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Dark Matter at DUSEL

Based on a community wide white paper
http://dmtools.brown.edu/DMWiki/images/c/c8/DMWG_DUSEL_White_Paper_April_2010.pdf

Fundamental and fascinating Science

an historic opportunity (with LHC and indirect detection methods)

Exciting technologies

poised to gain ≥3 orders of magnitude in sensitivity /number of events

DUSEL is an essential tool

Can accommodate two generation-3 experiments as corner stone of DUSEL initial program

This will maintain the US leadership of the last 20 years

A converging community with a coherent program

Dark Matter from TeV Scale Physics?

Dark Matter ≈ 25% of the energy density budget

≠baryons, neutrinos

central problem of cosmology

Particles in thermal equilibrium + decoupling when nonrelativistic

$$\Rightarrow \Omega_x h^2 = \frac{3 \cdot 10^{-27} cm^3 / s}{\langle \sigma_A v \rangle} \approx 0.12 \quad \Rightarrow \sigma_A \approx \frac{\alpha^2}{M^2_{EW}}$$

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale

(e.g. supersymmetry, global symmetry or additional dimensions)

=> Stable particle with appropriate cross section: significant amount of dark matter

Weakly Interacting Massive Particles (WIMPs)

At the moment favored candidate (but many others, e.g., axions)

Three methods:

Direct Detection in the Cosmos= Halo WIMP elastic scattering

Indirect Detection in the Cosmos= Annihilation products $\gamma, e^+, \overline{p}, \nu$

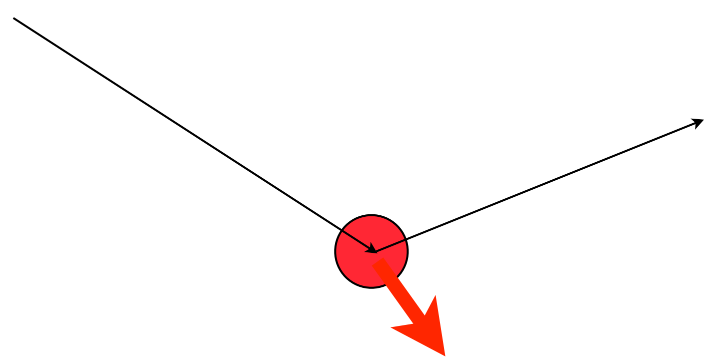
Production at the Large Hadron Collider

Historical opportunity: 3 methods ≈ same sensitivity + complementarity

(see additional material)

General Principles of Direct WIMP Search

Halo WIMP scattering on nucleus



Detect recoil of a nucleus

Essential to identify nuclear recoil in order to distinguish such rare events from e, γ background

-> electron recoils

Get rid of the neutrons

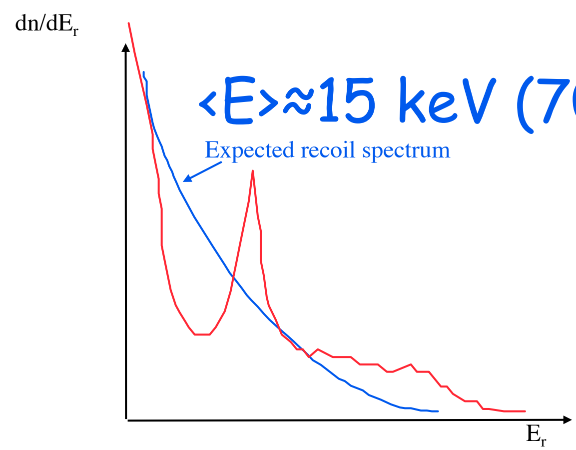
Depth

Water moderator

Active veto

Exponential energy distribution

$\langle E \rangle \approx 15$ keV ($70 GeV/c^2$)



Signatures

- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector

Linked to galaxy

- Annual modulation (but need several thousand events)
- Directionality (diurnal rotation in laboratory but 100 Å in solids)

Detection Challenge

A variety of novel and exciting techniques

Exquisite energy sensitivity
3 D reconstruction
At least two measurements to distinguish nuclear recoil from electron recoils
Decrease neutrons to negligible level (radio-purity, cosmogenic)

	Liquid Xenon	Liquid Argon	Low temp. Ge	Bubble Chamber
Ionization	√	√	√	high density
Scintillation	√	√		
Phonons			√	
Other		Pulse shape	Pulse shape	Acoustic

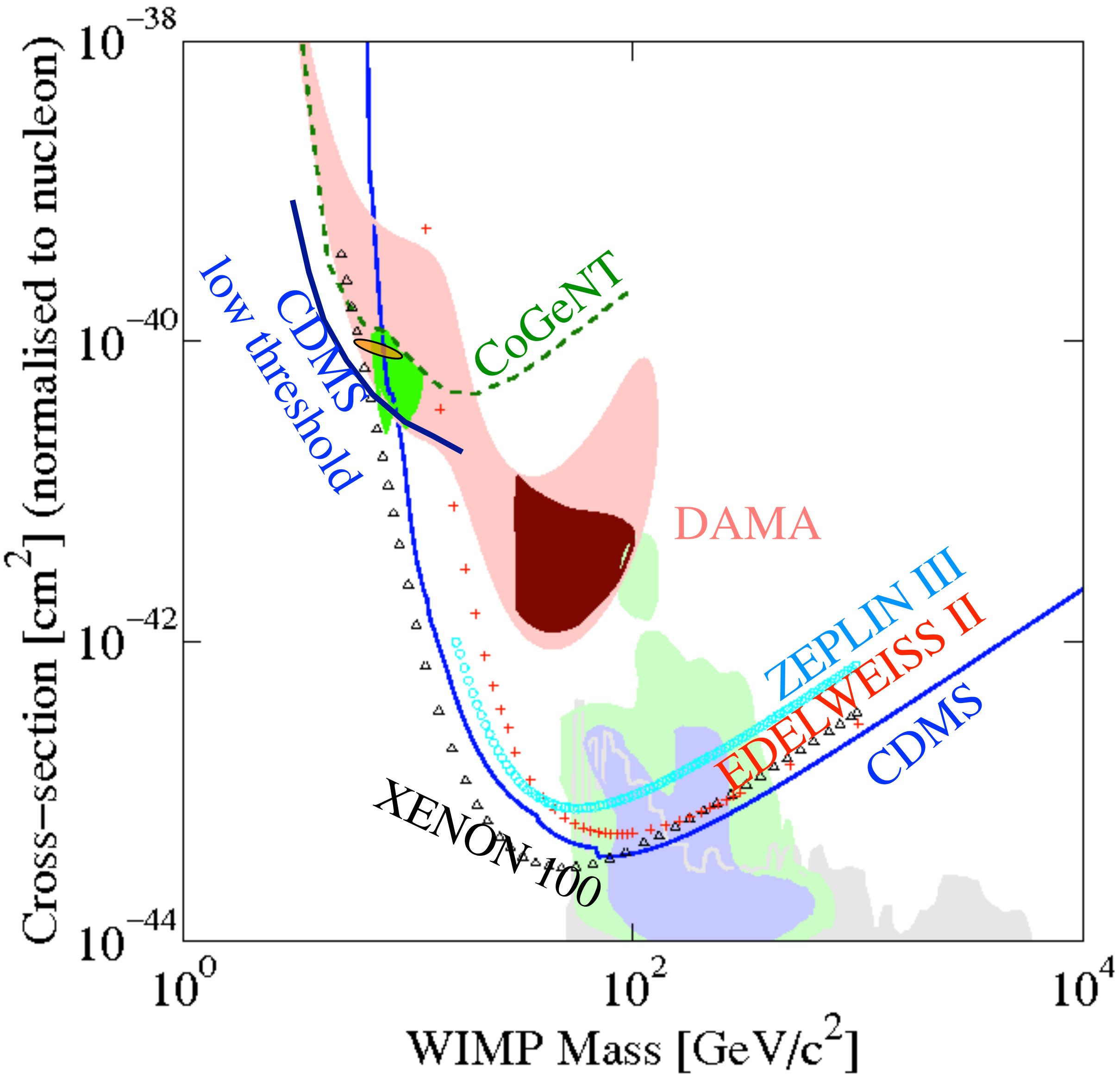
Challenges

10^{-47} cm^2/nucleon ≈ 1 evt/ton/year (e.g. 70 GeV/c^2, Ge, 10 keV threshold)

Liquid Xenon: Liquid purity, HV, radio-purity high enough for self-shielding
Liquid Argon: Liquid purity, HV, ^{39}Ar depletion
Low temp. Ge: Cost/yield for large # of detectors high Ø Ge
Bubble chamber: Liquid purity, α acoustic rejection
Directionality: How to get large enough mass at reasonable cost?

+ scale-up: engineering and safety

Current Situation (Scalar Interactions)



2 regions of interest

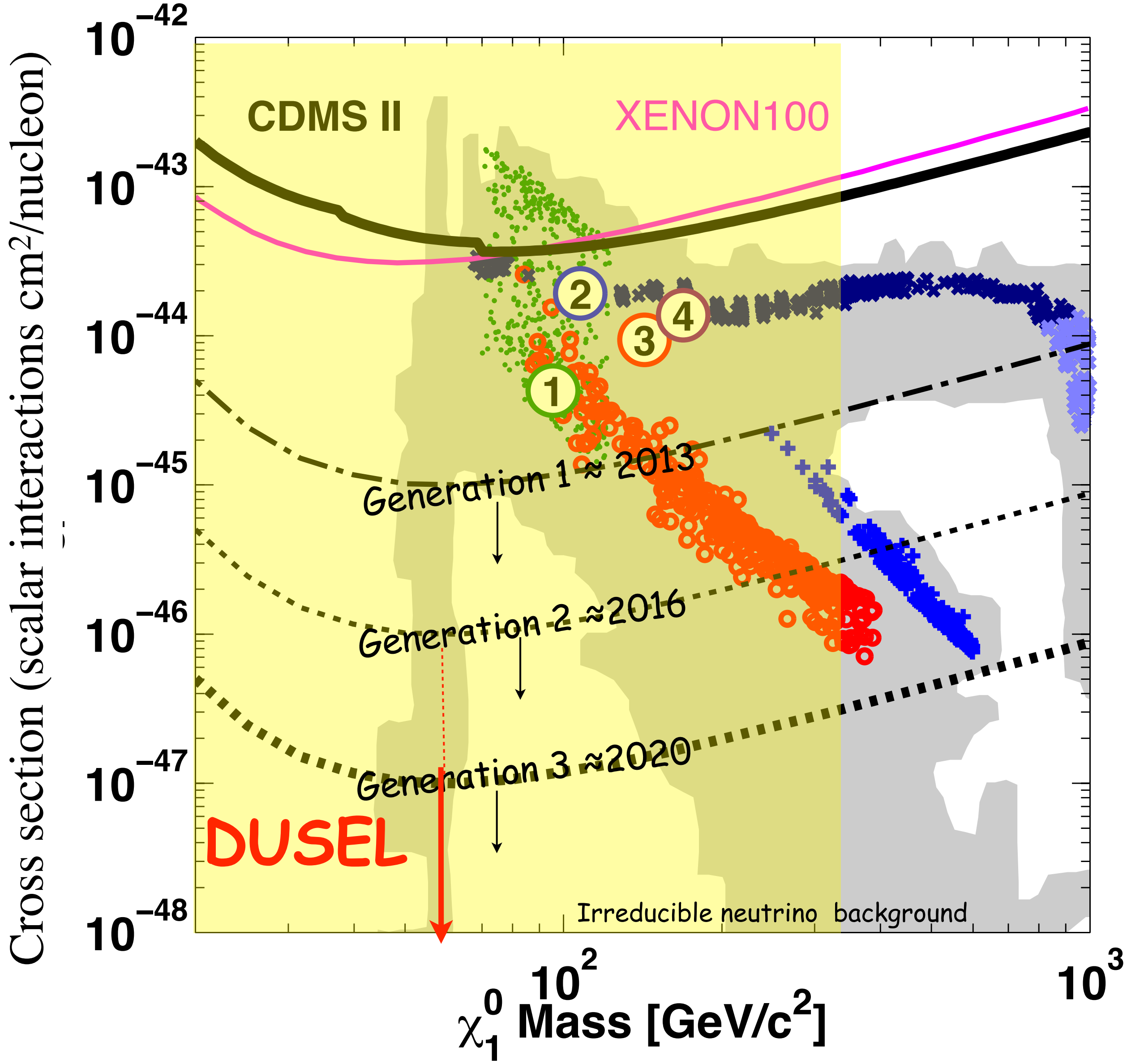
1) "Supersymmetry region"
Mass > 50 GeV

2) Low mass region
Recent claim of Hooper et al.
Could explain CoGeNT and DAMA (Na)
Probably in trouble

Similar situation with spin dependent interactions!
(see additional material)

Successive Generations

Following PASAG (2009)



International Context

See tabulation of experiments worldwide in additional material

Intense competition of Generation-1 → 10^{-45} cm^2/nucleon

liquid Xe , liquid Ar, Low temperature Ge, Bubble Chamber

US+Canada

Europe

Japan

Rising interest in China (Jing Ping 7000 m.w.e. laboratory)

Proposals underway for Generation-2 → 10^{-46} cm^2/nucleon

Consensus that competition is still best way to

- Make rapid progress on science
- Explore rapidly the limits of the various technologies

Generation-3 → 10^{-47} cm^2/nucleon

10^{-48} ≈ solar neutrino background limit

Scale of effort (≈ $50-100M range) becomes significant

- Some regional unification necessary (DUSEL Dark Matter Working Group)
- Some inter-regional coordination initiated

either at scientific level (CDMS/GEODM with Edelweiss/Eureca)

or at official level (OECD Megascience working group on Astroparticle physics)

DUSEL: A Dark Matter Observatory

By housing ≥ 2 large highly sensitive generation-3 WIMP detectors, a timely DUSEL could provide

- **A discovery if no discovery has been made before**
  or only at the LHC, e.g., prove that the particle responsible for missing energy at LHC is stable

- **The confirmation by high statistics** of a discovery by previous generation detectors (which would likely be tentative)
  Can then establish the cross section and the mass (important to resolve ambiguity in LHC reconstruction of decay chain/new physics parameters

  →A Dark Matter Observatory:
  careful measurements of energy distribution (streams, inelastic channels)
  annual modulation
  eventually directional detectors (diurnal rotation)

- Or an exploration at a sensitivity level which makes the WIMP hypothesis unattractive: **Change of paradigm**

Current proposals described in additional materials

In the long run an essential tool

Laboratory infrastructure and multiple detectors with size, sensitivity, background suppression, and depth will allow a broad range of explorations.

Why Two Generation 3 Experiments?

Vital to maintain US leadership of the last 20 years

Science

- Requires several targets
- Maximize impact, minimize technical risk of US program
  - => at least two techniques

Timing is natural for Generation-3

- DUSEL comes too late for generation-2
  - (although generation-2 experiments are considered for the Sanford laboratory, and could stay operational during DUSEL construction)
- Robust program, not too sensitive to minor delays

Strategy within the worldwide context

- Likely to be 3-5 generation-3 experiments worldwide
- US share is probably two
- Size of the community (≈200 and growing): Likely to be strong participants in at least 3 generation-3 experiments worldwide
- Having only 1 experiment at DUSEL: not a lot of savings in terms of science funding (if other groups are to be funded), but clear loss in leadership!

Advantages of co-location of 2 experiments in same lab

- Scientific exchanges
- Technological sharing
- Potentially significant cost saving

Depth Needs

The neutron problem

from muons →nuclear recoils

(experiments have also to control n from fission and α-n but not depth dependent)

Best published study so far

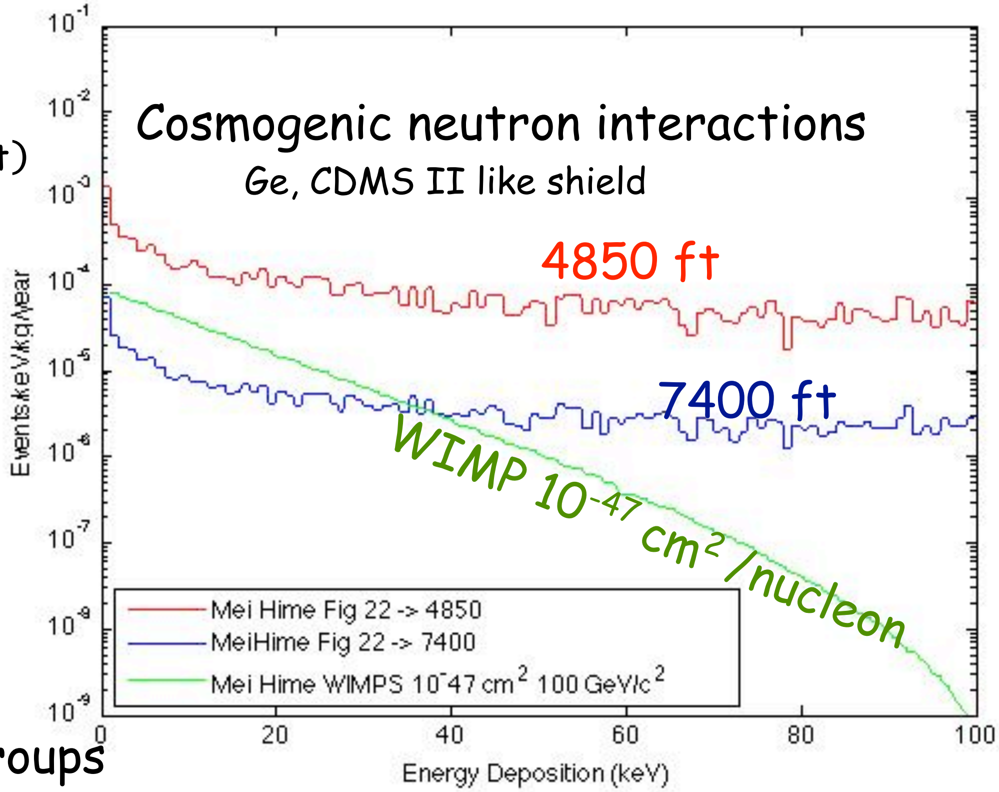
Mei and Hime (2006)

BUT

- No veto by accompanying hadrons: factor 15?
- No multiple scattering cut: factor >10?

Other studies in progress

with some cross checks between groups



Major uncertainty in high energy neutron tail

(>100 MeV difficult to moderate!) Measurements in progress

+ Neutron multiplication in material

Spallation products

with decay in energy region of interest (e.g., K and L peaks).

High energy decay ≈few hundred per ton per year. Low energy ?

Electron recoil rejection should make this subdominant, but we have to check!

Depth Needs

Current studies

With a sufficiently "complex" shield (water shield, neutron veto), we can work at any depth below 3000 or 4000 m.w.e.

A multidimensional problem

Balance between scientific risks and issues of timing, access, technical heritage

Different choices made by the generation-3 DUSEL proponents

- 7400 ft: COUPP, GEODM (cf. Double beta decay expts)
  - Simpler shield
  - Lower inherent risk
  - Heritage
- 4850 ft: LZD, MAX
  - Access and timing
  - 5m (LZS)-7m (MAX) water shield
  - Neutron veto with B doped scintillator (1m, MAX)

Unification of the US Community

Shared goals

- Develop a common vision for a powerful WIMP search/study program for the 2015–2025 timeframe, using several complementary targets and technologies.
- Ensure world leadership for the dark matter search program at DUSEL .
- Continue the emphasis on strong R&D to maintain leadership in the field

Shared implementation plan

- Common roadmap
- Tentative agreement on date of technical choice (≈ 3.5 years before beneficial occupancy)

Strategy to shift from competition to collaboration

- Start studies on issues of common interest
  first: depth related backgrounds
- Eventual merging of S4 studies
  Start with noble liquids then open to others
  Goal: one design for each of the four targets: Xenon, Argon, Germanium, High spin nuclei (e.g.,Fluorine)
- Compile->coordinate information from the competing generation-1 and generation-2, as input for generation-3 decisions.

What if No DUSEL?

We will try to use other facilities

The physics is too important!

The size of the US community is such that it can be involved in three generation-3 experiments

- Gran Sasso (may be too shallow)
- Modane extension ≈4850ft (not yet approved,designed for 1 db & 1 dm)
- SNOLAB ≈7400ft
- Jing Ping (China) 7000 m.w.e. How big?

BUT 5 potential problems

- A blow to US leadership of the last 20 years
  - Local (non US) teams likely to be leading the collaborations (e.g. in Europe, Japan or China)
  - We would contribute our innovation and significant R&D funded by NSF and DOE (DUSEL R&D, S4) to projects for which we might not receive full recognition.
  - This will fragment the US community.
- Potential lack of deep enough space worldwide
  - e.g. SNOLAB : at most 2 dark matter generation-3 expts or 1 dark matter and 1 double beta decay
- The US community would miss the support from a US underground lab
  - Scale generates Engineering and Safety challenges which are better handled in a dedicated national lab.
  - Possibility of course of DOE national lab support, but potentially more difficult for foreign enterprise without specific agreement such as the LHC one.
- Missed opportunities for interdisciplinary collaborations
  - e.g., low radioactivity methods for geo-biology research
- Impact on education and outreach (e.g., contact with home university, involvement of US teachers)

Impacts from Project Choices

A delay in DUSEL occupancy would decrease immediate impact

If DUSEL is delayed beyond 2018-2019, this will be a lost opportunity for generation-3 dark matter experiments, which will try to go elsewhere (even at the cost of worse conditions!)

Of course, DUSEL would remain an asset for following generations and dark matter observations if a discovery is made!

Importance of the 7400ft level

COUPP and CDMS/GEODM would have little incentive to go up to 4850ft instead of staying at SNOLAB (a little shallower than 7400ft).

Some unsuspected depth related backgrounds may appear.

cf. ^{11}C for solar neutrino experiments

More generally,

neutrinoless double beta decay may have stronger arguments for depth

e.g. $n + {}^{76}Ge \rightarrow {}^{77m}Ge$ ($\rightarrow$naked beta)

new physics may require the depth

e.g., potentially a new urgency of solar neutrino experiments

If only 4850, definite loss in flexibility

would make the facility less competitive compared to foreign facilities.

Conclusions

Dark Matter: A central scientific question!

Understanding the nature of Dark Matter would be transformational

Weakly Interactive Massive Particles: An attractive candidate, where we can make a discovery fundamental for cosmology and particle physics.

Extraordinary fecundity in detector technologies

with a real chance to increase sensitivity by 3-4 orders of magnitude

Importance of DUSEL

Could house two generation-3 experiments if timely (Occupancy ≈ 2018)

A cornerstone of the DUSEL initial program

Otherwise a lost opportunity

Maintain historical US leadership in dark matter

Collateral advantages: intellectual vitality, interdisciplinary, outreach

Importance of 7400ft level

A converging community with a coherent program

Broad consensus on roadmap

Agreement on time scale of generation-3 technological choice

Beginning of organization -> S4 coordination /merging-> full collaboration

Additional Material

Complementarity of Three Approaches

LHC

Could see quite rapidly some missing energy: New Physics!
But cannot prove that the new particles are stable and form the Dark Matter
e.g., χ-> gravitino +⋯ ("Super-WIMP")

Need to detect those particles in the cosmos

Elastic scattering of halo WIMPs in the laboratory

Very clean + would prove that these particles are stable
But can only measure approximately a cross section and a mass:

Little input on the fundamental physics

Although is likely to help resolve ambiguities in LHC reconstruction

Annihilation products in the galactic halo

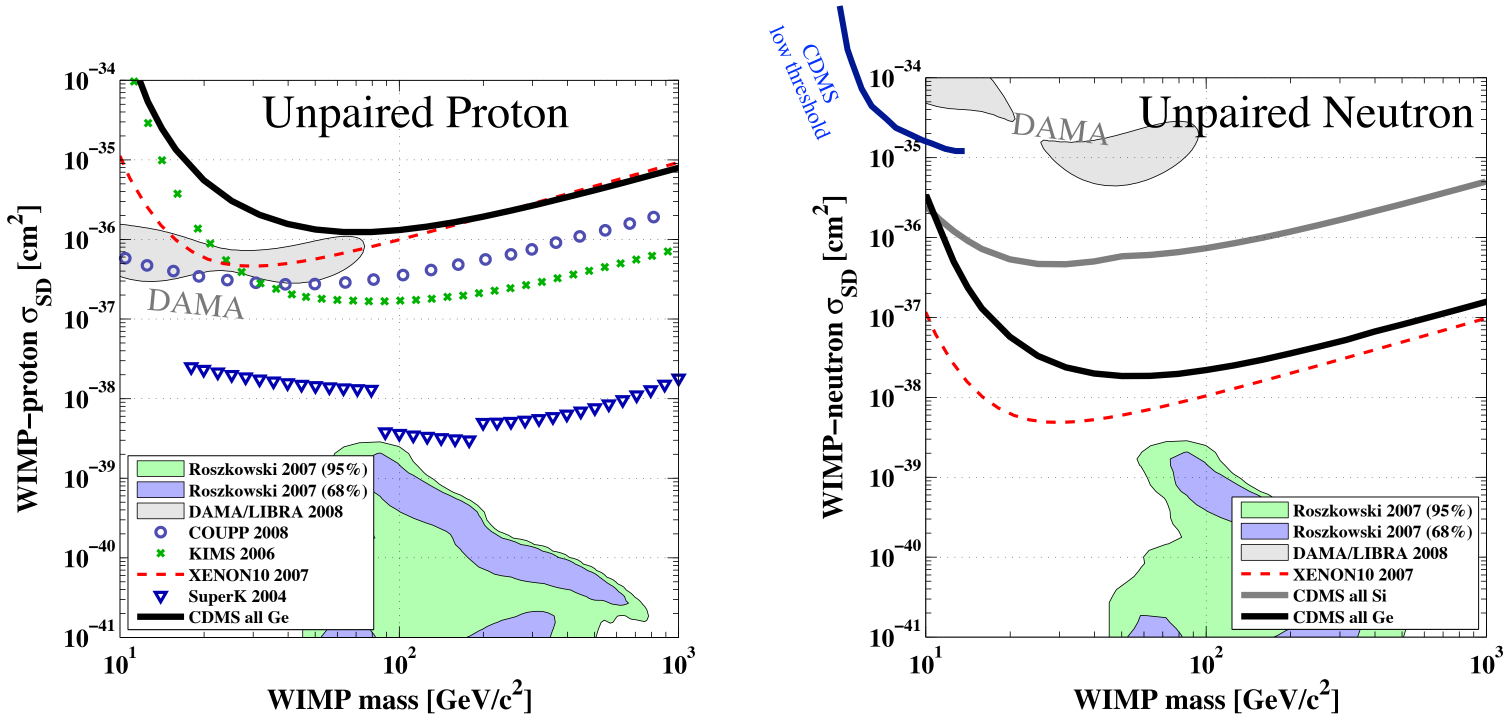
Most evidence will be ambiguous <- variety of astrophysics phenomena

Would need confirmation

Possible complexity of the dark sector=> need as much information as possible.

Situation Spin Dependent

Additive quantum number is spin



Proposed Dark Matter Program at DUSEL

In order to have a program

- at the frontier of the field worldwide
- resilient to potential political and technical delays of the facility
- with strong flexibility

the US WIMP search community proposes no less than two generation-3 experiments with a cost envelope of $150M -$200M.

- 2 different technologies, with at least 2 nuclei
  - with different technological risks
  - with different backgrounds
- Technology choice to be made later on view of current and generation-2 results (flexibility)

Current proposals described in additional materials

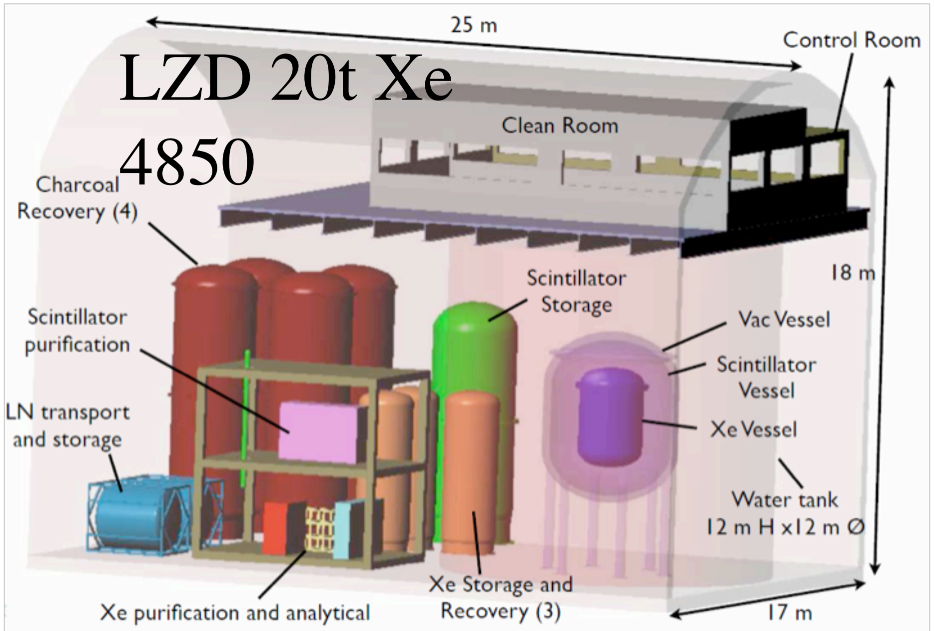
DUSEL Dark Matter Experiments

=S4 funding

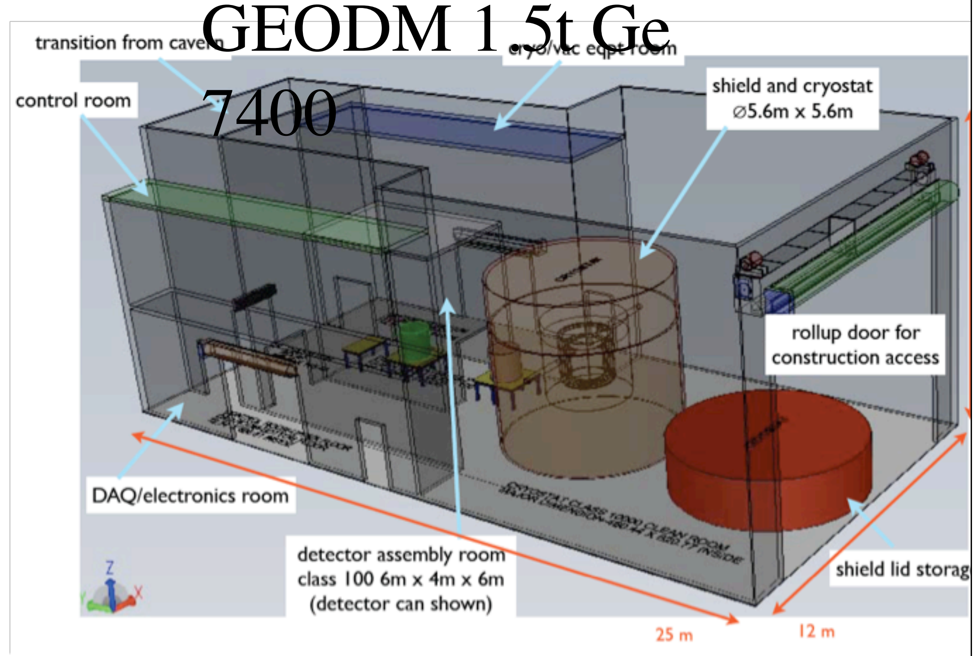
Experiment	Mass Target	Sensitivity Scalar cm^2	Location Install. Date	Strengths	Challenges R&D	Estimated Costs
COUPP	16x500kg CF3I bubble ch.	dependent on α contamination	4850 ft 2017	γ rejection Cheap SD target	α(Acoustic Discrim.) Threshold detector	$21+11M
LZD	20t Xe dual phase	10^{-48}	4850 ft 2017	3D imaging Self shielding Low radioact. PMT Scalable	Liquid purity HV	$55+28M
Max	20t depleted Ar 6t Xe dual phase	10^{-47}	4850 ft 2017	3D imaging Self shielding QUPID Pulse shape rejection (Ar)	Liquid purity HV ^{39}Ar depletion	$70+35M
GEODM	1.5 t Ge phonons +ionization	2 10^{-47}	7400 ft 2017	Rejection + Background demonstrated 3D imaging	Cost/yield for large # of detectors high Ø Ge	$55+28M
CLEAN	50 t Ar single phase	few 10^{-47}	7400 ft 2017	Pulse shape rejection n self shielding Scalable	Rn contamin. Liquid purity	$60+30M

Dark Matter @DUSEL

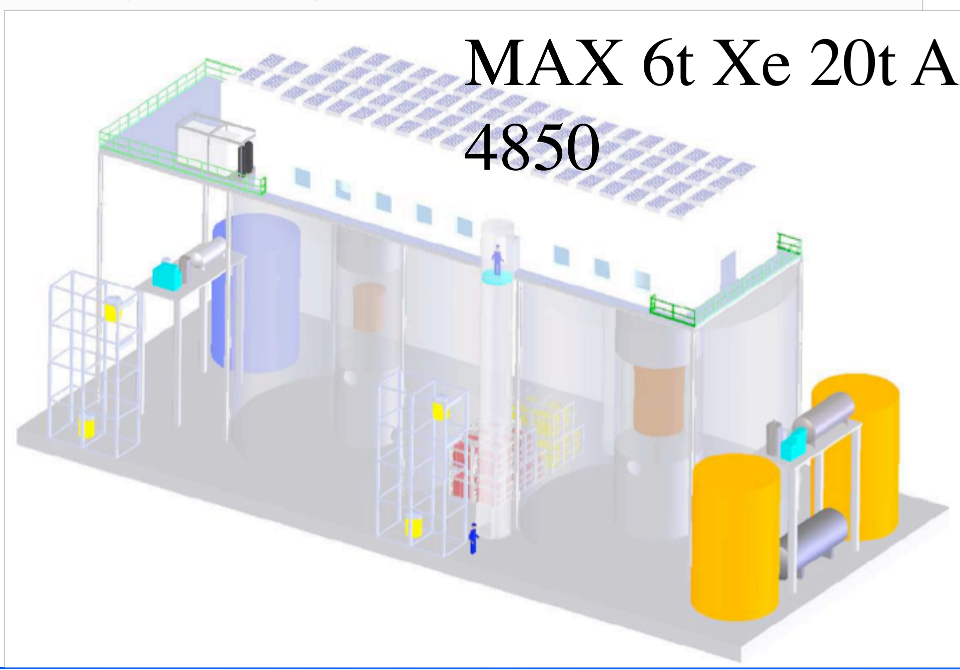
LZD 20t Xe
4850



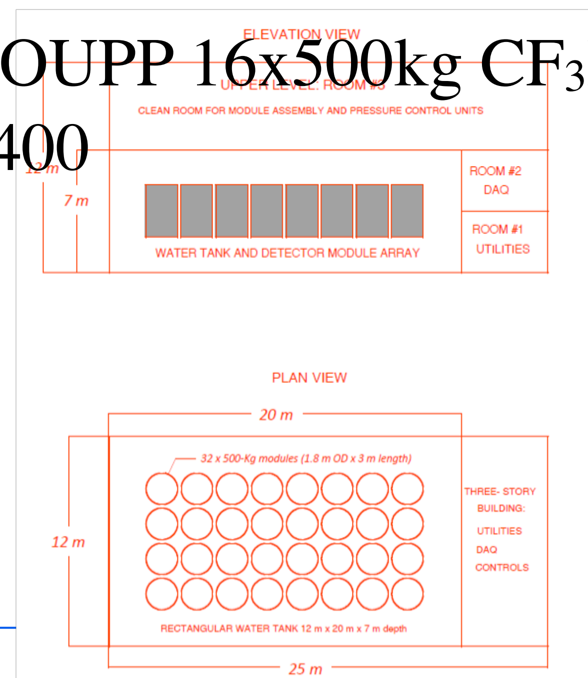
GEODM 1.5t Ge
7400



MAX 6t Xe 20t Ar
4850



COUPP 16x500kg CF_3I
7400



For reference: International Context

Region	Current Generation (Gross Mass)	Current Status	Generation 2 (Gross Mass)	Current Status	Generation 3	Current Status
US	LUX 350kg Xe Sanford Lab	Assembly 2011 Install	LZS 1.5-3t Xe Sanford Lab	Design Same water tank as LUX	LZD 20t Xe DUSEL	S4, R&D 2017
UK/Portugal /Russia	ZEPLIN III 10 kg Xe Boulby, UK	Running (2009-2010)				
US	Darkside 50kg Ar LNGS	Design DAr under procurement 2011-2012	1t	Design Same shield of DarkSide-50	MAX 6t Xe 20t DAr DUSEL	S4, R&D 2017 Install
US/Europe /China	XENON100 80kg Xe Gran Sasso	Running	XENON1t 2.4t Xe	Designing 2012 Install		
US/Canada	SCDMS 10kg Ge Soudan	Construction 2011 Install	SCDMS 100kg Ge SNOLAB	R&D 2014 Install	GEODM 1.5t DUSEL	S4, R&D 2018
US	COUPP 60kg CF3 SNOLAB	Construction NUMI test 2010	500 kg	2011 Design 2013 Install	16t scale	S4 R&D
Canada	PICASSO 2.6 kg SNOLAB	Running	PICASSO II 25kg	2010/11 Install	PICASSO III > 500 kg	2012/13 Install
US/Canada	MiniCLEAN 500kg Ar	Construction 2011 Install	DEAP-3600 3.6t	Funded 2012 Install	CLEAN 50t Ar/Ne	Planning R&D
Europe	Edelweiss Now 3 kg =>24 kg Ge 2011 Modane	Running 24kg funding secured	EURECA 100kg Ge Interleaved Ge/ scintillator Modane Extension *Merging of CRESST and Edelweiss*	Active R&D 2013 Install	EURECA 1t Ge / scintillator LS Modane Extension	Planning 2016
Europe	CRESST 5 kg of CaWO- Gran Sasso	Running				
Europe	ArDM 800kg Ar Canfranc	Construction 2011 Install				
Europe/US	WARP 140kg Ar Gran Sasso	Running				
Japan	XMASS 800kg Xe Kamioka	Installation Running 2010	XMASS II 5t	R&D 2014 Install	XMASS III 10t	Planning 2016
China	Jin-Ping lab. Ge and/or Xe	Planning	100kg	2015 R&D	>1t	2020

Table I: International Context (non-directional detectors): Compilation of the plans of various WIMP search collaborations across the world. All masses shown are the active masses of the central detectors. (DAr means Ar depleted in 39Ar.)

Date of Technology Choice

3 principles

- The choice of technology for the initial suite of experiments at DUSEL should not be made before DUSEL is approved and its time scale established.
- At least two dark matter experiments should be ready at the time of beneficial occupancy of the laboratory.
- In order to take optimum account of the latest scientific results, maximize the scientific reach and minimize risk for the initial suite of dark matter experiments, the technology choice should be made at the latest date compatible with the second goal above.

Compromise: 3.5 years before beneficial occupancy

with DUSEL available Jan 2017 **1 July 2013**

but

need better estimate of experiment construction time
keep monitoring procurement time and impact on costs (e.g., Xe)
7400 ft availability

Generic Schedule (2017 beneficial occupancy)

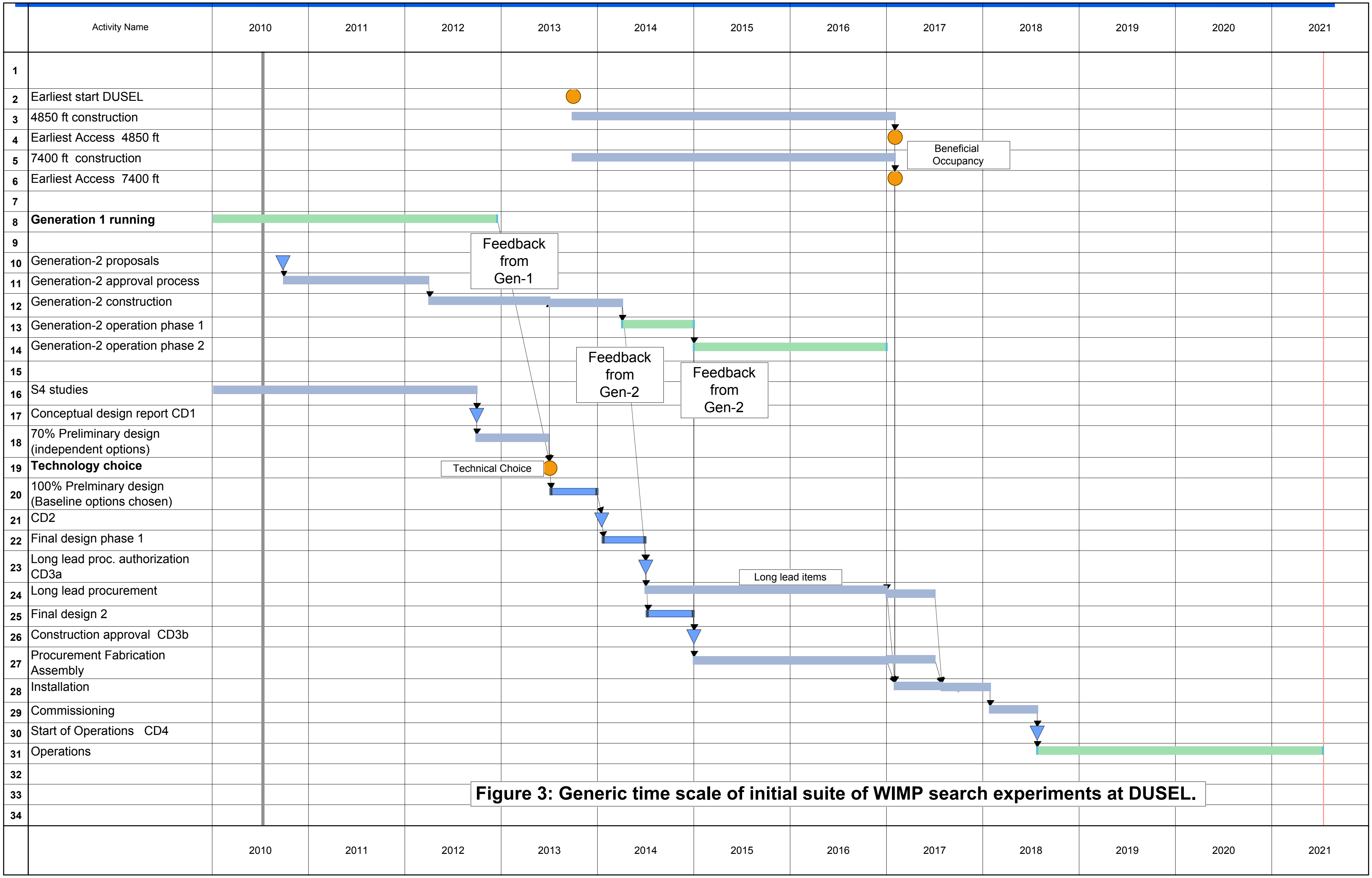
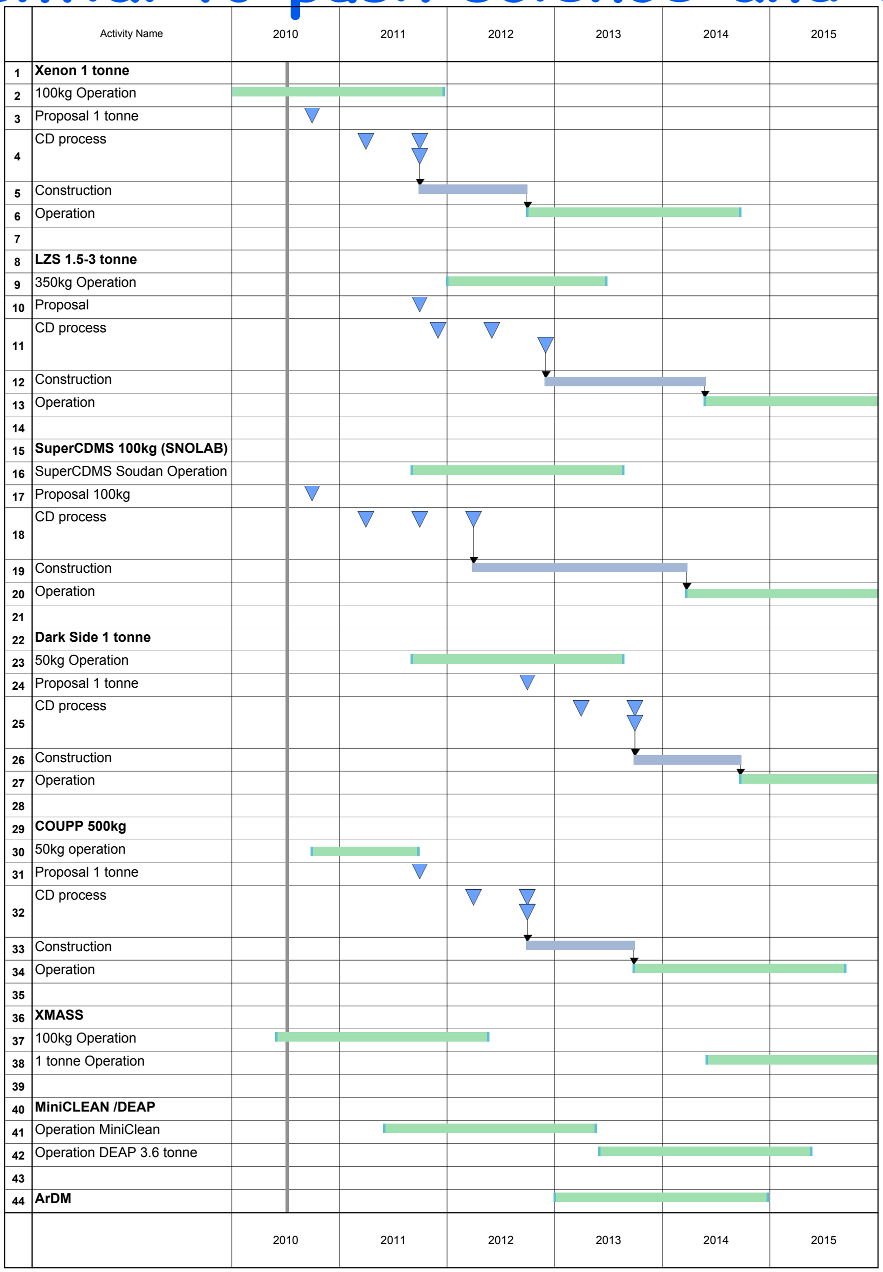


Figure 3: Generic time scale of initial suite of WIMP search experiments at DUSEL.

Generation 2 Experiments

Essential to push science and explore limit of technologies



Come too late to limit extrapolation

Major impact on DUSEL

- Engineering studies
- Fold in experience
- Validate DUSEL choices

Experiment	US Cost	Remarks
Xenon 1 tonne	$4M	Shielding paid by Europe
LZ 3 tonne	$11.5M	Same shield as LUX
SuperCDMS SNOLAB	$26M	
DarkSide 1 tonne	$4M	Same shield as 50kg
COUPP 500kg	$7M	

Projected costs of generation-2 experiments proposed in the US (equipment+ engineering/technical staff, DOE+NSF)

Space Requirements and Costs

Table II: Experimental Space Requirements

Experiment	Detector Size	Depth	Footprint (W x L x H) m^3	Staging needed
R&D		4850	17 x 25 x 18	
COUPP	32 x 500 kg 16 ton	7400	12 x 25 x 12	
GEODM	1.5 ton Ge	4850 7400	17 x 25 x 14 12 x 25 x 14	25m
LZ20	20 ton LXE	4850	17 x 25 x 18	25m
MAX	20 ton LAr 6 ton LXe	4850	17 x 50 x 21	25m
CLEAN	50 t LAr or LNe	4850	15m ϕ x 15m water tank in pit Facilities above tank	25m
Directionality	TBD		17 x50x 18?	

d. Costs

Table III indicates the estimated costs provided by the various projects. The scale of a program including two generation-3 experiments is such that, in order to be successful, it requires a major mobilization of the community, strong support from NSF and DOE and a sustained engineering involvement of the national laboratories.

Experiment	Size	Cost
CLEAN	50 t LAr /10 t LNe	\$60M (+\$30M Contingency)
COUPP	16t CF_3I	\$21M (+\$11M Contingency
GEODM	1.5t Ge	\$55M (+\$28M Contingency)
LZD	20t Xe	\$50M (+\$25M Contingency)
MAX	6t Xe, 20t DAr	\$70M (+\$35M Contingency)

Table III: Estimated cost of the various experiments proposed for the initial suite of WIMP search experiments at DUSEL (equipment + engineering/technical personnel).