Dark Matter Direct Detection: Current state and new ideas

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Brookhaven Forum 2017: In Search of New Paradigms

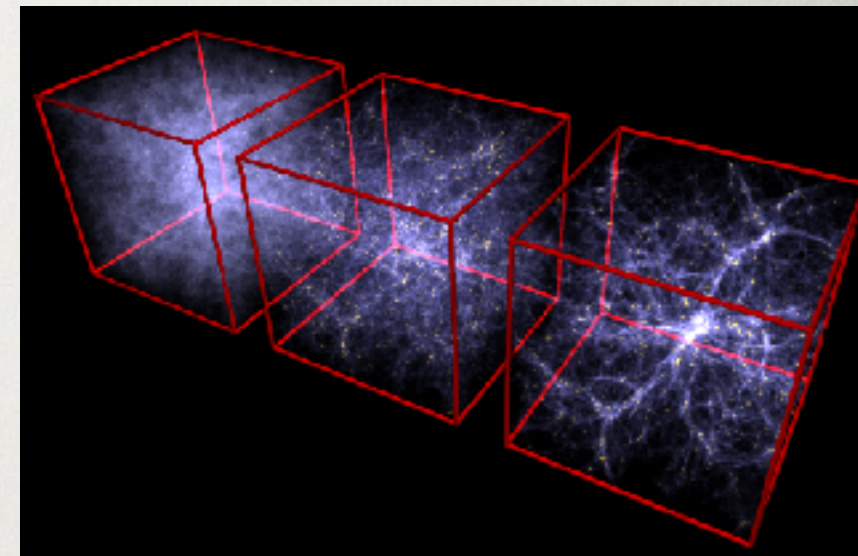
Brookhaven National Laboratory, Upton, NY, 13 October 2017

Dark-Matter Evidence

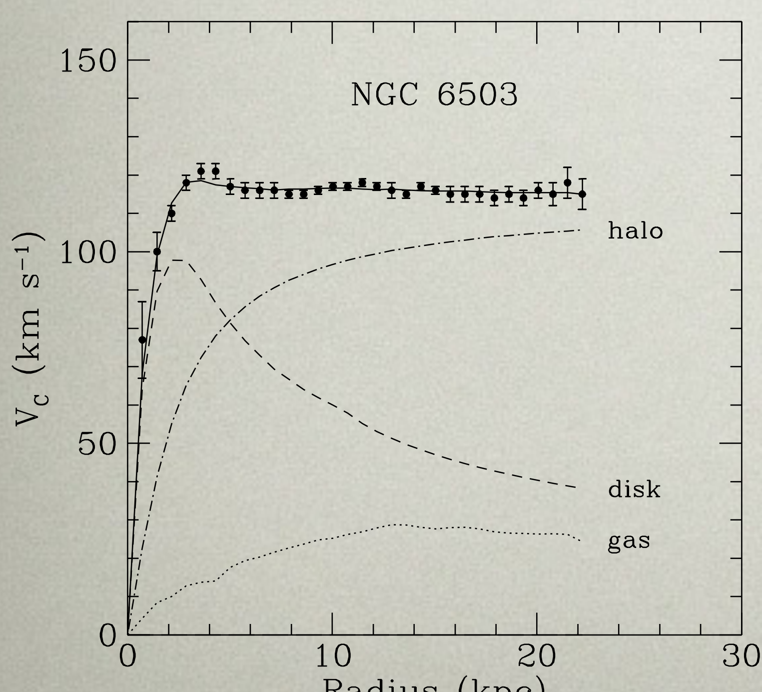
- This slide isn't so necessary for this audience, and doesn't cover all DM evidence anyways.
- This is mainly eye candy.
- **Dark Matter: arguably the strongest evidence we have for physics beyond SM.**

Interacting clusters

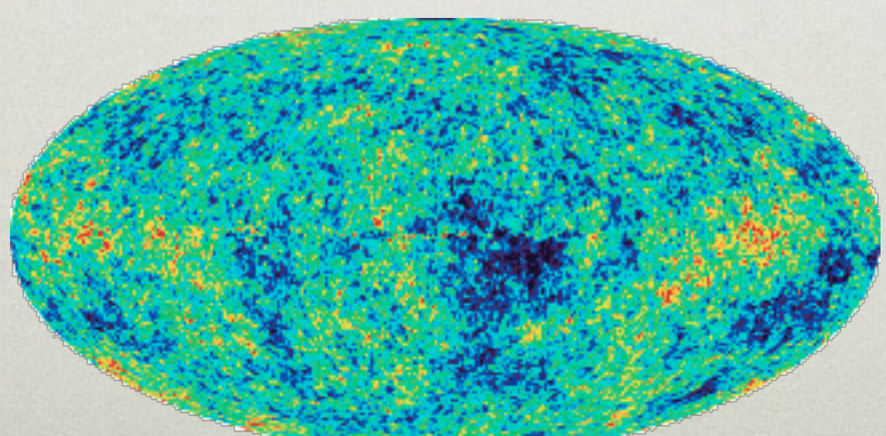
Large-scale structure



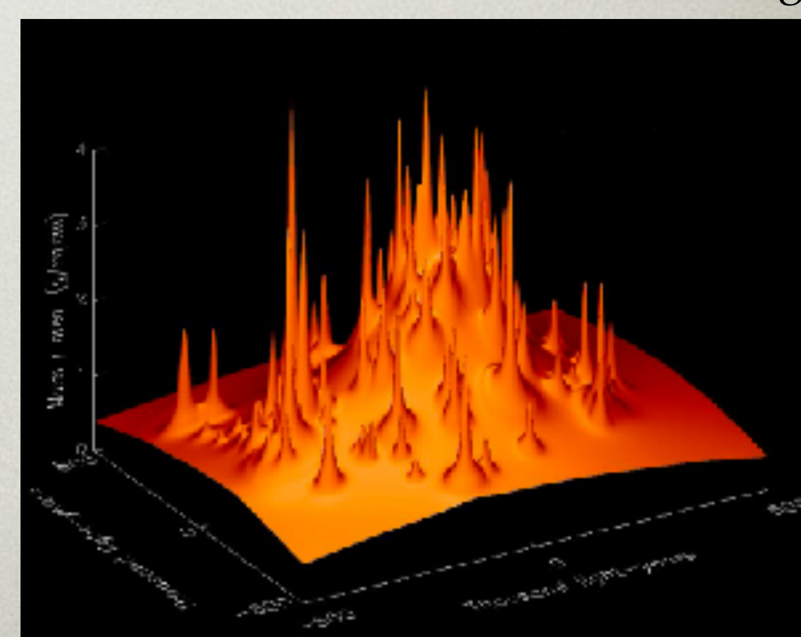
Galactic rotational velocities



CMB



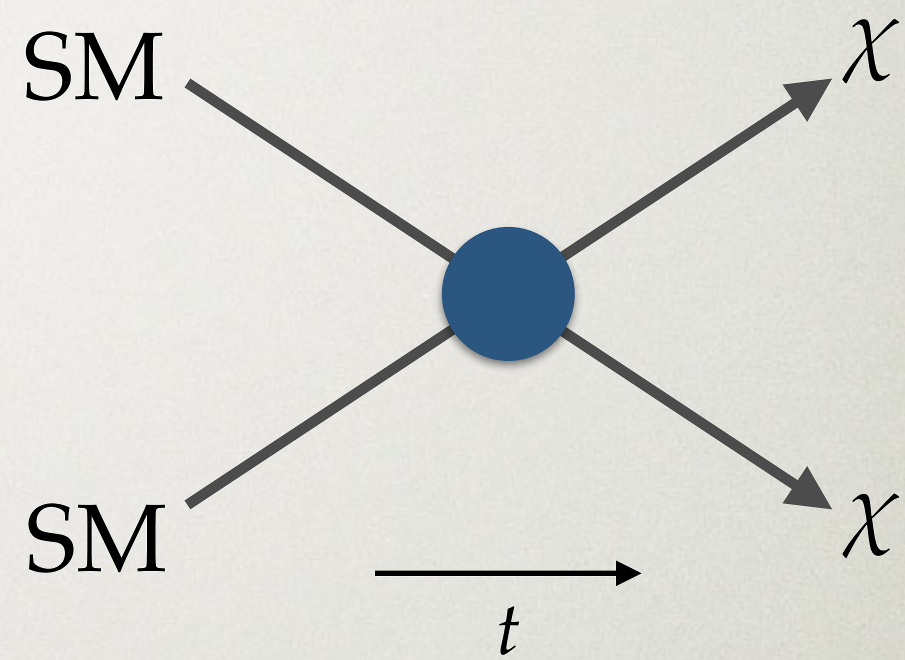
Gravitational lensing



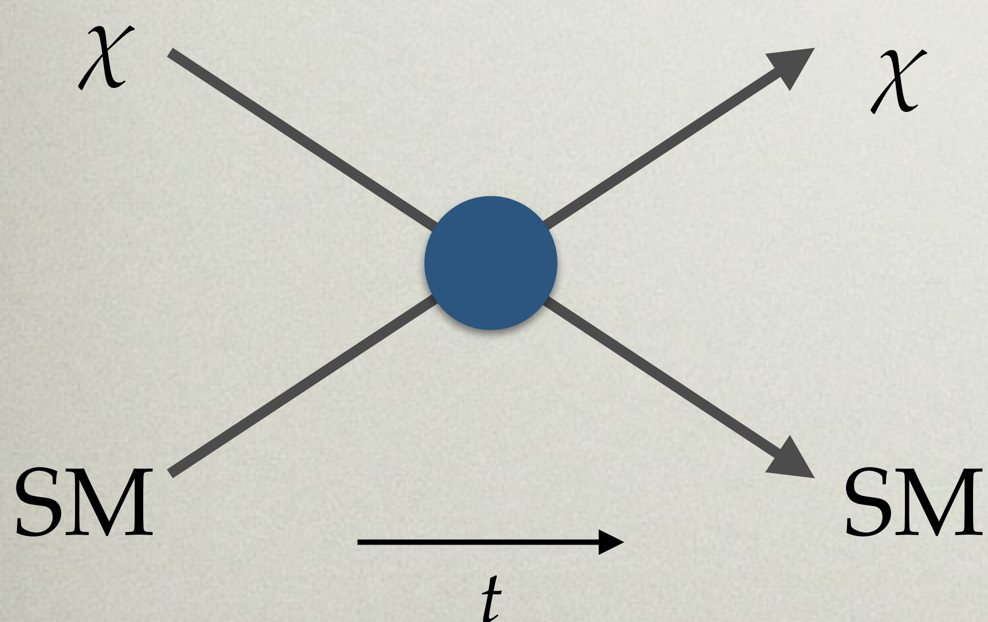
Detection of dark matter

- Detecting dark matter involves exploiting interactions with SM
- Three possible ways that a WIMP and SM particles can interact:

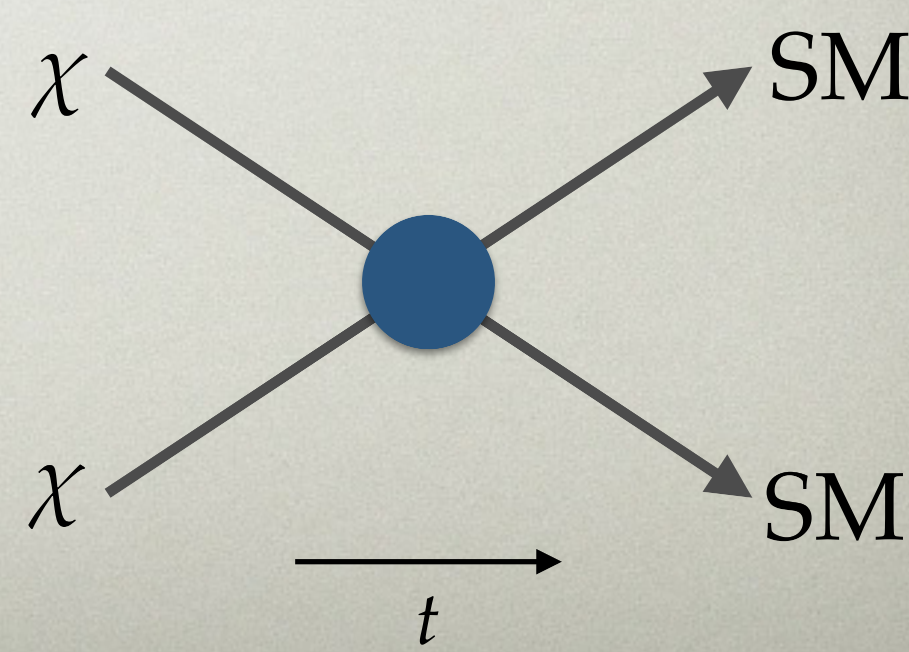
Direct Production



Direct Detection



Indirect Detection



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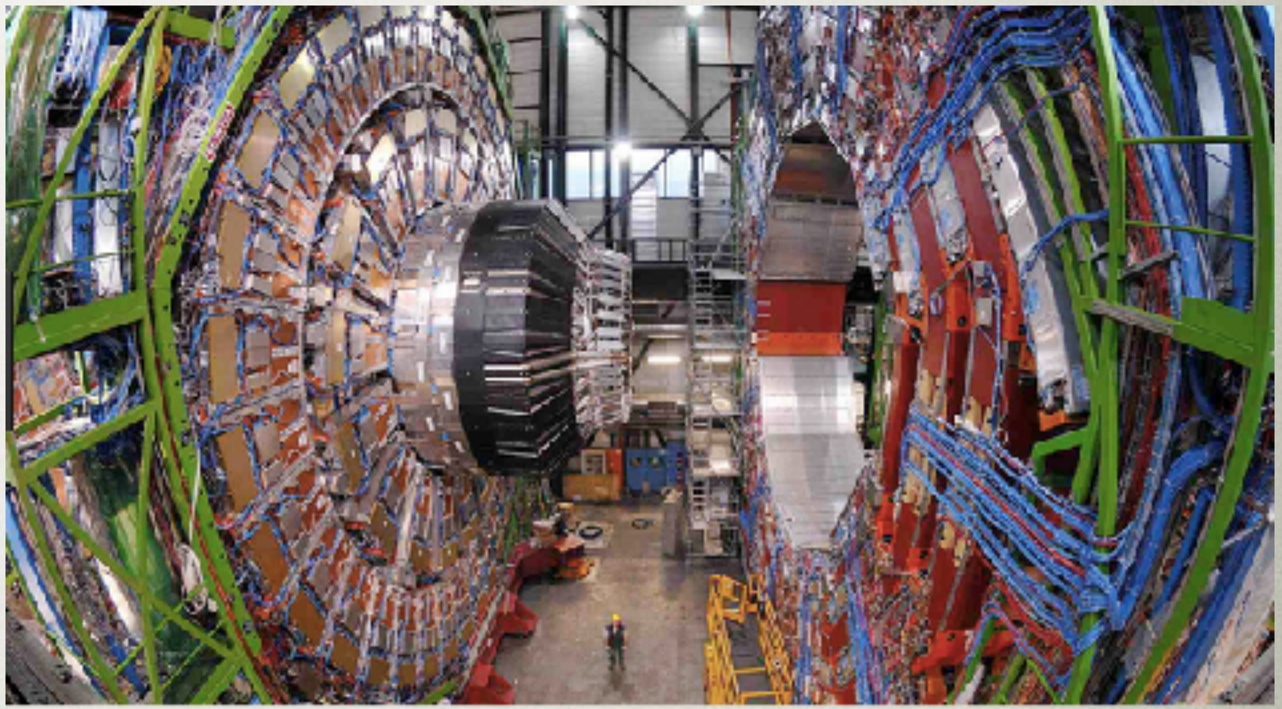

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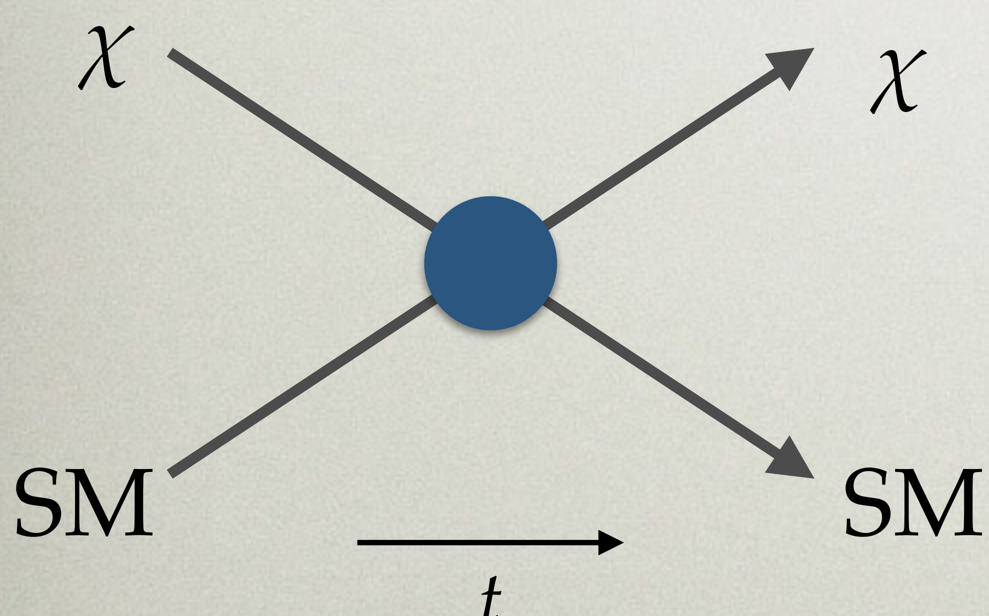
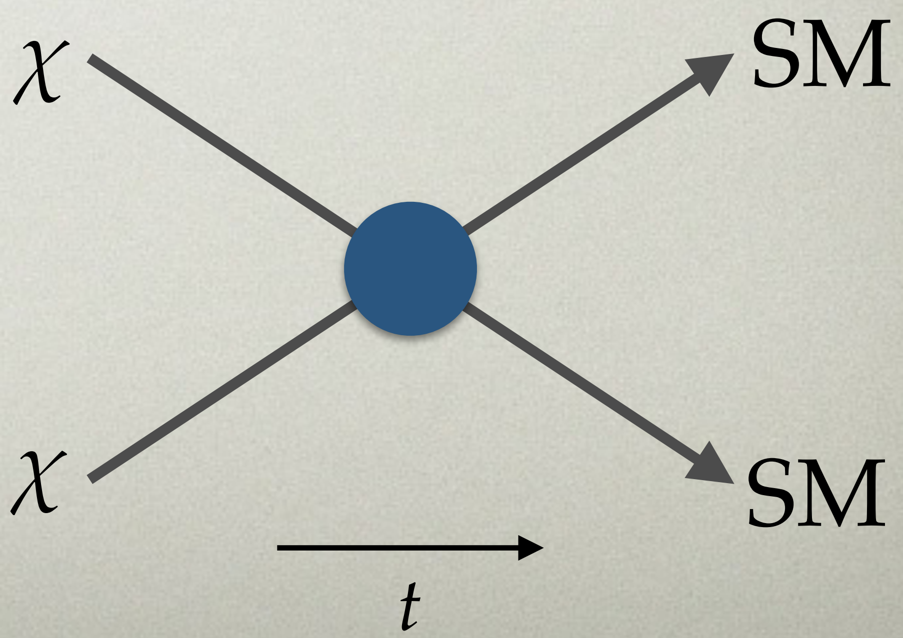


Indirect Detection



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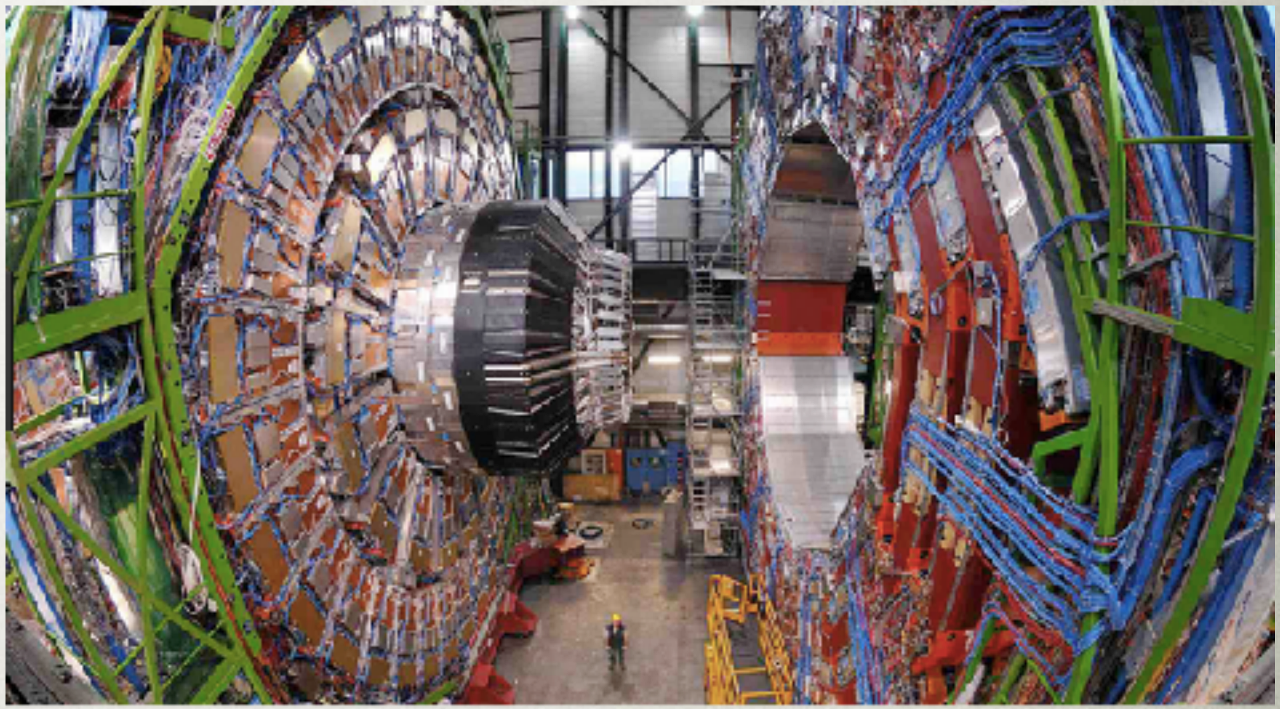

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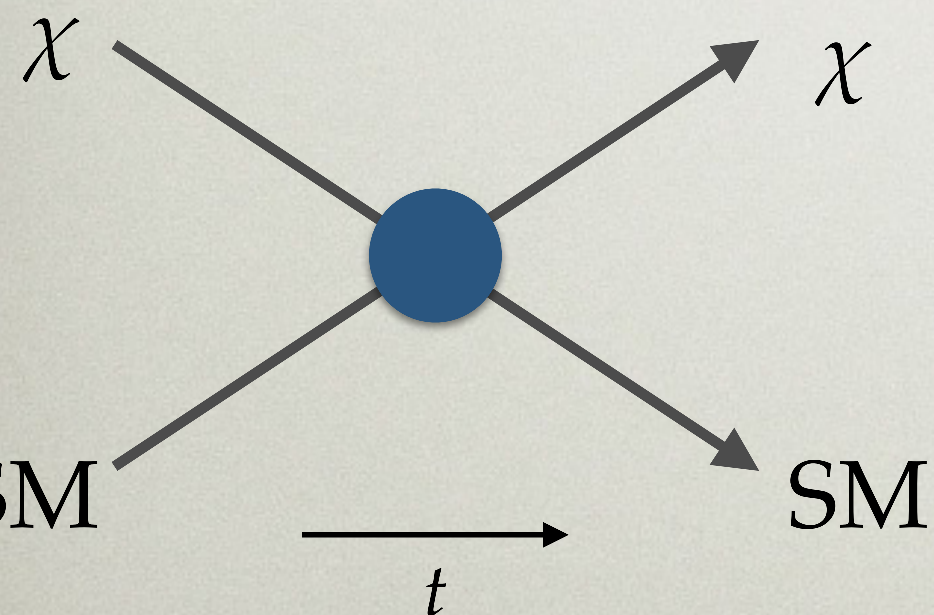

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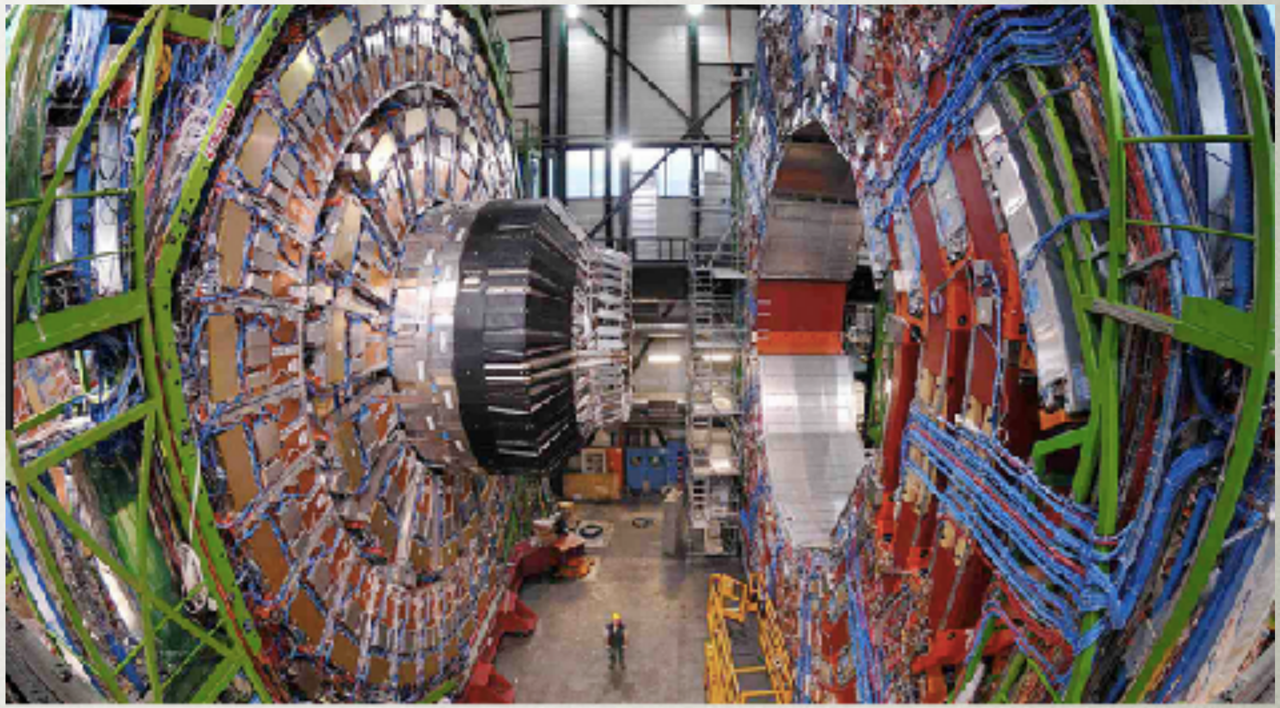

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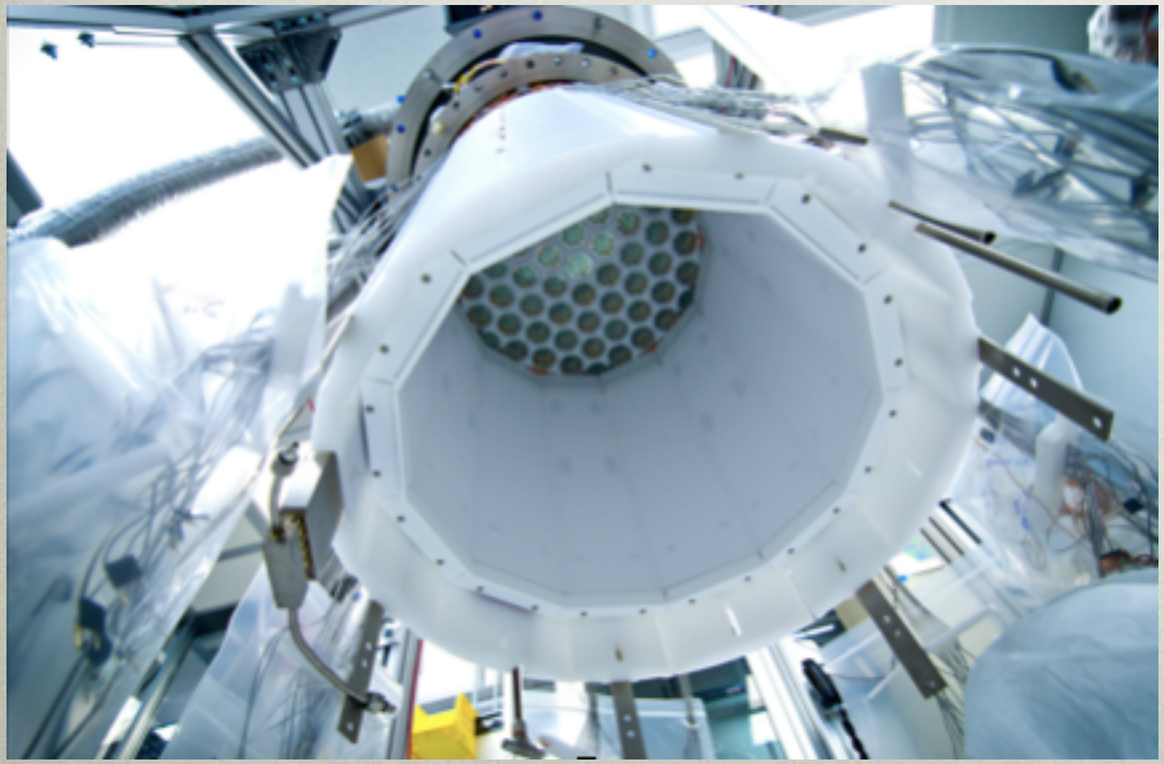
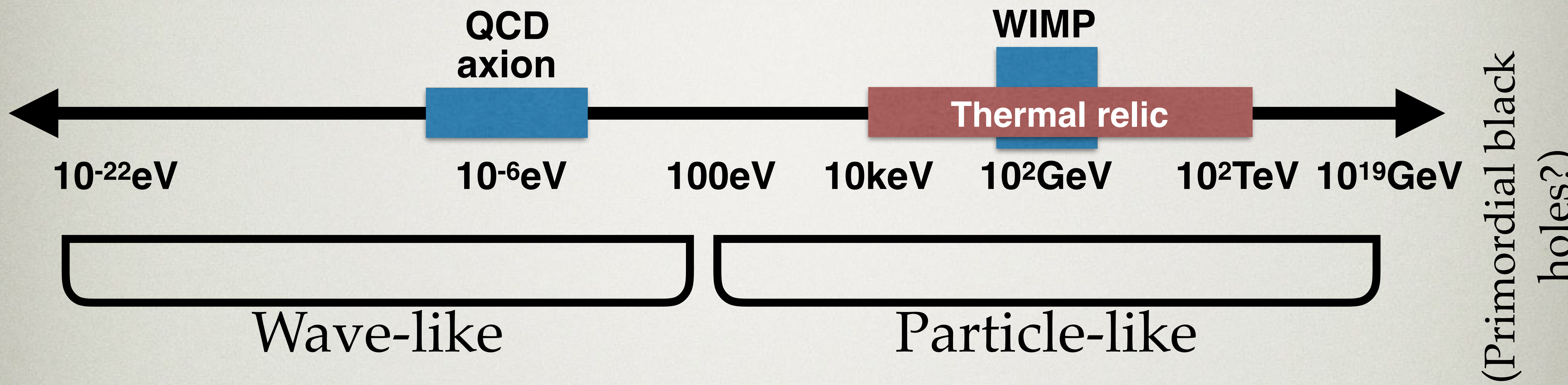


Indirect Detection

Dark matter mass



- M≲10-100 eV, DM must be bosonic
- Light DM: detection is essentially classical
- I'm only talking about particle-like DM
- WIMPs have historically dominated this search.

The WIMP

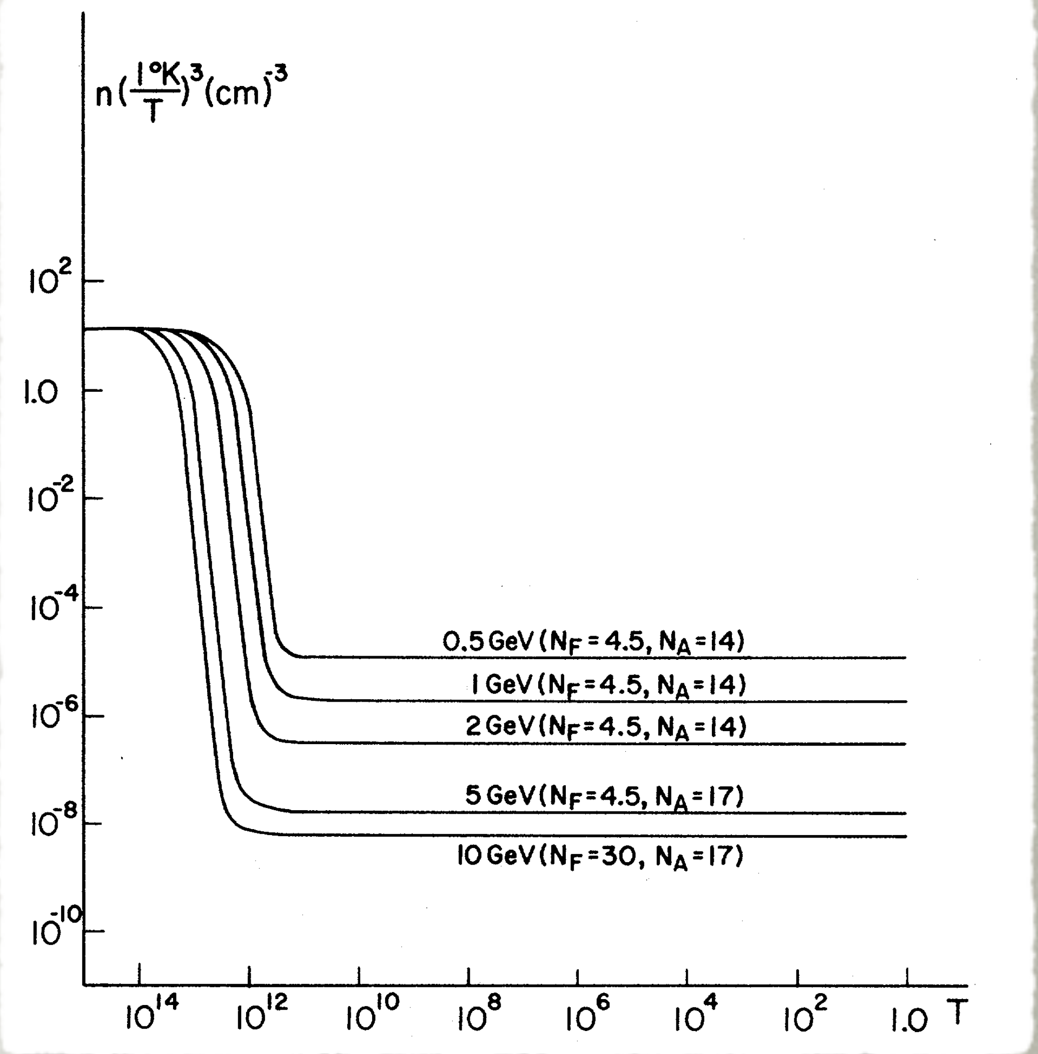
PHYSICAL REVIEW LETTERS

VOLUME 39 — 25 JULY 1977 — NUMBER 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] Batavia, Illinois 60510
and
Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

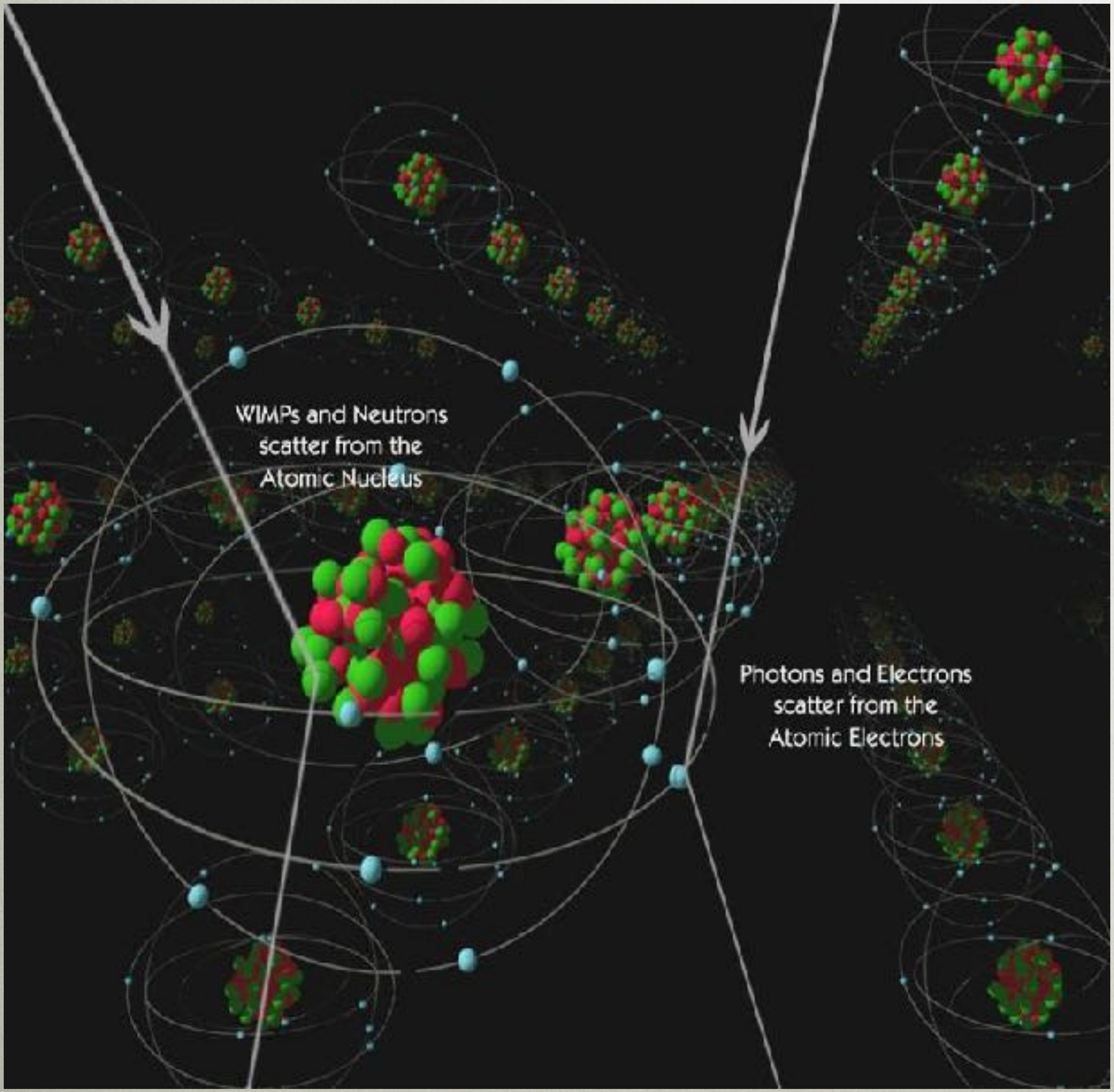
The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



"WIMP miracle":

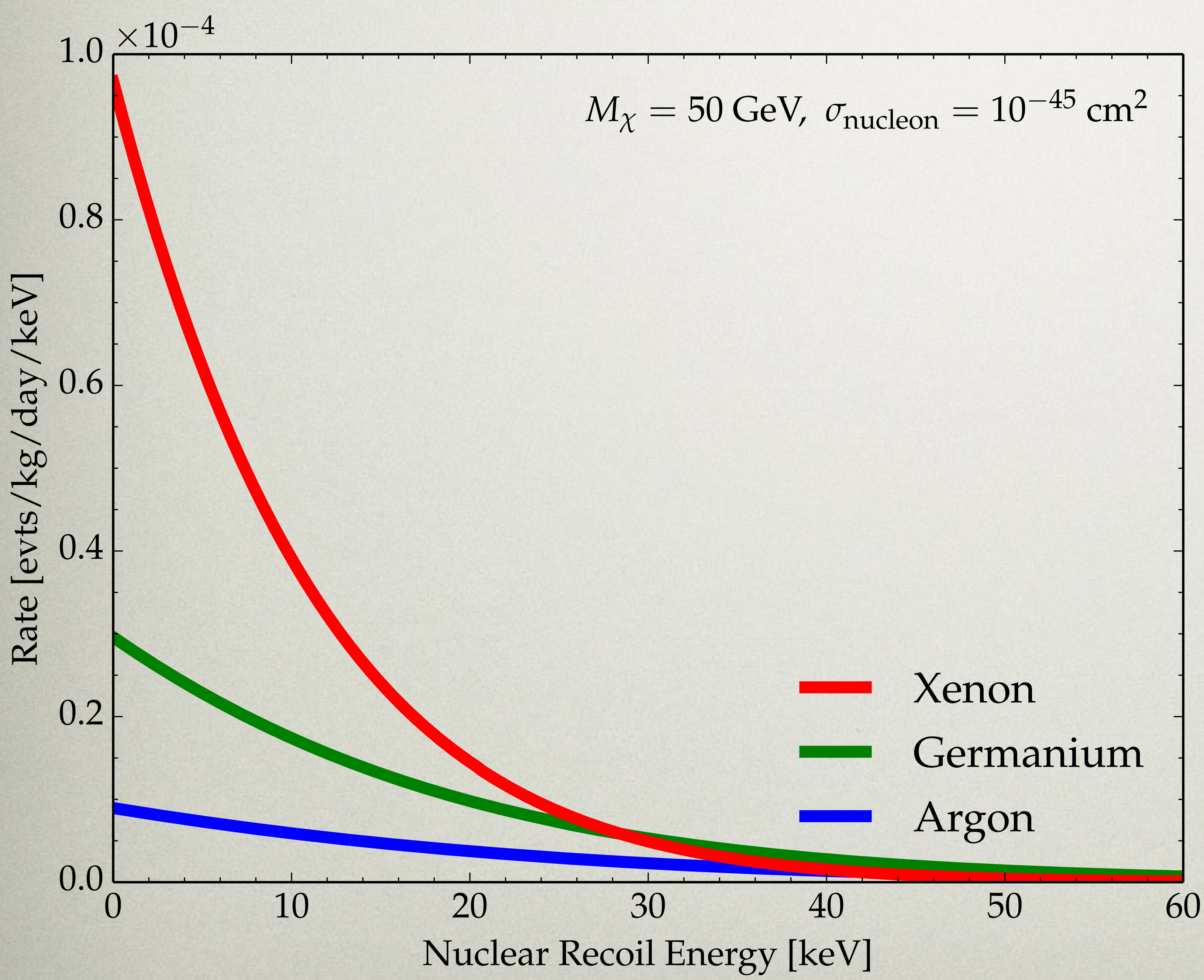
- Essentially model-independent thermal production
- Possible candidates of interest to hierarchy problem
- Compelling: WIMPs have driven most of historical work on dark matter detection

WIMP detection



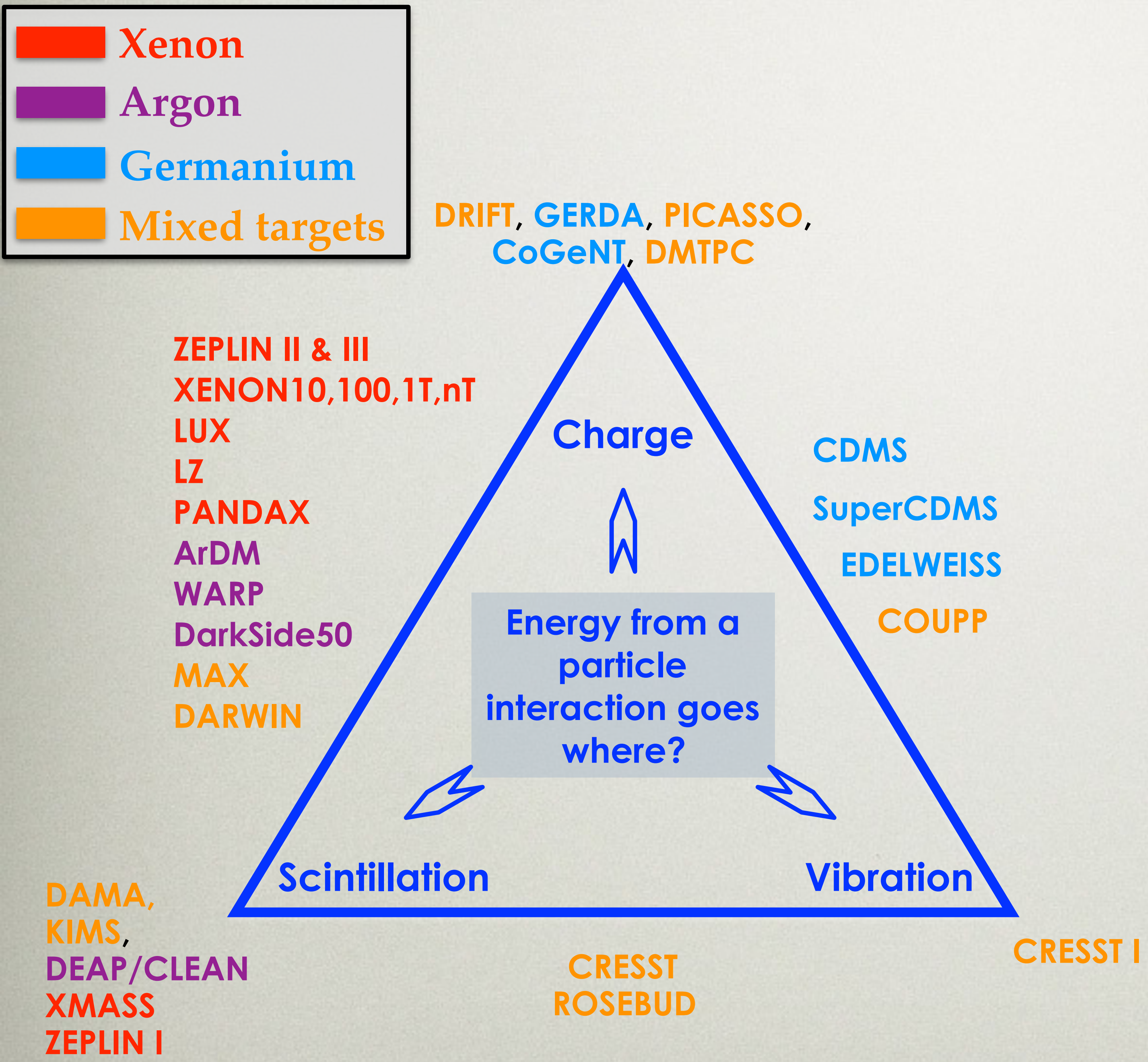
- Observable interactions between WIMPs and matter dominated by nuclear recoils
- Most backgrounds produce electronic recoils

WIMP detection



- WIMP-nucleus elastic scatters expected to produce ~featureless recoil spectra.
- Spin-independent couplings scale as A^2.

WIMP detection general strategy

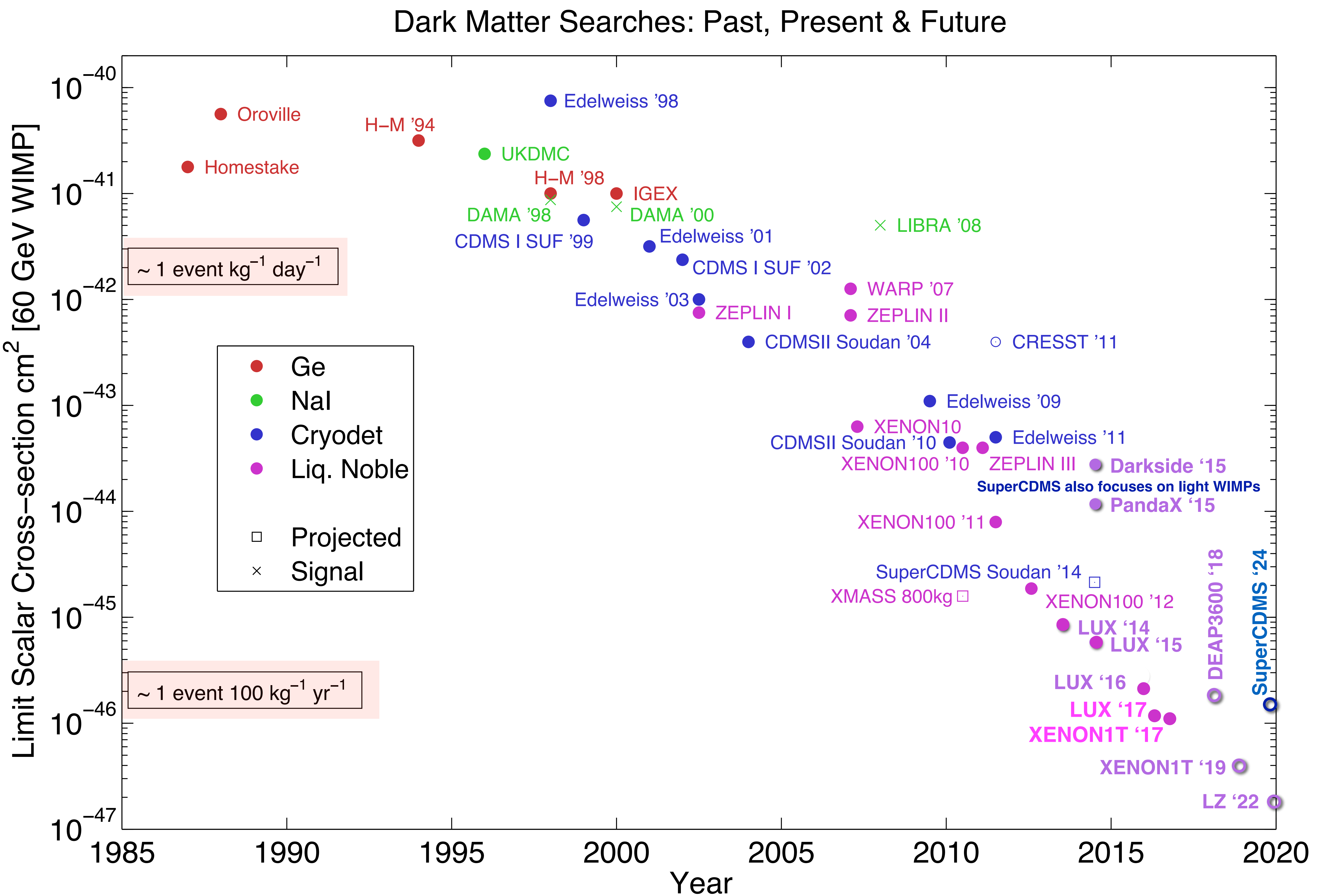


Universal theme:

- Backgrounds
- Backgrounds
- Backgrounds

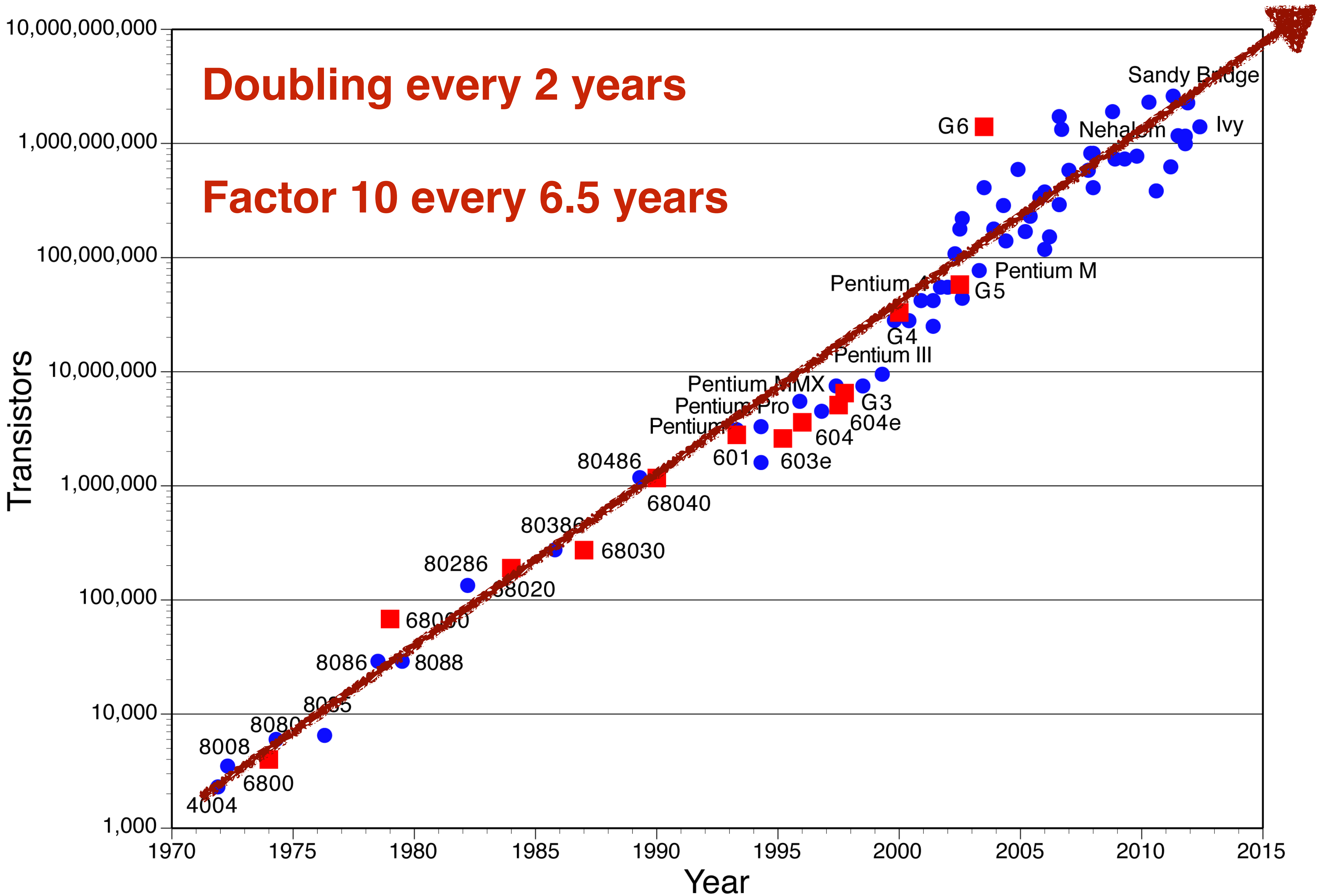
To separate signal from background, most experiments measure energy deposition in two channels.

- Proportion of Ch1 to Ch2 gives info on signal or background

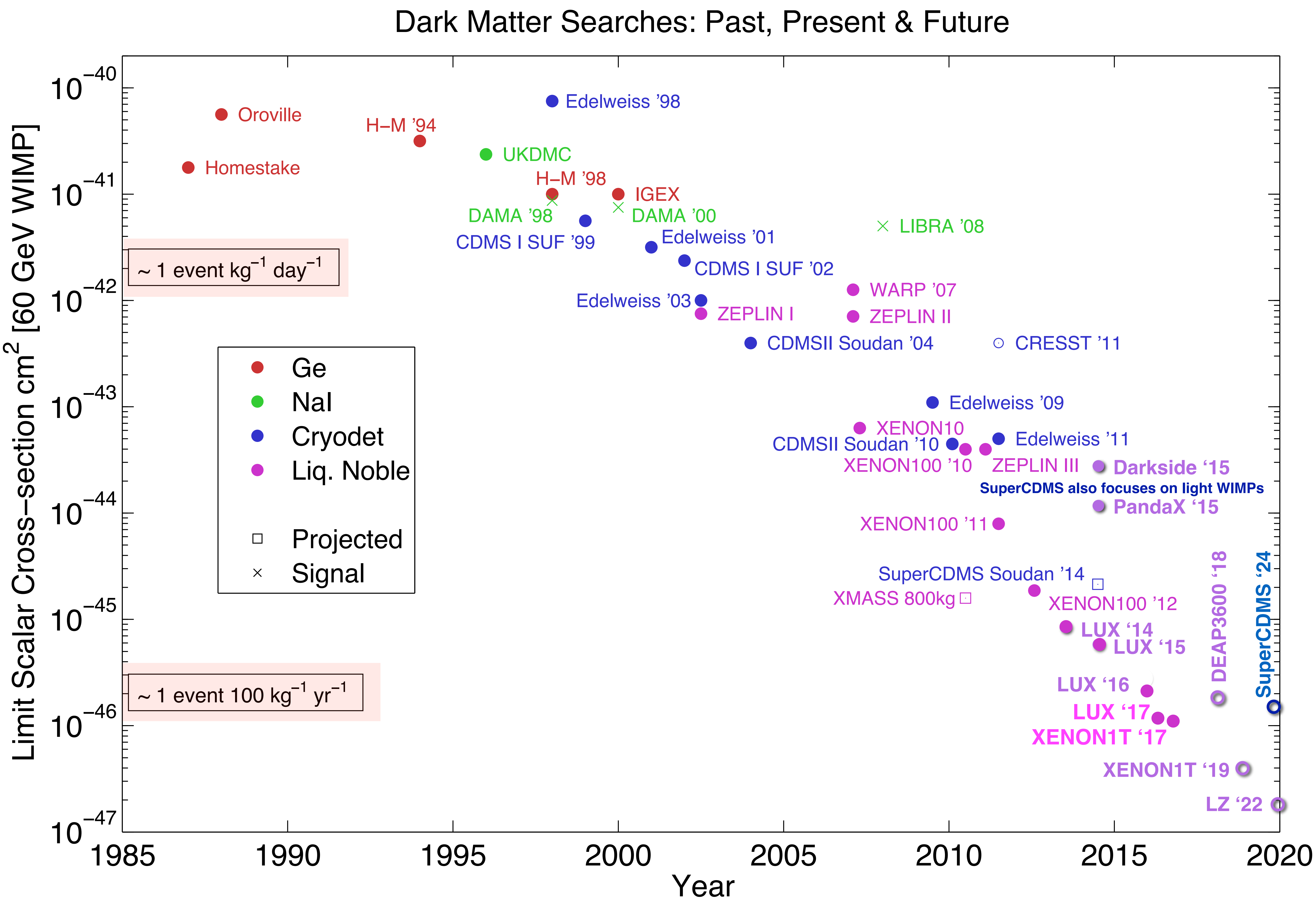


Courtesy R. Gaitskell

Moore’s Law



Doubling every 2 years
Factor 10 every 6.5 years
Transistors
Year
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
4004
8008
6800
8080
8085
8086
8088
68000
80286
68020
80386
68030
80486
68040
Pentium
601
603e
604
604e
Pentium Pro
Pentium MMX
G3
Pentium III
G4
Pentium 4
G5
Pentium M
G6
Nehalem
Sandy Bridge
Ivy



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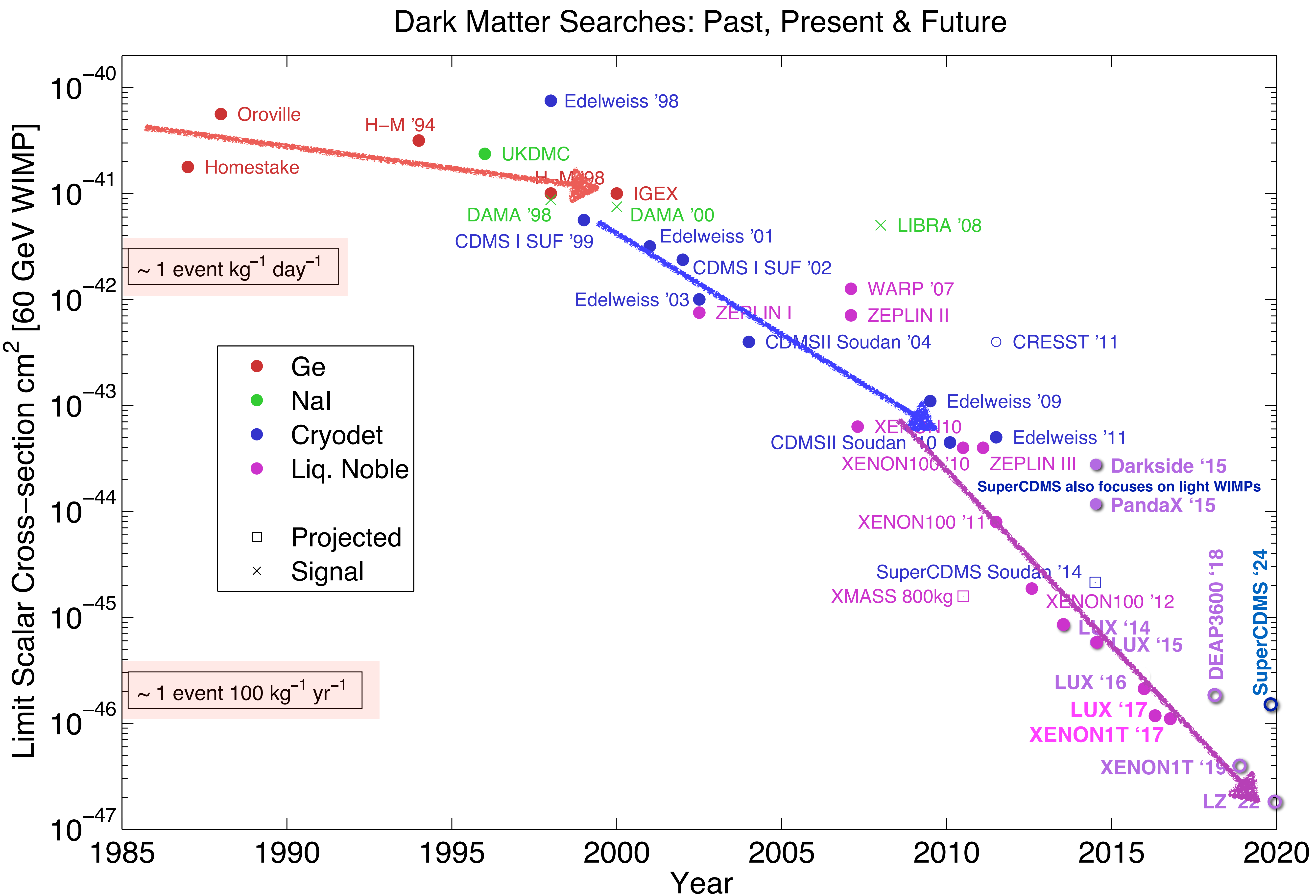

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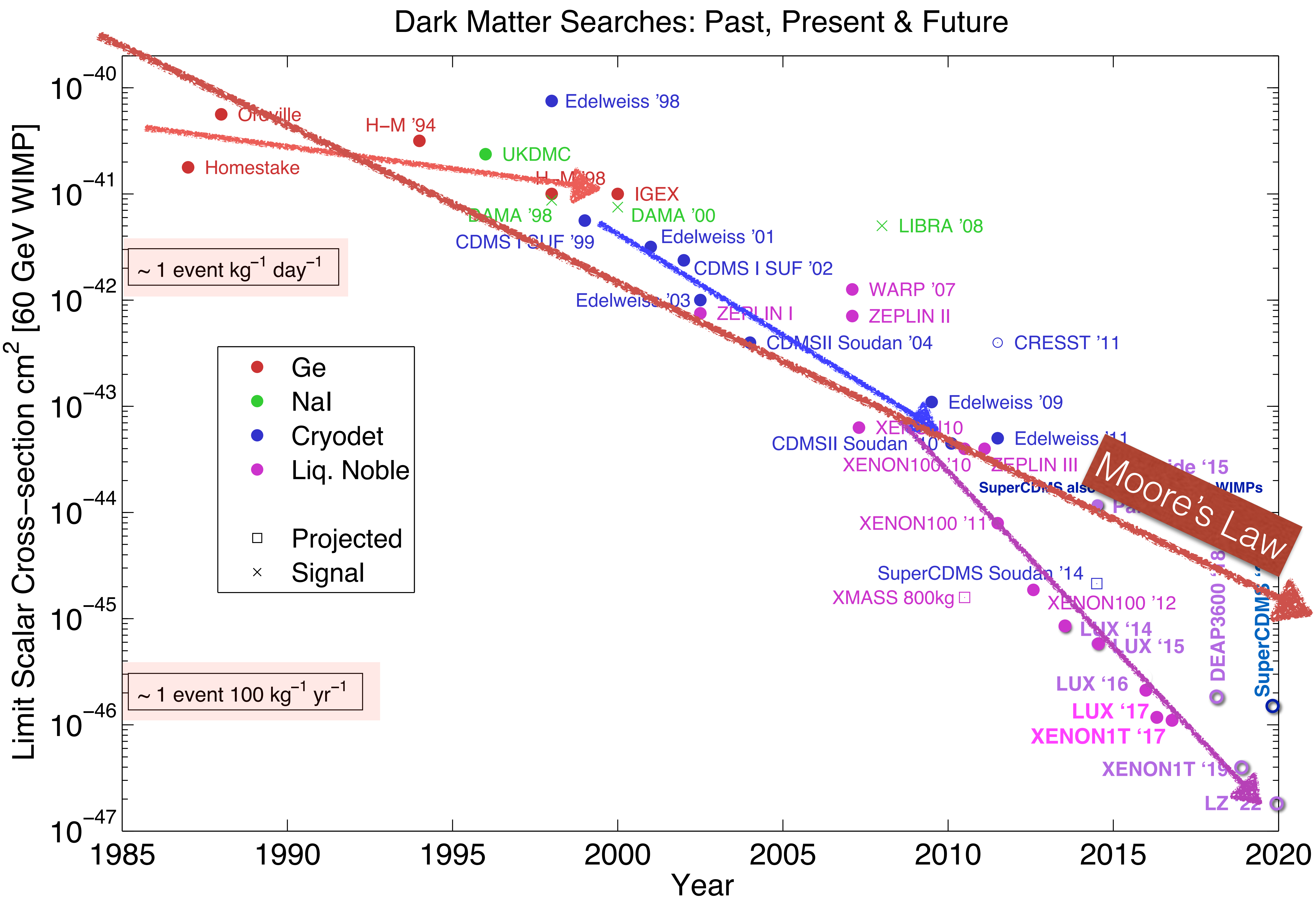


Courtesy R. Gaitskell

WIMP detection: current status

Current WIMP searchers*:

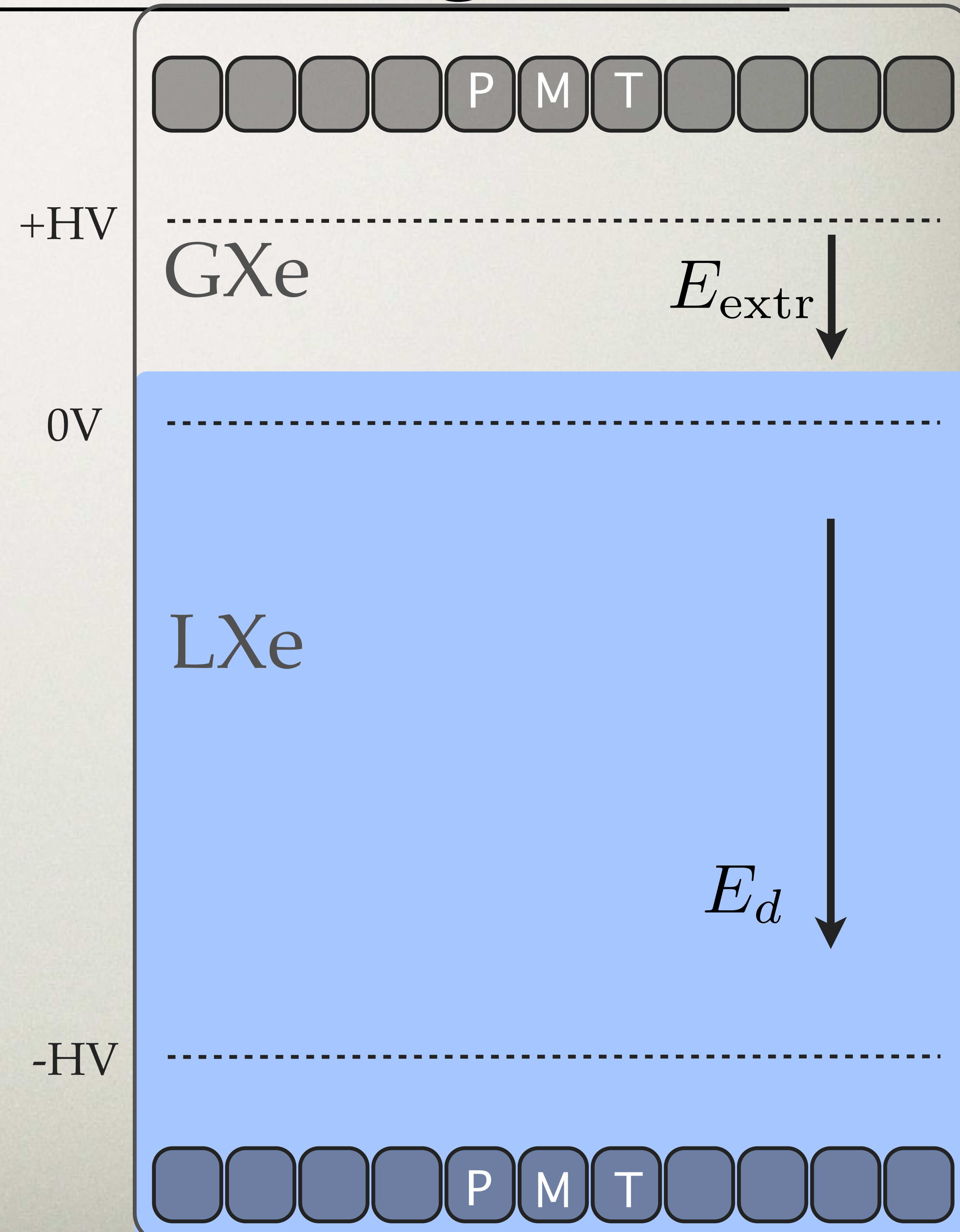
- LUX, PandaX-II, XENON1T, DarkSide (dual-phase TPC)
- DEAP3600
- SuperCDMS, CRESST
- PICO

Blue: noble liquids
Purple: cryogenic
Green: other

*Note: I am necessarily leaving out many experiments, and am instead attempting to pull several currently notable experiments

Dual-phase xenon / argon TPC

- Dual-phase Time Projection Chamber (TPC).
- The liquid portion acts as a calorimeter.



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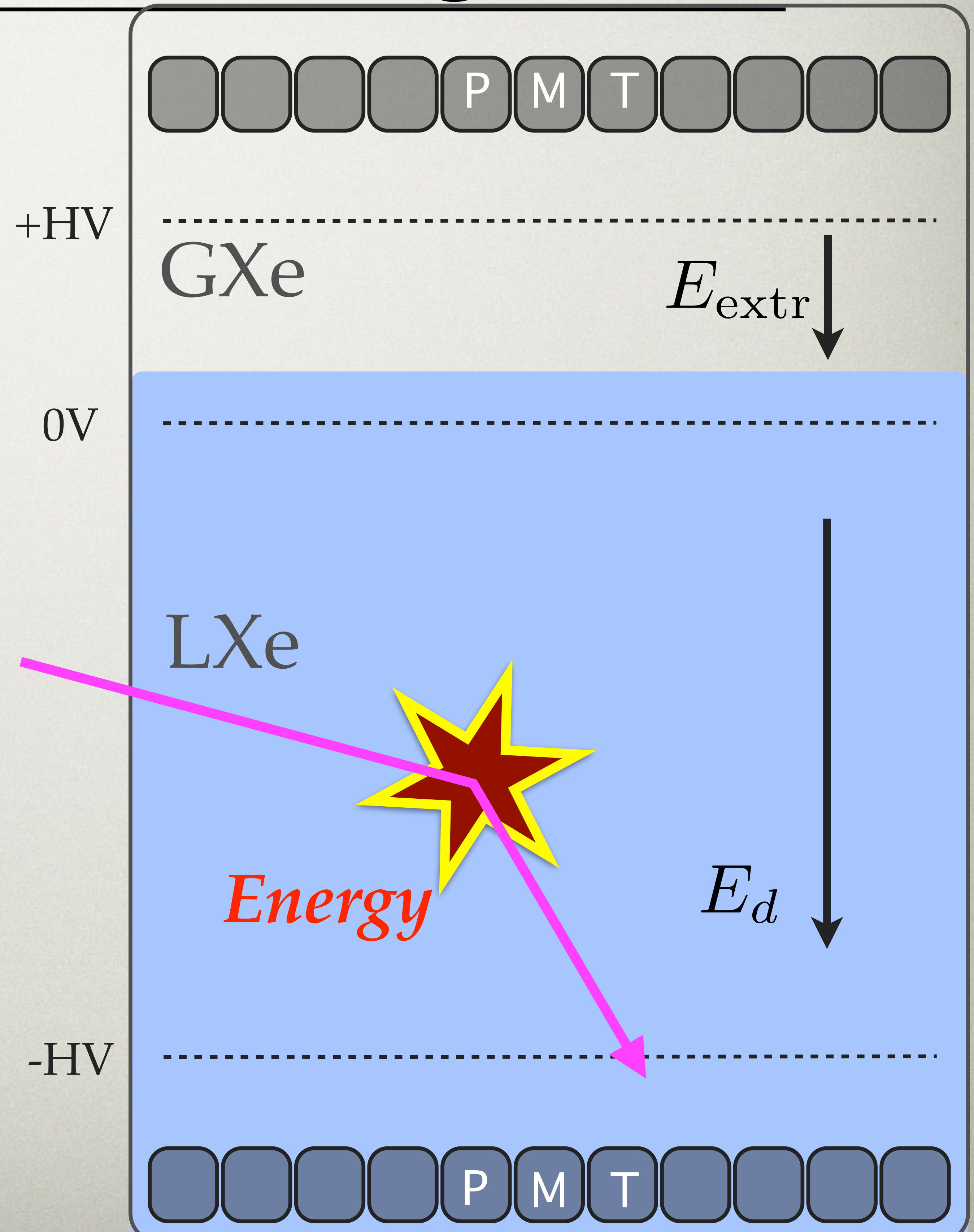

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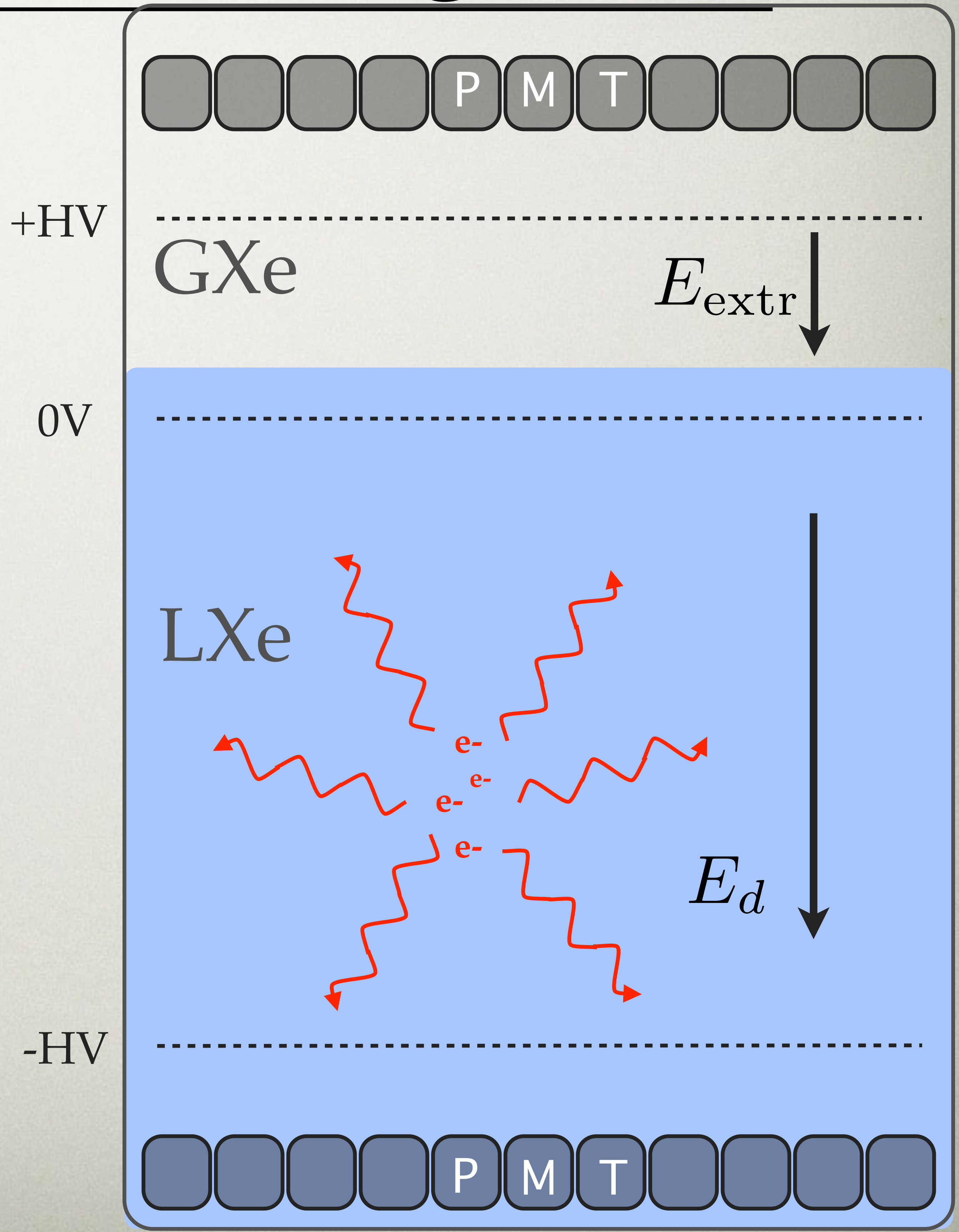

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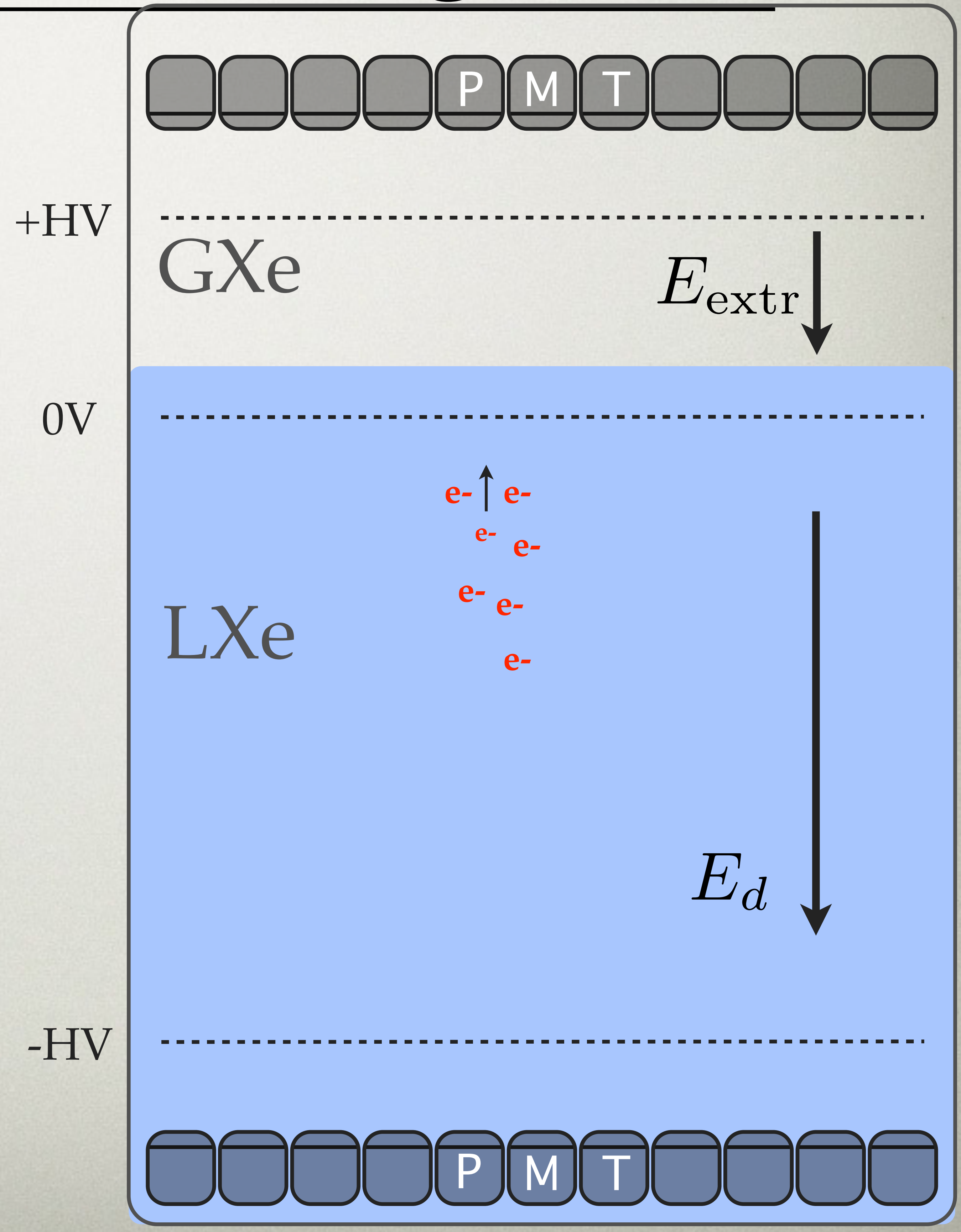
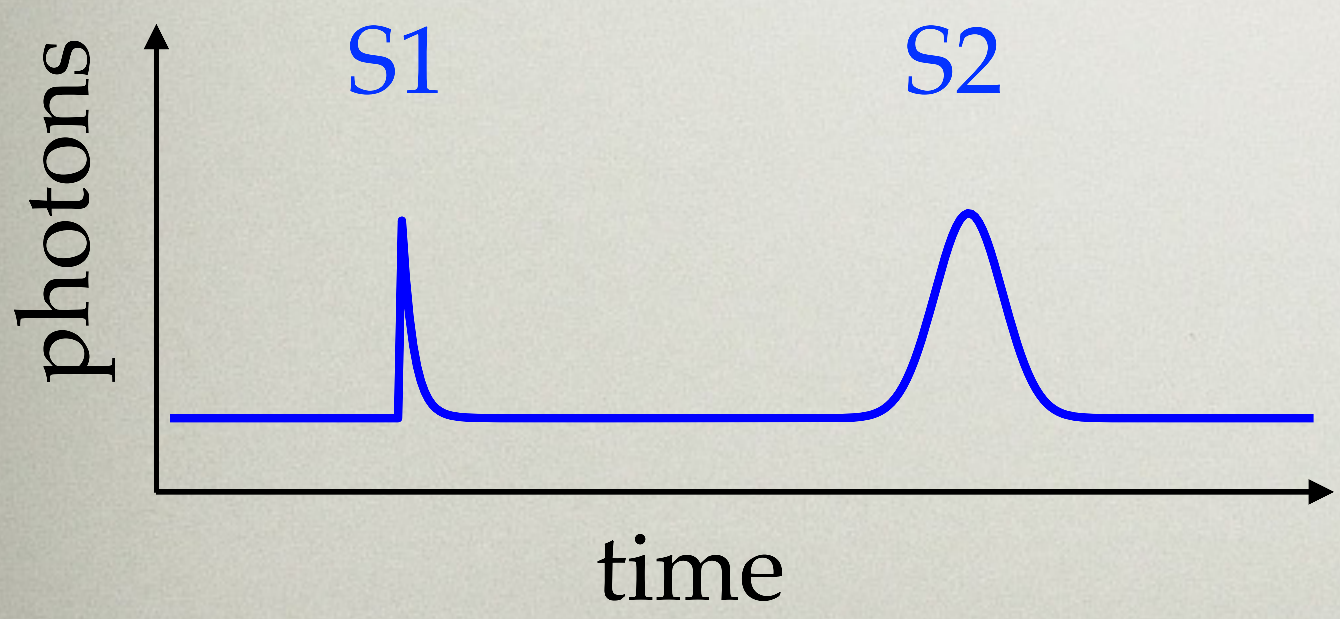
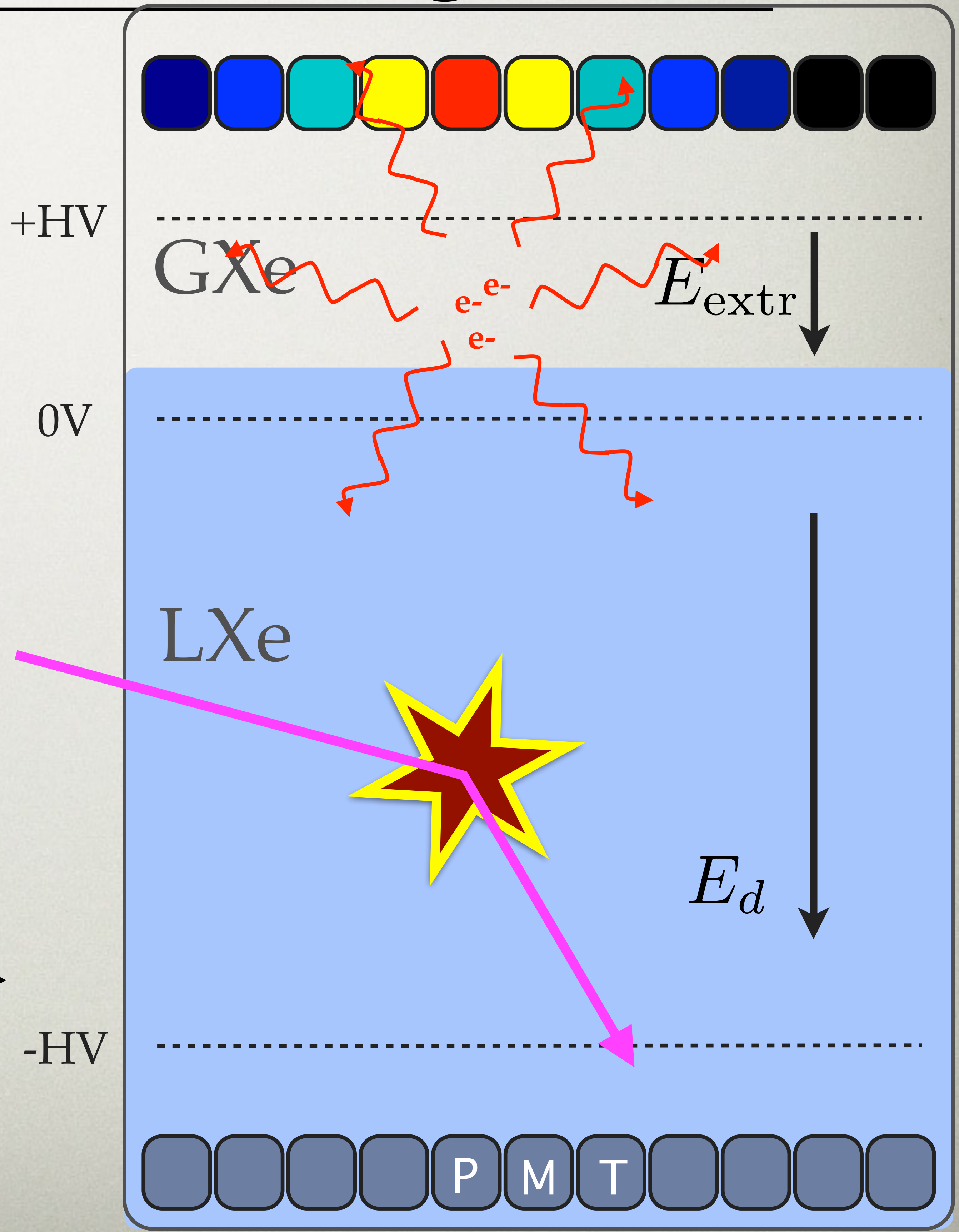
- Electrons are extracted from liquid to gas. They collide with gas Xe atoms and produce electroluminescence light, also detected by the PMTs.



Dual-phase xenon / argon TPC

- S1: primary scintillation
- S2: secondary scintillation (from ionization)
- 3-D position reconstruction possible (~mm resolution)





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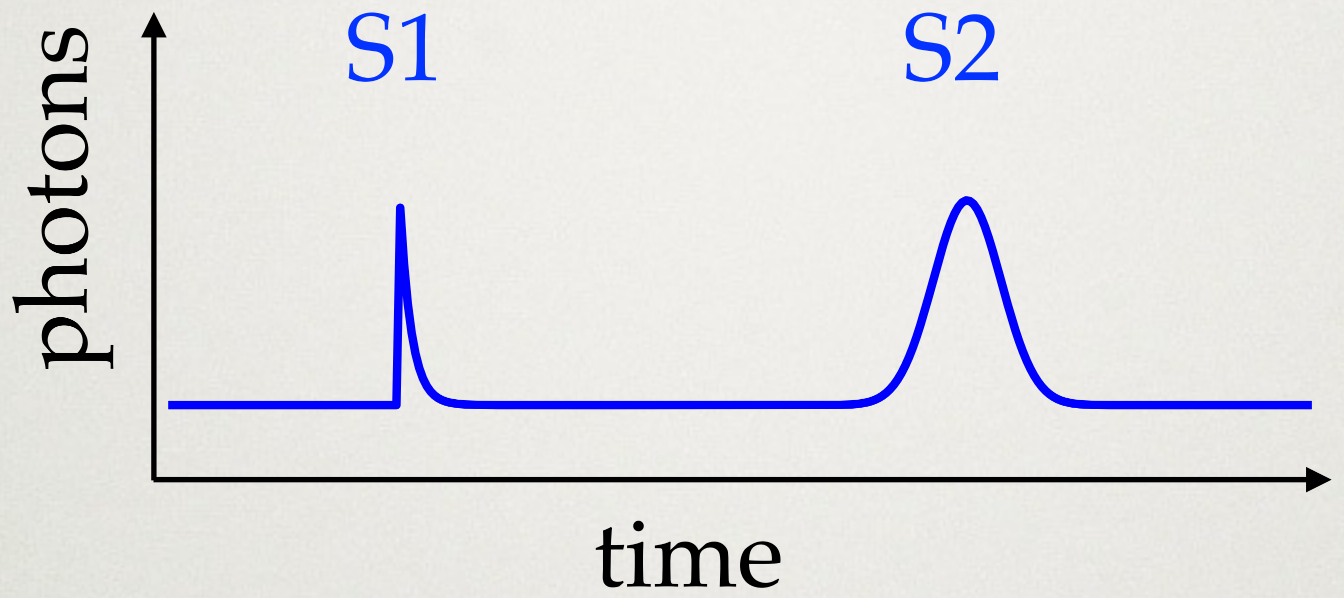


- S2/S1 ratio gives recoil type (electronic, nuclear)
- S1 decay time gives recoil type (more powerful for argon)

Noble liquid TPCs

(Existing)

LUX
(300 kg Xe)

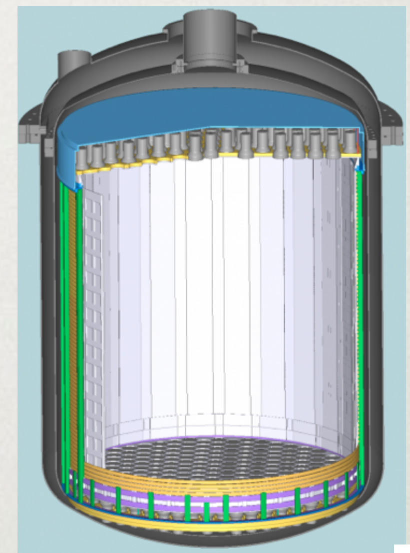
PandaX-II
(500 kg Xe)

XENON1T
(3 tonne Xe)

DarkSide50
(50 kg Ar)

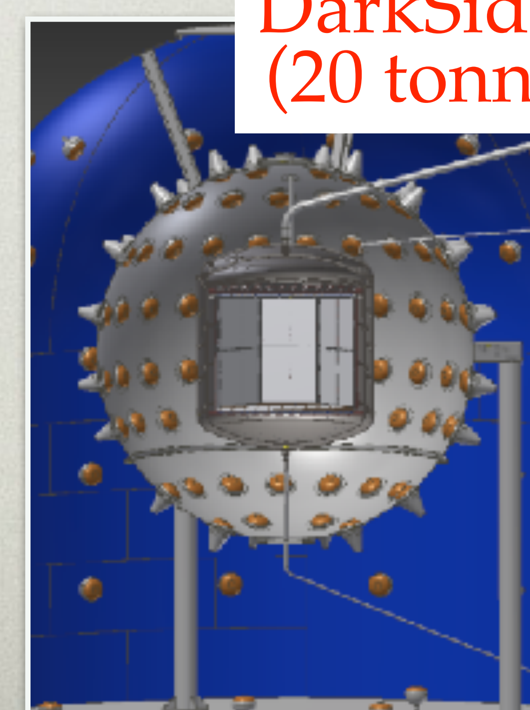
(Future)

XENONnT
(8 tonne Xe)



LZ
(10 tonne Xe)

DarkSide-20k
(20 tonne Ar)



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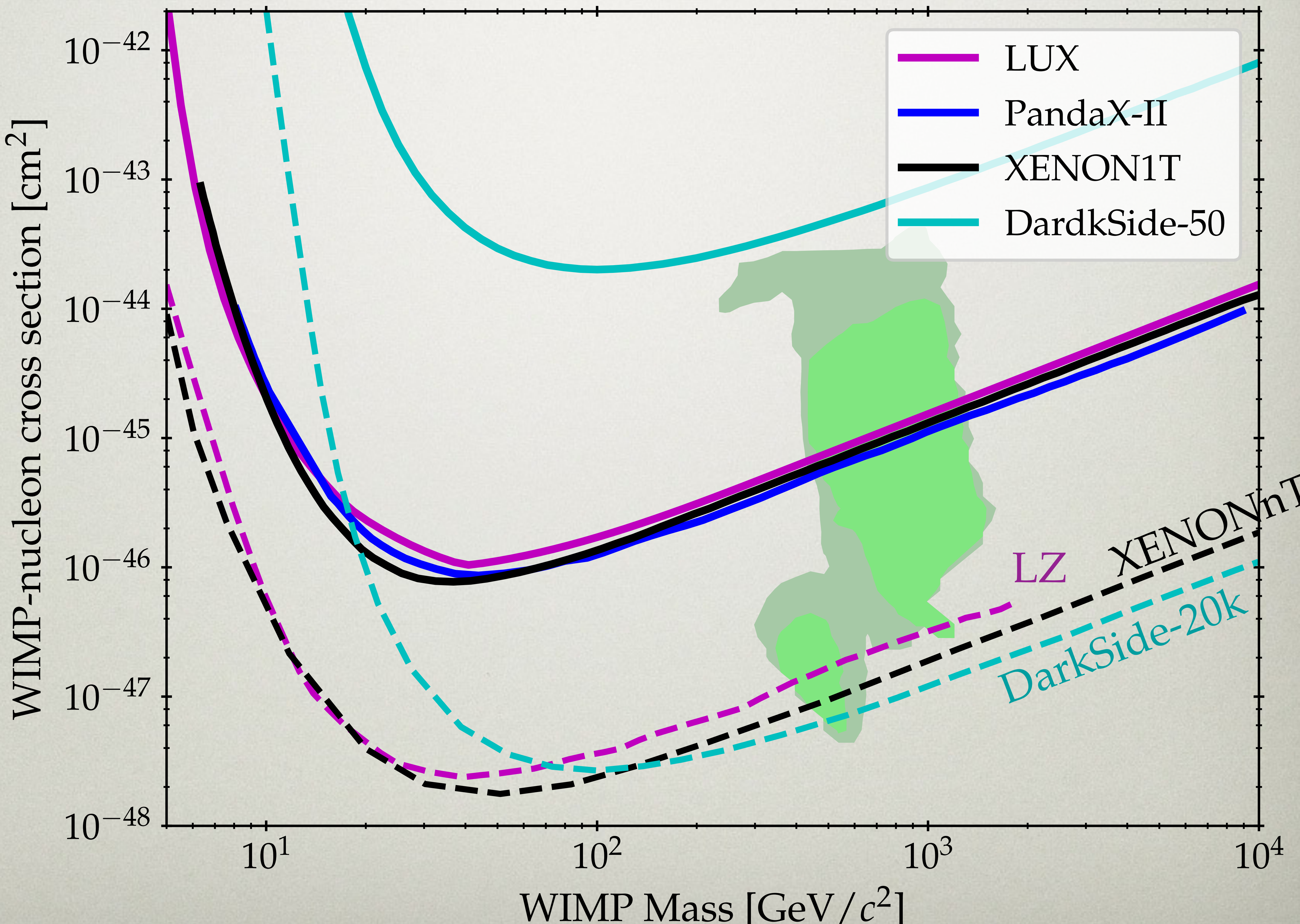

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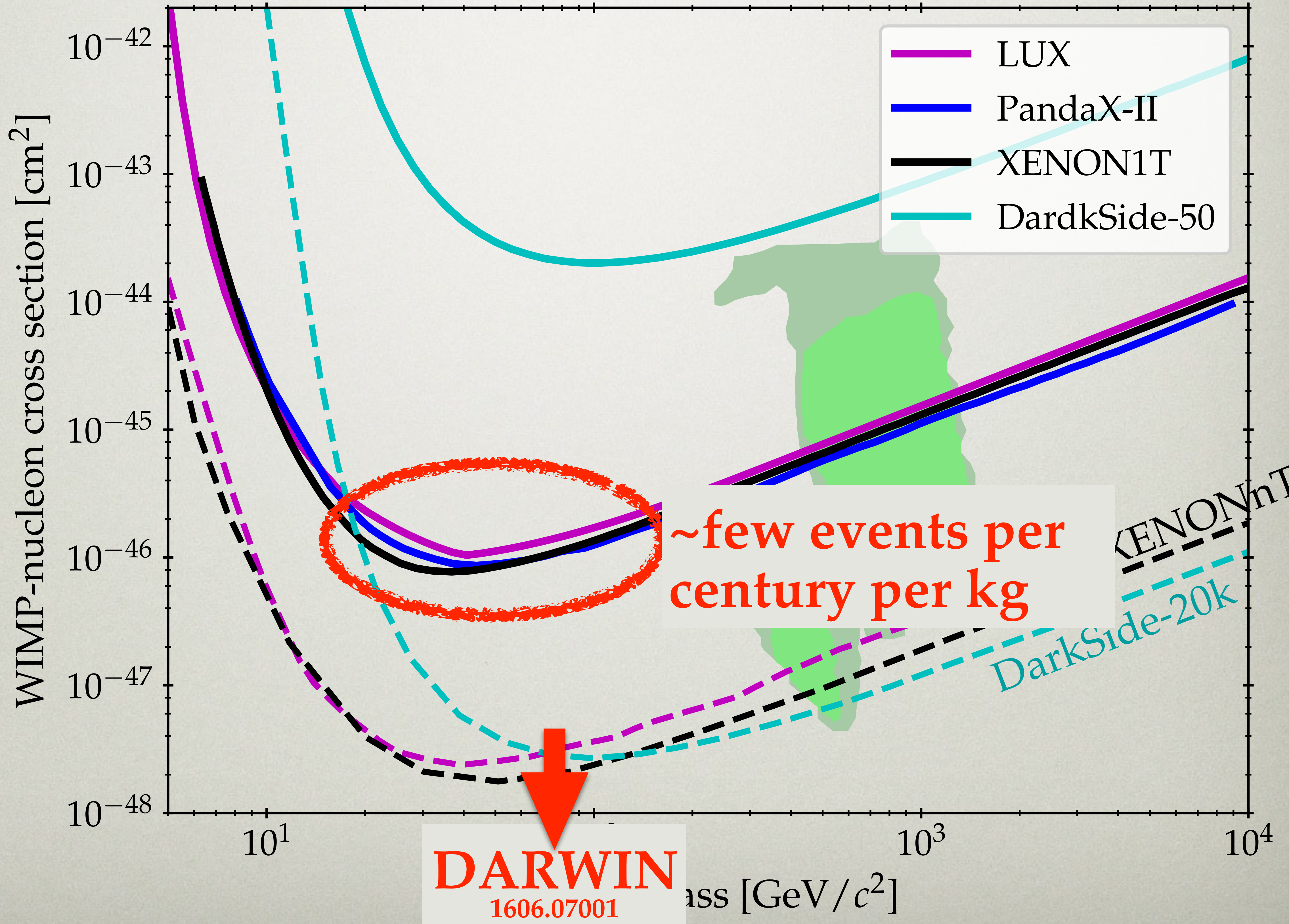
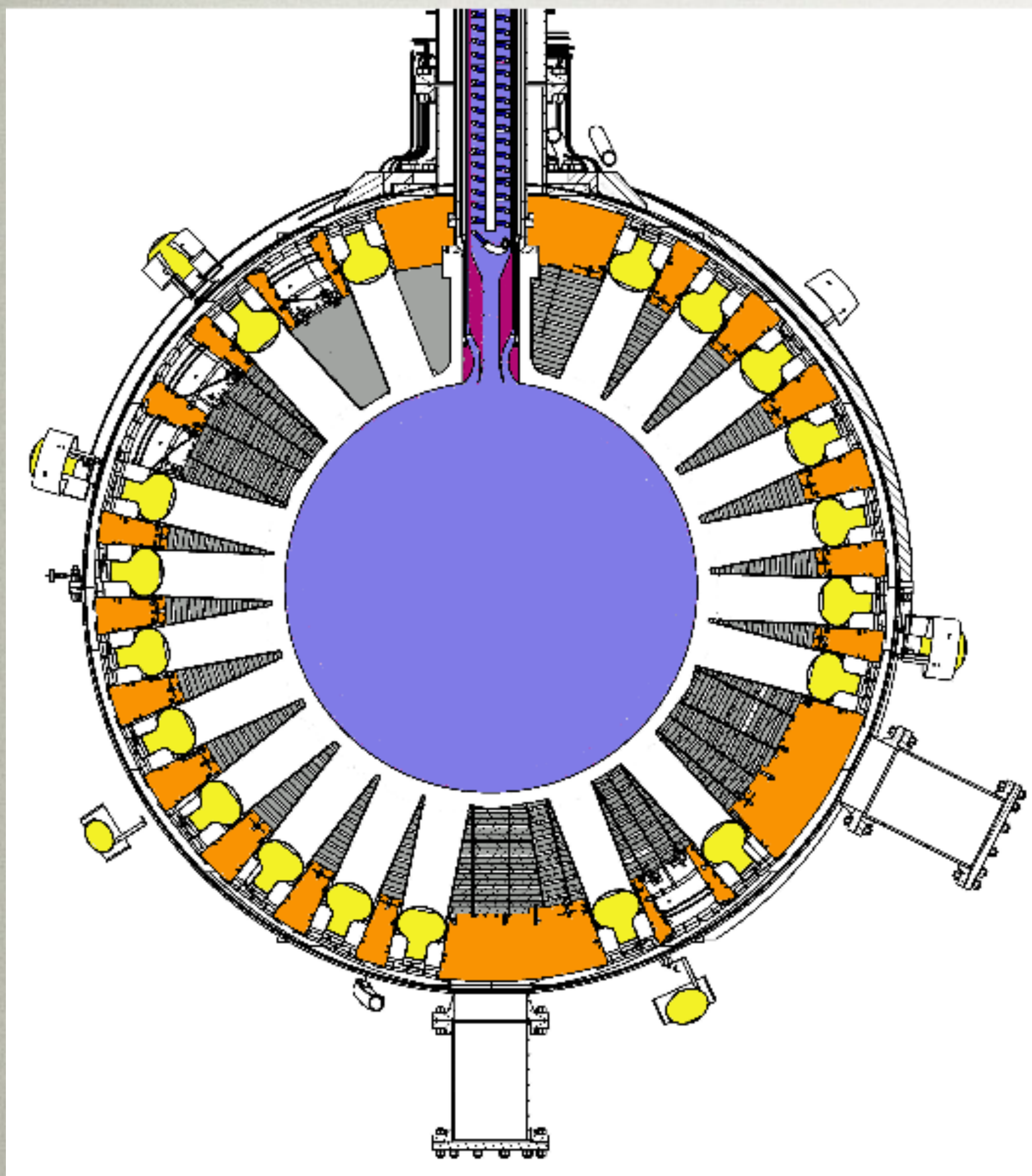
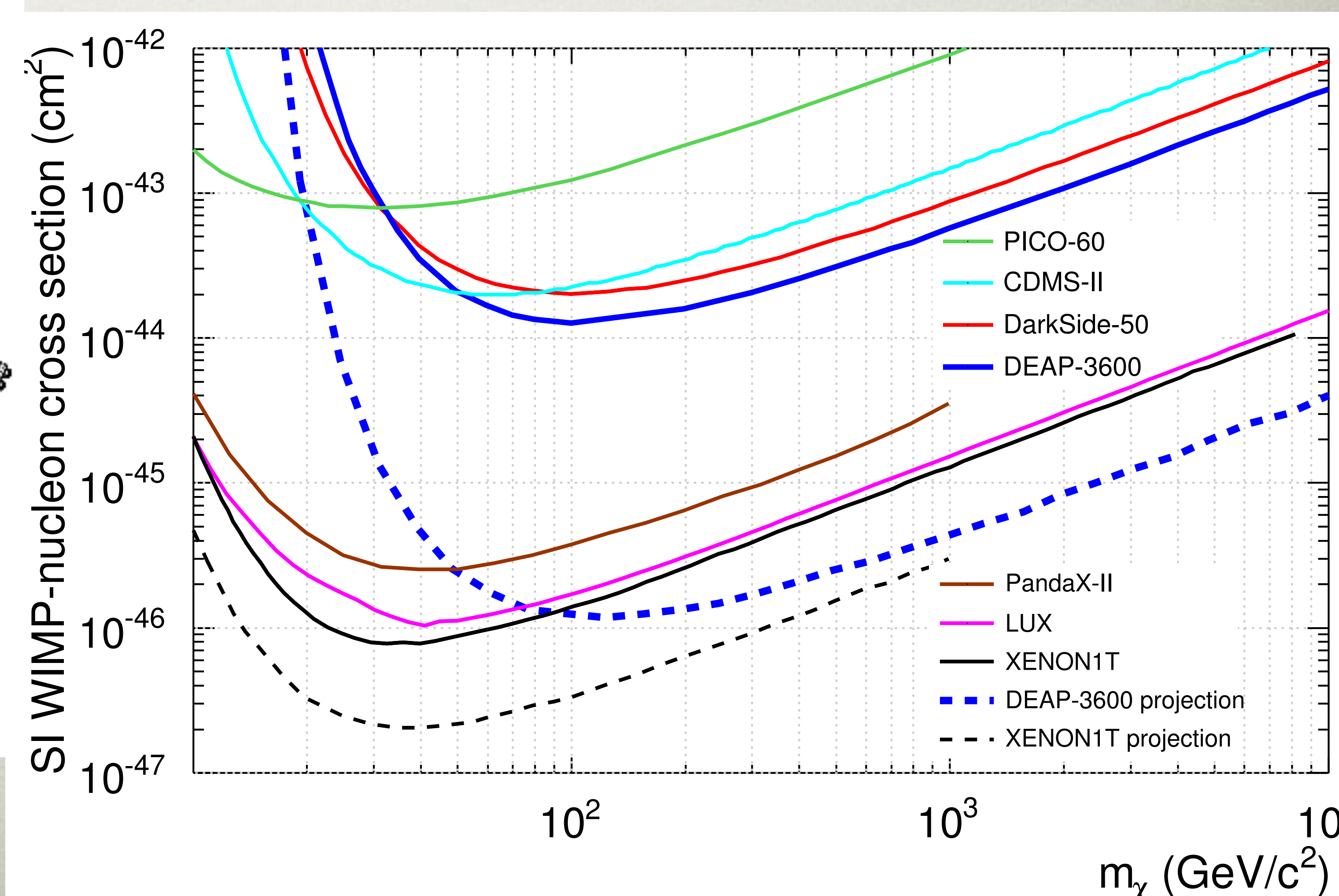


DEAP-3600

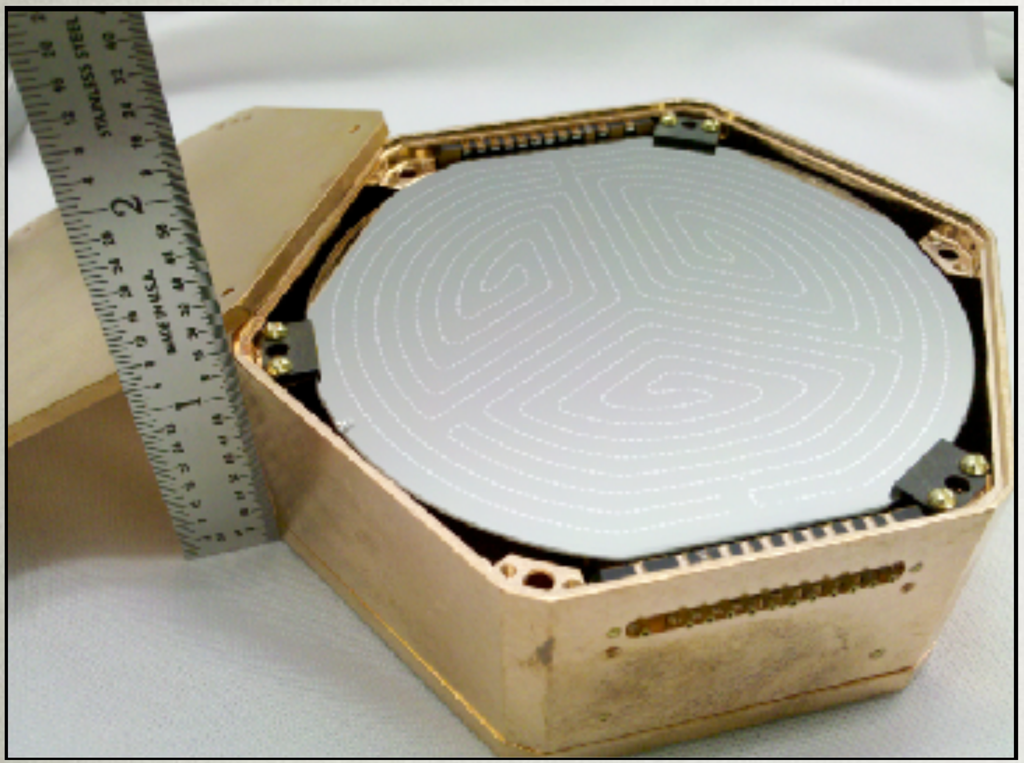
- 3.6 tonne liquid argon
- single phase
- BG rejection by scintillation pulse shape alone



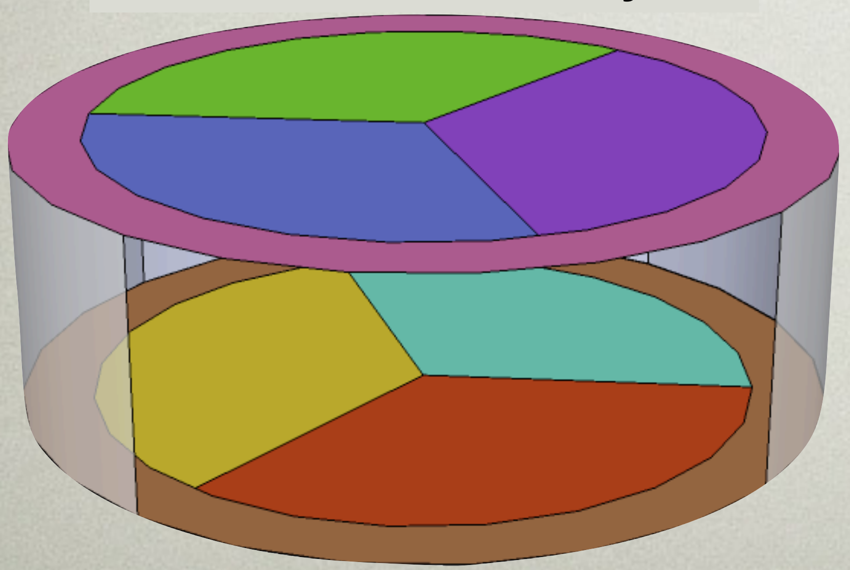


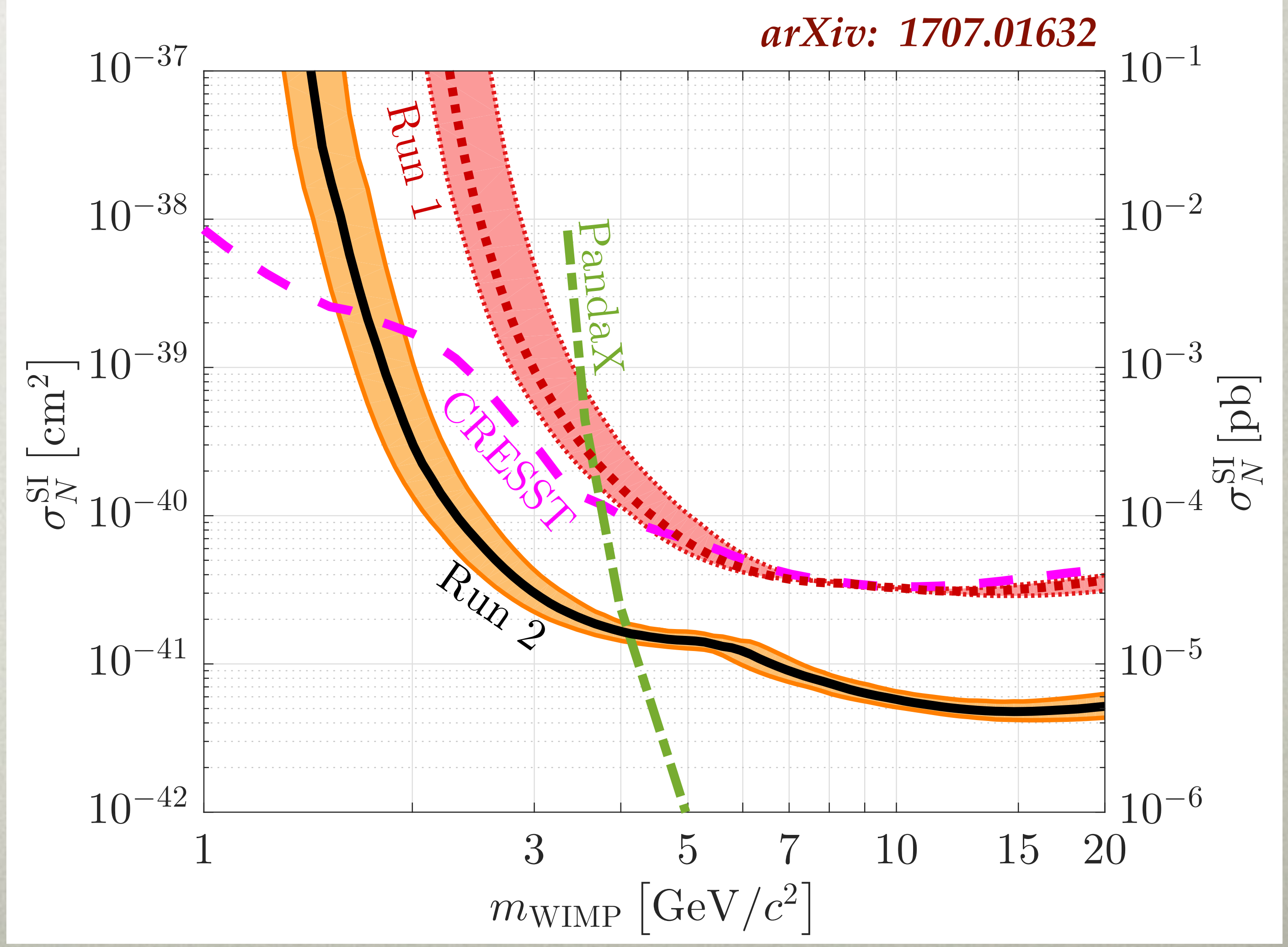
SuperCDMS

- Ge @ ~50 mK
- Measure ionization and prompt phonons
- Difficult to scale: good at low-mass WIMPs



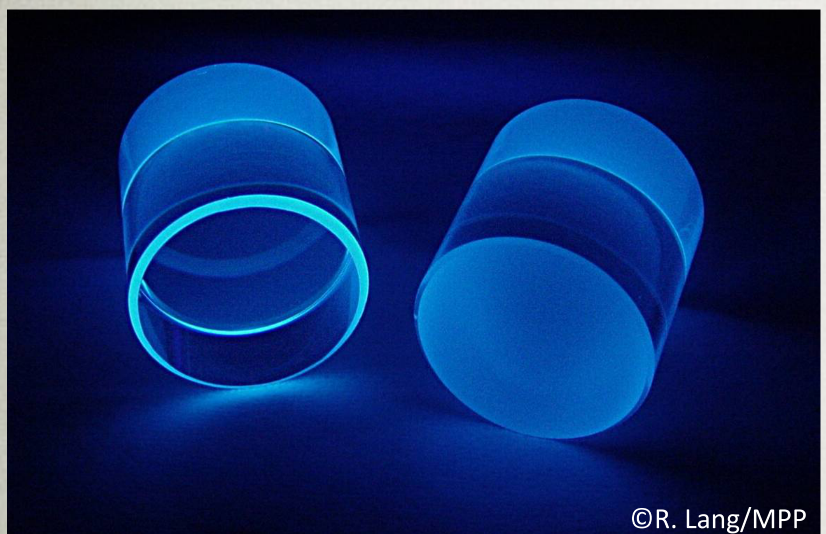
Phonon sensor layout

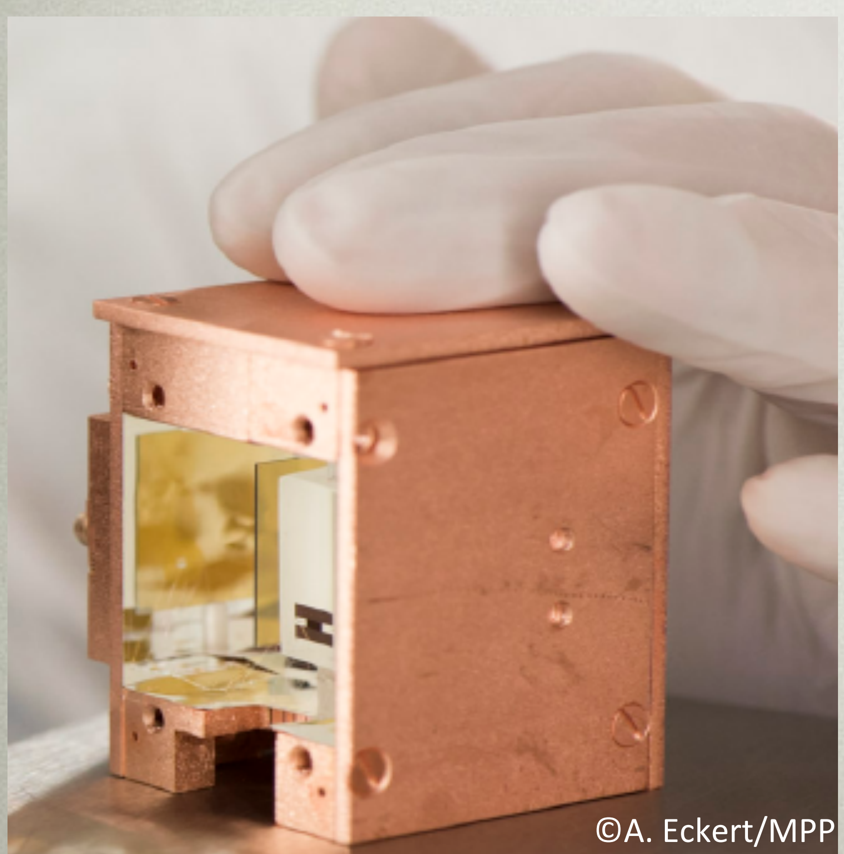




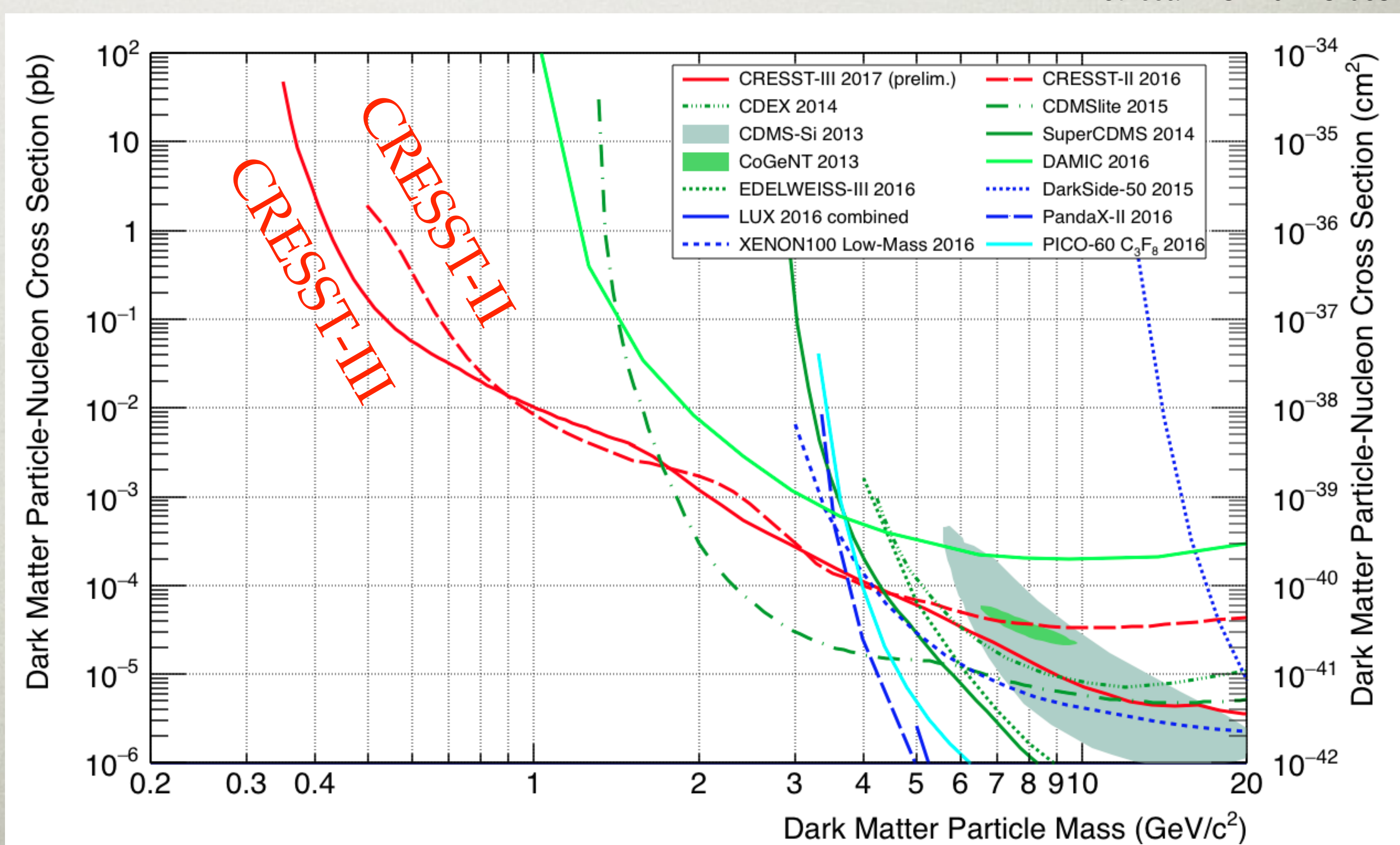
CRESST-III

- $CaWO_4$ @ ~15 mK
- Measure scintillation and phonons
- Difficult to scale: good at low-mass WIMPs

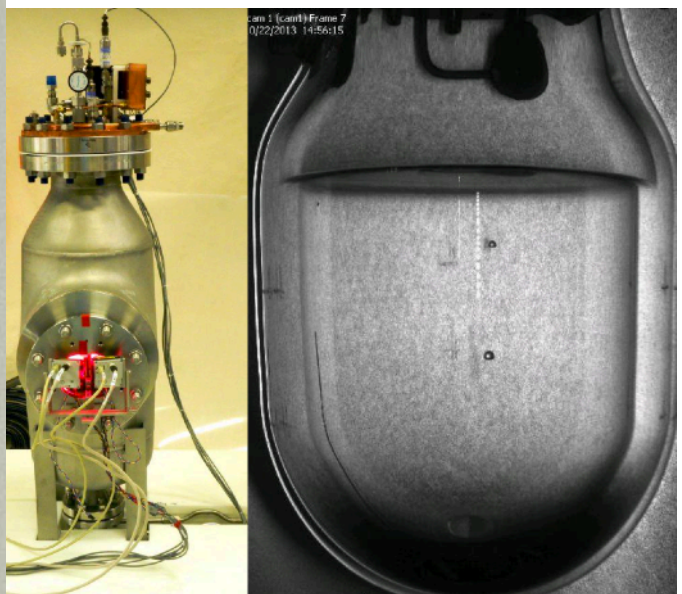




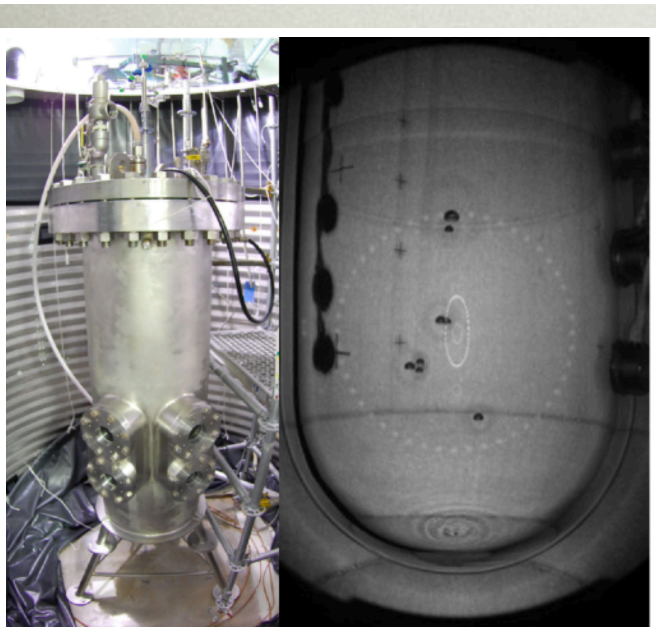
F. Petricca TAUP2017 slides



PICO

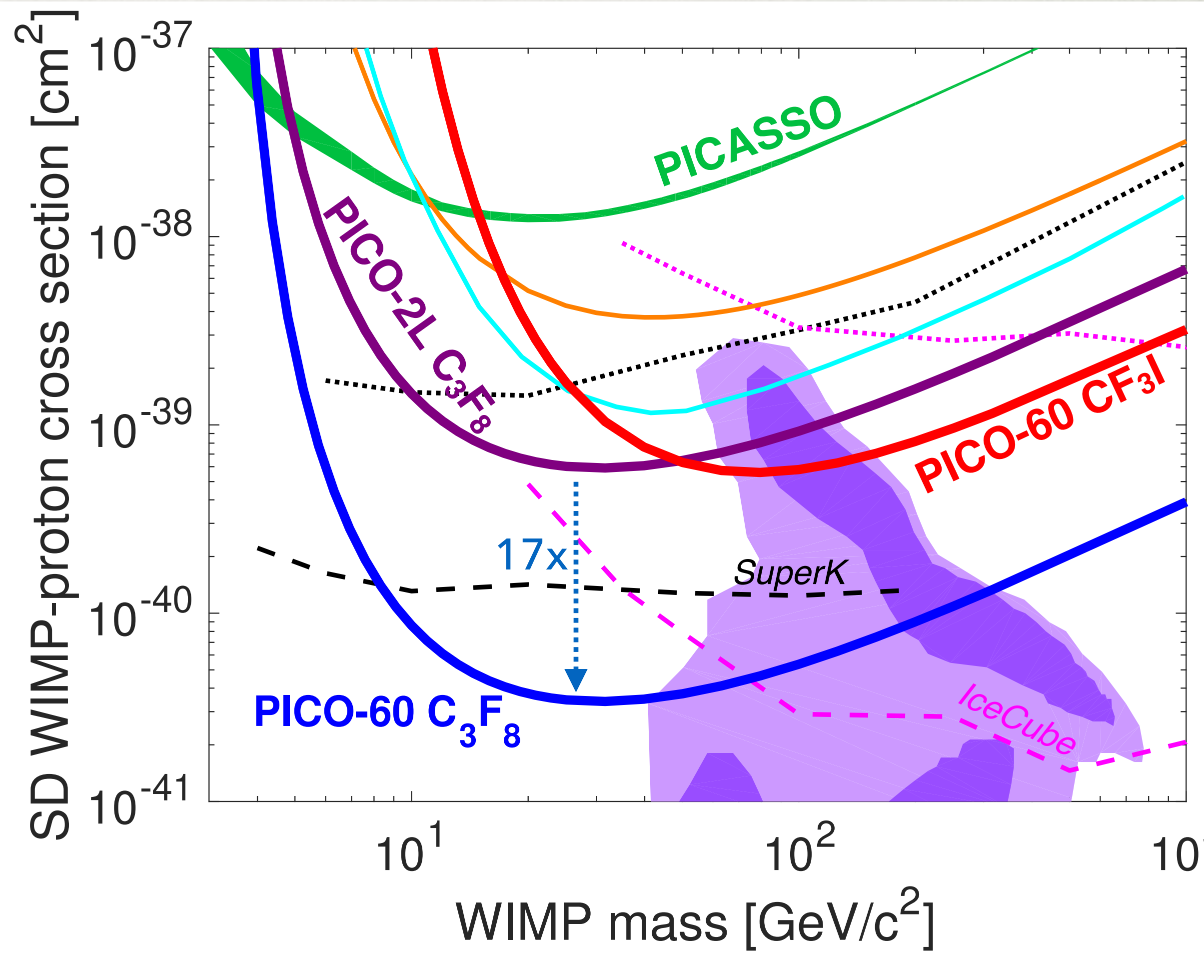


PICO-2L
C_3F_8



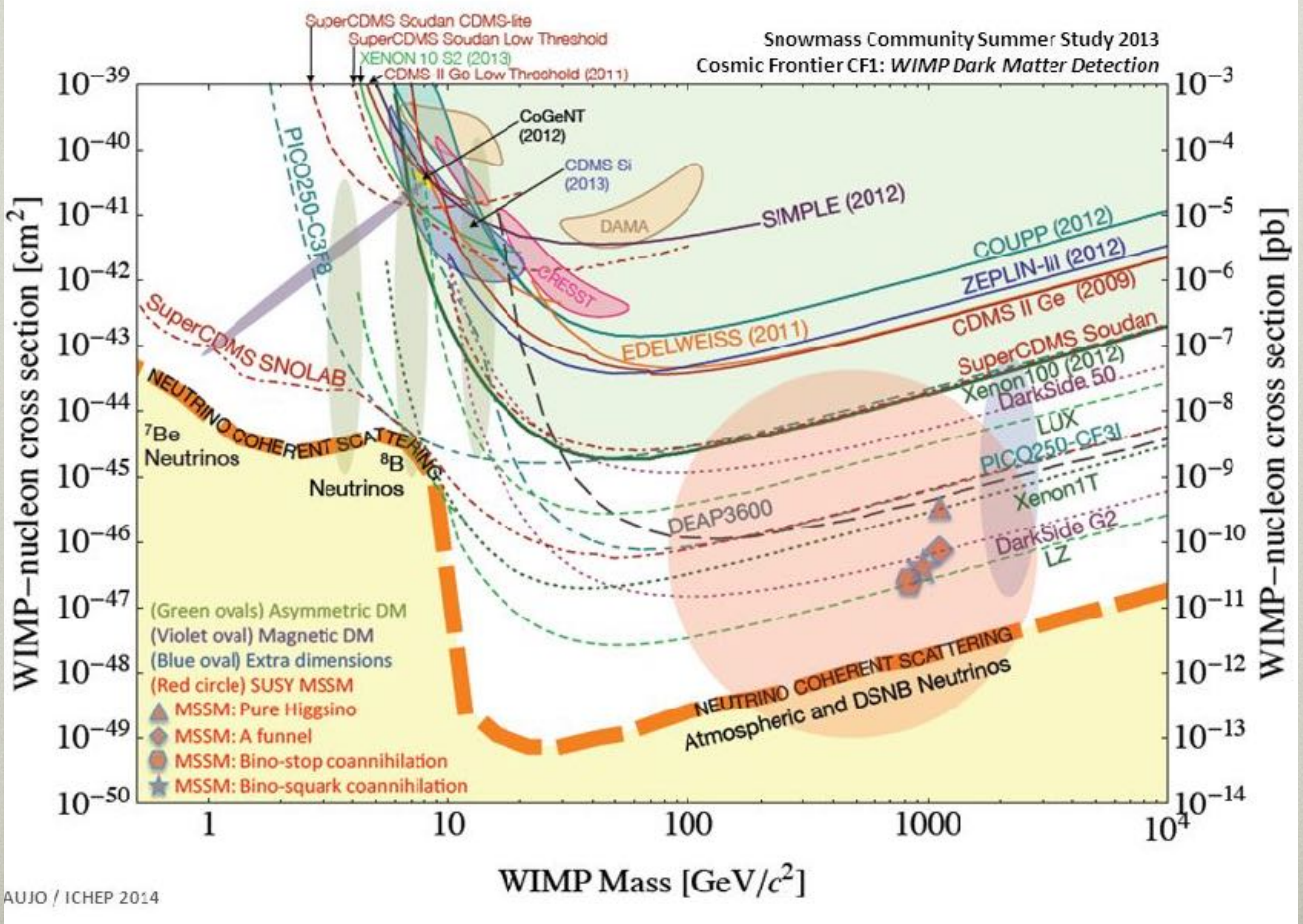
COUPP-60 → **PICO-60**
CF_3I, C_3F_8

- Superheated bubble chamber
- Thermodynamically insensitive to EM backgrounds
- Chosen media have unpaired protons: sensitive to pure-proton SD couplings



12 *C. Amole *et al.*, Phys. Rev. Lett. **118**, 251301 **(2017)**

Neutrino "floor"



The more general WIMP

- WIMPs can couple to nuclei in more ways than simply "spin independent" and "spin dependent".
- Sixteen possible effective operators for WIMP-nucleus scattering: we're not sensitive to UV details.
- Recently, WIMP experiments have started reporting results in this form as well.

$$\mathcal{O}_1 = 1$$
$$\mathcal{O}_2 = (v^\perp)^2$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot (\vec{q} \times \vec{v}^\perp)$$
$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$$
$$\mathcal{O}_6 = (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q})$$
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$$
$$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \vec{q})$$
$$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{v}^\perp)$$
$$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \vec{q})((\vec{S}_N \times \vec{v}^\perp) \cdot \vec{q})$$
$$\mathcal{O}_{16} = -((\vec{S}_\chi \times \vec{v}^\perp) \cdot \vec{q})(\vec{S}_N \cdot \vec{q})$$

Where are we going?

The WIMP

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Cosmological Lower Bound on Heavy-Neutrino Masses

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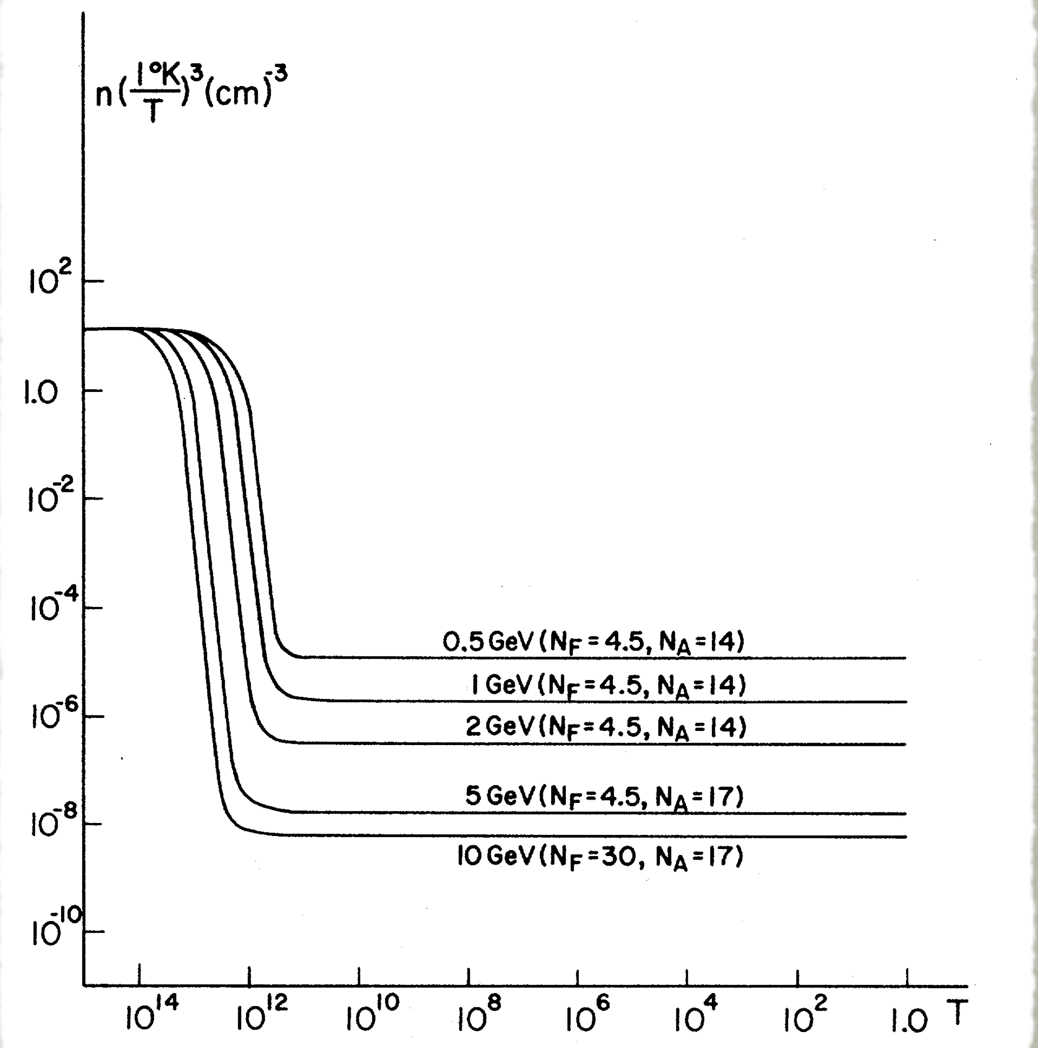
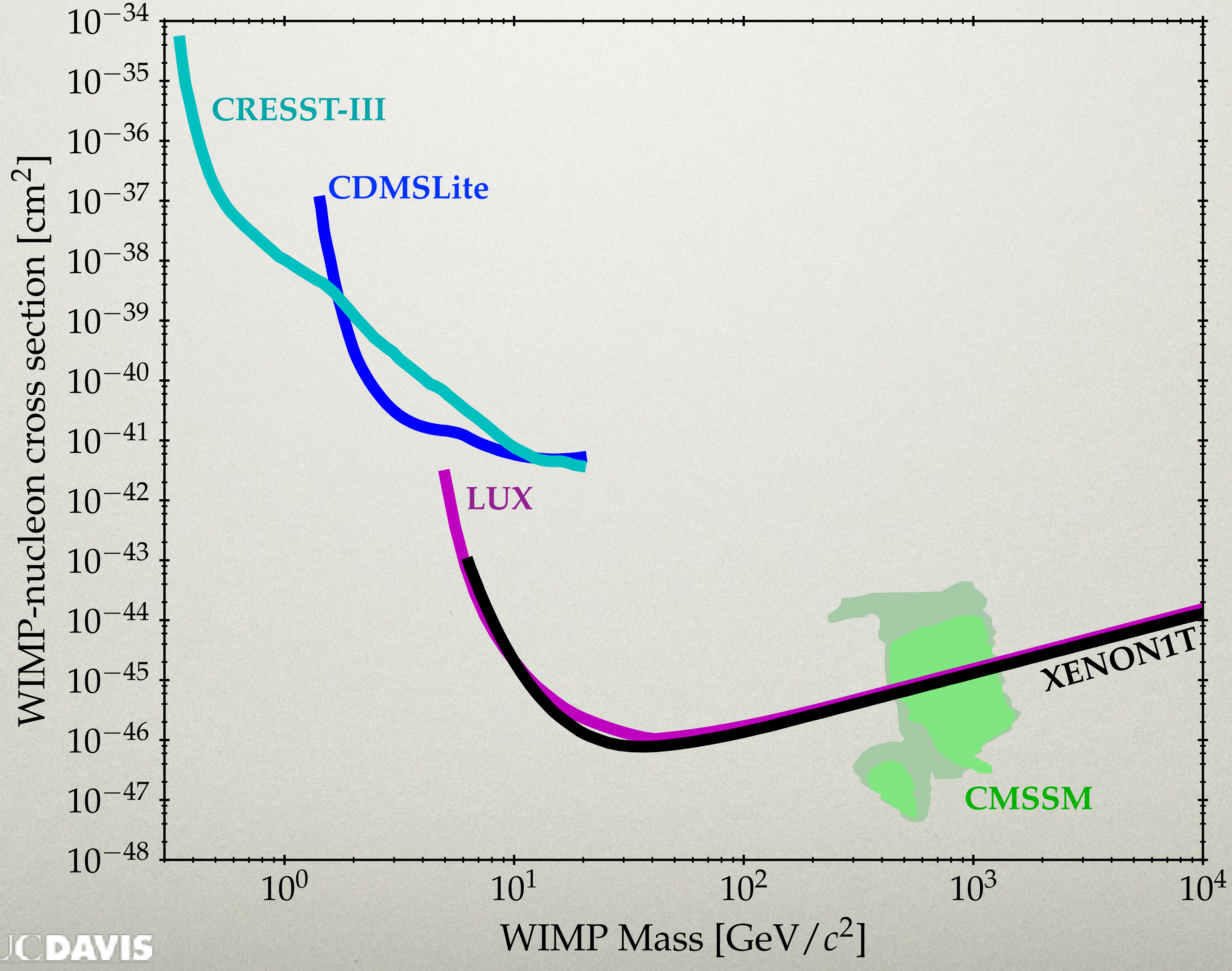


Q: If the WIMP is a miracle, why haven't we detected it yet?

Is the WIMP a miracle?

What is expected for a

weakly interacting massive particle ?



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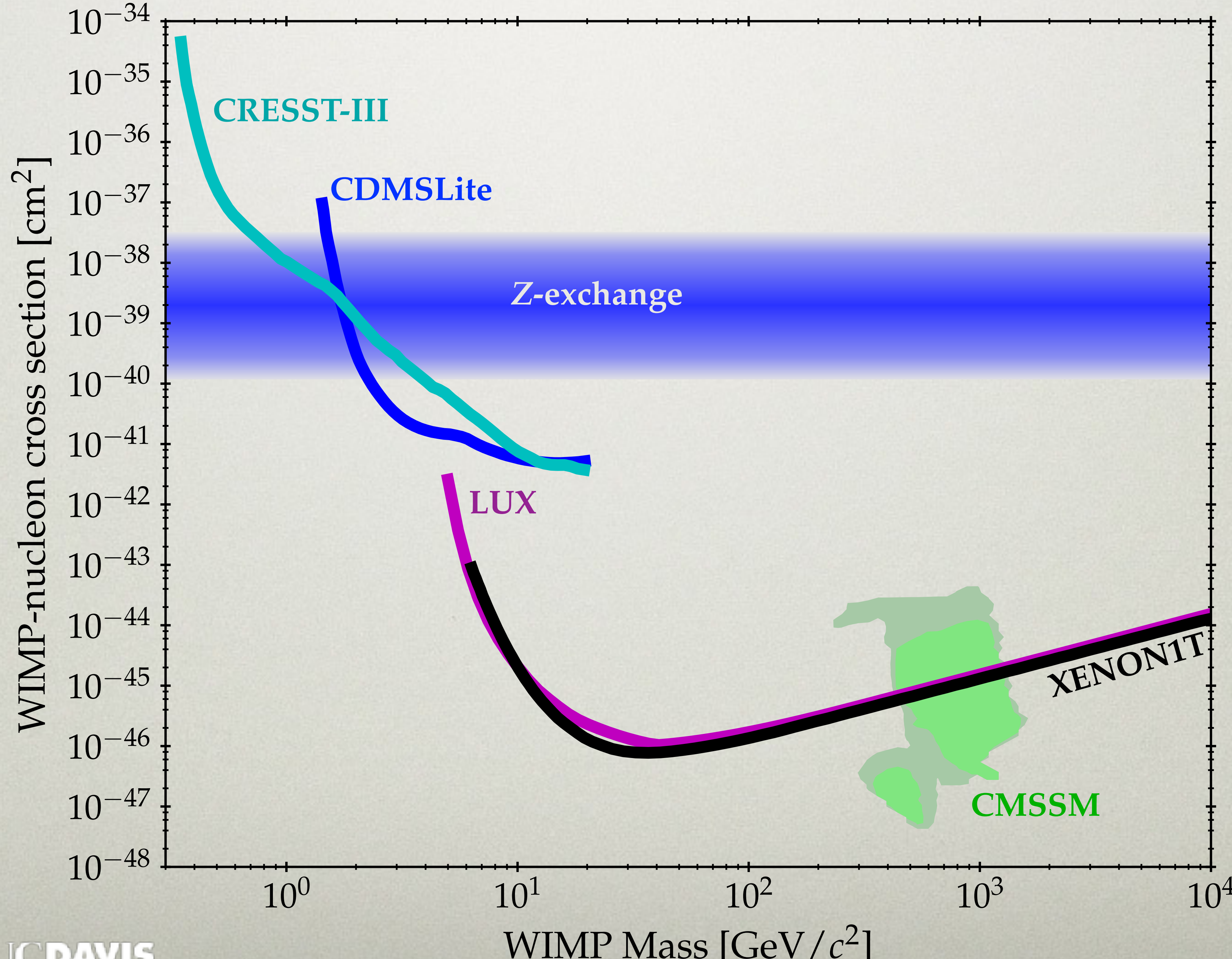

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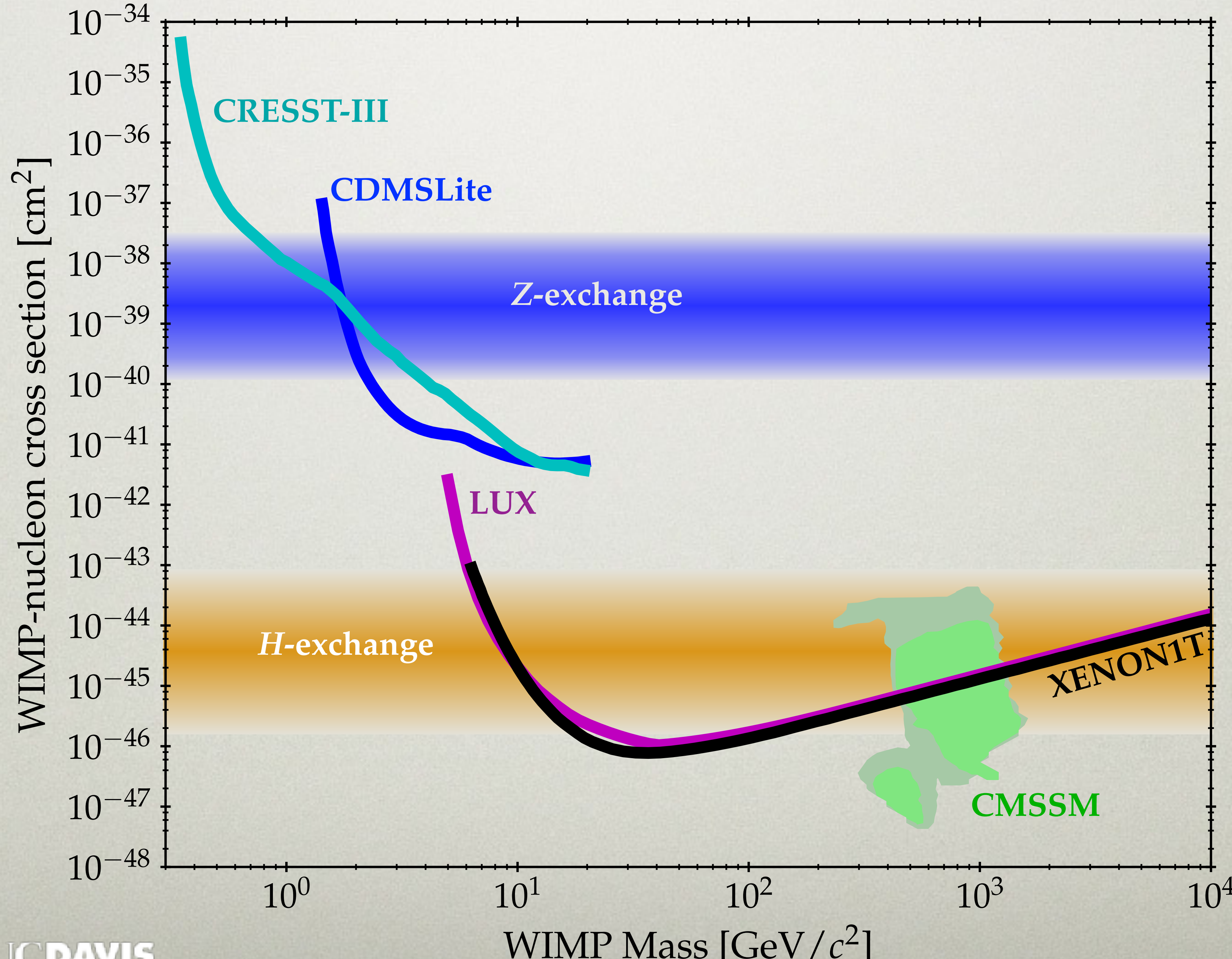
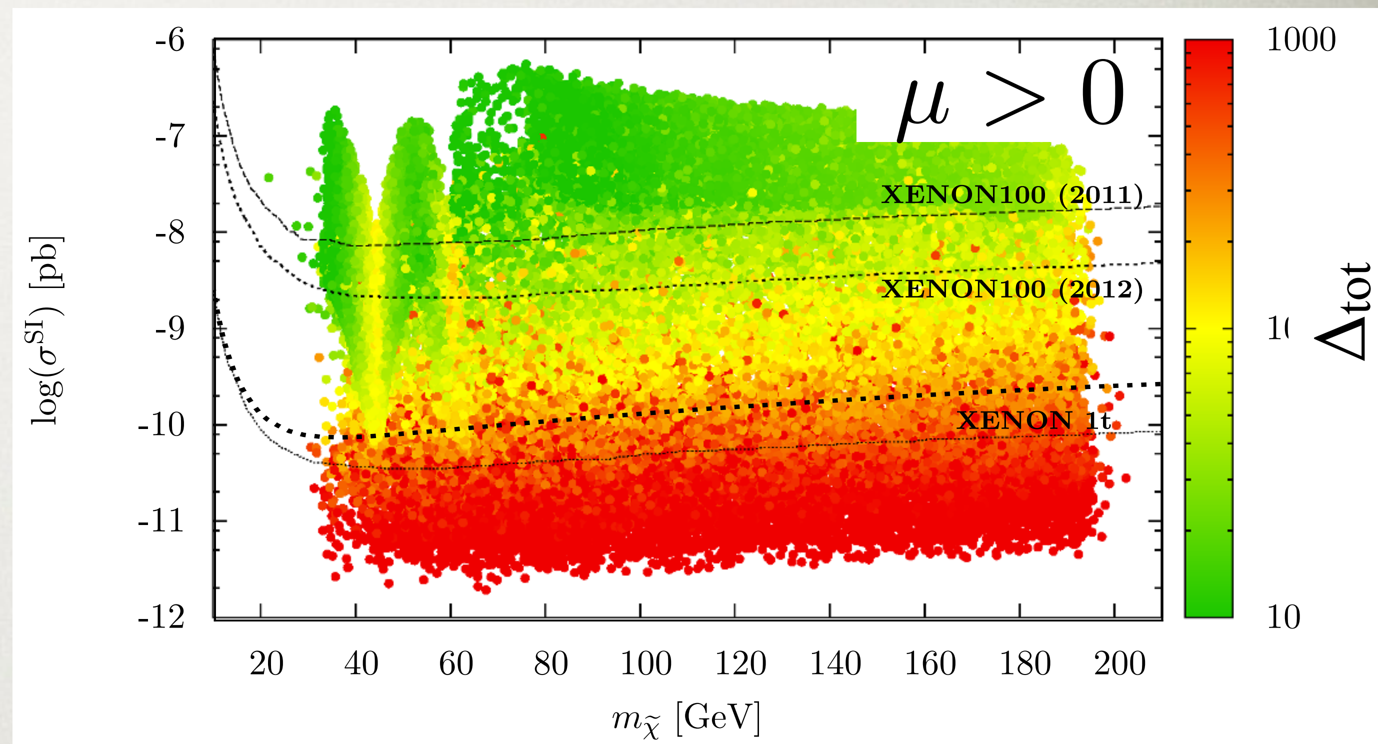
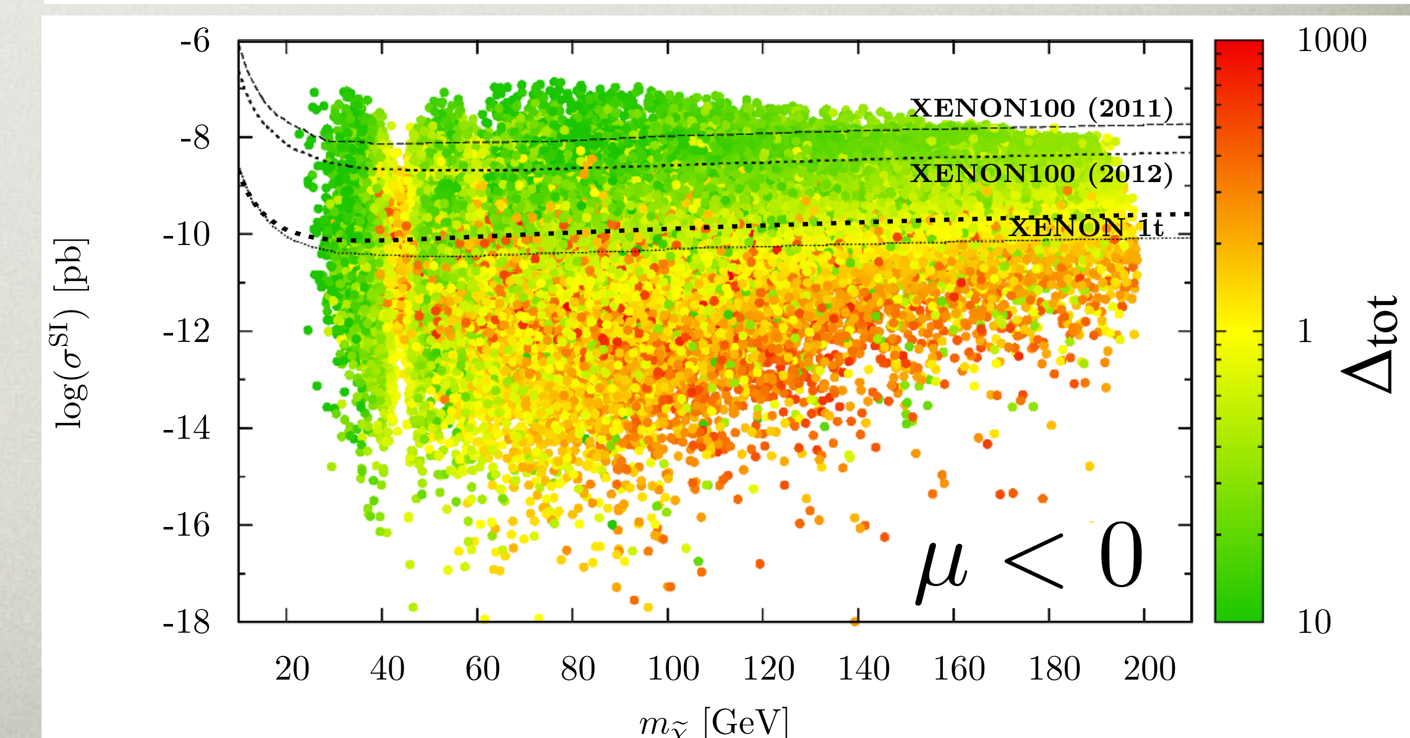


WIMP naturalness (in pMSSM)

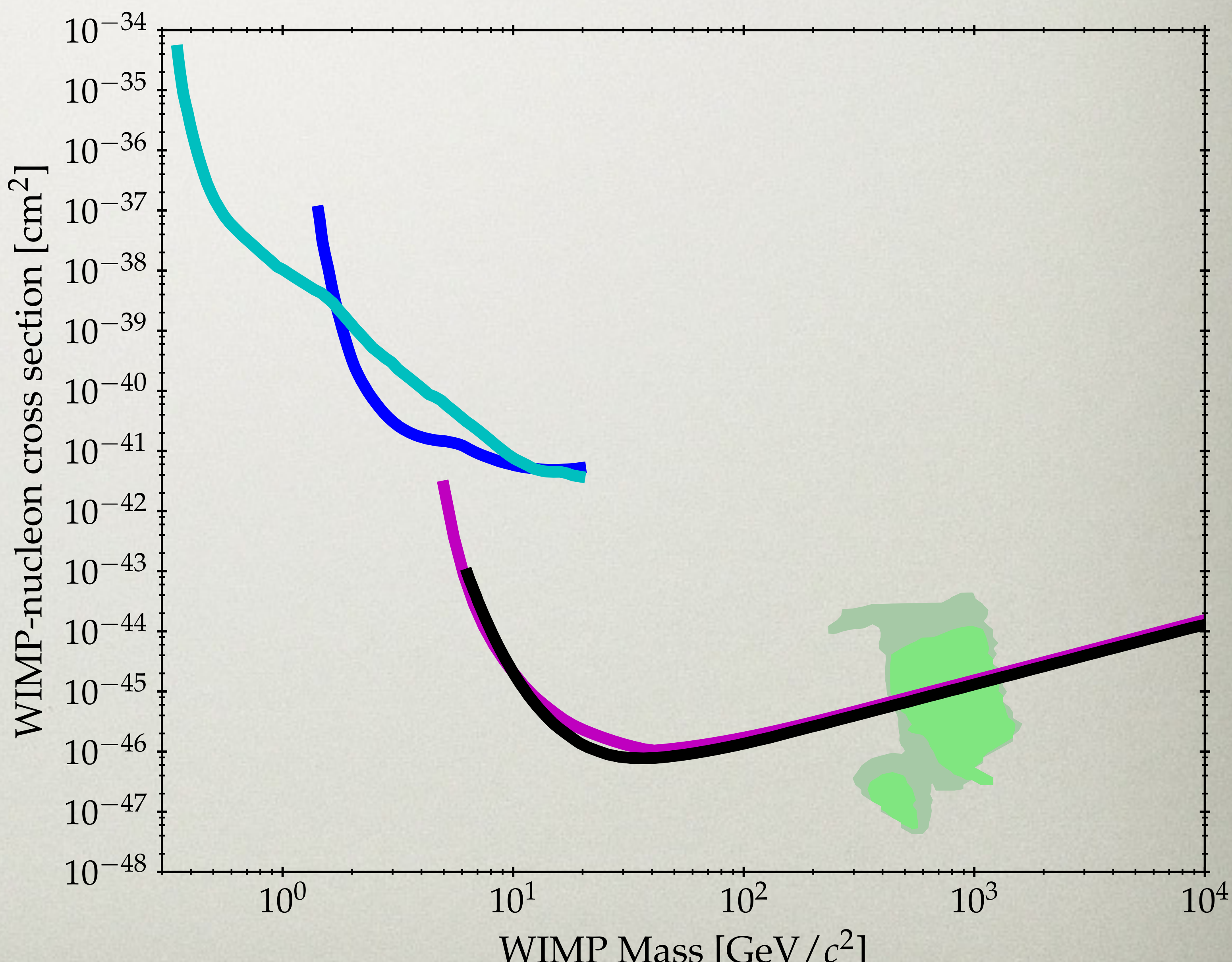
P. Grothaus, M. Lindner, Y. Takanishi, JHEP07 (2013) 094, arXiv:1207.4434

- Each point corresponds to a random sampling in [19-dim] pMSSM space.
- Color gives value of fine-tuning parameter, Δ_{tot} , at that point.
- Red = more finely tuned
- Does the WIMP lose motivation if it requires fine tuning?





Pushing frontiers



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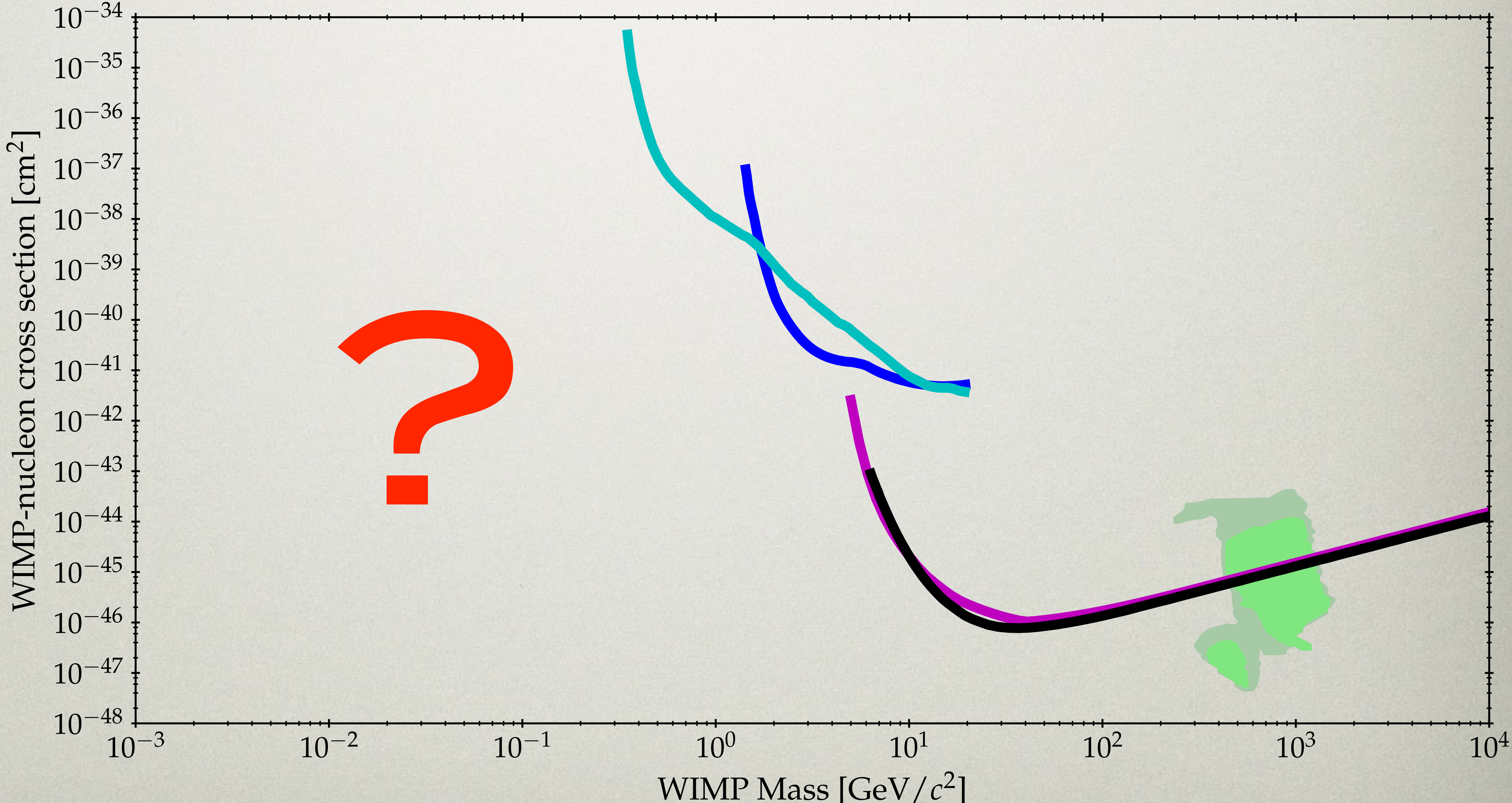
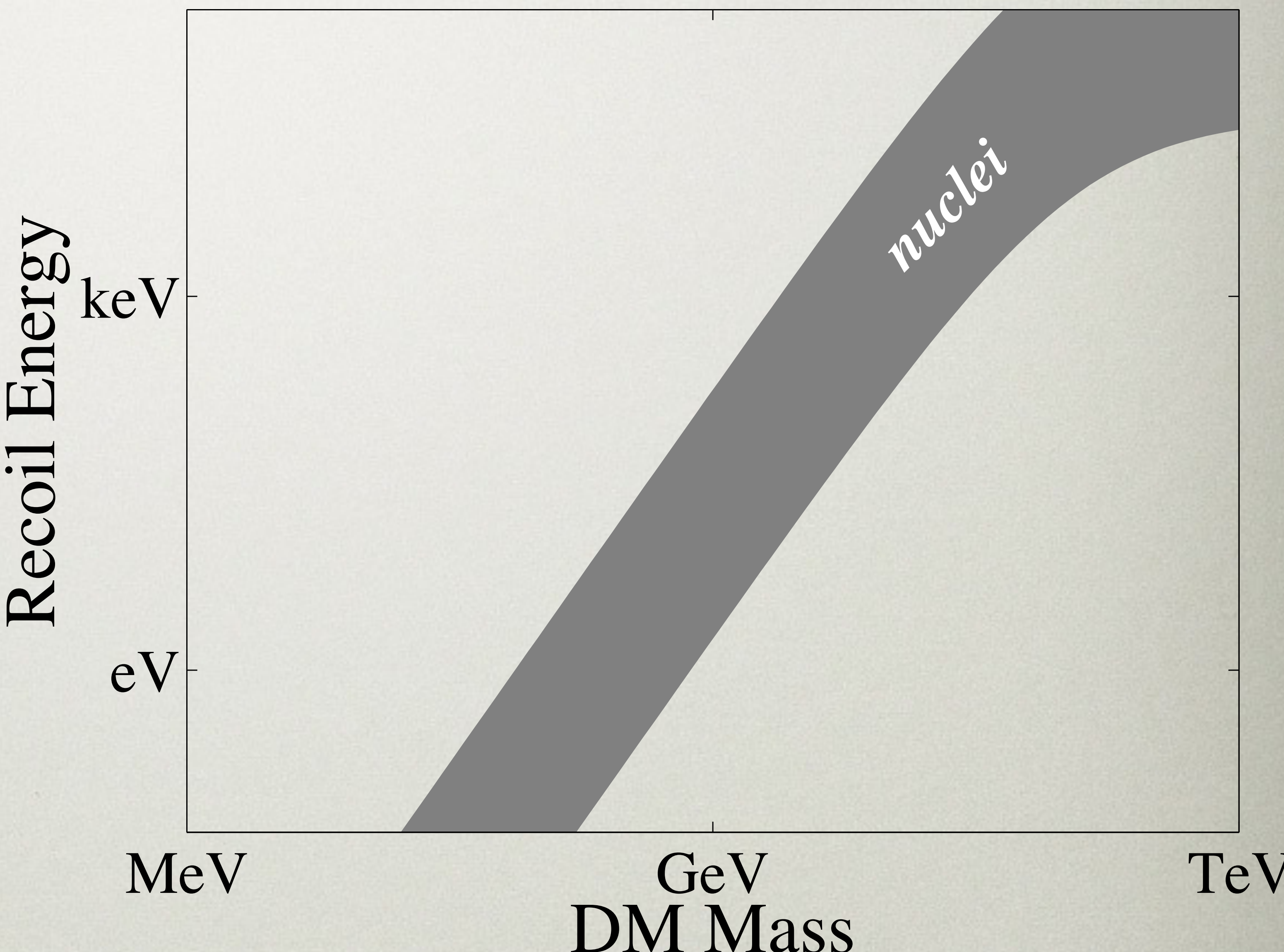


Looking below a GeV

Canonical WIMP-search technique is unhelpful: kinematics simply don't allow for the observation of nuclear recoils from sub-GeV DM scatters.



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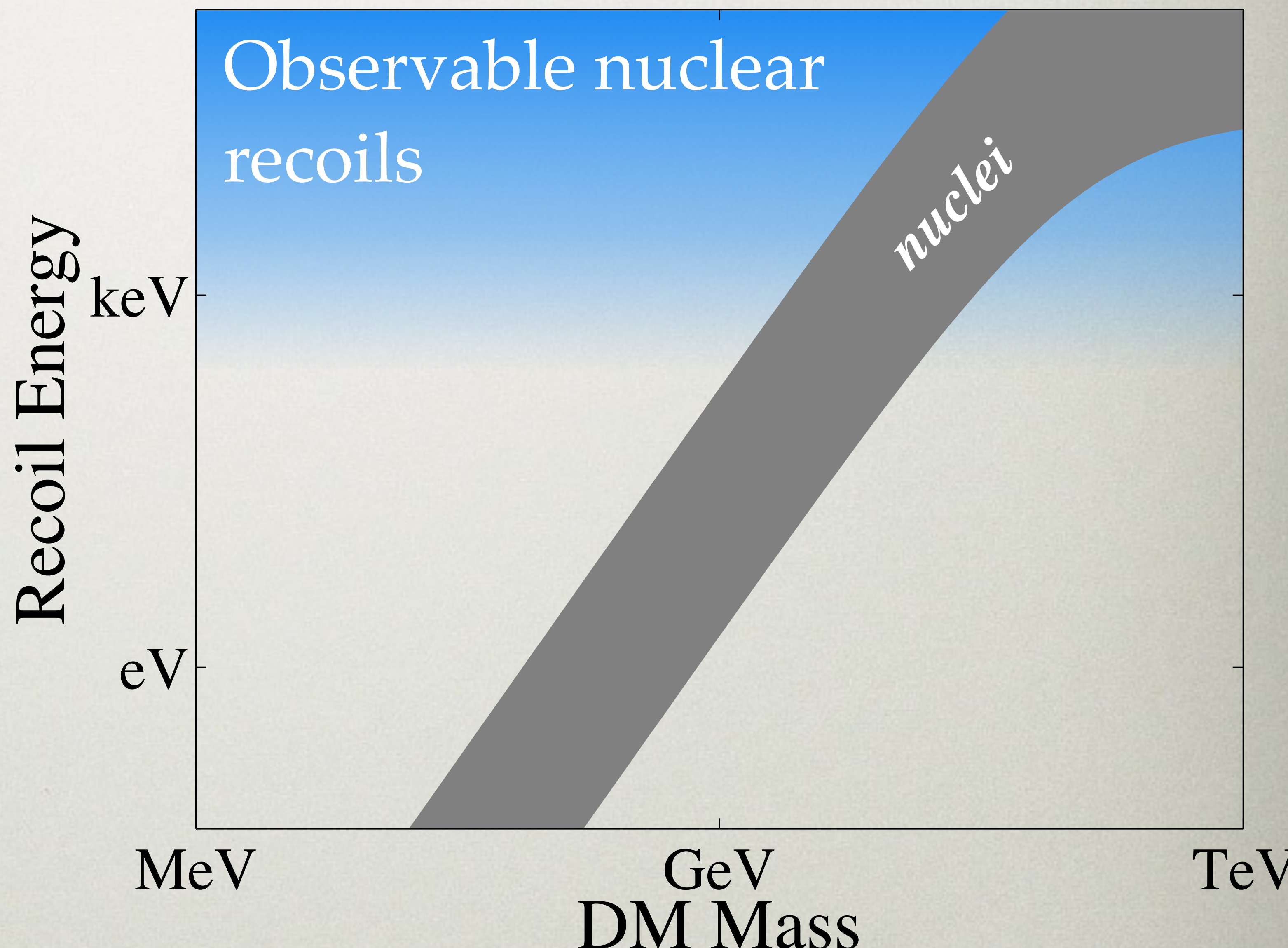
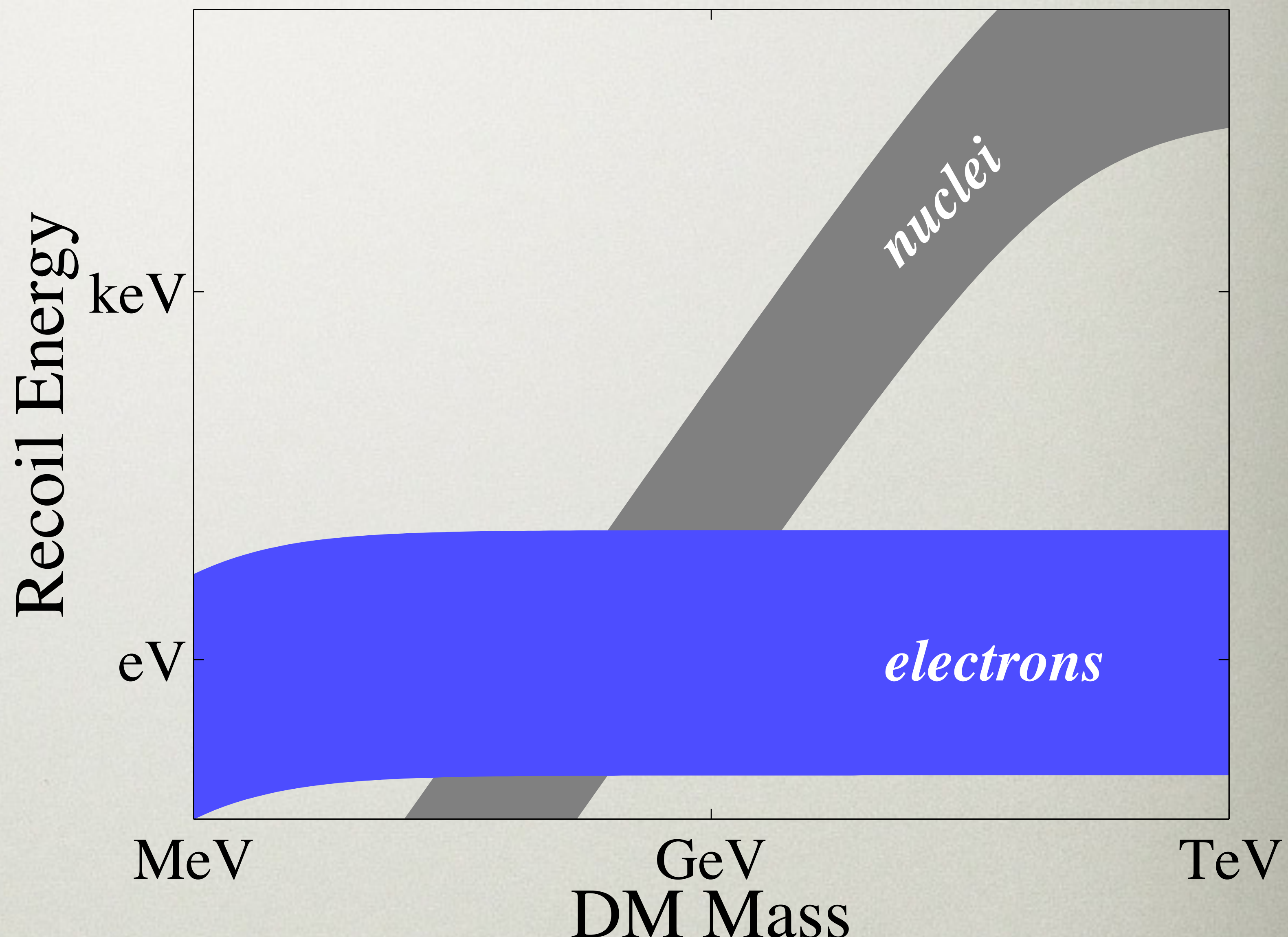


Looking below a GeV

Electronic recoil energies, on the other hand, stay relatively flat for $m_{DM} \gtrsim$ MeV



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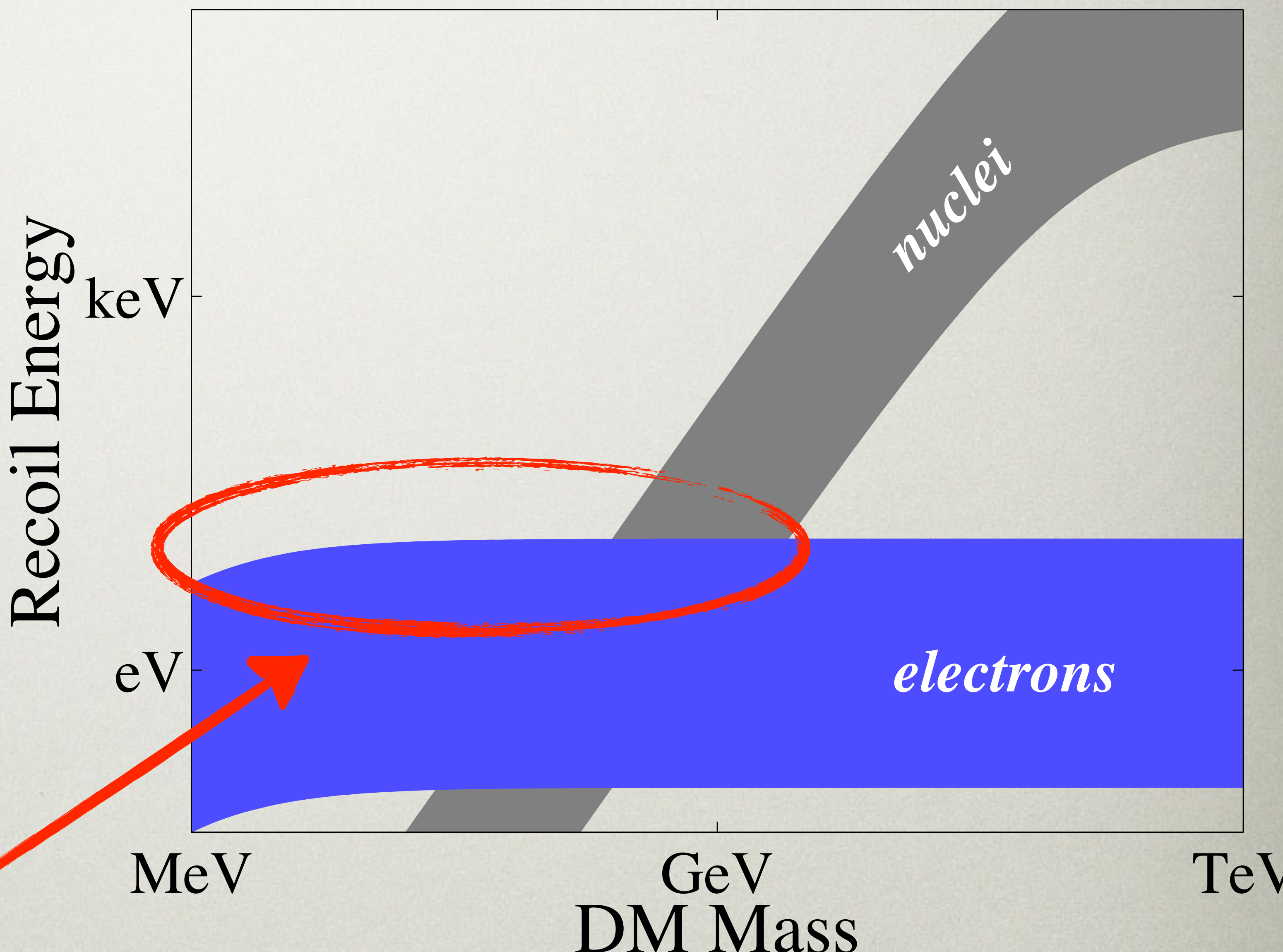
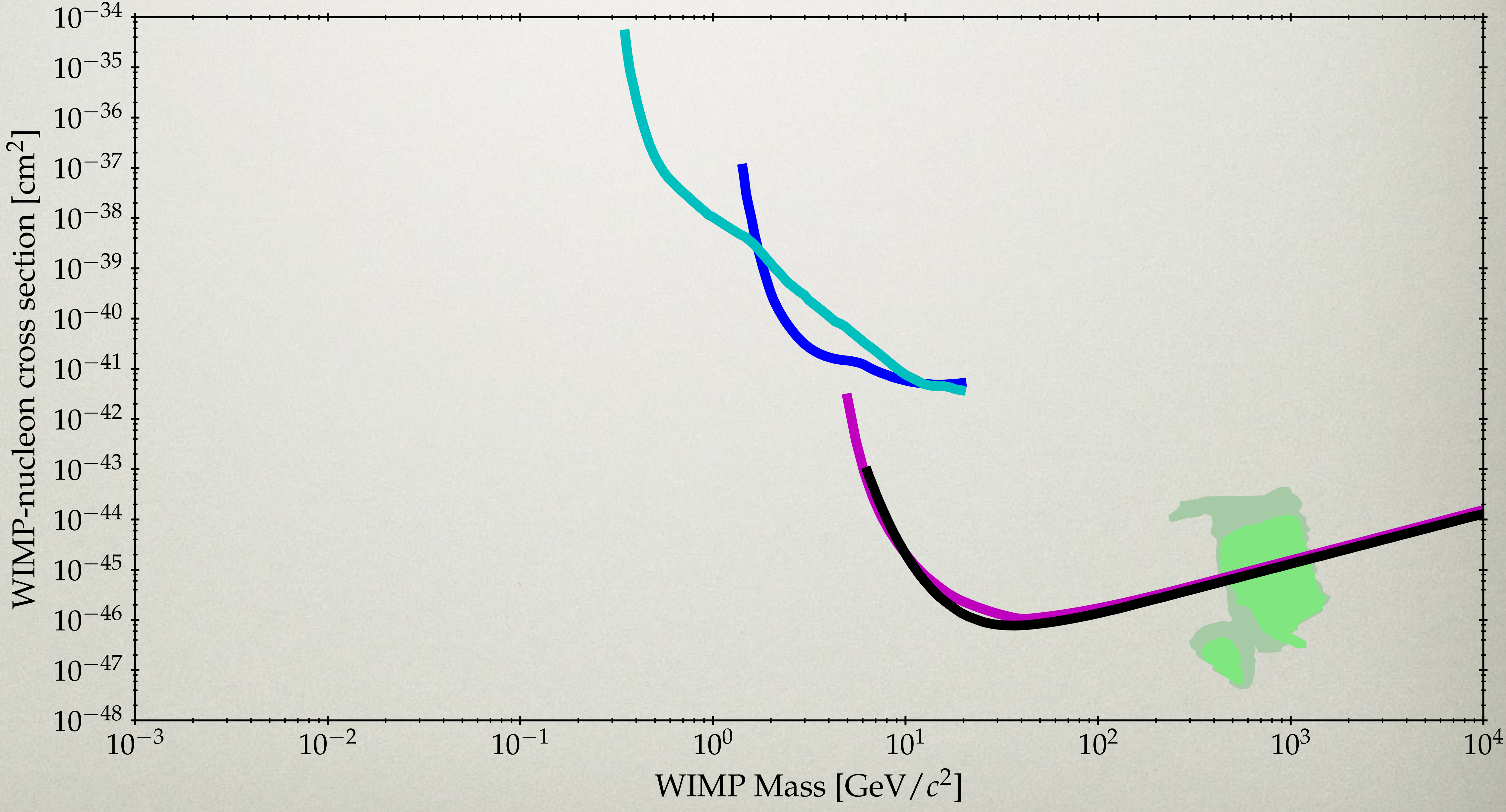
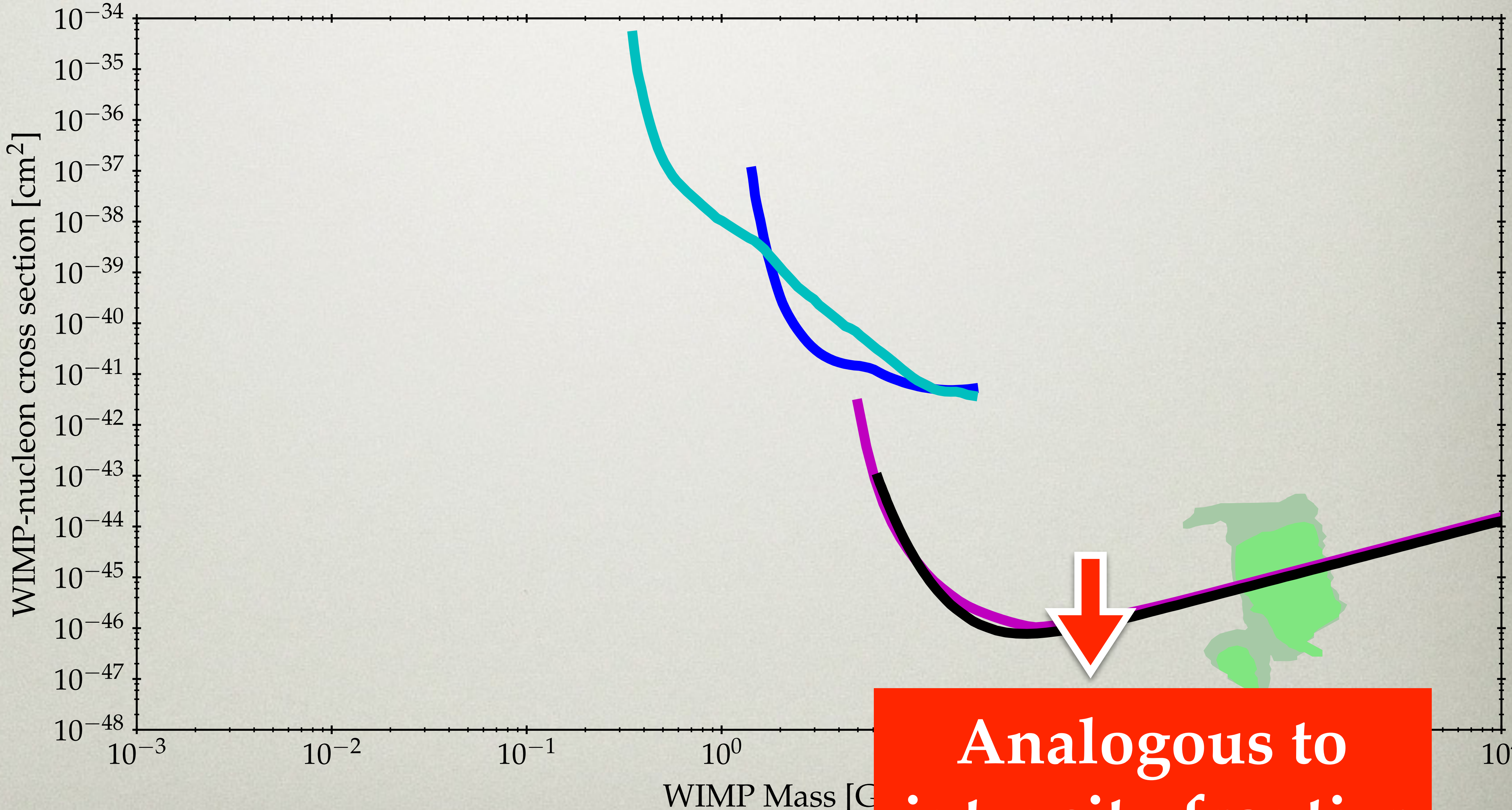


atomic ionization range

Pushing frontiers

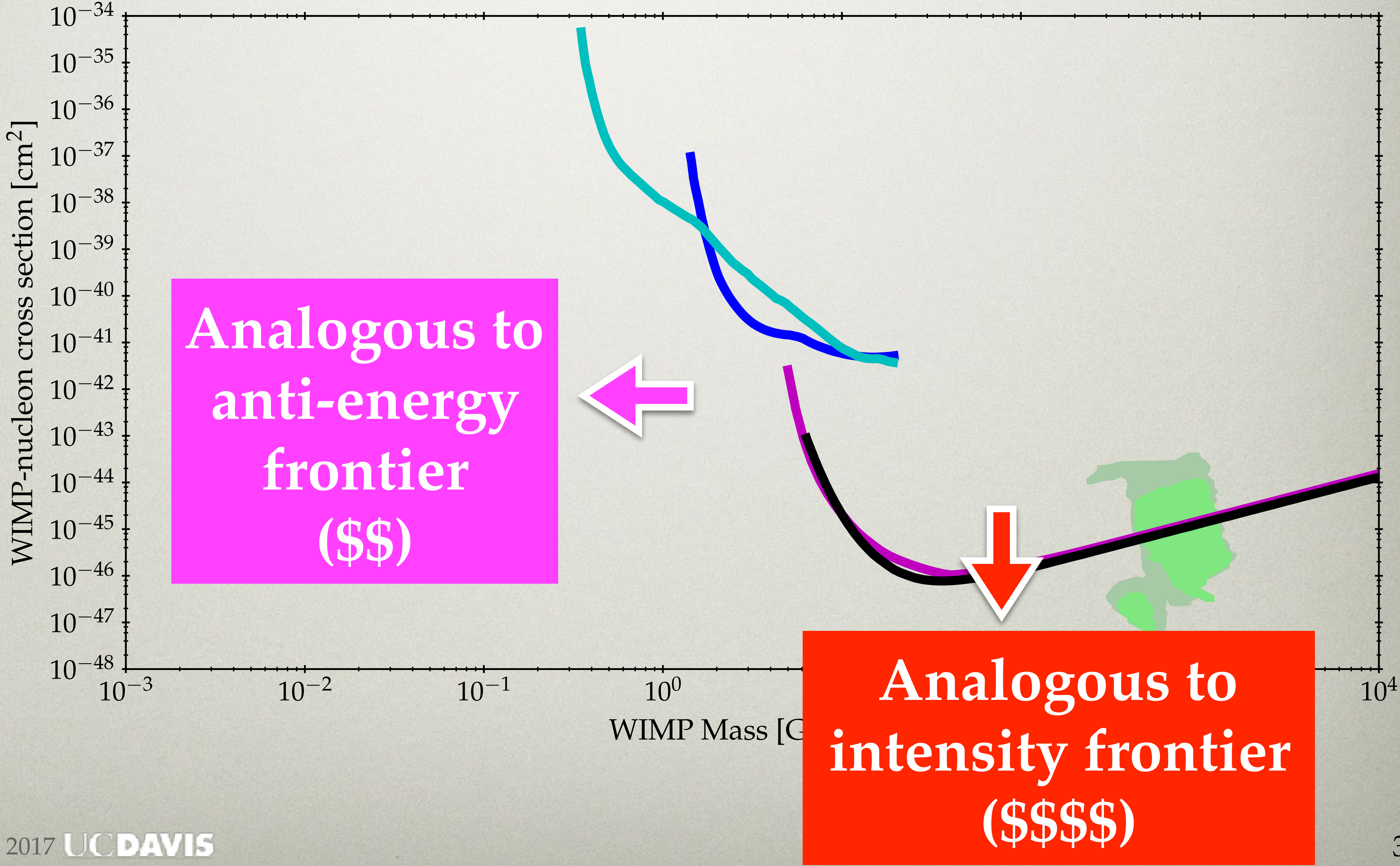


Pushing frontiers



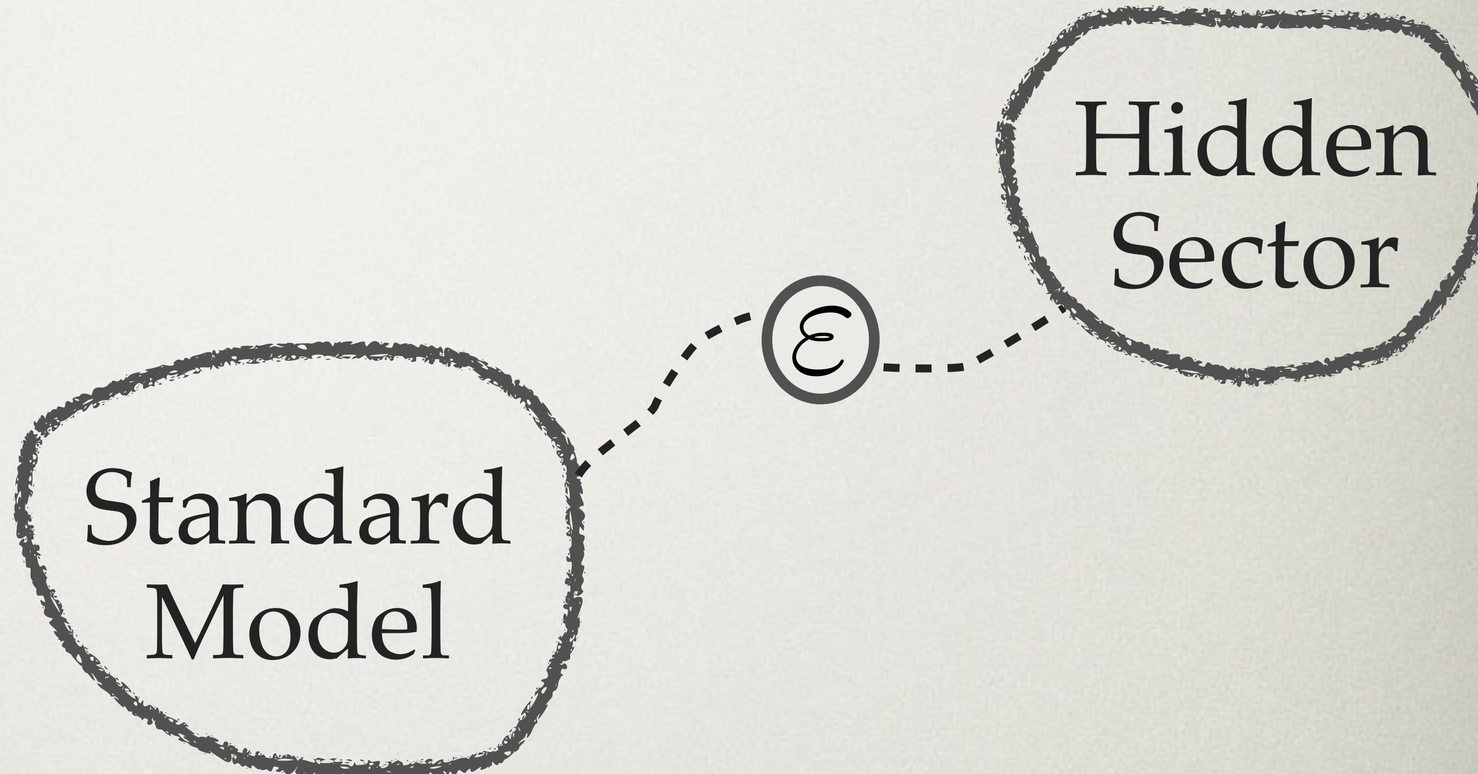
Analogous to intensity frontier ($$$$)

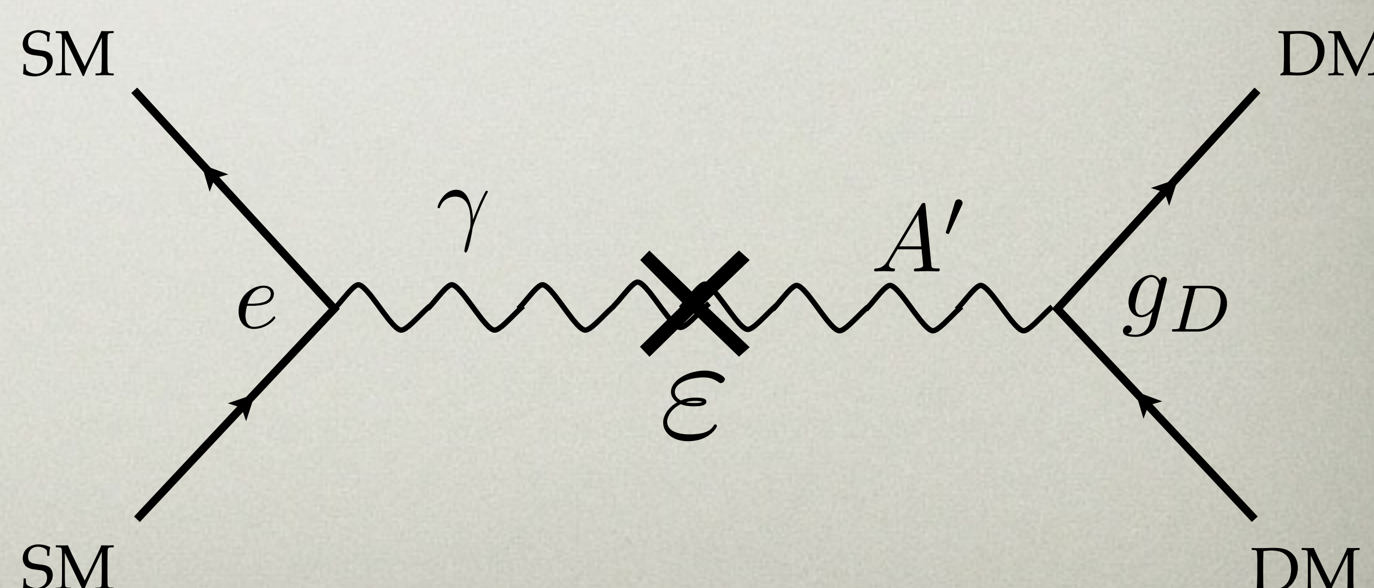
Pushing frontiers



What's out there?

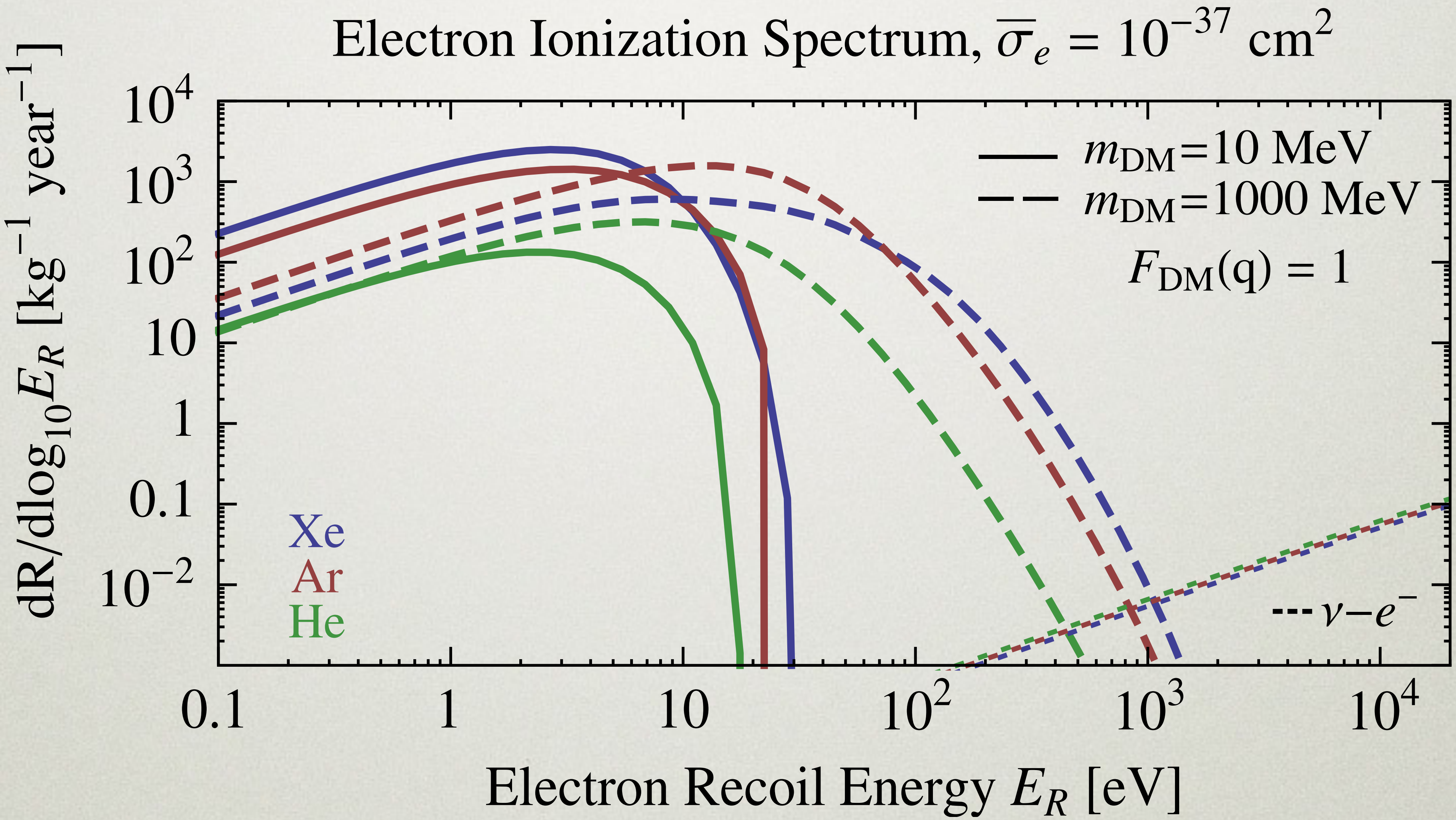
- Many viable DM candidates in "hidden sector" models
- e.g. "Vector portal": Additional fermions charged under a hidden U(1)' gauge symmetry
- SM photon and dark photon can kinematically mix, giving a small coupling between DM and charge particles.





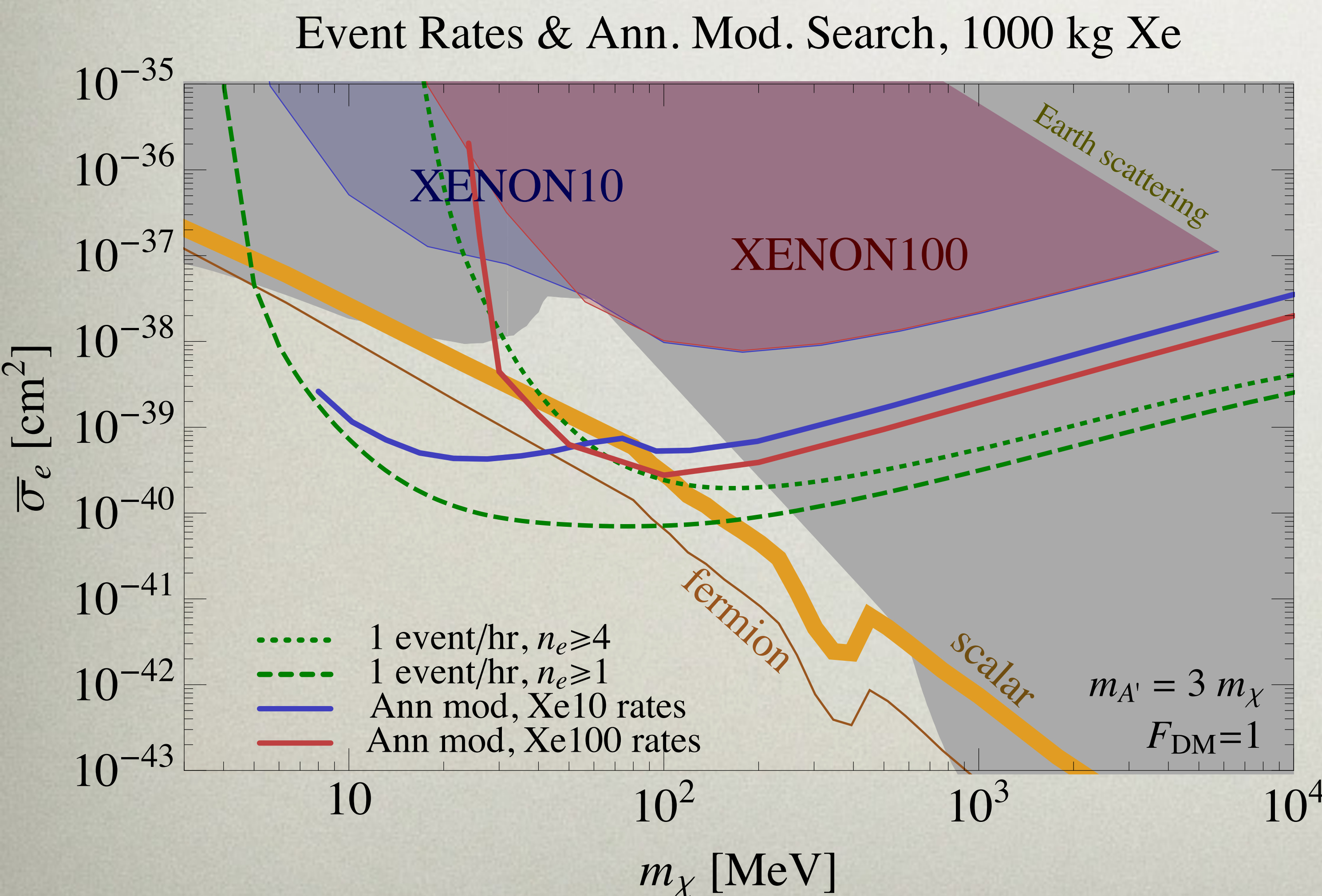
Signature of O(1-1000) MeV DM

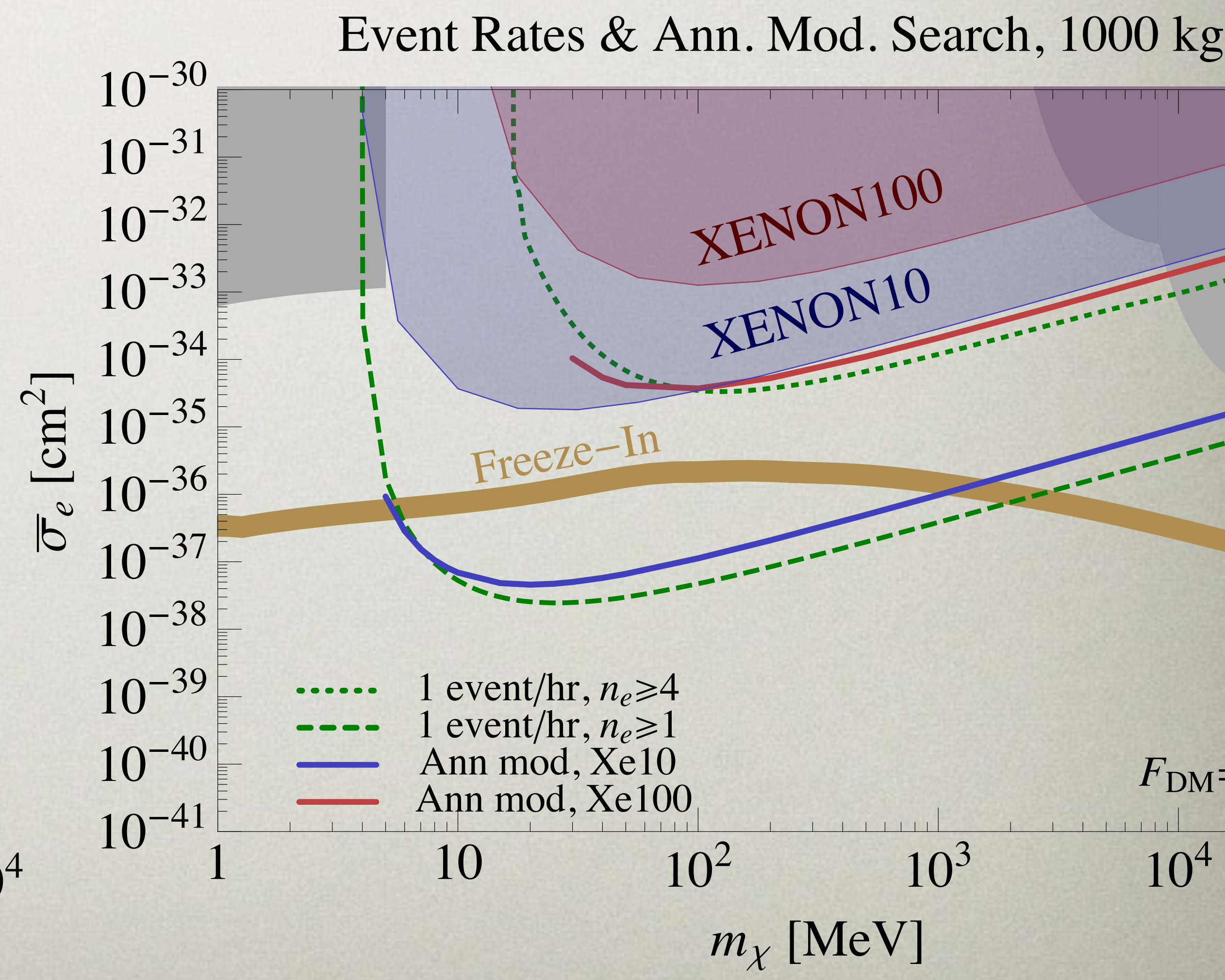
R. Essig, J. Mardon, T. Volansky, PRD **85** (2012), 076007, arXiv:1108.5383



Liquid xenon

- XENON10 and XENON100 data already place constraints on sub-GeV dark matter. Bandgap O(10 eV)
- These (and other similar experiments) are plagued by high rates of ionization-only background; not fully understood.
- XENON10 constraint here comes from a data set with 1.2 kg and 12.5 days.

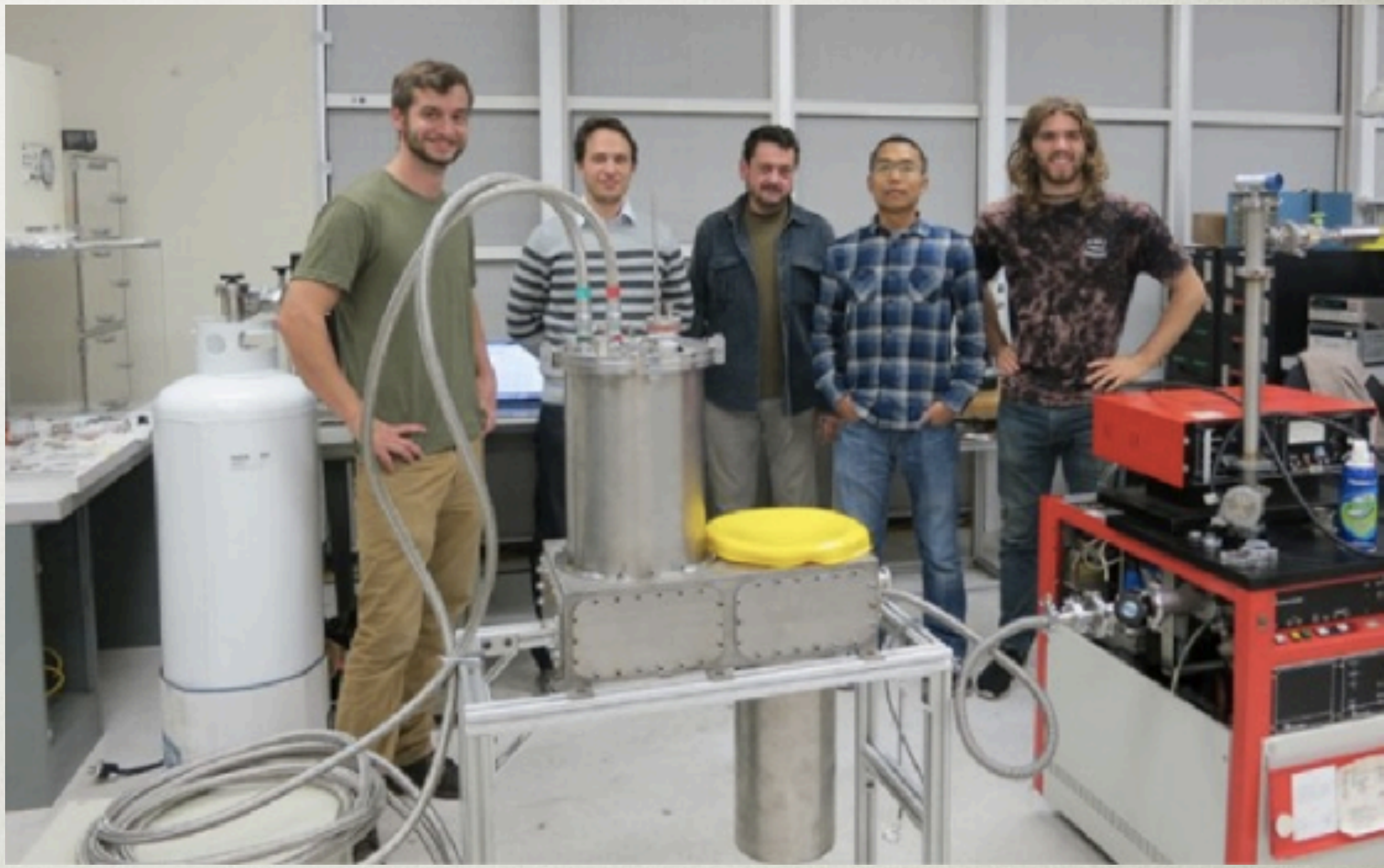




Liquid xenon

$U_{A'}(1)$ experiment:

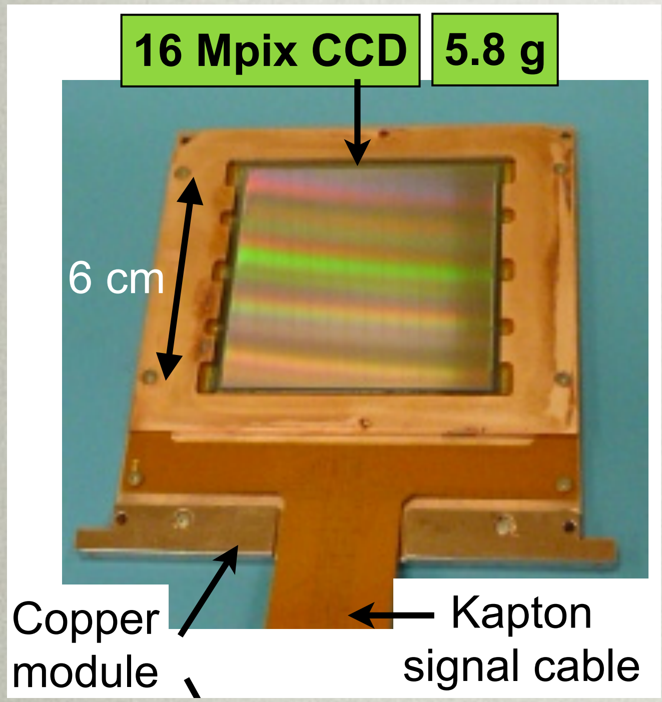
- R&D: study small ionization backgrounds, develop mitigation strategies.
- Build a small O(10kg) LXe TPC focusing on clean, small ionization signals.
- LBL, LLNL, Purdue, UCSD, Stonybrook, CERN



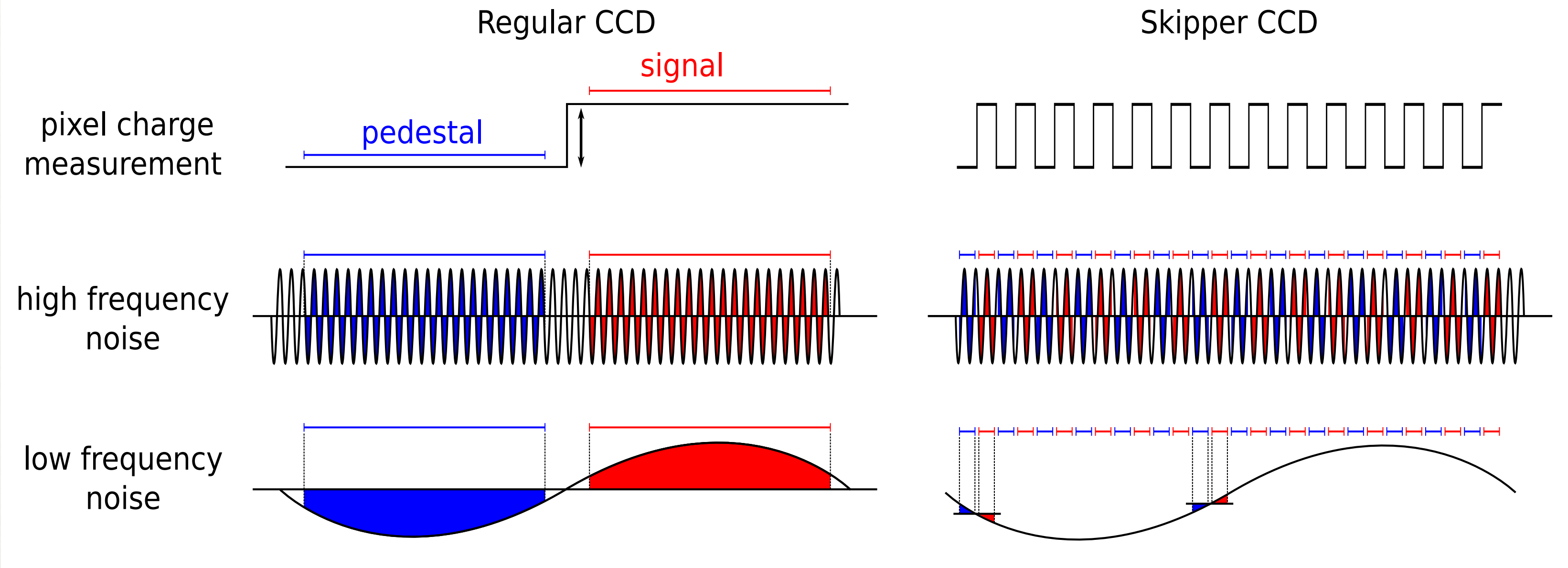
prototype at LLNL

CCDs

DAMIC example

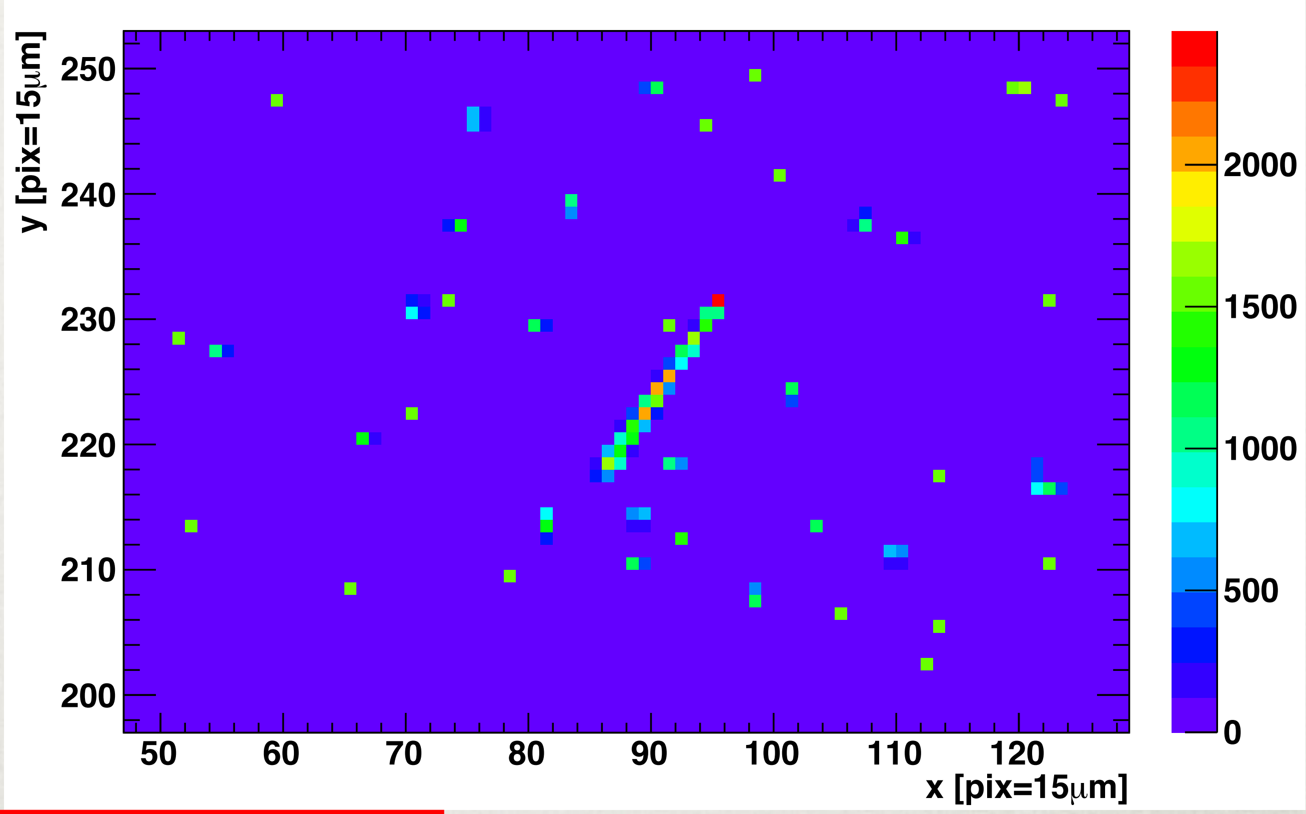


Noise reduction: Skipper CCD

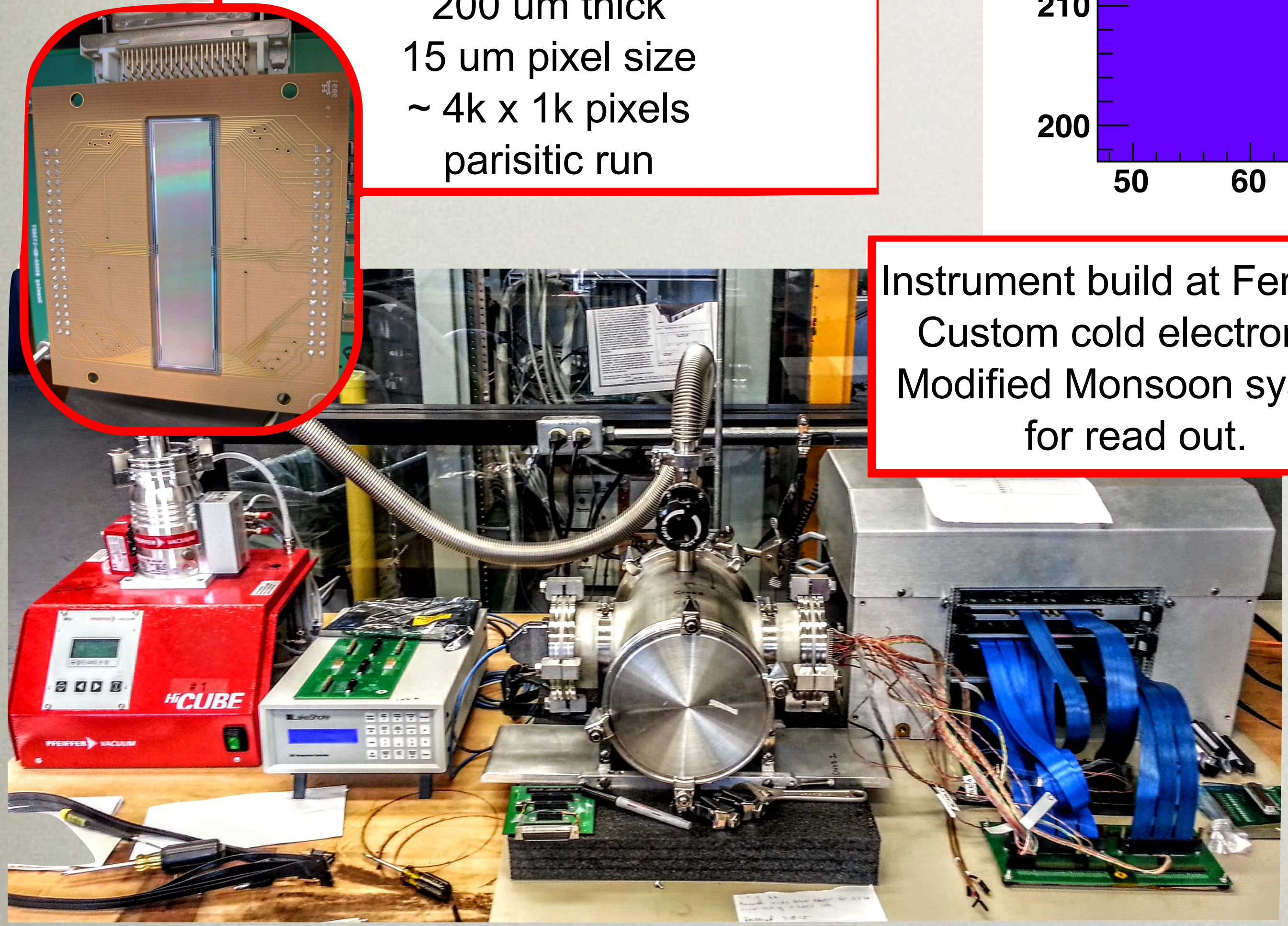


Skipper CCD: each pixel is read out many many times, greatly reducing the noise.

Sensei

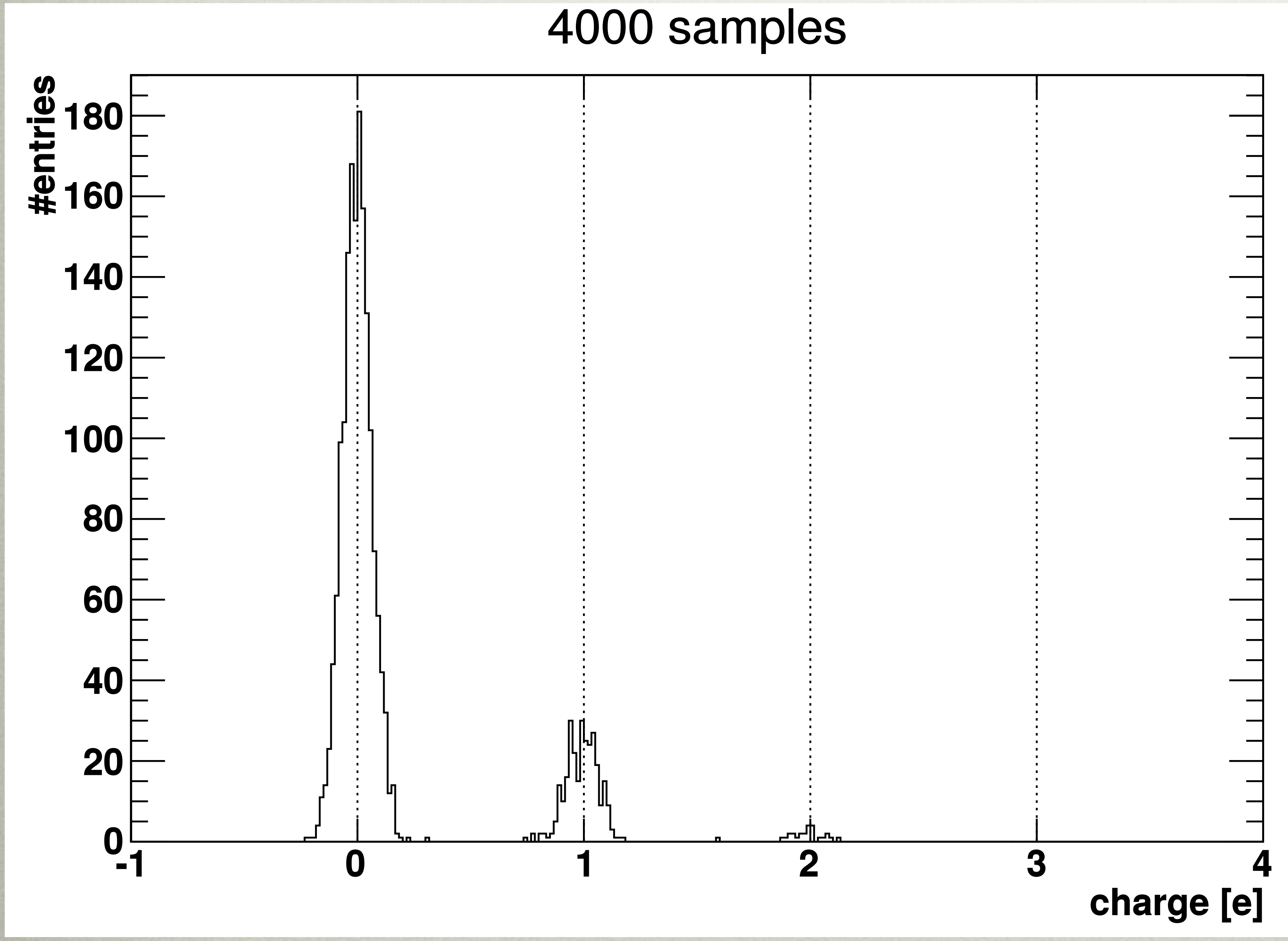


Skipper-CCD prototype designed by LBL MicroSystems Lab
200 um thick
15 um pixel size
~ 4k x 1k pixels
parisitic run



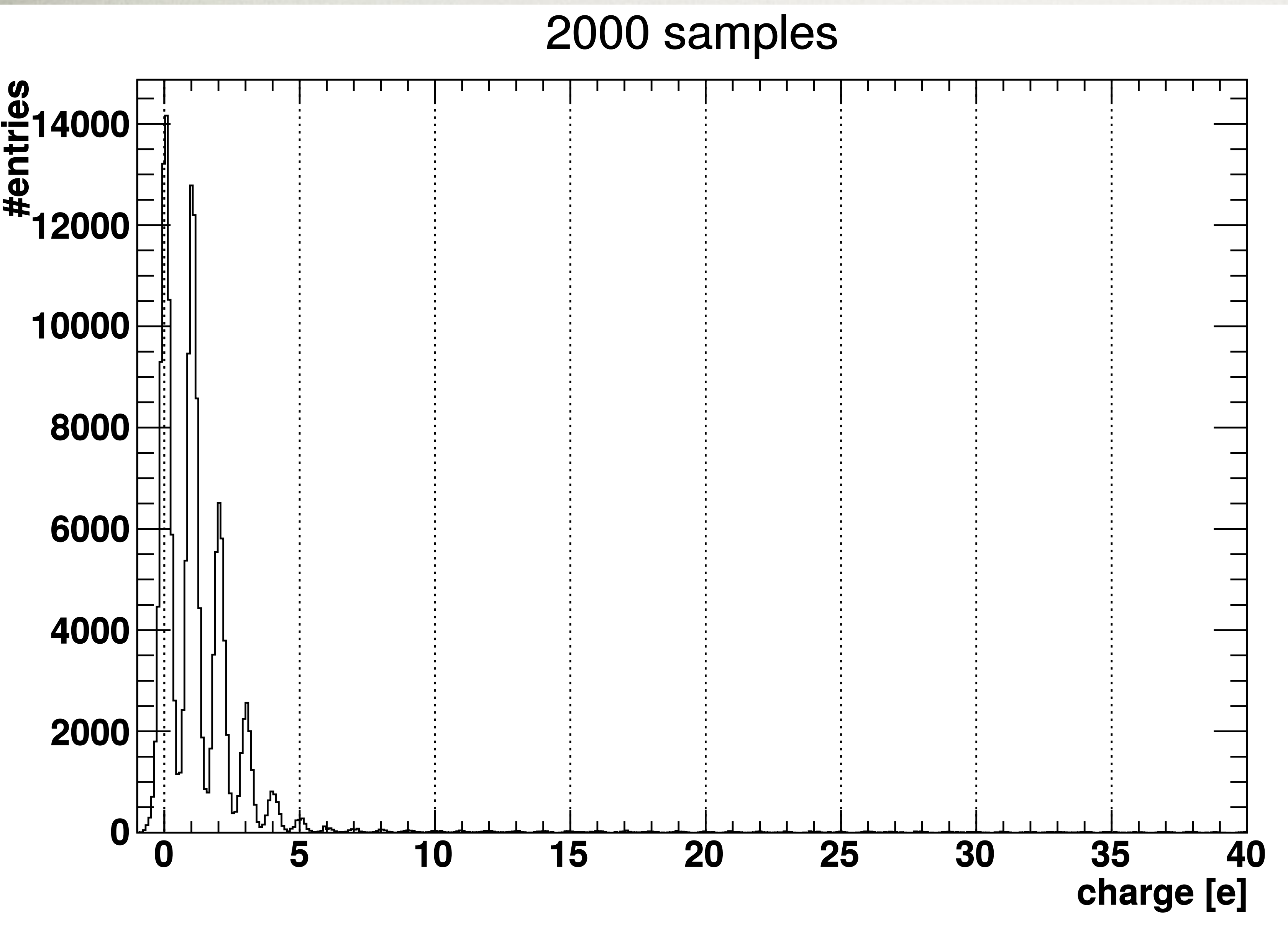
Instrument build at Fermilab
Custom cold electronics
Modified Monsoon system for read out.

Sensei



- Sensitivity to **single electrons*!!***
- AFAIK, first demonstration of this in a semiconductor.

Sensei



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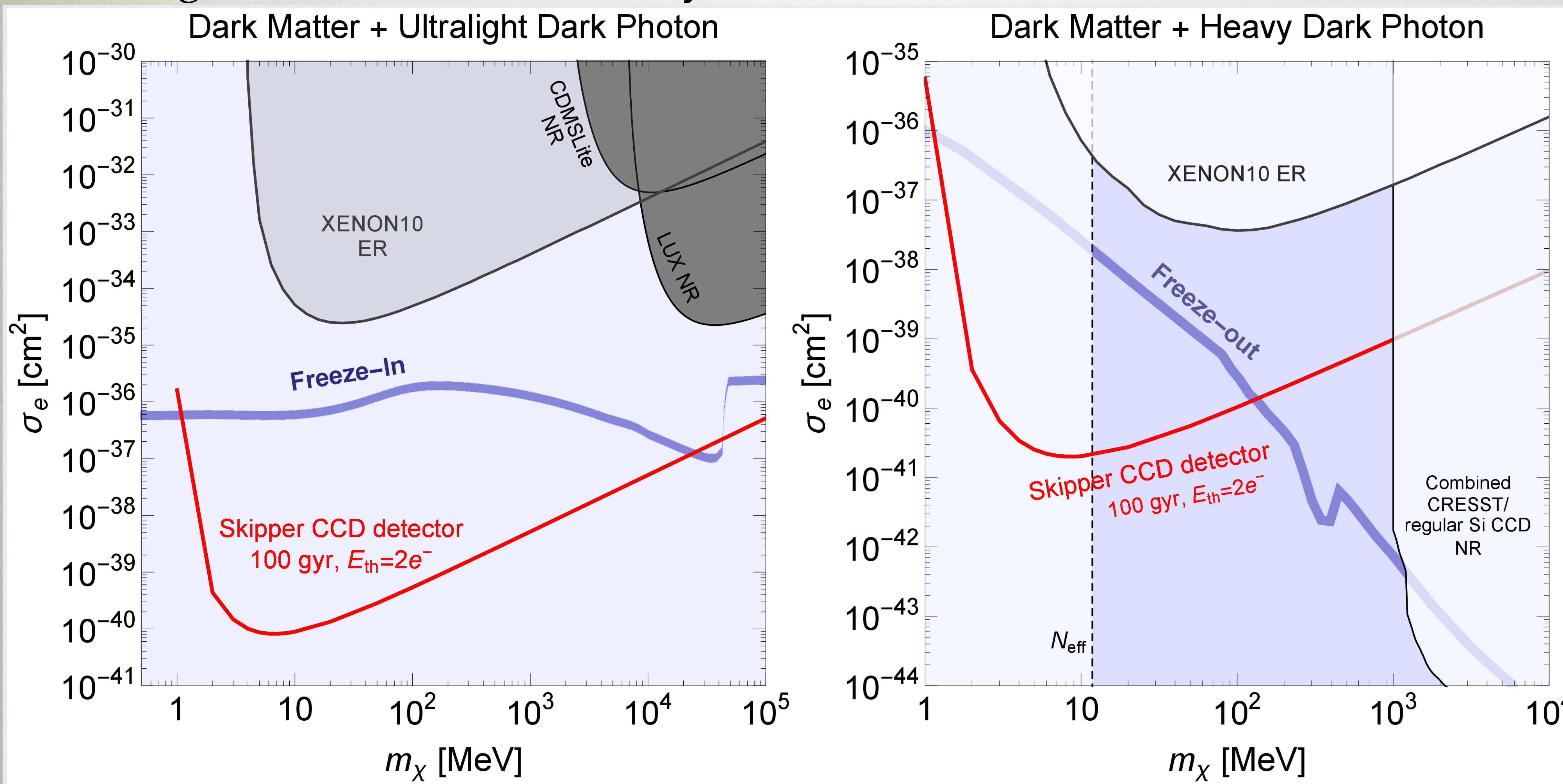
Sensei

R. Essig, J. Mardon, T. Volansky, T.-T. Yu



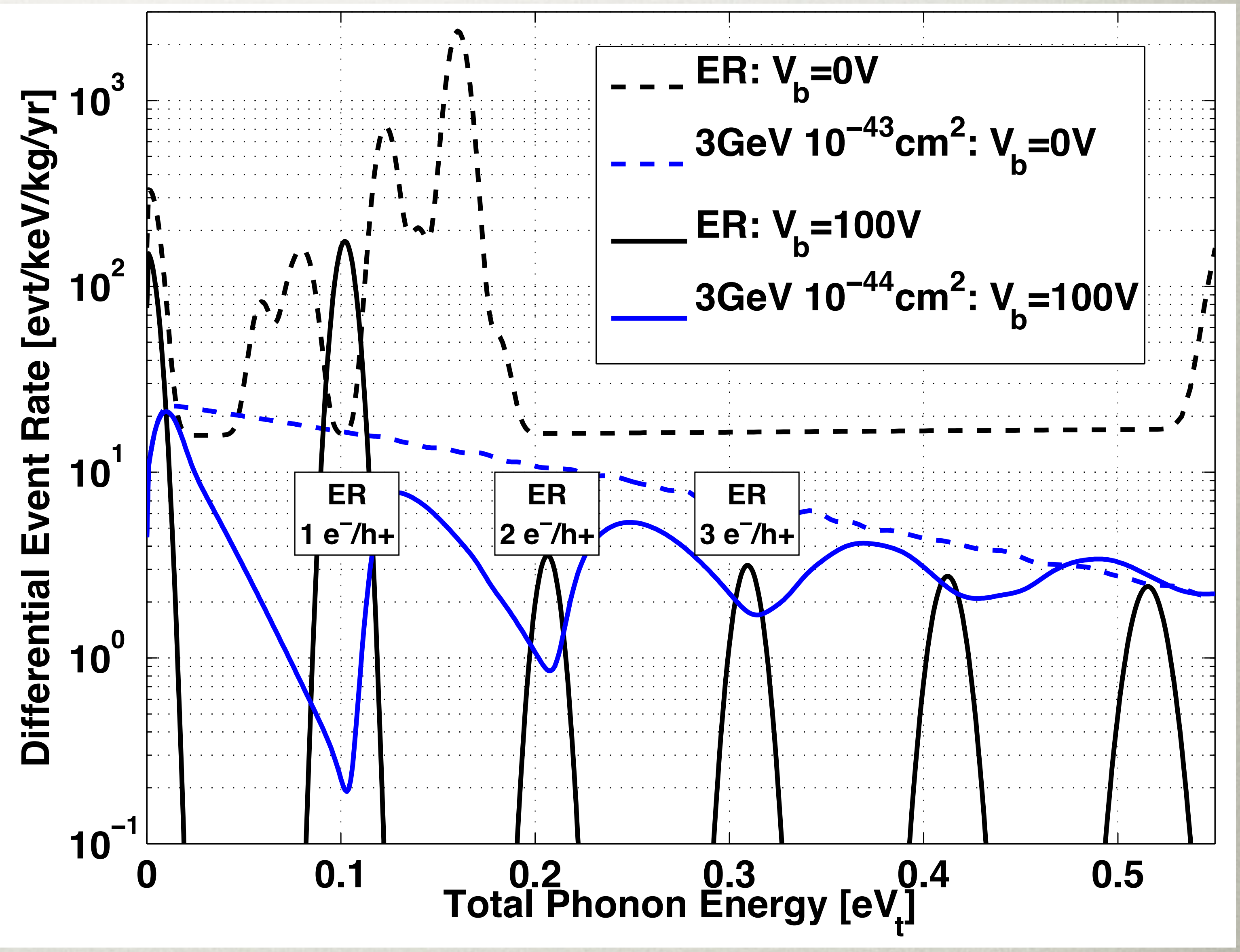
Silicon: bandgap

O(1 eV)

CDMS with high voltage

M. Pyle's talk, Berkeley Workshop on Dark Matter 2015

- Voltage amplifies the phonons/electron conversion ("Luke phonons").
- Amplification increased to see single electrons (projected).
- Nuclear recoils add phonons to the Luke phonons: distinguish from electronic recoils.
- Low threshold and low background.



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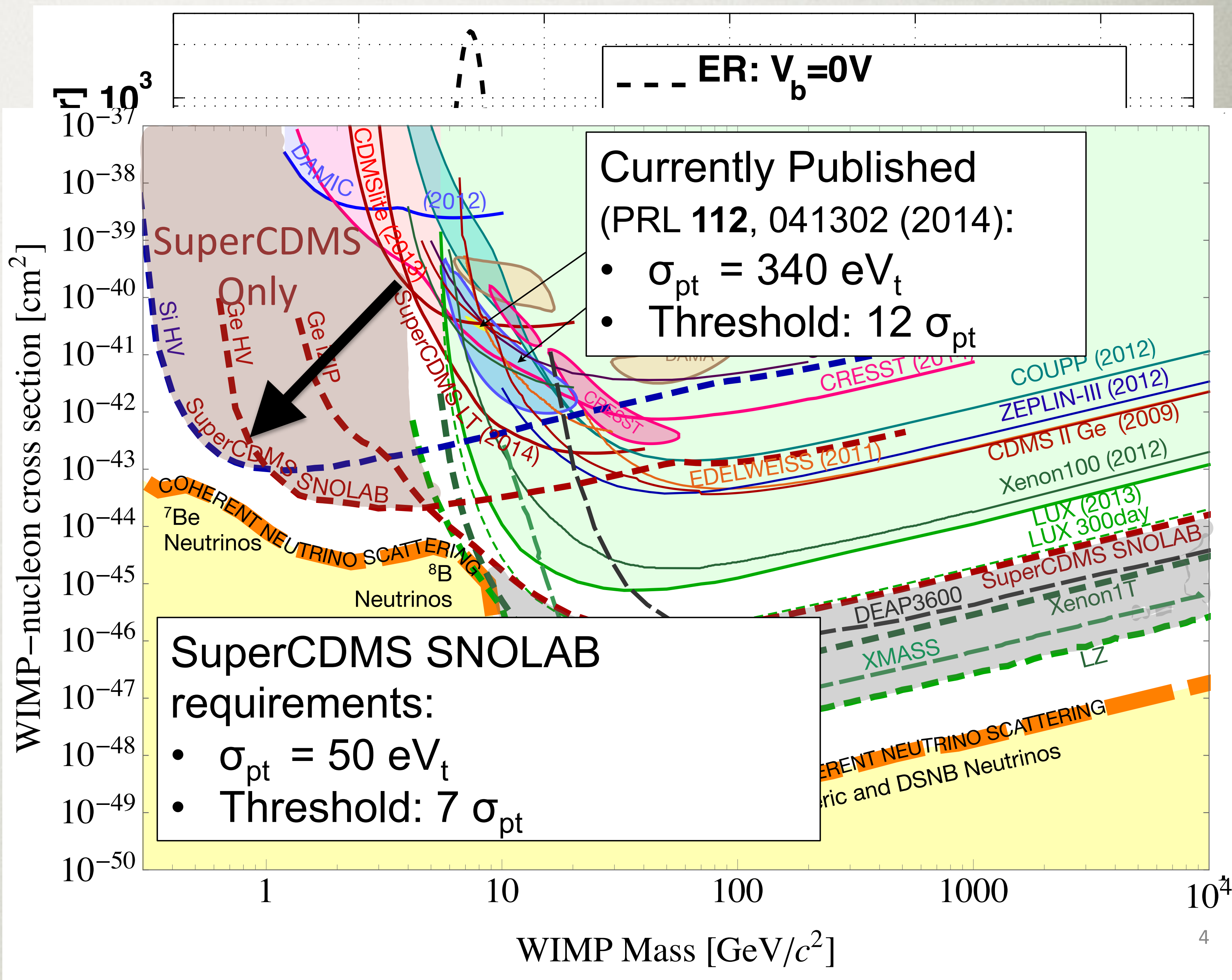

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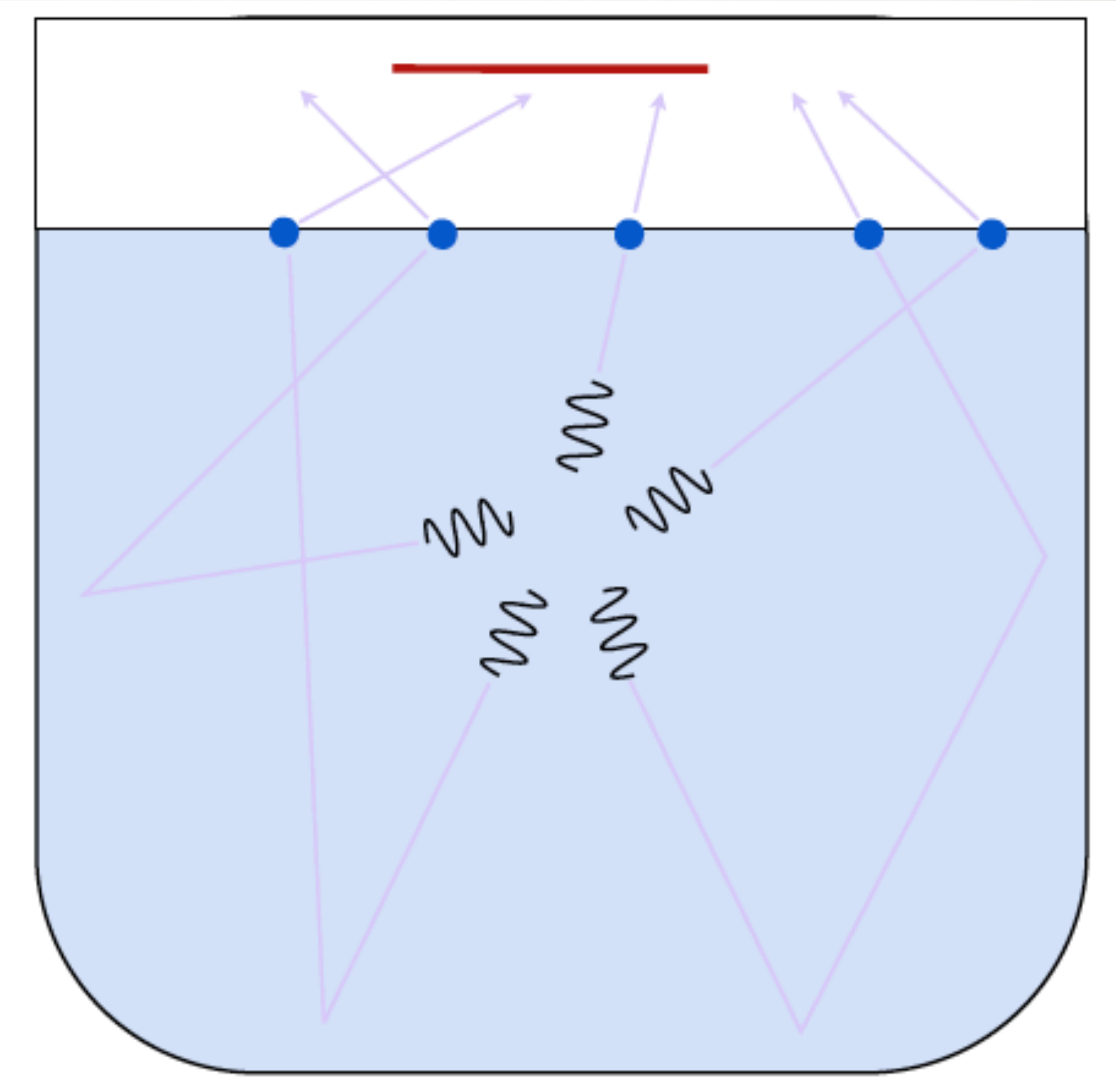
Superfluid He

- Collective excitations (photons, rotons) have energies O(meV) (little ‘m’).
- rotons are absorbed by atom on surface and travel toward calorimeter with O(10 meV).



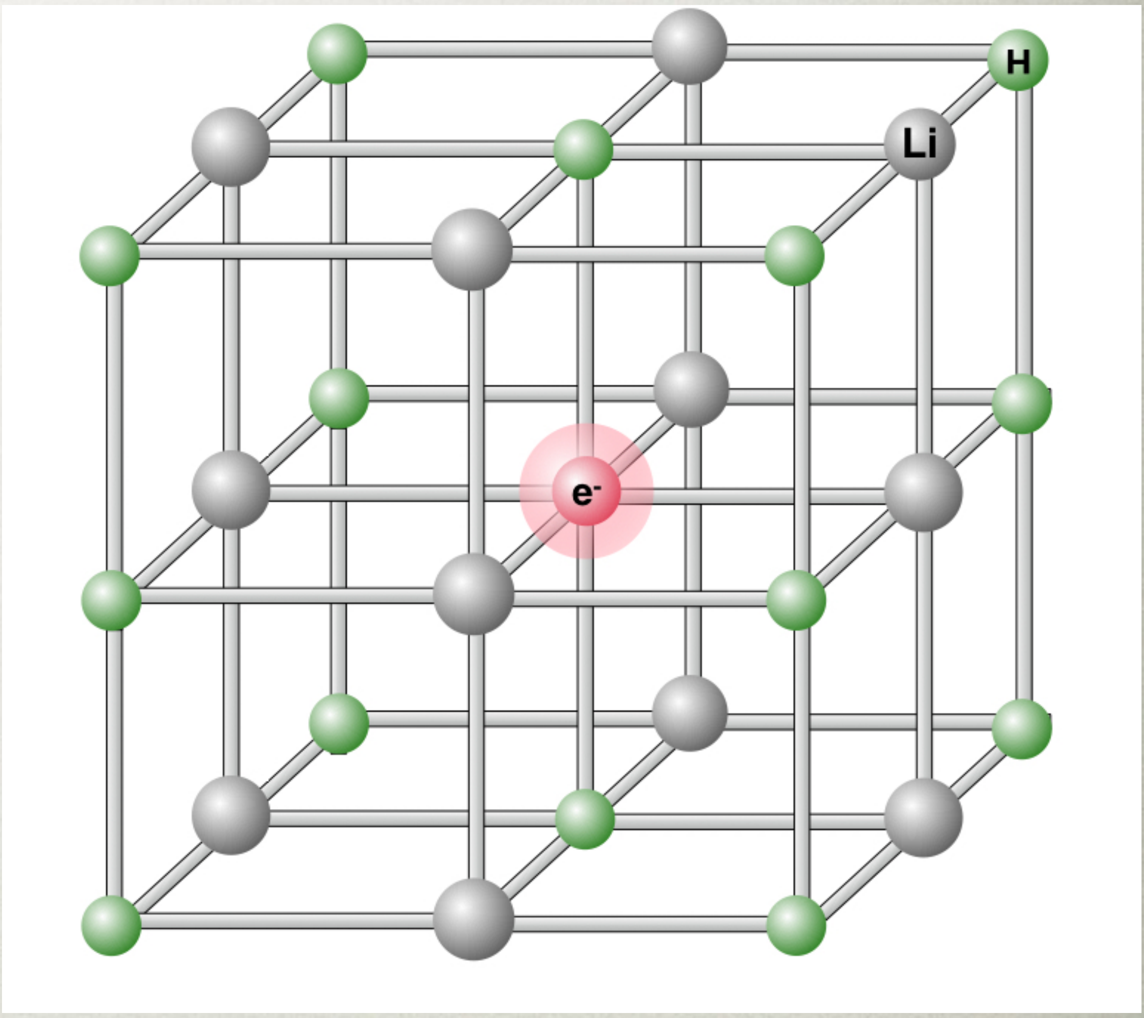
S. Hertel, Berkeley Dark Matter Workshop 2015: https://indico.physics.lbl.gov/indico/event/191/contribution/22/material/slides/0.pdf

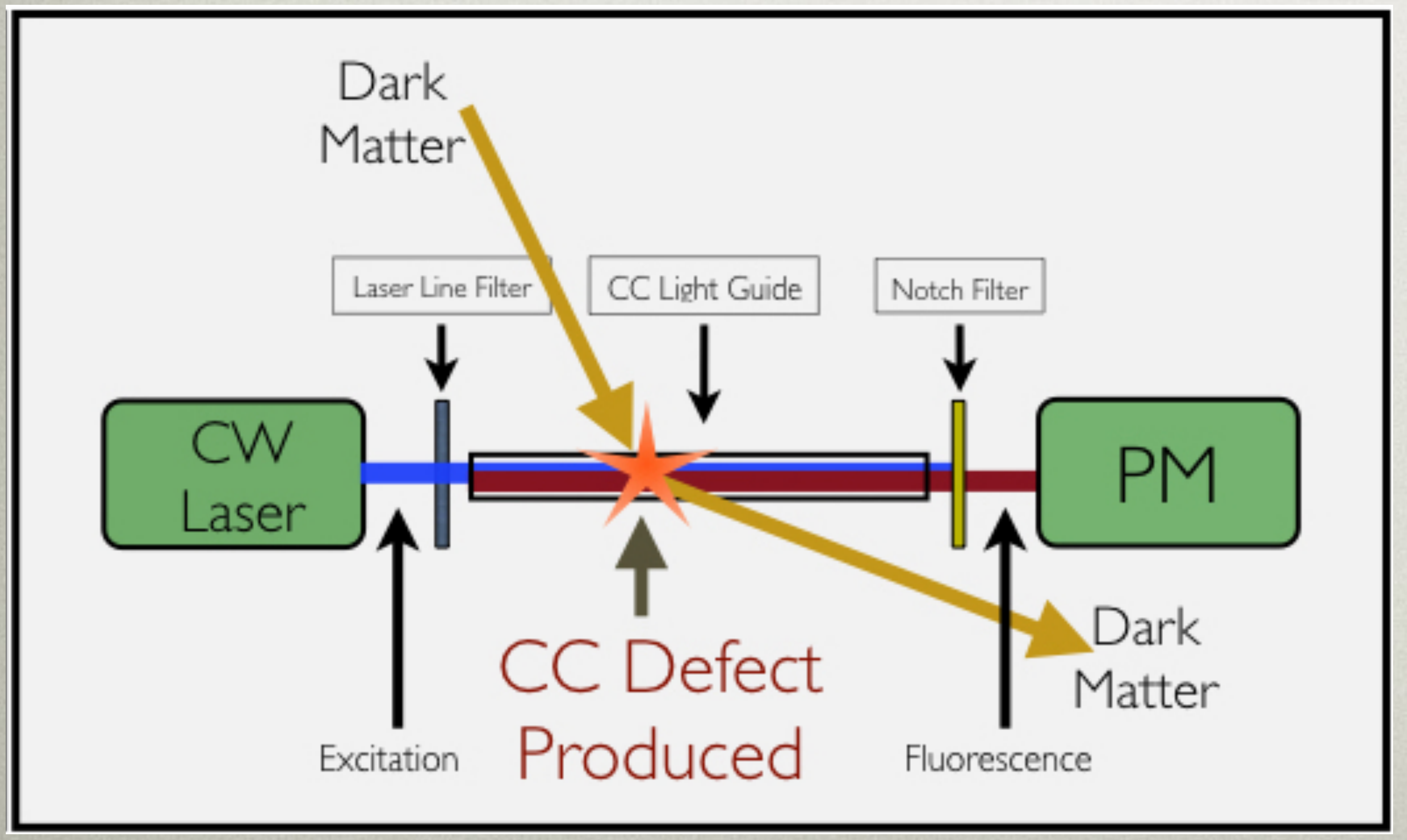
Guo, McKinsey (1302.0534)

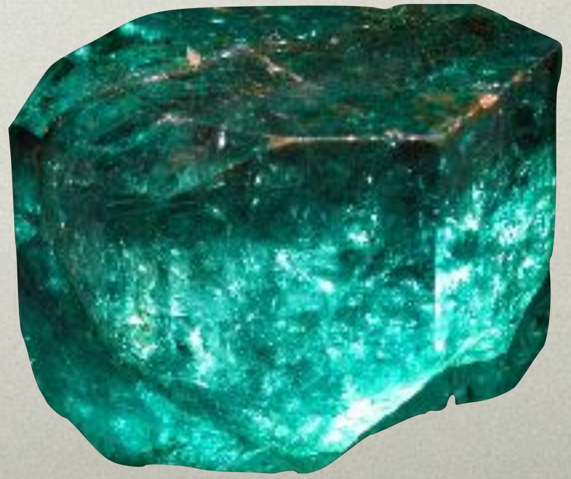
Color centers

- Many gems get their color from "color centers"
- An electron fills a lattice site from which an atom has become displaced. This electron fluoresces.
- Energies required to displace an atom are O(1-10 eV)

R. Budnik et al. 1705.03016







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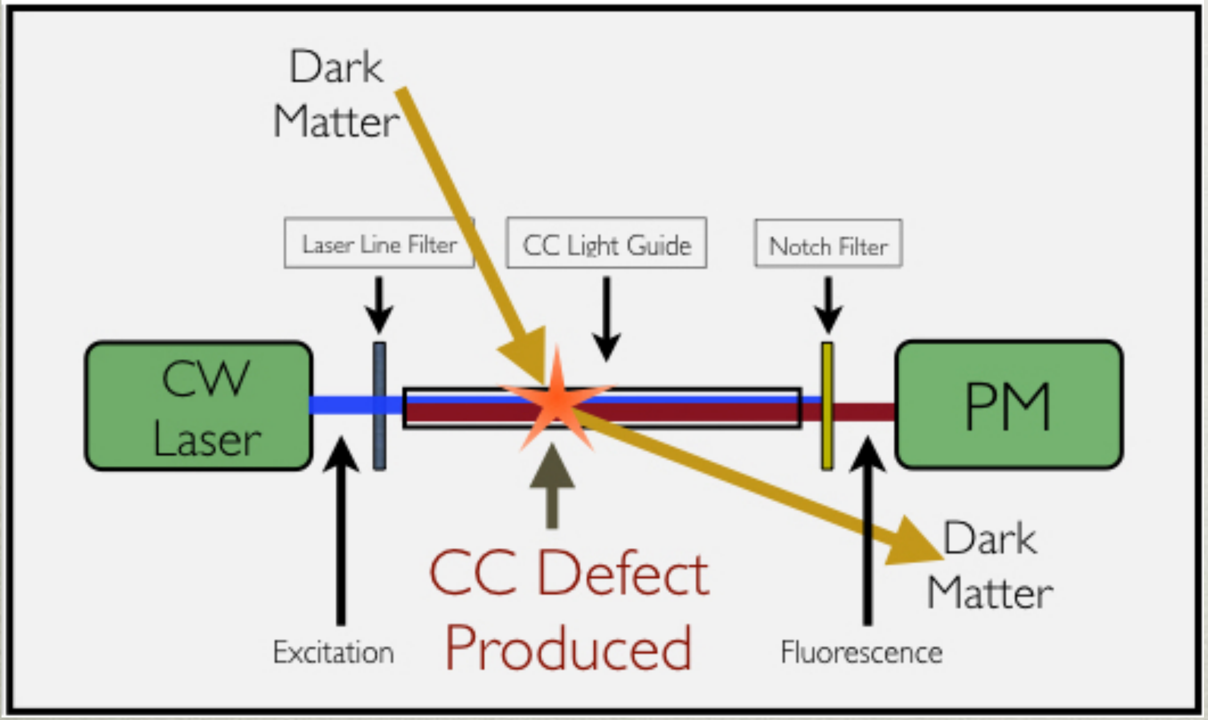

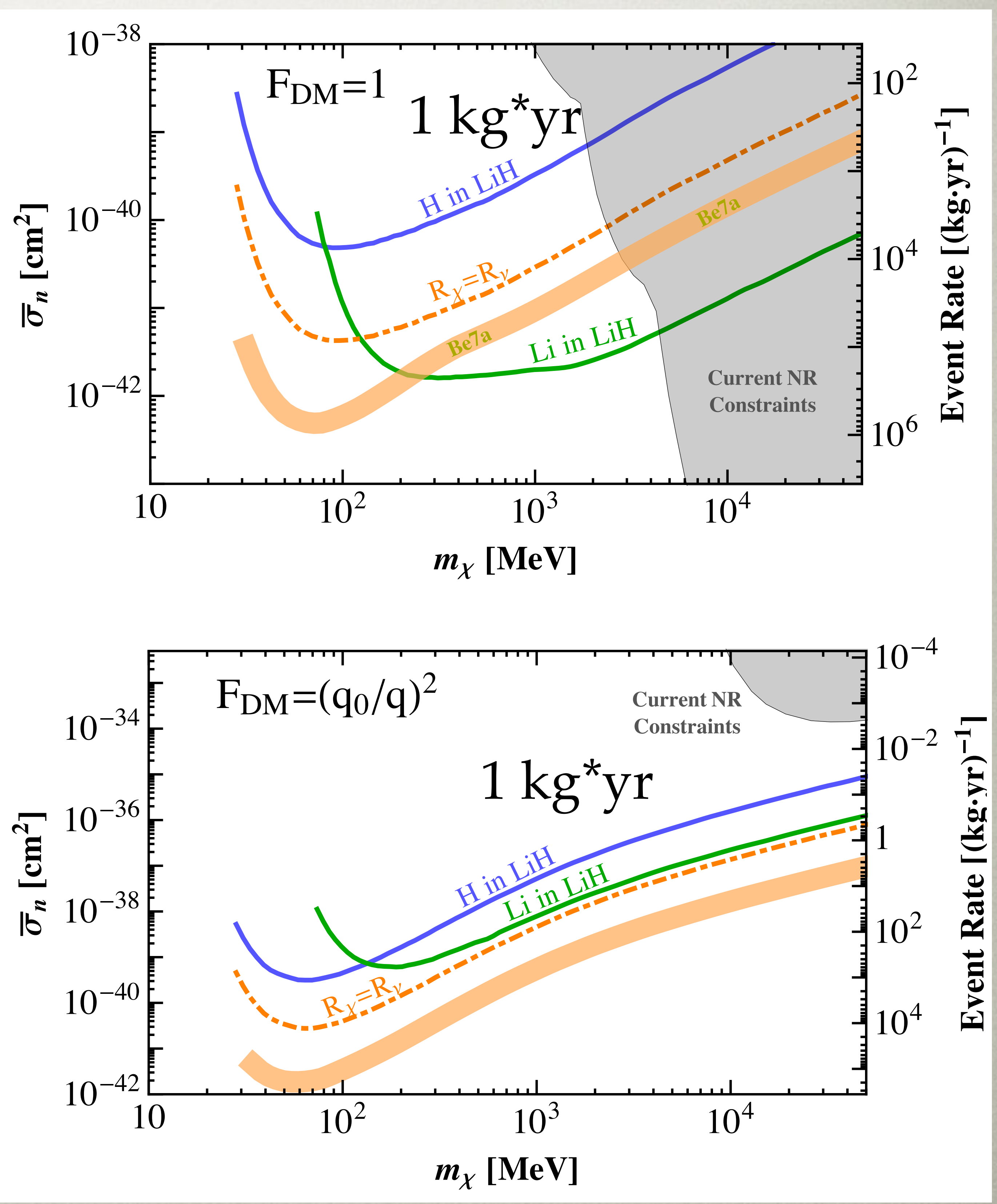

Light DM: Approaches

Many ideas (too many to discuss), some listed here:

- Superconductors: O(meV) gap energies
- Superfluid ^{4}He: O(meV) collective excitations (phonons, rotons). Triplet electron excitations are long lived O(10 eV).
- Novel semiconductor techniques: Doped GaAs as a scintillator, germanium avalanche ionization, electron extraction

… and many more. See the Cosmic Visions community report for a longer list: 1707.04591