The DarkSide

Dark Matter Program

IPP Tour
April, 2012

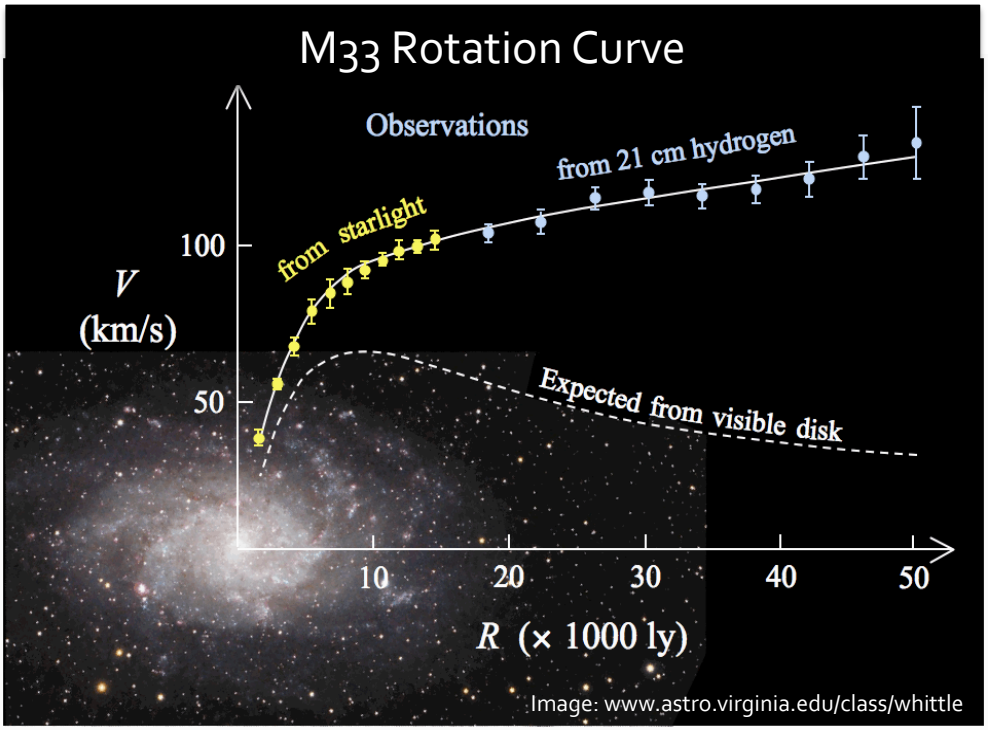
Alex Wright
Princeton University

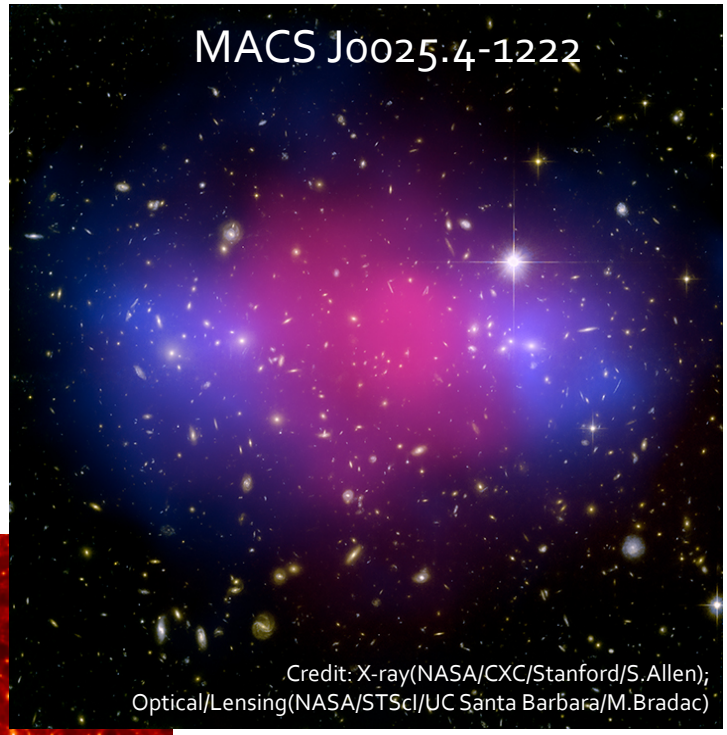
Outline

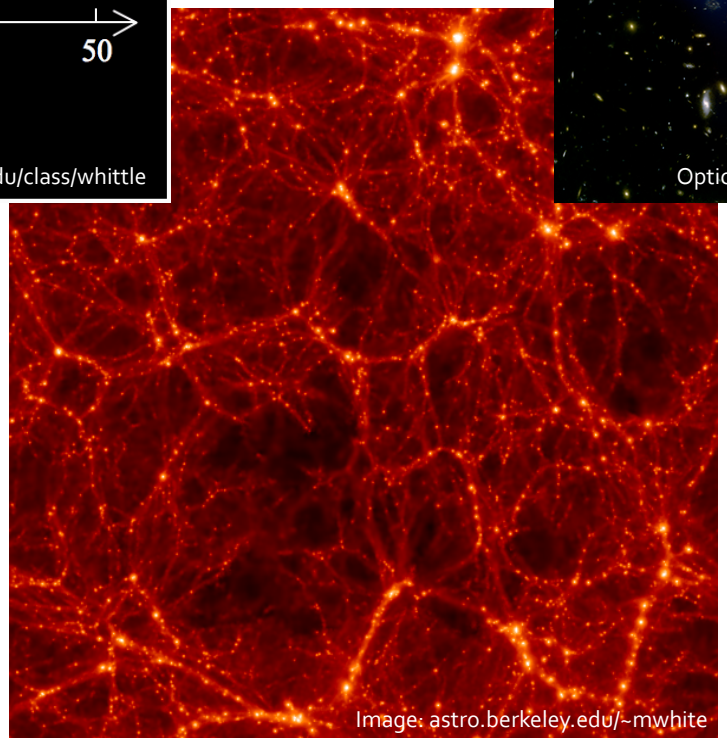
- Dark matter review
  - Evidence & known properties
- Searching for dark matter
  - Direct detection experiments
- The DarkSide experiment
  - Strategy
  - Technical progress
  - Future

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

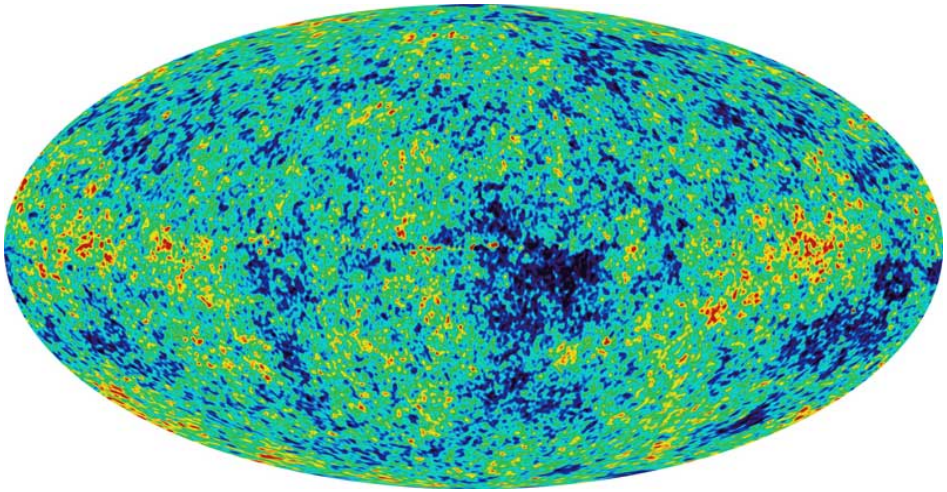
Evidence for Dark Matter

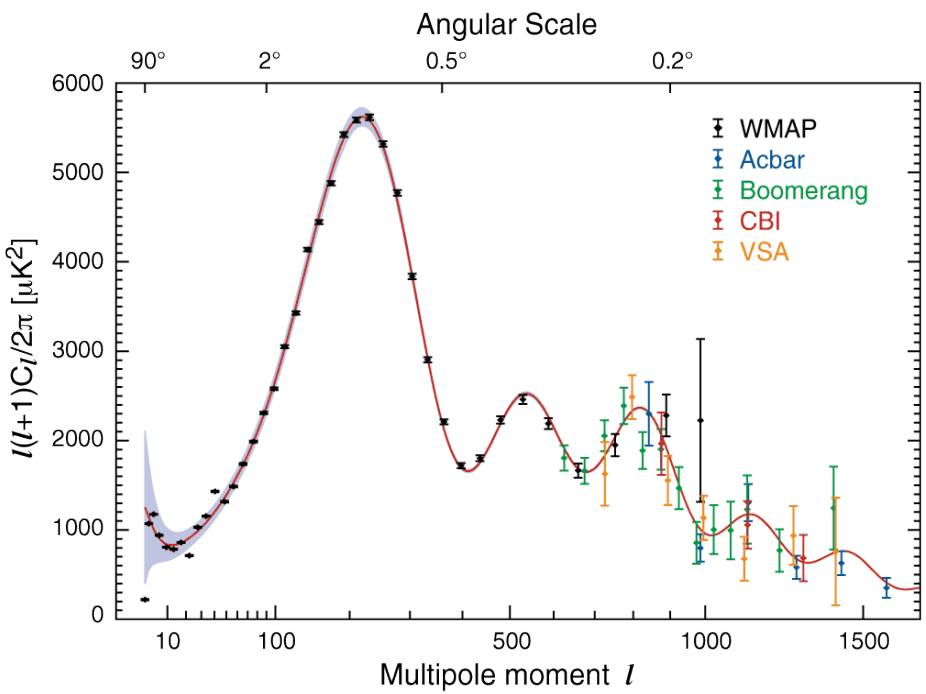






Evidence for Dark Matter





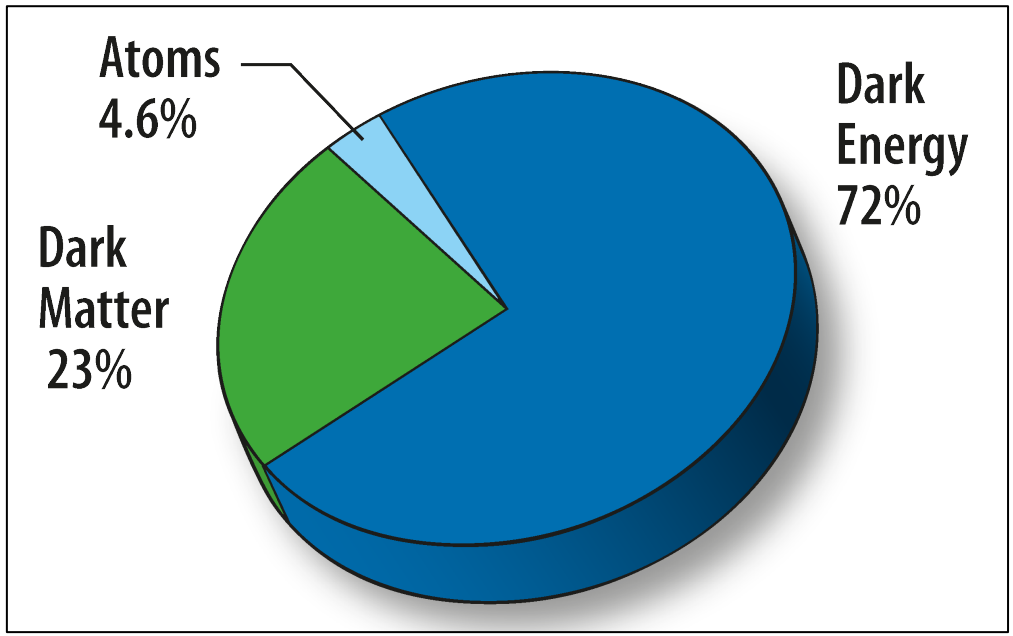
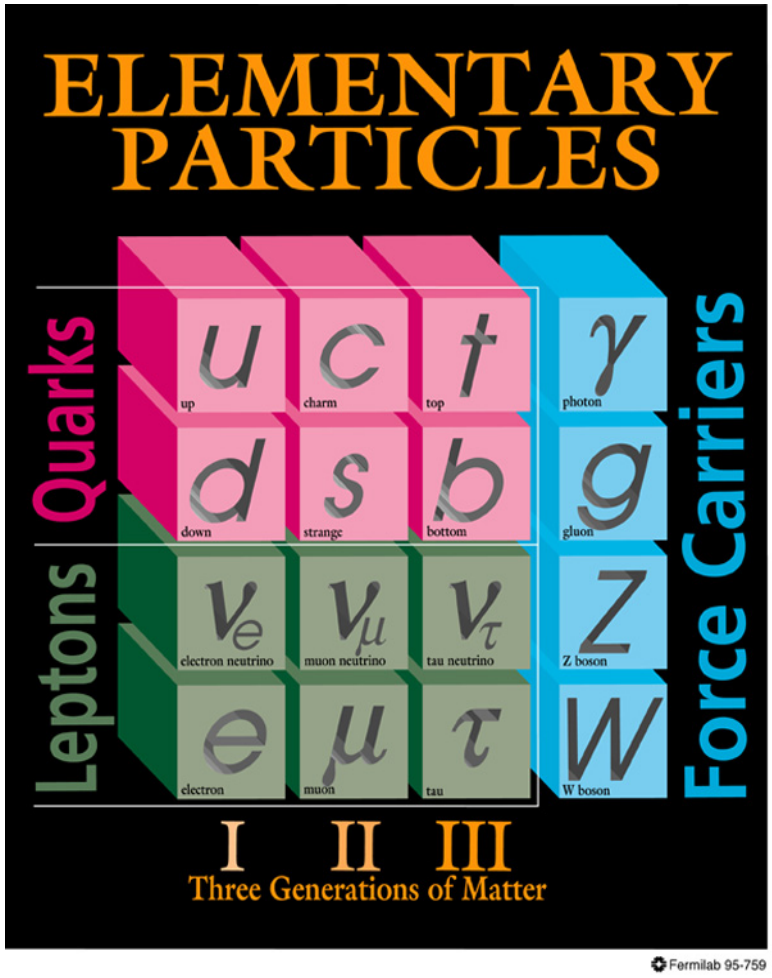


Image credits: WMAP Science Team, NASA

Dark Matter Properties

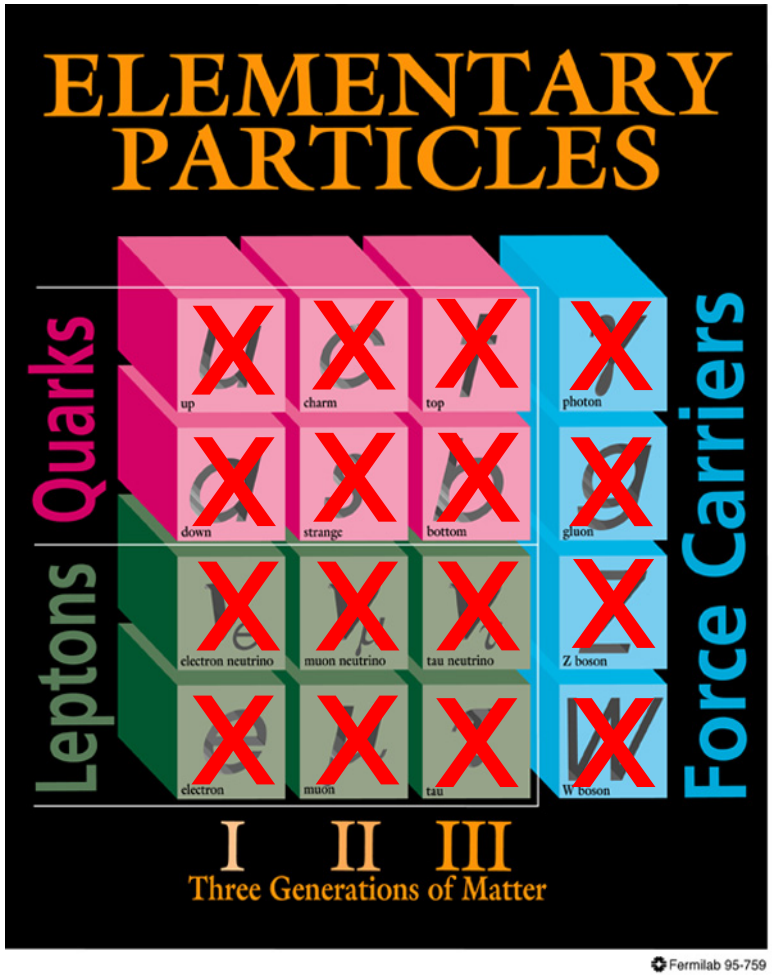
- ~23% of the energy density of the universe is dark matter
  - Gravitationally interacting
  - Neutral
  - Long lived
  - Non-baryonic
  - "Cold" (i.e. non-relativistic at early times)



Fermilab 95-759

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)



This excludes all Standard Model particles:

strong evidence for physics beyond the Standard Model!

Dark Matter Candidates

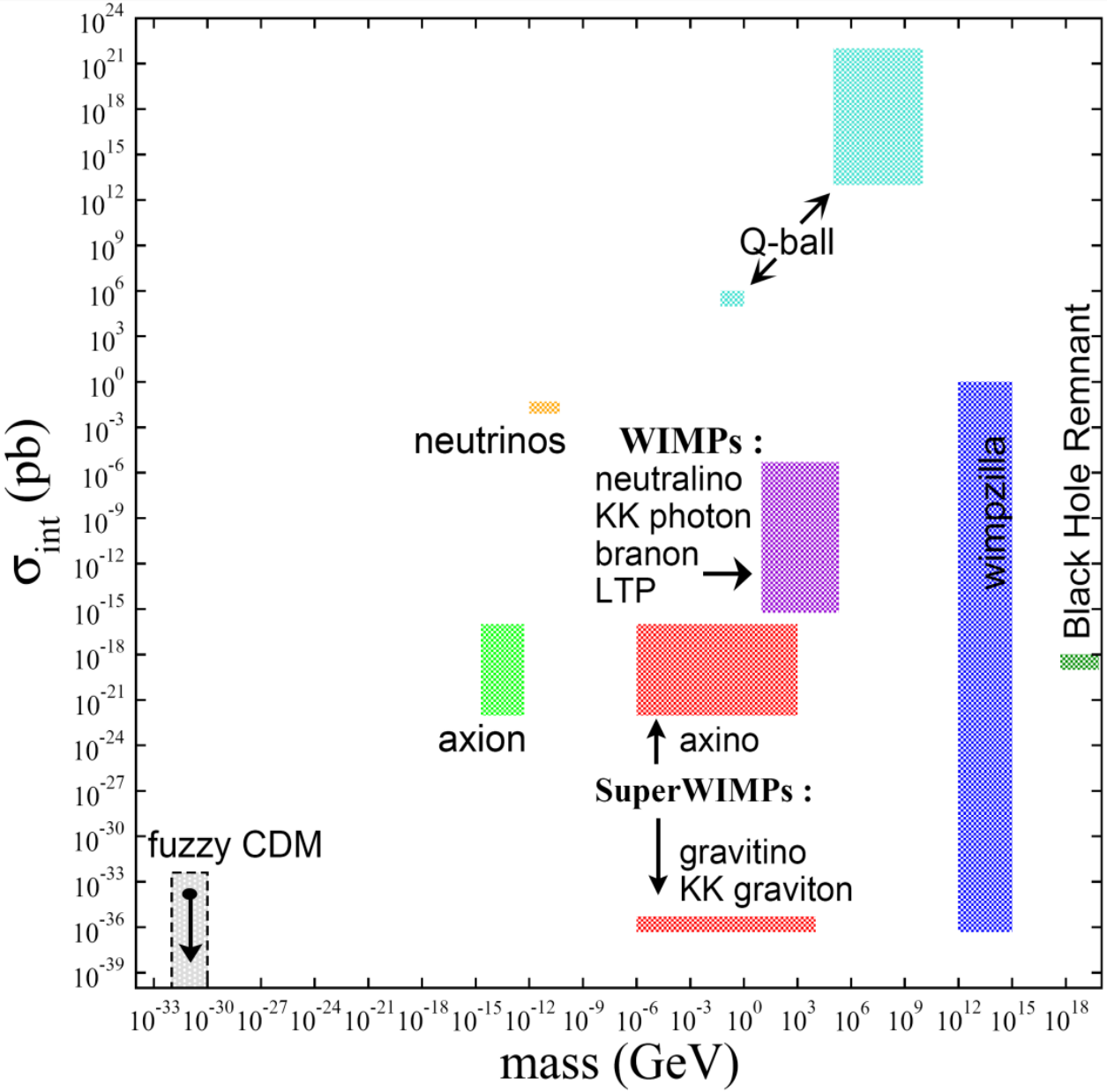
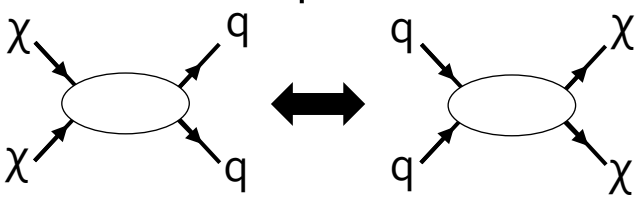


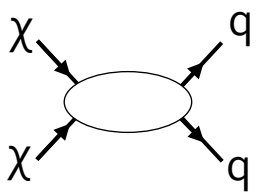
Image credit: HEPAP/AAAC DMSAG Subpanel (2007)

Thermal Relics

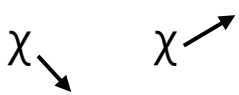
1) WIMPs are produced in thermal equilibrium

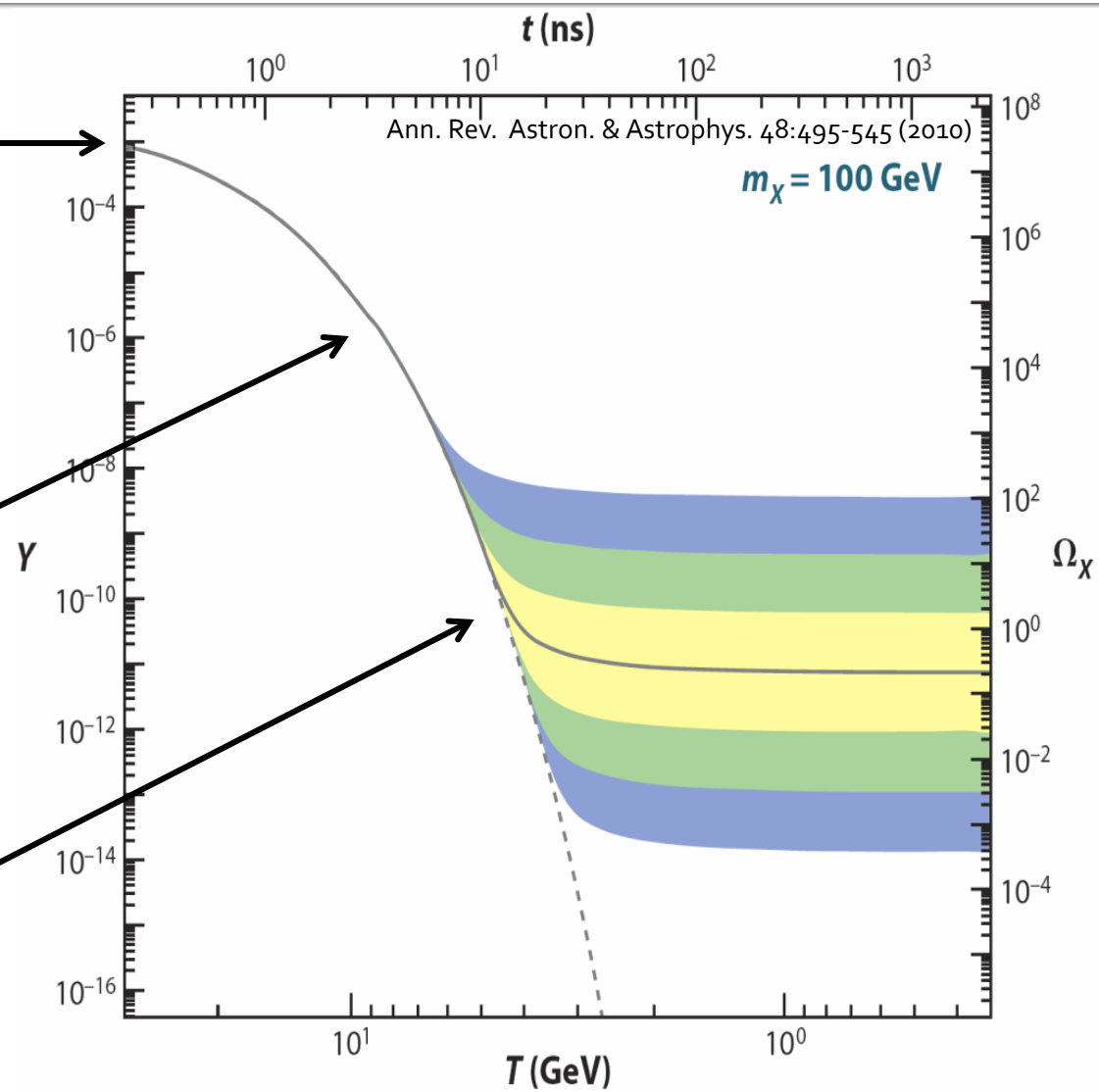


2) WIMP density decays as the universe cools



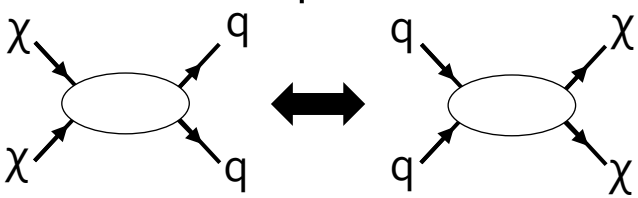
3) WIMP density "freezes out" based on coupling strength



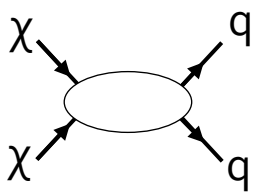


The "WIMP Miracle"

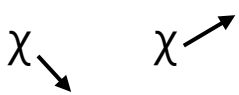
1) WIMPs are produced in thermal equilibrium

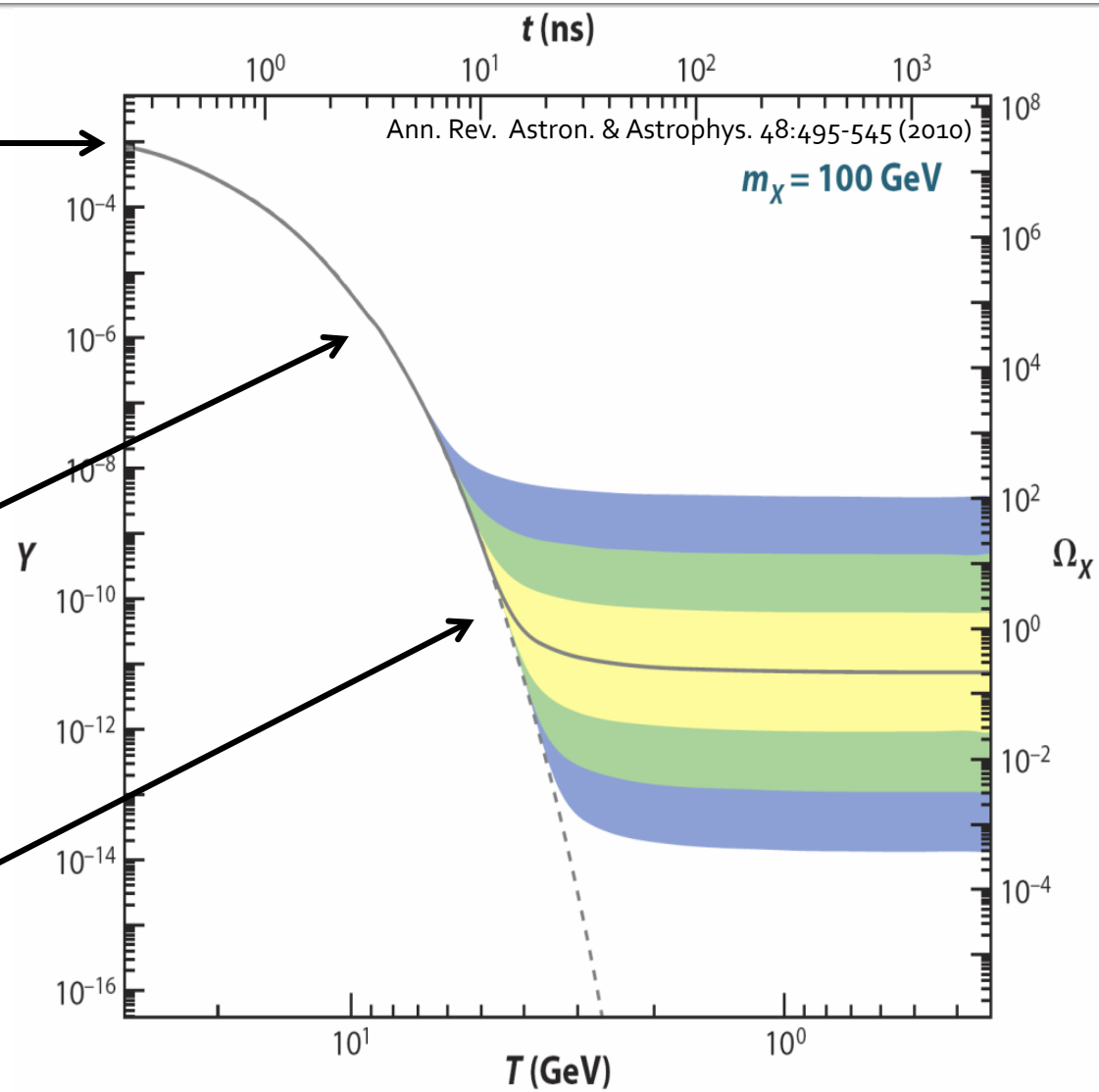


2) WIMP density decays as the universe cools



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

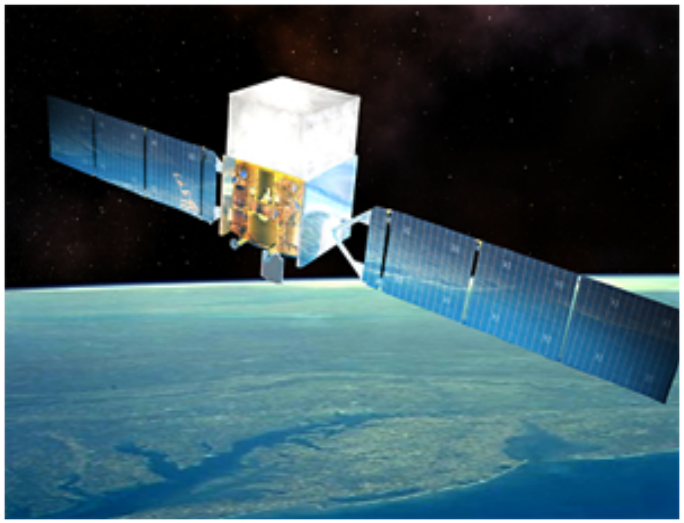


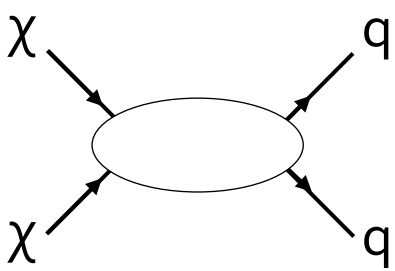


Weak mass & coupling give just the right relic density for dark matter!

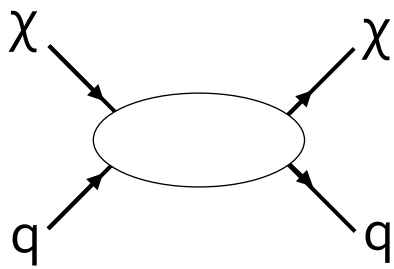
Searching for WIMPs

Aboveground

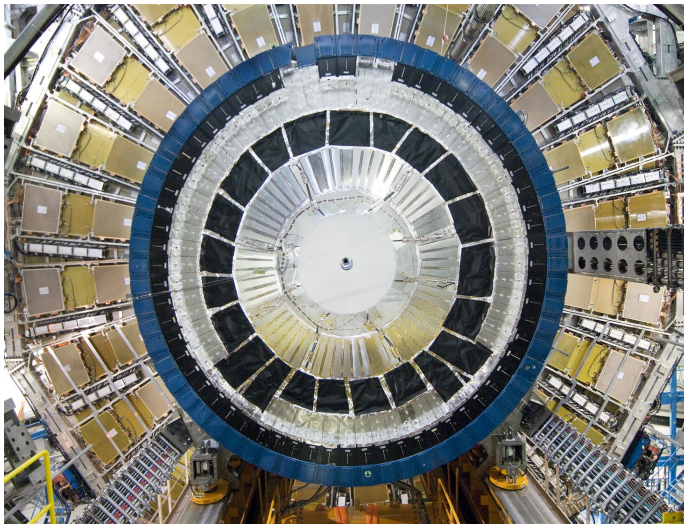




Underground



At Accelerators



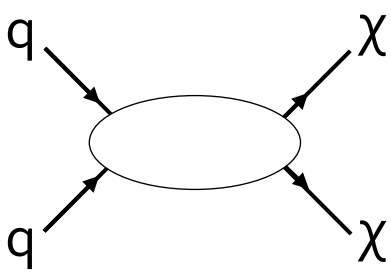


Image credits: NASA, discovermagazine.com, atlas.ch

Local Dark Matter

- Galaxy embedded in a dark matter "halo"
- Local density ≈ 0.3 GeV/c²/cm³
- Independent galactic orbits
  - Typical $v_{orbit} \approx 220$ km/s

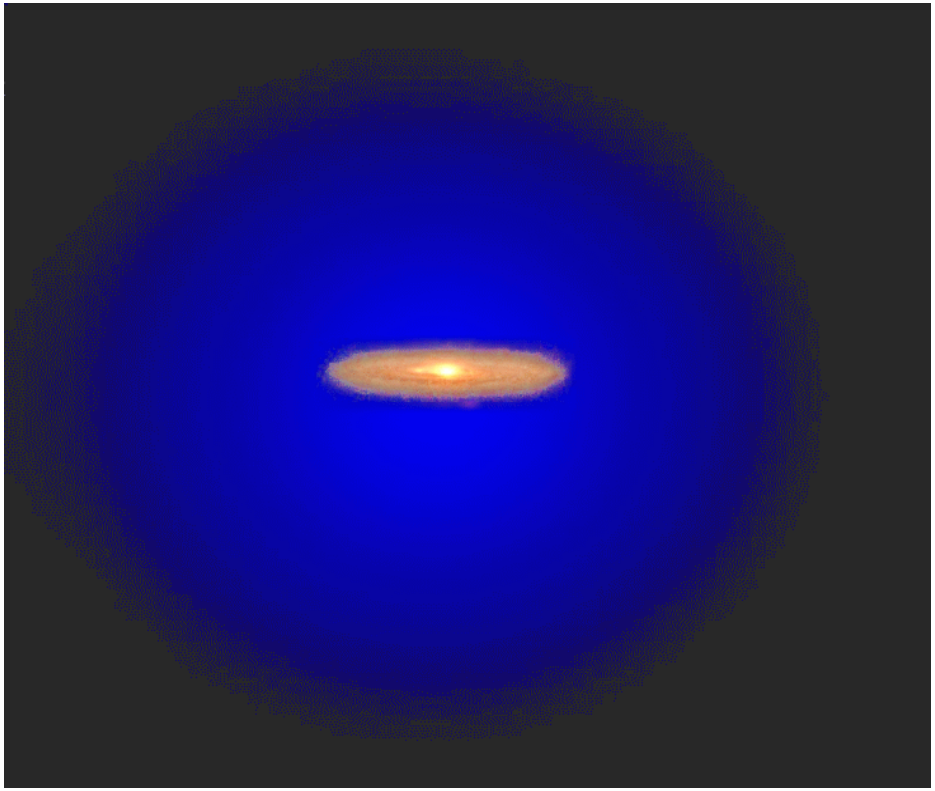


Image credit: J. Kormendy, chandra.as.utexas.edu/~kormendy

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

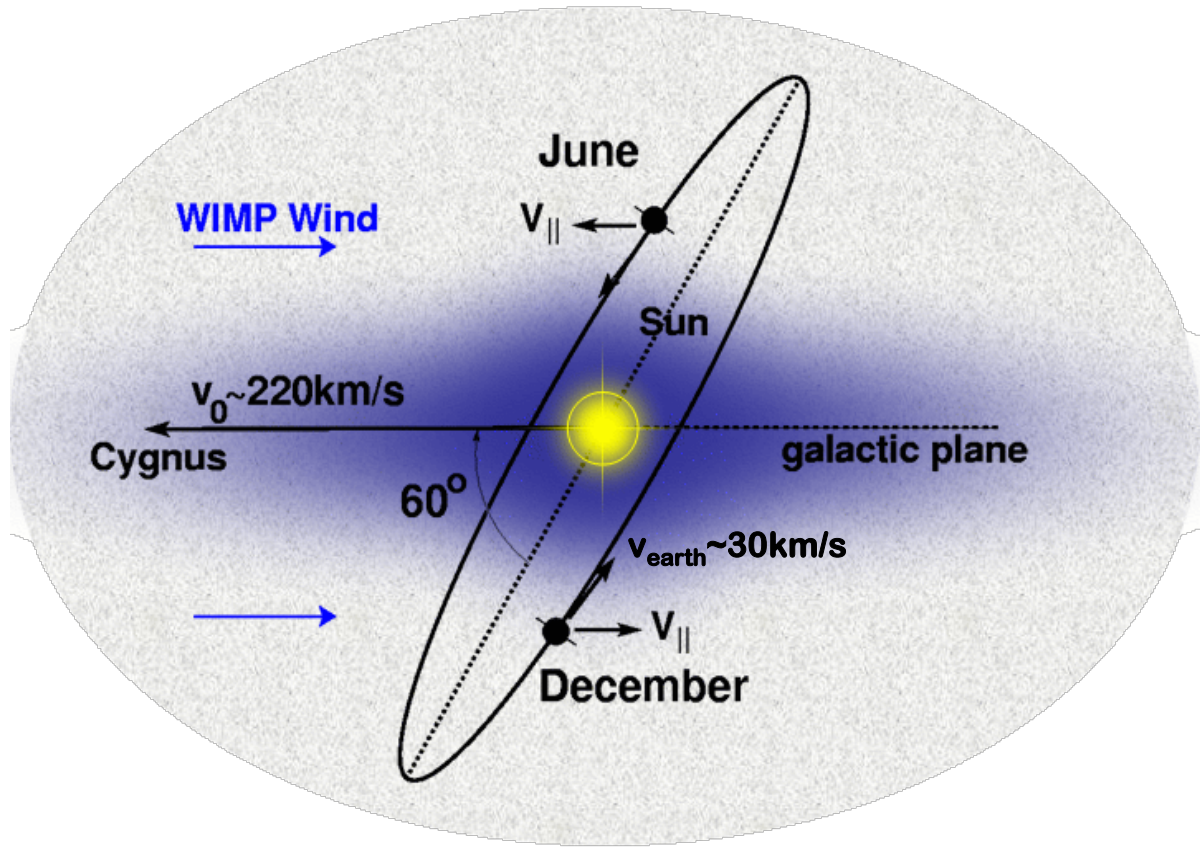
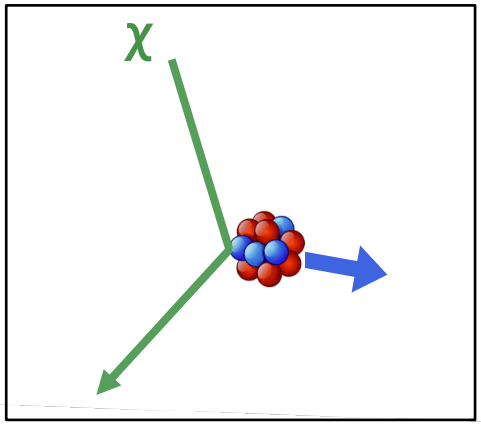


Image credit: www.hep.shef.ca.uk/research/dm/intro.php

WIMP Direct Detection

- WIMPs scatter elastically from nuclei, inducing low energy nuclear recoils
  - <~100 keV
- Cross section of $10^{-44} - 10^{-45}$ cm² *per nucleon* for "standard" WIMP
  - ~10-100 interactions/tonne/yr



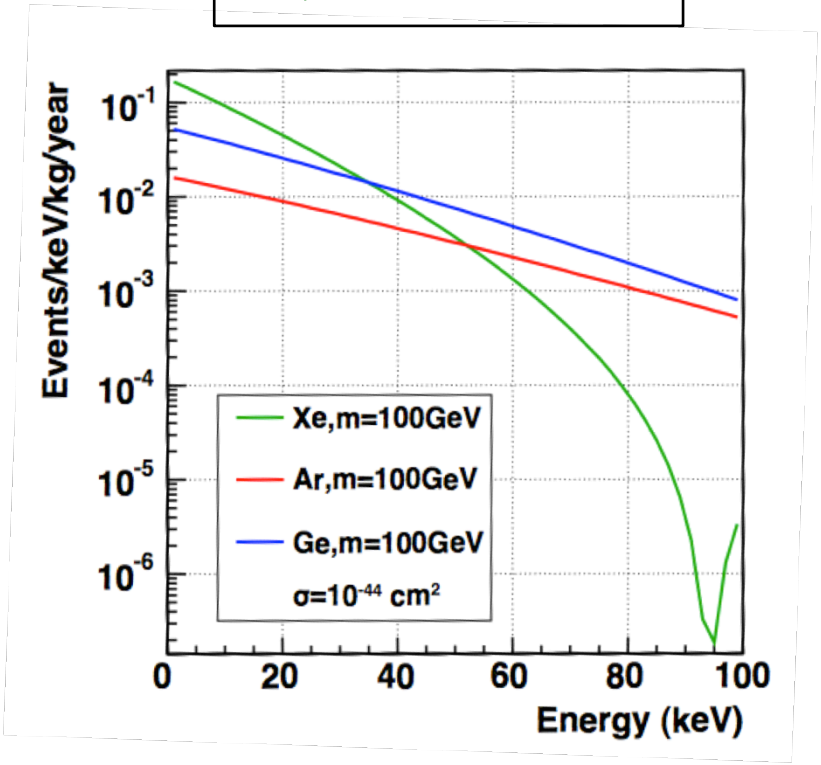
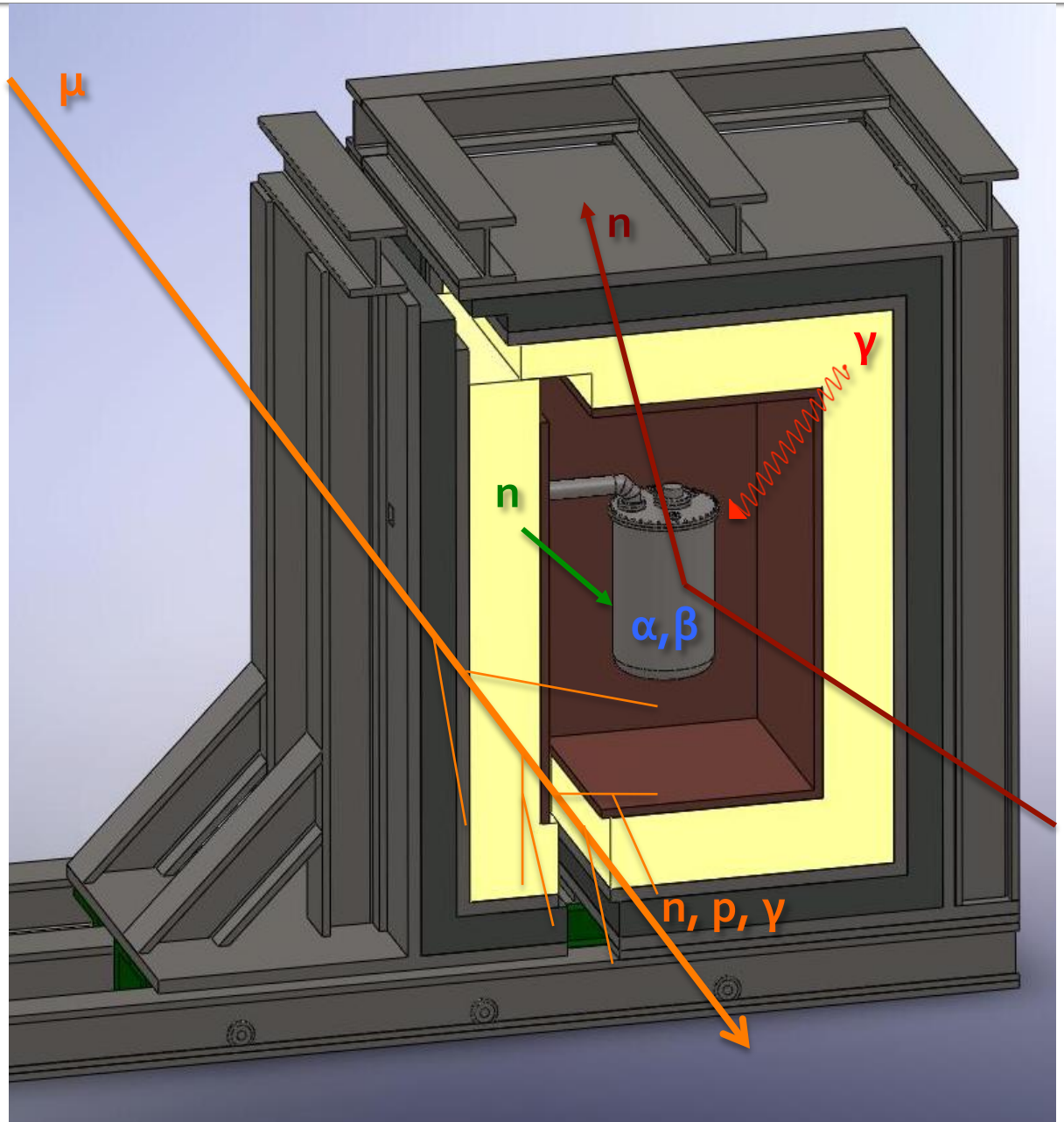


Image credit:777icons.com

Central Challenge: Background



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

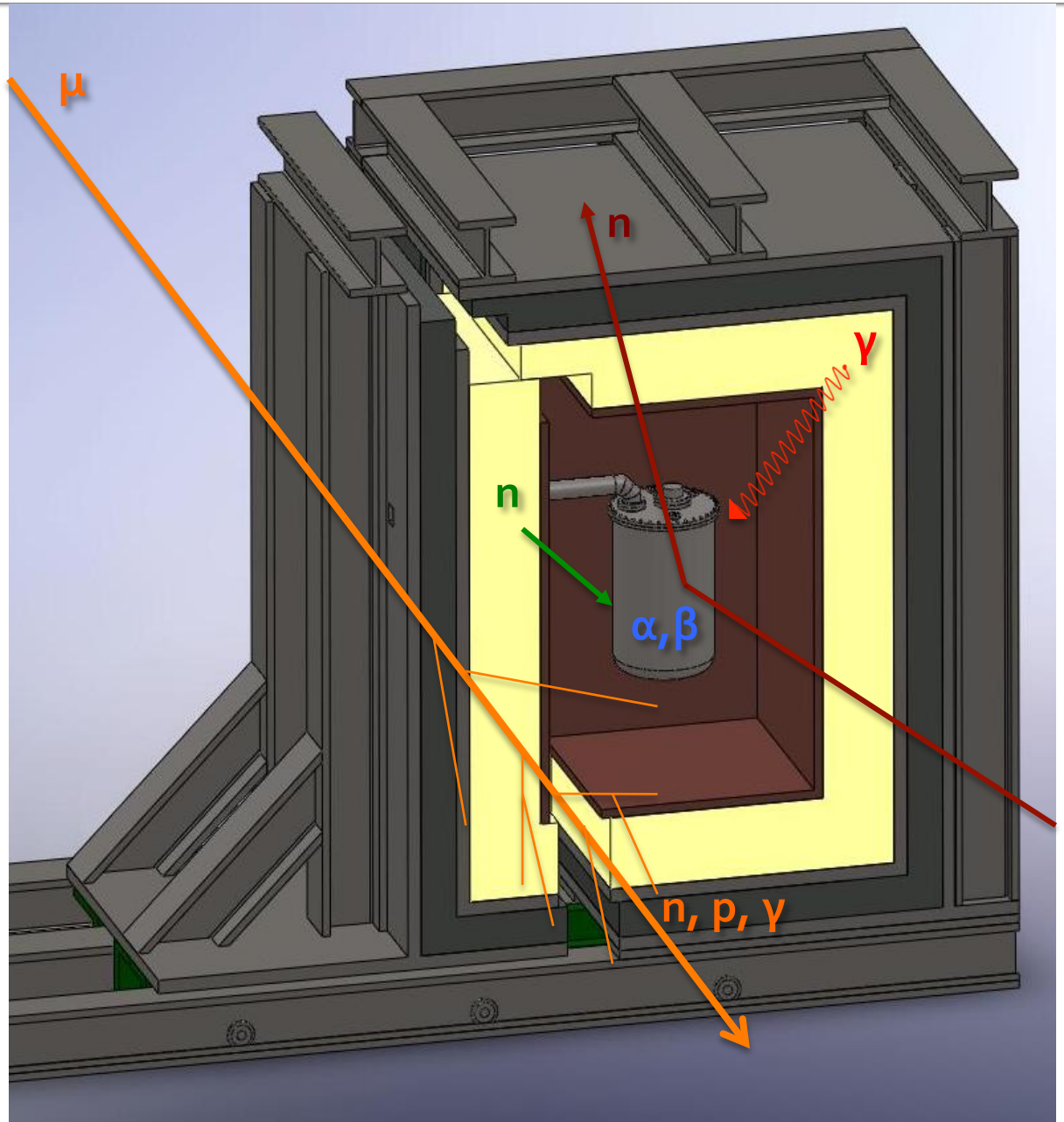
Gamma Rays
external and from shielding

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

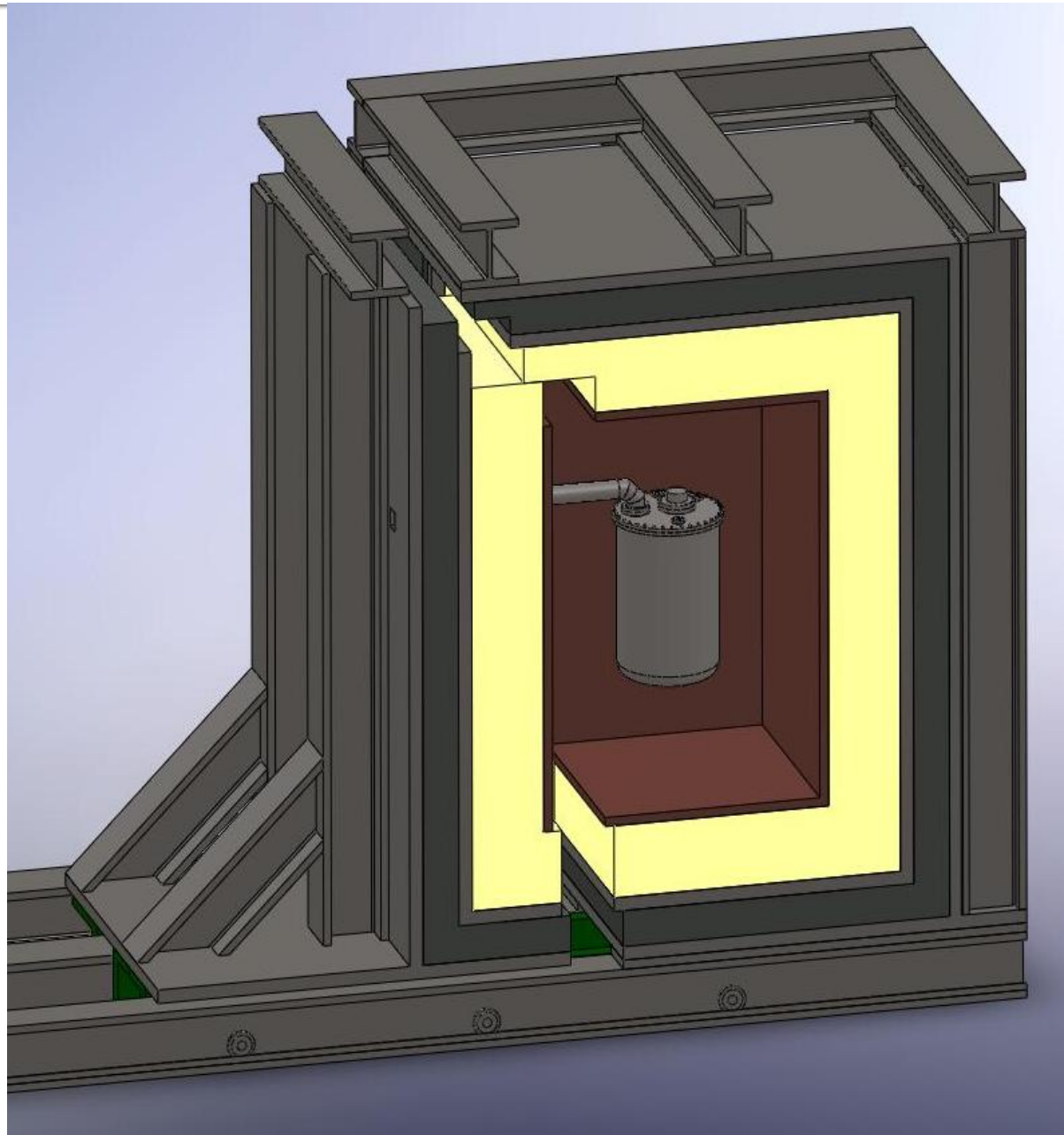
Dust: ~7000 decays/mg-yr

Air: >300 decays/mL-yr

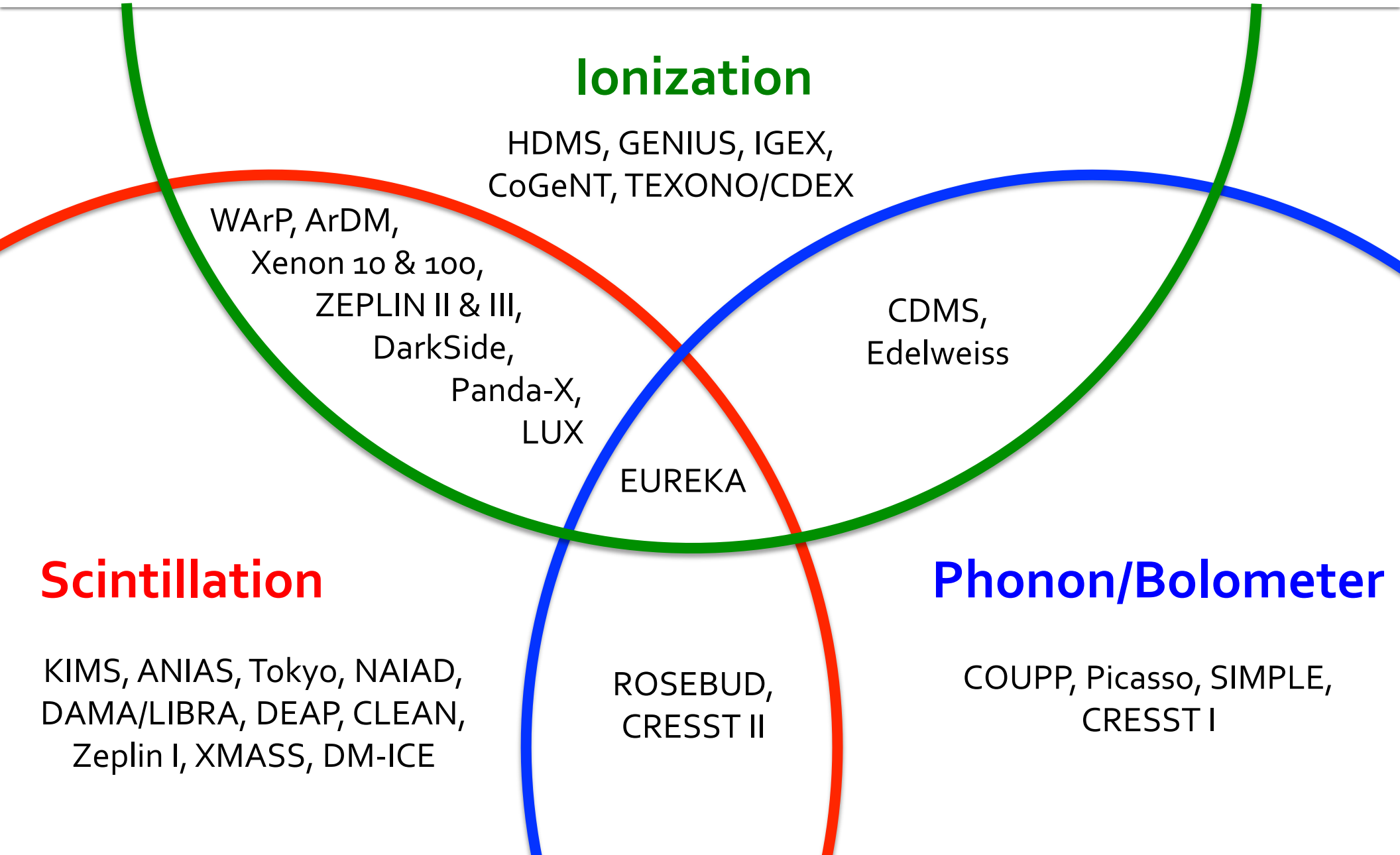
Fingerprint: ~10 decays/yr

Ideal WIMP Detector

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

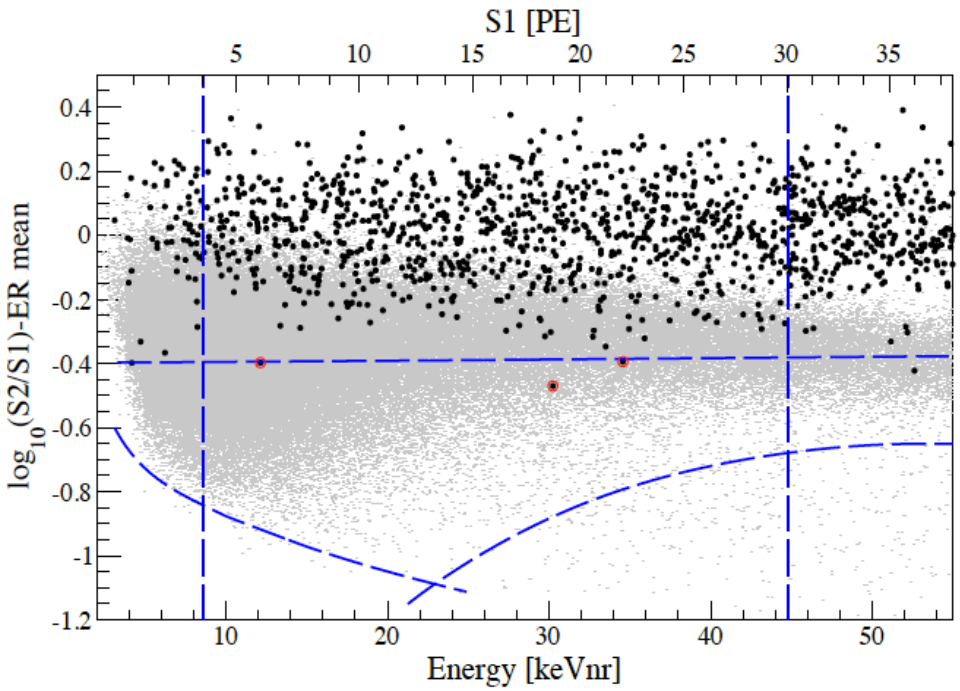


WIMP Detection Experiments



Leading Experiments

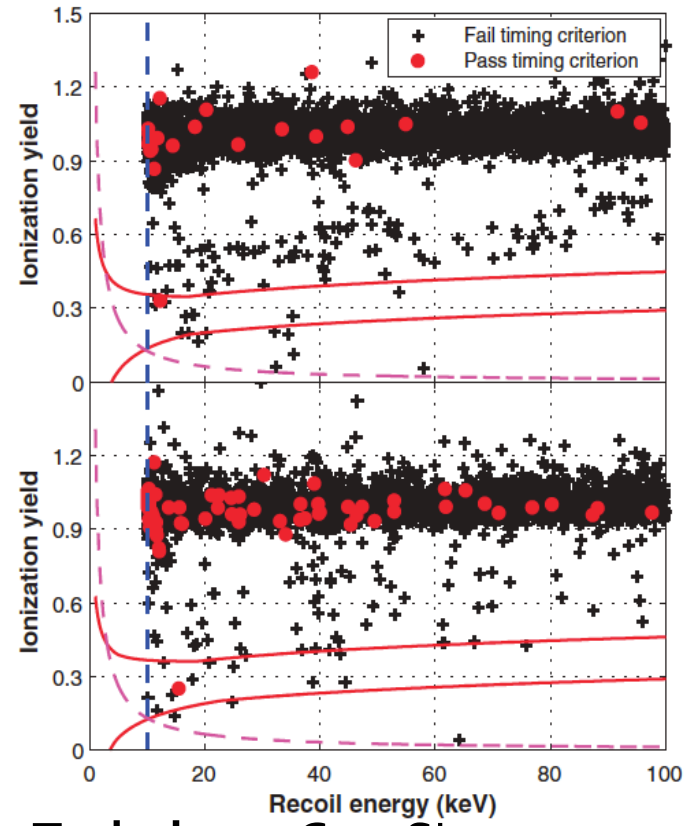
Xenon100



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

PRL **107**:131302 (2011)

CDMS

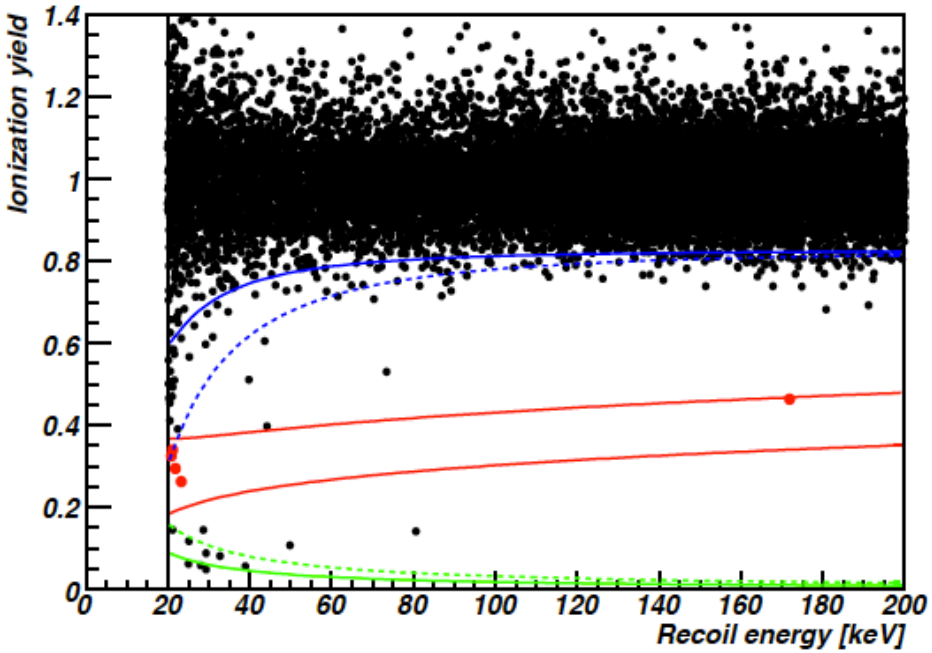


Technique: Ge + Si,
Ionization + bolometric
Exposure: 612 kg-days
Expect: 0.9 ± 0.2 background events
Observe: 2 events

Nature **327**:1619 (2010)

Leading Experiments

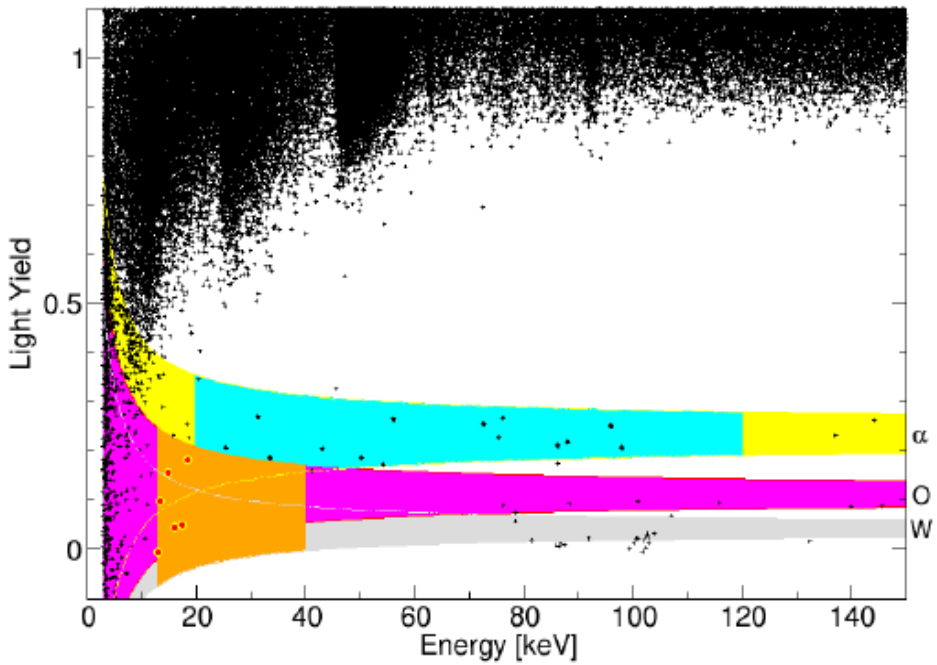
Edelweiss



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

PLB **702**:329 (2011)

Cresst

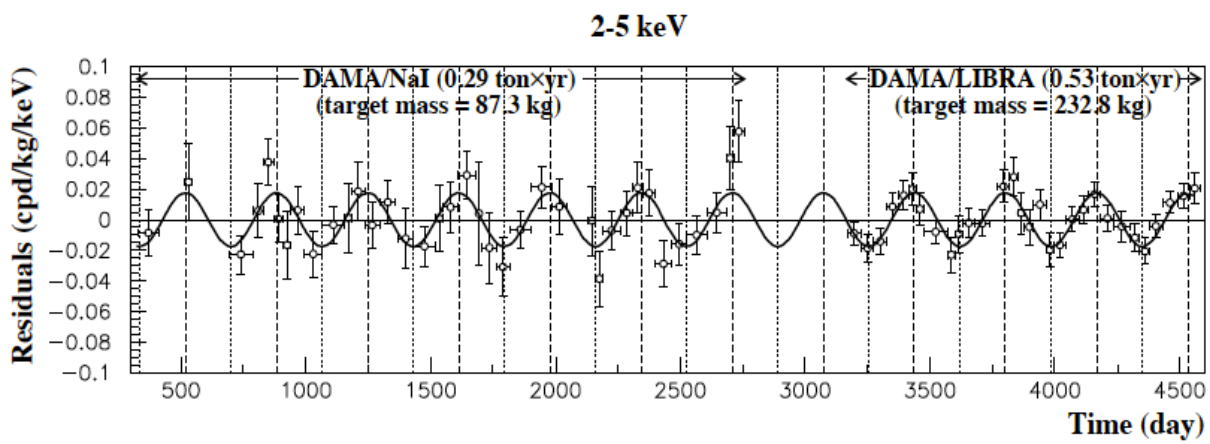


Technique: $CaWO_4$,
scintillation + bolometric
Exposure: 730 kg-days
Observe: $29.4^{+8.6}_{-7.7}$ ($24.2^{+8.1}_{-7.2}$) events above background of 42-48 events

arXiv:1109.0702

Leading Experiments

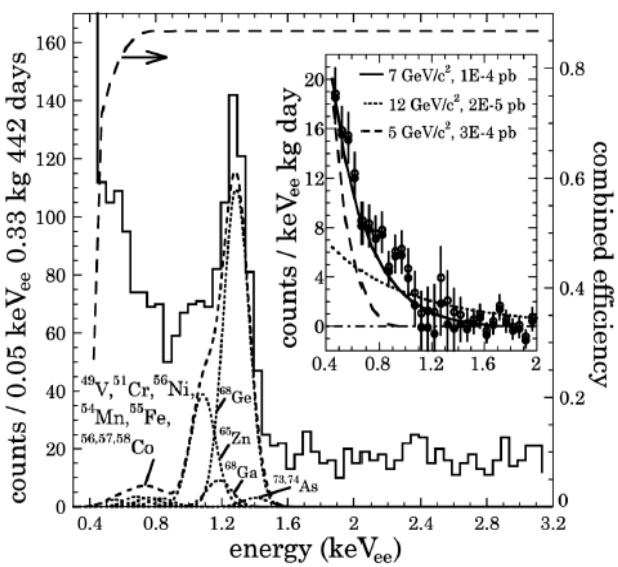
DAMA/LIBRA



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

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

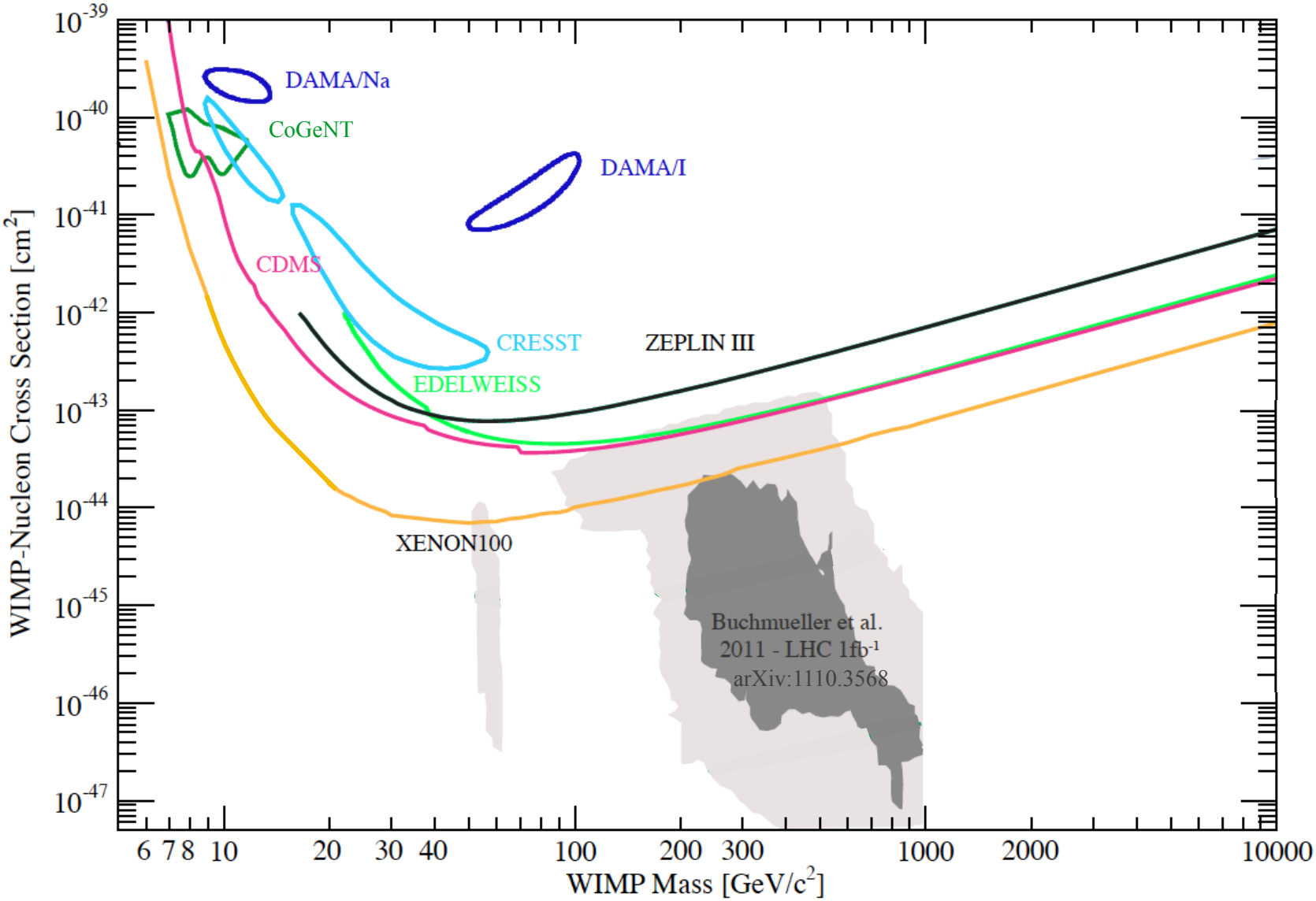
CoGeNT



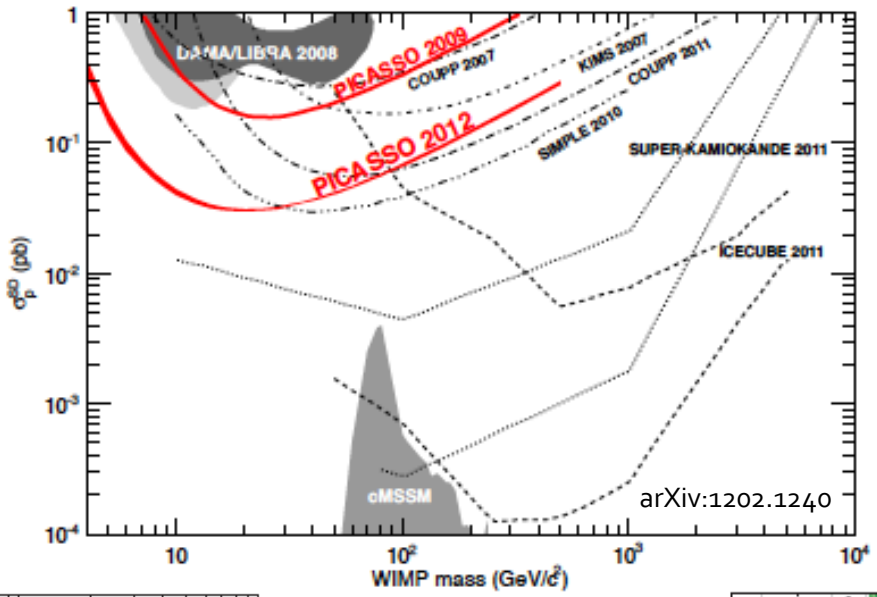
Technique: Ge, ionization
Exposure: 146 kg-days
Observe: Excess events at low energy, probably an annual modulation

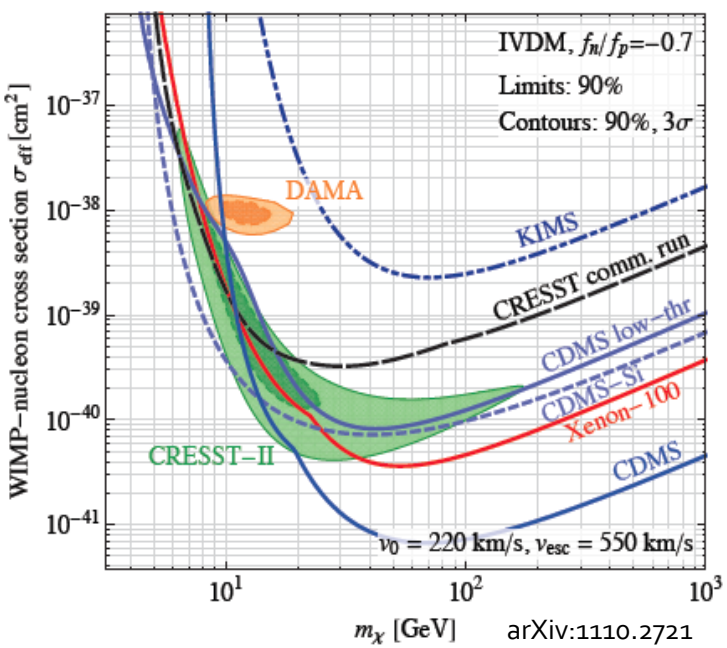
PRL **106**:131301 (2011),
PRL **107**:141301 (2011)

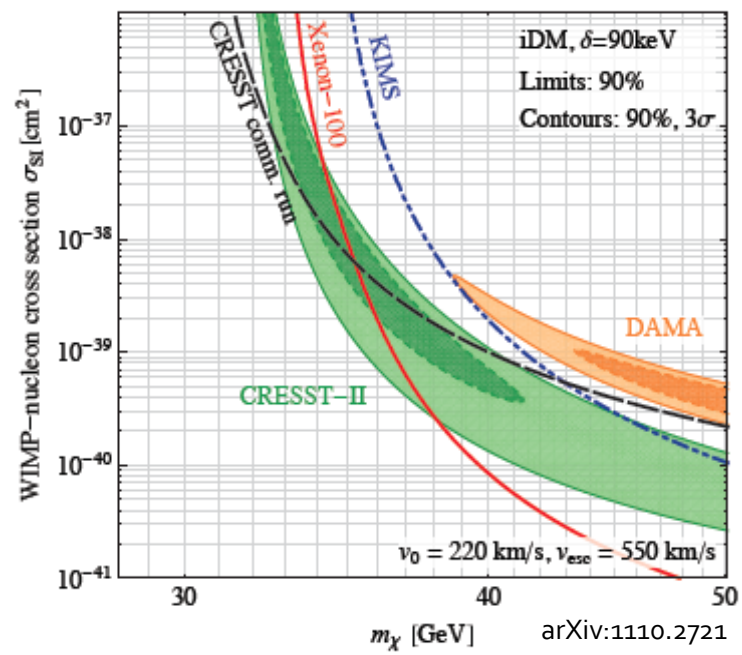
The Current Status



The Current Status







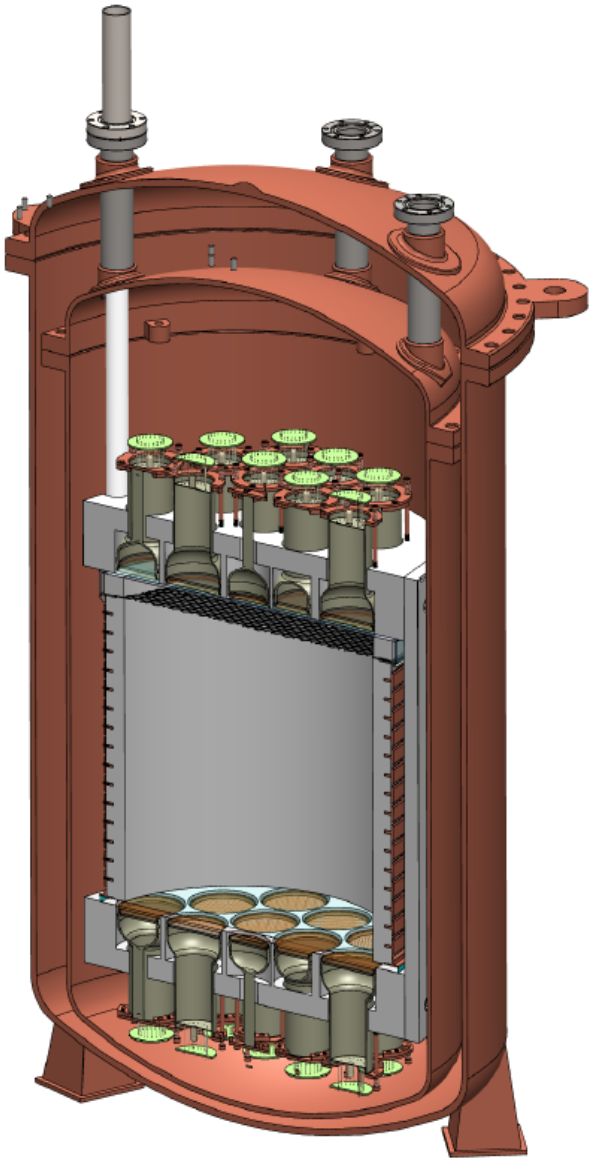
The Current Status

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

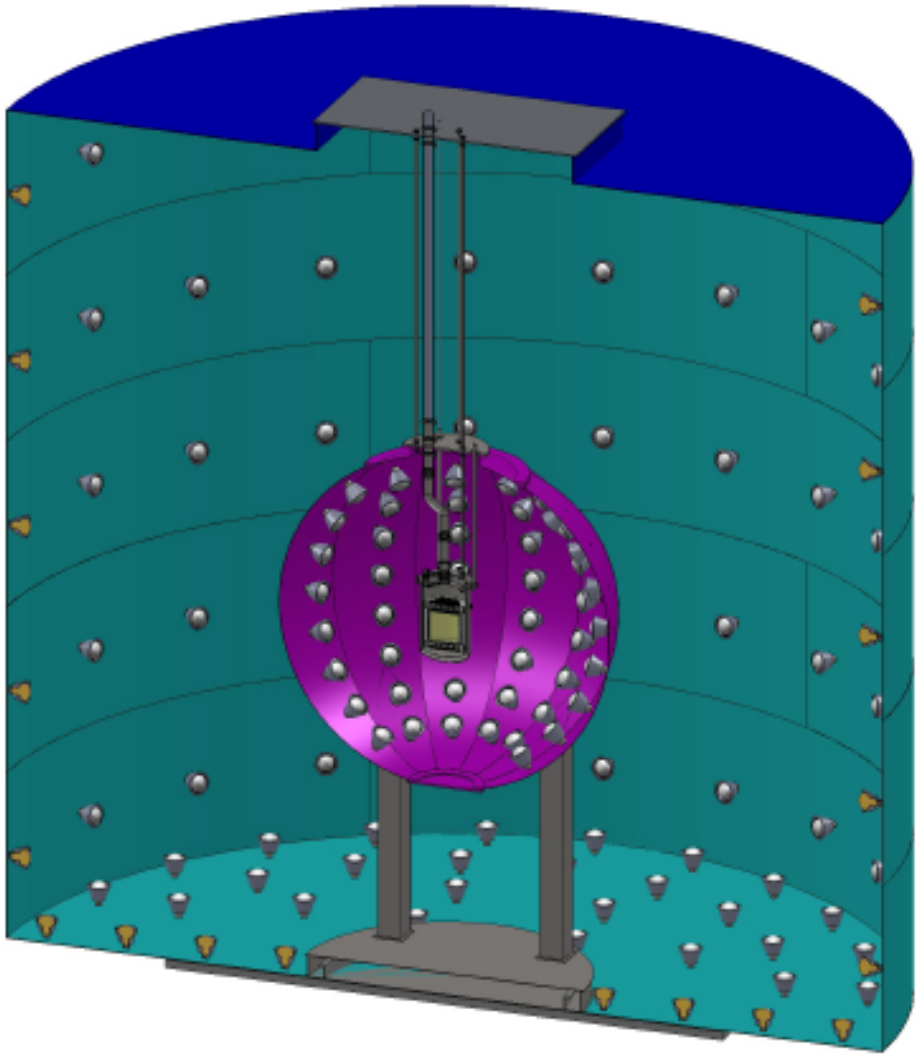
DarkSide

- 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



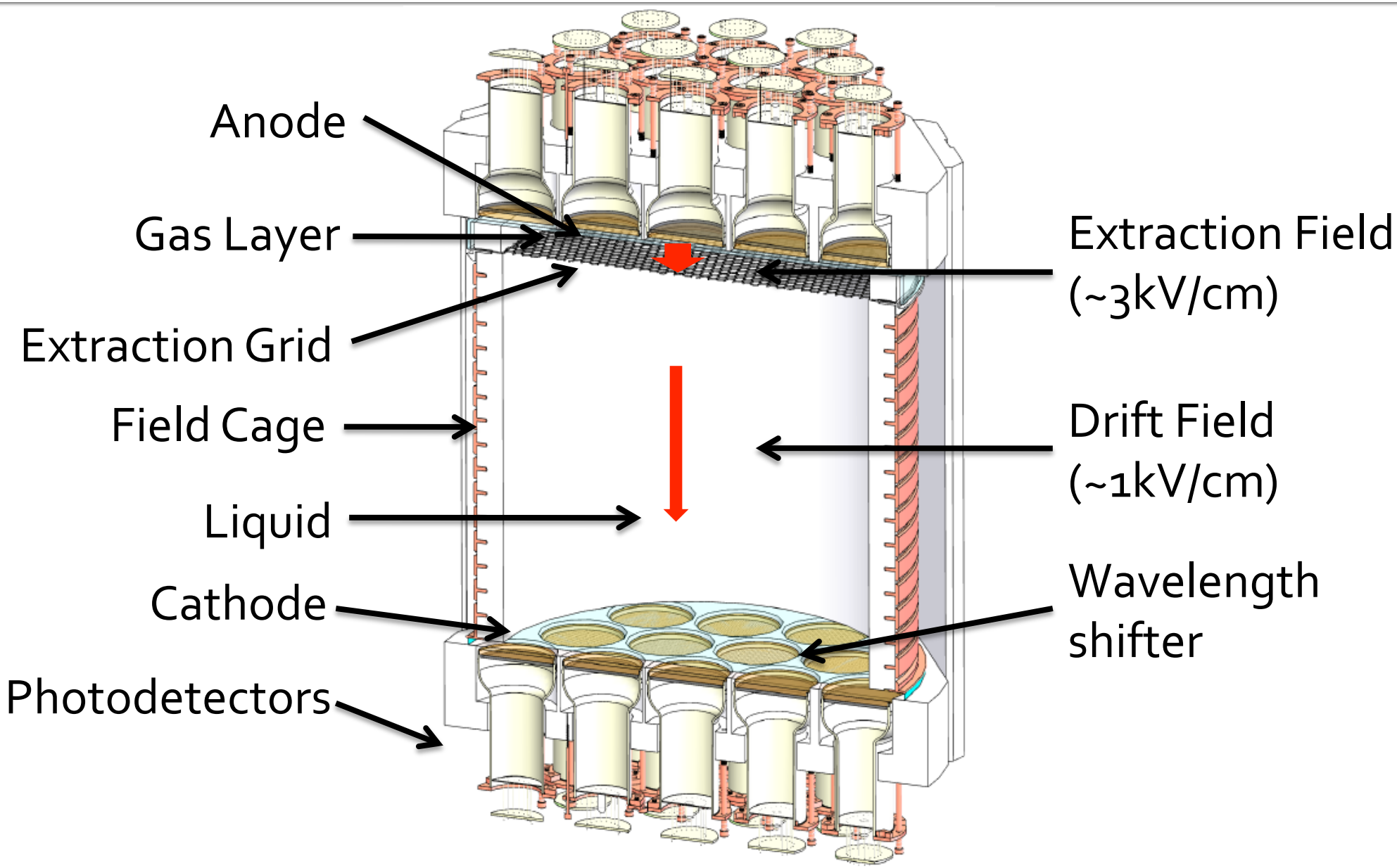
Darkside Collaboration

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?

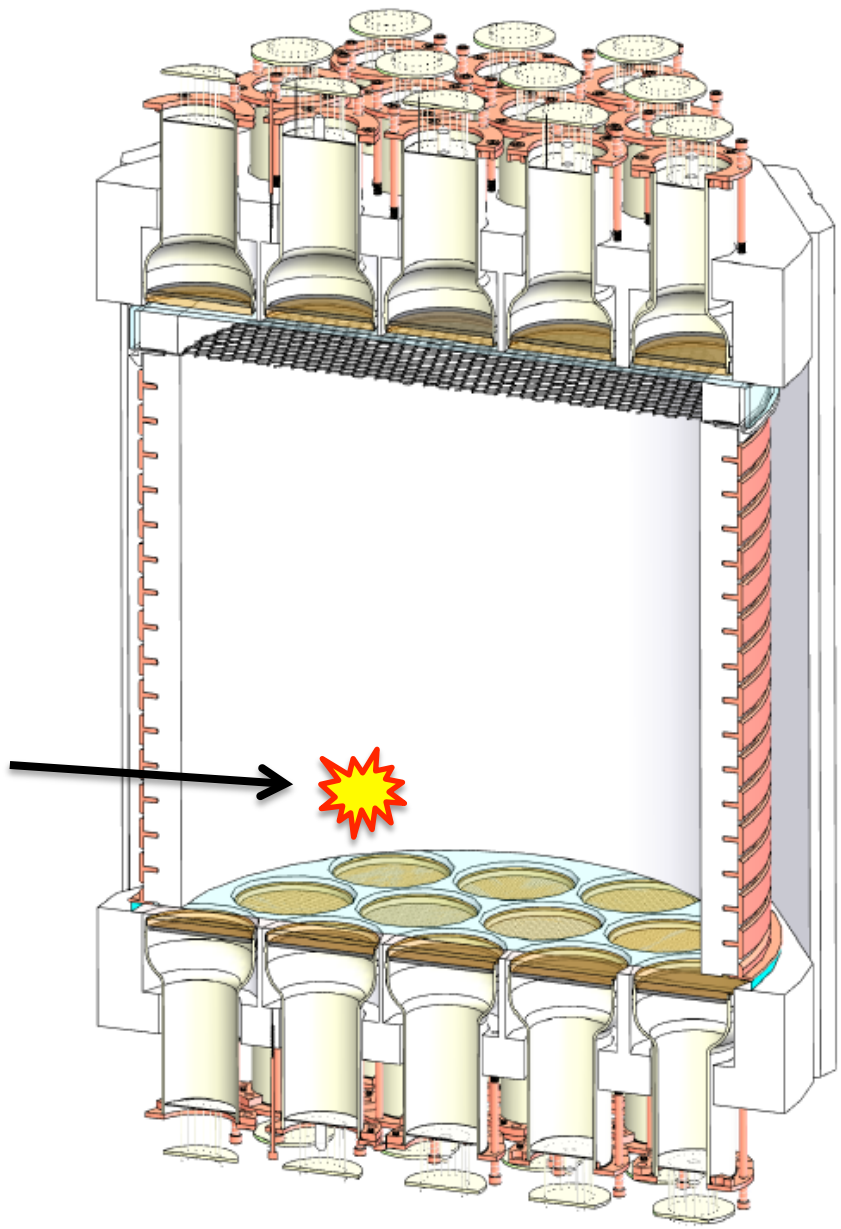
- Liquid argon is a great dark matter target
  - Good scintillator (~40,000 photons/MeV)
  - Very transparent to its own scintillation light
  - Easily purified
- Relatively inexpensive technology, could be scaled to multi-tonne detectors
  - Need to suppress ^{39}Ar
- Very powerful rejection capability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

2-Phase Argon TPC

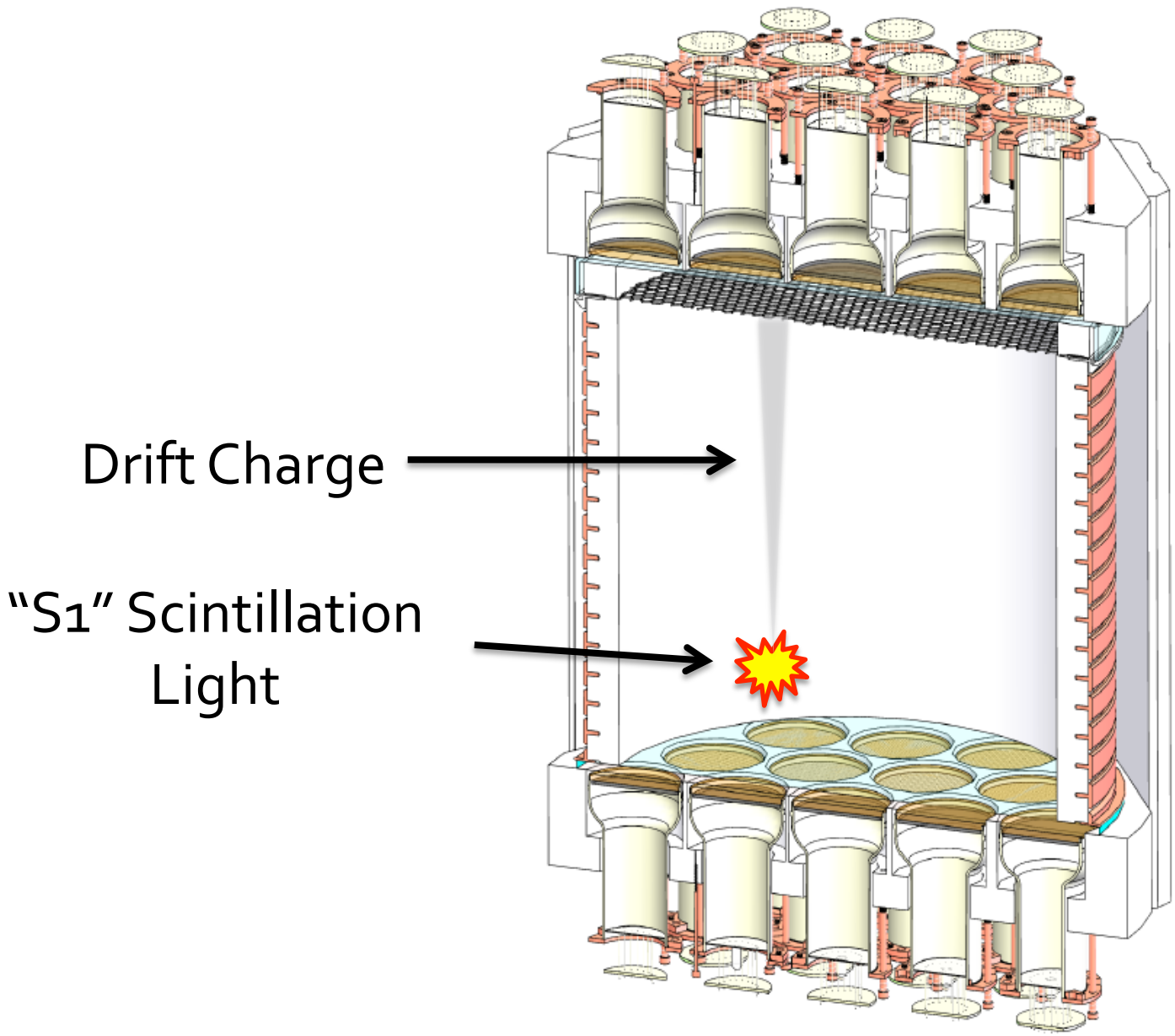


Two Phase Argon TPC

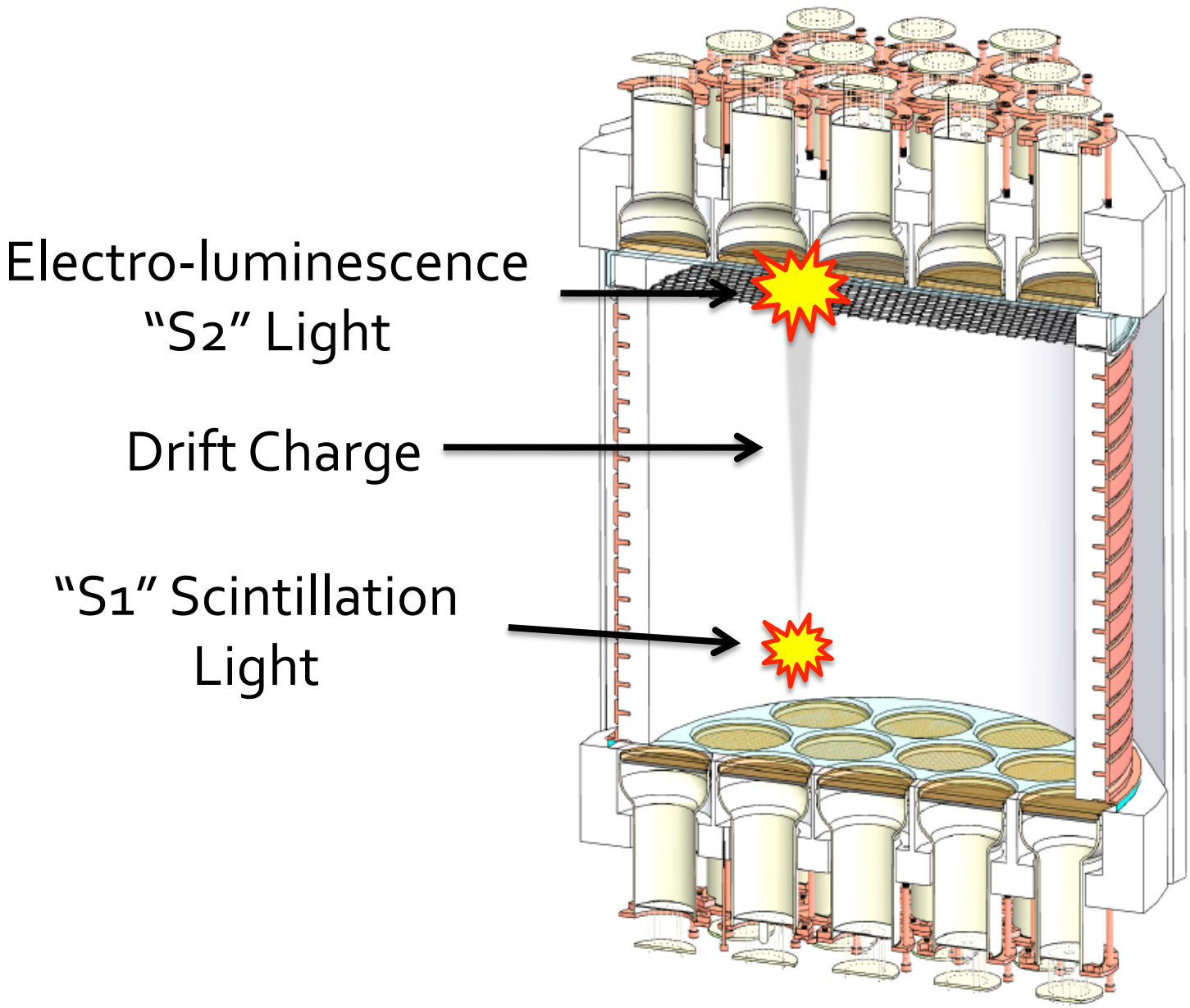
"S1" Scintillation Light



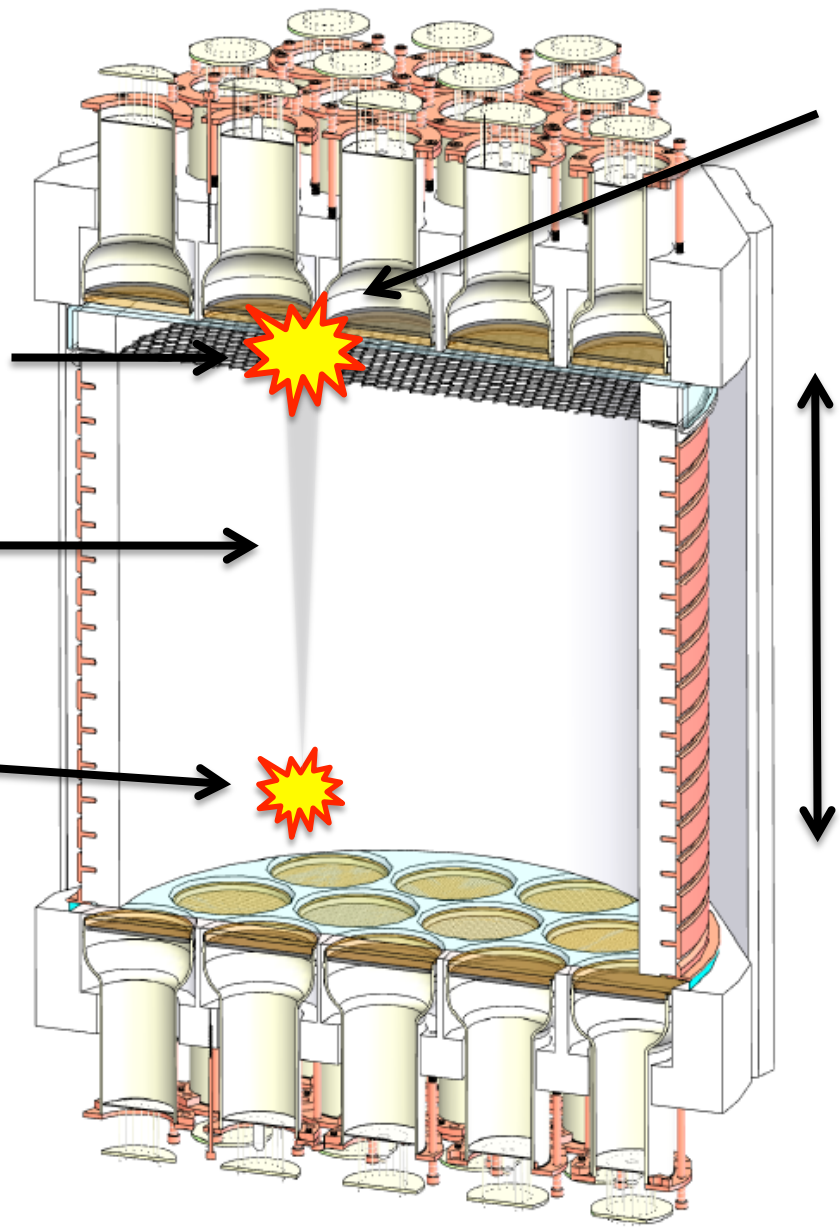
Two Phase Argon TPC



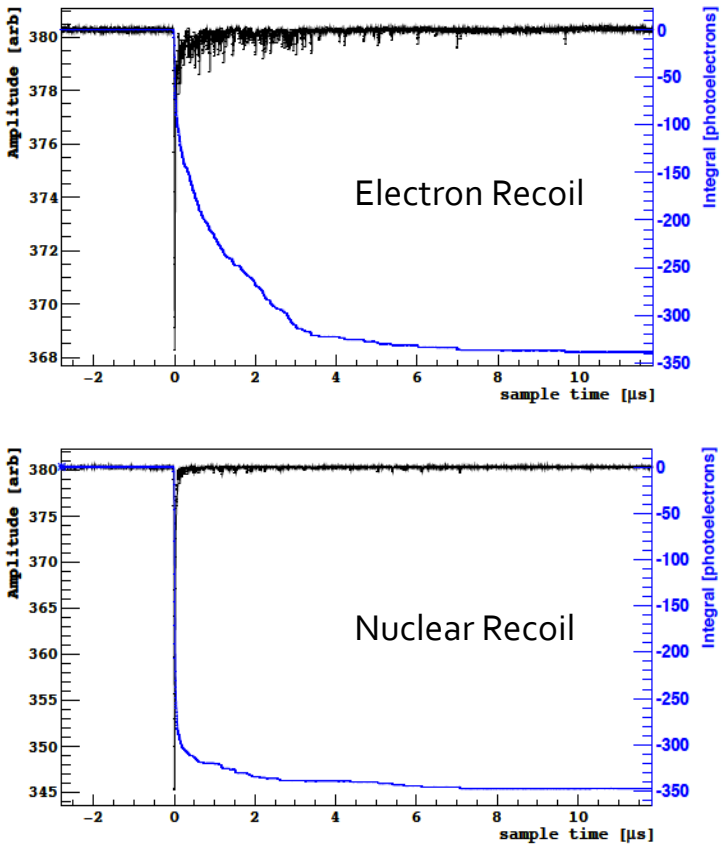
Two Phase Argon TPC

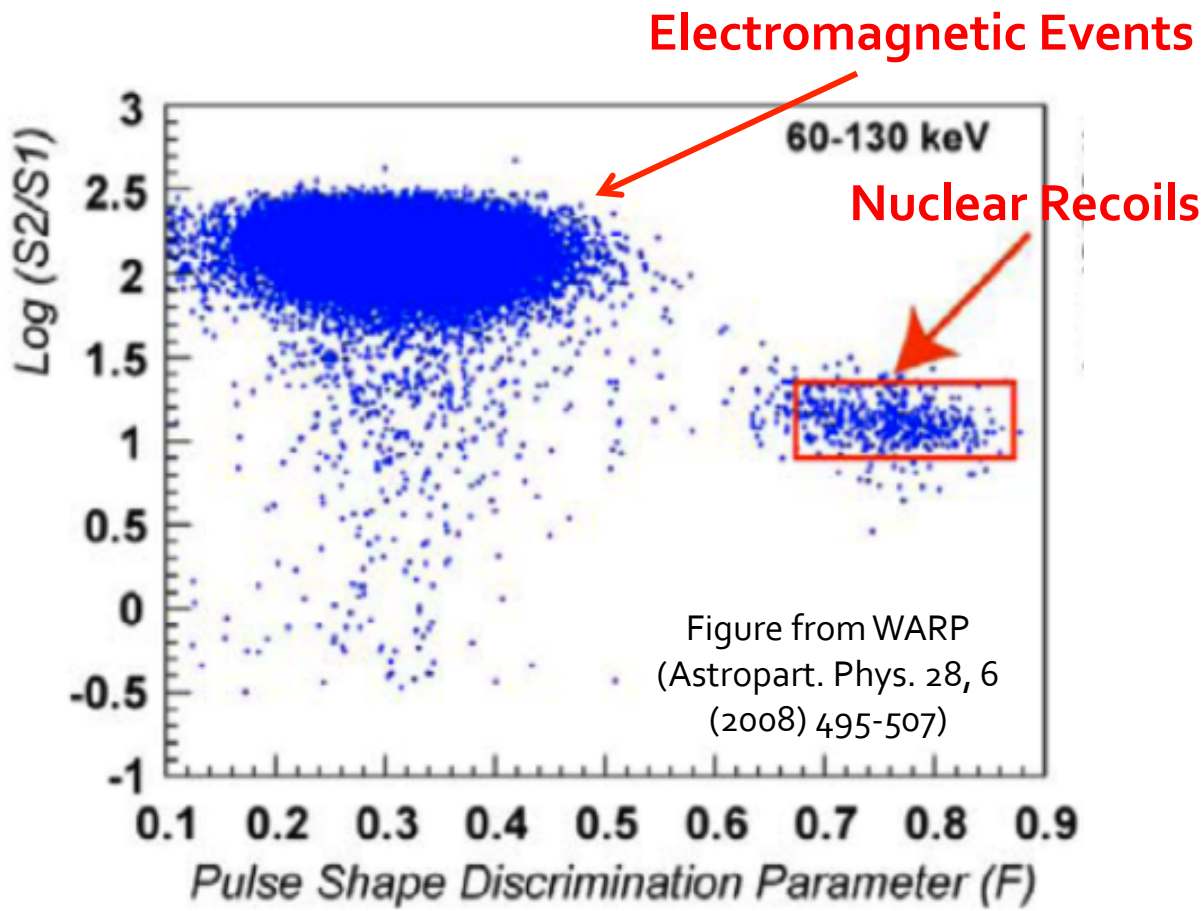


Two Phase Argon TPC



"S1" Electron Recoil Discrimination

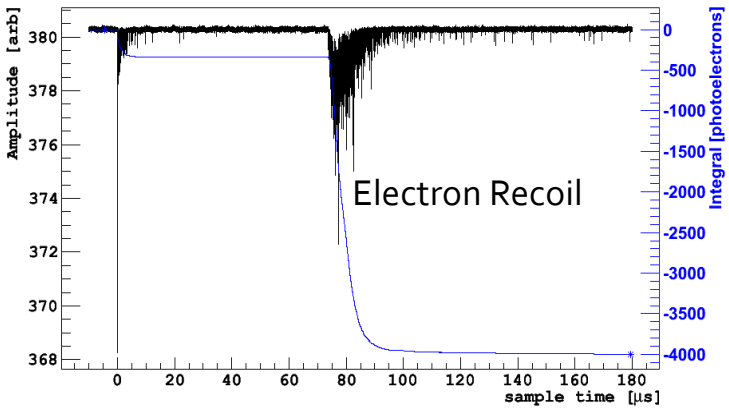


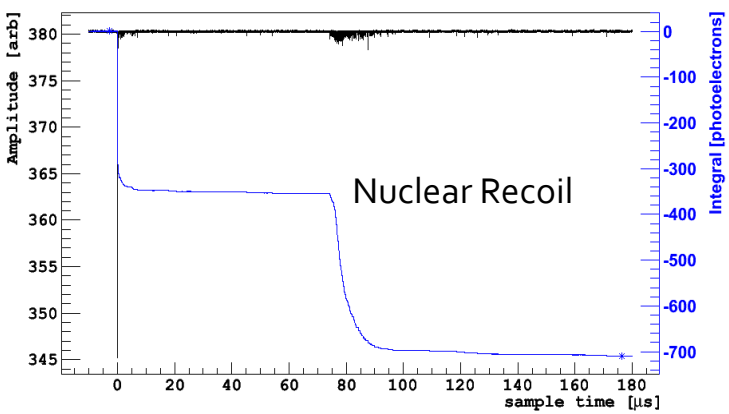


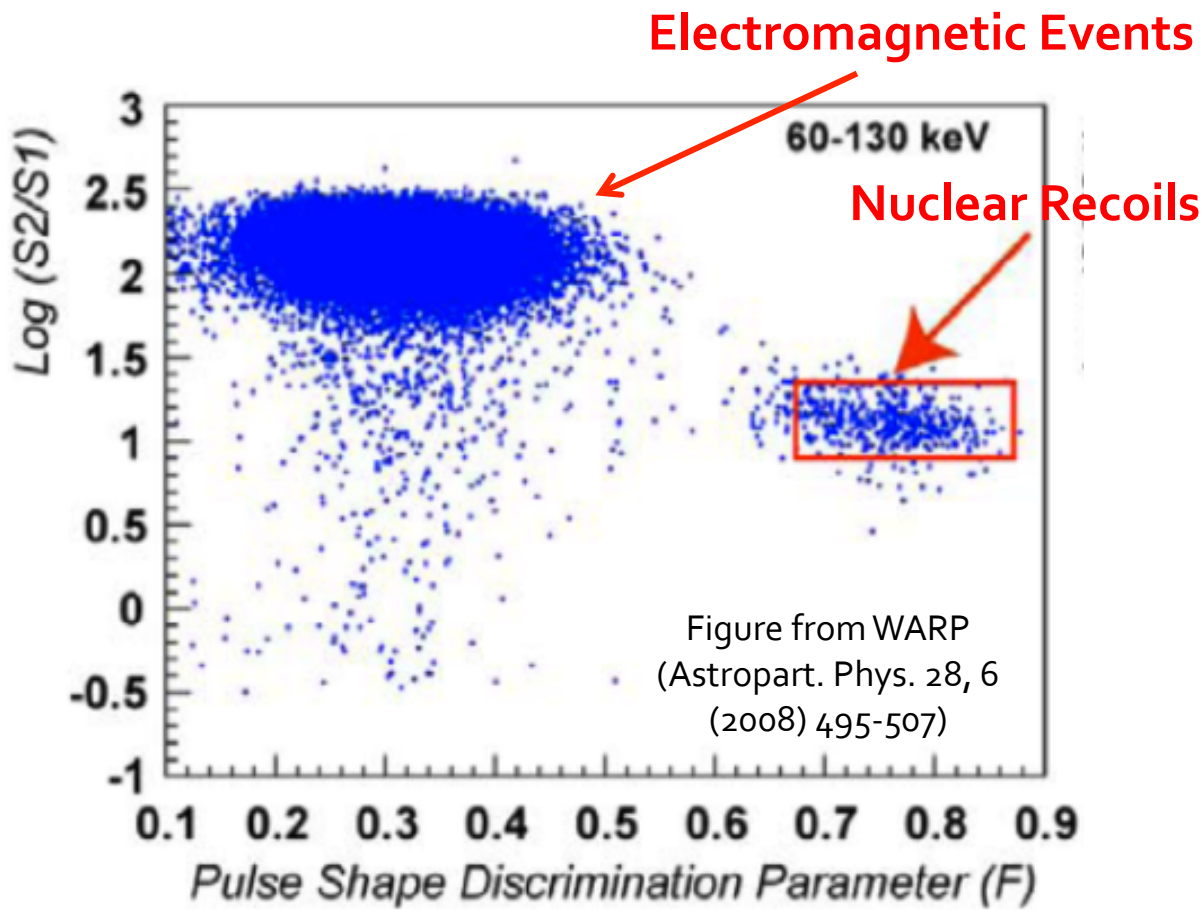
- The ratio of light from singlet (~7 ns decay time) and triplet (1.6 µs decay time) depends on ionization density

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

"S2/S1" Electron Recoil Discrimination



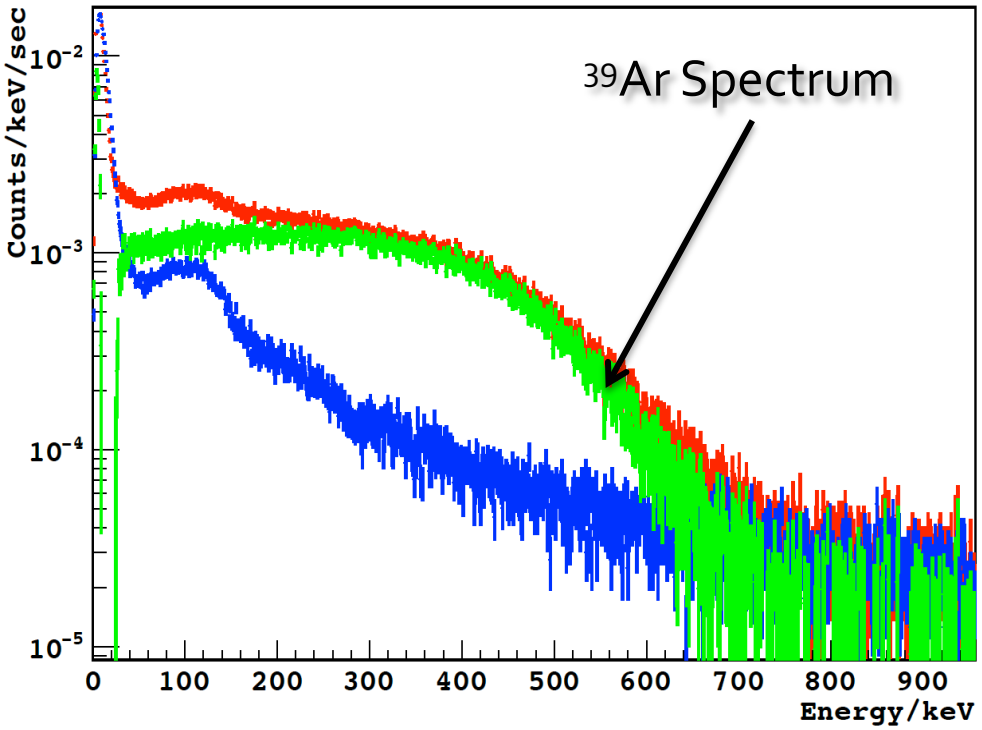




- The recombination probability (and hence the ratio of S2:S1 light) also depends on ionization density
  - ➡ 10^2-10^3 additional discrimination
  - ➡ *>10^{10} total electron recoil rejection in 2D*

^{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!



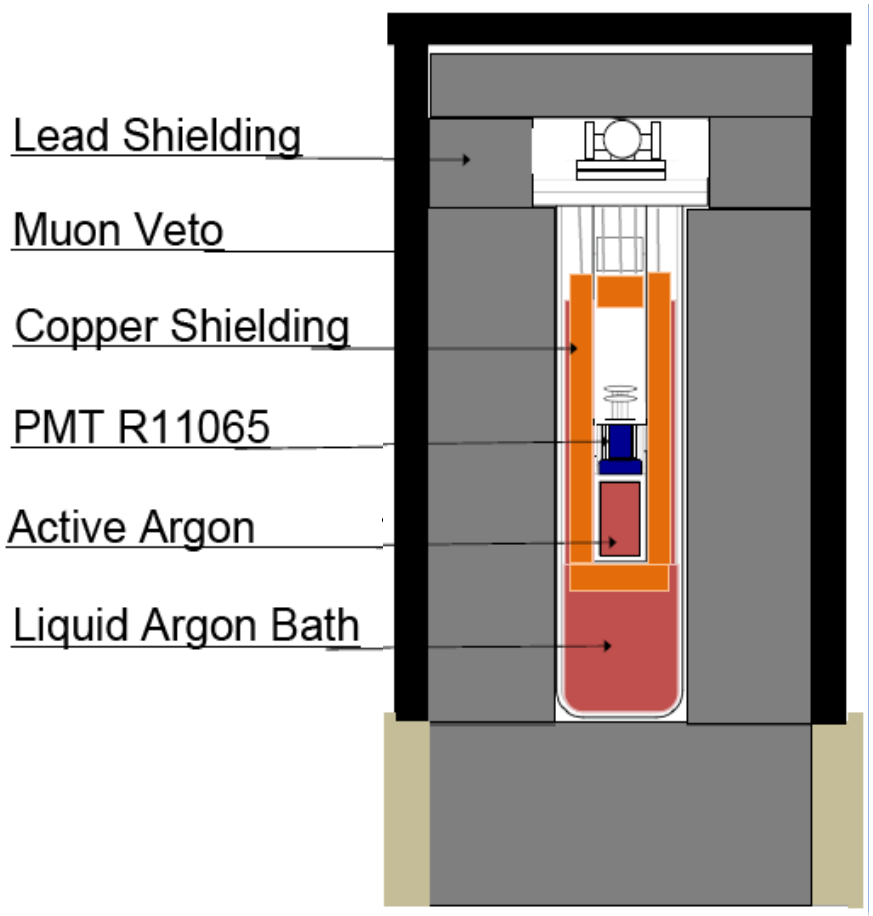
Underground Argon

- Underground argon is shielded, 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)

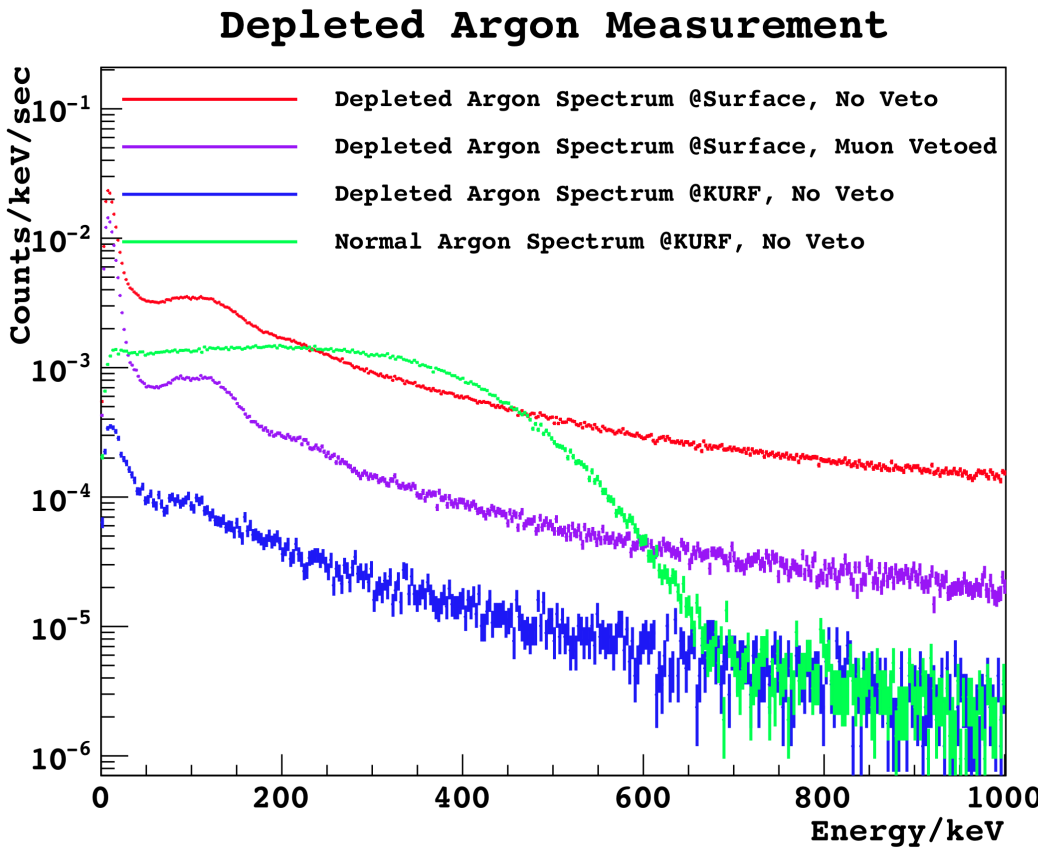
Underground Argon Counting

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

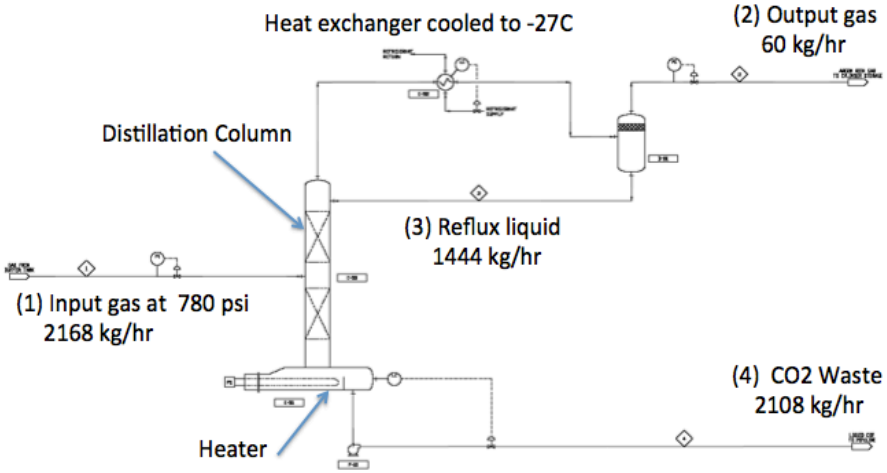


Multi-ton argon experiments possible with underground argon!

Multi-Tonne Underground Argon

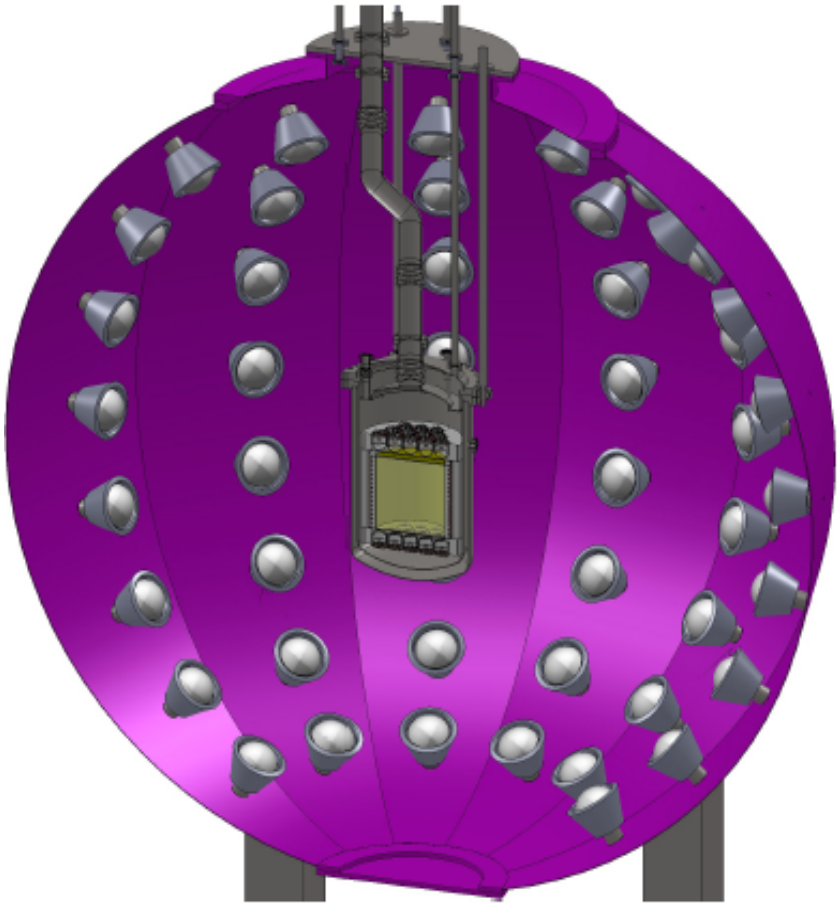
- DarkSide and DEAP will collaborate to expand the argon extraction facility in Cortez
  - 5000 kg for DarkSide
  - 4000 kg for DEAP
- Install a high-pressure "pre-distillation" to increase the argon concentration in the gas that is fed to the current pressure swing adsorption system
  - Aim for 50 kg/day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

Process Flow Diagram



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

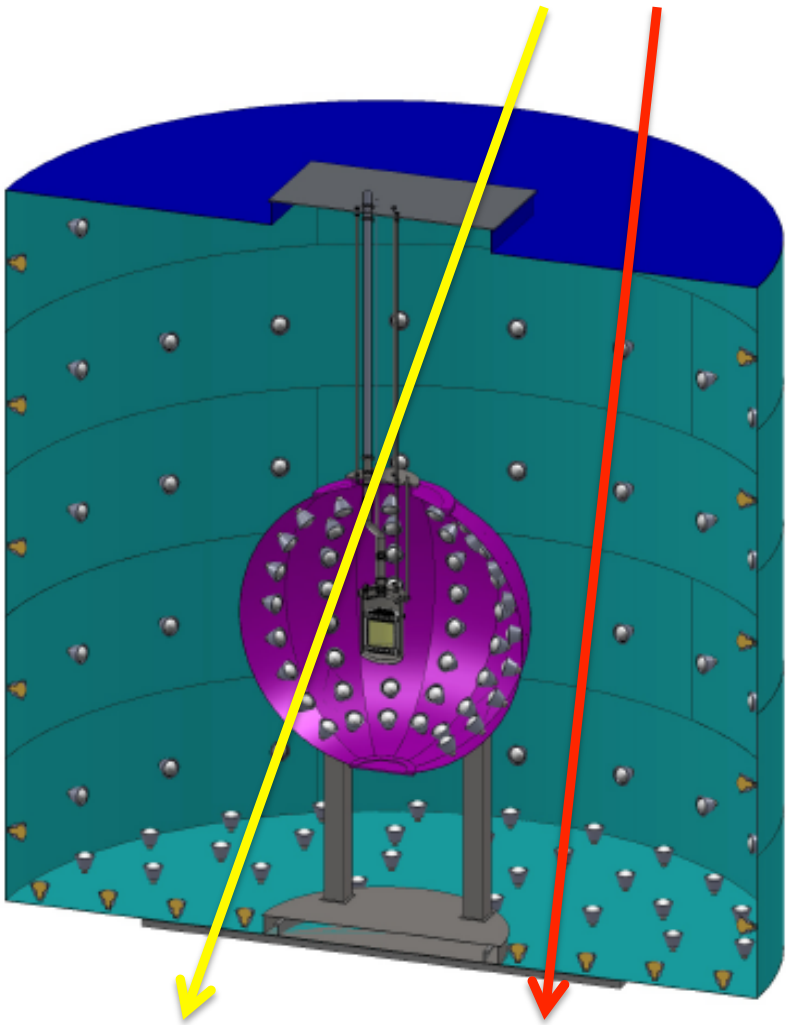
$$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha \rightarrow {}^{7}Li + \alpha + 478\ \text{keV}\ \gamma \qquad (93.7\%)$$
$$\rightarrow {}^{7}Li + \alpha \qquad (6.4\%)$$

- 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)

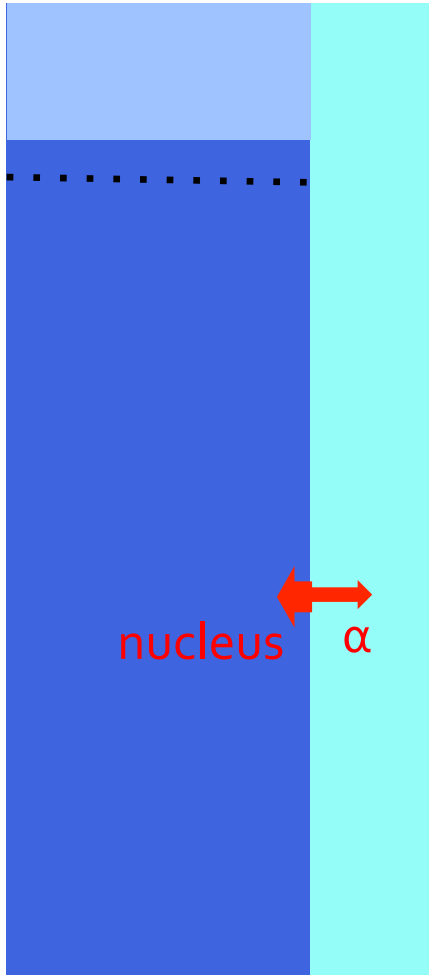
Cosmogenic Neutrons

- 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 $>>10^3$



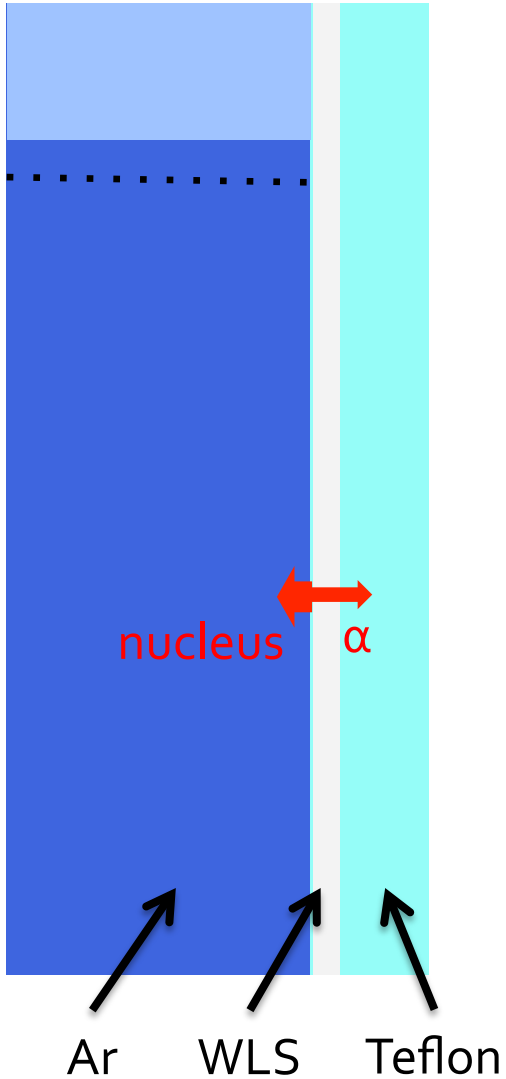
Surface Background

- 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



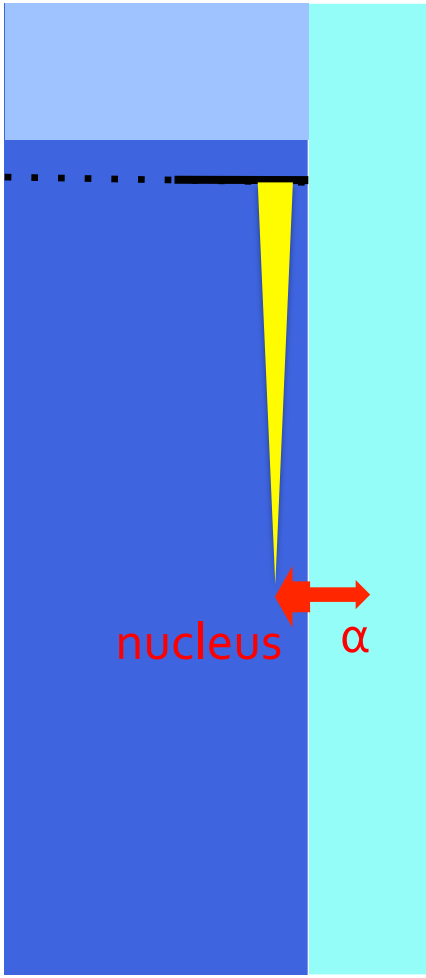
Surface Background

- 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):

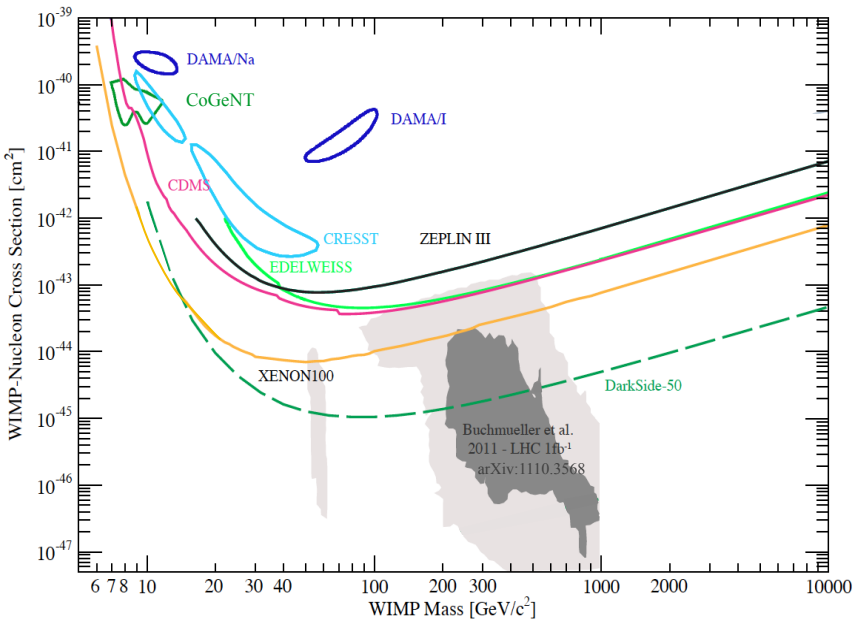
Detector Element	Electron Recoil Backgrounds		Radiogenic Neutron Recoil Backgrounds		Cosmogenic Neutron Recoil Backgrounds	
	Raw	After Cuts	Raw	After Cuts	Raw	After Cuts
^{39}Ar (<0.01 Bq/kg)	$<6.3\times10^{6}$	$<4\times10^{-3}$	–	–	–	–
Fused Silica	3.3×10^{4}	2.0×10^{-5}	0.17	4.3×10^{-4}	0.21	1.3×10^{-5}
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

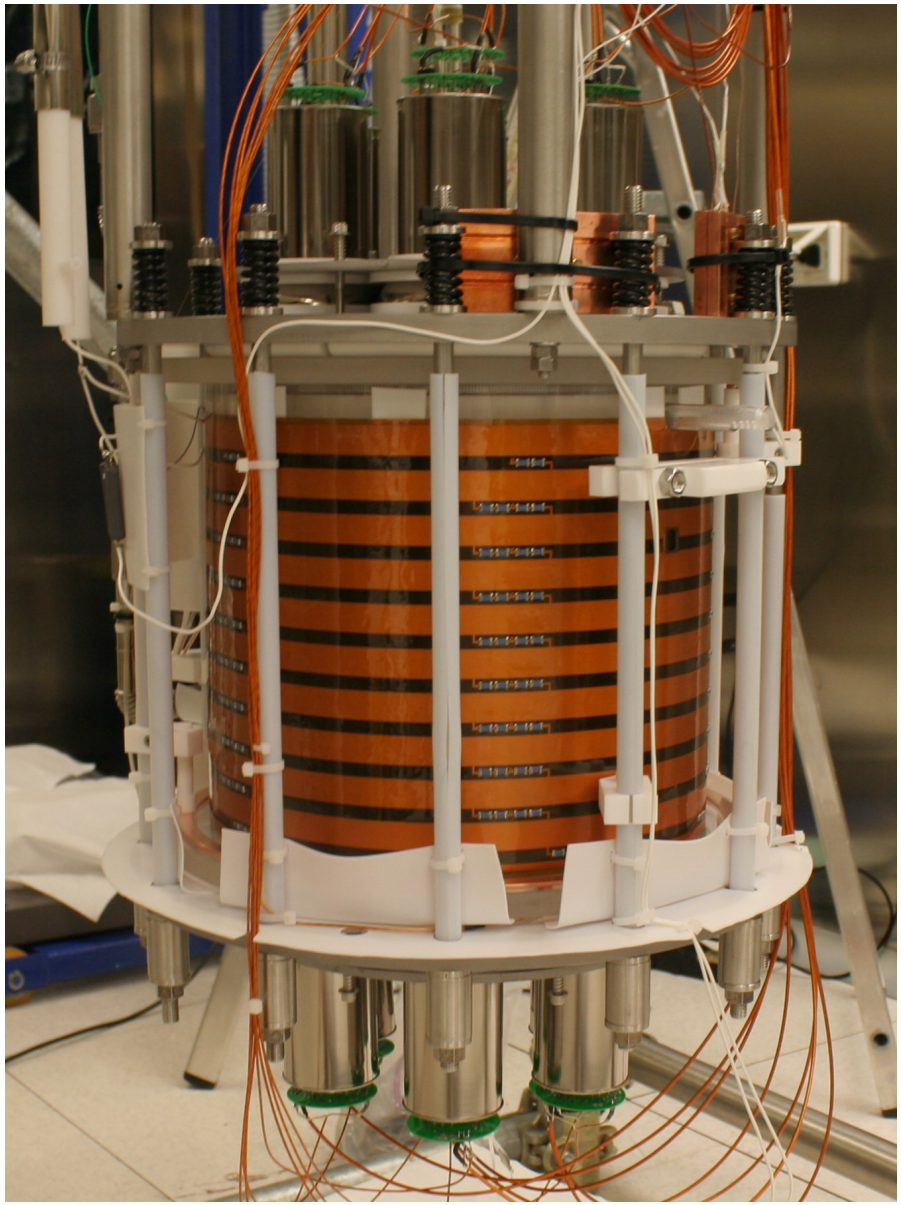
- Background free operation for 0.1 tonne-yr gives 10^{-45}cm² sensitivity
- Background measurement from active suppression gives precise understanding of residual background rate
  - Credible detection claim possible based on a few observed events!



Detector commissioning expected in late 2012.

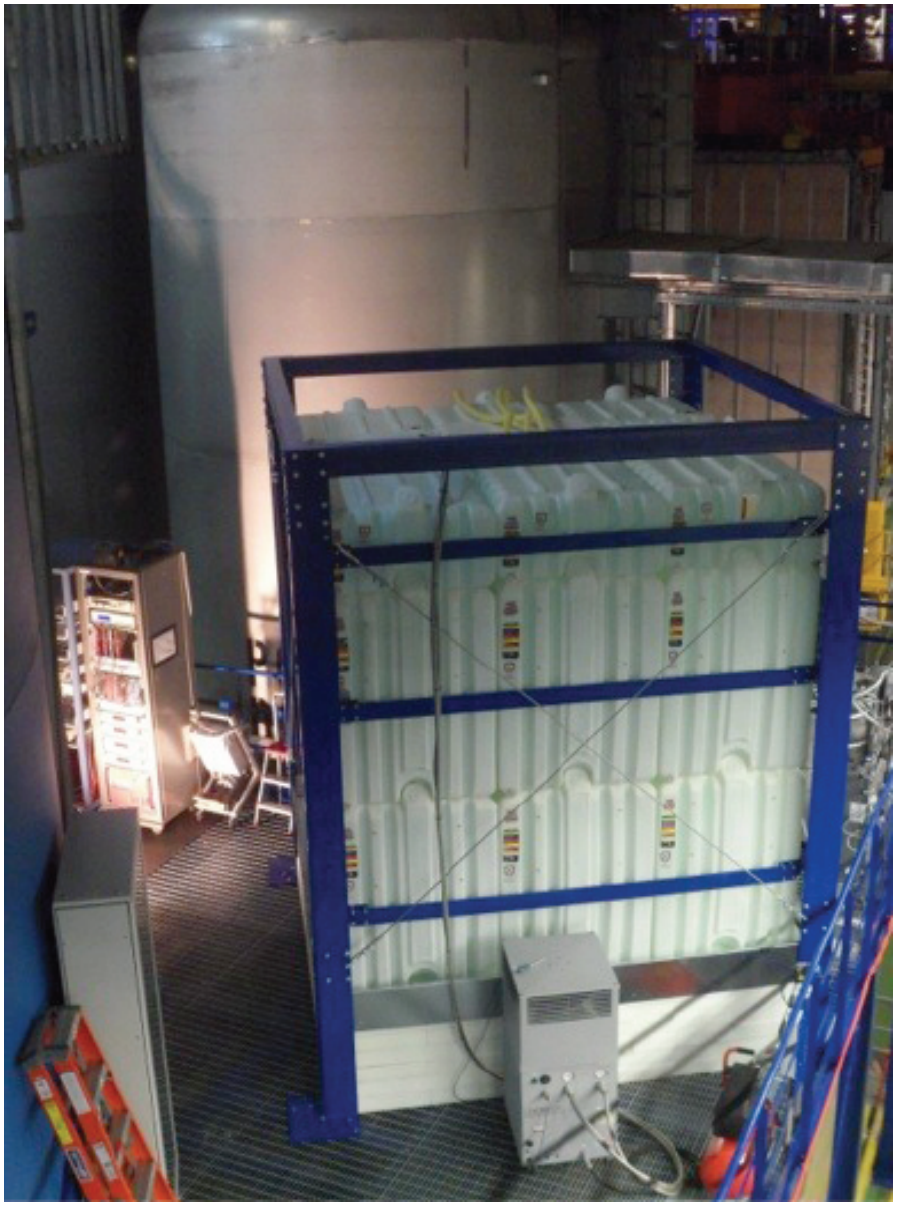
DarkSide-10 Prototype

- 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



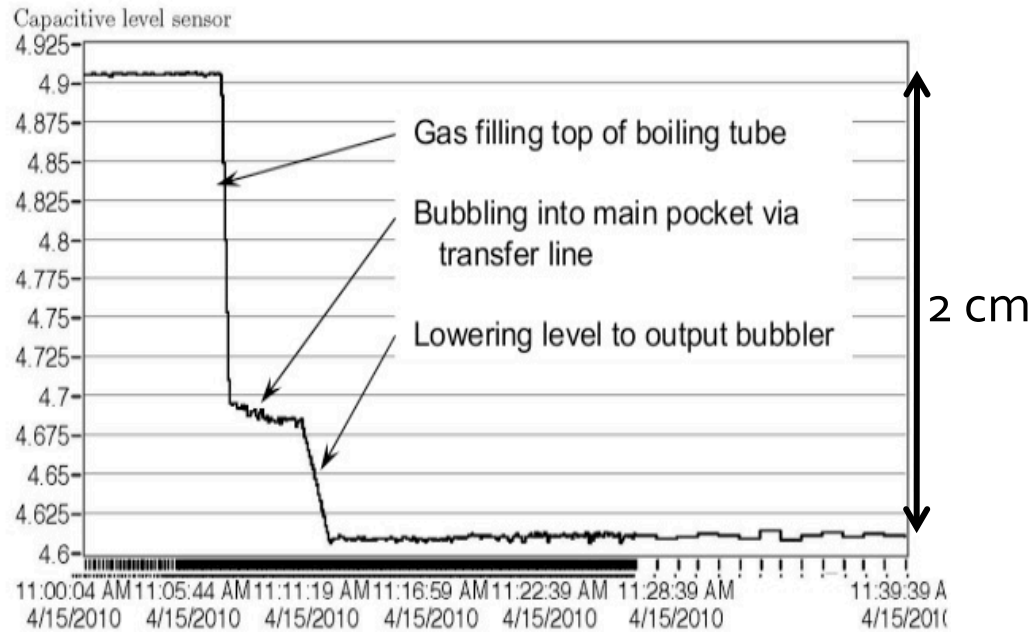
DarkSide-10 Prototype

- 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

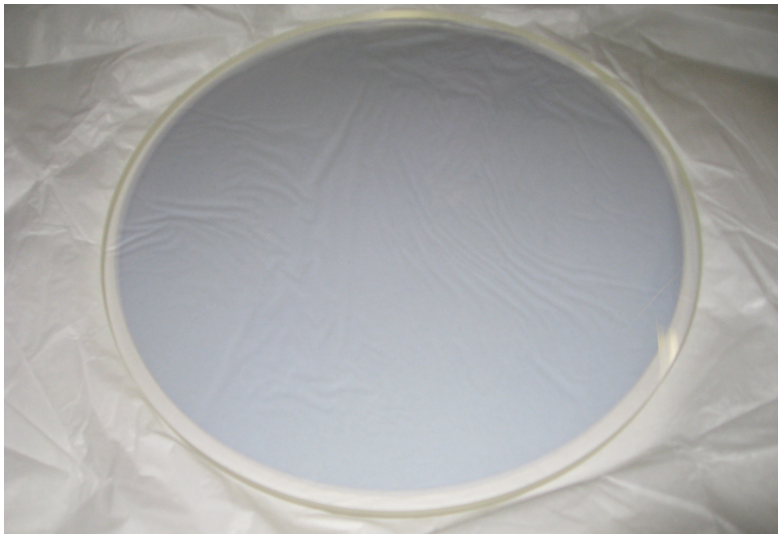


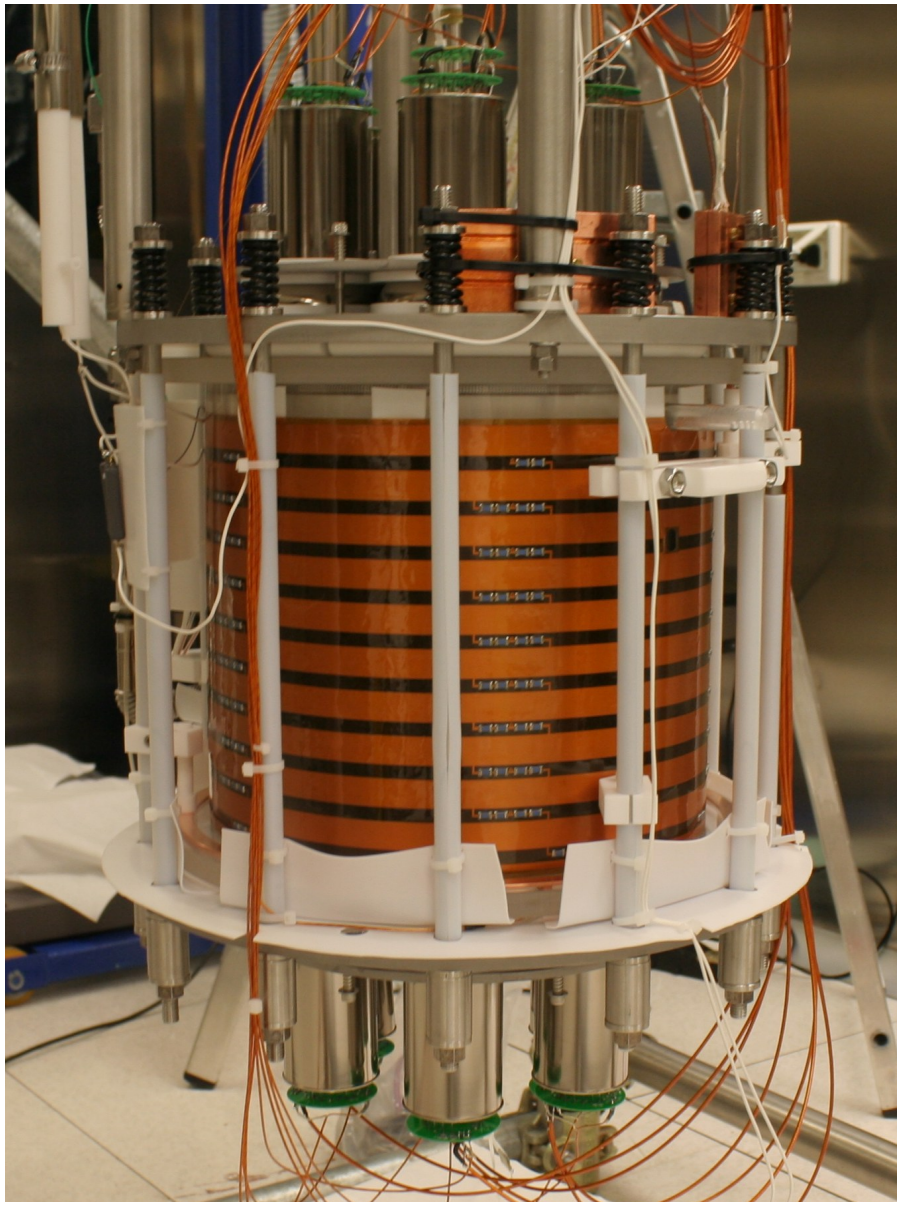
Gas Layer

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
11:39:39 A 4/15/201(

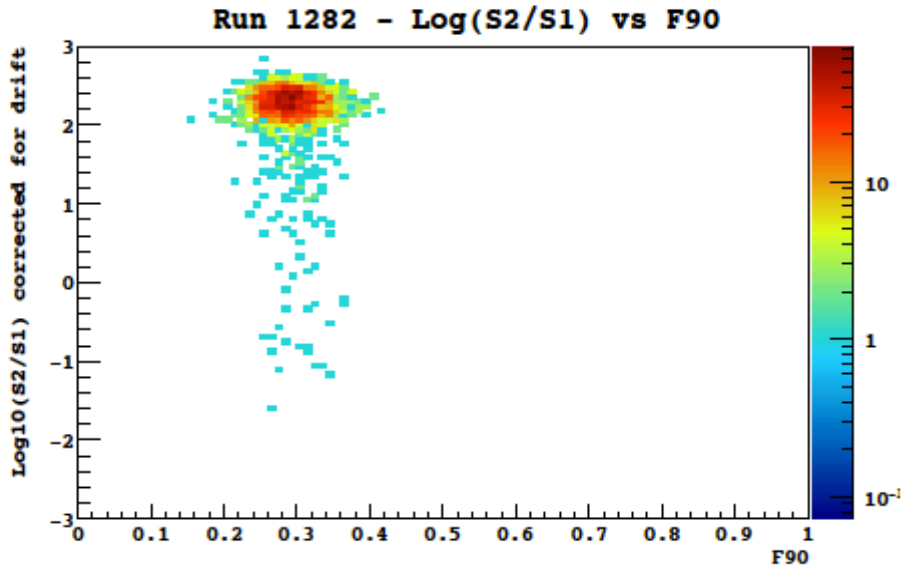
Electric Field Creation



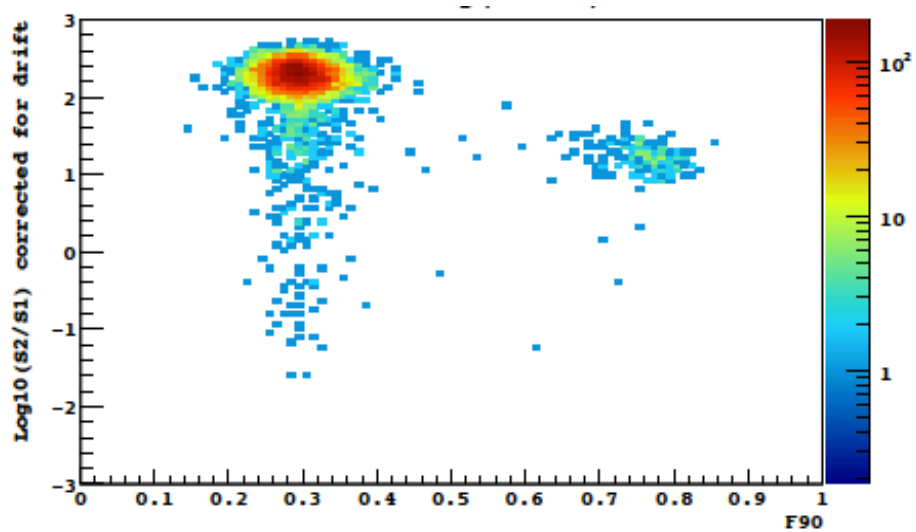


Two-Phase Operation!

Gamma Source:

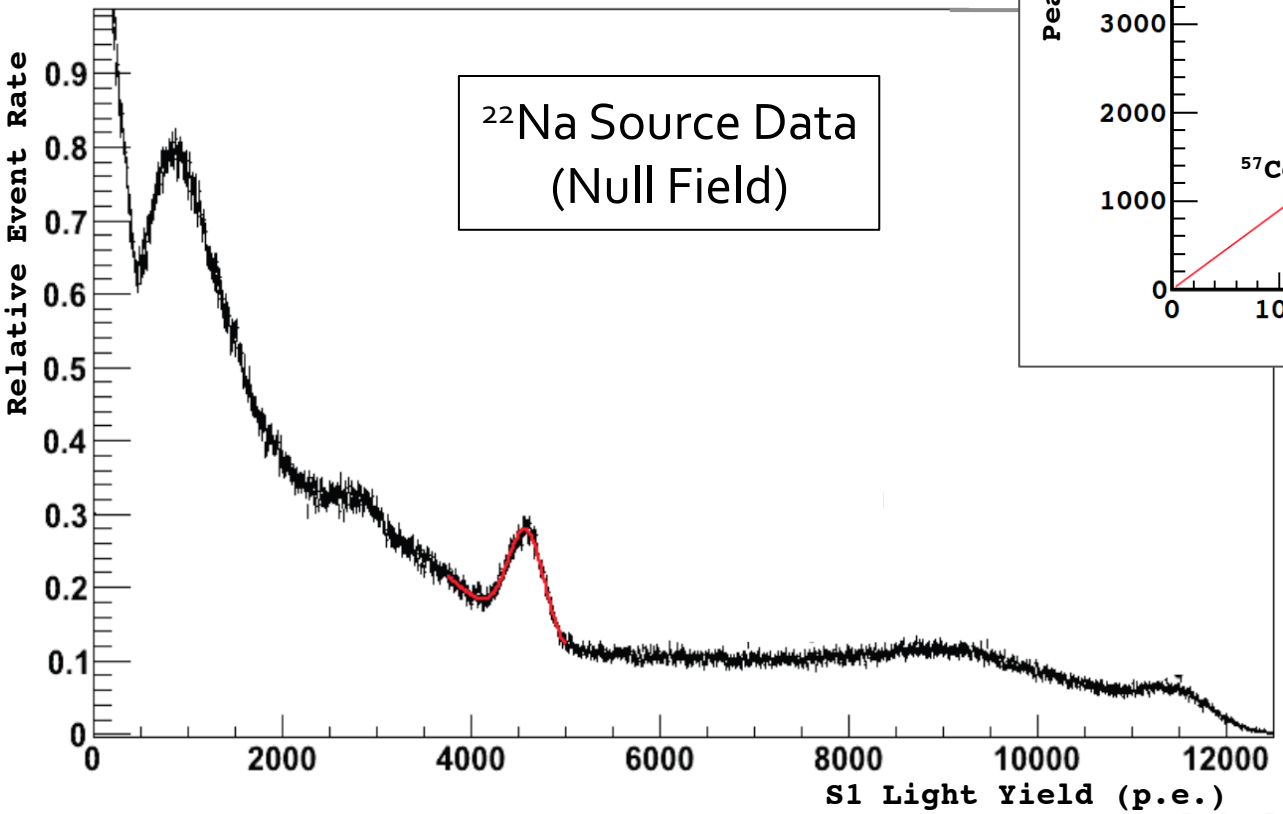


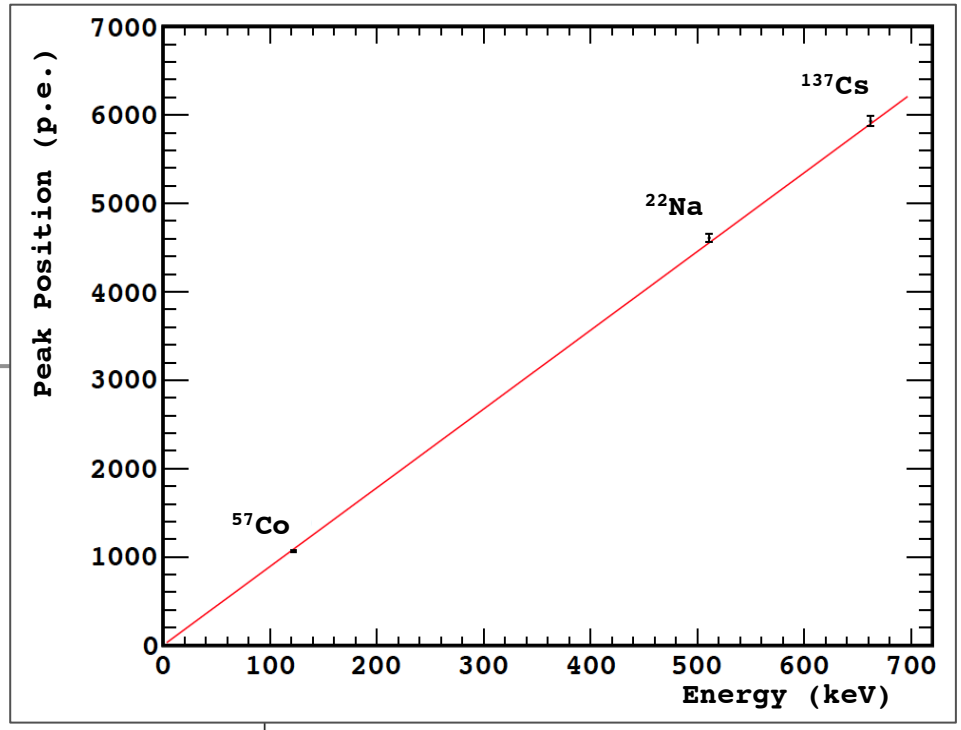
Neutron Source:



Light Yield

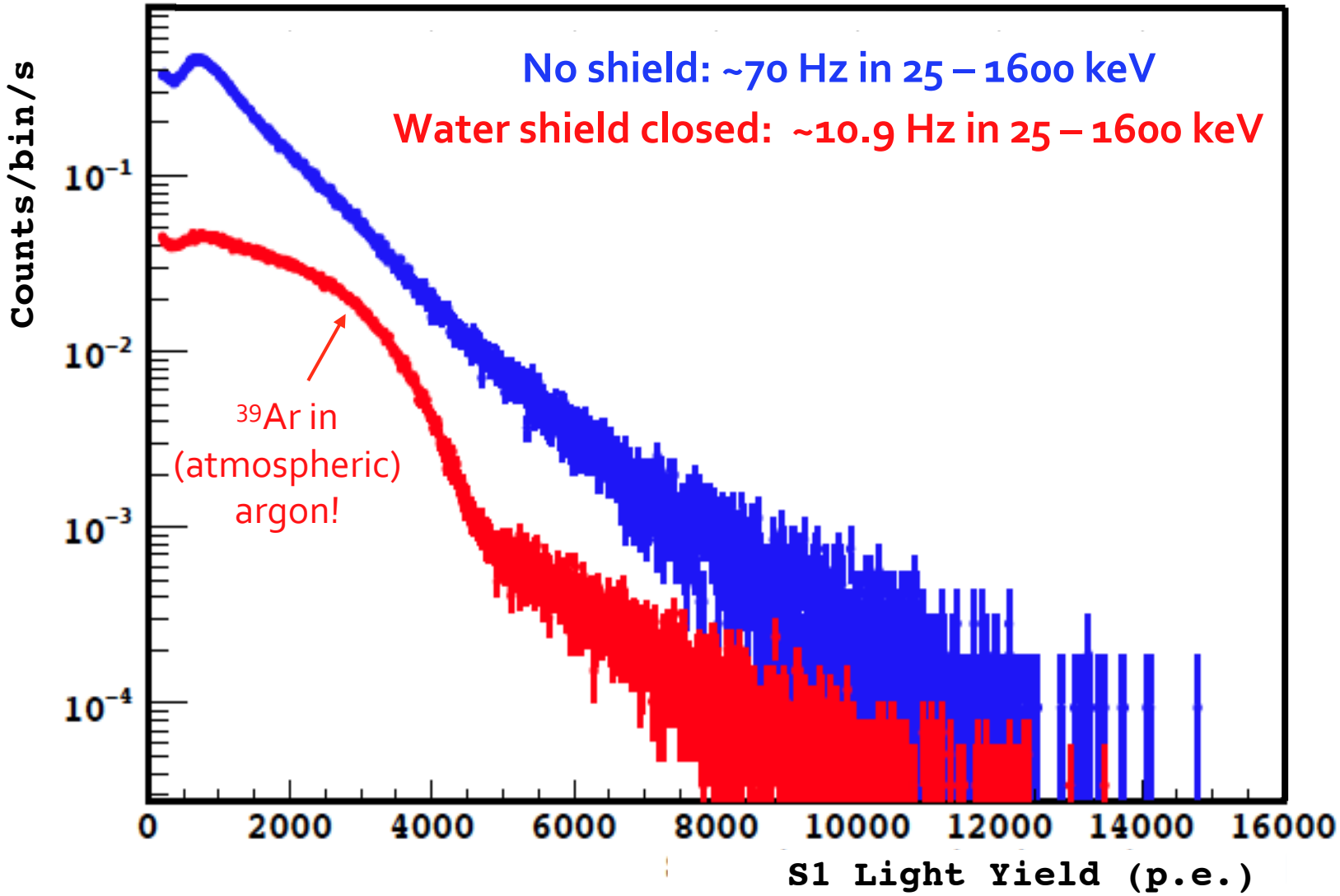
9.0 ± 0.1 p.e./keV!





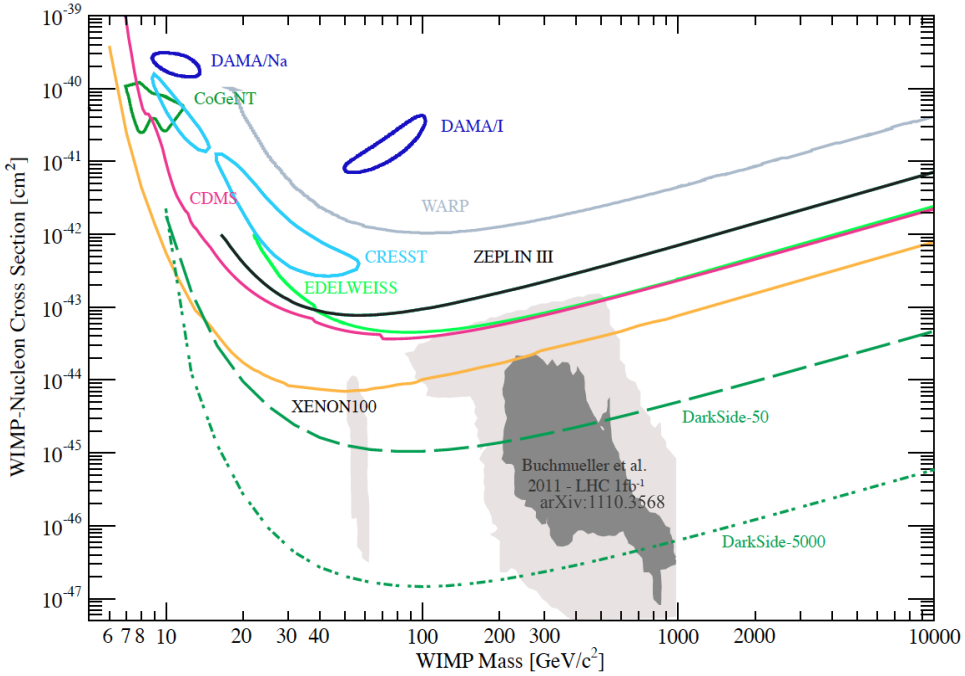
Shielded Operation

Event Rate in DarkSide-10 (without PSD)



DarkSide Future

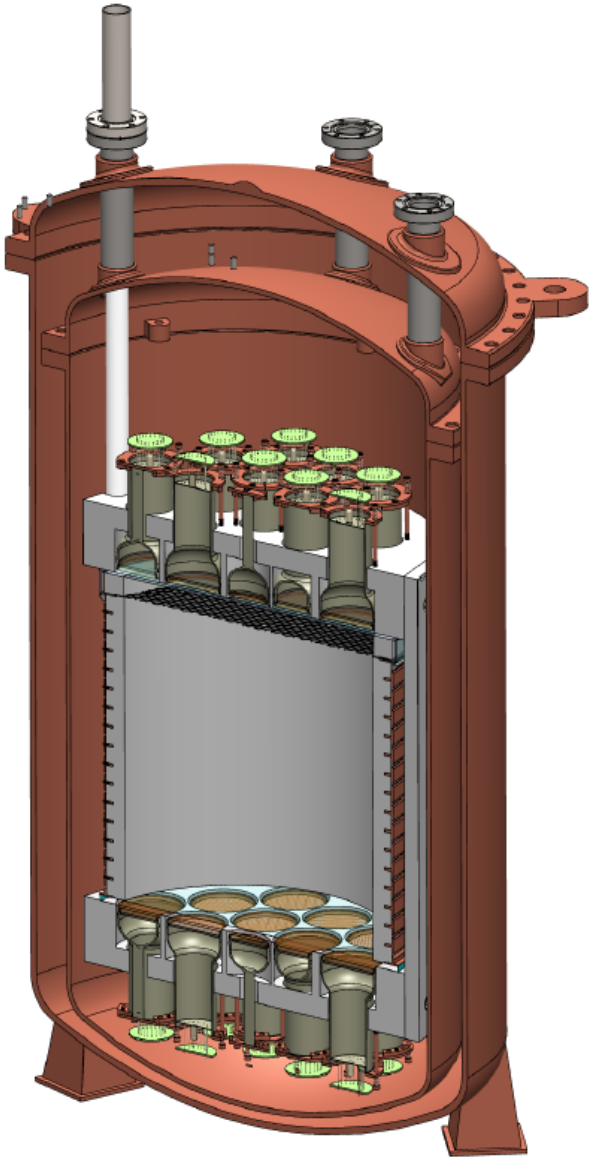
- Continued DarkSide-10 operation to gain experience with 2-phase operation, study backgrounds
- DarkSide-50 to deploy later this year
  - Reach 10^{-45} cm² in 3 years background free operation
- Tonne-scale experiment could reach 10^{-47} cm² using the same active shielding as DarkSide-50



Spare Slides

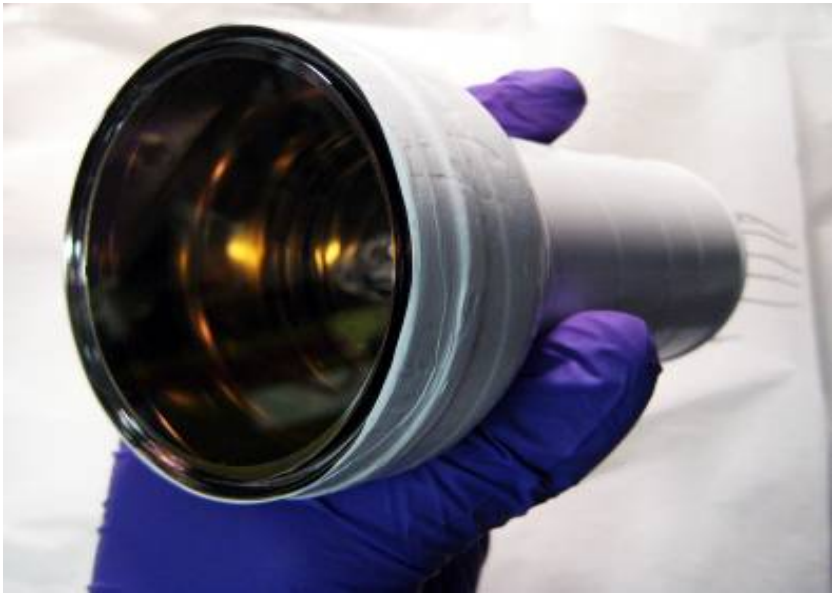
The DarkSide Program

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



Low Background Photon Detectors

R11065 PMT



- Metal bulb, fused silica window
  - <60 mBq gammas
  - <3 neutrons/PMT/yr
- Cryogenic operation
- High quantum efficiency (~35%)

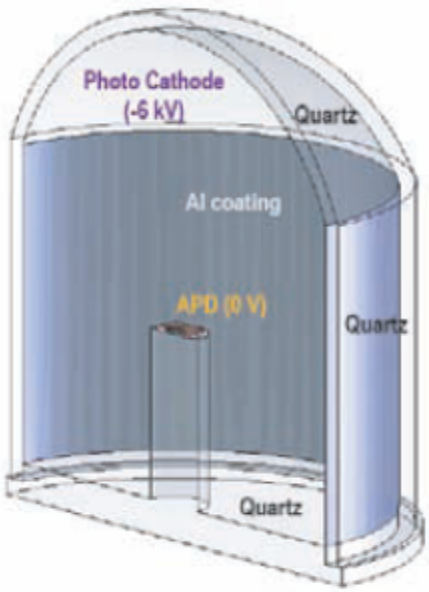
Quartz Photon Intensifying Device

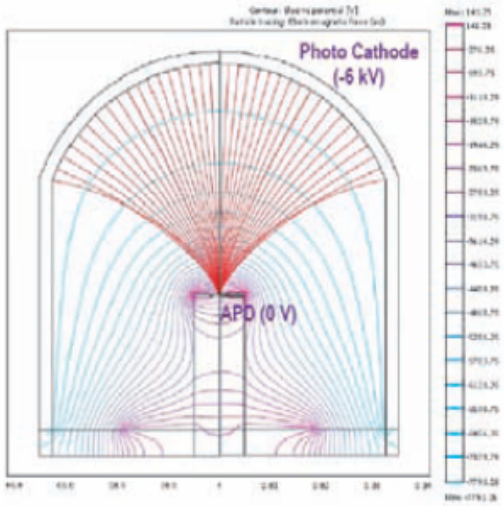
- All fused silica construction
- Photoelectrons accelerated directly onto a low background APD
- Potential for extremely low background
- Cryogenic operation
- High quantum efficiency

arXiv:1103.3689v1

Quartz Photon Intensifying Detectors (QUPIDs)

- Developed by Hamamatsu and our UCLA collaborators
  - Will be used for both DarkSide and Xenon
- Fused silica construction except for APD
- Bialkali-LT photocathode allows low temperature operation

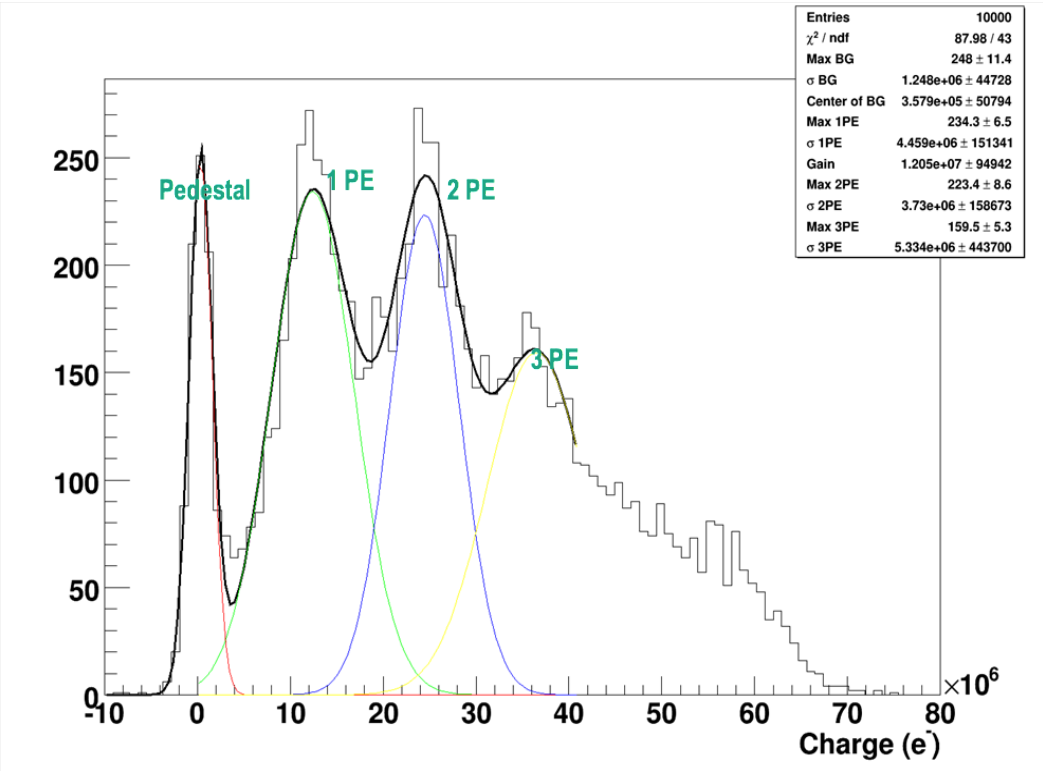




Contaminant	^{238}U	^{226}Ra	^{232}Th	^{40}K	^{60}Co
Activity (mBq/ QUPID)	<17.3	0.3 ± 0.1	0.4 ± 0.2	5.5 ± 0.6	<0.18

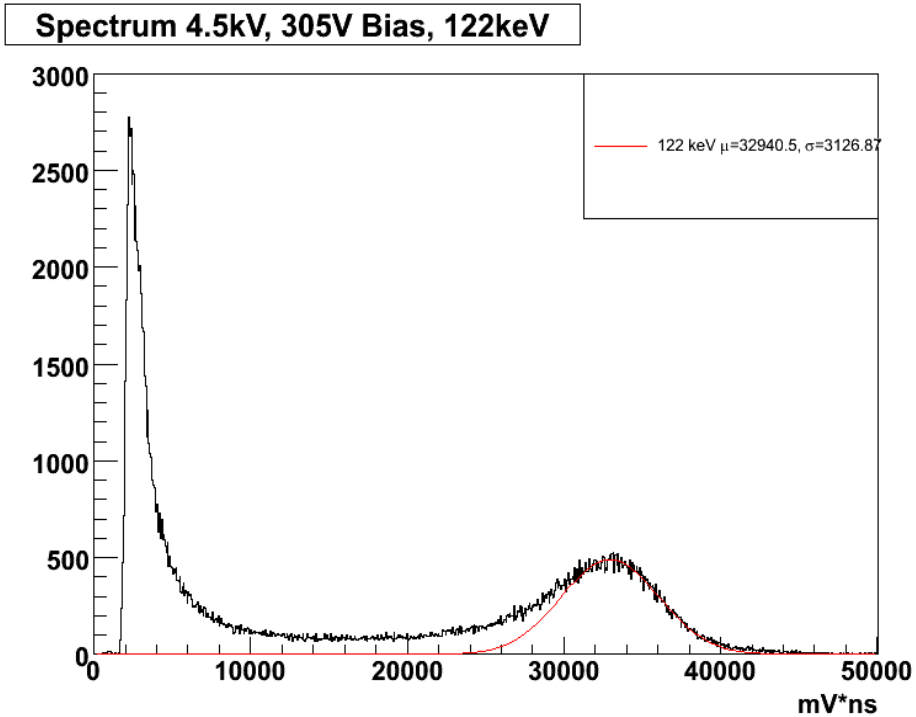
→ ~0.8 n/yr/QUPID

QUPID Data



Hamamatsu Data

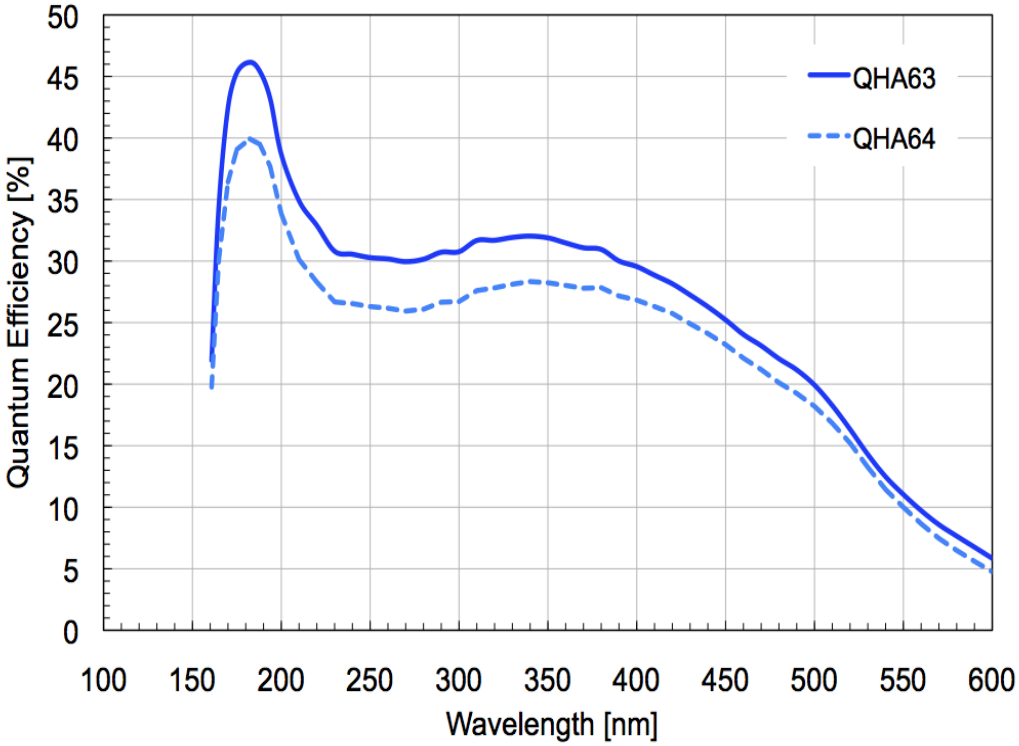
^{57}Co in liquid xenon



[Data from a development version QUPID with fairly low Q.E. at UCLA]

QUPID Quantum Efficiency

- Optimizing photocathode for xenon (178 nm) has achieved >45% Q.E.
  - Optimization for Ar + WLS to begin in October



Production Version QUPIDs

- First three production version QuPIDs have been delivered, are being evaluated
- Production of DarkSide QUPIDs could begin as early as the end of the year

	Old Version (FY2009)	Production Version (FY2010)
Production Method	Vacuum Transfer	Exactly the same as PMT
Quartz Tip	No	Yes (for external vacuum pump)
Production Rate	1 QUPID / 2 days	6 QUPID / day (> 1,000 QUPID / year)
Cost	~ $25,000	< $7,000
Photocathode	Bialkali (with Aluminum Pattern)	Bialkali-LT (Low Resistivity at Low Temperature)
APD diameter	3 mm ϕ Front illuminated	5 mm ϕ Back illuminated
No. of Leads	5	4 (2 for APD, 2 for Getter)
6 kV difference	at the bottom (no resistive layer)	on side (with resistive layer)

Production Version QUPIDs

- First three production version QuPIDs have been delivered, are being evaluated
- Production of DarkSide QUPIDs could begin as early as the end of the year

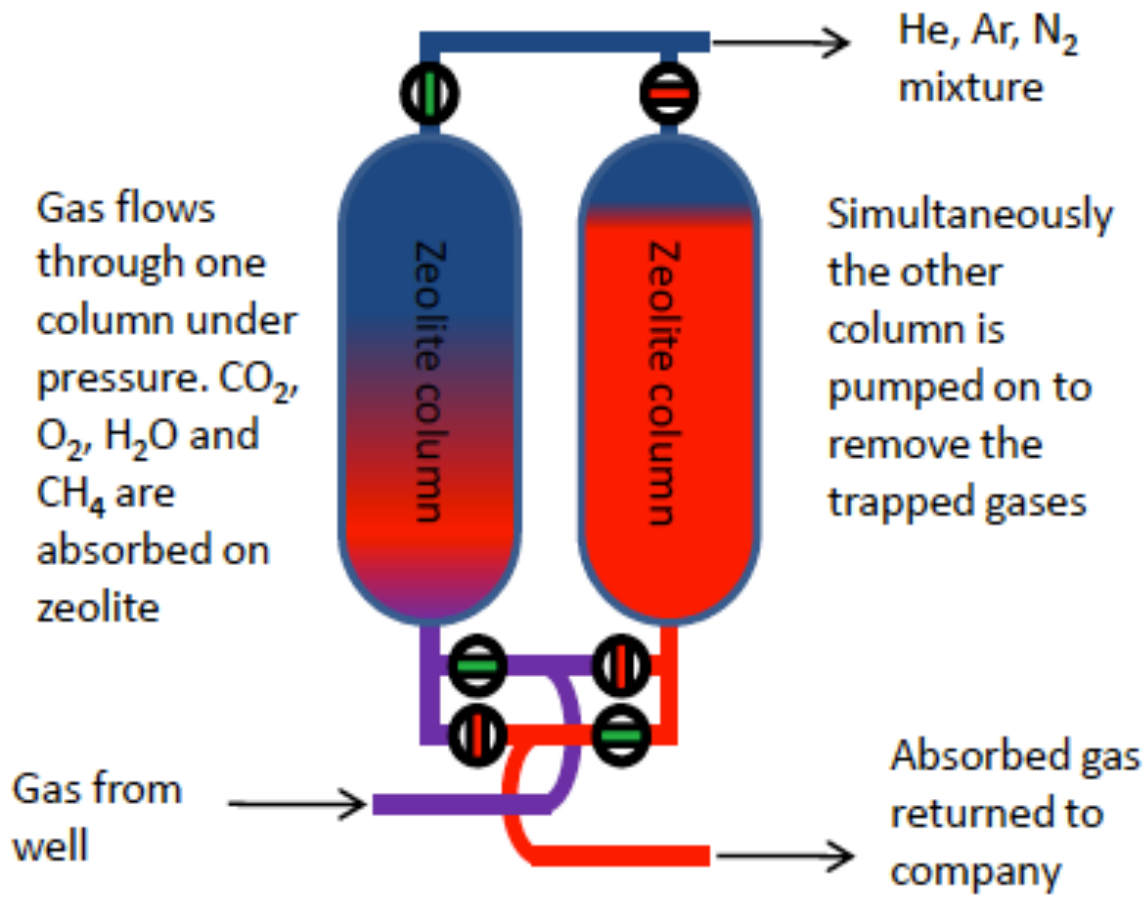
	Old Version (FY2009)	Production Version (FY2010)
Production Method	Vacuum Transfer	Exactly the same as PMT
Quartz Tip	No	Yes (for external vacuum pump)
Production Rate	1 QUPID / 2 days	6 QUPID / day (> 1,000 QUPID / year)
Cost	~ $25,000	< $7,000
Photocathode	Bialkali (with Aluminum Pattern)	Bialkali-LT (Low Resistivity at Low Temperature)
APD diameter	3 mm ϕ Front illuminated	5 mm ϕ Back illuminated
No. of Leads	5	4 (2 for APD, 2 for Getter)
6 kV difference	at the bottom (no resistive layer)	on side (with resistive layer)

Depleted Argon

- CO_2 from Kinder Morgan Doe Canyon Complex (Cortez, CO) contains ~600 ppm Argon
  - Wells produce 3 tons/day of Ar (mostly not collected)
  - ^{39}Ar content at least a factor of 25 reduced compared to atmospheric

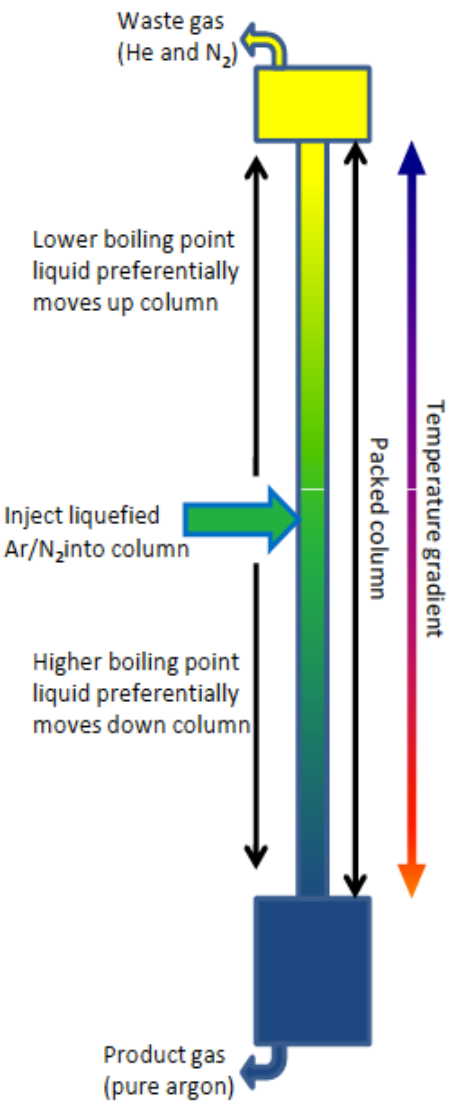
Collecting Depleted Argon

- Gas from well:
  - 96% - CO_2
  - 2.4% - N_2
  - 5,700 ppm – CH4
  - 4,300 pmm – He
  - 2,100 ppm – other hydrocarbons
  - 1,000 ppm – H2O
- Output gas:
  - 70% - N2
  - 27.5% - He
  - 2.5% - Ar
- 26 kg of argon collected so far



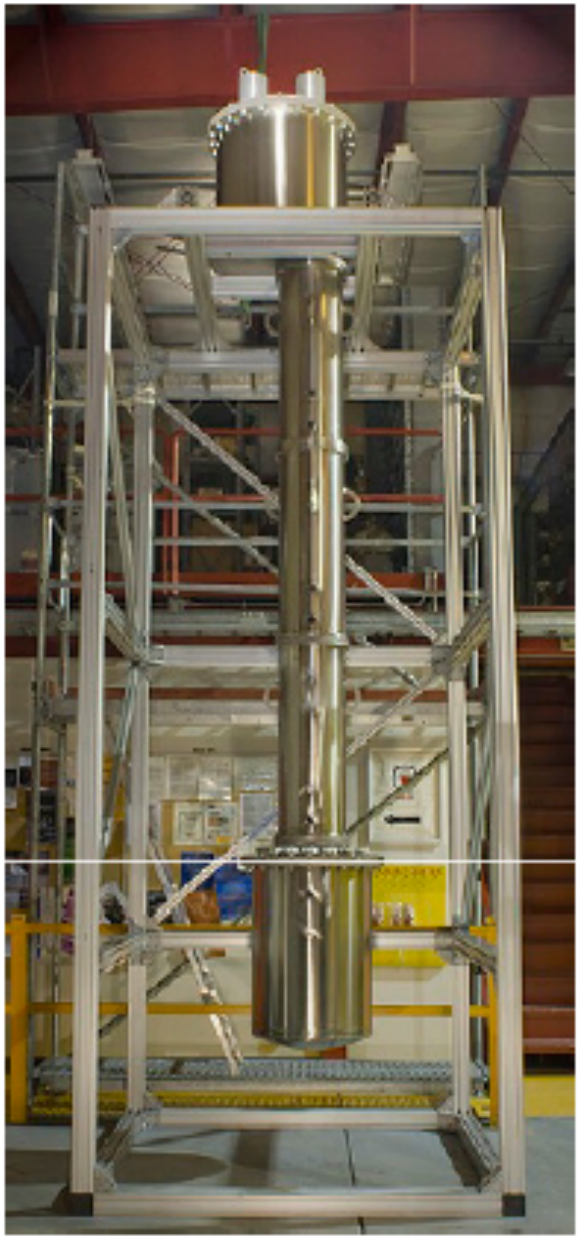
Purifying Depleted Argon

- Continuous flow cryogenic distillation
  - 2 cm diameter x 320 cm long packed column
  - 40 theoretical stages
- Theoretical performance:
  - 99.9999% pure argon
  - 5 kg / day
- Assembled at Fermilab



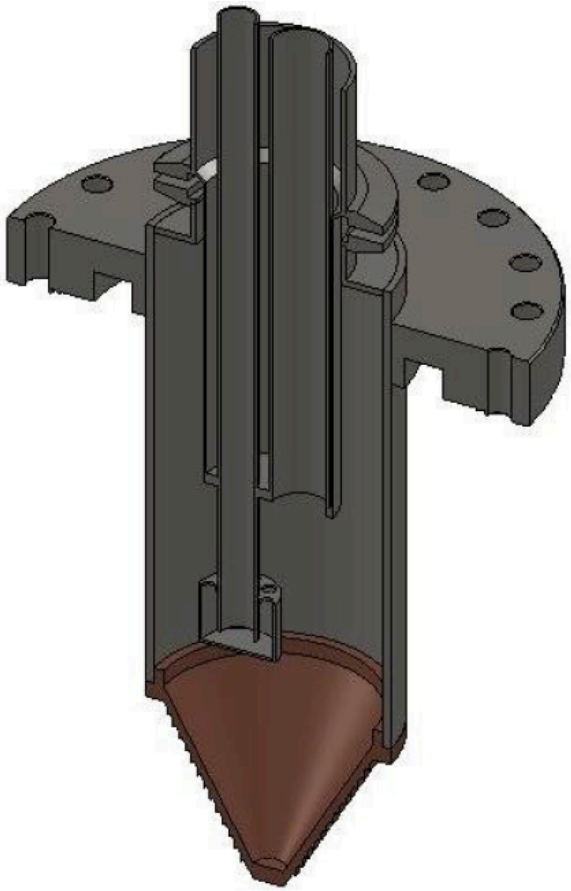
Purifying Depleted Argon

- Continuous flow cryogenic distillation
  - 2 cm diameter x 320 cm long packed column
  - 40 theoretical stages
- Theoretical performance:
  - 99.9999% pure argon
  - 5 kg / day
- Assembled at Fermilab



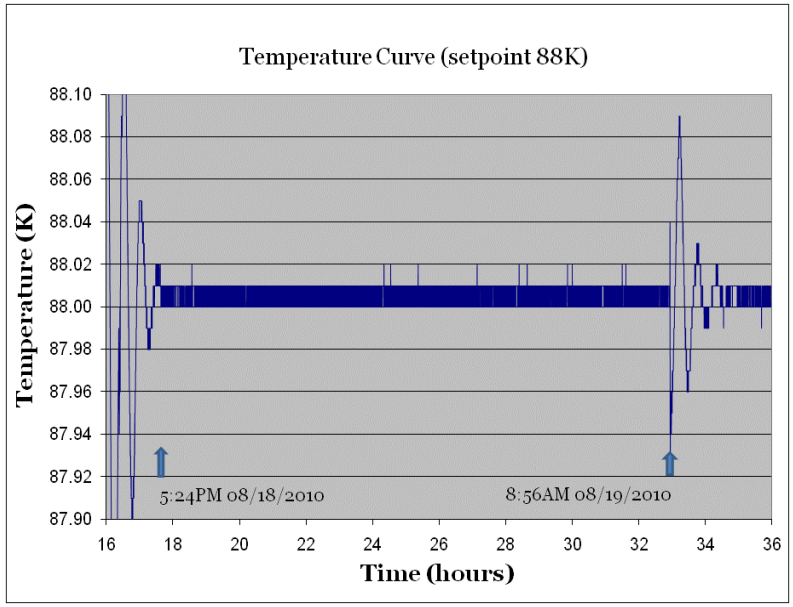
"Remote" LN_2 Cryocooler

- LN_2 supplied by low pressure dewar/gravity feed
- Flow controlled by throttling boil-off gas
- Provide kW of cooling at liquid Ar temperatures (depending on size) but very little cooling when "off"
- Can be made from clean materials



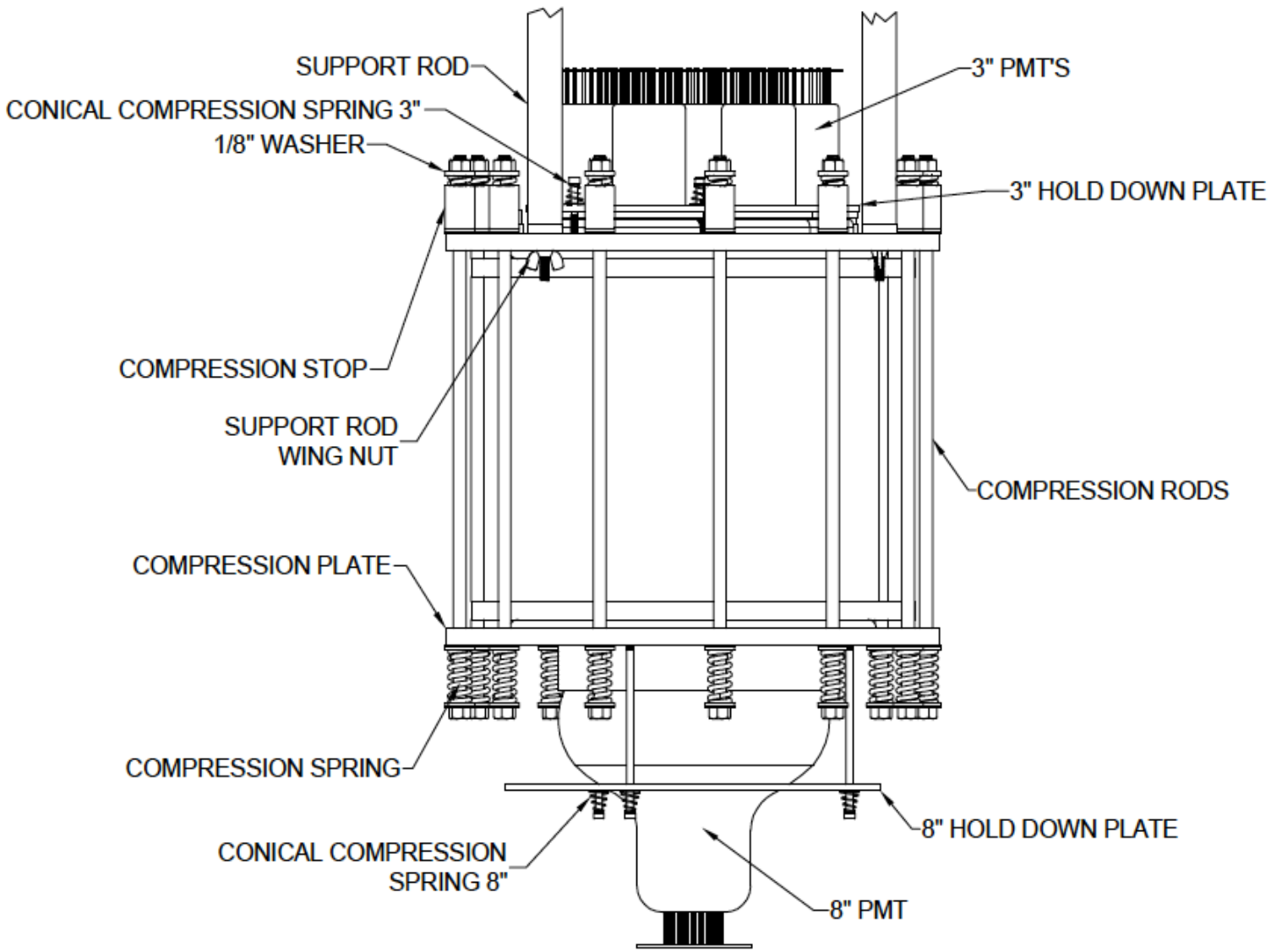
"Remote" LN_2 Cryocooler

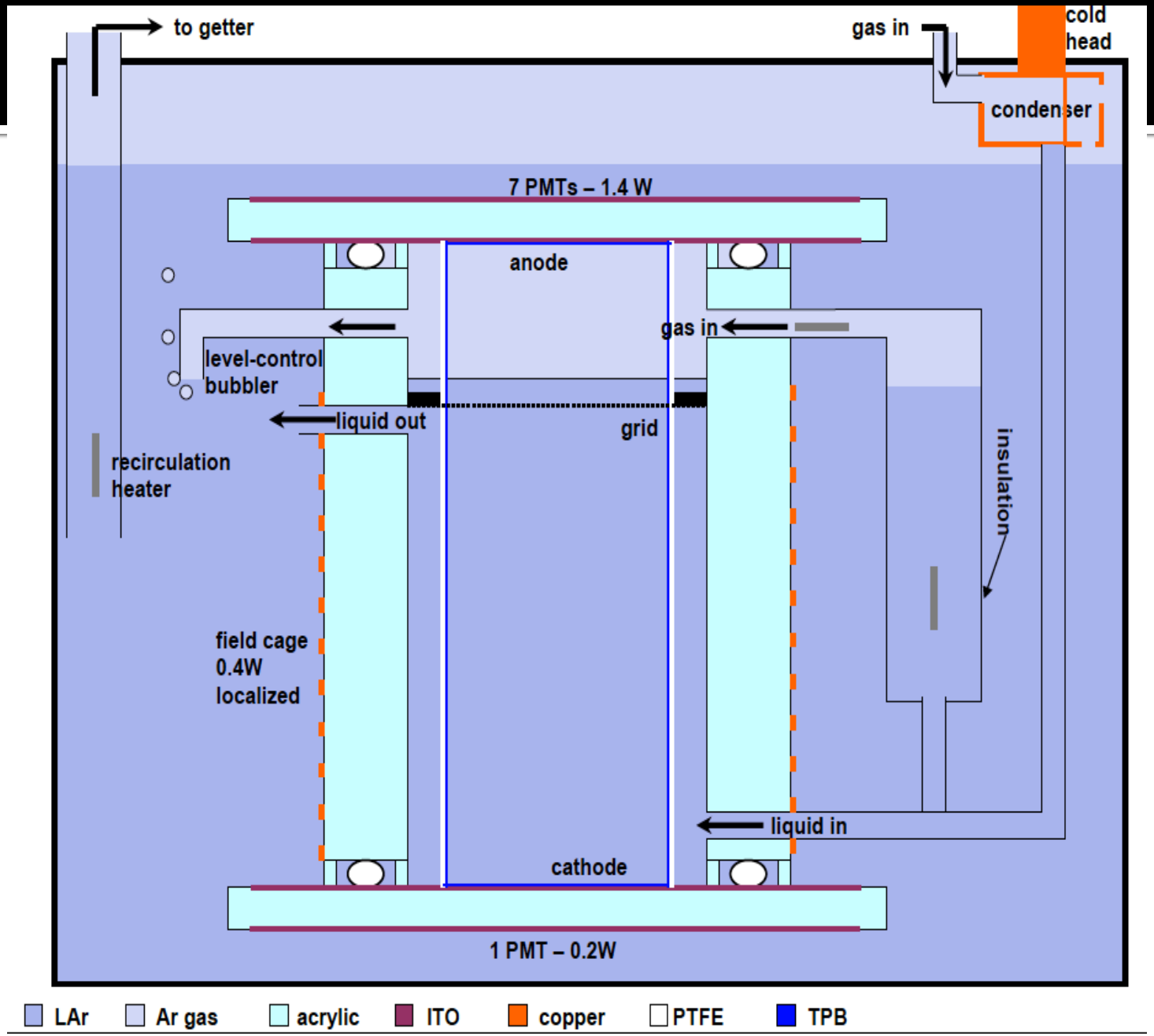
- Small (~100W) cold heads tested at UCLA and Princeton
- Cold head temperature stable to a fraction of a degree
- Nitrogen delivery through 20' of vacuum jacketed flex line



10 kg Prototype

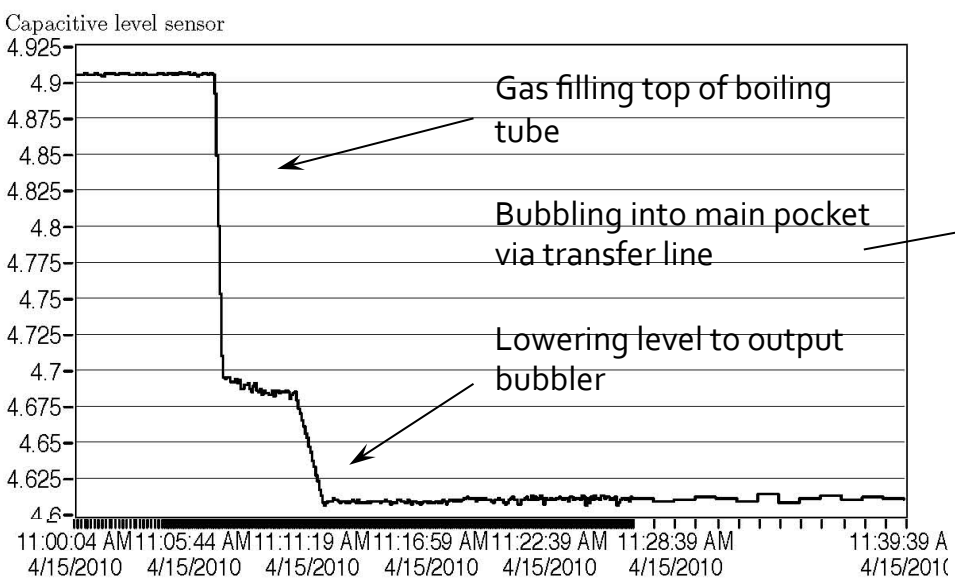
- Test some critical aspects of the DarkSide design
  - Light yield
  - Control of gas layer
  - Charge drift and S2 light collection
  - Surface background rejection

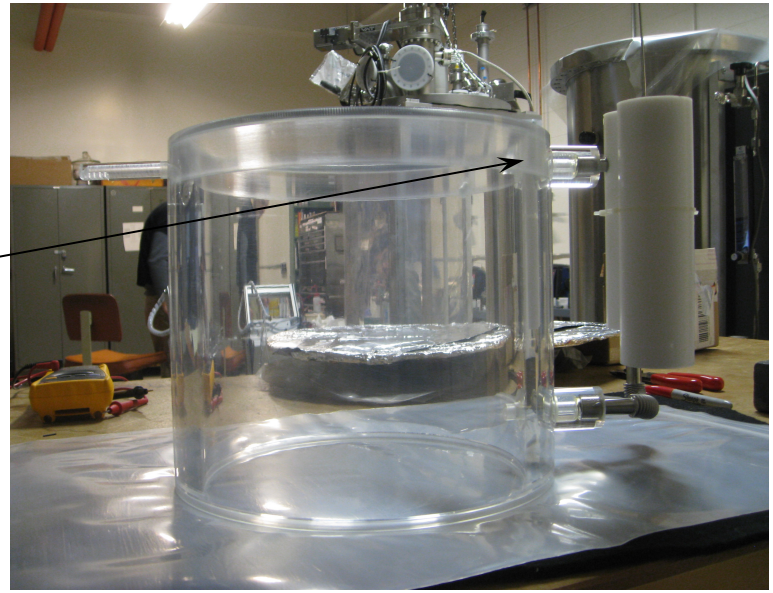

SUPPORT ROD
CONICAL COMPRESSION SPRING 3"
1/8" WASHER
3" PMT'S
3" HOLD DOWN PLATE
COMPRESSION STOP
SUPPORT ROD
WING NUT
COMPRESSION RODS
COMPRESSION PLATE
COMPRESSION SPRING
8" HOLD DOWN PLATE
CONICAL COMPRESSION
SPRING 8"
8" PMT


to getter
gas in
cold head
condenser
7 PMTs – 1.4 W
anode
gas in
level-control bubbler
liquid out
grid
recirculation heater
insulation
field cage 0.4W localized
liquid in
cathode
1 PMT – 0.2W
LAr
Ar gas
acrylic
ITO
copper
PTFE
TPB

Preliminary Run

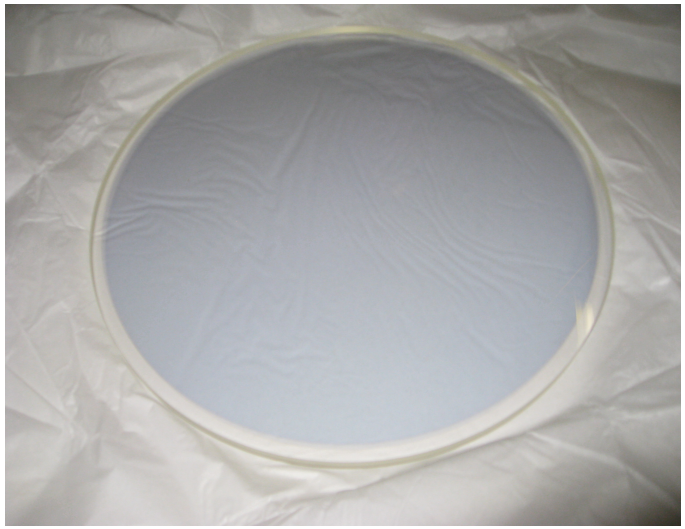
- No electric fields
- Light yield of 3-5 p.e./keV
- Successful production/maintenance of gas pocket





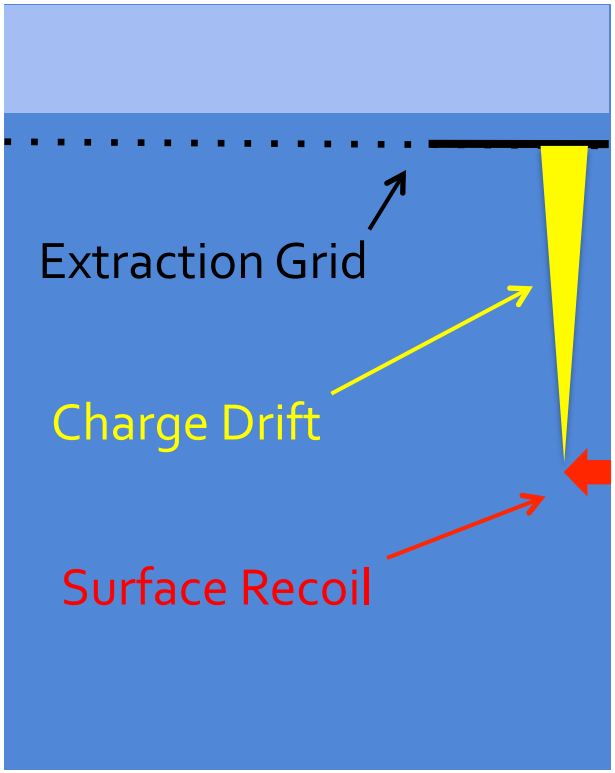
Deployment II: Electric Field

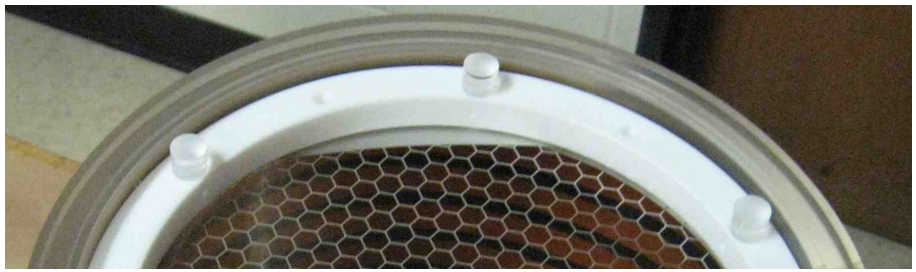
- Install field cage, extraction grid and conducting ITO windows
- Affix weak alpha sources to vertical walls to study surface backgrounds
  - "Charge interruption" technique for surface background rejection



Deployment II: Electric Field

- Install field cage, extraction grid and conducting ITO windows
- Affix weak alpha sources to vertical walls to study surface backgrounds
  - "Charge interruption" technique for surface background rejection



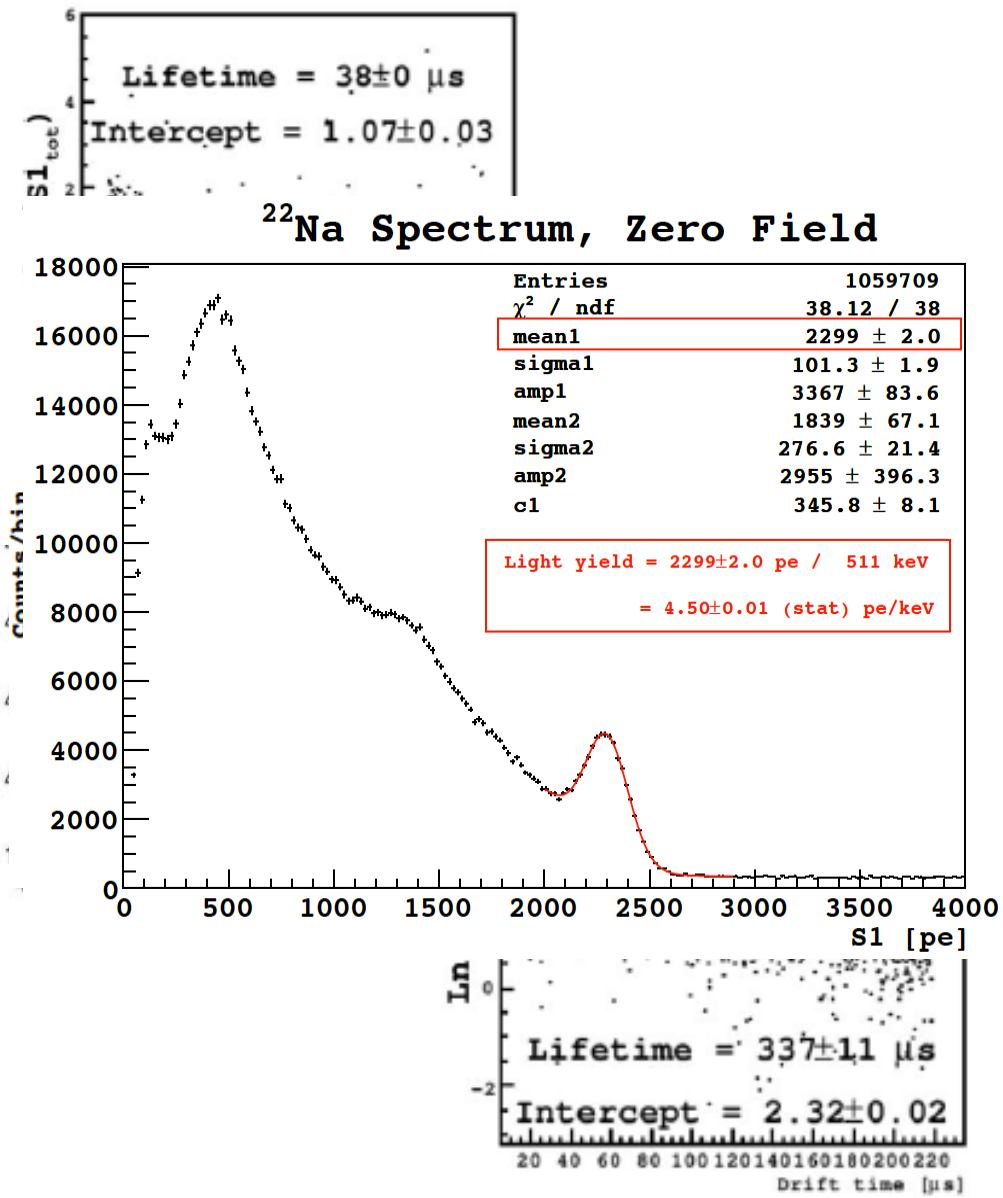


DarkSide-10 Prototype

- Give us experience in building and operating a 2-phase Ar detector
- Not particularly radiopure, for speed and flexibility
- Test key DarkSide techniques
  - High-efficiency, low background PMTs
  - (Quasi) sealed inner vessel
  - High light yield using side reflectors
  - Submerged upper PMTs (gas pocket formation and control)
  - Uniform anode and cathode planes
  - Study surface background events

DarkSide-10 Results

- Two runs (7 months total) at Princeton
- Gas pocket successfully maintained
- Argon successfully purified (<10 ppb O_2)
- R11065 PMTs performed as expected
- High light yield (4.3p.e./ keV_{ee}) achieved

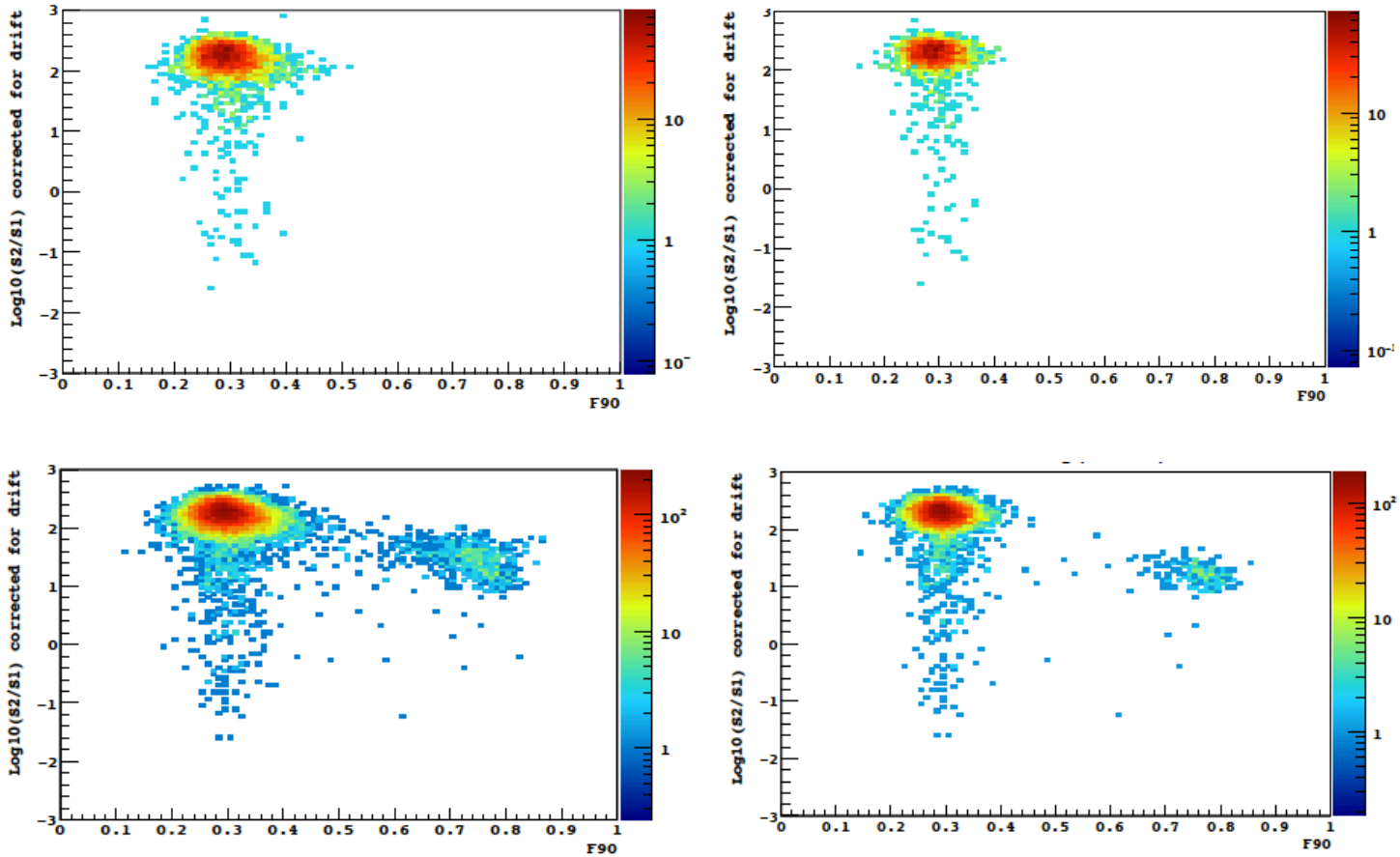


Two-Phase Operation

E_m=3.85kV/cm and E_d=0.5kV/cm

Gamma Source:

AmBe Source:

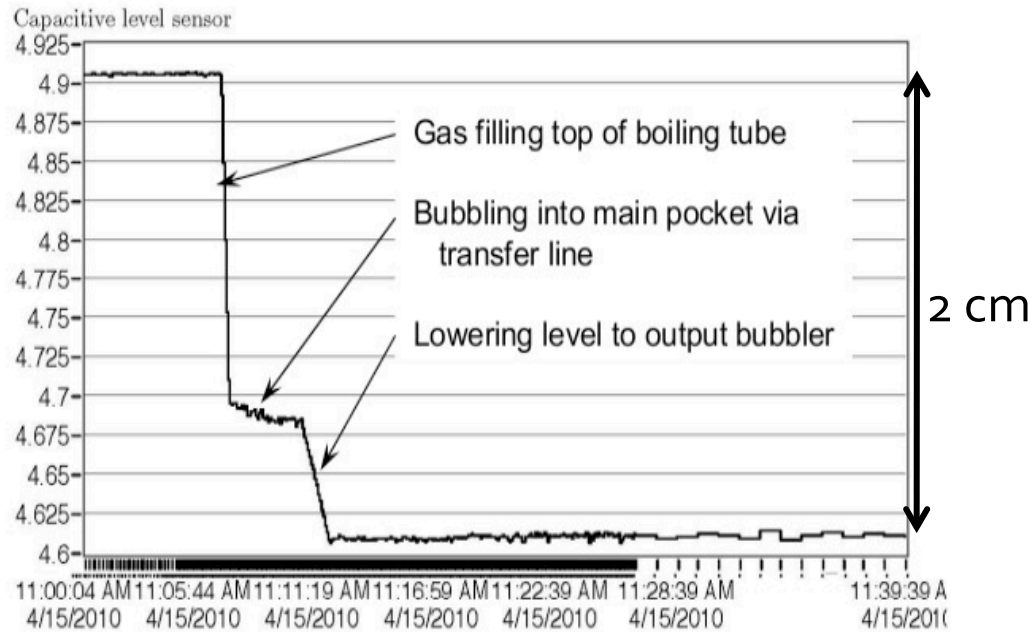


S1>50p.e.

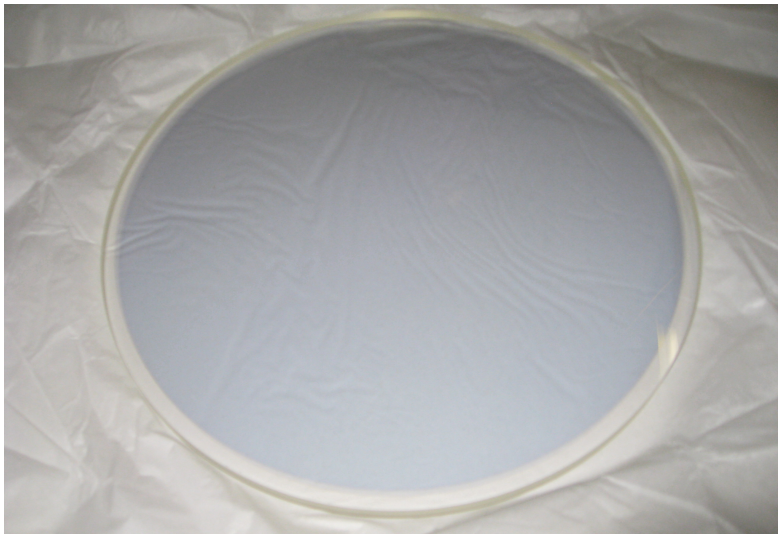
S1>200p.e.

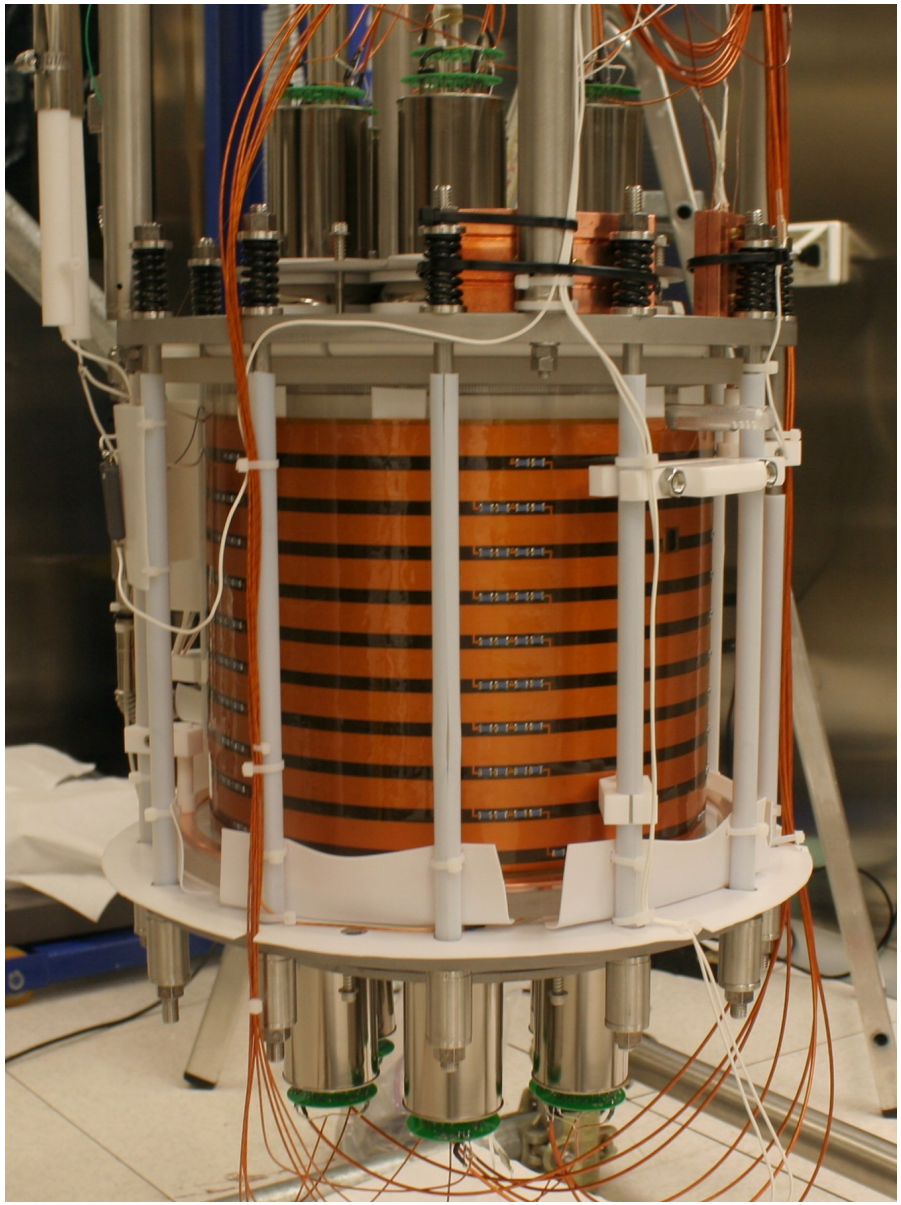
Gas Layer

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
11:39:39 A 4/15/201(

Electric Field Creation





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

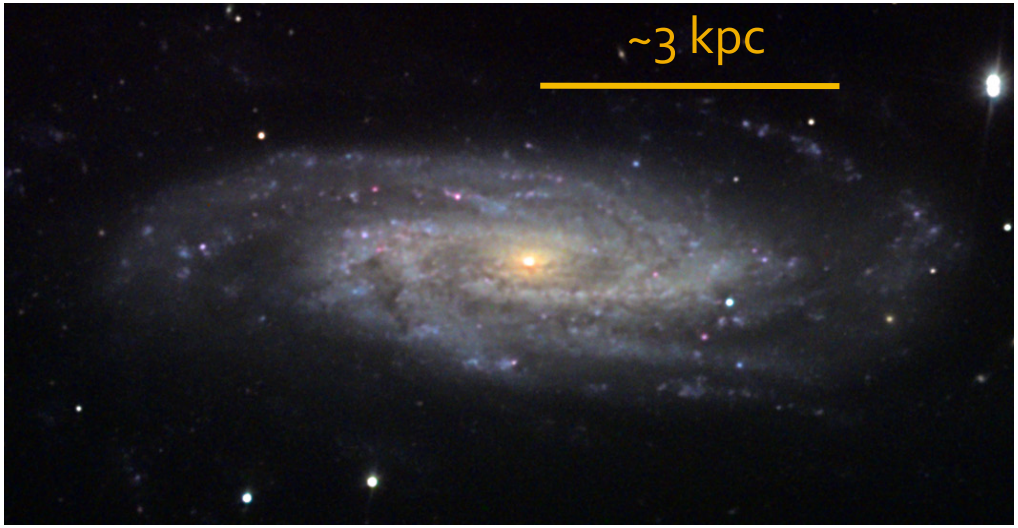
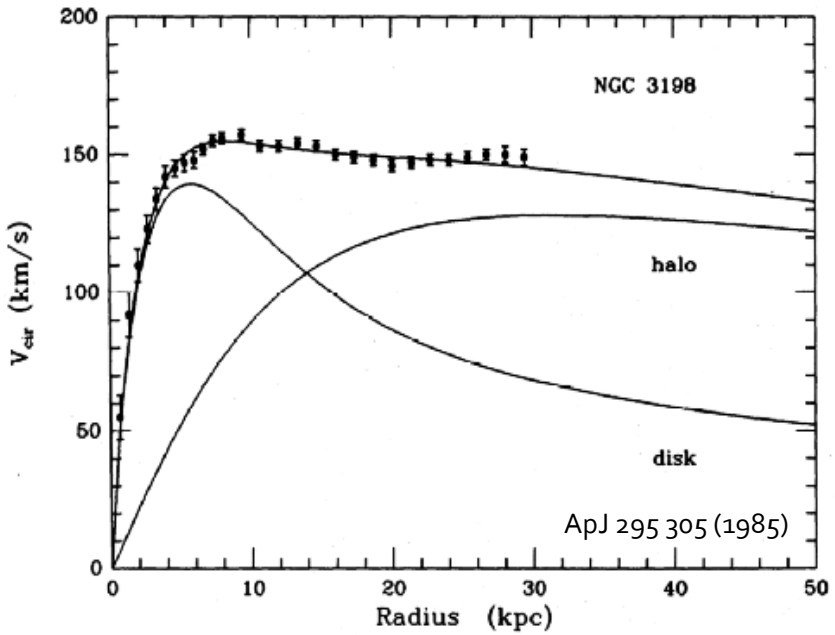


Image credit: John Vickery and Jim Matthes/Adam Block/NOAO/AURA/NSF



- 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

Large-Scale Structure Formation

- The observed baryonic matter alone would (probably) not result in the large-scale structure we observe
  - Need dark matter to encourage "clumping" of baryons

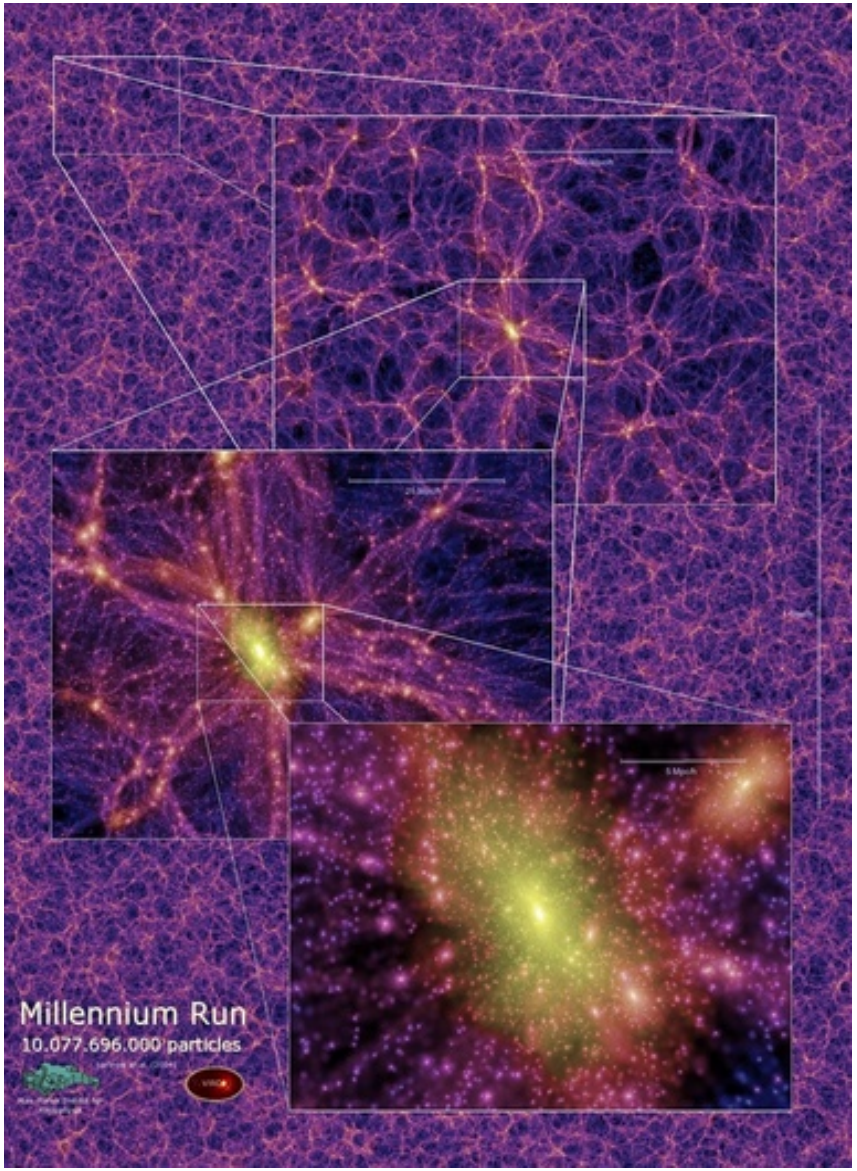
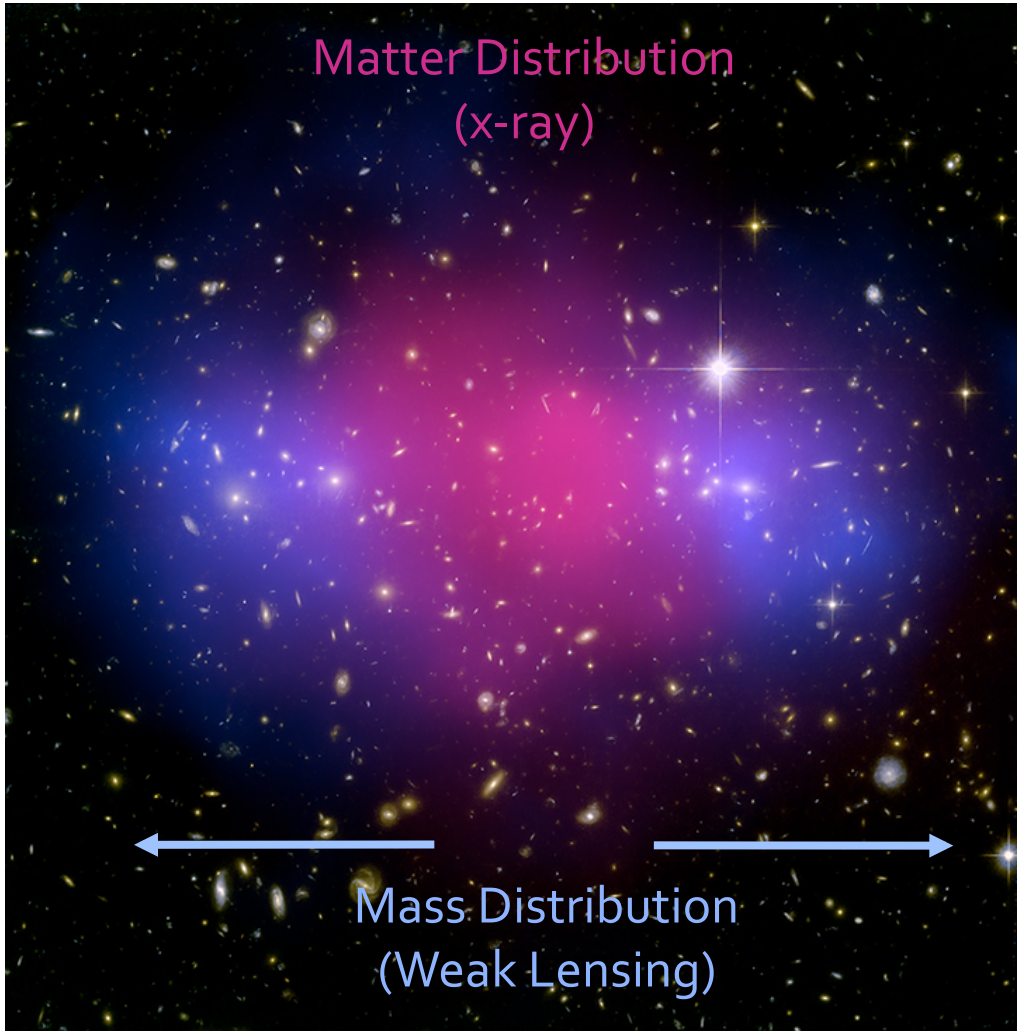


Image credit: http://www.mpa-garching.mpg.de/galform/millennium/, astro-ph/0504097

Weak Gravitational Lensing

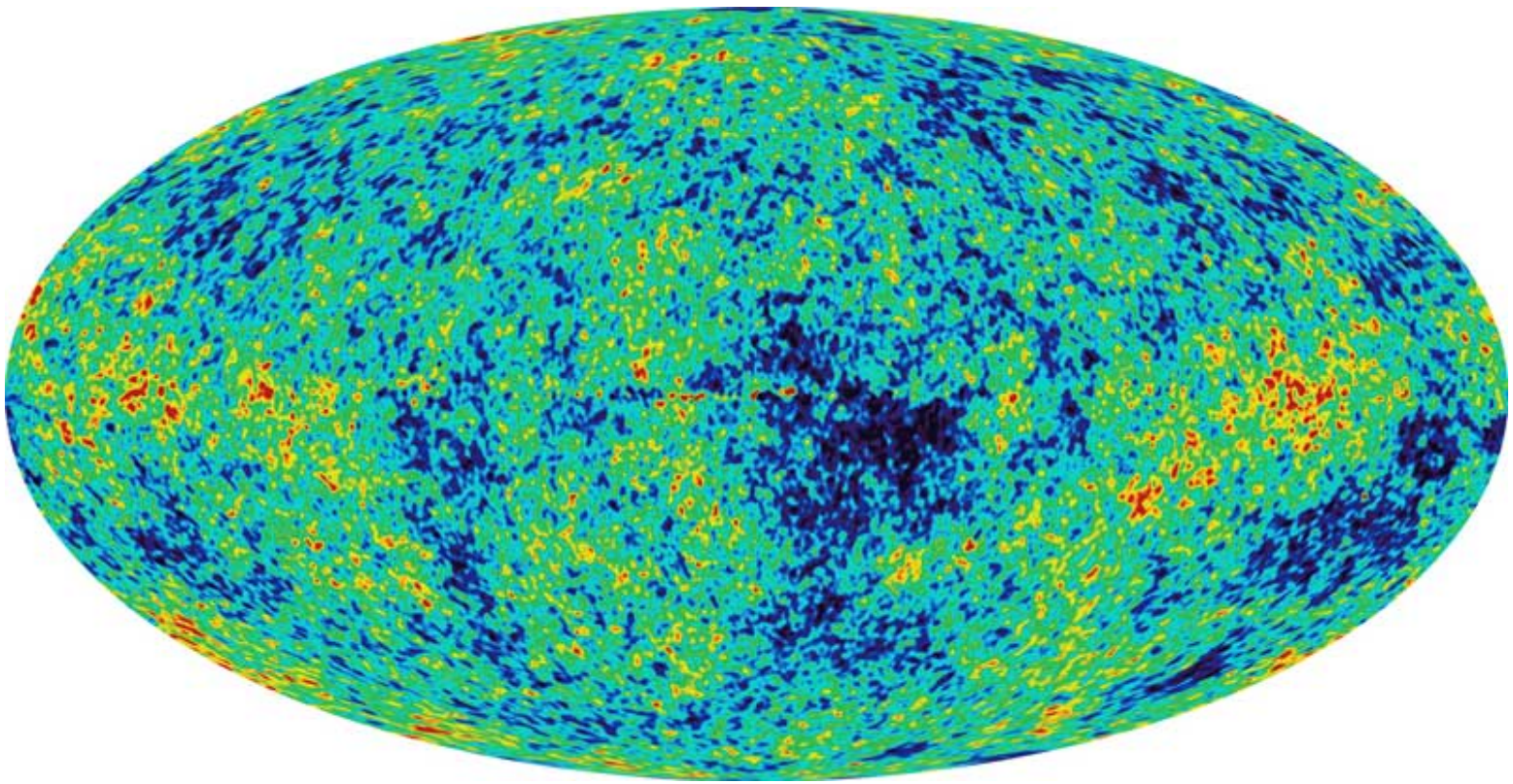
- Distortions in the appearance of background galaxies can be used to measure the mass and mass distribution of foreground objects
  - Confirm that galaxies are much heavier than their stars
  - Observe galaxy collisions

MACS J0024.4-1222



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

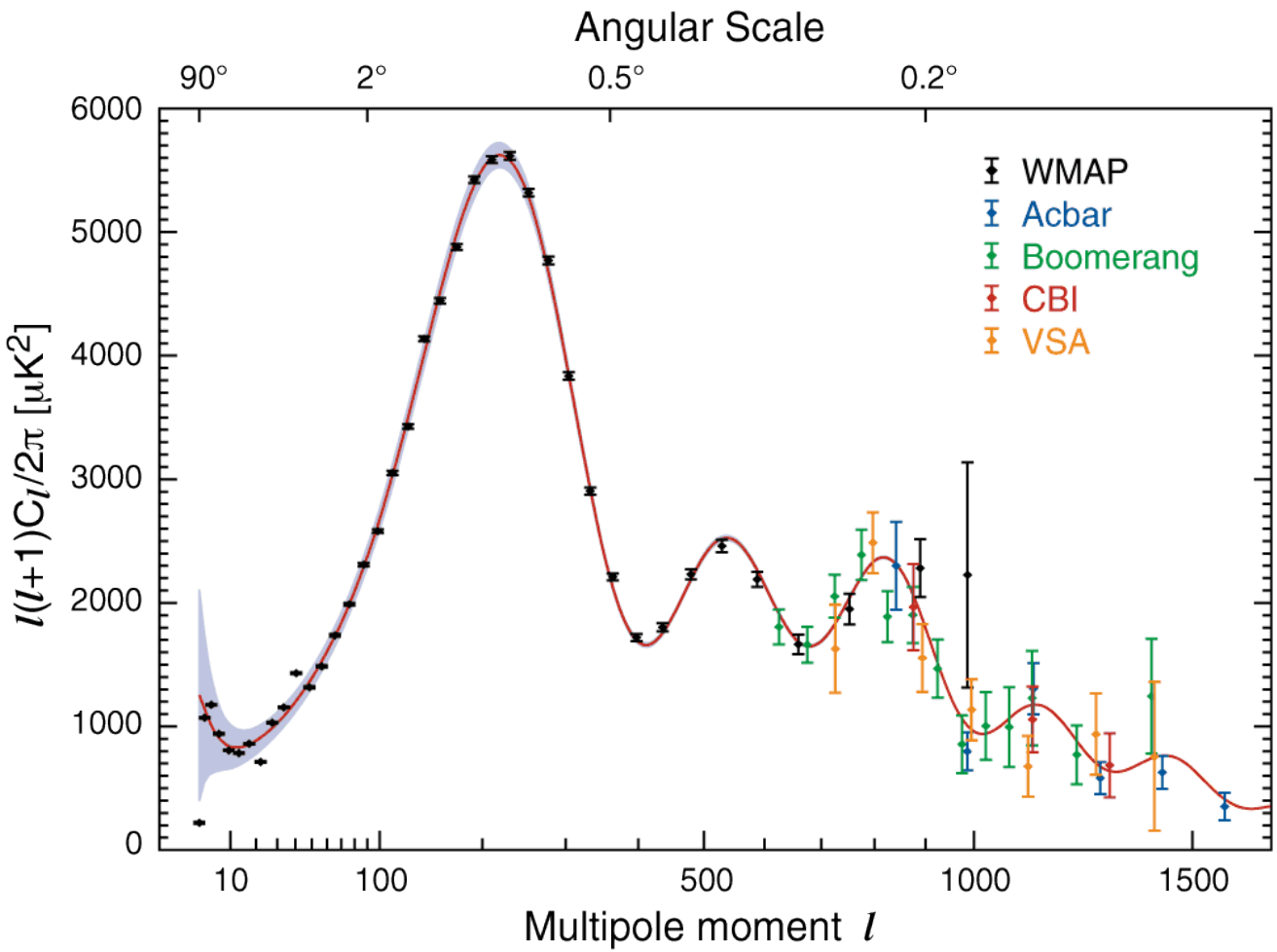
Cosmic Microwave Background



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

- After inflation, universe is filled with fluid (~at rest) with small density fluctuations
- Additional matter gravitationally "accretes" in over-dense regions
- Scale of the possible accretions is set by "sound speed" and time to recombination

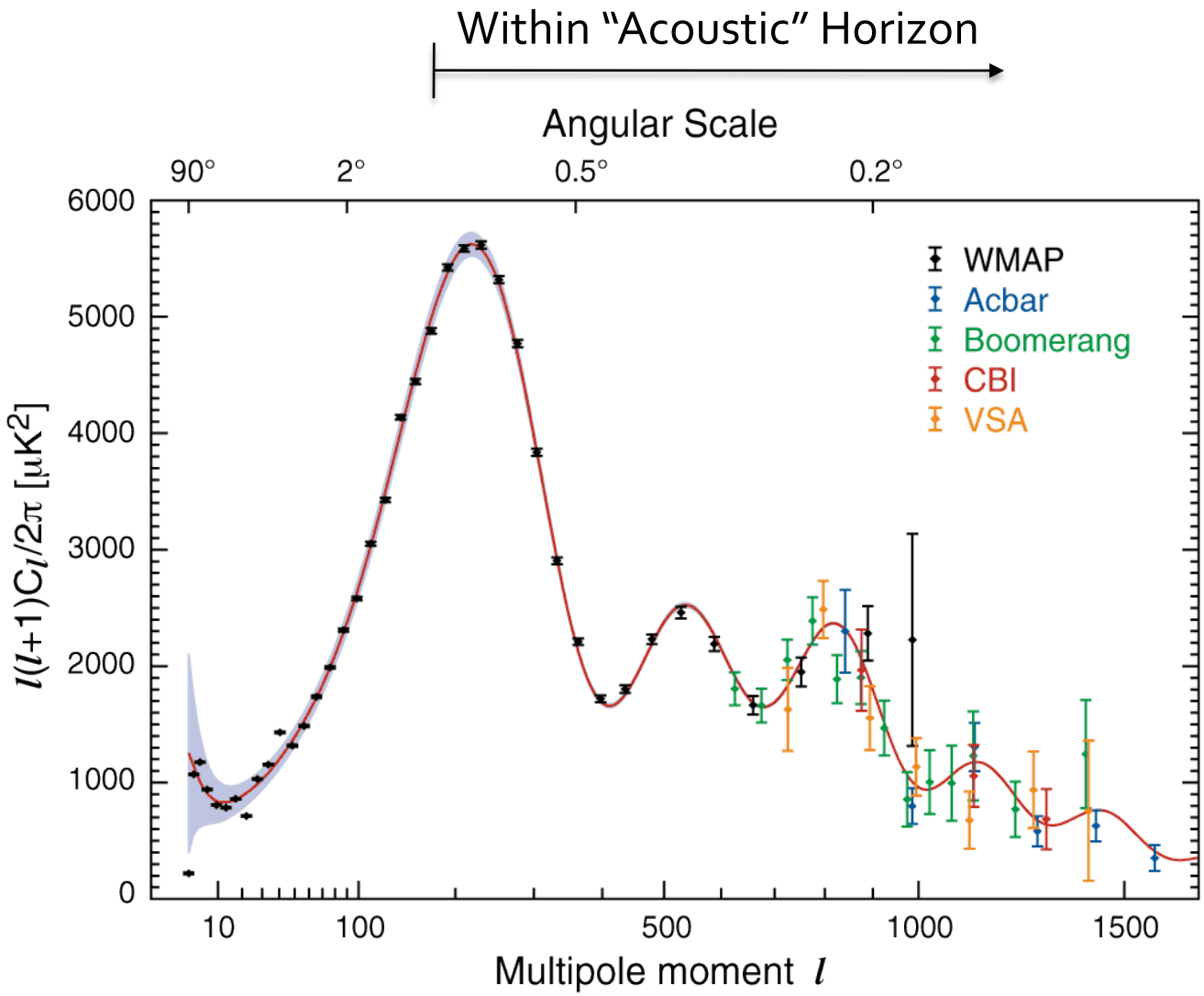


Image Credit: WMAP Science Team

Cosmic Microwave Background

- Correlation scale produces "1st acoustic peak"
- Successive rarefactions and compressions produce higher peaks
- The relative heights of the peaks depend on the matter and baryon densities

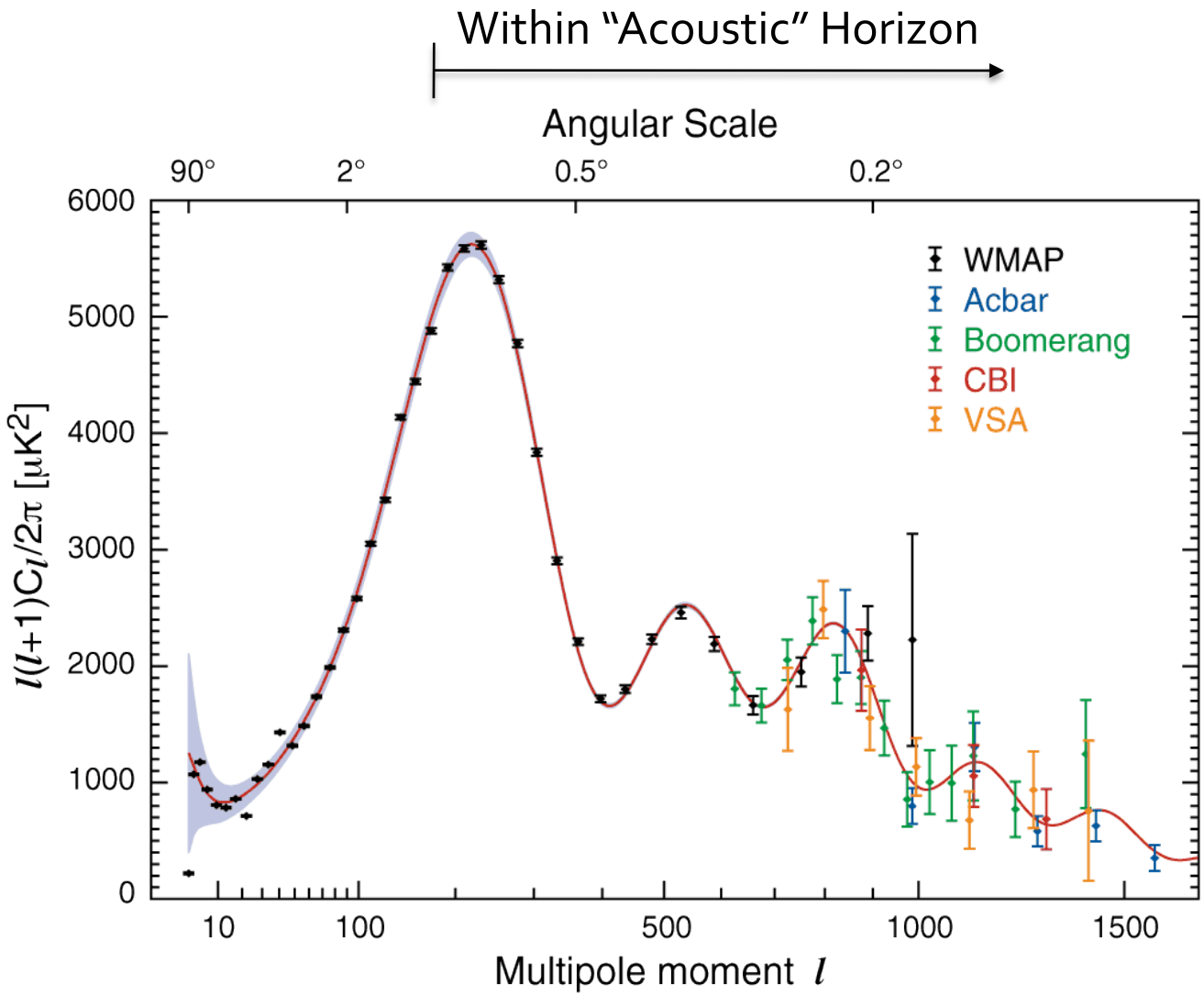


Image Credit: WMAP Science Team

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

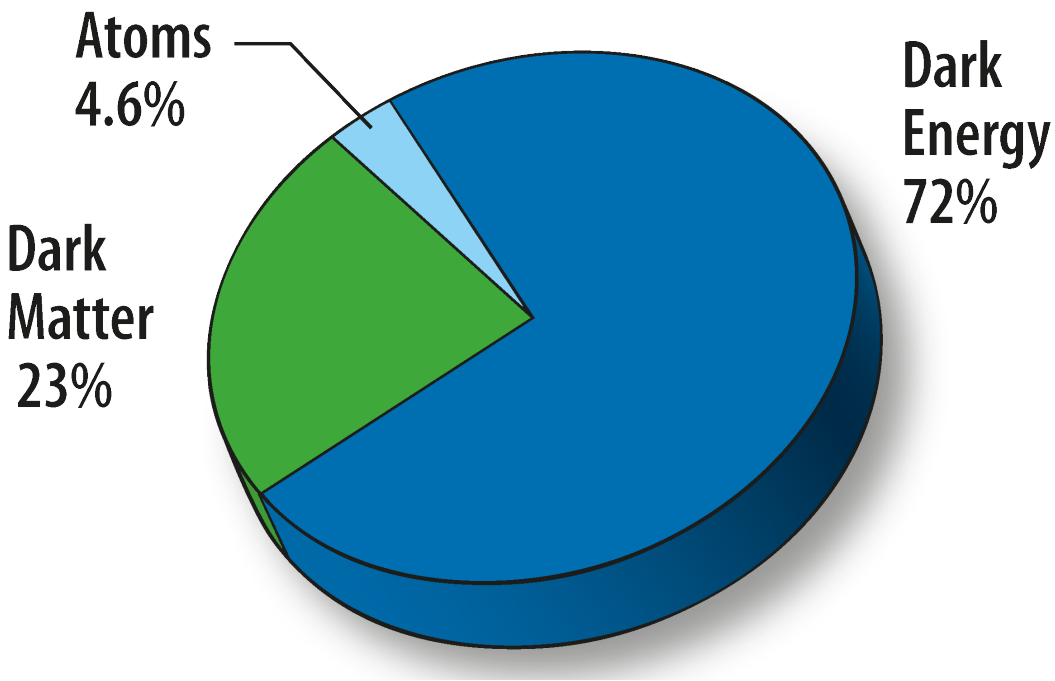
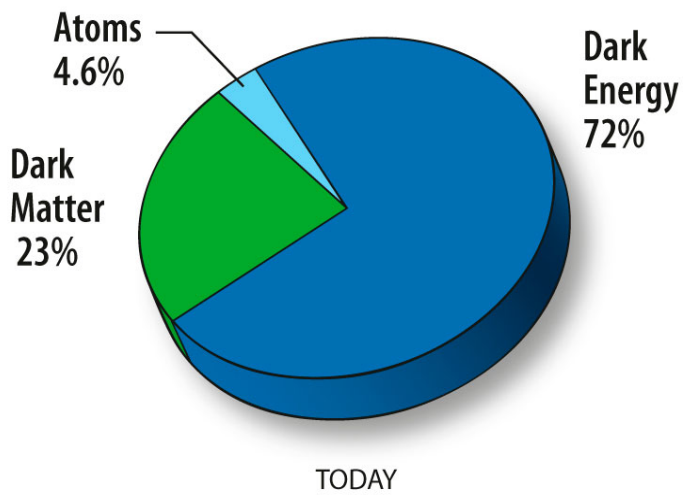
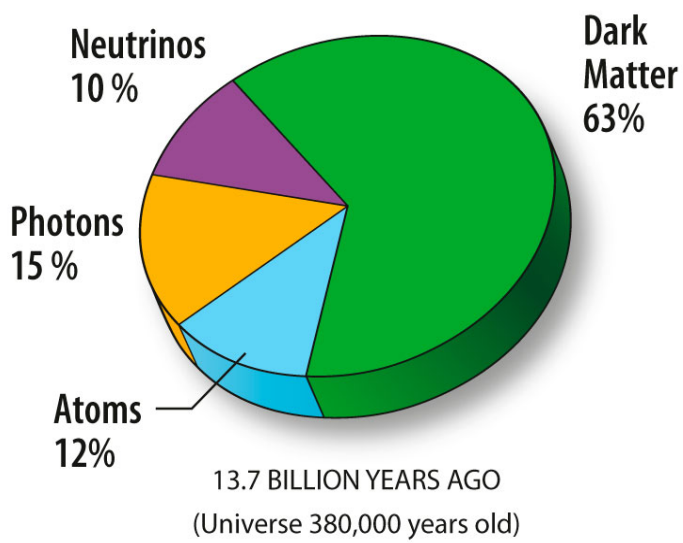


Image credit: NASA/WMAP Science Team

Time Dependence





Weakly Interacting Massive Particles

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

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

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

Neutralinos – The Favourite WIMP

- Supersymmetry predicts "superpartners" for standard model particles
- If R-parity is conserved, the lightest supersymmetric particle is stable
- This LSP is a neutralino, χ, which is a superposition of the superpartners of the W, Z and H
- Predicted to be
  - Electrically neutral
  - Weakly interacting
  - Massive

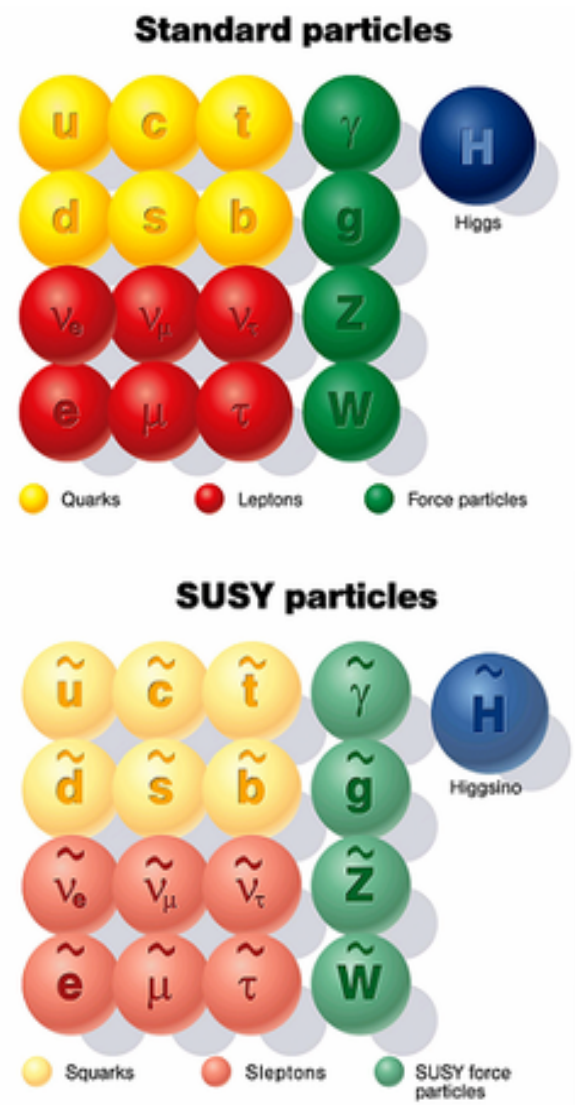


Image credit: DESY

DAMA/LIBRA

- The DAMA/LIBRA NaI experiment
- Have long seen an annual modulation, which they attribute to dark matter
  - >8σ effect
  - Amplitude ~1%
  - Period consistent with 1 yr
  - Phase peaks May 9 – June 2 (predicted peak: June 2)
- Result is not widely accepted – interpretation as WIMP signal challenged by other experiments

Beta/Gamma Backgrounds

- Most numerous background, total of 3×10^7 / 0.1 ton-yr
- Dominated by ^{39}Ar (1 Bq/kg in atmospheric argon - factor 25 depletion shown)
- Gamma-ray background enters at a depletion factor of 200-1000
- Need ~10^9 discrimination

Source	Bkg / 0.1 ton-yr
^{39}Ar	$<2.5\times10^7$
Fused Silica	3.6×10^5
PTFE	306
Copper	2,146
QUPIDs	7.0×10^4
R11065 PMTs	2.6×10^6
Titanium	2.4×10^4
Veto Scintillator	70
Veto PMTs	2.5×10^6
Veto tank	1.7×10^5
Water	6,100
CTF tank	8,300
LNGS Rock	920

Electron Recoil Backgrounds

- Combined (PSA + S1/S2) discrimination of ~2x10^9
- Two-dimensional discrimination means that discrimination power can be investigated *in situ*
- Lower thresholds possible, depending on argon depletion

Detector Element	Background / 0.1 ton-yr	
	Raw	After Cuts
^{39}Ar	$<2.5\times10^{7}$	<0.02
Fused Silica	3.6×10^{5}	1.4×10^{-4}
PTFE	306	1.2×10^{-7}
Copper	2,146	8.6×10^{-7}
QUPIDs	7.0×10^{4}	2.8×10^{-5}
R11065 PMTs	2.6×10^{6}	1.0×10^{-3}
Titanium	2.4×10^{4}	9.6×10^{-6}
Veto Scintillator	70	2.8×10^{-8}
Veto PMTs	2.5×10^{6}	1.0×10^{-3}
Veto tank	1.7×10^{5}	6.8×10^{-5}
Water	6,100	2.4×10^{-6}
CTF tank	8,300	3.3×10^{-6}
LNGS Rock	920	3.7×10^{-7}
Total	–	0.021 (0.022)

QUPIDs R11065s

Radiogenic Neutrons

- Also produced inside the detector
- Even with the cleanest materials, expect O(1) background/yr from internal neutrons
- Difficult to reliably predict very low background levels from screening measurements, as handling can be the dominant background source (e.g. Rn daughters)

Source	Bkg / 0.1 ton-yr
^{39}Ar	–
Fused Silica	1.8
PTFE	0.024
Copper	0.0024
QUPIDs	0.31
R11065 PMTs	19.4
Titanium	1.1
Veto Scintillator	0.030
Veto PMTs	0.023
Veto tank	6.7×10^{-5}
Water	6.7×10^{-4}
CTF tank	3.5×10^{-3}
LNGS Rock	0.061

Radiogenic Neutrons

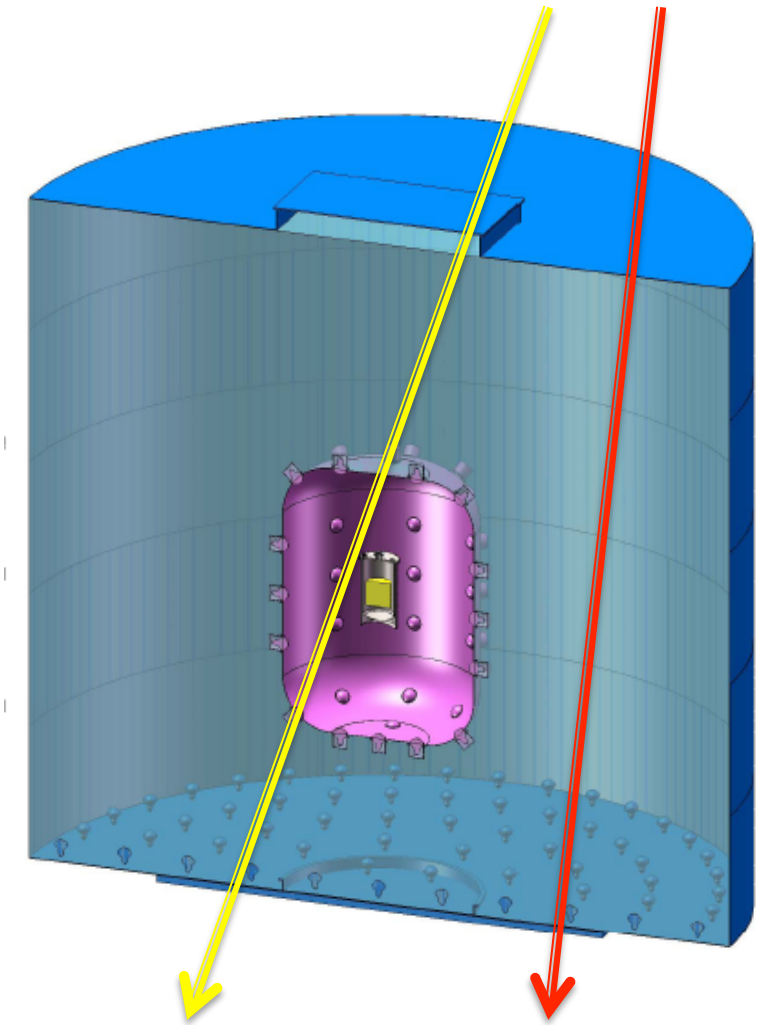
- Suppressed by a factor of ~2 with multiple recoil cut, ~200 by the neutron veto
- The residual background can be measured at < 0.01 ev/ 0.1 ton-yr

Detector Element	Radiogenic Neutron Recoil Backgrounds	
	Raw	After Cuts
^{39}Ar	–	–
Fused Silica	1.8	4.5×10^{-3}
PTFE	0.024	6.0×10^{-5}
Copper	0.0024	6.0×10^{-6}
QUPIDs	0.31	7.8×10^{-4}
R11065 PMTs	19.4	4.9×10^{-2}
Titanium	1.1	2.8×10^{-3}
Veto Scintillator	0.030	7.5×10^{-5}
Veto PMTs	0.023	5.7×10^{-5}
Veto tank	6.7×10^{-5}	1.7×10^{-7}
Water	6.7×10^{-4}	1.7×10^{-6}
CTF tank	3.5×10^{-3}	8.7×10^{-6}
LNGS Rock	0.061	1.5×10^{-4}
Total	–	0.0082 (0.056)

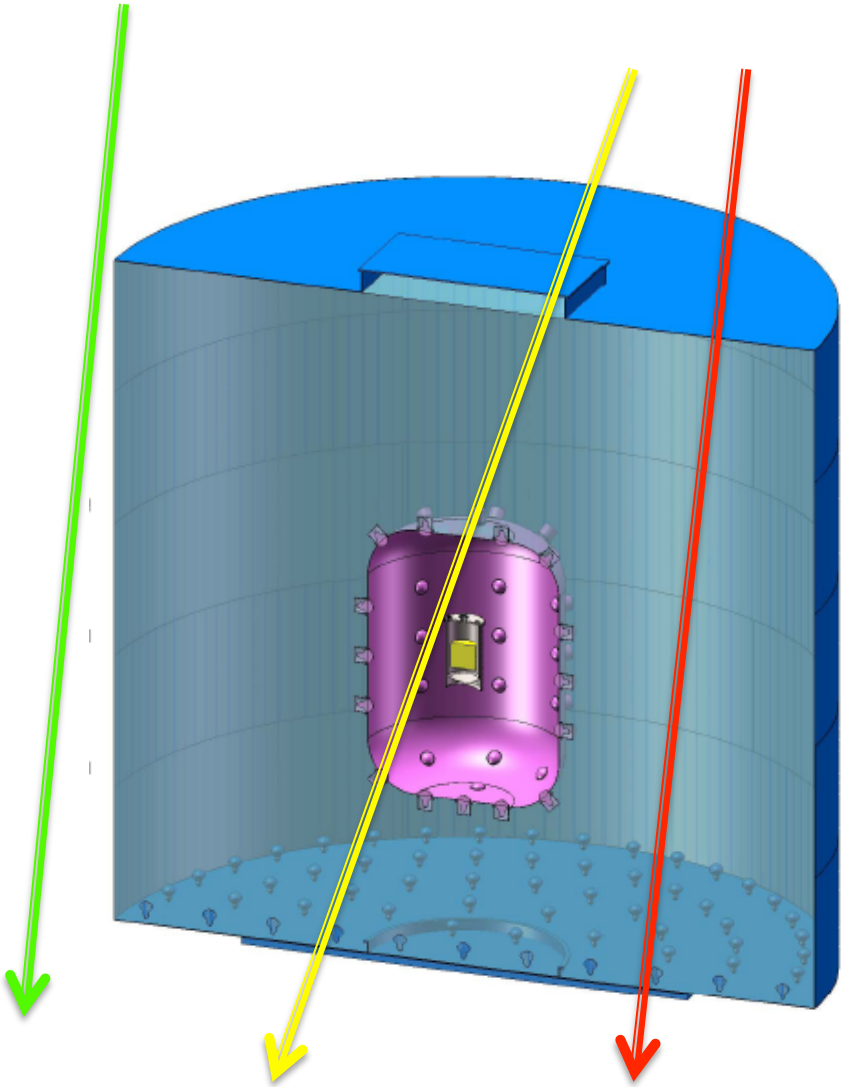
QUPIDs R11065s

Cosmogenic Neutrons

- Produced by muon spallation
- Low rates underground (O(1)/ m^2/day at LNGS, where muon flux is 10^6 less than on surface)
- GeV energies, with meter-scale interaction lengths, makes them hard to shield (or veto!)
- O(50) recoil backgrounds in DarkSide-50 per year at LNGS



Cosmogenic Neutrons



Detector Element	Cosmogenic Neutron Recoil Backgrounds	
	Raw	After Cuts
^{39}Ar	–	–
Fused Silica	2.3	1.4×10^{-4}
PTFE	0.17	1.0×10^{-5}
Copper	0.72	4.3×10^{-5}
QUPIDs	0.34	2.0×10^{-5}
R11065 PMTs	0.34	2.0×10^{-5}
Titanium	13	7.7×10^{-4}
Veto Scintillator	26	0.0015
Veto PMTs	–	–
Veto tank	19	0.0076
Water	19	0.0076
CTF tank	0.068	2.7×10^{-5}
LNGS Rock	0.31	0.012
Total	–	0.030 (0.030)

Rejection Efficiency

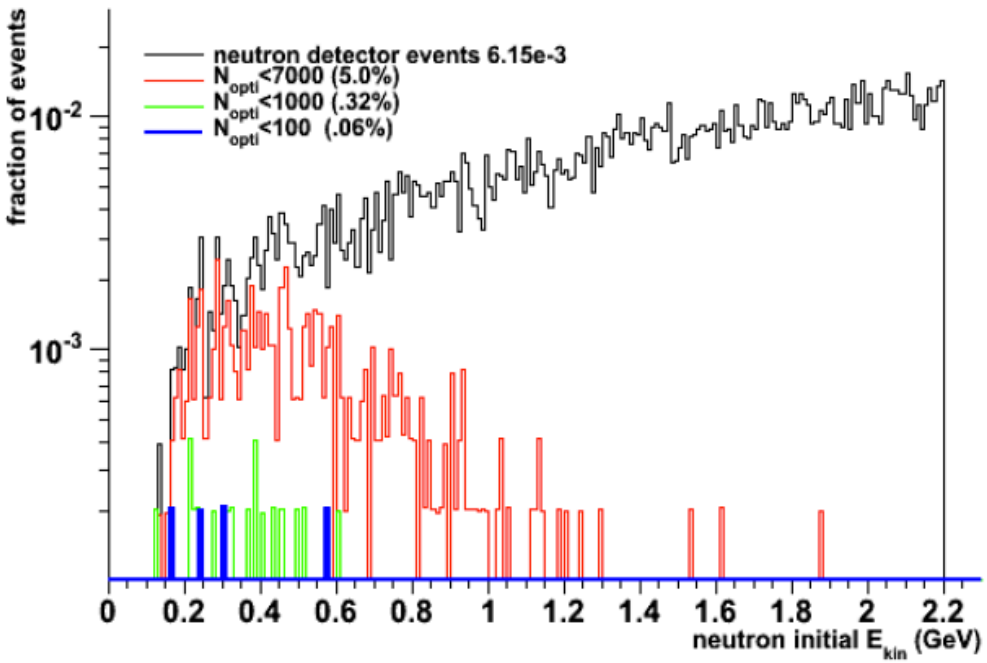
99.992% (muon) & 25% (neutron)

99% (muon) & 95% (neutron) & 25% (neutron)

95% (neutron) & 25% (neutron)

Cosmogenic Backgrounds in CTF

- Simulations suggest that CTF water tank + scintillator veto suppress cosmogenic backgrounds to ~0.3 / T•yr
  - Perhaps even further
    - Simulated only single neutrons
    - High energy neutrons can produce Cerenkov particles in water as well
- A ton-scale experiment is possible in the CTF!



Summary

Detector Element	Electron Recoil Backgrounds		Radiogenic Neutron Recoil Backgrounds		Cosmogenic Neutron Recoil Backgrounds	
	Raw	After Cuts	Raw	After Cuts	Raw	After Cuts
^{39}Ar	$<2.5\times10^{7}$	<0.02	–	–	–	–
Fused Silica	3.6×10^{5}	1.4×10^{-4}	1.8	4.5×10^{-3}	2.3	1.4×10^{-4}
PTFE	306	1.2×10^{-7}	0.024	6.0×10^{-5}	0.17	1.0×10^{-5}
Copper	2,146	8.6×10^{-7}	0.0024	6.0×10^{-6}	0.72	4.3×10^{-5}
QUPIDs	7.0×10^{4}	2.8×10^{-5}	0.31	7.8×10^{-4}	0.34	2.0×10^{-5}
R11065 PMTs	2.6×10^{6}	1.0×10^{-3}	19.4	4.9×10^{-2}	0.34	2.0×10^{-5}
Titanium	2.4×10^{4}	9.6×10^{-6}	1.1	2.8×10^{-3}	13	7.7×10^{-4}
Veto Scintillator	70	2.8×10^{-8}	0.030	7.5×10^{-5}	26	0.0015
Veto PMTs	2.5×10^{6}	1.0×10^{-3}	0.023	5.7×10^{-5}	–	–
Veto tank	1.7×10^{5}	6.8×10^{-5}	6.7×10^{-5}	1.7×10^{-7}	19	0.0076
Water	6,100	2.4×10^{-6}	6.7×10^{-4}	1.7×10^{-6}	19	0.0076
CTF tank	8,300	3.3×10^{-6}	3.5×10^{-3}	8.7×10^{-6}	0.068	2.7×10^{-5}
LNGS Rock	920	3.7×10^{-7}	0.061	1.5×10^{-4}	0.31	0.012
Total	–	0.021 (0.022)	–	0.0082 (0.056)	–	0.030 (0.030)

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

(All in ev / 0.1 ton-yr for QUPIDs (R11065s))

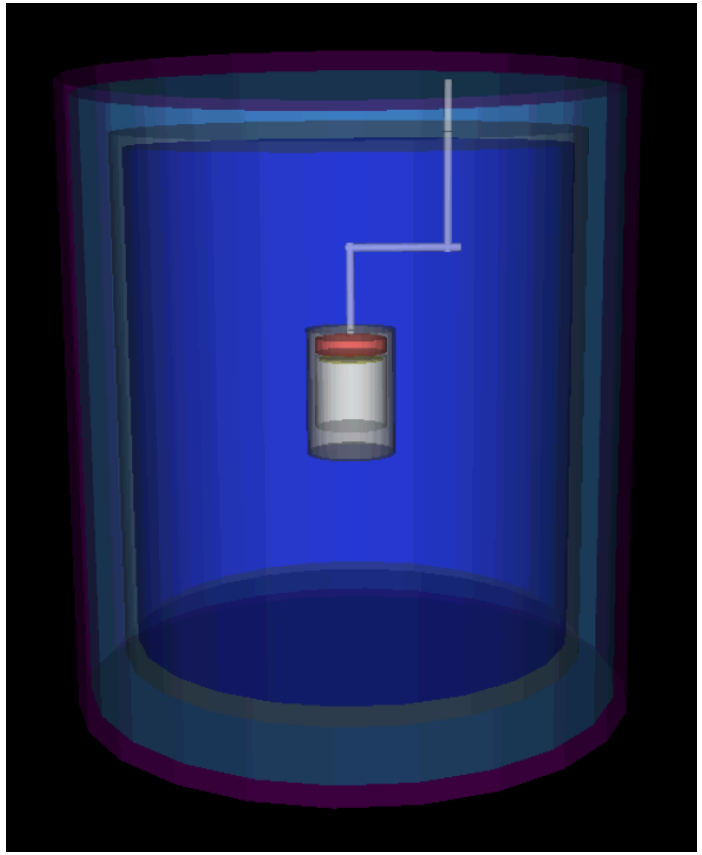
Backgrounds Estimates

For DarkSide-50 with neutron veto in CTF

Background	Recoil-like Events in WIMP Energy Region $(T\text{-}yr)^{-1}$
Radiogenic Neutrons	0.01
External Cosmogenics	0.2
Internal Cosmogenics	0.1
Beta/Gamma	0.08 (at factor 25 ^{39}Ar reduction, 10^8 rejection)
Total	0.4

Technical Details

- Background simulations done in Geant4, with radiogenic neutron production from Sources4A
  - Approximate, cylindrical geometry
- Internal contaminants taken at best measured value (or limit)
  - Both QUPIDs and R11065 PMTs
- Quote total backgrounds in 30-200 keV_r in 0.1 ton-yr
- 6 p.e./keV_{ee} (equals 3.0 p.e./keV for γ's and 1.8 p.e./keV_r for nuclear recoils at 1 kV/cm drift field)
- Conservative approximations, estimate "factor of 2" uncertainties

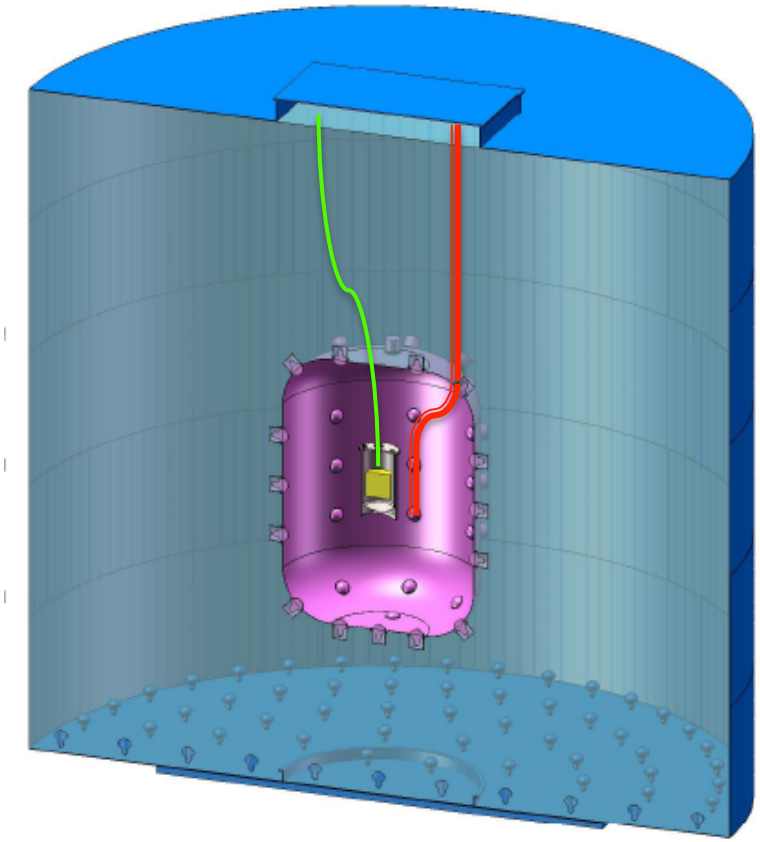


Assumed Radiopurity

Component	^{238}U		^{232}Th		^{210}Pb		^{40}K		Comments
	(Bq/kg)	Ref	(Bq/kg)	Ref	(Bq/kg)	Ref	(Bq/kg)	Ref	
PTFE (Dupont Teflon)	$<9.6\times10^{-6}$	[6]	$<1.1\times10^{-6}$	[6]	~0.20	[7]	$\sim1.0\times10^{-4}$	[6]	Cs, Co
Copper (OFHC)	$<3.6\times10^{-5}$	[6]	$<9.8\times10^{-6}$	[6]	~0.30	[7]	$<1.6\times10^{-3}$	[6]	Cs, Co
Acrylic (Perspex)	$<1.4\times10^{-5}$	[8]	$<4.5\times10^{-6}$	[8]			~0.022	[7]	
Fused Silica (Suprasil)	$\sim2.5\times10^{-3}$	[7]	$\sim8.1\times10^{-4}$	[7]			$\sim9.3\times10^{-4}$	[7]	
Titanium	$<2.5\times10^{-4}$	[9]	$<2.0\times10^{-4}$	[9]	<1.3	[7]	$<1.2\times10^{-3}$	[9]	Cs, Co, Sc
HDPE	$<2.5\times10^{-3}$	[10]	$<8.1\times10^{-4}$	[10]	~0.60	[7]	~0.26	[7]	Cs, Co
Steel (304SS)	<0.002	[7]	<0.001	[7]	<0.30	[7]	<0.004	[7]	Cs, Co, Mn
Ship Steel	$<7.4\times10^{-4}$	[11]	~0.0011	[11]			<0.013	[11]	Mn
Lead (Doe Run)	$<3.7\times10^{-5}$	[6]	$<1.2\times10^{-5}$	[6]	~29	[6]	$\sim1.6\times10^{-4}$	[6]	
TPB	<0.026	[12]	<0.023	[12]			~0.41	[12]	
Boron Loaded PC	$\sim1.9\times10^{-8}$	[4, 13]	$\sim1.2\times10^{-10}$	[4, 13]	$<1.0\times10^{-4}$	[4]	$<3.1\times10^{-10}$	[4]	
Water	$<8.0\times10^{-6}$	[2]	$\sim2.8\times10^{-8}$	[2]			$\sim3.1\times10^{-7}$	[2]	
Argon									
	(Bq/tube)	Ref	(Bq/tube)	Ref	(Bq/tube)	Ref	(Bq/tube)	Ref	
3″ QUPID	$<4.9\times10^{-4}$	[1]	$<4.0\times10^{-4}$	[1]			$<2.4\times10^{-3}$	[1]	Co
R11065 PMT	~0.0147	[14]	~0.00068	[14]	~0.0157	[14]	~0.0420	[14]	Co
8″ PMT	~0.43	[15]	~0.020	[15]	~0.13	[15]	~0.0420	[14]	

Calibration

- Point source calibrations (neutron and gamma) through fixed guide tubes
  - Light yield + stability
  - Electron/nuclear recoil response
  - Veto efficiency
- Laser calibrations through fibre optics
  - Photodetector gain, stability and timing
- Distributed sources ($^{83}Kr^{m}$, ^{220}Rn)
  - Energy response
  - Detector stability



Demonstrating Discrimination

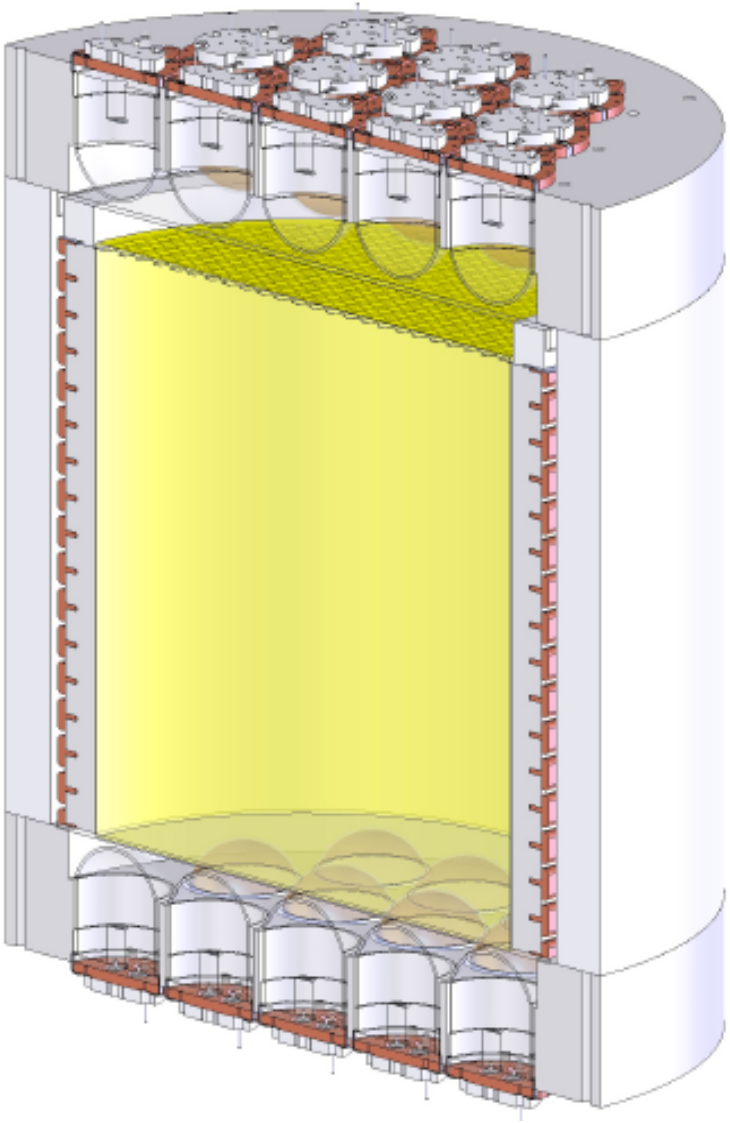
- Electron rejection
  - Use S2/S1 vs. PSA to understand rejection in situ
  - ^{39}Ar spike, if necessary
- Radiogenic neutrons
  - Calibrate efficiency of the neutron veto using point sources (using argon-scintillator co-incidences)
  - Monte Carlo to extrapolate to distributed sources
- Cosmogenic neutrons
  - Use distributions of 'tagged' cosmogenic neutrons, as observed in water, scintillator, and argon, in conjunction with Monte Carlo to understand rejection

Demonstrating Discrimination

- Surface background rejection
  - Spike with ^{220}Rn
    - Spike empty detector with ^{220}Rn gas
    - ^{212}Pb (10 hr half life) on surfaces supports $^{212}Bi/^{212}Po$ alpha activity
    - Refill detector quickly

DarkSide-50

- The first physics detector in the DarkSide program
  - 50 kg active mass
  - 39 QUPIDs/R11065 PMTs immersed in liquid
  - ITO coated fused silica "diving bell" and lower window
  - PTFE structure and high-reflectivity PTFE reflectors
  - TPB wavelength shifter coats inner surfaces
    - Detector is insensitive to light from outside inner volume



Goals of DarkSide-50

- Show that very low backgrounds can be achieved and demonstrated *in situ* with a liquid argon TPC and a neutron veto
- DarkSide-50 aims to be able to demonstrate ~0.05 background events in 0.1 ton-years
  - A 3σ "observation" possible with 2 observed events, or a 5σ "discovery" possible with 4 events (~5×10^{-45} cm^2)
  - Direct extrapolation to backgrounds in a ton-scale experiment possible

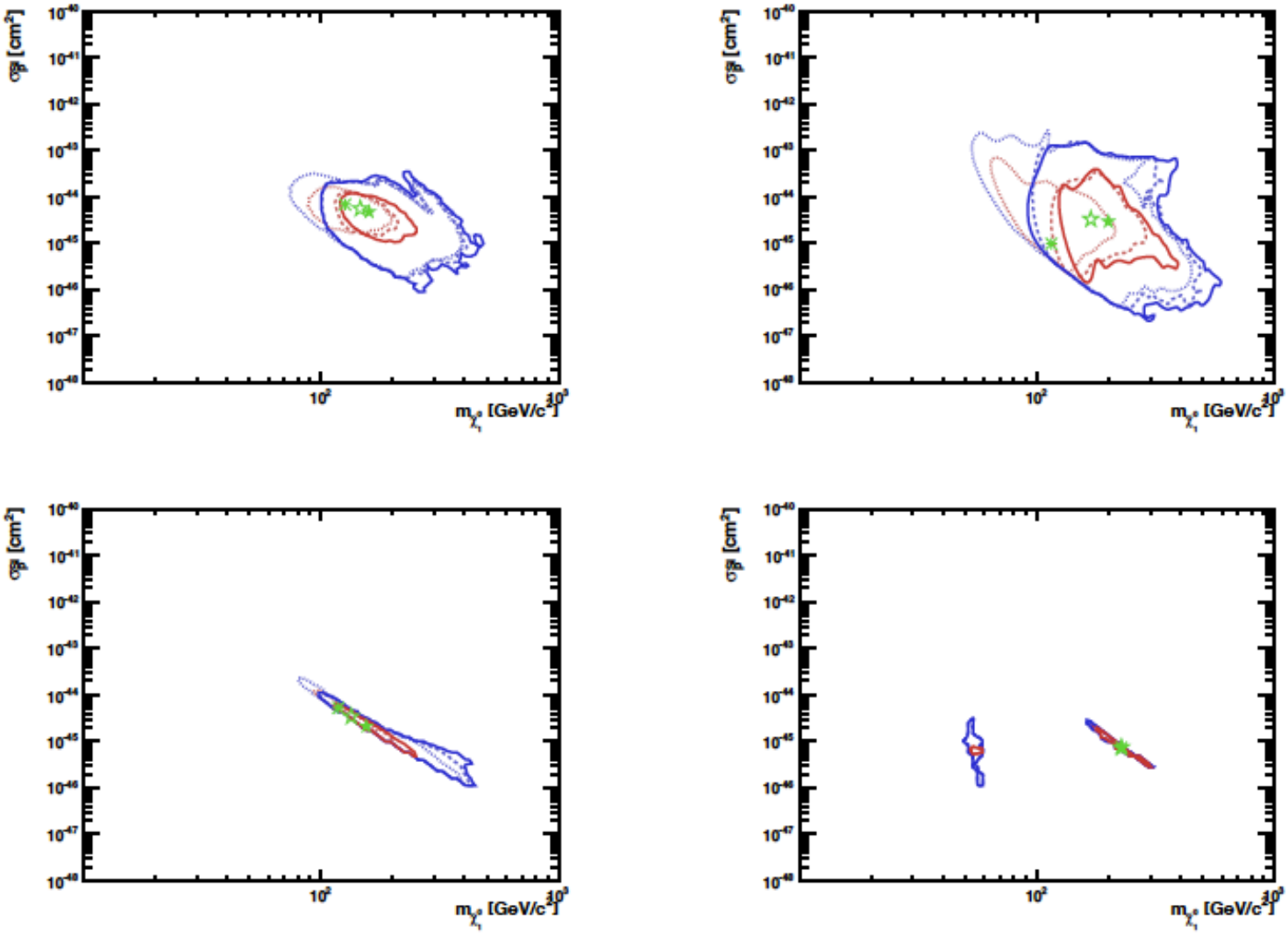


Figure 7. *The regions of the* $(m_{\tilde{\chi}_1^0}, \sigma_p^{\rm SI})$ *planes in the CMSSM (upper left), NUHM1 (top right), VCMSSM (lower left) and mSUGRA (lower right) favoured at the 68% and 95% CL including the CMS constraint (solid lines) and excluding it (dashed lines). The best-fit points after (before) the CMS and ATLAS constraints [19,20] are shown as open (solid) green stars, and the best pre-LHC fits as green 'snowflakes'. The results are calculated assuming* $\Sigma_{\pi N} = 64$ MeV.

arXiv:1102:4585

Scattering Cross Sections

Spin Independent vs Spin Dependent

In general, a Lorentz invariant Lagrangian **L** has S, P, V, A interactions.
The WIMPs can be a fermion or a boson or a scalar particle
However, galactic WIMPs are non-relativistic ➔ divide into two categories

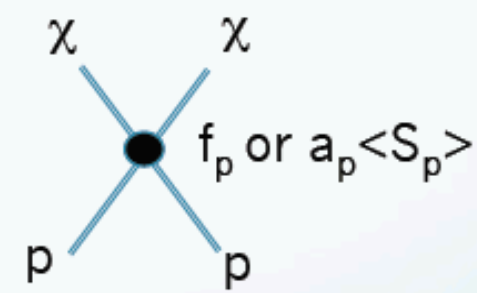
(a) $\mathbf{L}_{S+V}$: Scalar interaction as μA^2
(large λ_{dB} ➔ coherent interaction)

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2}\left[Zf_p + (A-Z)f_n\right]^2$$

(b) $\mathbf{L}_A$ Spin-spin interaction couples to net nuclear spin J_N

$$\sigma_{SD} = \frac{32}{\pi}G_F^2\frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2}\frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

f and a are effective couplings and <S> gives the spin content



Direct Detection of Neutralinos

- [e. g., Lewin & Smith; and Jungman, Kamionkowski & Griest]
- The observed differential rate of events is given by

$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi}\, v_0 m_\chi m_r^2} F^2(Q) T(Q) \eta(Q)$$

R in evts/kg - d, typically $\sigma_{0,scalar} >> \sigma_{0,spin}$; ρ_0 WIMP (χ) at earth, $\sim$ 0.3 GeV/cm^3

v_0 velocity of sun around galaxy, $\sim$ 220 km/s

m_χ, m_N mass of neutralino & nucleus, $m_r = \frac{m_\chi m_N}{m_\chi + m_N}$; recoil energy $Q = \frac{m_r^2 v^2}{m_N}(1 - \cos\theta^*)$

- For a Maxwell distribution of incident velocities

$$T(Q) = \exp\left[-(v_{\min}/v_0)^2\right] \text{ where } v_{\min} = \sqrt{Q m_N / m_r}$$

$\eta(Q)$ is the detector efficiency as a function of Q

Slide by B. Cabrera

Spin independent scalar cross section

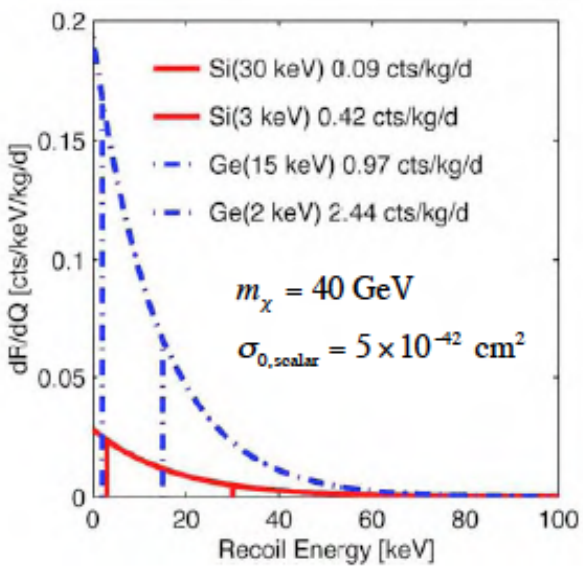
- To compare the coherent rates of different materials

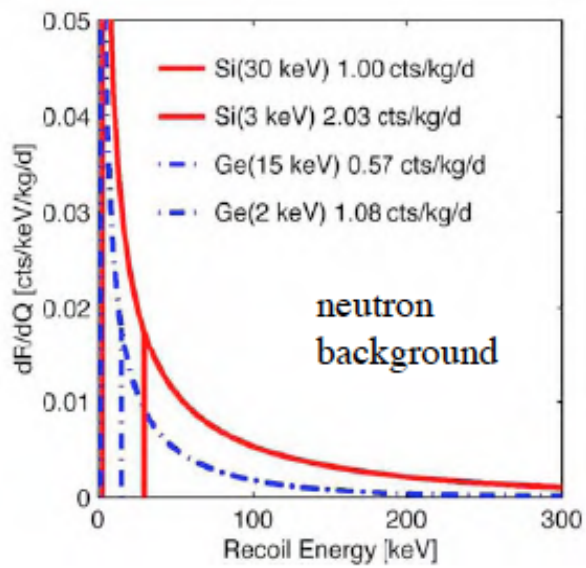
$$\sigma_{0\,scalar} = \frac{4 m_\chi^2 m_N^4}{\pi \left(m_\chi + m_N\right)^2} \left(\frac{f_n}{m_n}\right)^2 \text{, where } f_n \cong f_p \text{ is the WIMP - nucleon coupling}$$

- We define the fundamental WIMP-nucleon cross section

$$\frac{\sigma_{0\,Wn}}{m_{r\chi n}^2} = \frac{4}{\pi} f_n^2 = \frac{\sigma_{0\,scalar}}{A^2 m_{r\chi N}^2}, \text{ which gives } \sigma_{0\,Wn} \text{ in terms of } \sigma_{0\,scalar} \text{ with } A \cong m_N / m_n$$

- Two target materials such as Si and Ge very powerful

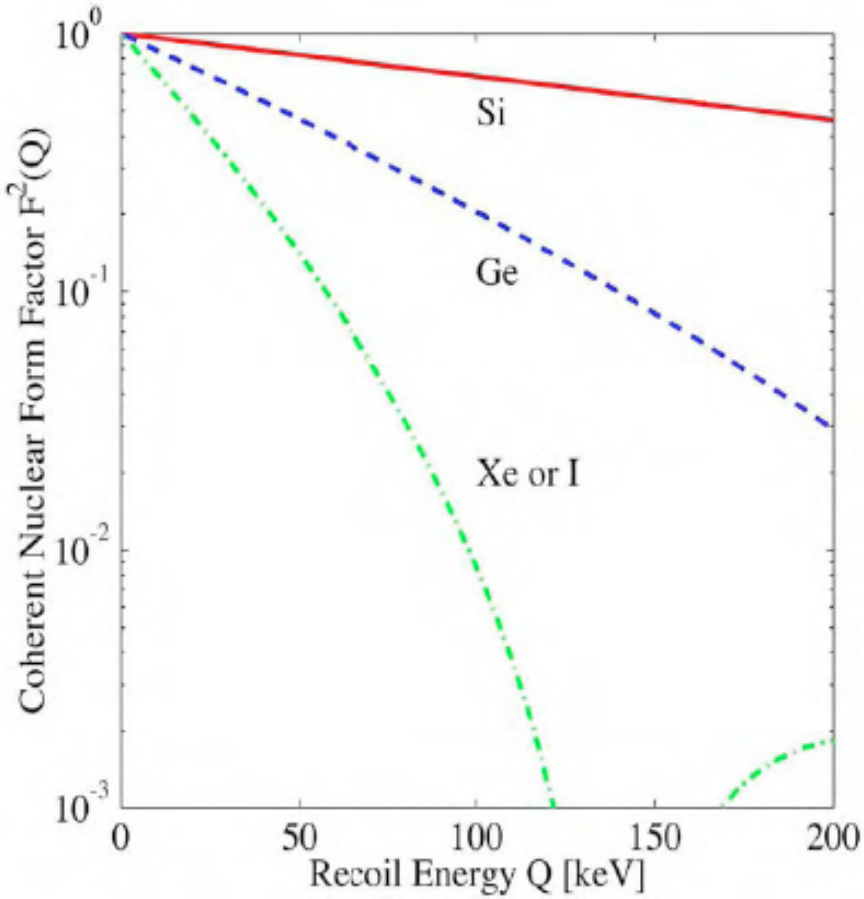


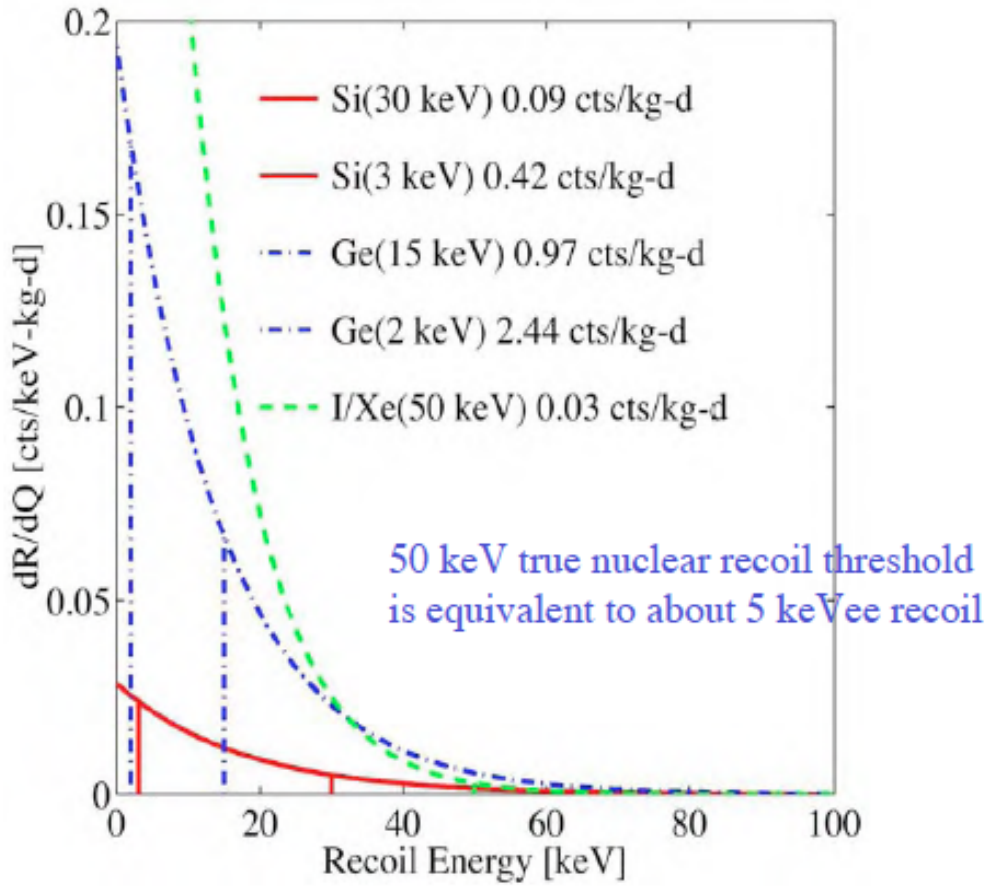


Slide by B. Cabrera

Nuclear form factor suppression

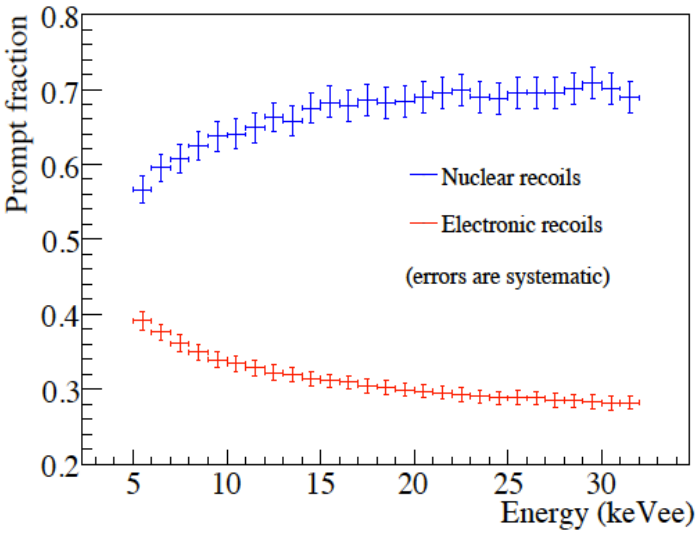
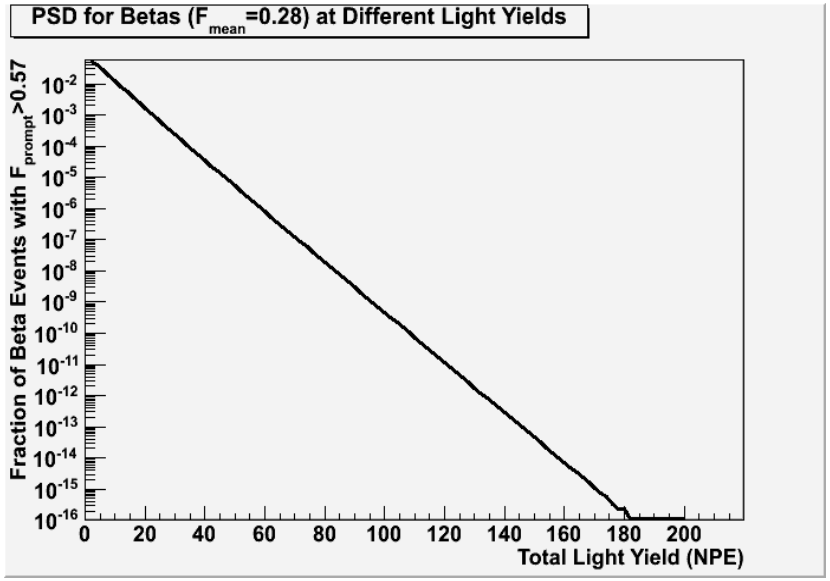
- For spin-independent or coherent interactions the form factor $F^2(Q)$ suppression is shown below and results in suppressed rates for heavy





$$F(Q) = 3\frac{j_1(Qr_n/\hbar c)}{Qr_n/\hbar c} exp\left[-(Qs/\hbar c)^2/2\right], \text{ where } r_n \approx \left(0.89\,A^{1/3} + 0.3\right) \text{ fm and } s \sim 1 \text{ fm}$$

Slide by B. Cabrera

Pulse Shape Discrimination

- "Noise" (electronic and real p.e.) can worsen PSD
- Better discrimination parameters can improve it
- MC study where MC p.e.'s are added to baselines from data and then analyzed
- This does not seriously impact the overall experiment, just our threshold