Direct Detection

A short review …
… and the XENON1T excess

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Kashiwa Dark Matter Symposium
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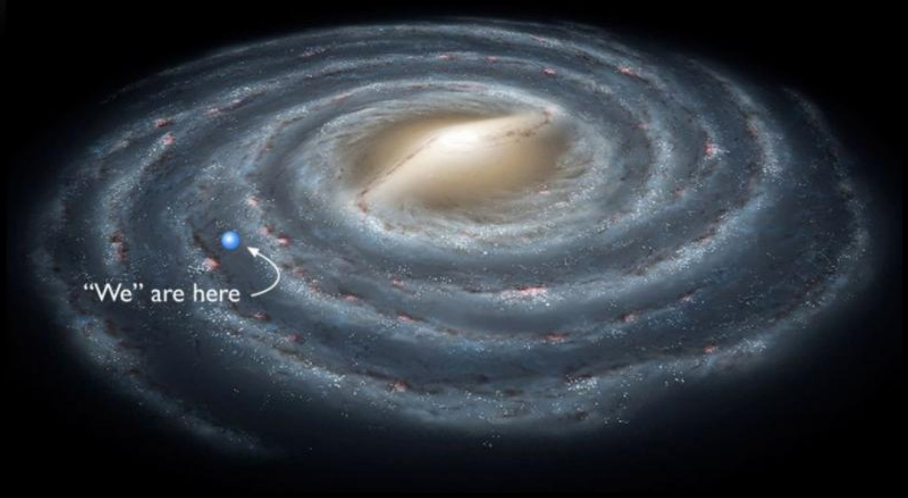
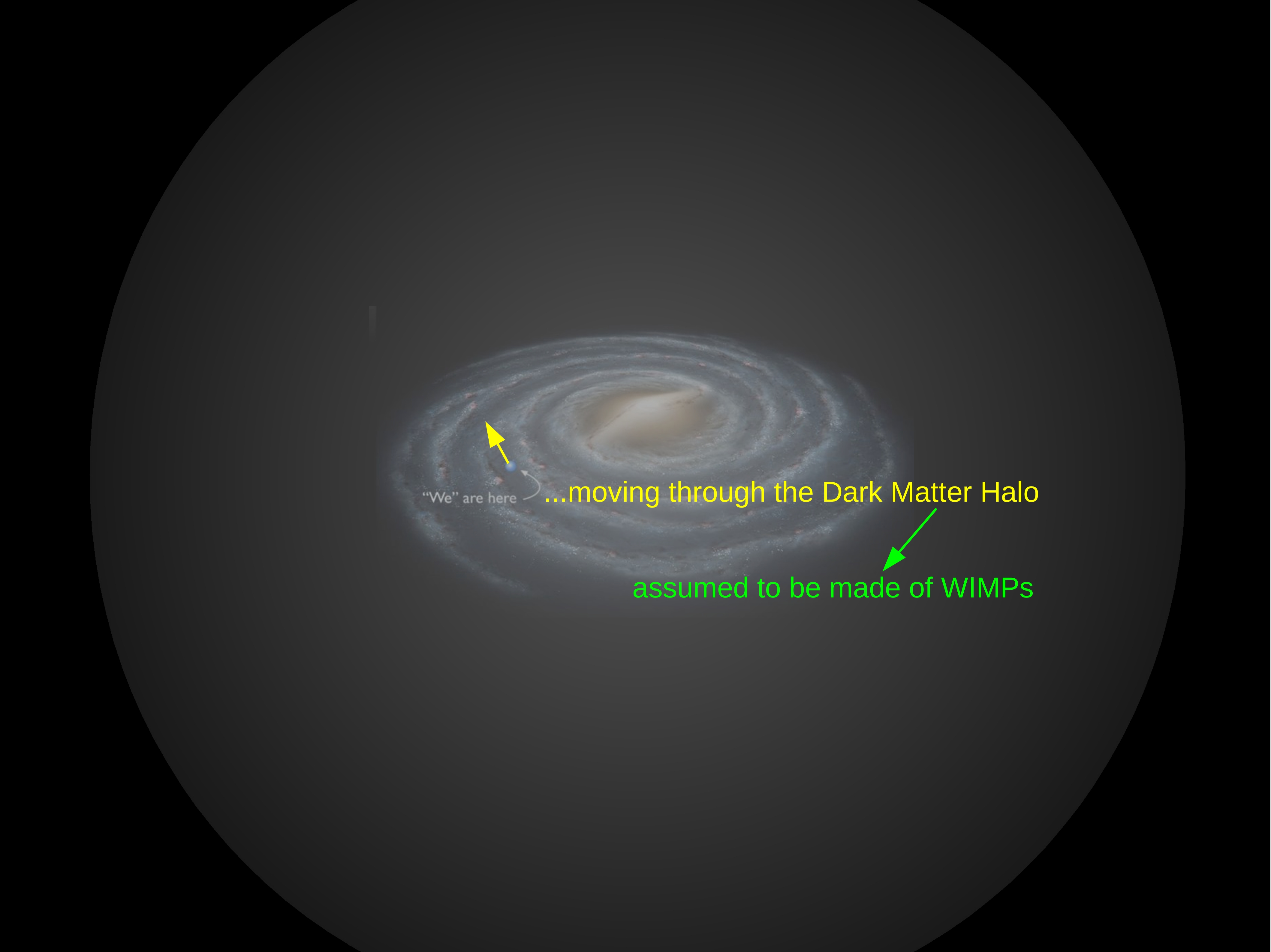
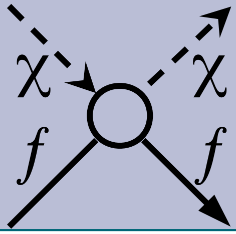

“We” are here

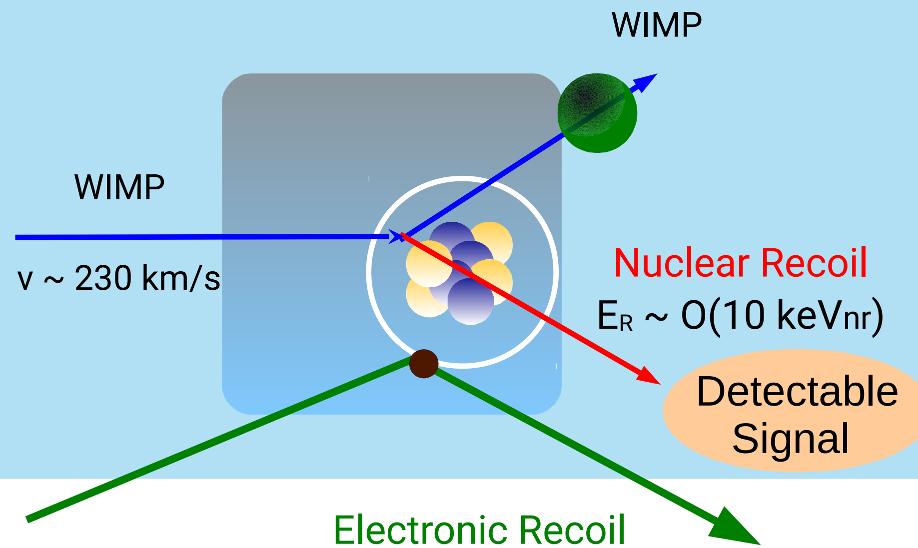


"We" are here
...moving through the Dark Matter Halo
assumed to be made of WIMPs

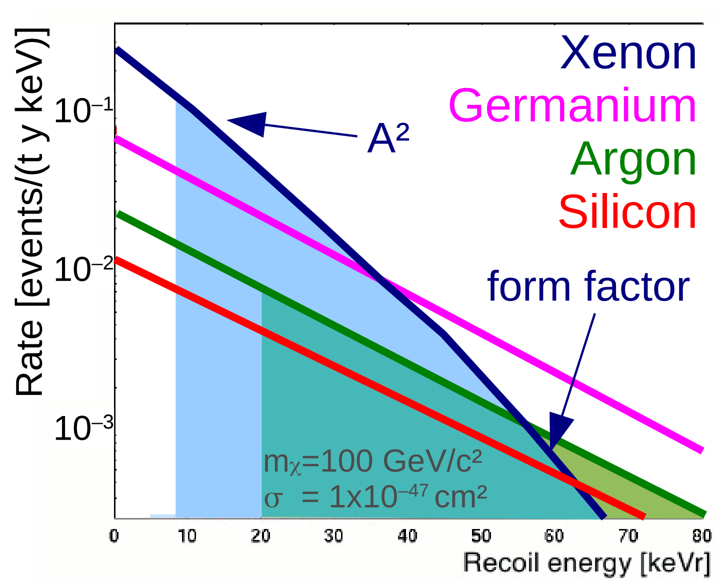


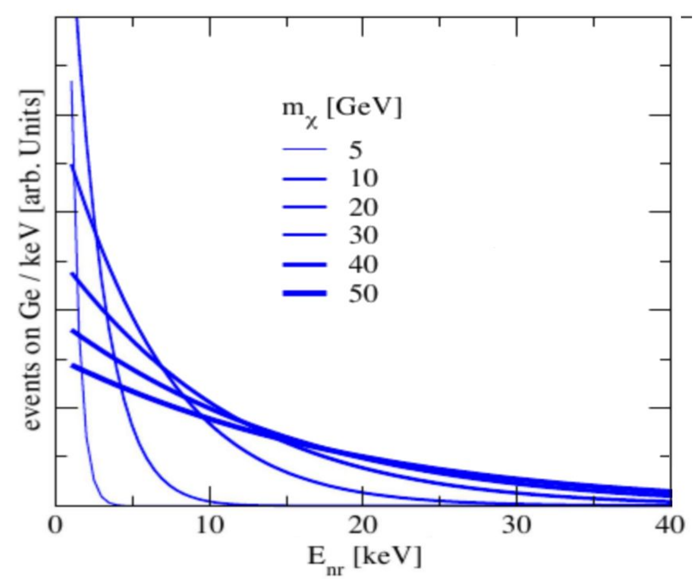
Direct WIMP Search

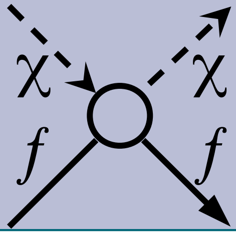
Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



Recoil Spectra:







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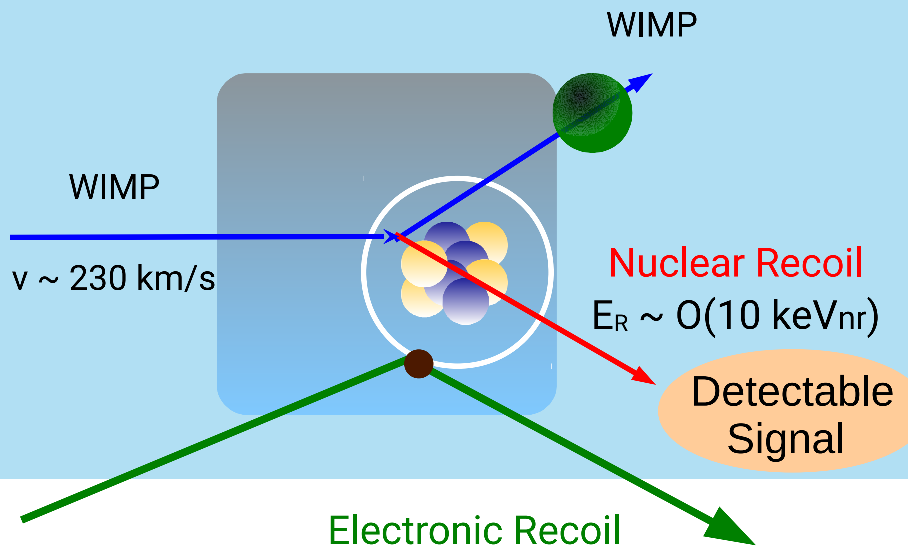
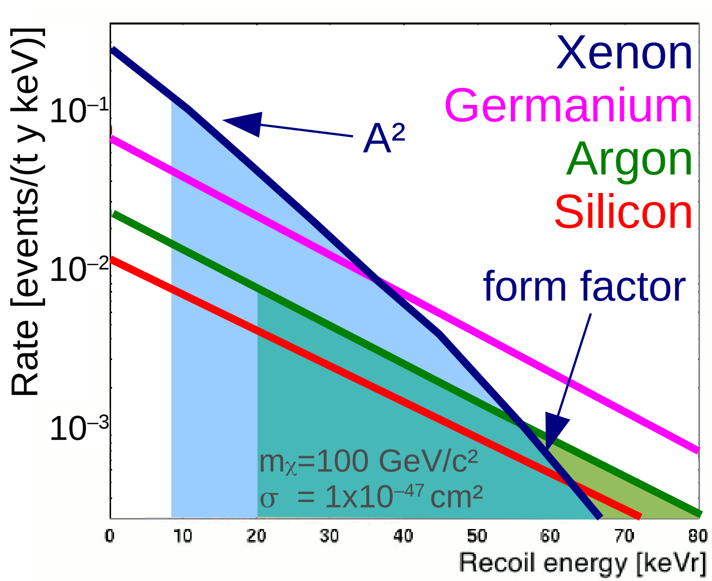
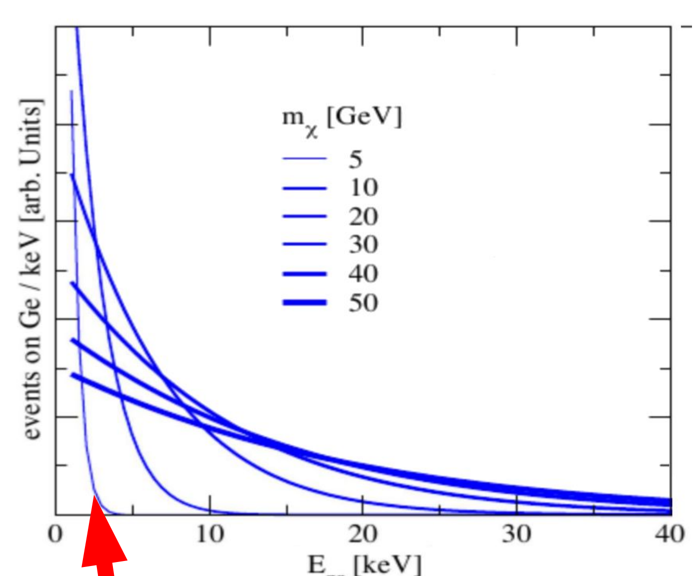


Recoil Spectra:

tiny!



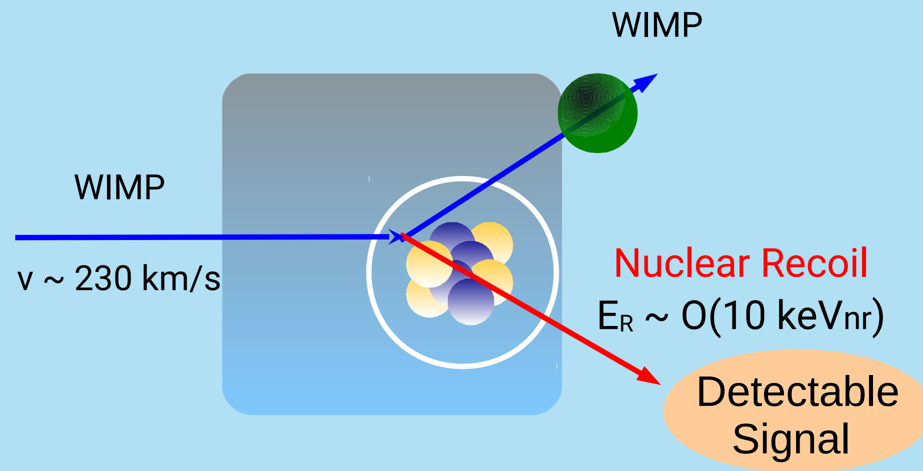


tiny!

low mass → low threshold

Direct WIMP Search

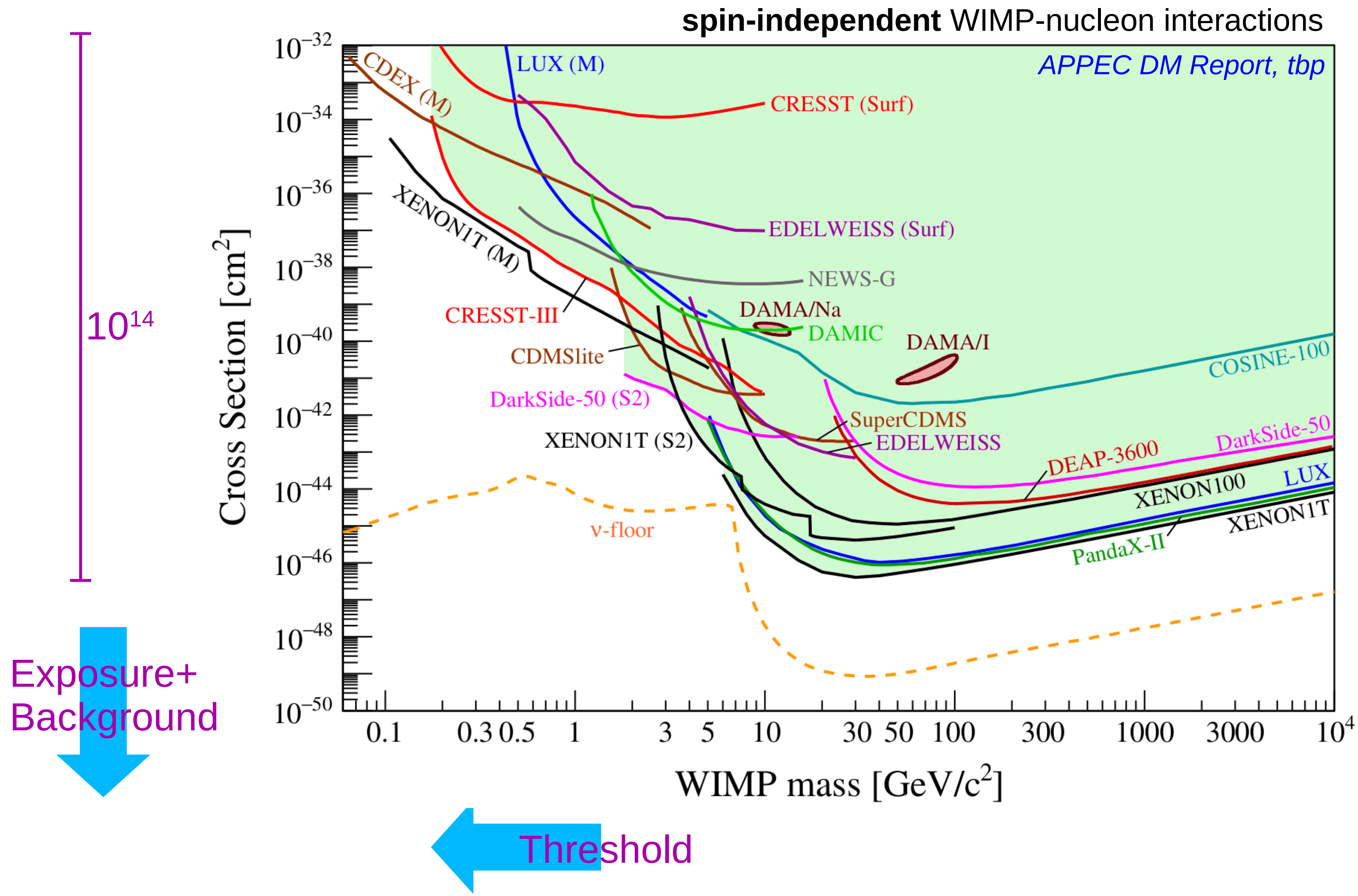
Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



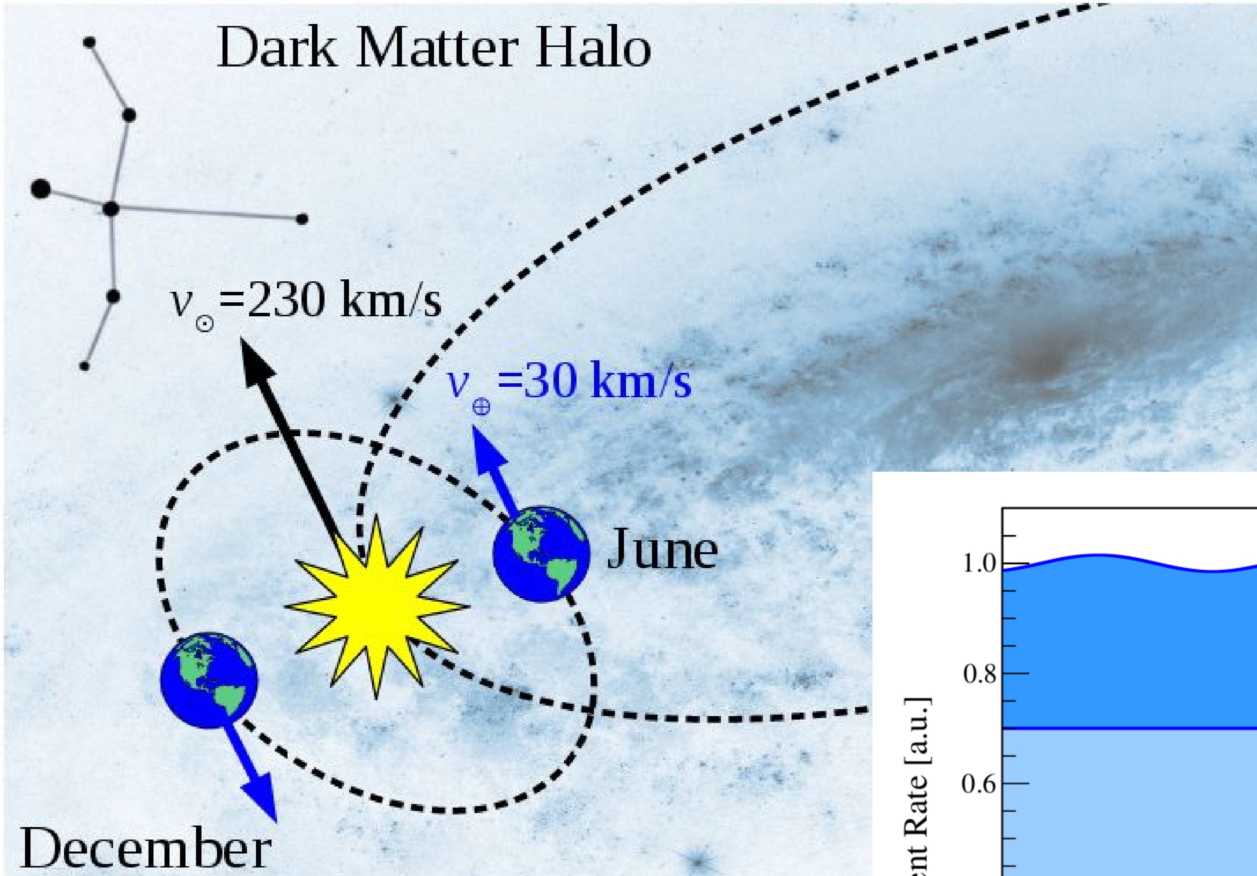
Experimental Strategy

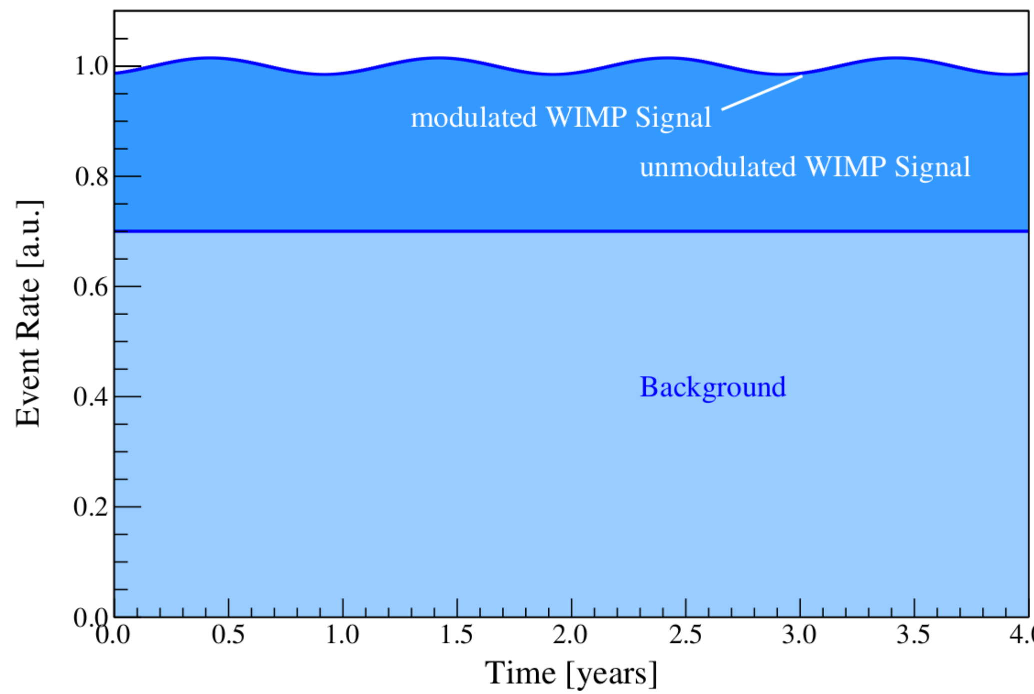
- search for low-E nuclear recoil signals
- aim for „zero“ background in search region
  → note: now we use flexible PL analyses without hard borders
- lowest possible threshold
- largest possible exposure

Current Status



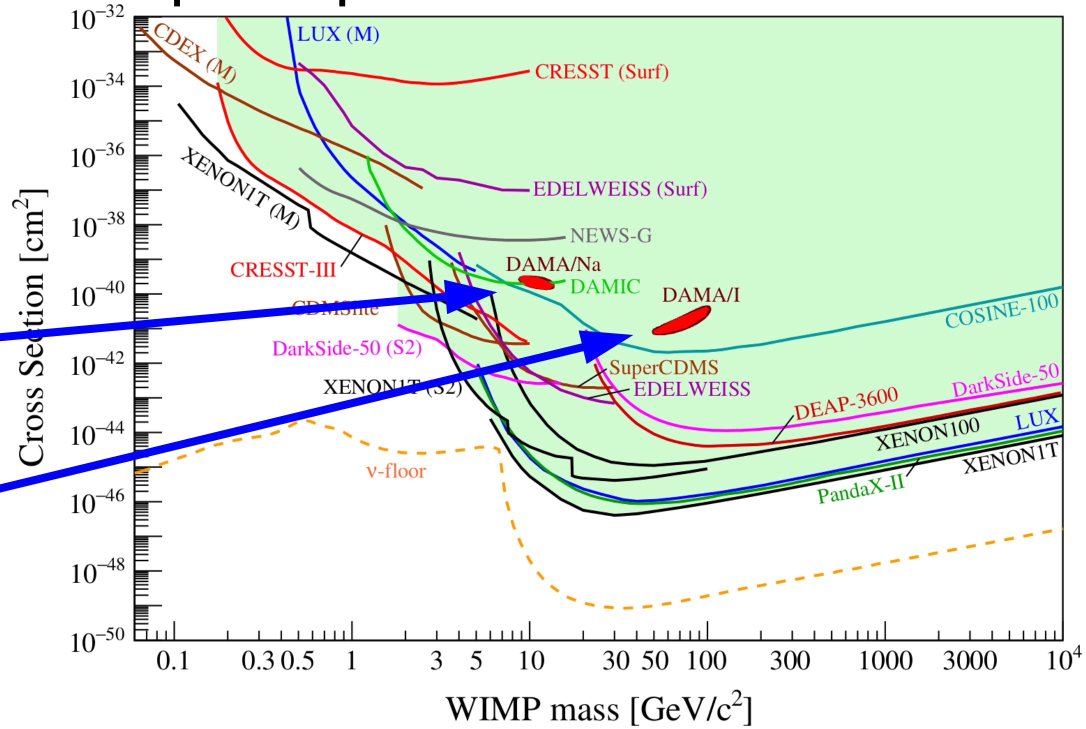
Annual Modulation



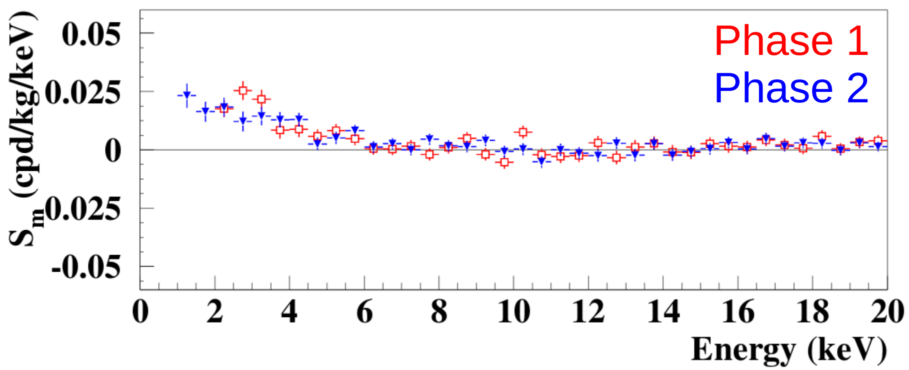


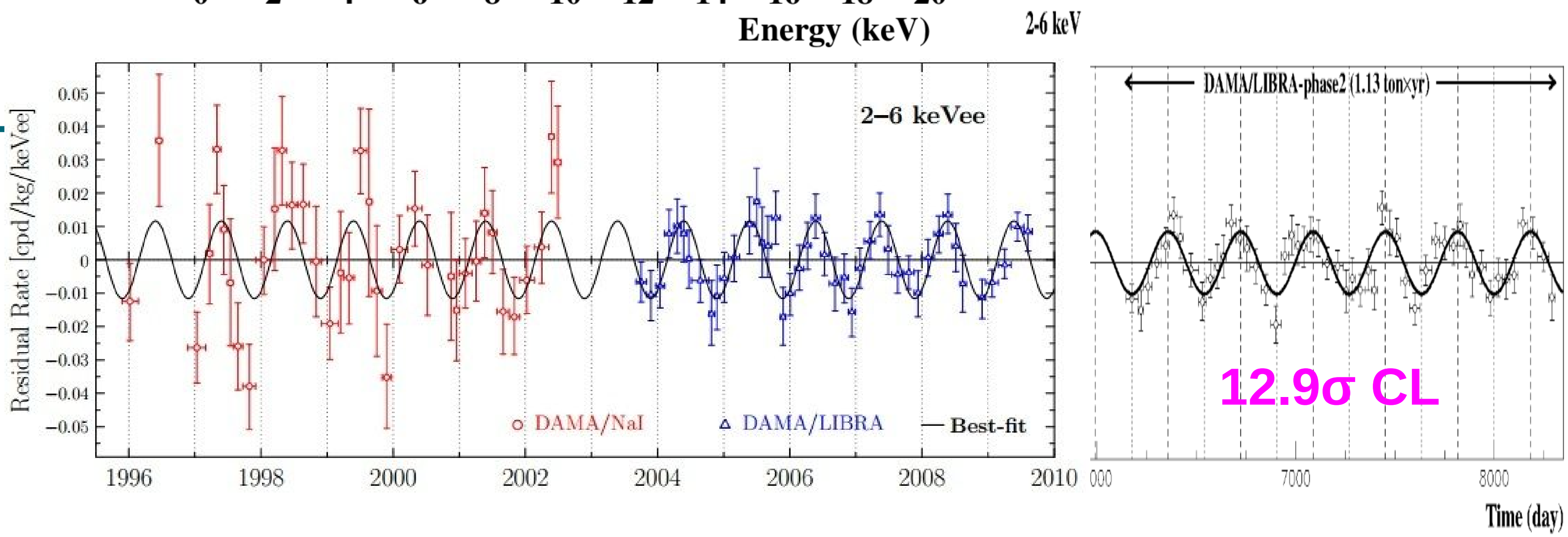
DAMA/LIBRA

spin-independent WIMP-nucleon interactions



Universe 4 (2018) 116

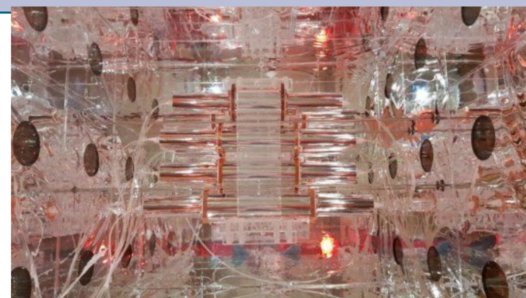




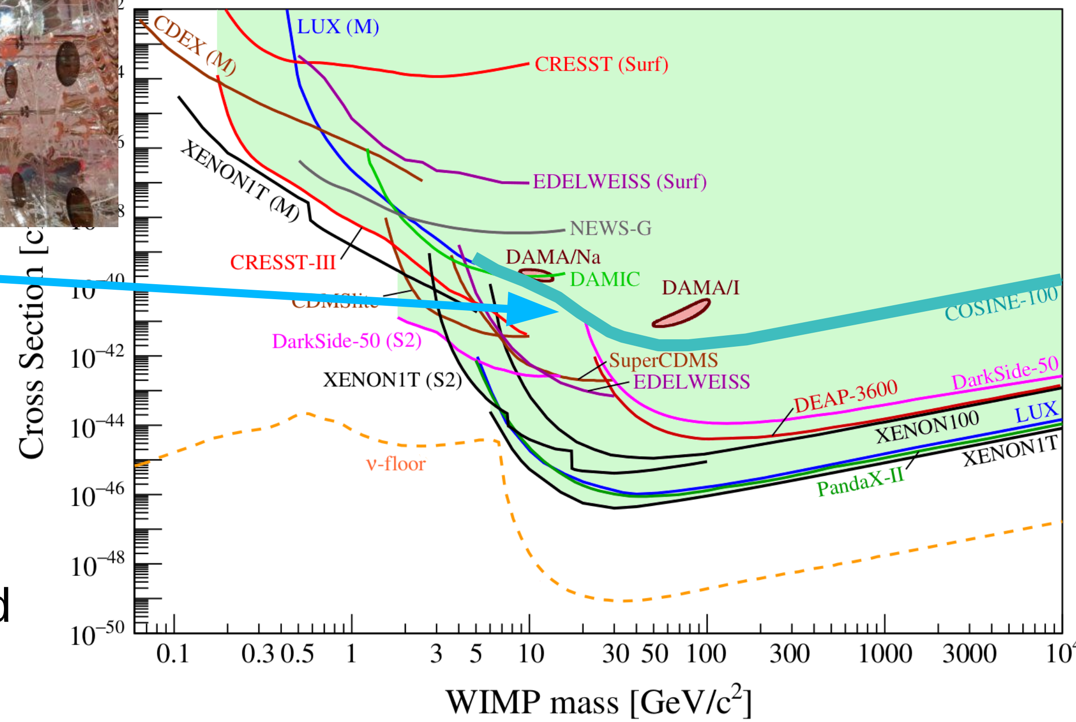
~250 kg NaI(Tl)

New data:
– 1 keVee threshold
– 6 annual cycles

DAMA: Tests and Challenges



spin-independent WIMP-nucleon interactions



NaI(Tl) Experiments

COSINE100 *Nature 564, 83 (2018), PRL 123, 031302 (2019)*

- excludes DAMA interpreted as SI interaction with standard halo model
- modulation analysis still inconclusive

ANAIS *PRL 123, 031301 (2019), J. Phys.: Conf. 1468, 012014 (2020)*

- same threshold but ~3x higher background
- data consistent with no modulation; incompatible with DAMA at 2.6σ

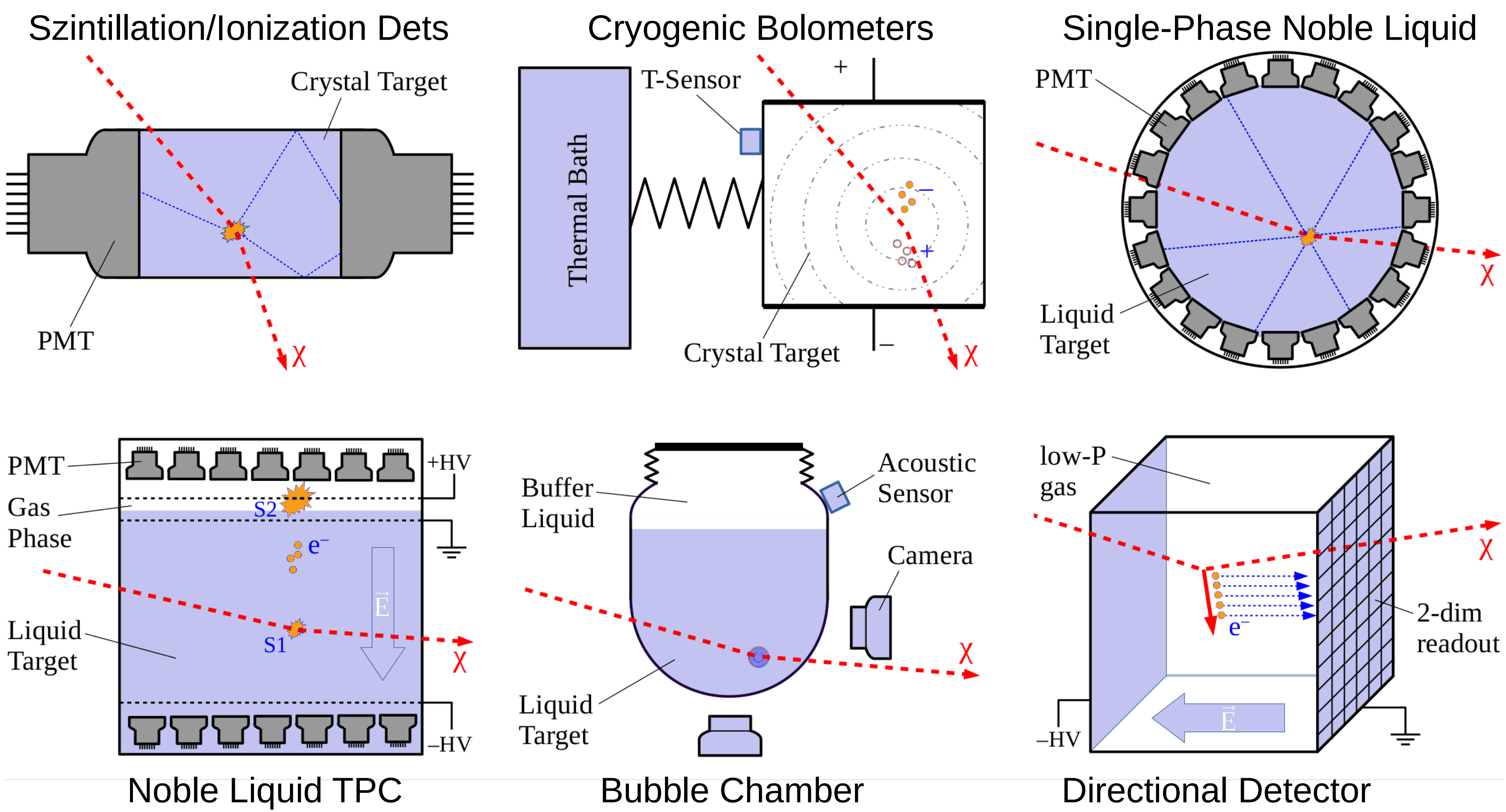
SABRE, PICOLON, COSINUS under preparation

Others

- SI-induced nuclear recoils ruled out by many experiments with much lower backgrounds (and NR identification)
- Modulation from DM-e scattering challenged by LXe TPCs XENON100, LUX

PRL 118, 101101 (2017) *PRD 98, 062005 (2018)*

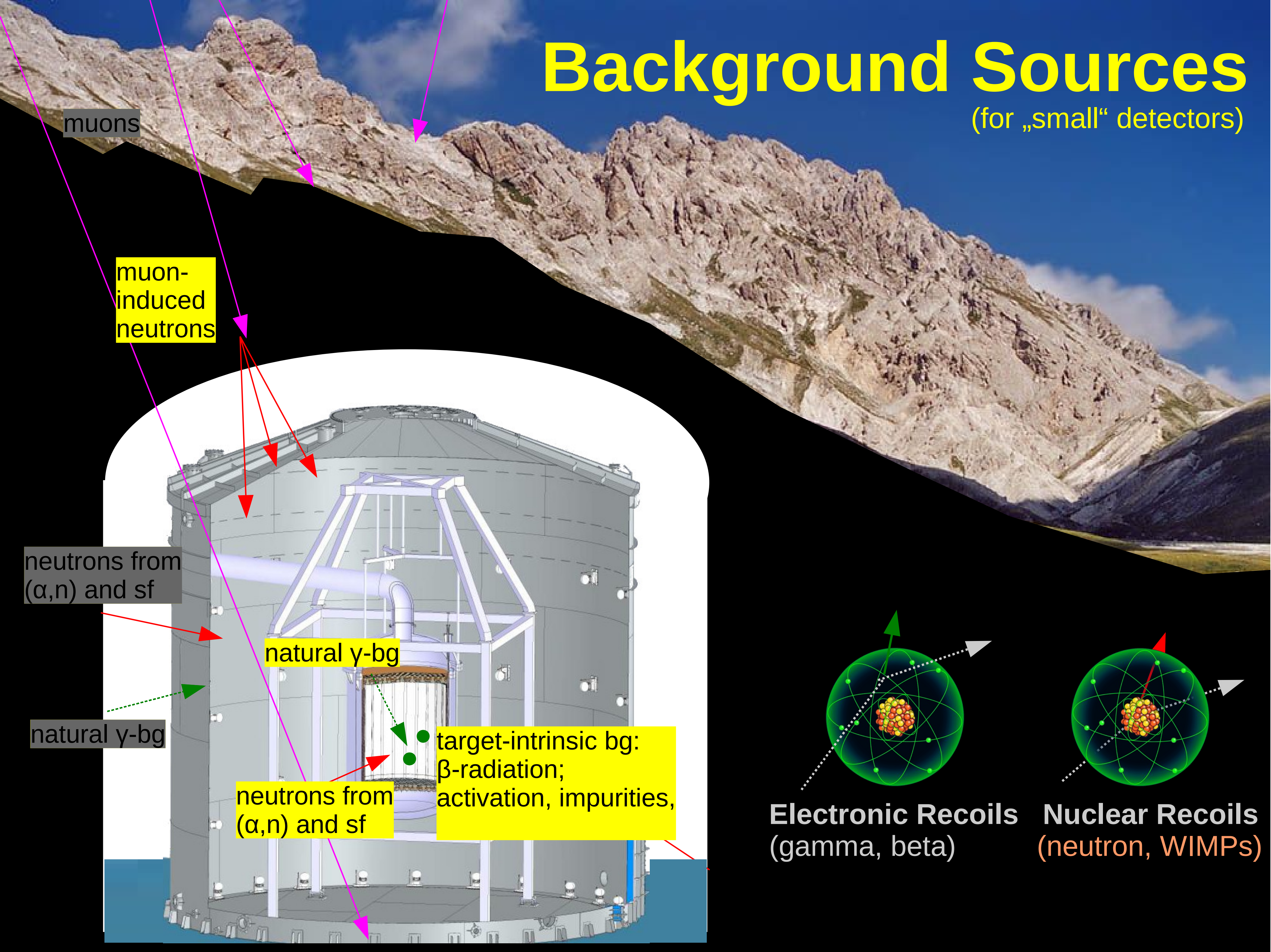
Direct Detection Technologies



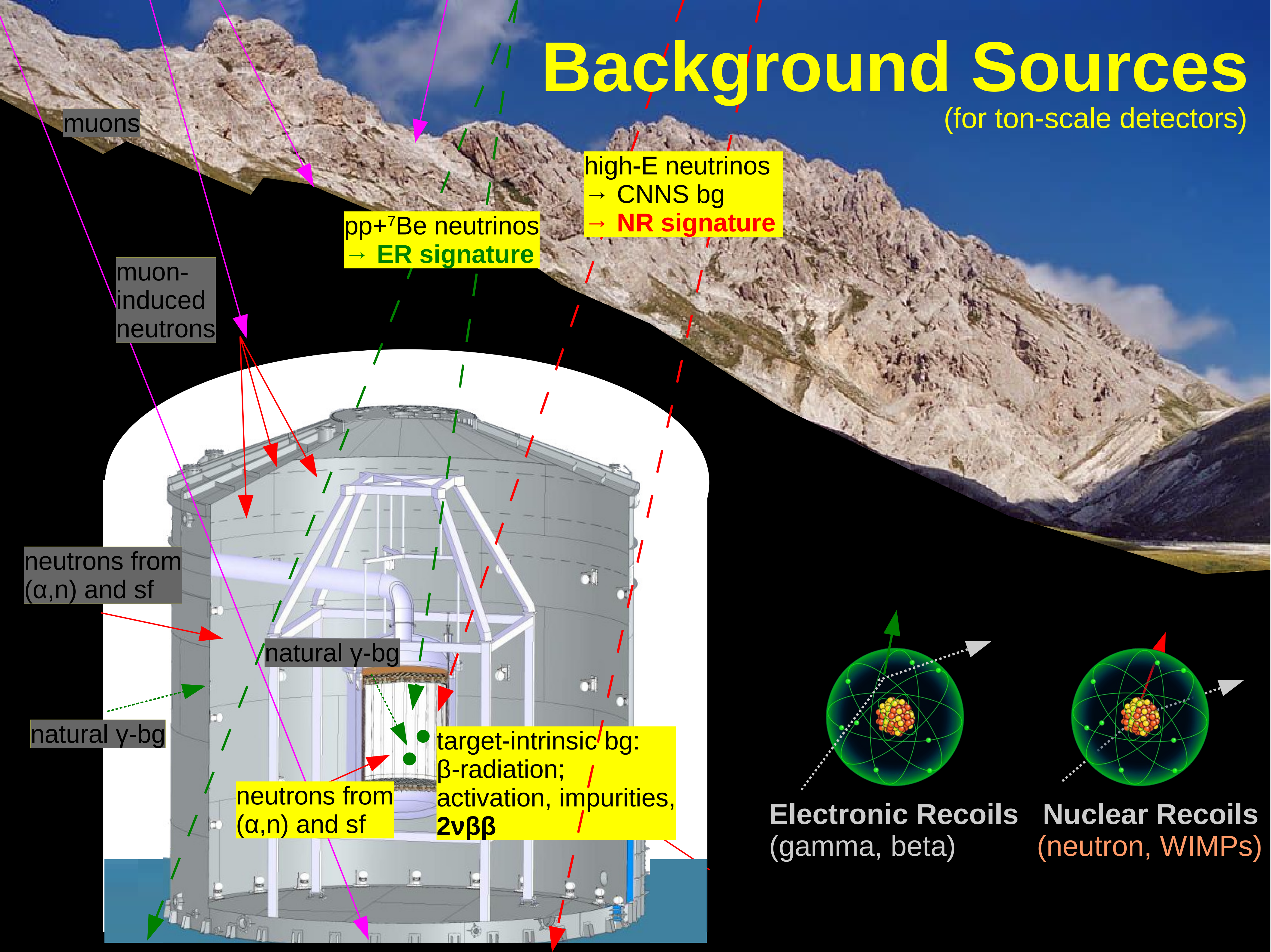
J. Phys. G 46, 103003 (2019)

Background Sources

(for „small“ detectors)



Background Sources
(for ton-scale detectors)



Active ER Background Rejection

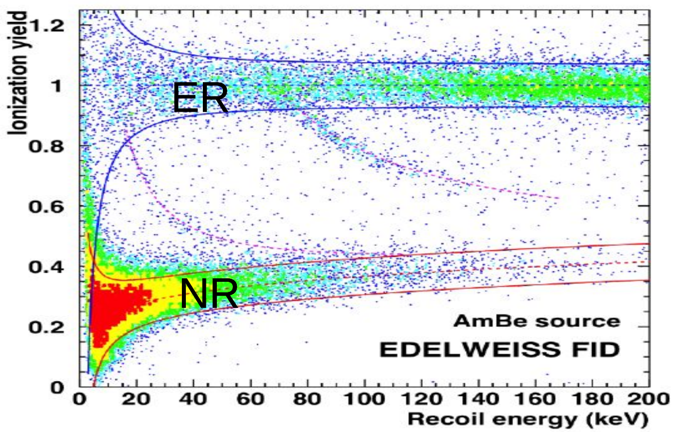
Exploit different energy-loss mechanisms (quenching effects) to distinguish ERs (background) from NRs (signal).

Ionization/scintillation yield
→ *Cryogenic Bolometers*

Charge-to-Light Ratio
→ *LXe/LAr TPCs*

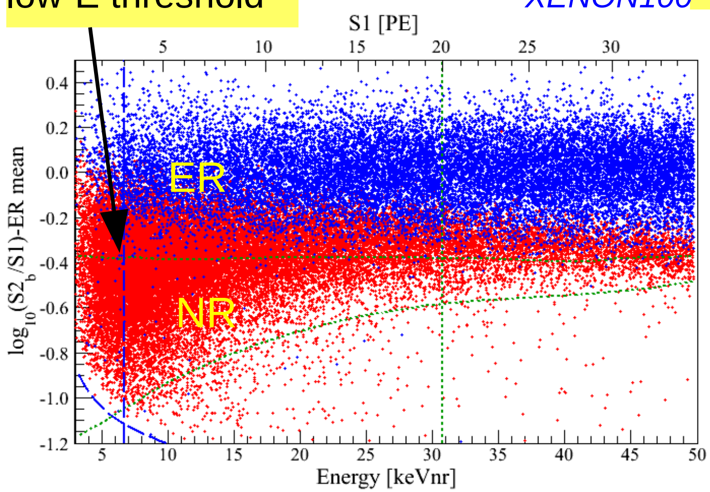
Scintillation Pulse-Shape
→ *LAr detectors*

JINST 12, P08010 (2017)



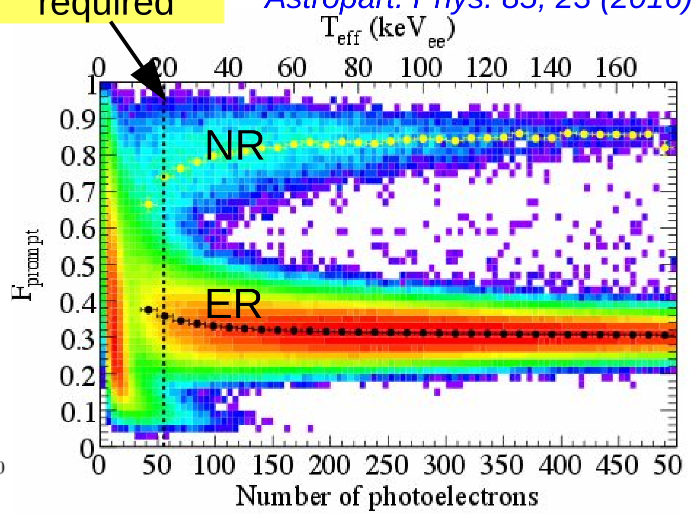
works down to low-E threshold

XENON100



high threshold required

Astropart. Phys. 85, 23 (2016)

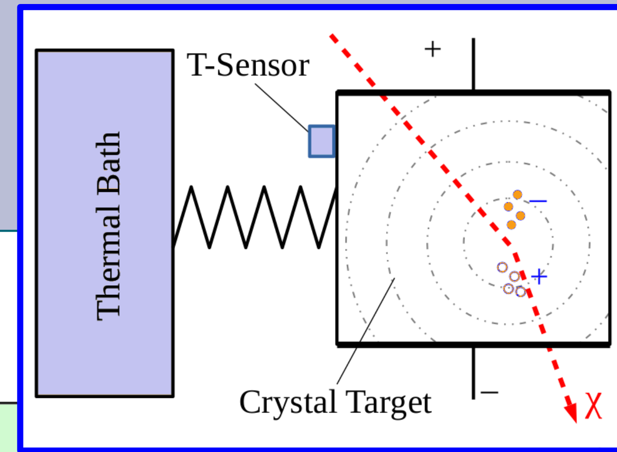


~10^{-6} @ 100% NR acc.

~10^{-3} @ 50% NR acc.

~10^{-8} @ 100% NR acc.

Cryogenic Bolometers



CRESST
Scintillating Bolometer

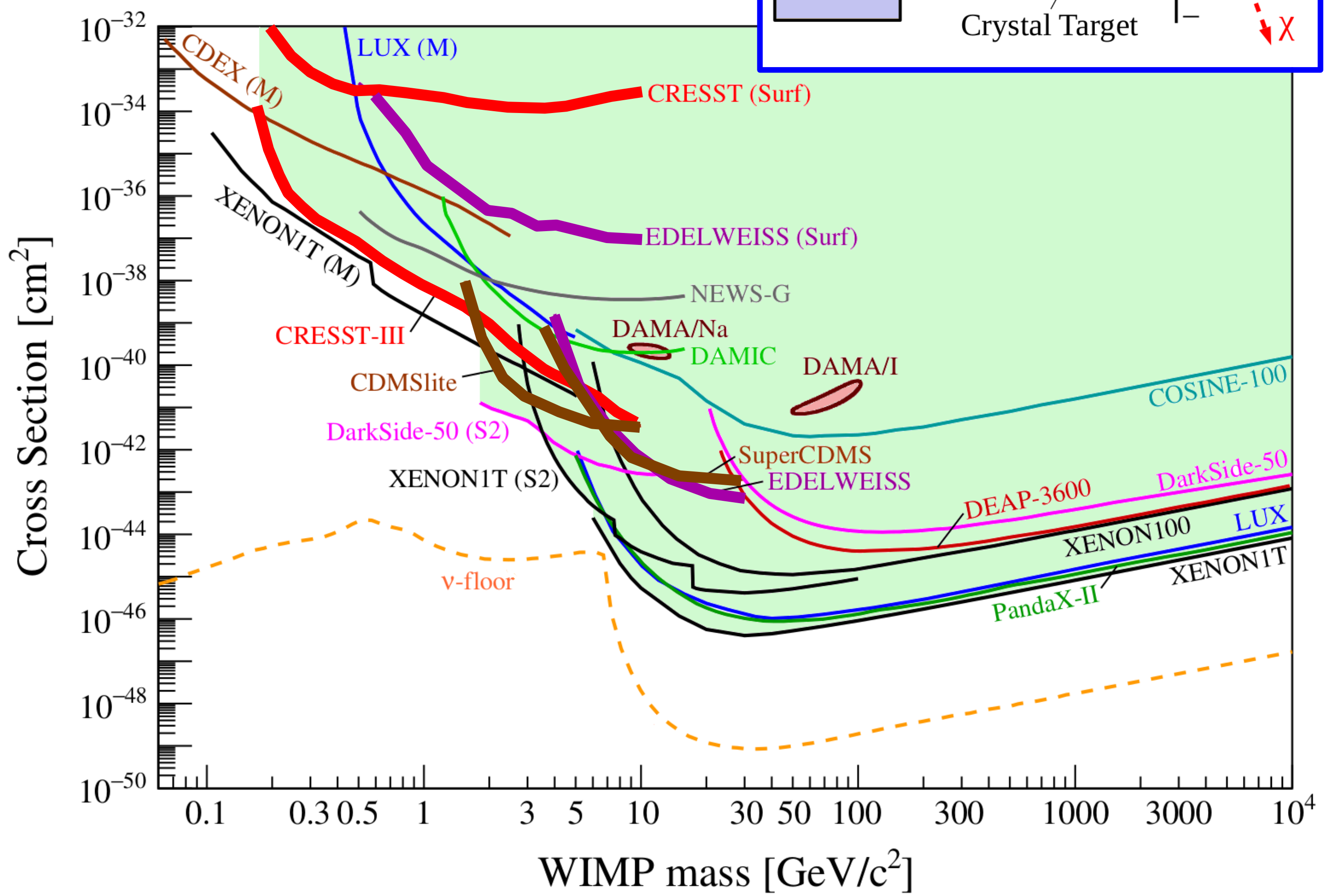
24g $CaWO_4$, E_{thresh}=30 eV
EPJ C 77 (2017)

CDMS / EDELWEISS
Ge Bolometers

„Lite"-Mode: convert charge into heat
→ reduce threshold but no ER rejection

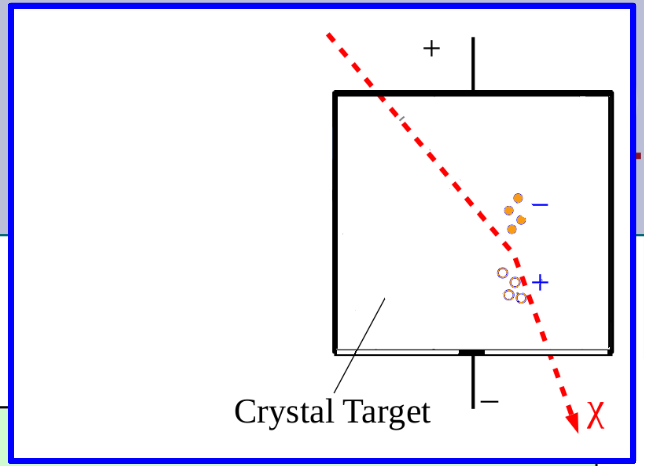
CDMSLite
600g Ge, E_{thresh}=70 eV
PRD 99, 062001 (2019)

EDELWEISS (Surf)
33g Ge, E_{thresh}=60 eV
PRD 99, 082003 (2019)



Threshold

P-type Point Contact Ge



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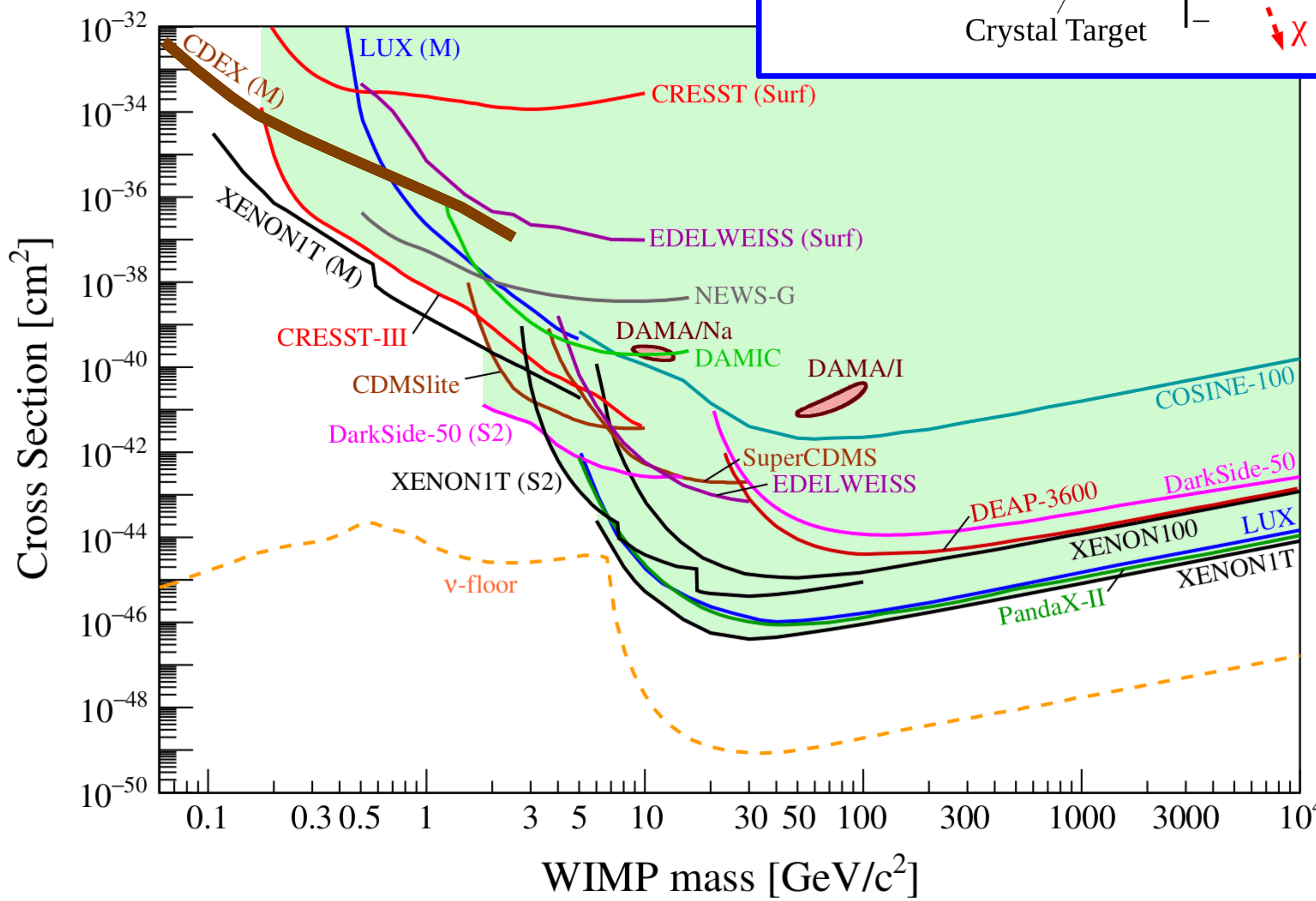
600g Ge, E_{thresh}=70 eV
PRD 99, 062001 (2019)

EDELWEISS (Surf)
33g Ge, E_{thresh}=60 eV
PRD 99, 082003 (2019)

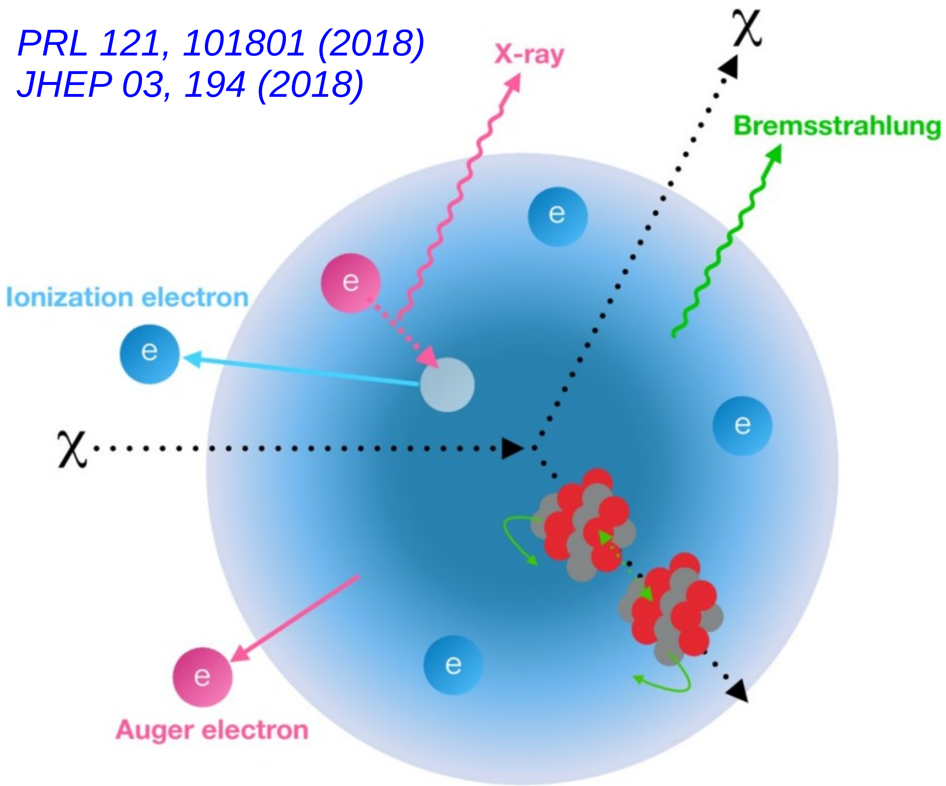
CDEX
p-type point contact Ge
939g Ge, E_{thresh}=160 eV
PRL 123, 161301 (2019)



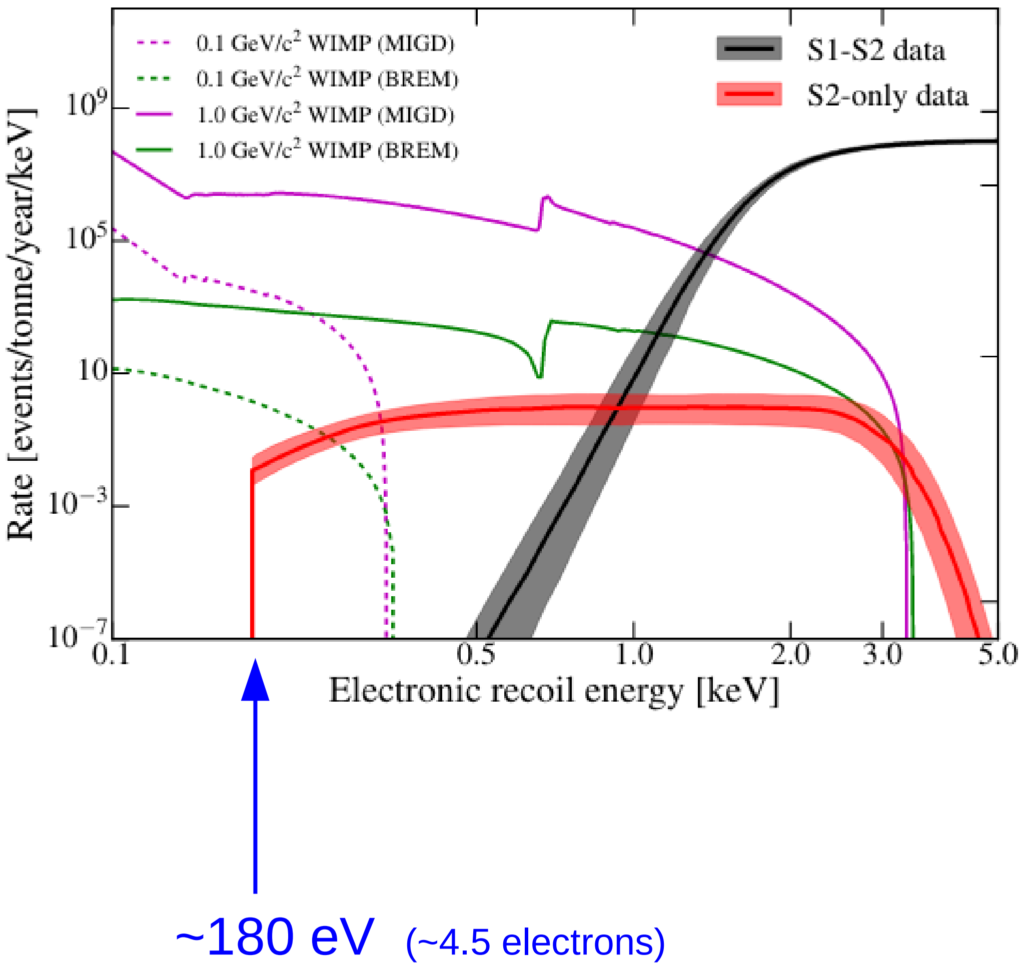
Threshold

Migdal Effect (Bremsstrahlung)

PRL 121, 101801 (2018)
JHEP 03, 194 (2018)



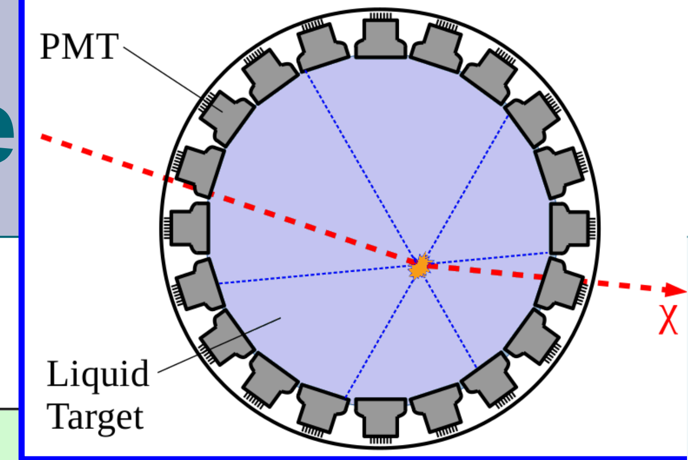
XENON1T: PRL 123, 241803 (2019)



– exploit expected effects after nuclear recoil
→ very low threshold

– caveat: effect not yet observed in calibration

Noble Liquids: Single Phase



Xenon and Argon are excellent szintillators
→ realize large target masses in liquid state

XMASS

832kg Xe

PLB 789, 45 (2019)

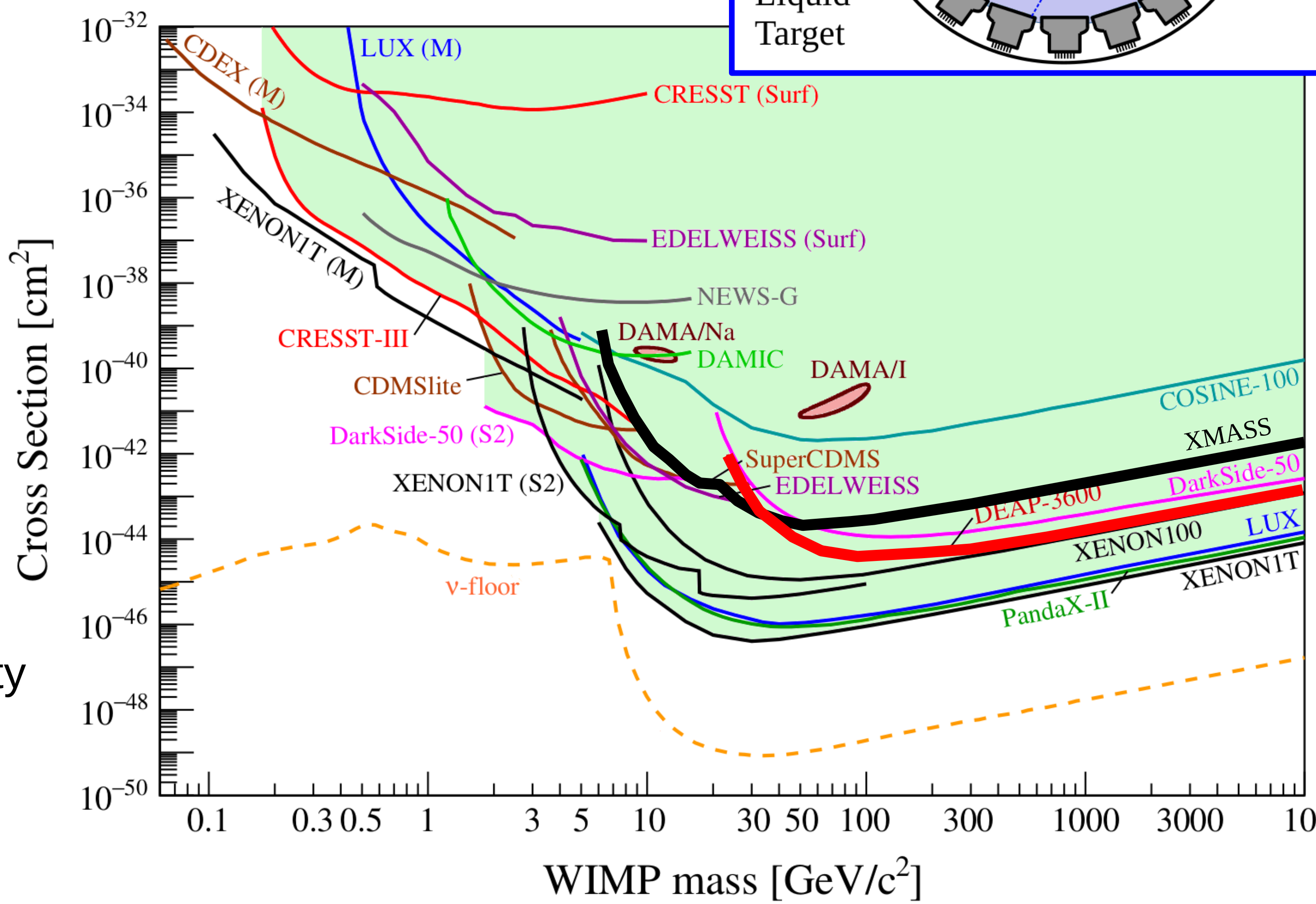
DEAP-3600

3280kg Ar

PRD 100, 022004 (2019)

→ despite large target masses, both projects have no leading sensitivity

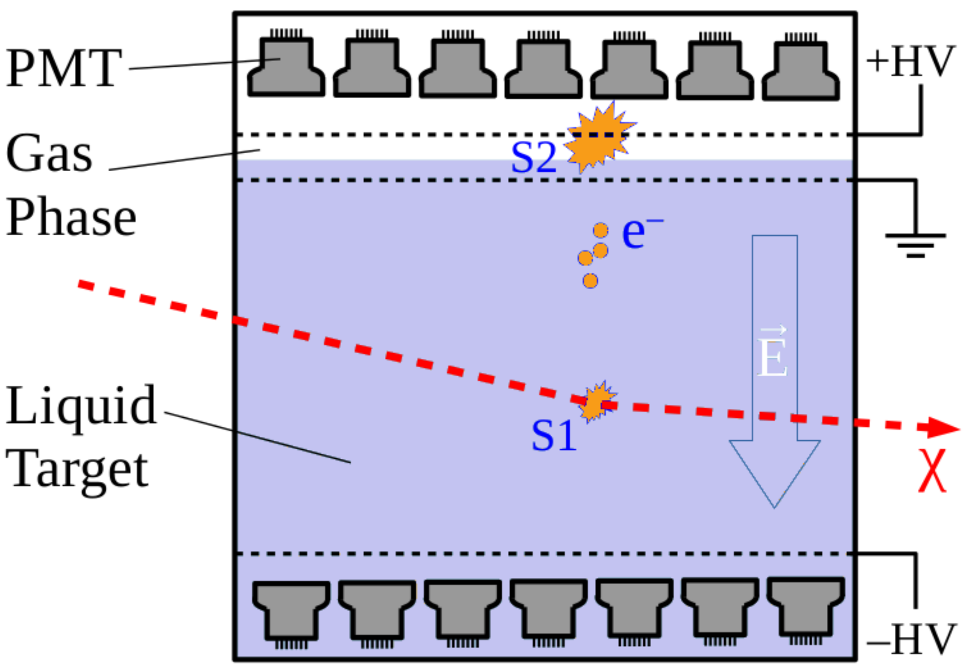
→ consolidation of field:
DEAP joined DarkSide
XMASS joined XENON



Threshold

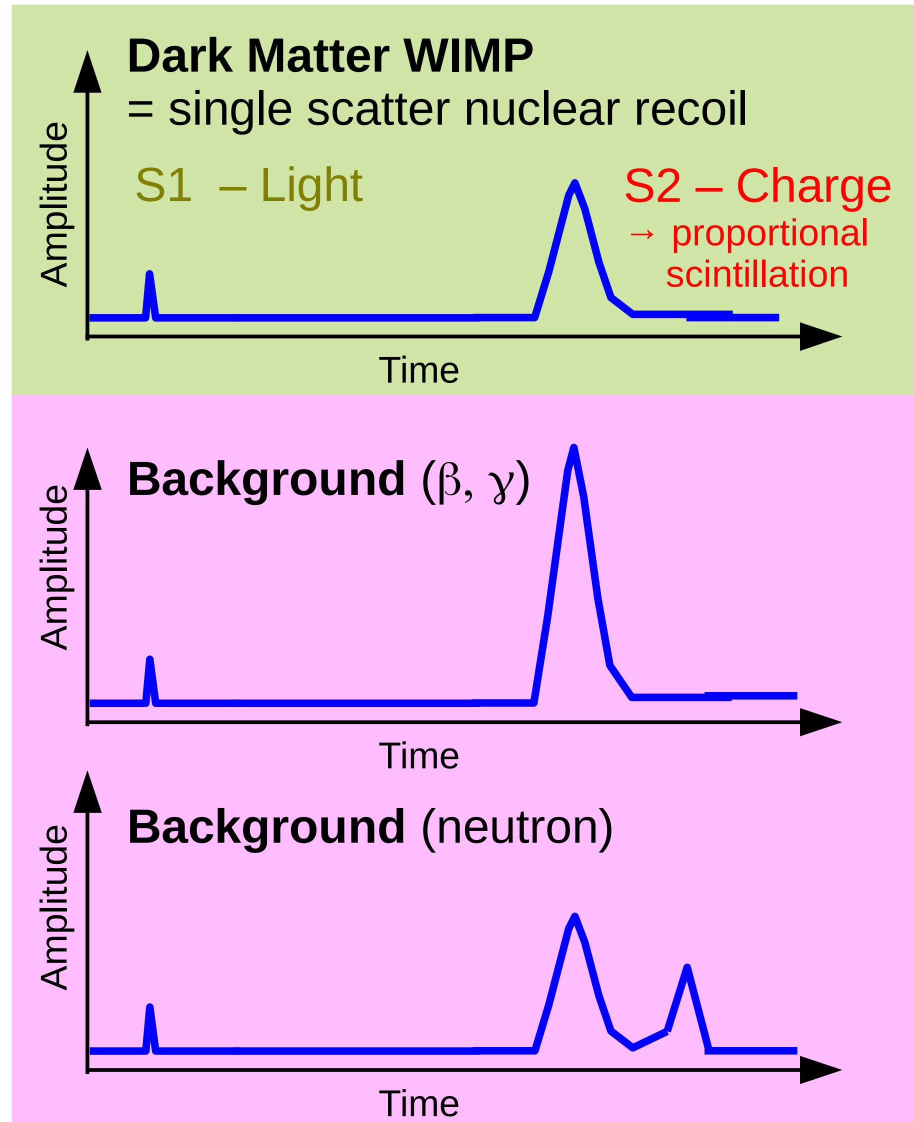
Dual-Phase TPC

Xenon and Argon are excellent **szintillators** and can be **ionized** easily



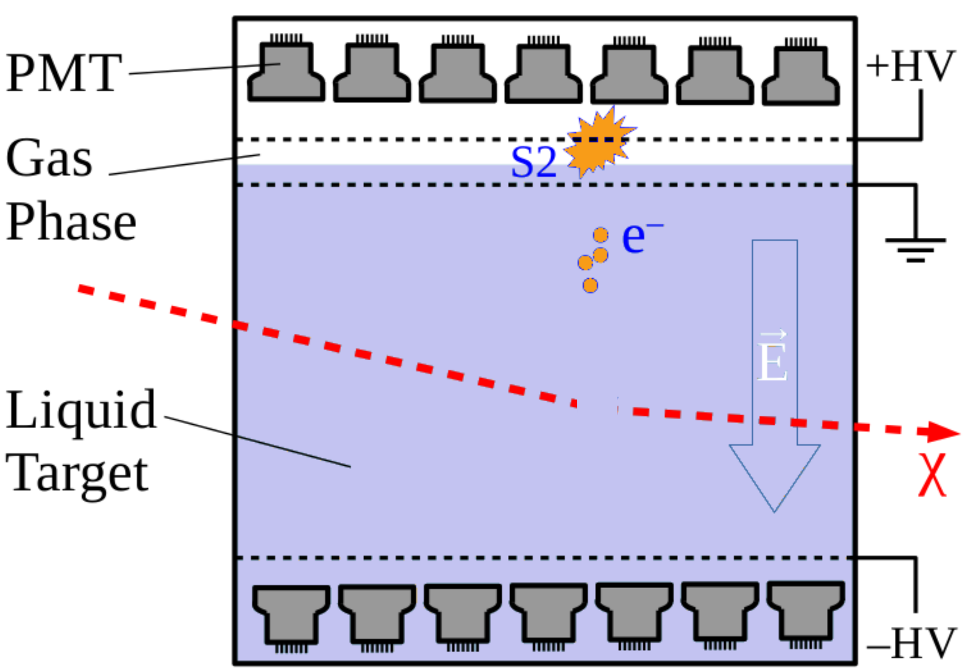
- 3d position reconstruction
  → target fiducialization
- background rejection

TPC = time projection chamber



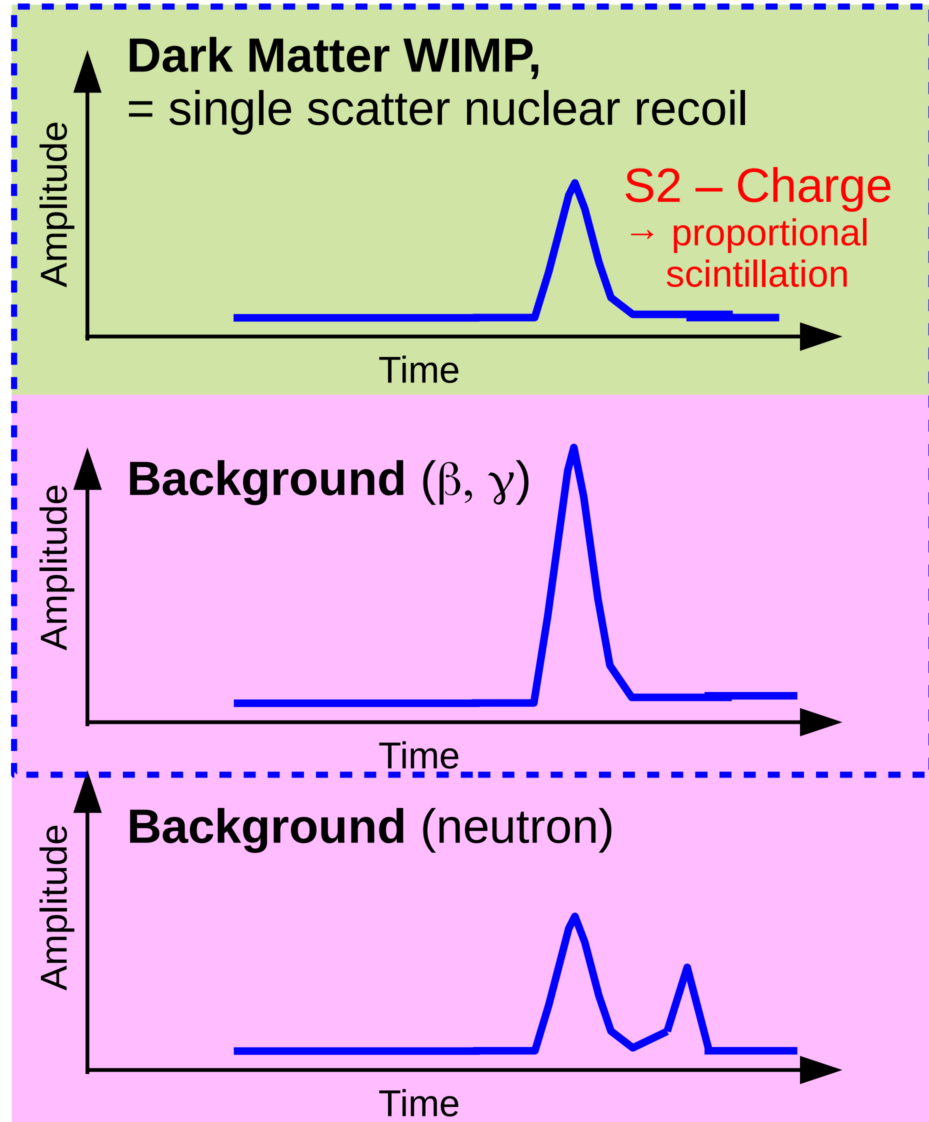
Dual-Phase TPC – Charge Only

Xenon and Argon ~~are excellent **szintillators** and~~ can be **ionized** easily

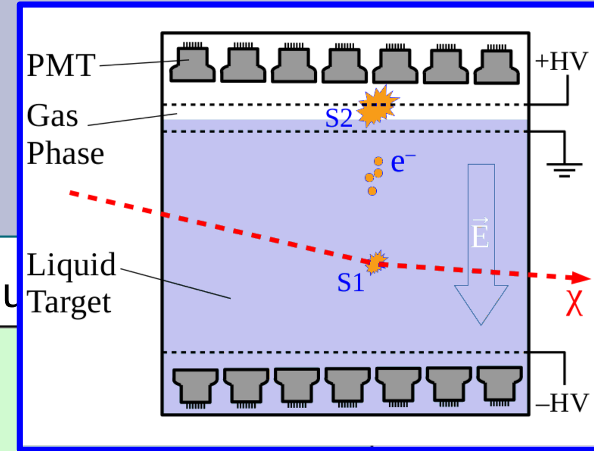


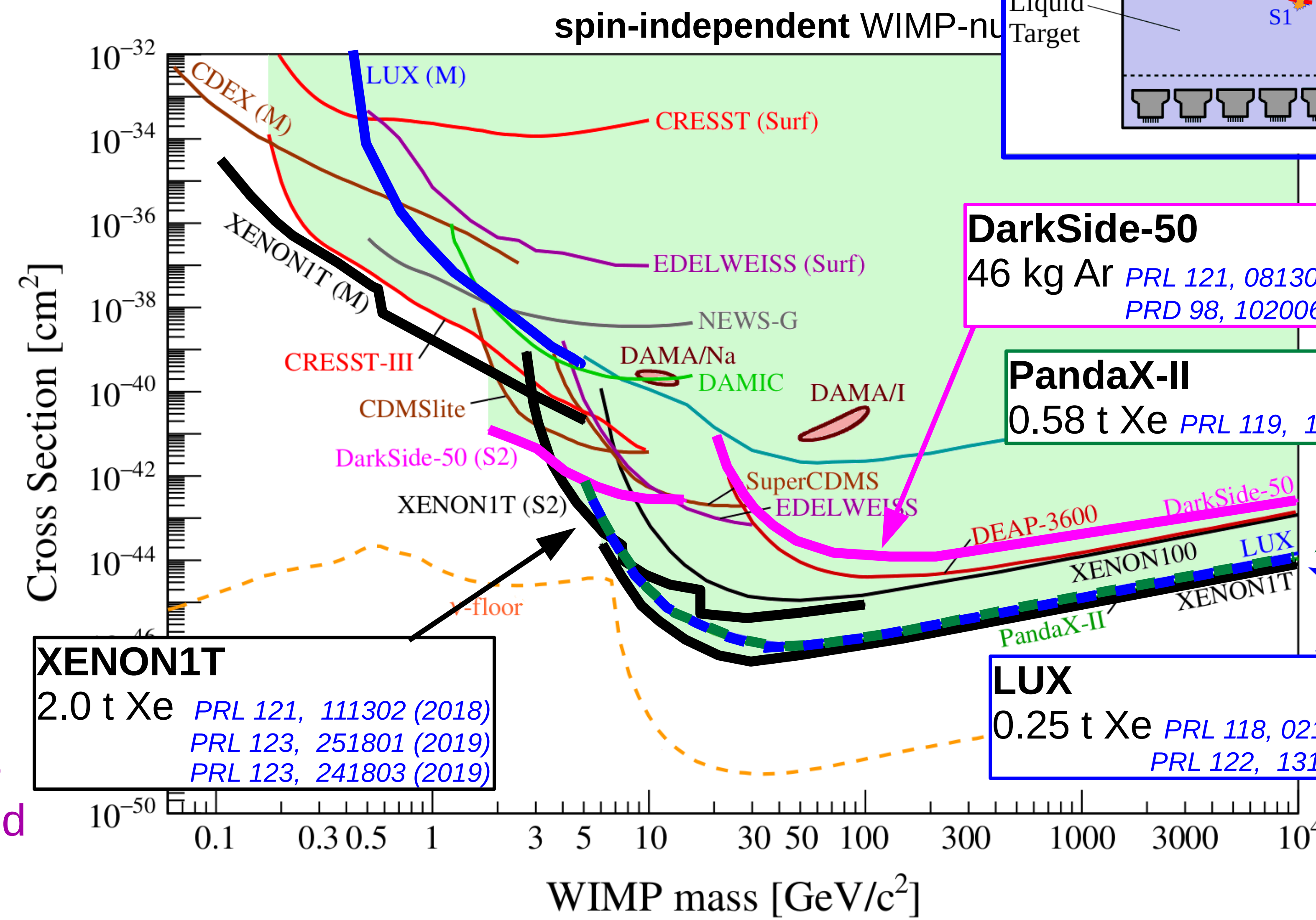
- **2d** position reconstruction
  → **limited** target fiducialization
- ~~background rejection~~
- reduced threshold

TPC = time projection chamber



Noble Liquids: Dual Phase





DarkSide-50
46 kg Ar *PRL 121, 081307 (2018)*
PRD 98, 102006 (2018)

PandaX-II
0.58 t Xe *PRL 119, 181302 (2017)*

XENON1T
2.0 t Xe *PRL 121, 111302 (2018)*
PRL 123, 251801 (2019)
PRL 123, 241803 (2019)

LUX
0.25 t Xe *PRL 118, 021303 (2017)*
PRL 122, 131301 (2019)

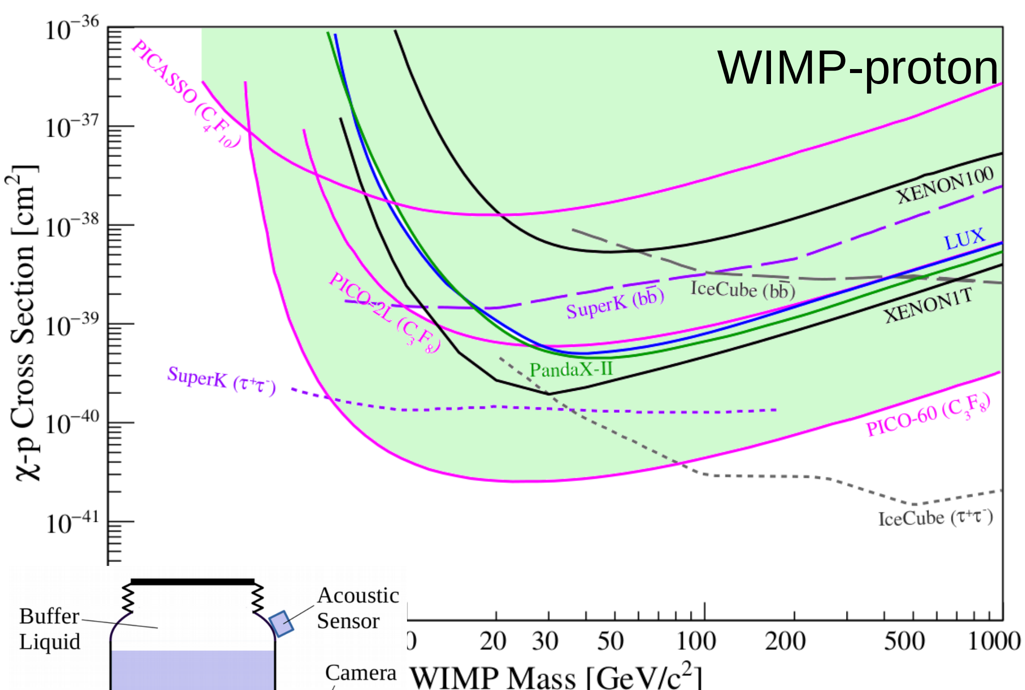
Exposure+
Background

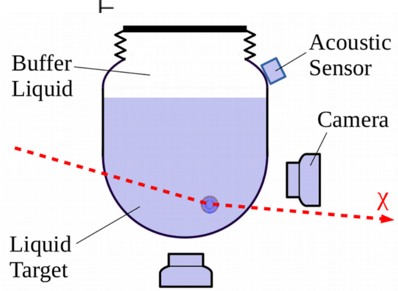
Threshold

Status Spin-Dependent Couplings

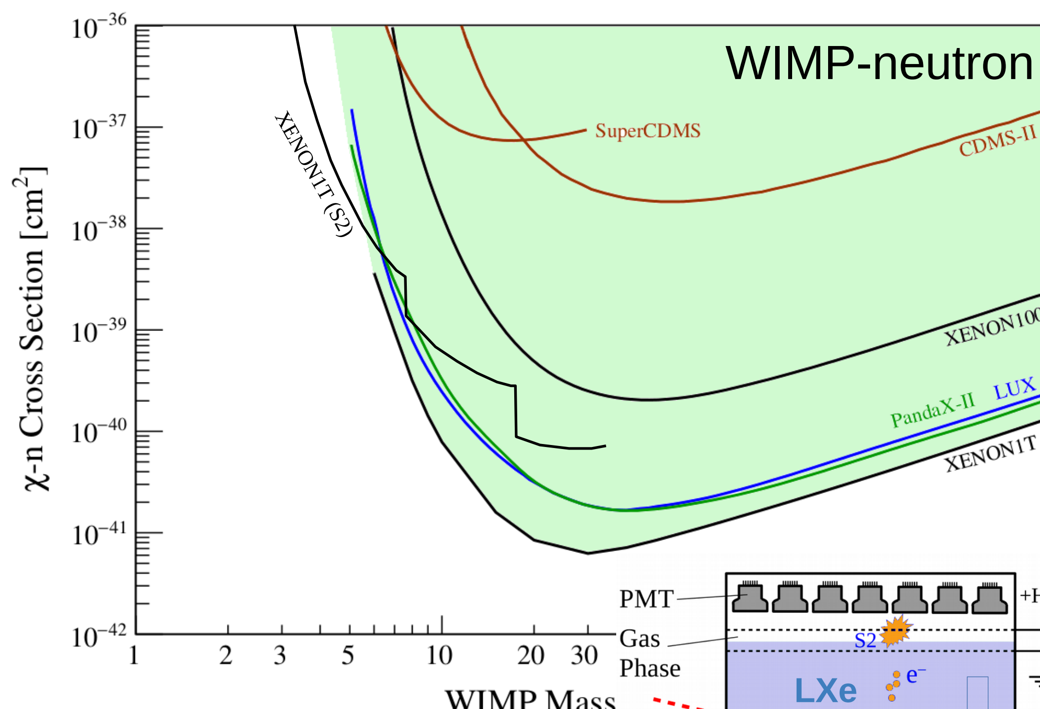
- coupling of WIMP to unpaired nucleon spins
- traditionally separated in proton-only and neutron-only
- same parameter space explored by indirect and collider searches

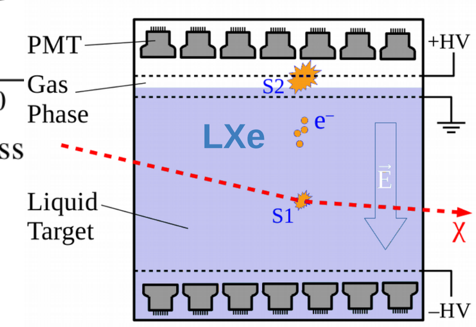
Isotope	Abundance	Spin	Unpaired Nucleon	Relative Strength
^{7}Li	92.6%	3/2	proton	12.8
^{19}F	100.0%	1/2	proton	100.0
^{23}Na	100.0%	3/2	proton	1.3
^{29}Si	4.7%	1/2	neutron	9.7
^{73}Ge	7.7%	9/2	neutron	0.3
^{127}I	100.0%	5/2	proton	0.3
^{131}Xe	21.3%	3/2	neutron	1.7





Best: Bubble Chambers

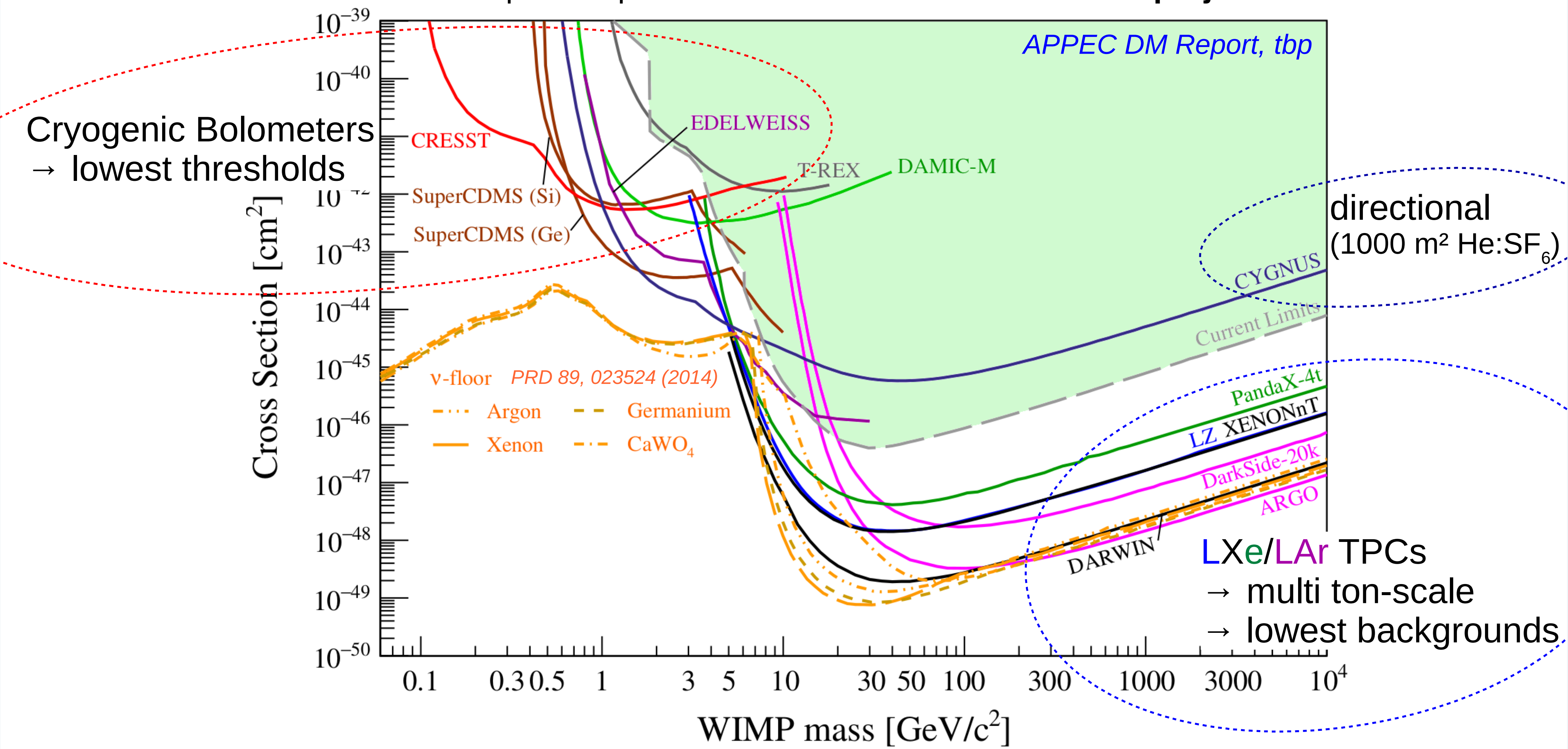




Best: LXe TPCs

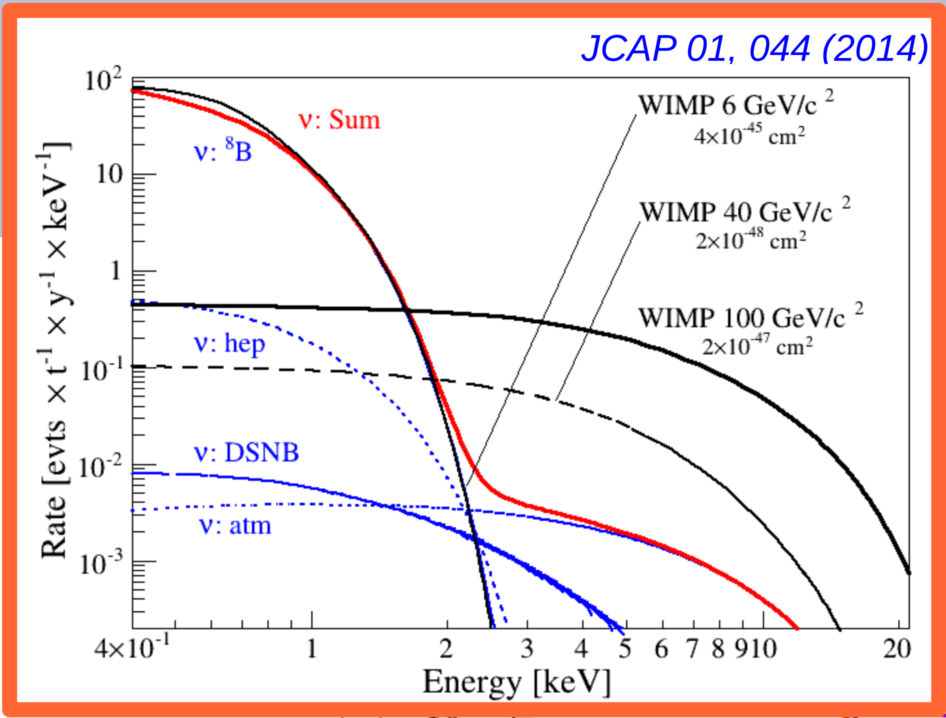
Upcoming Projects

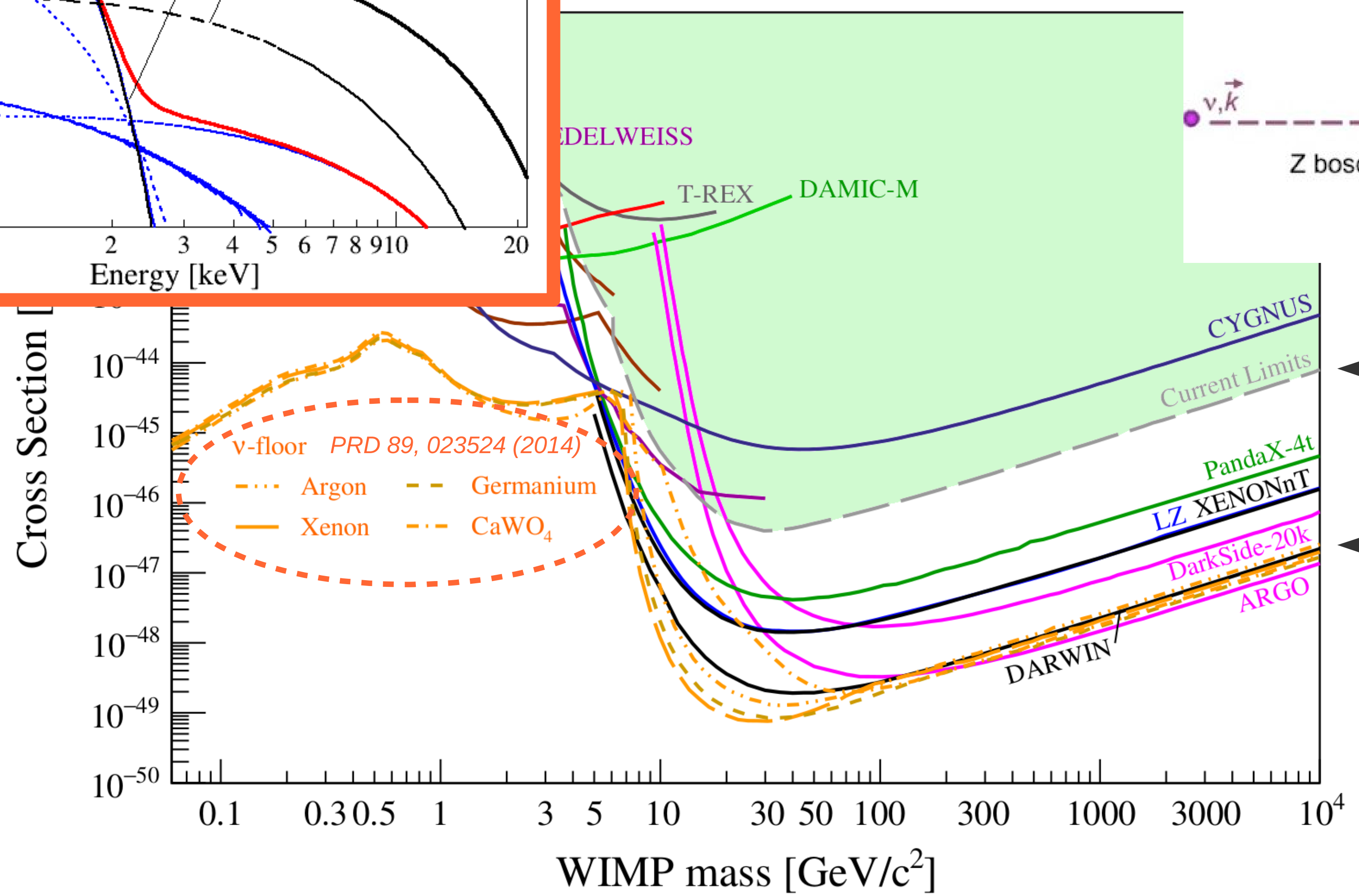
spin-independent WIMP-nucleon interactions – **projections**

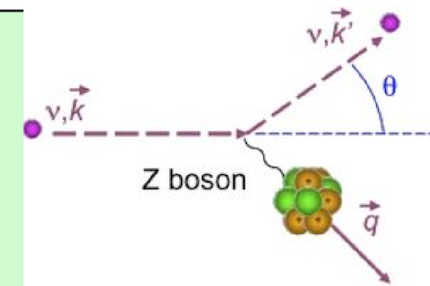


The Limit

Coherent neutrino-nucleus scattering will dominate
→ **ultimate background** for direct detection





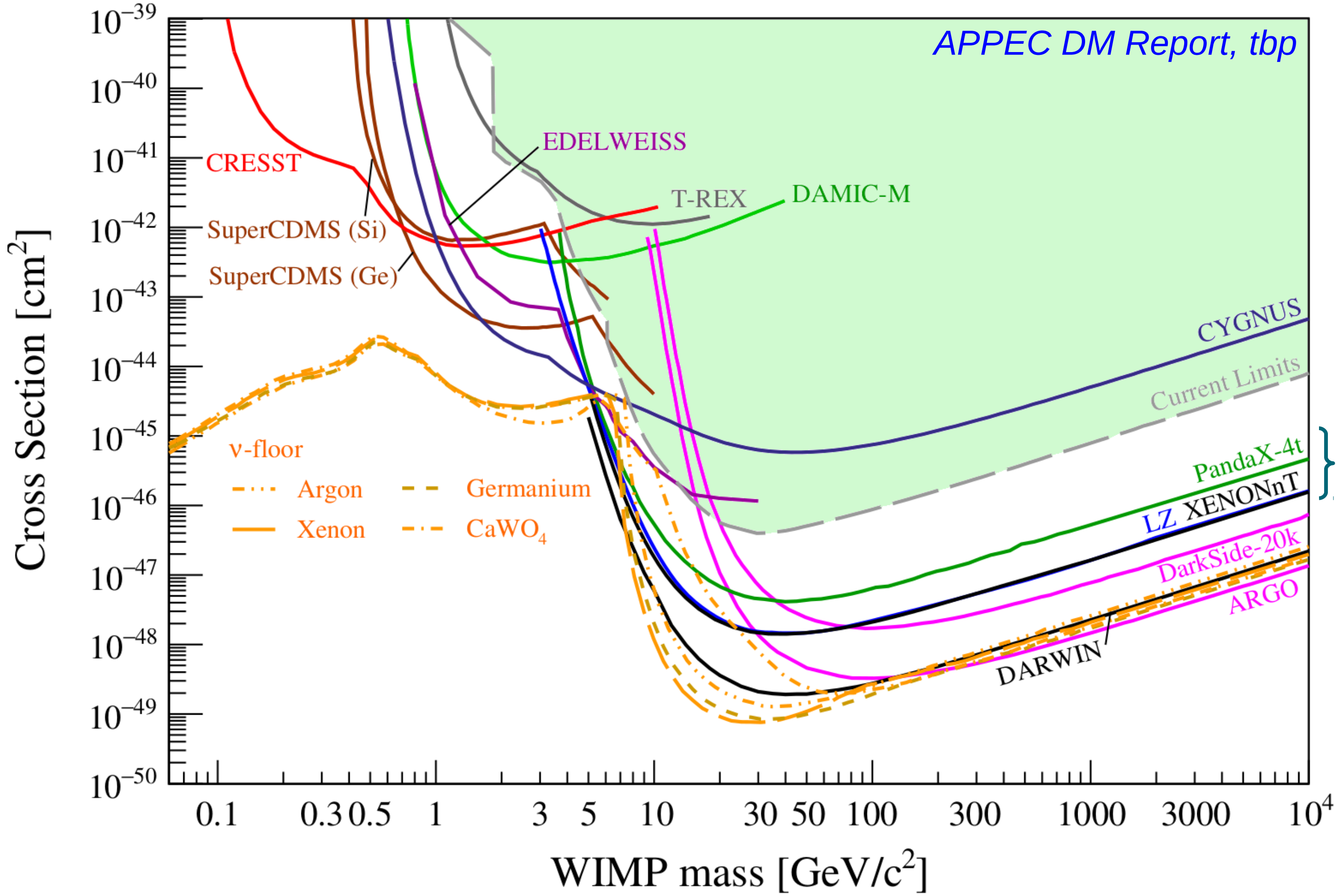


1 t×y (LXe)

200 t×y (LXe)

Exposures of ~200 t×y (LXe), ~1000 t×y (LAr) needed to „reach" atm-ν ~~floor~~ *fog*

Exciting Times for Direct Detection



under construction/ commissioning

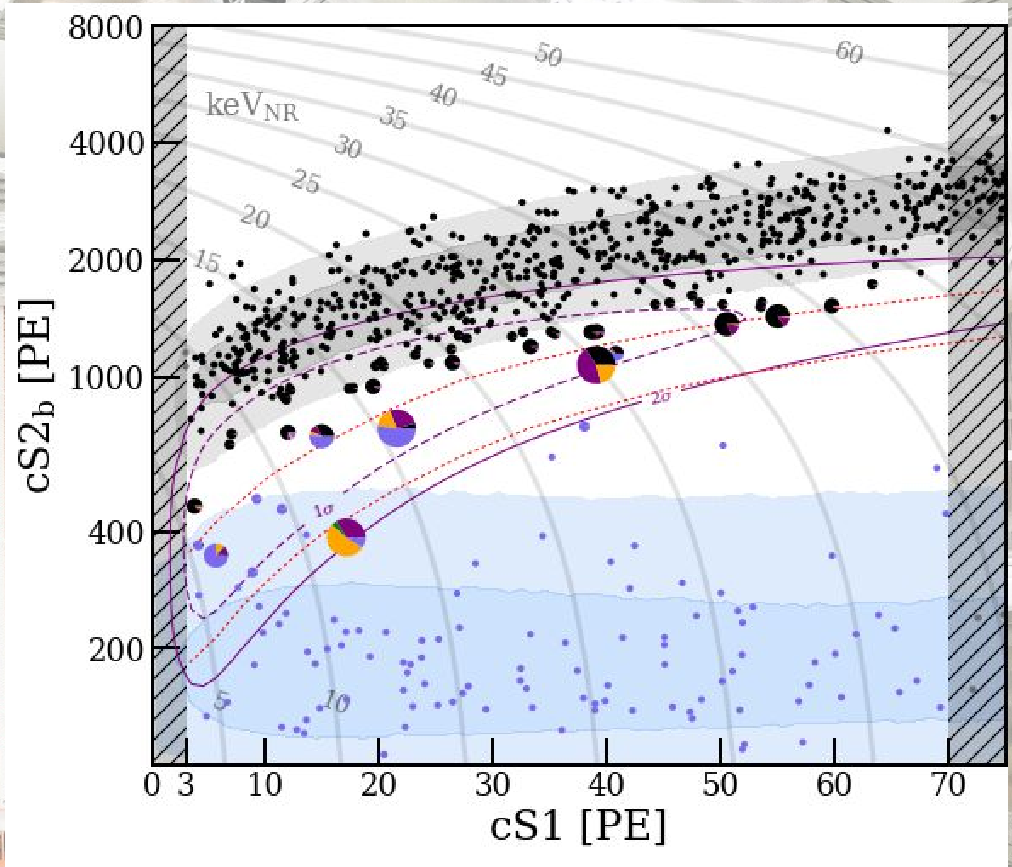
- very diverse experimental landscape – many different projects
- 3 multi ton-scale LXe experiments will get online soon
- very good prospects to reach neutrino floor in next decade

XENON Dark Matter Project

largest LXe TPC ever operated
- cylinder: 96 cm
- active LXe target: 2.0t (3.2t total)
- 248 PMTs

Low-energy electronic recoils in XENON1T

PRD 102, 072004 (2020)



Low-energy electronic recoils in XENON1T

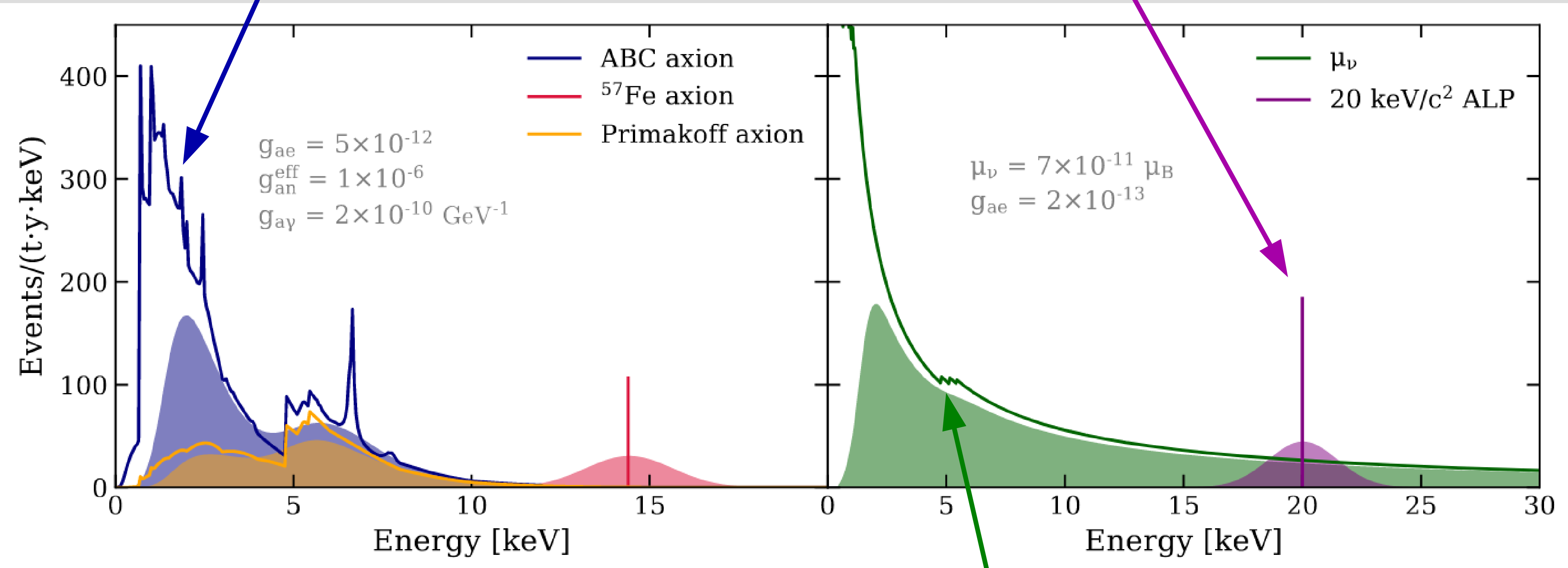
PRD 102, 072004 (2020)

New Physics in ER Data

Many models predict signatures from new physics in low-E ER data.
Our selection:

Solar Axions
- axions: solve strong CP problem and CDM candidate
- if axions exist, production in Sun with E_{kin} ~ keV

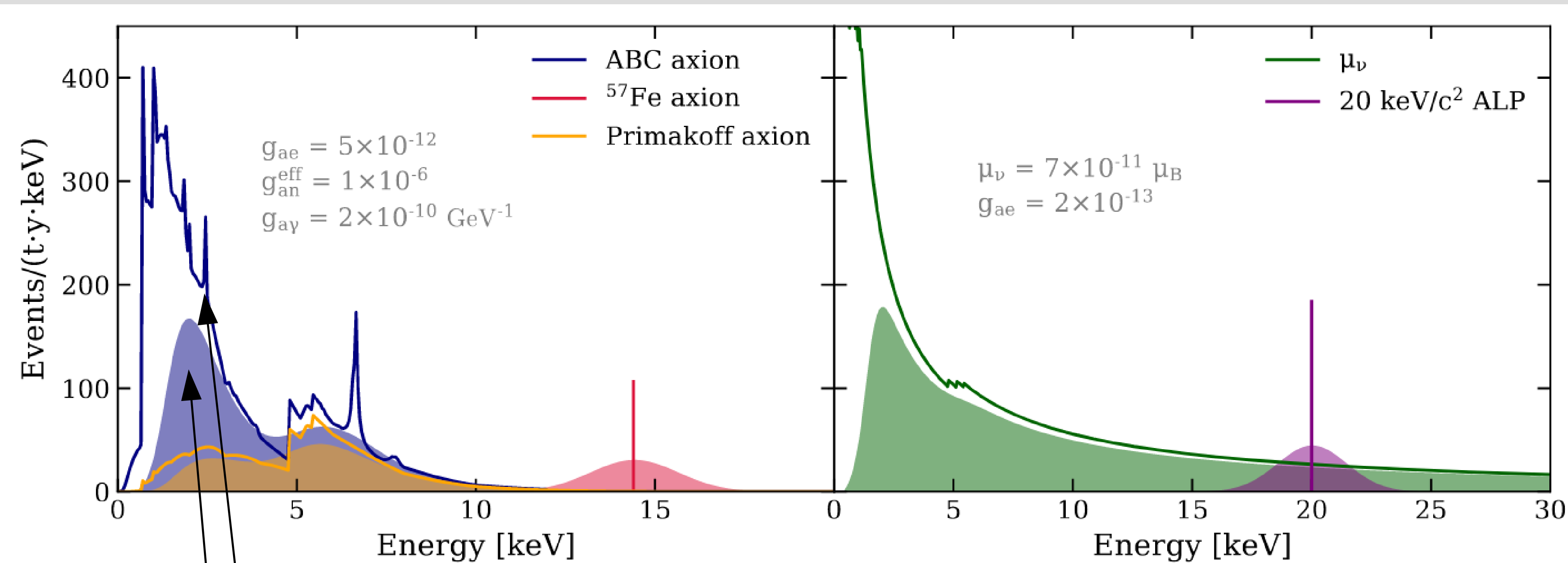
Axion-like Particle (Bosonic ALPs)
- assume all DM is made of non-relativistic ALPs
- expect mono-energetic peak at unknown m_a



Enhanced Neutrino Magnetic Moment
- BSM physics could enhance μ_ν;
- i/a cross-section increases with μ_ν^2/E_ν

Detection

- neutrinos: elastic νe-scattering
- axions/ALPs: **axio-electric effect** → $\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$
- detector effects need to be considered: *E*-resolution, detection efficiency

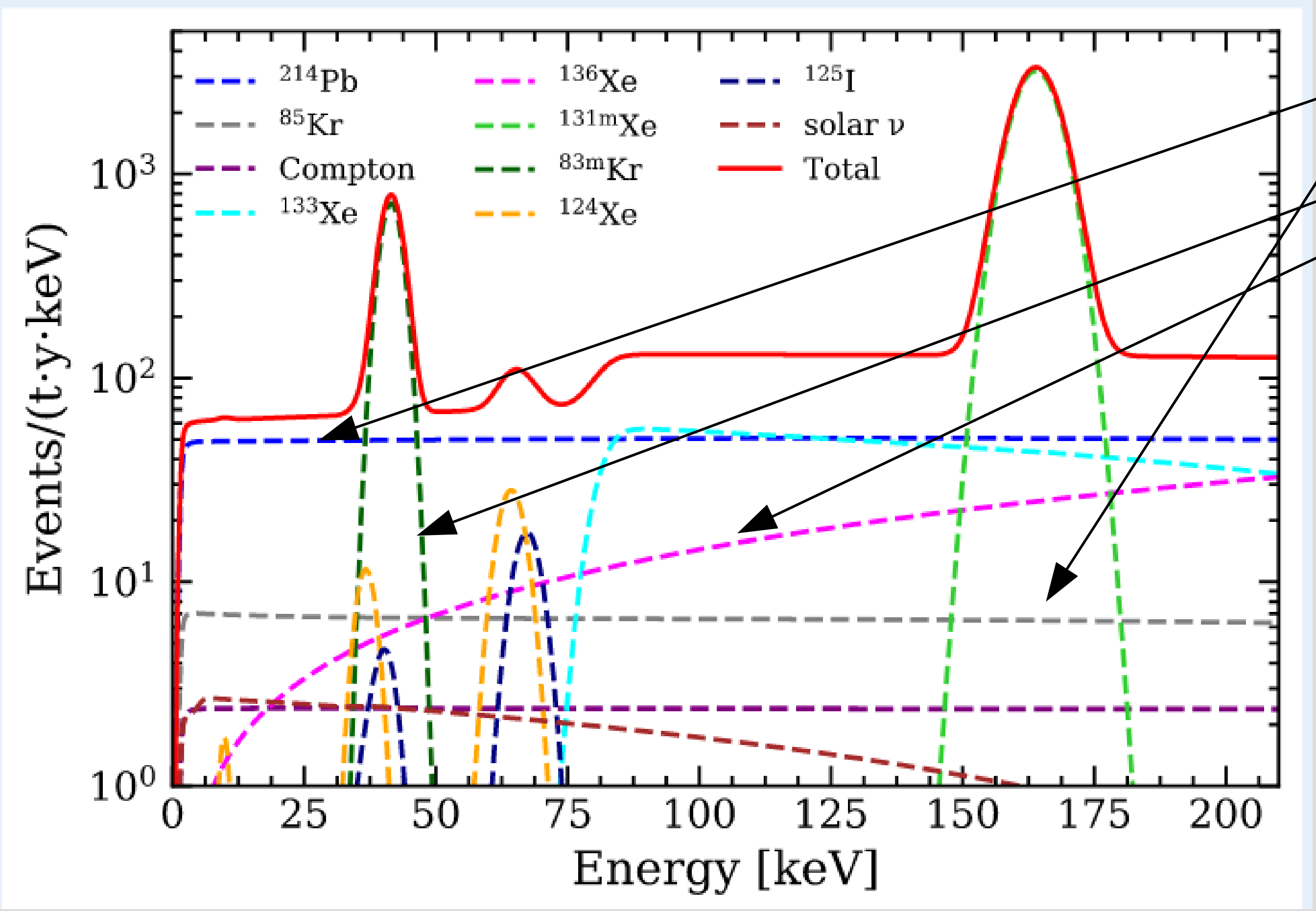


Production ⊗ Detection

Production ⊗ Detection ⊗ Reconstruction

Background Model

10 components



LXe intrinsic:

^{214}Pb (from 222Rn)

^{85}Kr

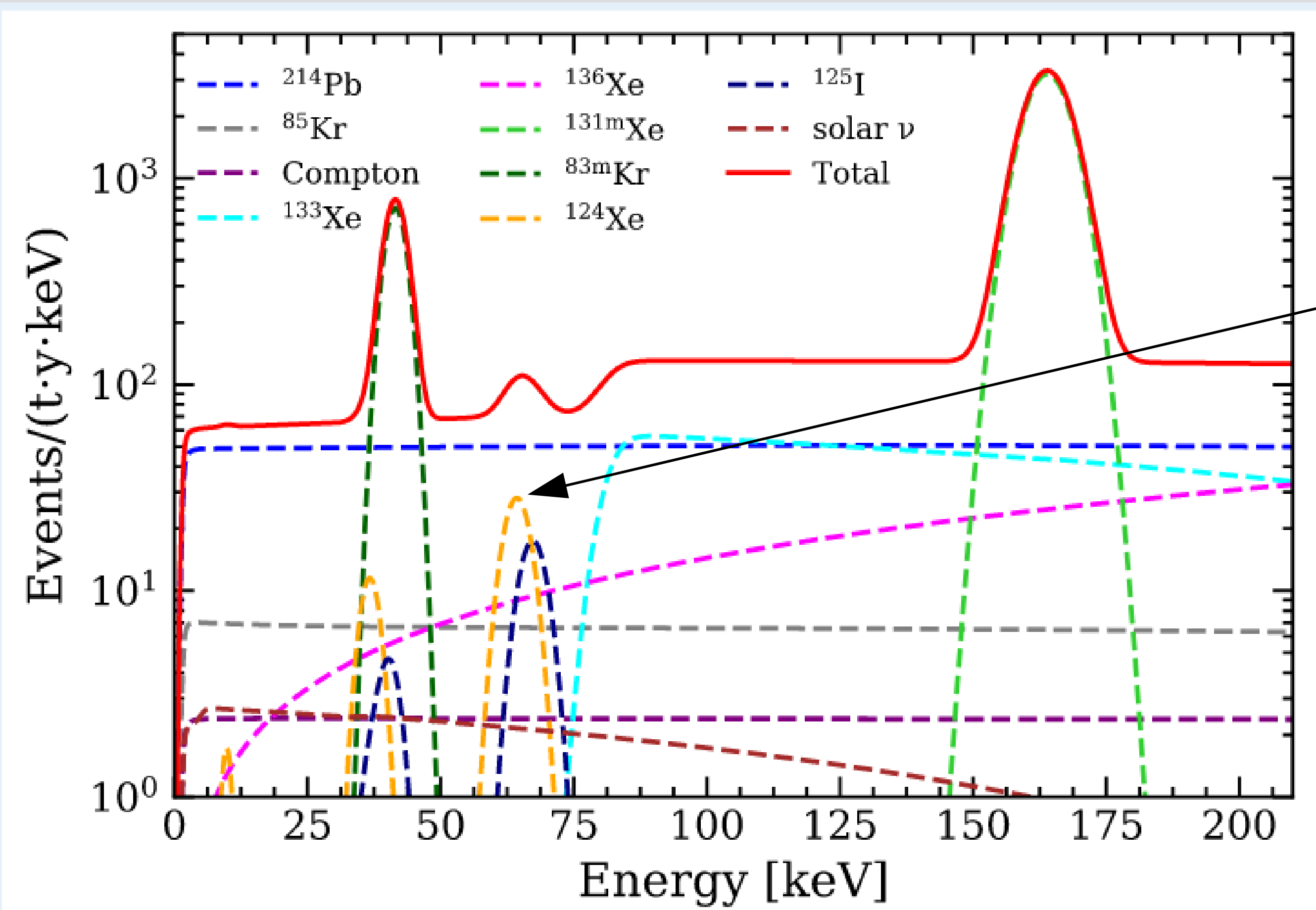
^{83m}Kr (from calibration)

^{136}Xe (2νββ)

^{124}Xe (2νDEC)

Background Model

10 components



LXe intrinsic:

^{214}Pb (from 222Rn)

^{85}Kr

^{83m}Kr (from calibration)

^{136}Xe (2νββ)

^{124}Xe (2νDEC)

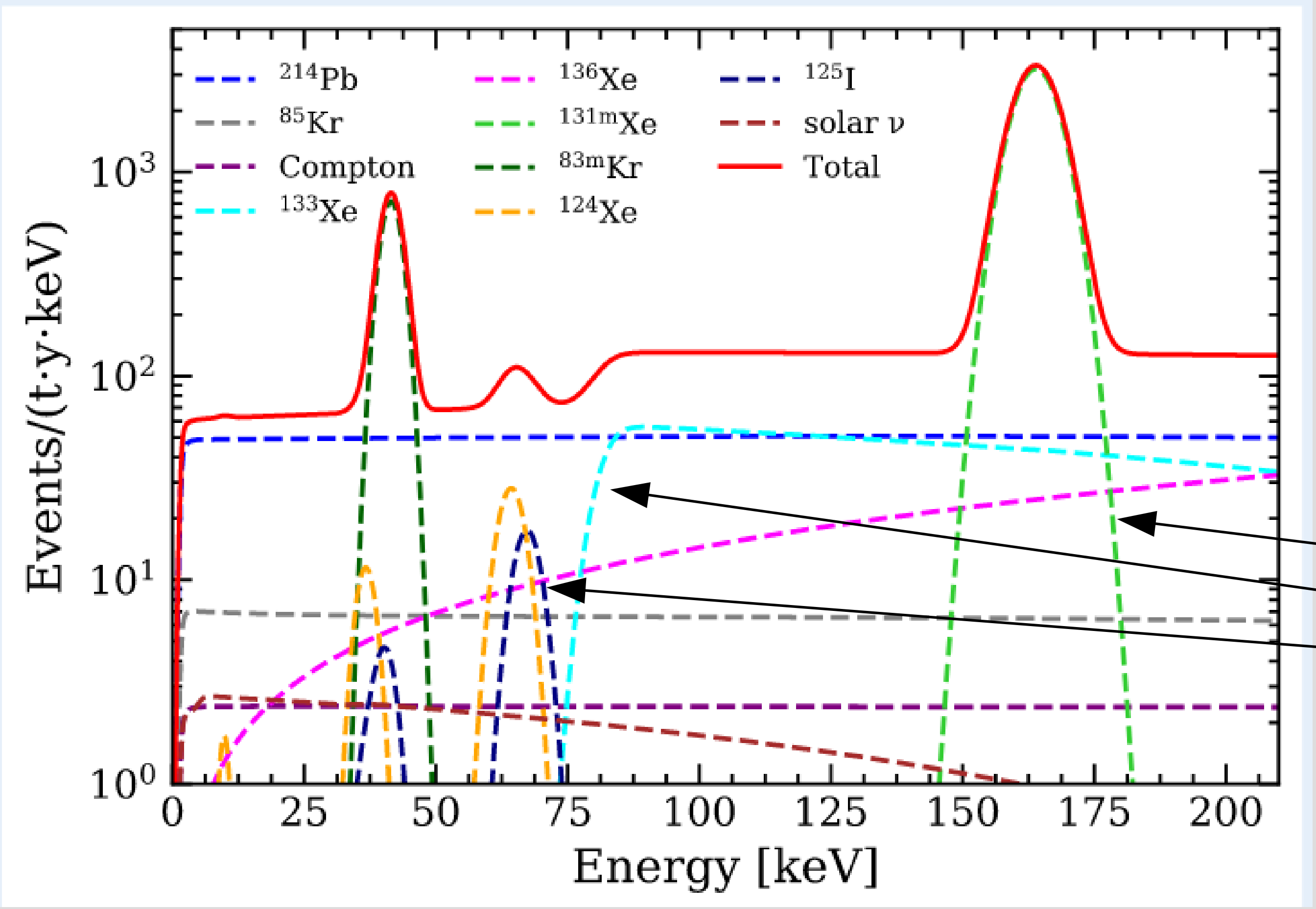
→ *today's signal is tomorrow's background*

Nature 568, 532 (2019)

- **$T^{2\nu ECEC}_{1/2} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y**
- **longest half life ever measured directly**

Background Model

10 components

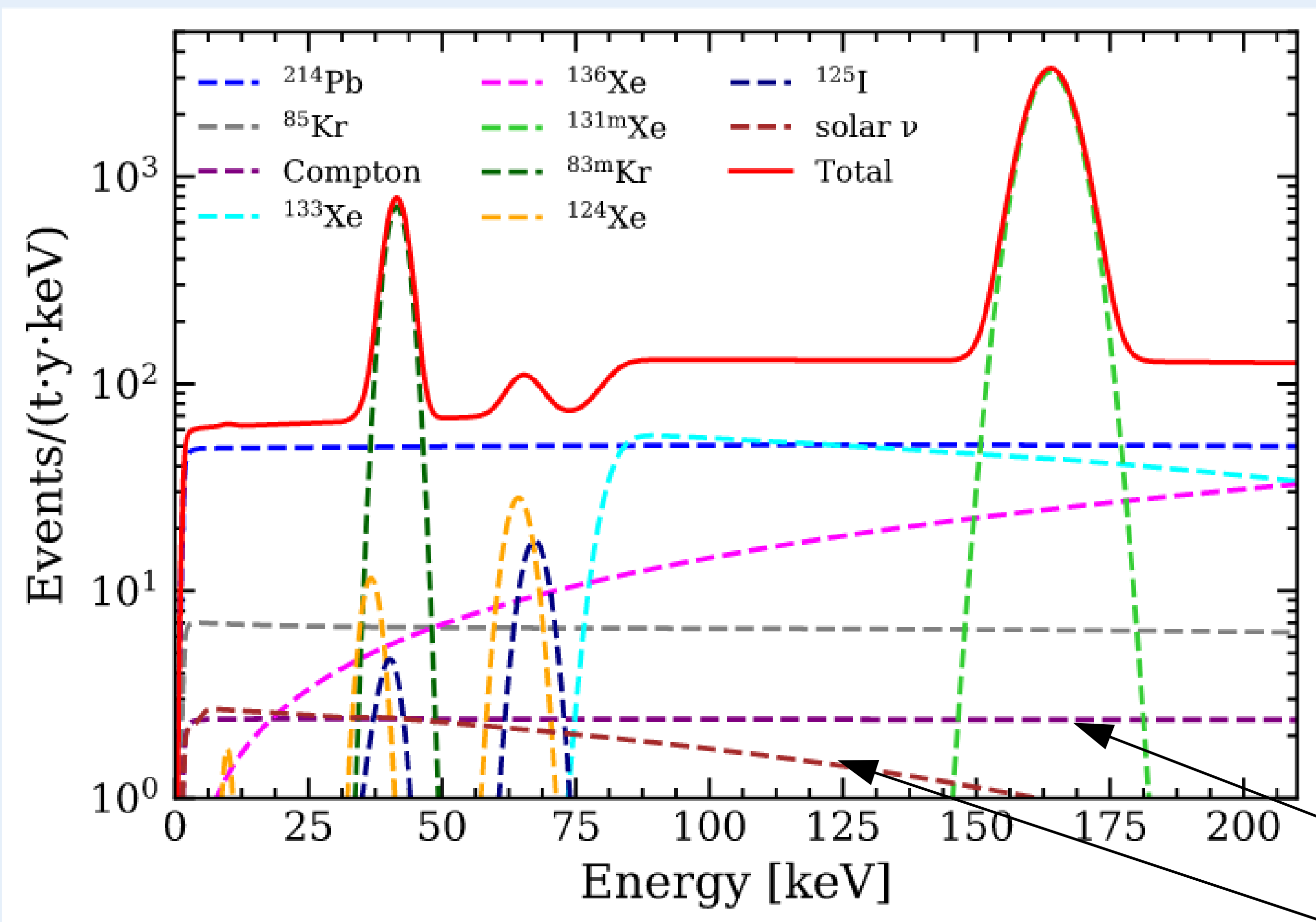


LXe intrinsic:
^{214}Pb (from 222Rn)
^{85}Kr
^{83m}Kr (from calibration)
^{136}Xe (2νββ)
^{124}Xe (2νDEC)
→ *today's signal is tomorrow's background*

From neutron-activation:
^{131m}Xe (IC)
^{133}Xe (β+81 keV γ)
^{125}I (EC)

Background Model

10 components



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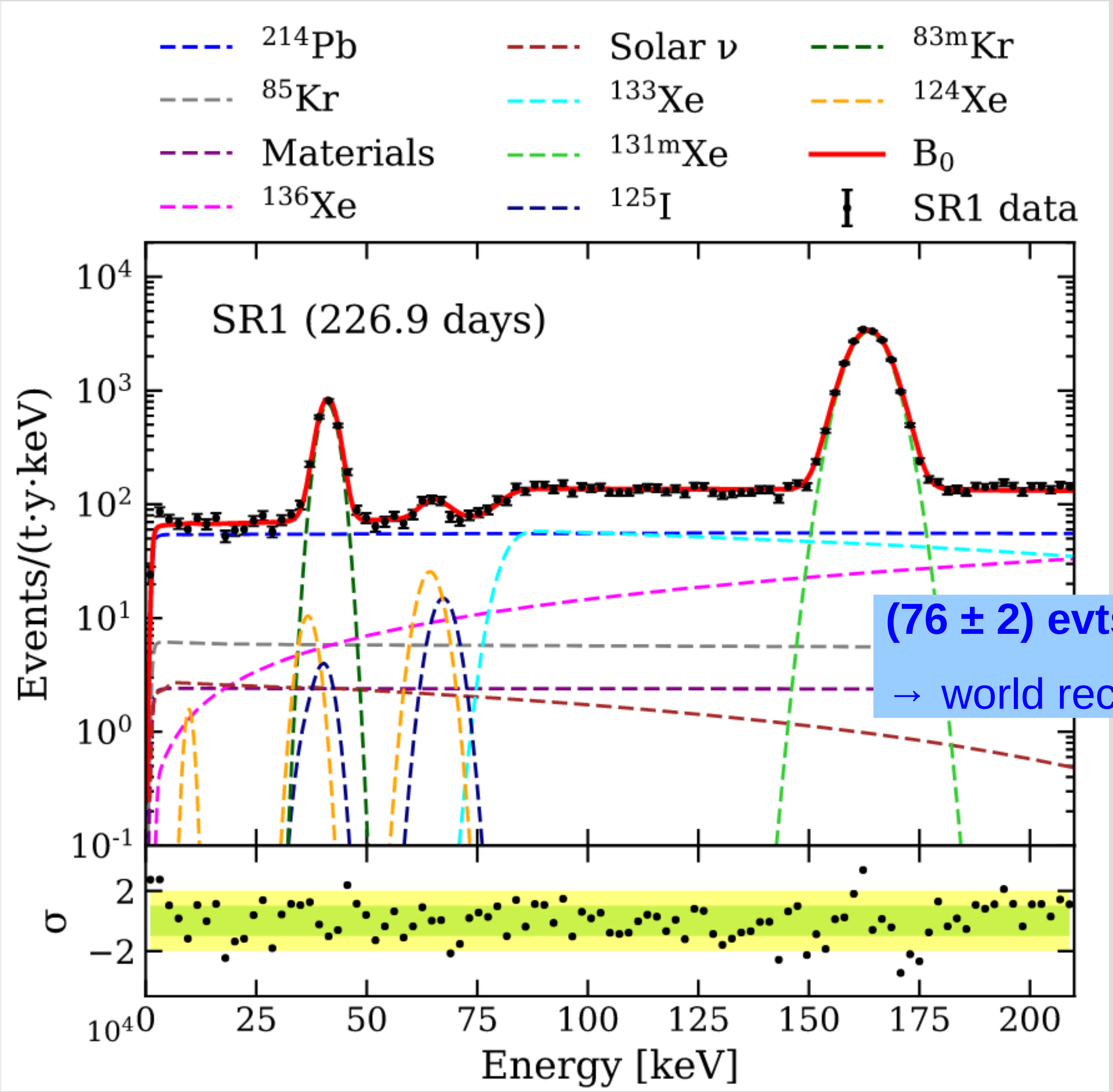
Detector materials

Solar neutrinos

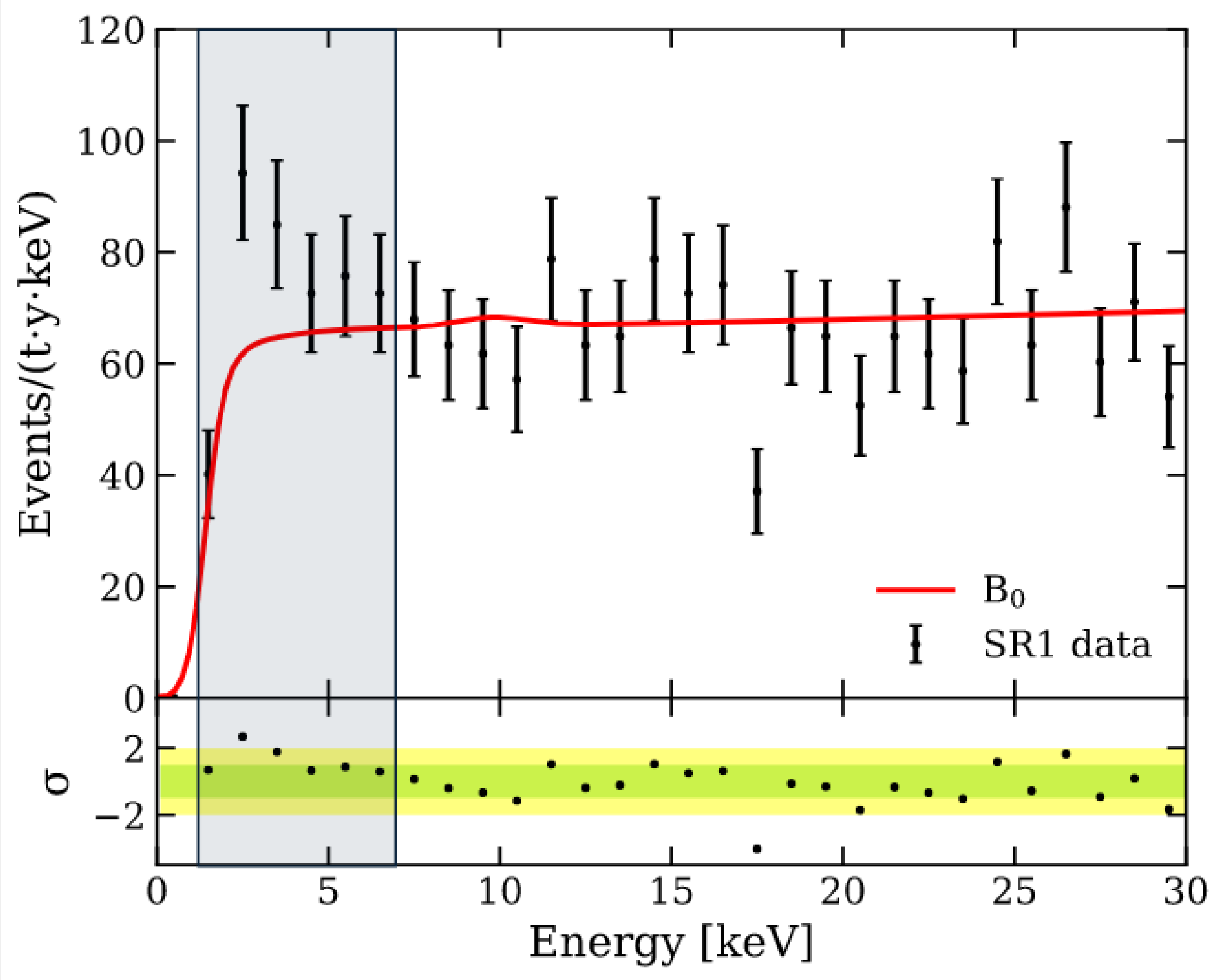
Background Fit



(76 ± 2) evts/(t y keV) in 1-30 keV

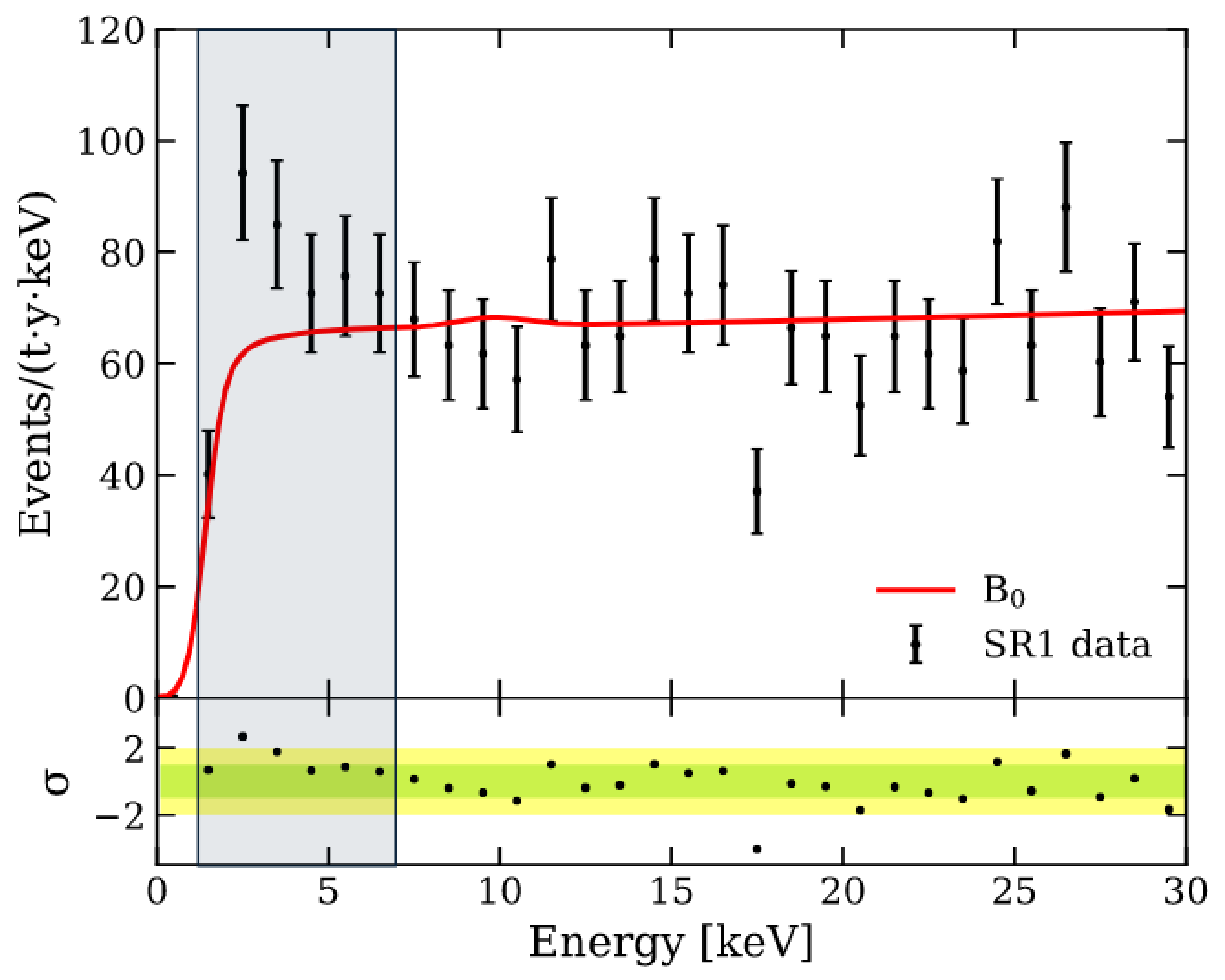
→ world record background level!

Excess of Events



- **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)
- far away from typical WIMP artefact backgrounds
  – accidental coincidences
  – surface background
- efficiency and reconstruction validated down to threshold via calibration

Excess of Events



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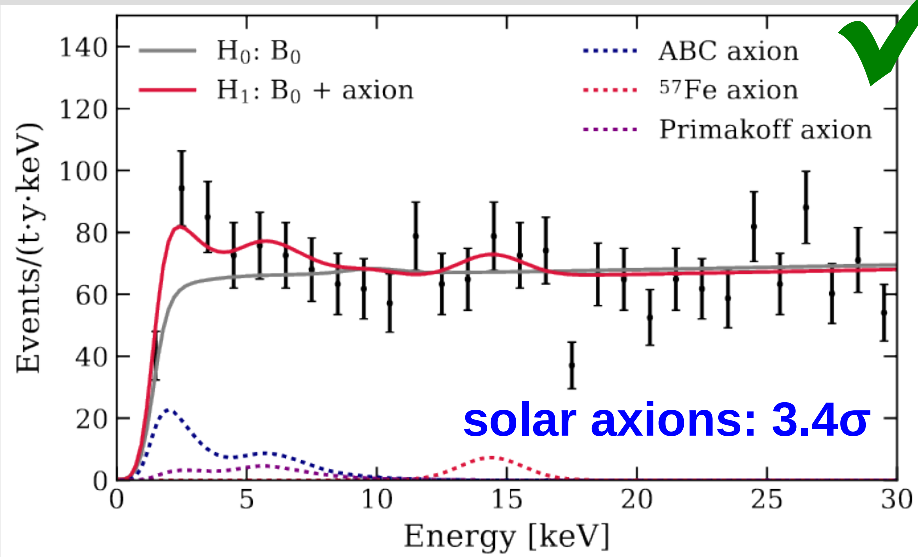
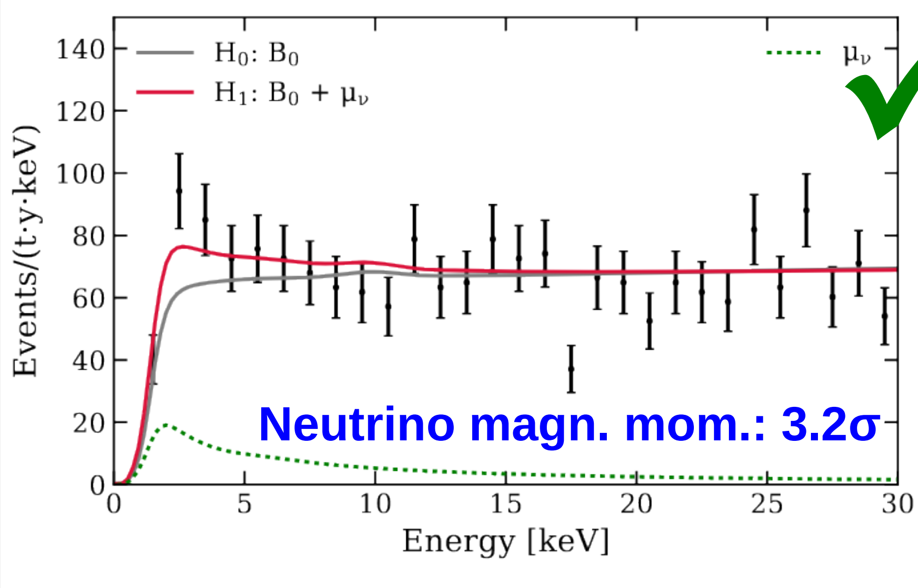
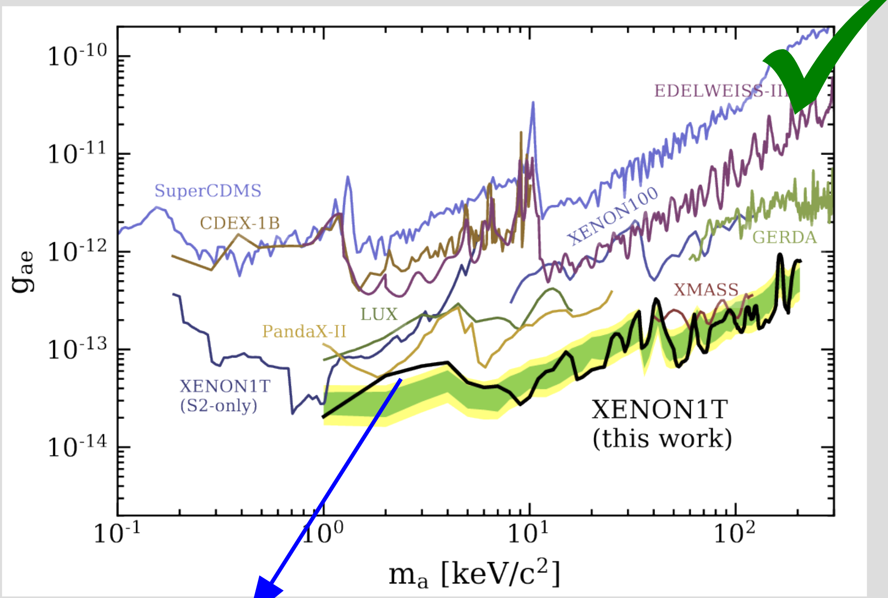
What causes it????

BSM Signal Models?





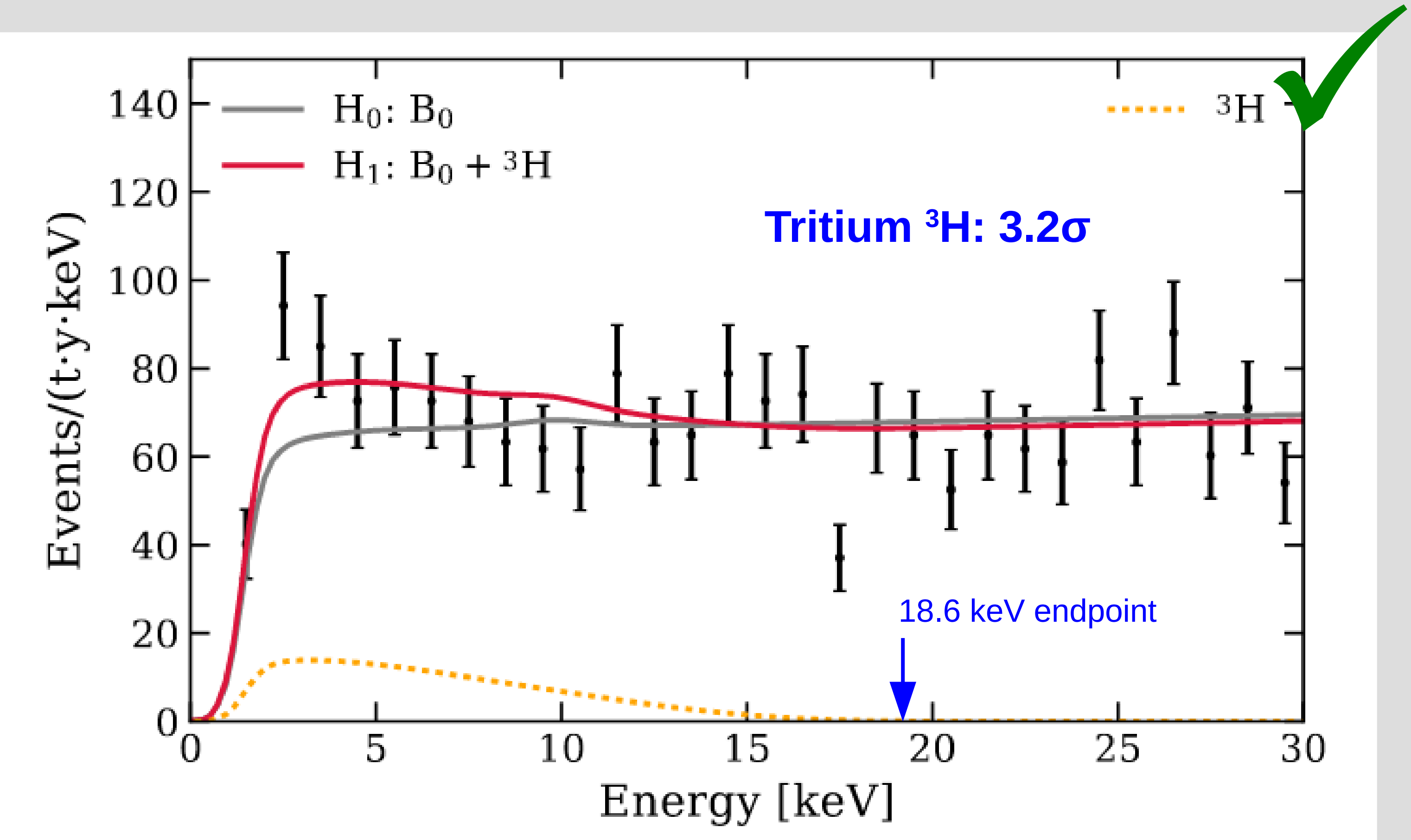


Bosonic ALPs
3.0σ global (4.0σ local)
@ m_a=2.3±0.2 keV

… and many others since we made our result public.

BUT...

Tritium: A new background?



- **cosmogenic production** by Xe-spallation or present in H_2O (outgassing from walls)
  → ONLY above-ground activation relevant!
- half-life = 12.3 y → ~constant in our dataset   from fit: <3 ^{3}H atoms per kg of Xe
- **we can neither confirm nor exclude the Tritium hypothesis at this point**

Excess Summary

PRD 102, 072004 (2020)

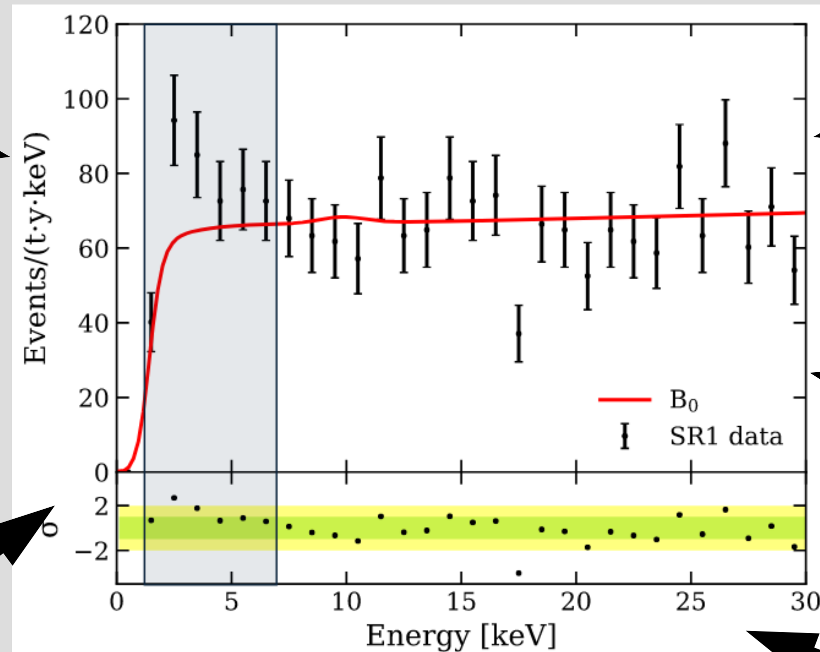
We see an excess of low-E ER events above our known backgrounds.

Tritium ^3H

Argon ^{37}Ar
peak @ 2.8 keV

Neutrino μ_ν

Artefacts



Solar Axions

Bosonic ALPs

and many others...

Excess electronic recoil events in XENON1T #1

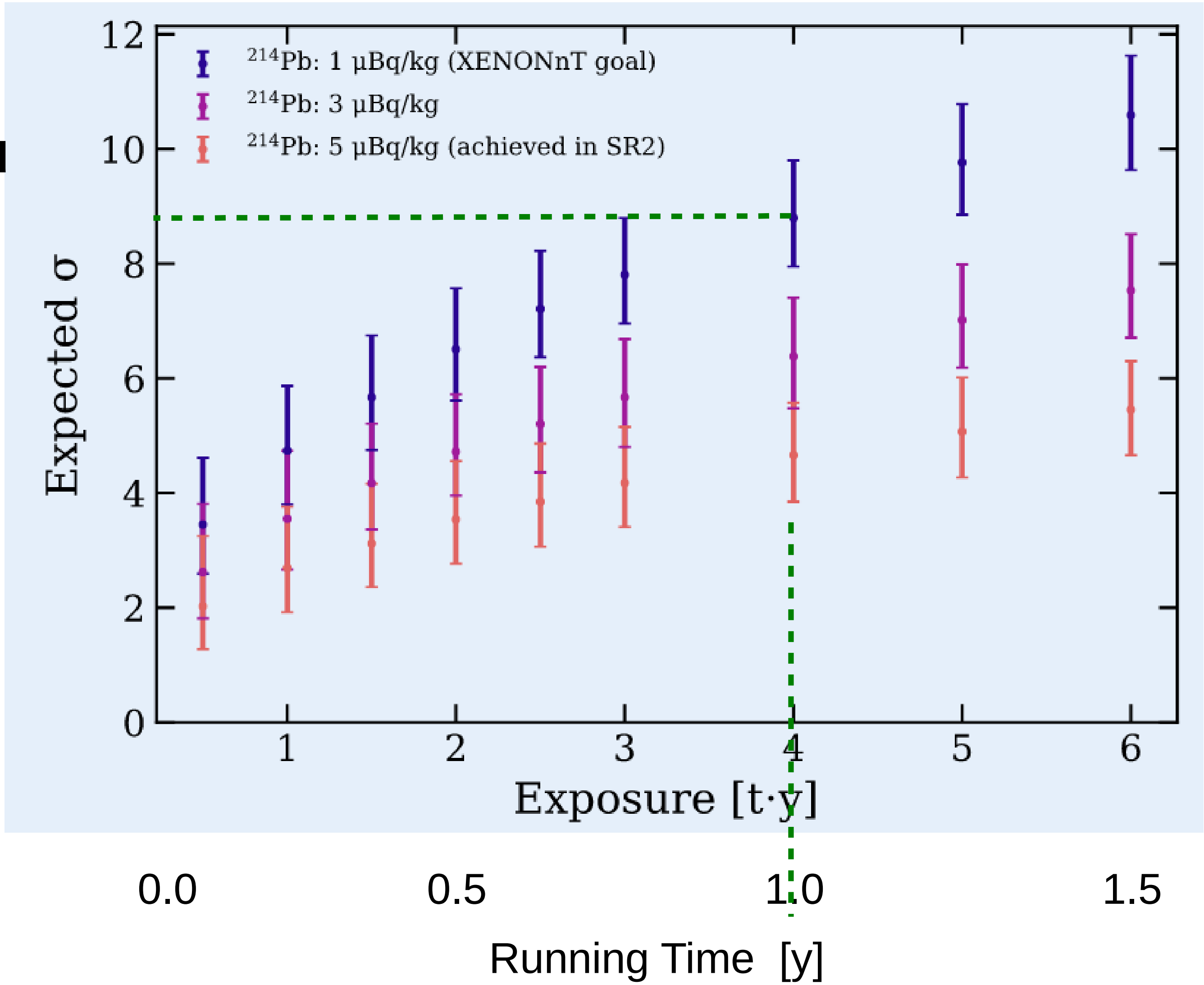
XENON Collaboration • E. Aprile (Columbia U.) et al. (Jun 17, 2020)

Published in: *Phys.Rev.D* 102 (2020) 7, 072004 • e-Print: 2006.09721 [hep-ex]

pdf links DOI cite 152 citations

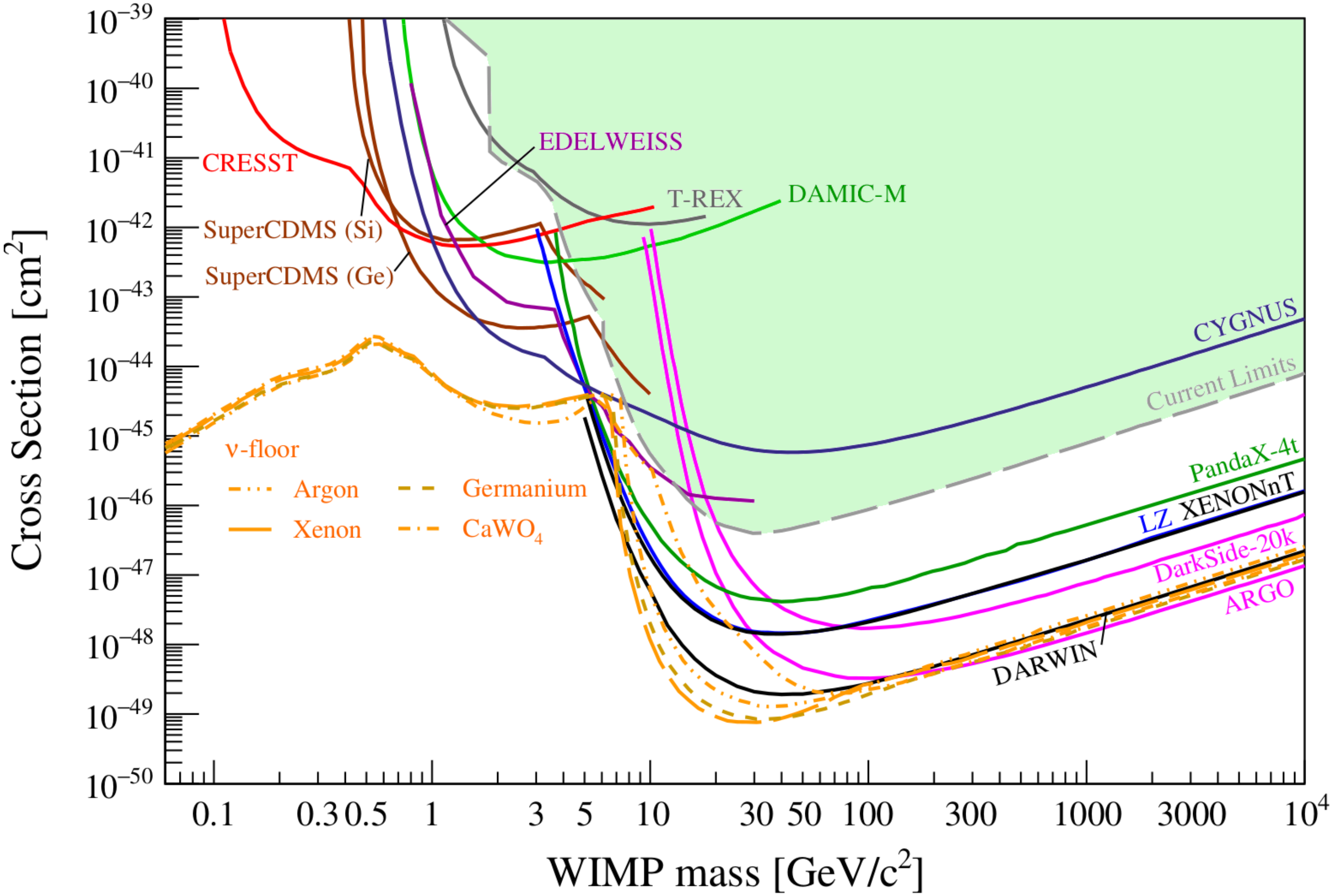
XENONnT: Axions vs. Tritium

- assume excess persists and is from solar axions
- **How much data is needed to distinguish it from ^3H?**
- exploit differences in spectral shape
- sensitivity depends on background level



assume 4t FV and no calibration

Exciting Times for Direct Detection



- very diverse experimental landscape – many different projects
- 3 multi ton-scale LXe experiments will get online soon
- very good prospects to reach neutrino floor in next decade