# (Direct) **Dark Matter Searches and** (some) **Implications for Theory**

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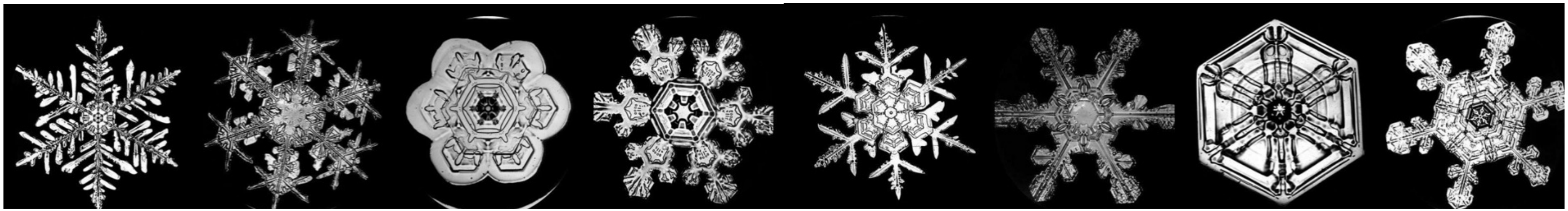
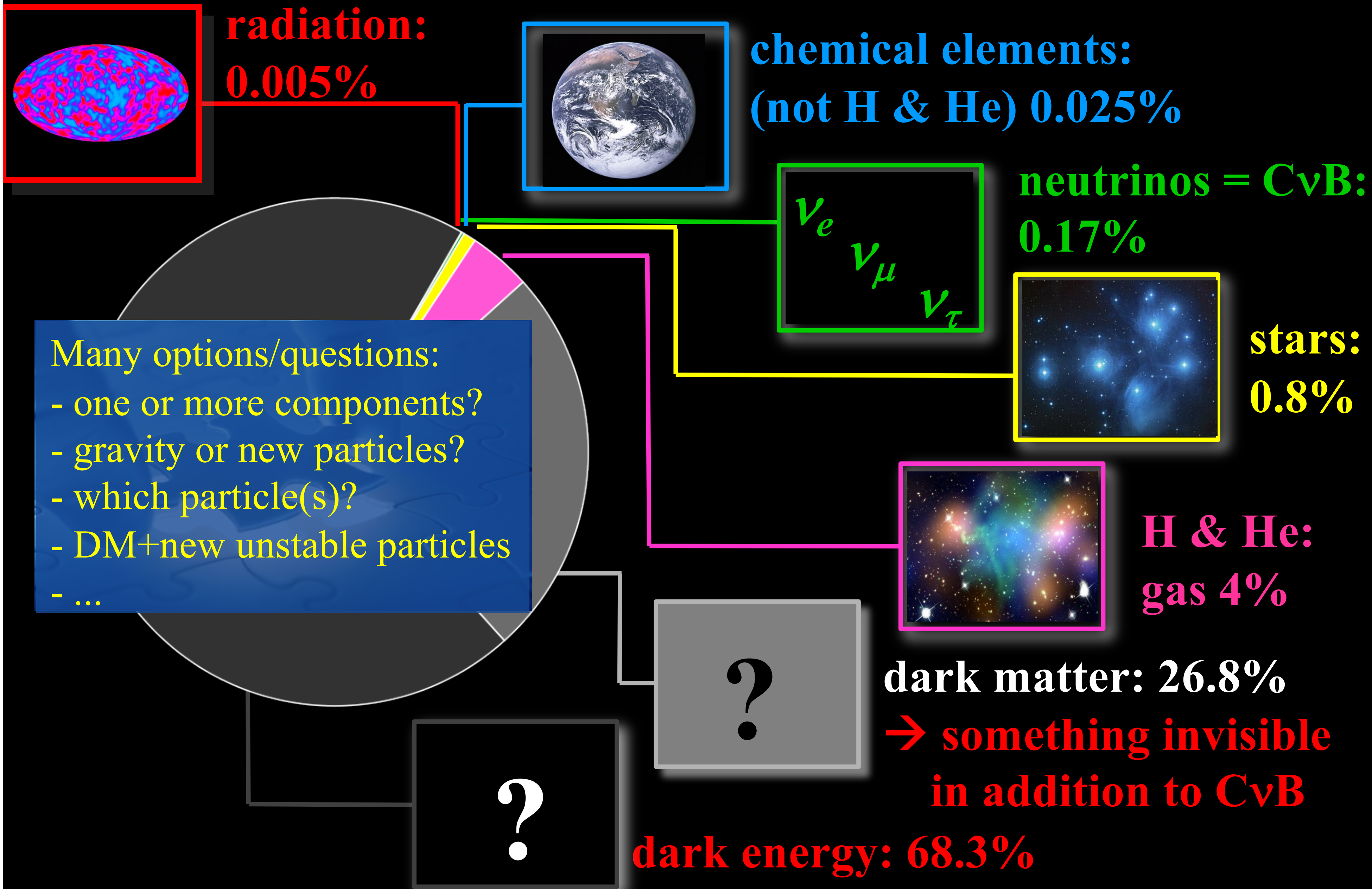
**DISCRETE 2020-2021, Bergen, Norway, Nov 29 - Dec. 3, 2021**



# The cosmic Matter Balance



# Competing Dark Matter Directions

## Gravity

**MOND**
a simple one scale modification
→ fails badly

**Other**
new GR modifications

or

a suitable population (mass, number) of black holes

## Particles

**BSM physics motivated by SM problems**
- WIMPs (neutralinos)
- axions
- sterile $\nu$'s
- …

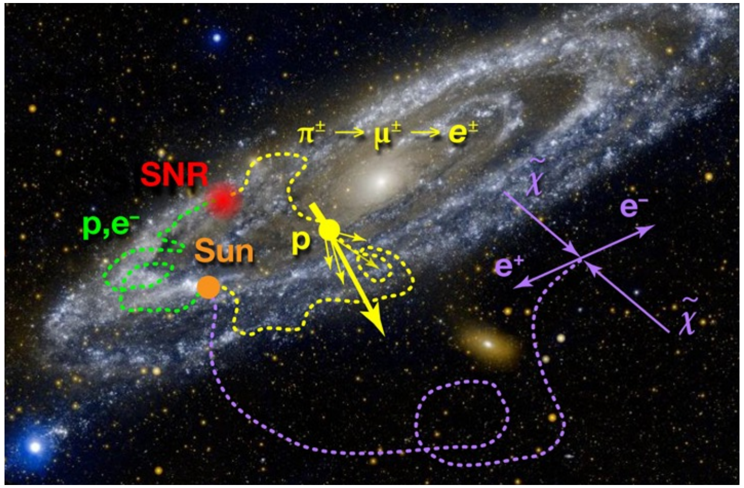
**Models with correct abundance**
- WIMPs
- dark photons
- ALPs
- other new particles

**WIMPs** combine both aspects in an attractive way: **BSM + abundance**

# Hunting WIMPS in different Ways

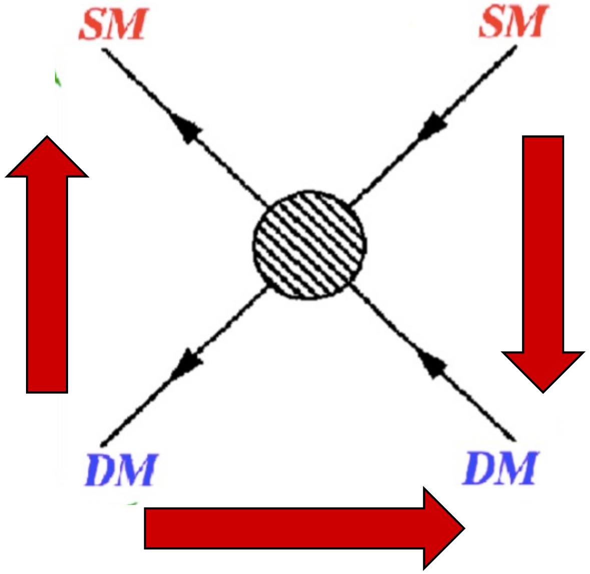
**known Standard Model (SM) particles interact with WIMPs: assumptions…**

indirect detection

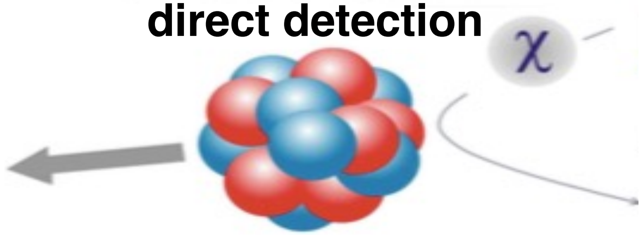



FERMI, PAMELA, AMS, HESS, IceCube, CTA, HAWC…

astronnomical uncertainties...
→ is the signal without doubt from DM?
keV lines ↔ atomic physics



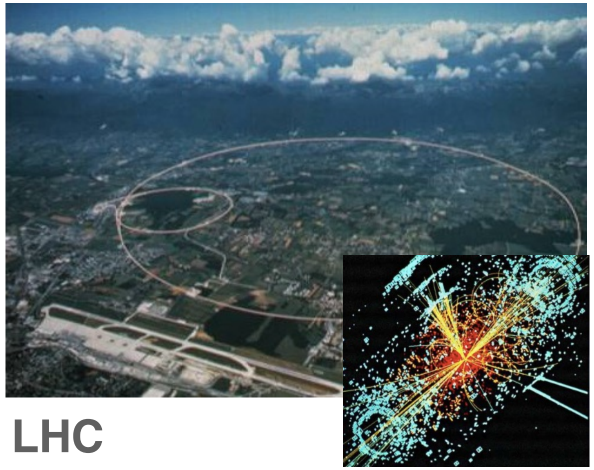

direct detection




WIMP wind : 220km/s from Cygnus

→ modelling
→ rare event backgrounds

colliders



LHC
may detect new particles, but is it DM (lifetime, abundance)?
So far nothing seen…
- → impact on theory…
- → SUSY → higher scale
- → other SB motivated WIMPs
- → new ideas/candidates

# Generic WIMP Cross Section

- **Quantum mechanics: wavelength $\lambda \sim 1/\text{mass}$**

“size = area” of a particle: $\pi\lambda^2 = \pi/m^2$

➔ cross section: area ✖ coupling strength

$\sigma \sim O(0.001\text{-}1.0)^2 \quad g_2^2 \quad \pi/m^2$ **or tuning, symmetry, …**

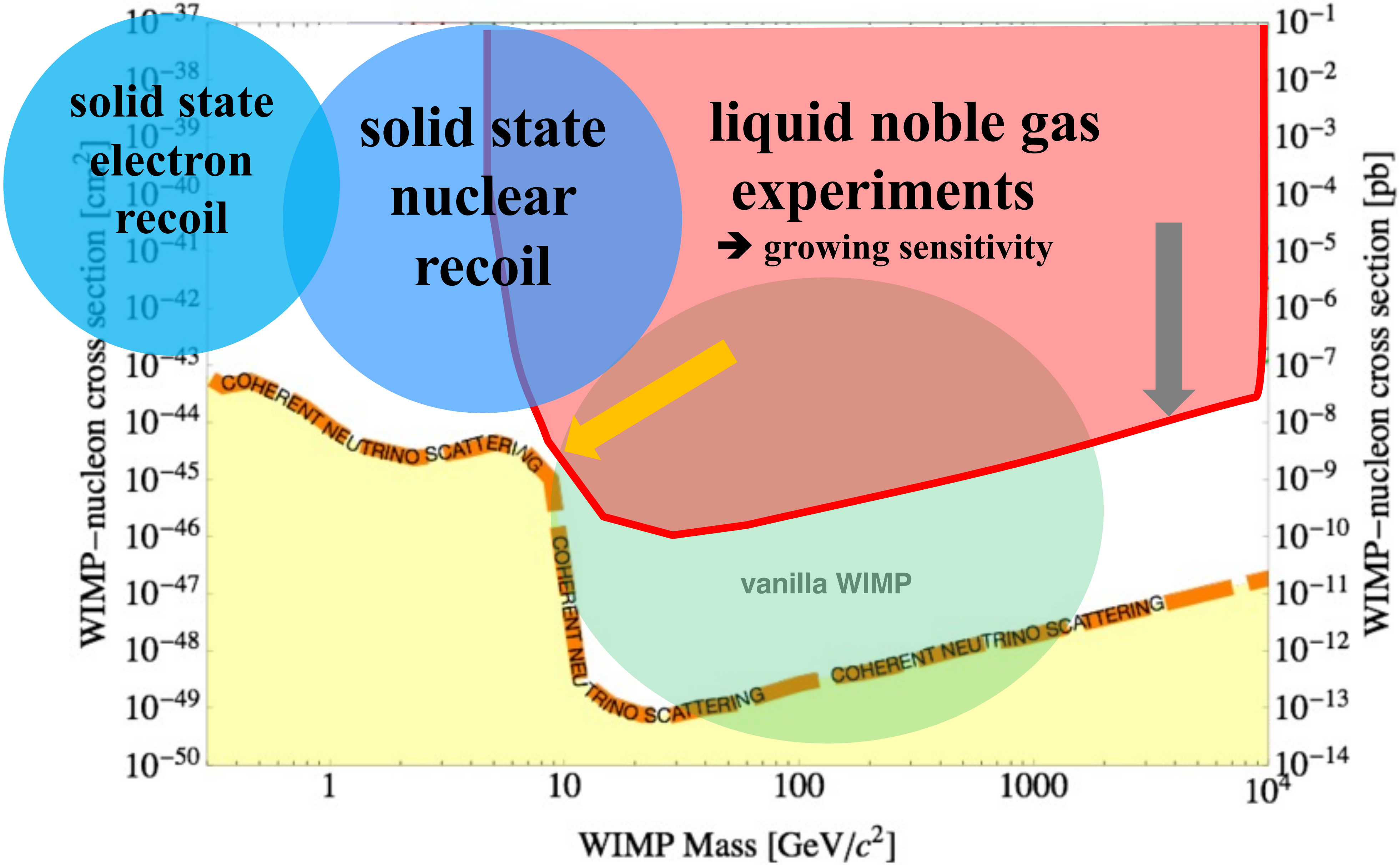
model parameters — some weak coupling — area

- **natural range for a 50GeV WIMP: $\sigma \sim 10^{-42} - 10^{-48}\ \text{cm}^2$**
- **known DM abundance**

**➔ WIMP flux ➔ known rate @direct detection**

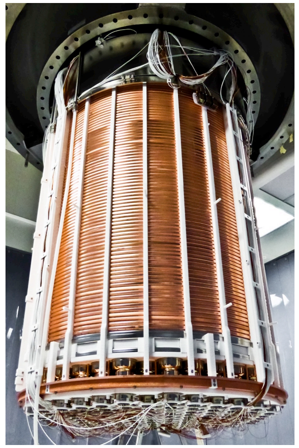
**➔ generic WIMP range ←➔ find it or exclude WIMPs**

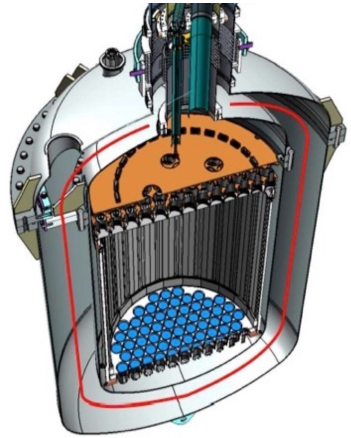
# Pushing into new Territory



# The XENON Dark Matter Program

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

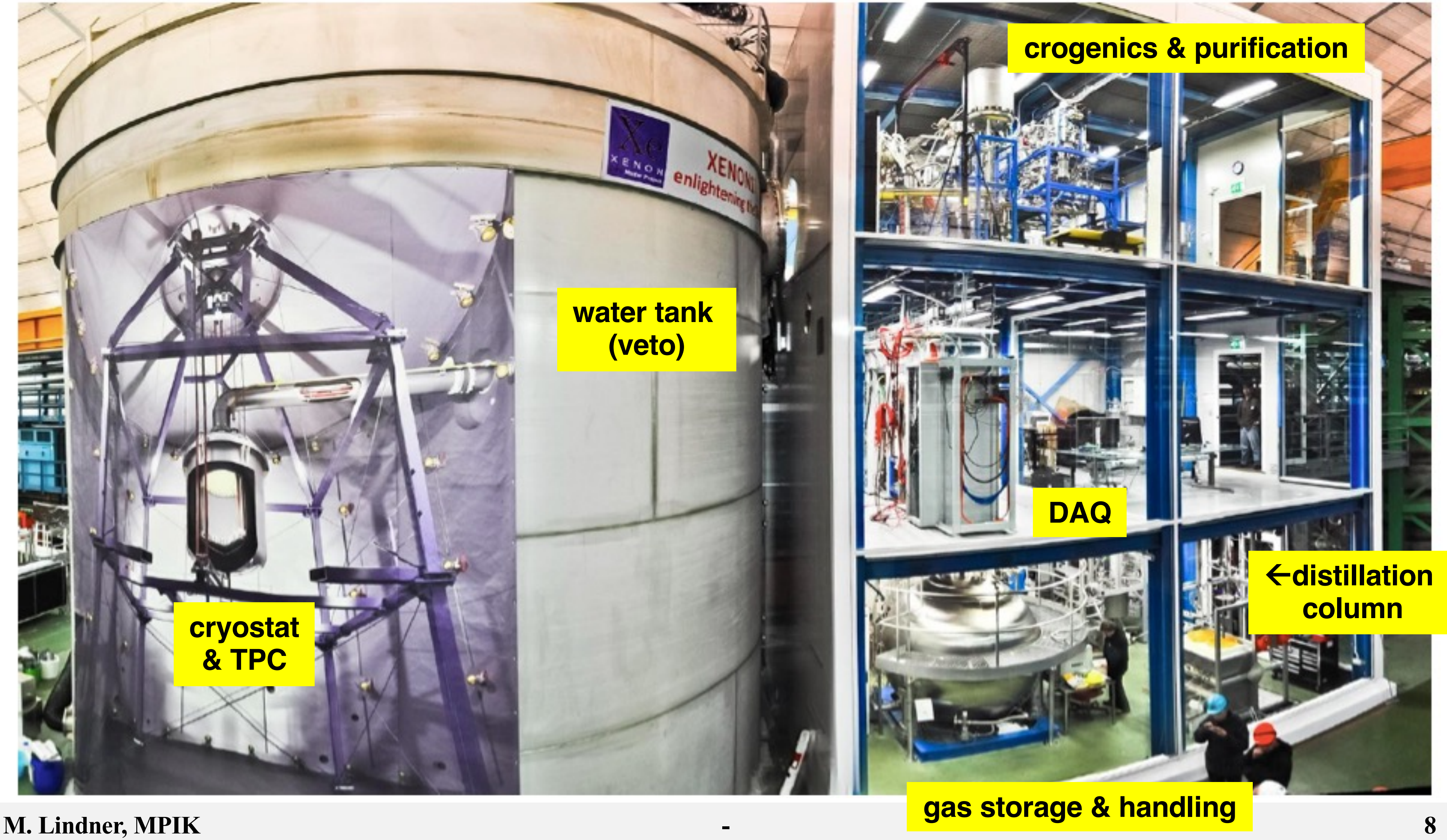


| | XENON10 | XENON100 | XENON1T | XENONnT |
|---|---|---|---|---|
| **Period** | **2005-2007** | **2008-2016** | **2012-2018** → | **2020-2024** |
| **Total mass** | 25 kg | 161 kg | 3200 kg | ~8000 kg |
| **Drift length** | 15 cm | 30 cm | 100 cm | 150 cm |
| **Status** | Completed (2007) | Completed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

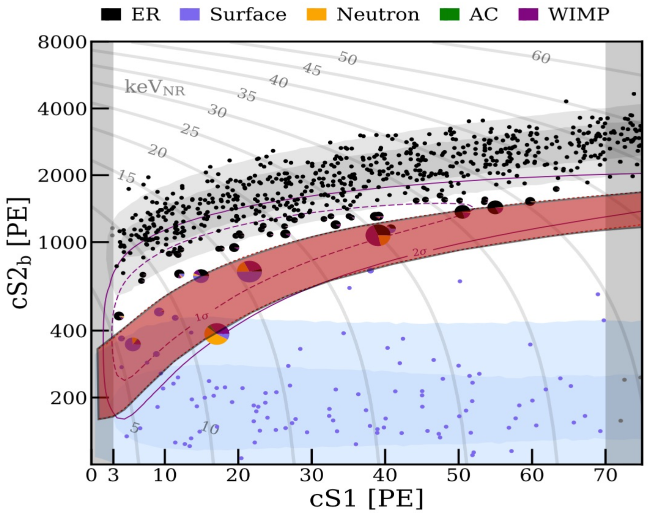
**XENONnT was prepared while XENON1T took data**
**➔ switching gears ➔ XENONnT started 2020**

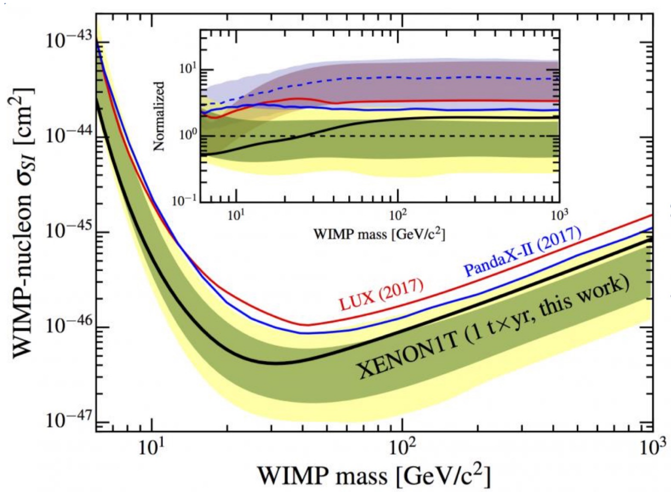
# XENON1T @ LNGS: Running until 12/2018

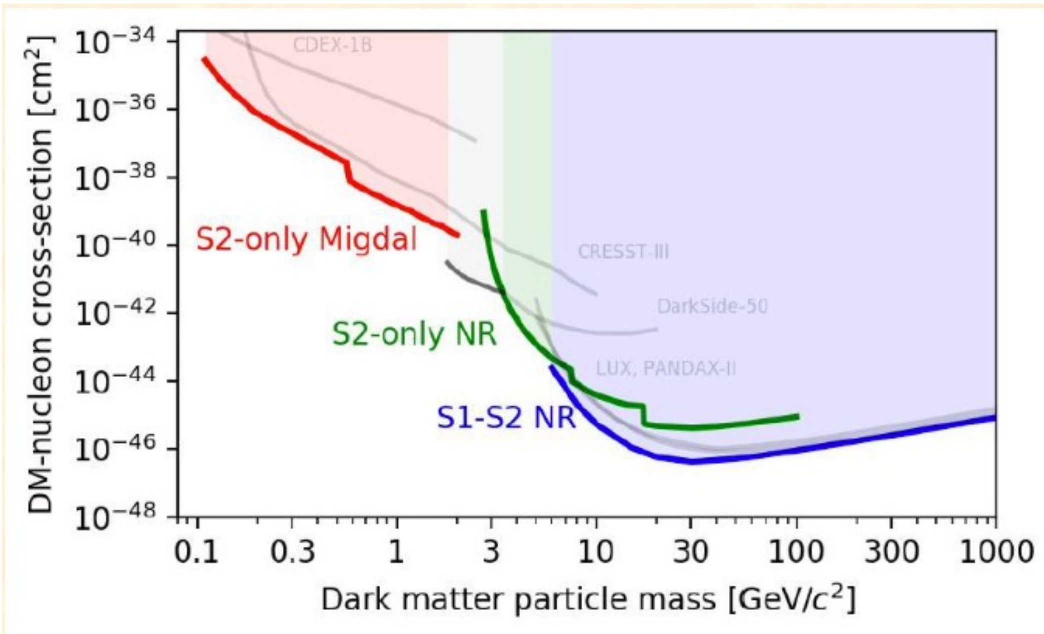
→ Goal: two orders of magnitude improvement in sensitivity with respect to XENON100



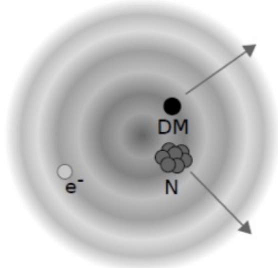
# XENON1T: Nuclear Recoil Searches




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

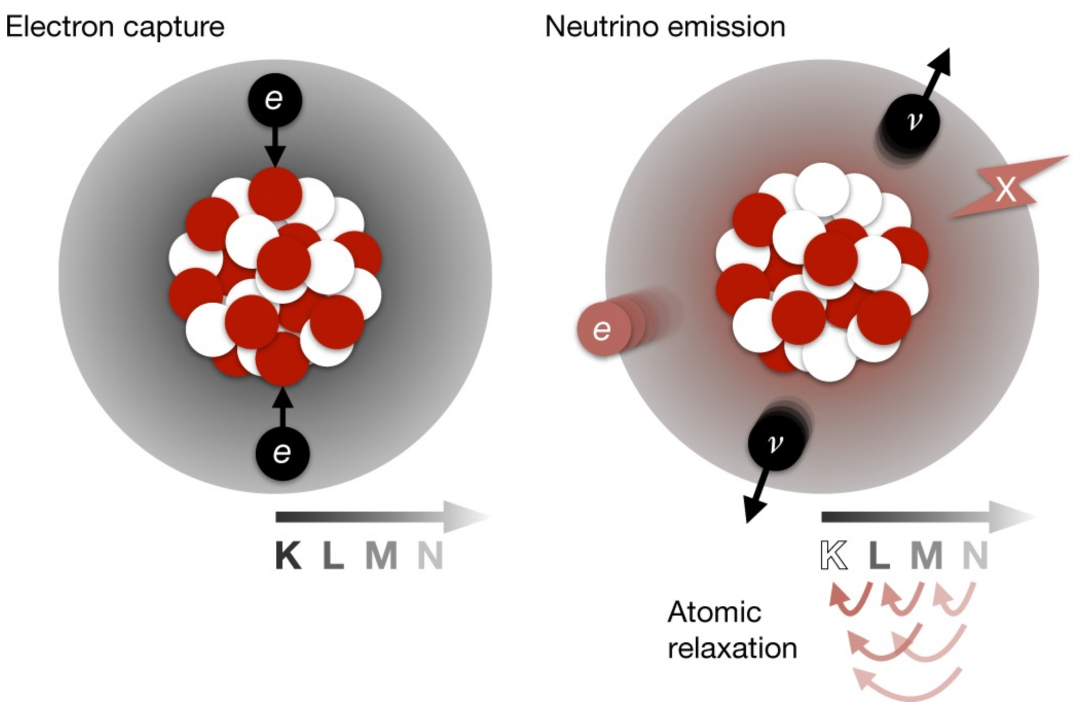



**➔ SI WIMP limits down to 3 GeV/c²**
**[PRL 121, 111302 + PRL 123, 251801]**

**recently confirmed by PandaX: arXiv:2107.13438**

**PRL 123, 241803 - Migdal effect**
**PRL 123, 251801 - light dark matter**

# Double Electron Capture of $^{124}Xe$





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

No rejection significane: $4.4\sigma$

➔ **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

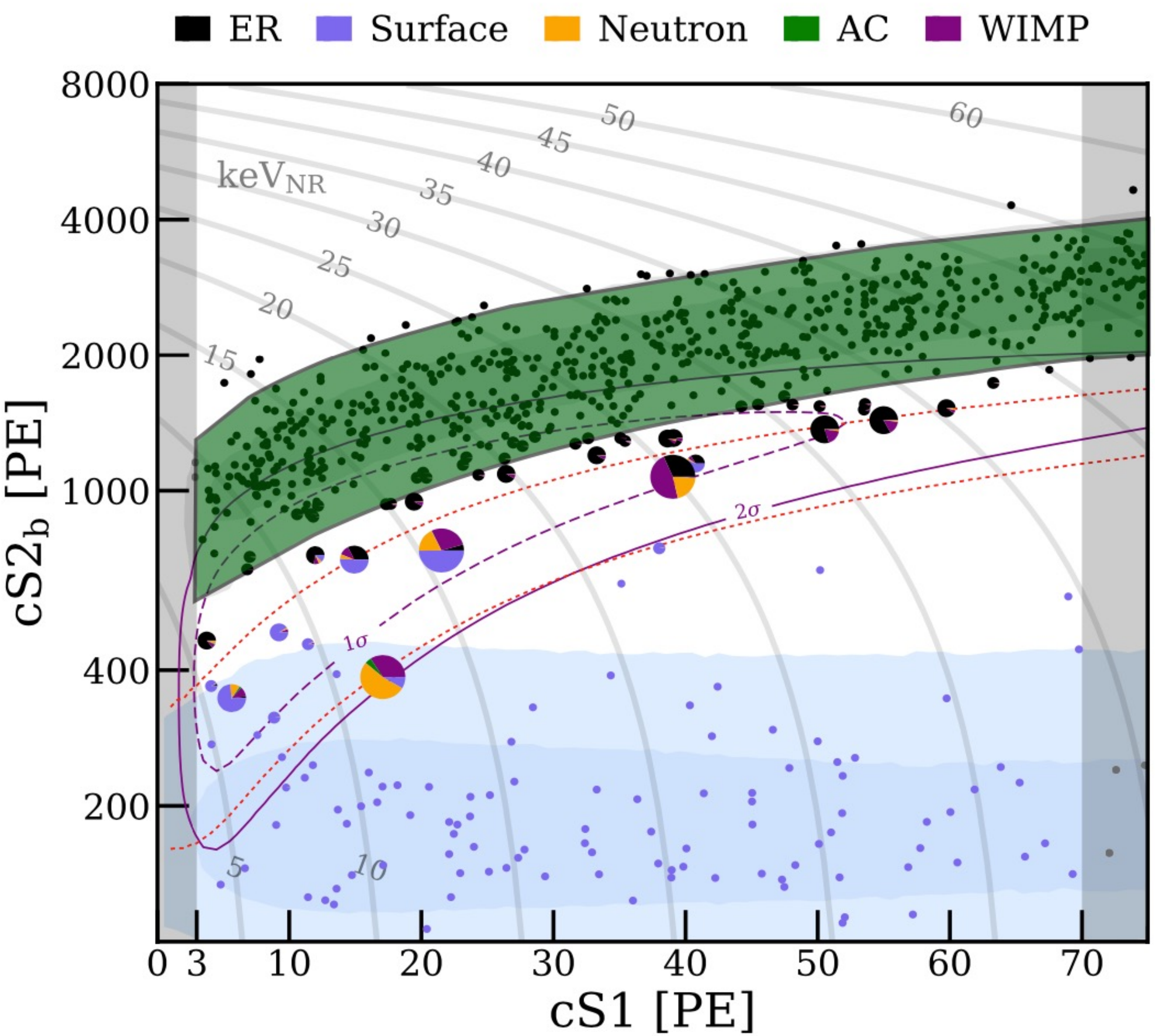
Phys. Rev. D 102, 072004

**Large exposure:**
**0.65 tonne-years**

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

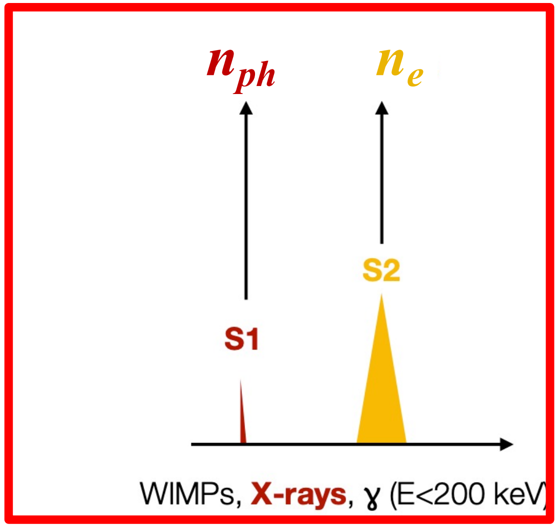
**Low threshold:**
**1 $keV_{ee}$**

**➔ excess events!?**



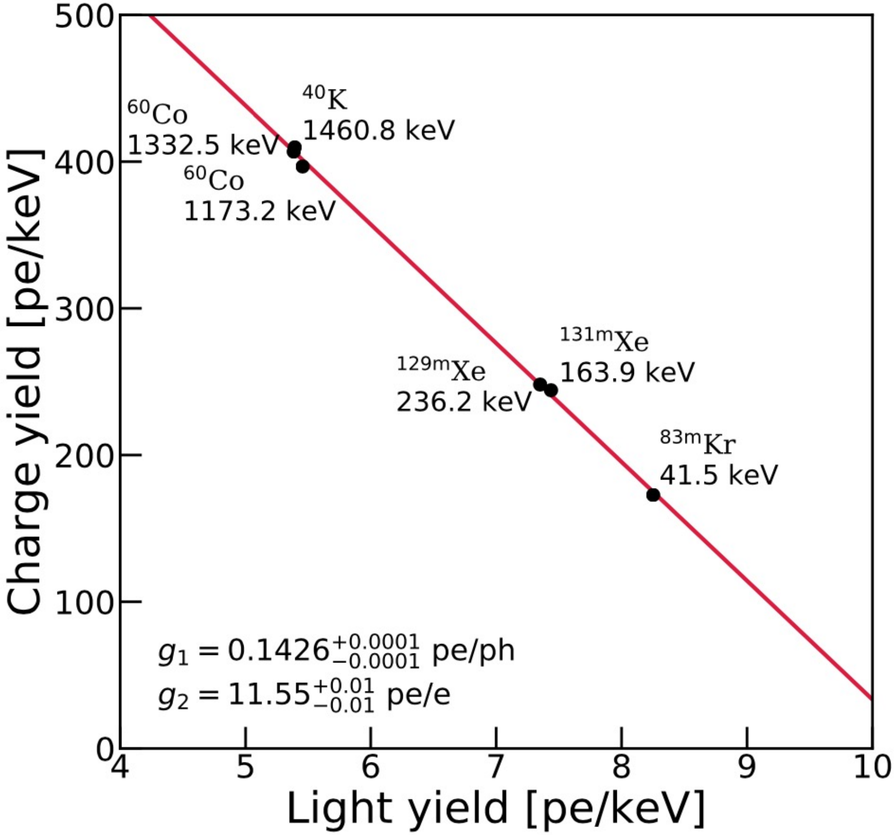
# Energy Reconstruction and Resolution

**Combine light and charge**

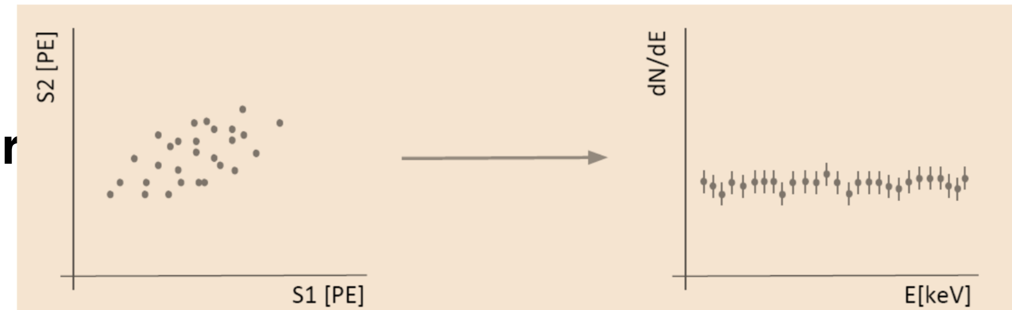



$$E = W \cdot (n_{ph} + n_e)$$
$$= W \cdot \left( \frac{S1}{g_1} + \frac{S2}{g_2} \right)$$

➔ **detector constants $g_1$ and $g_2$**



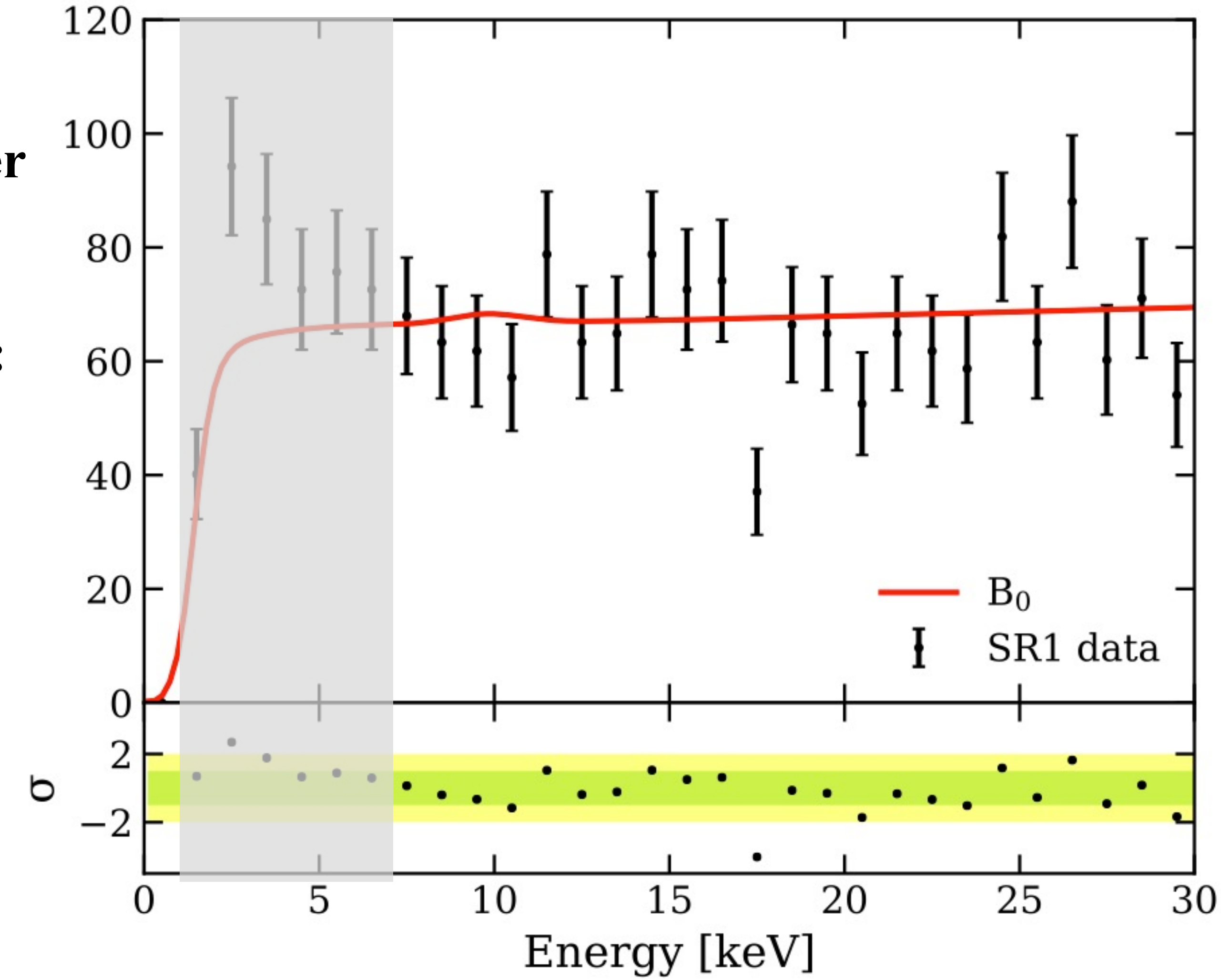

- **Anti-correlation between light and char**
  ➔ **checked with calibration sources**
- **Energy resolution < 5 % at 50 keV**



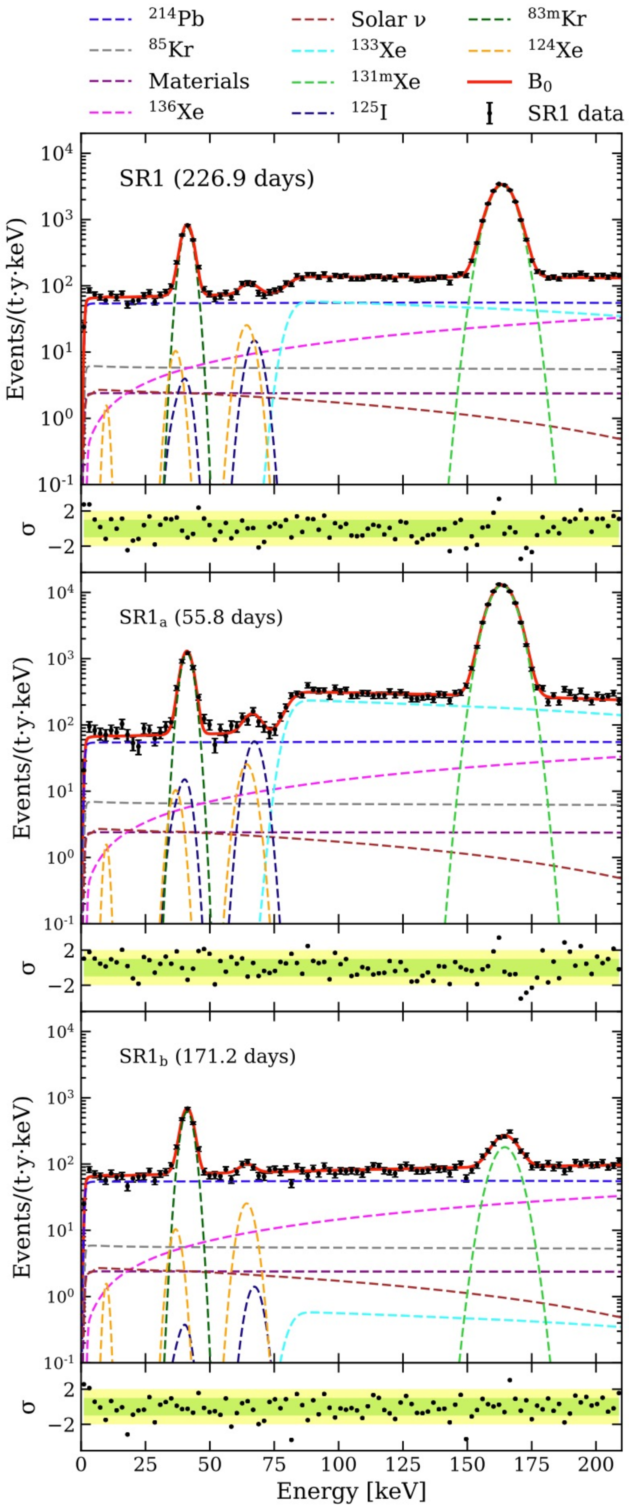
# The Result

- **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




**<u>Explanation #1:</u>**
**3.5σ fluctuation**




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

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

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

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

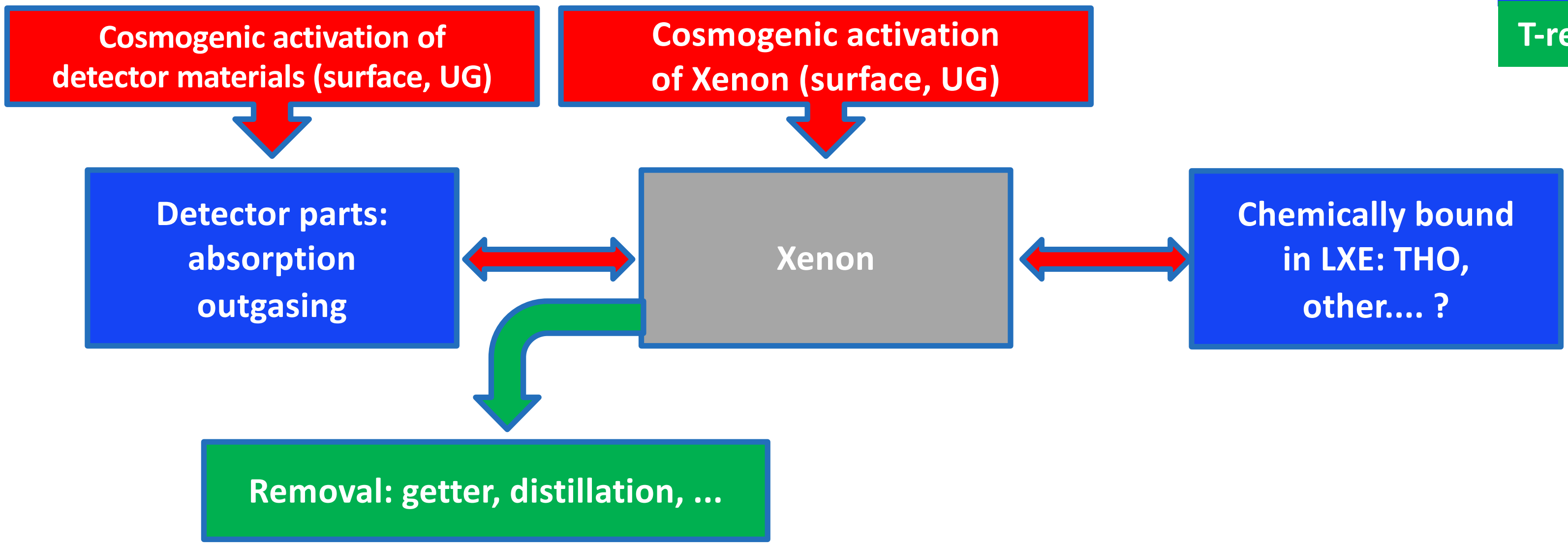
**Lowest bg rate ever achieved in this energy range**

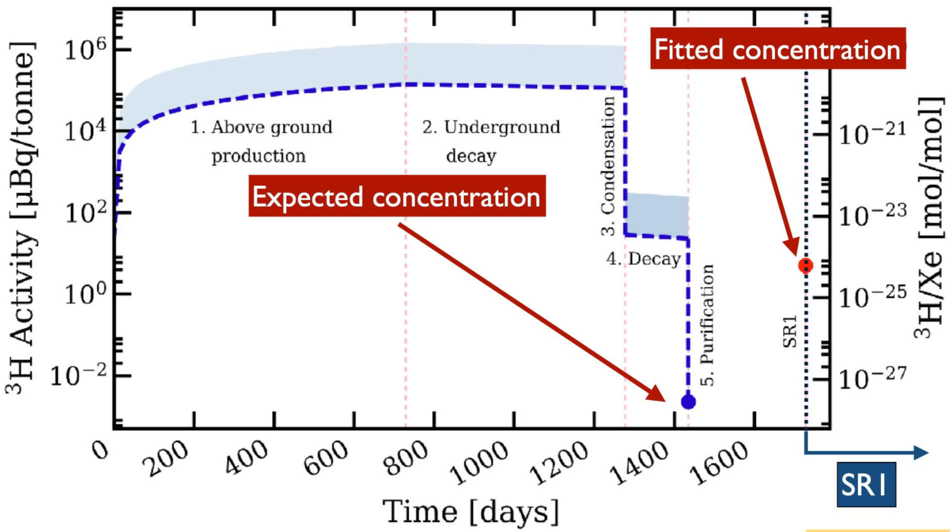
**Explanation #2:**

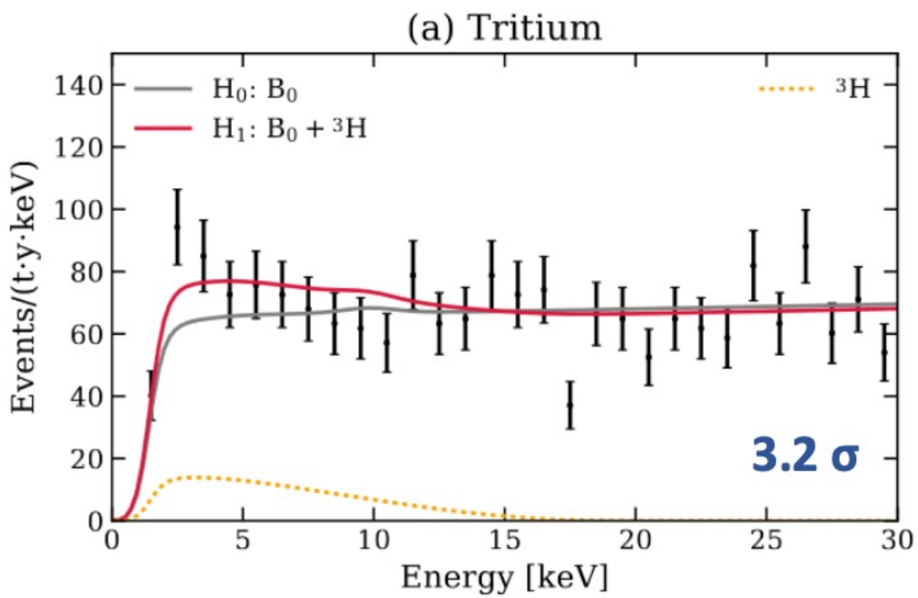
**Some unexpeccted new background?**

# 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**

# New Physics

- **A singal from where?**
- **Sun:**
  **- neutrinos (exist, but CEνNS too small ←→ neutrino floor is close...)**
  **→ 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?**

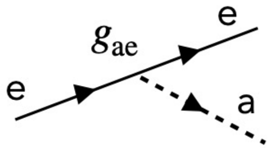
- **Diffuse background of invisible particles**
  **←→ consistency with other searches/limits**

**So far >300 citations... → mostly theory explanations**
**→ 3 main directions: Axions, ν's, light bosons**

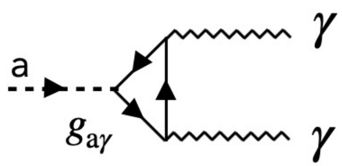
# Signal Interpretaion: Solar Axions?

## Production:

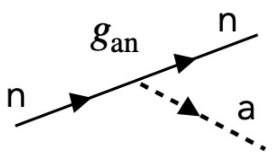
1. ABC



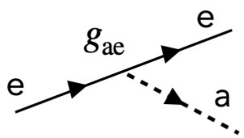

2. Primakoff




3. $^{57}$Fe

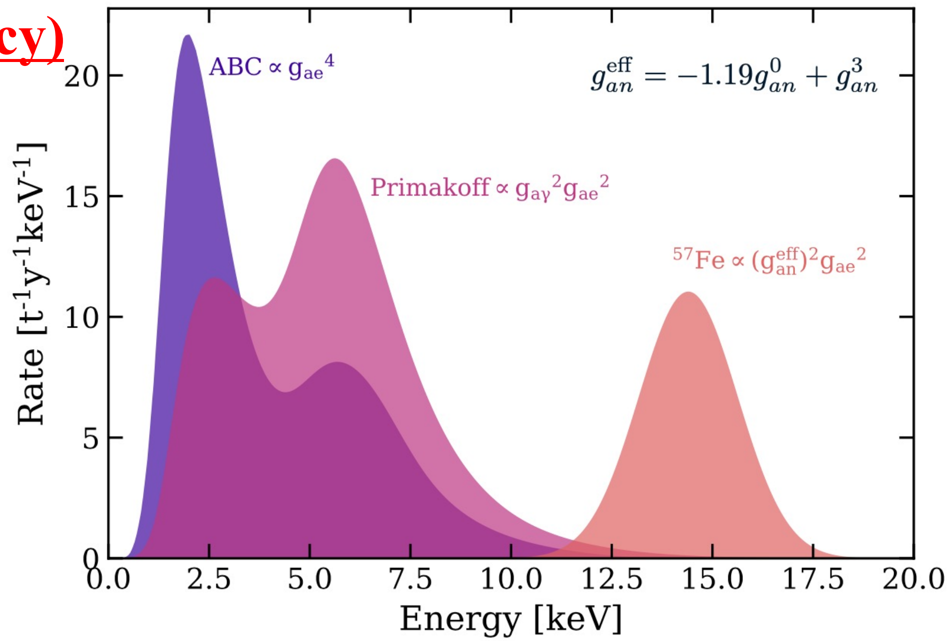



## Detection via axio-electric effect

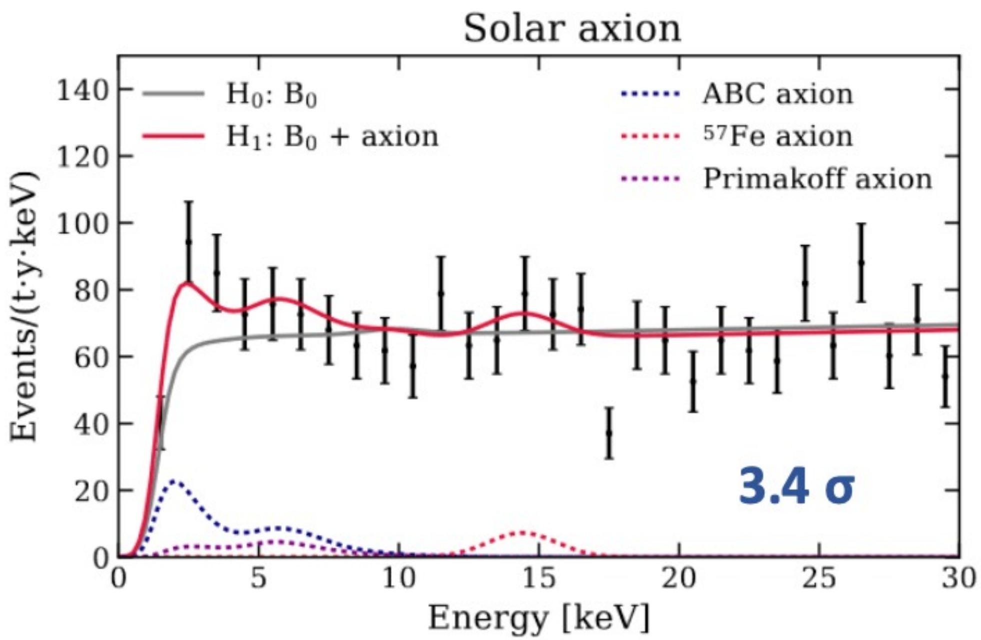



$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

## Reconstruction in XENON1T (resolution, efficiency)

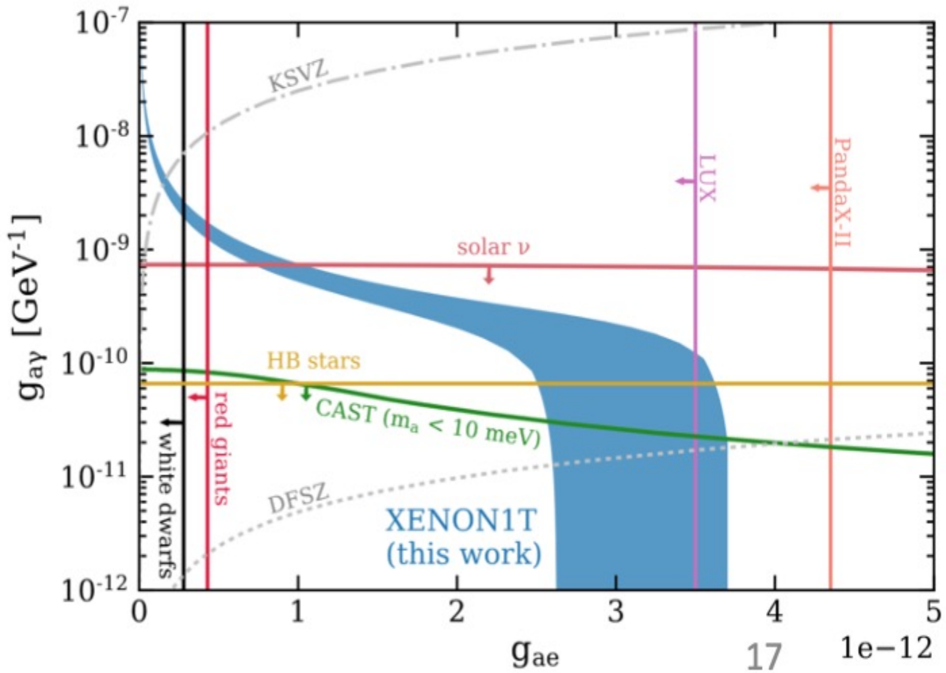



[Phys. Rev. D 102, 072004]




**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 Axion-like Dark Matter and its implications for Stellar Cooling Anomaly,**

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

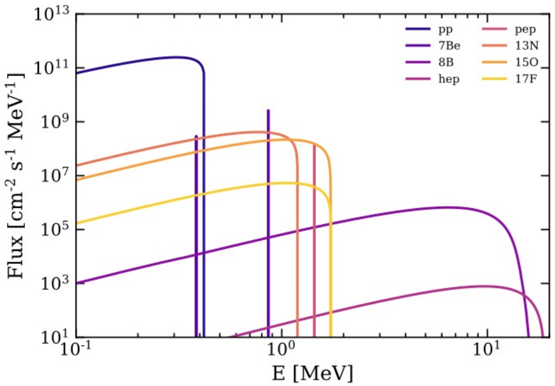
**WD and RG explained simultaneously better when ALP constitutes about 10% of DM**

# Large Neutrino magnetic Moment

[Phys. Rev. D 102, 072004](#)

## Solar neutrino spectrum

➔ **MeV-ish**

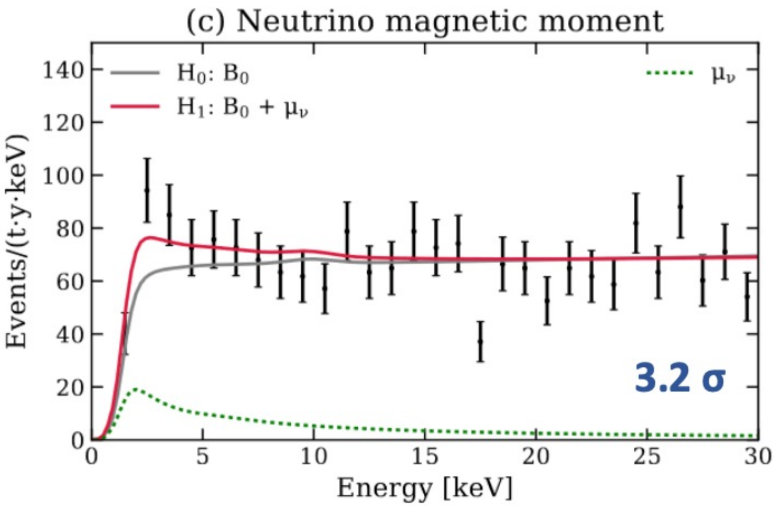


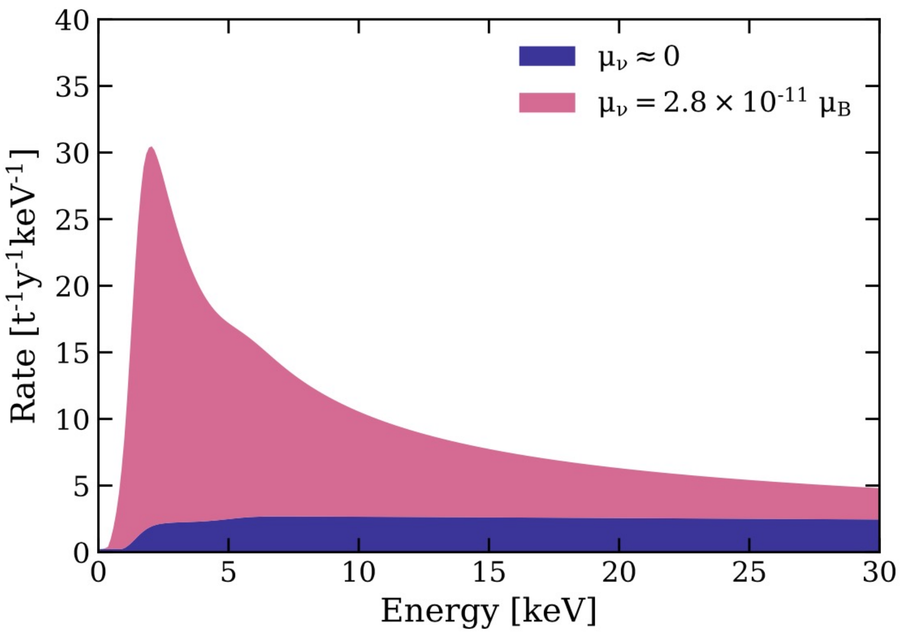

## Detection

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

**~ $1/E_r$**

**Reconstruction in XENON1T (resolution, efficiency,**



# $\mu_\nu$ in the Standard Model + $\nu_R$

**Dirac:**

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

**$\mu_\nu$ and ν mass operators have the same chiral structure**
**➔ $\mu_\nu$ typically proportional to $m_\nu$**

**SM+$\nu_R$:**

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

**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$(10^{-23})$ $\mu_B$**

**➔ all orders of magnitude too small!**

## ➔ BSM models significantly enhance $\mu_\nu$

## e.g. MSSM with L violation by R-parity violation ~ $\lambda'$

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

$A_l$ ←→ SUSY breaking trilinear coupling

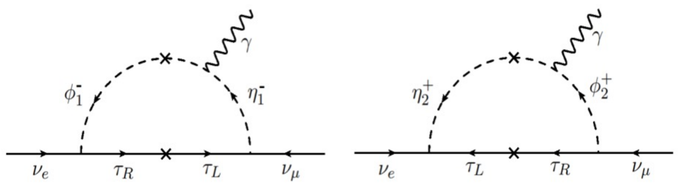
$M_{\tilde{\ell}}$ ←→ slepton mass

**BUT ➔ $\mu_\nu \leq 10^{-13}\,\mu_B$**

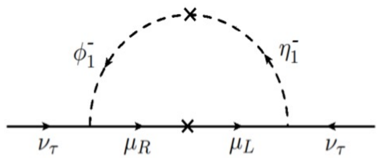
**Rather general: Most BSM models with TeV-ish scales allow/predict $\mu_\nu \leq 10^{-13}\,\mu_B$**

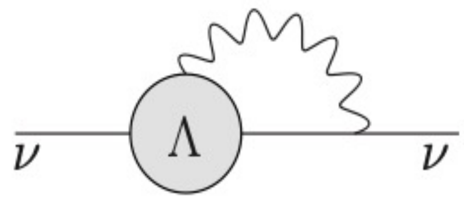
**Pushing higher often leads to two problems:**

- 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**

**However:** **Symmetries can decouple μ and neutrino masses**

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

**symmetries for ν mass patterns ➔ non-trivial $m_\nu$ ←→ $\mu_\nu$ relation**

**K.S. Babu, S. Jana, ML, JHEP 10 (2020) 040 ➔ see talk by S. Jana**

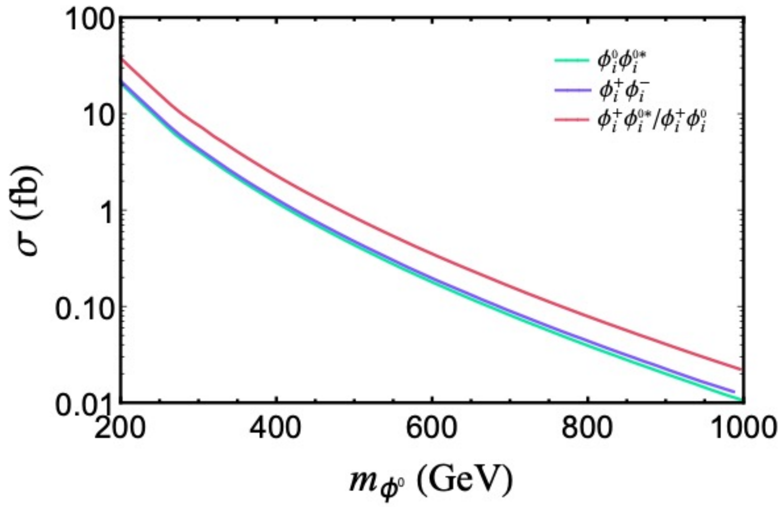
**Horizontal $SU(2)_H$ broken by muon Yukawa coupling**

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

**$\mathcal{L}_{\text{mass}}$ is not invariant ➔ $m_\nu = 0$ in the $SU(2)_H$ limit while $\mu_\nu$ is allowed**

**+ corrections ➔ elegantly generates the correct ν mass scale**

**➔ LHC prospects**

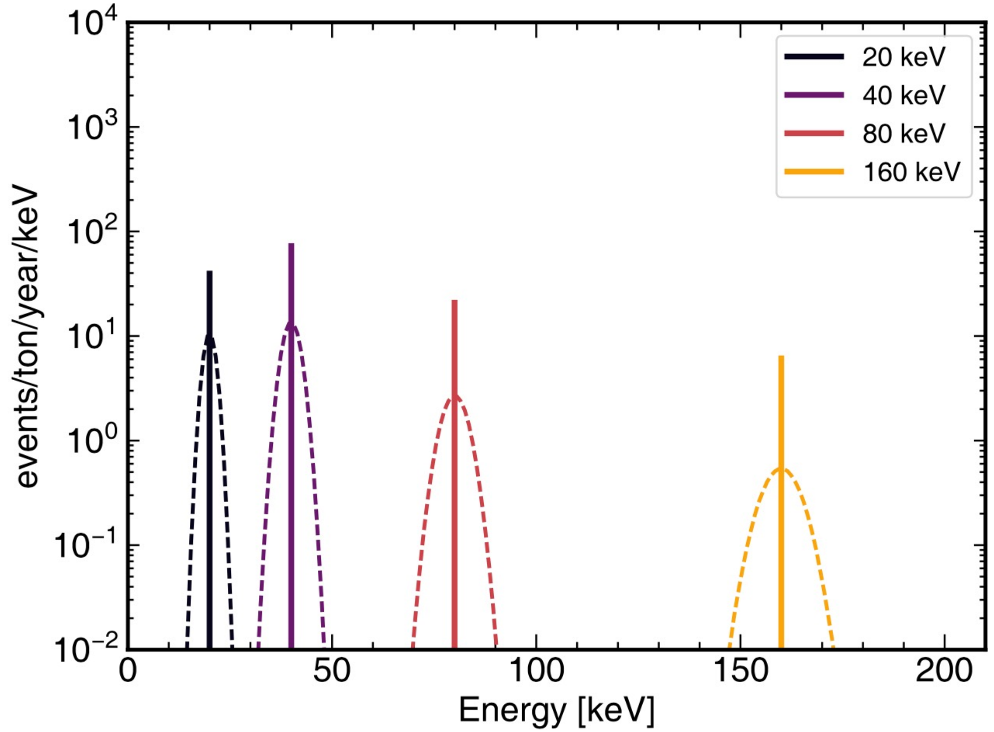


# Bosonic Dark Matter

**E.g. axion-like pareticles (ALPs) – not related to strong CP problem, but interesting ➔ avoids strict mass-coupling relation ➔ more freedom**

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

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



# Many Solutions: Hidden Dark Sectors

**Receipe: Dark sector + light particles + weak coupling**

**A few examples:**

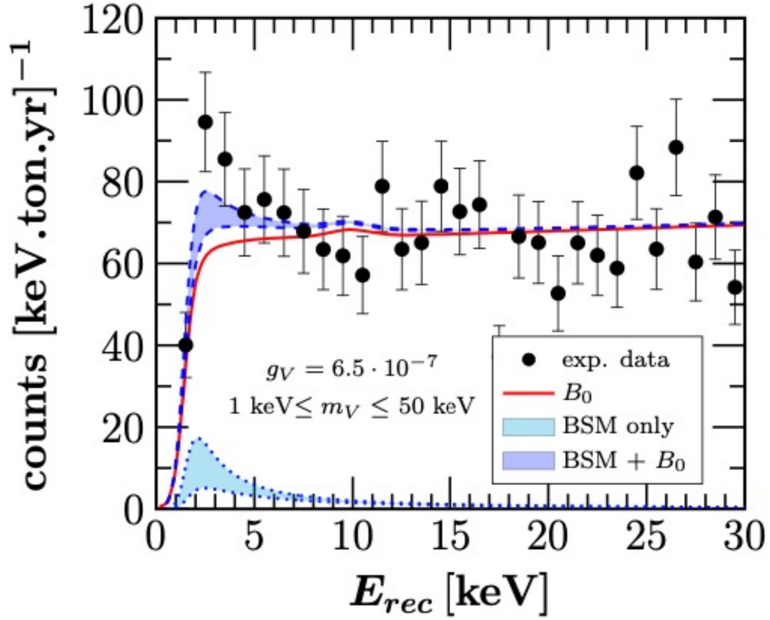
**- Light new physics in XENON1T**
**C. Bœhm, D. Cerdeno, M. Fairbairn, P. Machado, A. Vincent, arXiv:2006.11250**
**- Light vector mediators facing XENON1T data**
**D. Aristizabal Sierra, V. De Romeri, L.J. Flores, D.K. Papoulias, PLB 809 (2020) 135681**
**- Shining dark matter in Xenon1T**
**G. Paz, 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, 16180**

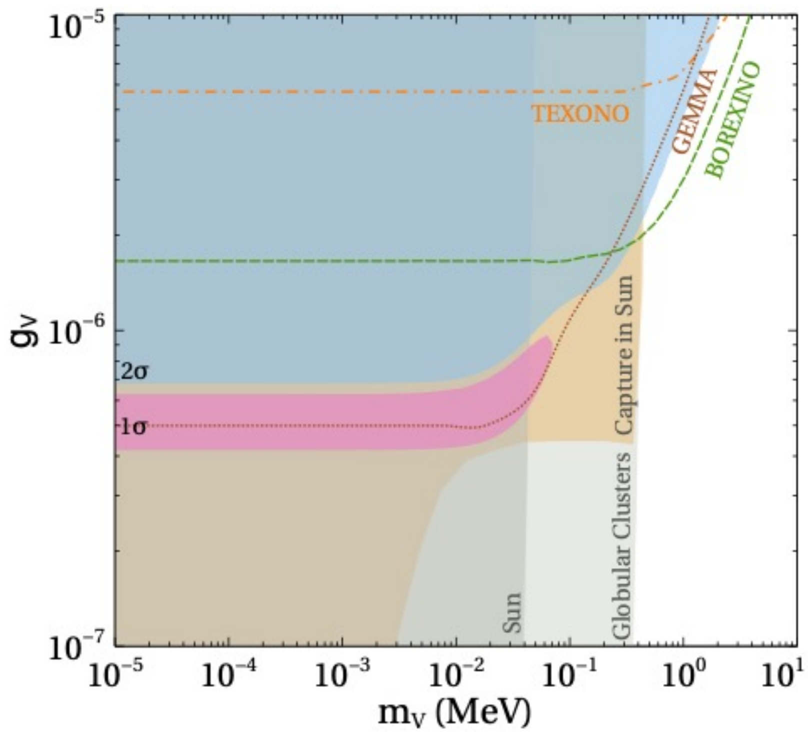
**+ many more**

# 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 with a fast Component

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

**elastic DM+e → DM+e′ scattering**

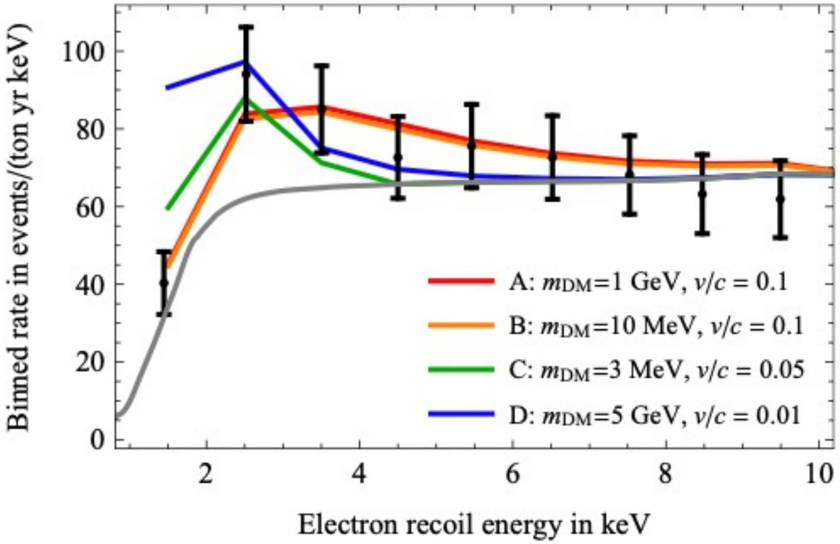
**DM with initial velocity: $\vec{v}_{DM}$**

**initial/final e velocity: $\vec{v}_e$ → $\vec{v'}_e$**

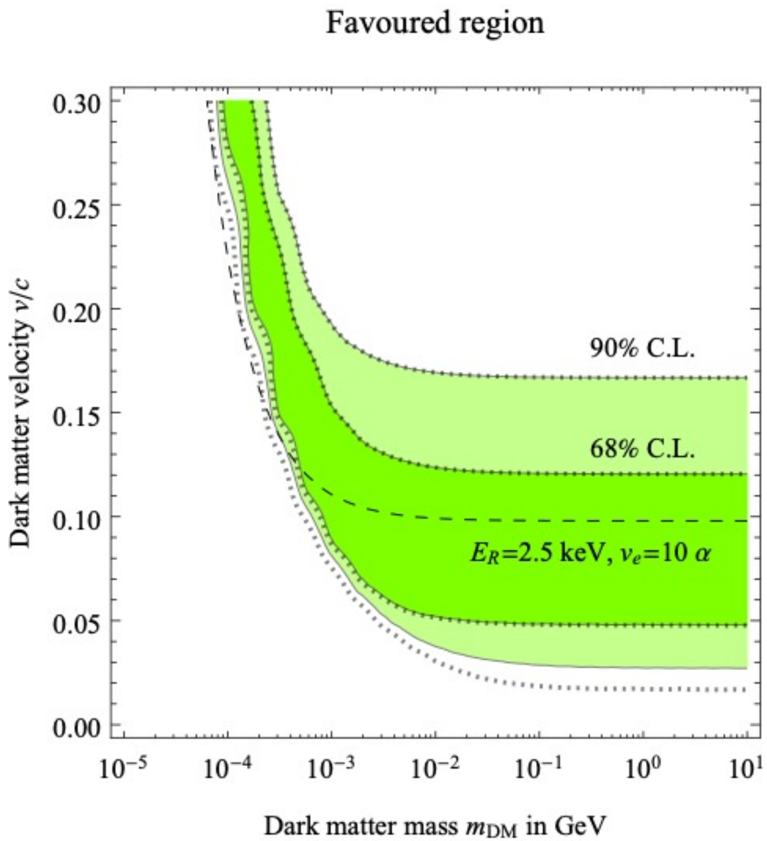
**→ Momentum transfer:**

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

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




→

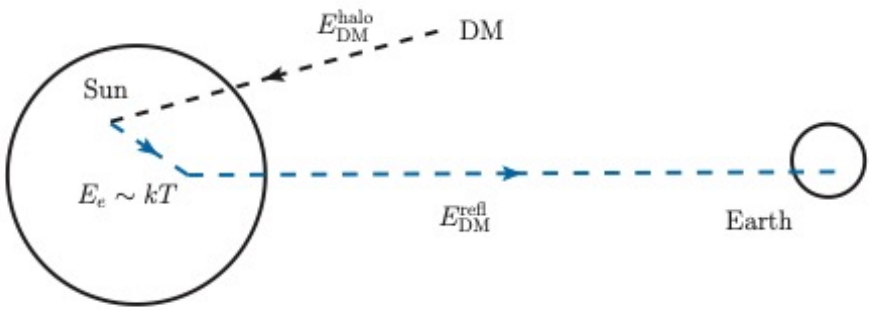


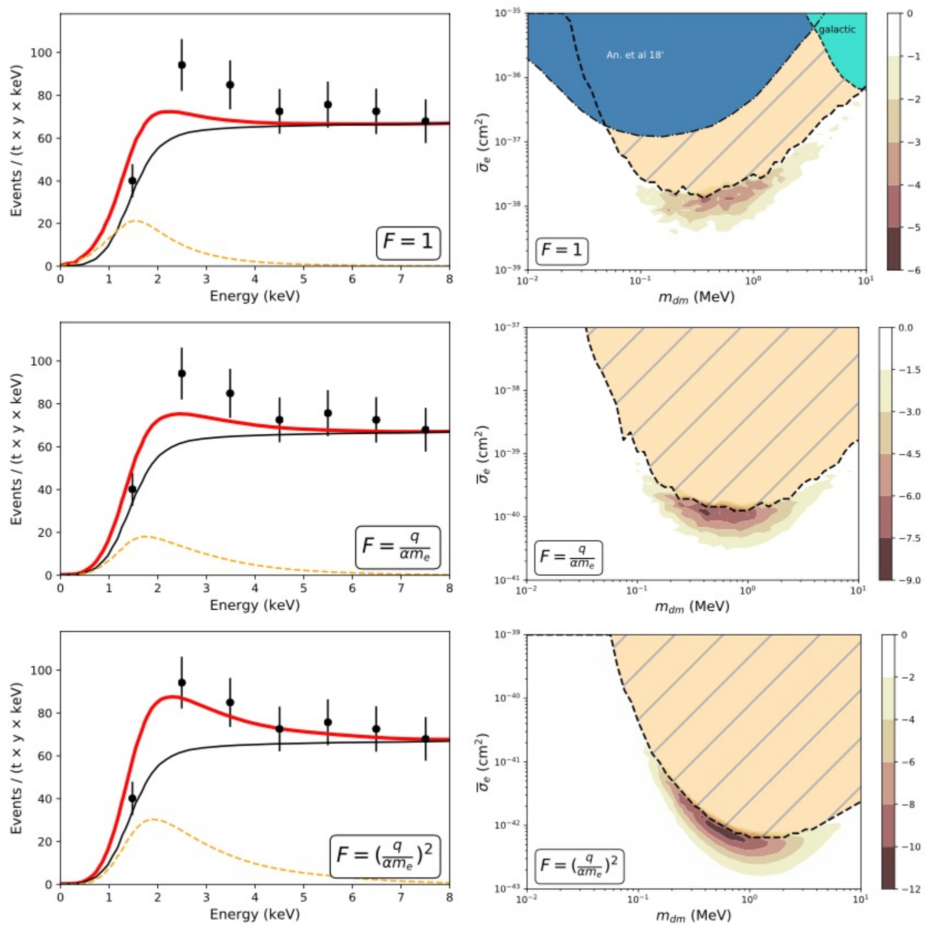

**Fast component gravitationally not bound to galaxy → ...decays, sub-halo, ...**

# 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 ($\approx 1.5 \times 10^7$ K)



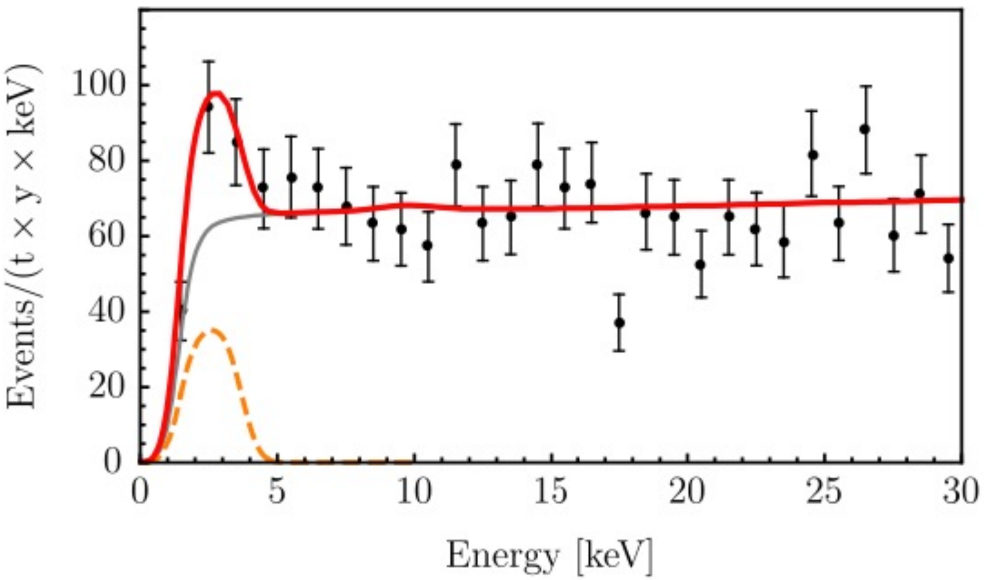

- high-temperature plasma inside the Sun
  ➔ heat-up light DM particles to keV energies
  H. An, M. Pospelov, J. Pradler, A. Ritz, PRL120, 141801 (2018)

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

- 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**

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

# More Directions

**- non-relativistic particles gravitationally bound to the Milky Way**
**- DM particles “store” energy, which they release in the detector**

- **Exothermic DM ($X^*$ + e- → strong signal preference X + e-)**
  **Baryakhtar et al., arXiv:2006.13918**

- **Luminous DM ($X^* \rightarrow$ strong signal preference $X + \gamma$)**
  **Bell et al., arXiv:2006.12461**

**This would require a slightly heavier state**
**→ populated either in the early Universe or via up-scattering**
**Aboubrahim et al., arXiv:2011.08053, Eby et al., arXiv:1904.09994**

**- millicharged neutrinos**
**Kahn, arXiv:2006.12887, ...**

# Summary of the current Situation

**Excess between 1-7 keV:**

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

**Interpretations :**

**a) A fluctuation**

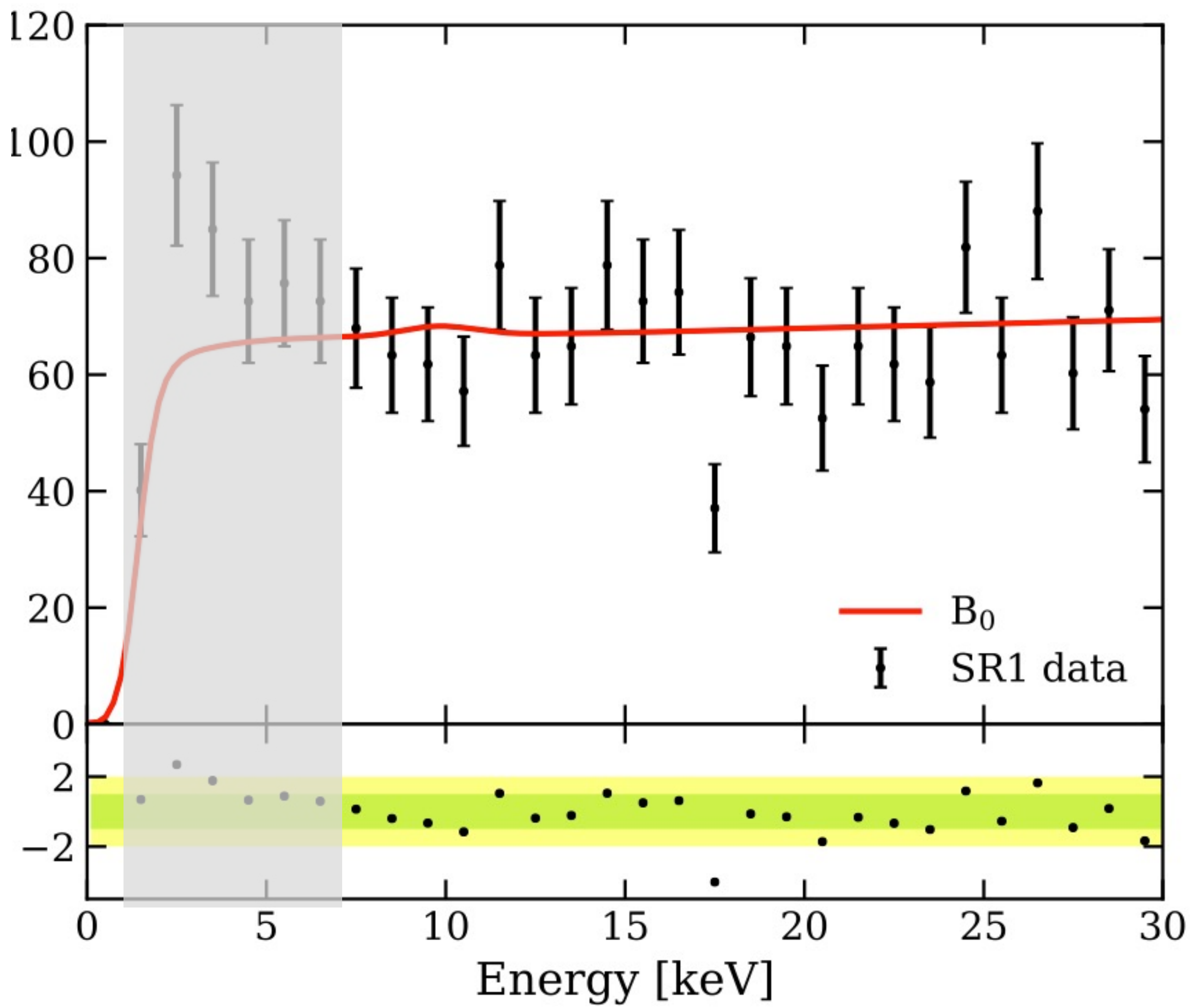
**b) Some new background**

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

**c) New physics**

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

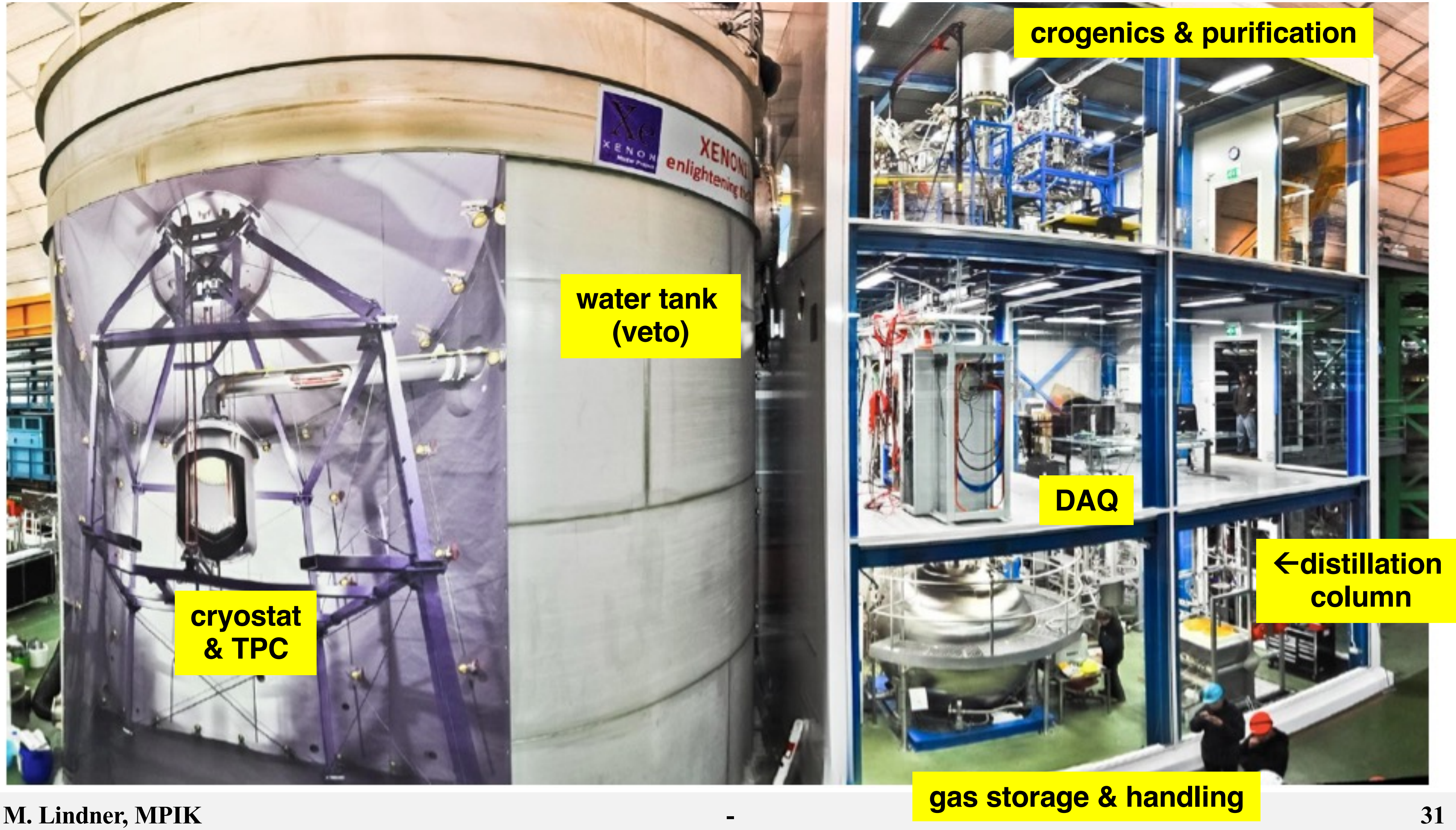
**>100 papers in 2 months**




**All ~3σ → more data soon from XENONnT**

# XENON1T → XENONnT

Changes, re-assembly, filling, commissioning done last year!
→ data taking → SR0 results... soon... → more data & checking



# Conclusions

- **The WIMP search will continue**
  - XENONnT...
- **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?
    - ➔ ...
- **Results on low $E_R$ excess have a substantial impact**
  - ➔ a hot signal to explain or unique limits on many ideas