The XENON1T Excess, Interpretations, and theoretical Implications

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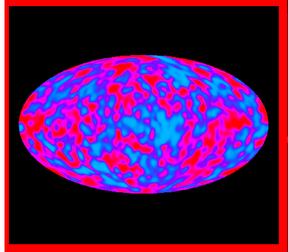
on behalf of the XENON collaboration

The cosmic Matter Balance



radiation:
0.005%

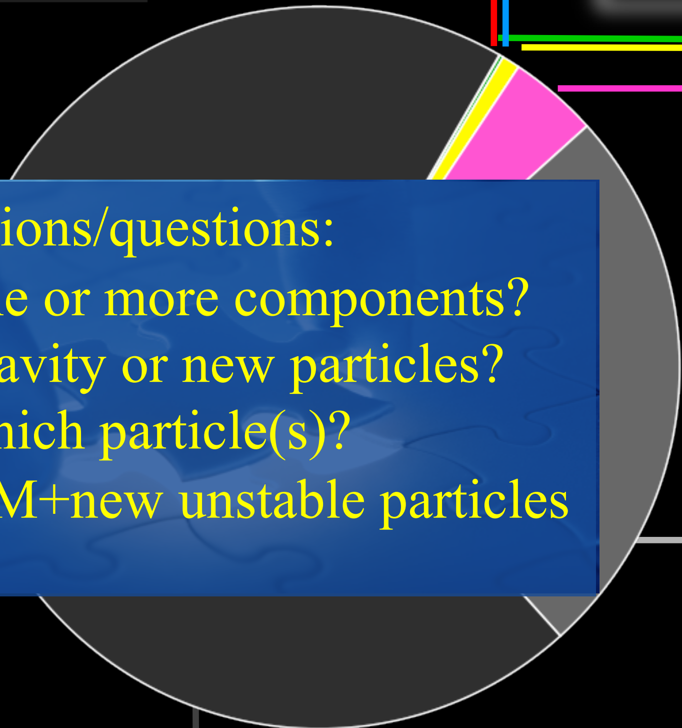
chemical elements:
(not H & He) 0.025%

ν_e ν_μ ν_τ

neutrinos = CνB:
0.17%

stars:
0.8%

H & He:
gas 4%



Options/questions:
- one or more components?
- gravity or new particles?
- which particle(s)?
- DM+new unstable particles
- ...

?

dark matter: 26.8%
→ something invisible
in addition to CνB

?

dark energy: 68.3%

Direct DM Detection: Billard with invisible Balls

- WIMPs scatter off atoms in a detector → **detect the signal… or set limits**
- Maximal momentum transfer ➔ $M_{WIMP} \sim M_{atom}$
  Additionally: clean, transparent, high density, no free charges, …

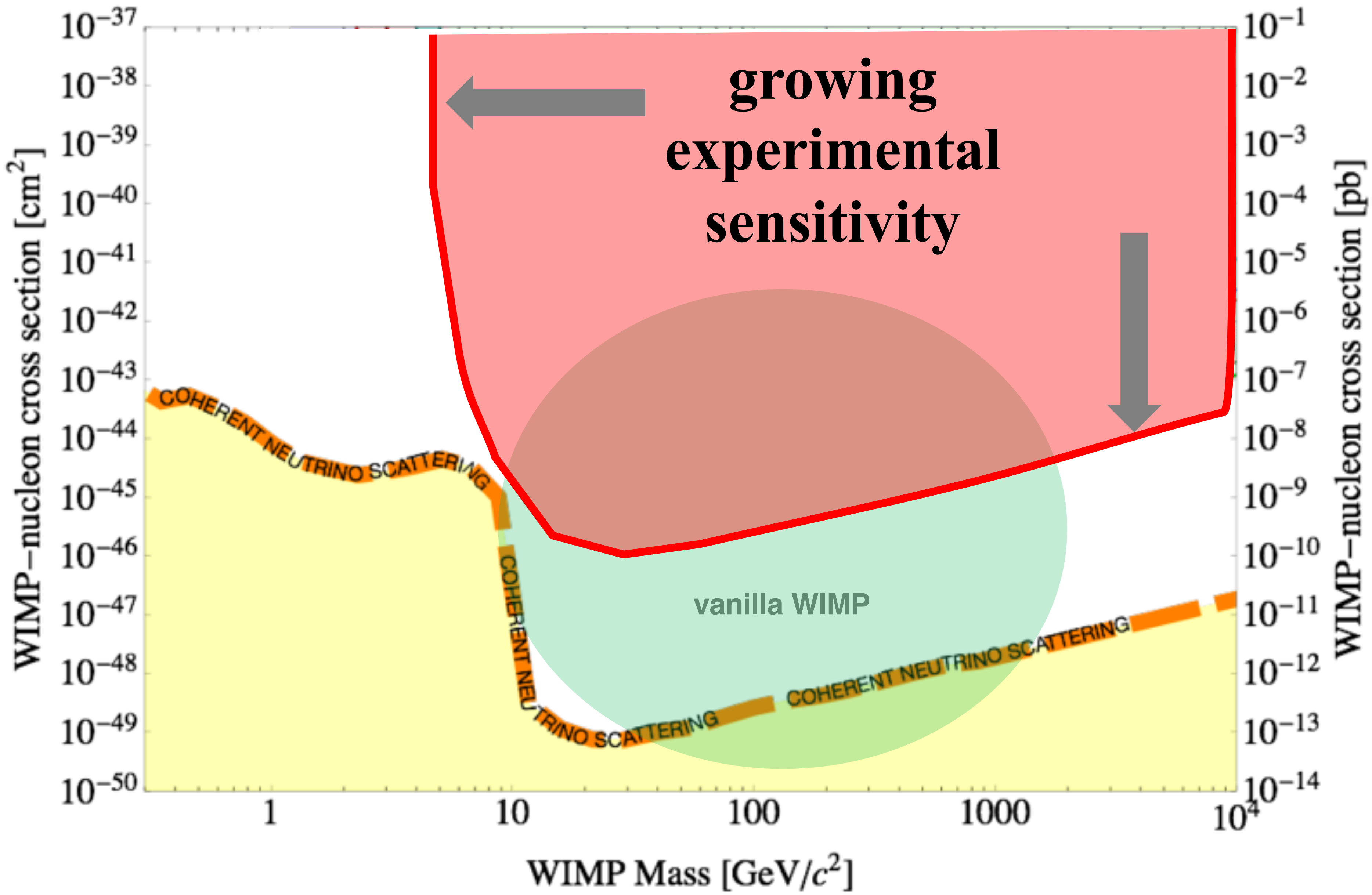
  ➔ **liquid Xenon** (ca. -100 degree) ⇦⇨ rarest stable element

Goal:

1) **Maximal signal** ←→ rare process
   → many atoms → big detector
2) **Minimal background**
   → requires extremely low radioactive background

➔ **Signal/limits for WIMPs, axions, ...**
➔ **room for surprises!**

Pushing into new Territory



The XENON Collaboration

Columbia KIT Nikhef Muenster Stockholm Mainz MPIK, Heidelberg Freiburg Zurich Tsinghua

Chicago

UCSD

Rice

Purdue

Tokyo

Nagoya

Kobe

NYUAD

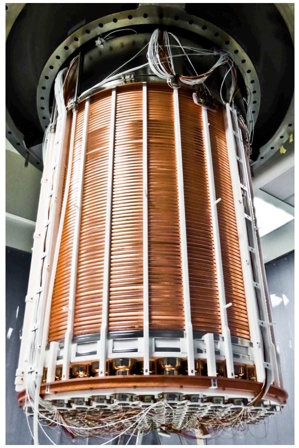
Weizmann

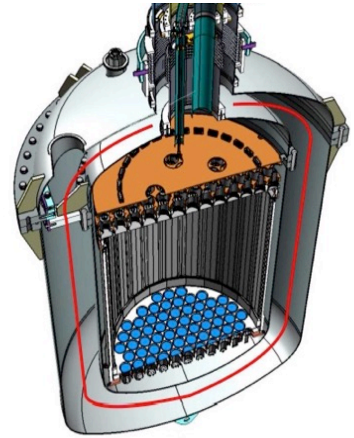
Subatech Coimbra LPNHE IJCLab Torino Bologna L'Aquila LNGS Napoli

XENON Collaboration: ~170 scientists

The XENON Dark Matter Program

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



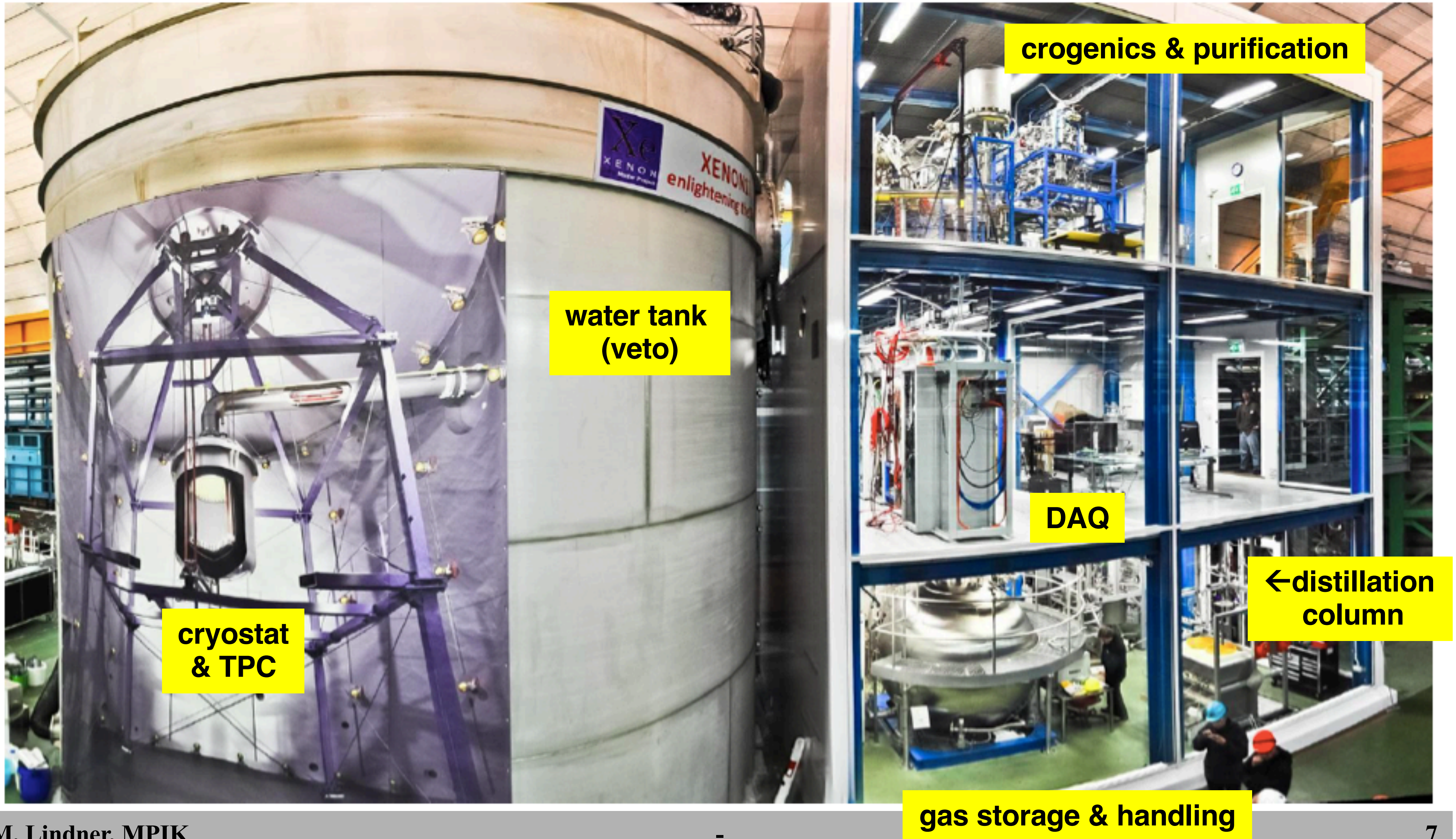


	XENON10	XENON100	XENON1T	XENONnT
Period	**2005-2007**	**2008-2016**	**2012-2018** →	**2020-2024**
Total mass	25 kg	161 kg	3200 kg	~8000 kg
Drift length	15 cm	30 cm	100 cm	150 cm
Status	Completed (2007)	Completed (2016)	Running	Construction
σ_{SI} limit (@50 GeV/c²)	8.8×10^{-44} cm²	1.1×10^{-45} cm²	1.6×10^{-47}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

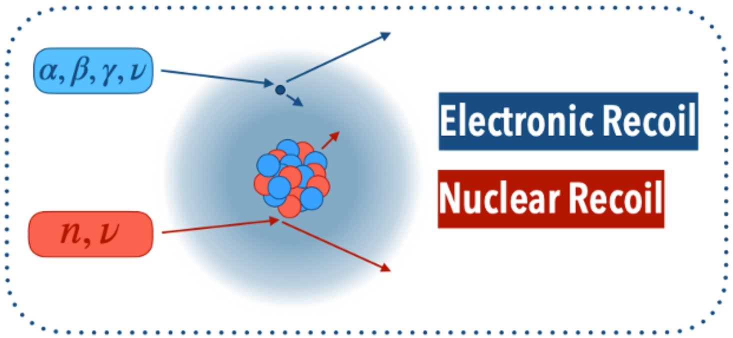
XENONnT was prepared while XENON1T took data
→ switching gears → filling started recently

XENON1T @ LNGS: Running until 12/2018

→ Goal: two orders of magnitude improvement in sensitivity with respect to XENON100



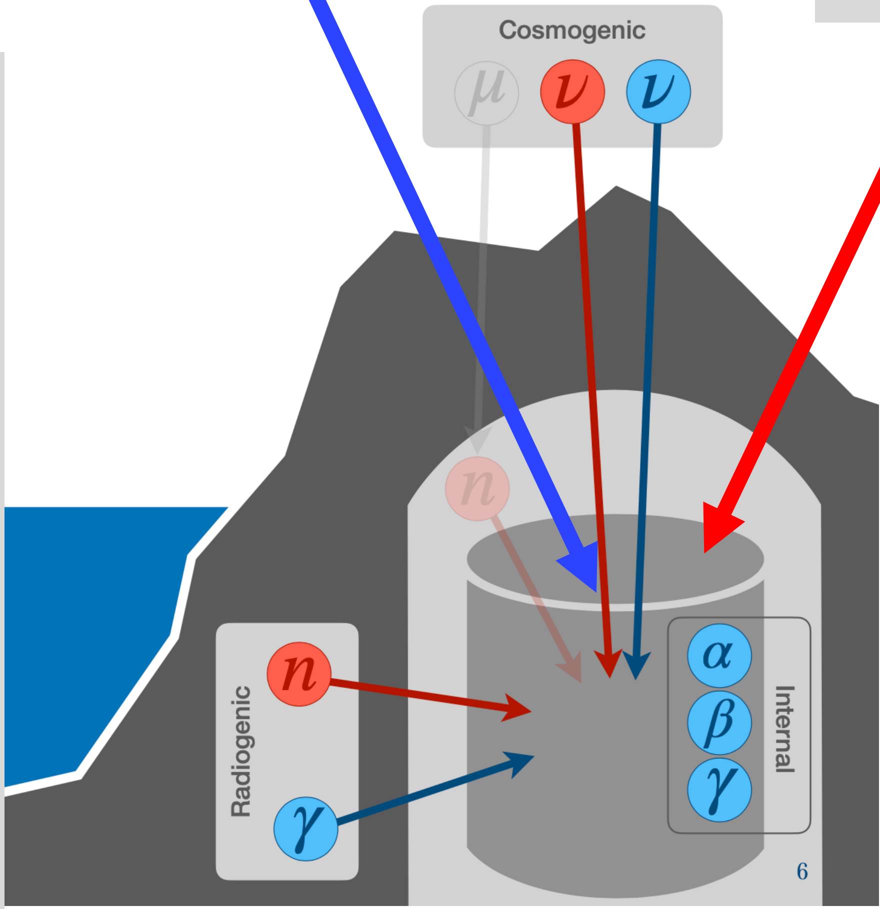
Dark Matter Detectors in UG Laboratoties



WIMPs
→ nuclear recoils

Sun:
- Neutrinos
- Axions ?
- ???

SM: too weak
→ should not show up



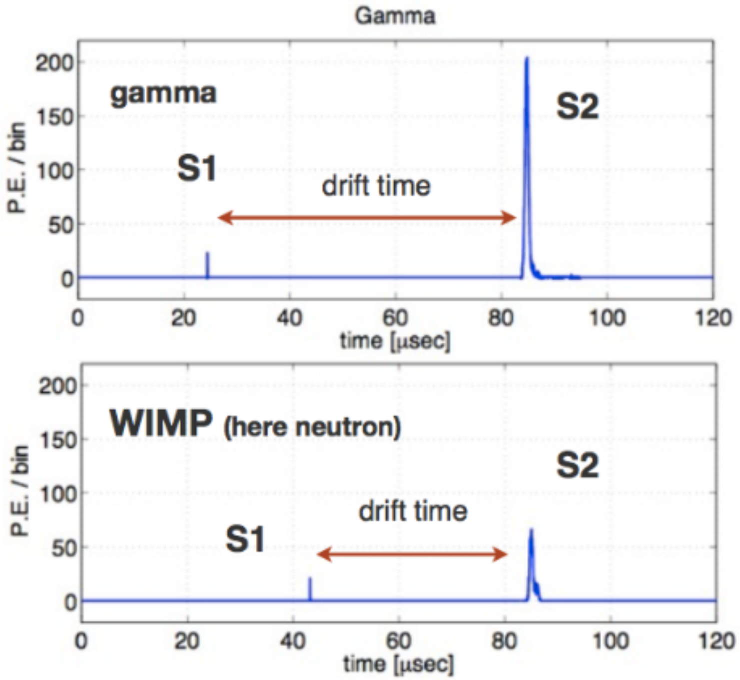
Background reduction

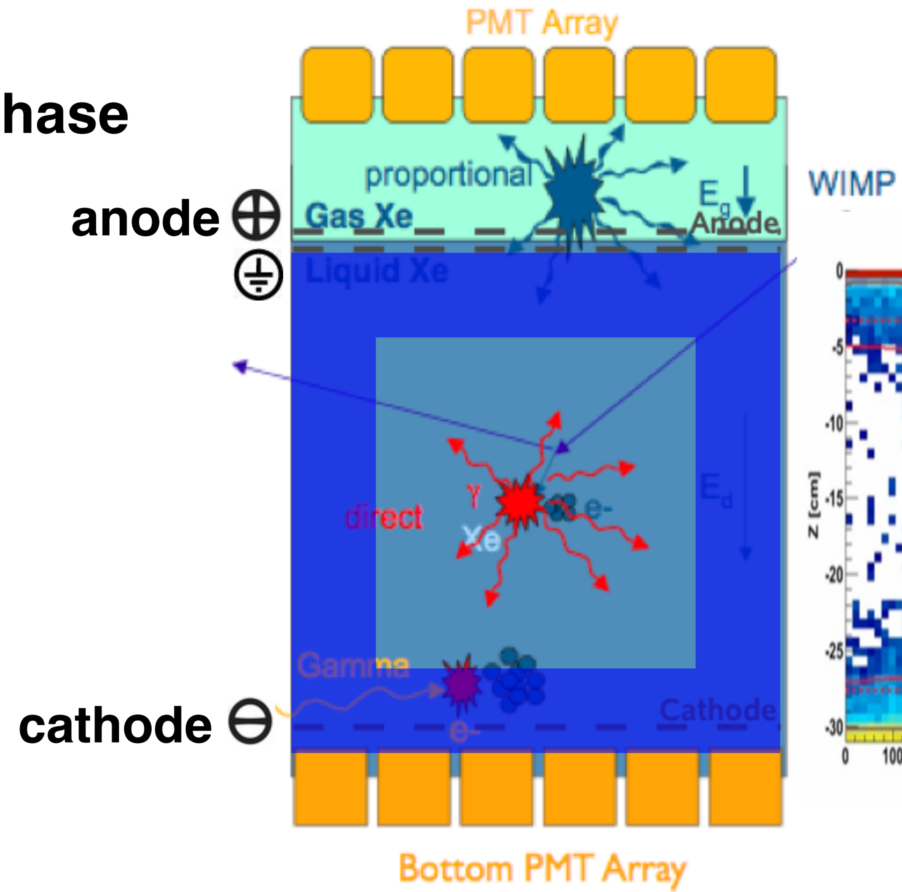
➔ extremely challenging:

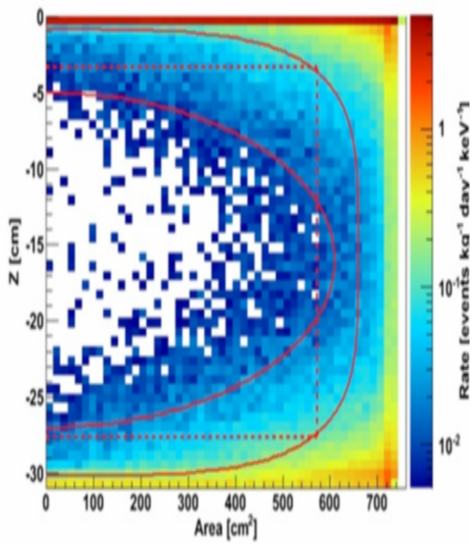
- material selection
- screening (γ, Rn, …)
- graded shielding
  - deep underground
  - veto systems
  - water
- cryogenic distillation
- pulse shape analysis
- …

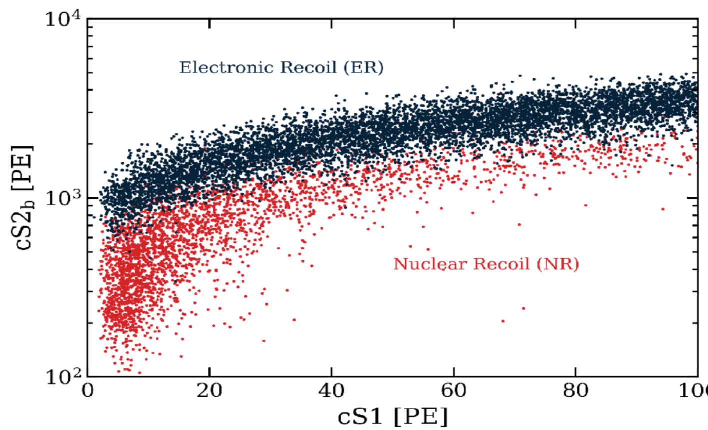
A powerful Device: Dual-Phase TPC

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







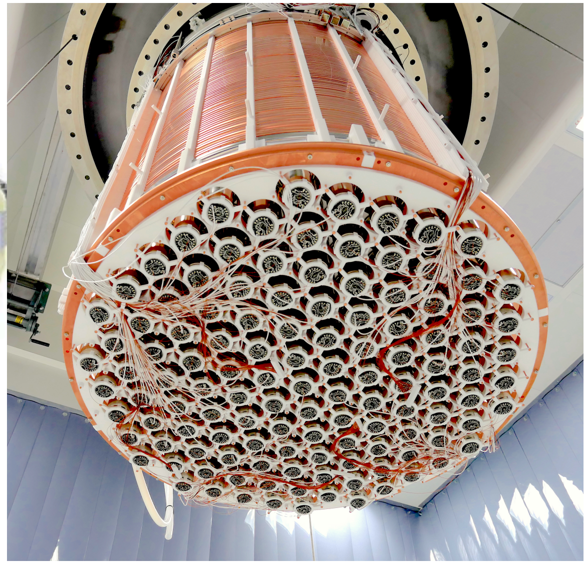


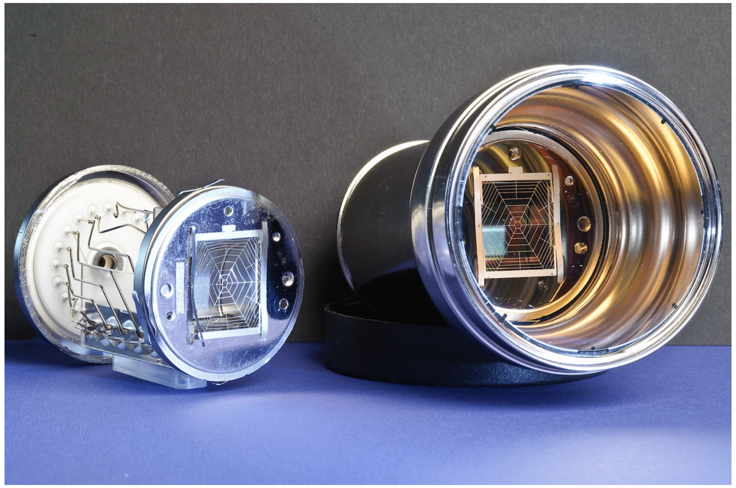
→ **excellent 3D position reconstruction**

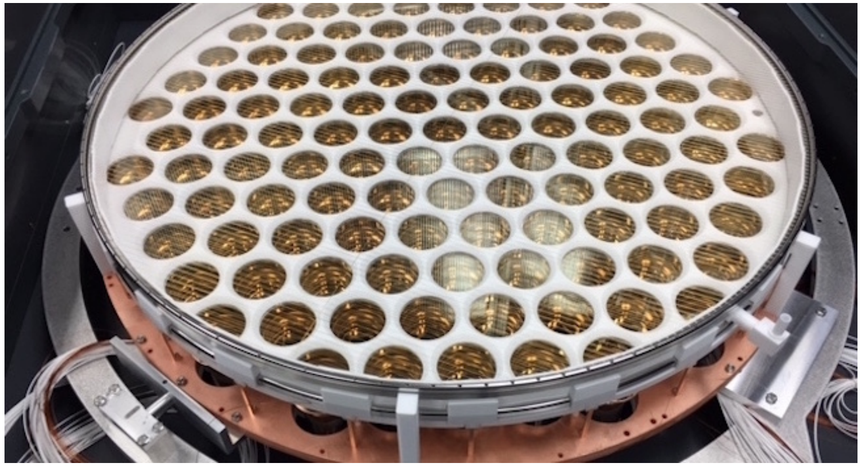
→ **fiducialization** = exclude known backgrounds from 'dirty' surfaces

→ **S2/S1 discrimination of ER / NR**

The XENON1T TPC

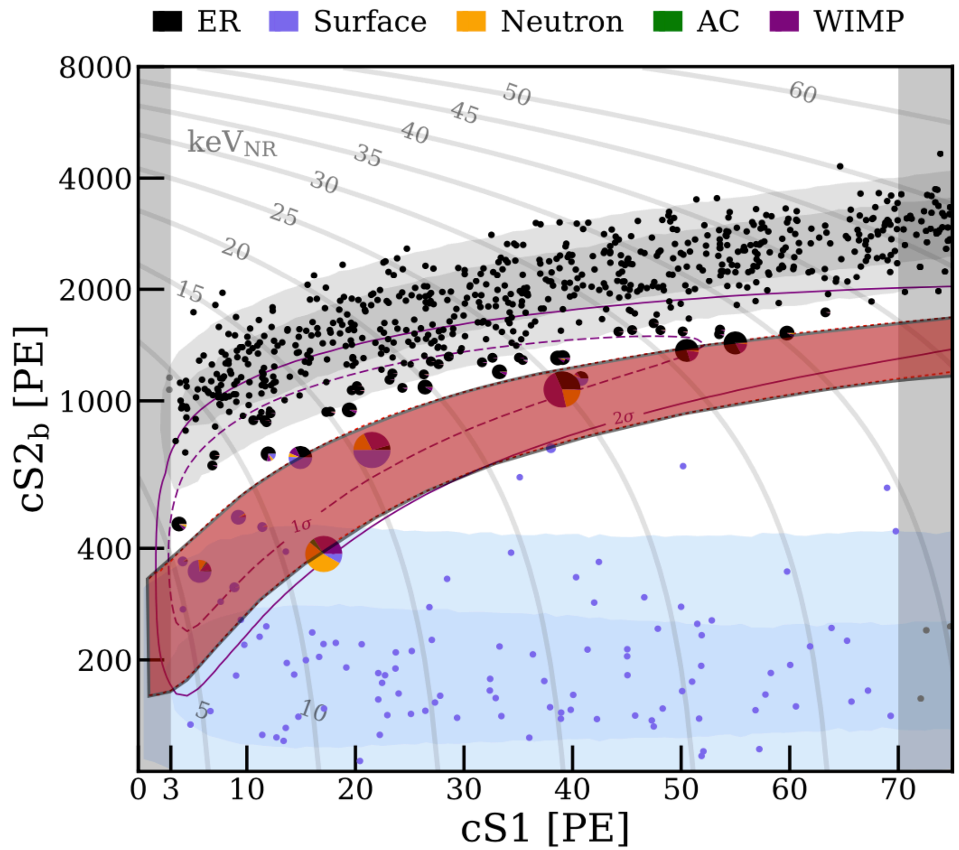


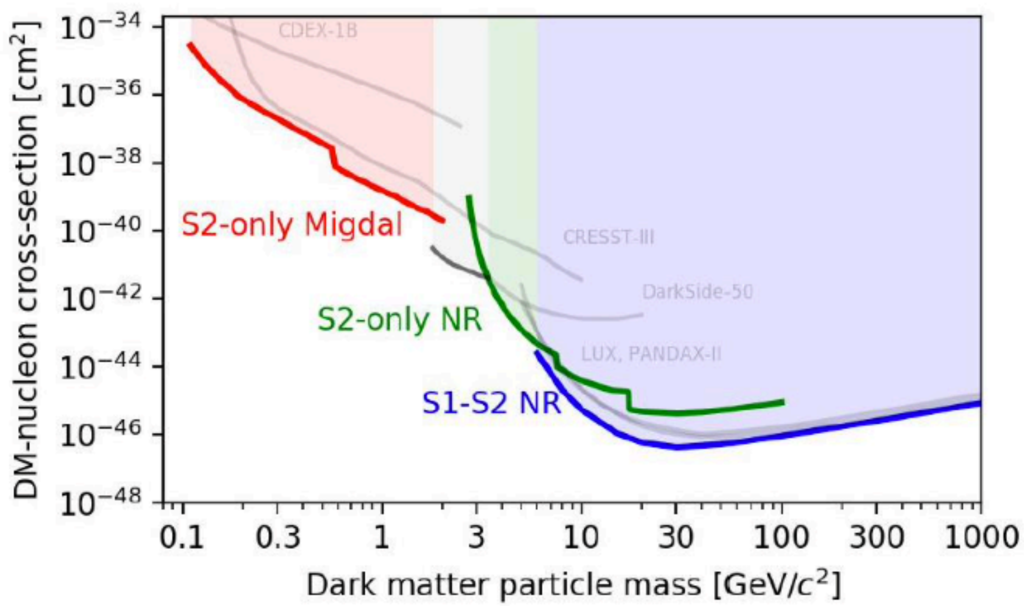


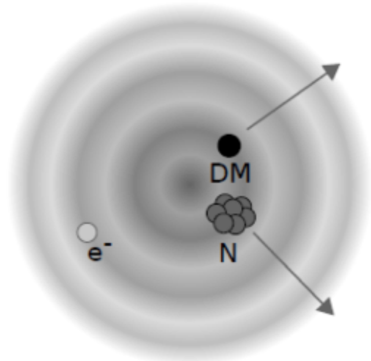


+ many other sophisticated sub-systems based on lot's of R&D

XENON1T: Nuclear Recoil Searches



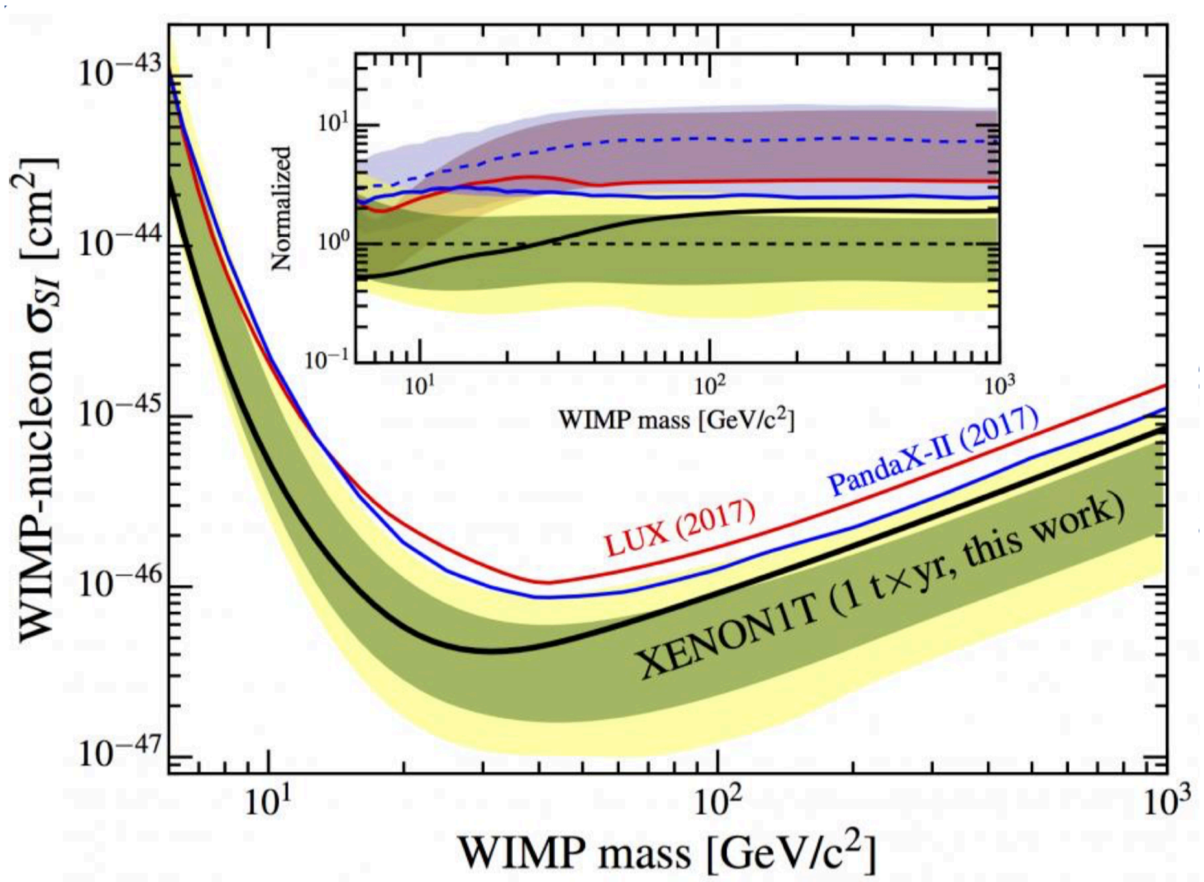




PRL 121, 111302 - Main WIMP search
PRL 123, 241803 - Migdal effect
PRL 123, 251801 - light dark matter

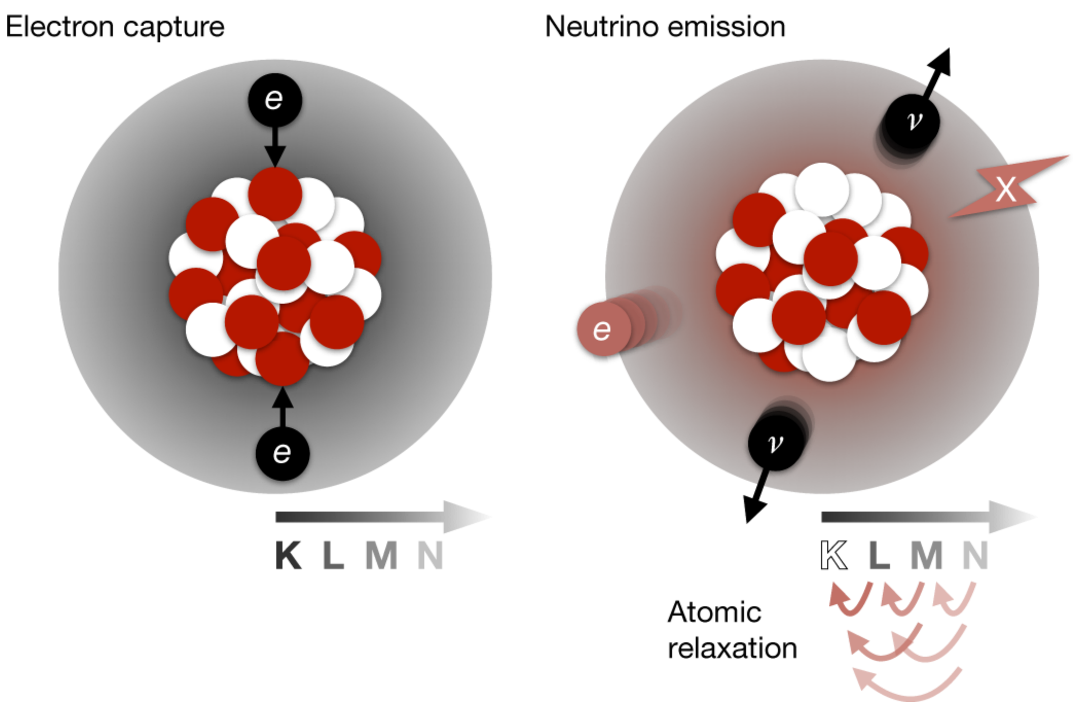
Migdal: ...it takes time for the electron to catch up

XENON1T: Results on WIMPs



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

Double Electron Capture of ^{124}Xe



$T = 1.8 \pm 0.5_{stat} \pm 0.1_{sys} \times 10^{22}\, yr$

No rejection significane: 4.4σ

➔ about one trillion times the age of the Universe

➔ longest half-life ever measured directly

Nature 568 (2019) 7753, 532-535

Search for New Physics with ER Events

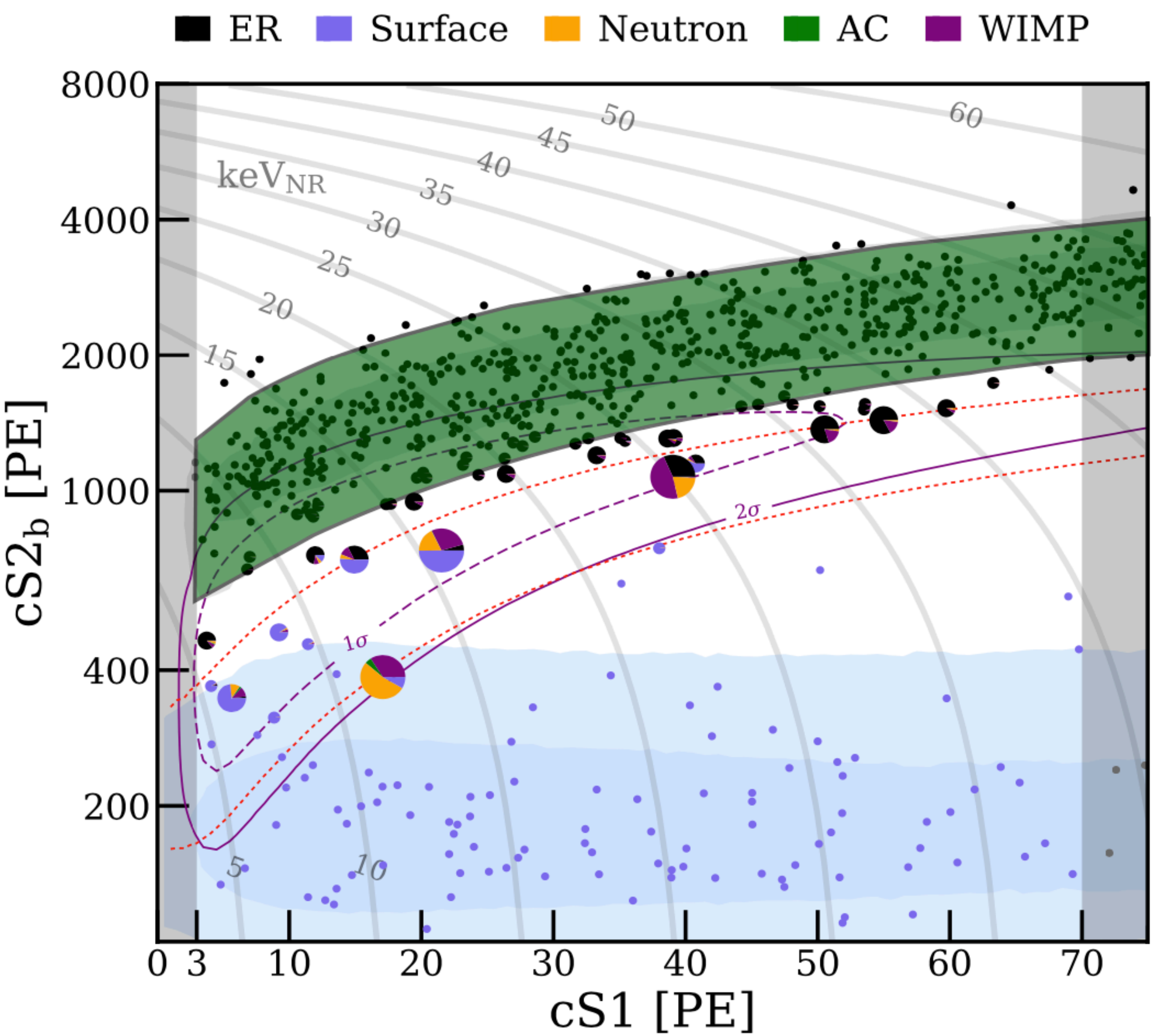
Phys. Rev. D 102, 072004

Large exposure:
0.65 tonne-years

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

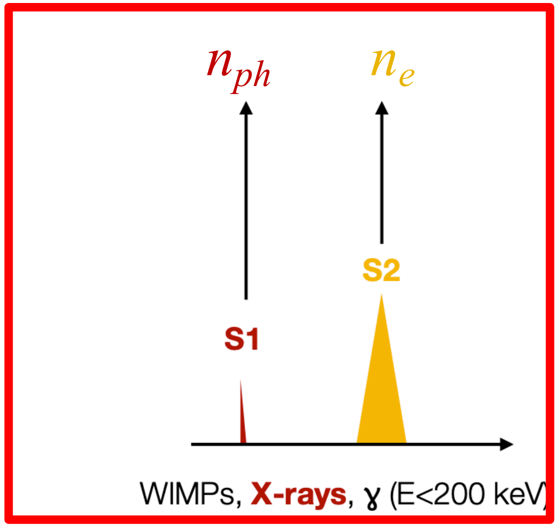
Low threshold:
1 keV_{ee}

➔ **excess events!?**

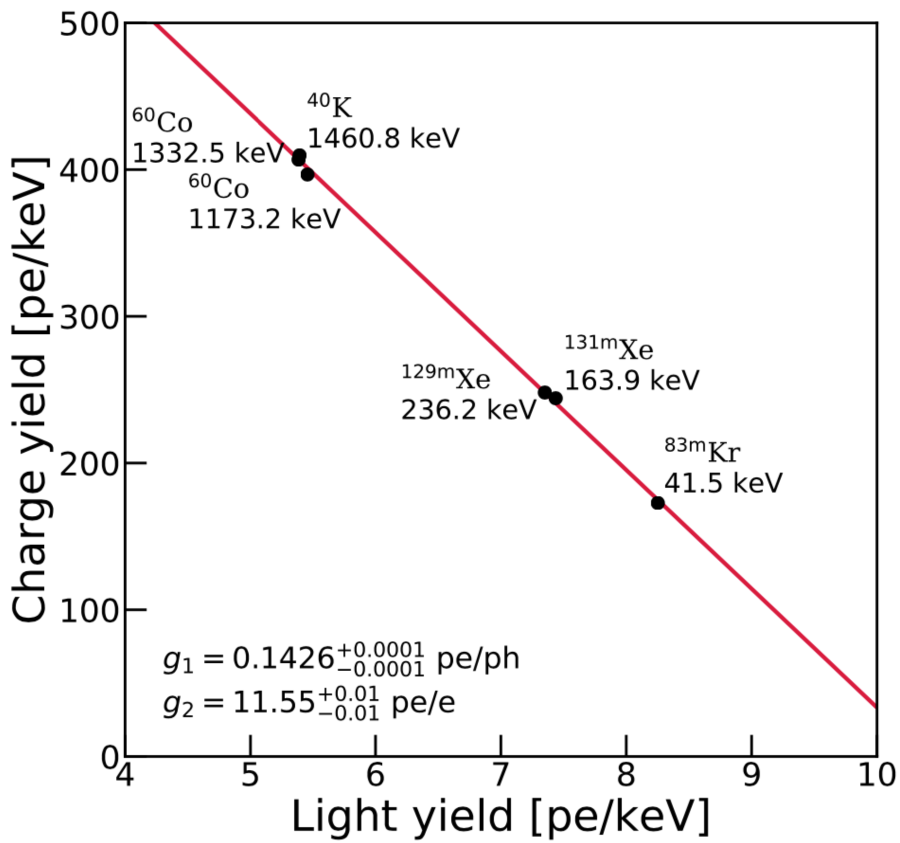


Energy Reconstruction and Resolution

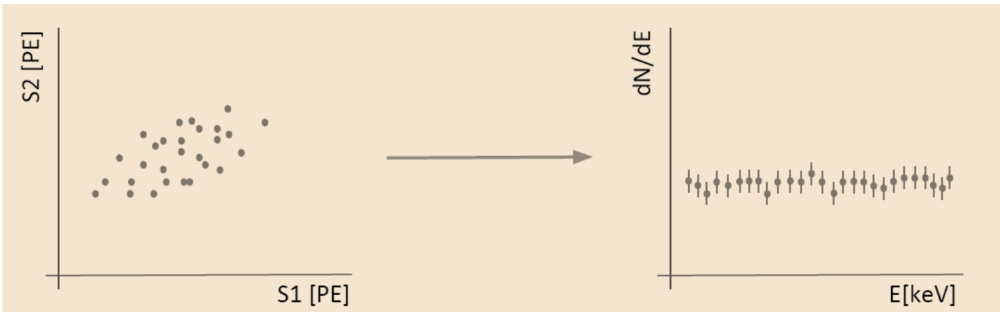
Combine light and charge



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



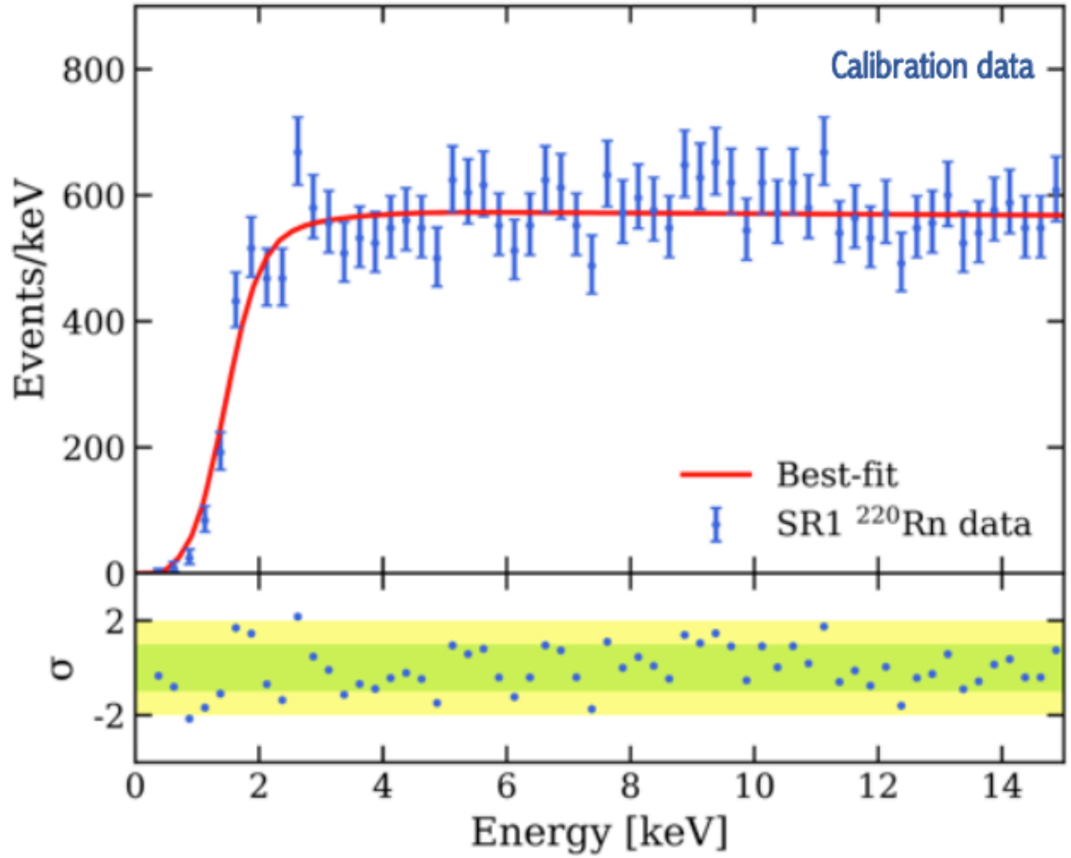
➔ **detector constants g_1 and g_2**



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

Detector Calibration

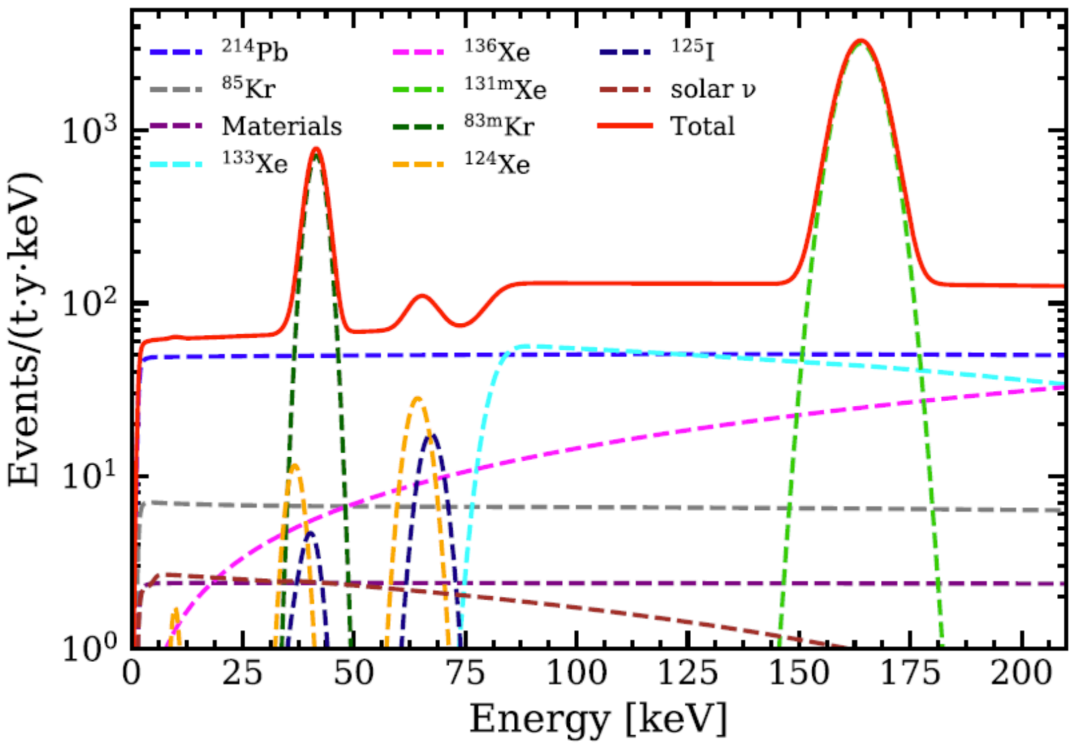
- ^{220}Rn (^{212}Pb, β-decay) calibration data validates our model even below 1keV
- No threshold excess
- No large systematics
- Uses the aame un-binned likelihood framework as in the main analysis



Background Model

Background prediction in [1,210] keV interval based on:

- knowledge from material screening and control measurements
- GEANT4 simulations smeared with detector effects
- 10 components



Internal (uniform in volume)

^{214}Pb (main contribution)

^{85}Kr (distilled out)

^{136}Xe, ^{124}Xe [Nature 568,532]

^{83m}Kr (calibration source issue)

Neutron induced

^{131m}Xe, ^{133}Xe, ^{125}I

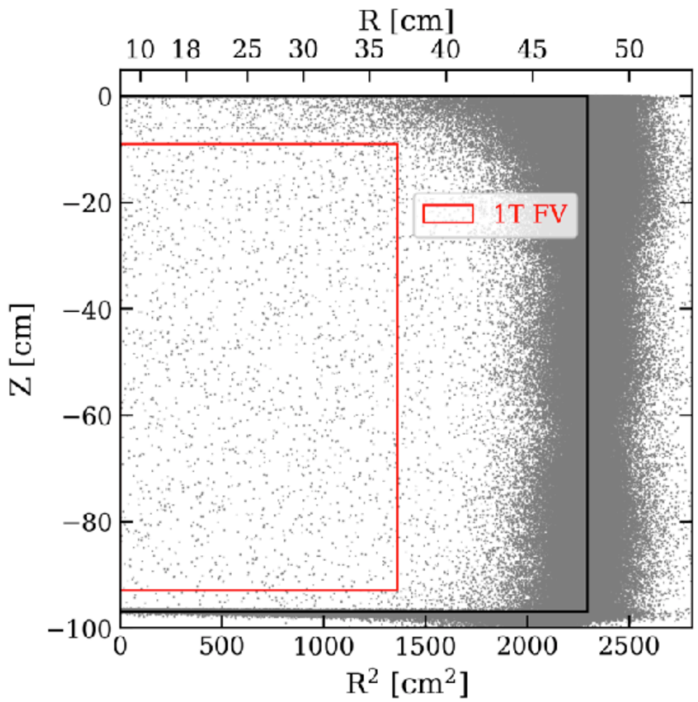
Solar neutrinos

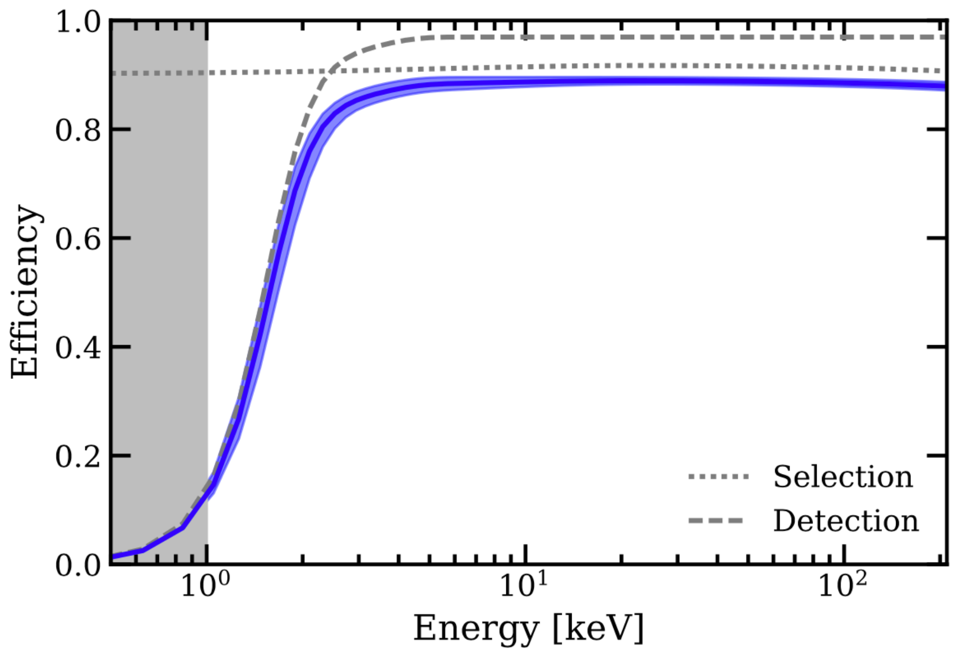
Materials←→radio-essay & GEANT4

Time-dependency

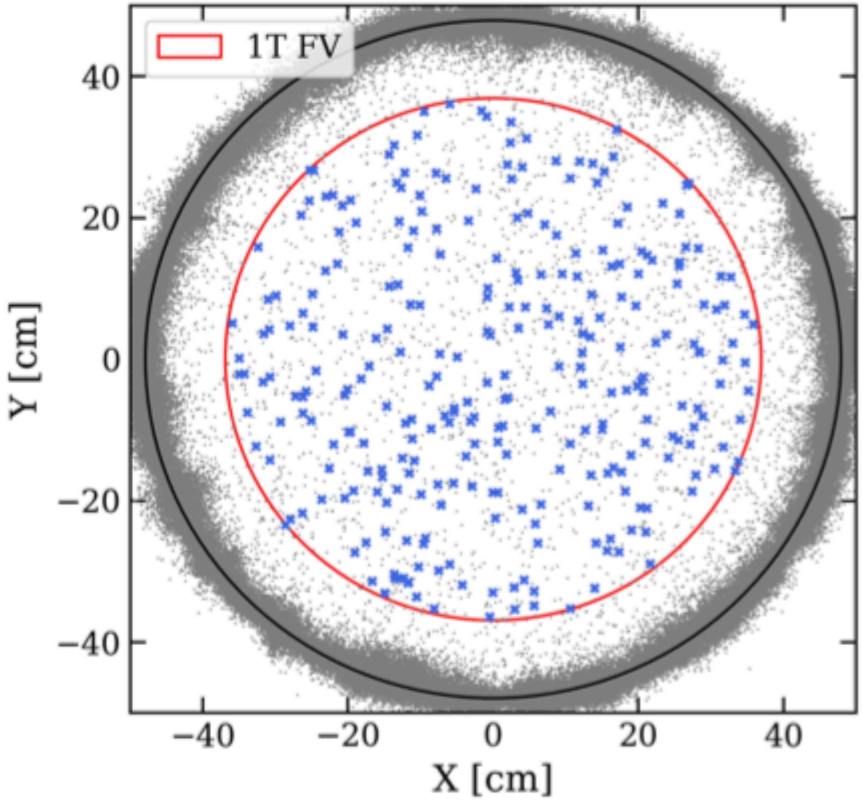
Data Selection and Detection Efficiency

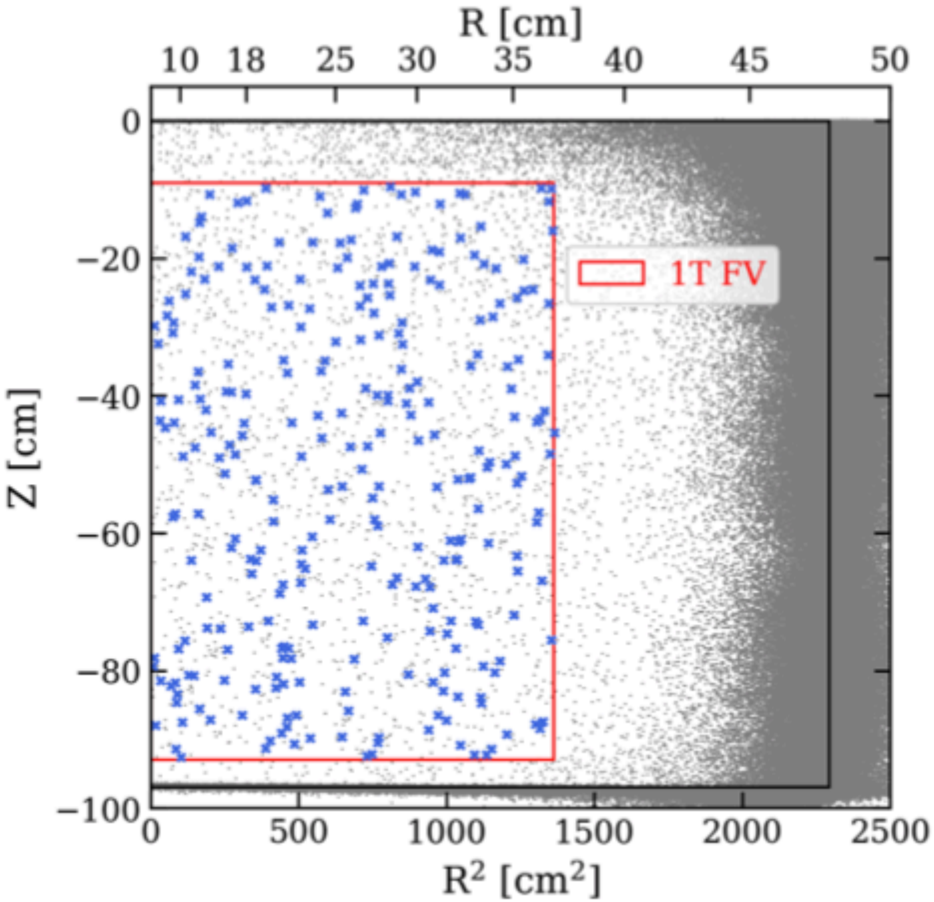
- **Science Run I:** Feb. 2017 - Feb. 2018 ➔ 226.9 live days
- Fiducial volume: 1 tonne
- Energy range for single scatter events: [1,210] keV_{ee}
- Data quality cuts
- Include reconstruction efficiency & threshold at 10% detection efficiency





Distribution of Events



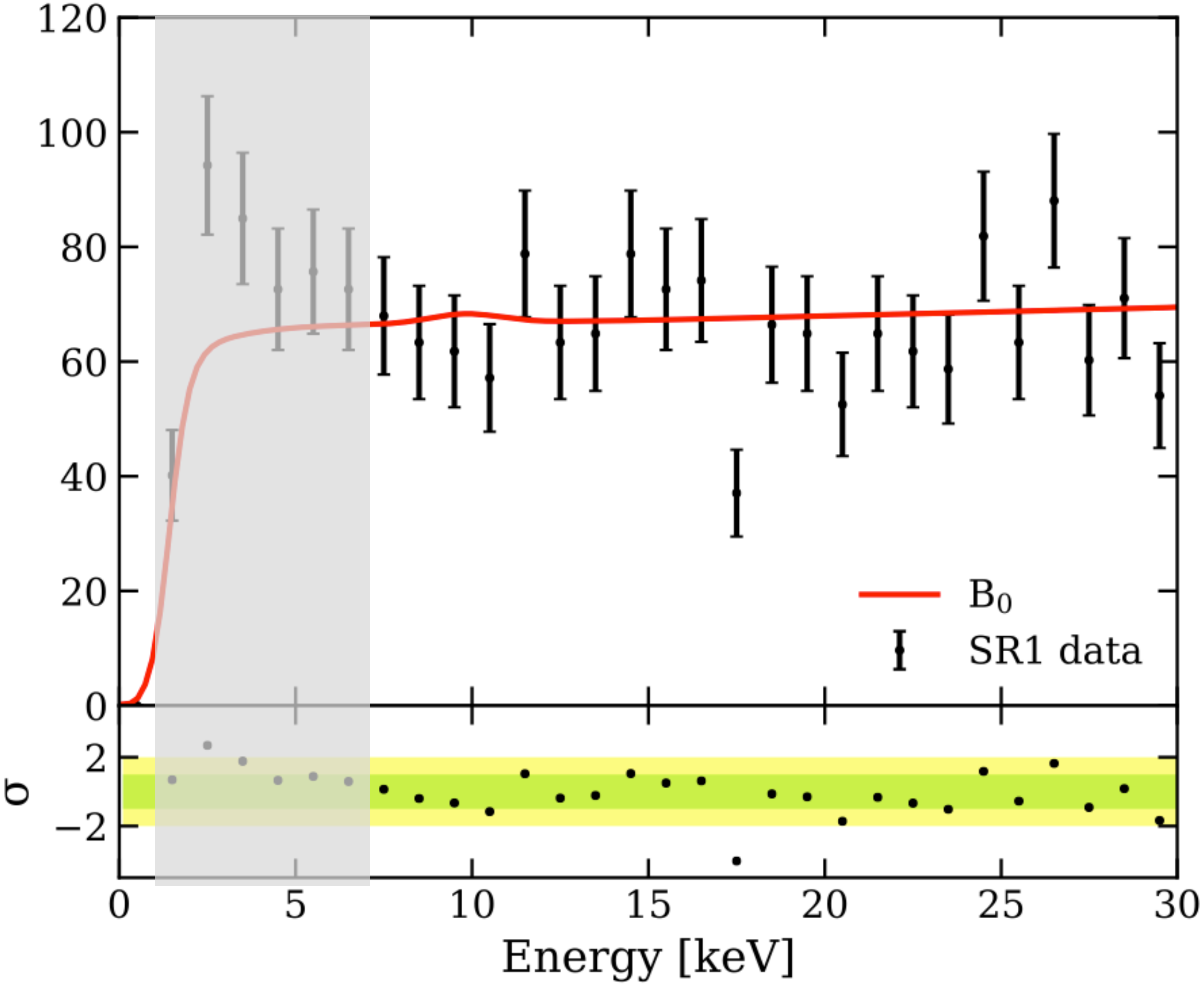


- [1 - 120] keV
- [1 - 7] keV

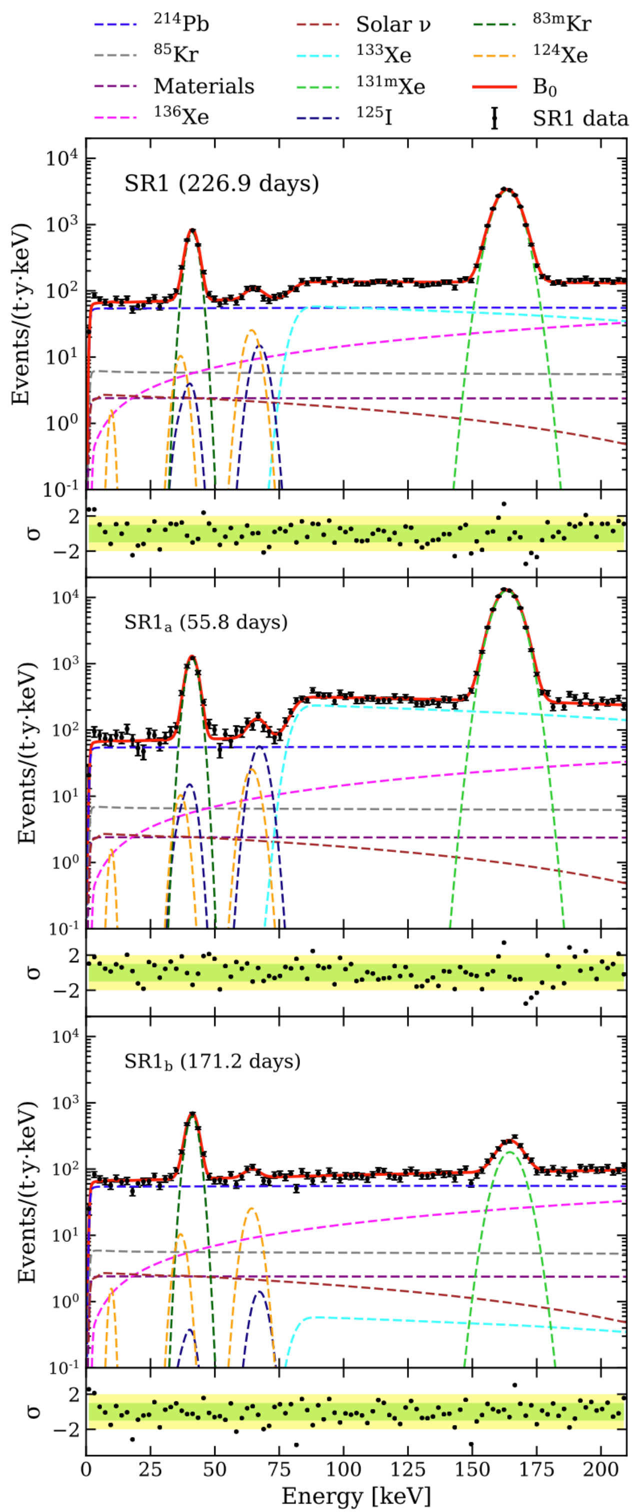
The Result

- **Exposure: 0.65 t*y**
- **Single scatter events within [1,210] keV_{ee}**
- **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



- Good fit observed over most of the energy range
- Consistent with expectations
- Unbinned maximum likelihood fit profiling over nuisance parameters:

$$\mathcal{L}(\mu_s, \boldsymbol{\mu_b}, \boldsymbol{\theta}) = \mathrm{Poiss}(N|\mu_{tot}) \times \prod_i^N \left(\sum_j \frac{\mu_{b_j}}{\mu_{\mathrm{tot}}} f_{b_j}(E_i, \boldsymbol{\theta}) + \frac{\mu_s}{\mu_{\mathrm{tot}}} f_s(E_i, \boldsymbol{\theta}) \right) \times \prod_m C_{\mu_m}(\mu_{b_m}) \times \prod_n C_{\theta_n}(\theta_n),$$

$$\mu_{\mathrm{tot}} \equiv \sum_j \mu_{b_j} + \mu_s,$$

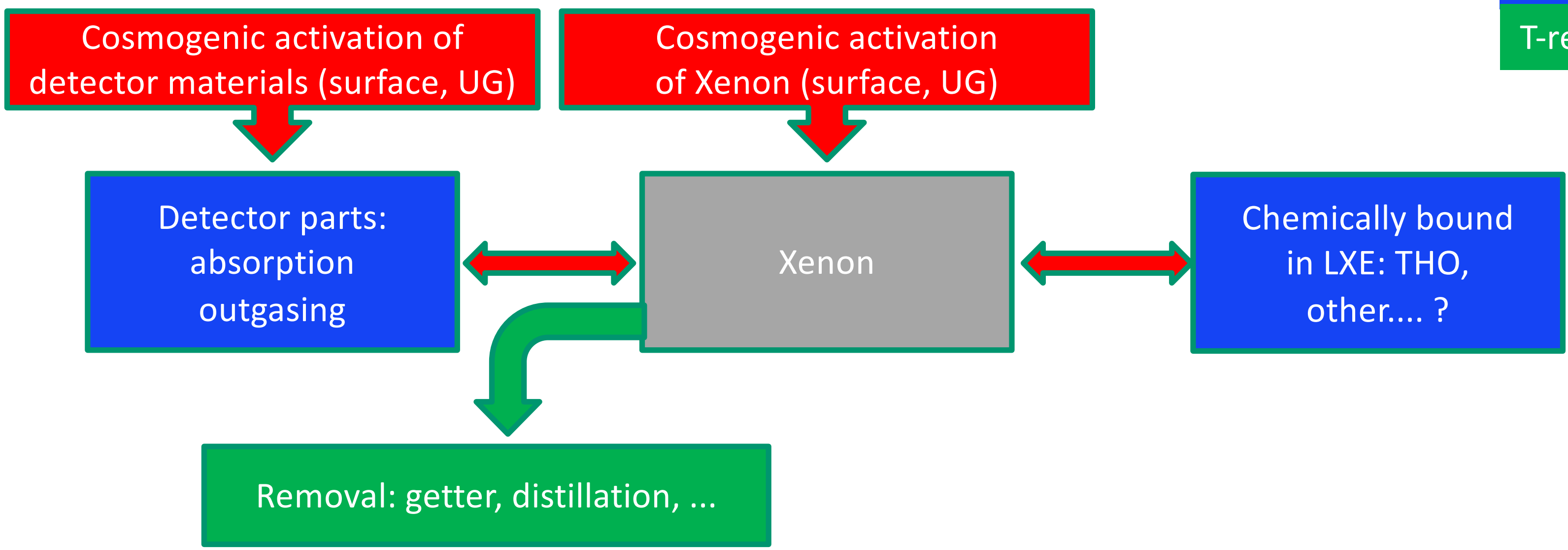
➔ (76 ± 2) events / (t*y*keV) in [1,30] keV window

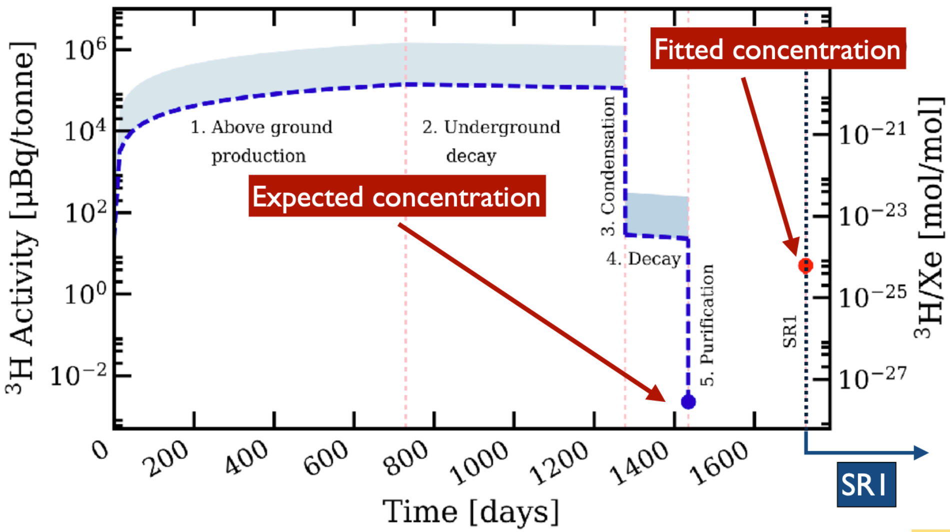
Lowest bg rate ever achieved in this energy range

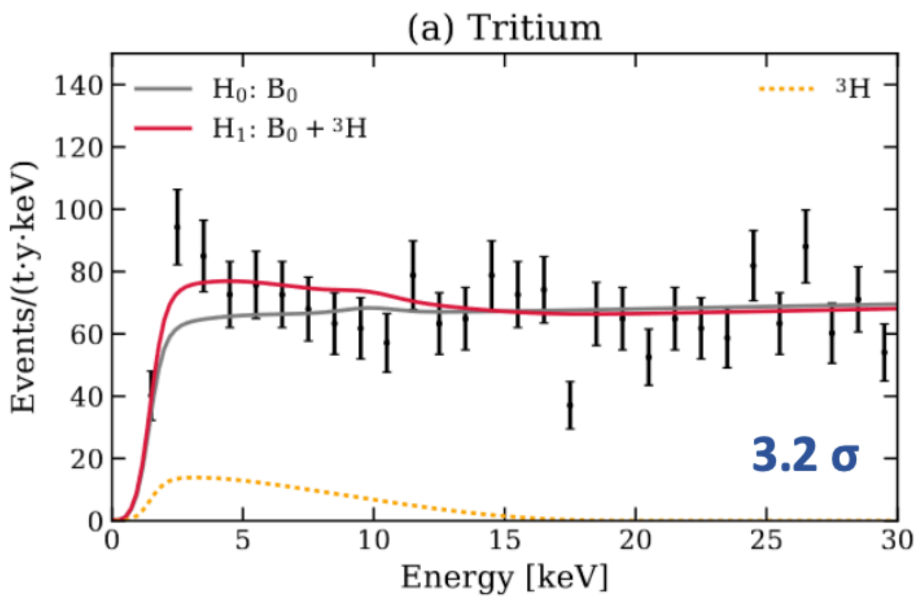
<u>Explanation #2:</u>
Some unexpeccted new background?

Not expected, but being discussed: E.g. Tritium, ...

T-sources & paths
T-reservoirs
T-removal







No indication of T; cannot cross-check now
A fit would require less than 3T per kg of LXe

M. Lindner, MPIK

New Physics

- **A singal from where?**
- **Sun:**

  - neutrinos (exist, but CEνNS too small ←→ neutrino floor)

  → some non-standard ν interaction with electrons

  - axions or ALPS produced in the sun

- **DM density/flow**

  - some new particle

  → not WIMPs

  → light and not hot DM? A new light boson?

- **Diffuse background of invisible particles**

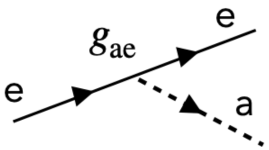
  ←→ consistency with other searches/limits

So far O(175) papers in a few months which cite the XENON1T result
→ mostly theory explanations with 3 main directions: Axions, ν's, light bosons

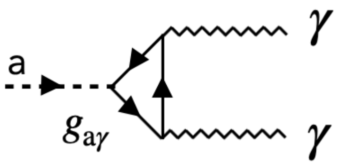
Signal Interpretaion: Solar Axions?

Production:

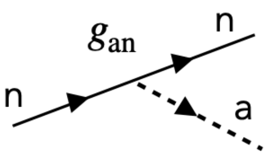
1. ABC



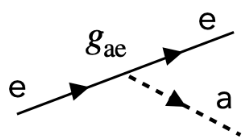
2. Primakoff



3. ^{57}Fe

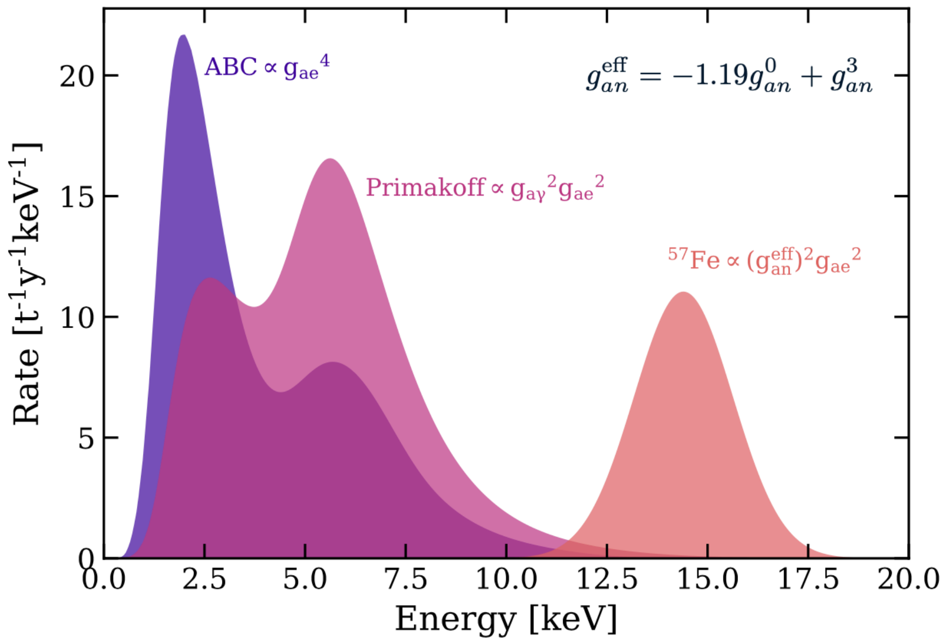


Detection via axio-electric effect

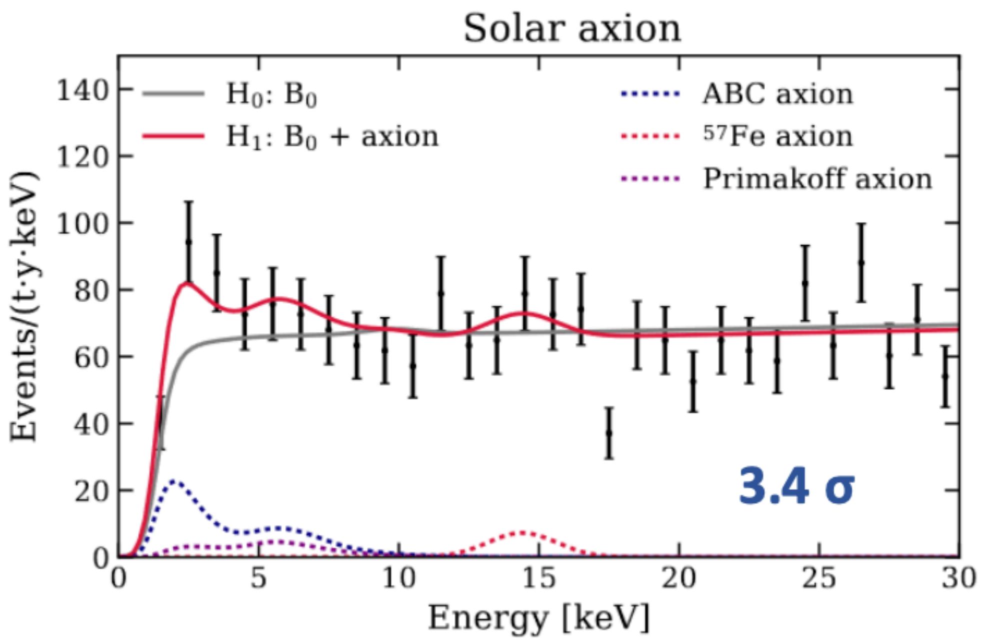


$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

Reconstruction in XENON1T (resolution, efficiency)

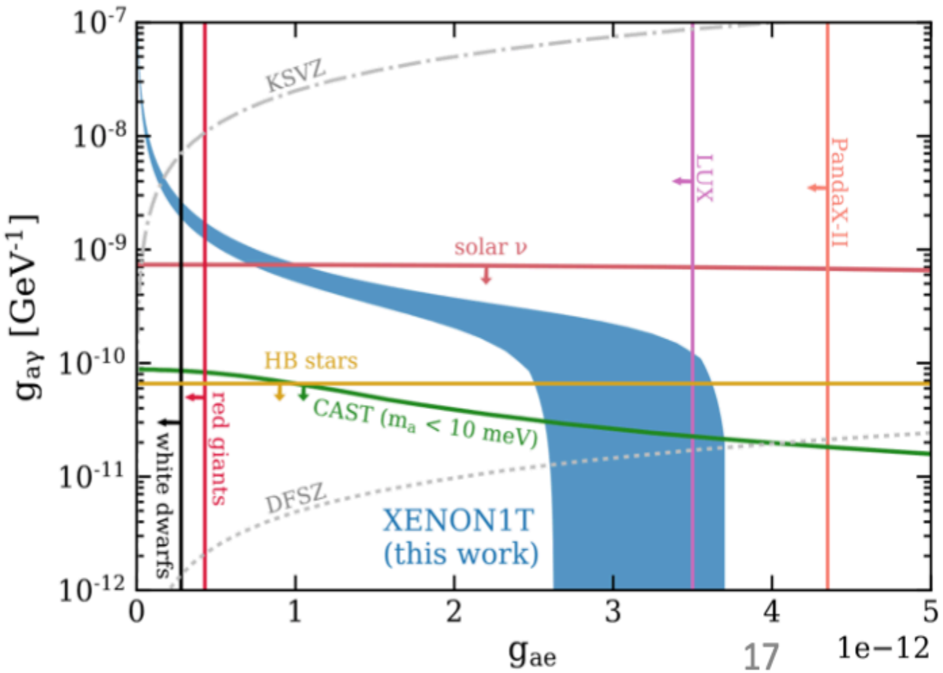


Phys. Rev. D 102, 072004



Three possible components:

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



But: Tension with constraints

- stellar cooling
- solar neutrinos

➔ Ways around?

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

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

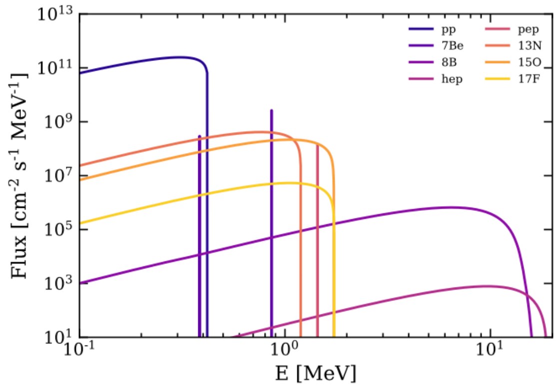
WD and RG explained simultaneously better when ALP constitutes about 10% of DM

Large Neutrino magnetic Moment

Phys. Rev. D 102, 072004

Solar neutrino spectrum

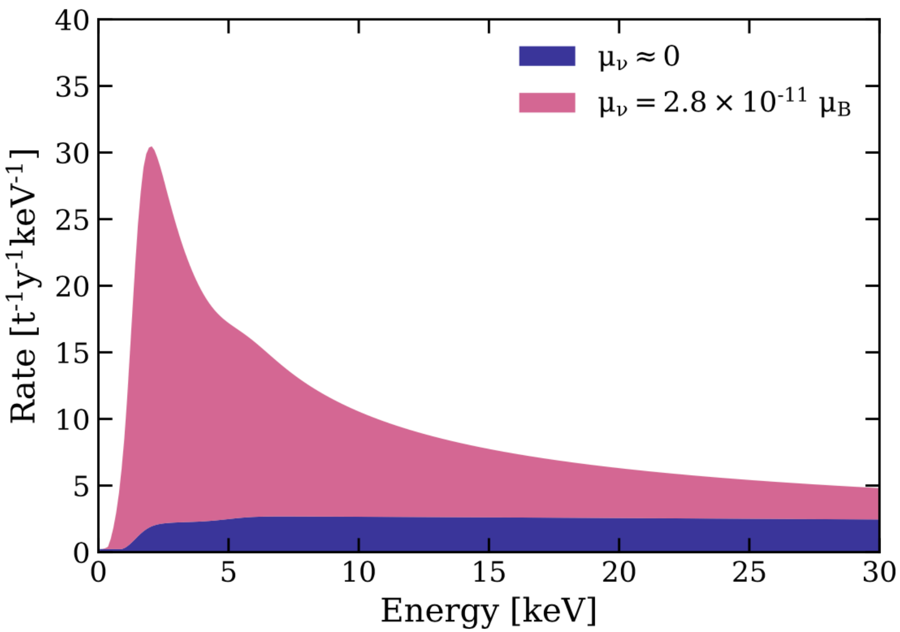
➔ MeV-ish

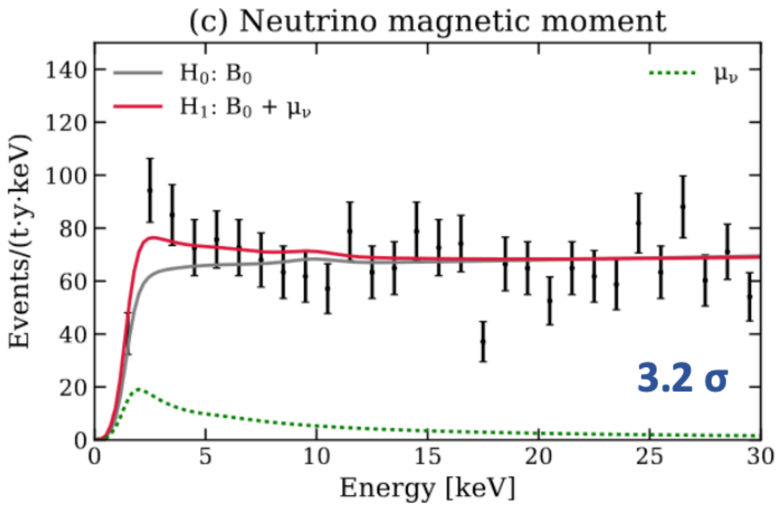


Detection

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

Reconstruction in XENON1T
(resolution, efficiency, threshold)





μ_ν in the Standard Model + ν_R

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:

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

➔ BSM models significantly enhance 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

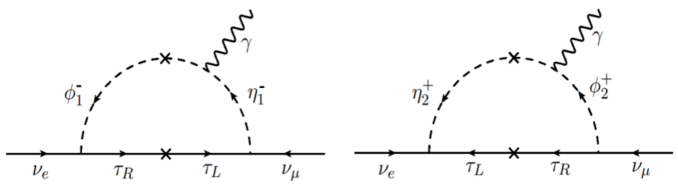
BUT ➔ $\mu_\nu \leq 10^{-13}\ \mu_B$

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

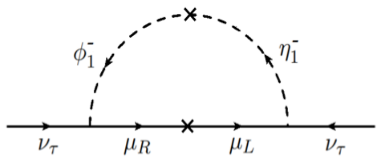
Pushing higher often leads to two problems:

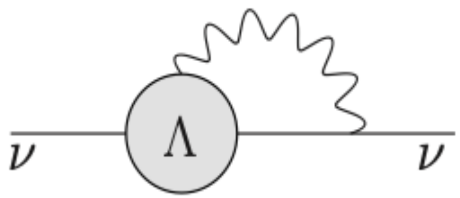
- light new particles that should have been discovered

- 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 avoid problems

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

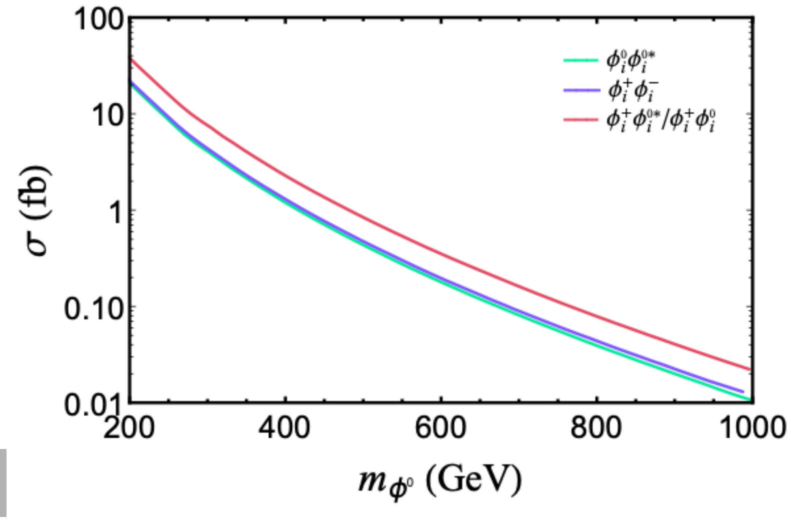
Horizontal $SU(2)_H$ broken by muon Yukawa coupling

Main point:

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

$\mathcal{L}_{\text{mass}}$ 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**

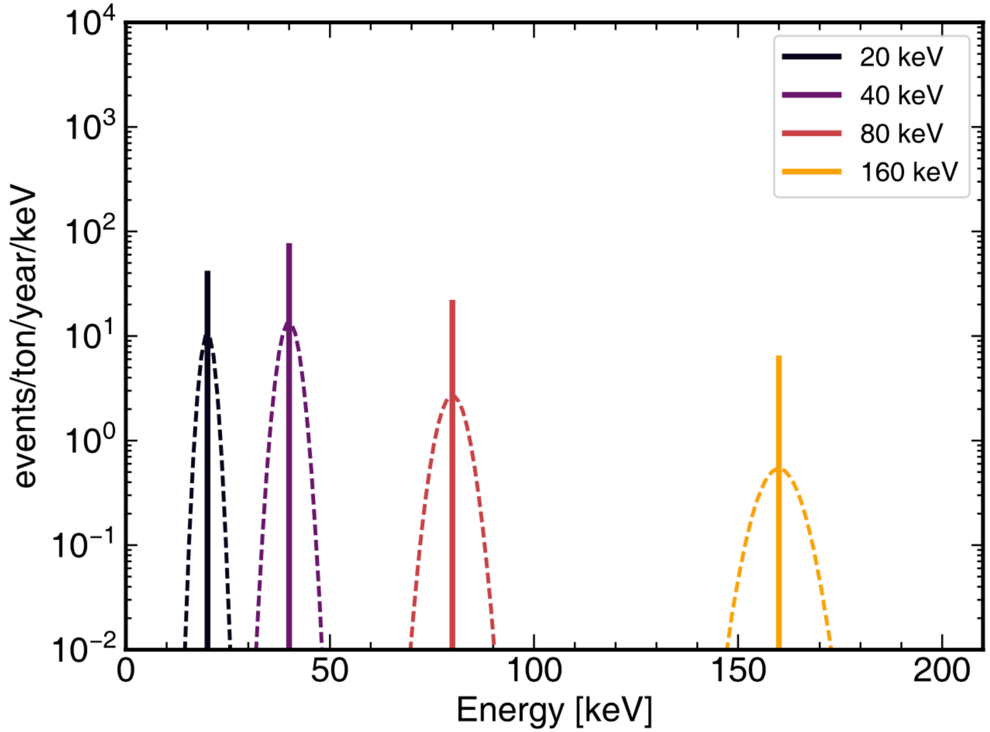


Bosonic Dark Matter

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



Many Solutions: Hidden Dark Sectors

Receipe: Dark sector + light particles + weak coupling

A few examples:

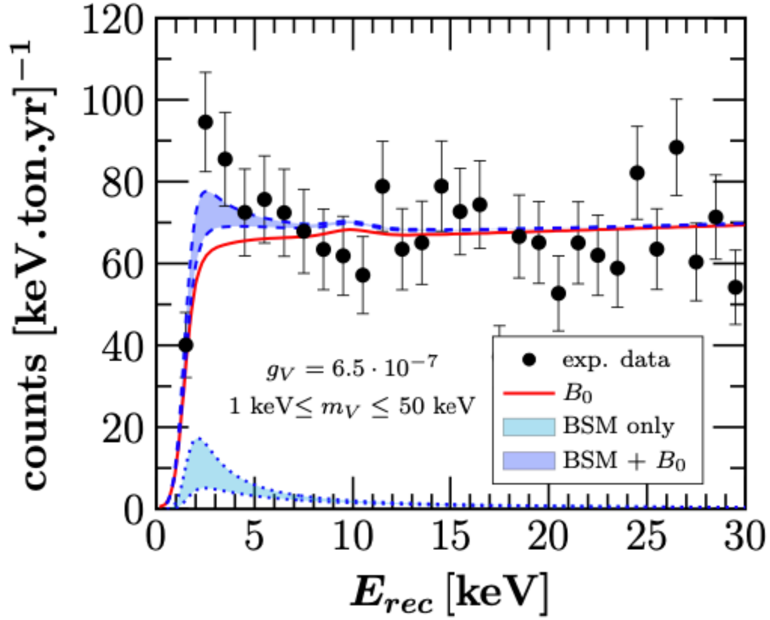
- Light new physics in XENON1T
  C. Bœhm, D. Cerdeno, M. Fairbairn, P. Machado, A. Vincent, arXiv:2006.11250
- Light vector mediators facing XENON1T data
  D. Aristizabal Sierra, V. De Romeri, L.J. Flores, D.K. Papoulias,
  PLB 809 (2020) 135681
- Shining dark matter in Xenon1T
  G. Paz, A. Petrov, M. 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

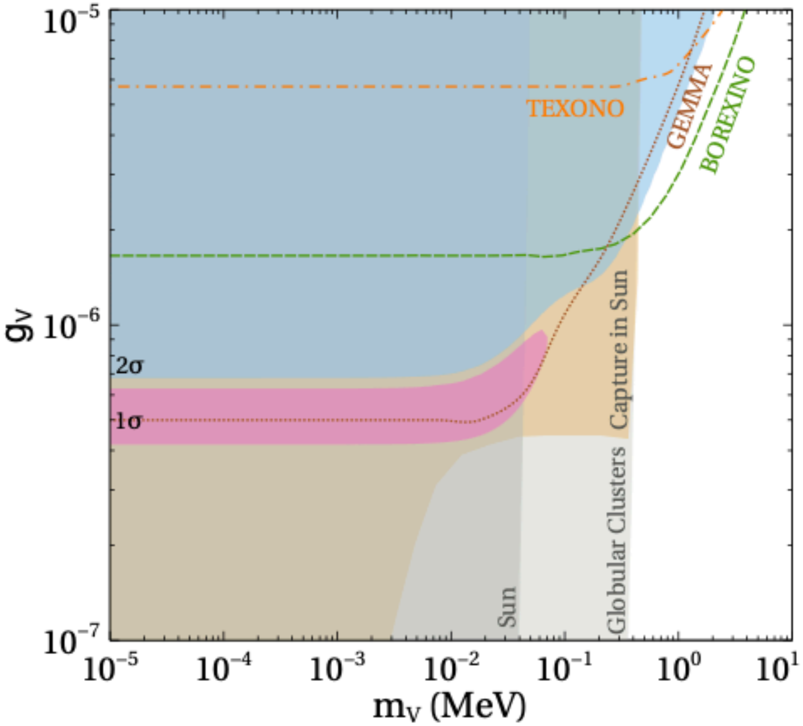
+ many more

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 interactions with leptons mediated by a light vector particle





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

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

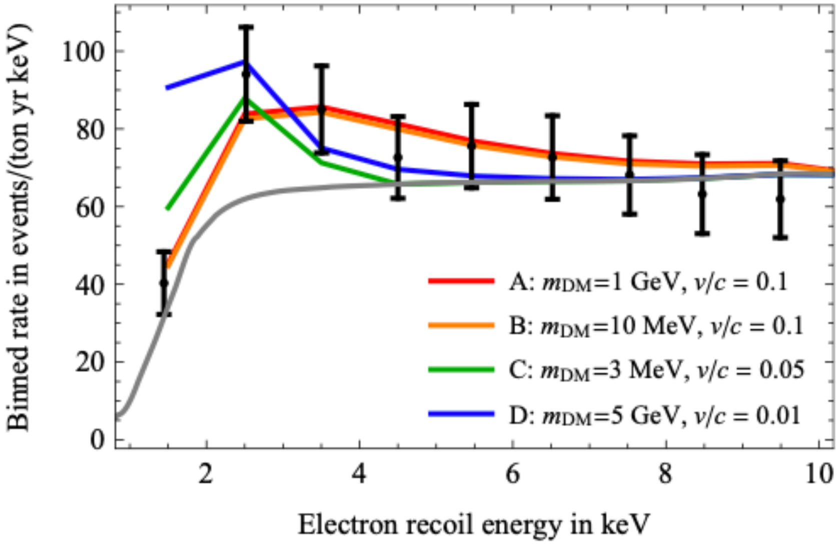
DM Particles with a fast Component

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

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

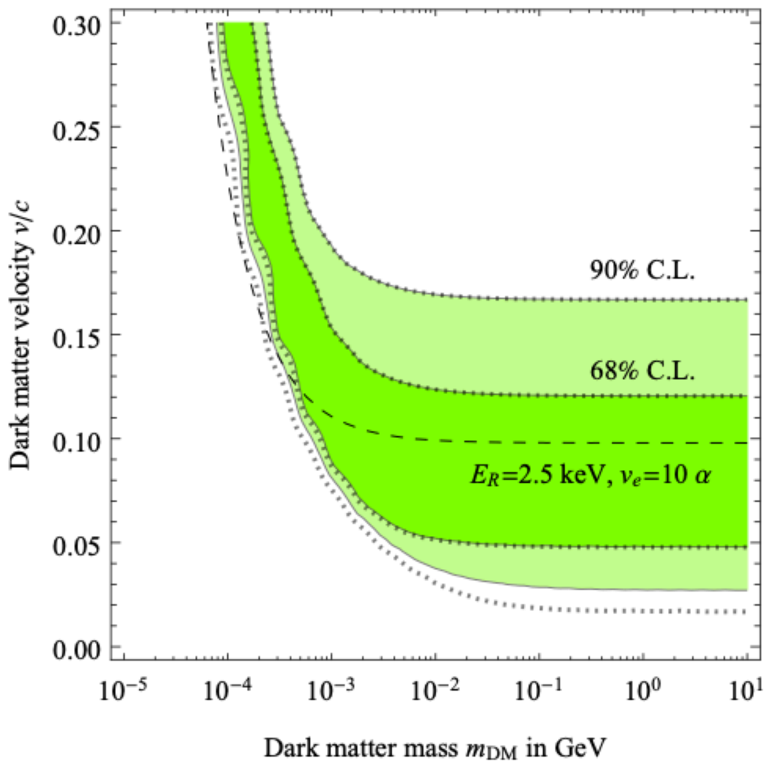
$$q \equiv m_{\rm DM}(v'_{\rm DM} - v_{\rm DM}) = -2\mu v_{\rm rel} \simeq - \begin{cases} 2m_{\rm DM}(v_{\rm DM} - v_e) & \text{for } m_{\rm DM} \ll m_e \\ 2m_e(v_{\rm DM} - v_e) & \text{for } m_{\rm DM} \gg m_e \end{cases}$$

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



➔

Favoured region

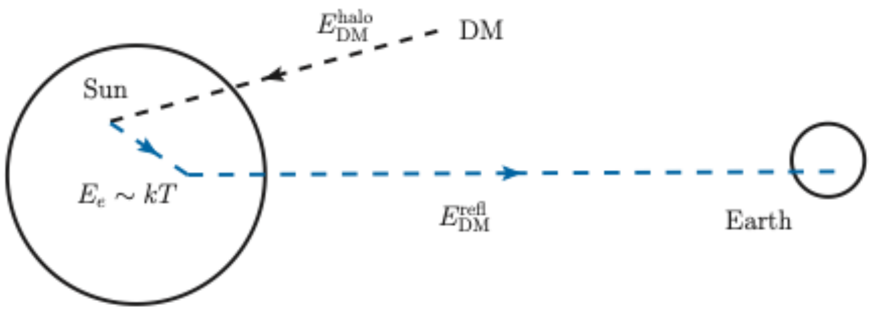


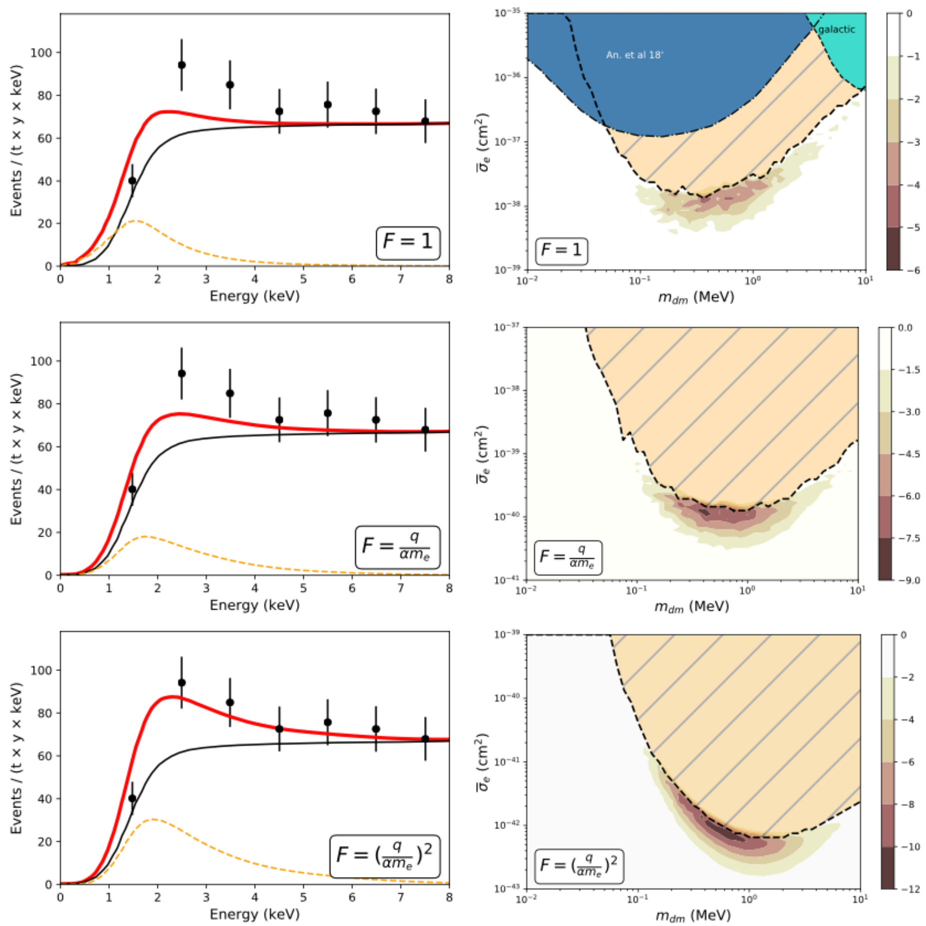
Problem: Fast component gravitationally not bound to galaxy ➔ ...decays, sub-halo, ...

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)

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

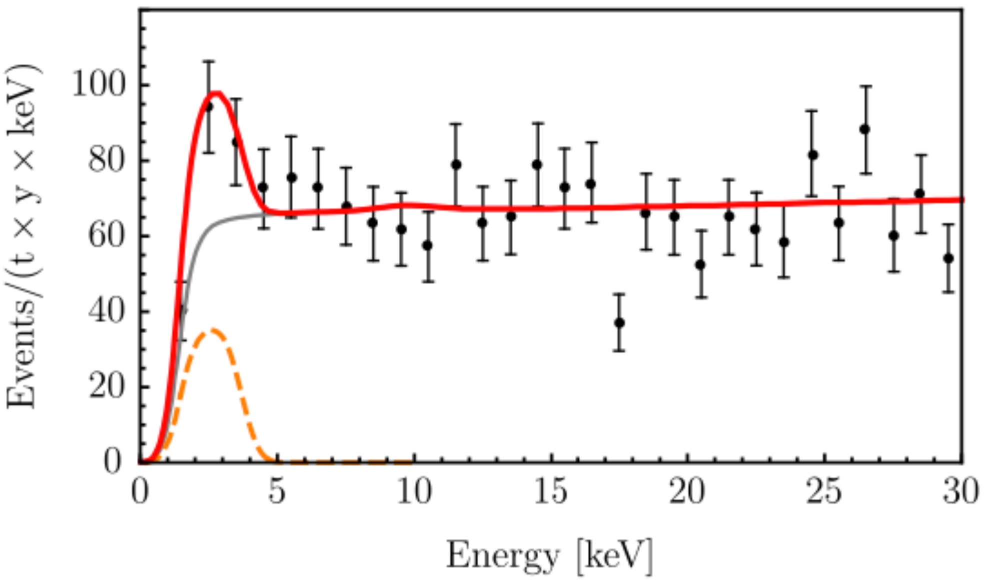
- same DM-electron interaction in the detector
- Best fit, F(...), XENON1T limits
- Expect annual modulation w/o ν's or axions

Boosted Dark Matter

B. Fornal, P. Sandick, J. Shu, M. Su, Y. Zhao, PRL 125 (2020) 16

BDM: particles with velocities ≫ typical of virialized dark matter

➔ naturally produce keV electron recoils

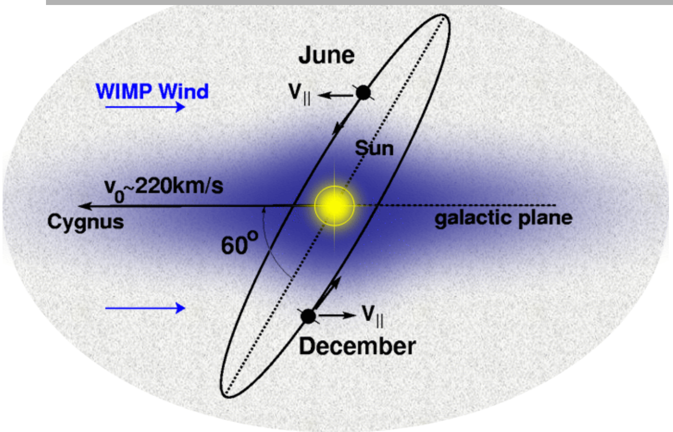


required BDM-electron scattering cross sections can be easily realized in simple models, e.g. with a heavy vector mediator

- BDM flux ➔ could originate from the Galactic Center or from halo DM annihilation
- daily modulation of the BDM signal expected for mediator masses < 10-100 GeV

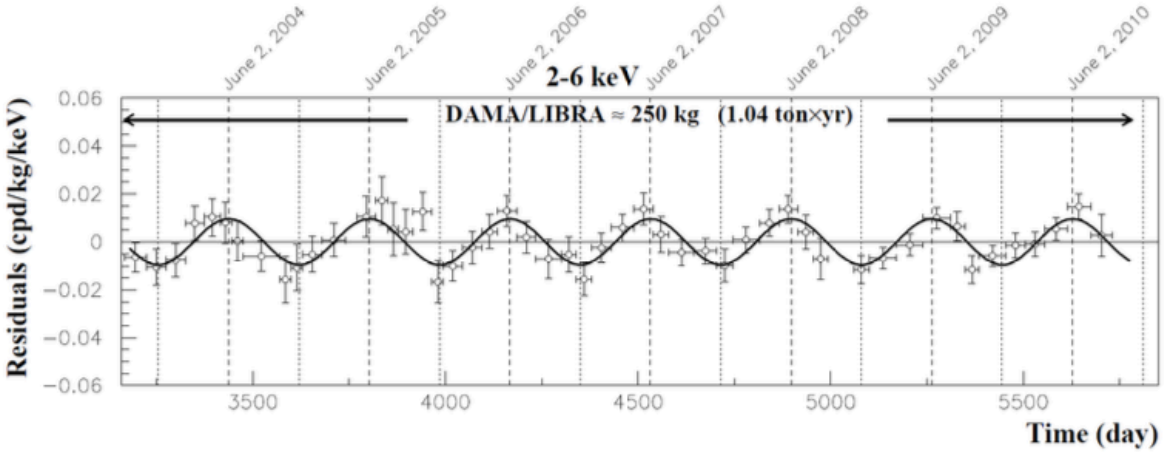
$$L_{fs,E} \simeq 60\,\mathrm{m} \times \left(\frac{10^{-28}\,\mathrm{cm}^2}{\sigma_{\mathrm{elec}}}\right)$$

Connection to the DAMA Annual Modulation?



moving thru the WIMP wind around the sun
➔ small annual modulation on top of average rate

DAMA/LIBRA
1.33 t*year exposure of NaI crystals (13 annual cycles)



Annual modulation at 12.9σ
➔ DM or something else?

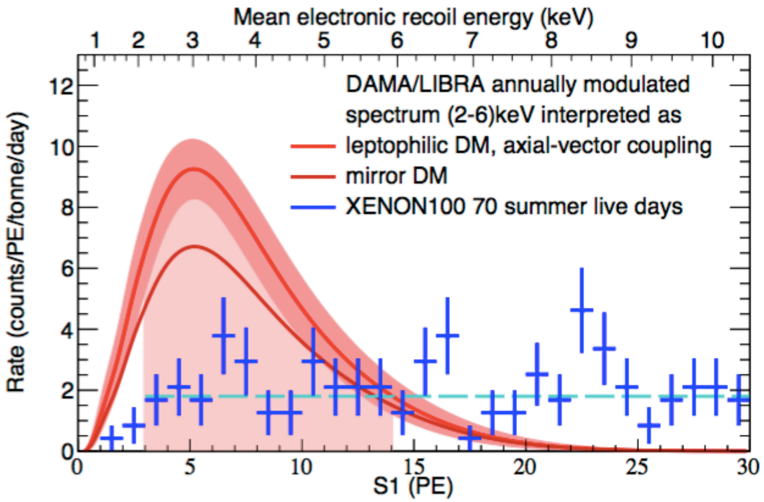
Various periodic backgrounds (atmosphere ←→ μ flux, water levels ←→n, Rn, …)

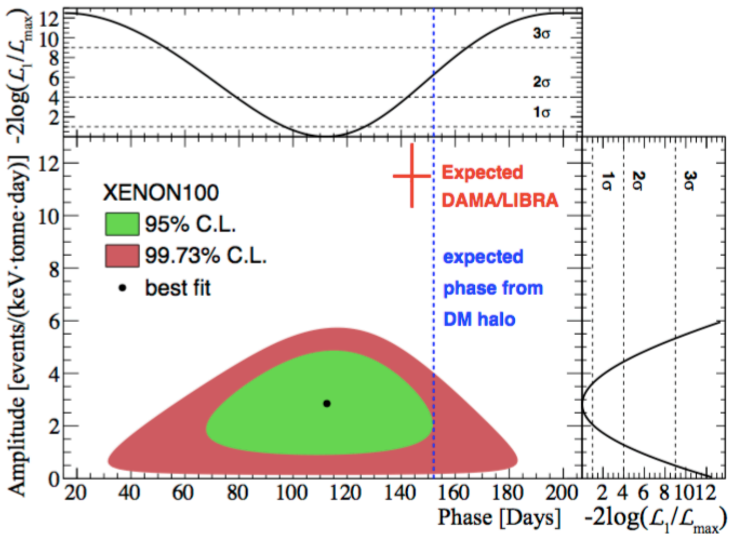
Problem:
- **Backgrounds: So far no accepted explanation**
- **Signal: Other detectors (direct detection, indirect detection, LHC) do not see the corresponding overall rate which matches to the modulation**

Proposed way out: DM particles which scatter on electrons (leptophilic...)
➔ would be seen by DAMA/LIBRA, but not by others

Modulation of Electronic Recoils in XENON100

477 life days (48kg*year) aquired 2010-2014; improved signal & bckg. modelling





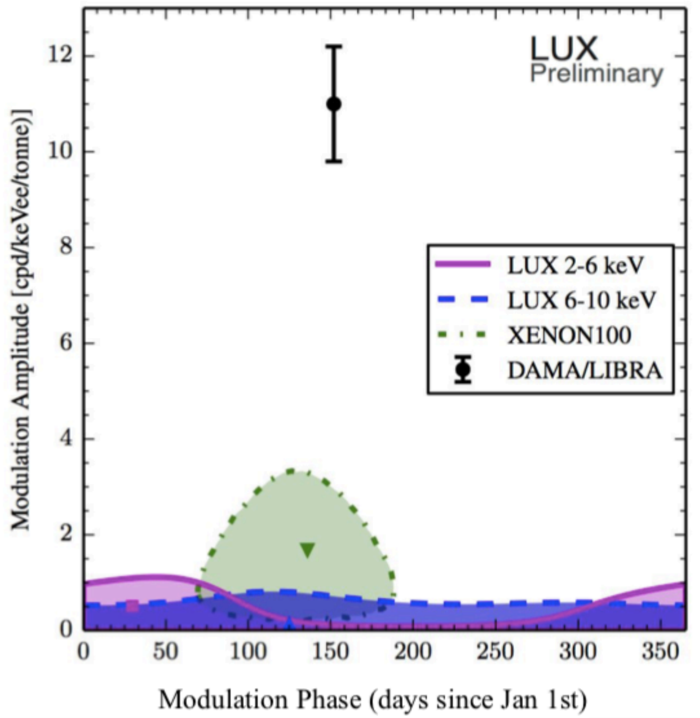
➔ **DAMA signal excluded @5.7σ**

➔ **leptophilic models excluded**

➔ **DAMA modulation not understood**

LUX: J. Xu @UCLA DM

➔ **no modulation**

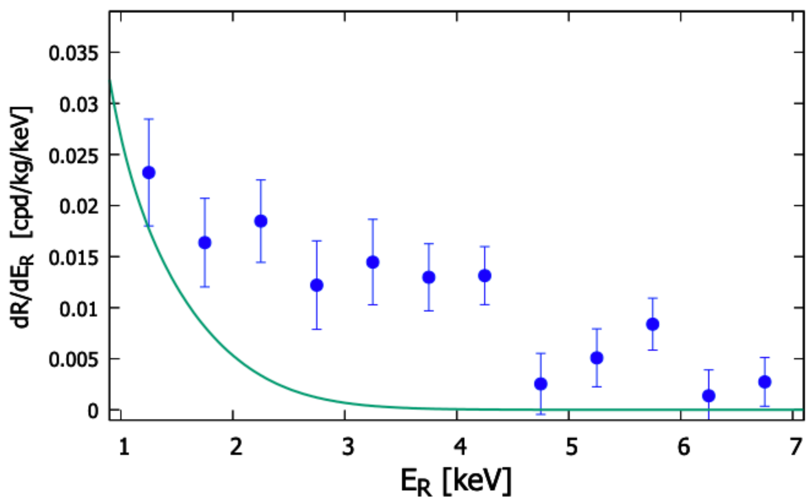


Future: check DAMA ➔ clarify modulation ➔ new projects:

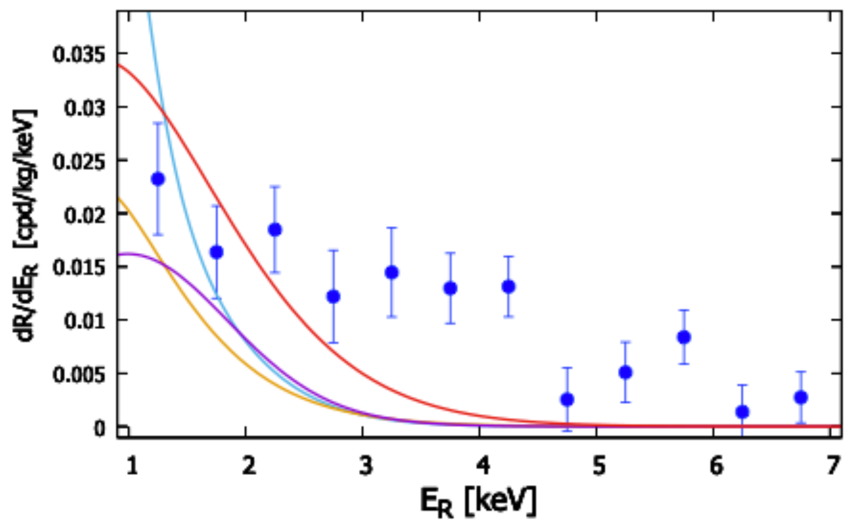
SABRE, COSINUS, COSINE-100, ANAIS, KIMS-NaI, DM-Ice

Could DAMA/LIBRA see the same Physics?

R. Foot, arXiv: 2011.02590 ; D. Adams, S. Jacobsen, Ch. Kelso, arXiv:2011.03079
Assume DM that might explain DAMA/LIBRA
➔ what should XENON1T see in the electron recoil spectrum



Comparison of DAMA/LIBRA data with model predictions which fit the XENON1T excess



Does not fit even if one believes that a small energy scale offset could exist

Summary of the current Situation

Excess between 1-7 keV:

285 events observed
(232 ±15) expected
from best-fit

Interpretations :

a) A fluctuation

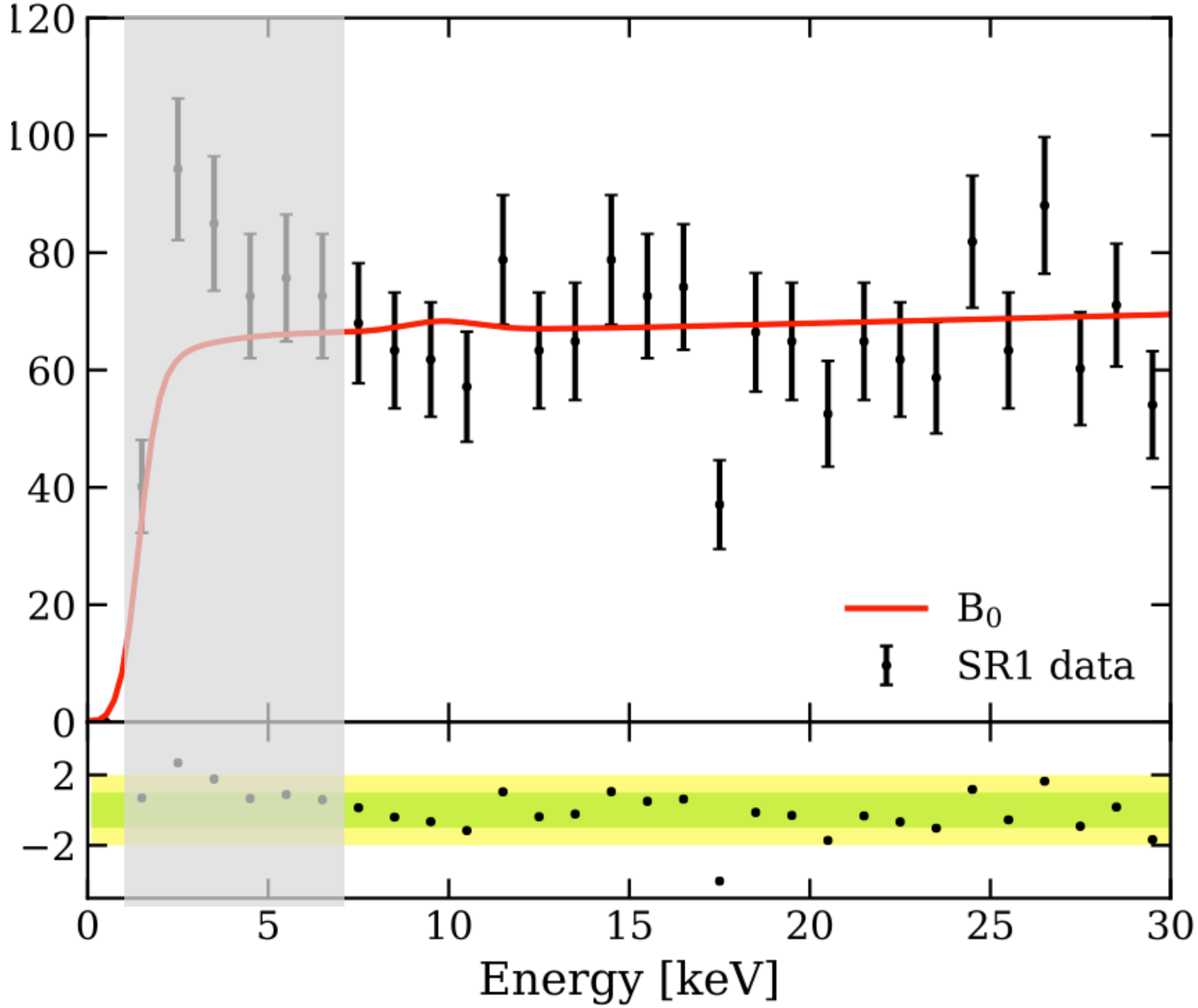
b) Some new background

- Tritium
- ^{37}Ar
- ...

c) New physics

- solar axions
- large ν mag. Moment
- bosonic DM, dark Z, ...

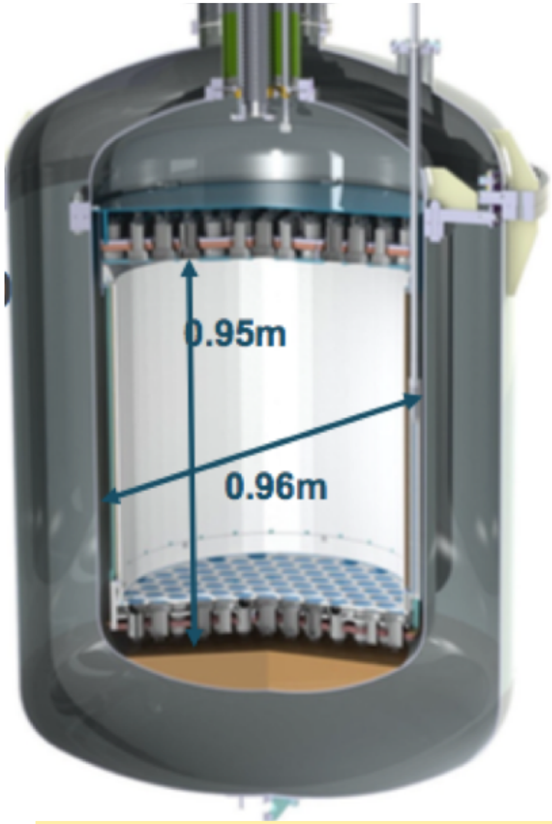
>100 papers in 2 months



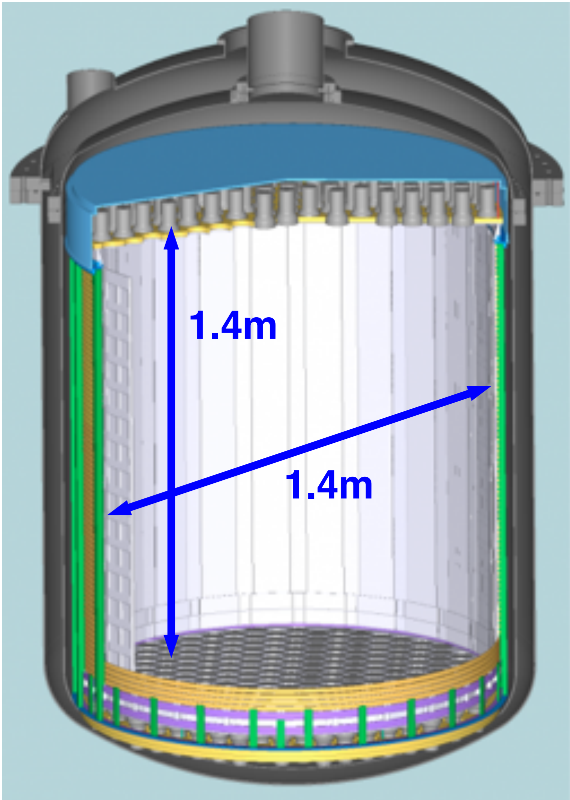
All ~3σ ➔ Collect more data with XENONnT

The XENONnT Upgrade

XENON1T



XENONnT



2012-2018
3.2t LXe
running

2019-2023
ca. 8t LXe
under preparation
goal @50GeV: $1.6*10^{-48}$ cm^2

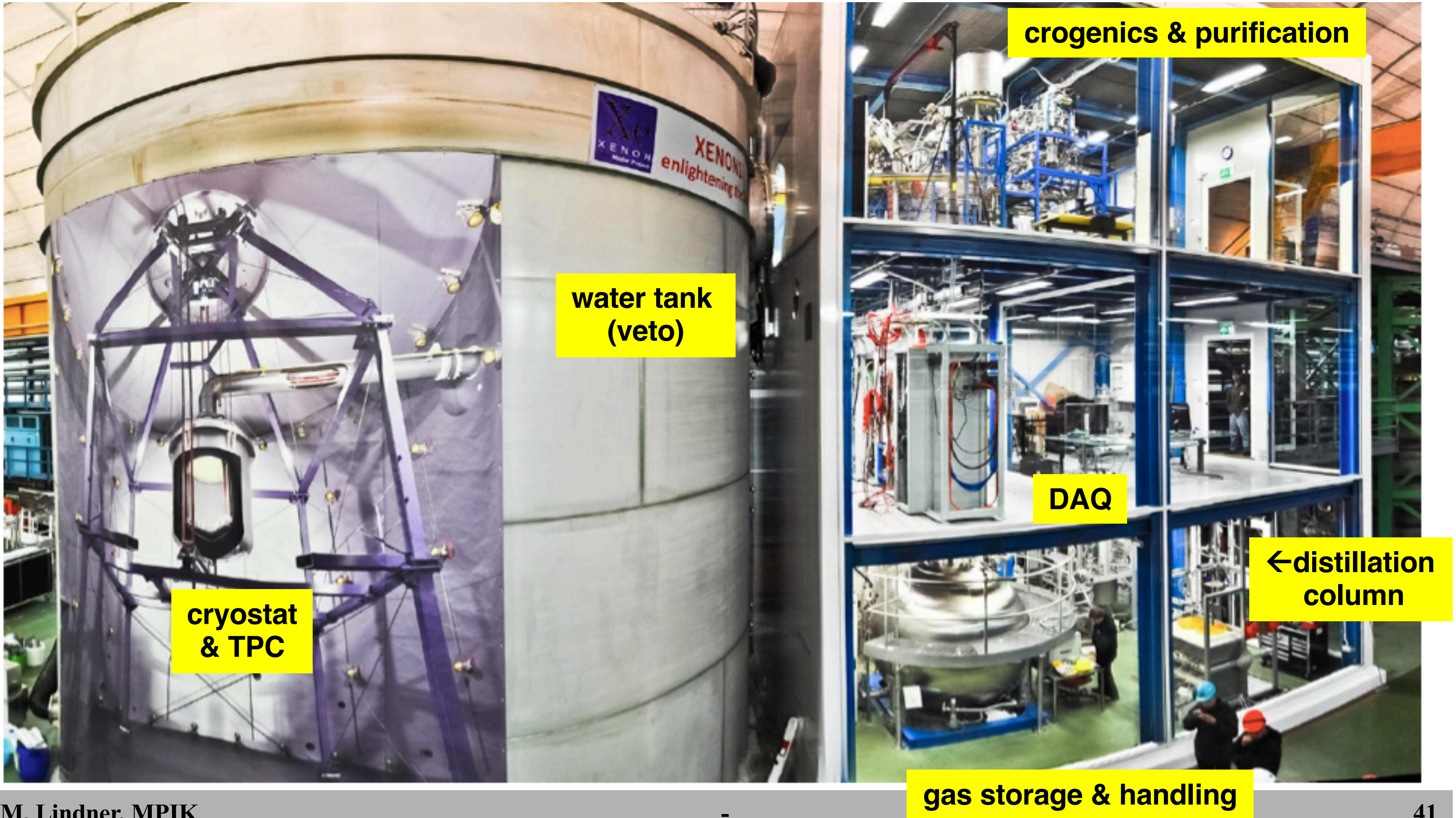
being prepared while XENON1T runs ➔ switching gears

Existed/operational/tested:
muon veto
cryostat support
outer cryostat
in-LXe cabeling
LXe storage system (Restox)
cryogenic system
purification system
Kr removal
DAQ & 95% electronics
slow control system
calibration system
> 8t of Xenon gas & 260 PMTs
screening facilities

Added:
230 more PMTs ordered
➔ being delivered & tested
new materials
TPC & inner cryostat design
n-veto
γ and Rn screening
Rn reduction system
improved purification
2nd Restox & more Xenon gas

XENON1T → XENONnT

Changes and re-assembly done → filling → commissioning
→ data taking as soon as possible



Ways to check

XENONnT: Much more statistics with a few months of data

- **Fluctuation? ←→ does the signal persist?**
- **Does the signal show an annual modulation?**
  - in phase with the distance earth-Sun? ←→ solar axions, large μ_ν
  - in phase with the preferred direction of DM flow? ←→ light bosons
- **Ideas for diffuse particle flows w/o modulation?**
- **How does the signal scale with the detector surfaces and volume?**

Further improve understanding of tiny backgrounds in XENON1T

- **Further consistency checks**
- **Study T-production**
- **Try to measure backgrounds (like we do for other isotopes)**

Conclusions

- **The WIMP search will continue**
  - XENONnT is getting ready...
- **Direct detection will make good progress soon (XENONnT, LZ, ...)**
  - even better WIMP sensitivity
  - sensitivity to axions, neutrino physics (DEC, $0\nu\beta\beta$, solar ν's, SN, coherent scattering,…)
  - low E_R excess may be statistics, background or new physics
    ➔ more pronounced with more data from XENONnT?
    ➔ annual modulation?
    ➔ ...
- **Substantial impact even if nothing will be found**