Doping liquid xenon with light noble gases

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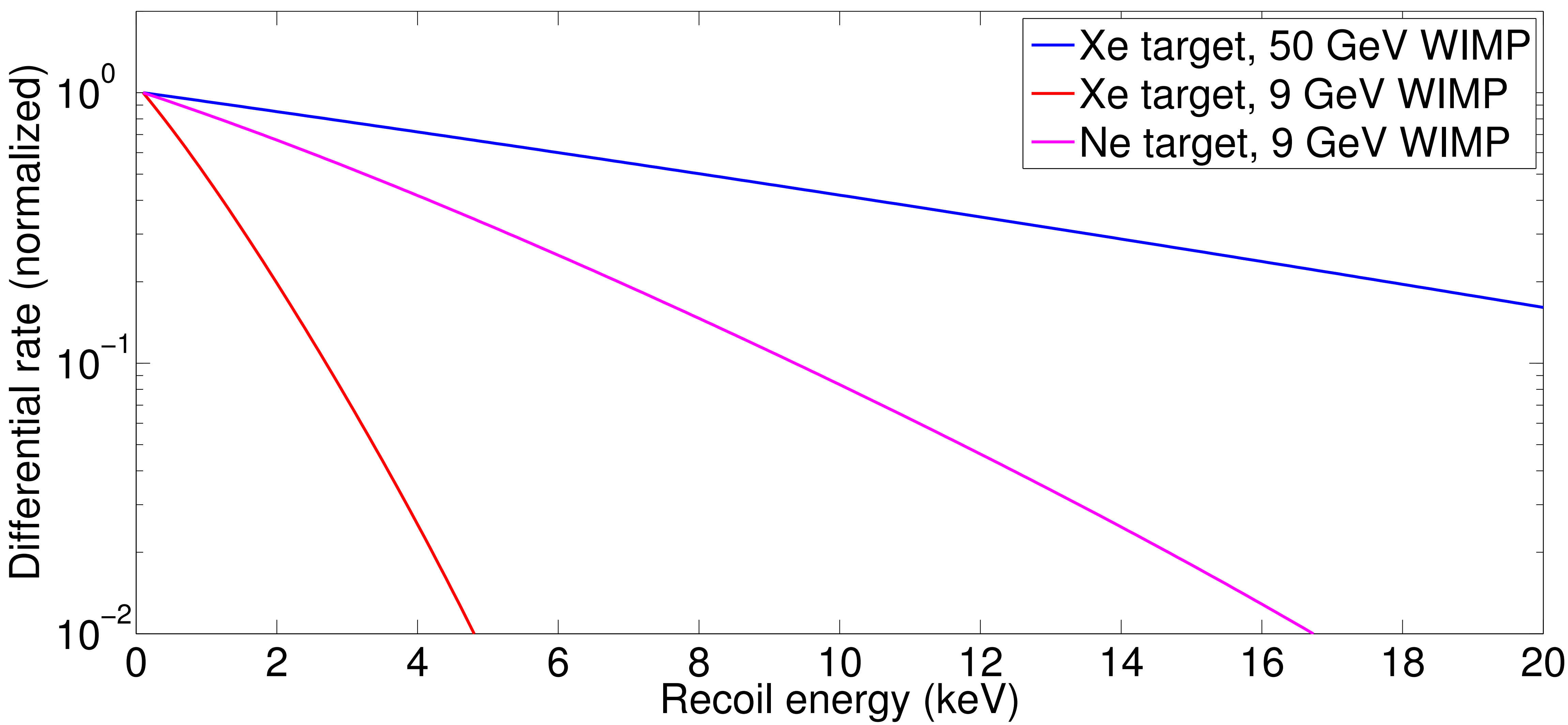
Low Mass Dark Matter (<10 GeV)

- An original DM candidate (Lee and Weinberg 1977)
- "Ruled out" (or at least not thought about much) for many years
- DAMA excess brings them back - turns out they weren't ruled out
    - In last decade, several anomalies add excitement
        - e.g. Pamela/FERMI CoGeNT/CDMS-Si/CRESST
- Many anomalies are now resolved, but excitement remains
    - "I think light WIMPs are *more* theoretically motivated than 10 years ago" - Neal Weiner, CIPANP 2015
- Supersymmetry, asymmetric dark matter, minimalist, dark sector, etc.
    - Many existing candidates that evade all constraints, including collider constraints

What do you need for low mass?

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



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$$v_m = \sqrt{Q m_N / 2 m_r^2}$$

$$v_{esc} = 544 \, \mathrm{km/s} \; (\text{current value})$$

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 $m_n = m_\chi$

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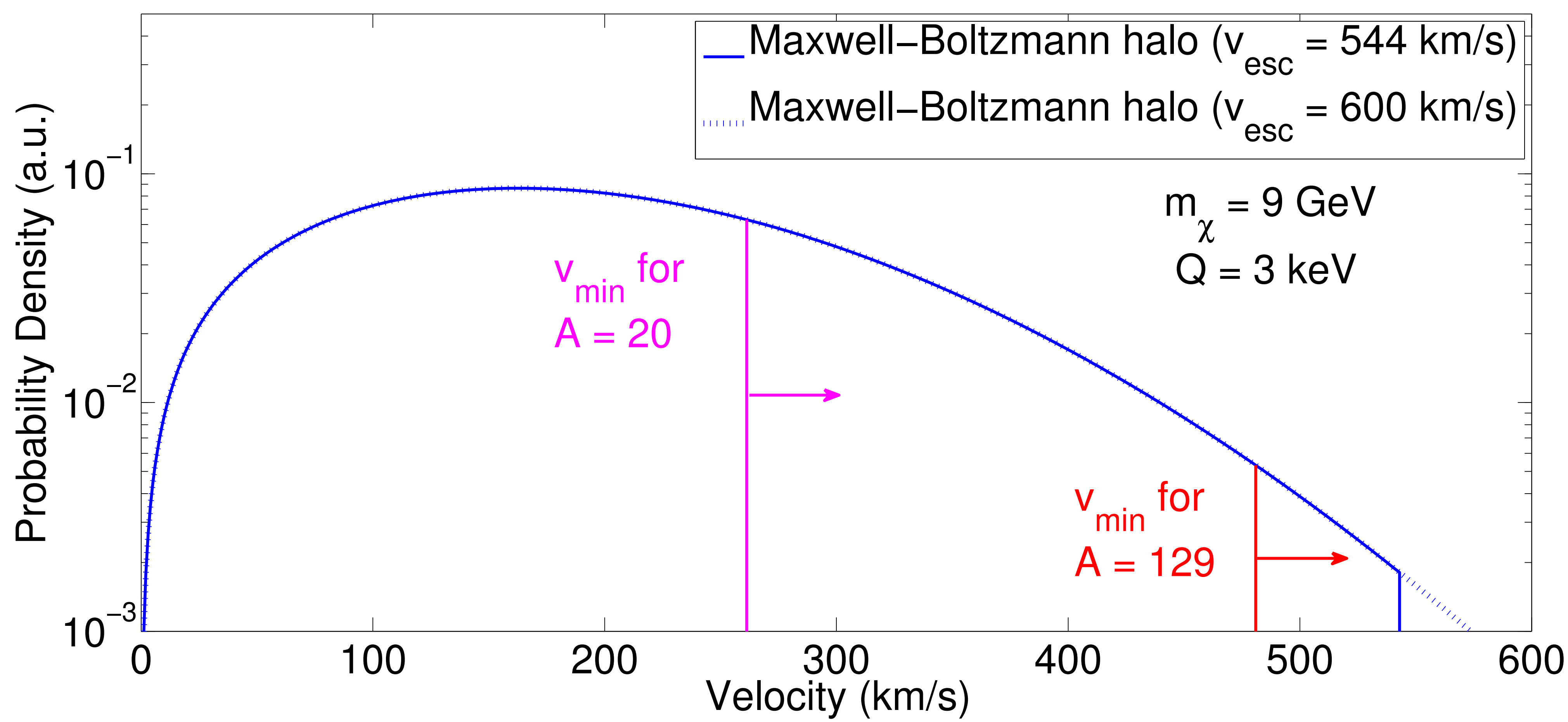
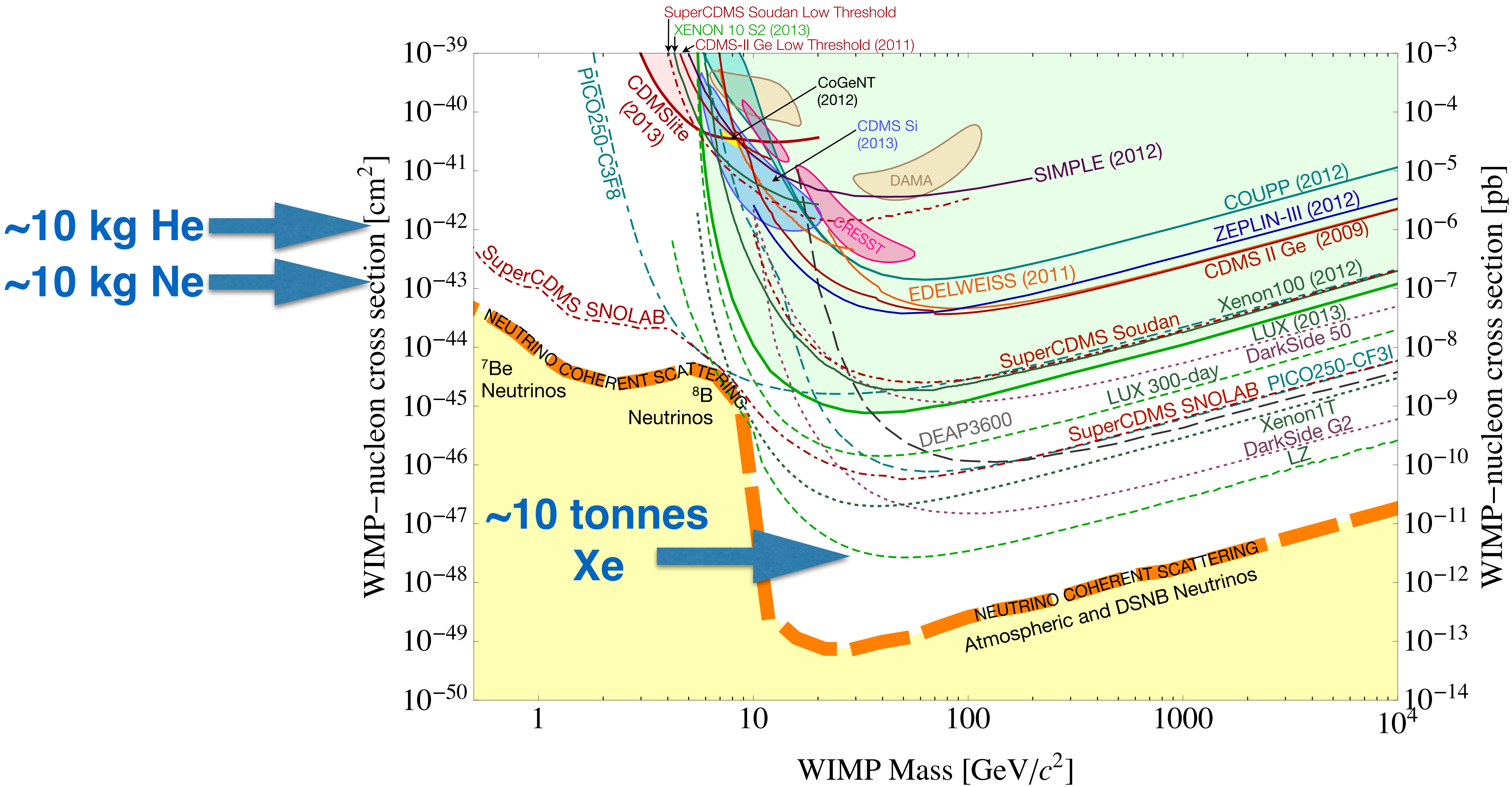


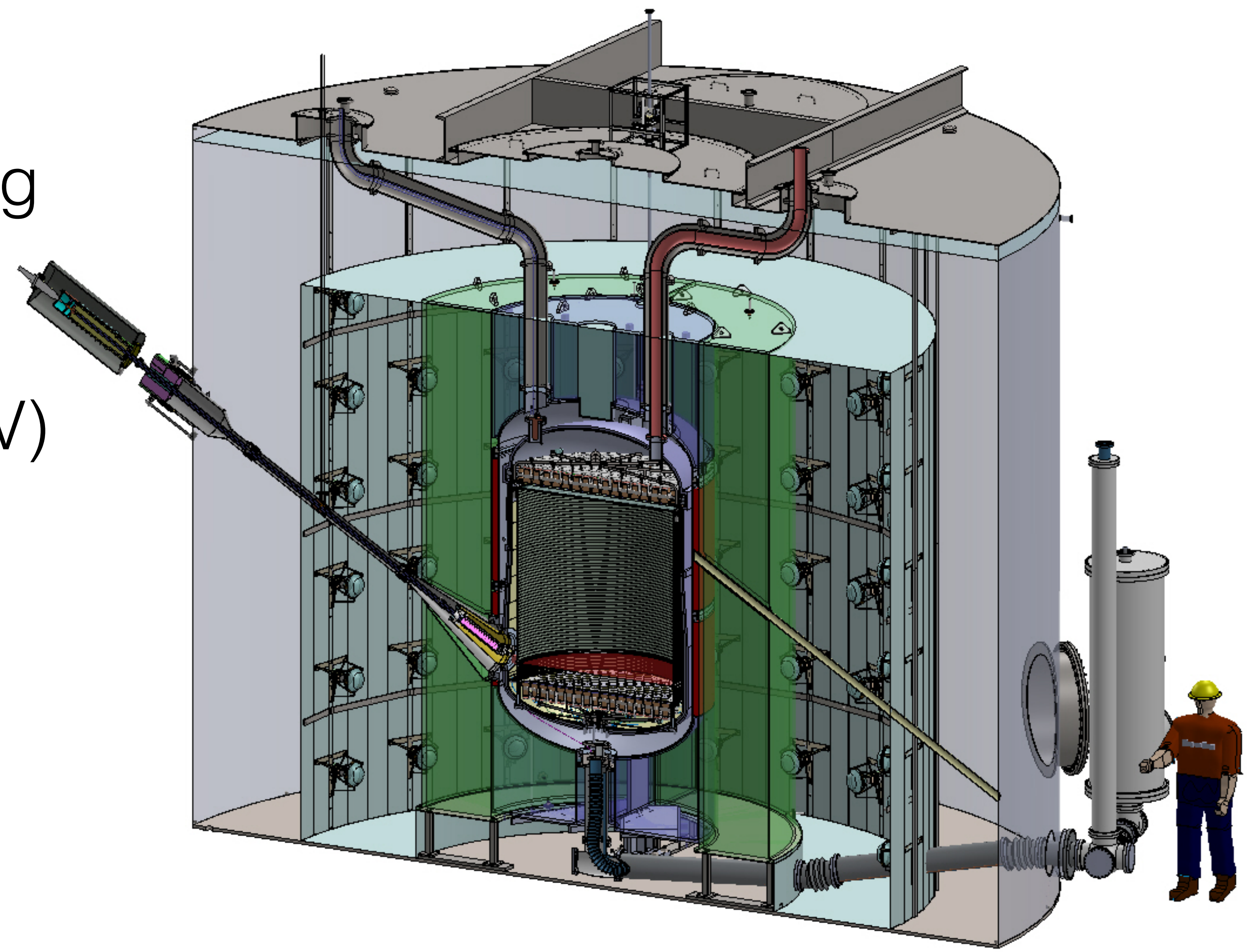
What don’t you need for low mass?

- A lot of mass



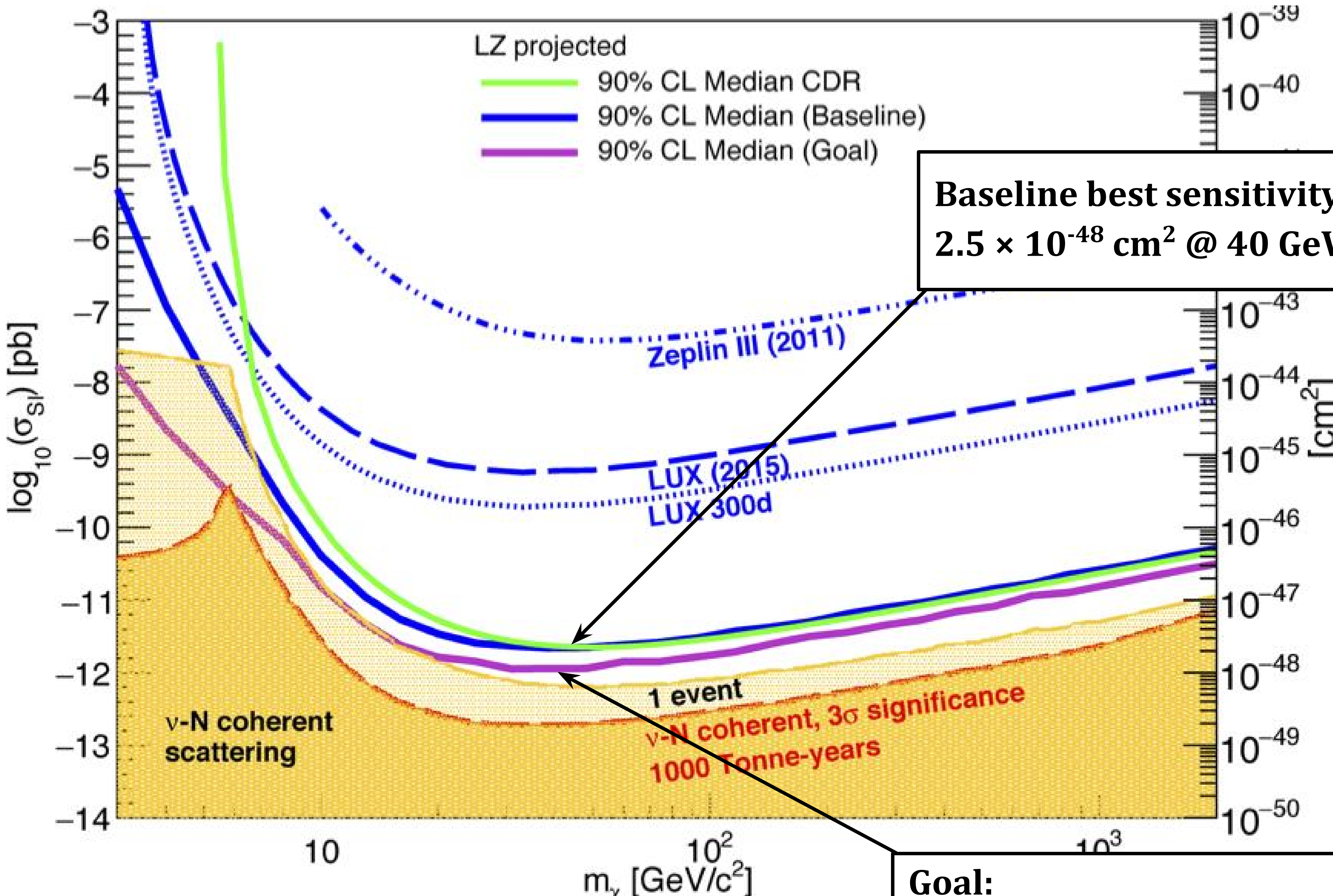
LUX-Zeplin (LZ)

- 7 tonne active LXe TPC
  - Heavy target
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
- 31 institutions, ~200 people
- To be located at Sanford Lab in SD



LUX-Zeplin (LZ)

5600 kg fiducial, 1000 live-day exposure



Baseline best sensitivity:
2.5×10^{-48} cm^2 @ 40 GeV/c^2

Goal:
1.3×10^{-48} cm^2 @ 40 GeV/c^2

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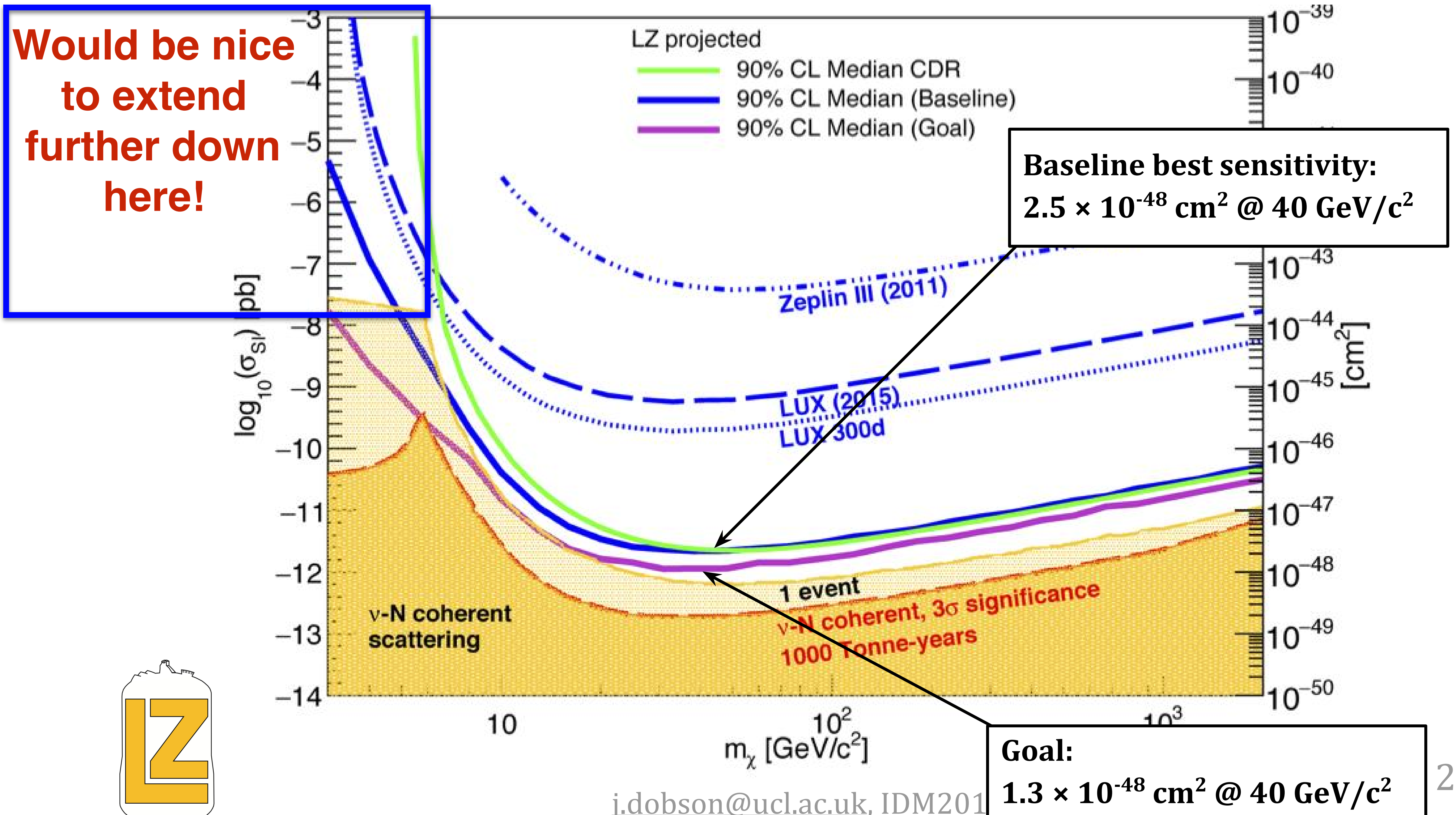
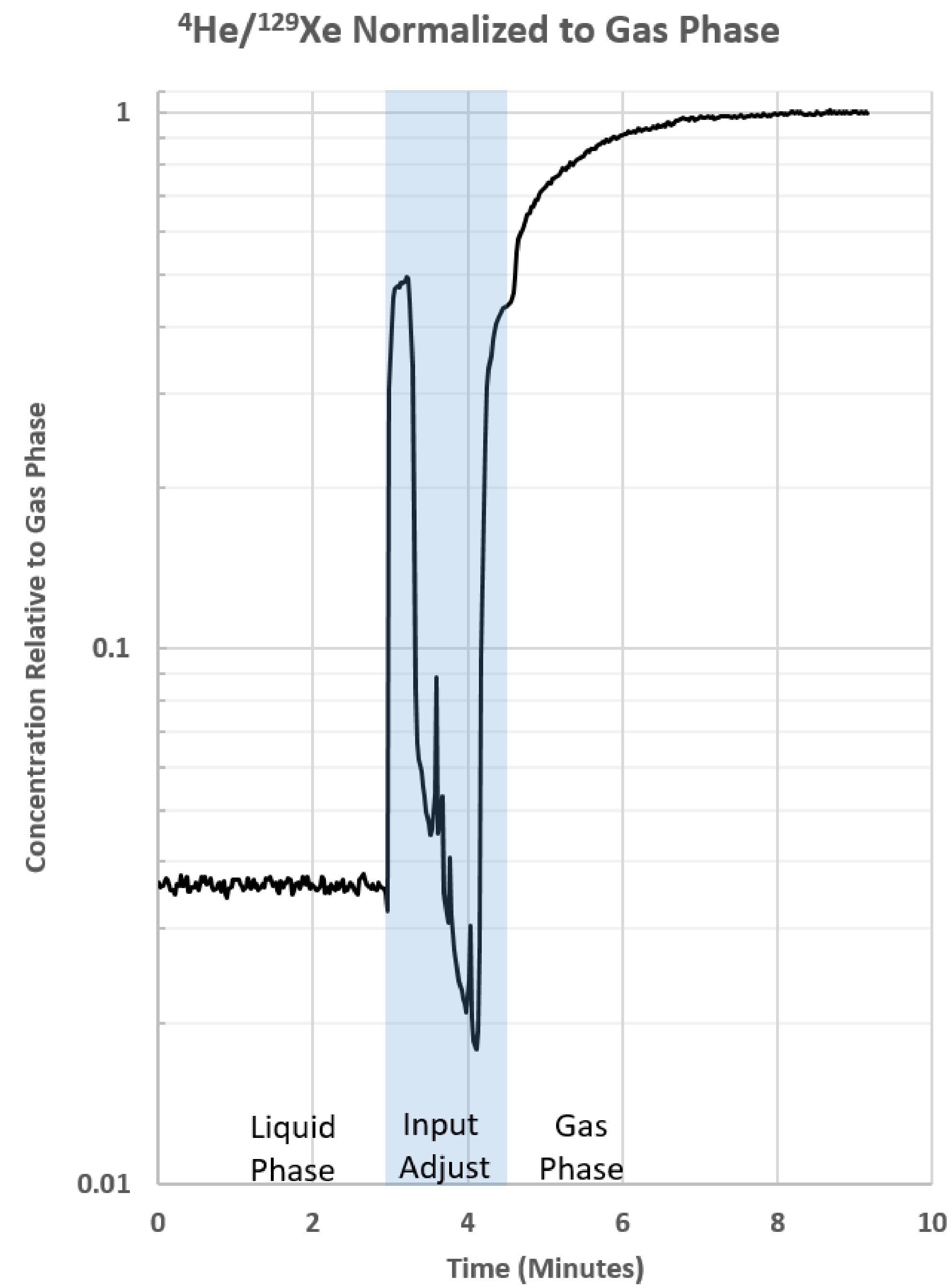


Can we add He/Ne to LXe?

- Dissolve small quantities of He or Ne in liquid xenon
- Extend the reach of a detector like LZ (or Xenon1T or PandaX, etc)
- Add new targets to field of direct detection
  - No current experiments using helium or neon
- Capitalize on investment in large detectors by adding flexibility

How much could we get in?

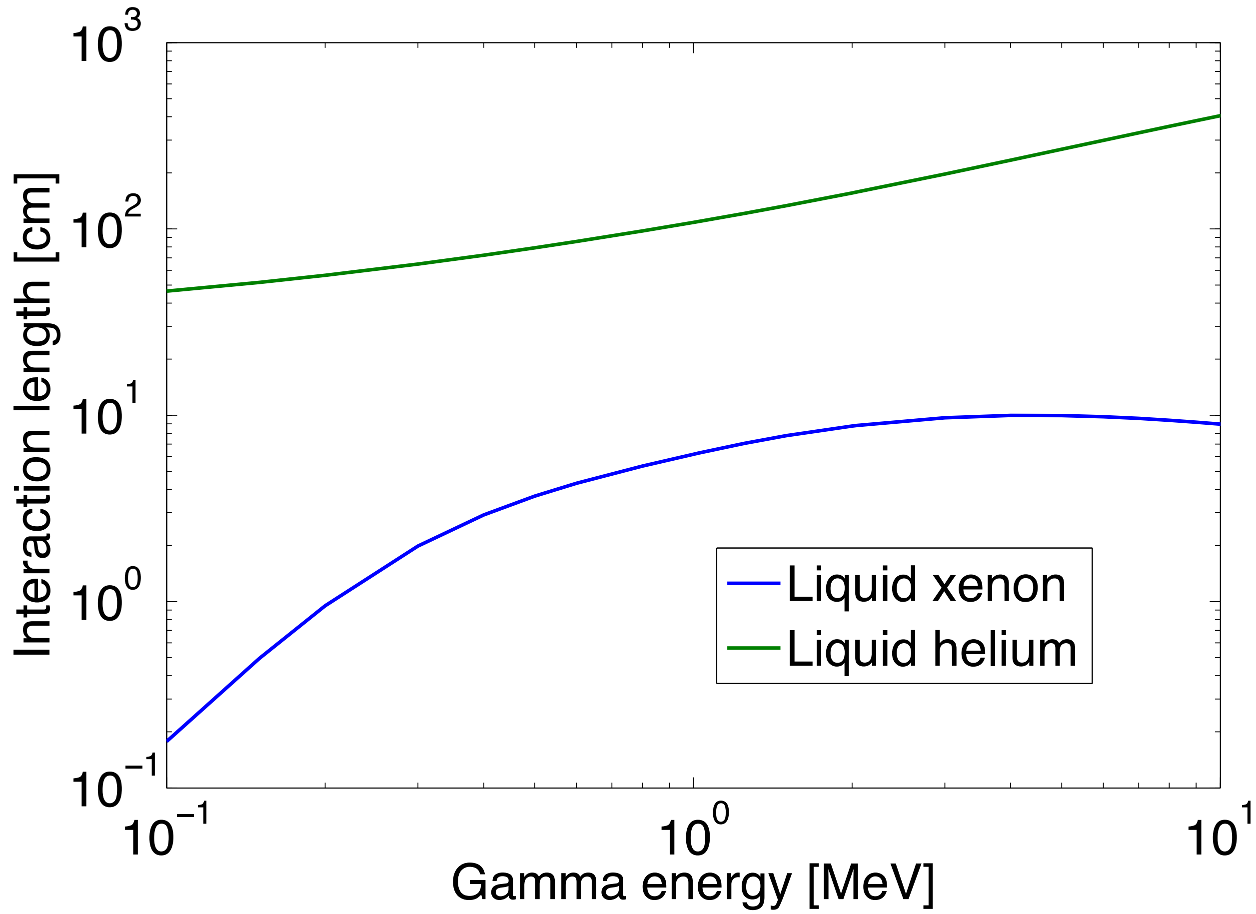
- No published measurements
- Preliminary test at Fermilab shows 0.1% He in LXe by mass is easily achievable
  - 1 bar of partial pressure
  - Consistent with measurements from LUX
- Expected to scale with mass ratio (e.g. 0.5% Ne)
- Can we get more in?
  - Temperature dependence?



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

Backgrounds

- Helium and neon have no long lived isotopes
    - No new backgrounds introduced
- Detector is already built of low background materials



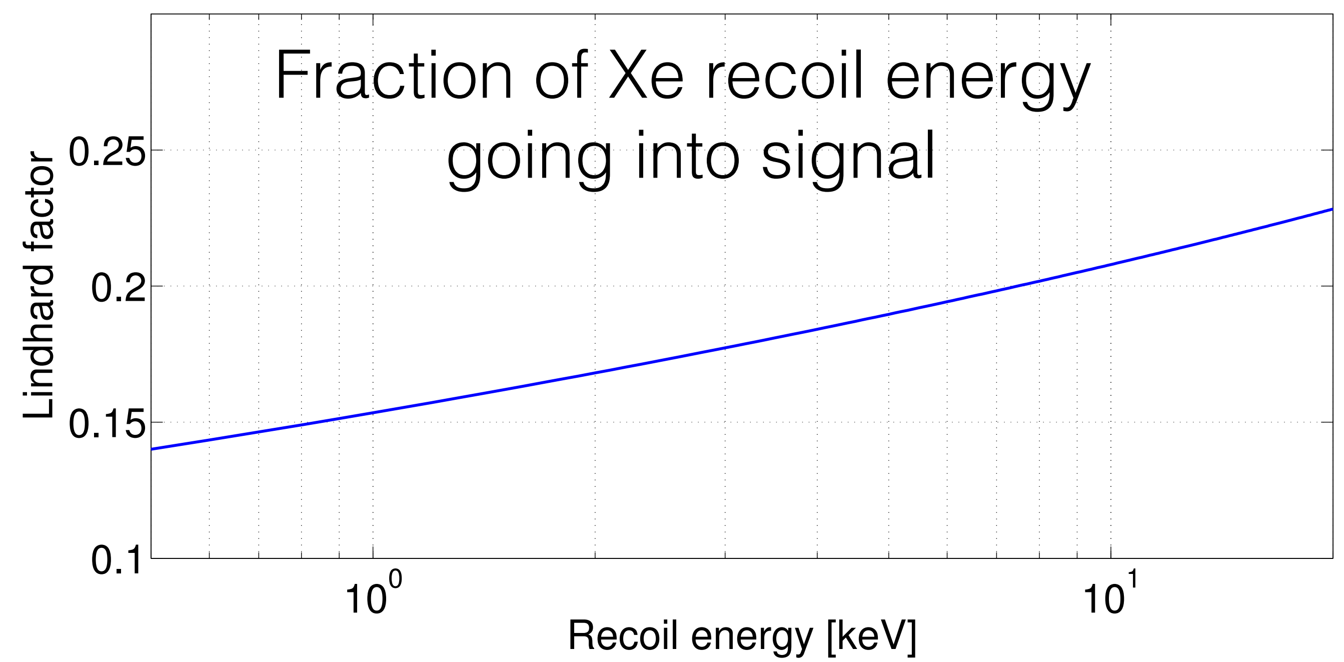
- Keep excellent self shielding of LXe (not possible with LNe or LHe-only detector)

Signal detection

- Helium and neon scintillate in harder UV
    - 80 nm vs 175 nm in LXe
- Those photons will wavelength shift in the xenon to 175 nm
    - See, for example, xenon doped in argon (JINST 9, P06013, among others)
- Keep same photon detection scheme!

Signal yield

- Strong quenching factor for nuclear recoils in liquid xenon (Lindhard factor)
    - Less than 20% of a 7 keV recoil event goes into detectable signal
    - The rest goes into nuclear collisions that lead to heat



- Helium/Neon are light nuclei, meaning more energy goes into electronic channels -> more signal

Signal yield

Recoil	Lindhard	SRIM
Xenon	0.02	0.02
Neon	0.20	0.09
Helium	0.68	0.69

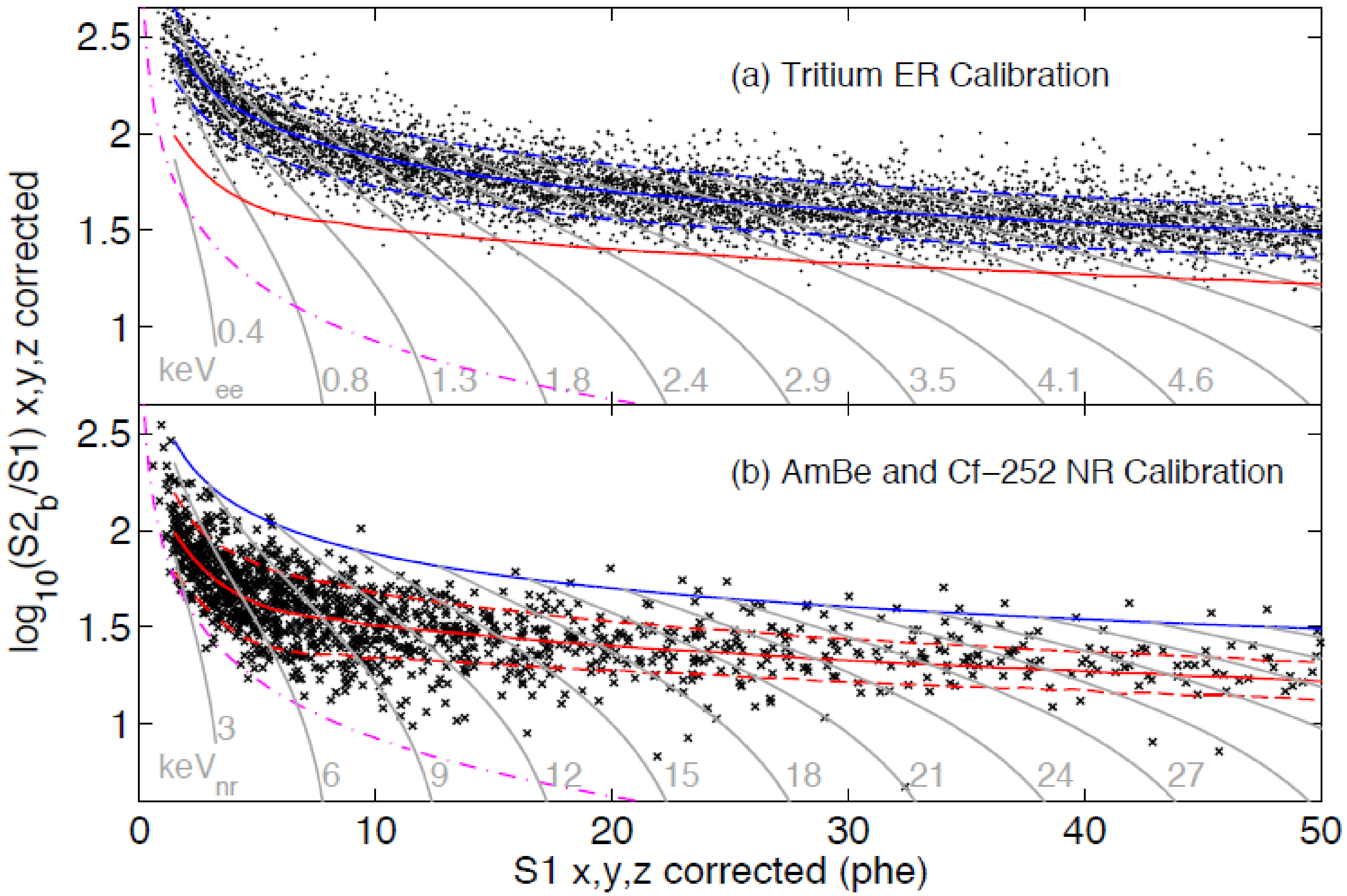
Table 1: Estimated fraction of energy given to electronic stopping for nuclear recoils (not accounting for secondary cascades) from Xe, He, and Ne recoils in LXe, calculated using Lindhard theory [41] or the SRIM simulation package [42].

- At worst, we can expect a factor of 3.5 more signal for helium recoils in LXe

Even lower thresholds with the light target!

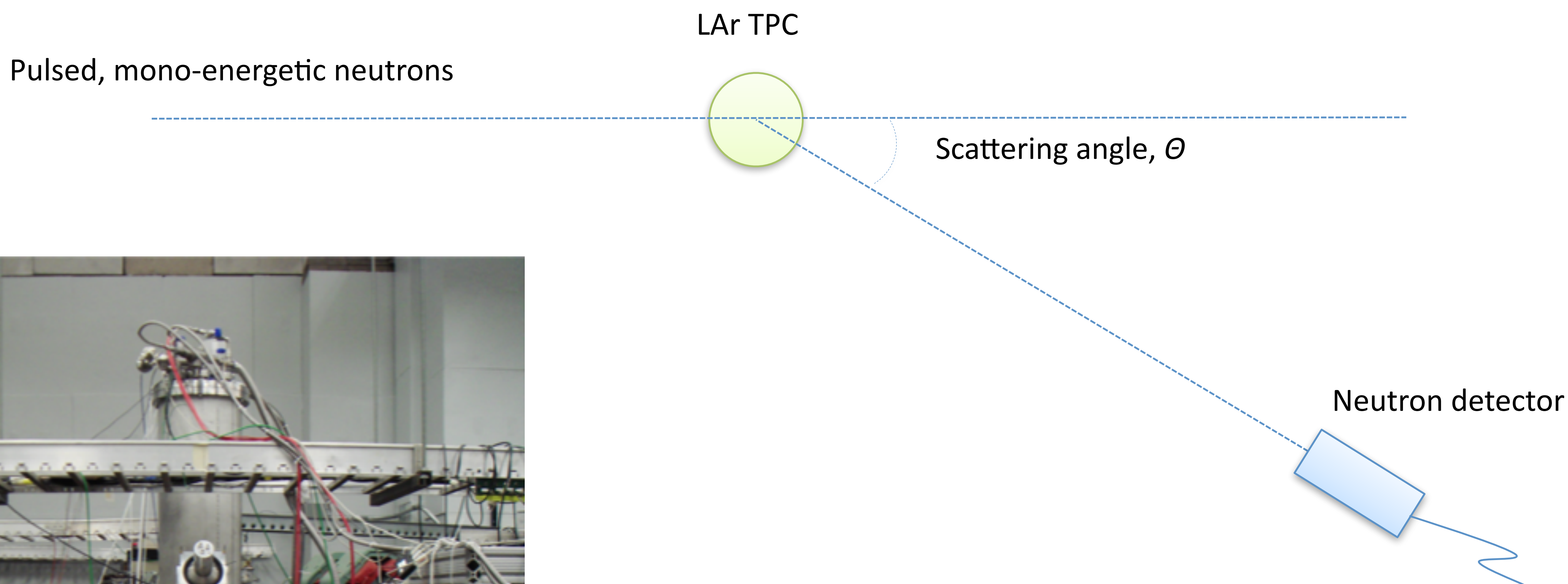
Key questions

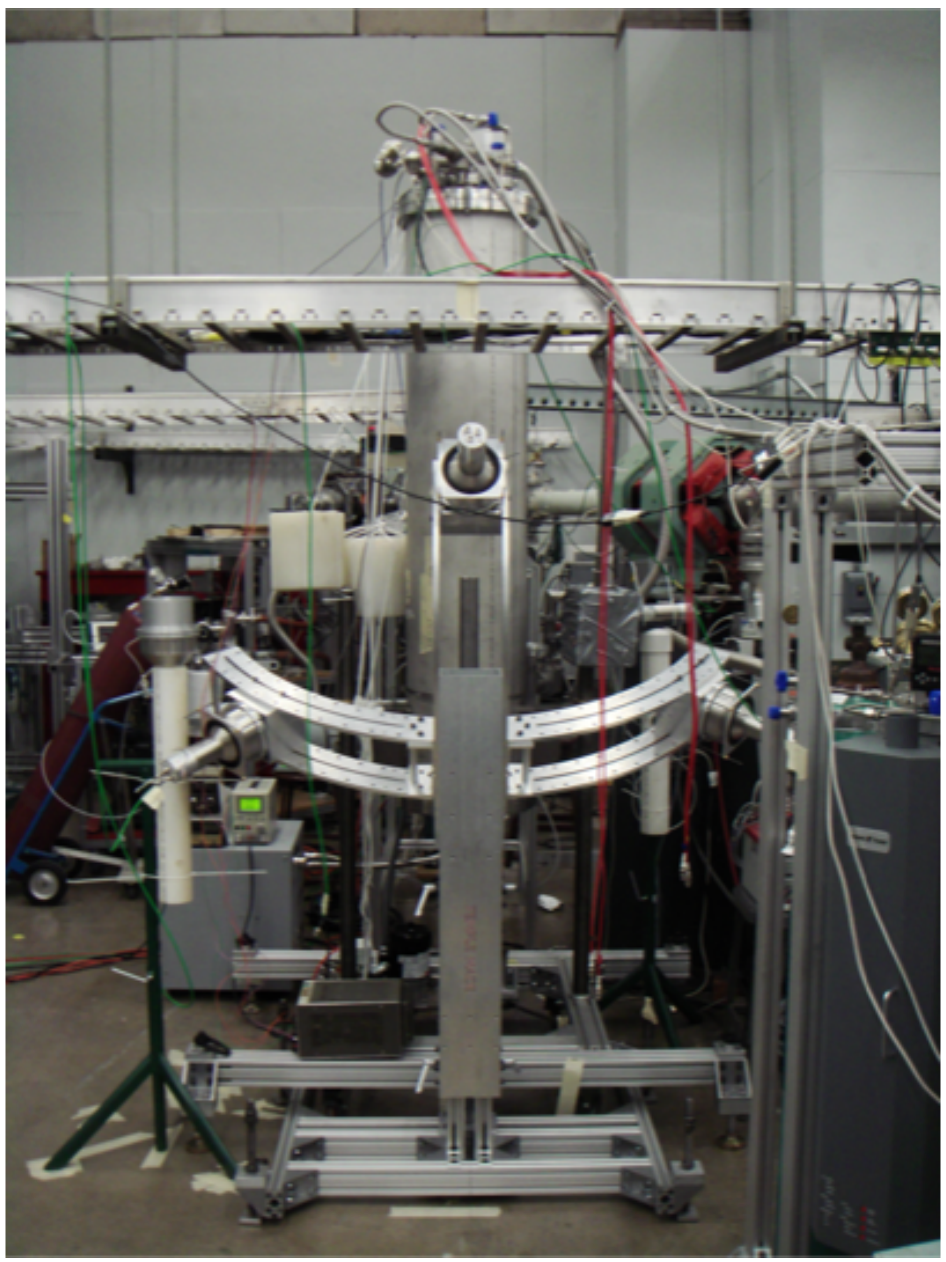
- What is the true signal yield?
- What happens to discrimination?



LUX data
PRL 112, 091303

SCENE

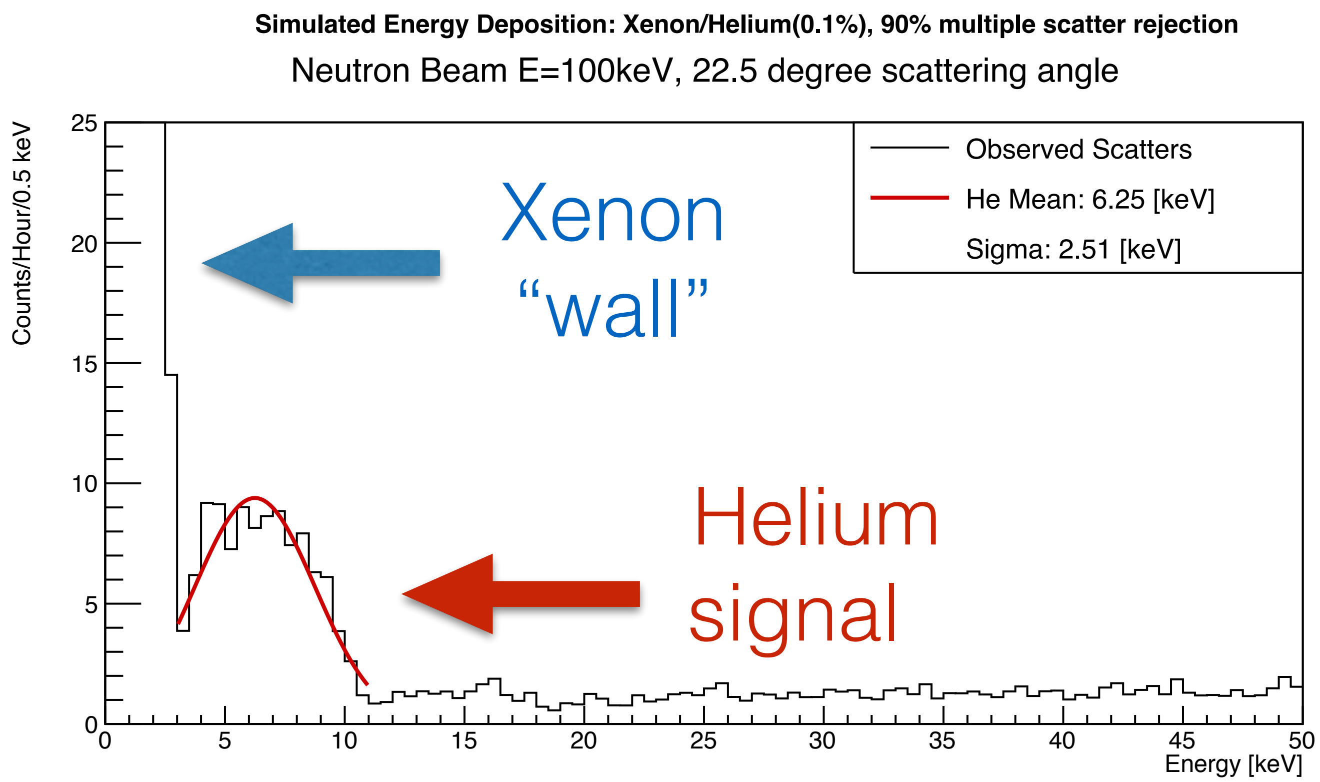


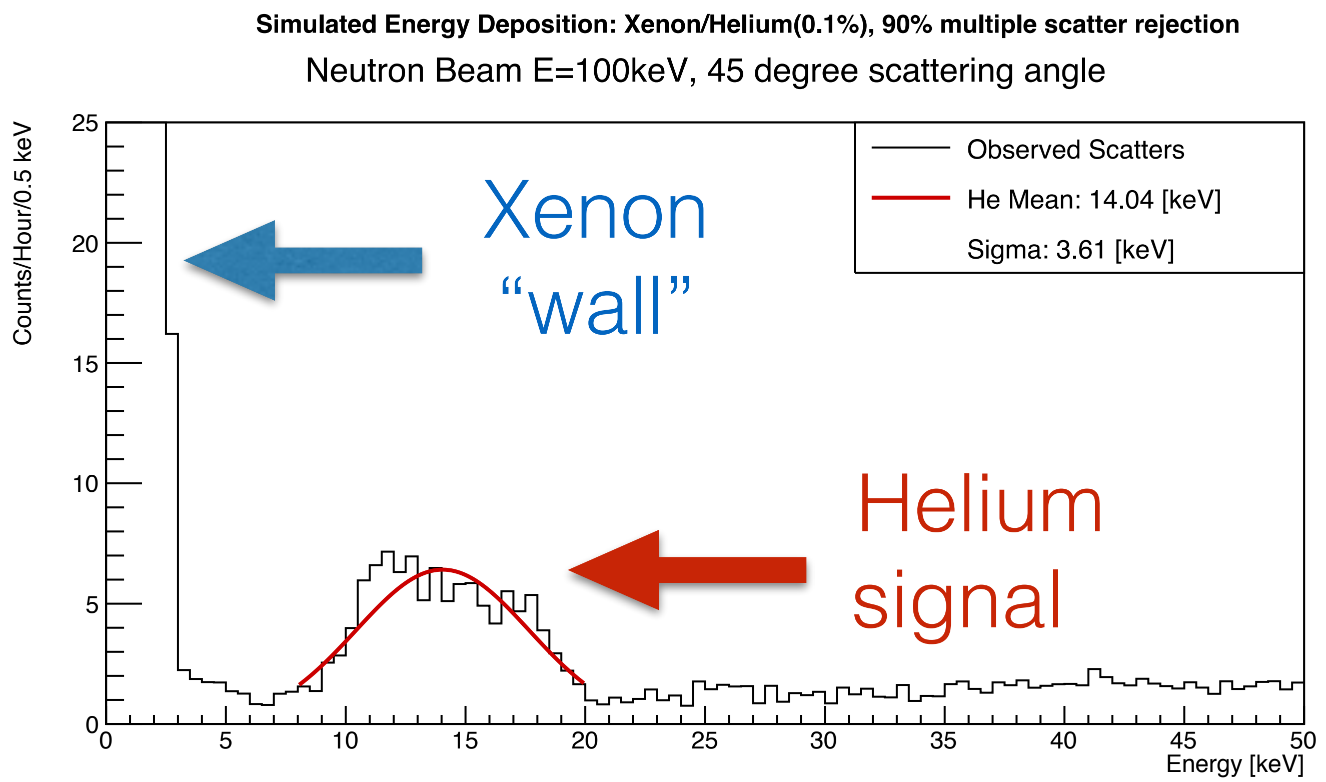


- Pulsed, monoenergetic beam (at Notre Dame) to measure response of to nuclear recoils of known energy
- Tunable nuclear recoil energy by changing the neutron energy and the scattering angle
  - Neutrons of 500 keV - 1.5 MeV
  - Recoils of a few keV up to 50 keV
  - Successful measurements in LAr (1406.4825, 1306.5675)

SCENE

- For doping measurement, for a given scattering angle, He/Ne recoils have more energy
  - Before accounting for increased signal
- Pushes the peak out past the xenon background





SCENE-like measurement measures yield and S1/S2 response v. energy!

He/Ne 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/Ne recoils ✓
    - Lower energy thresholds for WIMP-He/Ne scattering ✓
- Properties measurable using existing techniques ✓

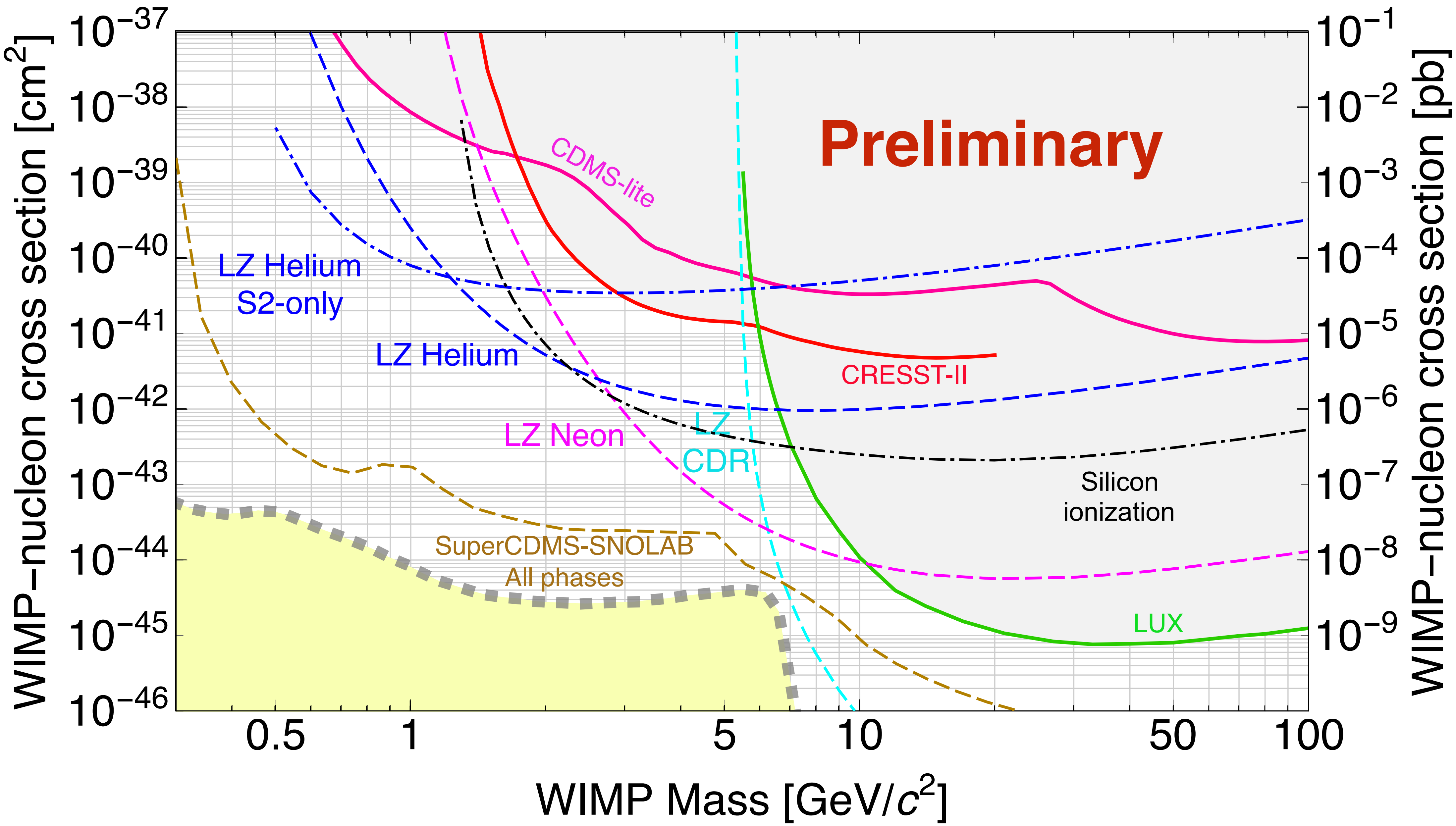
What's the catch?

- 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

Preliminary projection



- Location of LZ Helium lines depends critically on assumed signal yield (conservative assumption of factor of 3 shown here)
  - Can get around neutrino backgrounds with more He signal
- Currently not using any spectral information (cut and count is not ideal)

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- Coherent neutrino scattering background ⚠
- Possible mitigation with higher signal or spectral analysis ?

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- Possible mitigation with higher signal or spectral analysis

Worth further exploration!

Backup

He diffusion through PMT

- After pulsing from helium diffusion in tubes is a well known problem
- Diffusion exponentially suppressed by temperature (Arrhenius relationship)
- R11410 has a surprisingly thick window (3 mm)
- Calculation suggests 10 years at 1 bar/165 K before reaching significant after pulsing
- Needs confirmation…

Example for ET9226 PMT