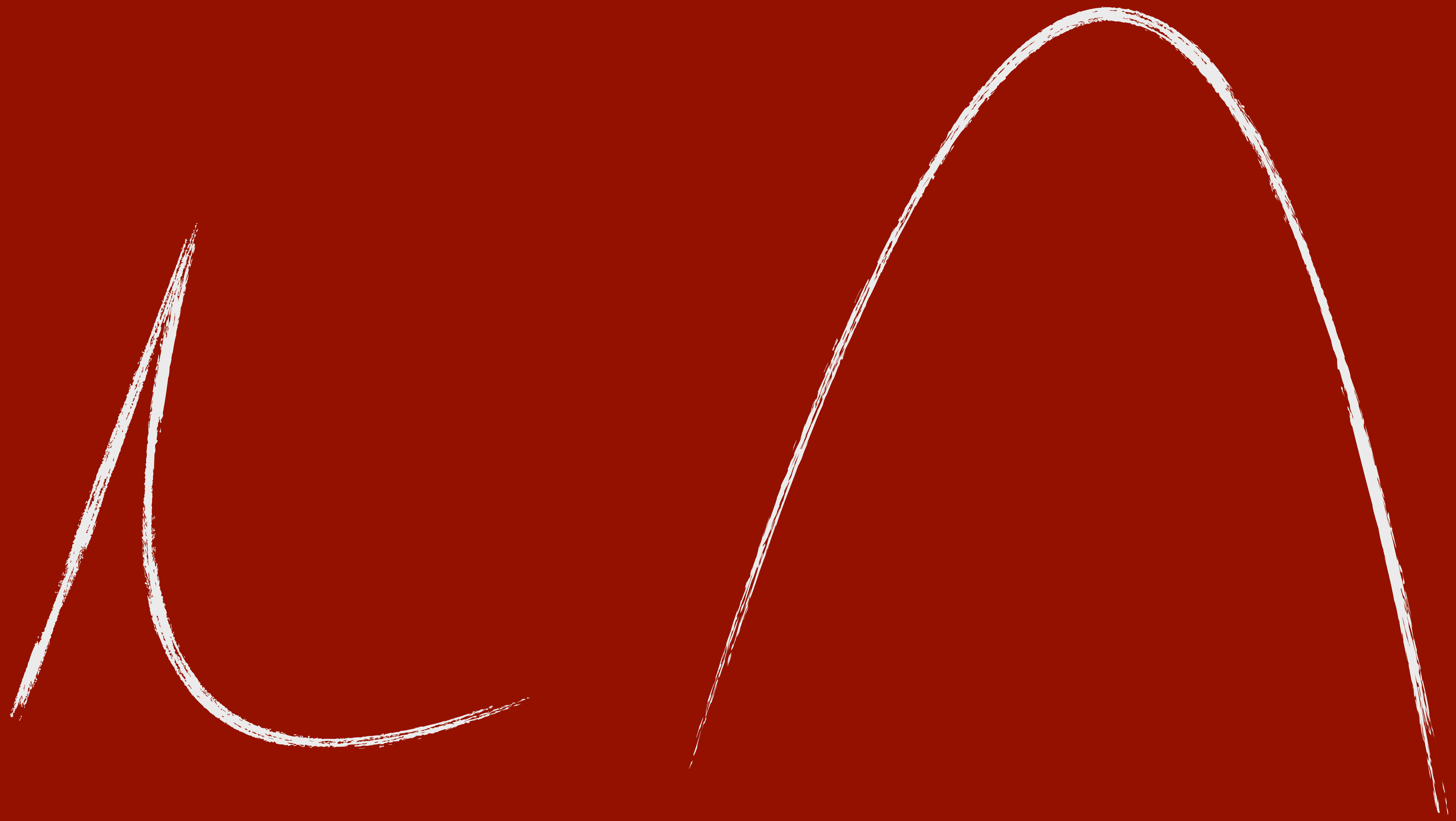
Neutrino-induced recoils in liquid xenon TPCs

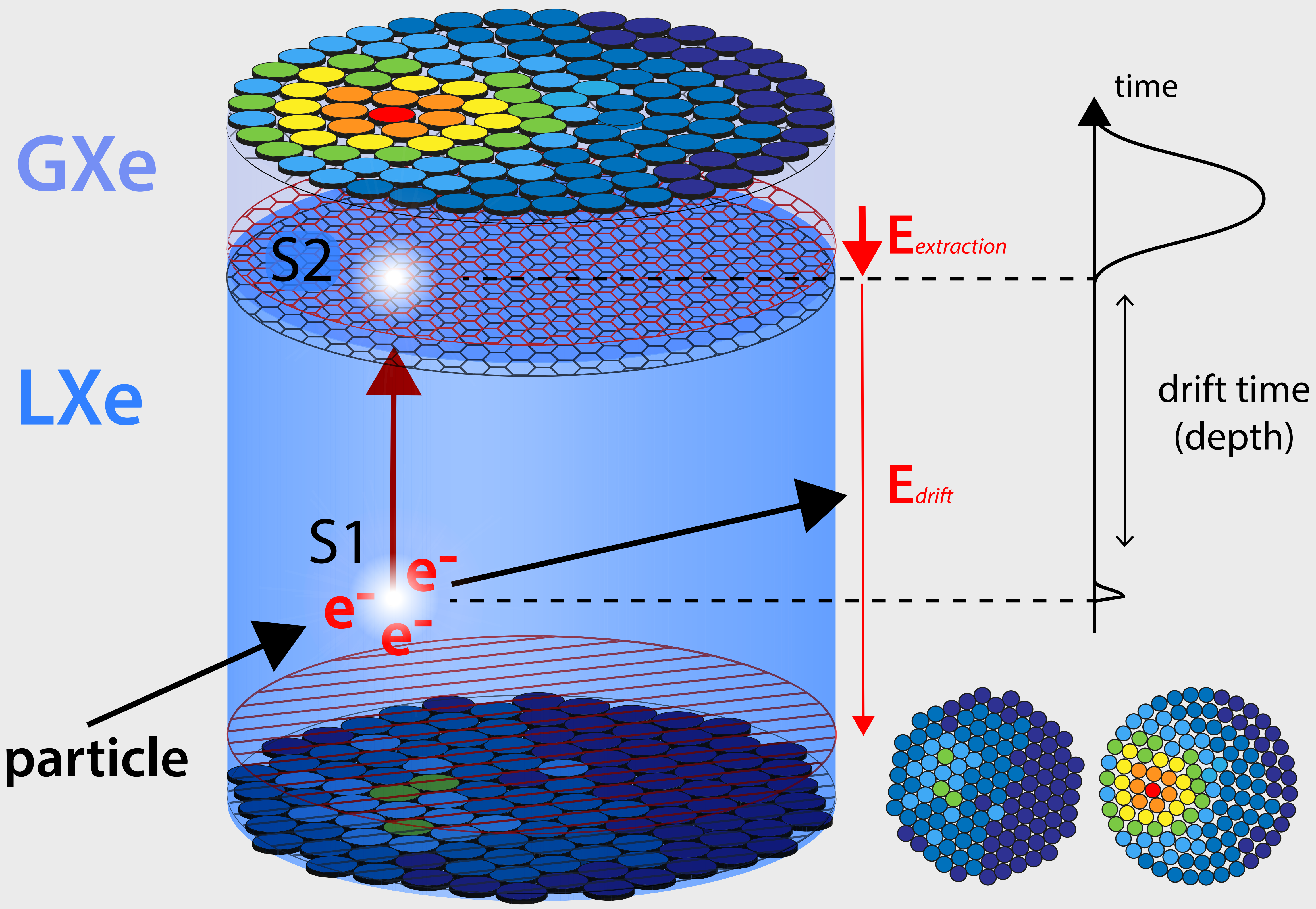


ν-e Scattering at Low Energies
ACFI, UMass Amherst
April 2019

Evan Shockley
Kavli Institute for Cosmological Physics
& University of Chicago

Dual-Phase Time Projection Chambers

- ✦ Low-threshold, low-background detectors that are scalable
  - Noble liquids, w/ focus on xenon here
- ✦ Scintillation (S1) and ionization (S2) signals allow for:
  - 3D position reconstruction
  - Energy reconstruction
  - Particle identification
    - Electron recoil (ER) from γ, β, ν
    - Nuclear recoil (NR) from neutron, ν, WIMP?



Experiments

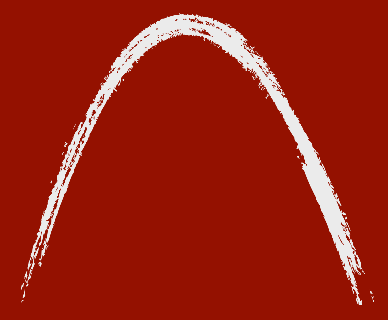
XENON program, LUX, LZ, Panda-X, DarkSide

Two analysis thresholds

1. S1 + S2

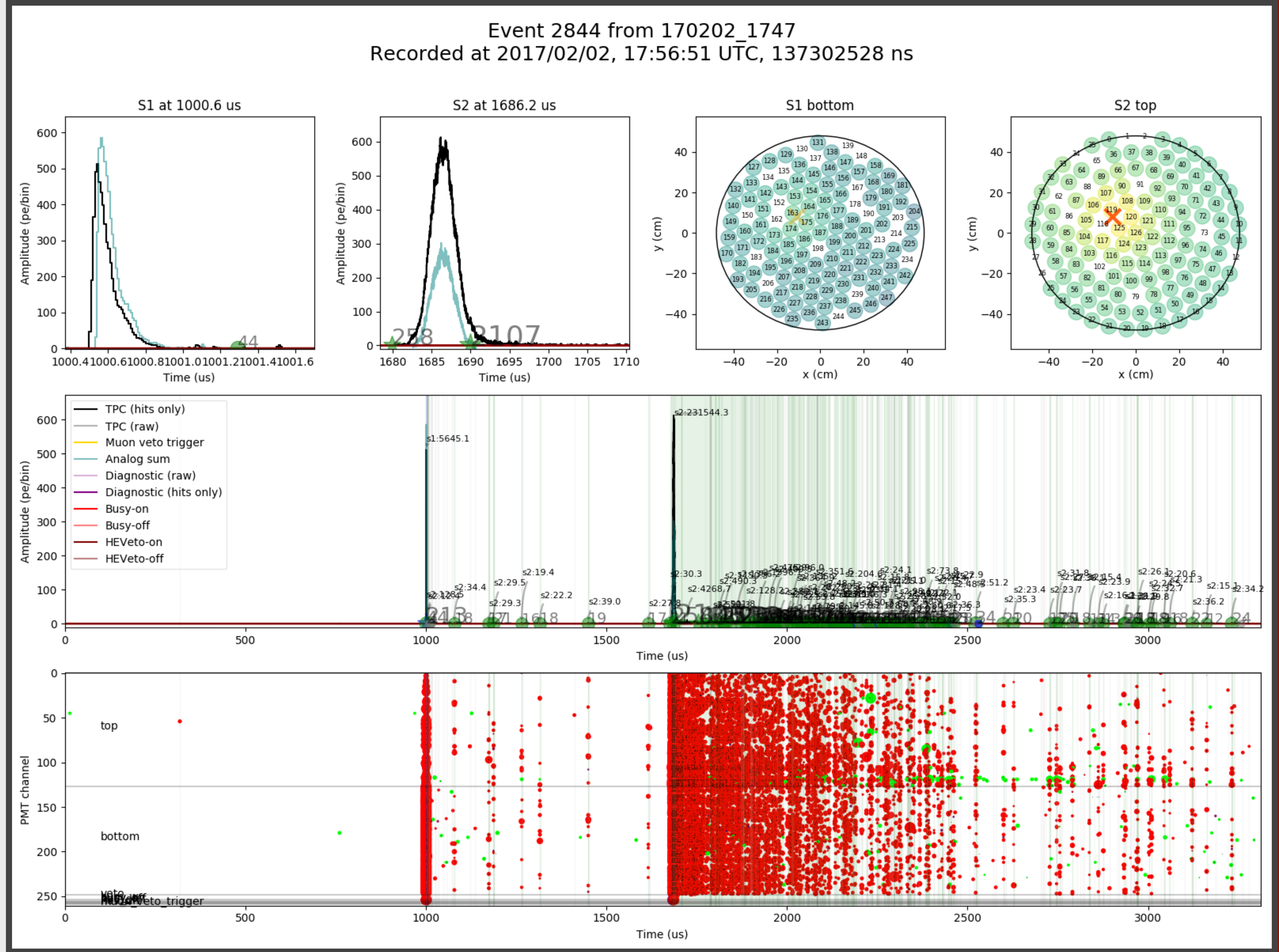
- ~1 keV energy threshold
  - driven by light yield & S1 coincidence requirement (3 PMTs most likely)
- Stronger position reconstruction
- Stronger background modeling & rejection
- 'discovery' analyses

2. S2-only



- O(100) eV energy threshold
- Complete background model difficult —> typically 'limit-only' analyses

See Graham's talk (next)



Low threshold...

High-energy event from XENON1T showing correlated S2 events

Two analysis thresholds

1. S1 + S2

- ~1 keV energy threshold
  - driven by light yield & S1 coincidence requirement (3 PMTs most likely)
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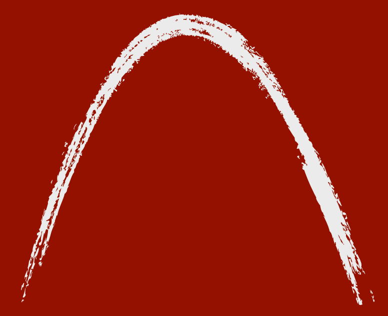
- 'discovery' analyses

2. S2-only



- O(100) eV energy threshold
- Complete background model difficult —> typically 'limit-only' analyses

See Graham's talk (next)

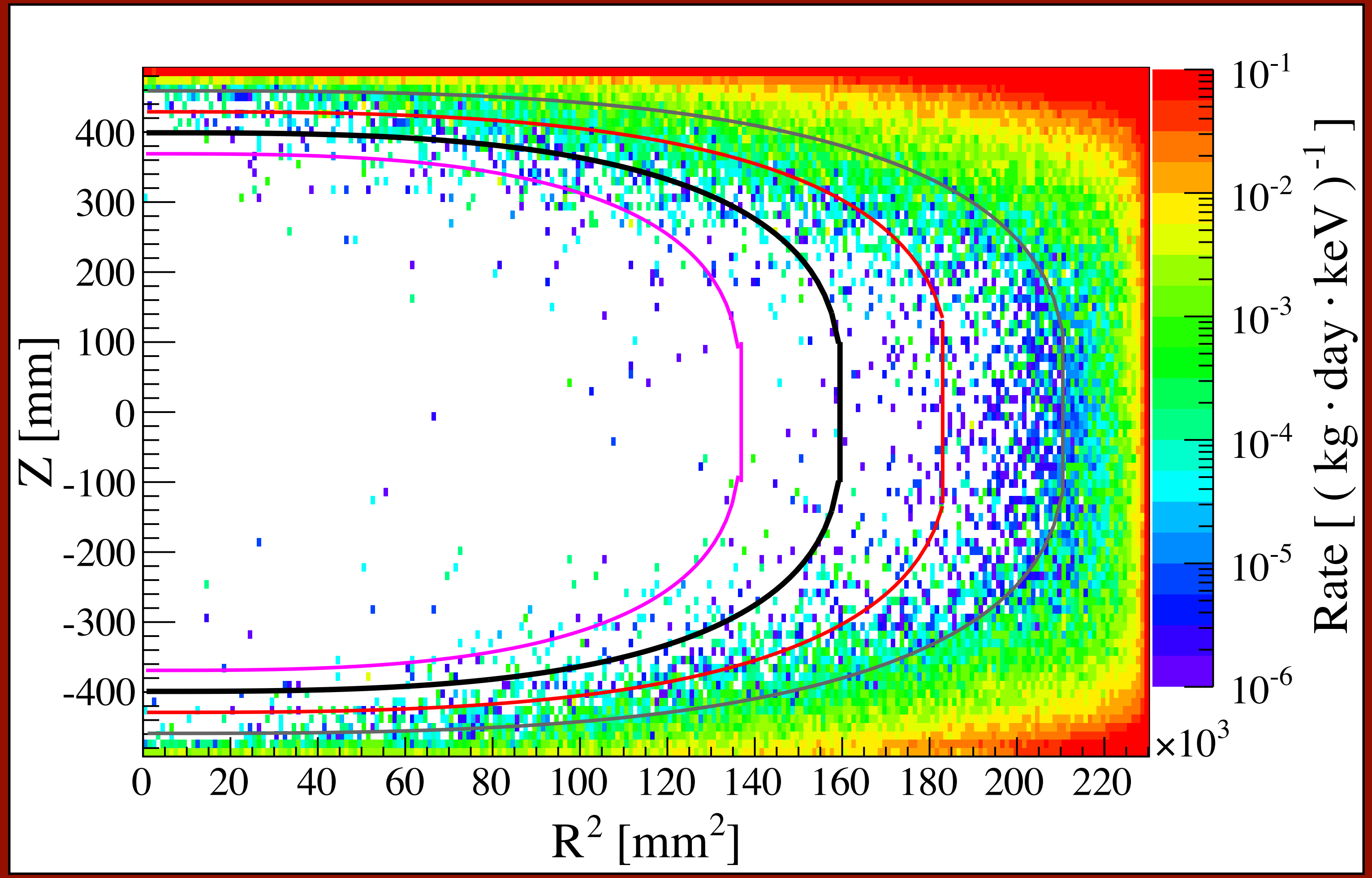
Low threshold...

Focus mainly on S1 + S2

…low background…

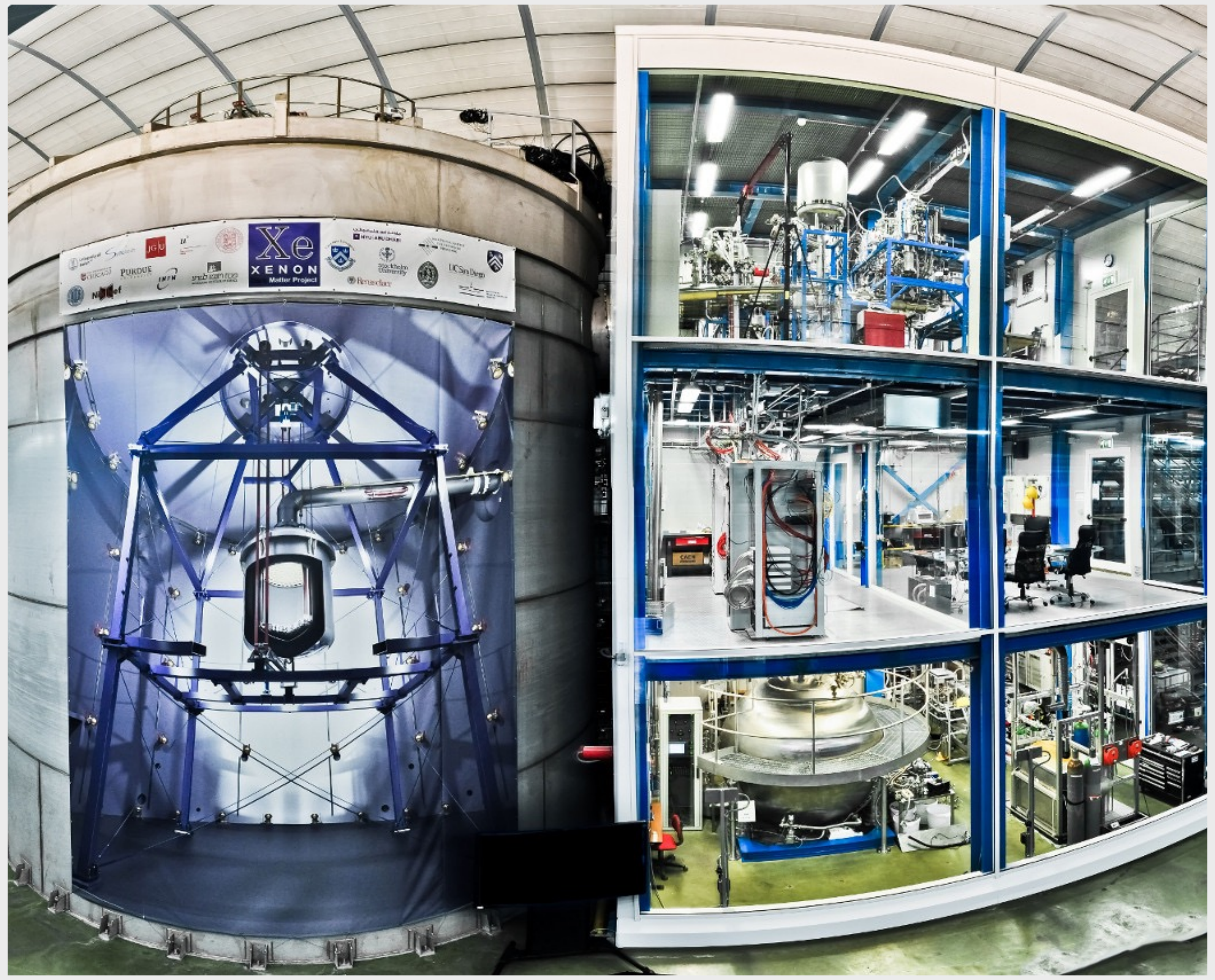
Backgrounds overview

- Shielding: underground + muon veto
- γ-ray from materials reduced via screening + fiducialization



- "Intrinsic" sources: 222Rn, 85Kr, 136Xe
  - more details later
- ν-e elastic scattering

ER

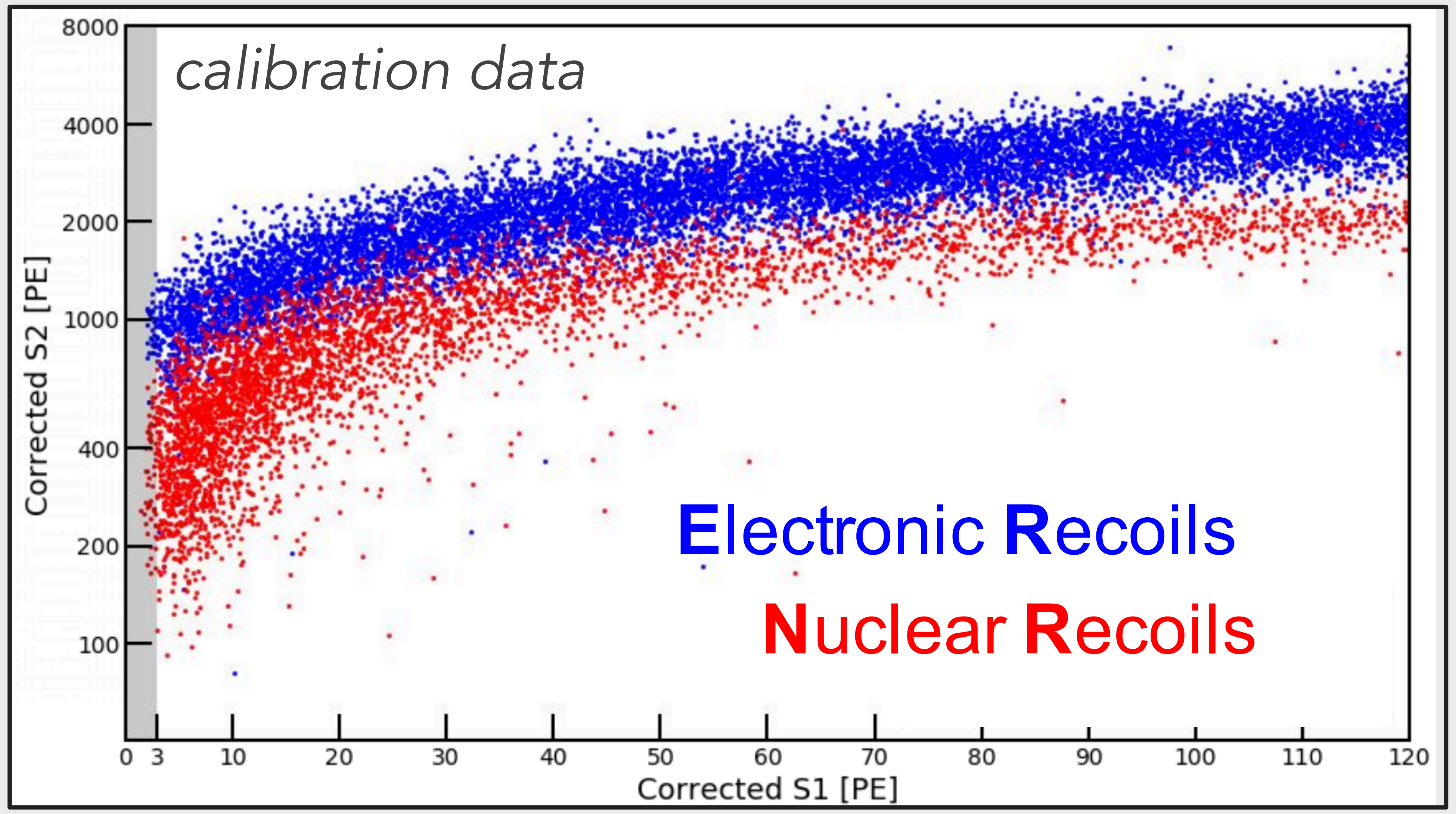


- Neutrons
- Coherent elastic ν-nucleus scattering (CEνNS)

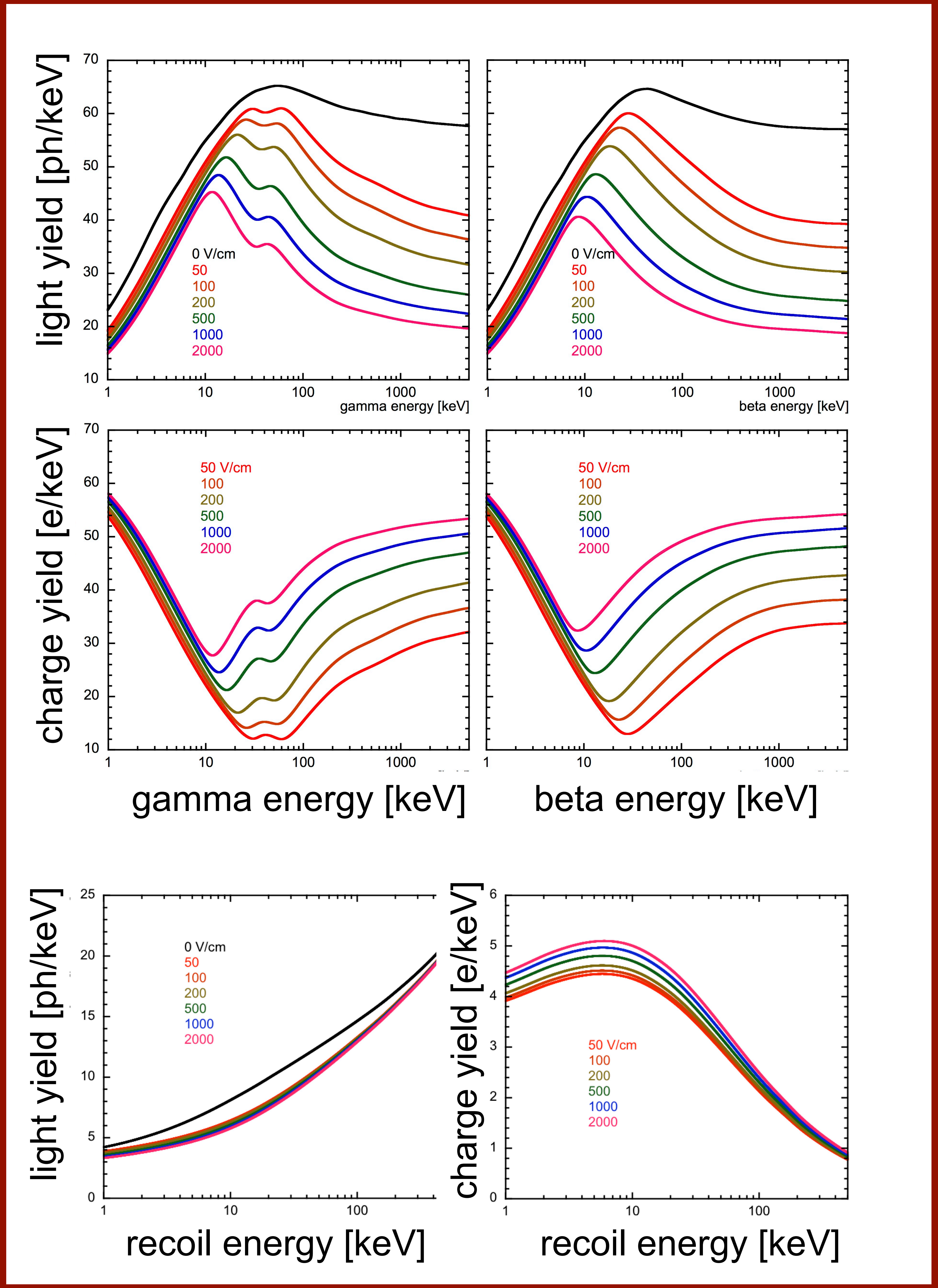
NR

ER/NR discrimination

- ✦ ER vs NR discrimination > 99%
  - NRs display less ionization (S2) for given scintillation (S1) due to more electron-ion recombination
- ✦ That < 1% ER leakage still dominant background — suppressing ER is critical!



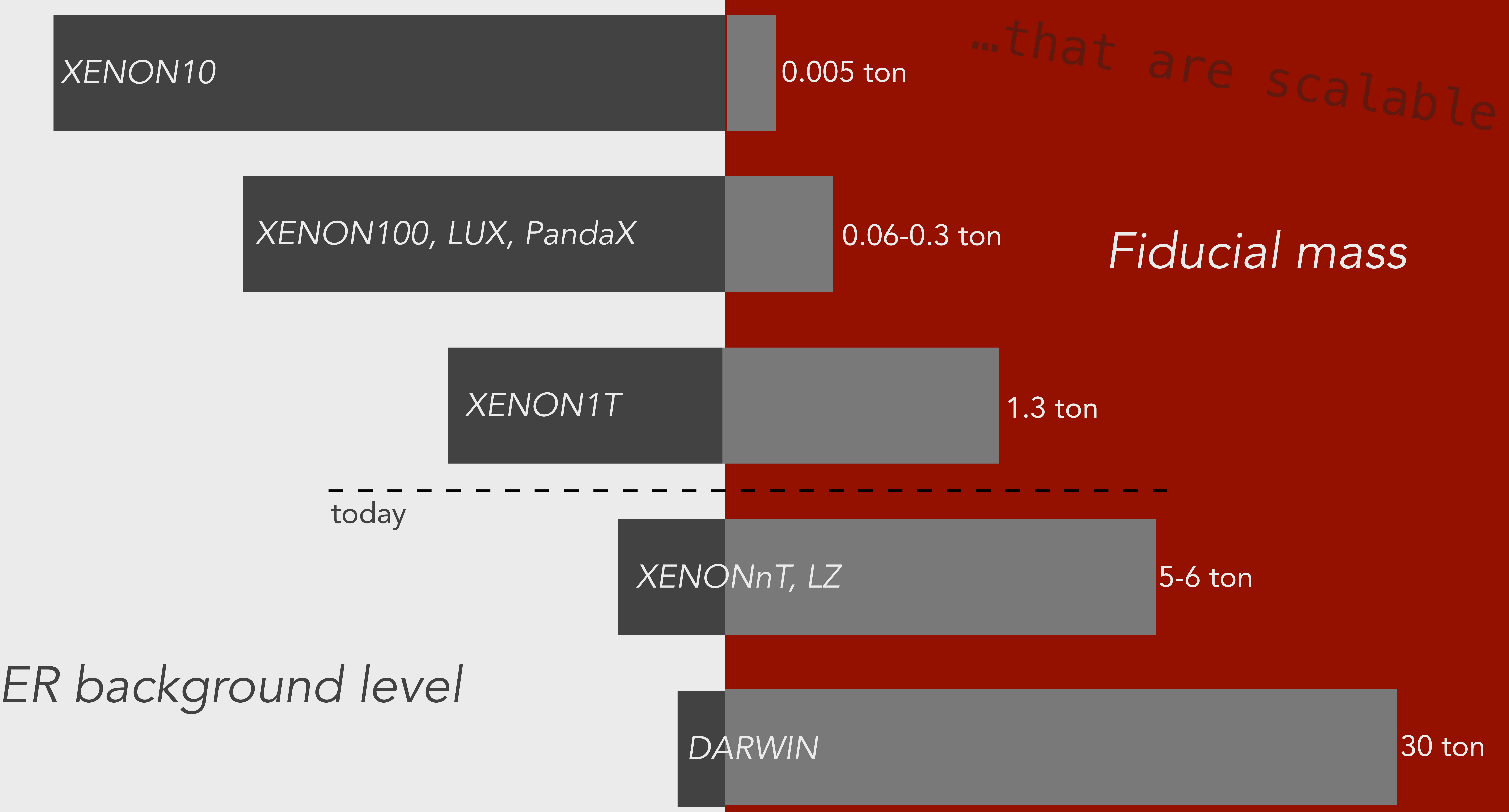
- ✦ NR signals 'quenched' due to energy loss to heat — different energy scales



ER

NR

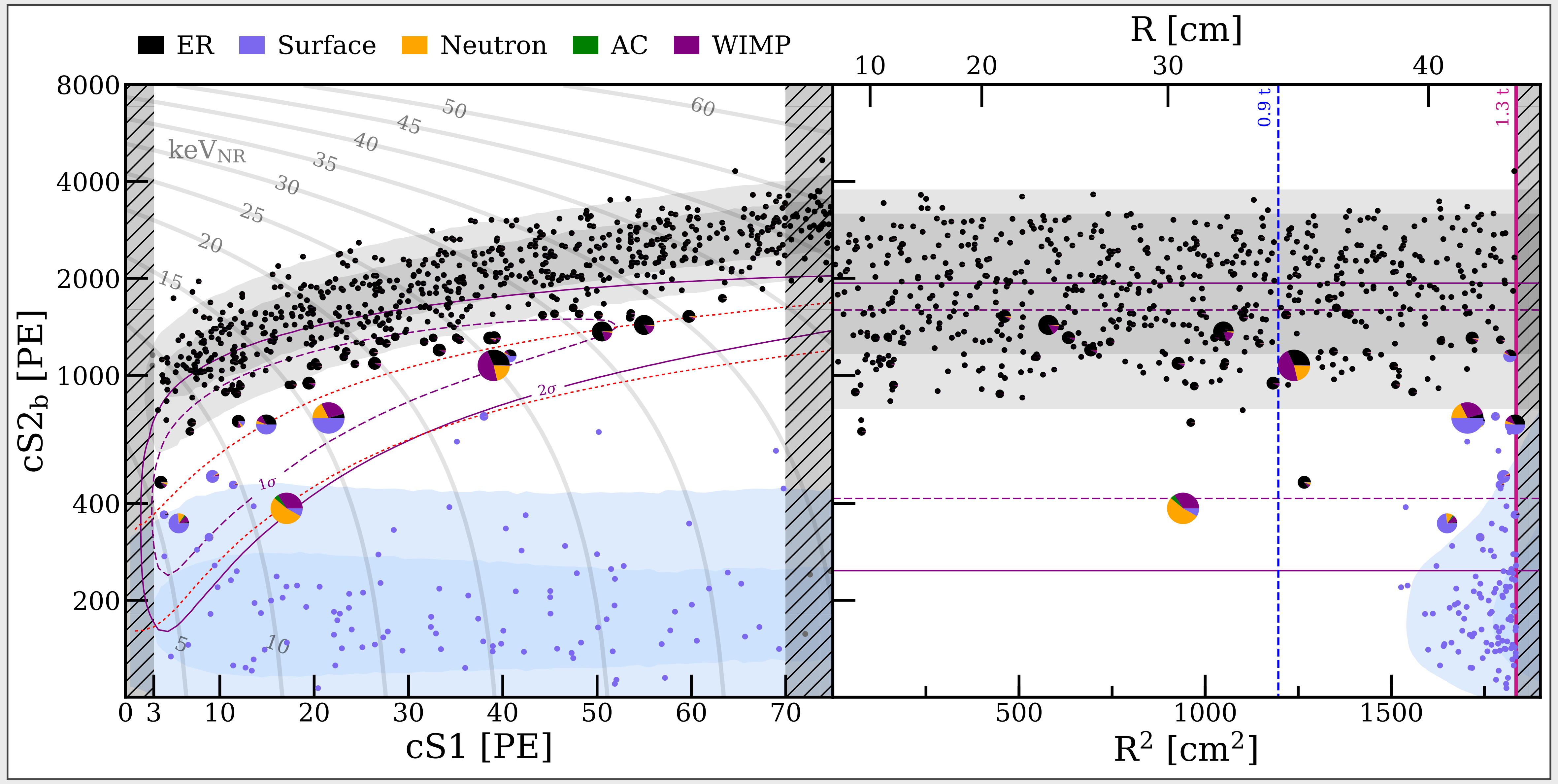
NEST model
arXiv 1307.6601

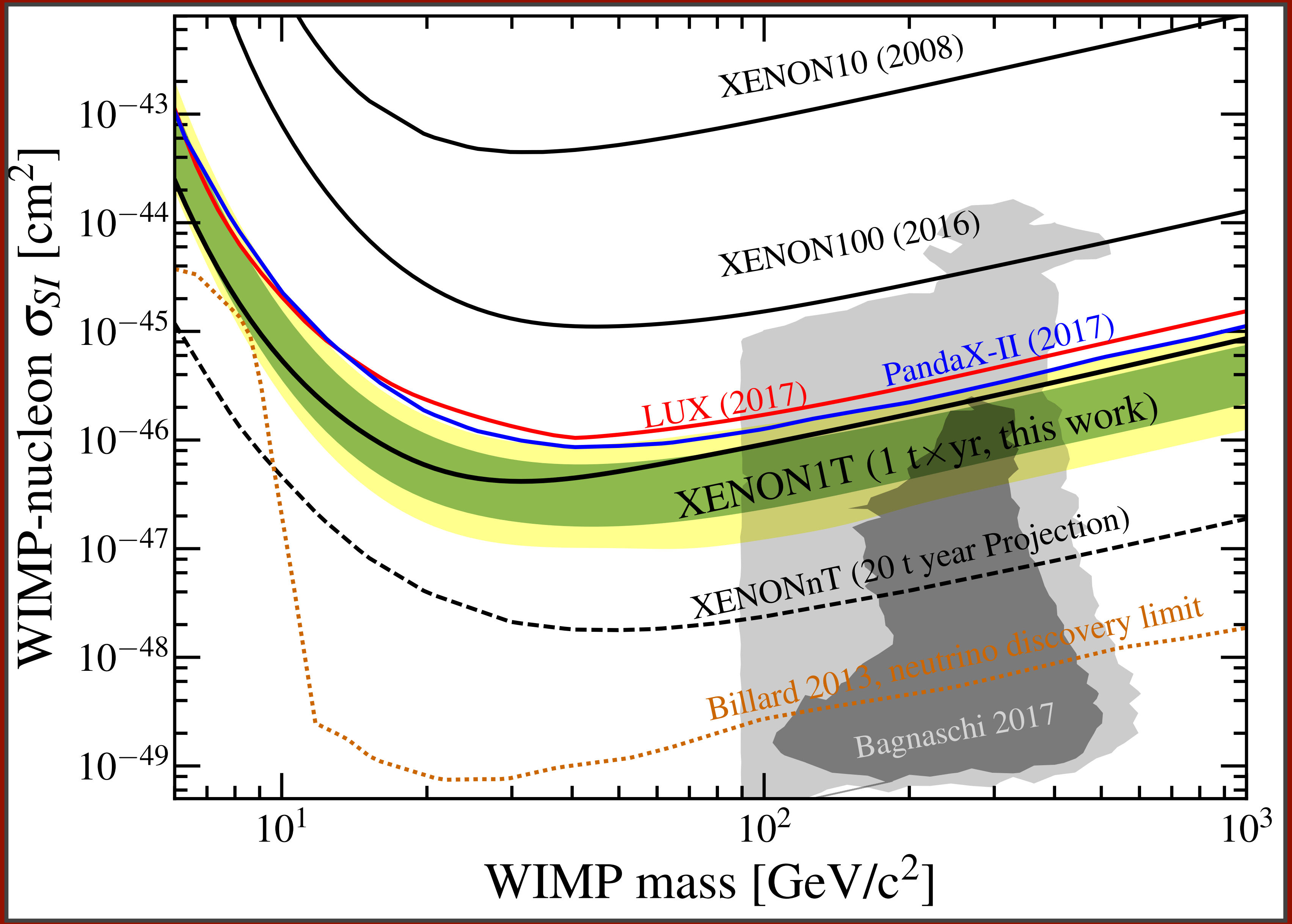


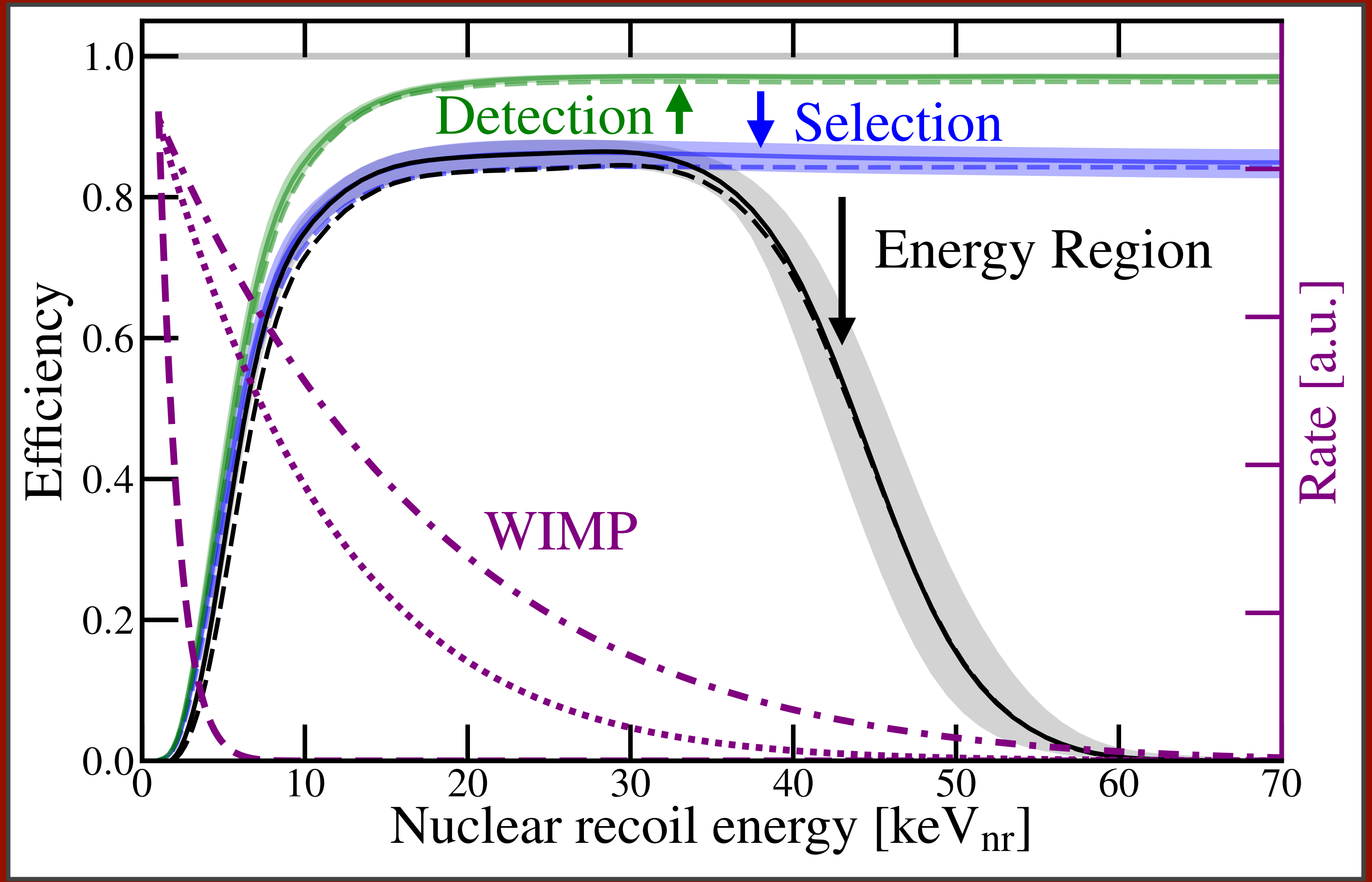
…that are scalable
XENON10
0.005 ton
XENON100, LUX, PandaX
0.06-0.3 ton
Fiducial mass
XENON1T
1.3 ton
today
XENONnT, LZ
5-6 ton
ER background level
DARWIN
30 ton

XENON1T WIMP analysis

- Search for NR above background
- Profile-likelihood analysis in (at least) S1 + S2 space
- ~800 total events in 1 ton*year exposure







XENON1T: Phys. Rev. Lett. 121, 111302 (2018)

Beyond the WIMP search: ER signals

Combined Energy Scale

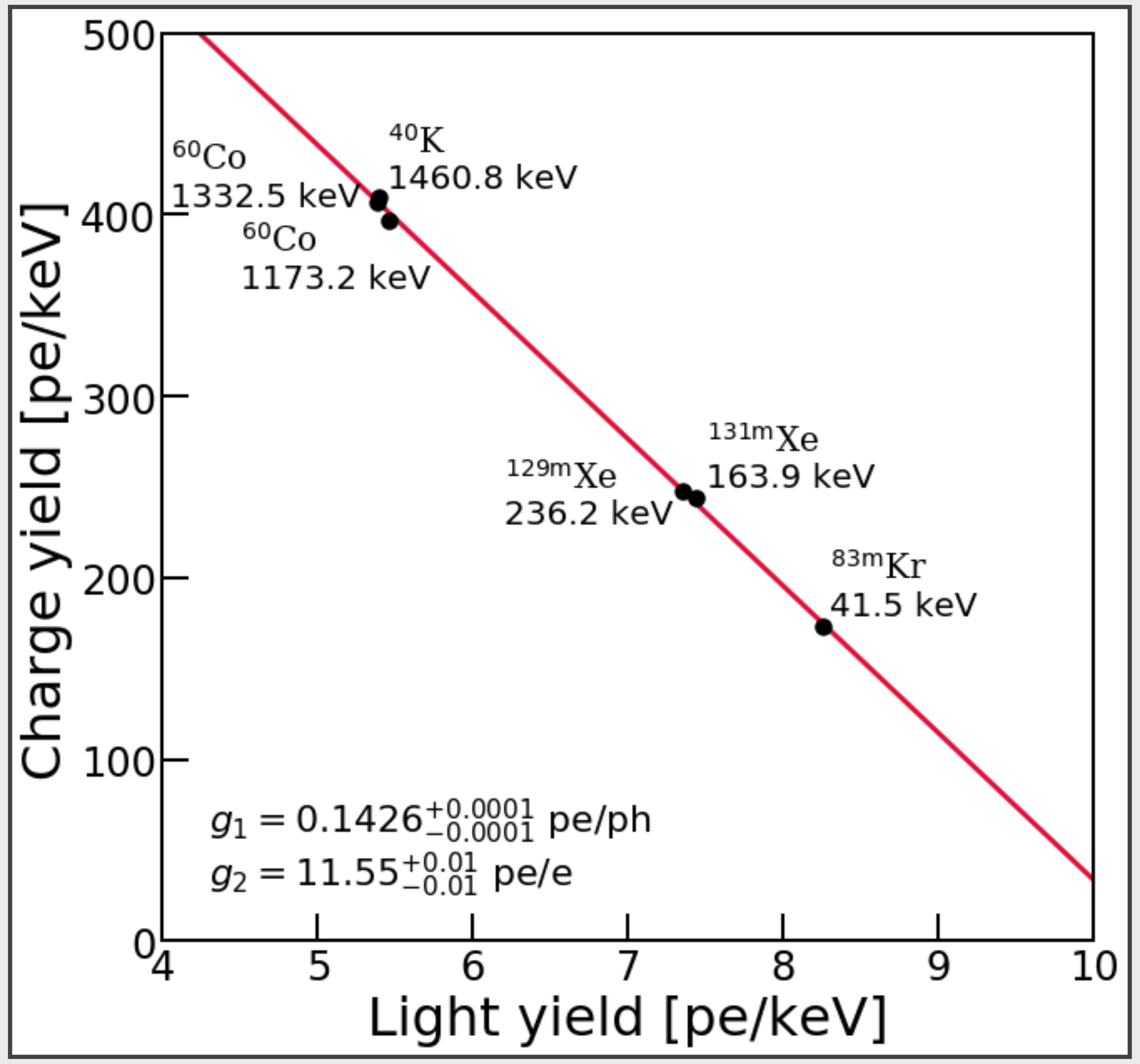
$$E = W(n_{ph} + n_e)$$

$$\frac{E}{W} = \frac{S_1}{g_1} + \frac{S_2}{g_2}$$

$$\frac{S_2}{E} = -\frac{g_2}{g_1}\frac{S_1}{E} + \frac{g_2}{W}$$

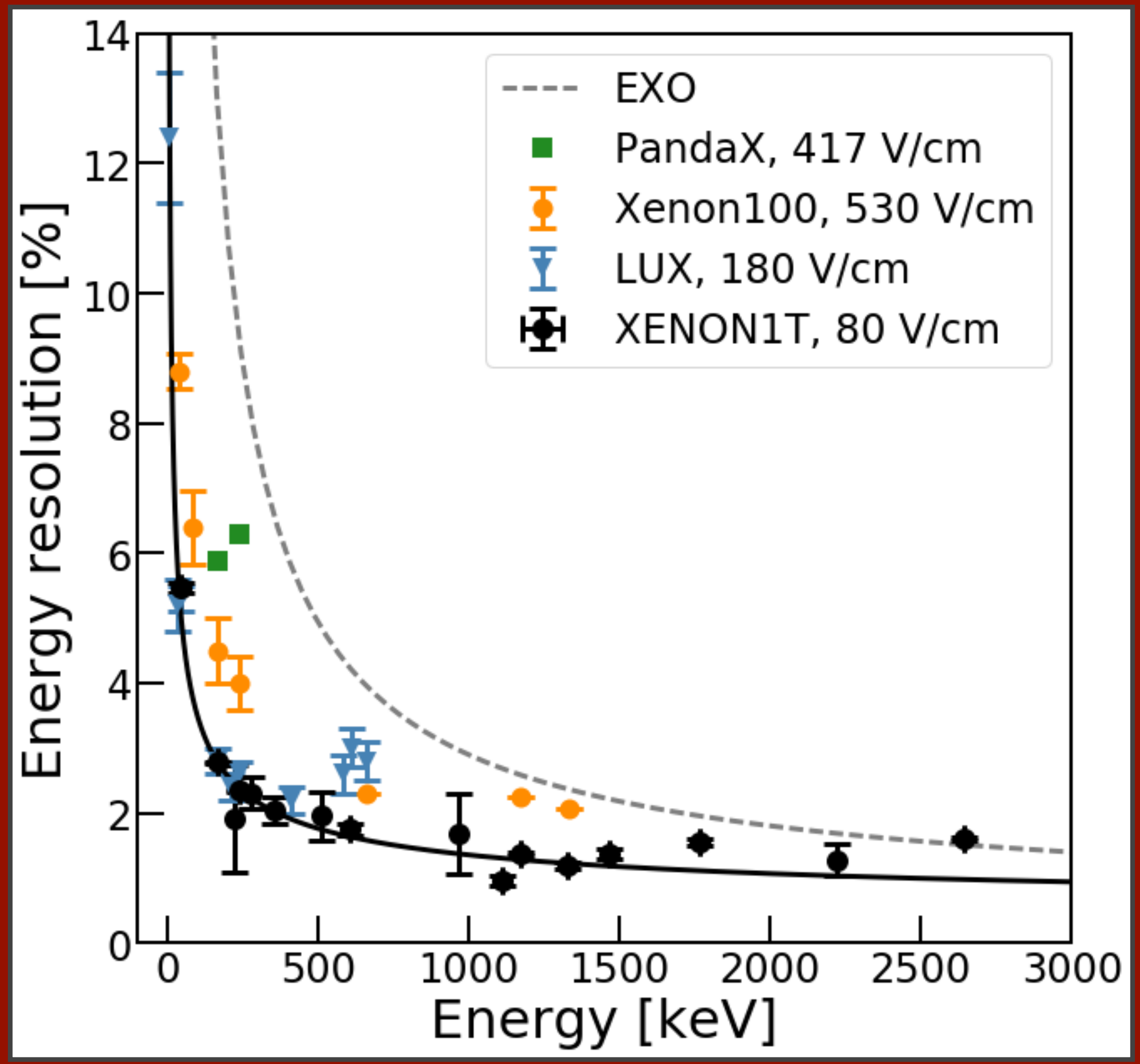
$$Q = -\frac{g_2}{g_1}L + \frac{g_2}{W}$$

$$W = 13.7 \text{ eV}$$

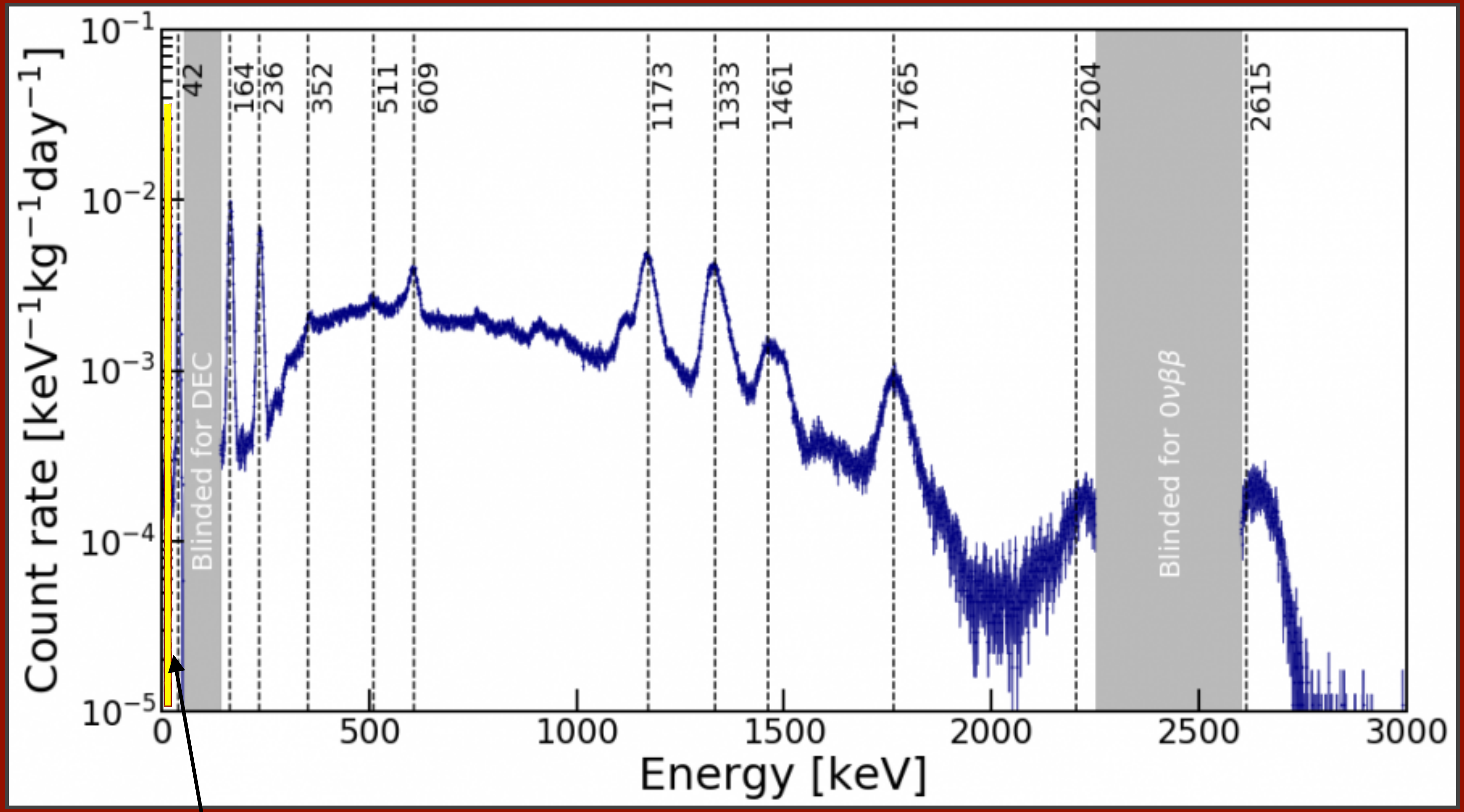


- Use anti-linearity of S1 & S2 to define 'combined energy scale' (CES)
- Easy to model — no need to worry about energy dependence of photon/charge yields
- With knowledge of g1 & g2, easy to reconstruct energy from S1, S2

Energy resolution of several xenon TPCs



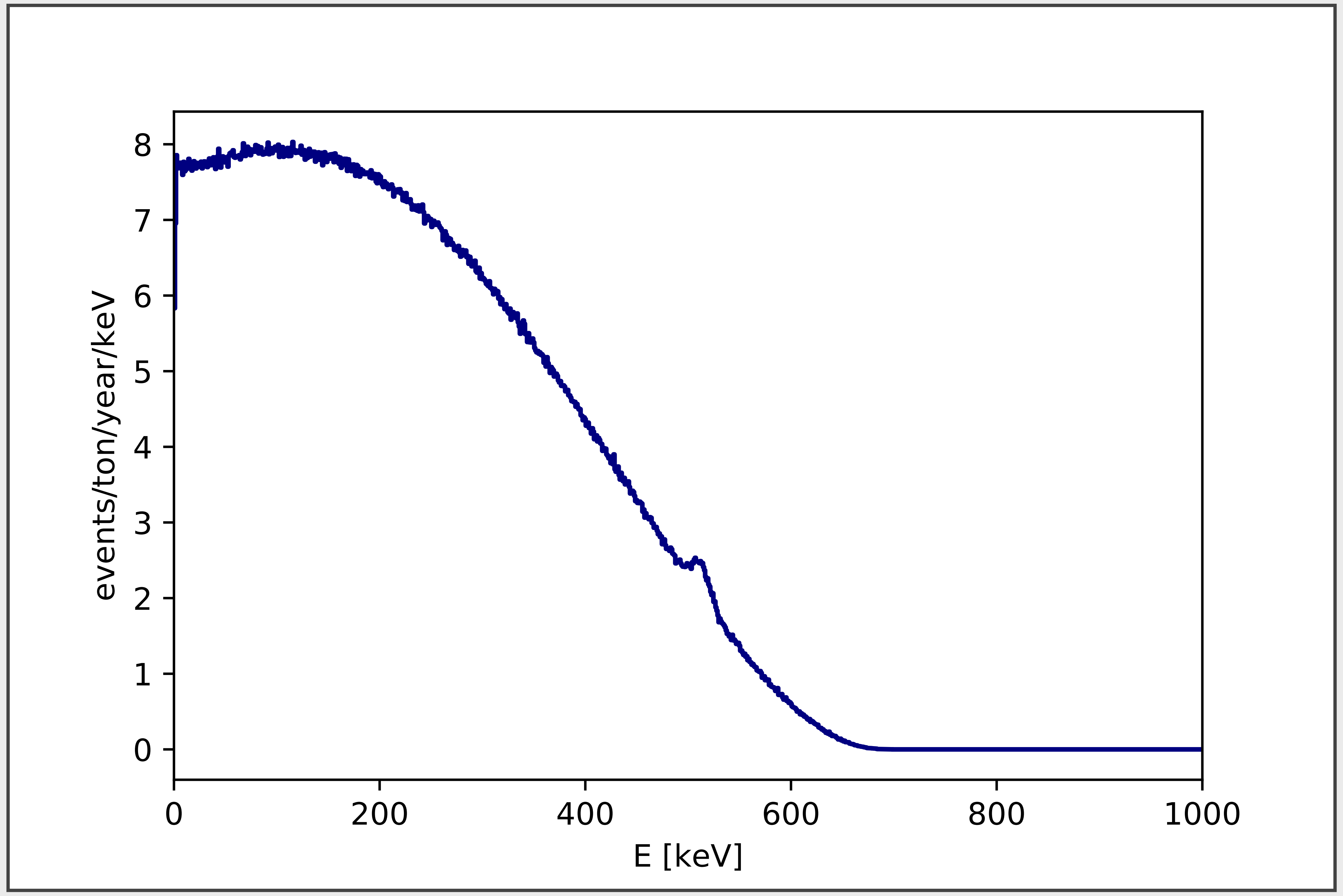
A CES spectrum from XENON1T

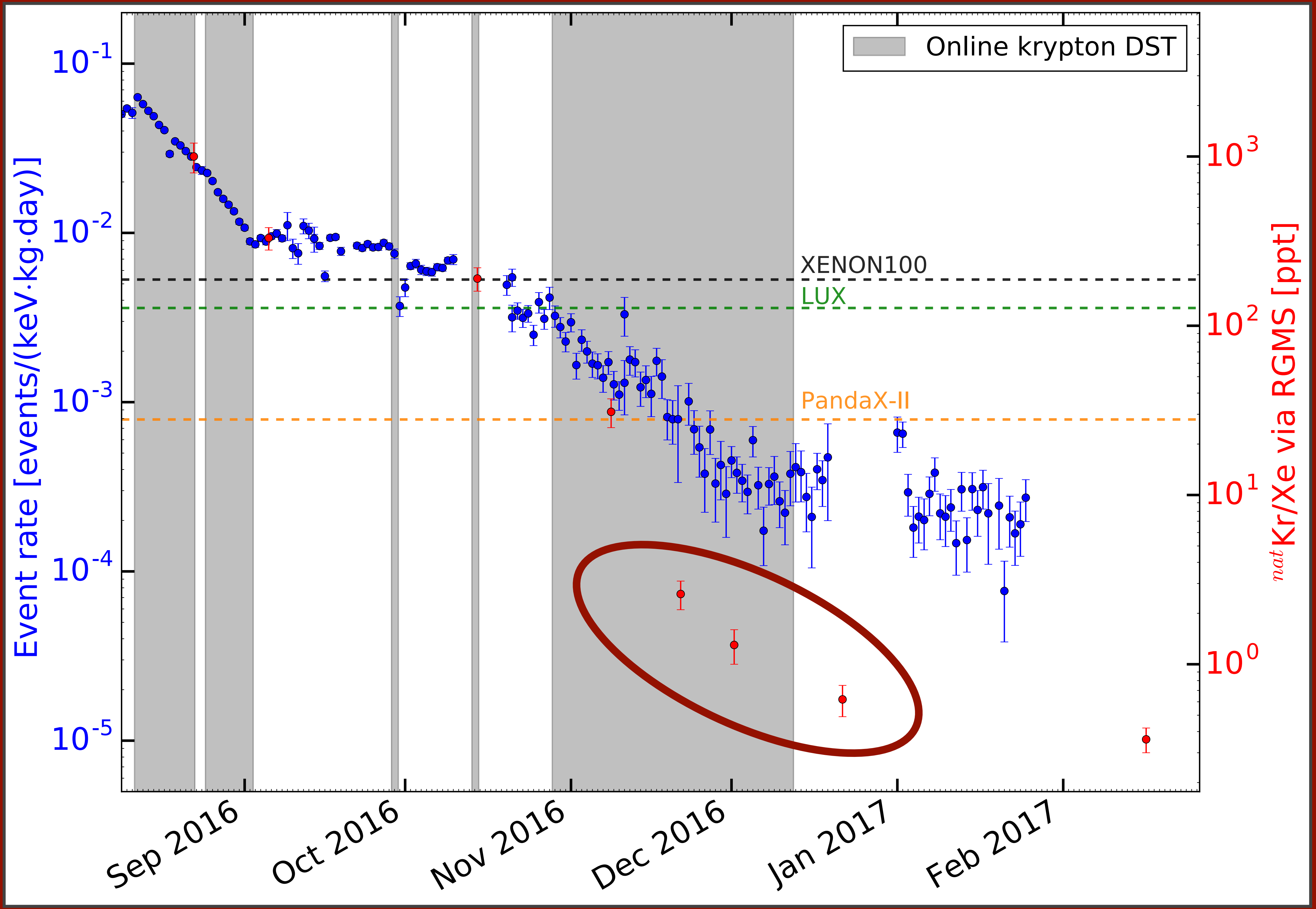


WIMP search ROI

ER Backgrounds: Kr85

- β-emitting noble gas, distributed uniformly in xenon liquid/gas
  - not removed by fiducialization cuts, *in situ* purification (getters)



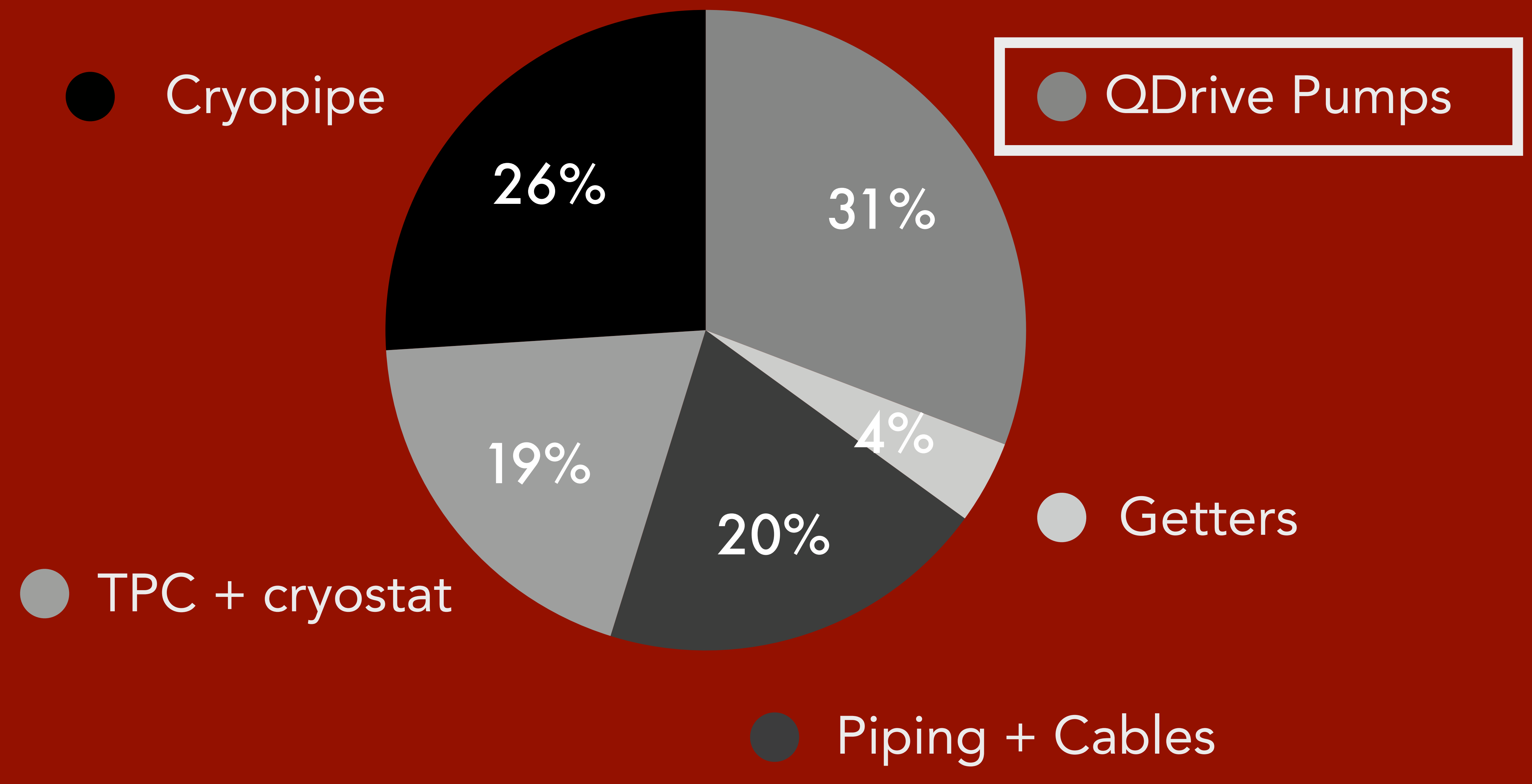


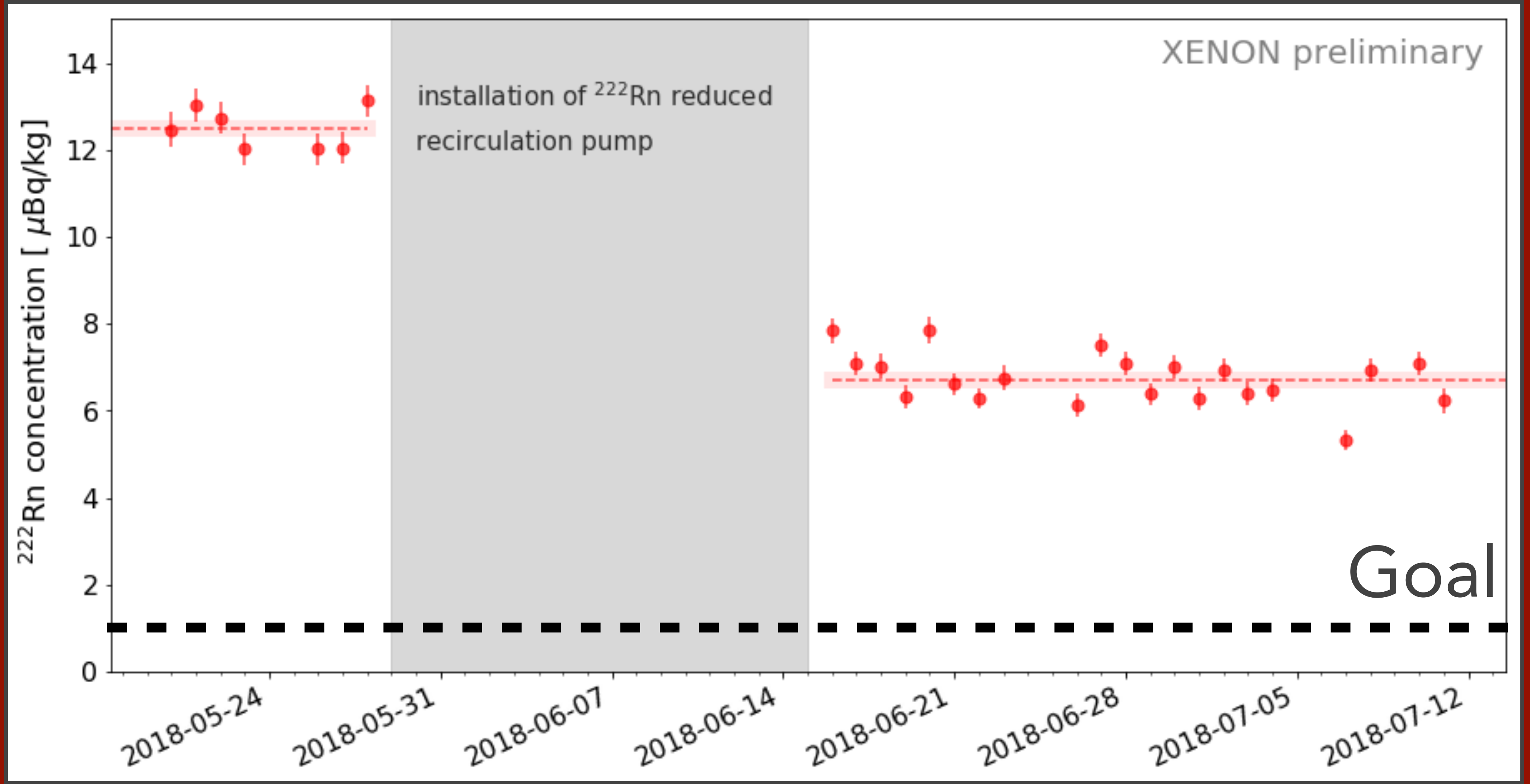
- Removed via cryogenic distillation (XENON1T/nT) or gas charcoal chromatography (LUX/LZ)
  - 100 ppb to 0.66 ppt in XENON1T
  - Level of 0.026 ppt already reached in the lab
  - goal of ~0.01 ppt in XENONnT/LZ/DARWIN

Eur. Phys. J. C (2017) 77:275

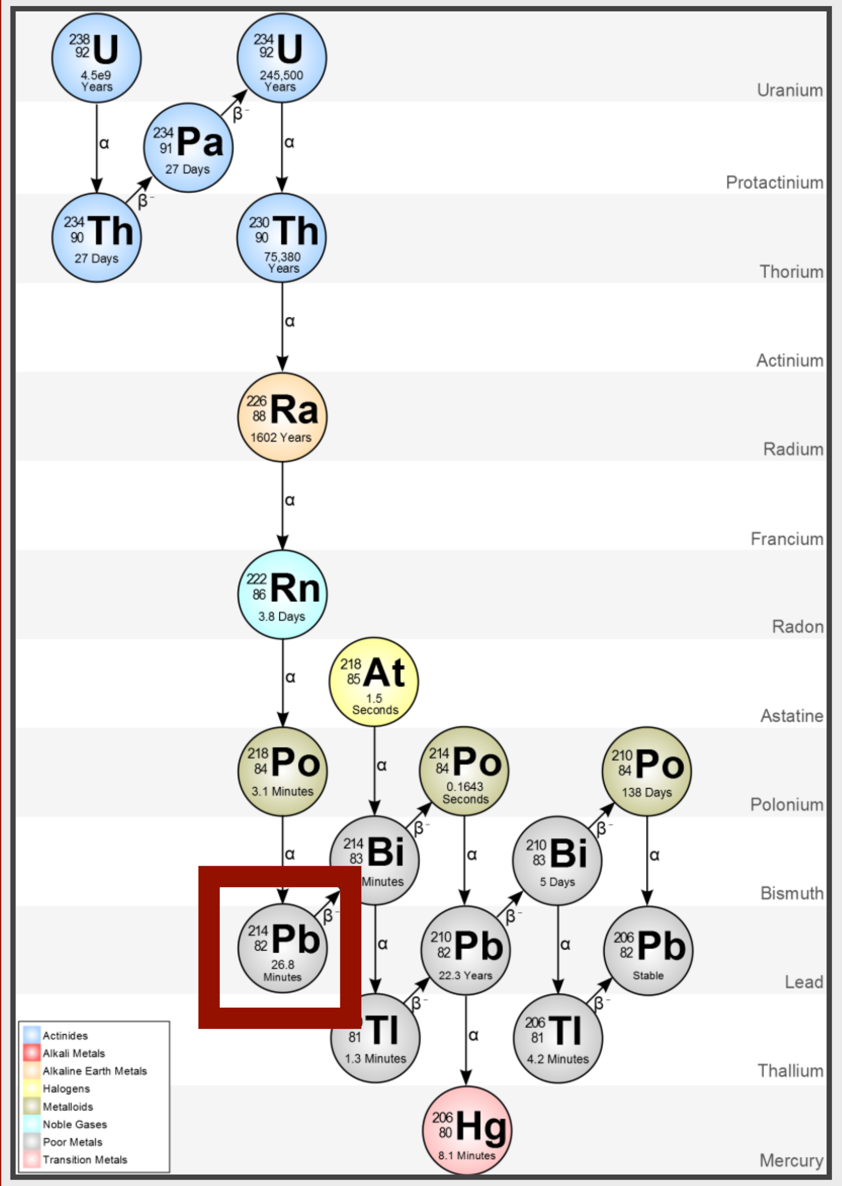
ER Backgrounds: Rn222

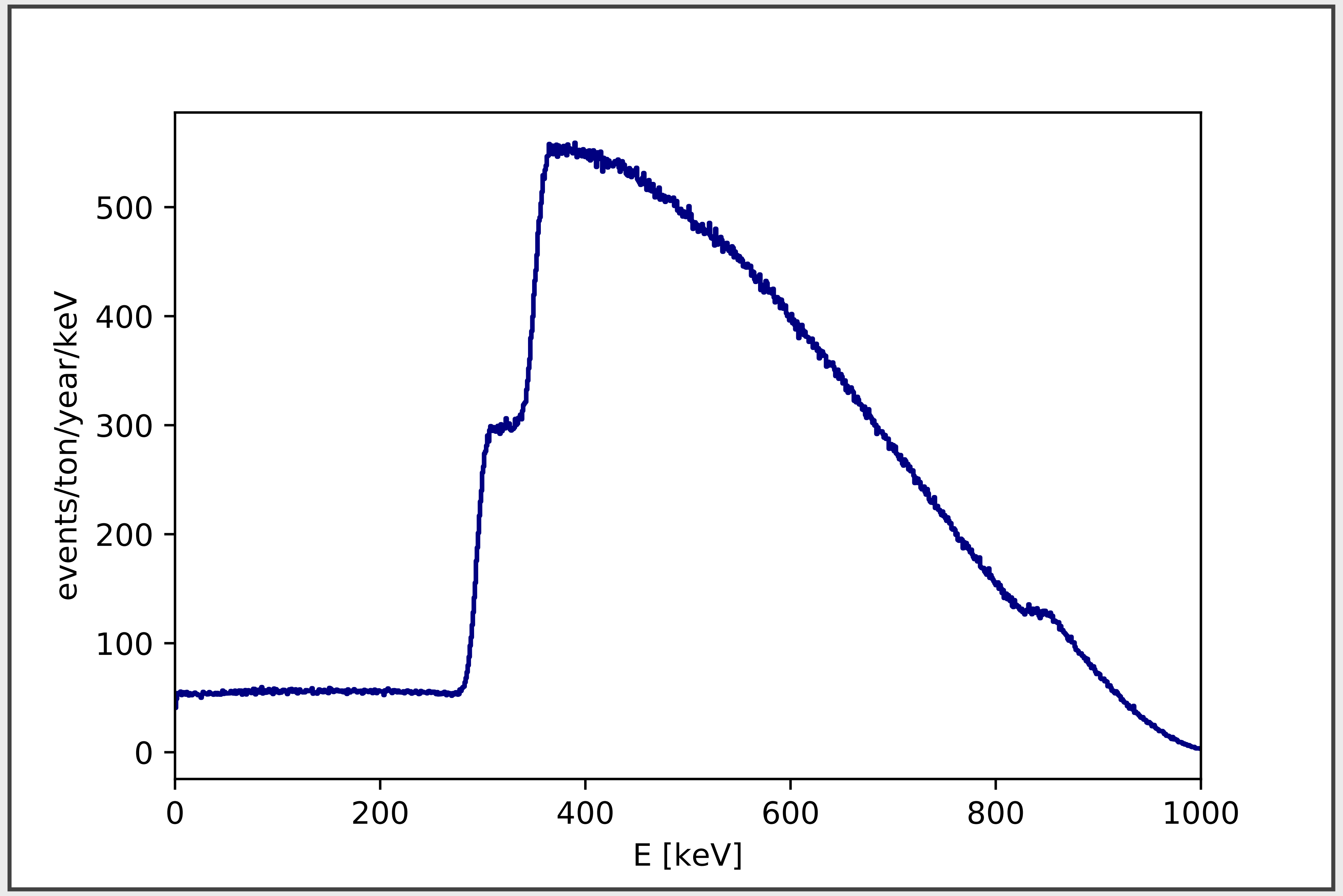
XENON1T Rn Budget





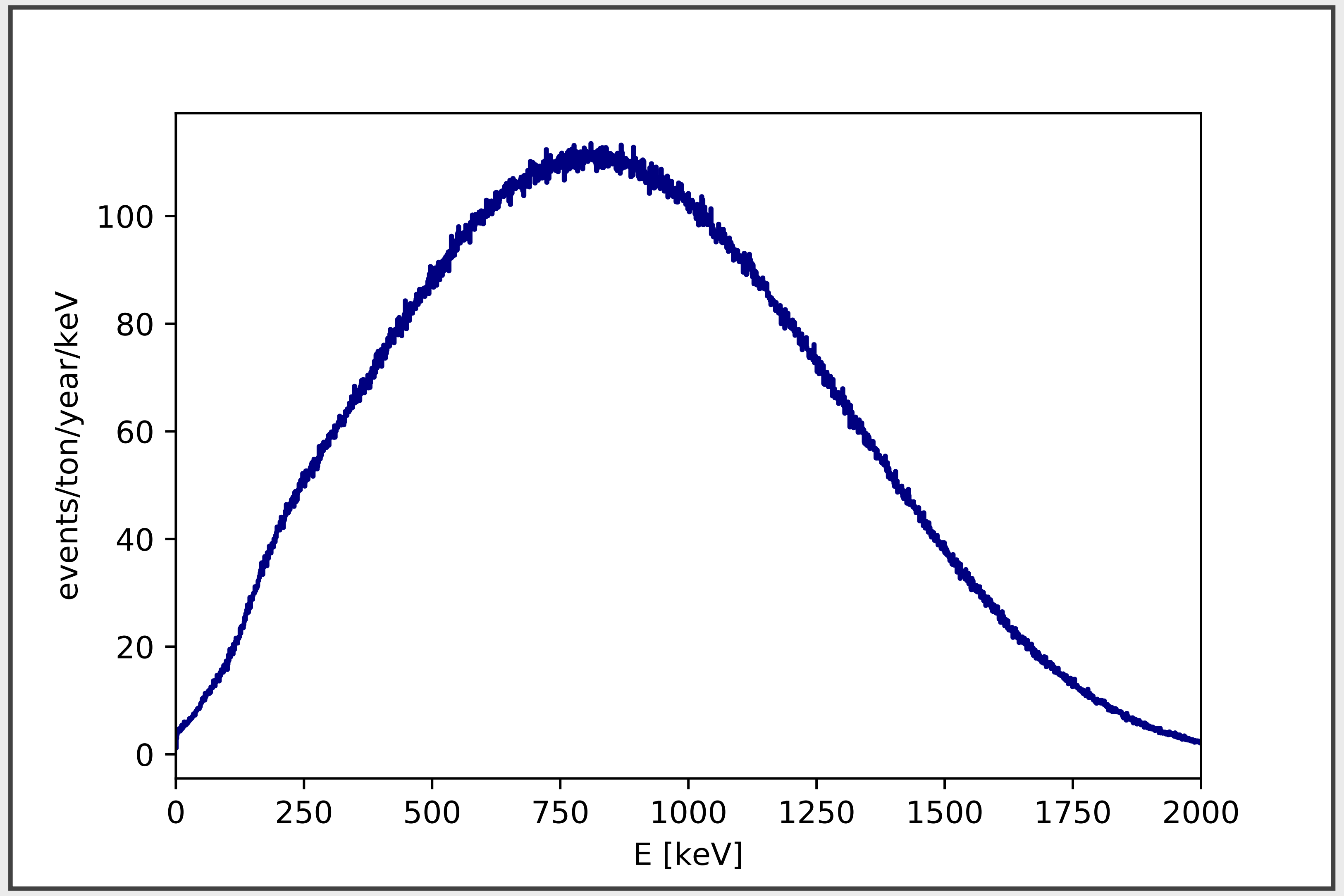
- ✦ β-decay of Pb214 - distributed uniformly in liquid/gaseous xenon
- ✦ Online Rn distillation column in future detectors
  - Test with XENON1T saw ~20% decrease in Rn
- ✦ Goal: 1 µBq/kg Rn concentration (factor of 10 improvement)





ER Backgrounds: Xe136

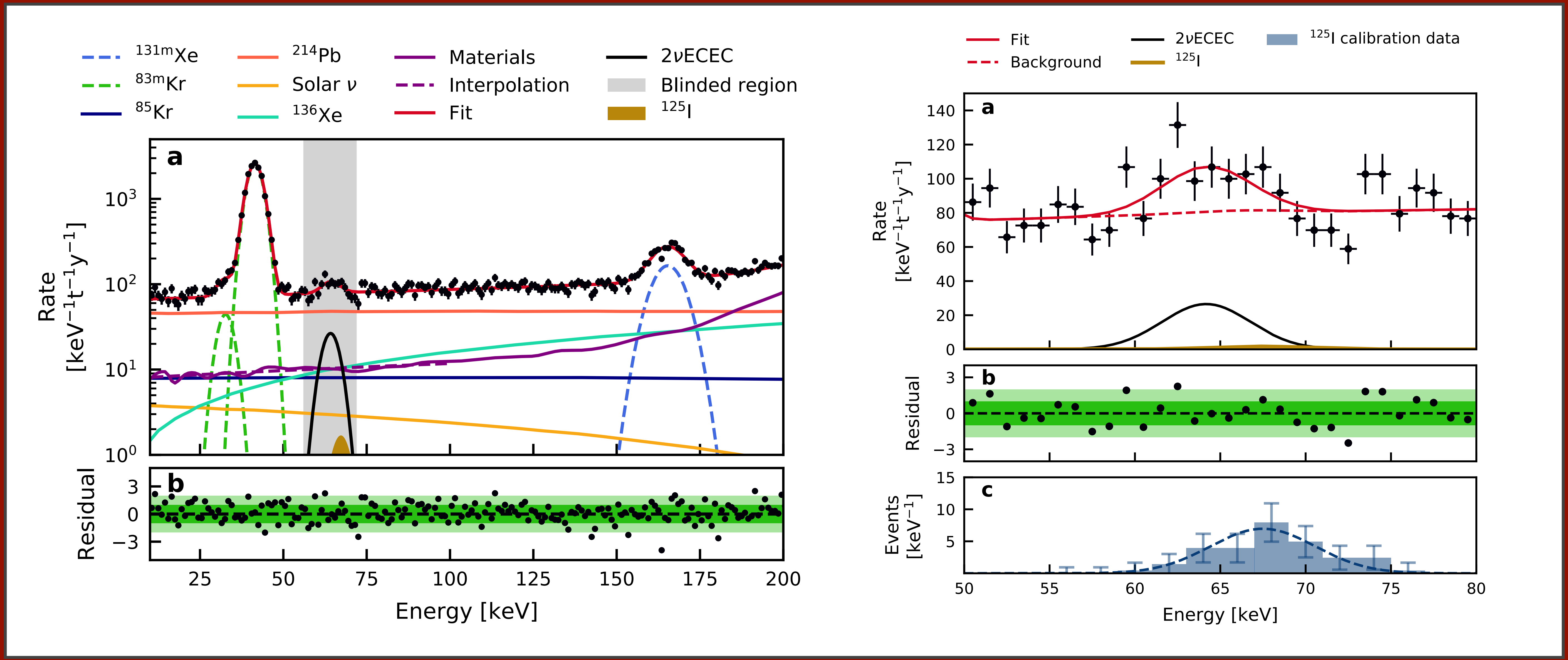
- 2νββ decay with $T_{1/2} \sim 10^{21}$ year
- 8.8% natural abundance
  - Could be removed by isotopic depletion?



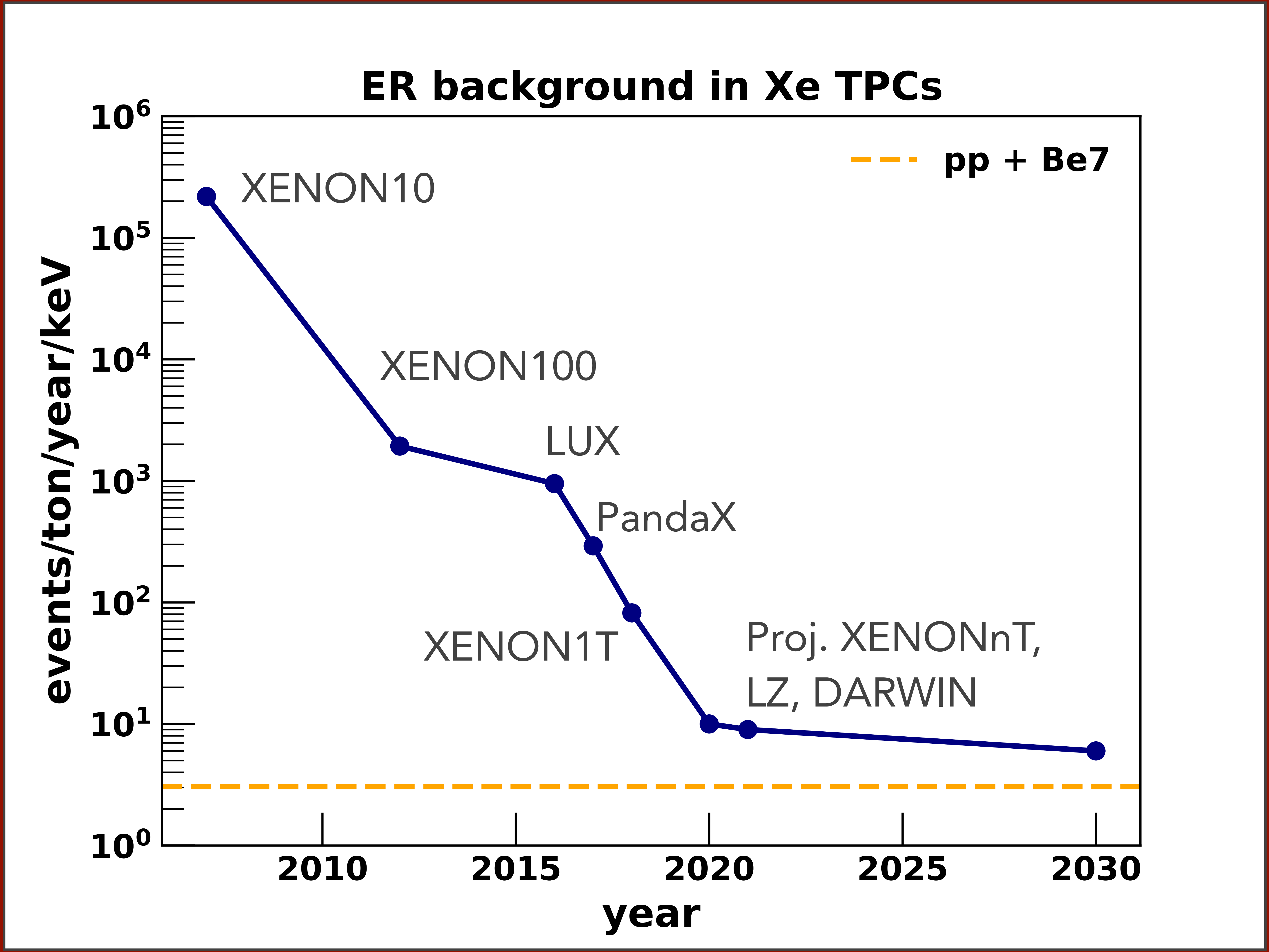
ER Backgrounds: Xe124 (!!!)

- 2νECEC decay with $T_{1/2} \sim 10^{22}$ years, the longest half-life measured to date
- Peak at 64.3 keV, so not too relevant for ν searches

Nature 568 7753 (2019)



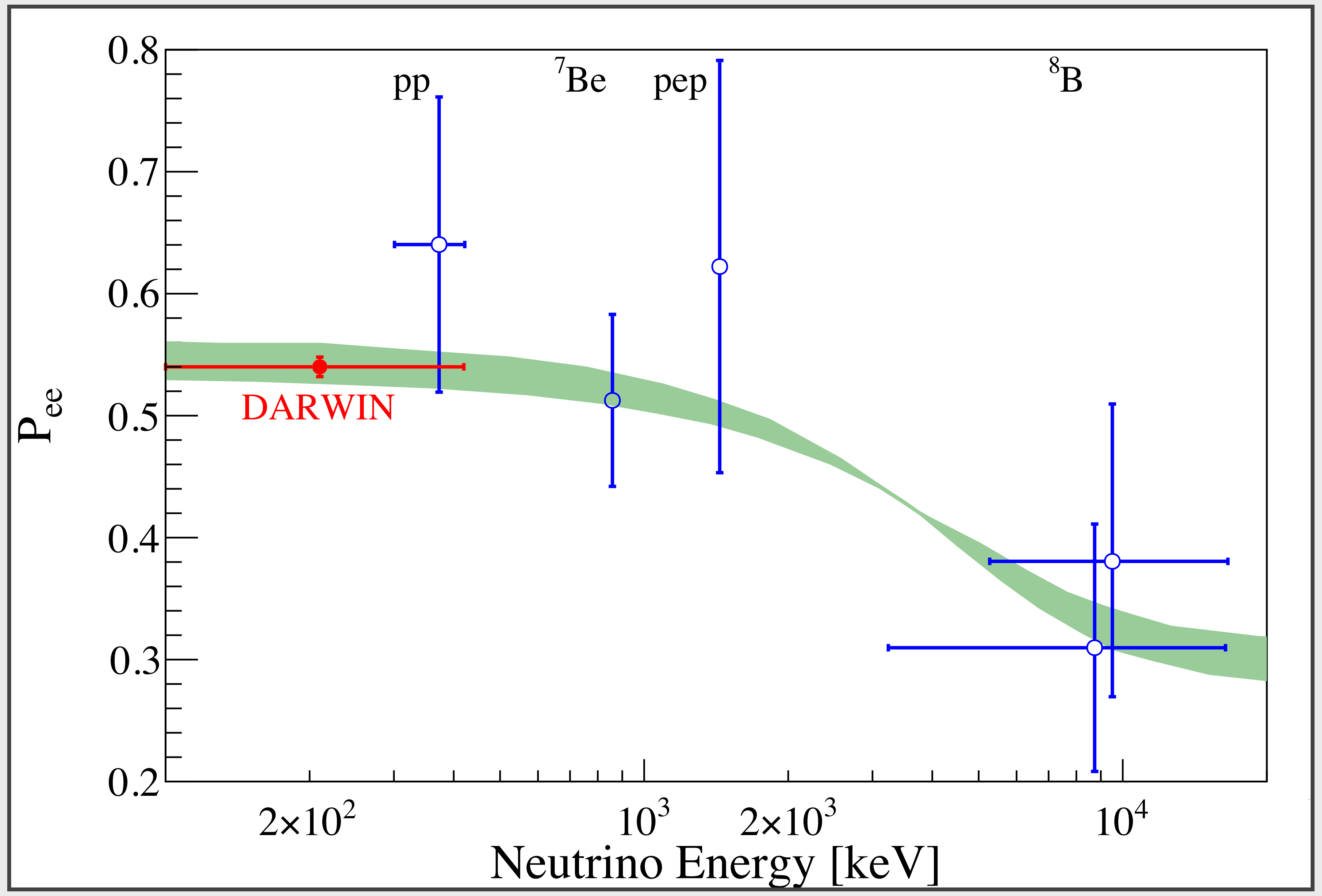
Progress/projections of total ER background (low energy)

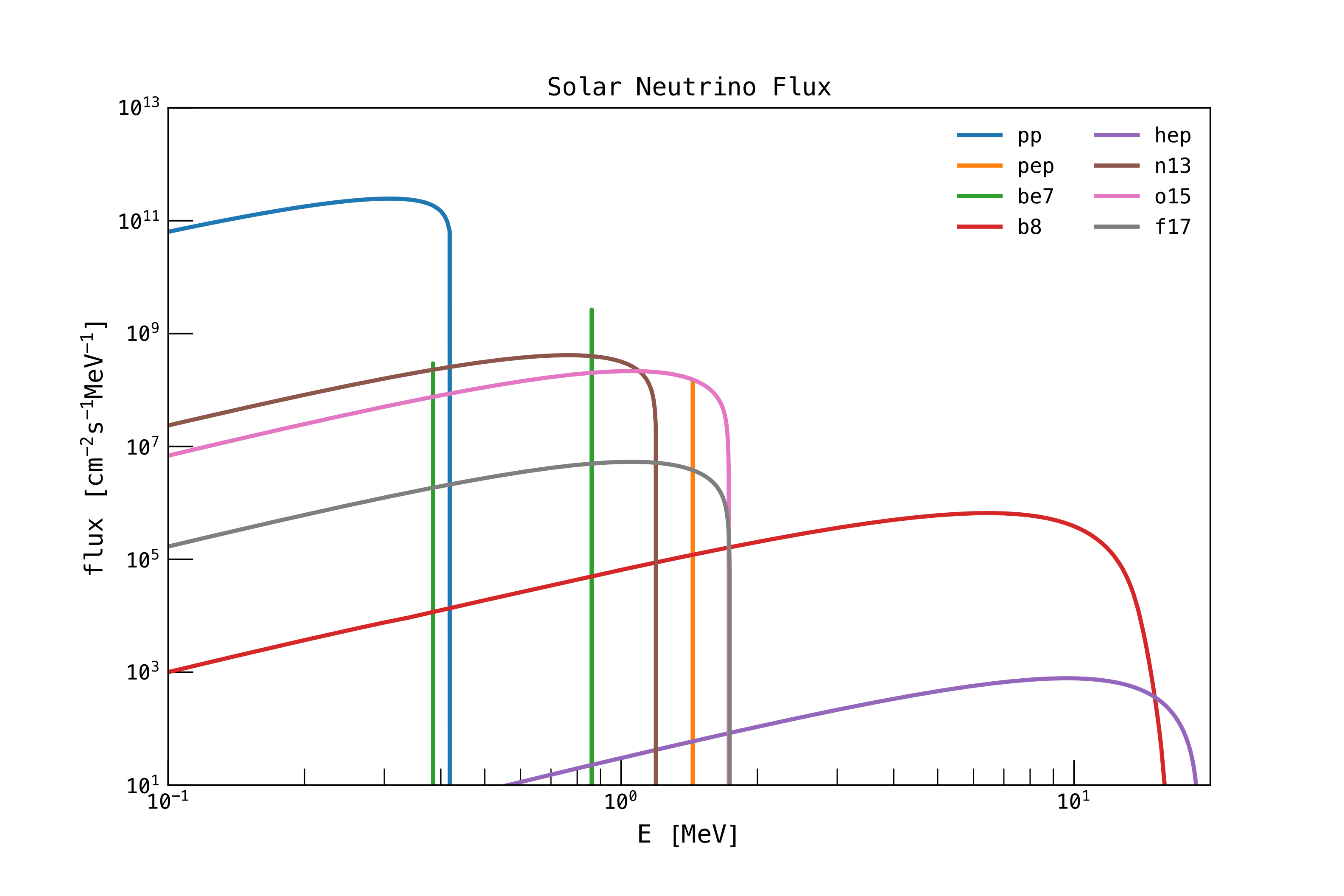


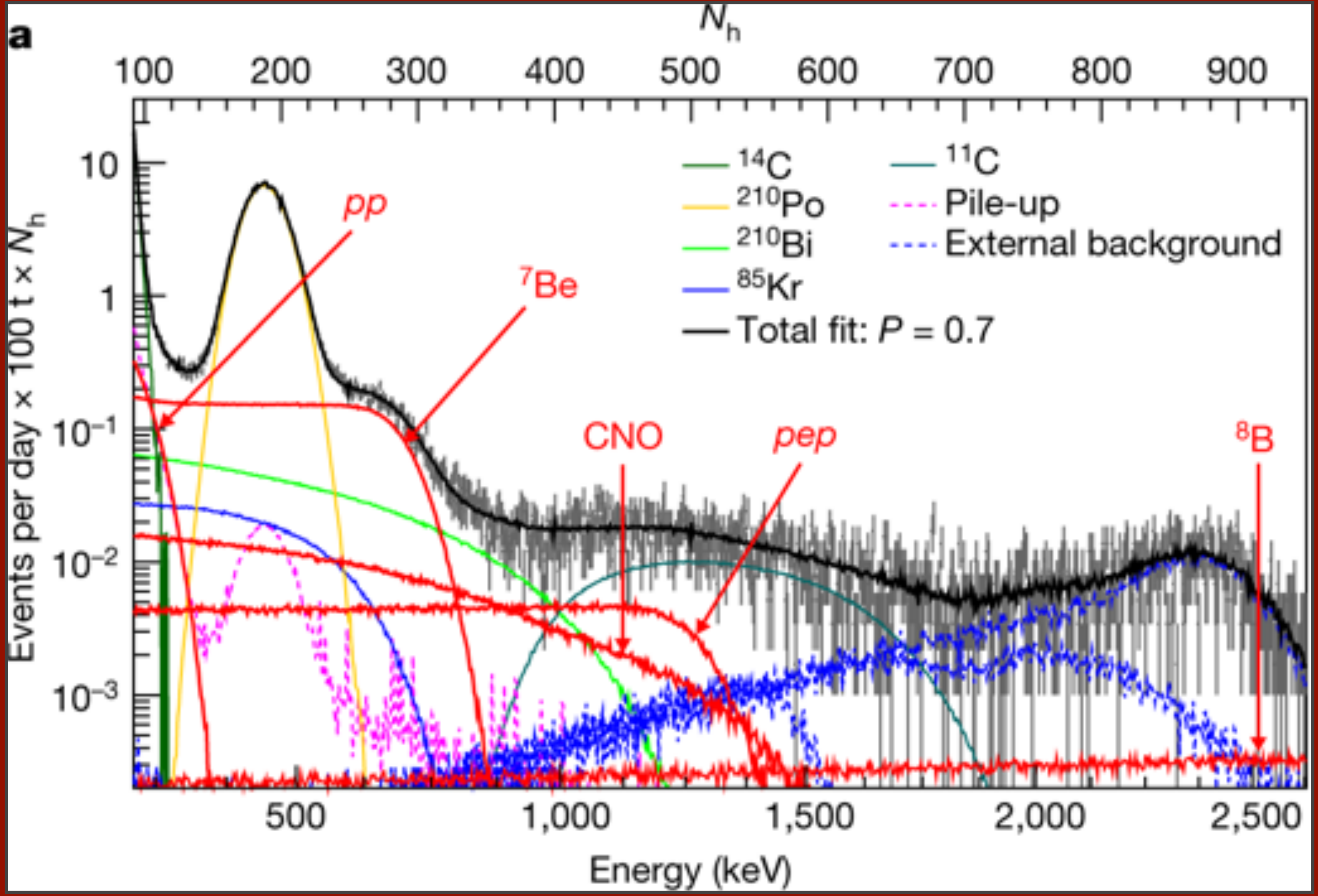
ER *Signals*: solar neutrinos

- ✦ Precision measurement of the dominant pp ν flux
  - Constrain stellar physics such as energy production
  - ν oscillations at low energy
- ✦ CNO measurements possible in Darwin?
  - See Newstead, Strigari, Lang (2018); and Louis' talk from Thurs.
- ✦ Physics beyond SM?

JCAP 1611 (2016) no.11, 017



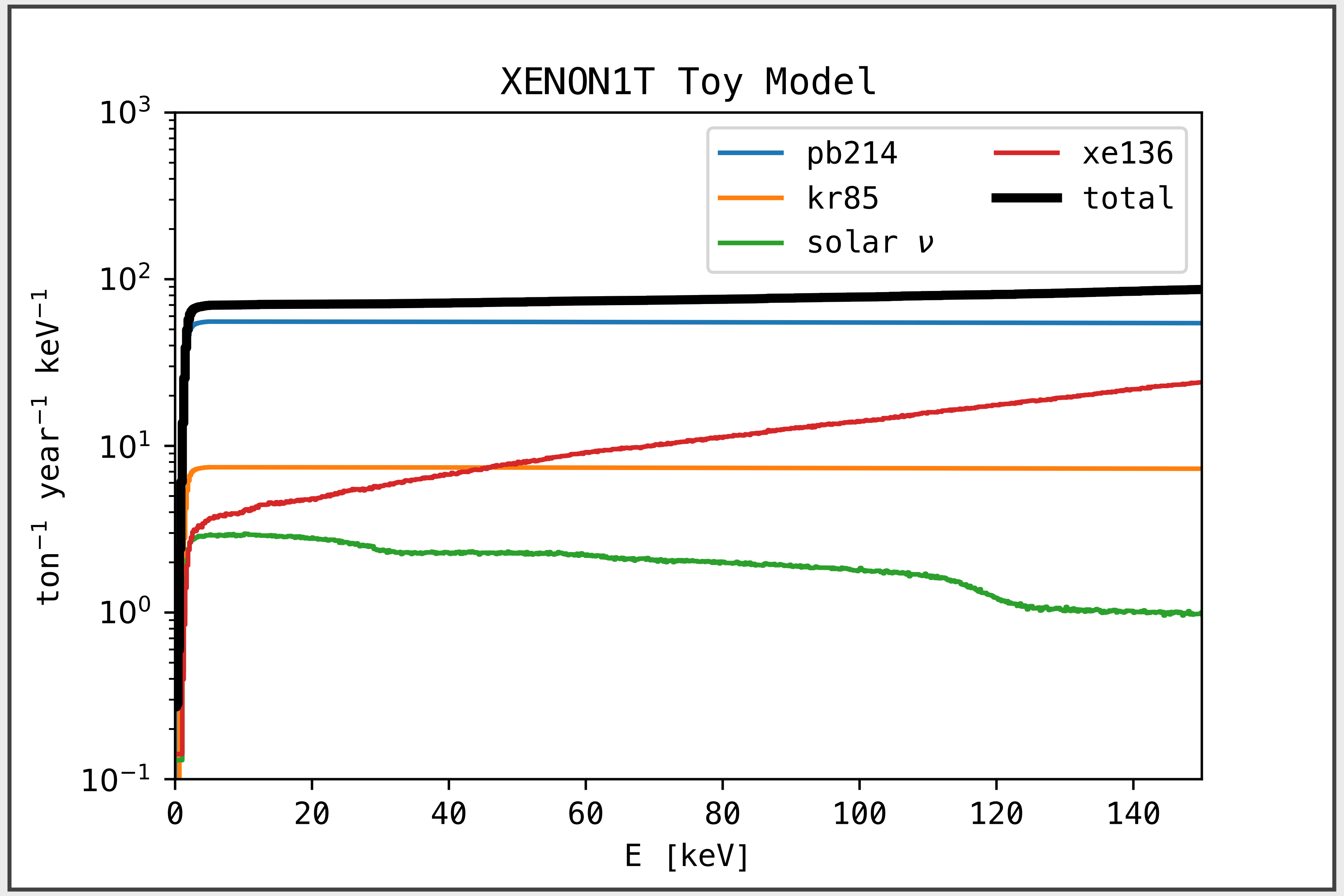


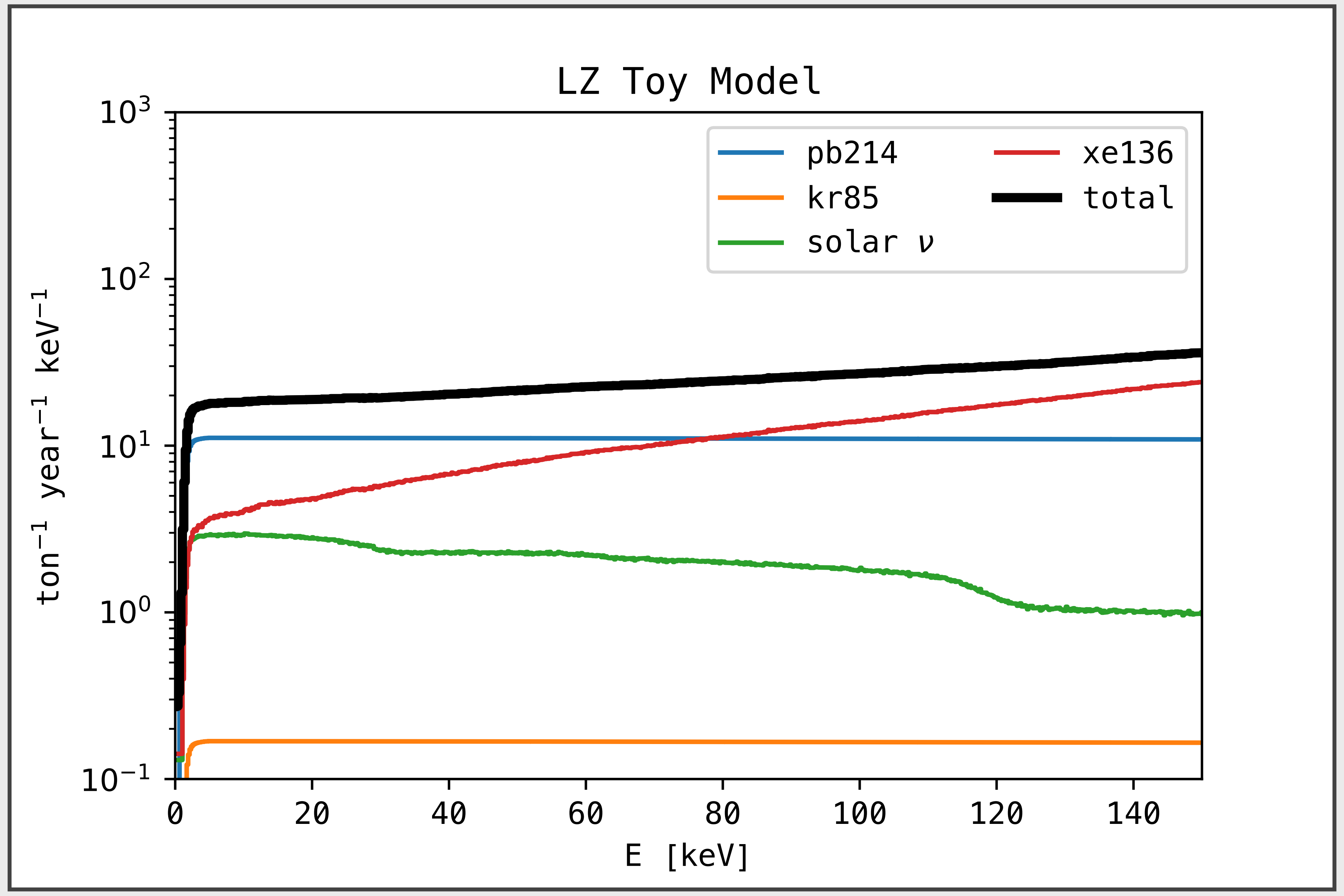


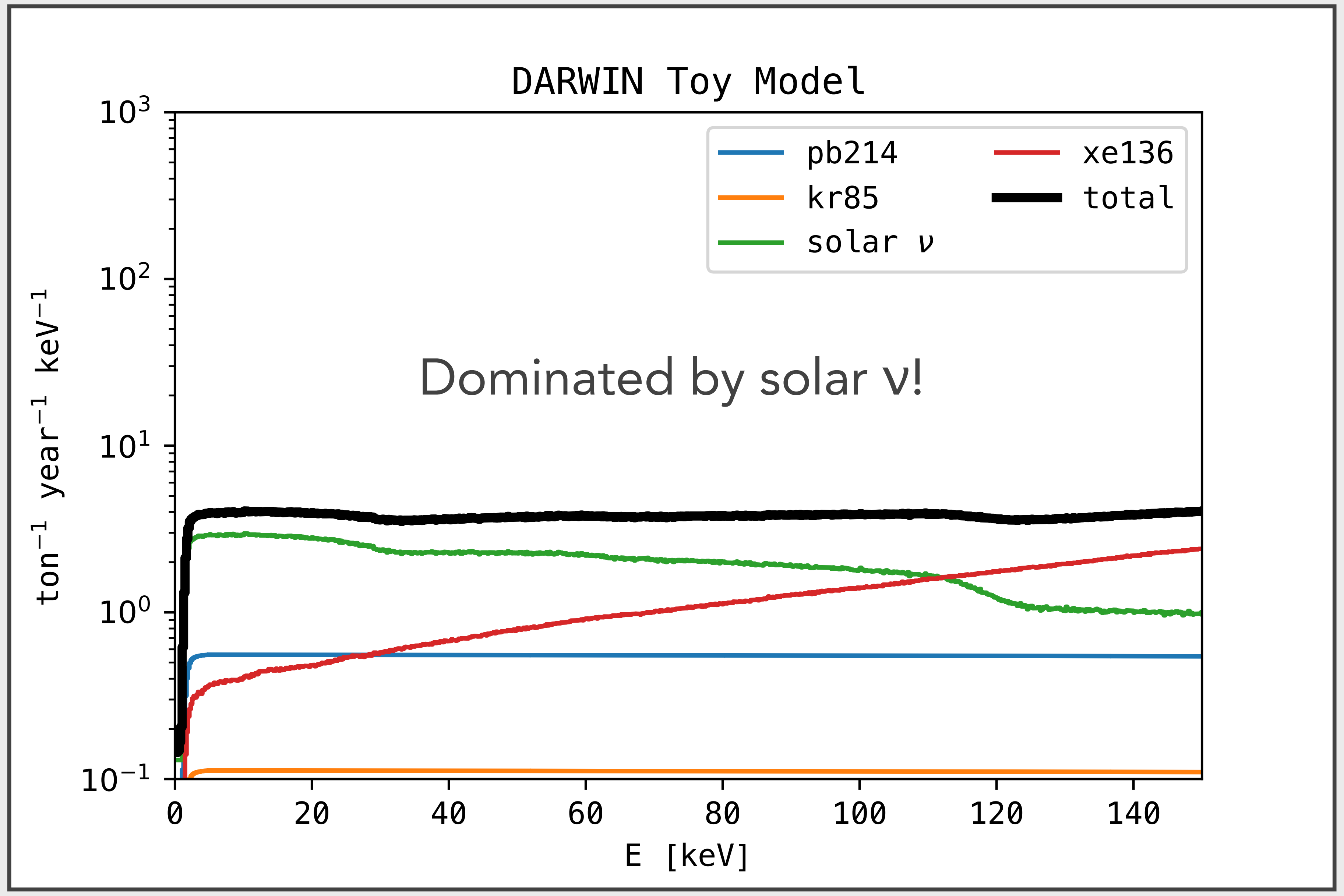
Borexino: *Nature* **562**, 505–510 (2018)

Solar ν toy models

	Kr85 (ppt)	Rn222 (μBq/kg)	Xe136 depleted?
XENON1T	0.66	10	no
1703.09144 LZ/XENONnT	0.015/0.01	2/1	no
1606.0700 DARWIN	0.01	0.1	10%



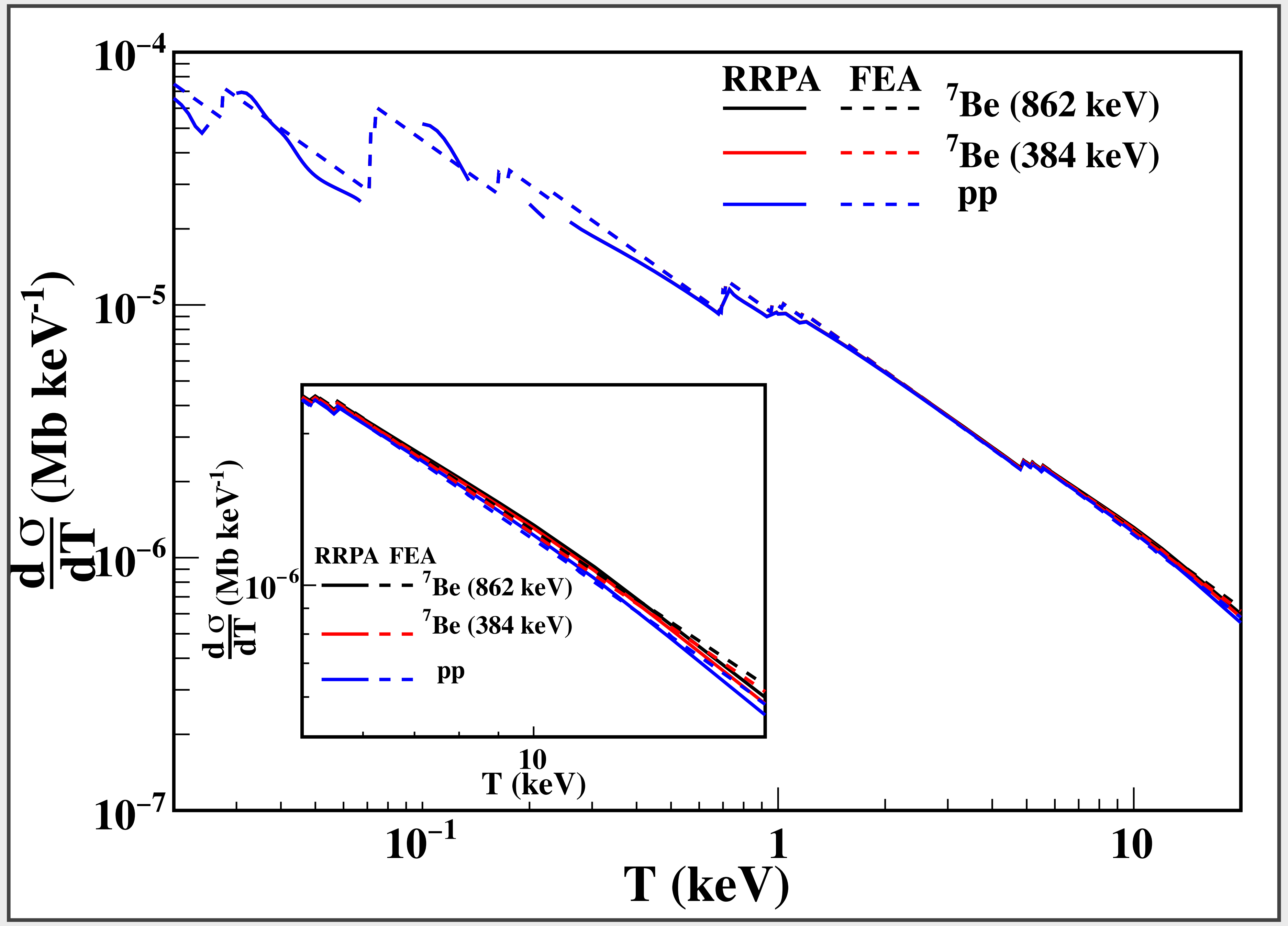




Neutrino Magnetic Moment

$$\frac{d\sigma}{dT} \sim \mu^2 \left(\frac{1}{T} - \frac{1}{E_\nu} \right)$$

- Rough sensitivity estimates using low-energy ER framework of XENON1T
  - assumes XENON1T efficiency and resolution
  - FEA assumed (See Chih-Pan's talk Friday)



	μ_{eff} (μ_B)	Fiducial mass (tons)	Livetime (days)	Kr85 (ppt)	Rn222 (μBq/kg)	Xe136 depletion?
XENON1T		1	250	0.66	10	no
LZ/nT		5.6	1000	0.015	2	no
DARWIN		40	1000	0.01	0.01	10%

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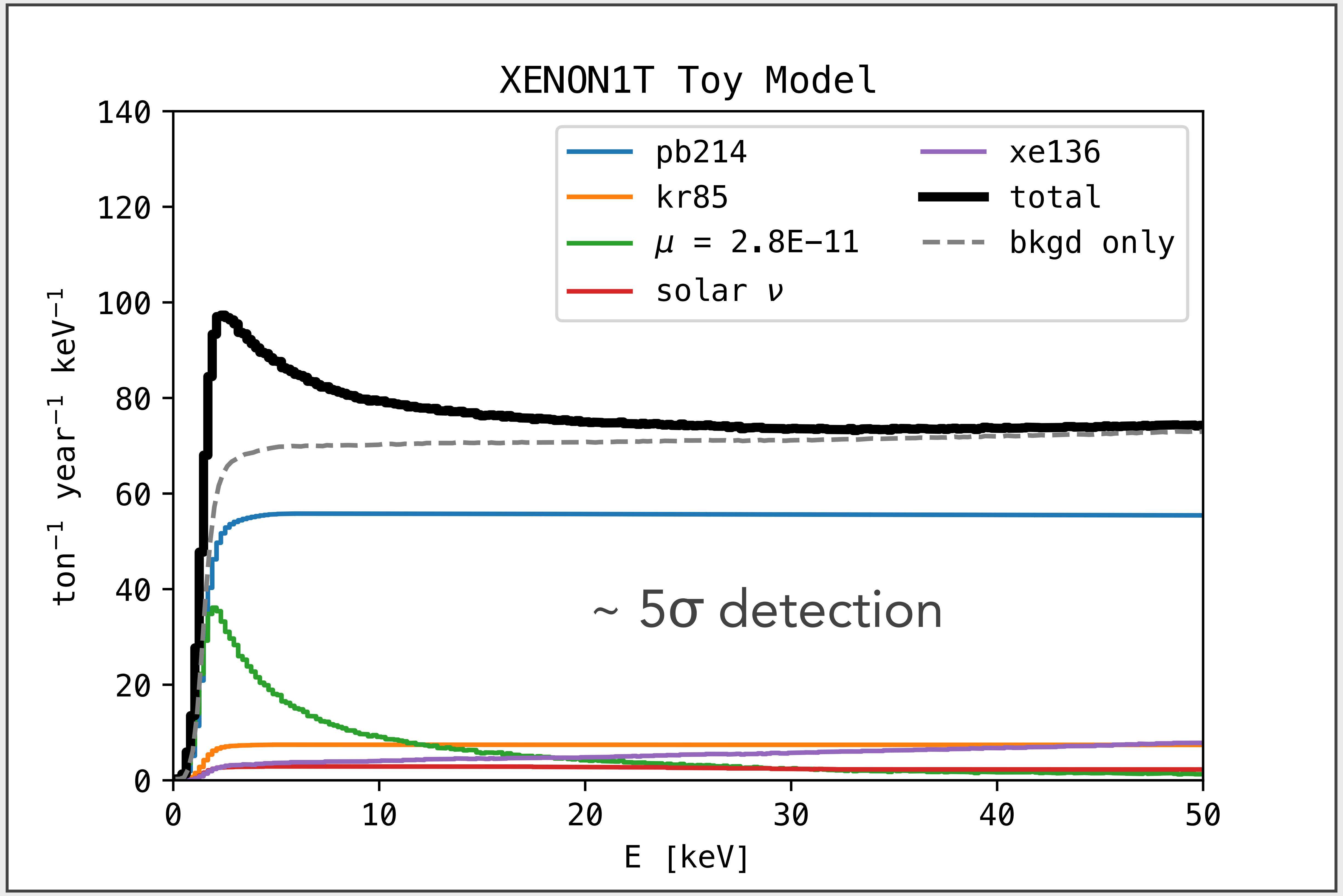

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- ✦ Rough sensitivity estimates using low-energy ER framework of XENON1T
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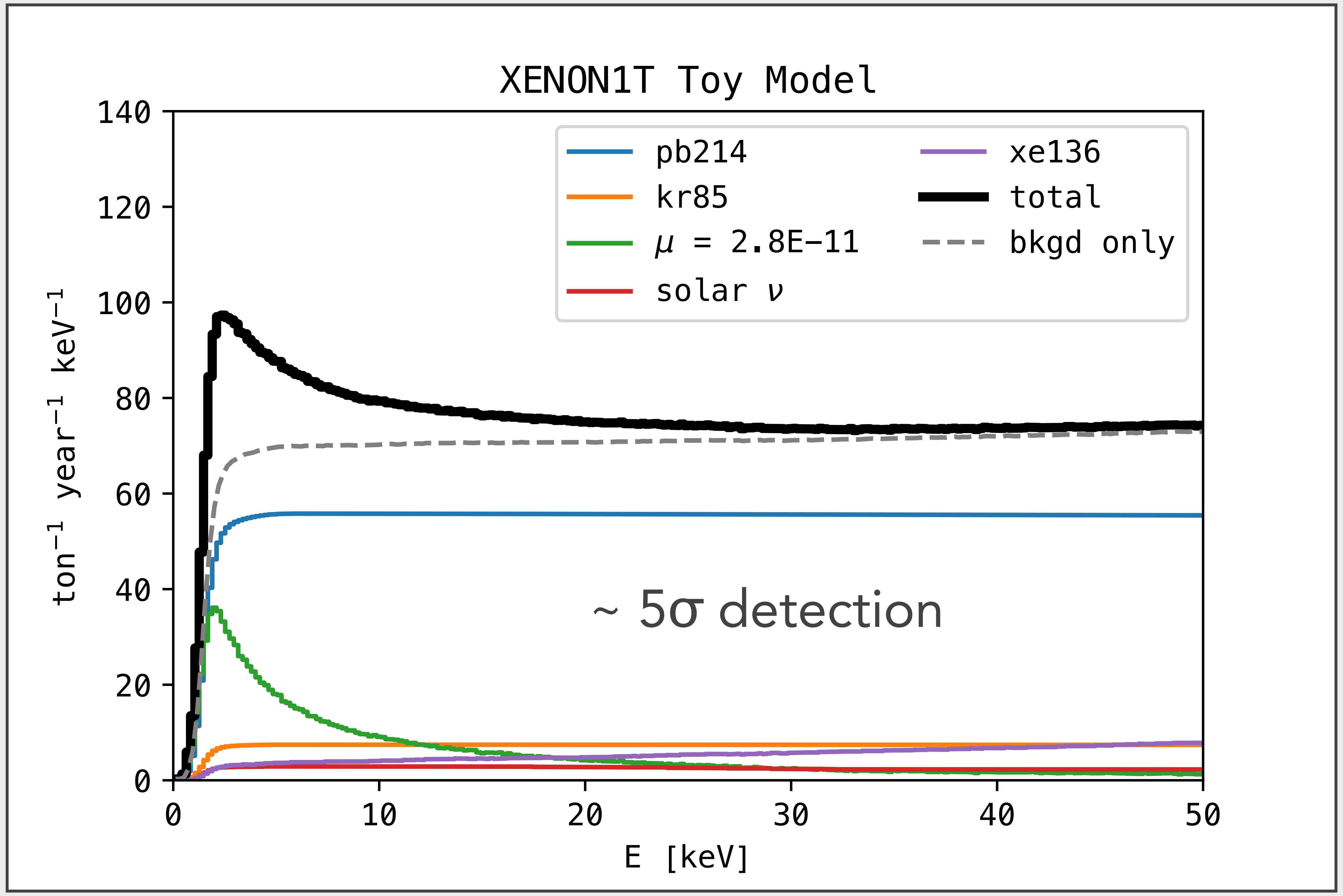
  - FEA assumed (See Chih-Pan's talk Friday)
- ✦ Likely world-leading sensitivity!



	μ_{eff} (μ_B)	Fiducial mass (tons)	Livetime (days)	Kr85 (ppt)	Rn222 (μBq/kg)	Xe136 depletion?
XENON1T	1.0E-11	1	250	0.66	10	no
LZ/nT	1.5E-12	5.6	1000	0.015	2	no
DARWIN	8.4E-13	30	1000	0.01	0.01	10%

Neutrino Magnetic Moment

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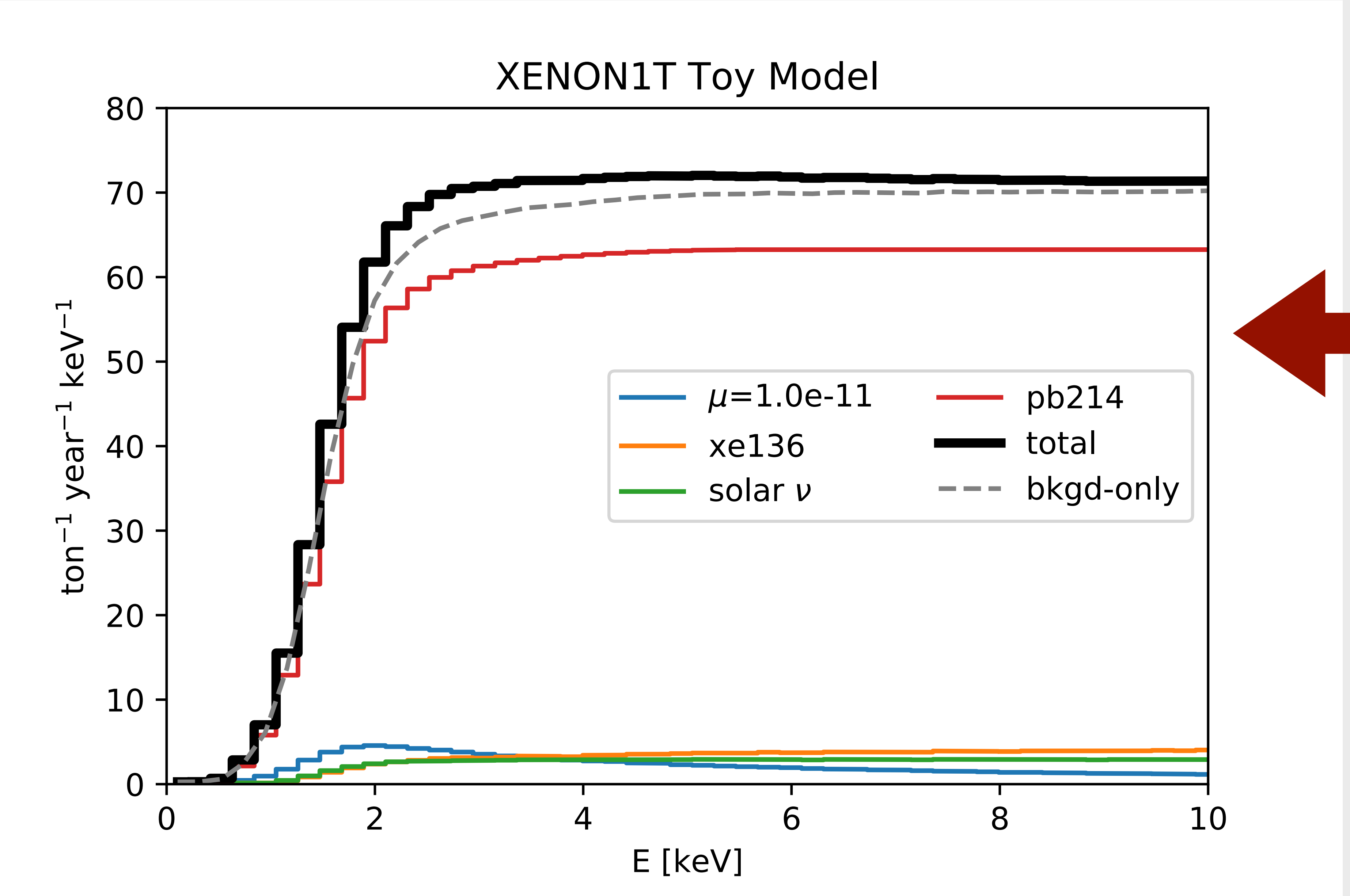

Caveats

You're the first people I've shown this to

Here's the model at sensitivity value — seems a bit optimistic.

Systematic uncertainties such as efficiency ignored

Nuclear recoils ignored

Maybe fudge factor of ~2?

	μ_{eff} (μ_B)	Fiducial mass (tons)	Livetime (days)	Kr85 (ppt)	Rn222 (μBq/kg)	Xe136 depletion?
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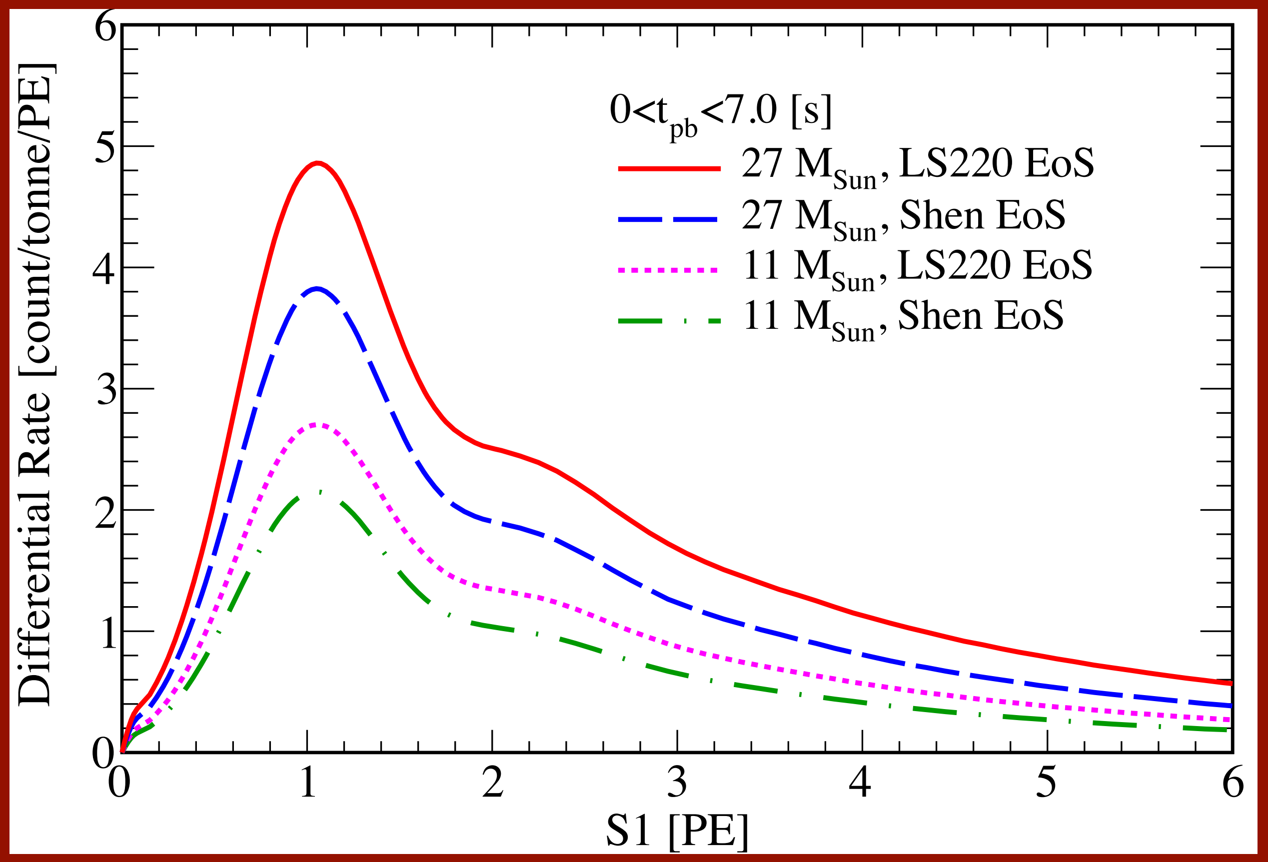
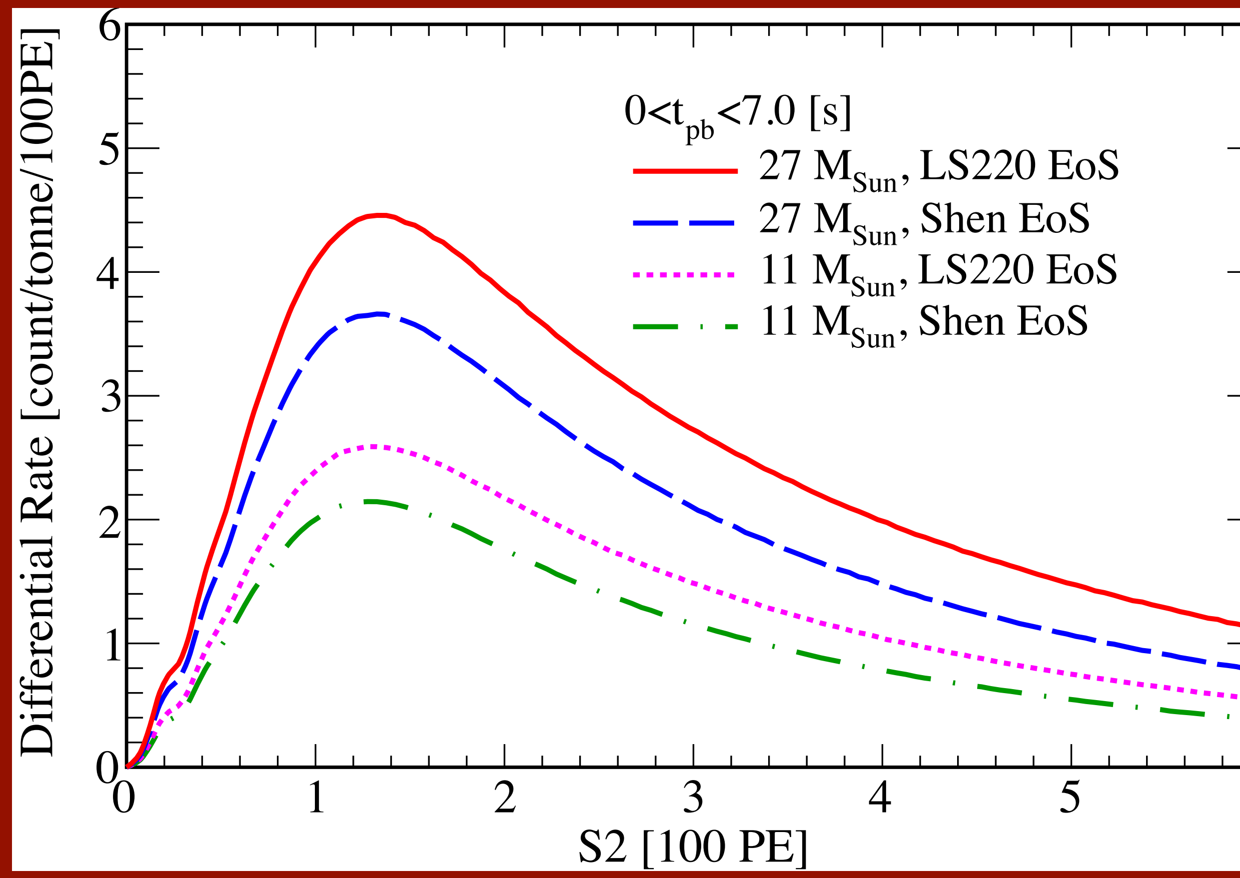
DARWIN	8.4E-13	30	1000	0.01	0.01	10%

Supernova Neutrinos

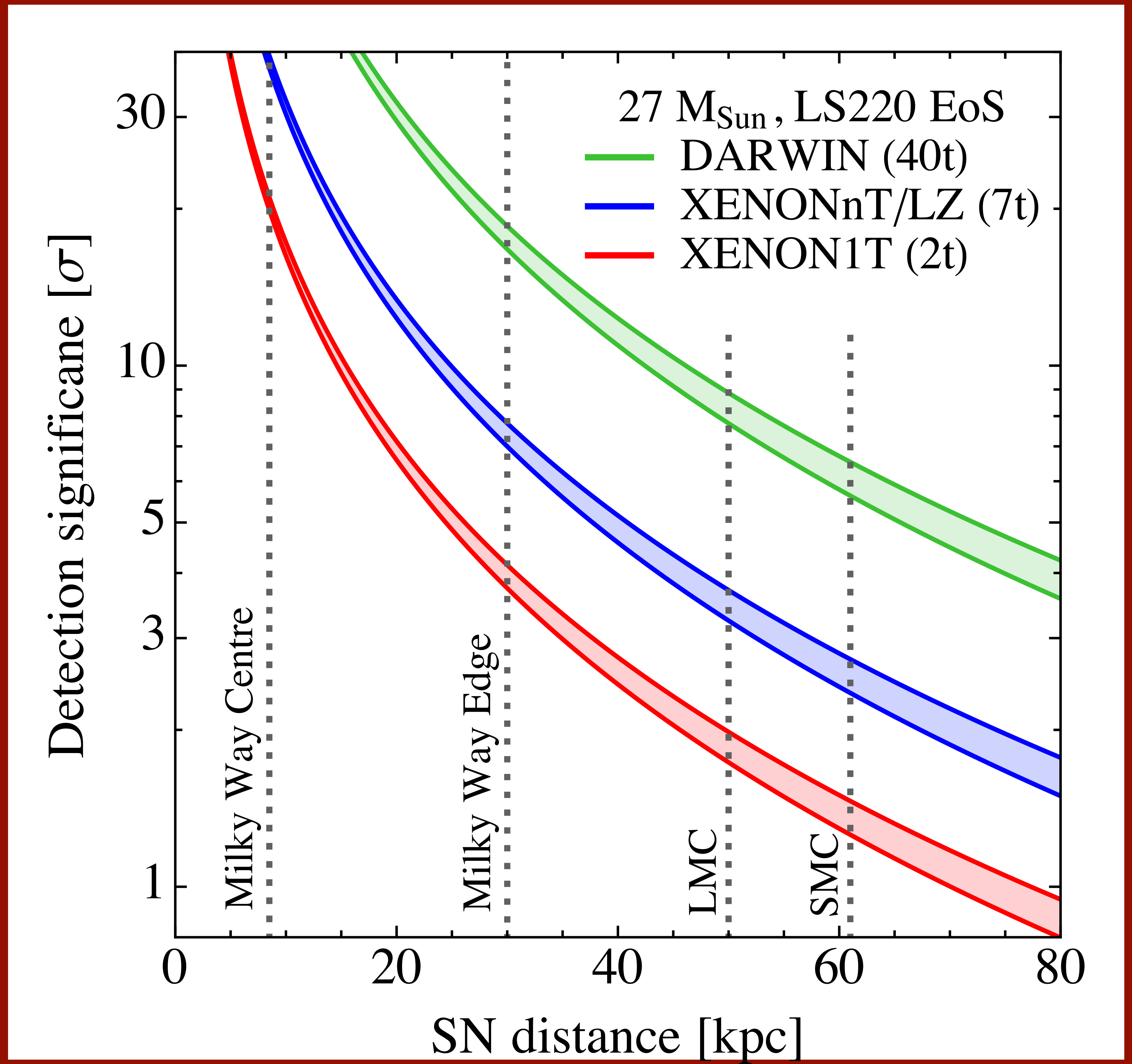
- ✦ XENON1T + future TPCs subscribe to SNEWS ("supernova trigger")
- ✦ Look for CEvNS from SN neutrinos
  - flavor-independent
  - requires S2-only analysis, but..
  - Timing information allows for discovery analysis

Lang et. al. arXiv 1606.09243



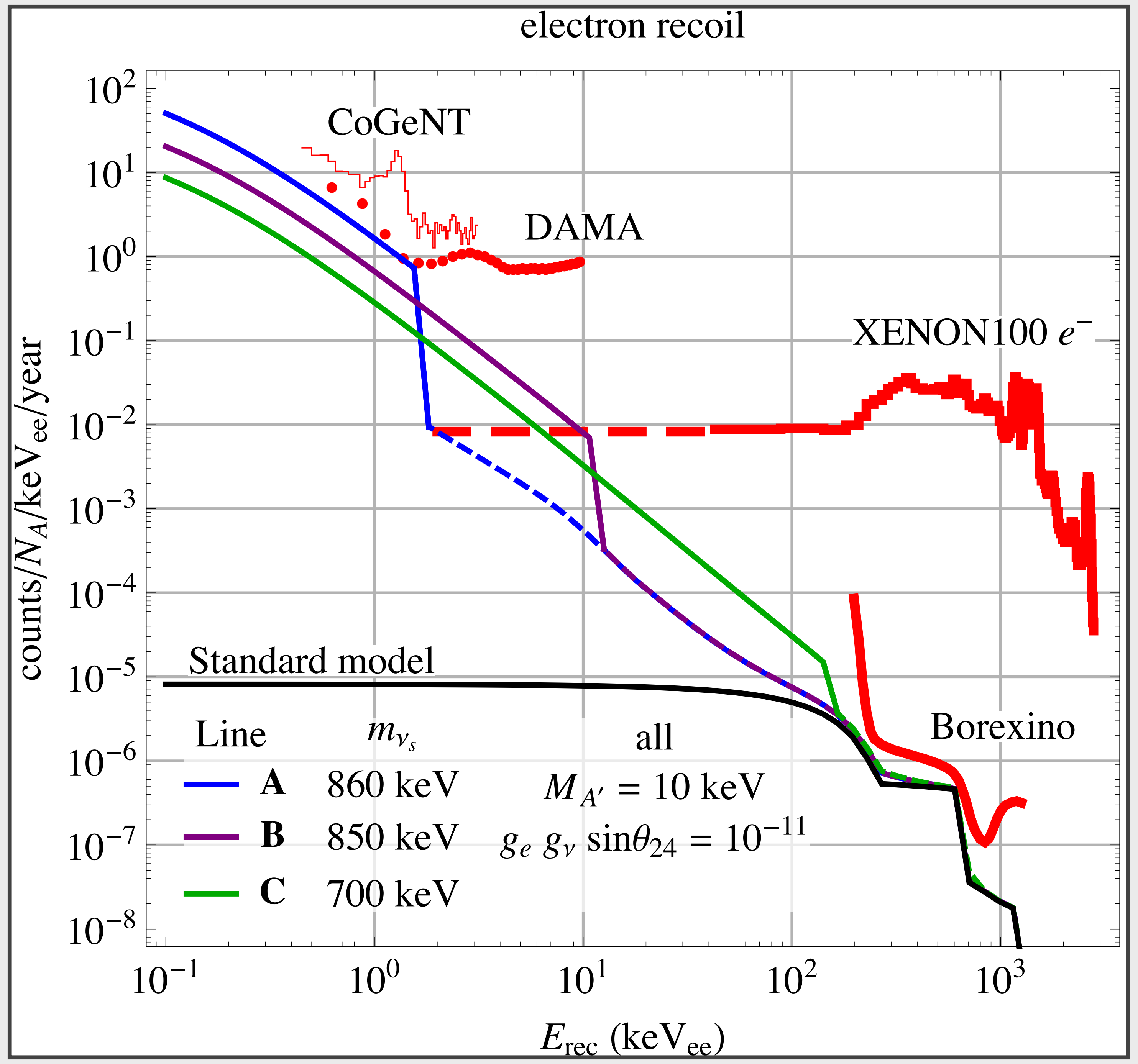


S1 falls mostly below threshold

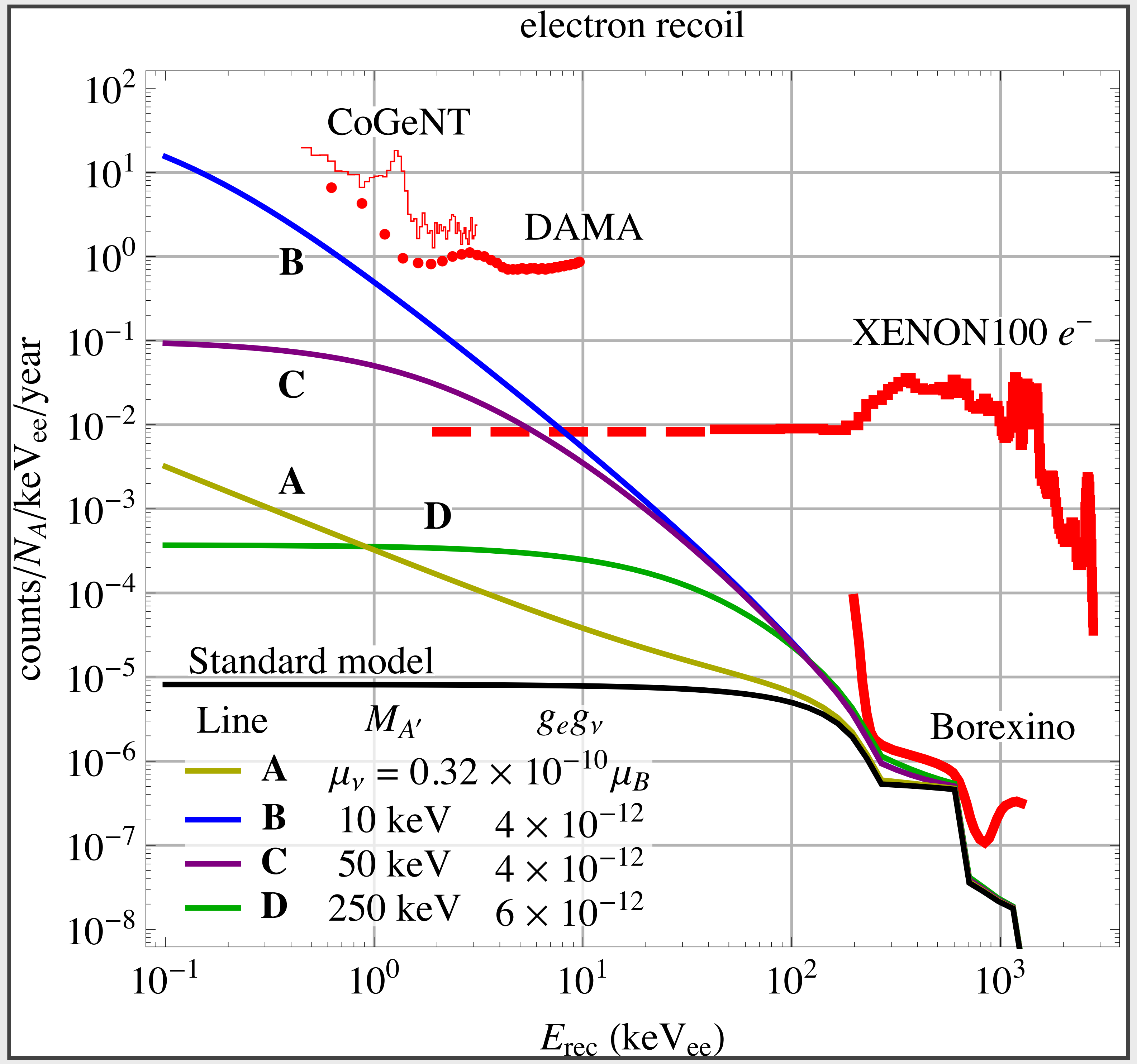


Other signals?

- Neutrino millicharge
- Charge radius
- Dark photon + (heavy) sterile neutrino
- What's interesting? Please advise.



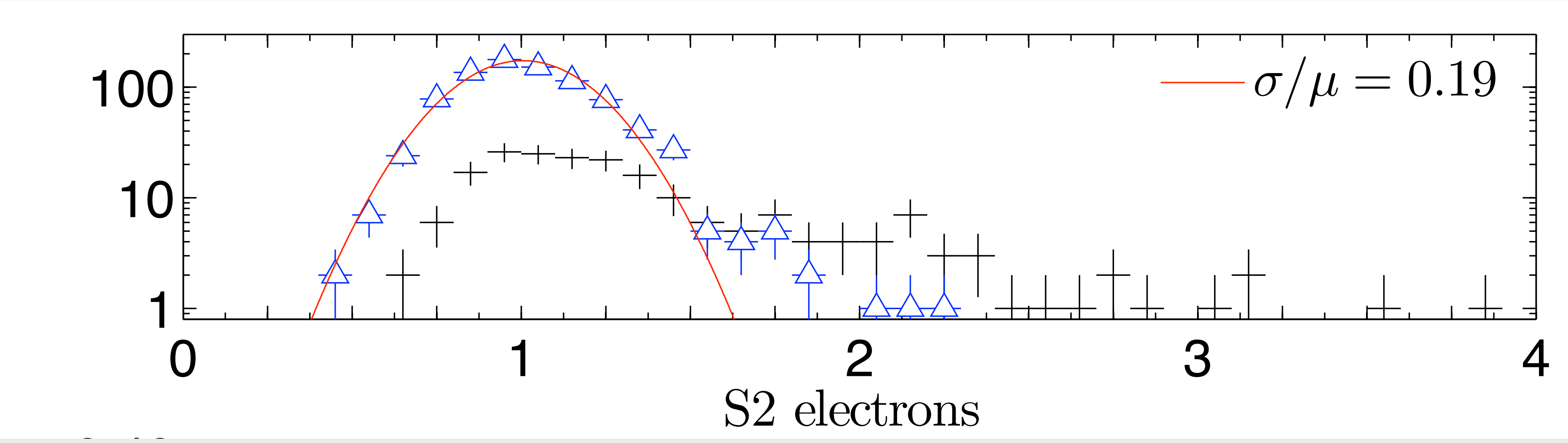
Harnik, Kopp, Machado (2012)



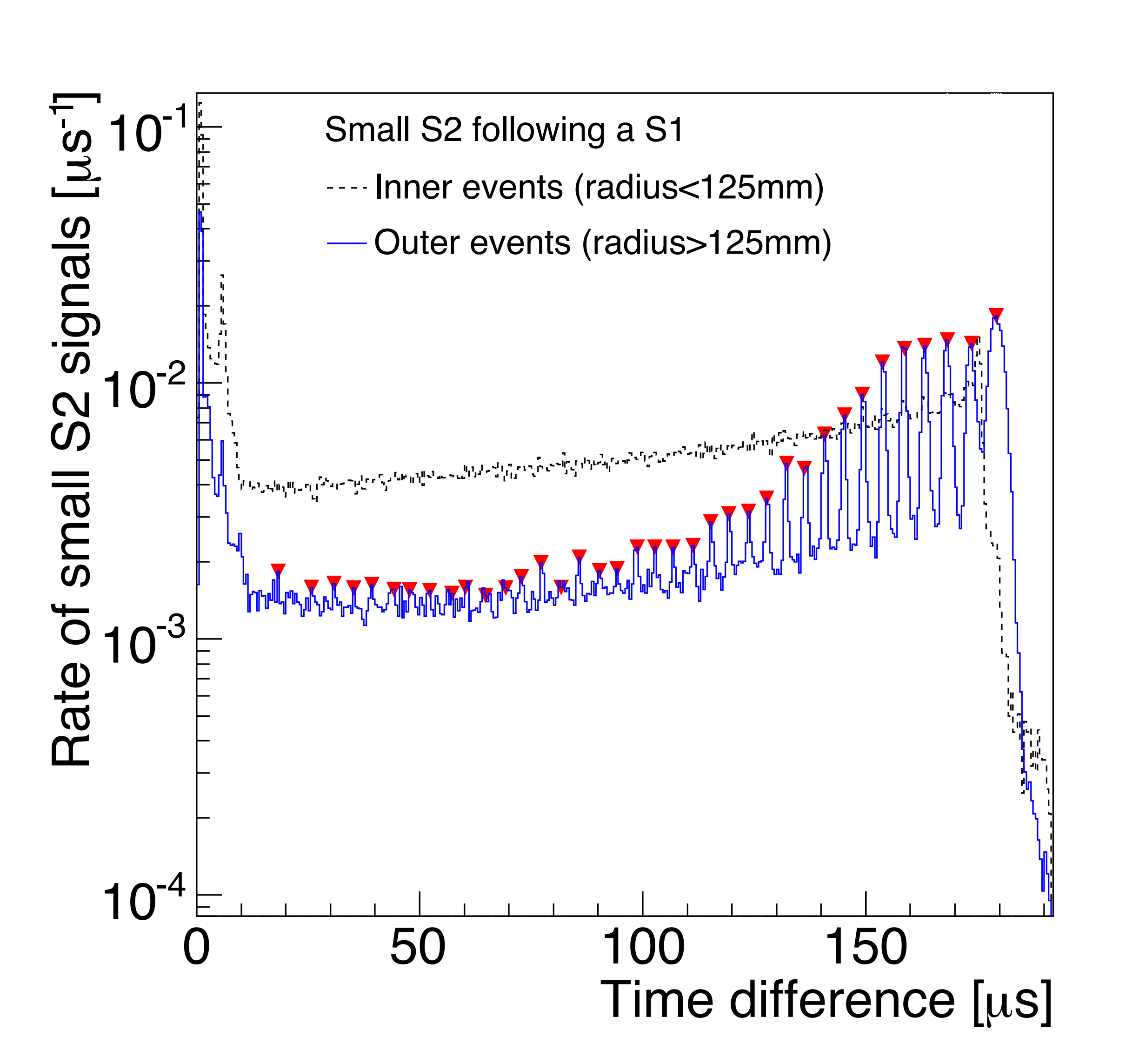
A bit more on S2-only

- S2-only is difficult, but we're not ignoring it
- LBECA group working on small LXe TPC focused on single electron studies
  - couldn't find a paper, but here are some slides from P. Sorensen via google: http://online.itp.ucsb.edu/online/hepfront-c18/sorensen/pdf/Sorensen_HEPFront18Conf_KITP.pdf
- Backgrounds (that we ~ know of)
  - Photoionization
  - Delayed extraction?
  - Impurities!
  - Grids, rings etc.
- Work ongoing to suppress/understand backgrounds

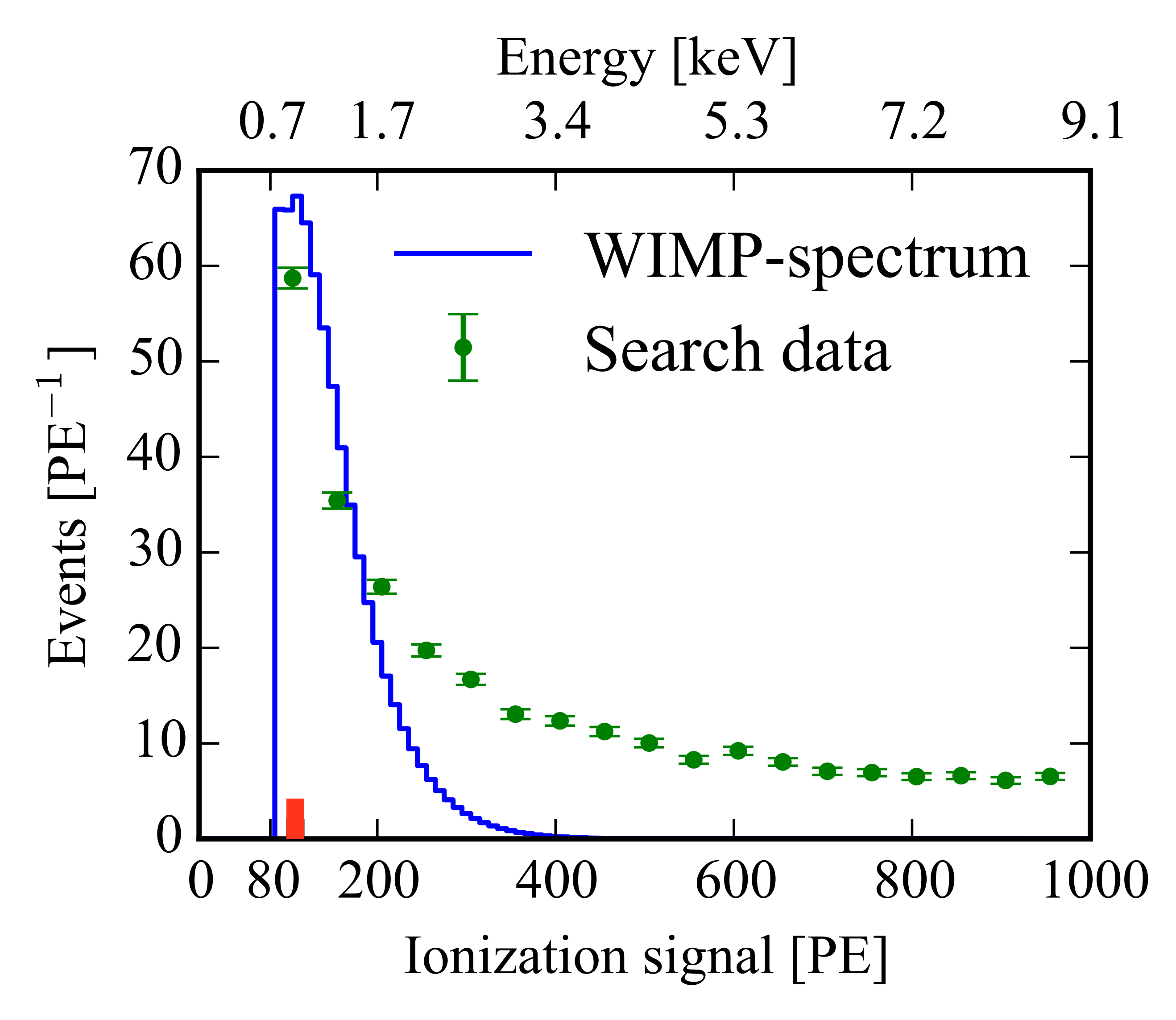
XENON10 1104.3088



XENON100 1311.1088



XENON100 1605.06262



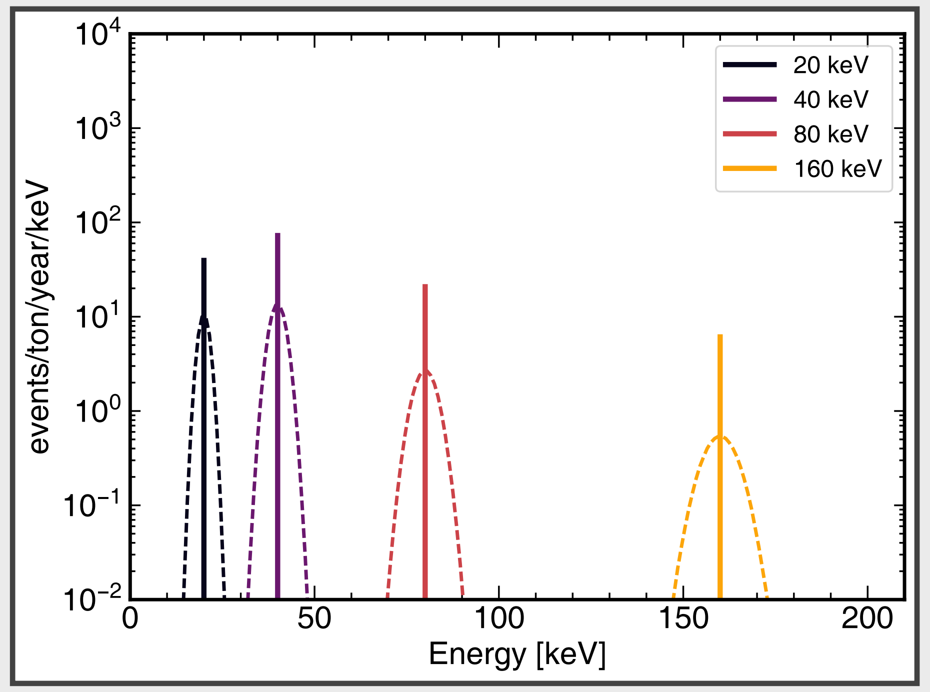
Summary

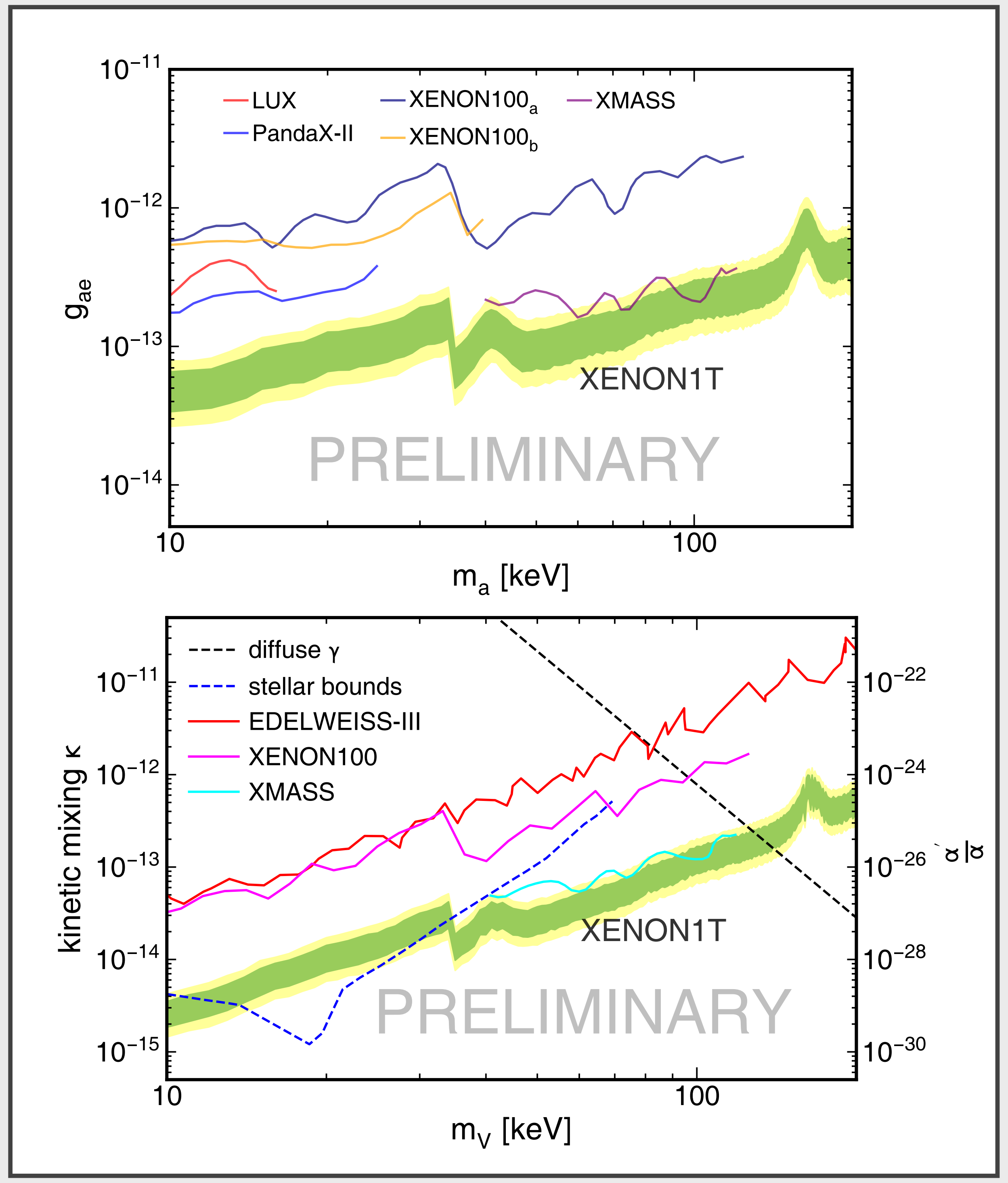
- Liquid xenon TPCs are low-threshold, low-background detectors that are scalable
    - Sensitive to much more than just WIMPs!
- Dominant ER backgrounds will continue to be suppressed in future TPCs, eventually being dominated by solar neutrinos
- XENON1T could set world-leading constraints on neutrino magnetic moment right now
    - LZ/nT gain additional order of magnitude with long exposure
- Future xenon TPCs such may probe μ_{eff} <1E-12 μ_B with optimistic (but not unrealistic) assumptions

Thank You.

Backup

Dark absorption & solar axions

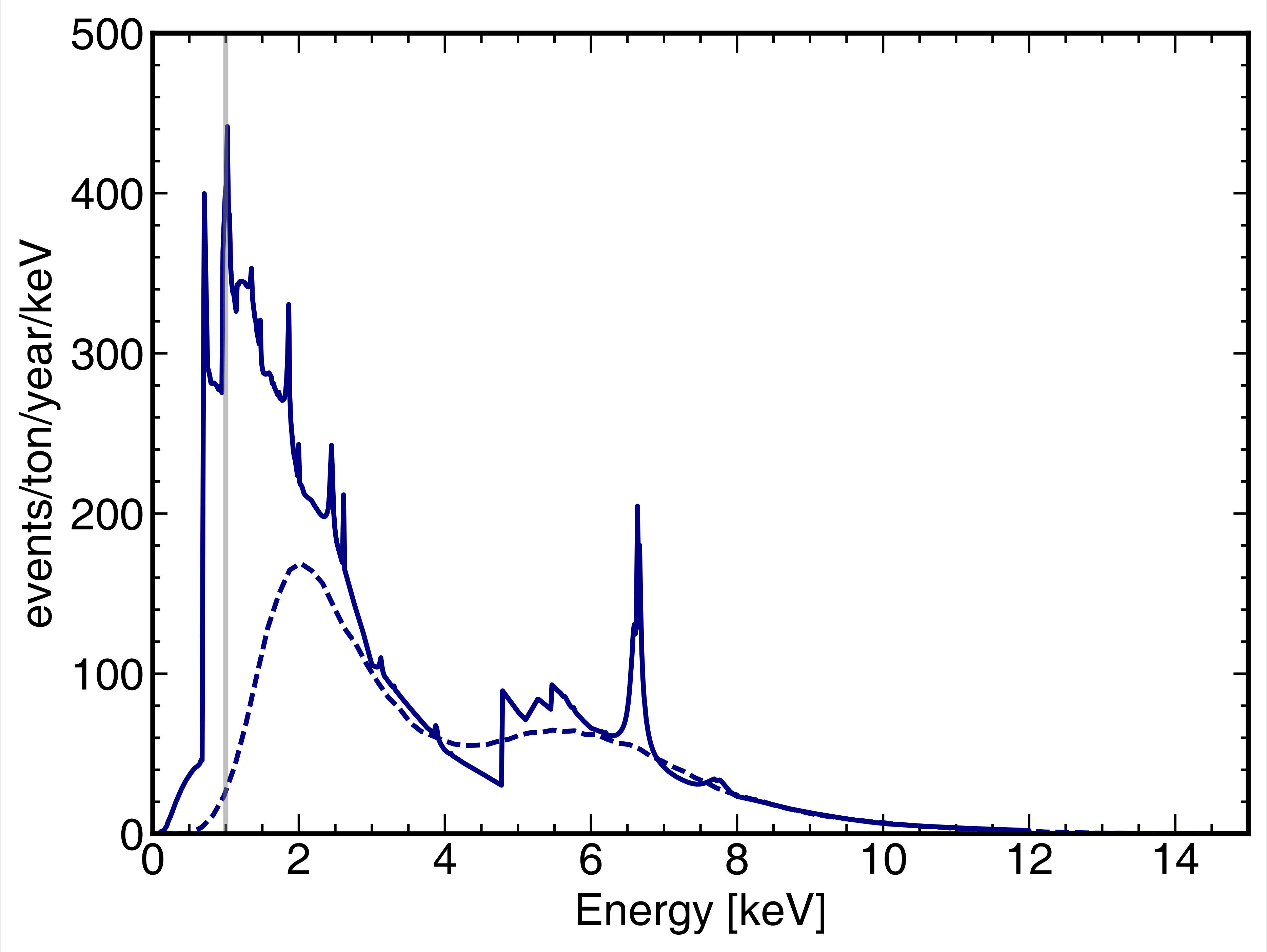




QCD axions produced in the sun

- not dark matter

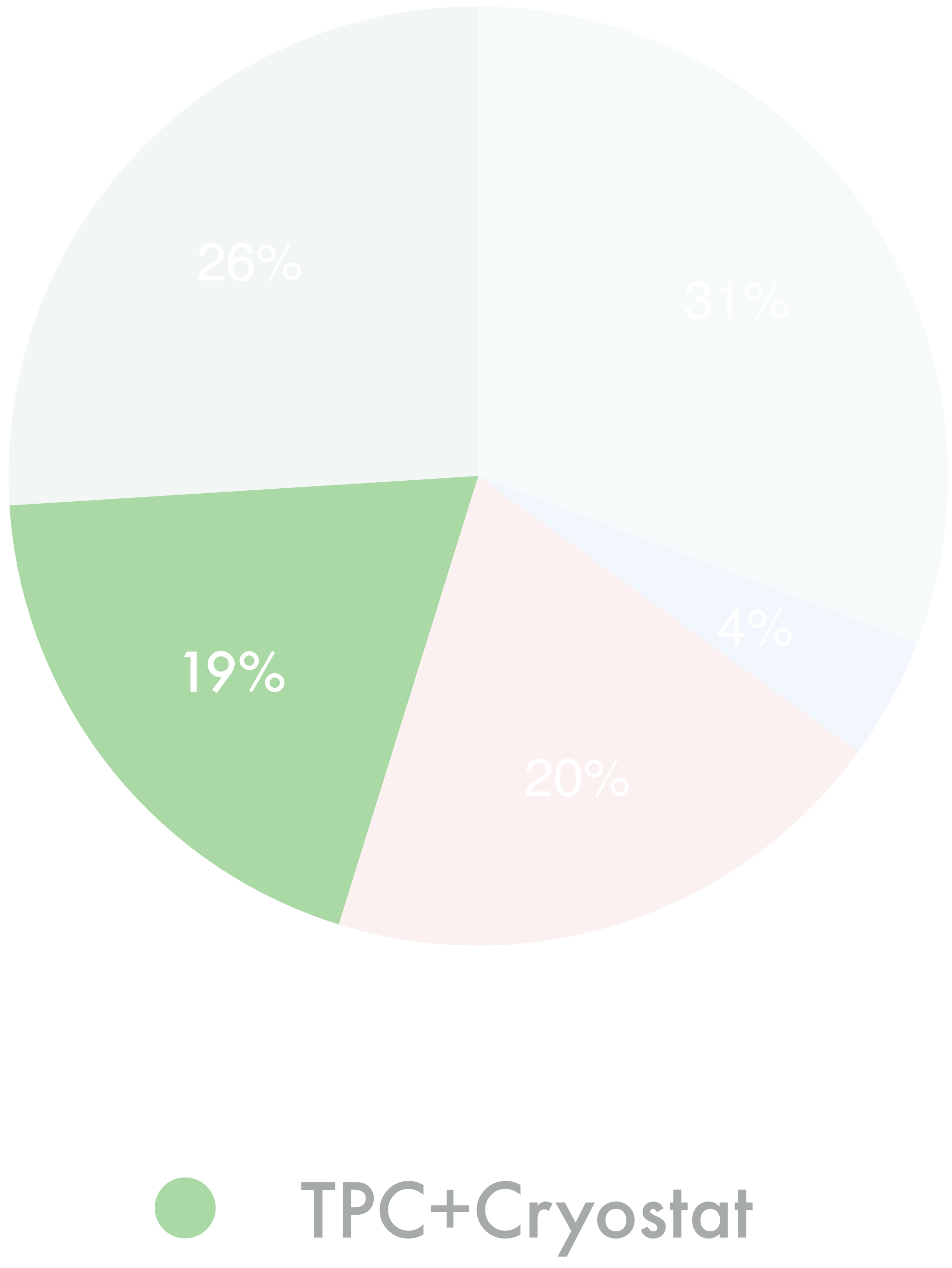
Absorbed via axio-electric effect



- ✦ Dark absorption of axion-like particles (ALPs) or dark photons
- ✦ Non-relativistic: mono-energetic electron recoil

Slide credit: L. Grandi

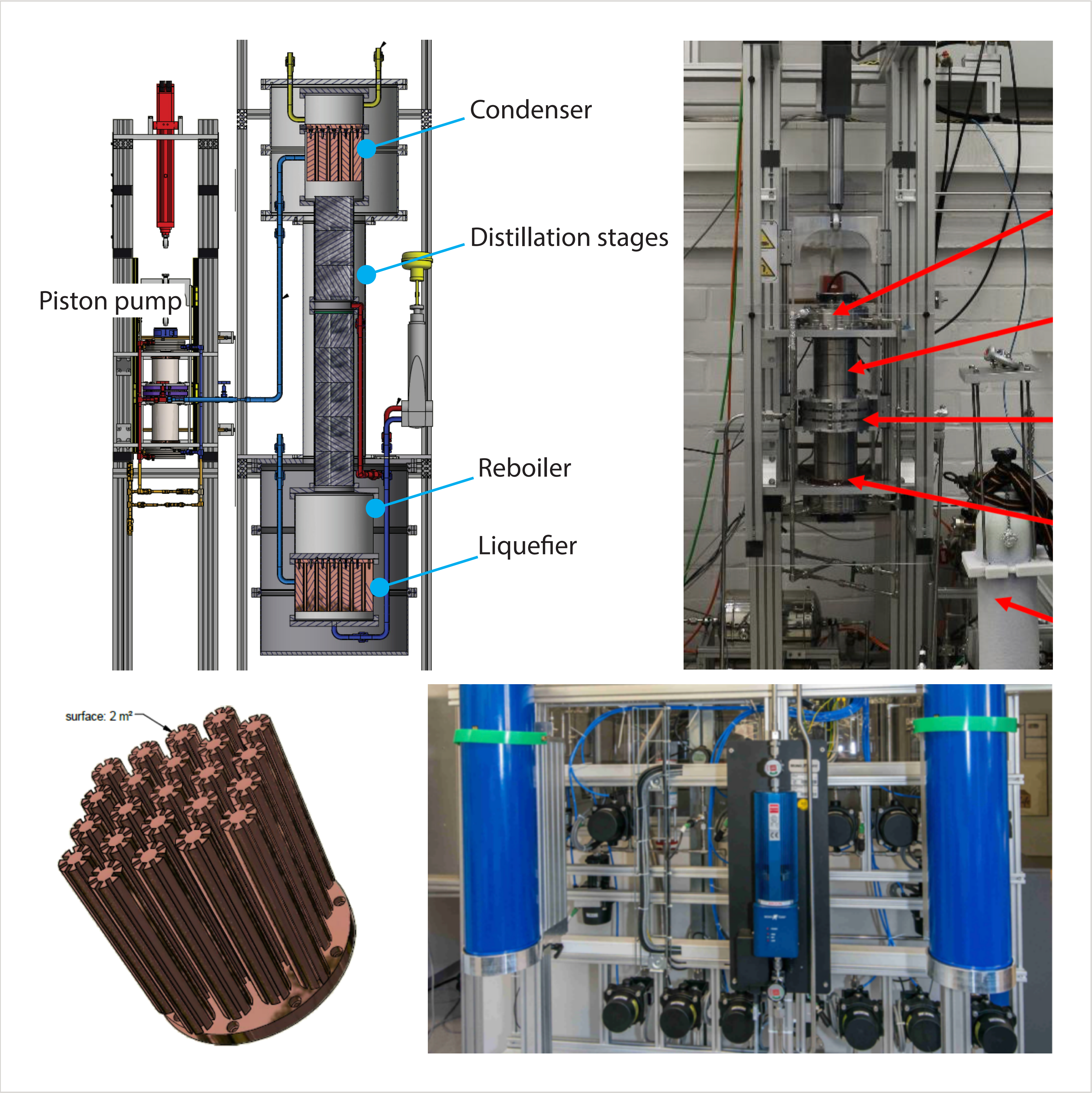
Online removal of Rn from **Type-I** Sources



- For Type-I Sources the Rn-concentration in the active volume depends only on *circulation rate*.
  - ➡ *Distill the xenon fast enough wrt ^{222}Rn* mean lifetime (5.5 days).

- *High-flux online cryogenic distillation column*:
  - ➡ *Same concept as other tested columns, just more powerful (~3kW)*
  - ➡ *Extracting xenon from active volume @ 200slpm (8t in ~ 5d);*
  - ➡ *Intrinsic reduction factor ~100;*
  - ➡ *Overall reduction in the active volume ~2;*
  - ➡ *Designed to be upgradable to ~600slpm*

~0.3%
~0.04%
~0.2%
~0.3%
~9.5%

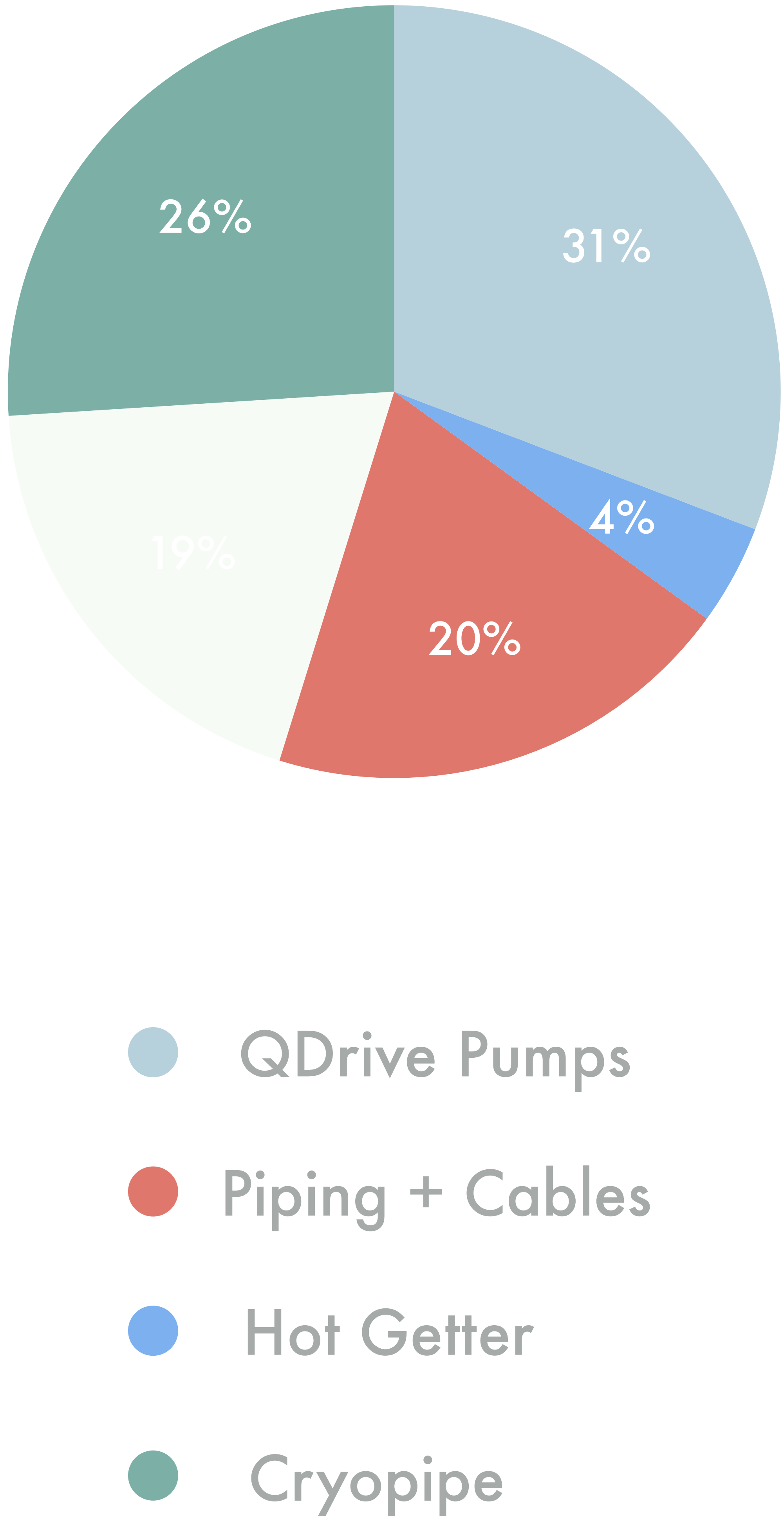


Radon reduction Strategy

- A single dedicated column to remove Rn emanated in ***gaseous*** and ***liquid phase***.
- ***Under assembly*** @ MÜNSTER
- ***Integrated*** within existing ***liquid*** and ***gaseous recirculation system***.
- ***Radon-screening facility*** @ MPIK working at full load to certify material and cleaning procedures, to further reduce Rn-sources wrt to XENON1T.

Slide credit: L. Grandi

Online removal of Rn from **Type-II** Sources



NEW dedicated cryogenic distillation column:

- operated *continuously* to extract xenon gas (from pipes, etc, ...) and *remove* ^{222}Rn emanated by Type-II sources:
- *extraction* flow of xenon gas ~*20slpm*;
- *reduction* factor ~*100*.

~0.3%

~0.04%

~0.2%

~0.3%

The concept was:

- **Successfully tested** in **XENON100** *[EPJ C 77 (2017) 358]*
- **Successfully tested** in **XENON1T**
  - ➡ *operated Kr-column in reverse mode to mimic a Rn-column (@ 3slpm, non-optimized).*
  - ➡ *Measured **20% reduction** of the background (despite not being optimized).*