Dark Matter Searches

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US-ATLAS workshop
August 6, 2019

Dark matter : We don't know much

Lower mass bound: 10^{-30} GeV
(galaxy-scale deBroglie wavelength)

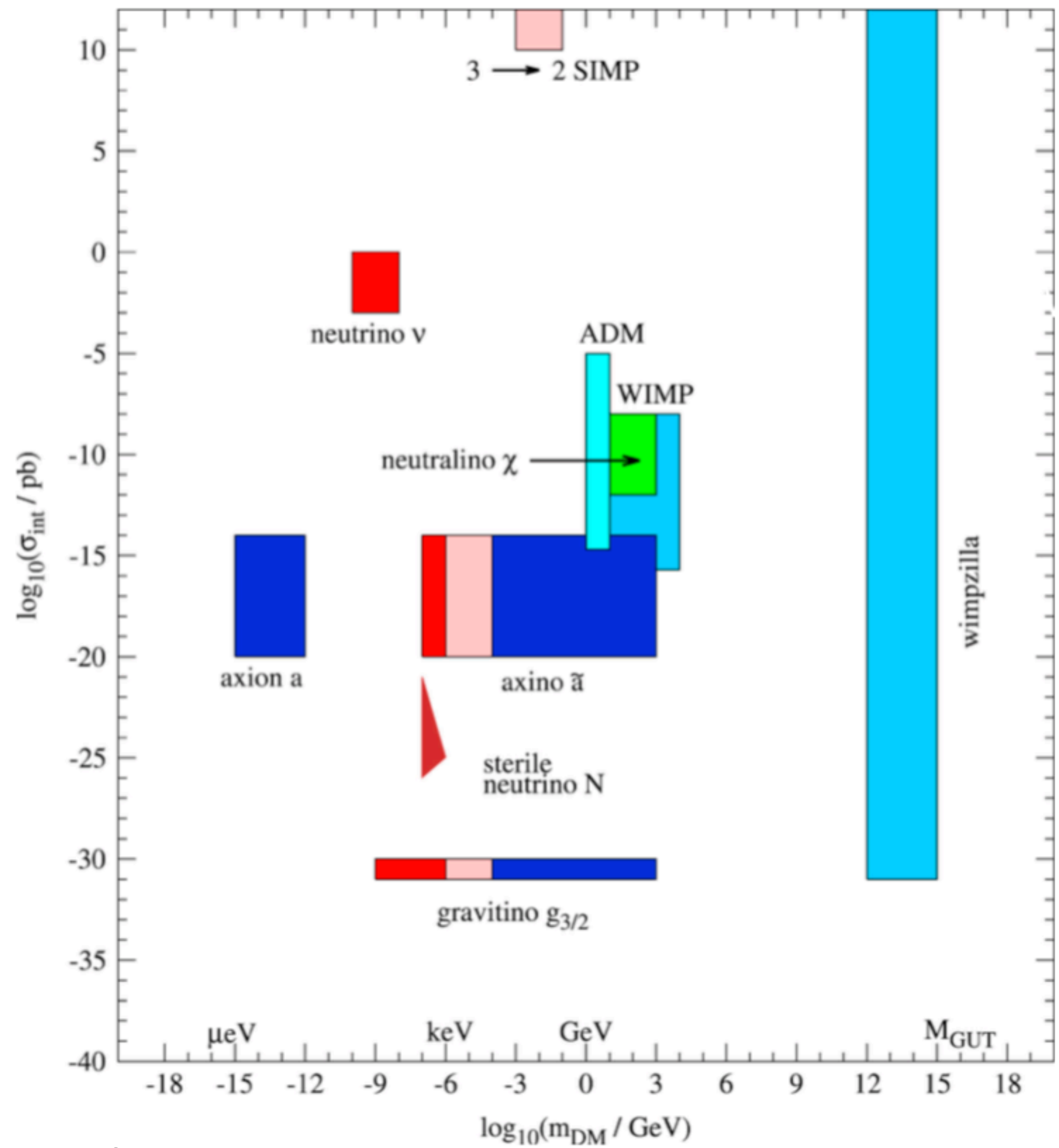
Upper mass bounds:

10^{16} GeV
(GUT scale)

10^{60} GeV
(clumps, primordial black holes, etc.)

Interaction strength axis:
Just as unconstrained!
(*some* constraints at *some* masses)

arxiv:1407.0017



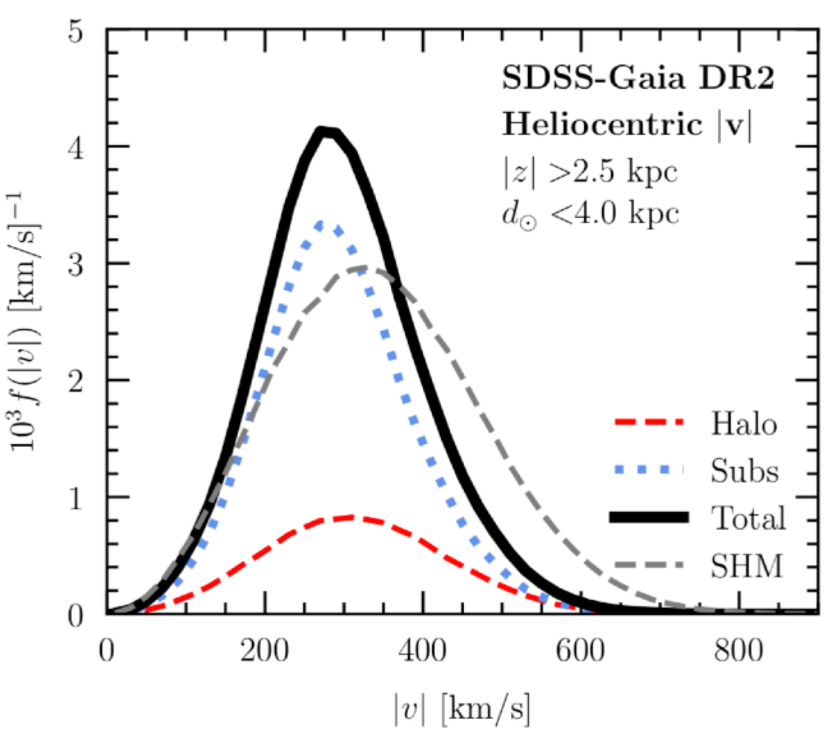
Dark Matter : The few things we do know

1) Mass-density at cosmological scale $\Omega_c = 0.2589 \pm 0.0057$

2) Distribution at galaxy and cluster scales

3) Mass-density and velocity distribution *here in this room*

$$0.33^{+0.26}_{-0.075}\,\mathrm{GeV\,cm^{-3}}$$



"a couple proton masses per teaspoon"

"a few hundred km/s"

How we look for dark matter depends on what it is…   v1

10^{-30} GeV **~keV** **10^{20} GeV**

high number density
long wavelength

“field-like”

look for couplings
at field’s natural
wavelength

low number density
short wavelength

“particle-like”

look for discrete
energy deposits
from individual particles

The theorist's WIMP miracle

DM abundance might result from thermal equilibrium terminated by freezing out (density too low to self-annihilate).

Implies a rough scale of the DM self-annihilation cross section:

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \ \mathrm{s}^{-1}$$

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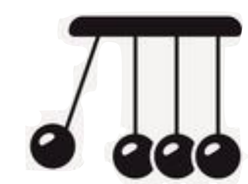
The experimentalist's WIMP miracle

We have easy access to similar-mass target particles (atomic nuclei).



These target particles see a coherence boost to electroweak interactions at these energies (~N^2).

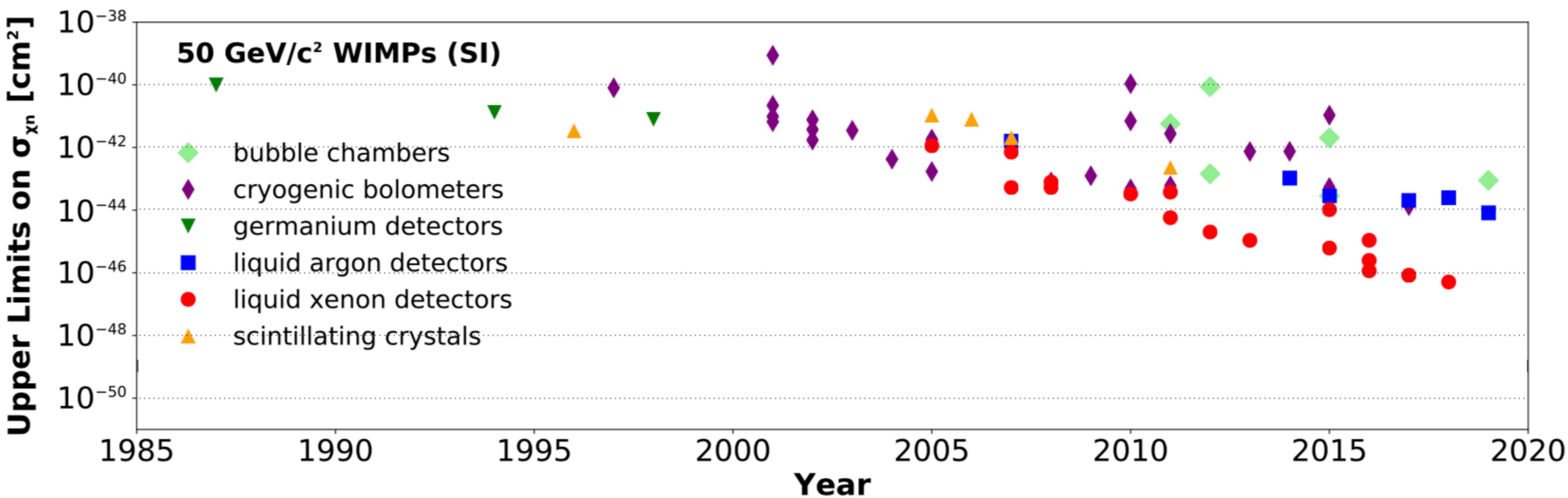
The recoil energies are of keV scale, enough to excite electrons and produce signals.

The WIMP race

1. Gather as many high-Z nuclei as you can.

2. Instrument them such that a keV-scale recoil is visible.
   (lower energy helps capture more of the recoil spectrum)

3. Shield and purify such that radioactivity does not cover up your signal.
   (use particle ID to reject electron recoil backgrounds as necessary)



Liquid Nobles

1. Extreme purity is possible (chemical getting, distillation, etc.)

2. Extreme scale is possible (tons or bigger)

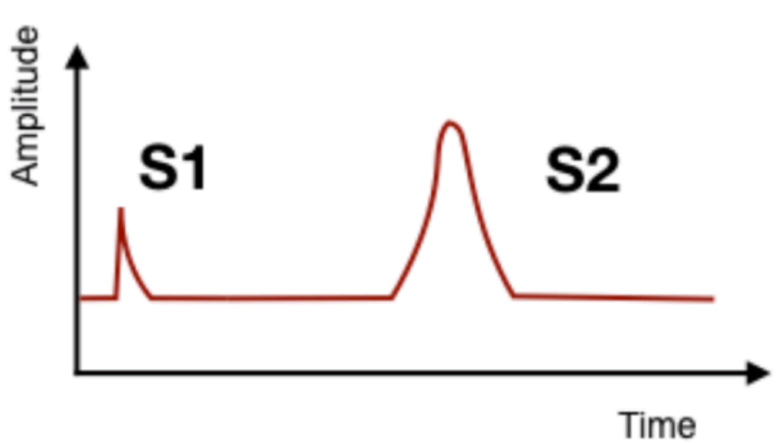
3. Multiple signal channels means copious recoil information (ionization, scintillation)

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

The two-phase Time Projection Chamber

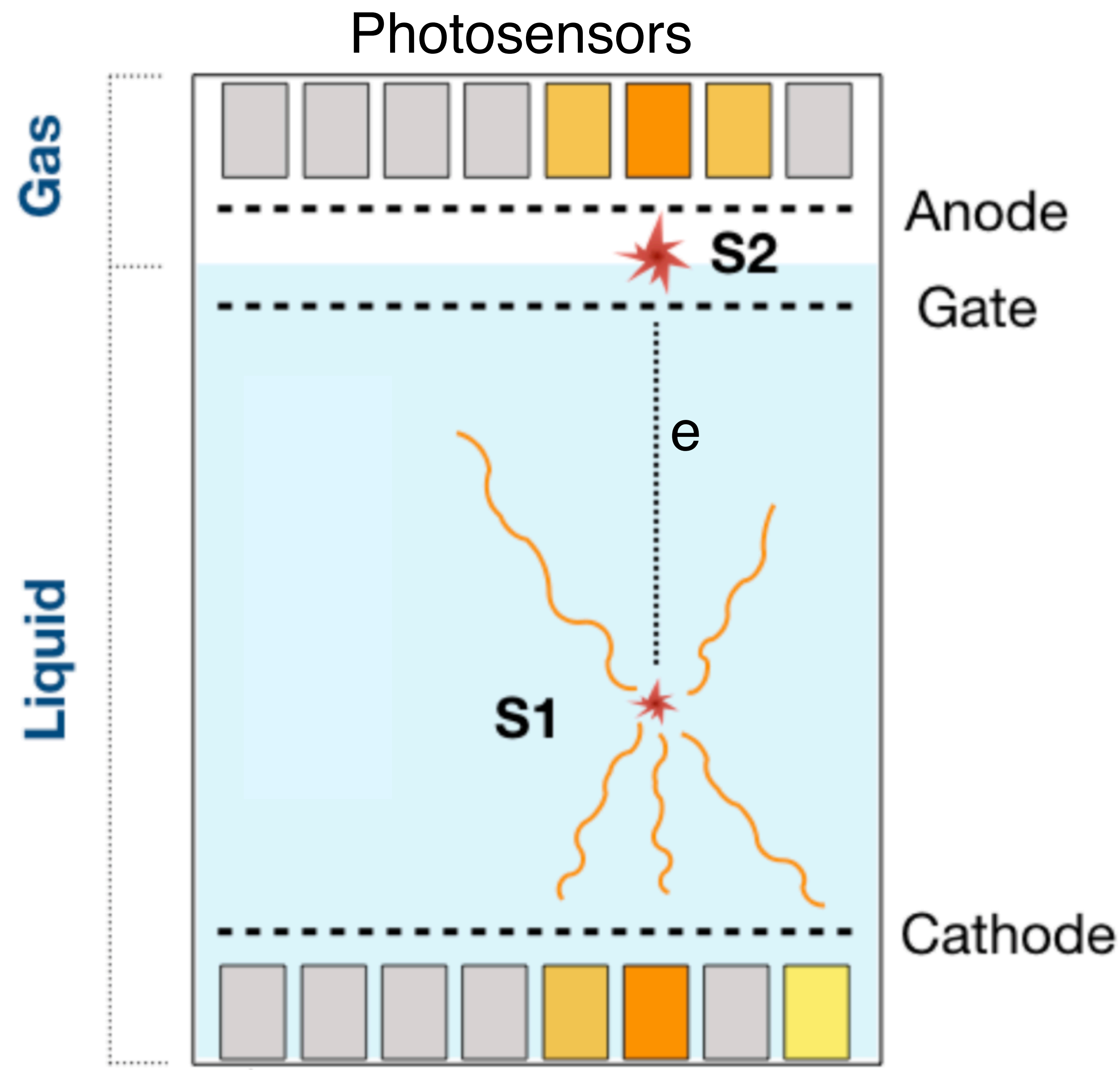
first: a flash of scintillation (S1)

second: electrons drifted to gas, produce delayed scintillation flash there (S2)



Time between flashes indicates Z

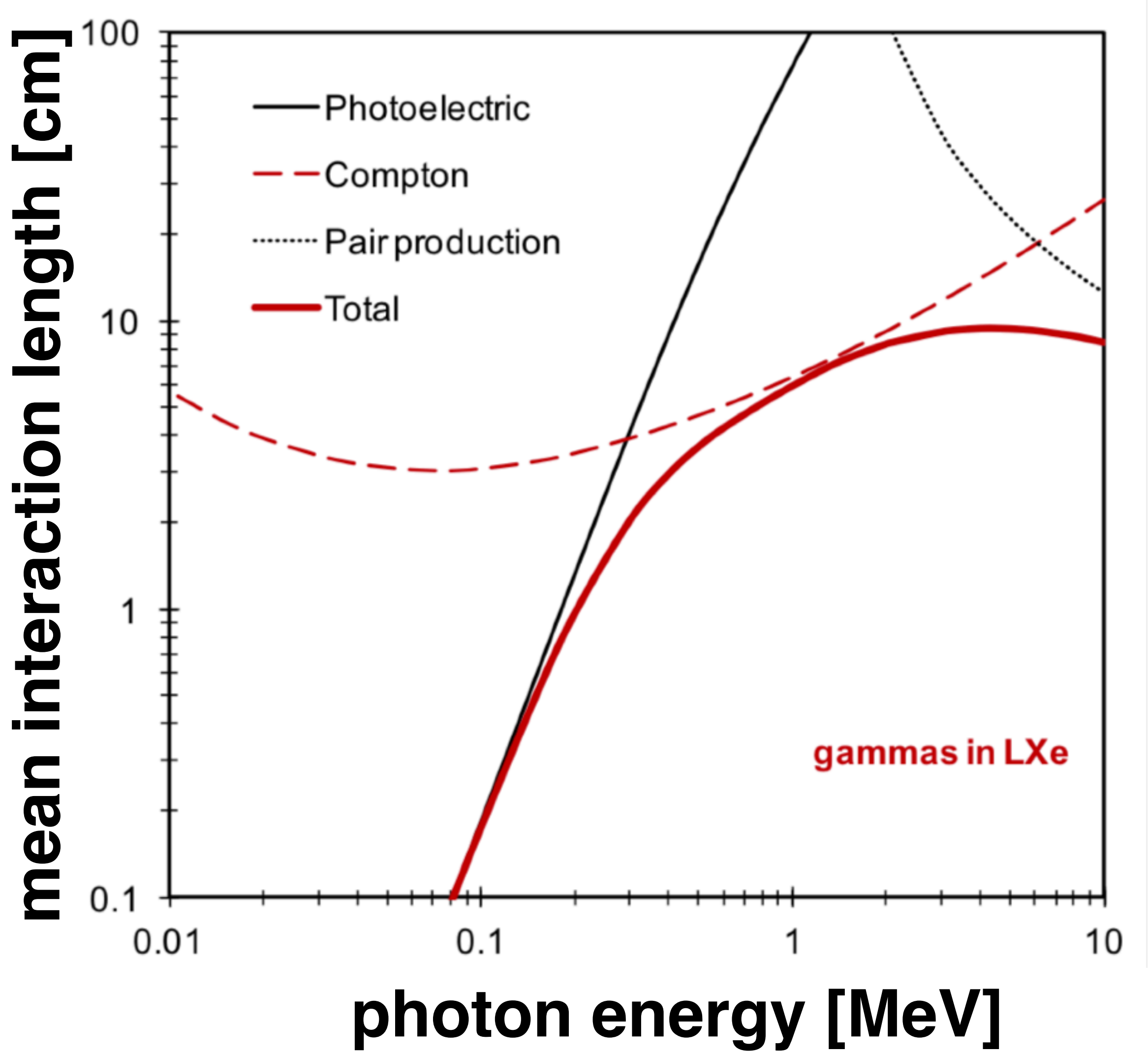
S2 pattern indicates XY position

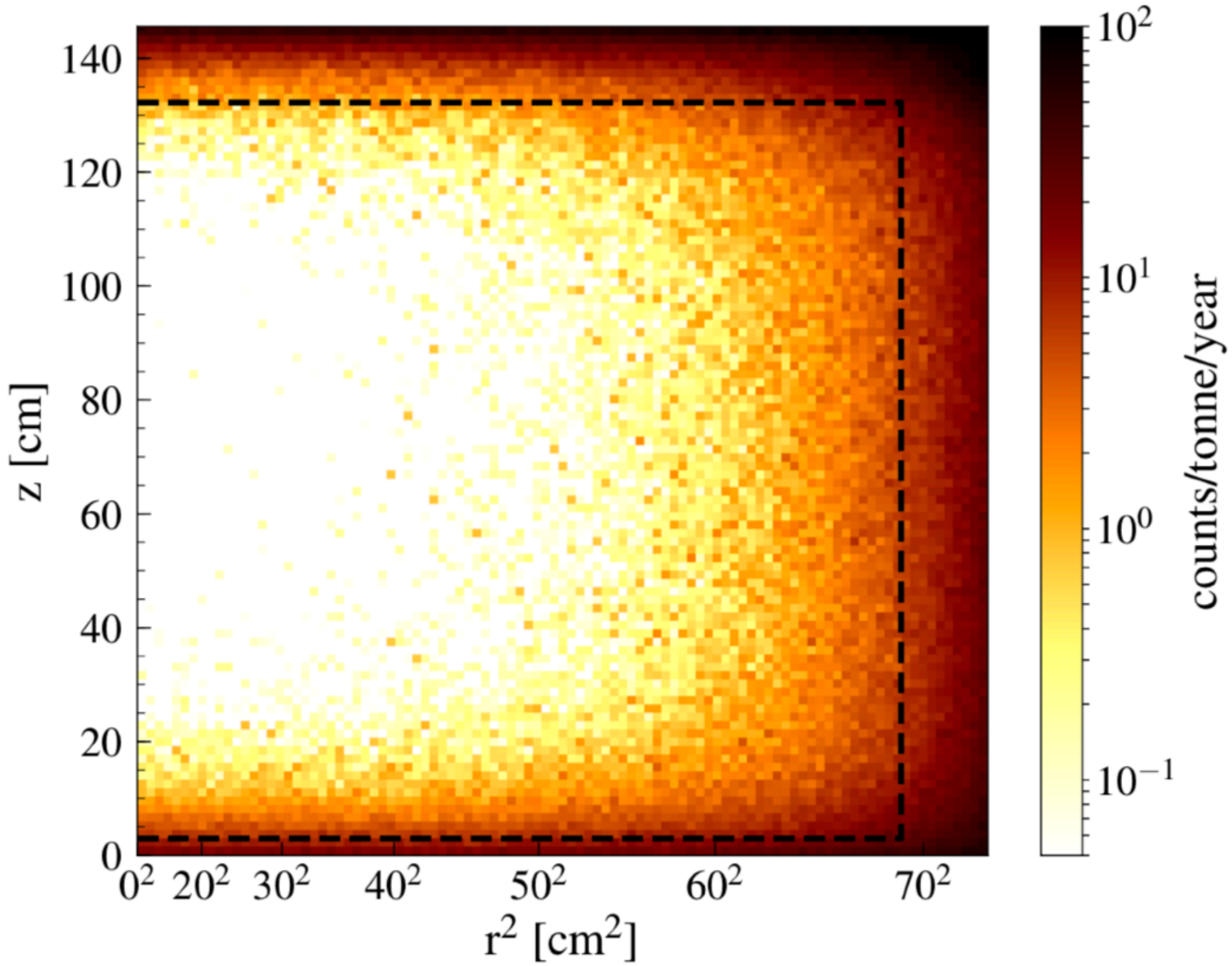


The importance of position information

Large detector volume, with short gamma penetration depth: a very `quiet' central volume.

…but only if your position reconstruction works well!

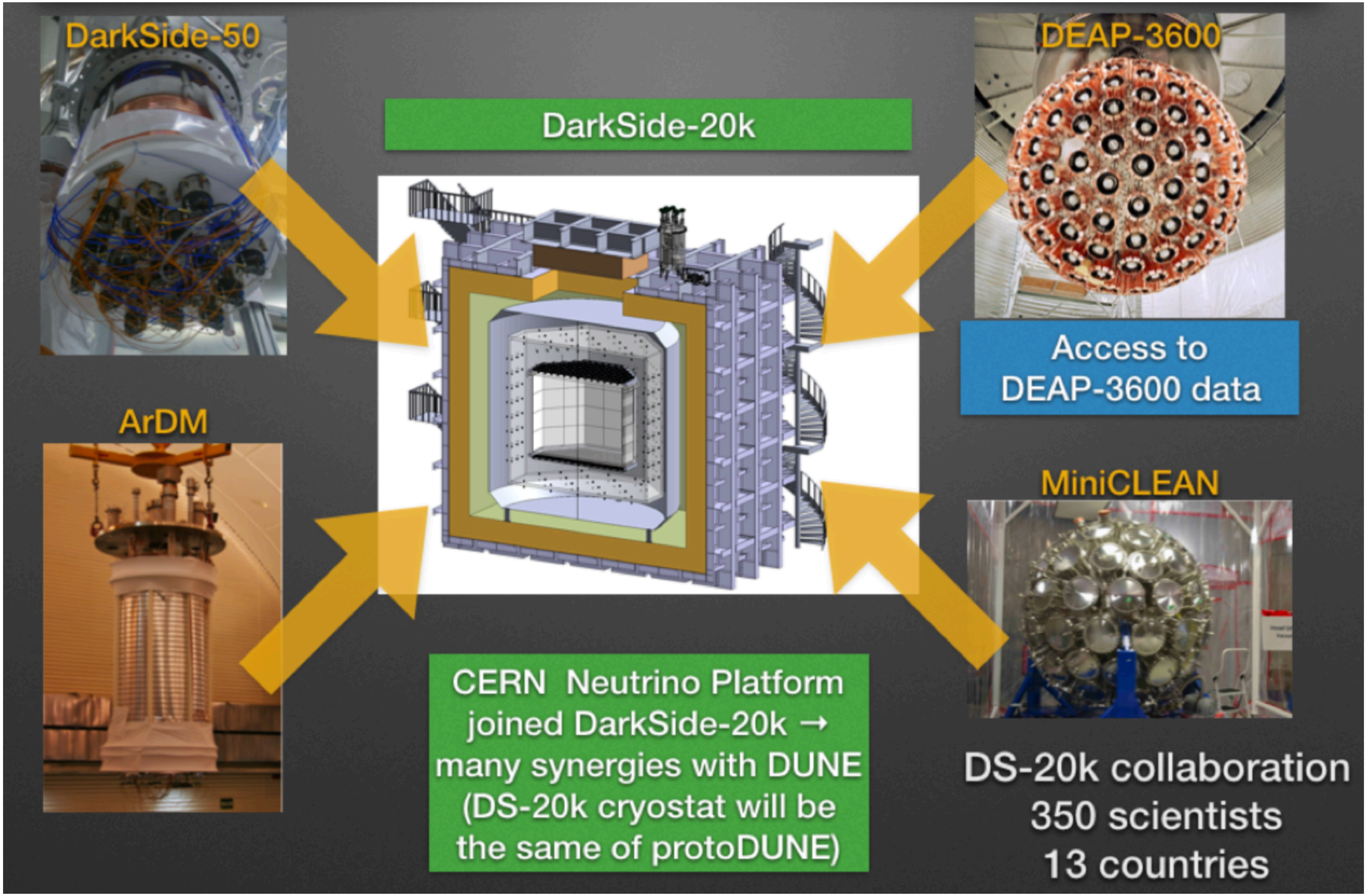




Comparing Argon and Xenon

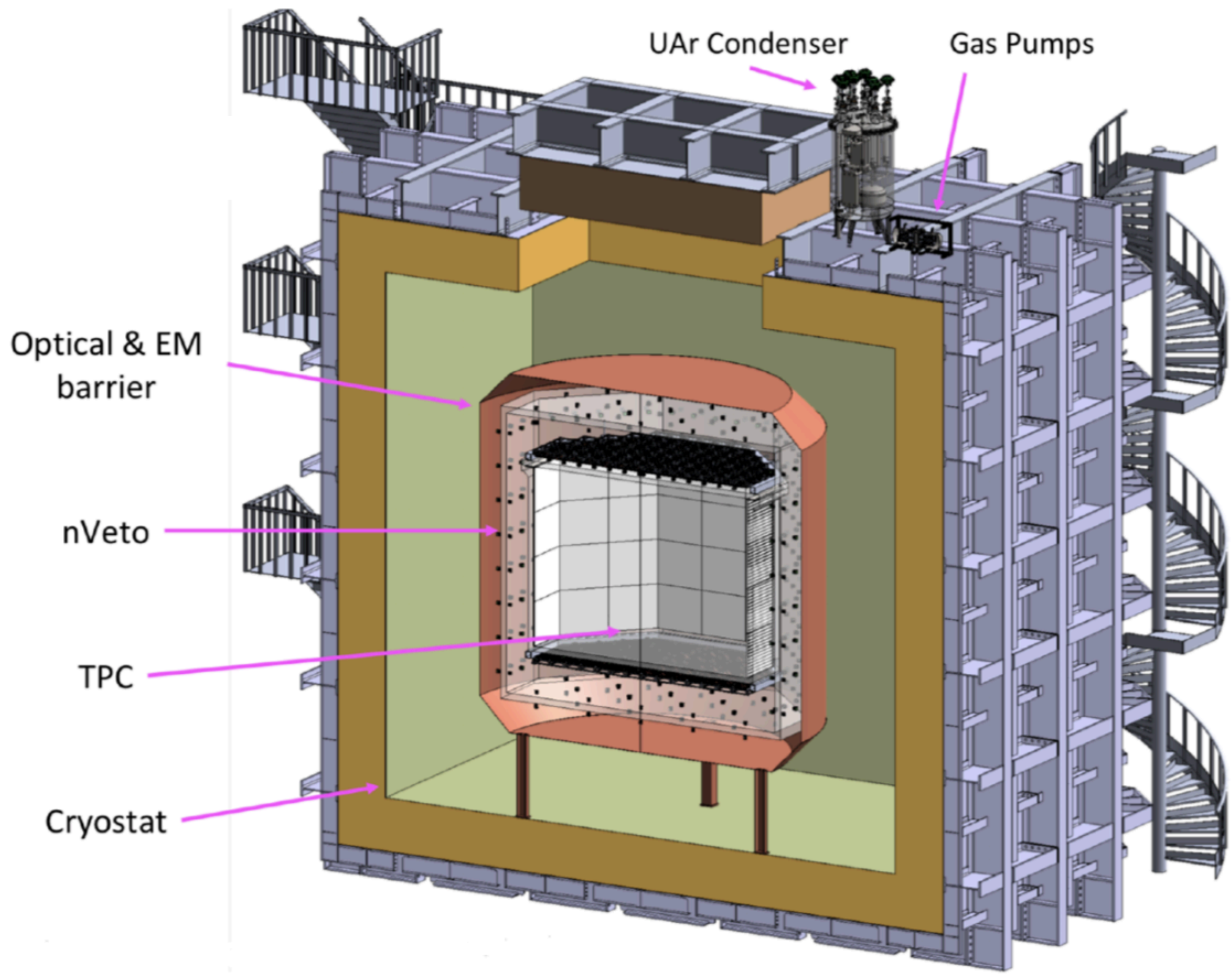
	Ar	**Xe**
Backgorund Discrimination	scintillation pulse shape (10^8)	ionization:excitation (10^3)
Discrimination Threshold	~50 keV	~2 keV
Radioisotopes	39-Ar, 269y (typically ~1Bq/kg)	(only short-lived)
Material Cost	set by 39-Ar mitigation	~$1000/kg
Temperature	87 K (less Rn emanation)	166 K (more Rn emanation)
Density	1.4 g/cm3 (worse self-shielding)	3.1 g/cm3 (better self-shielding)

The Liquid Argon Landscape



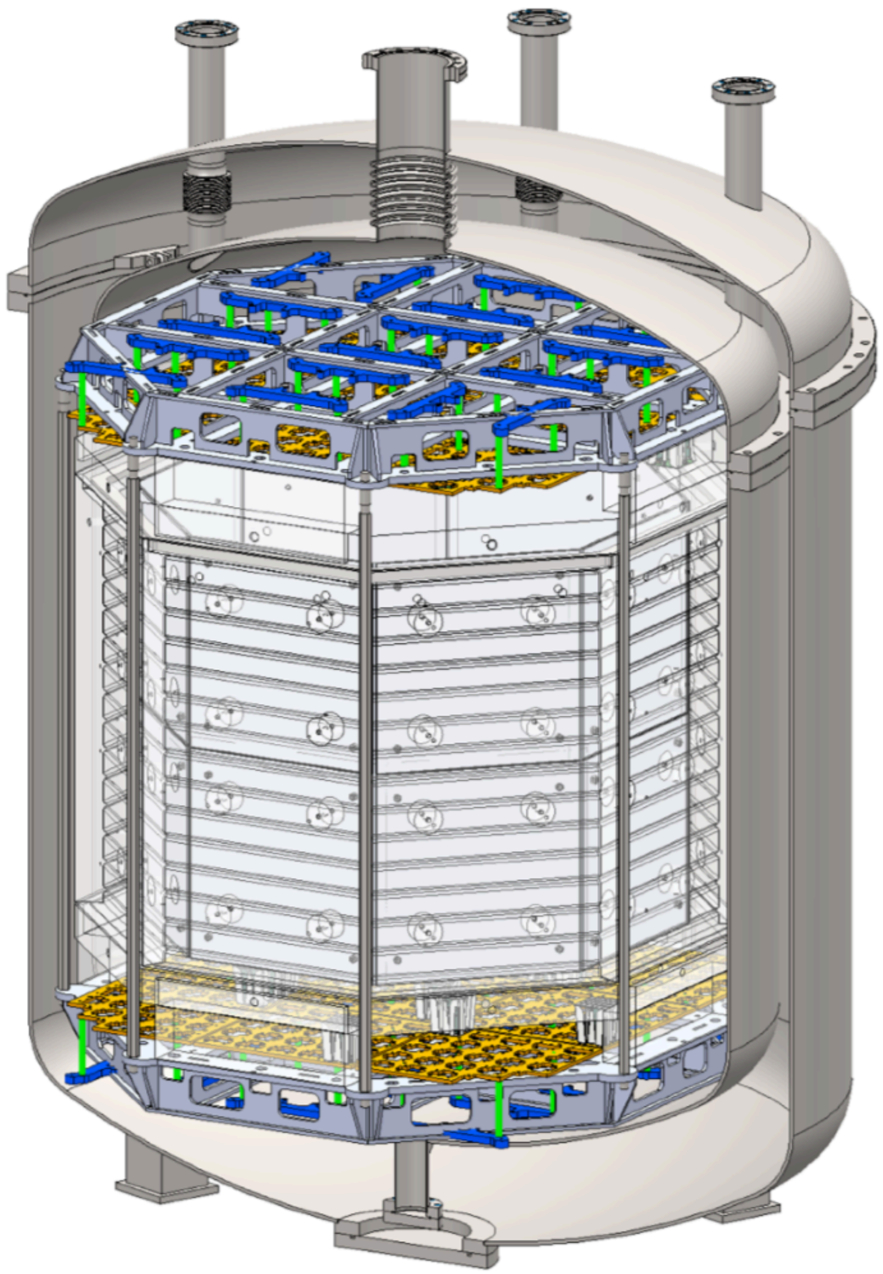
Liquid Argon : DarkSide 20k

- Inner detector: Sealed acrylic dual phase TPC filled with ~ 50 tonnes Underground Argon (UAr);
- Membrane cryostat filled with ~700 tonnes Atmospheric Argon (AAr);
- Veto detector: 2% Gd doped acrylic panels as neutron veto;
- Copper Faraday cage;
- SiPMs as photosensors: 8280 channels for TPC, ~3000 channels for Veto.
- ~2022



Liquid Argon : DarkSide 20k

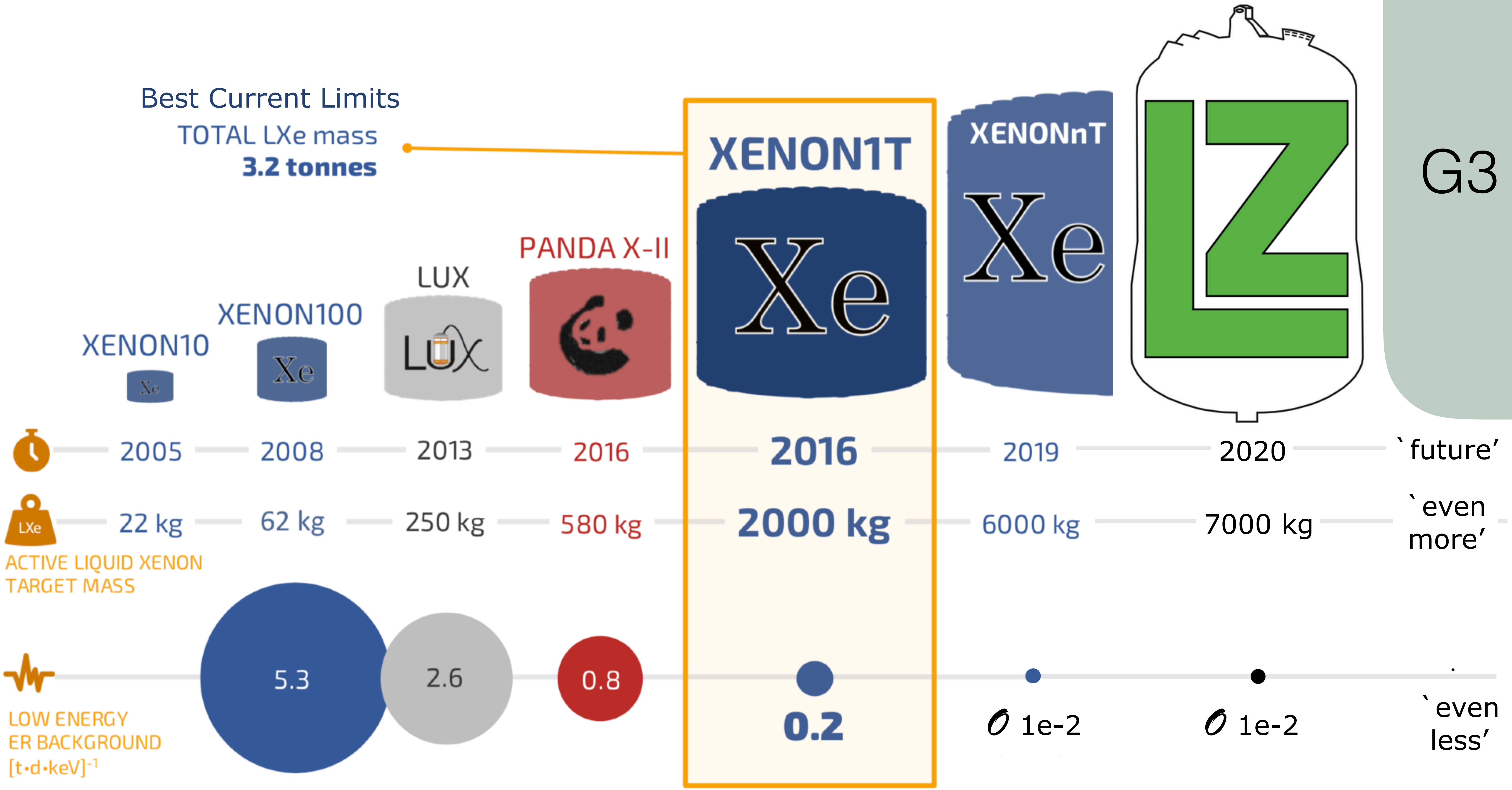
technology testbed: Proto 1ton
summer 2020



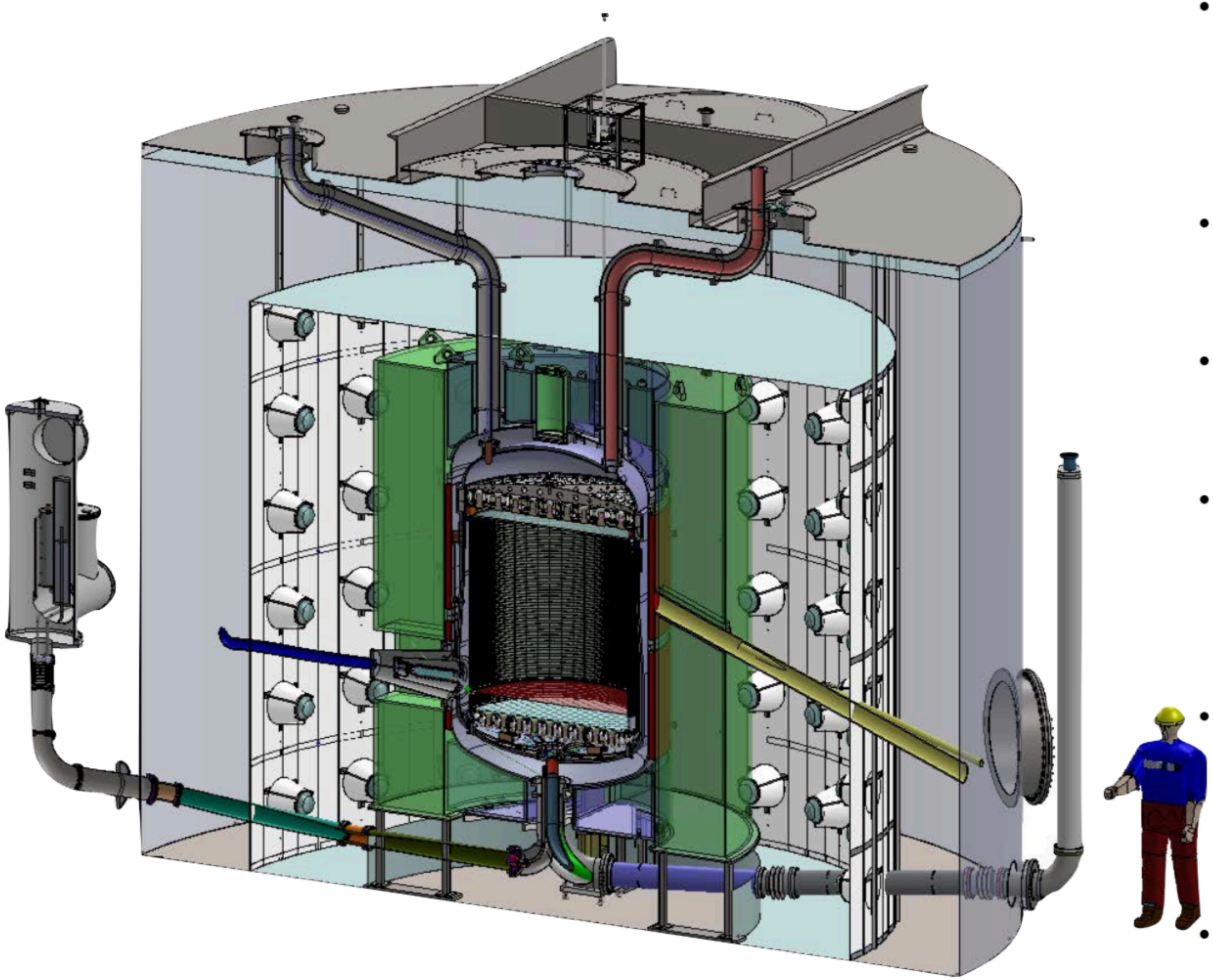
developing underground Ar supply,
manufacturing of 39-Ar distillation

Liquid Xenon : many TPCs

sensitivity scales faster than linear,
thanks to self shielding and surface:volume ratio



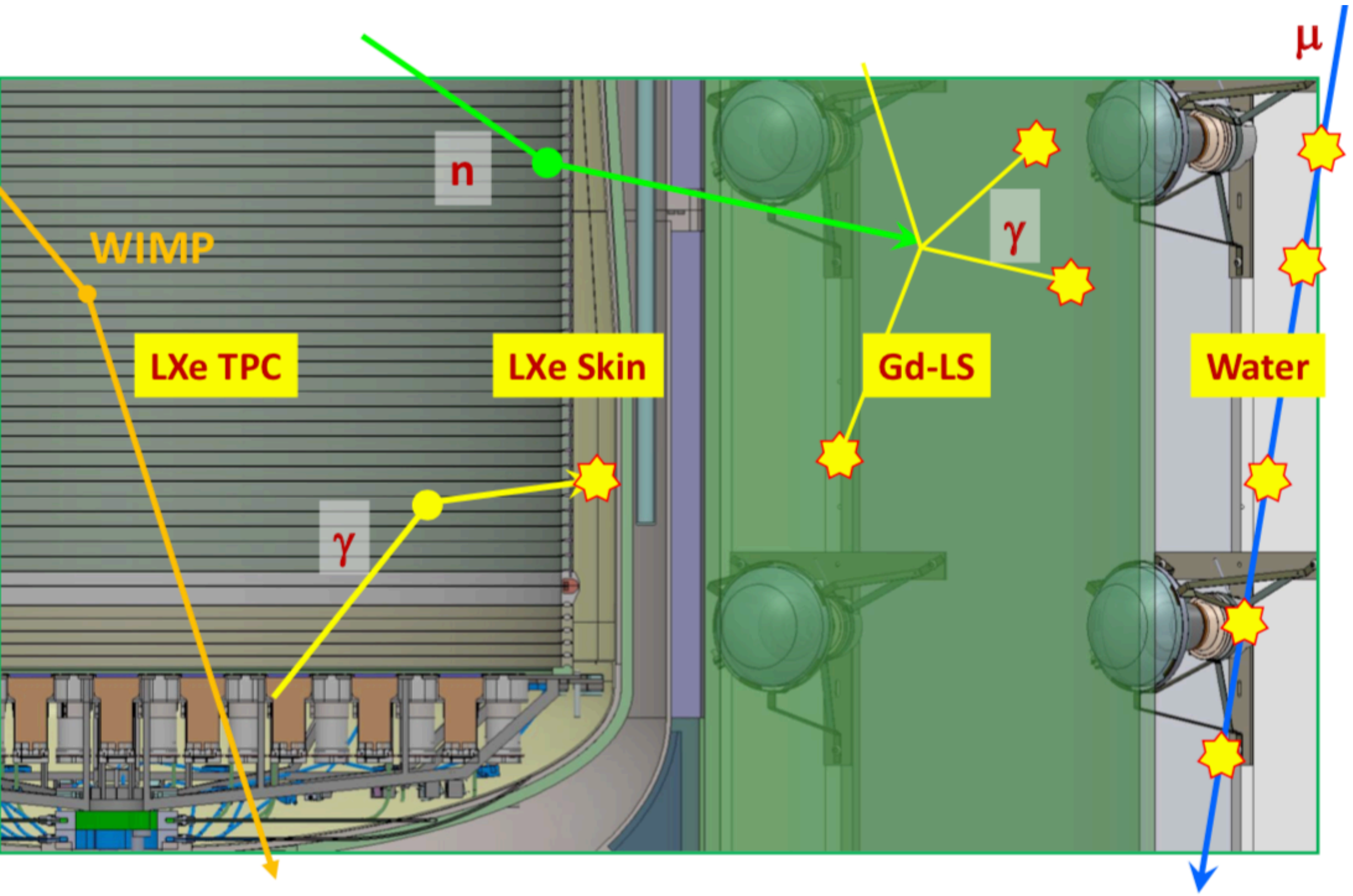
Liquid Xenon : LZ

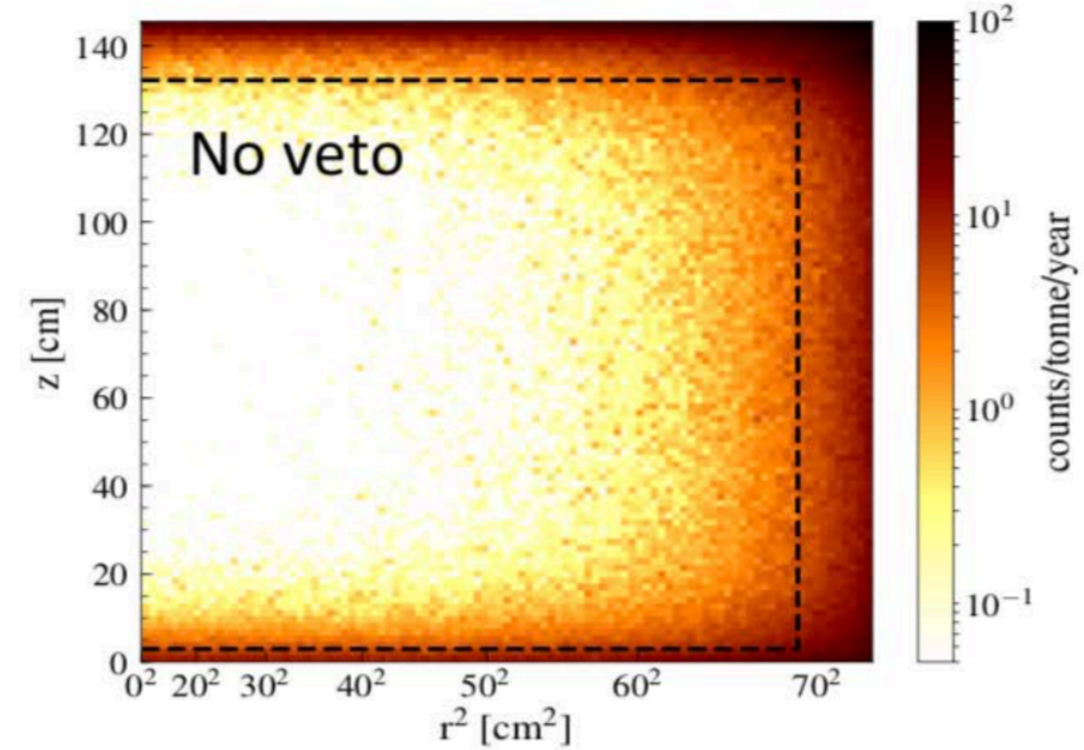


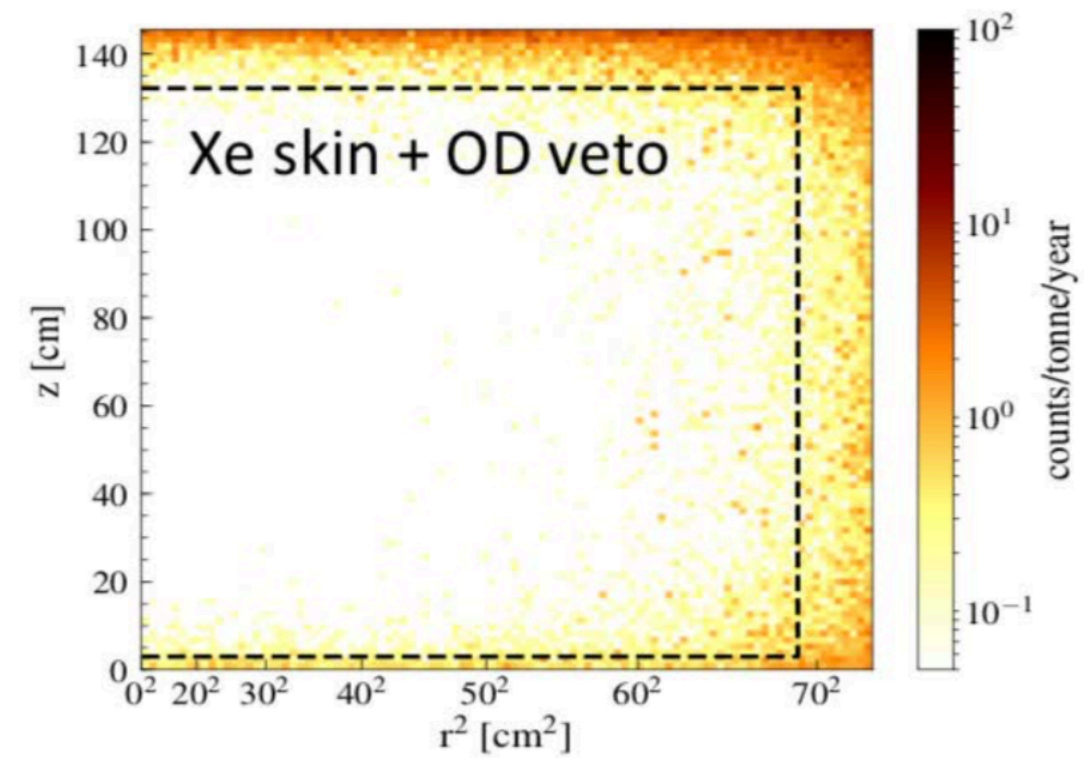
Technical Design Report, arXiv:1703.09144

- 10 t liquid Xenon
  (7 t active, 5.6 t fid.Vol.)
- 494 3" PMTs
- 50 kV cathode
- Xenon skin detector
  (131 1" & 2" PMTs)
- liquid scintillator outer detector (120 8" PMTs)
- high purity water shield
- 4850L Sanford Lab

Liquid Xenon : LZ

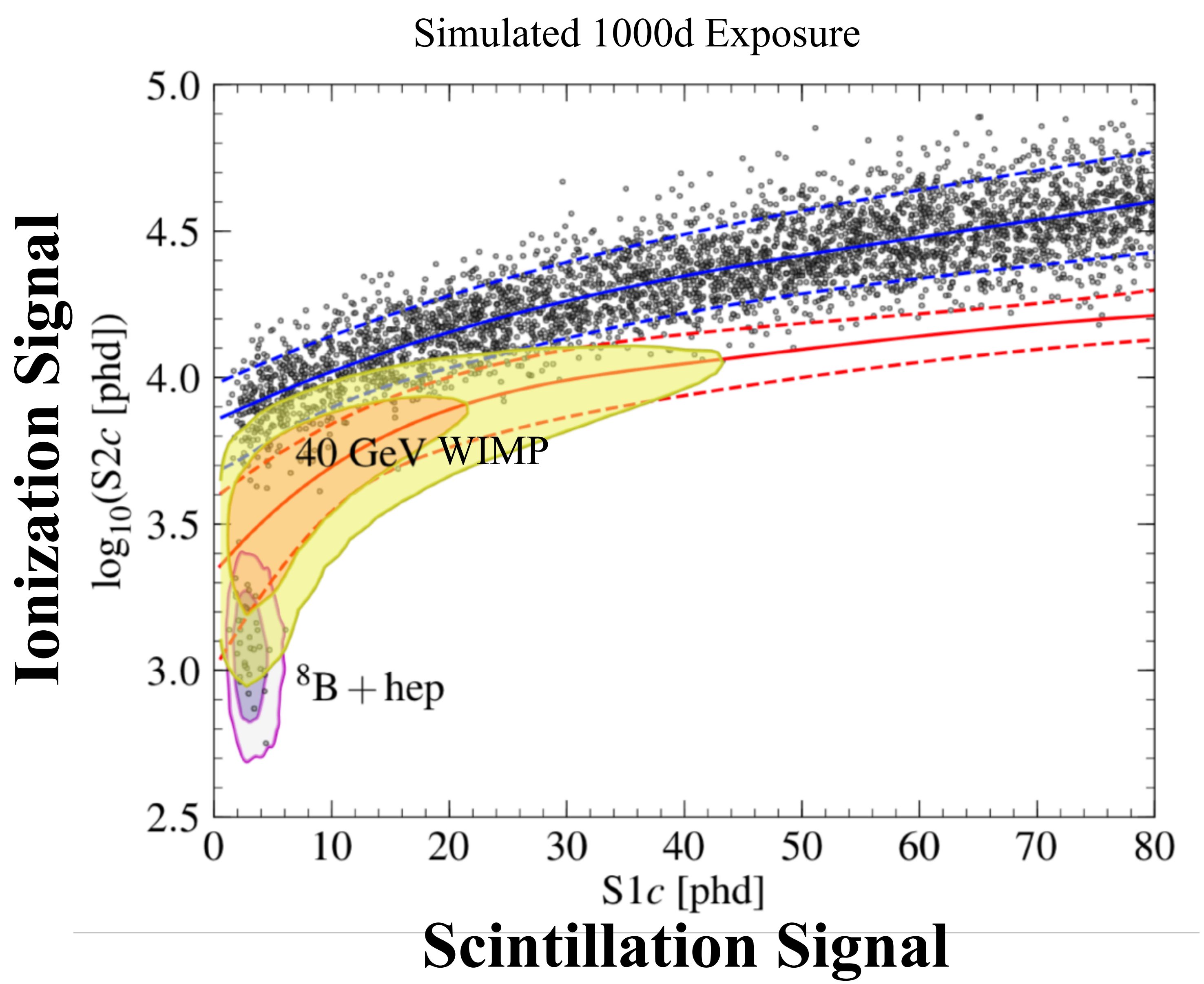




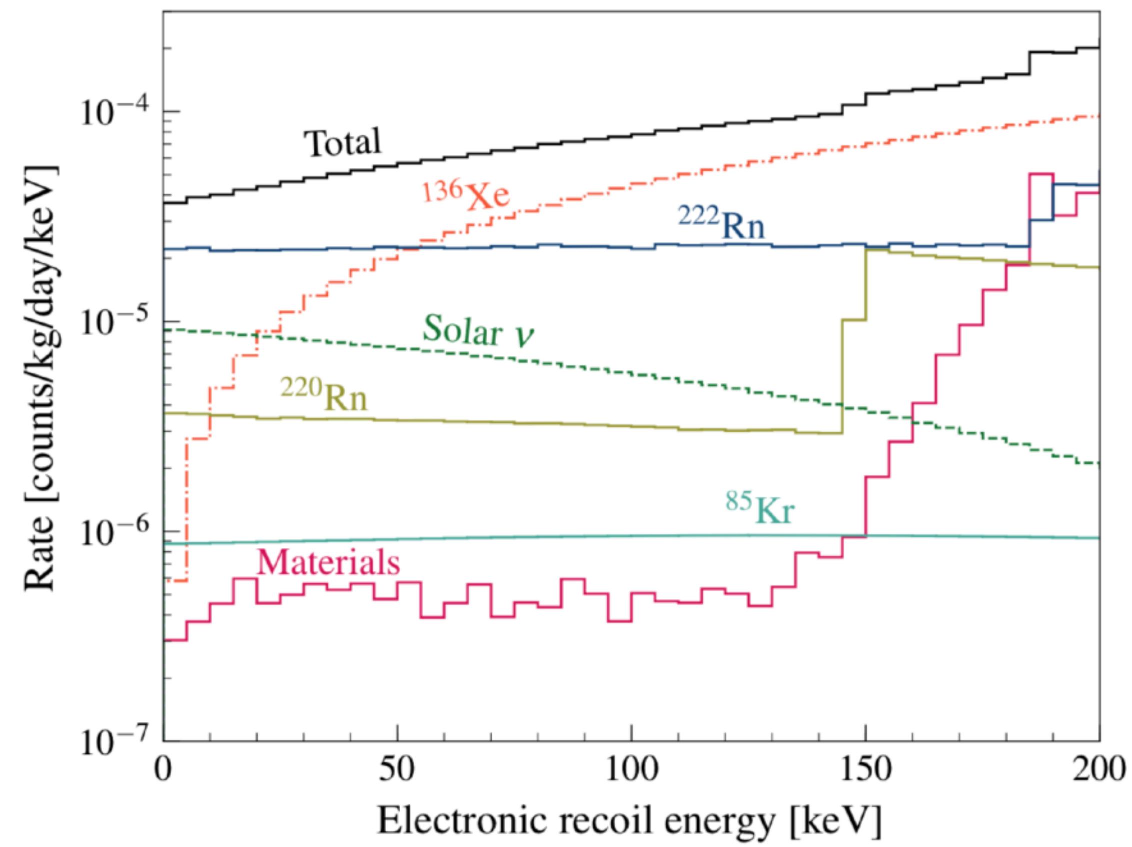


- Instrumented xenon skin - gamma-ray tagging
- Gd-LS - thermalize and capture neutrons

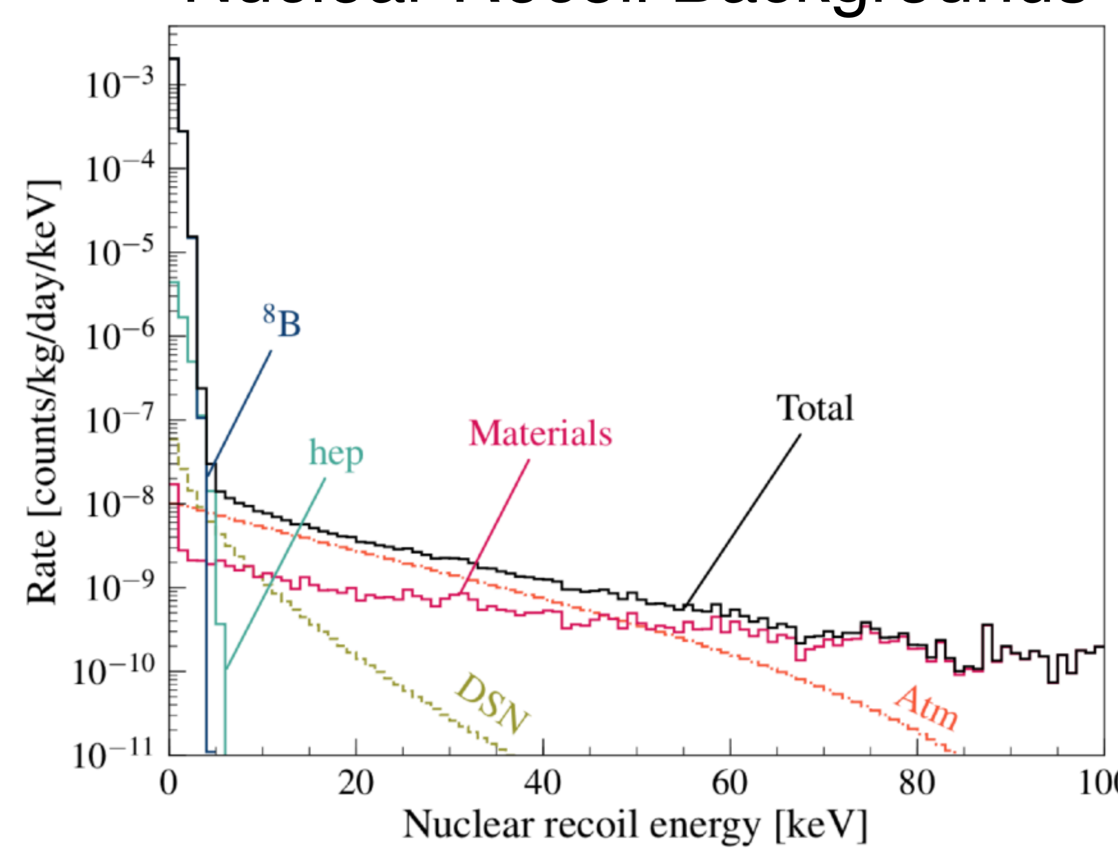
Liquid Xenon : LZ



Electron Recoil Backgrounds

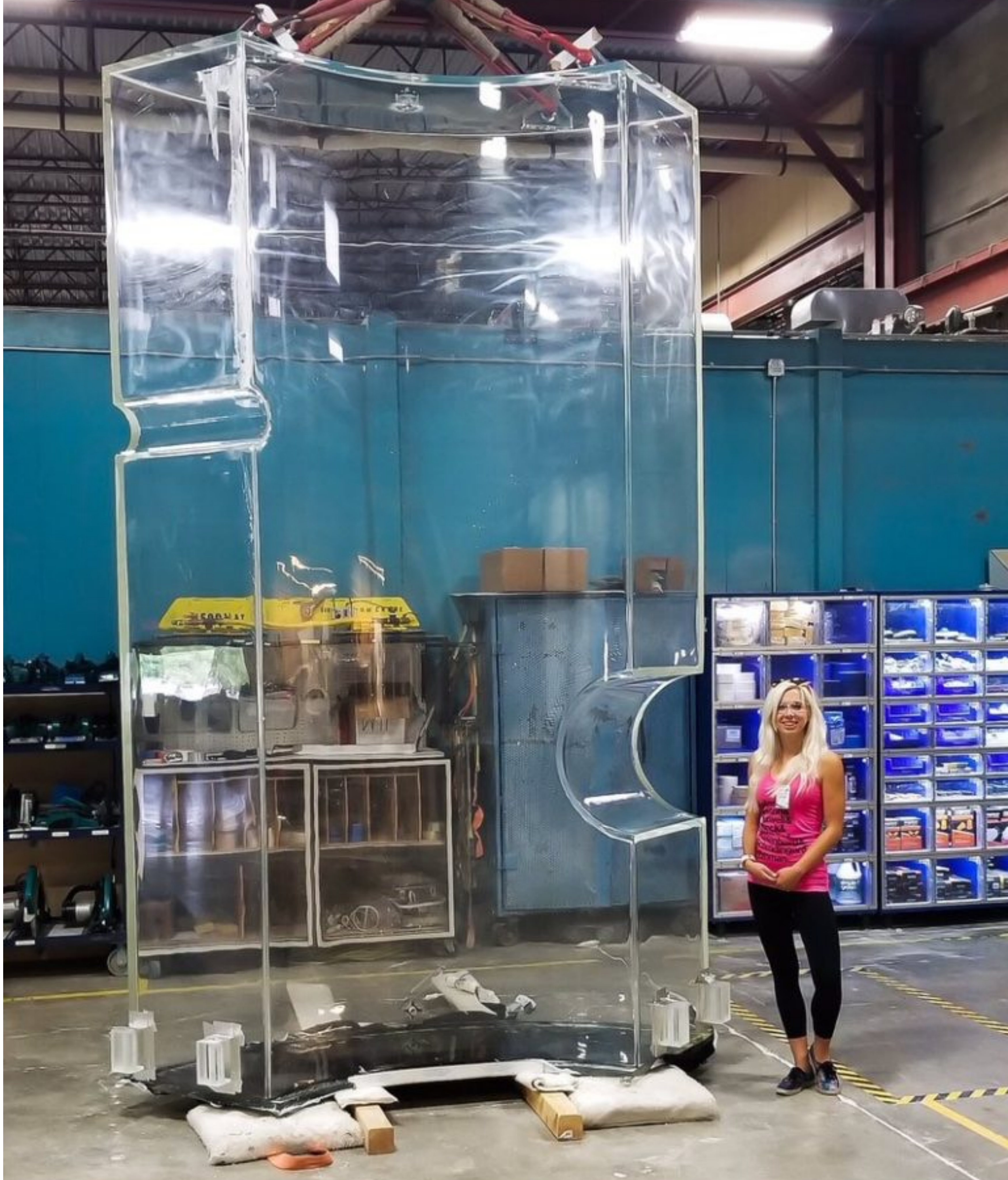


Nuclear Recoil Backgrounds



LZ
show & tell

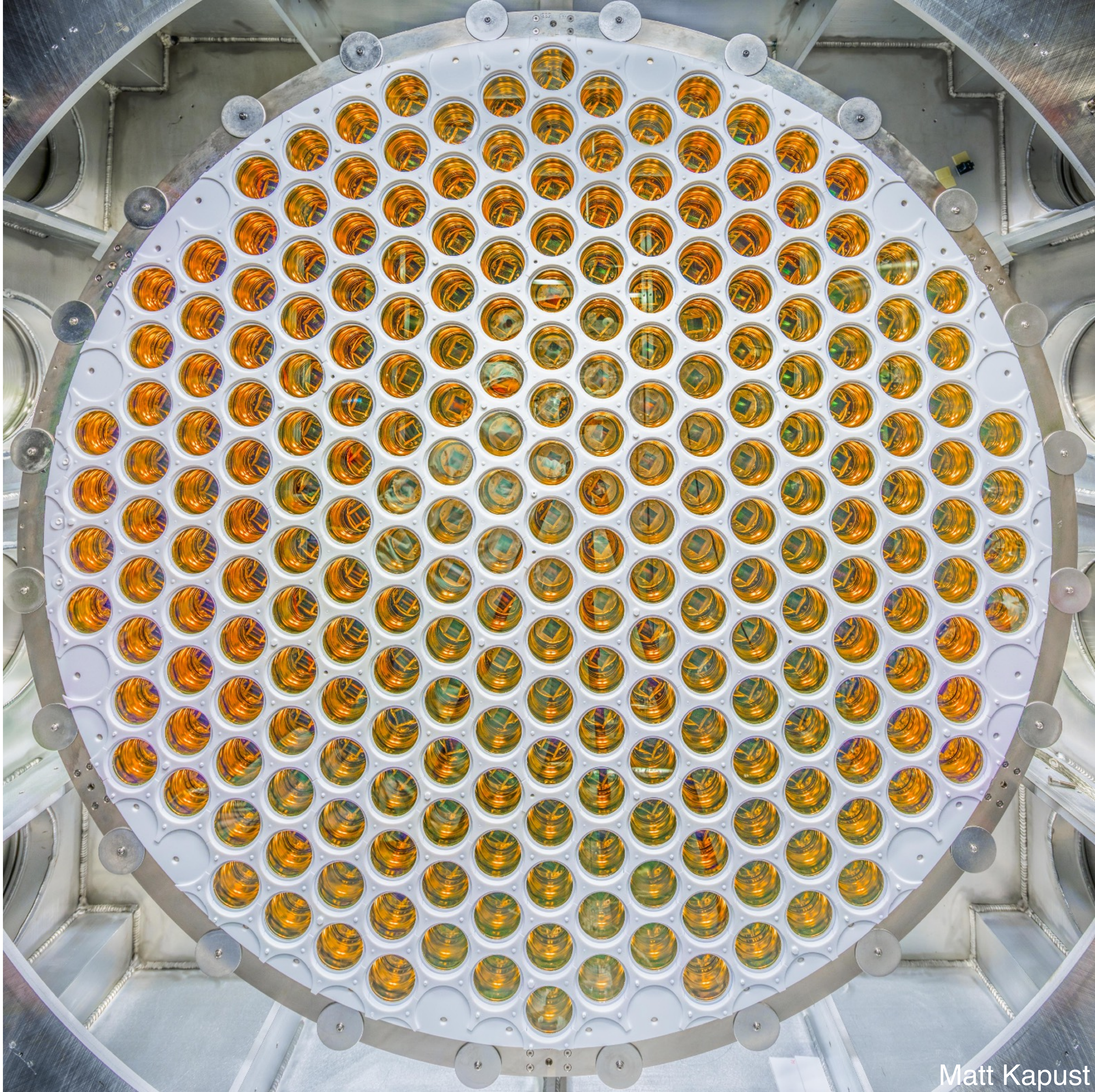
LZ
show & tell



LZ
show & tell

Matt Kapust

LZ
show & tell



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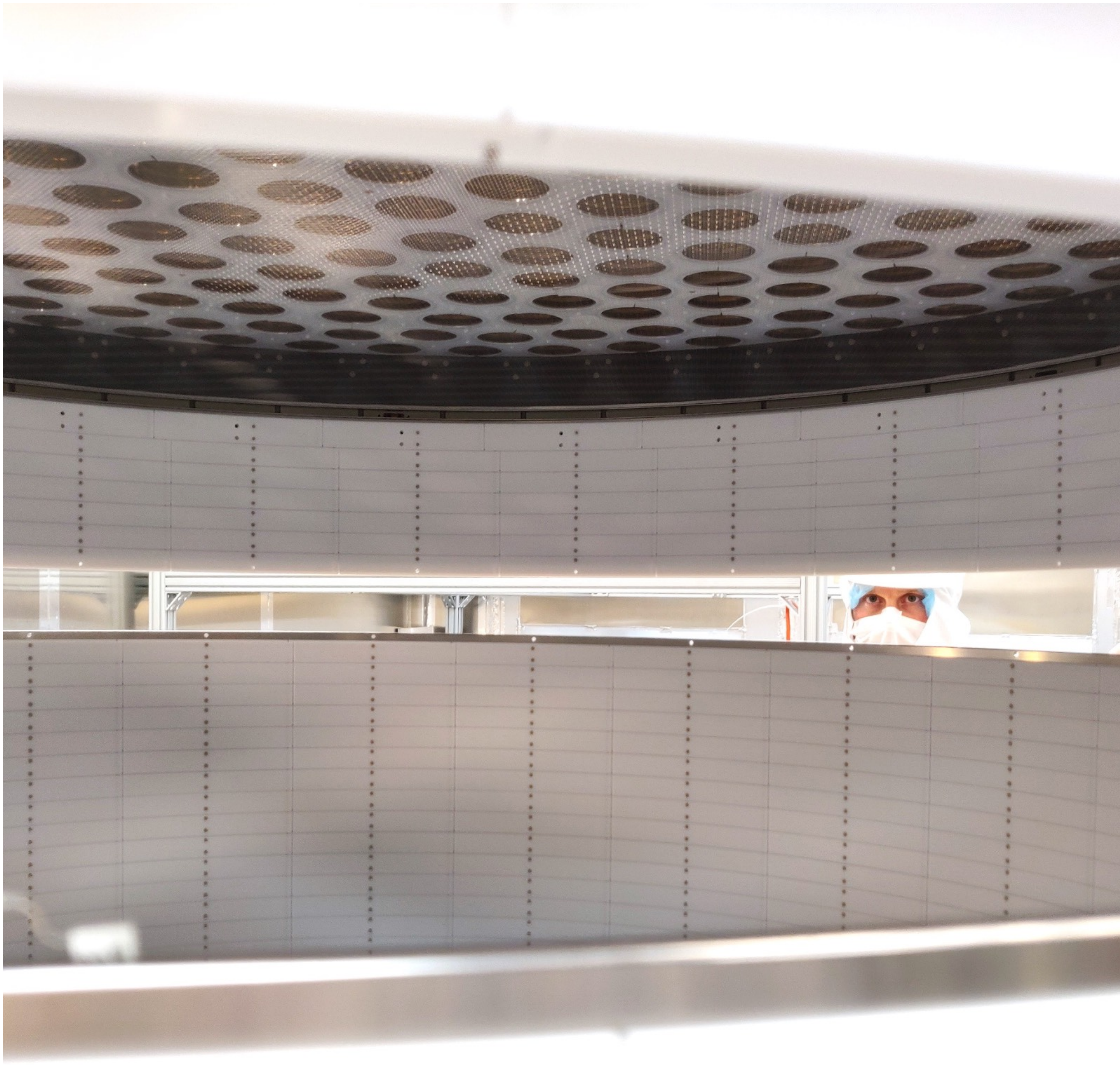

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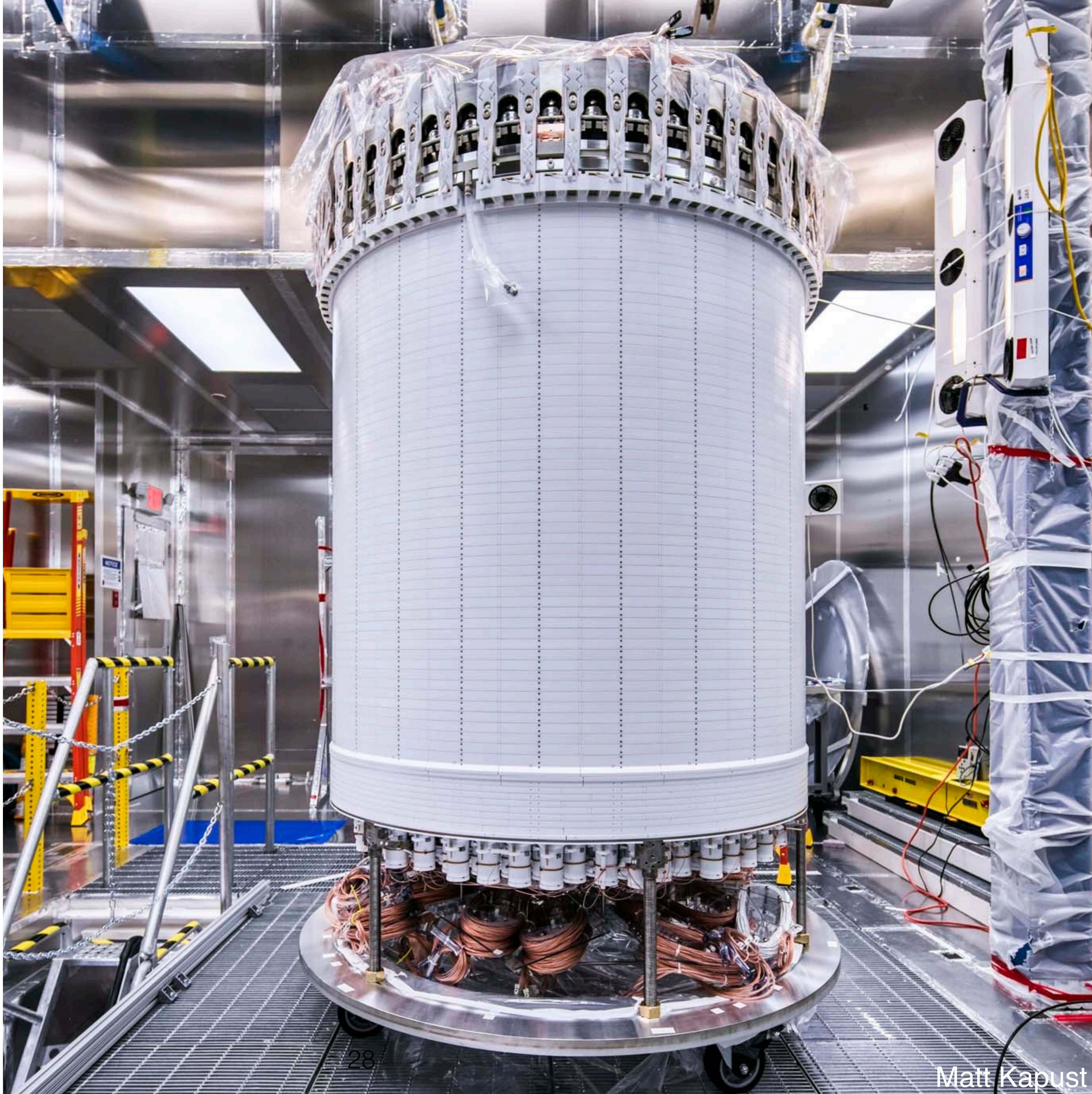
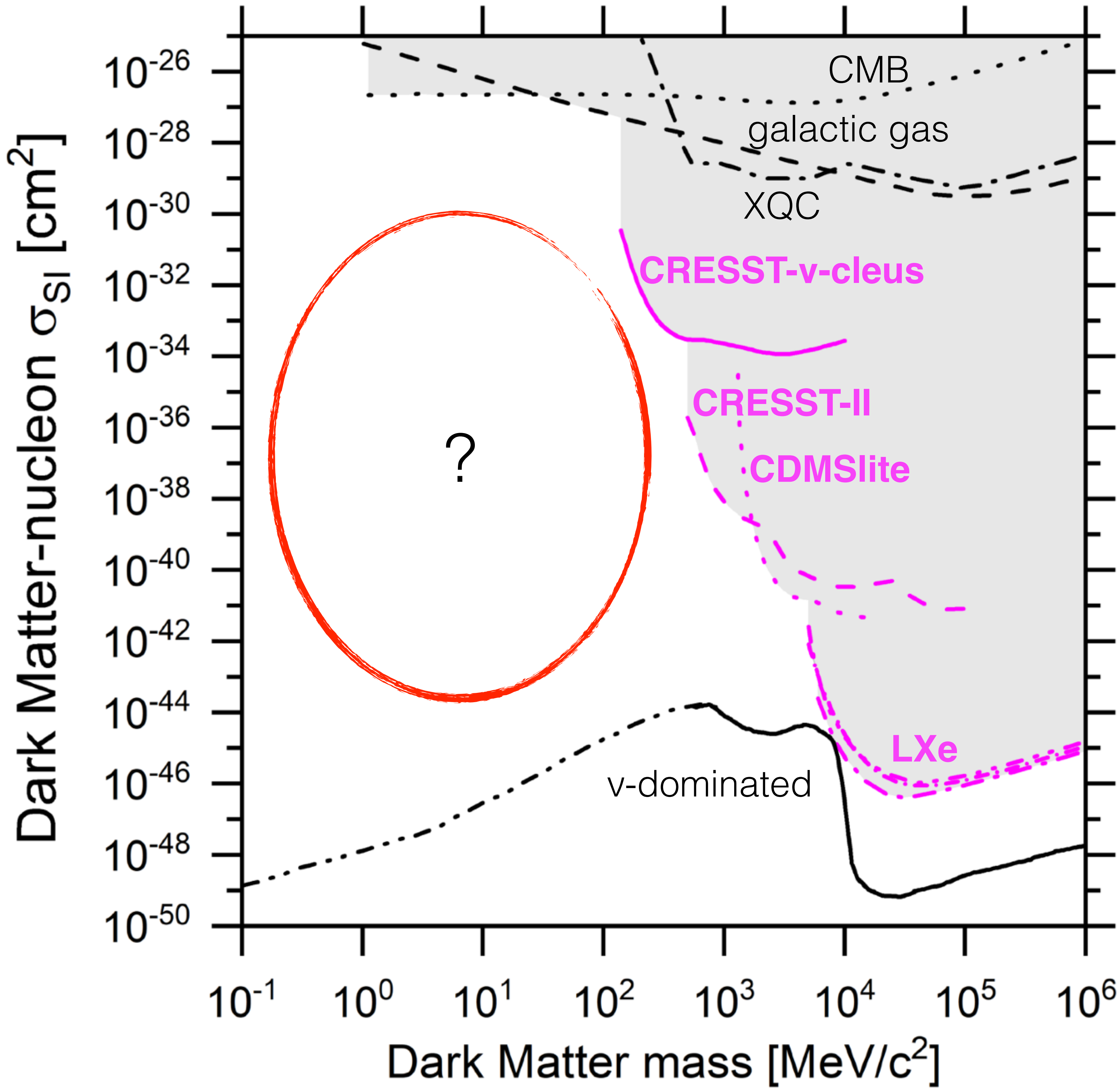


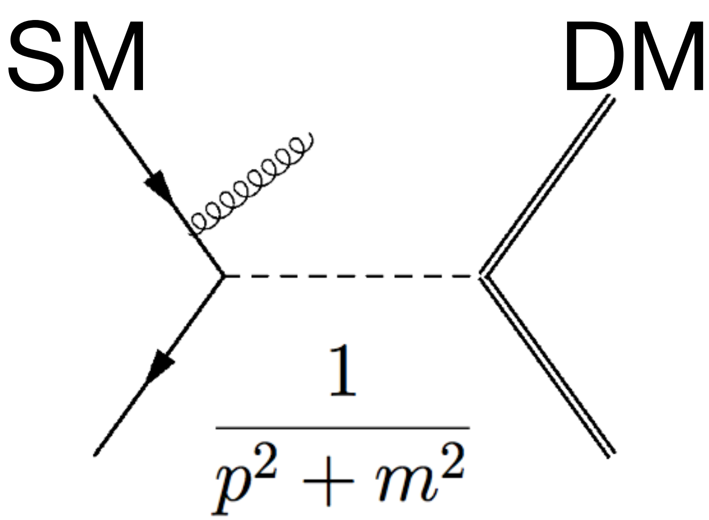
LZ is a lot of effort… are we looking in the right place?

LZ is a lot of effort… are we looking in the right place?

More specifically, could dark matter be hiding in the keV-MeV mass range?



But haven't the colliders already probed lower masses?

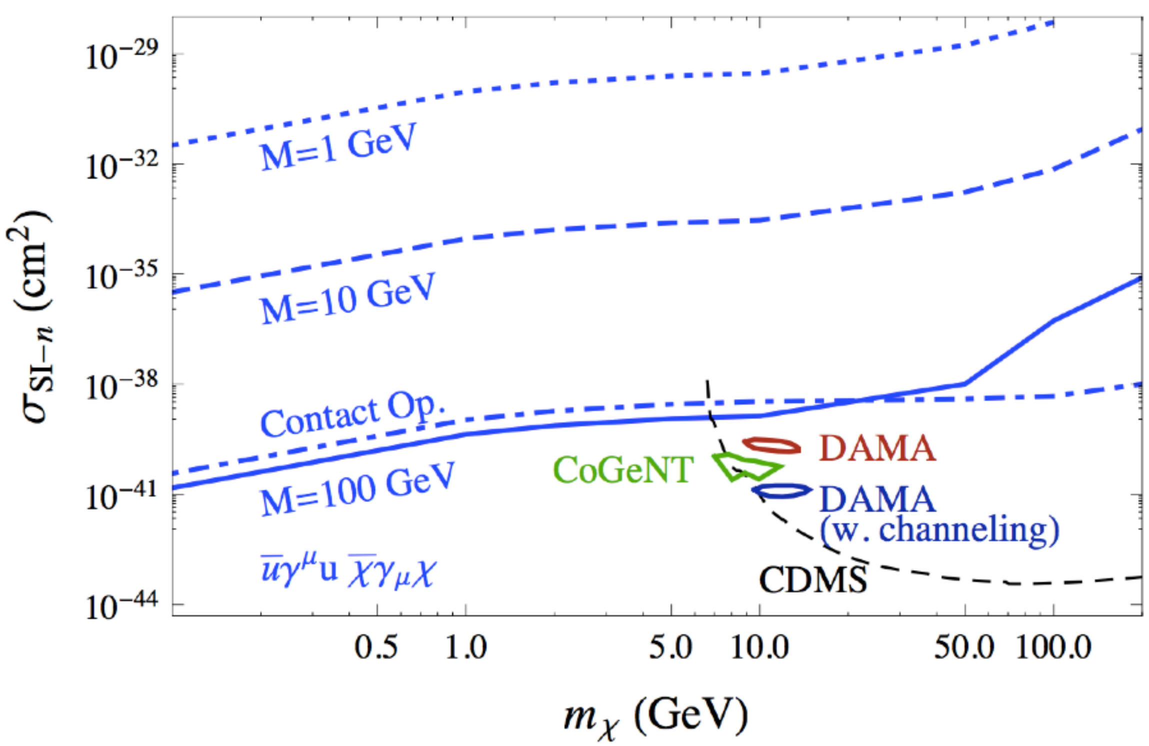


mediator mass has different effect at high and low energies

collider : p large , σ insensitive to m

early universe and
direct detection : p small , σ goes as m^-4

arXiv:1005.3797v2



Relative LHC sensitivities quickly 'evaporate' as the mediator mass is reduced.

Punchline:
IF we assume a new low-mass mediator, then
1) keV-MeV range not tested by LHC
2) simple thermal histories still work

But what about the WIMP miracle?

DM abundance might result from thermal equilibrium terminated by freezing out (density too low to self-annihilate).

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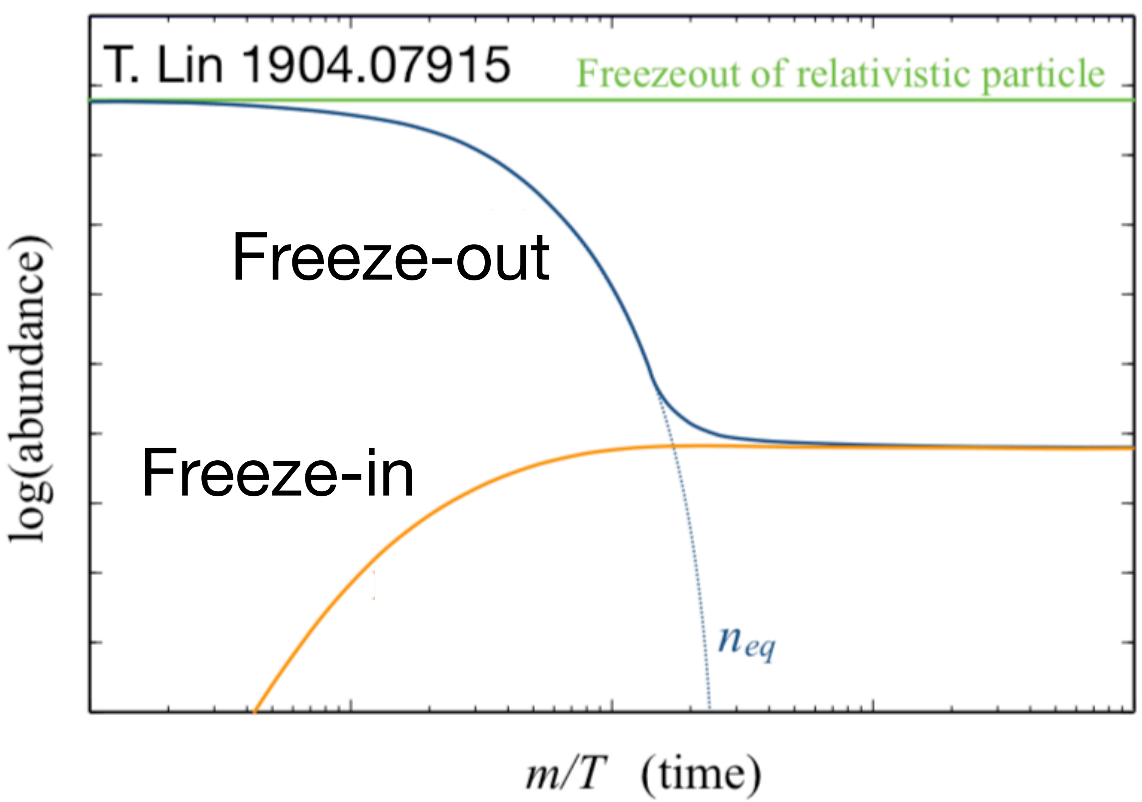
Other similarly-simple cosmologies…
… we've had blinders on the past 20y.



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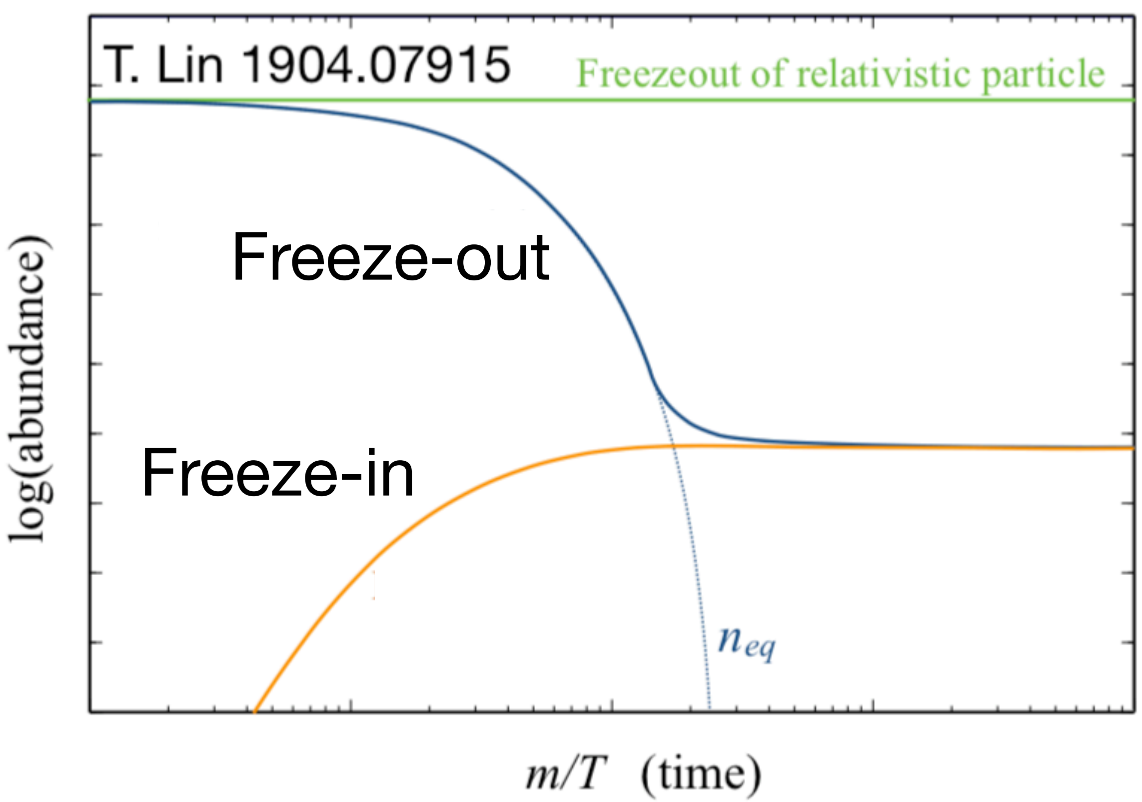


In light of LHC, the theory landscape is … "broadening."

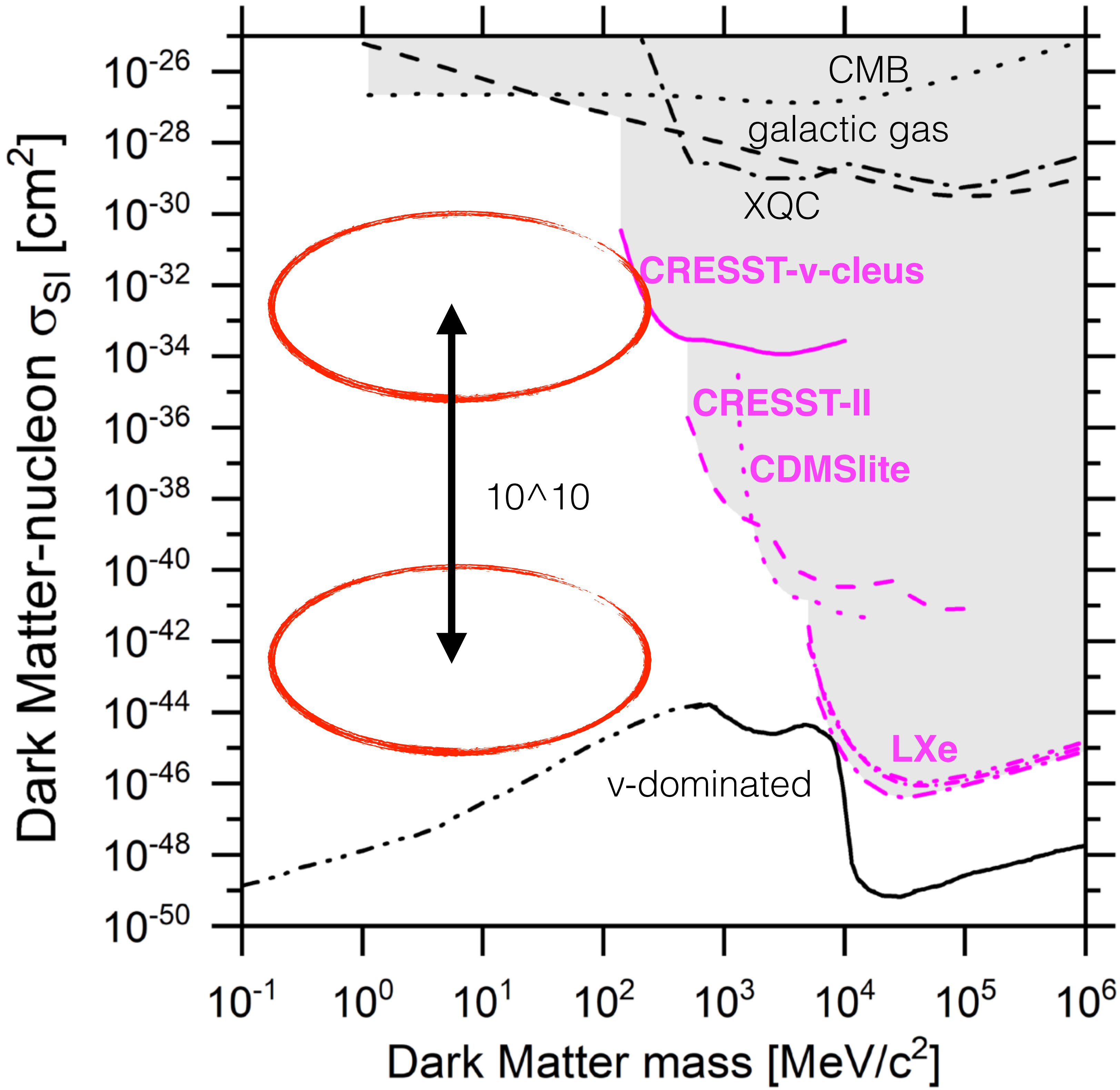
keV-MeV mass Dark Matter

The good news:

ANY sensitivity would be new and interesting.

world-leading WIMP exposure: ton-y @ keV threshold

world-leading MeV exposure: g-d @ eV threshold

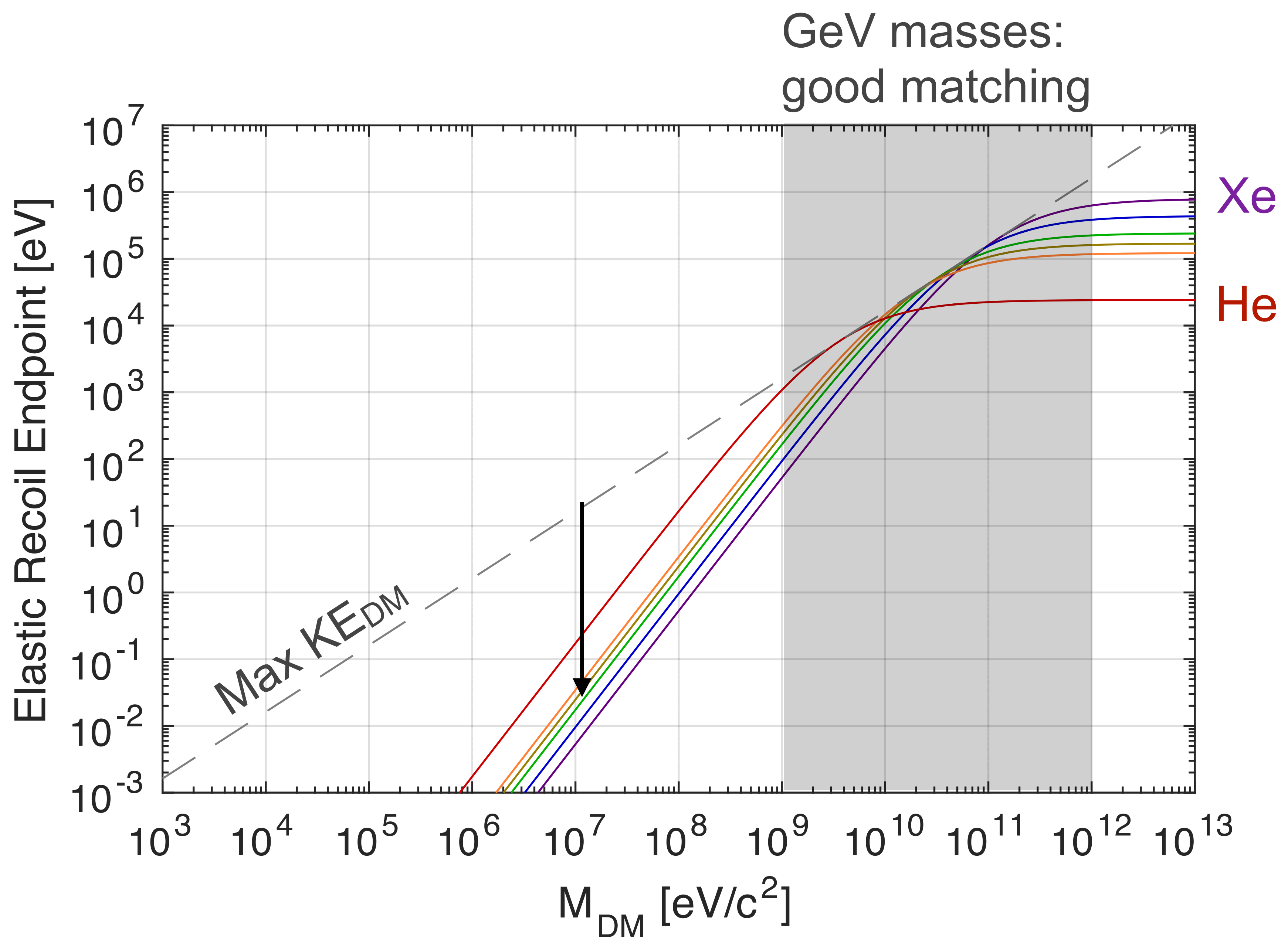


keV-MeV mass Dark Matter

The bad news:

At this DM mass, we are terribly mis-matched with the nuclear mass scale.

(Only a tiny fraction of the kinetic energy can be captured by the nucleus.)

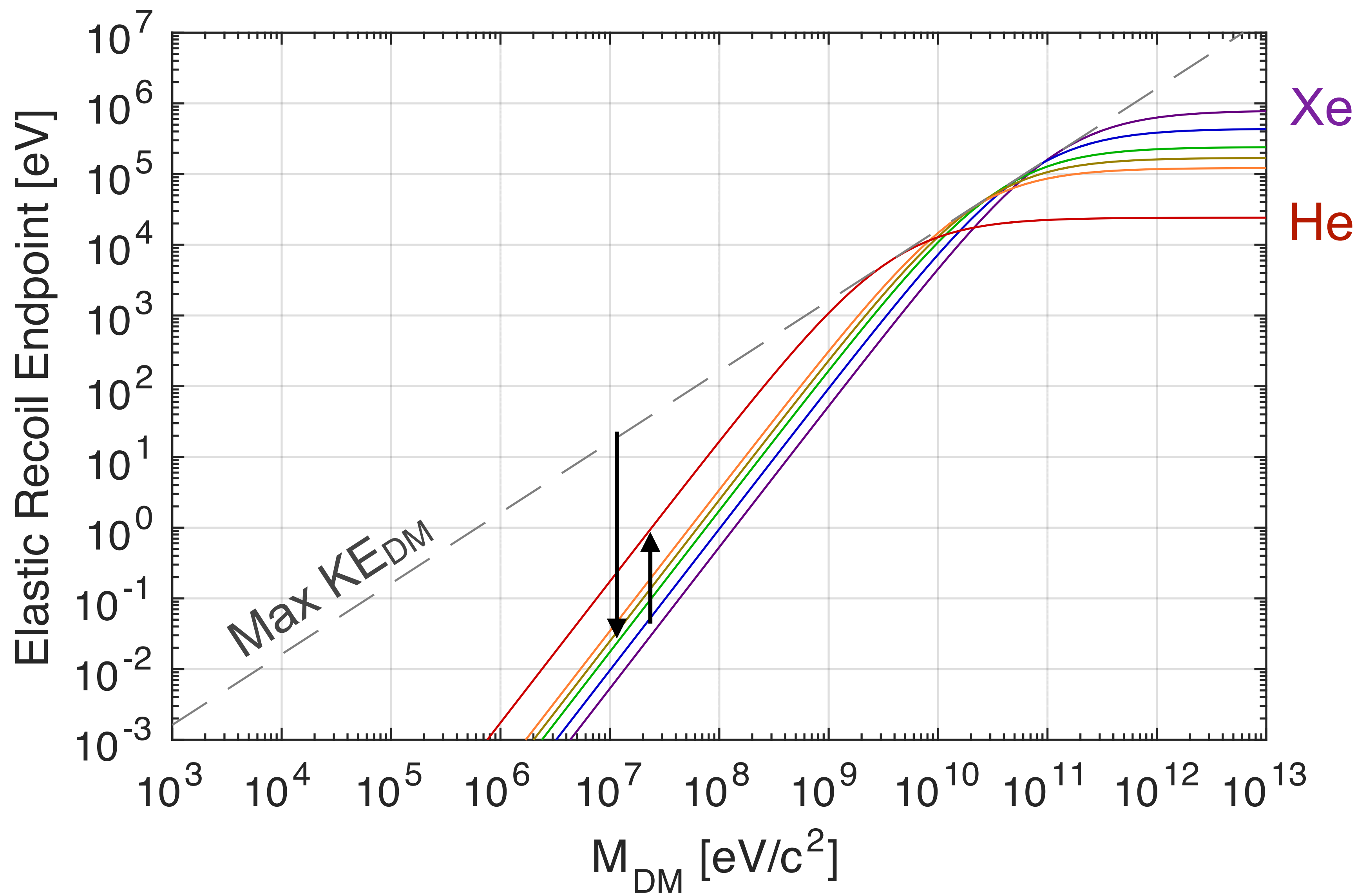


keV-MeV mass Dark Matter

strategy 1

Move to the lightest nucleus you can.

(gain about 1 order of magnitude on spectrum endpoint)

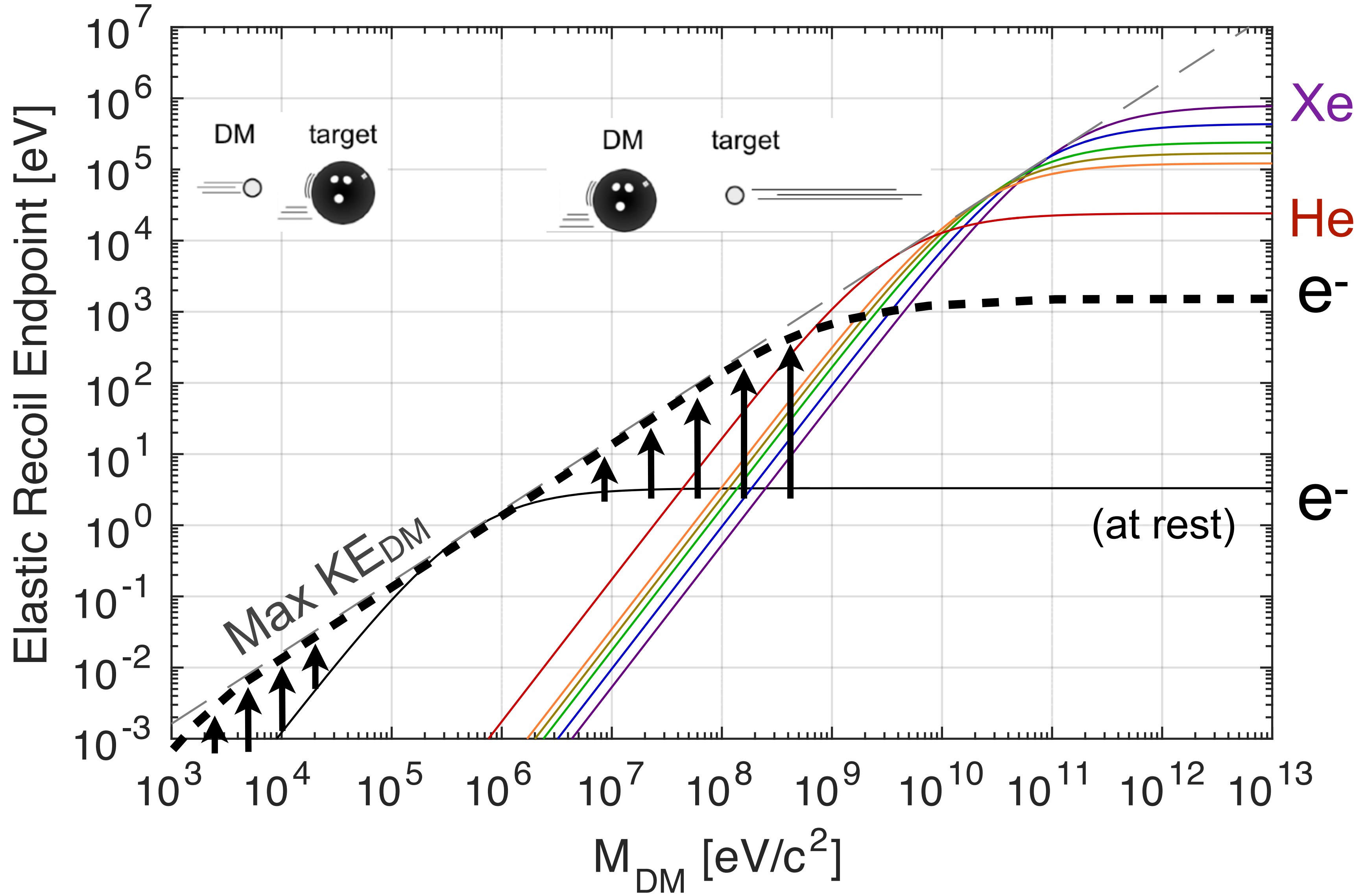


keV-MeV mass Dark Matter

strategy 2

Give up on nuclei, and instead use bound electrons as the target.

Take advantage of distribution of initial momenta (allows complete capture of KE_{DM})

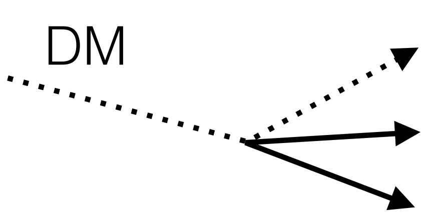


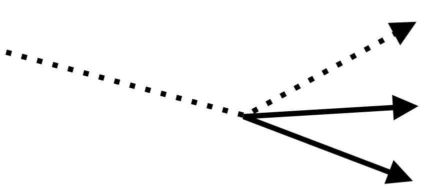
keV-MeV mass Dark Matter

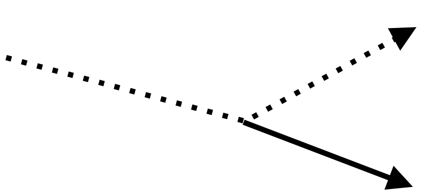
strategy 3

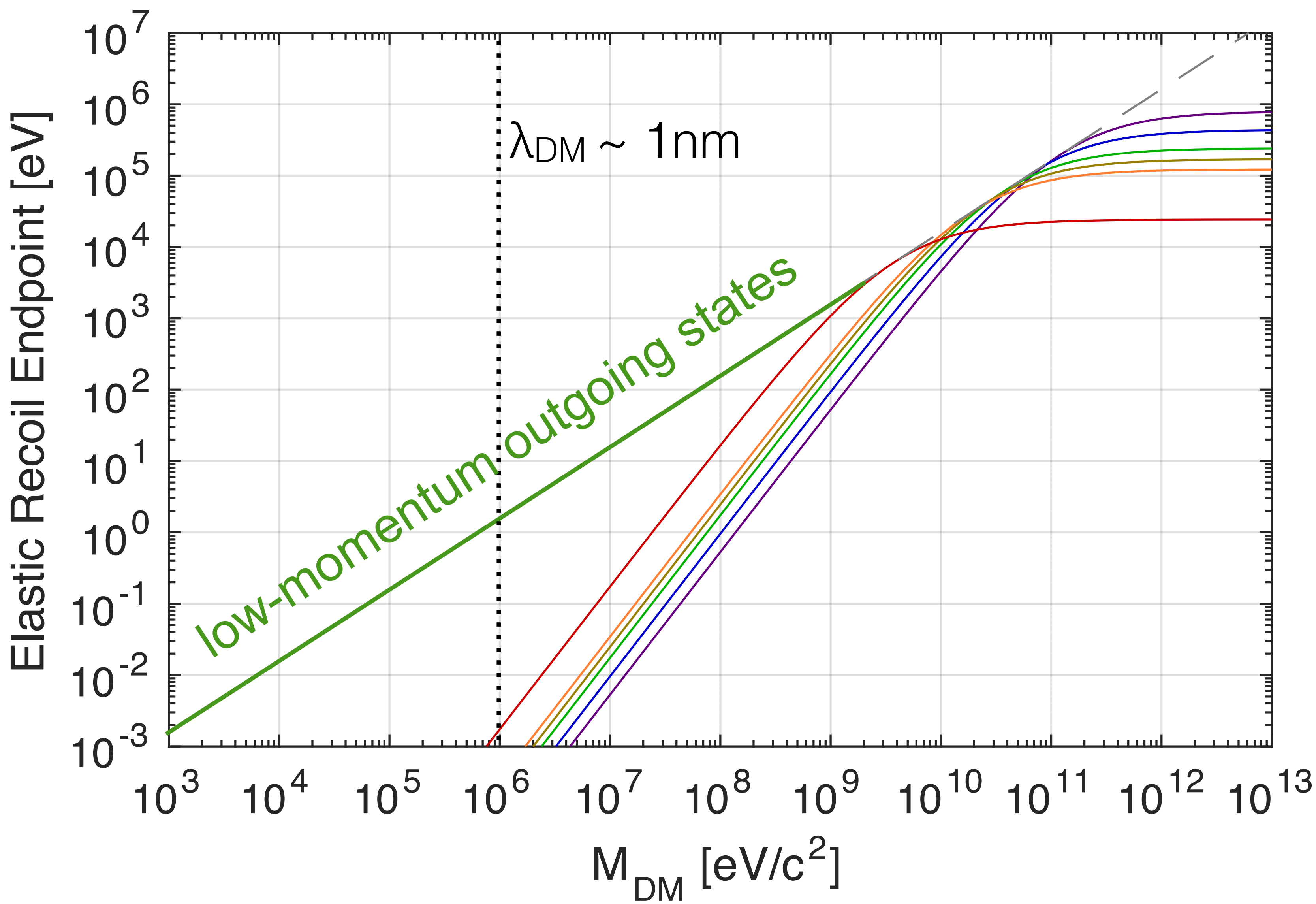
Excite low-momentum outgoing states, avoiding the massive nuclear dispersion relation.

Examples:

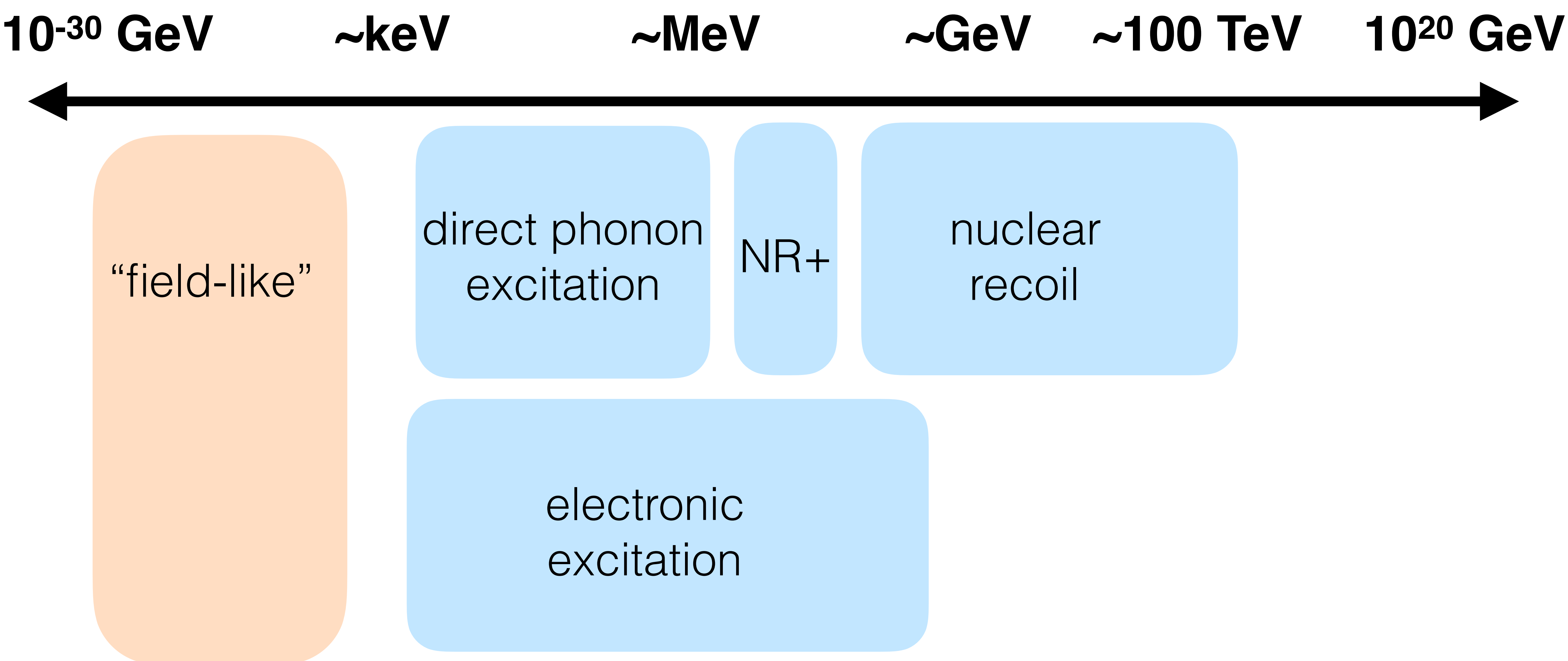








How we look for dark matter depends on what it is…   v2

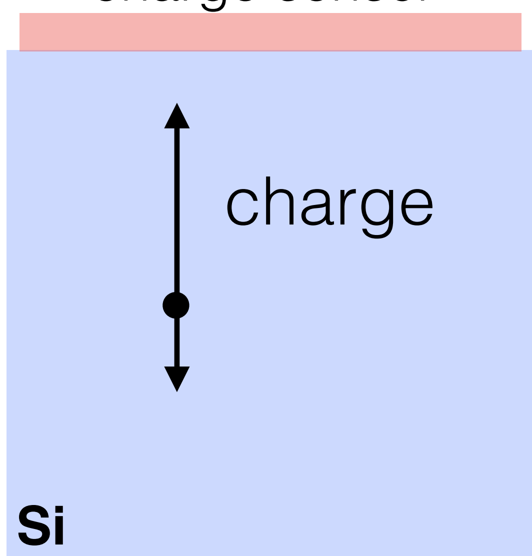


sensing electron recoils

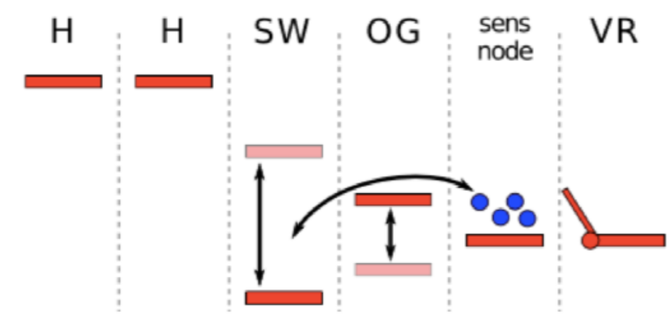
Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:

charge sensor

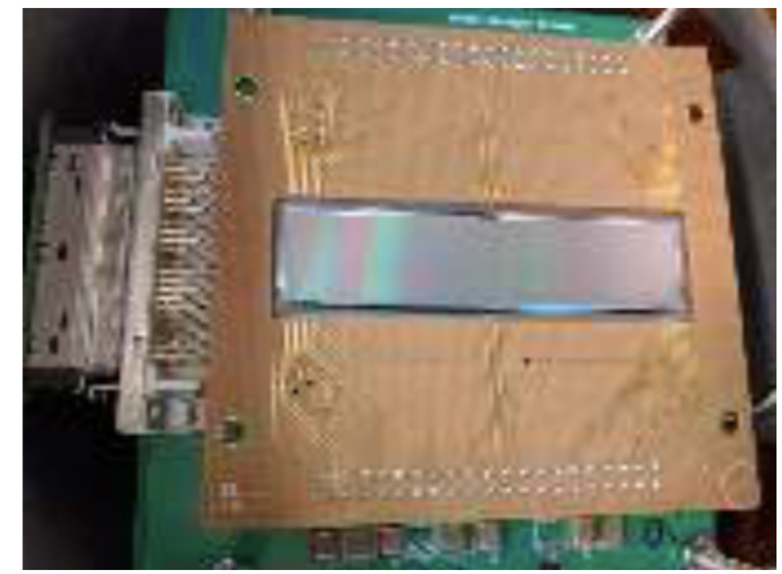


DAMIC
SENSEI

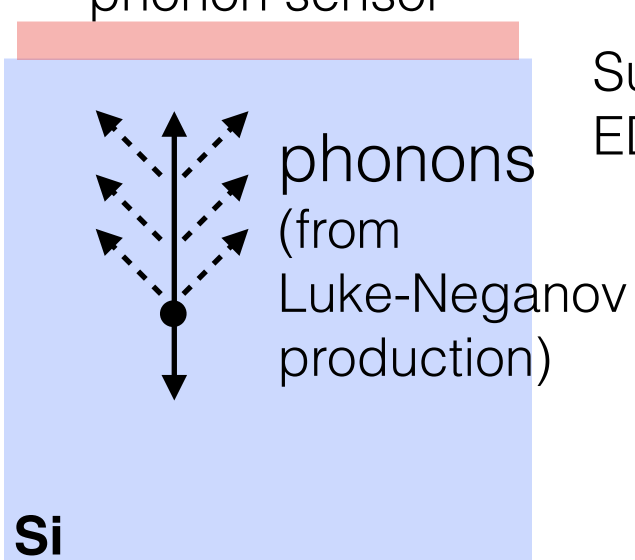


skipper ccd
(repeated sensing)

4k x 1k :   0.5g

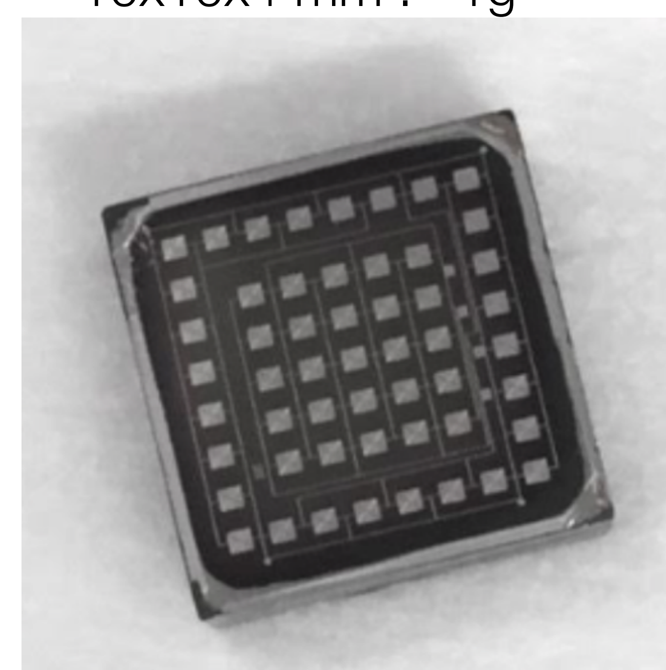


phonon sensor



SuperCDMS
EDELWEISS

10x10x4 mm :   1g



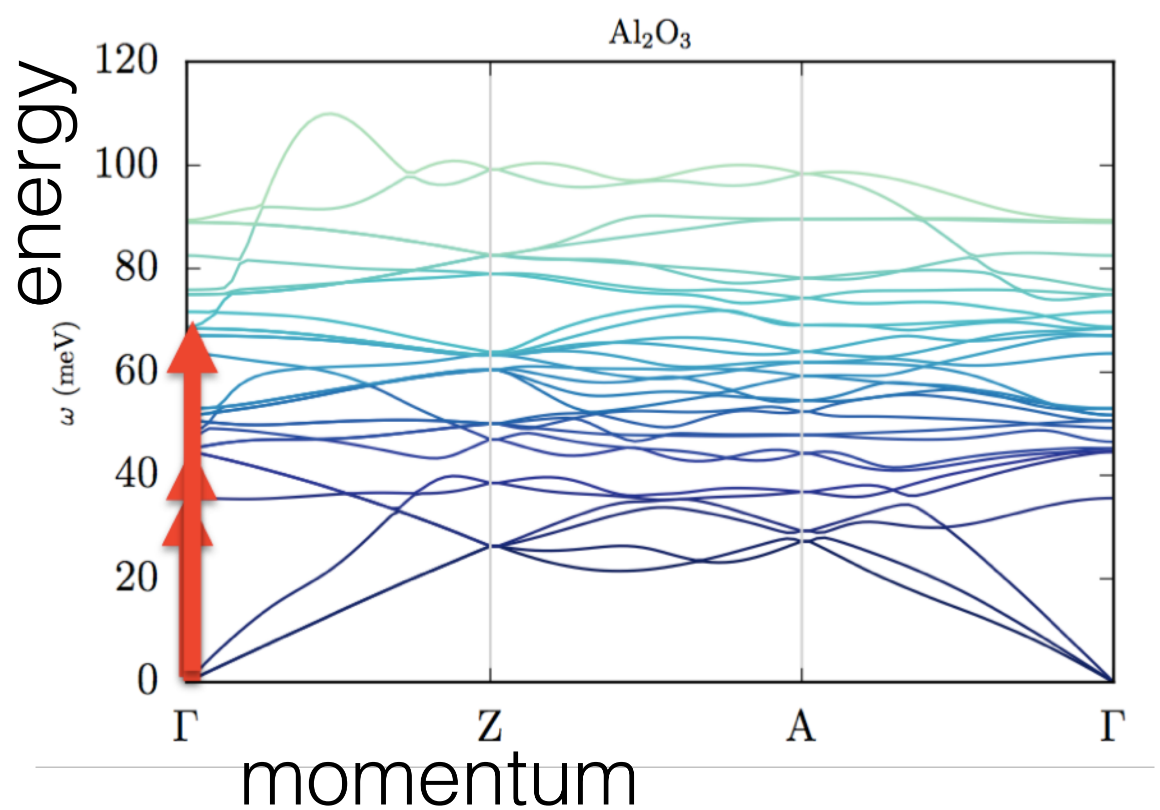
sensing nuclear recoils

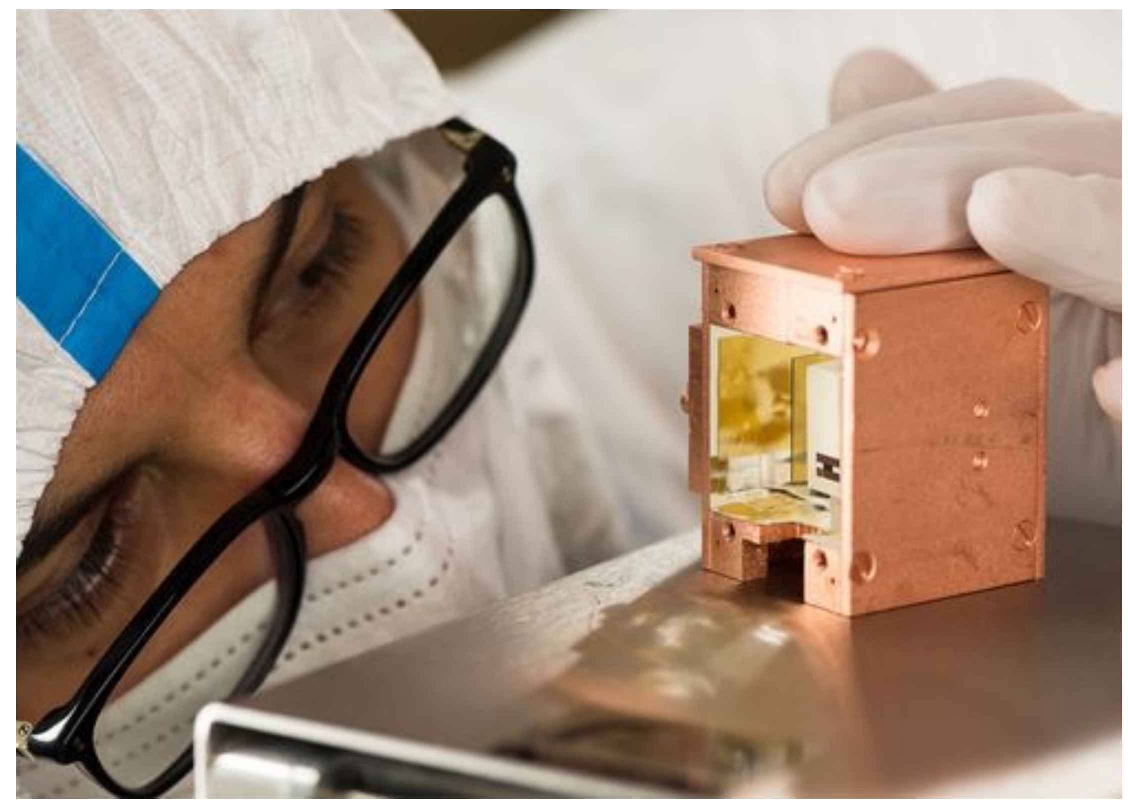
1: use material excitations of low effective mass

- low-mass nucleus
- low-momentum phonon states

2: push calorimetry threshold as low as possible

- pull energy from target into sensor,
- match sensor and signal timescales,
- push heat capacities down (low T, low mass)





CRESST

Summary

We know next to nothing about dark matter.

But at least we know a bit.

We are continuing to accomplish great things at the 100 GeV scale.

Exciting projects coming online the next few years.

We are also broadening the search, "loosening the priors”.

Rapidly evolving, who knows what this will look like in a few years.

Baby Scott assembling
ATLAS MDT endcaps (2006)