

# Dark Matter Direct Detection Experiment Review

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LUX and LZ Experiments supported by US DOE HEP

see information at

<http://particleastro.brown.edu>

<http://cfpu.brown.edu>

<http://lz.lbl.gov>

If the S.I. Unit of Ignorance is the

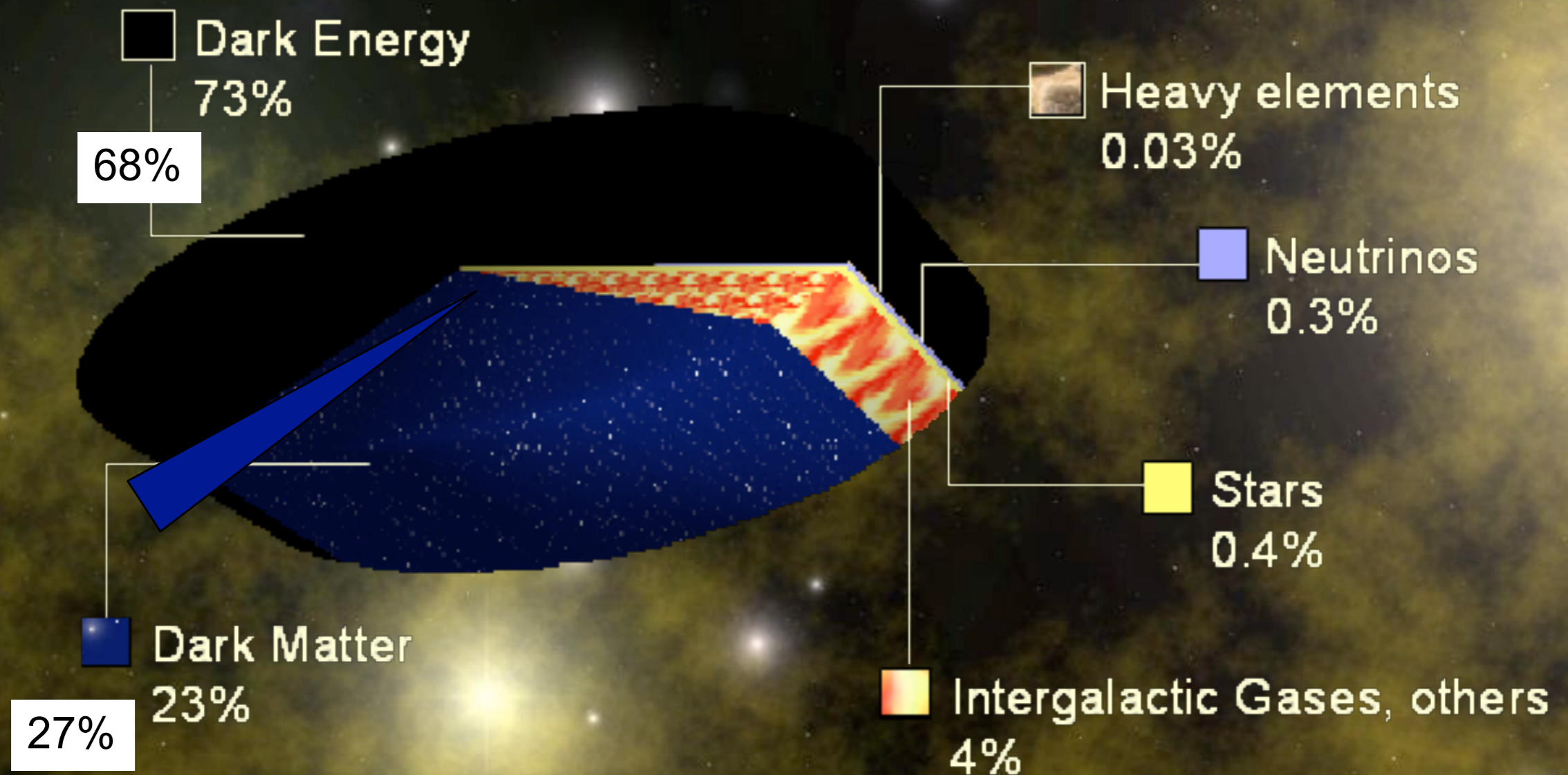
"IDK"

Then we still rate

950 milli-IDK

for the Composition of the Universe

# What is the Universe made of ?



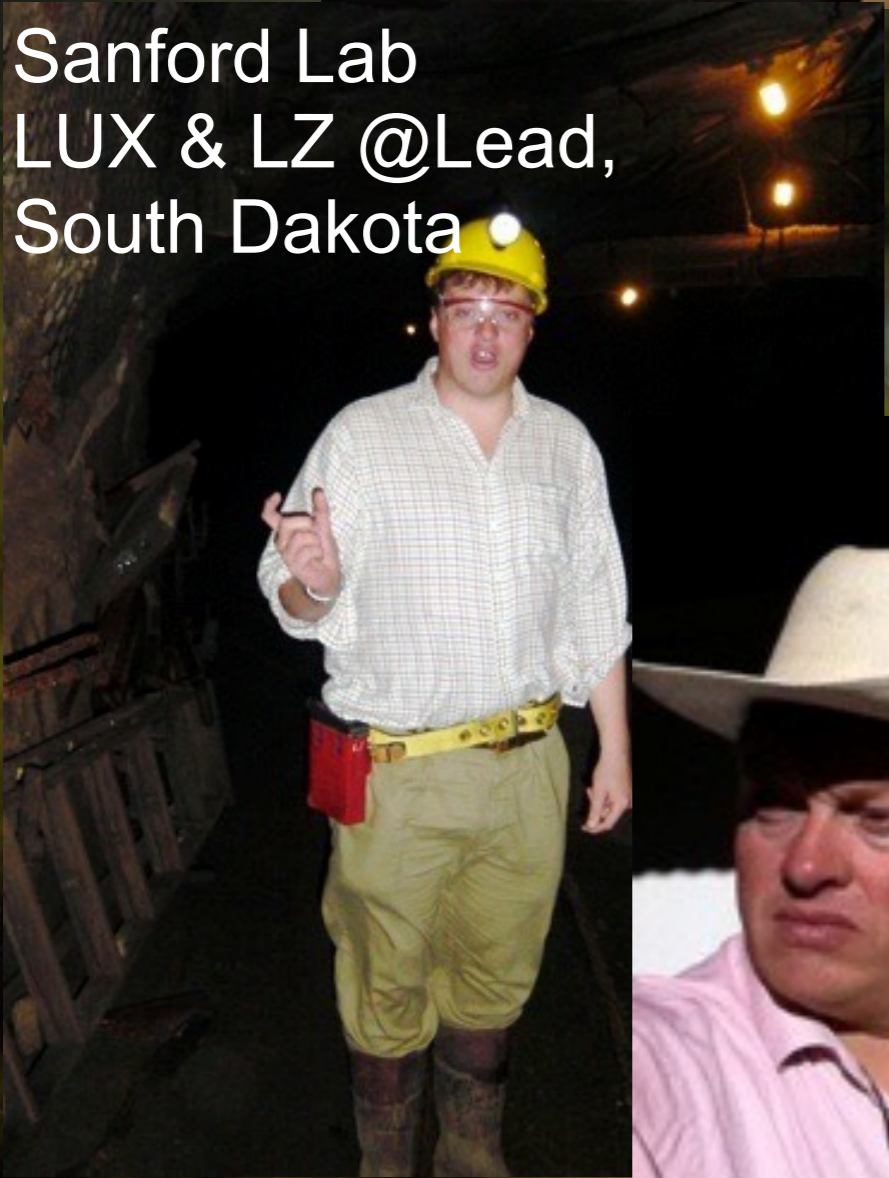
"But Actual Composition  
950 milli I Don't Know"

# 30 years in dark matter



CDMS II: Winter  
@Soudan Minnesota

Sanford Lab  
LUX & LZ @Lead,  
South Dakota



PHYSICS ITALIAN  
STYLE XENON10  
@ Gran Sasso



# Many International Efforts Over Last 20 Years



# Sanford Lab @ South Dakota



LUX, Sanford Lab, 2011



# Sanford Lab, May 2012

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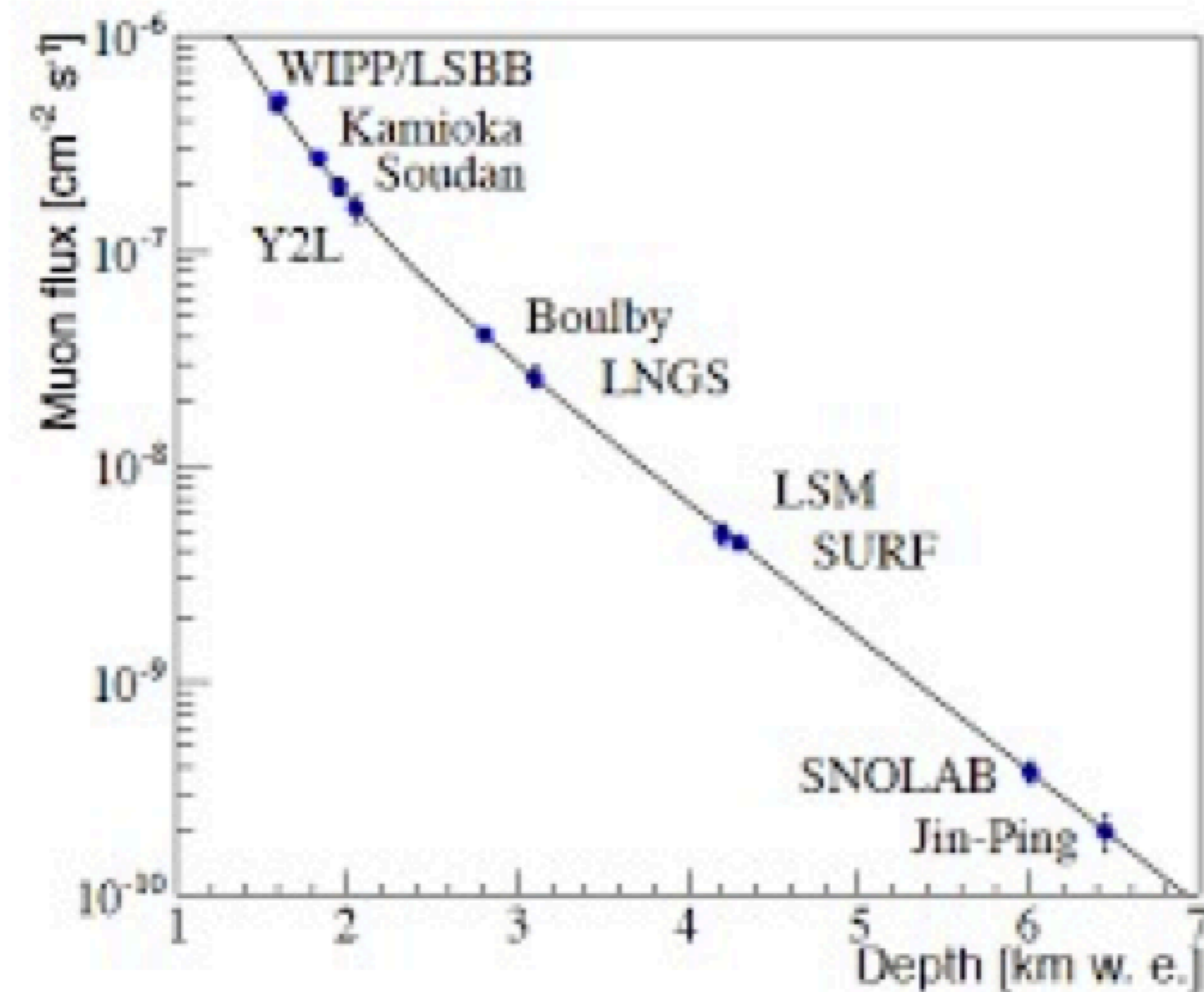


# Where are you today?

- April 28, 2021 - 1 mile underground at Sanford Lab



# Deep Underground Laboratories - Escaping Cosmic Muons



# How Many Gammas/Day?

Governor Rounds visits  
Sanford Lab, 2010

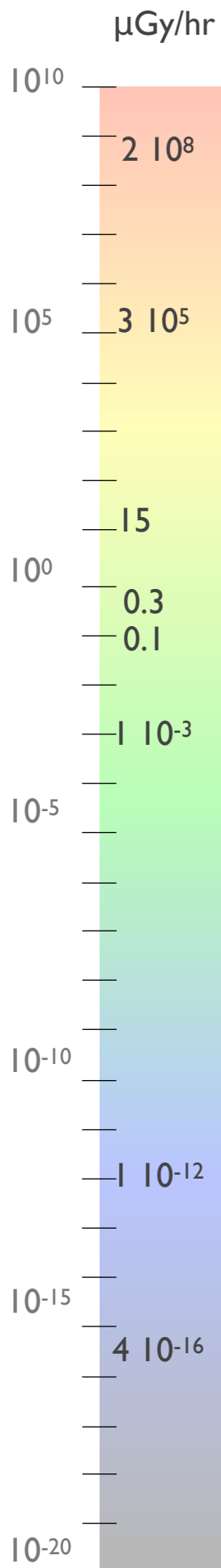
$>1,000 \gamma / \text{second/human}$

# Inside 9 m diameter water shield (Not Filled) at SURF



(David Malling, June 2012)

# Effective Radiation Exposure per Hour from Gamma Rays



Reactor building directly after Chernobyl accident



Full body CT scan



Average in Ramsar, Iran

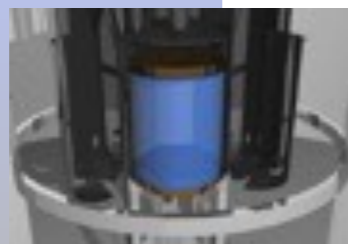
Average in US (including Radon gas in air)  
Average in US (excluding Radon gas in air)



Davis Cavern - 4850' underground



Middle of Water Tank



Middle of Detector

# Dark Matter Underground Searches - 1987

- First publication on an underground experimental search for cold dark matter (Ahlen et al. 1987. PLB 195, 603-608).



Volume 195, number 4

PHYSICS LETTERS B

17 September 1987

## LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN <sup>a</sup>, F.T. AVIGNONE III <sup>b</sup>, R.L. BRODZINSKI <sup>c</sup>, A.K. DRUKIER <sup>d,e</sup>, G. GELMINI <sup>f,g,1</sup>  
and D.N. SPERGEL <sup>d,h</sup>

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<sup>c</sup> *Pacific Northwest Laboratory, Richland, WA 99352, USA*

<sup>d</sup> *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

<sup>e</sup> *Applied Research Corp., 8201 Corporate Dr., Landover MD 20785, USA*

<sup>f</sup> *Department of Physics, Harvard University, Cambridge, MA 02138, USA*

<sup>g</sup> *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*

<sup>h</sup> *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy. Using a realistic model for the galactic halo, large regions of the mass-cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent  $Z^0$  exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is  $< 0.4 \text{ GeV/cm}^3$  for masses between 17.5 GeV and 2.5 TeV, at the 68% confidence level.

- 1986 operating a 0.8 kg Ge ionization detector at Homestake Mine, SD (adjacent to Ray Davis's operating Solar Neutrino Experiment)

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**LIMITS ON COLD DARK MATTER CANDIDATES  
FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER**

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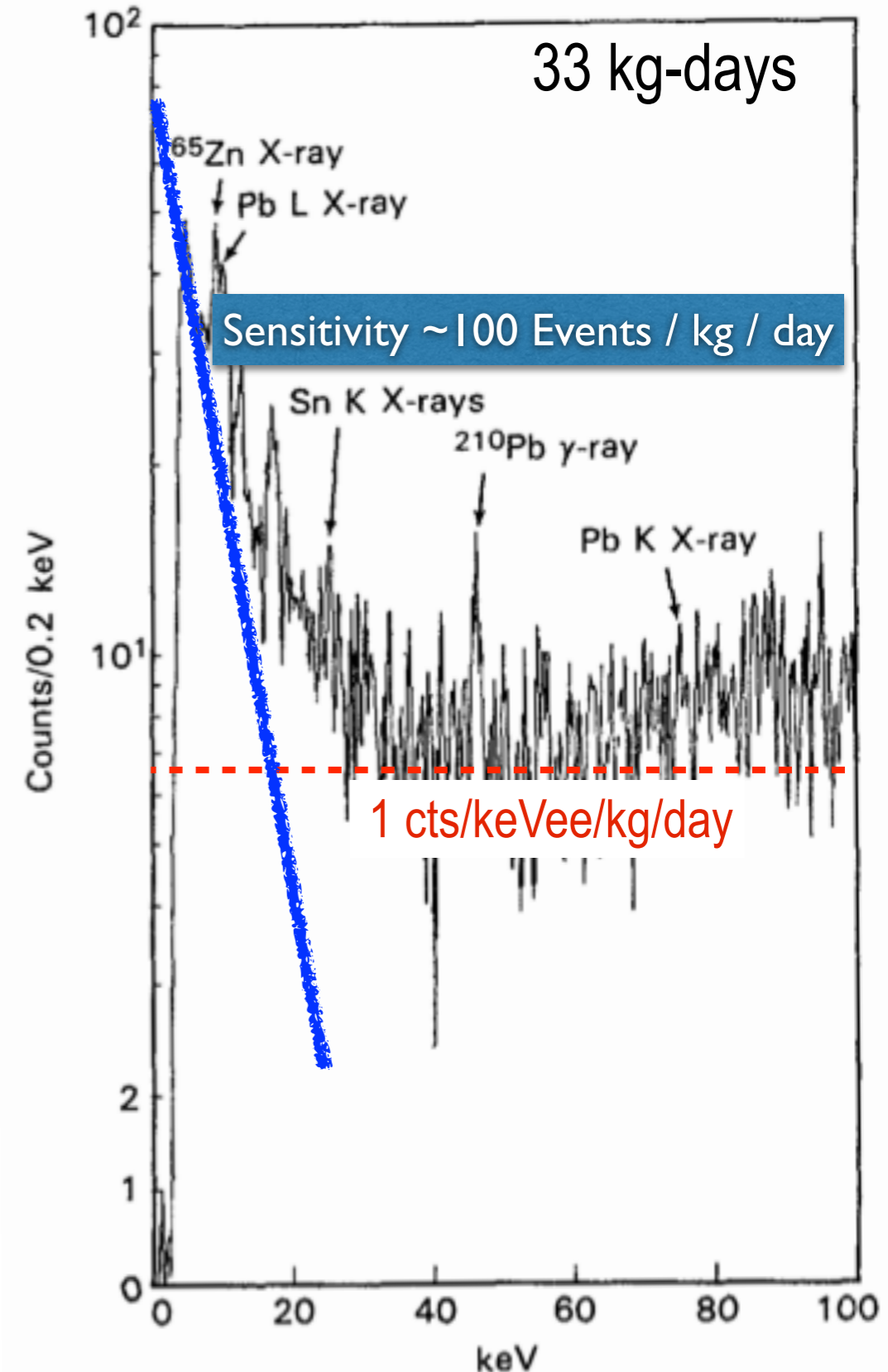
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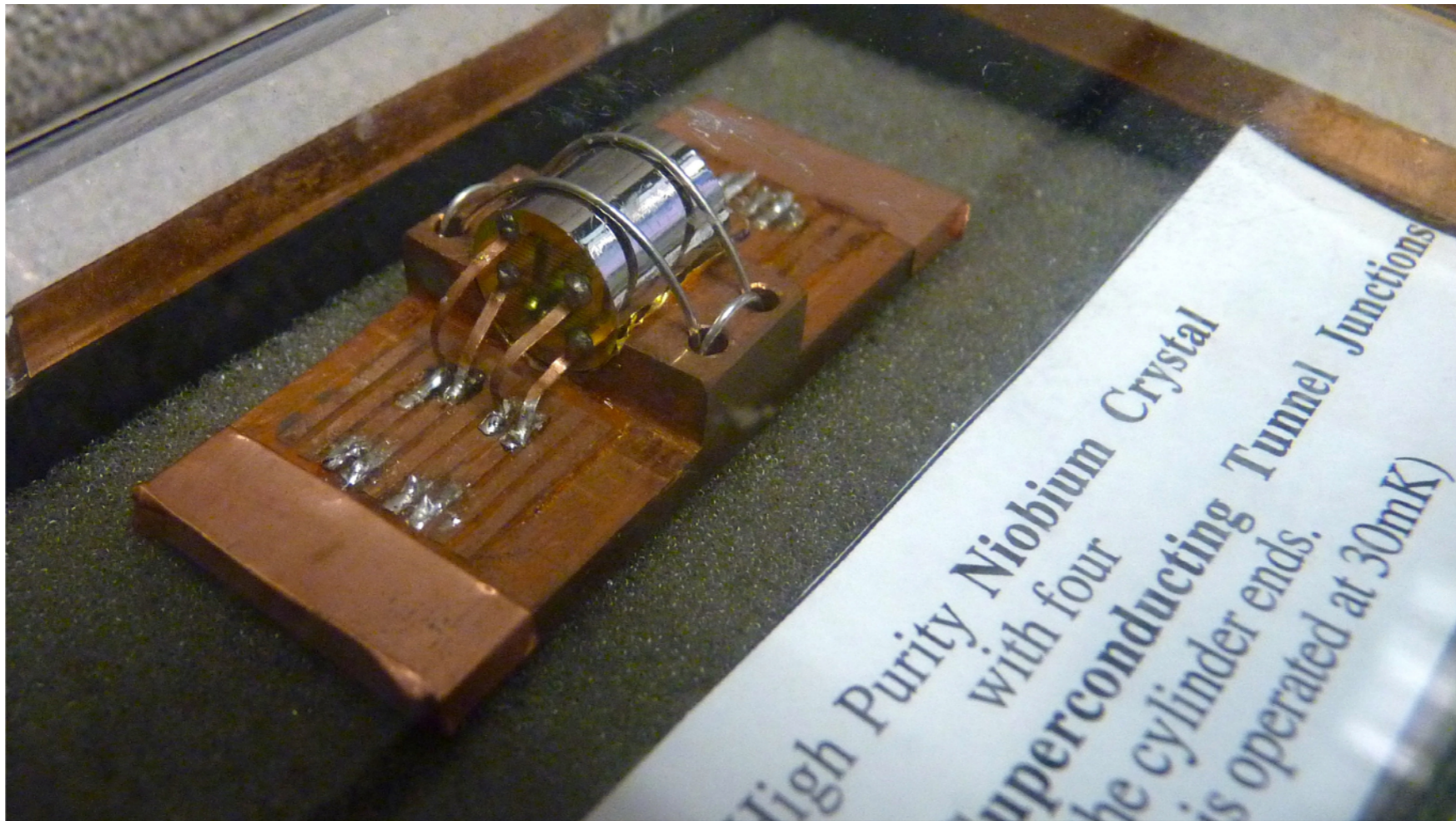
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# Gaitskell (Graduate Work) Superconducting Nb Single Crystal Detector

- 1 cm long - 12 g - 250 eV Threshold - “State of the Art in 1991”
- Superconducting Tunnel Junction arrays detecting phonons and quasiparticles from Nb



In Early 1990's we studied exotic lattice photon and quasiparticle states to build sensitive dark matter detectors - today we appear to be coming full circle as see new proposals for MeV DM search experiments based on meV excitons



# Dark Matter Direct Detection MeV - TeV

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- I prepared a List of the Search Experiments that have been
  - Recently Completed (last 4 years), or
  - About to Start, or
  - Some of the Future (out 10 years)

(not exhaustive, doesn't include more speculative ideas still in R&D)

- Dates indicate the Start of Detector Operation and Science
- (Forgive me for an omissions or slight errors in dates)



Dar

- TeV

XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioko
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction/Run	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/Run	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Planning	2028	2033	LNGS/SURF/Boulby
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Planning/Construct	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	Nal	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	Nal	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	Nal	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	Nal	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	Nal	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	Nal	?		Planning	2023	?	LNGS
SABRE PoP	Scintillator	Nal	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	Nal	50 kg		Planning	2022	2027	LNGS
SABRE (South)	Scintillator	Nal	50 kg		Planning	2022	2027	SUPL
CDEX-10	Ionization (77K)	Ge	10 kg	103 kg d	Running	2016	?	CJPL
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg		Planning	202X		CJPL
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	Surface Lab
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Running	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g	80 g d	Running	2019		LSM
CRESST-II	Bolometer Scintillator	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillator	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillator	CaWO4			Running	2020		LNGS
PICO-2	Bubble Chamber	C3F8	2 kg		Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber	C3F8	35 kg		Running	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I,C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction/Run	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
CYGNUS???								
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction/Run	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction/Run	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction/Run	2021	2023	SNOLAB
ALETHEIA	TPC	He			R&D			China Inst. At. Energy
TESSERACT	Cryo TES	He			R&D			LBL

R&D
Planning
Construction
Running
Ended



# The Practical Matter of a Rare Event Search

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- Improvements in Dark Matter Search Reach
  - Progress is Incremental...but by orders of magnitude
    - e.g. x10 increases in target mass
- Innovation
  - e.g. Entirely new target materials C<sub>3</sub>F<sub>8</sub>
  - e.g. Higher Field Operation of Ge Bolometric Target
  - e.g. Skipper Amp CCD Readout
  - e.g. Light nuclei (He) for Low Mass WIMP searches

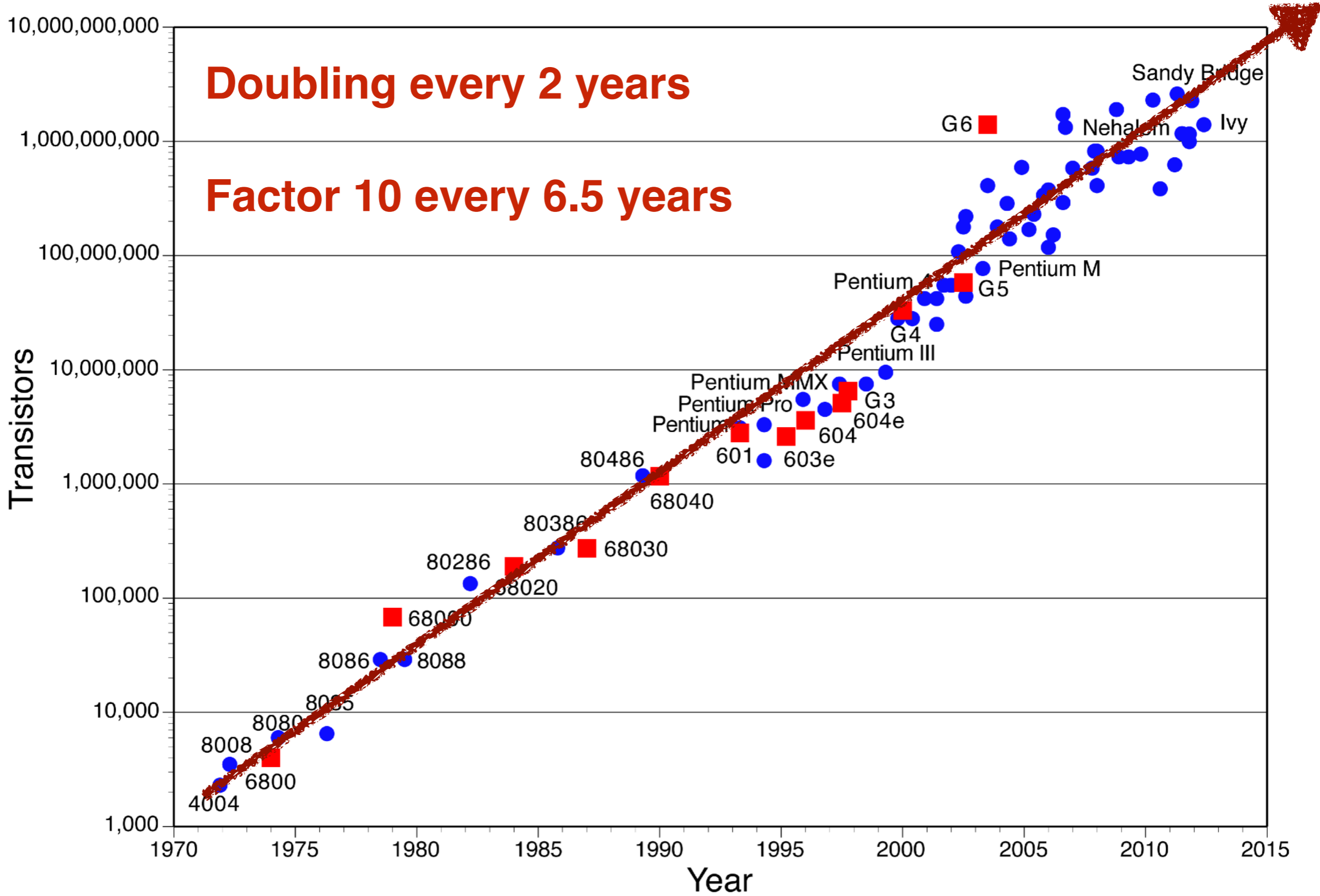
# The Practical Matter of a Rare Event Search

- In ~33 rd year of searching - now at a sensitivity that  $10^6$  better than the first round - we need detectors with a

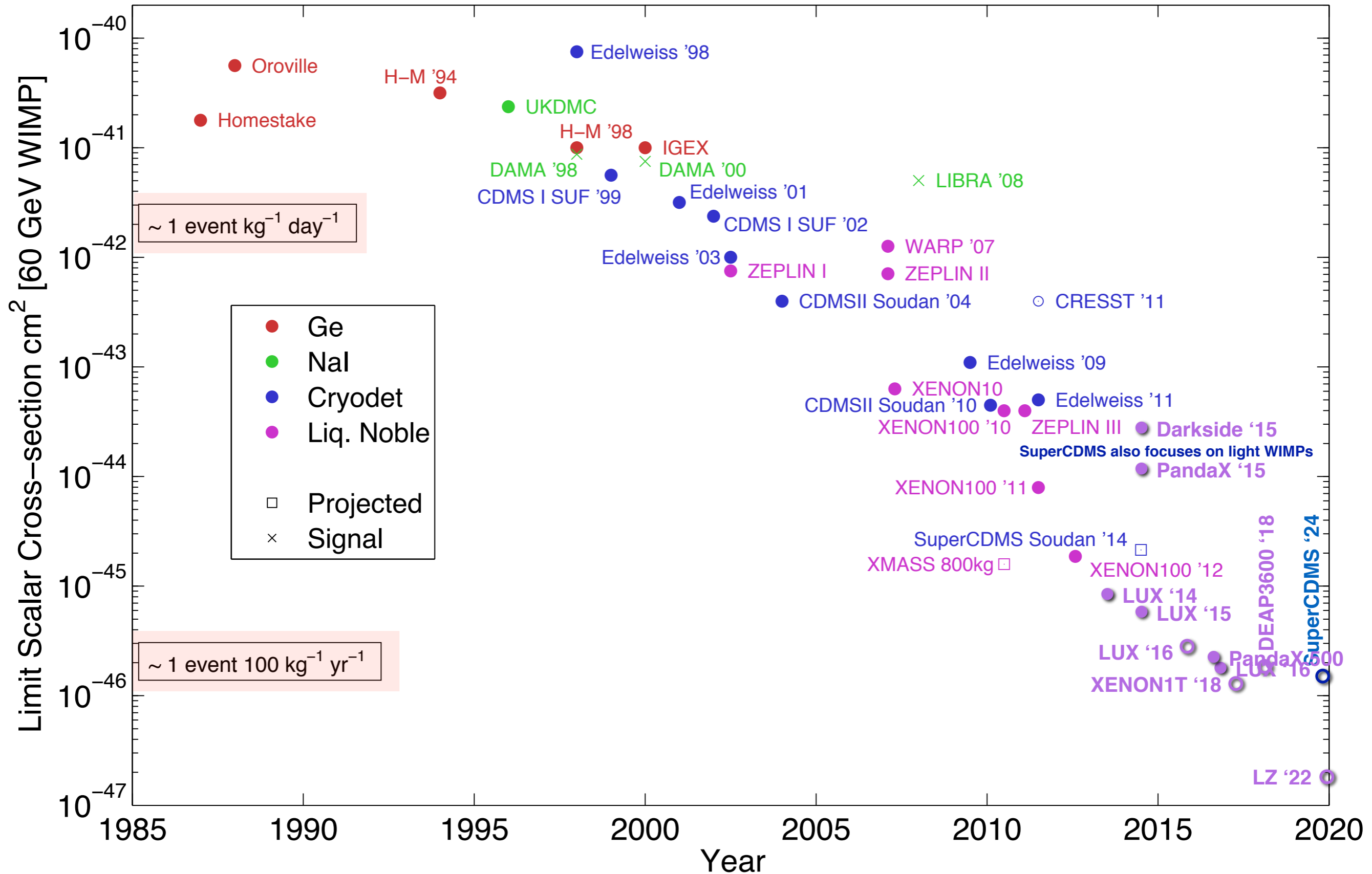
## Low Sisyphean Index †

- They must want to work correctly / do so without misleading us / low complexity - mustn't roll back down the hill when we stop paying attention for a moment
- And we will need to push them (pun indented) by another  $10^2$  before we reach the irreducible coherent neutrino backgrounds

† Experimentalist's Perspective of the Technology itself, not the definition that the task can never be completed

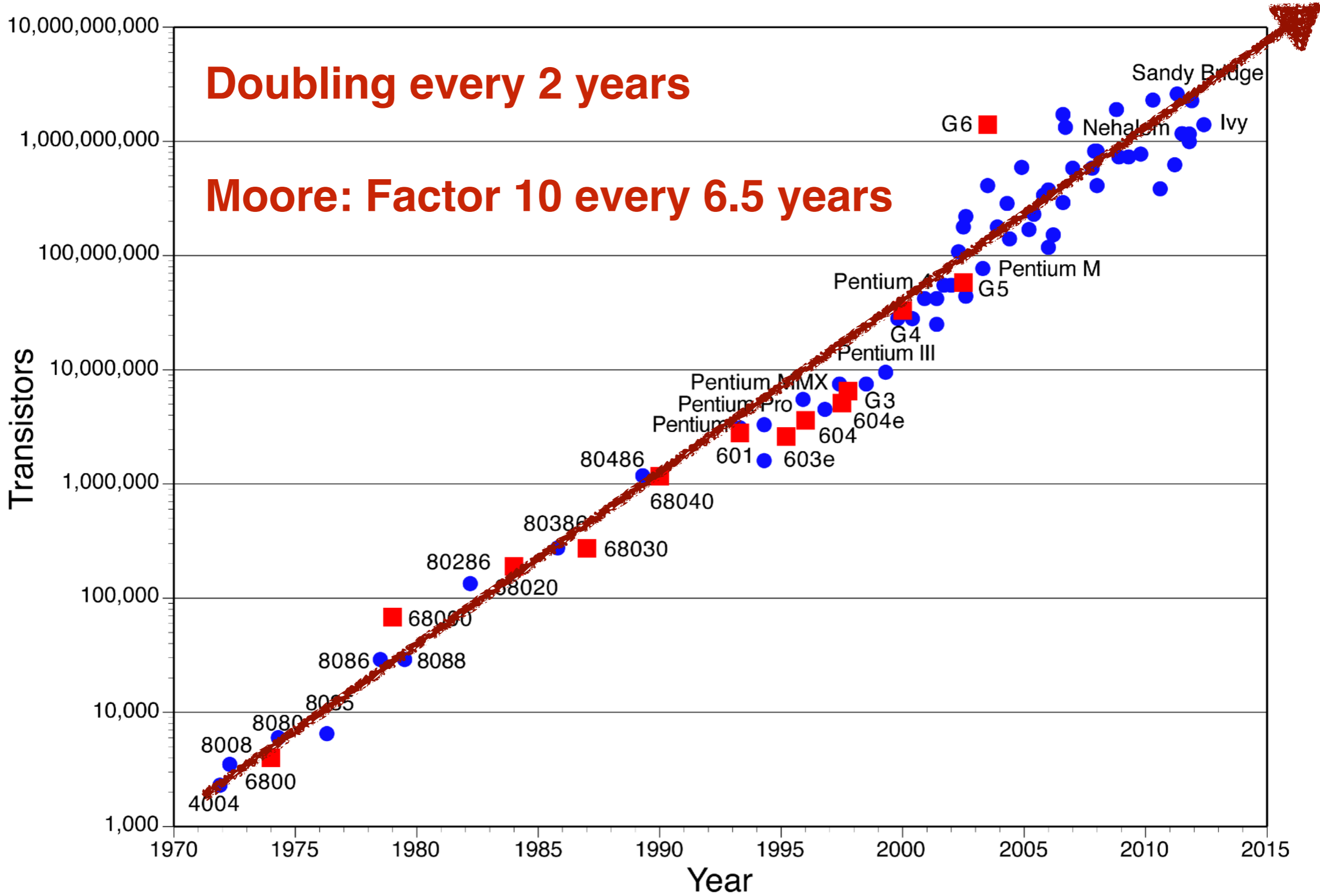


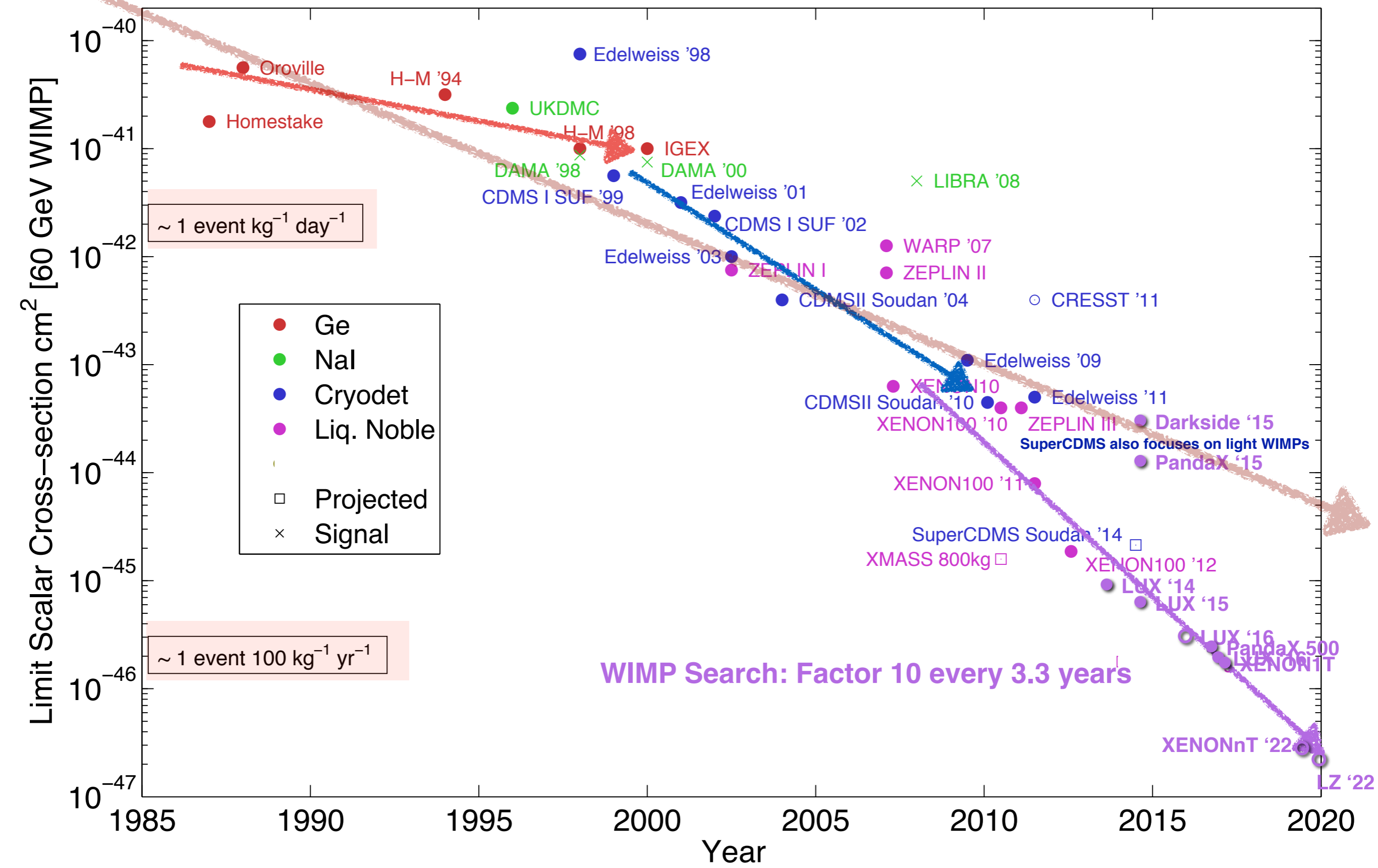
# Dark Matter Searches: Past, Present & Future





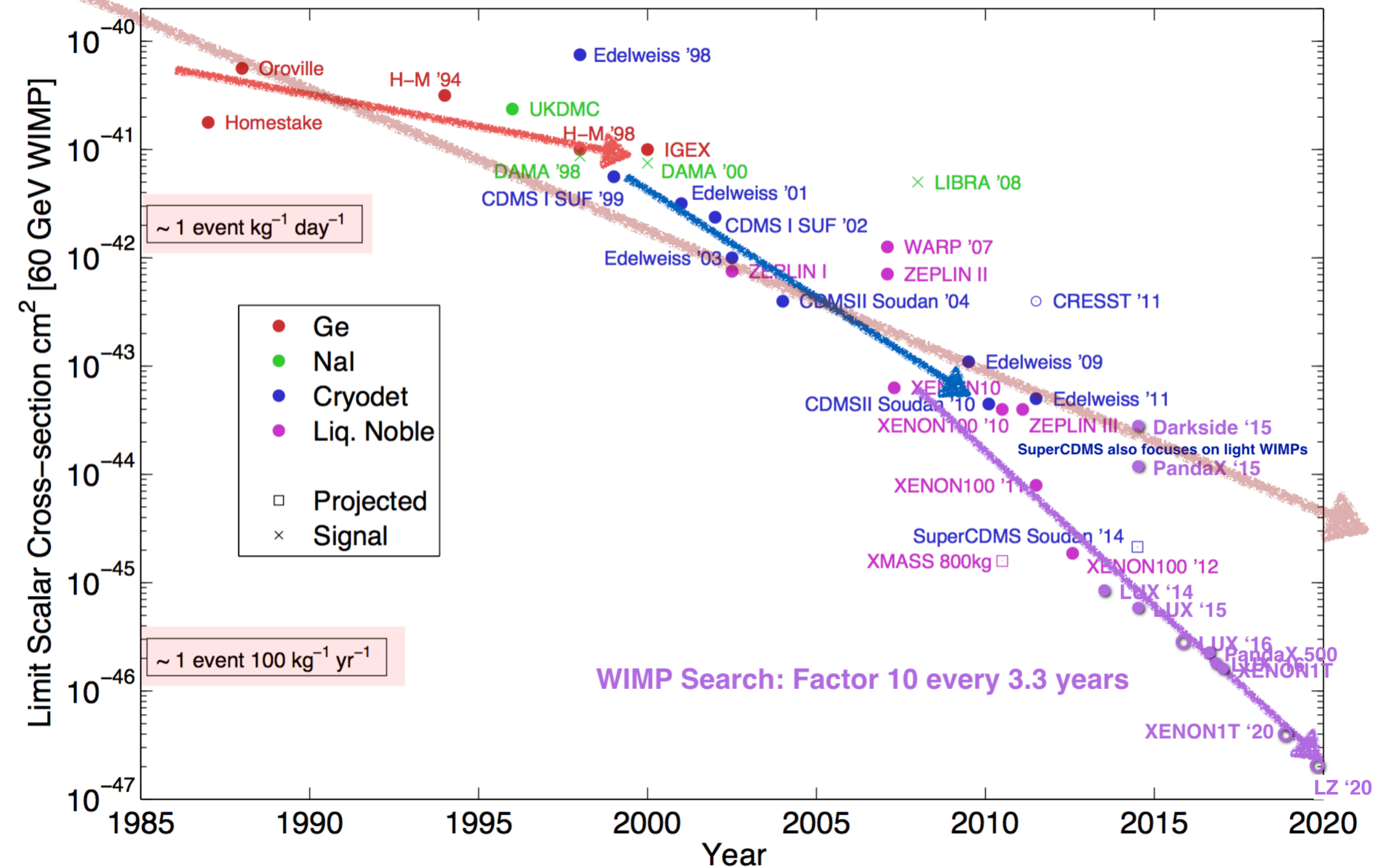






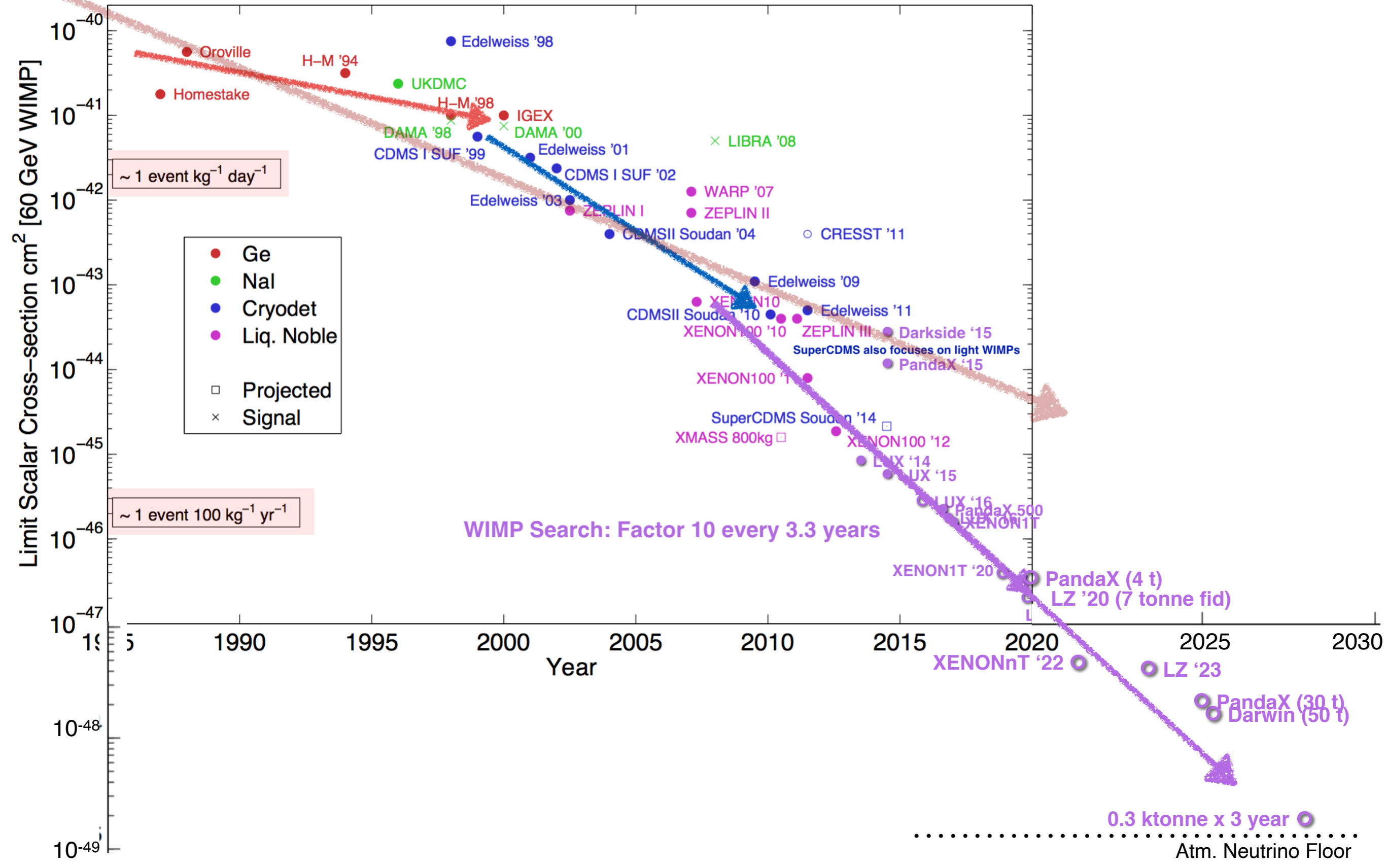
# Moore: Factor 10 every 6.5 years

## Dark Matter Searches: Past, Present & Future



**Moore: Factor 10 every 6.5 years**

**Dark Matter Searches: Past, Present & Future**



# Journey Through the Theoretical Landscape

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- Cumulative Theoretical work

(Thanks to Dan Hooper, Fermilab )

For history - Bertone and Hooper, arXiv:1605.04909

- 1966-1977 Massive Standard Model Neutrinos

- Includes 1966 Gershtein & Zeldovich .... 1977 Dicus, Kolb & Teplitz,

- 1977-83 Other candidates, including supersymmetric particles

- Includes 1977 P. Hut .... 1983 Ellis, Hagelin, Nanopoulos, Olive & Srednicki

- So WIMPs coined in 1984 by Turner and Steigman (term has evolved in modern use)

- Weak Mass Scale and Weakly Interacting

- By the late 1980s, it was widely appreciated that these specific candidates were but a few examples of a broader class of “WIMPs”

- WIMPs have been the major focus of dark matter candidates

- mass  $>3$  MeV to avoid altering successful BBN (Big Bang Nucleosynthesis) predictions

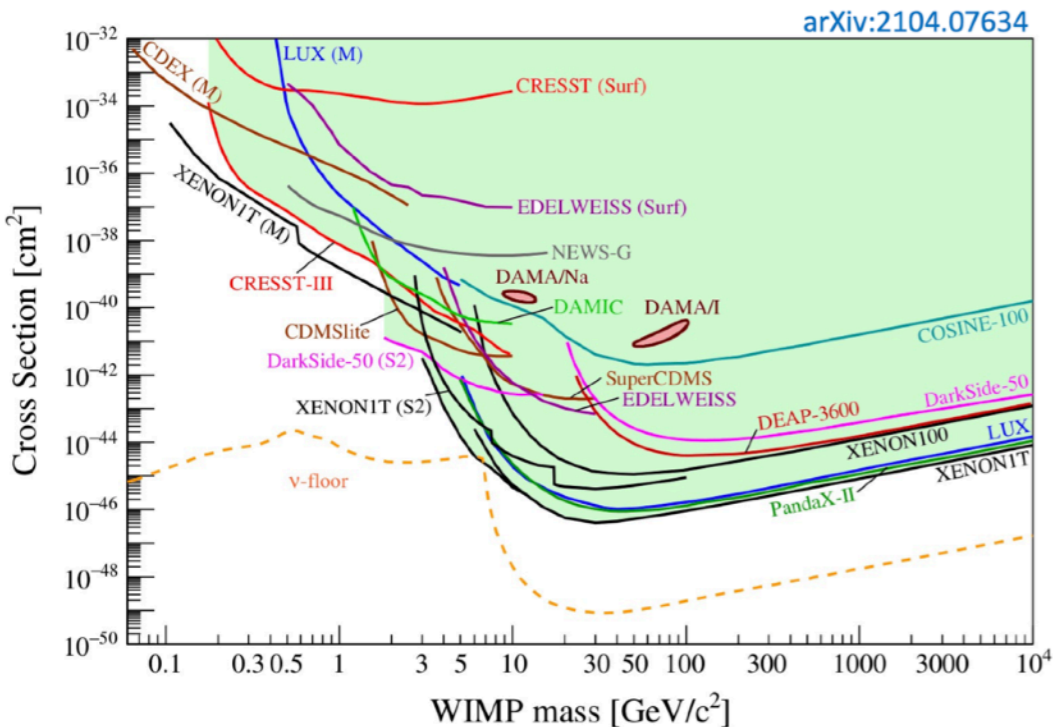
- mass  $<100$  TeV to ensure  $\Omega_{\text{matter}} < 0.3$

- WIMP is a very natural solution if we assume particle is in thermal equilibrium during early annihilation phase and are present in a radiation dominated early universe

# WIMPs

(Thanks to Dan Hooper, Fermilab)

- The thermal relic abundance calculation provides us with a collection of well-motivated benchmark models and experimental targets
  - Many of the most attractive WIMP candidates were expected to fall within the reach of planned direct detection and accelerator experiments
  - We have covered 6 orders of magnitude in sensitivity – and yet no WIMPs have appeared
  - The LHC has increase energy and intensity, and yet no compelling signs of dark matter (or other Beyond SM physics) have been discovered



ATLAS SUSY Searches\* - 95% CL Lower Limits  
July 2020

ATLAS Preliminary  $\sqrt{s} = 13$  TeV

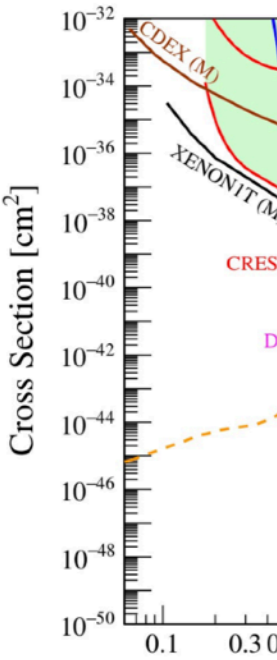
Model	Signature	$\mathcal{L}_{int} (\text{fb}^{-1})$	Mass limit	Reference
Inclusive Searches	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2.8 jets $E_T^{miss} > 130$	1.9	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 1-2 jets $E_T^{miss} > 130$	0.31, 0.71, 1.15-1.98, 2.25	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	1 c.m. 2-6 jets $E_T^{miss} > 130$	Forbidden	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 7-11 jets $E_T^{miss} > 130$	1.2, 1.97	ATLAS-CDFP-2019-040
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	1.10, 1.25, 2.25	ATLAS-CDFP-2019-040
	0 c.m. 6 jets $E_T^{miss} > 130$	36.1	1.10, 1.25, 2.25	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	1.10, 1.25, 2.25	ATLAS-CDFP-2019-040
	0 c.m. 6 jets $E_T^{miss} > 130$	36.1	1.10, 1.25, 2.25	ATLAS-CDFP-2019-040
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	Multiple	36.1	Forbidden	ATLAS-CDFP-2019-040
	Multiple	139	Forbidden	ATLAS-CDFP-2019-040
	Multiple	139	0.74, 0.9, 0.13-0.90, 0.23-1.25	ATLAS-CDFP-2019-040
	Multiple	139	0.34-0.59, 1.25	ATLAS-CDFP-2019-040
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
	0 c.m. 2 jets $E_T^{miss} > 130$	36.1	0.36, 0.95, 1.15	ATLAS-CDFP-2019-040
EW modes	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.95	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.42	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.74, 1.0	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.16-0.21, 0.124-0.29	ATLAS-CDFP-2019-040
Long-lived particles	Direct $\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 1 jet $E_T^{miss} > 130$	0.15, 0.45	ATLAS-CDFP-2019-040
	Stable $\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	Multiple	2.0	ATLAS-CDFP-2019-040
	Metastable $\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	Multiple	2.00, 2.6	ATLAS-CDFP-2019-040
	Stable $\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	Multiple	2.0	ATLAS-CDFP-2019-040
RPV	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.82, 1.25, 1.9	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.82, 1.25, 1.9	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.82, 1.25, 1.9	ATLAS-CDFP-2019-040
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 c.m. 2 jets $E_T^{miss} > 130$	0.82, 1.25, 1.9	ATLAS-CDFP-2019-040

# LHC (ATLAS) SUSY Particle Searches

## ATLAS SUSY Searches\* - 95% CL Lower Limits July 2020

ATLAS Preliminary  
 $\sqrt{s} = 13$  TeV

Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$ ]	Mass limit	Reference		
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, $\mu$ mono-jet	$\tilde{q}$ [10x Degen.] $\tilde{q}$ [1x, 8x Degen.]	1.9 0.43 0.71	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV	ATLAS-CONF-2019-040 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, $\mu$ 2-6 jets	$\tilde{g}$	Forbidden 2.35 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{g}) = 1000$ GeV	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 e, $\mu$ 2-6 jets	$\tilde{g}$	2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	ee, $\mu\mu$ 2 jets	$\tilde{g}$	1.2	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 e, $\mu$ 7-11 jets	$\tilde{g}$	1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	ATLAS-CONF-2020-002
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS e, $\mu$ 6 jets	$\tilde{g}$	1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, $\mu$ SS e, $\mu$ 3 b 6 jets	$\tilde{g}$	2.25 1.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 1909.08457
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 / t\tilde{\chi}_1^+$	Multiple Multiple	$\tilde{b}_1$	Forbidden 0.9 Forbidden 0.74	$m(\tilde{\chi}_1^0) = 300$ GeV, $BR(b\tilde{\chi}_1^0) = 1$ $m(\tilde{\chi}_1^+) = 200$ GeV, $m(\tilde{\chi}_1^0) = 300$ GeV, $BR(t\tilde{\chi}_1^+) = 1$	1708.09266, 1711.03301 1909.08457
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$	0 e, $\mu$ 2 $\tau$ 2 b	$\tilde{b}_1$	Forbidden 0.23-1.35 0.13-0.85	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 e, $\mu$ $\geq 1$ jet	$\tilde{t}_1$	1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 e, $\mu$ 3 jets/1 b	$\tilde{t}_1$	0.44-0.59	$m(\tilde{\chi}_1^0) = 400$ GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$	1 $\tau + 1$ e, $\mu, \tau$ 2 jets/1 b	$\tilde{t}_1$	1.16	$m(\tilde{\tau}_1) = 800$ GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, $\mu$ 2 c	$\tilde{t}_1$	0.85	$m(\tilde{\chi}_1^0) = 0$ GeV	1805.01649
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 e, $\mu$ mono-jet	$\tilde{t}_1$	0.46 0.43	$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50$ GeV $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 1711.03301
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 e, $\mu$ 1-4 b	$\tilde{t}_1$	0.067-1.18	$m(\tilde{\chi}_2^0) = 500$ GeV	SUSY-2018-09	
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, $\mu$ 1 b	$\tilde{t}_2$	Forbidden 0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	SUSY-2018-09	
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via WZ	3 e, $\mu$ ee, $\mu\mu$ $\geq 1$ jet	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ $\tilde{\chi}_1^+/\tilde{\chi}_2^0$	0.64 0.205	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 5$ GeV	ATLAS-CONF-2020-015 1911.12606
	$\tilde{\chi}_1^+\tilde{\chi}_1^+$ via WW	2 e, $\mu$	$\tilde{\chi}_1^+$	0.42	$m(\tilde{\chi}_1^0) = 0$	1908.08215
	$\tilde{\chi}_1^+\tilde{\chi}_2^0$ via Wh	0-1 e, $\mu$ 2 b/2 $\gamma$	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$	Forbidden 0.74	$m(\tilde{\chi}_1^0) = 70$ GeV	2004.10894, 1909.09226
	$\tilde{\chi}_1^+\tilde{\chi}_1^+$ via $\tilde{\nu}_L/\tilde{\nu}$	2 e, $\mu$	$\tilde{\chi}_1^+$	1.0	$m(\tilde{\nu}_L, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$	$\tilde{\tau}$	0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, $\mu$ ee, $\mu\mu$ $\geq 1$ jet	$\tilde{\ell}$	0.7	$m(\tilde{\chi}_1^0) = 0$	1908.08215
	$\tilde{\ell}$	2 e, $\mu$ ee, $\mu\mu$ $\geq 1$ jet	$\tilde{\ell}$	0.256	$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	1911.12606
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, $\mu$ 4 e, $\mu$ $\geq 3$ b 0 jets	$\tilde{H}$	0.13-0.23 0.55	0.29-0.88 $BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $BR(\tilde{\chi}_1^+ \rightarrow Z\tilde{G}) = 1$	1806.04030 ATLAS-CONF-2020-040	
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk 1 jet	$\tilde{\chi}_1^+$	0.46 0.15	Pure Wino Pure higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	Multiple	$\tilde{g}$	2.0	$m(\tilde{\chi}_1^0) = 100$ GeV	1902.01636, 1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple	$\tilde{g}$	[ $\tau(\tilde{g}) = 10$ ns, 0.2 ns] 2.05 2.4	$m(\tilde{\chi}_1^0) = 100$ GeV	1710.04901, 1808.04095
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, $\mu$	$\tilde{\chi}_1^+/\tilde{\chi}_1^0$ [BR(Z $\tau$ )=1, BR(Ze)=1]	0.625 1.05	Pure Wino	ATLAS-CONF-2020-009
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	e $\mu$ , e $\tau$ , $\mu\tau$	$\tilde{\nu}_\tau$	1.9	$\lambda'_{311} = 0.11, \lambda'_{132}/\lambda'_{133}/\lambda'_{233} = 0.07$	1607.08079
	$\tilde{\chi}_1^+\tilde{\chi}_1^+/\tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 e, $\mu$ 0 jets	$\tilde{\chi}_1^+/\tilde{\chi}_2^0$ [ $\lambda'_{133} \neq 0, \lambda'_{124} \neq 0$ ]	0.82 1.33	$m(\tilde{\chi}_1^0) = 100$ GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}\tilde{\chi}_1^0$	4-5 large-R jets Multiple	$\tilde{g}$ [ $m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV] $\tilde{g}$ [ $\lambda'_{112} = 2e-4, 2e-5$ ]	1.05 1.3 1.9 1.05 2.0	Large $\lambda'_{112}$ $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
	$\tilde{u}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple	$\tilde{t}$ [ $\lambda'_{323} = 2e-4, 1e-2$ ]	0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow bbs$	$\geq 4$ b	$\tilde{t}$	Forbidden 0.95	$m(\tilde{\chi}_1^+) = 500$ GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 jets + 2 b	$\tilde{t}_1$ [qq, bs]	0.42 0.61		1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{\ell}$	2 e, $\mu$ 1 $\mu$ DV	$\tilde{t}_1$	1.0 0.4-1.45 1.6	$BR(\tilde{t}_1 \rightarrow b\tilde{\ell}/b\tilde{\nu}) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\tilde{\mu}) = 100\%, \cos\theta = 1$	1710.05544 2003.11956	



\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

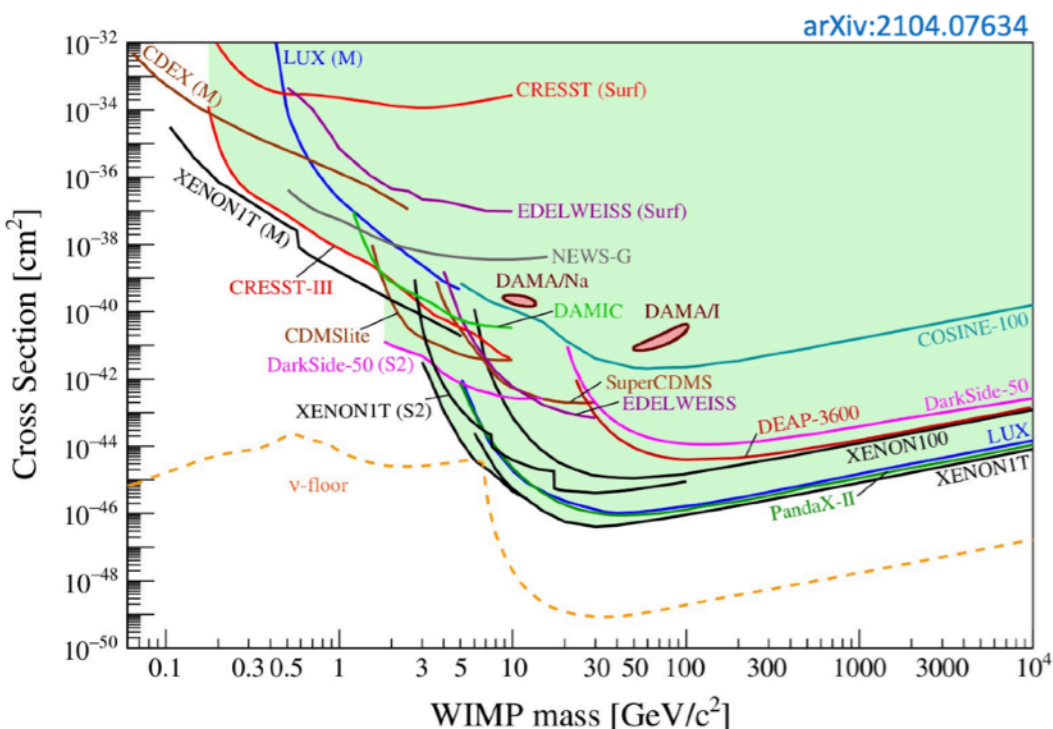
WIMP mass [GeV/c<sup>2</sup>]

Mass scale [TeV]

# WIMPs

(Thanks to Dan Hooper, Fermilab)

- The thermal relic abundance calculation provides us with a collection of well-motivated benchmark models and experimental targets
  - Many of the most attractive WIMP candidates were expected to fall within the reach of planned direct detection and accelerator experiments
  - We have covered 6 orders of magnitude in sensitivity – and yet no WIMPs have appeared
  - The LHC has increase energy and intensity, and yet no compelling signs of dark matter (or other Beyond SM physics) have been discovered



ATLAS SUSY Searches\* - 95% CL Lower Limits  
July 2020

ATLAS Preliminary  
 $\sqrt{s} = 13$  TeV

Model	Signature	$\mathcal{L} \cdot dt$ ( $\text{fb}^{-1}$ )	Mass limit	Reference	
Inclusive Searches	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*$	0 $e, \mu$ 2-6 jets $E_{T}^{\text{miss}}$	139	$\tilde{g}$ [15k Deger]	$m(\tilde{g}) < 400$ GeV
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	mono-jet	1-3 jets $E_{T}^{\text{miss}}$	$\tilde{g}$ [15k, 30k Deger]	$m(\tilde{g}) < 150$ GeV
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	0 $e, \mu$ 2-6 jets $E_{T}^{\text{miss}}$	139	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	1 $e, \mu$ 2-6 jets $E_{T}^{\text{miss}}$	139	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	0 $e, \mu$ 2 jets $E_{T}^{\text{miss}}$	36.1	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	0 $e, \mu$ 7-11 jets $E_{T}^{\text{miss}}$	139	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	SS $e, \mu$ 6 jets $E_{T}^{\text{miss}}$	139	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	0 $e, \mu$ 3 b $E_{T}^{\text{miss}}$	79.8	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	SS $e, \mu$ 6 jets $E_{T}^{\text{miss}}$	139	$\tilde{g}$	Forbidden
	$\tilde{g}\tilde{g} \rightarrow \gamma\tilde{g}^*\tilde{g}^*$	Multiple	36.1	$\tilde{g}$	Forbidden
1 <sup>st</sup> spin, s-wave annihilation	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	0 $e, \mu$ 6 b $E_{T}^{\text{miss}}$	139	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	2 $\tau$	2 b $E_{T}^{\text{miss}}$	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	0 $e, \mu$ $\geq 1$ jet $E_{T}^{\text{miss}}$	139	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	1 $e, \mu$ 3 jets/1 b $E_{T}^{\text{miss}}$	139	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	1 $\tau + 1 e, \mu, \tau$ 2 jets/1 b $E_{T}^{\text{miss}}$	36.1	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	0 $e, \mu$ 2 c $E_{T}^{\text{miss}}$	36.1	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	0 $e, \mu$ mono-jet $E_{T}^{\text{miss}}$	36.1	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	1-2 $e, \mu$ 1-4 b $E_{T}^{\text{miss}}$	139	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	3 $e, \mu$ 1 b $E_{T}^{\text{miss}}$	139	$\tilde{b}_1$	Forbidden
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}_1^*\tilde{g}^*$	Multiple	36.1	$\tilde{b}_1$	Forbidden
EW direct	$\tilde{t}\tilde{t}^*$ via WZ	3 $e, \mu$ $\geq 1$ jet $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via WW	2 $e, \mu$ $\geq 1$ jet $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via Wb	0-1 $e, \mu$ 2 b/2 $\gamma$ $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_1^*$	2 $e, \mu$ $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_2\tilde{t}_2^*$	2 $\tau$ $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	0 jets $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	0 $e, \mu$ $\geq 1$ jet $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	4 $e, \mu$ 0 jets $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	0 $e, \mu$ $\geq 3$ b $E_{T}^{\text{miss}}$	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	0 jets $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
Long-lived particles	Direct $\tilde{t}\tilde{t}^*$ prod. long-lived $\tilde{t}_1^*$	Disapp. trk	1 jet $E_{T}^{\text{miss}}$	$\tilde{t}_1^*$	Forbidden
	Stable $\tilde{t}$ R-hadron	Multiple	36.1	$\tilde{t}$	Forbidden
	Metastable $\tilde{t}$ R-hadron, $\tilde{t} \rightarrow \gamma\tilde{t}_1^*$	Multiple	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}_1^*\tilde{t}_1^*$ via WZ	3 $e, \mu$ $\geq 1$ jet $E_{T}^{\text{miss}}$	139	$\tilde{t}_1^*$	Forbidden
	LFV $\tilde{t}_1^*\tilde{t}_1^* \rightarrow X, Y, \nu\mu, \nu\tau, \nu e$	0 jets $E_{T}^{\text{miss}}$	36.1	$\tilde{t}_1^*$	Forbidden
	$\tilde{t}_1^*\tilde{t}_1^*$ via WW	4 $e, \mu$ 0 jets $E_{T}^{\text{miss}}$	36.1	$\tilde{t}_1^*$	Forbidden
	$\tilde{t}_1^*\tilde{t}_1^*$ via Wb	4-5 large # jets $E_{T}^{\text{miss}}$	36.1	$\tilde{t}_1^*$	Forbidden
	$\tilde{t}_1^*\tilde{t}_1^*$ via $\tilde{t}_1\tilde{t}_1^*$	Multiple	36.1	$\tilde{t}_1^*$	Forbidden
	$\tilde{t}_1^*\tilde{t}_1^*$ via $\tilde{t}_2\tilde{t}_2^*$	Multiple	36.1	$\tilde{t}_1^*$	Forbidden
	$\tilde{t}_1^*\tilde{t}_1^*$ via $\tilde{t}_1\tilde{t}_2^*$	$\geq 4b$ $E_{T}^{\text{miss}}$	139	$\tilde{t}_1^*$	Forbidden
RPV	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_1^*$	Multiple	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	$\geq 4b$ $E_{T}^{\text{miss}}$	139	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	2 jets + 2 b $E_{T}^{\text{miss}}$	36.7	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	2 jets + 2 b $E_{T}^{\text{miss}}$	36.7	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	1 $\mu$ DV $E_{T}^{\text{miss}}$	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	2 $e, \mu$ DV $E_{T}^{\text{miss}}$	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	1 $\mu$ DV $E_{T}^{\text{miss}}$	136	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	Multiple	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	Multiple	36.1	$\tilde{t}$	Forbidden
	$\tilde{t}\tilde{t}^*$ via $\tilde{t}_1\tilde{t}_2^*$	Multiple	36.1	$\tilde{t}$	Forbidden

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



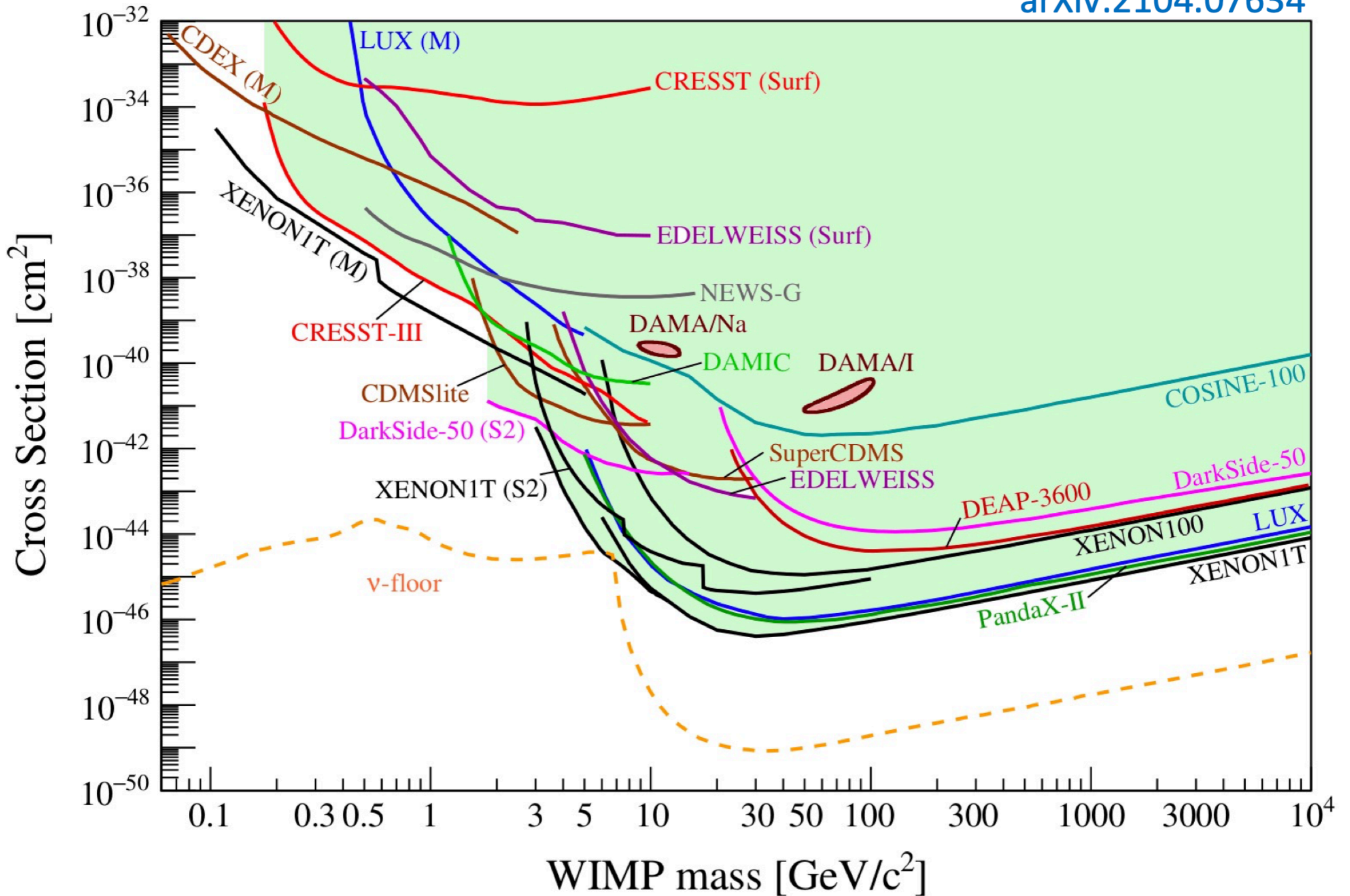
- 
- In order to Reconcile Dark Matter With Current Constraints from Cosmology, Astrophysics, Accelerator and Direct Detection.

What do WIMP models look like?

- Need to ensure normal rate of annihilation in the early universe, UNSUPPRESSED, but the scattering probability on nucleons is SUPPRESSED.

- For example:

- Co-annihilations with another particle in dominates the direct  $\chi\chi$  annihilation in early universe.
- Annihilations to  $W/Z$  and/or Higgs bosons; but then scattering with nuclei occur through highly suppressed loop diagrams
  - wino-like and higgsino-like neutrinos...they have predicted c-s around those about to be probed
- Scattering cross sections contain powers of velocity (or momentum)
- Many models with  $m_\chi < 1$  GeV (not the classic WIMP) but  $> 3$  MeV (BBN)
  - Requires new types of detector with light nuclear targets and very low thresholds



Dar

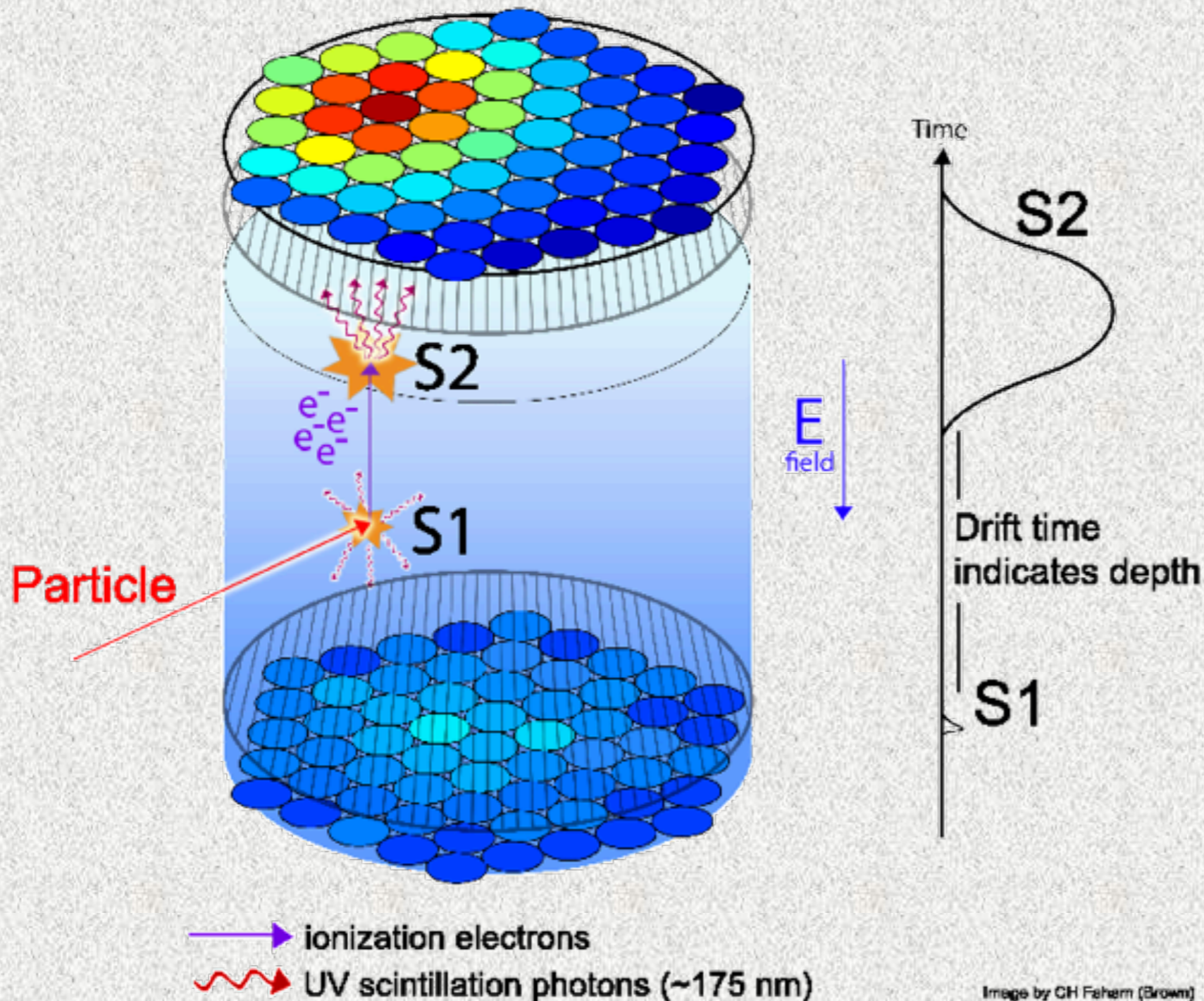
TeV

XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioko
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction/Run	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/Run	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Planning	2028	2033	LNGS/SURF/Boulby
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Planning/Construct	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	NaI	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	NaI	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	NaI	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	NaI	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	NaI	?		Planning	2023	?	LNGS
SABRE PoP	Scintillator	NaI	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	NaI	50 kg		Planning	2022	2027	LNGS
SABRE (South)	Scintillator	NaI	50 kg		Planning	2022	2027	SUPL
CDEX-10	Ionization (77K)	Ge	10 kg	103 kg d	Running	2016	?	CJPL
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg		Planning	202X		CJPL
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSlite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	Surface Lab
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Running	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g	80 g d	Running	2019		LSM
CRESST-II	Bolometer Scintillator	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillator	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillator	CaWO4			Running	2020		LNGS
PICO-2	Bubble Chamber	C3F8	2 kg		Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber	C3F8	35 kg		Running	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I,C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction/Run	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
CYGNUS???								
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction/Run	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction/Run	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction/Run	2021	2023	SNOLAB

# Dark Matter Direct Detection MeV - TeV

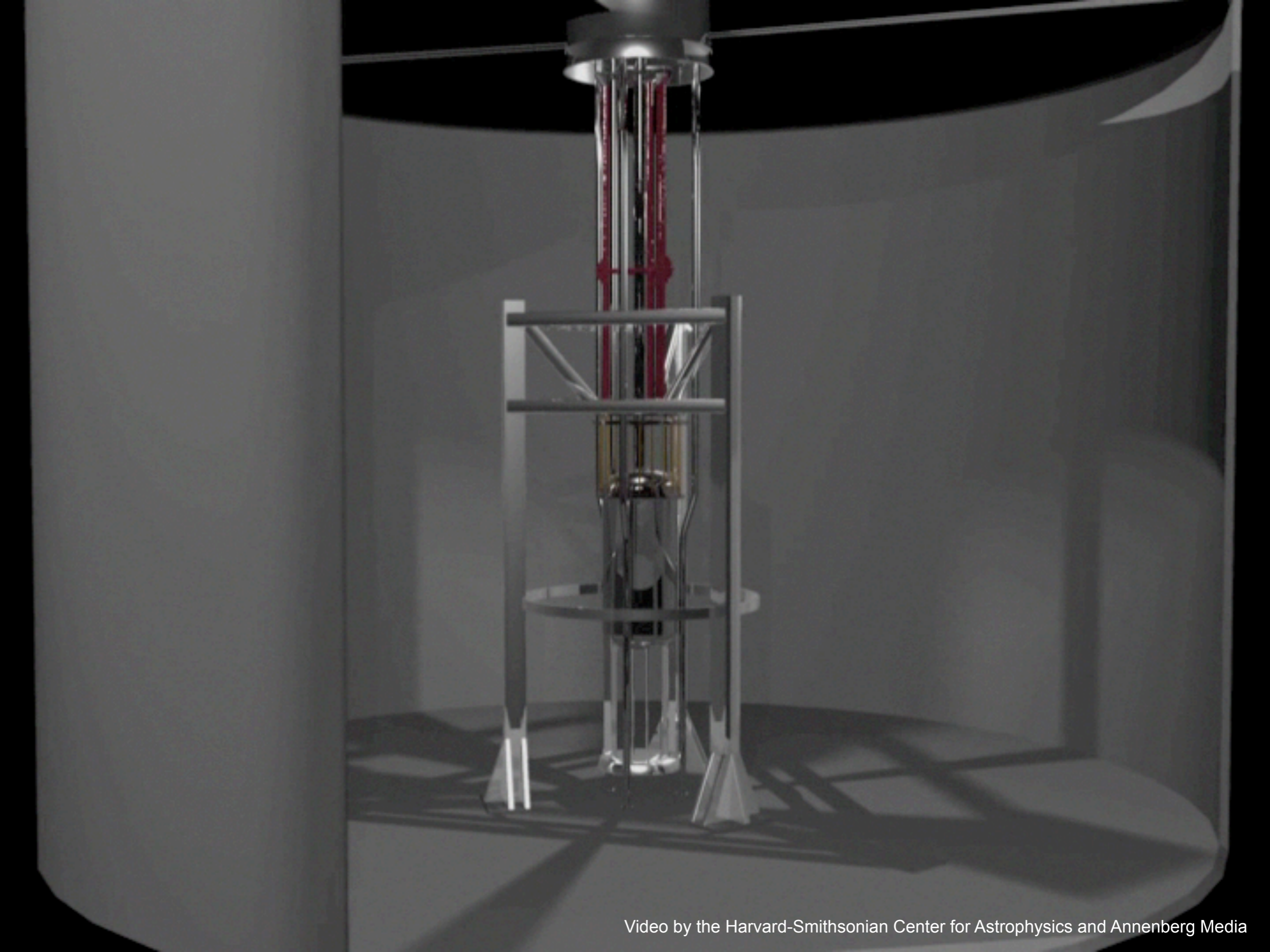
Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioke
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction/Run	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/Run	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Planning	2028	2033	LNGS/SURF/E
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Planning/Construct	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	Nal	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	Nal	112 kg	Goal 5 years	Running	2017	2022	Canfranc

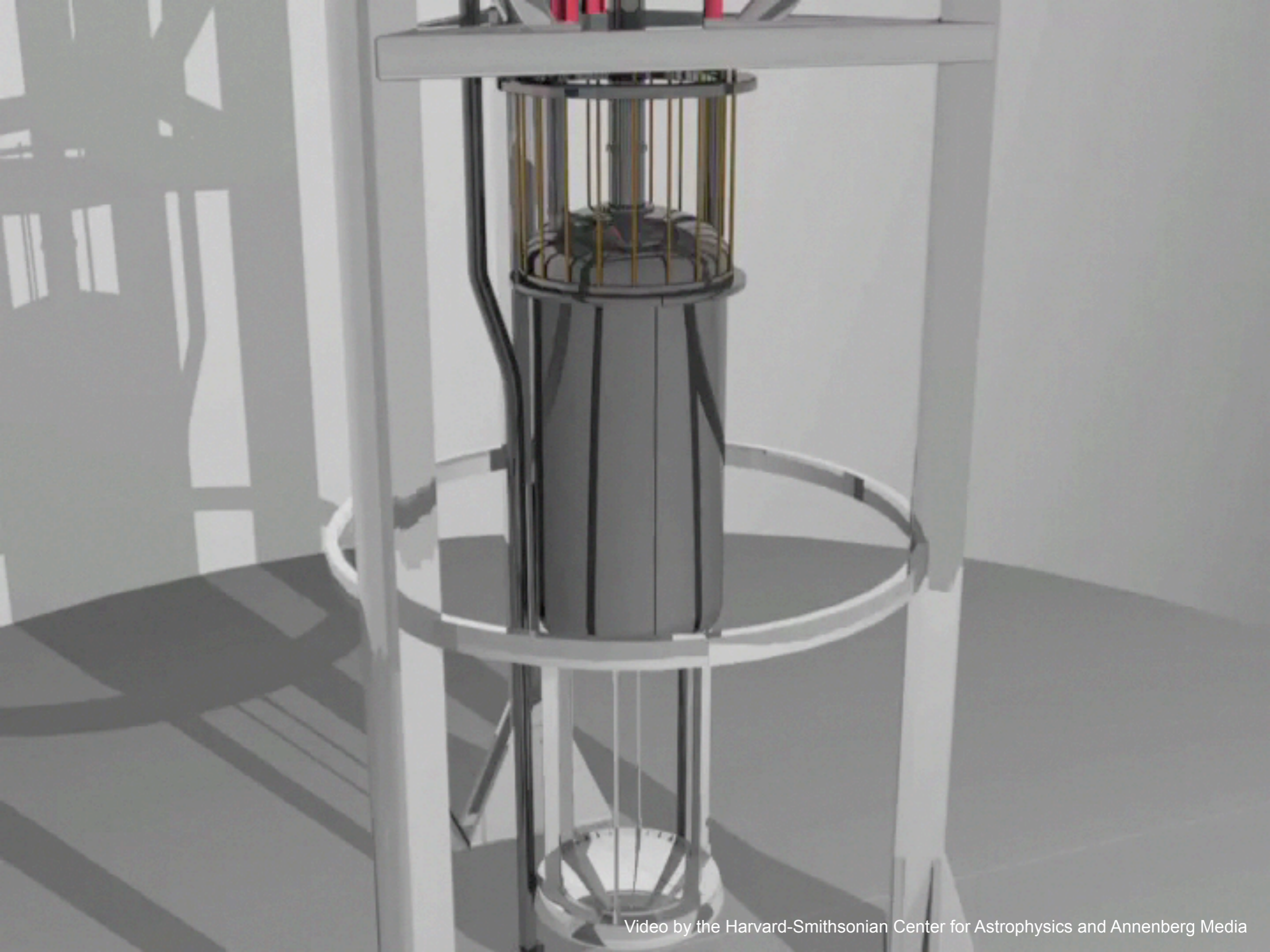
# Principle of WIMP detection in LXe TPC



- Liquid xenon time projection chamber – LXe TPC.
- S1 – primary scintillation.
- S2 – secondary scintillation, proportional to ionisation.
- Position reconstruction based on the light pattern in the PMTs and delay between S2 and S1.

Image by CH Faham (Brown)





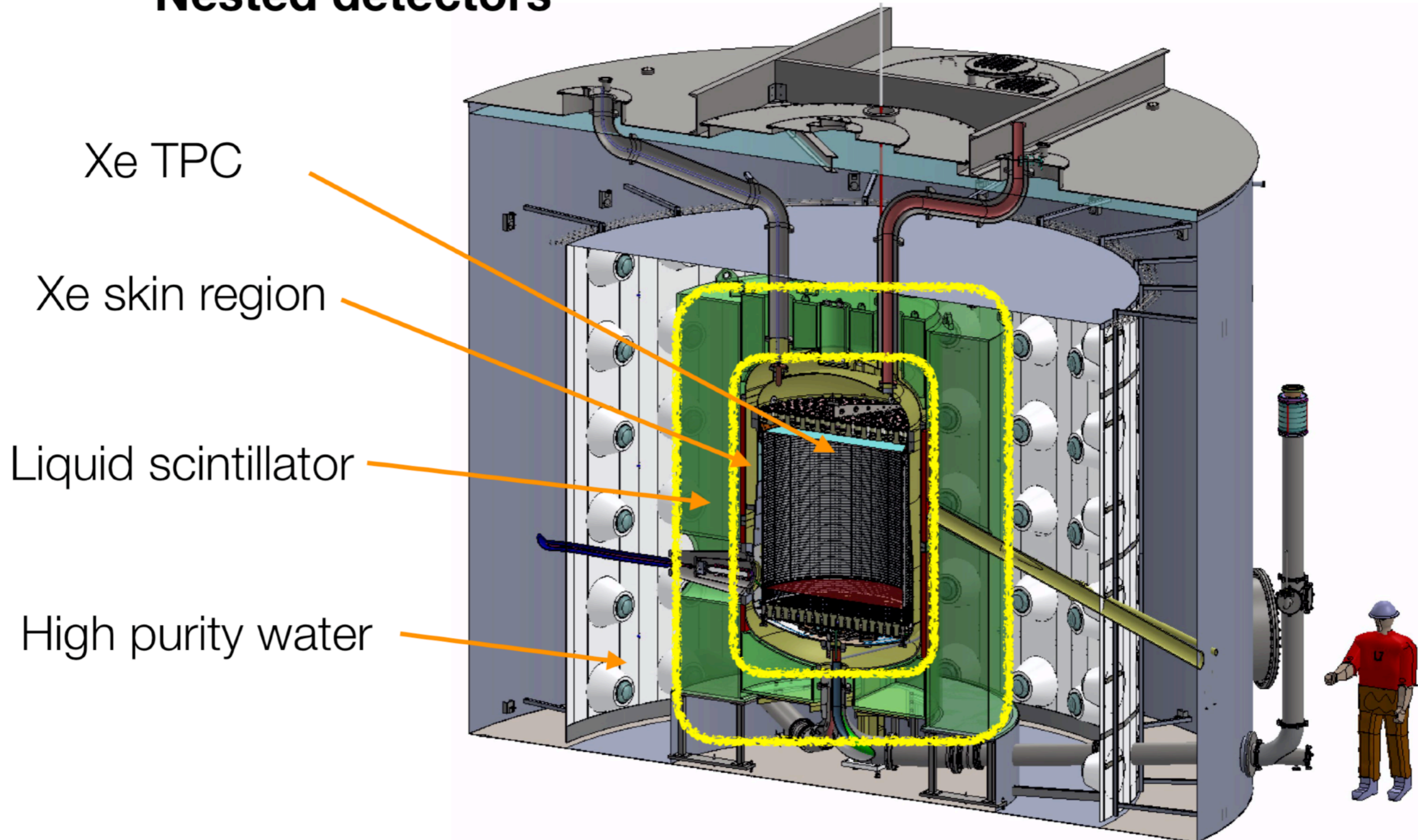


# LUX-ZEPLIN @ Sanford Lab

## (Full Operations Start in 2021)

LZ TDR [arXiv:1703.09144](https://arxiv.org/abs/1703.09144)

### Nested detectors



Xe TPC

Xe skin region

Liquid scintillator

High purity water



# How have we spent the last few years at Brown?

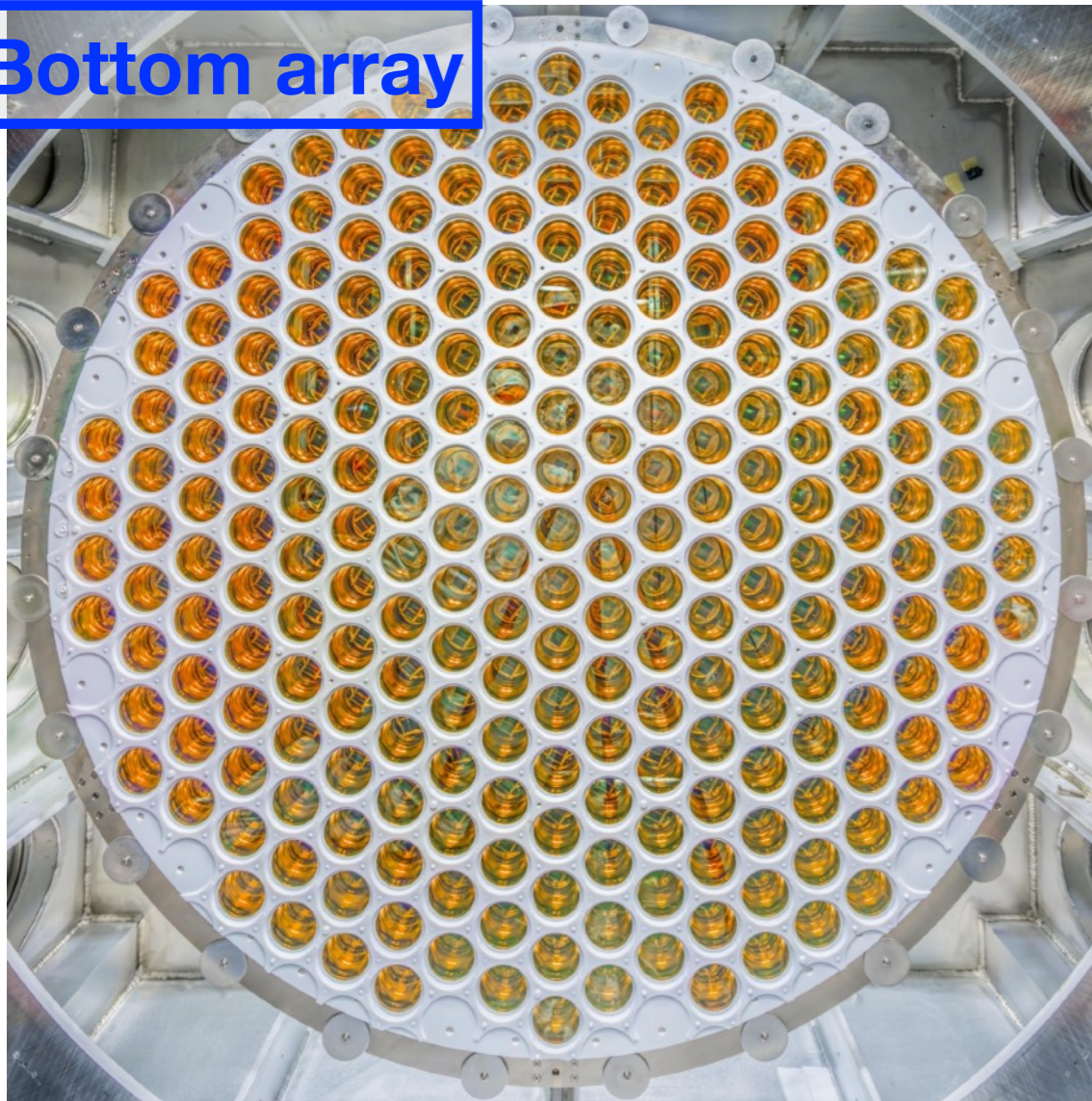
Construction of the Central PMT Arrays for LZ at Brown University  
Cleanrooms --> Installation at Sanford Lab, SD



# TPC: PMT arrays

253 (top) + 241 (bottom)  
3" Hamamatsu R11410-22  
PMTs

Bottom array



Top array

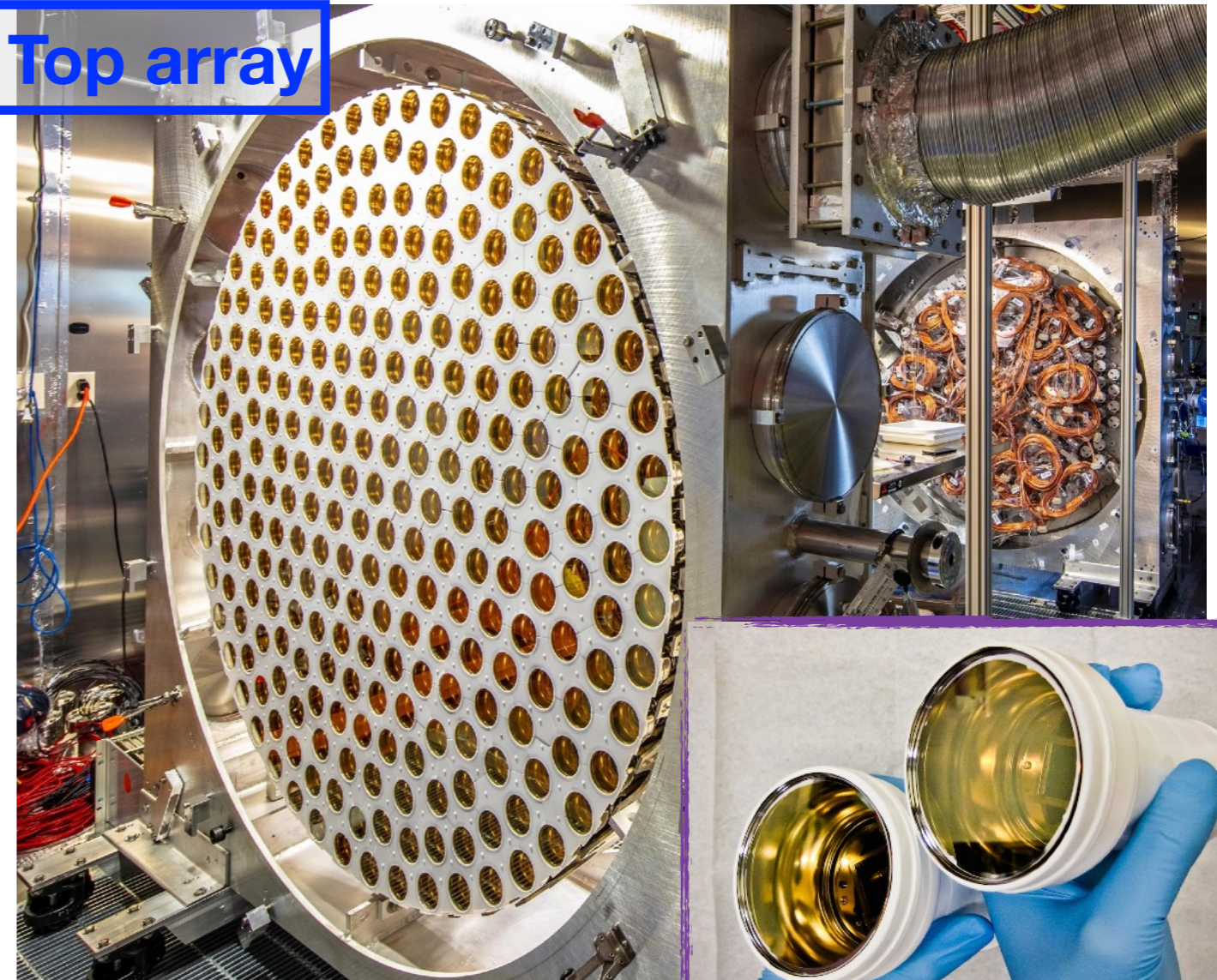
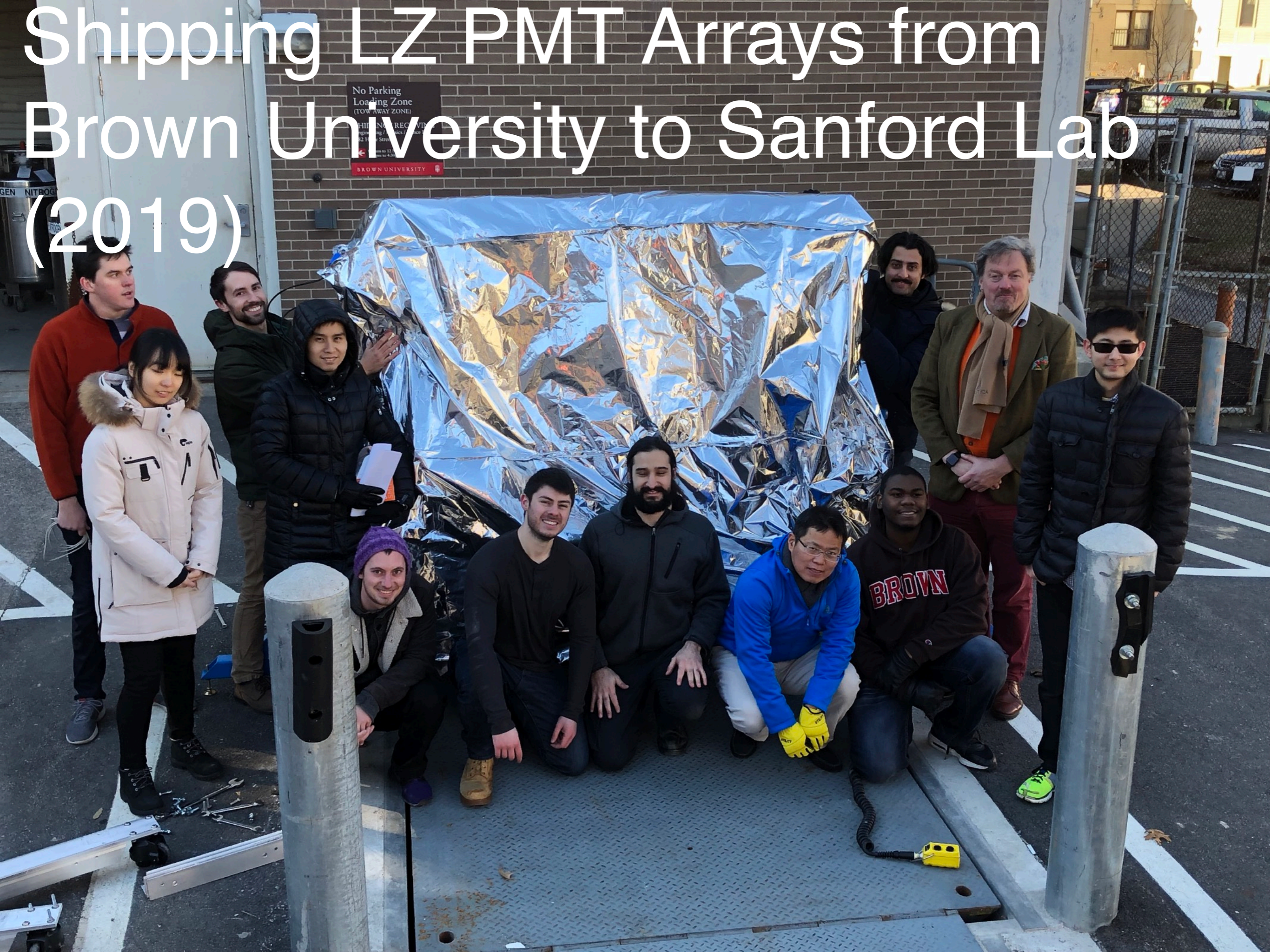


Photo credit: Matt Kapust, SDSTA

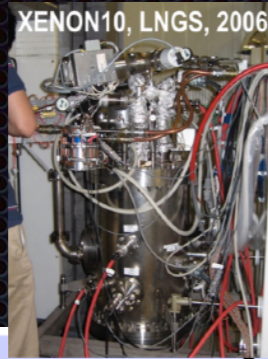
# Shipping LZ PMT Arrays from Brown University to Sanford Lab (2019)



# Genealogy

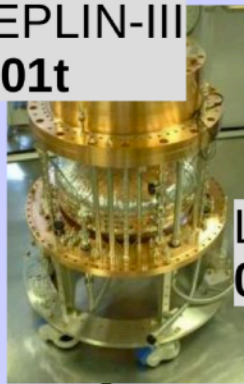
# of The Noble Target Field

(ZEPLIN I + II)



XENON10, LNGS, 2006

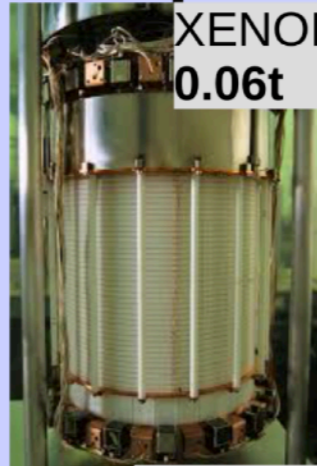
ZEPLIN-III  
0.01t



LUX  
0.25t



XENON100  
0.06t



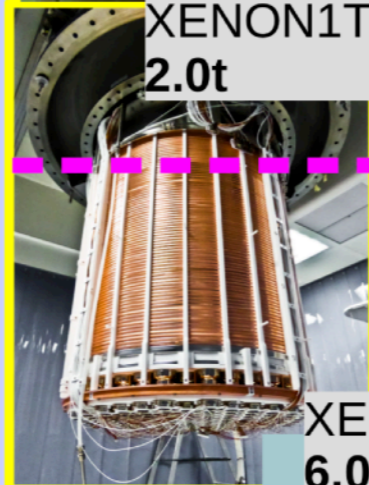
XMASS  
0.8t



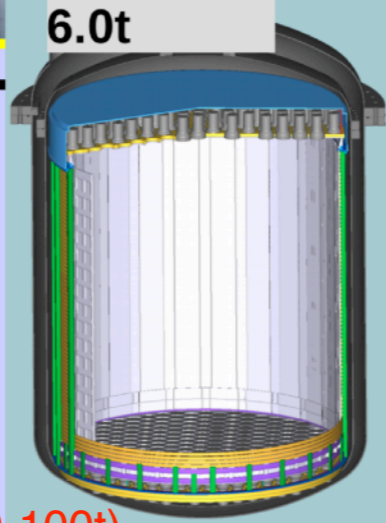
PandaX-II  
0.5t



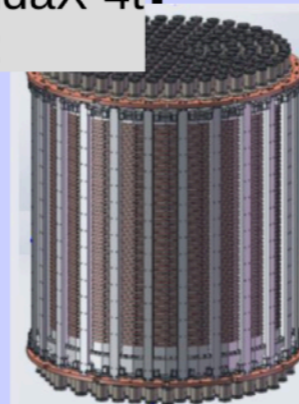
XENON1T  
2.0t



XENONnT  
6.0t

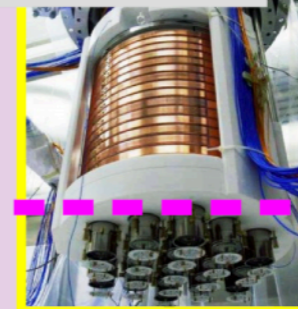


PandaX-4t  
4.0t

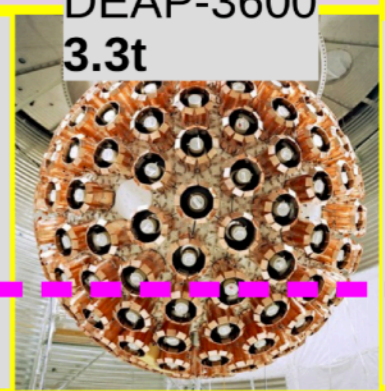


LAr

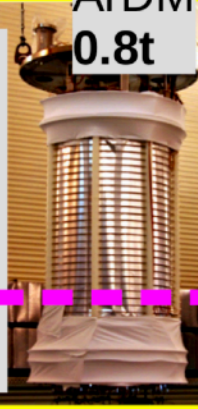
DarkSide-50  
0.04t



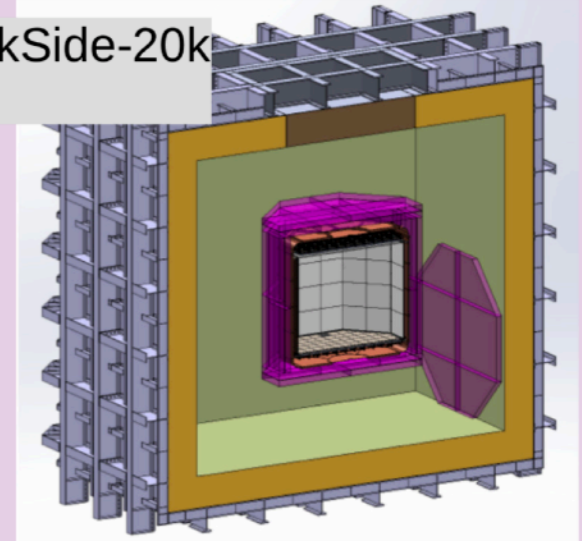
DEAP-3600  
3.3t



ArDM  
0.8t



DarkSide-20k  
30t

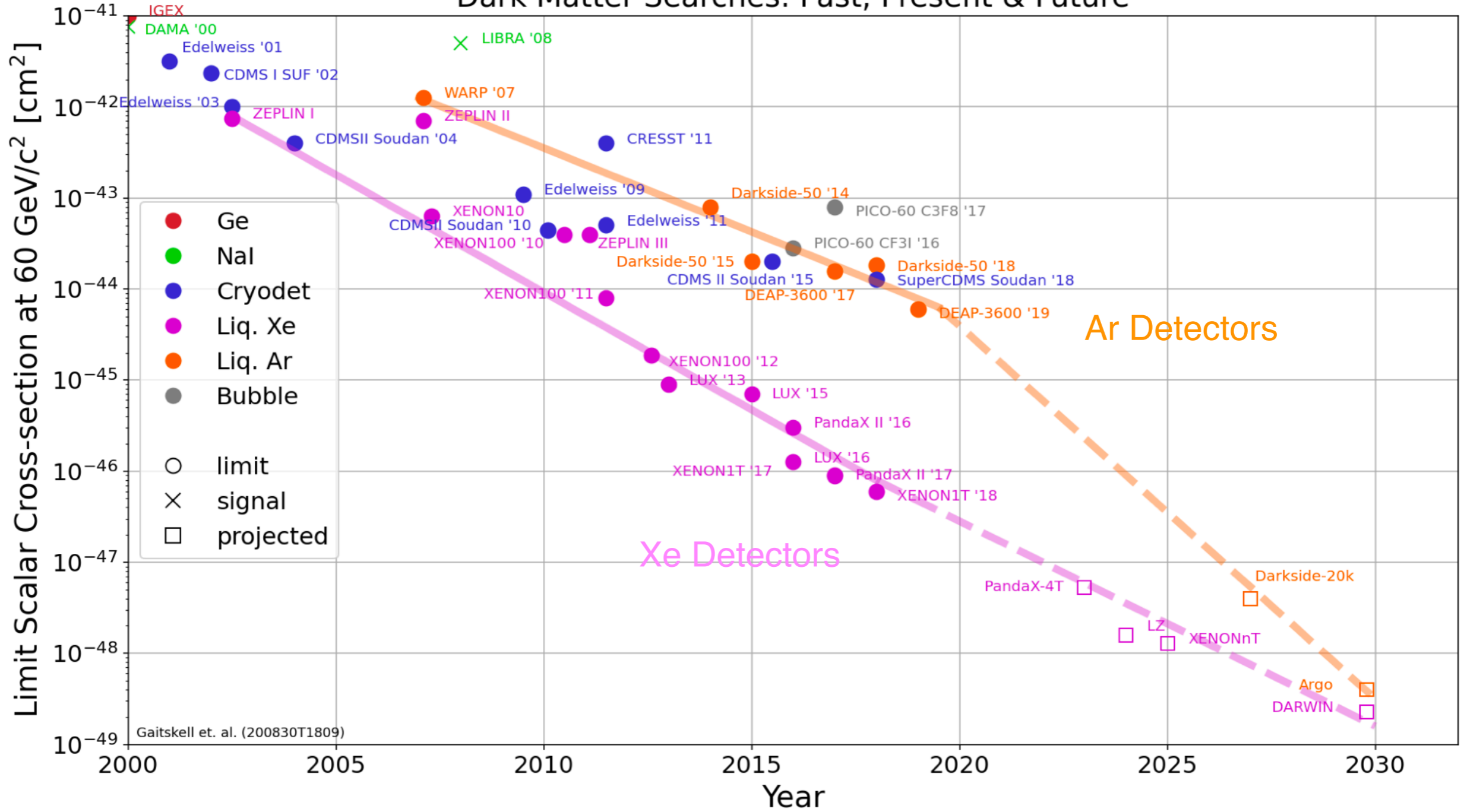


(followed by DARWIN 50-100t)

thanks to M. Schumann (Freiburg)

now

# Dark Matter Searches: Past, Present & Future



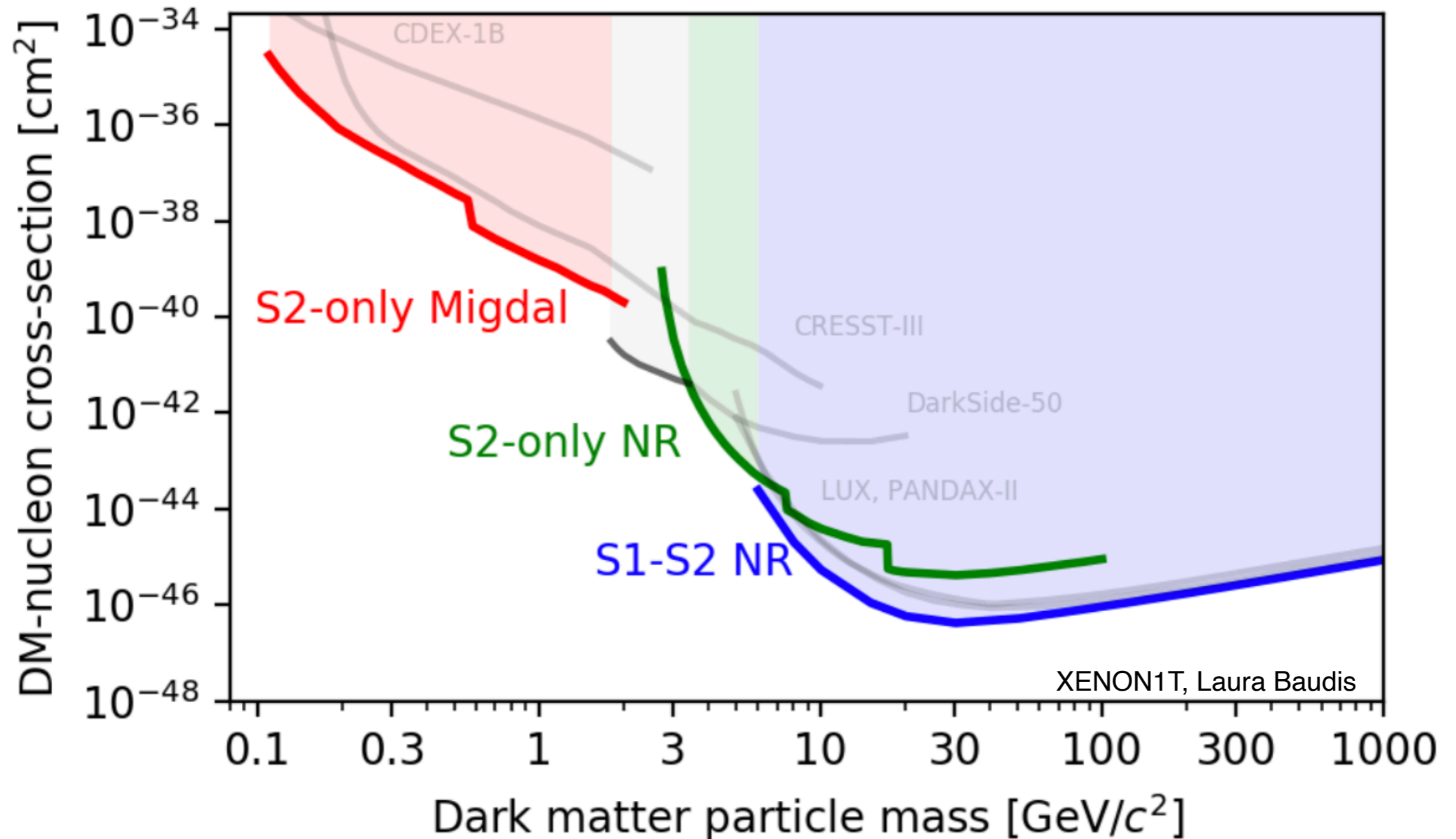
Gaitskell et. al. (200830T1809)

Ar Detectors

Xe Detectors

# LXe TPC's Improving Sensitivity on Multiple Fronts

## Dark matter nucleus scattering



# XENON1T (slightly more sensitive than latest Panda-X II and LUX results)

**XENON1T TPC**

**Xe**  
XENON  
Dark Matter Project

Particle detector with

- low background,**  $< 100 \text{ events}/(\text{t}\cdot\text{y}\cdot\text{keV}_{\text{ee}})$
- low threshold,**  $\sim 1 \text{ keV}_{\text{ee}}$  ( $5 \text{ keV}_{\text{nr}}$ )
- large exposure**  $\sim 1 \text{ t}\cdot\text{y}$

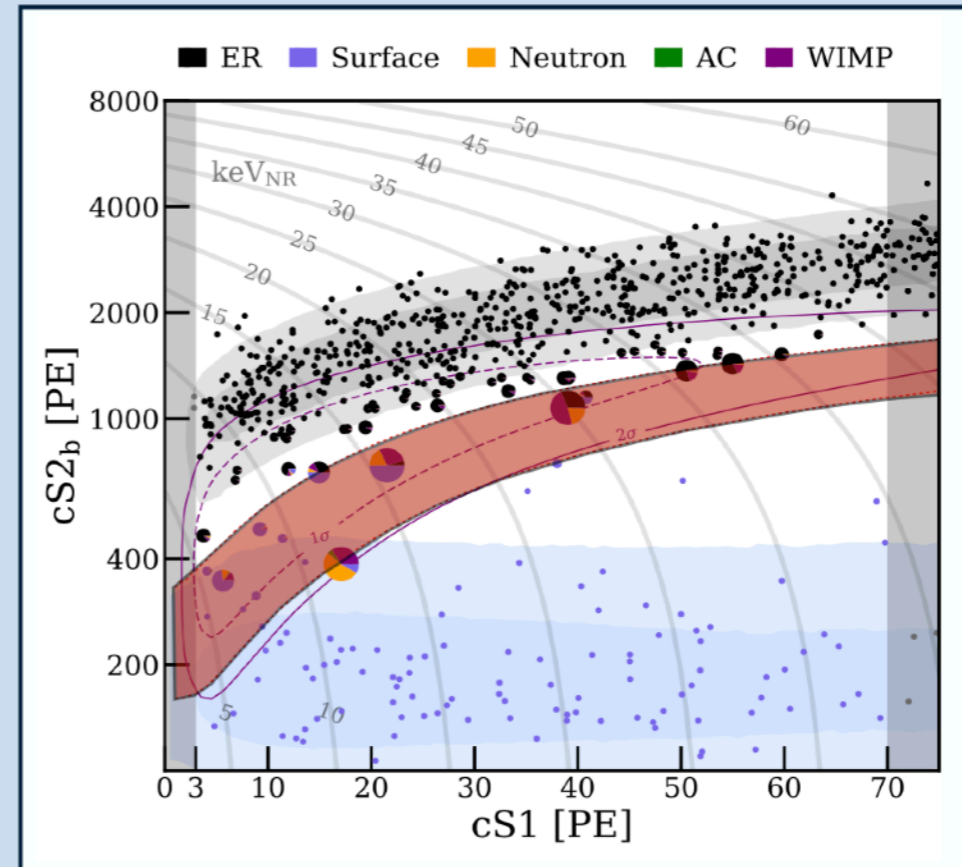
Particle ID

- Electronic Recoil (ER)
- Nuclear Recoil (NR)

Energy + 3D Position Reconstruction

E. Shockley for XENON | LNGS Webinar | 17 June 2020

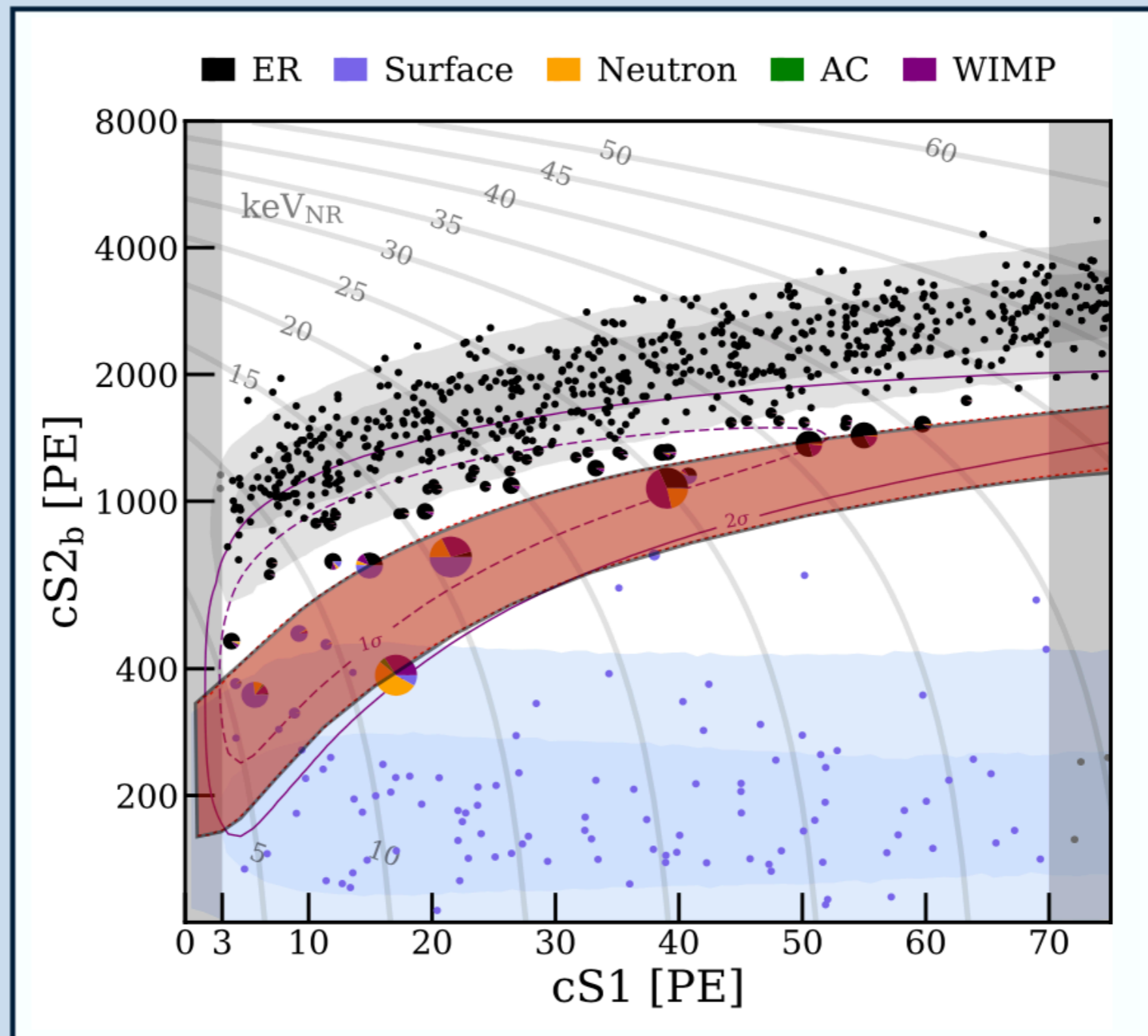
## NR searches...



**Most stringent result on WIMP Dark Matter down to  $3 \text{ GeV}/c^2$  masses [PRL 121, 111302 + PRL 123, 251801]**

XENON1T (slightly more sensitive than latest Panda-X II and LUX results)

# NR searches...



(ee)



# Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioke
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction/Run	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/Run	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Planning	2028	2033	LNGS/SURF
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Planning/Construct	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	NaI	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc

# Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	40,000 kg	200 t yr	Planning	2028	2033	LNGS / SURF
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Construction	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	NaI	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100						2016	2021	YangYang
COSINE-200						2022	2025	YangYang
COSINE-200 South Pole	Scintillator	NaI	200 kg		Planning	2023	?	South Pole

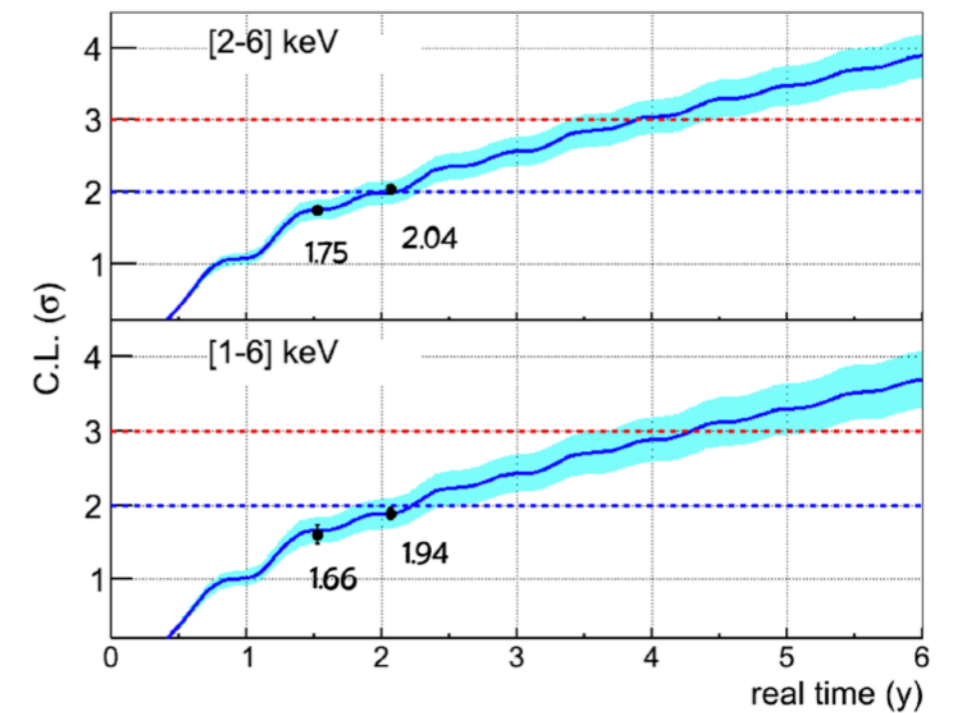
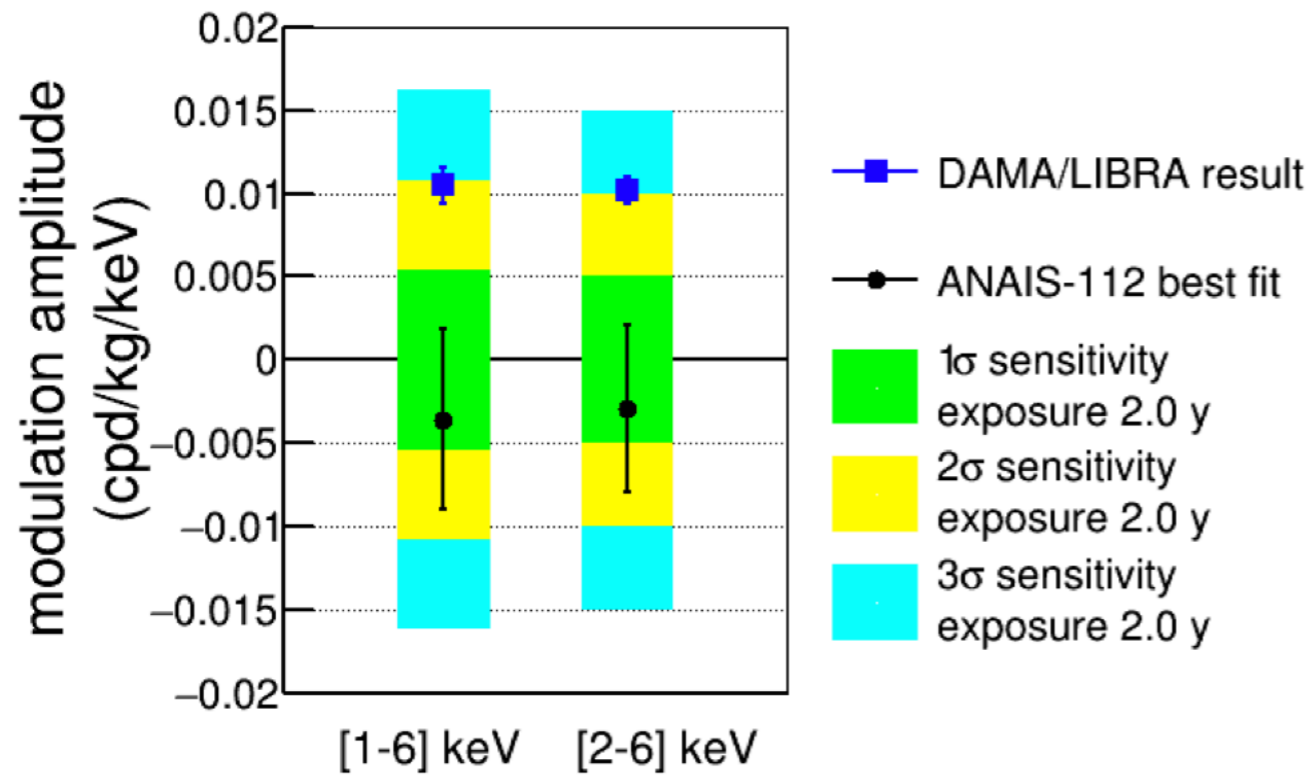
**Future Experiments with Noble Liquid**

# Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
DAMA/LIBRA	Scintillator	Nal	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	Nal	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	Nal	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	Nal	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	Nal	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	Nal	?		Planning	2023	?	LNGS
SABRE PoP	Scintillator	Nal	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	Nal	50 kg		Planning	2022	2027	LNGS
SABRE (South)	Scintillator	Nal	50 kg		Planning	2022	2027	SUPL
CDEX-10	Ionization (77K)	Ge	10 kg	103 kg d	Running	2016	?	CJPL
CDEX-100 / 1T	Ionization	Ge			Planning	202X		CJPL
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	SNOLAB
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Construction	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g		Running	2019		LSM
CRESST-II	Bolometer Scintillation	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillation	CaWO4	240 g		Ended	2016	2018	LNGS

Modulation of DM Signals

# • ANAIS 100 kg NaI



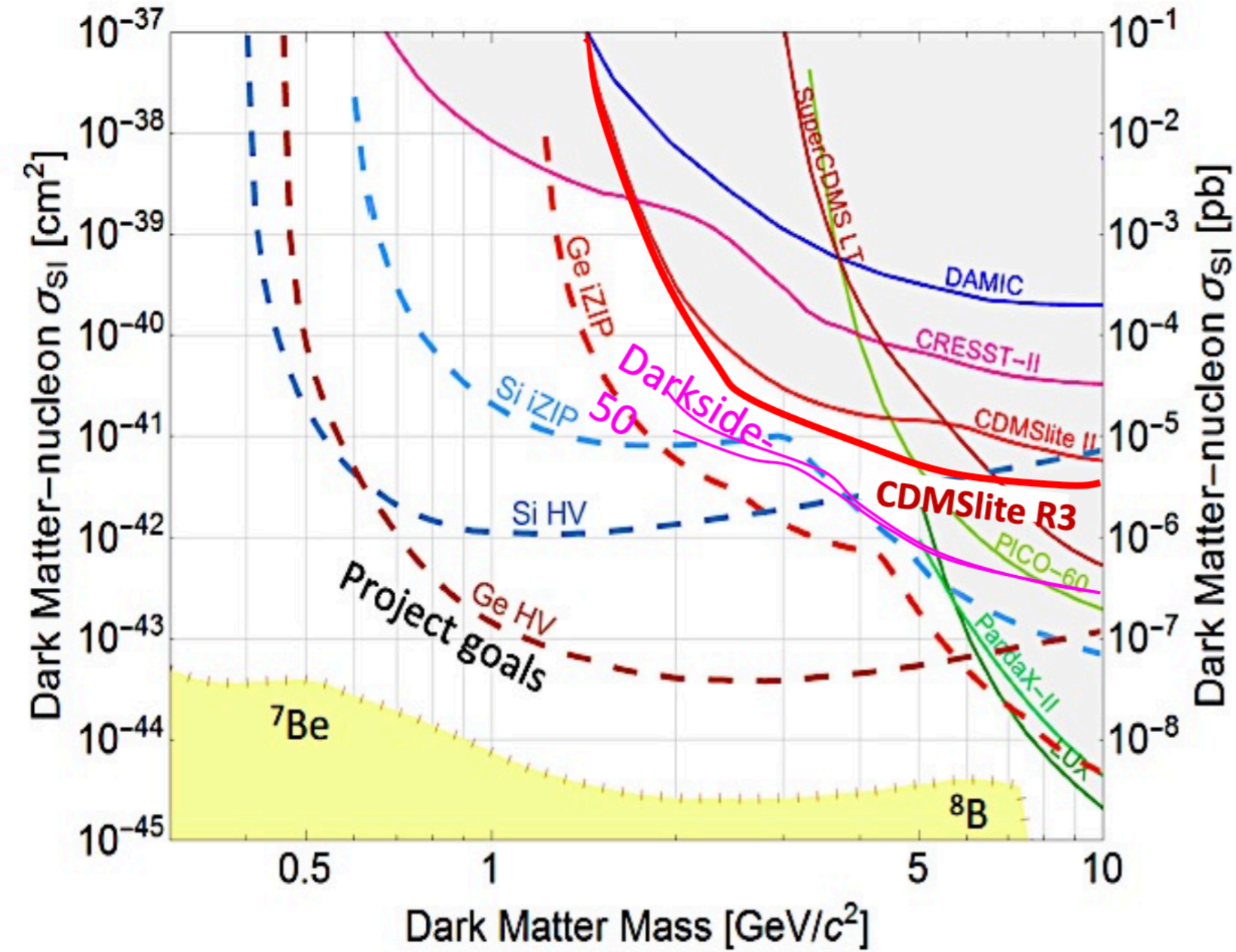
<https://arxiv.org/pdf/1910.13365.pdf>

# Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	SNOLAB
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Construction	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g		Running	2019		LSM
CRESST-II	Bolometer Scintillation	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillation	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4			Running	2020		LNGS
PICO-2	Bubble Chamber				Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber				Construction	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I, C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB

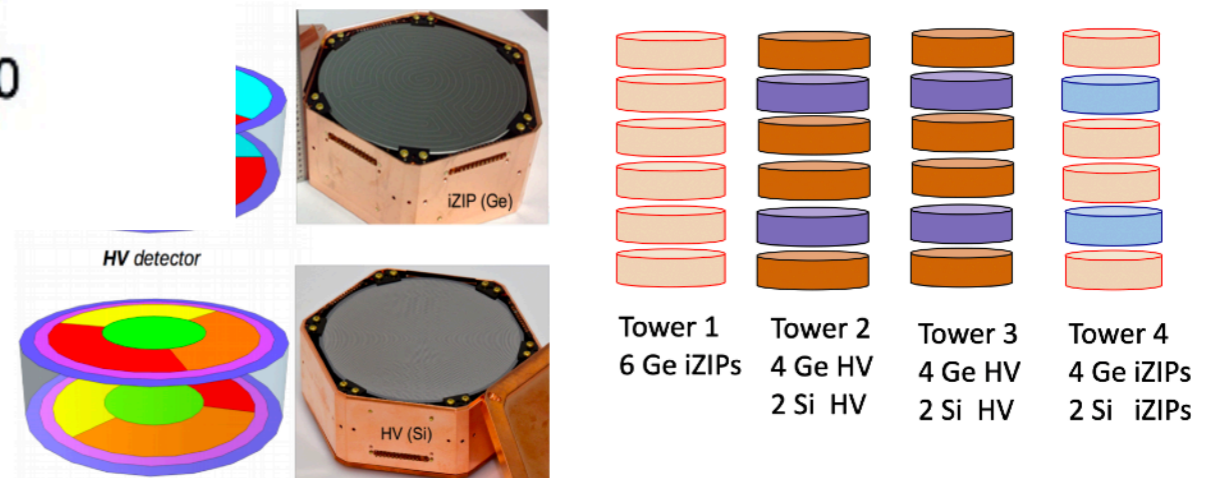
Future Cryogenic Detectors

# SuperCDMS @ SNOLAB



of Detectors

Initial 4-tower payload



Prisca Cushman, SuperCDMS, UMinn / Nigel Smith, SNOLAB

# Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
PICO-2	Bubble Chamber	C3F8	2 kg		Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber	C3F8	35 kg		Running	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I,C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction/Run	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
CYGNUS???								
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction/Run	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction/Run	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction/Run	2021	2023	SNOLAB
ALETHEIA	TPC	He			R&D			China Inst. At. E
TESSERACT	Cryo TES	He			R&D			LBNL

# Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction	2021	2023	SNOLAB



Dark

/ - TeV

XMASS	Scintillator	LXe	832 kg		Ended	2010	2019	Kamioke
XENON100	TPC	LXe	62 kg		Ended	2012	2016	LNGS
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction/Run	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/Run	2021	2025	CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&D	2026		SURF
Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Planning	2028	2033	LNGS/SURF/Boulby
DEAP-3600	Scintillator	LAr	3,300 kg		Running	2016	202X	SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	Planning/Construct	2025	2030	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Planning	2030	2035	SNOLAB
DAMA/LIBRA	Scintillator	Nal	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	Nal	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	Nal	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	Nal	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	Nal	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	Nal	?		Planning	2023	?	LNGS
SABRE PoP	Scintillator	Nal	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	Nal	50 kg		Planning	2022	2027	LNGS
SABRE (South)	Scintillator	Nal	50 kg		Planning	2022	2027	SUPL
CDEX-10	Ionization (77K)	Ge	10 kg	103 kg d	Running	2016	?	CJPL
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg		Planning	202X		CJPL
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
CDMSlite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 kg d	Ended	2012	2015	Soudan
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	0.5 g d	Ended	2018	2018	Surface Lab
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Running	2020	2022	SNOLAB
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
EDELWEISS III	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g	80 g d	Running	2019		LSM
CRESST-II	Bolometer Scintillator	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillator	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillator	CaWO4			Running	2020		LNGS
PICO-2	Bubble Chamber	C3F8	2 kg		Ended	2013	2015	SNOLAB
PICO-40	Bubble Chamber	C3F8	35 kg		Running	2020		SNOLAB
PICO-60	Bubble Chamber	CF3I,C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction/Run	2021		SNOLAB
DRIFT-II	Gas Directional	CF4	0.14 kg		Ended			Boulby
NEWAGE-03b'	Gas Directional	CF4	14 g	4.5 kg d	Ended	2013	2017	
CYGNUS???								
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS-G	Gas Drift	CH4			Construction/Run	2020	2025	SNOLAB
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction/Run	2021	2024	LSM
SENSEI	CCD Skipper	Si	2 g Si	2g x 24 d	Running	2019	2020	Fermilab u/g
SENSEI	CCD Skipper	Si	100 g Si		Construction/Run	2021	2023	SNOLAB
ALETHEIA	TPC	He			R&D			China Inst. At. Energy
TESSERACT	Cryo TES	He			R&D			LBL

R&D
Planning
Construction
Running
Ended

**Our Goal Remains to Create the ...**

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# **QUIETEST KNOWN PLACES IN THE UNIVERSE**

**Our Goal Remains to Create the ...**

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**QUIETEST KNOWN PLACES IN THE  
UNIVERSE**

**BUT NOT TOO QUIET  
WE REALLY ARE LOOKING FOR A  
SIGNAL**

# Our Goal Remains to Discover Dark Matter ...

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**We have been beating Moore's Law in terms of progress in the search-space c-s for some specific DM particle types.**

**(It's a big space so we need to make rapid progress :-)**

**However, new models/experiments are also spreading laterally in the search-space in terms of candidate particle mass. A challenge will be to ensure that we have multiple experiments able to test possible signals that occur.**

**New technologies can often introduce new pathologies for backgrounds and we will need a way to differentiate between real DM-related signals and unwanted background pathologies.**

# Conclusions - Direct Detection

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- The Enthusiasm of Experimentalist Pursuing Direct Dark Matter Grows Unabated
  - LUX / PandaX-II / XENON1T reported final results
  - DAMA/LIBRA Phase 2 > 1 tonne x year - Annual Modulation Signal is still there
- US G2 “Generation 2” Dark Matter Experiments: LZ, SuperCDMS, ADMX
  - LZ goal of operating at Sanford Lab in 2021 (US-DOE, UK)
- Worldwide
  - XENONnT goal of operating at LNGS in 2021 (German, Swiss, US-NSF)
  - PandaX-4T goal of operating at Jinping in 2021 (China)
  - DarkSide20k (20 tonne - major upgrade on previous 50 kg instrument) seeking approval from multiple agencies
- Low Mass DM signal(s) - many new technologies now aimed at sub-GeV and MeV candidates
- Improving Search Sensitivity Continues Apace
  - New larger detectors are being delivered in order to keep rate of improvement for WIMP >5 GeV regime
  - Reductions in threshold deliver major advances in low mass sensitivity (then the challenge will be to scale detector mass)
  - Critically there has also been an improvement in our understanding of potential systematics in detector response
  - This Focus - Has brought the best out of people. Yes, we are combative, but that is the spice that makes the best sauce, and it has caused us to hone our arguments, and improve our detailed understanding of the detectors/backgrounds
  - Calibration strategies that can provide abundant statistics, and have low systematic uncertainties are critically important
- The Spectre of Discovery is always upon us, and is a great responsibility
  - Clearly, multiple detectors / multiple techniques will be required to build a robust case of discovery



SLIDES END