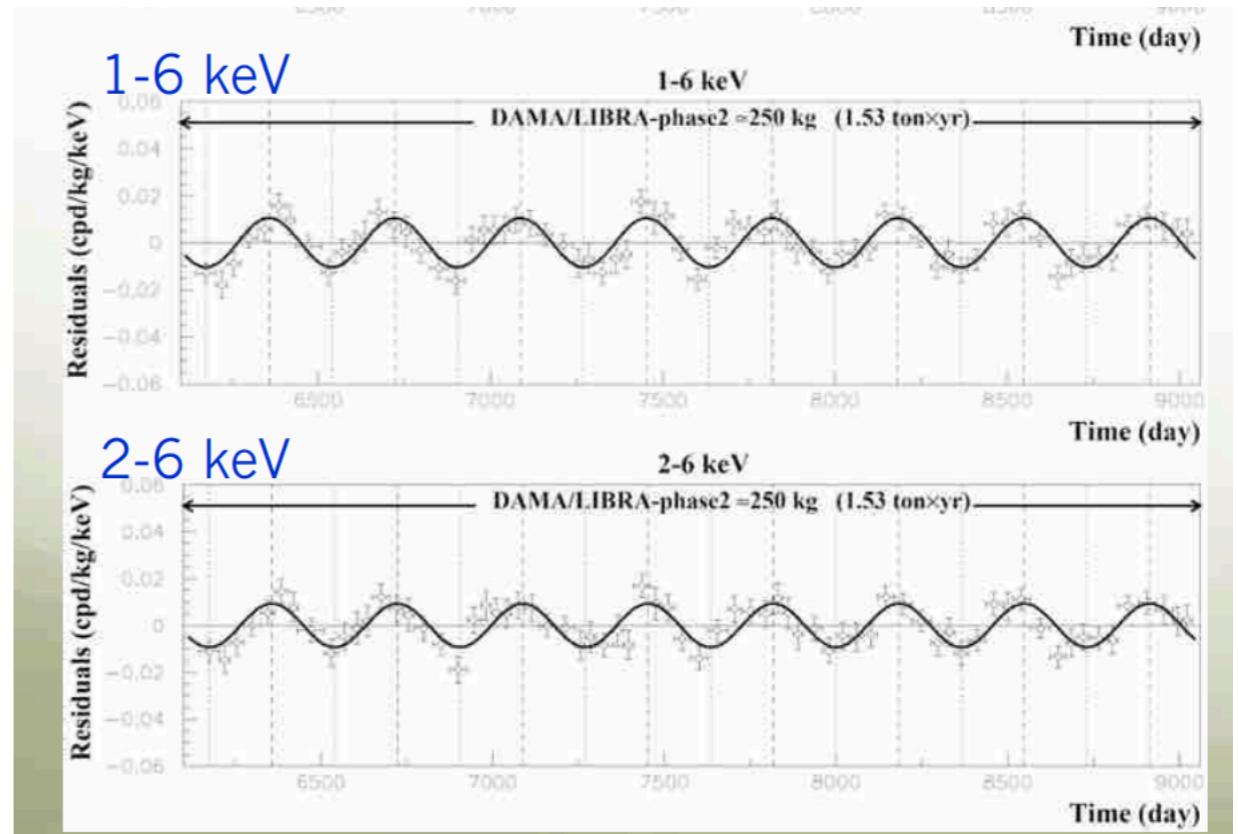
**Very hard to attribute it to
neutrons, muons, or worst ... neutrinos !!!**



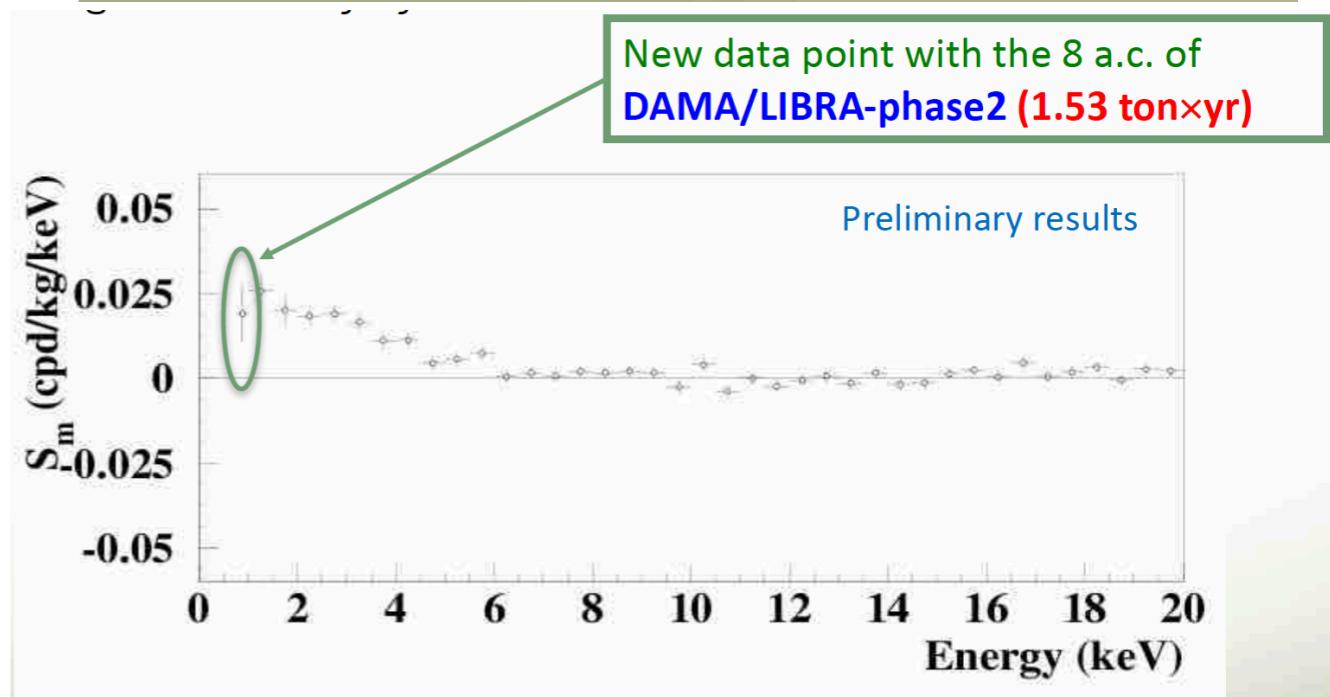
DAMA-LIBRA new results

Two additional annual cycles released in summer 2021

Annual Cycles	Period	Mass (kg)	Exposure (kg x d)	$(\alpha - \beta^2)$
I	Dec 23, 2010 – Sept. 9, 2011		commissioning	
II	Nov. 2, 2011 – Sept. 11, 2012	242.5	62917	0.519
III	Oct. 8, 2012 – Sept. 2, 2013	242.5	60586	0.534
IV	Sept. 8, 2013 – Sept. 1, 2014	242.5	73792	0.479
V	Sept. 1, 2014 – Sept. 9, 2015	242.5	71180	0.486
VI	Sept. 10, 2015 – Aug. 24, 2016	242.5	67527	0.522
VII	Sept. 7, 2016 – Sept. 25, 2017	242.5	75135	0.480
VIII	Sept. 25, 2017 – Aug. 20, 2018	242.5	68759	0.557
IX	Aug. 24, 2018 – Oct. 3, 2019	242.5	77213	0.446

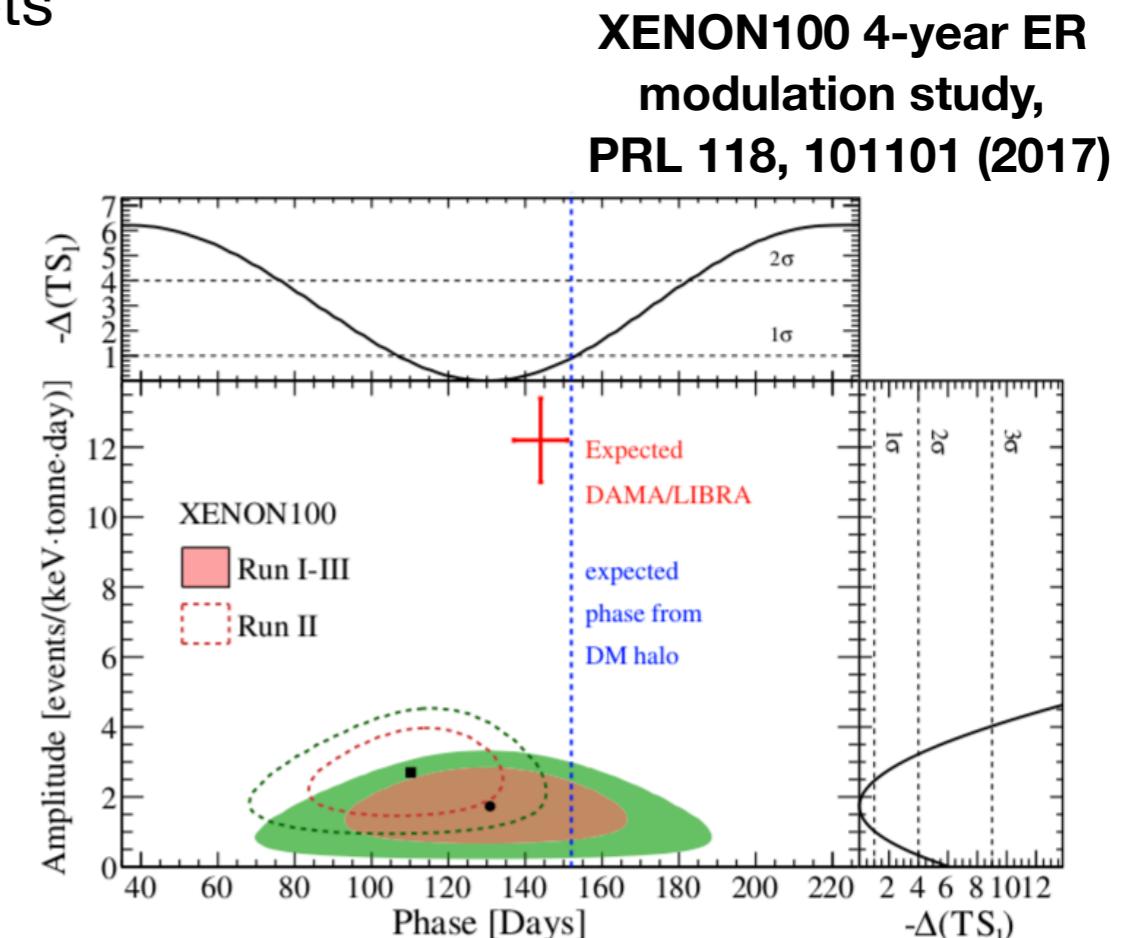
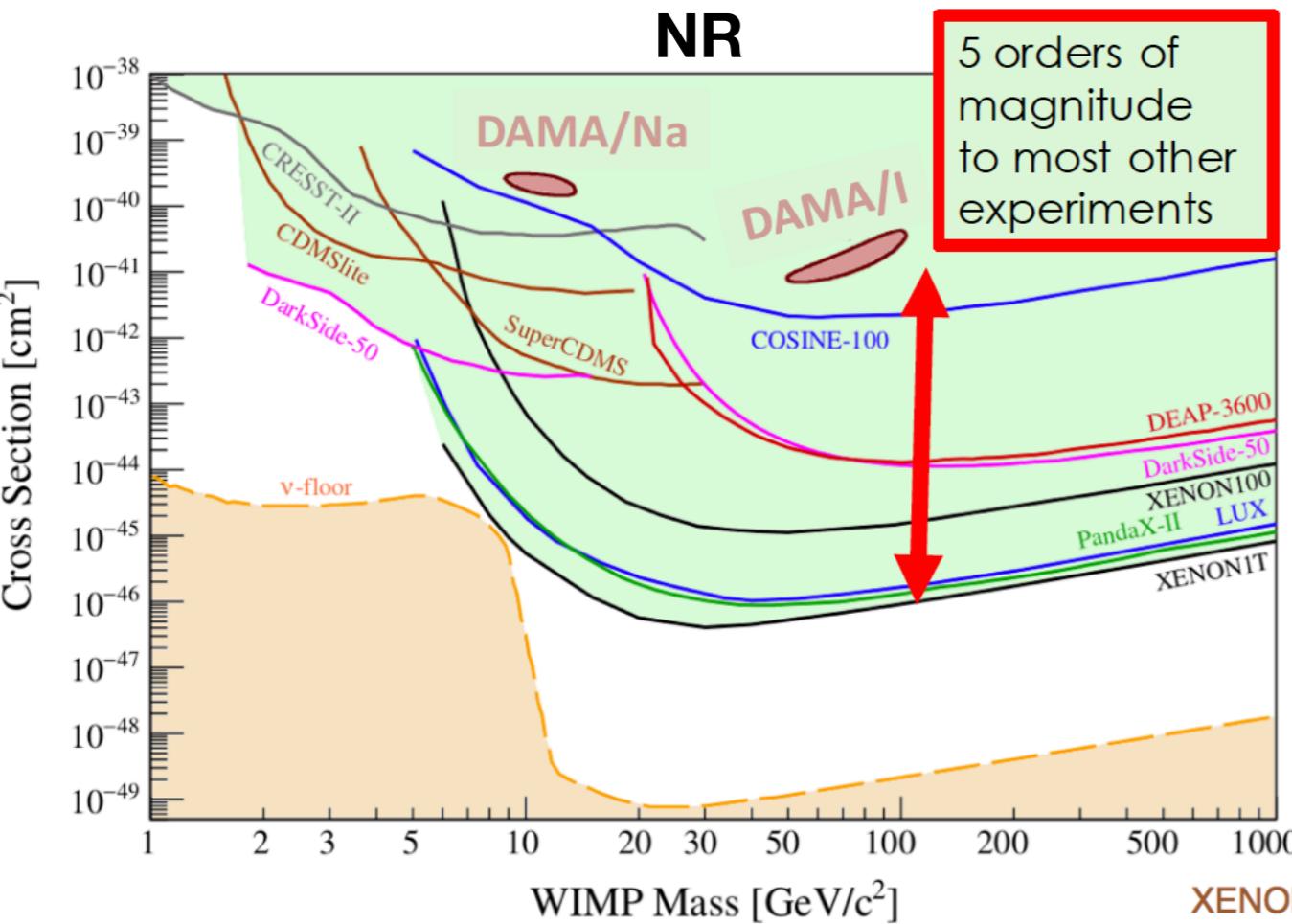


	ΔE	A(cpd/kg/keV)	T=2π/ω (yr)	t_0 (day)	C.L.
DAMA/LIBRA-ph2	(1-3) keV	0.0191±0.0020	0.99952±0.00080	149.6±5.9	9.6σ
	(1-6) keV	0.01058±0.00090	0.99882±0.00065	144.5±5.1	11.8σ
	(2-6) keV	0.00954±0.00076	0.99836±0.00075	141.1±5.9	12.6σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.00959±0.00076	0.99835±0.00069	142.0±4.5	12.6σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.01014±0.00074	0.99834±0.00067	142.4±4.2	13.7σ

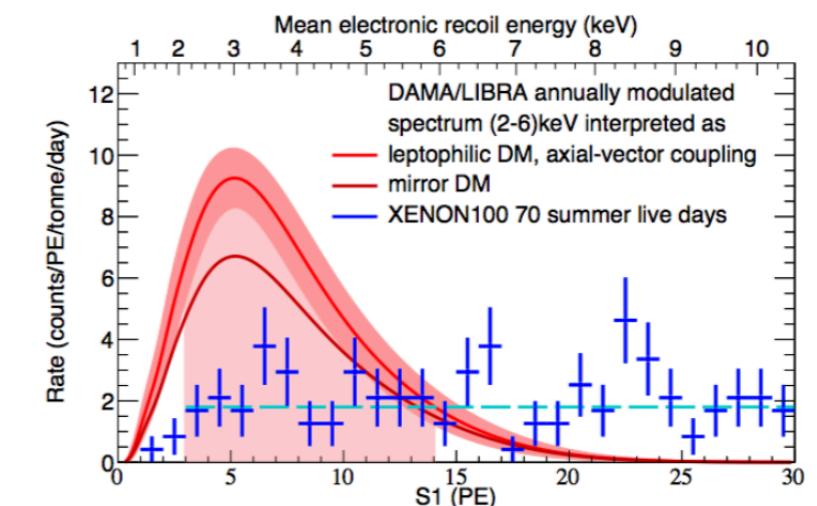
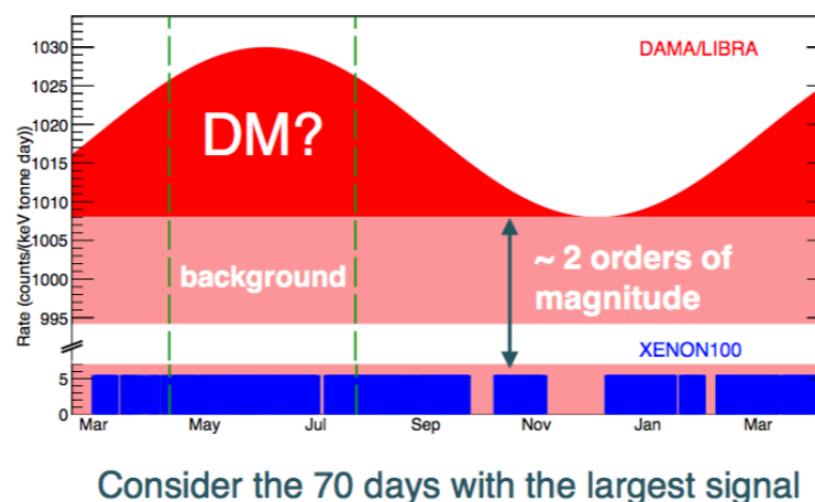


Comparing DAMA with others

- not compatible with experiments with other targets



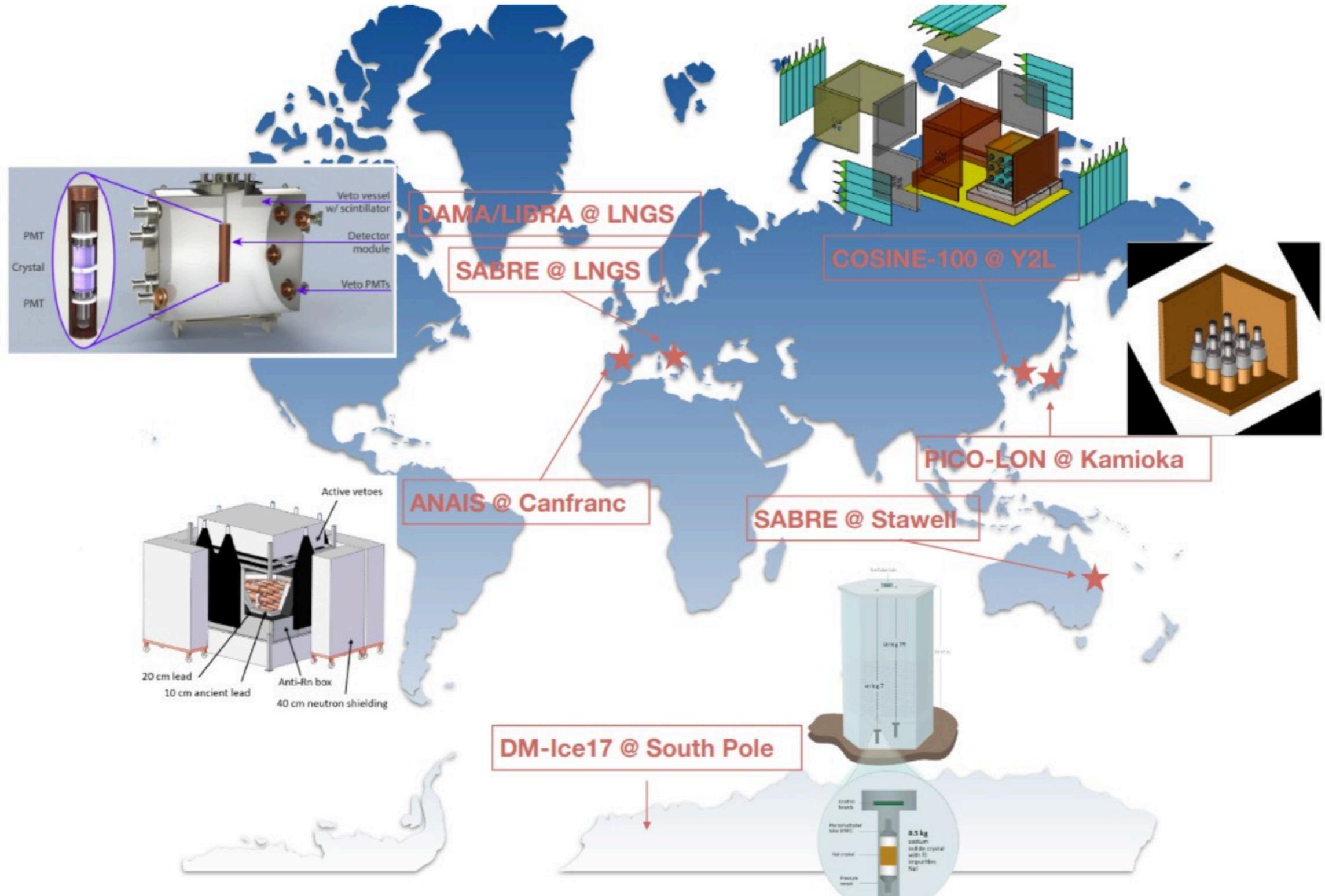
XENON collaboration, arXiv: 1507.07747, Science 349, 2015



DAMA/LIBRA modulated spectrum as would be seen in XENON100 (for axial-vector WIMP-e scattering)

...but also with ER models,
i.e. leptophilic

Other NaI detectors

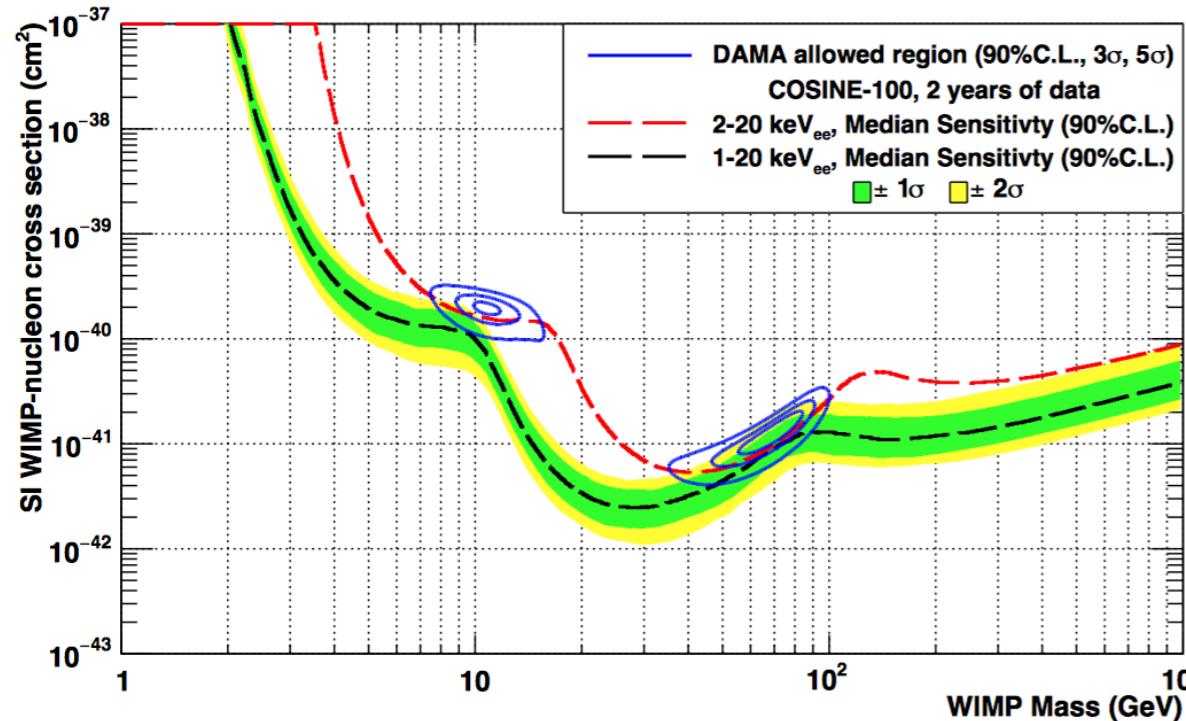


Other Nal detectors

- COSINUS (light & phonons)
- COSINE100 running since September 2016
- ANAIS 112 started operations in August 2017 and will have 3 σ significance after 5 years

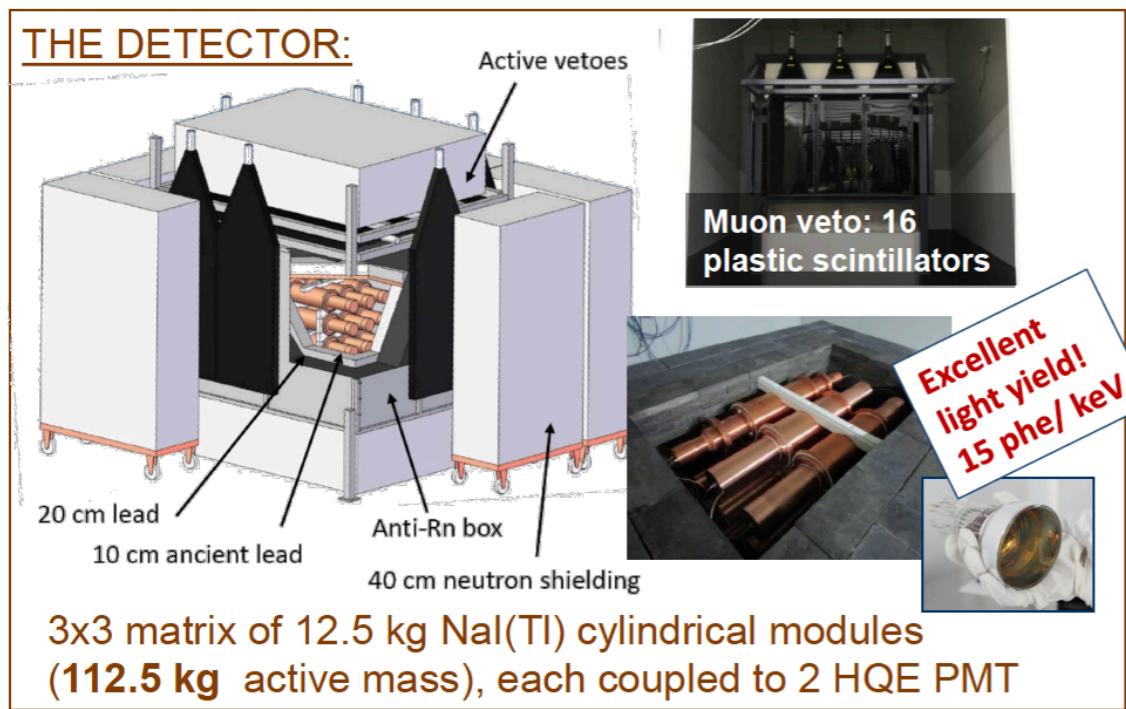


- SABRE 5 kg proof of principle
- SABRE South (50 kg in Australia)
- DAMA/LIBRA phase 3 → R&D underway

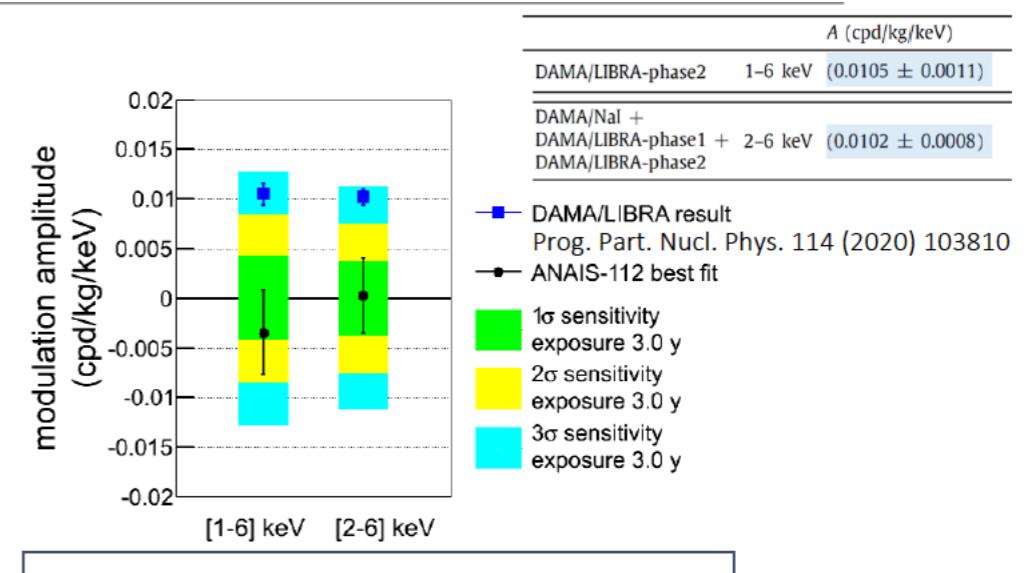


Other NaI detectors: ANAIS-112

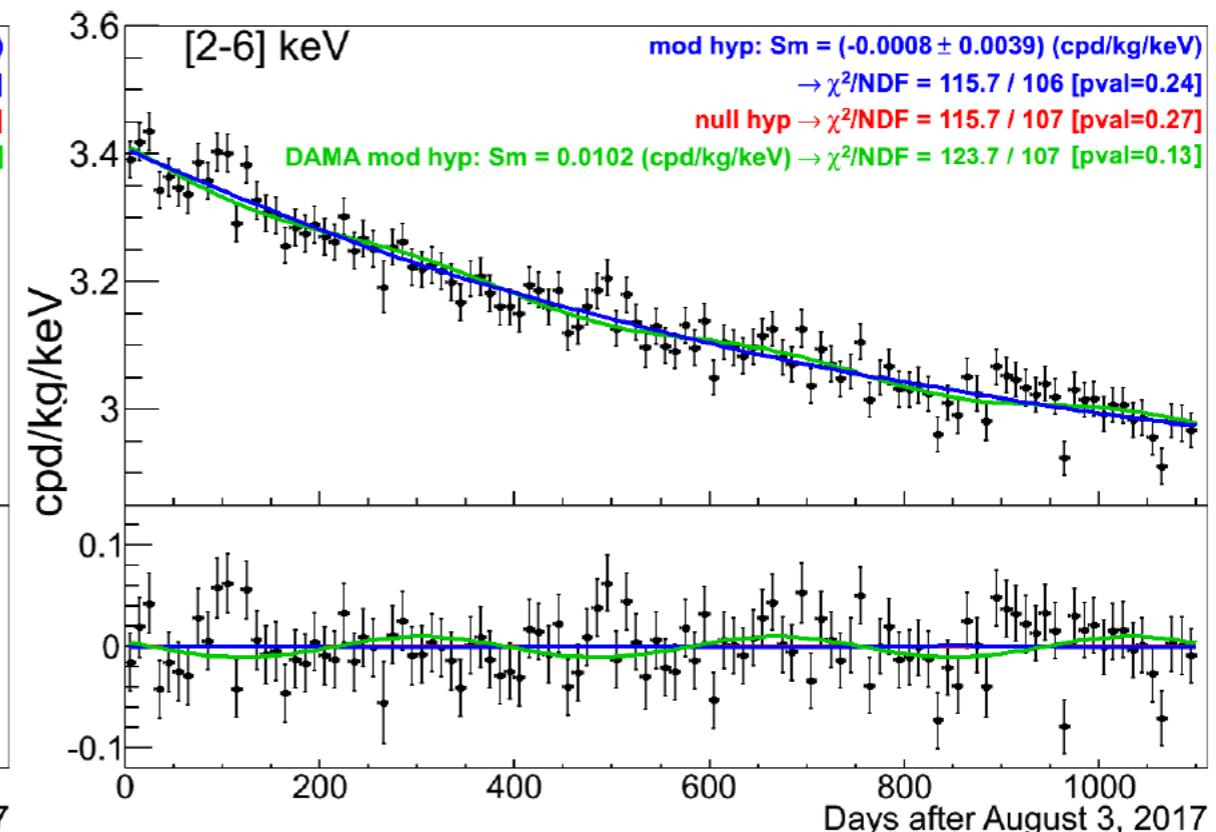
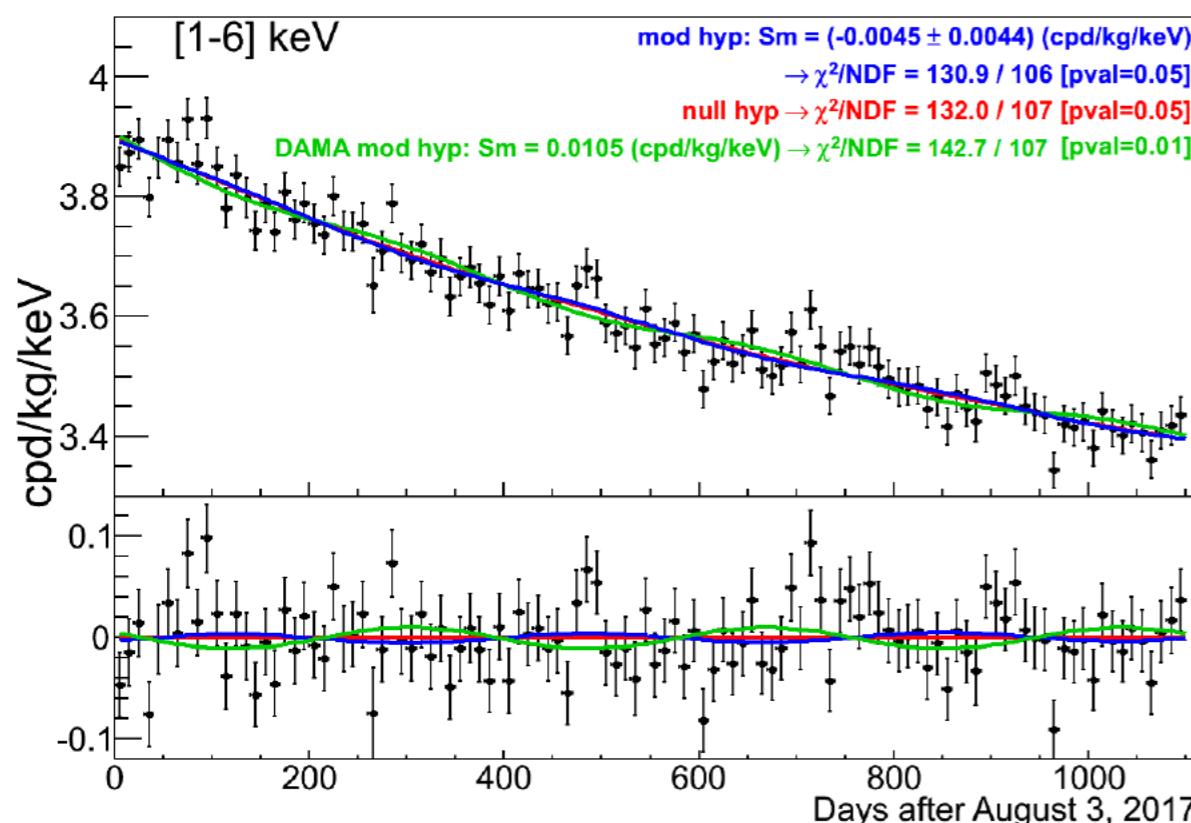
Phys. Rev. D 103, 102005 (2021)



taking data since August 2017
>>400 kg × y exposure by now

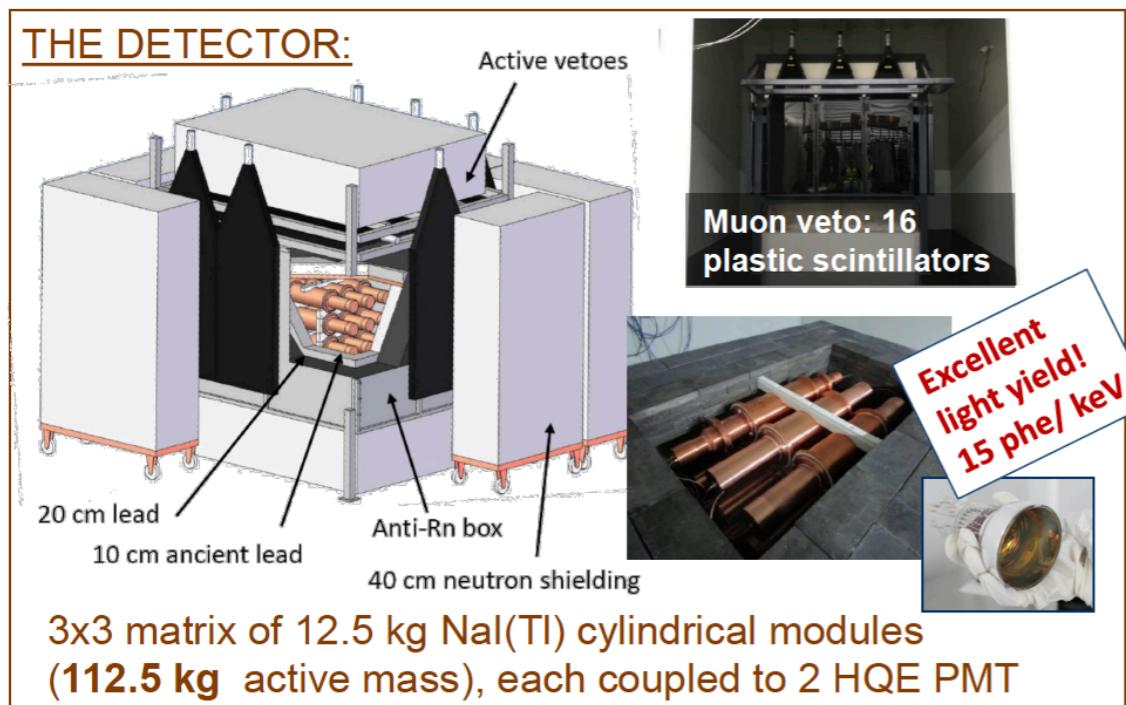


Current sensitivity: 2.5σ [1-6] keV
 2.7σ [2-6] keV

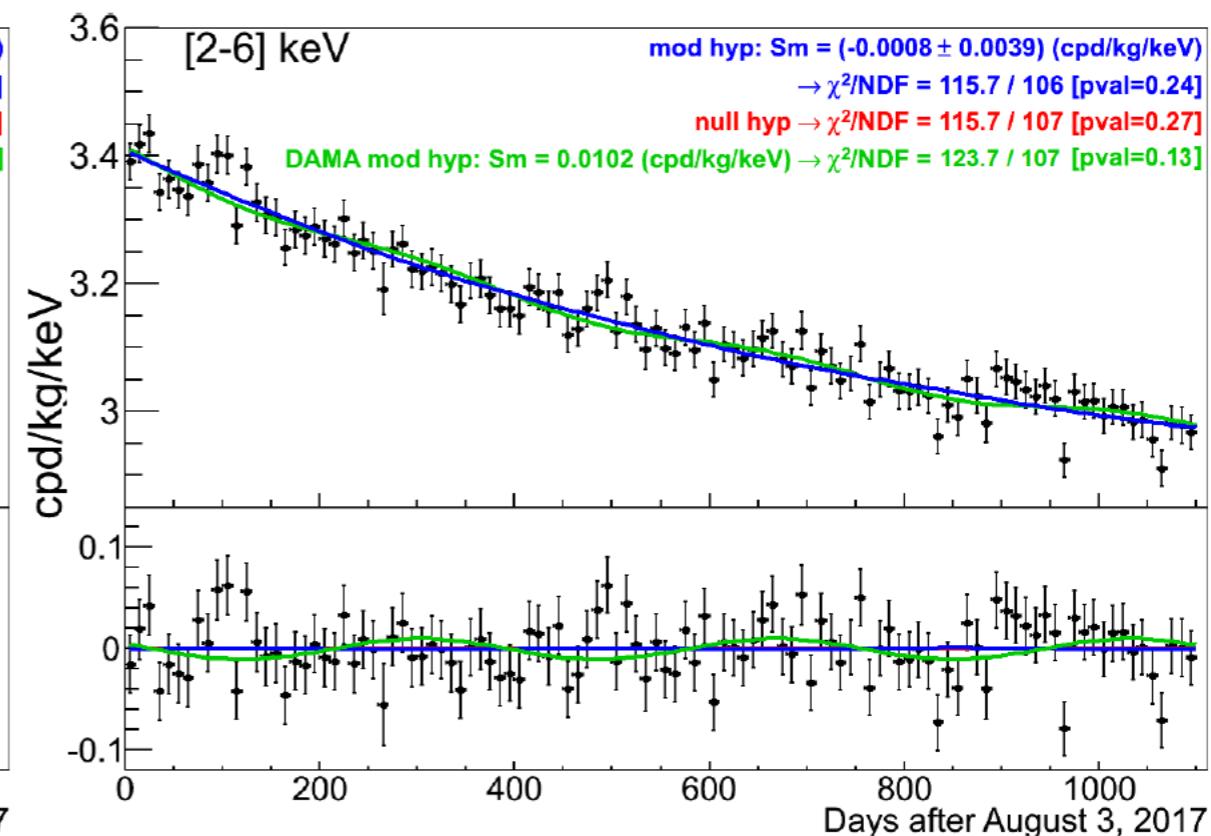
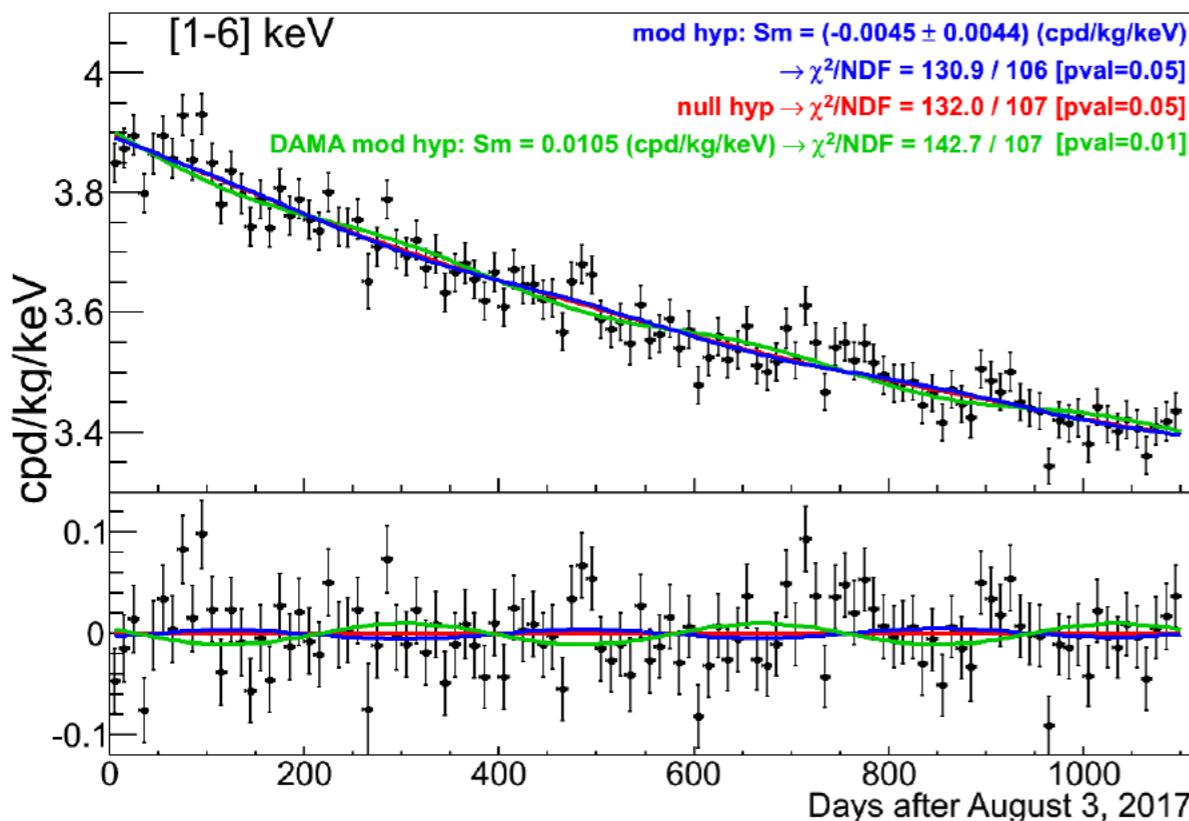
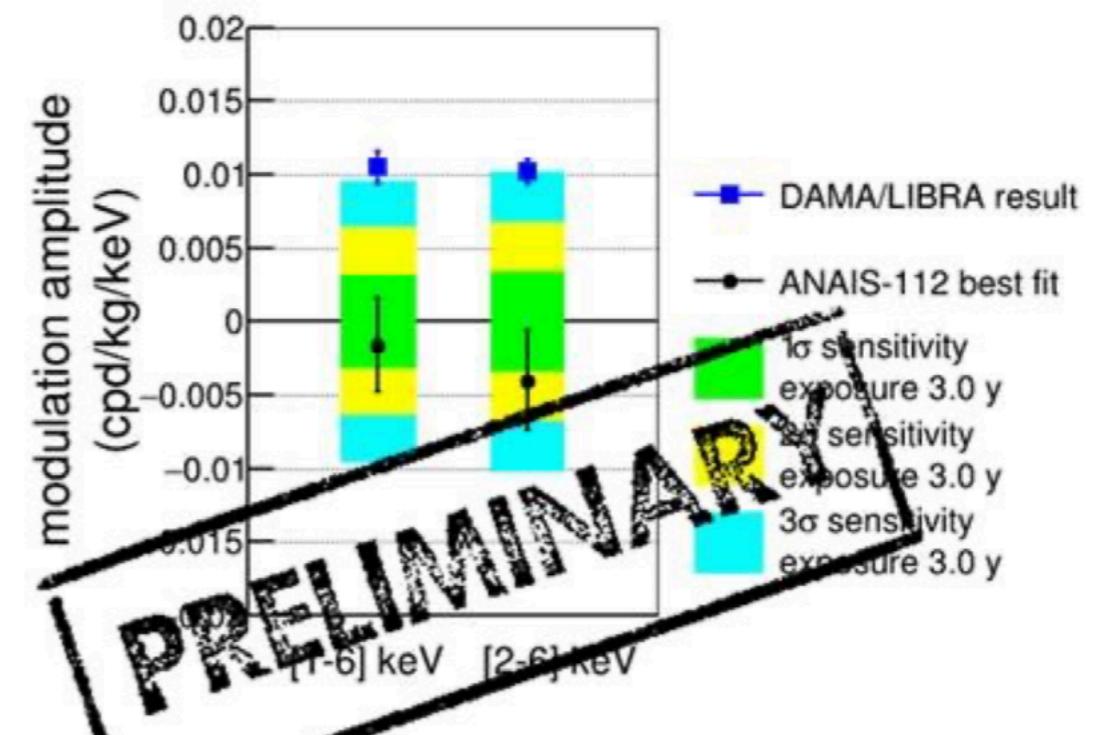


Other NaI detectors: ANAIS-112

presented at IDM2022

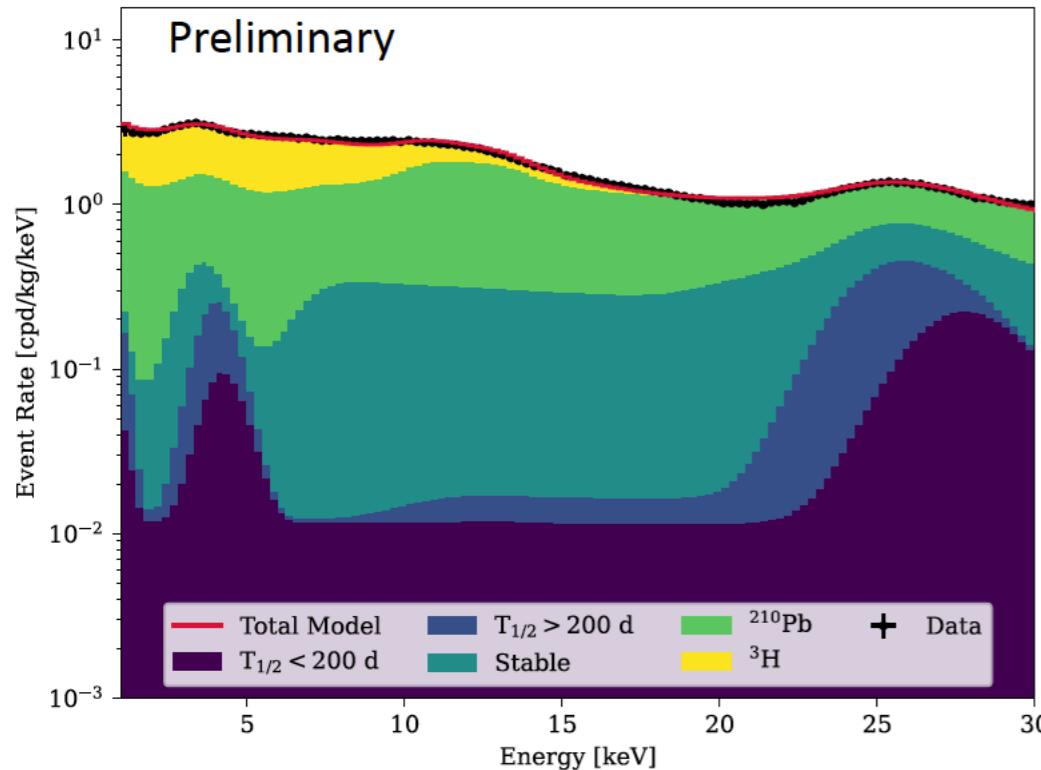


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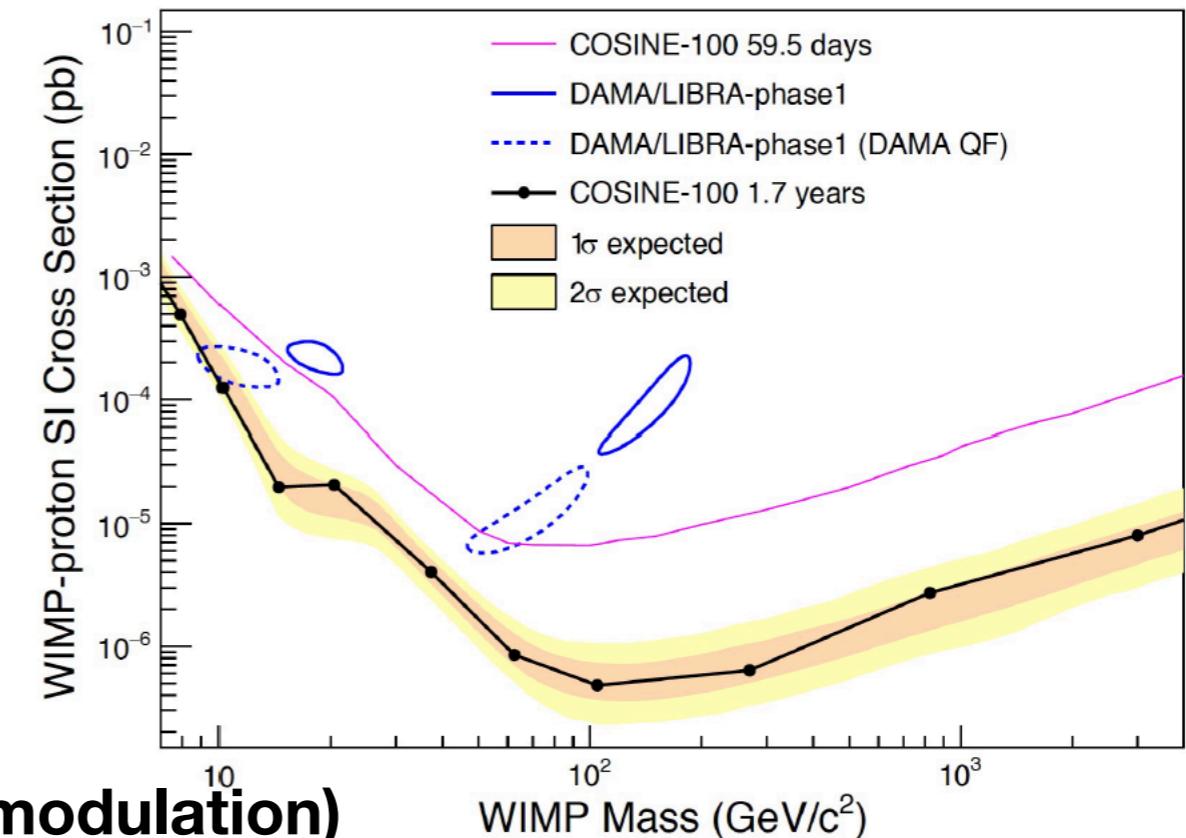


Other NaI detectors: COSINE-100

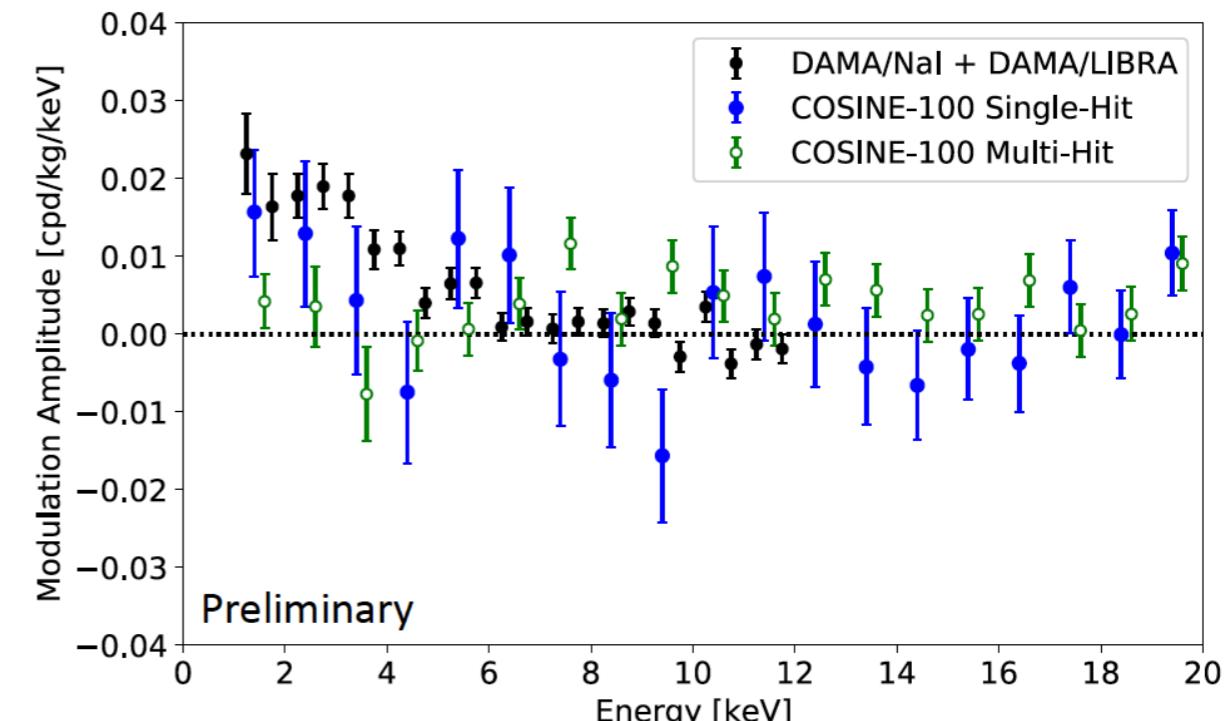
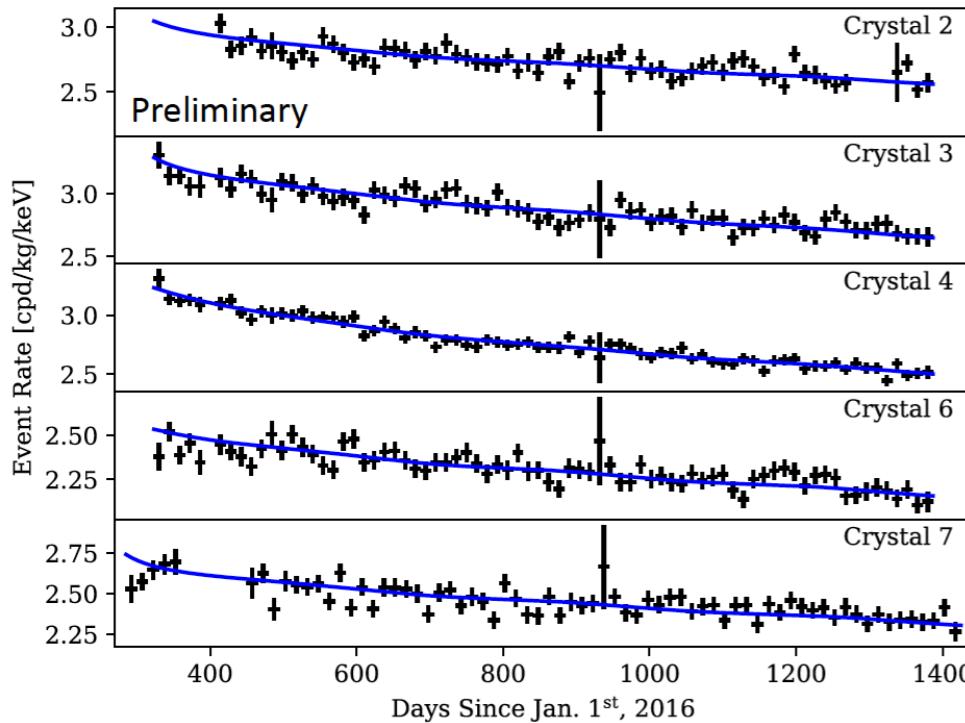
First approach: model dependent vs background



arXiv:2104:03537
New data release: 1.7y vs 59days

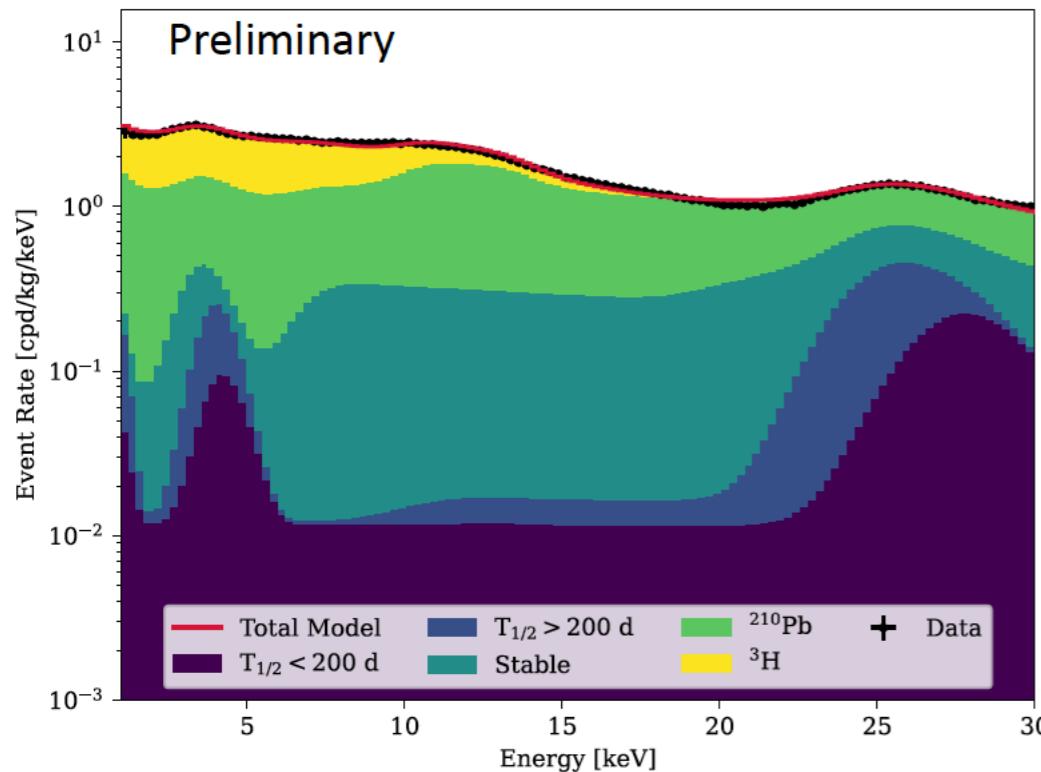


2nd approach: model independent (annual modulation)

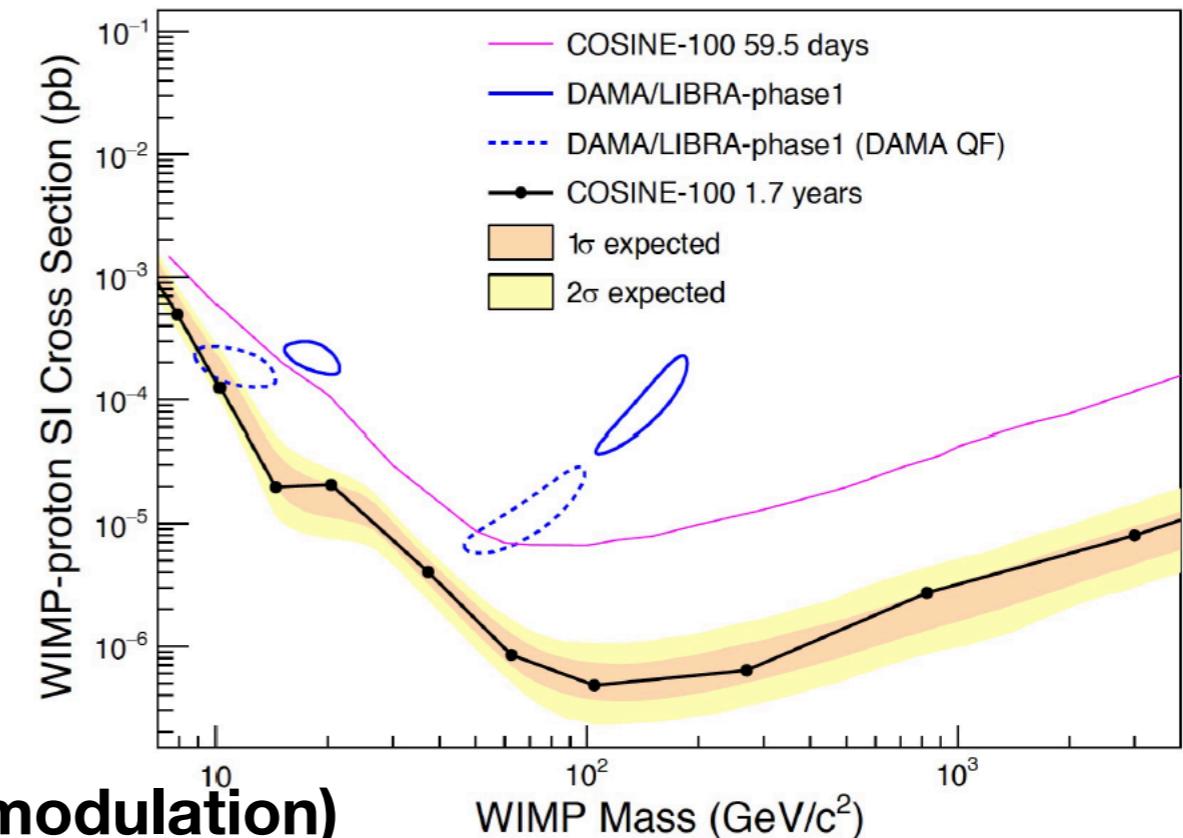


Other NaI detectors: COSINE-100

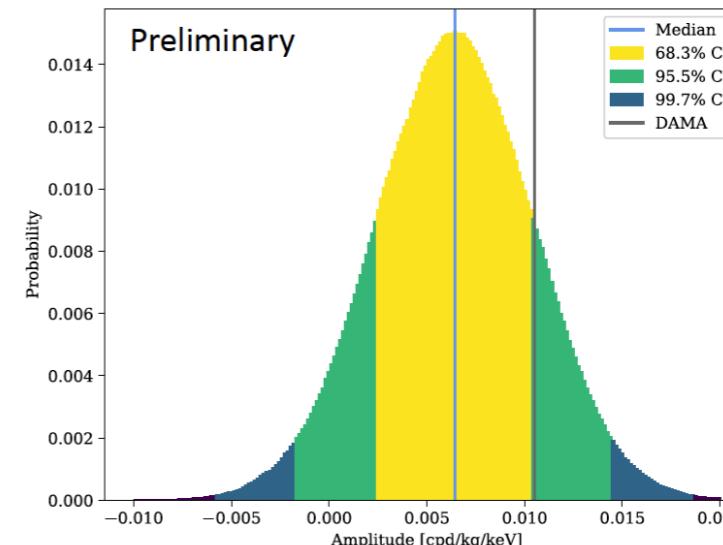
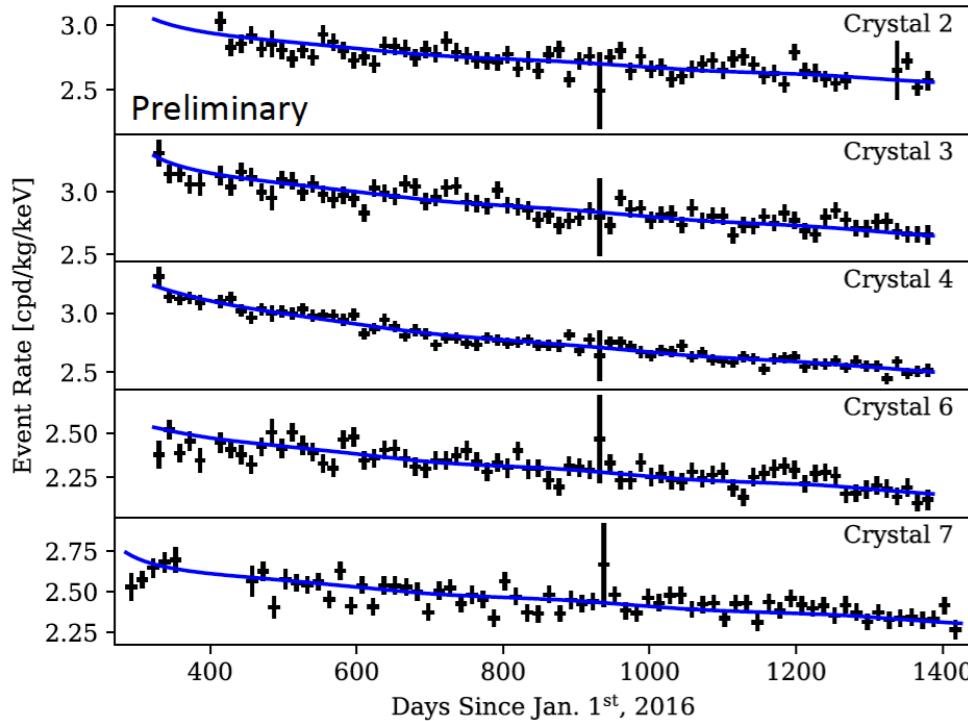
First approach: model dependent vs background



arXiv:2104:03537
New data release: 1.7y vs 59days



2nd approach: model independent (annual modulation)



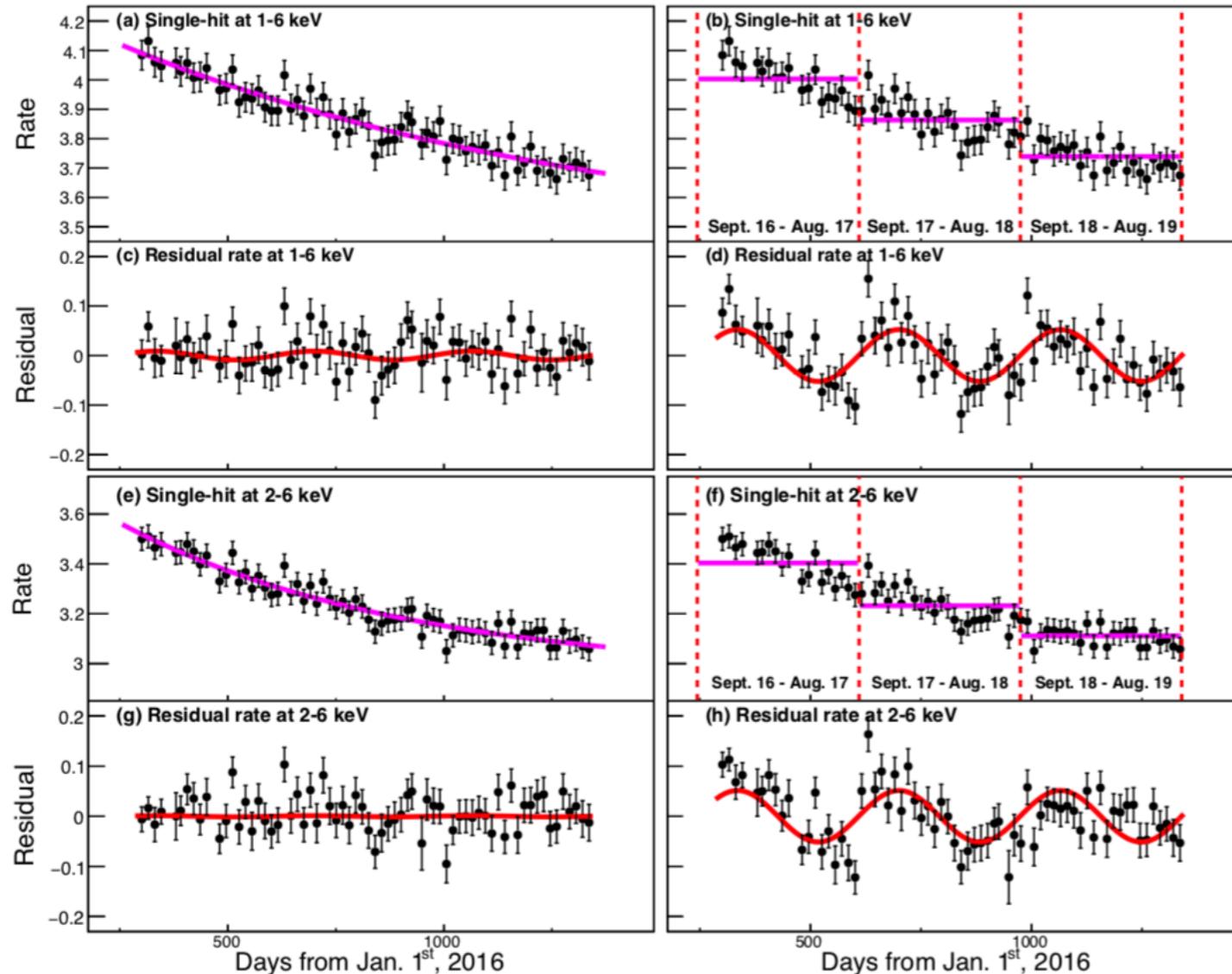
Best-fit modulation amplitude of
 0.0064 ± 0.0040 cpd/kg/keV at 1-6 keV

Nal: COSINE-100 data analyzed “a la DAMA”

An induced annual modulation signature in COSINE-100 data by DAMA/LIBRA’s analysis method

arXiv:2208.05158

Single-hit event rate in COSINE100 data



**Exponential decrease
(due to ^{3}H or ^{210}Po)**

**Average rate
in each year**

**No surprise: it’s not an oscillation pattern,
but a saw-teeth one (with opposite phase)**

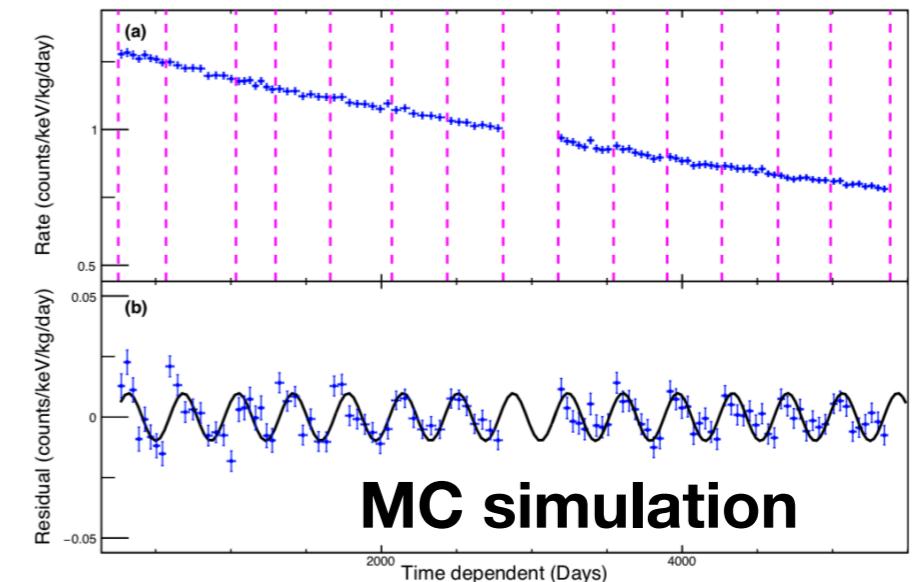


FIG. 7. An example of a simulation of the the DAMA/LIBRA experiment in the single-hit 2–6 keV

TABLE III. Annual modulation amplitudes from various experiments. The amplitudes of the annual modulation fits using the DAMA-like method to the COSINE-100 3 years data (this work) are compared with results from DAMA/LIBRA [1, 2], COSINE-100 [16], and ANAIS-112 [17] in both 1–6 keV and 2–6 keV regions.

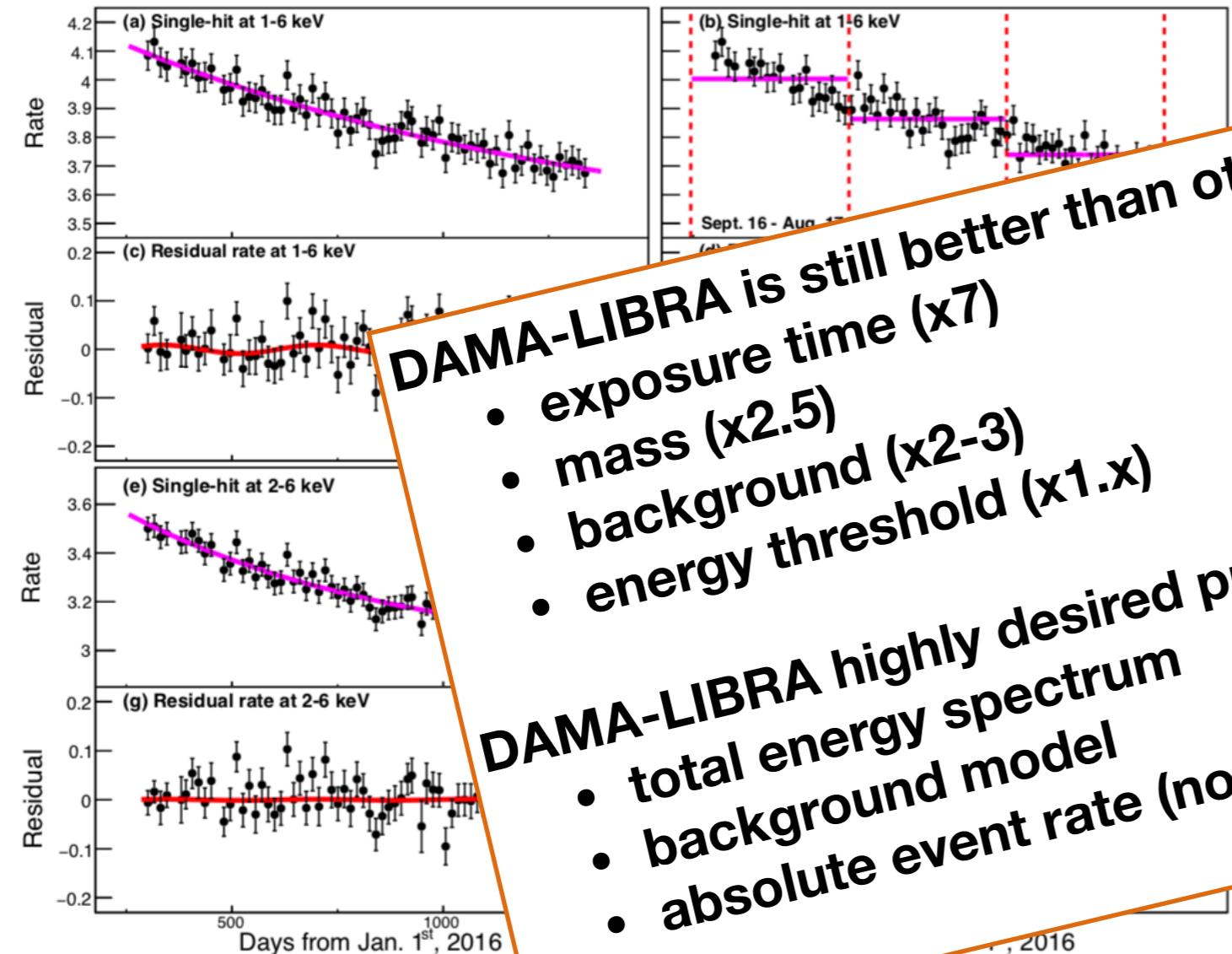
	counts/kg/keV/day	1–6 keV	2–6 keV
This work	-0.0441 ± 0.0057	-0.0456 ± 0.0056	
DAMA/LIBRA	0.0105 ± 0.0011	0.0095 ± 0.0008	
COSINE-100	0.0067 ± 0.0042	0.0050 ± 0.0047	
ANAIS-112	-0.0034 ± 0.0042	0.0003 ± 0.0037	

Nal: COSINE-100 data analysed “a la DAMA”

An induced annual modulation signature in COSINE-100 data by DAMA/LIBRA’s analysis method

arXiv:2208.05158

Single-hit event rate in COSINE100 data



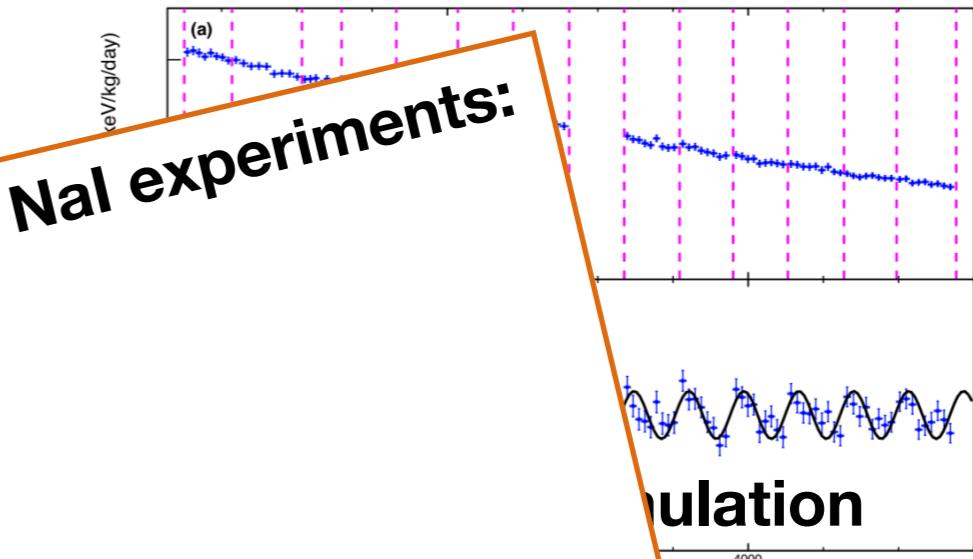
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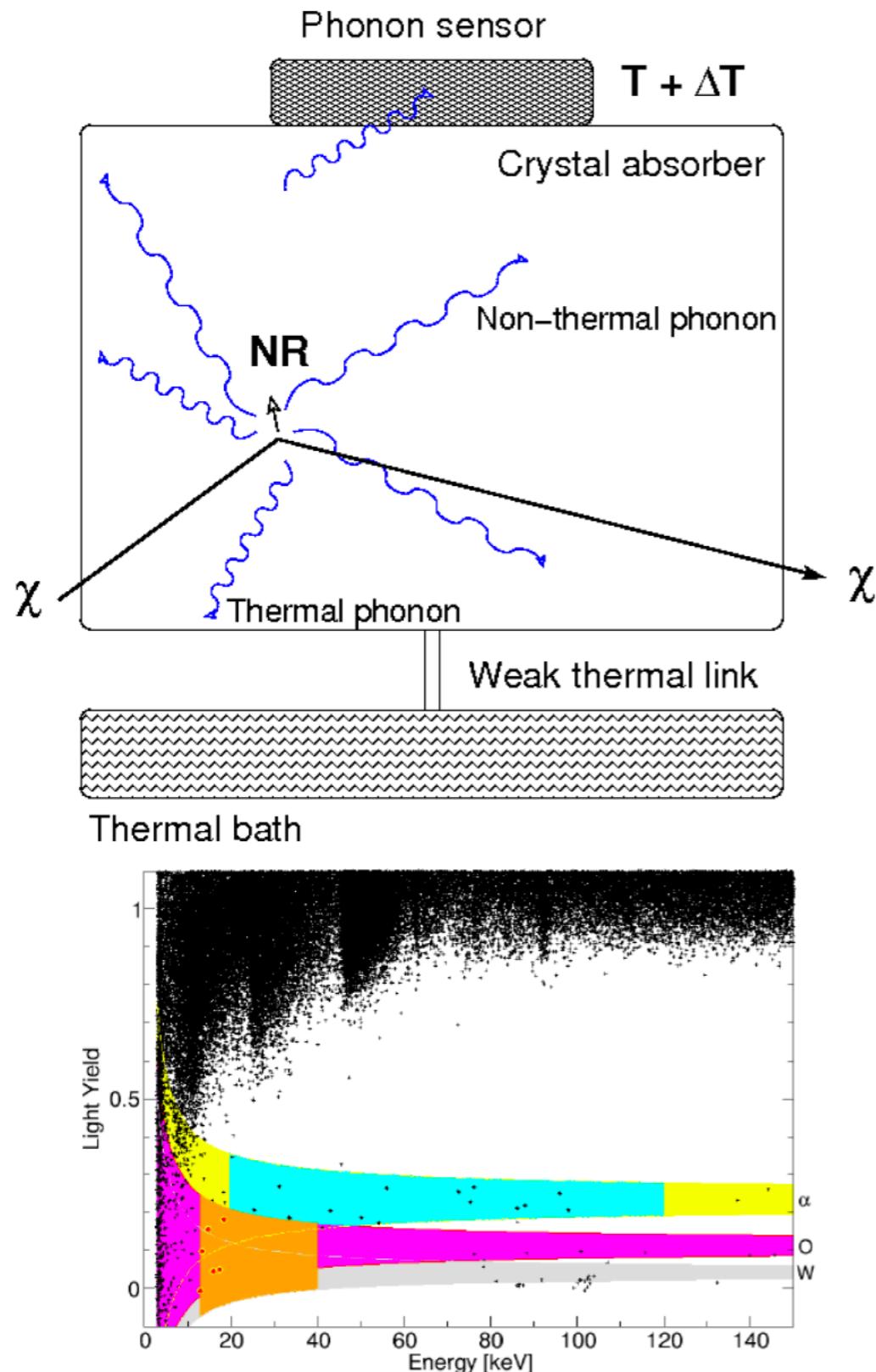
- DAMA-LIBRA is still better than other Nal experiments:
- exposure time (x7)
- mass (x2.5)
- background (x2-3)
- energy threshold (x1.x)

- DAMA-LIBRA highly desired public information:
- total energy spectrum
- background model
- absolute event rate (not just residuals)



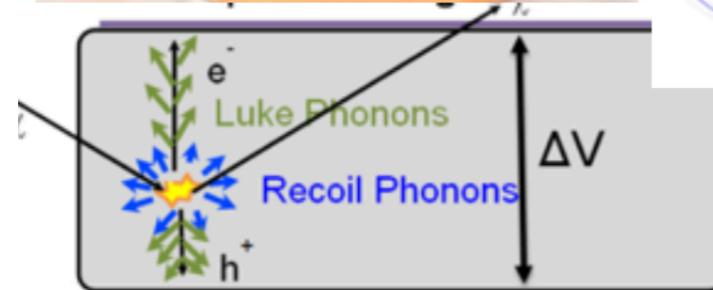
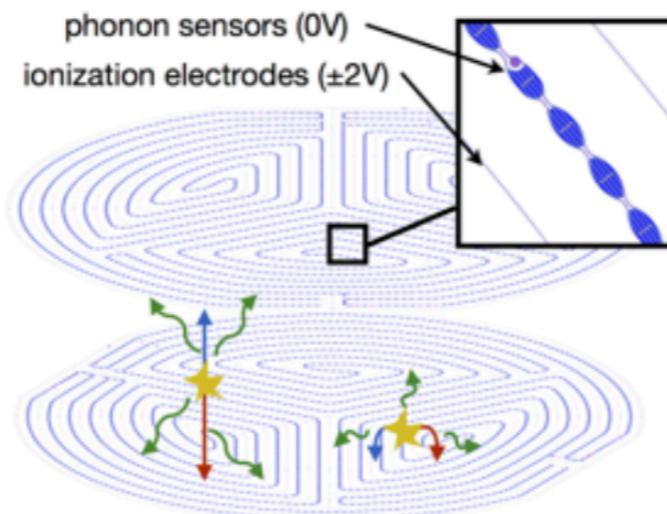
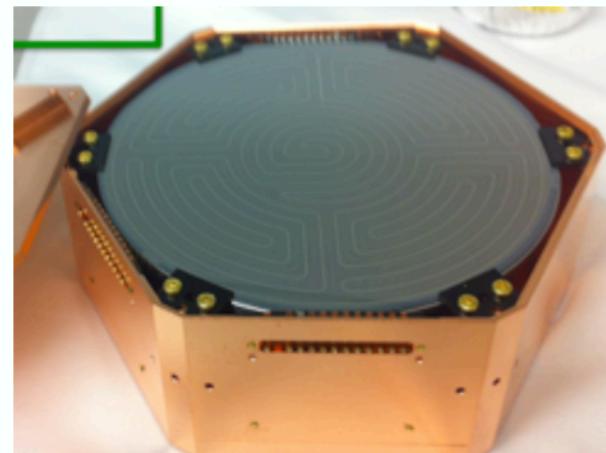
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This work	-0.0441 ± 0.0057	-0.0456 ± 0.0056	
DAMA/LIBRA	0.0105 ± 0.0011	0.0095 ± 0.0008	
COSINE-100	0.0067 ± 0.0042	0.0050 ± 0.0047	
ANAIS-112	-0.0034 ± 0.0042	0.0003 ± 0.0037	

Cryogenic bolometers



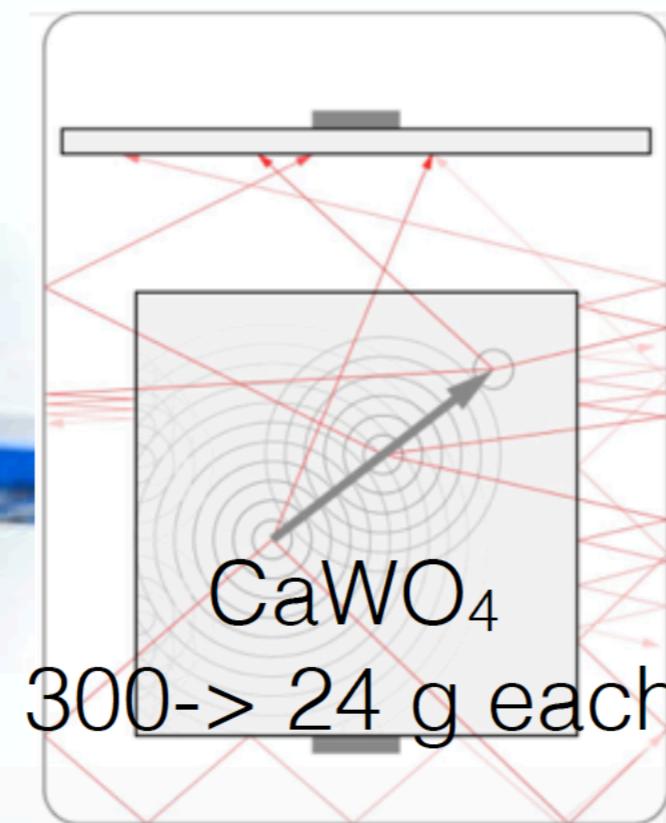
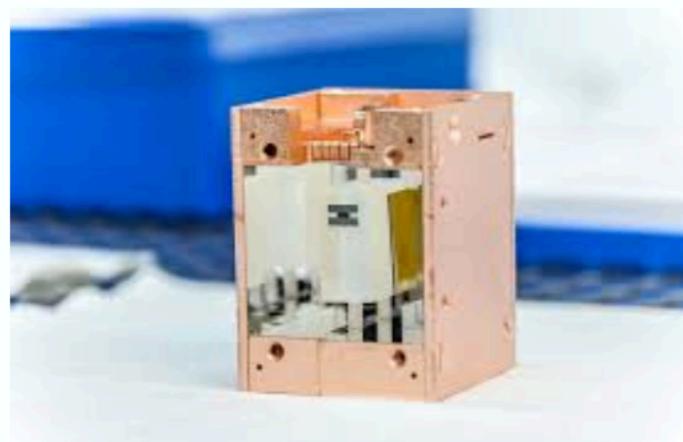
- Crystals at (10 – 100) mK
 - Temperature rise:
 $\Delta T = E/C(T)$
E.g. Ge at 20 mK, $\Delta T = 20 \mu\text{K}$ for few keV recoil
 - Measurements of ΔT
NTD: neutron transmutation-doped Ge sensors
TES: Transition edge sensors
 - Discrimination: combination with **light** or **charge** read-out
 - Large separation of electronic and nuclear recoil bands
- Example from CRESST, EPJC 72 (2012) 1971

Cryogenic bolometers

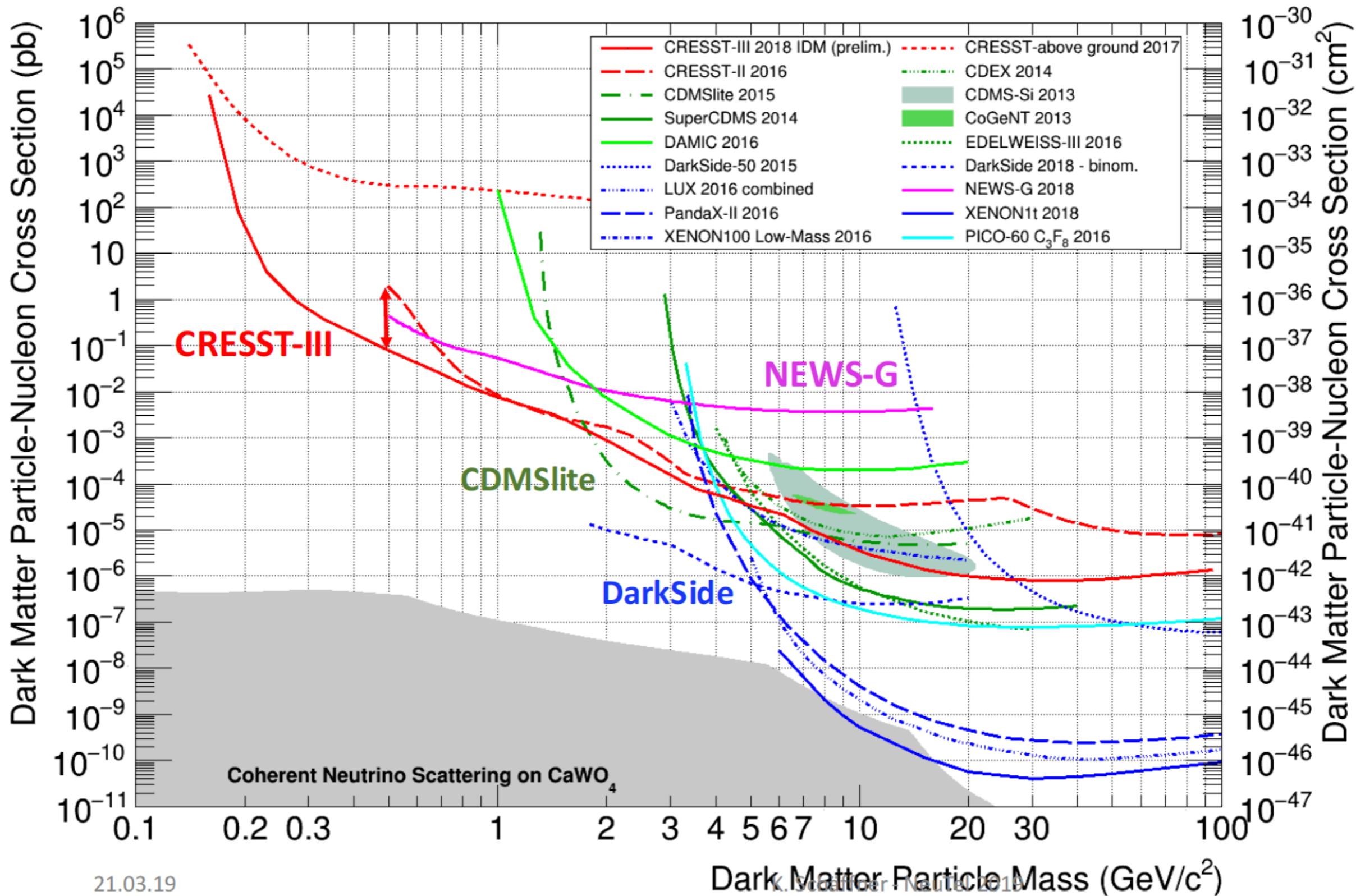


Ge, Si ~1 kg each

- SuperCDMS/EDELWEISS 2 techniques
 - HV (CDMSlite): Luke phonons: low threshold, but no discrimination
 - iZIP/FID: ionization and phonon signals with interleaved sensors discriminate against electronic recoils and surface events
- CRESST
 - CaWO₄ crystals for phonons and scintillation
- DAMIC
 - Si CCD



Summary of low mass Dark Matter searches



21.03.19

K. Schaffner-Naujok 2019

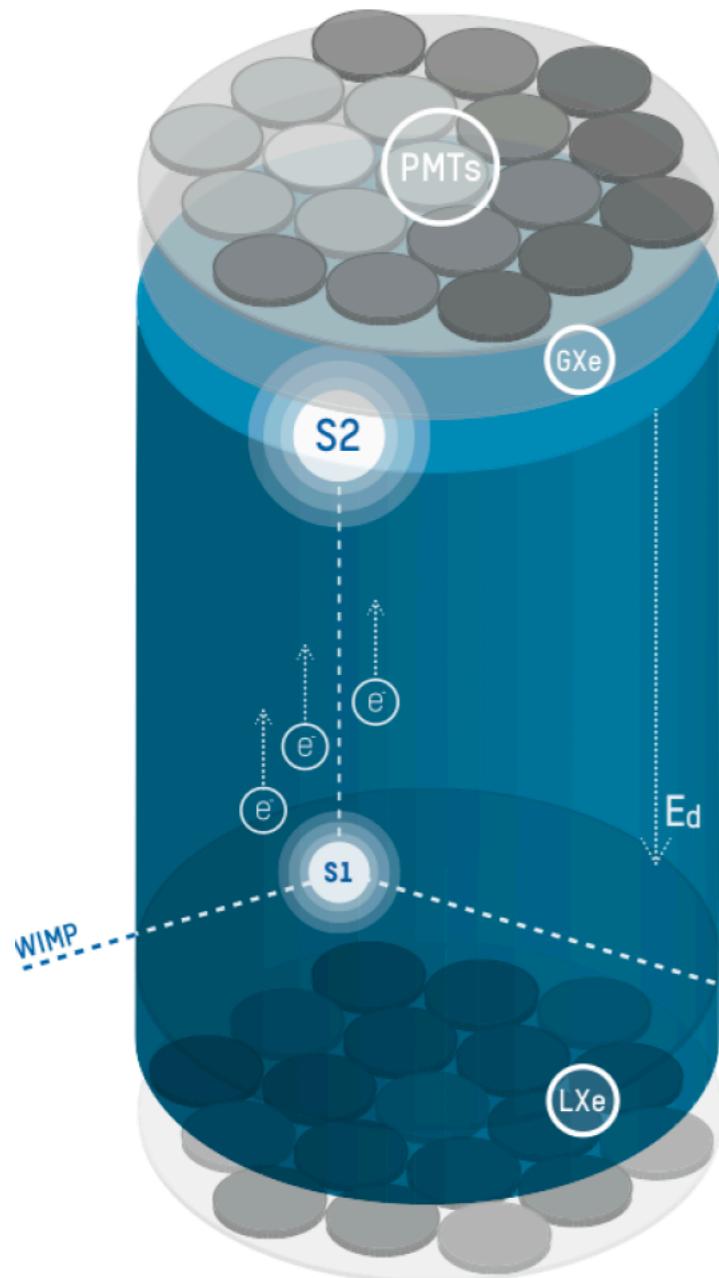
Liquid Noble Detectors

- Large masses and homogeneous targets (LNe, LAr & LXe)
Two detector concepts: single & double phase
- 3D position reconstruction → fiducialization
- Transparent to their own scintillation light

	LNe	LAr	LXe
Z (A)	10 (20)	18 (40)	54 (131)
Density [g/cm ³]	1.2	1.4	3.0
Scintillation λ	78 nm	125 nm	178 nm
BP [K] at 1 atm	27	87	165
Ionization [e ⁻ /keV]*	46	42	64
Scintillation [γ /keV]*	7	40	46

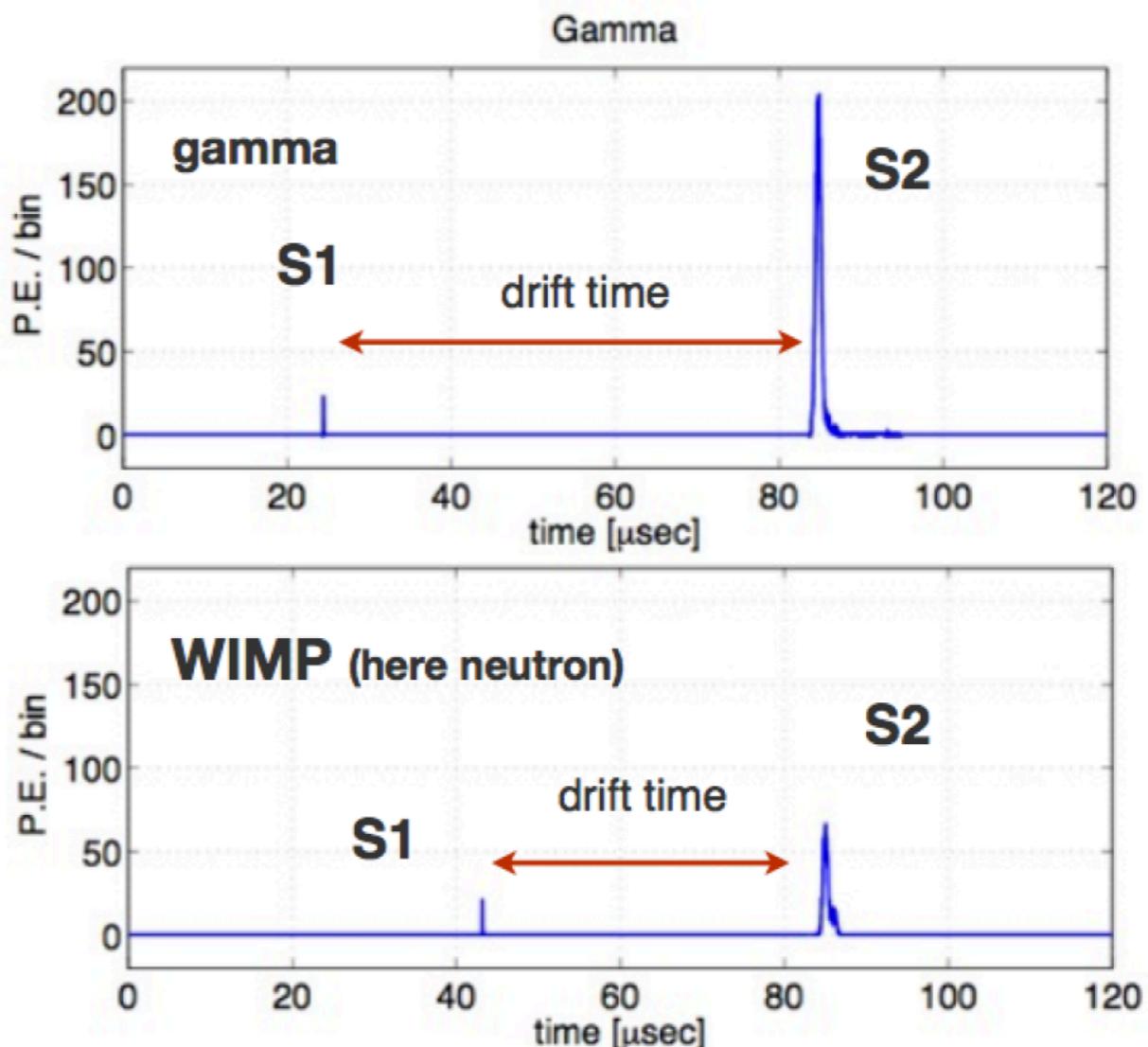
* for electronic recoils

Liquid Noble Detectors: Double Phase TPC



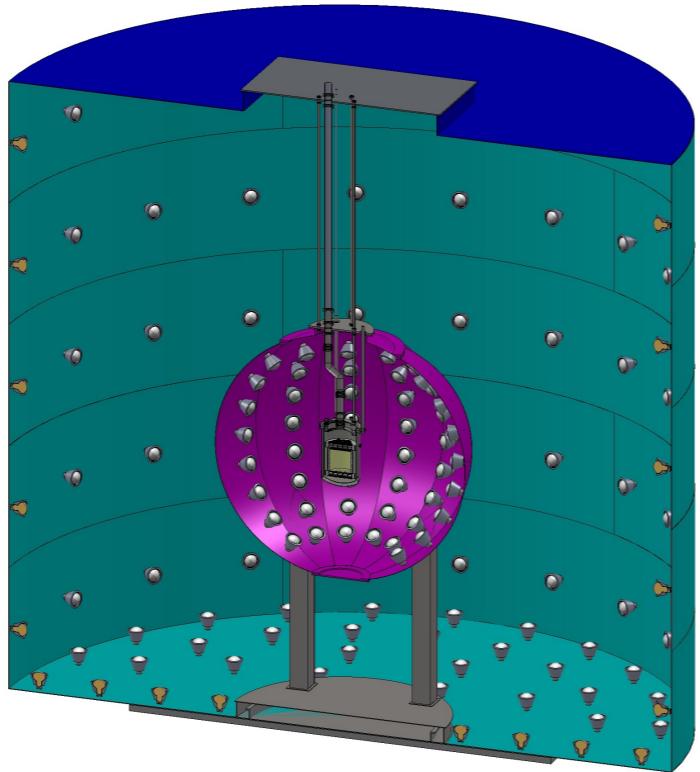
- Drift field
- Electronegative purity
- Position resolution

- Scintillation signal (S1)
 - Charges drift to the liquid-gas surface
 - Proportional signal (S2)
- Electron- /nuclear recoil discrimination



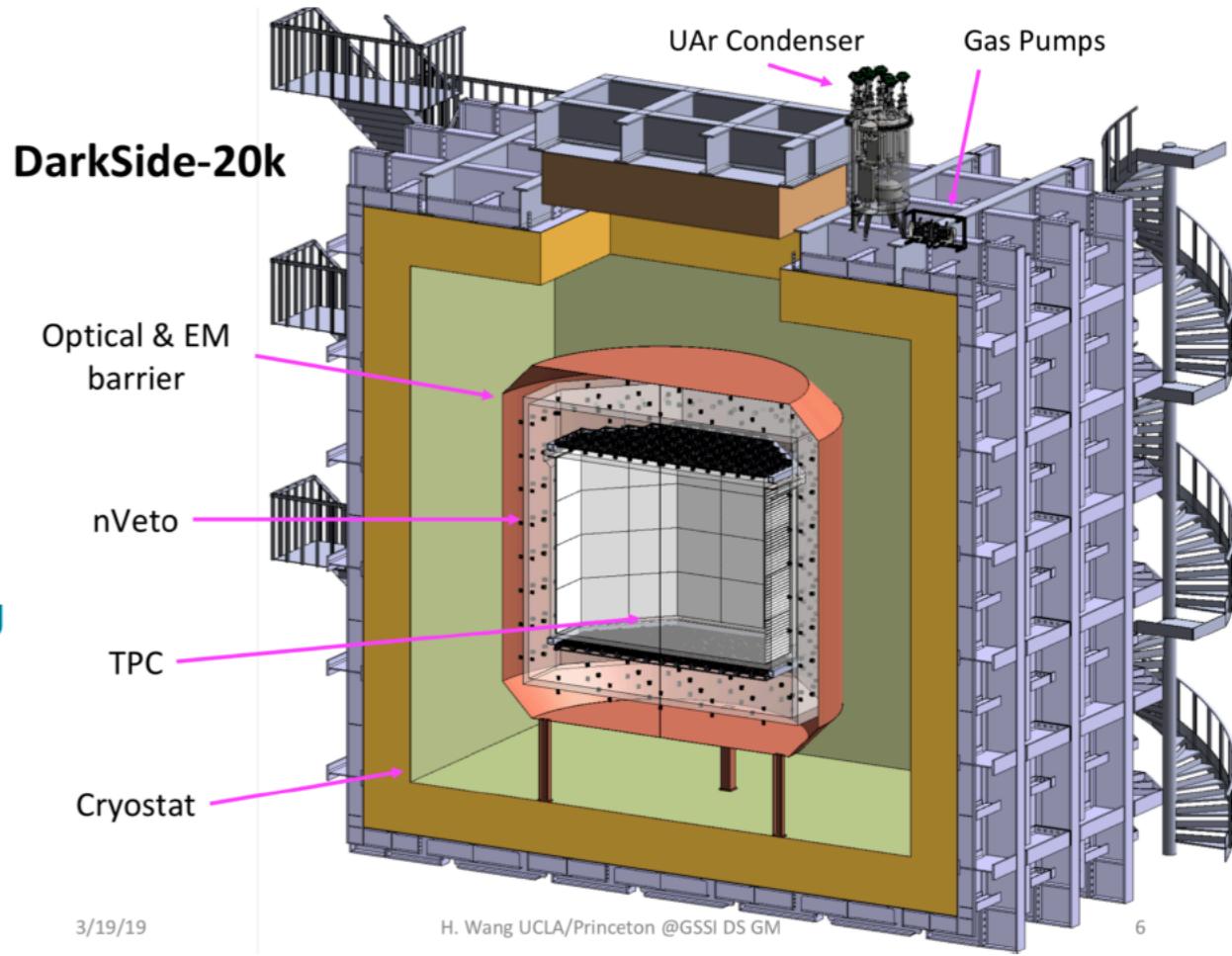
DarkSide-50 and -20k

DarkSide-50

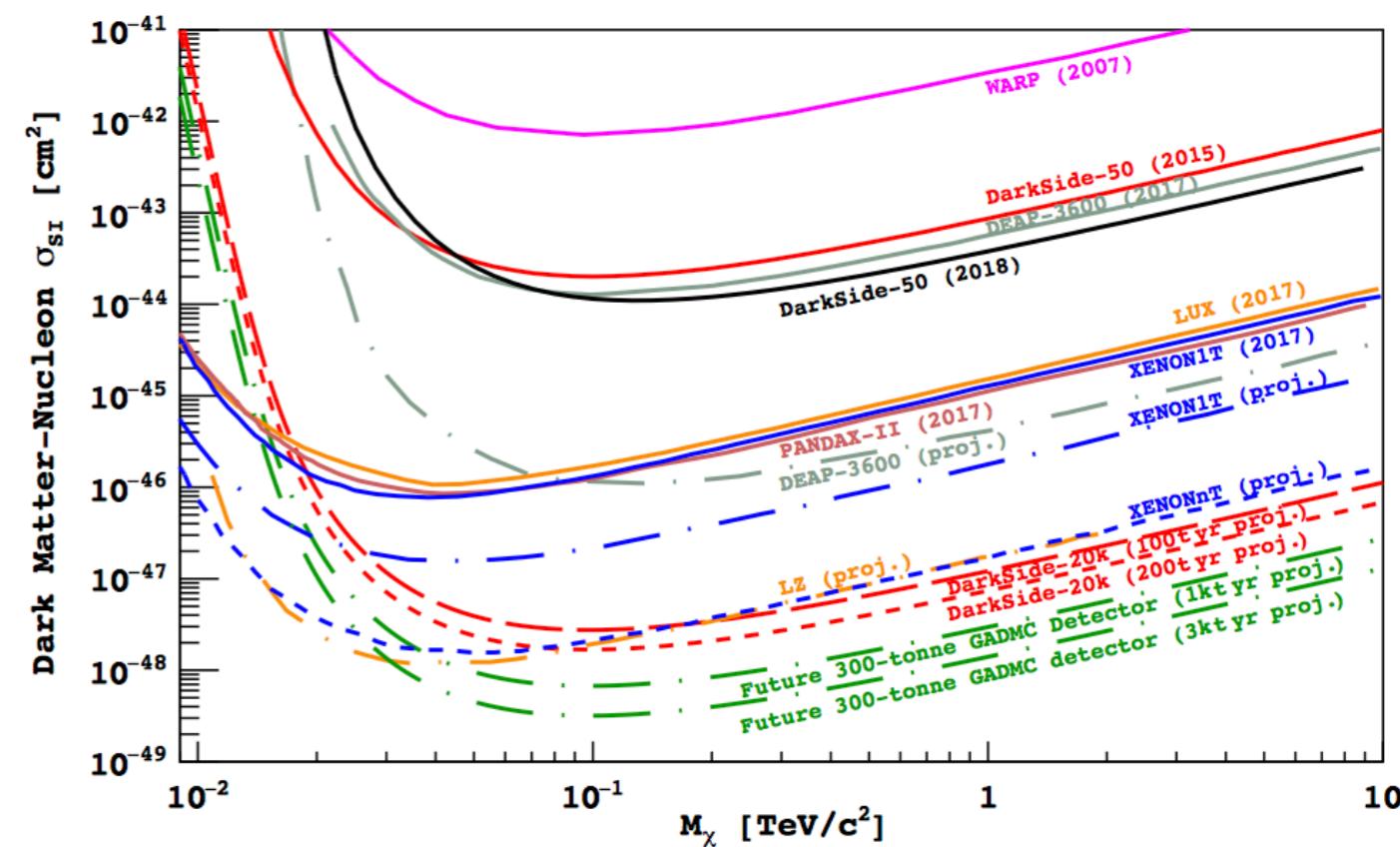
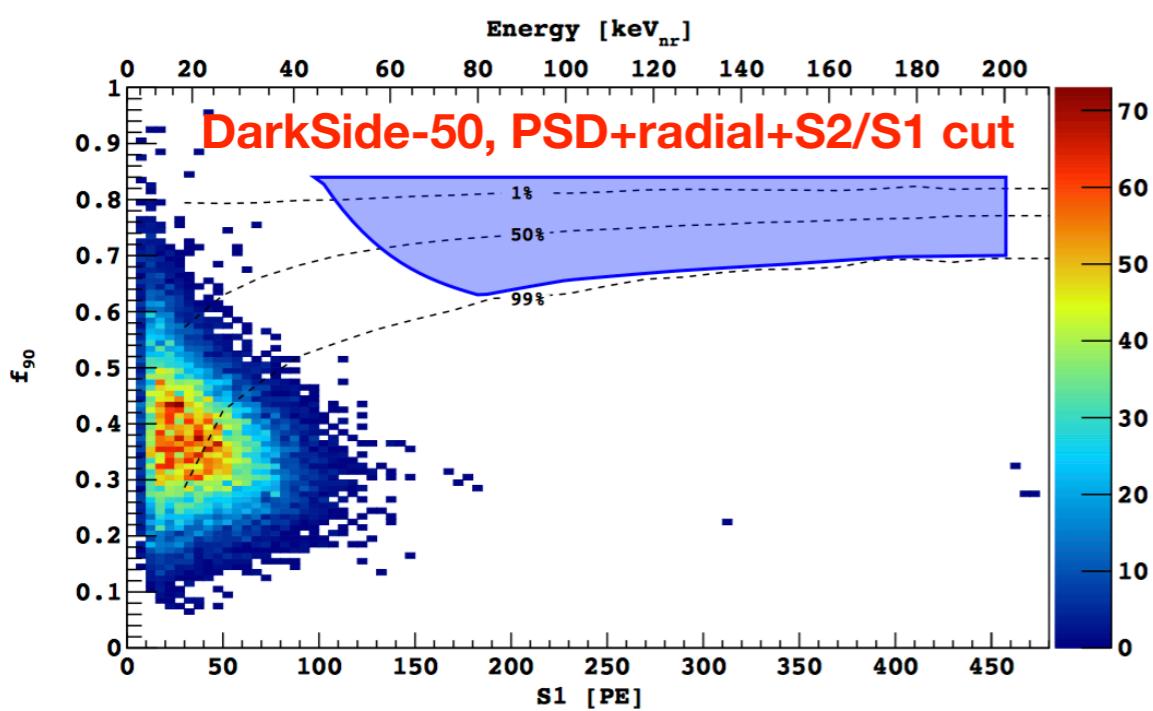
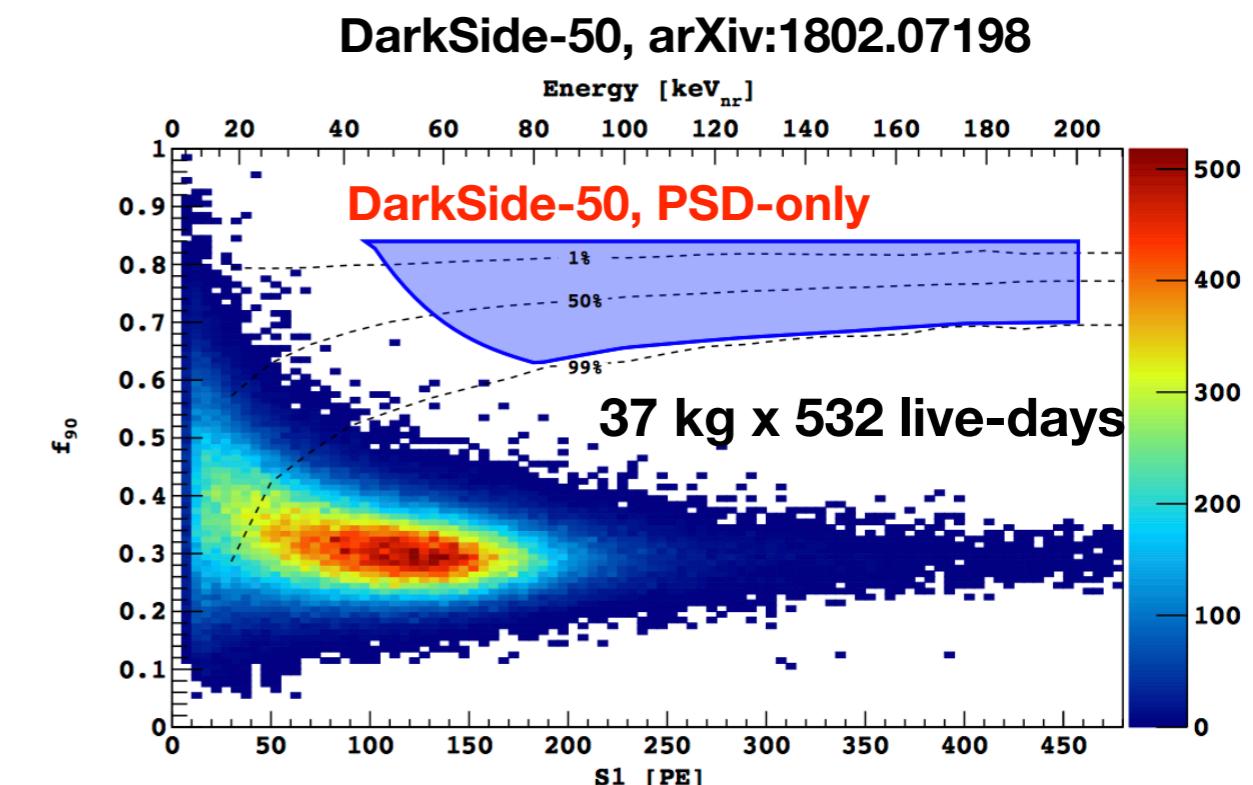
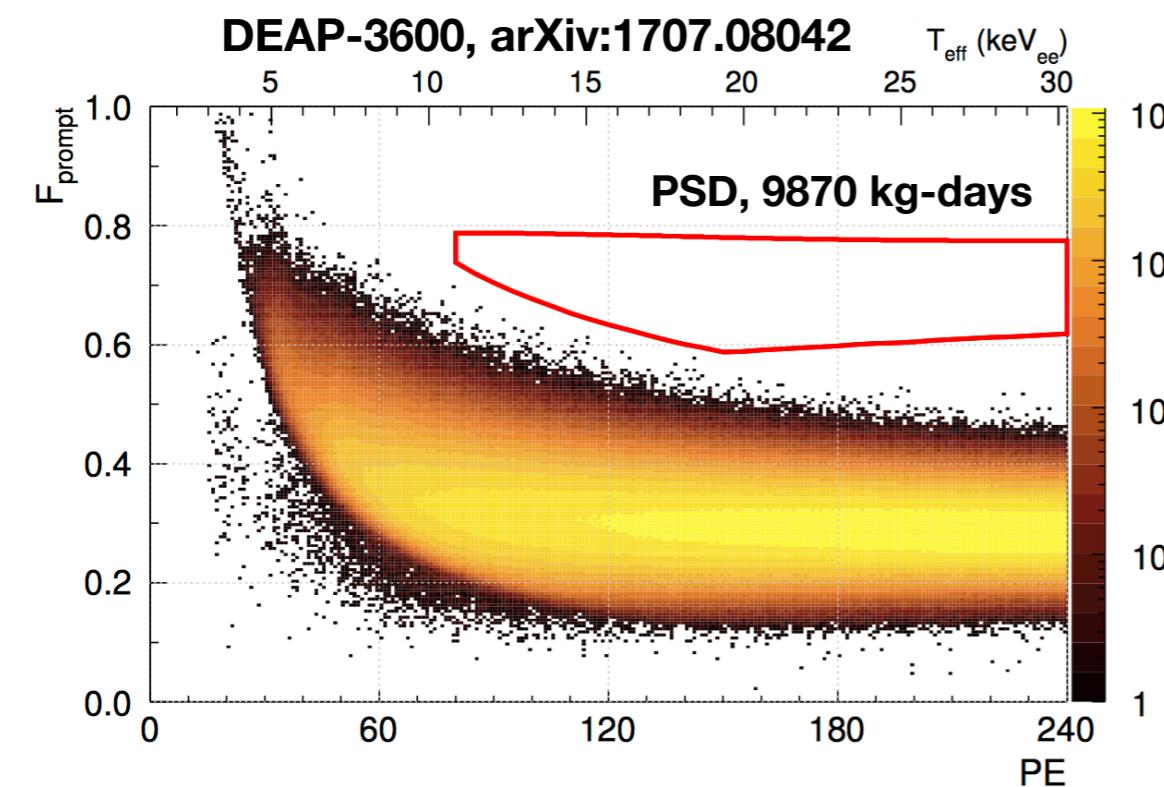


- Detector inside Borexino counting facility at LNGS (Italy)
- 50 kg depleted argon from underground sources
 > 1000 reduction in ^{39}Ar level
- Pulse shape & charge/light ratio for particle discrimination
Pulse-shape separation $> 10^7$
- Hamamatsu R11065 as photosensor
Challenge: operation of PMTs at LAr temperatures
→ plan to use SiPMs in the next generation detector

- **DarkSide-20k**
 - Scheduled for 2024-25?
 - Utilizing underground argon
 - Atmospheric LAr veto, DUNE style cryostat possible
 - Background free
 - Global Argon Dark Matter Collaboration



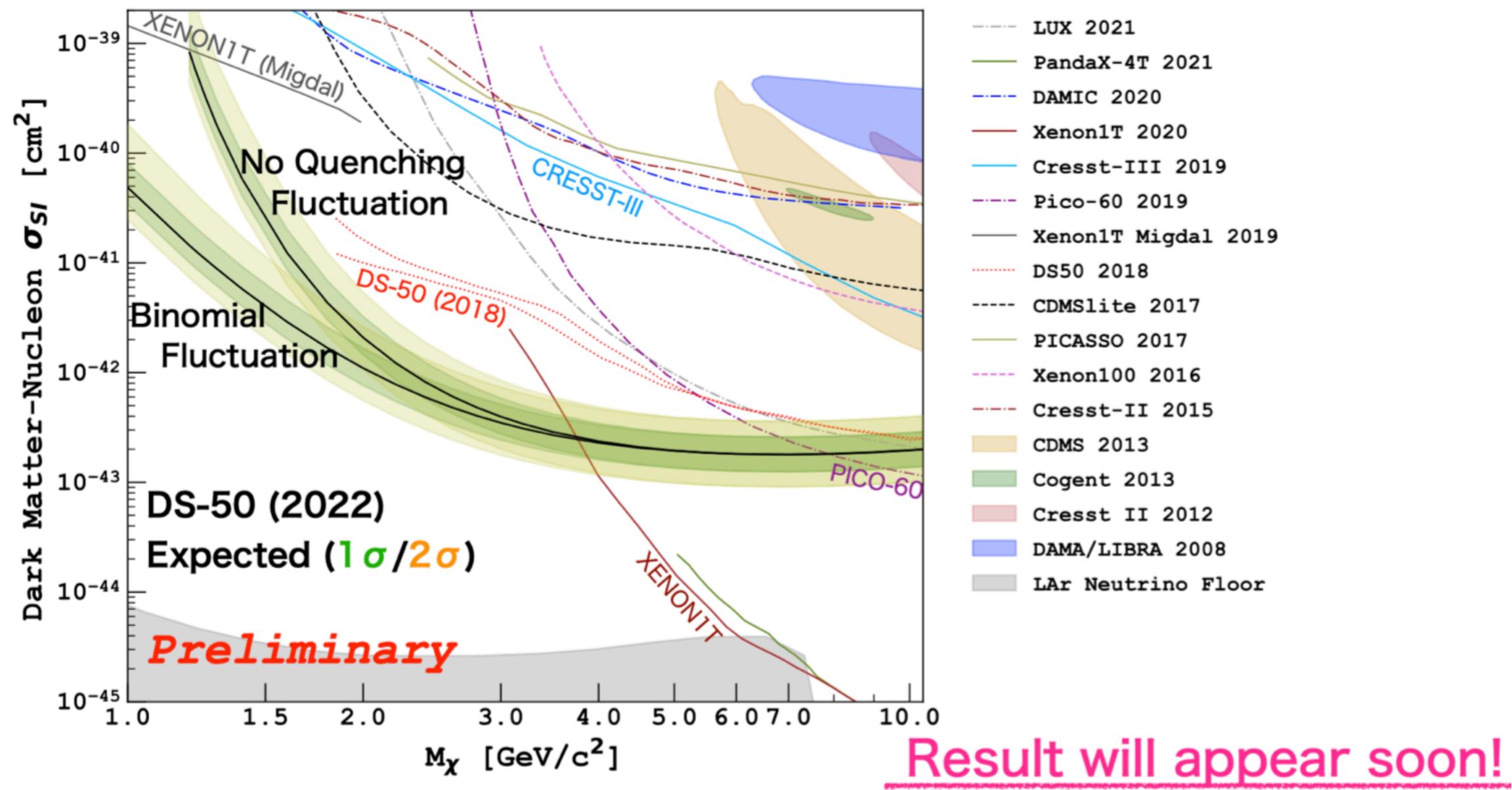
Liquid Argon results: DarkSide-50 & DEAP-3600



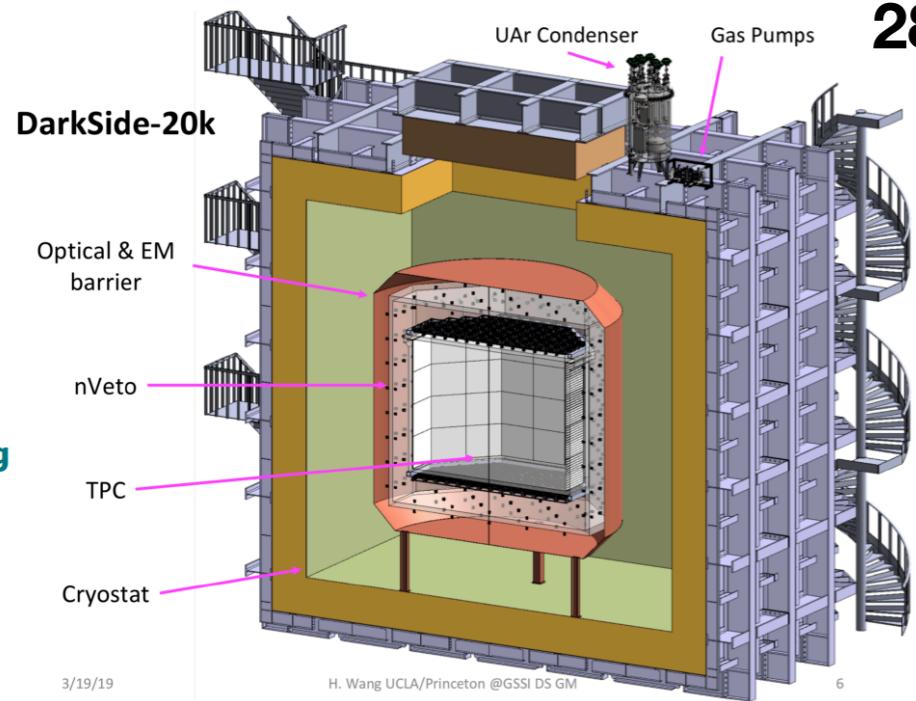
Liquid Argon: DarkSide-50 new S2-only result

Masato Kimura | IDM22 - 19 July '22

Projected Sensitivity



The future LAr TPC: DarkSide-20k



28 m² of PhotoDetectors with SiPM

8280 PDM's

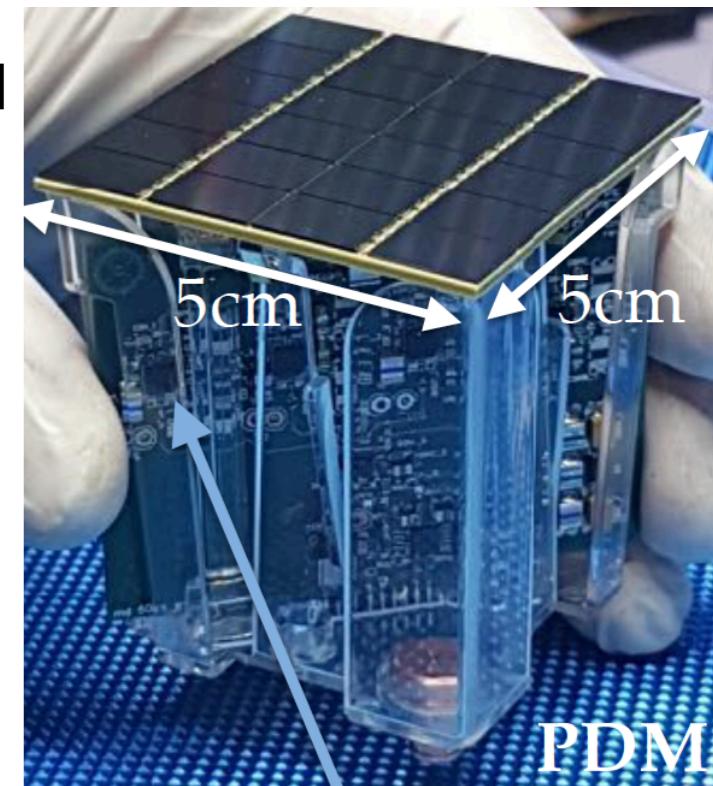
drift length 3.5m

50tons of depleted argon

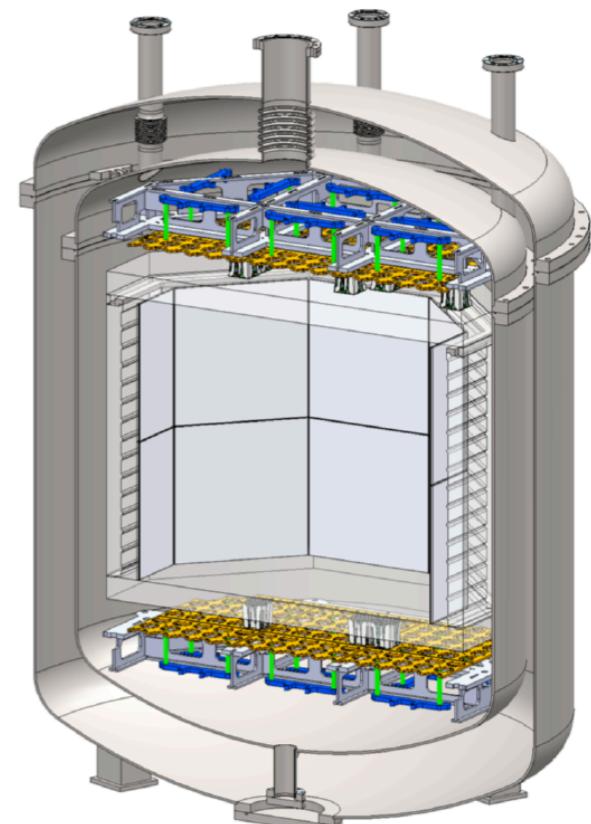
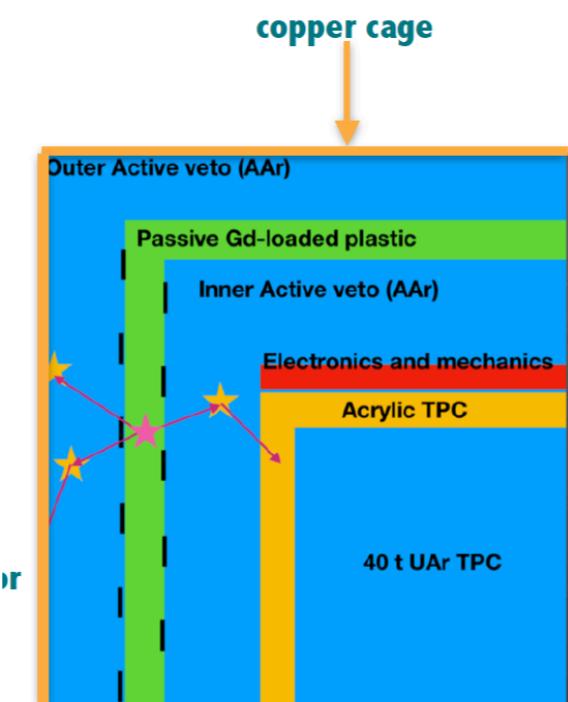
40tons fiducial mass with 5cm from the walls

70% of background from top and bottom

optimisation of further z cut for DM search ongoing



Organic scintillator-free design: the only liquid around is argon (and nitrogen). Most of the TPC and VETO material is acrylic (PMMA). Gadolinium (2% in mass) in the VETO is embedded in a solid matrix of PMMA.



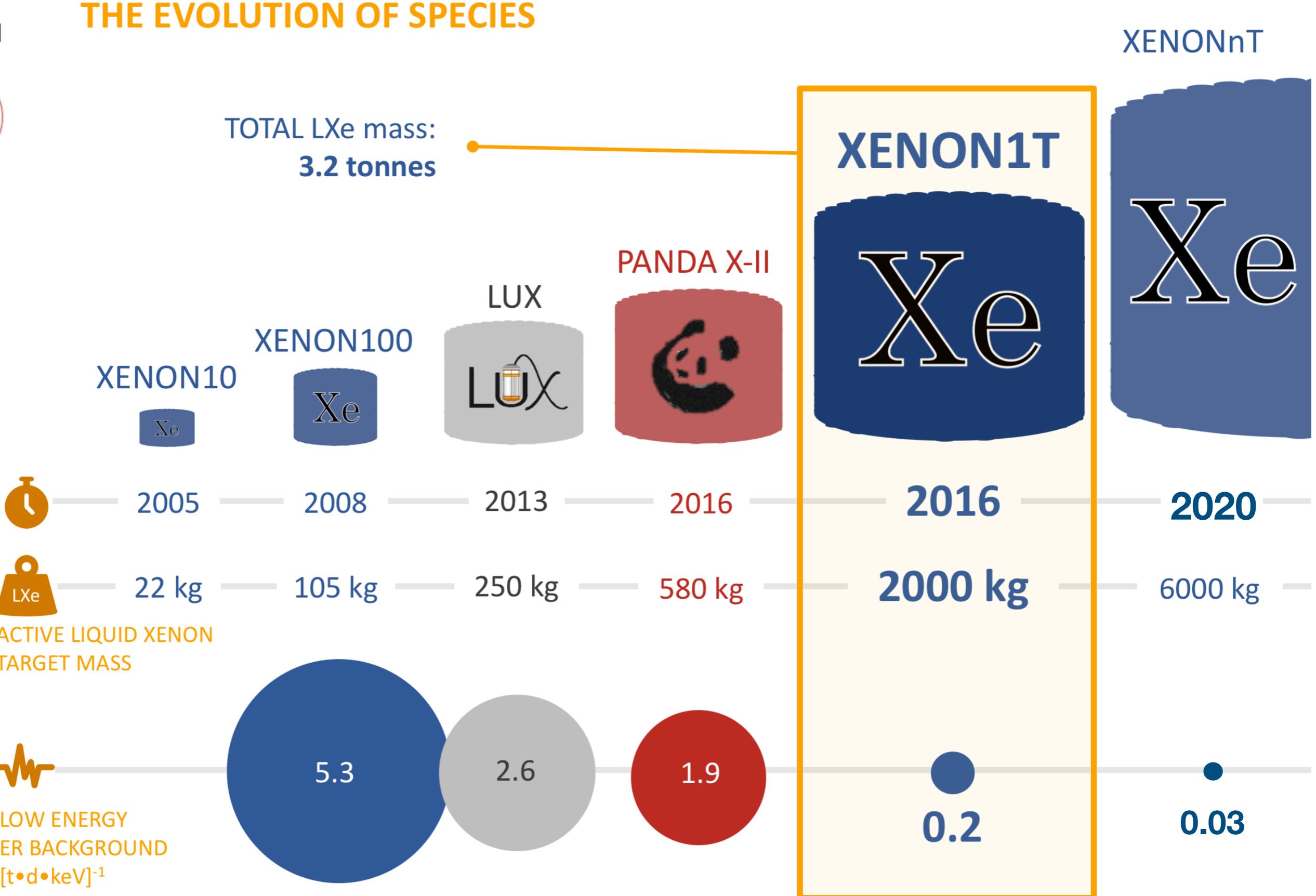
LAr filling expected in 2026

Evolution of LXeTPC detectors

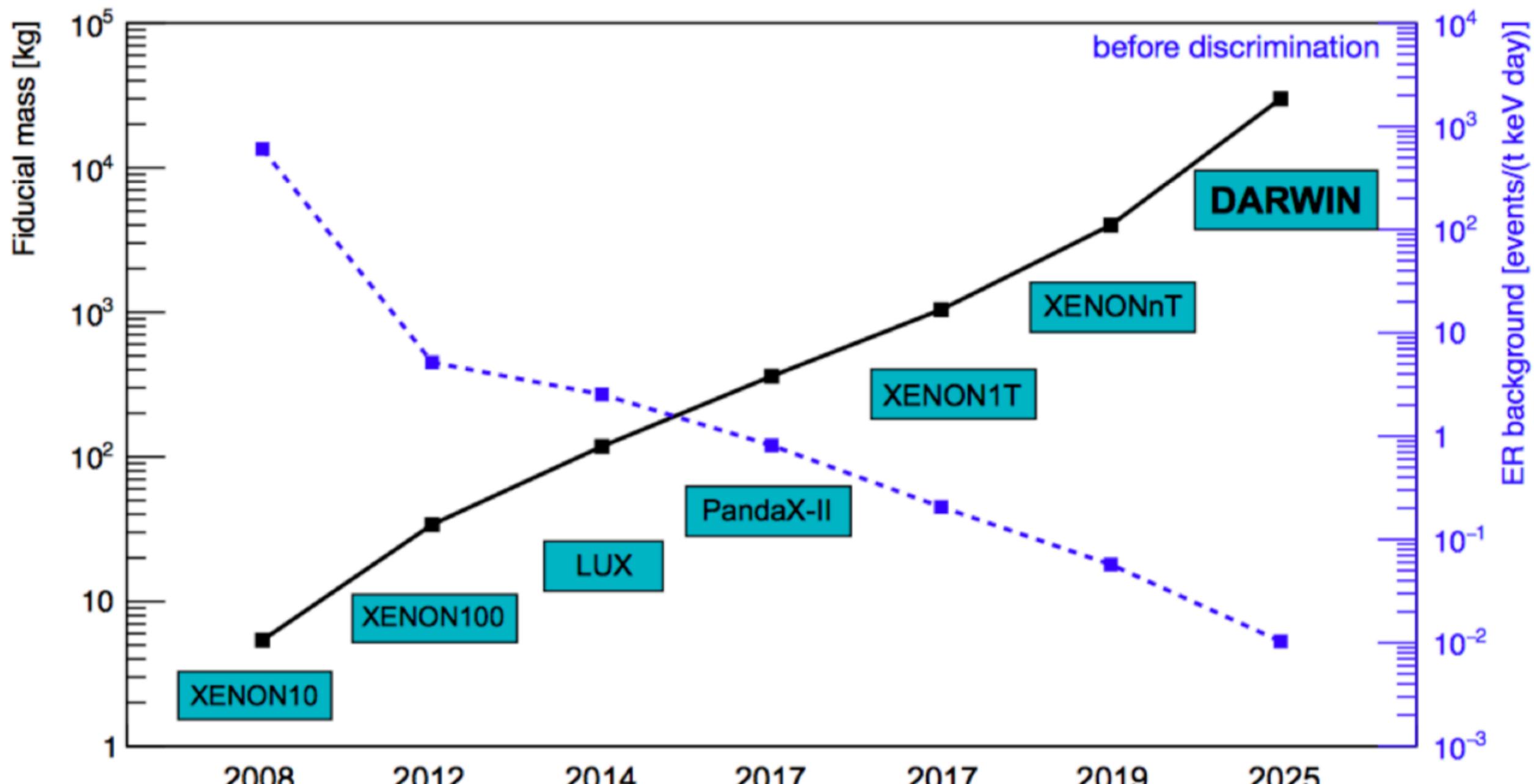
N

THE EVOLUTION OF SPECIES

XENON
MORNING



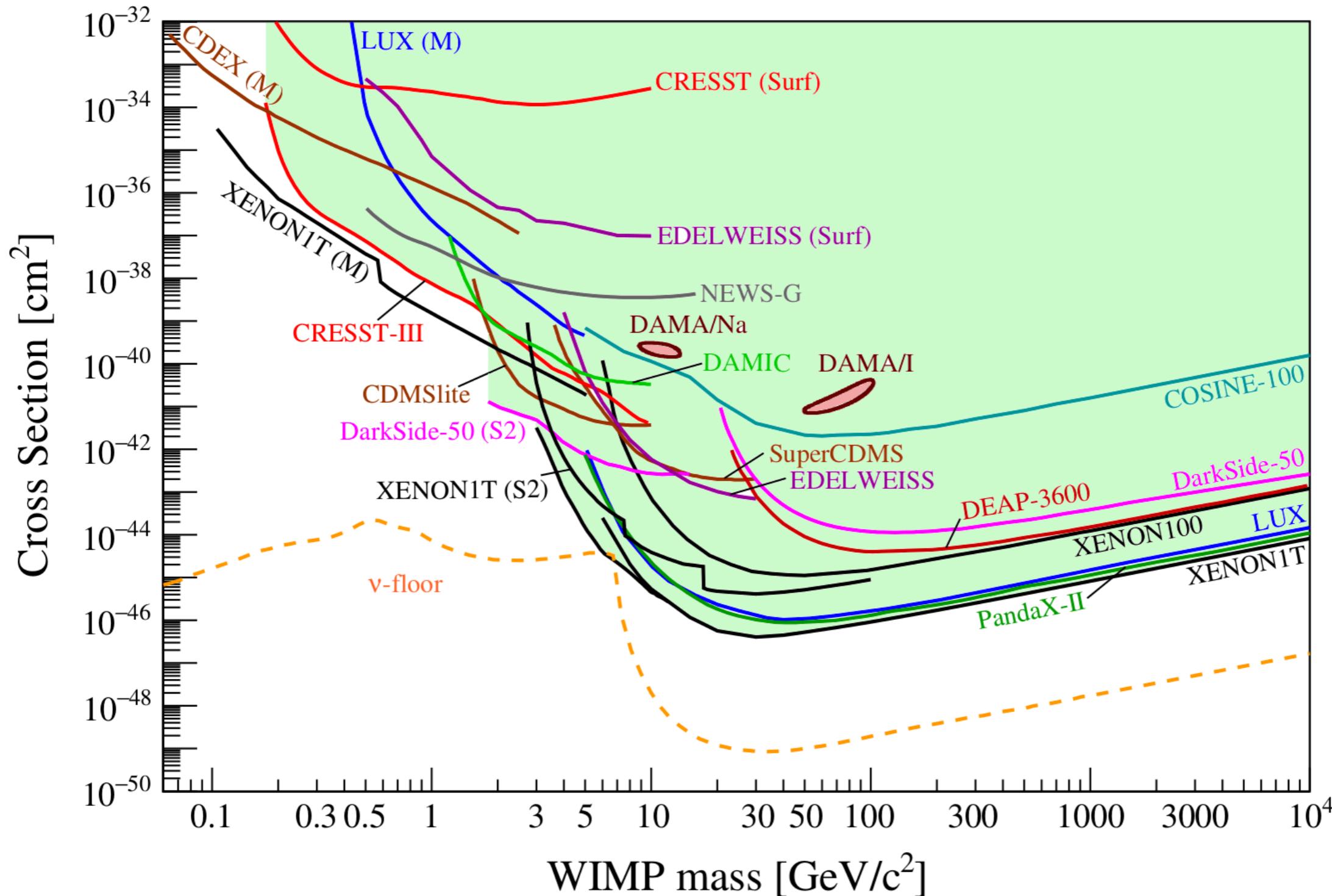
Evolution of LXeTPC detectors



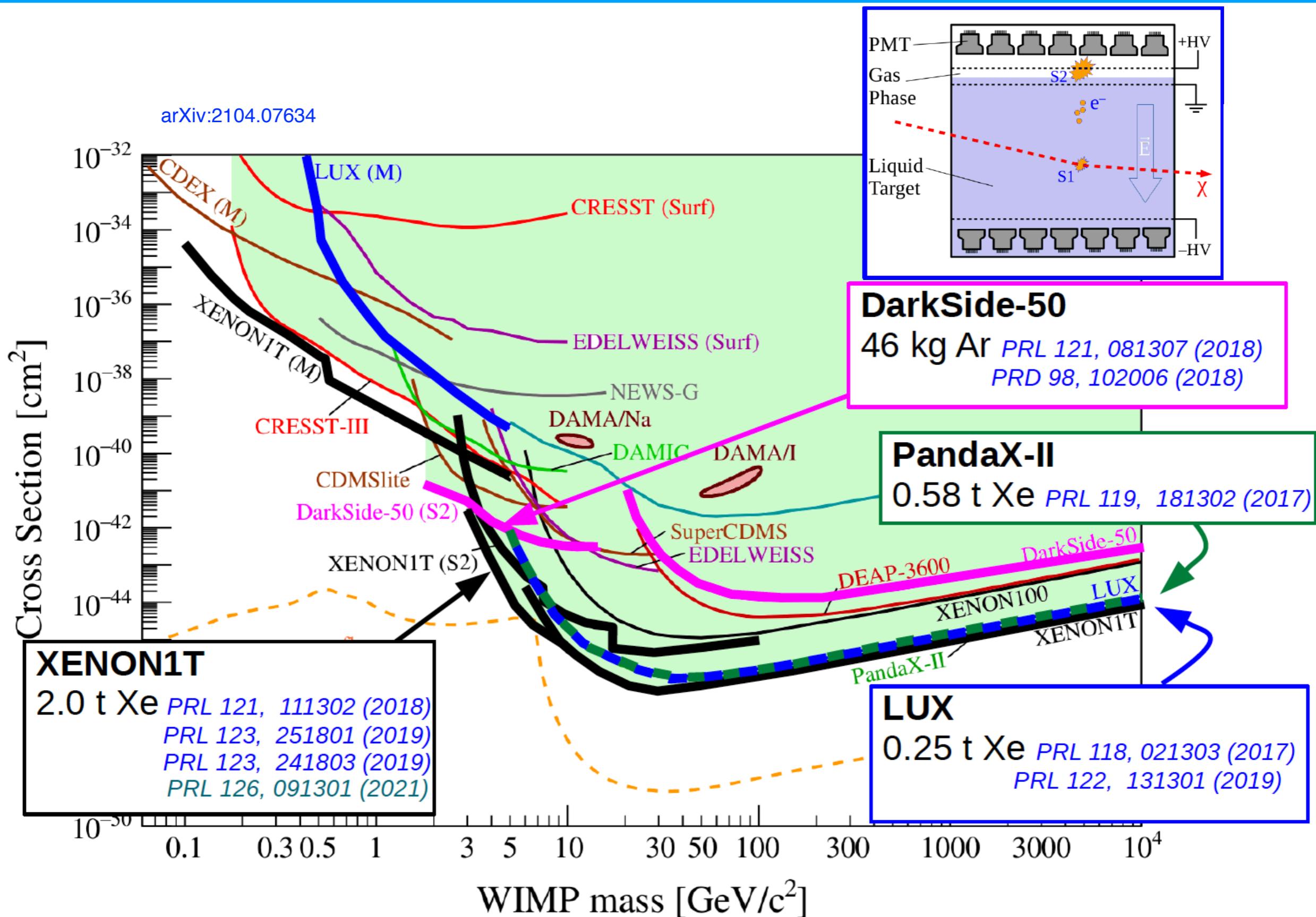
(from T. Marrodan)

Summary of prev-gen Noble Liquid results

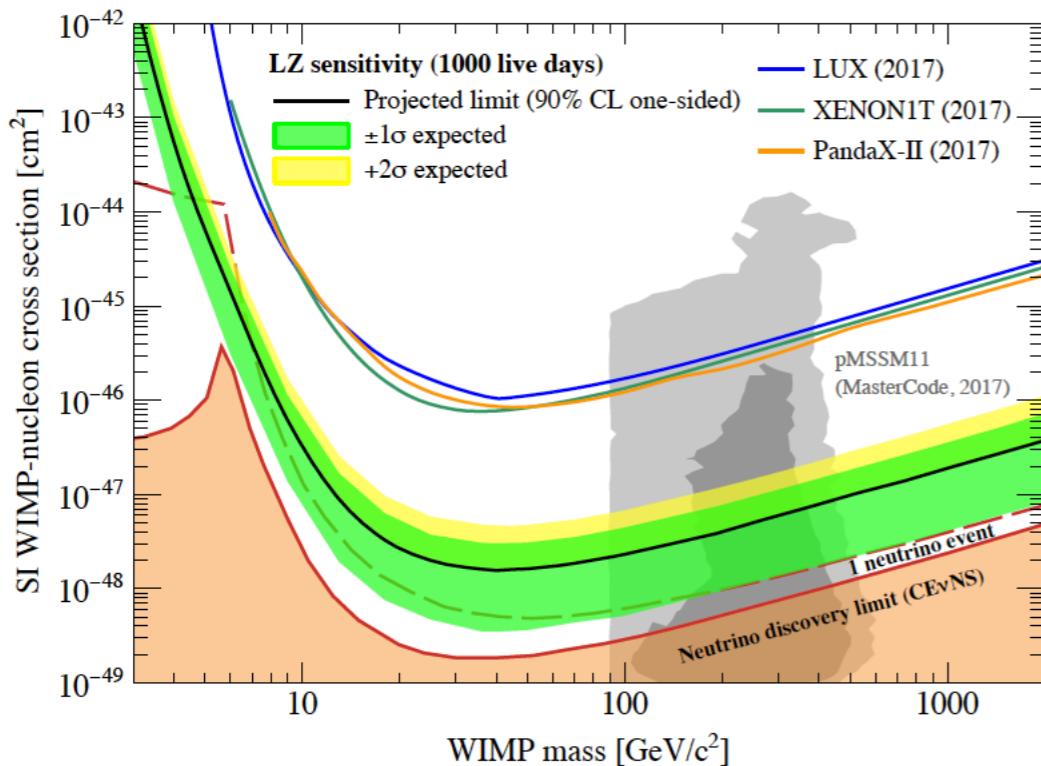
arXiv:2104.07634



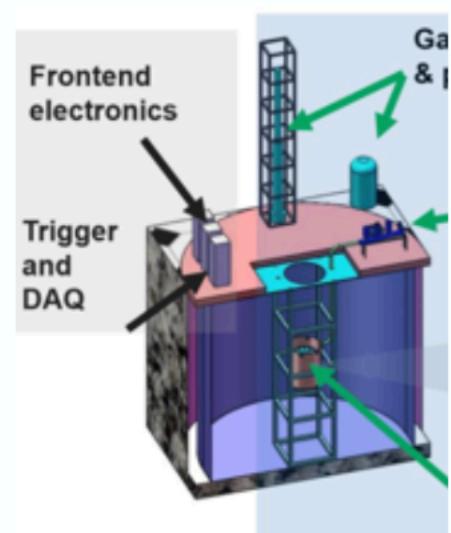
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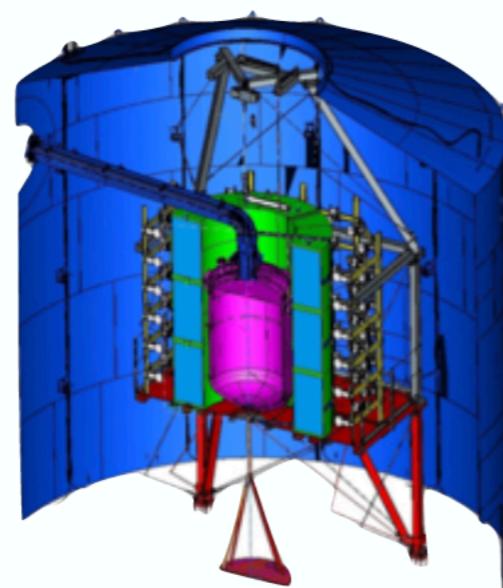
Current and next steps: LXe TPCs



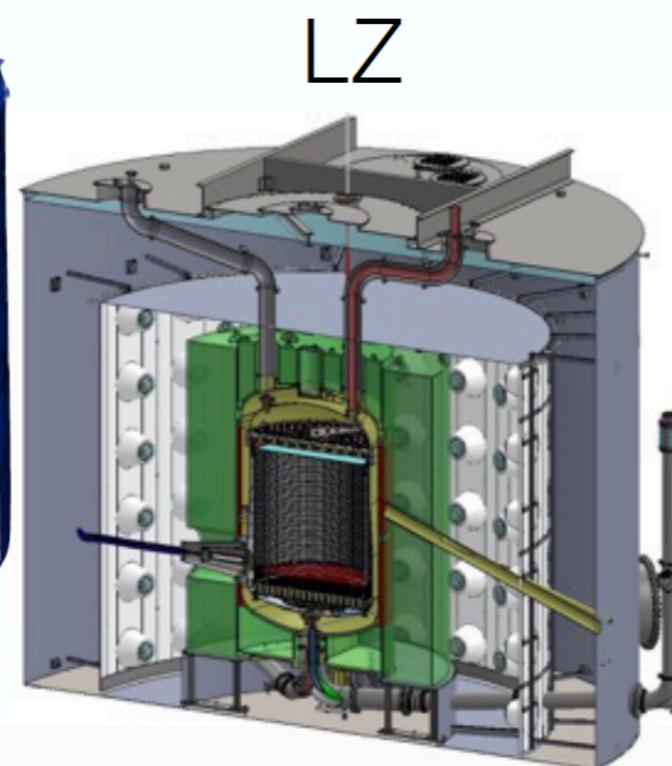
- Results from running experiments and secondary results from completed ones
- XENONnT: 2019 8t, 4t fiducial
- PandaX-4T: 2020 4t
- LZ: 2020 10t, 5.6t fiducial
- DARWIN: 2024 50t



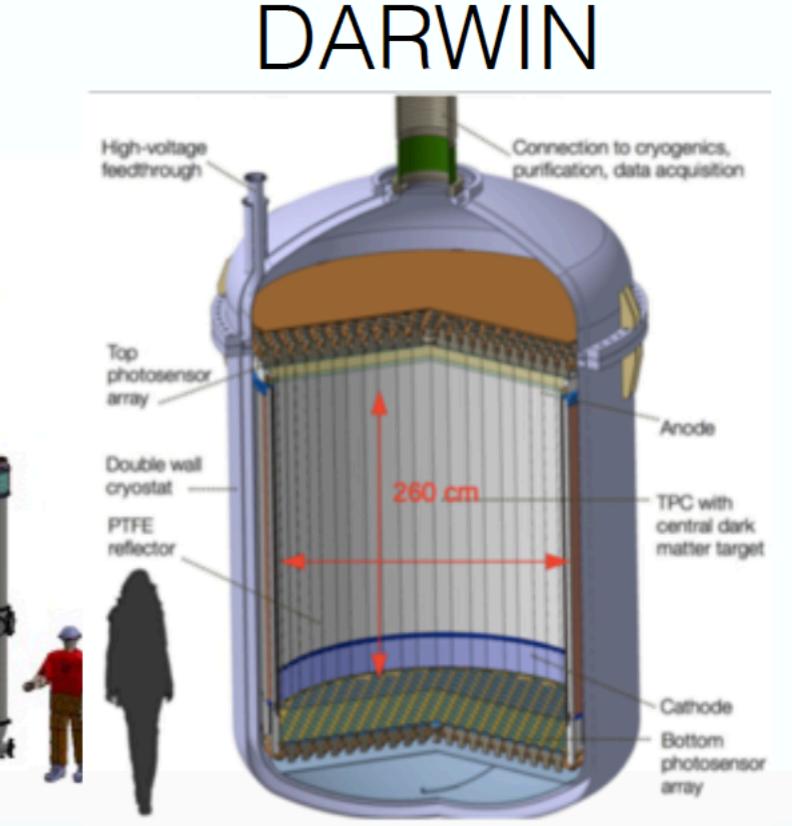
PandaX-4T



XENONnT



LZ



DARWIN

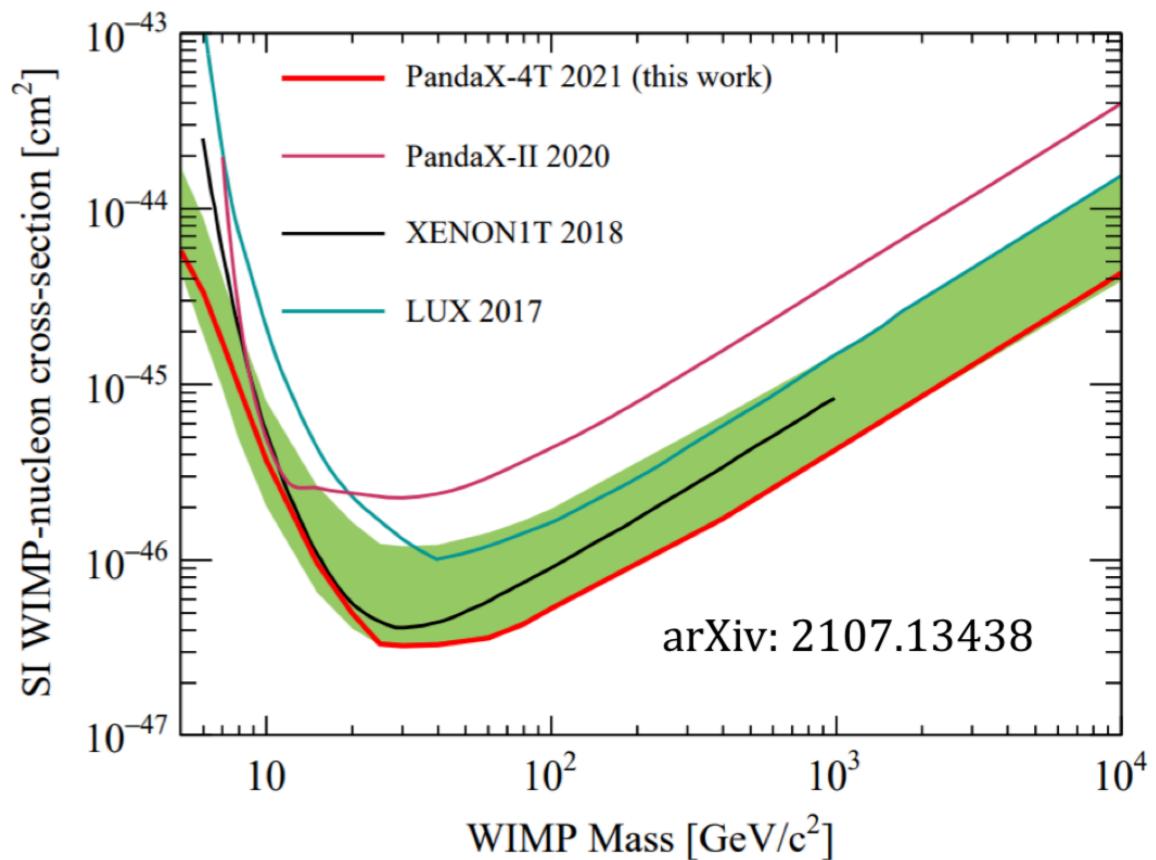
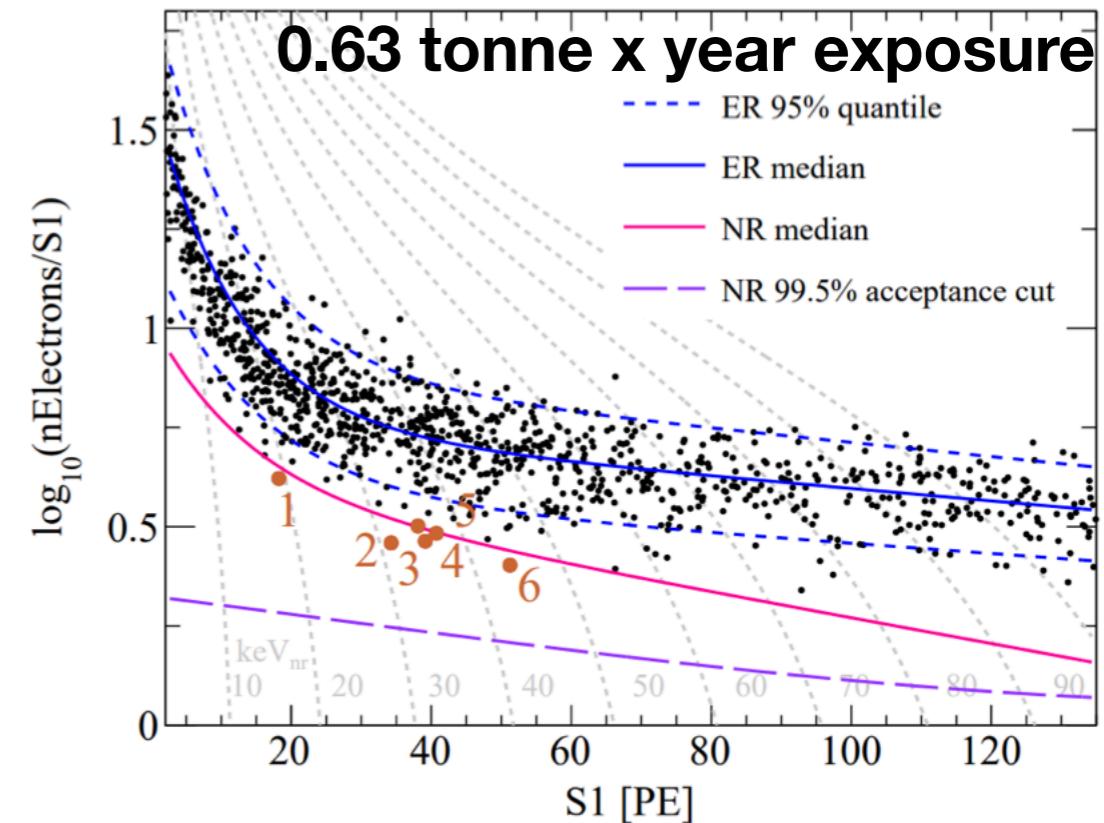
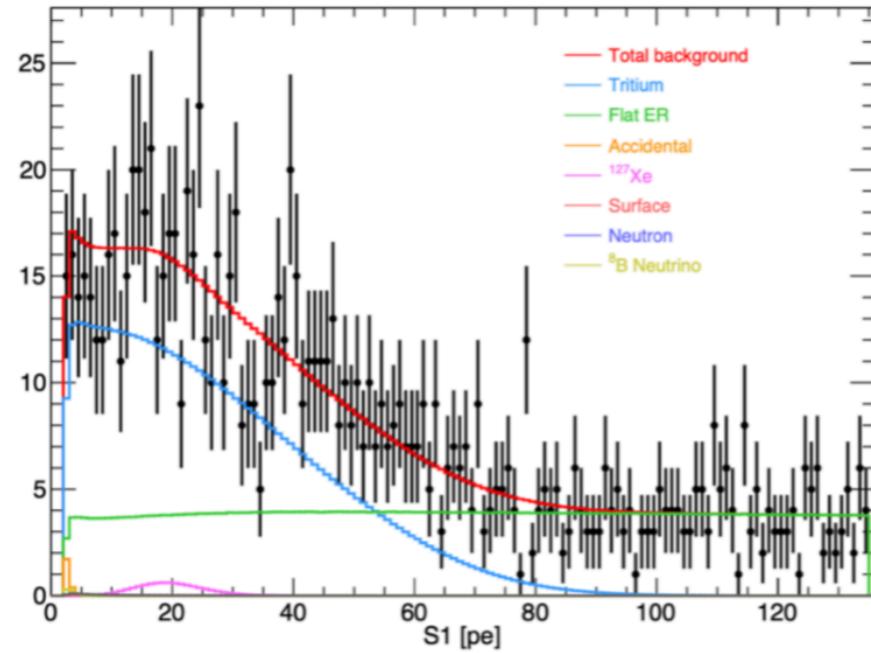
PandaX-4T



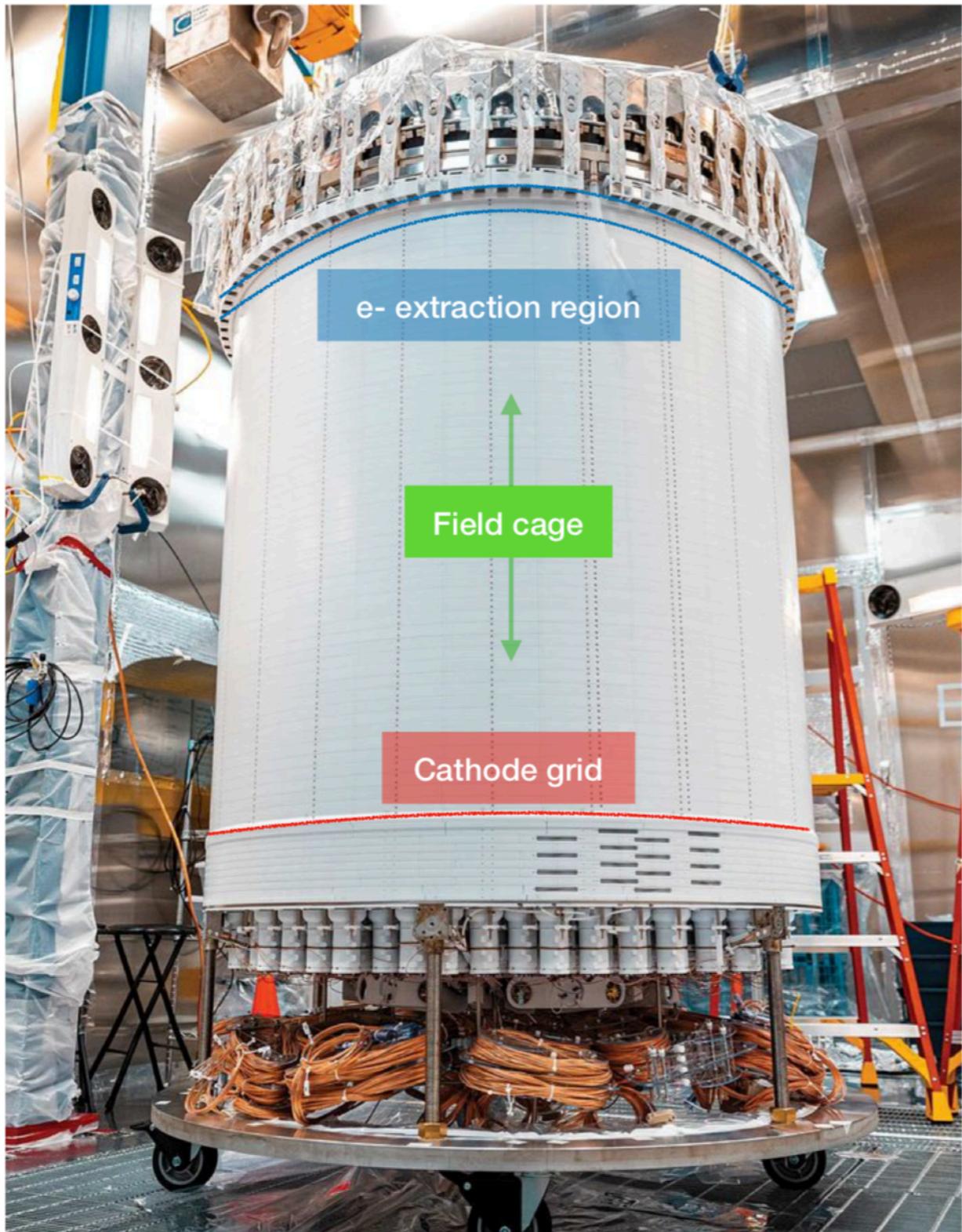
PANDAX
PARTICLE AND ASTROPHYSICAL XENON TPC

July 2021/arXiv:2107.13438

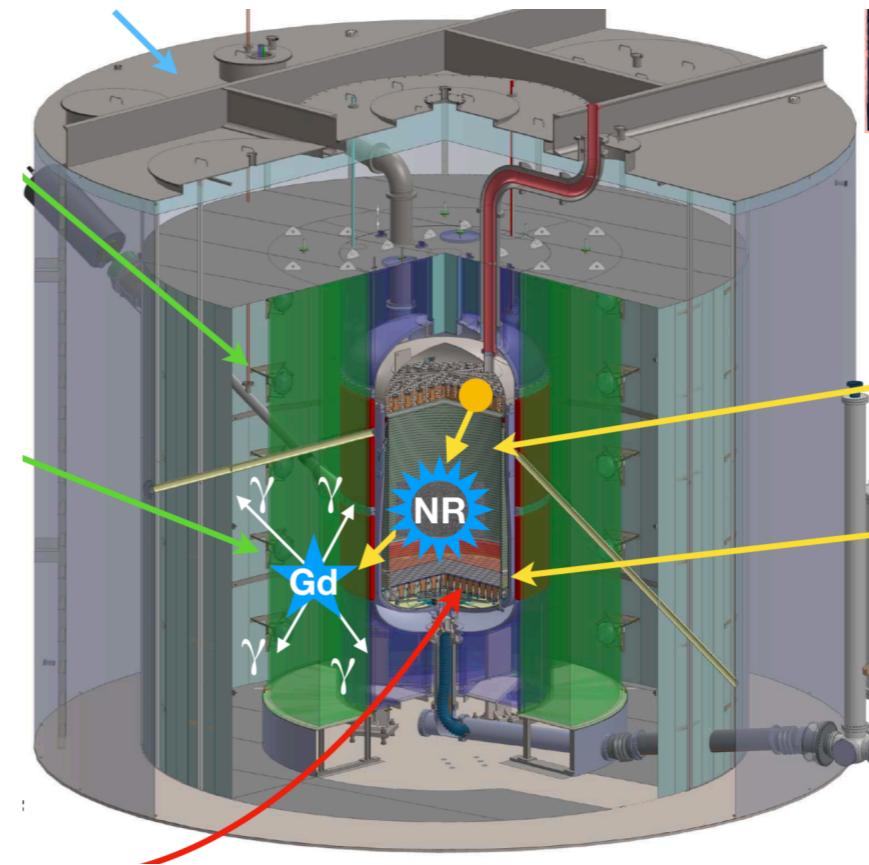
- PandaX-4T: A dual-phase Xe TPC based experiment with 3.7 tonne liquid xenon in sensitive volume (see Qing's talk)
- Ultrapure water shield: 13 m (H) x 10 m (D) $\sim 900 \text{ m}^3$
- TPC: 1.2 m (H) x 1.2 m (D)
- 3-in PMTs: 169 top/199 bottom



LUX-ZEPLIN



Construction in radon reduced clean room at surface assembly lab completed in 2019



- PTFE field cage maximizes light collection efficiency.
- 494 3" PMTs in total - Hamamatsu R11410-22.
- Woven electrode grids to generate electric-field in the active xenon region (7 tonnes of LXe)
- Nominal cathode voltage of -50 kV (drift field ~ 300 V/cm)
- ~ 2 tonne instrumented skin region between the outside of the TPC and the inner wall of the cryostat vessel.
- First (not blinded) results presented in July '22

LUX-ZEPLIN new results (July 2022)

Rn level:

Rn222 ($\mu\text{Bq/kg}$)	Pb214 ($\mu\text{Bq/kg}$)	Po214 ($\mu\text{Bq/kg}$)
$4.37 \pm 0.31 \text{ (stat)}$	$3.26 \pm 0.13 \text{ (stat)} \pm 0.57 \text{ (sys)}$	$2.56 \pm 0.21 \text{ (stat)}$

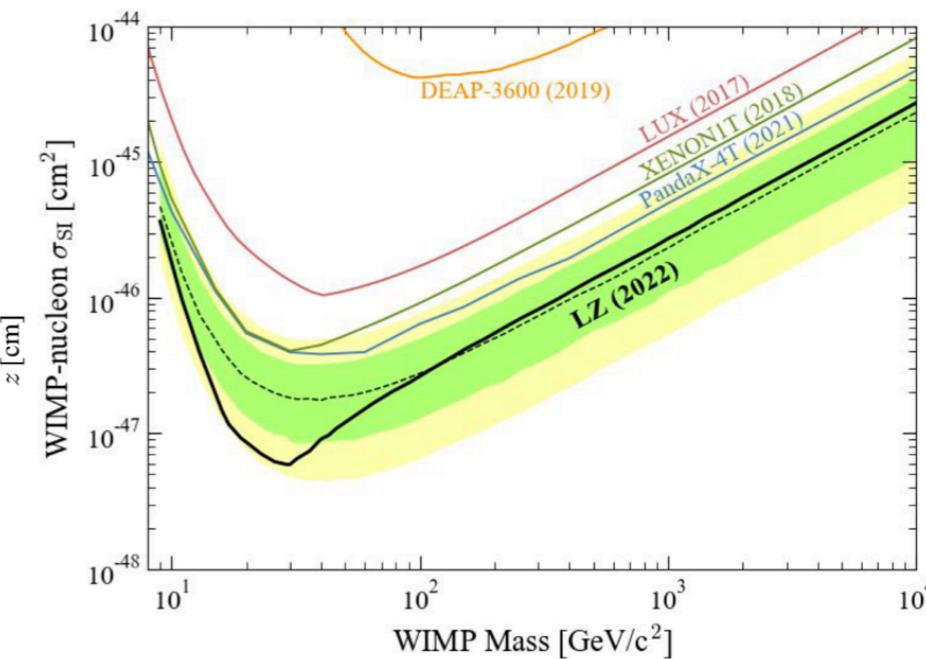
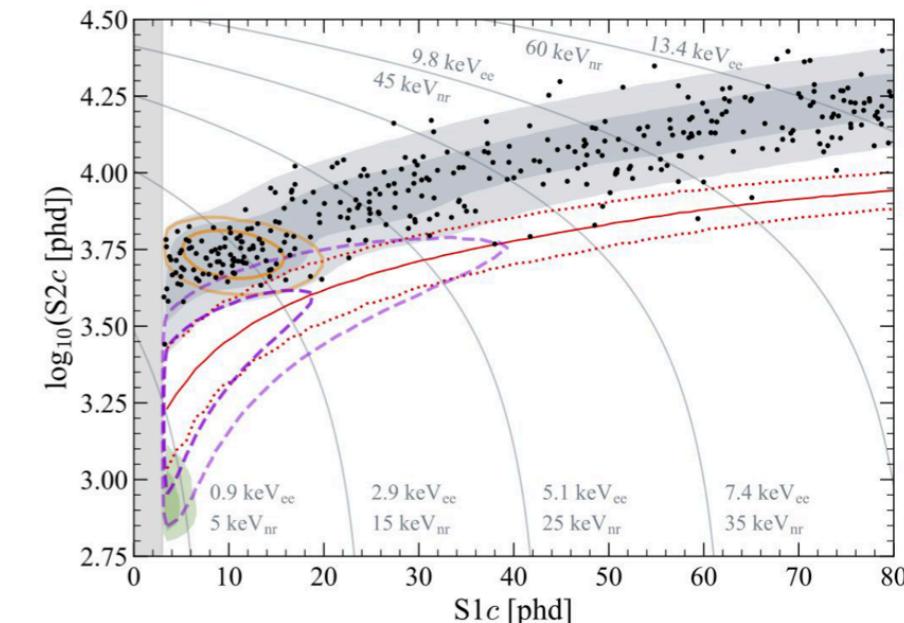
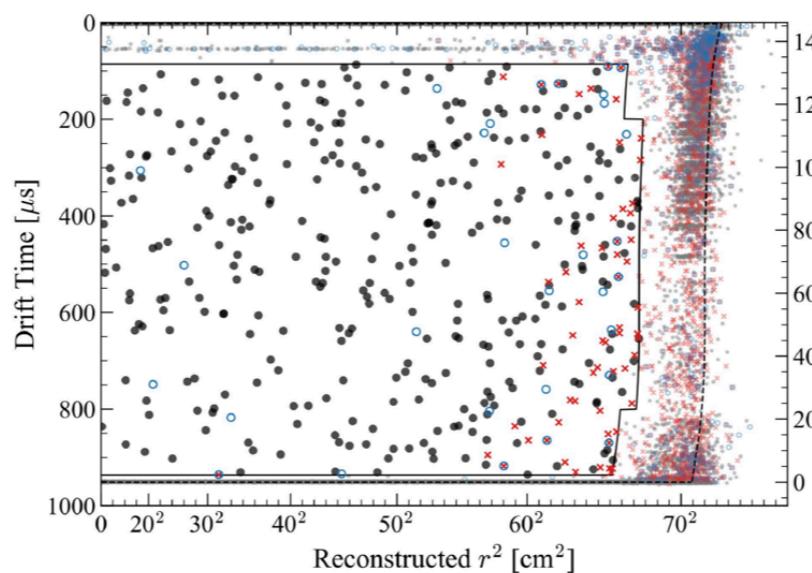
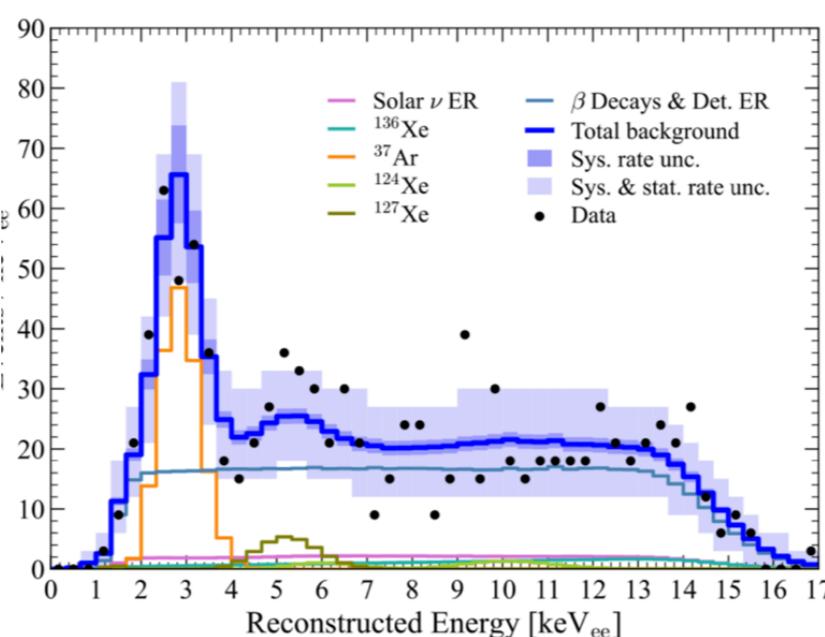
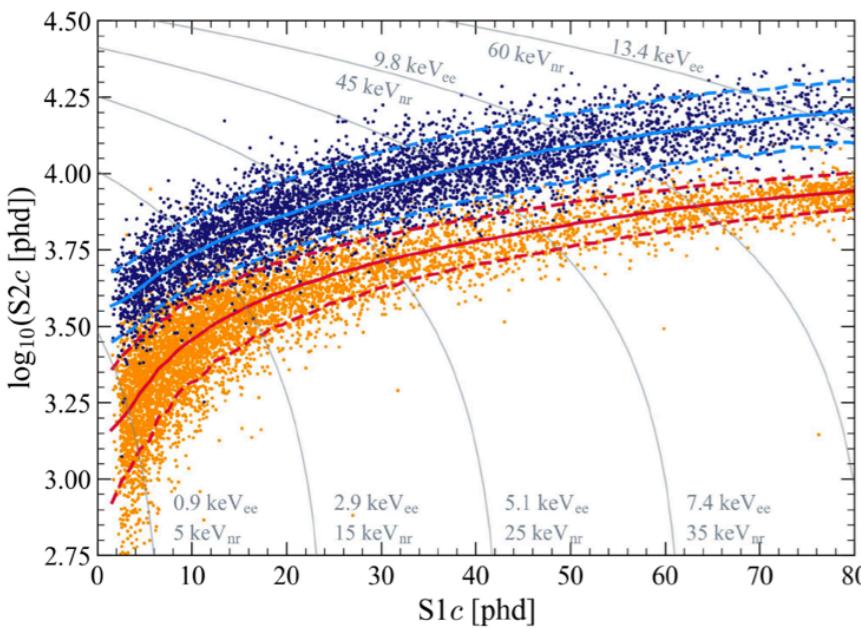
- Science Run 1 - ~3.5 month run, exposure is 60 live days x 5.5 tonnes fiducial
 - (7t active in TPC+2t Xe skin+17t Gd-loaded LS)

arXiv:2207.03764

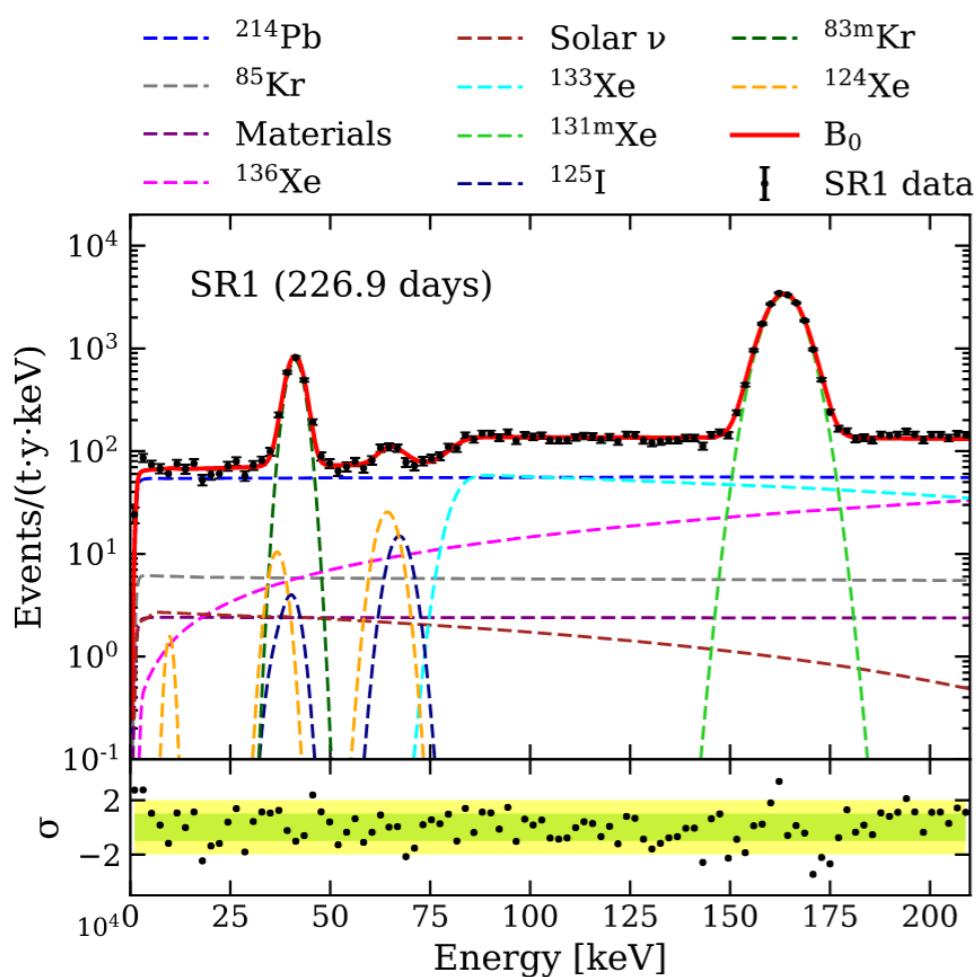
nVeto performances:

- OD neutron tag settings:
 - $\geq 200 \text{ keV}$
 - $\Delta t \leq 1200 \mu\text{s}$
- Single-scatter neutron tagging efficiency [measured]: $88.5 \pm 0.7\%$
- Livetime hit: 5%

ER and NR calibrations:

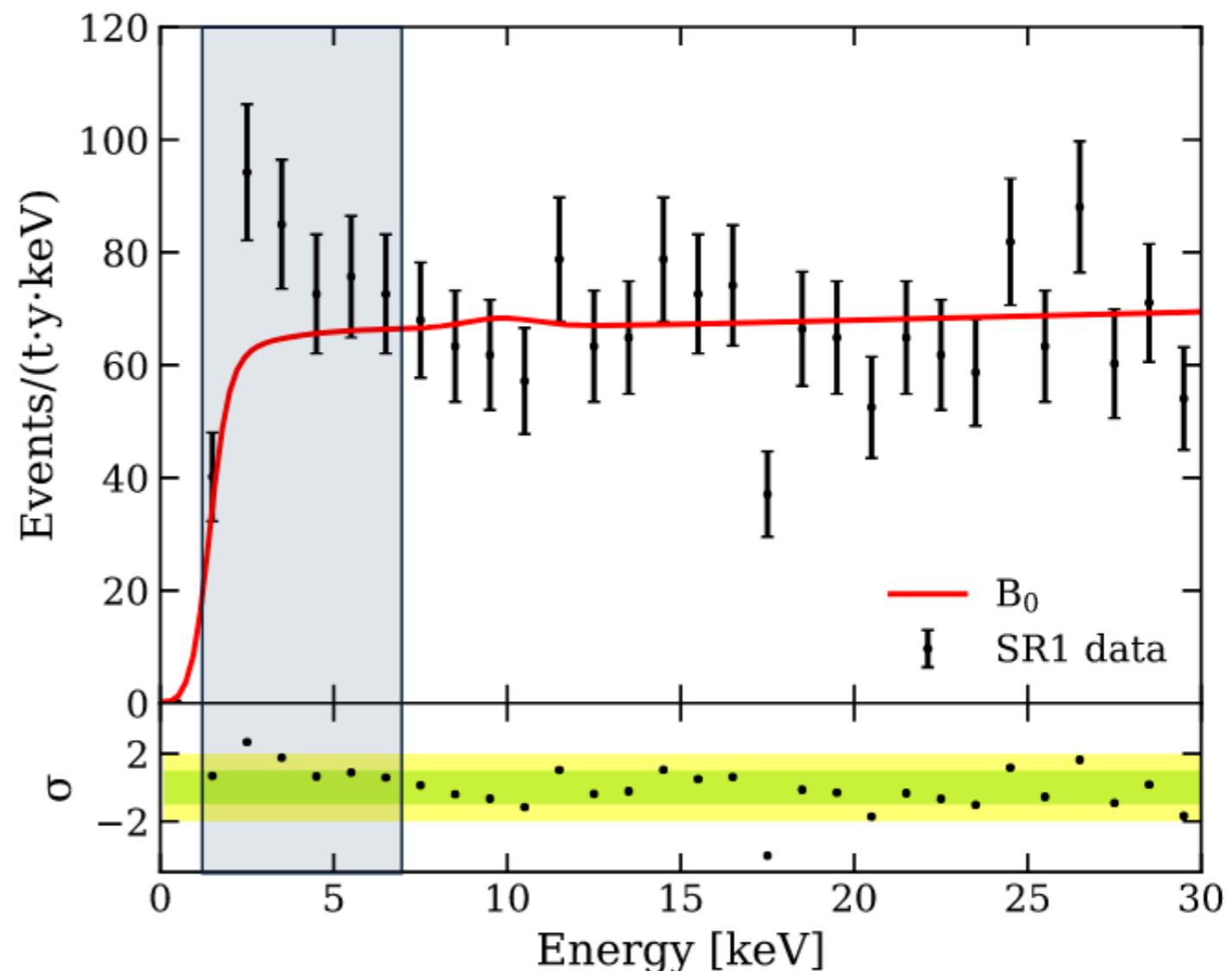


The XENON1T ER excess



- **excess in 1-7 keV range**
285 evts observed vs
 232 ± 15 expected
→ **(naive) 3.3σ fluctuation**

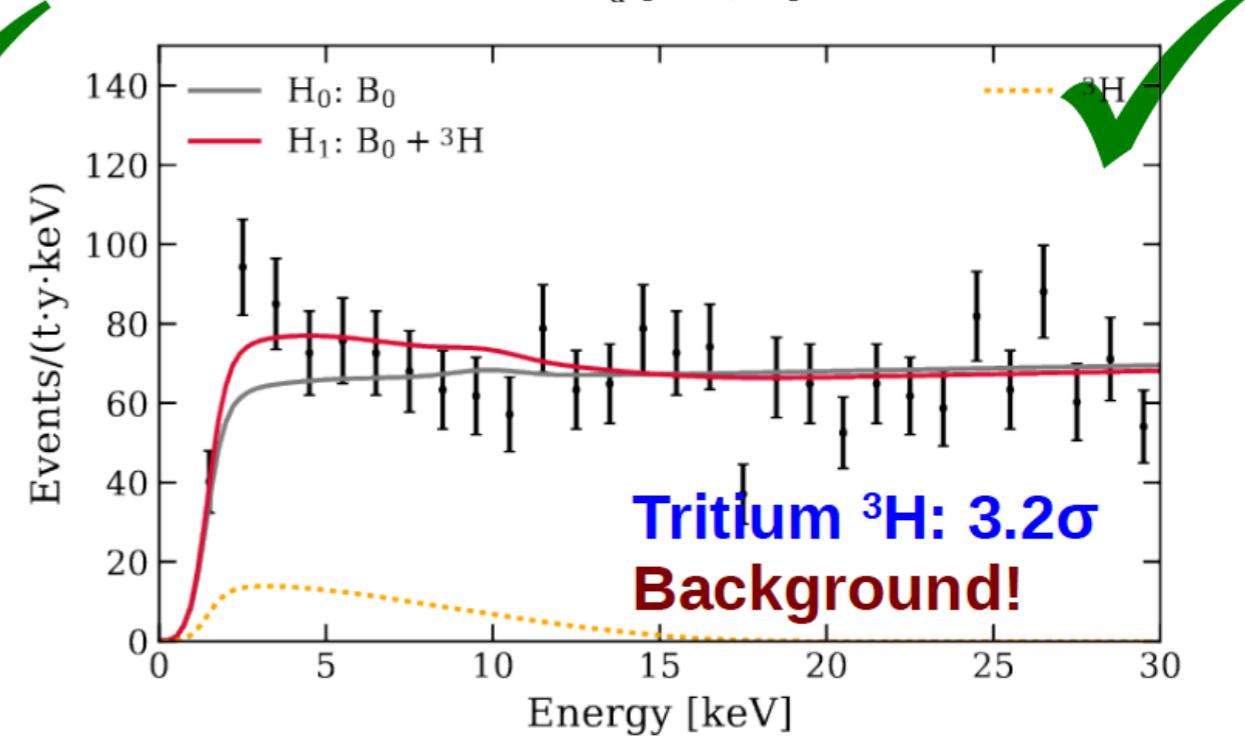
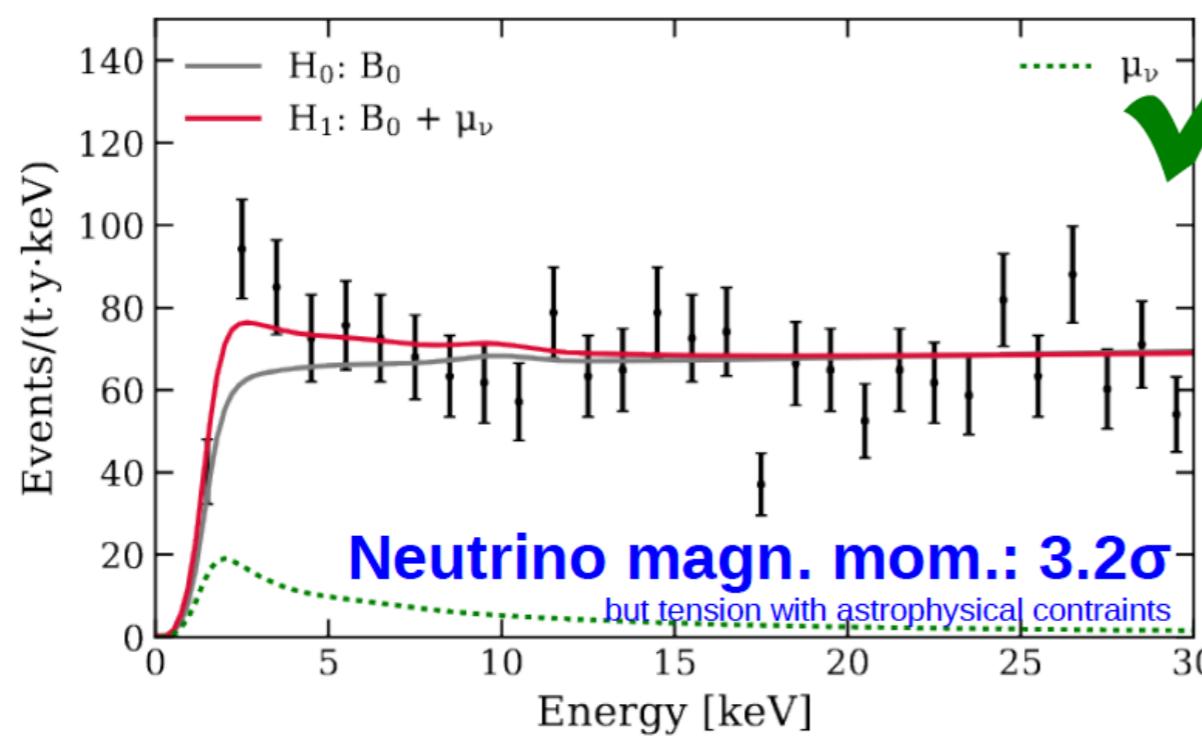
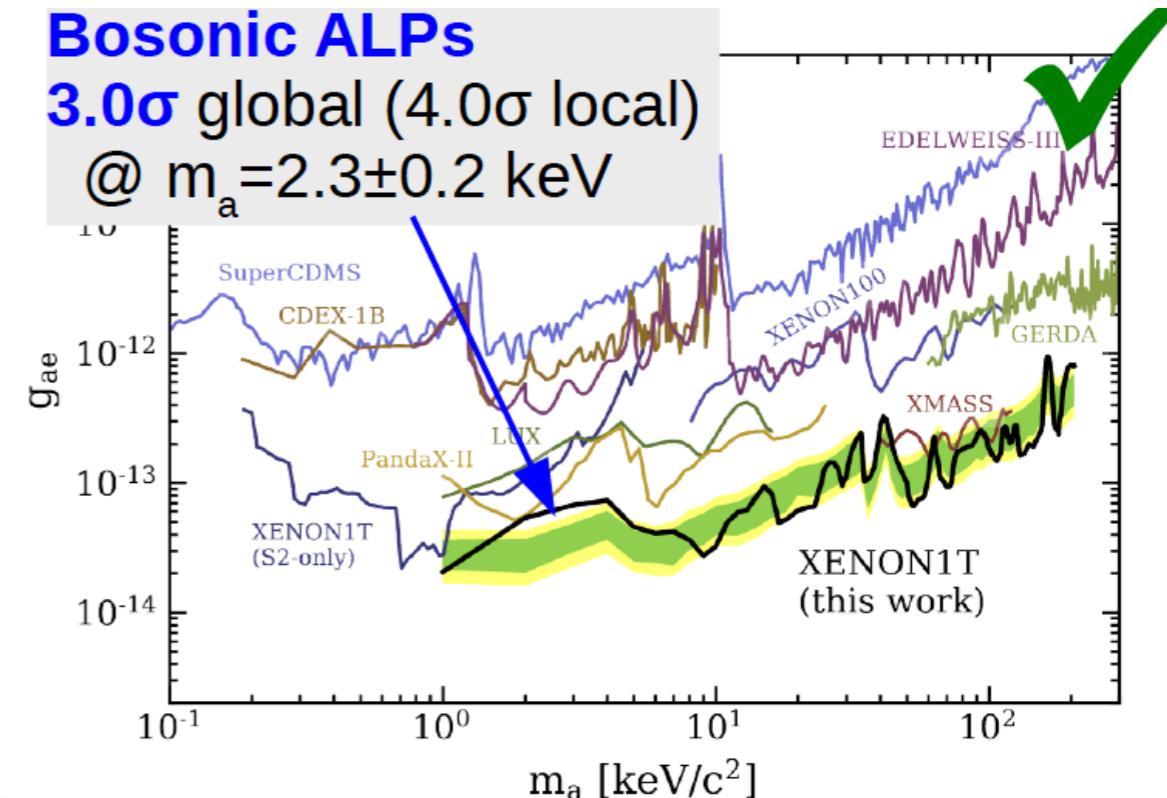
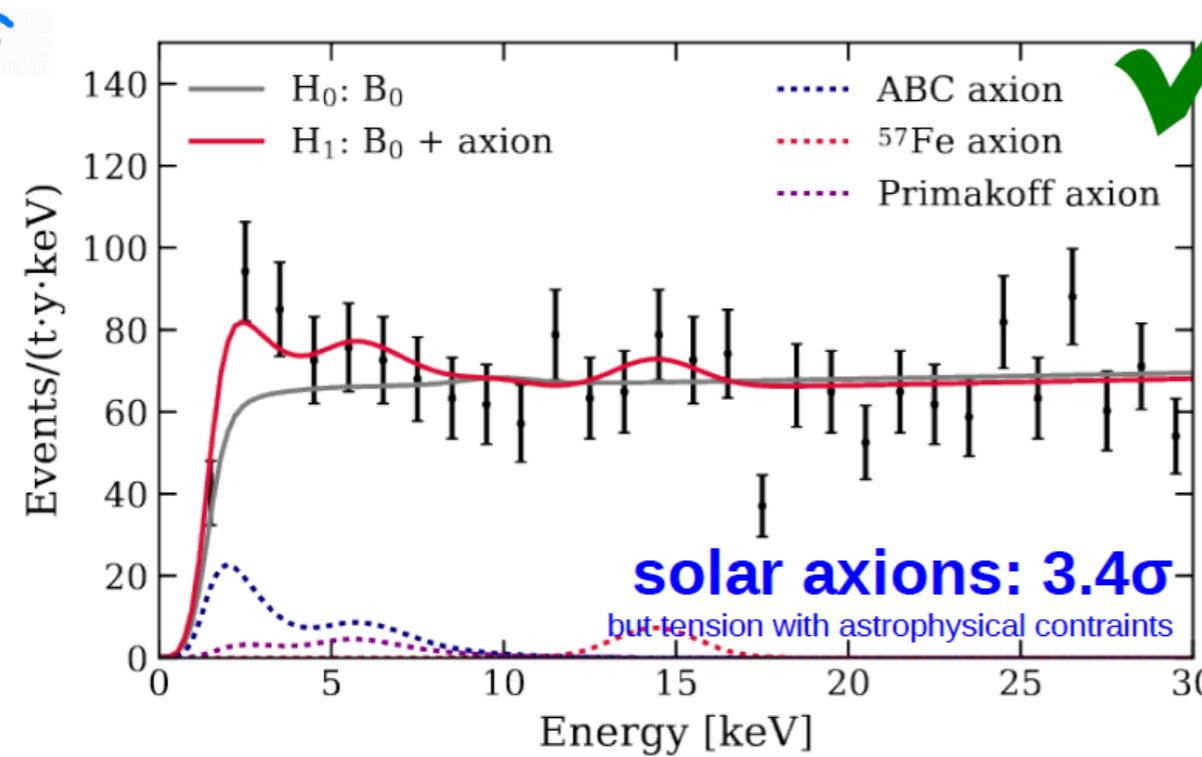
- events uniformly distributed
 - in space
 - in time (but low stats)



The XENON1T ER excess

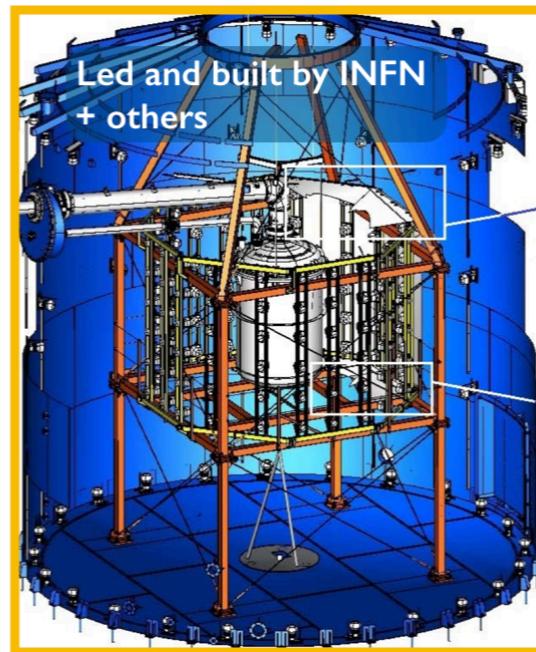
Possible interpretations:

PRD 102, 072004 (2020)



Larger TPC

- Total 8.4 t LXe
- 5.9 t in TPC
- ~ 4 t fiducial
- 248 → 494 PMTs



Neutron veto

- Inner region of existing muon veto
- optically separate
- 120 additional PMTs
- Gd in the water tank
- 0.5 % $\text{Gd}_2(\text{SO}_4)_3$



^{222}Rn distillation

- Reduce Rn (^{214}Pb) from pipes, cables, cryogenic system
- New system, PoP in XENON1T

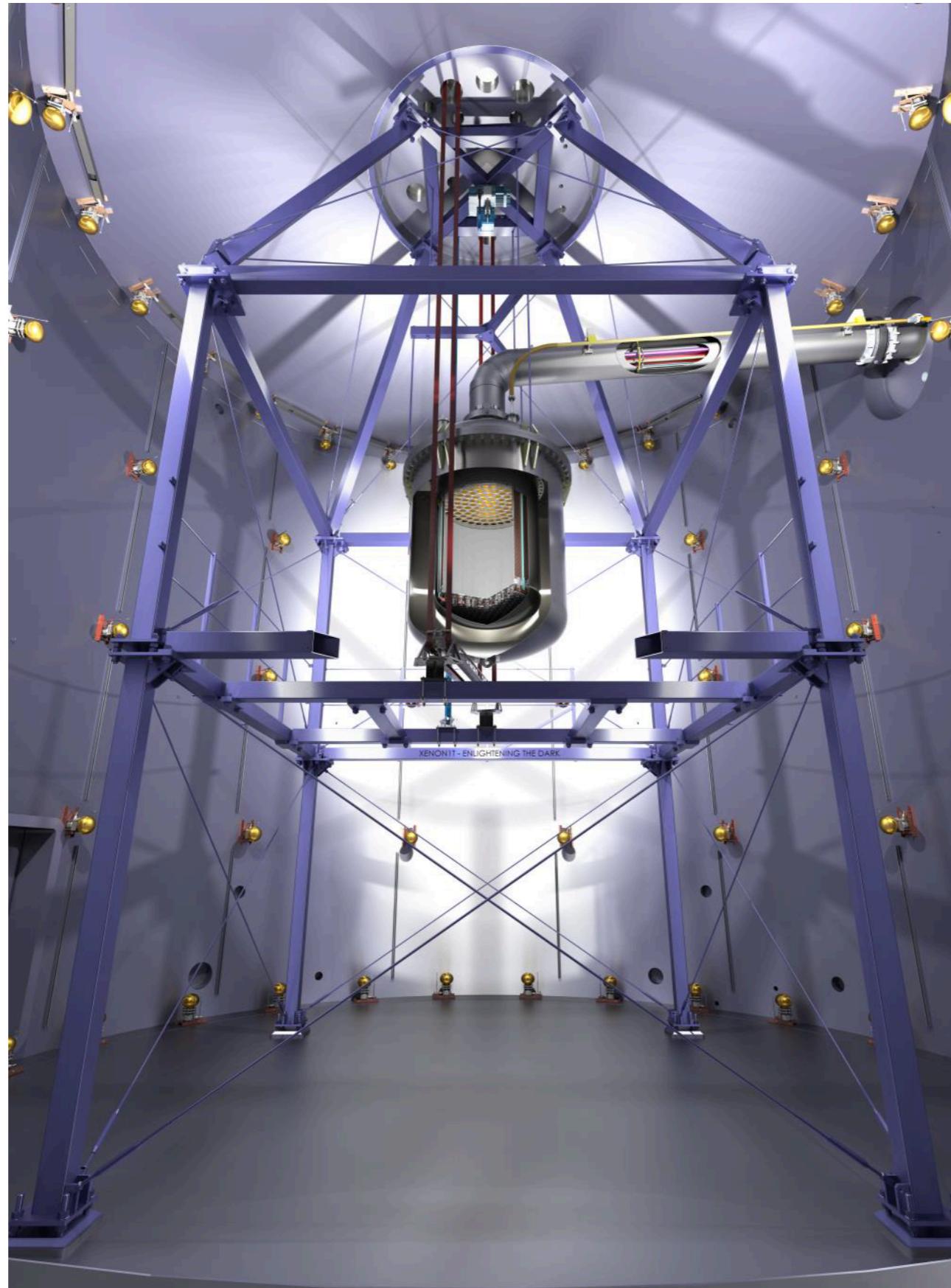


LXe purification

- Faster xenon cleaning
- 5 L/min LXe (2500 slpm)
- XENON1T ~ 100 slpm

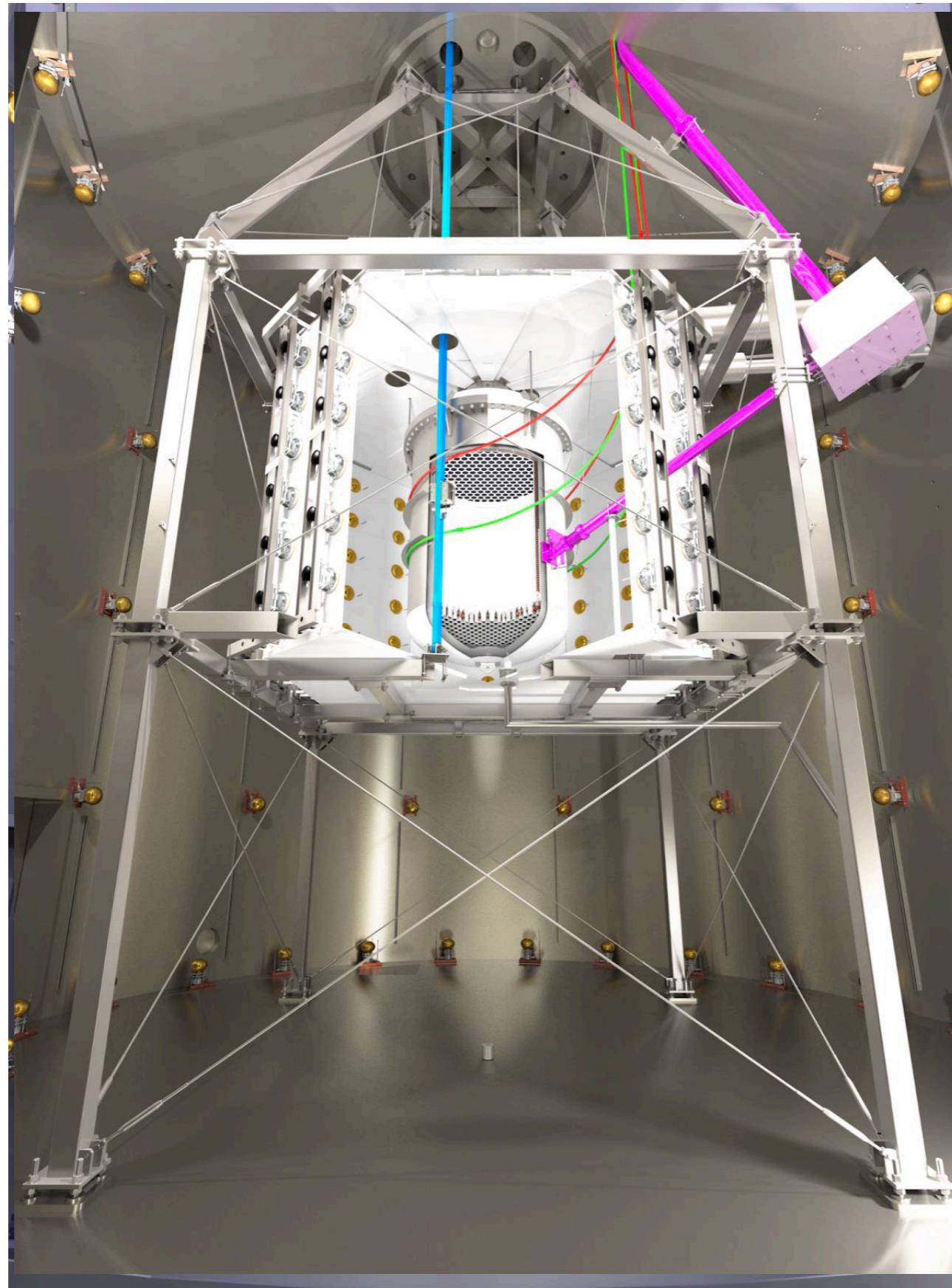
- Completed construction in 2020
- Commissioning in first half of 2021
- Currently in Science Run

XENONnT



**Gd-loaded
Water Cerenkov
Neutron Veto**

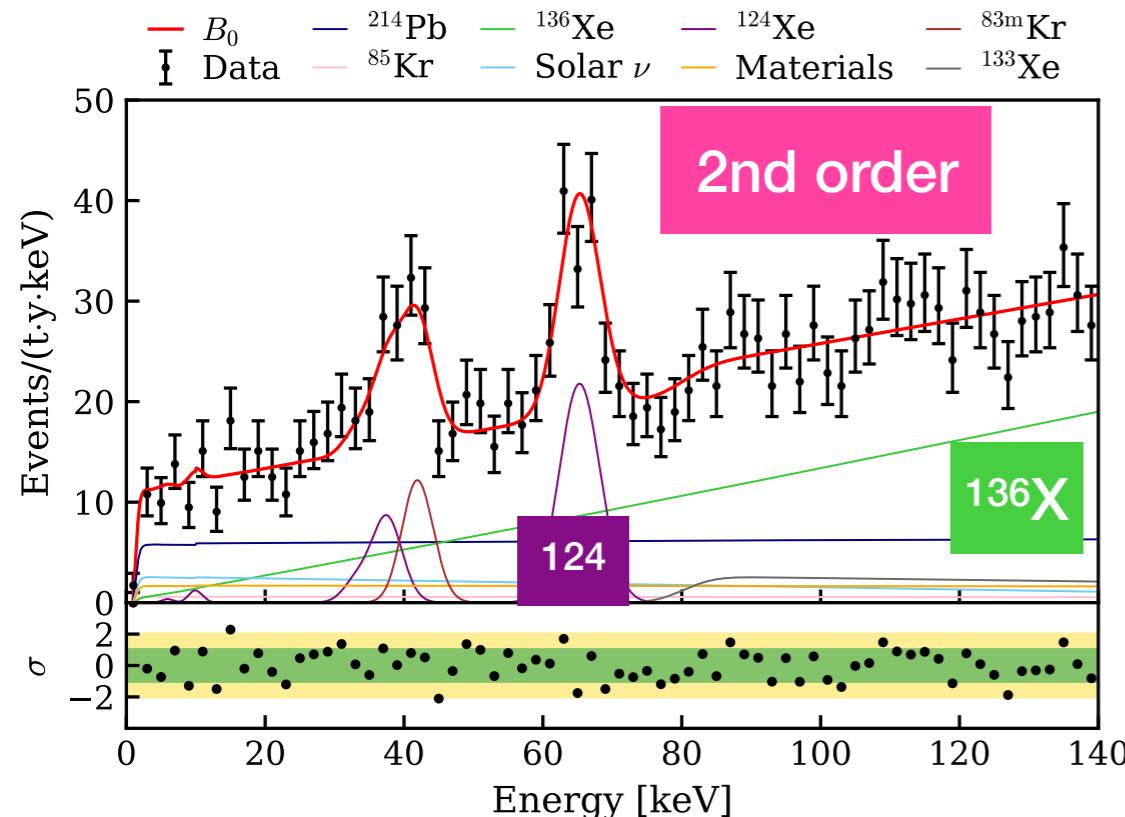
XENONnT



**Gd-loaded
Water Cerenkov
Neutron Veto**

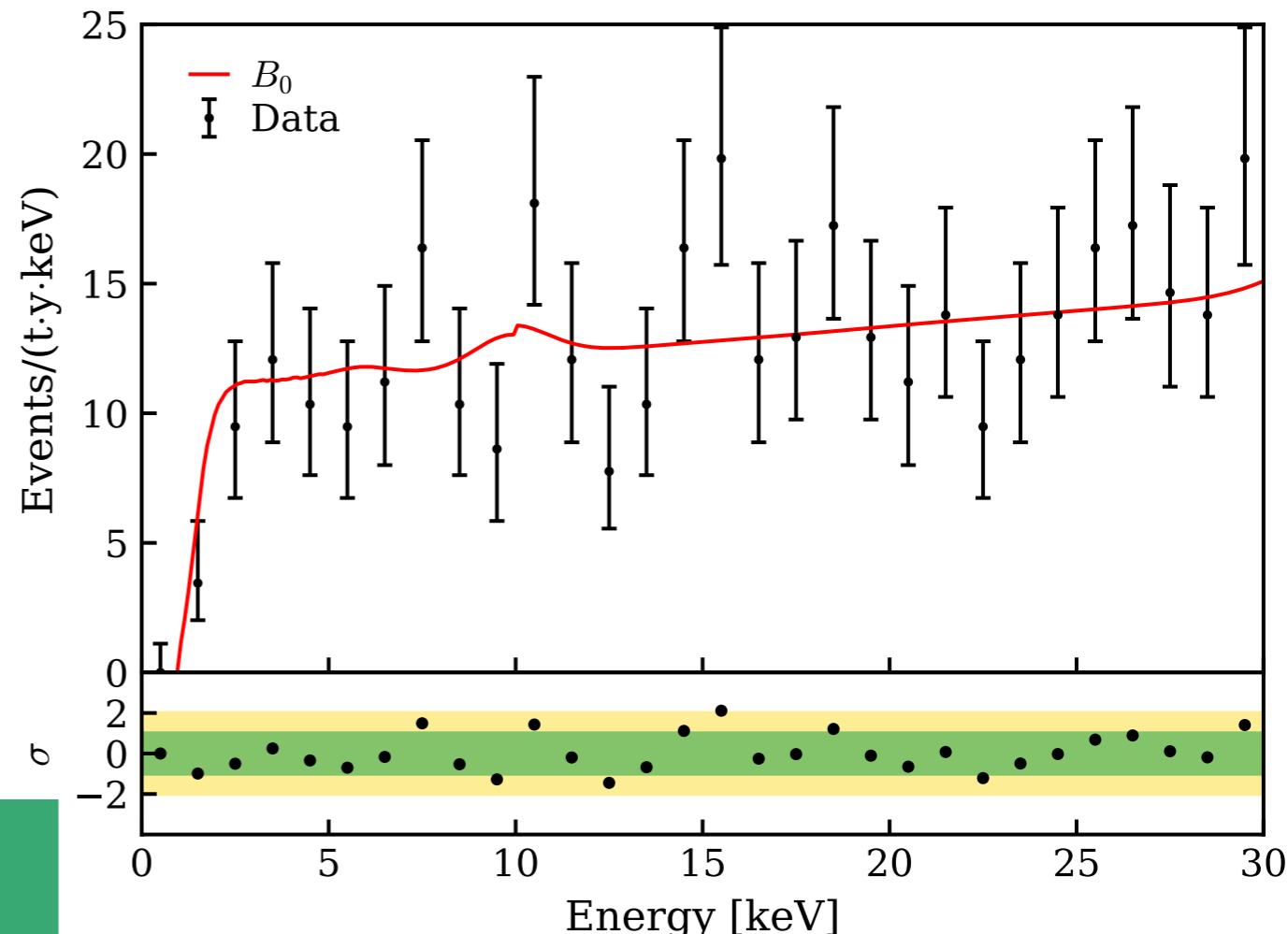
XENONnT new results (July 2022)

Energy spectrum dominated by 2nd-order weak processes



XENONnT key performances in SR0:
> 10 ms electron lifetime,
 $1.77 \pm 0.01 \mu\text{Bq/kg}$ radon concentration

Zoom in the low-energy region: no discrepancy from the bkg model



arXiv:2207.11330, accepted by PRL

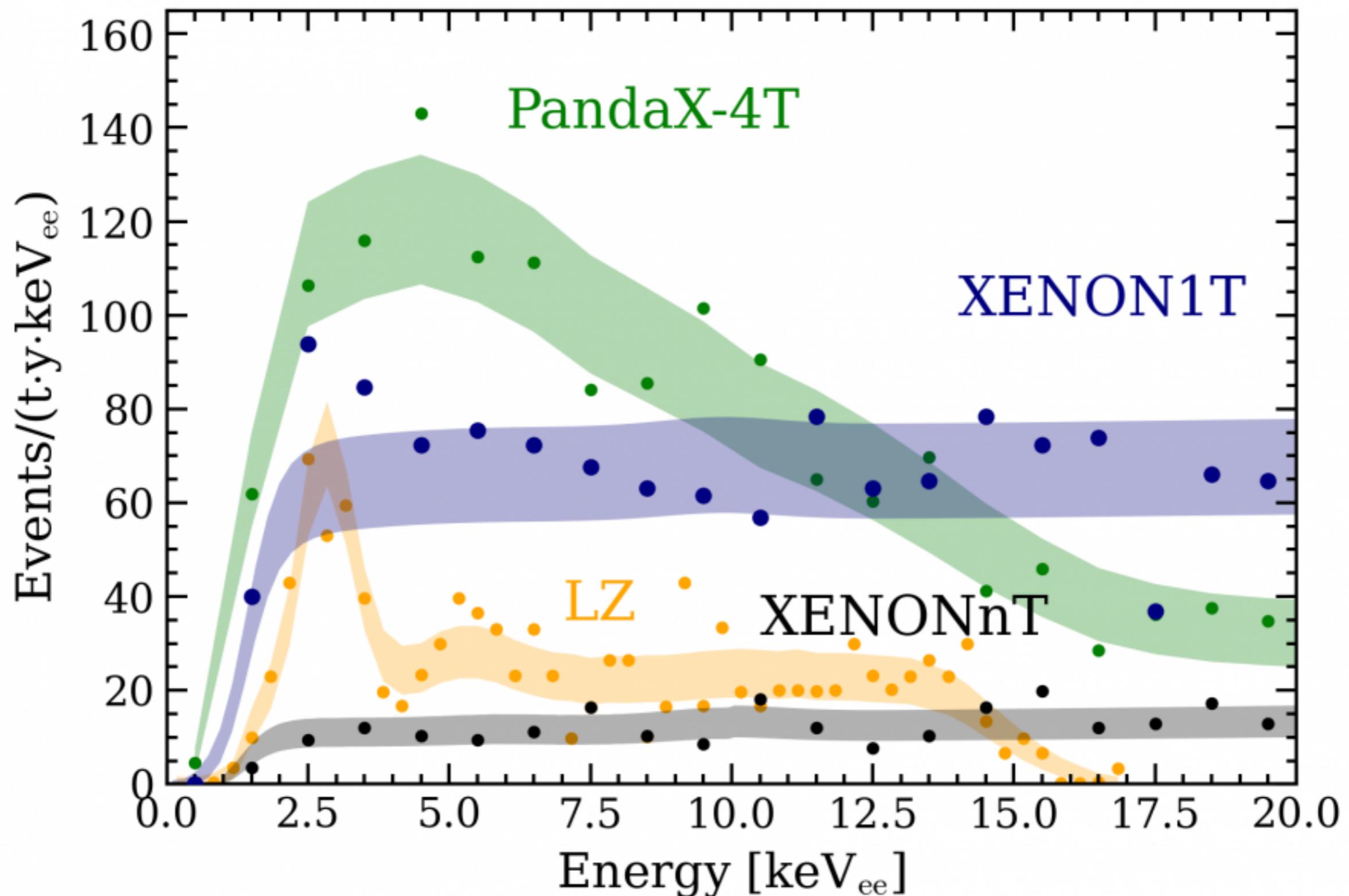
Excellent agreement with our background model.
Lowest ER background ever achieved in a DM experiment:
 $(16.1 \pm 0.3) \text{ events}/(t \times \text{yr} \times \text{keV})$

No trace of ^3H , even in the Tritium-enhanced run

Set new best limits on Solar Axions, ν magnetic moment, ALPs, ...

Nuclear recoil data are still blinded
WIMP search results soon

Comparison of the ER bkg in LXe detector



XLZD -> next-gen LXe detector

XLZD Consortium

- MOU between LZ, XENON, DARWIN
- Successful XLZD meeting 27-29 June 2022 at Karlsruhe Institute of Technology
- <https://xlzd.org/>
- [White paper \(2203.02309\)](#)

Leading Xenon Researchers unite to build next-generation Dark Matter Detector

SURF is distributing this press release on behalf of the DARWIN and LZ collaborations

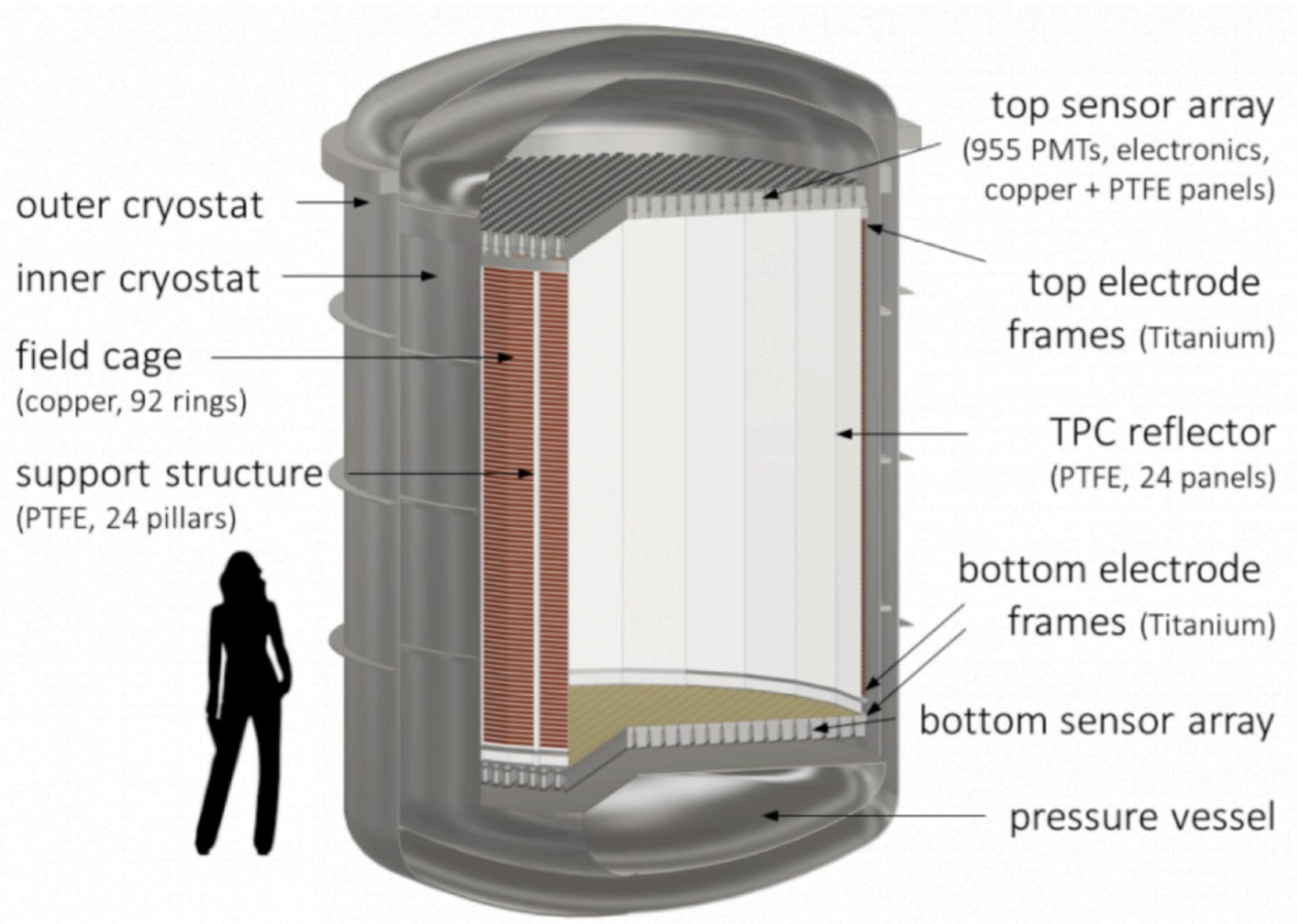
A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

J. Aalbers,^{1,2} K. Abe,^{3,4} V. Aerne,⁵ F. Agostini,⁶ S. Ahmed Maouloud,⁷ D.S. Akerib,^{1,2} D.Yu. Akimov,⁸ J. Akshat,⁹ A.K. Al Musalhi,¹⁰ F. Alder,¹¹ S.K. Alsum,¹² L. Althueser,¹³ C.S. Amarasinghe,¹⁴ F.D. Amaro,¹⁵ A. Ames,^{1,2} T.J. Anderson,^{1,2} B. Andrieu,⁷ N. Angelides,¹⁶ E. Angelino,¹⁷ J. Angevare,¹⁸ V.C. Antochi,¹⁹ D. Antón Martin,²⁰ B. Antunovic,^{21,22} E. Aprile,²³ H.M. Araújo,¹⁶ J.E. Armstrong,²⁴ F. Arneodo,²⁵ M. Arthur,¹⁴ P. Asadi,²⁶ S. Baek,²⁷ X. Bai,²⁸ D. Bajpai,²⁹ A. Baker,¹⁶ J. Balajthy,³⁰ S. Balashov,³¹ M. Balzer,³² A. Bandyopadhyay,³³ J. Bang,³⁴ E. Barberio,³⁵ J.W. Bargemann,³⁶ L. Baudis,⁵ D. Bauer,¹⁶ D. Baur,³⁷ A. Baxter,³⁸ A.L. Baxter,⁹ M. Bazyk,³⁹ K. Beattie,⁴⁰ J. Behrens,⁴¹ N.F. Bell,³⁵ L. Bellagamba,⁶ P. Beltrame,⁴² M. Benabderrahmane,²⁵ E.P. Bernard,^{43,40} G.F. Bertone,¹⁸ P. Bhattacharjee,⁴⁴ A. Bhatti,²⁴ A. Biekert,^{43,40} T.P. Biesiadzinski,^{1,2} A.R. Binon,⁹ R. Bloudi,⁴⁵ Y. Bloudi,⁵ H.J. Birch,¹⁴ F. Bishara,⁴⁶ A. Bismarck,⁵ C. Blanco,^{47,19} G.M. Blockinger,⁴⁸



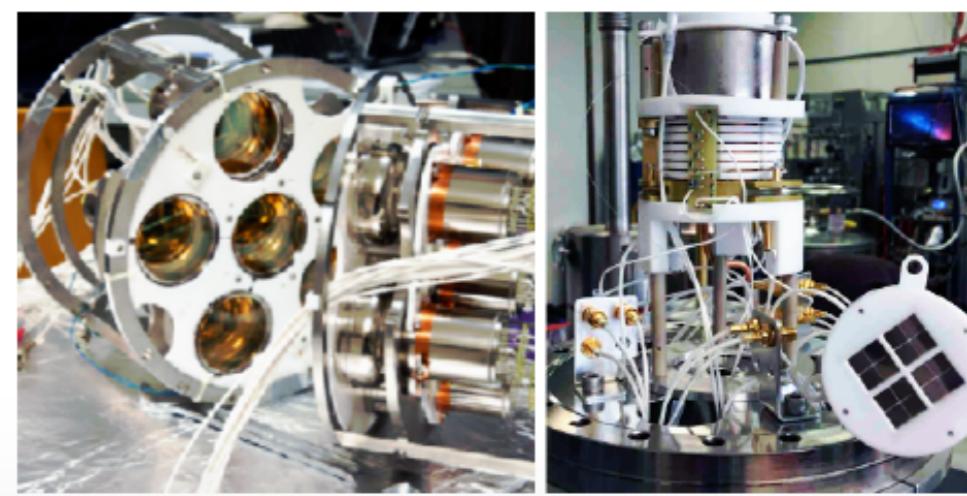
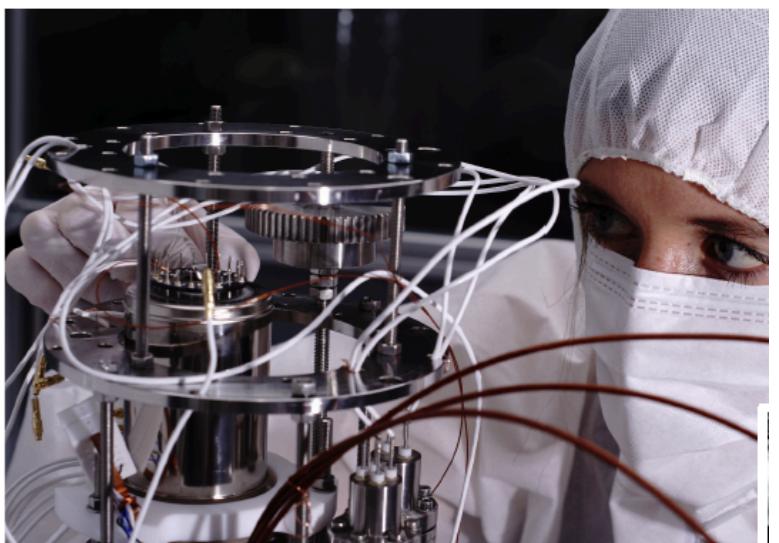
XLZD -> next-gen LXe detector (DARWIN)

Various ongoing R&D on Rn, photosensors, electrodes

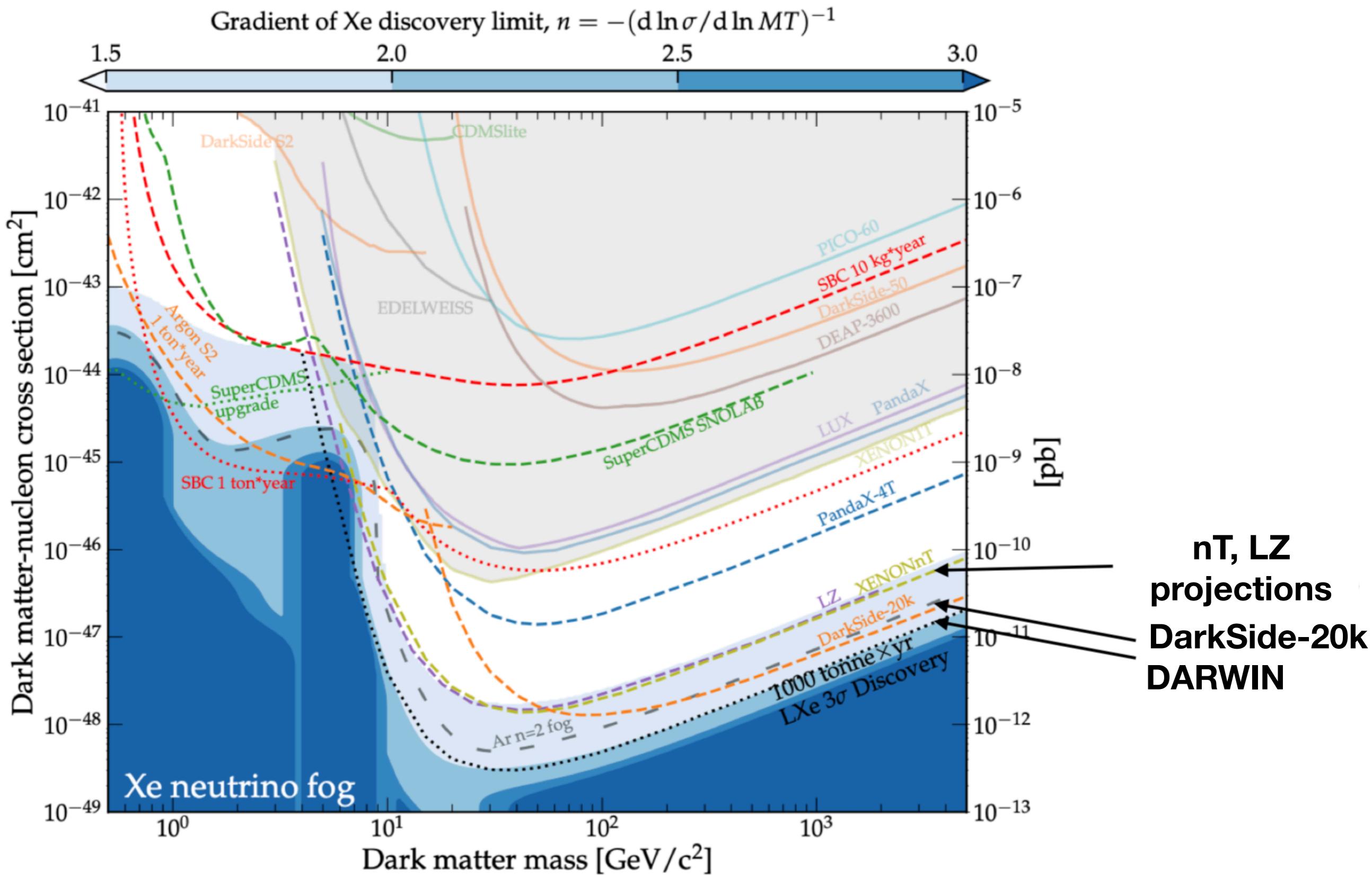


<http://darwin-observatory.org/>

- Baseline design for a large liquid xenon dark matter detector
- TPC of about 2.6 m \varnothing & 2.6 m drift length
- 50 t LXe total mass (40 t inside the TPC)



Direct Detection of WIMPs by 2030?



Thanks !

Marco Selvi
INFN Bologna



Vulcano Workshop, 26 September 2022, Isola d'Elba