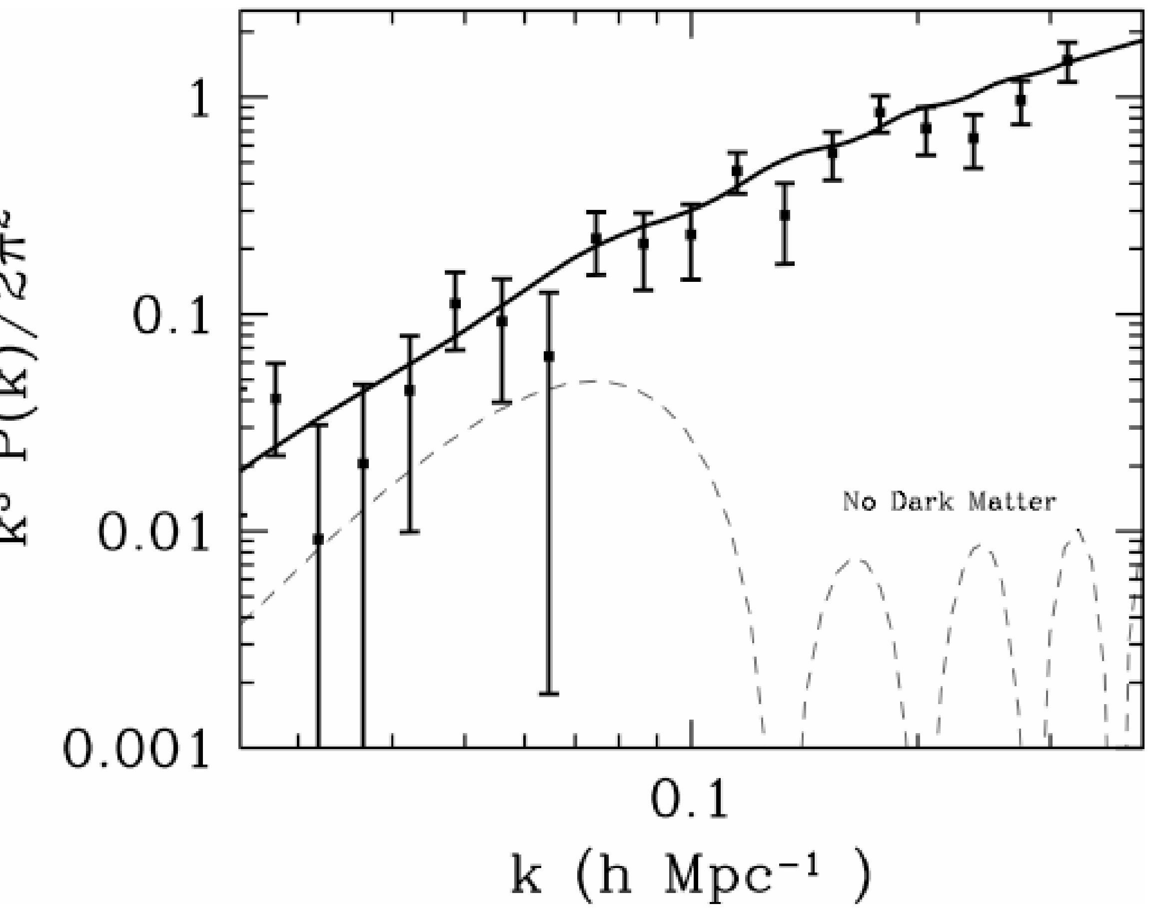
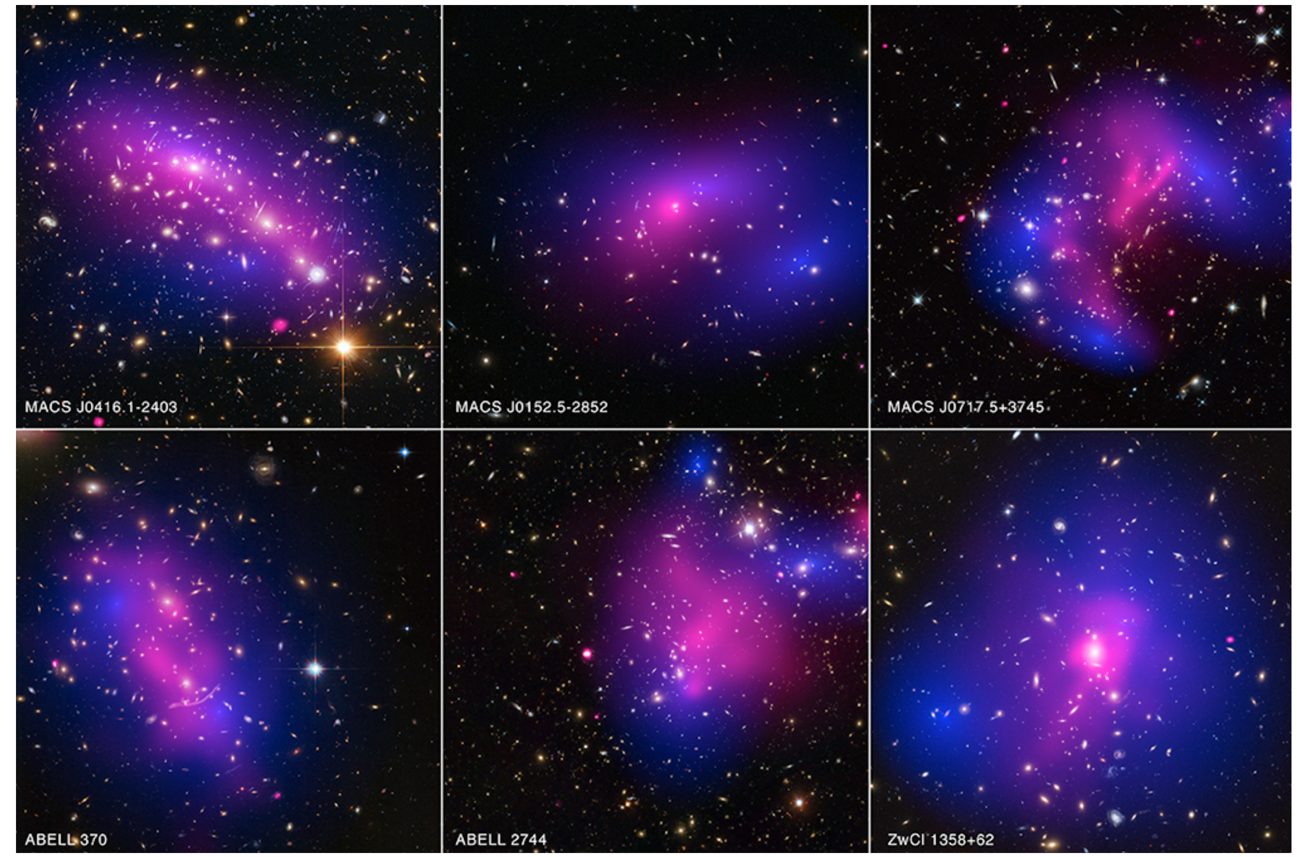
Searching for (light) dark matter (by doping helium in xenon)

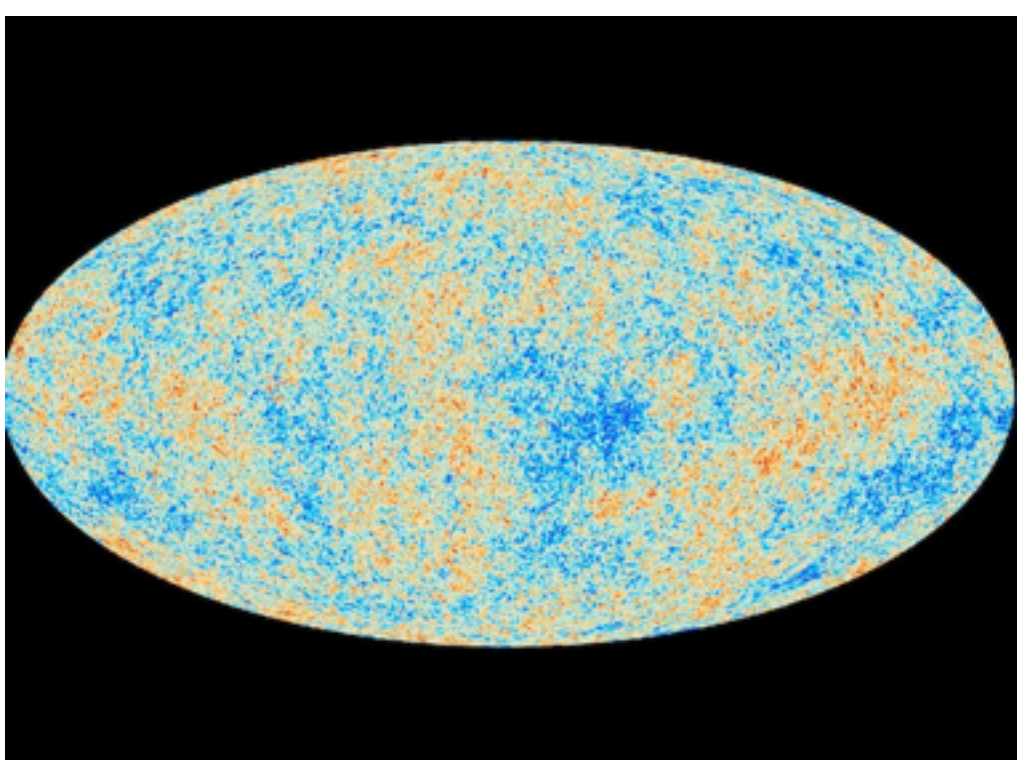
Hugh Lippincott, Fermilab

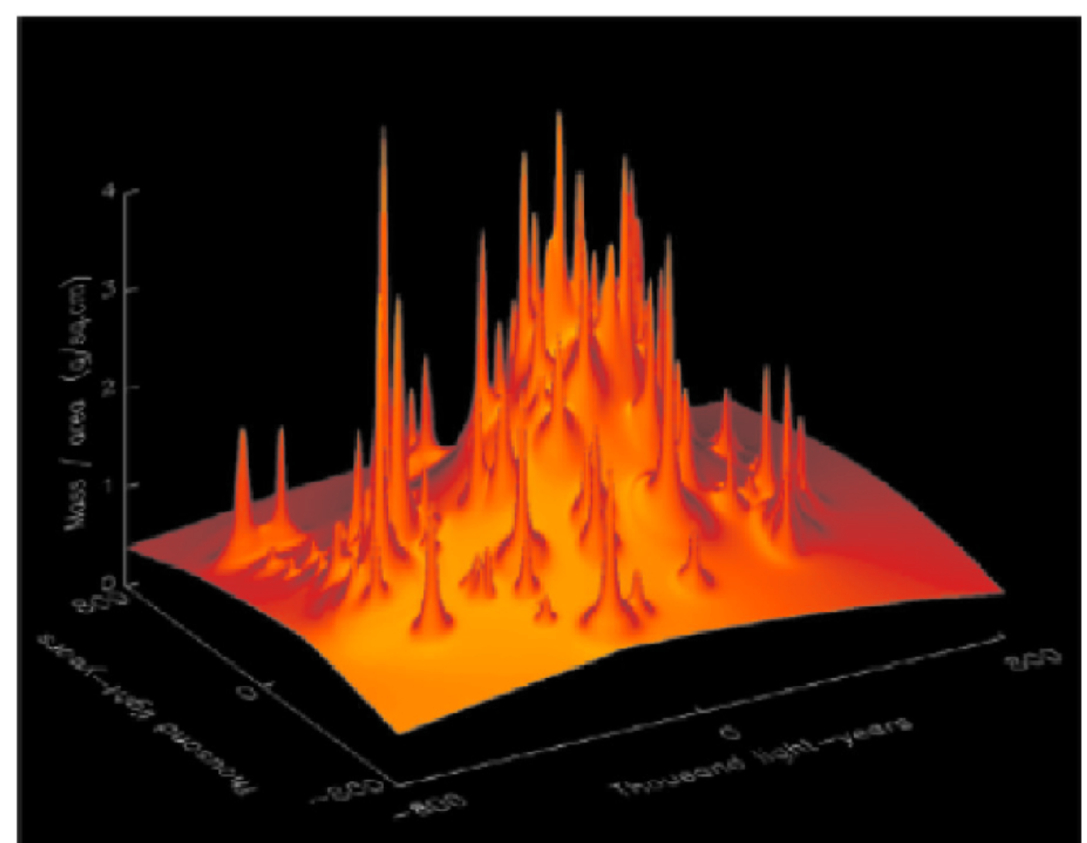
KITP
HEP at the Sensitivity Frontier
April 24, 2018

The case for dark matter



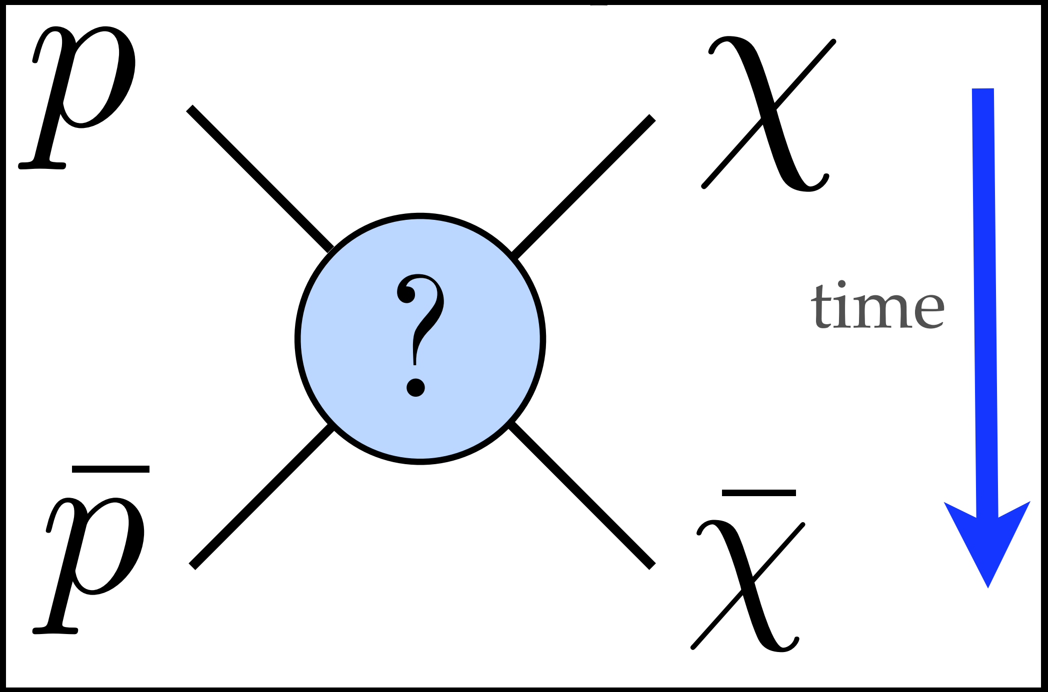






How do we find it? Direct Detection

- Calculate rate based on assumptions about the dark matter distribution and interaction
- Historically two interactions are considered (by DM experimentalists)
  - Spin independent (SI) - couples to all nucleons
    - Enhancement for large nuclei
  - Spin dependent (SD) - couples to the spin of the nucleus (unpaired spin of one nucleon)



Rate calculation

- The differential cross section (for spin-independent interactions) in events/kg/keV mass per unit recoil energy is

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv \qquad (3)$$

- Dark matter density component, from local and galactic observations with historically a factor of 2 uncertainty

- The unknown particle physics component σ_0 (where $\mu_p = m_p m_\chi/(m_p + m_\chi)$ is the reduced mass of the proton)
  - Proportional to A^2 for most models

- The nuclear part, approximately given by $F^2(Q) \propto e^{-Q/Q_0}$ where $Q_0 \sim \frac{80}{A^{5/3}}$ MeV

- The velocity distribution of dark matter in the galaxy - of order 30% uncertainty (not-statistical), and $v_m = \sqrt{Q m_N / 2 m_r^2}$ (here $m_r = m_N m_\chi/(m_N + m_\chi)$ is the reduced mass of the nucleus)

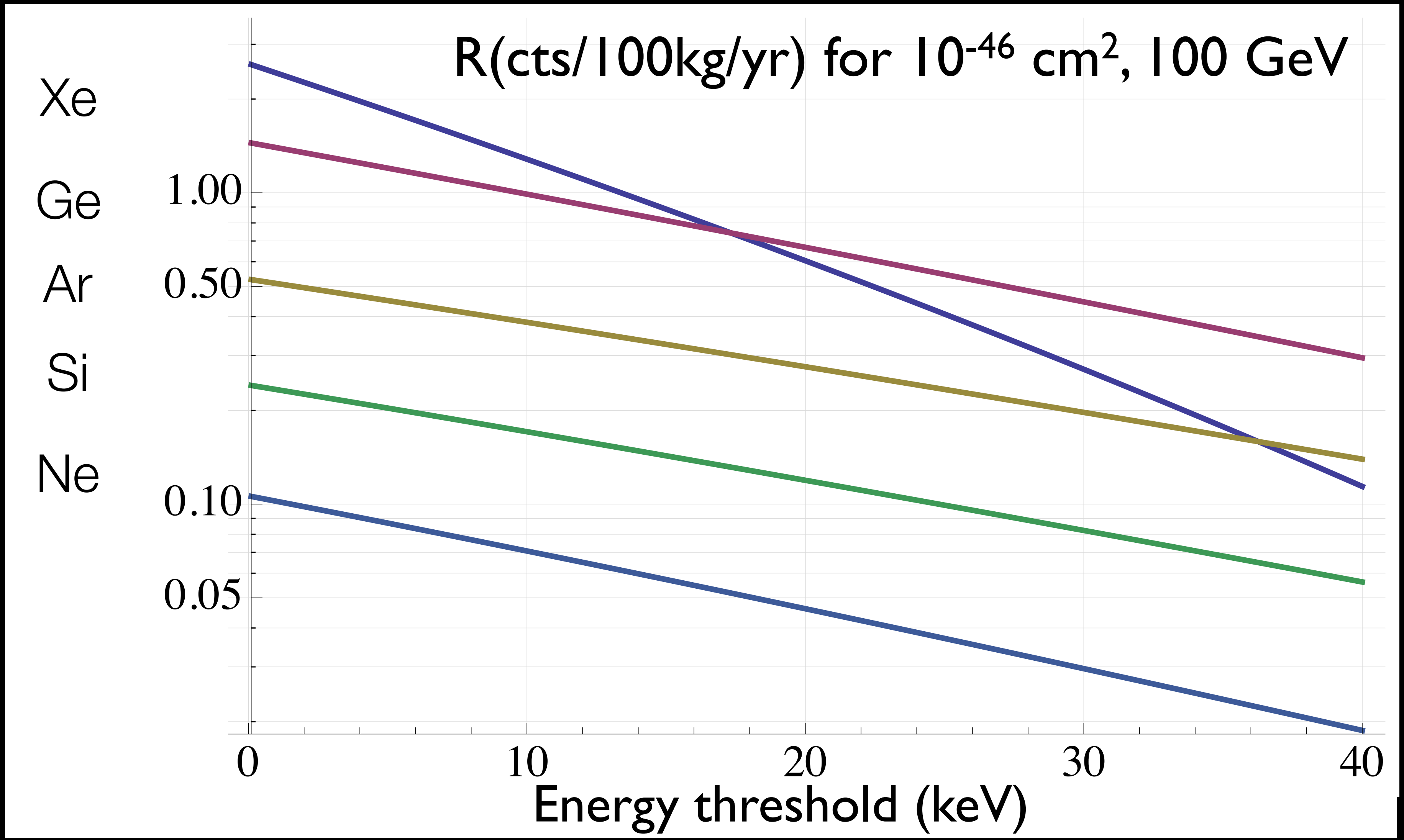
The energy scale

- Energy of recoils is O(keV)
- Entirely driven by kinematics, elastic scattering of things with approximately similar masses (100 GeV) and v ~ 0.001c

$$\frac{1}{2} m_N v_N^2 = \frac{1}{2} \times 100\,\mathrm{GeV} \times 10^{-6} = 50\,\mathrm{keV}$$

How do we find it?

- Very low rate process (~events/year)



- Rate depends crucially on WIMP mass and threshold

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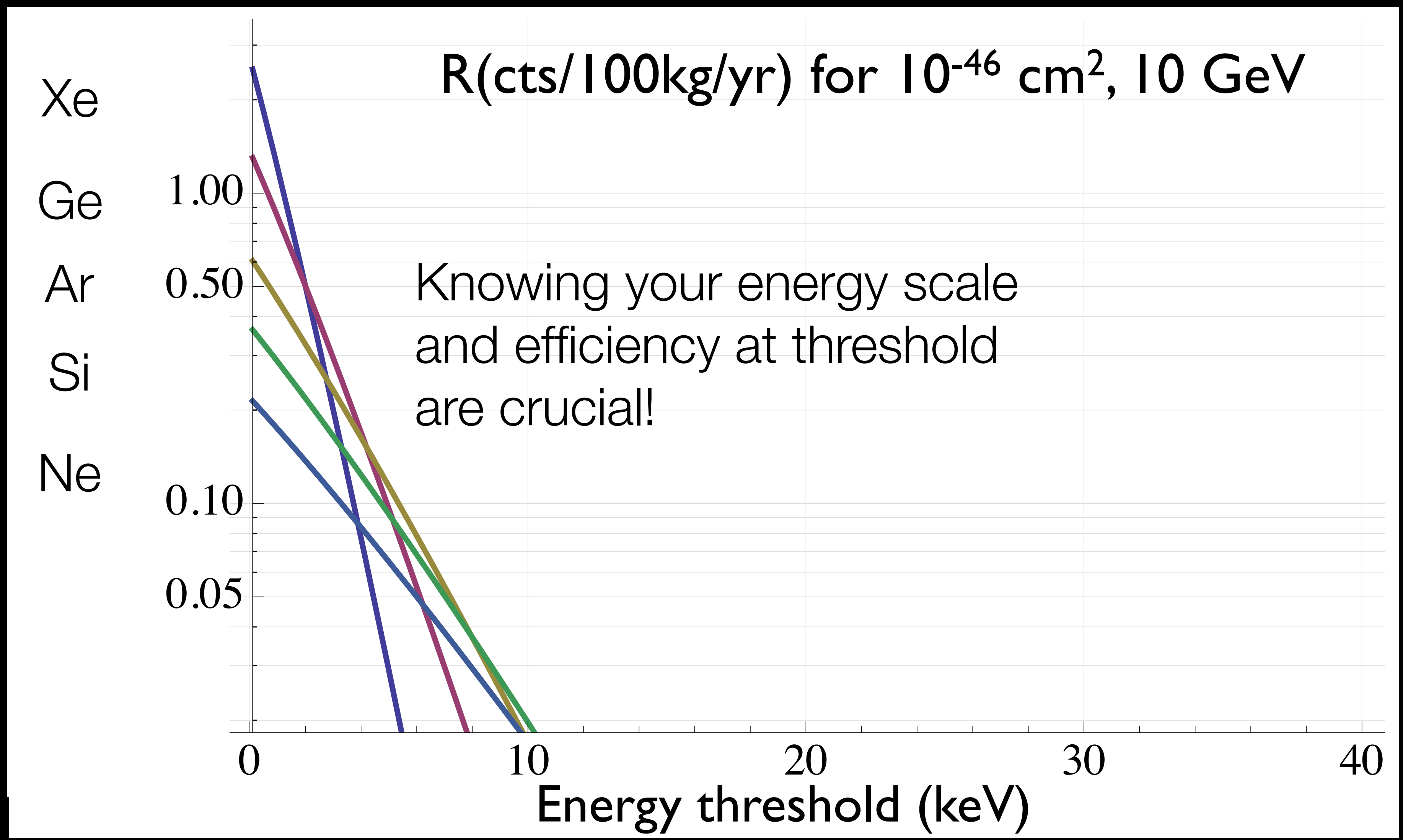

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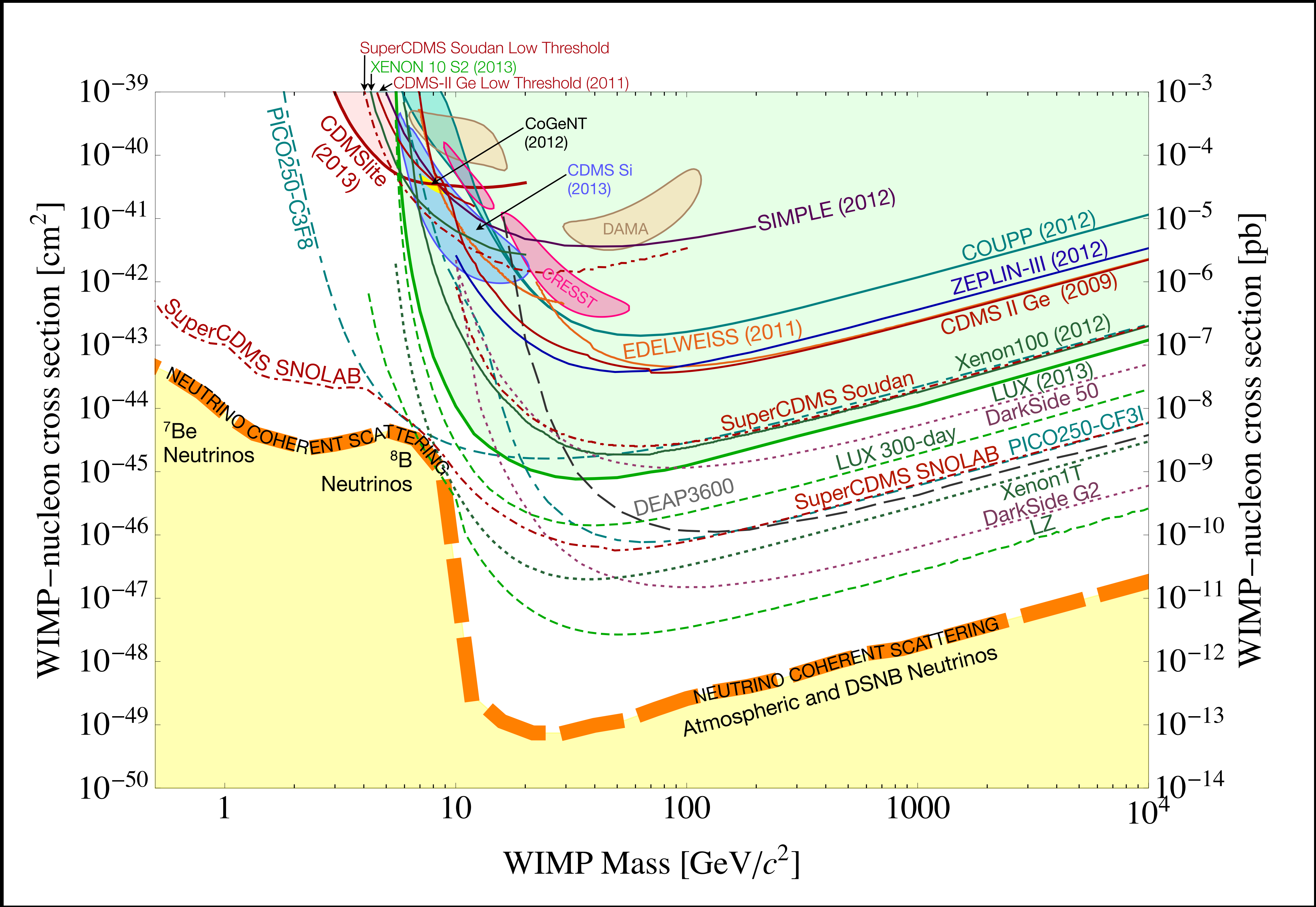


- Limited at low mass by detector threshold
- Limited at high mass by density
- Eventually limited by neutrinos

So we look for WIMPs

- A billion WIMPs pass through us per second - we might expect a handful of counts in a detector per year

So we look for WIMPs

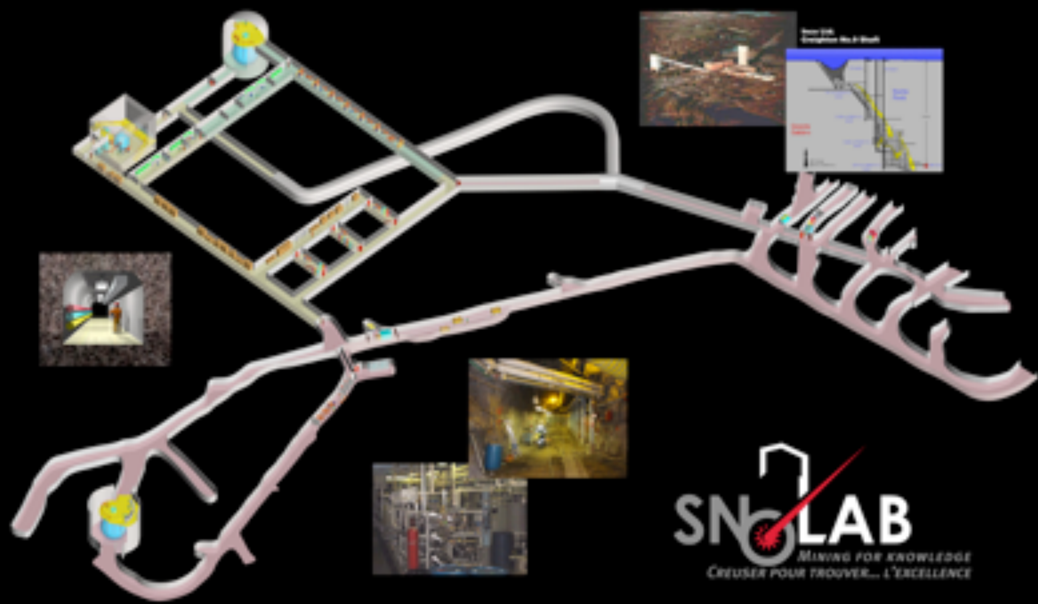
- A billion WIMPs pass through us per second - we might expect a handful of counts in a detector per year
- The problem is that background radioactivity is everywhere!

100 events/second/kg = 3,000,000,000,000 events/year in a ton-scale experiment

Backgrounds!

Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays


SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

Background sources

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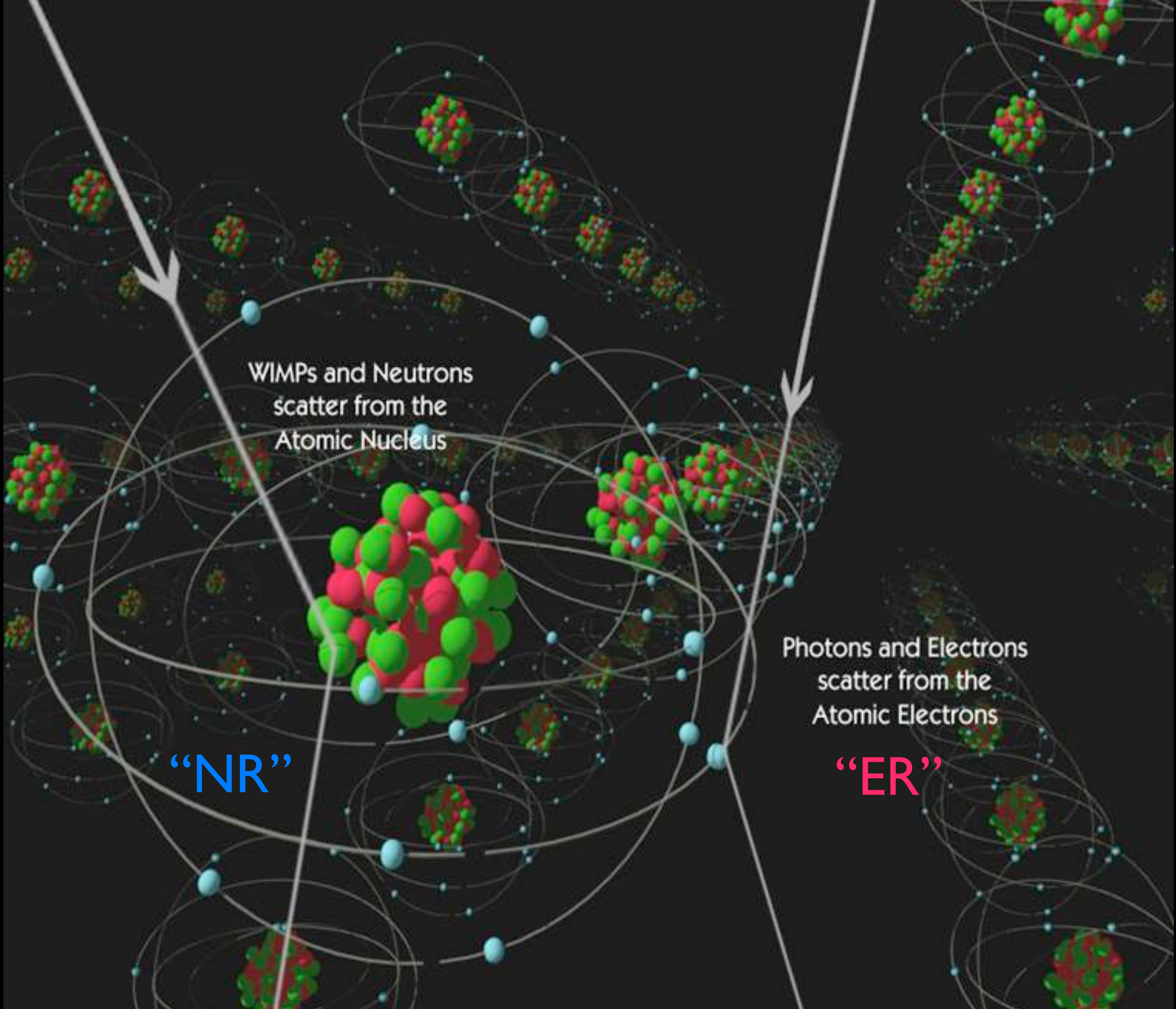
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding

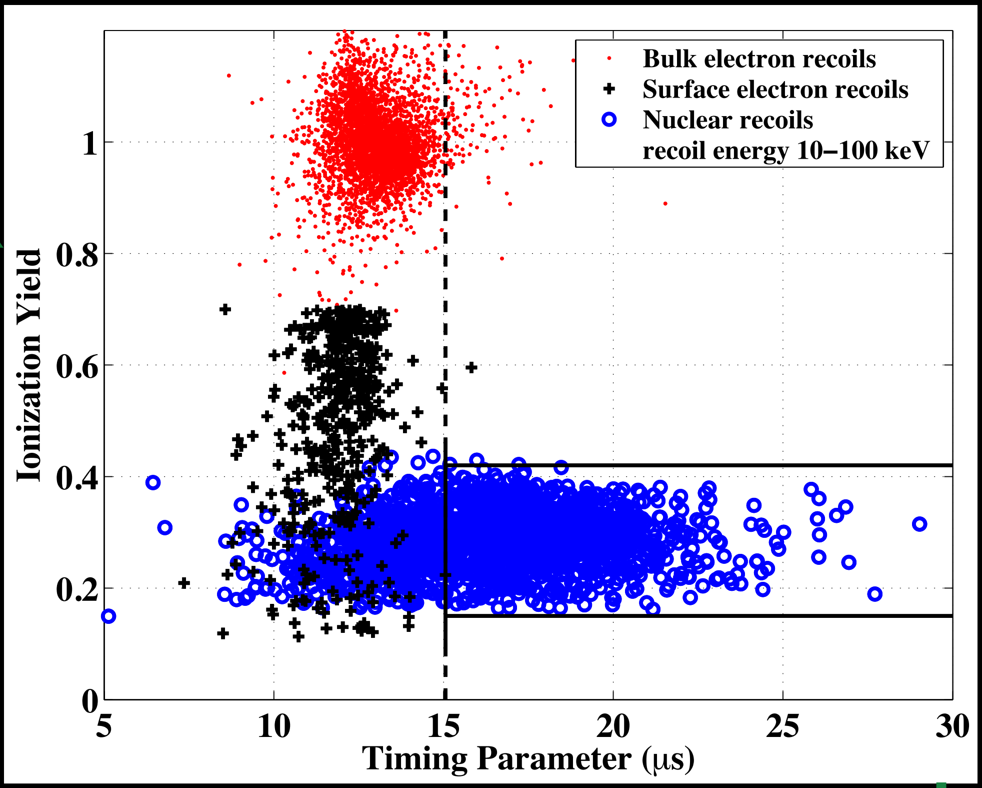
Background sources

- Cosmic rays are constantly streaming through
  - All experiments have to go underground to get away from cosmic rays
- Radioactive contaminants - rock, radon in air, impurities
  - Emphasis on purification and shielding
- The detector itself - steel, glass, detector components
  - Self-shielding to leave a clean inner region
  - Discrimination - can you tell signal from background (gamma rays, alphas, neutrons, etc)?

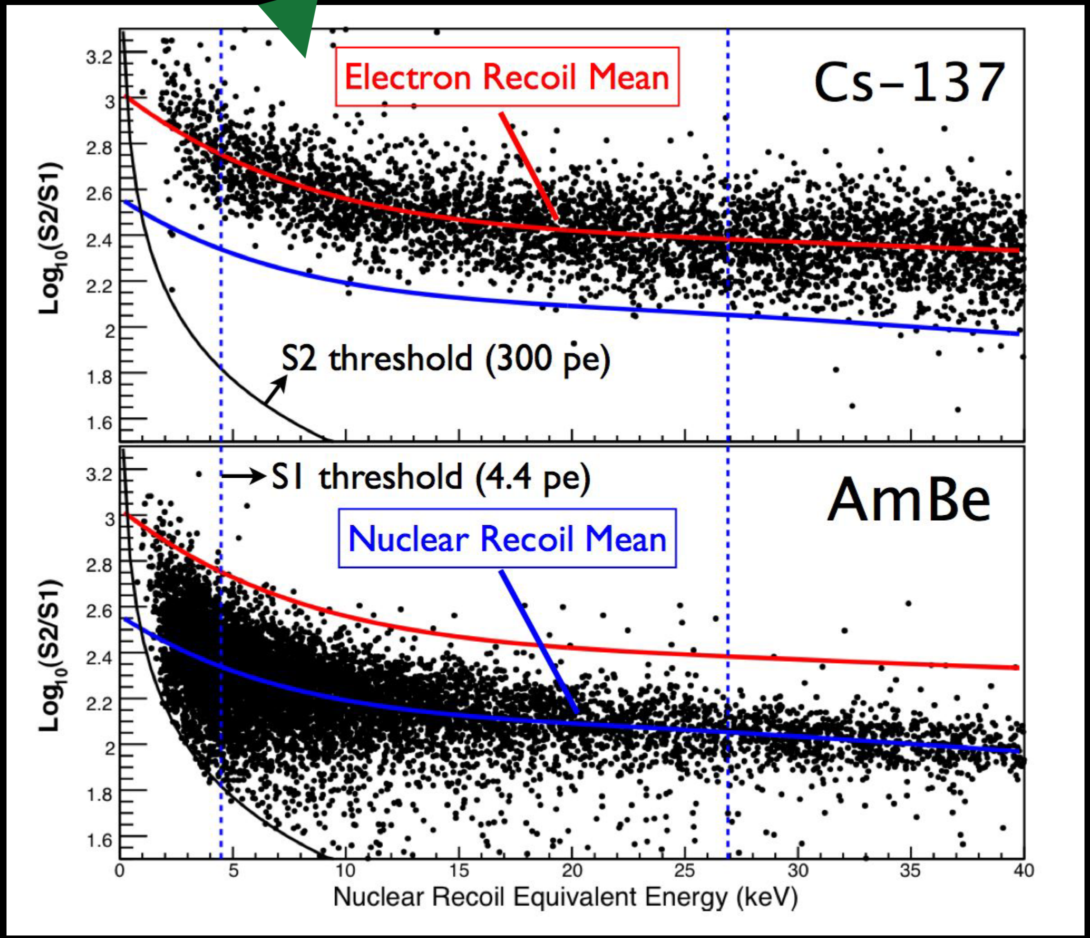

WIMPs and Neutrons
scatter from the
Atomic Nucleus
"NR"
Photons and Electrons
scatter from the
Atomic Electrons
"ER"

Electronic recoils (gammas) vs. nuclear recoils (WIMPs)

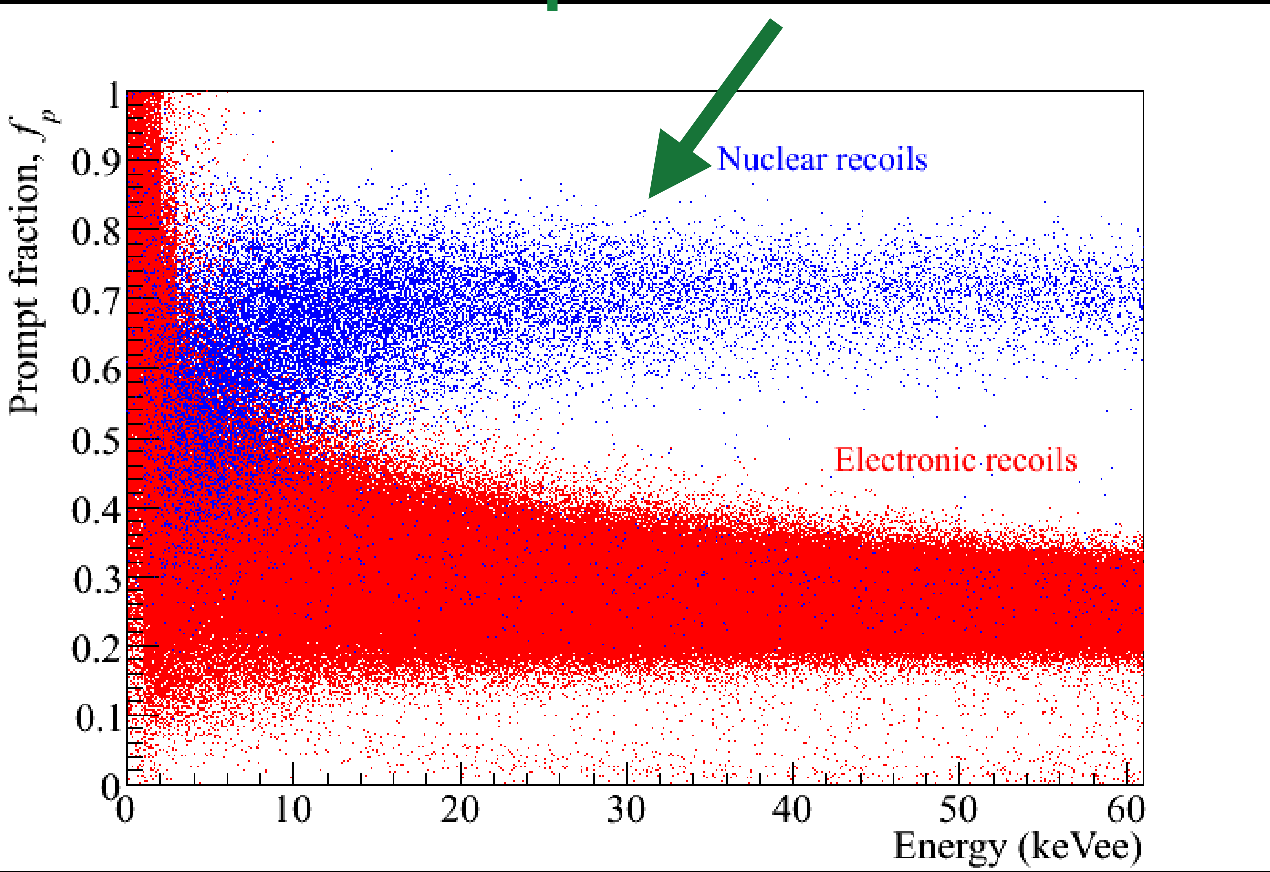
CDMS - Charge to heat



Xenon TPCs - Charge to light



Argon - Pulse shape discrimination

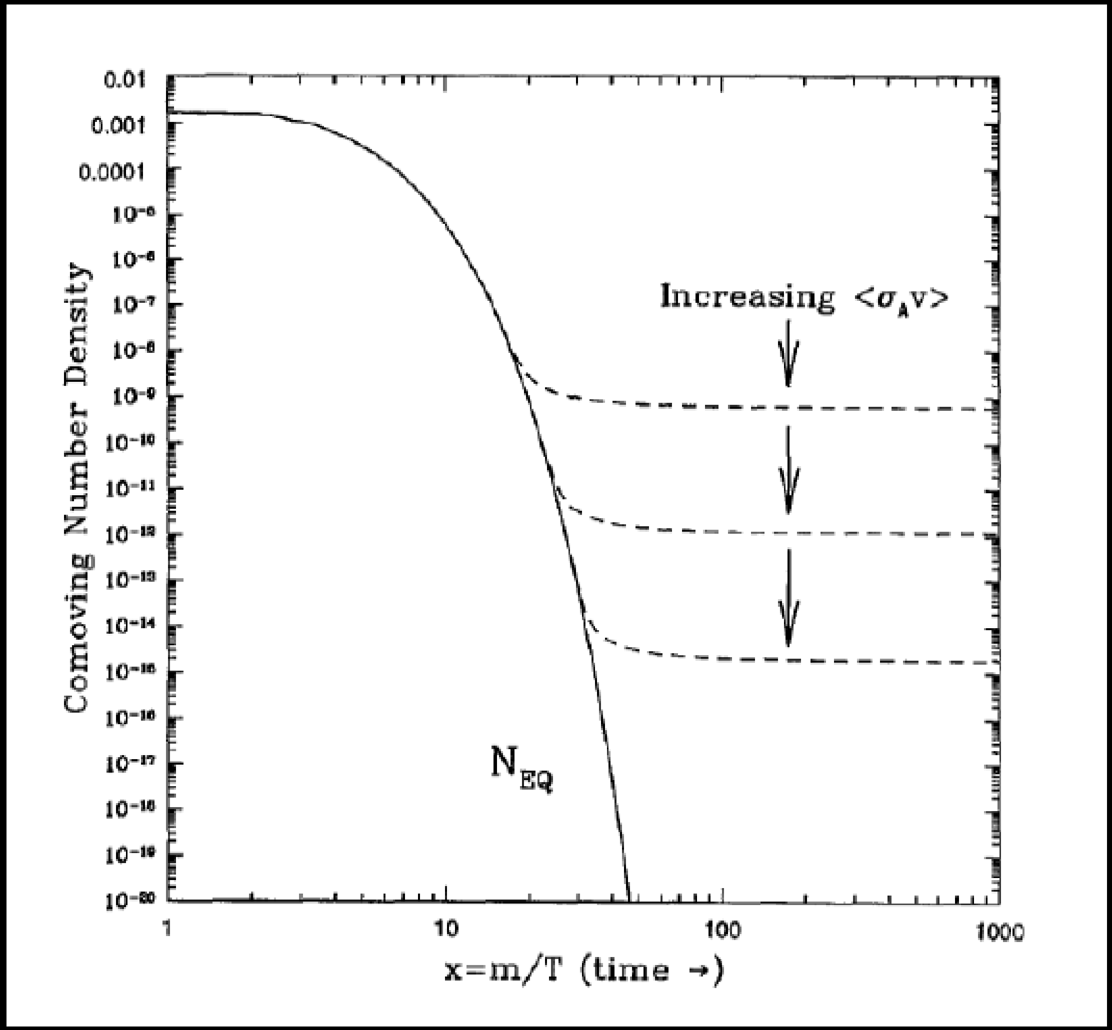


Custom dark matter detectors

Challenge	Solution
Extremely rare interaction	Large target mass - scalable
Energy depositions of ~10 keV or below	Low energy thresholds
Backgrounds - Impurities	Purification
Backgrounds - Detector	Self shielding
Backgrounds - Internal/Detector	Discrimination
Unknown particle physics	Sensitivity to multiple types interaction

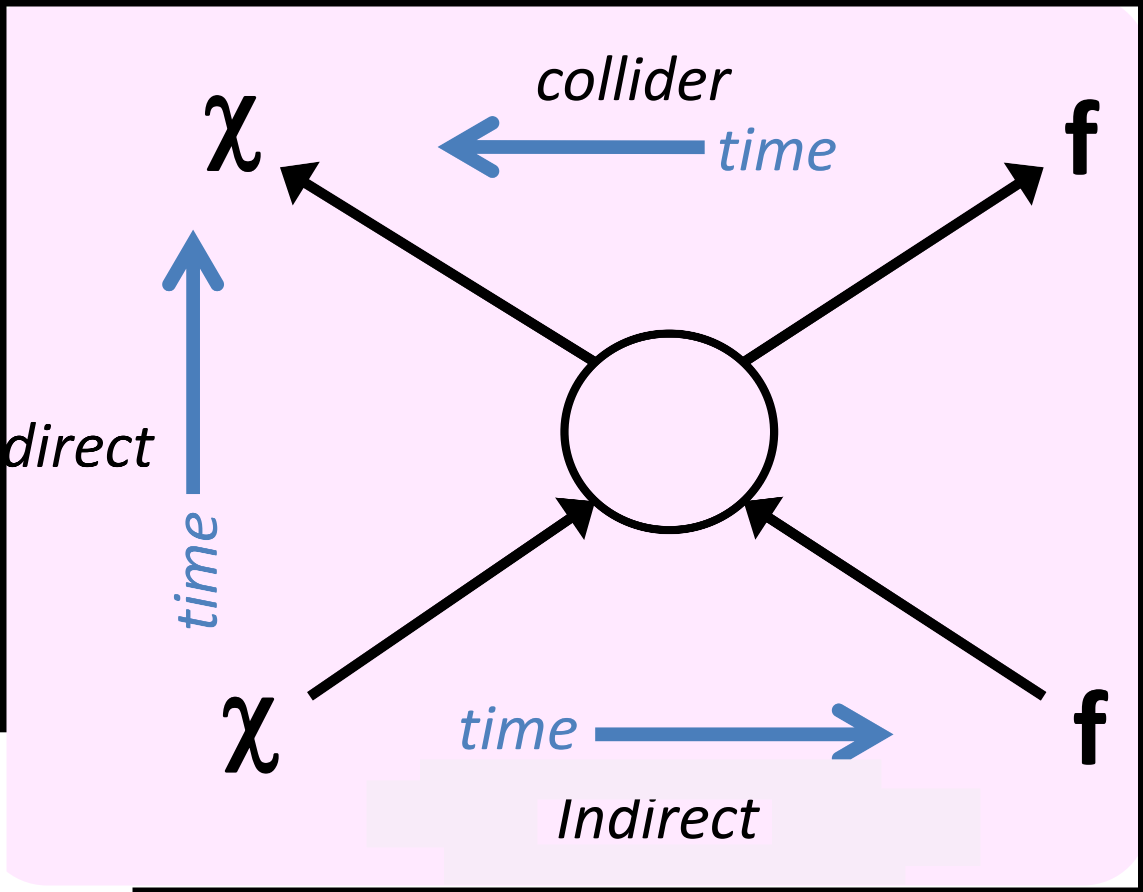
WIMPs

- Most discussed candidate is Weakly Interacting Massive Particle
  - Produced during big bang
  - Decouples from ordinary matter as the universe expands and cools
  - Still around today with densities of about a few per liter

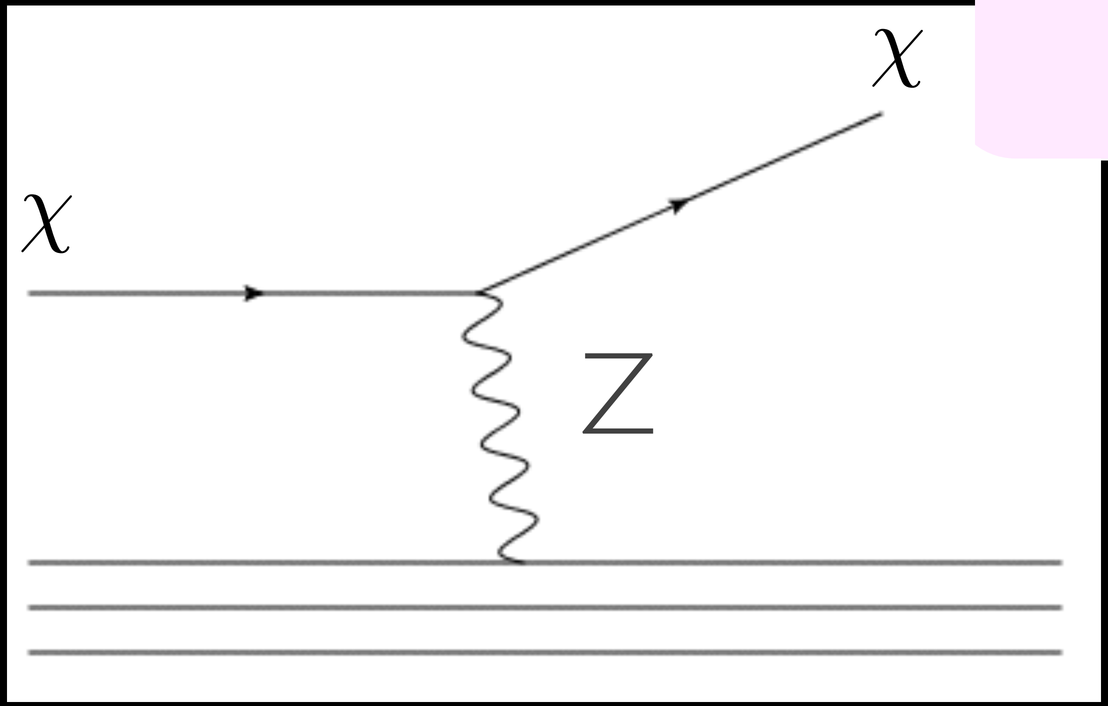


- Supersymmetry produces a theoretical candidate (LSP), but others exist (e.g. Kaluza-Klein particles, ...)

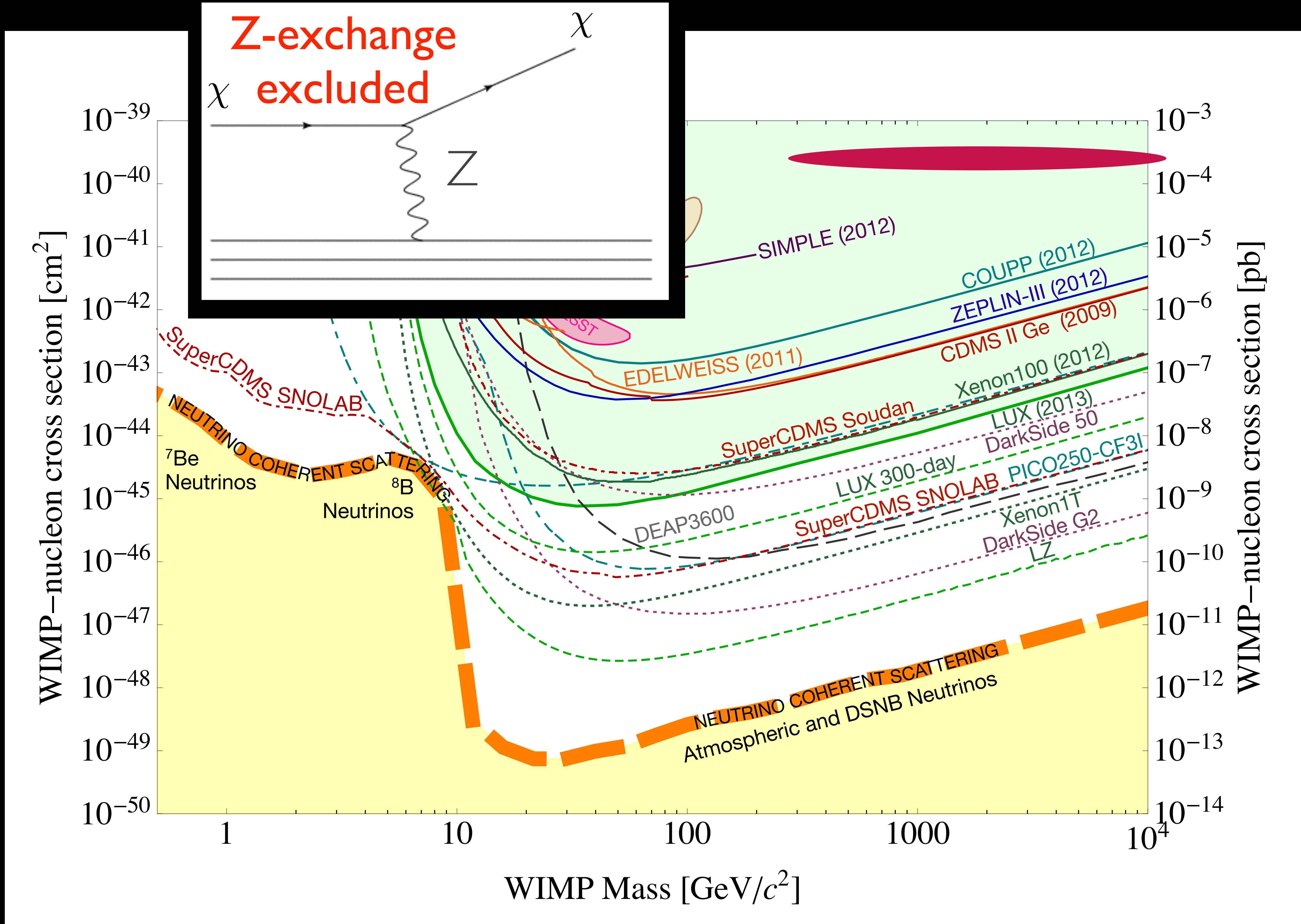
$$< \sigma v >_{ann} \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{sec}^{-1} \approx \frac{\alpha^2}{(200\mathrm{GeV})^2}$$



Coupling e.g. to light quarks



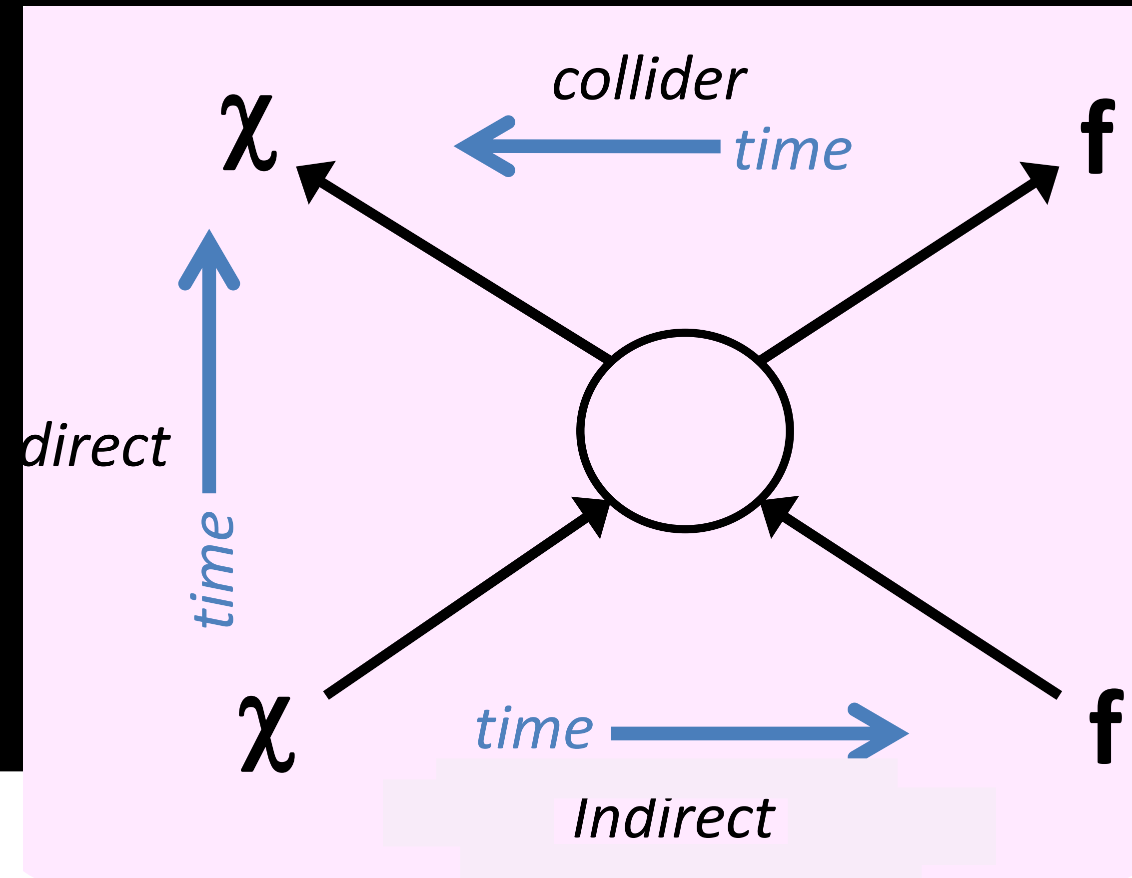
$$\sigma_0 \approx \frac{G_f^2 \mu^2}{2\pi} \sim 10^{-39} \mathrm{cm}^2$$

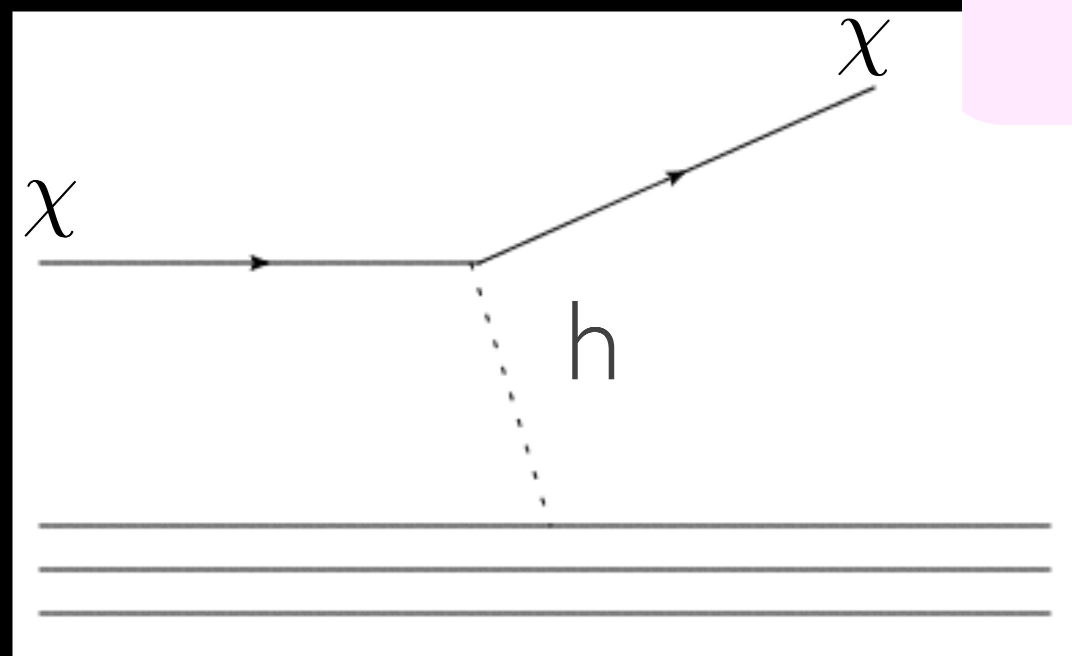


Z-exchange
excluded
χ
χ
Z
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be
Neutrinos
8B
Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]
1
10
100
1000
104
10−39
10−40
10−41
10−42
10−43
10−44
10−45
10−46
10−47
10−48
10−49
10−50
10−3
10−4
10−5
10−6
10−7
10−8
10−9
10−10
10−11
10−12
10−13
10−14

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

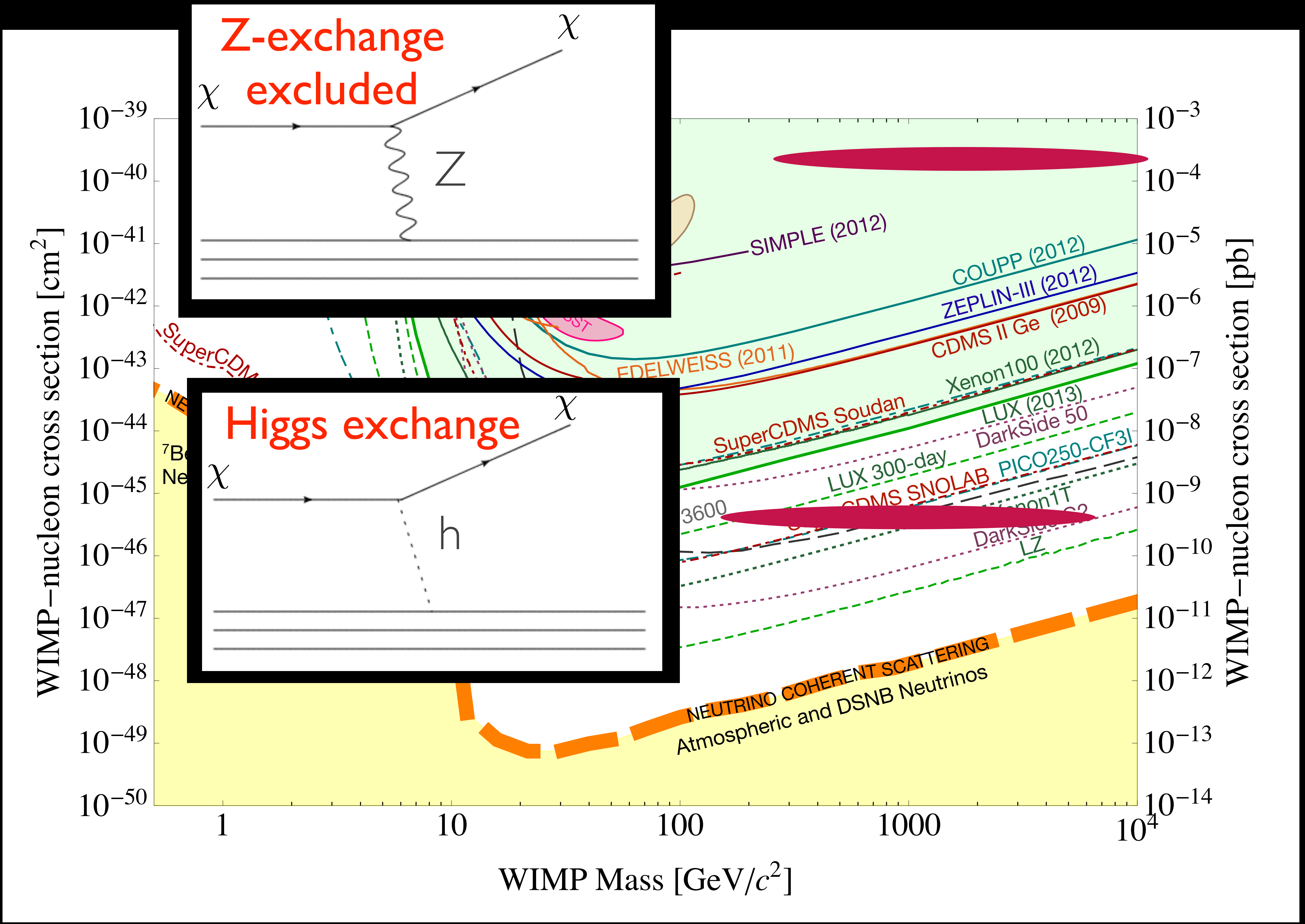
Coupling proportional to mass (e.g. via higgs)





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

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



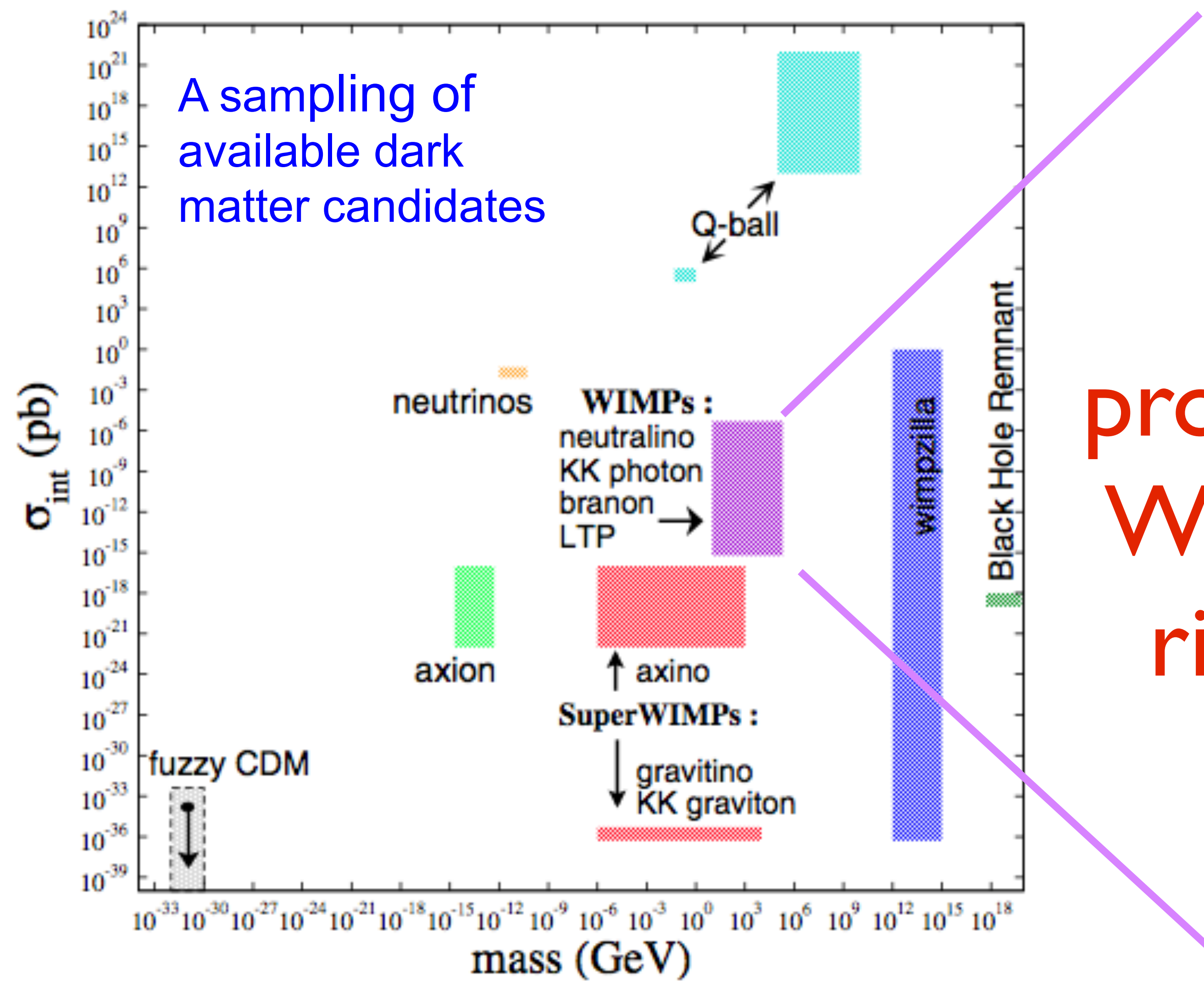
"This era will answer the question: does the dark matter couple at O(0.1) to the Higgs boson"

N. Weiner, CIPANP 2015

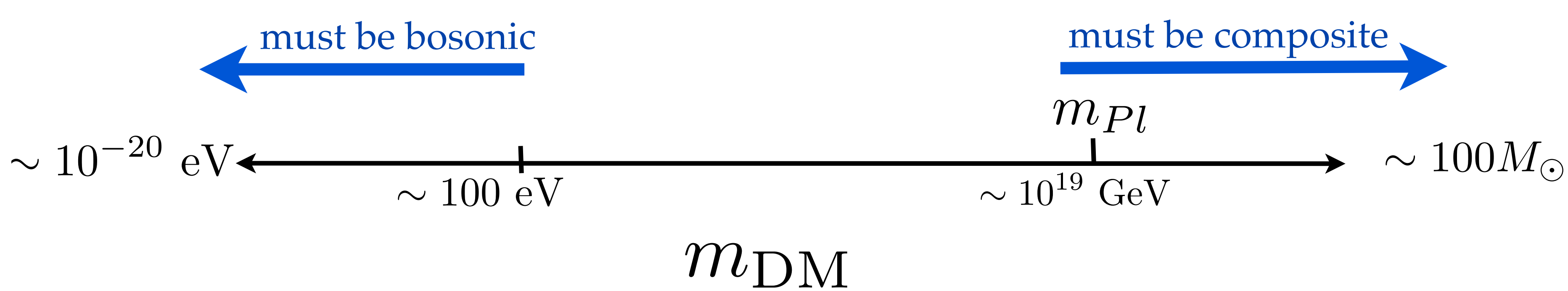
The case for dark matter

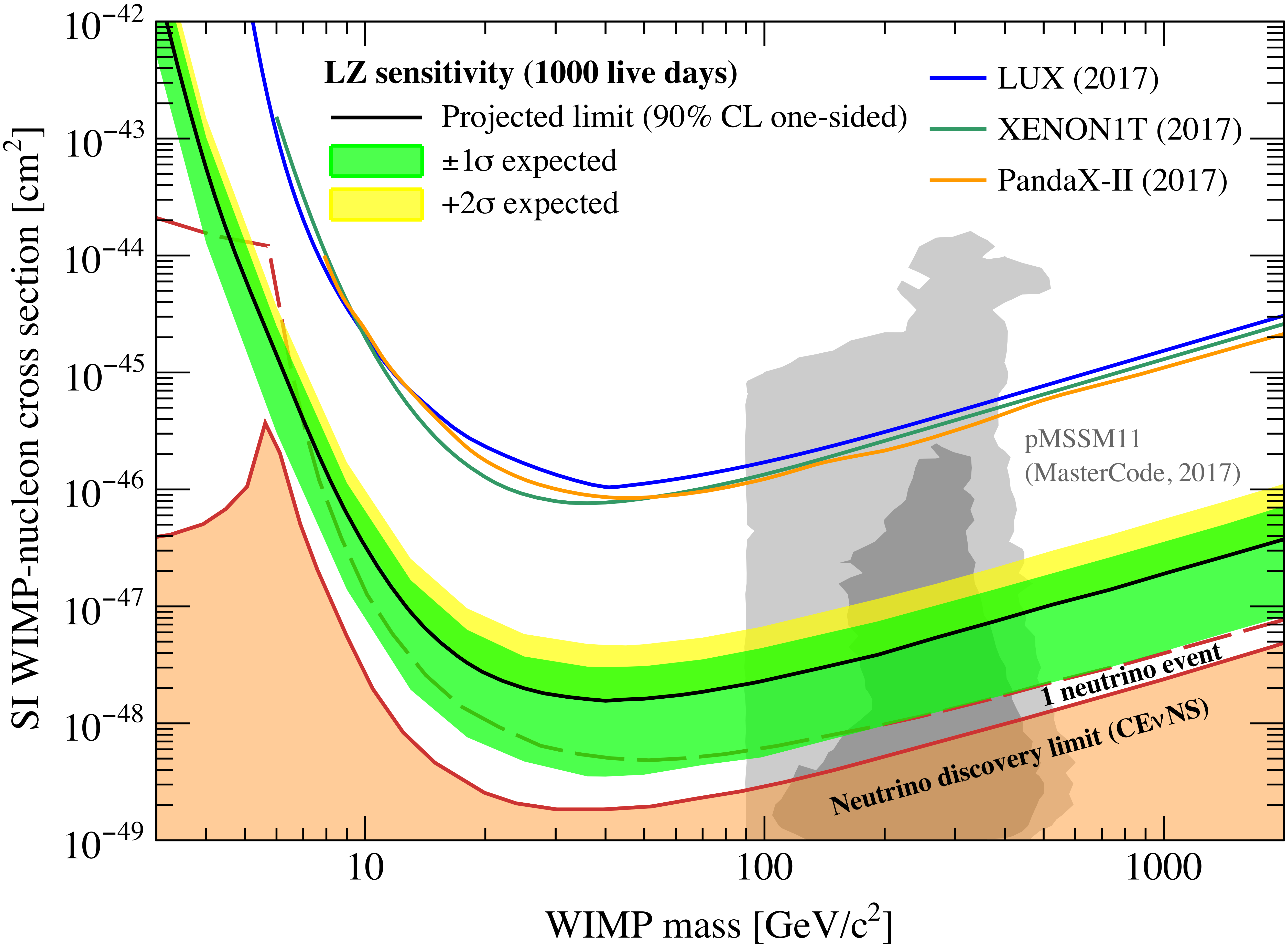
- We know it interacts gravitationally
- It is “dark” - should not interact with light or electromagnetism
- Nearly collision less
- Slow

Particle Physics

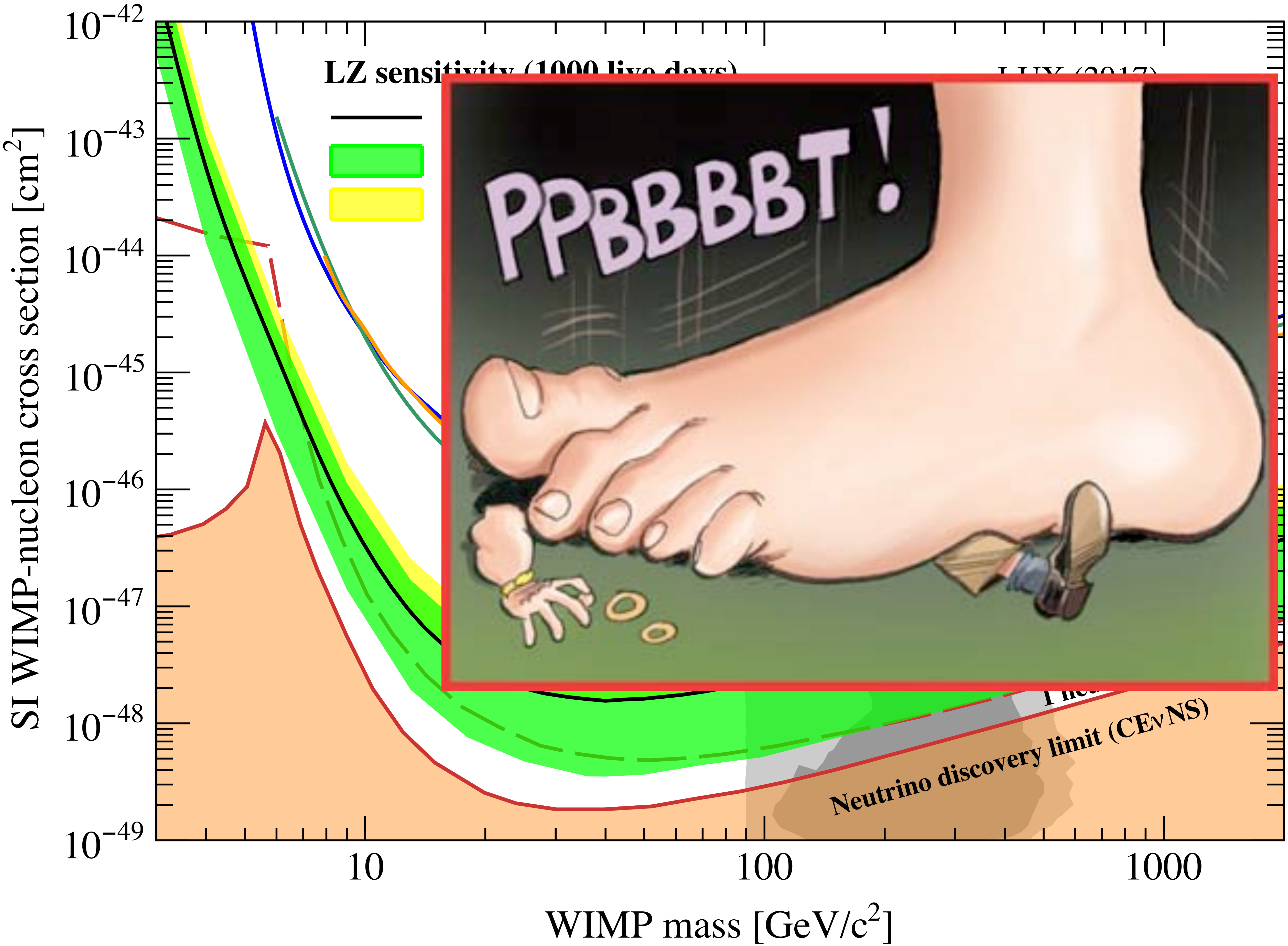


It’s probably WIMPs, right?

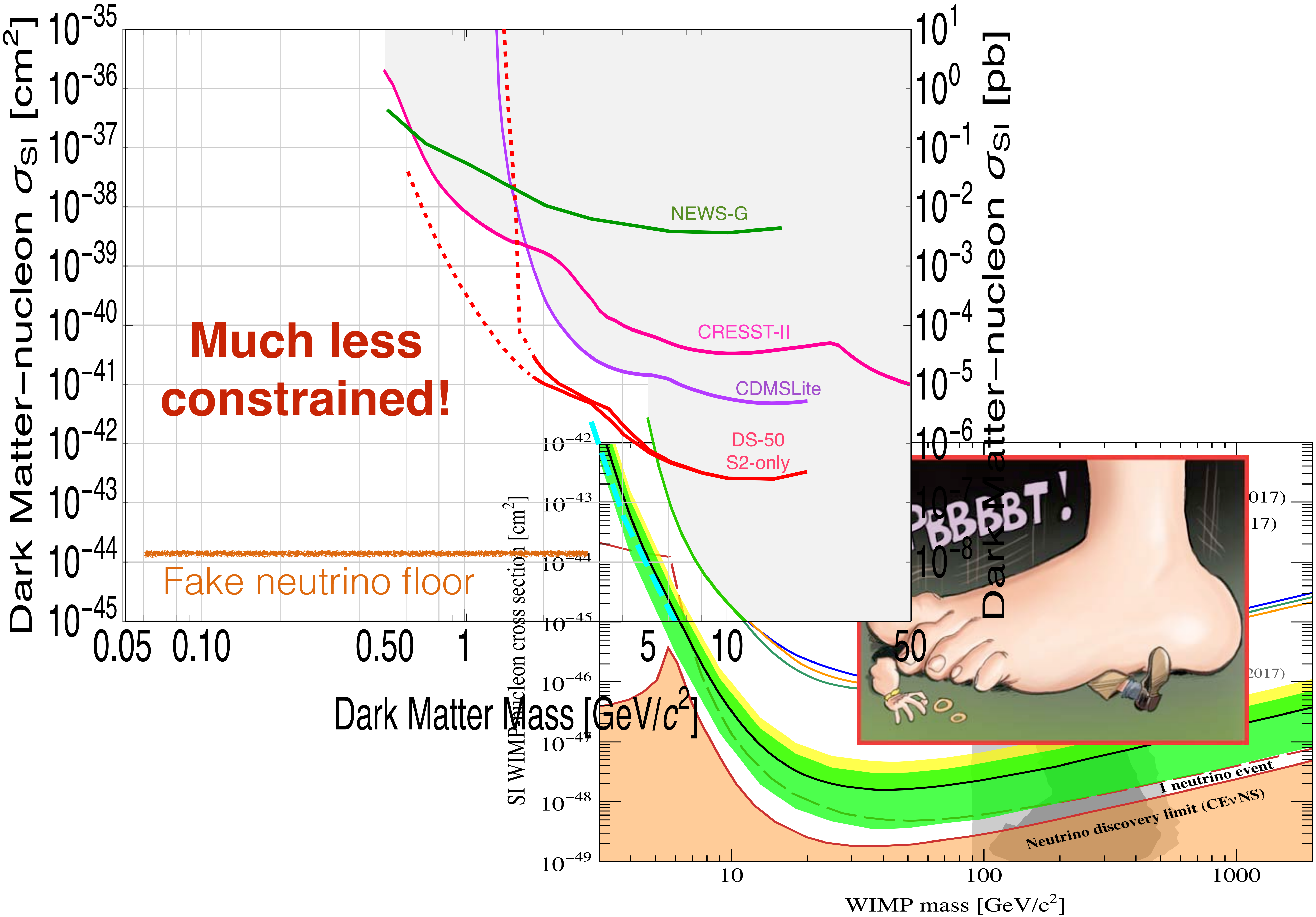




LZ sensitivity (1000 live days)
Projected limit (90% CL one-sided)
±1σ expected
+2σ expected
LUX (2017)
XENON1T (2017)
PandaX-II (2017)
pMSSM11
(MasterCode, 2017)
1 neutrino event
Neutrino discovery limit (CEνNS)
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]
10^-42
10^-43
10^-44
10^-45
10^-46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



SI WIMP-nucleon cross section [cm²]
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10
100
1000
WIMP mass [GeV/c²]
Neutrino discovery limit (CEνNS)
PPBBBBT!


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]
SI WIMP-nucleon cross section [cm^2]
WIMP mass [GeV/c^2]
1 neutrino event
Neutrino discovery limit (CEνNS)
BBBBT!

DM Prognosis?

Bad news: DM-SM interactions are not obligatory

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

Courtesy G. Krnjaic

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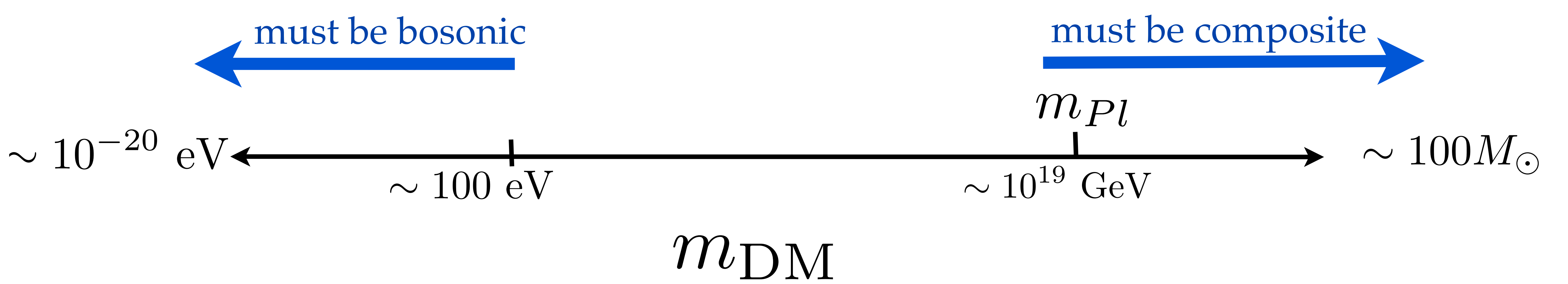


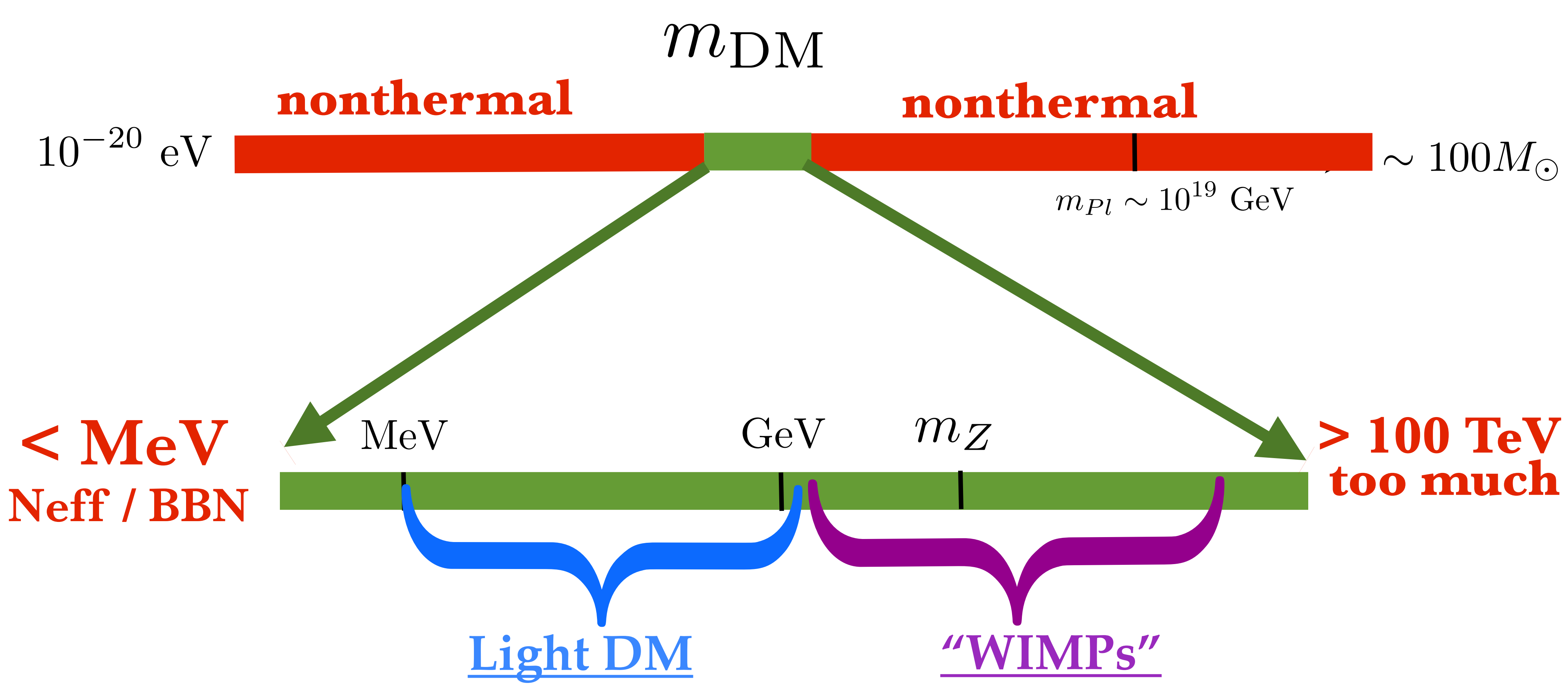
Good news: most *discoverable* DM candidates are in thermal equilibrium with us in the early universe

Why is this good news?

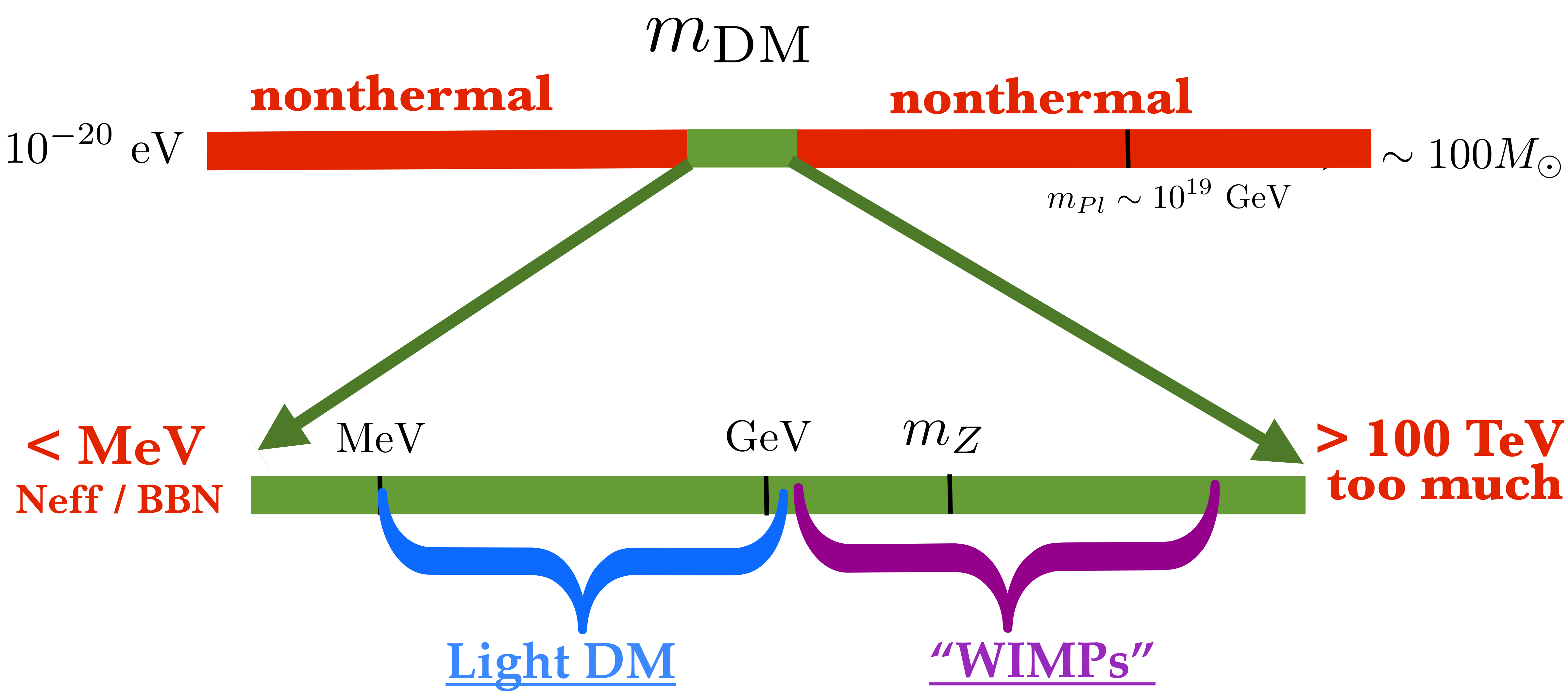
Courtesy G. Krnjaic

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

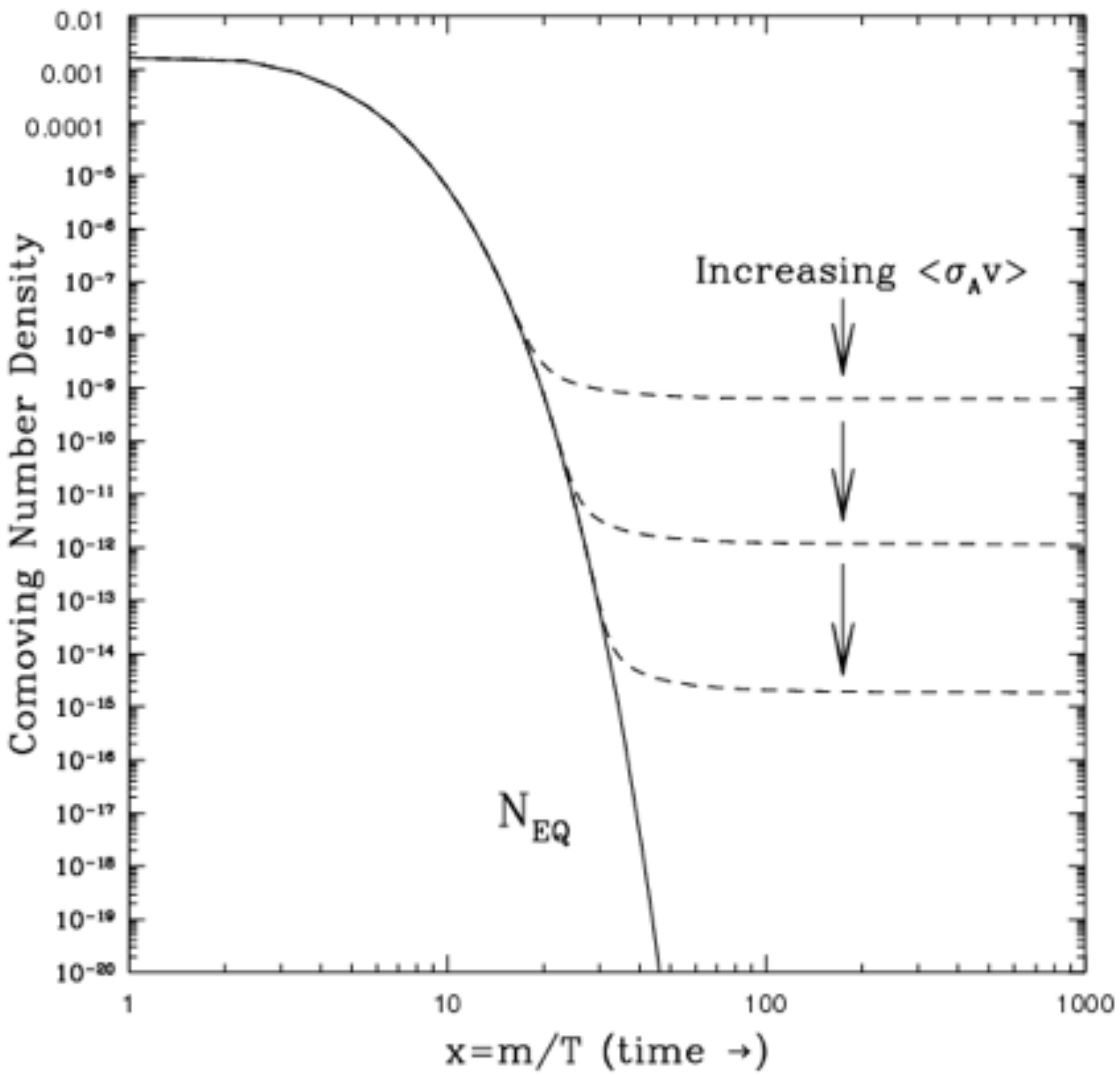


Wide open

LZ, LAr, PICO, LHC, etc

Mature >5 GeV program

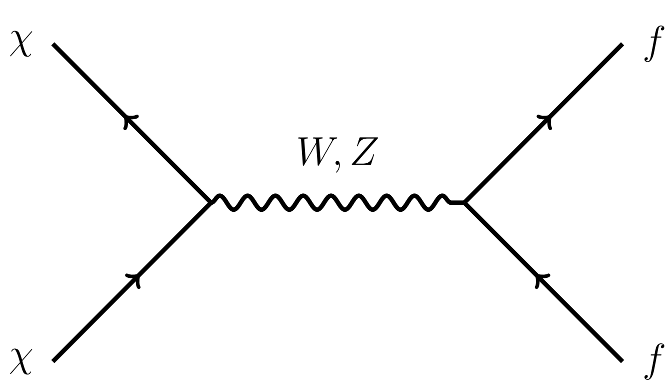
Are there actual candidates?



- 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

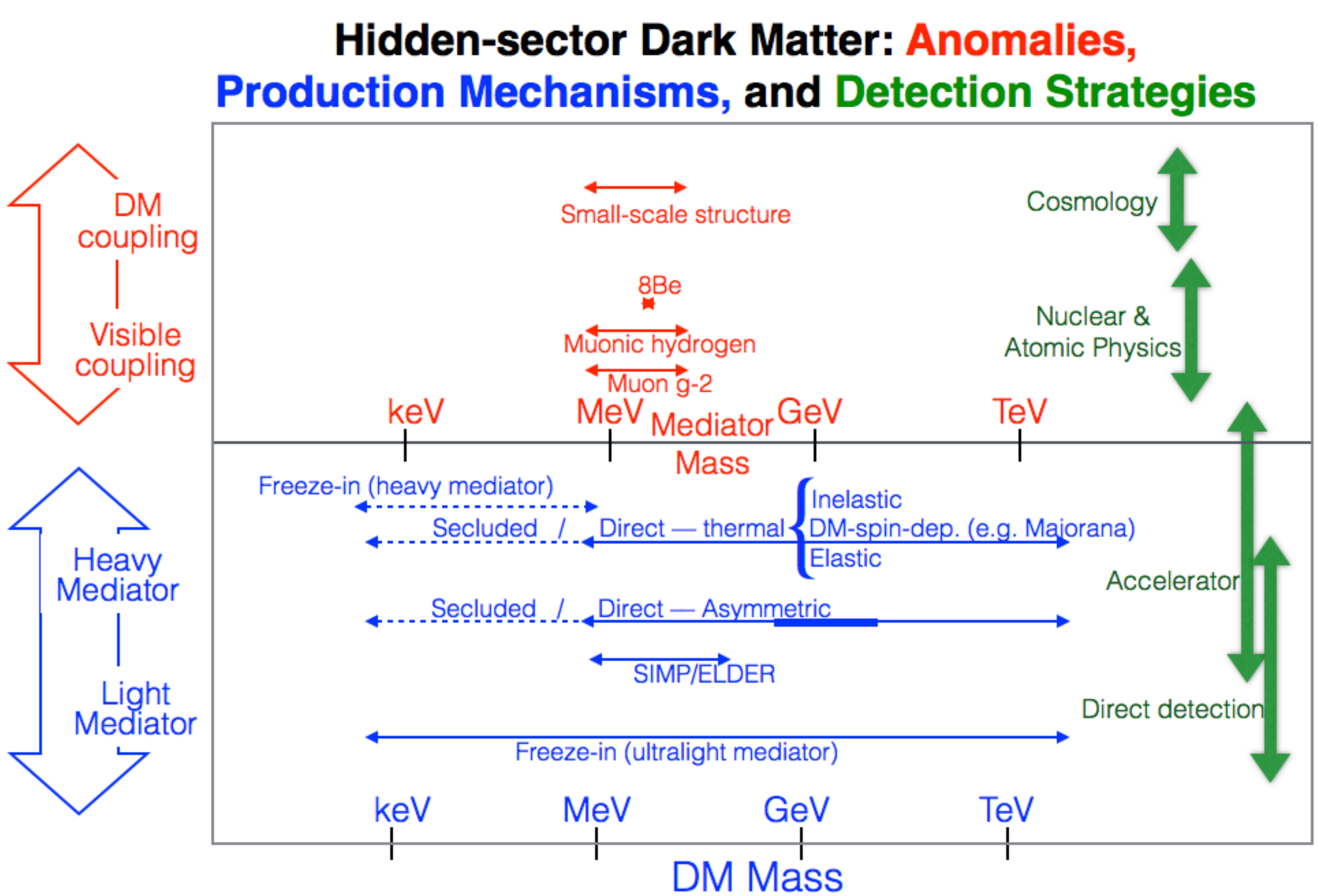


$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{m_\chi}{\mathrm{GeV}} \right)^2$$

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

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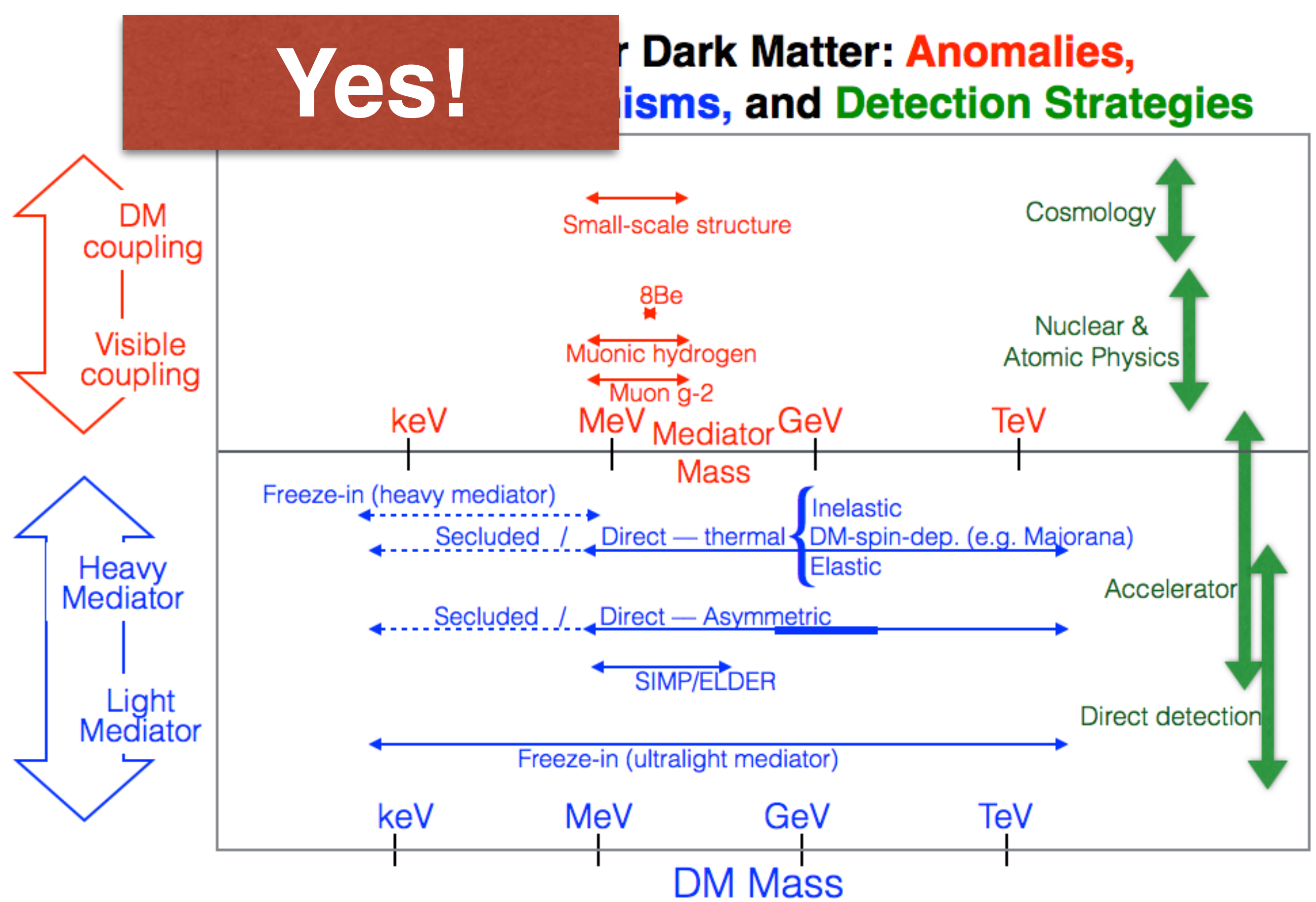
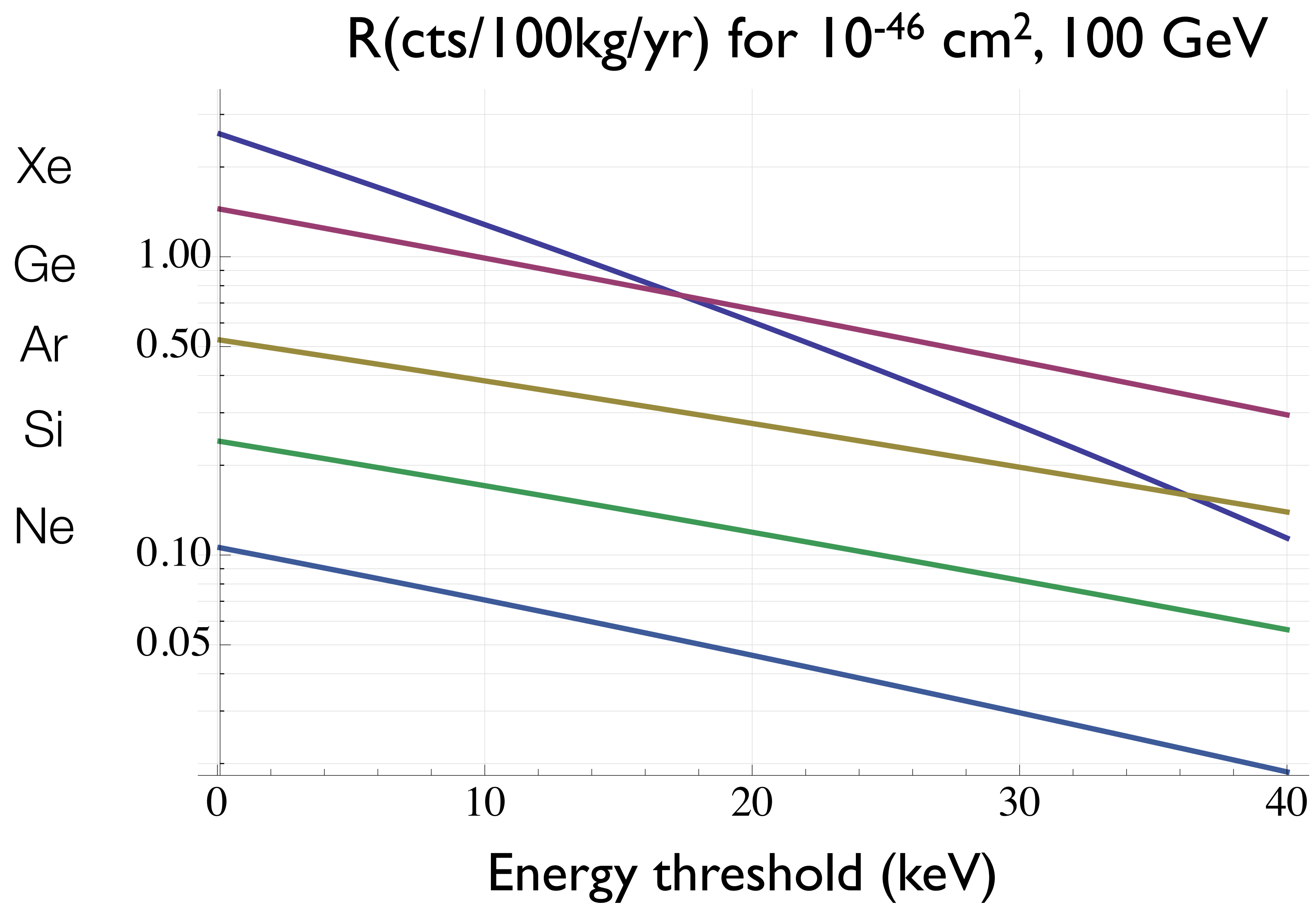


1707.04591

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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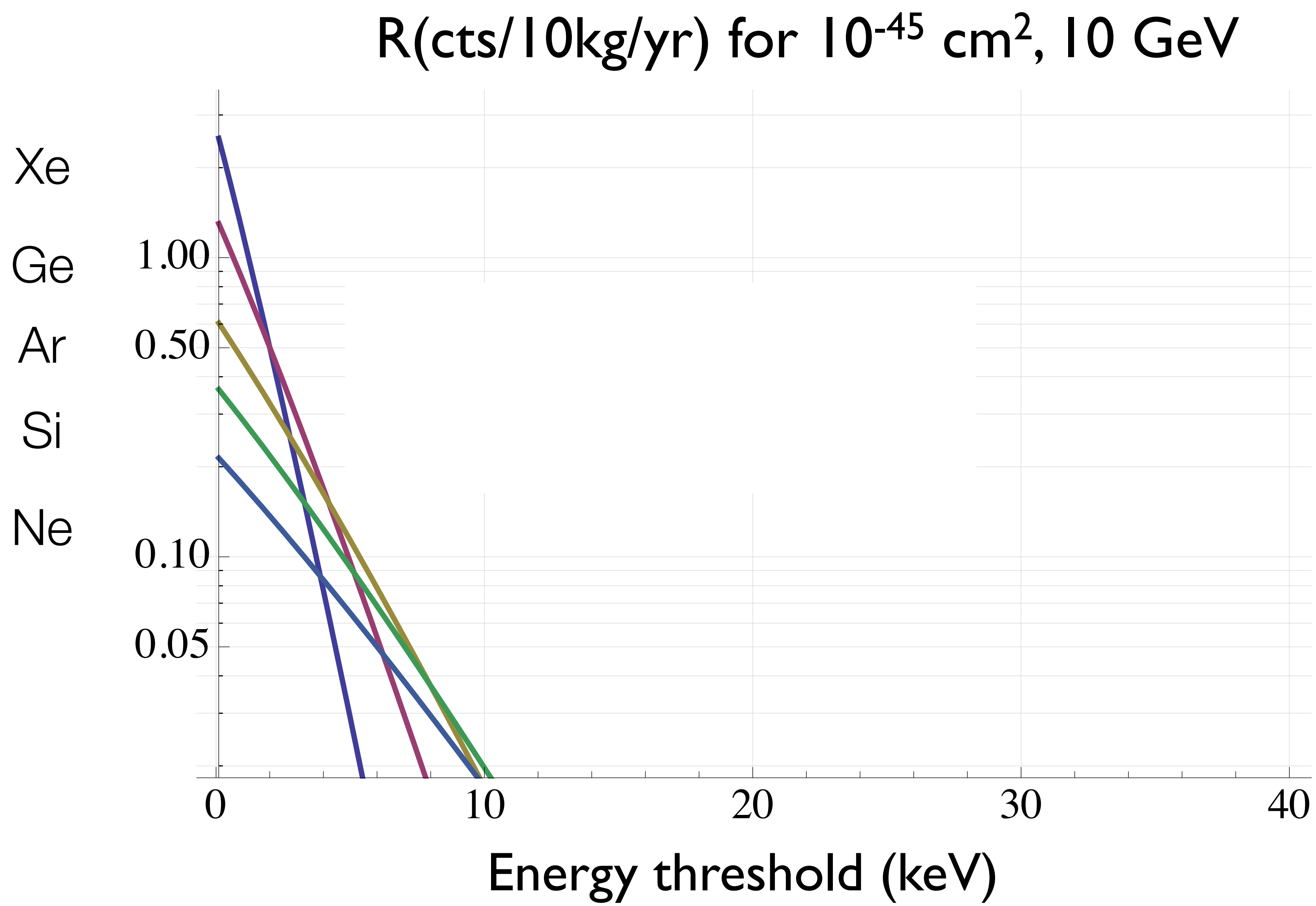

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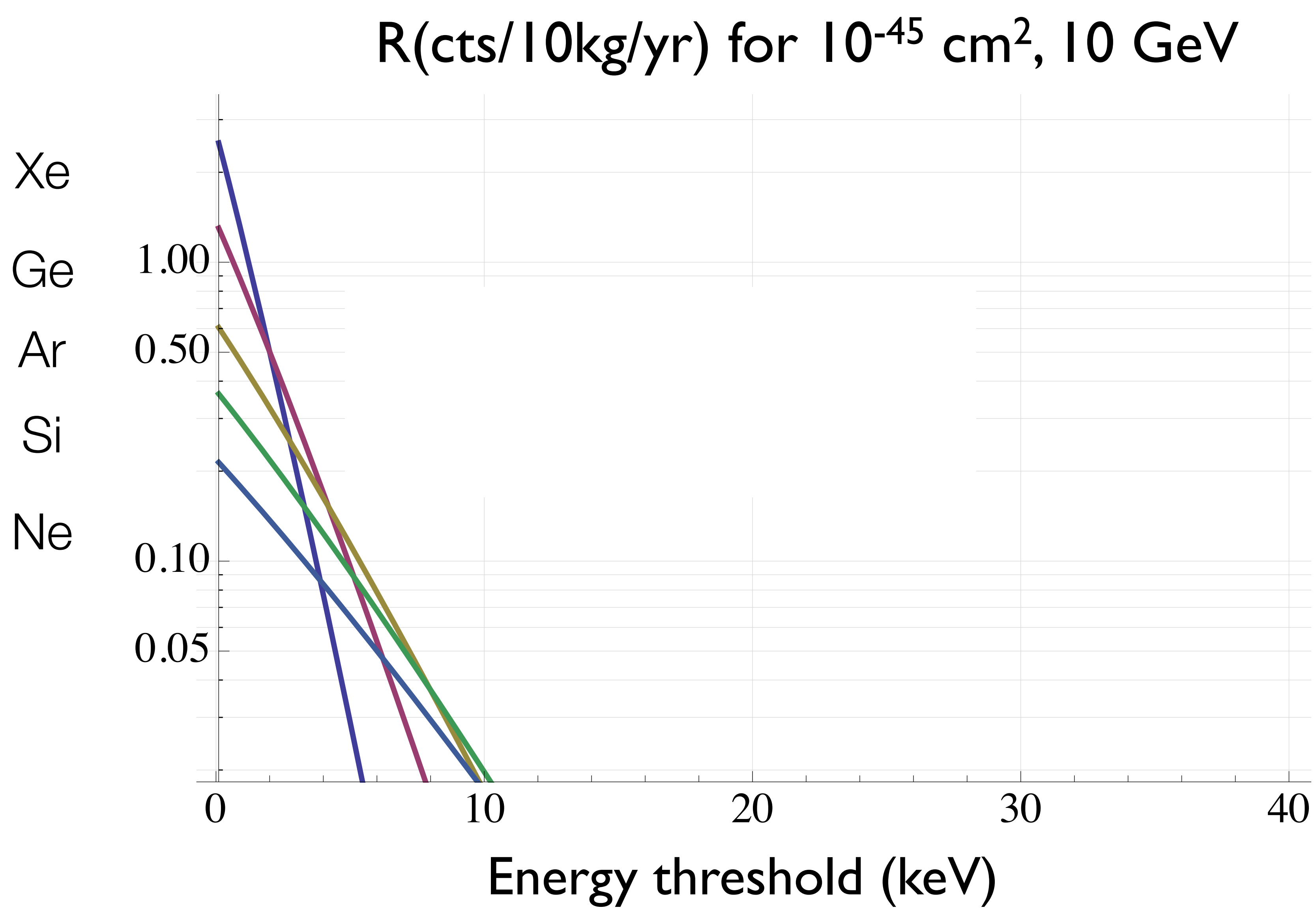

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$$v_m = \sqrt{Q m_N / 2m_r^2}$$

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

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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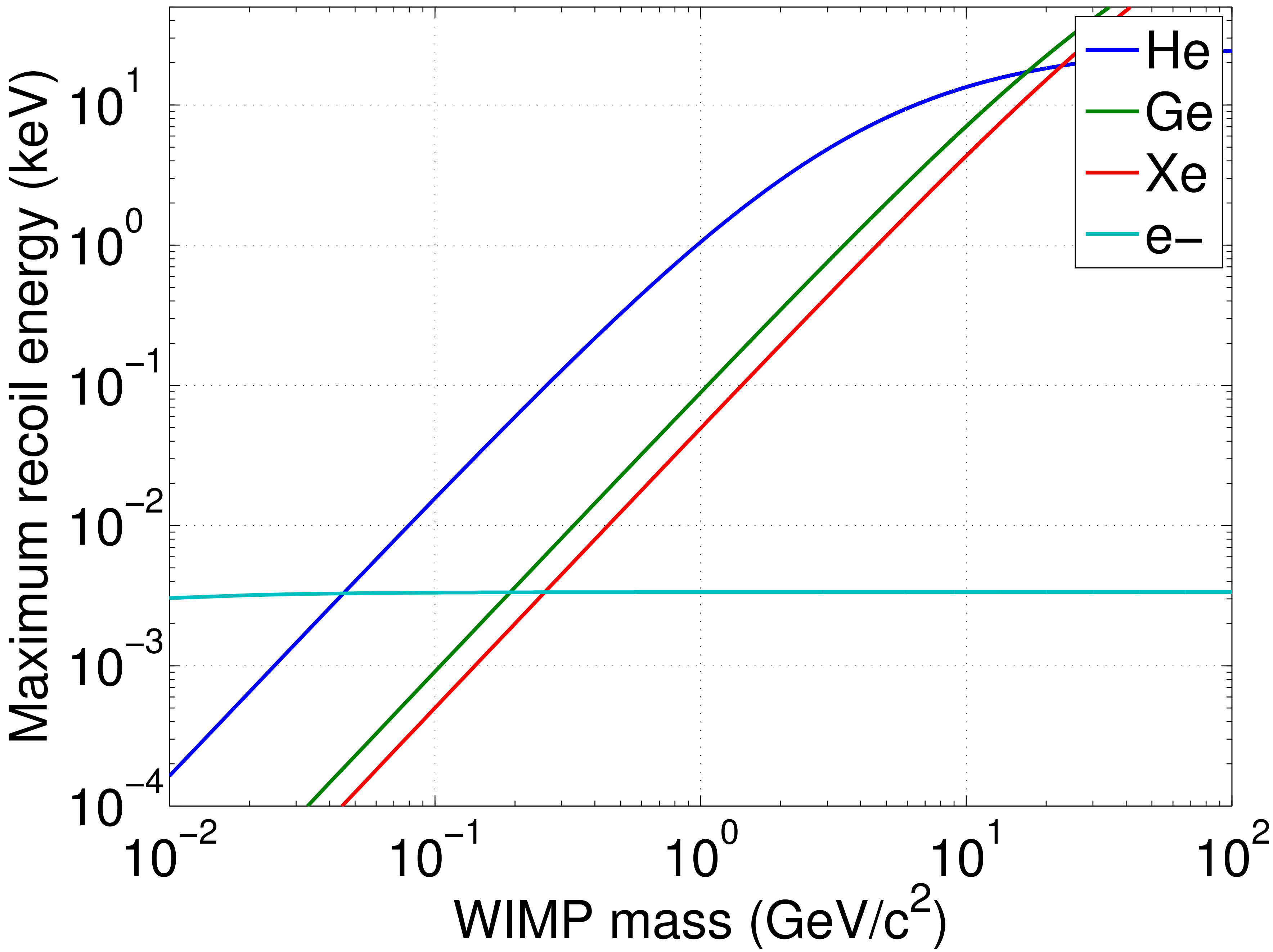

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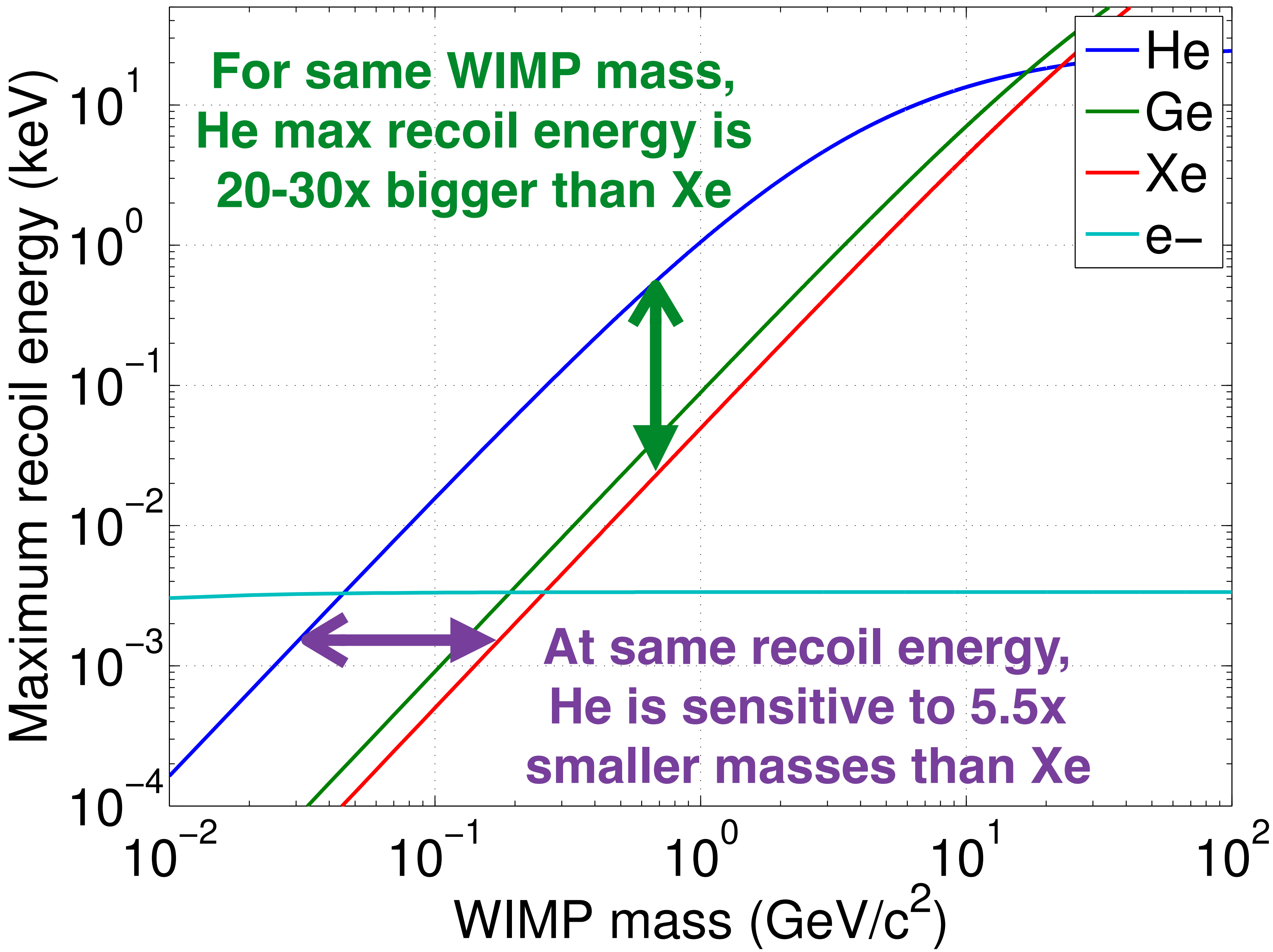
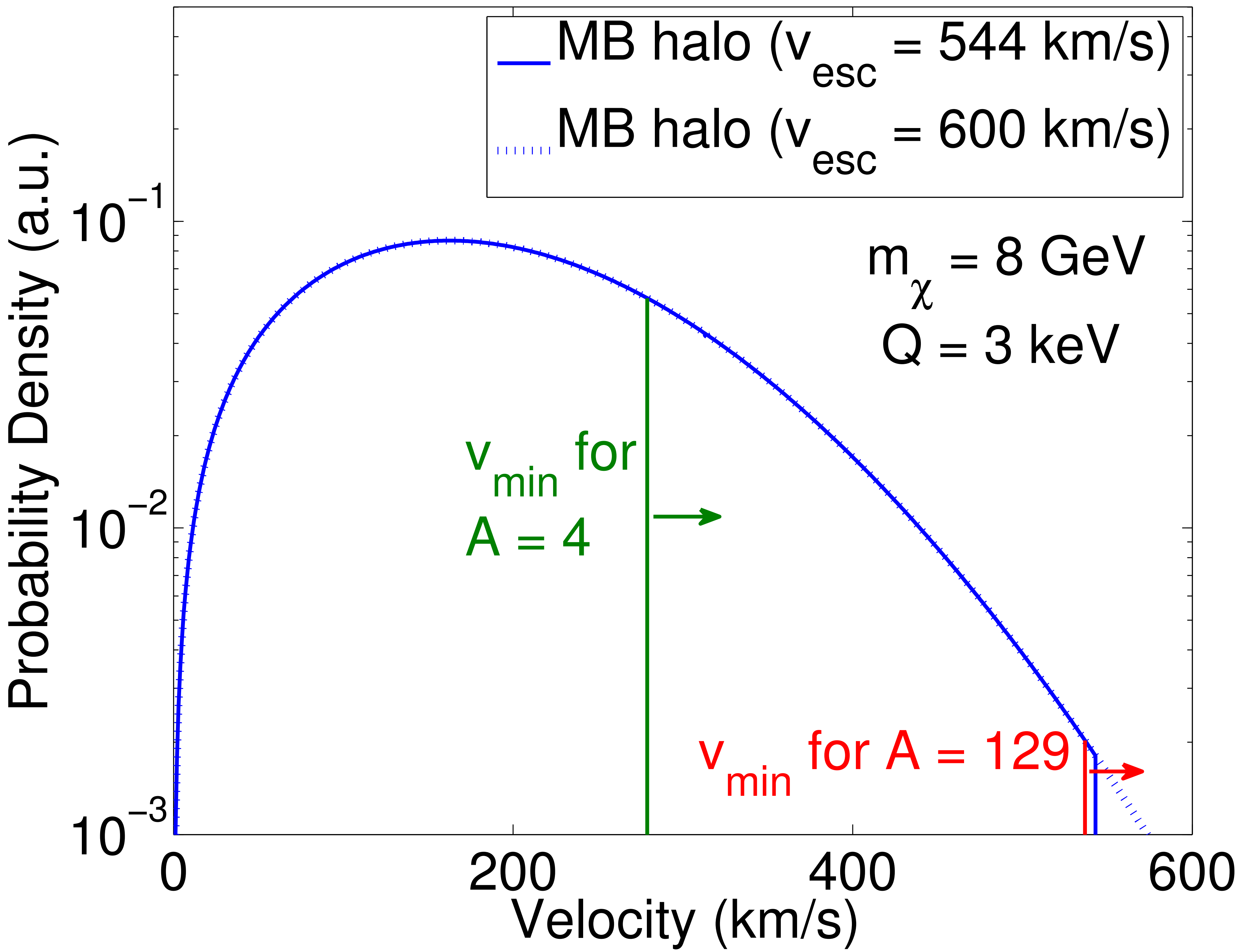


Light targets less sensitive to halo uncertainty

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



Custom dark matter detectors

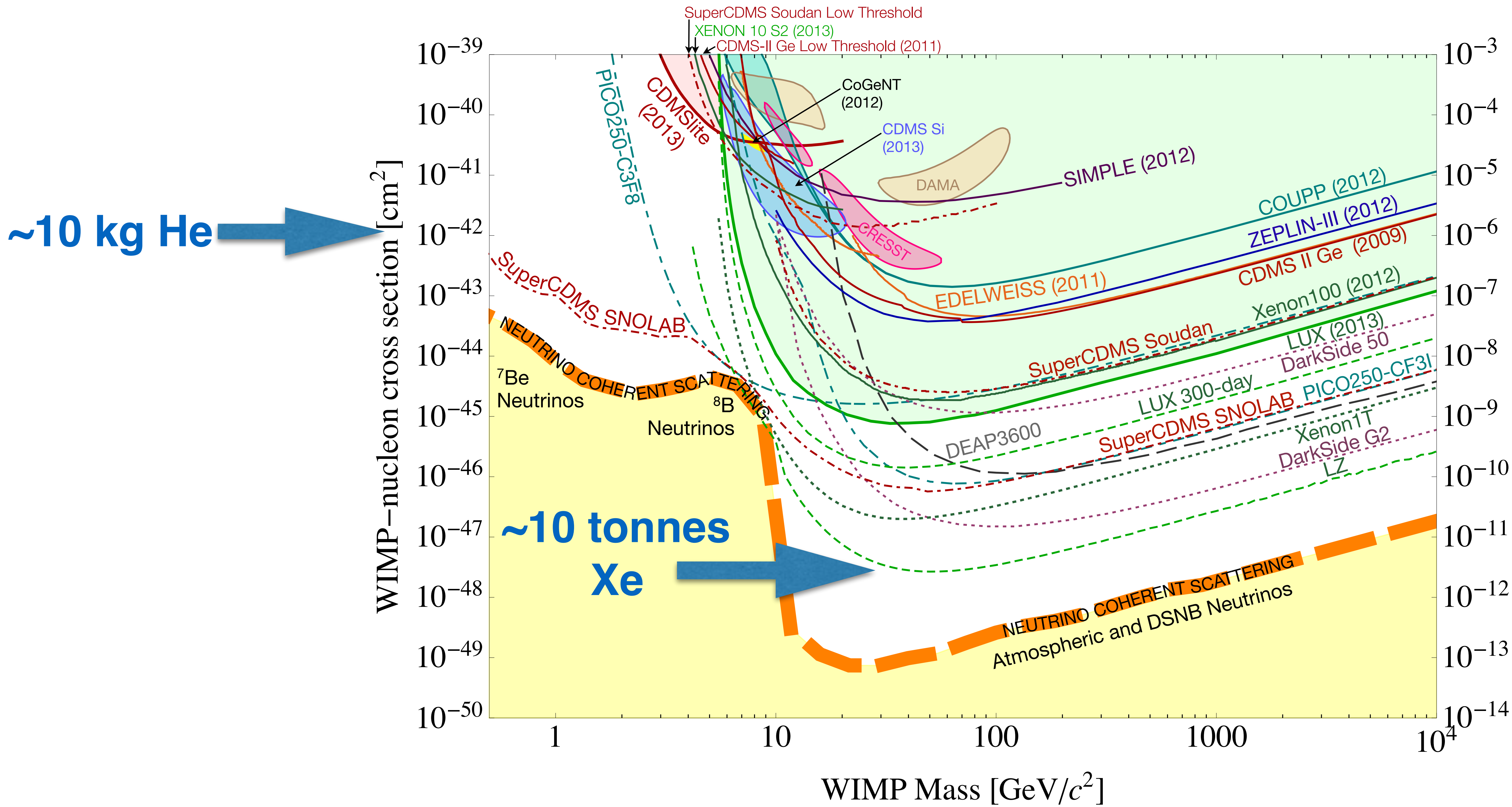
Challenge	Solution
Extremely rare interaction	Large target mass - scalable
Energy depositions of ~10 keV or below	Low energy thresholds
Backgrounds - Impurities	Purification
Backgrounds - Detector	Self shielding
Backgrounds - Internal/Detector	Discrimination
Unknown particle physics	Sensitivity to multiple types interaction

Custom light dark matter detectors

Challenge	Solution
Extremely rare interaction	~~Large~~ target mass - scalable
Energy depositions of ~1 keV or below	Very Low energy thresholds
Backgrounds - Impurities	Purification
Backgrounds - Detector	Self shielding
Backgrounds - Internal/Detector	Discrimination
Unknown particle physics	Sensitivity to multiple types interaction
Kinematics	Light target

What don't you need for low mass?

- A lot of mass



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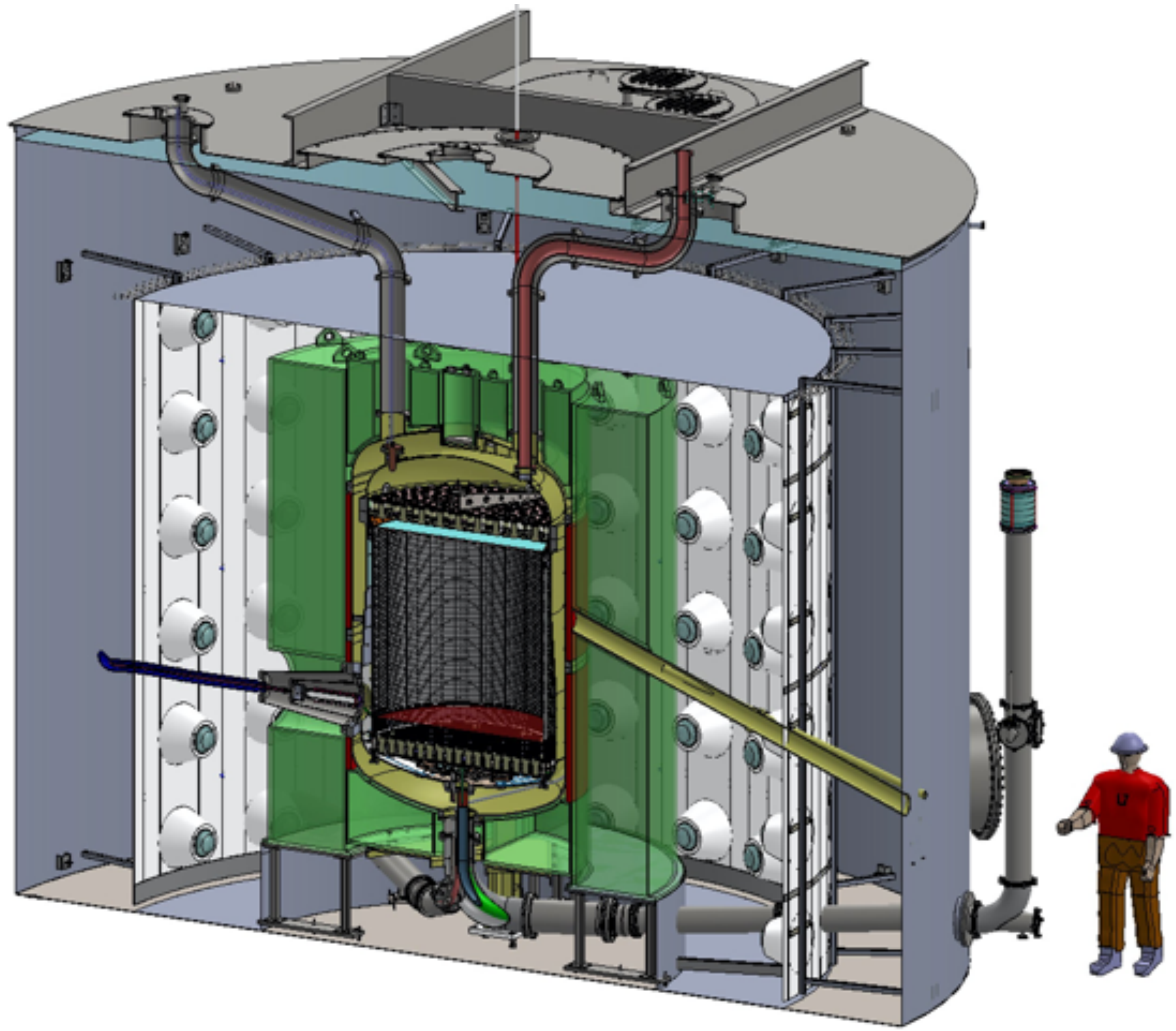
Backgrounds - Internal/Detector	Discrimination
Unknown particle physics	Sensitivity to multiple types interaction
Kinematics	Light target

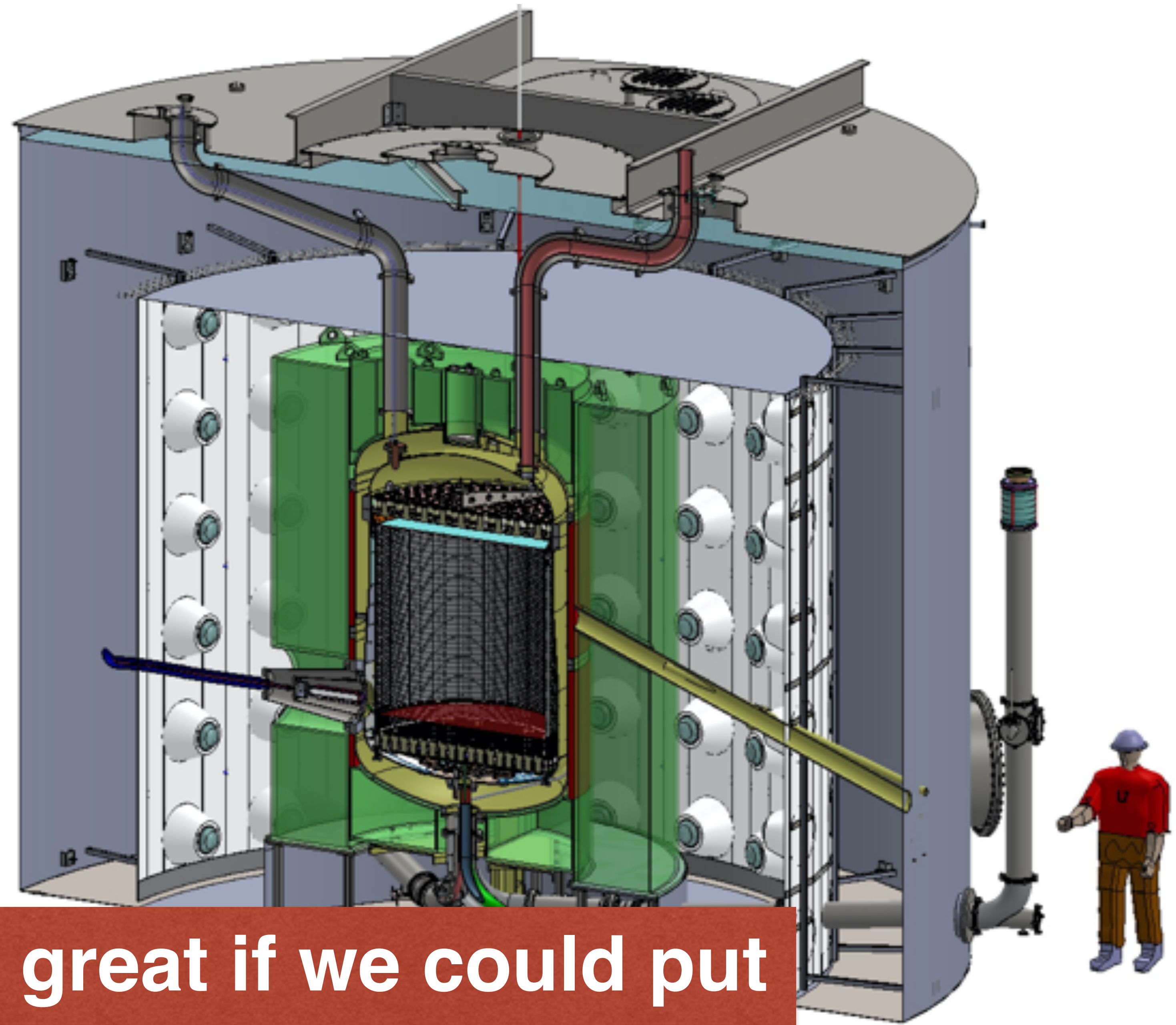
LUX-Zeplin (LZ)

- 7 tonne active LXe TPC
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
  - Huge effort to make it clean and low background
  - Is going to exist!
  - Heavy target



LUX-Zeplin (LZ)

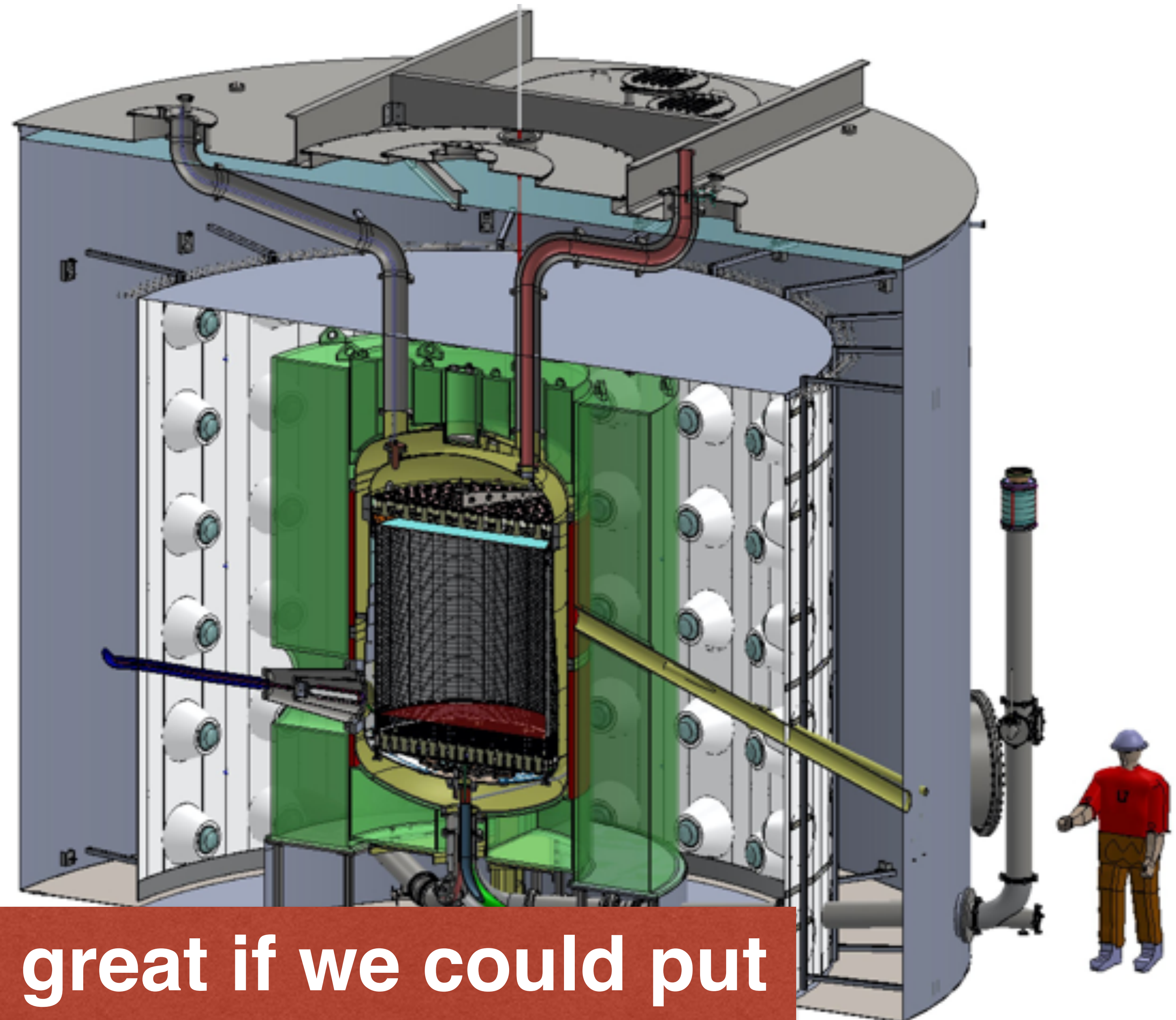
- 7 tonne active LXe TPC
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
  - Huge effort to make it clean and low background
  - Is going to exist!
  - Heavy target



Wouldn't it be great if we could put a light atomic target in LZ?

He-Doped LUX-Zeplin (HeLZ)

- 7 tonne active LXe TPC
  - Excellent self shielding
  - Good discrimination
  - Low threshold (<3 keV)
  - Huge effort to make it clean and low background
  - Is going to exist!
  - Heavy target



Wouldn't it be great if we could put a light atomic target in LZ?

Dissolving He in LXe?

THE JOURNAL OF CHEMICAL PHYSICS VOLUME 29, NUMBER 1 JULY, 1958

Solubility of Helium and Neon in Liquid Argon. An Approximation to the Entropy of Lattice Vacancy Formation in Liquid Argon*

F. E. KARASZ† AND G. D. HALSEY, JR.‡
Department of Chemistry, University of Washington, Seattle, Washington

(Received January 14, 1958)

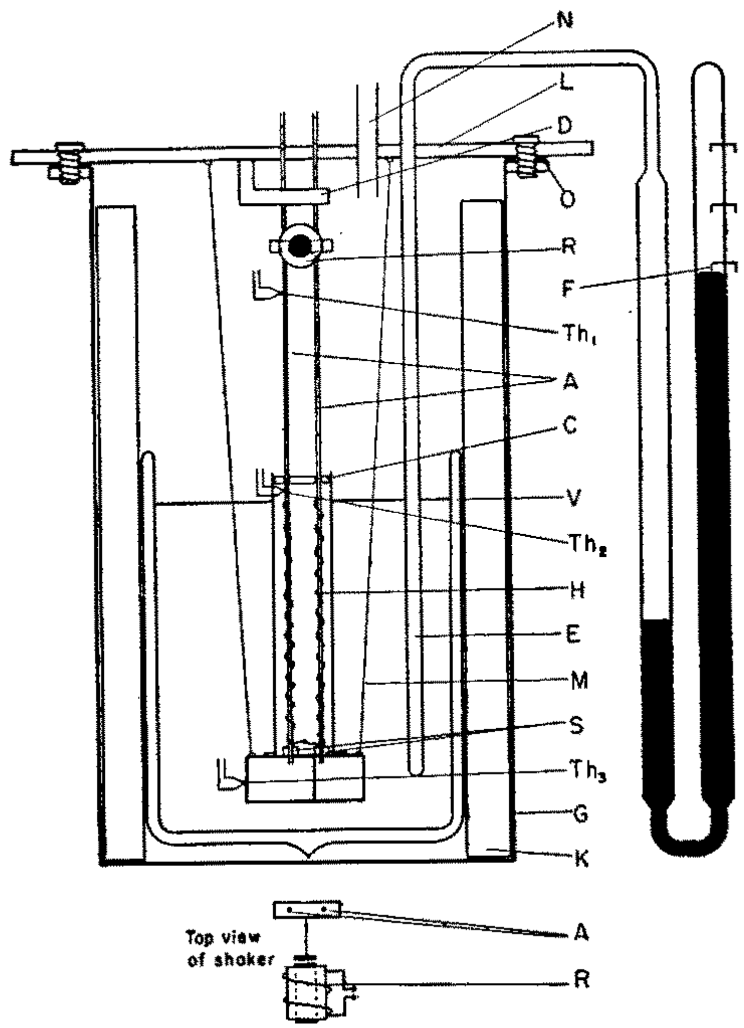
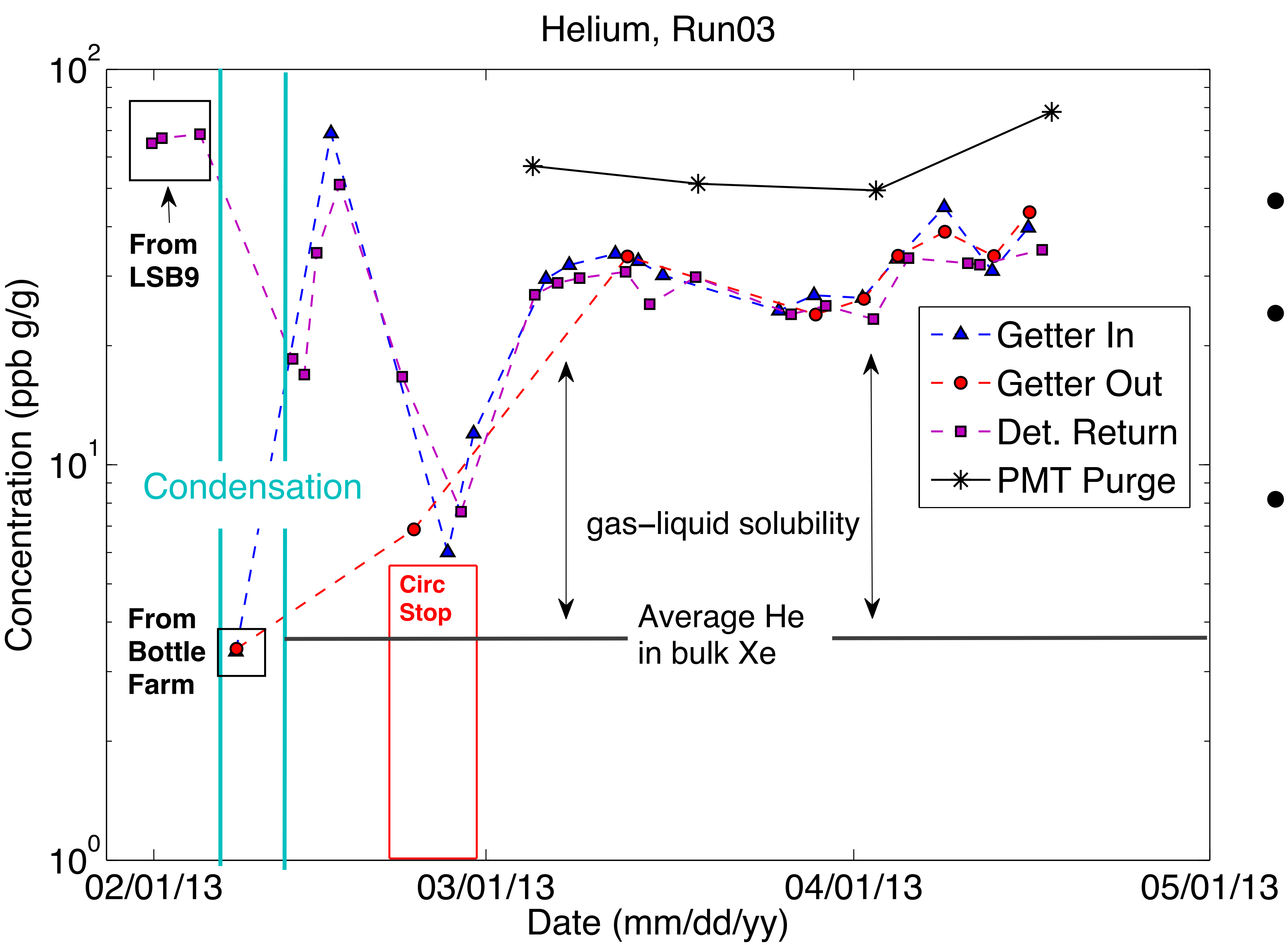


FIG. 1. Details of cell: A, stems; C, Teflon spacer; D, clamp to hold stems; E, vapor pressure thermometer for cryostat control; F, electric contact; G, steel container; H, stem heaters; K, asbestos insulation; L, top plate; M, nylon supporting lines; N, pumping line for cryostat; O, rubber gasket; R, electromagnetic agitator; S, brass sleeves; Th_1, Th_2, Th_3, copper-constantan thermocouples; V, 4 l. Dewar vessel.

- Data exists for LAr
- Not promising
  - 2e-5 mass fraction at 1 atm of partial pressure
- No published data in LXe

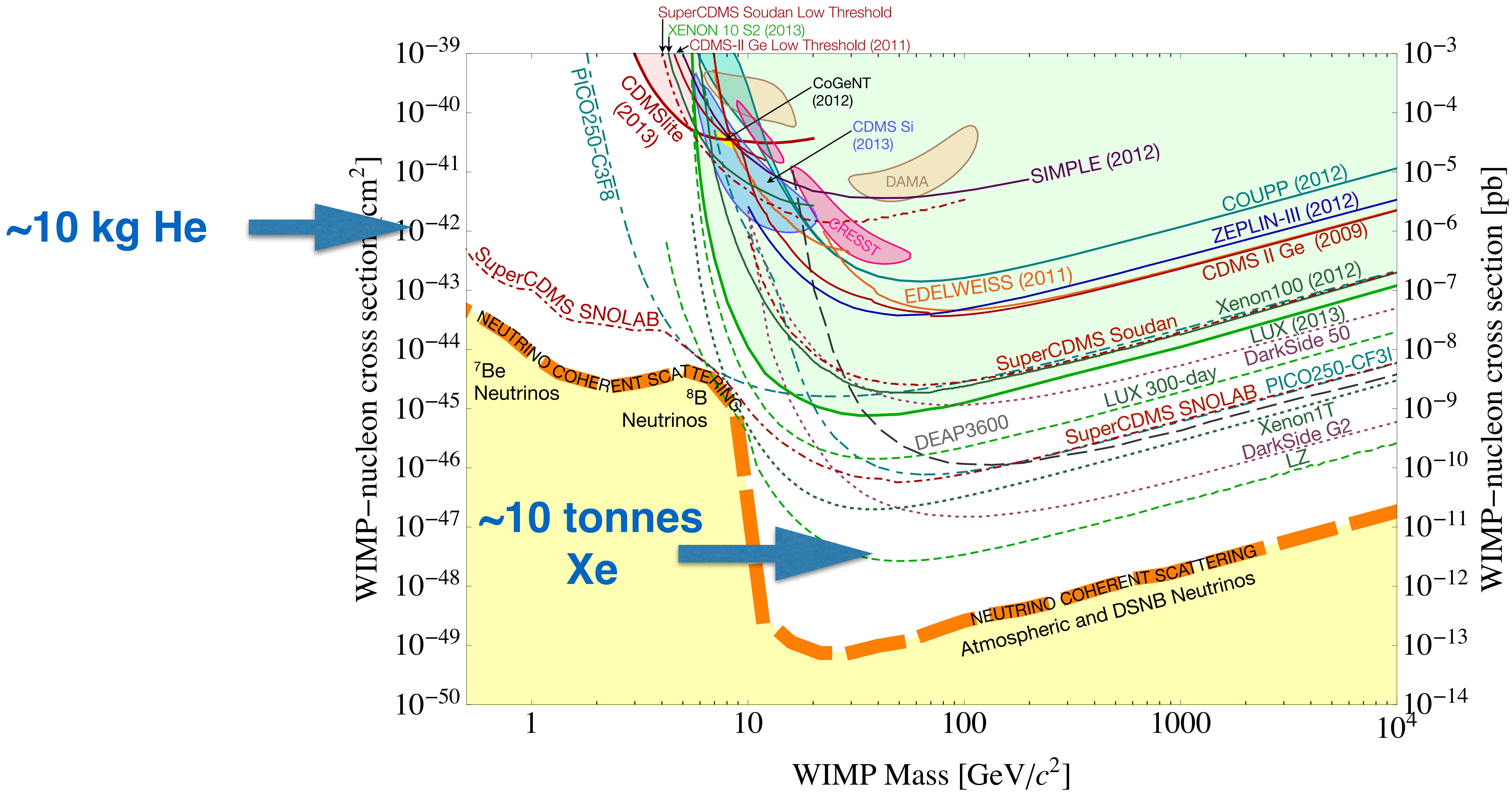
Dissolving He in LXe?



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

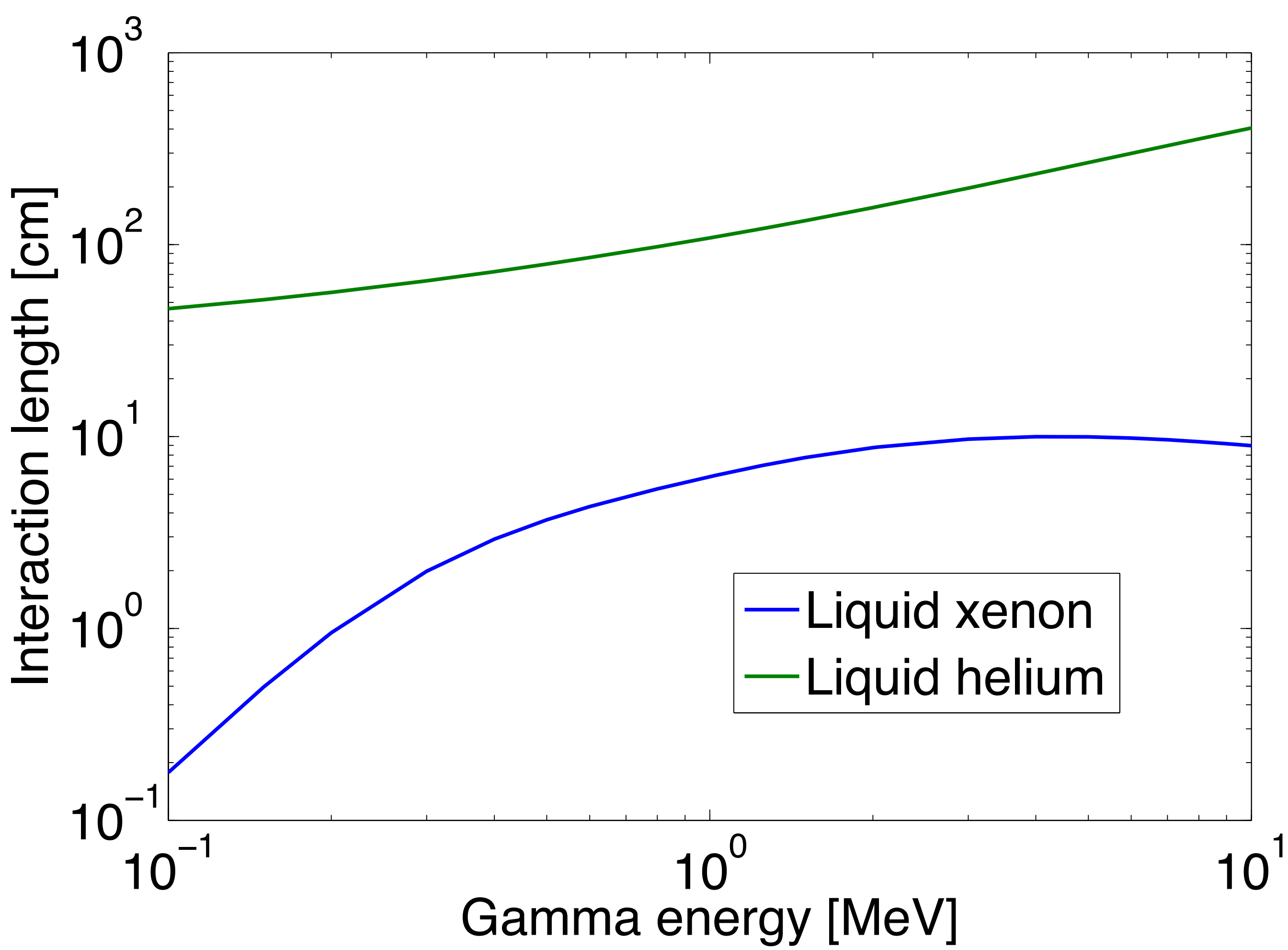
What don't you need for low mass?

- A lot of mass



Backgrounds

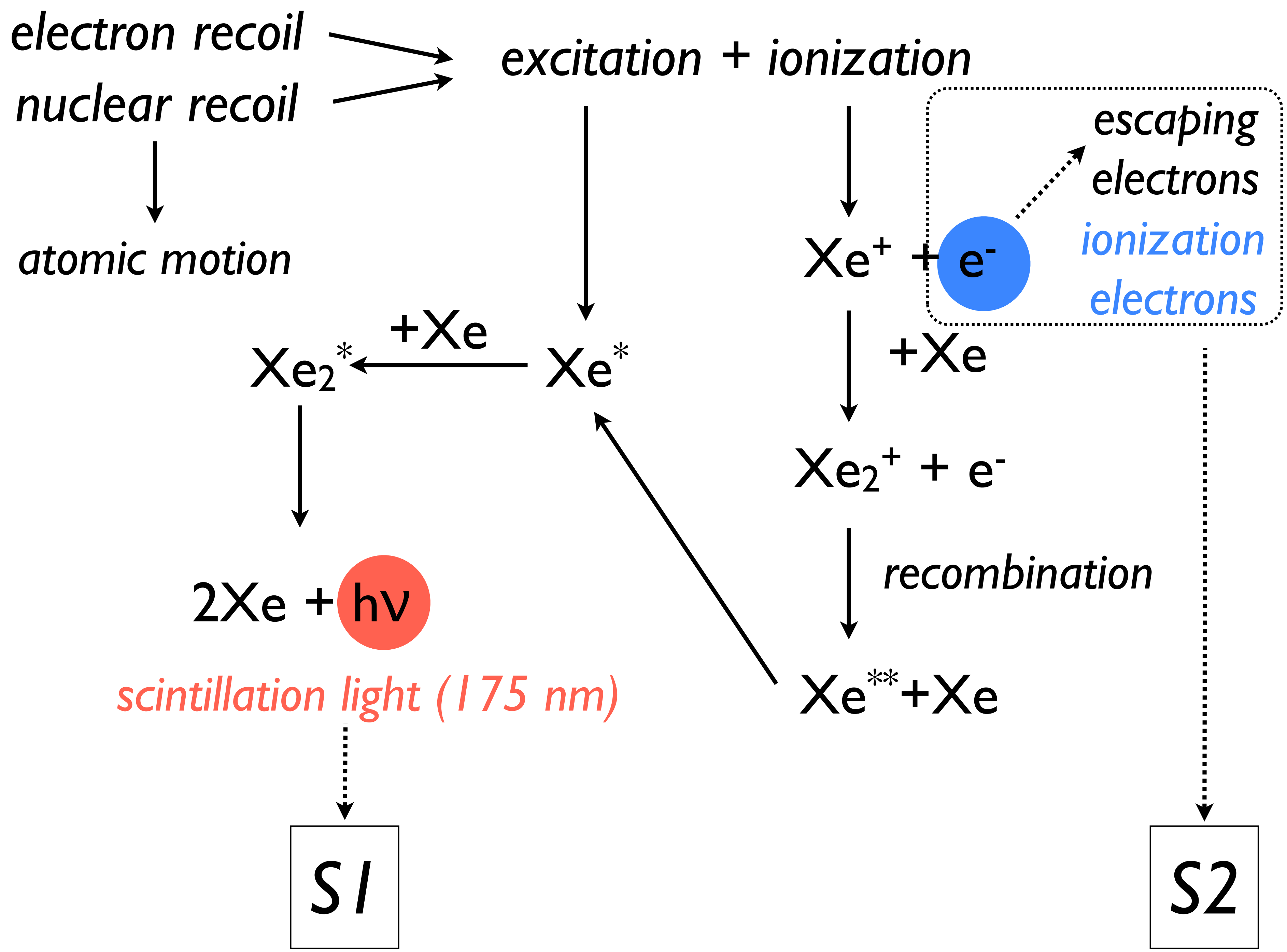
- The longest known radioisotope of He (^{6}He) decays in <1 s
    - No new backgrounds introduced



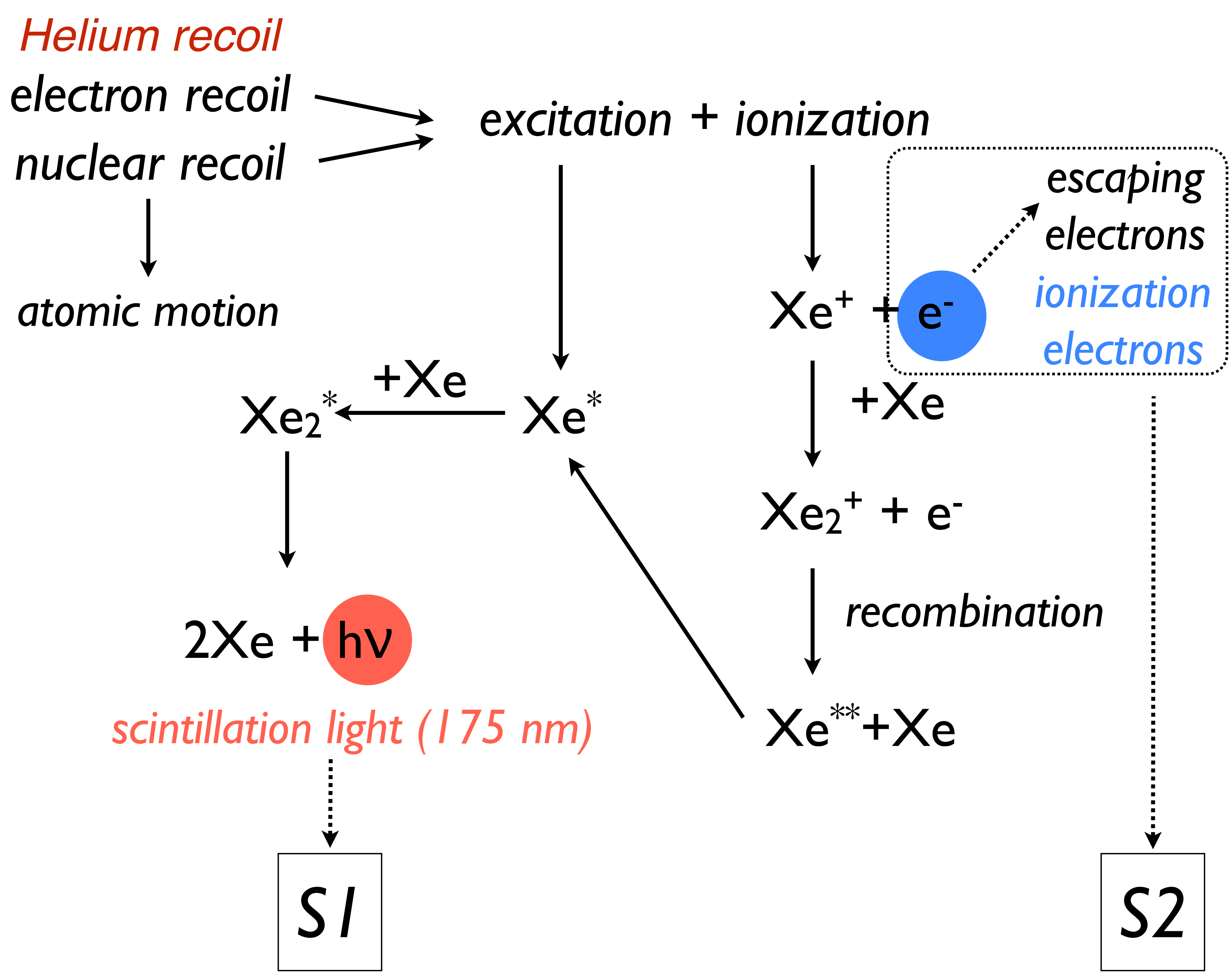
Size of LZ	Size of 10 kg LHe
150 x 150 cm	30 x 30 cm

- Self shielding is not effective in He-only detector

Signal detection



Signal detection



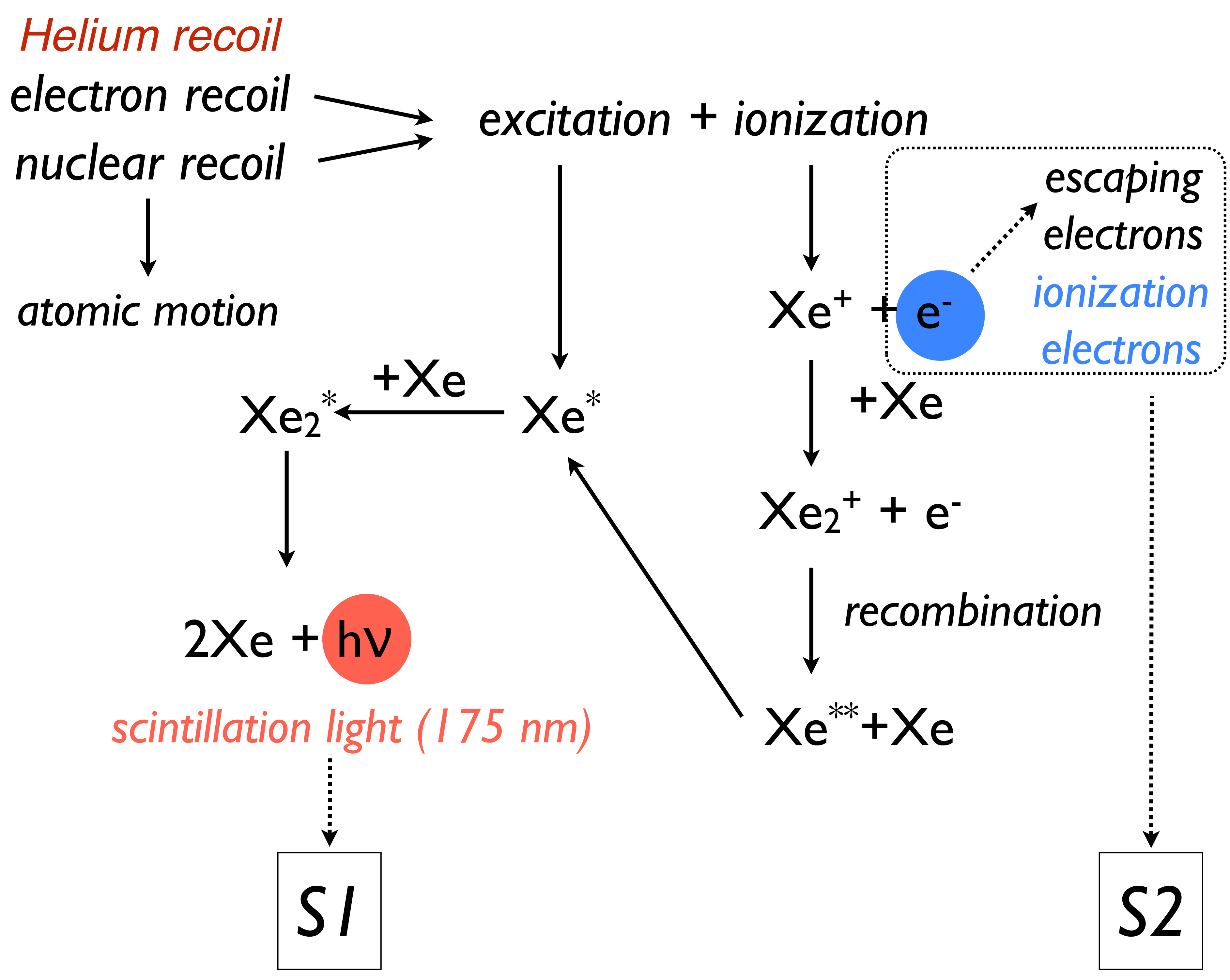
Signal detection

- Even if we get direct excitation of helium:
  - Helium scintillate in harder UV
  - 80 nm vs 175 nm in LXe
  - Those photons will wavelength shift in the xenon to 175 nm
    - ppm levels of Xe in LAr lead to near complete shift to Xe wavelength
- Keep same photon detection scheme!

R11410

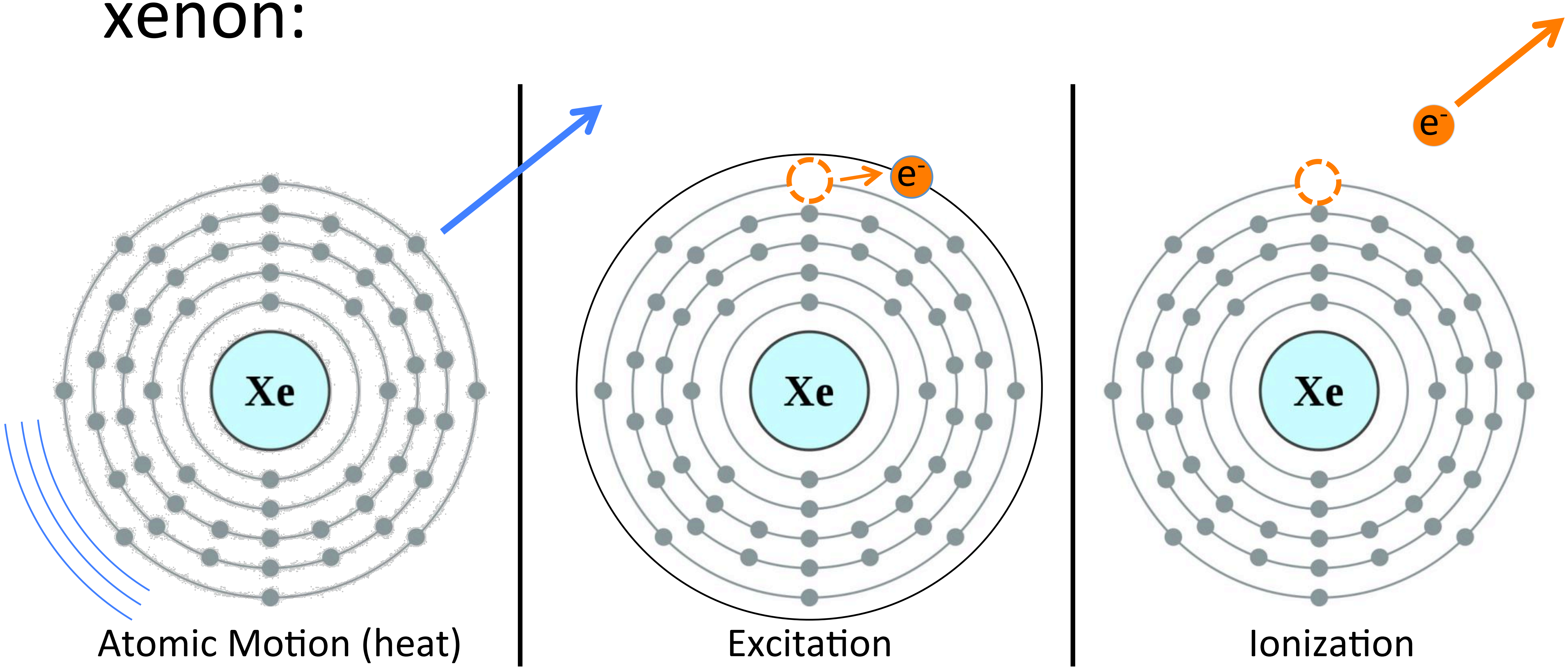
R8520

Signal generation



Signal generation

- There are three ways for recoiling particles in our energy range to lose energy in liquid xenon:

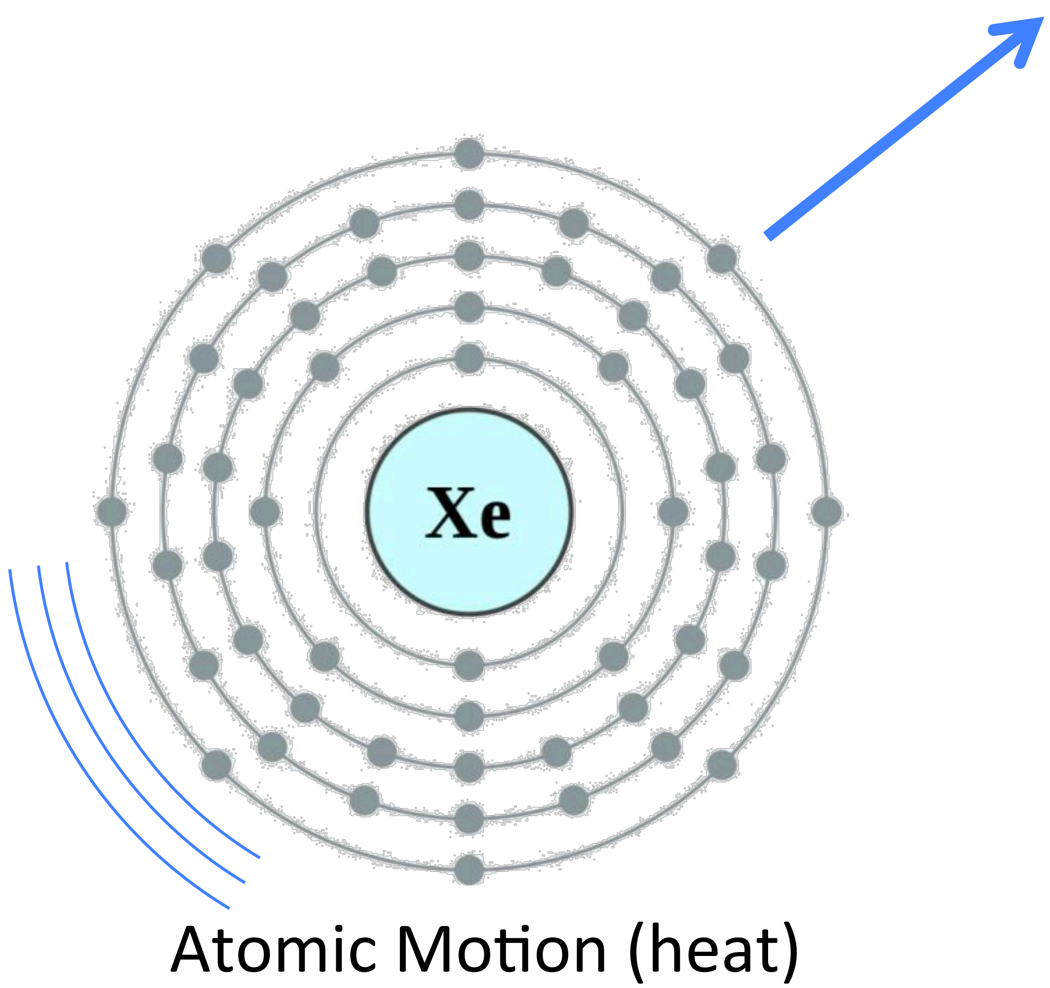


Atomic Motion (heat) | Excitation | Ionization

Courtesy C.E. Dahl

Signal generation

- Heat: This energy is undetectable for LZ

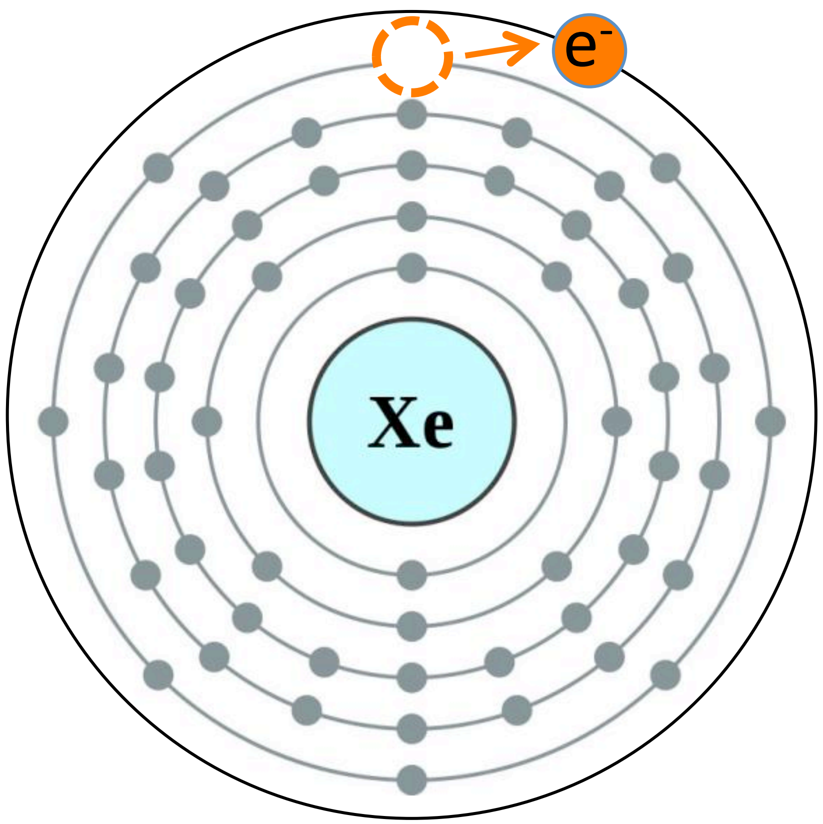


Courtesy C.E. Dahl

Signal generation

- Excitation: Produces scintillation light as it de-excites, measured as S1

$$Xe^* + Xe \longrightarrow Xe_2^* \longrightarrow 2Xe + \gamma \quad \text{(simplified)}$$



Excitation

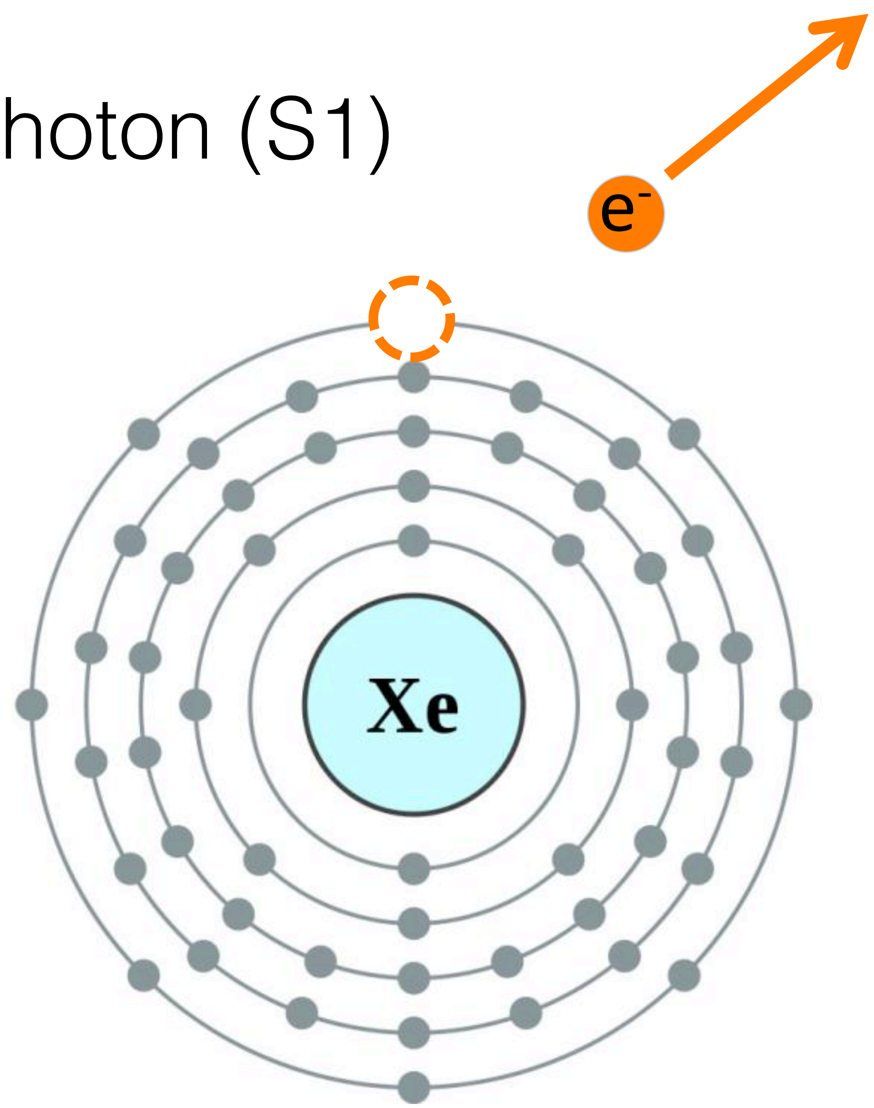
Courtesy C.E. Dahl

Signal generation

- Ionization: Can be extracted by an external electric field, measured as S2
- Or can recombine and give scintillation photon (S1)

$$Xe + Xe^{+} + e^{-} \longrightarrow Xe_2^{*} \longrightarrow 2Xe + \gamma$$

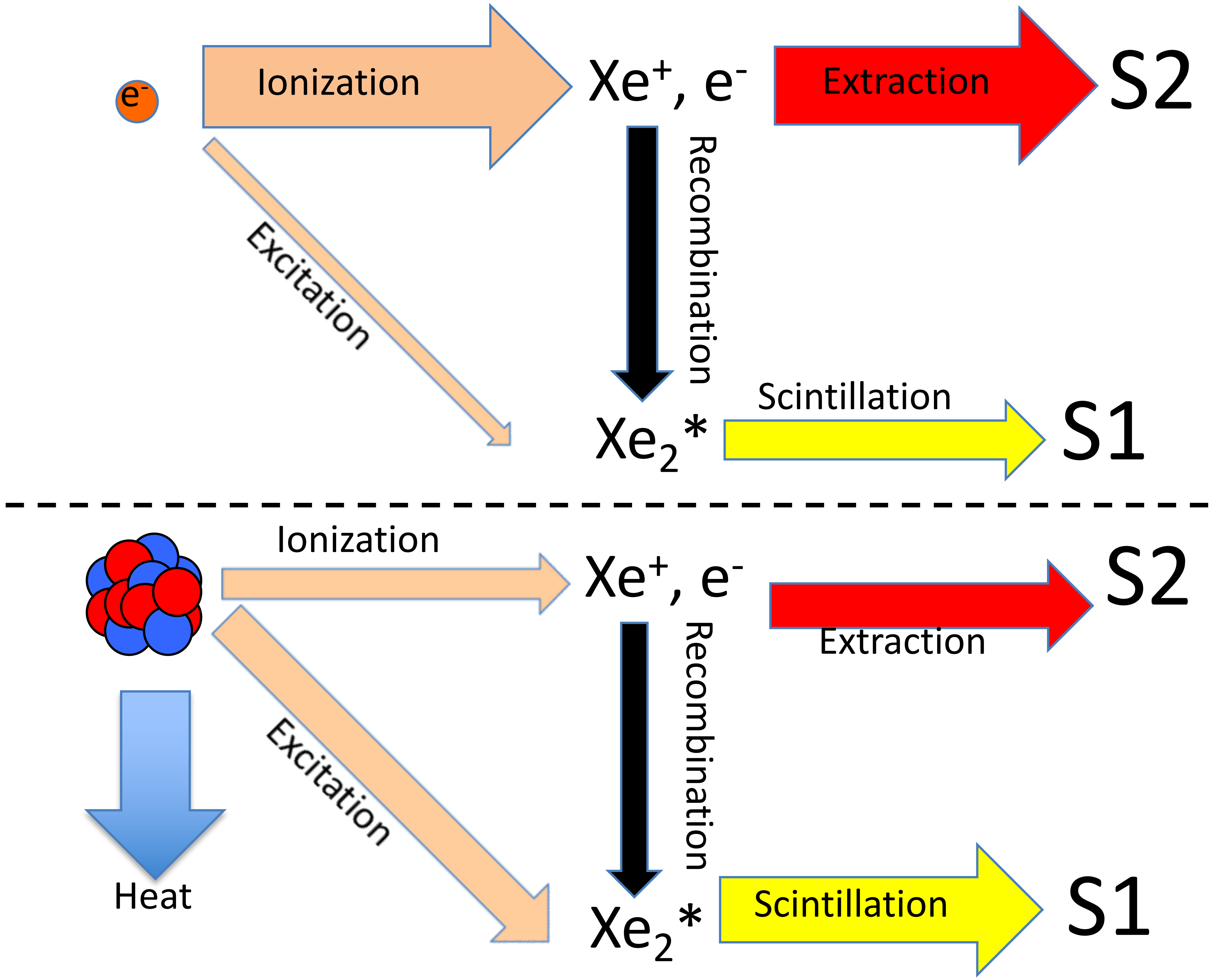
(simplified)



Ionization

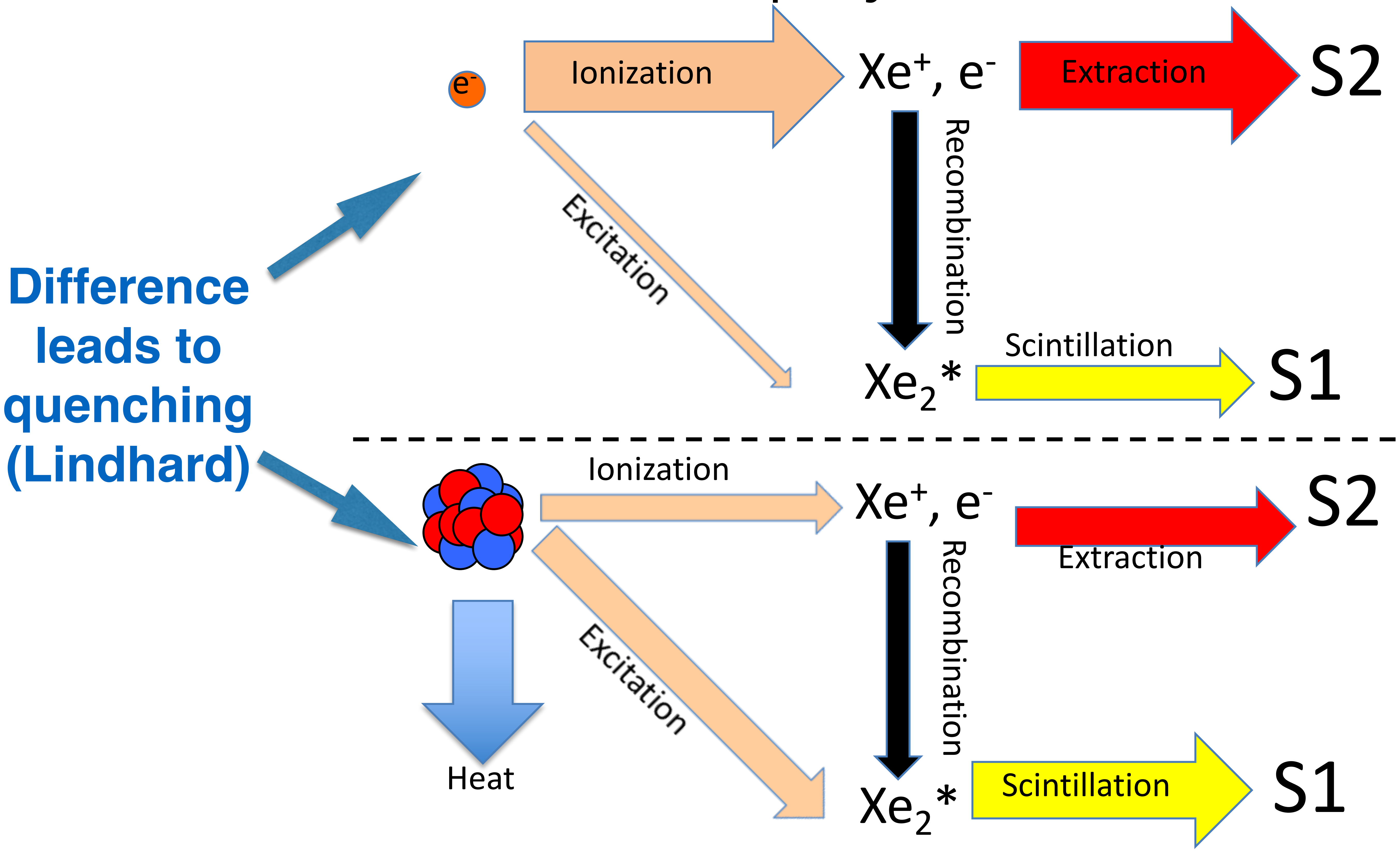
Courtesy C.E. Dahl

Xenon microphysics



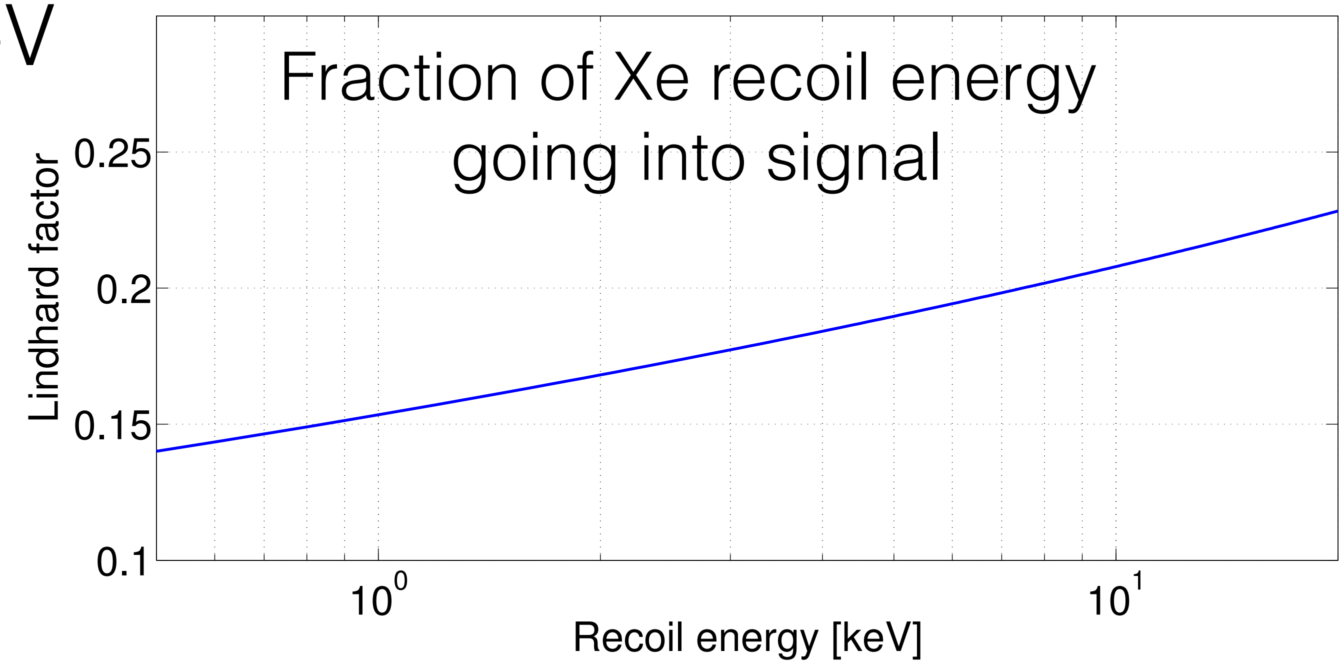
Courtesy C.E. Dahl

Xenon microphysics

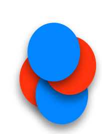


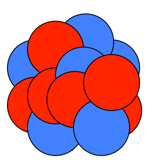
Xenon microphysics

- 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

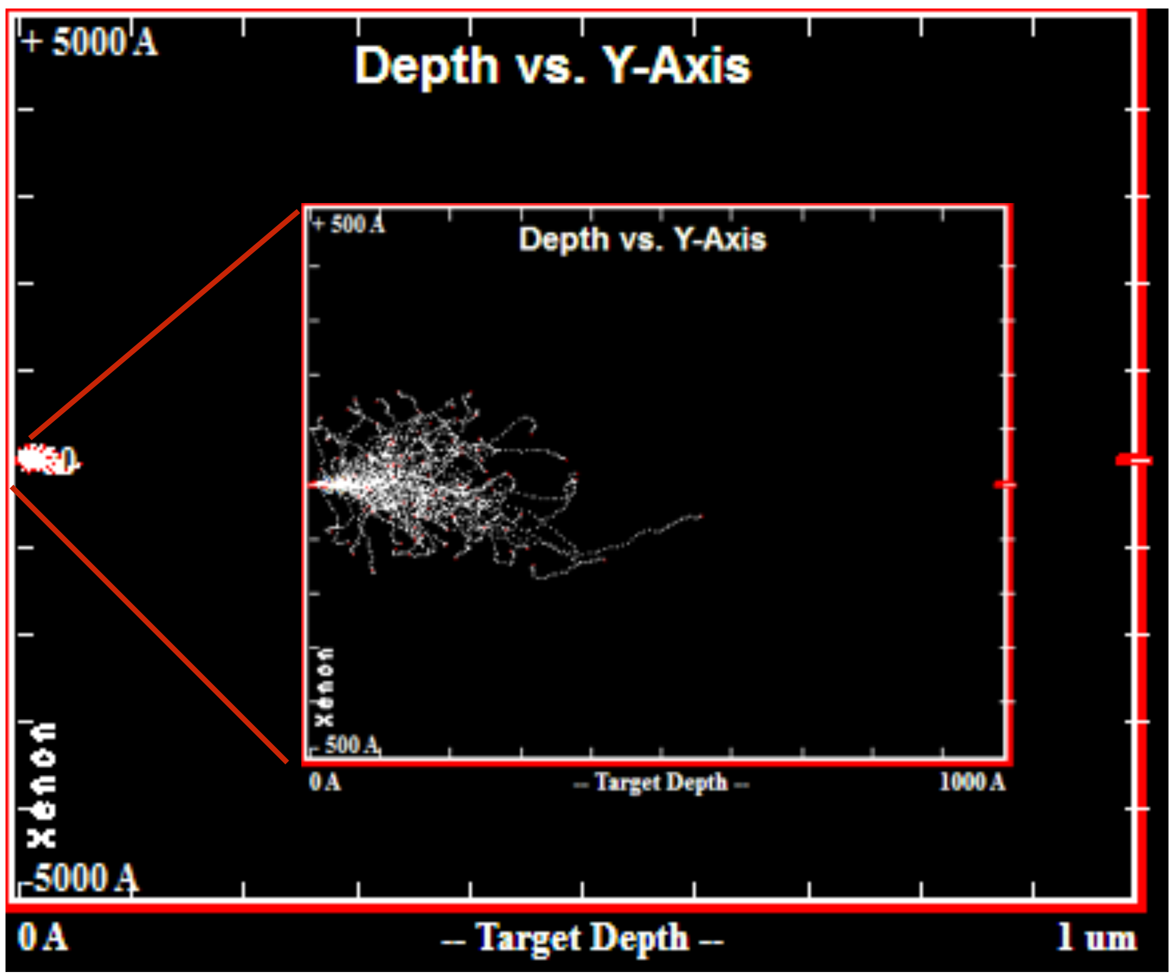




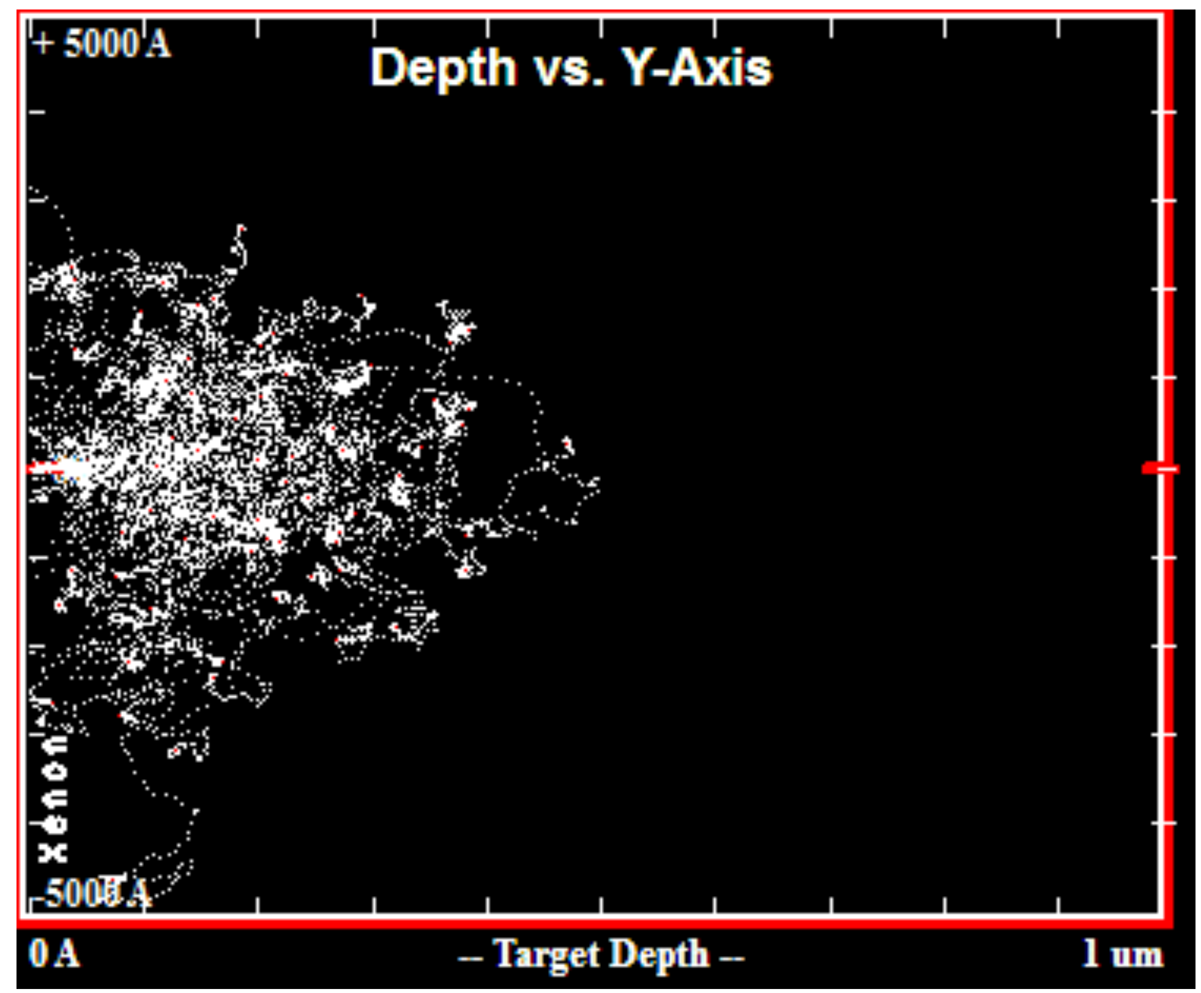
Not to scale

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



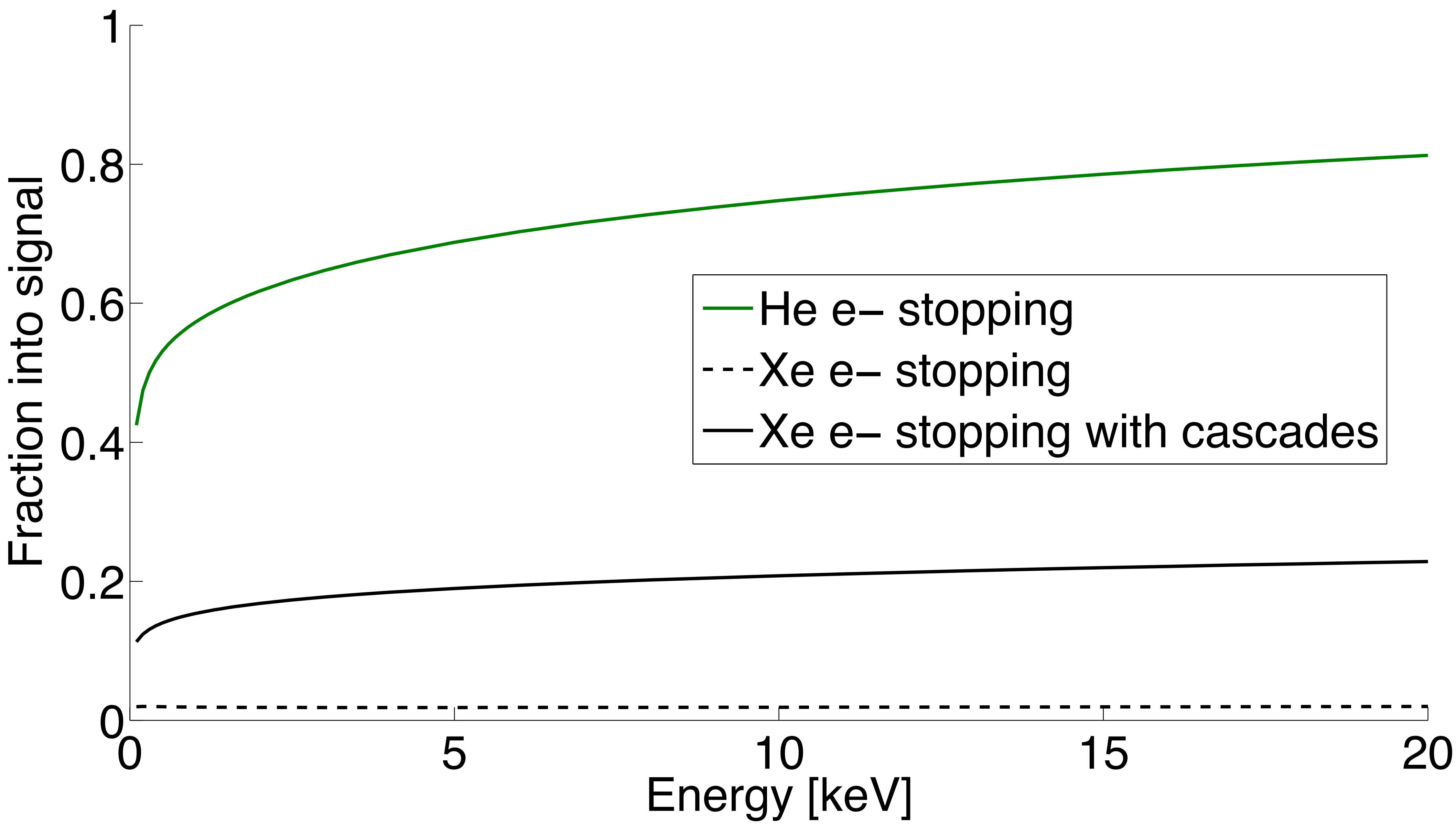
10 keV Xe in LXe
~100 A ranges



10 keV He in LXe
~1000 A ranges

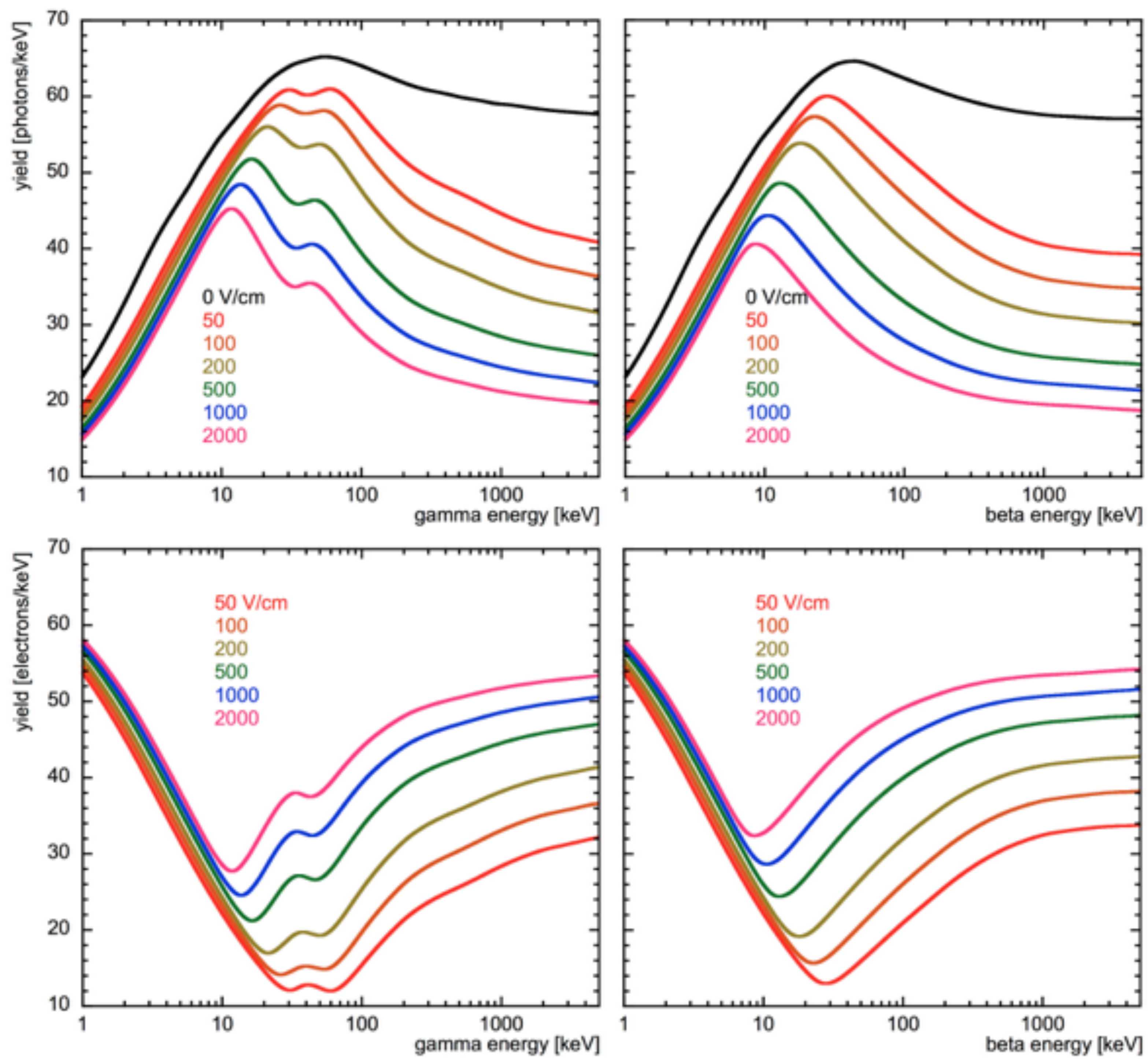
Modeling He recoils in LXe (v1)

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



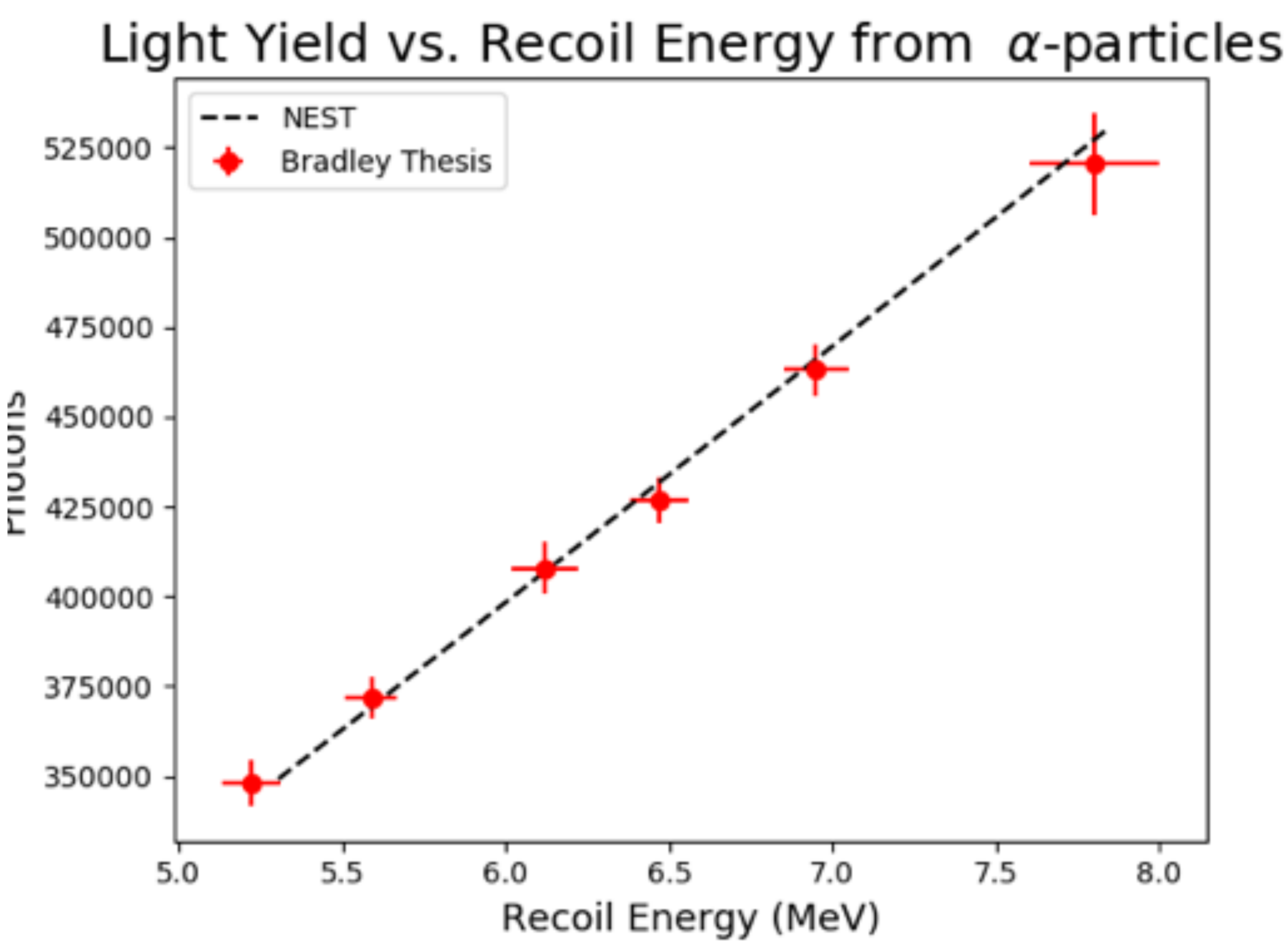
Modeling He recoils in LXe (v2)

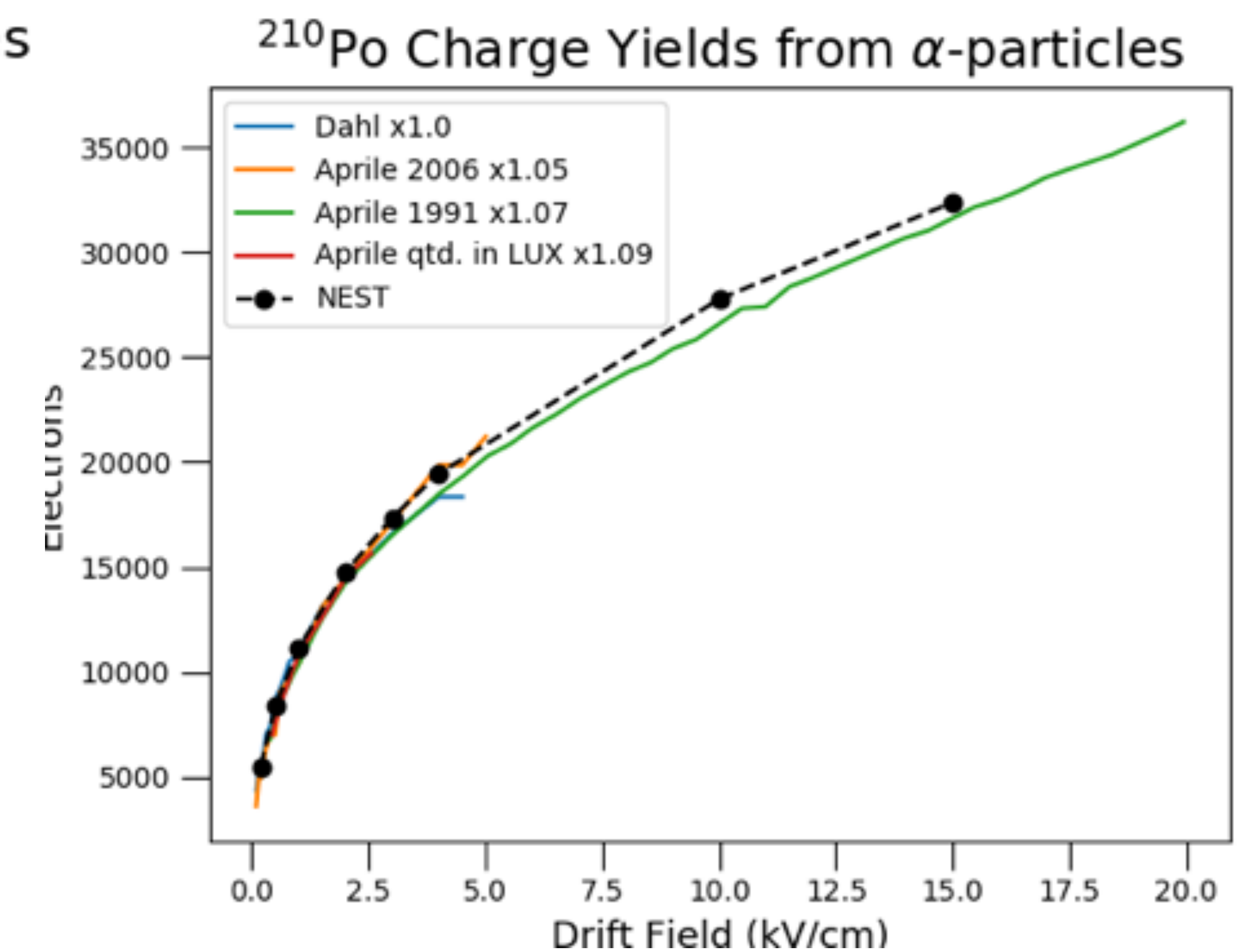
- Noble Element Simulation Technique (NEST)
    - Szydagis et al, and others: http://nest.physics.ucdavis.edu/site/
- Data driven model for signal processes in LXe
- NEST v2.0 about to come out



Modeling He recoils in LXe (v2)

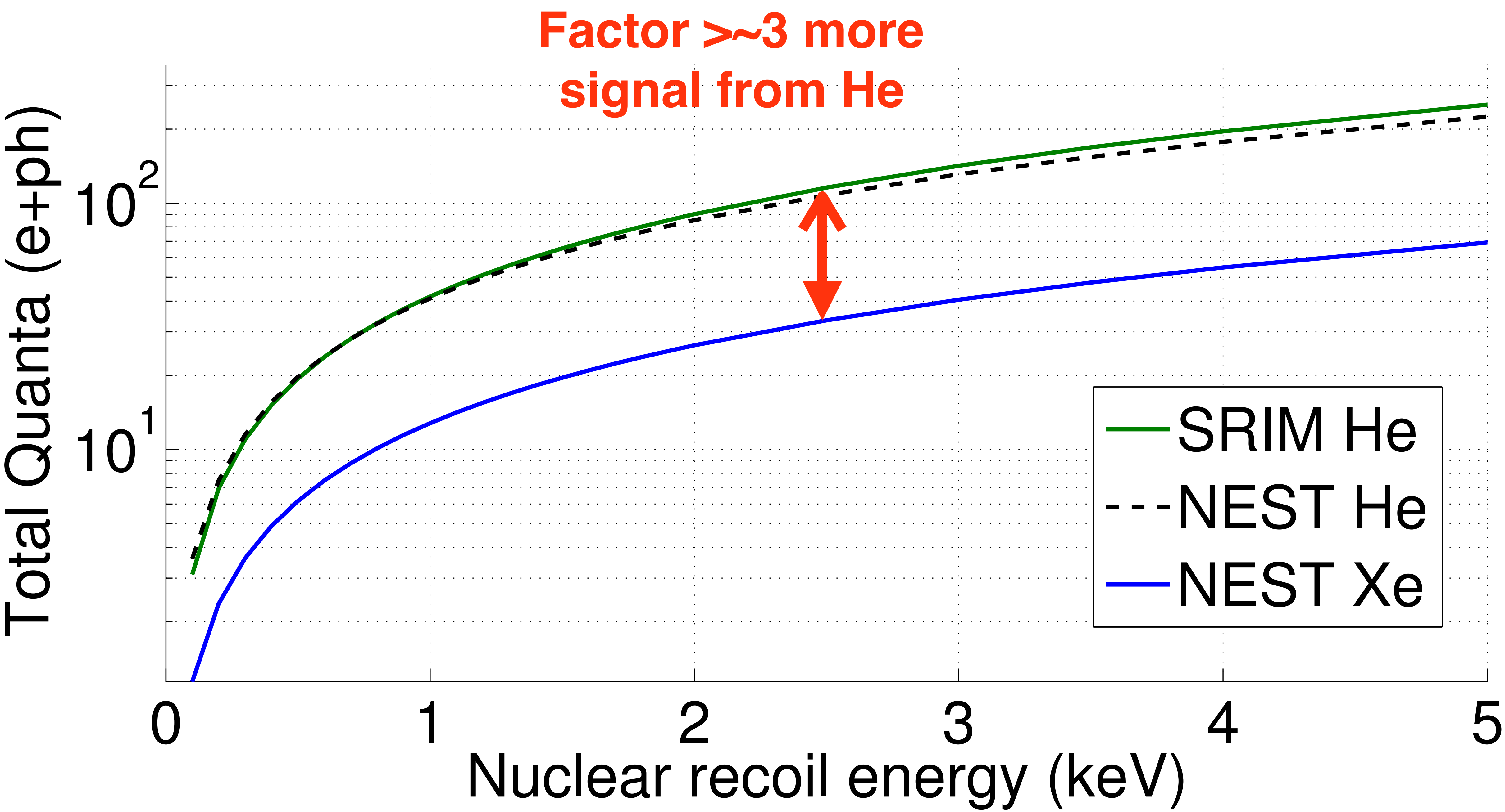
- Alpha data from LUX and test chambers incorporated into NEST2.0
- High energies, but at least it's real He nuclei in LXe



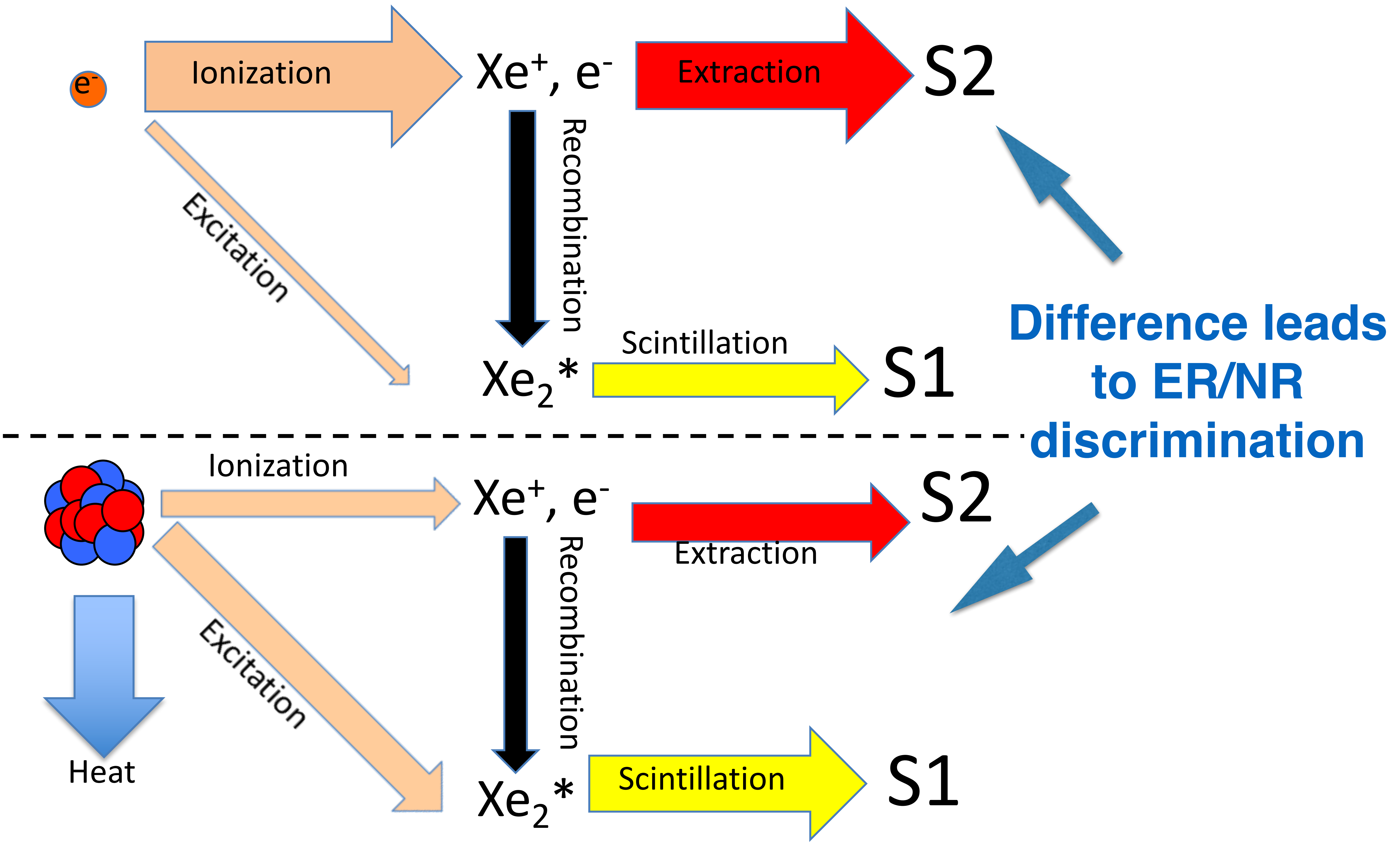


Modeling He recoils in LXe (v1+2)

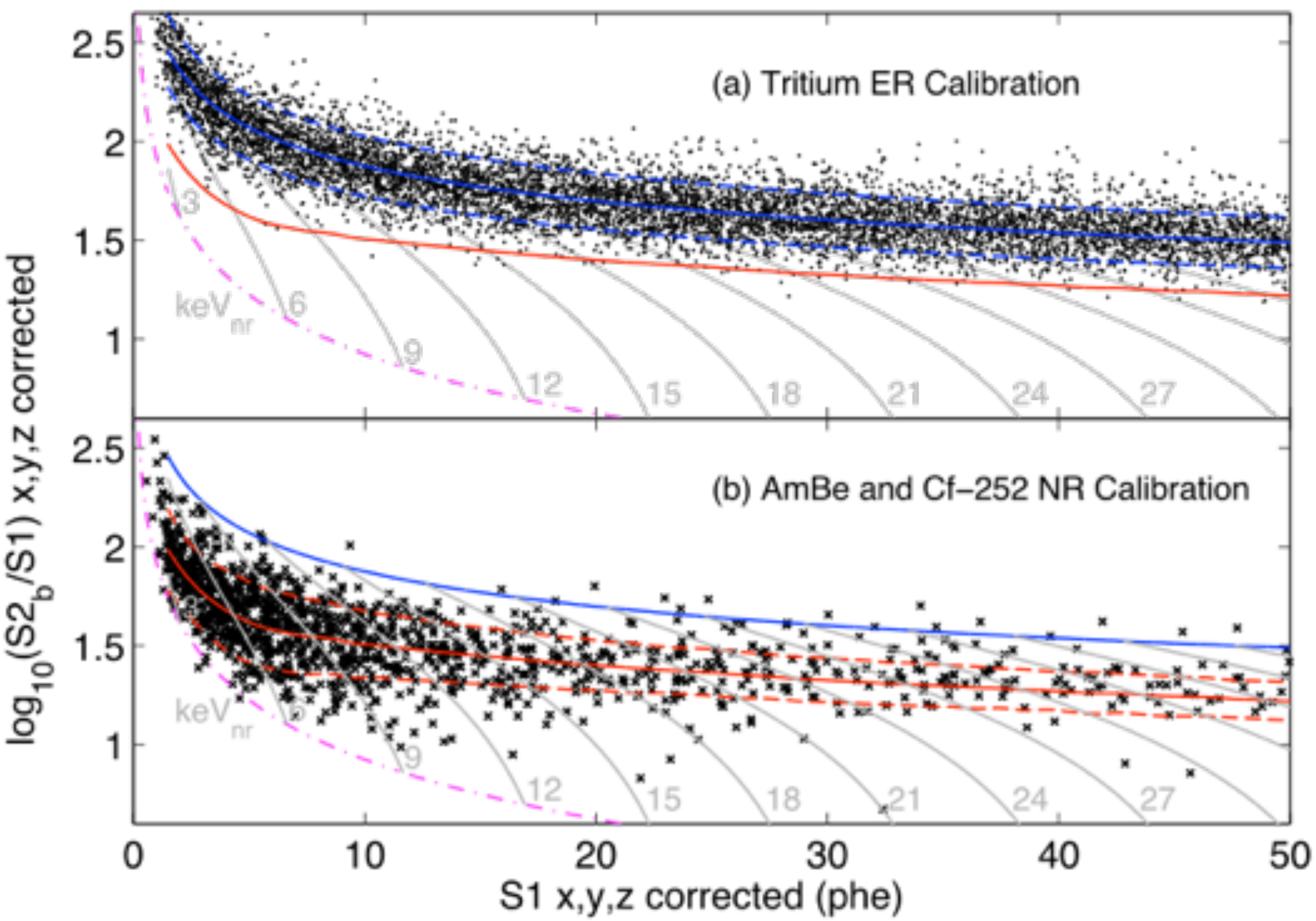
Total quanta = hν + e⁻



Xenon microphysics



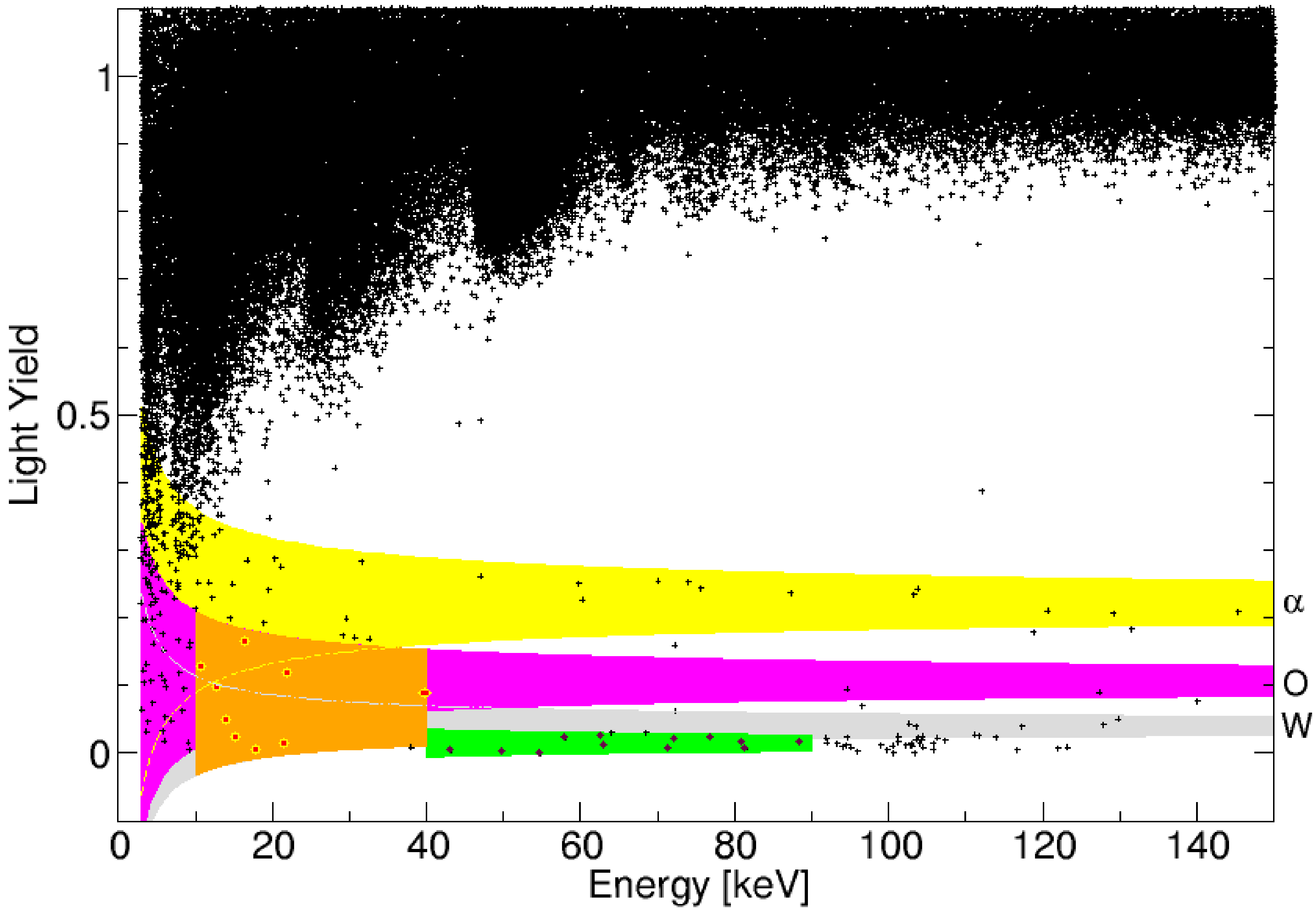
Xenon microphysics



Difference leads to ER/NR discrimination

Xenon microphysics

- What happens to S2/S1 partitioning?



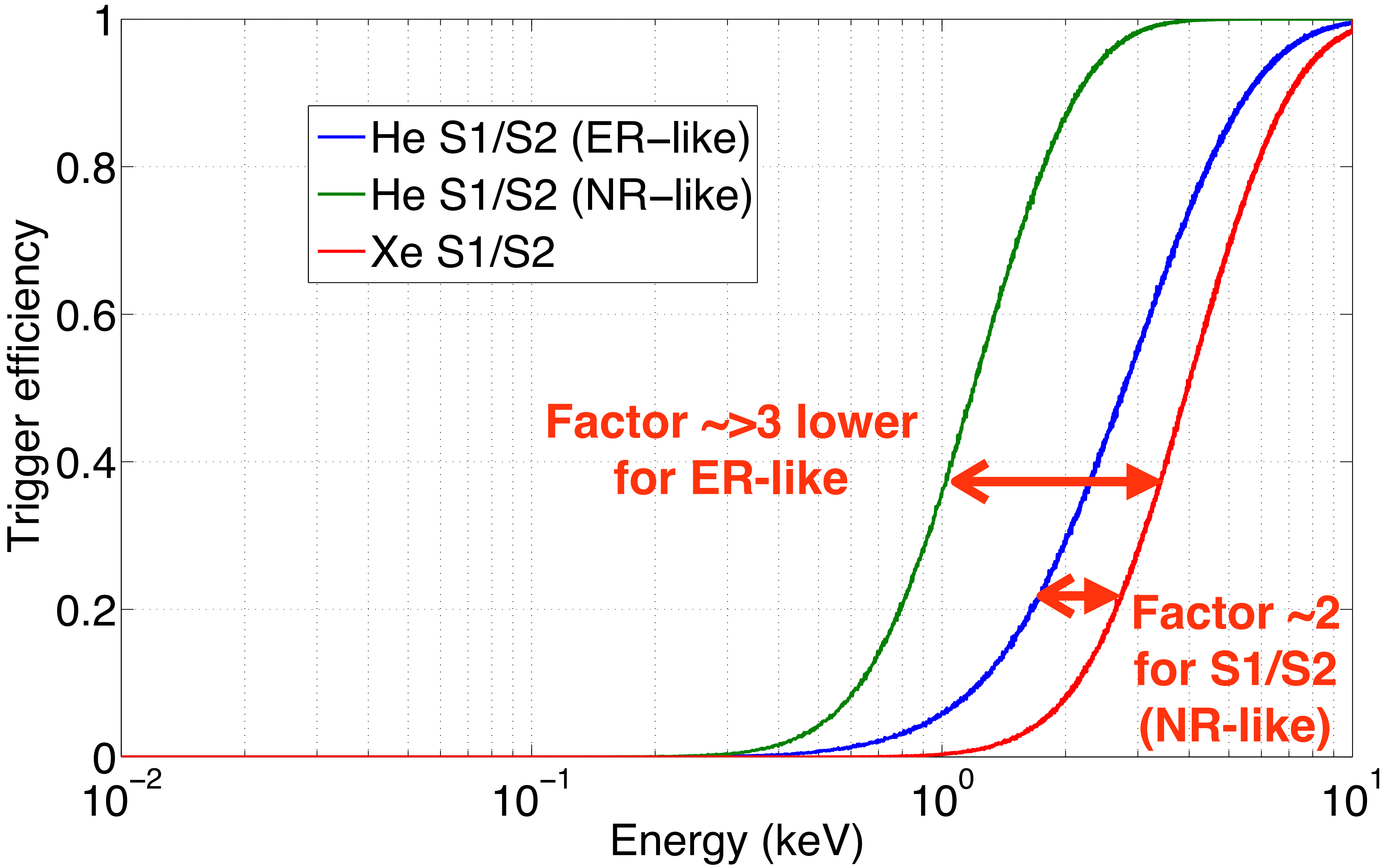
CRESST data in scintillating bolometers

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

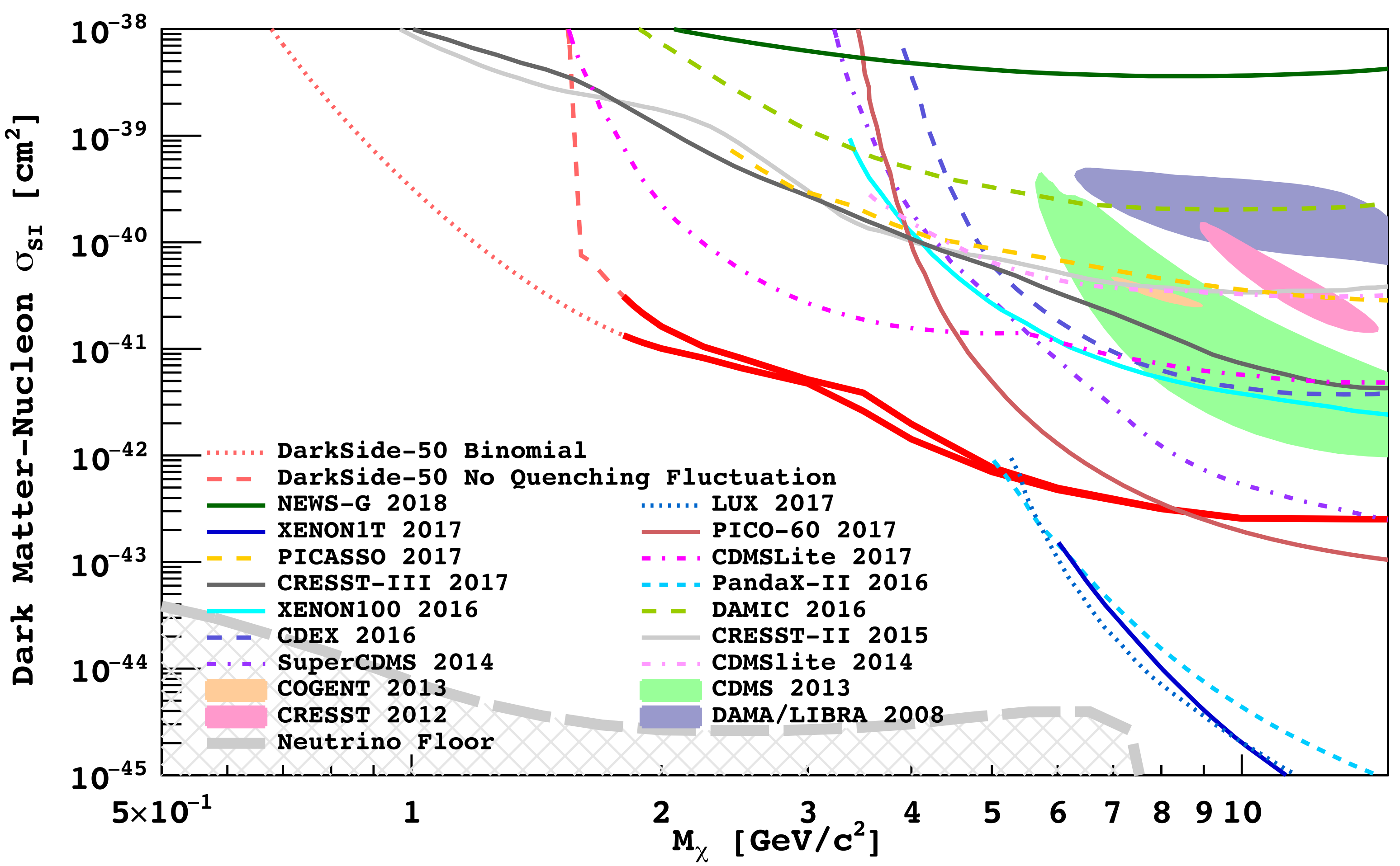
Energy threshold



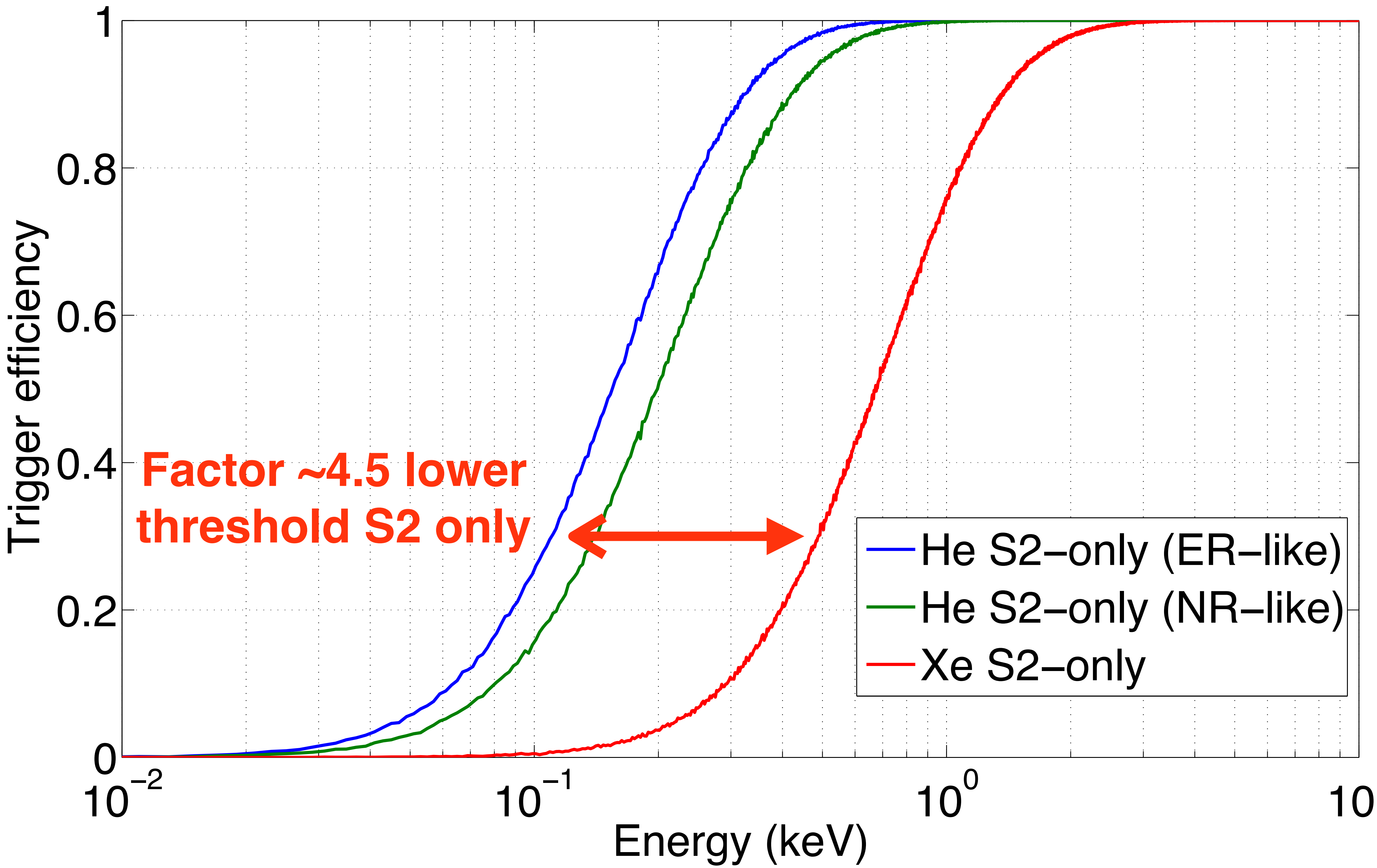
S2-only analysis

- 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)

What’s next

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

What's next

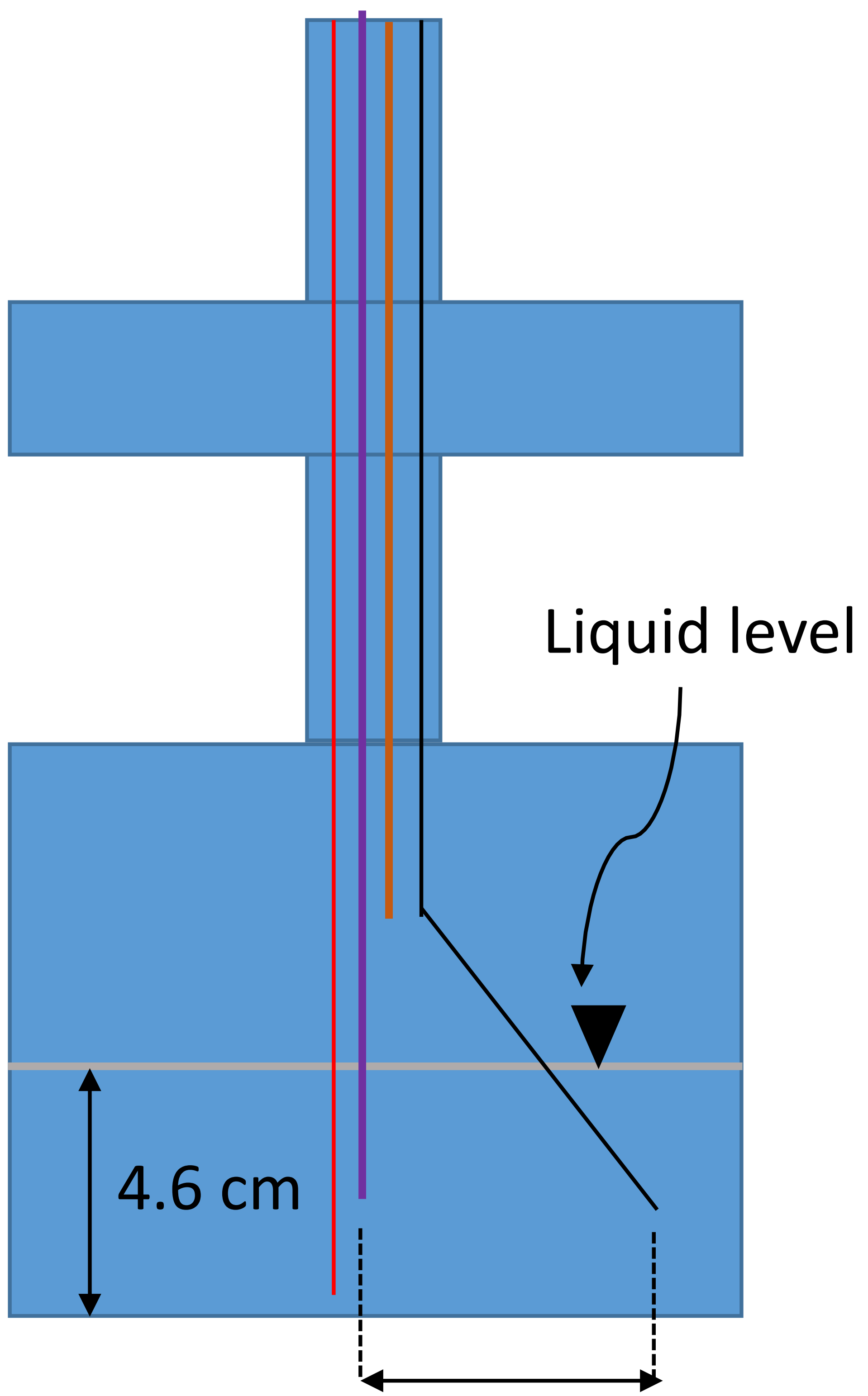
- This is still fairly speculative
  - Henry's coefficients not comprehensively measured
    - Temperature dependence, diffusion, etc?
  - Signal yields depend on modeling and MeV scale data

CALIBRATION!

Henry's coefficient

- How much helium can we get in
- Test stand at Fermilab - "Henry"
  - State of the art RGA system reading gas admixture via capillaries

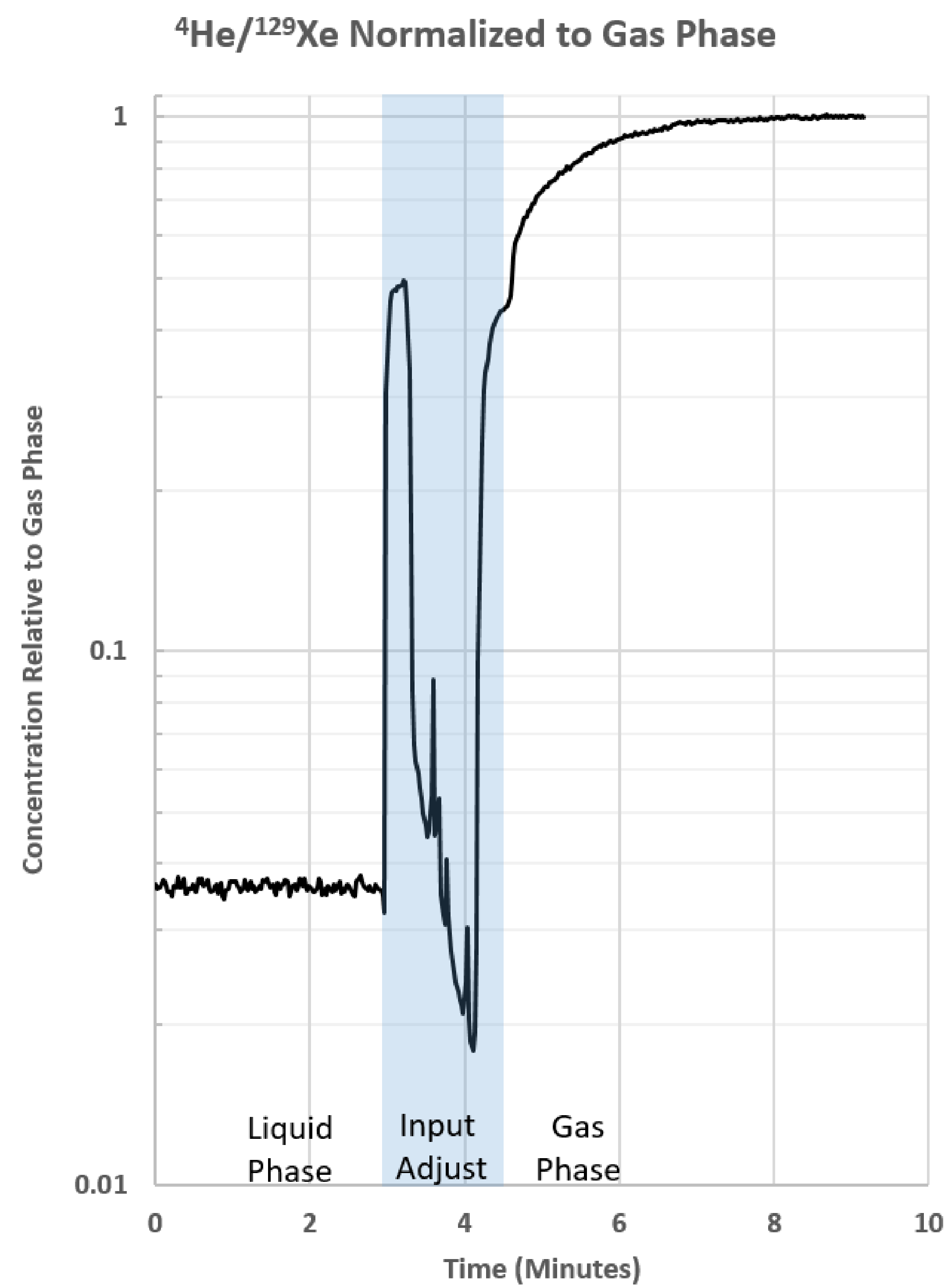
Capillaries:
-Bubbling tube 221mm
-Liq. center cap. 204 mm
-Liq. Side cap. 204 mm
-Gas cap. 151 mm



Henry's coefficient

How much could we get in?

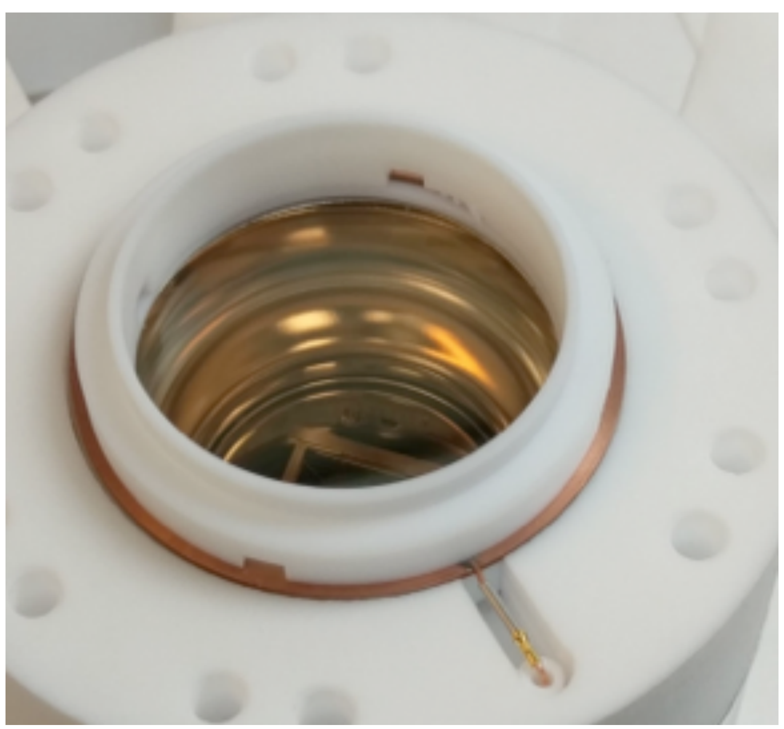
- Preliminary test on Henry got 0.1% He in LXe by mass in first pass
- Can we get more in?
  - Temperature dependence?
- Basically inactive since student left two years ago

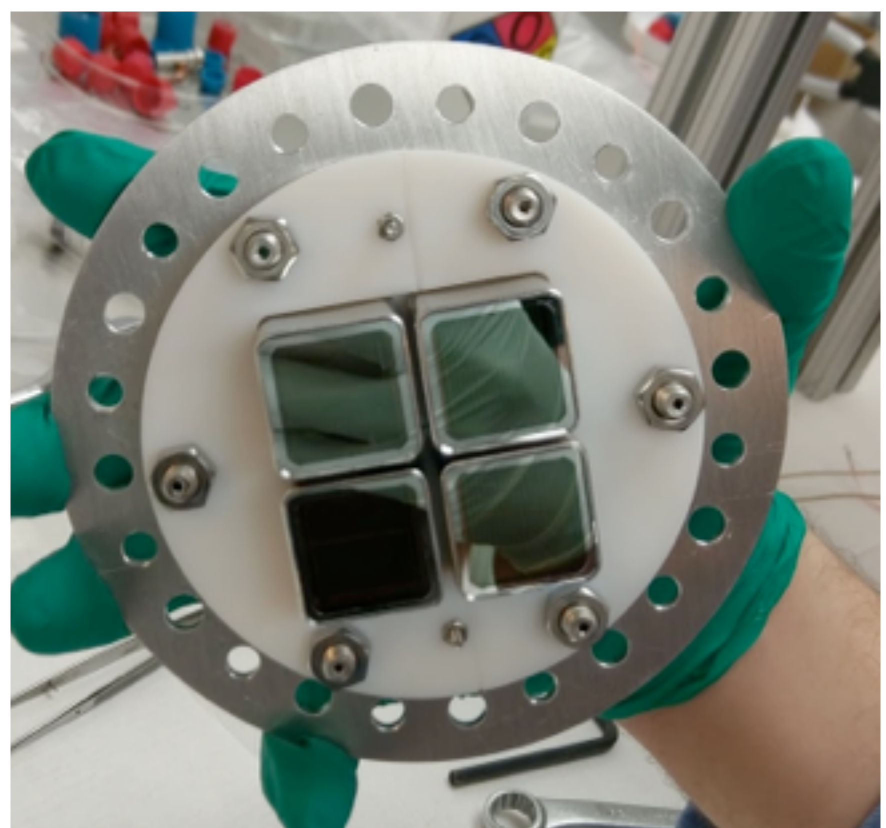


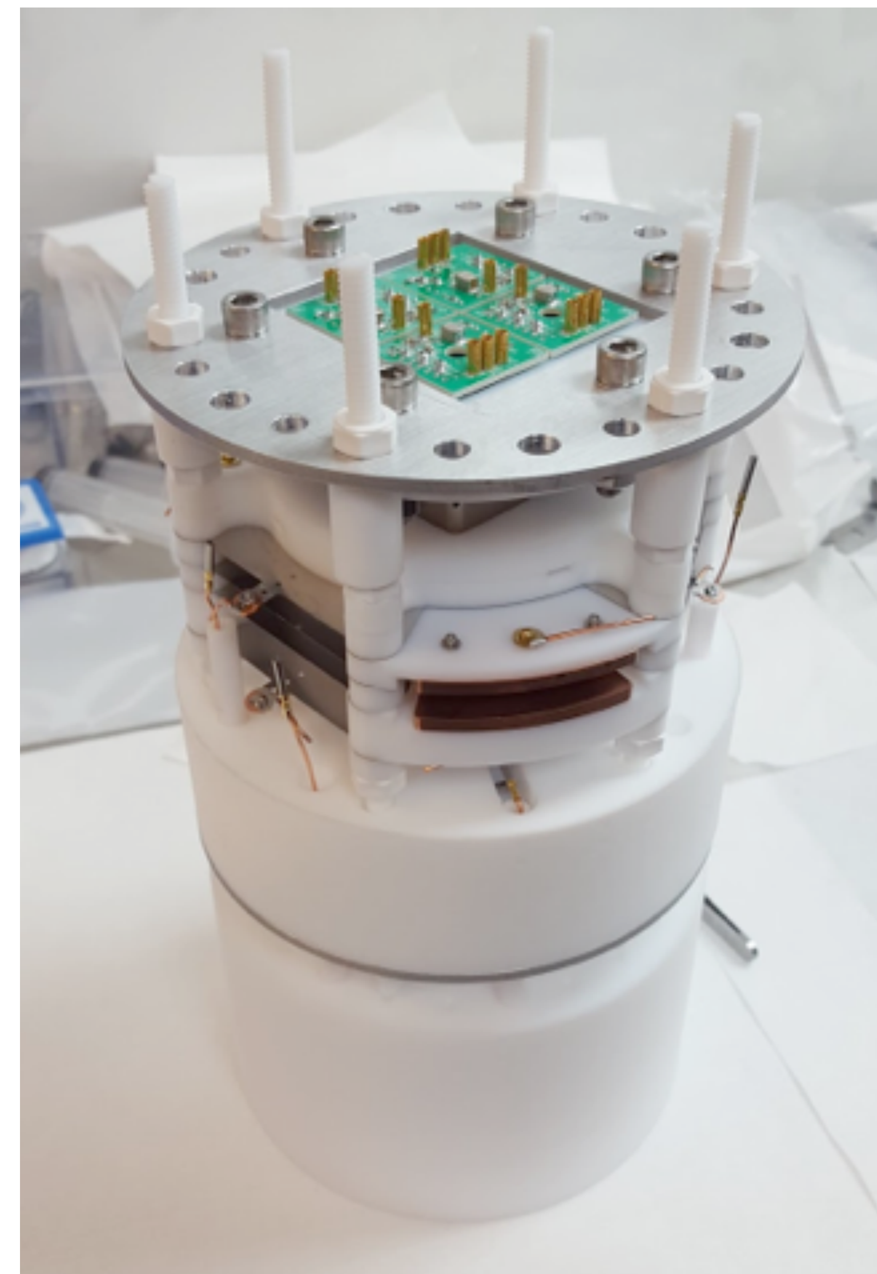
0.037 mol He/mol Xe x M_{He}/M_{Xe} ~ 0.1%

Measuring He-doped LXe

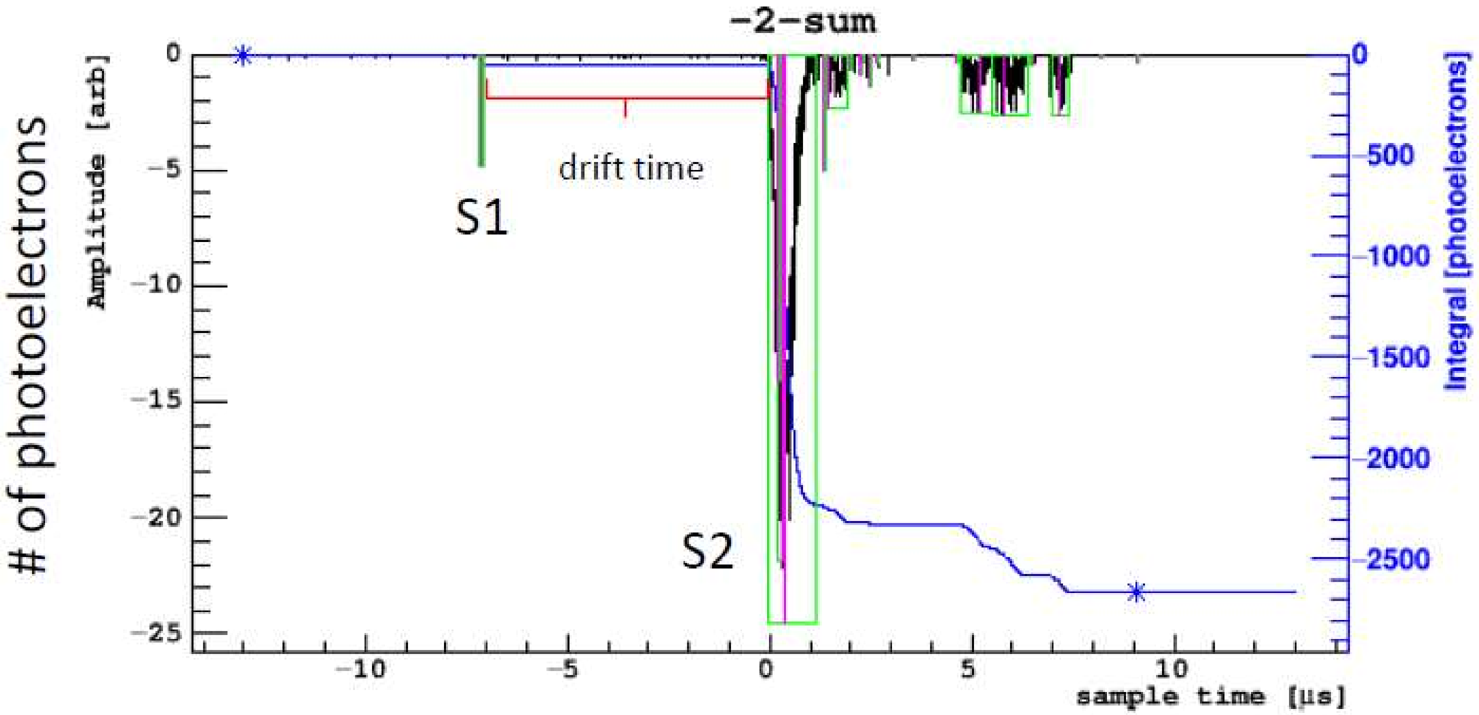
- Small TPC constructed at Fermilab (XELDA) for a different purpose
  - Testing limits of ER discrimination for inner shell vacancies
- One 3” PMT facing four 1” PMT
- Now available for doping measurements







XELDA waveforms and data analysis



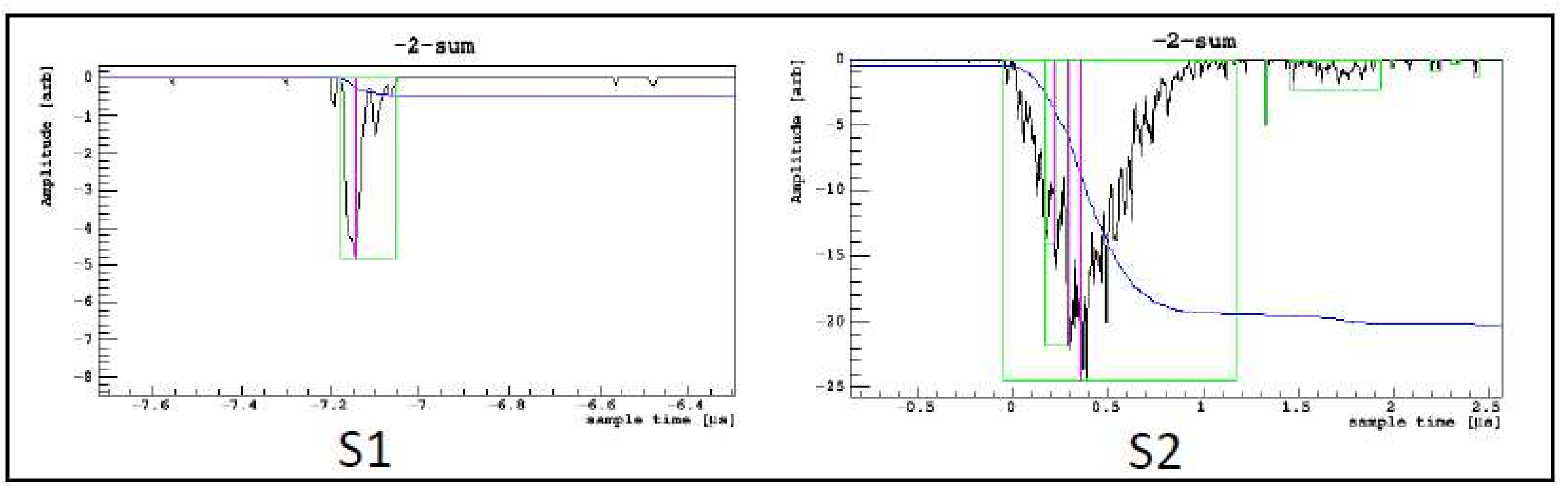
$$E = W(n_\gamma + n_e)$$

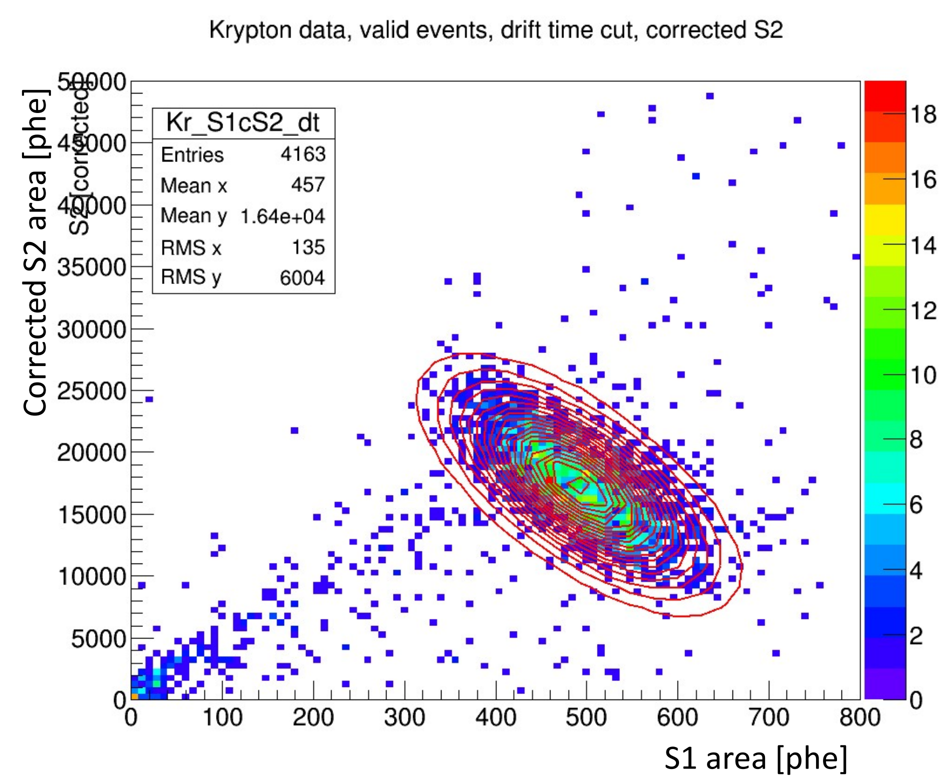
$$n_e = S2/g_2$$
$$n_\gamma = S1/g_1$$

Determined by field strength and energy of calibration source

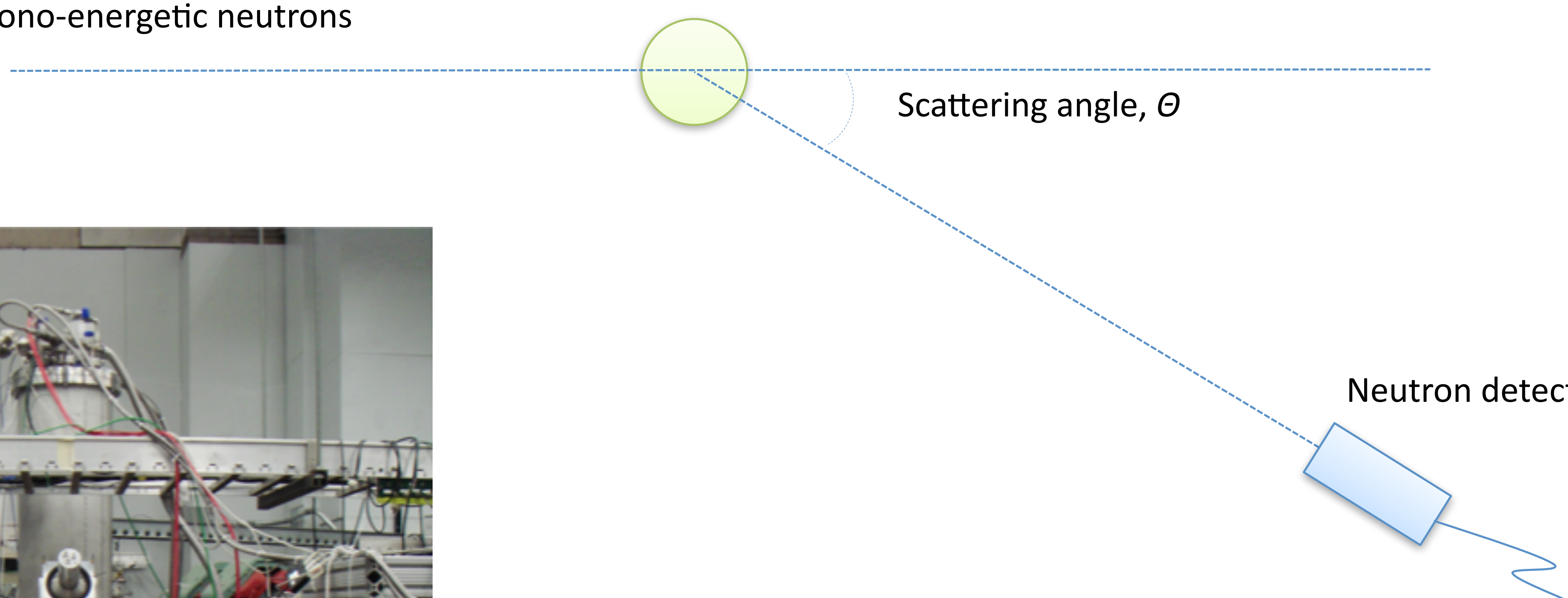
g1 = 0.226 +/- 0.0009
g2 = 20.25 +/- 0.141

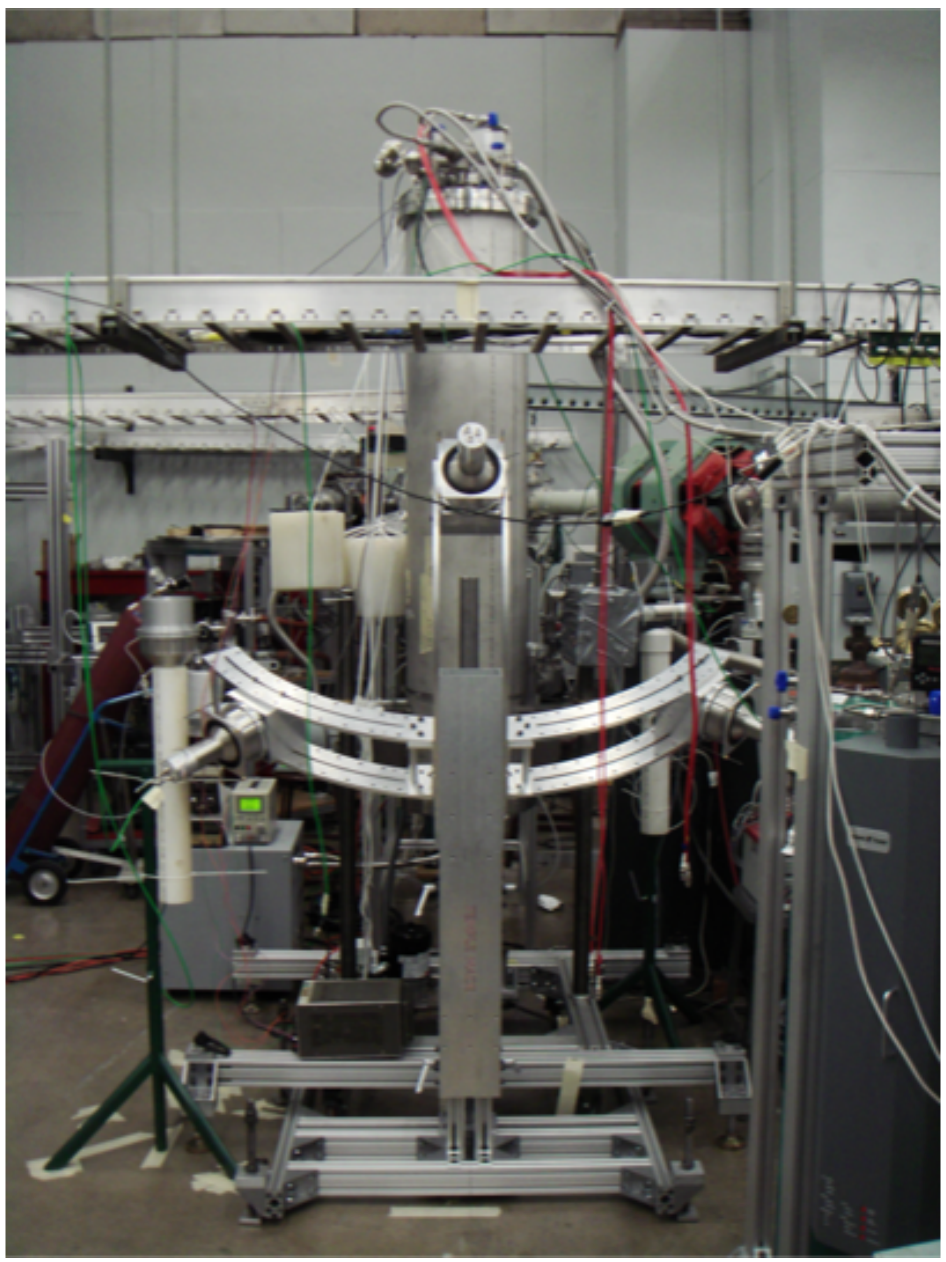
g1: photons detected per photon emitted
g2: photons detected per electron emitted





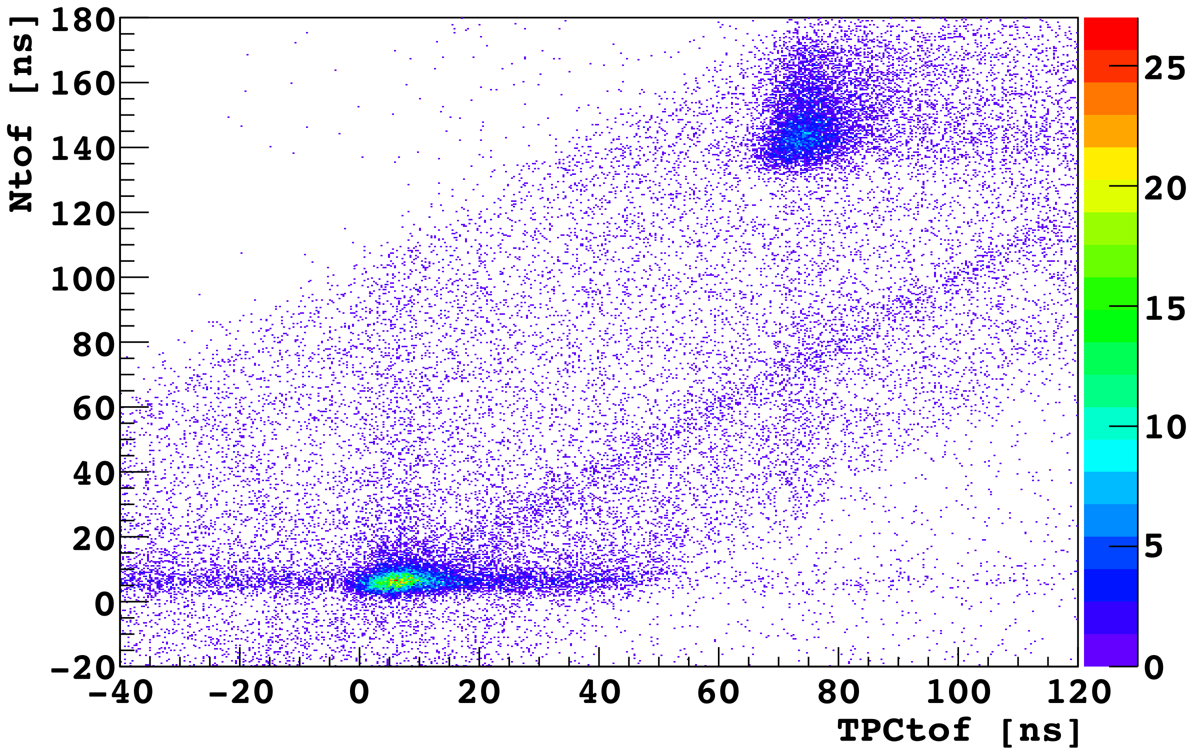
Neutron scattering measurement



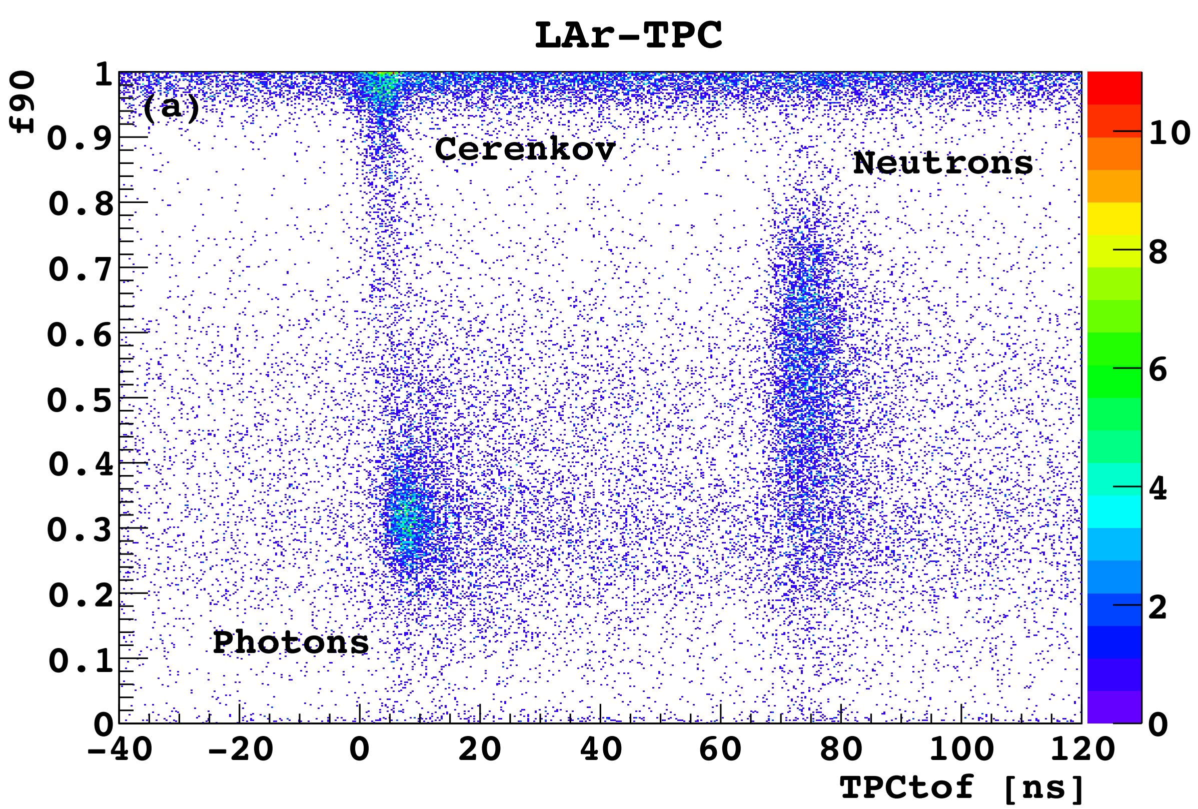


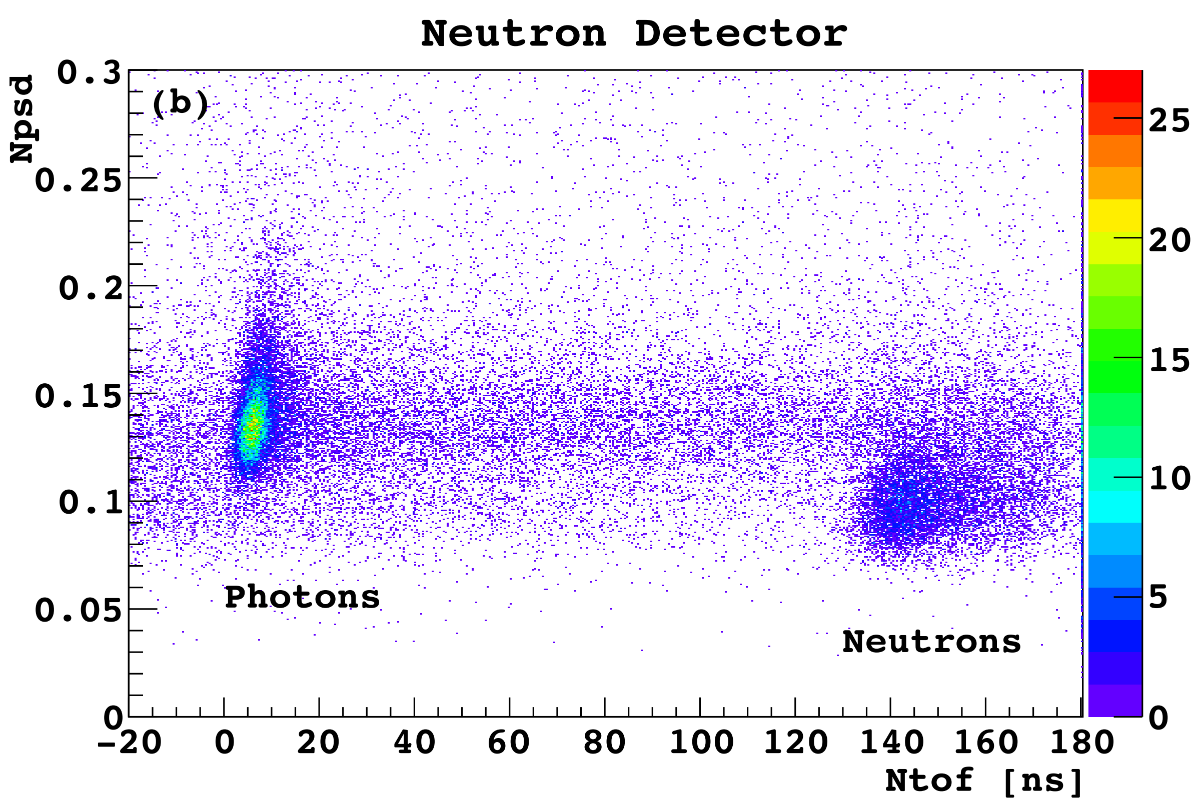
- Pulsed, monoenergetic beam (at Notre Dame or elsewhere) to measure response of to nuclear recoils of known energy
- Tunable nuclear recoil energy by changing the neutron energy and the scattering angle
  - Neutrons of 100 keV - 1.5 MeV
  - Recoils of ~1 keV up to 50 keV
  - Successful measurements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

Neutron scattering in SCENE



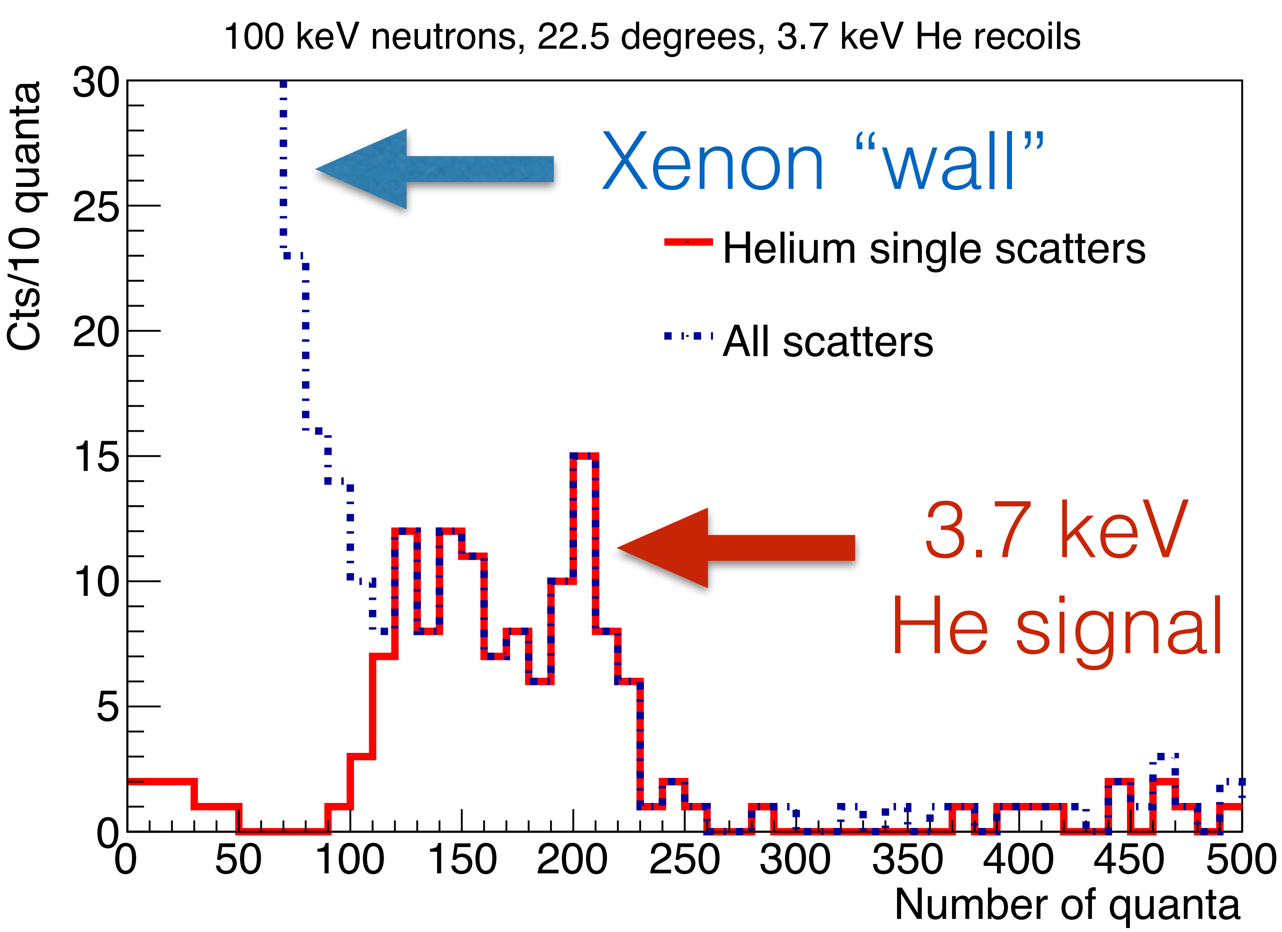
- Time of flight to measure the neutron timing
- Pulse shape discrimination(PSD) to select neutrons in the detectors
- Ntof - time between beam pulse and neutron detector
- TPCtof - time between beam pulse and LAr detector
- f90 - PSD in LAr
- Npsd - PSD in neutron detector

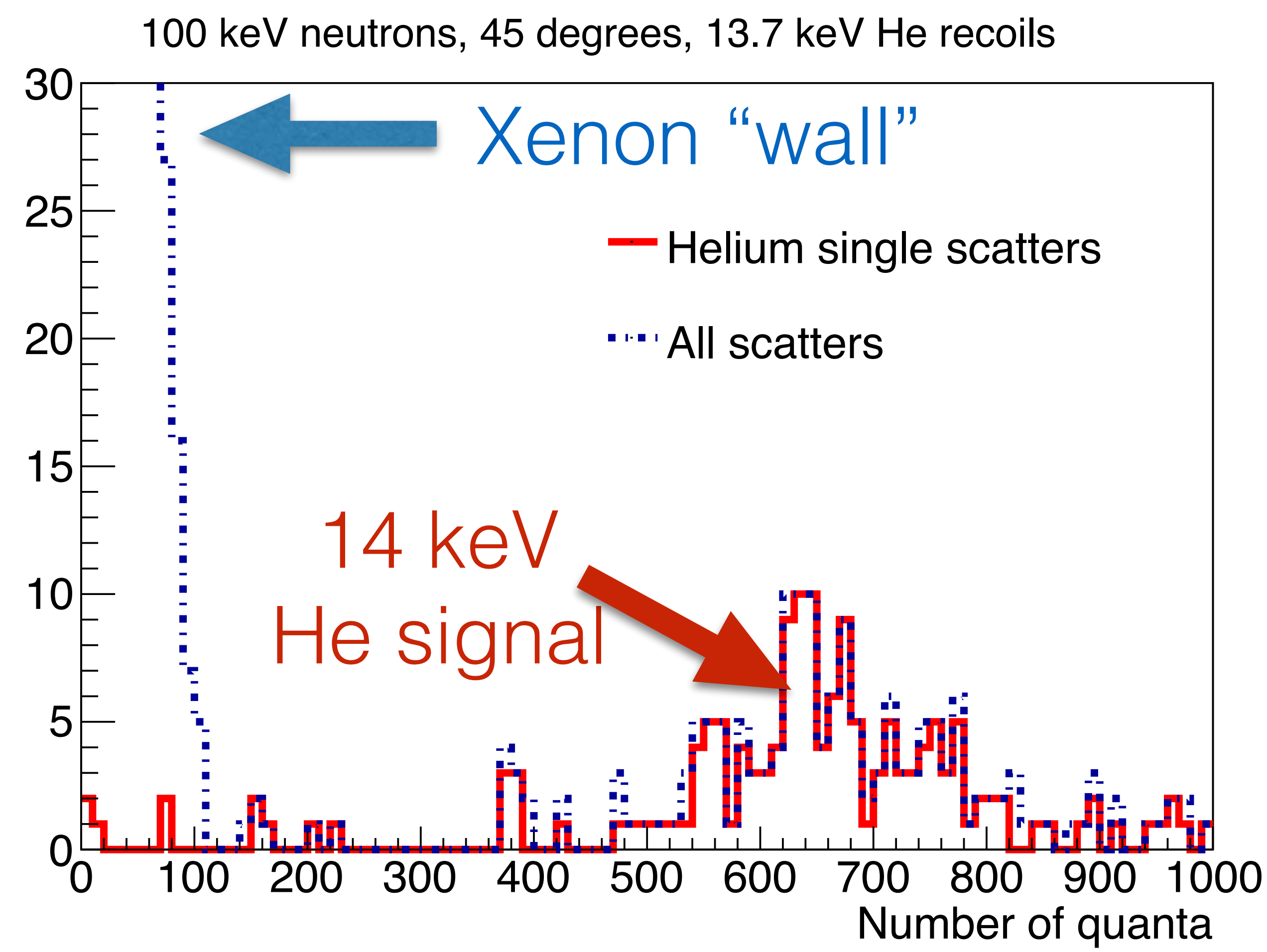




Neutron scattering with He in LXe

- 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

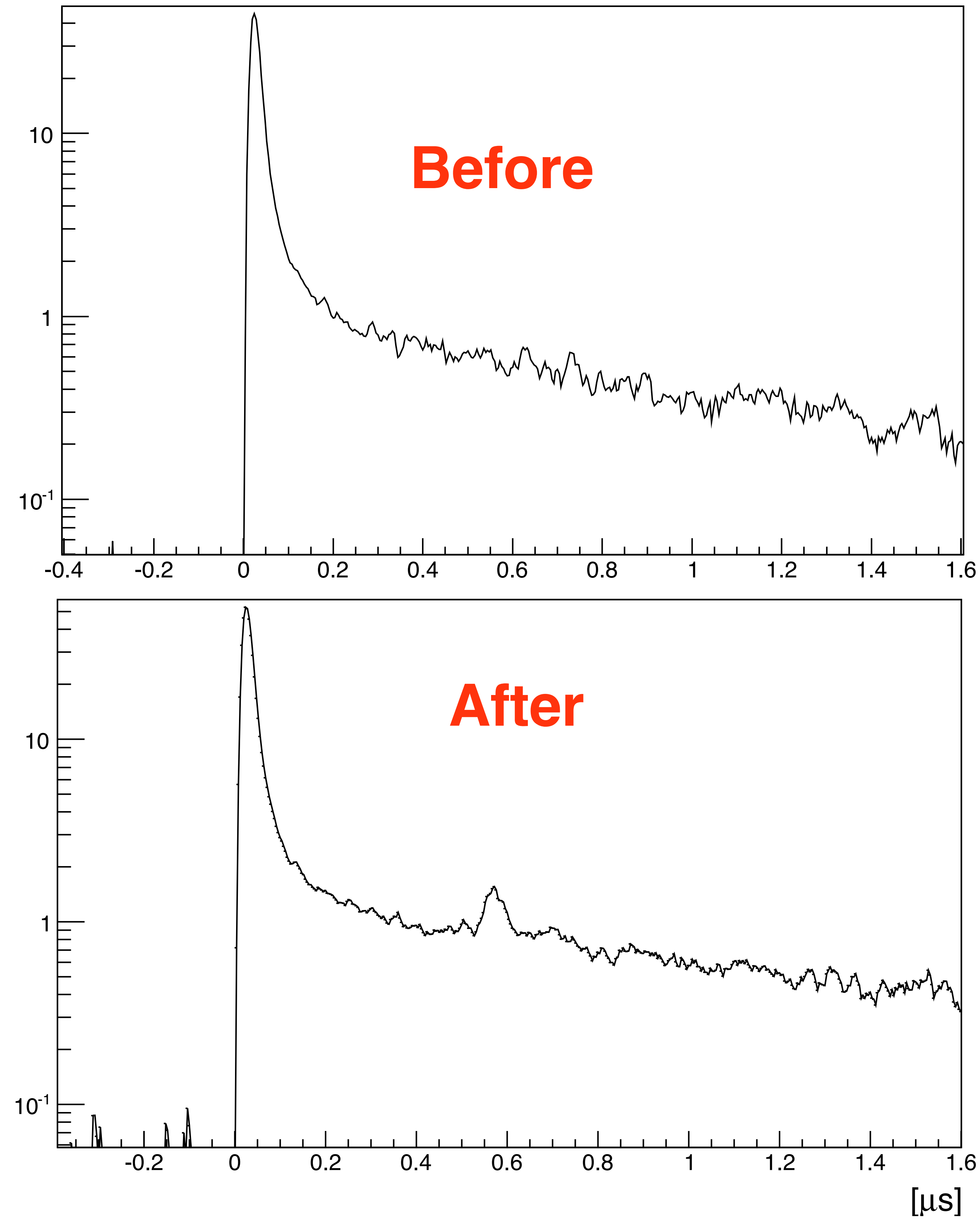




Measures yield and S1/S2 response v. energy!

What do I worry about?

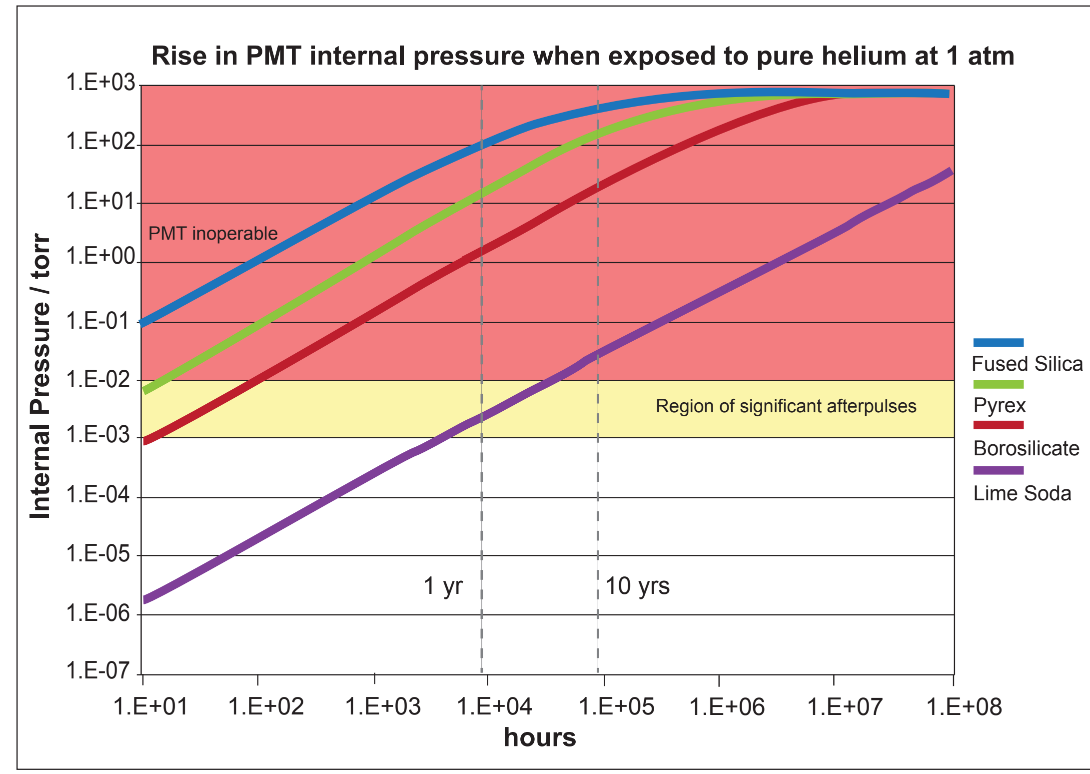
- Helium gas and PMTs are not a good mix
  - Diffuses through glass
  - Electron cascade ionizes He, leading to an after pulse
- In SCENE we got a bottle of UHP argon that was 10% He
  - ~1 day of exposure at various temperatures



Helium diffusion

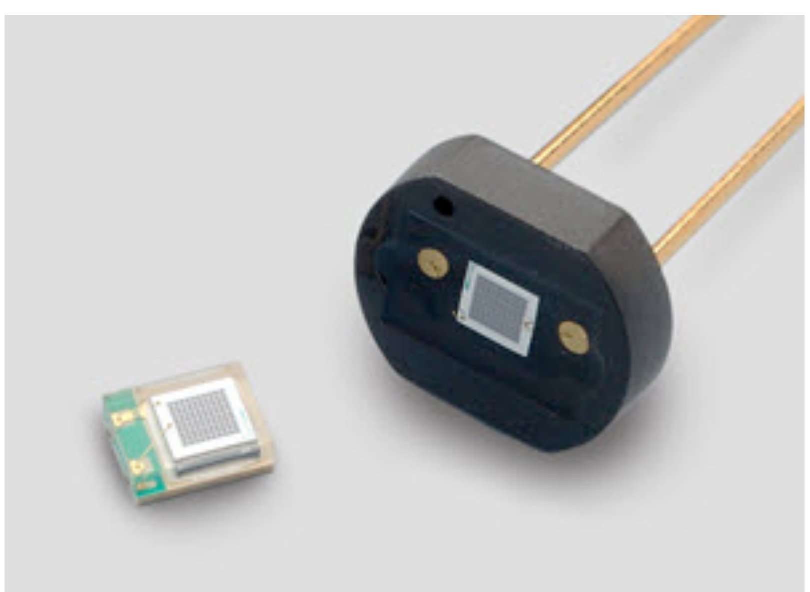
- Diffusion exponentially suppressed by temperature (Arrhenius relationship)
- R11410 has a surprisingly thick window (3 mm)
- Calculation suggests 500 days at 1 bar/165 K before tube becomes inoperable
- That's pretty tight…
- Needs to be tested

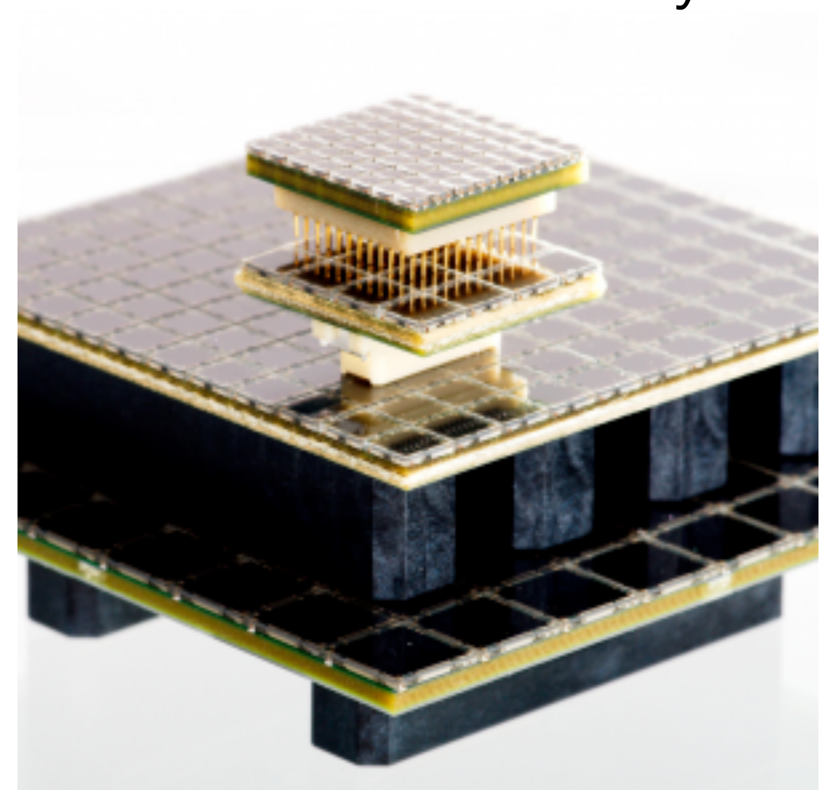
Example for ET9226 PMT



Possible solution

- Silicon PMs are VUV sensitive and will not have a He after pulsing problem
- Could eventually replace the upper LZ PMT array with SiPMs
  - Lower backgrounds, might be valuable for double beta decay studies
  - Other dark matter experiments already looking at this (DarkSide)
- Plan to implement in XELDA already, just so we don't have to worry about the top array





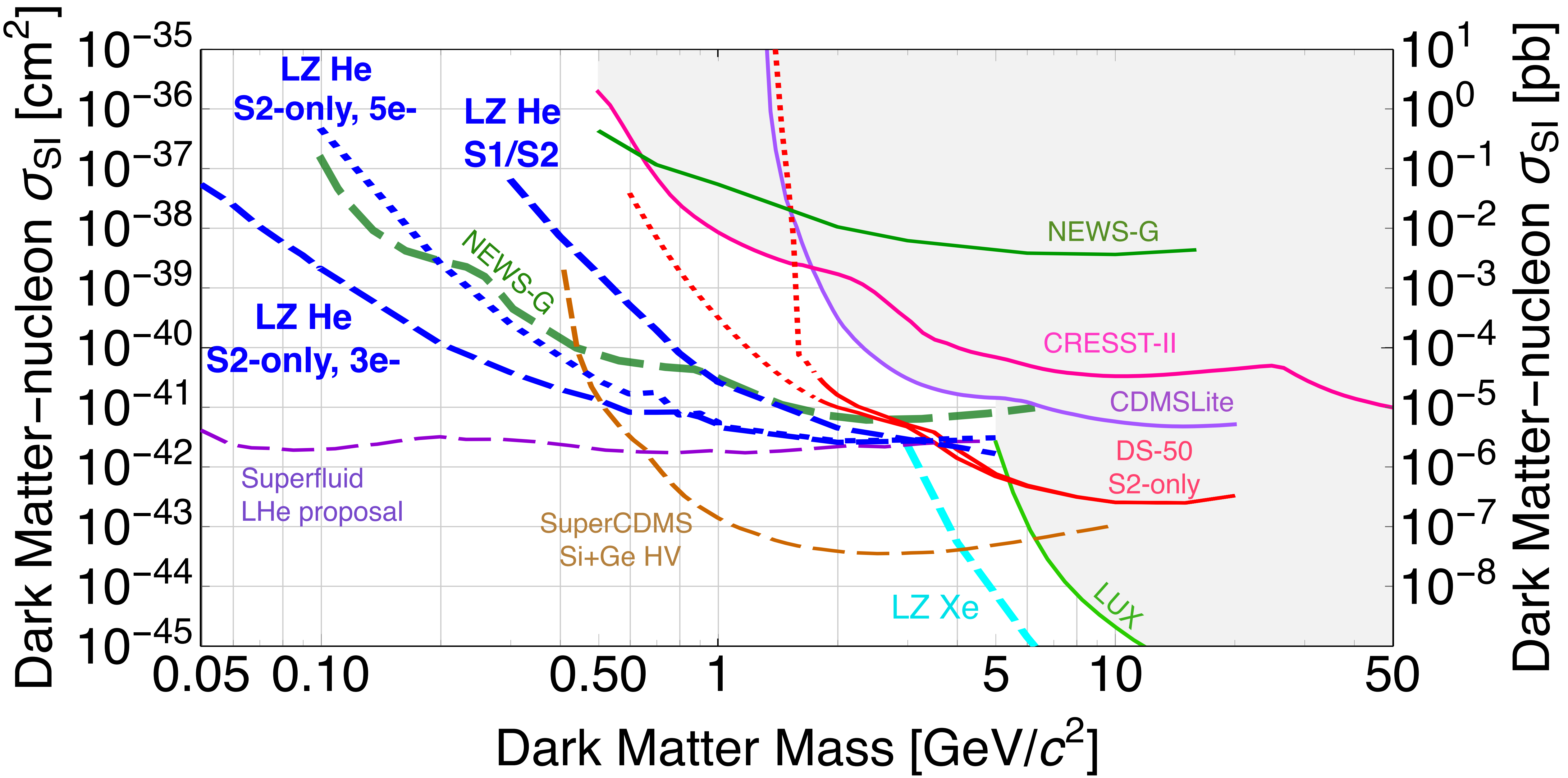
He doping in LXe

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

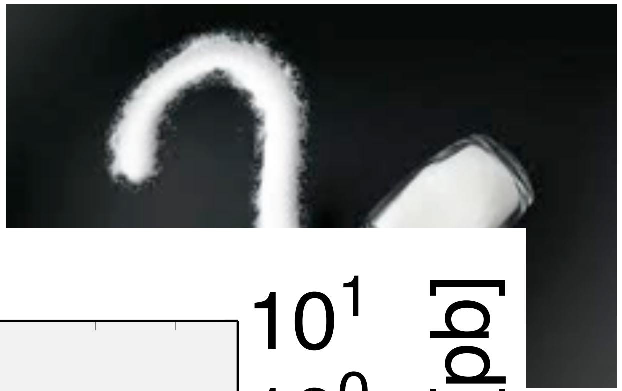
Making projections

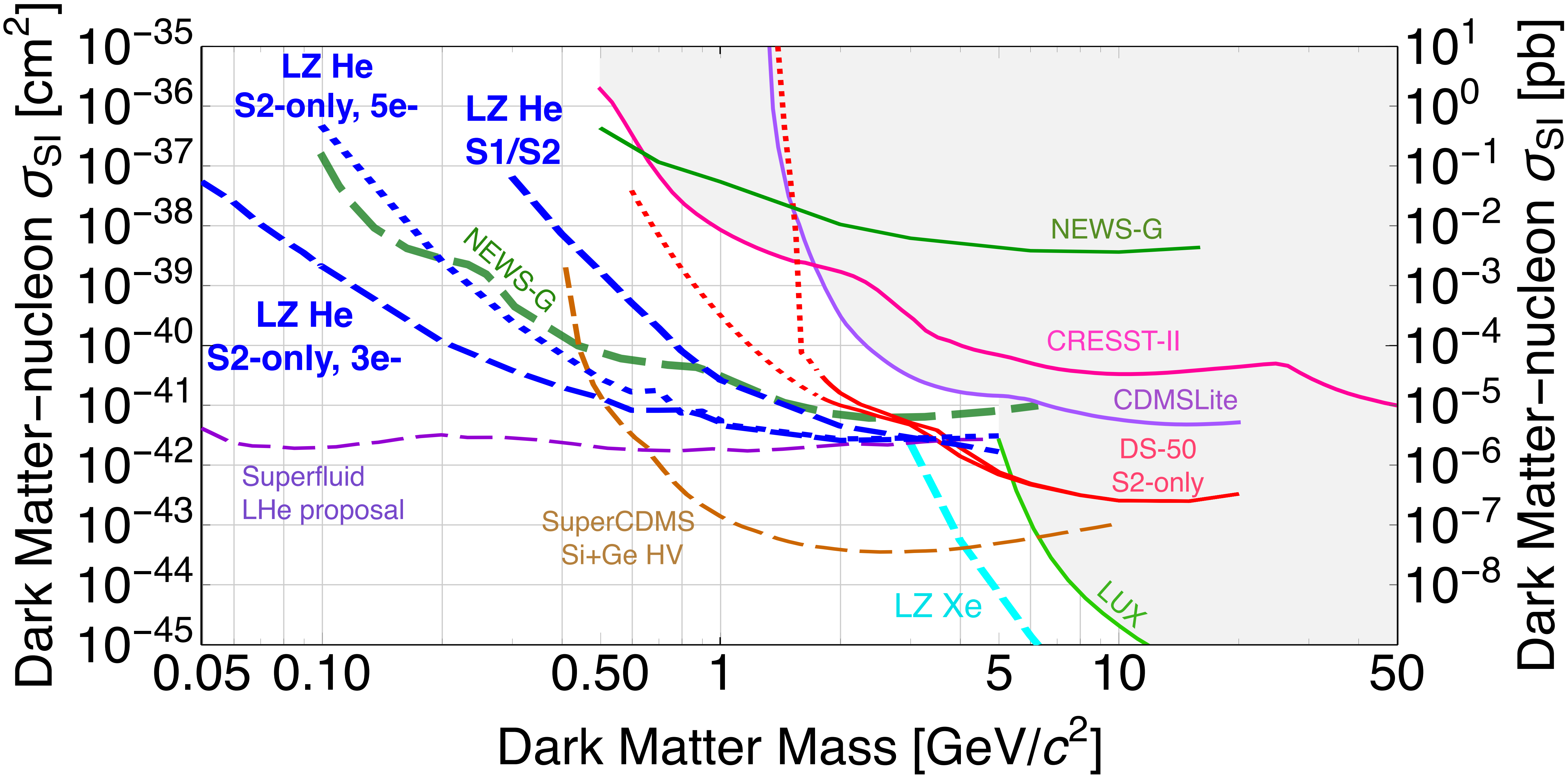
- Using the NEST 2.0 alpha model, the LZ simulation, and expected LZ backgrounds
- Analysis and sensitivity using the LZ Profile Likelihood Ratio package
- For now, I assume ER-like partitioning of photons and electrons in He recoils
  - more conservative with regard to background rejection and S1/S2 sensitivity, slightly more optimistic for S2-only

Making projections



Making projections



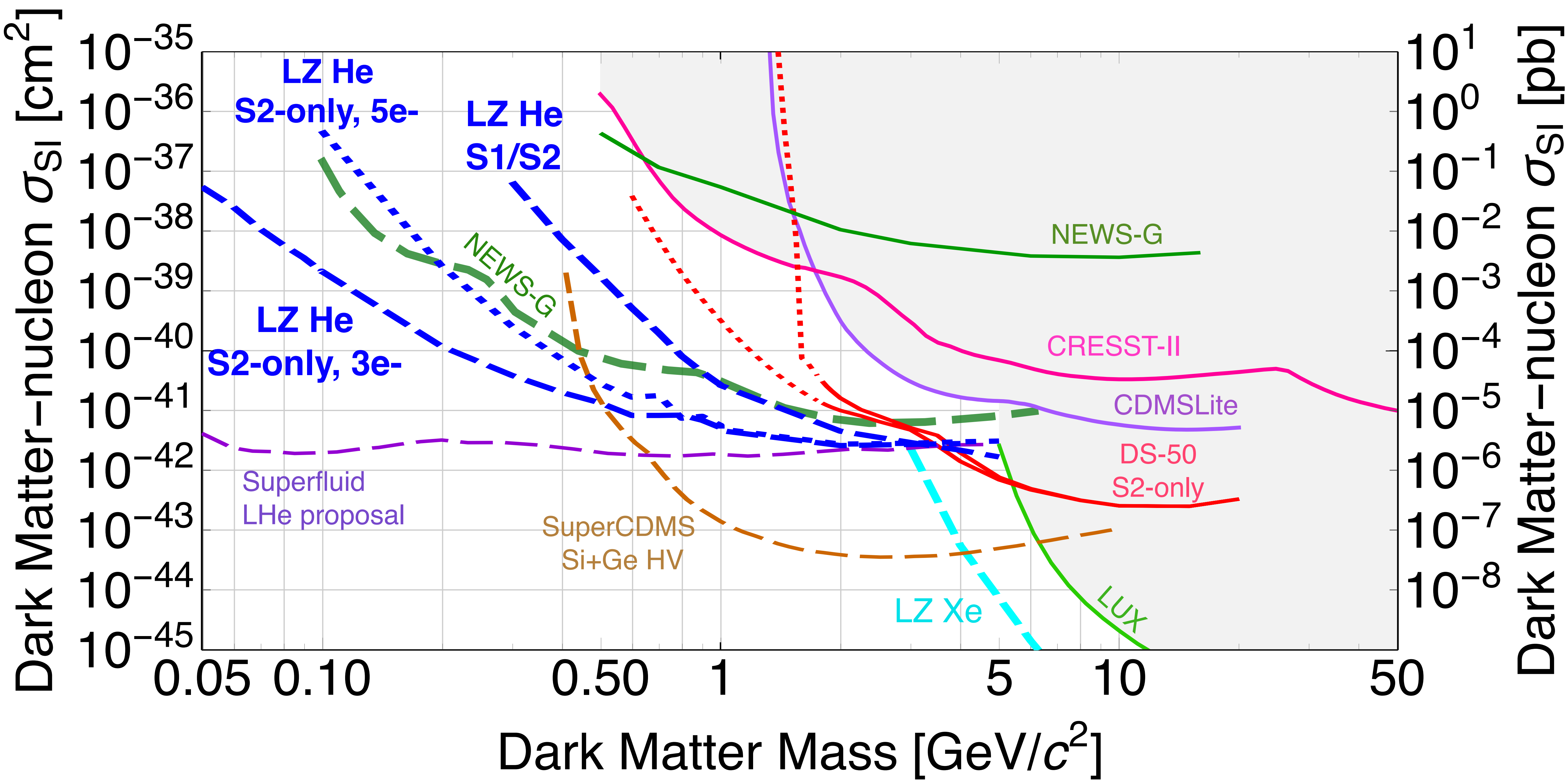


- Location of LZ Helium lines depends critically on assumed signal yield
  - ~225 events/day/pb for 100 MeV WIMP with this yield
- S2-only line is for 20 live days - limited by neutrino rate on xenon
- Also looked at more conservative 5e- S2-only threshold

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 recoils ✓
    - Lower energy thresholds for WIMP-He scattering ✓
- Properties measurable using existing techniques ✓
- Potential reach to well below 1 GeV dark matter

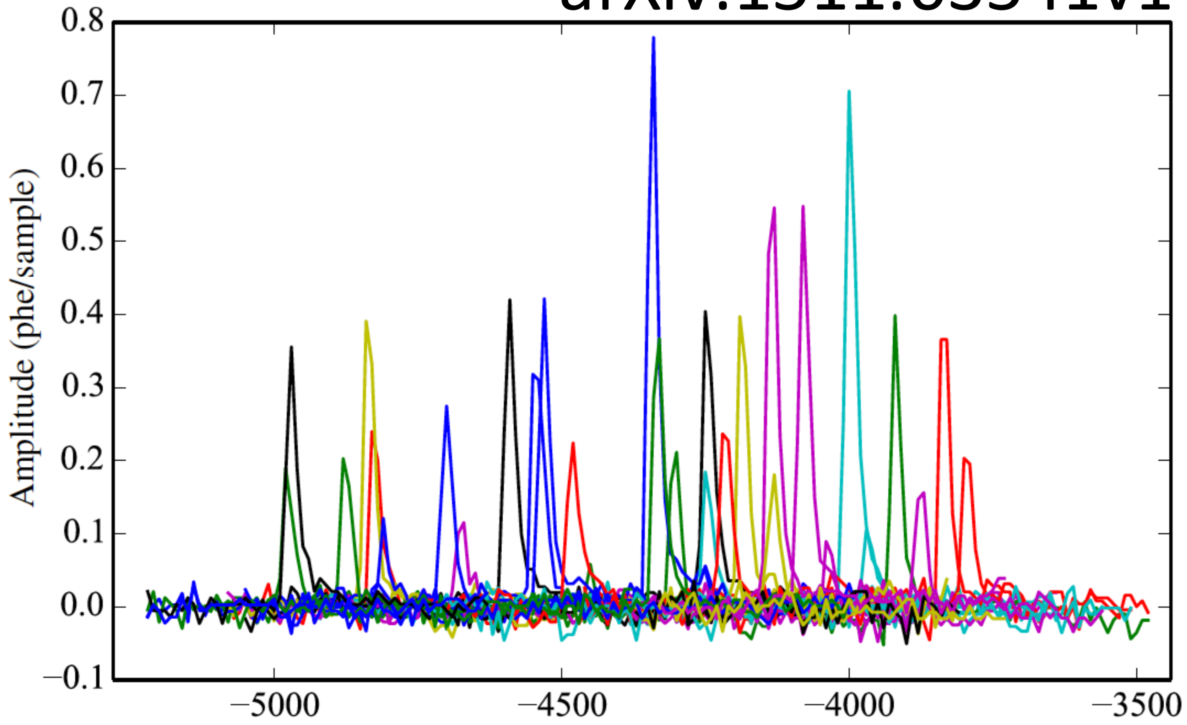
- Depends on properties that need to be measured ?

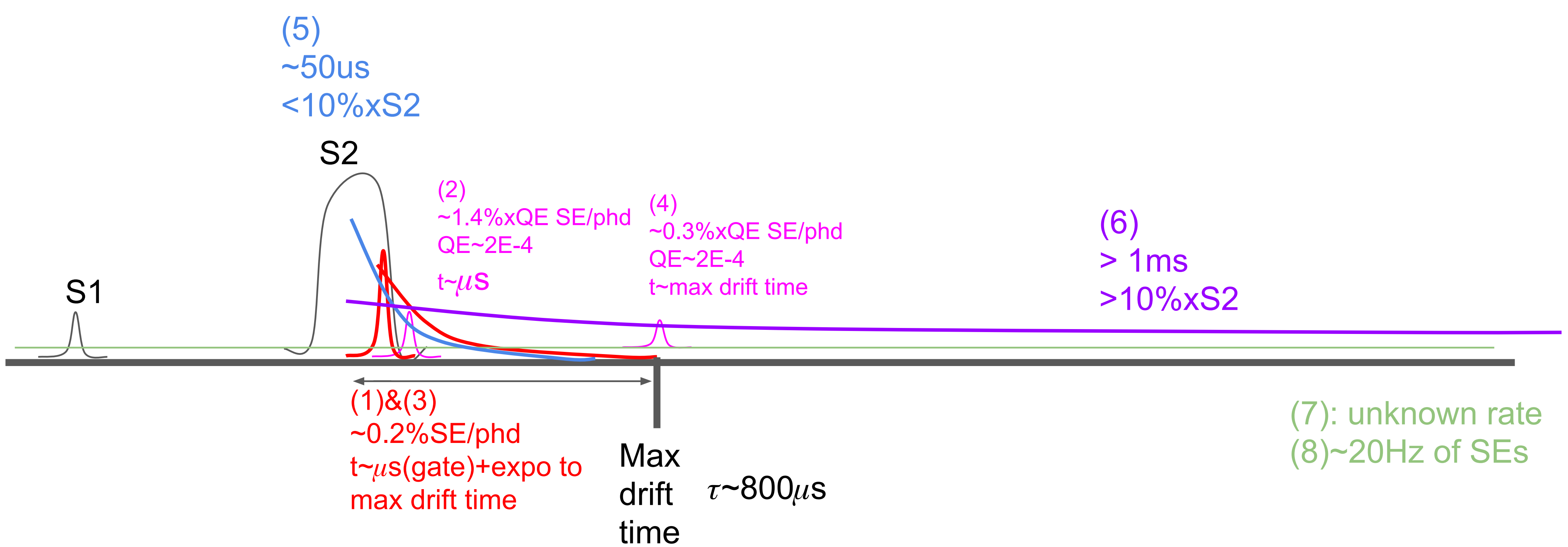

LZ He
S2-only, 5e-
LZ He
S1/S2
LZ He
S2-only, 3e-
NEWS-G
NEWS-G
CRESST-II
CDMSLite
DS-50
S2-only
Superfluid
LHe proposal
SuperCDMS
Si+Ge HV
LZ Xe
LUX
Dark Matter–nucleon σ_{SI} [cm^2]
Dark Matter–nucleon σ_{SI} [pb]
Dark Matter Mass [GeV/c^2]
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
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
0.10
0.50
1
5
10
50

Electron (S2-only) backgrounds

- LUX/XENON have seen significant electron noise - e-trains, e-burps, etc
  - Photoionization on impurities, grids
  - Delayed electron extraction
  - …
- Area of active work by LZ Electron Backgrounds WG

arXiv:1511.03541v1





Electron (S2-only) backgrounds

Table

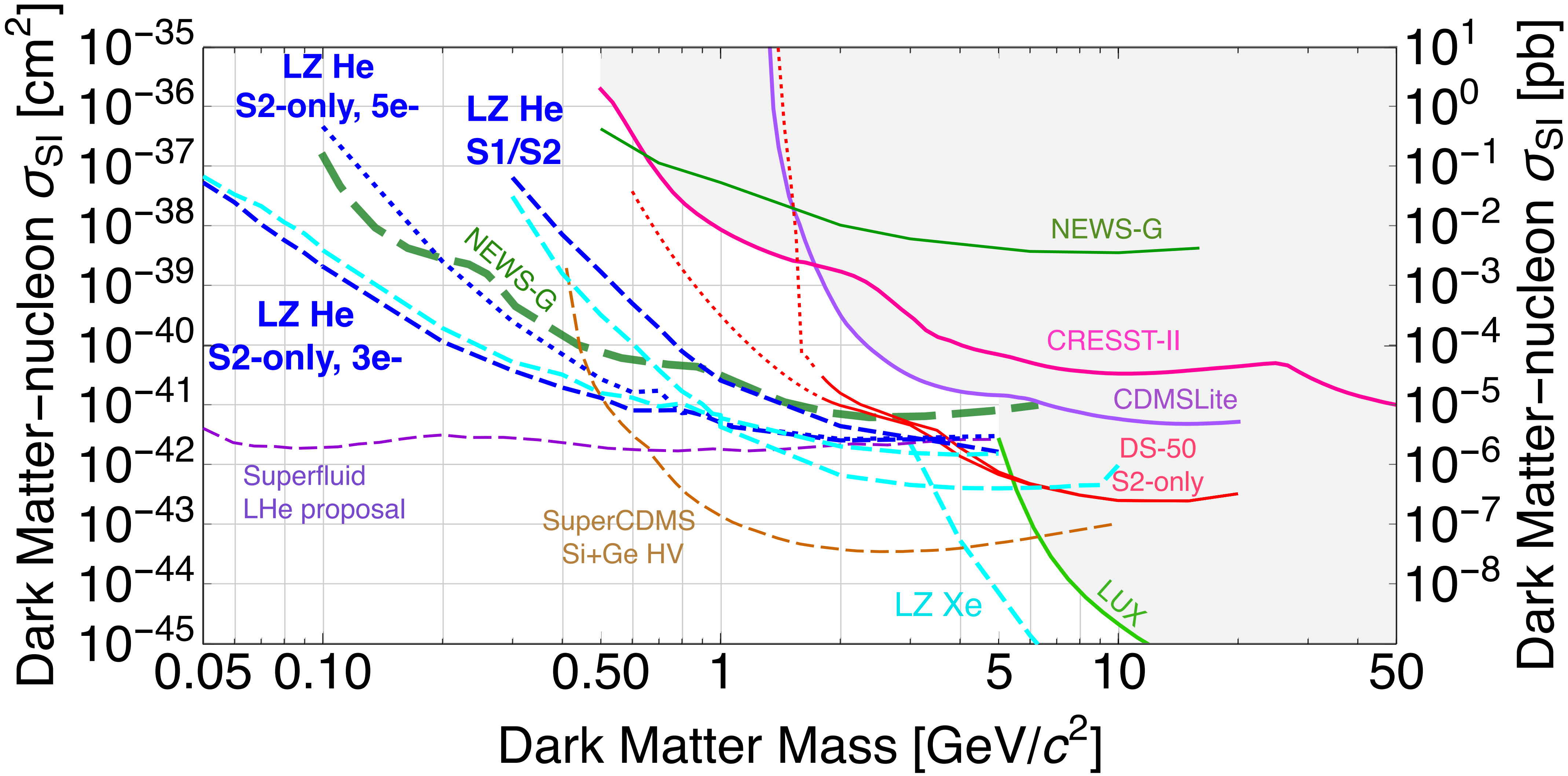
ID	background	timing (us)	cause	effect on analysis	Physics affected
1	photoionization of impurities in LXe above gate grid	<2.5	suspect mostly O_2	S2 size determination	energy resolution
2	photoionization of gate grid	2.5	175 nm on SS	S2 size determination	energy resolution
3	photoionization of impurities in bulk LXe	3—806	suspect mostly O_2	complicates multiple scatter tagging	-
4	photoionization of cathode grid	806	175 nm on SS	not a problem	not a problem
5	fast component of delayed emission	O(100)	**emission of thermalized electrons from initial ionizing event**	S2 size determination	energy resolution
6	slow component of delayed emission	O(1000+)	unknown	S2-only analysis	8B, low-mass DM
7	e-burps	seems random?	?	S2-only analysis for very small burps	8B, low-mass DM
8	faint grid emission	random	asperities on wires		

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



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

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!