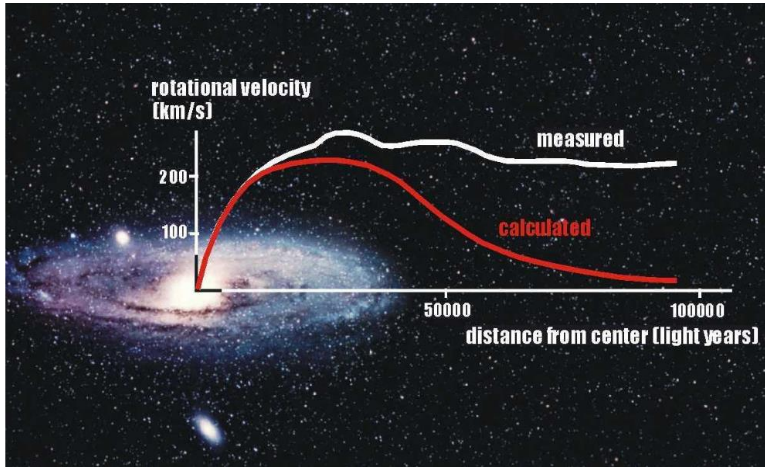
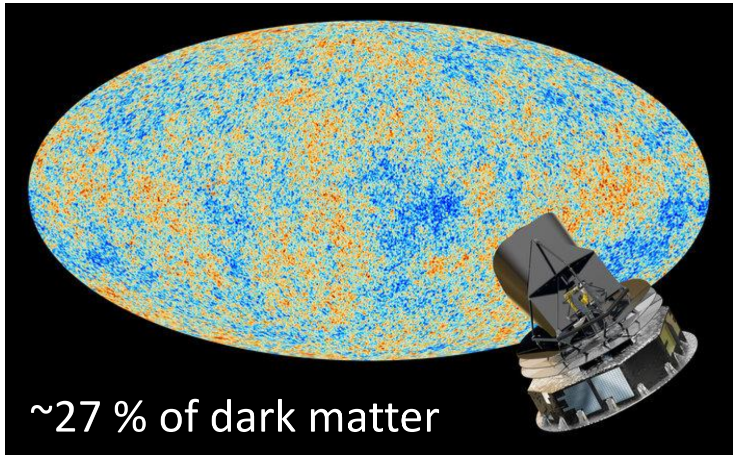
Junji Naganoma, Rice University
on behalf of the XENON collaboration

Exploring the role of electroweak currents in Atomic Nuclei
@ ECT*, Trento, Italy 04/27/2018

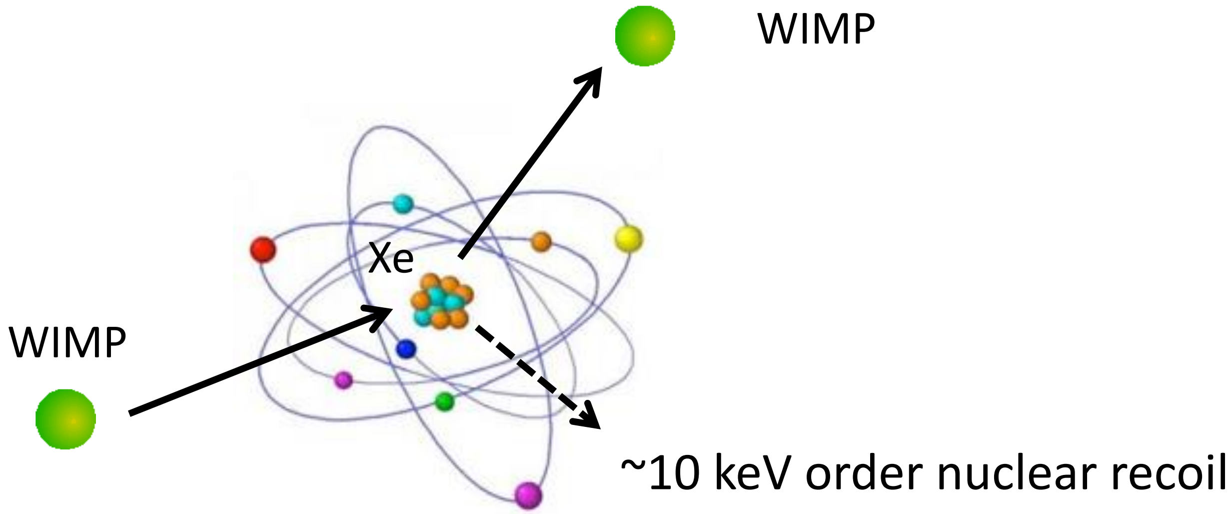
Direct Dark Matter Detection with XENON

Aim of the XENON experiment





Direct detection of Weakly Interacting Massive Particle (WIMP)

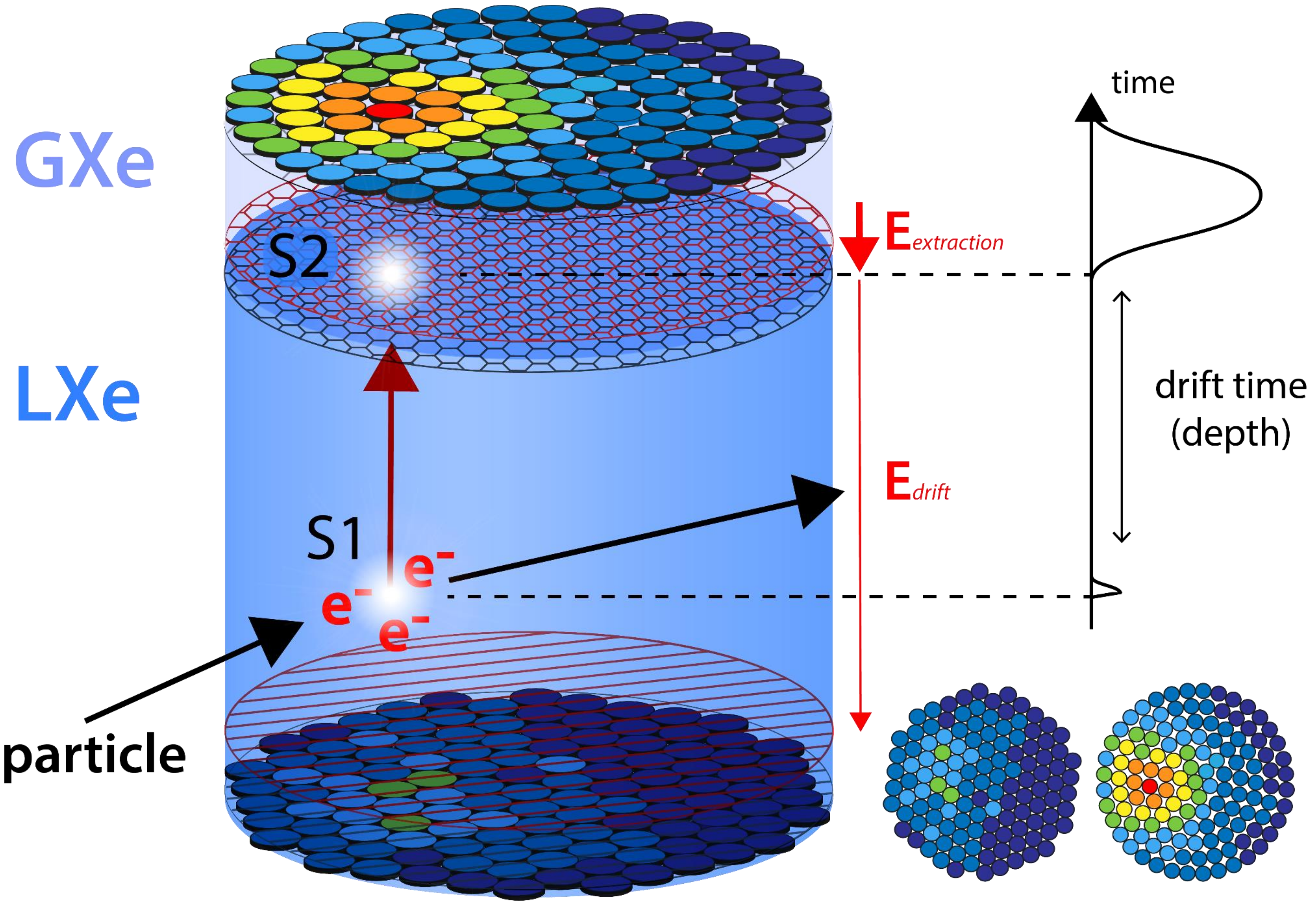


Why LXe as target?

- High mass number A=131
  → high spin-independent rate (prop. to A^2)
- 50% odd-isotopes
  → spin-dependent interaction
- High stopping power of LXe (ρ=3 g/cm^3)
  → self-shielding
- scintillation and ionization signals
  → fiducialization, ER/NR discrimination

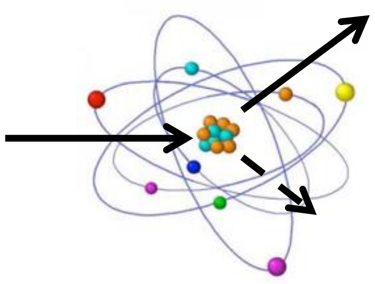
Dual phase Xe TPC detection technique

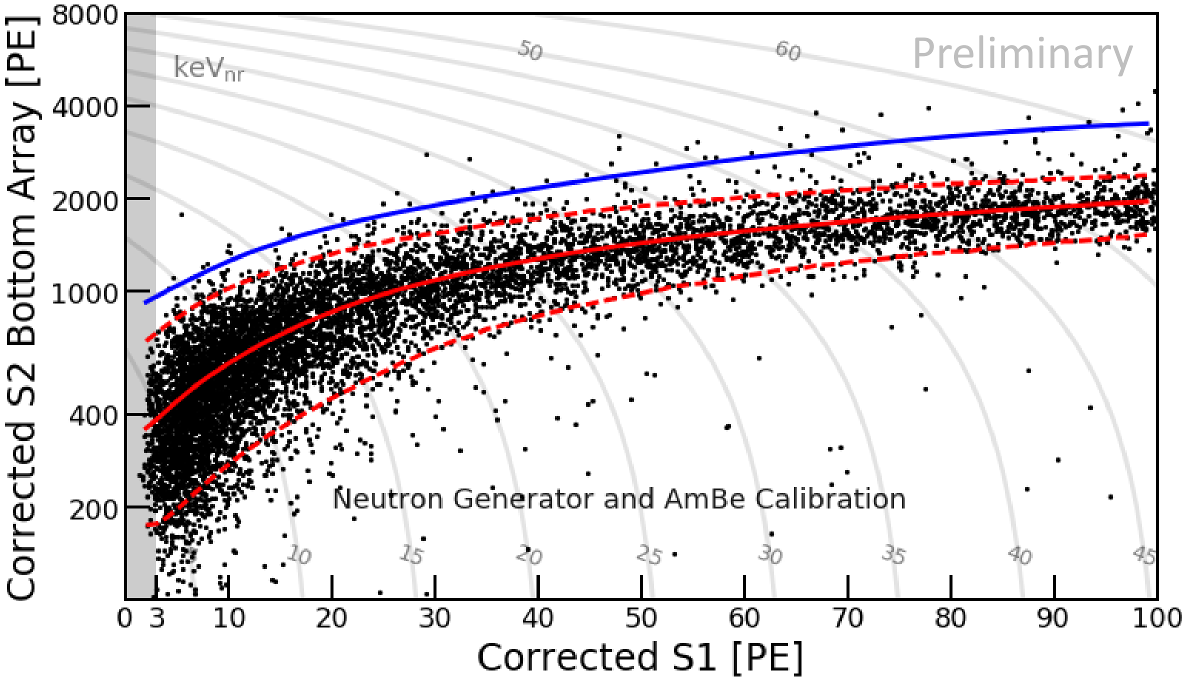
XENON
LUX/LZ
PandaX



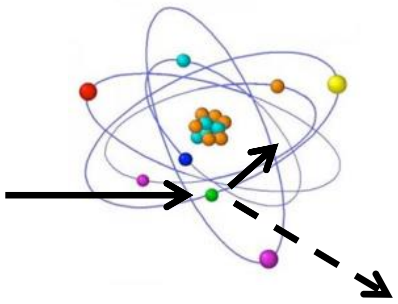
Nuclear/Electronic Recoil Discrimination

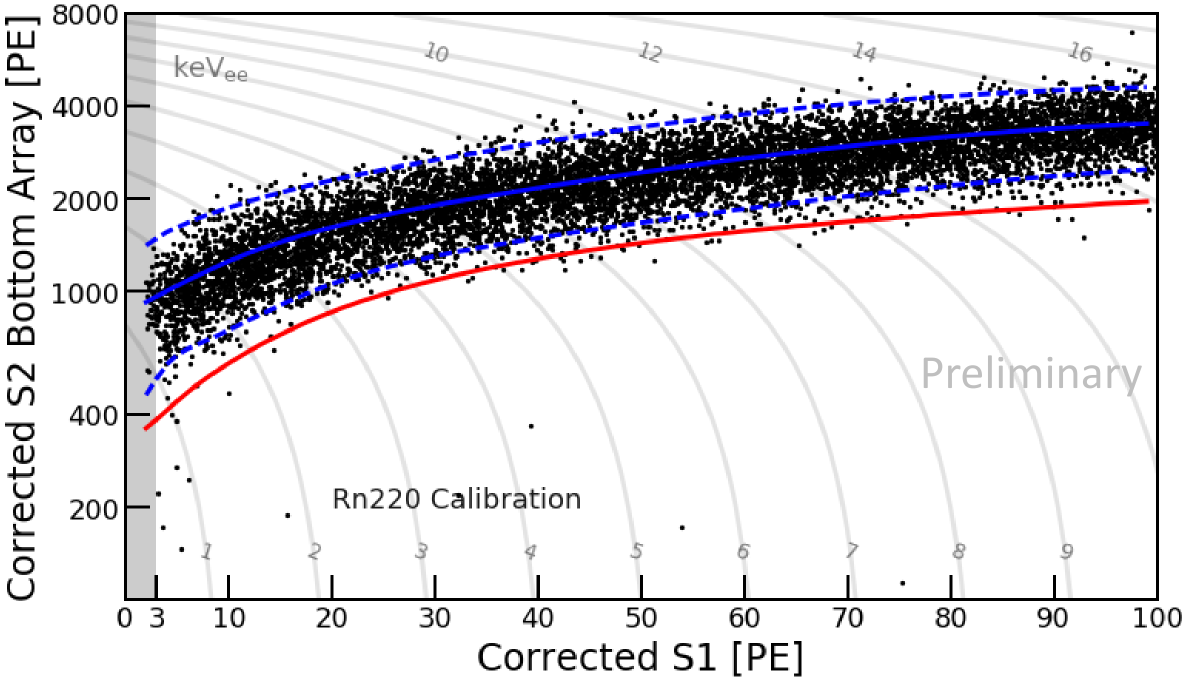
Nuclear Recoil





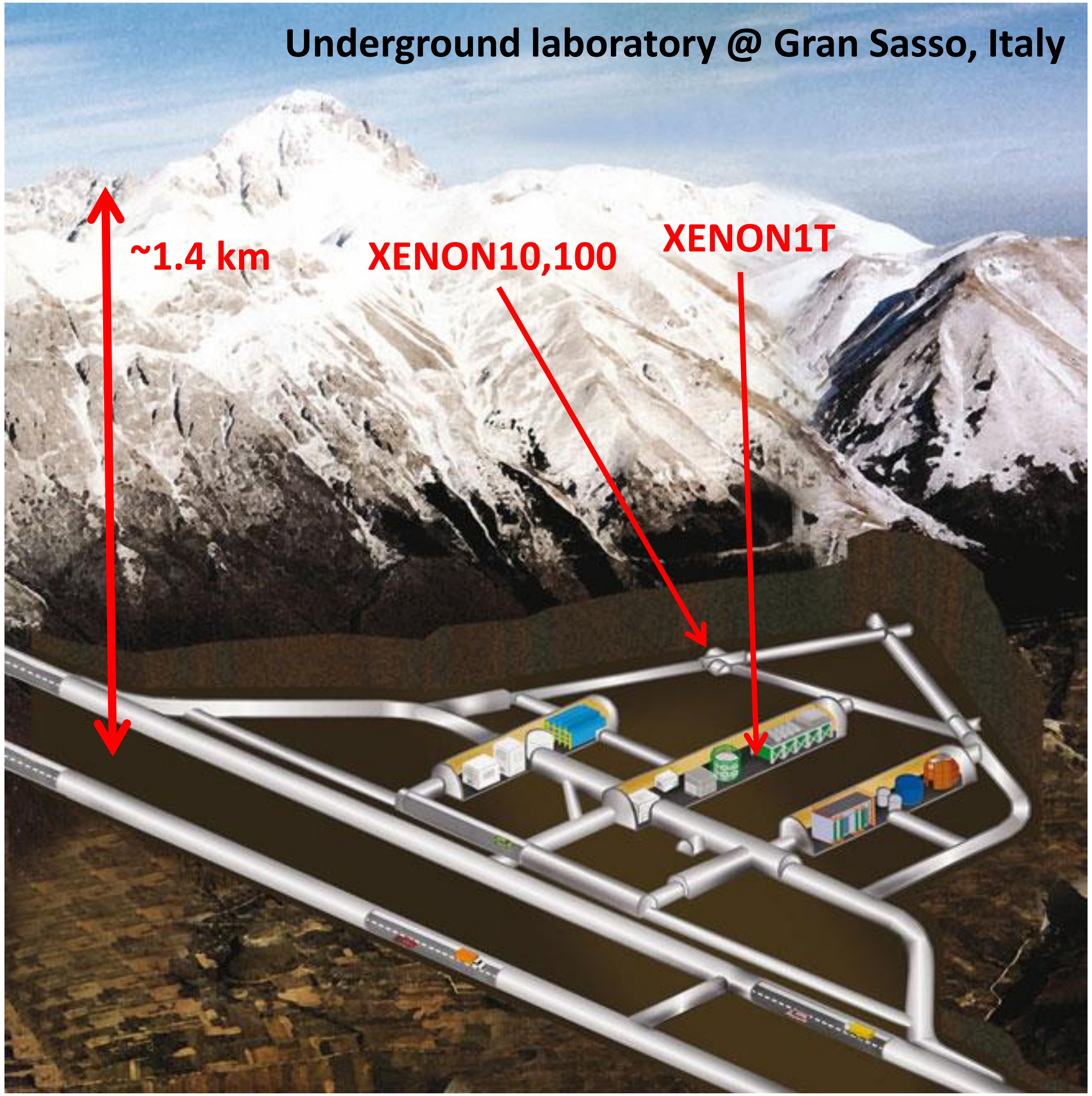
Electronic Recoil

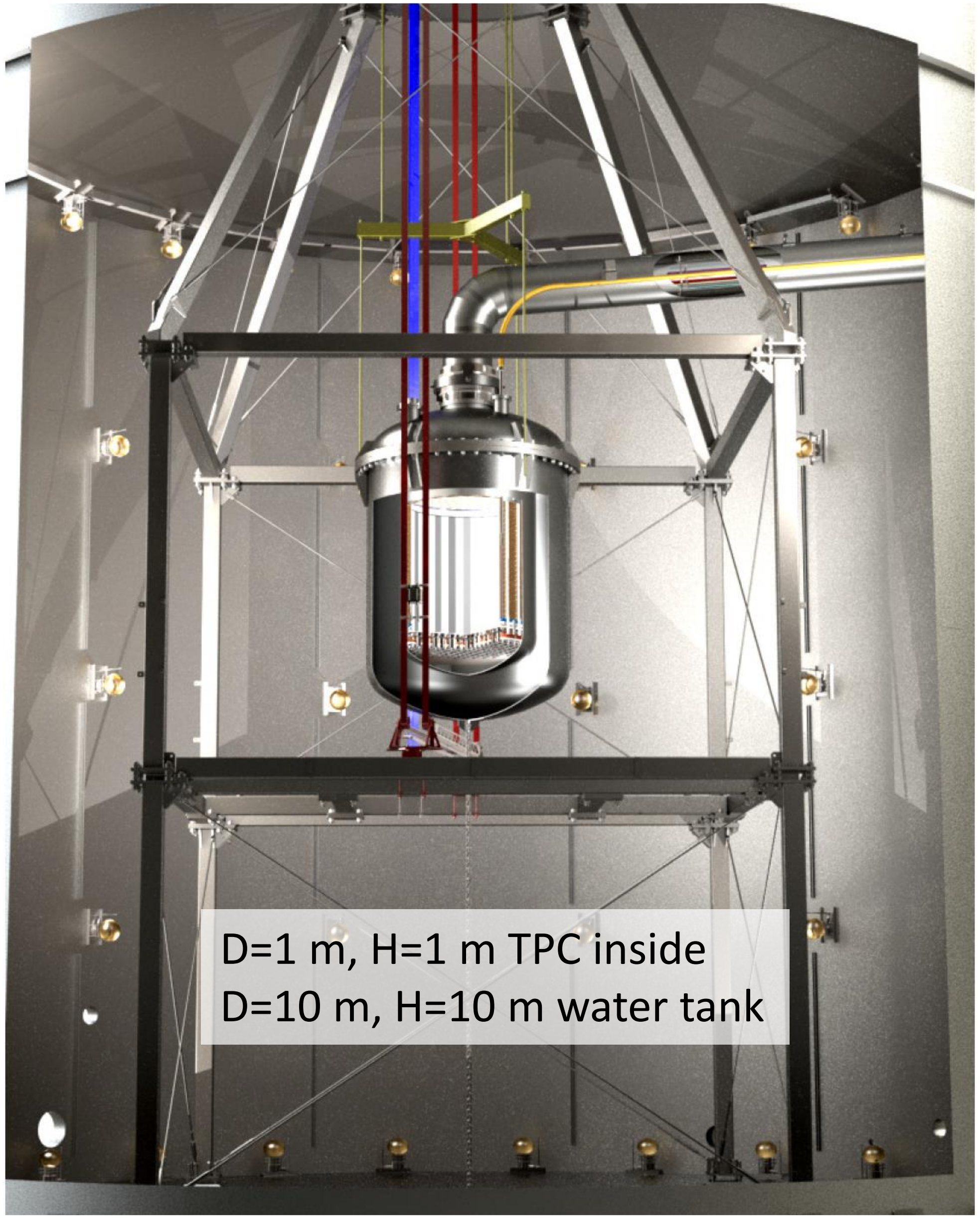




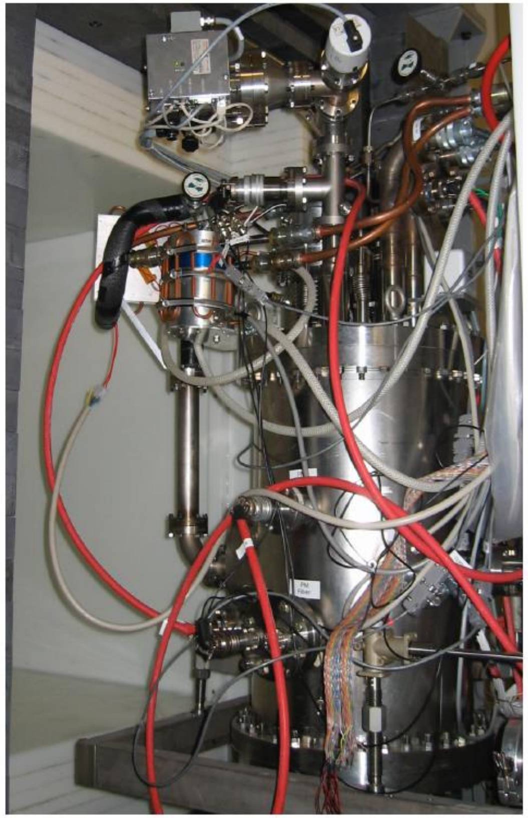
- Different charge signal at given light signal
- Only ~25 % of NR energy goes to detectable signal

XENON1T experiment



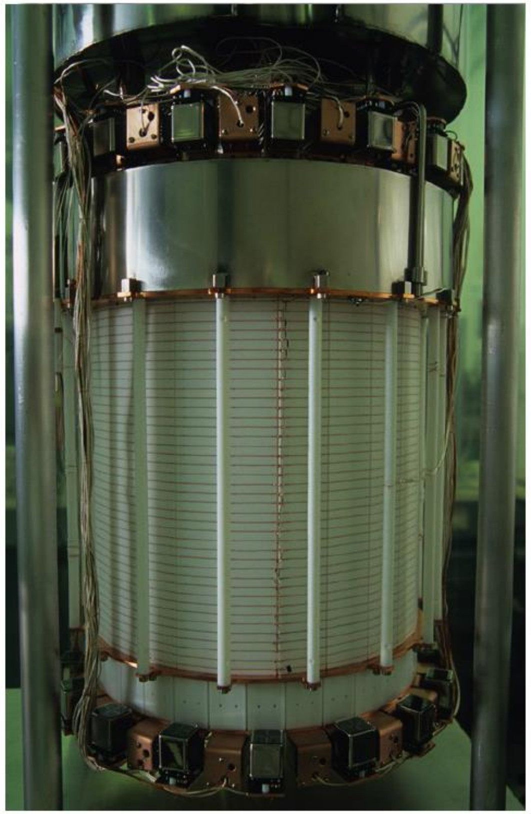


The XENON dark matter program



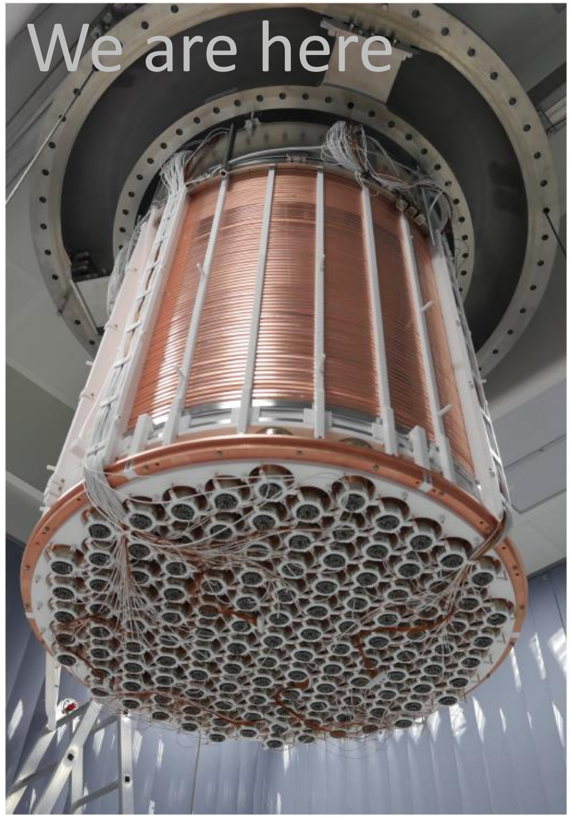
XENON10
2005-2007
Total Xe mass: 25 kg

Achieved upper limit
8.8×10^{-44} cm^2
@ 100 GeV (2007)



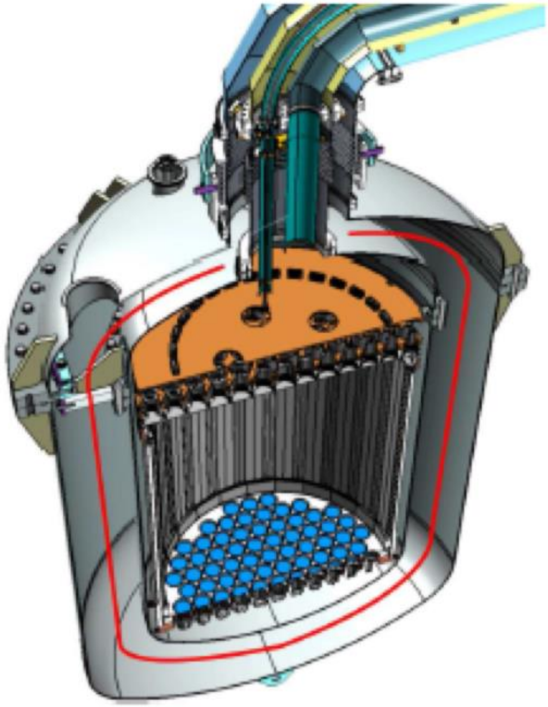
XENON100
2008-2016
Total Xe mass: 161 kg

Achieved upper limit
1.1×10^{-45} cm^2
@ 50 GeV (2016)



XENON1T
2012-2018
Total Xe mass: 3200 kg

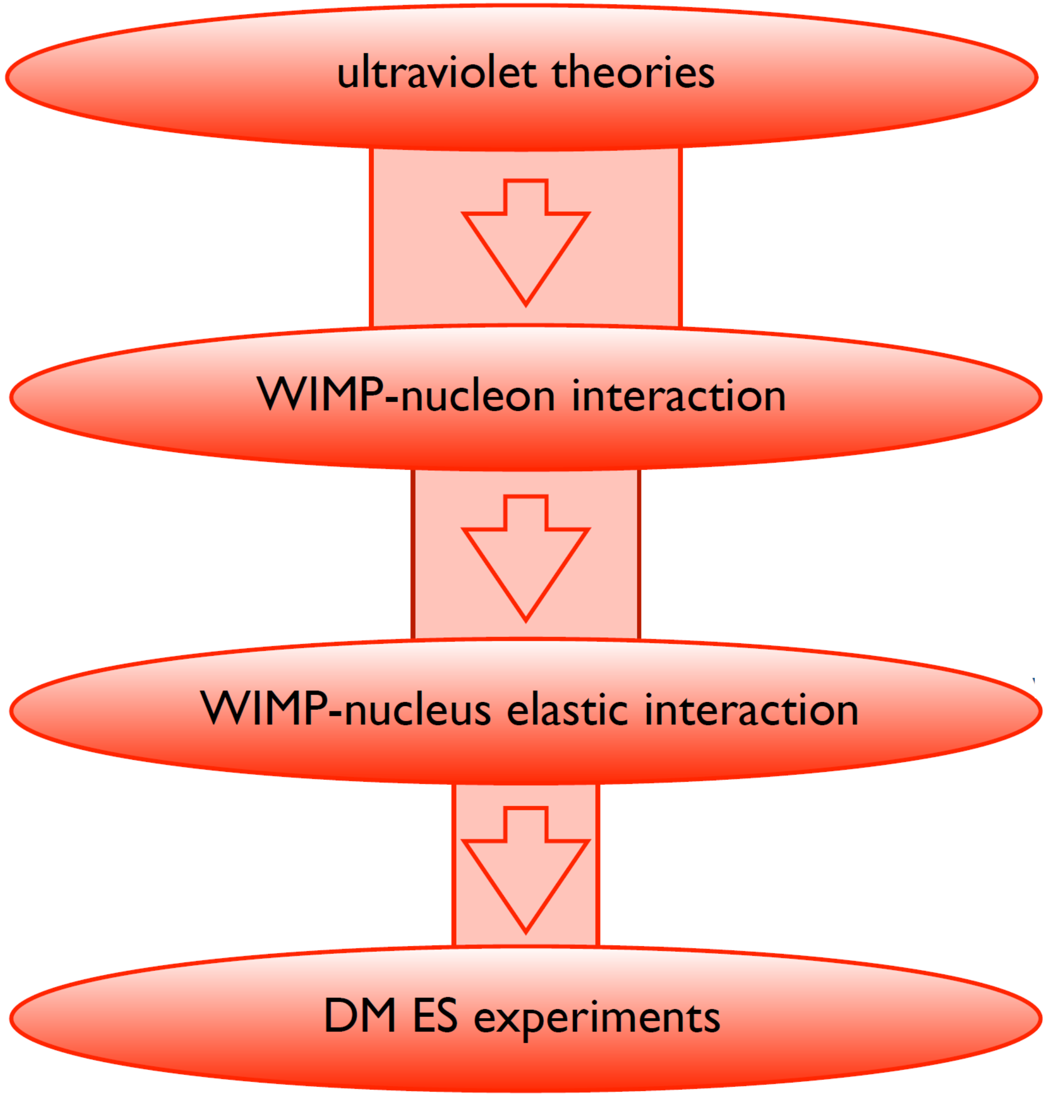
Achieved upper limit (34-day)
7.7×10^{-47} cm^2
@ 35 GeV (2017)



XENONnT
2019-2023
Total Xe mass: 7500 kg

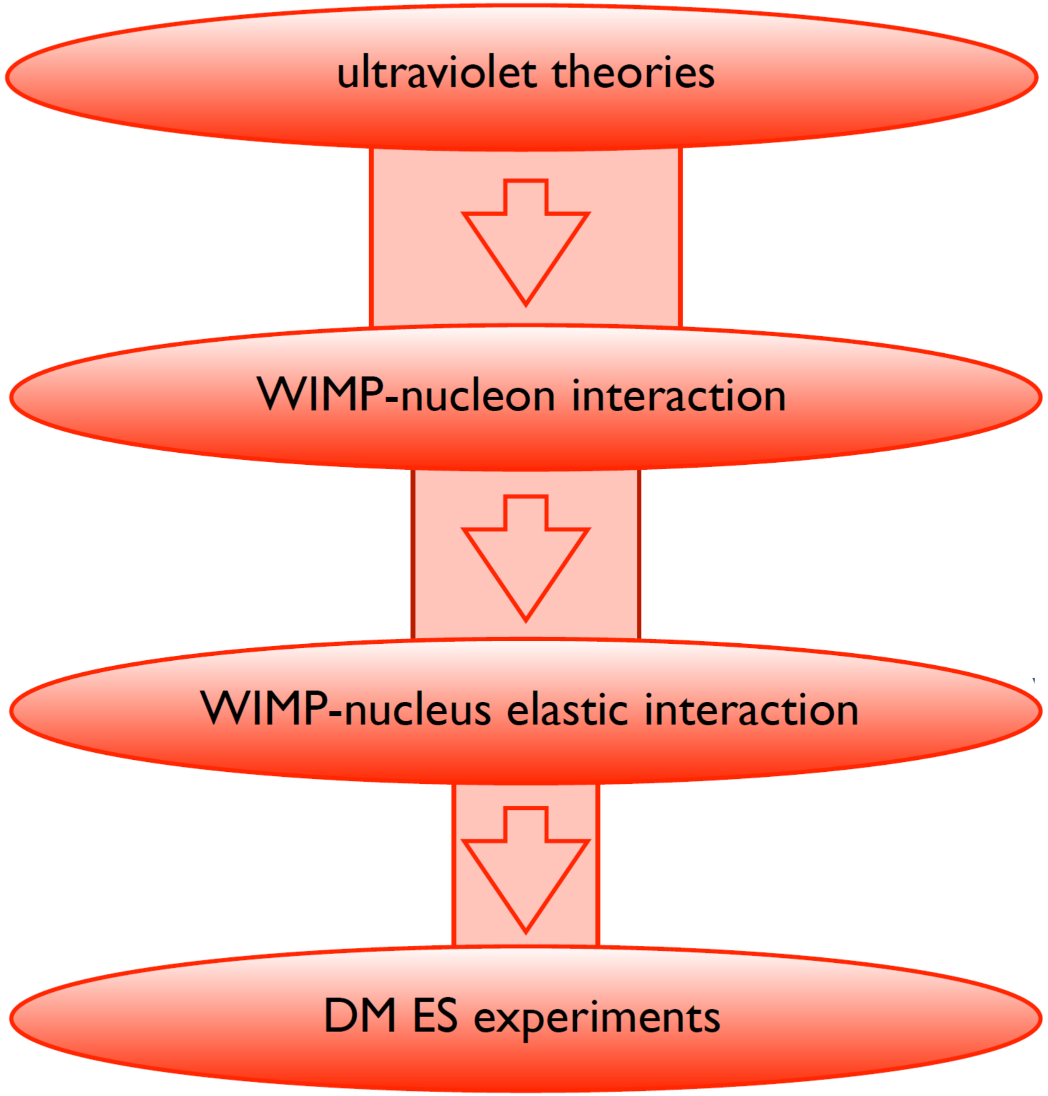
Projected sensitivity
1.6×10^{-48} cm^2
@ 50 GeV (2023)

Direct Dark Matter Search Experiment



Stolen from Wich Haxton

Direct Dark Matter Search Experiment



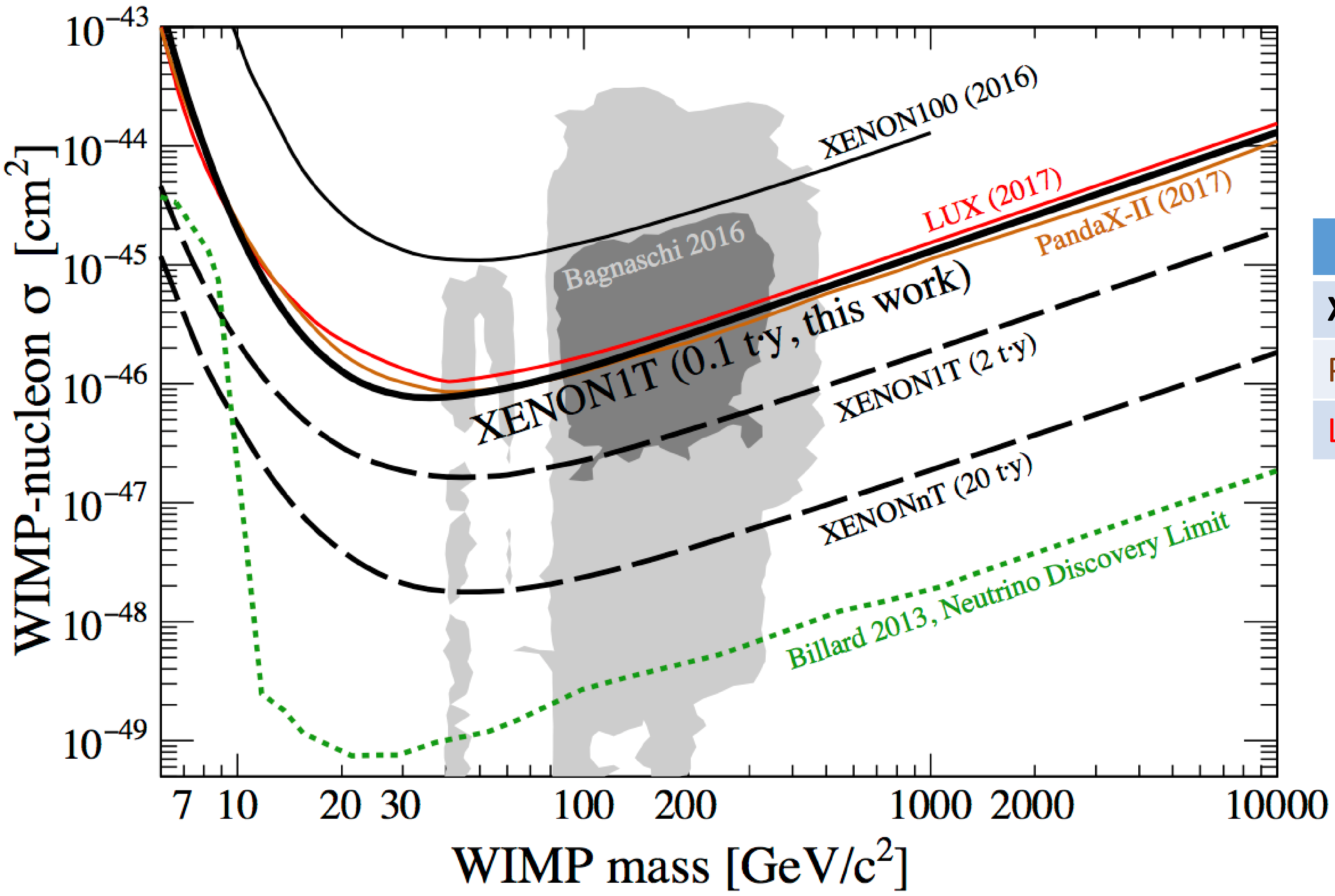
Translate up to here
with astrophysical assumptions

Our effort

1. Recoiled nucleus/electron
2. Observable energy deposition
3. Detector response
4. Rate and spacial dependence, etc.

Stolen from Wich Haxton

2017 WIMP Search Result



	Target mass	Live-days
XENON1T	**2 tons**	**34.2**
PandaX II	580 kg	156.7
LUX	300 kg	427

Outline

- ❑ “Standard” WIMP and Interaction Assumptions
- ❑ Nuclear/Electronic Recoil to Detector Response
- ❑ XENON1T Results and Prospect
- ❑ Other Selected Searches from XENON Experiment
  - Effective Field Theory
  - Xe-124 Double Electron Capture

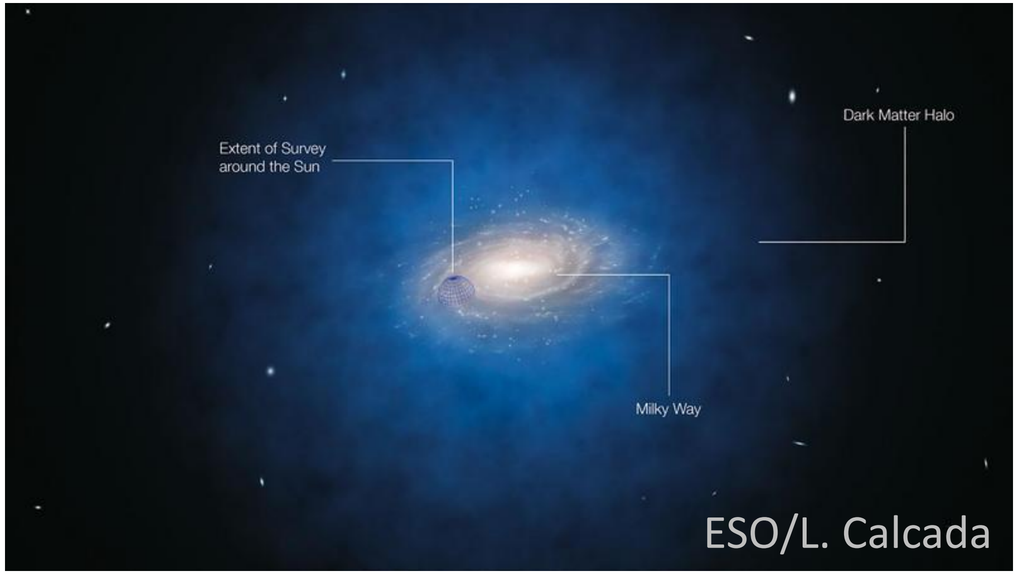
“Standard” Dark Matter Halo Assumptions

Differential rate

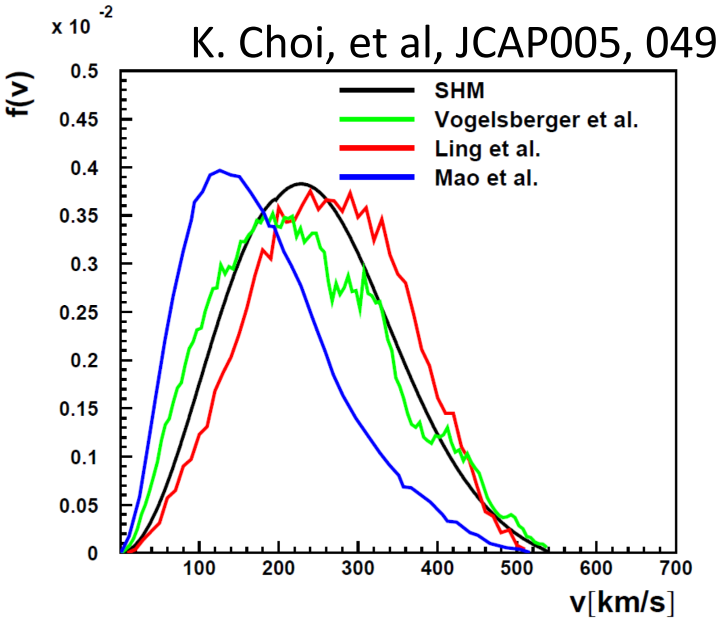
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_N m_\chi} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_R} dv$$

- ρ_0: DM density near Sun, 0.3 GeV/cm^3
- *f(v)* : Maxwell distribution with v_0 = 220 km/s
- v_{esc}: DM escape velocity from Milky Way, 544 km/s

No uncertainty included in our results



K. Choi, et al, JCAP005, 049 (2014)



"Standard" WIMP-Nucleus Interaction

Simplest assumption: spin-independent (SI) interaction

$$\frac{d\sigma_{SI}}{dq^2} = \frac{4}{\pi}\mu_{\chi N}^2 \left[Z f_p + (A-Z) f_n\right]^2 F^2(q)$$

"Standard" assumptions

- $f_p = f_n$
- $F(q)$: Helm form factor
  - Loss of coherence at higher q
  - Uniformly distributed nucleons

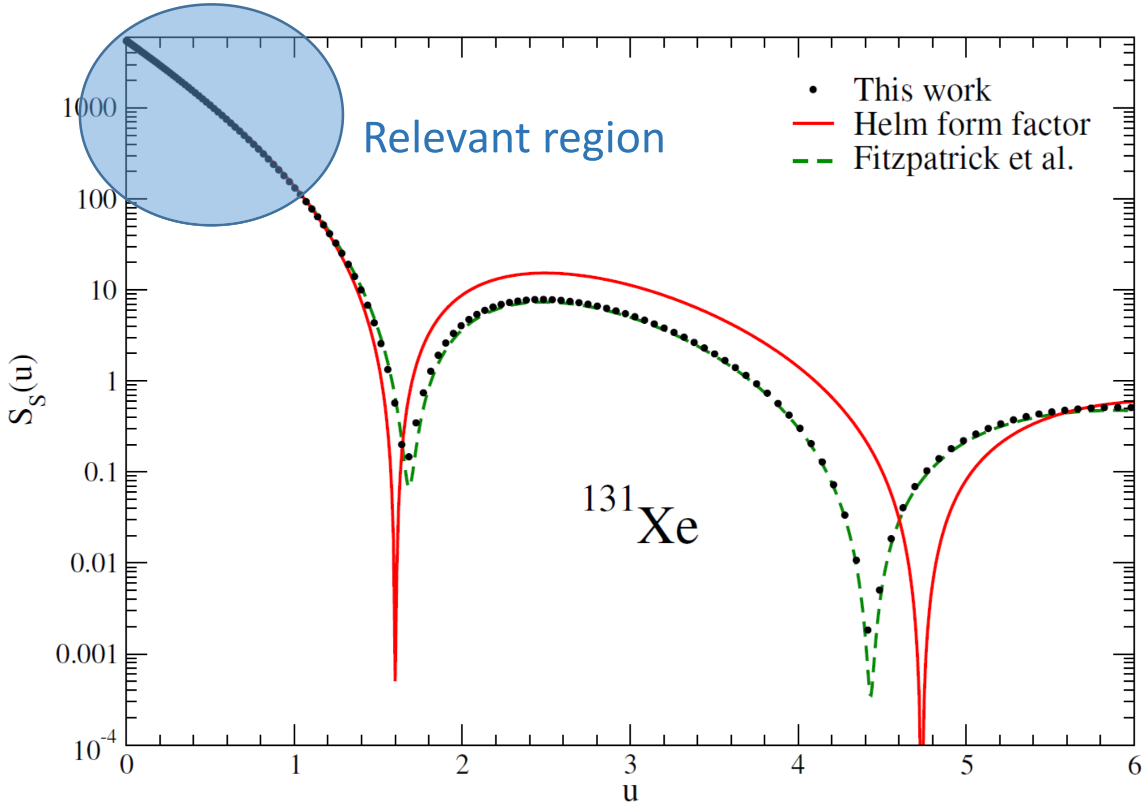
$$F(qr_n) = 3\frac{j_1(qr_n)}{qr_n} \times e^{-(qs)^2/2}$$

nuclear radius: $r_n{}^2 = c^2 + \frac{7}{3}\pi^2 a^2 - 5s^2$ $\quad a \simeq 0.52$ fm, $c \simeq 1.23 A^{1/3} - 0.60$ fm

skin thickness: $s = 1.0$ fm

Parameter choice from Lewin, Smith (1996)

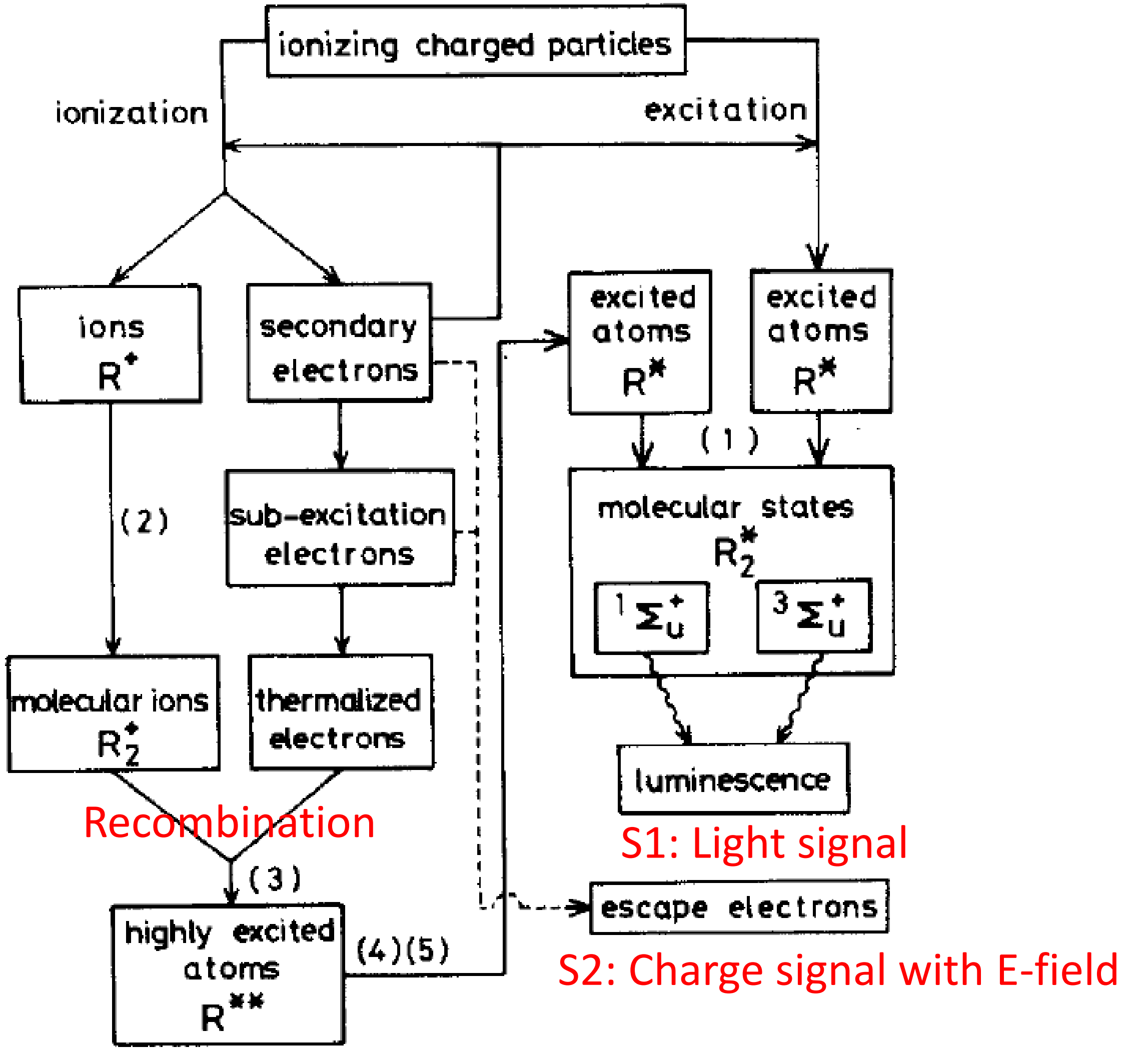
L. Vietze, et al, Phys. Rev.D91, 043520 (2015)



Electronic Recoil to Excitation/Ionization

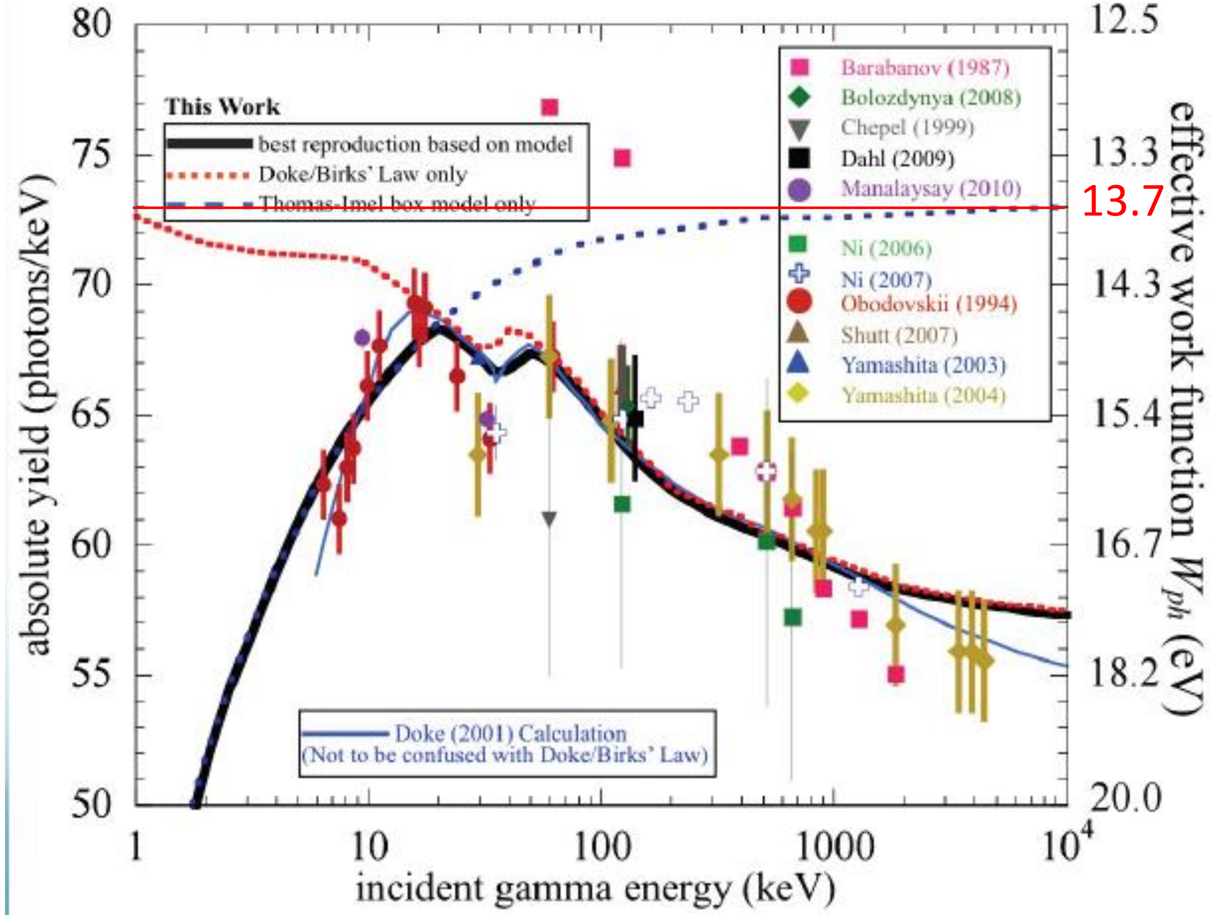
XENON Dark Matter Project

Noble gas response; M. Suzuki, 1982



Zero-field Scintillation yield

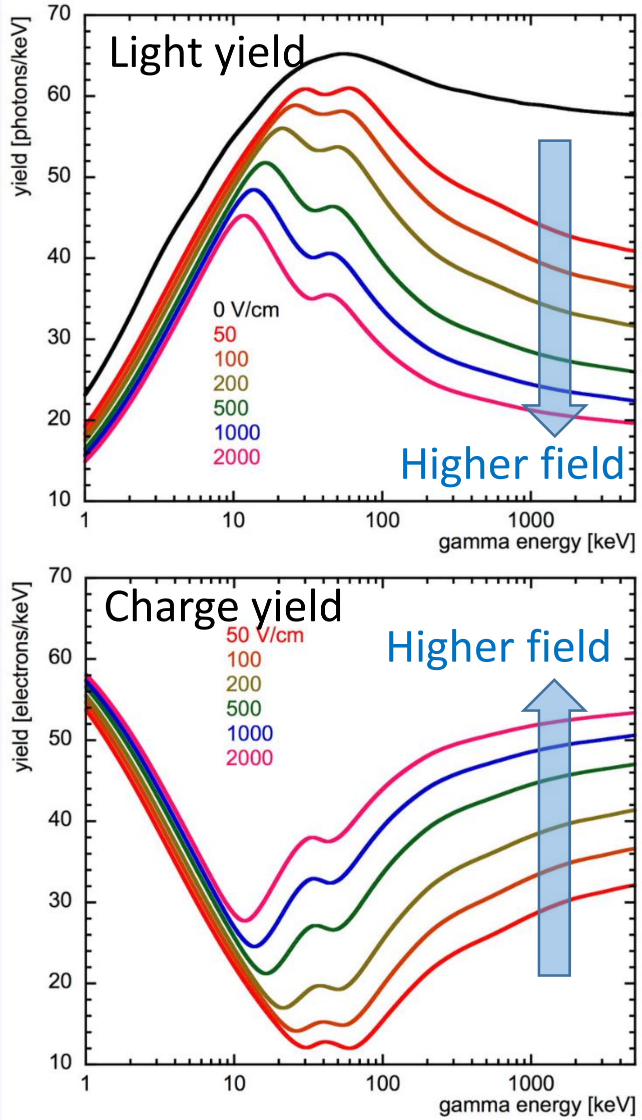
NEST model; M. Szdagis, et al 2011



- Smaller number of e^-/Xe^+ in a box (r_{th}~5 μm) at lower energy
- Smaller dE/dx at higher energy

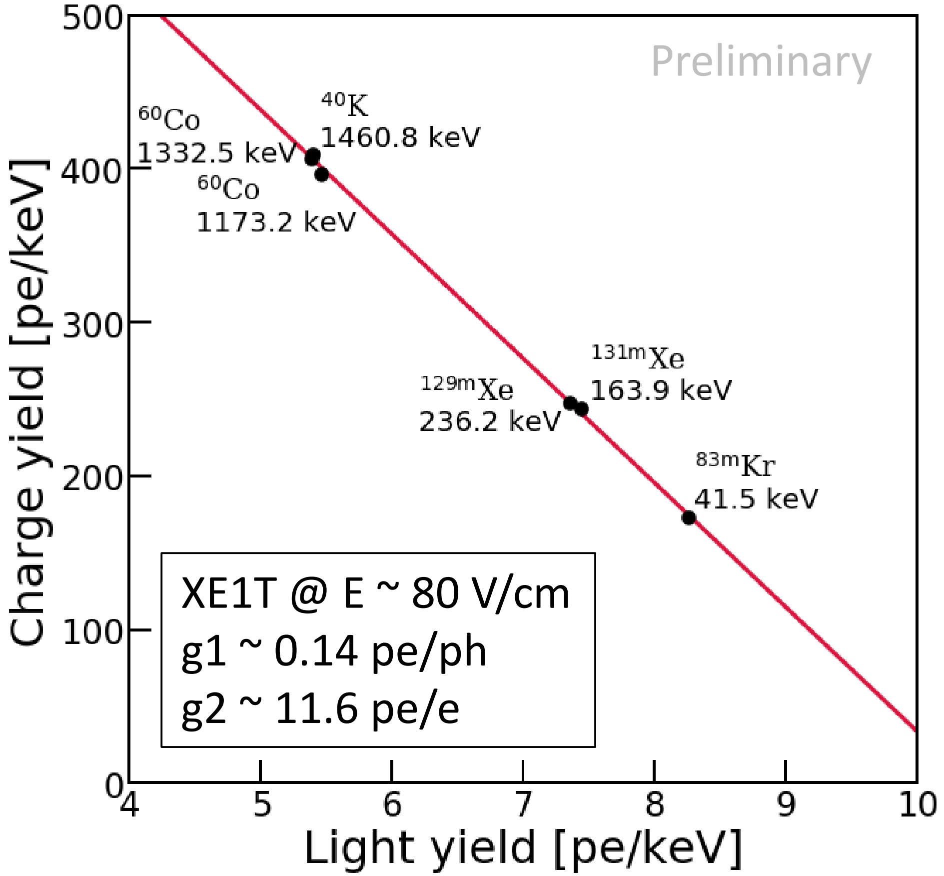
ER: Light and Charge Yields with E-Field

NEST: Empirical parameterization on E-field dependence



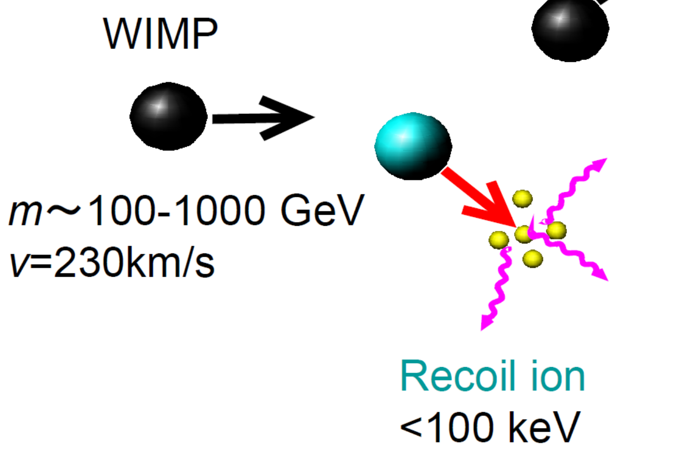
$$E = (n_{ph} + n_e)W = (\frac{S1}{g_1} + \frac{S2}{g_2})W$$

W = 13.7 eV

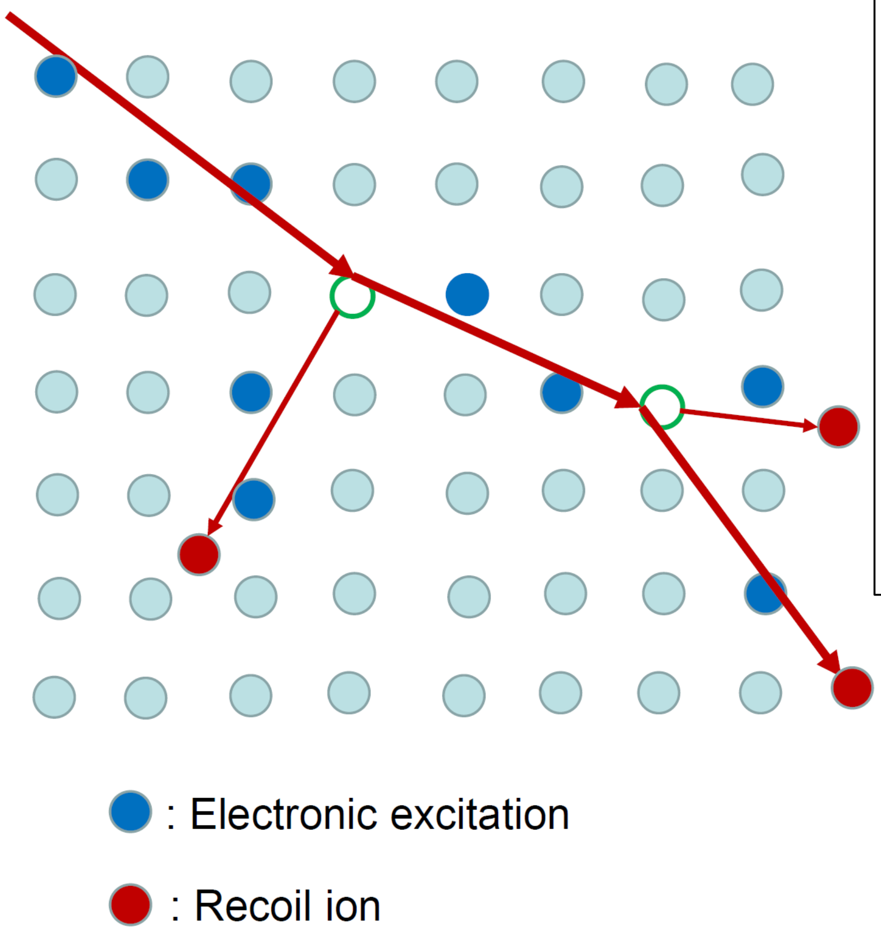


Nuclear Recoil Quenching

Lindhard factor $q_{nc} = \eta/\varepsilon$



Collision cascades



Comprehensive picture by A. Hitachi

1, Nuclear quenching:

$$q = \frac{Electronic\ energy\ (detectable)}{Initial\ recoil\ energy}$$

2, Bi-excitonic quenching:

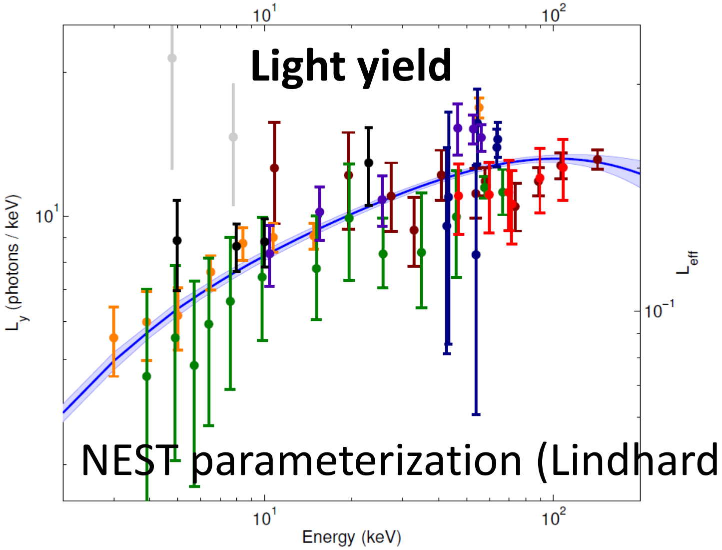
One visible element from two excitons due to dense energy deposition

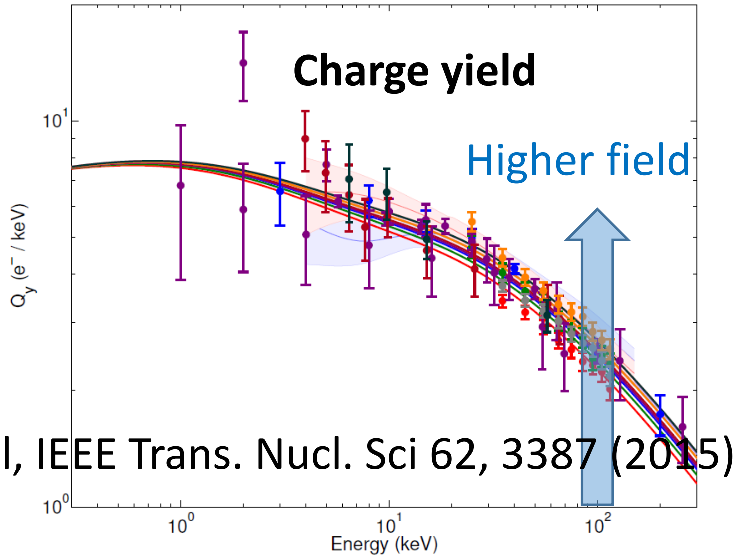
$Xe^* + Xe^* \rightarrow Xe + Xe^+ + e^-$

NR: 10 keV recoil ion/atom range: ~20 nm

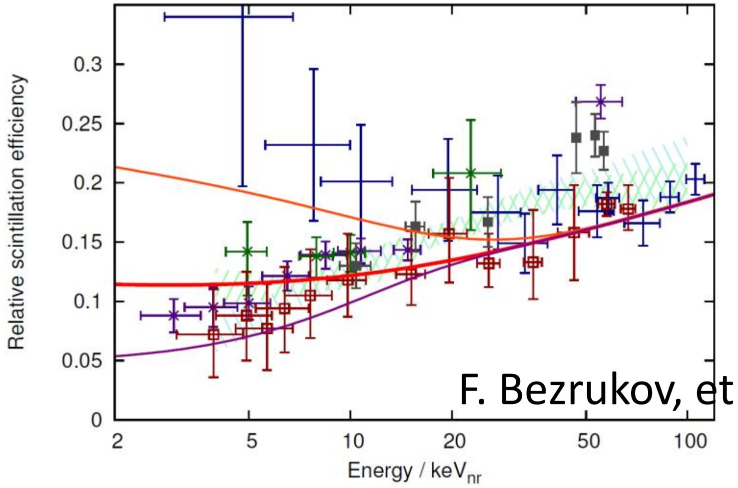
ER: 10 keV recoil electron range: ~2 µm

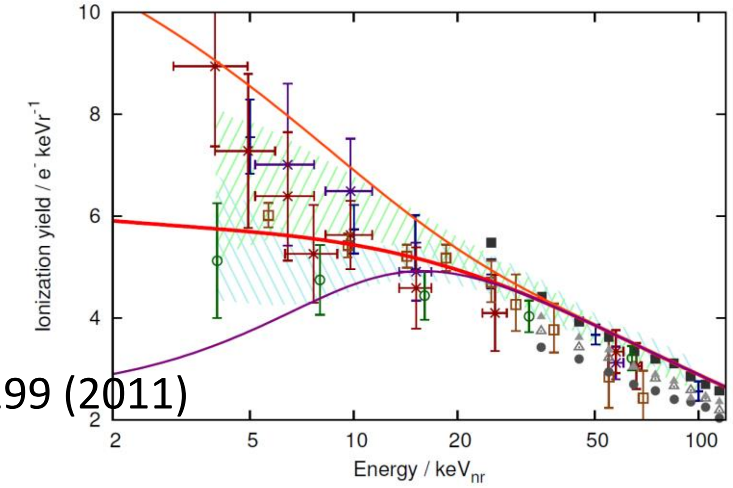
NR: Light and Charge Yields





NEST parameterization (Lindhard-based); B. Lenardo, et al, IEEE Trans. Nucl. Sci 62, 3387 (2015)



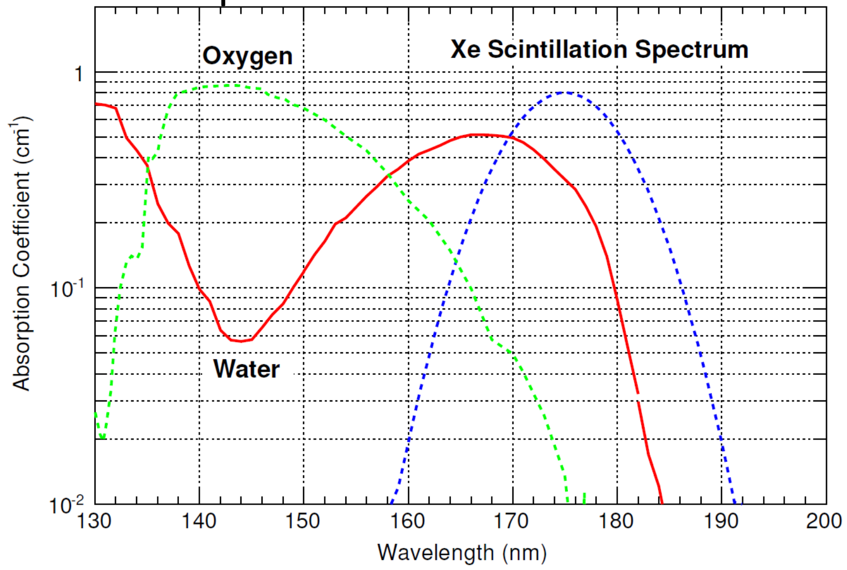


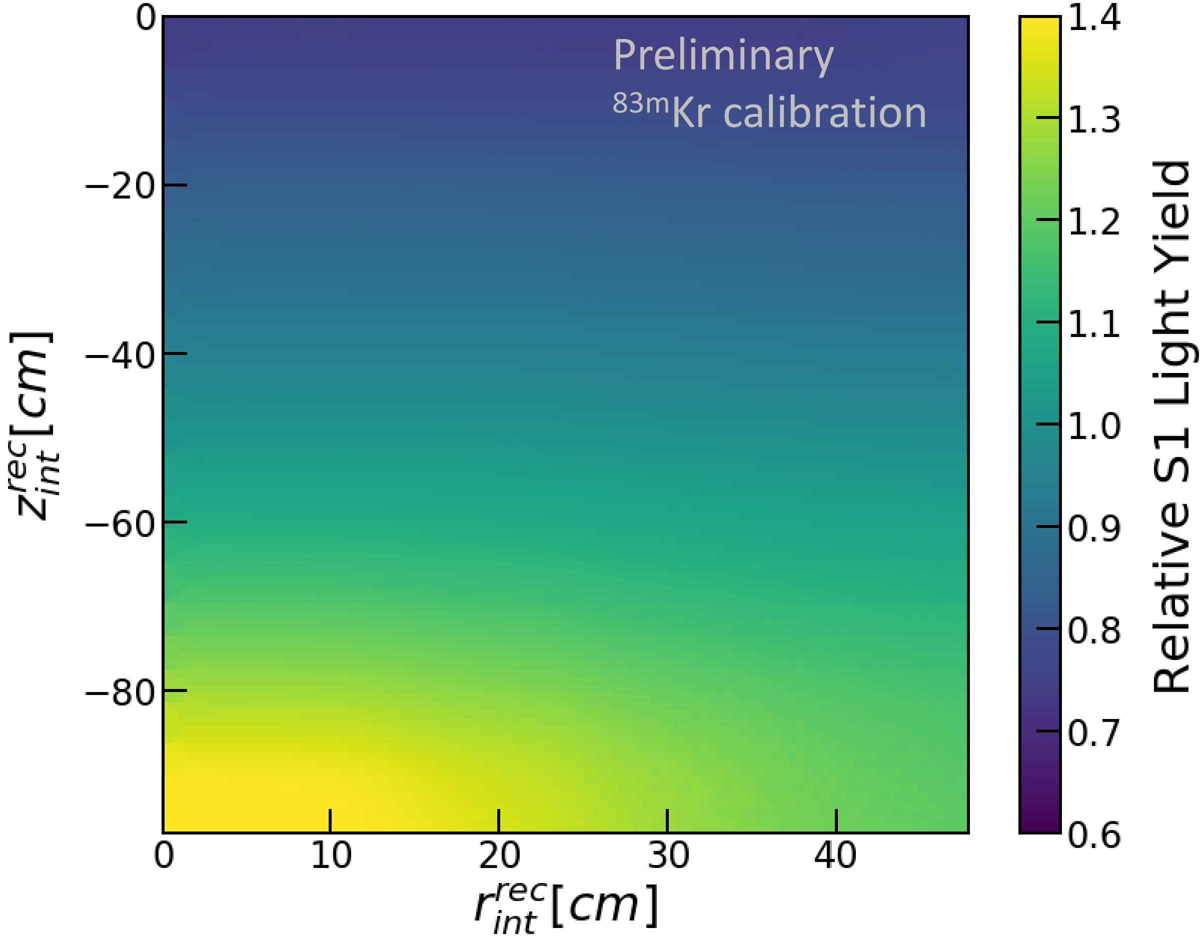
F. Bezrukov, et al, Astropart. Phys. 35, 199 (2011)

Light Signal (S1) Detections

- Scintillation (178 nm) from Xe_2^* is transparent in Xe
  - Absorption length ~50 m
  - Can be absorbed by impurities
- Teflon reflectivity ~99 %
- Reflection at GXe/LXe interface
- Can be absorbed by electrodes

V. Chepel 2013

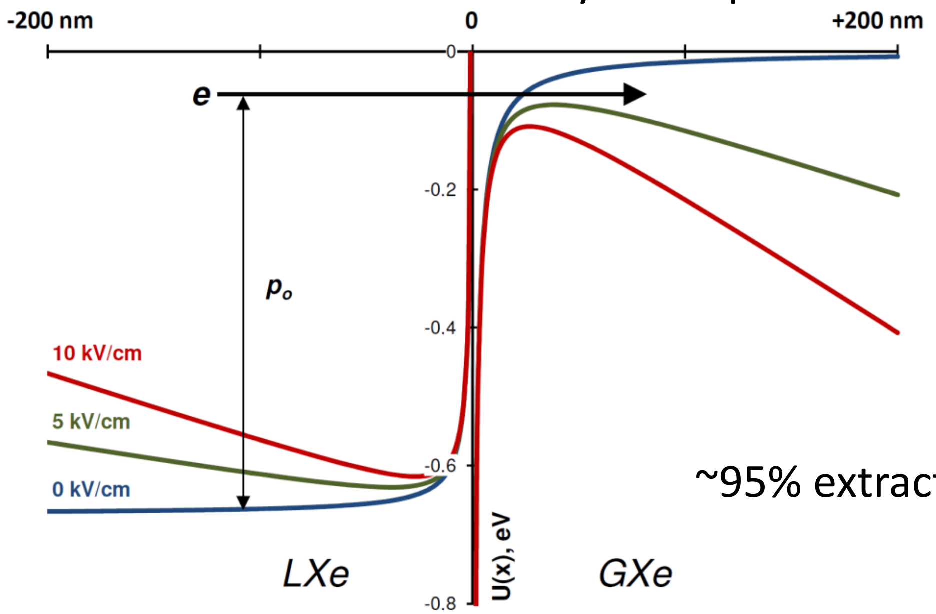




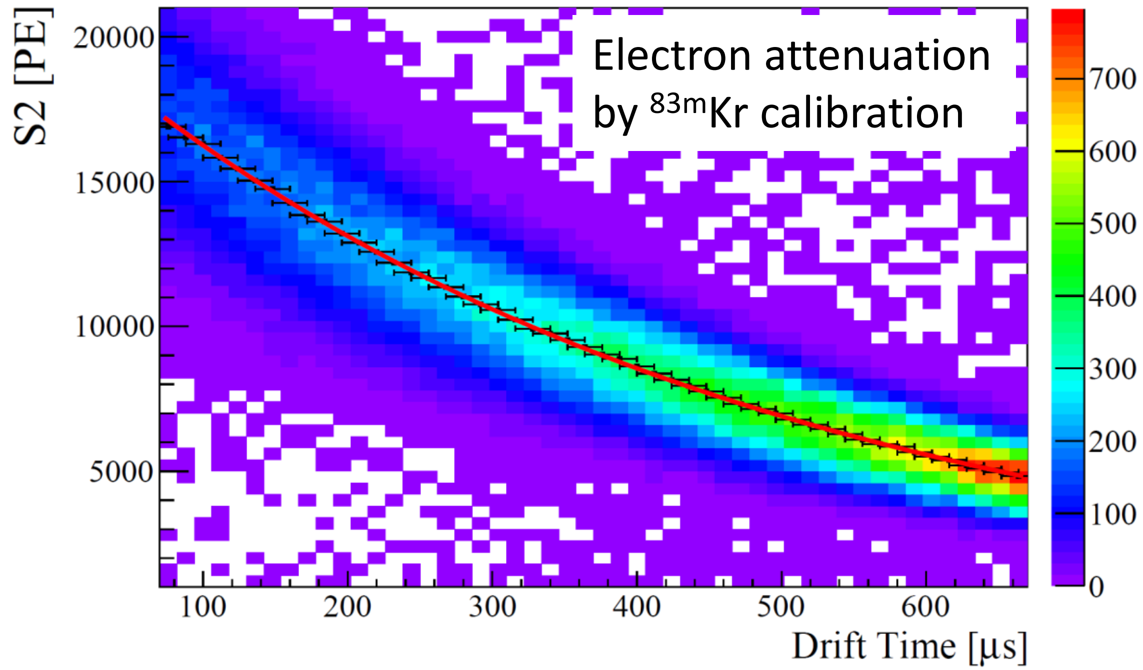
Charge Signal (S2) Detection

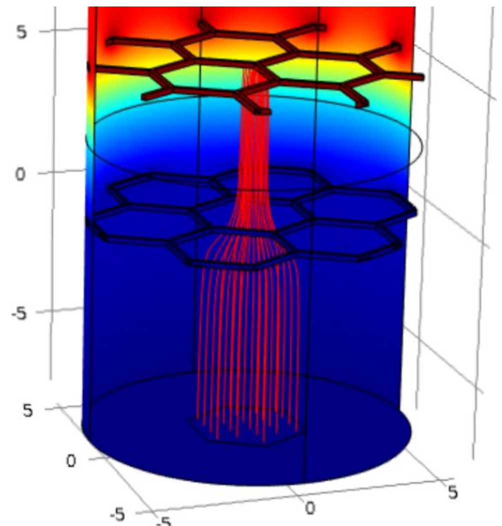
1. Applied field moves electrons up (Xe-ion down)
2. Consecutive elastic collisions with Xe atom
3. Constant drift speed & diffusion
4. Electronegative impurity captures electrons
5. Electrons are extracted into GXe through dielectric barrier
6. Consecutive inelastic collisions (excitation) in GXe

Potential by V. Chepel 2013

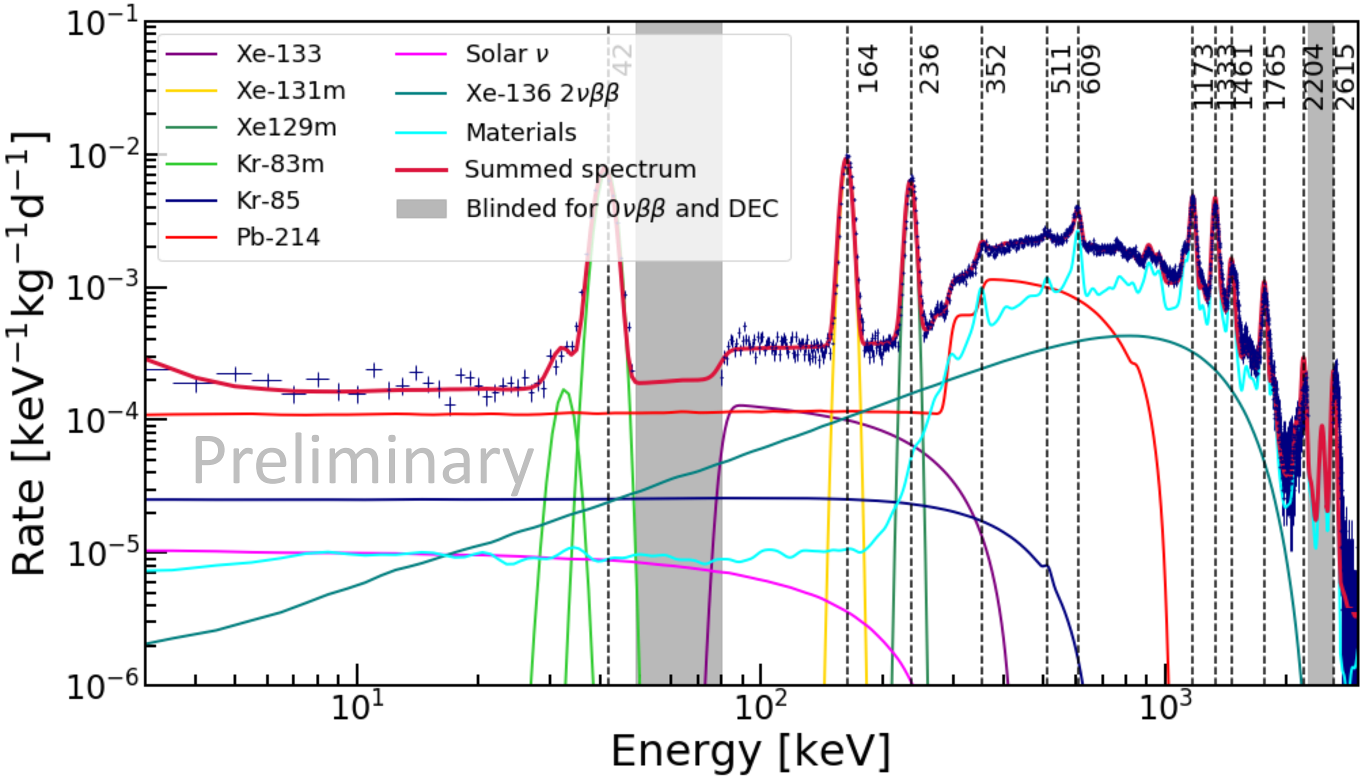


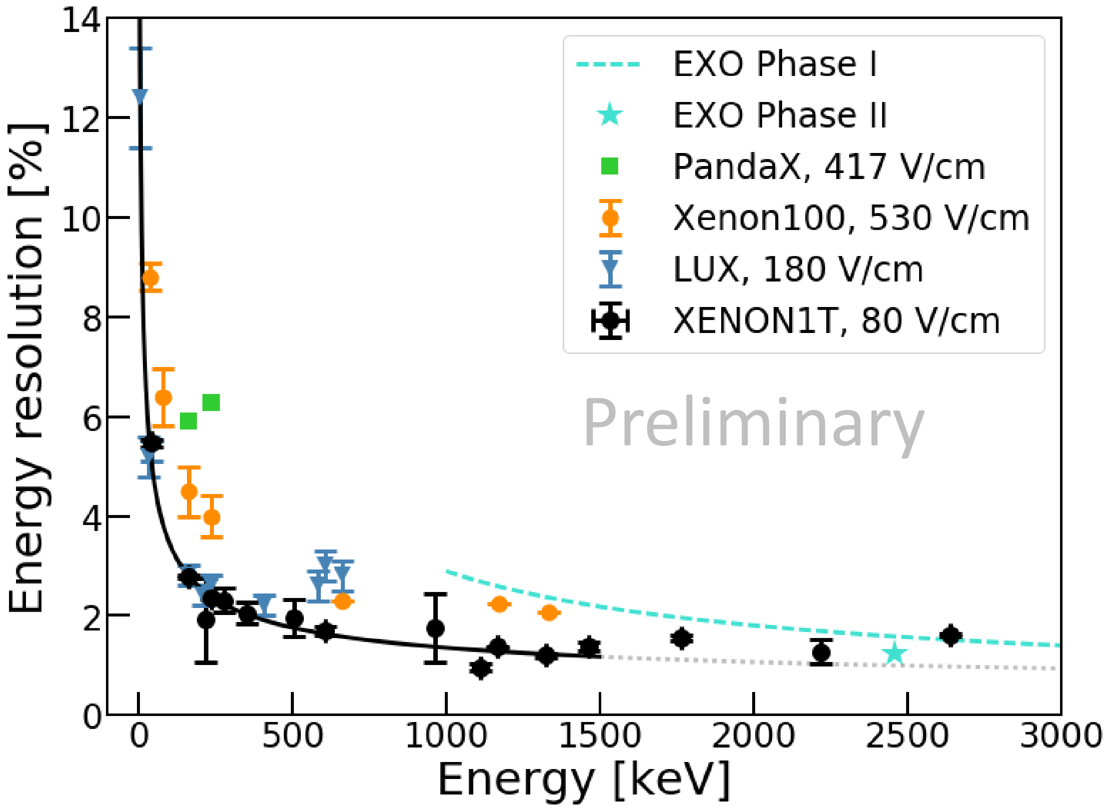
~95% extraction in XE1T





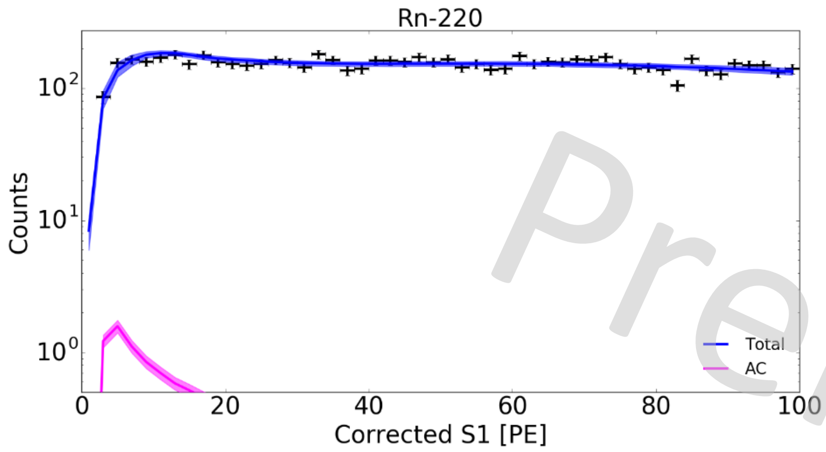
Energy Spectrum and Resolution



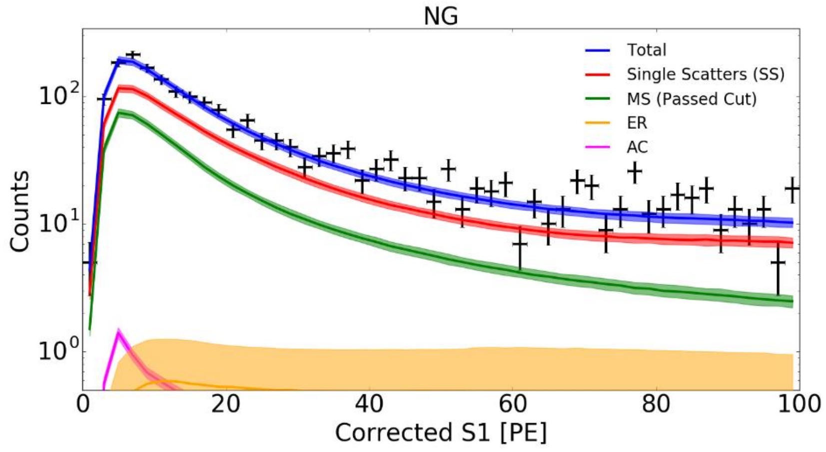


In-situ Electronic/Nuclear Calibration Fittings

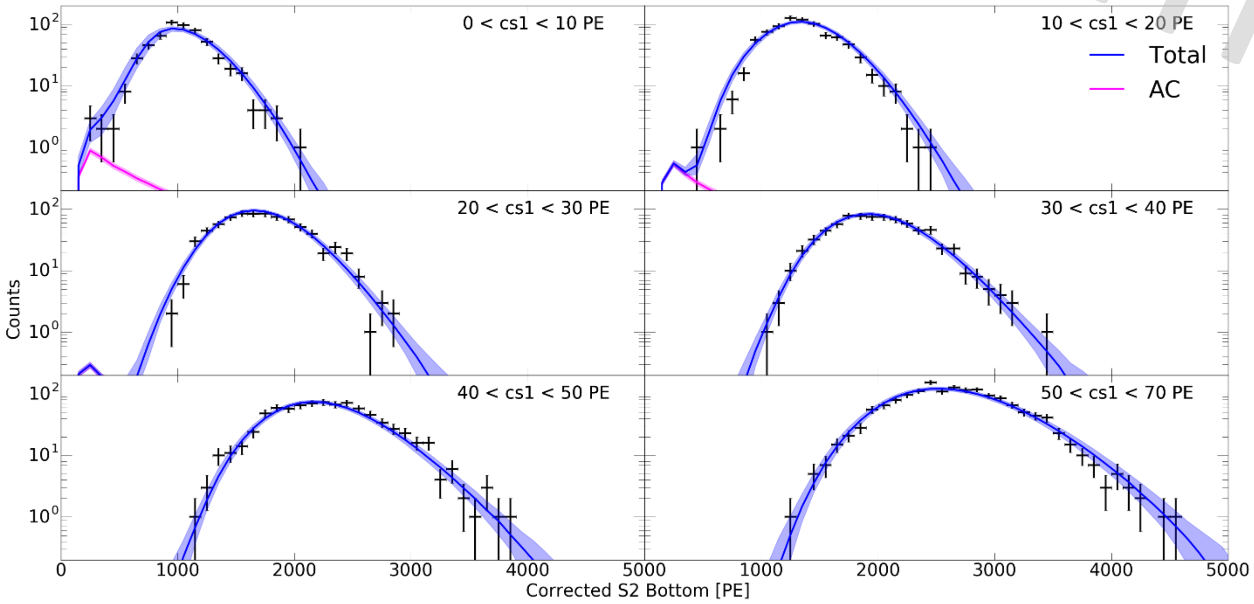
Electronic Recoil

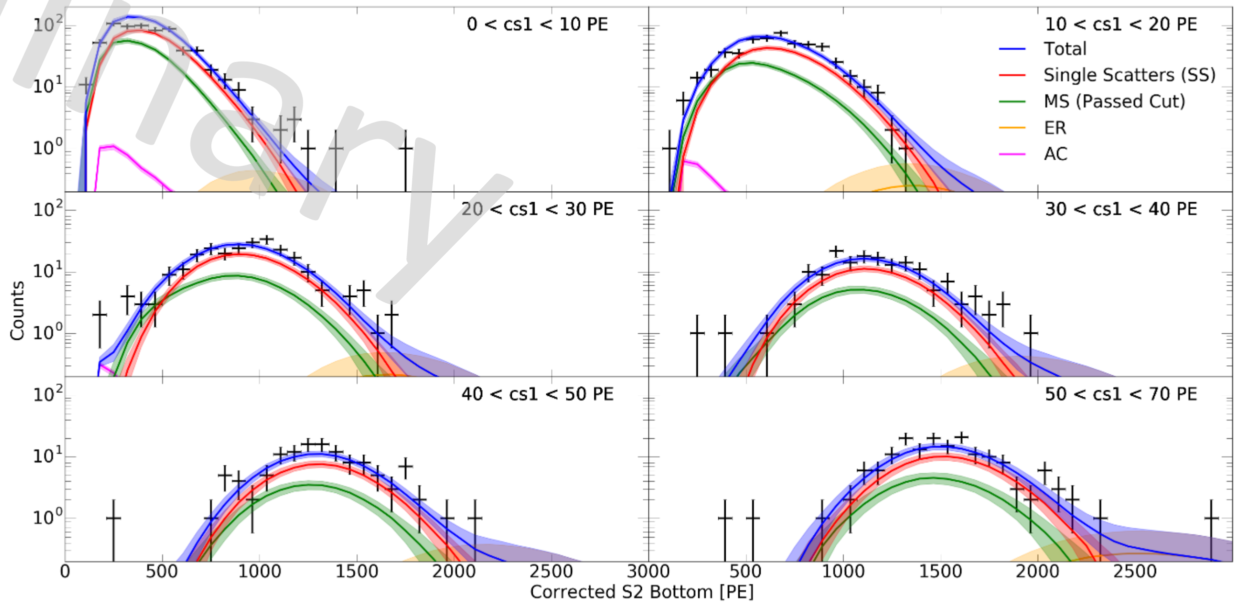


Nuclear Recoil

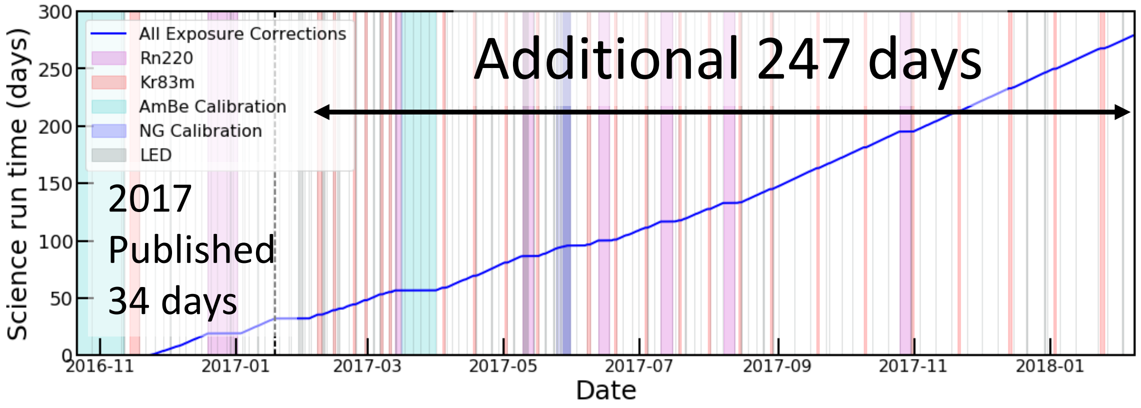


Preliminary





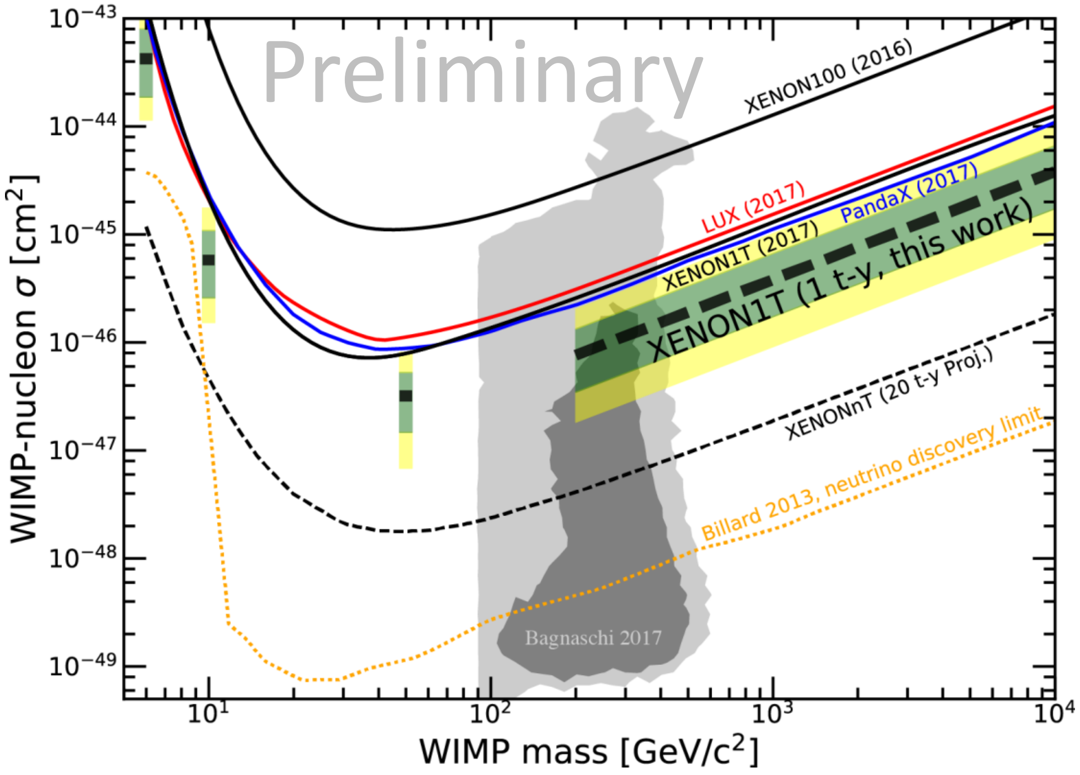
XENON1T Prospect



Background expectation in the 247-day data

- S1: [3,70] PE ↔ NR: ~[5,40] keV, ER: ~[1.5,10] keV
- ER/NR discrimination: NR [-2σ, median]

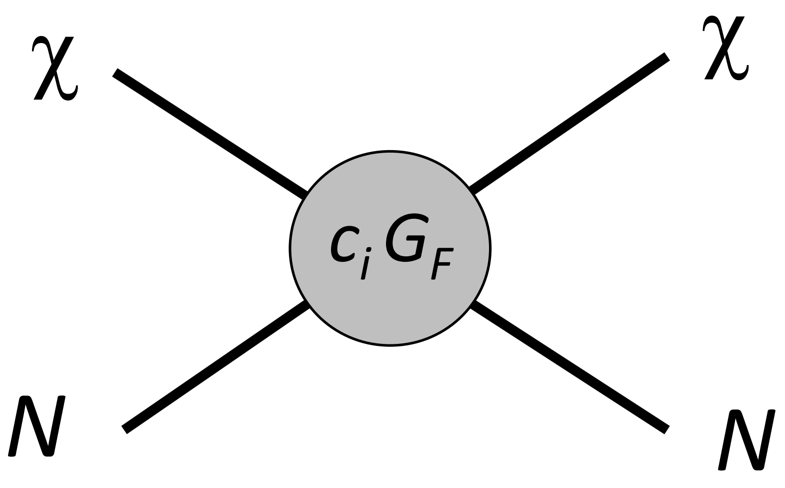
Source	1.3 ton	Inner 1 ton
ER	1.8 ± 0.2	1.4 ± 0.2
Radiogenic neutron	0.6 ± 0.3	0.4 ± 0.2
CNNS	0.04 ± 0.01	0.03 ± 0.01
Accidental coincidence	0.2 ± 0.1	0.1
Surface	6.1 ± 0.3	0.1
Total	**8.7 ± 0.5**	**2.0 ± 0.3**



Factor ~3 improvement expected

Effective Field Theory (EFT)

Fitzpatrick, et al, JCAP 1302, 004 (2013)
Anand, et al, Phys.Rev. C89, 065501 (2014)



Formulation includes

- Spin independent (SI)
- Spin dependent (SD)
- Angular-momentum dependent
- Spin and angular-momentum dependent

$$\mathcal{O}_1 = 1_\chi 1_N \quad \text{SI}$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \quad \text{SD}$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \left(\frac{\vec{q}}{m_N}\right)$$

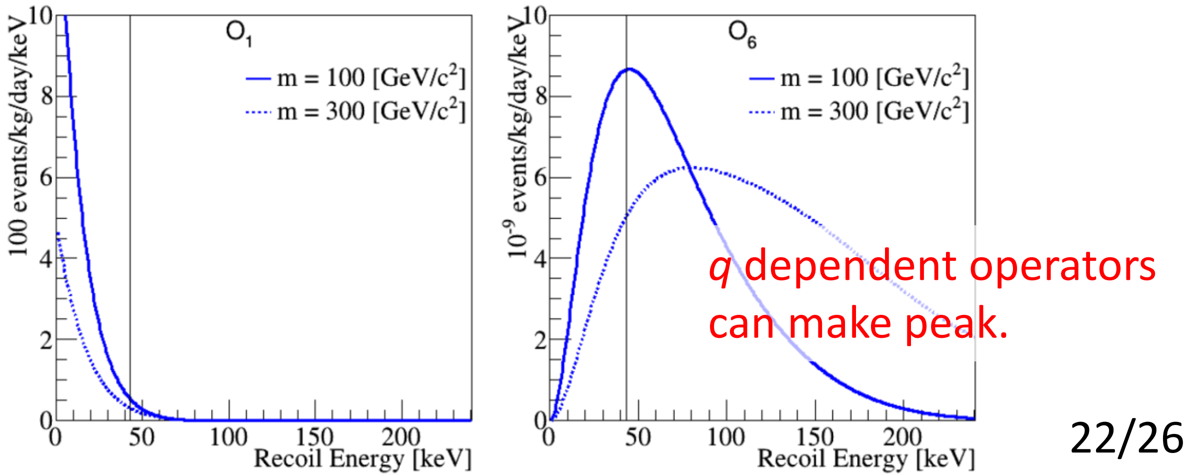
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp\right)$$

$$\mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}^\perp\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

$$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}^\perp\right)$$

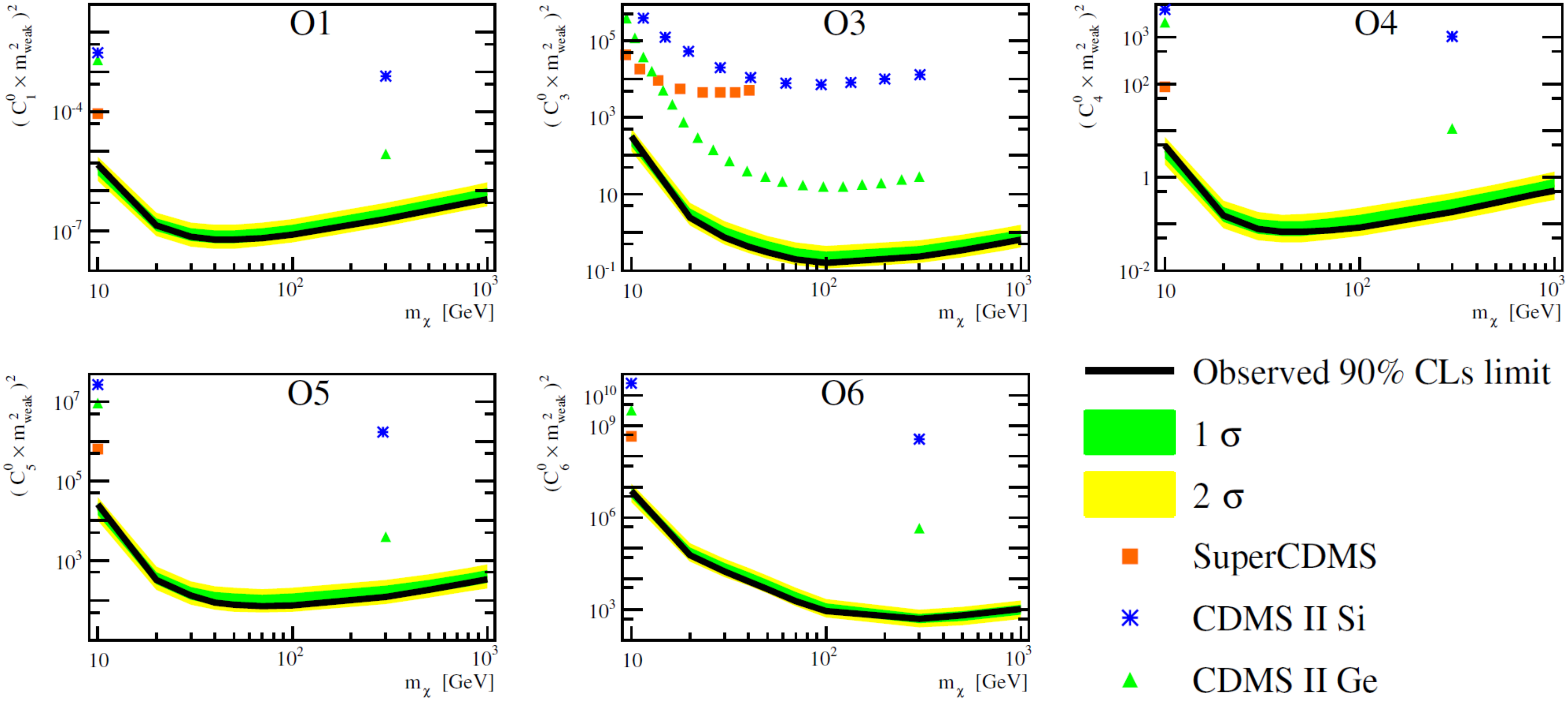
$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$



XENON100 Elastic Scattering Result on EFT

Spin-Independent

Spin-dependent



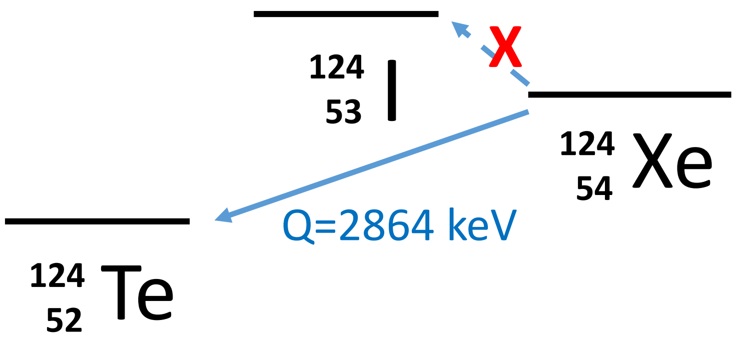
Results expressed relative to SM weak scale

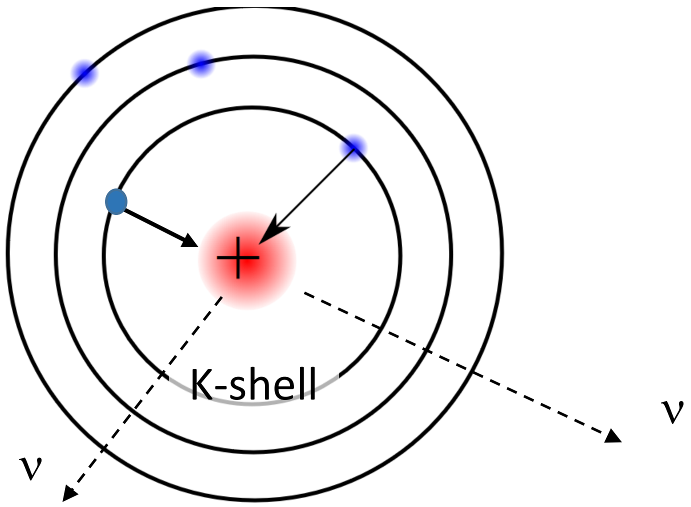
Complete results at Phys.Rev.D96, 042004 (2017)

^{124}Xe Double Electron Capture Search

- Two-neutrino double electron capture (2ν2EC) observed
  1. ^{130}Ba : $T_{1/2} = 2.2 \times 10^{21}$ years
  2. ^{78}Kr : $T_{1/2} = 9.2 \times 10^{21}$ years

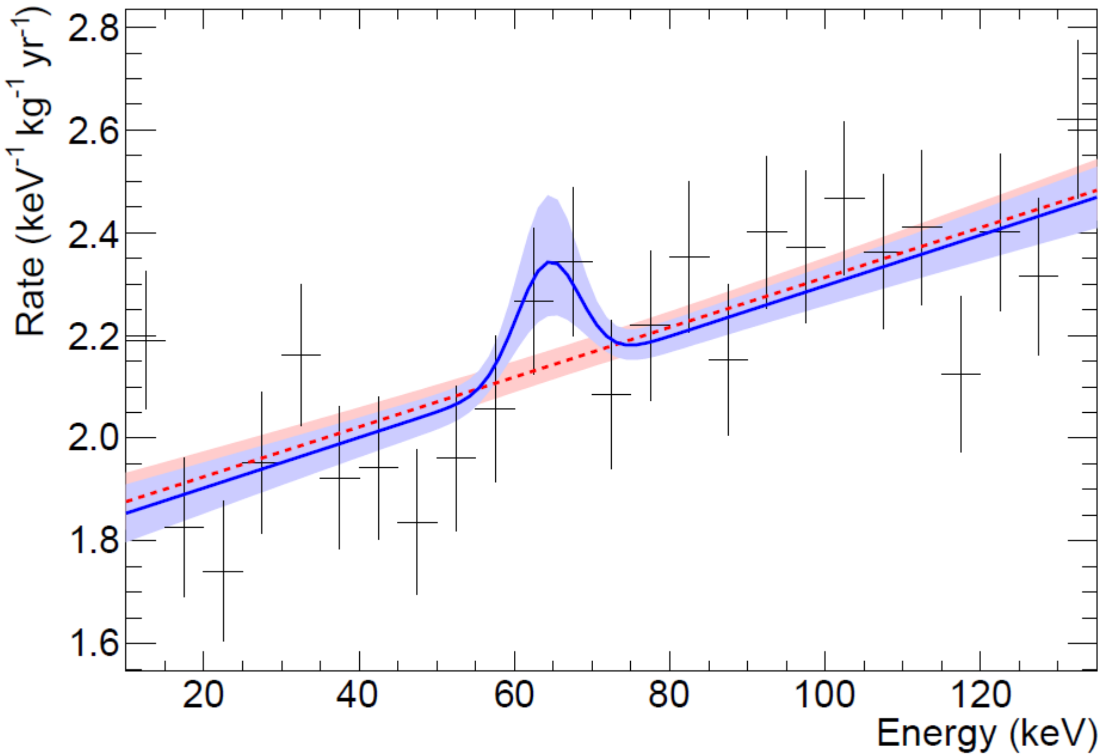
- ^{124}Xe (0.1 % NA) can decay into ^{124}Te through 2ν2EC
  - Highest Q-value out of 35 candidates
  - **Signature: 64.3 keV** (X-ray + Auger electron)
  - Theoretical calculations: $T_{1/2} = 10^{21} - 10^{24}$ years



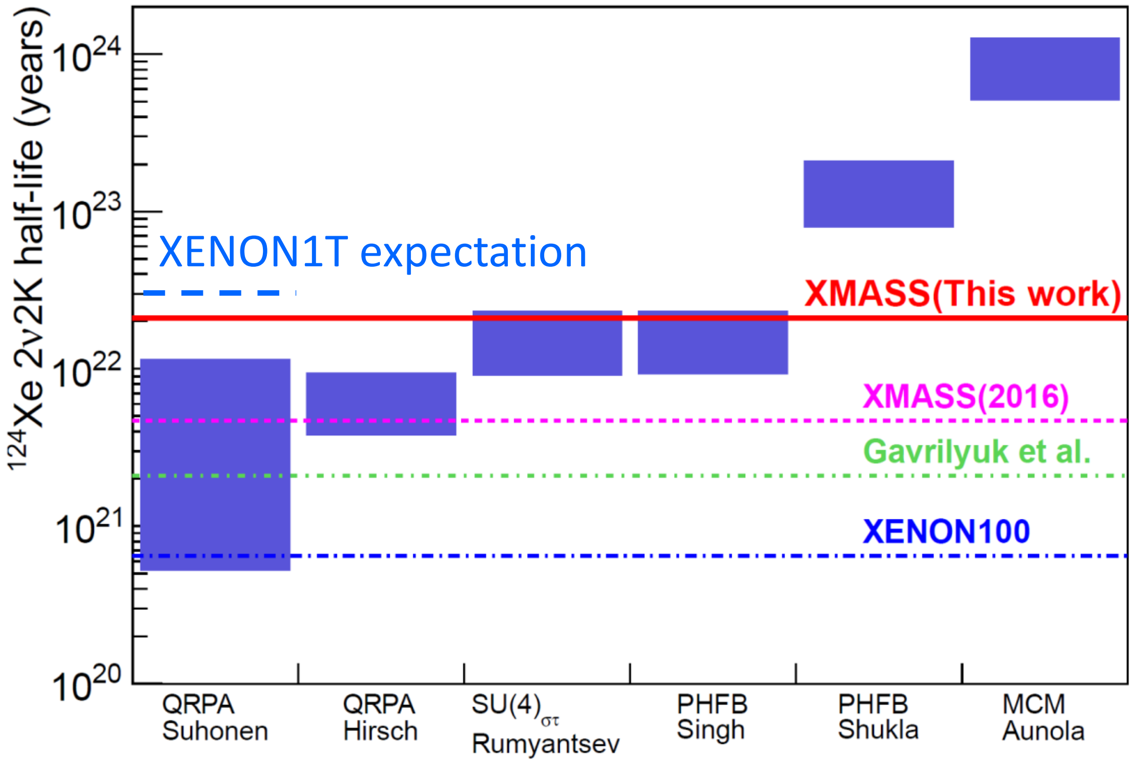


^{124}Xe 2ν2EC Search XENON100 Result

225 days, 29 g of ^{124}Xe (out of 34 kg xenon)



XMASS (2018): arXiv:1801.0325



$T_{1/2} > 6.5 \times 10^{20}$ years @ 90 % C.L.

Phys. Rev. C95, 024605 (2017)

Summary

- Physics description of energy response in LXe is not complete
  - Need help from theorists
  - Still good parameterization, thanks to *in-situ* calibrations

- New XENON1T SI search result coming soon, and more on later

- XENONnT (~6 ton target) will be ready in 2019