Doping liquid xenon with light noble gases

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LIDINE
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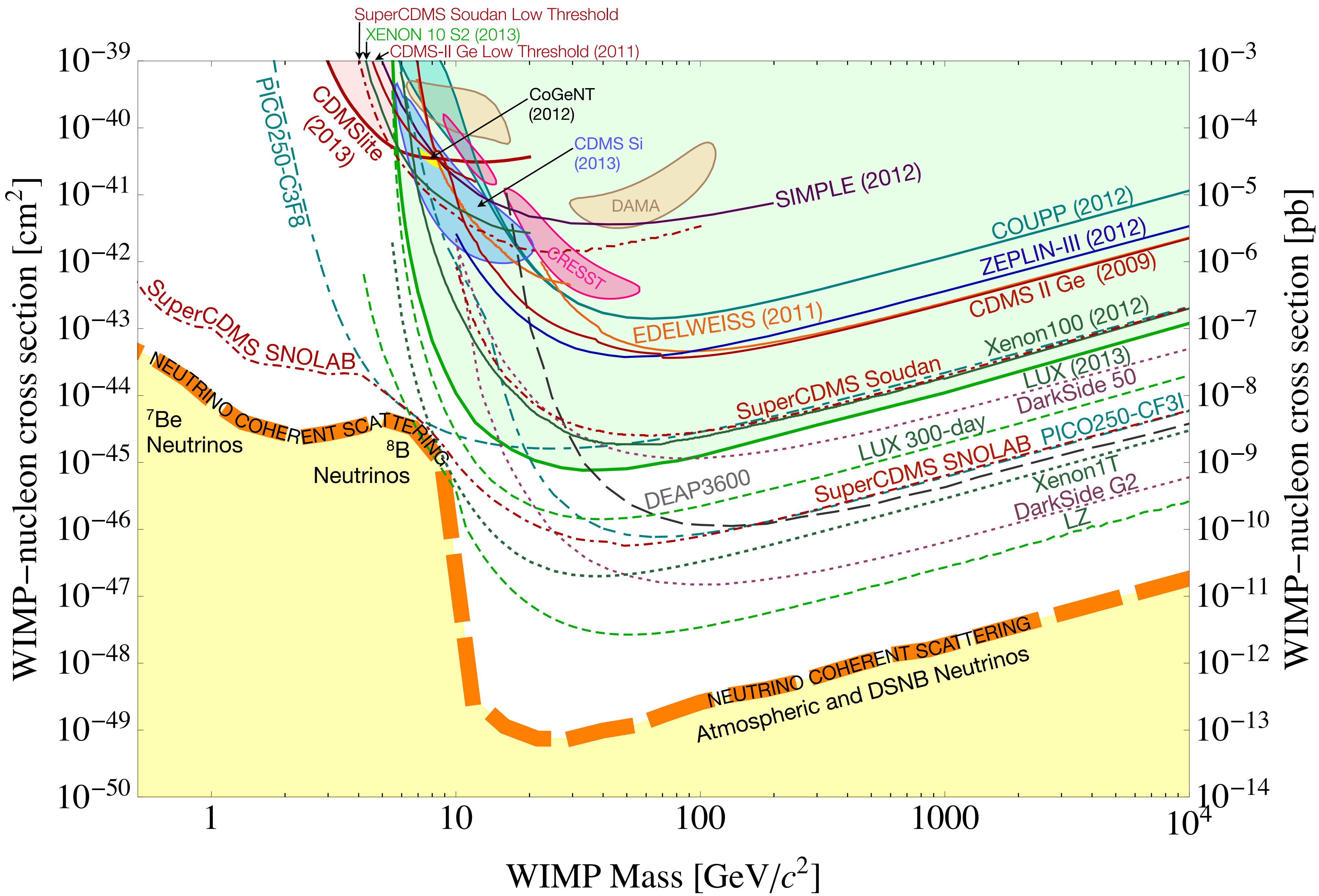
Low Mass Dark Matter (<10 GeV)



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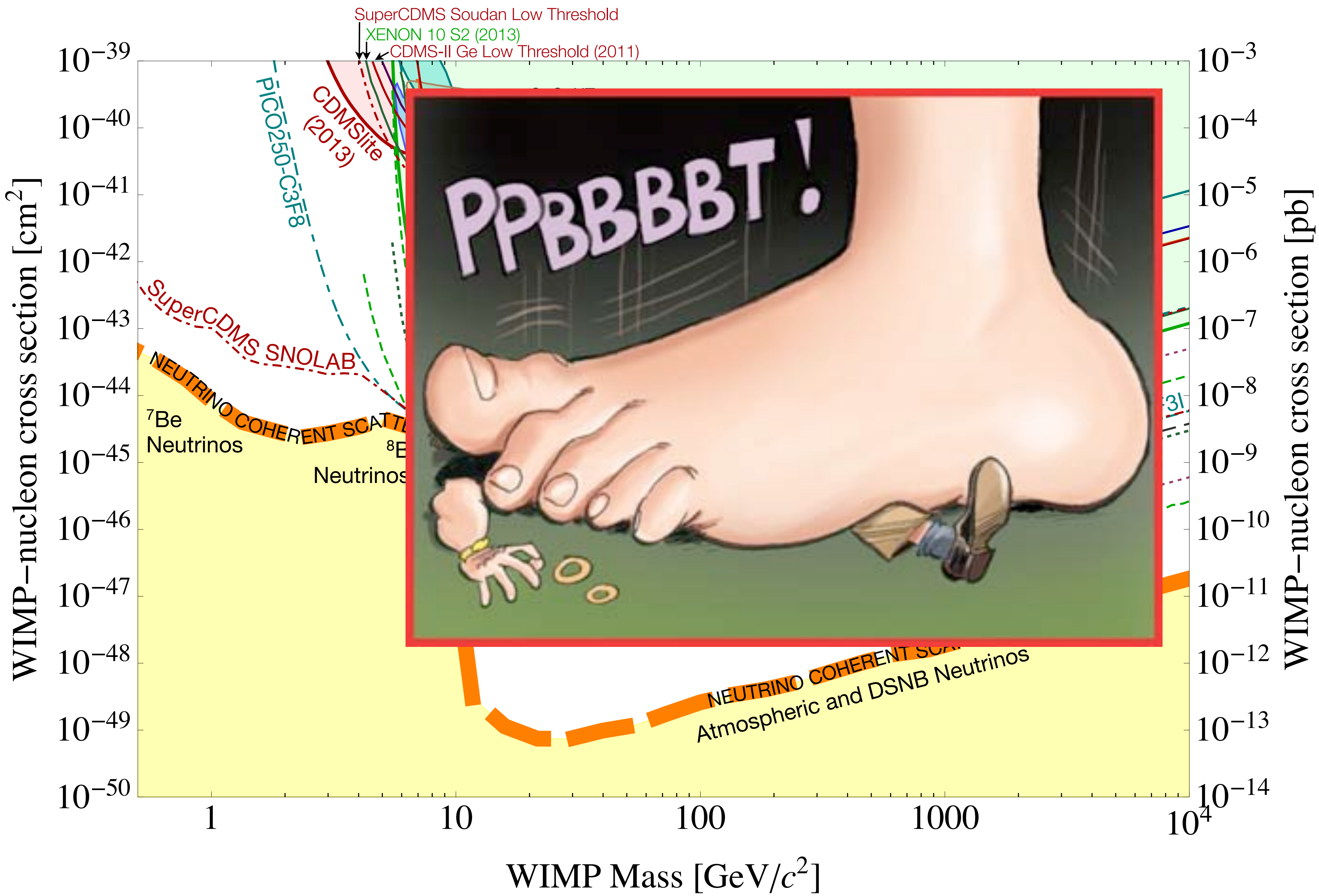
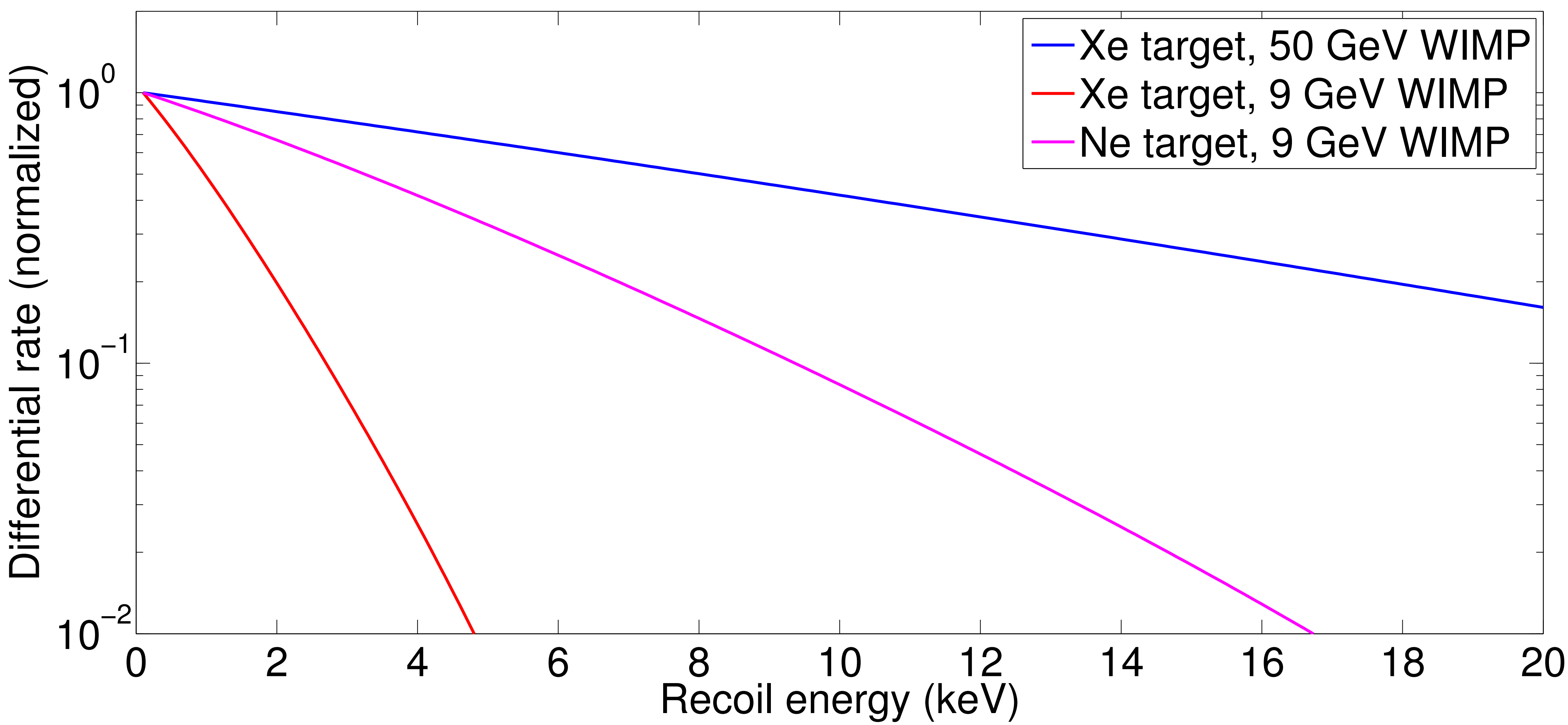


What do you need for low mass?

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



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

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

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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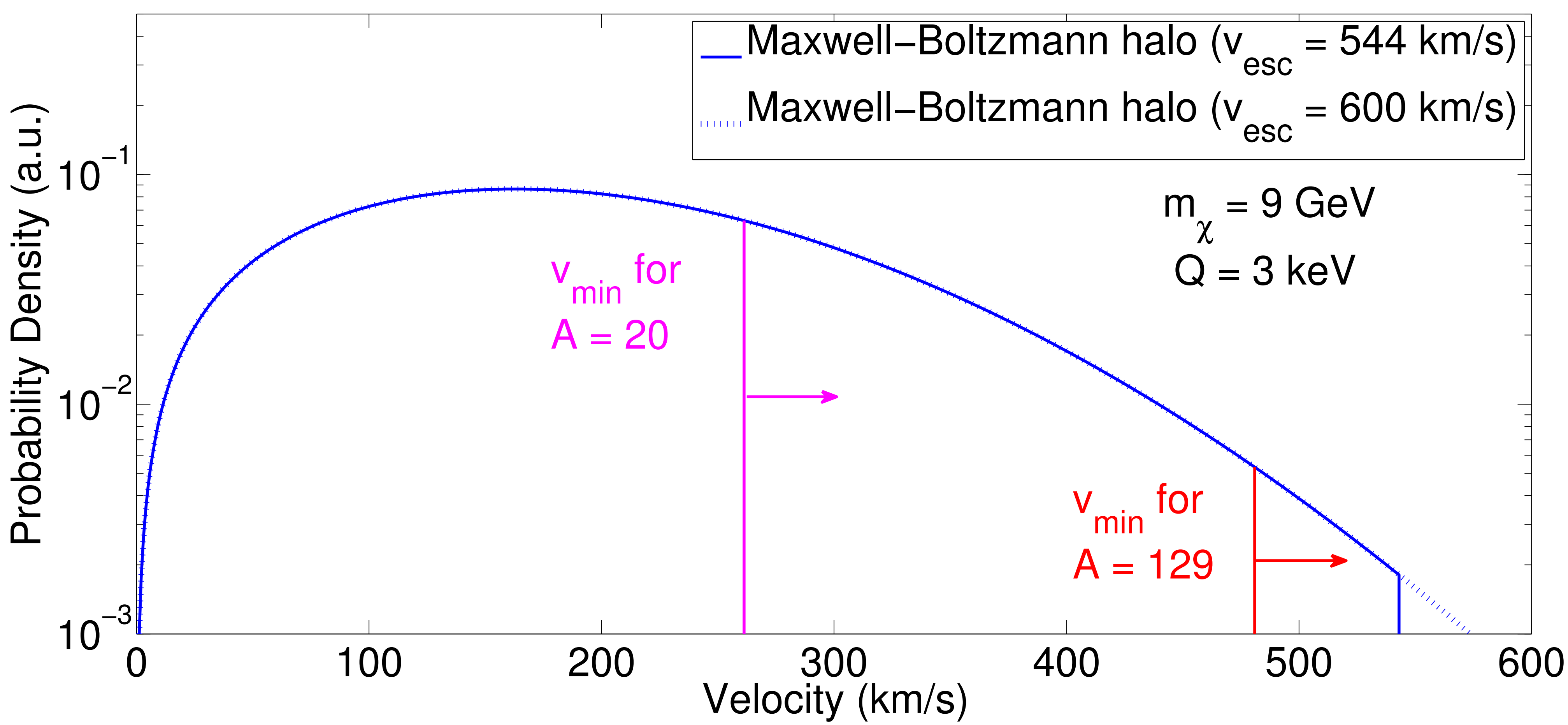
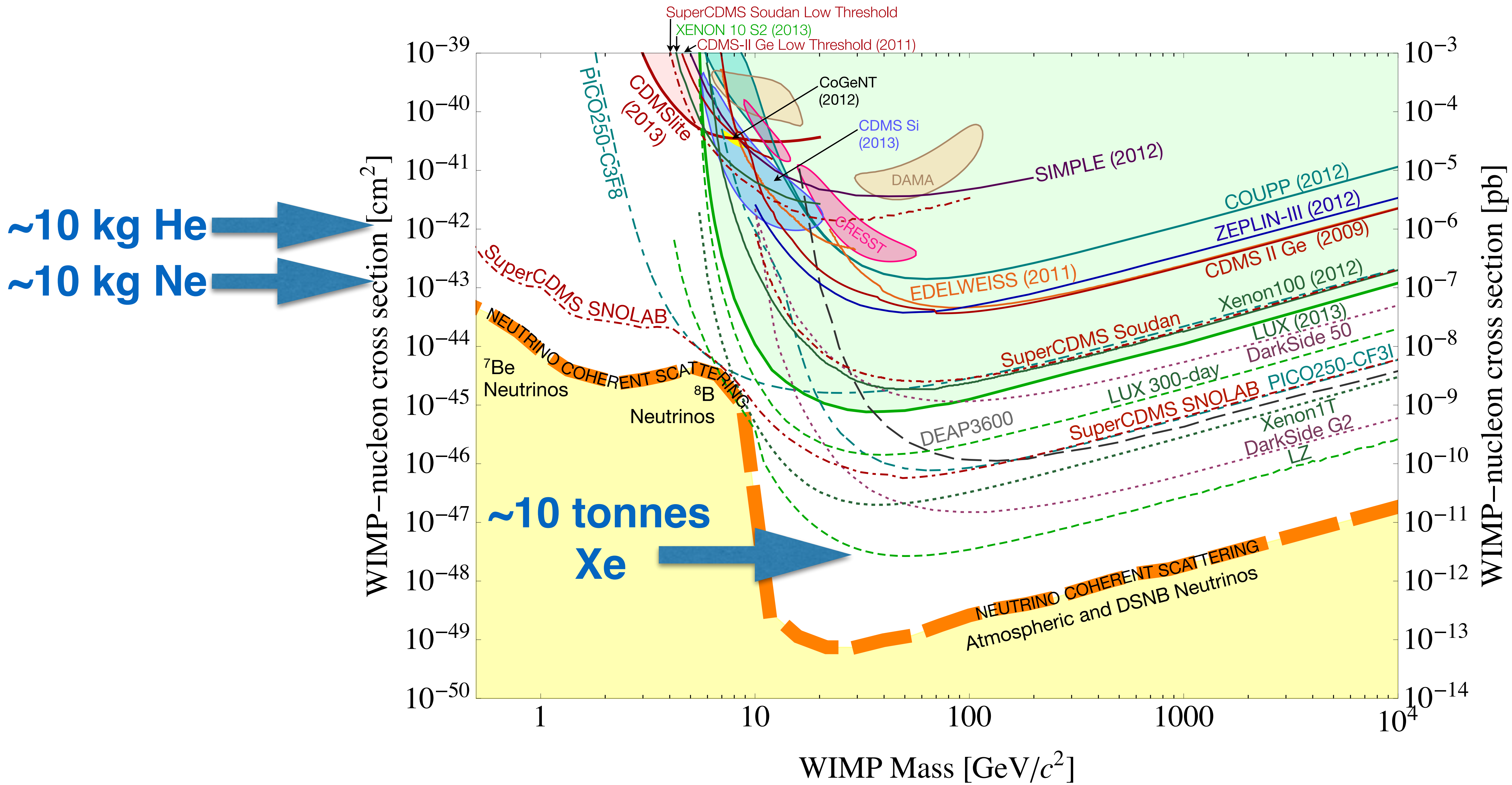


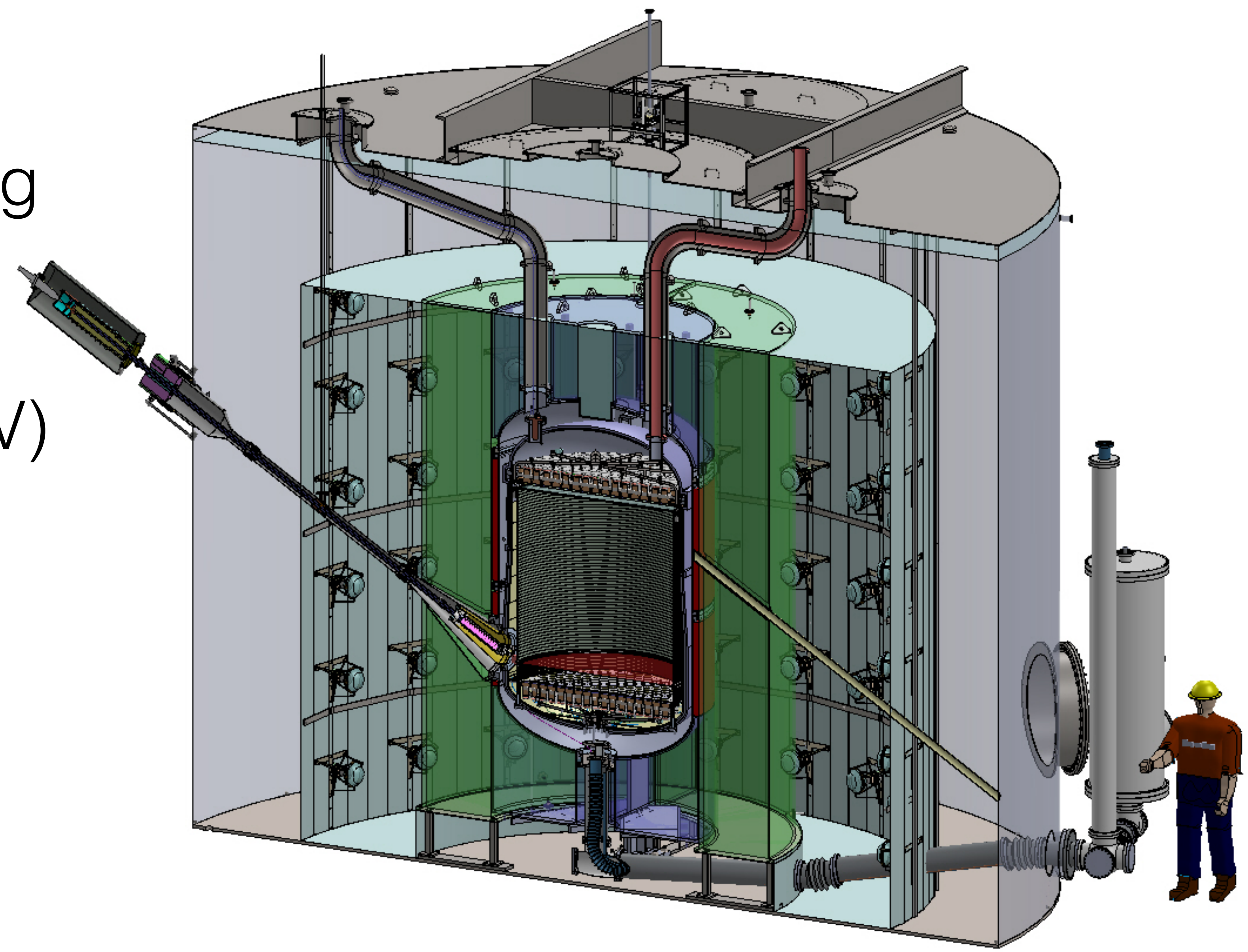
What don't you need for low mass?

- A lot of mass

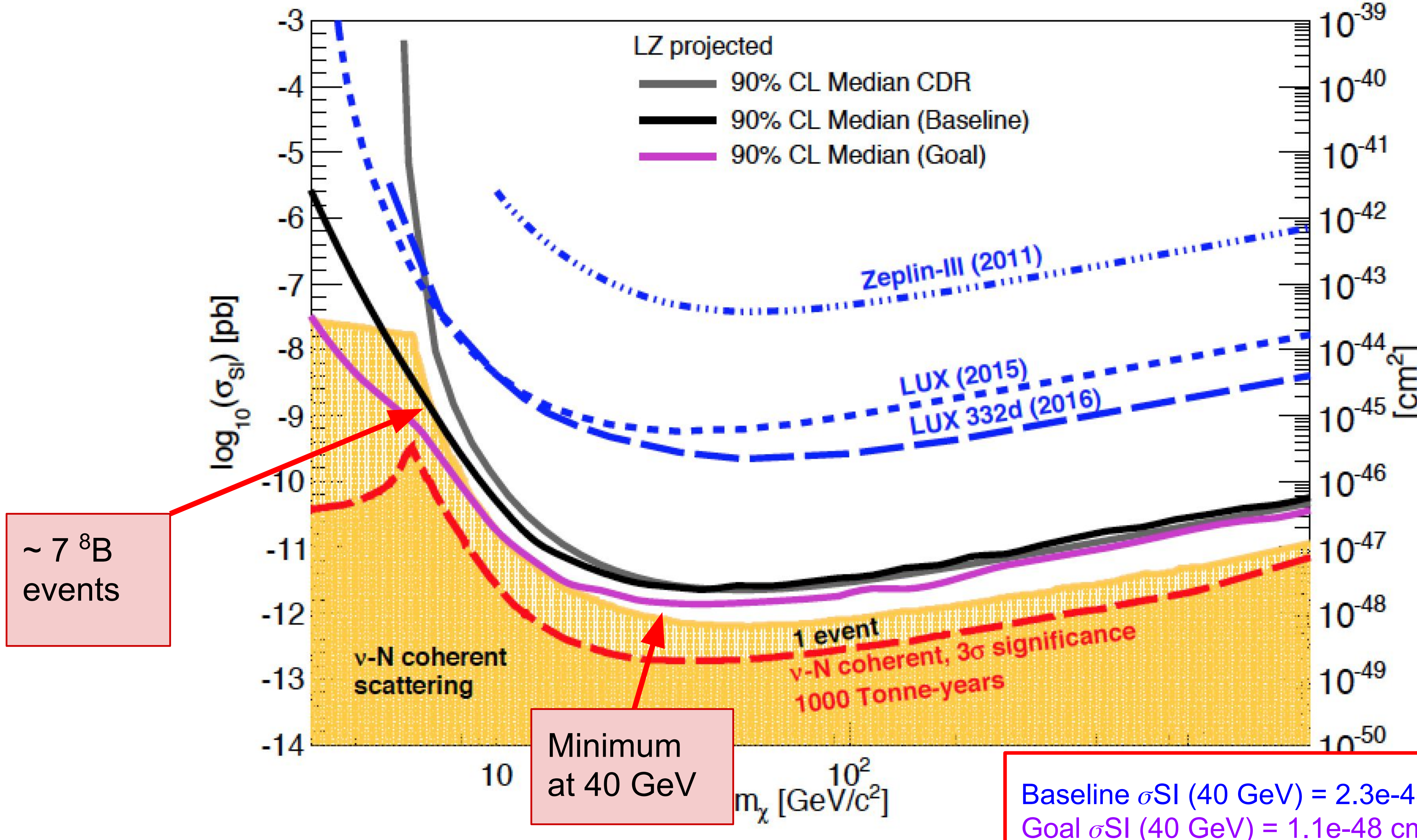


LUX-Zeplin (LZ)

- 7 tonne active LXe TPC
  - Heavy target
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
- >30 institutions, ~200 people
- To be located at Sanford Lab in SD



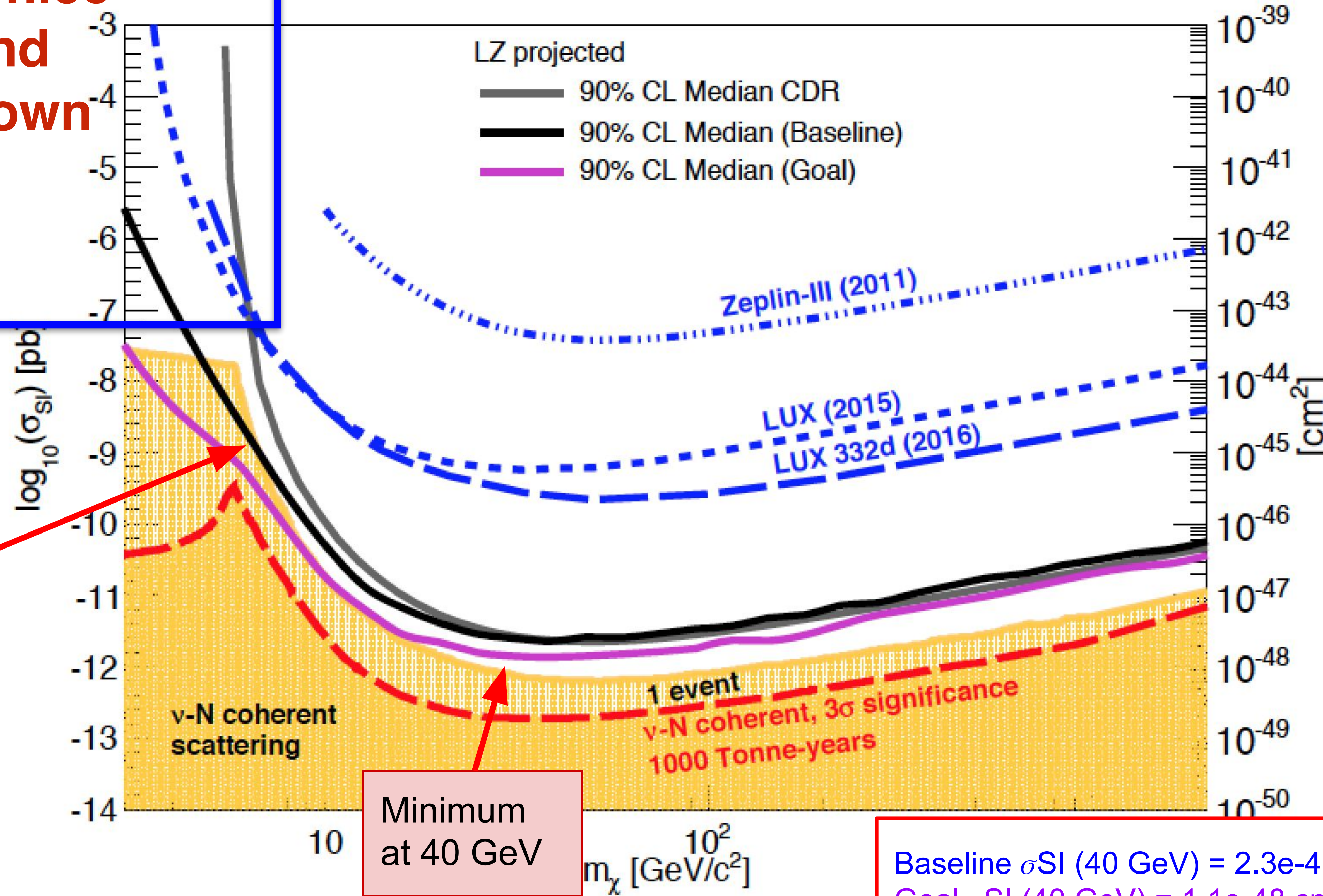
LZ sensitivity projections - 1000 live-days



Baseline σSI (40 GeV) = 2.3e-48 cm^2
Goal σSI (40 GeV) = 1.1e-48 cm^2

LZ sensitivity projections - 1000 live-days

Would be nice to extend further down here!



~ 7 ^{8}B events

Minimum at 40 GeV

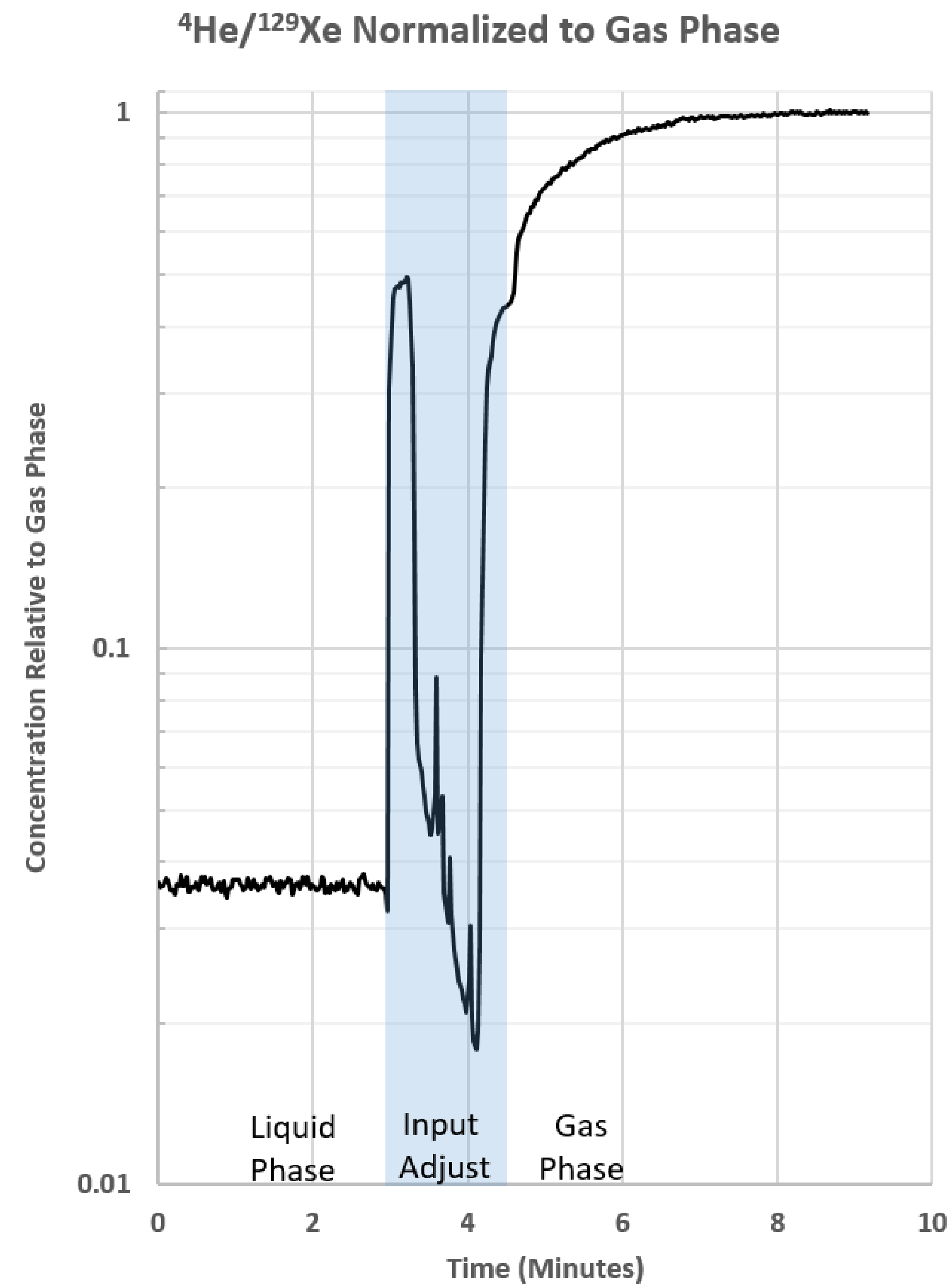
Baseline σSI (40 GeV) = 2.3e-48 cm^2
Goal σSI (40 GeV) = 1.1e-48 cm^2

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 existing experiments using helium or neon (see J. Lin talk later today)
- Capitalize on investment in large detectors by adding flexibility

How much could we get in?

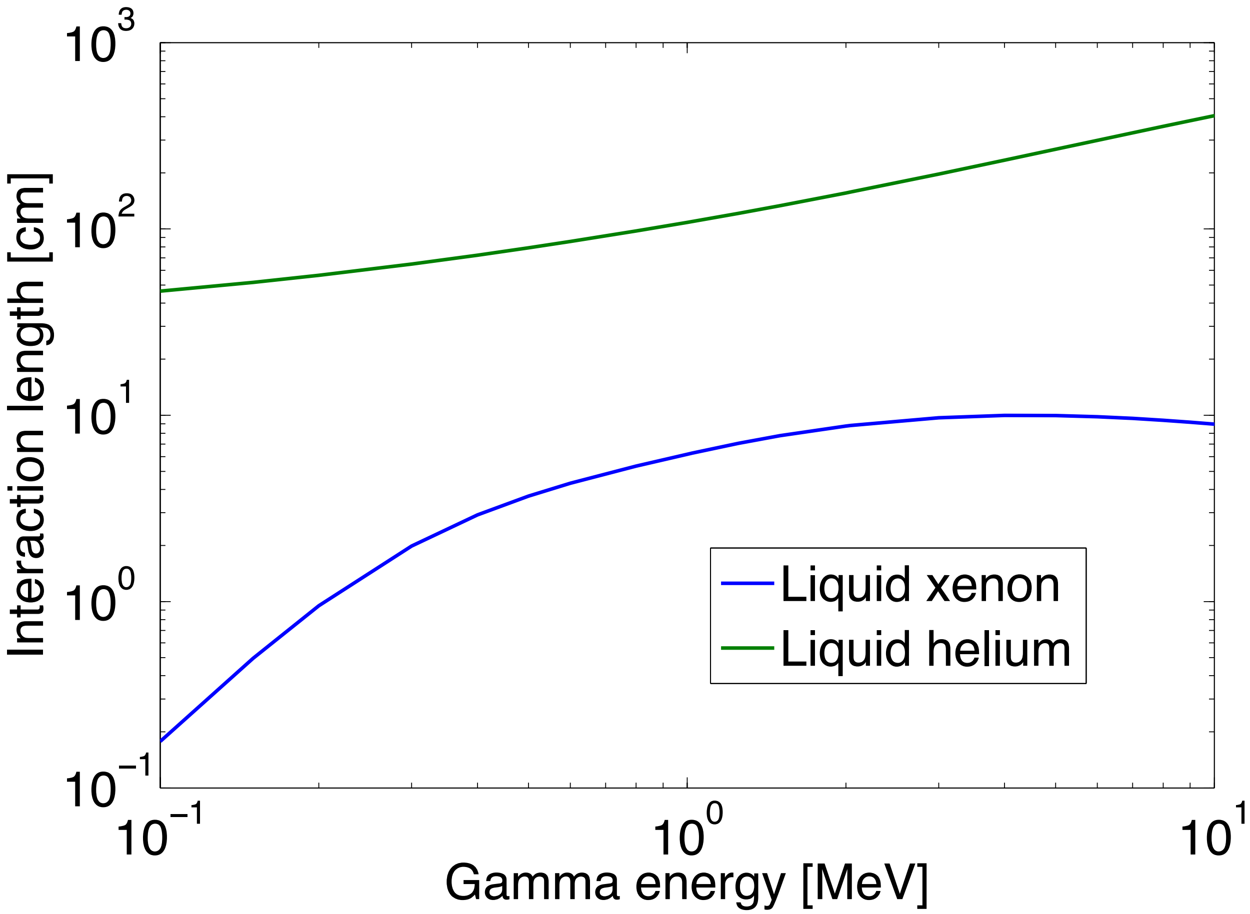
- No published measurements
- Preliminary test at Fermilab shows 0.1% He in LXe by mass is easily achievable
  - 1 bar of partial pressure
  - LUX measurements shows a little more (~0.3%)
  - ~17 kg of He
- Can we get more in?
  - Temperature dependence?



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

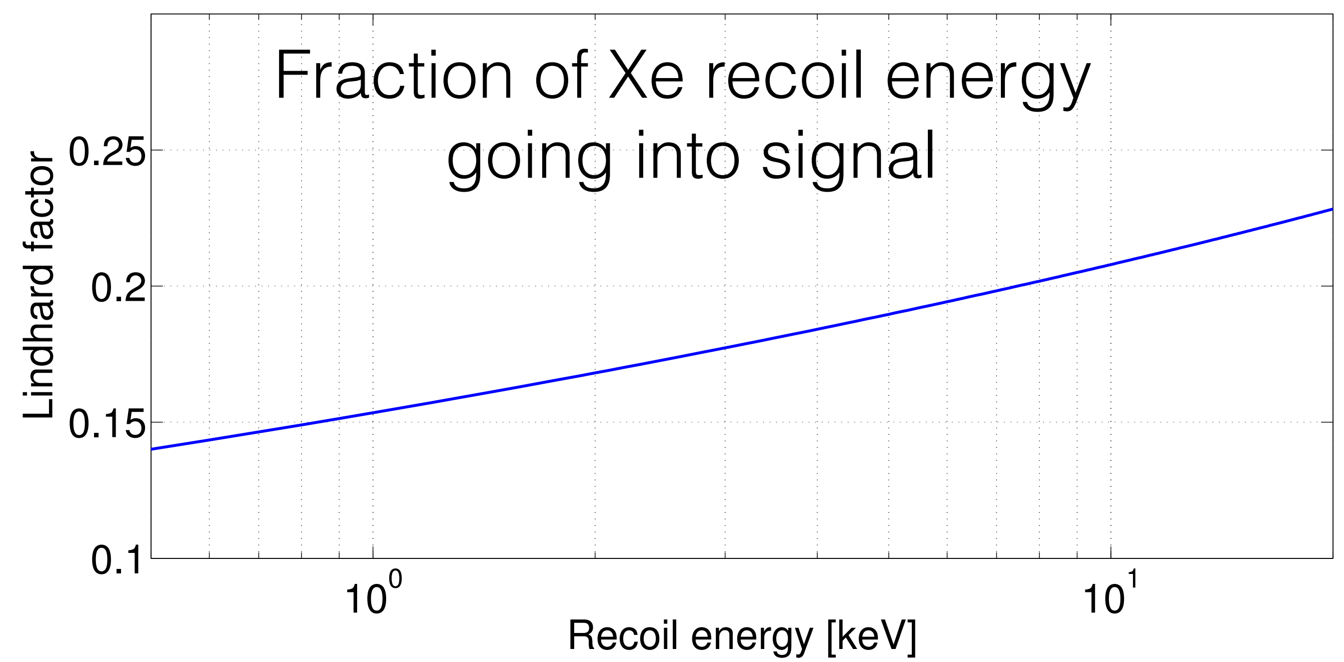
- Helium and neon scintillate in harder UV
  - 80 nm vs 175 nm in LXe
- Either:
  - Those photons will wavelength shift in the xenon to 175 nm
  - Or recoil energy will be deposited in collisions with xenon electrons and atoms in the usual way, and it will be generated at 175 nm
- Keep same photon detection scheme!

R11410

R8520

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

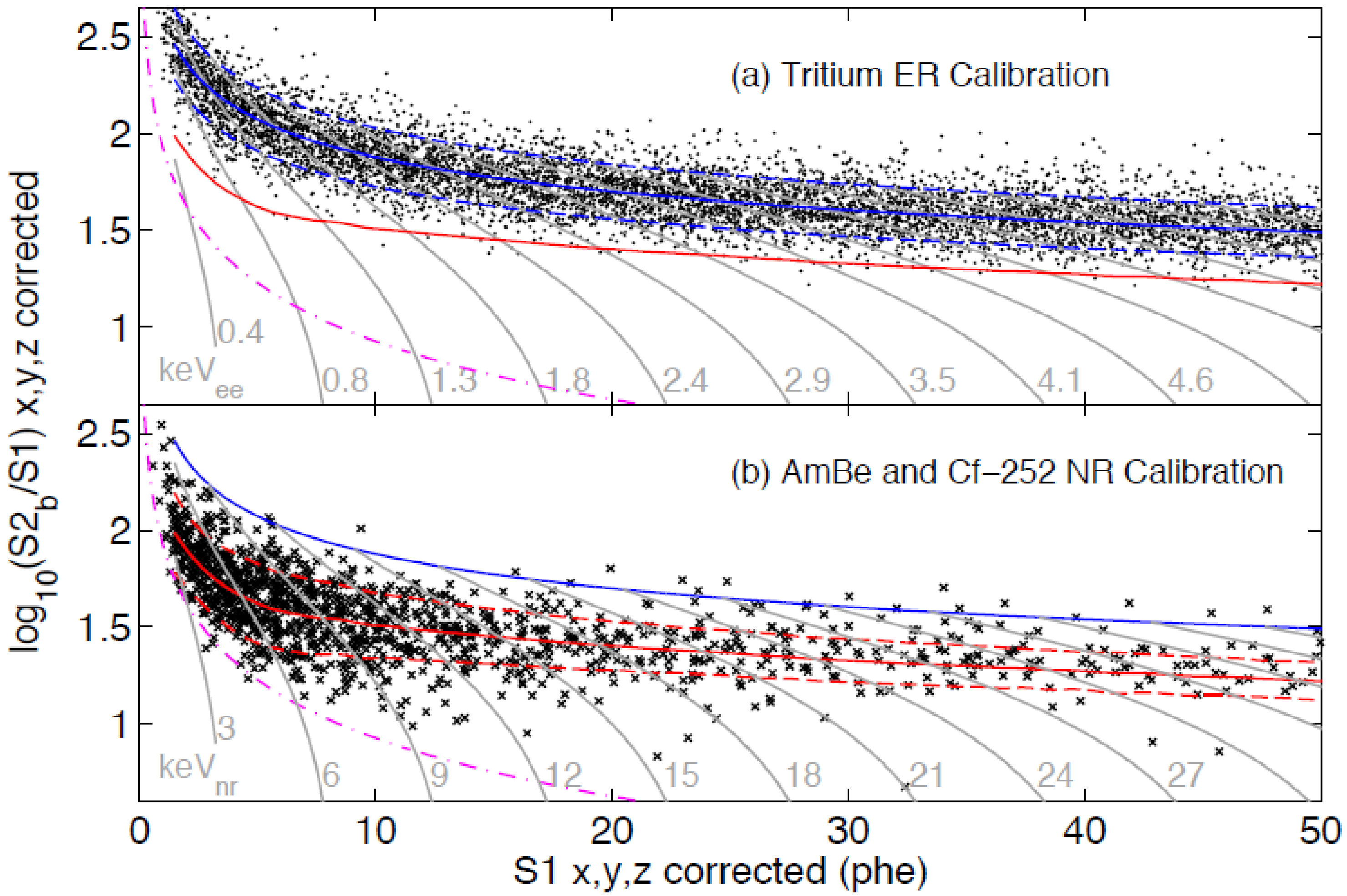


- Helium/Neon are light nuclei, meaning more energy goes into electronic channels -> more signal

Even lower thresholds with the light target!

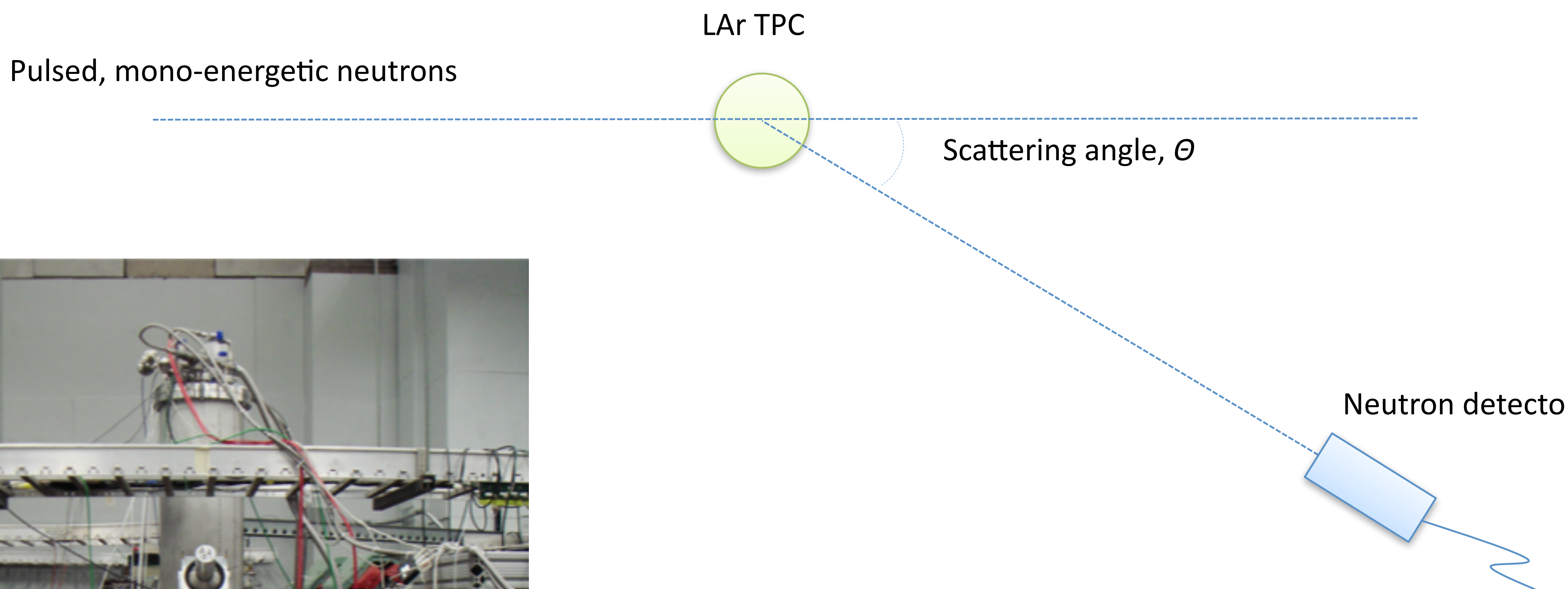
Some key questions

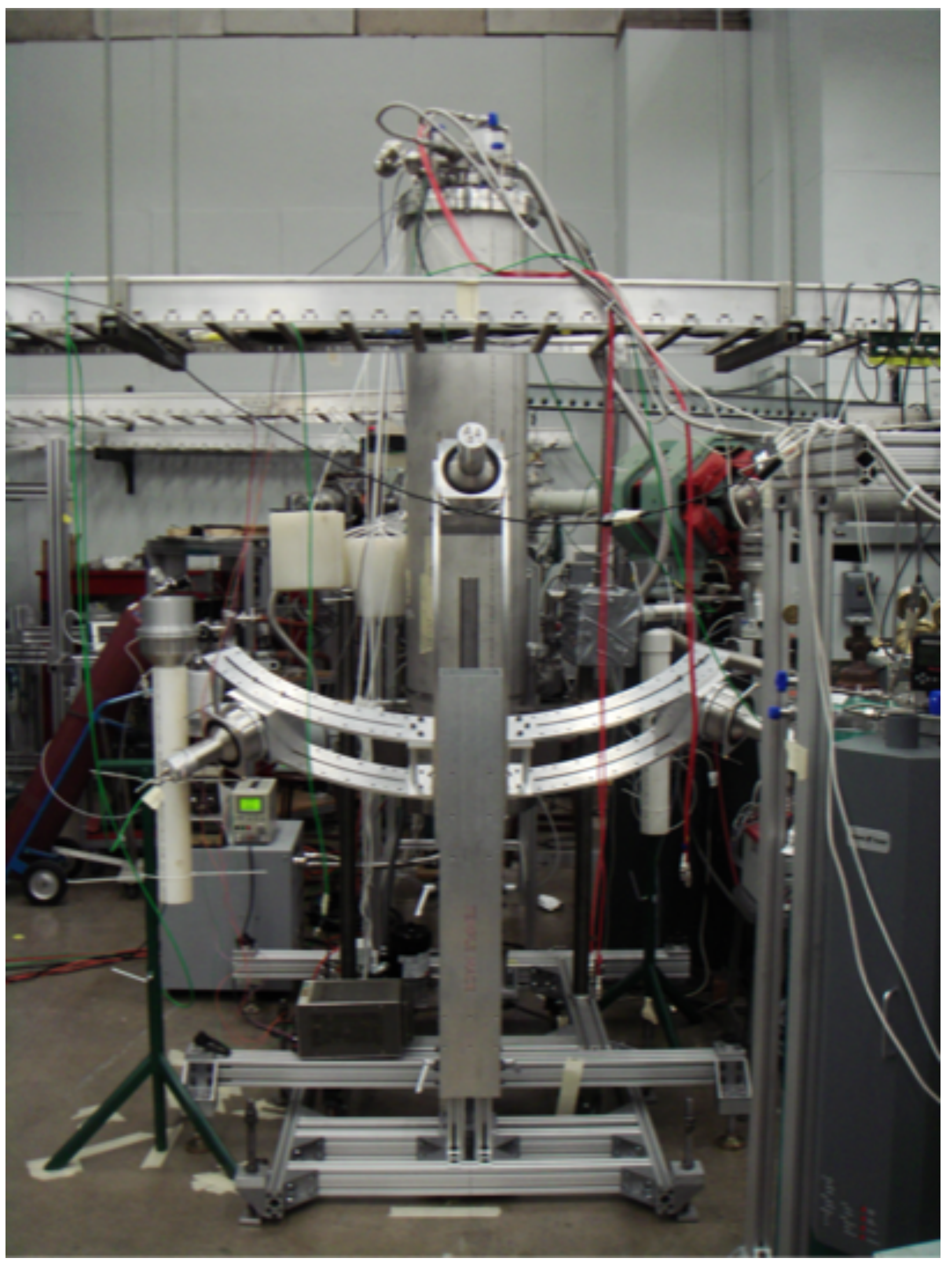
- What is the true signal yield?
- What happens to S2/S1 partitioning?



LUX data
PRL 112, 091303

SCENE-like measurement

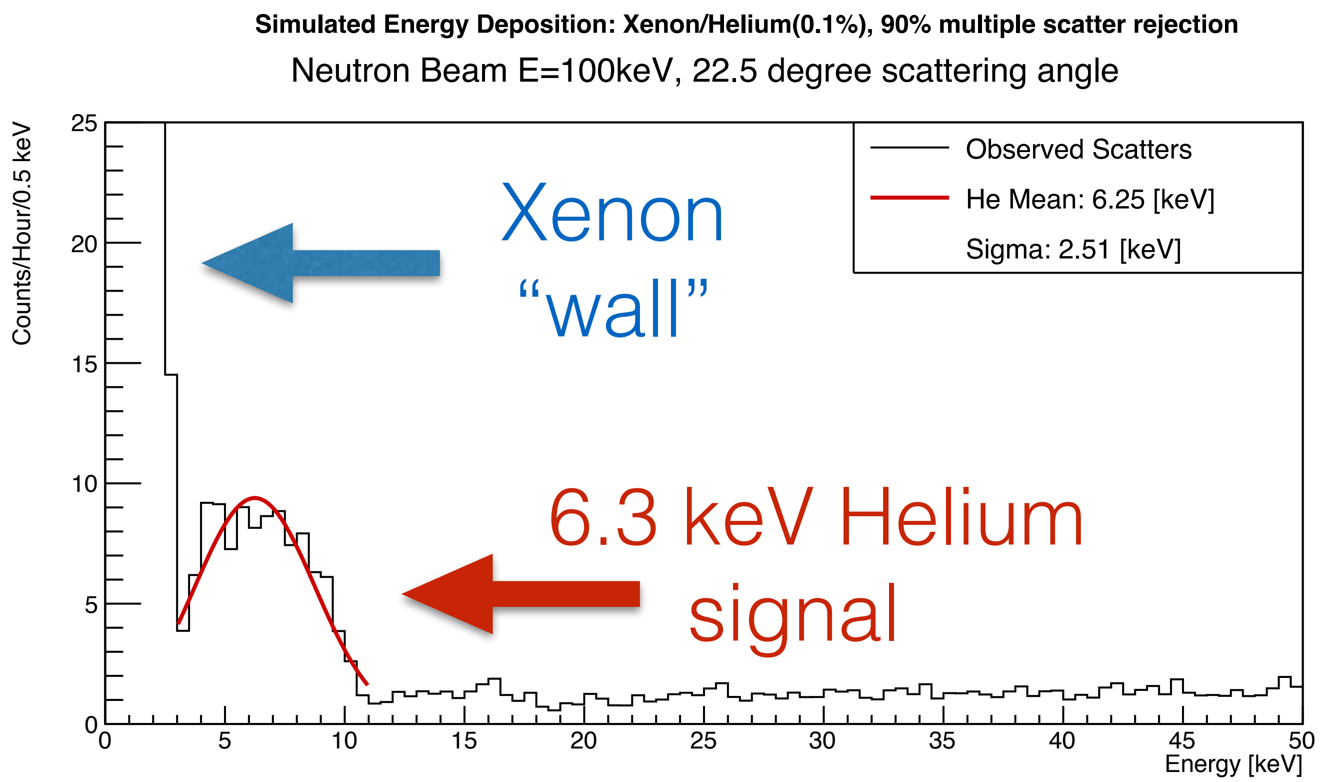


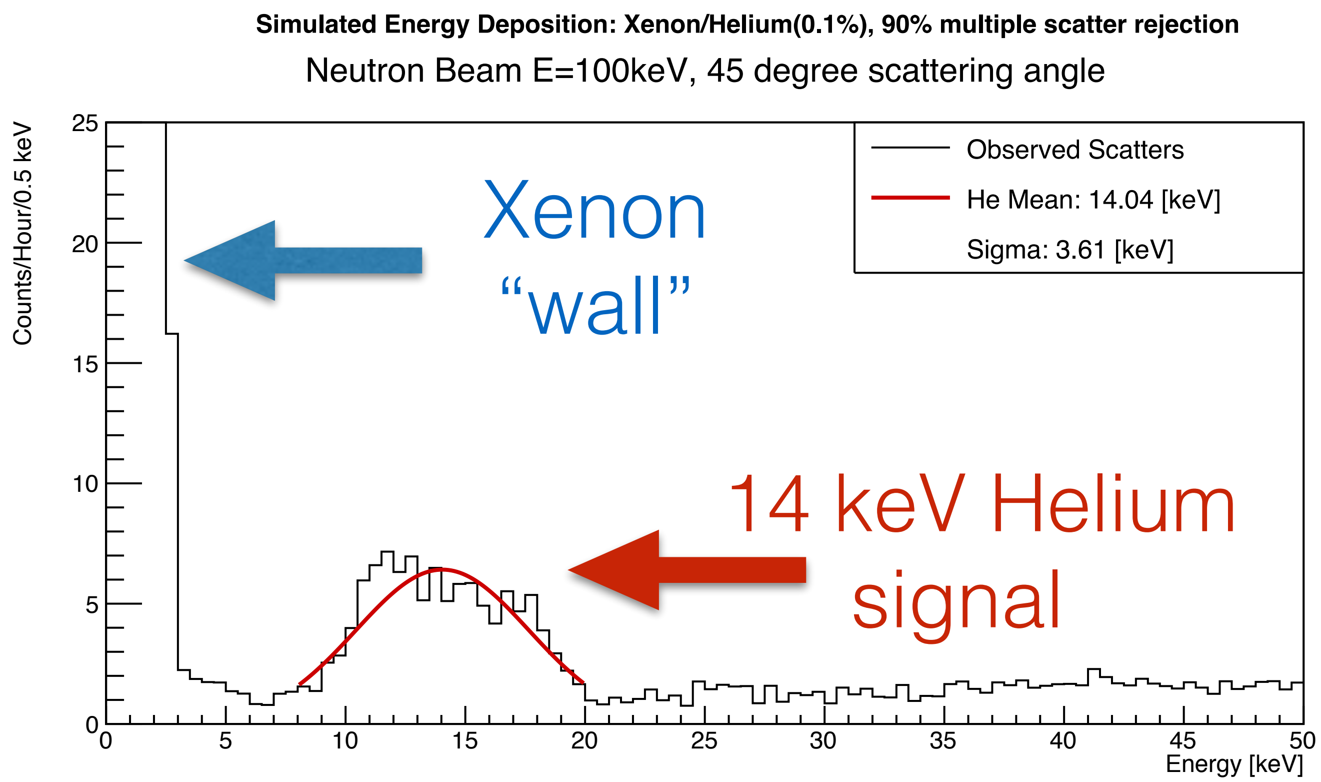


- Pulsed, monoenergetic beam (at Notre Dame or elsewhere) to measure response of to nuclear recoils of known energy
- Tunable nuclear recoil energy by changing the neutron energy and the scattering angle
  - Neutrons of 500 keV - 1.5 MeV
  - Recoils of a few keV up to 50 keV
  - Successful measurements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

SCENE

- In a 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





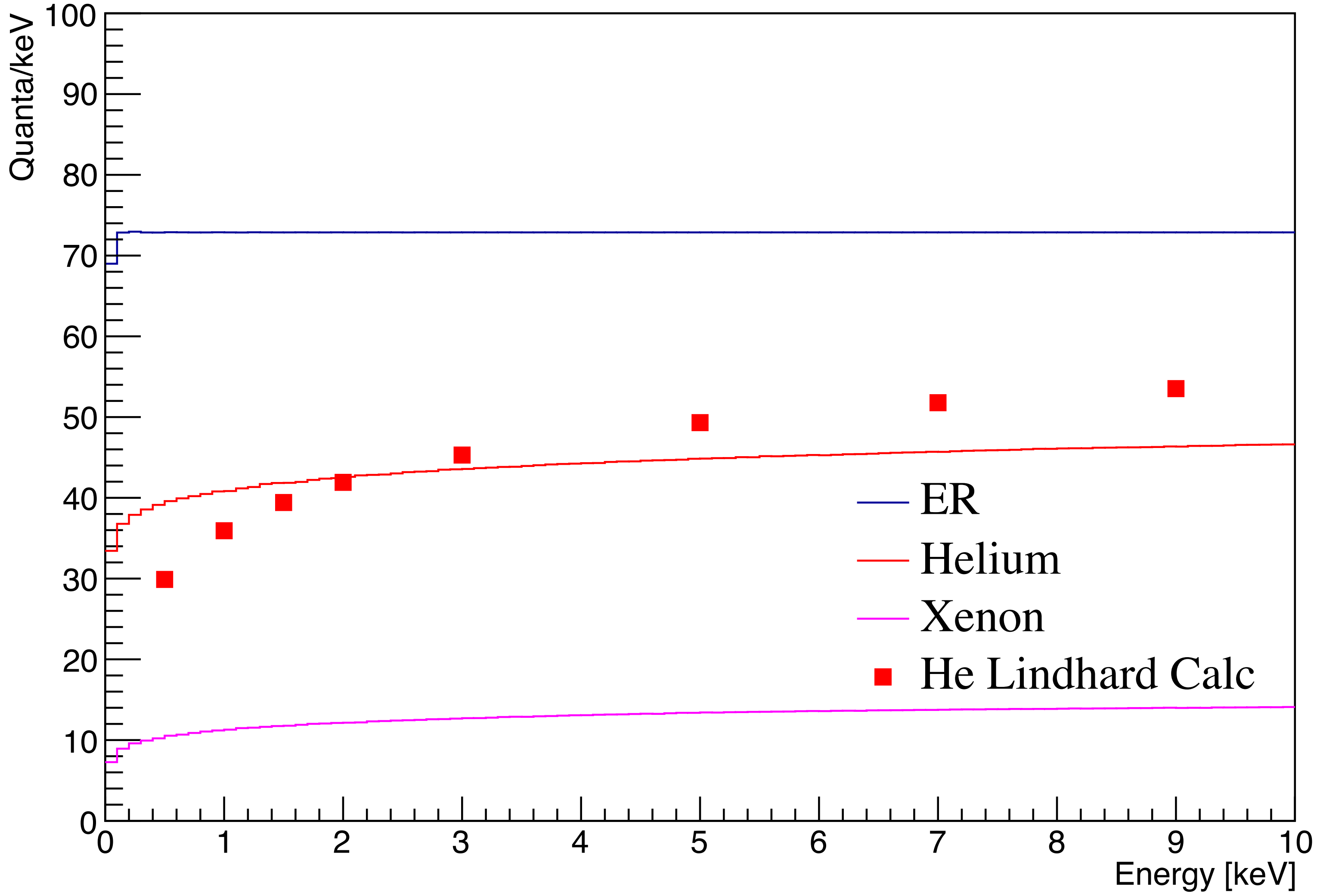
SCENE-like measurement measures yield and S1/S2 response v. energy!

He/Ne doping in LXe

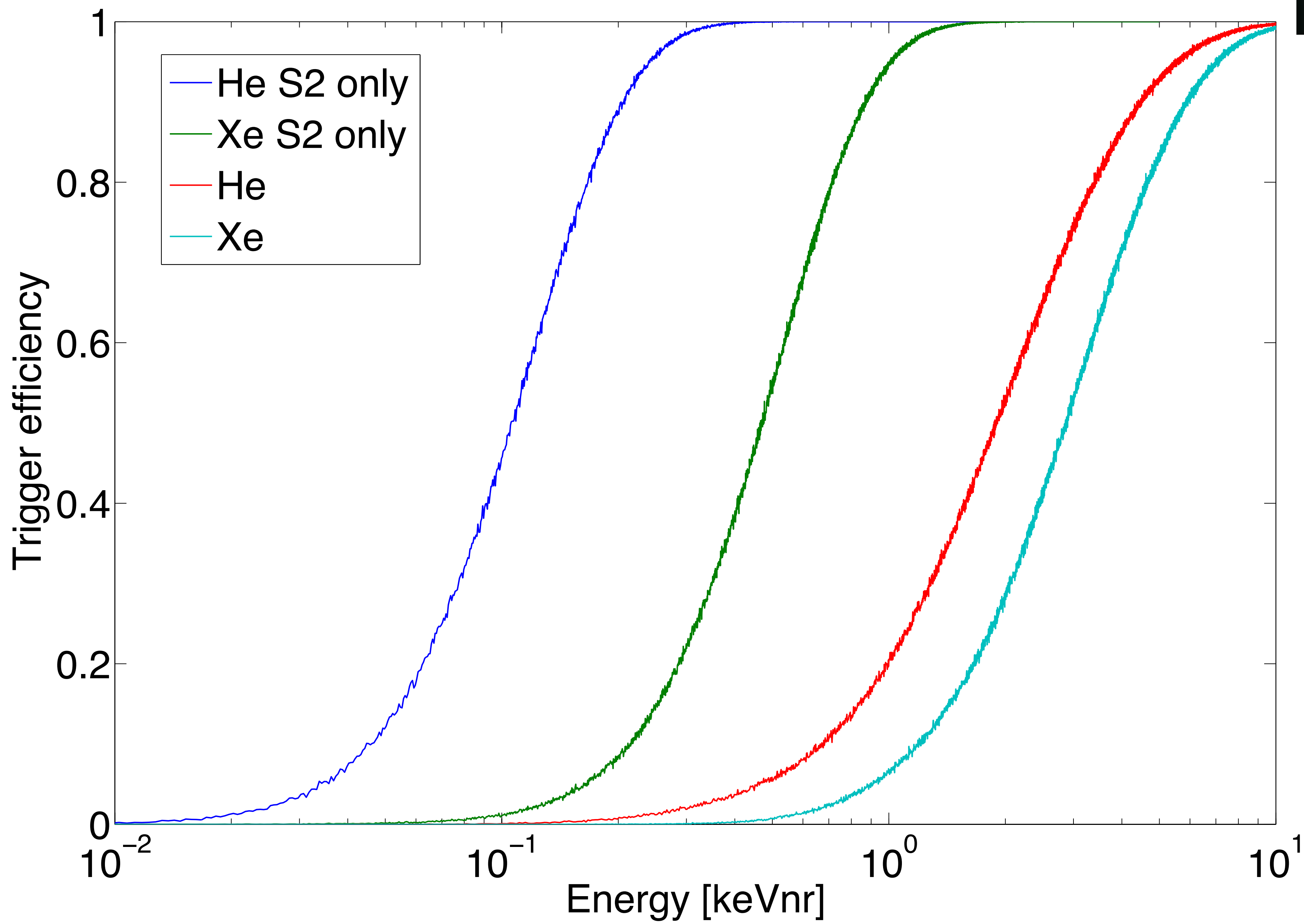
- Physically possible ✓
- Keep low background level achieved in LXe TPC ✓
- Same signal readout with LXe sensitive light detectors ✓
- Increased signal yield from He/Ne recoils ✓
    - Lower energy thresholds for WIMP-He/Ne scattering ✓
- Properties measurable using existing techniques ✓

Making projections

- Early version of an alpha recoil model from NEST 2.0 (see J. Brodsky, yesterday) can be projected down to low energies
  - Agrees moderately well with a basic Lindhard calculation

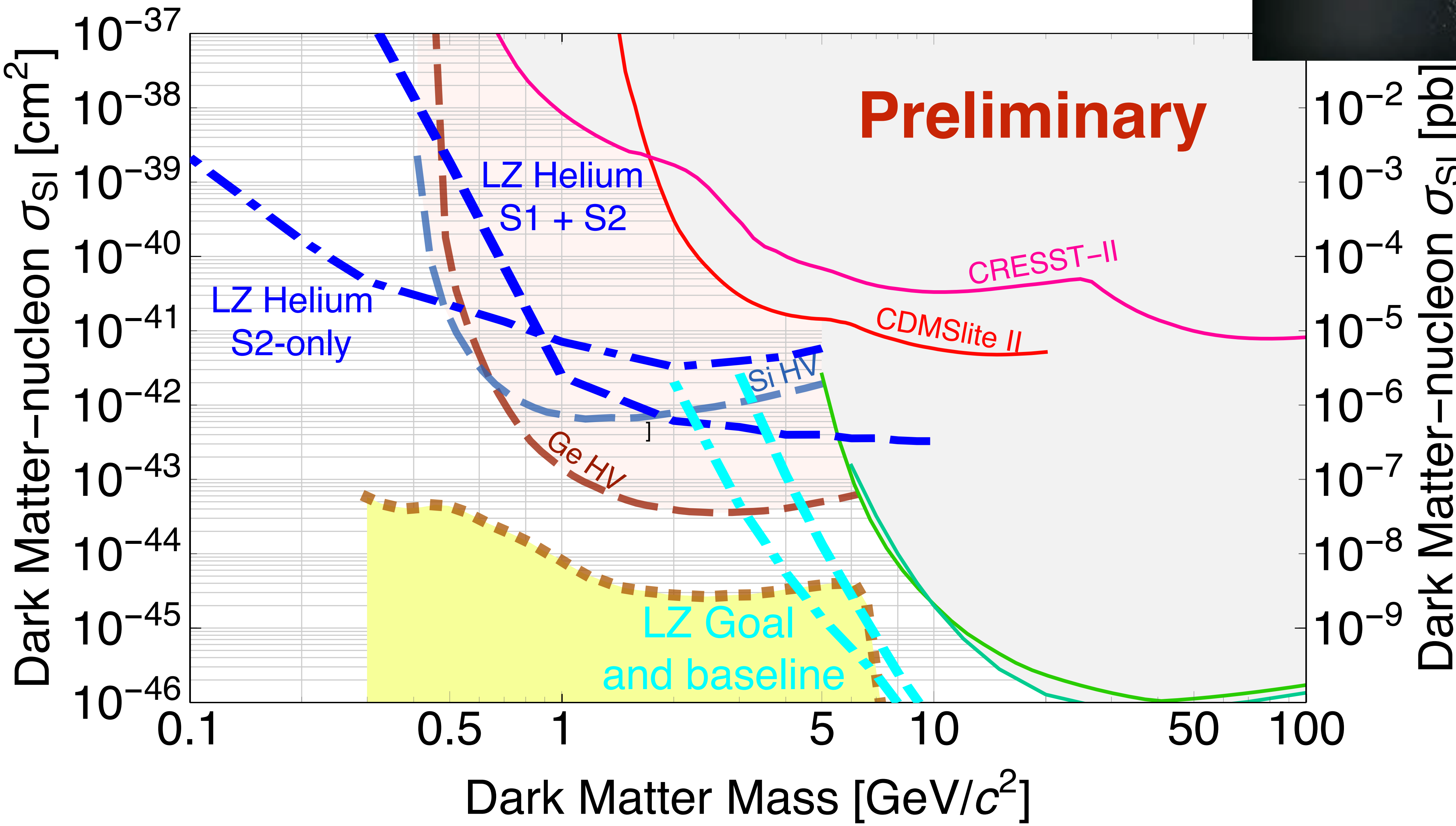


Making projections



- Assuming “goal” detector parameters (see LZ TDR)
- S2-only assumes a 3 e- signal threshold (~285 pe)

Making projections



- Location of LZ Helium lines depends critically on assumed signal yield
  - ~225 events/day/pb for 100 MeV WIMP with this yield
- S2-only line is for 20 live days - limited by neutrino rate on xenon

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- Potential reach to well below 1 GeV dark matter

- Depends crucially on actual signal yields ?

He/Ne doping in LXe

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- Keep low background level achieved in L
- Same signal readout ... light detectors
- Increa... from He/Ne recoils
    - Lower energy thresholds for WIMP-He/Ne scattering
- Properties measurable using existing techniques
- Potential reach to well below 1 GeV dark matter
- Depends crucially on true signal yields

Worth further exploration!

Backup

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].

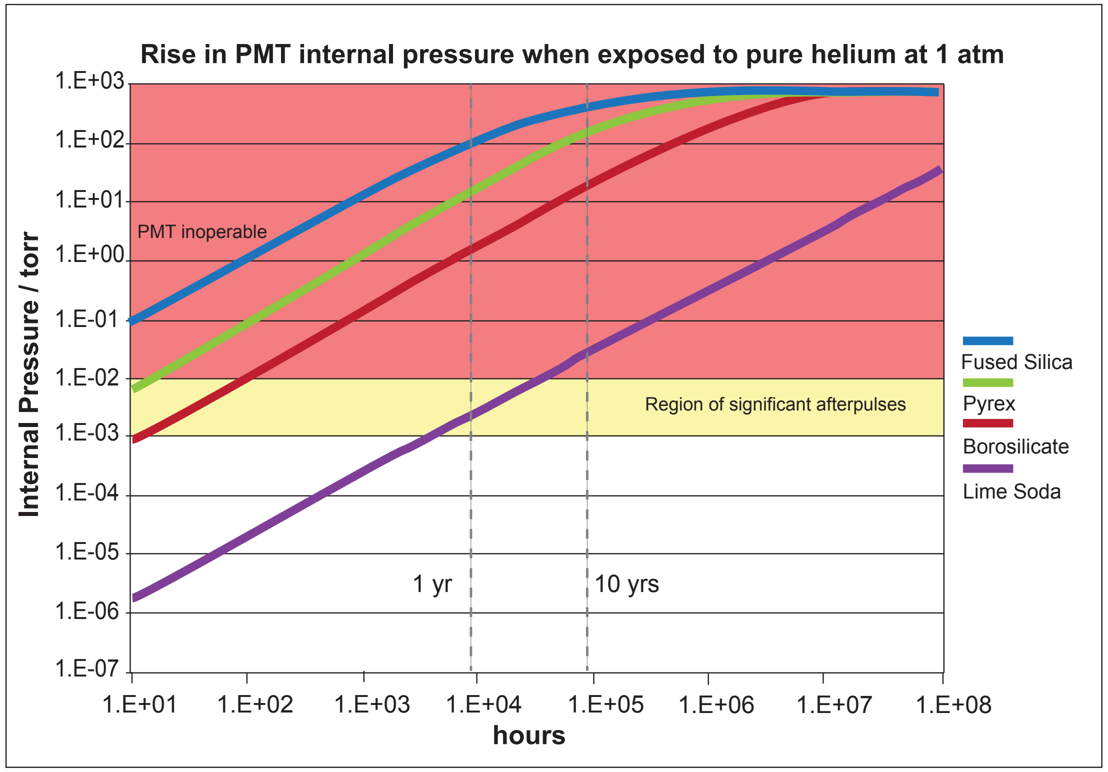
- At worst, we can expect a factor of 3.5 more signal for helium recoils in LXe

Even lower thresholds with the light target!

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…
- Or SiPMs

Example for ET9226 PMT



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