Shedding Light

On The Dark Universe

IPP Tour 2012

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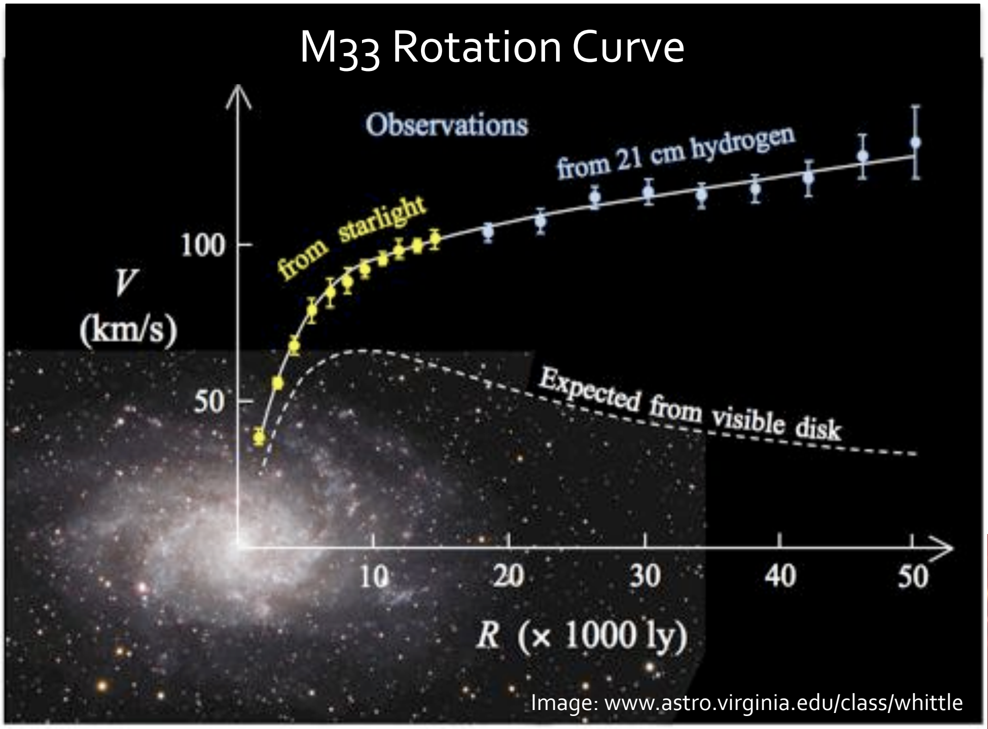
Princeton University

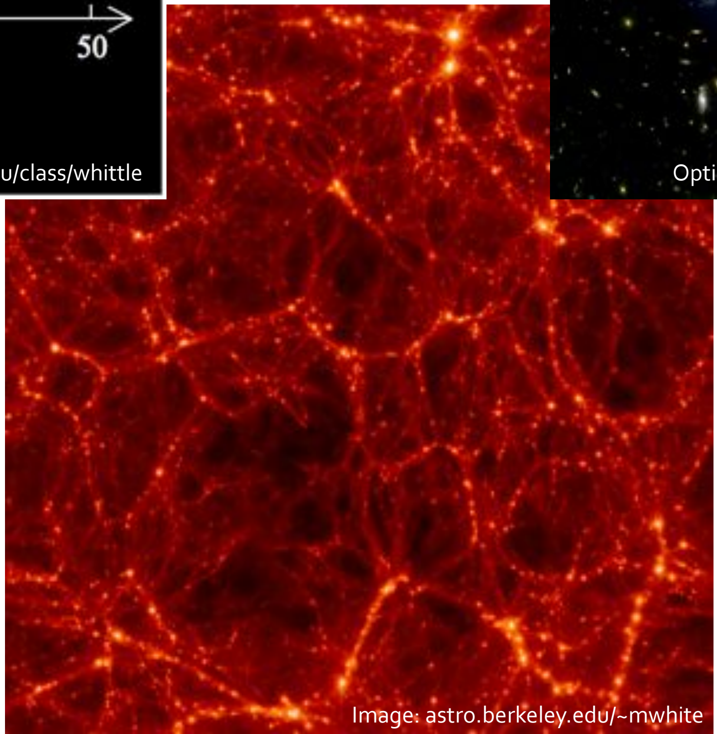
Outline

- Dark matter review
  - Evidence & known properties
- Searching for dark matter
  - Direct detection experiments
- The DarkSide experiment
  - Strategy
  - Technical progress
  - Future

Background Image credit: www.arcetri.astro.it/~ciardi

Evidence for Dark Matter





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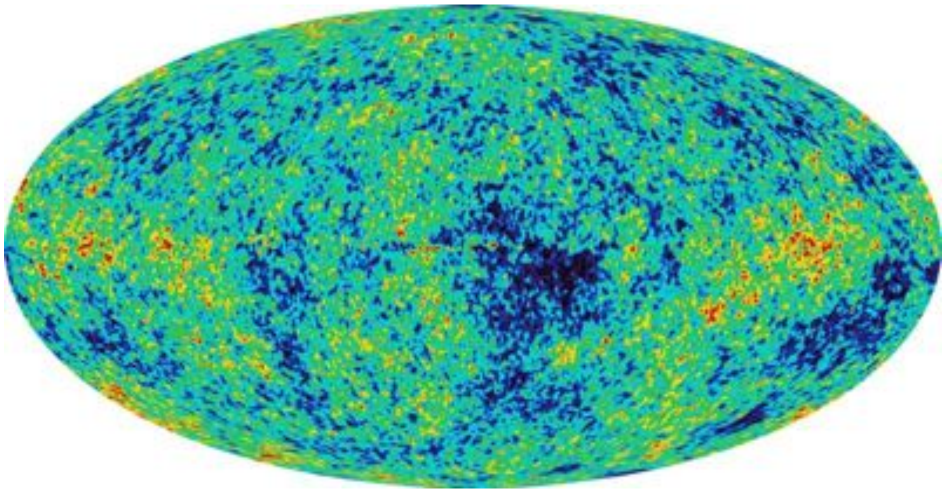
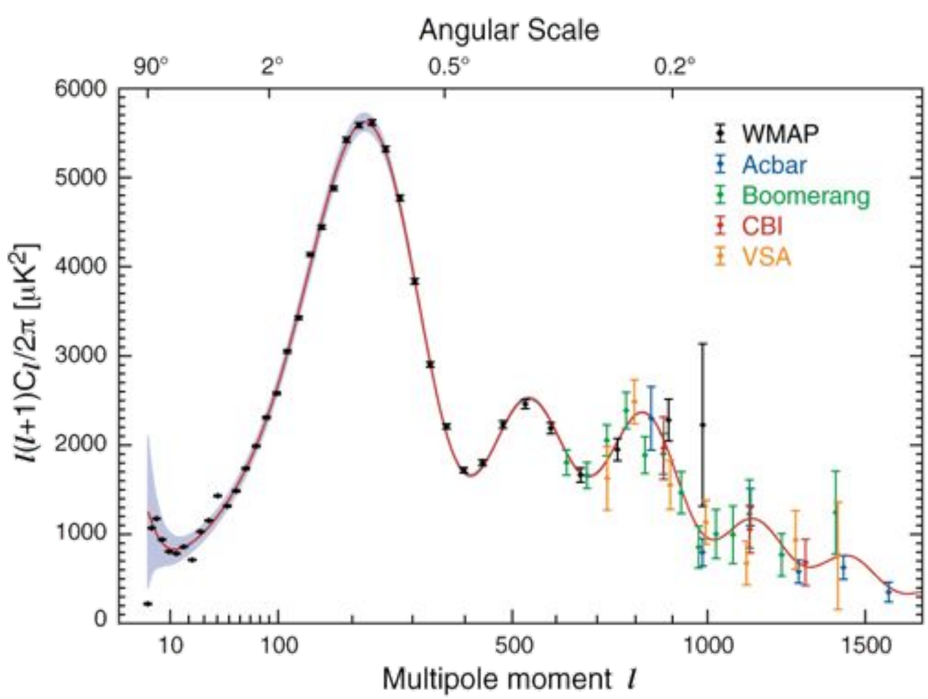




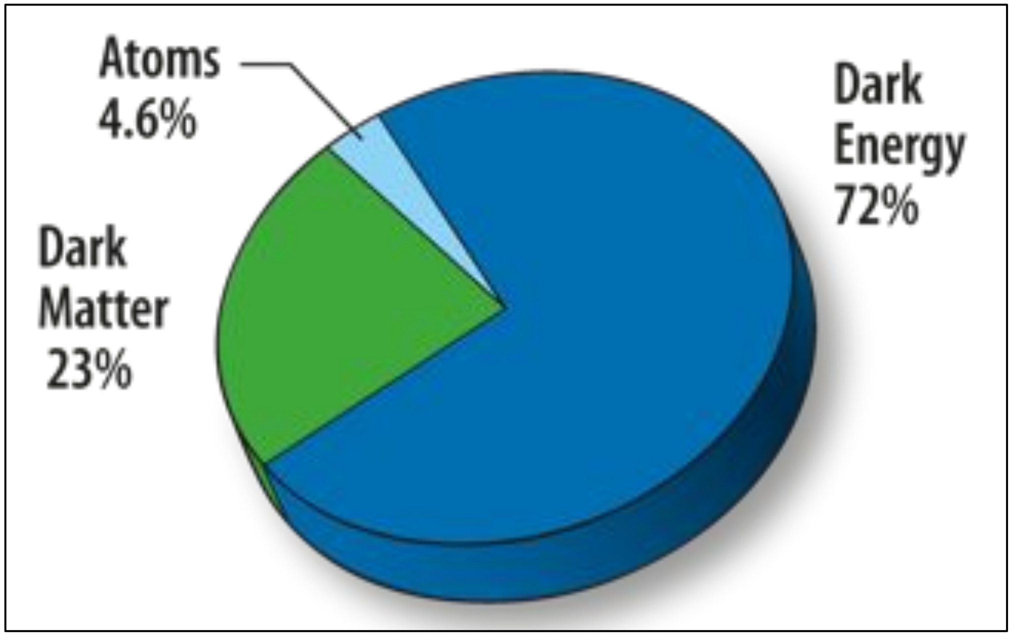
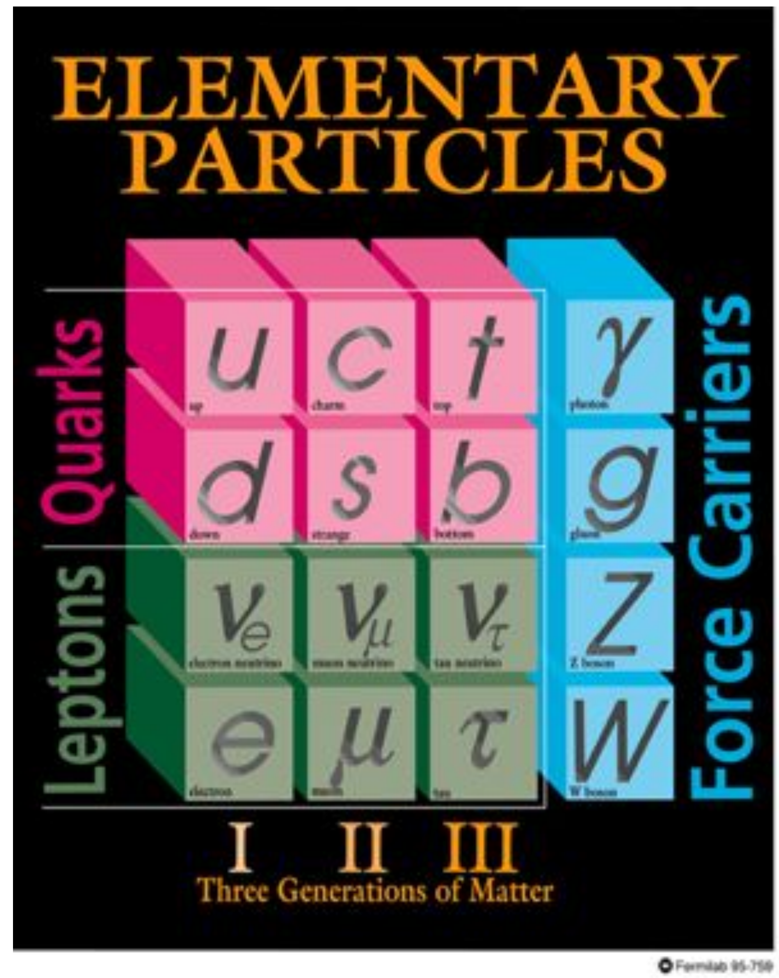


Image credits: WMAP Science Team, NASA

Dark Matter Properties

- ~23% of the energy density of the universe is dark matter
  - Gravitationally interacting
  - Neutral
  - Long lived
  - Non-baryonic
  - “Cold” (i.e. non-relativistic at early times)



Dark Matter Properties

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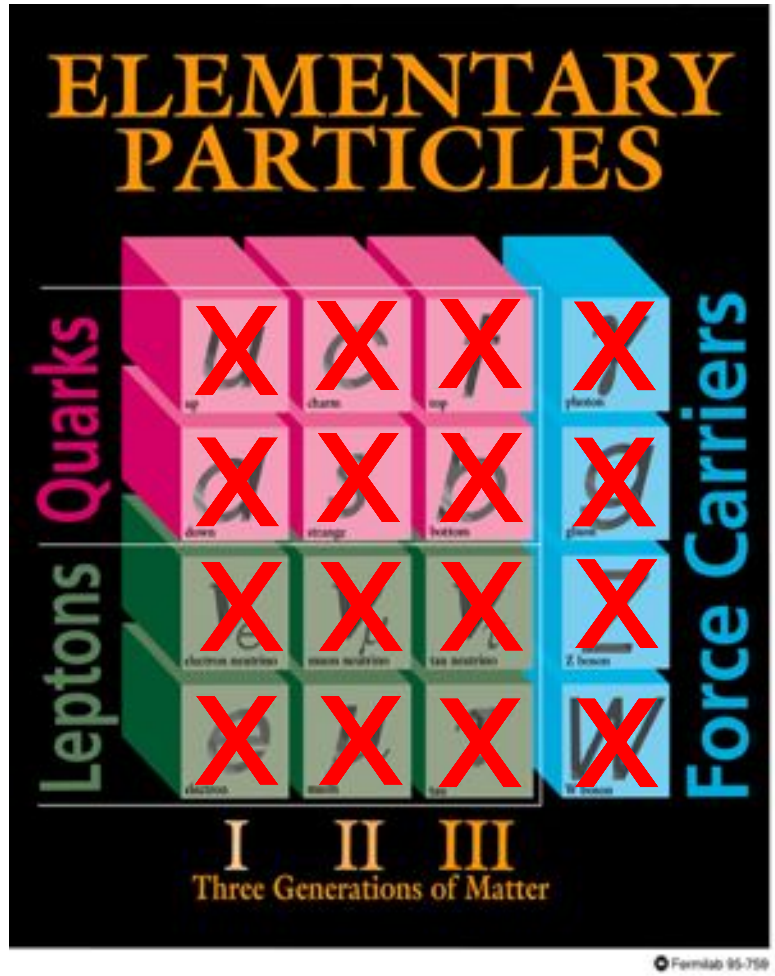


This excludes all Standard Model particles:
strong evidence for physics beyond the Standard Model!

Dark Matter Candidates

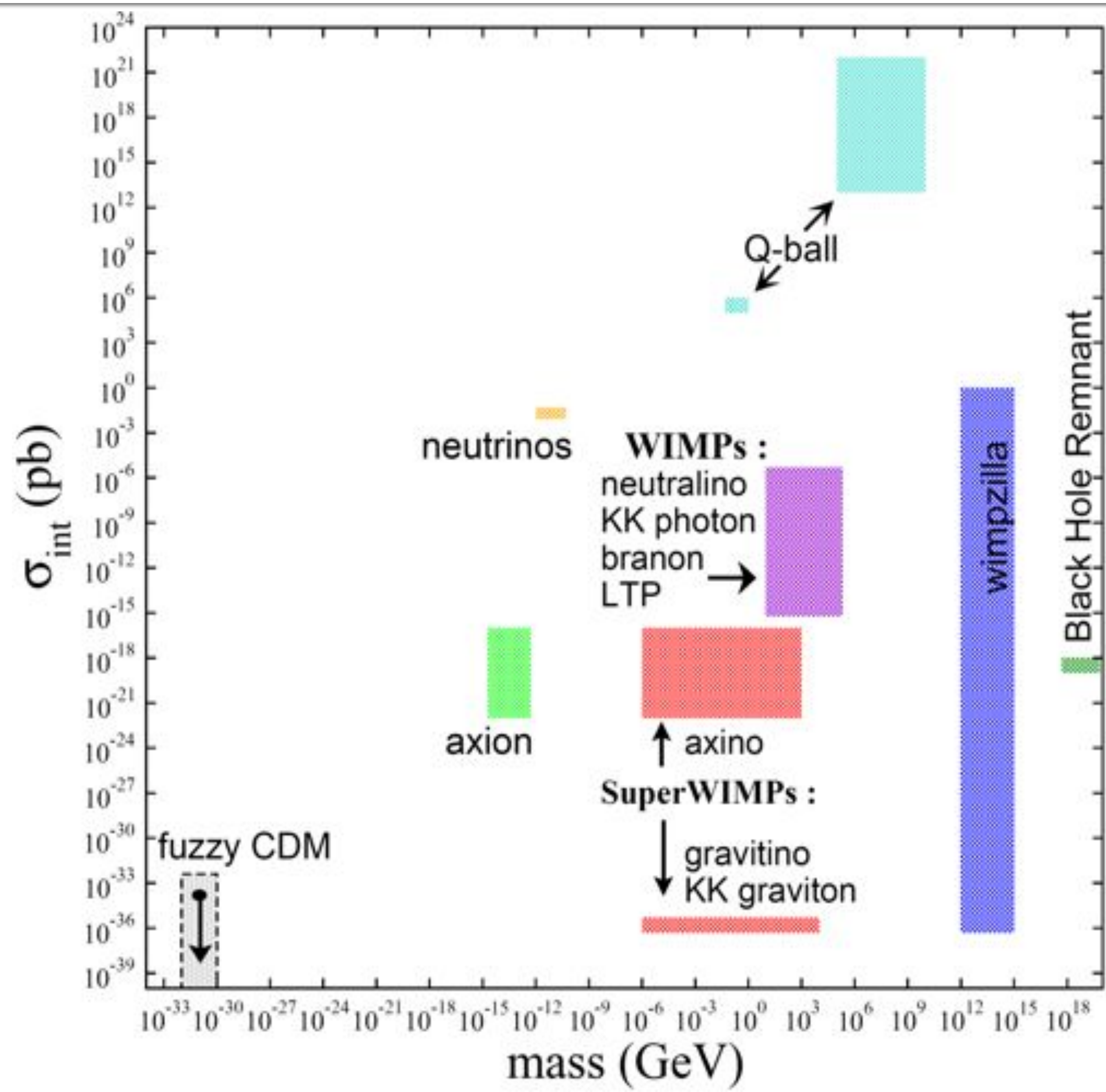
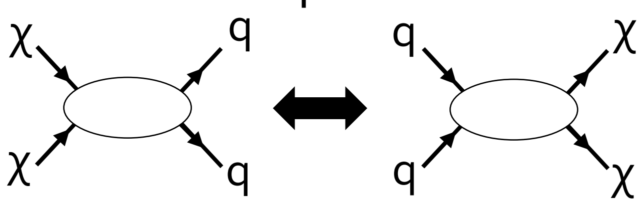


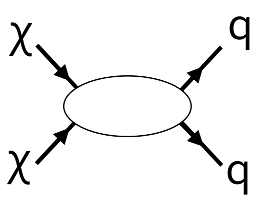
Image credit: HEPAP/AAAC DMSAG Subpanel (2007)

Thermal Relics

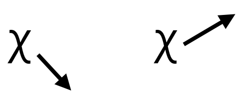
1) WIMPs are produced in thermal equilibrium

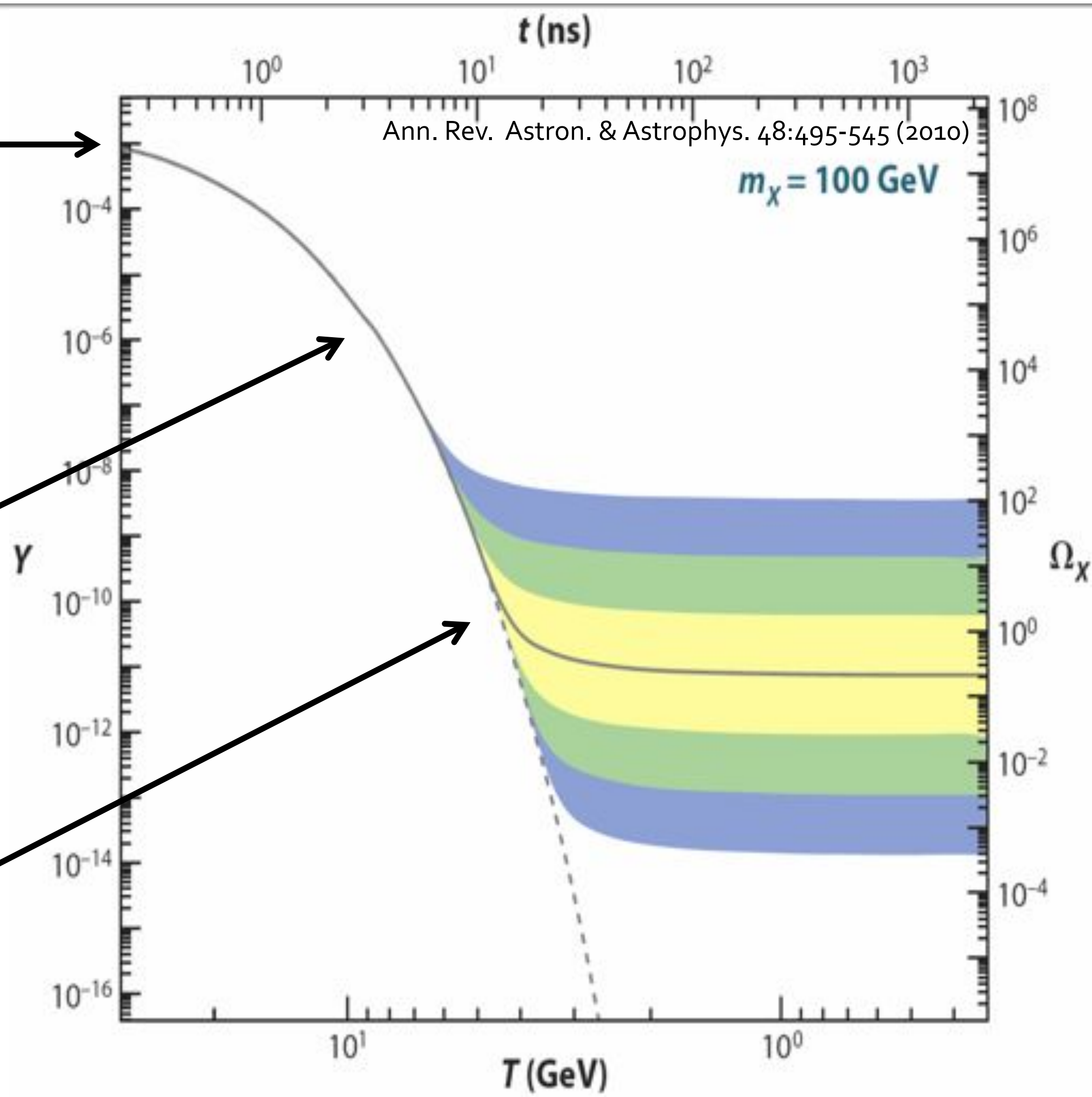


2) WIMP density decays as the universe cools



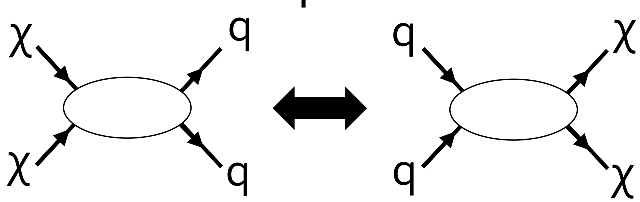
3) WIMP density "freezes out" based on coupling strength





The "WIMP Miracle"

1) WIMPs are produced in thermal equilibrium



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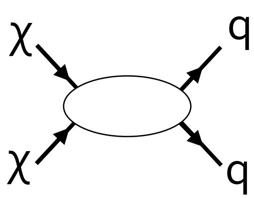

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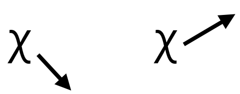
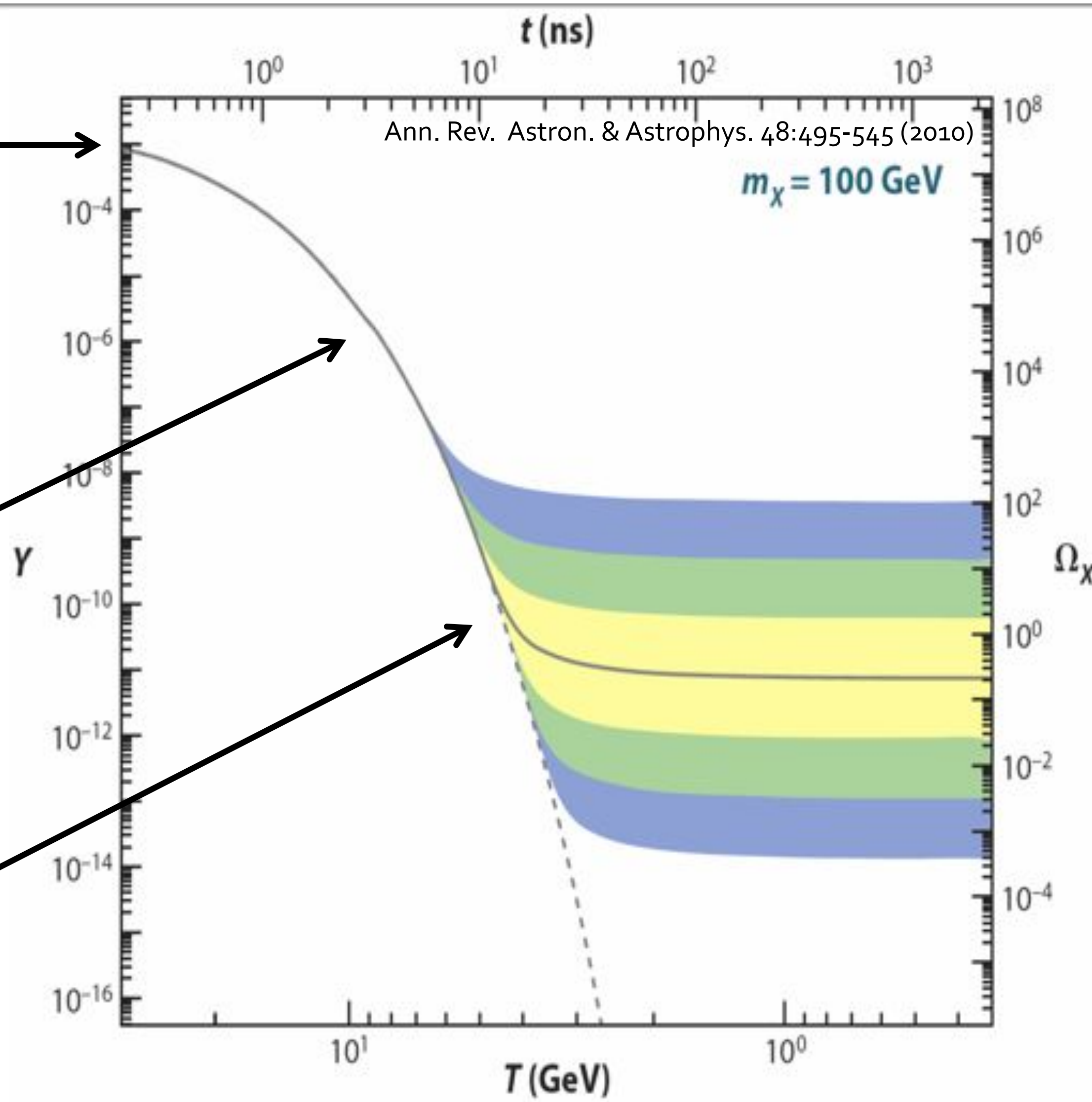
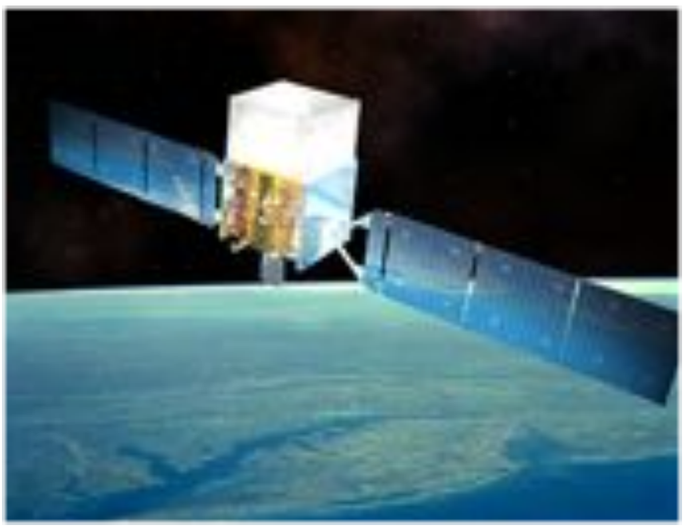


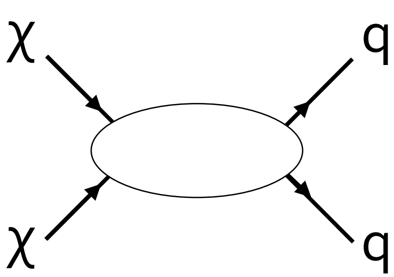


Weak mass & coupling give just the right relic density for dark matter!

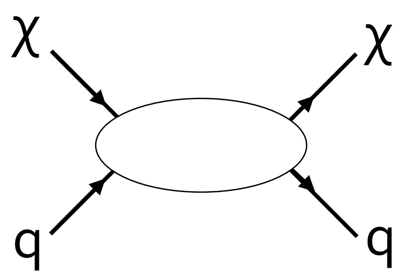
Searching for WIMPs

Aboveground

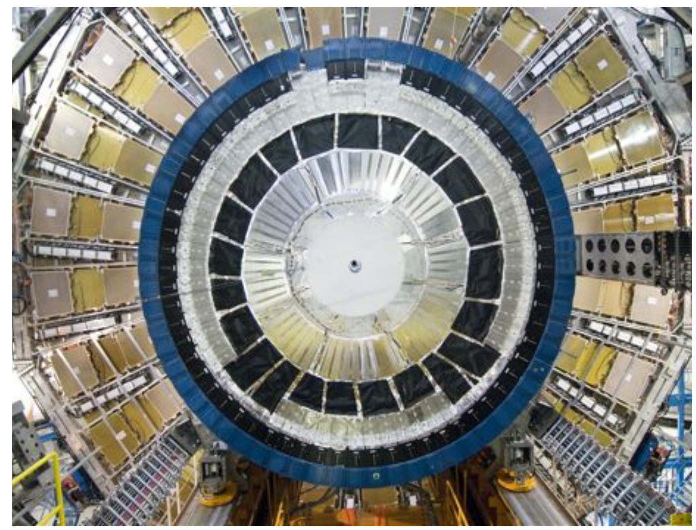




Underground



At Accelerators



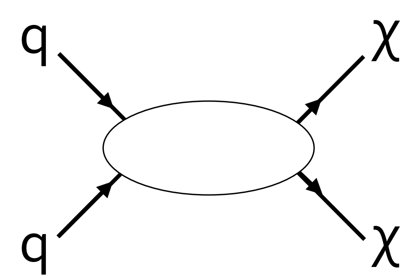


Image credits: NASA, discovermagazine.com, atlas.ch

Local Dark Matter

- Galaxy embedded in a dark matter "halo"
- Local density ≈ 0.3 $GeV/c^2/cm^3$
- Independent galactic orbits
  - Typical v_{orbit} ≈ 220 km/s

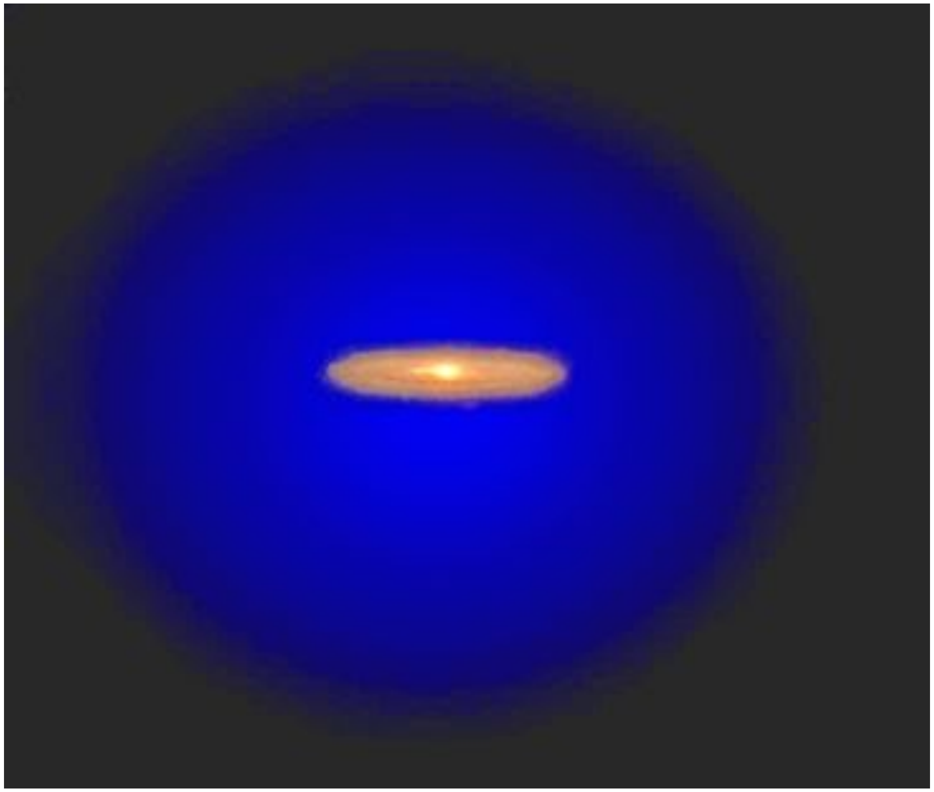


Image credit: J. Kormendy, chandra.as.utexas.edu/~kormendy

WIMP "Wind"

- Motion of the sun around the galaxy induces a WIMP "wind"
- Rotation of the earth about the sun produces a seasonal modulation in the velocity of the wind

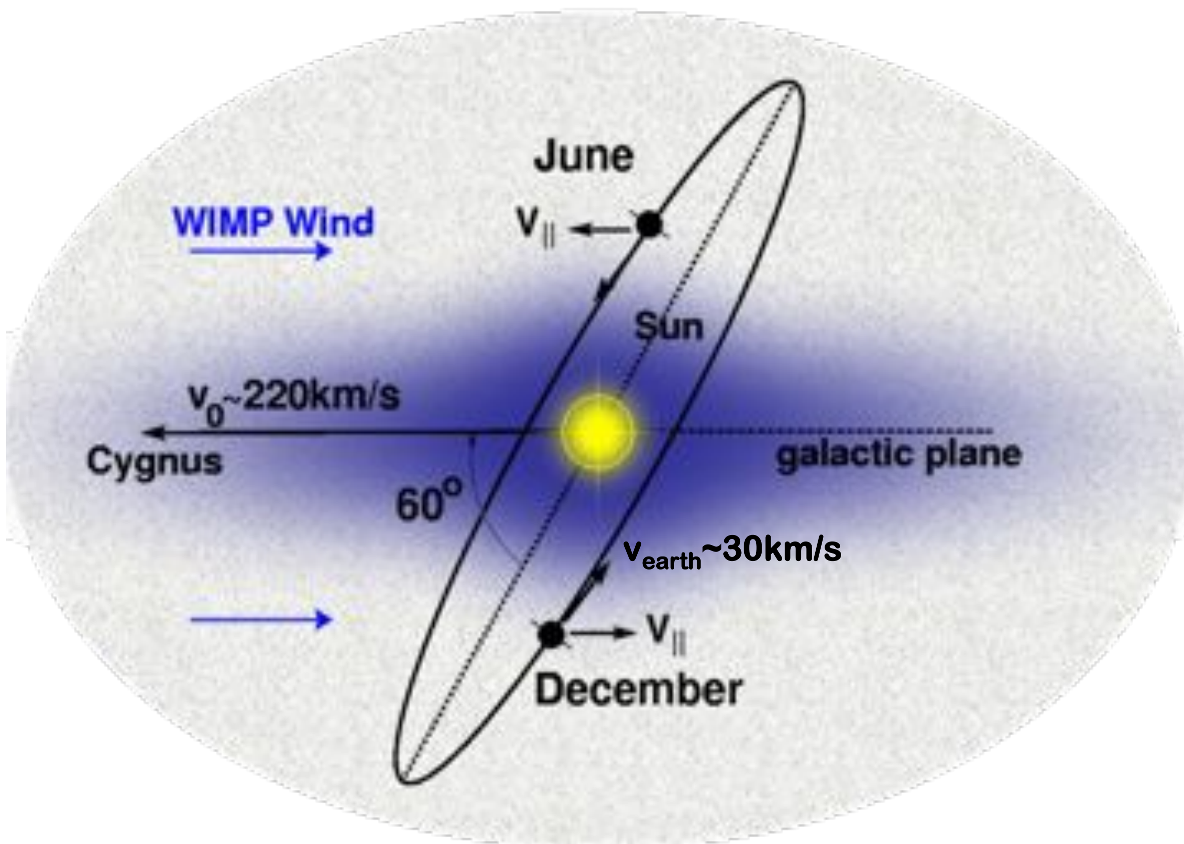
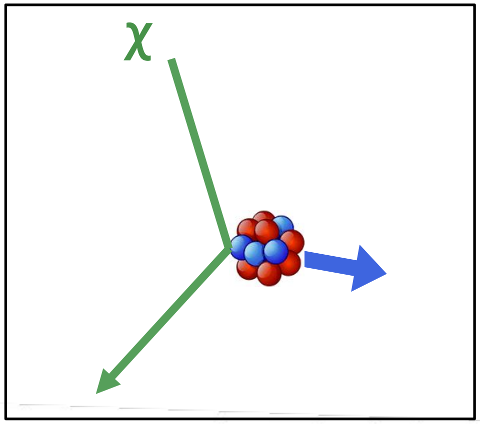


Image credit: www.hep.shef.ca.uk/research/dm/intro.php

WIMP Direct Detection

- WIMPs scatter elastically from nuclei, inducing low energy nuclear recoils
  - <~100 keV
- Cross section of $10^{-44} – 10^{-45}$ cm^2 *per nucleon* for "standard" WIMP
  - ~10-100 interactions/tonne/yr



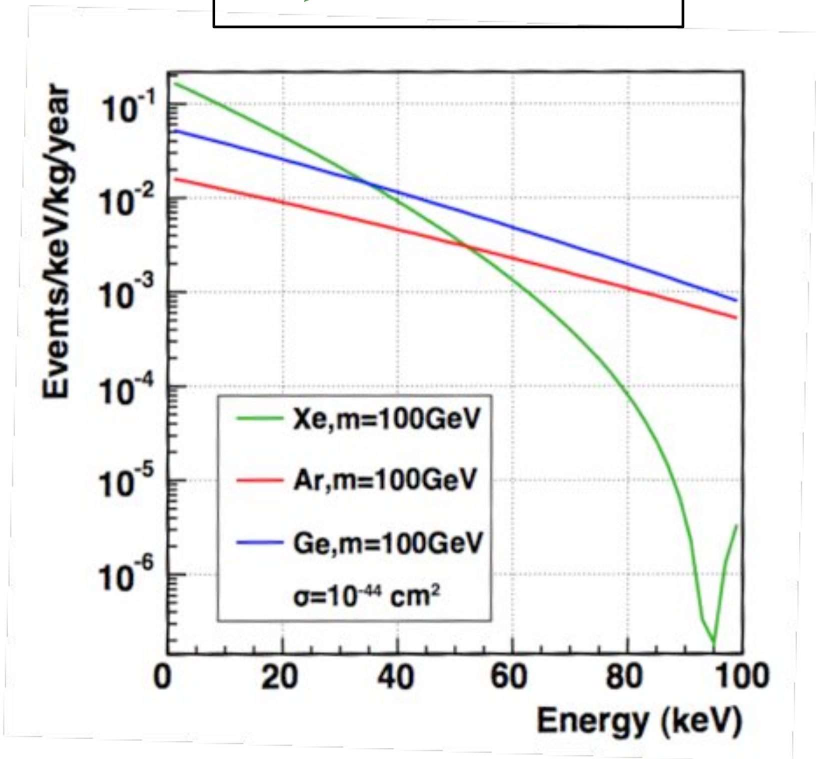
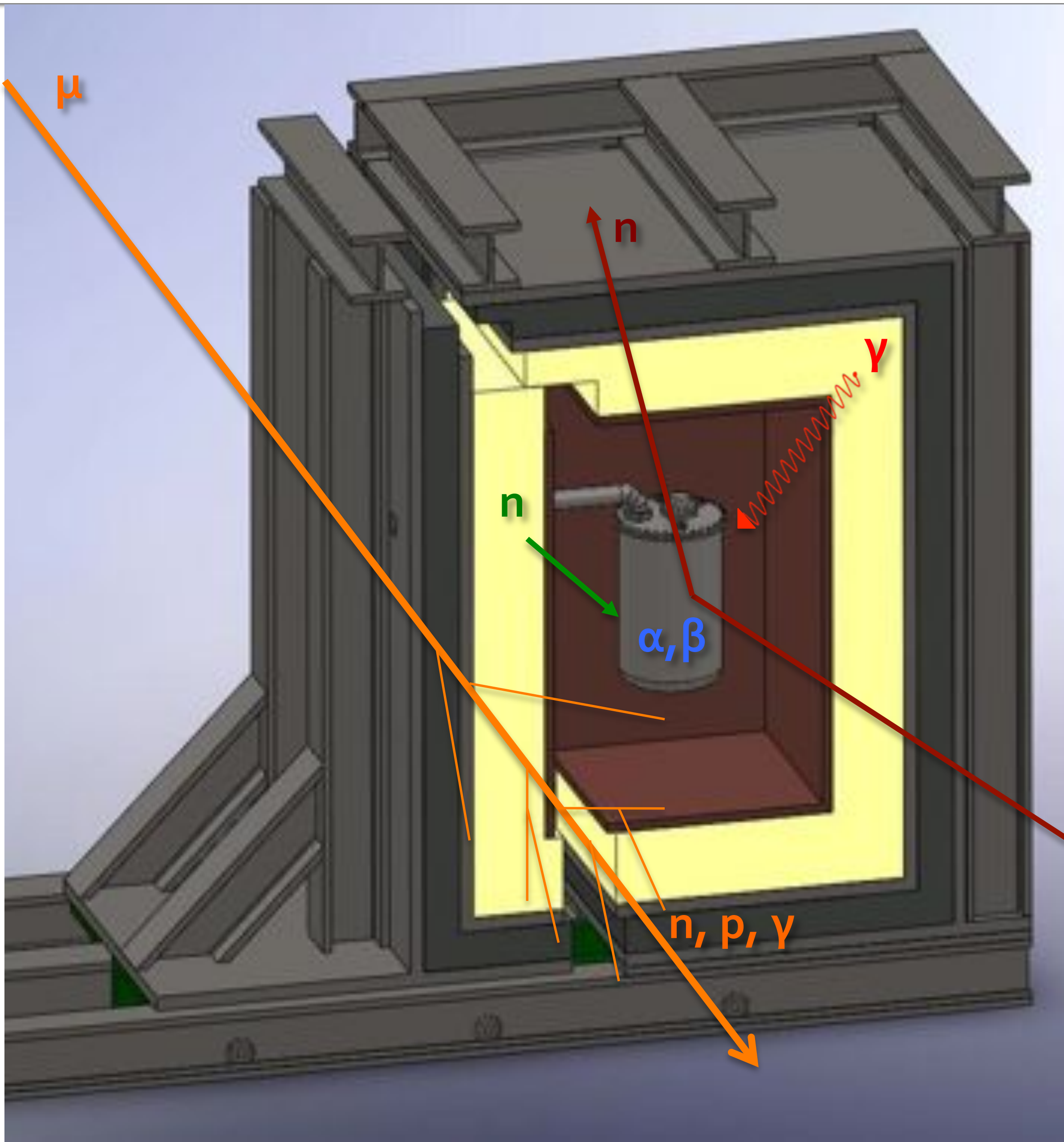


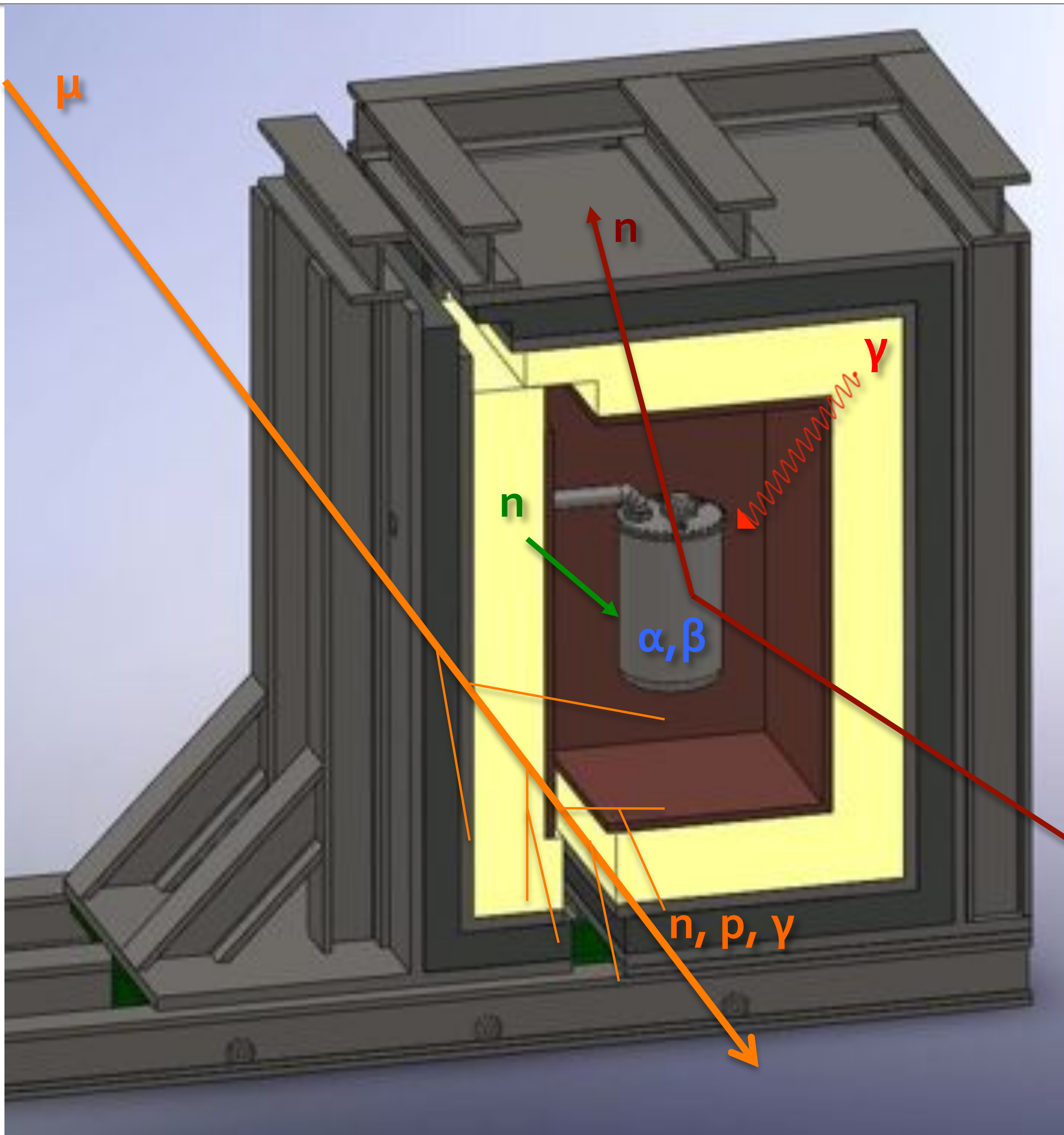
Image credit:777icons.com

Central Challenge: Background



Internal Radioactivity
^{238}U, ^{232}Th, etc.
Gamma Rays
external and from shielding
Cosmic Muons
Radiogenic Neutrons
from spontaneous fission and (α,n), externally and in shielding
Fast Neutrons
from muons in the shield and beyond

Central Challenge: Background



WIMP signal: <100 ev/T-yr

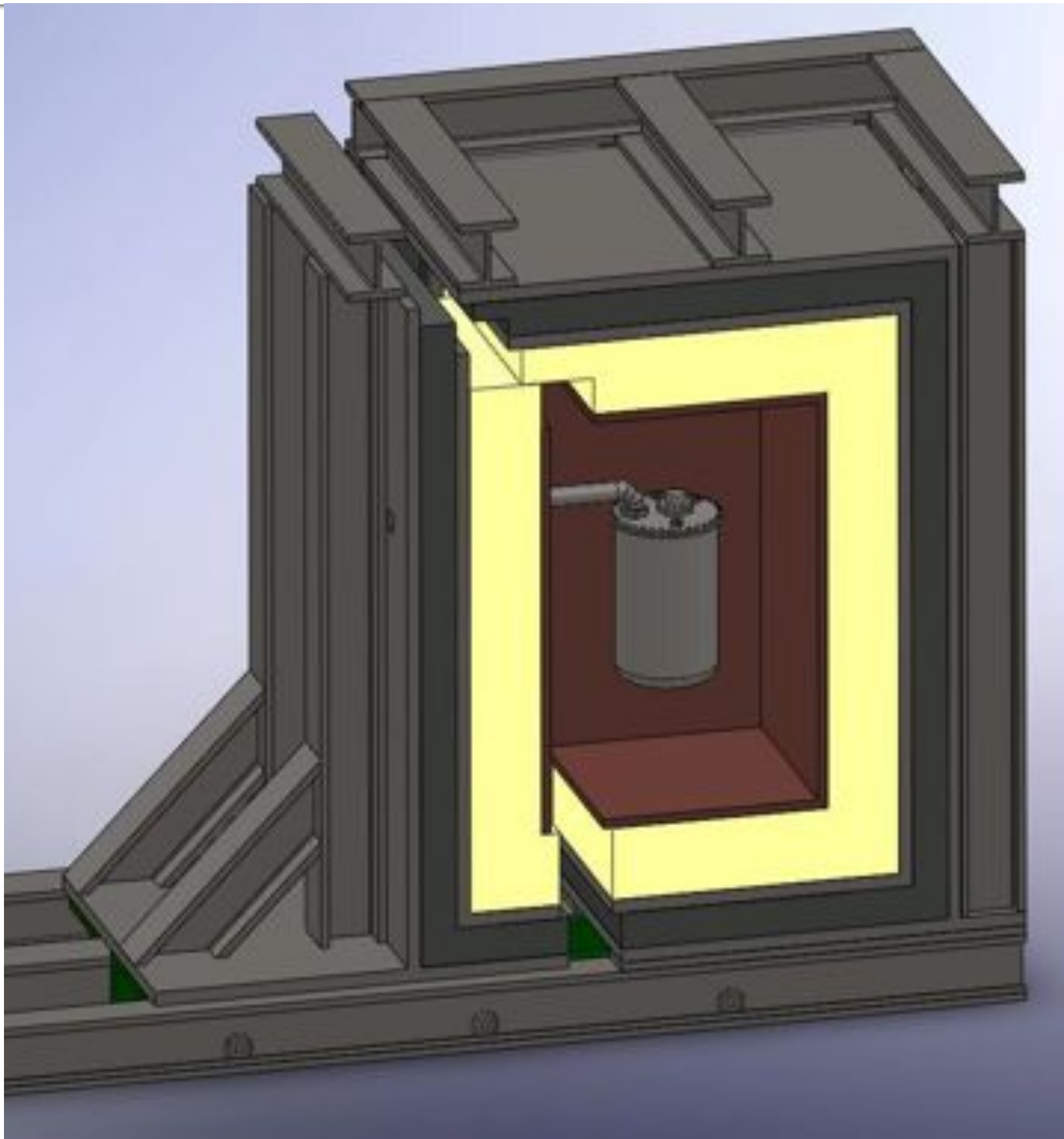
Dust: ~7000 decays/mg-yr

Air: >300 decays/mL-yr

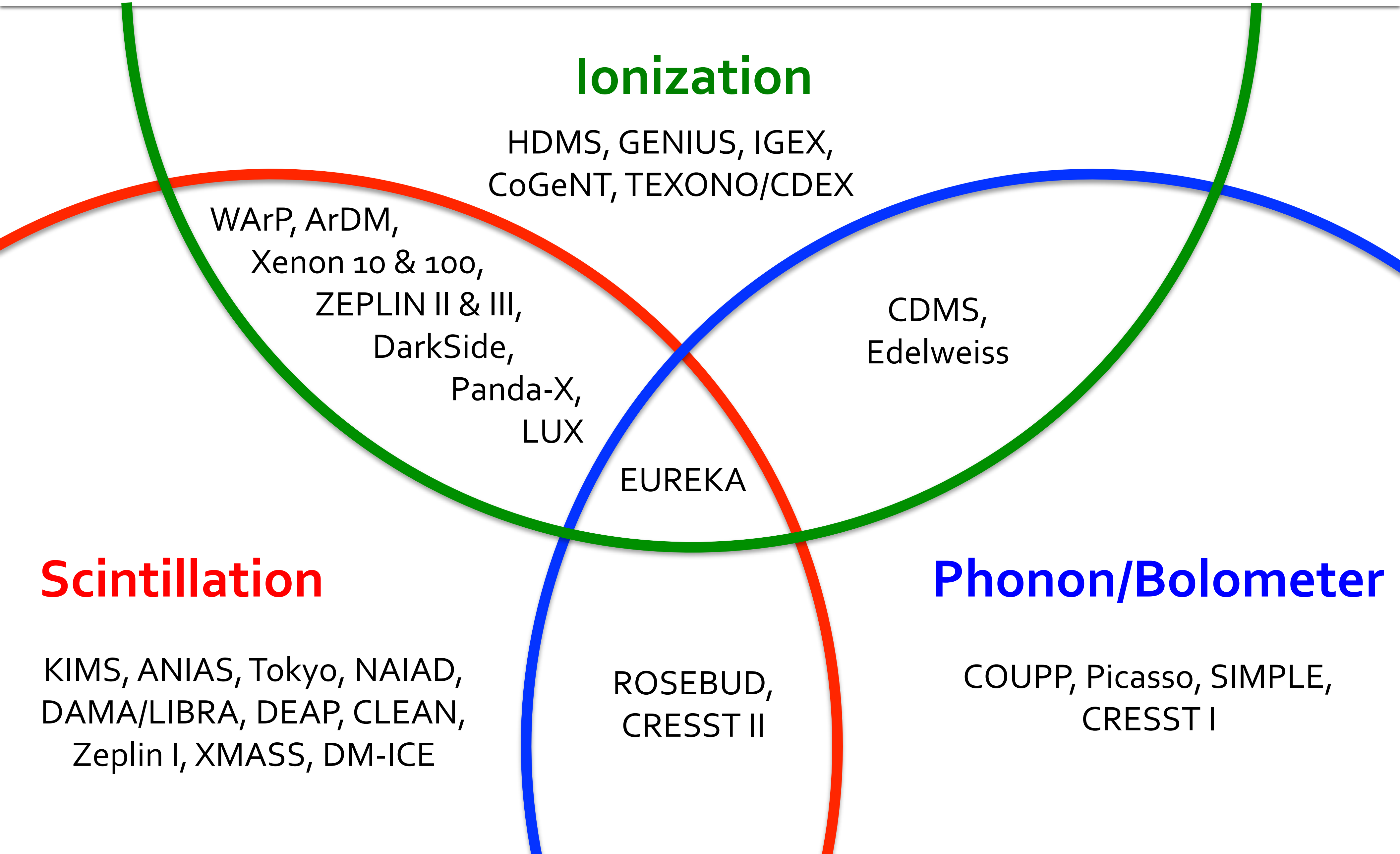
Fingerprint: ~10 decays/yr

Ideal WIMP Detector

- Large mass, long exposure
- Low threshold
- Low background
- Background discrimination

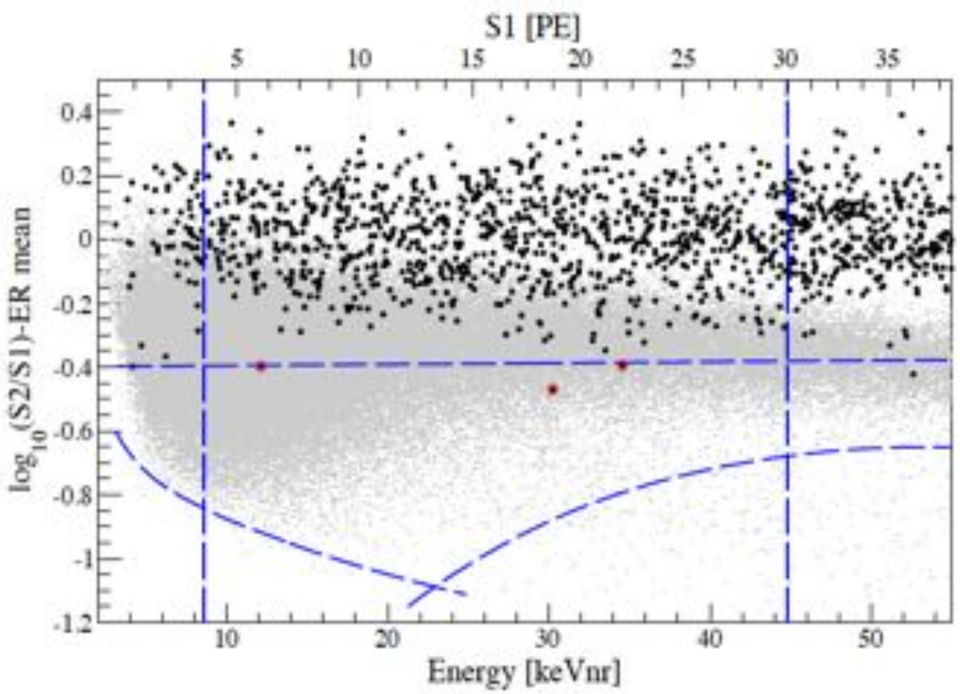


WIMP Detection Experiments



Leading Experiments

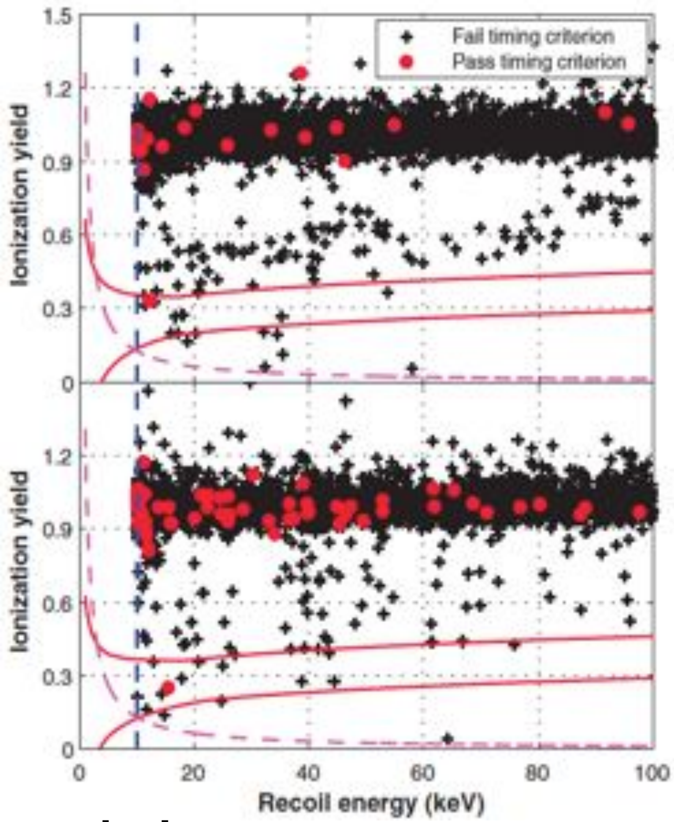
Xenon100



Technique: Xe, scintillation + ionization
Exposure: 1471 kg-days
Expect: 1.8±0.6 background events
Observe: 3 events

PRL **107**:131302 (2011)

CDMS

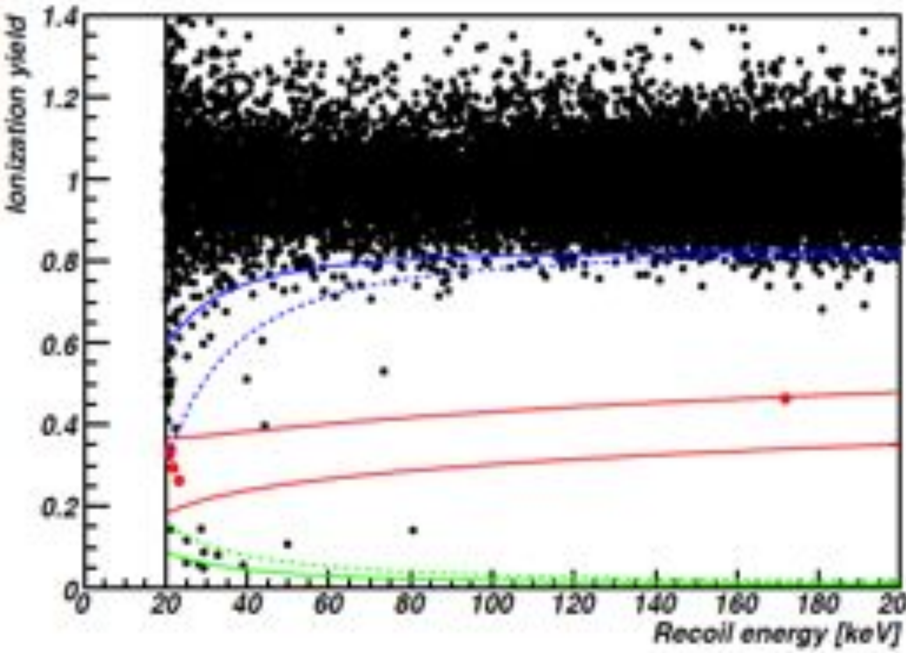


Technique: Ge + Si, Ionization + bolometric
Exposure: 612 kg-days
Expect: 0.9 ± 0.2 background events
Observe: 2 events

Nature **327:**1619 (2010)

Leading Experiments

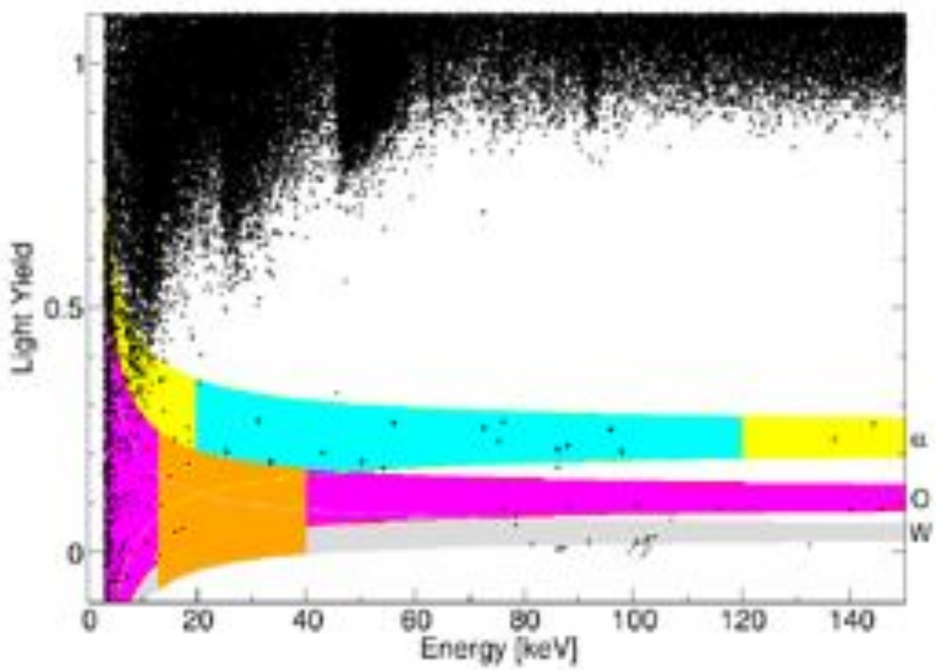
Edelweiss



Technique: Ge,
ionization + bolometric
Exposure: 384 kg-days
Expect: <3 background events
Observe: 5 events

PLB **702**:329 (2011)

Cresst

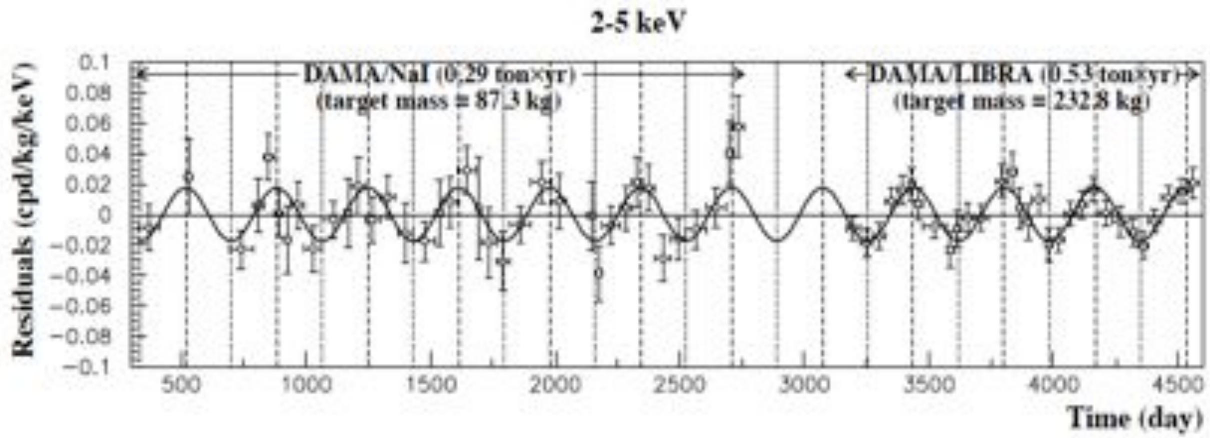


Technique: $CaWO_4$,
scintillation + bolometric
Exposure: 730 kg-days
Observe: $29.4^{+8.6}_{-7.7}$ ($24.2^{+8.1}_{-7.2}$) events
above background of 42-48 events

arXiv:1109.0702

Leading Experiments

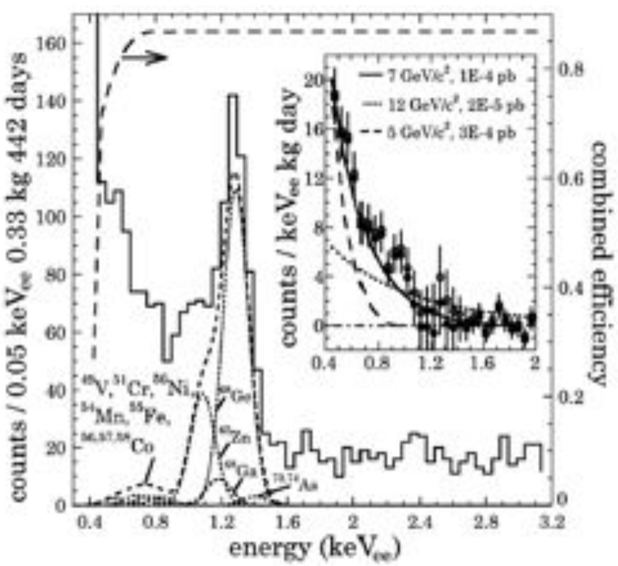
DAMA/LIBRA



Technique: NaI, scintillation
Exposure: 4.3×10^5 kg-days
Observe: Annual modulation in event rate.

Eur. Phys. J. C **56**:333-355 (2008)

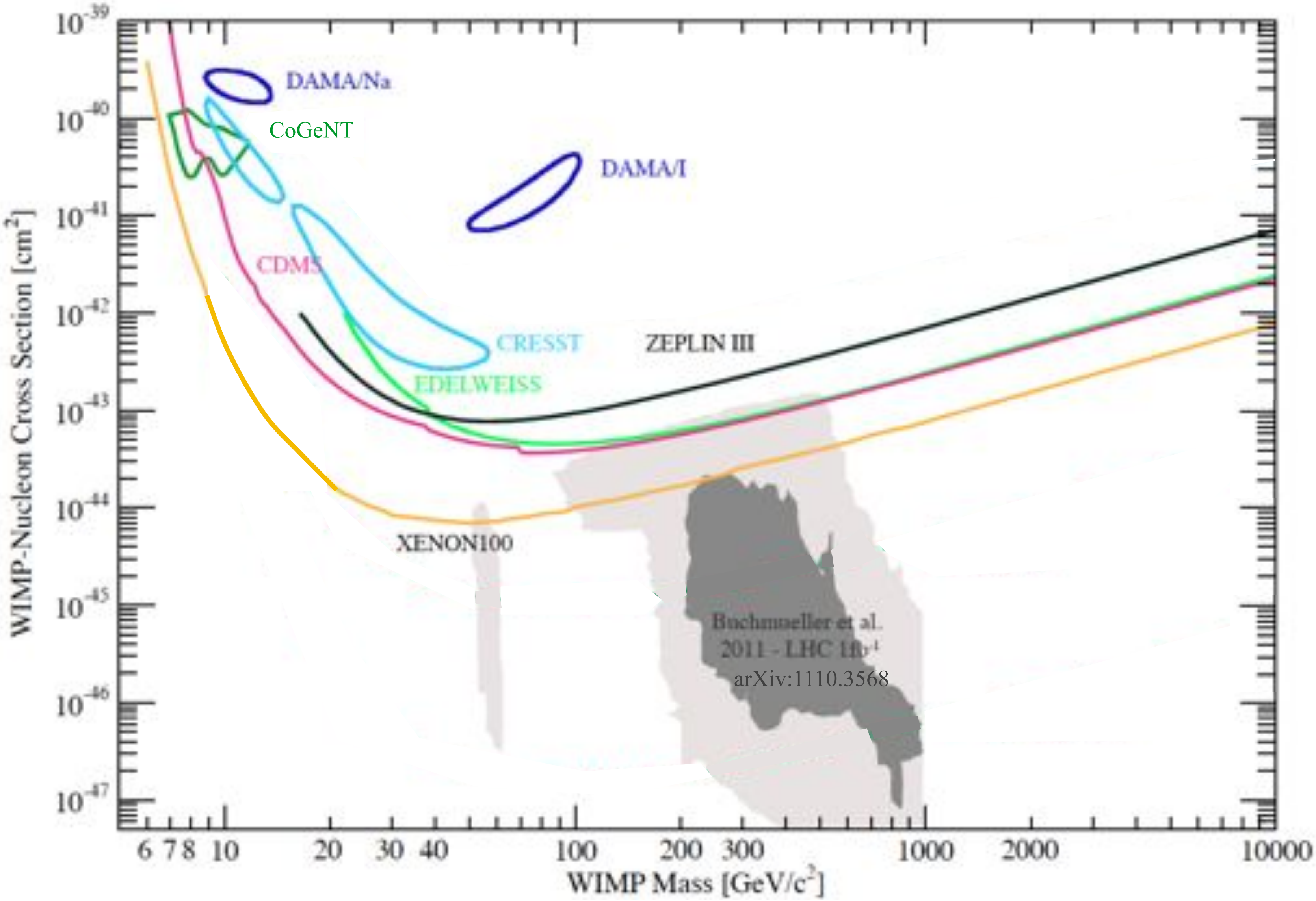
CoGeNT



Technique: Ge, ionization
Exposure: 146 kg-days
Observe: Excess events at low energy, probably an annual modulation

PRL **106**:131301 (2011),
PRL **107**:141301 (2011)

The Current Status



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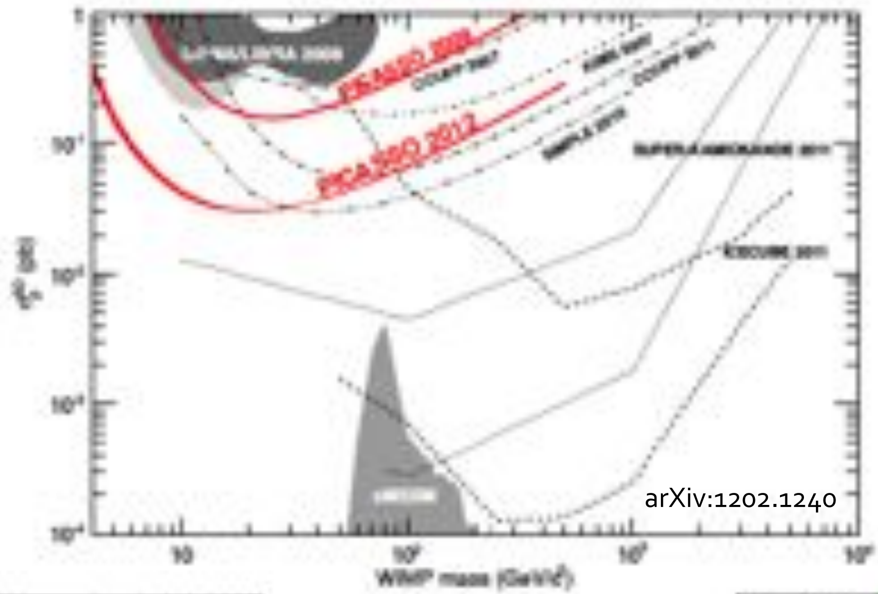
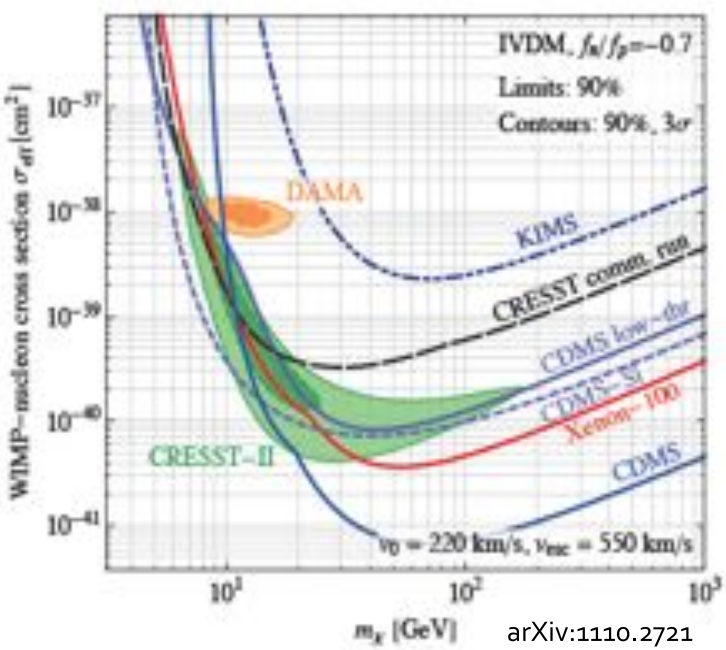
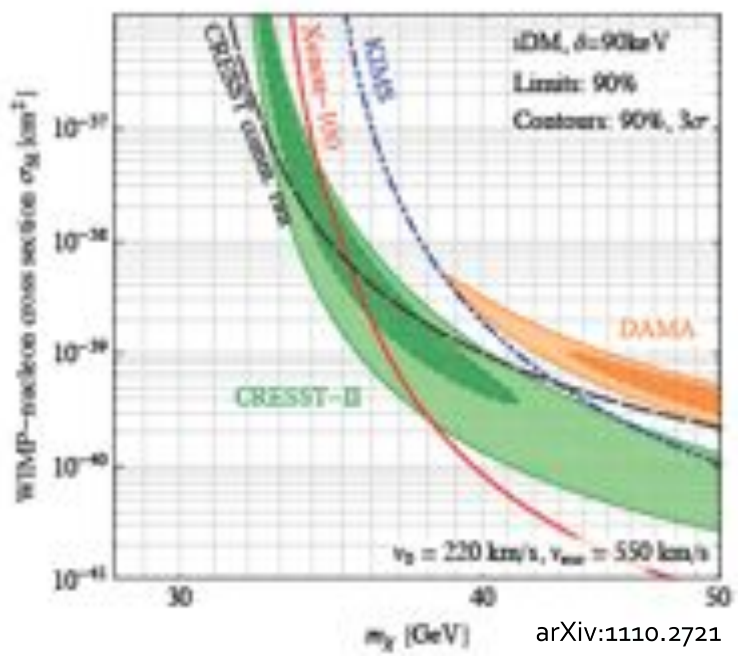


arXiv:1202.1240



arXiv:1110.2721



arXiv:1110.2721

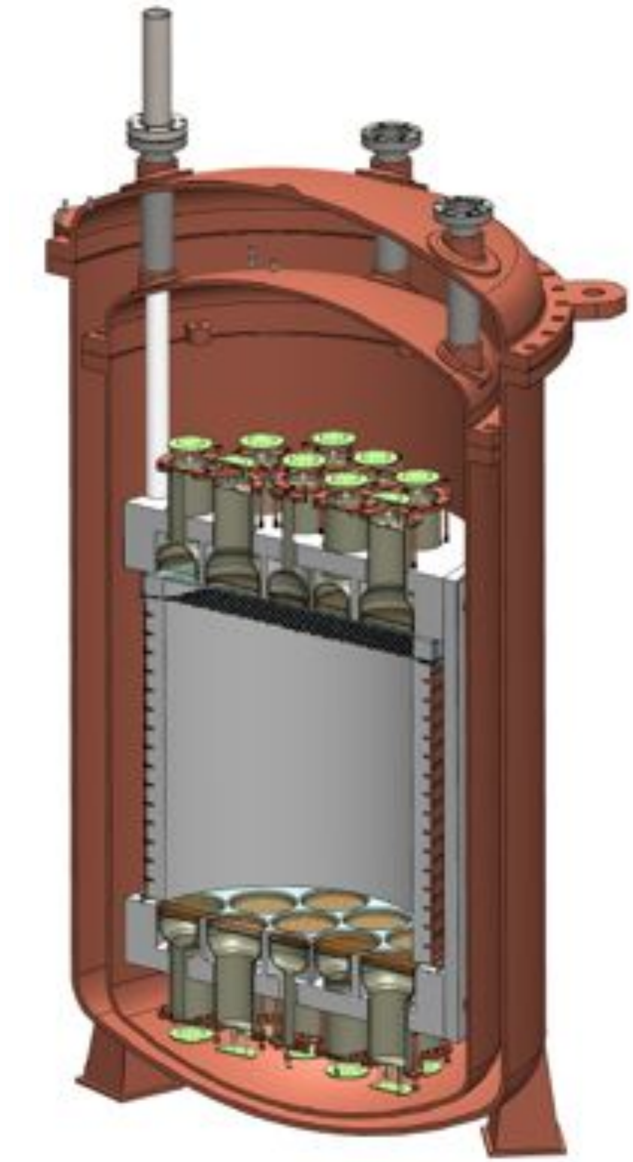
The Current Status

In dark matter searches, the trouble starts when you see something.

- All leading dark matter experiments expect background and they see it
- Progress contingent on achieving lower, better controlled backgrounds

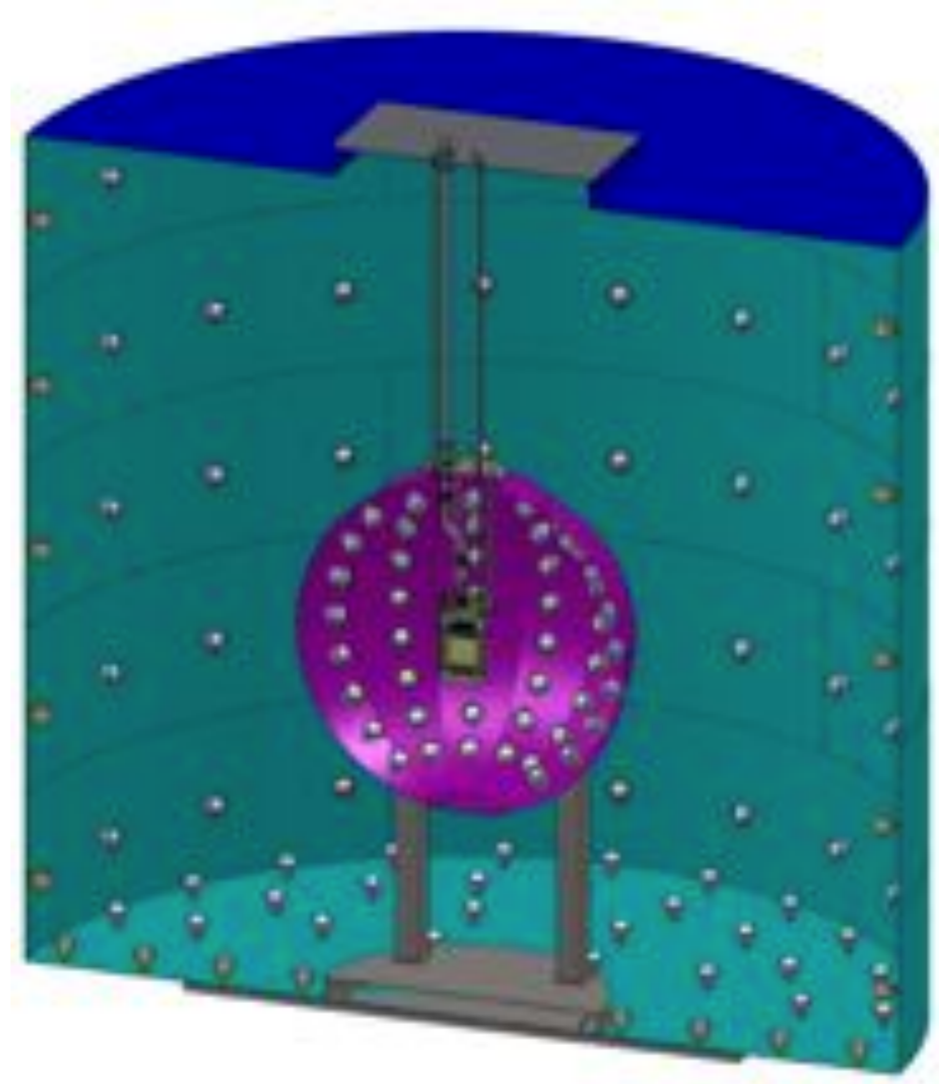
DarkSide

- A dark matter program based on 2-phase underground argon time projection chambers (TPCs)
- First physics detector will be “DarkSide-50”



DarkSide Background Strategy

- Designed to have very low, very well understood background
- Underground argon and other novel technologies give very low background levels
- Further suppress backgrounds and assay them *in situ* using active background suppression techniques



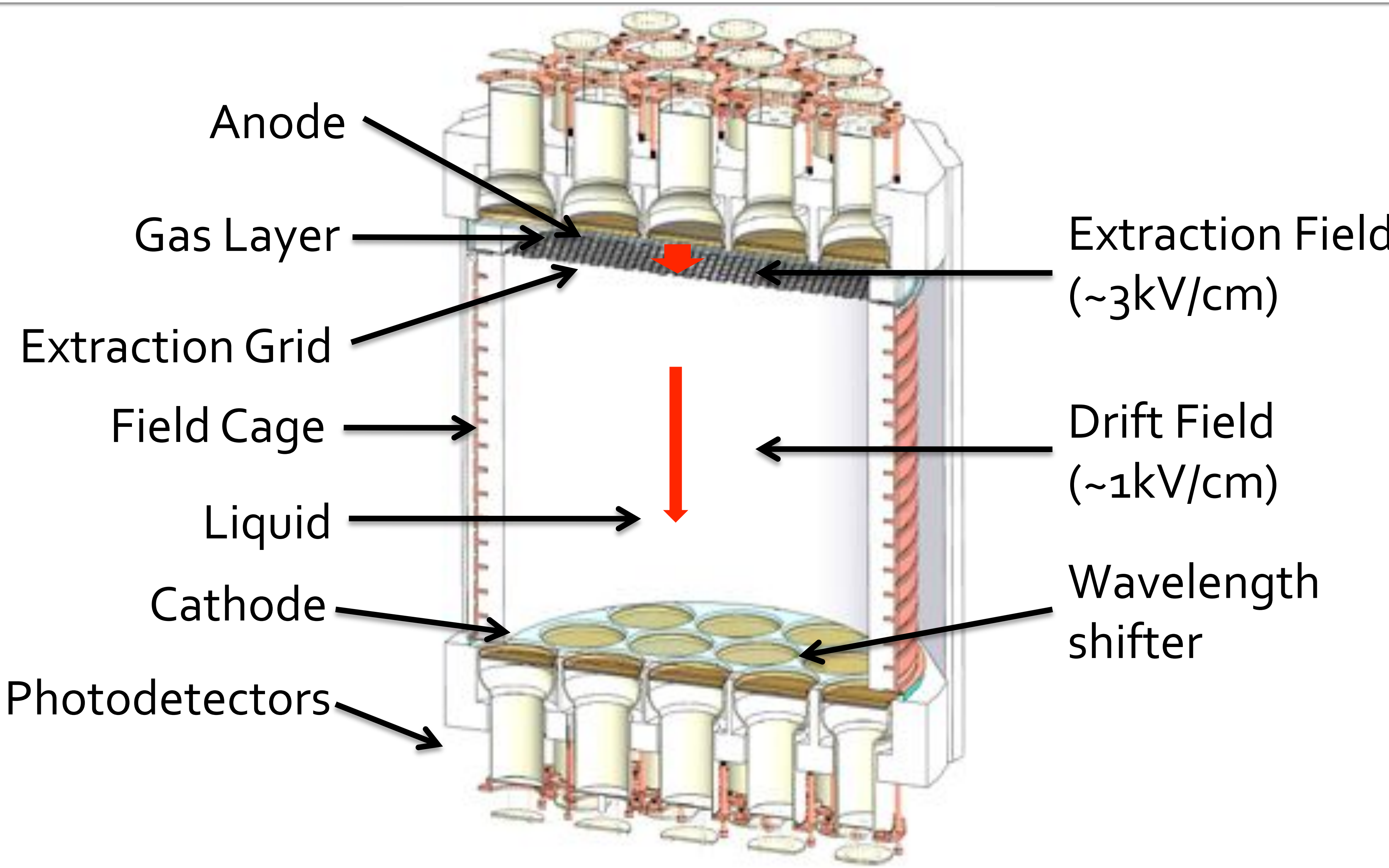
Darkside Collaboration

Augustana College – SD, USA
Black Hill State University – SD, USA
Fermilab – Il, USA
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN and Università degli Studi Genova, Italy
INFN and Università degli Studi Milano, Italy
INFN and Università degli Studi Naples, Italy
INFN and Università degli Studi Perugia, Italy
Institute for High Energy Physics – Beijing, China
Joint Institute for Nuclear Research – Dubna, Russia
Lomonosov Moscow State University, Russia
Princeton University, USA
RRC Kurchatov Institute – Moscow, Russia
St. Petersburg Nuclear Physics Institute – Gatchina, Russia
Temple University – PA, USA
University of Arkansas, USA
University of California, Los Angeles, USA
University of Houston, USA
University of Massachusetts at Amherst, USA
Virginia Tech, USA

Why Argon?

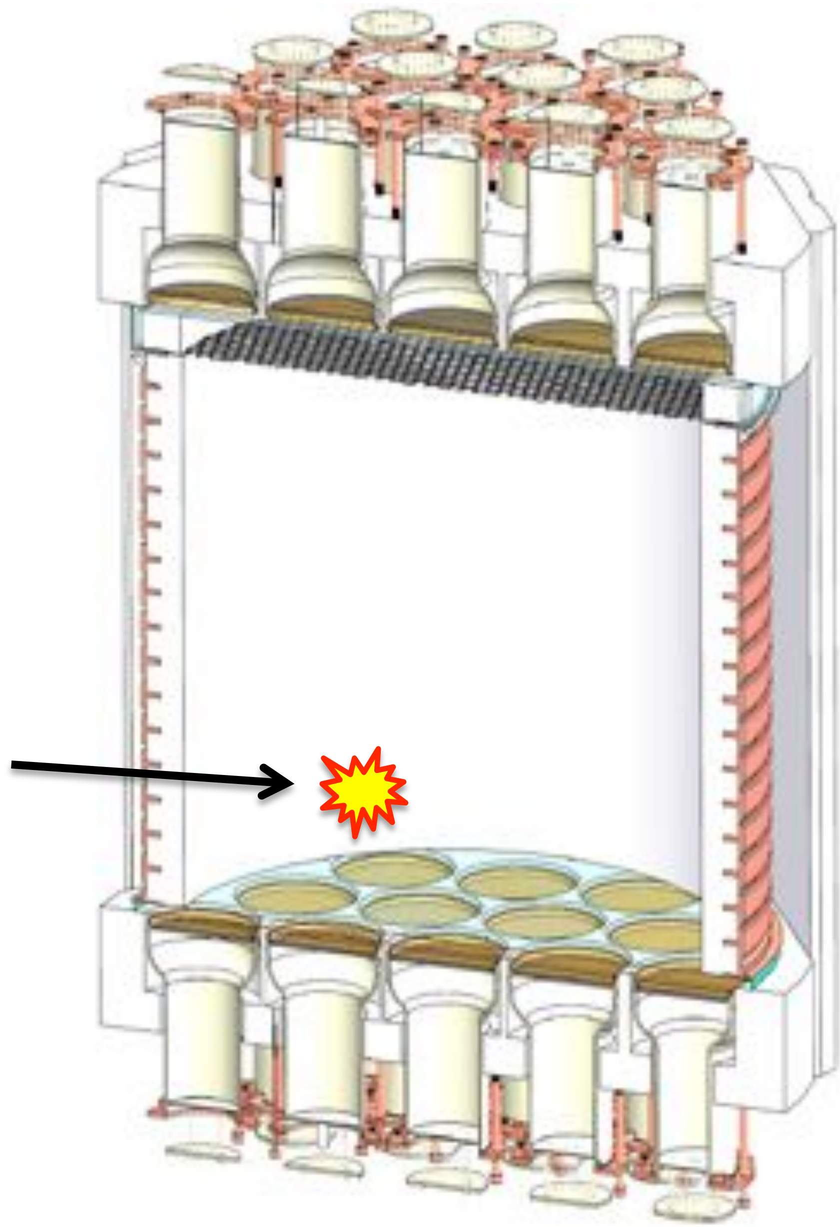
- Liquid argon is a great dark matter target
  - Good scintillator (~40,000 photons/MeV)
  - Very transparent to its own scintillation light
  - Easily purified
- Relatively inexpensive technology, could be scaled to multi-tonne detectors
  - Need to suppress ^{39}Ar
- Very powerful rejection capability for electron recoil background

2-Phase Argon TPC

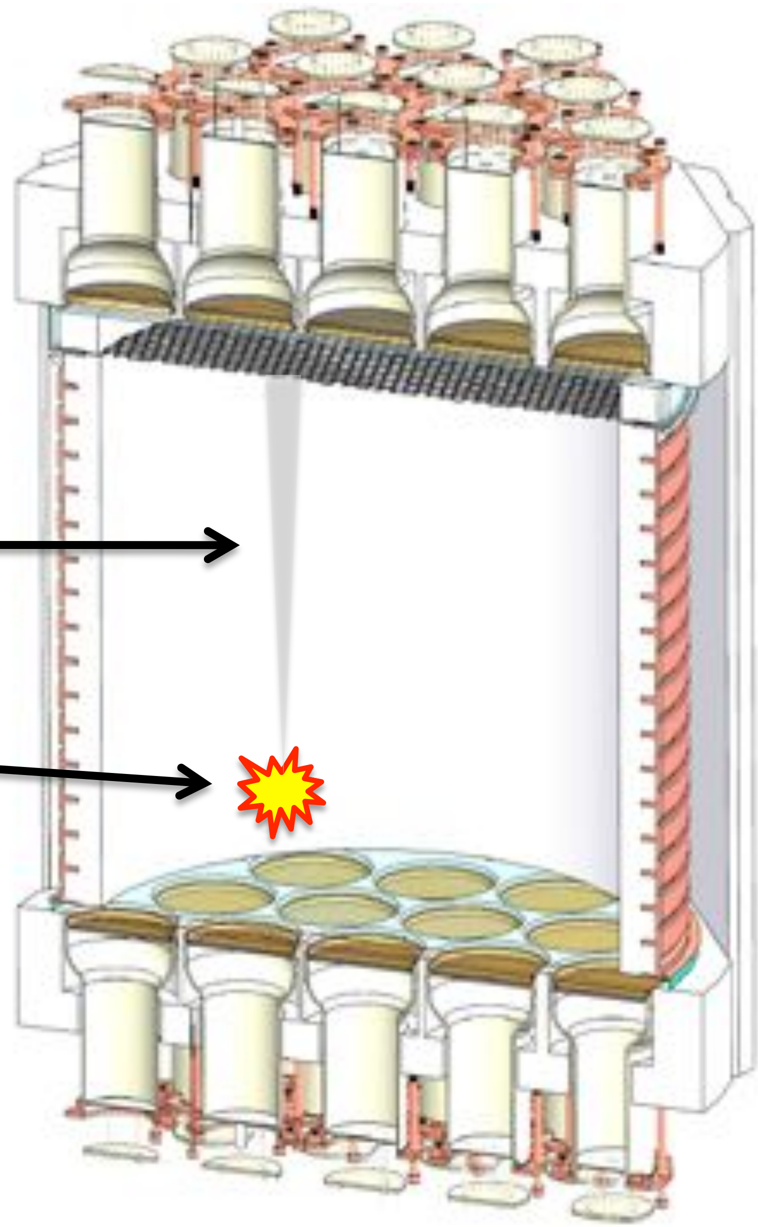


Two Phase Argon TPC

“S1” Scintillation
Light



Two Phase Argon TPC

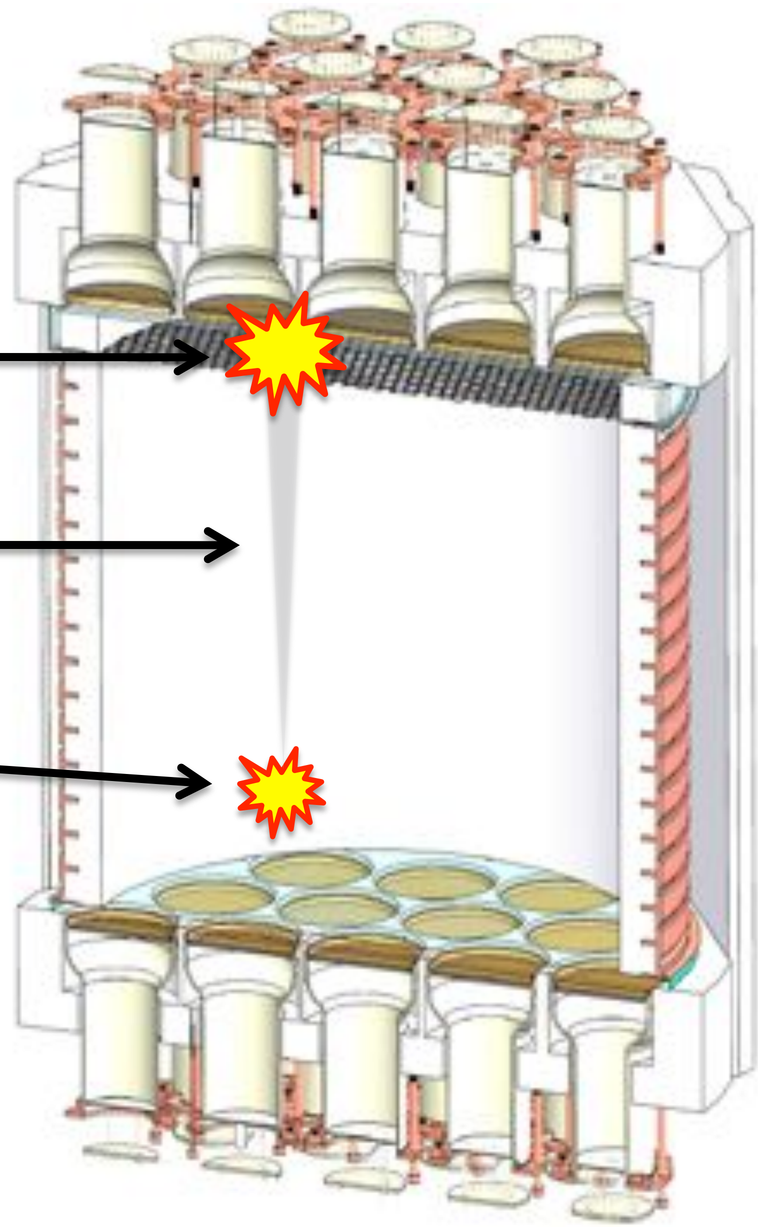


Two Phase Argon TPC

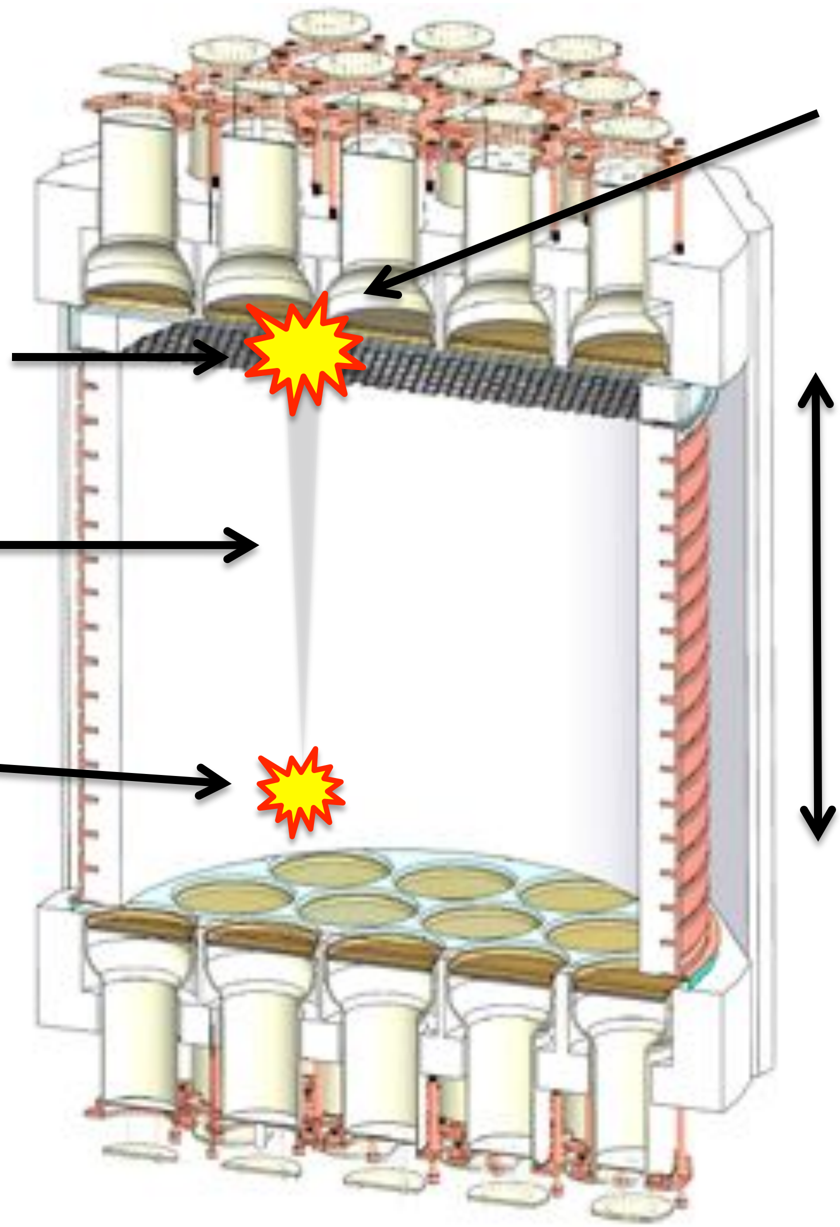
Electro-luminescence
"S2" Light

Drift Charge

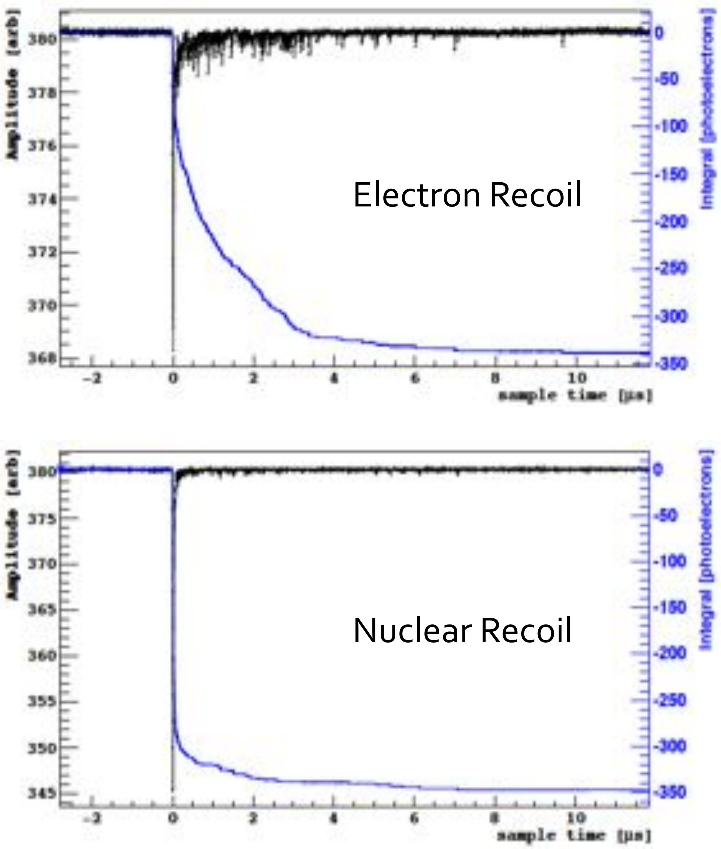
"S1" Scintillation
Light

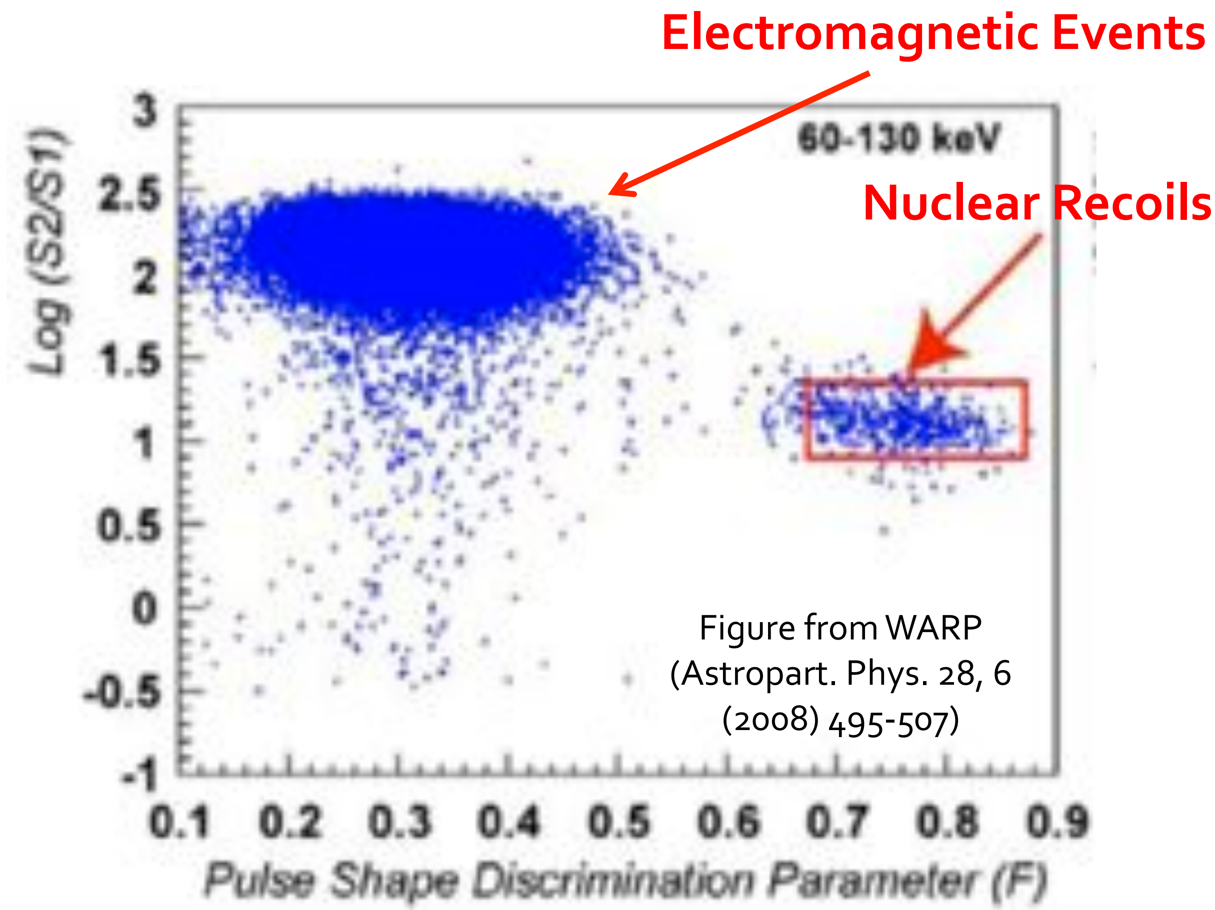


Two Phase Argon TPC



"S1" Electron Recoil Discrimination

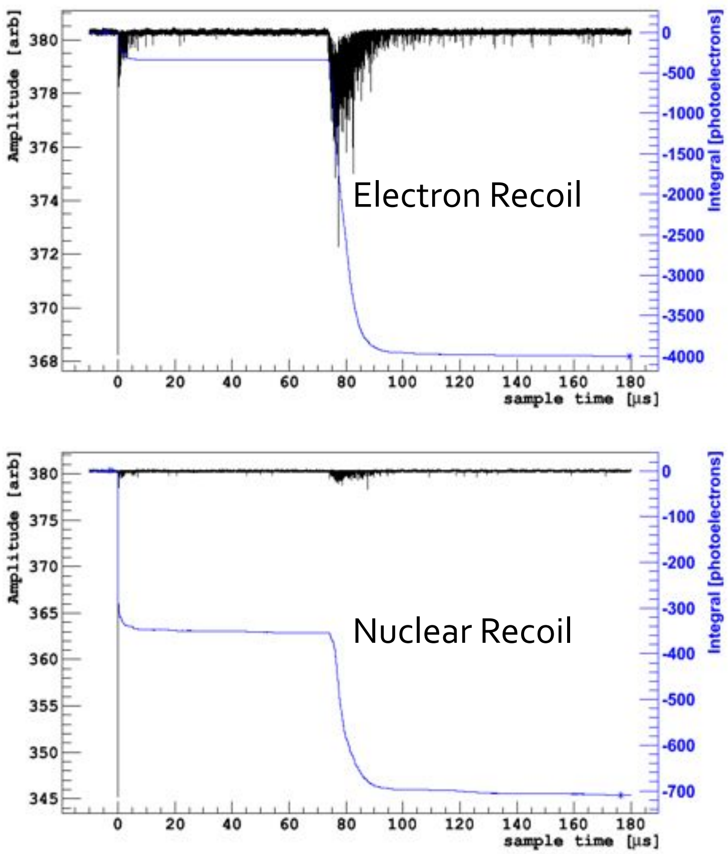




- The ratio of light from singlet (~7 ns decay time) and triplet (1.6 µs decay time) depends on ionization density

➡ *$>10^8$ discrimination from pulse shape*

"S2/S1" Electron Recoil Discrimination



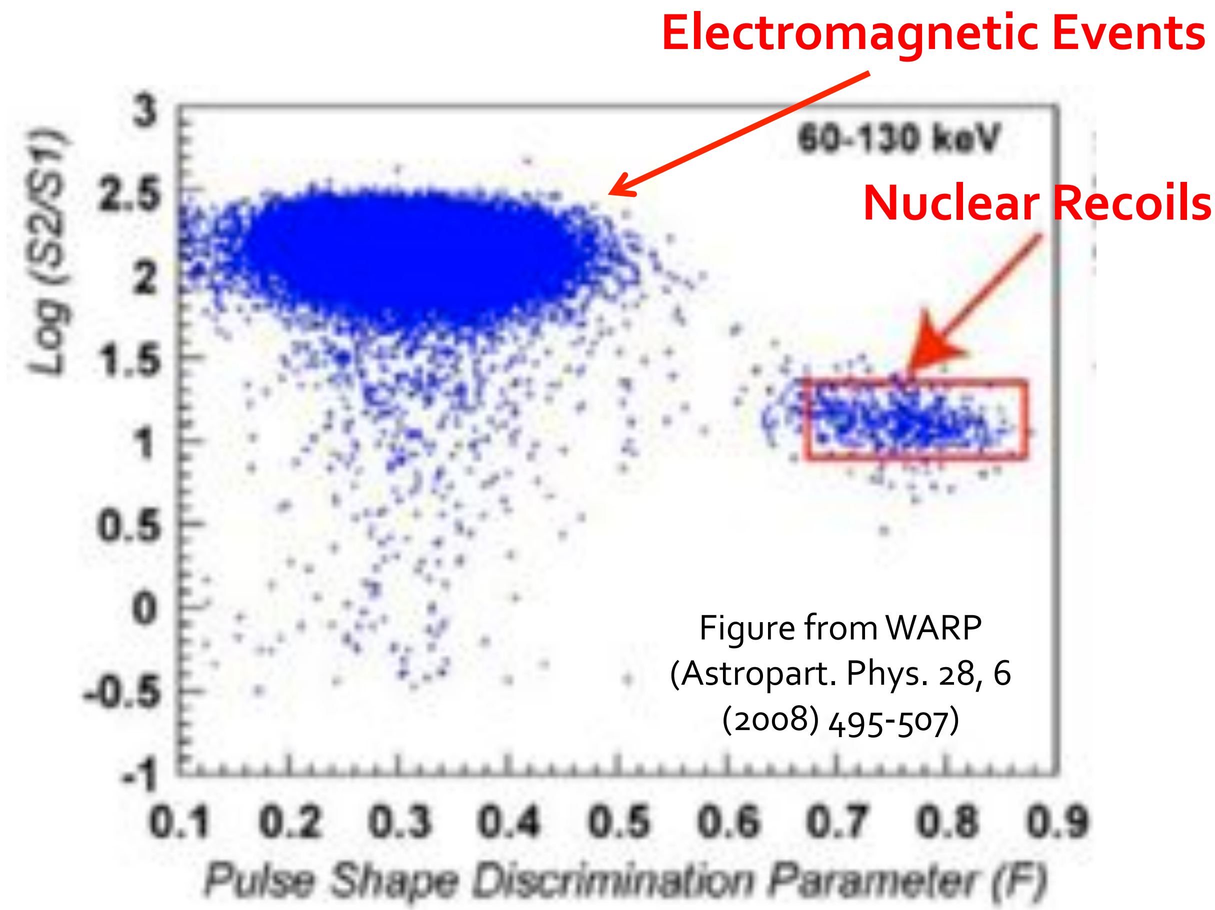
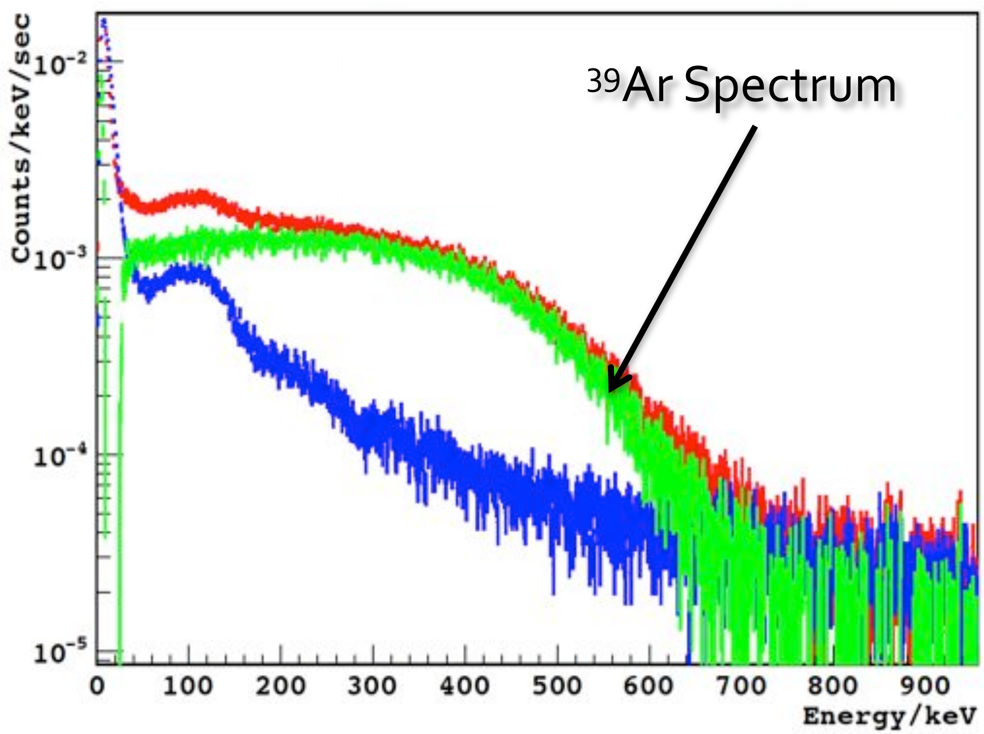


Figure from WARP (Astropart. Phys. 28, 6 (2008) 495-507)

- The recombination probability (and hence the ratio of S2:S1 light) also depends on ionization density
  - ➡ 10^2-10^3 additional discrimination
  - ➡ *>10^{10} total electron recoil rejection in 2D*

^{39}Ar

- Radioactive, β-decay, $T_{1/2}$ = 269 years
- Cosmogenic
  - $^{40}Ar(n,2n)^{39}Ar$ in the atmosphere
- ~1 Bq/kg in atmospheric argon
  - 3×10^{10} events in 1.0 ton-year!



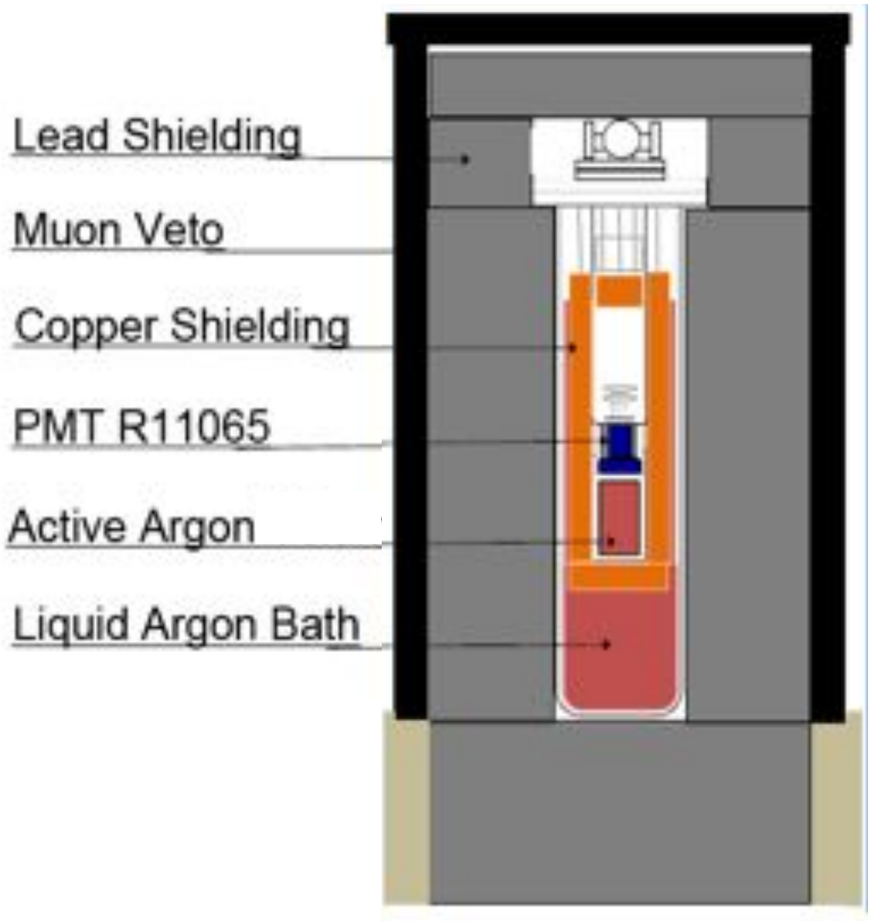
Underground Argon

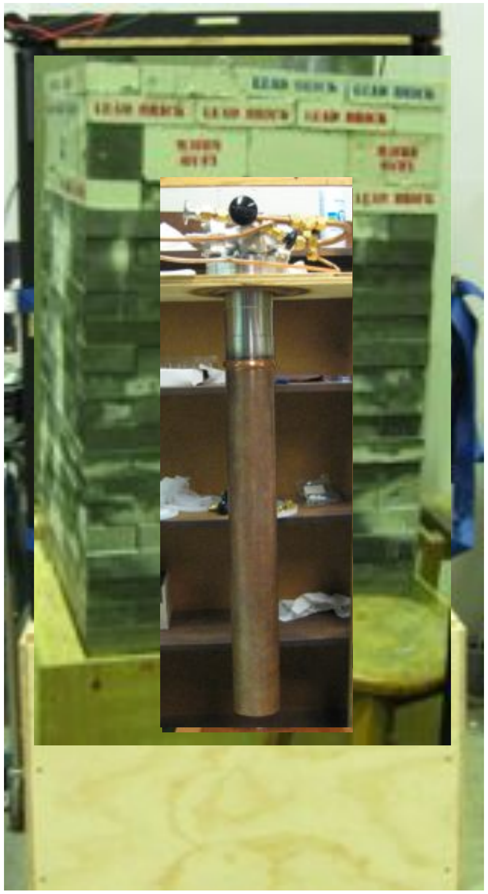
- Underground argon is shielded, so can contain less ^{39}Ar
- CO_2 from Kinder Morgan Doe Canyon Complex (Cortez, CO) contains ~600 ppm Argon
  - 3 tons Ar produced/day
- ~85 kg of argon collected so far

For details: NIM A **587**:46-51 (2008), AIP Conf. Proc. 1338:217-220 (2011)

Underground Argon Counting

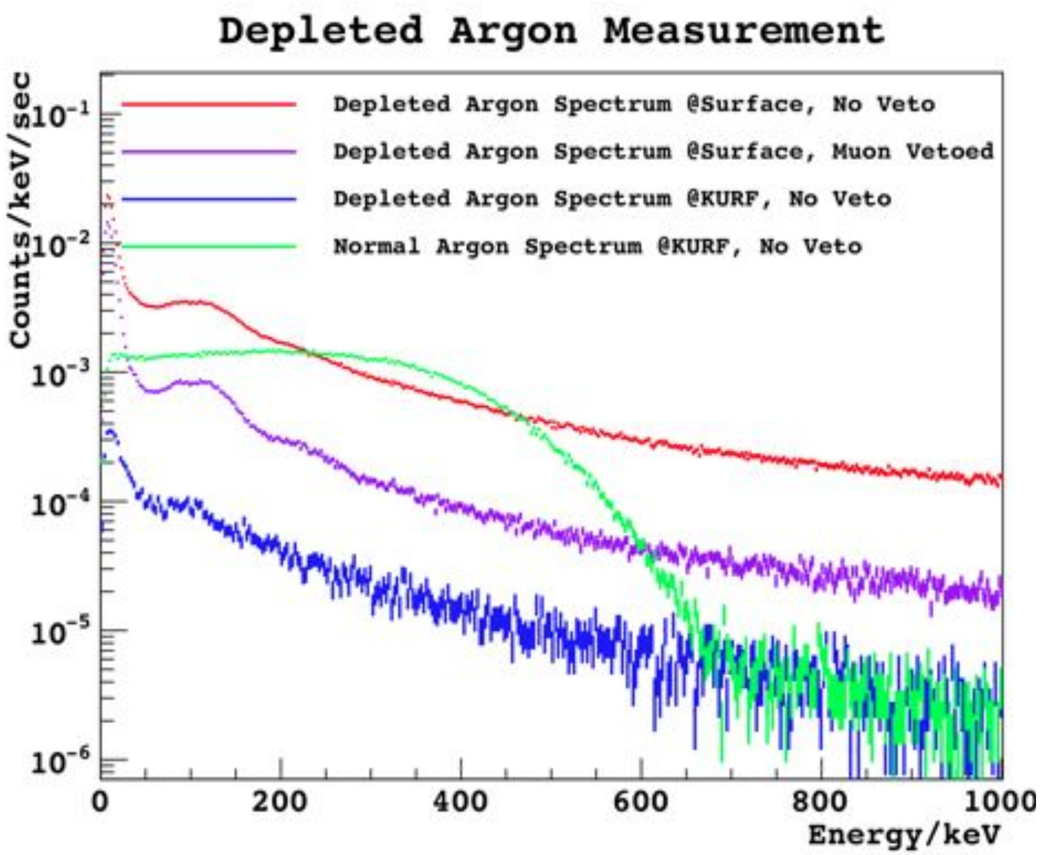
The "Low Background Detector"





Underground Argon Counting

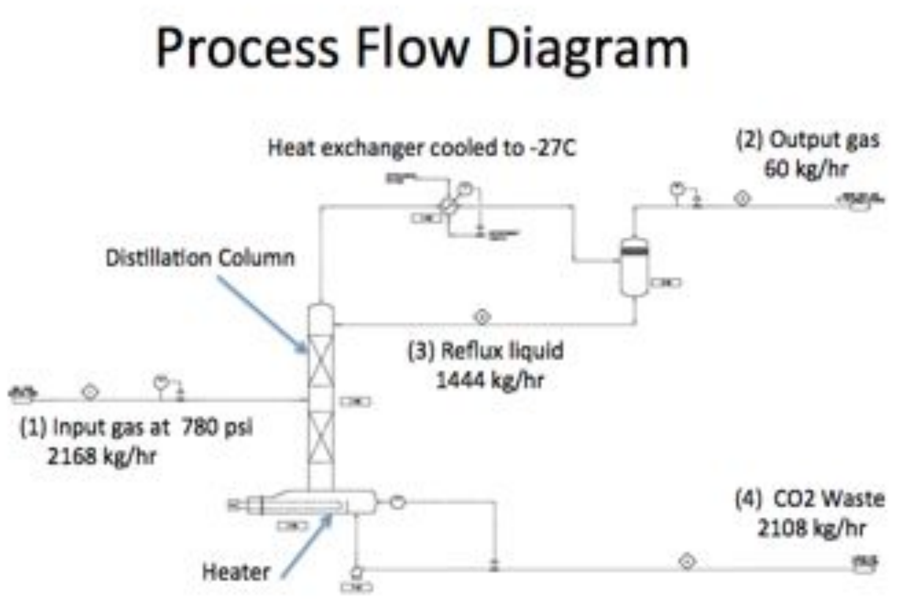
- Detector operated both on surface (Princeton) and underground (KURF, 1400 m.w.e.)
- Background rate of 0.002 Hz in 300-400 keV at KURF
- ^{39}Ar depletion factor >100



Multi-ton argon experiments possible with underground argon!

Multi-Tonne Underground Argon

- DarkSide and DEAP will collaborate to expand the argon extraction facility in Cortez
  - 5000 kg for DarkSide
  - 4000 kg for DEAP
- Install a high-pressure "pre-distillation" to increase the argon concentration in the gas that is fed to the current pressure swing adsorption system
  - Aim for 50 kg/day argon collection rate
- Upgrade could begin in 2013



Highly-Efficient Neutron Veto

- Neutron scattering events can be a "perfect" WIMP background
- Surround DarkSide with boron-loaded liquid scintillator
- Efficiently detect escaping neutrons and veto any associated nuclear recoil backgrounds
  - >99.5% efficiency for radiogenic neutrons
  - >95% efficiency for cosmogenic neutrons
- Sized to accept multi-tonne detector

For details: NIM A **664**:18-26 (2011)

Why Boron-loading?

- High capture cross section on ^{10}B via

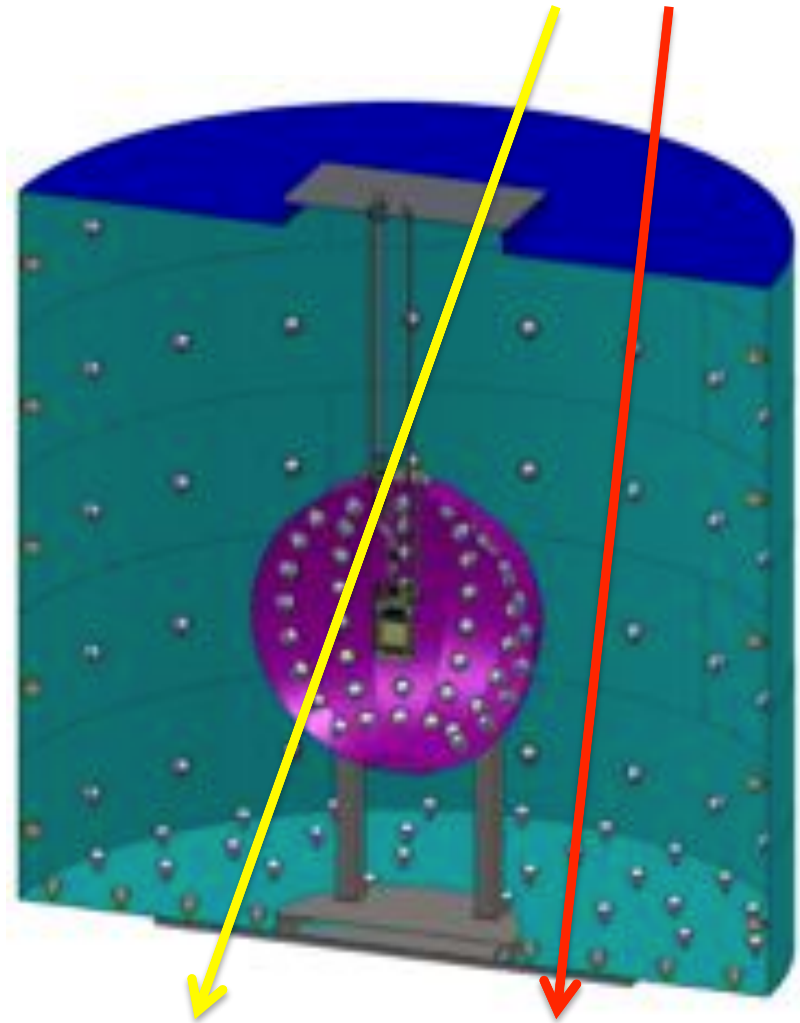
$$^{10}\text{B} + n \rightarrow {}^{7}\text{Li}^* + \alpha \rightarrow {}^{7}\text{Li} + \alpha + 478 \text{ keV } \gamma \quad (93.7\%)$$
$$\rightarrow {}^{7}\text{Li} + \alpha \quad (6.4\%)$$

- Recoil products can be detected directly (~50 keVee)
  - No need to contain neutron capture gamma rays
  - Makes smaller vetoes more efficient
- "Outcompete" neutron capture on inner detector components
- Reduce neutron capture time (~2 μs in boron scintillator vs. ~250 μs in pure scintillator)
  - Smaller veto windows reduces dead time from veto background rate
  - Allows simpler construction (e.g. 8" glass PMTs)
- Radiopure, optically efficient tri-methyl borate loaded scintillator was demonstrated for Borexino

For details: NIM A **664**:18-26 (2011)

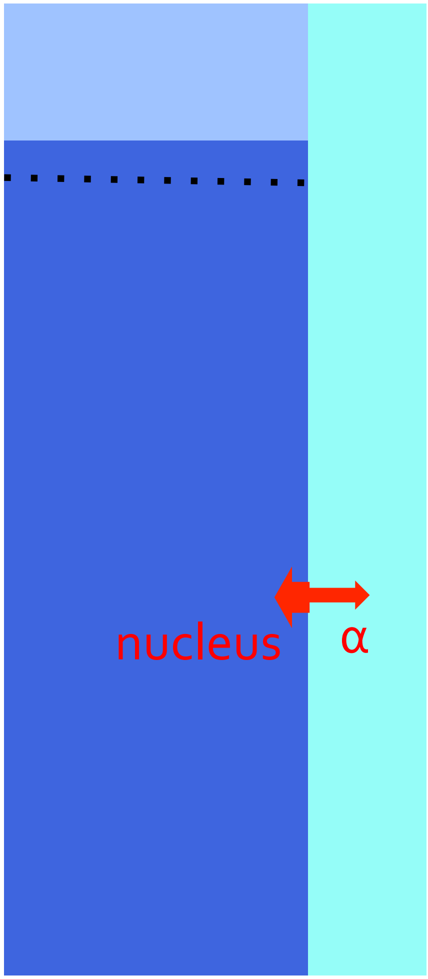
Cosmogenic Neutrons

- Install DarkSide within the Borexino CTF tank in LNGS, Italy
  - Muon flux reduced by 10^6
- Detect the Cerenkov light produced by the muons and other shower particles
  - Veto the neutron-induced background events
- CTF tank + neutron veto reduce cosmogenic backgrounds by $>>10^3$



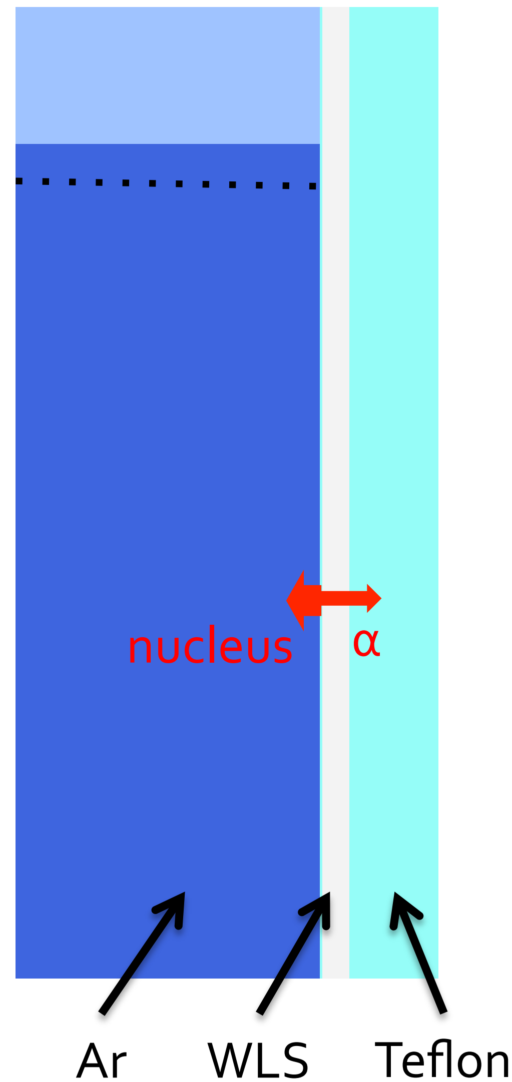
Surface Background

- Alpha decays on the surface can produce a recoil nucleus in the active volume
  - Surface activity builds up during air exposure due to radon-daughters
  - Activity on Borexino nylon vessel balloon is ~10α/m²/day – we can likely do better!
    - Would give a few thousand events in DarkSide-50
    - Need $>10^5$ rejection



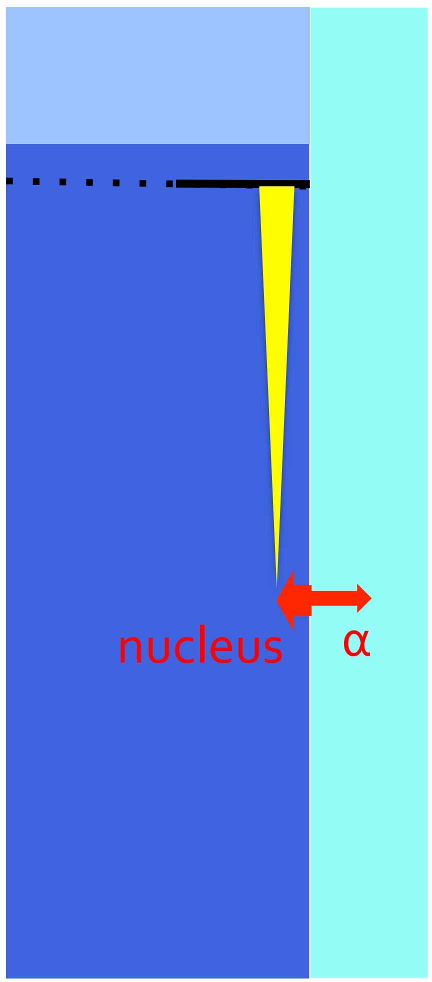
Surface Background

- Wavelength shifter scintillation
  - Alphas passing through the WLS produce light
  - Push a large fraction of the event above the WIMP recoil region
  - Pulse shape may also be different
- Position reconstruction
  - Reject events near the walls
  - Expect O(1cm) resolution in x-y (distribution of S2 light)
  - 'Tails' in position reconstruction are important



Surface Background

- Charge interruption
  - A conducting ring could be used to interrupt the drifting charge from surface events, removing their S2 light
- Studies of all three methods ongoing
- Combination of methods should reduce surface backgrounds to acceptable levels
- Note that this gets easier in larger detectors!



DarkSide-50 Background Estimates

Total WIMP background in (ev / 0.1 tonne-yr) for R11065 (QUPIDs):

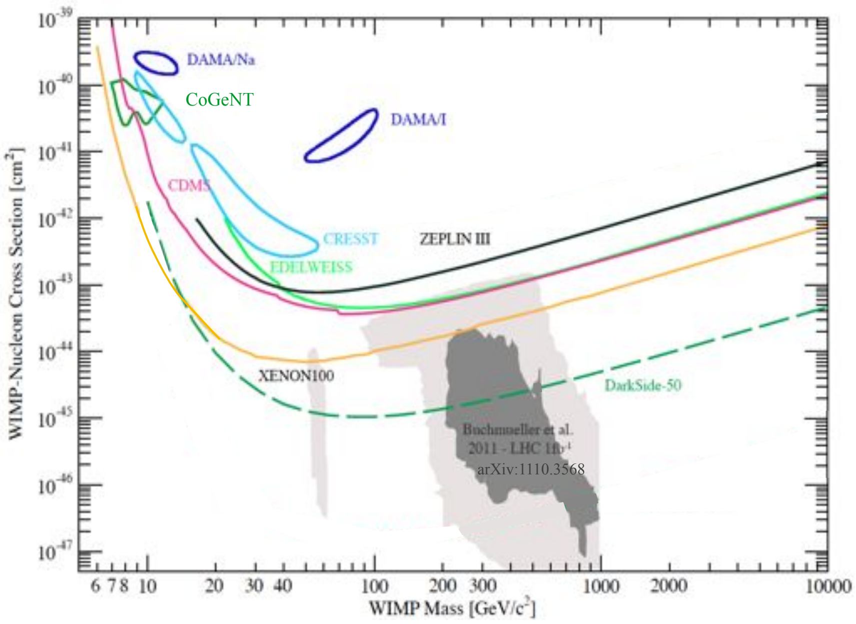
Detector Element	Electron Recoil Backgrounds		Radiogenic Neutron Recoil Backgrounds		Cosmogenic Neutron Recoil Backgrounds	
	Raw	After Cuts	Raw	After Cuts	Raw	After Cuts
^{39}Ar (<0.01 Bq/kg)	$<6.3\times10^{6}$	$<4\times10^{-3}$	–	–	–	–
Fused Silica	3.3×10^{4}	2.0×10^{-5}	0.17	4.3×10^{-4}	0.21	1.3×10^{-5}
PTFE	4,800	3.0×10^{-6}	0.39	9.8×10^{-4}	2.7	1.6×10^{-4}
Copper	4,500	2.8×10^{-6}	5.0×10^{-3}	1.3×10^{-5}	1.5	9.0×10^{-5}
R11065 PMTs	2.6×10^{6}	1.6×10^{-3}	19.4	4.8×10^{-2}	0.34	2.0×10^{-5}
QUPIDs (1 mBq)	7.0×10^{4}	4.2×10^{-5}	0.31	7.8×10^{-4}	0.34	2.0×10^{-5}
Stainless Steel	5.5×10^{4}	3.4×10^{-5}	2.5	6.3×10^{-3}	30	0.0018
Veto Scintillator	70	4.3×10^{-8}	0.030	7.5×10^{-5}	26	0.0016
Veto PMTs	2.5×10^{6}	1.6×10^{-3}	0.023	5.8×10^{-5}	–	–
Veto tank	1.7×10^{5}	1.1×10^{-4}	6.7×10^{-5}	1.7×10^{-7}	19	0.0071
Water	6,100	3.8×10^{-6}	6.7×10^{-4}	1.7×10^{-6}	19	0.0071
CTF tank	8,300	5.1×10^{-6}	3.5×10^{-3}	8.7×10^{-6}	0.068	2.6×10^{-5}
LNGS Rock	920	5.7×10^{-7}	0.061	1.5×10^{-4}	0.31	0.012
Total	–	0.007 (0.006)	–	0.055 (0.008)	–	0.030 (0.030)

Surface Backgrounds	
Raw	After cuts
4.5×10^{3}	<0.01

Very conservative estimates: DarkSide should demonstrate background free ton-yr exposures!

DarkSide-50 Physics Reach

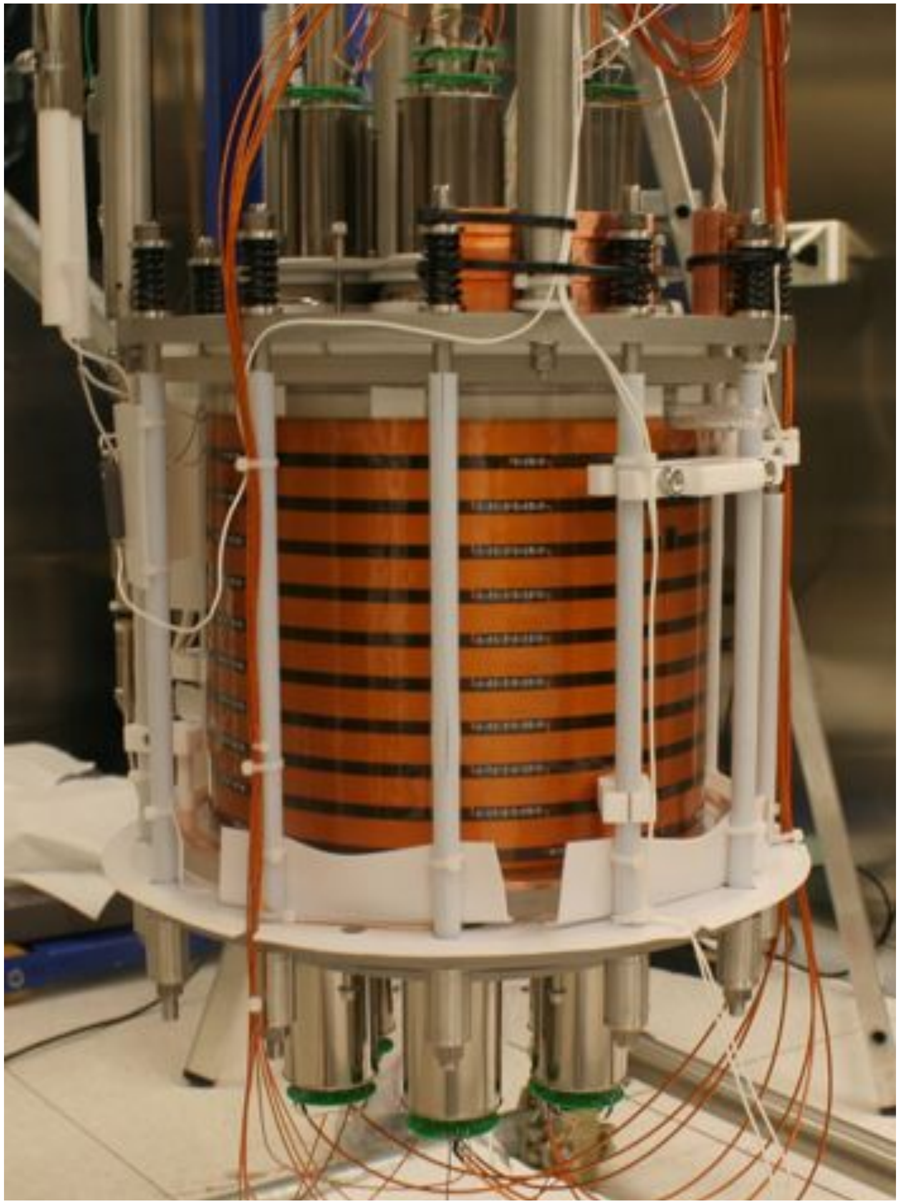
- Background free operation for 0.1 tonne-yr gives 10^{-45}cm^2 sensitivity
- Background measurement from active suppression gives precise understanding of residual background rate
  - Credible detection claim possible based on a few observed events!



Detector commissioning expected in late 2012.

DarkSide-10 Prototype

- Test key technical concepts for DarkSide-50
- Practice running a 2-phase TPC, investigate backgrounds
- 12+ months of operation since 2010
- Initial runs at Princeton, now running underground at LNGS



DarkSide-10 Prototype

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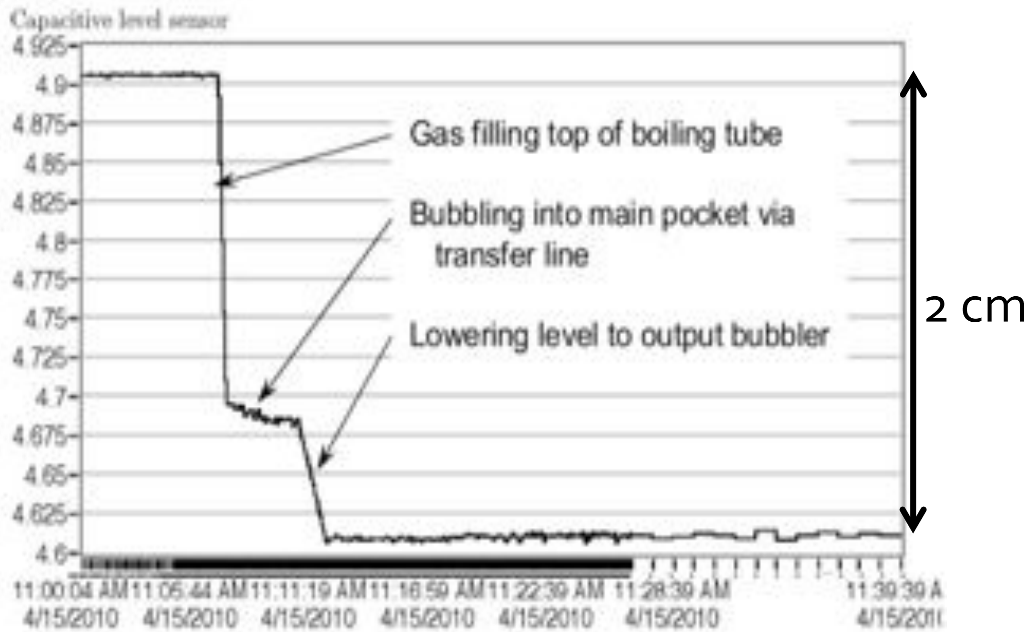
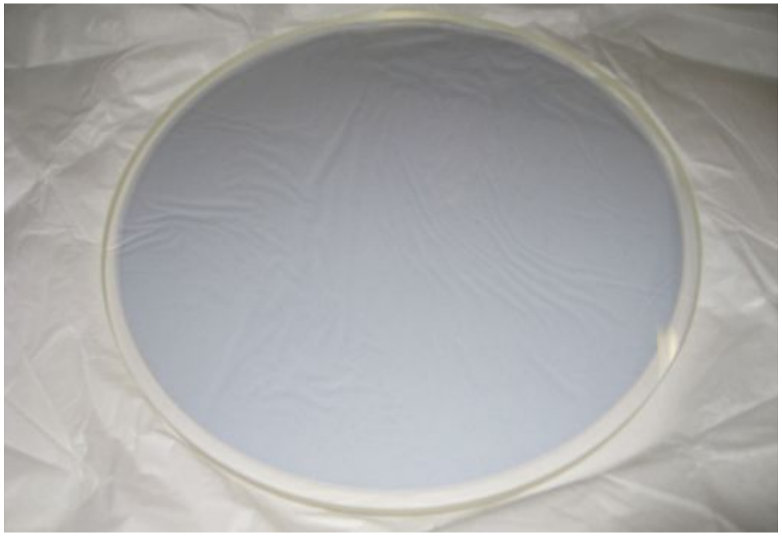
Gas Layer

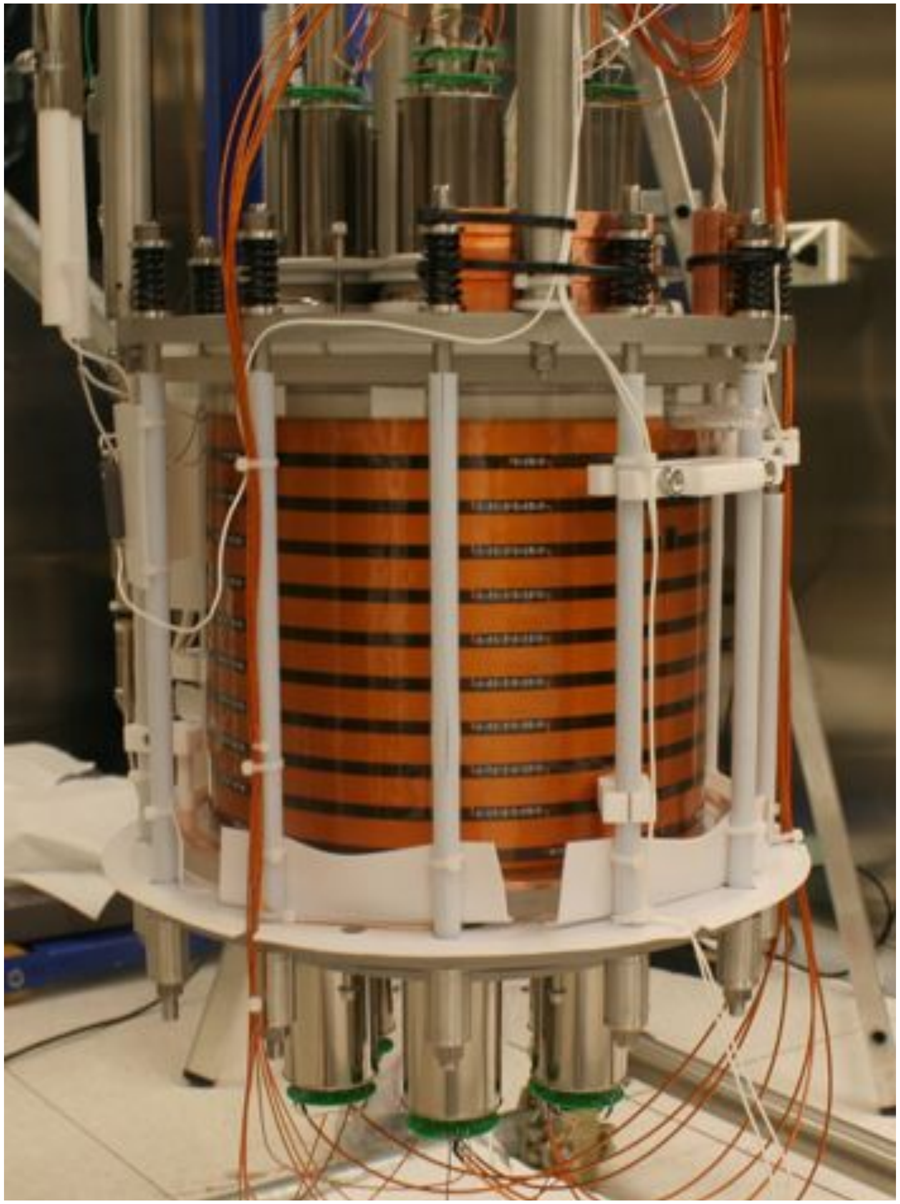
bubbler



Capacitive level sensor
4.925
4.9
4.875
4.85
4.825
4.8
4.775
4.75
4.725
4.7
4.675
4.65
4.625
4.6
Gas filling top of boiling tube
Bubbling into main pocket via transfer line
Lowering level to output bubbler
2 cm
11:00:04 AM 4/15/2010
11:05:44 AM 4/15/2010
11:11:19 AM 4/15/2010
11:16:59 AM 4/15/2010
11:22:39 AM 4/15/2010
11:28:39 AM 4/15/2010

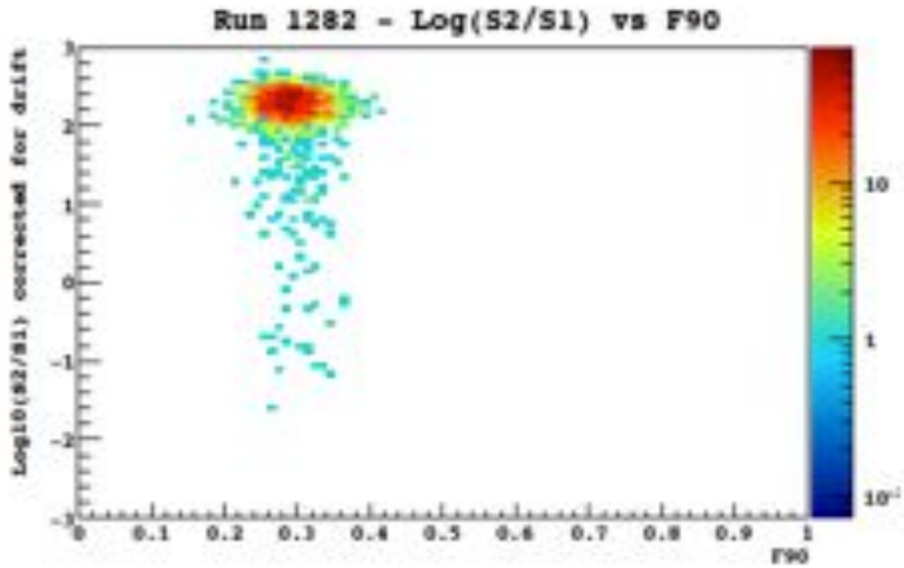
Electric Field Creation



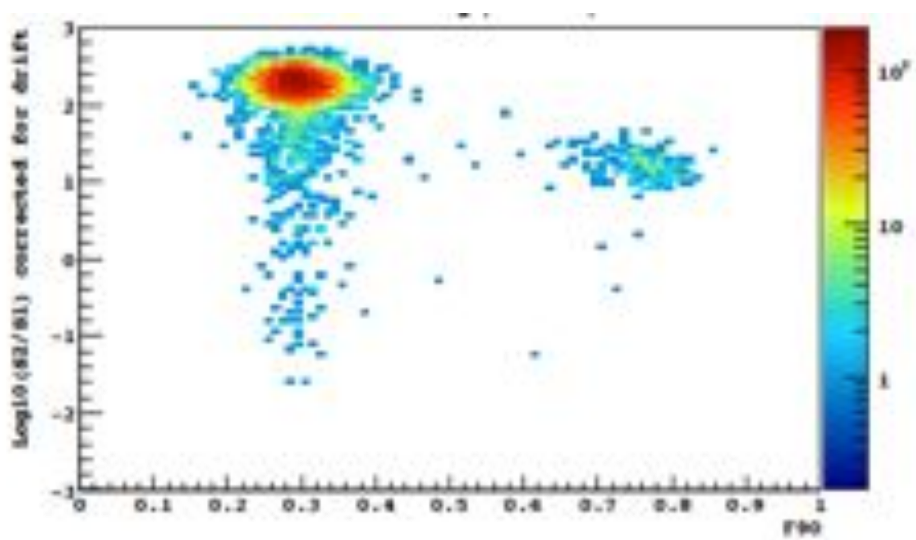


Two-Phase Operation!

Gamma Source:

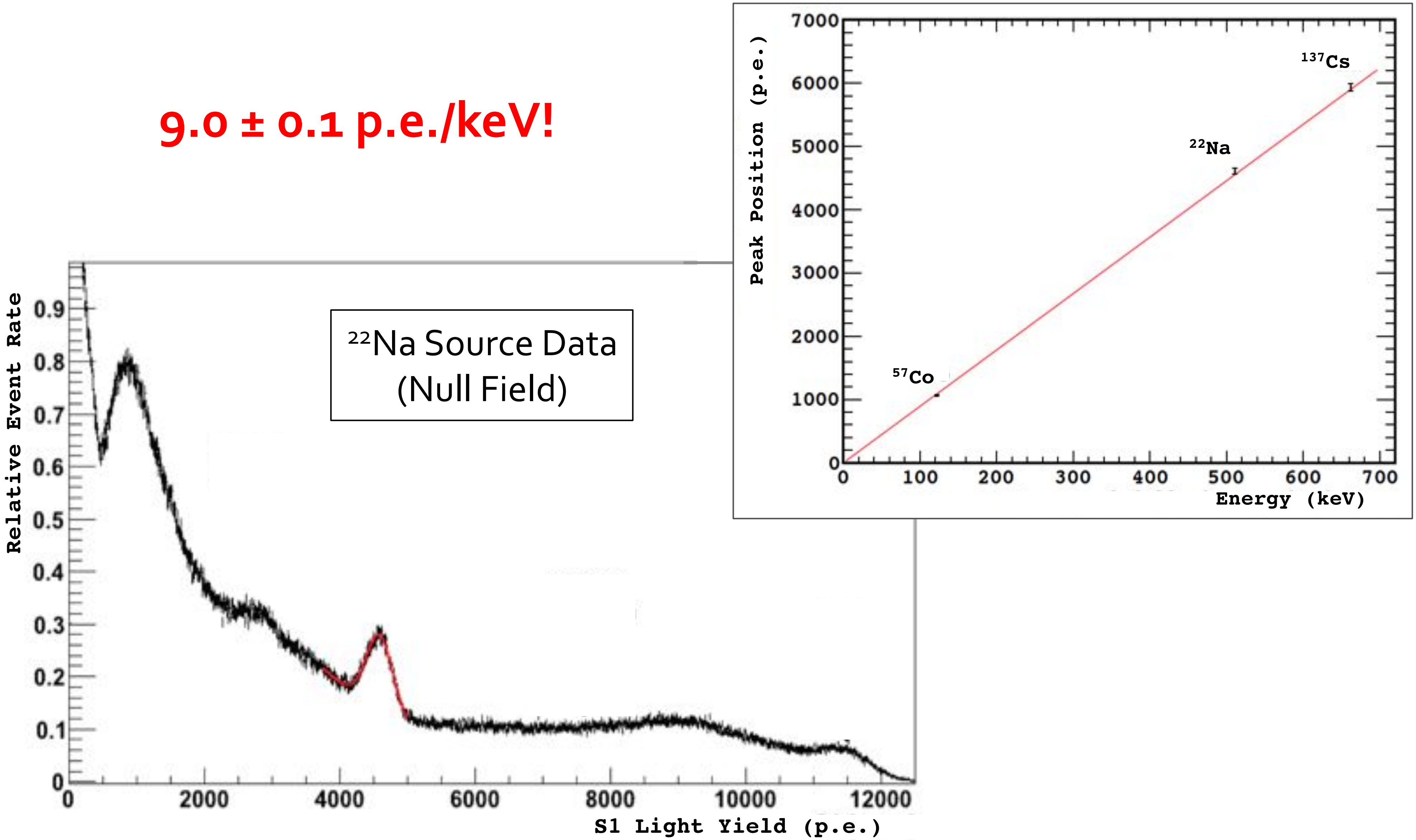


Neutron Source:



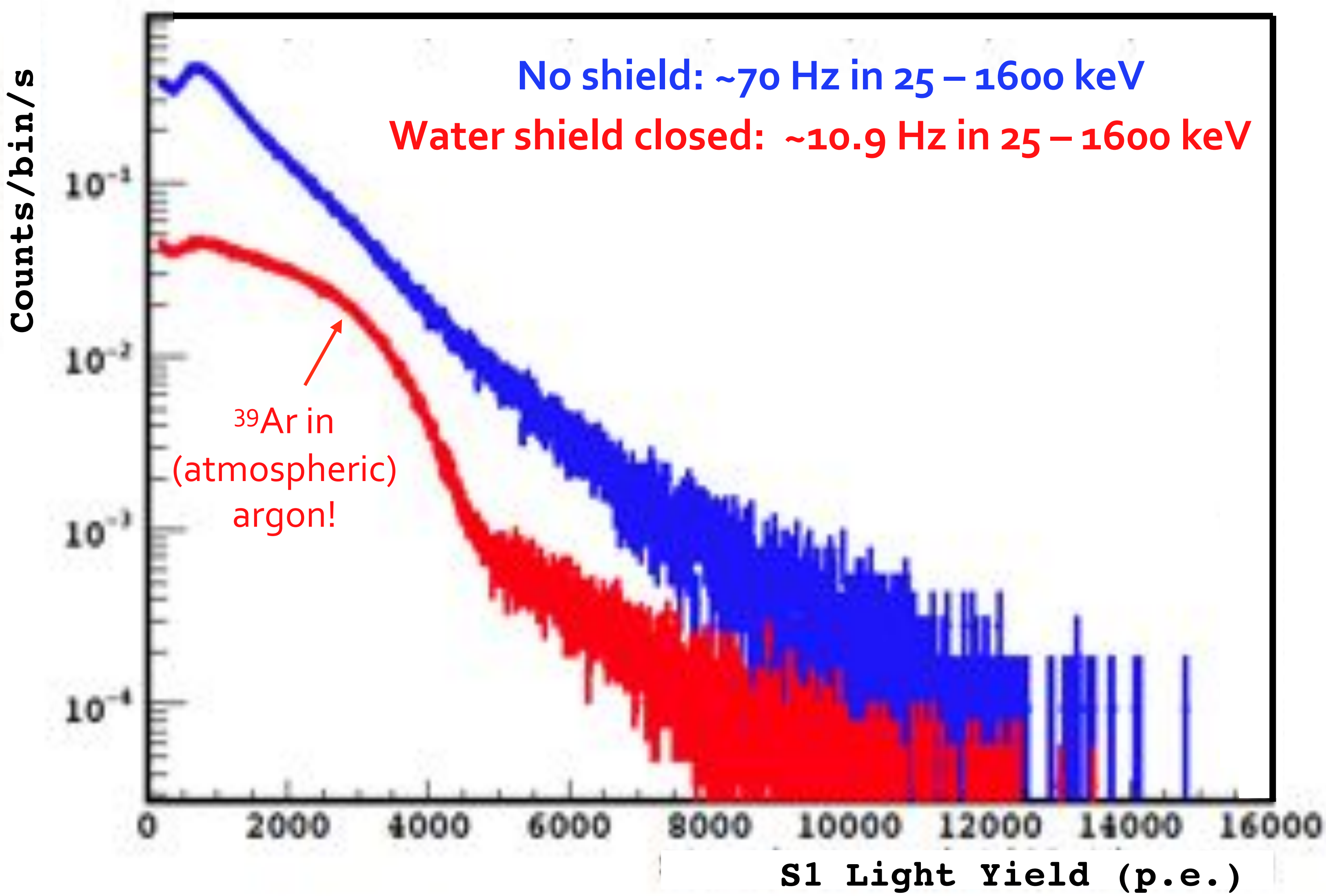
Light Yield

9.0 ± 0.1 p.e./keV!



Shielded Operation

Event Rate in DarkSide-10 (without PSD)



DarkSide Future

- Continued DarkSide-10 operation to gain experience with 2-phase operation, study backgrounds
- DarkSide-50 to deploy later this year
  - Reach 10^{-45} cm^2 in 3 years background free operation
- Tonne-scale experiment could reach 10^{-47} cm^2 using the same active shielding as DarkSide-50