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Doping liquid xenon with light elements

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COFI
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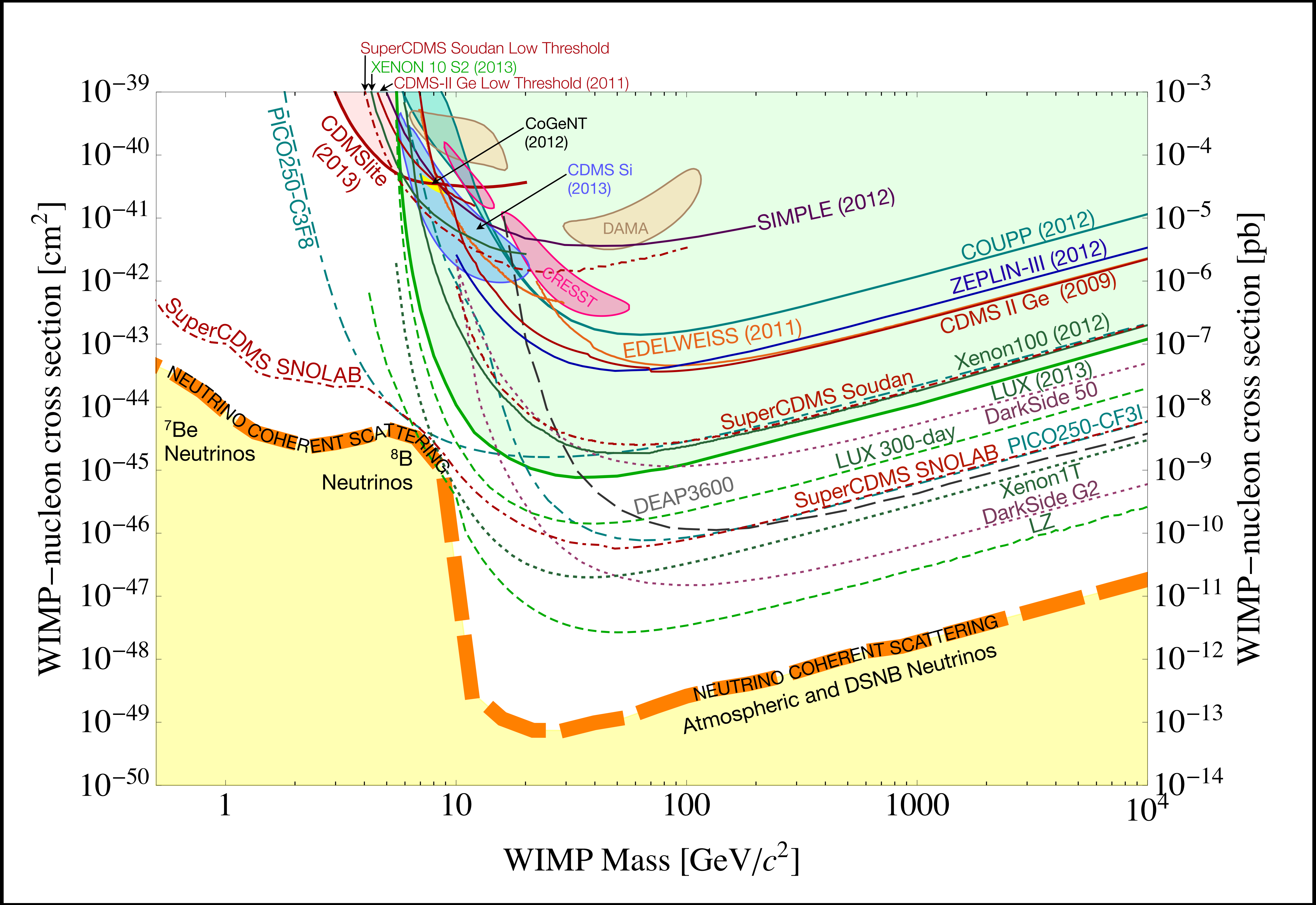
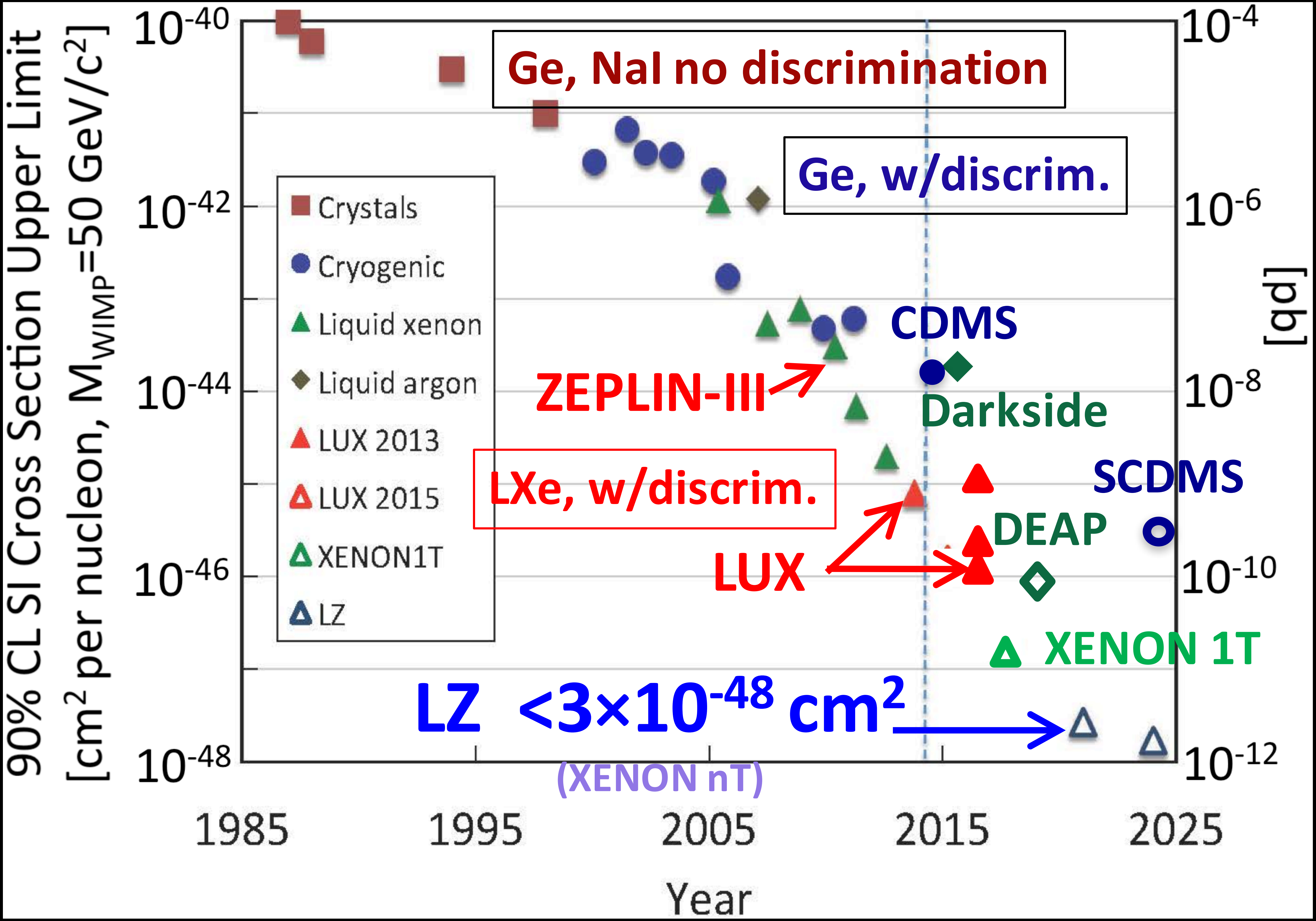
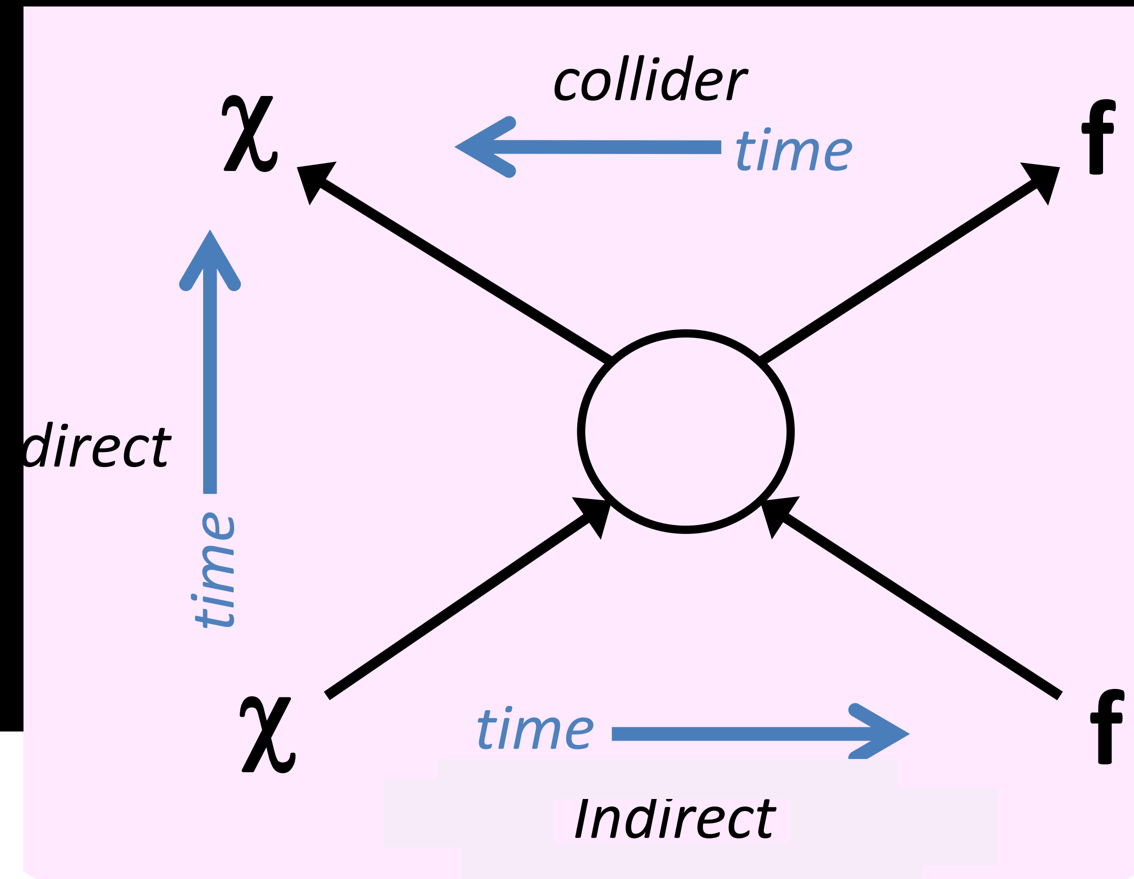


- Limited at low mass by detector threshold
- Limited at high mass by density
- Eventually limited by neutrinos

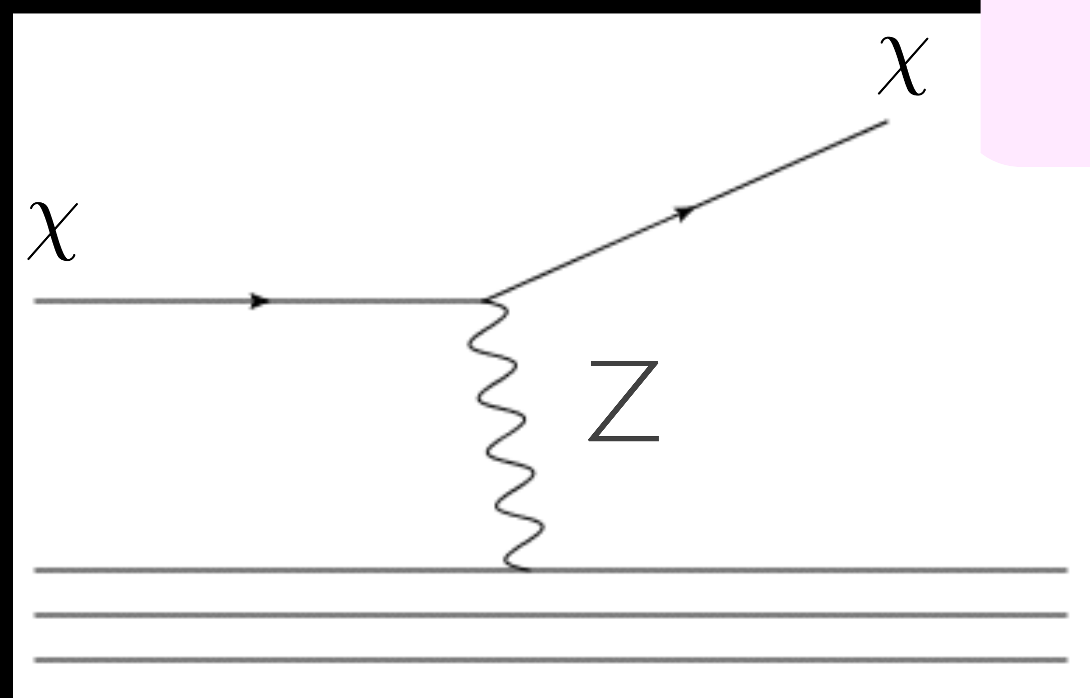
So where are we? (LZ edition)



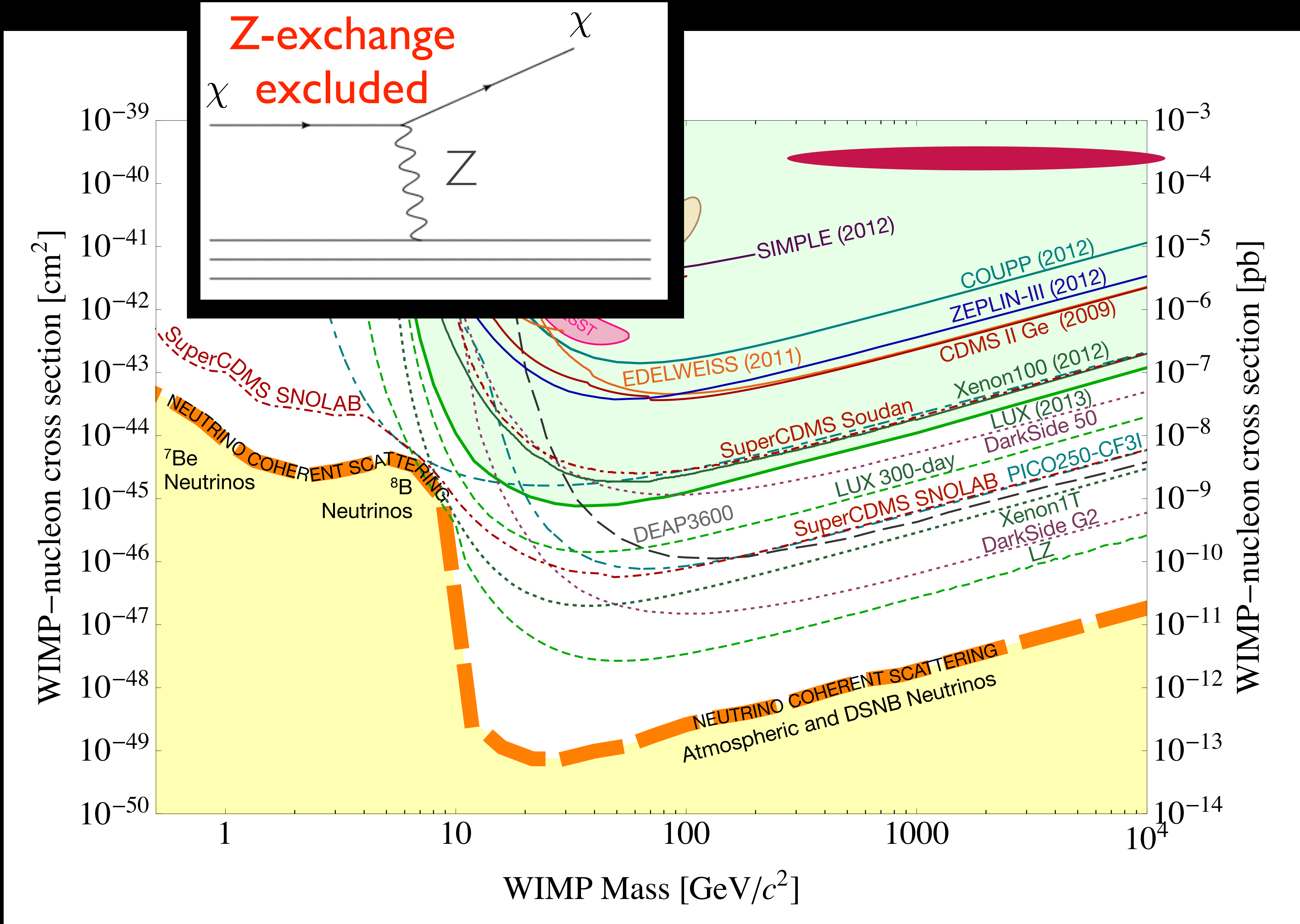
$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$
$$\approx \frac{\alpha^2}{(200 \mathrm{GeV})^2}$$



Coupling e.g. to light quarks

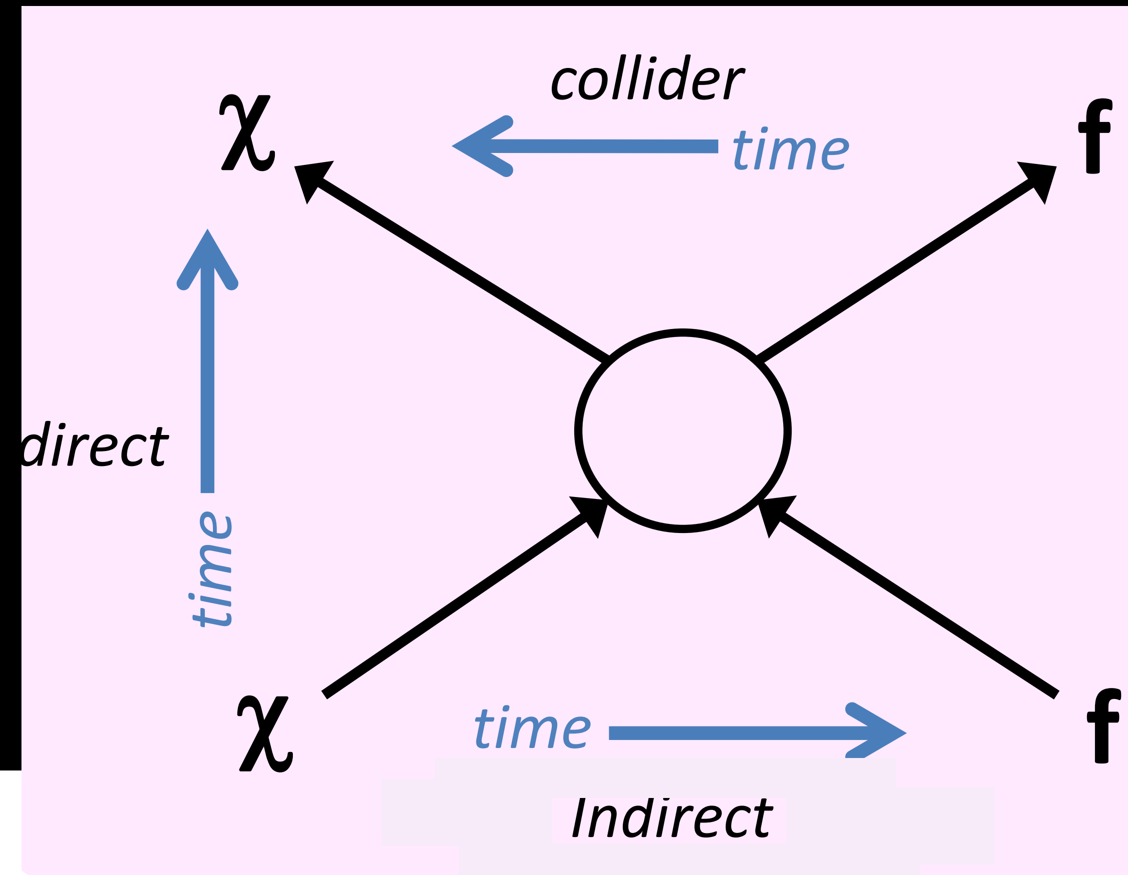


$$\sigma_0 \approx \frac{G_f^2 \mu^2}{2\pi} \sim 10^{-39} \mathrm{cm}^2$$

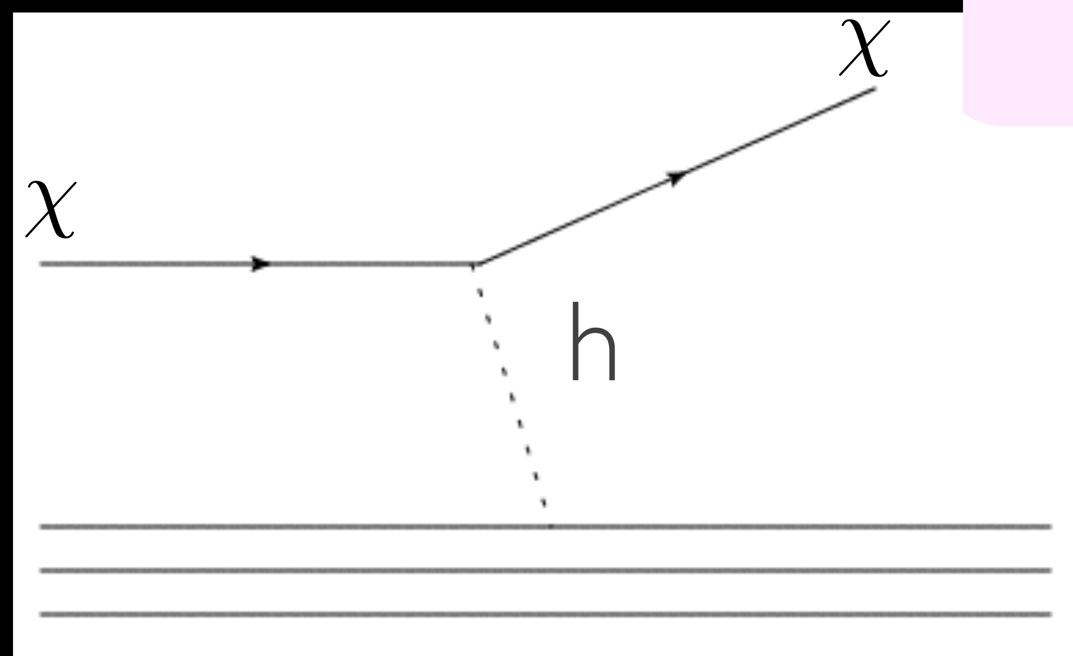


Z-exchange
excluded
χ
χ
Z
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos

$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1} \approx \frac{\alpha^2}{(200 \mathrm{GeV})^2}$$

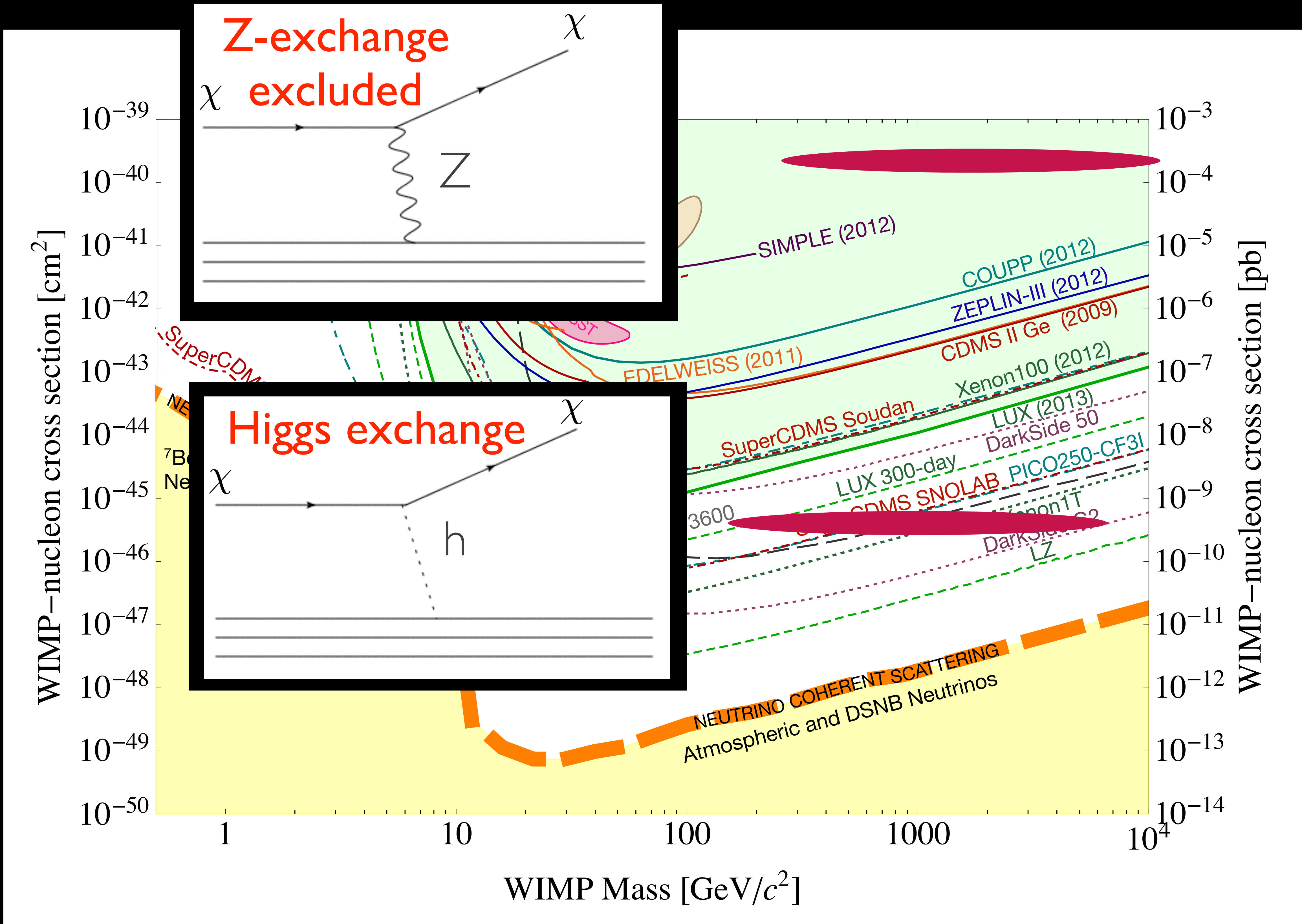


Coupling proportional to mass (e.g. via higgs)



$$g \sim 1 \Rightarrow y_p \sim \frac{1}{\mathrm{few}} \frac{m_p}{v}$$

$$\sigma_0 \sim 10^{-39} \mathrm{cm}^2 \times 10^{-6} \sim 10^{-45} \mathrm{cm}^2$$

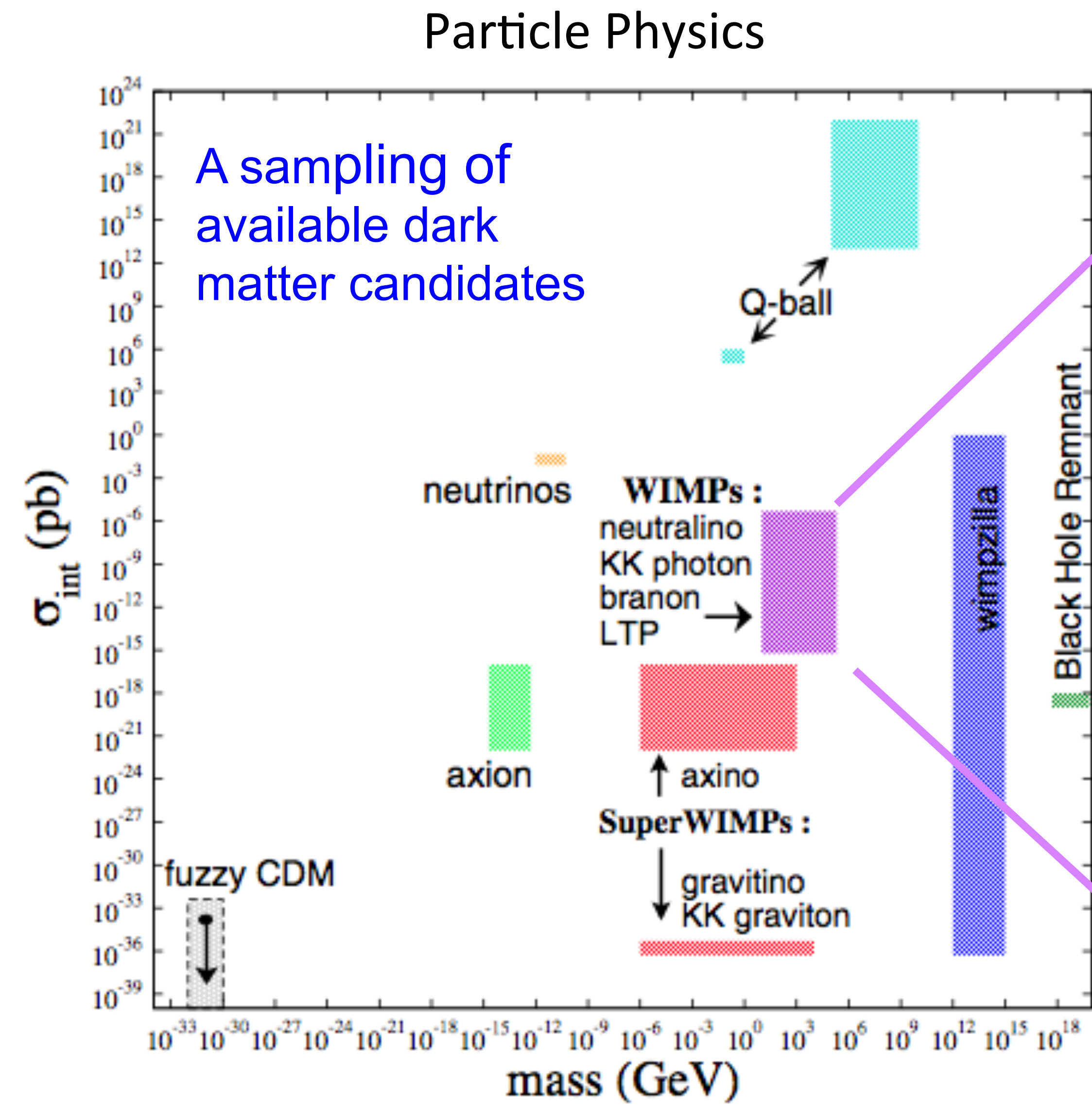


"This era will answer the question: does the dark matter couple at O(0.1) to the Higgs boson"

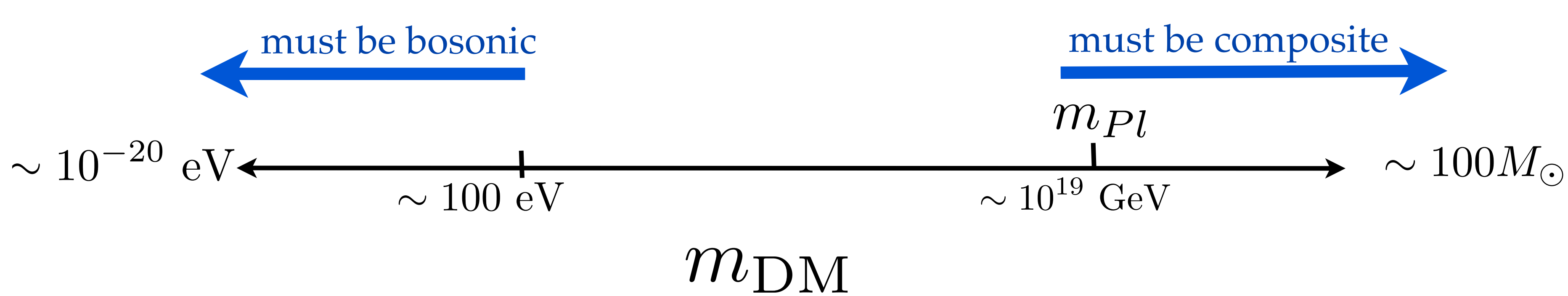
N. Weiner, CIPANP 2015

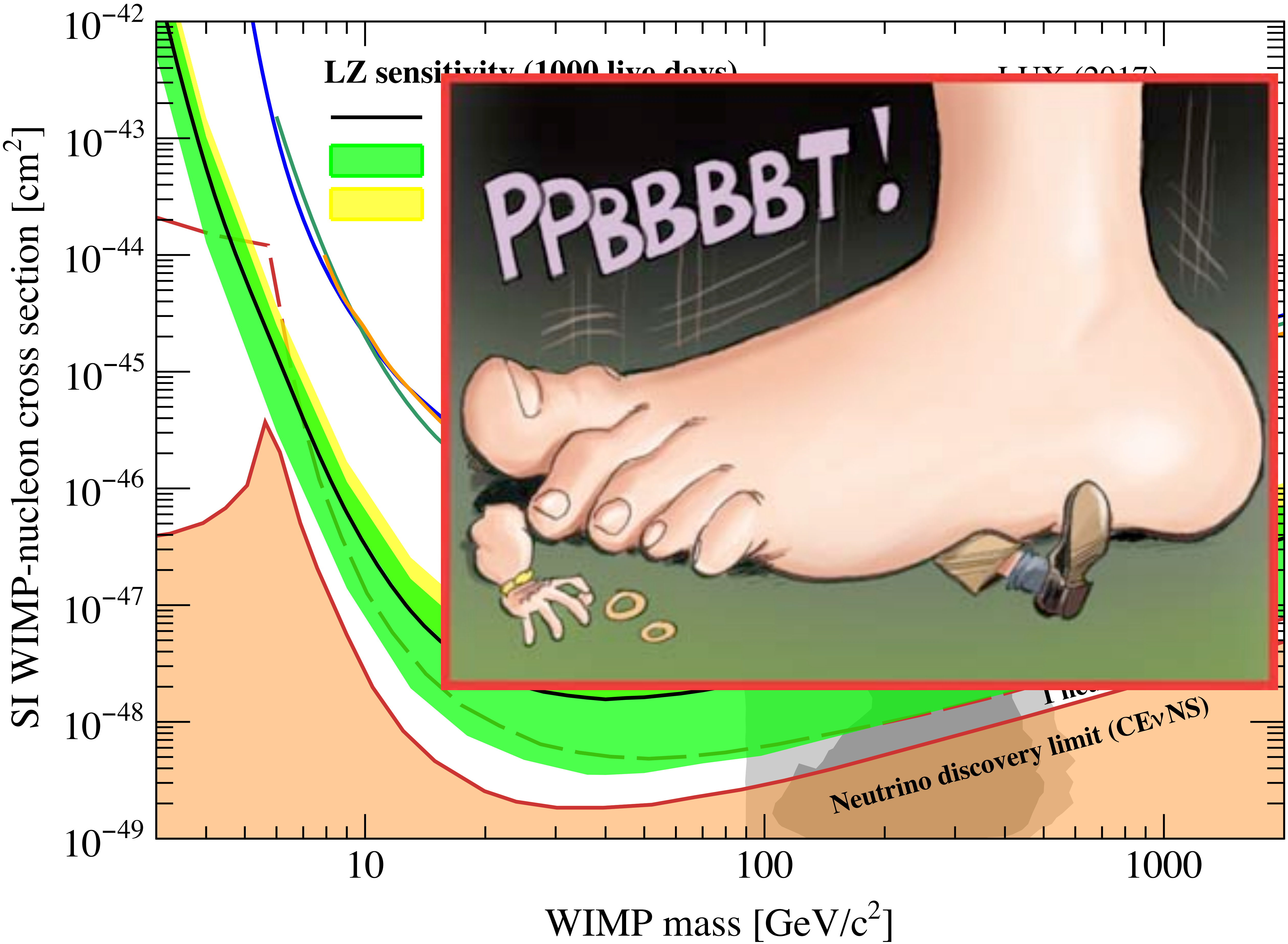
The case for dark matter

- We know it interacts gravitationally
- It is “dark” - should not interact with light or electromagnetism
- Nearly collision less
- Slow

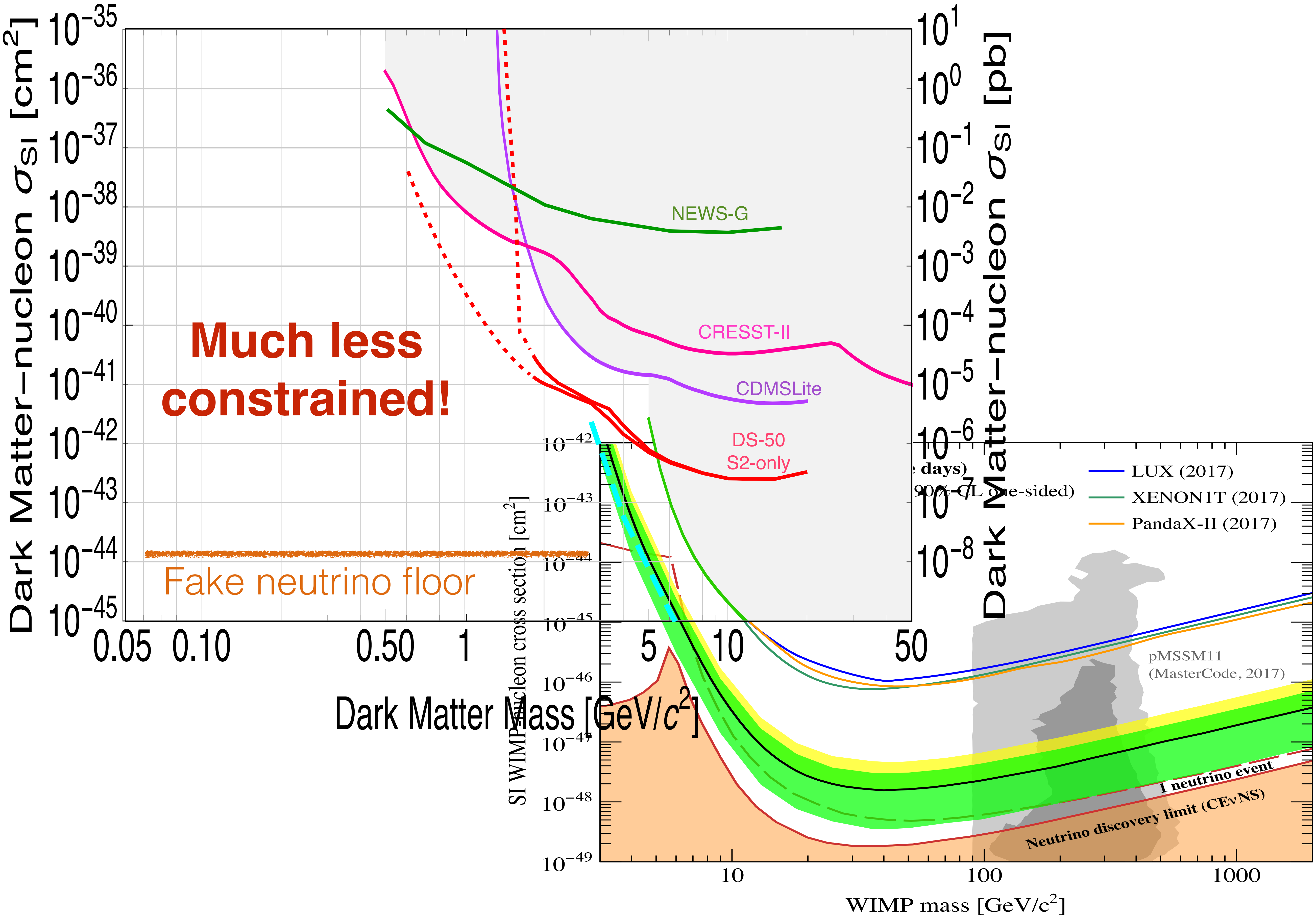


It’s probably WIMPs, right?





PPBBBBT!
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10
100
1000
Neutrino discovery limit (CEνNS)


Much less constrained!
Fake neutrino floor
NEWS-G
CRESST-II
CDMSLite
DS-50
S2-only
Dark Matter−nucleon σ_{SI} [cm^2]
Dark Matter−nucleon σ_{SI} [pb]
Dark Matter Mass [GeV/c^2]
LUX (2017)
XENON1T (2017)
PandaX-II (2017)
pMSSM11
(MasterCode, 2017)
1 neutrino event
Neutrino discovery limit (CEνNS)
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

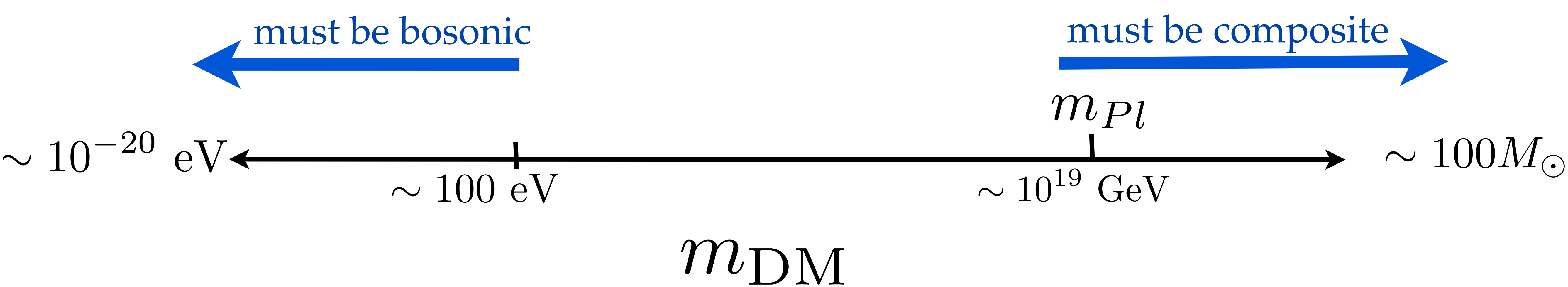
If nature is unkind, we may never know the right scale

Courtesy G. Krnjaic

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

If nature is unkind, we may never know the right scale



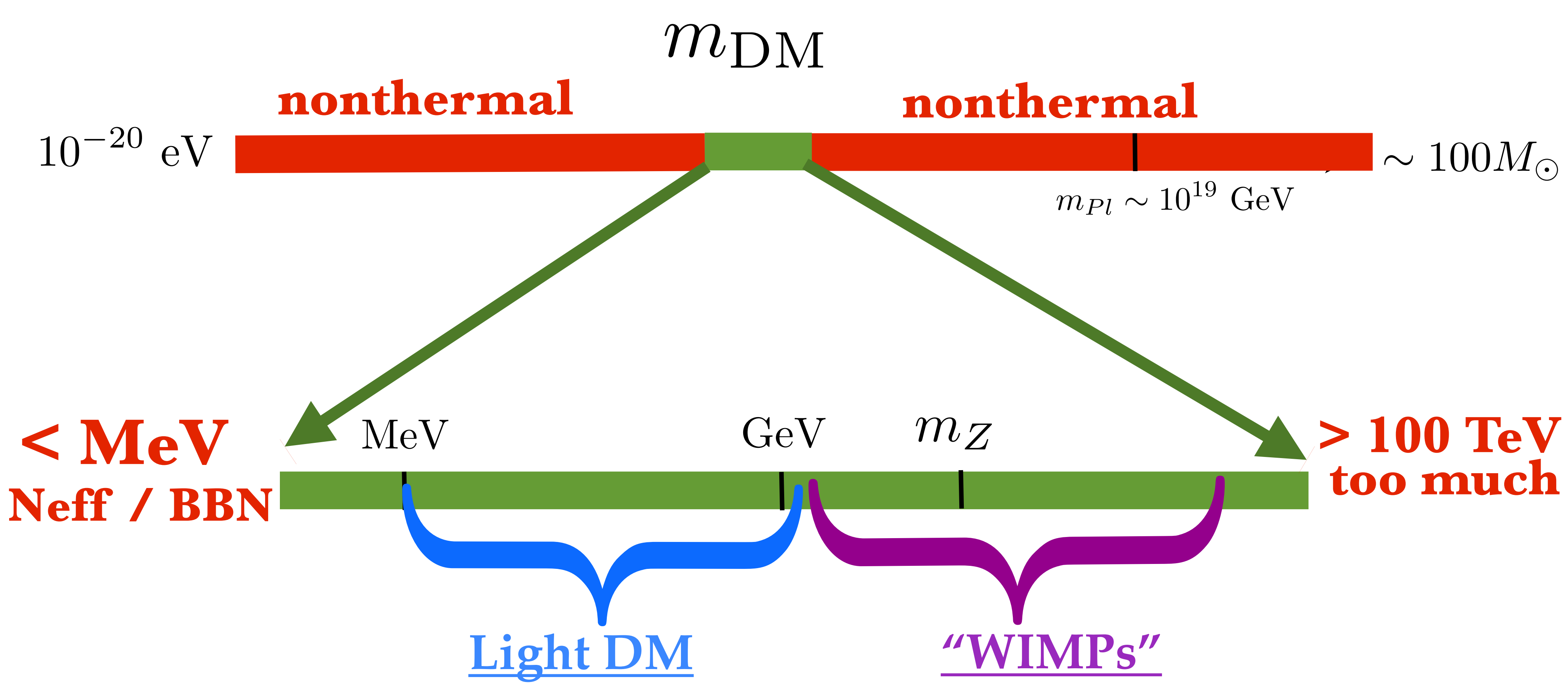
Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

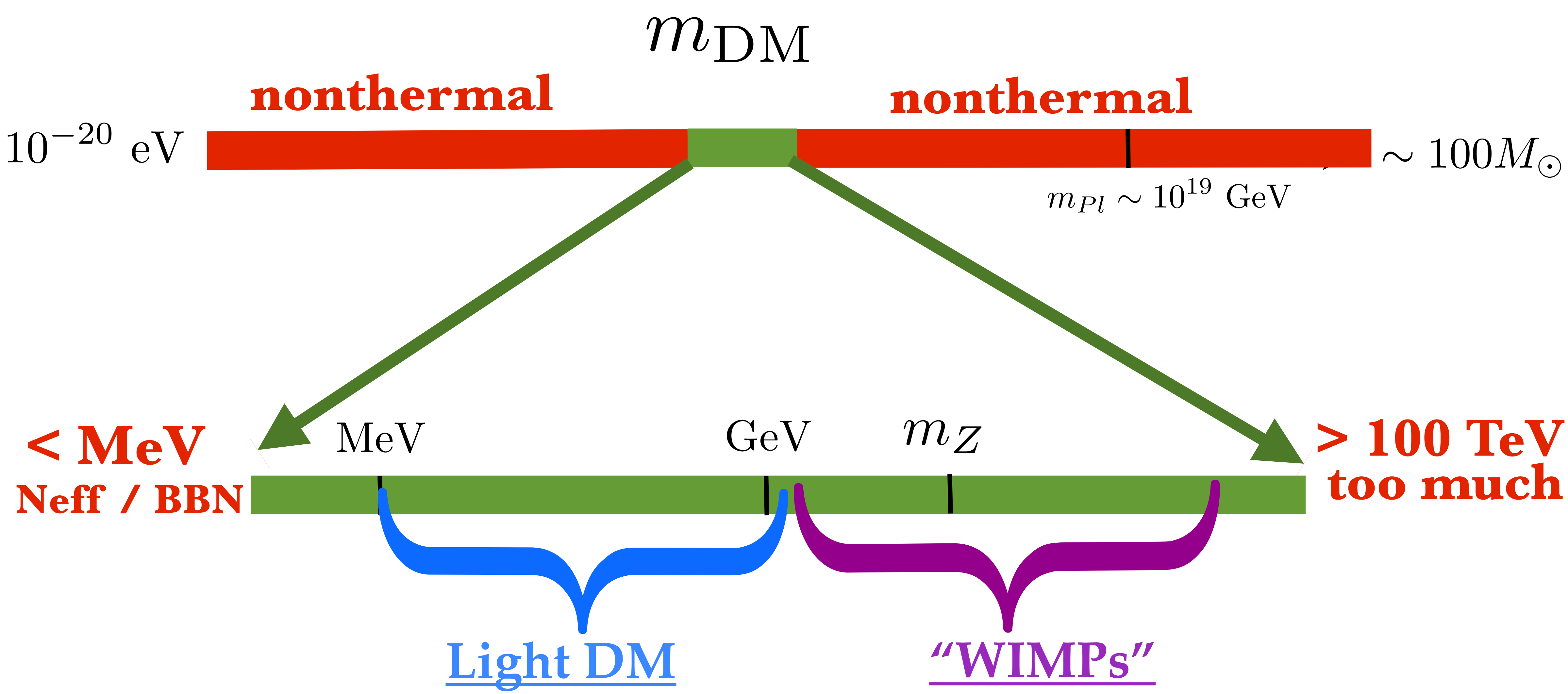
Courtesy G. Krnjaic

Thermal dark matter

- "Most discoverable DM candidates are in thermal equilibrium" - G. Krnjaic
  - If we can detect it, it's likely that it was in equilibrium (e.g. interacted enough)
  - Thermal dark matter has minimum annihilation rate (to set relic density)
  - Doesn't care about initial conditions (washed out by thermal bath) - makes modeling easier
  - Limited viable mass range (to a range that is basically within reach)



Thermal dark matter

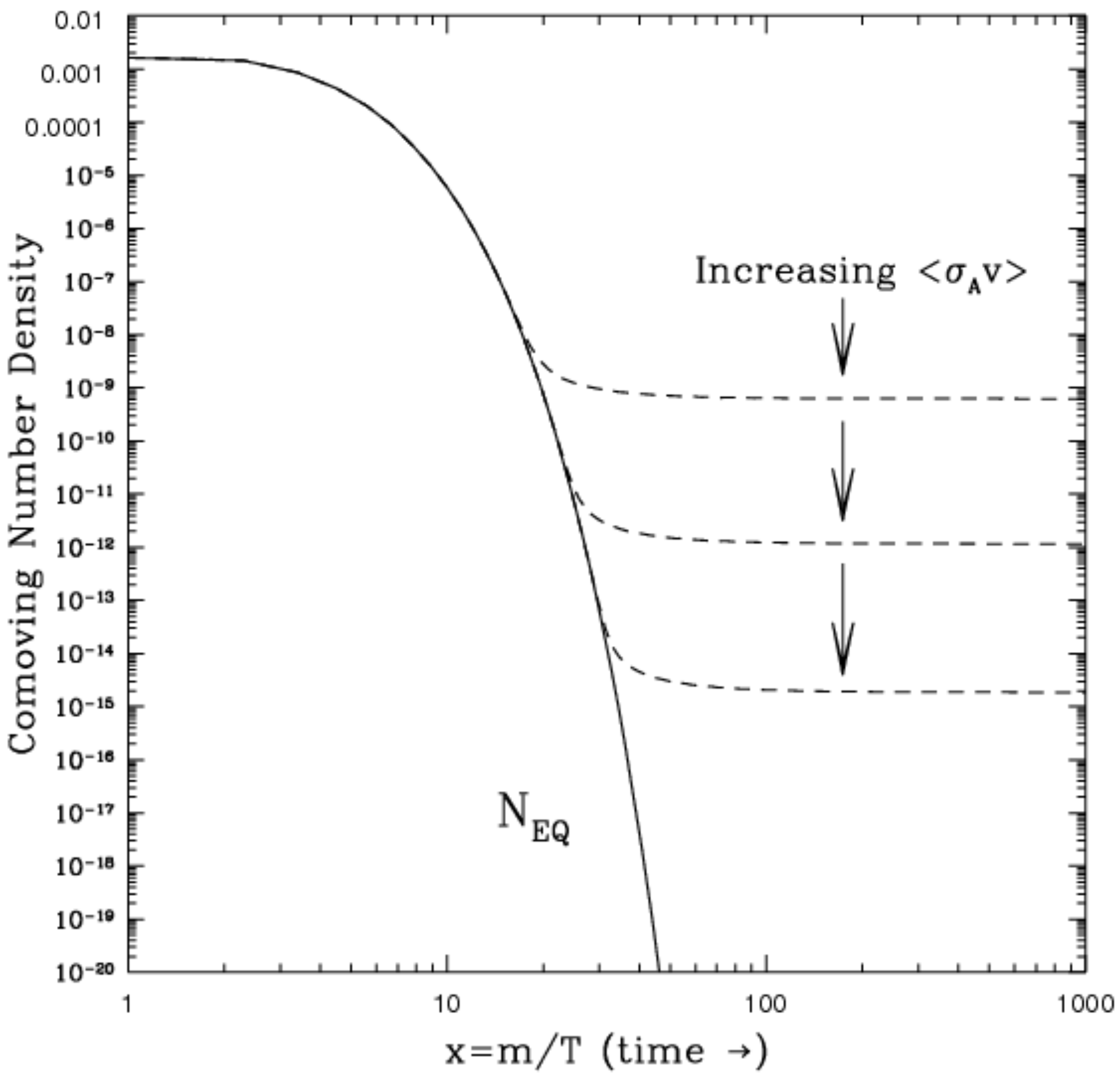


Wide open

LZ, LAr, PICO, LHC, etc

Mature >5 GeV program

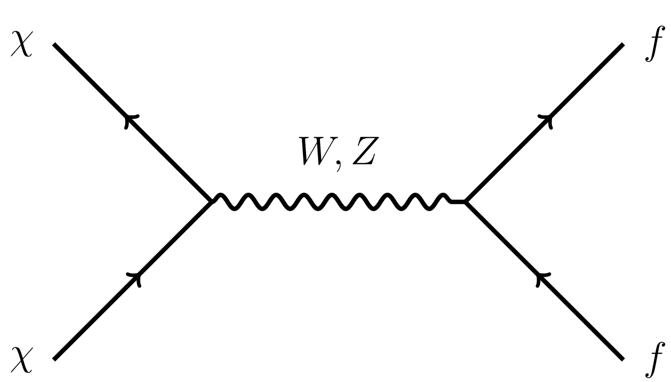
Are there actual candidates?



- Annihilation cross section needed for the relic abundance

$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1}$$

- New weak scale particle has to be heavier than ~a few GeV
  - Lee and Weinberg, PRL 39 (1977) 165-168

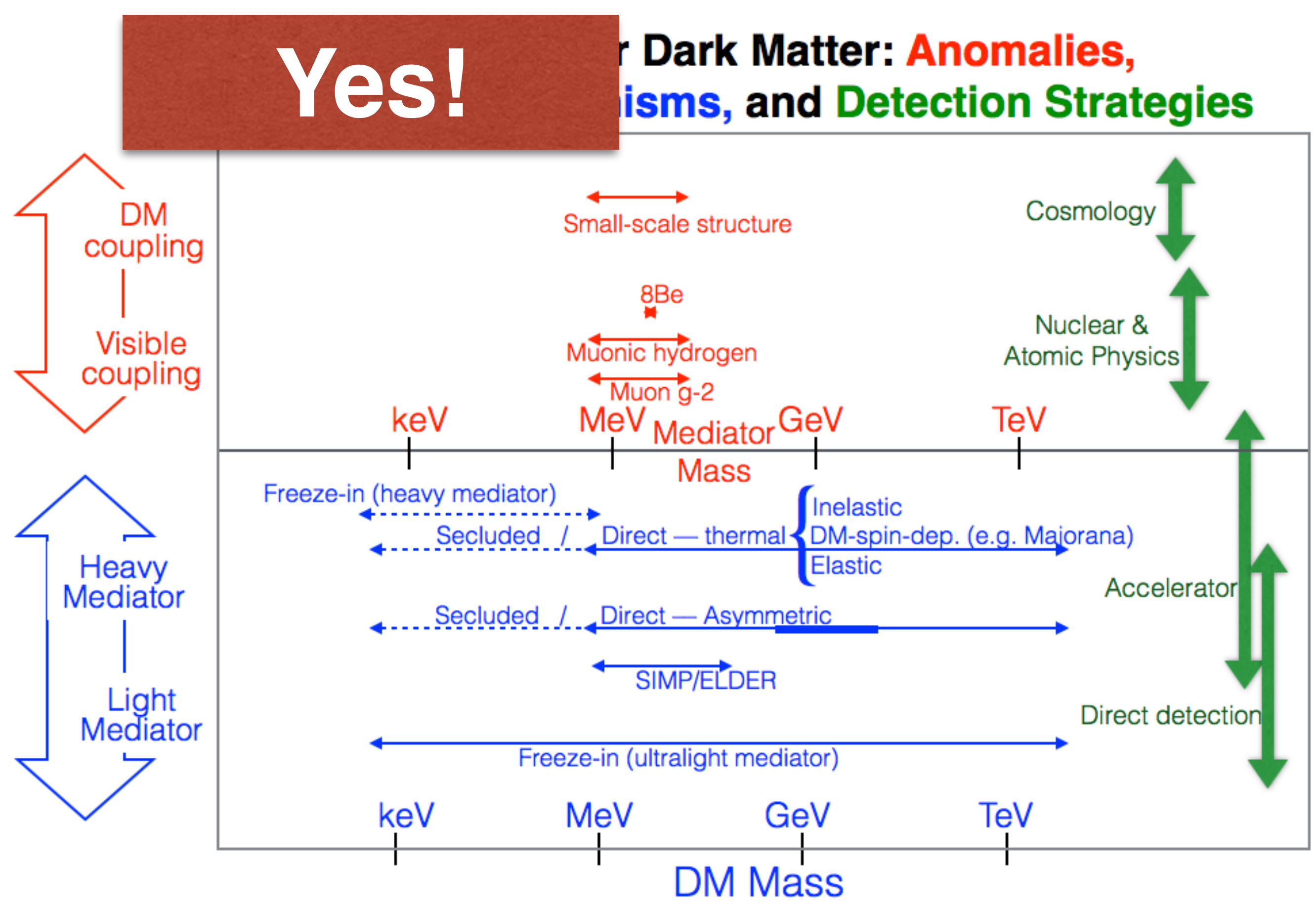


$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{m_\chi}{\mathrm{GeV}} \right)^2$$

Are there actual candidates?

- Light dark matter needs new forces (although we might already be there in canonical WIMP dark matter anyway)
  - Asymmetric DM
  - Secluded DM
  - Forbidden DM
  - SIMP
  - ELDER
  - Freeze in models

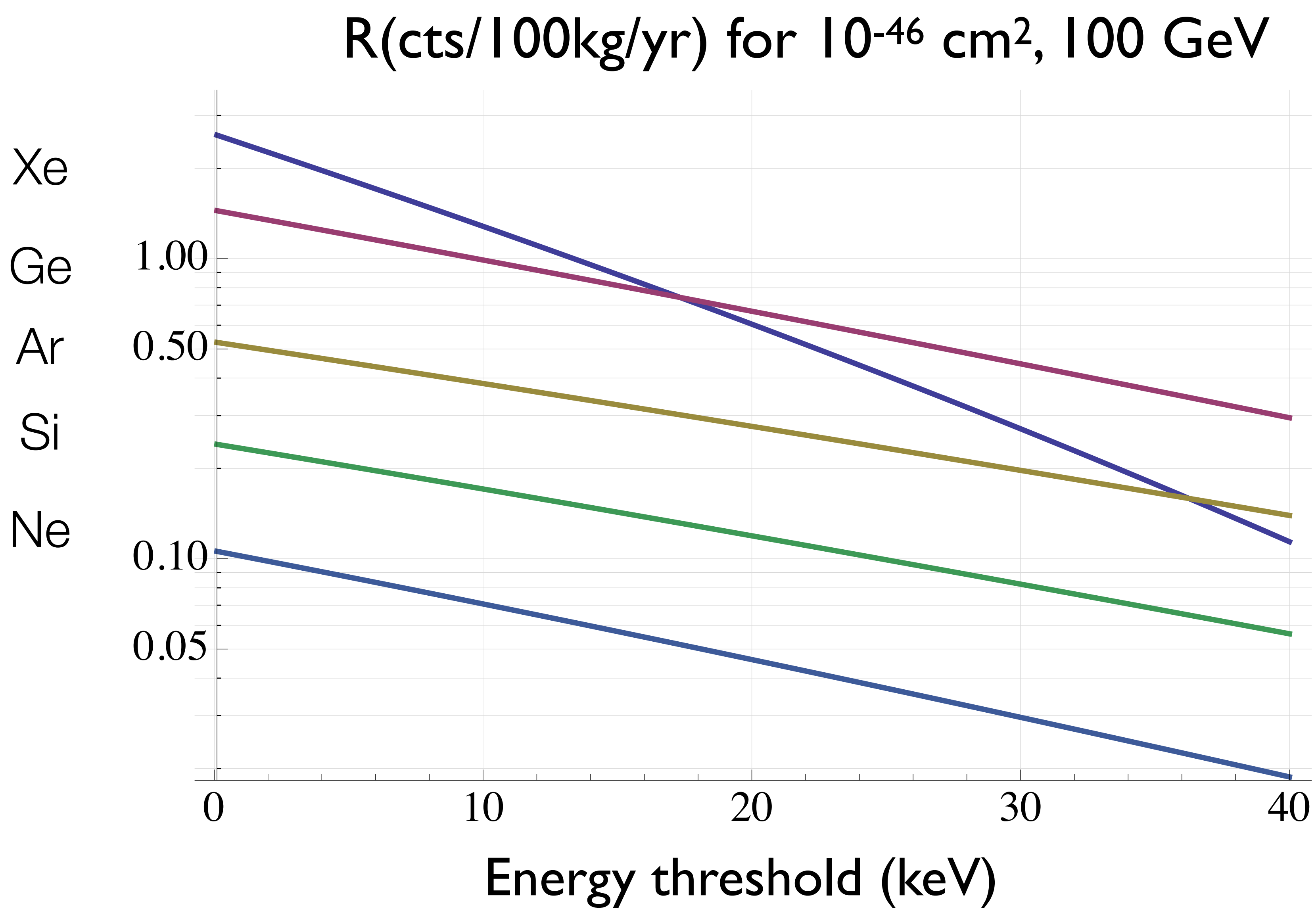
US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report



1707.04591

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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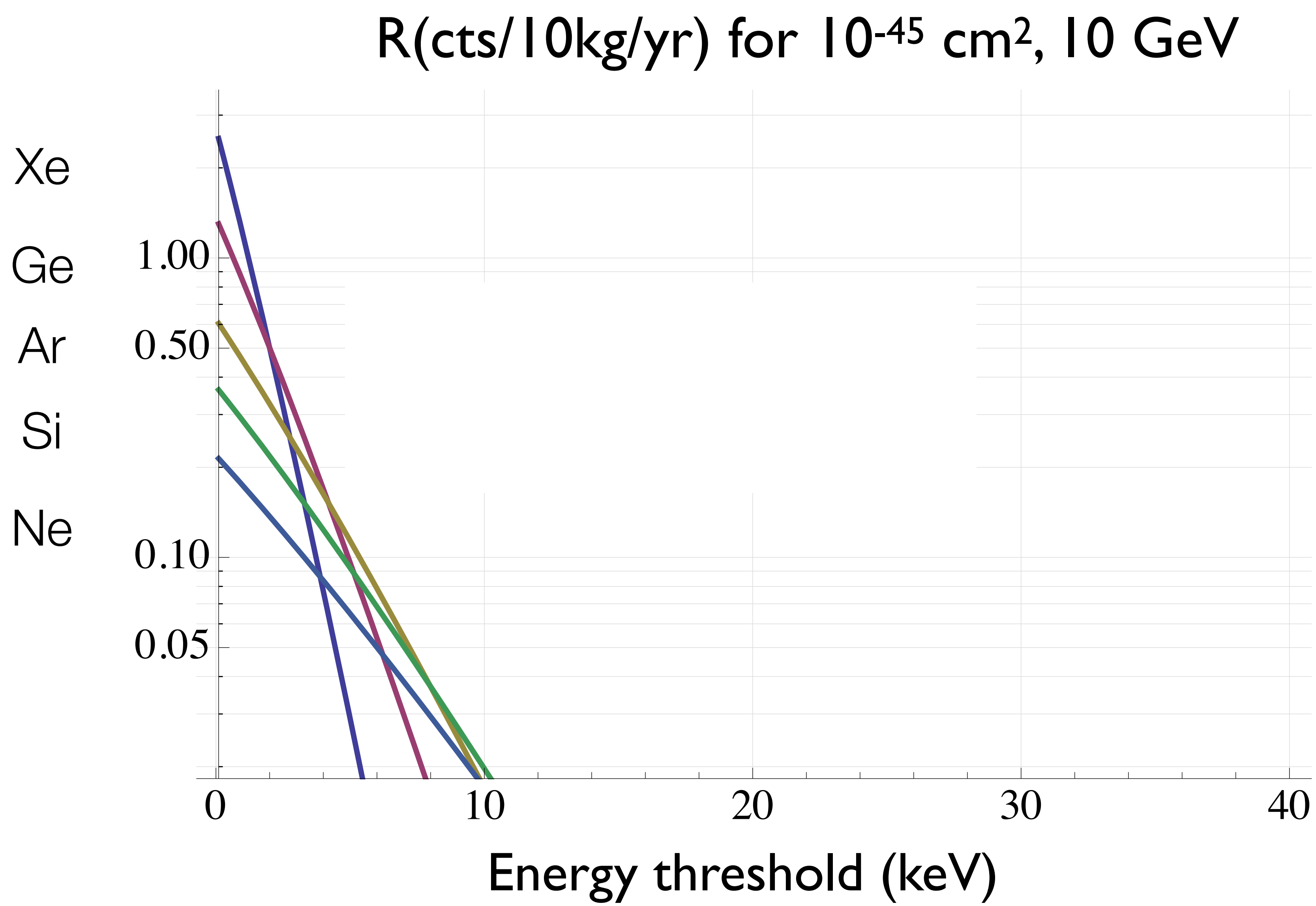

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$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2m_p^2} \times F^2(Q) \times \int_{v_m}^{v_{esc}} \frac{f(v)}{v} dv$$

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

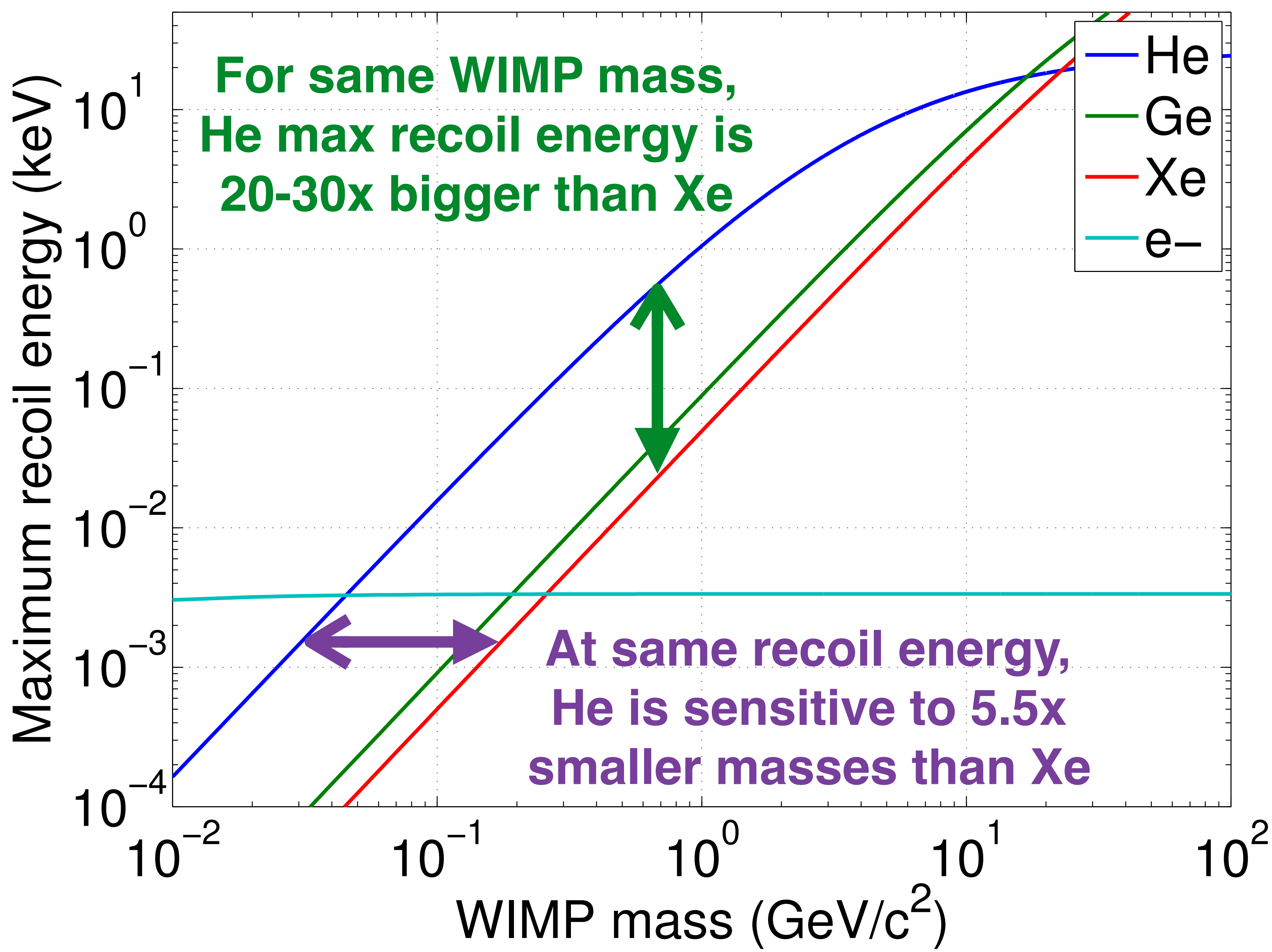
m_N is mass of nucleus

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

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

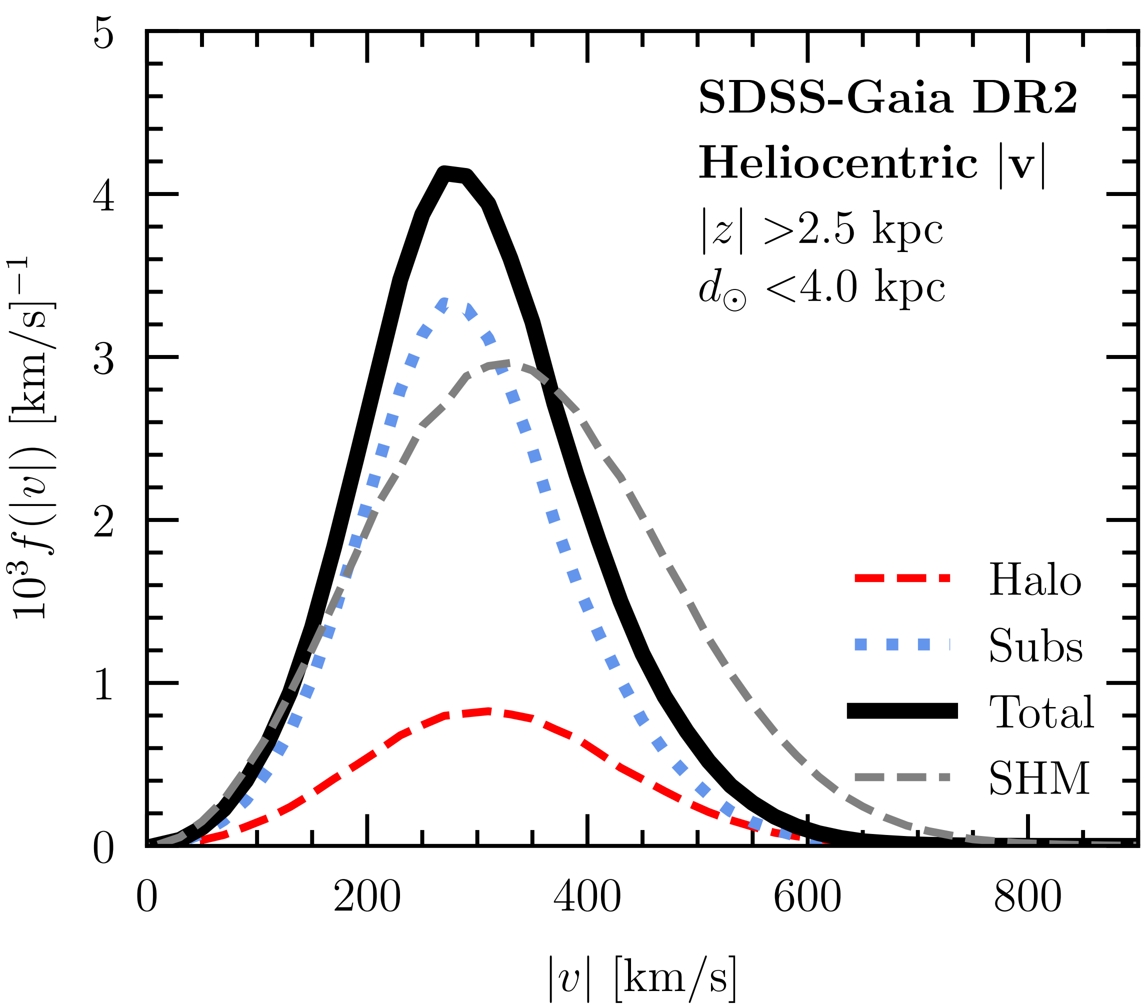
What do you need for low mass?

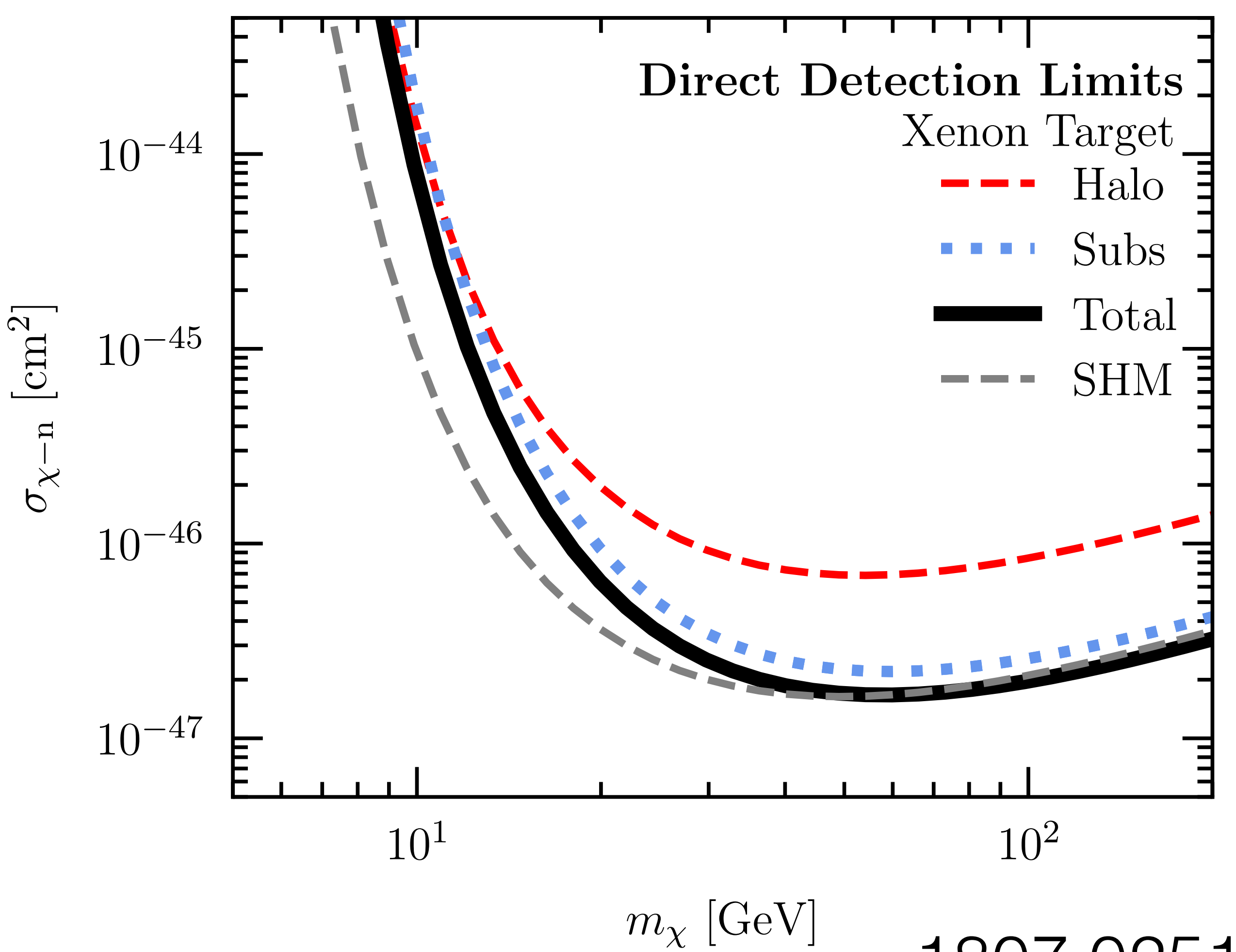
$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2m_p^2} \times F^2(Q) \times \int_{v_m}^{v_{esc}} \frac{f(v)}{v} dv$$



Light targets less sensitive to halo uncertainty

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





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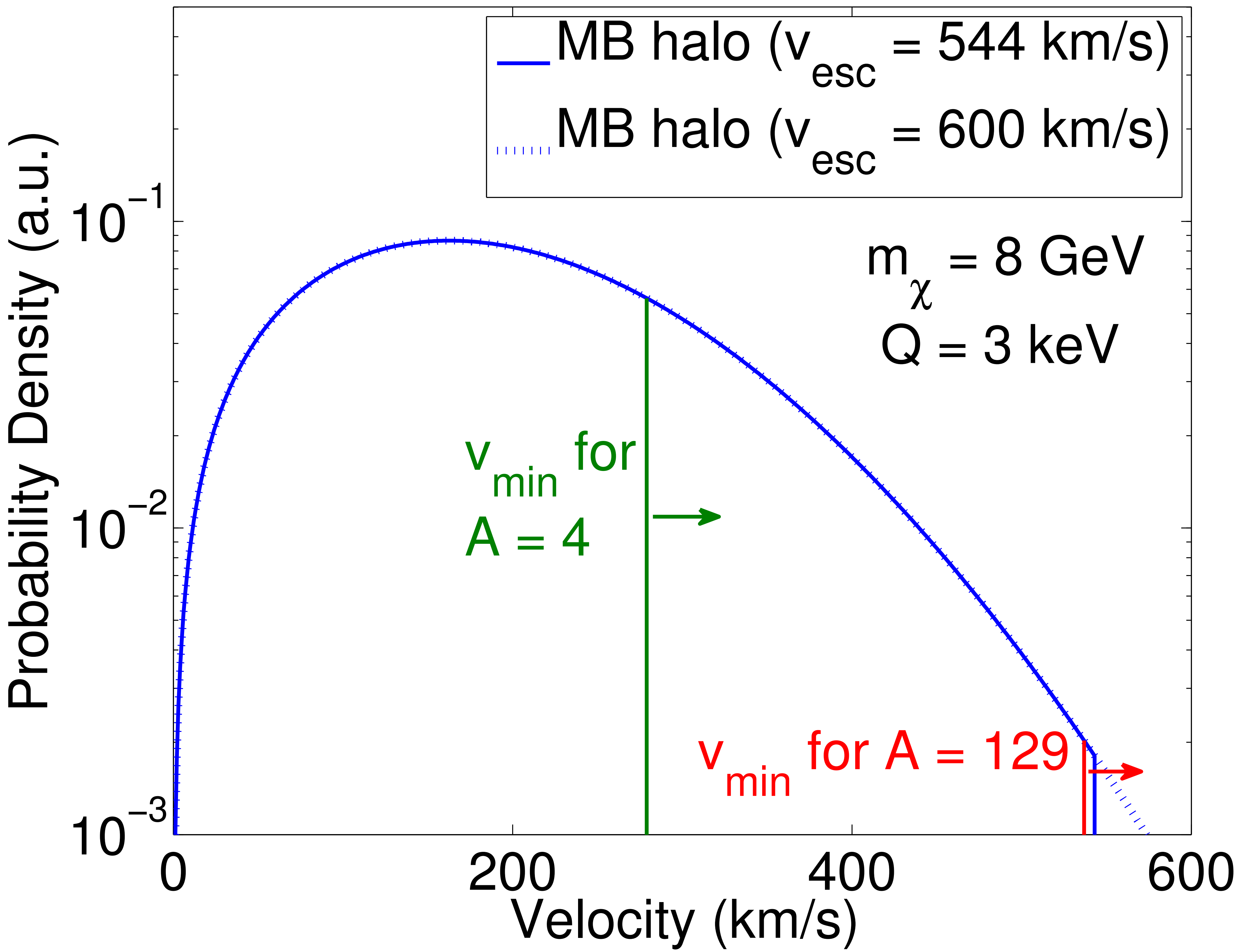
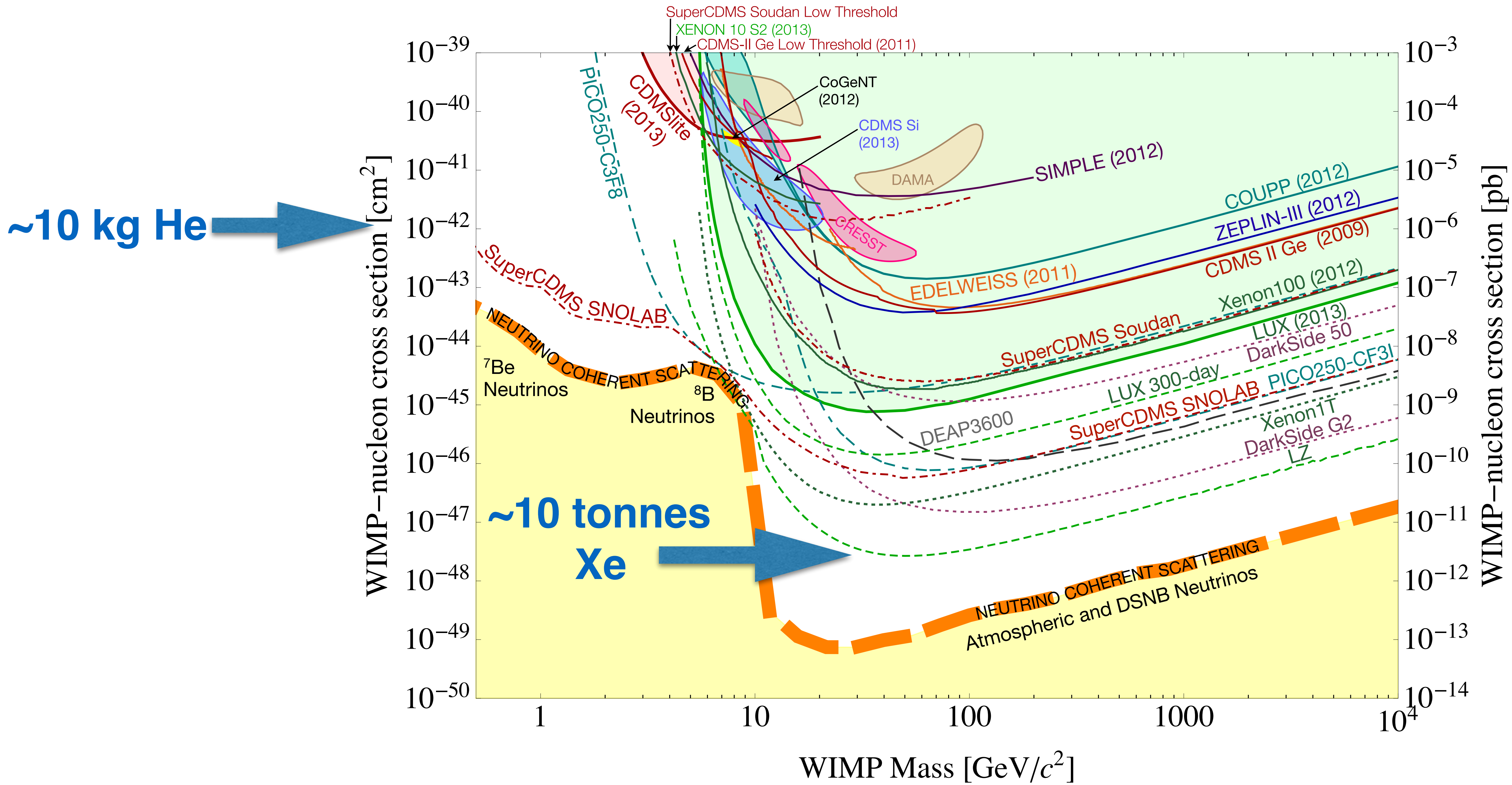
Light targets less sensitive to halo uncertainty

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



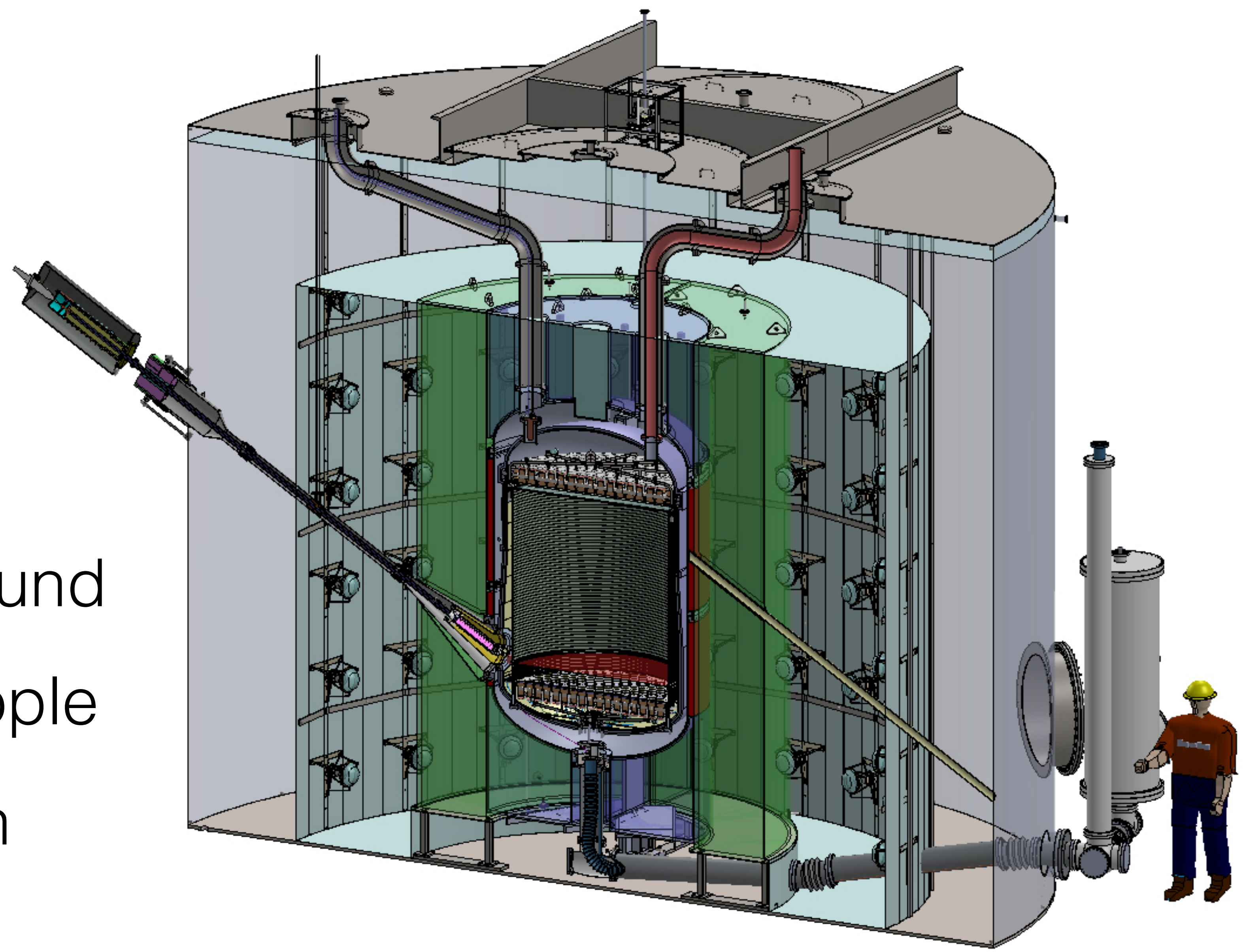
What don't you need for low mass?

- A lot of mass



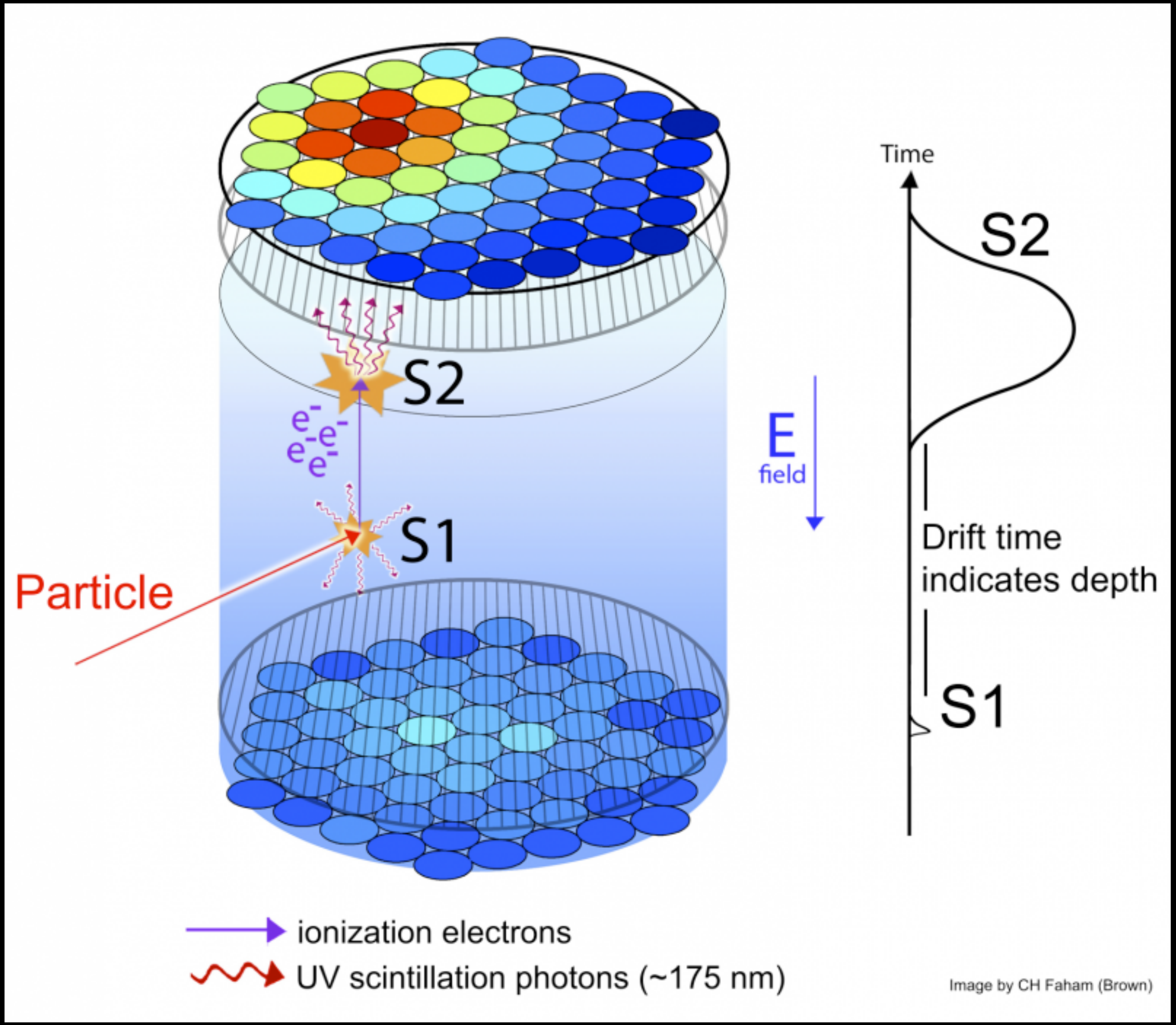
LUX-Zeplin (LZ)

- 7 tonne active LXe TPC
  - Heavy target
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
  - Huge effort to make it clean and low background
- >30 institutions, ~200 people
- Now under construction in Lead, SD



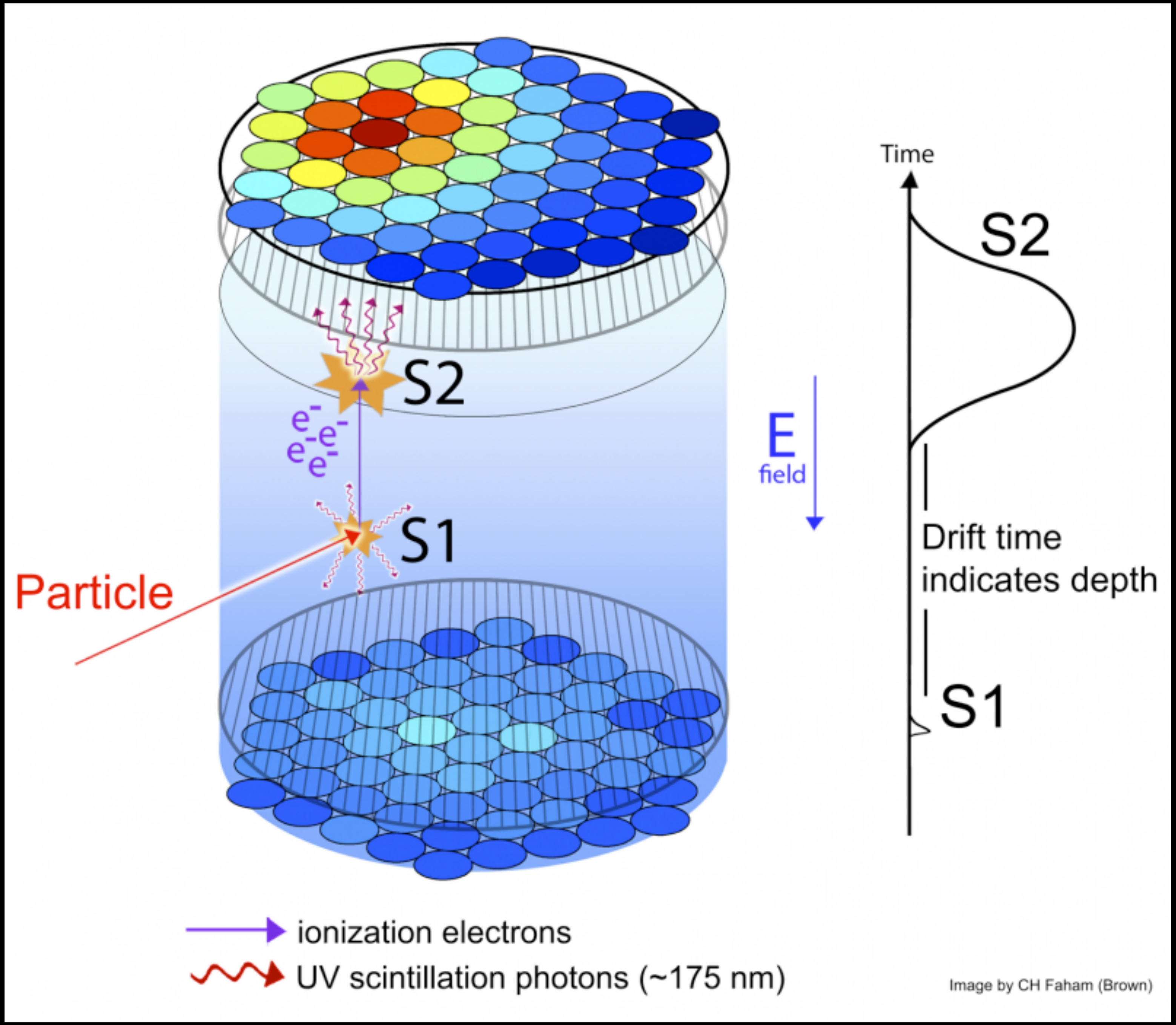
Two phase Xenon TPCs

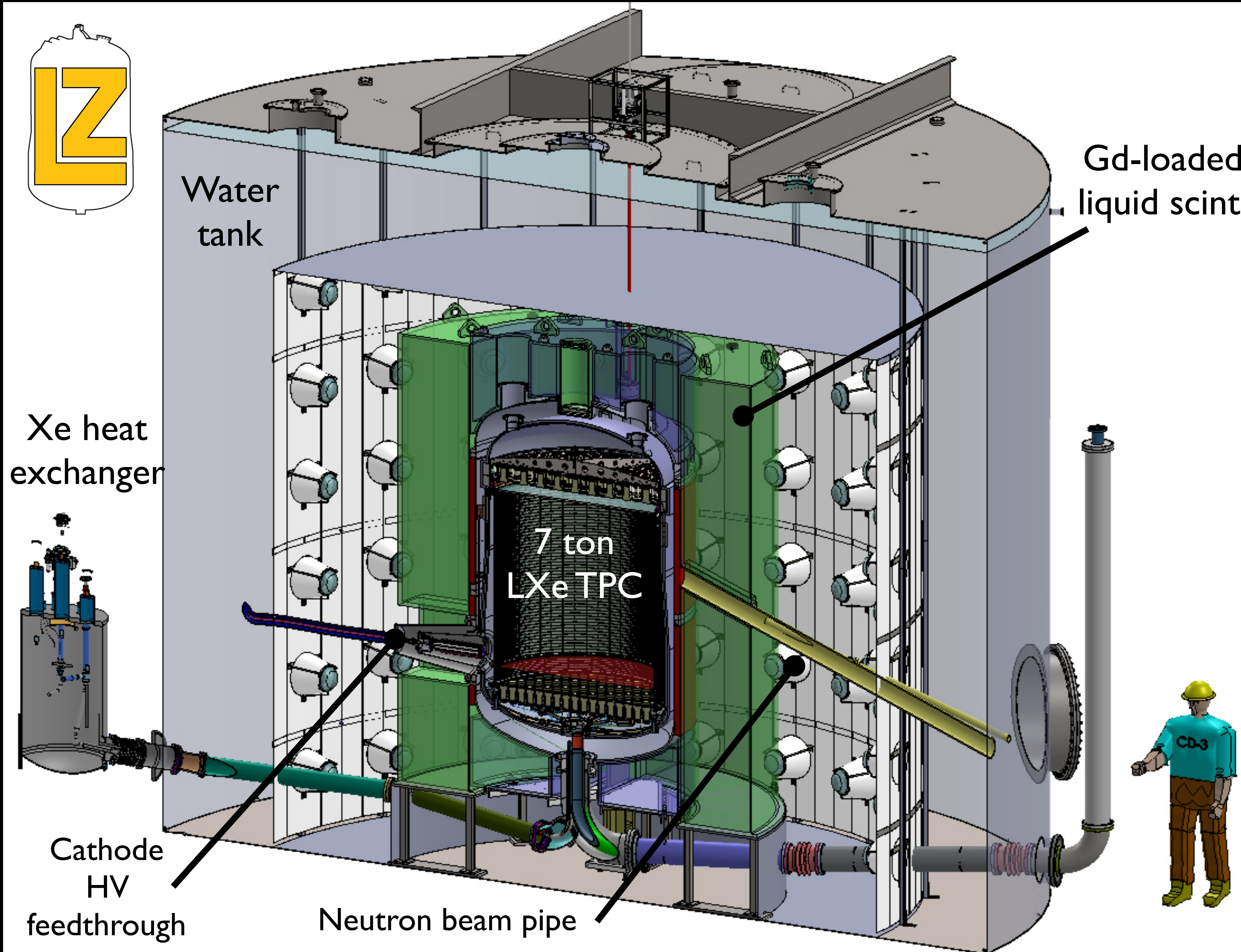
- Interaction in the xenon creates:
  - Scintillation light (~10 ns) - called S1
  - ionization electrons
- Electrons drift through electric field to liquid/gas surface
  - Extracted into gas and accelerated creating proportional scintillation light - called S2



Two phase Xenon TPCs

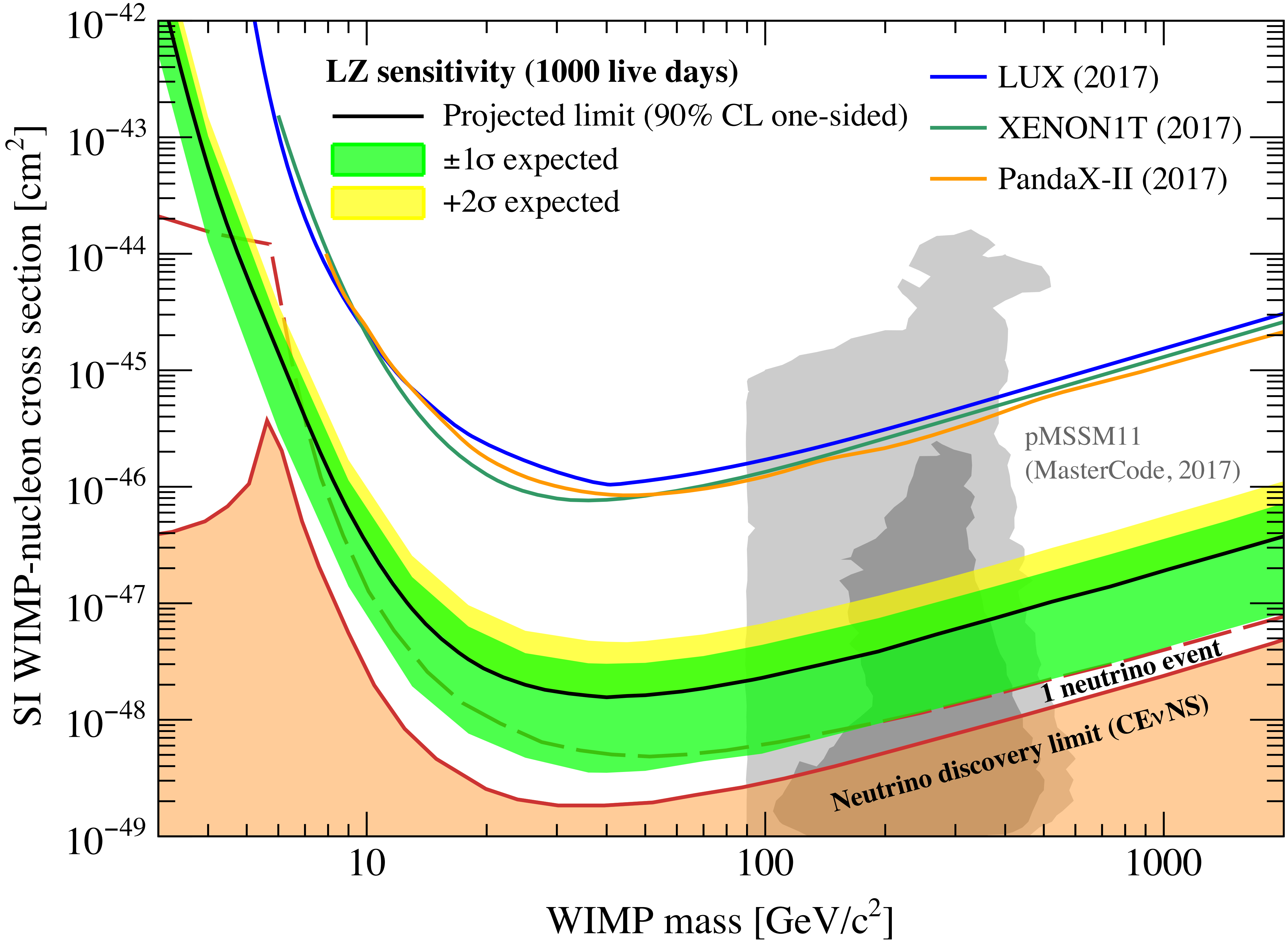
- Excellent 3D reconstruction (~mm)
  - Z position from S1-S2 timing
  - XY position from hit pattern of S2 light
  - Allows for self shielding, rejection of edge events
- Ratio of charge (S2) to light (S1) gives particle ID
  - Better than 99.5% rejection of electron recoil events



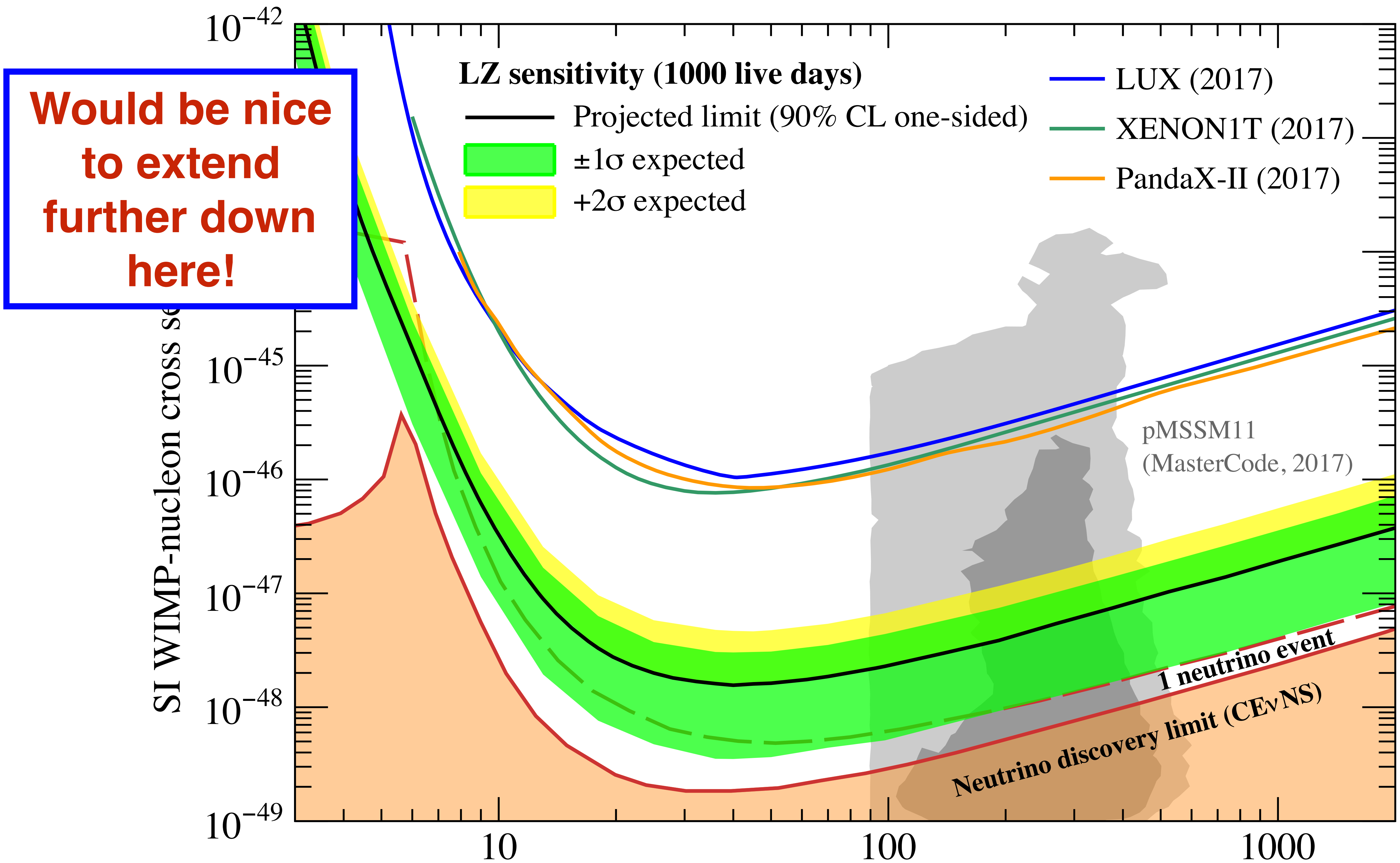


LZ
Water tank
Gd-loaded liquid scint.
Xe heat exchanger
7 ton LXe TPC
Cathode HV feedthrough
Neutron beam pipe
CD-3

LUX-Zeplin (LZ)



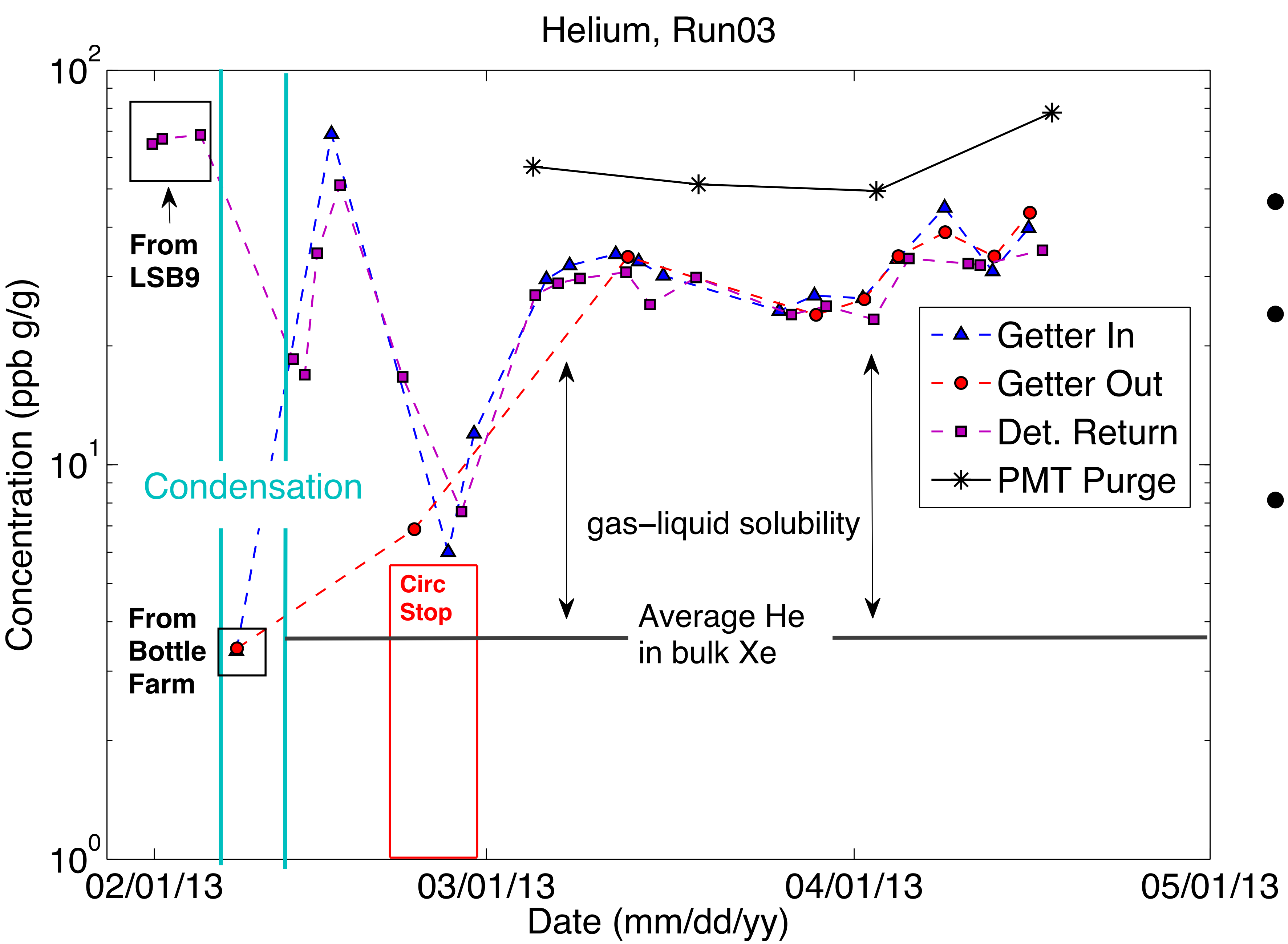
LUX-Zeplin (LZ)



Can we add He or H_2 to LXe?

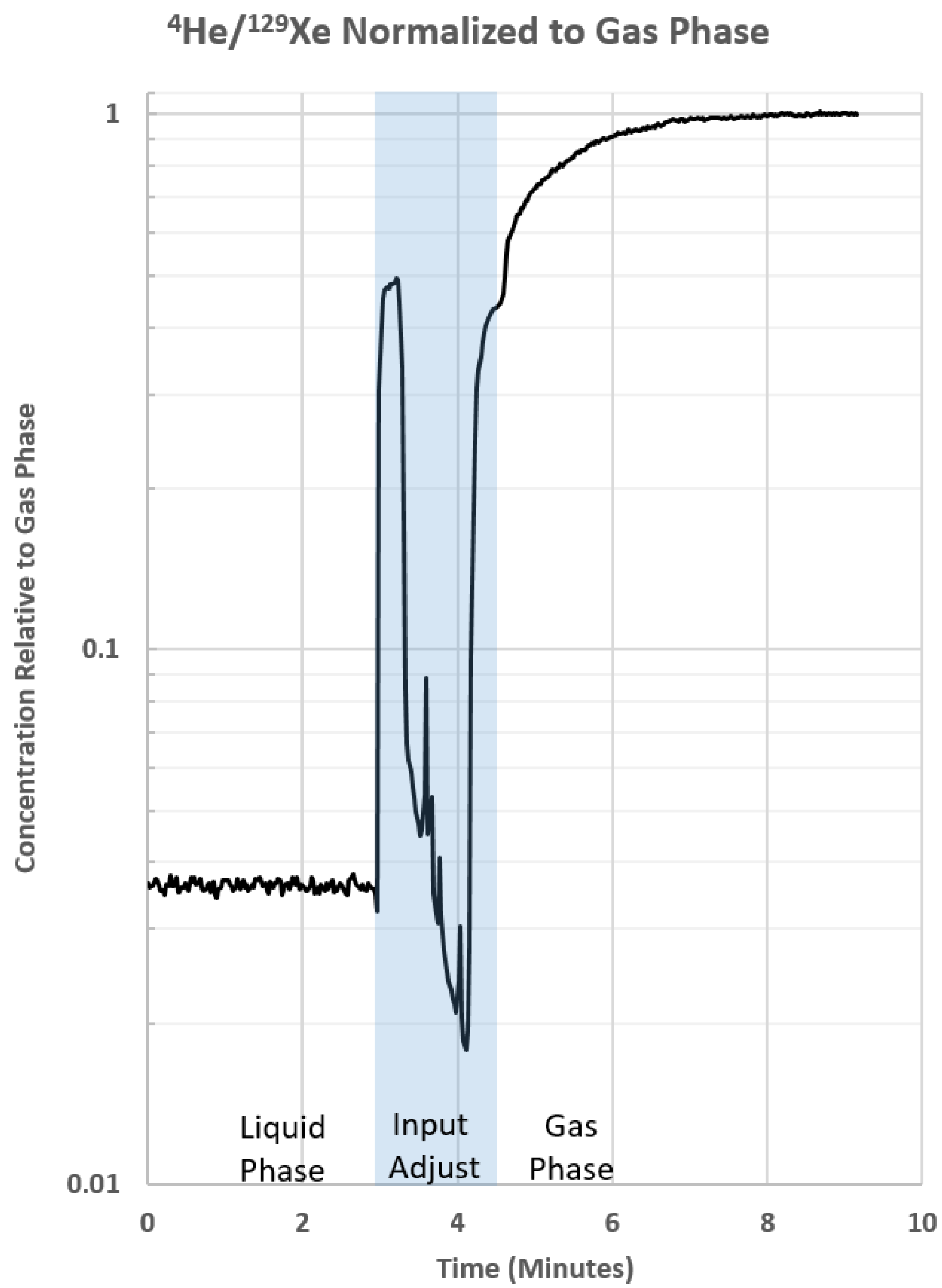
- Dissolve small quantities of He/H_2 in liquid xenon
- Extend the reach of a detector like LZ (or XENONnT or PandaX, etc)
- Add new targets to field of direct detection
  - No existing experiments using either
    - Talk on HeRALD by H. Pinckney next
    - NEWS-G gas detector in Canada another contender
- Capitalize on investment in large detectors by adding flexibility

Dissolving He/H 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/H in LXe?

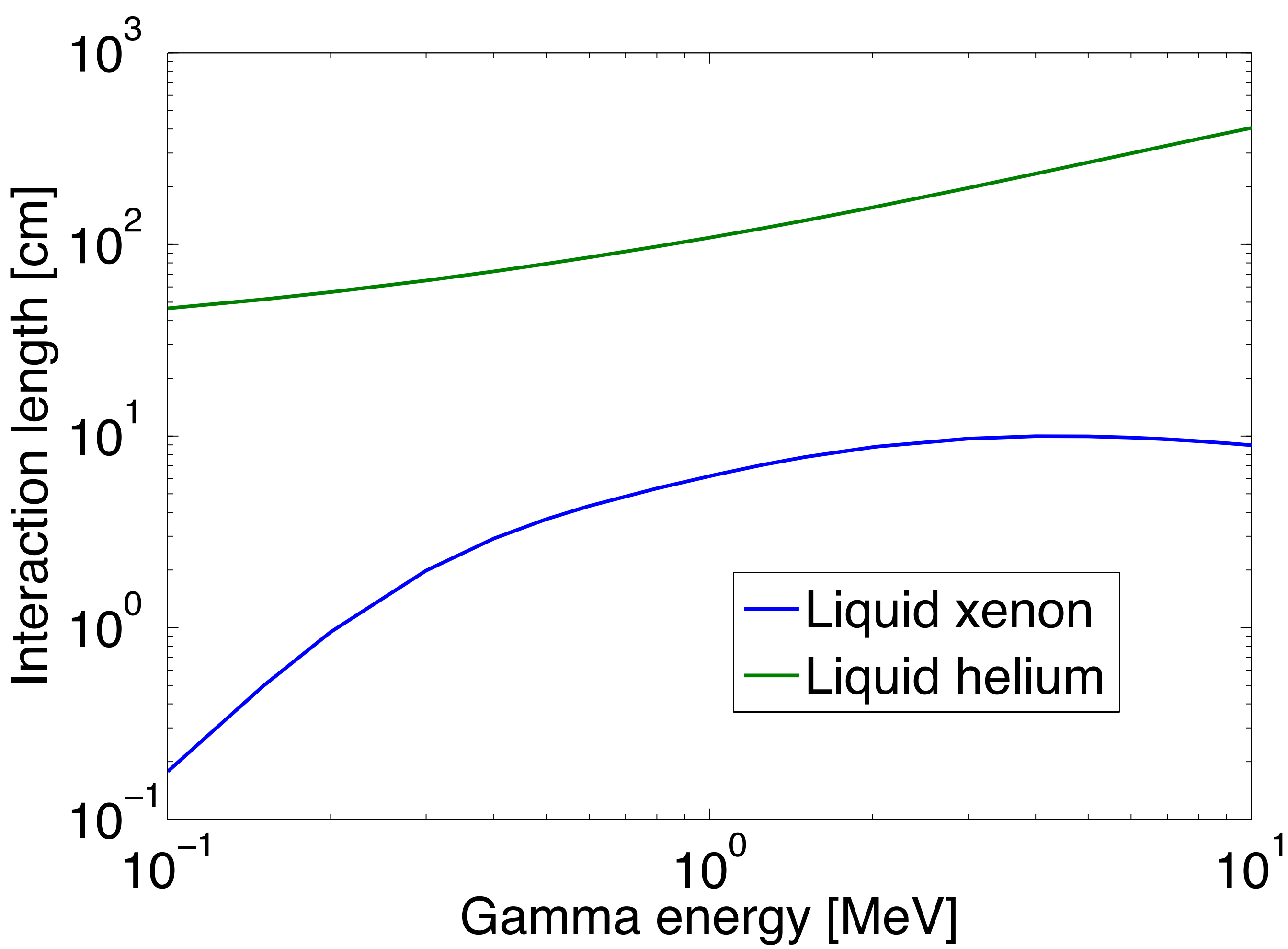


0.037 mol He/mol Xe x M_{He}/M_{Xe} ~ 0.1%

- He fraction confirmed in preliminary test at Fermilab
  - Achieved 0.1% He in LXe by mass on first attempt at 1 bar of partial pressure
- No data for H_2 in xenon, but scaling by argon data, 25% better than He

Backgrounds

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



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

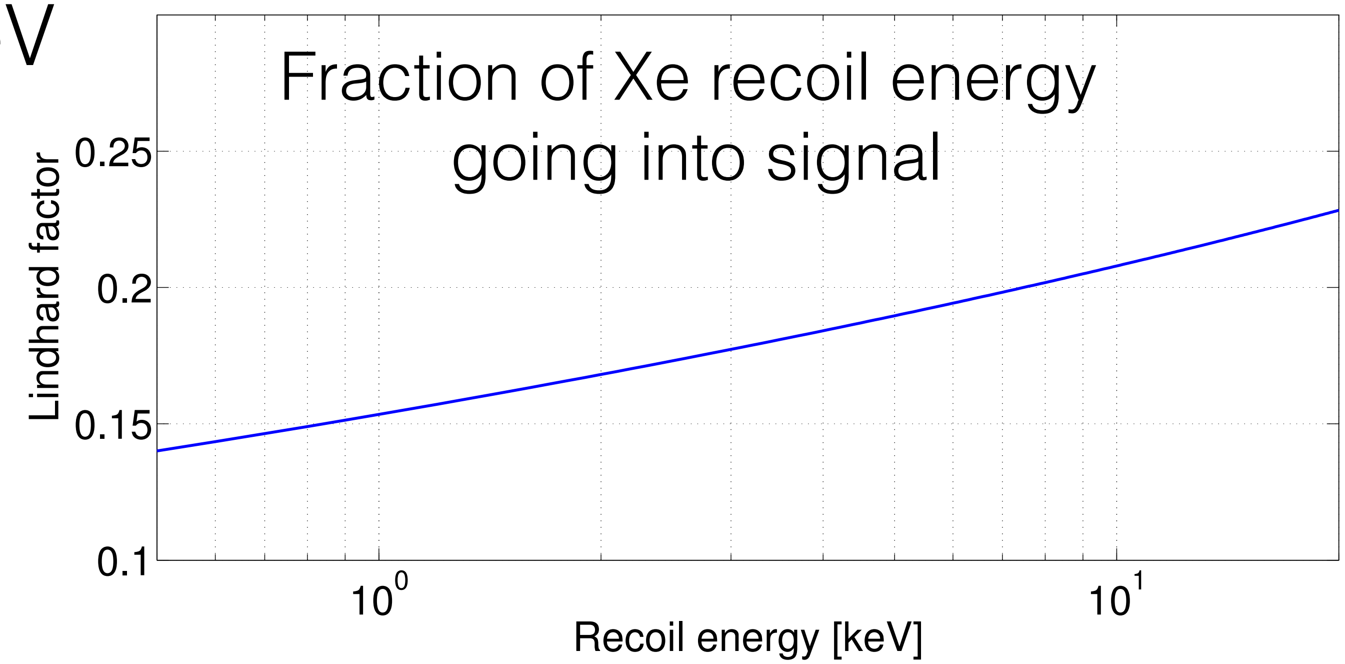
- Self shielding is not effective in He/H-only detector

Signal detection

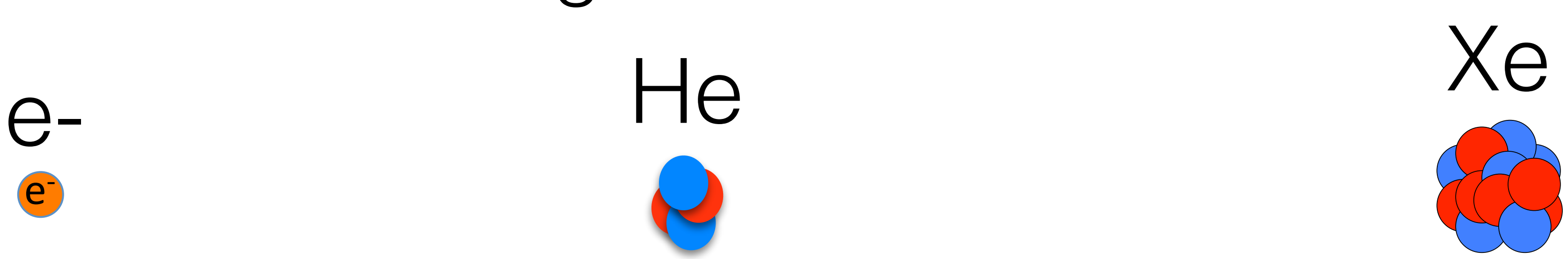
- Helium or Hydrogen recoils will interact with xenon atoms and electrons
  - Excitations will be xenon excitations
  - Alpha particles for example
- Keep same photon detection scheme!

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



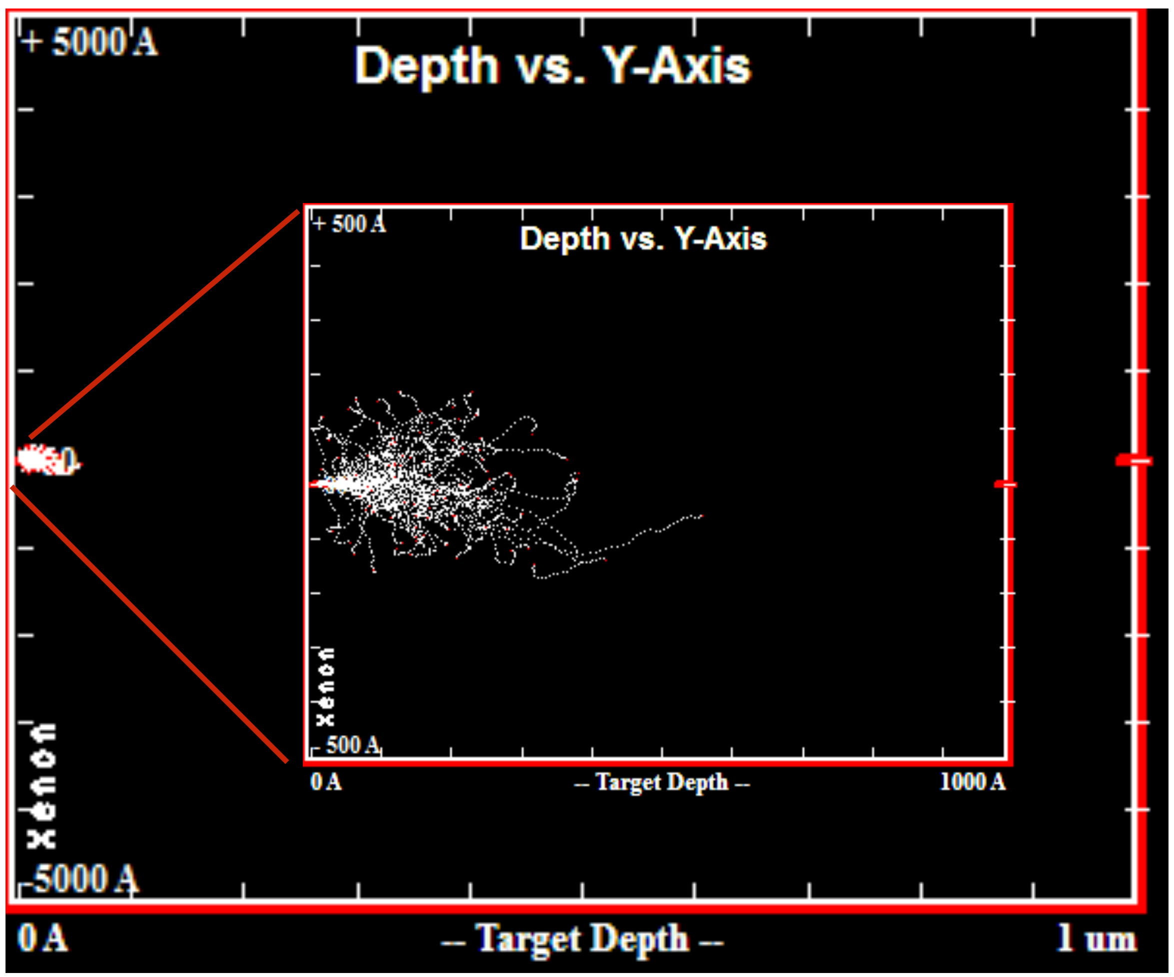
- Light nuclei - fewer strong nuclear collisions



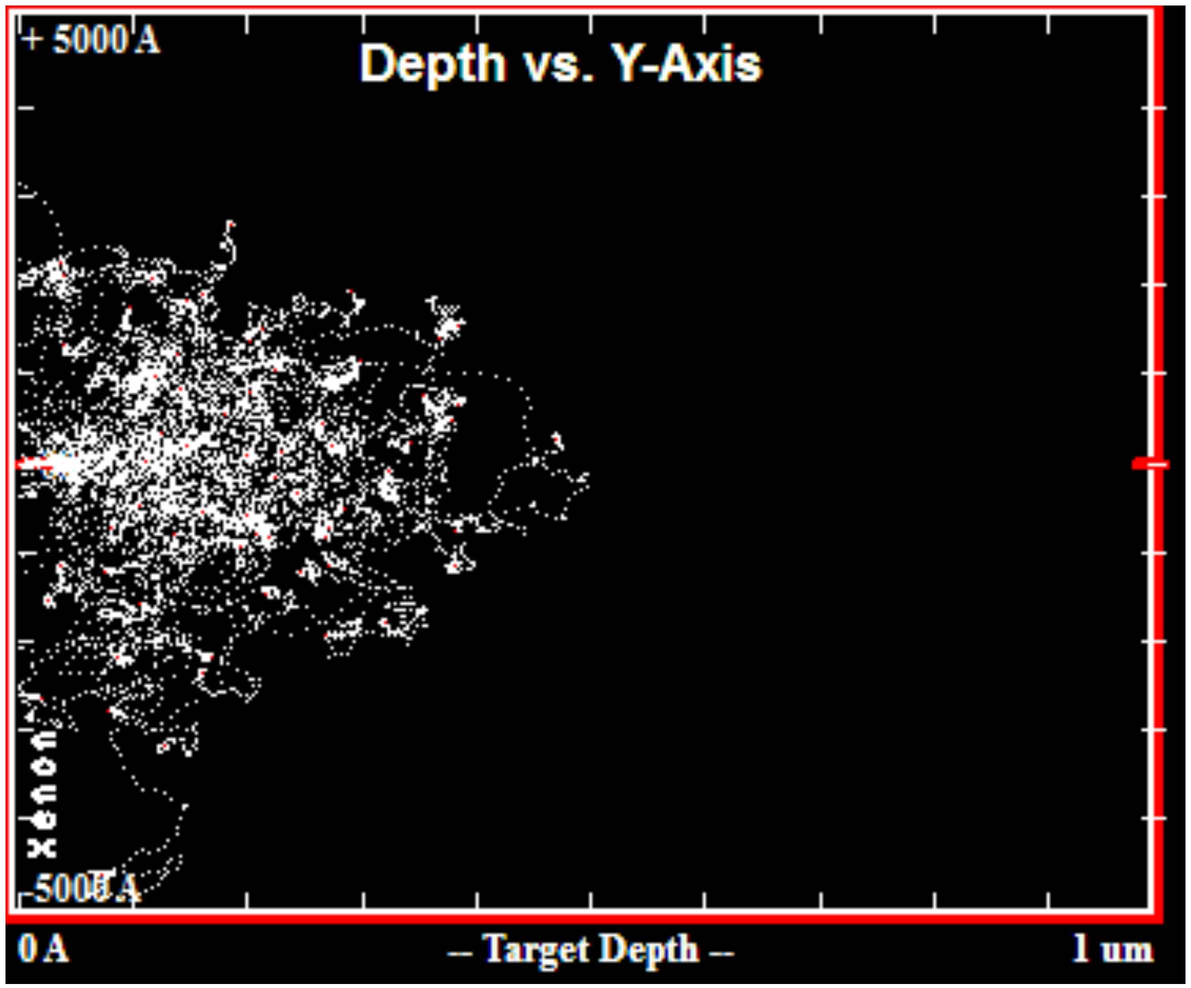
Not to scale

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



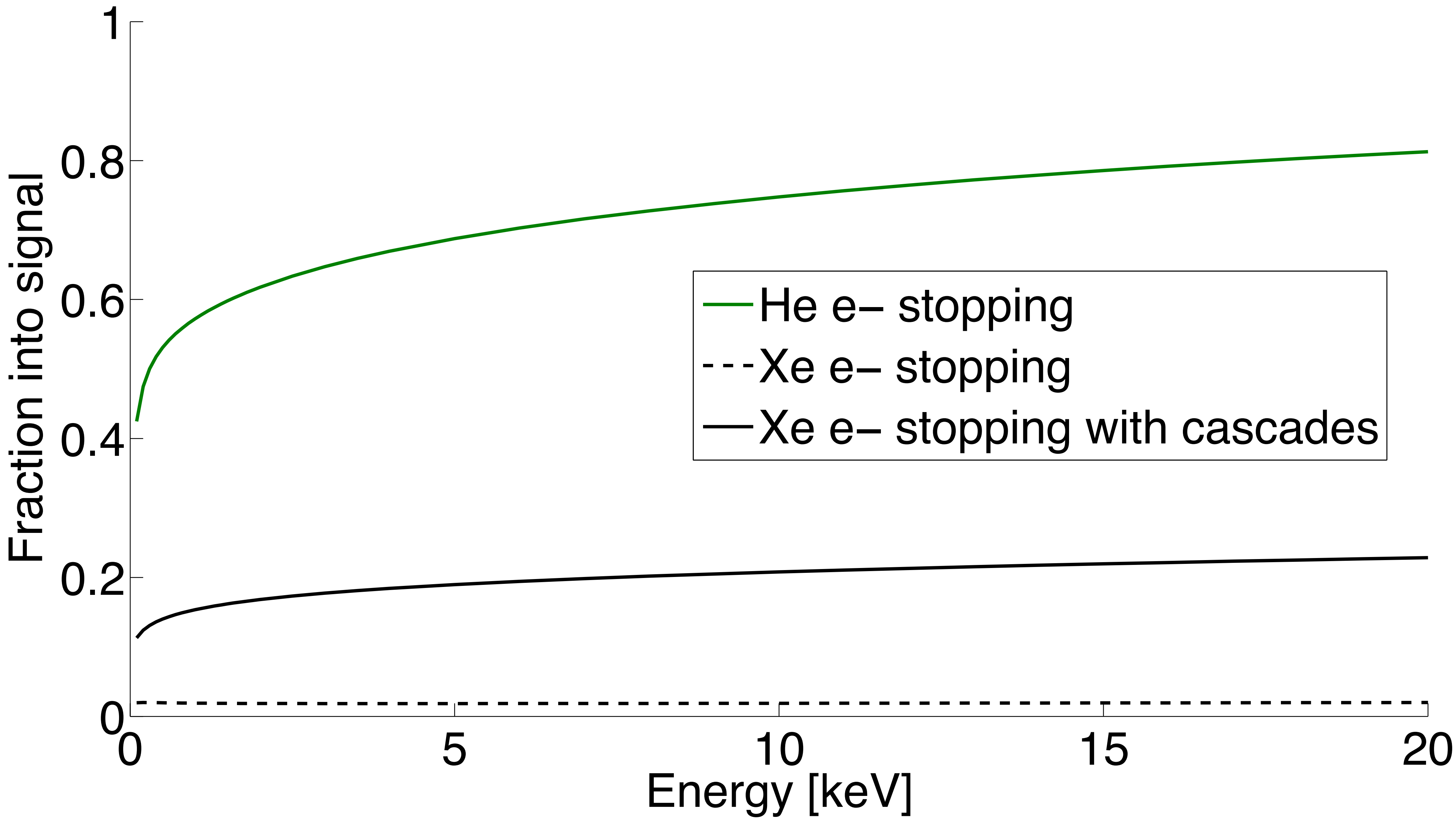
10 keV Xe in LXe
~100 A ranges



10 keV He in LXe
~1000 A ranges

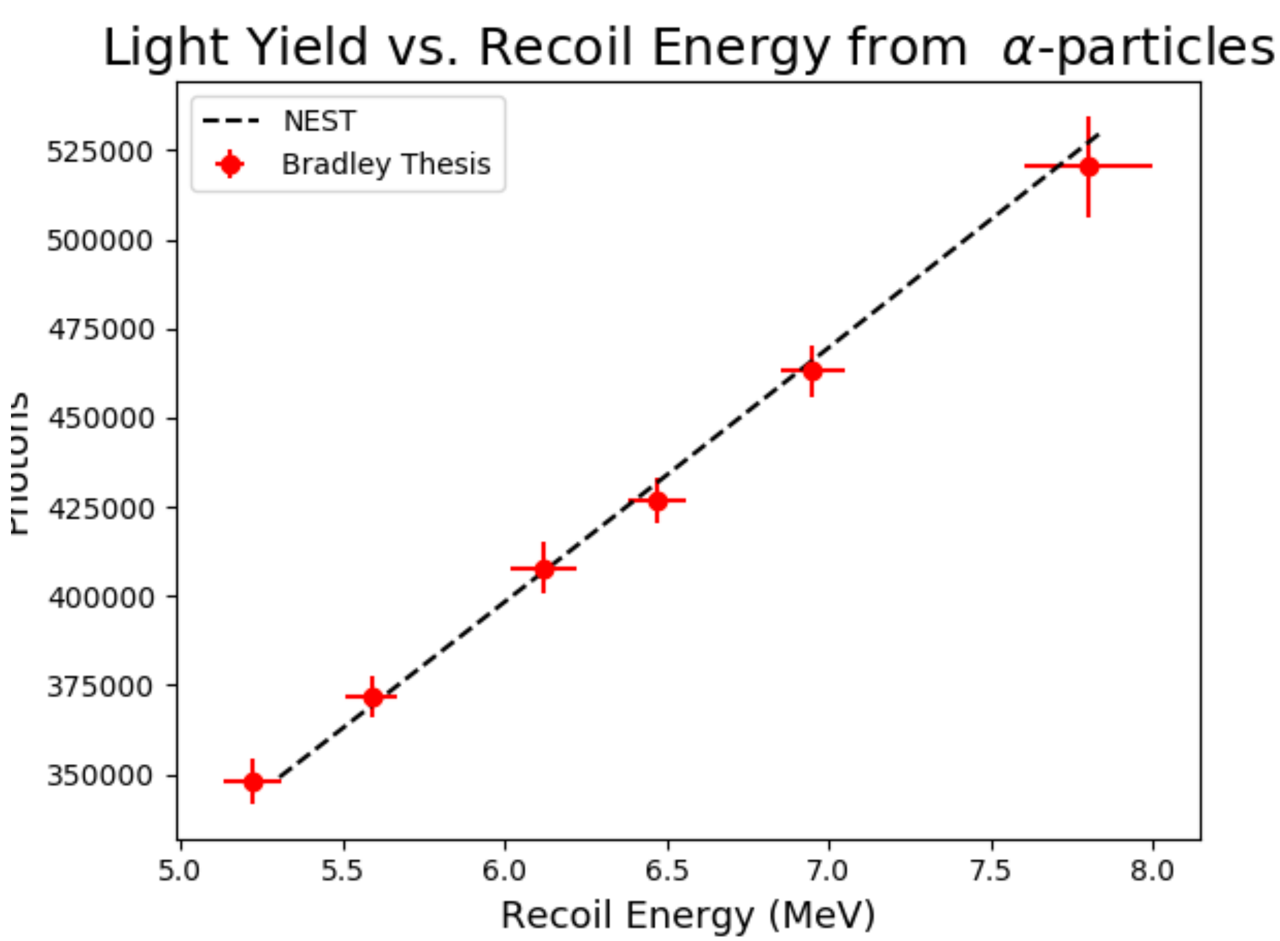
Modeling He recoils in LXe (v1)

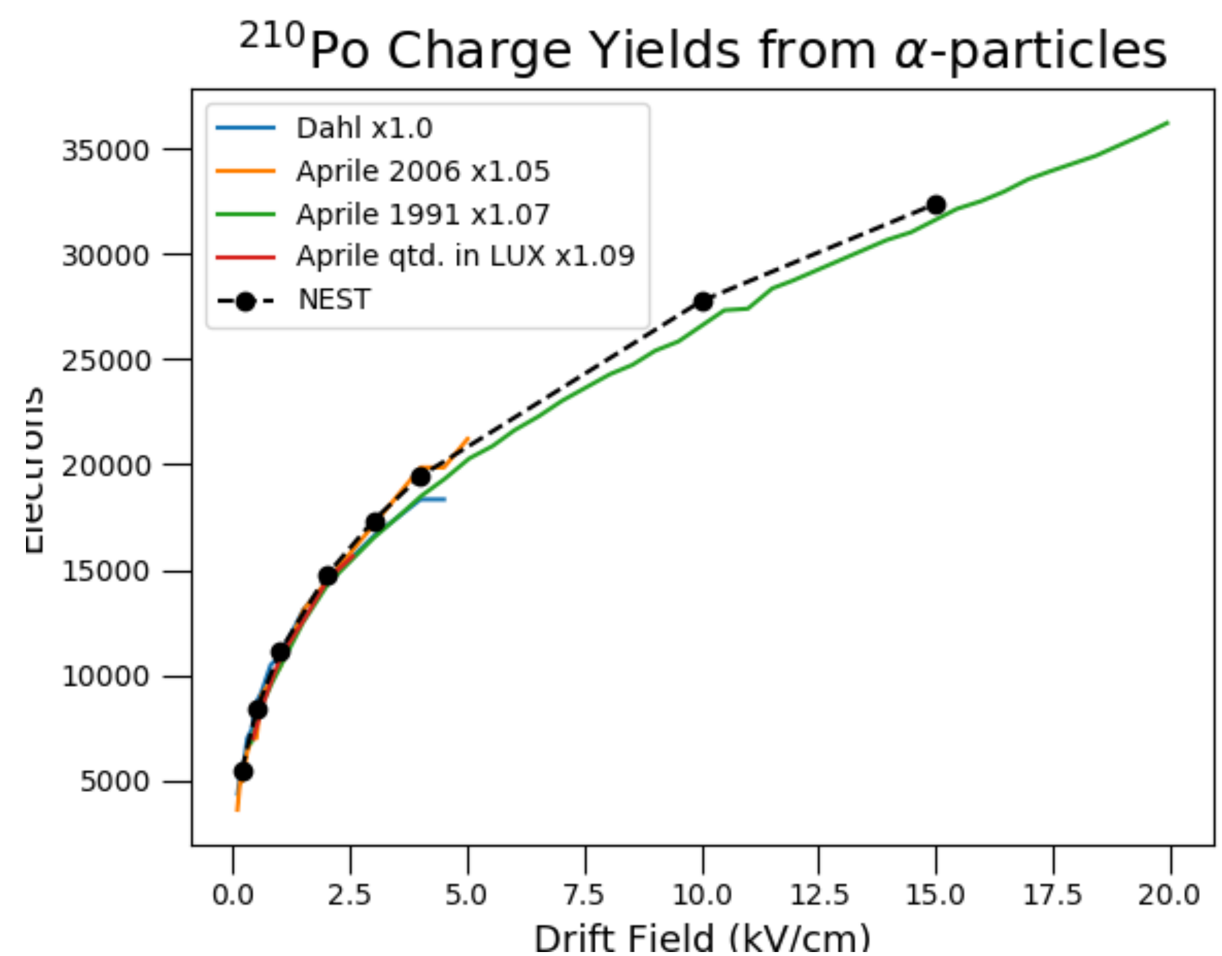
- Stopping and Range of Ions in Matter (SRIM)
- Calculate the energy lost to nuclear (heat) and electronic (signal) stopping



Modeling He recoils in LXe (v2)

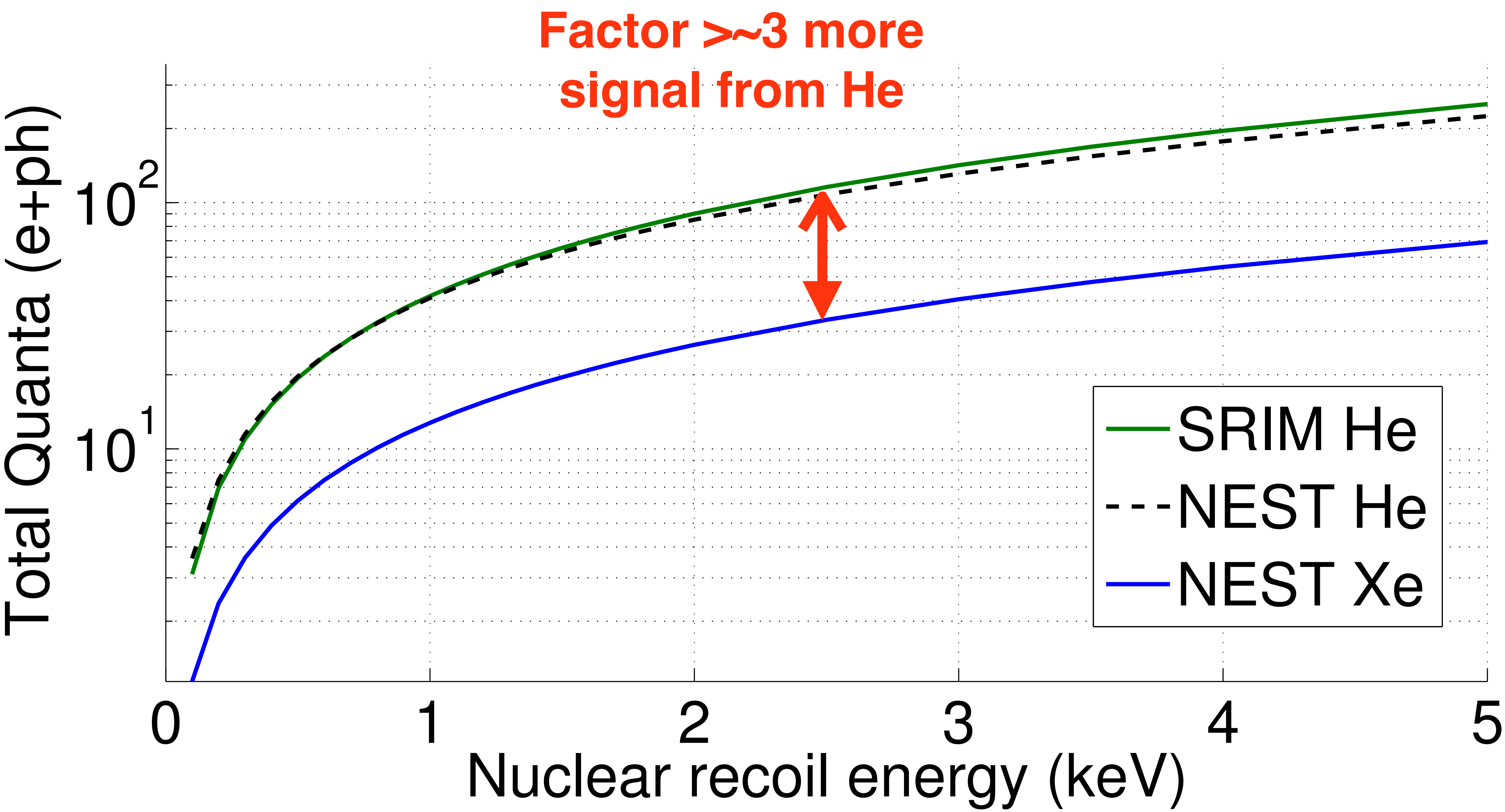
- Noble Element Simulation Technique (NESTv2)
  - Data driven model for signal processes in LXe, including alpha data from LUX and test chambers
  - High energies, but at least it's real He nuclei in LXe



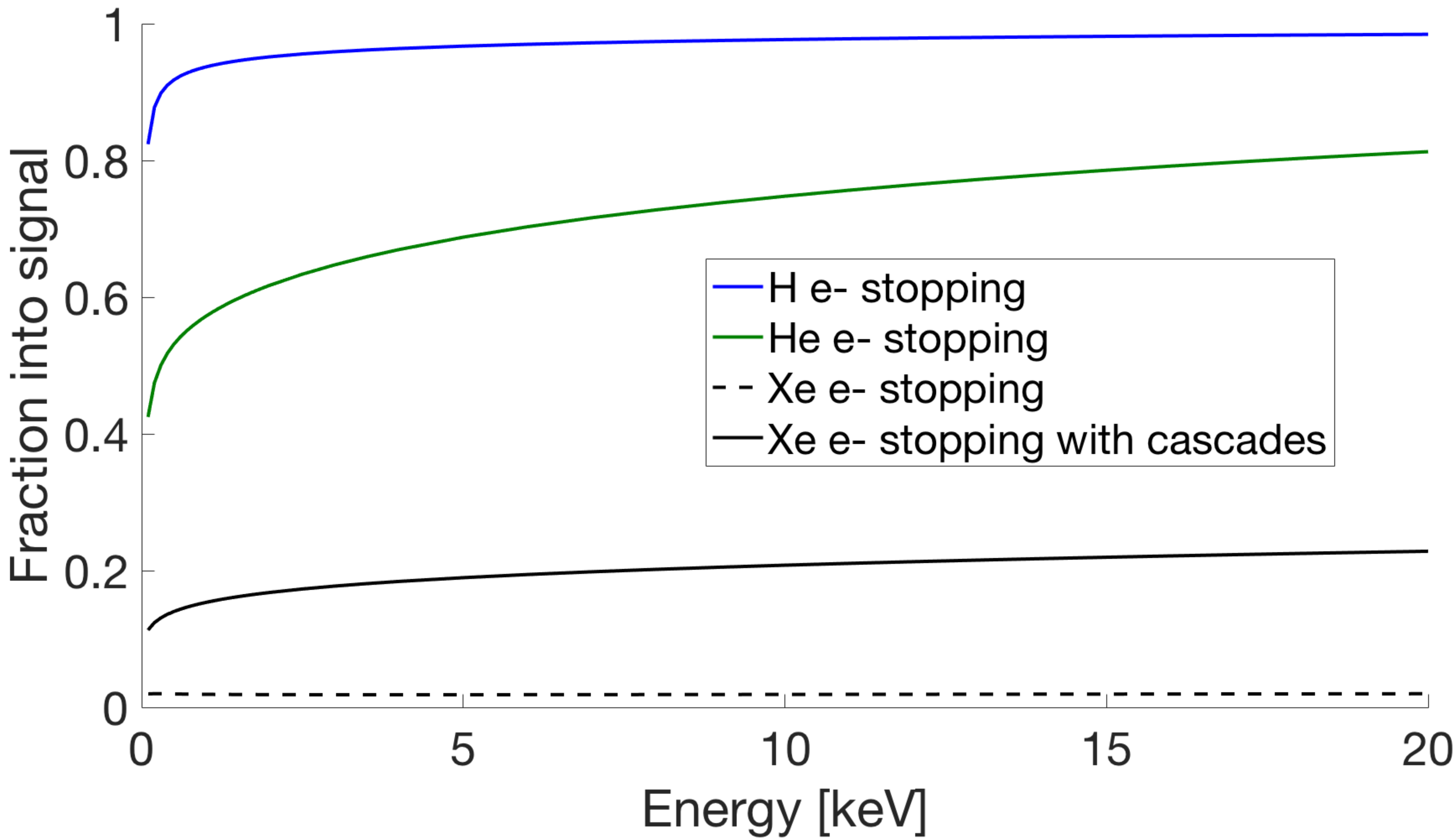


Modeling He recoils in LXe (v1+2)

Total quanta = hν + e⁻

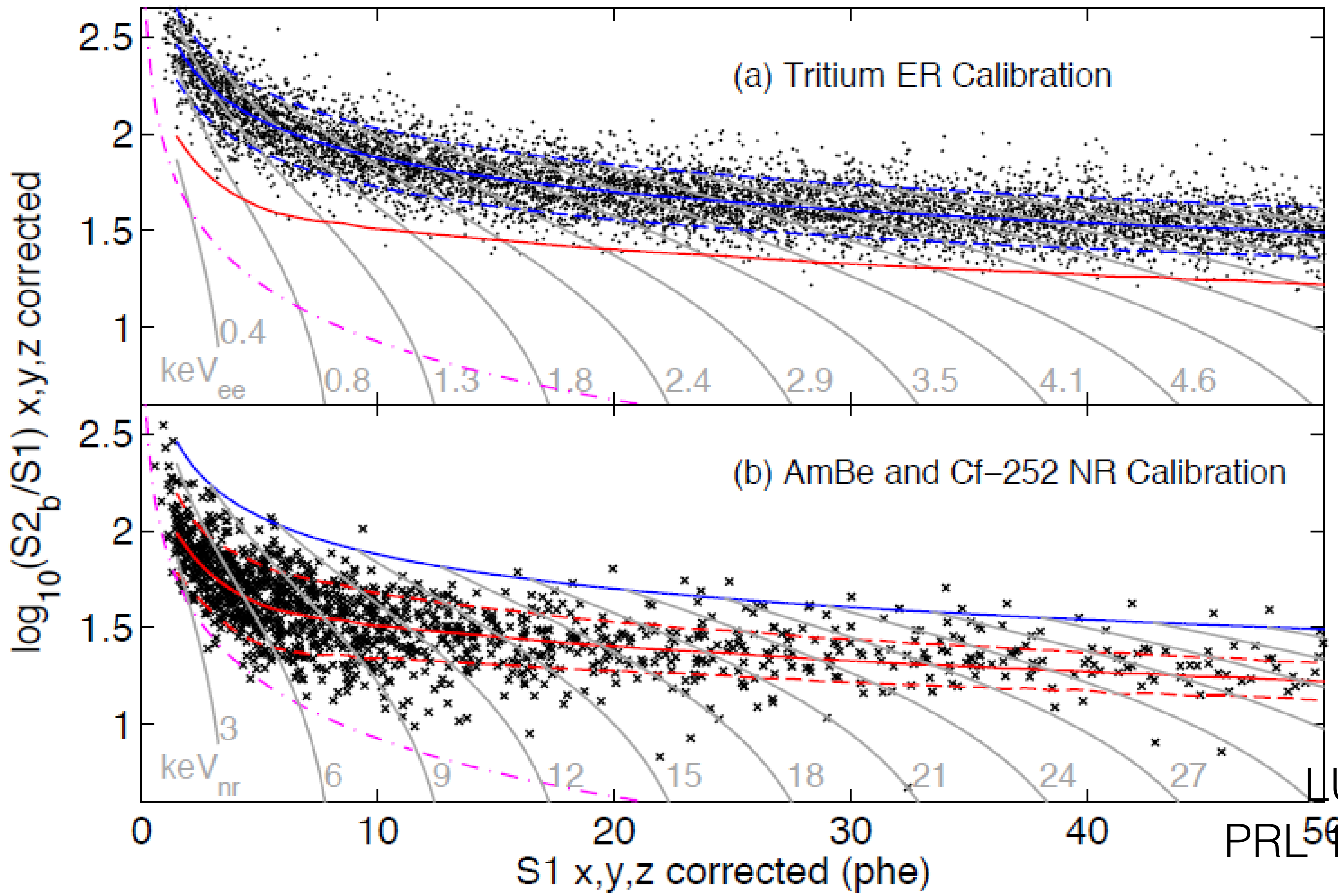


Modeling H recoils in LXe (SRIM)



A key question

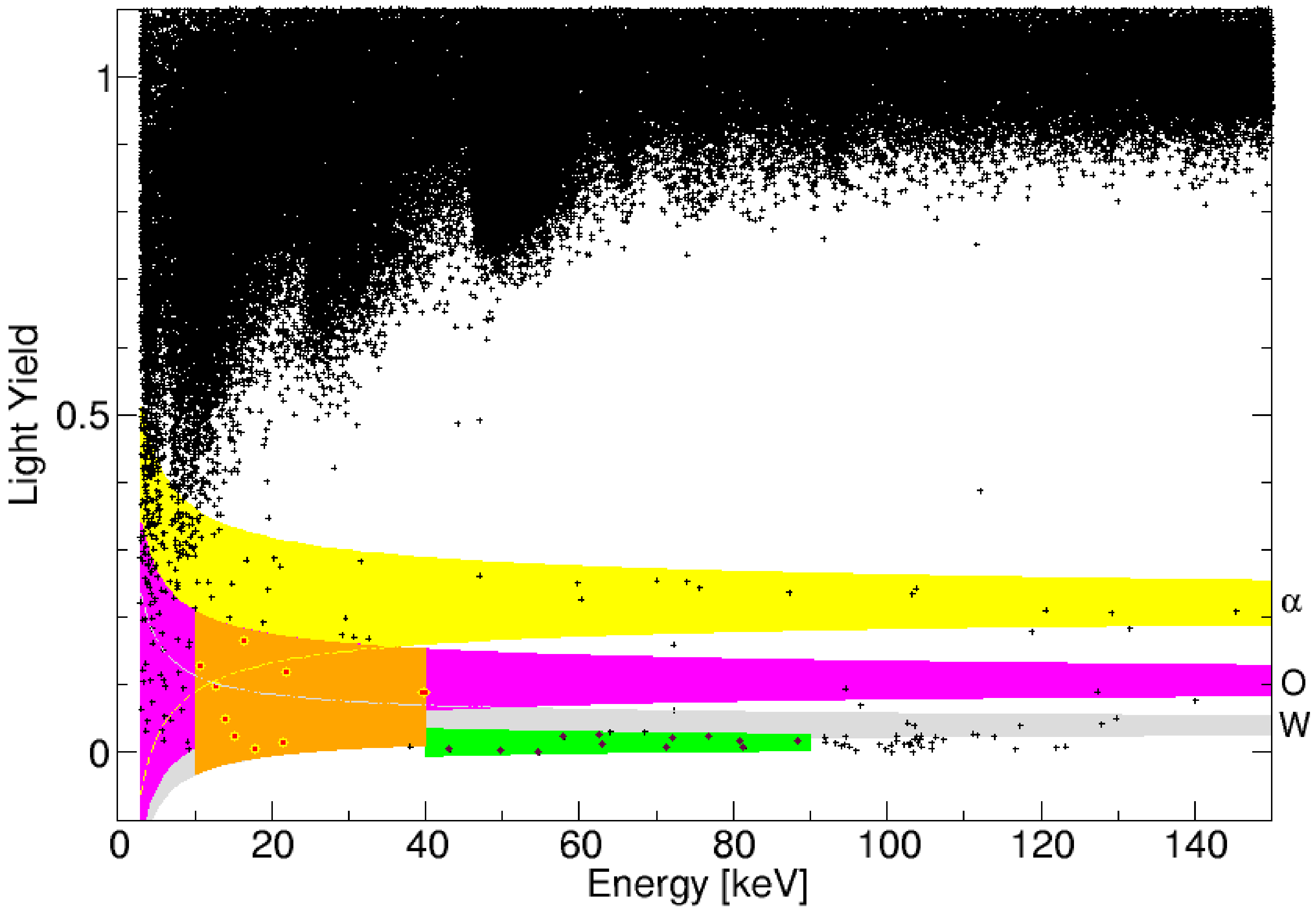
- What happens to S2/S1 partitioning?



LUX data
PRL 112, 091303

Xenon microphysics

- What happens to S2/S1 partitioning?



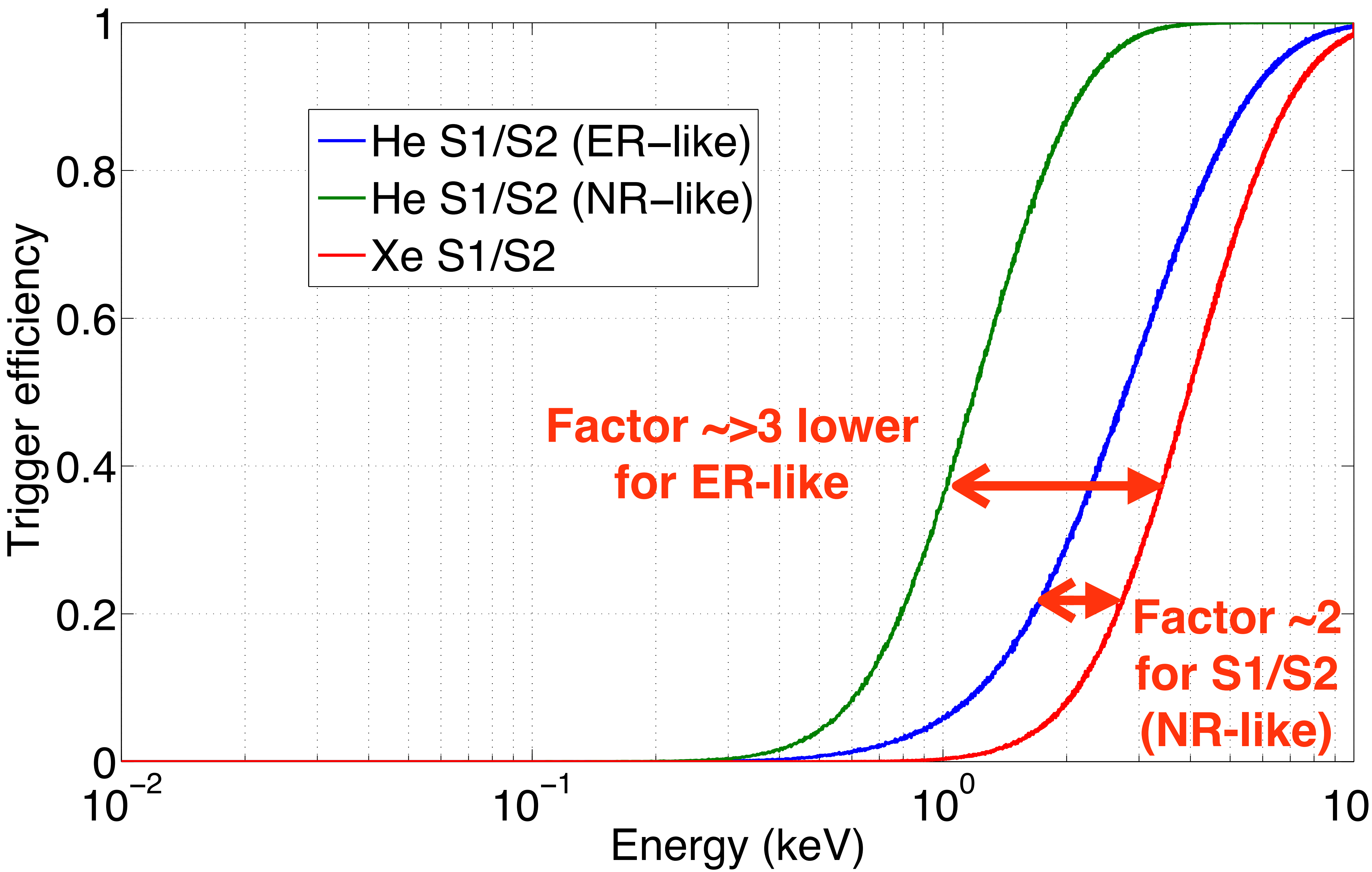
CRESST data in scintillating bolometers

NB: Different microphysical process (heat v. electronic)

What does it look like in LZ?

- Put this all together into single model
- Use the LZ Geant4 detector and optical transport model
  - See “Projected Sensitivity of LZ” (1802.06039)
- For S1/S2 analysis, threshold is determined by S1
  - Partitioning into photons and electrons matters
  - Run extreme cases for He - NR-like and ER-like
  - Used SRIM for H - looks similar but slightly better

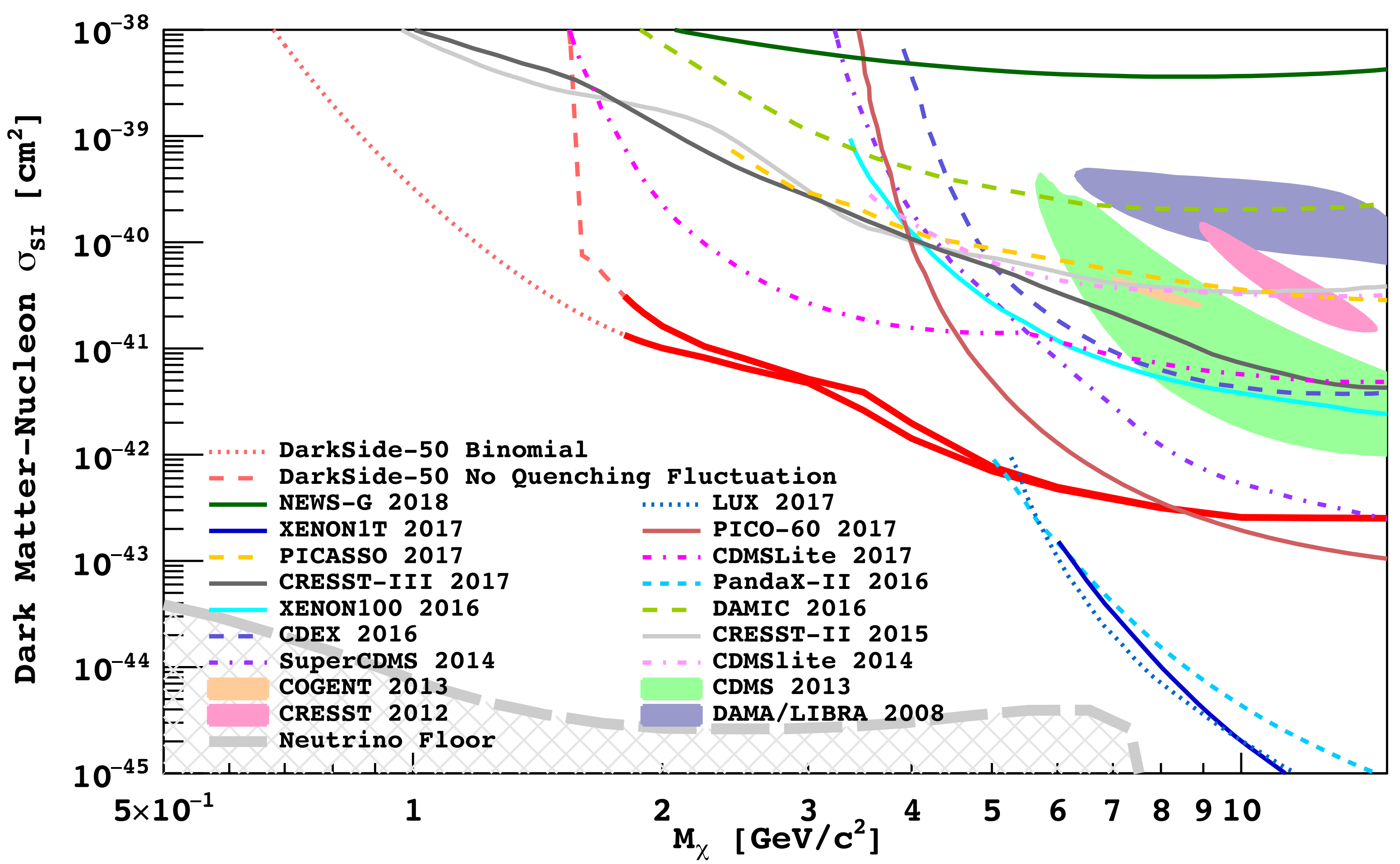
Energy threshold



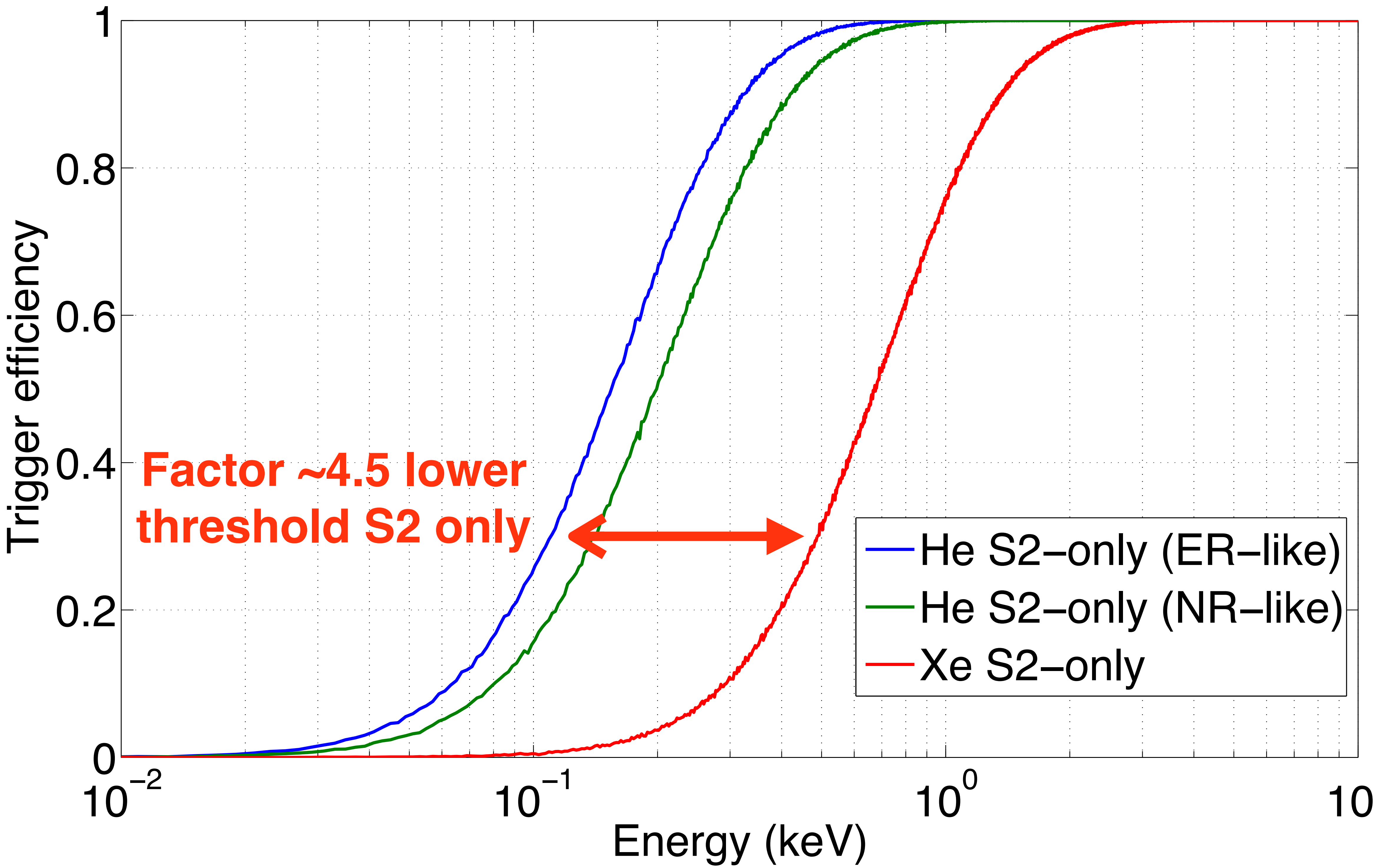
S2-only analysis

- 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

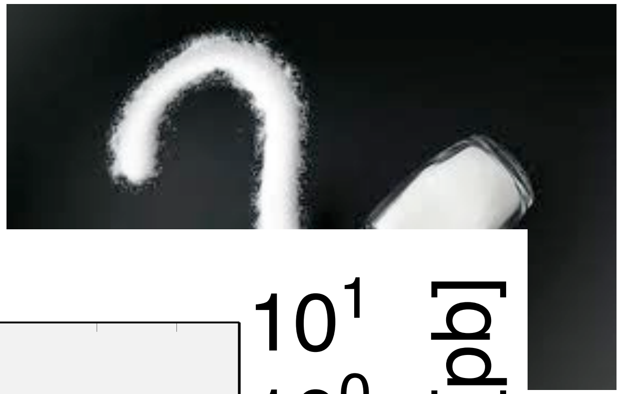


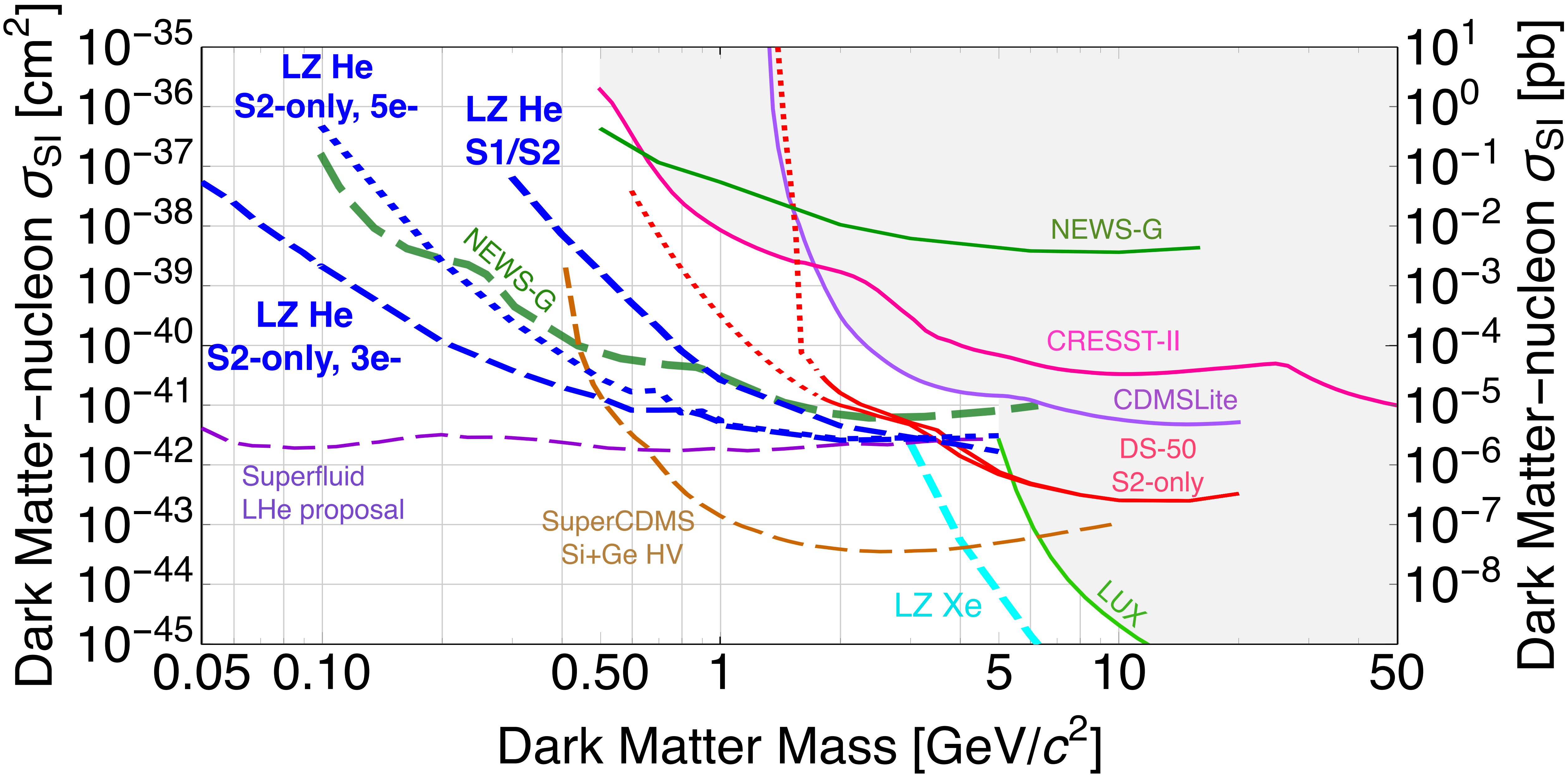
Energy threshold



- 3 electron threshold assumed for S2 (>250 photons)

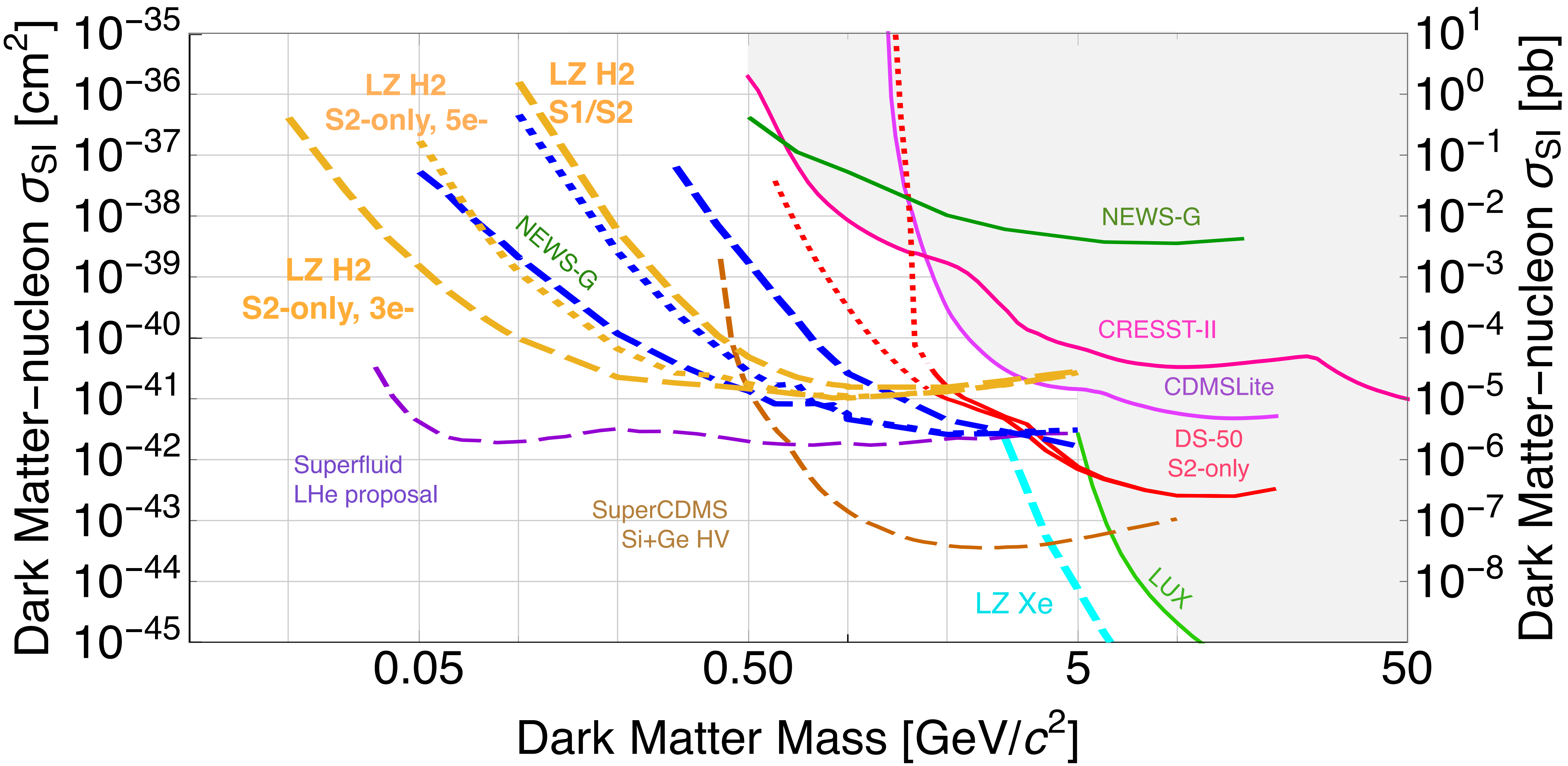
Making projections





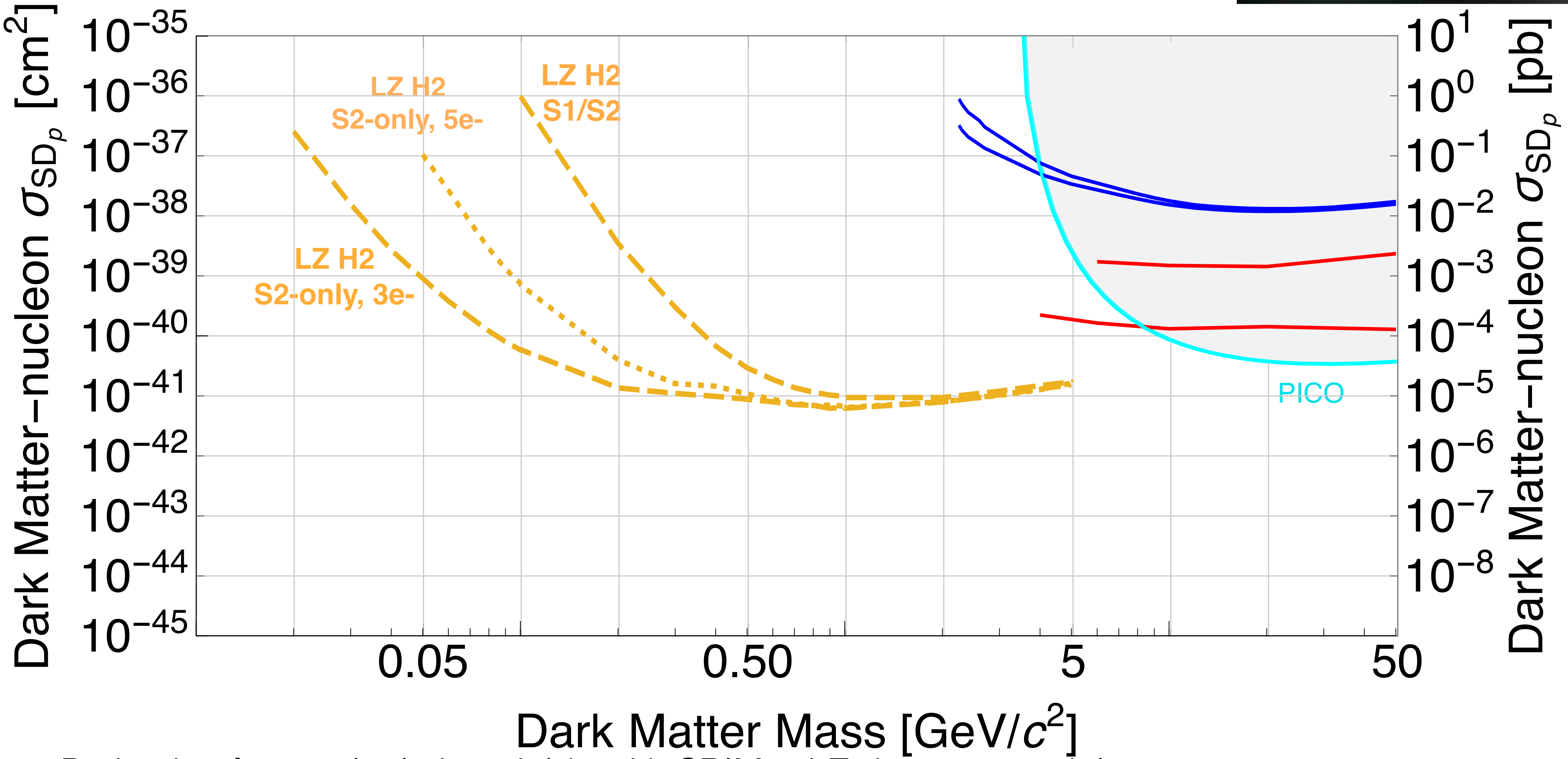
- 0.3% loading (1 bar partial pressure) - 15 kg, 20 days for S2-only, 100 days for S1/S2
- Location of LZ Helium lines depends critically on assumed signal yield
    - ~225 events/day/pb with S2 only at 100 MeV WIMP with this yield
- Dotted line is 5e- S2-only threshold

With Hydrogen



- Projection from calculating yields with SRIM + LZ detector model
  - Definitely to be taken with grain of salt
- 0.0375% H_2 (0.1 bar partial pressure), 1.9 kg, 500 days

SD Hydrogen

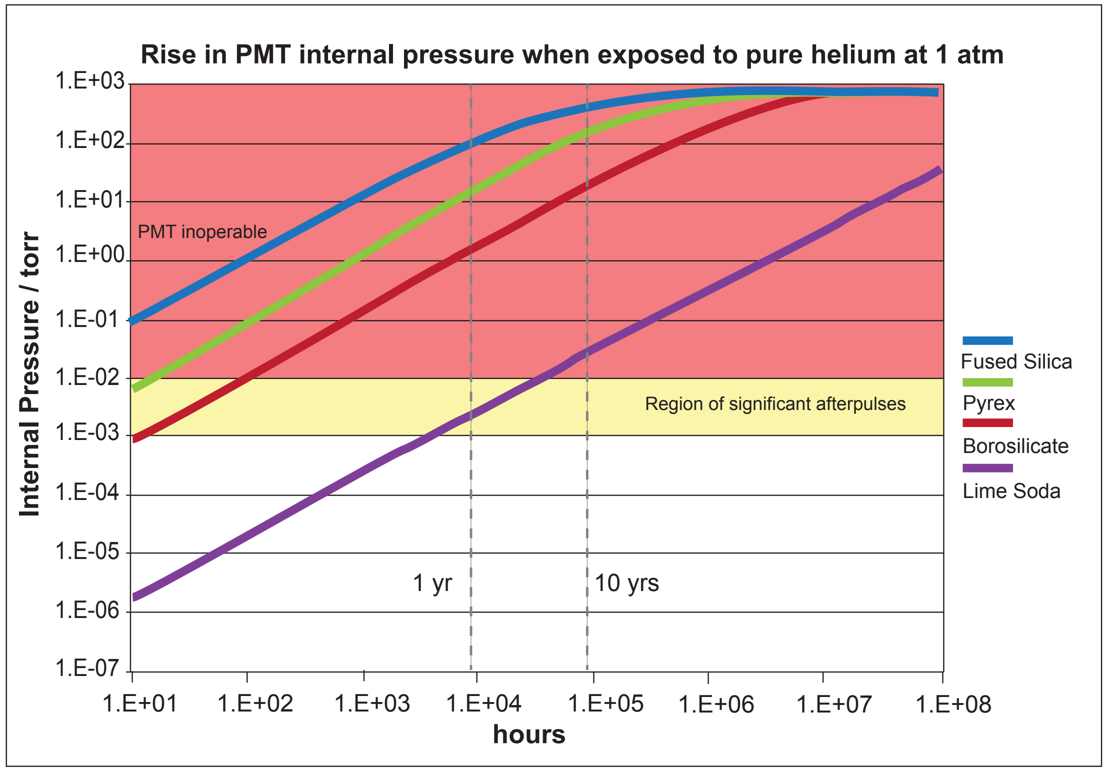


- Projection from calculating yields with SRIM + LZ detector model
  - Definitely to be taken with grain of salt
- 0.0375% H2 (0.1 partial pressure), 1.9 kg, 500 days

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…

Example for ET9226 PMT



What do I worry about (H)

- PMT diffusion is suppressed
- Hydrogen is flammable in mine environment
- Purification - getter will take out the H2
- Suppression of S2 production
    - Molecular modes can slow down electrons
    - Could recover with increased voltage

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

NEEDS CALIBRATION!

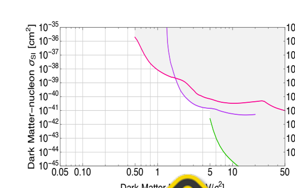
- Monoenergetic neutron scattering experiment is where I would start

What do I worry about

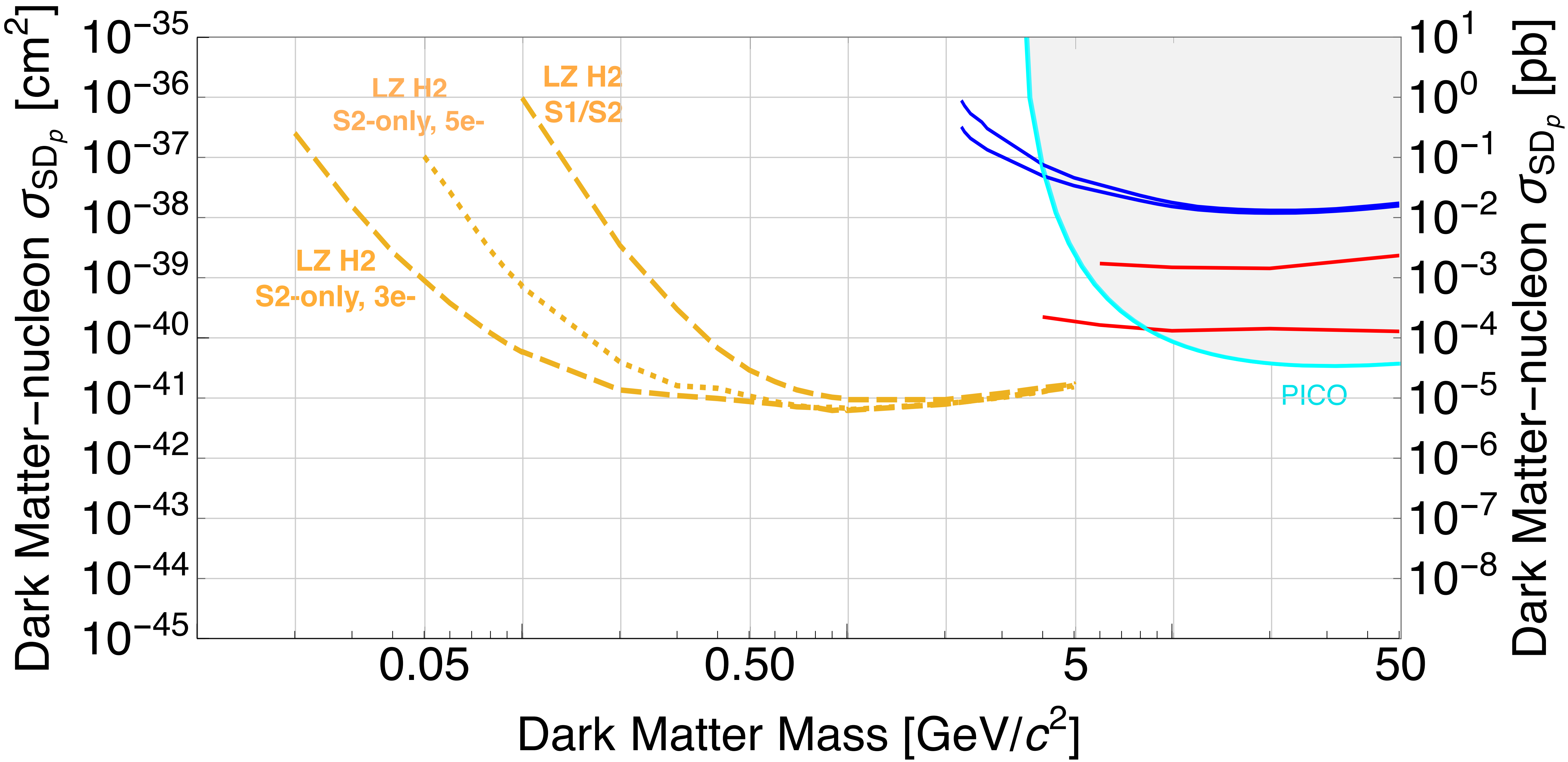
- Cryogenics - what does the presence of the non-condensible gas do to our cryogenics
    - Bubble He/H2 through the bottom of the cryostat?
    - Phase separated at weir drain (in LZ design)?
    - Should be distilled out fairly efficiently
    - Introduction and mixing that worries me the most

He/H 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



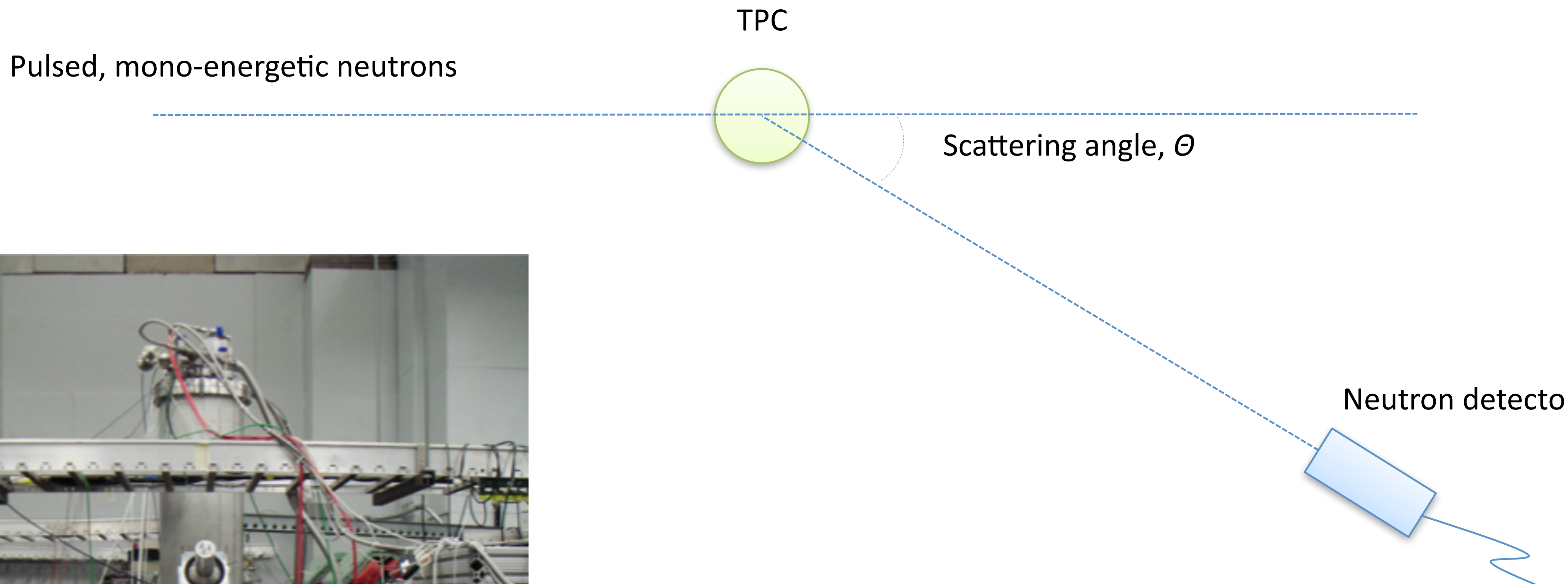
- Depends on properties that need to be measured

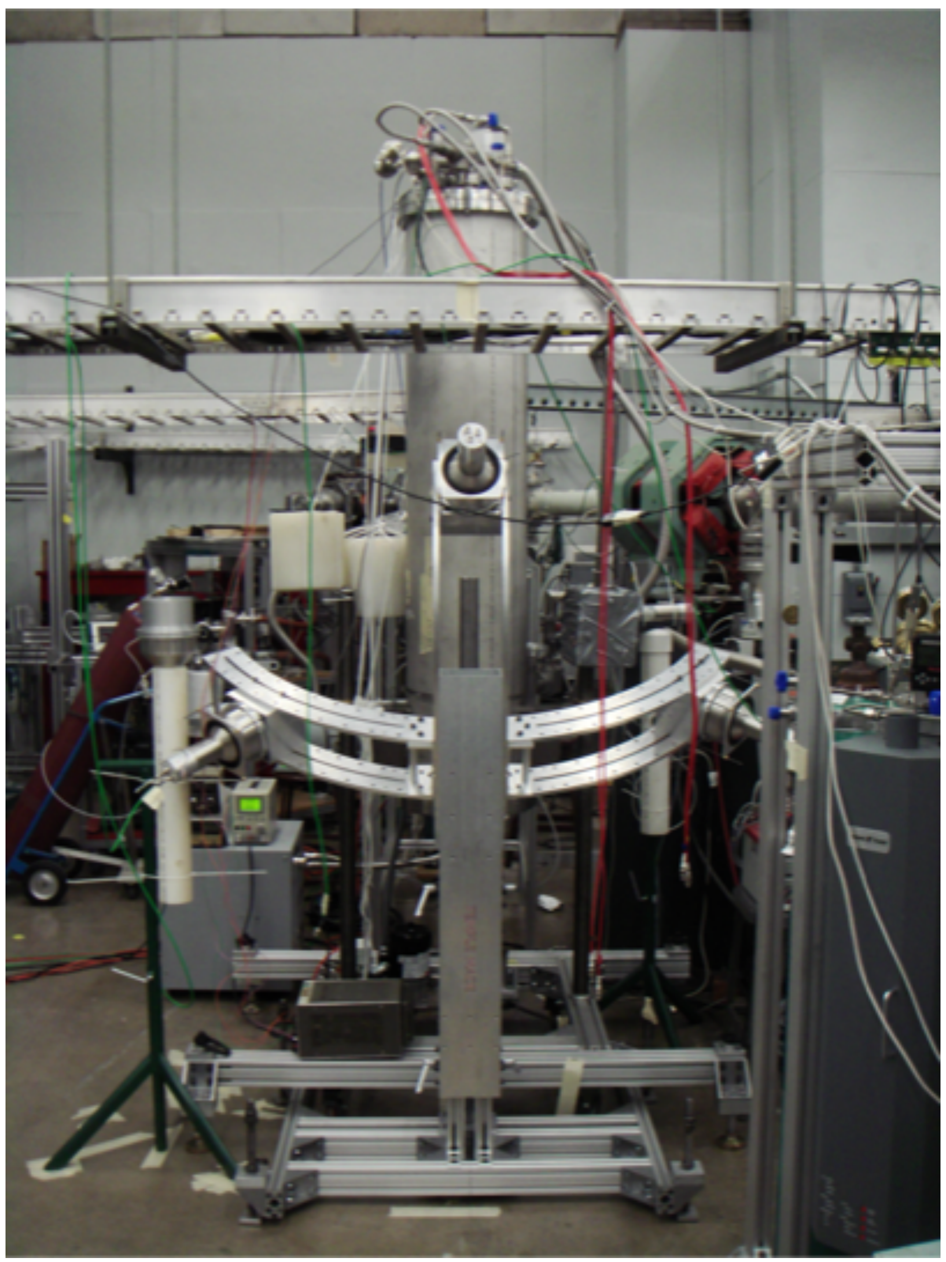


LZ H2
S2-only, 5e-
LZ H2
S1/S2
LZ H2
S2-only, 3e-
PICO
Dark Matter–nucleon σ_{SD_p} [cm^2]
Dark Matter–nucleon σ_{SD_p} [pb]
Dark Matter Mass [GeV/c^2]
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0.05
0.50
5
50

Backup

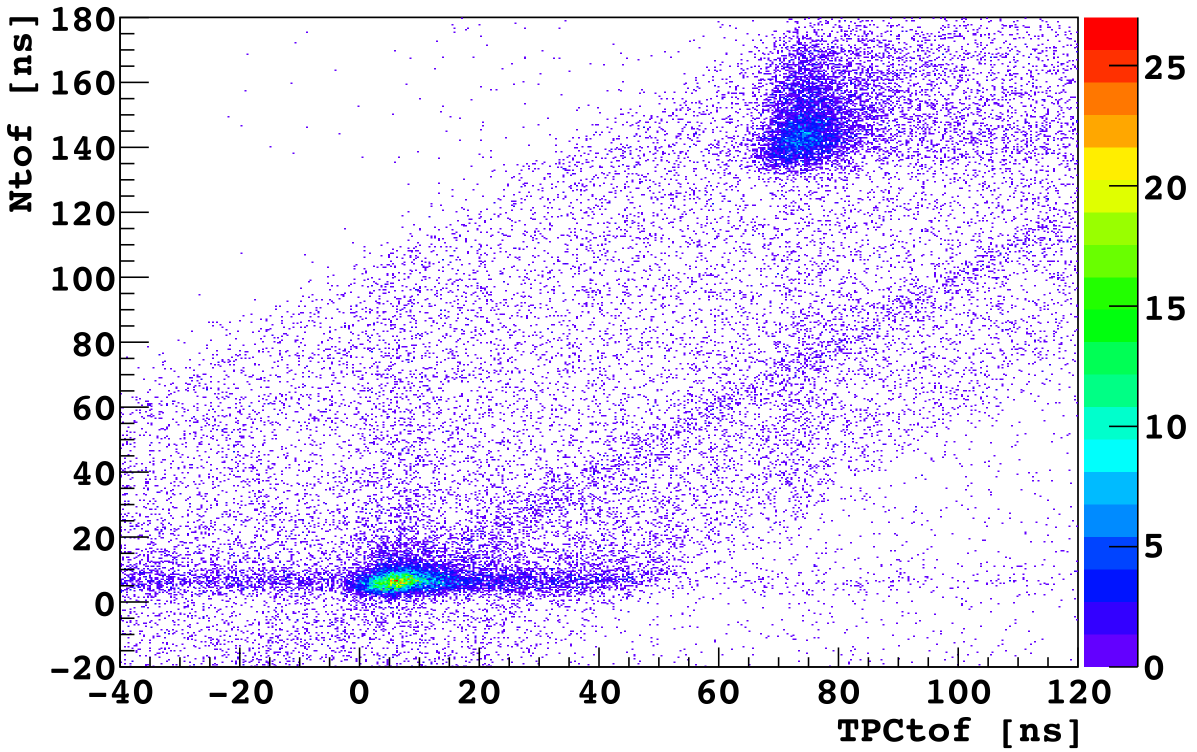
Neutron scattering measurement



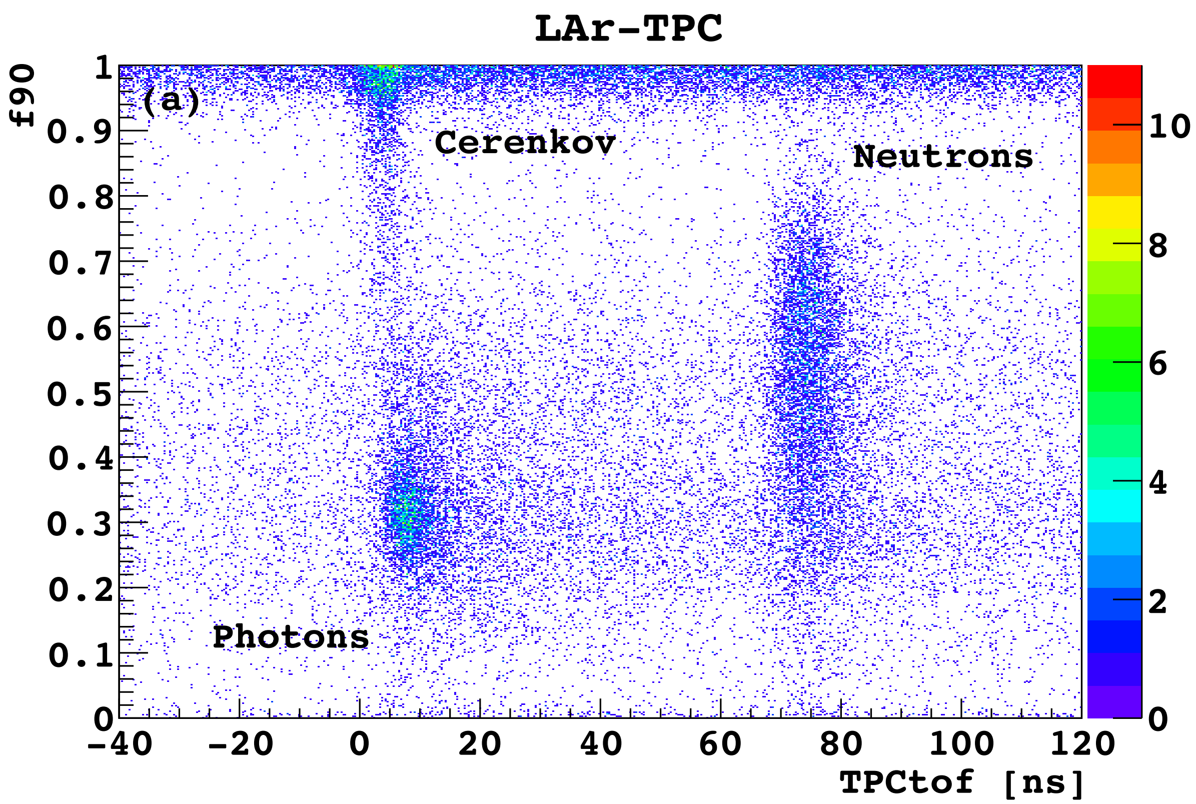


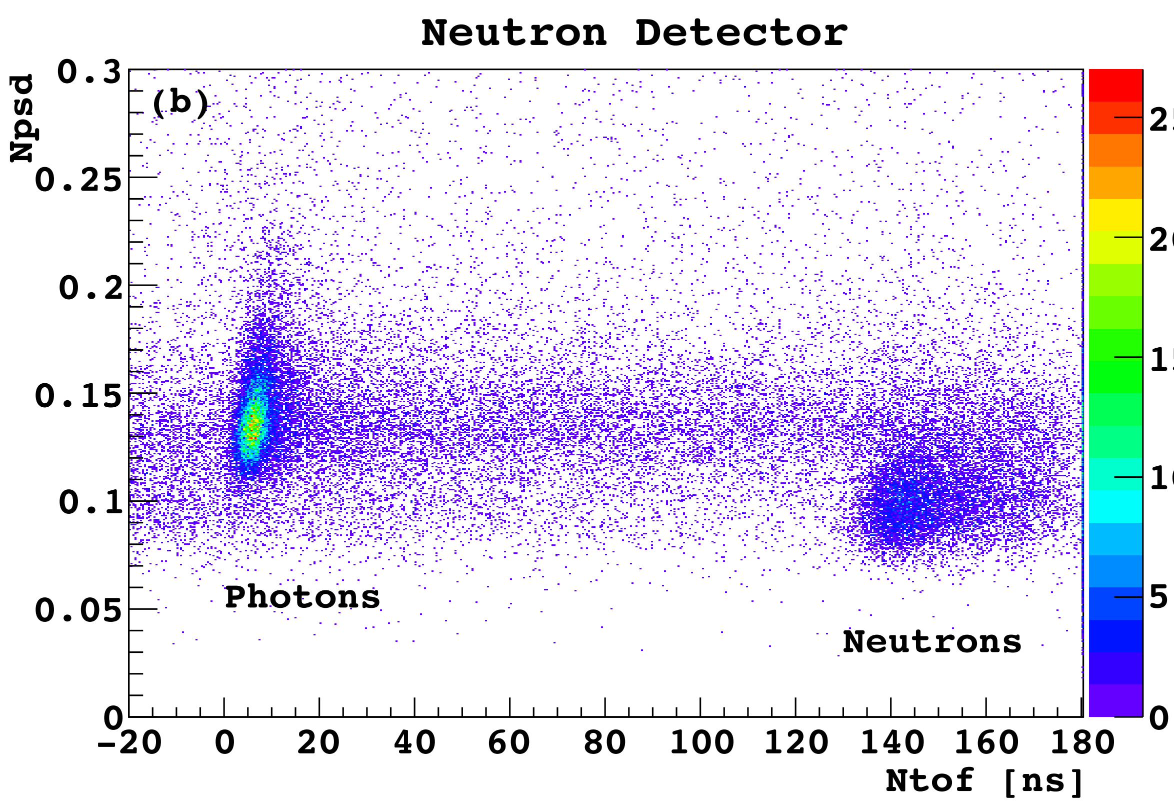
- Pulsed, monoenergetic beam (at Notre Dame or elsewhere) to measure response of to nuclear recoils of known energy
- Tunable nuclear recoil energy by changing the neutron energy and the scattering angle
  - Neutrons of 100 keV - 1.5 MeV
  - Recoils of ~1 keV up to 50 keV
  - Successful measurements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

Neutron scattering in SCENE



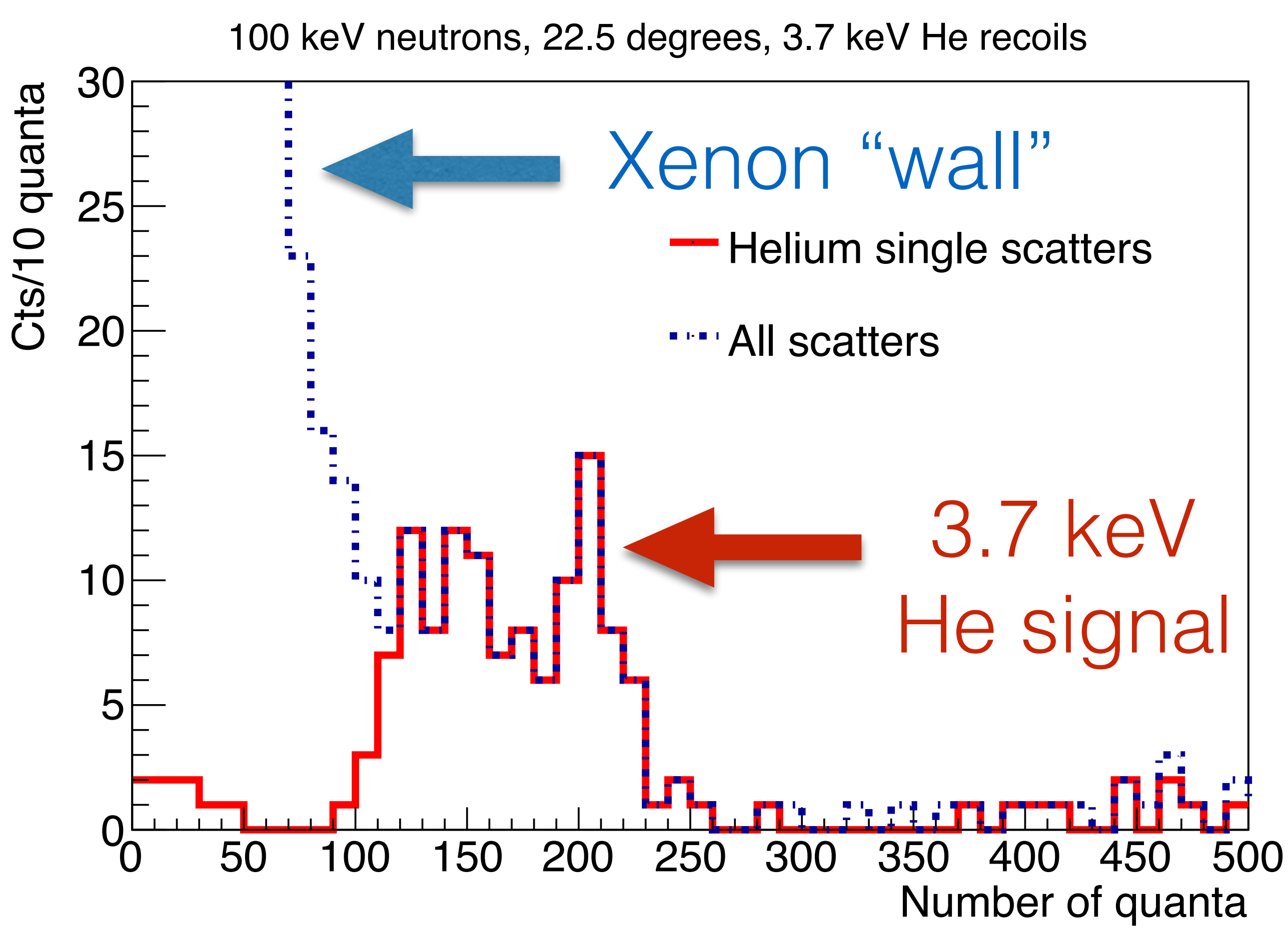
- Time of flight to measure the neutron timing
- Pulse shape discrimination(PSD) to select neutrons in the detectors
- Ntof - time between beam pulse and neutron detector
- TPCtof - time between beam pulse and LAr detector
- f90 - PSD in LAr
- Npsd - PSD in neutron detector

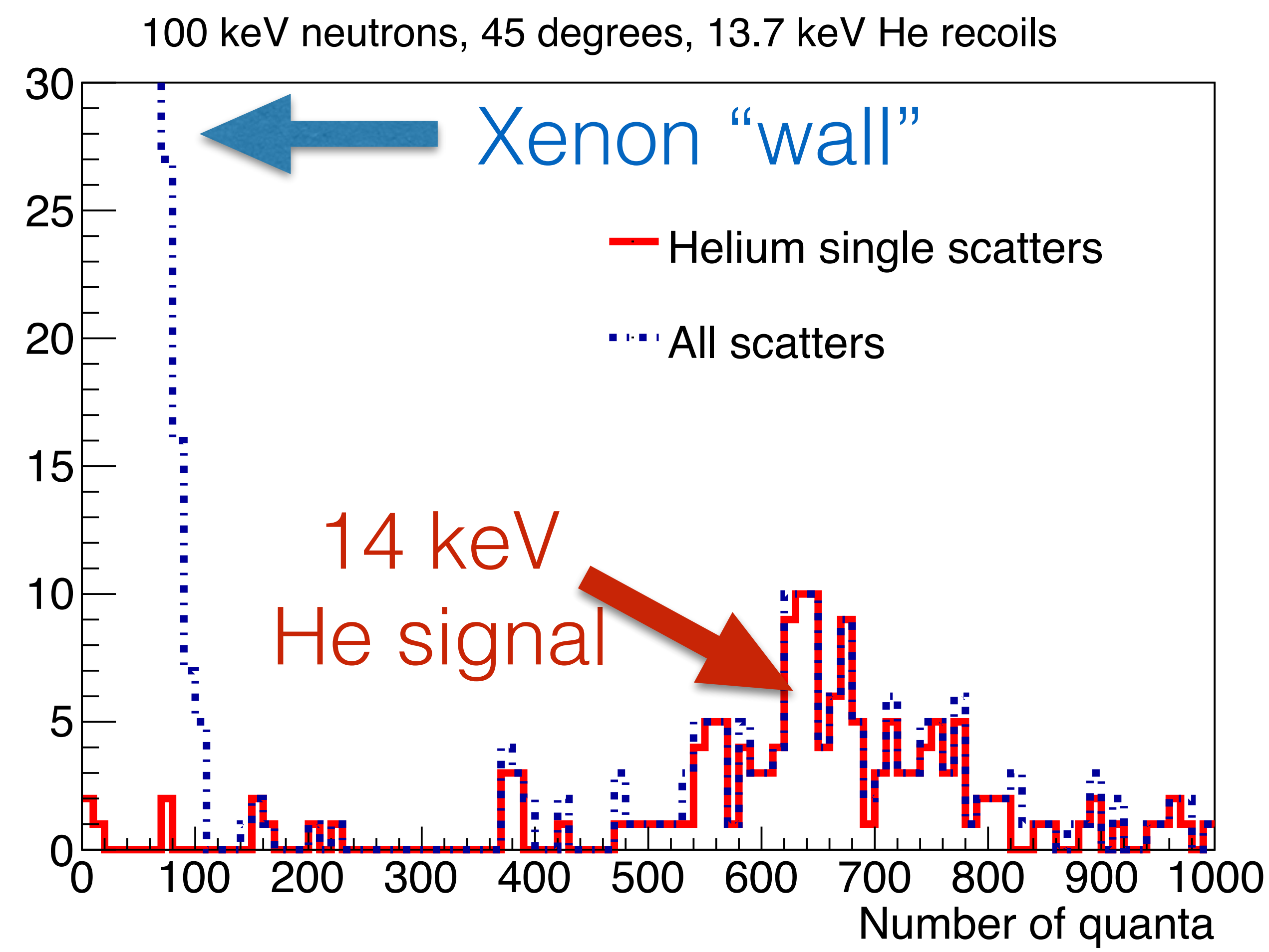




Neutron scattering with He in LXe

- 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!