Direct Dark Matter Search with Liquid Xenon Detector

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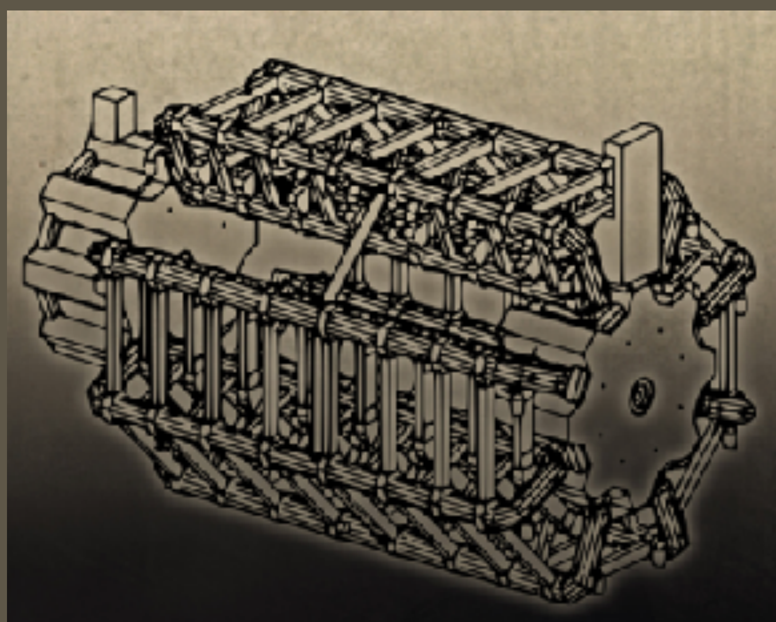
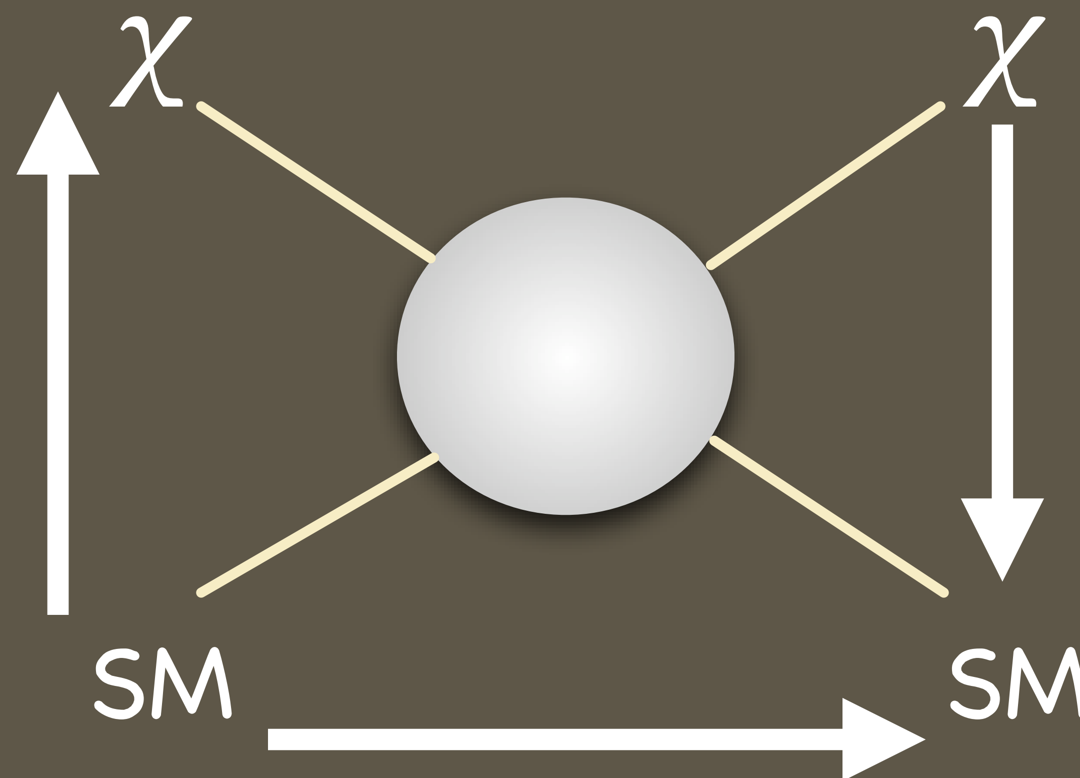
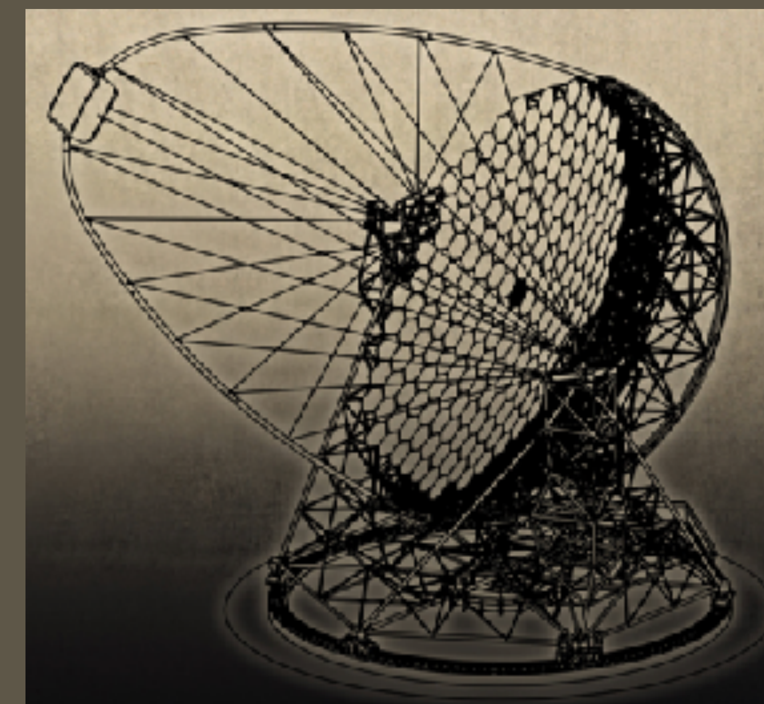
Dark Matter searches in the 2020s at the crossroads of the WIMP
11-13 November 2019
The University of Tokyo, Kashiwa Campus

Approaches to look for dark matter



Colliders





Indirect

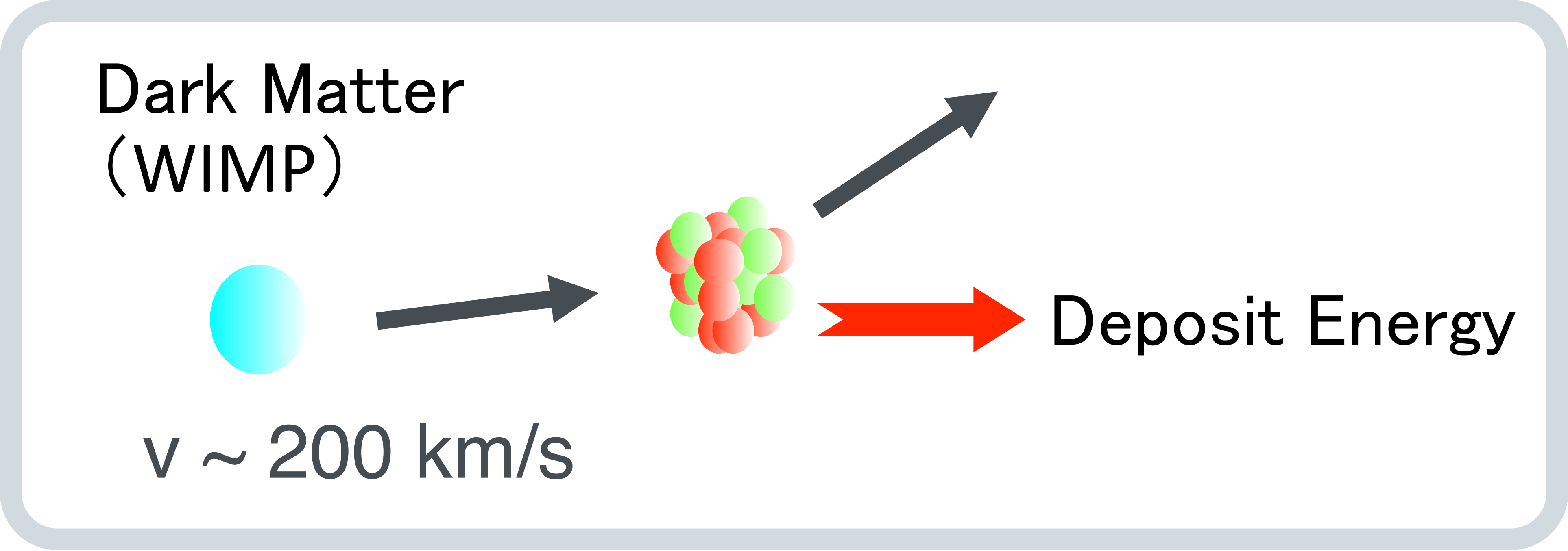
Direct

Masaki Yamashita

Contents

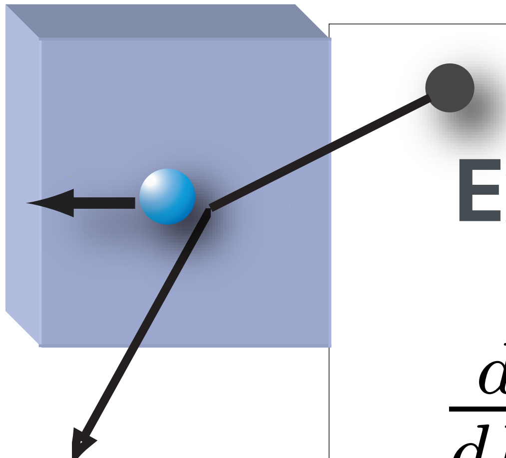
- What will we get from direct detection?
- Current status
  - Direct search status
  - Liquid rare gas detector for high mass WIMP
- Status for G2, G3 (~5 tonne , 2020-)
  - Challenge for G2
  - Prospects for G3

Elastically scattering target nuclei



- WIMP mean velocity is about 230 km/s at the location of our solar system.
- WIMPs interact with ordinary matter through elastic scattering off nuclei.
- As the velocity of scattered nuclei is non-relativistic, no more Bethe-Bloch energy loss but Lindhard for scintillator and ionization detectors.
- Typical nuclear recoil energies are of order of 1 to 100 keV.

Differential Rate (WIMP case)



Expected Energy spectrum:

$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}$$

R0: Event rate

F: Form Factor (depends on atomic nuclei)

motion dynamics => annual modulation

Maxwellian distribution for DM velocity is assumed.
V :velocity onto target,
VE: Earth's motion around the Sun

$$R_0 = \frac{377}{M_\chi M_N} \left(\frac{\sigma_0}{1\text{pb}}\right) \left(\frac{\rho_D}{0.3\text{GeVc}^{-2}\text{cm}^{-3}}\right) \left(\frac{v_0}{230\text{km s}^{-1}}\right) \text{kg d}^{-1}$$

Spin independent

$$\sigma_0 = A^2 \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}$$

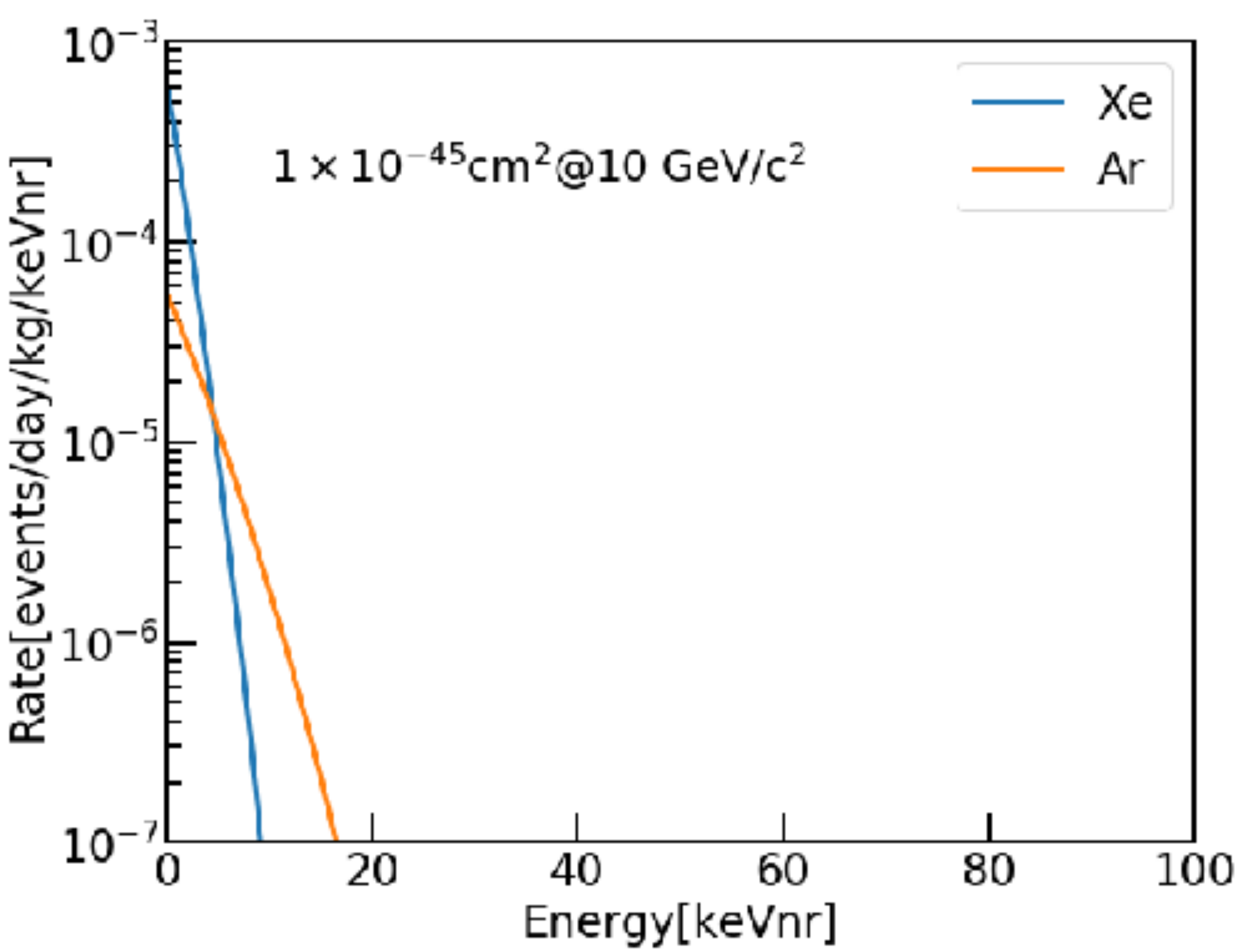
Spin dependent

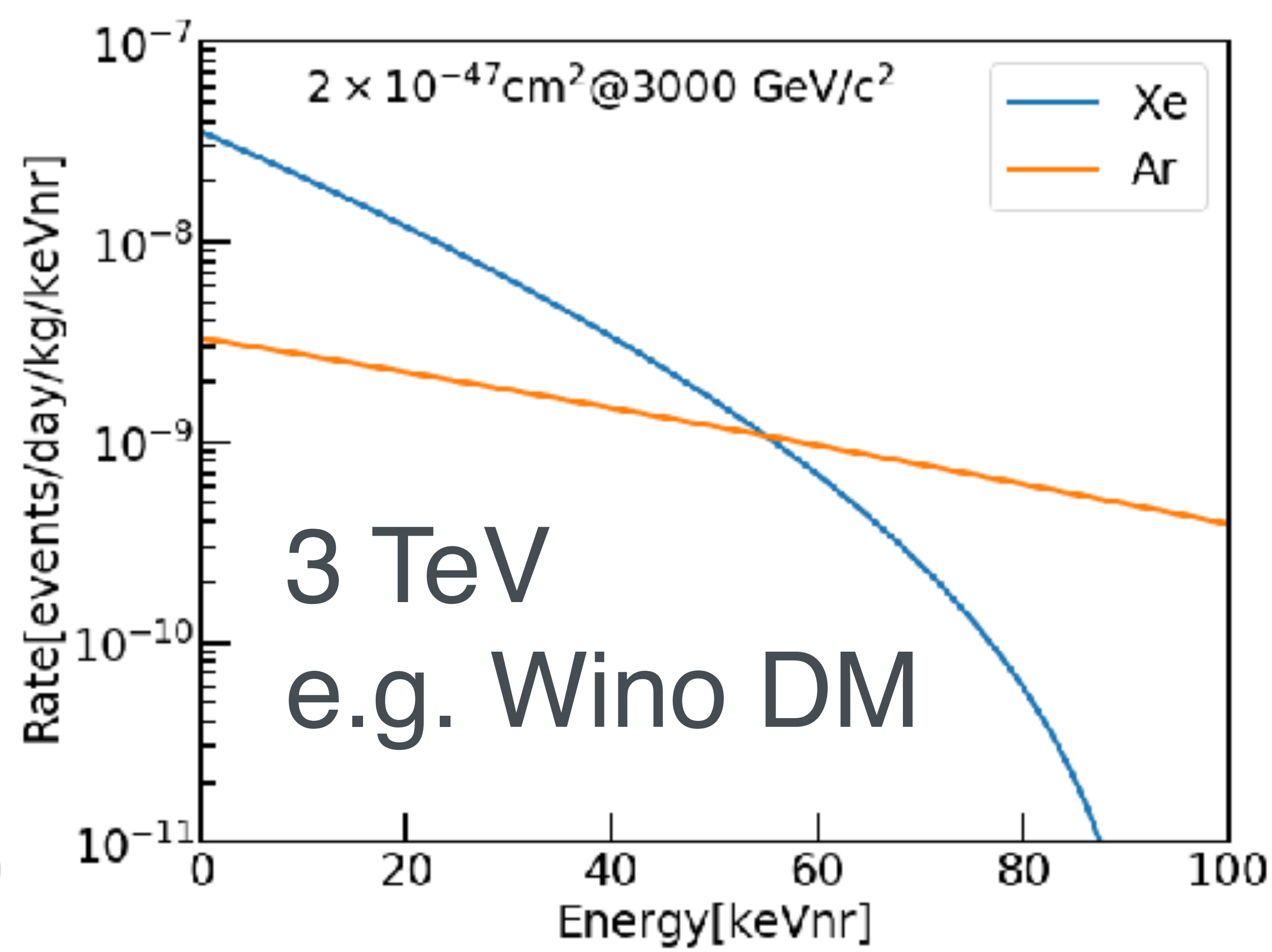
$$\sigma_0 = \frac{(\lambda_{N,Z}^2 J(J+1))^{\text{Nuclear}}}{(\lambda_{p,Z}^2 J(J+1))^{\text{proton}}} \frac{\mu_T^2}{\mu_p^2} \sigma_{\chi-p}$$

Differential Rate

ρ_{dm} = 0.3 GeV/cm3,
V_0 = 220 km/s
V_{esc} = 544 km/s

+ Standard Halo Model

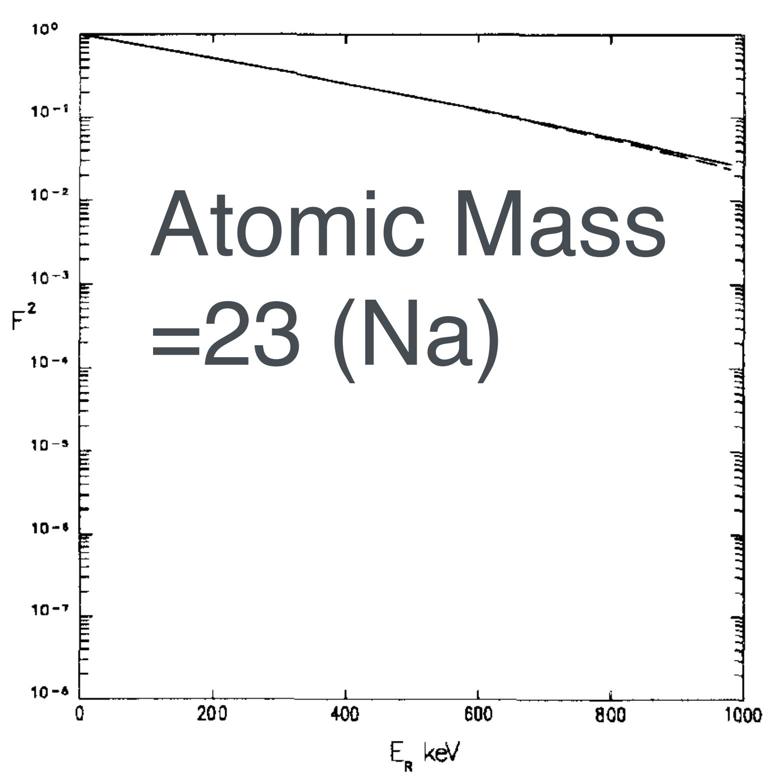


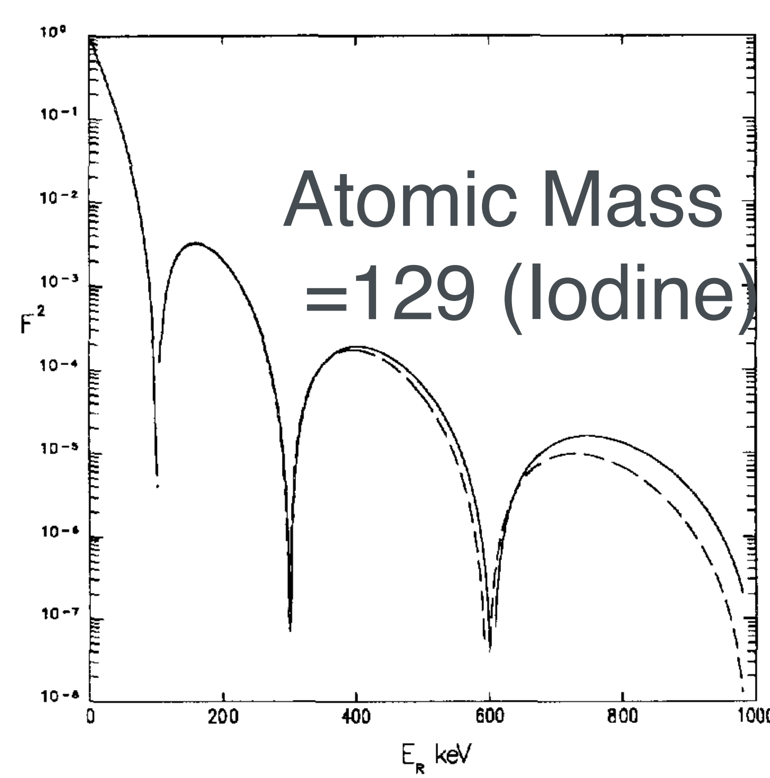


detector mass !

DM Count rate

Type	Signal Parameter	impact on signal
Particle physics	• DM mass (GeV-TeV) • Couplings	• rate, shape
Nuclear physics	• Form factor	• shape
Astrophysics	• Local DM density • DM velocity distribution	• rate (0.3 GeV/cm3) • shape (Standard Halo Model)





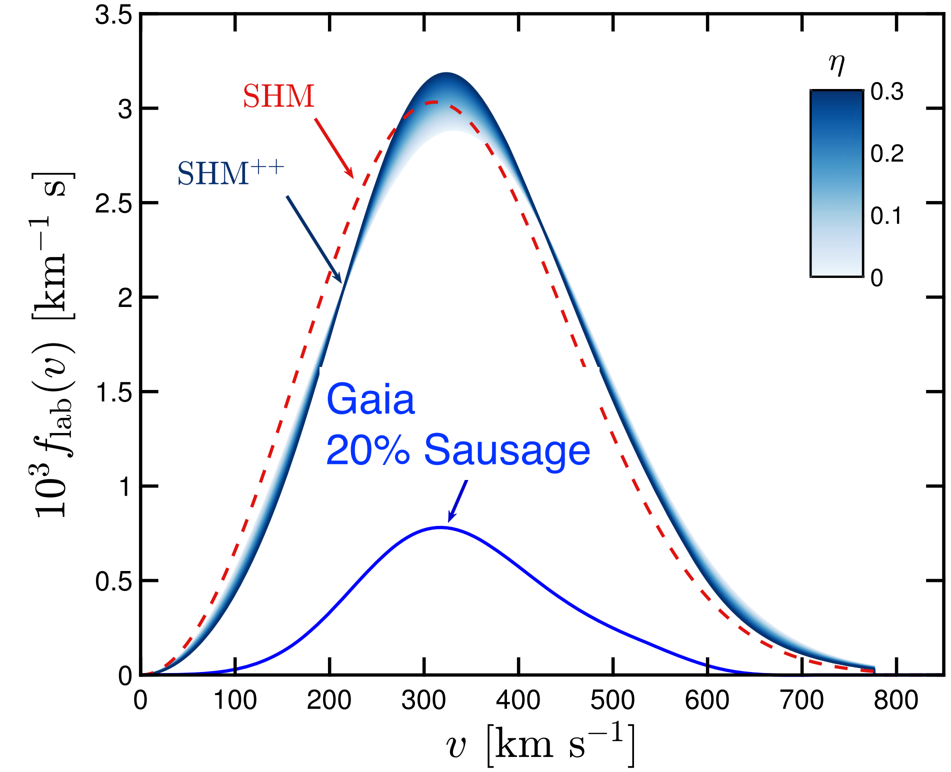
Form Factor

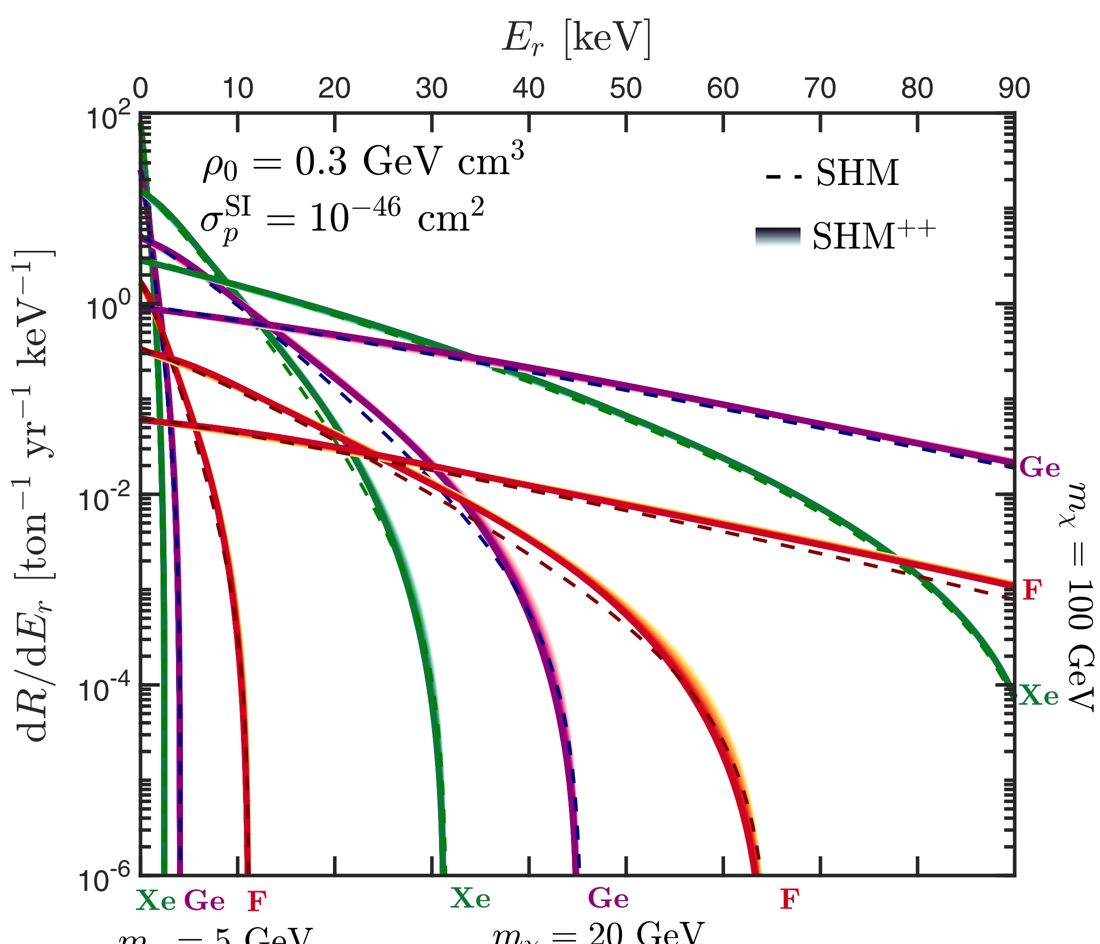
Lewin&Smith
1996, Astro. Phys.

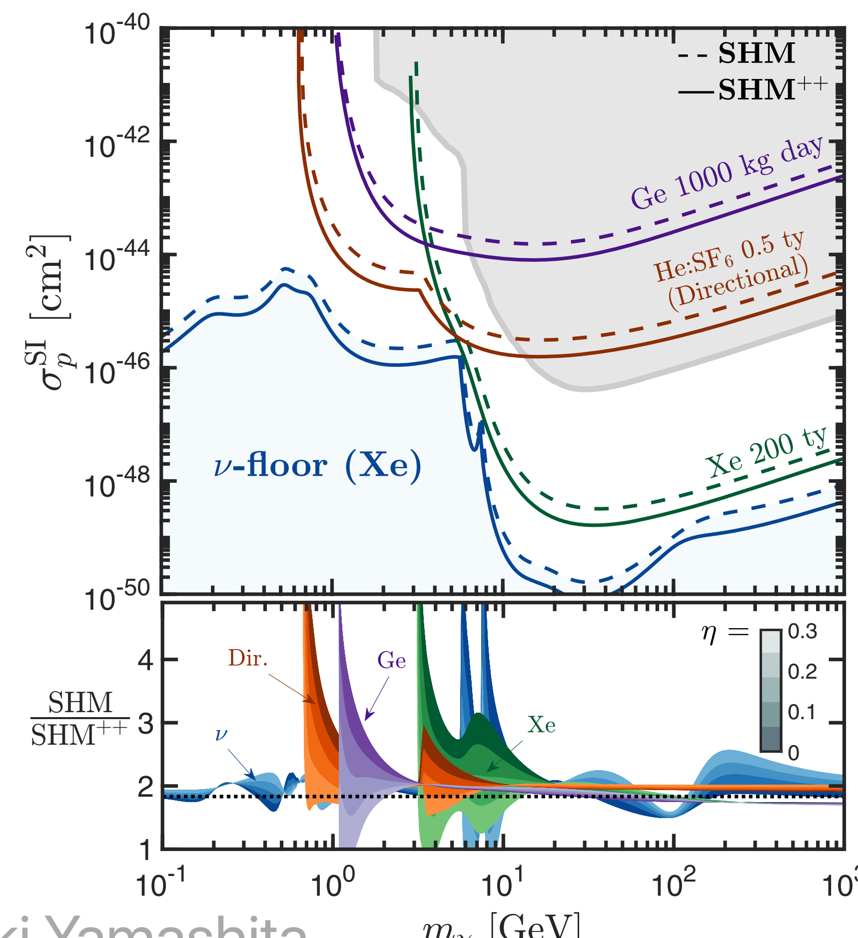
DM velocity distribution

N. Wyn Evans et al., PRD99, 023012 (2019)

SHM	Local DM density	ρ_0	$0.3\ \mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$220\ \mathrm{km\,s^{-1}}$
	Escape speed	$v_{\rm esc}$	$544\ \mathrm{km\,s^{-1}}$
	Velocity distribution	$f_{\rm R}(\mathbf{v})$	Eq. (1)
SHM^{++}	Local DM density	ρ_0	$0.55 \pm 0.17\ \mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$233 \pm 3\ \mathrm{km\,s^{-1}}$
	Escape speed	$v_{\rm esc}$	528^{+24}_{-25}
	Sausage anisotropy	β	0.9 ± 0.05
	Sausage fraction	η	0.2 ± 0.1
	Velocity distribution	$f(\mathbf{v})$	Eq. (3)







What we get from Direct Detection?

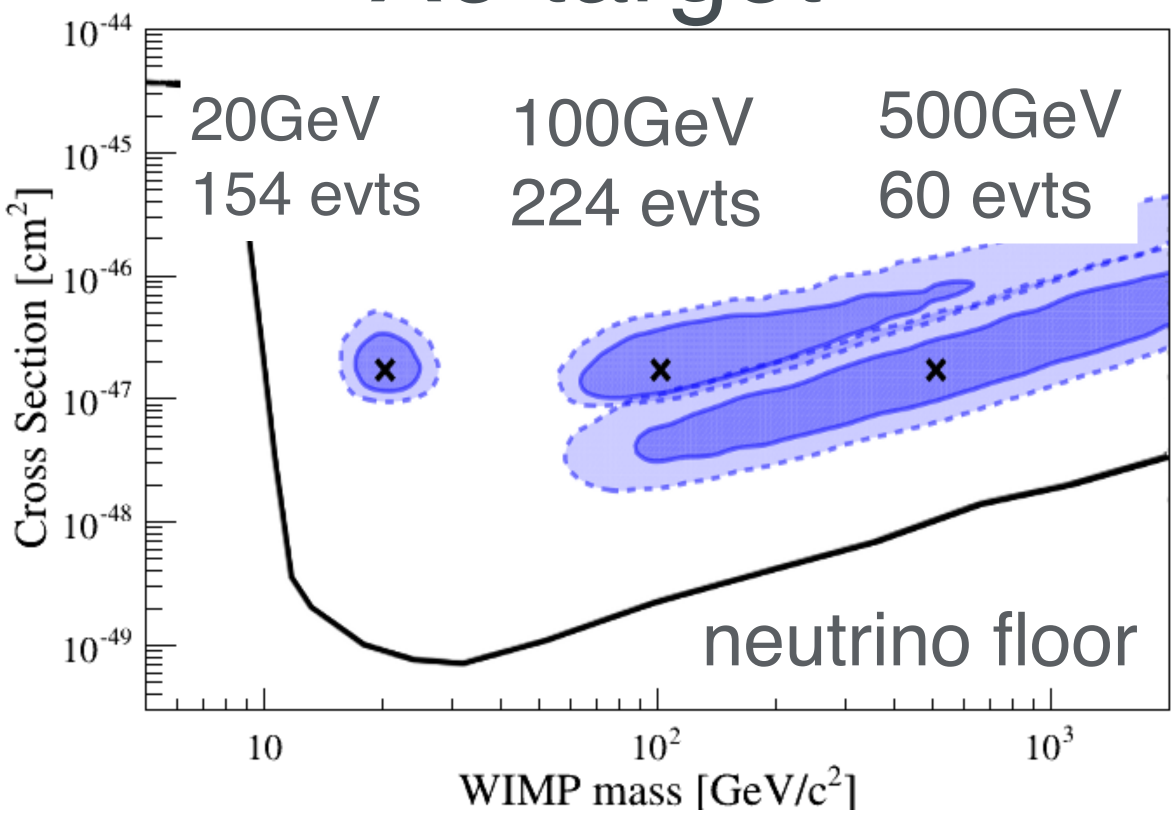
once we detect dark matter….

- DM particles are moving around us.
- Mass of DM particles
- DM-nucleus scattering cross section

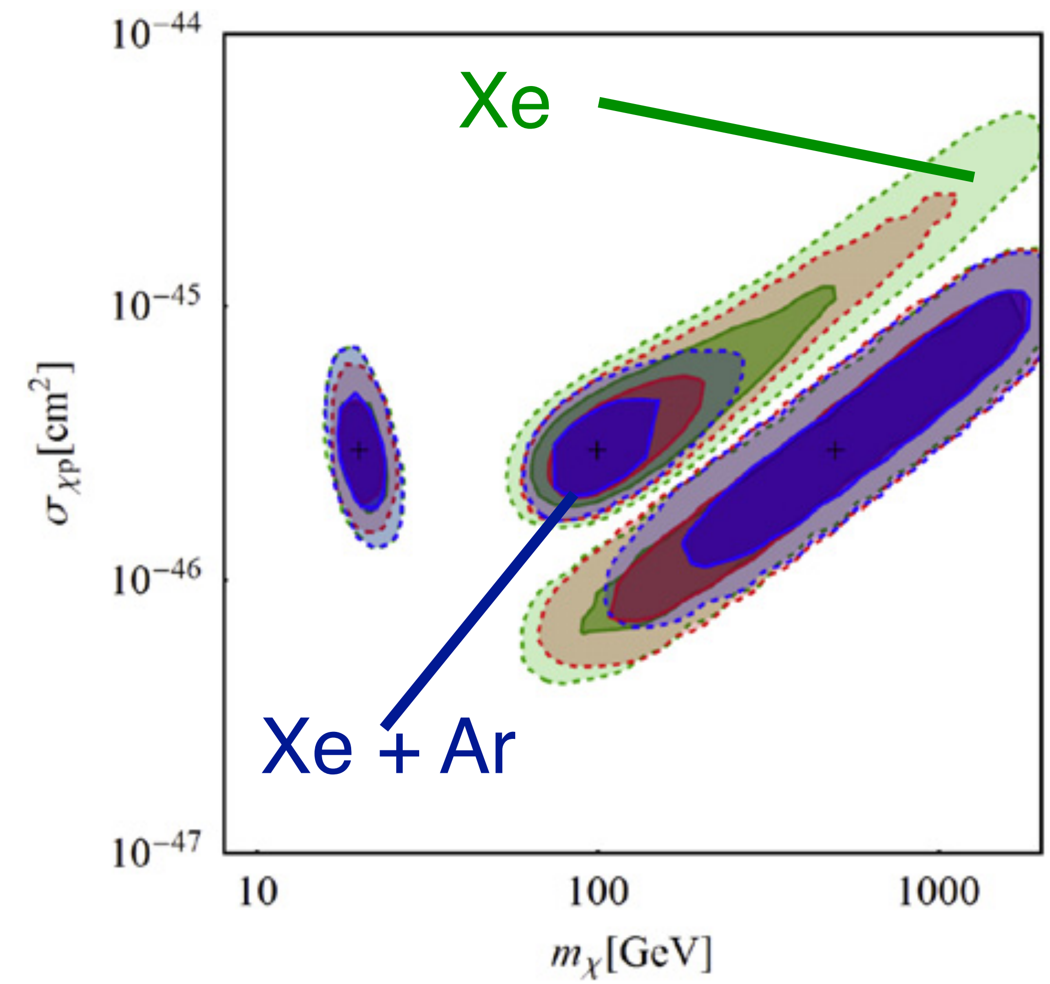
→ Complementarity of targets

- It will rely on ρ_{dm} (= 0.3 GeV/cm^3), Velocity distribution (= > Maxwellian, DM stream?)

Xe target



J. Aalbers *et al* JCAP11(2016)017



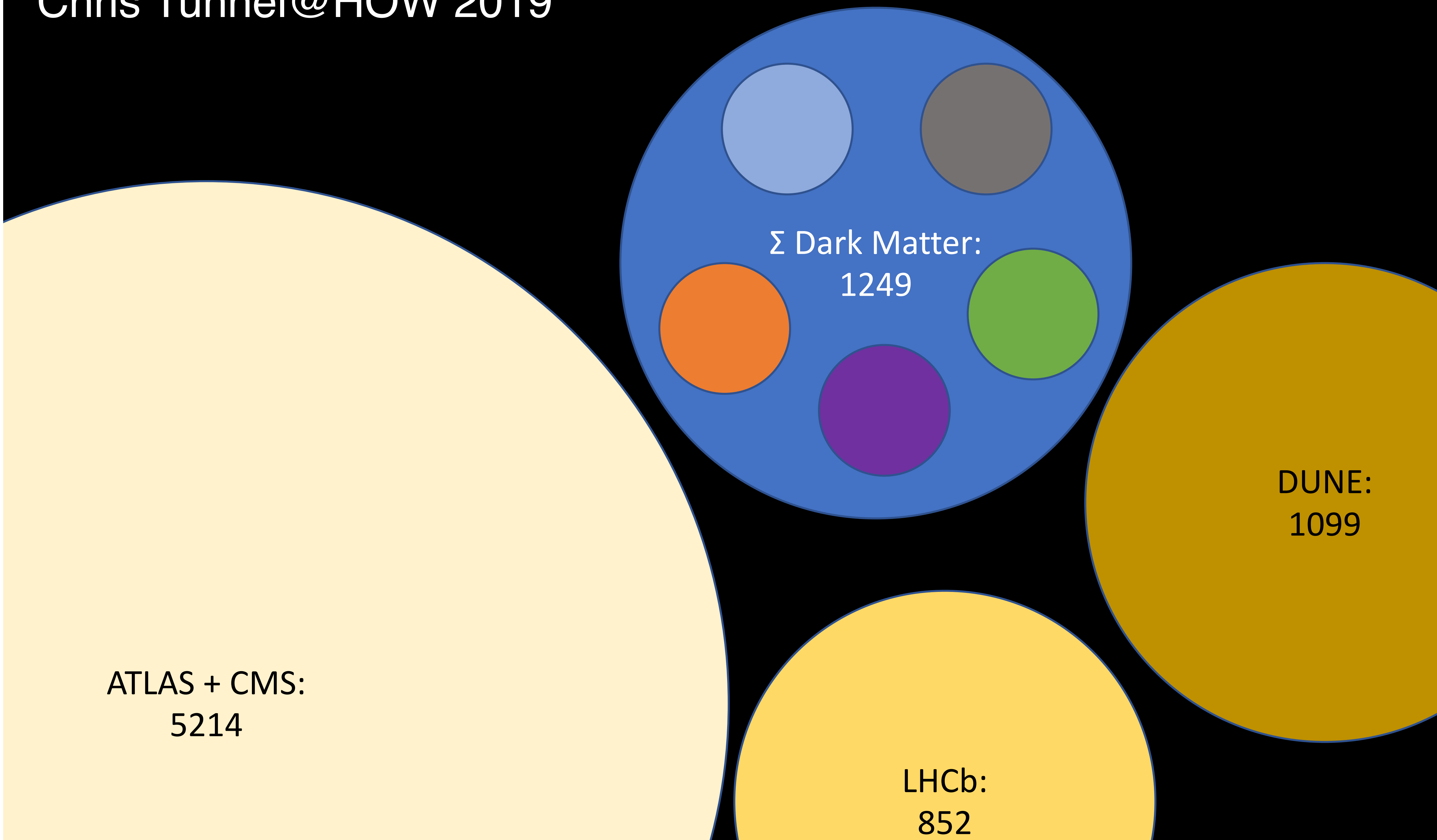
J. Newstead et al , PRD 88, 076011 (2013)

Nest of Dark Matter Hunters in the World

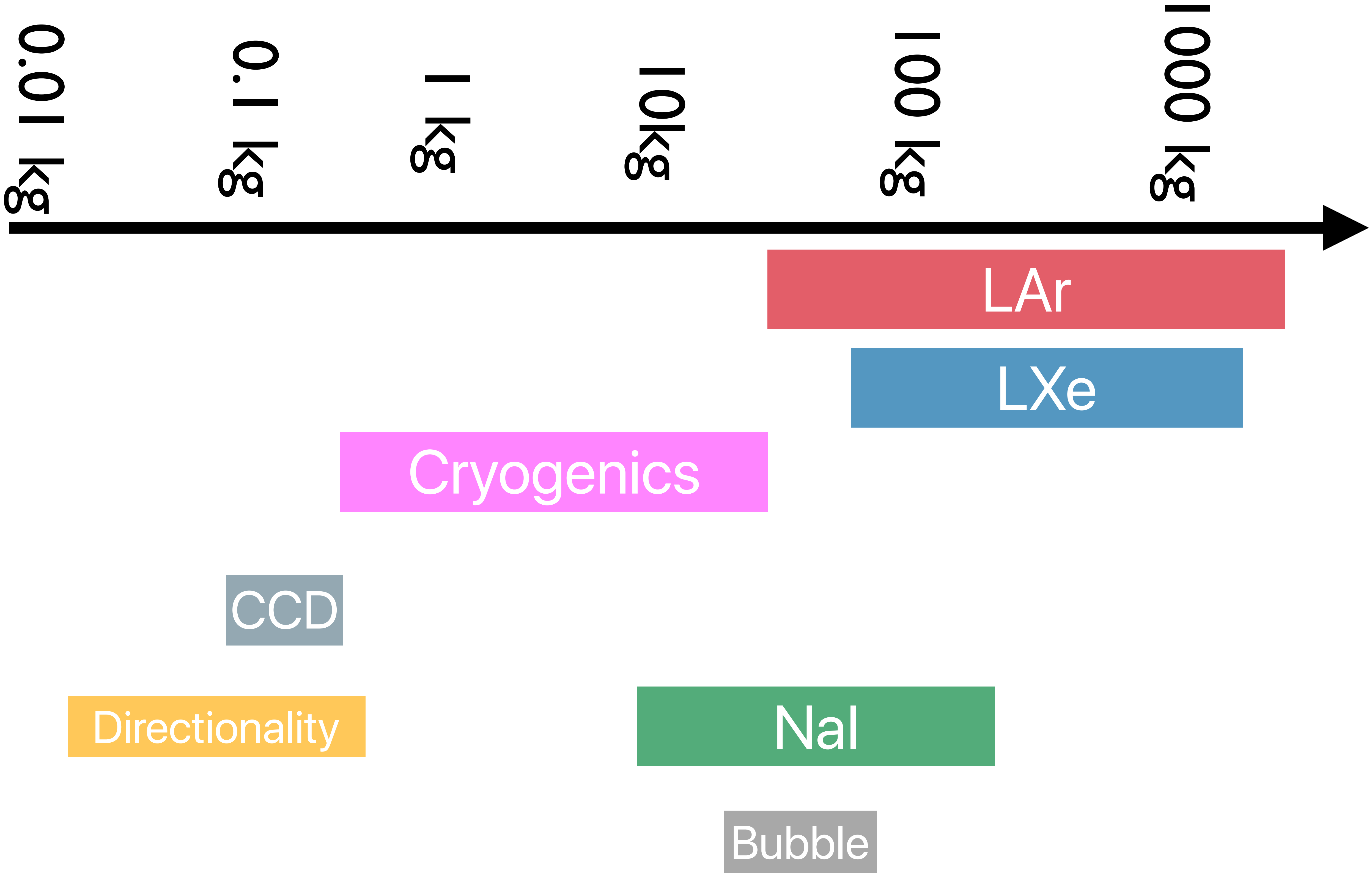
Dark Matter Detection community big

Area corresponds to number of people based on most recent publication from any experiment that has published scientific papers in the last two years. This relied on Inspire-HEP. I almost certainly missed an experiment . Number of authors also does not correspond to FTEs since not all experiments require collaborators be 100% committed to that experiment. See gist for calculation notes. 16/March/2019

Chris Tunnel@HOW 2019

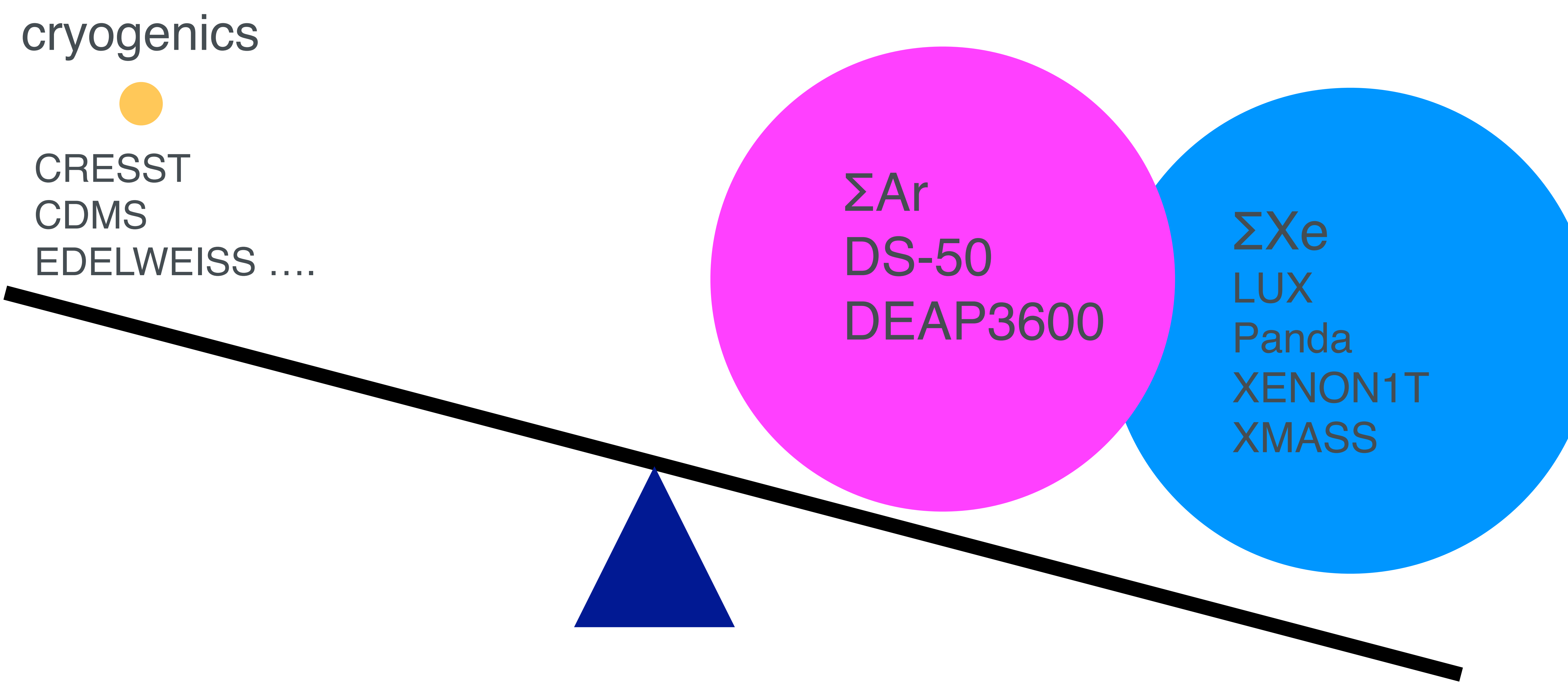


Technology & Detector Active Mass

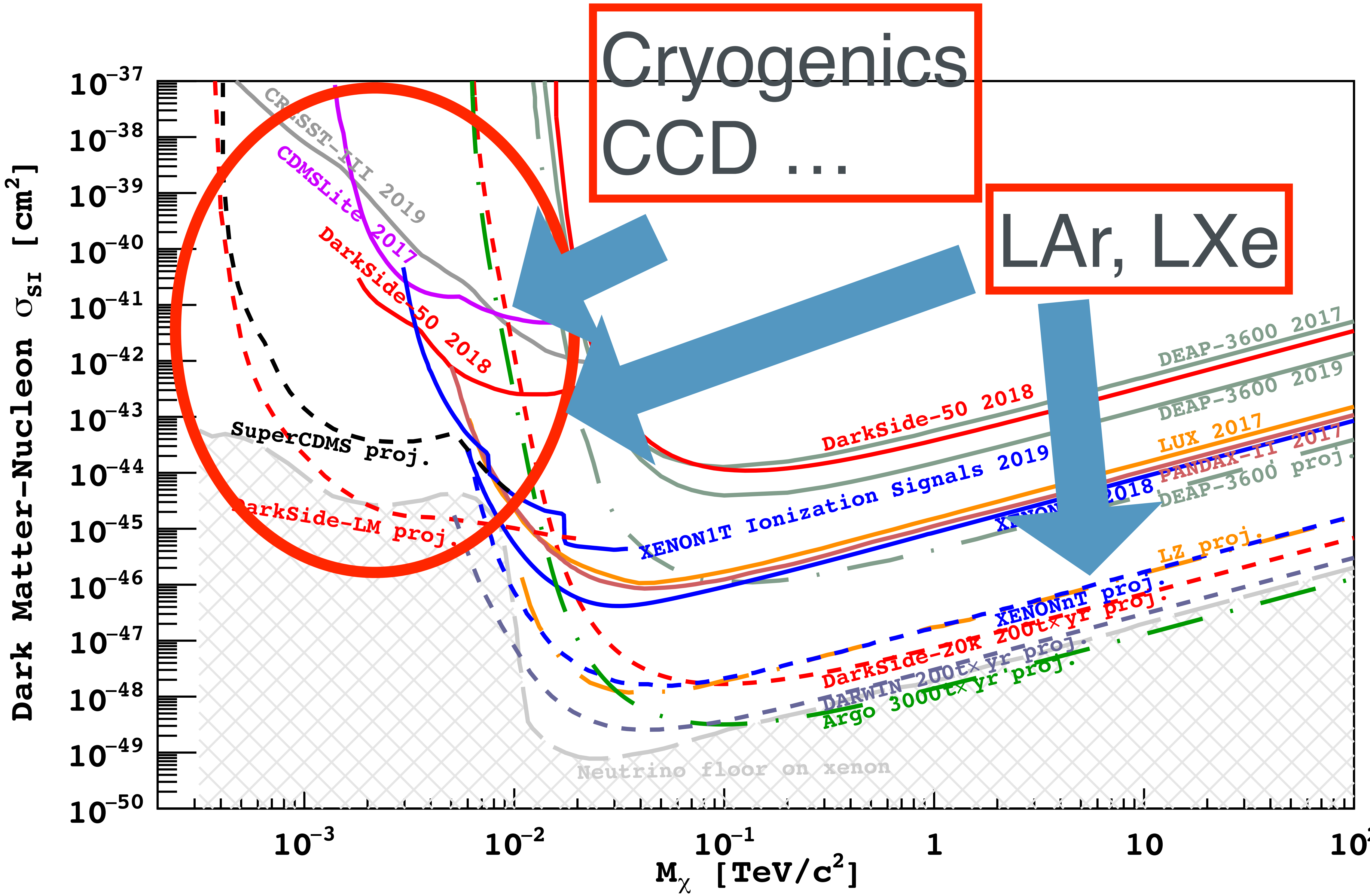


Detector Mass :

Area ∝ Active Mass



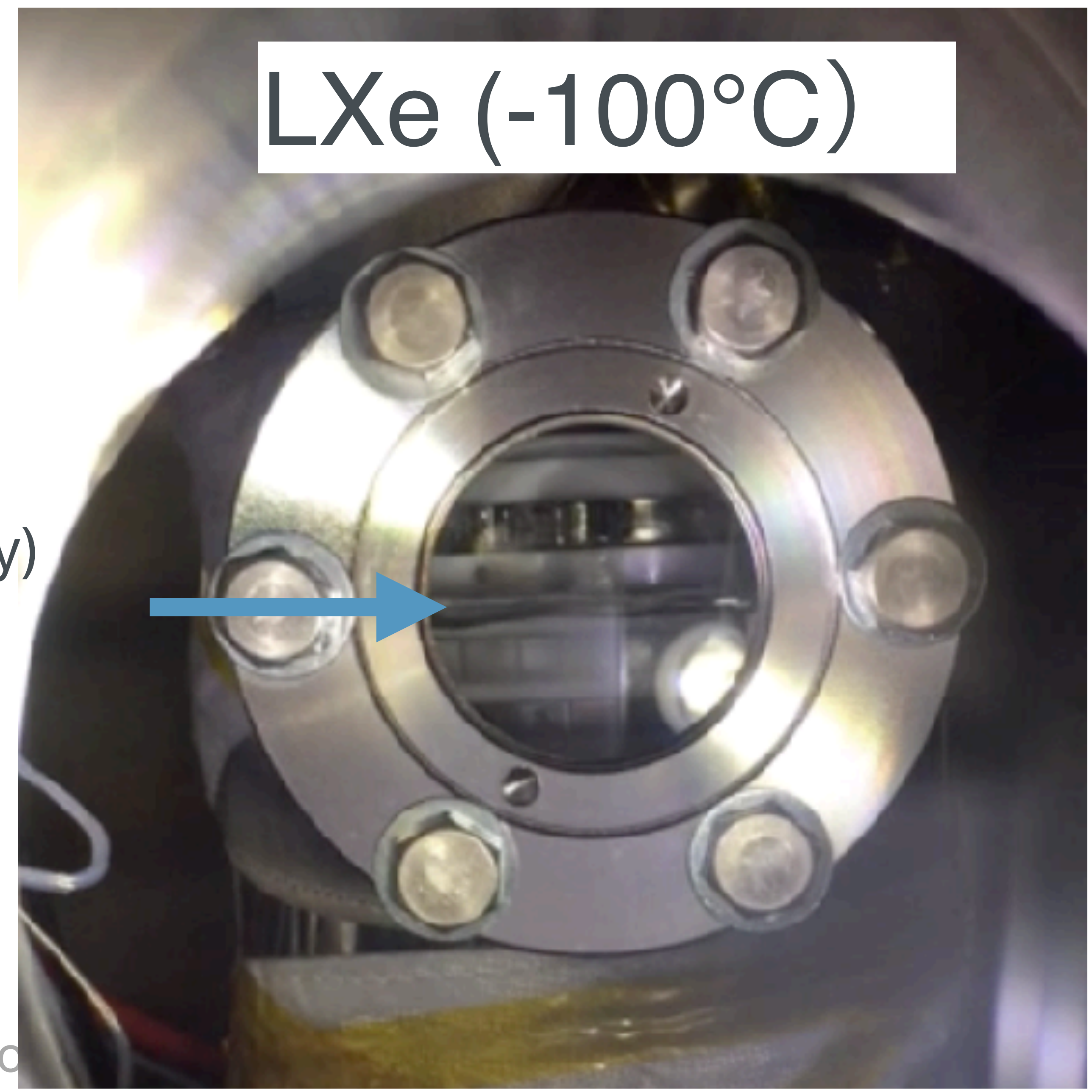
Low Mass by cryogenics detectors



arXiv:1910.11775v1

Liquid Rare Gas

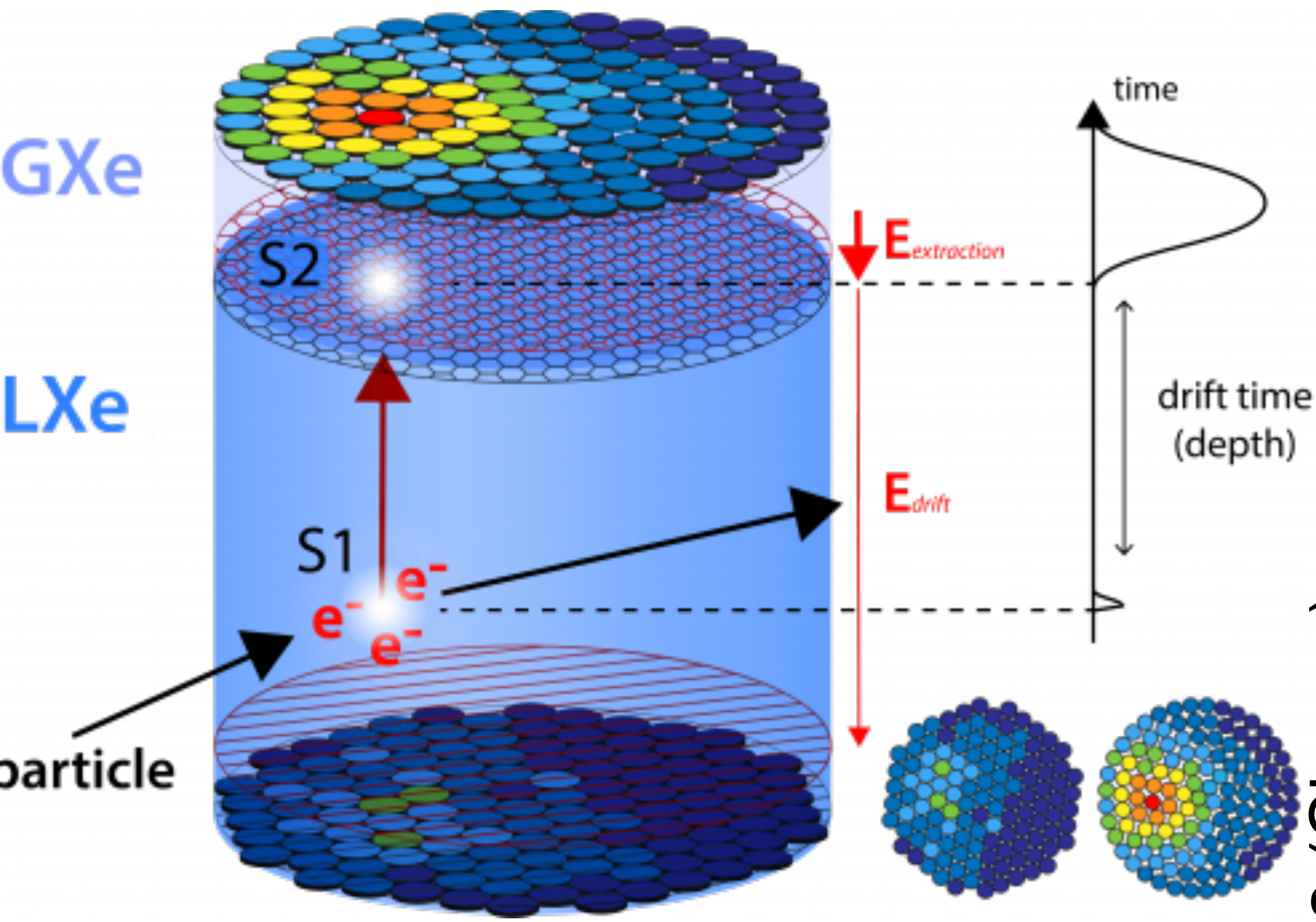
	Z(A)	Boiling Point at 1 atm [K]	Density [g/cm³]	ionization [e⁻/keV]	scintillation [photon/keV]
Ar	18(40)	87.3	1.40	42	40
Xe	54(131)	165	3.06	64	46



- **Large Mass** (multi tonne size)
- **Purification gas/liquid phase**
  - Online purification (getter ,distillation for both electro-negative and radio-impurity)
- **No long-half life radio isotope** except ^{136}Xe (double beta decay), ^{124}Xe (double electron capture)

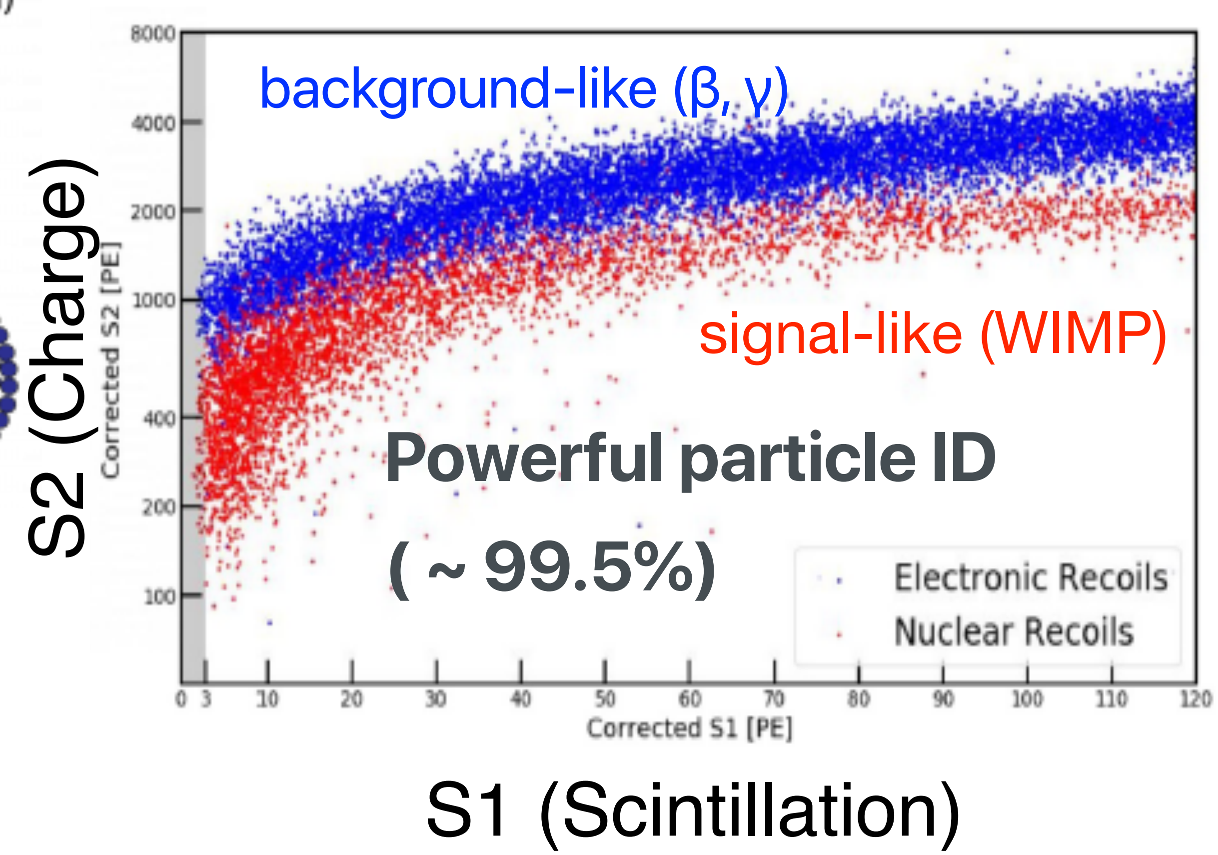
Dual Phase Time Projection Chamber

PMT array

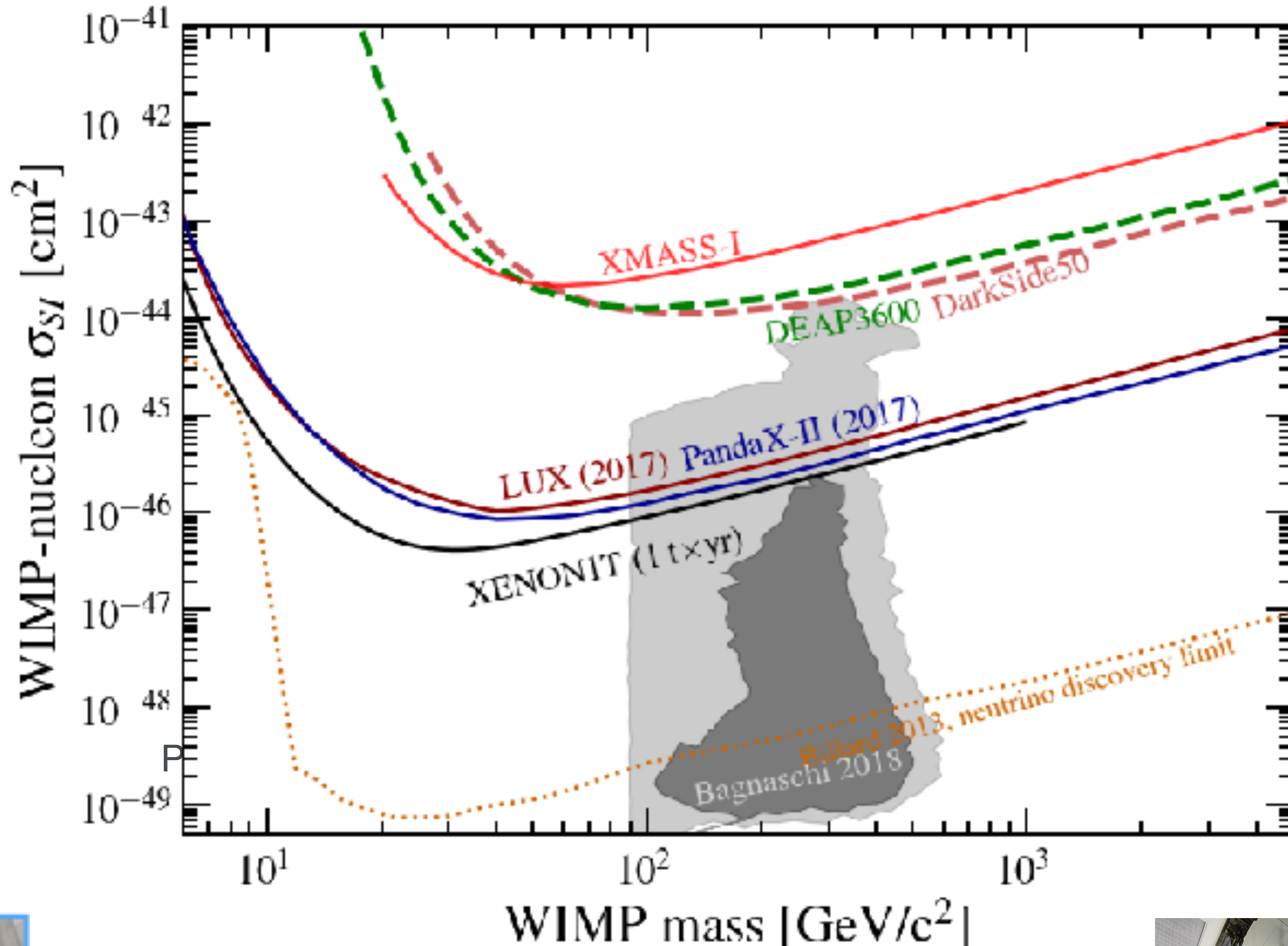


PMT array

- **Large Mass (multi tonne)**
- **3D position**
  - Fiducial volume
  - multi-site events cut
- **Particle Identification**



Current status (2019)

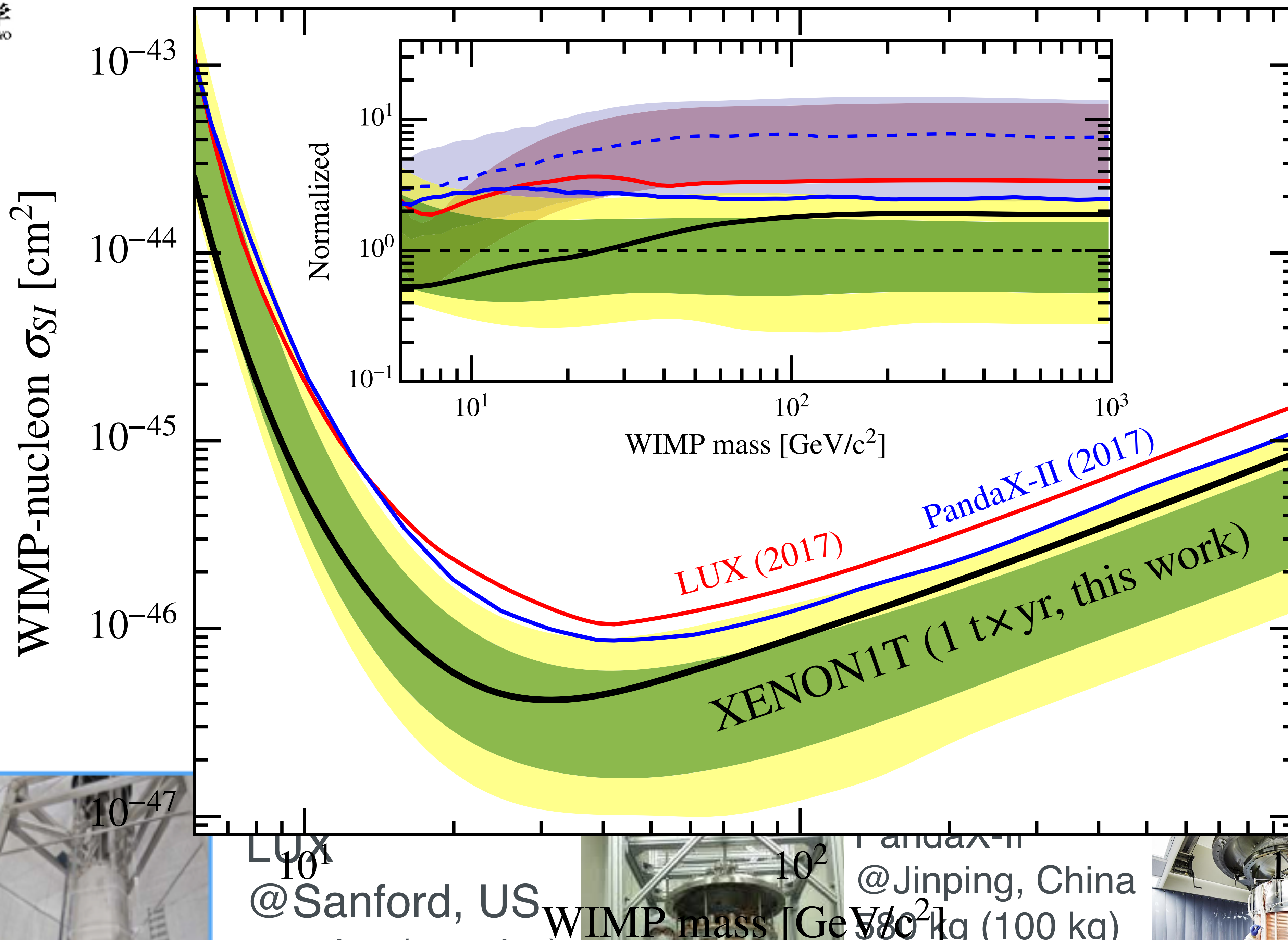


LUX
@Sanford, US
370 kg (100 kg)

PandaX-II
@Jinping, China
580 kg (100 kg)

XENON1T
@Gran Sasso
Italy
2 tonne
(1.3tonne)

Current status



LUX
@Sanford, US
370 kg (100 kg)

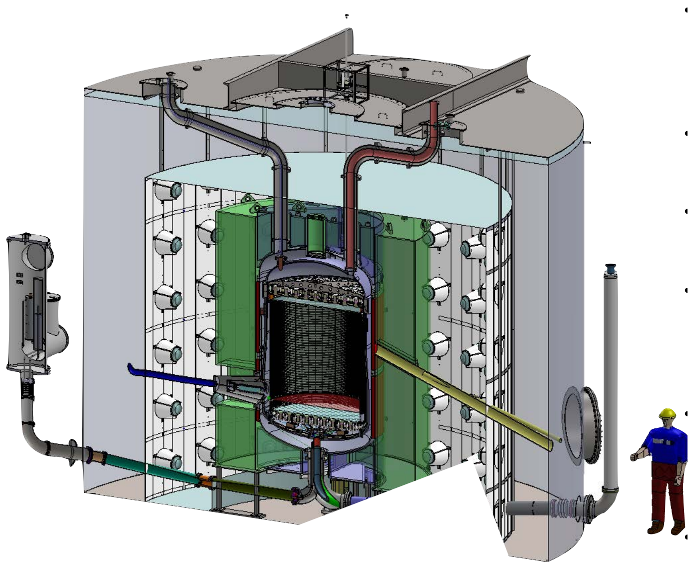
@Jinping, China
kg (100 kg)

XENON1T
@Gran Sasso
Italy
2 tonne
(1.3tonne)

Future experiments

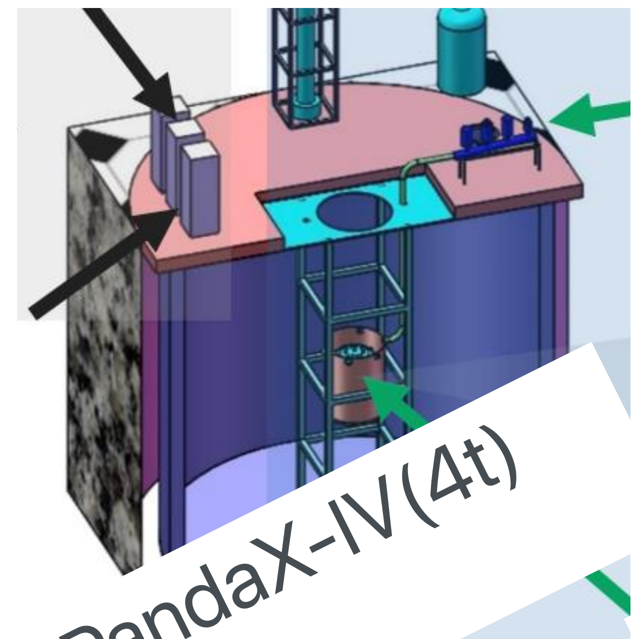
Generation 2 experiment 2019-2025

active mass about 4-7 ton will start commissioning soon.

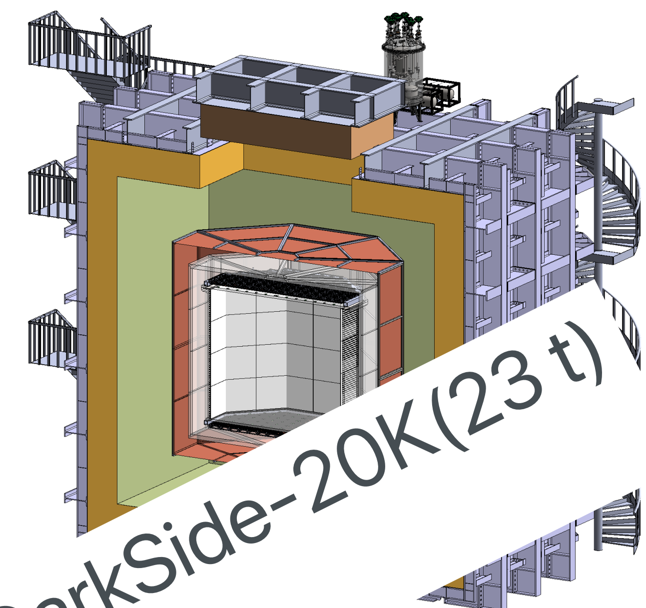


LZ(7t)
2020-

XENONnT (5.9t)
2019-



PandaX-IV(4t)
2020-



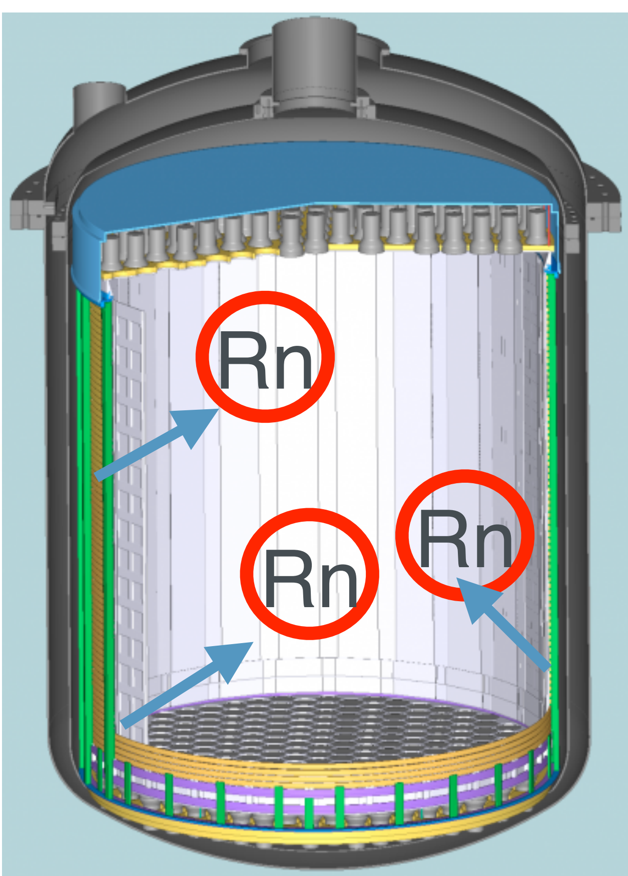
DarkSide-20K(23 t)
2022-

=> C. Galbiati

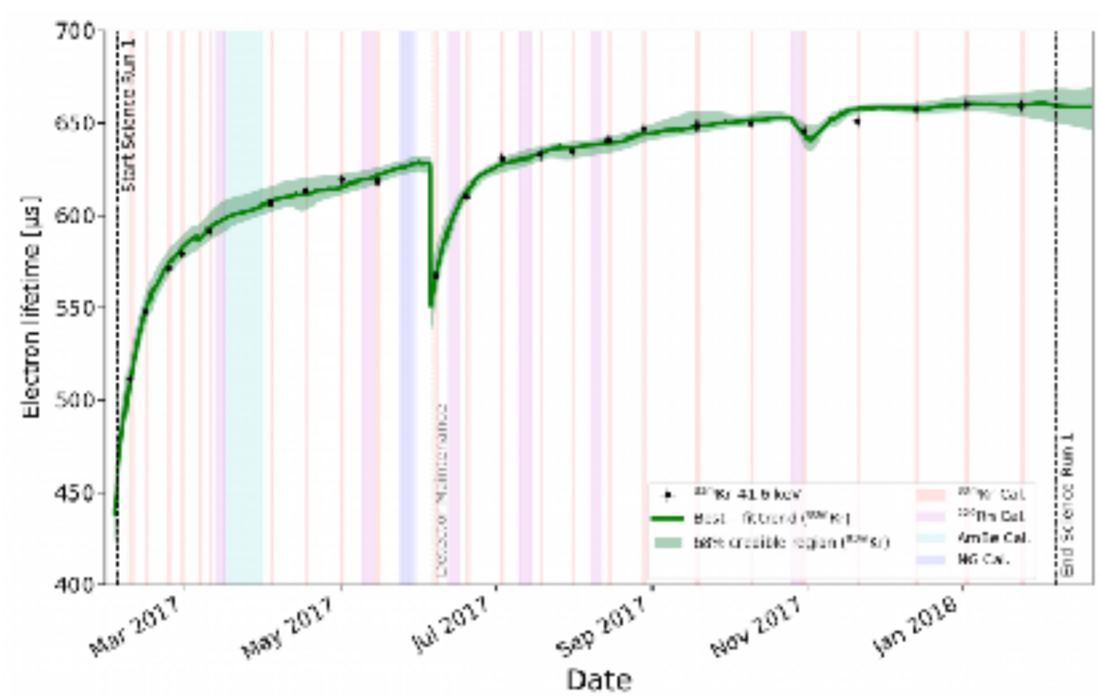
Challenges for G2 experiment

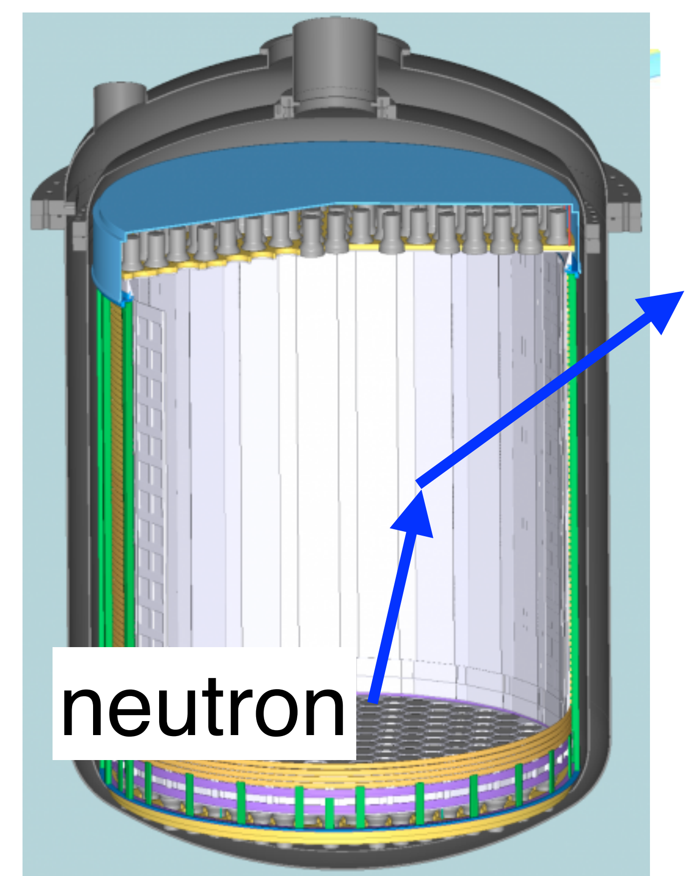
Target Mass about 4 - 7 ton, starting from 2019-2020

1. emanated Rn background (internal background)
2. Large amount of LXe purification (lifetime for drifted electrons)
3. Neutron veto



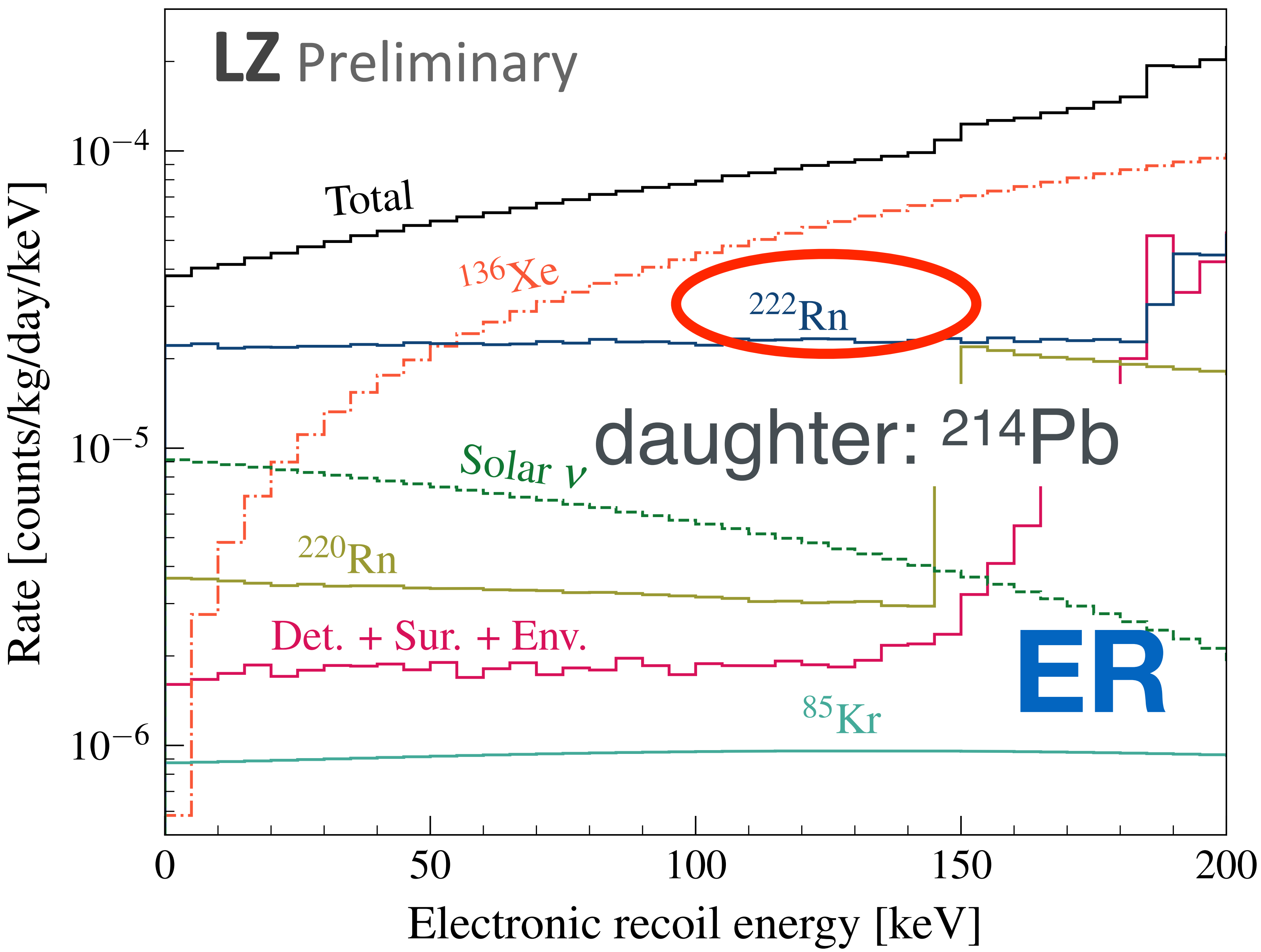
1.5 m drift length
~1.5 ms e-lifetime

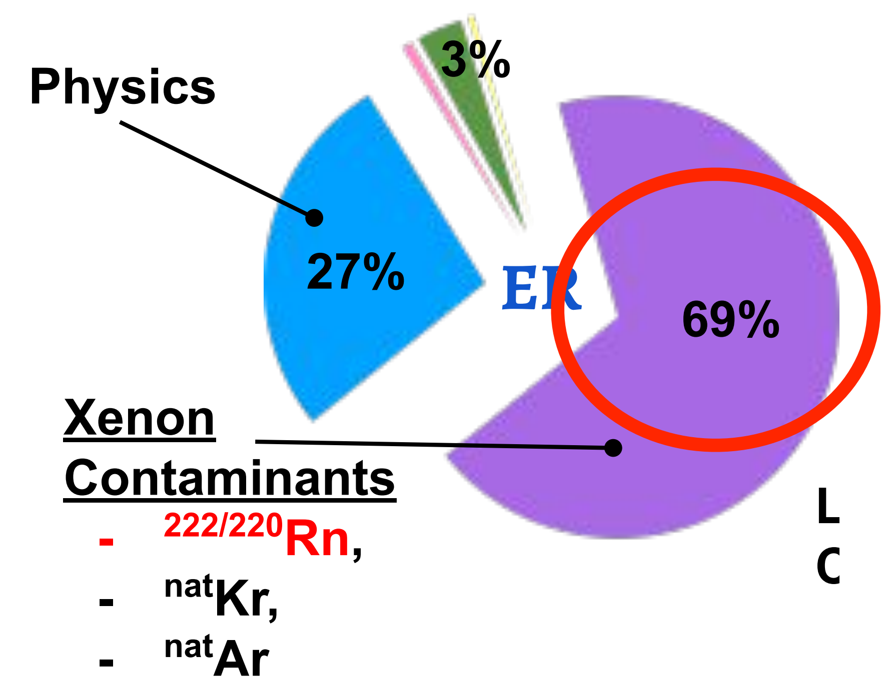




Background for G2 experiment (ER)

Before Particle ID

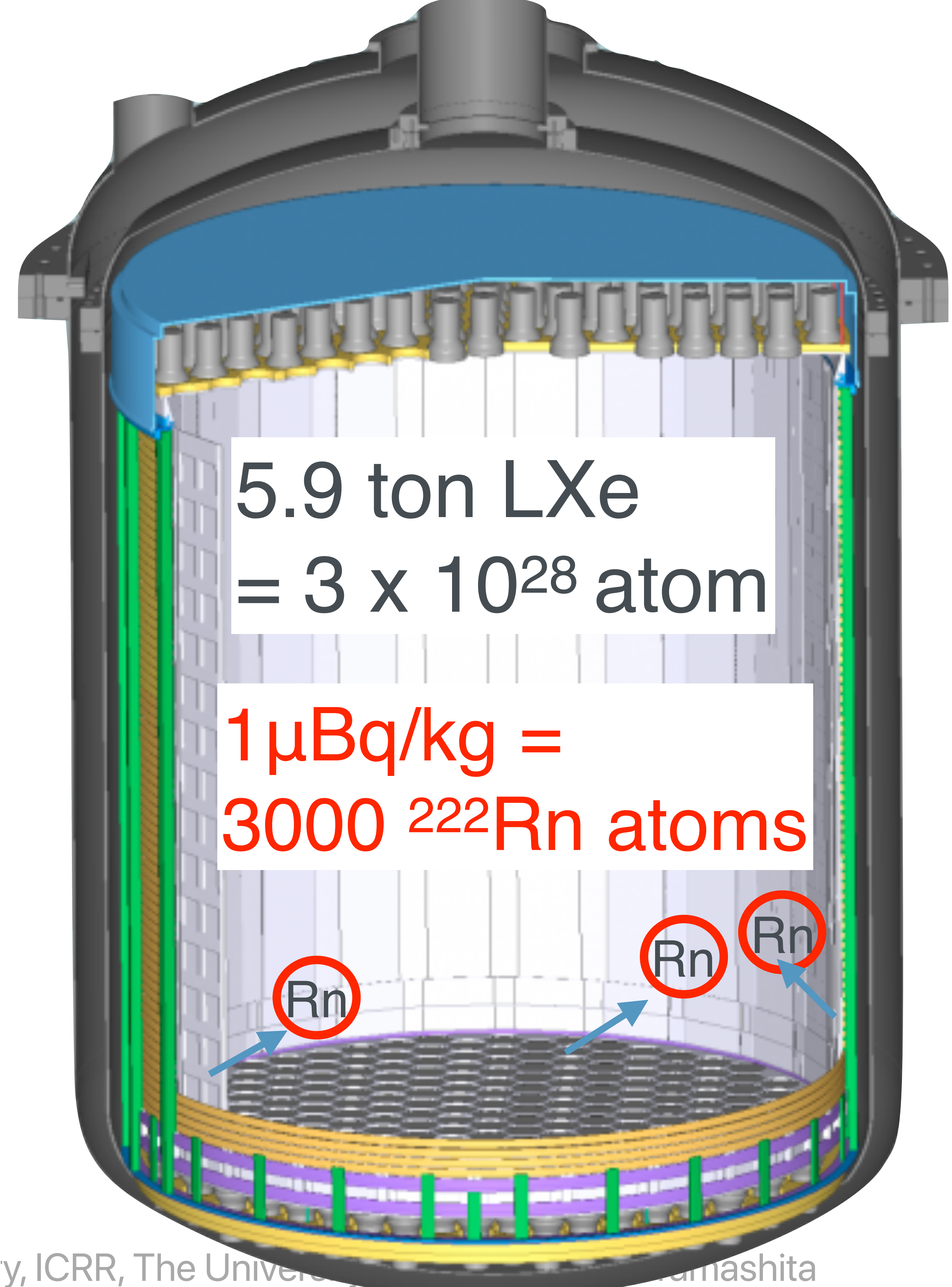


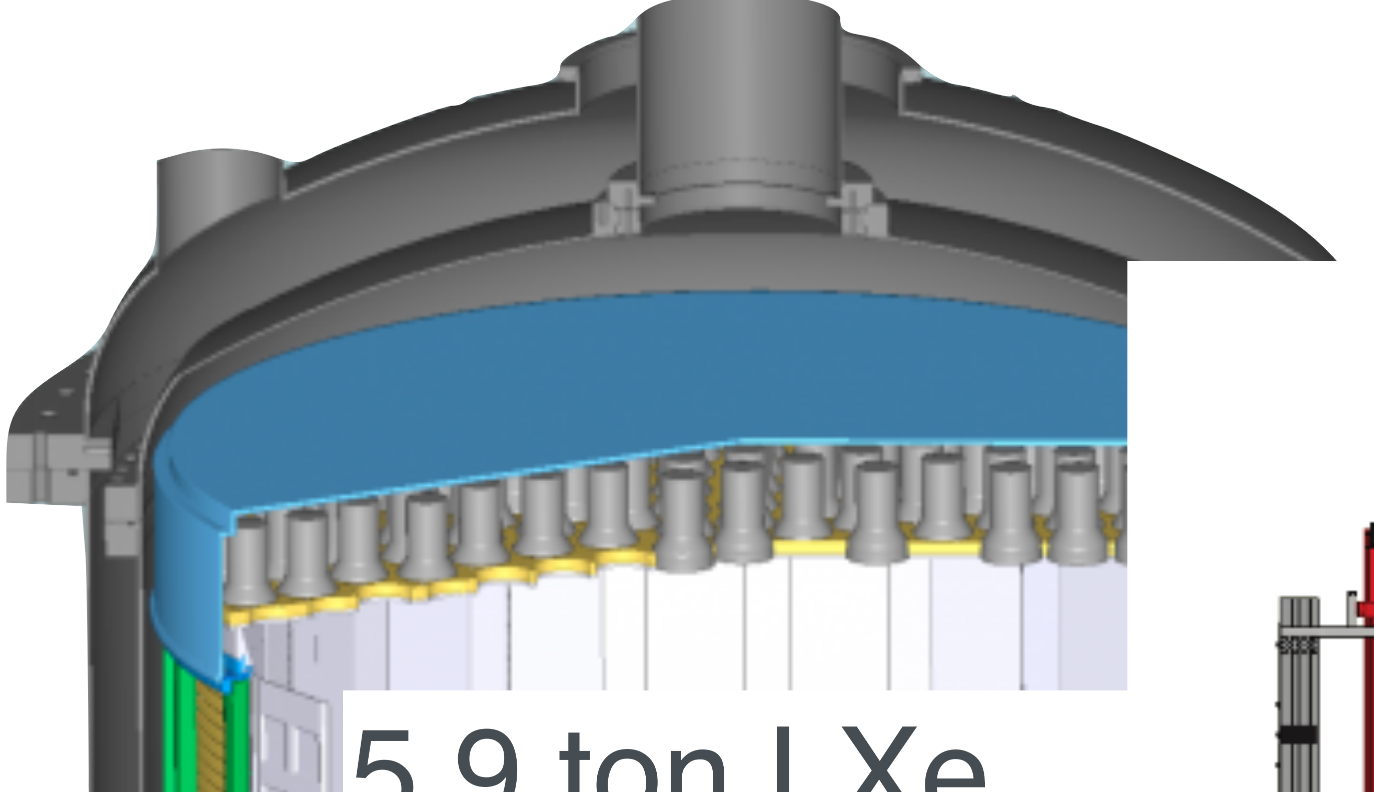


A. Kamaha, A. Cottele TAUP2019

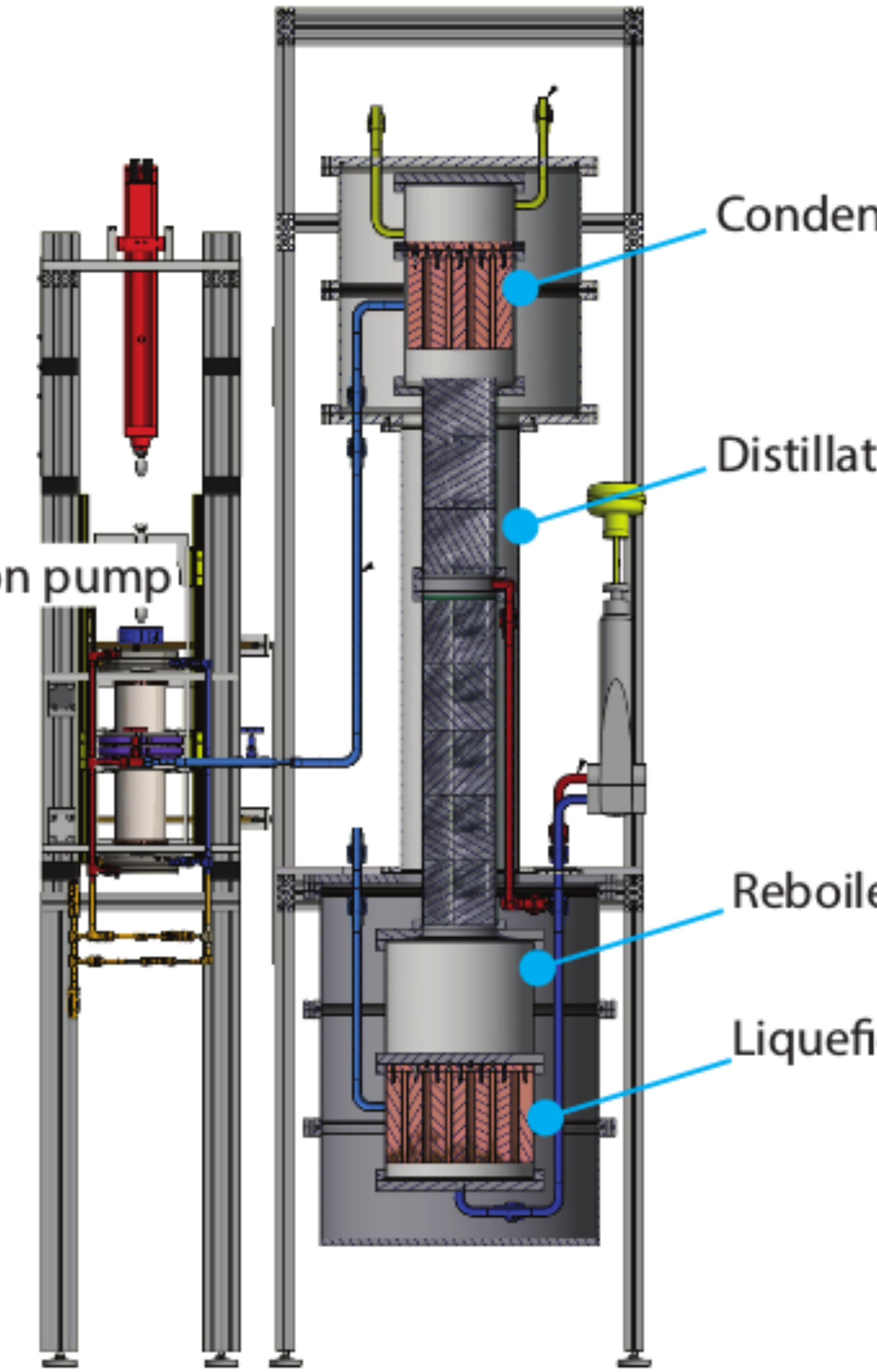
5.9 ton LXe
= 3 x 10^{28} atom

1 µBq/kg =
3000 ^{222}Rn atoms





On line Rn distillation



XENONnT

Challenge: neutron veto

Underground

↓

Material screening

↓

Water shield

↓

Particle ID

↓

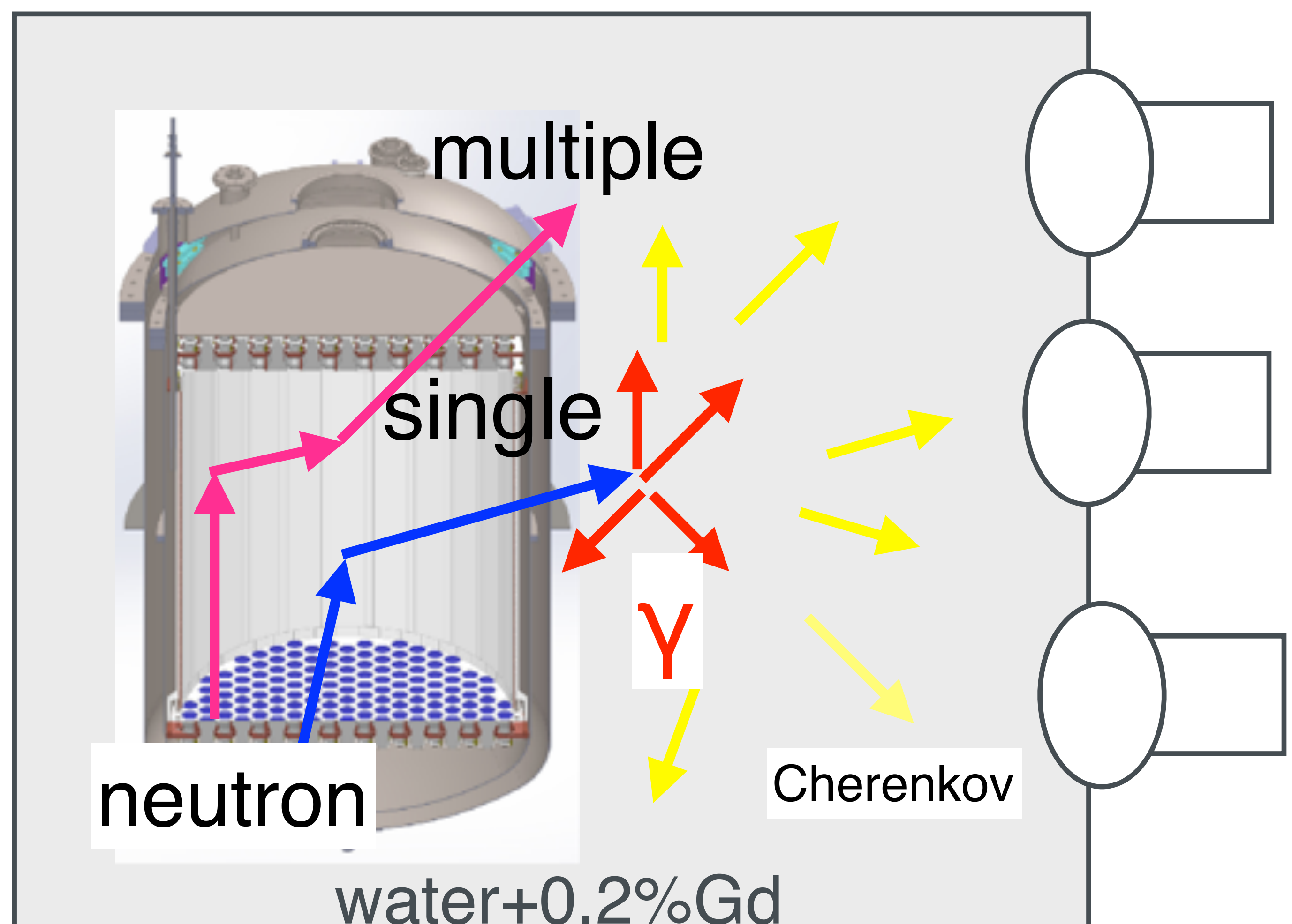
fiducial volume cut

↓

neutron Veto

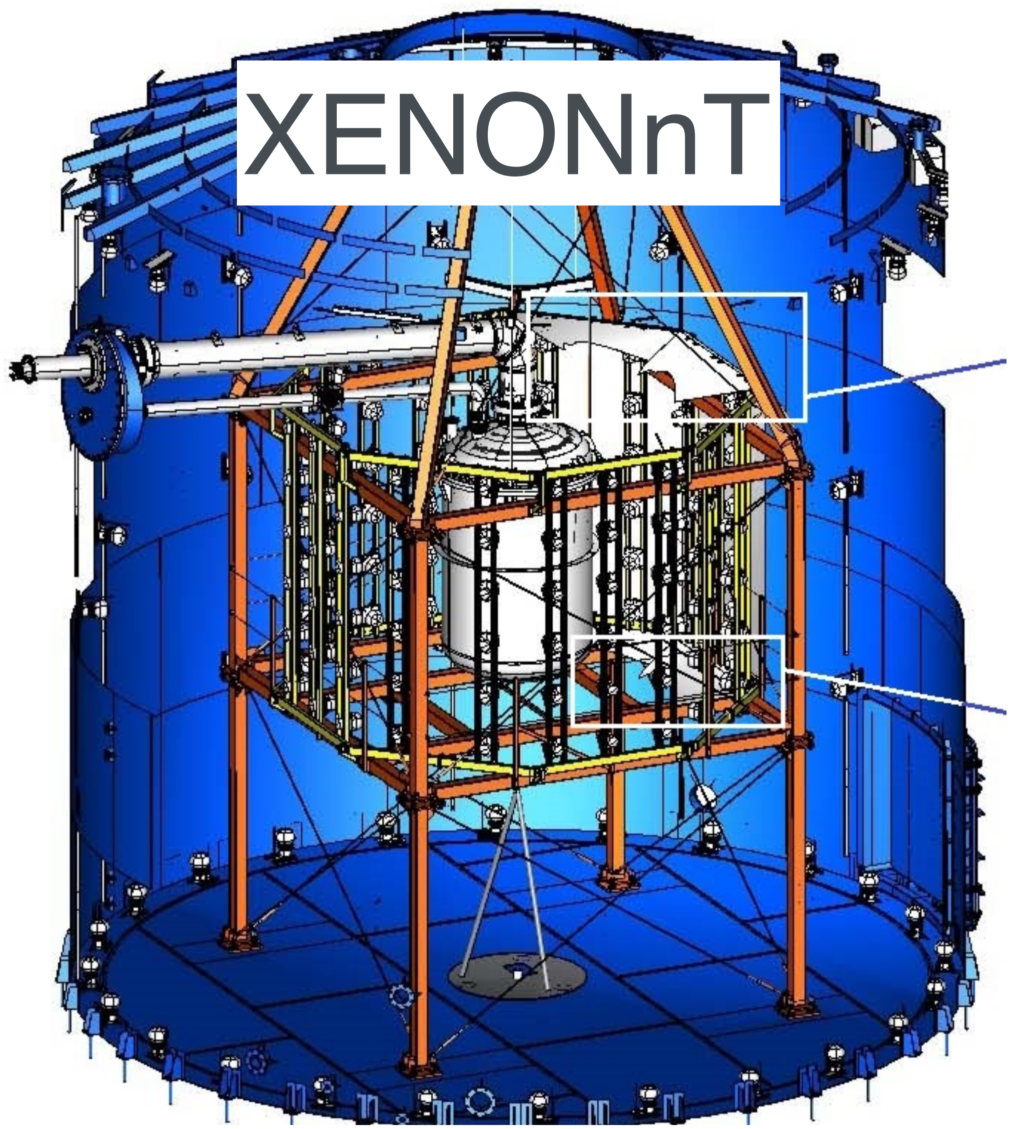
Generation2 (XENONnT, LZ DS-20K)

- fission from U/Th and (α,n) reaction(Cryostat, PMT, PTFE)
- 8 neutron/20 ton-year single scatter of neutrons
- irreducible background
- >85% neutron tagging efficiency for DM discovery.
- XENONnT (Water +Gd) (Technology from EGADS, SK-Gd)
- n + Gd -> total 8 MeV gamma



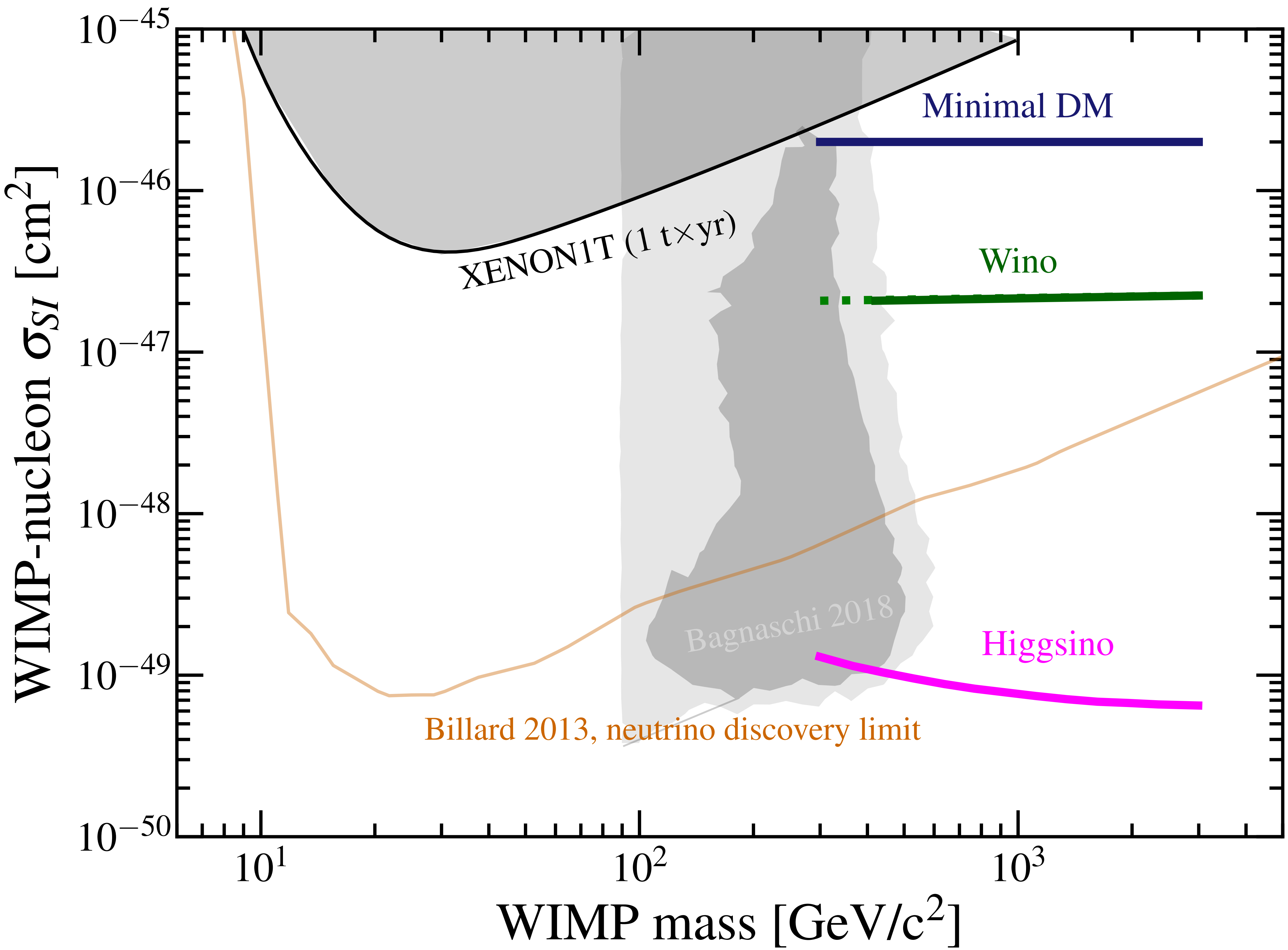
Challenge for G2 experiments

>85% neutron tagging efficiency for DM discovery.



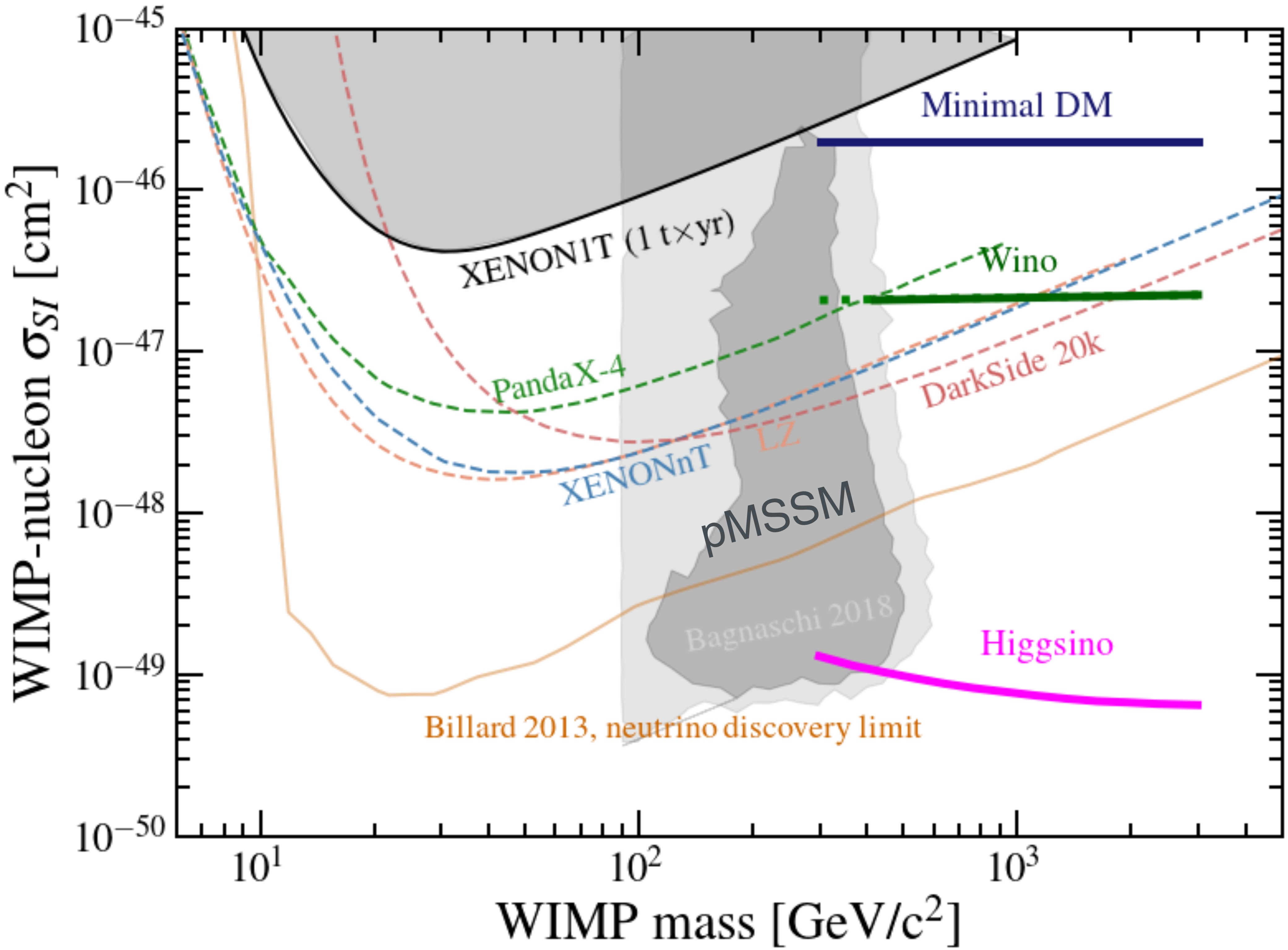
Water+0.2% Gd
(EGADS, SK-Gd technology)

Liquid Scintillator+Gd



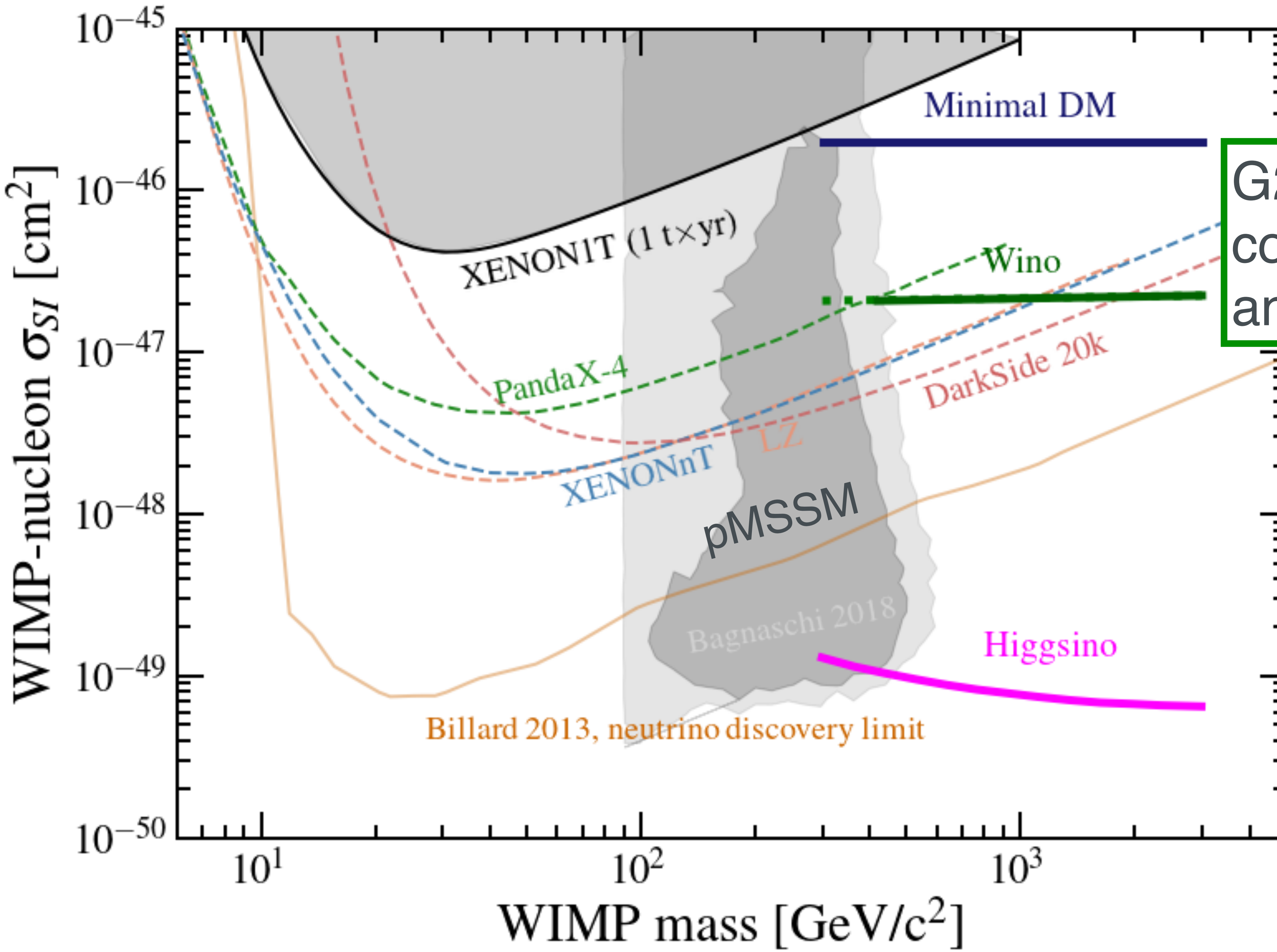
WIMP-nucleon σ_{SI} [cm^2]
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^1
10^2
10^3
WIMP mass [GeV/c^2]
XENON1T (1 t×yr)
Minimal DM
Wino
Bagnaschi 2018
Higgsino
Billard 2013, neutrino discovery limit

Generation2 : 2020-2025



Minimal DM, Wino, Higgsino :
J. Hisano et al. Eur.Phys.J. C78 (2018)

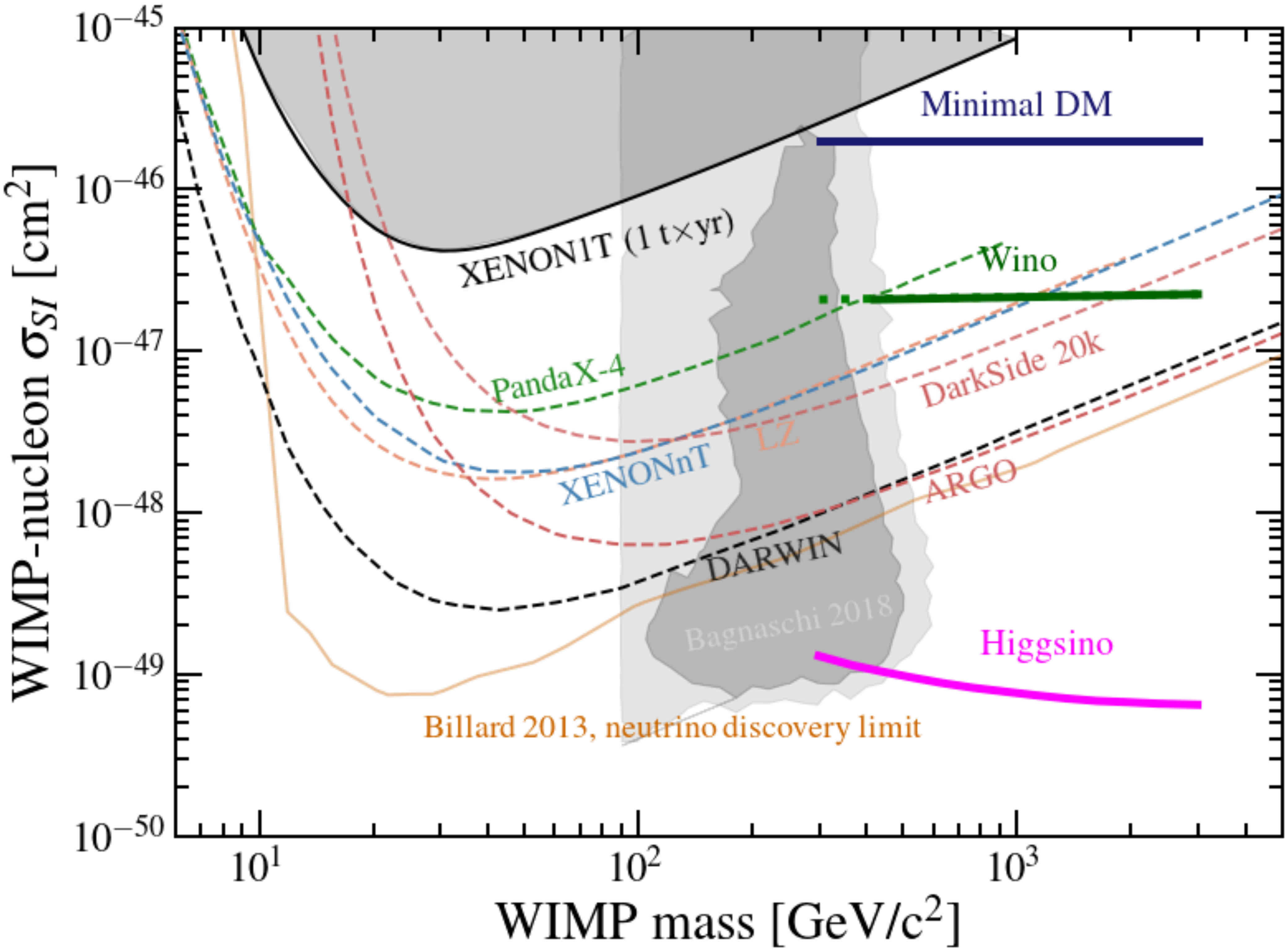
Generation2 : 2020-2025



G2 combined analysis ?

Wino, Higgsino :
J. Hisano et al. Eur.Phys.J. C78 (2018)

Generation3: 2026-



DS-20K, ARGO 1707.08145

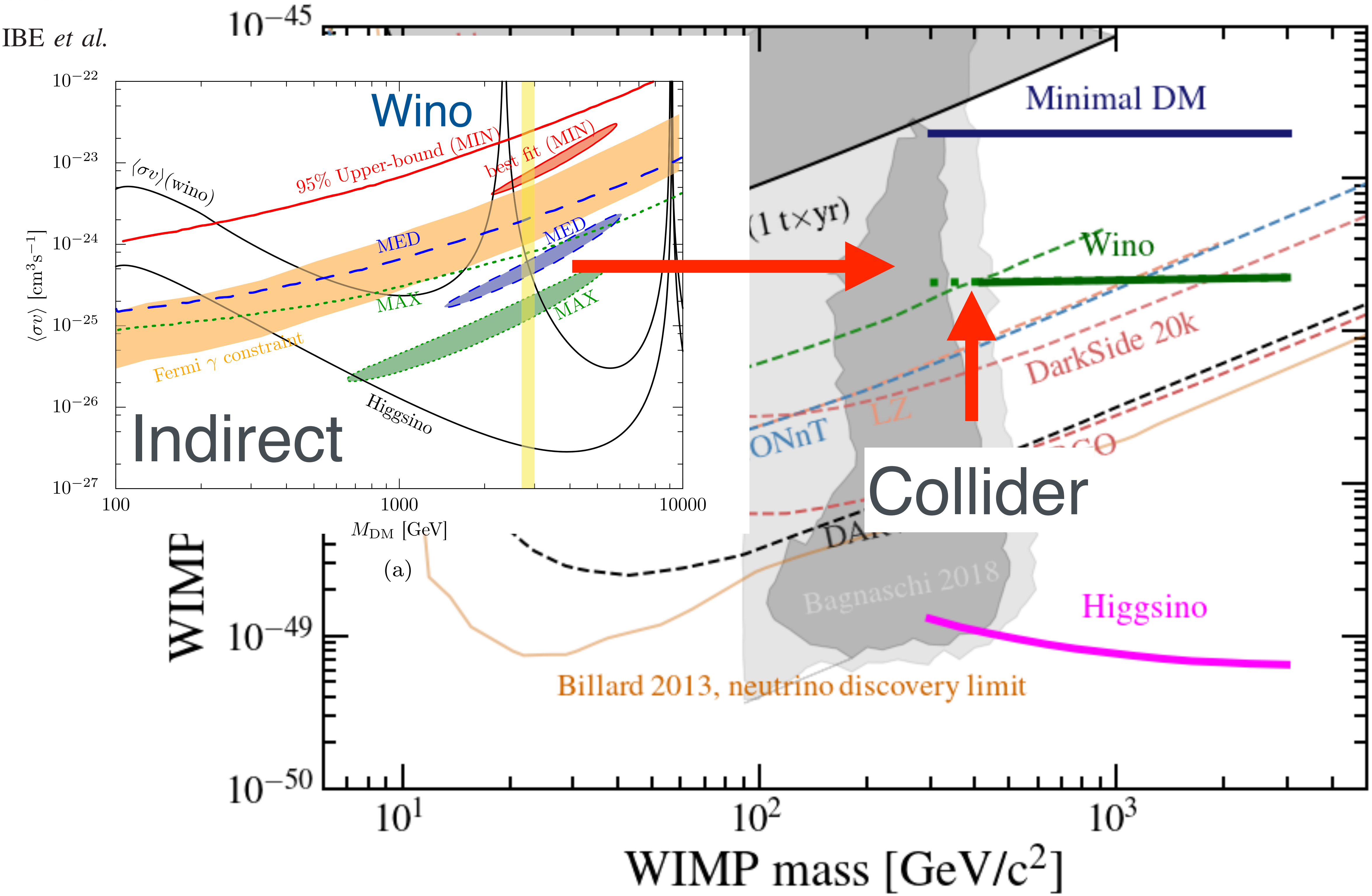
LZ, 1802.06039

XENON, PRL 121, 111302 (2018)

PandaX-4 Nature 2017

Wino, Higgsino : J. Hisano et al. Eur.Phys.J. C78 (2018)

Generation3: 2026-



DS-20K, ARGO 1707.08145

LZ, 1802.06039

XENON, PRL 121, 111302 (2018)

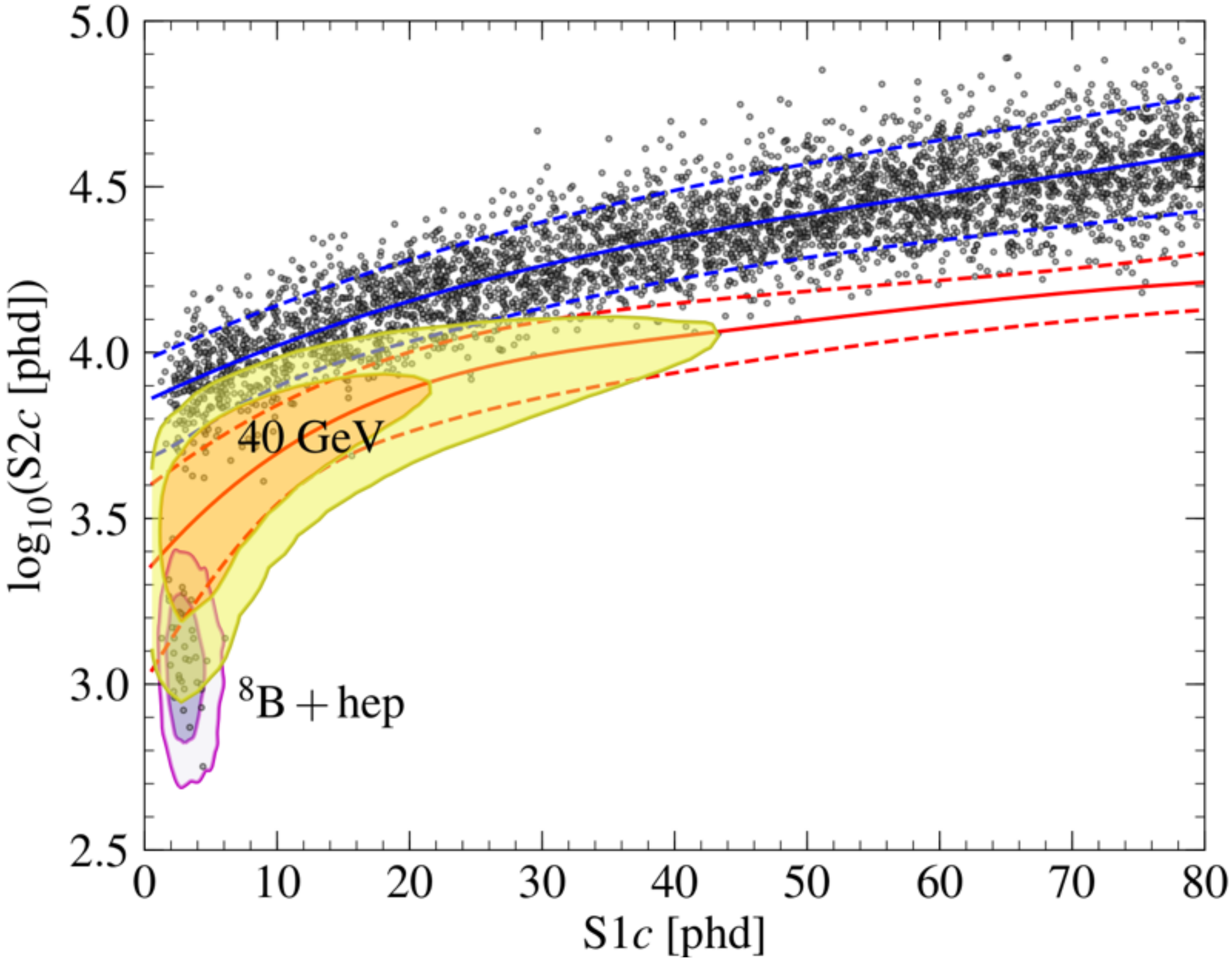
PandaX-4 Nature 2017

Wino, Higgsino : J. Hisano et al. Eur.Phys.J. C78 (2018)

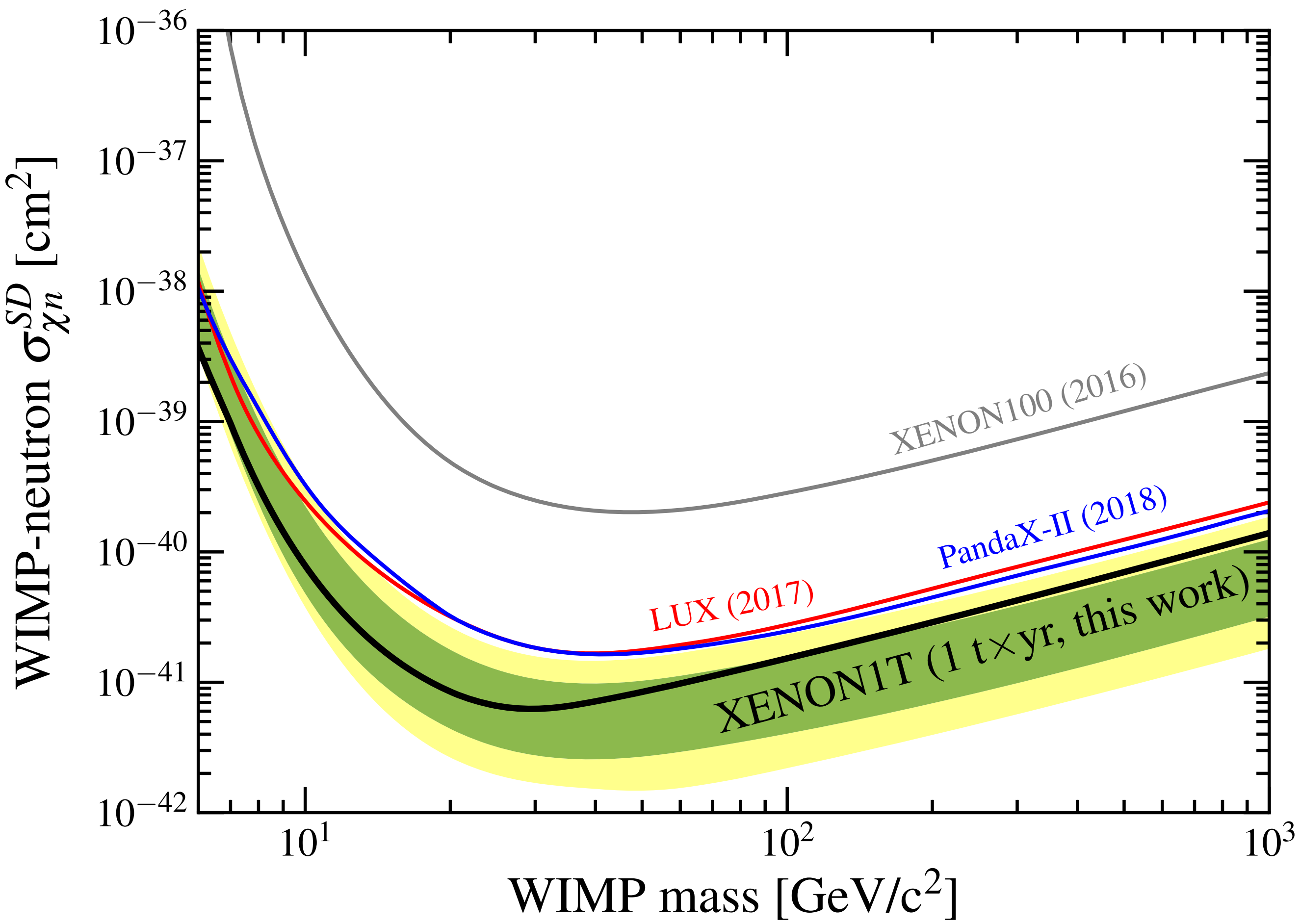
Summary

- **Direct DM search**
  - Liquid rare gas detectors are promising technology especially for heavy WIMP search.
- **G2 will start in 2020**
  - they will reach $\sigma \sim 10^{-48}$ cm^2 with 5 years exposure.
- **Challenges for G2 experiment**
  - rapid liquid xenon purification
  - Rn background
  - neutron veto
- **G3 experiments**
  - are aiming to explore close to neutrino floor region.

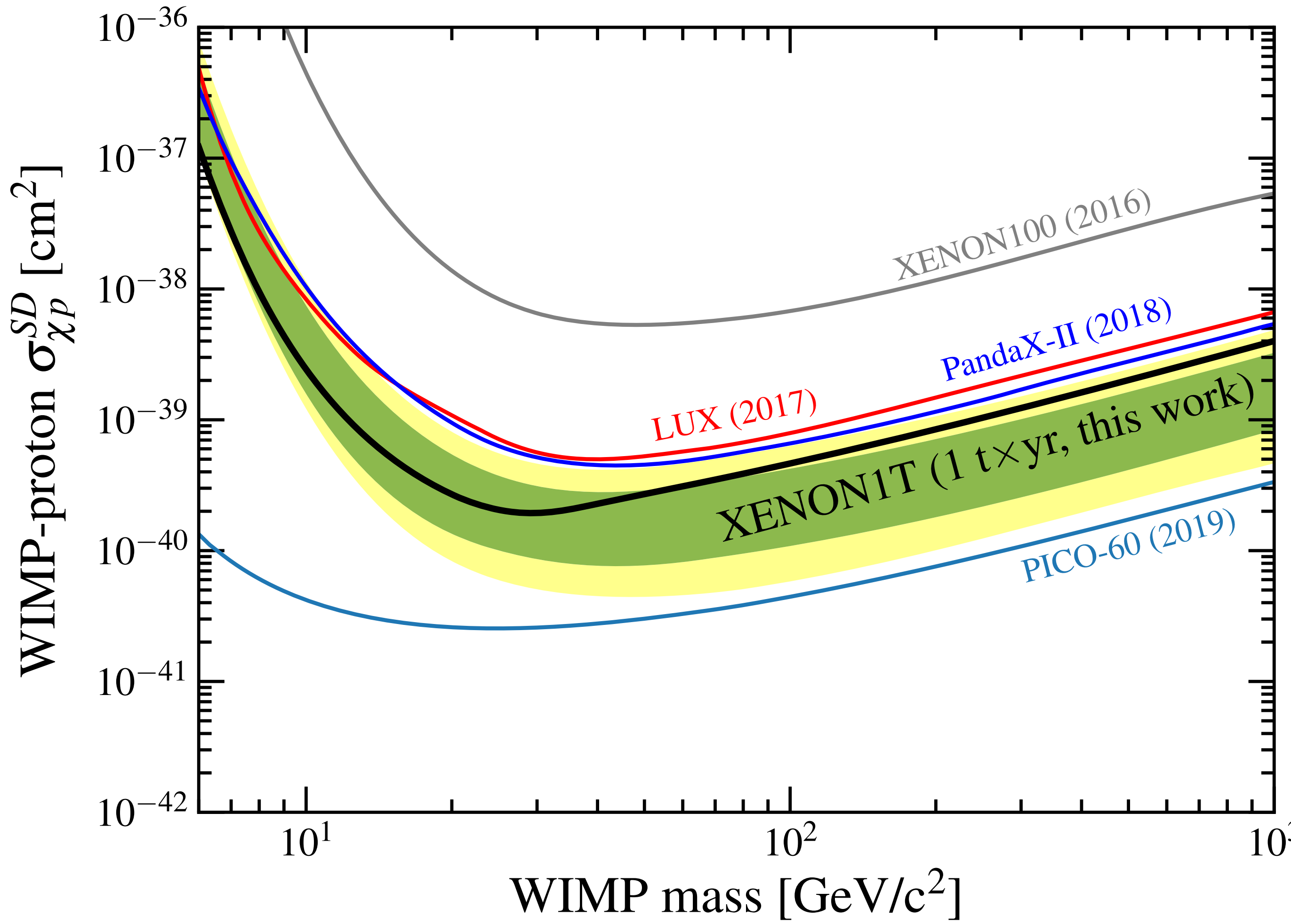
Simulation of a 1000 day run of LZ



D.S. Akerib et al (LZ collaboration) 2018 arXiv:1802.06039

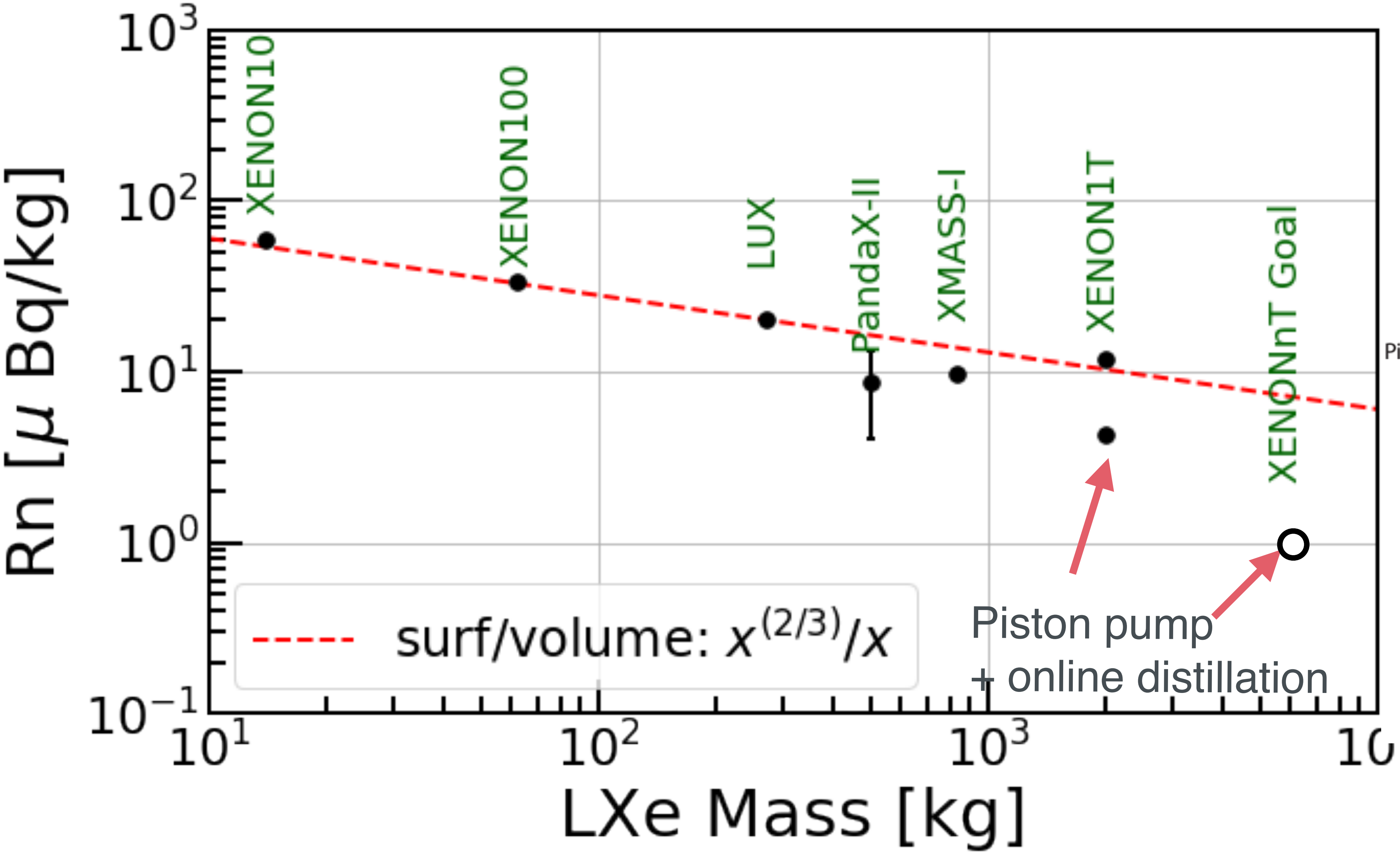


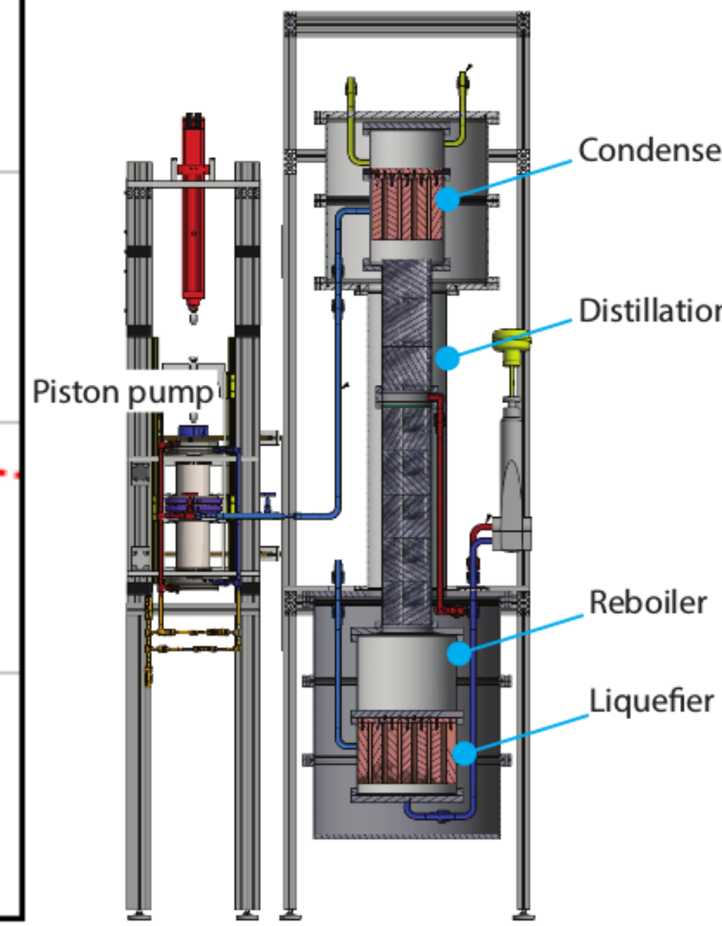
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
WIMP-neutron $\sigma_{\chi n}^{SD}$ [cm^2]
XENON100 (2016)
PandaX-II (2018)
LUX (2017)
XENON1T (1 t×yr, this work)
10^1
10^2
10^3
WIMP mass [GeV/c^2]



10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
WIMP-proton $\sigma_{\chi p}^{SD}$ [cm^2]
XENON100 (2016)
PandaX-II (2018)
LUX (2017)
XENON1T (1 t×yr, this work)
PICO-60 (2019)
10^1
10^2
10^3
WIMP mass [GeV/c^2]

Challenge:emanated Rn in LXe

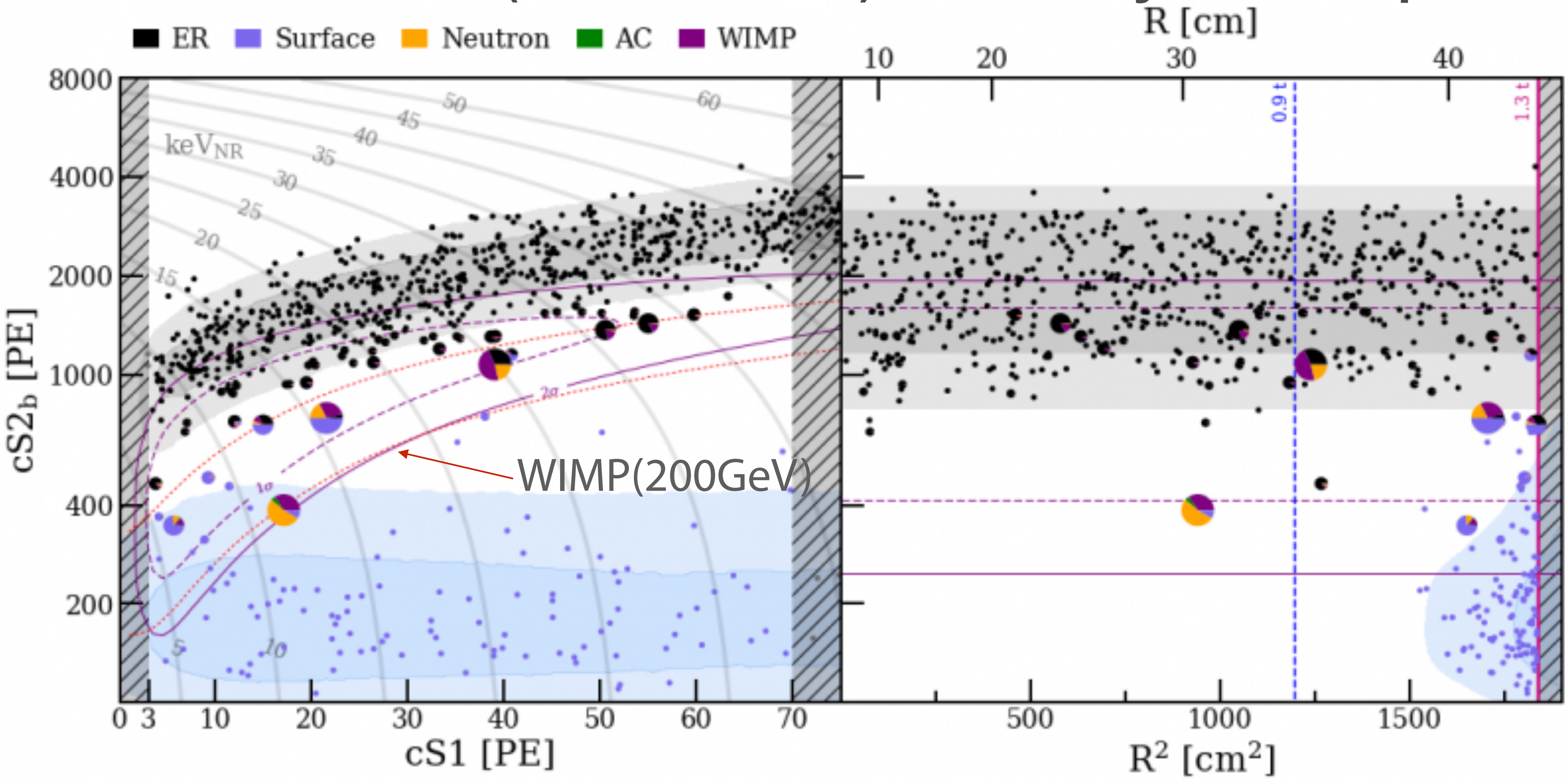




On line Rn distillation

1uBq/kg ~ pp solar neutrino event rate

XENON1T (PRL2018) 1 ton year exposure



Mass (ton)	1.3	1.3	0.9	0.65
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627 ± 18	1.62 ± 0.30	1.12 ± 0.21	0.60 ± 0.13
Neutron	1.43 ± 0.66	0.77 ± 0.35	0.41 ± 0.19	0.14 ± 0.07
CEνNS	0.05 ± 0.01	0.03 ± 0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106 ± 8	4.84 ± 0.40	0.02	0.01
Total BG	735 ± 20	7.36 ± 0.61	1.62 ± 0.28	0.80 ± 0.14
WIMP$_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2