Interpretation of the XEON1T low ER anomaly in the light of XENONnT

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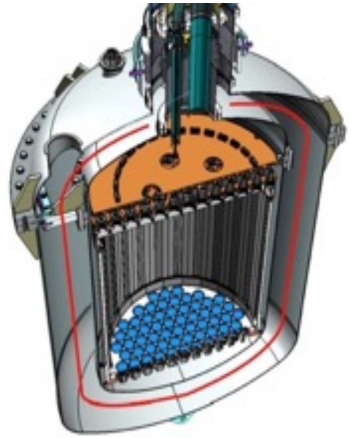
DMnet symposium, MPIK Heidelberg, Sept. 13-15, 2022

The XENON Dark Matter Program

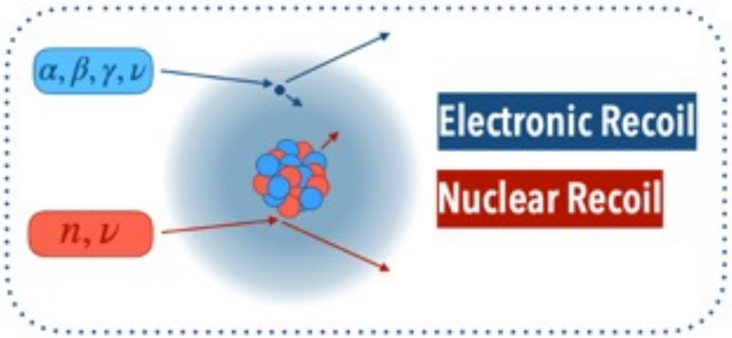
The XENON program at Gran Sasso, Italy (3600 mwe)



	XENON10	XENON100	XENON1T	XENONnT
Period	**2005-2007**	**2008-2016**	**2012-2018** →	**2020-2024**
Total mass	25 kg	161 kg	3200 kg	~8000 kg
Drift length	15 cm	30 cm	100 cm	150 cm
Status	Completed (2007)	Completed (2016)	Running	Construction
σ_{SI} limit (@50 GeV/c²)	8.8×10^{-44} cm²	1.1×10^{-45} cm²	1.6×10^{-47} cm² (2018)	1.6×10^{-48} cm² (2023)

XENONnT was prepared while XENON1T was running
➔ switching gears

Sensitivity: Bigger & less Background



Background reduction

→ extremely challenging:

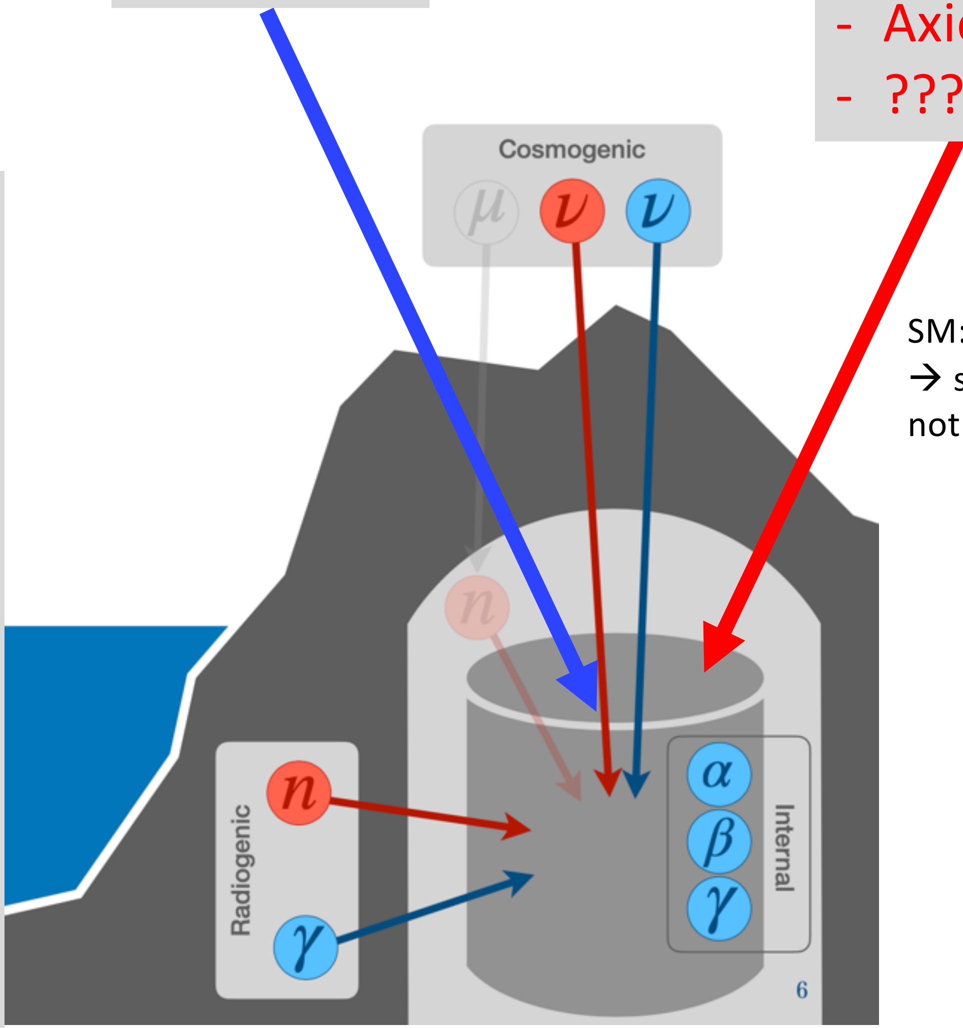
- material selection
- screening (γ, Rn, …)
- graded shielding
  - deep underground
  - veto systems
  - water
- cryogenic distillation
- pulse shape analysis
- …

WIMPs

→ nuclear recoils

Sun:

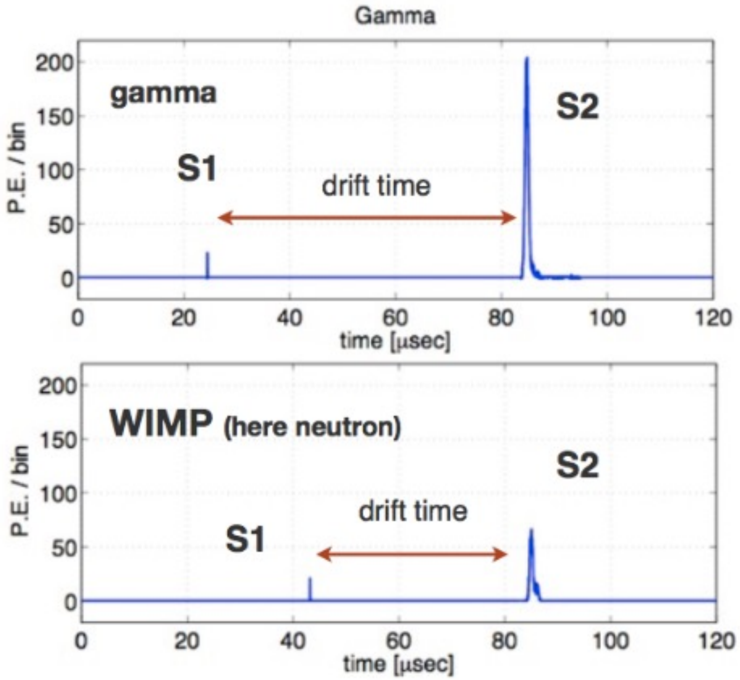
- Neutrinos
- Axions ?
- ???

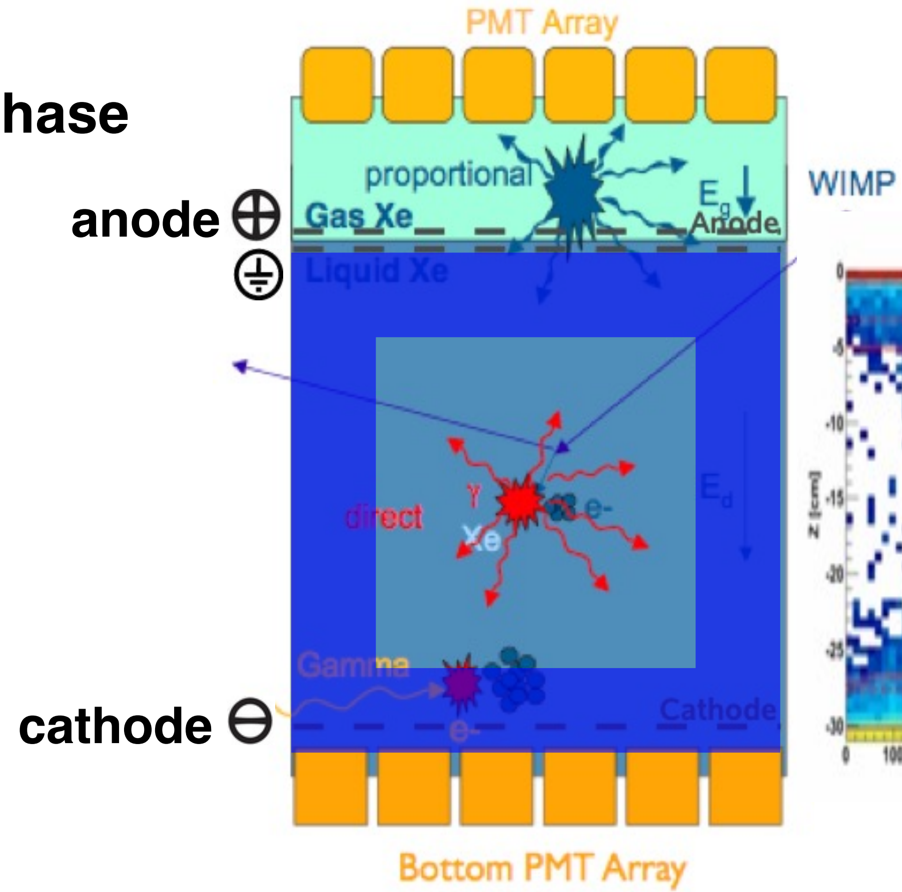


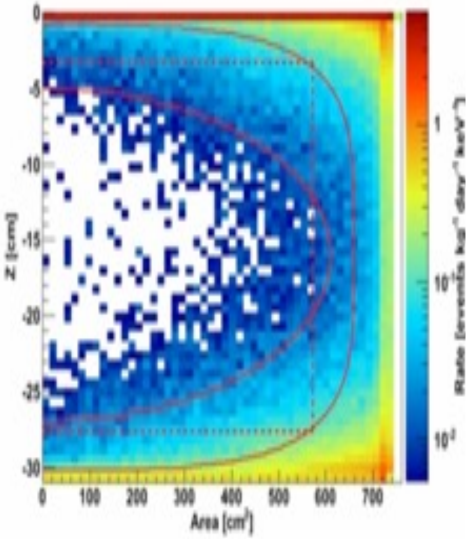
SM: too weak
→ should
not show up

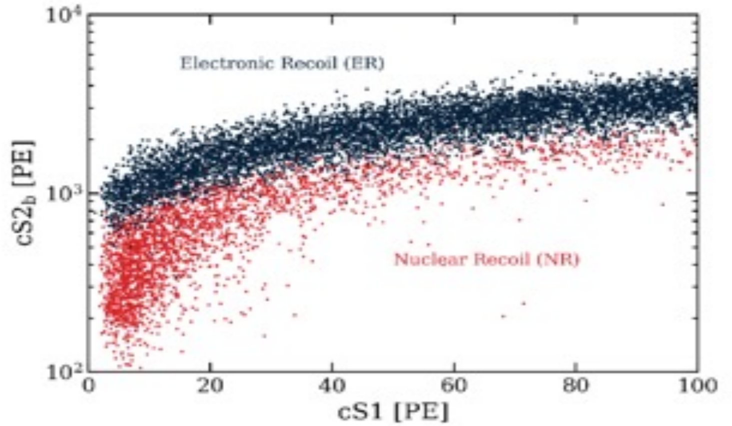
Powerful Devices: Dual-Phase TPCs

1) direct light singal → S1
2) drift of electrons to gas phase
3) 2nd light signal → S2



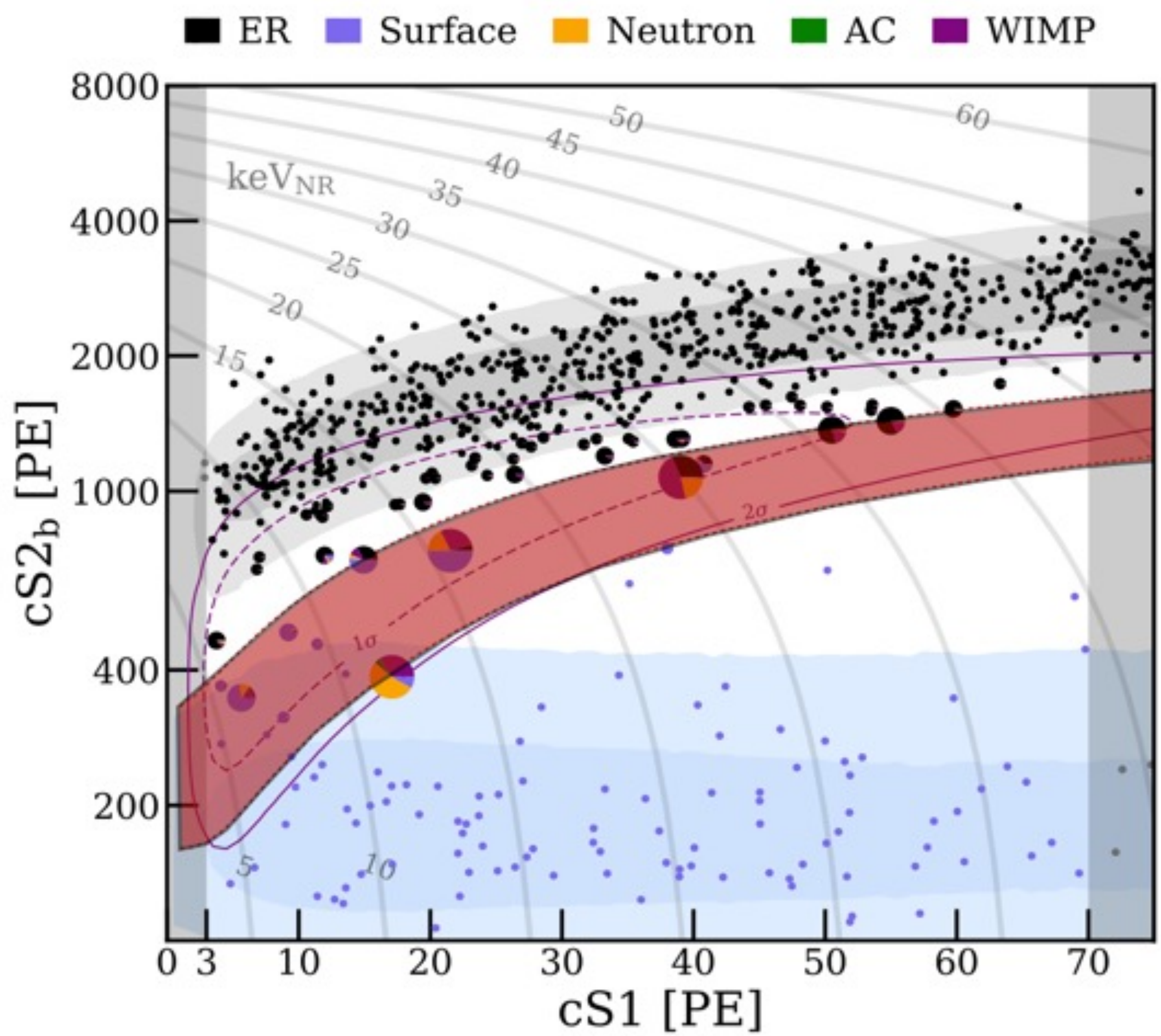




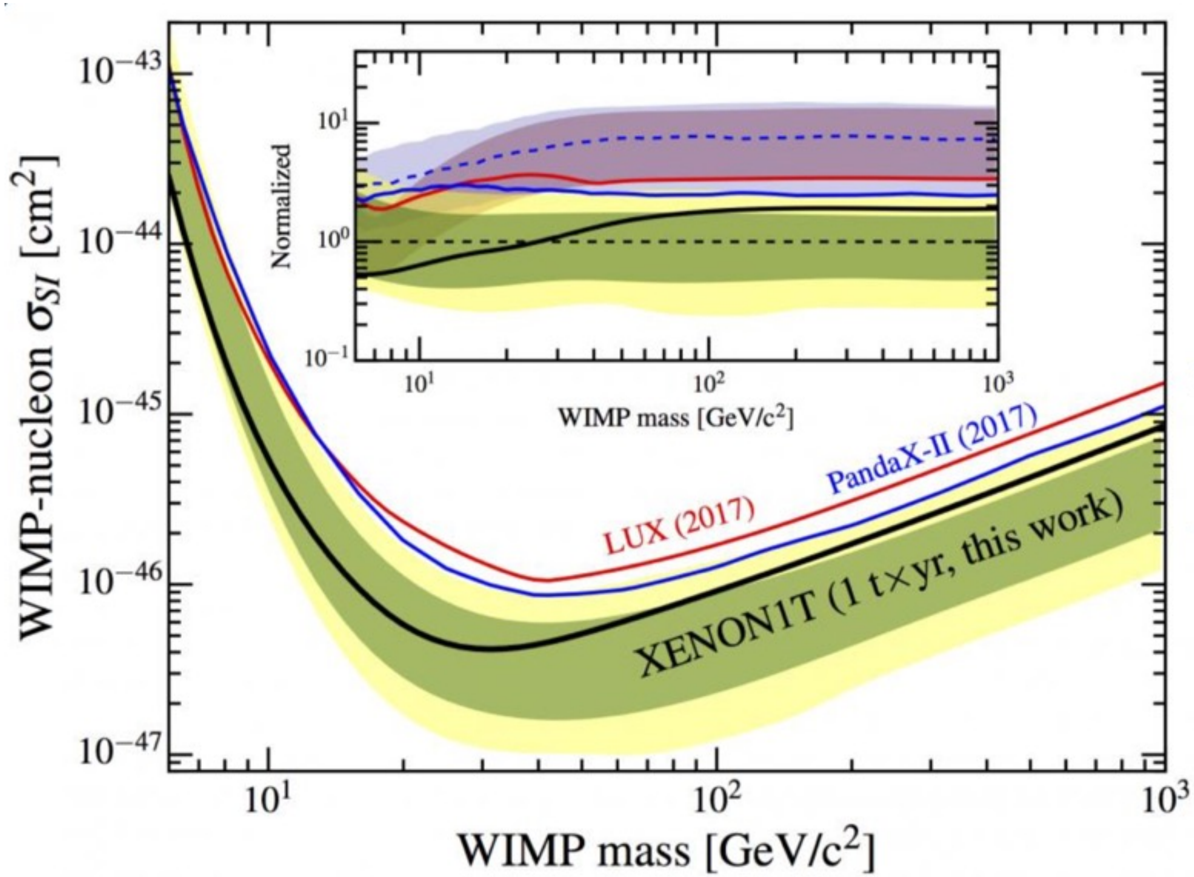


→ excellent 3D position reconstruction
→ fiducialization = exclude known backgrounds from 'dirty' surfaces
→ S2/S1 discrimination of ER / NR

XENON1T: NR Search for WIMPs



XENON1T: Results on WIMPs



1. **World best constraint on WIMP Dark Matter.** Most stringent exclusion limits (@ 90% CL) for WIMPs > 6 GeV/c^2;
2. **×7 improved sensitivity** compare to previous experiments (LUX, PANDAX-II);
3. **Upper limit:** $\sigma_{SI} < 4.1 \times 10^{-47}$ cm^2 @ 30 GeV/c^2.

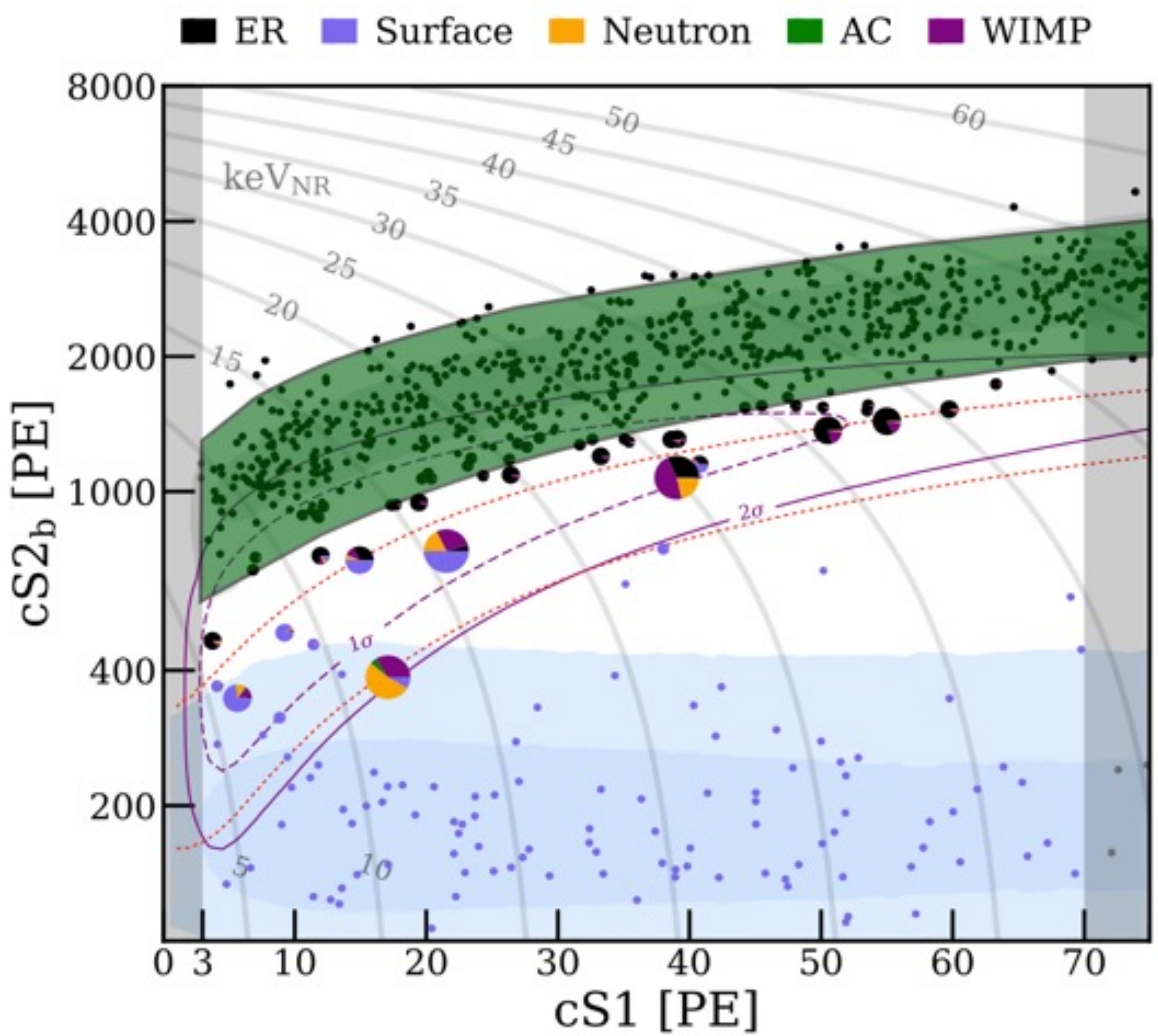
➔ **Most stringent result on SI scattering of WIMP Dark Matter down to 3 GeV/c^2 masses** [PRL 121, 111302 + PRL 123, 251801]

Search for New Physics with ER Events

Very low background:
76 ± 2 events/t/yr/keV

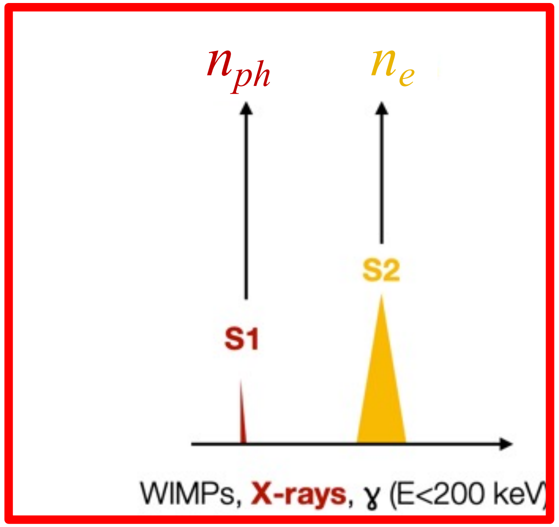
Low threshold:
1 keV_{ee}

Large exposure:
~1 tonne x year



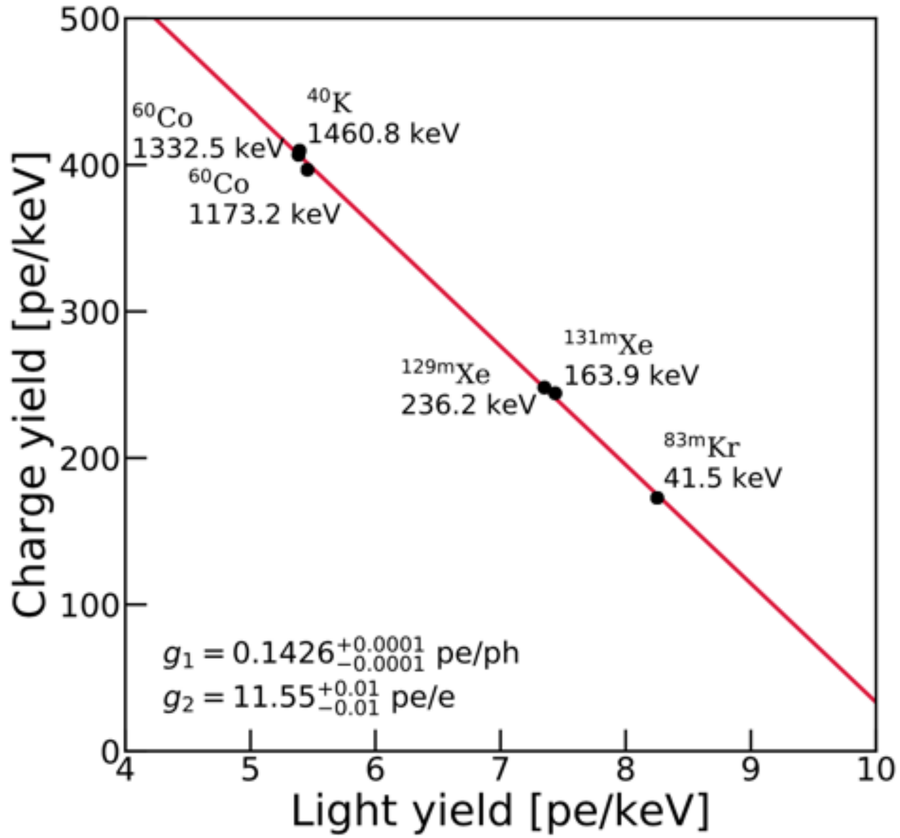
Energy Reconstruction and Resolution

Combine light and charge



$$E = W \cdot (n_{ph} + n_e)$$
$$= W \cdot \left(\frac{S1}{g_1} + \frac{S2}{g_2}\right)$$

➔ **detector constants g_1 and g_2**



- Anti-correlation between light and charge
  ➔ checked with calibration sources
- Energy resolution < 5 % at 50 keV

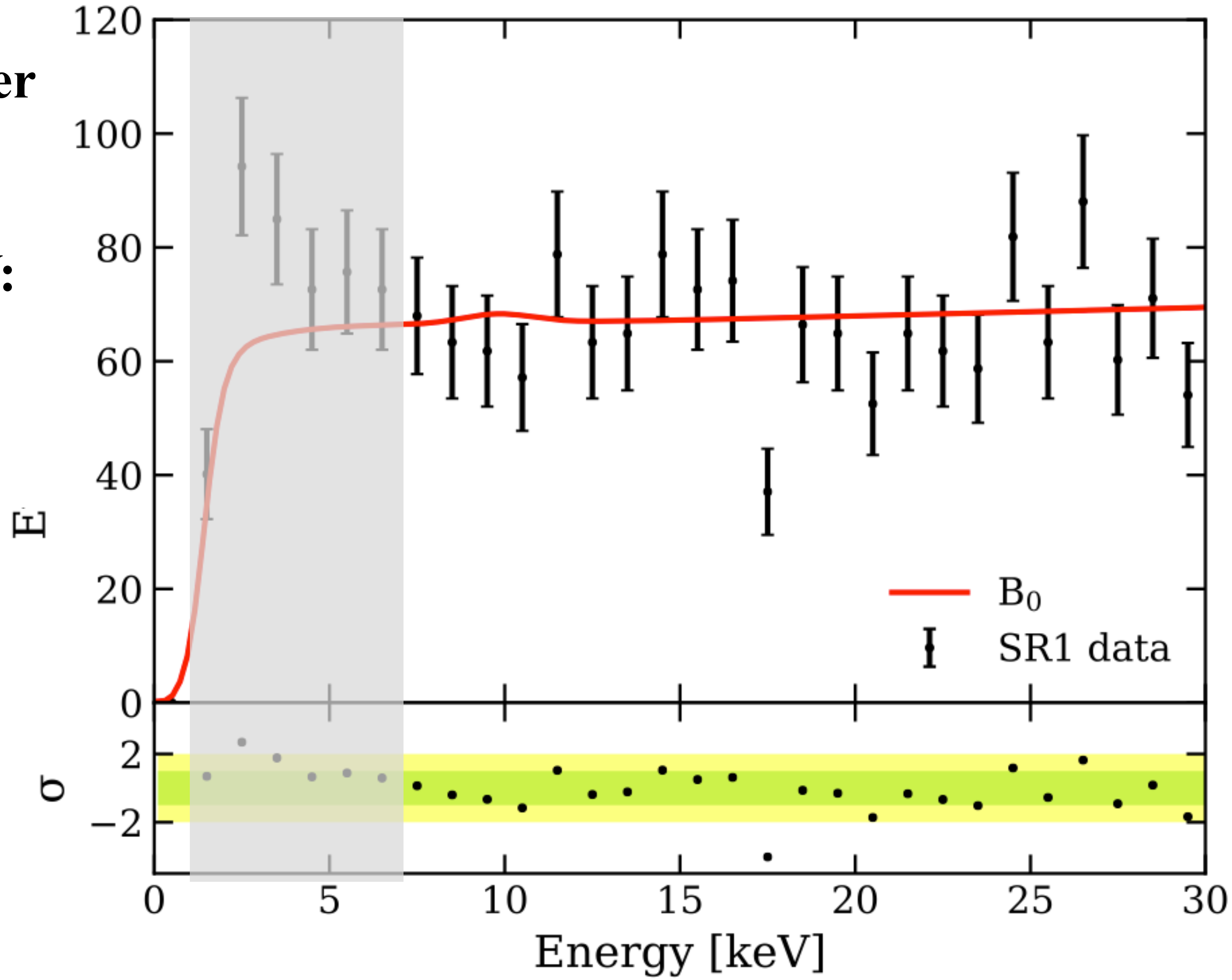
The XENON1T low E_R excess

- **Exposure: 0.65 t*y**
- **Nice agreement at higher recoil energies**

➔ **Excess between 1-7 keV:**

285 events observed

(232 ±15) expected from best-fit

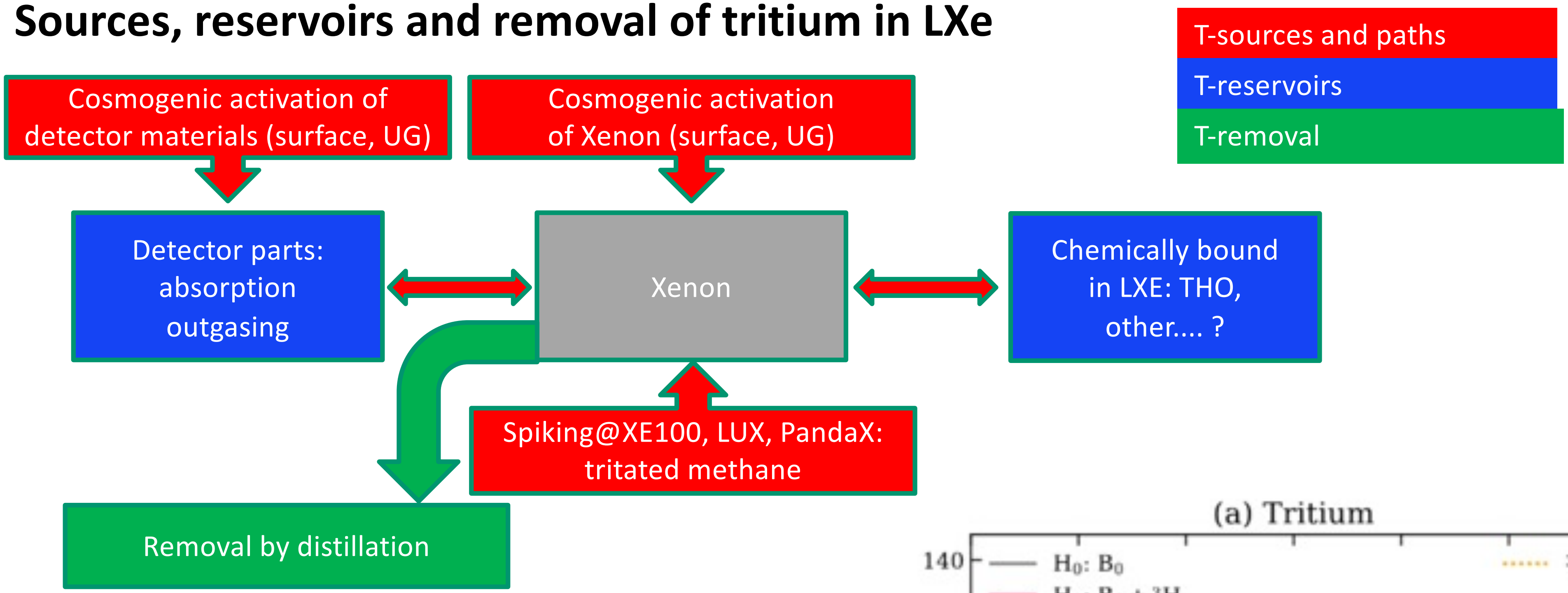


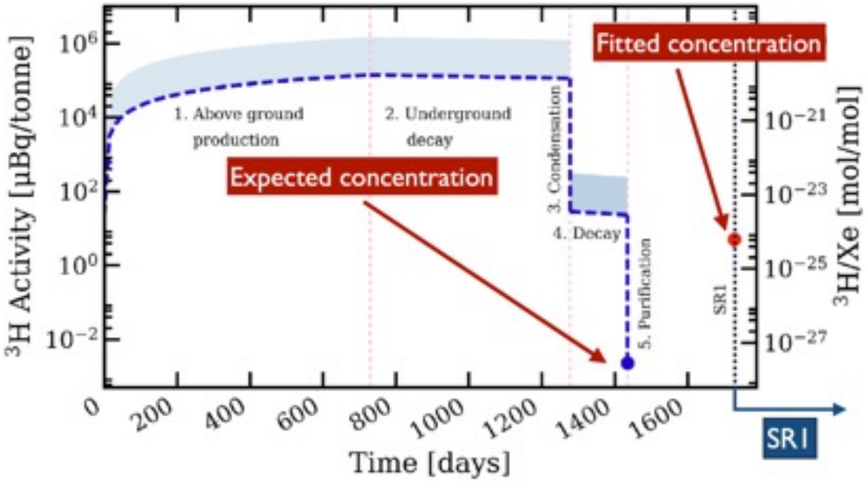
Explanation #1:
3.5σ fluctuation

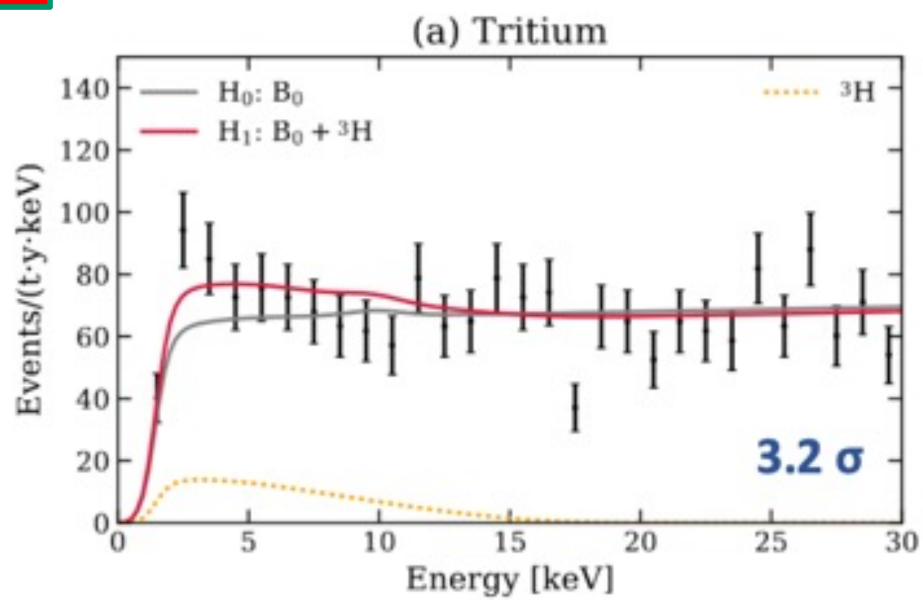
Explanation #2:
Some unexpeccted new background?

Not expected, but various options were studied: Tritium, ^{37}Ar, ...

Sources, reservoirs and removal of tritium in LXe







No indication of T; could not cross-check directly
Best fit: Less than 3T per kg of LXe

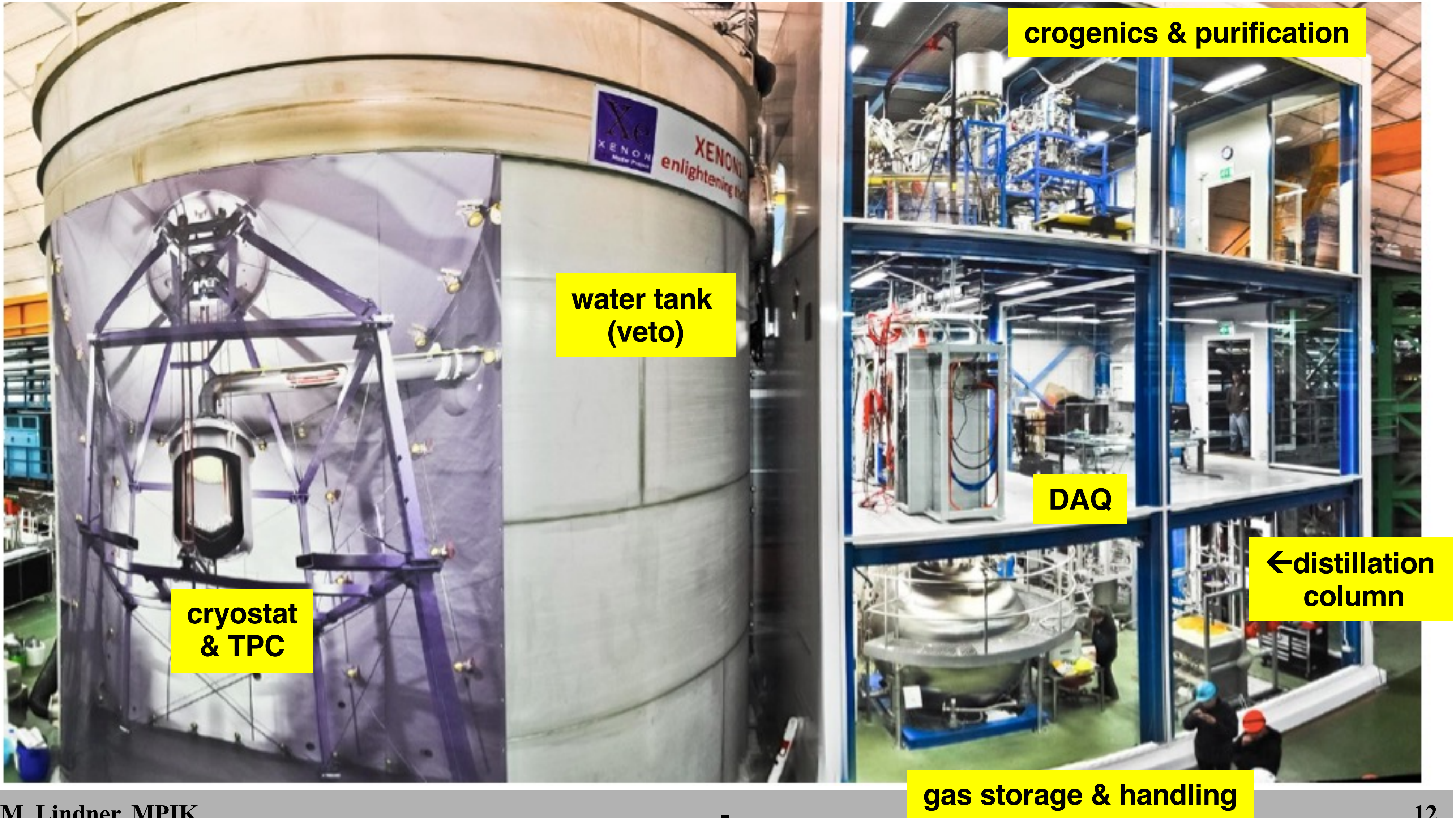
Explanation #3: New Physiccs

- **A singal from where?**
- **Sun:**
  - neutrinos (exist, but CEνS too small ←→ ν-floor)
    → BUT close: Maybe some non-standard interaction with electrons
  - axions produced in the sun
- **DM flow**
  - some new particle
    → not WIMPs
    → light and not hot DM? A new light boson?
- **Diffuse background of invisible particles**
  ←→ consistency with other searches/limits

So far O(450) papers which cite the XENON1T result
→ mostly theory explanations with 3 main directions: Axions, ν's light bosons

XENON1T → XENONnT

Meanwhile: Changes and re-assembly done → filling → commissioning → data taking: SR0 – during Covid times!



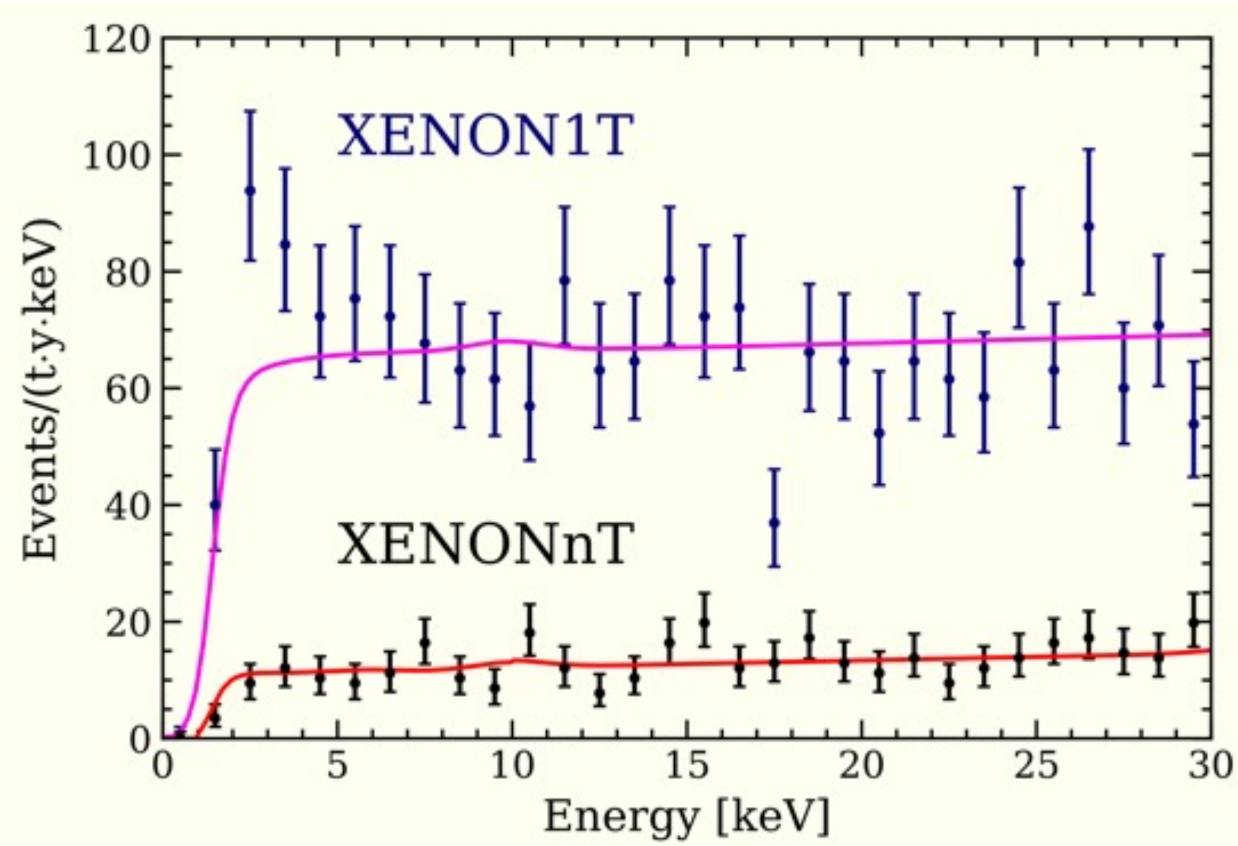
A few weeks ago: XENONnT

arXiv: 2207.11330

Exposure:
1.16 tonne-years
➔ x2

Background:
(16.1 ± 0.3) evts/(t x yr x keV)
in 1-30 keV range ➔ x 0.2

➔ XENONnT:
best fit signal strength: 0



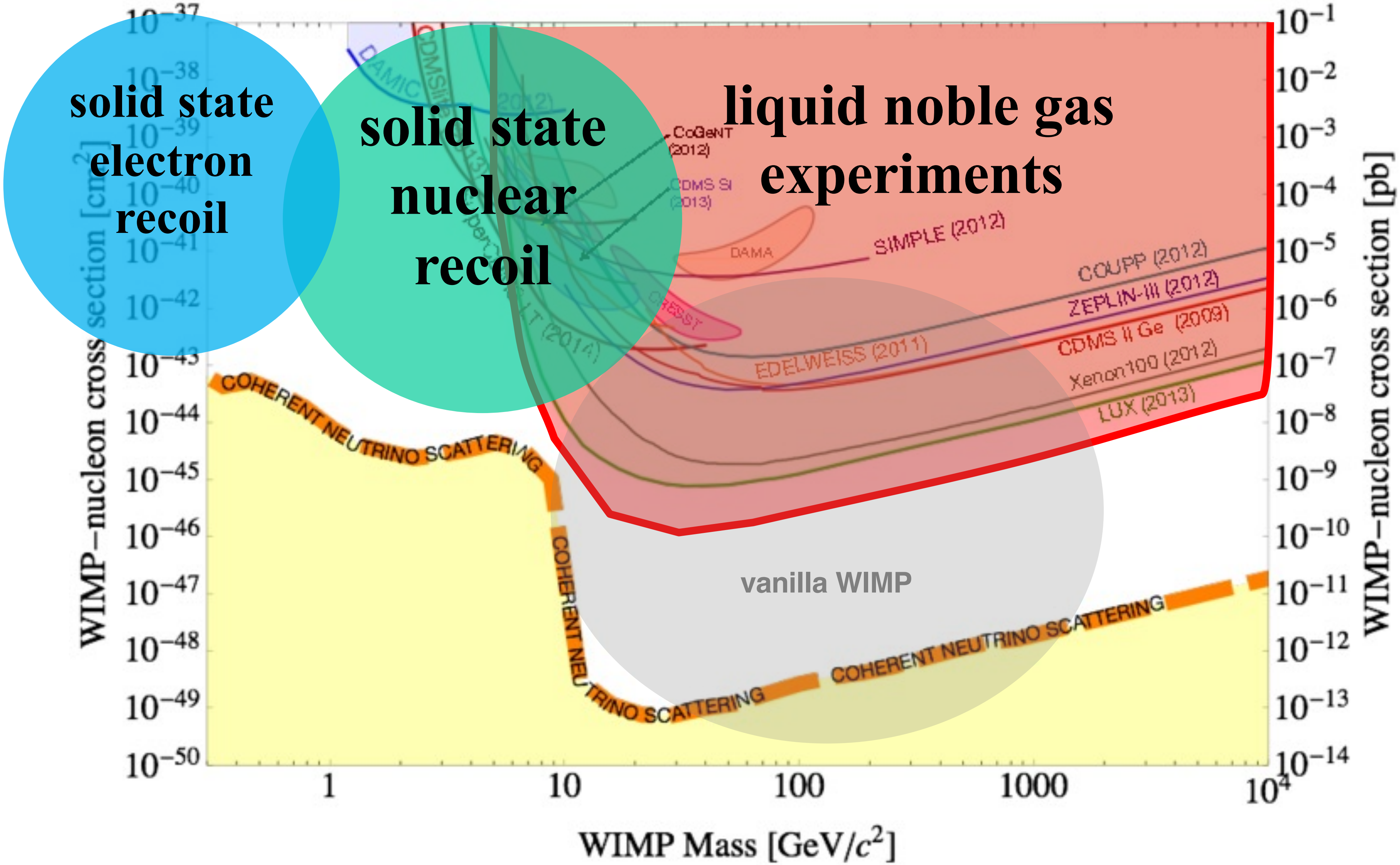
Most likely / plausibel explanation: A tiny ^3H contamination in XENON1T

Consequence:

➔ **need no longer explain an excess**

➔ **very interesting lessons (new limits) on all kind of new physics**

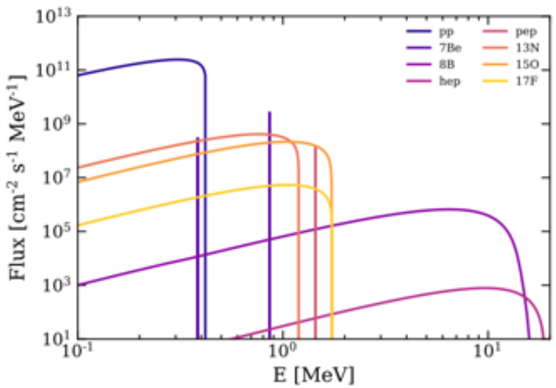
Proximity to the Neutrino Floor: Enhancements?



Large Neutrino Magnetic Moment

Solar neutrino spectrum

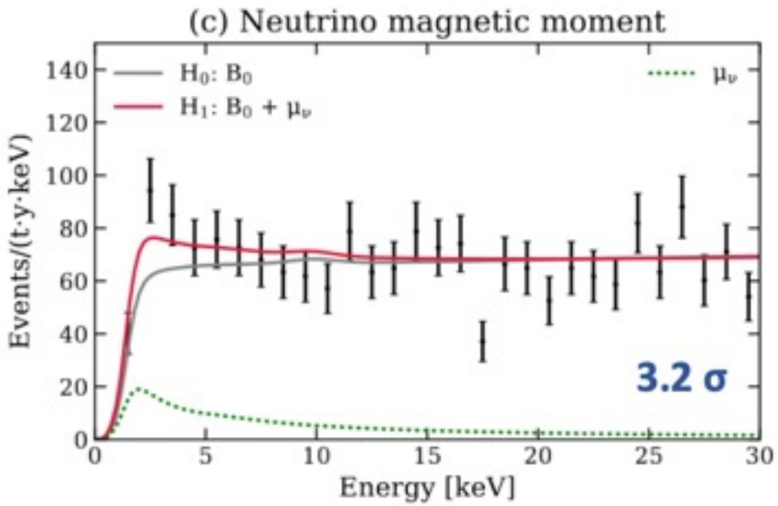
➔ MeV-ish



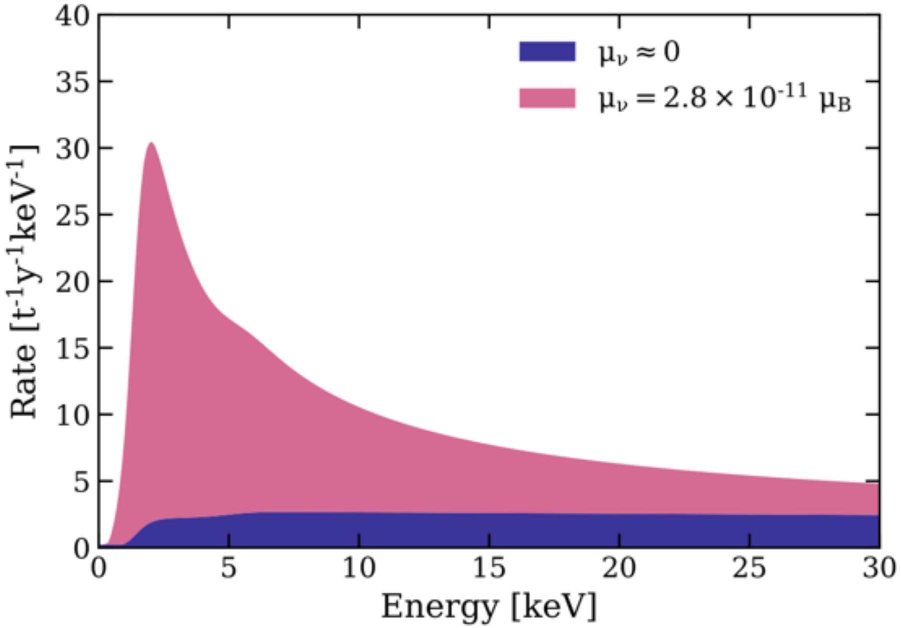
Detection

$$\frac{d\sigma_\mu}{dE_r} = \mu_\nu^2 \alpha \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right)$$ ~ $1/E_r$

Reconstruction in XENON1T
(resolution, efficiency, threshold)



⬅



μ_ν in the Standard Model and beyond

Dirac: $$\mathcal{L} \supset \mu_\nu \overline{\nu}_L \sigma_{\mu\nu} \nu_R F^{\mu\nu} + m_\nu \overline{\nu}_L \nu_R + \text{H.c.}$$

μ_ν and ν mass operators have the same chiral structure
➔ μ_ν typically proportional to m_ν

SM+ν_R: $$\mu_\nu = \frac{eG_F m_\nu}{8\sqrt{2}\pi^2} = 3 \times 10^{-20} \mu_B \left(\frac{m_\nu}{0.1 \text{ eV}}\right)$$

Transition mag. moment for Majorana ν's:

$$\mu_{ij} = -\frac{3eG_F}{32\sqrt{2}\pi^2}(m_i \pm m_j) \sum_{\ell=e,\mu,\tau} U^*_{\ell i} U_{\ell j} \frac{m_\ell^2}{m_W^2}$$ ➔ $O(10^{-23})$

➔ BSM models significantly enhance neutrino μ_ν

e.g. MSSM with L violation by R-parity violation ~ λ'

$$\mu_\nu \sim \lambda'^2/(16\pi^2) m_\ell^2 A_\ell / M_{\tilde{\ell}}^4$$

A_l ←→ SUSY breaking trilinear coupling

$M_{\tilde{\ell}}$ ←→ slepton mass

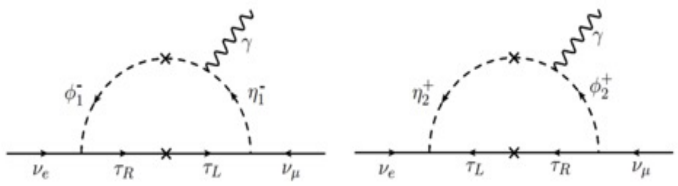
➔ $\mu_\nu \leq 10^{-13}\ \mu_B$

Rather general: Most BSM models with TeV-ish scales allow/predict $\mu_\nu \leq 10^{-13}\ \mu_B$

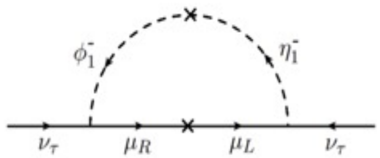
Pushing higher often leads to two problems:

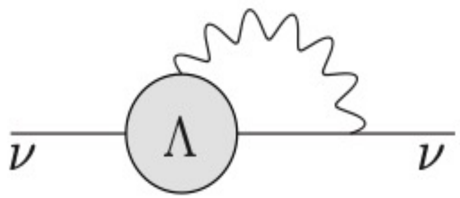
- light new particles that should have been discovered

- intrinsic relation between magnetic moment and radiative neutrino masses



➔ ν mass





➔ neutrino mass shifts which are much bigger than allowed w/o fine-tuning

But: Symmetries can unlock the MM/radiative mass problem

See e.g.: ML, B. Radovčić, J. Welter, JHEP 07 (2017) 139

symmetries for ν mass patterns ➔ impact on m_ν ←→ μ_ν relation

K.S. Babu, S. Jana, ML, JHEP 10 (2020) 040

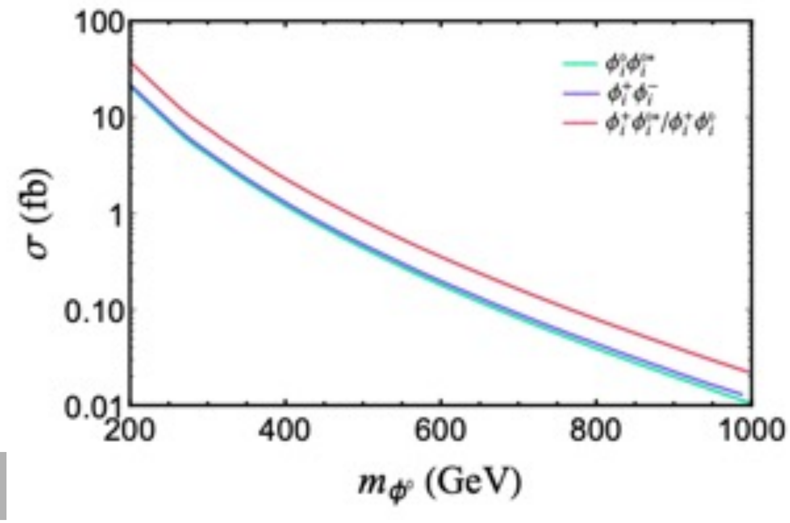
Horizontal $SU(2)_H$ broken by muon Yukawa coupling

Main point:

$$\mathcal{L}_{\rm mag.} = (\nu_e^T \;\; \nu_\mu^T) C^{-1} \sigma_{\mu\nu} \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} F^{\mu\nu} \;\; \Leftrightarrow \;\; \mathcal{L}_{\rm mass} = (\nu_e^T \;\; \nu_\mu^T) C^{-1} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

$\mathcal{L}_{\rm mass}$ is not invariant ➔ $m_\nu = 0$ in the $SU(2)_H$ limit while μ_ν is allowed
+ corrections ➔elegantly generates the correct ν mass scale

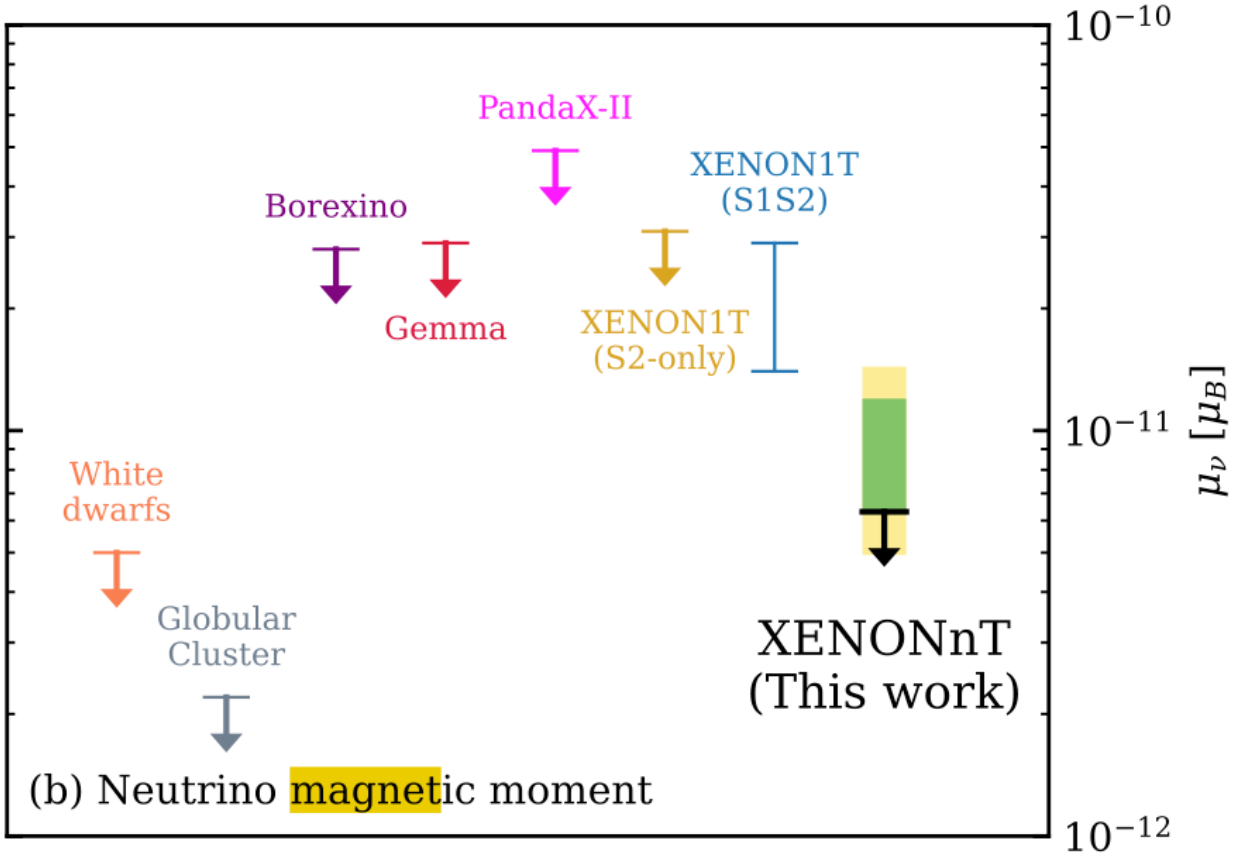
➔ LHC prospects



XENONnT

arXiv: 2207.11330

No need to enhance solar neutrino interactions

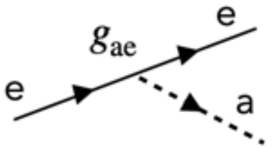


➔ **strongest laboratory limits on neutrino magnetic moments**
➔ **no need to decouple magnetic moments and radiative masses**

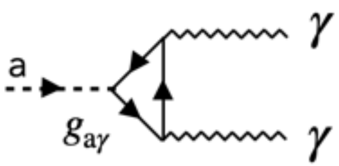
Signal Interpretaion: Solar Axions?

Production:

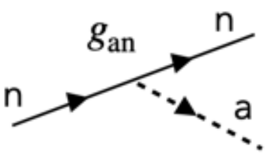
1. ABC



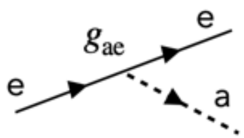
2. Primakoff



3. ^{57}Fe M1 transition

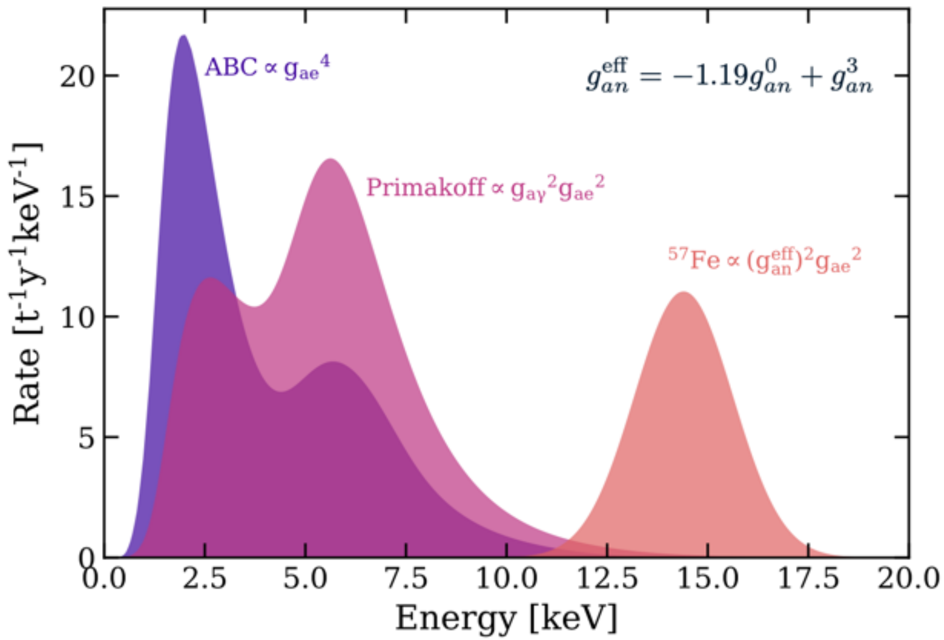


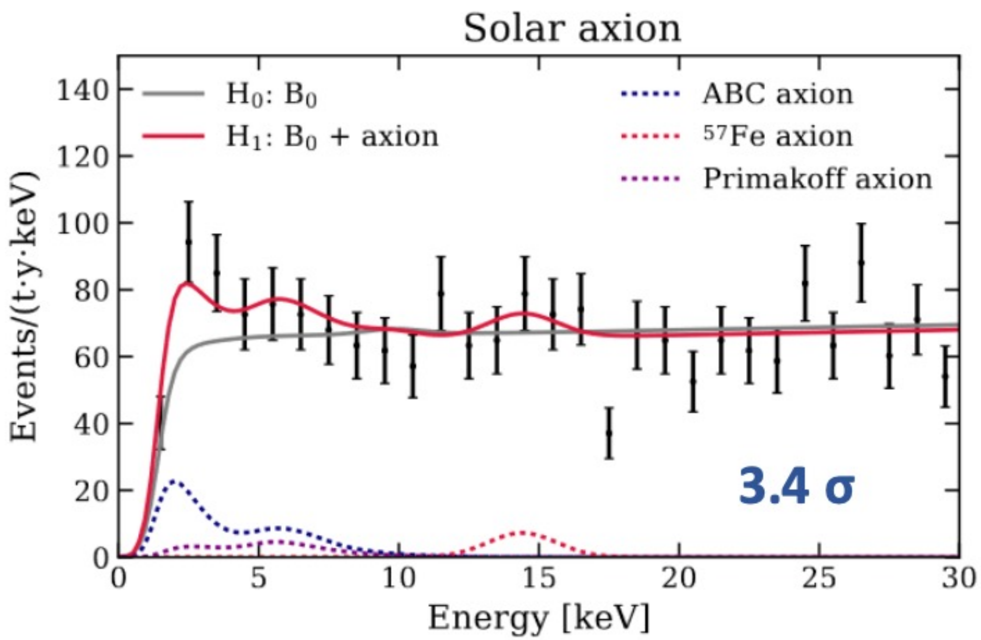
Detection via axio-electric effect



$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$$

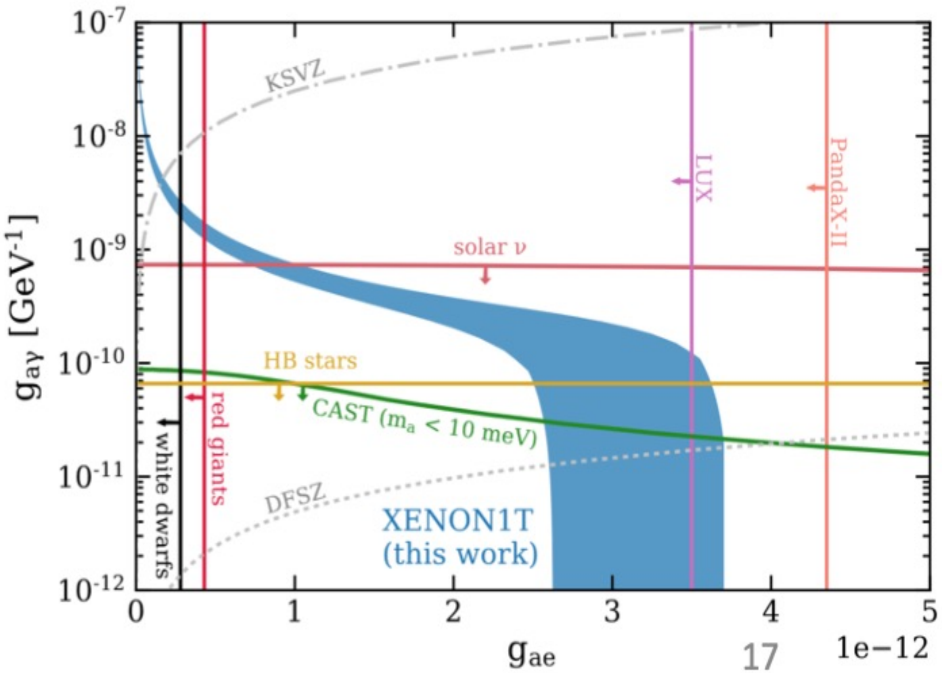
Reconstruction in XENON1T (resolution, efficiency)





Fit with three components:

- **ABC**
- **Primakoff**
- **^{57}Fe**



But: Tension with constraints

- stellar cooling
- solar neutrinos

➔ Ways around?

See e.g.: XENON1T excess from anomaly-free Axion-like Dark Matter and its implications for Stellar Cooling Anomaly,

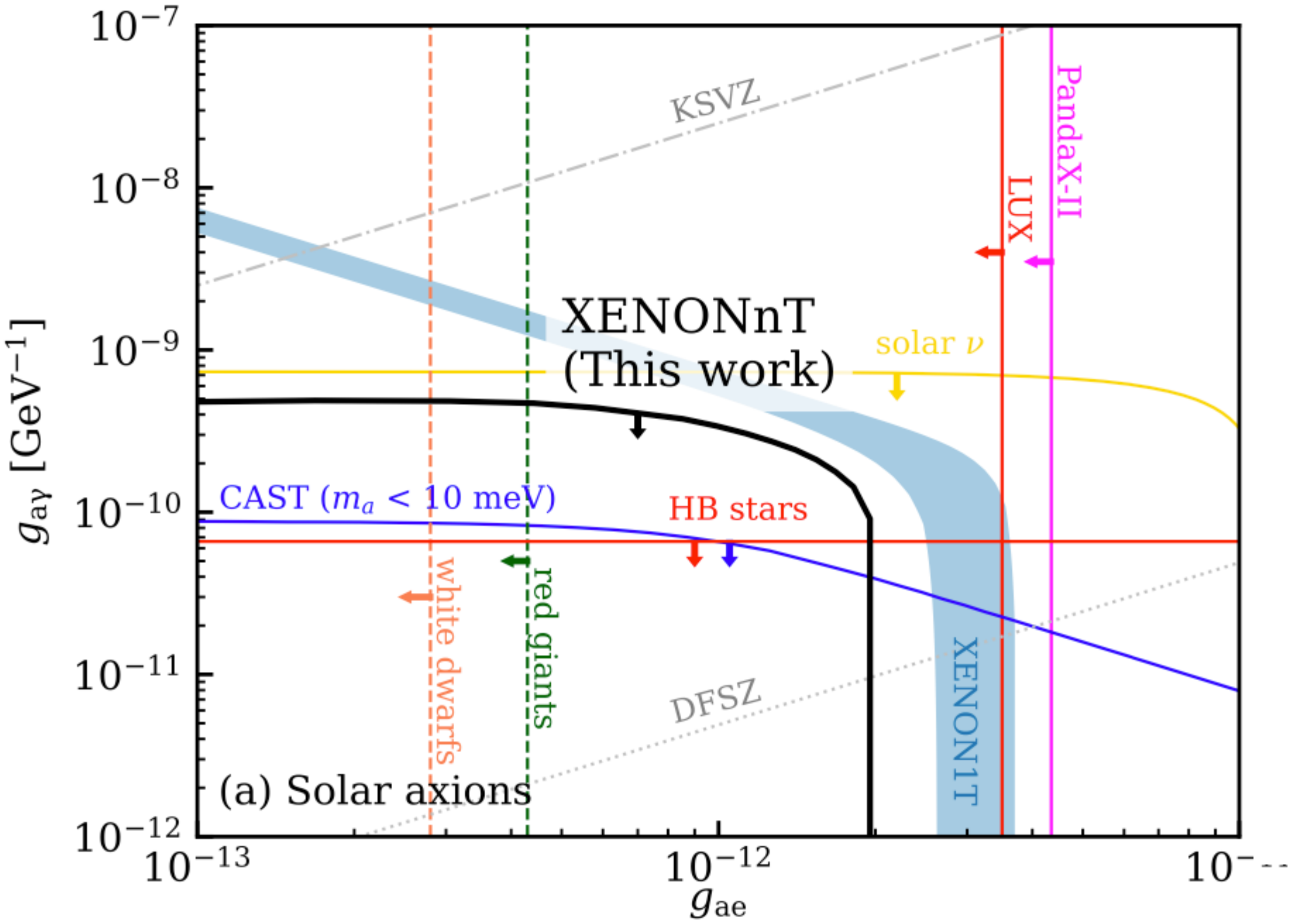
F. Takahashi, M. Yamada, W. Yin, PRL 125 (2020) 16, 161801

WD and RG explained simultaneously better when ALP constitutes about 10% of DM

XENONnT

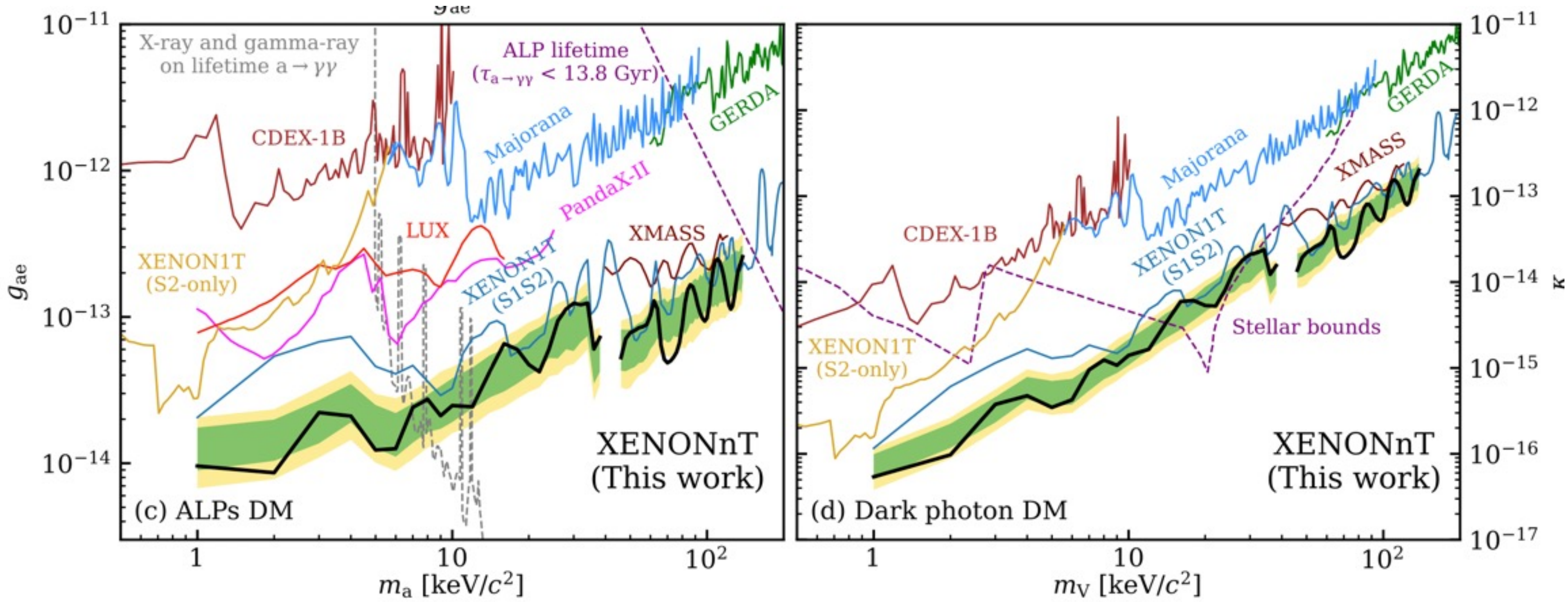
arXiv: 2207.11330

Improved limits on axion couplings:



➔ **No need to argue for enhancements which avoid astronomical conflicts** arXiv: 2207.11330

➔ **strong laboratory limits on ALPs and dark photons**

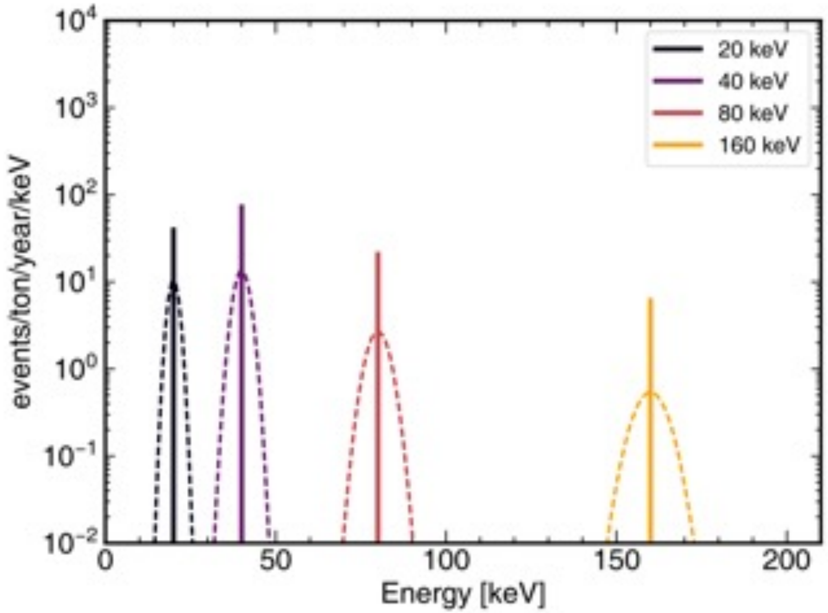


Bosonic Dark Matter

E.g. axion-like pareticles (ALPs) – not related to strong CP problem, but interesting
➔ no strict mass-coupling relation

$$R \simeq \frac{1.5 \times 10^{19}}{A} g_{\mathrm{ae}}^2 \left(\frac{m_{\mathrm{a}}}{\mathrm{keV}/c^2}\right)\left(\frac{\sigma_{\mathrm{pe}}}{\mathrm{b}}\right) \mathrm{kg}^{-1}\mathrm{d}^{-1}$$

➔ **Expect a monoenergetic peak around the rest mass**



➔ **But: Why should the mass be close to XENON1T threshold?**

Many Solutions: Hidden Dark Sectors

Receipe: Dark sector + light particles + weak coupling

A few examples:

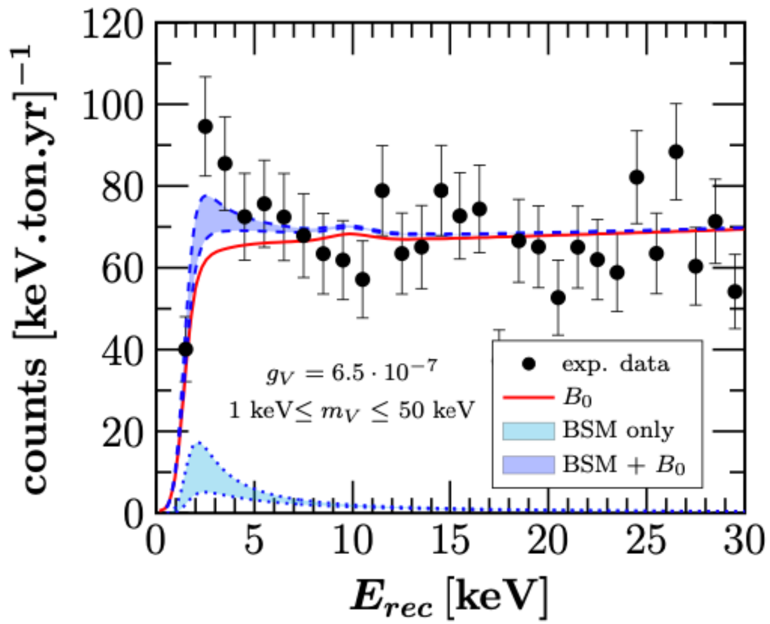
- Light new physics in XENON1T
  C. Bœhm, D. Cerdeno, M. Fairbairn, P. Machado, A. Vincent, arXiv:2006.11250
- Light vector mediators facing XENON1T data
  D. Aristizabal Sierra, V. De Romeri, L.J. Flores, D.K. Papoulias, PLB 809 (2020) 135681
- Shining dark matter in Xenon1T
  G. Paz, A. Petrov, M. Tammaro, J. Zupan, arXiv: e-Print:2006.12462
- Mirror Dark Matter and Electronic Recoil Events in XENON1T
  L. Zu, G.W. Yuan, L. Feng, Y.Z. Fan, arXive:2006.14577
- XENON1T Anomaly: A Light Z'
  ML, Y. Mambrini, T. de Meloc, F.S. Queiroz, arXiv:2006.14590
- Boosted Dark Matter Interpretation of the XENON1T Excess
  B. Fornal, P. Sandick, J. Shu, M. Su, Y. Zhao, Phys.Rev.Lett. 125 (2020) 16, 161804

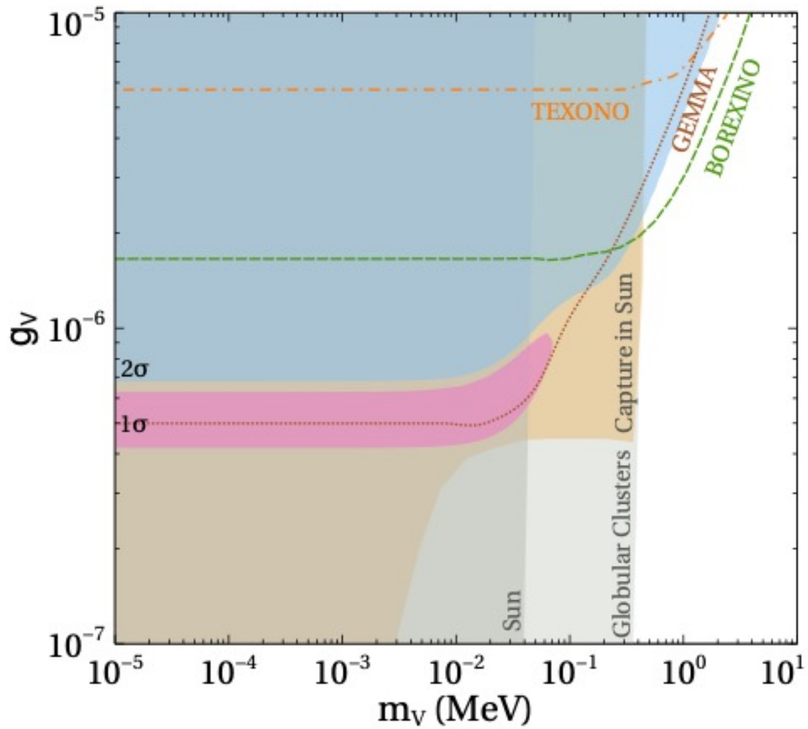
+ many more

Light Dark Sectors ⇔ E_R Spectrum

D. Sierra, V. De Romeri, L. Flores, D. Papoulias, arXiv:2006.12457
Also:
C. Boehm, D. Cerdeno, M. Fairbairn, P. A. Machado, A. Vincent, ArXiv:2006.11250
A. Bally,S. Jana,A. Trautner, PRL 125 (2020) 16, 161802

➔ new neutrino-lepton interactions mediated by a light vector particle





➔ 1σ allowed , 2σ excluded regions
in the m_V - g_V plane

➔ now: limits on masses & couplings

comparison to limits from:
- TEXONO
- GEMMA
- Borexino
- astrophysics

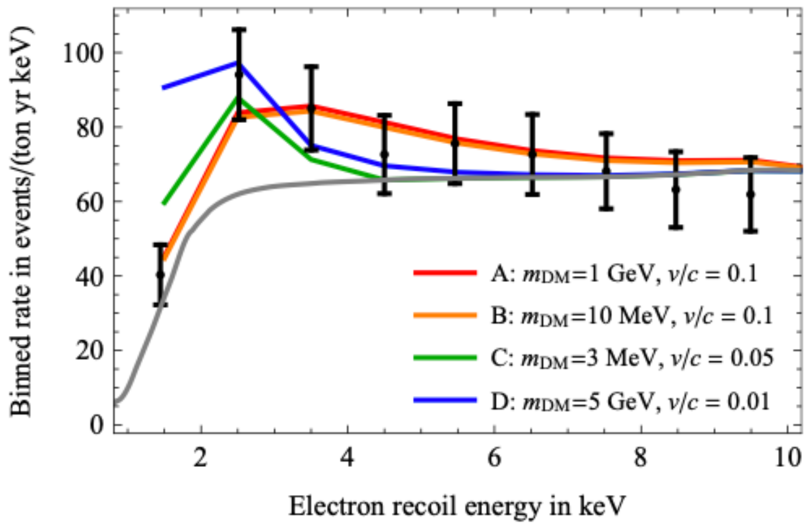
DM Particles with a fast Component

K Kannike, M. Raidal, H. Veermae, A. Strumia, arXiv:2006.10735

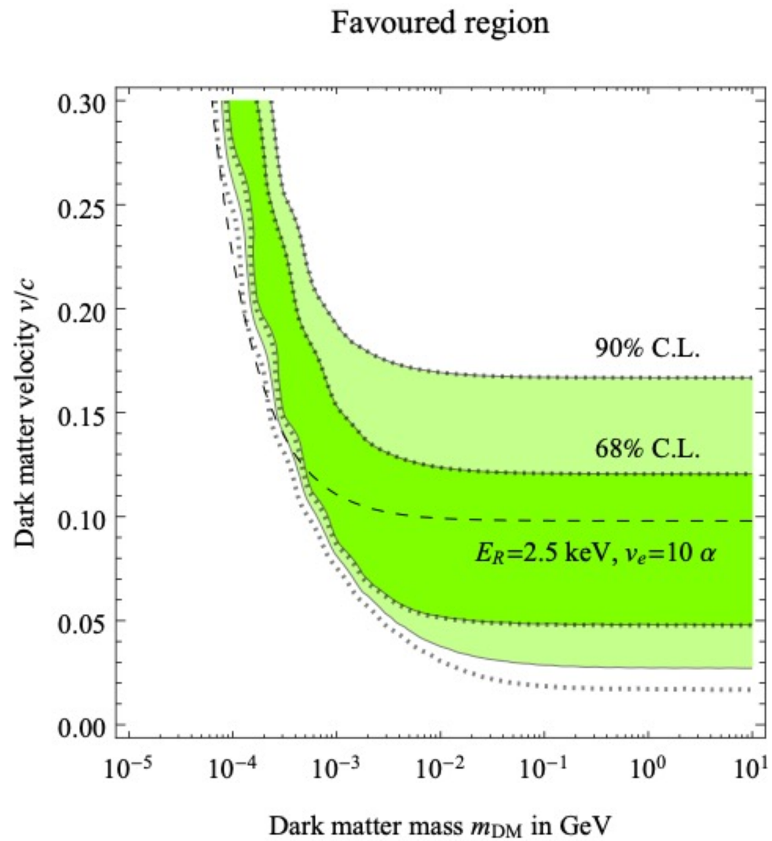
elastic DM+e → DM+e′ scattering
DM with initial velocity: $\vec{v}_{DM}$
electron initial/final velocity: $\vec{v}_e$ ➔ $\vec{v'}_e$
➔ Momentum transfer:

$$q \equiv m_{\rm DM}(v'_{\rm DM} - v_{\rm DM}) = -2\mu v_{\rm rel}$$
$$\simeq -\begin{cases} 2m_{\rm DM}(v_{\rm DM} - v_e) & \text{for } m_{\rm DM} \ll m_e \\ 2m_e(v_{\rm DM} - v_e) & \text{for } m_{\rm DM} \gg m_e \end{cases}$$

➔ $E_R \approx 2.4$keV for $m_{DM} \gg m_e$ with $v_{DM} \approx 0.1$



➔

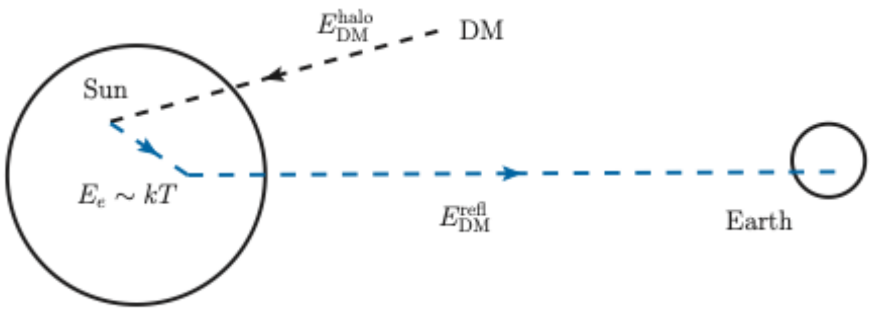


Problem: Fast component gravitationally not bound to galaxy ←➔ sub-dominant…
➔ limits on up-scattering of fast components

Sun heated MeV-Scale Dark Matter

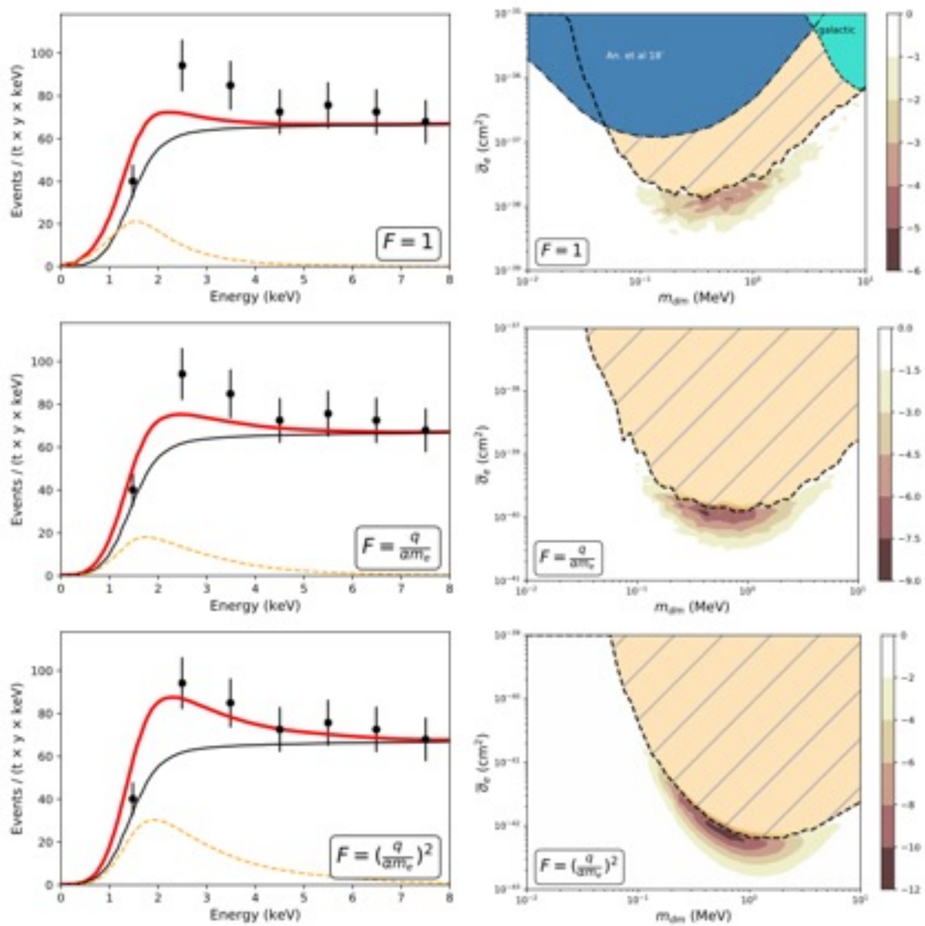
Y. Chen, M.Y. Cui, J. Shu, X. Xue, G.W. Yuan, Q. Yuan, arXiv:2006.12447

Explain signal by the MeV-scale dark matter heated inside the Sun (≈1.5 x 10^7 K)



- high-temperature plasma inside the Sun
  ➔ heat-up light DM particles to keV energies
  H. An, M. Pospelov, J. Pradler, A. Ritz, PRL120, 141801 (2018)

$$\Phi_{\rm heat} \sim \frac{\Phi_{\rm halo}}{4} \times \begin{cases} \frac{4S_g}{3}\left(\frac{R_{\rm core}}{d}\right)^2 \frac{R_{\rm core}}{\lambda}, & R_{\rm core} \ll \lambda \\ S_g\left(\frac{R_{\rm scatt}}{d}\right)^2, & R_{\rm core} \gg \lambda \end{cases}$$



- same DM-electron interaction in the detector
- Best fit, F(...), XENON1T limits
- Expect annual modulation w/o ν's or axions

Conclusions

- **Recent results of XENONnT on low E_R:**
  - impressive improvements (background, exposure)
  - excess of low E_R events is gone

  ➔ **no need to explain extra events by some new physics**

  ➔ **very interesting lessons on and implications for new physics:**
    - strongest laboratory limit on magnetic moments
      → decoupling of MM from radiative masses is not required
    - strong limits on axion couplings, ALPs and dark photons
      → need not resolve tensions with astronomy
    - no need for various new dark sector bosons and/or mechanisms
    - ...

- **The WIMP search continues**
  - XENONnT: stay tuned...