Physics Opportunities and Site Requirements for 2nd and 3rd generation Noble Liquid detectors for direct Dark Matter Search

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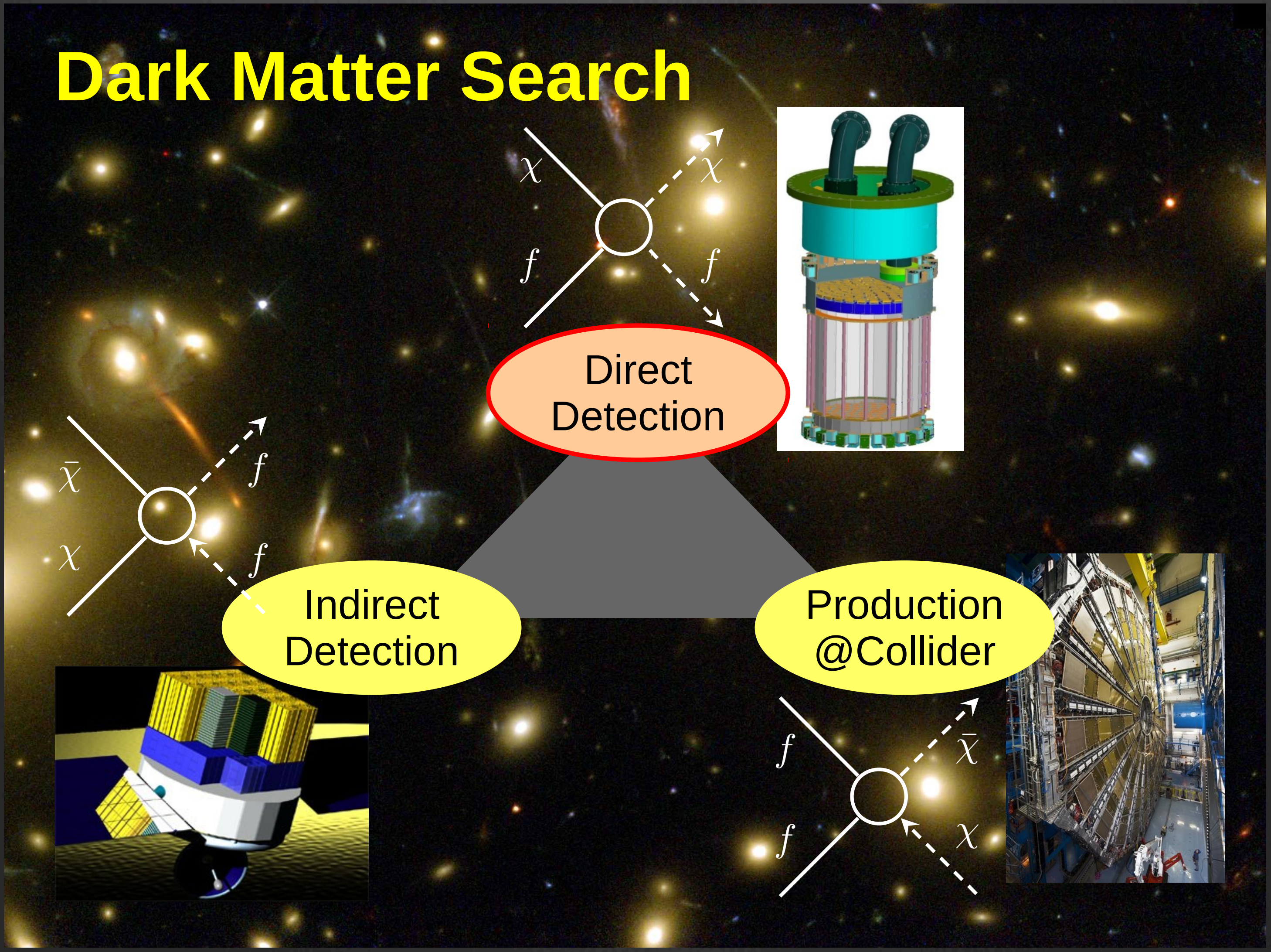
3rd Town Meeting – Monterey, CA – 8th Sep 2013

Outline

- Introduction
- Noble gases
- Single or double phase
- Current projects ArDM, DarkSide, Xenon, DEAP/miniCLEAN, XMASS, LUX
- G2 scale-up
- G3 scale-up
- Cosmogenic backgrounds

Complementary approaches

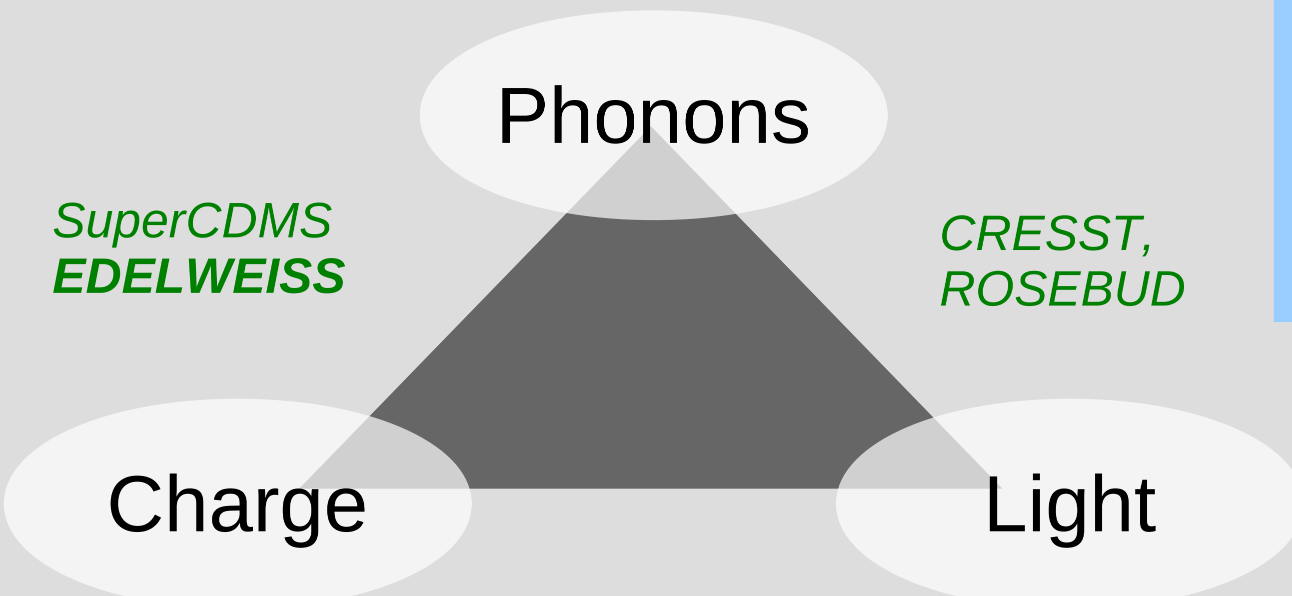


WIMP signature

Tracking:
DRIFT, DMTPC
MIMAC,
NEWAGE

Superheated Liquids:
COUPP
PICASSO
SIMPLE

CRESST-I
CUORE



SuperCDMS
EDELWEISS

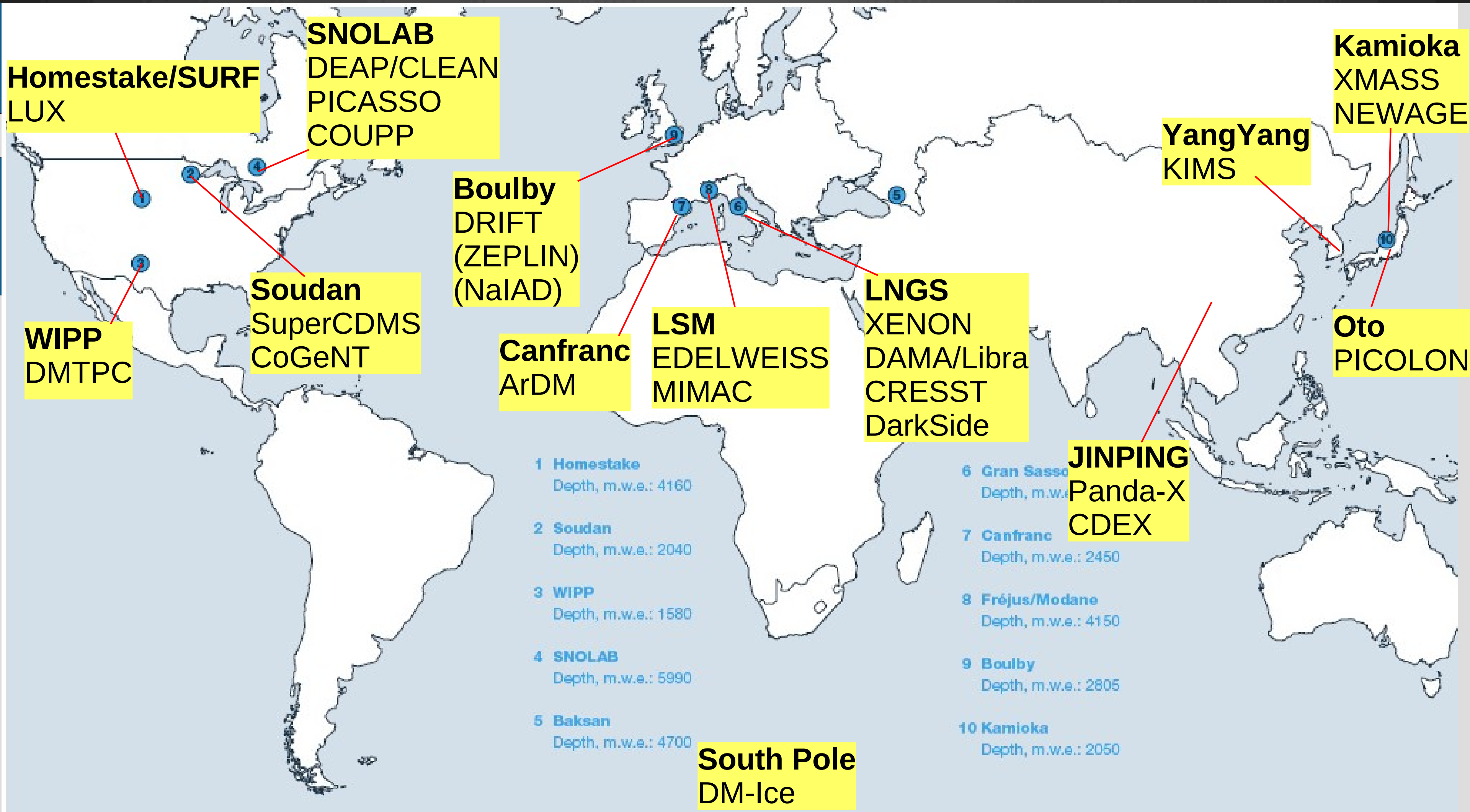
CRESST,
ROSEBUD

CoGeNT
*CDEX, **DAMIC***
Texono

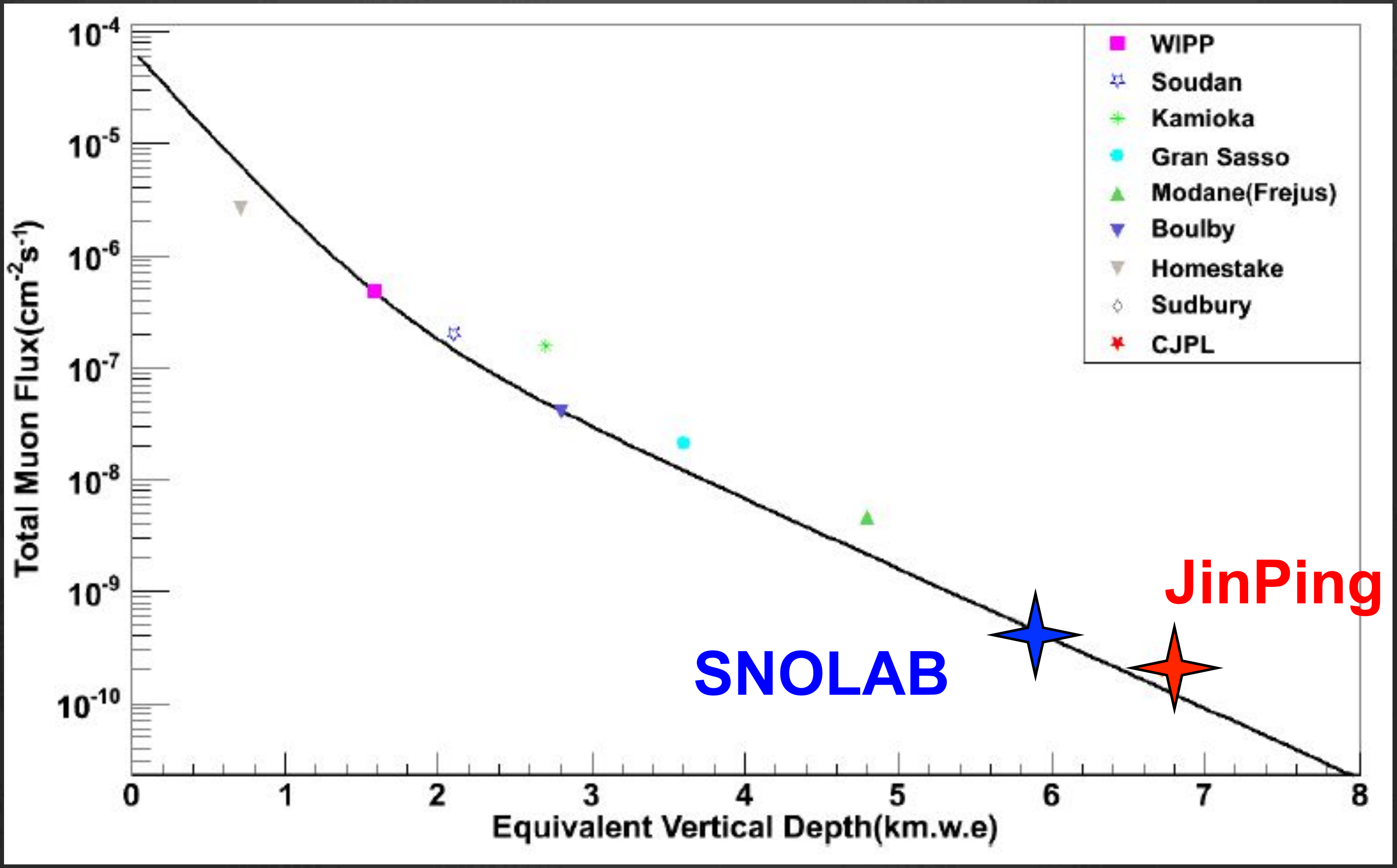
***XENON**, LUX*
ArDM, Panda-X
ZEPLIN, Darkside

DEAP/CLEAN
DAMA, KIMS
***XMASS**, DM-Ice*

Underground projects



Underground laboratories

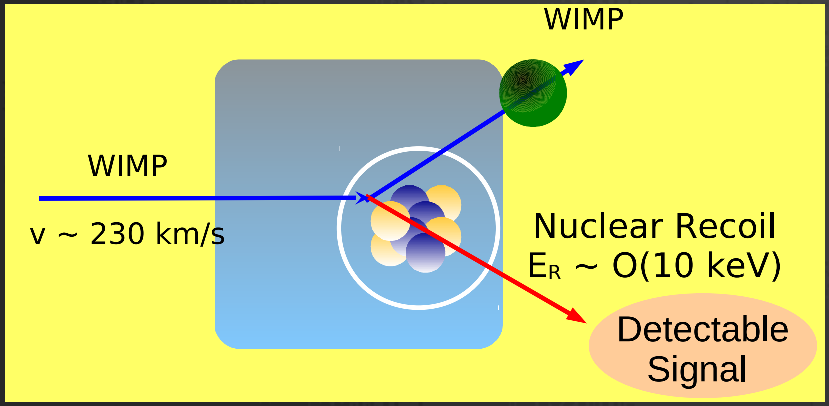


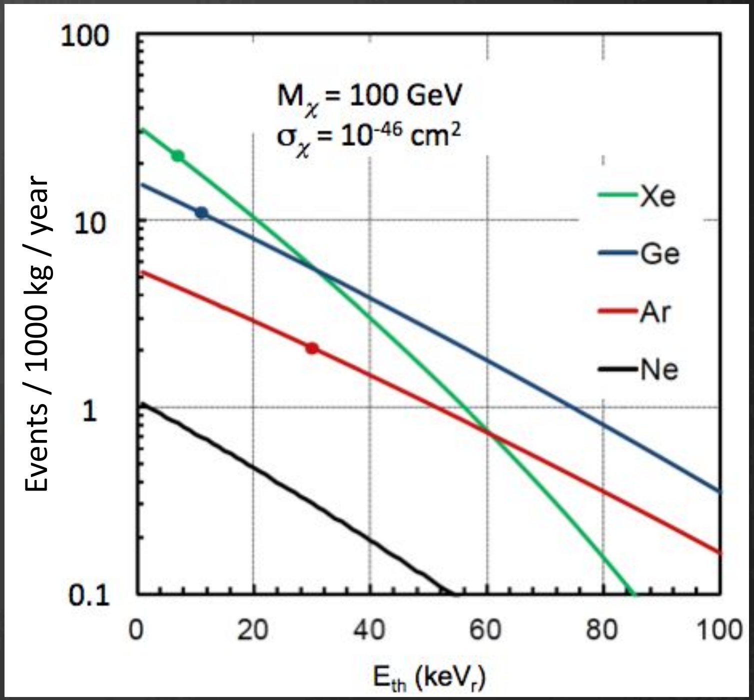
Noble gases	Neon	Argon	Xenon
Atomic Number	10	18	54
Atomic Mass	20.2	40.0	131.3
Boiling Point (T_b)	27.1 K	87.3 K	165.0 K
Liquid density at T_b (g/cm^3)	1.21	1.40	2.94
Fraction in atmosphere (ppm)	18.2	9340	0.09
Cost	$$	$	$$$$
Light Yield (ph/keV)	25	40	42
Prompt Time constant	2.2ns	6ns	2.2ns
Late Time constant	16us	1.6us	21ns
PSD	yes	yes ($3\ 10^{-8}$)	no
e^- drift velocity at 1kV/cm	2cm/s	$2\ 10^5$ cm/s	$2\ 10^5$ cm/s
S2/S1 discrimination	no	$2\ 10^{-2} – 10^{-3}$	$5\ 10^{-3} – 10^{-4}$
Open Project lines	(1)	3	3
Nuclear recoil L_{eff}		0.25 (>20keV)	~0.1 (@8keV)
WIMP ROI (keV)		30-200	8-45
Wimp Mass of peak sensitivity		~100GeV	~50GeV

Signal expected

- $\rho \approx 0.3$ Gev/cm^3
- <v>≈230 km/s
- a few tens of events/ton/year @$\sigma_\chi = 10^{-46}$

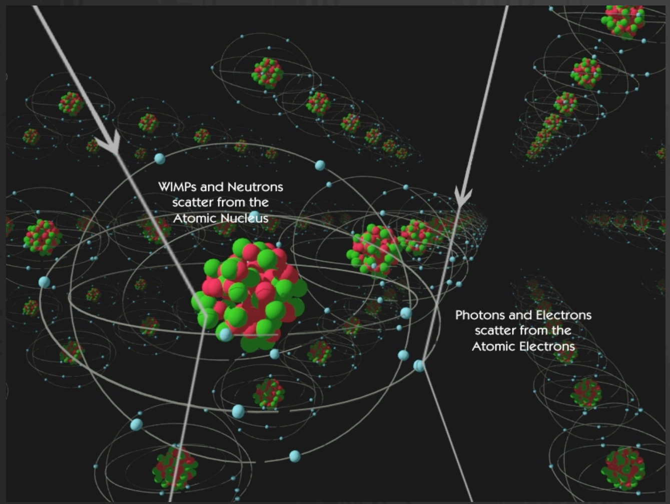
$$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$





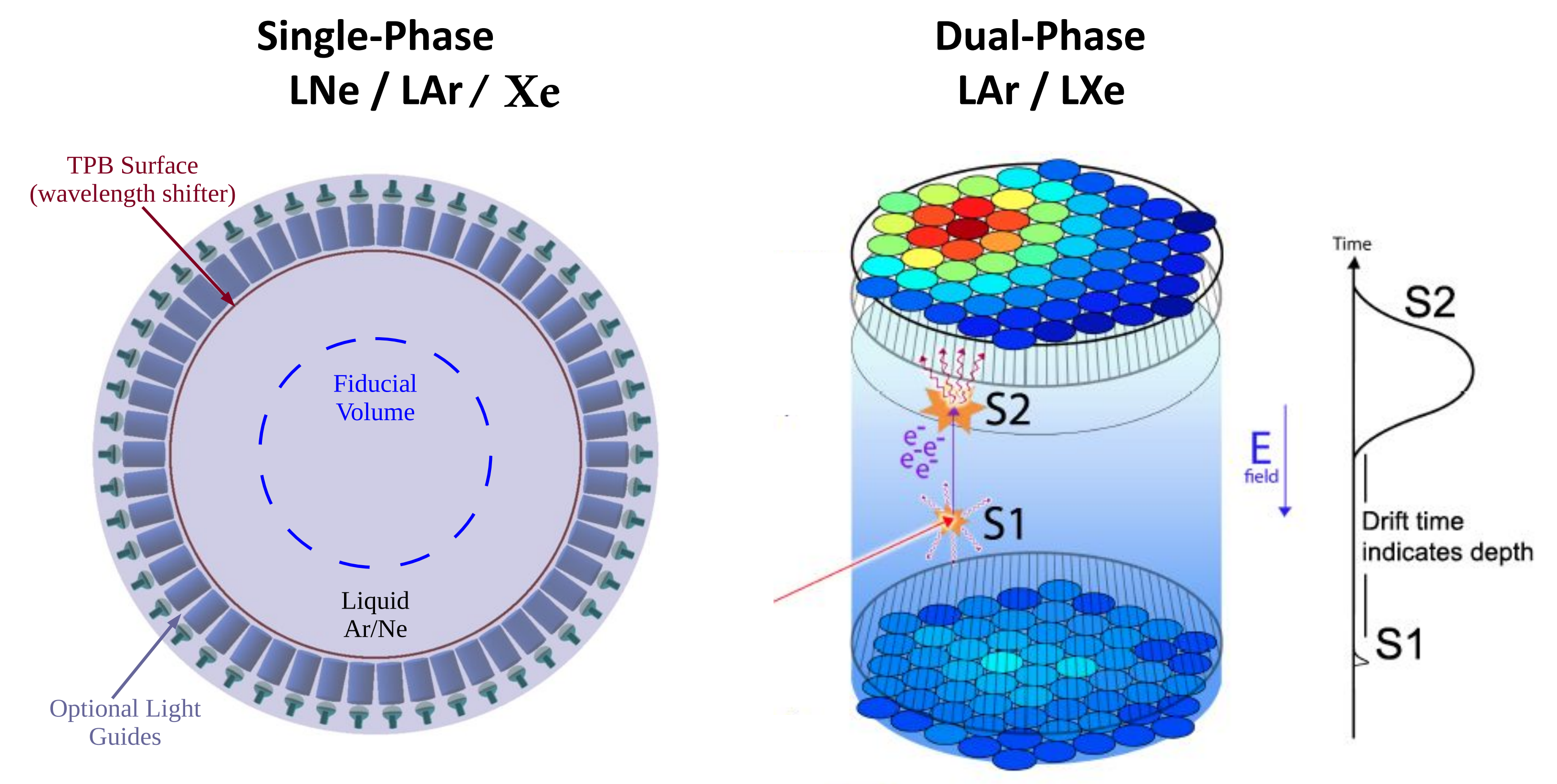
Background

- Sources of background:
  - Target material
  - Detector material
  - Site radioactivity (Radon, gammas, neutrons)
  - Cosmogenics
  - Solar neutrinos



- Strategy:
  - Target purification/depletion
  - Selection of Materials (e.g. QPIDs for PMTs)
  - ER/NR discrimination:
    - S2/S1 (better for Xe)
    - PSD (Ar only) x3x10^{-8}
    - single/multi sites (mostly TPC).
  - Self shielding/fiducialization
  - Site selection
  - Active veto
  - Passive Shielding

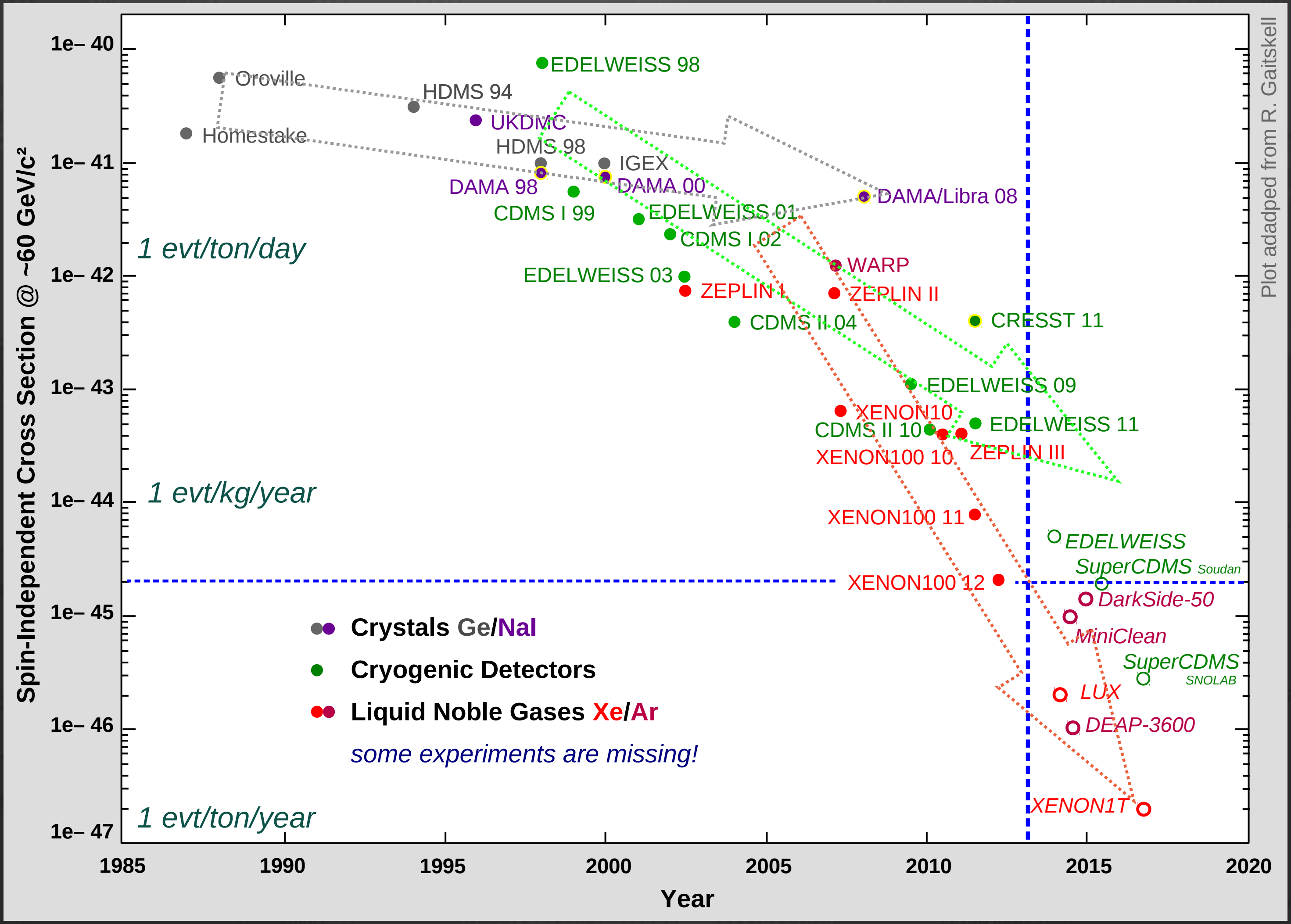
Single or Dual phase?

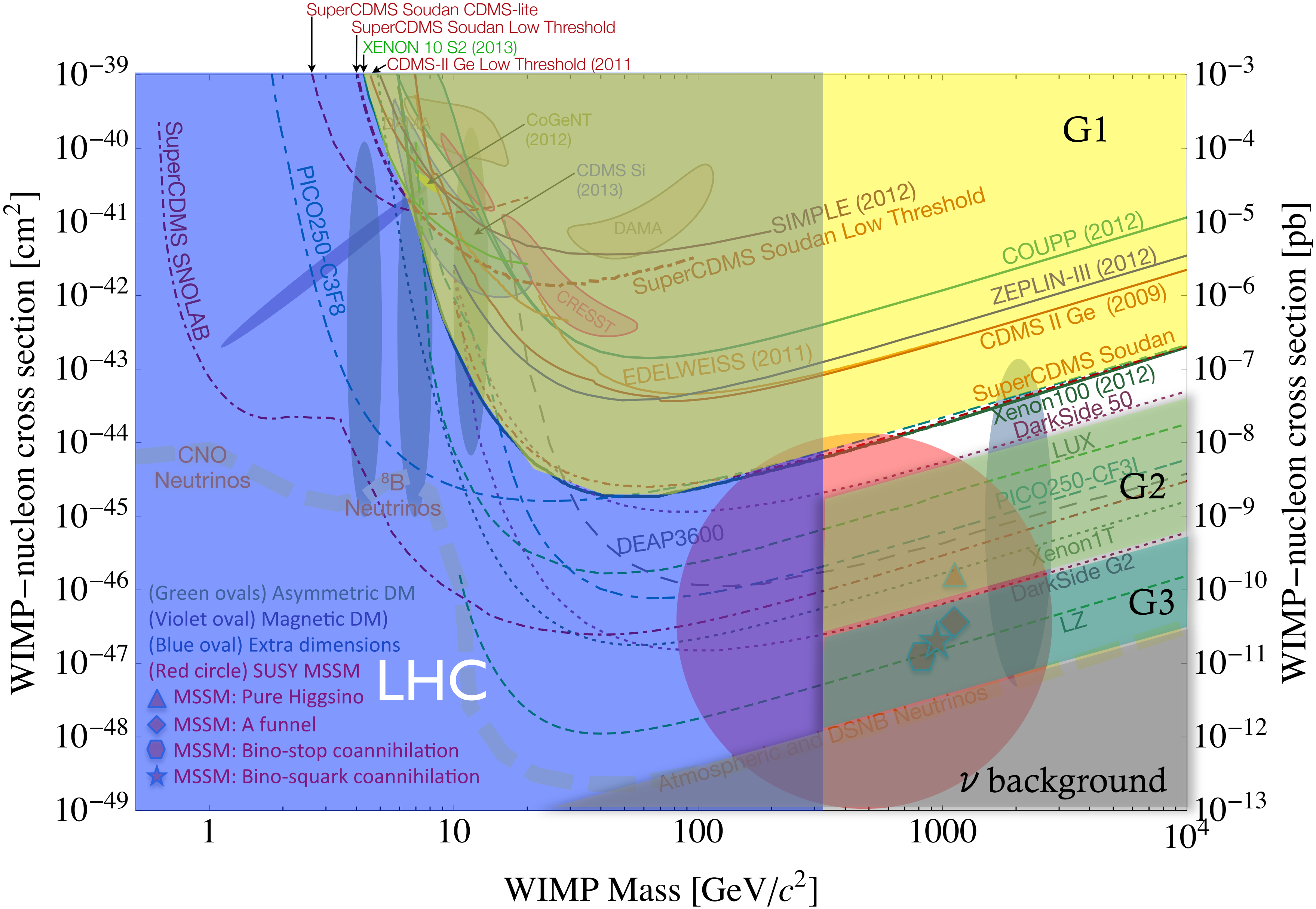


$\sigma \approx$10cm
No S2/S1 discrimination, but no pile-up
Strong fiducialization needed ~ 10%
high optical coverage~70-80% -> lower threshold

$\sigma_{x,y} \approx$3mm
$\sigma_z <$1mm
moderate fiducialization~50% - 70%
several kV electric field

Why noble gases?

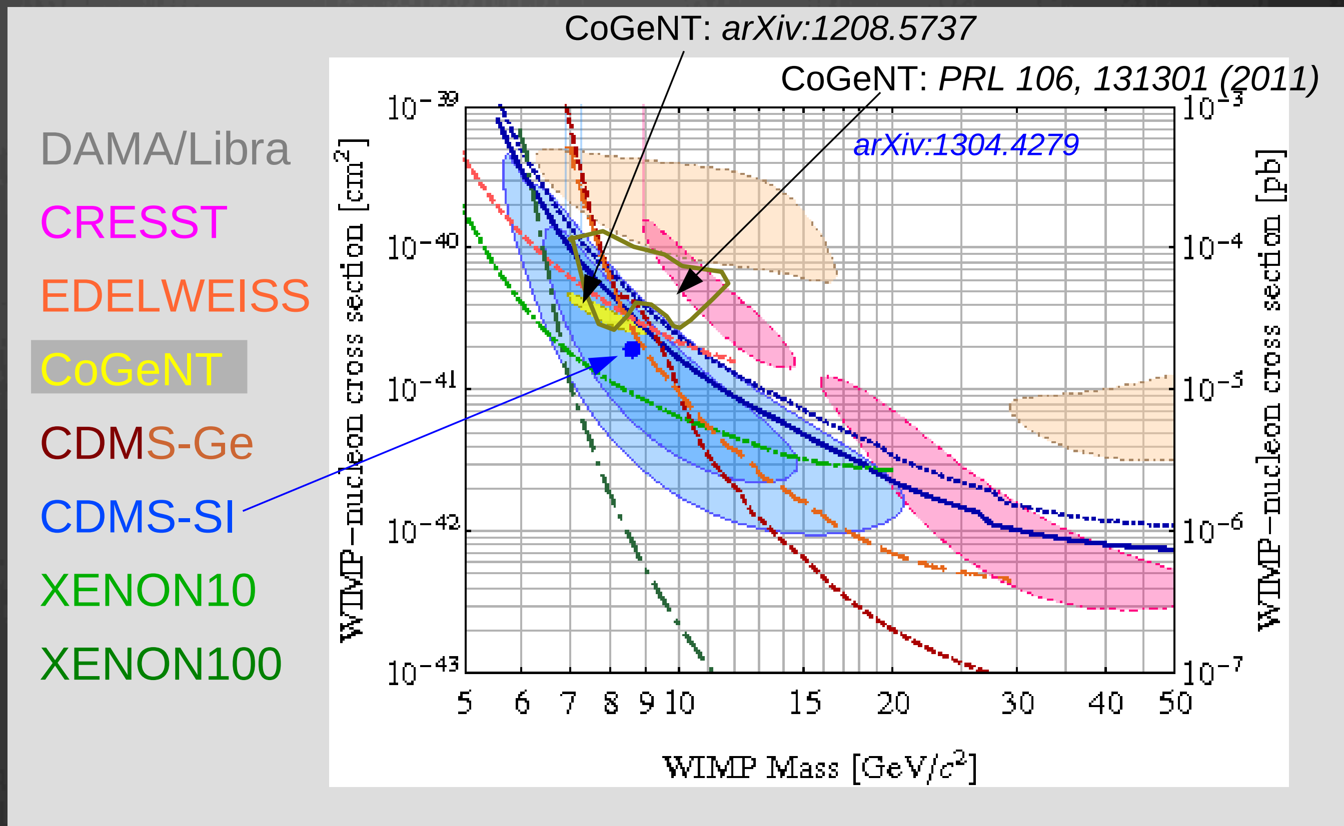




SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
SuperCDMS Soudan Low Threshold
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
PICO250-C3F8
CNO Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
G1
G2
G3
LHC
ν background
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM)
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

The low mass struggle

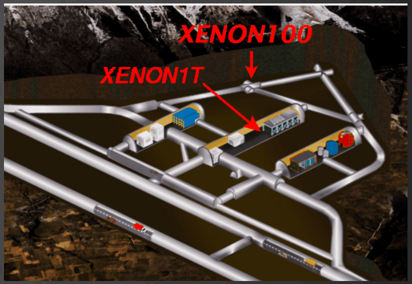
CDMS-Si favors a WIMP region of interest at 8.6 GeV with 1.9×10^{-41} cm^2 cross section. Consistent with CDMS Ge limits and with a WIMP interpretation of the COGENT experiment, not so much with DAMA and CRESST. In tension with limits from Xenon 10, Xenon 100 experiments



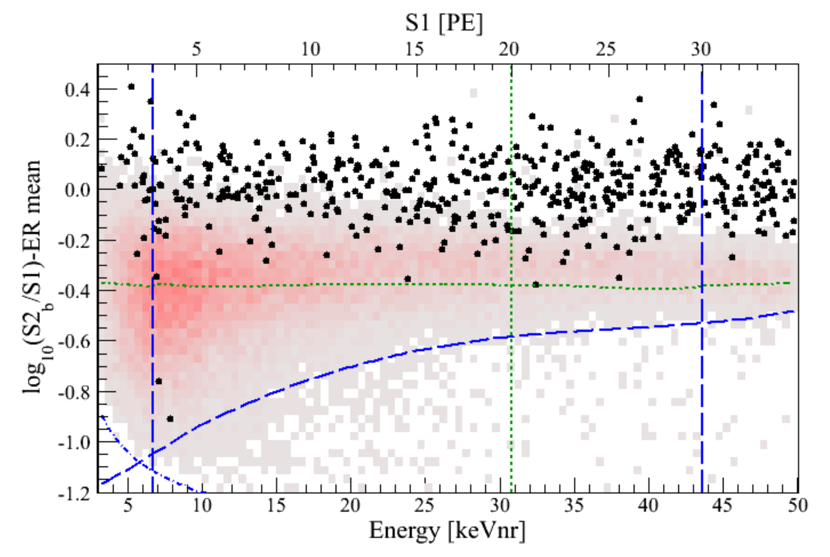
All region excluded by LHC:
if this is a WIMP, it's not the same one…

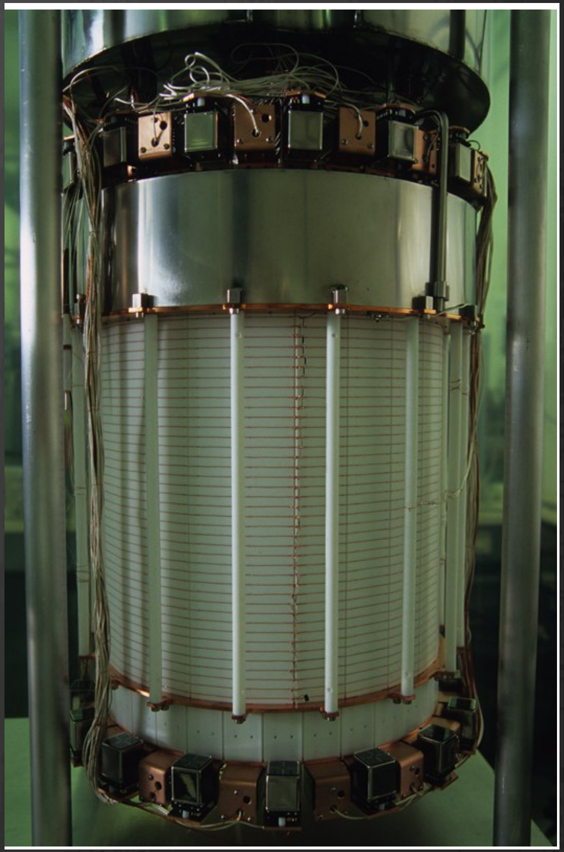
Generation 1
10^{-45} cm^2

Xenon 100

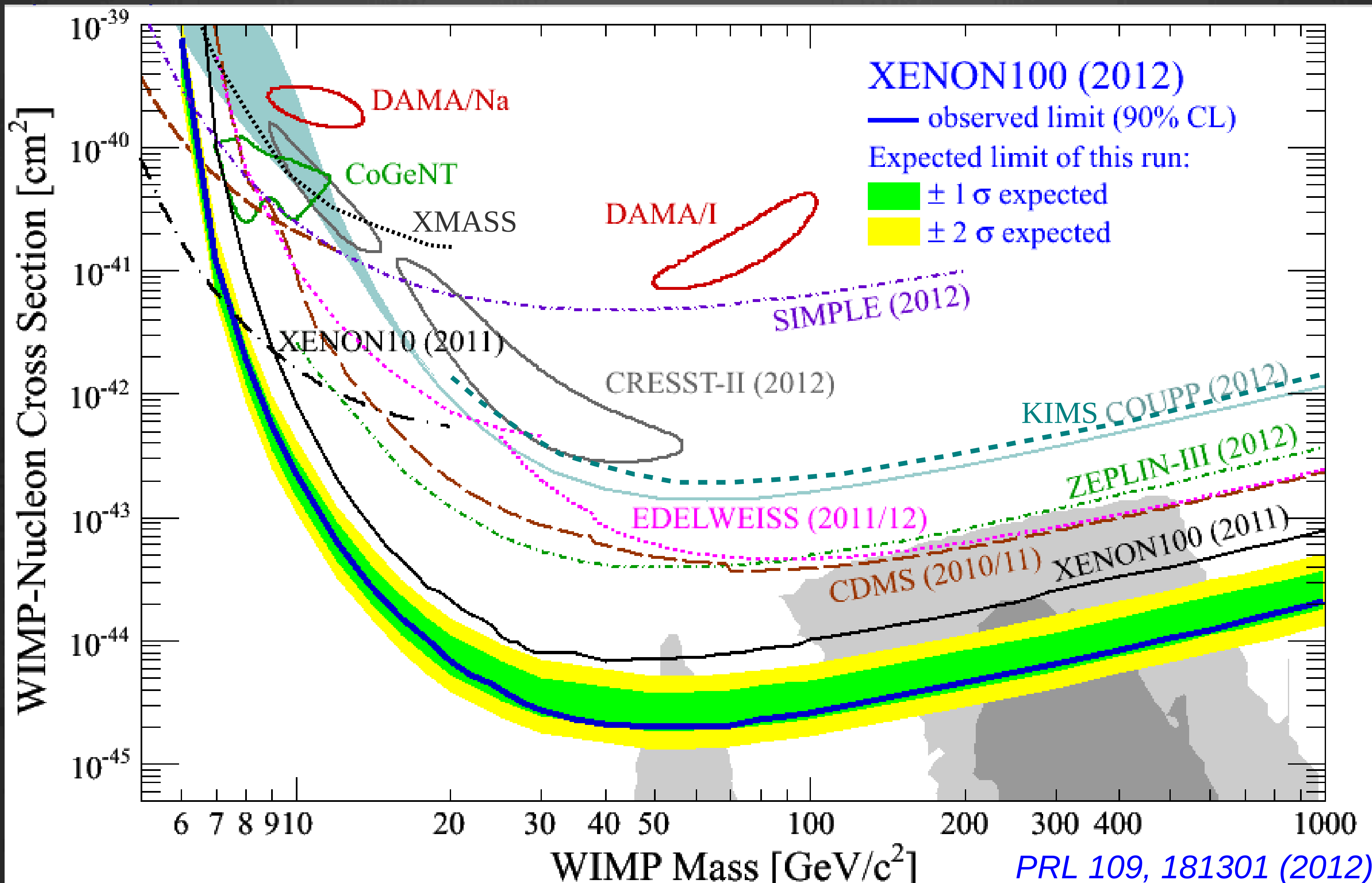


Located in LNGS (3800mwe)
62kg LXe (34kg FM)
dual phase TPC 30cm x 30cm
241 1" PMTs
in 2012 2 events observed
compatible with bkg expectations
Currently holding best limit for M_χ >10GeV

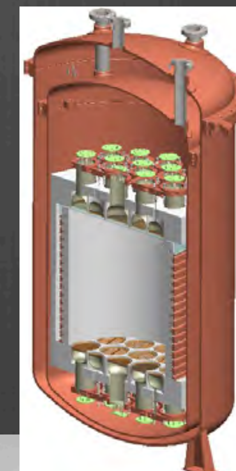


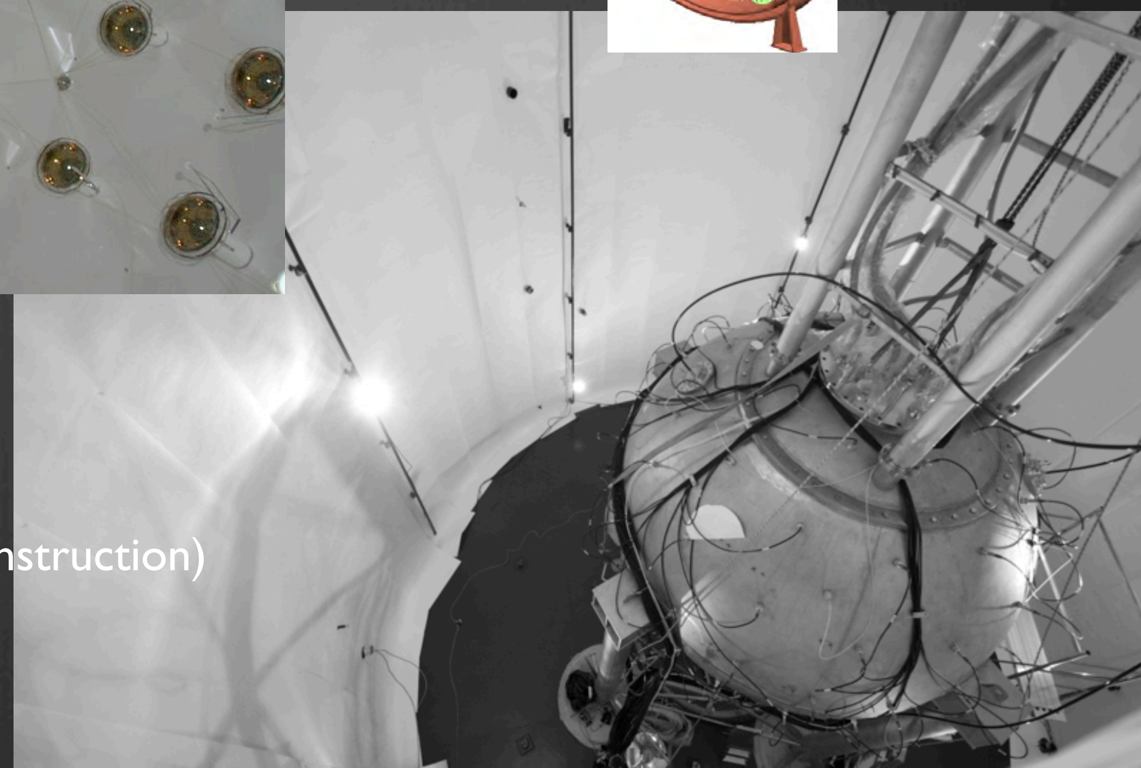


Xenon 100 and the present scenarion



Dark Side 50





2-phase argon TPC
Argon depleted from ^{39}Ar
Three-fold discrimination
(S1 pulse shape, S2/S1, sub-mm reconstruction)
50kg active target, 33kg fiducial
38 3" PMTs
Goal: 1.5 10^{-45} cm^2

Active Neutron Veto

Installed in LNGS Hall C, CTF of Borexino

30 tons liquid scintillator neutron veto

110 8' PMTs

Borated PC+PPO mixture

~60kev n capture

@0.6phe/keV

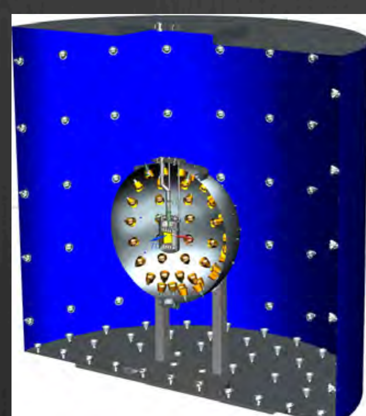
capture time reduced 250us -> 2.3us

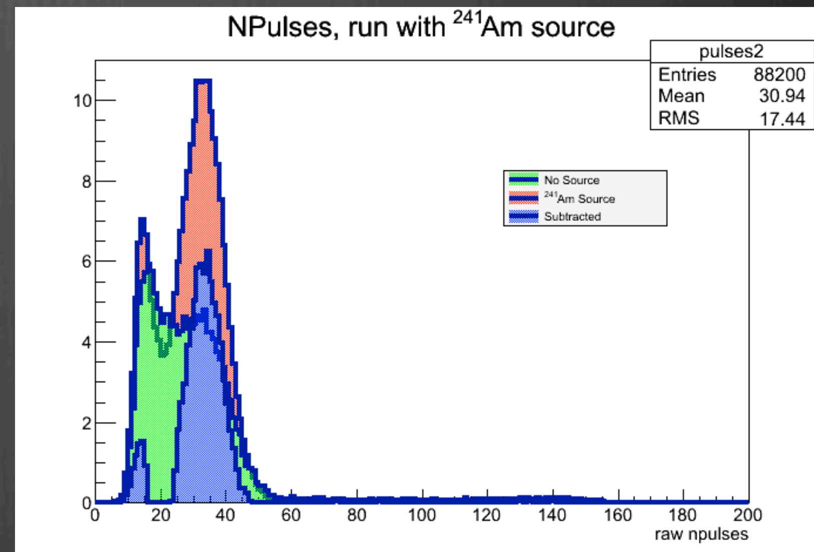
99.5% efficiency on radiogenic neutrons

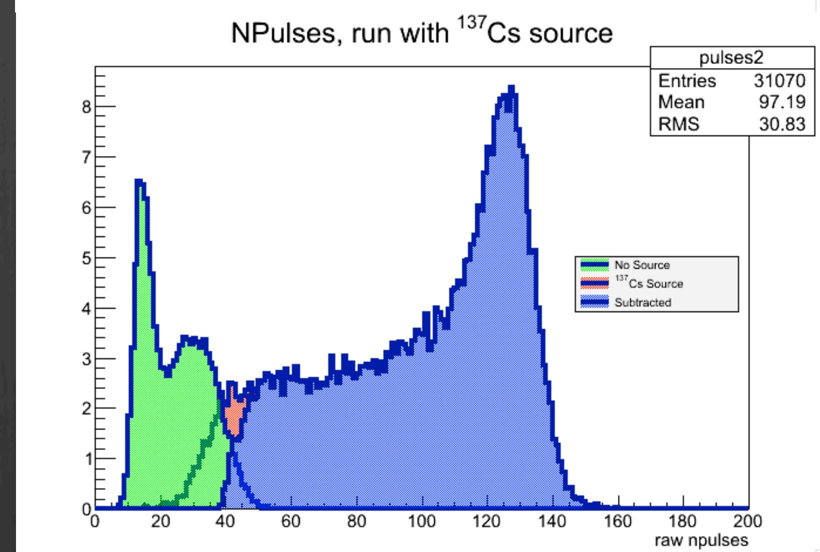
1,000 tons water Cherenkov muon veto

80 8' PMTs

99.9% effciency

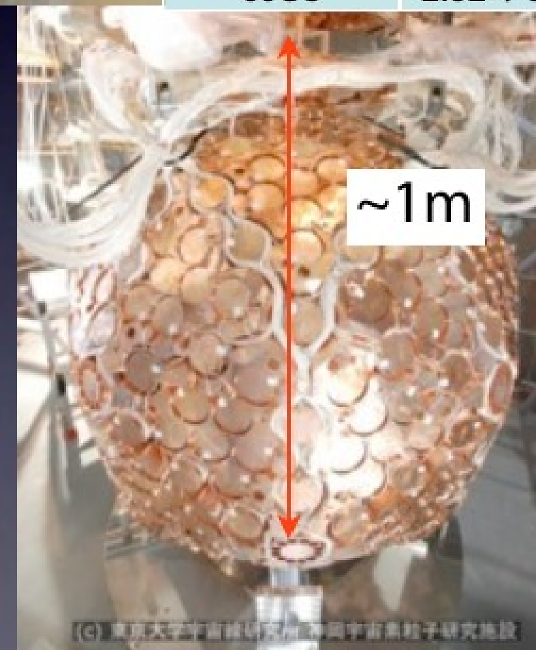






XMASS800kg in Kamioka

RI in PMT	Activity per 1PMT(mBq/
238U-chain	0.70+/-0.28
232Th-chain	1.51+/-0.31
40K	9.10+/-2.15
60Co	2.92+/-0.16



- φ10m x 10m ultra pure water shield with 20 inch x 70 PMTs for muon veto
- 642 ultra low background 2 inch PMTs
- 835 kg of LXe for sensitive volume.

Masaki Yamashita

Plans to scale to G2 (5t->1.5tFM) and G3(20t->12tFM)

Recent Result of XMASS

Masaki Yamashita

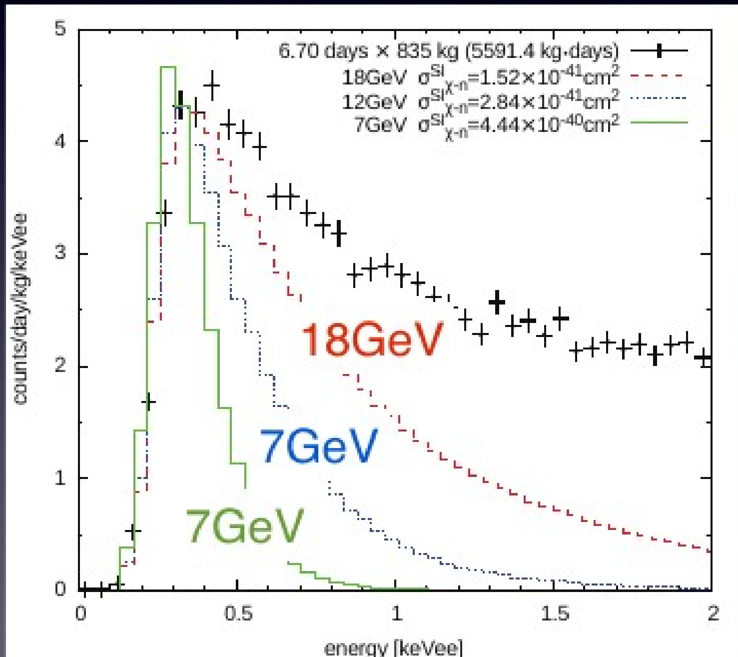
Light mass WIMP

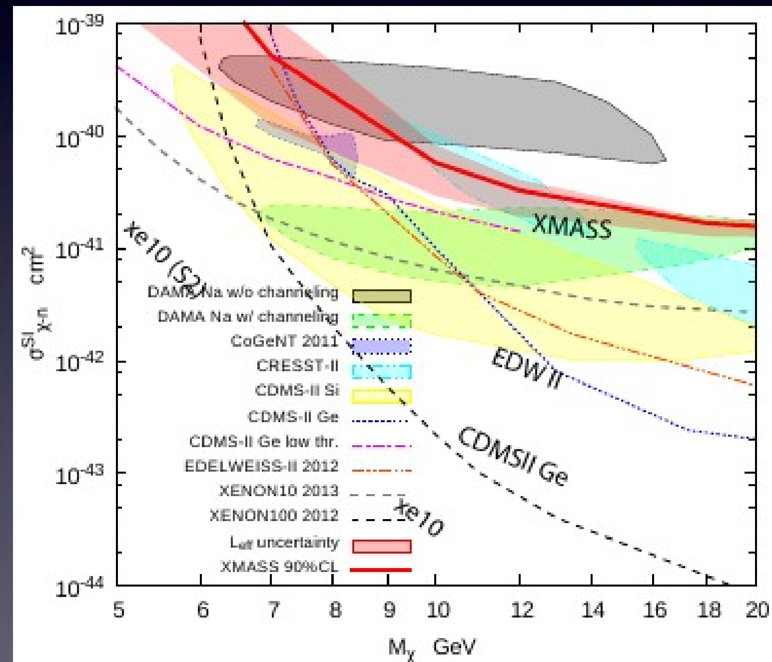
•Full volume analysis with 835 kg LXe.   (without fiducial volume cut.)

•Hight Light Yield 14.7 PE/keV

•Eth 0.3 keVee (scaled by 122keV)

• Scintillation Efficiency (Leff) from XENON (E.Aprile et al., Phys. Rev. Lett. 107 (2011) 131302)



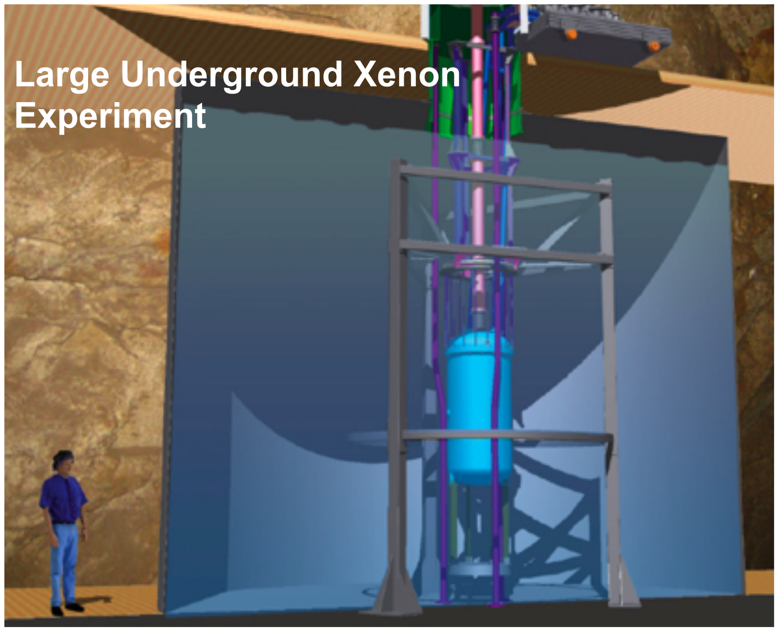


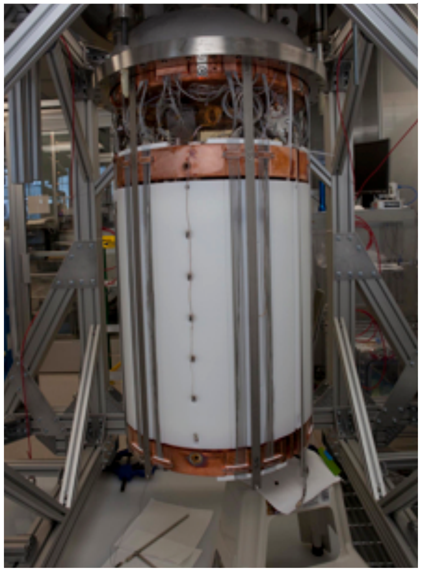
For higher WIMP mass, unexpected surface background.
In 2013 PMTs will be refurbished to handle this problem

LUX @ Sanford Lab 2013

[LUX/LZ Coll.]

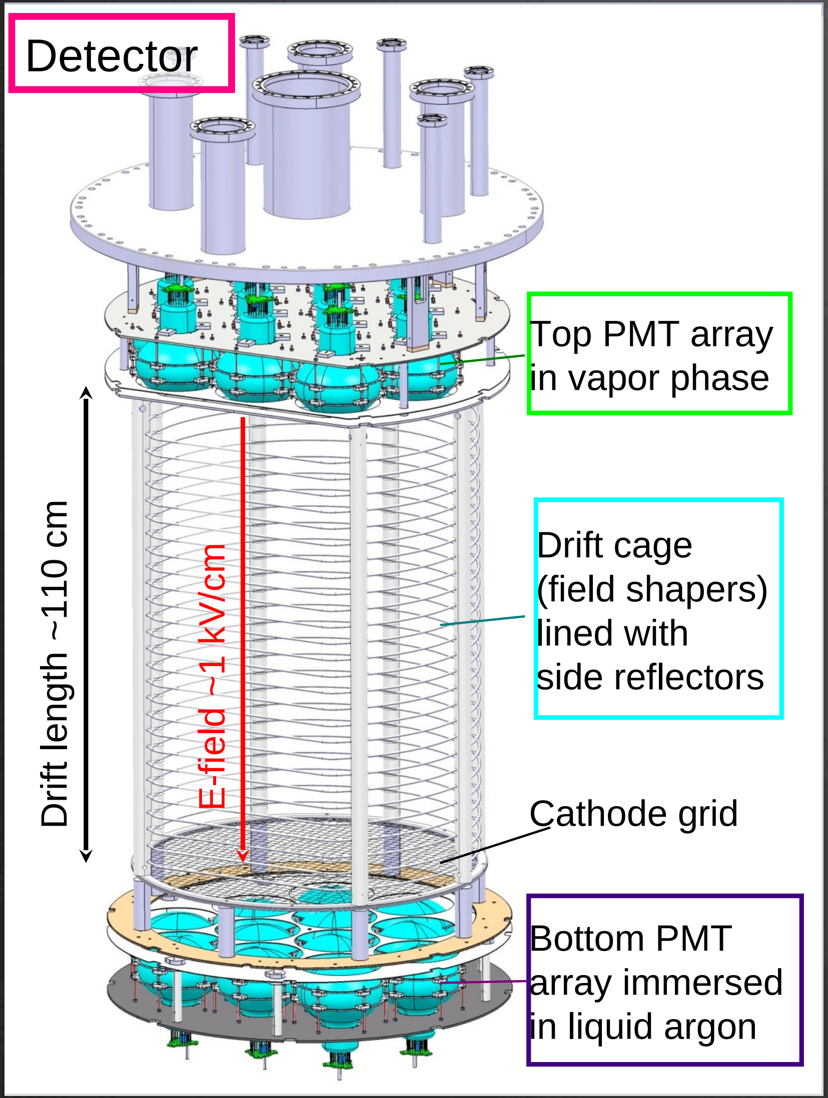
- LXe TPC - 300 kg active / 100 kg fid.
  - Installed in water shield at Sanford Lab Davis Campus 4850' level Aug 2012
  - Xenon condensed Feb 2013
- Detector
  - Circulating > 20 SLPM with 2-phase heat exchanger @ >90% eff.
  - Good purity after < 2 months (Electron drift attenuation >100 cm)
  - Excellent light yield - 8 phe/keVee, zero field, 122 keVee
  - ^{85}Kr @ 4ppt (less than PMT bkg.)
- WIMP Searches
  - Plan short (~ 60 day) WIMP search run - result by end 2013 - non-blind analysis
  - Full year-long WIMP search run to begin in 2014/5 - blind analysis





122 Hamamatsu R8778 Low bkg. PMTs

ArDM

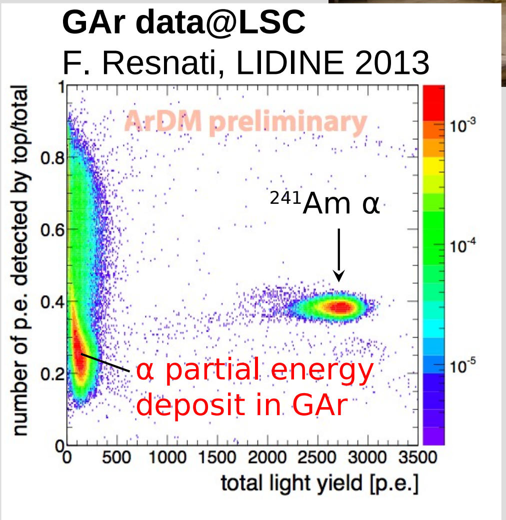


- Fully PMT-based readout:
  - 2 new arrays of 12 x 8" Hamamatsu PMTs (R5912-02MOD-LRI), TPB coating
  - primary scintillation light (in liquid)
  - charge via proportional scintillation (in vapor)
    - → discrimination with PSD, charge/light ratio
- Active LAr target: ~0.8 ton
- Tetratex® side reflectors coated with TPB
- Drift field : ~1 kV/cm
  - ~100 kV at cathode, supplied using VHV feedthrough

ArDM

ETHZ

Installed at Laboratorio Subterráneo de Canfranc (LSC)

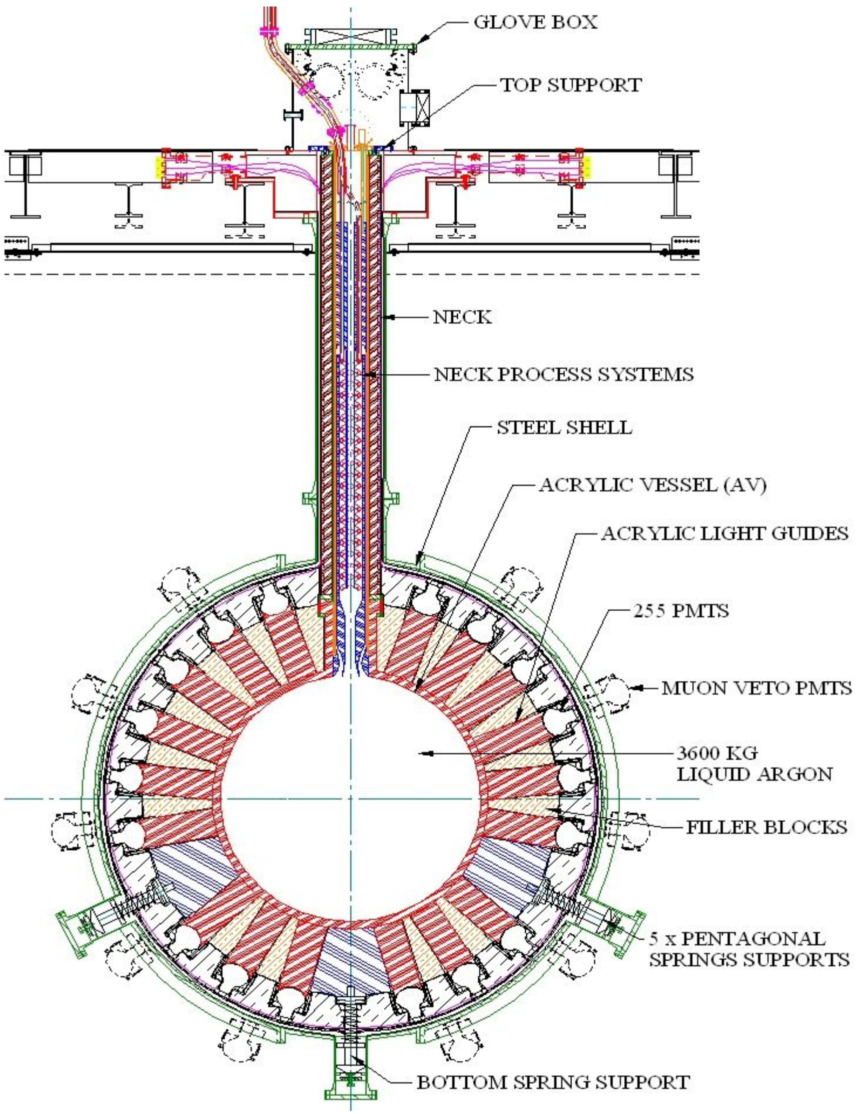


- Installation of ArDM finished March 2013
- **currently: commissioning with GAr**
  - improved uniformity. Detector is taking data.
  - LY=2 pe/keVee @ E=0 keV, measured with α
  - material screening with HPGE @ LSM
  - in-situ n-measurement with liquid scintillator
- **Next: LAr comissioning**
  - LAr tests: HV, purification, cryogenics...
  - expect physics run by 2014

Generation 2

10^{-47} cm^2

DEAP 3600



DEAP-3600 Detector

3600 kg argon target
(1000 kg fiducial)
in sealed ultraclean
Acrylic Vessel

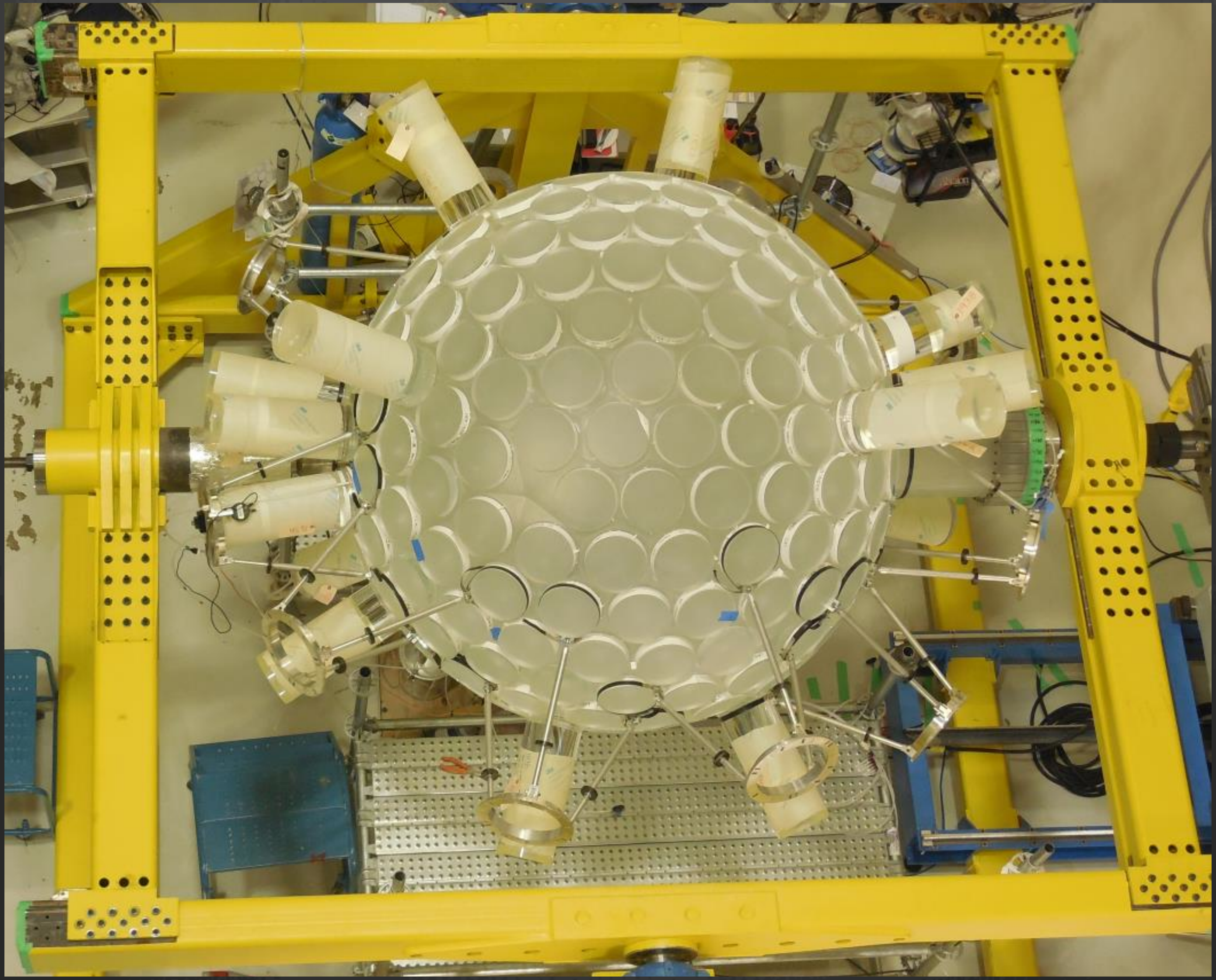
Vessel is “resurfaced”
in-situ to remove
deposited Rn daughters
after construction

255 Hamamatsu
R5912 HQE PMTs 8-inch
(32% QE, 75% coverage)

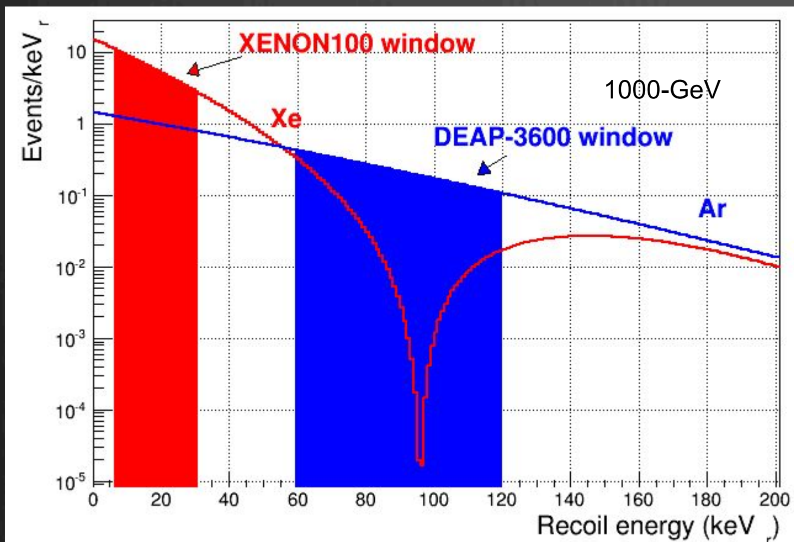
50 cm light guides +
PE shielding provide
neutron moderation

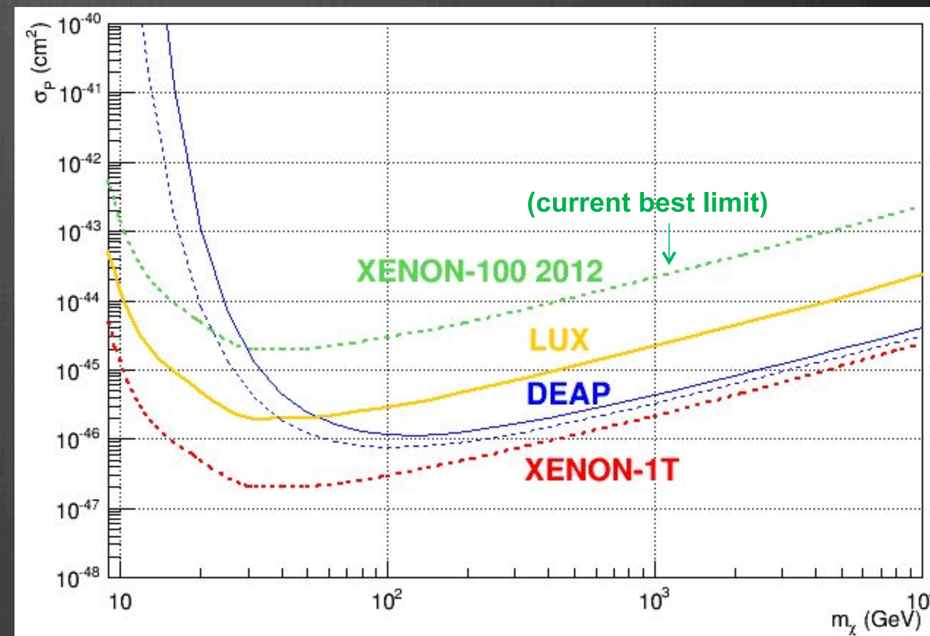
Detector in 8 m water
shield at SNOLAB

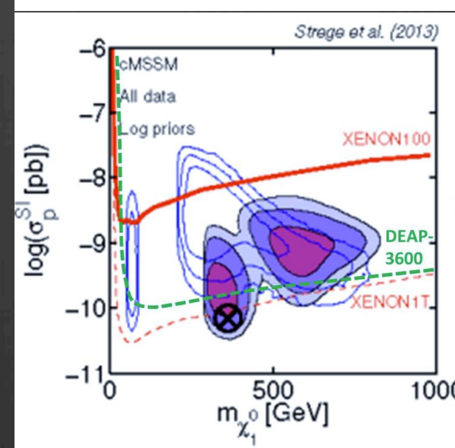
DEAP 3600

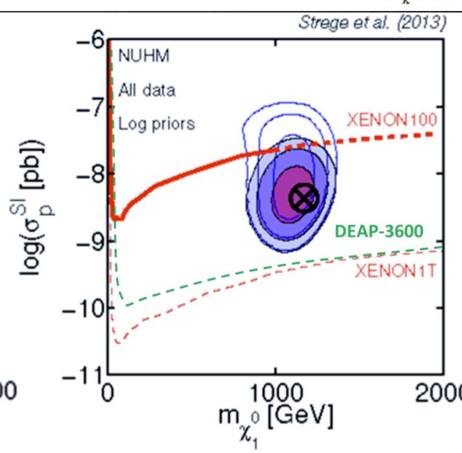


DEAP 3600 physics potential









Post LHC remaining minimal SUSY models
can be investigated at $m_\chi > 350$ GeV

DEAP 3600: scale-up

Tentative Project Schedule

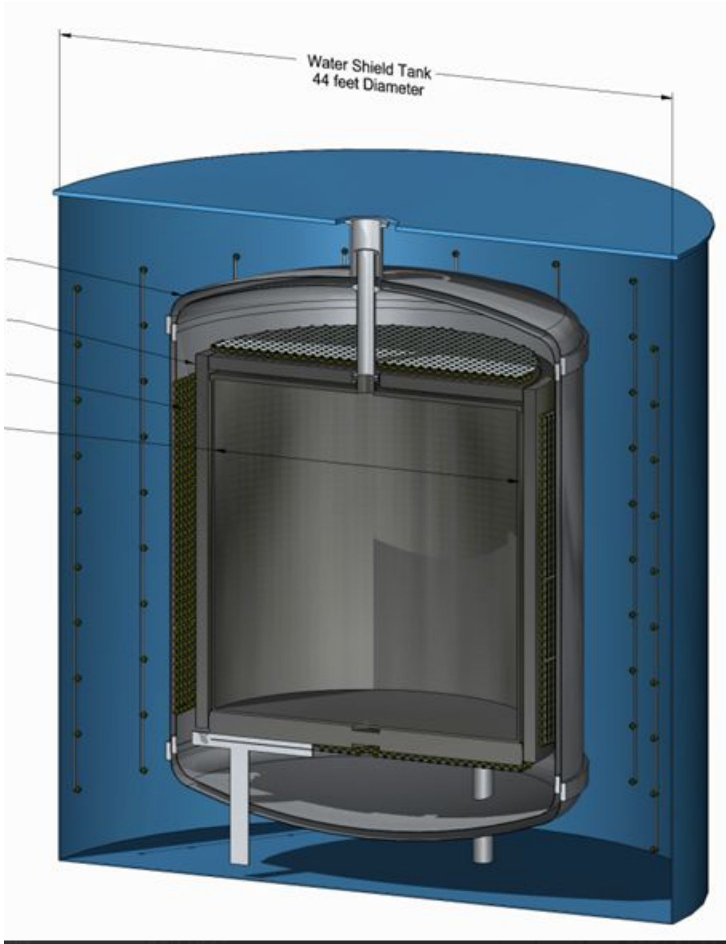
2013,2014:
- Conceptual design/safety analysis, develop budget
- Identify space requirements, submit space request and development requests
- (Start DEAP-3600 Data collection, focus of effort)

2014,2015:
- More detailed engineering for budgeting
- Design/plans for depleted argon storage and delivery

2015-2017:
- Detailed engineering for contracts/fabrication
- Implementation of DAr storage and argon collection start

2017-2020:
- Construction and Installation
- Continued DAr collection/storage
- (End DEAP-3600 Data collection)

2020-2025:
- Operation

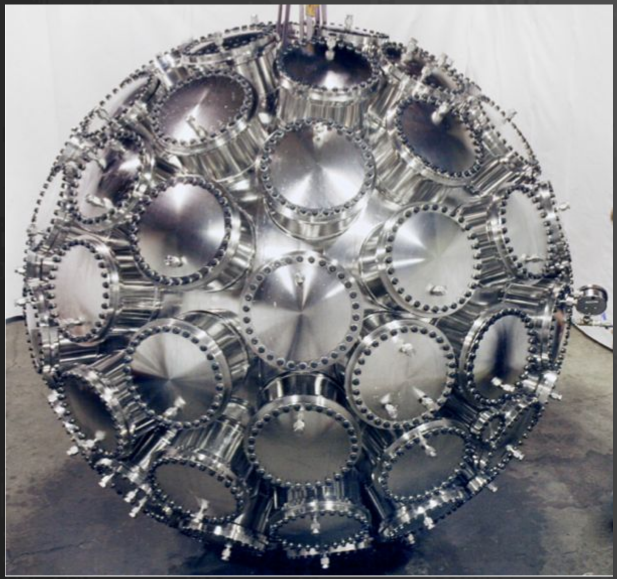


Depleted Argon

- Ordinary atmospheric argon contains cosmogenic ^{39}Ar
  - β -emitter (Q=565keV, τ =388yr)
  - ^{39}Ar/Ar = $8 \cdot 10^{-16}$ ➔ ~1Bq/kg.
- TPC drift times: ~ 500 μ s/m.
  - Above 1t pile-up becomes an issue.
- Undeground Argon facility established in 2011 in Colorado within DarkSide.
  - Will serve DarkSide50 and DEAP 3600.
- Production rate ~ 1kg/d
  - need to improve to >100kg/d for multi-ton detectors

depletion factor: >100

MiniCLEAN



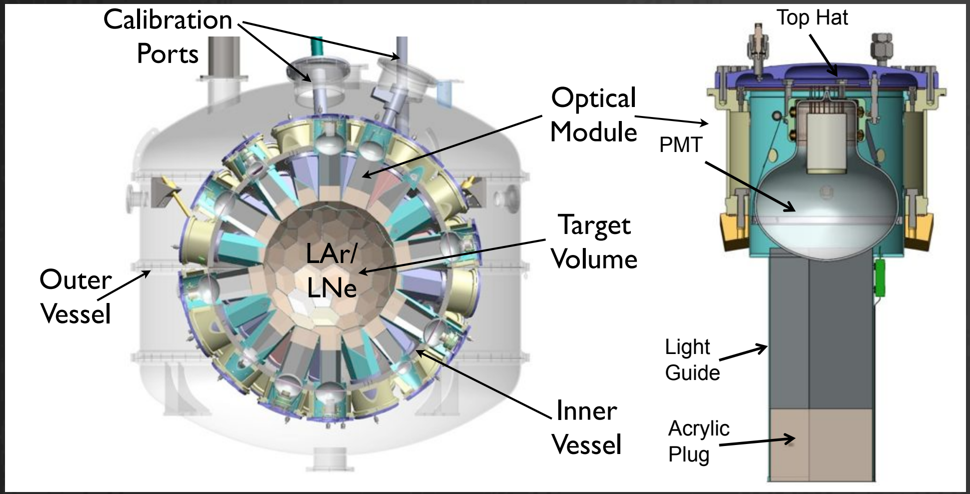
DEAP twin experiment:

investigation/confirmation

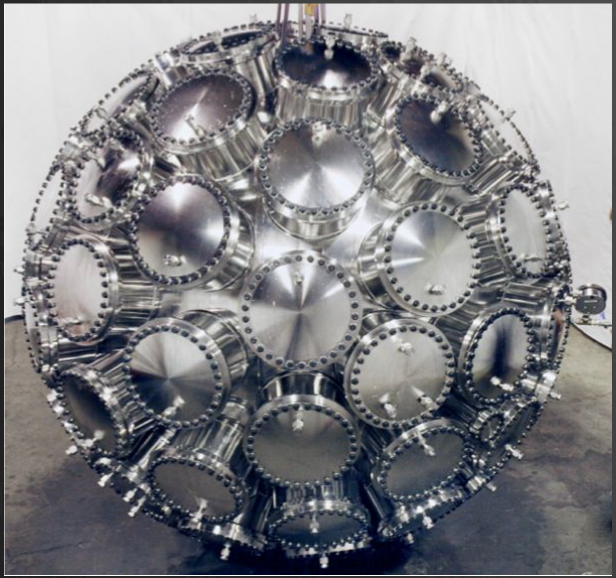
500kg/150kgFM

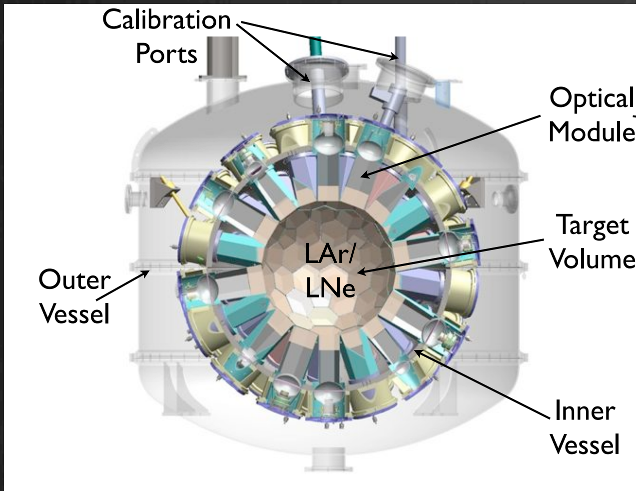
Dual target: LAR and LNe

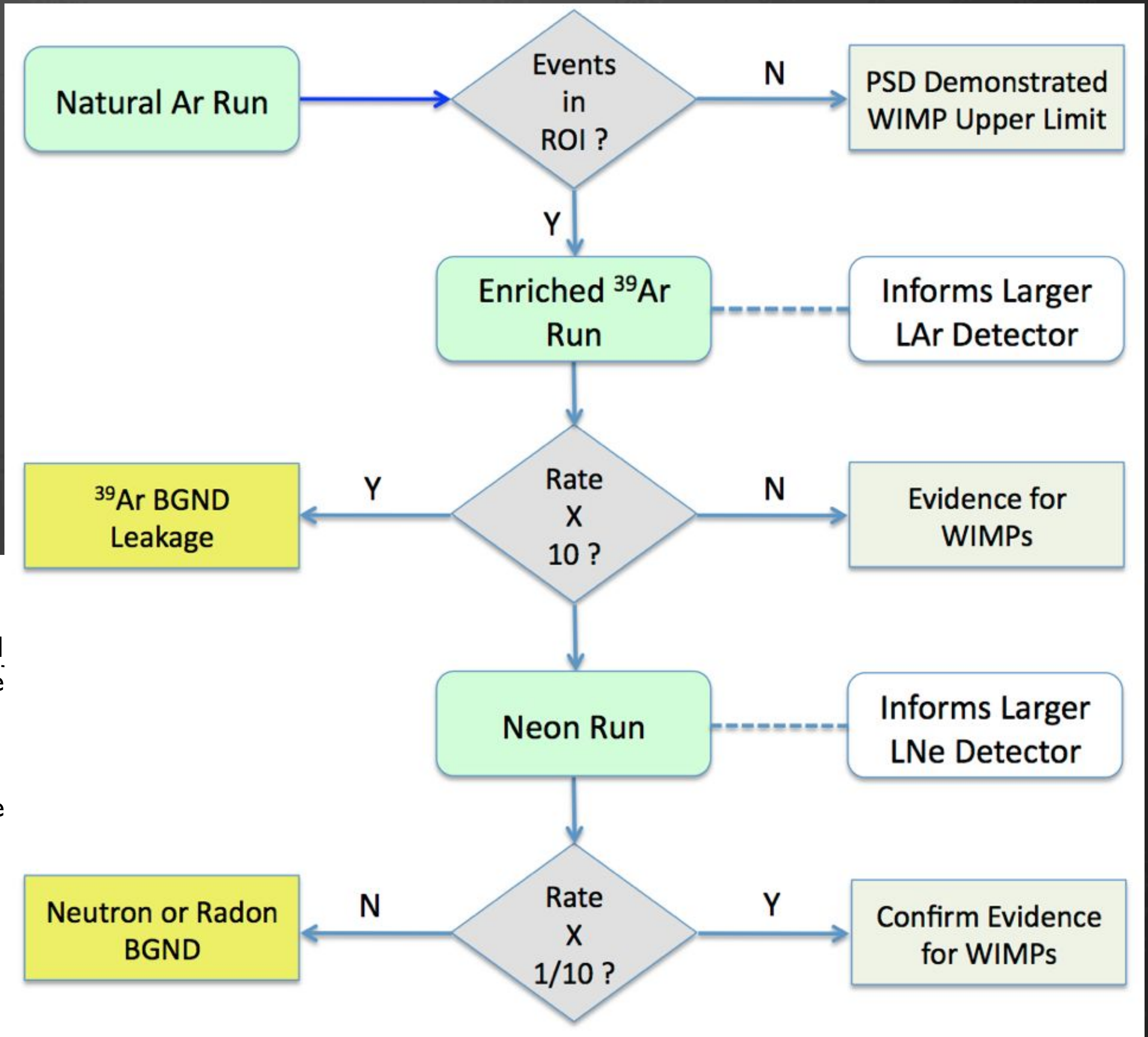
Plans to scale up to 45t



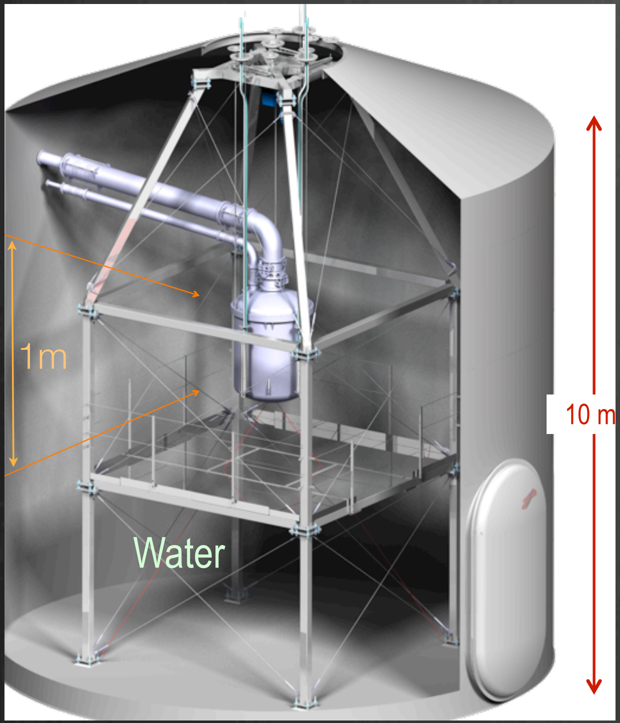
MiniCLEAN

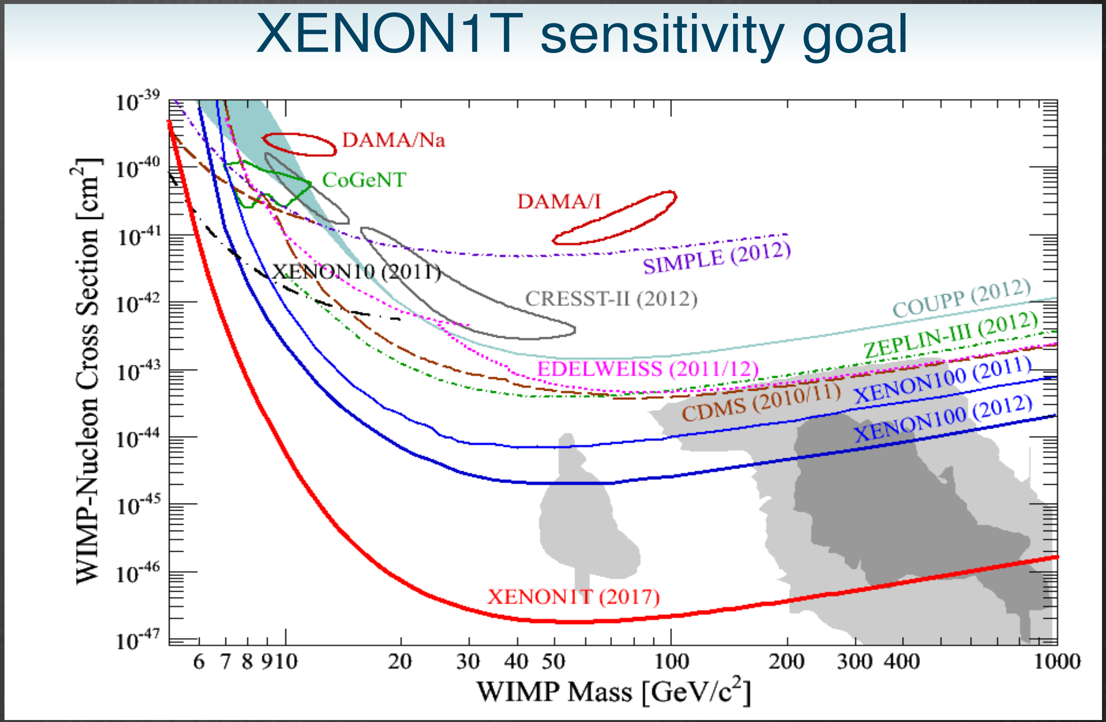



Calibration Ports
Optical Module
Target Volume
LAr/ LNe
Outer Vessel
Inner Vessel


Natural Ar Run
Events in ROI ?
N
PSD Demonstrated WIMP Upper Limit
Y
Enriched ^{39}Ar Run
Informs Larger LAr Detector
Rate X 10 ?
Y
^{39}Ar BGND Leakage
N
Evidence for WIMPs
Neon Run
Informs Larger LNe Detector
Rate X 1/10 ?
N
Neutron or Radon BGND
Y
Confirm Evidence for WIMPs

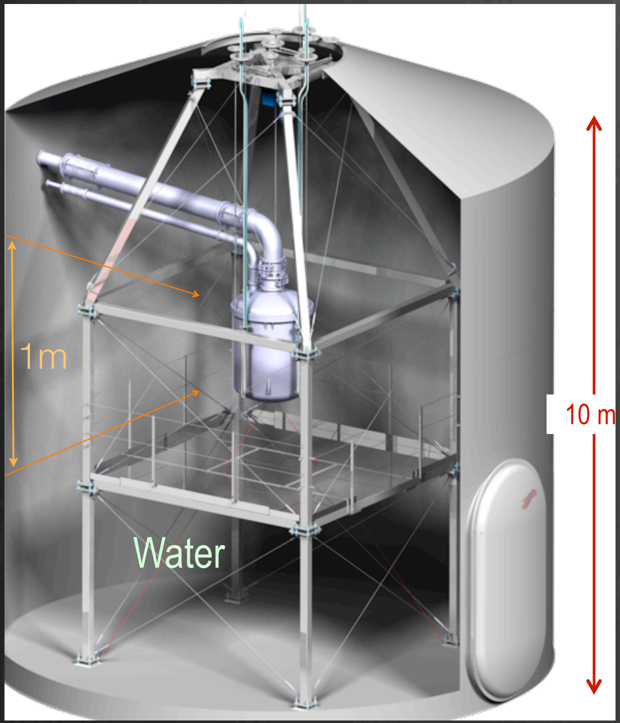
Xenon 1t

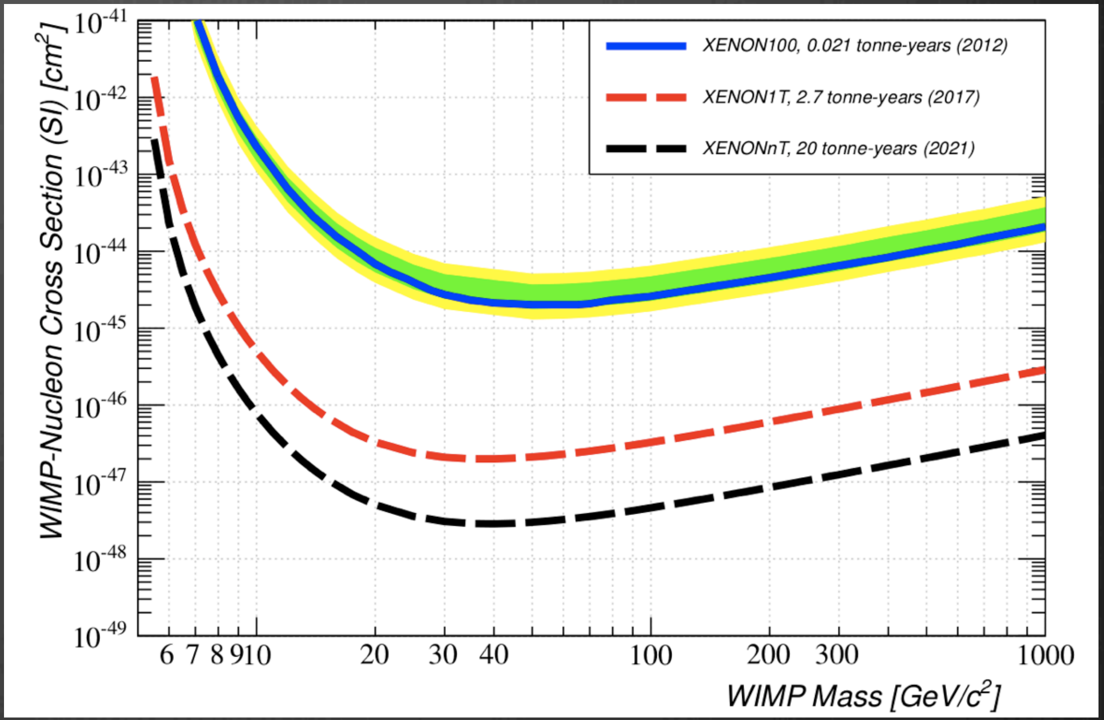




1mx1m dual-phase Xe TPC with 100kV
Construction started ~2months ago
3.5t active target: 2t fiducial
248 3” PMTs

Xenon 1t

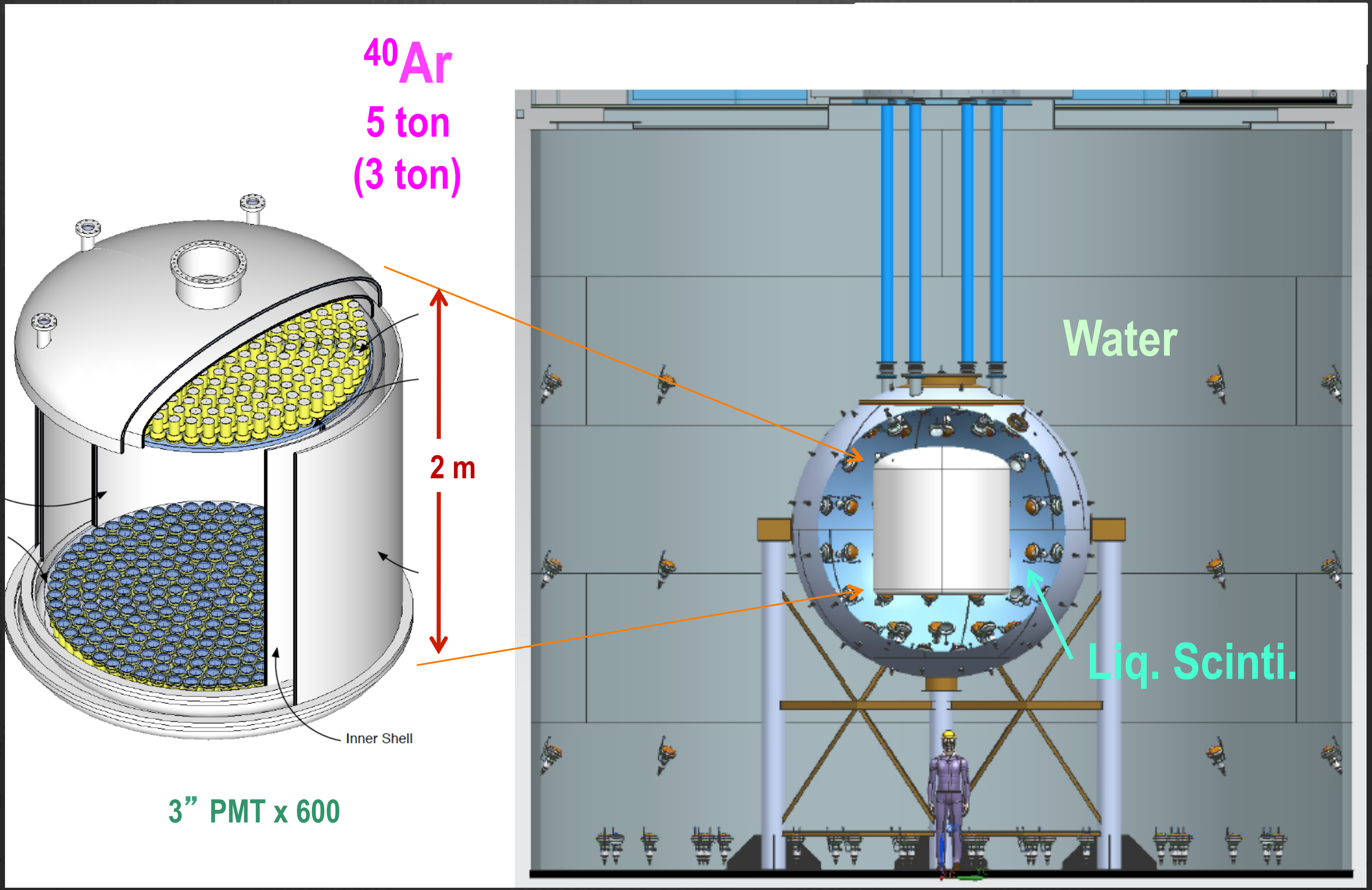




1mx1m dual-phase Xe TPC with 100kV
Construction started ~2months ago
3.5t active target: 2t fiducial
248 3" PMTs

Dark Side 5t

submitted for DOE approval in Novemer 2013



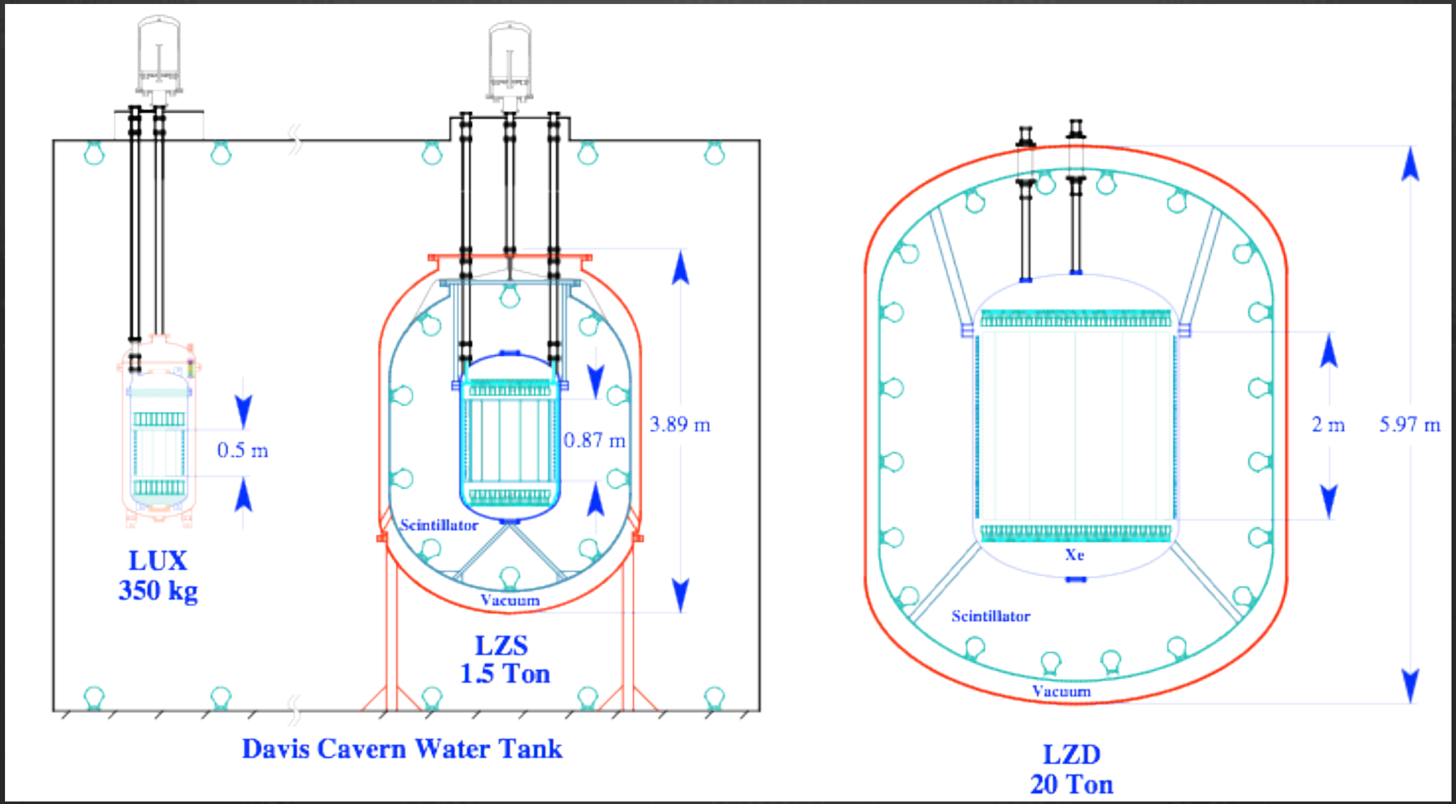
Generation 3

10^{-48} cm^2

(and beyond?)

LZ

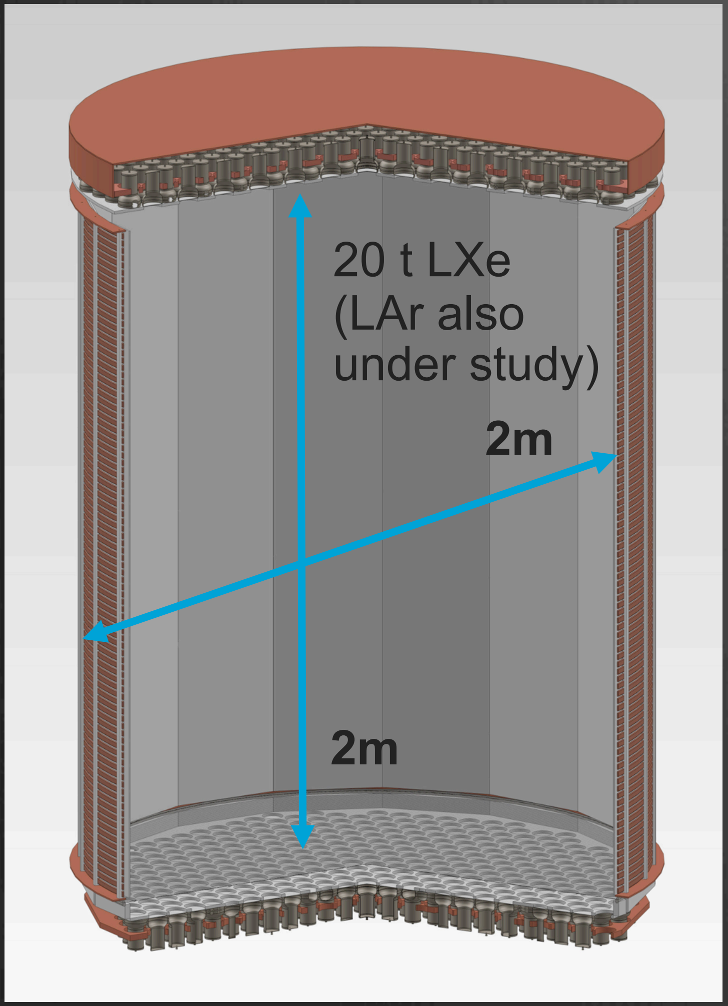
2 stages Scale-up of LUX, joint effort of Lux and Zepelin collaborations

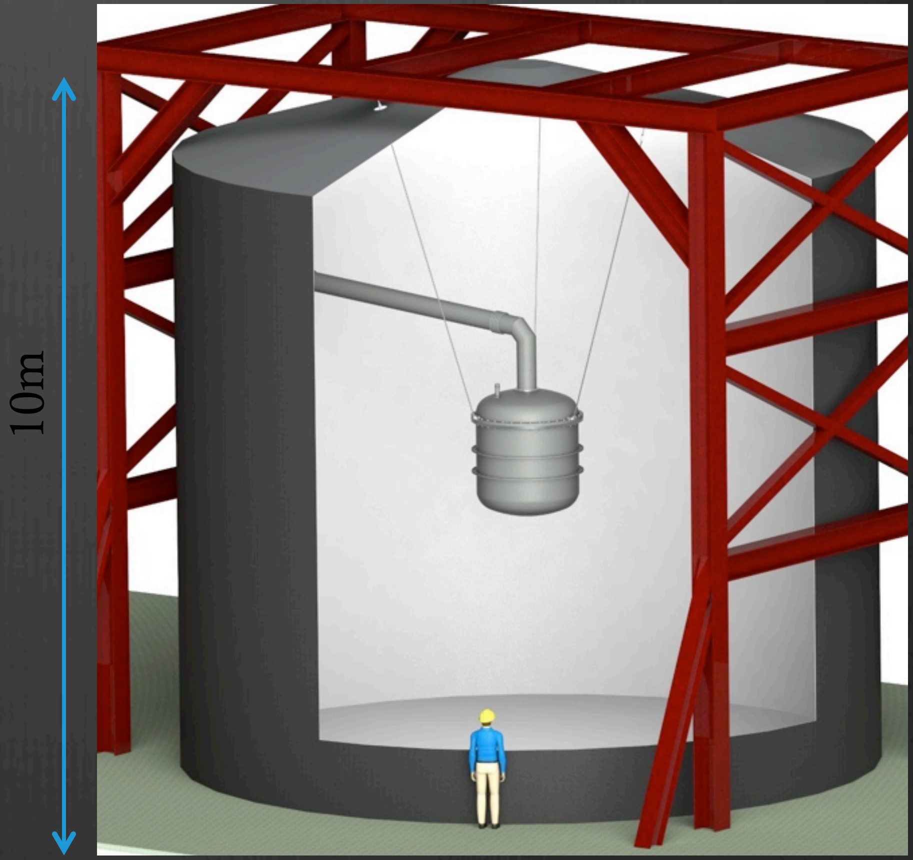


SANFORD underground laboratory

Darwin

20t LXe (~12t fiducial); ~ 1050 PMTs, physics run to start in 2020





Darwin: site radioactivity

Energy interval [kev]	LNGS: Hall A gamma flux $[m^{-2}d^{-1}]$	gamma flux $[cm^{-2}s^{-1}]$
0-500	$4.4 \cdot 10^8$	0.51
500-1000	$1.1 \cdot 10^8$	0.13
1000-2000	$7.0 \cdot 10^7$	0.081
2000-3000	$1.3 \cdot 10^7$	0.015
Entire spectrum	$6.3 \cdot 10^8$	0.74

C. Bucci et al., Eur. Phys. J. A 41, 155 (2009)

Lab	Neutron Flux ($\times 10^{-6}$ cm^{-2}s^{-1}) all energies	E>1MeV
LNGS [61] (measurements)	3.78±0.25	0.60±0.07 or 0.70±0.14
LNGS [61] (simulations)	3.75±0.67	0.58±0.13
LNGS - Hall A [62] (measurements)	3.8±1.2	1.2±0.4
LSM	≈2 [64]	1.06±0.1(stat)±0.59(syst) [63]

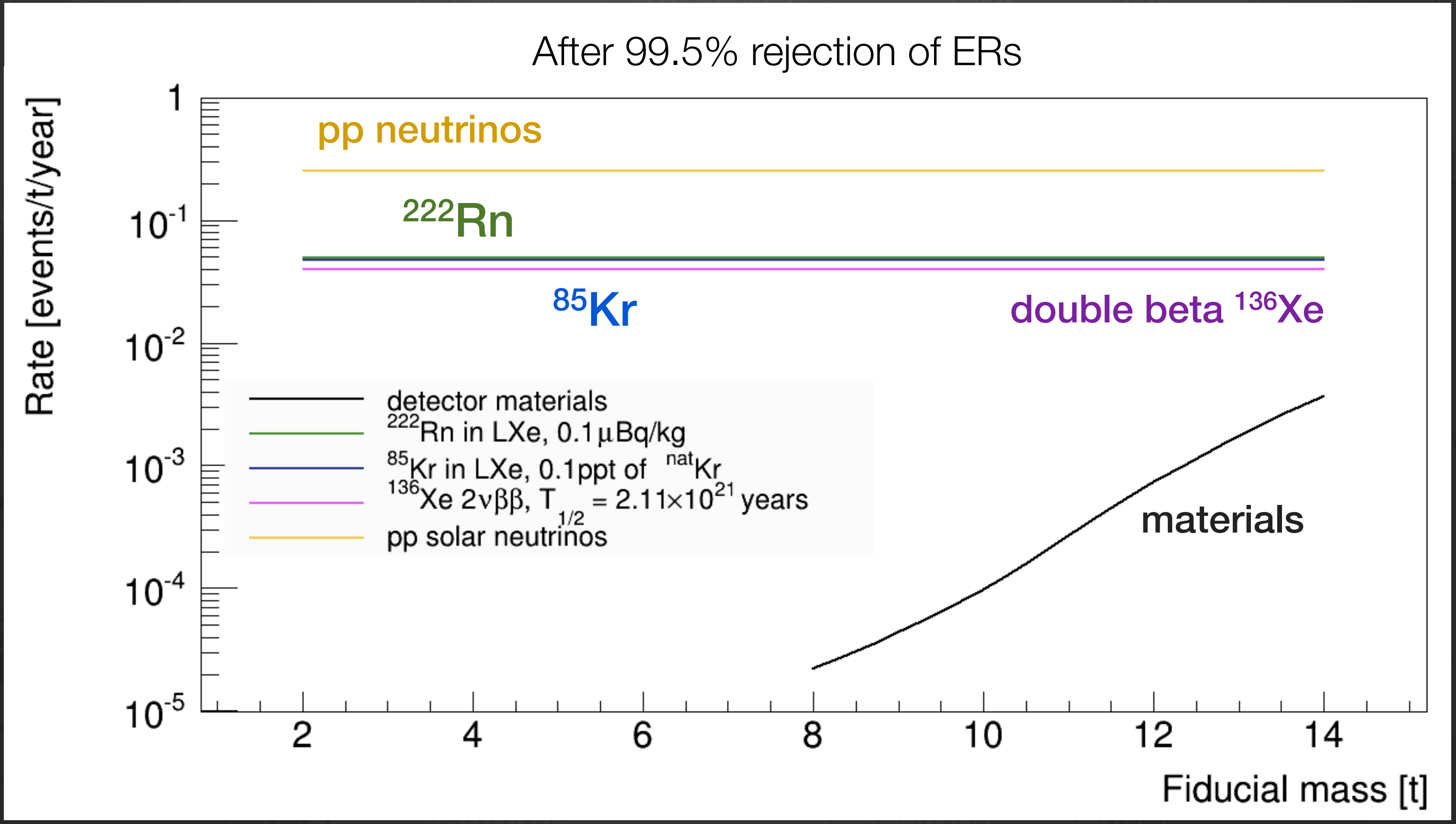
H. Wulandari et al., arXiv:hep-ex/0312050

Lab	Depth (m.w.e)	Equivalent vertical depth [65] (m.w.e.)	Muon flux (m^{-2} d^{-1})	Mean energy (GeV)	Muon-induced neutron flux (m^{-2} d^{-1})
LNGS	≈ 3750	≈ 3100	22.3±2.6	≈ 270	2.35
LSM	≈ 4800	≈ 4200	4.17±0.43	≈ 300	0.54

D.-M. Mei, A. Hime, Phys. Rev. D 73 (2006)

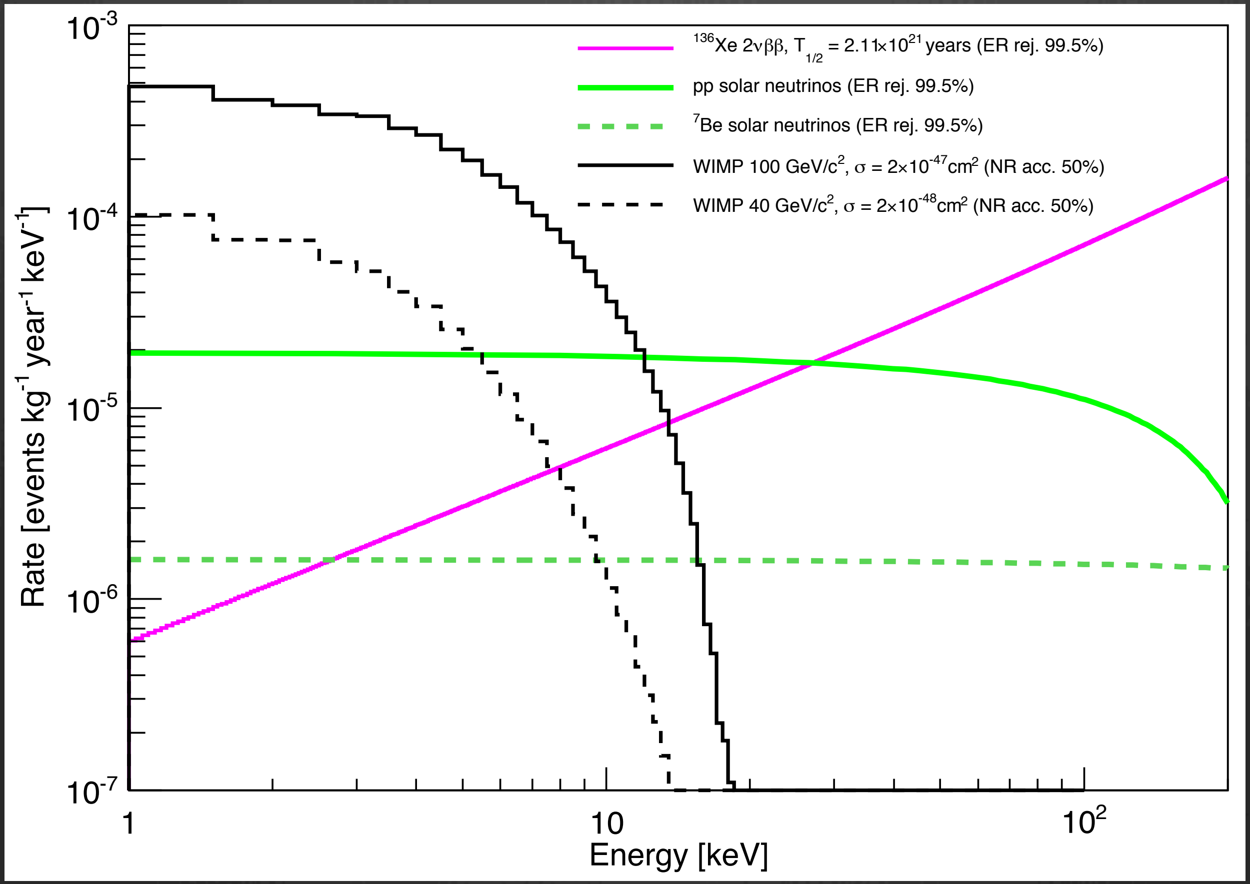
Darwin

In LNGS environment, NR backgrounds would be subdominant



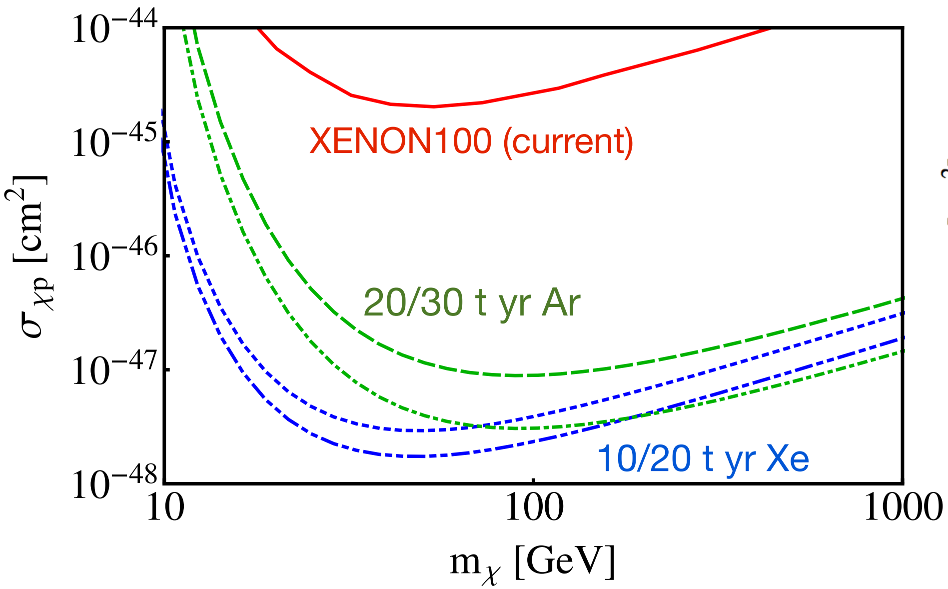
Darwin

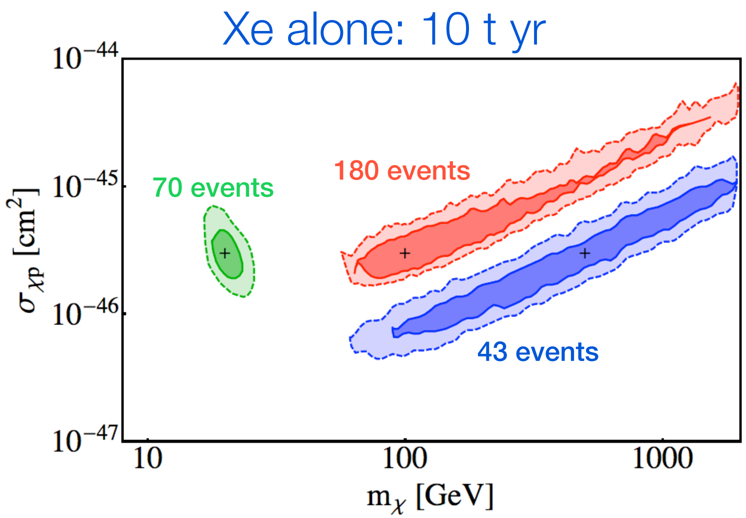
In LNGS environment, NR backgrounds would be subdominant

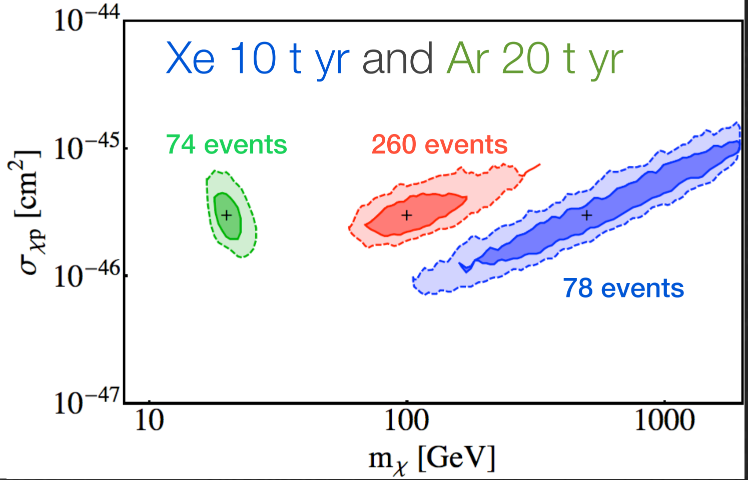


Darwin

arXiv:1306.3244





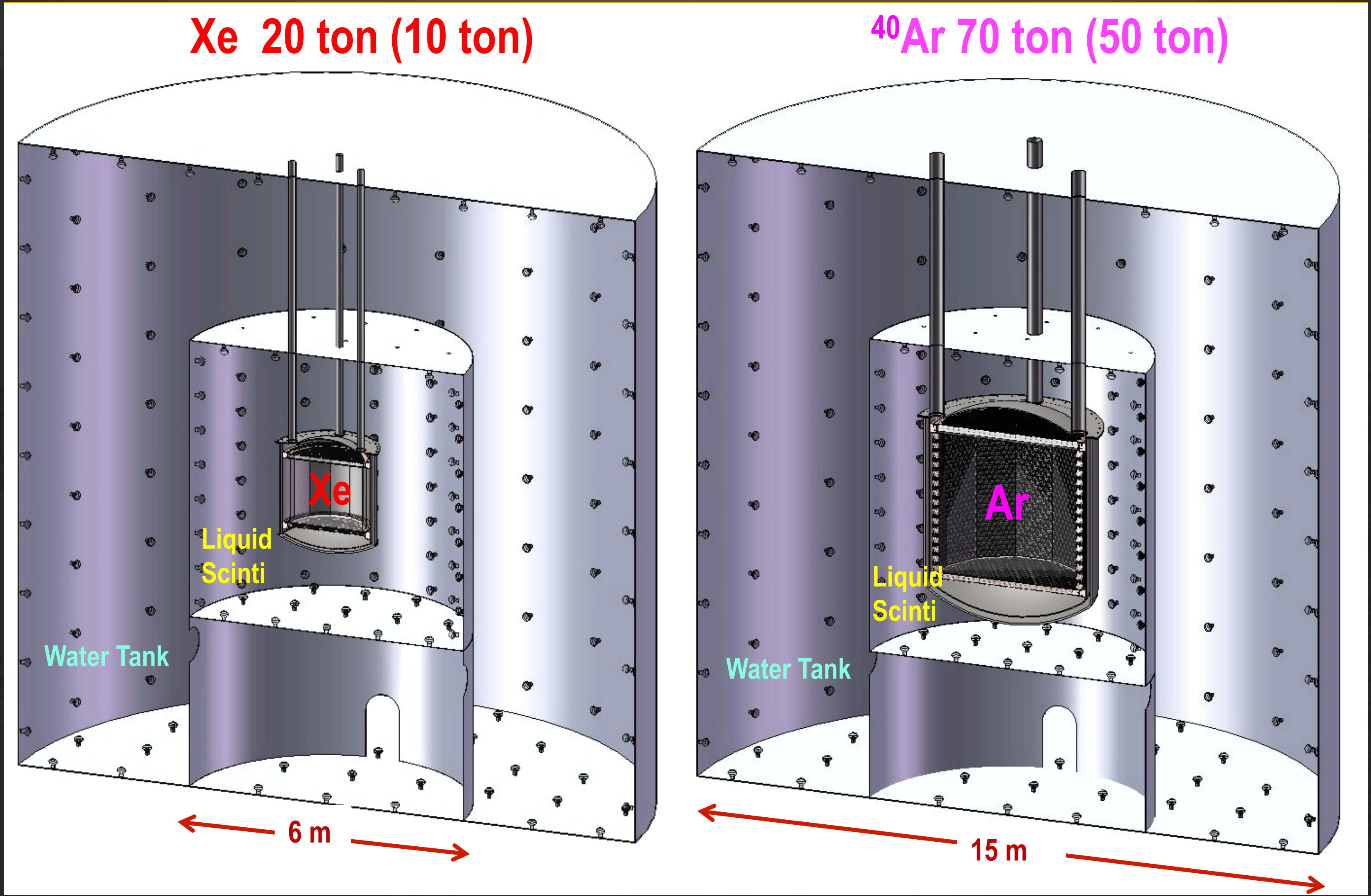


$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

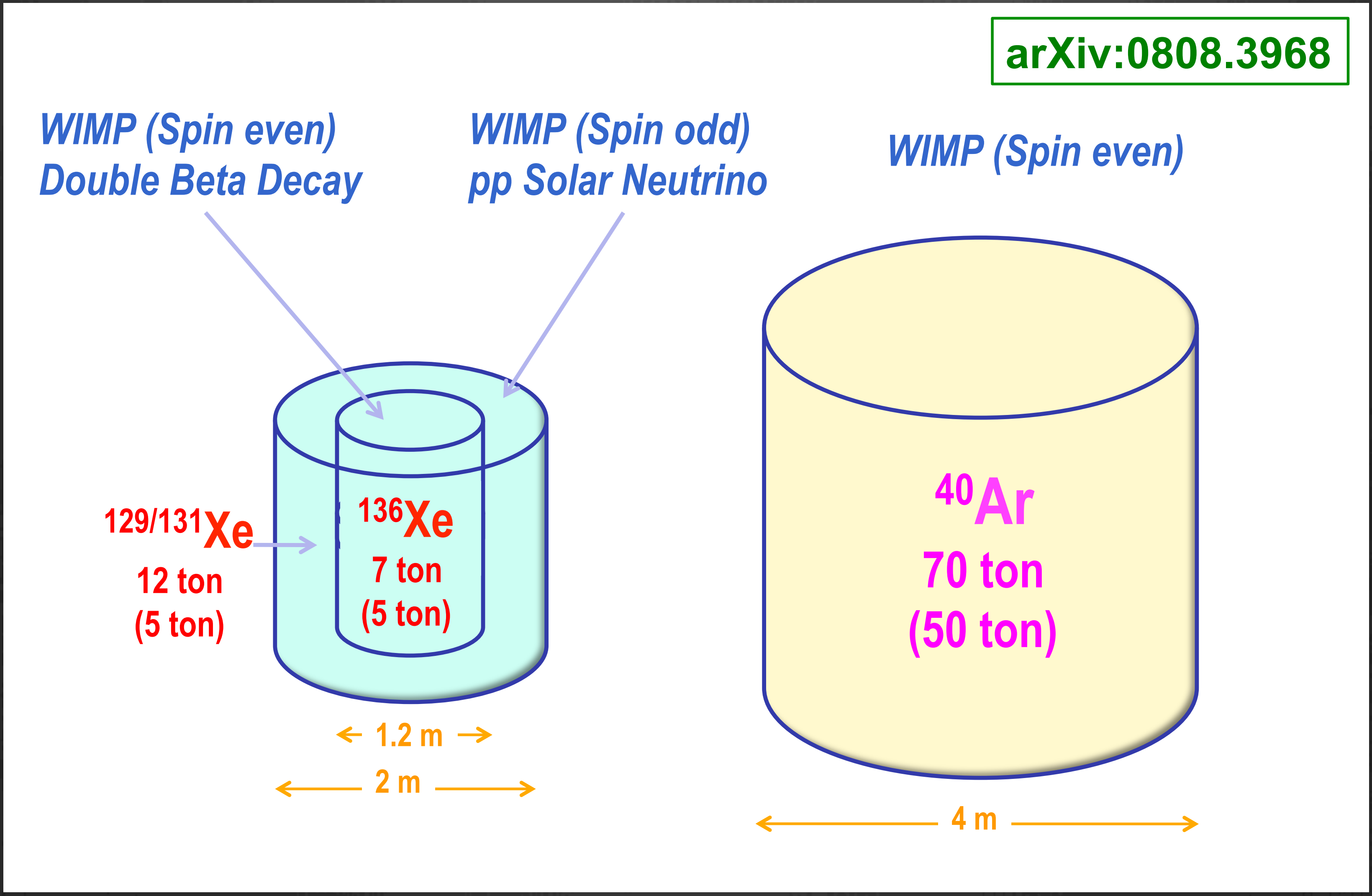
$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

MAX


Xe 20 ton (10 ton)
40Ar 70 ton (50 ton)
Xe
Liquid Scinti
Water Tank
6 m
Ar
Liquid Scinti
Water Tank
15 m

XAX



arXiv:0808.3968
WIMP (Spin even)
Double Beta Decay
WIMP (Spin odd)
pp Solar Neutrino
WIMP (Spin even)
129/131Xe
12 ton
(5 ton)
136Xe
7 ton
(5 ton)
40Ar
70 ton
(50 ton)
1.2 m
2 m
4 m

Projects summary

G	Experiment	Target	Detector	Location	Active mass	Fiducial mass	Year physics	Peak sensitivity
G1	Xenon 100	Xe	TPC	LNGS	62	34	2012	$2\ 10^{-45}$
G1	Dark Side 50	Ar	TPC	LNGS	50	33	2013	$1.5\ 10^{-45}$
G1	Xmass	Xe	single	Kamioka	800	100	2014?	???
G1	LUX	Xe	TPC	SURF	350	100	2014/5	$7\ 10^{-46}$
G1	ArDM	Ar	TPC	Canfranc	850	???	2014/5	???
G2	Deap 3600	Ar	single	SNOlab	3600	1000	2015	10^{-46}
G2	MiniClean	Ar/Ne	single	SNOlab	500	150	2015?	--
G2	Xenon 1t	Xe	TPC	LNGS	3500	2200	2017	$2\ 10^{-47}$
G2	DarkSide 5t	Ar	TPC	LNGS	5000	3000	2017	10^{-47}
G2	LZS	Xe	TPC	SURF	1500	800	2017	$4\ 10^{-47}$
G3	Darwin	Xe(Ar)	TPC	LNGS?	20t	12t	~2020	$\sim 10^{-48}$
G3	LZD	Xe	TPC	???	20t	12t	~2020	$\sim 10^{-48}$
G3	MAX/XAX	Xe+Ar	2TPCs	DUSEL???	20t+70t	12t+50t	~2020	$\sim 10^{-48}$

Borexino for Dark Matter?

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Cosmogenic Backgrounds in Borexino at 3800 m water-equivalent depth

The Borexino collaboration

JCAP08(2013)049

Cosmogenic Neutrons

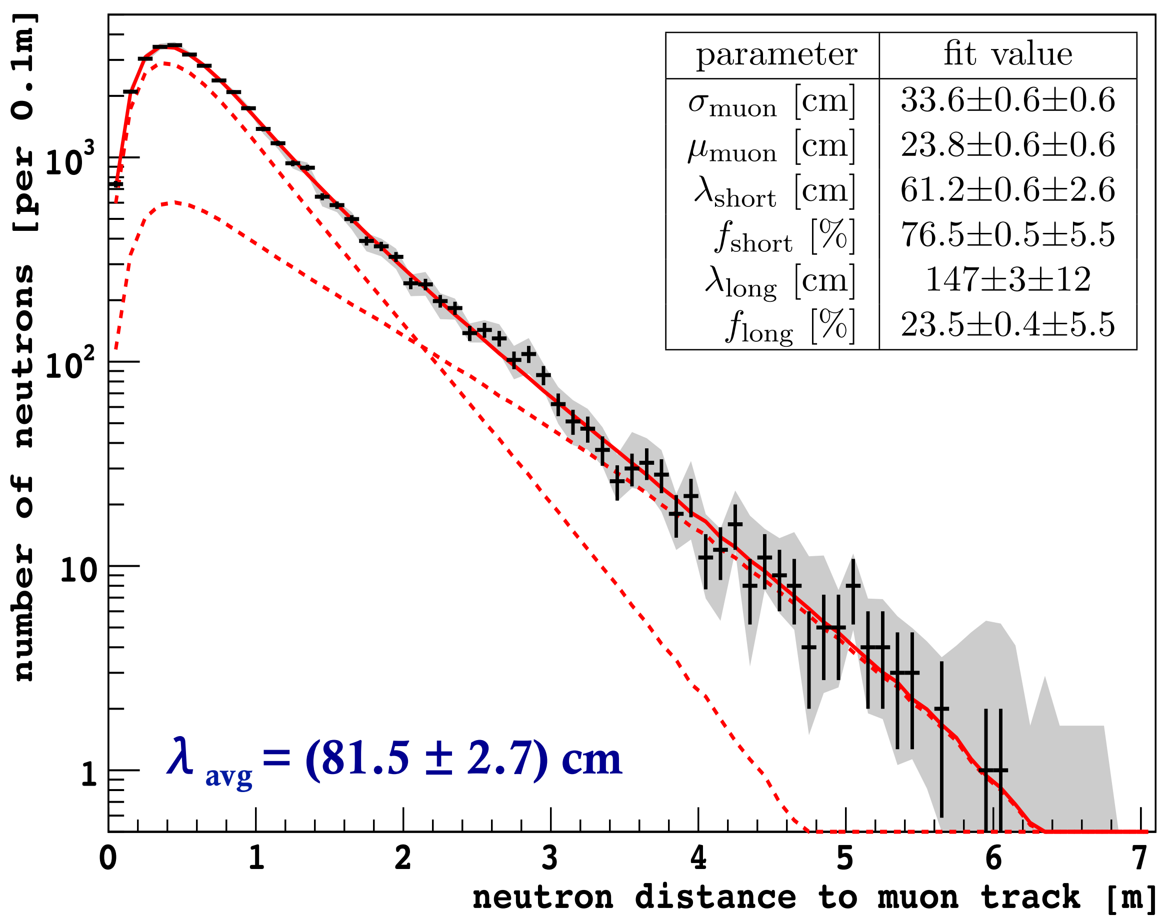
Cosmogenic neutron production in organic liquid scintillator:

Yield = $(3.10 \pm 0.07_{stat} \pm 0.08_{syst})\ 10^{-4}\ n/(\mu\ g/cm^2)$

Flux = $(7.31 \pm 0.17_{stat} \pm 0.19_{syst})\ n/m^2/d$

LNGS	Experiment	Year	$10^{-4}\ \mu\ m^{-2}\ s^{-1}$	$\mu\ m^{-2}\ d^{-1}$
Hall A	LVD	2009	3.31±0.03	28.5±0.2
Hall B	MACRO	1995	3.22±0.08	27.8±0.7
Hall C	BOREXINO	2012	3.41±0.01	29.46±0.08

Cosmogenic Neutrons

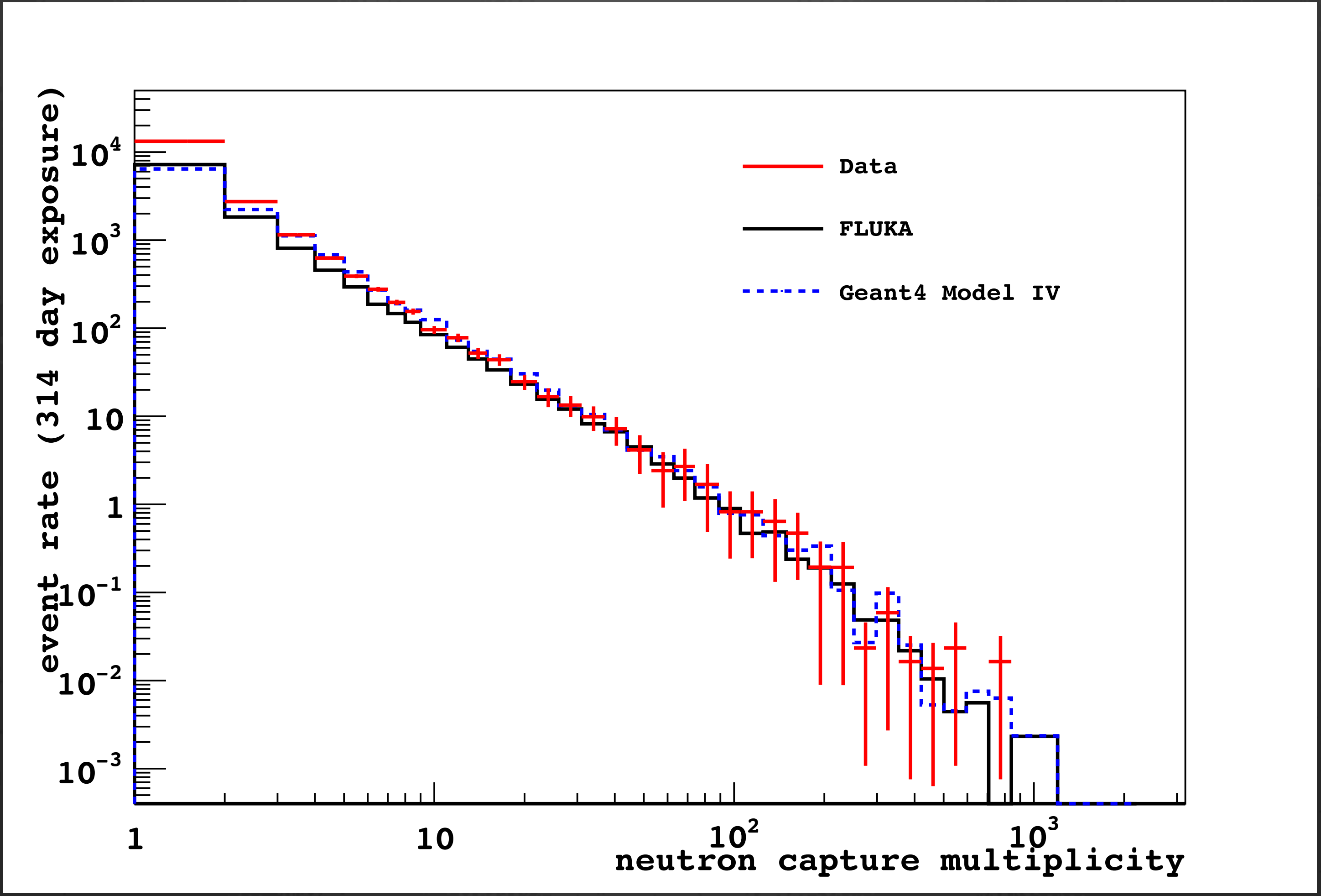


Comparing with simulations

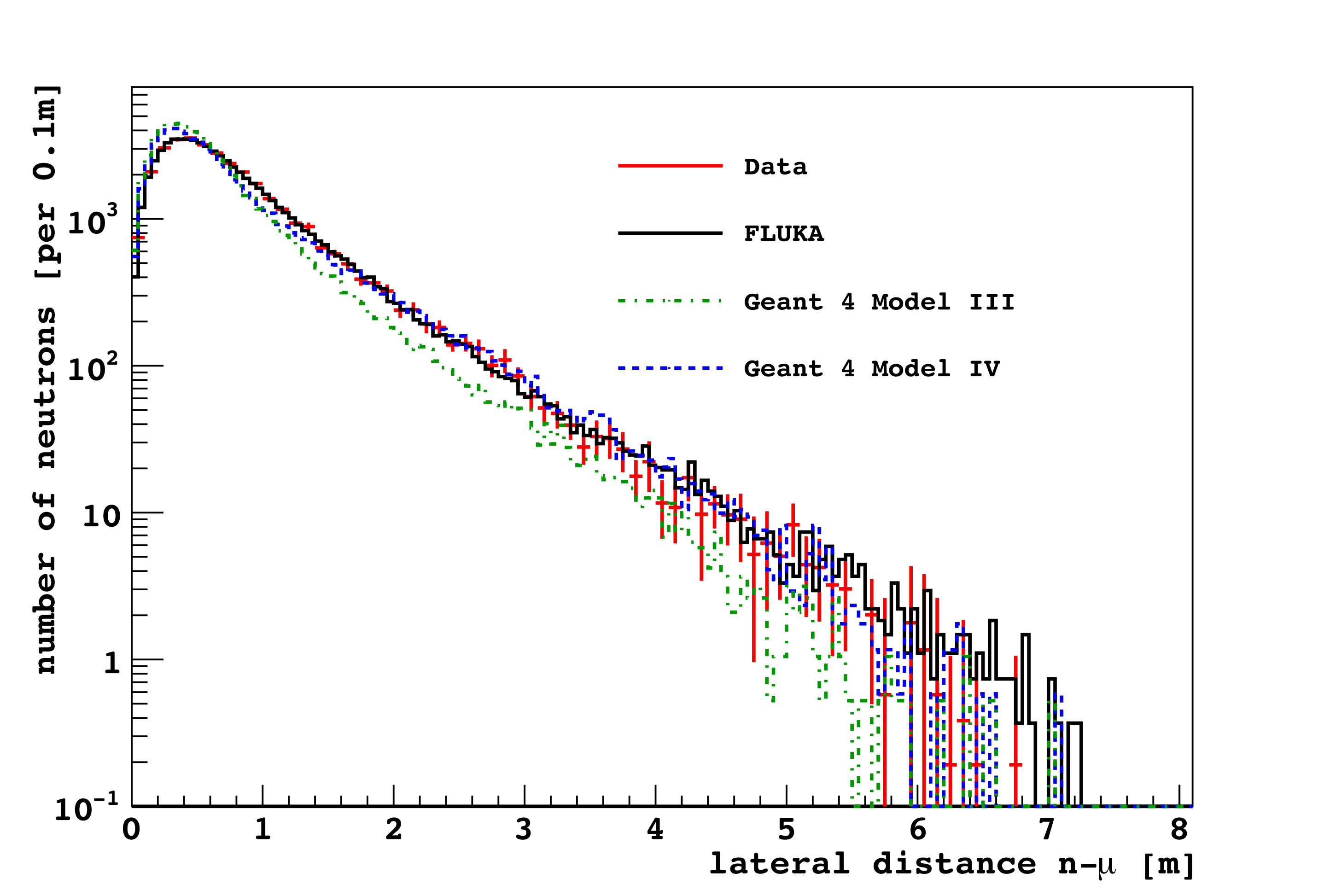
Borexino and surrounded area simulated
Muon energy and angular distributions from MACRO
$\mu^+ / \mu^- = 1.38$ from OPERA

	GEANT4 Model III	GEANT4 Model IV	FLUKA	Borexino	KamLAND
		— $\langle E_\mu \rangle = 283 \pm 19$ GeV —			$\langle E_\mu \rangle = 260 \pm 8$ GeV
Isotopes		Yield $[10^{-7} (\mu\, g/cm^2)^{-1}]$			
^{12}**N**	1.11 ± 0.13	3.0 ± 0.2	0.5 ± 0.2	< 1.1	1.8 ± 0.4
^{12}**B**	30.1 ± 0.7	29.7 ± 0.7	28.8 ± 1.9	56 ± 3	42.9 ± 3.3
^{8}**He**	< 0.04	0.18 ± 0.05	0.30 ± 0.15	< 1.5	0.7 ± 0.4
^{9}**Li**	0.6 ± 0.1	1.68 ± 0.16	3.1 ± 0.4	2.9 ± 0.3	2.2 ± 0.2
^{8}**B**	0.52 ± 0.09	1.44 ± 0.15	6.6 ± 0.6	14 ± 6	8.4 ± 2.4
^{6}**He**	18.5 ± 0.5	8.9 ± 0.4	17.3 ± 1.1	38 ± 15	not reported
^{8}**Li**	27.7 ± 0.7	7.8 ± 0.4	28.8 ± 1.0	7 ± 7	12.2 ± 2.6
^{9}**C**	0.16 ± 0.05	0.99 ± 0.13	0.91 ± 0.10	< 16	3.0 ± 1.2
^{11}**Be**	0.24 ± 0.06	0.45 ± 0.09	0.59 ± 0.12	< 7.0	1.1 ± 0.2
^{10}**C**	15.0 ± 0.5	41.1 ± 0.8	14.1 ± 0.7	18 ± 5	16.5 ± 1.9
^{11}**C**	315 ± 2	415 ± 3	467 ± 23	886 ± 115	866 ± 153
Neutrons		Yield $[10^{-4} (\mu\, g/cm^2)^{-1}]$			
	3.01 ± 0.05	2.99 ± 0.03	2.46 ± 0.12	3.10 ± 0.11	2.79 ± 0.31

Comparing n multiplicity



Comparing lateral distance



Laboratory needs

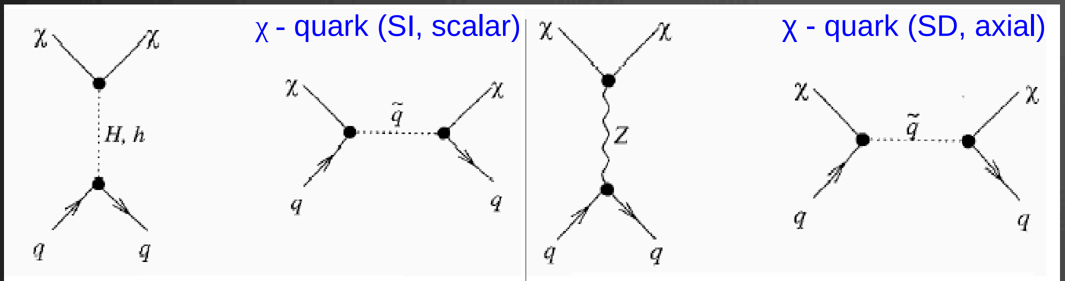
- Service lines: cooling, network,…
- Standard laboratory services
- Machine shop, chemistry lab, electronics lab,,computing.
- Desiderata:
  - Radon free clean room
  - PMT test facility (above ground)

Conclusions

- Noble gases are and will be driving dark matter searches at large masses (above LHC limit).
- LXe and (depleted) LAr will both be pursued as complementary approaches.
- 2014: G1 projects coming to a conclusion.
- 2017: G2 projects should perform physics runs.
- 2020: G3 projects at multi-ton scales plan to converge.

thanks for material to Marc Schumann, Laura Baudis, Cristiano Galbiati

Xenon 100 – Spin Dependant



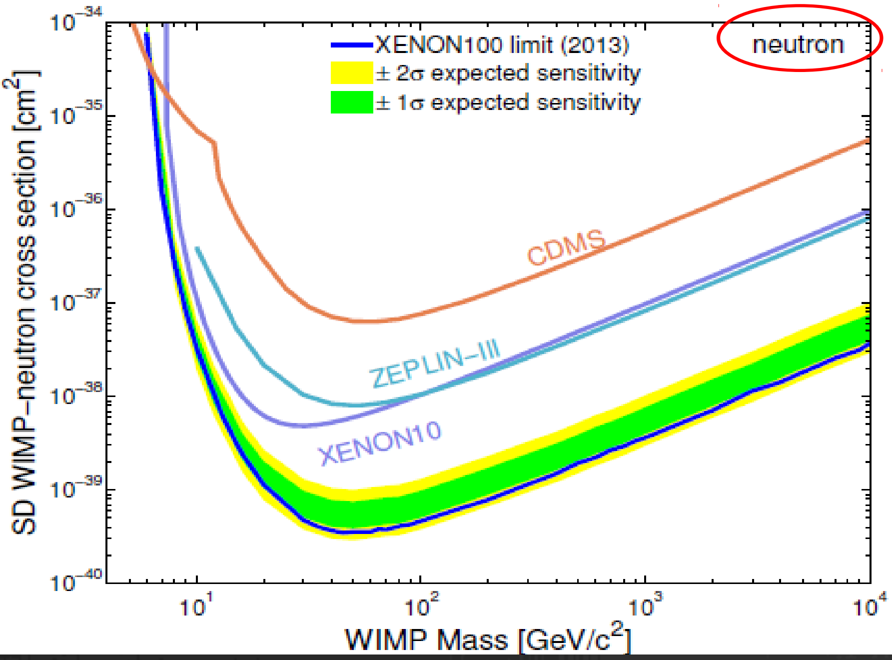
$\mathcal{L}_S \sim \tilde{\chi}\chi\bar{q}q \quad \propto A^2$

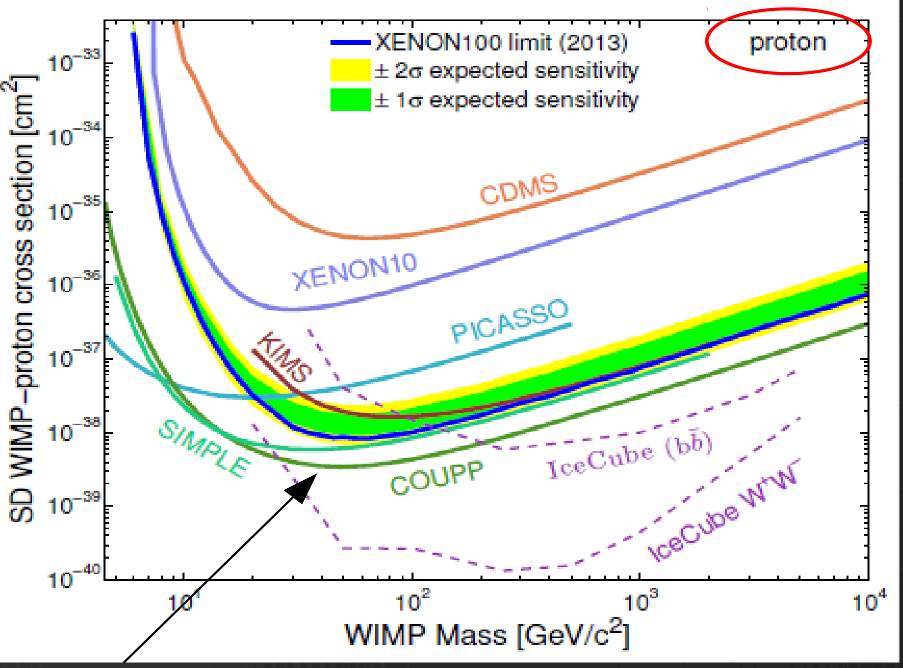
$\mathcal{L}_A \sim \tilde{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \quad \propto J(J+1)$

Jungmann et al. '96 Phys.Rep.

$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{spin}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)}$$

$$C_{spin} = \frac{8}{\pi}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}$$





Geant4 models

Model I	**HP**	**Binary**	**Bertini**	**FTF**
Protons		$0 \rightarrow 5\,\mathrm{GeV}$		$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Neutrons	$0 \rightarrow 20\,\mathrm{MeV}$	$19.9\,\mathrm{MeV} \rightarrow 5\,\mathrm{GeV}$		$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
π		$0 \rightarrow 5\,\mathrm{GeV}$		$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
K			$0 \rightarrow 5\,\mathrm{GeV}$	$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Model II	**HP**	**Bertini**		**FTF**
Protons		$0 \rightarrow 5\,\mathrm{GeV}$		$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Neutrons	$0 \rightarrow 20\,\mathrm{MeV}$	$19.9\,\mathrm{MeV} \rightarrow 5\,\mathrm{GeV}$		$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
π, K		$0 \rightarrow 5\,\mathrm{GeV}$		$4\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Model III	**HP**	**Binary**	**LEP**	**QGS**
Protons		$0 \rightarrow 9.9\,\mathrm{GeV}$	$9.5 \rightarrow 25\,\mathrm{GeV}$	$12\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Neutrons	$0 \rightarrow 20\,\mathrm{MeV}$	$19.9\,\mathrm{MeV} \rightarrow 9.9\,\mathrm{GeV}$	$9.5 \rightarrow 25\,\mathrm{GeV}$	$12\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
π, K		$0 \rightarrow 9.9\,\mathrm{GeV}$	$9.5 \rightarrow 25\,\mathrm{GeV}$	$12\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Model IV	**HP**	**Bertini**	**LEP**	**QGS**
Protons		$0 \rightarrow 9.9\,\mathrm{GeV}$	$9.5 \rightarrow 25\,\mathrm{GeV}$	$12\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
Neutrons	$0 \rightarrow 20\,\mathrm{MeV}$	$19.9\,\mathrm{MeV} \rightarrow 9.9\,\mathrm{GeV}$	$9.5 \rightarrow 25\,\mathrm{GeV}$	$12\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$
π, K		$0 \rightarrow 9.9\,\mathrm{GeV}$	$9.5 \rightarrow 25\,\mathrm{GeV}$	$12\,\mathrm{GeV} \rightarrow 100\,\mathrm{TeV}$