Dark Matter Direct Detection Experiment Review PANIC 2021, Lisbon, Portugal

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Ex-Spokesperson, LZ Collaboration
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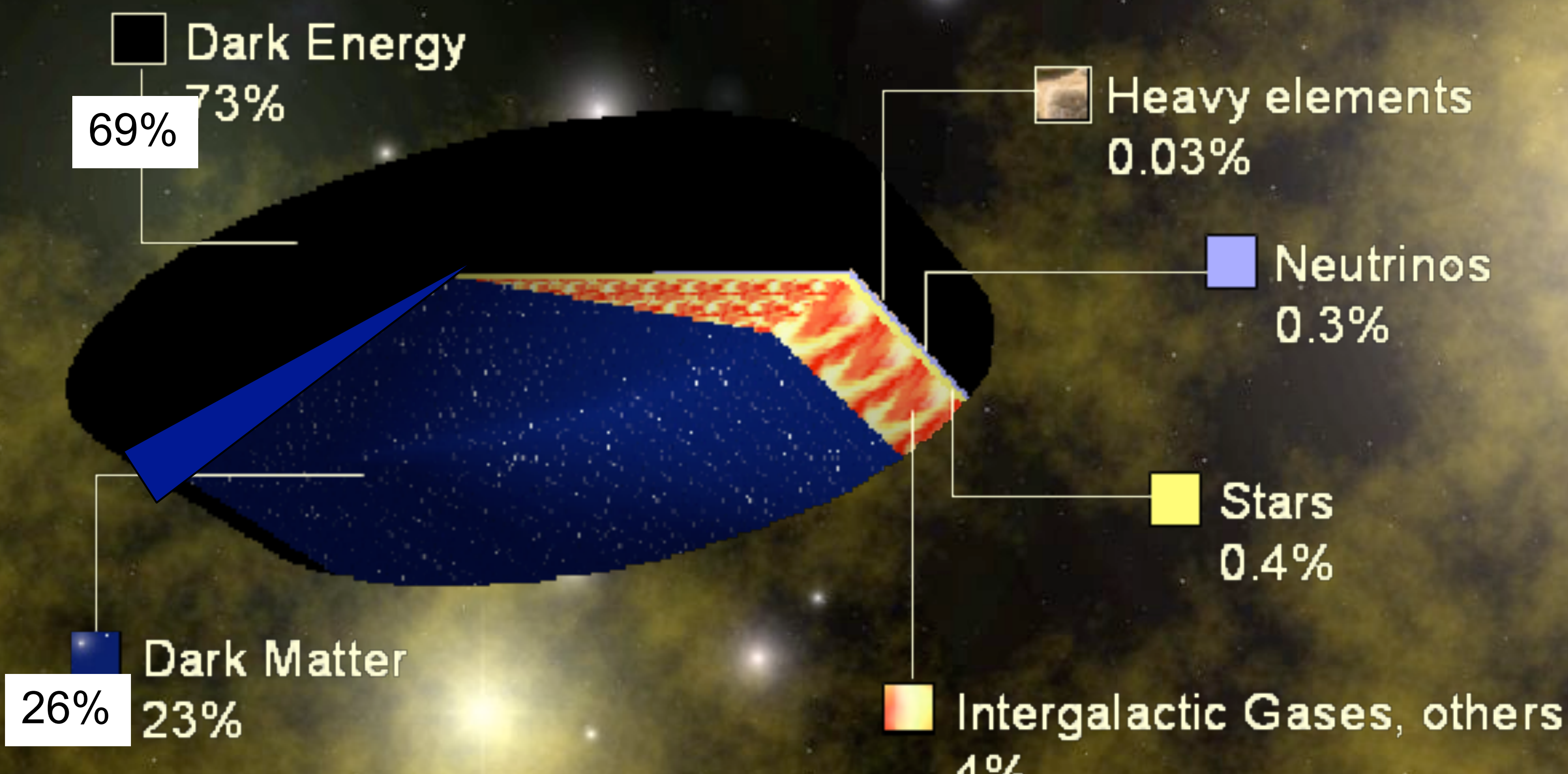
LUX and LZ Experiments supported by US DOE HEP

see information at

http://particleastro.brown.edu

http://cfpu.brown.edu http://lz.lbl.gov

What is the Universe made of ?



Uncertainties in main components now <1 %

"But Actual Composition 950 milli-IDK"

If the S.I. Unit of Ignorance is the "IDK"

Then we still rate 950 milli-IDK for the Composition of the Universe

Maybe we can reduce this to 680 milli-IDK in the near future with the observation or creation in the lab of DM particles

(*) IDK, I Don't Know, is easier to say than WDK

Exposure Time....
32 years searching for 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

Recent Photo from Sanford Lab

- 1 mile underground at Sanford Lab in Davis Cavern

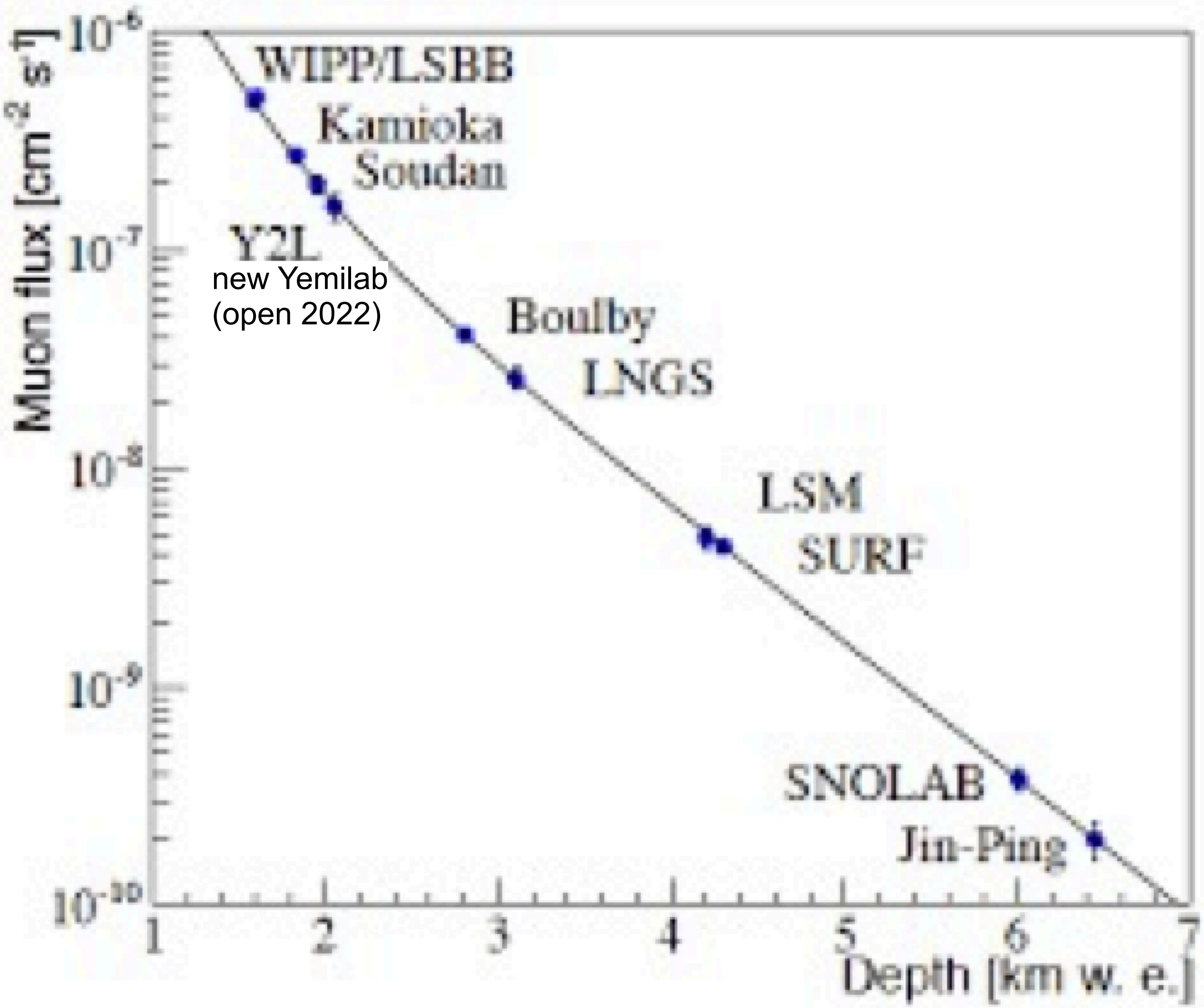
My colleagues -
LZ speakers at PANIC:
Alissa Monte (spoke yesterday, Sep 5th),
Paulo Brás/Braz (Sep 8th)

SURF / Sanford Lab @ South Dakota

LUX, Sanford Lab, 2011

Sanford Lab (SURF), May 2012

Deep Underground Laboratories - Escaping Cosmic Muons



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 [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

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[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr., Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *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 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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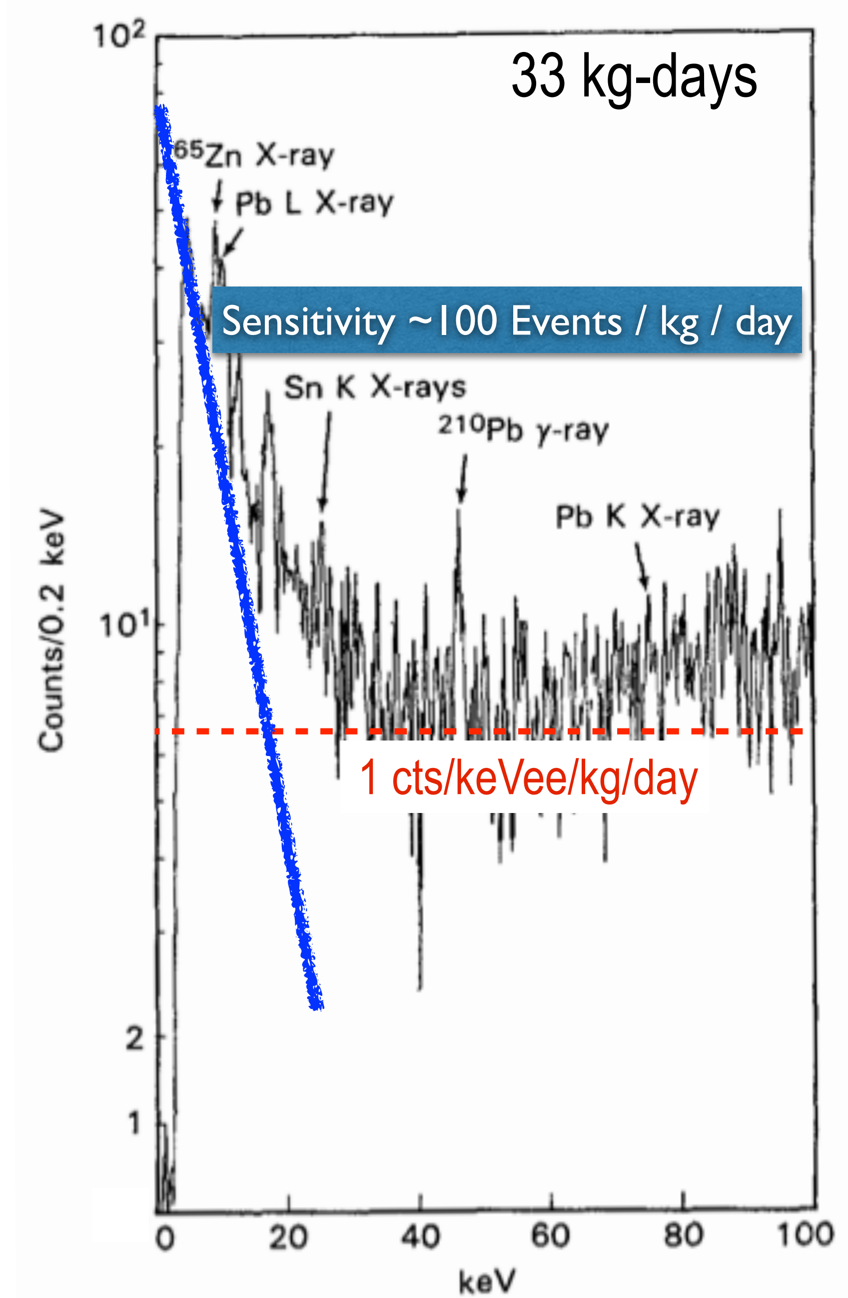
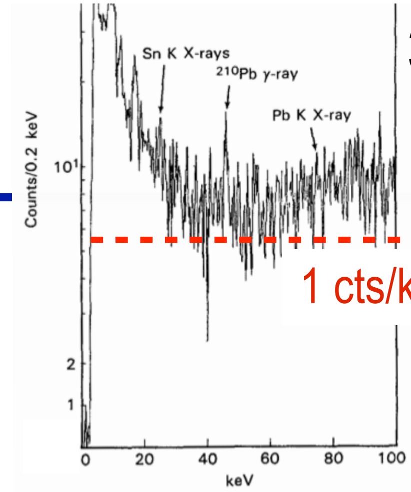




33 kg-days

1 cts/keVee/kg/day

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

- 2021 constructing/operating ~10 tonne targets at multiple sites

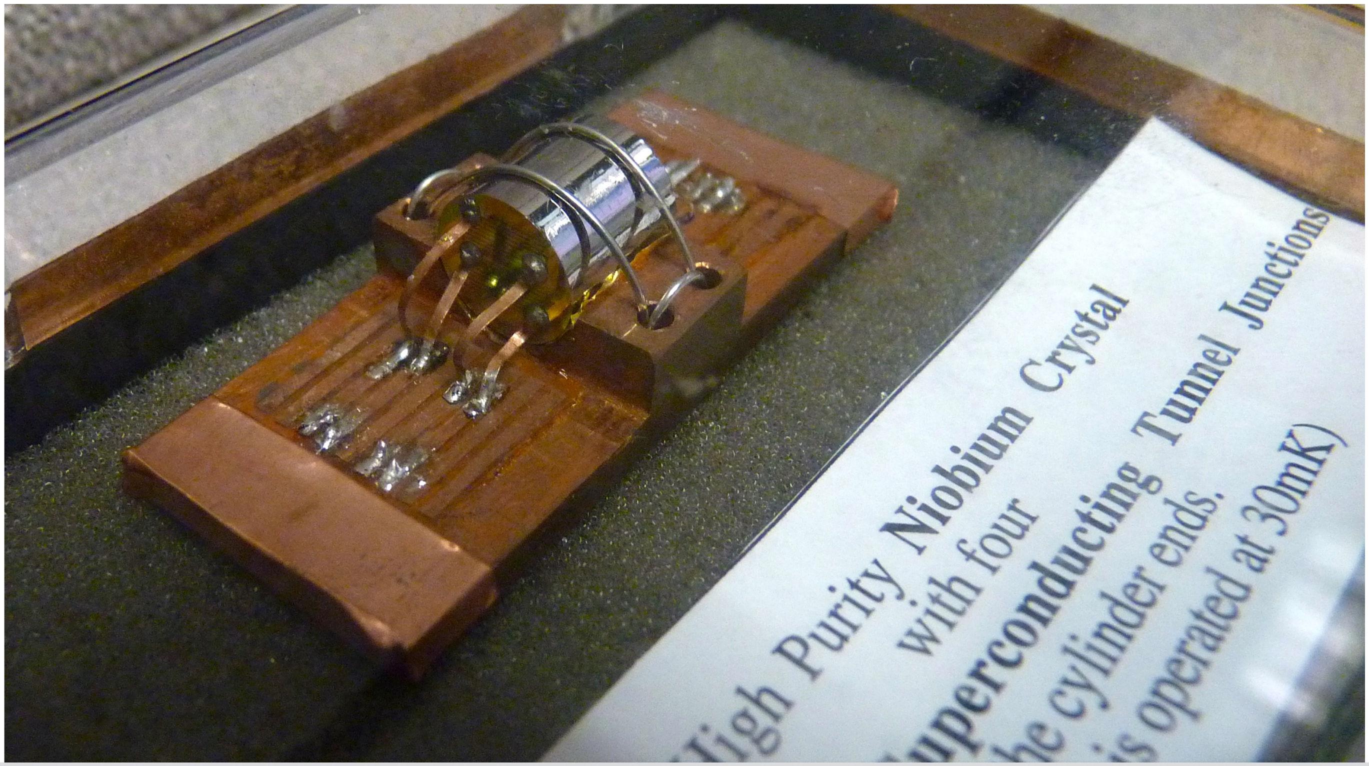
ER < 10^{-4} cts/keVee/kg/day

NR < 10^{-8} cts/keVnr/kg/day

Sensitivity ~1 Event / 50 tonnes / day

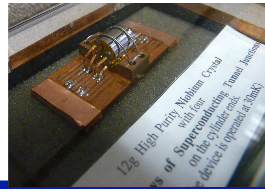
Gaitskell (Graduate Work) Superconducting Nb Single Crystal Detector

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



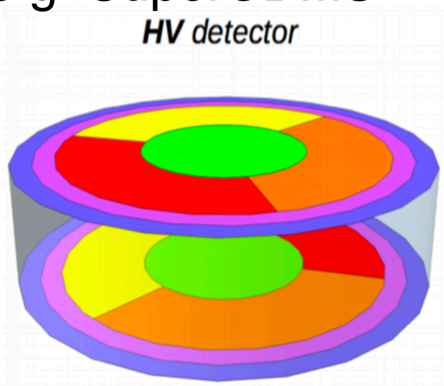
In Early 1990’s we studied exotic lattice photon and quasiparticle states to build sensitive dark matter detectors - today we appear to be coming full circle as see new proposals for MeV DM search experiments based on meV excitons

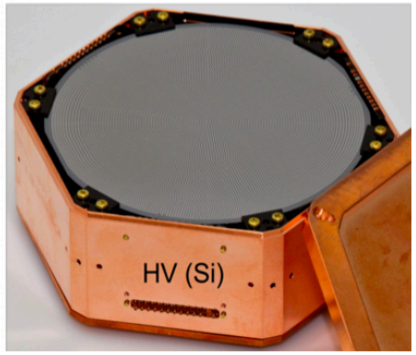
1 cm
in all photos



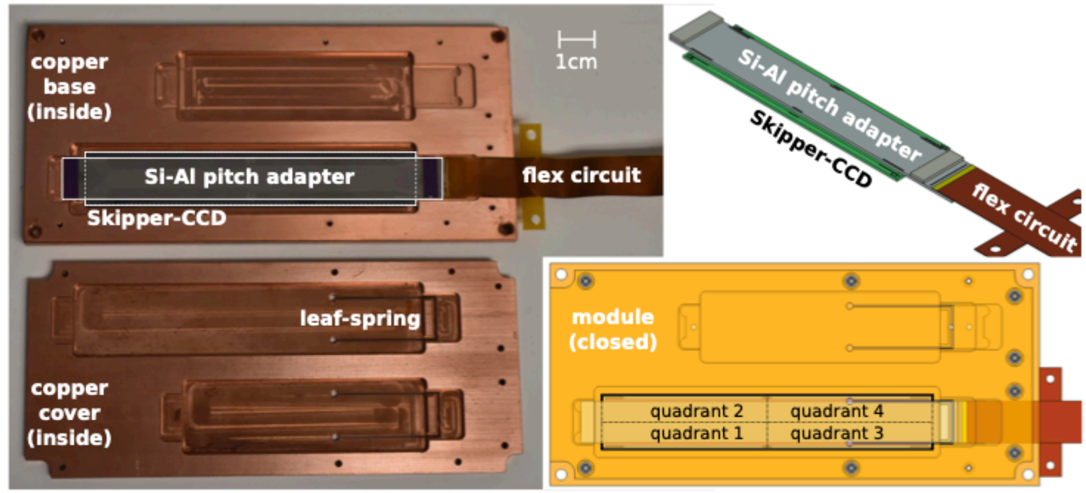
Low Thresholds

e.g. SuperCDMS





e.g. SENSEI 2 g Si-CCD (Electron scattering)



DM-e scattering best limits >500 keV/c^2

- 2021
  - ➡Transition Edge Sensors / CCDs 10 g-1 kg scale detectors with sensitivities to 10's eV nuclear recoils and also electron recoils (and Migdal Effect - still need to demonstrate calibration proving sensitivity)

Dark Matter Direct Detection MeV - TeV

- 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)

R&D
Planning
Construction
Running
Ended

Dar … - 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	Running	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 Scintillatior	CaWO4	5 kg		Ended	2012	2015	LNGS
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CRESST-III (HW Tests)	Bolometer Scintillatior	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
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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			LBNL

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The Practical Matter of a Rare Event Search

- 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 C3F8
    - 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

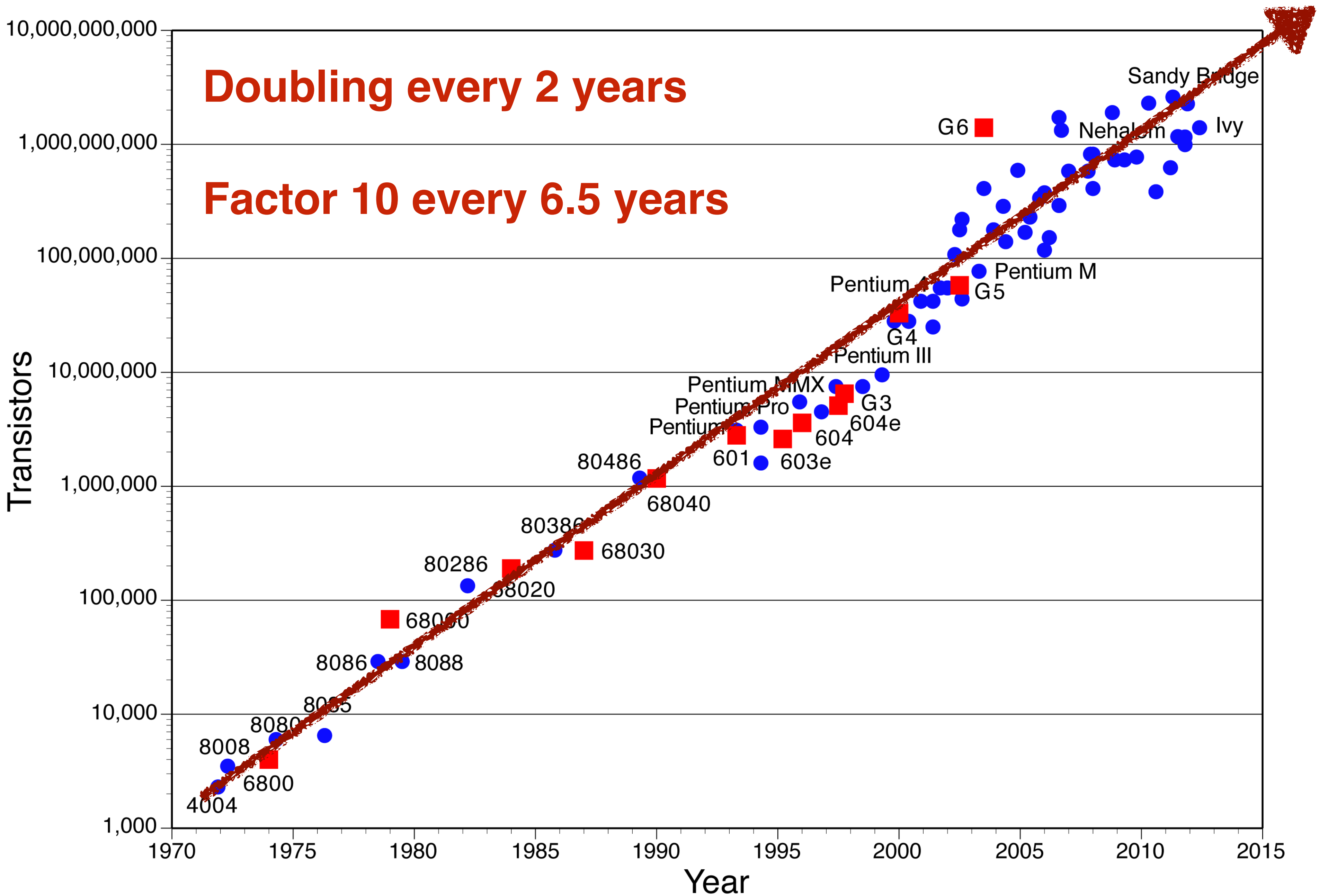
The Practical Matter of a Rare Event Search

- In ~35 th 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



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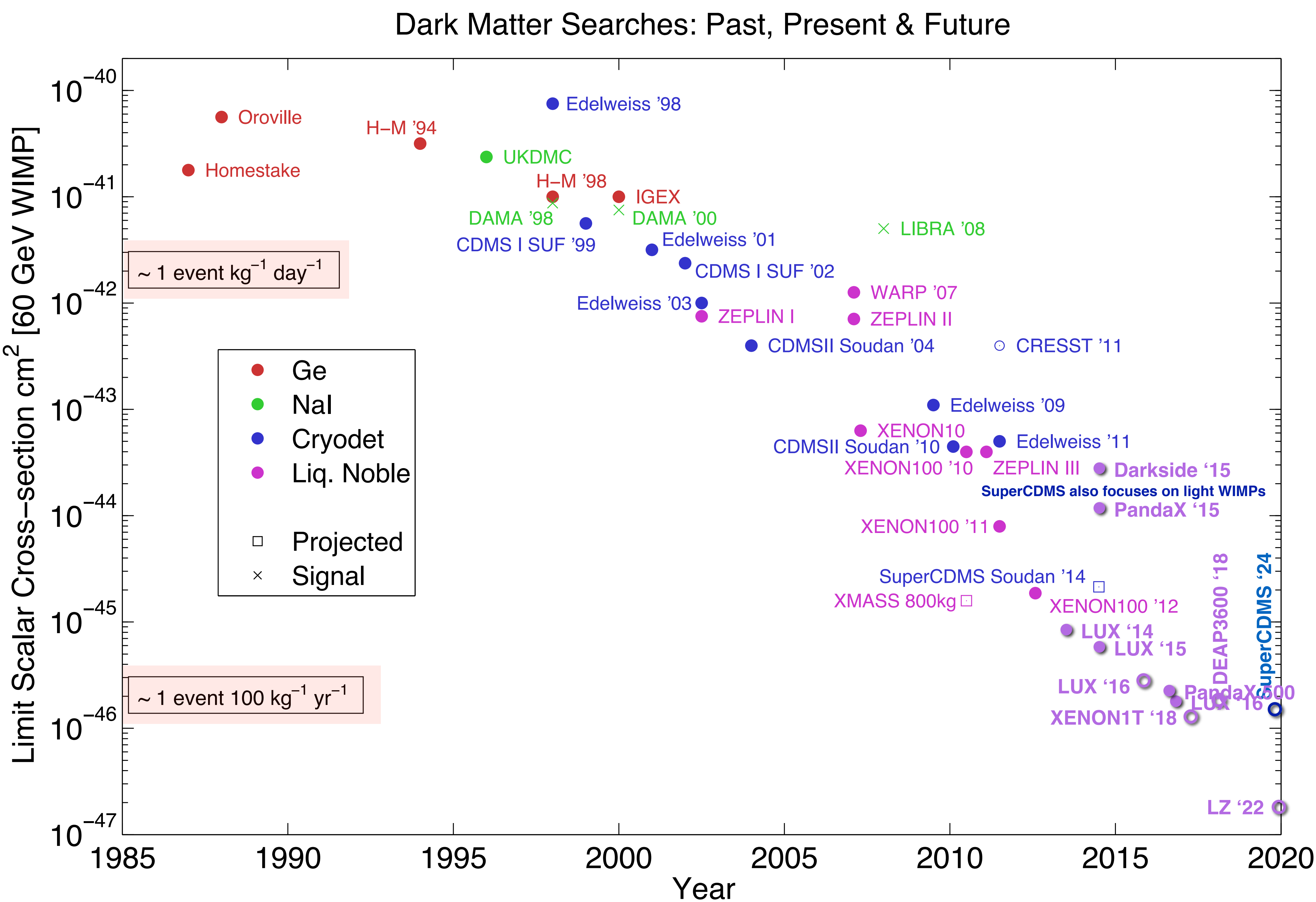
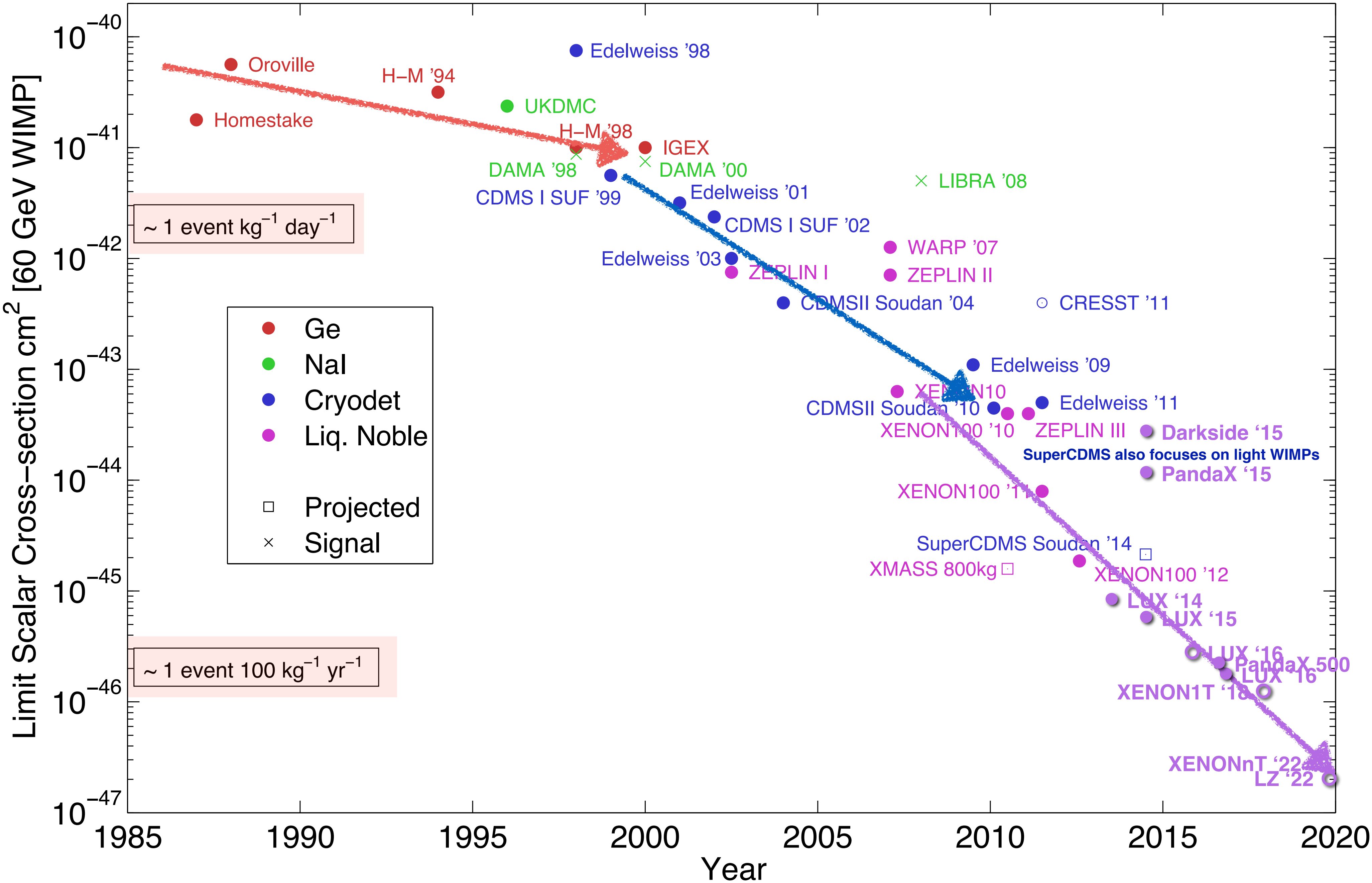
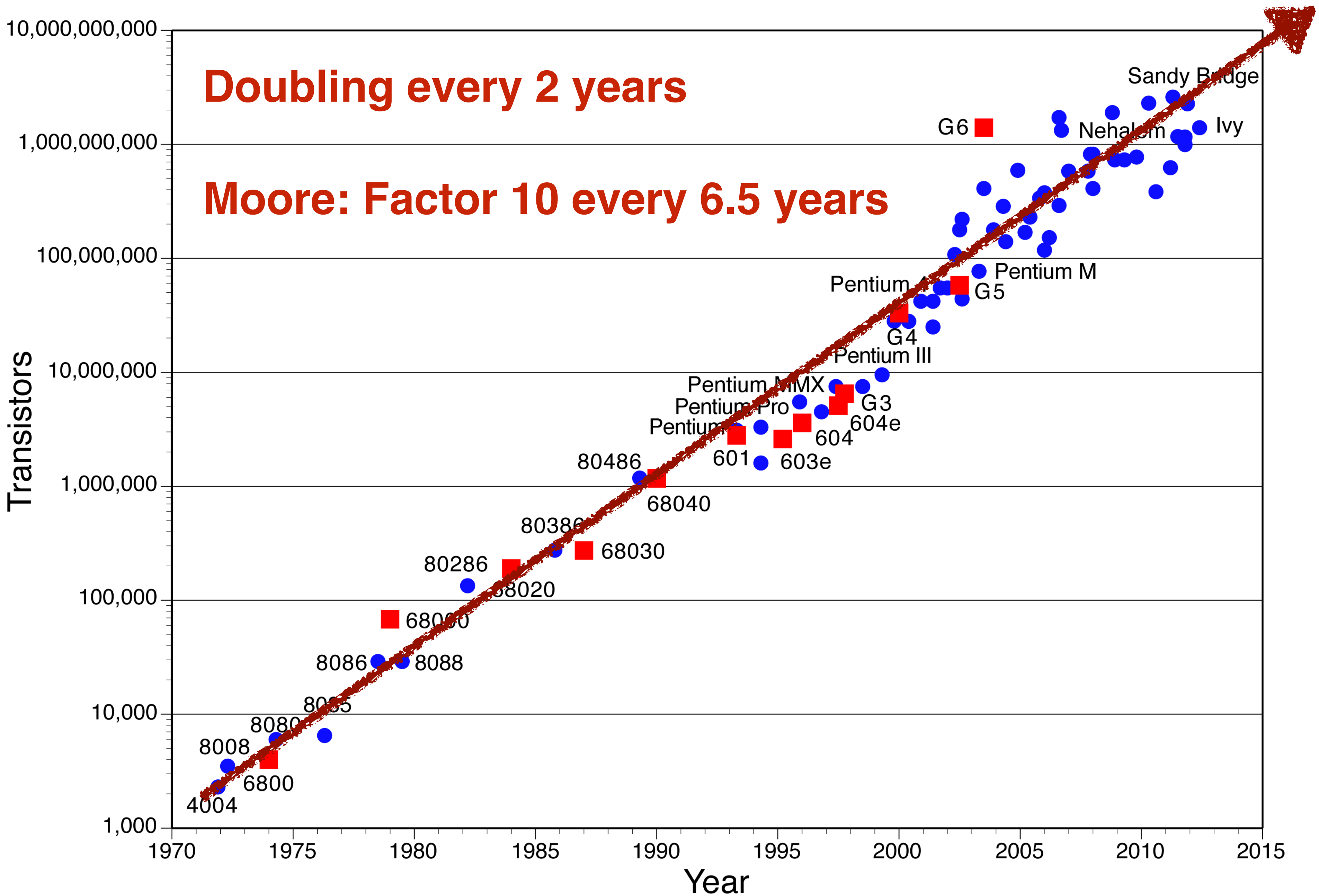

Dark Matter Searches: Past, Present & Future
Limit Scalar Cross-section cm² [60 GeV WIMP]
Year
Oroville
Homestake
H–M '94
Edelweiss '98
UKDMC
H–M '98
IGEX
DAMA '98
DAMA '00
CDMS I SUF '99
Edelweiss '01
LIBRA '08
CDMS I SUF '02
WARP '07
Edelweiss '03
ZEPLIN I
ZEPLIN II
CDMSII Soudan '04
CRESST '11
~ 1 event kg⁻¹ day⁻¹
Ge
NaI
Cryodet
Liq. Noble
Projected
Signal
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
Darkside '15
SuperCDMS also focuses on light WIMPs
PandaX '15
XENON100 '11
SuperCDMS Soudan '14
XMASS 800kg
XENON100 '12
LUX '14
LUX '15
DEAP3600 '18
SuperCDMS '24
LUX '16
PandaX 500
LUX '16
XENON1T '18
LZ '22
~ 1 event 100 kg⁻¹ yr⁻¹

Dark Matter Searches: Past, Present & Future





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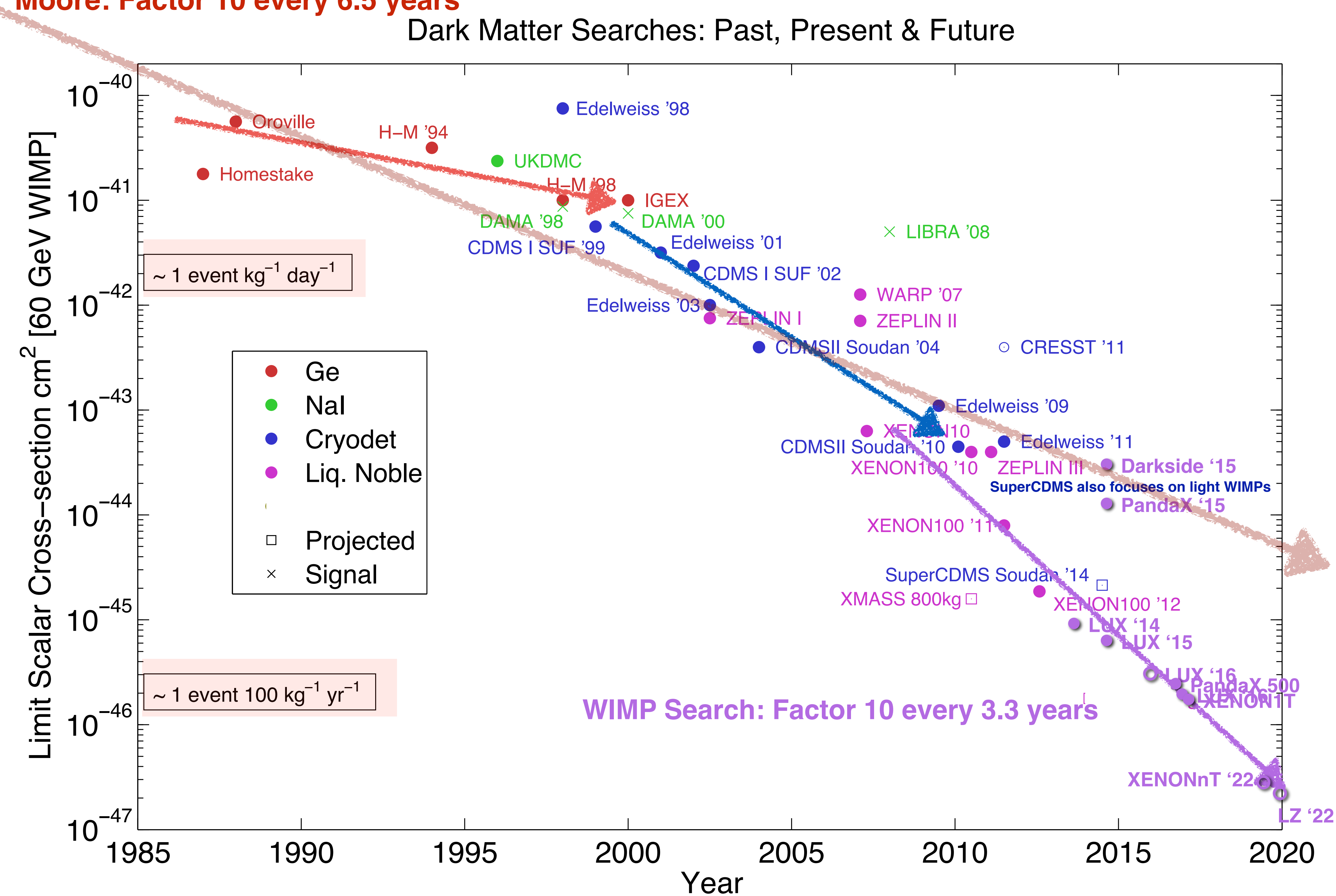
Moore: Factor 10 every 6.5 years



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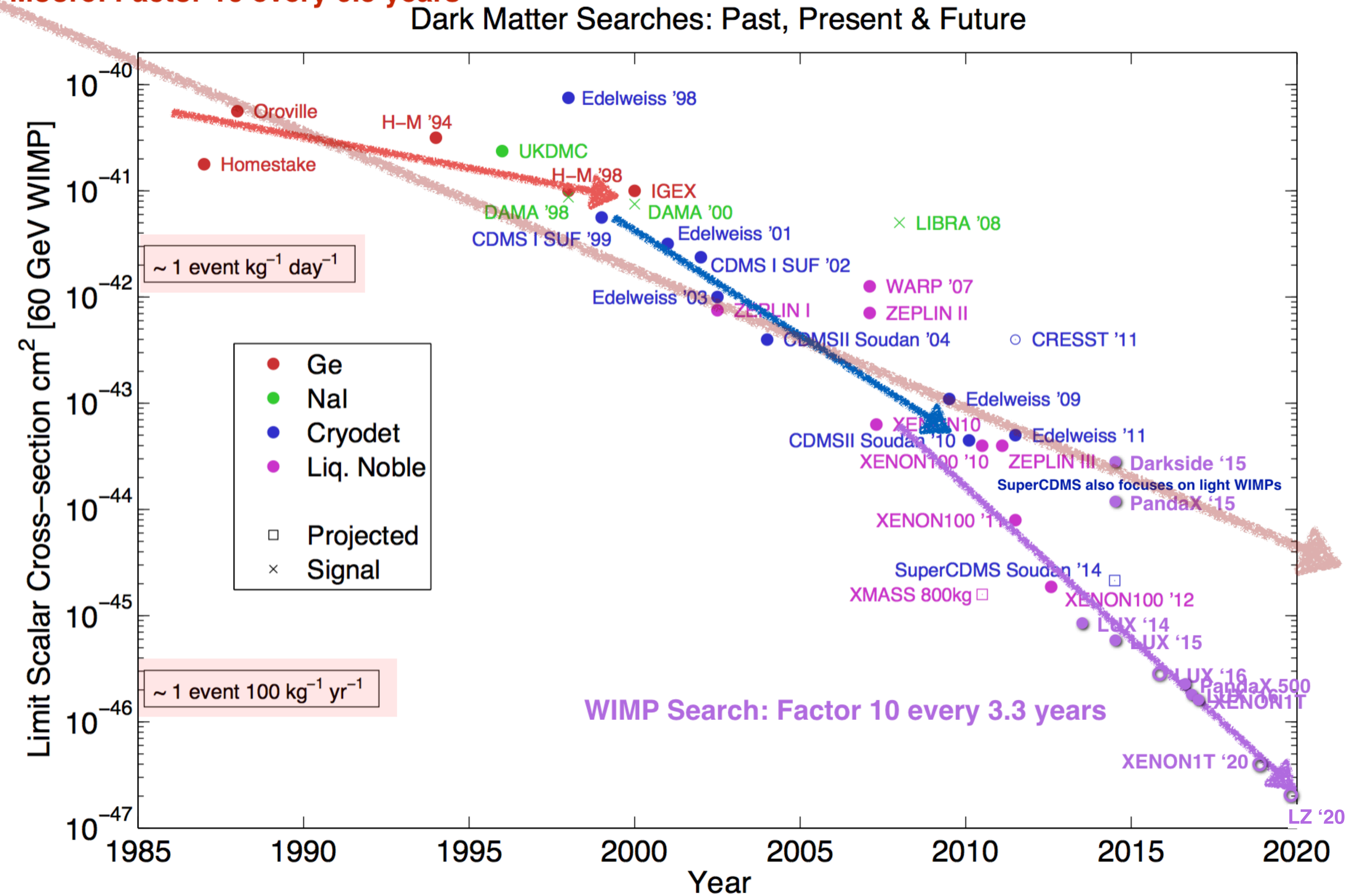

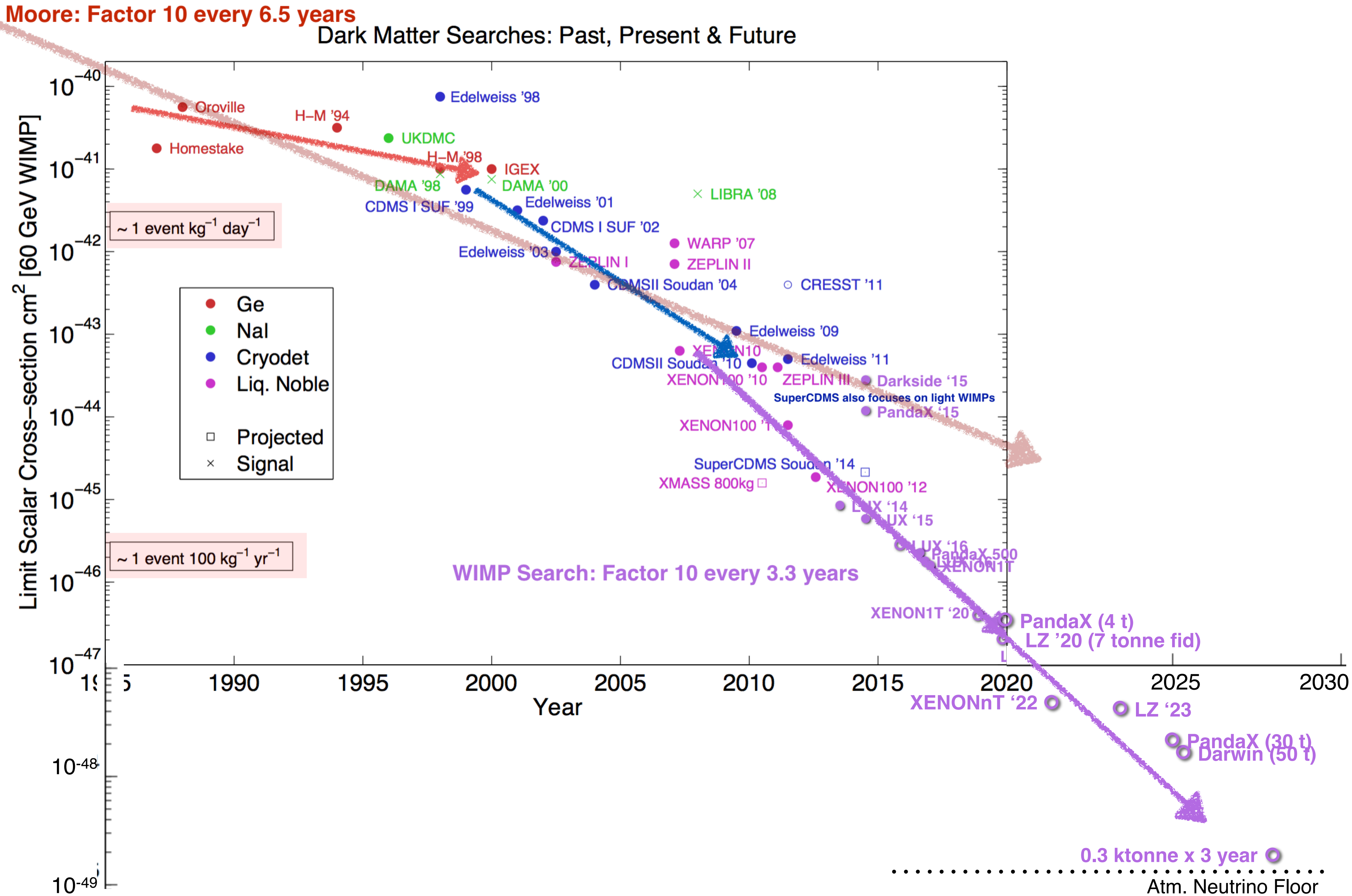
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ZEPLIN I
CDMSII Soudan '04
CRESST '11
Edelweiss '09
XENON10
CDMSII Soudan '10
Edelweiss '11
XENON100 '10
ZEPLIN III
Darkside '15
SuperCDMS also focuses on light WIMPs
PandaX '15
XENON100 '11
SuperCDMS Soudan '14
XMASS 800kg
XENON100 '12
LUX '14
LUX '15
LUX '16
PandaX 500
XENON1T
WIMP Search: Factor 10 every 3.3 years
XENON1T '20
PandaX (4 t)
LZ '20 (7 tonne fid)
XENONnT '22
LZ '23
PandaX (30 t)
Darwin (50 t)
0.3 ktonne x 3 year
Atm. Neutrino Floor
1990
1995
2000
2005
2010
2015
2020
2025
2030
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}

Journey Through the Theoretical Landscape

(Thanks to Dan Hooper, Fermilab)
For history - Bertone and Hooper, arXiv:1605.04909

My colleague Gianfranco Bertone will have covered this in his PANIC Talk

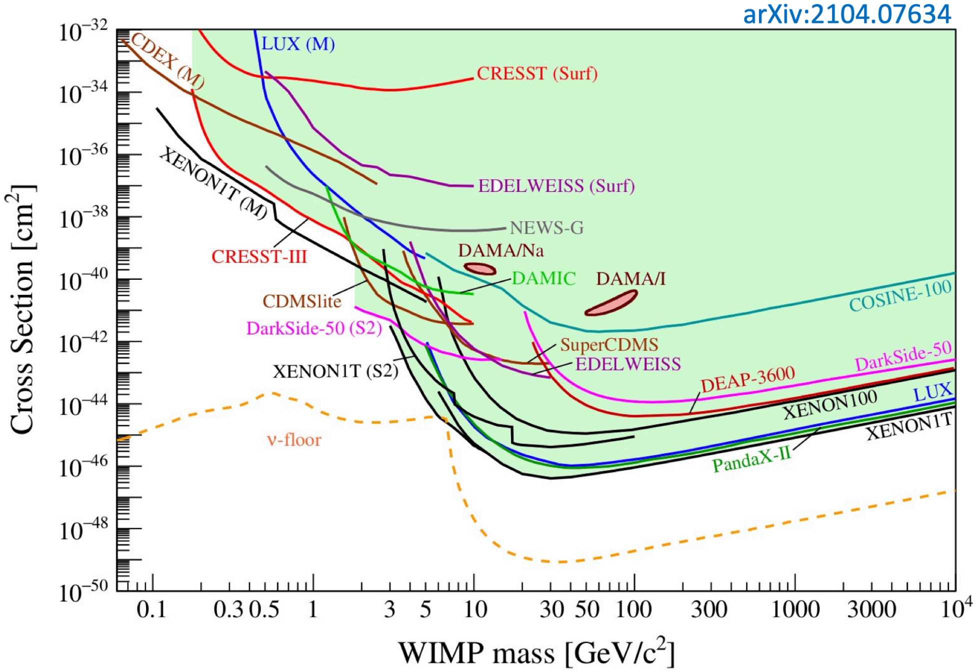
- Cumulative Theoretical work
  - 1966-1977 Massive Standard Model Neutrinos
    - Includes 1966 Gershtein & Zeldovich .... 1977 Dicus, Kolb & Teplitz,
  - 1977-83 Other candidates, including supersymmetric particles
    - Includes 1977 P. Hut .... 1983 Ellis, Hagelin, Nanopoulos, Olive & Srednicki
- 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 $\Omega_{matter} < 0.3$
- WIMP is a very natural solution if we assume particle is in <u>thermal equilibrium during early annihilation phase</u> and are present in a <u>radiation dominated early universe</u>

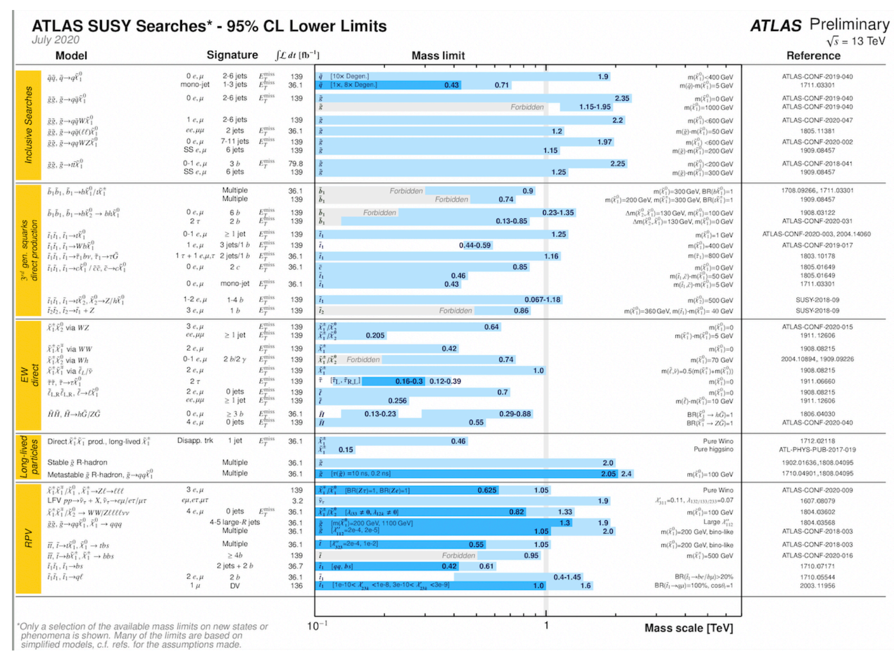
WIMPs

(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

arXiv:2104.07634

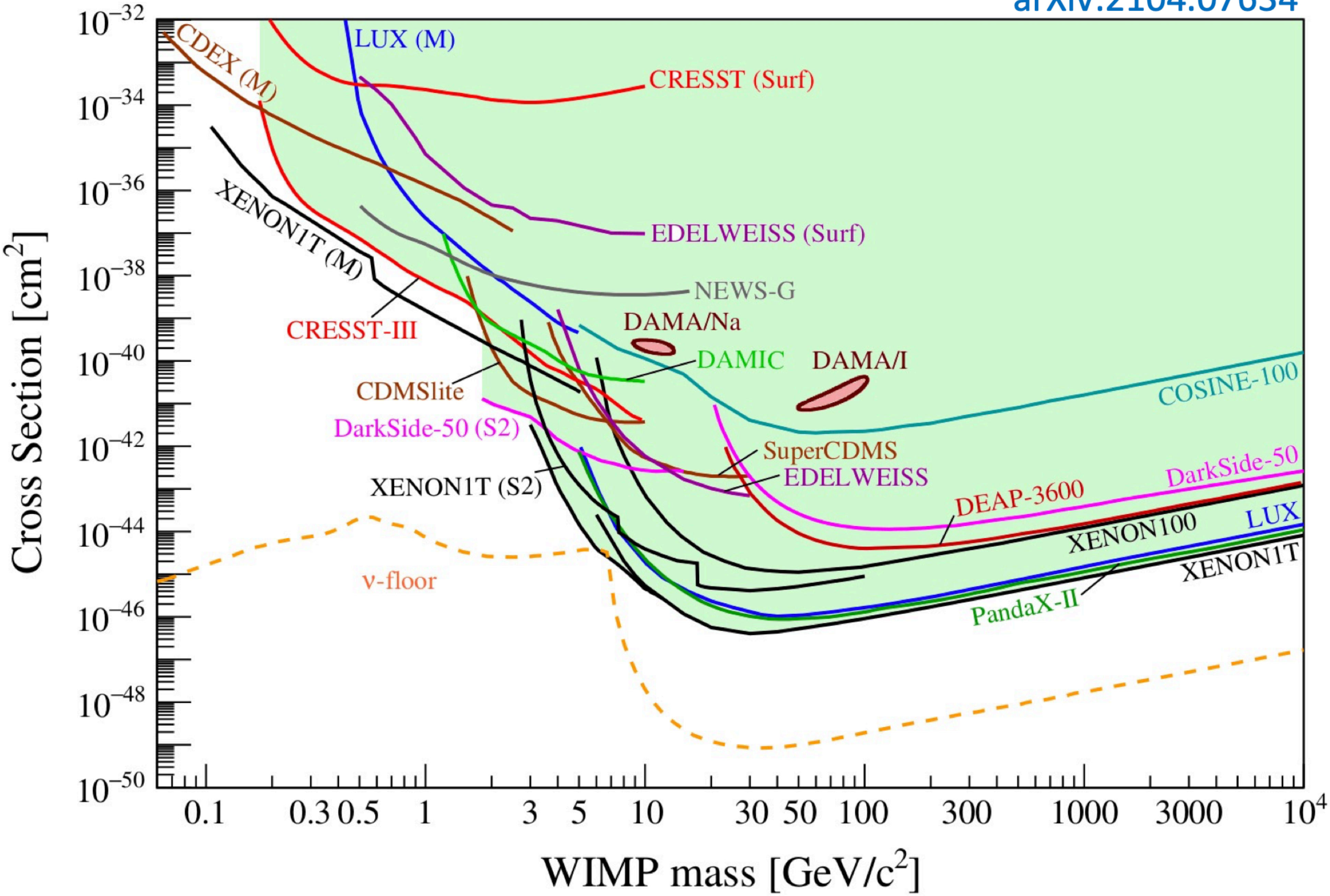




- In order to Reconcile Dark Matter With Current Constraints from Cosmology, Astrophysics, Accelerator and Direct Detection.
  What do WIMP models look like?
  - Need to ensure normal rate of annihilation in the early universe, UNSUPPRESSED, but the scattering probability on nucleons is SUPPRESSED.

- 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_χ < 1 GeV (not the classic WIMP) but > 3 MeV (BBN)
    - Requires new types of detector with light nuclear targets and very low thresholds

APPEC Committee Report
arXiv:2104.07634



Dar - 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	Running	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 Scintillatior	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillatior	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillatior	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			LBNL

R&D
Planning
Construction
Running
Ended

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
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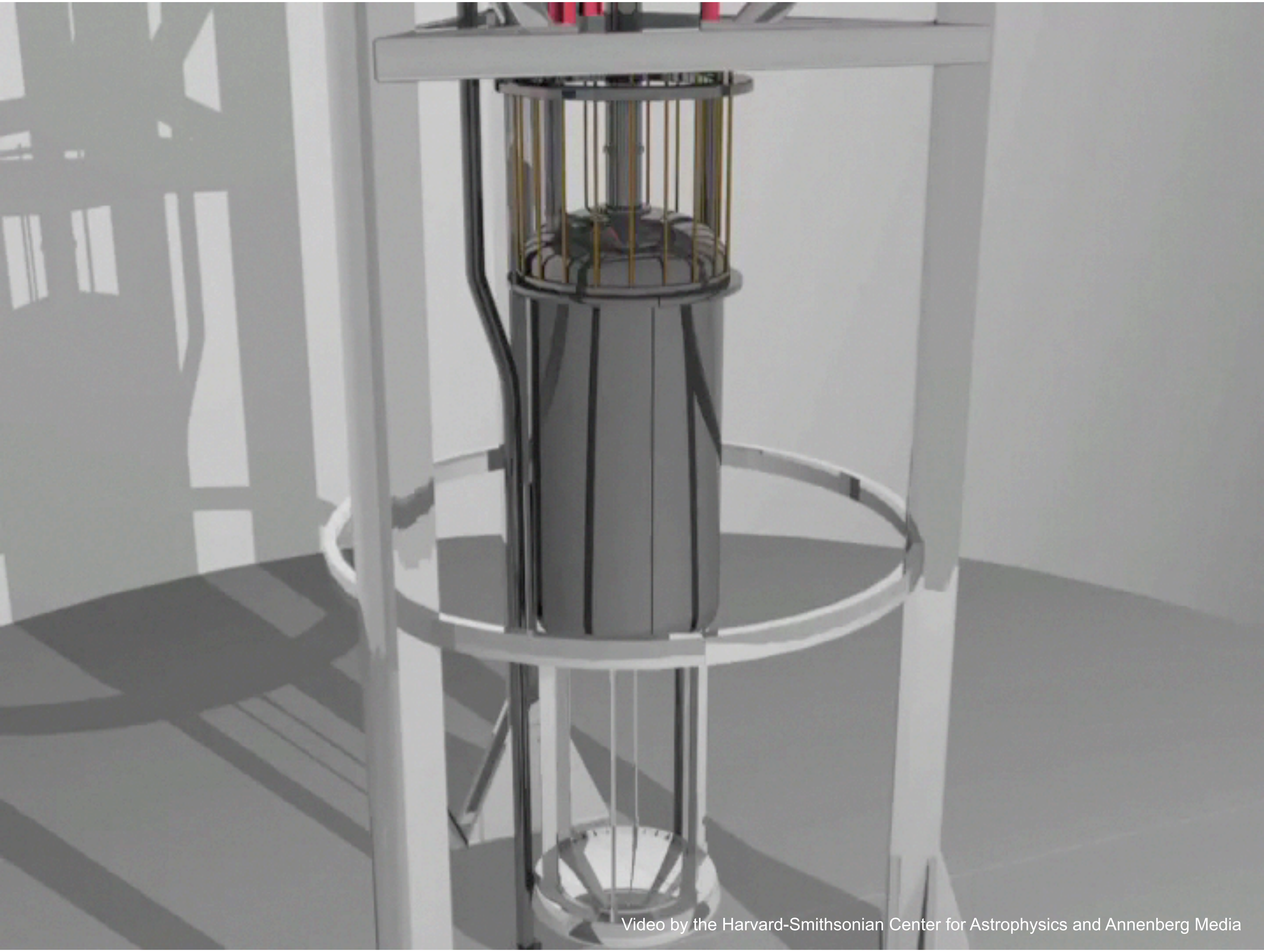
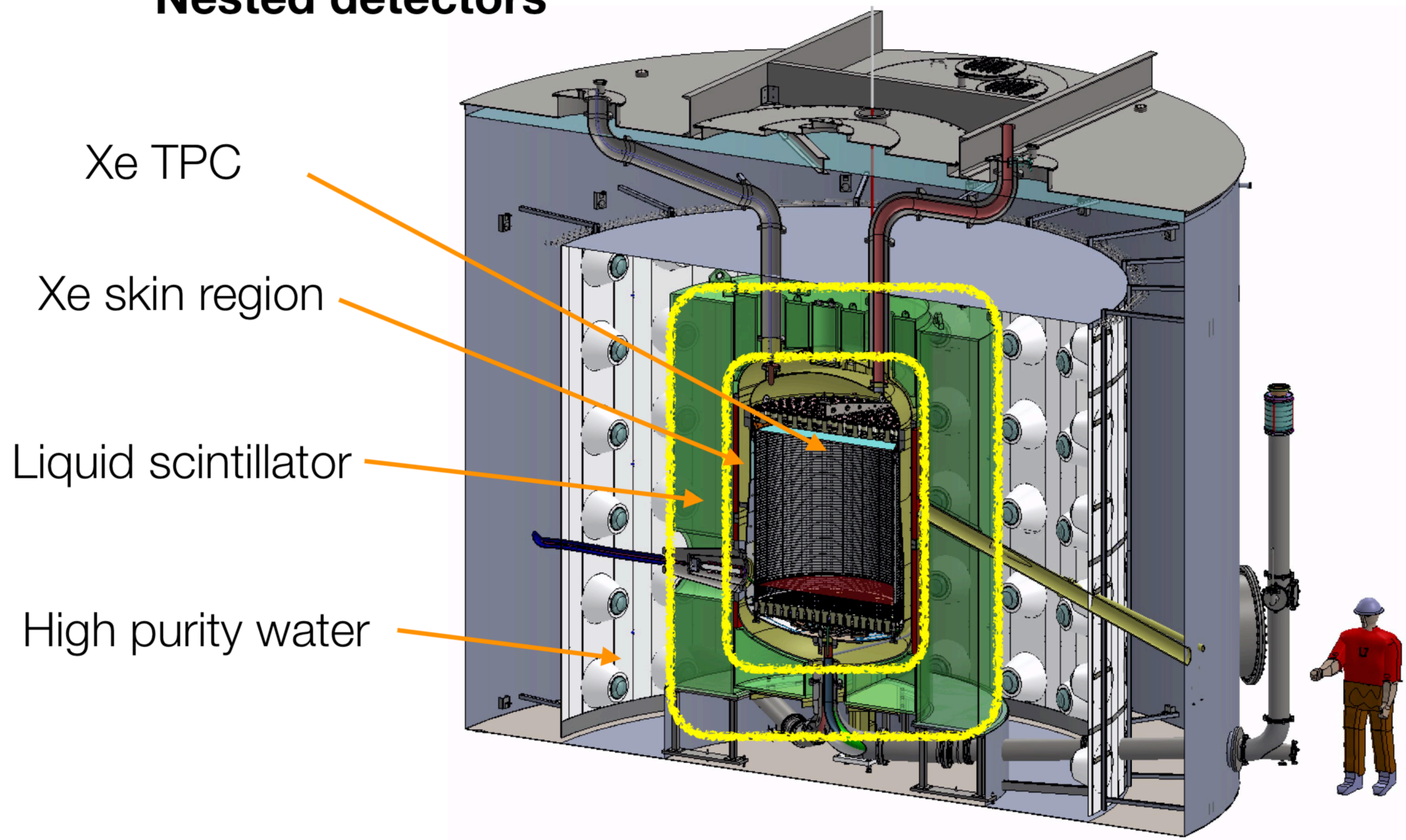
XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
XENON1T (Ionization)	TPC Ioniz.-only	LXe	1,995 kg		Ended	2017	2019	LNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg		Ended	2017	2019	SURF
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	Running	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	NaI	250 kg		Running	2003		LNGS
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc


Video by the Harvard-Smithsonian Center for Astrophysics and Annenberg Media

LUX-ZEPLIN @ Sanford Lab (Full Operations Start in 2021)

LZ TDR arXiv:1703.09144

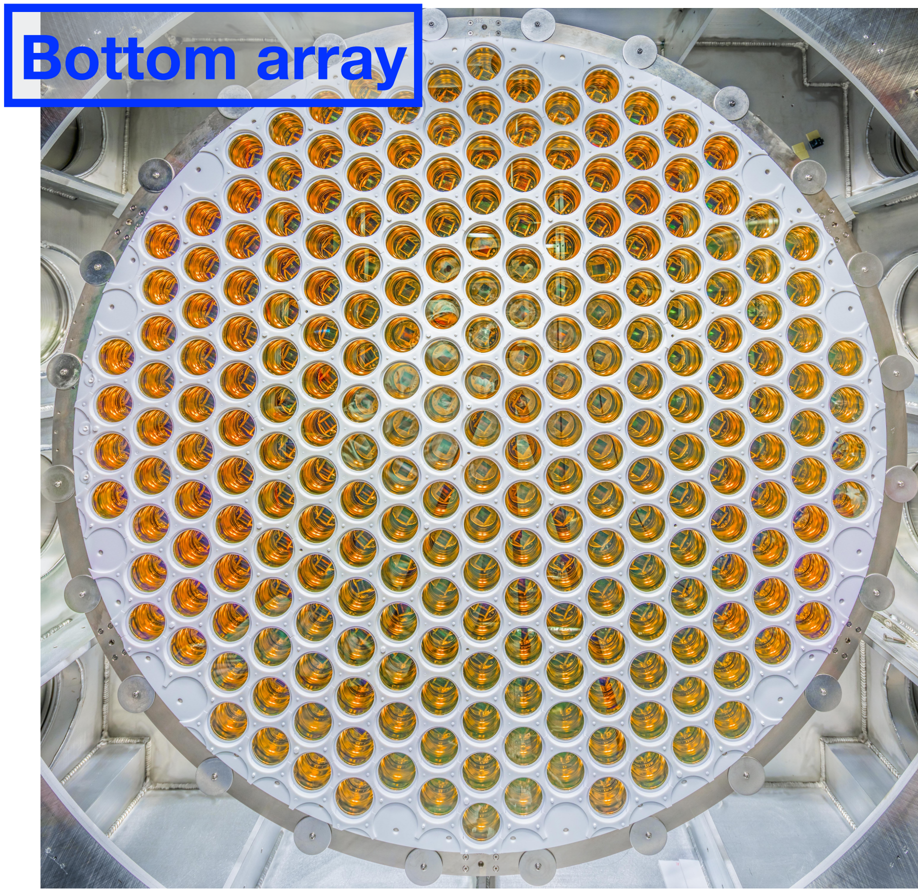
Nested detectors



How have we spent the last few years at Brown?

TPC: PMT arrays

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



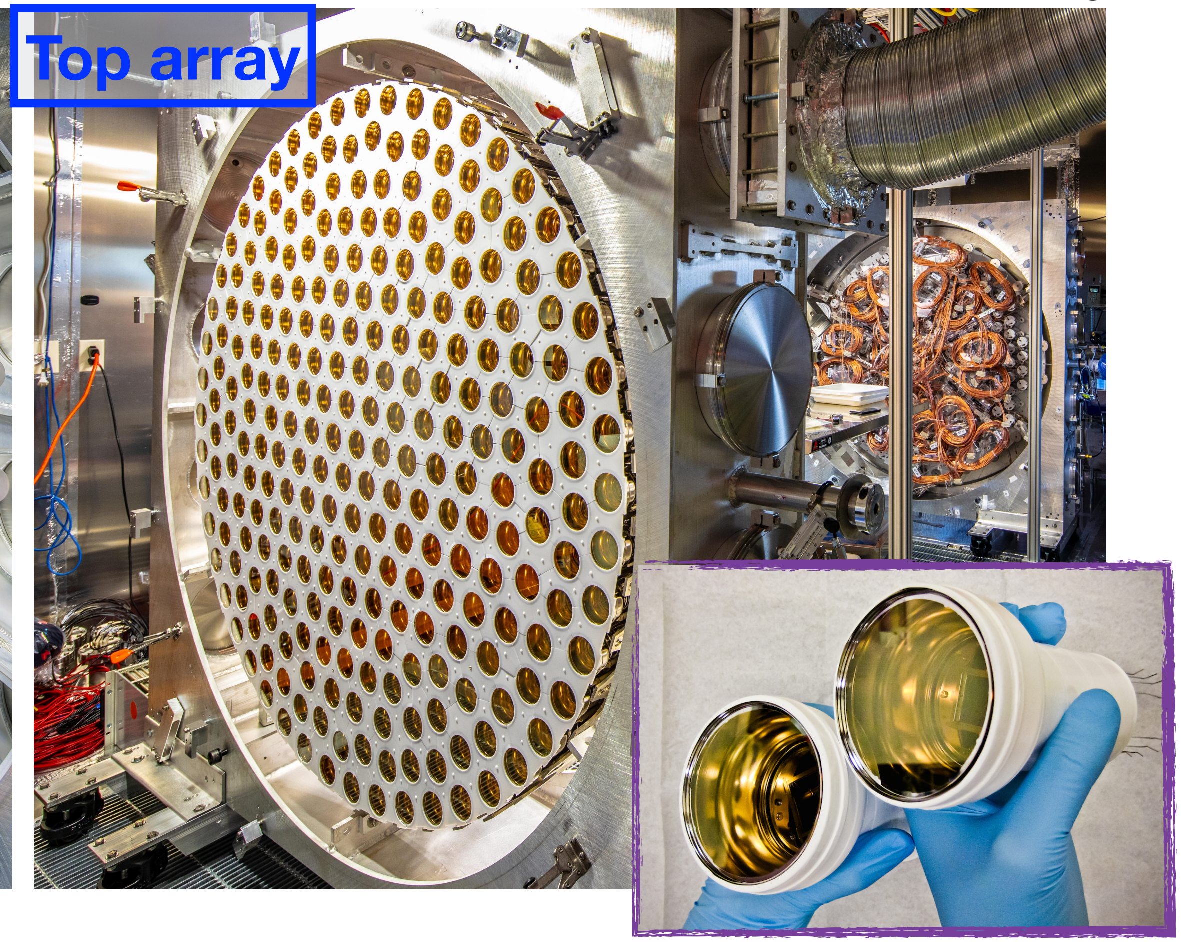
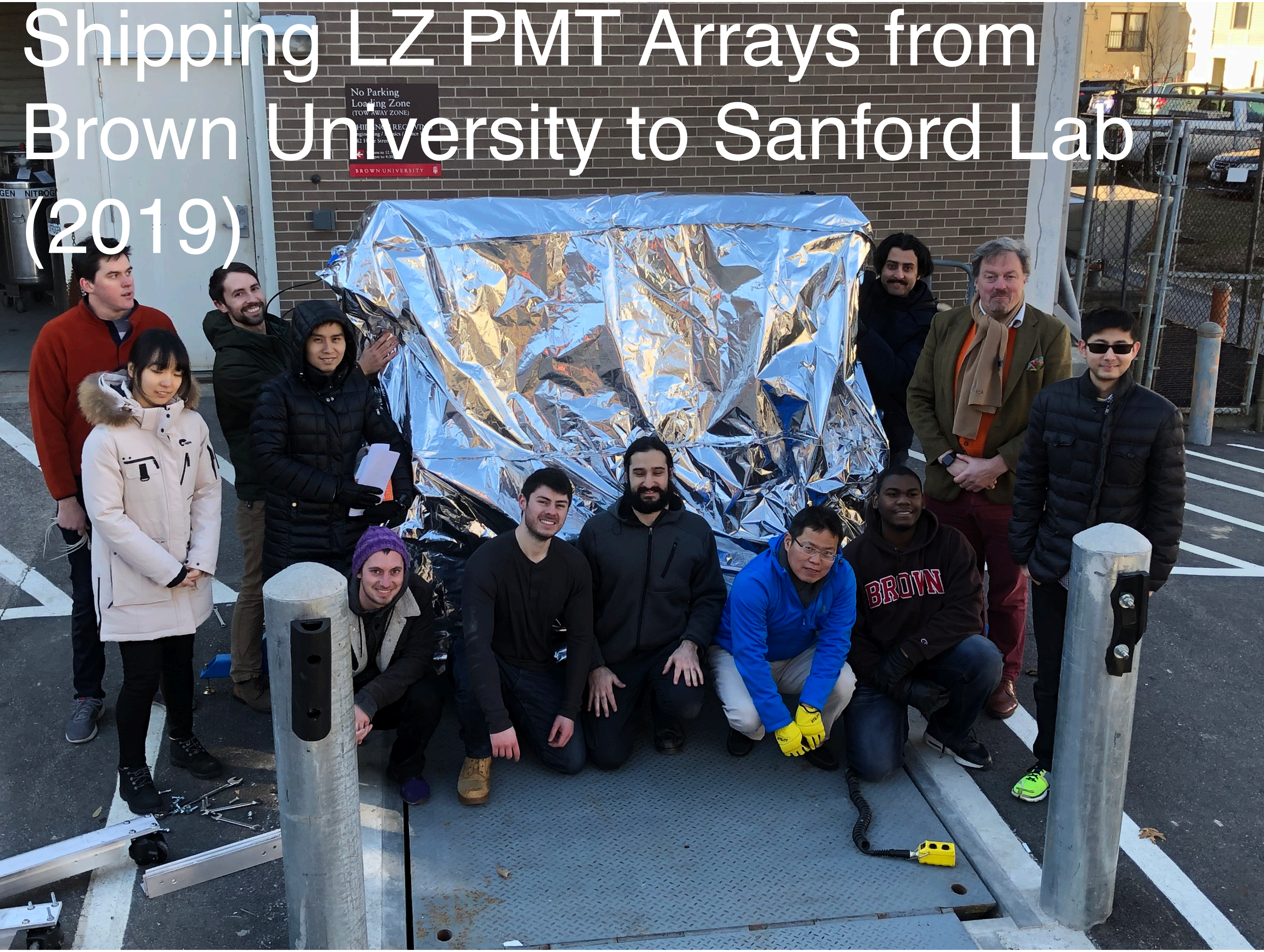
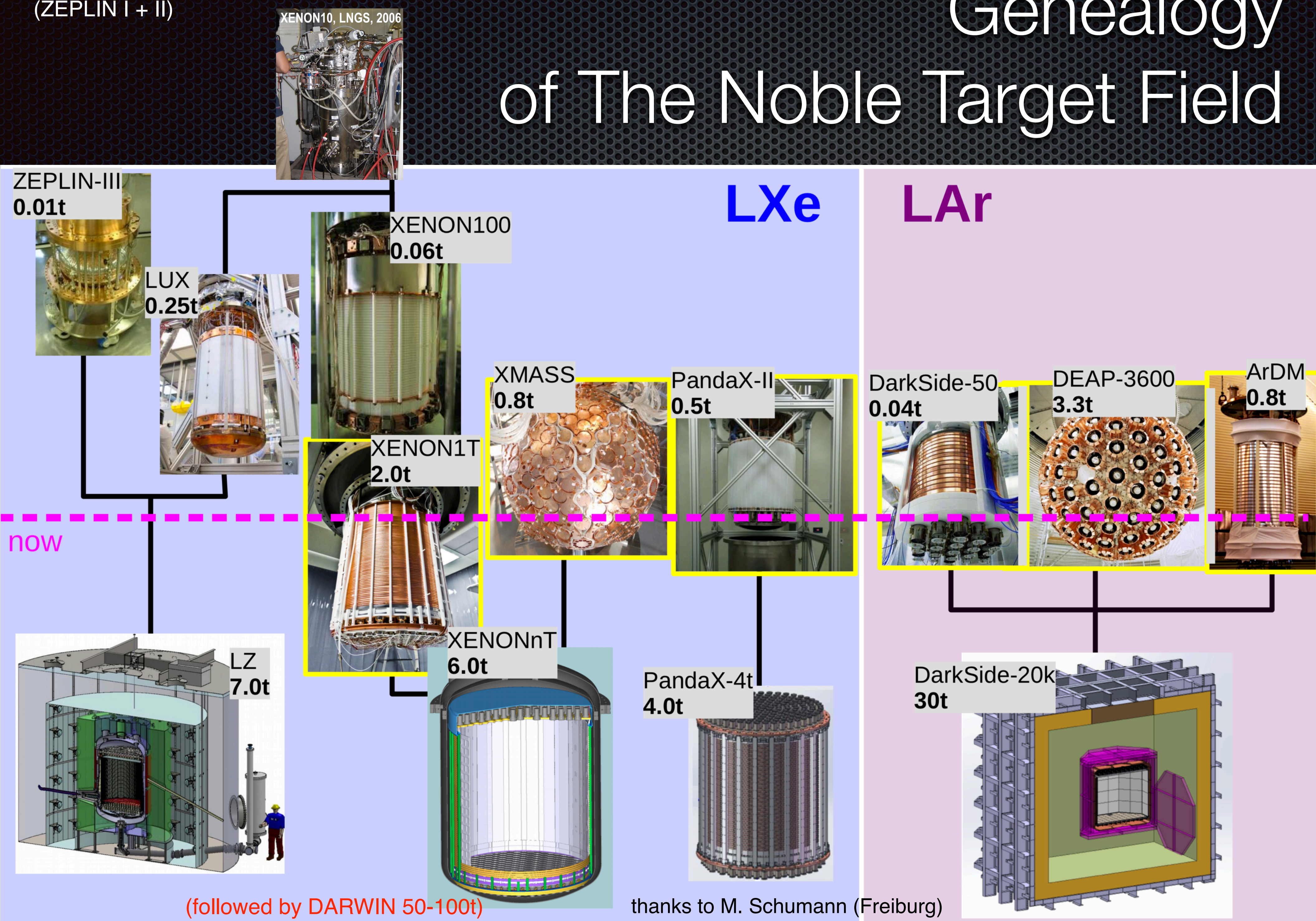


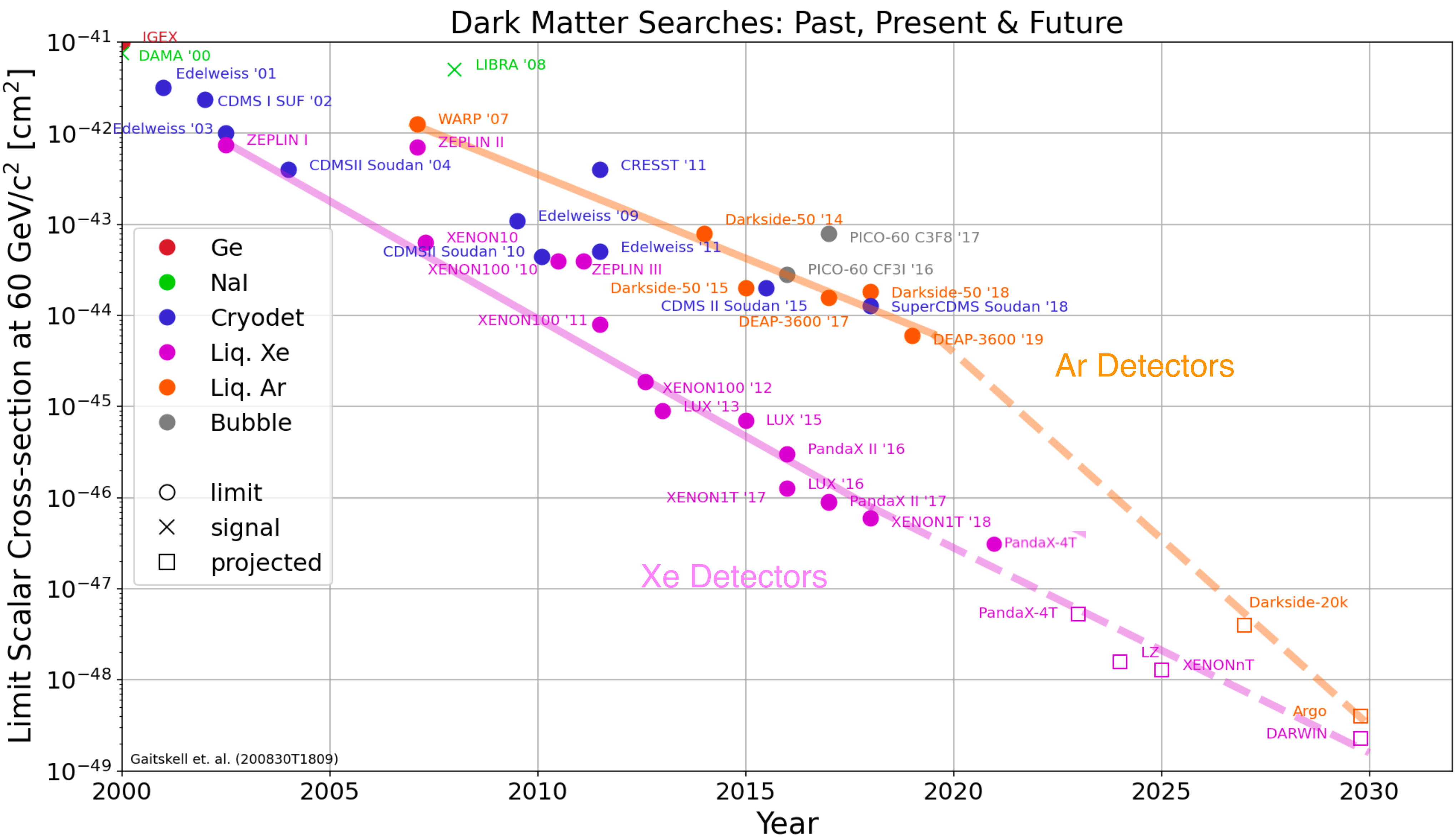
Photo credit: Matt Kapust, SDSTA

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



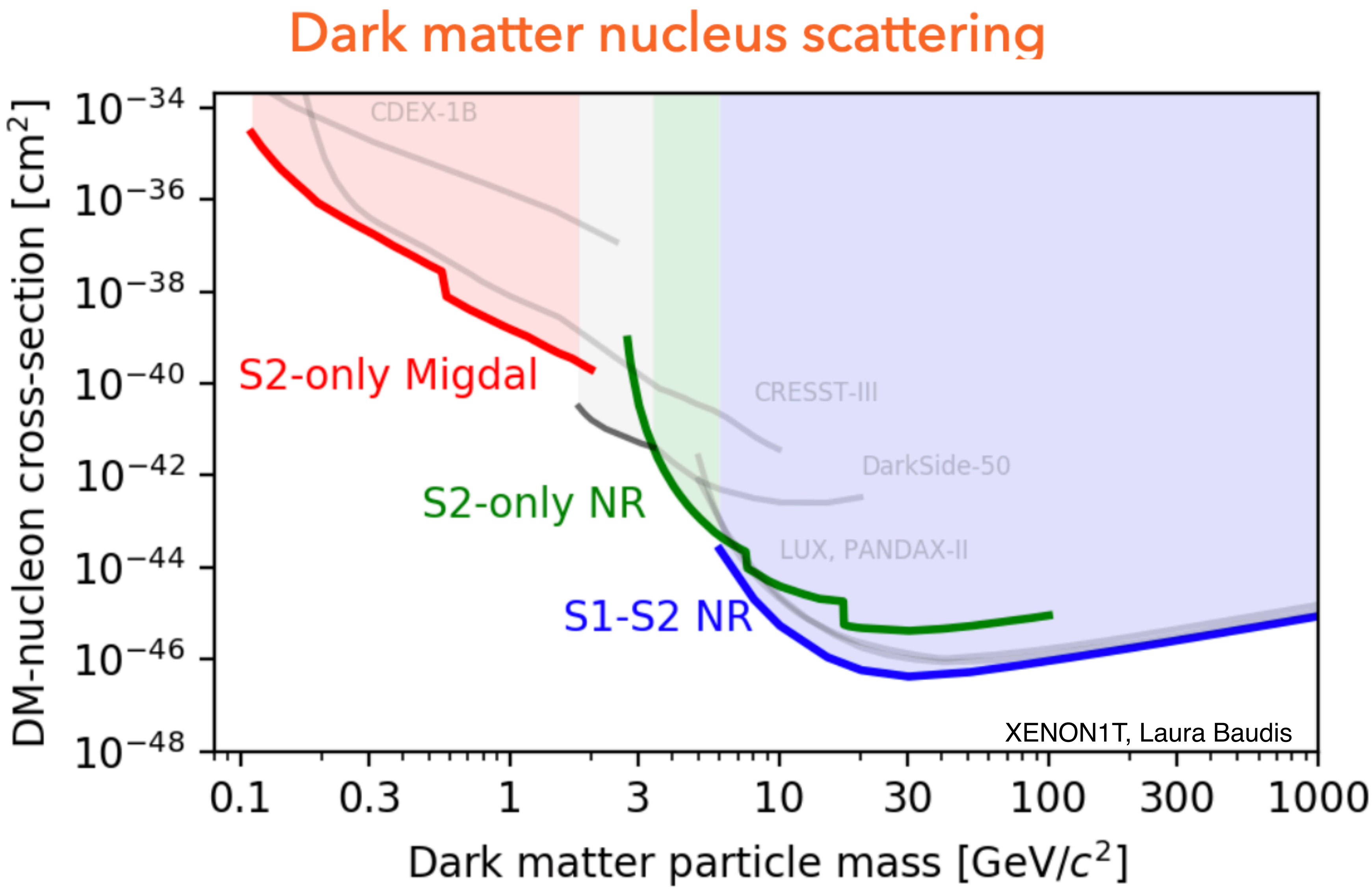
Genealogy of The Noble Target Field





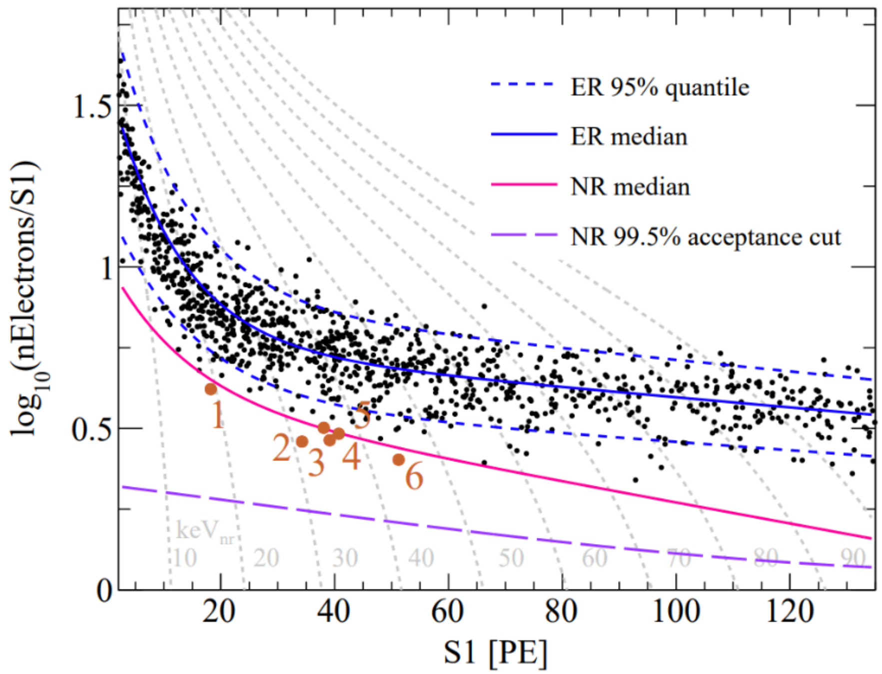
Dark Matter Searches: Past, Present & Future
Limit Scalar Cross-section at 60 GeV/c² [cm²]
Year
IGEX
DAMA '00
LIBRA '08
Edelweiss '01
CDMS I SUF '02
Edelweiss '03
ZEPLIN I
WARP '07
ZEPLIN II
CDMSII Soudan '04
CRESST '11
Edelweiss '09
Darkside-50 '14
PICO-60 C3F8 '17
XENON10
CDMSII Soudan '10
XENON100 '10
Edelweiss '11
ZEPLIN III
PICO-60 CF3I '16
Darkside-50 '15
CDMS II Soudan '15
Darkside-50 '18
SuperCDMS Soudan '18
DEAP-3600 '17
XENON100 '11
DEAP-3600 '19
Ar Detectors
XENON100 '12
LUX '13
LUX '15
PandaX II '16
LUX '16
XENON1T '17
PandaX II '17
XENON1T '18
PandaX-4T
Xe Detectors
PandaX-4T
Darkside-20k
LZ
XENONnT
Argo
DARWIN
Ge
NaI
Cryodet
Liq. Xe
Liq. Ar
Bubble
limit
signal
projected
Gaitskell et. al. (200830T1809)

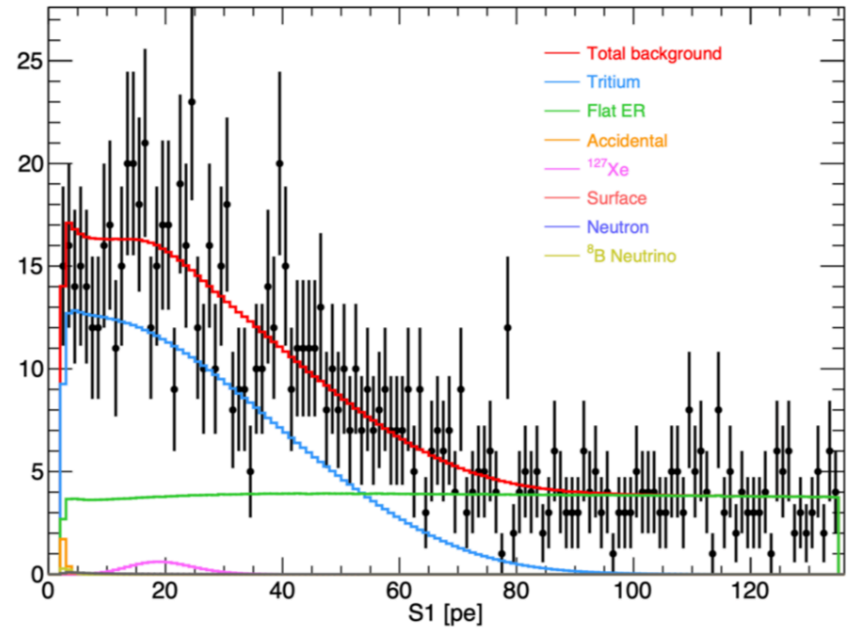
LXe TPC's Improving Sensitivity on Multiple Fronts



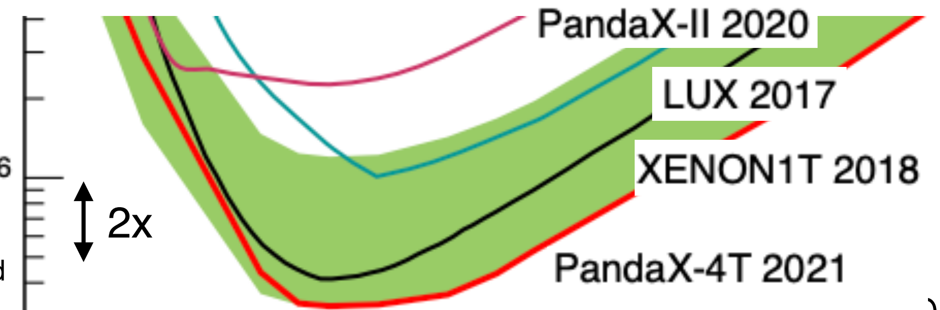
PandaX-4T

- Collaboration: 18 institutions, 84 scientists / 3.7 tonne active, 2.7 tonne fiducial
- New Search Results - July 2021/arXiv:2107.13438 Commissioning - 86 days of running





- General background similar to XE1T, however, tritium dominates at low energy. 3H was introduced during PandaX-II calibration with intrinsic 3H source. Working to remove.
- Currently crowded search space
  Look forward to significant improvements in search sensitivity over coming few years



Note PandaX-4T limit appears better than expected sensitivity / downward fluctuation of events rate compared to expected background

Any Newer News....

- PandaX-4T (Reported first commissioning result in July 2021 - 0.63~tonne year)
  - arXiv/2107.13438 - improved sensitivity just beyond XENON1T result

- Obviously, we keenly await the new results from
  - PandaX-4T (once removal of 3H contamination)
  - XENONnT (Science Run starts in 2021)
  - LZ (Science Run starts in 2021)

- All 3 have the scope to push >10x greater sensitivity than existing searches for >10 GeV WIMPs
  - Also capable of low mass searches through Migdal

- New News for LZ + DARWIN Next Generation Detector

Darwin-XENON-LZ Cooperation

- Future merger of DARWIN, XENON and LZ collaborations to build/operate next-generation liquid xenon experiment
  - Will form a new international collaboration
  - Comes after LZ and XENONnT are completed ~ 2026
- Paving the way now
  - First joint and very successful DARWIN LZ meeting April 26-27: https://indico.cern.ch/event/1028794/
  - MoU signed July 2021
    - 104 research group leaders from 16 countries

Links:
https://lz.lbl.gov/press/
https://darwin.physik.uzh.ch/news.html
https://www.brown.edu/news/2021-07-19/xenon

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
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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	Running	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/SUF
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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2016	2021	YangYang
COSINE-200	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	NaI	200 kg		Planning	2023	?	South Pole

Expect new results soon from >2.5 years of new exposure data (→ DEAP-3600)

Future Experiments with Noble Liquid

Dark Matter Direct Detection MeV - TeV

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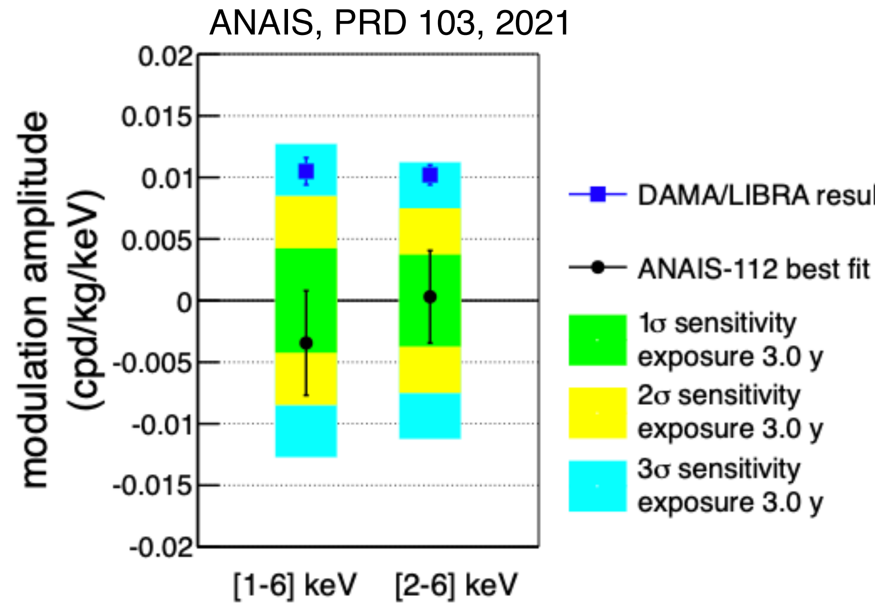
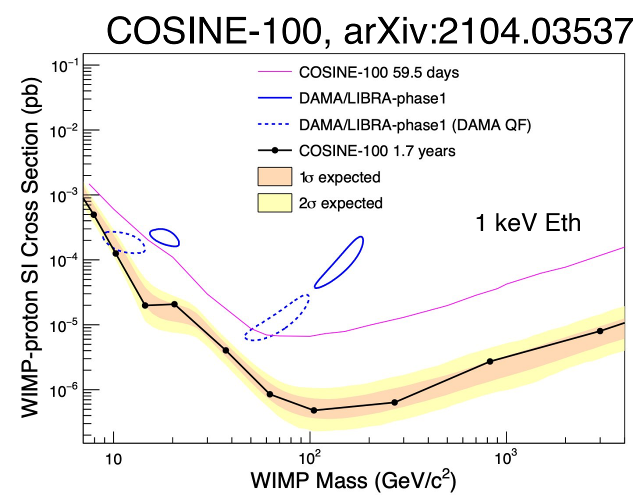
ANAIS-112	Scintillator	NaI	112 kg	Goal 5 years	Running	2017	2022	Canfranc
COSINE-100	Scintillator	NaI	106 kg		Running	2016	2021	YangYang
COSINE-200	Scintillator	NaI	200 kg		Construction	2022	2025	YangYang
COSINE-200 South Pole	Scintillator	NaI	200 kg		Planning	2023	?	South Pole
COSINUS	Bolometer Scintillator	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	[illegible]	[illegible]	Running	2016	?	CJPL
CDEX-100 / 1T	Ionizatio[illegible]	[illegible]	[illegible]	[illegible]	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

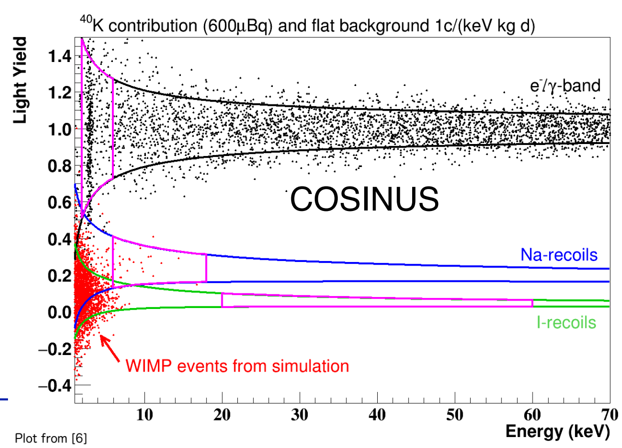
Modulation of DM Signals

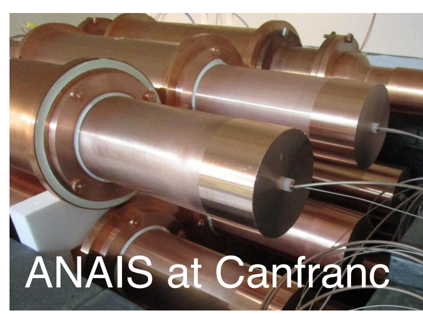
Sodium Iodide (NaI) experiments

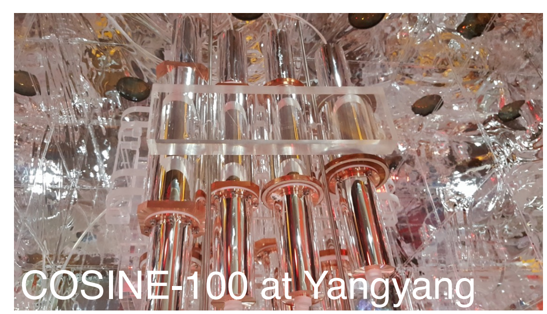
- DAMA/LIBRA observed annual modulation with NaI(Tl), now >9σ significance
  - DAMA Reported first observation in 1997 with 100 kg
  - DAMA/LIBRA Operating 200 kg since 2003
- So far, no evidence for annual modulation from
  - ANAIS-112 (100 kg, 3 y of data) Canfranc
    - PRD 103, 102005 (2021) - incompatible with DAMA/LIBRA at 3.3σ [1-6 keV]
      Note: Same threshold but BG is 3x that of DAMA/LIBRA
  - COSINE-100 (106 kg NaI, 1.7 y of data) Y2L
    - Nature 564, 83 (2018), PRL 123, 031302 (2019), arXiv:2104.03537 - excl. DAMA
- New experiments
  - COSINE-200 (200 kg, ultra pure NaI) Y2L
  - COSINUS: phonons+light in un-doped NaI => active background rejection; LNGS 2022/23





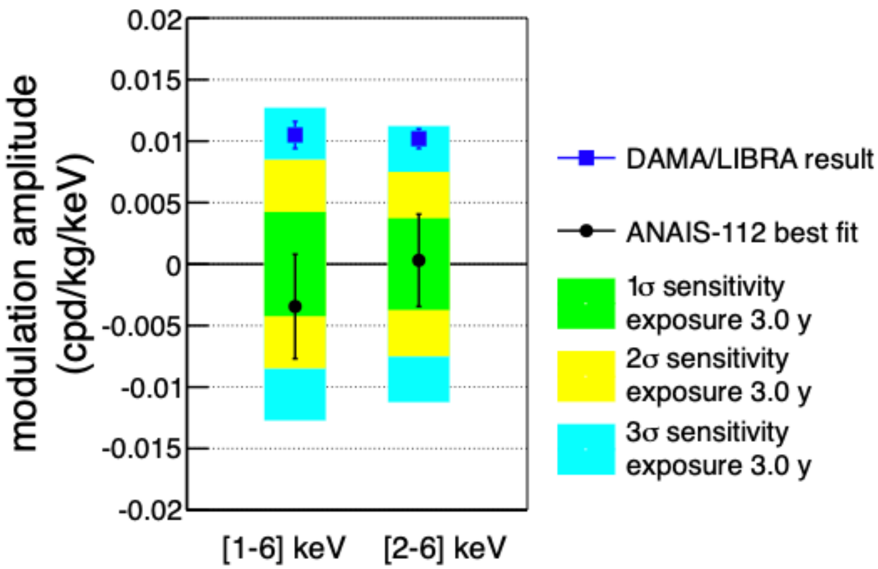




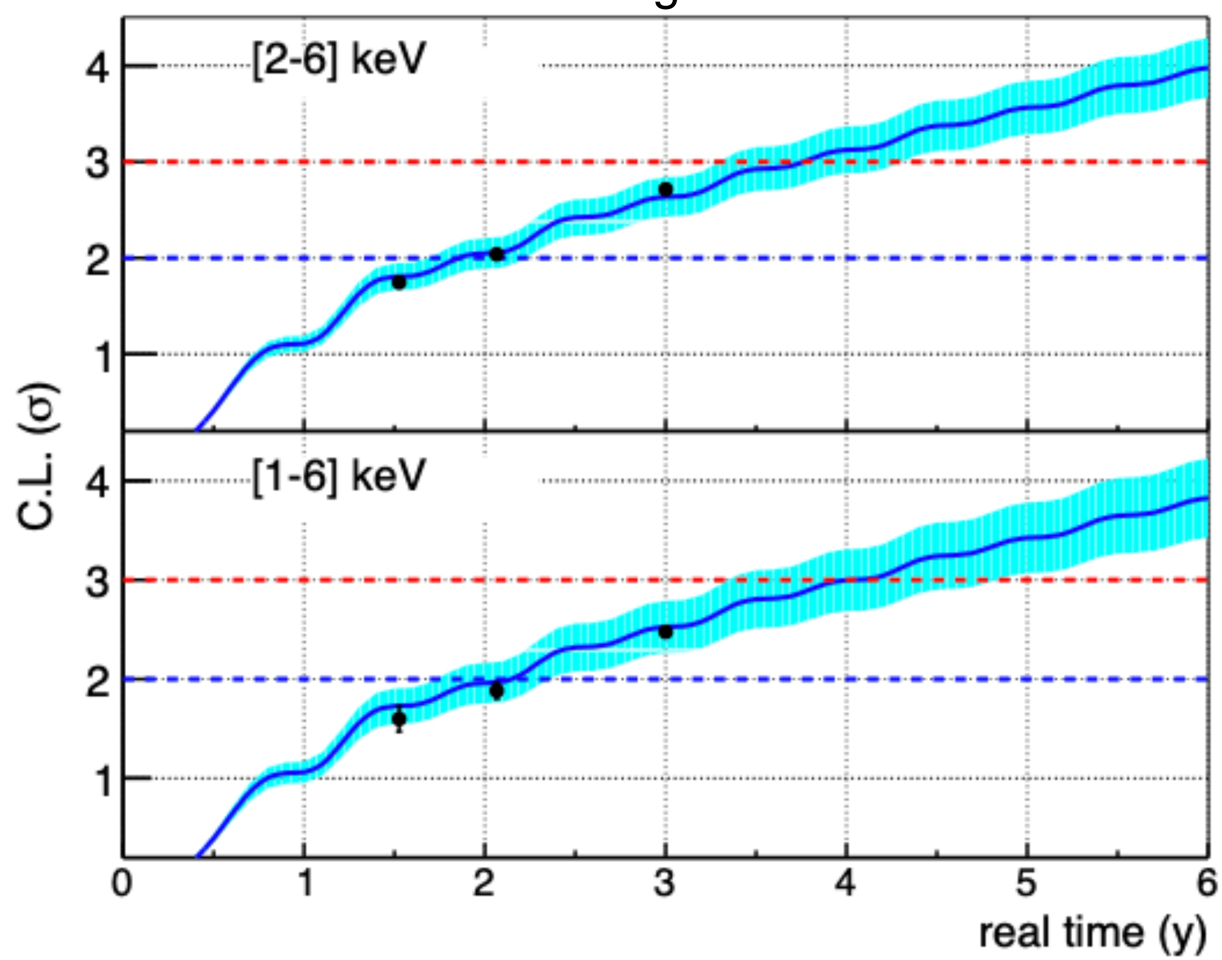


ANAIS-112 kg NaI Future Projected Sensitivity

- How rapidly will sensitivity improve further?



ANAIS-112 sensitivity to the DAMA/LIBRA signal in σ CL units



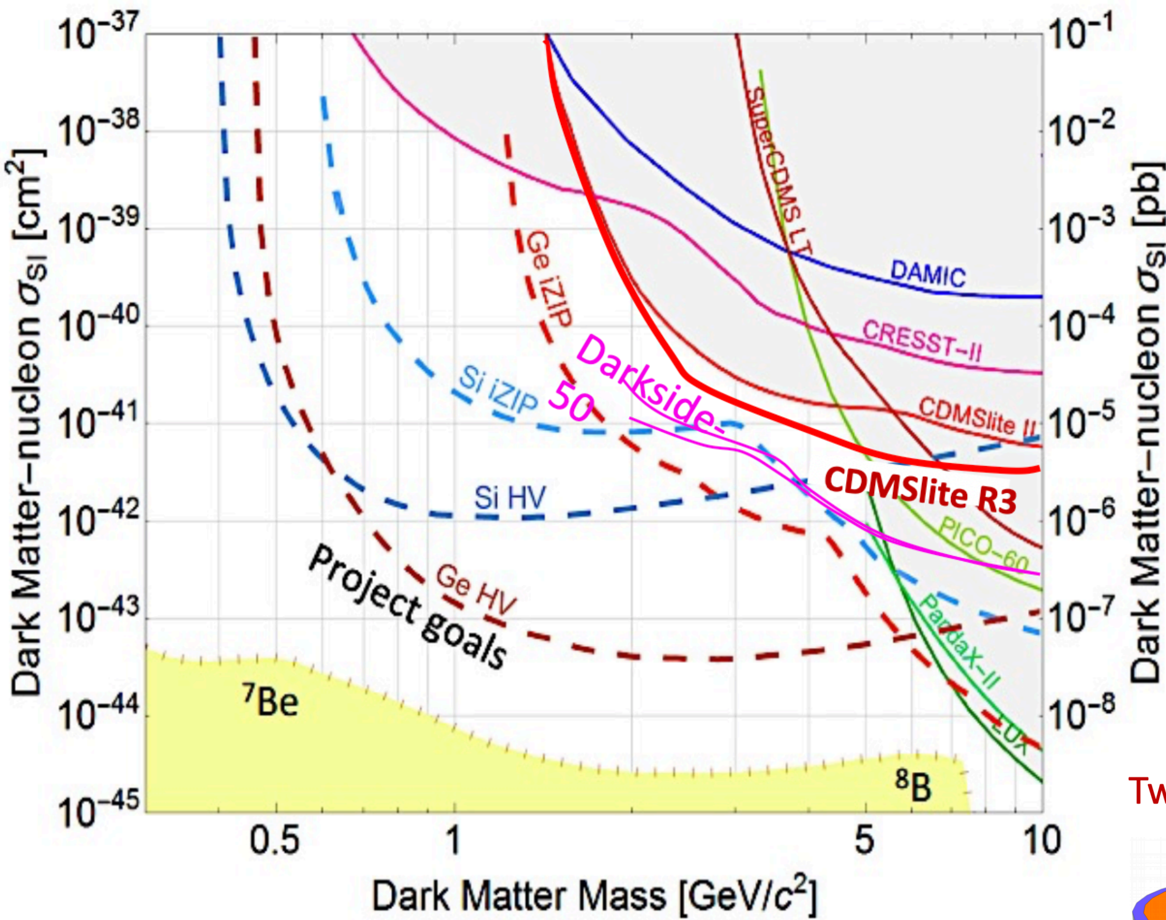
arxiv:2103.01175

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	Bubb				nded	2013	2015	SNOLAB
PICO-40	Bubb				uction	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

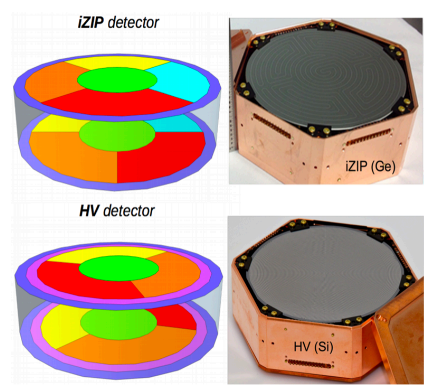
Future Cryogenic Detectors

SuperCDMS @ SNOLAB

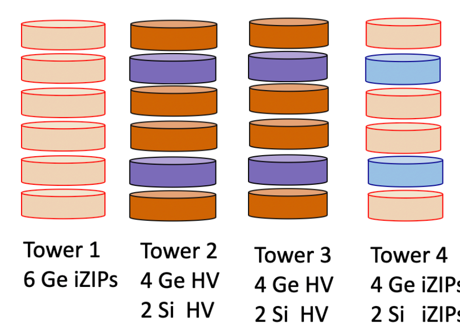


- New Cryogenic infrastructure being installed at SNOLab in order to allow 4-tower (and larger) payloads

Two Types of Detectors



Initial 4-tower payload



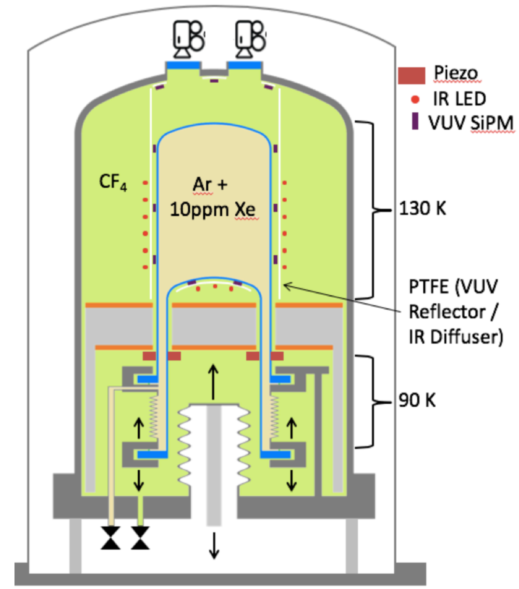
Dark Matter Direct Detection MeV - TeV

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

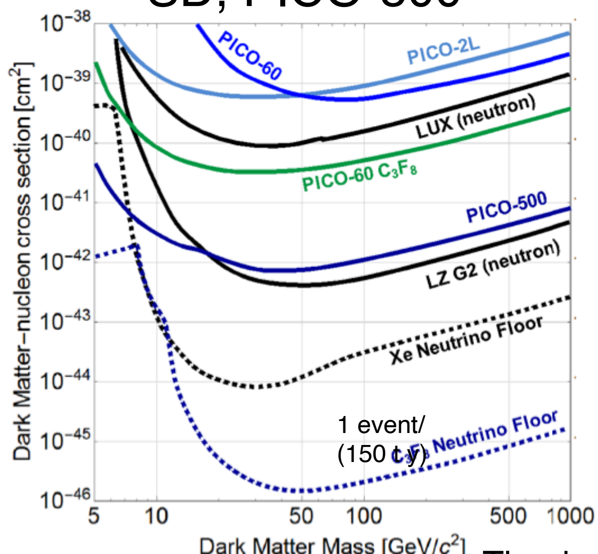
Bubble chambers

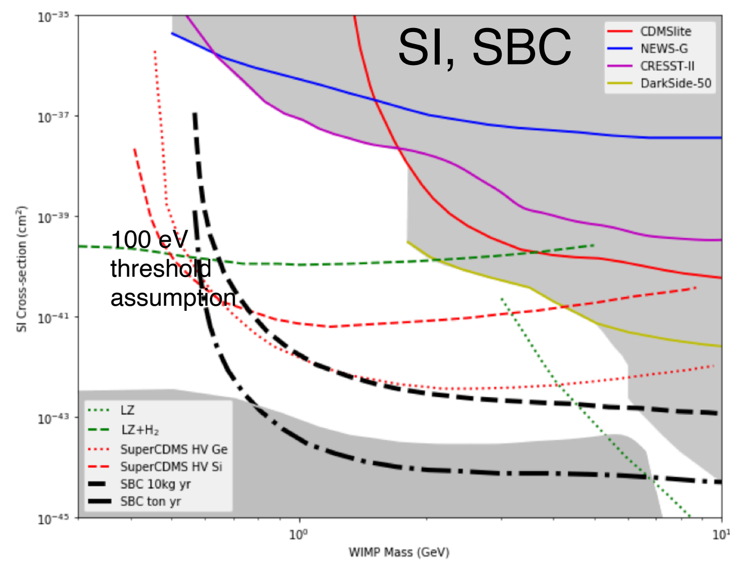
- PICO: superheated liquid C3F8
  - Acoustic + Visual (Camera) readout : ER event rejection
  - PICO-500 at SNOLAB: under design, installation/data in 2022/23
- New detector: the scintillating bubble chamber (SBC)
  - Superheated 10 kg Xe-doped LAr, cooled to 130 K, piezoelectric sensors + cameras readout + SiPMs for scintillation signal

SBC



SD, PICO-500





Thank you to Laura Baudis

Dark Matter Direct Detection MeV - TeV

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
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	[illegible]	[illegible]	[illegible]	Ended	2015	2015	SNOLAB
DAMIC	CCD	[illegible]	[illegible]	[illegible]	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

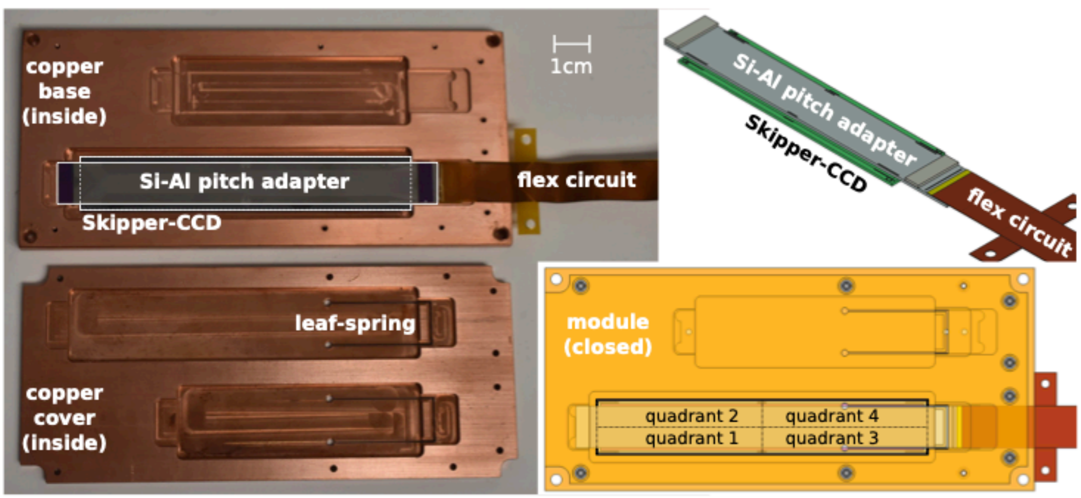
Directional Searches

Dark Matter Direct Detection MeV - TeV

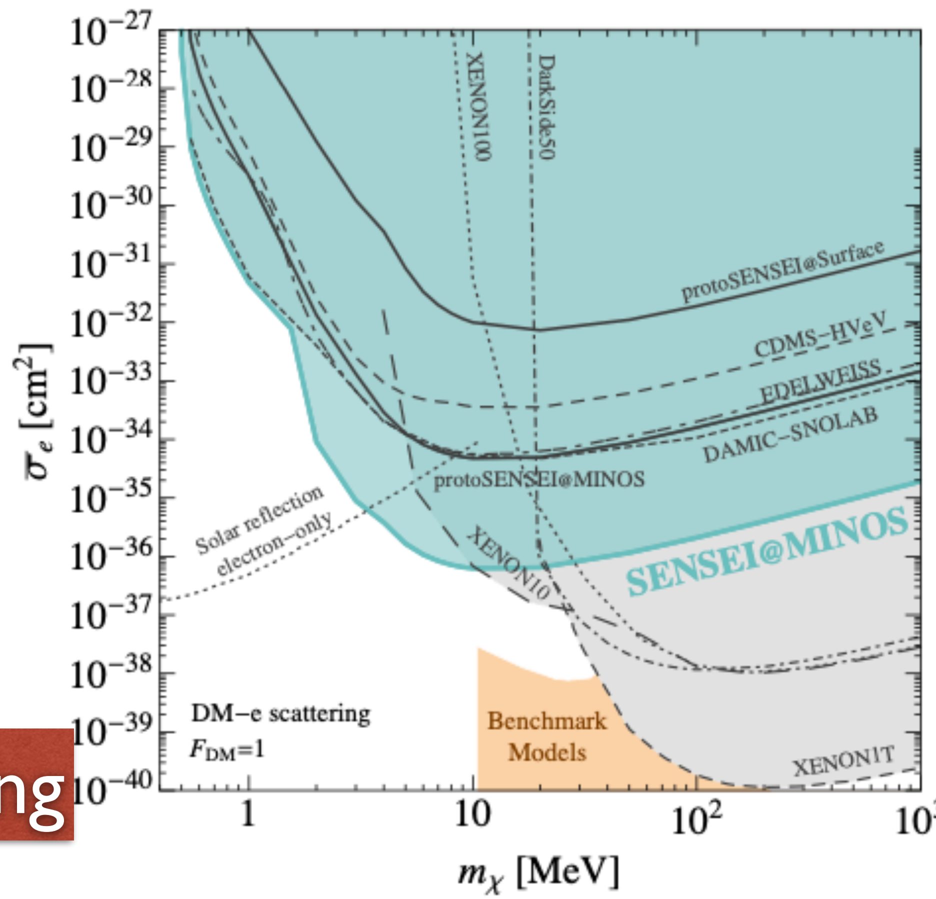
Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Location of Experiment
DAMIC	CCD	Si	2.9 g	0.6 kg d	Ended	2015	2015	SNOLAB
DAMIC	CCD	Si	40 g Si		Ended	2017	2019	SNOLAB
DAMIC100	CCD	Si	100 g Si		Not Built			SNOLAB
DAMIC-M	CCD Skipper	Si	1 kg Si		Construction	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

CCD + Skipper Amp: SENSEI @ SNOLAB / DAMIC-M @ LSM

- SENSEI
  - DM-Electron Scattering from SENSEI at FermiLab Minos Cavern
  - 2 g Skipper-CCD x 24 days observing 1,2,3,4-electron events => sub-GeV dark matter limits
  - Plan 100 g at SNOLAB



Note: There are other channels that data sets limits in see arXiv:2004.11378



DM Electron Scattering

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	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 Scintillatior	CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillatior	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillatior	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			LBNL

R&D
Planning
Construction
Running
Ended

Our Goal Remains to Create the …

QUIETEST KNOWN PLACES IN THE UNIVERSE

BUT LET'S HOPE NOT TOO QUIET

WE REALLY ARE LOOKING FOR A SIGNAL

Our Goal Remains to Discover Dark Matter …

We have been beating Moore's Law in terms of progress in the search-space (cross-section) 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

- 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 Ann. Mod. - but new NaI experiments in direct conflict with this result with growing CL
- Noble Targets
  - PandaX-4T operating at Jinping in 2021 (China) - released commissioning result July 2021 with new best sensitivity
  - LZ goal of operating at Sanford Lab in 2021 (US-DOE, UK, Portugal, S Korea ...)
  - XENONnT goal of operating at LNGS in 2021 (German, Swiss, US-NSF, Japan ...)
  - 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
  - Necessary technologies for 50 tonne+ detectors seems readily achievable - neutrino "fog"
    - We should see 8B solar neutrino signal in coming round of experiments (like ~6 GeV WIMP)
    - High Energy Atmospheric Neutrinos are still way off and will only begin to be seen in the 50 tonne+ detectors
      - Diffuse Supernova Background will hide under the Atm. Signal
  - 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
  - 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