Shedding Light

On The Dark Universe

Carleton University
May 3rd, 2011

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Outline

- Introduction to dark matter
  - How do we know it is there?
  - What do we know about it?
  - What might it be?
- Searching for dark matter
  - Search techniques
  - Direct detection experiments
- The DarkSide experiment

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

First Evidence for Dark Matter

In 1933 Fritz Zwicky used the relative motions of the galaxies in the Coma Cluster to infer the cluster mass

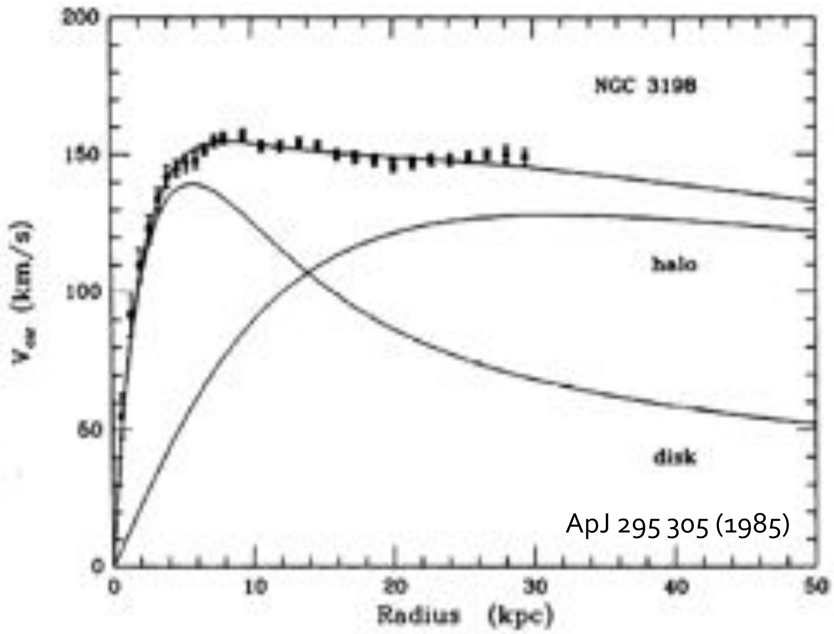
He found that the visible matter made up less than 1% of the mass!

Image Credit: NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center) et al.

Rotation Curves

- The rotation speed of stars in spiral galaxies, and galaxies in clusters, is related to the mass which gravitationally binds them

Image credit: John Vickery and Jim Matthes/Adam Block/NOAO/AURA/NSF

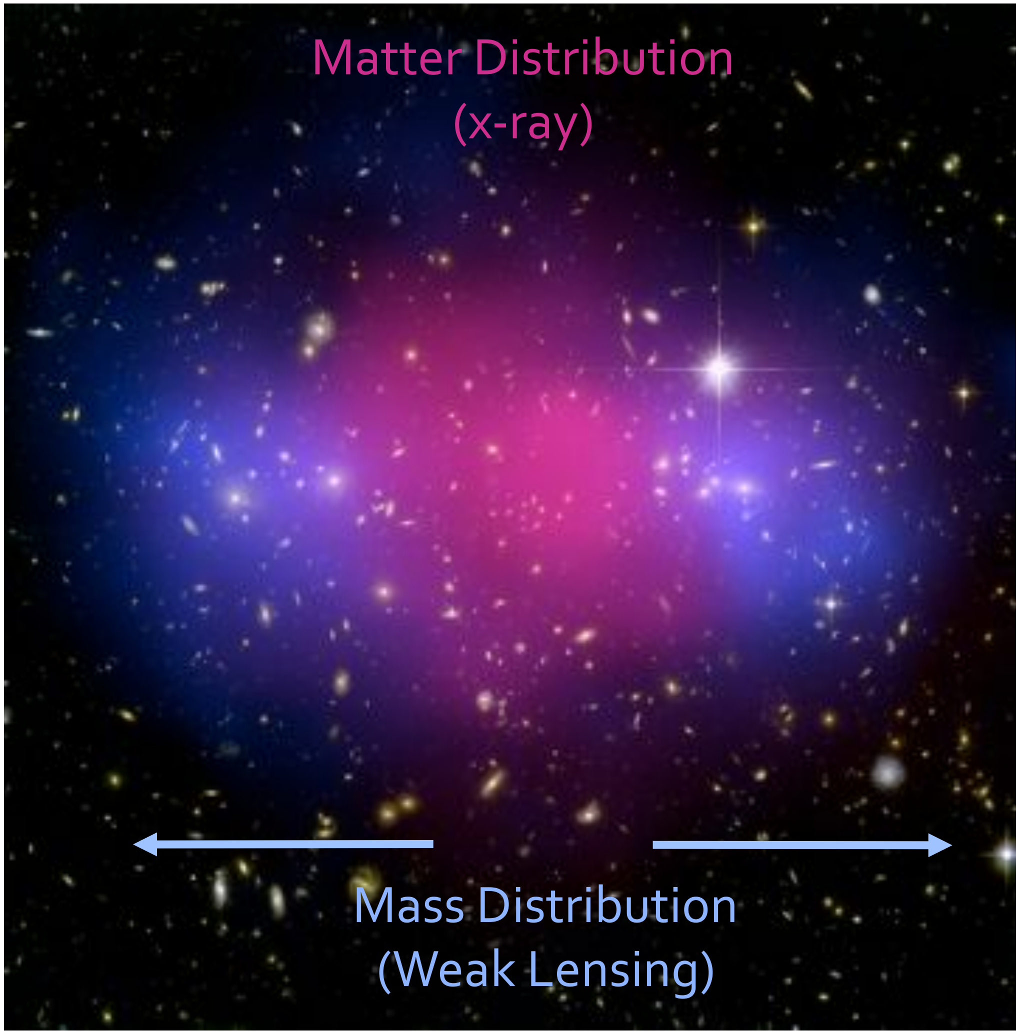


- The observed rotation speeds do not agree with predictions based on the observable matter
- Adding a spherical dark matter "halo" (~20 times the mass of the stars) gives good agreement

Weak Gravitational Lensing

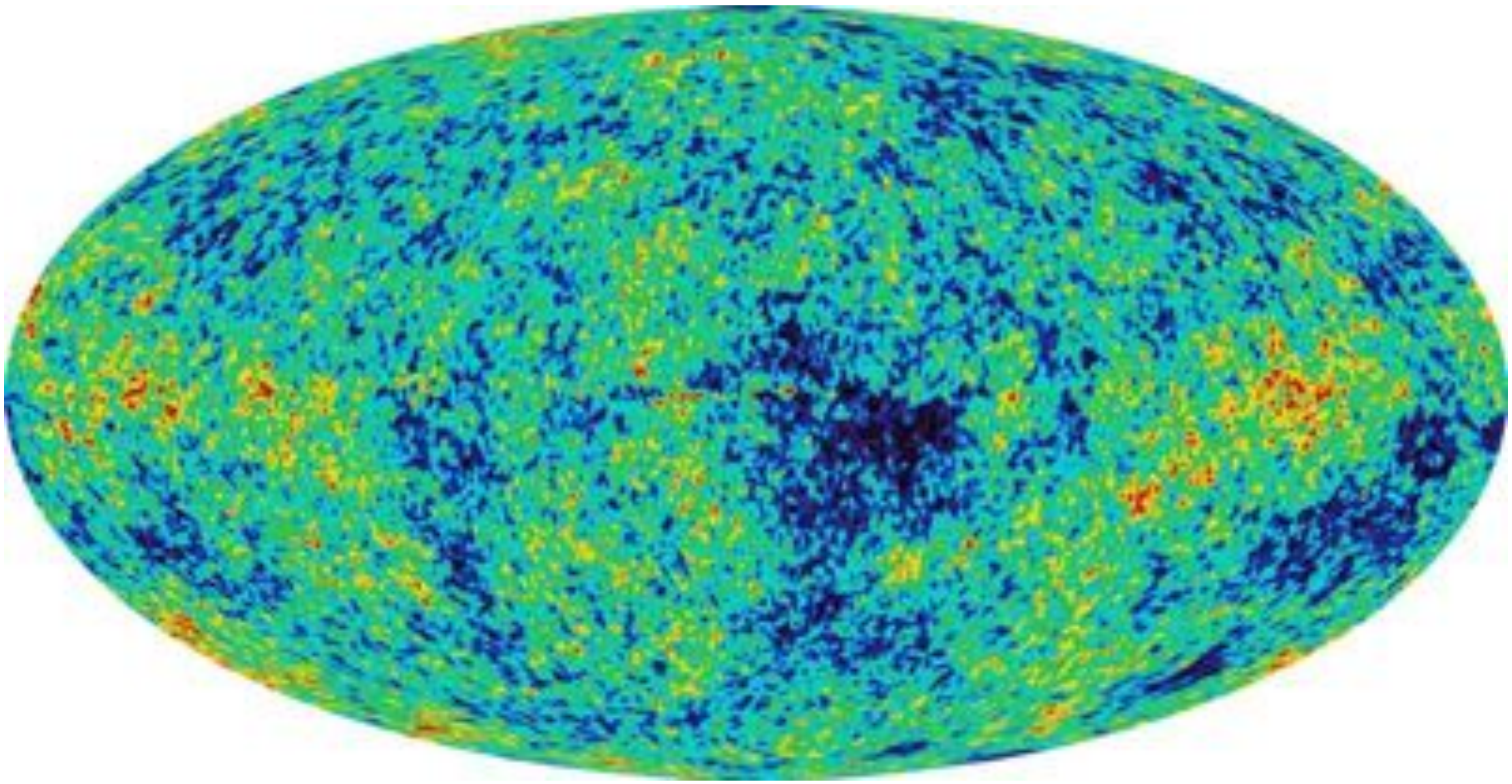
- Distortions in the appearance of background galaxies can be used to measure the mass and mass distribution of foreground objects
  - Confirm that galaxies are much heavier than their stars
  - Observe galaxy collisions

MACS J0024.4-1222



Credit: X-ray(NASA/CXC/Stanford/S.Allen); Optical/Lensing(NASA/STScI/UC Santa Barbara/M.Bradac)

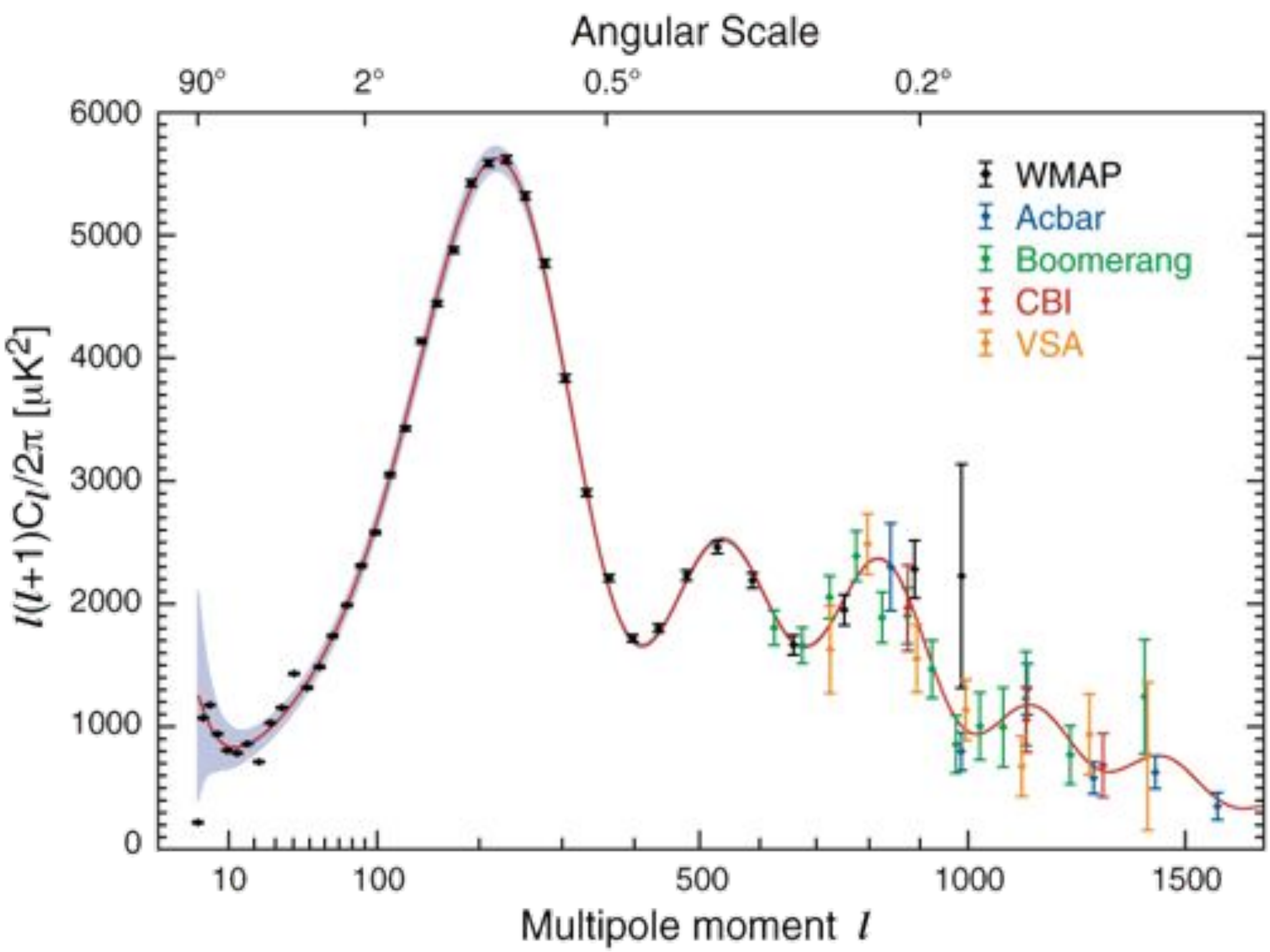
Cosmic Microwave Background



Temperature fluctuations in the CMB reflect density fluctuations in the universe at the time of recombination (380,000 years after the big bang, T~3,000 K)

Image credit: WMAP Science Team, NASA

Cosmic Microwave Background



"Angular Power Spectrum" gives relative quantities of baryonic matter, dark matter, etc

Image Credit: WMAP Science Team

Cosmic Microwave Background

- Dark Matter is responsible for about ¼ of the energy density of the Universe
- It is about 4-5 times more abundant than "ordinary" matter
- Good agreements between the different measurements

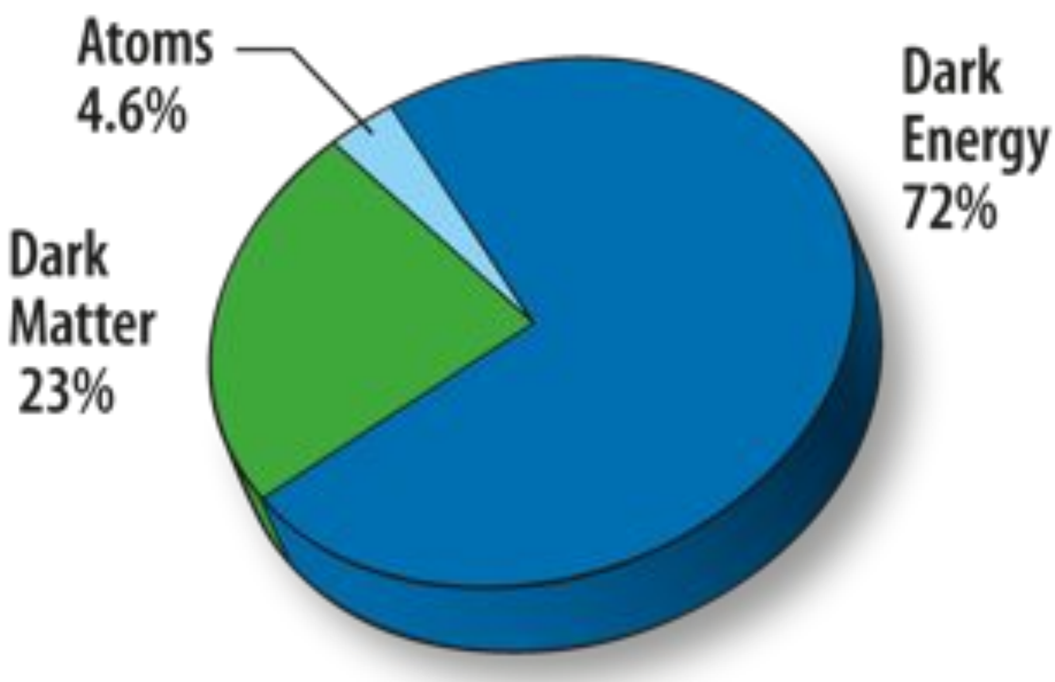
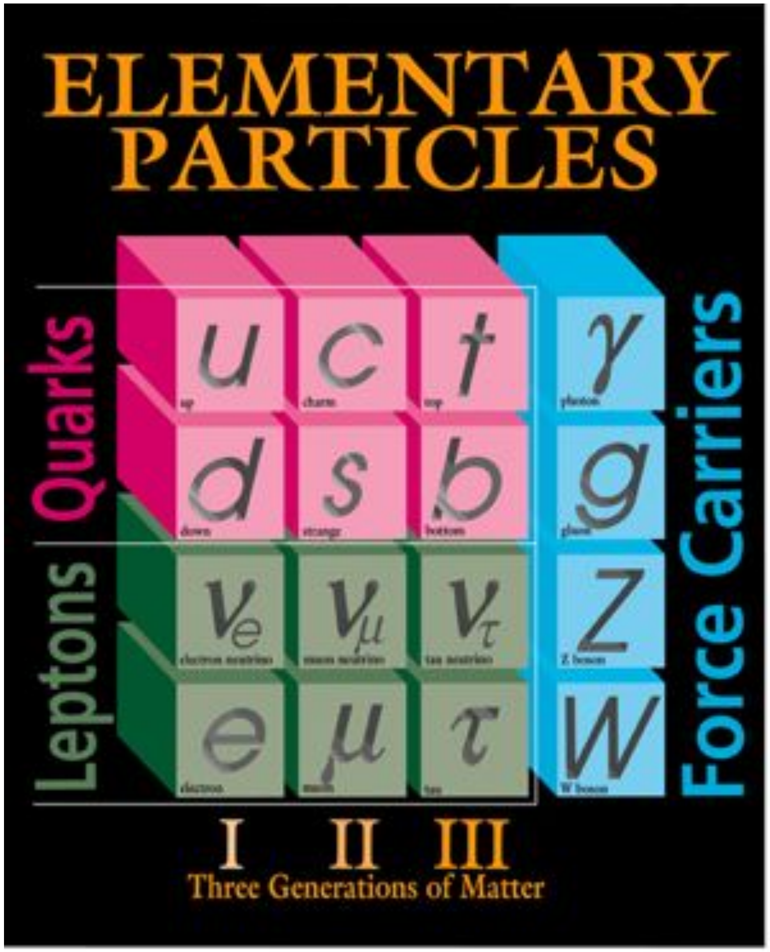


Image credit: NASA/WMAP Science Team

Dark Matter Summary

- ~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)



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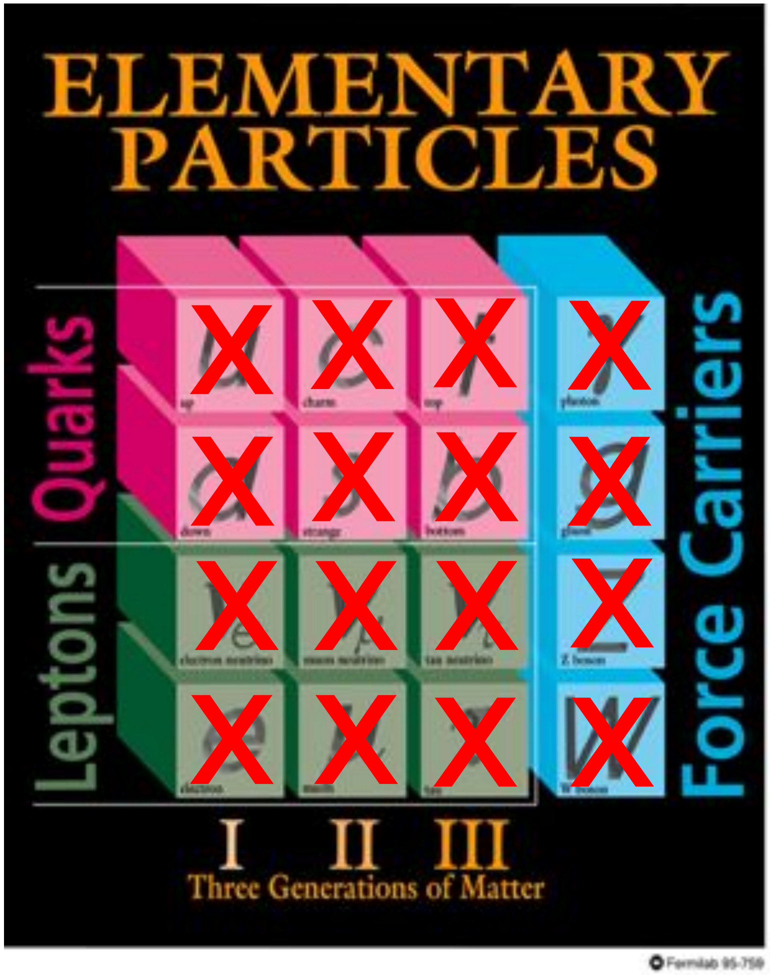


This excludes all Standard Model particles:
strong evidence for physics beyond the Standard Model!

Dark Matter Candidates

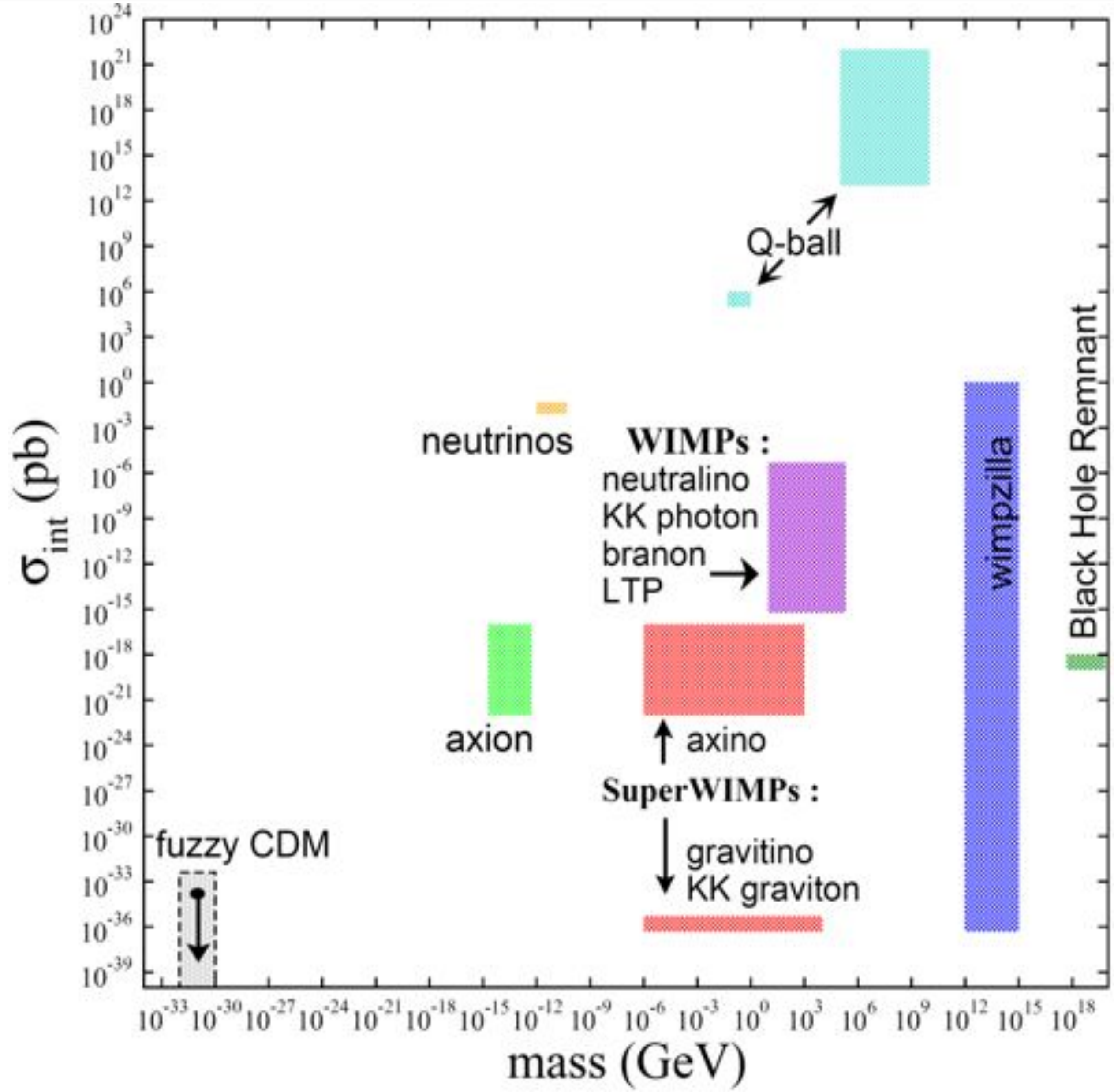


Image credit: HEPAP/AAAC DMSAG Subpanel (2007)

Weakly Interacting Massive Particles

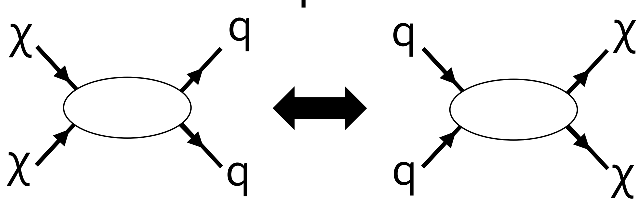
- The weak interaction strength is described by the Fermi Constant, $G_F = 1.1\text{x}10^{-5}$ GeV^{-2}
- This defines a "weak mass scale"

$$m_{weak} \approx G_F^{-1/2} \approx 100 \text{ GeV}/c^2$$

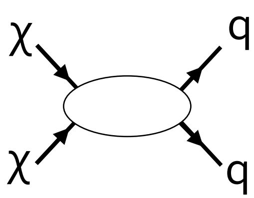
- Theoretical attempts to explain the weak coupling strength often introduce new particles at the weak scale

Thermal Relics

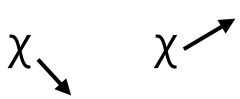
1) WIMPs are produced in thermal equilibrium

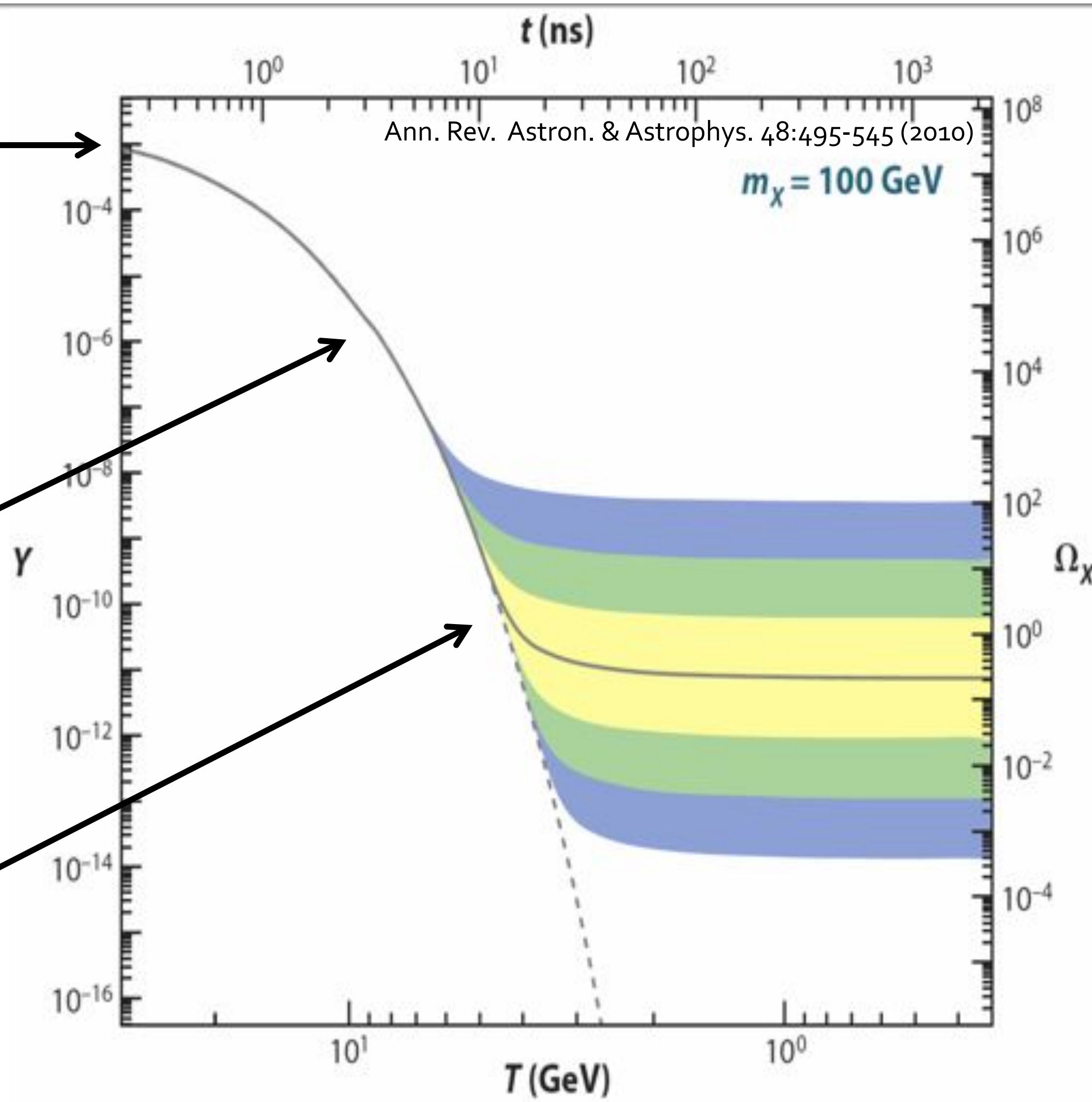


2) WIMP density decays as the universe cools



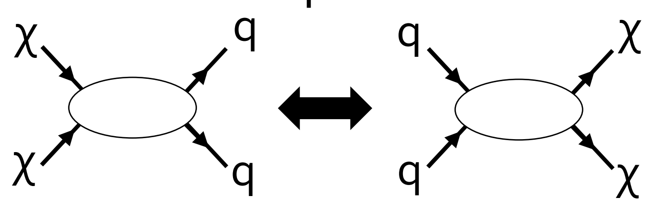
3) WIMP density "freezes out" based on coupling strength



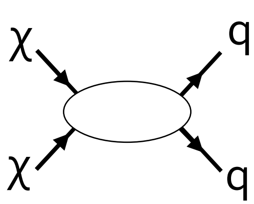


The "WIMP Miracle"

1) WIMPs are produced in thermal equilibrium



2) WIMP density decays as the universe cools



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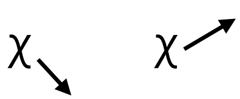
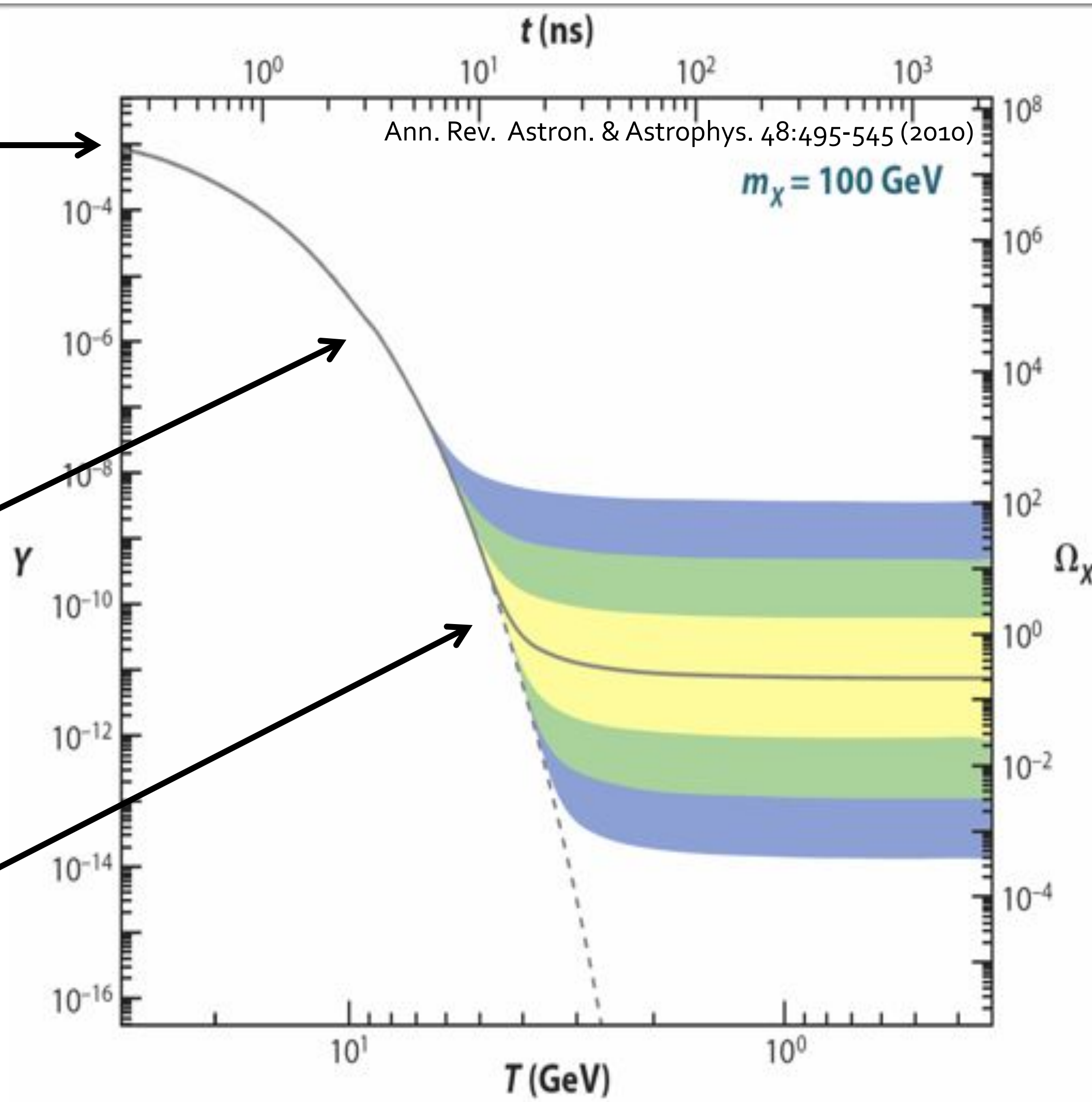
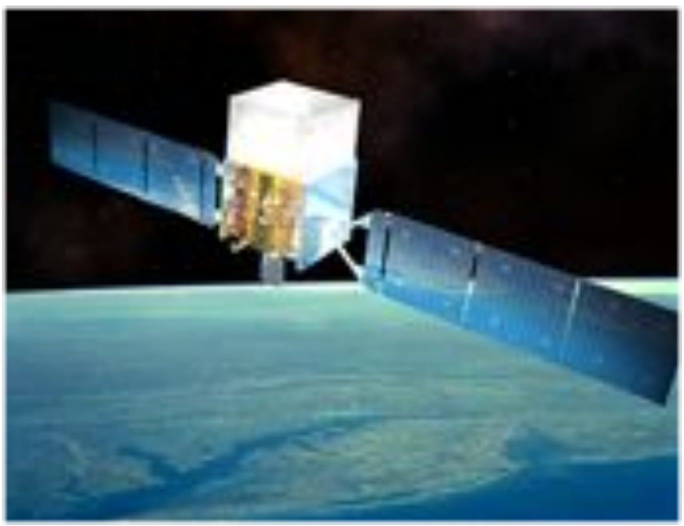


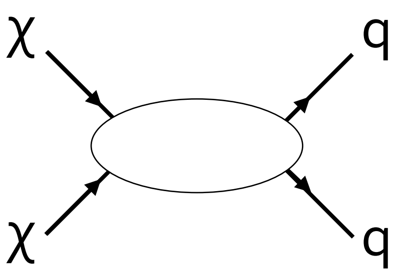


Weak mass & coupling give just the right relic density for dark matter!

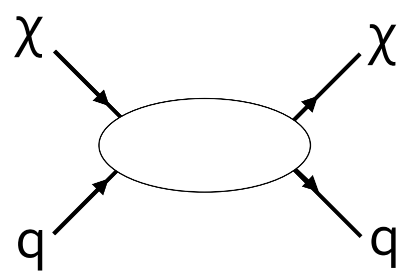
Searching for WIMPs

Aboveground

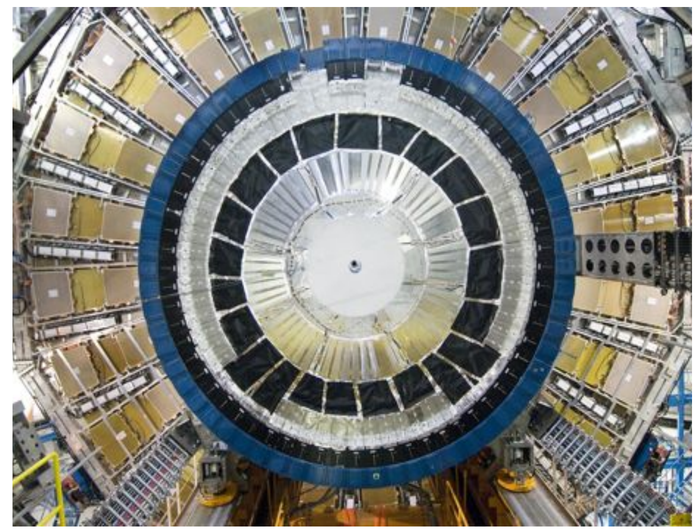




Underground



At Accelerators



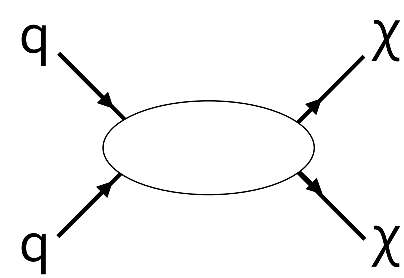


Image credits: NASA, discovermagazine.com, atlas.ch

Local WIMPs

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

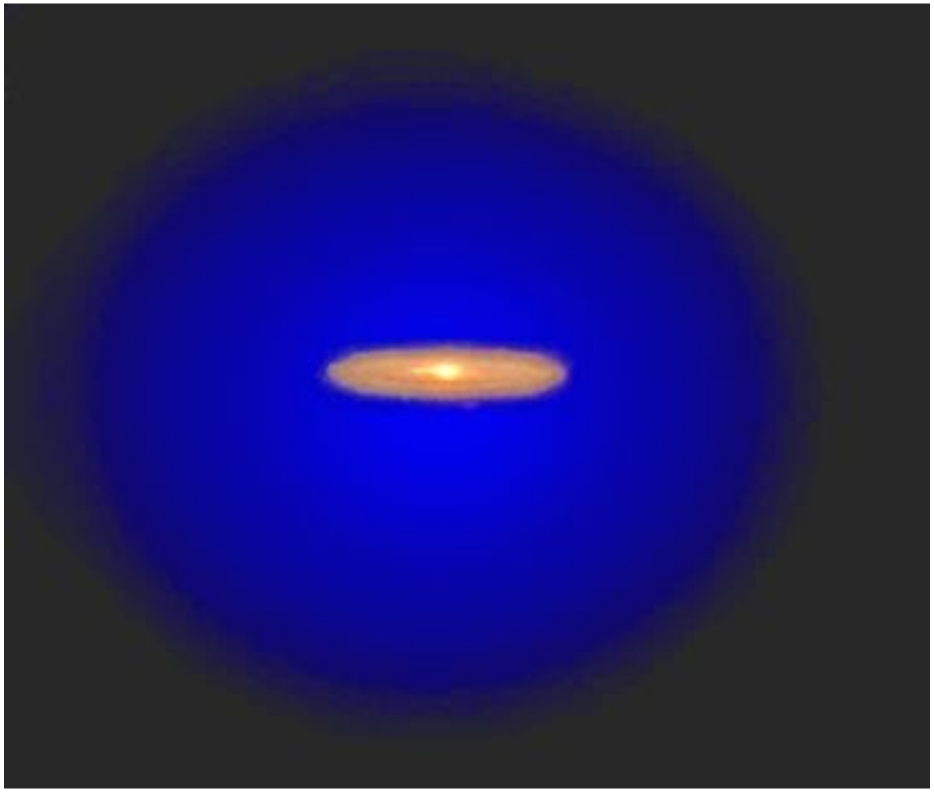


Image credit: J. Kormendy, chandra.as.utexas.edu/~kormendy

“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

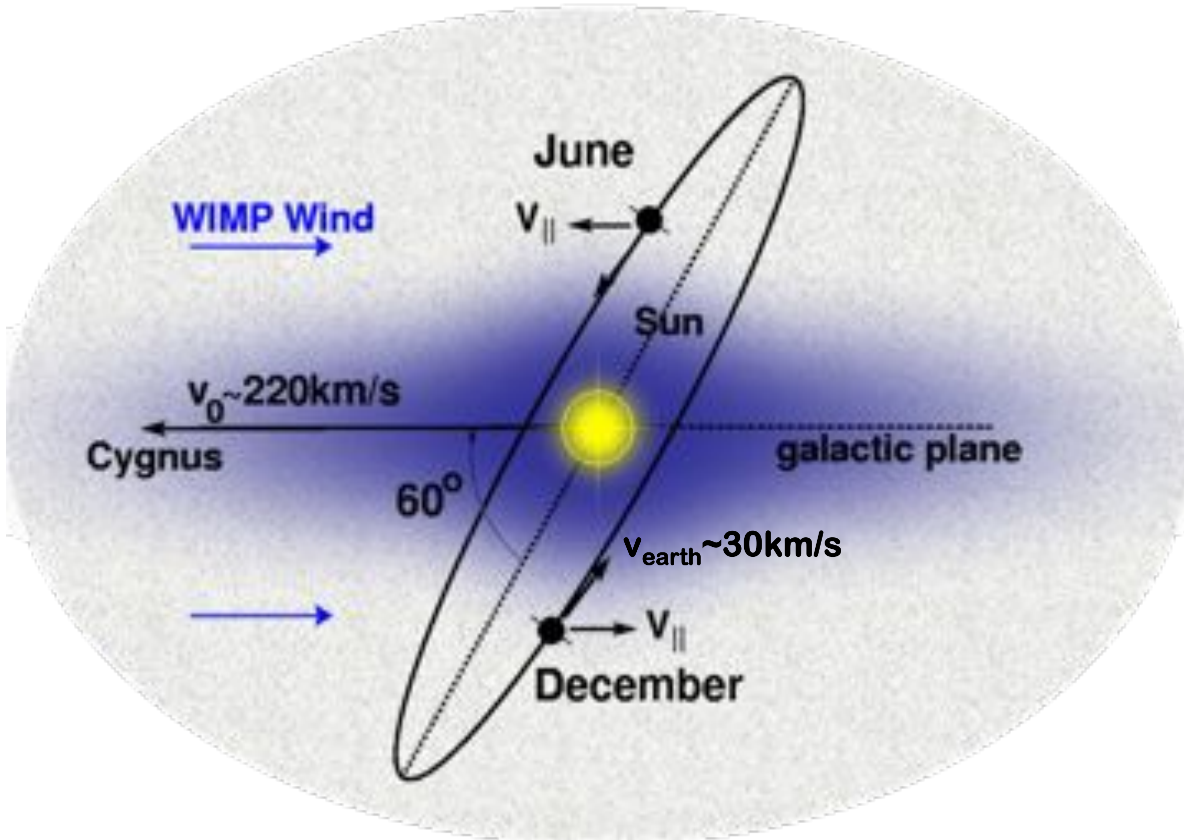
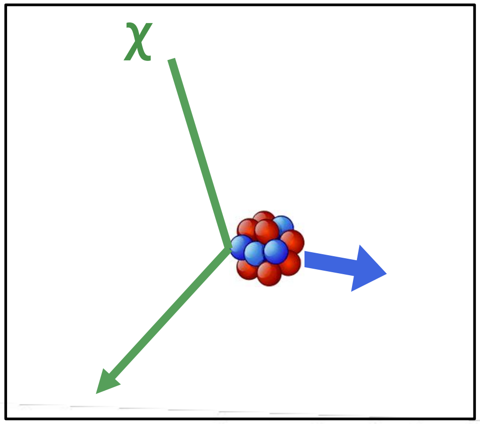


Image credit: www.hep.shef.ca.uk/research/dm/intro.php

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



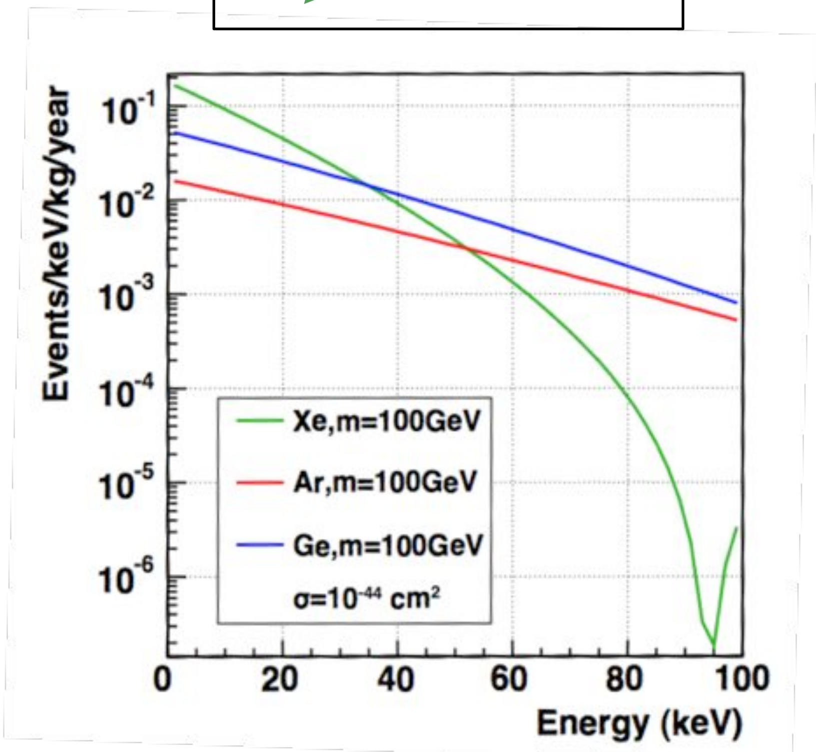
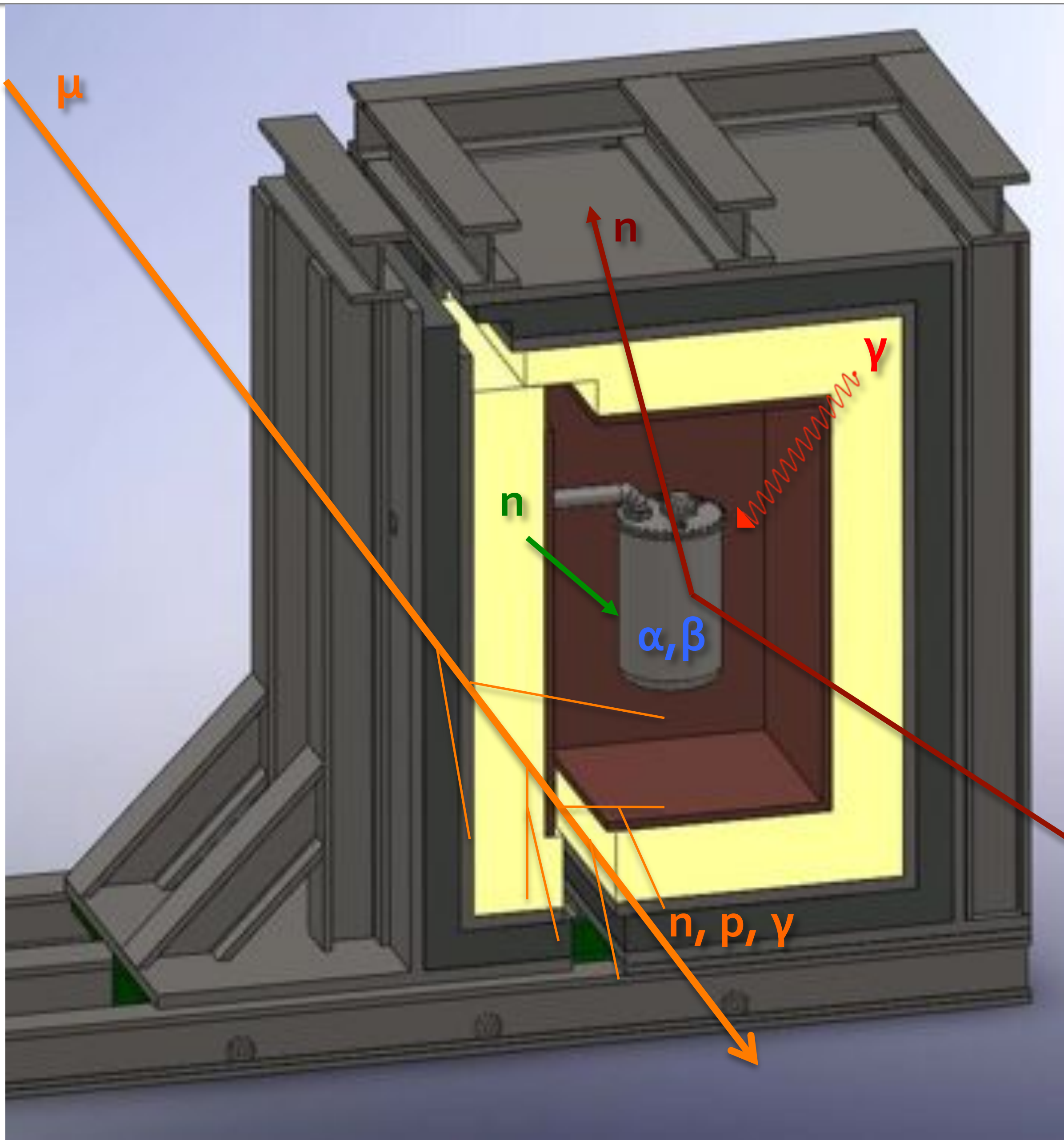


Image credit:777icons.com

Central Challenge: Background



Internal Radioactivity

^{238}U, ^{232}Th, etc.

Gamma Rays

external and from shielding

Cosmic Muons

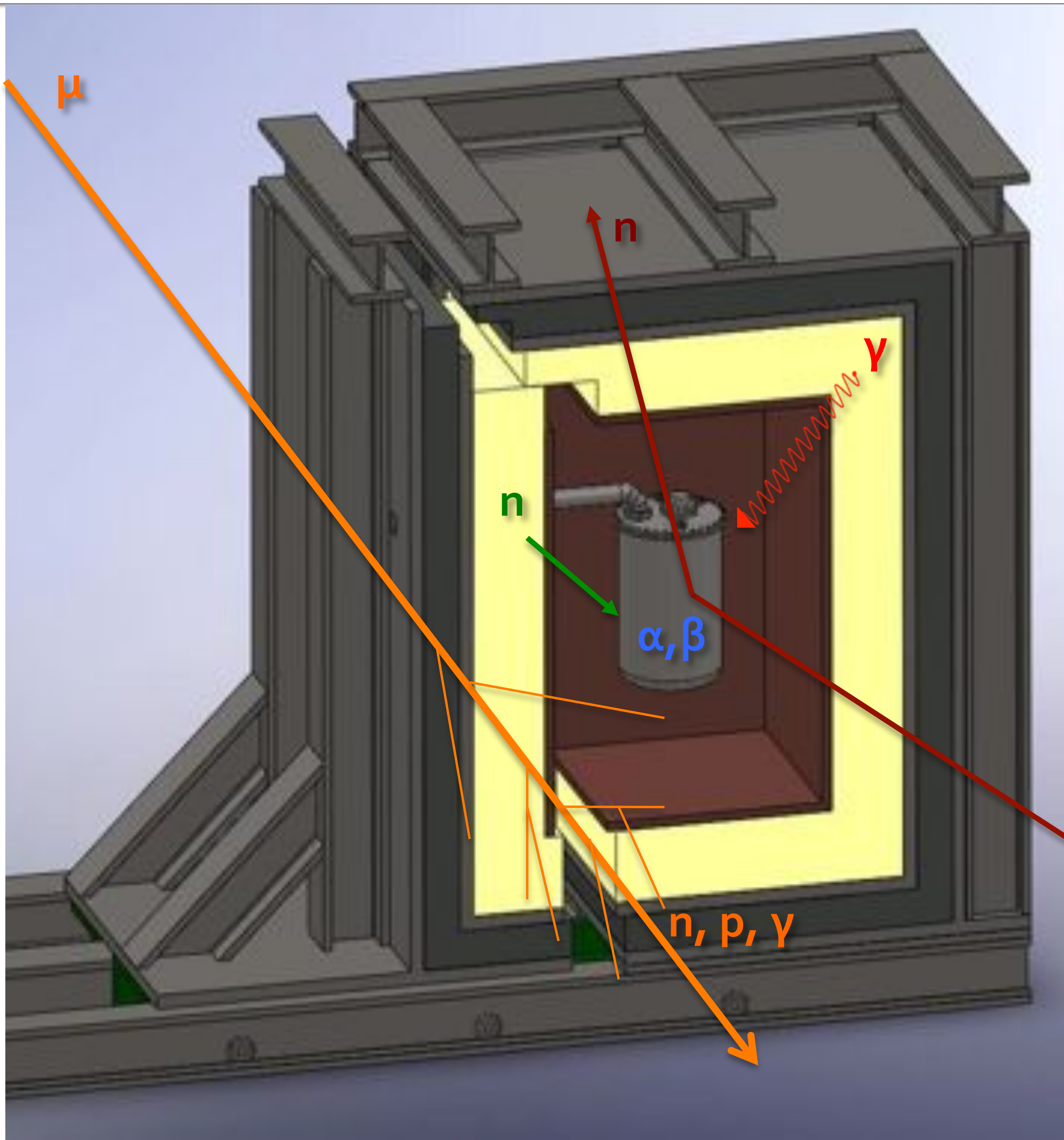
Radiogenic Neutrons

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

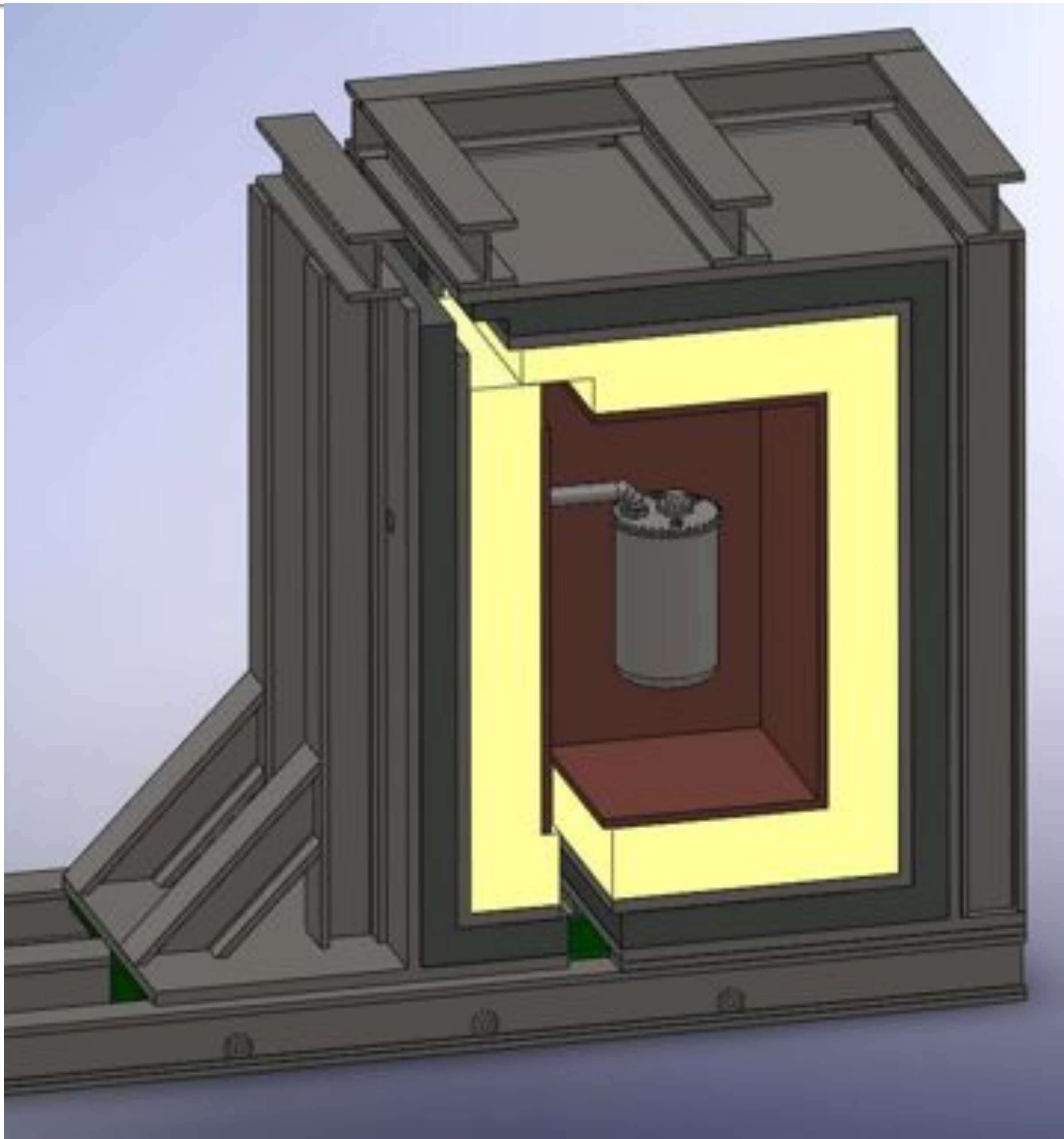
Dust: ~7000 decays/mg-yr

Air: >300 decays/mL-yr

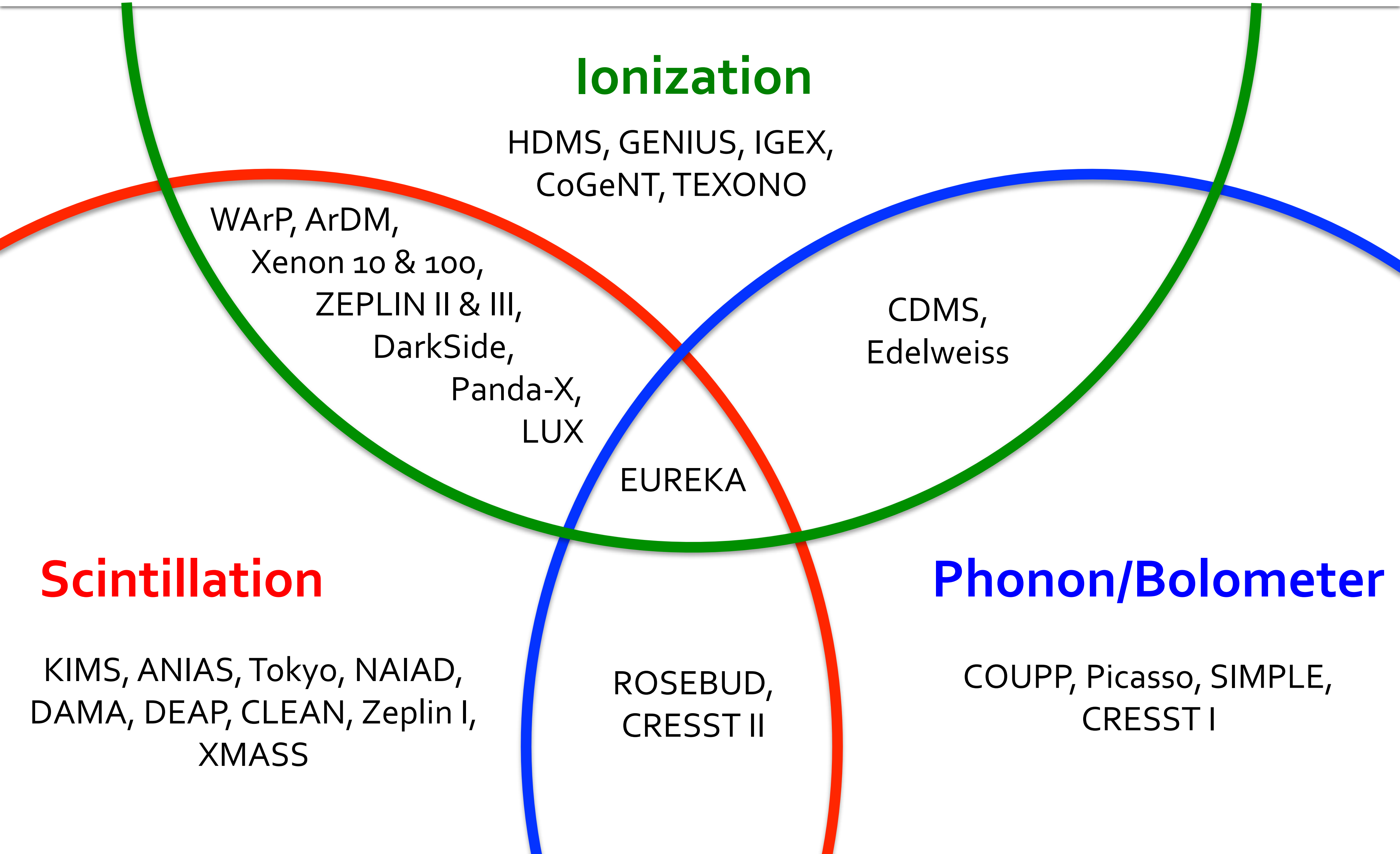
Fingerprint: ~10 decays/yr

Ideal WIMP Detector

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

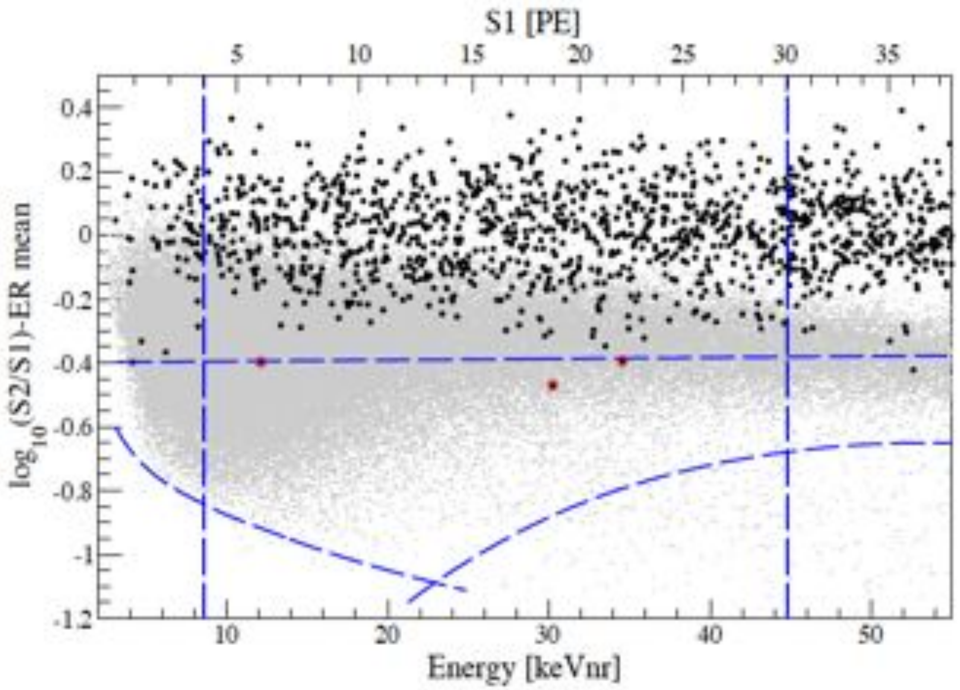


WIMP Detection Experiments



Leading Experiments

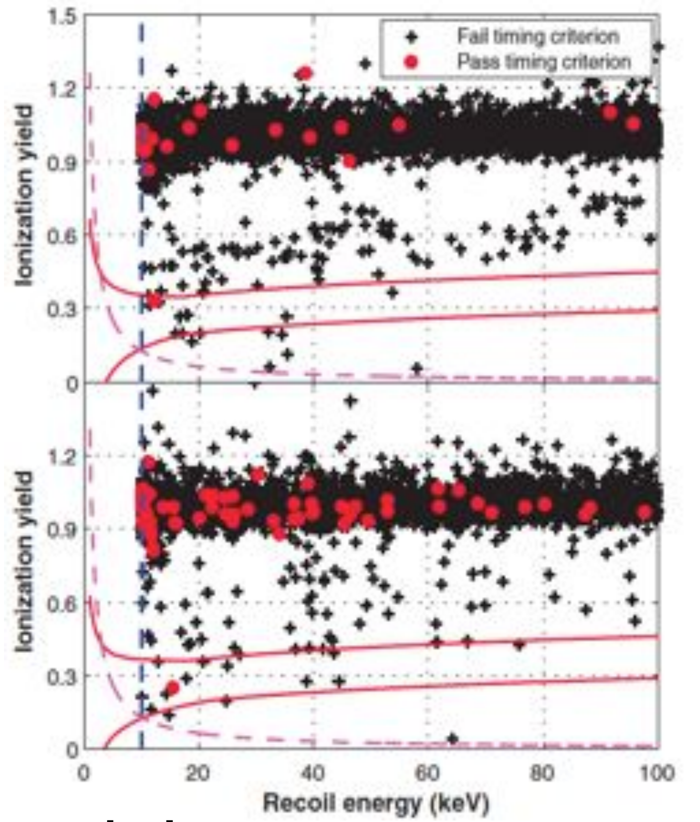
Xenon100



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

arXiv:1104.2549v1

CDMS

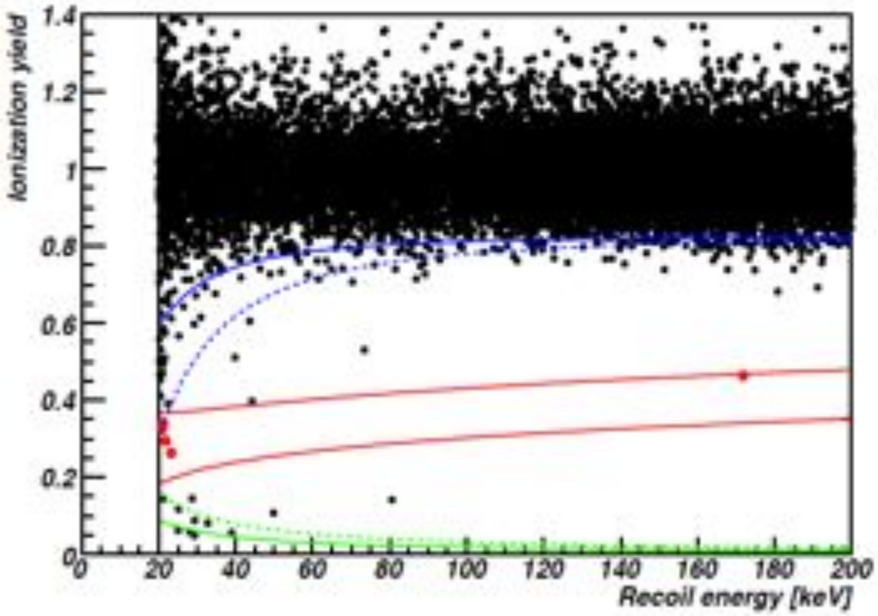


Technique: Ge + Si, Ionization + bolometric
Exposure: 612 kg-days
Expect: 0.9 ± 0.2 background events
Observe: 2 events

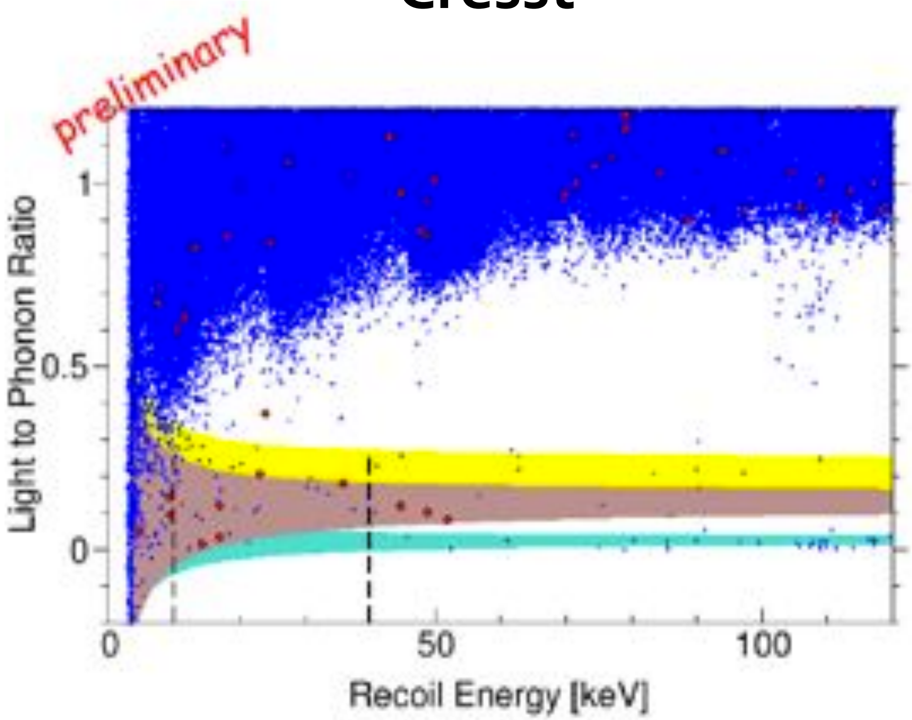
Nature 327:1619 (2010)

Leading Experiments

Edelweiss



Cresst



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

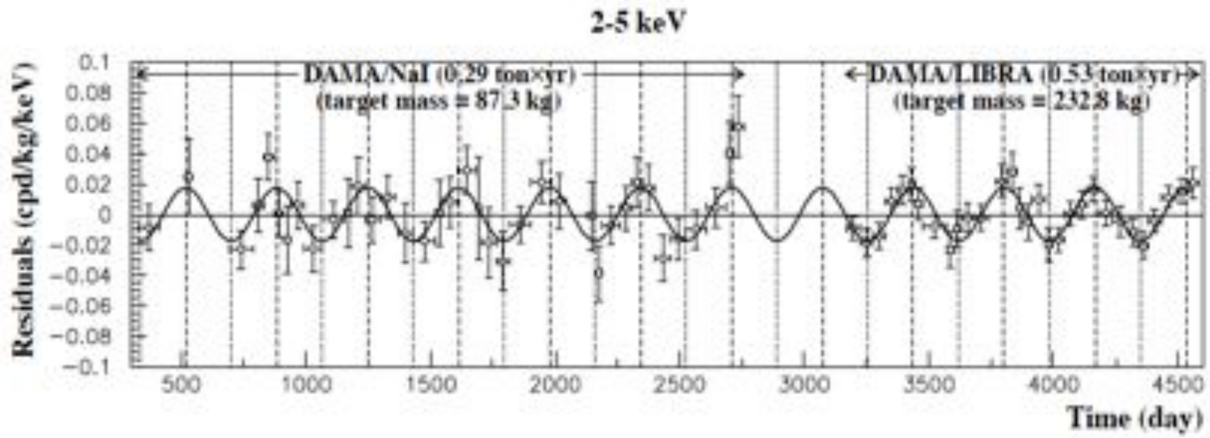
arXiv:1103.4070

Technique: $CaWO_4$,
scintillation + bolometric
Exposure: 333 kg-days
Observe: More events than expected from neutron background

W. Seidel, Wonder2010

Leading Experiments

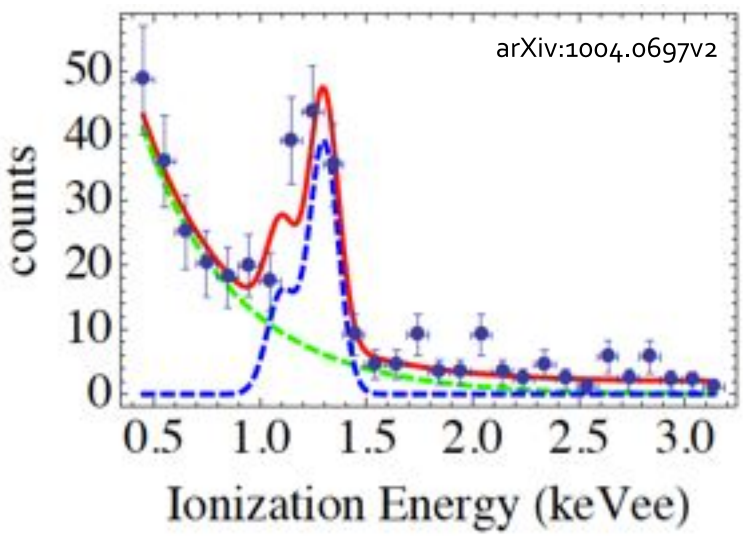
DAMA/LIBRA



Technique: NaI, scintillation
Exposure: 1.9×10^5 kg-days
Observe: Annual modulation in event rate.

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

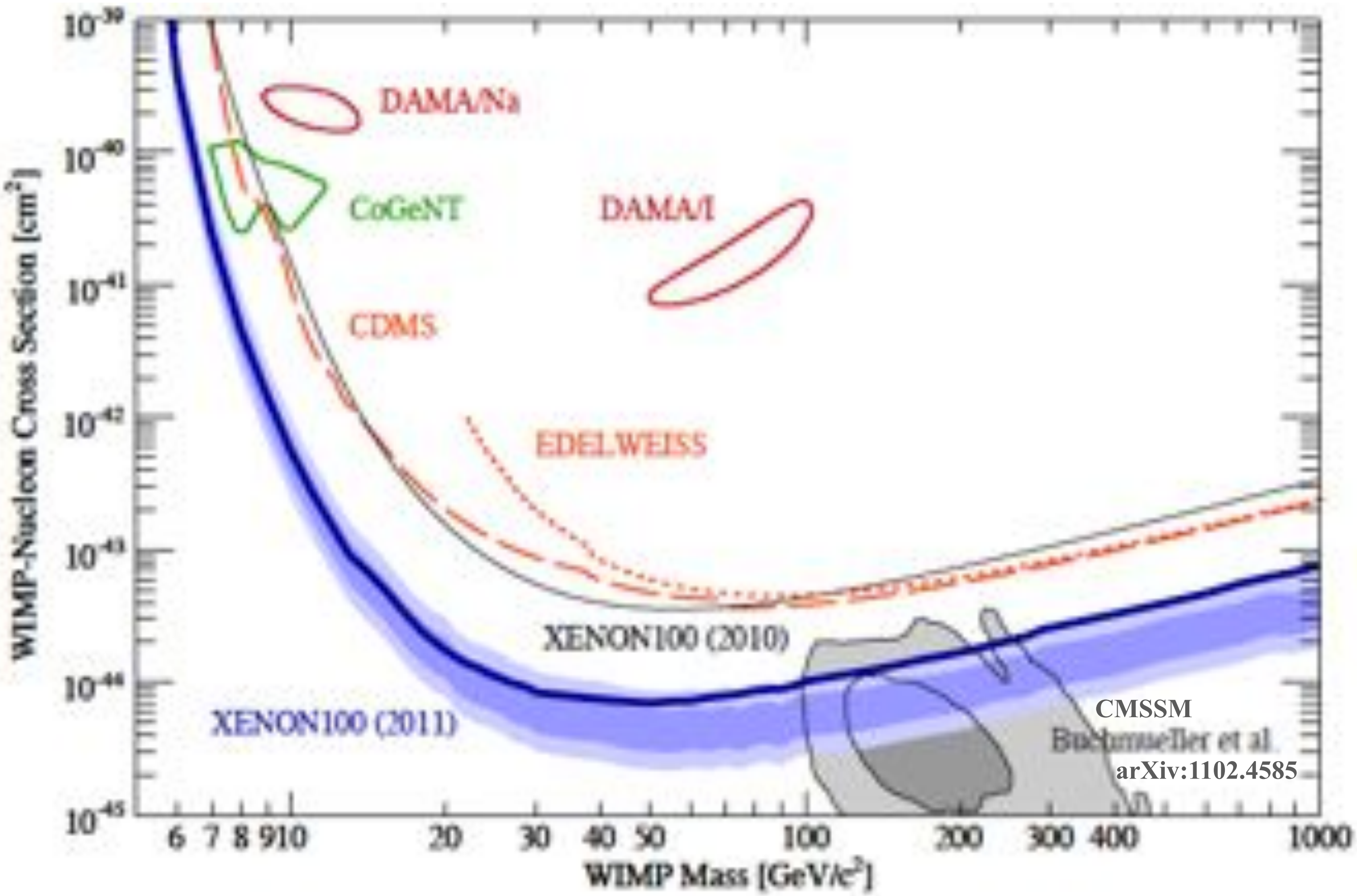
CoGeNT



Technique: Ge, ionization
Exposure: 18.4 kg-days
Observe: Excess events at low energy

PRL 106:131301, 2011

The Current Status



arXiv:1104.2549v1

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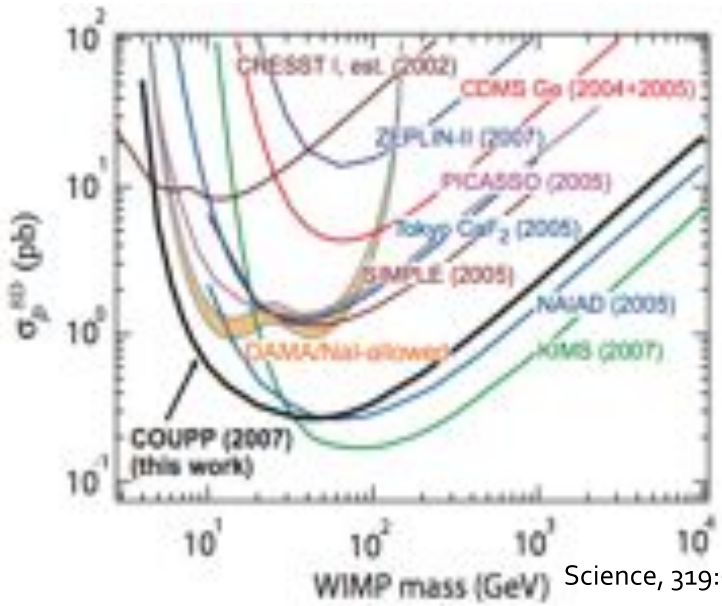
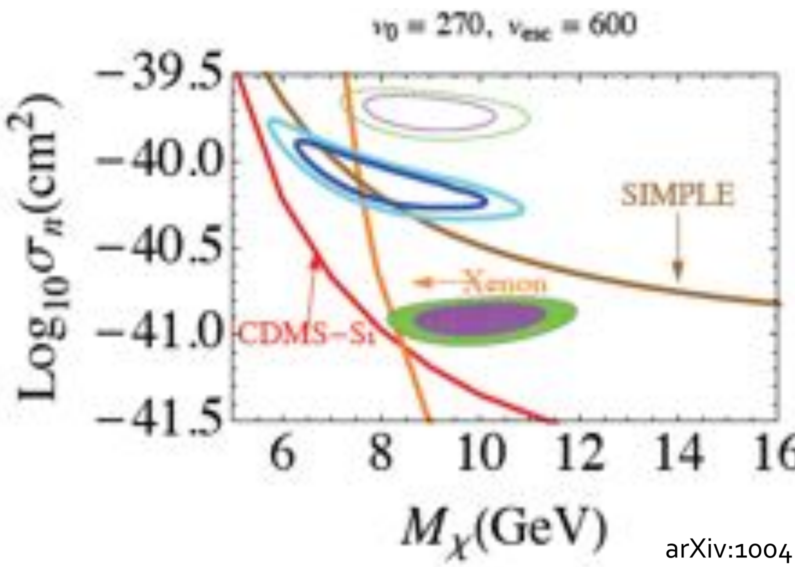
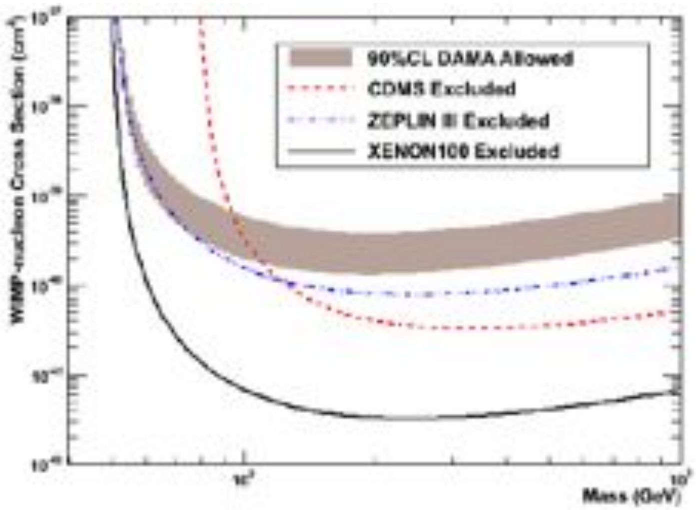


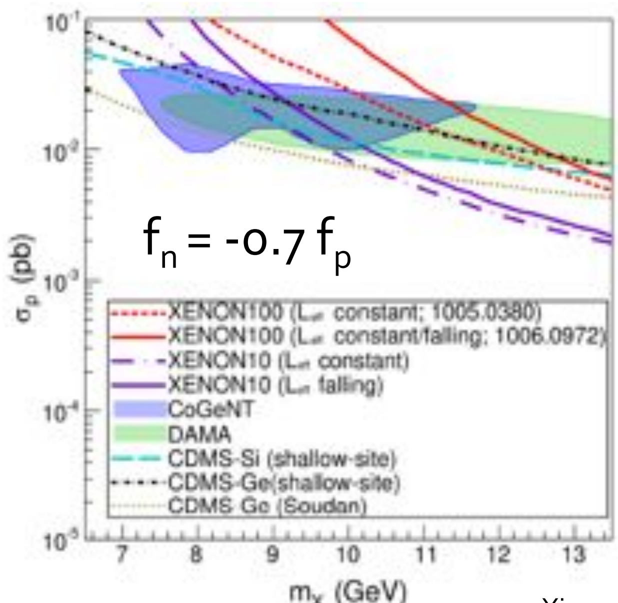
Science, 319:933, (2008)



arXiv:1004.0697v2



arXiv:1104.3121



arXiv:1102.4331v2

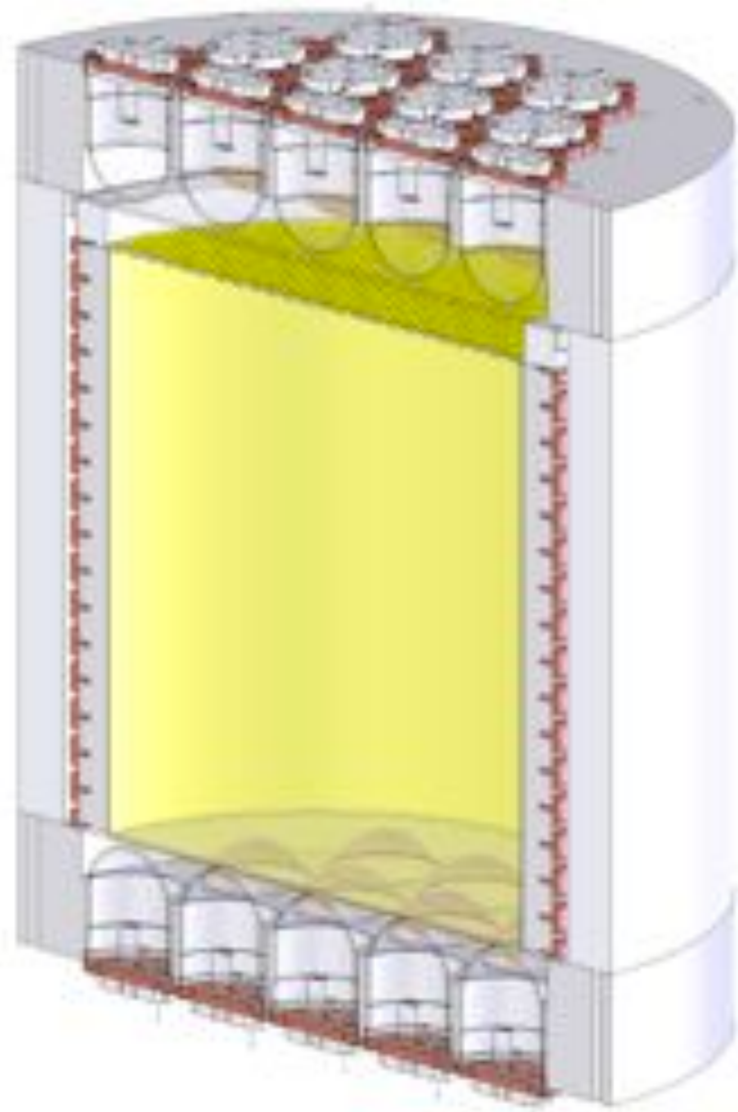
The Current Status

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

- All leading dark matter experiments expect background and they do
- Progress contingent on lowering backgrounds
- Detecting dark matter requires a better understanding of the backgrounds

The DarkSide Program

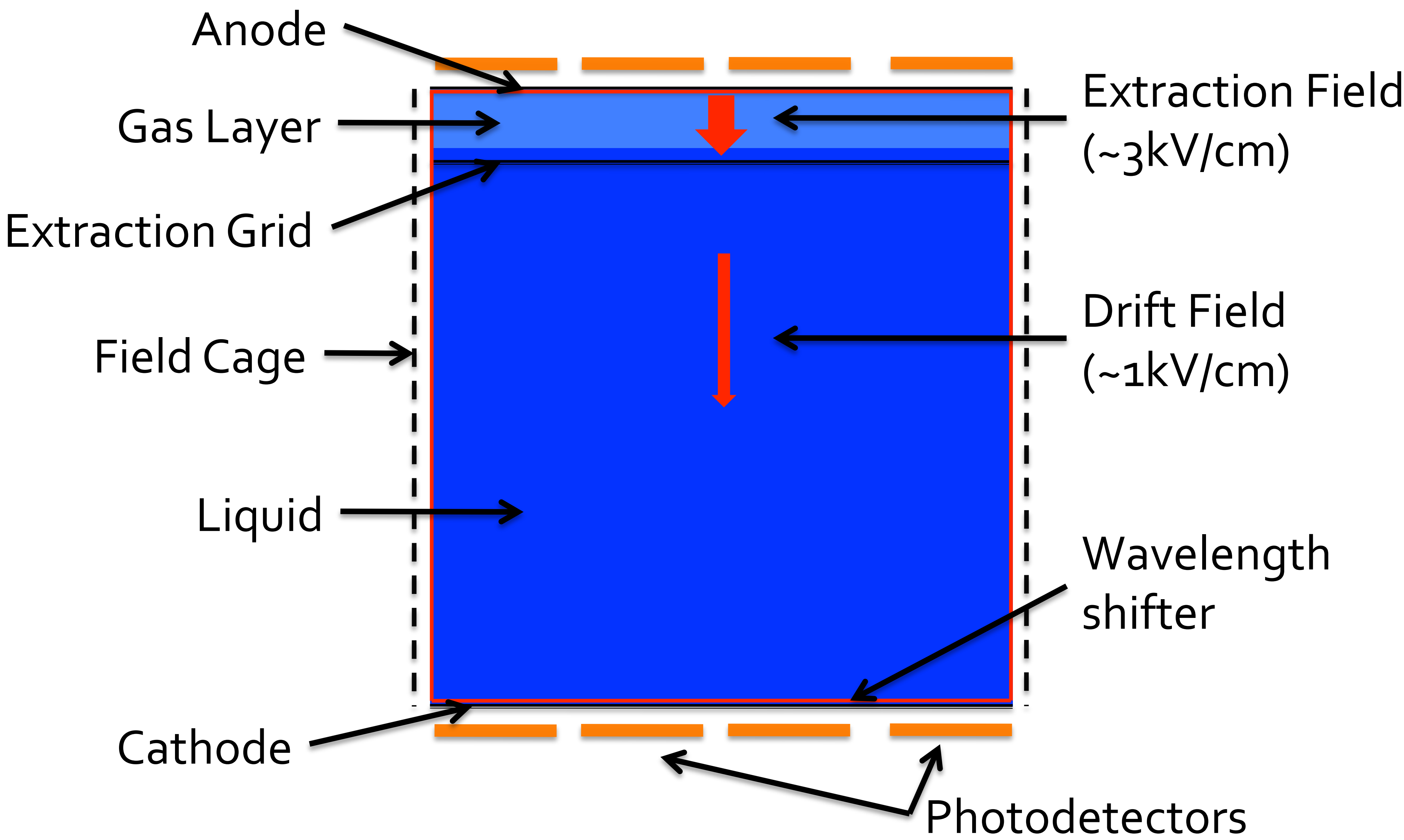
- A dark matter program based on 2-phase depleted argon time projection chambers (TPCs)
- First physics detector will be "DarkSide-50"



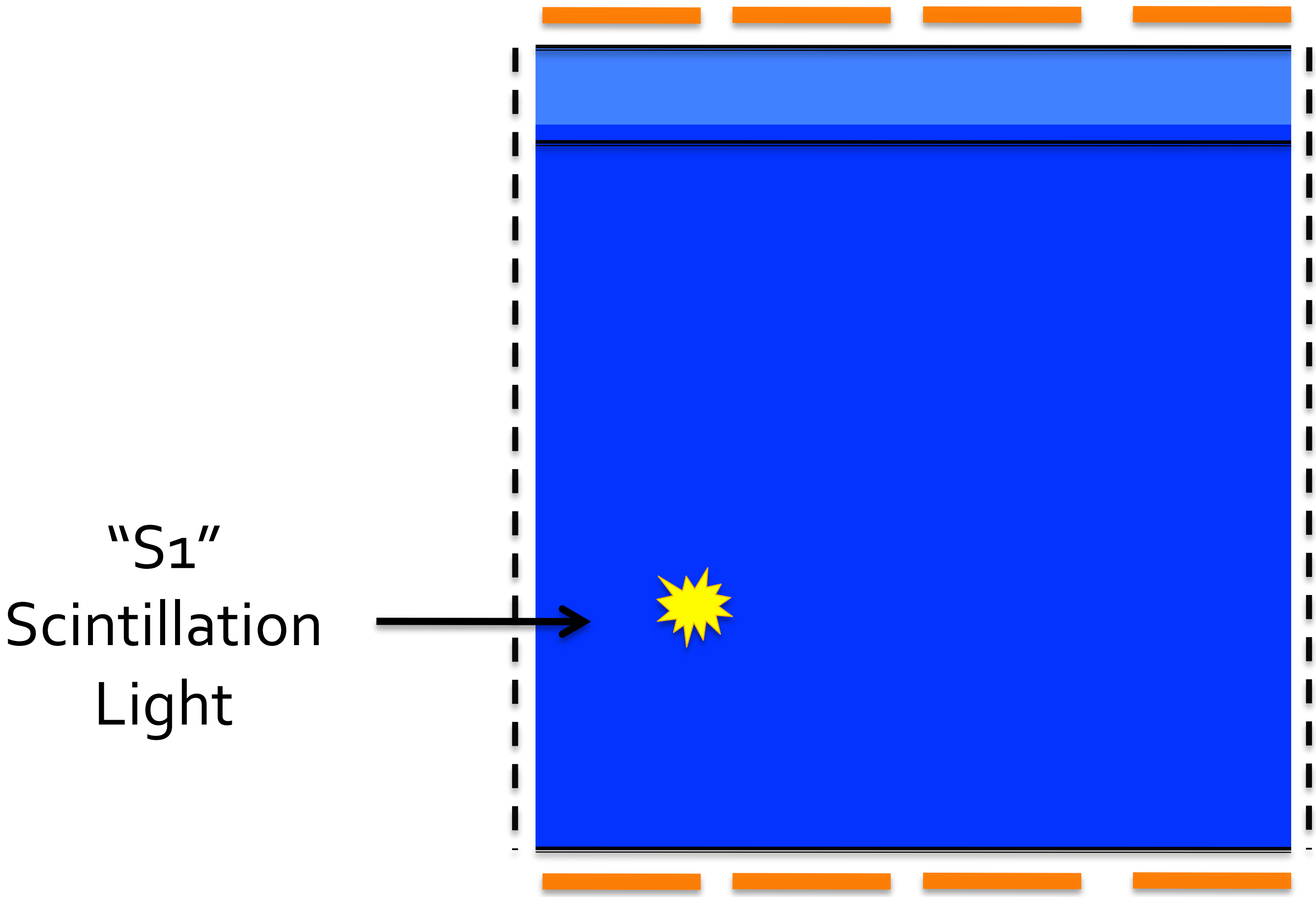
Why Two-Phase Argon?

- 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
  - Limited by ^{39}Ar
- Very powerful rejection capability for electron recoil background

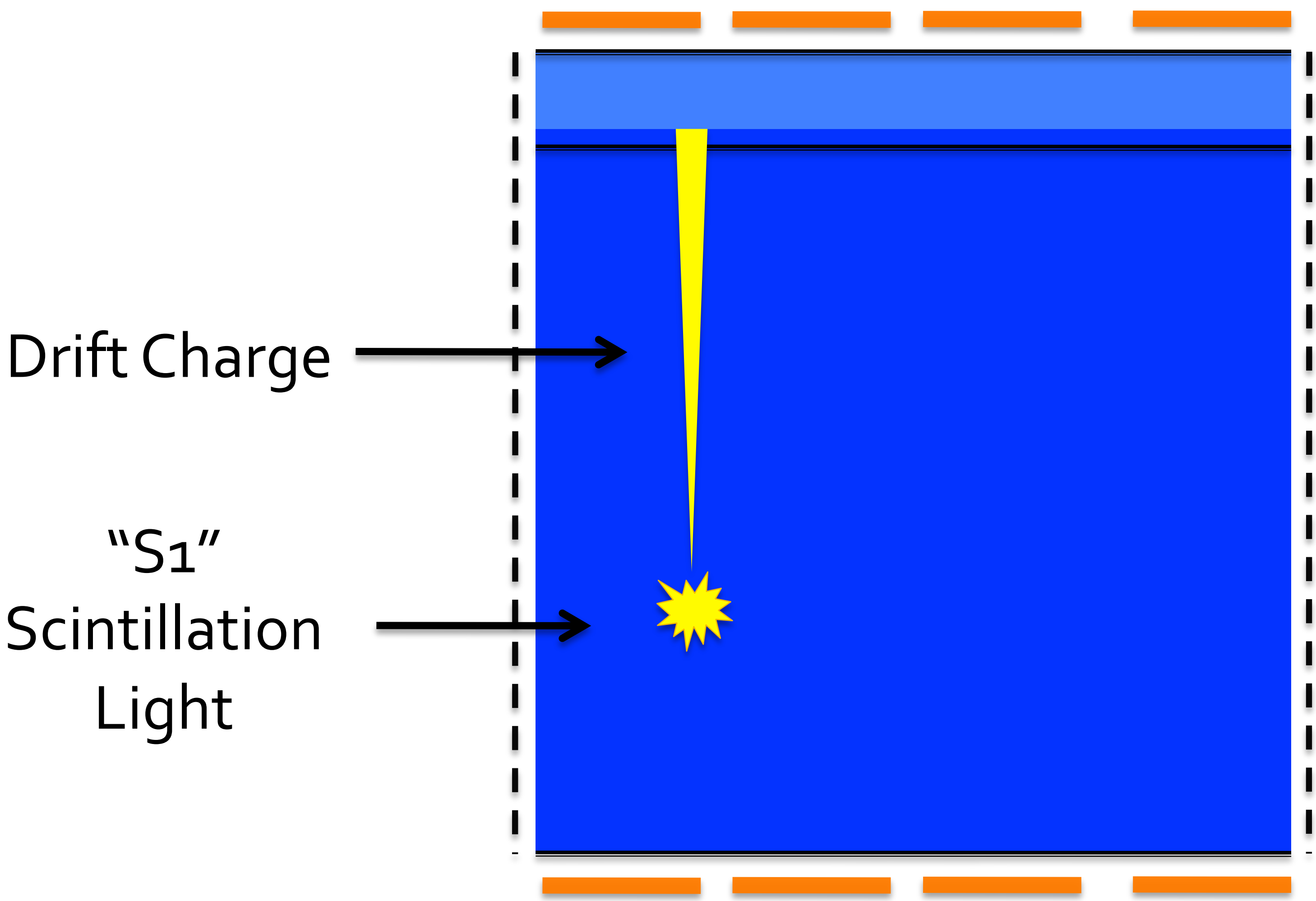
2-Phase Argon TPC



2-Phase Argon TPC



2-Phase Argon TPC

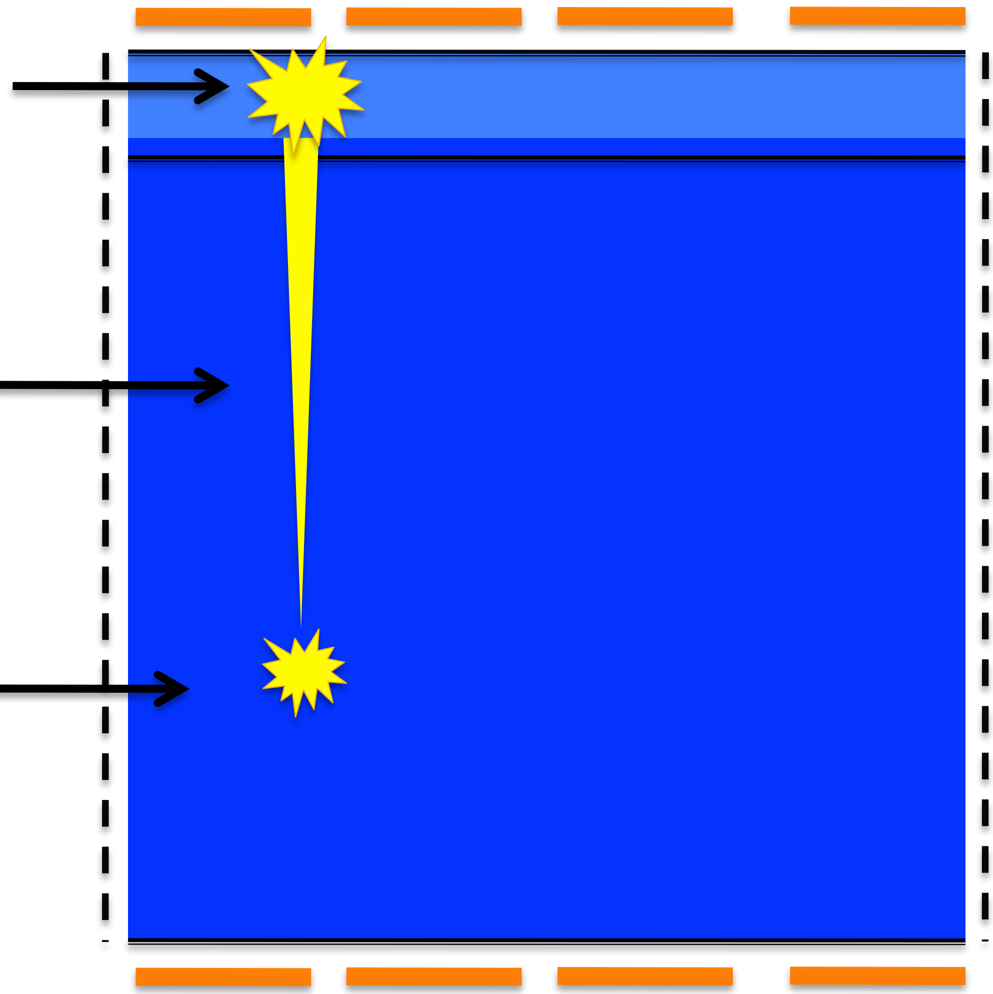


2-Phase Argon TPC

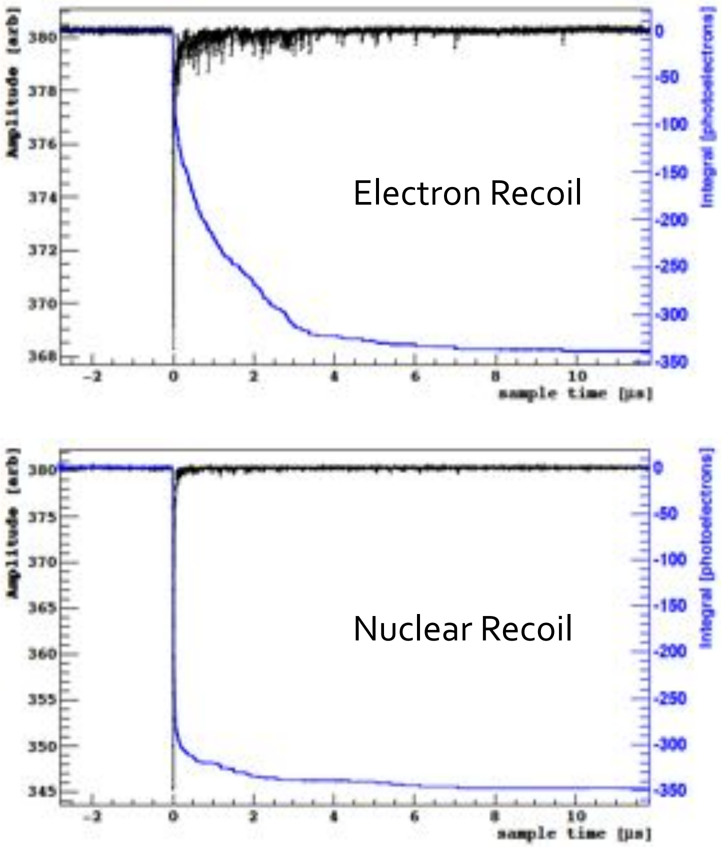
“S2” Electro-
luminescence
Light

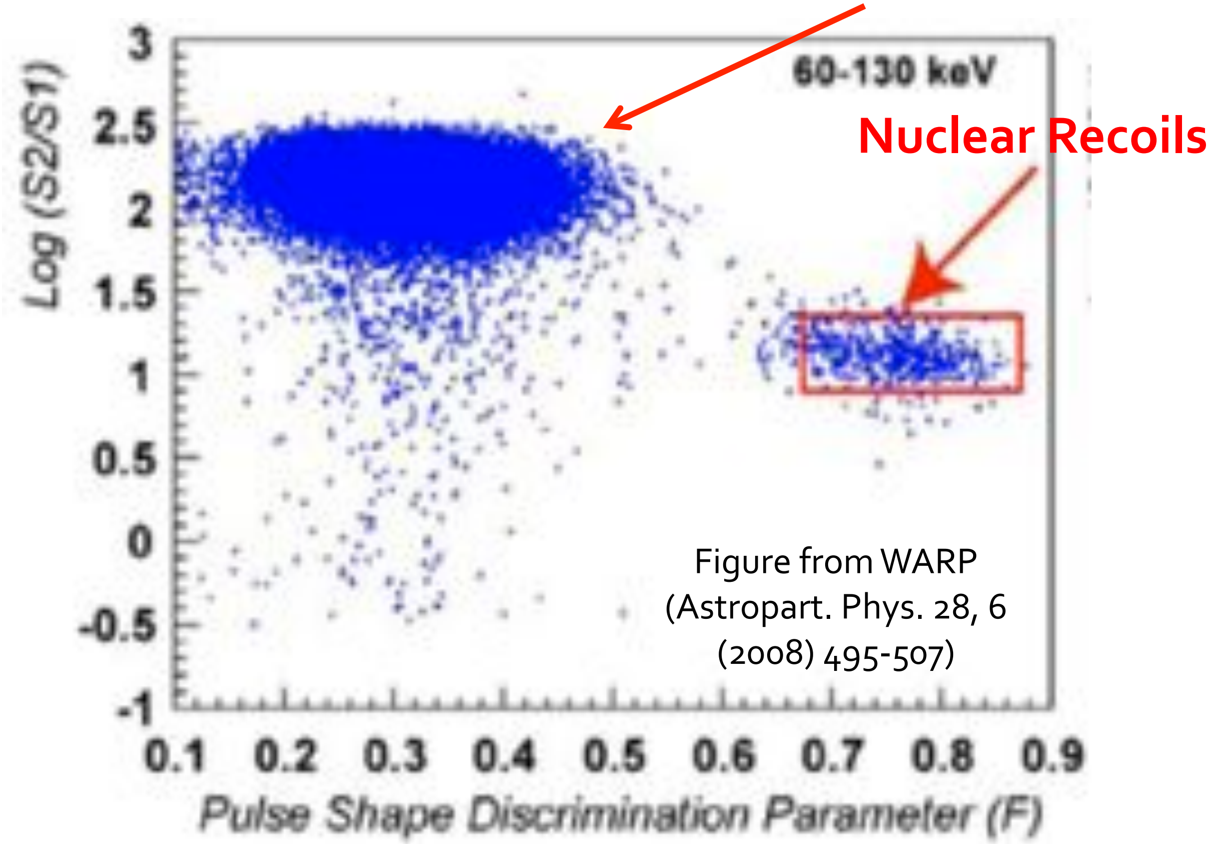
Drift Charge

“S1”
Scintillation
Light



"S1" Electron Recoil Discrimination

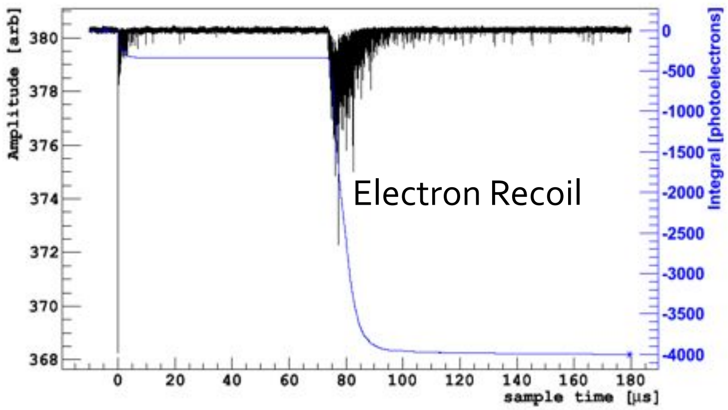


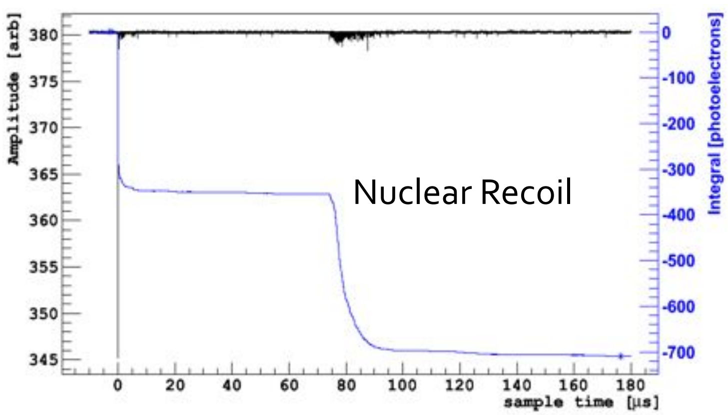


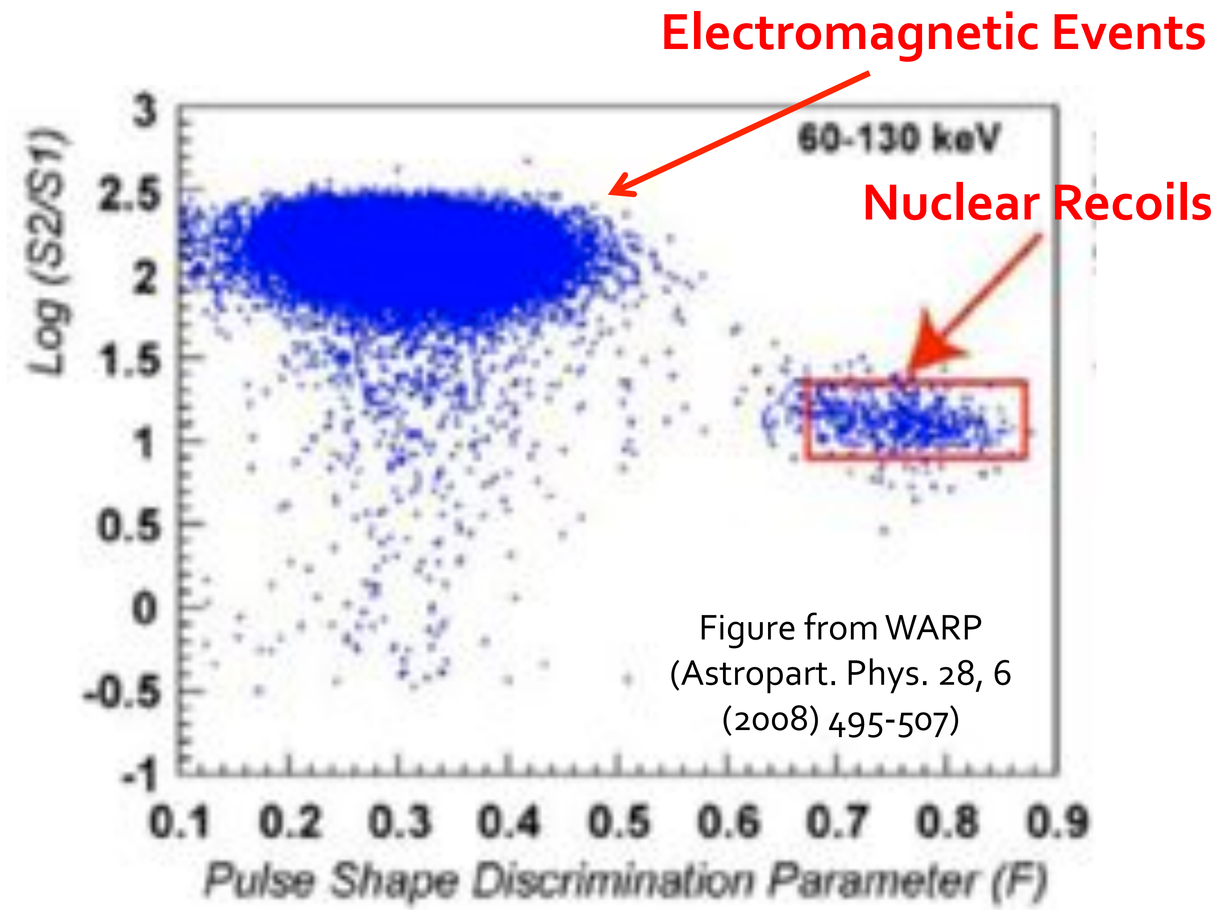
- The ratio of light from singlet (~7 ns decay time) and triplet (1.6 μs decay time) depends on ionization density

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

“S2/S1” Electron Recoil Discrimination



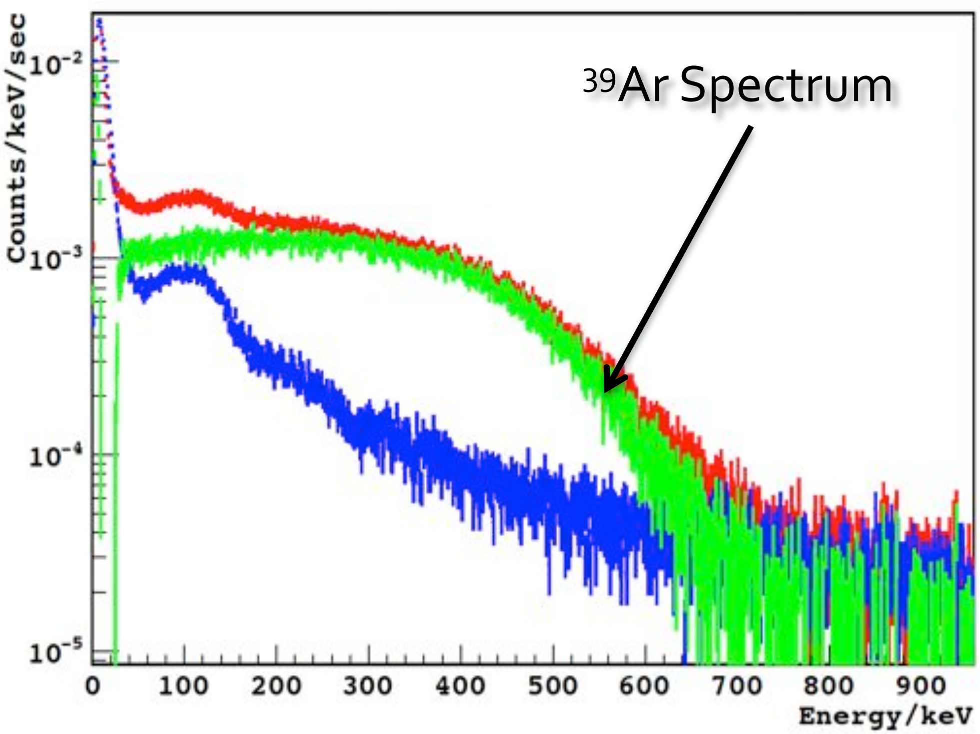




- The recombination probability (and hence the ratio of S2:S1 light) also depends on ionization density
  - ➡ 10^2-10^3 additional discrimination
  - ➡ *$>10^{10}$ total electron recoil rejection in 2D*

^{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
  - $3x10^{10}$ events in 1.0 ton-year!

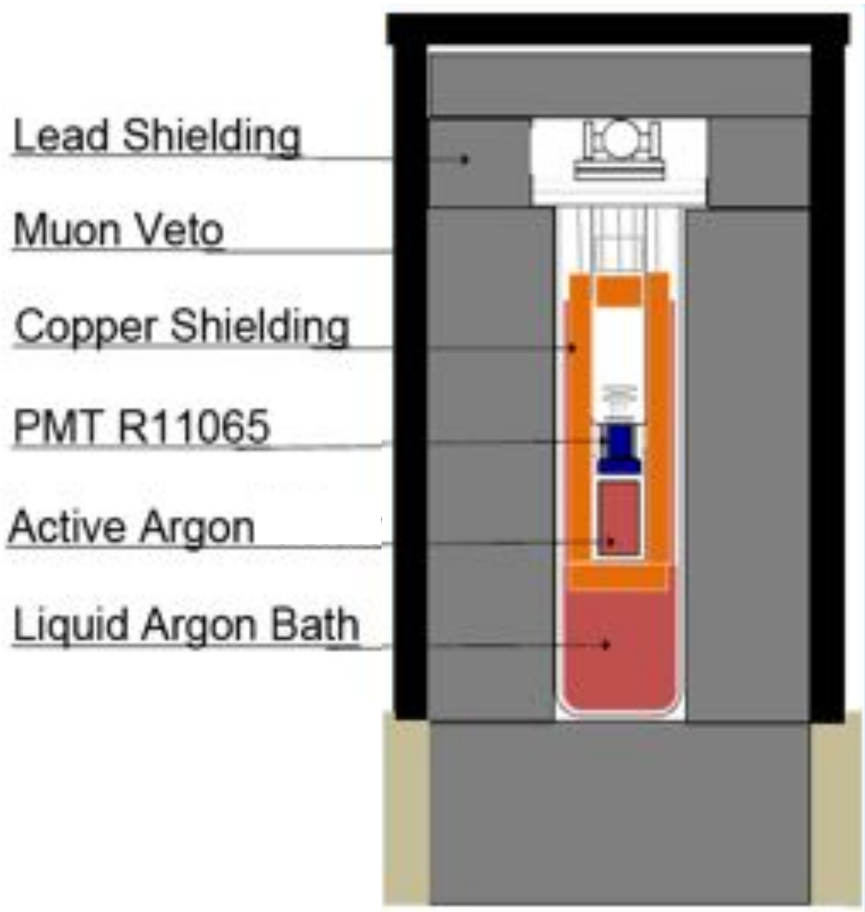


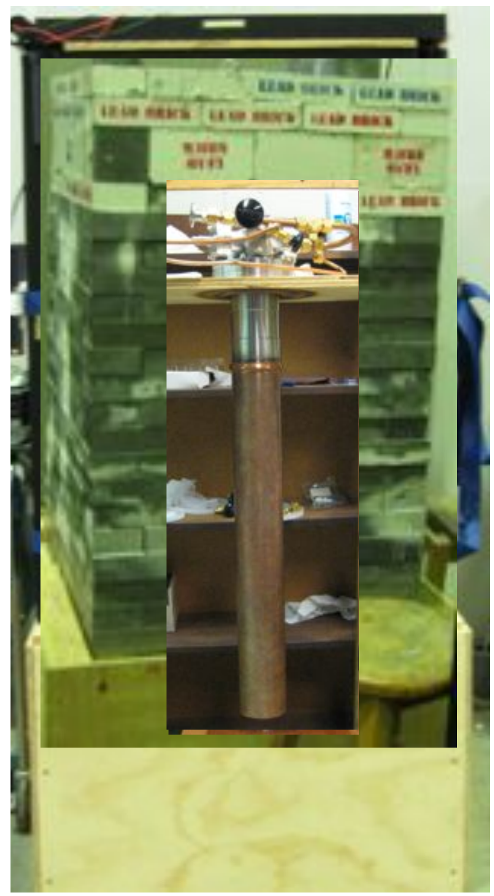
Underground Argon

- Underground argon is shielded from cosmic rays, so the ^{39}Ar can decay away
- CO_2 is industrially extracted from underground
  - Installed and are operating a small argon extraction plant
  - ~25 kg argon collected so far

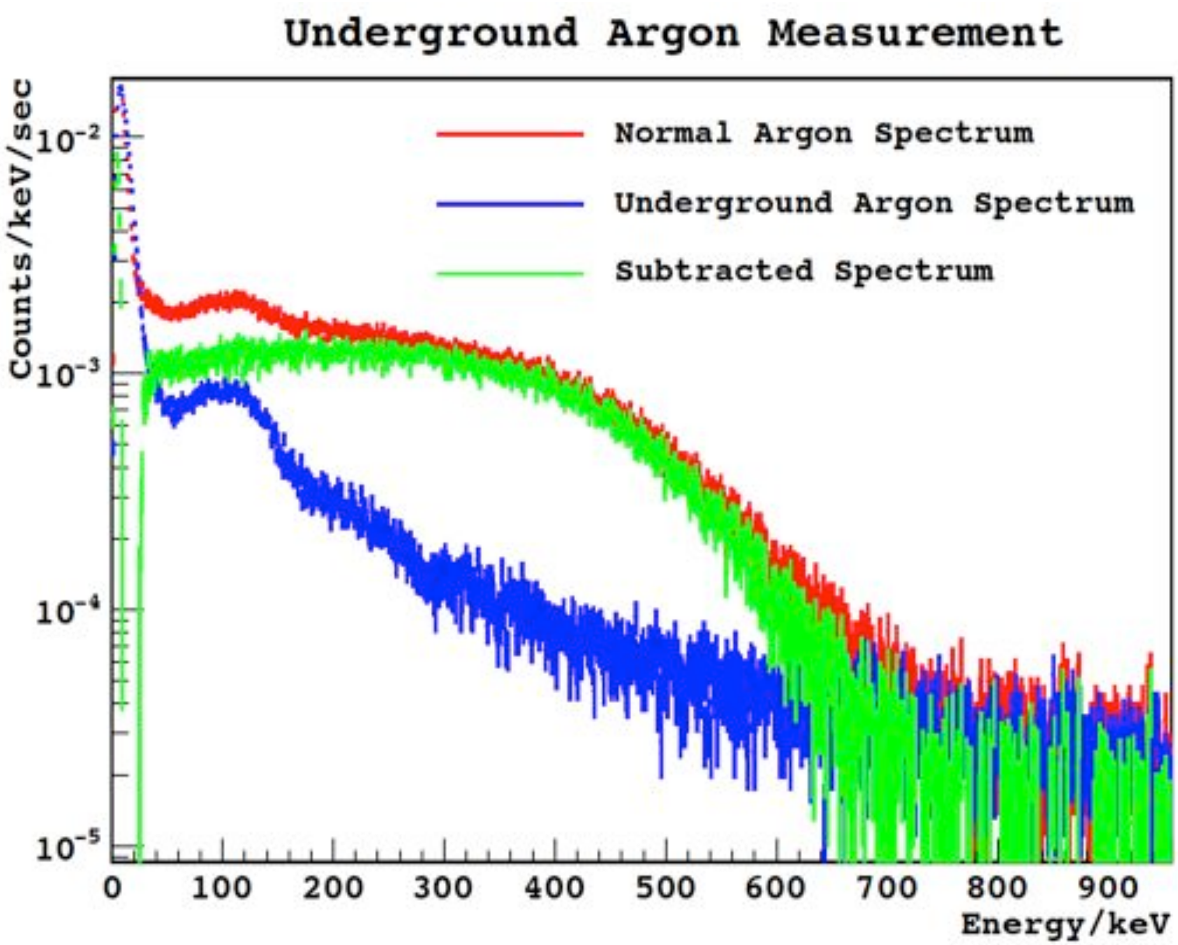
Depleted Argon Counting

The "Low Background Detector"





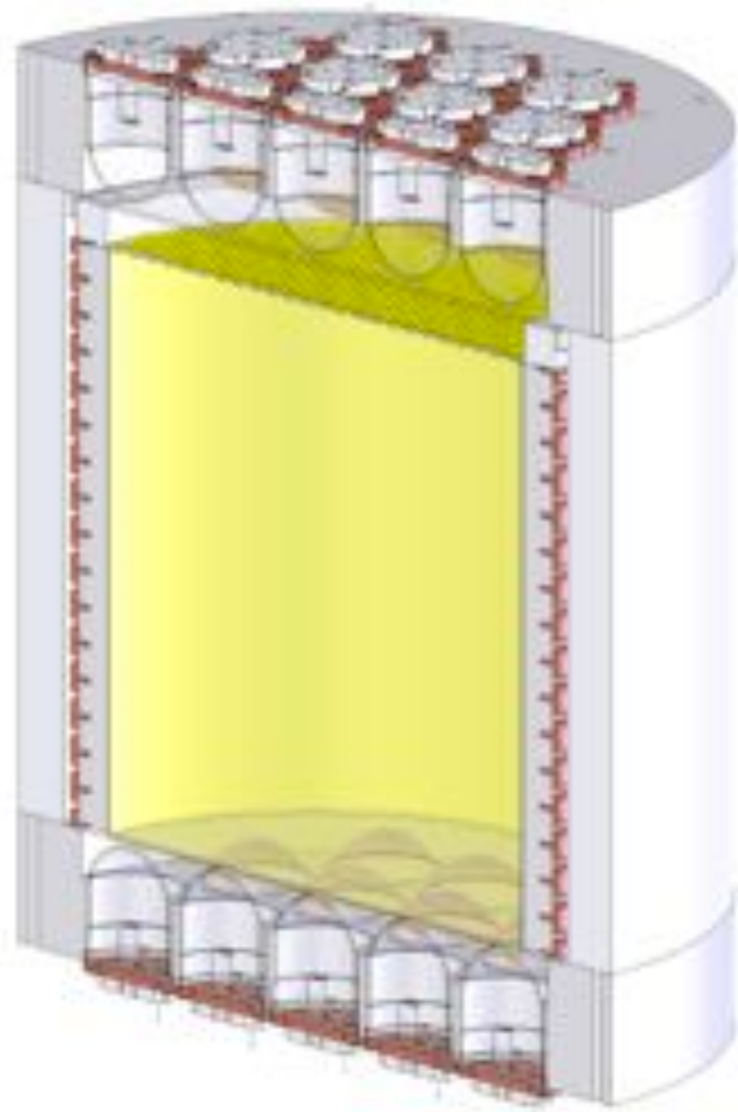
Depleted Argon Counting



Underground argon has at least 50 times less ^{39}Ar than atmospheric argon – multi-tonne experiments possible!

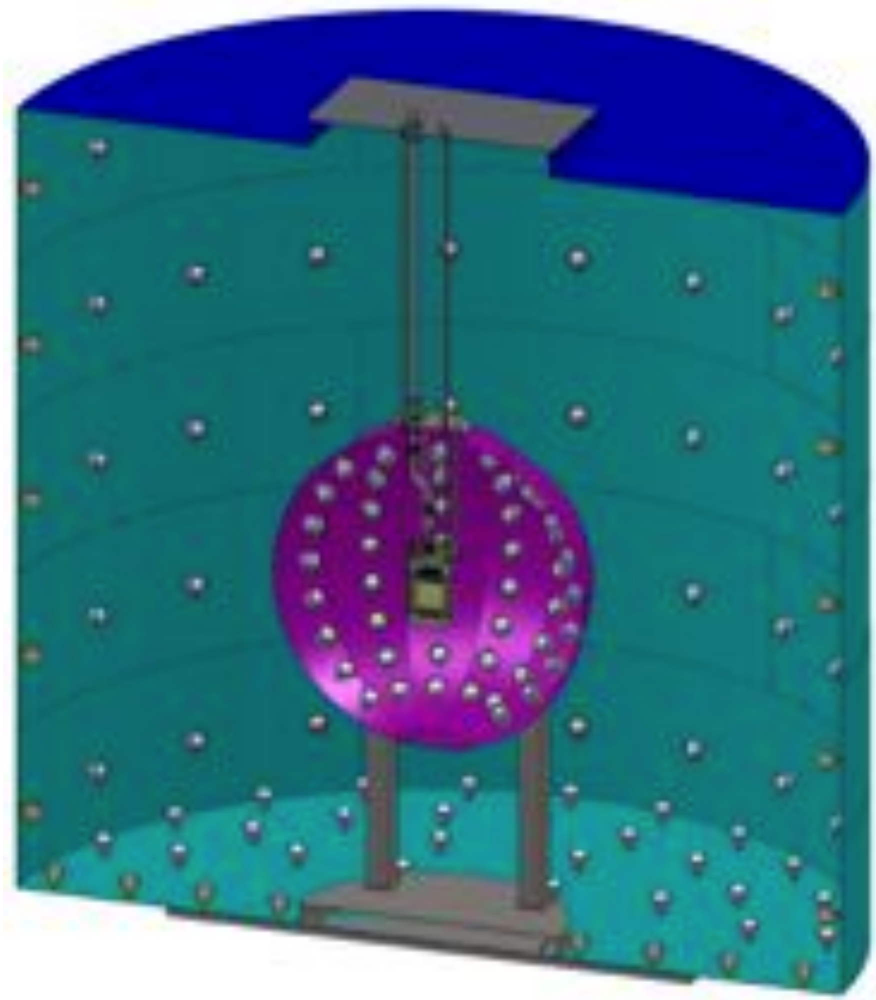
The DarkSide Program

- A dark matter program based on 2-phase depleted argon time projection chambers (TPCs)
- First physics detector will be "DarkSide-50"
- Tonne-scale experiments possible thanks to depleted argon



The DarkSide Background Strategy

- Have <<1 background event
- Understand backgrounds well enough to make a dark matter detection claim
- Powerful active suppression for each class of background:
  - Electron recoils
  - Radiogenic neutrons
  - Cosmogenic neutrons
  - Surface backgrounds



Radiogenic Neutrons

- Single scatter neutron events produce "genuine" nuclear recoils
- Produced internally by radioactive decays through (α,n) processes and spontaneous fission
  - Produced even in the cleanest materials

Source	Bkg / 0.1 ton-yr
^{39}Ar	–
Fused Silica	0.17
PTFE	0.39
Copper	5.0×10^{-3}
R11065 PMTs	19.4
QUPIDs (1 mBq)	0.31
Stainless Steel	2.5

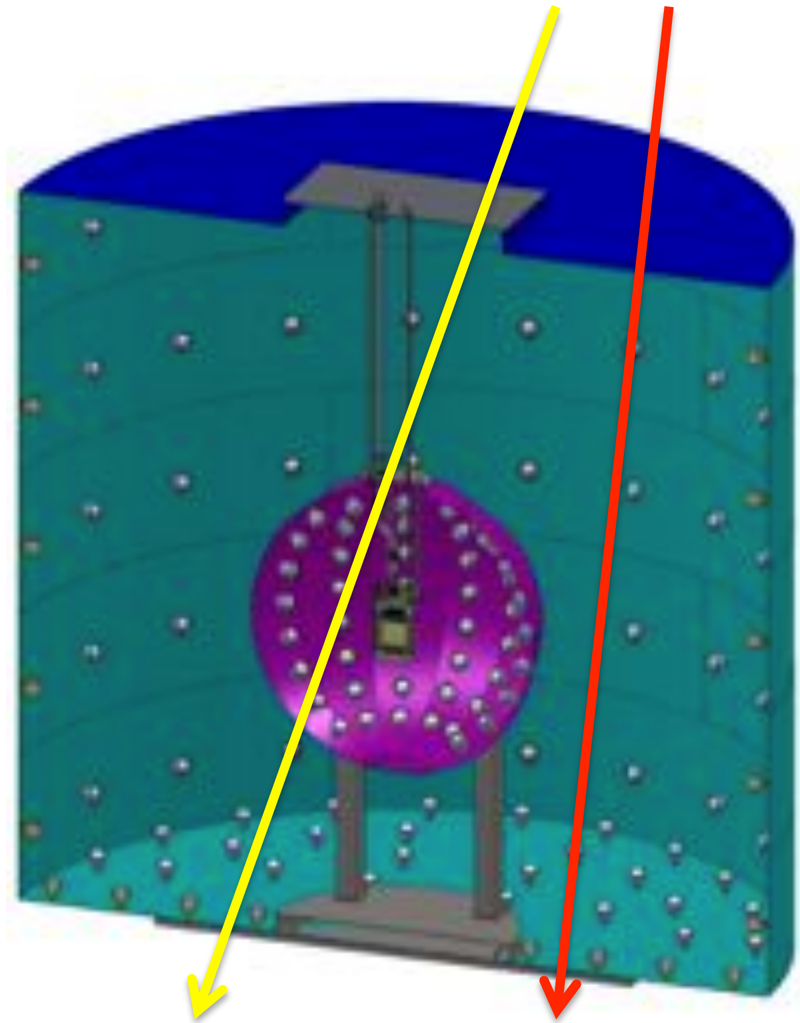
High-Efficiency Neutron Veto

- Surround DarkSide with boron-loaded liquid scintillator
  - Very clean, very effective at capturing neutrons
- Capture the escaping neutron and use it to reject the recoil background event
  - >200 rejection possible

arXiv:1010.3609, accepted by NIM A

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 (~simultaneous) neutron-induced background event
- CTF tank + neutron veto reduce cosmogenic backgrounds by $>>10^3$



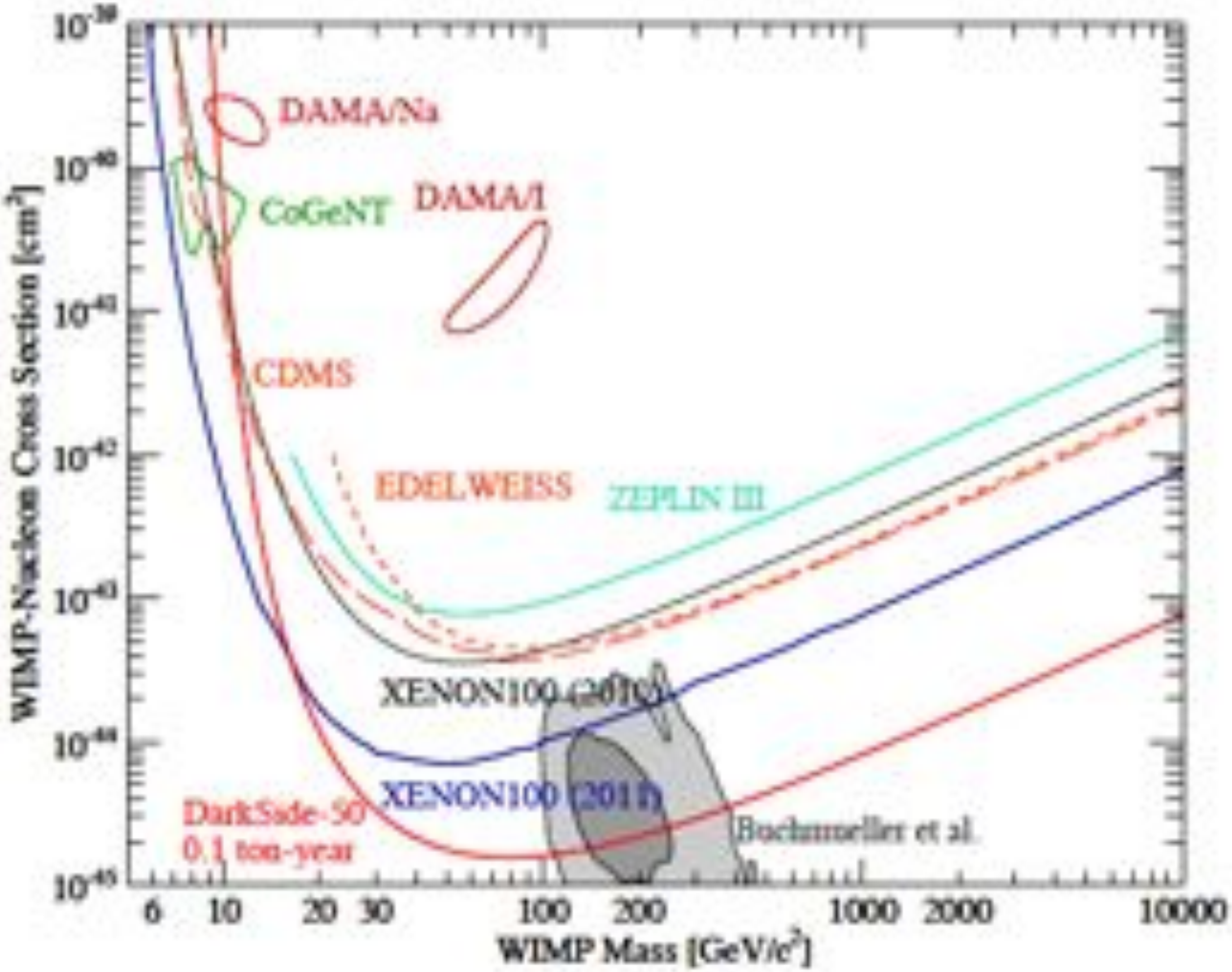
DarkSide-50 Background Estimates

Total Expected Background in 3.7×10^4 kg-day

Detector Element	Electron Recoil Backgrounds		Radiogenic Neutron Recoil Backgrounds		Cosmogenic Neutron Recoil Backgrounds	
	Raw	After Cuts	Raw	After Cuts	Raw	After Cuts
^{39}Ar	$<2.5\times10^7$	<0.016	–	–	–	–
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	–	0.019 (0.017)	–	0.055 (0.008)	–	0.030 (0.030)

DarkSide will be able to convincingly claim to be background free!

DarkSide-50 Physics Reach



First data in late 2012.

DarkSide-10 Prototype

- Test key technical concepts for DarkSide-50
- Two runs, seven months total, during 2010-2011
- Not much care taken about radiopurity, for speed and flexibility

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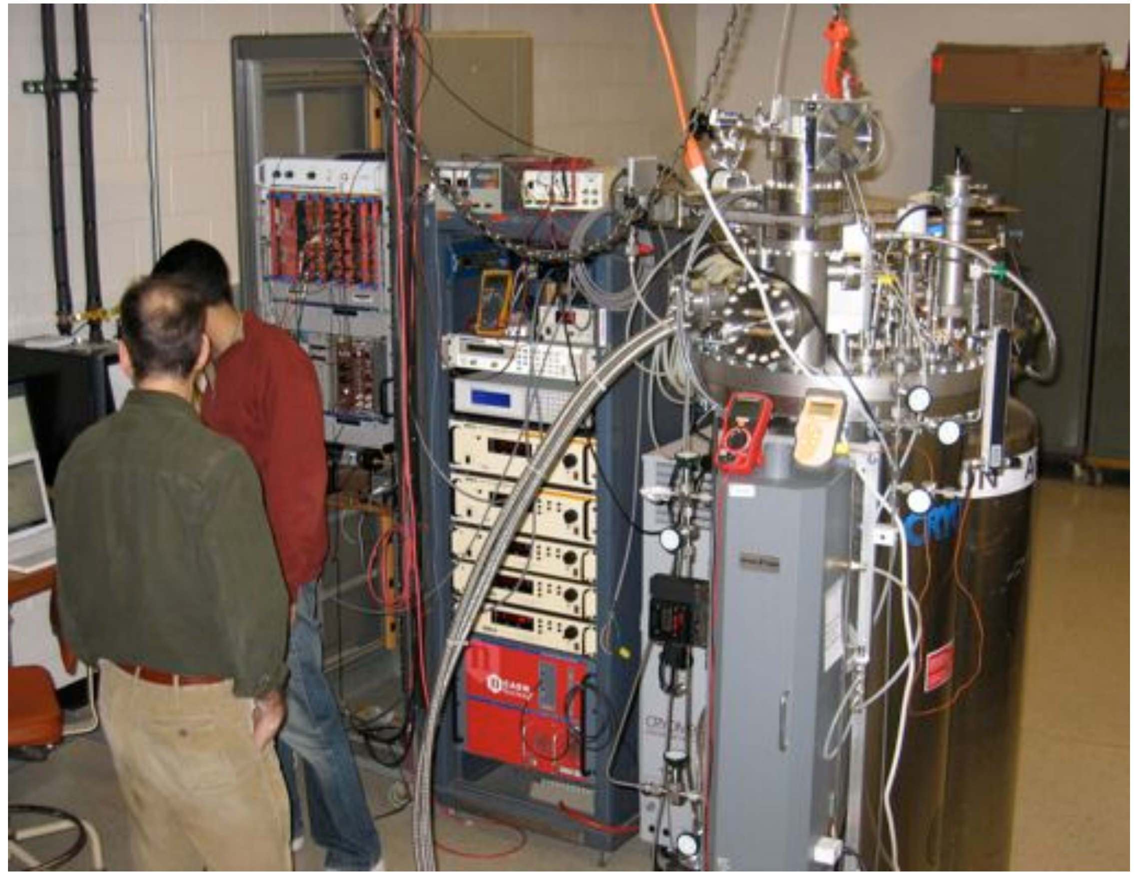
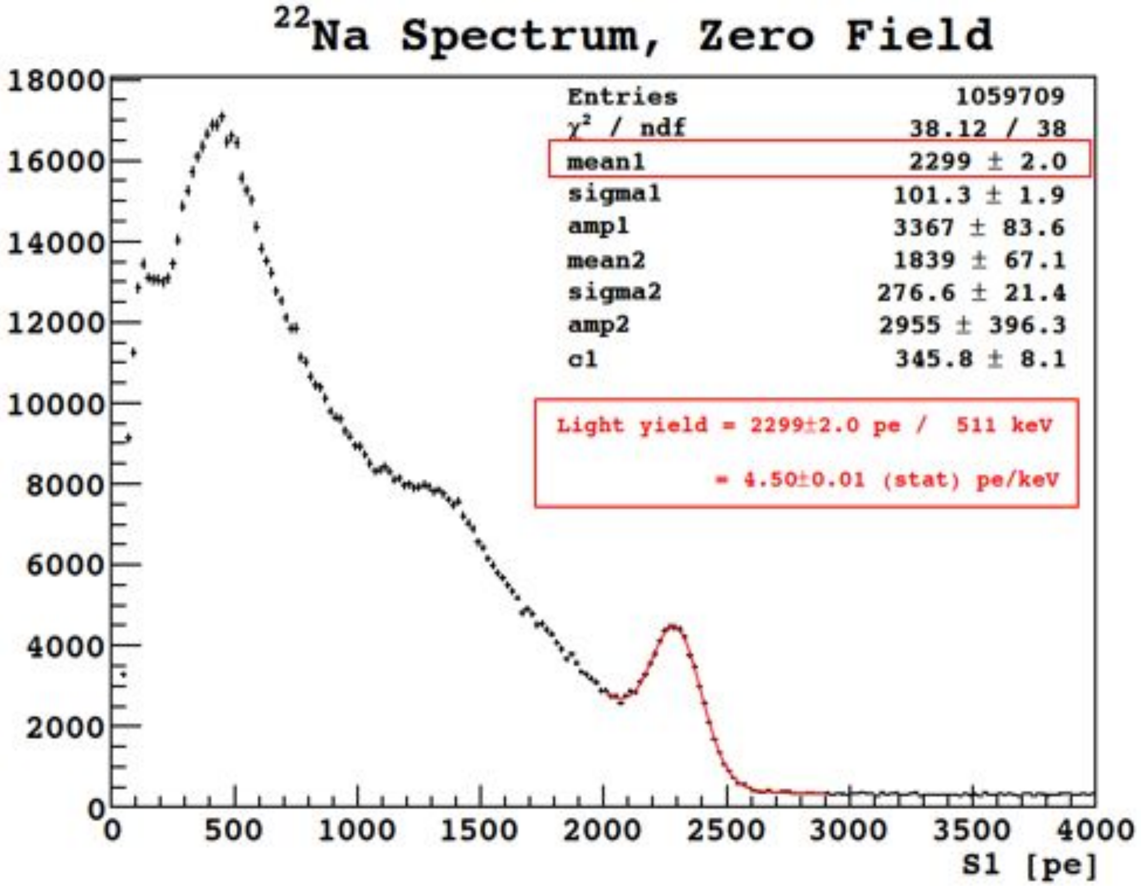


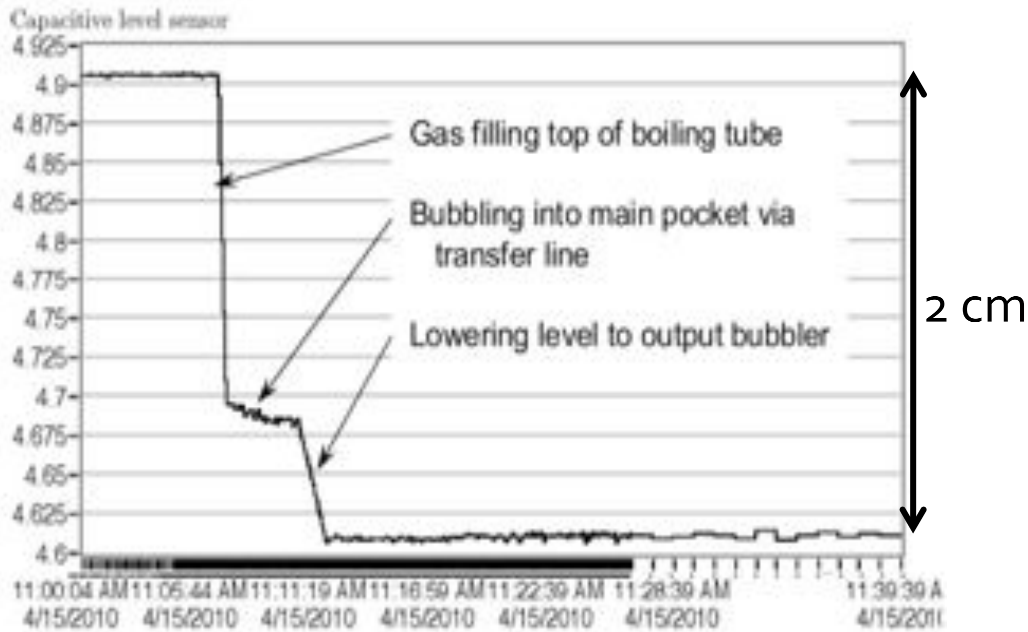
Light Yield



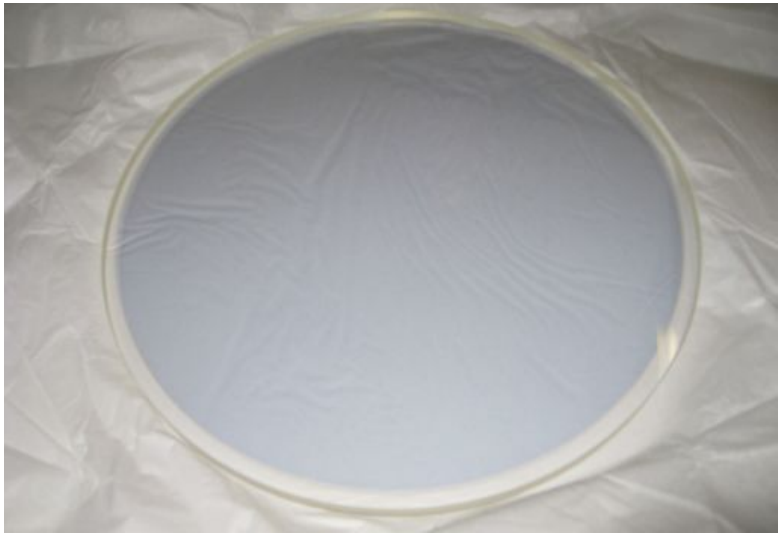
^{22}Na Spectrum, Zero Field
Entries 1059709
χ^2 / ndf 38.12 / 38
mean1 2299 ± 2.0
sigma1 101.3 ± 1.9
amp1 3367 ± 83.6
mean2 1839 ± 67.1
sigma2 276.6 ± 21.4
amp2 2955 ± 396.3
c1 345.8 ± 8.1
Light yield = 2299±2.0 pe / 511 keV
= 4.50±0.01 (stat) pe/keV
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
0
500
1000
1500
2000
2500
3000
3500
4000
S1 [pe]

Gas Layer


bubbler

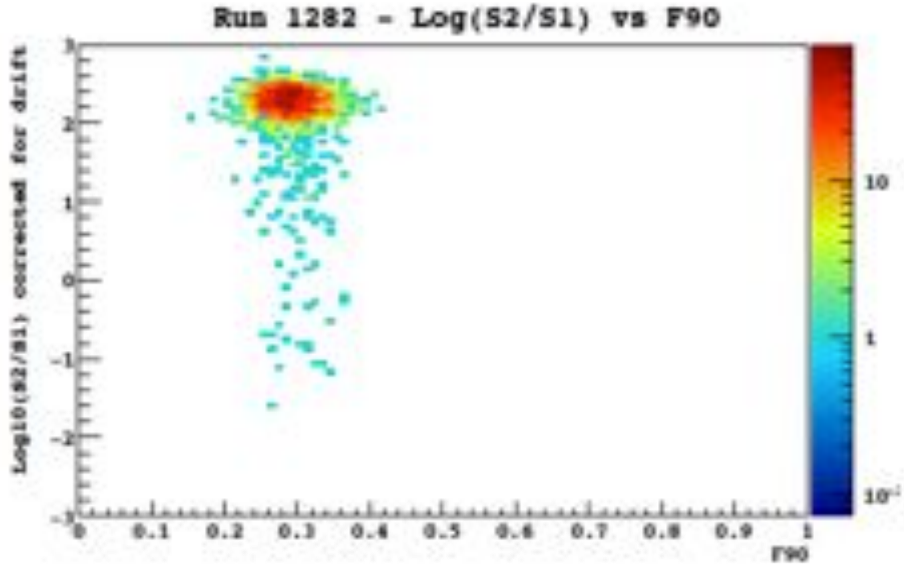

Capacitive level sensor
4.925
4.9
4.875
4.85
4.825
4.8
4.775
4.75
4.725
4.7
4.675
4.65
4.625
4.6
Gas filling top of boiling tube
Bubbling into main pocket via transfer line
Lowering level to output bubbler
2 cm
11:00:04 AM 4/15/2010
11:05:44 AM 4/15/2010
11:11:19 AM 4/15/2010
11:16:59 AM 4/15/2010
11:22:39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

Electric Field Creation

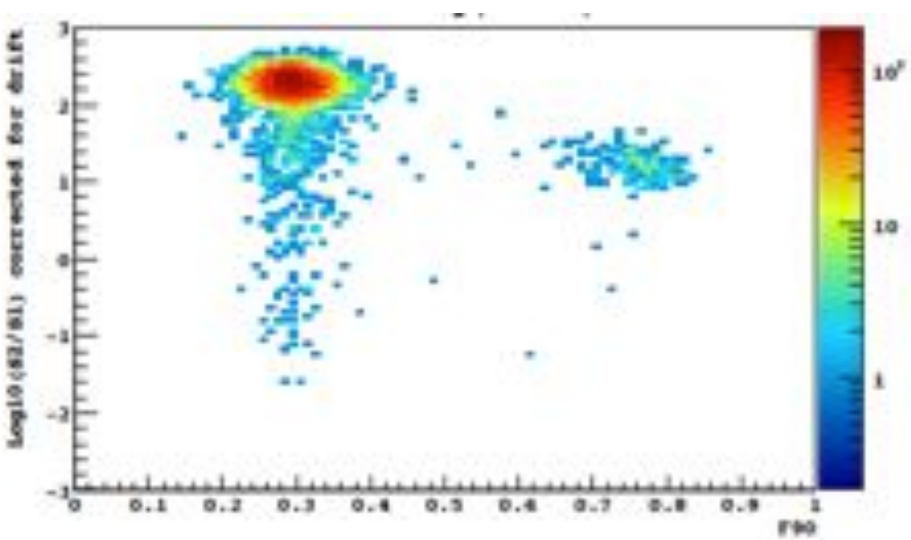


Two-Phase Operation!

Gamma Source:

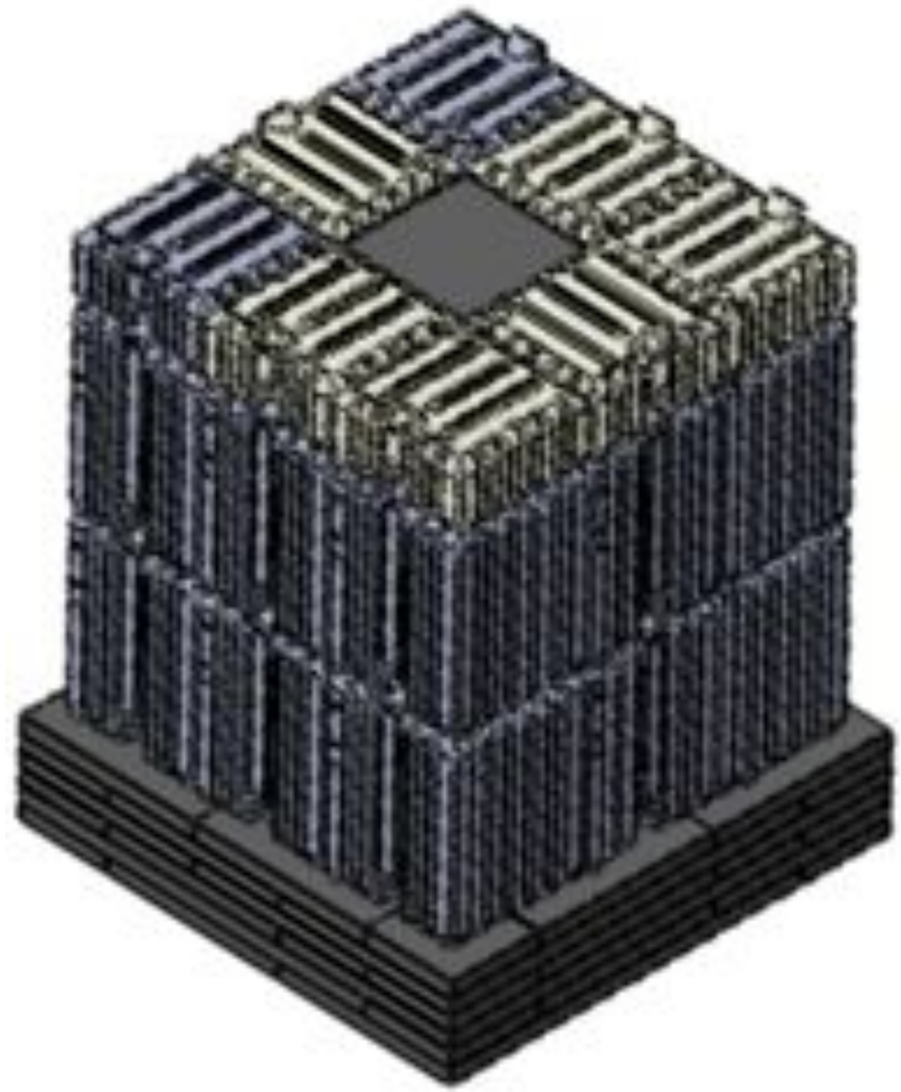


Neutron Source:



DarkSide-10 At LNGS

- Deploy DarkSide-10 in water shielding at LNGS
  - Careful study of electron and surface background rejection
- Detector is currently in transit!



Summary

- Strong evidence for dark matter
- WIMPs are well motivated dark matter candidates
- Direct-detection WIMP searches have just reached sensitivity to 10^{-44} cm²
- Depleted argon is a promising dark matter detection medium
- DarkSide well positioned to contribute to continuing program of ever more sensitive experiments