Dark Matter Direct Detection Experiment Review

Rick Gaitskell (<u>gaitskell@brown.edu</u>) Particle Astrophysics Group, Brown University, Department of Physics Co-Spokesperson, LUX Collaboration Ex-Spokesperson, LZ Collaboration Director of the Center for the Fundamental Physics of the Universe @ Brown LUX and LZ Experiments supported by US DOE HEP see information at <u>http://particleastro.brown.edu</u> <u>http://cfpu.brown.edu</u> <u>http://lz.lbl.gov</u>

Gaitskell / Brown University

If the S.I. Unit of Ignorance is the

"IDK"

Then we still rate

950 milli-IDK for the Composition of the Universe

Gaitskell / Brown University

What is the Universe made of?



30 years in dark matter 2341 FLET BELOW LEVEL

CDMS II: Winter @Soudan Minnesota

Sanford Lab LUX & LZ @Lead, South Dakota PHYSICS ITALIAN STYLE XENON10 @ Gran Sasso

Sanford Laboratory

Gaitskell / Brown University

Many International Efforts Over Last 20 Years



Dark Matter Searches

Rick Gaitskell, Brown University, LUX / DOE

Sanford Lab @ South Dakota





Sanford Lab, May 2012



Where are you today?

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



Dark Matter Searches

Deep Underground Laboratories - Escaping Cosmic Muons



How Many Gammas/Day?

Governor Rounds visits Sanford Lab, 2010

>1,000 γ / second/human

Gaitskell / Brown University

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



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).



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
- Department of Physics, Harvard University, Cambridge, MA 02138, USA
- 8 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 Z⁰ exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm3 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)

Volume 195, number 4

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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

- •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)



D	a	r
	J	

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 lonizonly	LXe	1,995 kg		Ended	2017	2019	LNGS	
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Run	2021	2025	LNGS	·IEV
LUX	TPC	LXe	250 kg	30,000 kg d	Ended	2013	2016	SURF	
LUX (Ionization)	TPC lonizonly	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 lonizonly	LAr	46 kg		Ended	2018	2019	LNGS	
Darkside-20k	TPC	LAr	30 t	200 t yr	lanning/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	Crvo Ionization	Ge	9 ka		Ended	2011	2015	Soudan	
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	~75 ka d	Ended	2012	2015	Soudan	
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 a	0.5 a d	Ended	2018	2018	Surface Lab	
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg	0.0 g u	Running	2020	2022	SNOLAB	
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB	
		00/01	n kg/o kg		Forded	2020	2020		
EDELWEISS III (High	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM	
Field)	Cryo Ionization HV	Ge	33 g	80 g d	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	C3F8	2 kg		Ended	2013	2015	SNOLAB	
PICO-40	Bubble Chamber	C3F8	35 kg		Running	2020	2010	SNOLAB	
	Bubble Chamber		50 kg		Fadad	2020	0047		
PICO-60	Bubble Chamber	C259	52 Kg		Construction/Bun	2013	2017	SNOLAB	
PICO-500	Bubble Chamber	CSFO	430 Kg		Construction/Run	2021		SINULAB	
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	
	TRO	11.							
ALETHEIA	IPC	He			R&D			China Inst. At. Energy	Judy Catholya

R&D

LBNL

Cryo TES

He

TESSERACT

R&D Planning Construction Running Ended

Dark Matter Searches

China Inst. At. Energy Rick Gaitskell, Brown University, LZ/DOE

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	TPC	LXe+H2	8,000 kg	1000	K&D	2026	0000	SURF
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DAMA/LIBRA	Scintillator	Nal	250 ka		Runnina	2003		LNGS
ANAIC 442	Cointillator		51011 51011	Cool E voore	o cuiran O	2100	0000	Confront
COSINE 100	Scintillator	Nal	112 Kg	Goal 5 years	Bunning	2016	2202	Vancyand
COSINE-200	Scintillator	Nal	200 kg		Construction	2022	2025	YandYand
COSINE-200 South Pole	Scintillator	Nal	200 kg		Planning	2023	2020	South Pole
COSINUS	Bolometer Scintillator	Nal	6		Planning	2023	· ~·	LNGS
SABRE PoP	Scintillator	Nal	5 kg		Construction	2021	2022	LNGS
SABRE (North)	Scintillator	Nal	50 kg		Planning	2022	2027	- RNGS
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SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan
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EDELWEISS III	Crvo Ionization	Ge	20 ka		Ended	2015	2018	TSM
EDELWEISS III (High		}						
Field)	Cryo Ionization HV	Ge	33 g	80 g d	Running	2019		LSM
CRESST-II	Bolometer Scintillatio	r CaWO4	5 kg		Ended	2012	2015	LNGS
CRESST-III	Bolometer Scintillatio	r CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HW Tests)	Bolometer Scintillatio	r CaWO4			Running	2020		LNGS
		0100			l	0.00	1	
PICO-2 PICO-40	Bubble Chamber Bubble Chamber	C3F8 C3F8	2 kg 35 kg		Runnina	2013	2015	SNOLAB
PICO-60	Bubble Chamber	CF31.C3F8	52 kg		Ended	2013	2017	SNOLAB
PICO-500	Bubble Chamber	C3F8	430 kg		Construction/Run	2021		SNOLAB
					T e t T e L			
NEWAGE O36	Gas Directional	CF4	0.14 Kg	ARKAA	Ended	2012	2017	bouidy
CYGNUS???		t 5	D t	n 64 c.t	FIINGO	2102	107	
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 a 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
	TPC	ЧP			R&D			China Inst. At. Energy
TERREACT	Chin TEC	Ha H			L S L			

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 ~33 rd year of searching - now at a sensitivity that 10⁶ 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 10² 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 Rick Gaitskell, Brown University, LZ/DOE



22

Dark Matter Searches: Past, Present & Future



Dark Matter Searches: Past, Present & Future





25

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

-28

Journey Through the Theoretical Landscape

•Cumulative Theoretical work

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

• Includes 1966 Gershtein & Zeldovich 1977 Dicus, Kolb & Teplitz,

1966-1977 Massive Standard Model Neutrinos

- 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</u> <u>early annihilation phase</u> and are present in a <u>radiation dominated early universe</u>

WIMPs

- The thermal relic abundance calculation provides us with a collection of wellmotivated 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

30

	Model	S	ignatur	e ∫	E dr [fb"	Mass limit				Reference
~	$\xi \hat{q}, \hat{q} \rightarrow q \hat{T}_{\pm}^{0}$	D.c.p mono-jet	2-6 jets 1-3 jets	Entra Line	139 36.1	[[10н Doger.] [[1x, tx Degen.] 0.43	0.71	1.9	m(7)~400 GeV m(0~m(7))=5 GeV	ATLAS-CONF-2019-040 1711.05501
vole	12.2-100 ⁰	0 <i>e</i> ,p	2-6 jets	\underline{E}_{T}^{min}	139		Forbidder	1.15-1.9	2.35 n(f)=0 GeV	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
8	73. 5-+	14.4	2-6 jets		139	2			2.2 m0 ²)-000 GeV	ATLAS-CONF-2020-047
	žž. ż→cötff)k	64. pp	2,015	Er	38.1	2		1.2	$m(g \cdot m(\tilde{r}_{1}^{c}))=50$ GeV	1805.11581
CIUSIT	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\bar{q}WZ\bar{\chi}_1^0$	0 e.p SS e,p	7-11 jets 6 jets	E_T^{min}	139 139			1.15	7 m(2) #600 GeV m(2)-m(2) #200 GeV	ATLAS-CONF-2020-002 1909.06457
al.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{t}_{1}^{(i)}$	0-1 c.p SS r.p	3.5 6,ets	E_T^{\min}	79.8 139			1.25	2.25 n(?))~200 GeV m(g)-m(?))=300 GeV	ATLAS-CONF-2018-041 1909-06457
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow \delta \tilde{t}_1^0 / \delta \tilde{t}_1^A$		Multiple Multiple		36.1 139	Forbidden Forbidden	0.9		m(X ⁰ ₁)=300 GeV, BR(M ⁰ ₁)=1 m(X ⁰ ₁)=200 GeV, m(X ⁰ ₁)=300 GeV, BR(X ⁰ ₁)=1	1708 05255, 1711.03901 1909.08457
	$\bar{b}_1\bar{b}_1, \bar{b}_1 \rightarrow b\bar{x}_2^0 \rightarrow 66\bar{x}_1^0$	0.0.0	6.5	E.m.s.	139	Foxbidden	0.05.0.05	0.23-1.35	$\operatorname{Am}(\tilde{r}_{1}^{0}, \tilde{k}_{1}^{0}) = 180 \text{ GeV}, \operatorname{m}(\tilde{r}_{1}^{0}) = 100 \text{ GeV}$	1908.05122
22	11 1 20	614-	2110	C.m.s.	199		0.13-0.03	1.25	anis_2011-000000, N(1)-0000	ATL # 0.07 ME . 2320.033 . 000 # 410
85	nn, n=with	100	Sints't à	TT.	132	0.44	0.50	1.25	mut_)=1 GeV	ATL 65-CONE-2019-017
2.8	$i_1i_1, i_1 \rightarrow w_{DK_1}$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_2 \rightarrow \tilde{r}_1hv, \tilde{r}_1 \rightarrow m\tilde{G}$	11+1047	2 jets/1 à	All in	36.1		0.20	1.15	mi7.1=800 GeV	1803.10176
88	64. 1. w. 177. 2 R.	D.c.p	20	C'min.	36.1		0.85		ntf:)=0GeV	1805.01649
2.6	and and only and	0 c.p	mono-jet	Ref. in	36.1	0.45 0.43			$m(\tilde{r}_1, z) \cdot m(\tilde{r}_1) = 50 \text{ GeV}$ $m(\tilde{r}_1, z) \cdot m(\tilde{r}_1) = 5 \text{ GeV}$	1805.01649 1711.00301
	6.6. L	1-2 e.u	1.4.5	C***	139		0.057	41.1B	m(2)=500 GeV	SUSY-2016-00
	$i_1i_1, i_1 \rightarrow i_2, i_2 \rightarrow i_1 + Z$	3 e. p	1.5	$E_{\rm T}^{\rm max}$	139	Forticition	0.86		$\mathfrak{m}(\tilde{r}_1^0)$ = 560 GeV, $\mathfrak{m}(\tilde{r}_1)$ $\mathfrak{m}(\tilde{r}_1)$ = 40 GeV	SUS7-2018-09
	$\tilde{x}_1 \tilde{x}_2$ via WZ	3.e.p (e,p)	≥ 1 jat	$\frac{E_T^{min}}{E_T^{min}}$	139 139	1 (x ² 1 (x ²) 1 (x ²) 0.205	0.64		$n(\hat{r}_1^2)=0$ $n(\hat{r}_1^2)=n(\hat{r}_1^2)=5$ GeV	ATLAS-CONF-2020-015 1911-12606
	8181 VA 1010	20.0		Emise.	139	0.42			$\operatorname{ra}(\mathbb{F}_1^0) = 0$	1908.06215
-	X1X2 via Wh	0-1 c.p	2 à/2 y	ET.	139	r it Forbidden	0.74		$m(\tilde{\kappa}_1^3)$ =70 GeV	2004.10894, 1909.09228
38	X1X1 Vis (c/2	24.4		AT.	139		1.0	2	$m(\tilde{c}_{i}J)=0.5(m(\tilde{c}_{1}^{n})-m(\tilde{c}_{1}^{n}))$	1908.06215
25	22, 7-+121	27		E.	139	PL-TRL 0.16-0.3 0.12-0.39			ra(E))=0	1911.06660
	$\tilde{t}_{\perp \mathbf{R}} \tilde{t}_{\perp \mathbf{R}}, \tilde{t}_{\rightarrow} \tilde{t} \tilde{t}_{\perp}^{*}$	2 e.p	> 1 int	a land	139	0.216	0.7		m(2))=0 m(2)_m(2)_=10 (bety	1908.00215
	$\hat{H}\hat{H}, \hat{H} \rightarrow l\hat{G}/2\hat{G}$	0 c.p 4 c.p	> 3.5 0 lets	Enter Filmer	36.1 139	0.13-0.28	0.29-0.88		$\frac{\partial P(\hat{x}_1^2 \rightarrow h\hat{G})*1}{\partial P(x_1^2 \rightarrow h\hat{G})*1}$	1806.04050 ATLAS-CONF-2020-040
S s	Direct $\hat{k}_1^* \hat{k}_1^*$ prod., long-lived \hat{k}_1^*	Disapp. trk	1 jot	Effin	36.1	0.45			Puer Wino	1712.60116
÷3						0.15			Purehiggero	ATL-PHYS-PUB-2017-019
25	Stable 3 R-hadron		Multiple		36.1	2		2	.0	1902.01636,1806.04395
. j u	Metastable g R-hadron, g-sppl"		Mutiple		36.1	[rtg)=10 rs, 0.2 rs]		2	05 2.4 m(t [*] ₁)=100 GeV	1710.04901,1808.04995
	$\tilde{\chi}_1^+ \tilde{\chi}_1^\pm / \tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow Z \ell \rightarrow \ell \ell \ell$	3.4.4			139	(1/(1) (R) (R)(Zr)=1, 8R(Zr)=1)	0.625 1.1	35	PateWire	ATLAS-CONF-2020-009
	LFV $pp \rightarrow \hat{r}_i + X_i \hat{r}_i \rightarrow e\mu/e\tau/\mu\tau$	91/27.07			8.2			1.9	Apr -0.11, App -0.07	1607.06079
	$\hat{X}_1 \hat{X}_1^{\pm} / \hat{X}_2^{\pm} \rightarrow WW/Z\ell\ell\ell\ell_{22}$	40.0	C jets	E_T^{max}	38.1	$\lambda_{1}^{4} (\hat{x}_{2}^{2} - [\lambda_{00} \neq 0, \lambda_{20} \neq 0]$	0.82	1.33	$m(k_1^2)=100$ GeV	1804.05802
~	$gg, g \rightarrow qqg U_1, X_1 \rightarrow qqq$	4	5 large - K je	es -	36.1	[mt4],=200 GeV, 1100 GeV]		1.3 1.9	Laige Z ₁₁₇	1894.03565 ATL 49.0004E-0010-000
d.			All cline		20.1	112 and 102	1.	2	mirijanu umijums-like	MILLO-DOW-2018 003
4	$\Pi, t \rightarrow i \mathcal{K}_1, \mathcal{K}_1 \rightarrow tha$		anutiple		26.1	(A ₂₀) (and (10.2) 0.	1.1	15	m(Y)=200 GeV, bing-like	ATLAS-CONF-2018-003
	$n_1 :\rightarrow m_1, X_1 \rightarrow m_2$ $k, k, k \rightarrow h_1$		2 40		139	Forbidden	0.85		m(h) =500 GeV	17:0:0017:
	hh. h-sof	20.0	26		38.1	0.42		0.4-1.45	BR/A Northaire 2015	1710,66544
		1.0	DV		135	(10-10< J [*] ₂₀₁ <10-0. 30-10< J [*] ₂₀₁ <30-9)	1.6	1.6	BP\$7,-+pit=102%,cost,=1	2003.11955

Dark Matter Searches

LHC (ATLAS) SUSY Particle Searches

	A Ju	TLAS SUSY Sea	rches*	- 95%	6 CL	Lov	ver Li	imits						ATLAS Preliminary $\sqrt{s} = 13$ TeV
		Model	S	ignatur	e ∫	<i>L dt</i> [fb ⁻	1]		Mass limit					Reference
	S	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0$	0 e, μ mono-jet	2-6 jets 1-3 jets	$\begin{array}{c} E_T^{\rm miss} \\ E_T^{\rm miss} \end{array}$	139 36.1	 <i>q</i> [10x De <i>q</i> [1x, 8x 	egen.] Degen.]	0.43	0.71		1.9	m($ar{\chi}_1^0$)<400 GeV m($ar{q}$)-m($ar{\chi}_1^0$)=5 GeV	ATLAS-CONF-2019-040 1711.03301
	arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0 <i>e</i> , <i>µ</i>	2-6 jets	$E_T^{\rm miss}$	139	ře ře			Forbido	len	2.35 1.15-1.95	$m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=1000 \text{ GeV}$	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
	Isive Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_{1}^{0}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_{1}^{0}$	1 e, μ ee, μμ 0 e, μ	2-6 jets 2 jets 7-11 jets	E_T^{miss} E_T^{miss}	139 36.1 139	ř ř				1.2	2.2	$m(\tilde{\chi}_{1}^{0}) < 600 \text{ GeV}$ $m(\tilde{g}) \cdot m(\tilde{\chi}_{1}^{0}) = 50 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0}) < 600 \text{ GeV}$	ATLAS-CONF-2020-047 1805.11381 ATLAS-CONF-2020-002
	Inclu	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	SS e, μ 0-1 e, μ SS e, μ	6 jets 3 <i>b</i> 6 jets	$E_T^{\rm miss}$	139 79.8 139	180 180				1.15	2.25	m(\tilde{g})-m($\tilde{\chi}_{1}^{0}$)=200 GeV m($\tilde{\chi}_{1}^{0}$)<200 GeV m(\tilde{g})-m($\tilde{\chi}_{1}^{0}$)=300 GeV	1909.08457 ATLAS-CONF-2018-041 1909.08457
		$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple Multiple		36.1 139	$\tilde{b}_1 \\ \tilde{b}_1$	Forbio	dden Forbidden	0.9		$m(\tilde{\chi}_{1}^{0})=200$	$m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$ GeV, $m(\tilde{\chi}_{1}^{+})=300 \text{ GeV}, BR(t\tilde{\chi}_{1}^{+})=1$	1708.09266, 1711.03301 1909.08457
	s	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 {\rightarrow} b\tilde{\chi}^0_2 {\rightarrow} bh\tilde{\chi}^0_1$	0 e, μ 2 τ	6 b 2 b	$\begin{array}{c} E_T^{\rm miss} \\ E_T^{\rm miss} \end{array}$	139 139	$\tilde{b}_1 \\ \tilde{b}_1$	Forbidden		0.13-0.85	0.23-1.35	5 Δm(2 Δr	$\tilde{x}_{2}^{0}, \tilde{x}_{1}^{0}$)=130 GeV, m (\tilde{x}_{1}^{0}) =100 GeV m $(\tilde{x}_{2}^{0}, \tilde{x}_{1}^{0})$ =130 GeV, m (\tilde{x}_{1}^{0}) =0 GeV	1908.03122 ATLAS-CONF-2020-031
	gen. squar	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b \nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0-1 e, μ 1 e, μ 1 τ + 1 e, μ, τ 0 e, μ	\geq 1 jet 3 jets/1 b 2 jets/1 b 2 c	E_T^{miss} E_T^{miss} E_T^{miss} E_T^{miss}	139 139 36.1 36.1	<i>ī</i> ₁ <i>ī</i> ₁ <i>ī</i> ₁ <i>č</i>		0.44	-0.59 0.85	1.25 1.16		$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=400 \text{ GeV}$ $m(\tilde{\tau}_{1})=800 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$	ATLAS-CONF-2020-003, 2004.14060 ATLAS-CONF-2019-017 1803.10178 1805.01649
	3rd dire	inter set energy set	0 e, µ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1 \\ \tilde{t}_1$		0.46 0.43				$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\tilde{t}}_1^0) = 50 \text{ GeV}$ $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\tilde{t}}_1^0) = 5 \text{ GeV}$	1805.01649 1711.03301
		$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0$ $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	1-2 e,μ 3 e,μ	1-4 b 1 b	E_T^{miss} E_T^{miss}	139 139	ι̃ 11 12		Forbidden	0.0 0.86	67-1.18	$m(\tilde{x}_1^0)$	$m(\tilde{\chi}_2^0)$ =500 GeV)=360 GeV, $m(\tilde{i}_1)$ - $m(\tilde{\chi}_1^0)$ = 40 GeV	SUSY-2018-09 SUSY-2018-09
		$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ	3 е, µ ее, µµ	≥ 1 jet	$E_T^{\rm miss}$ $E_T^{\rm miss}$	139 139	$\begin{array}{c} \tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2 \\ \tilde{\chi}^{\pm}_1/\tilde{\chi}^0_2 \end{array}$	0.205		0.64			$m(\tilde{\chi}_{1}^{n})=0$ $m(\tilde{\chi}_{1}^{n})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$	ATLAS-CONF-2020-015 1911.12606
		$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^{0}$ via Wh	2 e,μ 0-1 e,μ	$2 b/2 \gamma$	E_T^{miss} E_T^{miss}	139 139	$\begin{array}{cc} \tilde{\chi}_1^{\pm} \\ \tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0 & Fc \end{array}$	orbidden	0.42	0.74			$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{0})=70 \text{ GeV}$	1908.08215 2004.10894, 1909.09226
10 ⁻³²	EW	$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} \operatorname{via} \tilde{\ell}_{L} / \tilde{\nu}$ $\tilde{\tau} \tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_{1}^{0}$	2 e,μ 2 τ		E_T^{miss} E_T^{miss}	139 139	$\tilde{\chi}_1^{\pm}$ $\tilde{\tau} = [\tilde{\tau}_L, \tilde{\tau}_R]$.L] 0.16	0.12-0.39		1.0		$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ $m(\tilde{\chi}_{1}^{0})=0$	1908.08215 1911.06660
10 ⁻³⁴		$\tilde{\ell}_{1,R}\tilde{\ell}_{1,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, μ ee, μμ	0 jets ≥ 1 jet	E_T^{miss} E_T^{miss}	139 139	ĩ ĩ	0.256		0.7			$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\ell})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	1908.08215 1911.12606
		$\hat{H}\hat{H}, \hat{H} \rightarrow h\hat{G}/Z\hat{G}$	0 e, μ 4 e, μ	$\geq 3 b$ 0 jets	E_T^{miss} E_T^{miss}	36.1 139	Η Η	0.13-0.23	0	0.29-0.88			$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 ATLAS-CONF-2020-040
10-30 TENOWIT	-lived icles	$\operatorname{Direct} \tilde{\chi}_1^* \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^*$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} = 0.15 $	i	0.46				Pure Wino Pure higgsino	1712.02118 ATL-PHYS-PUB-2017-019
10 ⁻³⁸	Long	Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$		Multiple Multiple		36.1 36.1	\tilde{g} $\tilde{g} = [\tau(\tilde{g}) = 1$	10 ns, 0.2 ns]			-	2.0 2.05 2.4	$m(\tilde{\chi}_1^0)$ =100 GeV	1902.01636,1808.04095 1710.04901,1808.04095
10 ⁻⁴⁰		$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp} / \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{\pm} \rightarrow Z \ell \rightarrow \ell \ell \ell$ LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu / e\tau / \mu \tau$	3 е, µ еµ,ет,µт			139 3.2	$\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}^{0}$ [BF $\tilde{\nu}_{r}$	$R(Z\tau)=1$, $BR(Ze)=1$]	0.625	1.05	1.9	Pure Wino λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07	ATLAS-CONF-2020-009 1607.08079
10 ⁻⁴²		$\begin{split} \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 &\to WW/Z\ell\ell\ell\ell\nu\nu \\ \tilde{g}\tilde{g}, \tilde{g} \to qq \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq \end{split}$	4 e, μ 4	0 jets 5 large- <i>R</i> j∉ Multiple	E_T^{miss} ets	36.1 36.1 36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 = [\lambda_0]$ $\tilde{g} = [m(\tilde{\chi}_1^0) = \tilde{g}$ $\tilde{g} = [\chi_{112}'' = 2\epsilon$	33 ≠ 0, 3 _{12k} ≠ 0] 200 GeV, 1100 GeV e-4, 2e-5]	٧J	0.82	1.33 1.3 1.05	1.9 2.0	$m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ Large $\lambda_{112}^{\prime\prime}$ $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV, bino-like}$	1804.03602 1804.03568 ATLAS-CONF-2018-003
10-44	RP	$t\bar{t}, \bar{t} \rightarrow t\bar{\chi}_{1}^{0}, \bar{\chi}_{1}^{0} \rightarrow tbs$ $t\bar{t}, \bar{t} \rightarrow b\bar{\chi}_{1}^{+}, \bar{\chi}_{1}^{+} \rightarrow bbs$		Multiple $\ge 4b$		36.1 139	τ̃ [λ ₃₂₃ =2e τ̃	e-4, 1e-2]	0 Forbidder	.55	1.05		m($\tilde{\chi}_1^0$)=200 GeV, bino-like m($\tilde{\chi}_1^{\pi}$)=500 GeV	ATLAS-CONF-2018-003 ATLAS-CONF-2020-016
10 ⁻⁴⁶		$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e,μ 1 μ	2 jets + 2 b 2 b DV	,	36.7 36.1 136	$\tilde{t}_1 = [qq, bs]$ $\tilde{t}_1 = \tilde{t}_1 = [10-104]$	< X ₂₁₄ <1e-8, 3e-10	0.42)< 30-9]	0.61	0.4-1.	.45 1.6	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%$, $\cos\theta_i = 1$	1710.07171 1710.05544 2003.11956
10 ⁻⁴⁸	-	•												
10 ⁻⁵⁰ 0.1 0.3	*Only phen simp	a selection of the available ma nomena is shown. Many of the l lified models, c.f. refs. for the a	ss limits on r limits are ba ssumptions	new state sed on made.	s or	1	0-1				1	·	Mass scale [TeV]	

WIMP mass [GeV/c²]

 10^{-38}

 10^{-42}

 10^{-48}

Dark Matter Searches

Cross Section [cm²]

31

WIMPs

- The thermal relic abundance calculation provides us with a collection of wellmotivated 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

	Model	S	ignatur	e∫	L dt [fb	Ma	iss limit					Reference
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\ell}_1^0$	0 e, µ mono-jet	2-6 jets 1-3 jets	E_T^{miss} E_T^{miss}	139 36.1	<pre></pre>	0.43	0.71		1.9	m($\tilde{\chi}_{1}^{0}$)<400 GeV m($\tilde{\chi}_{1}^{0}$)=5 GeV	ATLAS-CONF-2019-040 1711.03301
rche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 e, µ	2-6 jets	E_T^{miss}	139	ž ž		Forbidden	1.	2.35	m($\tilde{\chi}_{1}^{0}$)=0 GeV m($\tilde{\chi}_{1}^{0}$)=1000 GeV	ATLAS-CONF-2019-040 ATLAS-CONF-2019-040
900	an amanwith	1.6.4	2-6 jets		139	2				22	m(20) c600 GeV	ATLAS-CONE-2020-047
0	22. 2→23(()) ⁰	ее.µµ	2 jets	E_{τ}^{miss}	36.1	2			1.2		m(2)-m(2)=50 GeV	1805.11381
Siv	$\tilde{r}\tilde{r}, \tilde{r} \rightarrow arWZ\tilde{\chi}_{1}^{0}$	0 e. µ	7-11 jets	Eriss	139	2				1.97	m(X ⁰ ₁) <600 GeV	ATLAS-CONF-2020-002
G		SS e, μ	6 jets		139	2			1.15		m(g)-m(x1)=200 GeV	1909.08457
5	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_{1}^{0}$	0-1 e,μ SS e,μ	3 b 6 jets	E_T^{miss}	79.8 139	100 100			1.25	2.25	$m(\tilde{\ell}_1^0)$ <200 GeV $m(\tilde{\varrho})$ - $m(\tilde{\ell}_1^0)$ =300 GeV	ATLAS-CONF-2018-041 1909.08457
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^+$		Multiple		36.1	kı Forbidden	Endeiddan	0.9			$m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$	1708.09266, 1711.03301
	0		maripio	ermine .	139	<i>b</i> ₁	Polbibben	0.74		m(r_1)=200 Ge	v, m(r1)=300 Gev, BH(rr1)=1	1909.00407
	$b_1b_1, b_1 \rightarrow b\chi_2^* \rightarrow bh\chi_1^*$	27	24	Eliss	139	b: Forbidden		0.13-0.85	0.23-1.35	Am(Y ₂ ,	χ_1^{-} = 130 GeV, m(χ_1^{-}) = 100 GeV χ_1^{0} χ_1^{0} = 130 GeV m(χ_1^{0}) = 0 GeV	1905.03122 ATLAS-CONE-2020-031
ž Š	77.7.00	0-1 c #	> liet	rmiss	139	ī.			1 25		m(10)-1000001(m(11)-0001	ATLAS-CONE-2020-003, 2004 1406
53	$i_1i_1, i_1 \rightarrow i_1 c_1$ $i_1i_2, i_2 \rightarrow WhF^0$	1.6.4	3 jets/1 b	Emiss	139	i.	0.44-0	0.59	1160		m(2)=400 GeV	ATLAS-CONF-2019-017
, 'n	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1 T + 1 e.µ.T	2 jets/1 b	E_T^{miss}	36.1	Î ₁			1.16		m(P1)=800 GeV	1803.10178
85	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / c \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0 e, µ	20	E_T^{miss}	36.1	ē		0.85			m(\$10)=0 GeV	1805.01649
of a		0 e.µ	mono-jet	$E_T^{\rm miss}$	36.1	i ₁ ī ₁	0.46 0.43				$m(\tilde{t}_1,\tilde{z})-m(\tilde{t}_1^0)=50 \text{ GeV}$ $m(\tilde{t}_1,\tilde{z})-m(\tilde{t}_1^0)=5 \text{ GeV}$	1805.01649 1711.03301
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}^0_{-2}, \tilde{\chi}^0_{-2} \rightarrow Z/h\tilde{\chi}^0_{-1}$	1-2 e, µ	1-4 b	E_T^{miss}	139	Ĩ1		0.067	-1.18		m(\tilde{k}_{2}^{0})=500 GeV	SUSY-2018-09
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ	1 <i>b</i>	E_T^{miss}	139	Ĩ2	Forbidden	0.86		$m(\tilde{\chi}_{1}^{0})=$	360 GeV, $m(\tilde{t}_1) \cdot m(\tilde{t}_1^0) = 40 \text{ GeV}$	SUSY-2018-09
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	3 e.μ ee.μμ	≥ 1 jet	$\begin{array}{c} E_T^{\rm miss} \\ E_T^{\rm miss} \end{array}$	139 139	$\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ $\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0}$ 0.205		0.64			$m(\tilde{\xi}_{1}^{0})=0$ $m(\tilde{\xi}_{1}^{0})-m(\tilde{\xi}_{1}^{0})=5 \text{ GeV}$	ATLAS-CONF-2020-015 1911.12606
	$\tilde{\chi}_1^* \tilde{\chi}_1^*$ via WW	2 e. µ		E_T^{miss}	139	ž ⁴	0.42				m(21)=0	1908.08215
~	$\tilde{\chi}_1^* \tilde{\chi}_2^0$ via Wh	0-1 e, µ	$2 b/2 \gamma$	E_T^{miss}	139	$\tilde{x}_{1}^{\pm}/\tilde{x}_{2}^{0}$ Forbidden		0.74			m(x ⁰ ₁)=70 GeV	2004.10894, 1909.09226
≥õ	$\hat{\chi}_1^* \hat{\chi}_1^*$ via $\hat{\ell}_L / \hat{\nu}$	2 e, µ		E_T^{miss}	139	k ^a ₁		1.0			$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\ell}_1^n) + m(\tilde{\ell}_1^0))$	1908.08215
шŝ	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	21		E_T^{max}	139	t [tL+tR,L] 0.16-0.3	0.12-0.39				m(t ²)=0	1911.06660
	$\ell_{L,R}\ell_{L,R}, \ell \rightarrow \ell \chi_1^{\prime}$	2 e, µ ee, µµ	> 1 iet	Fliss	139	2 0.256		0.7			$m(\tilde{t}_{1})=0$ $m(\tilde{t}_{2})=10$ GeV	1908.08215
	88 8-1070	0.6.11	> 3.6	Faiss	26.1	ñ 0.12.0.22		0 20-0 99			0000 . 1000	1906 04030
	nn, n→nG/2G	4 e,μ	0 jets	E_T^T	139	н 0.13-0.23 Й	0.5	0.29-0.66			$BH(\ell_1 \rightarrow BG)=1$ $BR(\ell_1^0 \rightarrow ZG)=1$	ATLAS-CONF-2020-040
00 Nec	$\operatorname{Direct} \tilde{\chi}_1^+ \tilde{\chi}_1^- \operatorname{prod.}, \operatorname{long-lived} \tilde{\chi}_1^+$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	λ ¹ μ ² 0.15	0.46				Pure Wino Pure biogsino	1712.02118 ATL_PHVS_PLIB.2017.019
52 62	Stable i Rubarkon		Multirio		26.1	2				2.0		1902 01636 1808 04095
pa o	Metastable # B-badron #-++02		Multiple		36.1	ğ [τ(ğ) =10 ns, 0.2 ns]			-	2.05 2.4	m(2 ⁰)=100 GeV	1710.04901,1808.04095
	And a second sec	2				17.28						
	$\chi_1\chi_1/\chi_1, \chi_1 \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 e, µ			139	$x_1/x_1 = [BH(Z\tau)=1, BR(Ze)=1]$		0.625 1.0	15	10	Pure Wino	AILAS-CONF-2020-009
	$\tilde{v}^{\dagger} \tilde{v}^{\dagger} \tilde{v}^{\dagger} \tilde{v}^{0} \rightarrow WW/ZIII/\infty$	40.0	0 ints	Emiss	36.1	$\hat{Y}_{i}^{\pm} / \hat{Y}_{i}^{0} = \{\lambda_{ij} \neq 0, \lambda_{ij} \neq 0\}$	_	0.82	1.33	1.5	m(x ⁰)=100 GeV	1804 03502
	$3131/32 \rightarrow ww/zeccorr$ $35 3 \rightarrow aax^0 x^0 \rightarrow aaa$	4	-5 large-R is	rts	36.1	₹ (m(k [*])=200 GeV, 1100 GeV1		0.02	1.3	1.9	Large X.	1804.03568
>	9919 - 44411-41 - 4444		Multiple		36.1	g [X'_12=20-4, 20-5]		1.0	15	2.0	m(t20)=200 GeV, bino-like	ATLAS-CONF-2018-003
H	$i\bar{t}, \bar{t} \rightarrow t\bar{\chi}_{1}^{0}, \bar{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	i [X" = 2e-4, 1e-2]	0.5	5 1.0	15		m(21)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_{1}^{\pi}, \tilde{\chi}_{1}^{\pi} \rightarrow bbs$		$\geq 4b$		139	ĩ	Forbidden	0.95			m(ℓ ₁ ⁿ)=500 GeV	ATLAS-CONF-2020-016
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$		2 jets + 2 b		36.7	$\tilde{t}_1 = [qq, bs]$	0.42	0.61				1710.07171
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, µ	26		36.1	In Datter F. stall 2010 - P.	<30.01		0.4-1.45		BR(<i>i</i> ₁ → <i>bc/by</i>)>20%	1710.05544
		1 µ	DV		135	x ₁ (10-10< x ₂₃₄ ≤10-8, 30-10< x ₂₅	4.00-04	1.0	1	.6	вн(/1→дµ)=100%, созе;=1	2003.11956

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

•For example:

- •Co-annihilations with another particle in dominates the direct χχ 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

arXiv:2104.07634

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 lonizonly	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 lonizonly	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	
DEAD-3600	Scintillator	l Ar	3 300 kg		Pupping	2016	202X		
DEAF-3000	Scintillator		3,300 Kg		Kunning	2010	2027	SNOLAB	
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ended	2013	2019	LNGS	
Darkside-LM (Ionization)	TPC Ionizonly	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 ka		Construction	2021	2022	LNGS	
SABRE (North)	Scintillator	Nal	50 kg		Planning	2022	2027	LNGS	
SABRE (South)	Scintillator	Nal	50 kg		Planning	2022	2027	SUPI	
	Continutor	11ui	50 kg		T idining	LULL	LULI		
CDEX-10	Ionization (77K)	Ge	10 ka	103 ka d	Running	2016	2	CJPI	
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg	100 kg u	Planning	2010	•	CIPI	
0DEX-1007 11		00	100-1000 kg		Fiaming	2027		OUL	
SuperCDMS	Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan	
CDMSLite (High Field)	Cryo Ionization	Ge	3 kg	a 75 kg d	Ended	2011	2015	Soudan	
		66	0.0 a	~75 kg d	Ended	2012	2015	Sutface Lab	
CDIVIS-FIVEV SI			0.9 g	0.5 g u	Bunning	2010	2010		
	Cryo Ionization / HV	Ge/Si	5 kg/1 kg		Construction	2020	2022	SNOLAB	
SuperCDMS SNOLAB	Gryo Ionization / HV	Ge/SI	ттку/з ку		Construction	2023	2020	SNULAB	
EDELWEISS III EDELWEISS III (High	Cryo Ionization	Ge	20 kg		Ended	2015	2018	LSM	
Field)	Cryo Ionization HV	Ge	33 g	80 g d	Running	2019		LSM	
CRESST-II	Bolometer Scintillation	r 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	210 g		Running	2020	2010	LNGS	
	Deletitieter Gentlinditer	ourro .			, talling	2020		2.100	
BIOD 0	Dubble Obersher	0050	0.1.0		Ended	2042	2045		
PICO-2	Bubble Chamber	C3F8	2 Kg 35 kg		Rupping	2013	2015	SNOLAB SNOLAB	
P100-40	Dubble Ohamber	0010	50 kg		Finded	2020	0047		
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???			, i i i i i i i i i i i i i i i i i i i						
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM	
NEWS-G	Gas Drift	CH4			Construction/Run	2020	2025	SNOLAB	
DAMIC	CCD	Si	2.9 a	0.6 kg d	Ended	2015	2015	SNOLAB	
DAMIC	CCD	Si	40 a Si		Ended	2017	2019	SNOLAB	
DAMIC100	CCD	Si	100 g Si		Not Built	2011	2010	SNOLAB	
DAMIC M	COD Shires	0	()		Construction (D	0004	2024		
	CCD Skipper	0	1 kg Si	2	Construction/Run	2021	2024	LOWI	
SENSEI	CCD Skipper	01	2 g Si	2g x 24 d	Construction (D	2019	2020	ENOLAR	k Gaitskel
A CHARTER AND AN						A		CONTRACTOR AND	

Dark Matter Searches

Gaitskell, Brown University, LZ/DOE

Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End L Ops E	ocation of Experiment
XMASS	Scintillator	LXe	832 kg		Ende	d 2010	201	9 Kamioke
XENON100	TPC	LXe	62 kg		Ende	d 2012	201	6 LNGS
XENON1T	TPC	LXe	1,995 kg		Ende	d 2017	201	UNGS
XENON1T (Ionization)	TPC Ionizonly	LXe	1,995 kg		Ende	d 2017	201	UNGS
XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/Ru	n 2021	202	5 LNGS
LUX	TPC	LXe	250 kg	30,000 kg d	Ende	d 2013	201	6 SURF
LUX (Ionization)	TPC Ionizonly	LXe	250 kg		Ende	d 2017	201	9 SURF
LZ	TPC	LXe	8,000 kg	20 t yr	Construction/Ru	n 2021	202	5 SURF
PandaX-II	TPC	LXe	580 kg		Ende	d 2016	201	B CJPL
PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/Ru	n 2021	202	5 CJPL
LZ HydroX	TPC	LXe+H2	8,000 kg		R&I	D 2026	1	SURF
Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Plannin	g 2028	203	3 LNGS/SURF/E
DEAP-3600	Scintillator	LAr	3,300 kg		Runnin	g 2016	202)	K SNOLAB
DarkSide-50	TPC	LAr	46 kg	46 kg year	Ende	d 2013	201	9 LNGS
Darkside-LM (Ionization)	TPC Ionizonly	LAr	46 kg		Ende	d 2018	201	9 LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	lanning/Construc	ct 2025	203	LNGS
ARGO	TPC	LAr	300 t	3000 t yr	Plannin	g 2030	203	5 SNOLAB
	Scintillator	Nal	250 kg		Ruppin	a 2003		INGS
	outiliator	I VCII	200 Kg	0.15	T Currinin	9 2003		LINGO
ANAIS-112	Scintillator	Nal	112 kg	Goal 5 years	Runnin	g 2017	202	2 Canfranc

Principle of WIMP detection in LXe TPC

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

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

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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 L

BROM

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

NR searches...

/_{ee})

	Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops (after construction)	End Ops	Loc Exp	cation of periment
	XMASS	Scintillator	LXe	832 kg		End	ed 20	10 2	019	Kamioke
	XENON100	TPC	LXe	62 kg		End	ed 20	12 2	016	LNGS
	XENON1T	TPC	LXe	1,995 kg		End	ed 20	17 2	019	LNGS
	XENON1T (Ionization)	TPC Ionizonly	LXe	1.995 ko		End	ed 20	17 2	019	LNGS
<pre>{</pre>	XENONnT	TPC	LXe	7,000 kg	20 t yr	Construction/R	un 20	21 2	025	LNGS
	LUX	TPC	LXe	250 kg	30,000 kg d	End	ed 20	13 2	016	SURF
e	LUX (Ionization)	TPC Ioniz -only	L Xe	250 kg		End	ed 20	17 2	019	SURF
L	LZ	TPC	LXe	8,000 kg	20 t yr	Construction/R	un 20	21 2	025	SURF
	PandaX-II	TPC	LXe	580 ko		End	ed 20	16 2	018	CJPI
	PandaX-4T	TPC	LXe	4,000 kg	20 t yr	Construction/R	un 20	21 2	025	CJPL
	LZ HydroX	TPC	LXe+H2	8,000 kg		Rð	&D 20	26		SURF
	Darwin / US G3	TPC	LXe	50,000 kg	200 t yr	Planni	ng 20	28 2	033	LNGS/SU
	DEAP-3600	Scintillator	LAr	3,300 kg		Runni	ng 20	16 20)2X	SNOLAB
	DarkSide-50	TPC	LAr	46 kg	46 kg year	End	ed 20	13 2	019	LNGS
	Darkside-LM (Ionization)	TPC Ionizonly	LAr	46 kg		End	ed 20	18 2	019	LNGS
	Darkside-20k	TPC	LAr	30 1	200 t yr	lanning/Constru	uct 20	25 2	030	LNGS
	ARGO	TPC	LAr	300 1	3000 t yr	Planni	ng 20	30 2	035	SNOLAB
	DAMA/LIBRA	Scintillator	Nal	250 kg	1	Runni	ng 20	03		LNGS
Da	ANAIS-112	Scintillator	Nal	112 kg	Goal 5 years	Runni	ng 20	17 2	022	Canfranc
Ja										

					Fiducial Live		Start	End	Location of
	Name	Detector	Target	Active Mass	Exposure	Status	Ops	Ops	Experiment
							(after construction)		
	XENON1T	TPC	LXe	1,995 kg		Ended	2017	2019	LNGS
	XENON1T (Ionization)	TPC Ionizonly	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 Ionizonly	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 Ionizonly	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	Nal	250 kg		Running	2003		LNGS
	ANAIS-112	Scintillator	Nal	112 ka	Goal 5 years	Running	2017	2022	Canfranc
	COSINE-100	ture Expe	rimen	ts with	Nohl	e Liquid	2016	2021	YangYang
	COSINE-200					e Eiquit	2022	2025	YangYang
Dar	COSINE-200 South Pole	Scintillator	Nal	200 kg		Planning	2023	?	South Pole

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	Name	Detector	Target	Active Mass	Fiducial Live Exposure	Status	Start Ops	End Ops	Location of Experiment	
							(after construction)			
	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)	60	10 ka	103 ka d	Running	2016	?	CJPL	
	CDEX-100 / 1T	Ionizatio Modu	Ilatio	n of D	M Sign	as 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	
De	CRESST-II	Bolometer Scintillation	CaWO4	5 kg		Ended	2012	2015	LNGS	
Dal	ODEOOT III	Delementer Cointillation	CalMOA	240 ~		Ended	2016	2010	LNCC	

•ANAIS 100 kg Nal

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

Name		Detector	Target	Active Mass	Fiducial Live	Status	Start	End	Location of	
Indiffe		Delector	larget	Active mass	Exposure	Olalus	(after construction)	Ops	Experiment	
SuperCDMS		Cryo Ionization	Ge	9 kg		Ended	2011	2015	Soudan	
CDMSLite (Hi	igh 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 S	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 (H	HW Tests)	Bolometer Scintillation	CaWO4			Running	2020		LNGS	
PICO-2		Bubb				Ended	2013	2015	SNOLAB	
PICO-40		Bubb Future	Crvc	genic	Detec	tors 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-03	b'	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	
Dai DAMIC		CCD	Si	2.9 a	0.6 ka d	Ended	2015	2015	SNOLAB	

SuperCDMS @ SNOLAB

Name	Detector	Target	Active Mass	Fiducial Live Exposure	e 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
DDIET II	Cas Directional	054	0.14 km		Ended			Daulhu
	Gas Directional	CF4	0.14 Kg	1 E ka d	Ended	2012	2017	Boulby
NEVVAGE-03D	Gas Directional	CF4	14 g	4.5 Kg a	Endea	2013	2017	
NEWS C	Gas Drift	CHA			Ended	2017	2010	
NEWS-G	Gas Drift				Construction/Pup	2017	2019	
NEWS-G	Gas Dint	UTH4			Construction/Run	2020	2025	SNOLAD
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.
TESSERACT	Cryo TES	Не			R&D			LBNL

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

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 Ionizonly	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 Ionizonly	LXe	250 kg		Ended	2017	2019	SURF
LZ	TPC	LXe	8.000 kg	20 t vr	Construction/Run	2021	2025	SURF
PandaX-II	TPC	LXe	580 kg		Ended	2016	2018	CJPL
PandaX-4T	TPC	LXe	4 000 kg	20 t vr	Construction/Run	2021	2025	CJPI
	TPC	LXe+H2	8,000 kg	2019	R&D	2026	2020	SURF
Danwin / US G3	TPC		50,000 kg	200 t vr	Planning	2020	2033	LNGS/SURE/Boulby
Darwin / 03 03	IFC	LAG	30,000 kg	200 t yi	Fianning	2020	2000	LINGS/SORF/Bouldy
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 Ionizonly	LAr	46 kg		Ended	2018	2019	LNGS
Darkside-20k	TPC	LAr	30 t	200 t yr	lanning/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	cour o youro	Running	2016	2021	VanaVana
	Scintillator	Nal	200 kg		Construction	2010	2021	Yang Yang
COSINE 200 South Bolo	Scintillator	Nal	200 kg		Blooping	2022	2023	Fariy fariy
COSINE-200 South Pole	Scintiliator	Nai	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	Crvo Ionization / HV	Ge/Si	11 kg/3 kg		Construction	2023	2028	SNOLAB
	Cruc Ionization	Go	20 kg		Ended	2015	2019	ISM
	Cryo Ionization	Ge	20 Kg		Ended	2015	2010	LOW
Field)	Crvo Ionization HV	Ge	33 a	80 a d	Running	2019		LSM
CRESST-II	Bolometer Scintillation	CaWO4	5 kg	0090	Ended	2012	2015	LNGS
	Delemeter Ceintillation		240 -		Ended	2016	2010	
	Bolometer Scintillation	CaWO4	240 g		Ended	2016	2018	LNGS
CRESST-III (HVV Tests)	Bolometer Scintillation	Cavv04			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 a	4.5 kg d	Ended	2013	2017	
CYGNUS???								
NEWS-G	Gas Drift	CH4			Ended	2017	2019	LSM
NEWS C	Gas Drift				Construction/Bun	2017	2013	
NEWS-G	Gas Dilit	004			Construction/Run	2020	2025	SNULAD
DAMIC	CCD	Ci	20-	06 44 4	Ended	2015	2015	
DAMIC	000	0	2.9 g	0.6 Kg d	Ended	2015	2015	
DAMIC	CCD	51	40 g Si		Ended	2017	2019	SNULAB
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

/ - TeV

R&D Planning Construction Running Ended

Rick Gaitskell, Brown University, LZ/DOE

Our Goal Remains to Create the ...

QUIETEST KNOWN PLACES IN THE UNIVERSE

QUIETEST KNOWN PLACES IN THE UNIVERSE

BUT 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 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

- •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