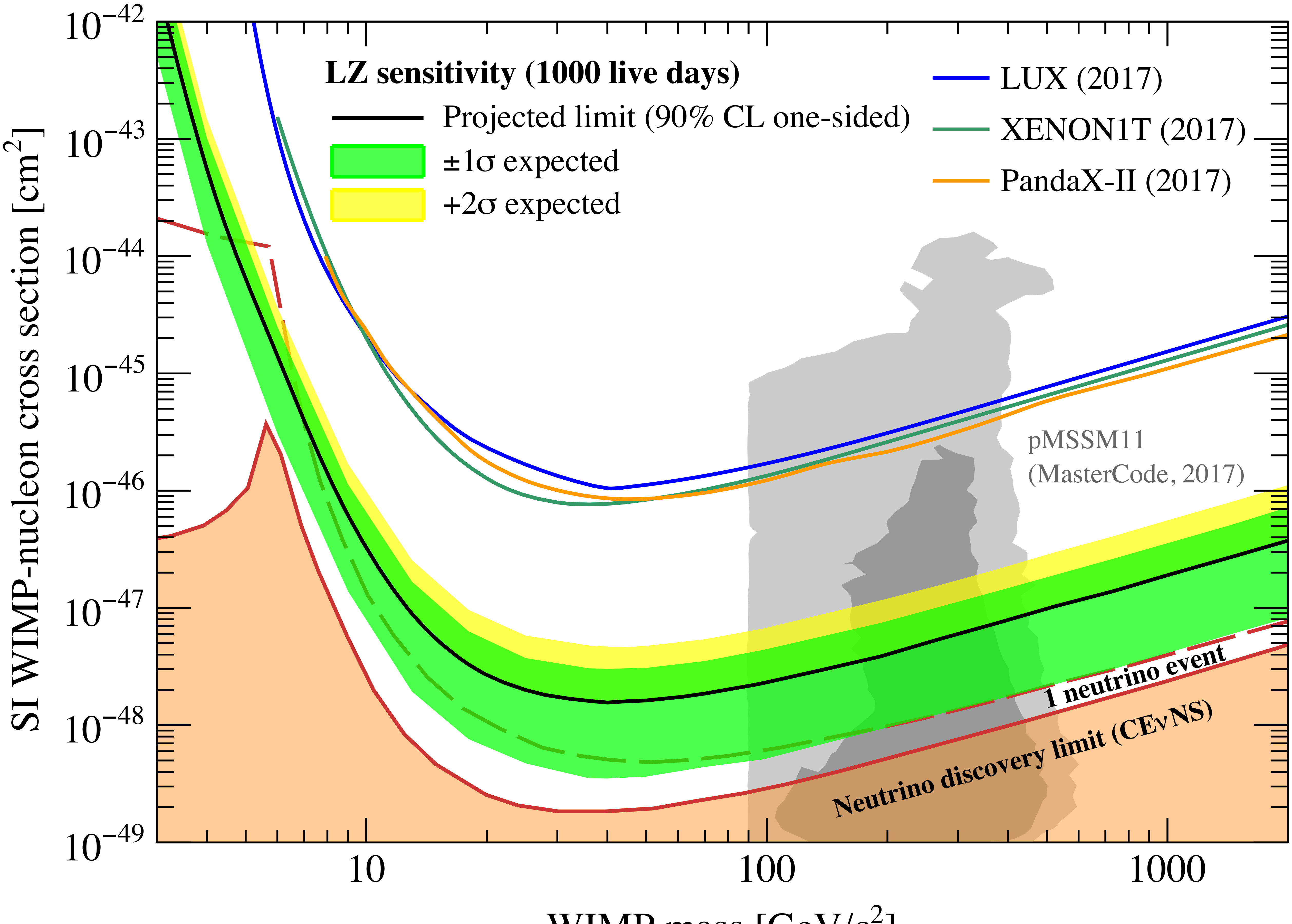
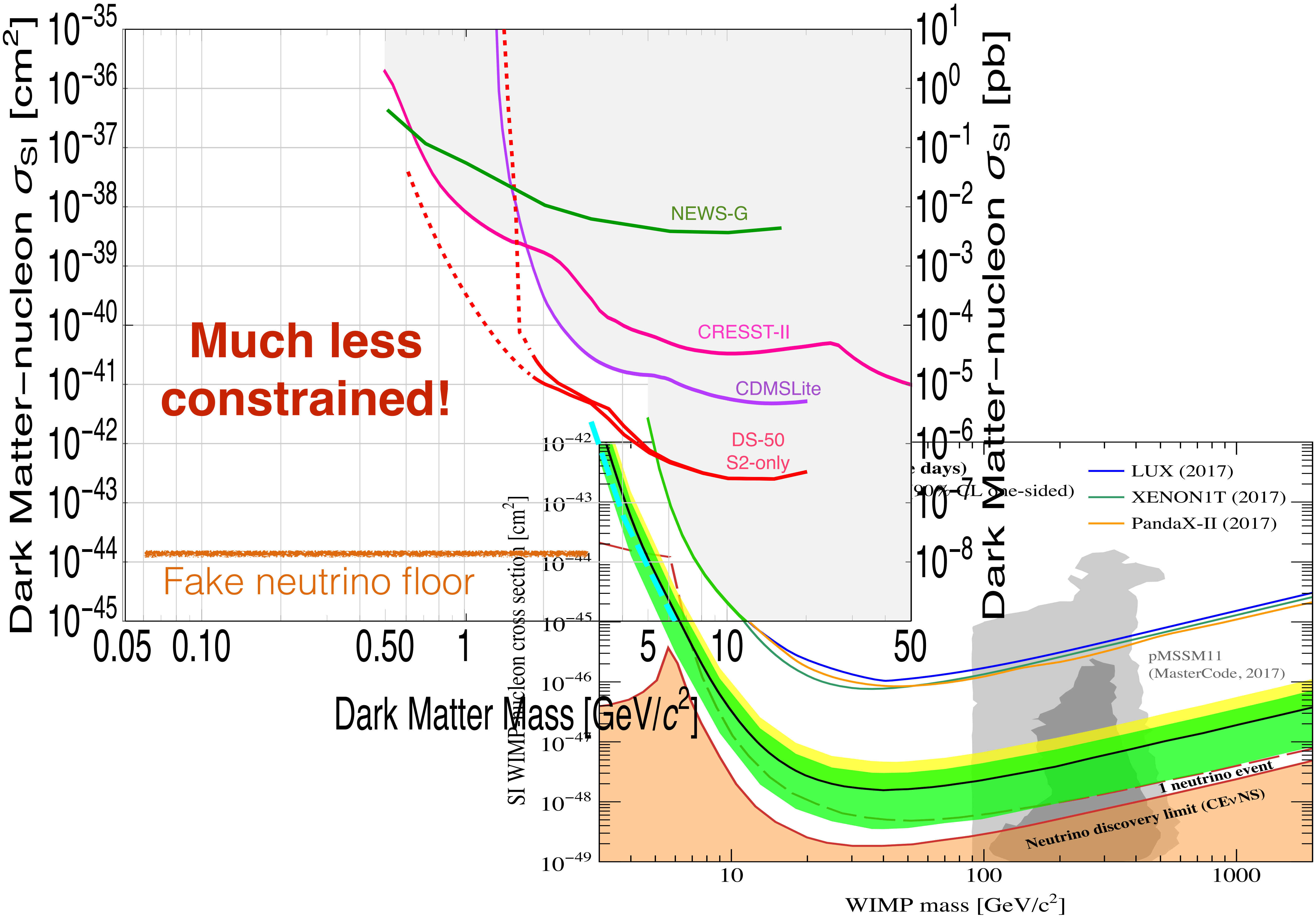
# Doping liquid xenon with helium

Hugh Lippincott, Fermilab

IDM
July 22-27, 2018



LZ sensitivity (1000 live days)
Projected limit (90% CL one-sided)
±1σ expected
+2σ expected
LUX (2017)
XENON1T (2017)
PandaX-II (2017)
pMSSM11
(MasterCode, 2017)
1 neutrino event
Neutrino discovery limit (CEνNS)
SI WIMP-nucleon cross section [cm²]
WIMP mass [GeV/c²]
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10
100
1000


Much less constrained!
Fake neutrino floor
NEWS-G
CRESST-II
CDMSLite
DS-50
S2-only
Dark Matter−nucleon $\sigma_{SI}$ [cm$^2$]
Dark Matter−nucleon $\sigma_{SI}$ [pb]
Dark Matter Mass [GeV/$c^2$]
LUX (2017)
XENON1T (2017)
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1 neutrino event
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SI WIMP-nucleon cross section [cm$^2$]
WIMP mass [GeV/c$^2$]

# What do you need for low mass?

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2m_p^2} \times F^2(Q) \times \int_{v_m}^{v_{esc}} \frac{f(v)}{v} dv$$

$$v_m = \sqrt{Q m_N / 2 m_r^2} \qquad v_{esc} = 544\,\mathrm{km/s}\ \text{(current value)}$$

$m_N$ is mass of nucleus

$$m_r = \frac{m_N m_\chi}{m_N + m_\chi}$$

- Low threshold
- Low mass target (for better kinematic match to the dark matter mass)
    - For given $Q$, $v_m$ is minimized when $m_n = m_\chi$

# What do you need for low mass?

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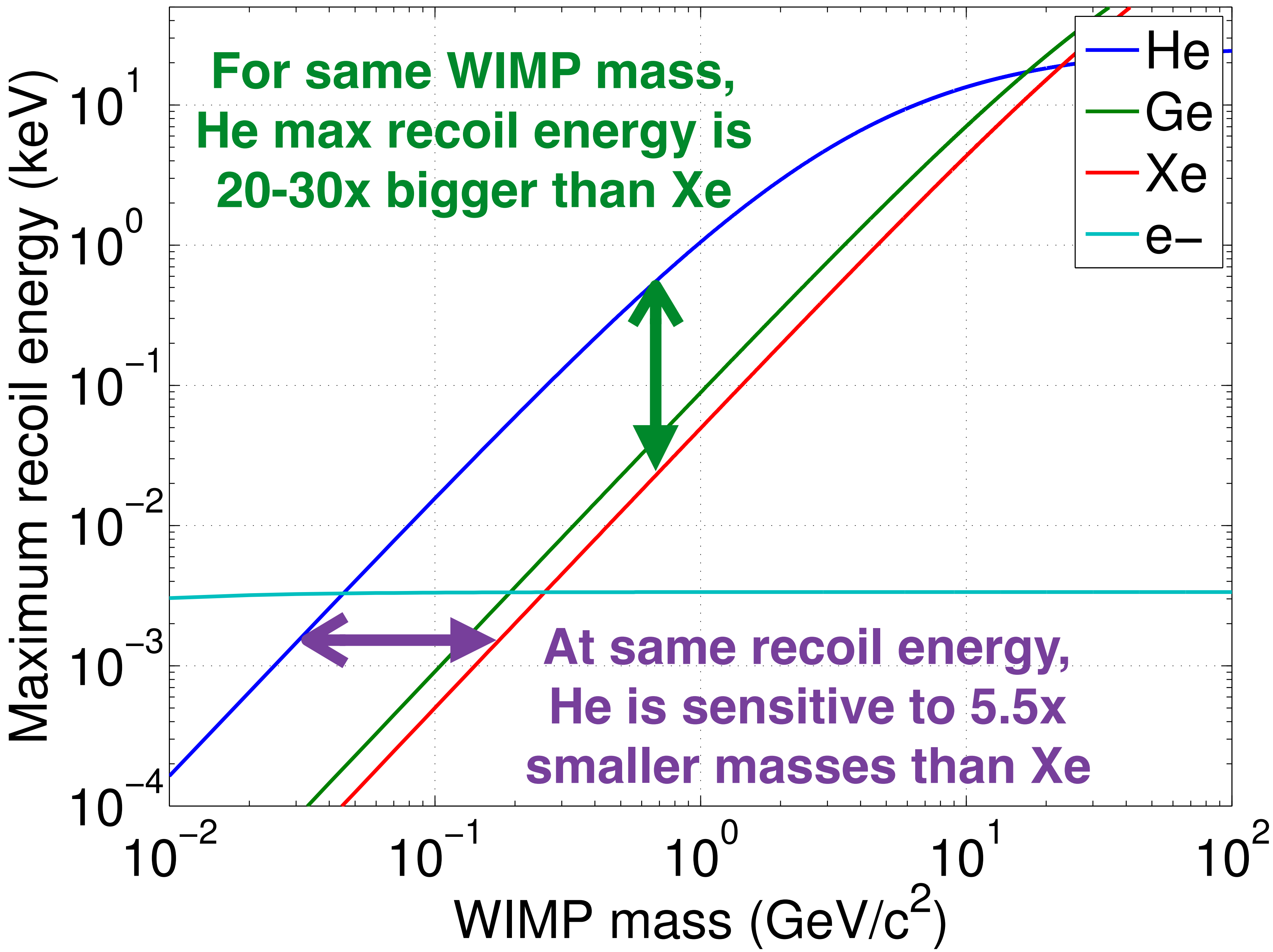
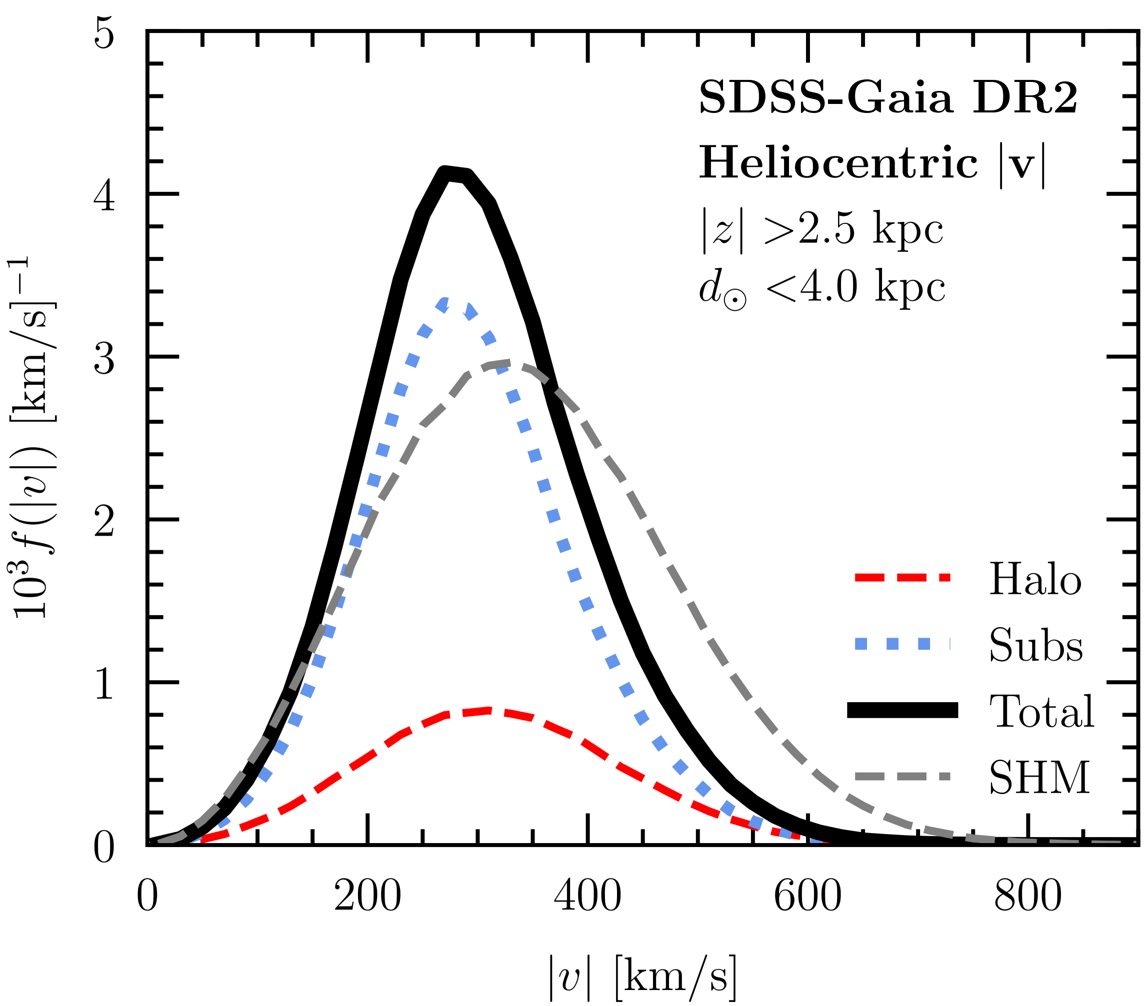
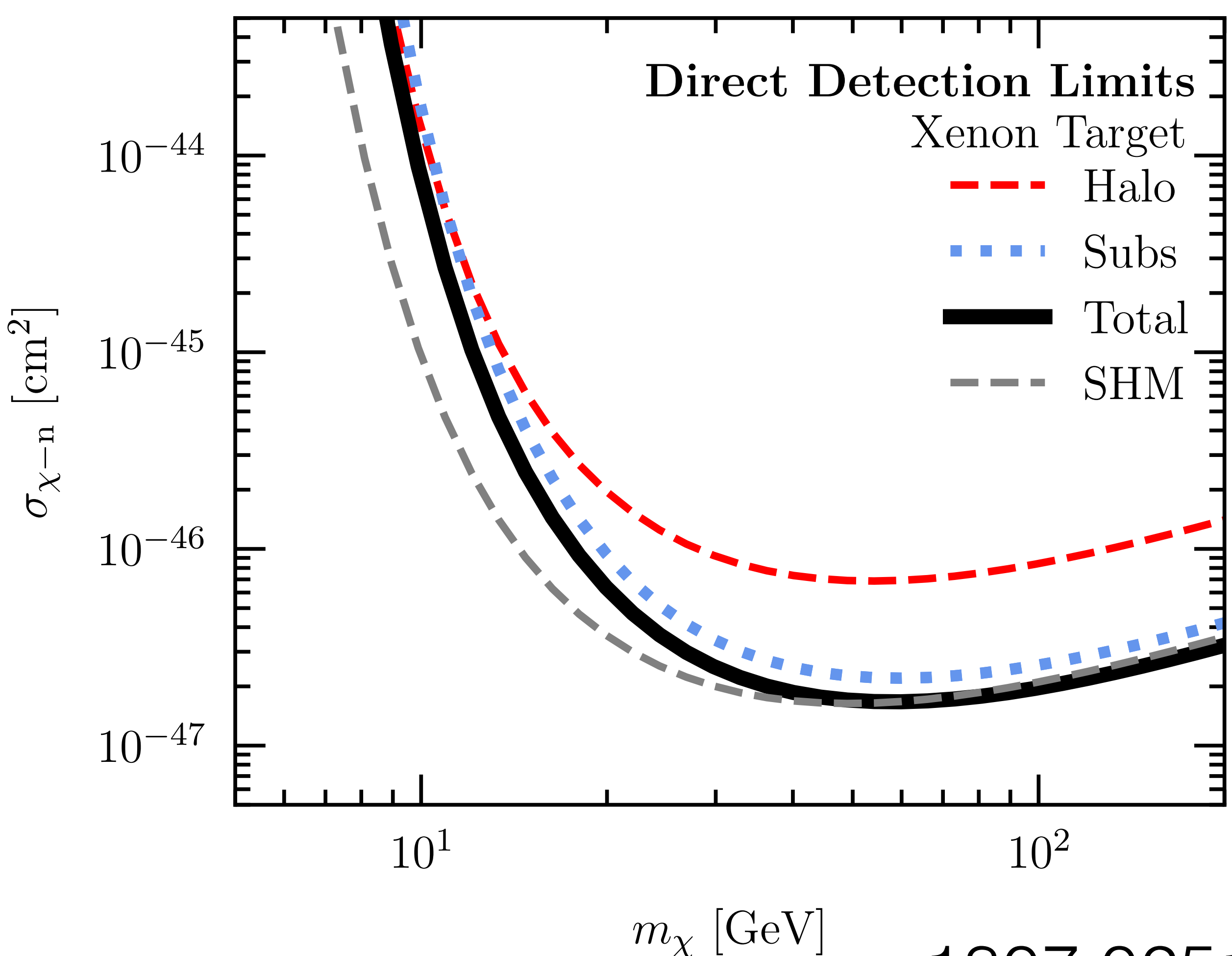


# Light targets less sensitive to halo uncertainty

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2m_p^2} \times F^2(Q) \times \int_{v_m}^{v_{esc}} \frac{f(v)}{v} dv$$

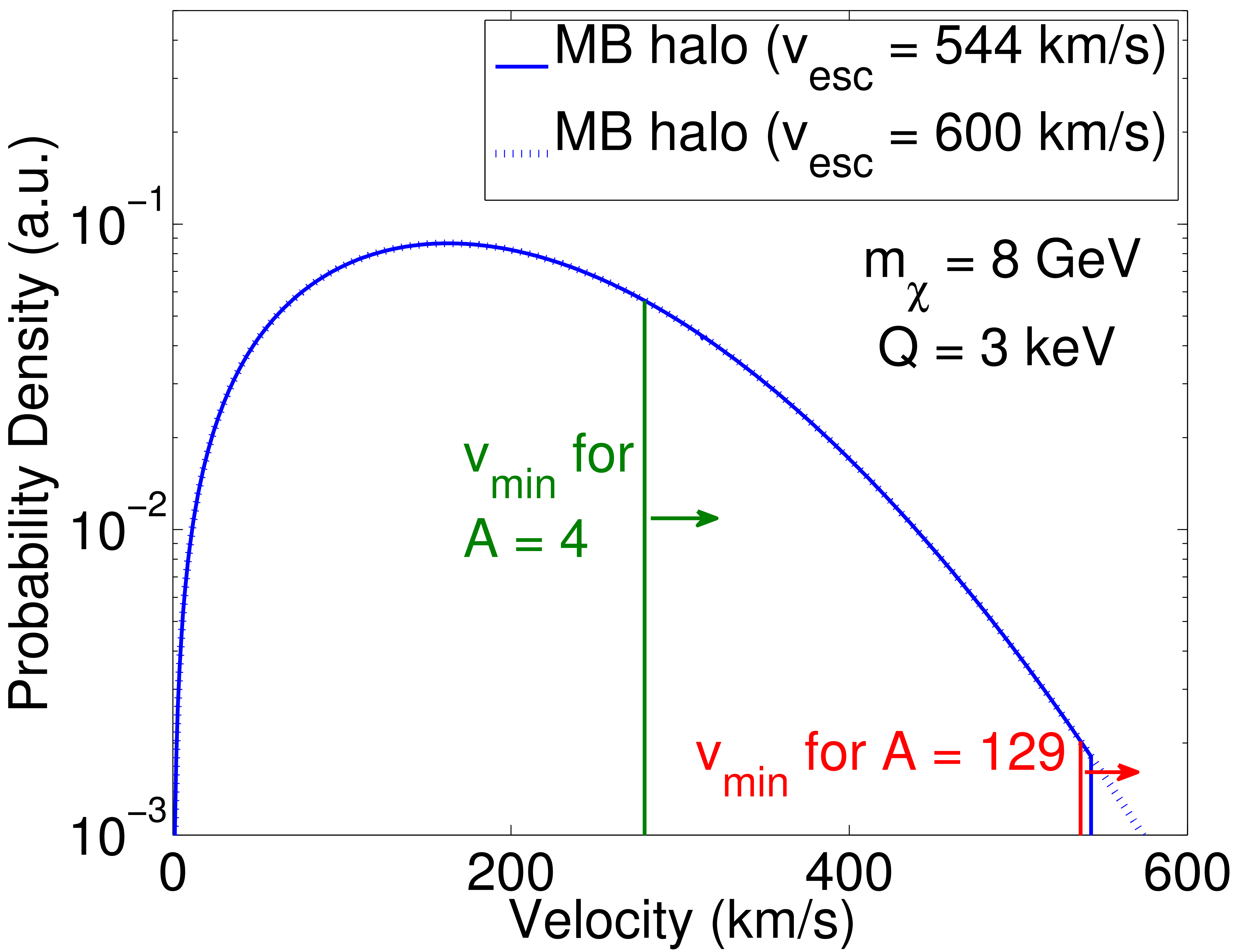



1807.02519

# Light targets less sensitive to halo uncertainty

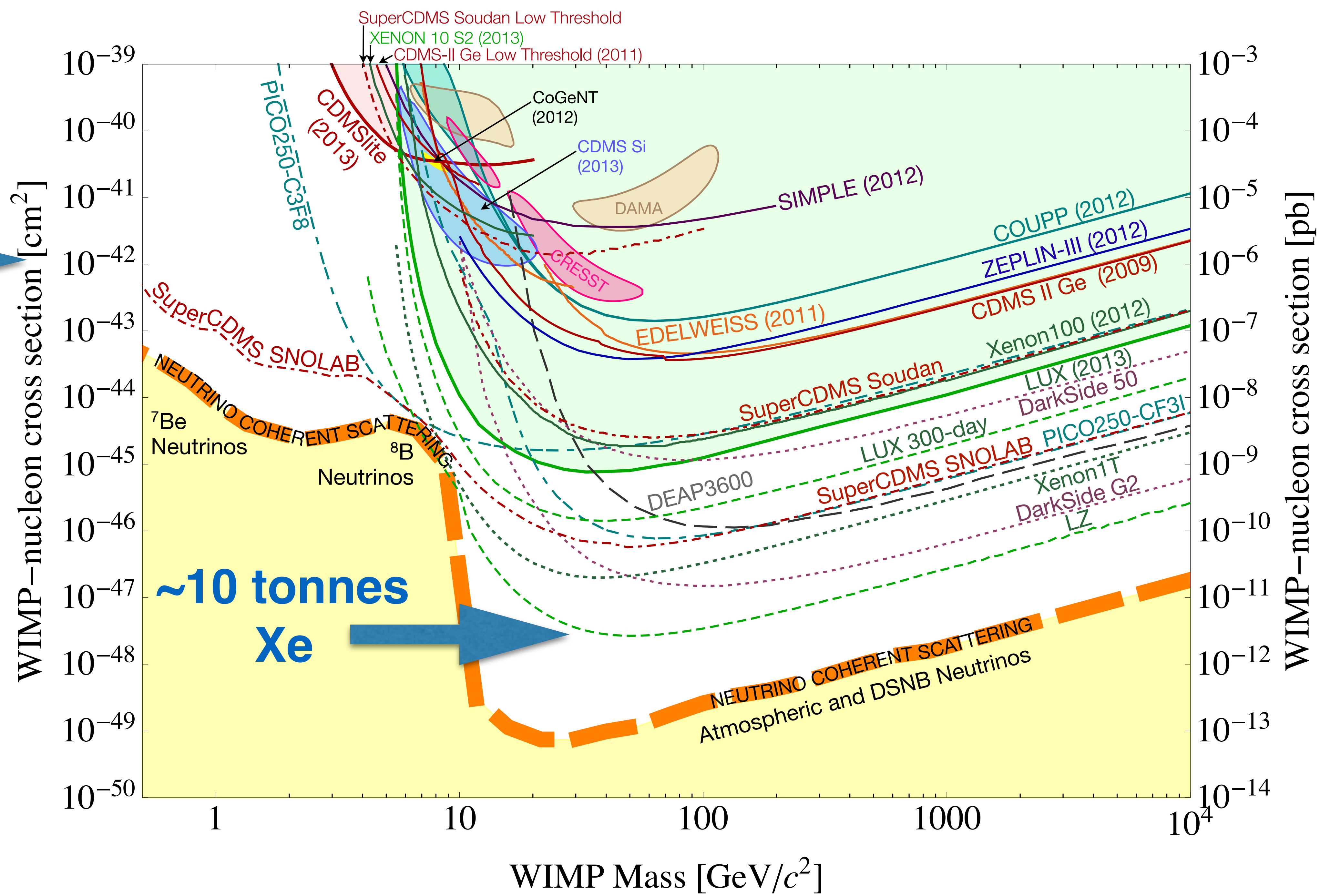
$$\int_{v_m}^{v_{esc}} \frac{f(v)}{v} dv$$



# What don’t you need for low mass?

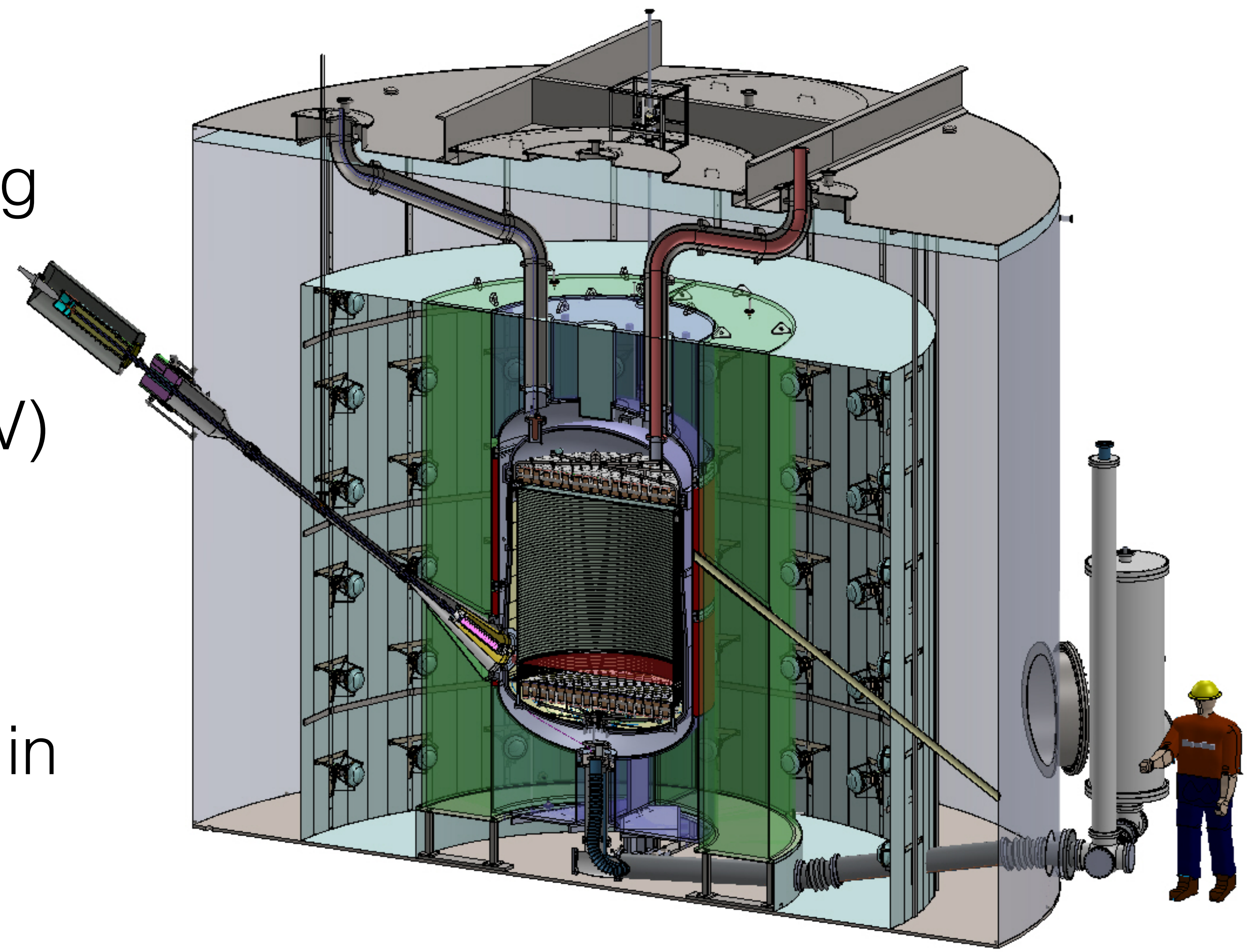
- A lot of mass

~10 kg He



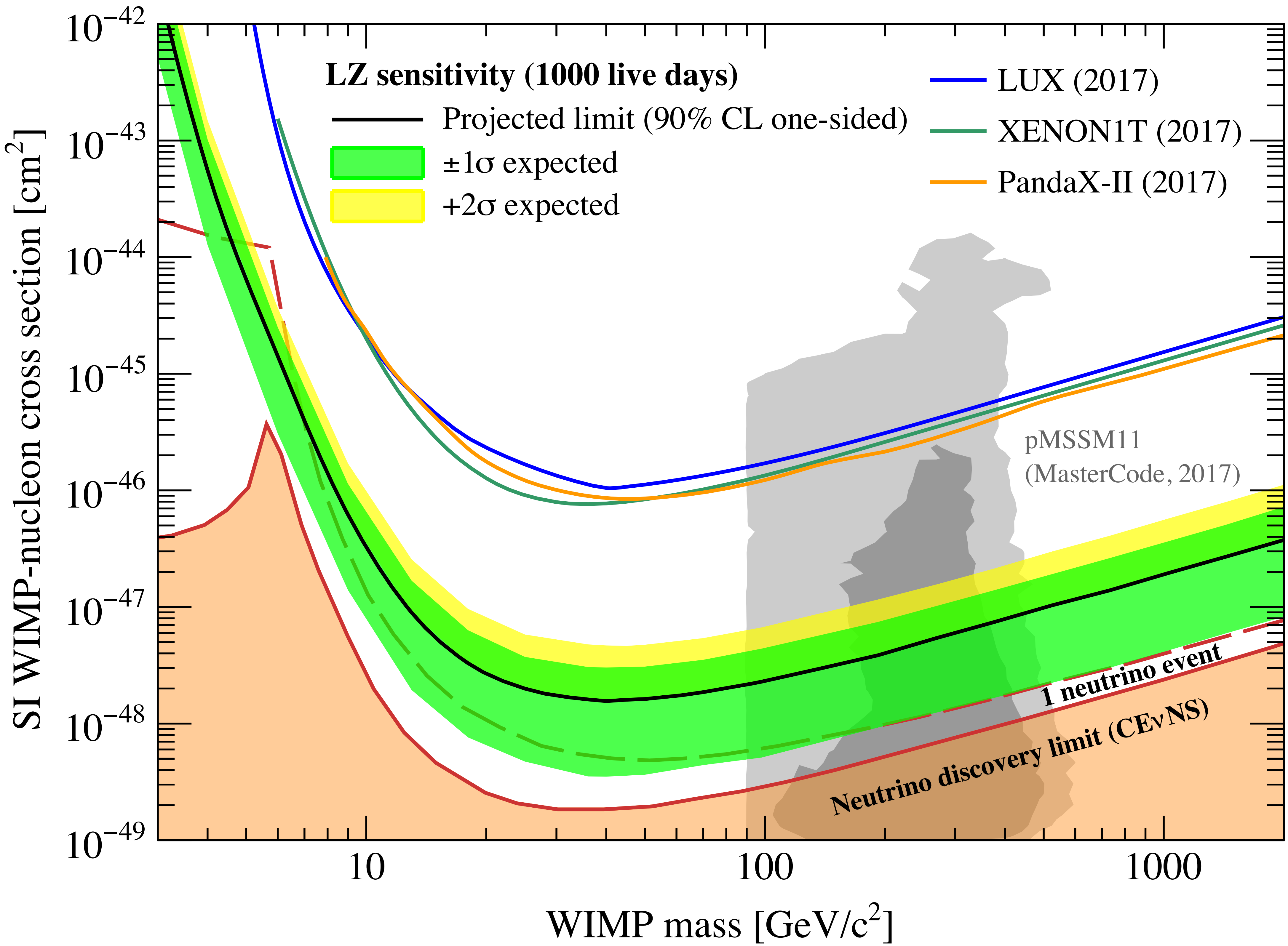
# LUX-Zeplin (LZ)

- 7 tonne active LXe TPC
  - Heavy target
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
- >30 institutions, ~200 people
- Now under construction in Lead, SD

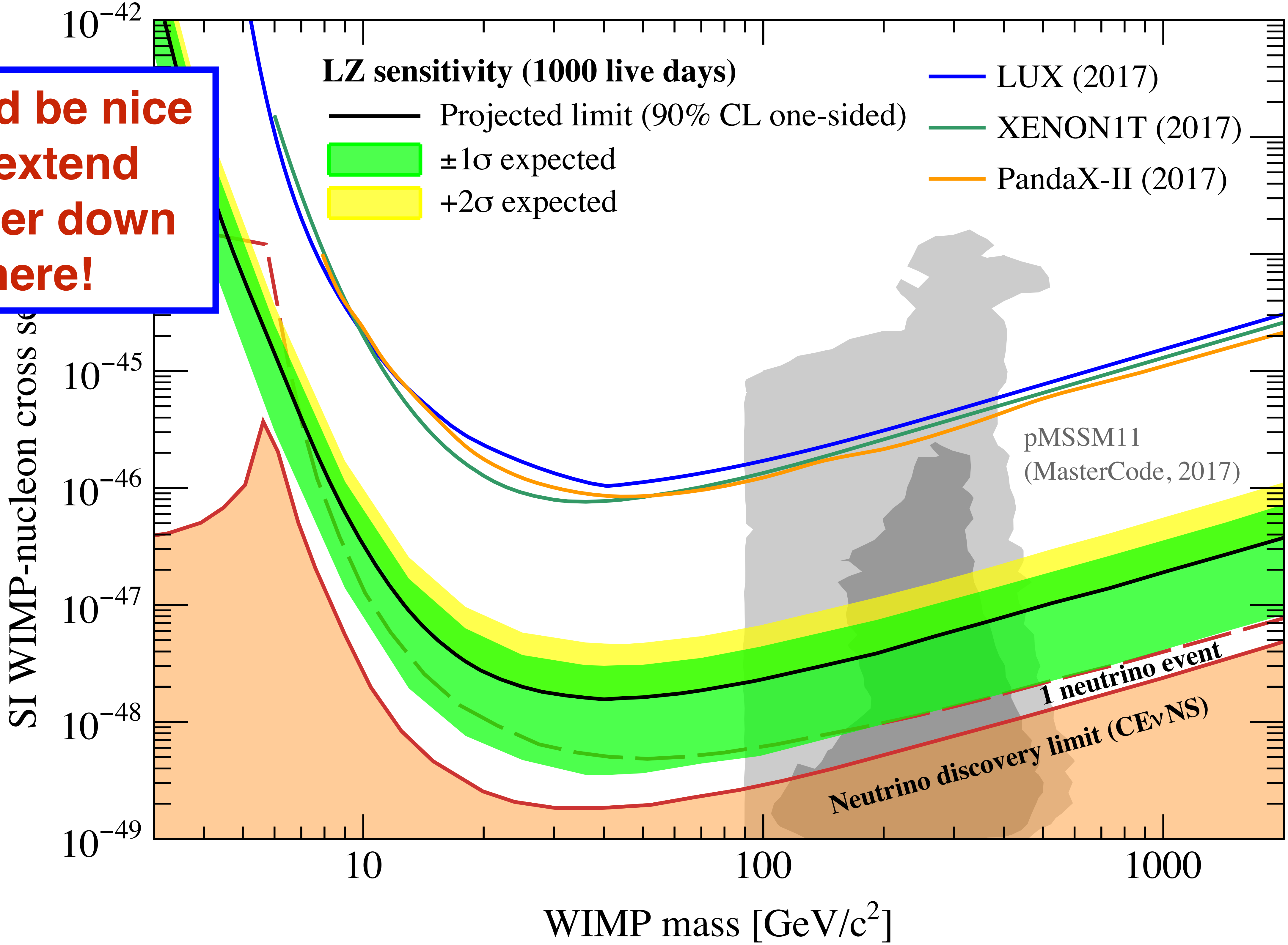


See C. Hall, M.E. Monzani, V. Kudryavtsev, R. Mannino on Tuesday, L. Korley on Friday, along with many other LUX/Xenon talks for more

# LUX-Zeplin (LZ)



# LUX-Zeplin (LZ)

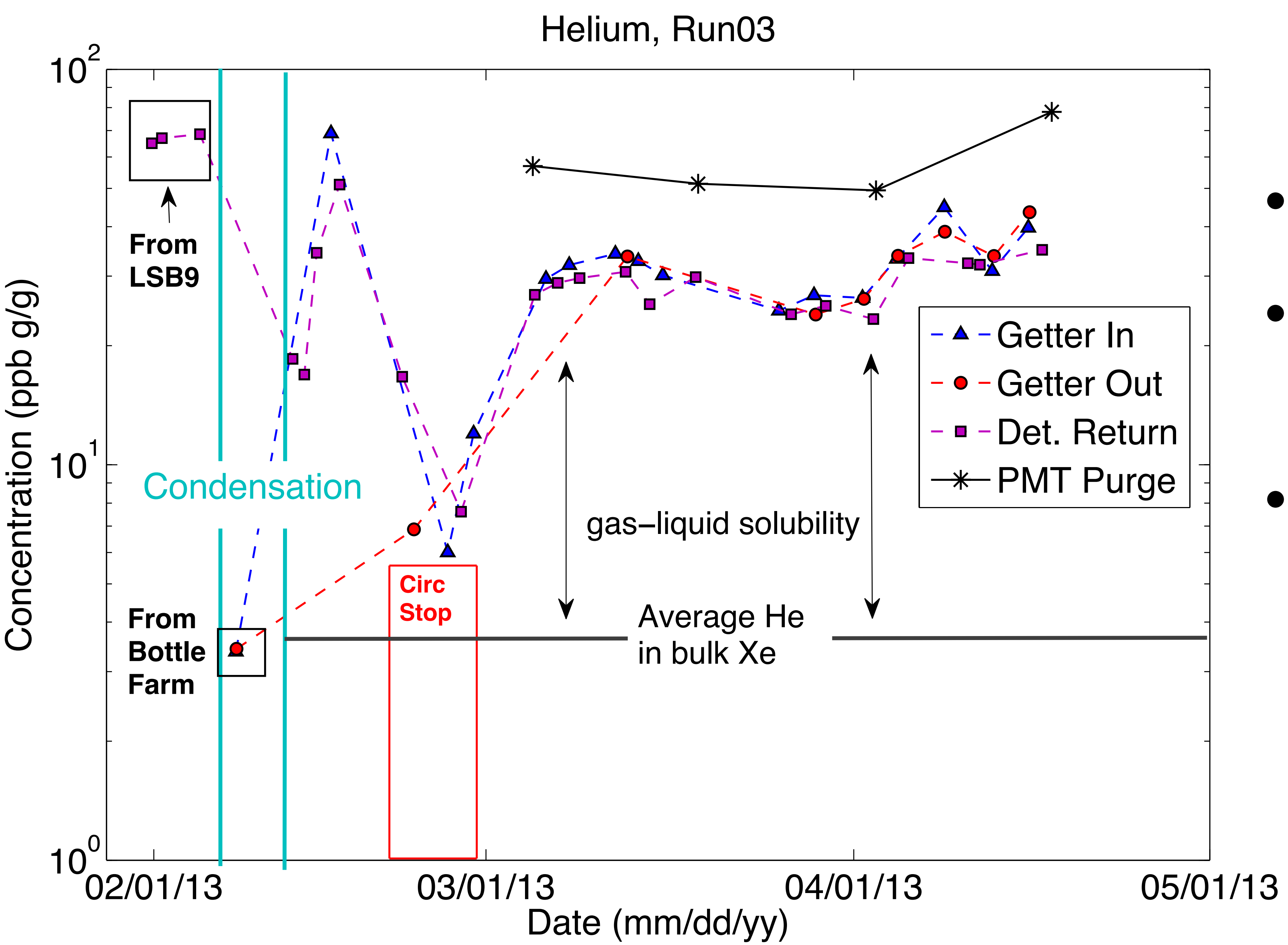



**Would be nice to extend further down here!**

# Can we add He or other light gases to LXe?

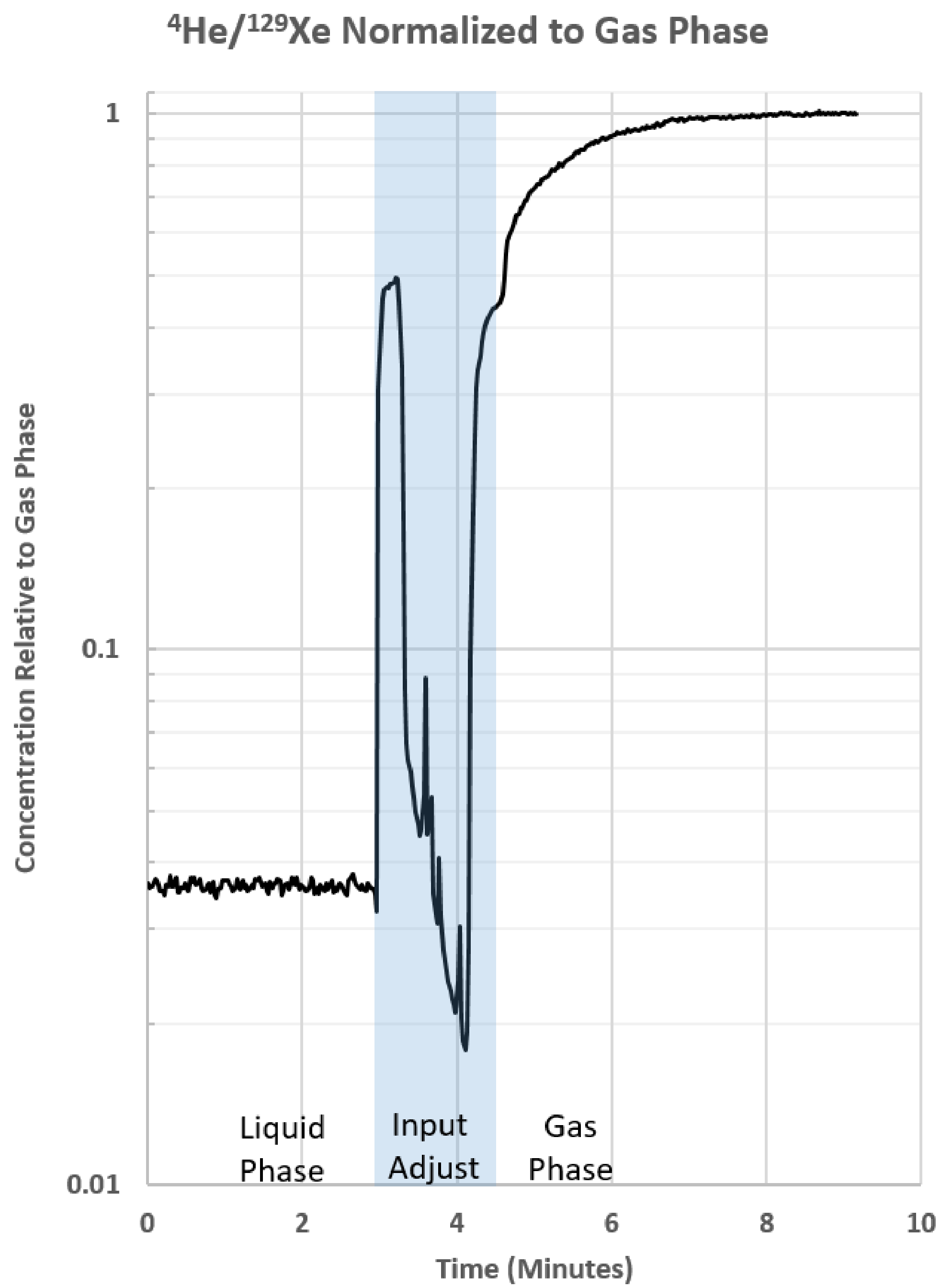
- Dissolve small quantities of He in liquid xenon
- Extend the reach of a detector like LZ (or XENONnT or PandaX, etc)
- Add new targets to field of direct detection
  - No existing experiments using helium
    - S. Hertel talk on HeRALD later today
    - I. Katsioulas on NEWS-G gas detectors on Friday
- Capitalize on investment in large detectors by adding flexibility

# Dissolving He in LXe?




- LUX fill data
- Some residual He in the source bottles
- Data imply 3e-3 mass fraction for 1 atm partial pressure

# Dissolving He in LXe?

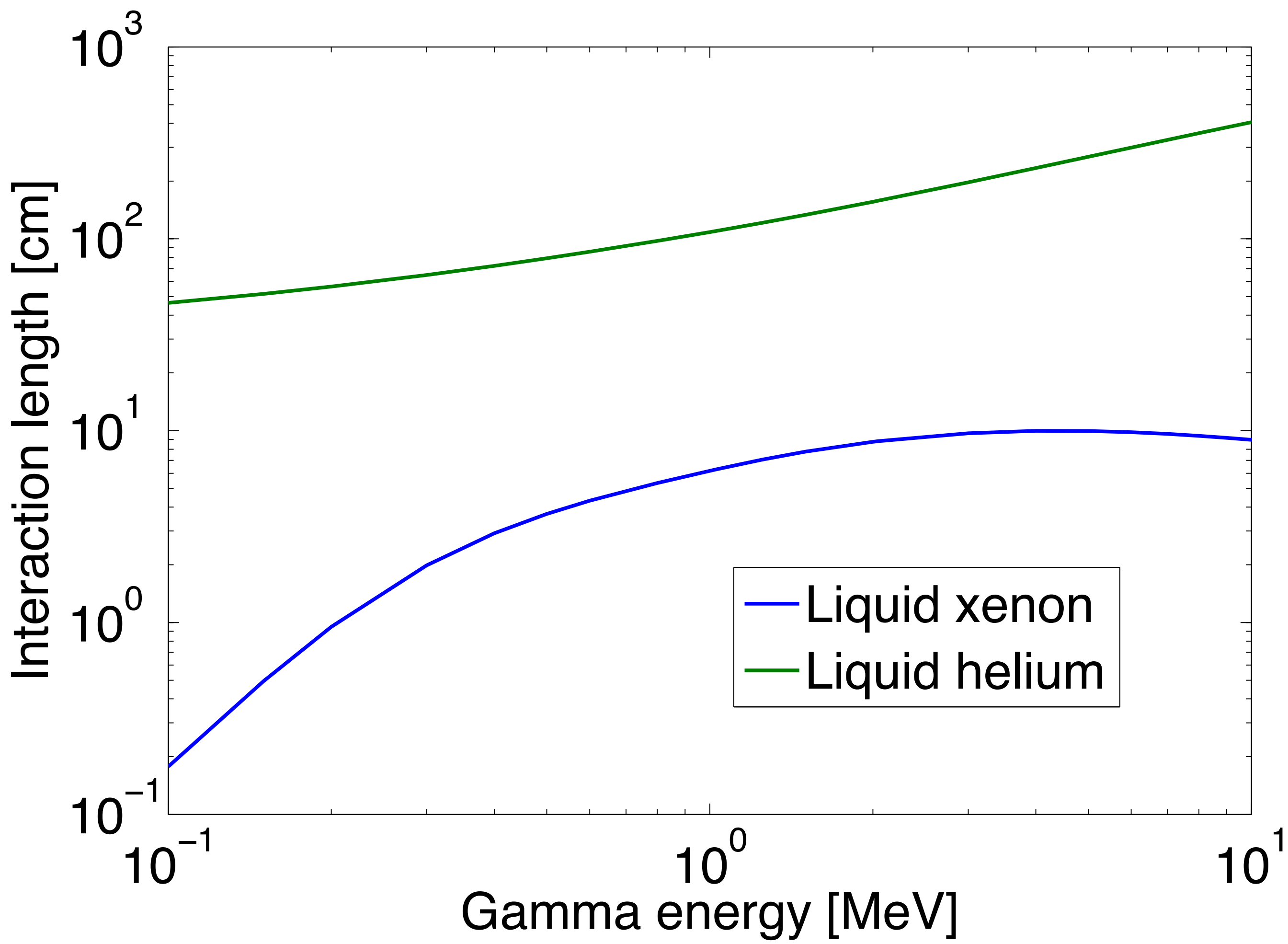



0.037 mol He/mol Xe x $M_{He}/M_{Xe}$ ~ 0.1%

- Confirmed in preliminary test at Fermilab
  - Achieved 0.1% He in LXe by mass on first attempt at 1 bar of partial pressure

# Backgrounds

- The longest known radioisotope of He ($^6$He) decays in <1 s
    - No new backgrounds introduced




| Size of LZ | Size of 10 kg LHe |
|---|---|
| 150 x 150 cm | 30 x 30 cm |

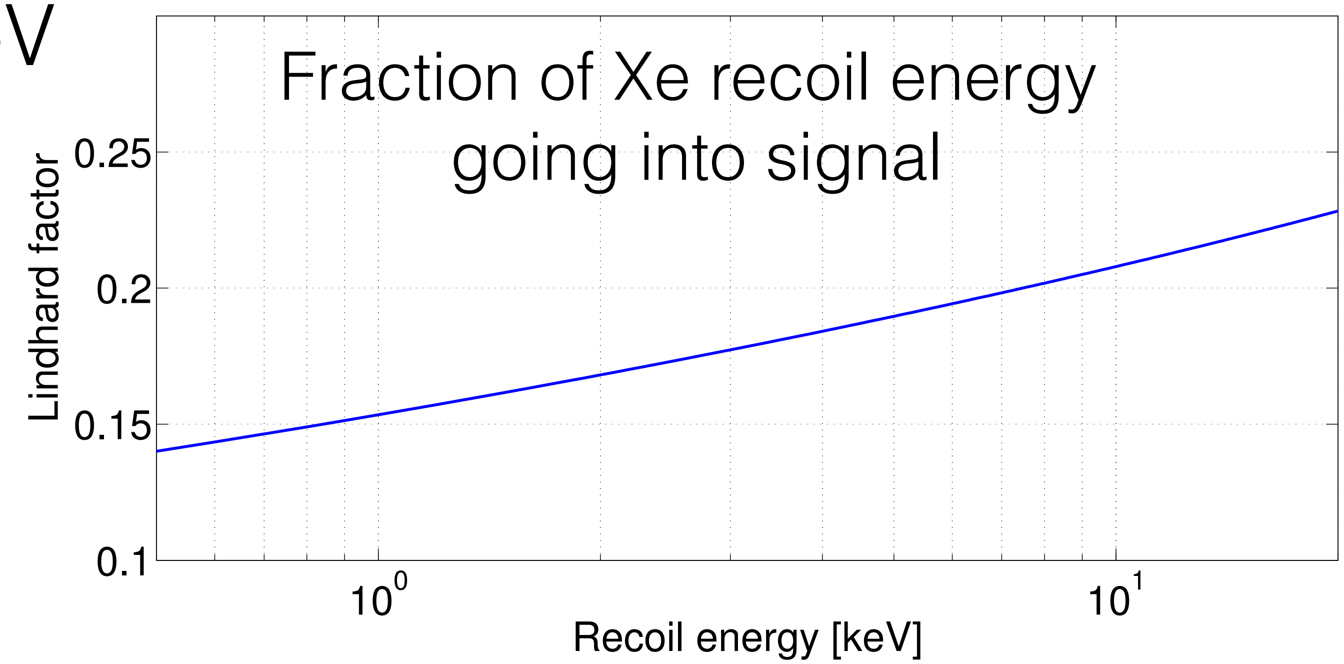
- Self shielding is not effective in He-only detector

# Signal detection

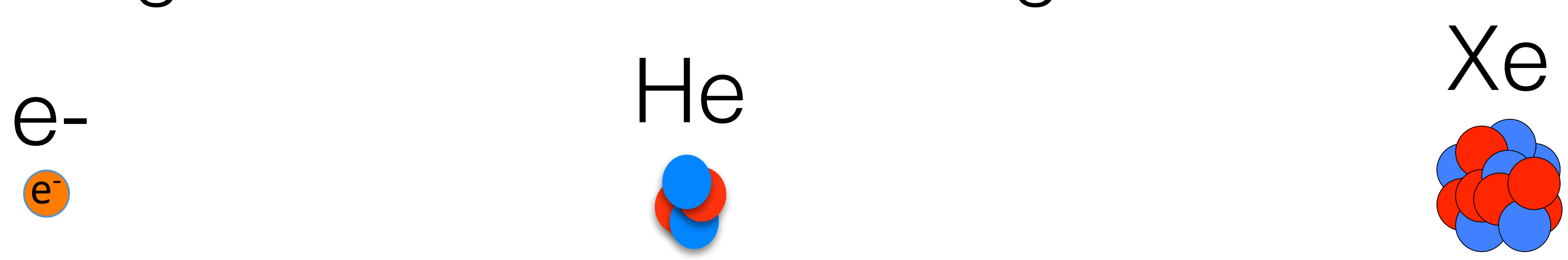
- Helium and neon scintillate in harder UV
  - 80 nm vs 175 nm in LXe
- But:
  - Recoil energy will tend to be deposited in collisions with xenon electrons and atoms in the usual way, and it will be generated at 175 nm
  - Any He2 decay photons will wavelength shift in the xenon anyway
- Keep same photon detection scheme!

# Xenon microphysics

- Xenon recoils in LXe lose a lot of energy to heat (Lindhard factor)
    - Less than 20% of a ~<7 keV recoil goes into detectable signal
    - The rest goes into nuclear collisions that lead to heat



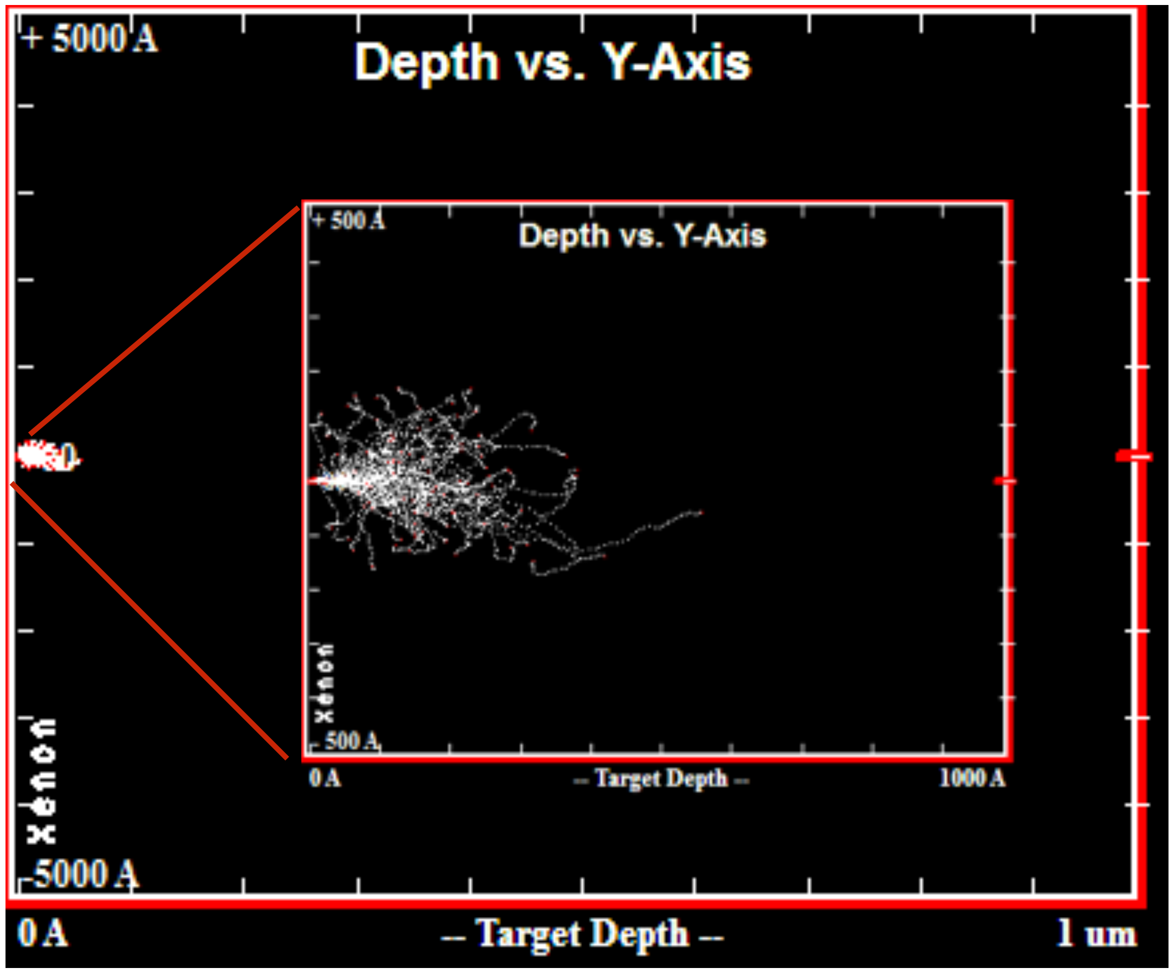

- Helium is a light nucleus - fewer strong nuclear collisions



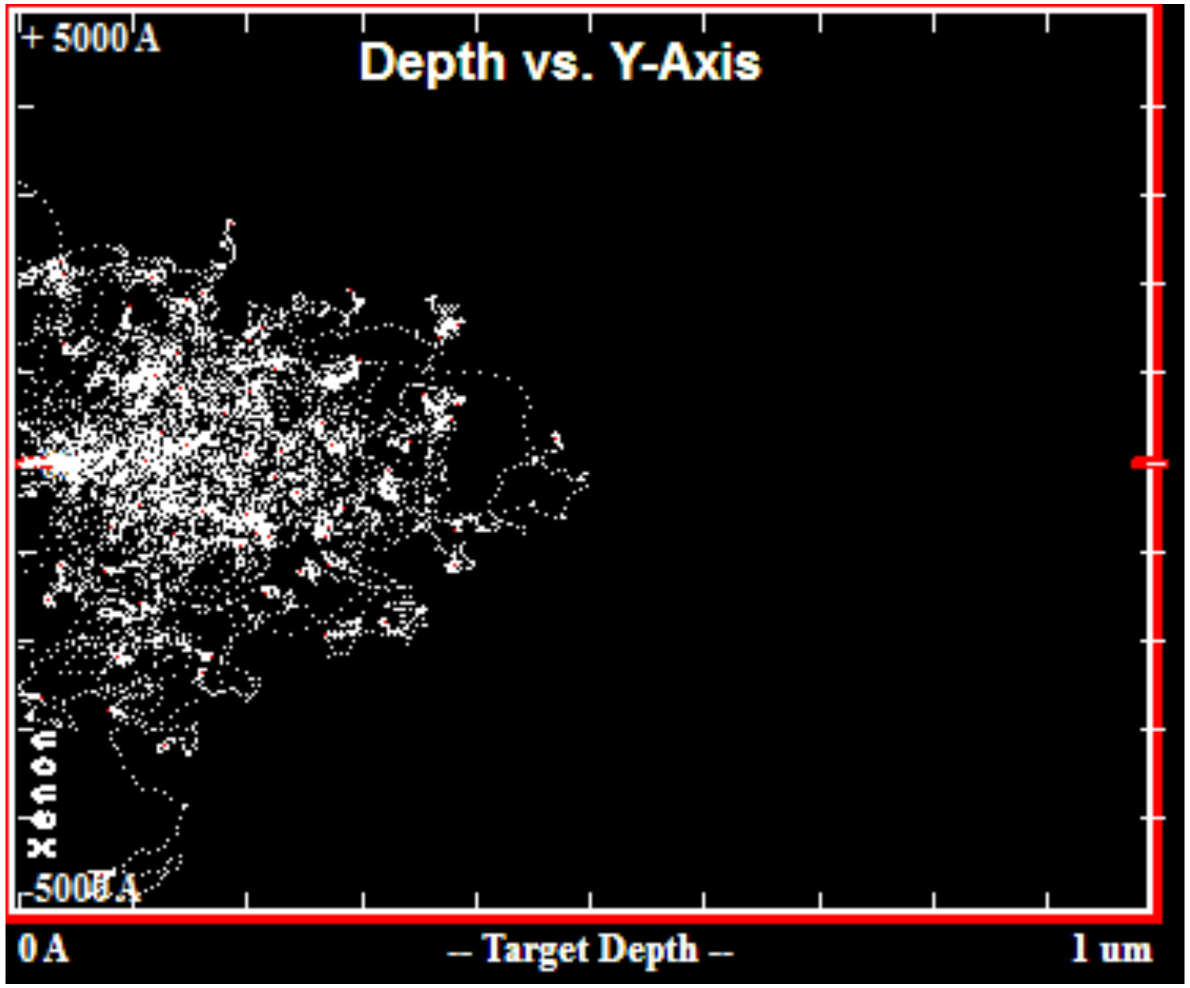

Not to scale

# Modeling He recoils in LXe (v1)

- Stopping and Range of Ions in Matter (SRIM)
- Calculate the energy lost to nuclear (heat) and electronic (signal) stopping




10 keV Xe in LXe
~100 A ranges




10 keV He in LXe
~1000 A ranges

# Modeling He recoils in LXe (v1)

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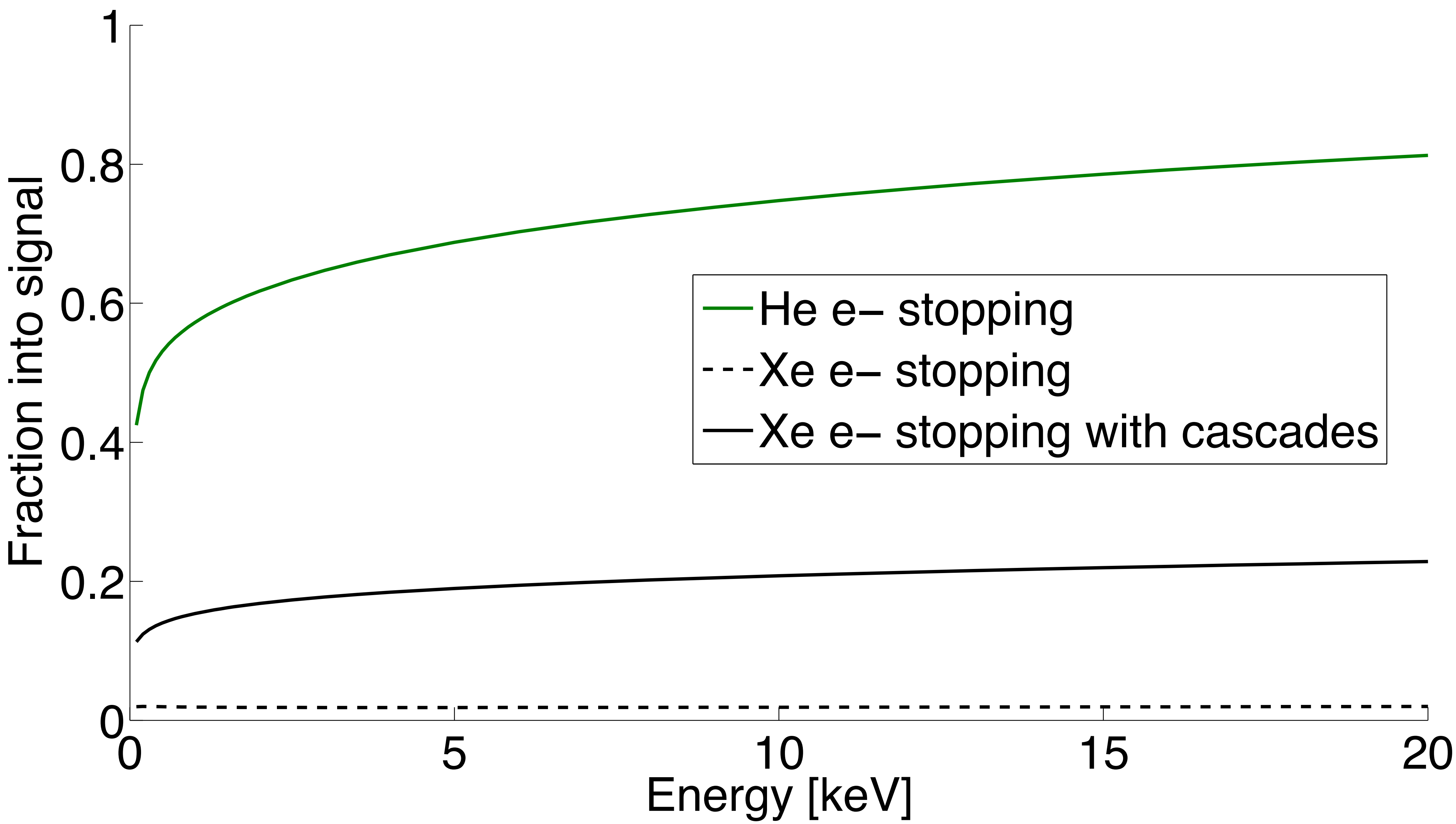
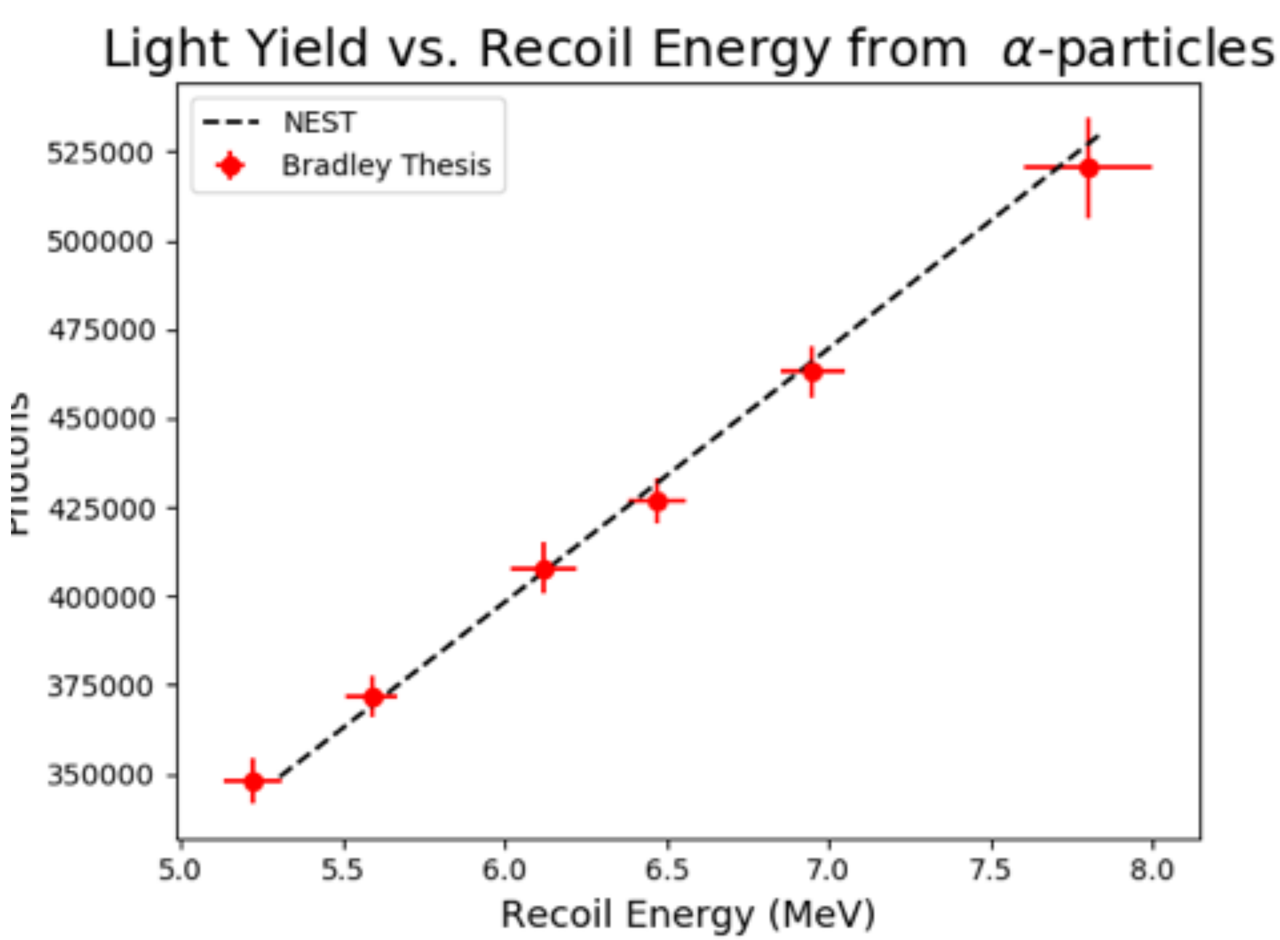
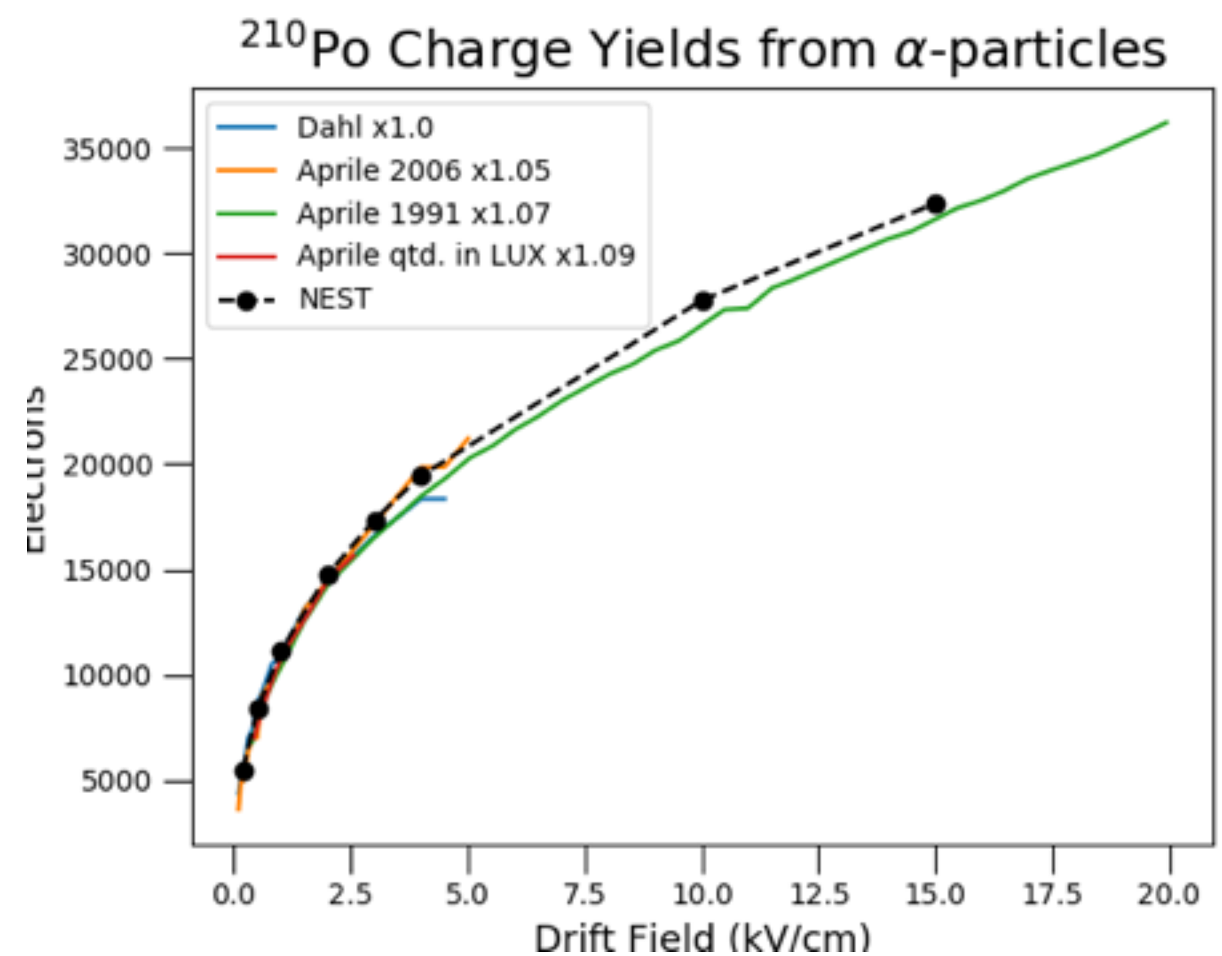


# Modeling He recoils in LXe (v2)

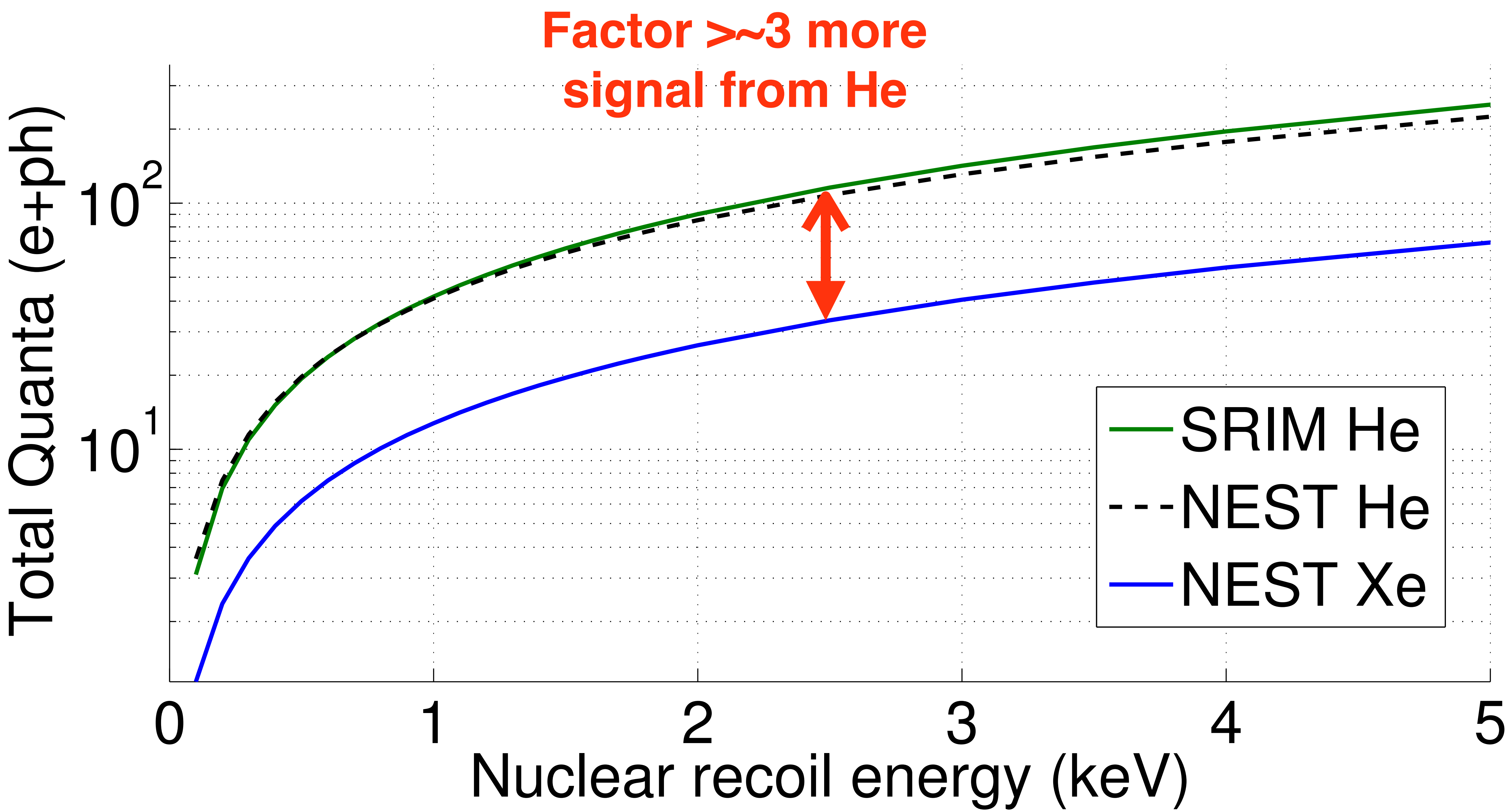
- Noble Element Simulation Technique (NEST)
  - Data driven model for signal processes in LXe
- NEST v2.0 released at this conference (G. Rischbieter, Thursday)
  - Alpha data from LUX and test chambers incorporated into NEST2.0
  - High energies, but at least it's real He nuclei in LXe



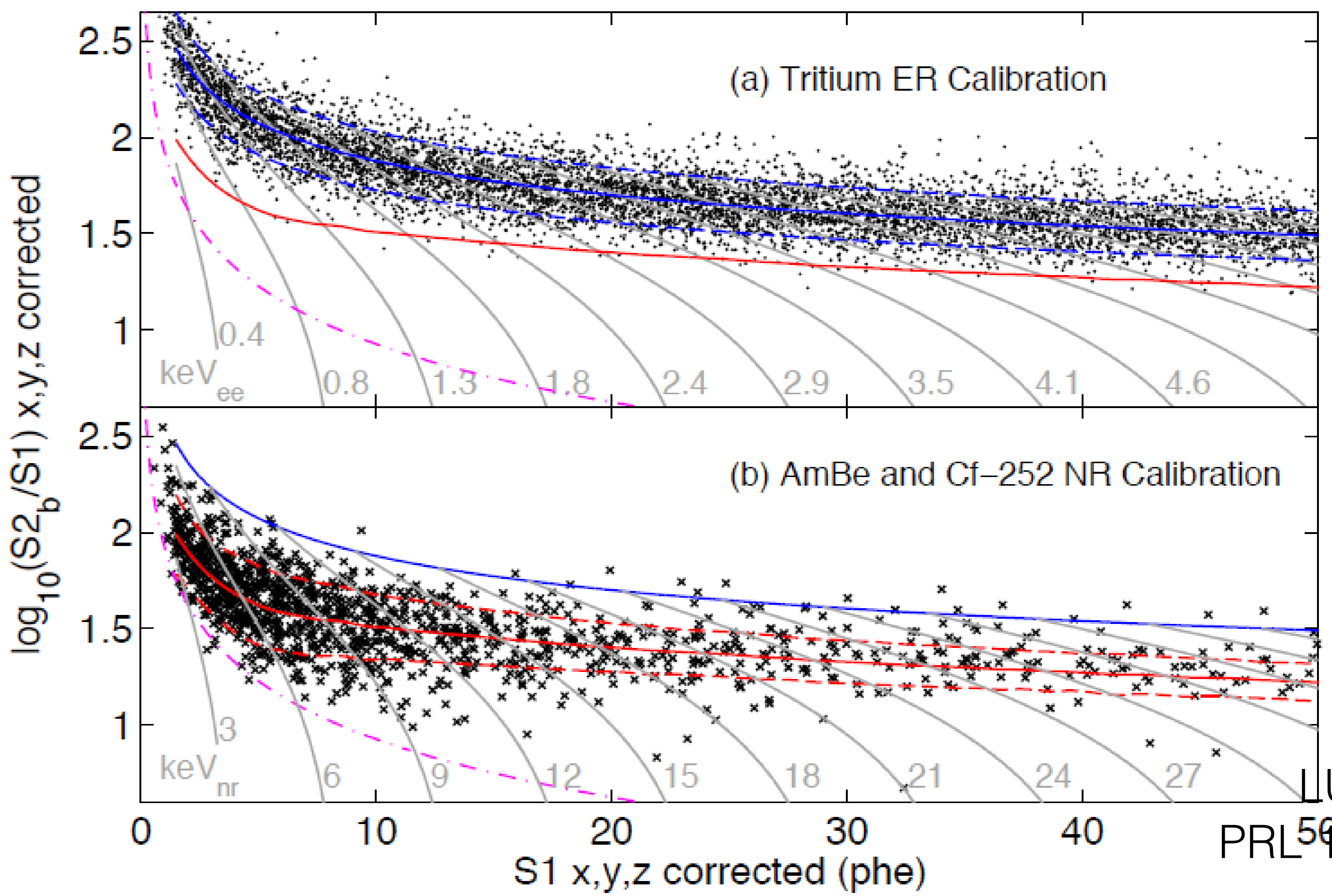
# Modeling He recoils in LXe (v1+2)

**Total quanta =** hν **+** e⁻



# A key question

- What happens to S2/S1 partitioning?

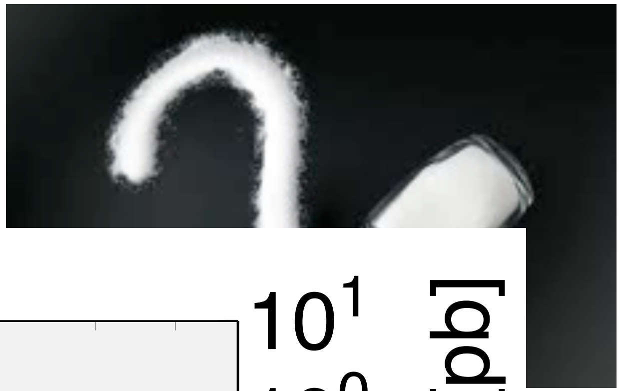


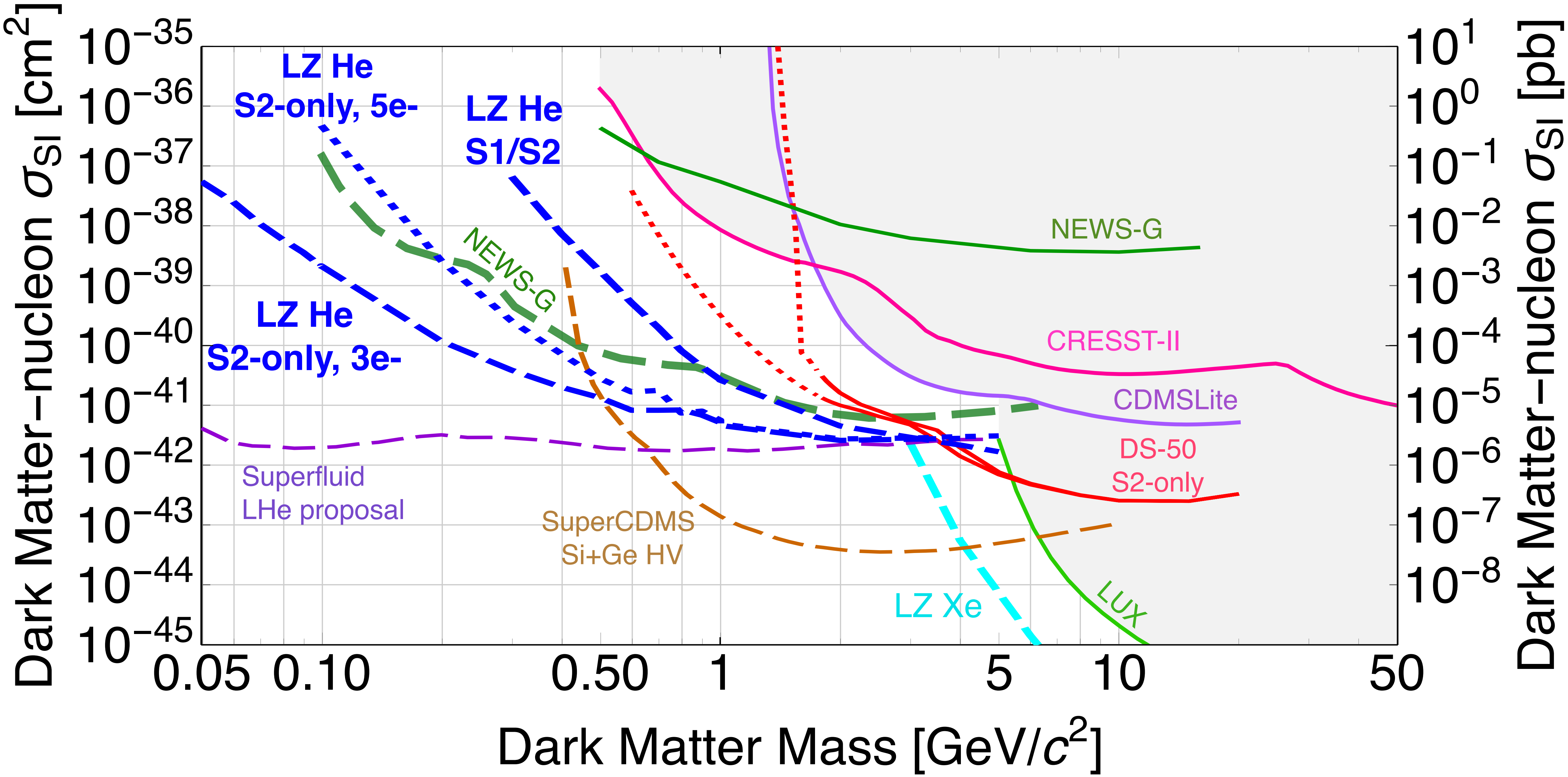

LUX data
PRL 112, 091303

# Making projections

- Using the NEST 2.0 alpha model, the LZ simulation, and expected LZ backgrounds
- Analysis and sensitivity using the LZ Profile Likelihood Ratio package
- For now, I assume ER-like partitioning of photons and electrons in He recoils
    - more conservative with regard to background rejection and S1/S2 sensitivity, slightly more optimistic for S2-only
- Assume ~15 kg of He (0.3 % loading of LZ fiducial volume by mass)

# Making projections






- Location of LZ Helium lines depends critically on assumed signal yield
    - ~225 events/day/pb with S2 only at 100 MeV WIMP with this yield
- S2-only line is for 20 live days
- Dotted line is 5e- S2-only threshold

# What do I worry about

- This is still fairly speculative
  - Henry's coefficients not comprehensively measured
    - Temperature dependence, diffusion, etc?
  - Signal yields depend on modeling and MeV scale data

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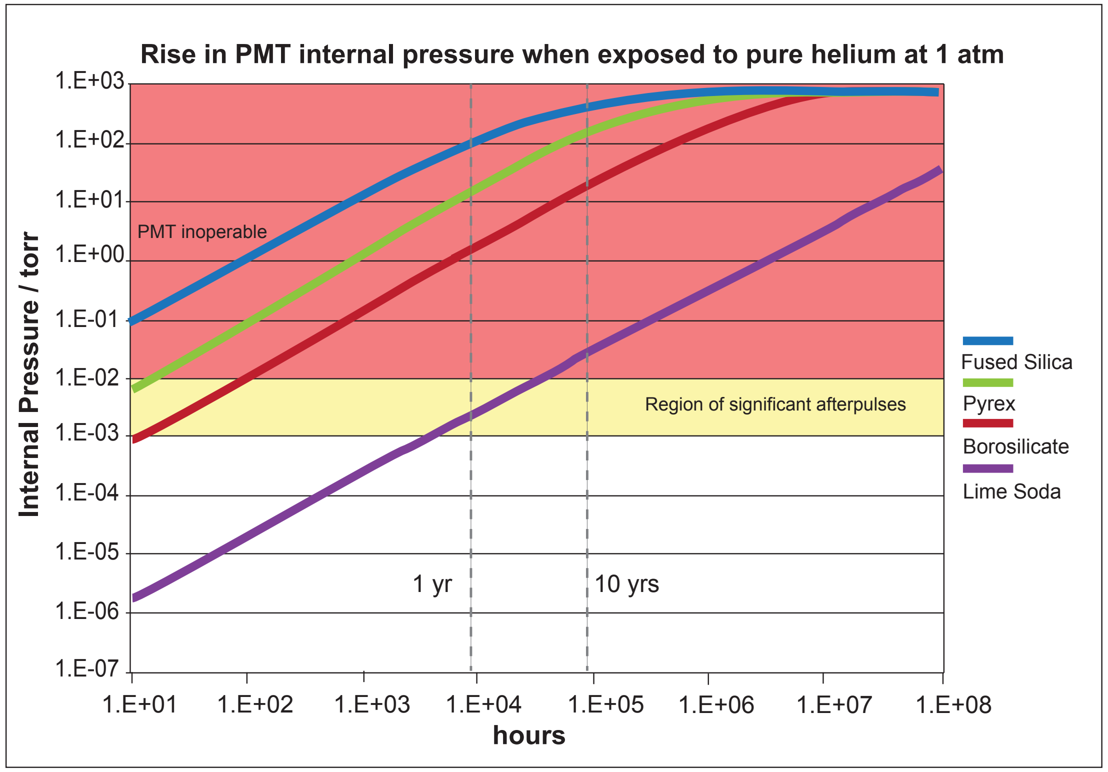
**NEEDS CALIBRATION!**

- SCENE-style neutron scattering experiment is where I would start

# What do I worry about

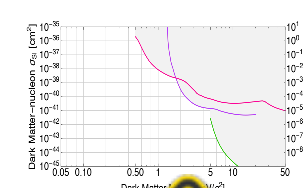
- Helium gas and PMTs are not a good mix
- Diffusion exponentially suppressed by temperature (Arrhenius relationship)
- Calculation suggests 500 days at 1 bar/ 165 K before tube becomes inoperable
- Exquisitely sensitive to temperature, and that's pretty tight…
- Needs to be tested
- Could use SiPMs…
- Could use H2?…

Example for ET9226 PMT

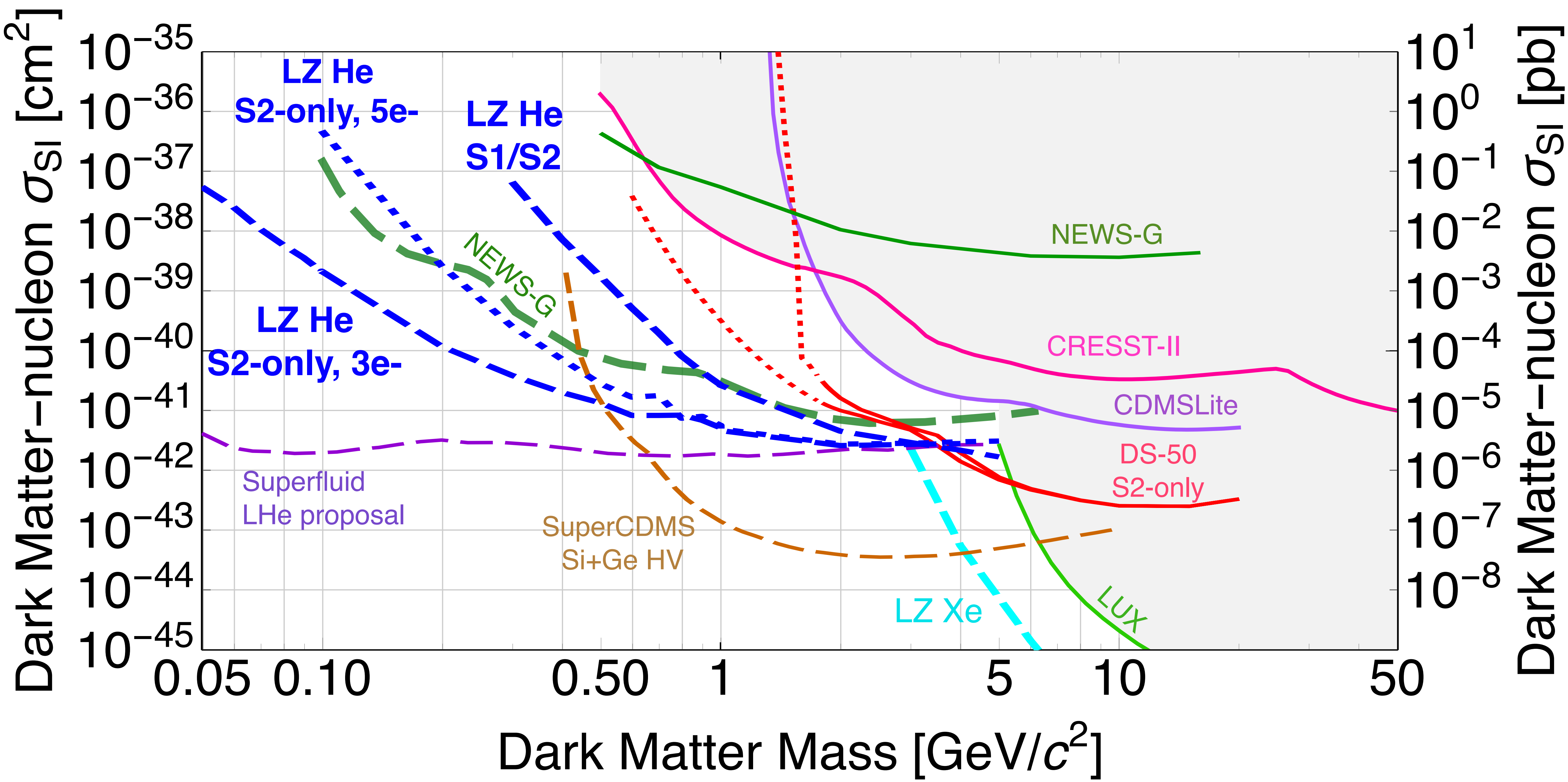



# He doping in LXe

- Physically possible
- Keep low background level achieved in LXe TPC
- Same signal readout with LXe sensitive light detectors
- Increased signal yield from He recoils
  - Lower energy thresholds for WIMP-He scattering
- Properties measurable using existing techniques
- Potential reach to well below 1 GeV dark matter



- Depends on properties that need to be measured

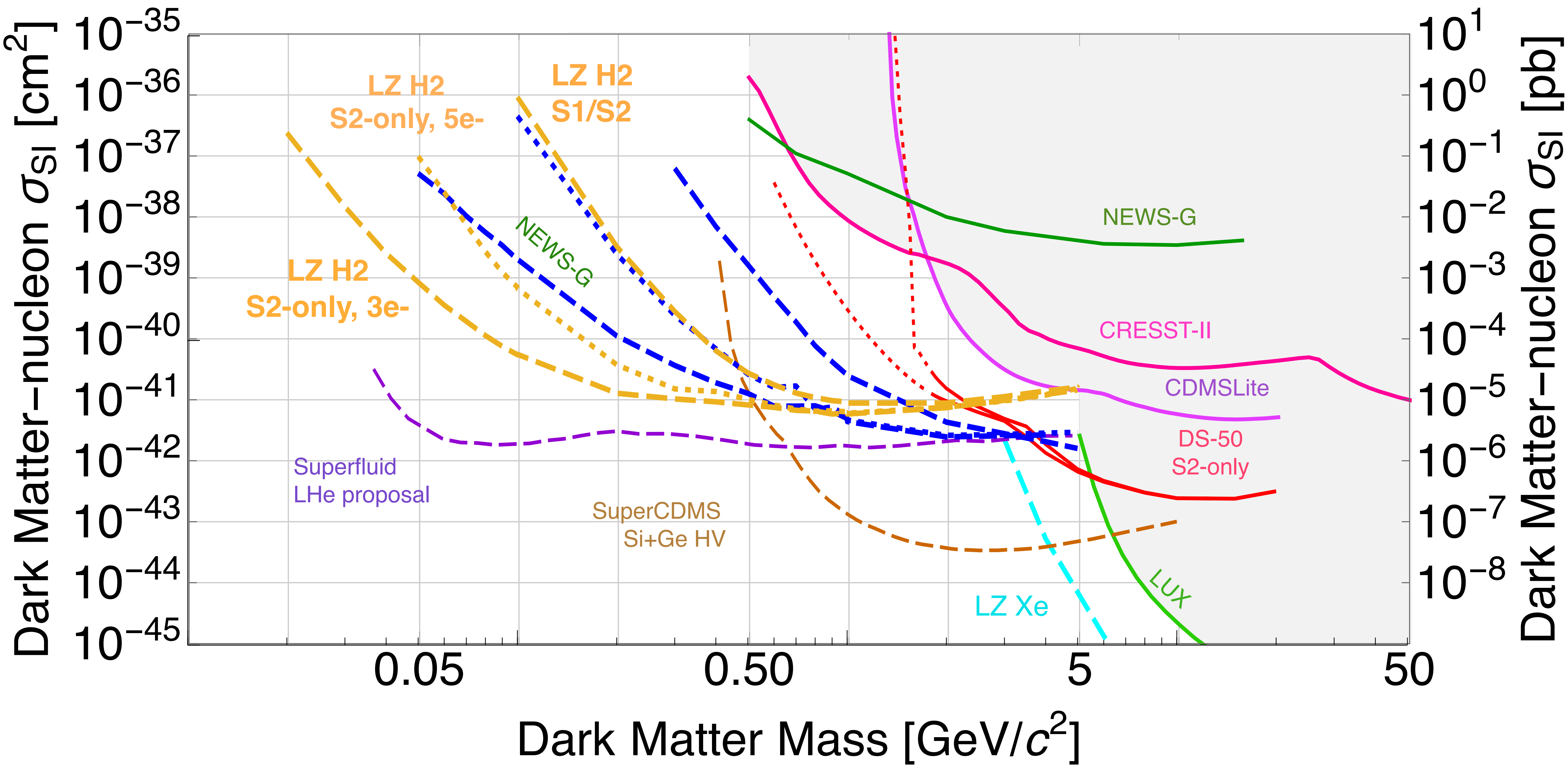

LZ He
S2-only, 5e-
LZ He
S1/S2
LZ He
S2-only, 3e-
NEWS-G
NEWS-G
CRESST-II
CDMSLite
DS-50
S2-only
Superfluid
LHe proposal
SuperCDMS
Si+Ge HV
LZ Xe
LUX
Dark Matter–nucleon σSI [cm²]
Dark Matter–nucleon σSI [pb]
Dark Matter Mass [GeV/c²]

Backup

# Hydrogen alternative

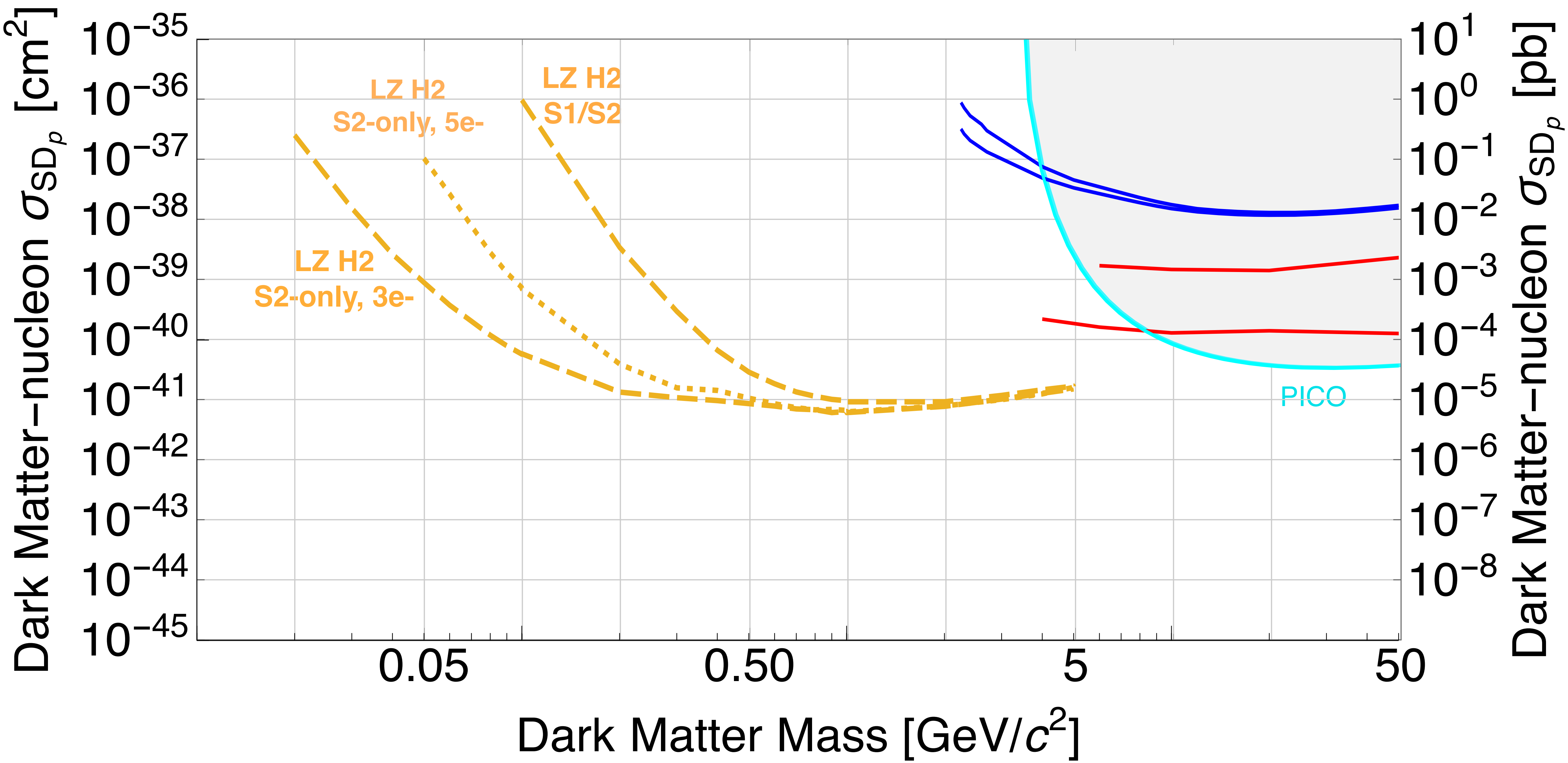
- PMT diffusion is greatly suppressed at high temperature
  - Molecular nature of H2
- More readily dissolves in liquid (based on measurements in argon)
- Even more kinematically favorable!
- Even more signal!
- Sensitive to spin dependent interactions
- Effect on S2? - may quench S2 production

# Hydrogen alternative




- Projection from calculating yields with SRIM + LZ detector model
  - Definitely to be taken with grain of salt

# Hydrogen alternative

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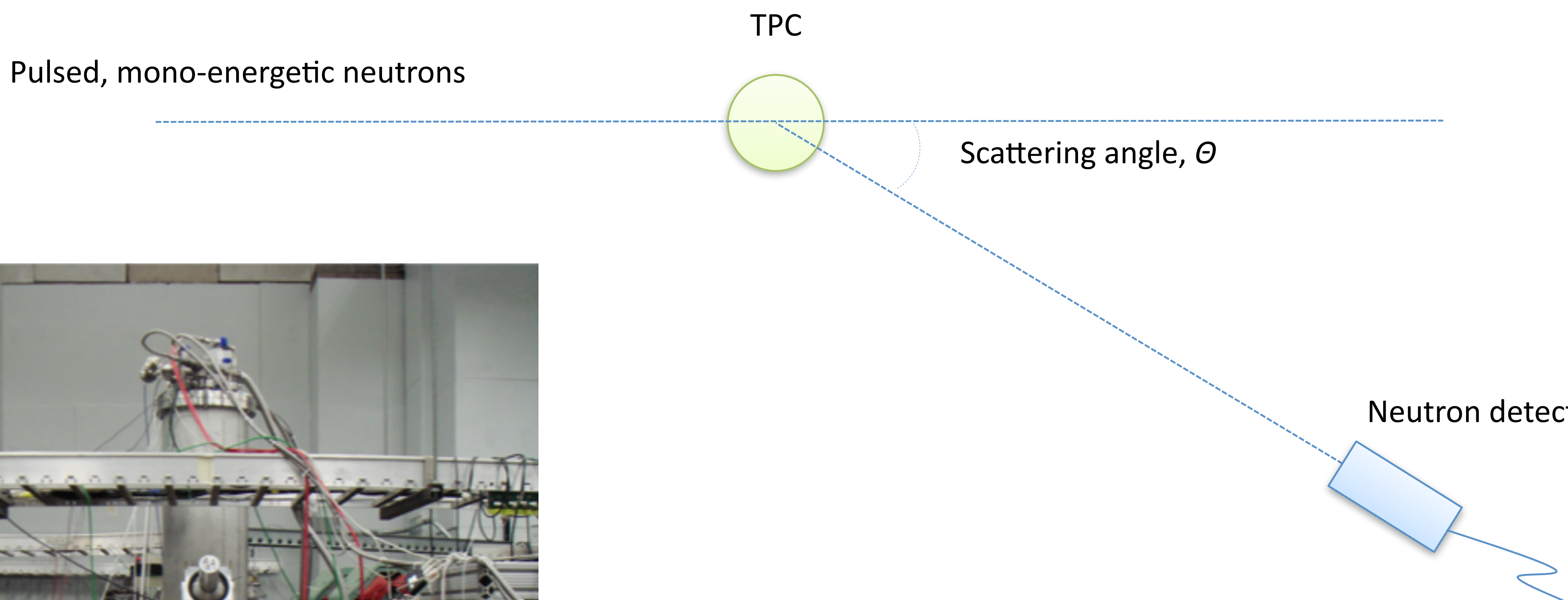
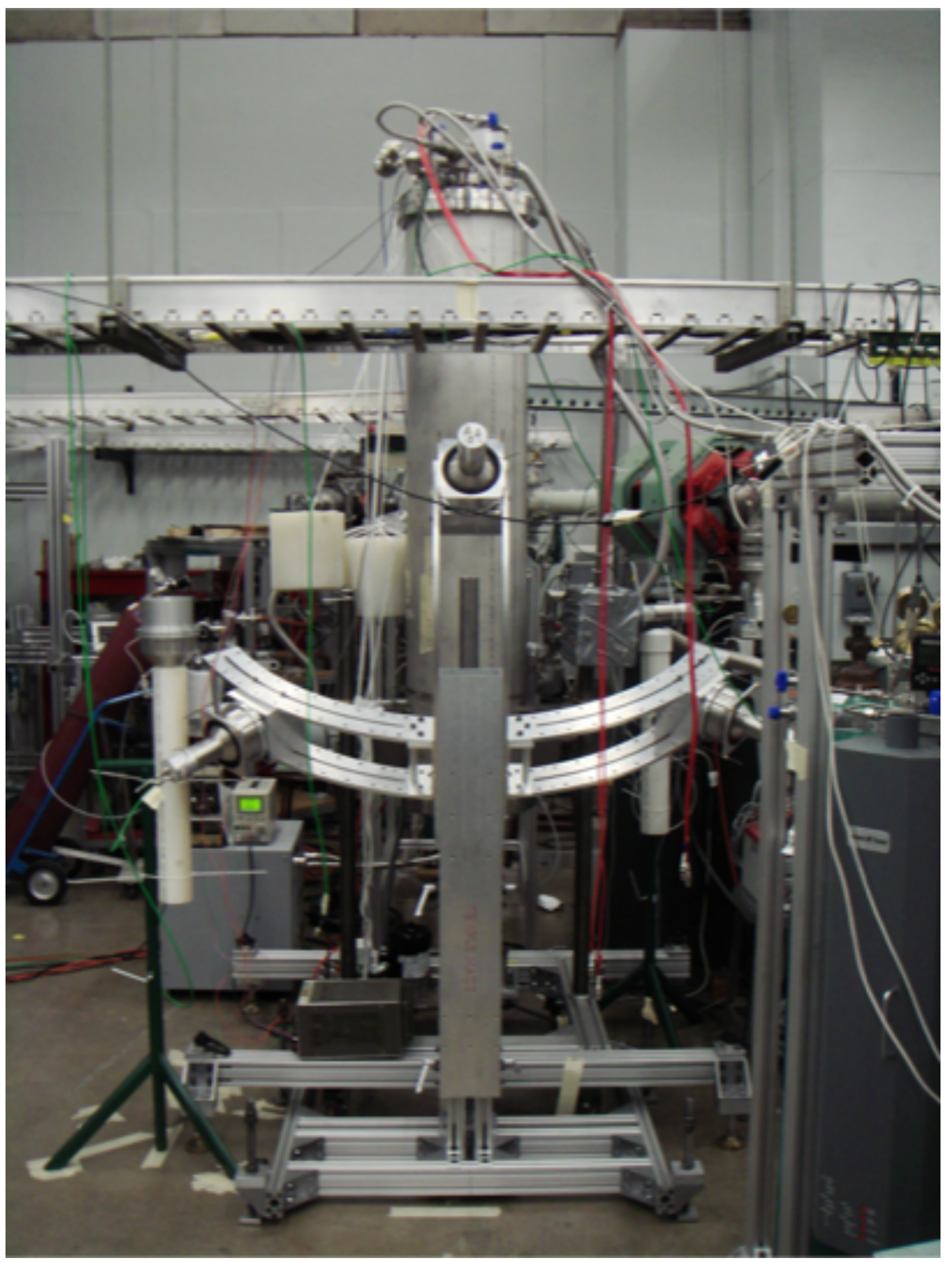
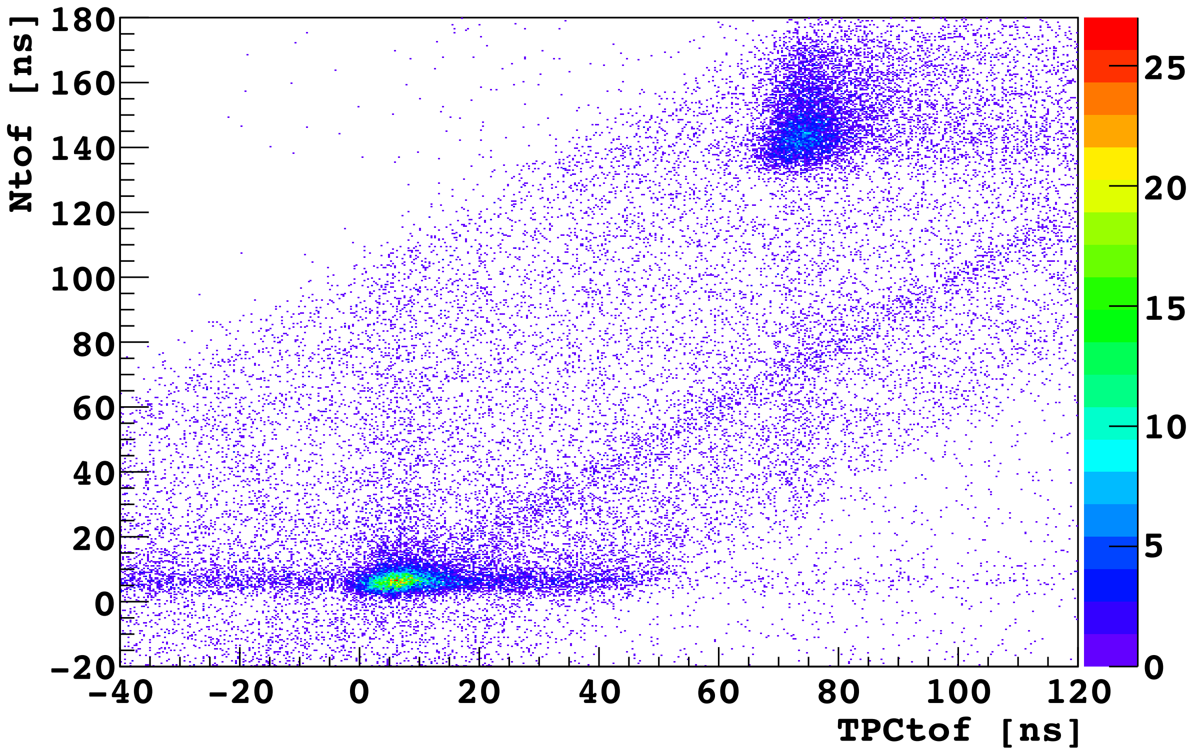
# Neutron scattering measurement



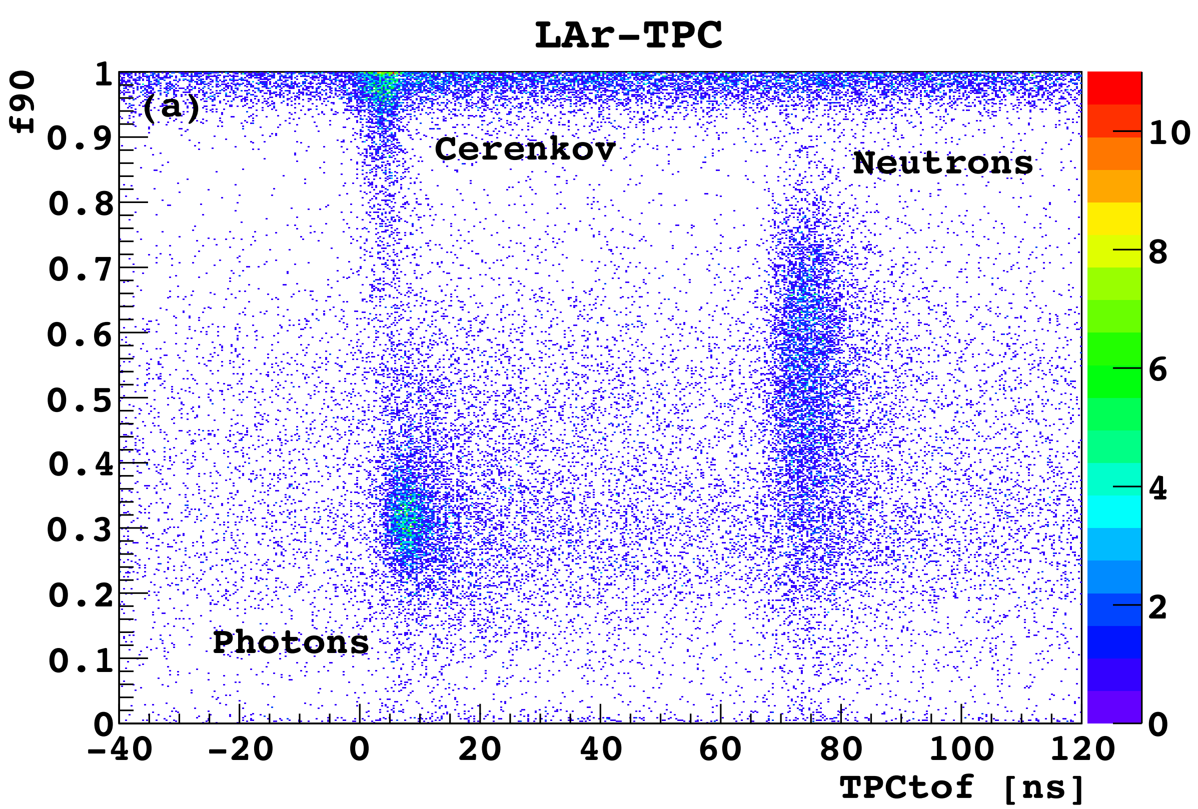



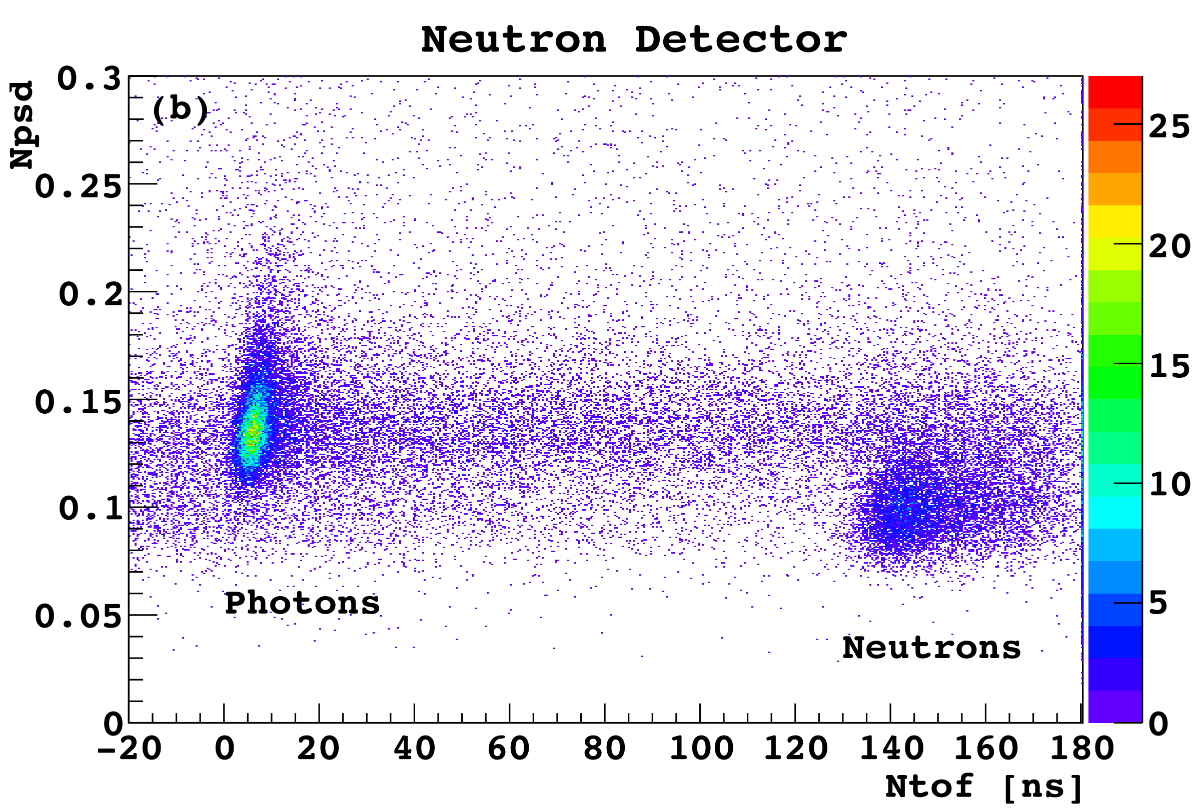
- Pulsed, monoenergetic beam (at Notre Dame or elsewhere) to measure response of to nuclear recoils of known energy
- Tunable nuclear recoil energy by changing the neutron energy and the scattering angle
  - Neutrons of 100 keV - 1.5 MeV
  - Recoils of ~1 keV up to 50 keV
  - Successful measurements in LAr (1406.4825, 1306.5675, SCENE)

# Neutron scattering in SCENE



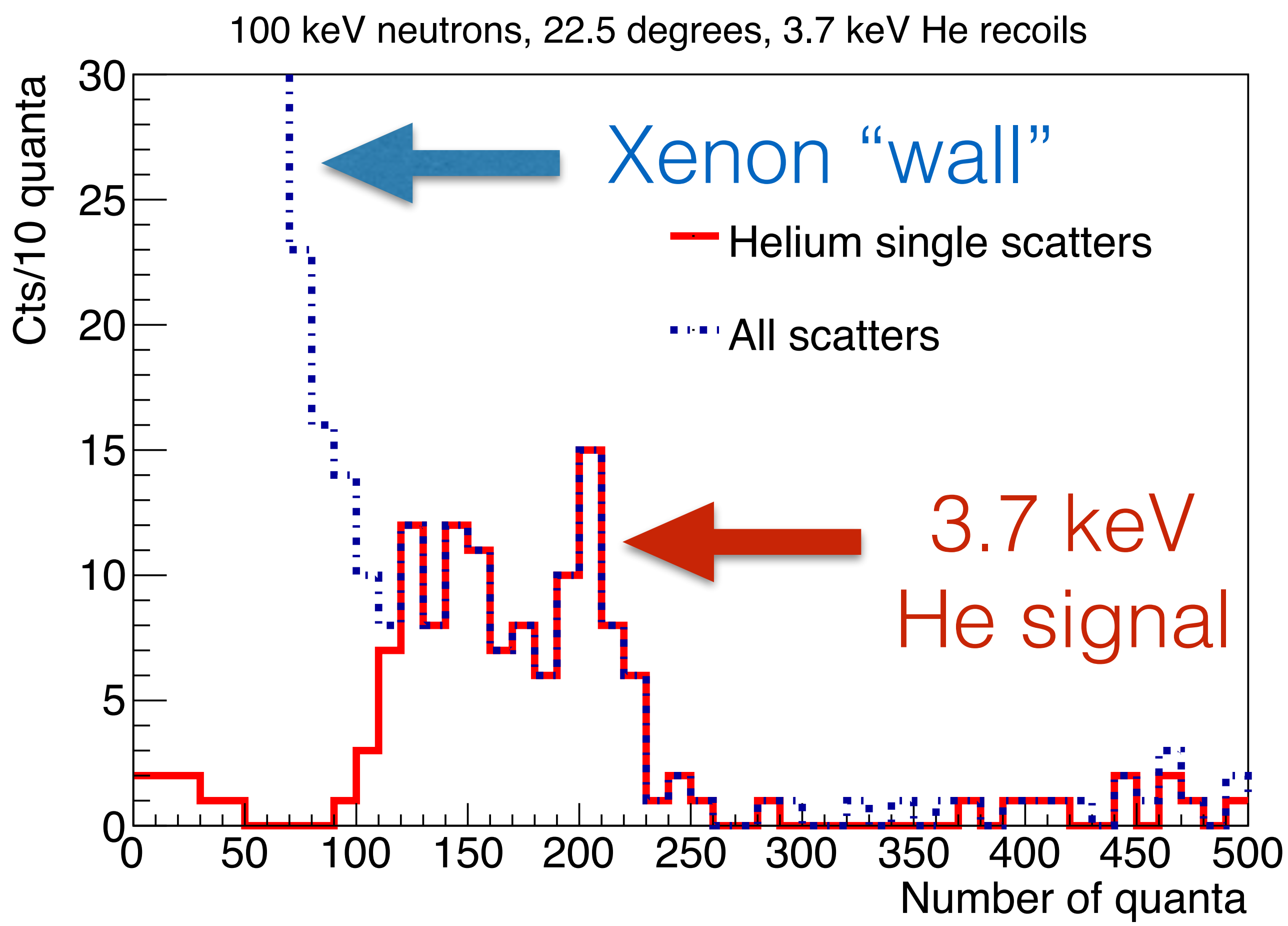

- Time of flight to measure the neutron timing
- Pulse shape discrimination(PSD) to select neutrons in the detectors
- Ntof - time between beam pulse and neutron detector
- TPCtof - time between beam pulse and LAr detector
- f90 - PSD in LAr
- Npsd - PSD in neutron detector

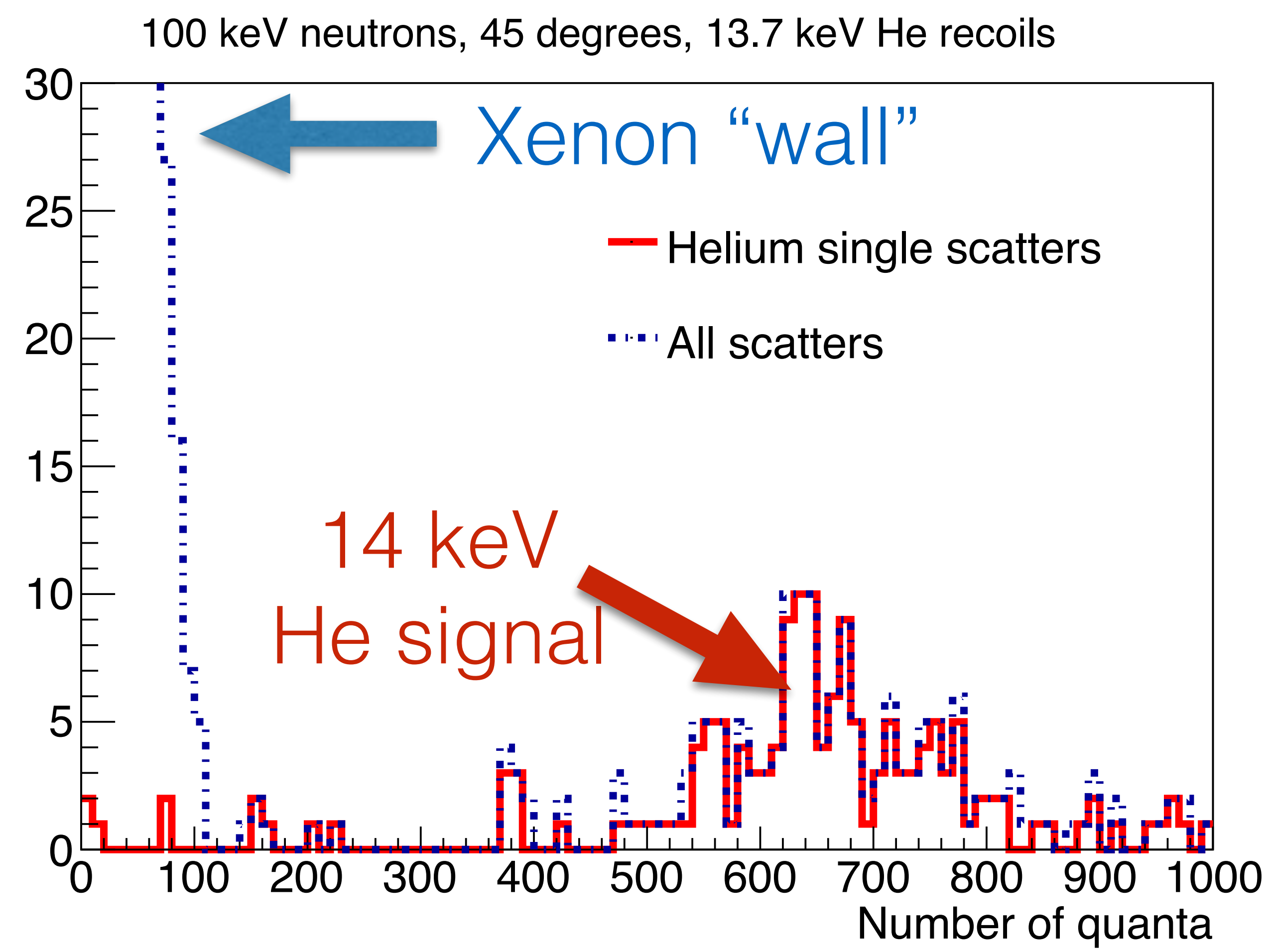


# Neutron scattering with He in LXe

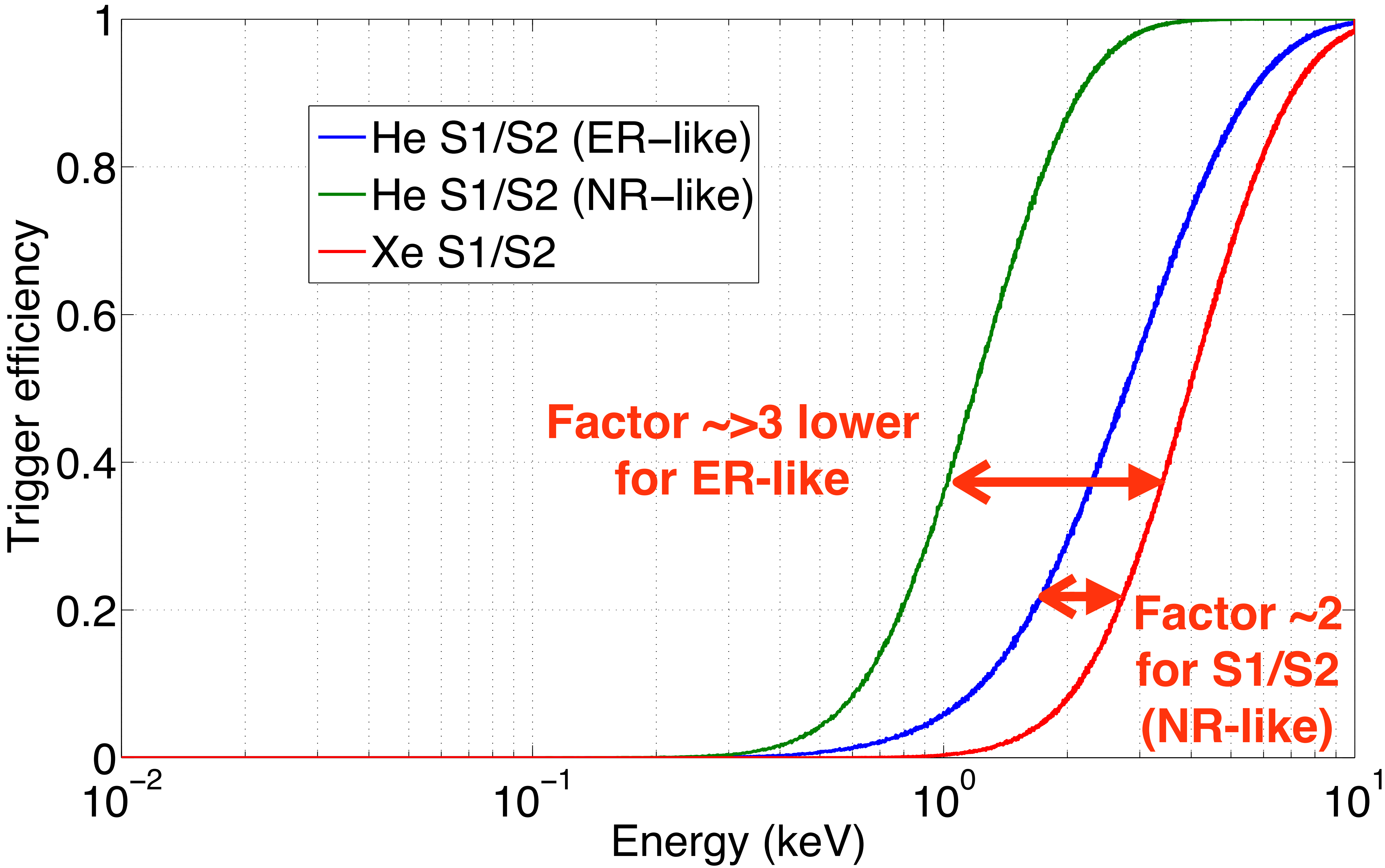
- In a doping measurement, for a given scattering angle, He recoils have more energy
  - Increased signal on top of that
- Pushes the peak out past the xenon background




Measures yield and S1/S2 response v. energy!

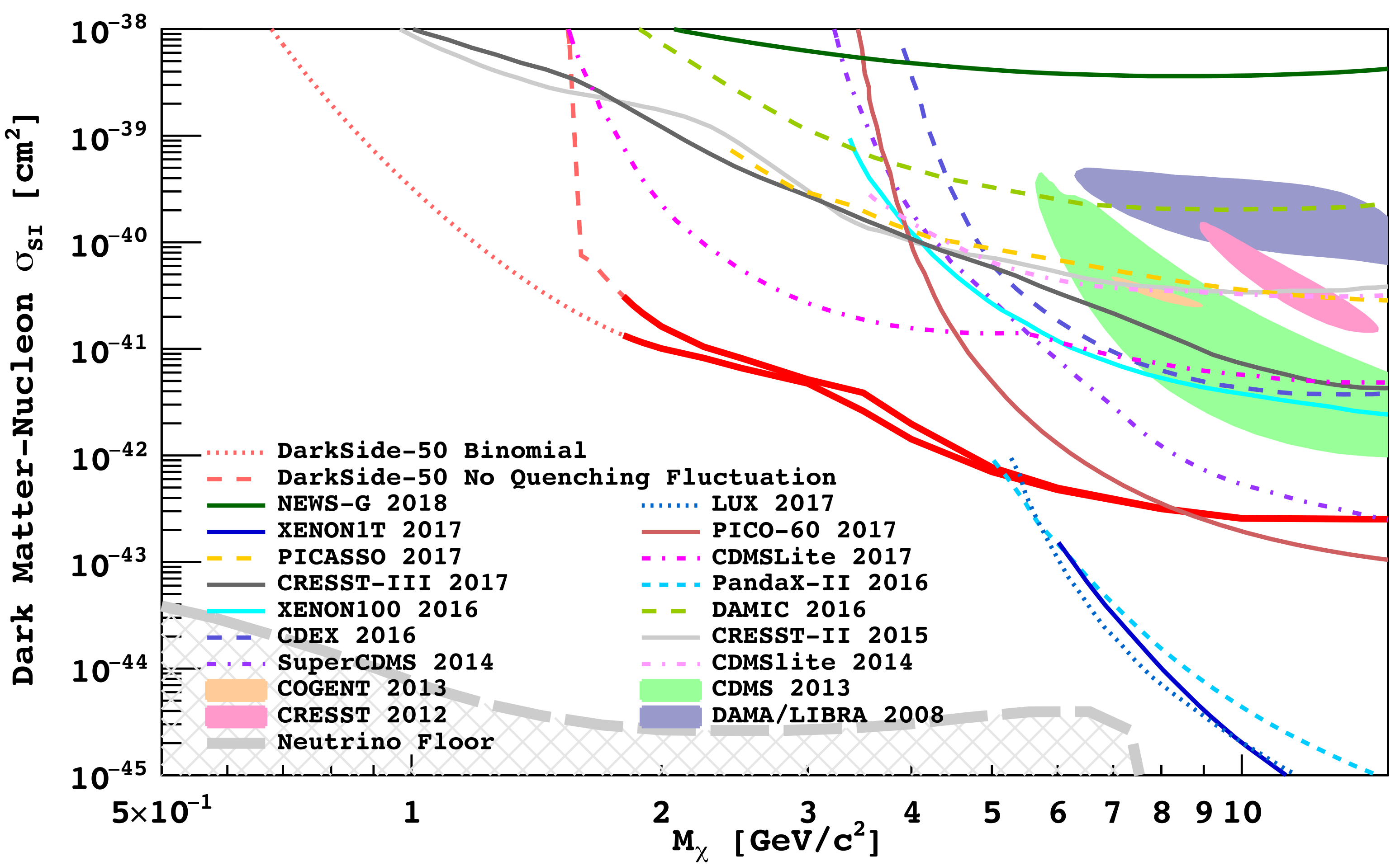
# Energy threshold



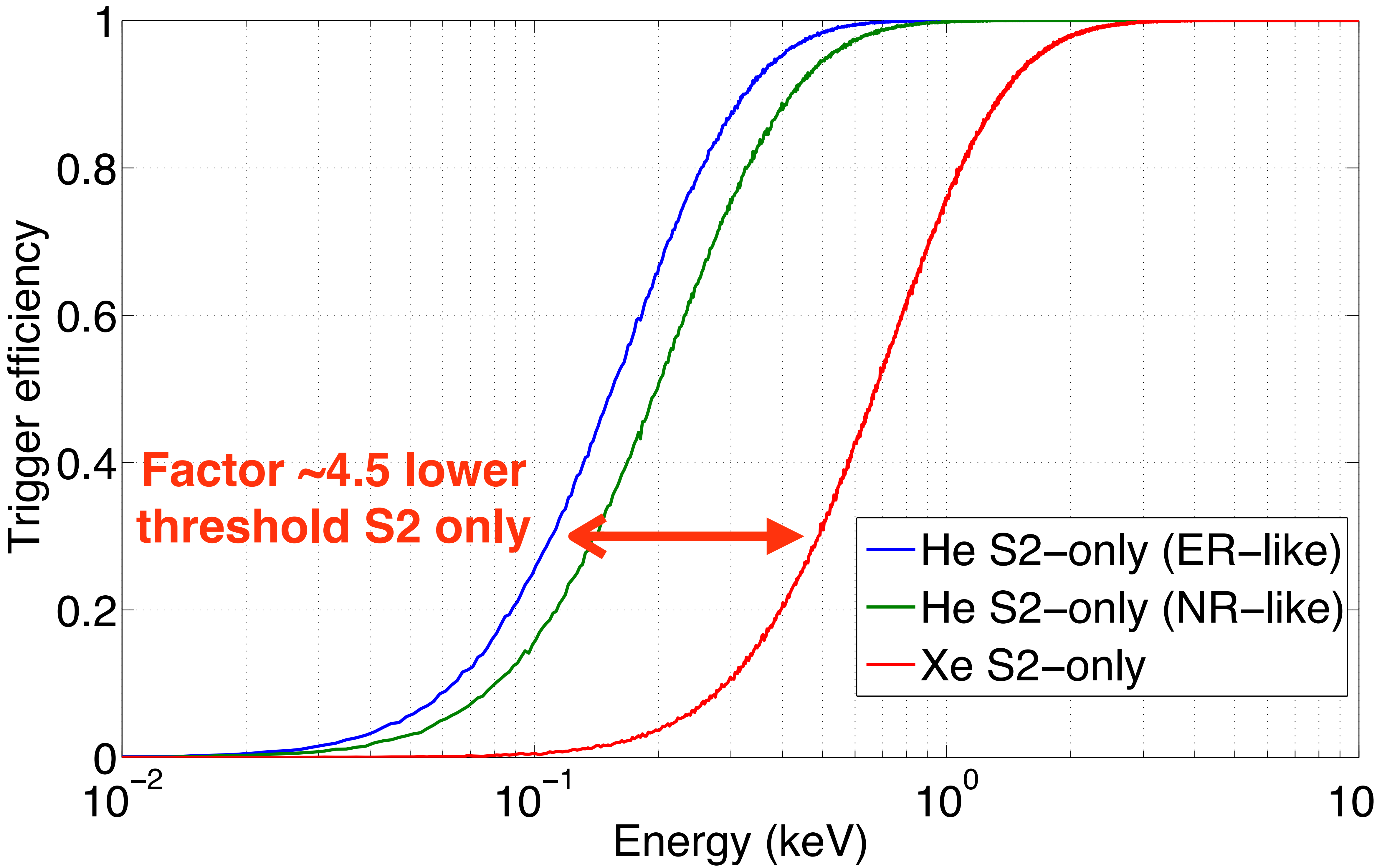
# S2-only analysis

- Photon detection efficiency (S1) is about 10%
- Electron detection efficiency is (we hope) about 100%
  - High gain on S2 channel (80 phd/e-)
- Enables much lower threshold if you look at “S2-only”

- Give up ER/NR discrimination
- Subject to single electron noise
- Still very powerful



# Energy threshold




- 3 electron threshold assumed for S2 (>210 photons)

# Making projections

- At very low thresholds (where we want to go), we hit coherent scattering of neutrinos

$$\frac{R_{\nu,\mathrm{coh}}}{R_\chi} \sim N^2/A^2$$

- In doped LXe, N is still ~70, but A is now 4 or 20, instead of ~130
- Hit the neutrino background at x1000 higher WIMP cross section for helium