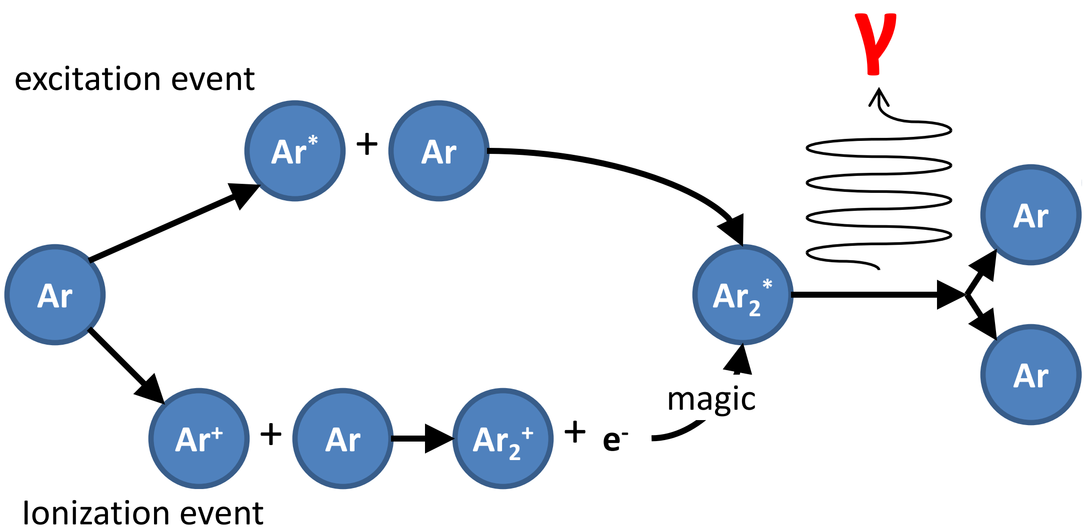
DarkSide and its low radioactivity argon target

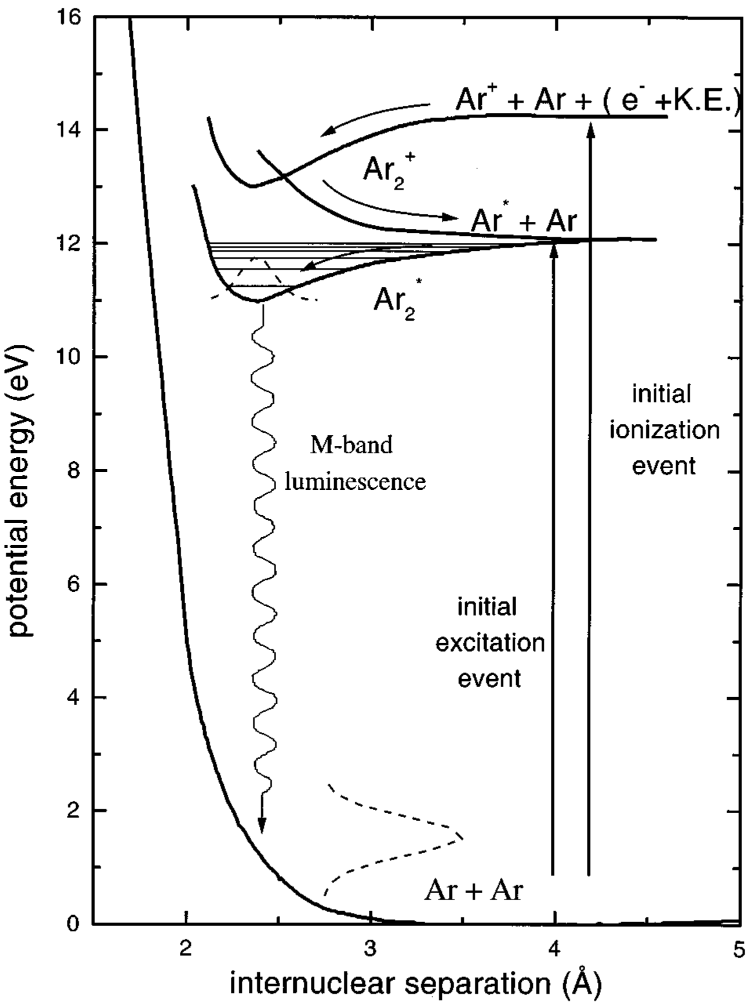
Henning O. Back – Princeton University

FCPA Seminar, 22 February 2012

ARGON SCINTILLATION

Excited argon dimer production

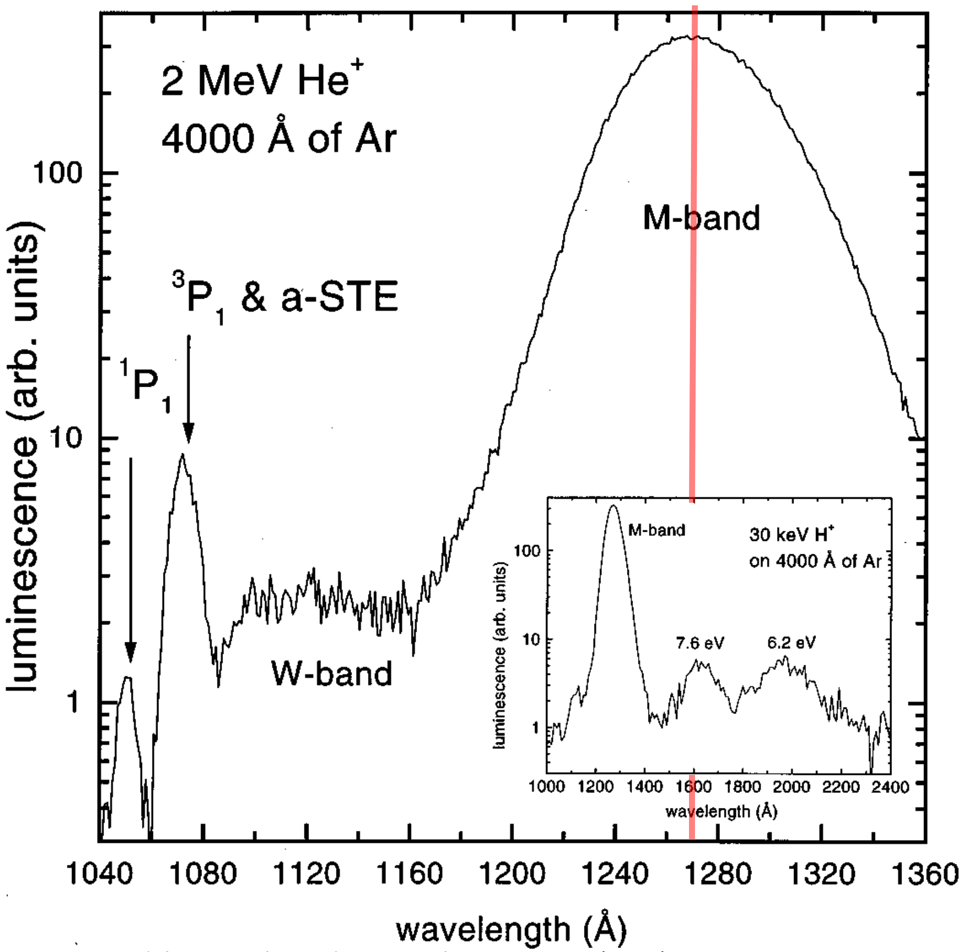




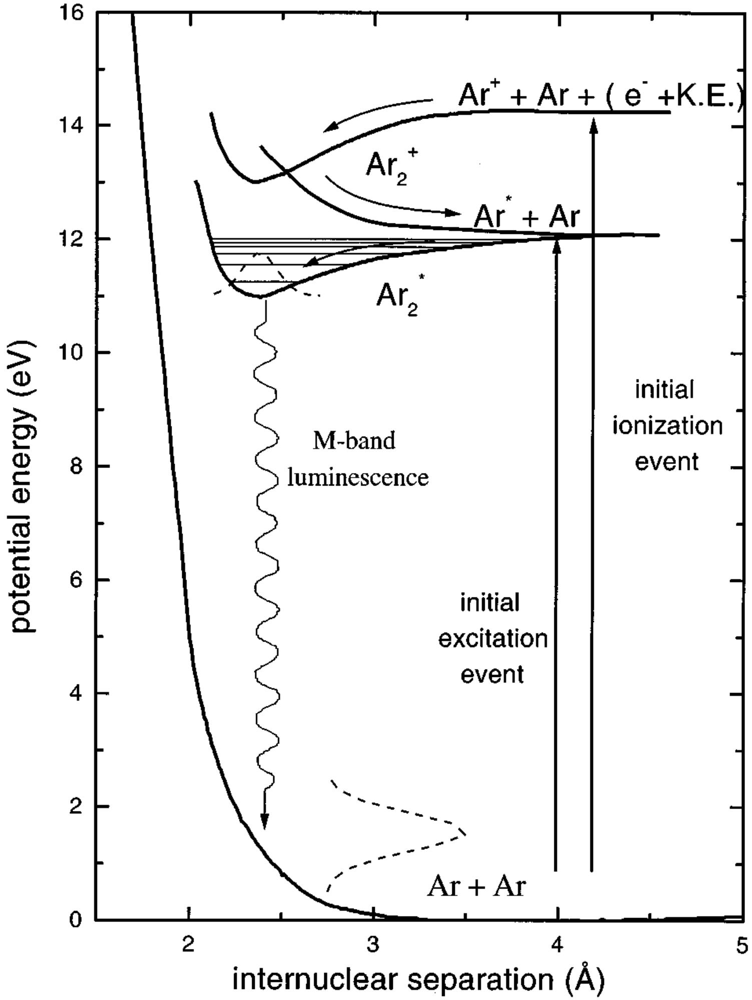
Grosjean, Vidal, Baragiola, And Brown, Phys. Rev. B **56** (1997) 6975-6981

Argon light output

9.8 eV



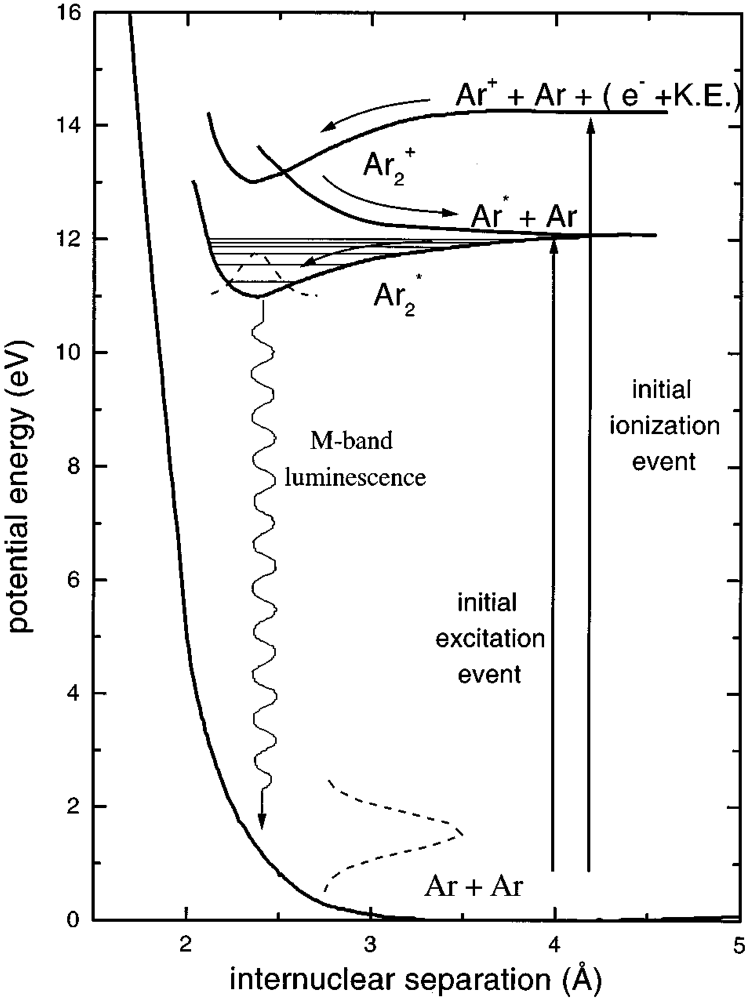
Grosjean, Vidal, Baragiola, And Brown, Phys. Rev. B **56** (1997) 6975-6981



Grosjean, Vidal, Baragiola, And Brown, Phys. Rev. B **56** (1997) 6975-6981

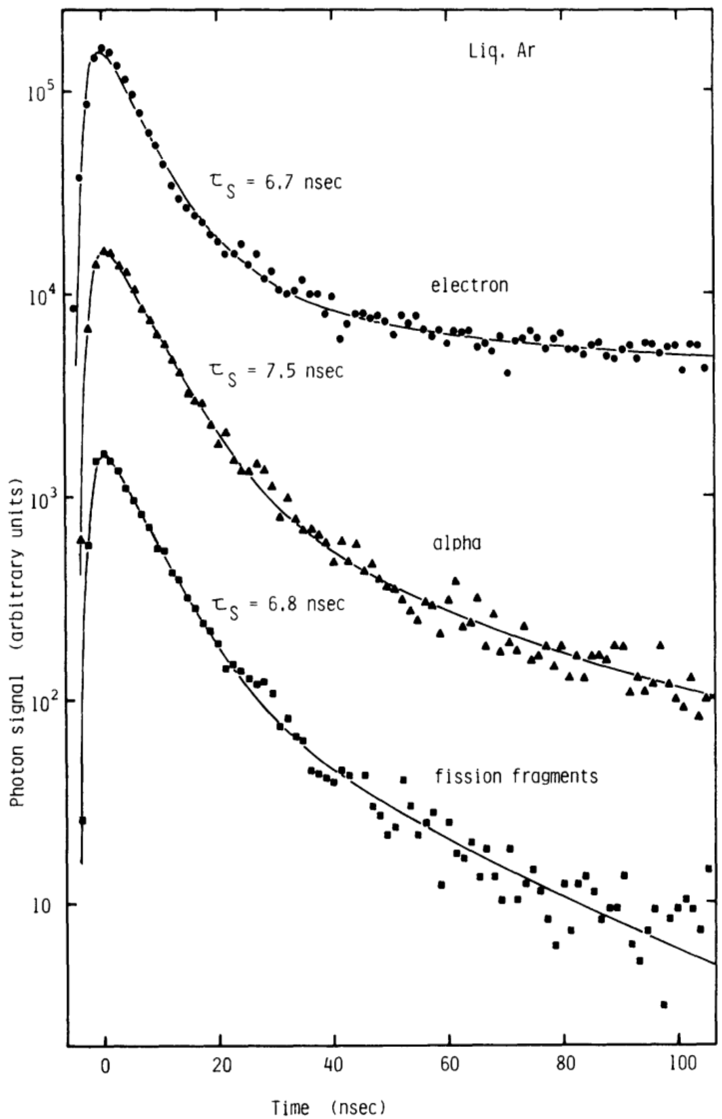
Pulse shape

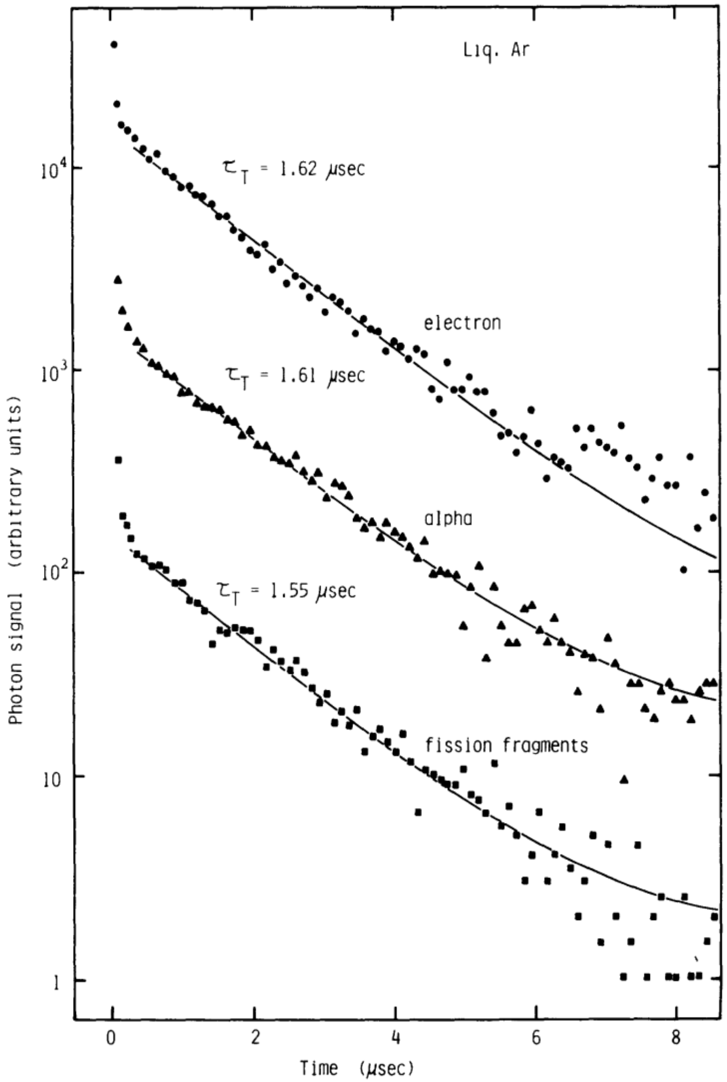
- Excited Ar dimer has 2 lowest energy states
  - Singlet
    - lifetime ~ 7 ns
  - Triplet (forbidden decay)
    - Lifetime ~1.6 μsec
  - States populated differently depending on ionization density
- Allows for pulse shape discrimination



Grosjean, Vidal, Baragiola, And Brown, Phys. Rev. B **56** (1997) 6975-6981

Pulse shape for different radiation

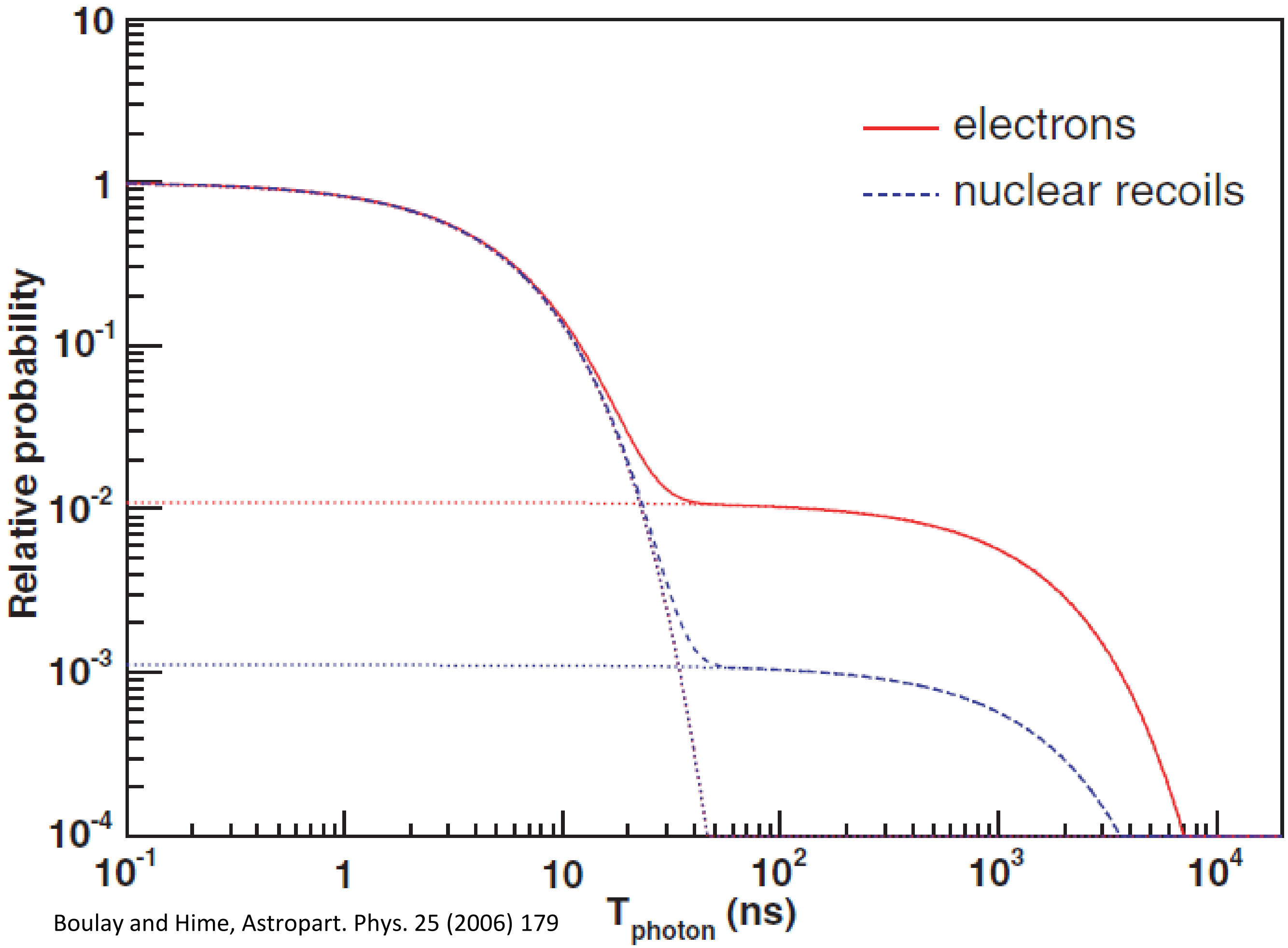




Hitachi, et al., Phys. Rev. B **27** (1983) 5279

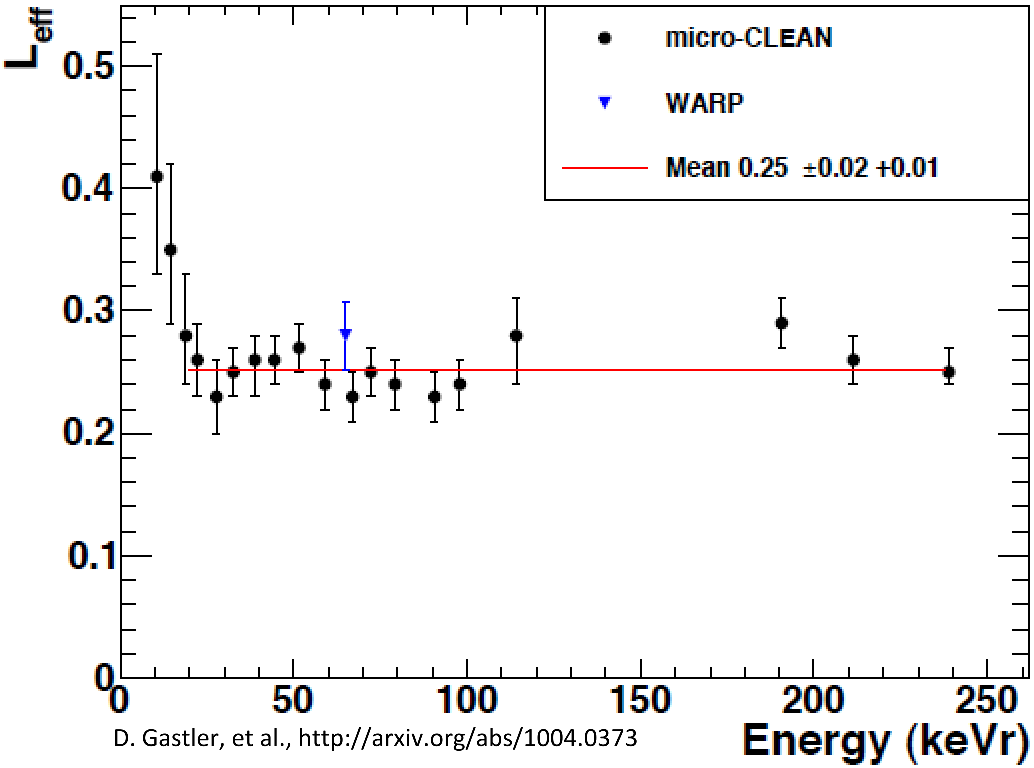
Pulse shape for nuclear recoils

- Dark matter will only scatter off of argon nucleus
- Recoiling nucleus cause argon excitation and ionization



Boulay and Hime, Astropart. Phys. 25 (2006) 179

Argon light yield



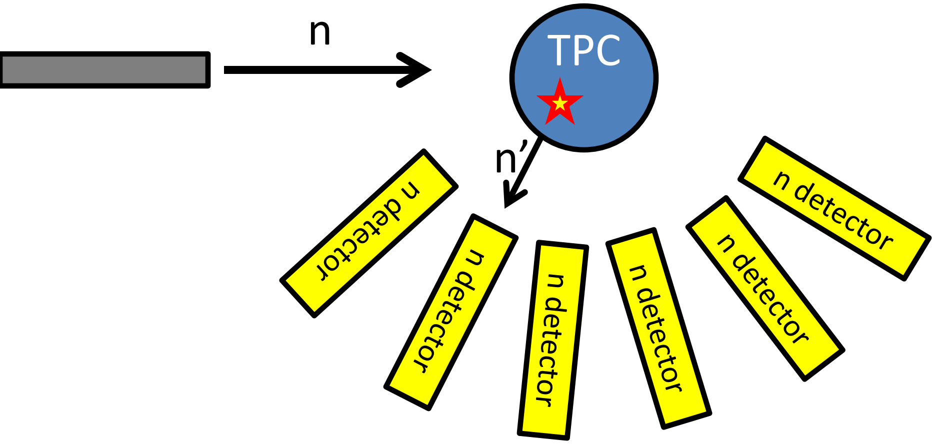
D. Gastler, et al., http://arxiv.org/abs/1004.0373

- Incident radiation may loose energy other than through excited dimer formation
- Ionization density dependent

$$L_{eff} = \frac{nuclear\ recoil\ scintillation}{electron\ scintillation}$$

Scintillation Efficiency of Noble Elements (Scene)

Fermilab - F. DeJongh, W. H. Lippincott, B. Loer, S. Pordes, A. Sonnenschein, C. Stoughton, J. Yoo
Princeton - H. O. Back, F. Calaprice, H. Cao, C. Galbiati, L. Grandi, P. Meyers, P. Mosteiro, A. Wright
Temple University- C. J. Martoff, C. Martin
UCLA - H. Wang, Y. Meng
Universit`a Federico II and INFN, Naples, Italy - A. Cocco and G. Fiorillo
University of Notre Dame - P. Collon and W. Tan



- Pulsed low energy neutron beam at Notre Dame
- Small dual phase TPC
- Several neutron detectors used in coincidence with TPC

- Measure scintillation efficiency due to nuclear recoils as a function of
  - Recoil energy
  - Applied E-field
- Will also measure free charge

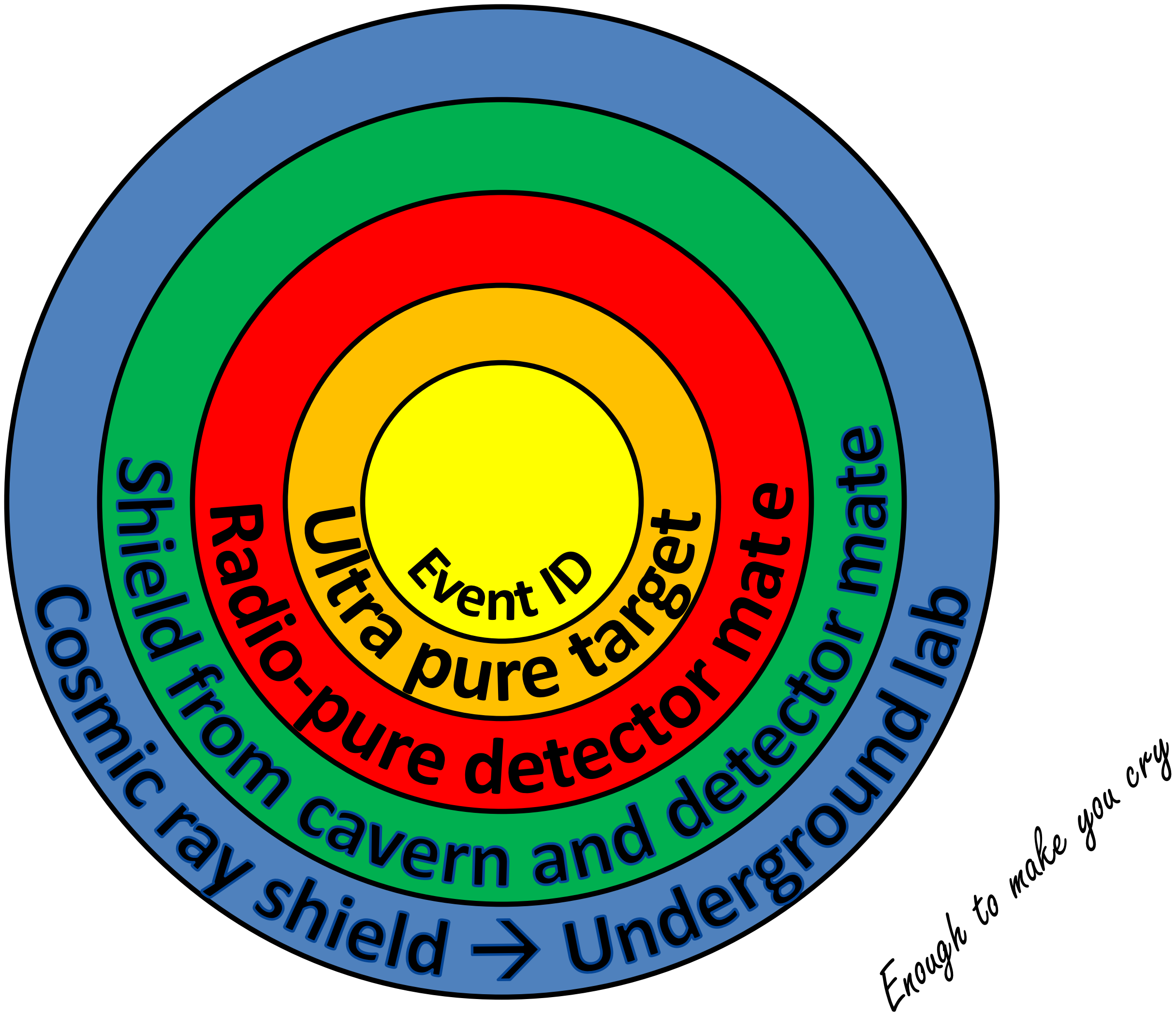
DARKSIDE

Taking advantage of argon properties for dark matter searches

DarkSide Collaboration

Augustana College – SD, USA
Black Hills 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
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

The onion peel of ultra low level background reduction



DarkSide event ID

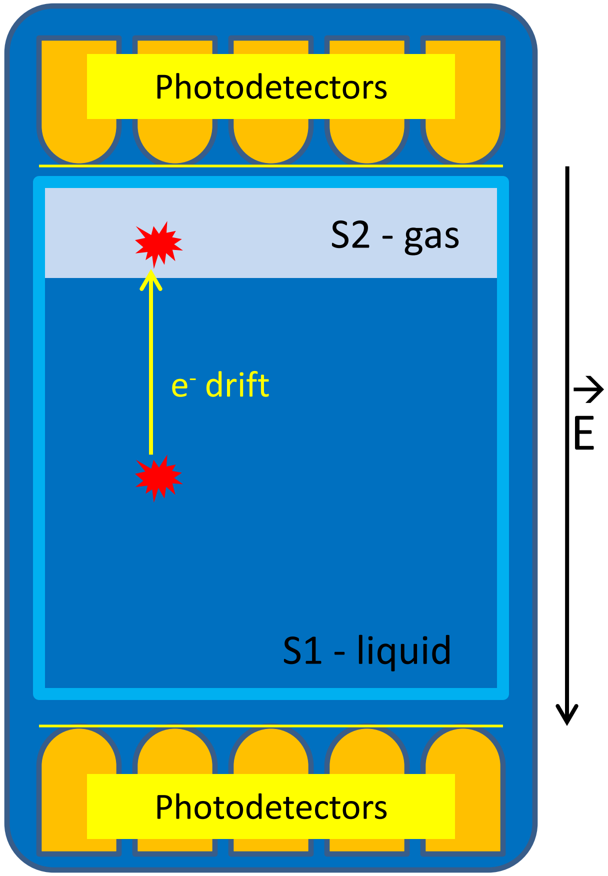
- Use argon scintillation and ionization properties
  - Scintillation pulse shape analysis
  - Ionization/Scintillation analysis

Dual phase TPC principle

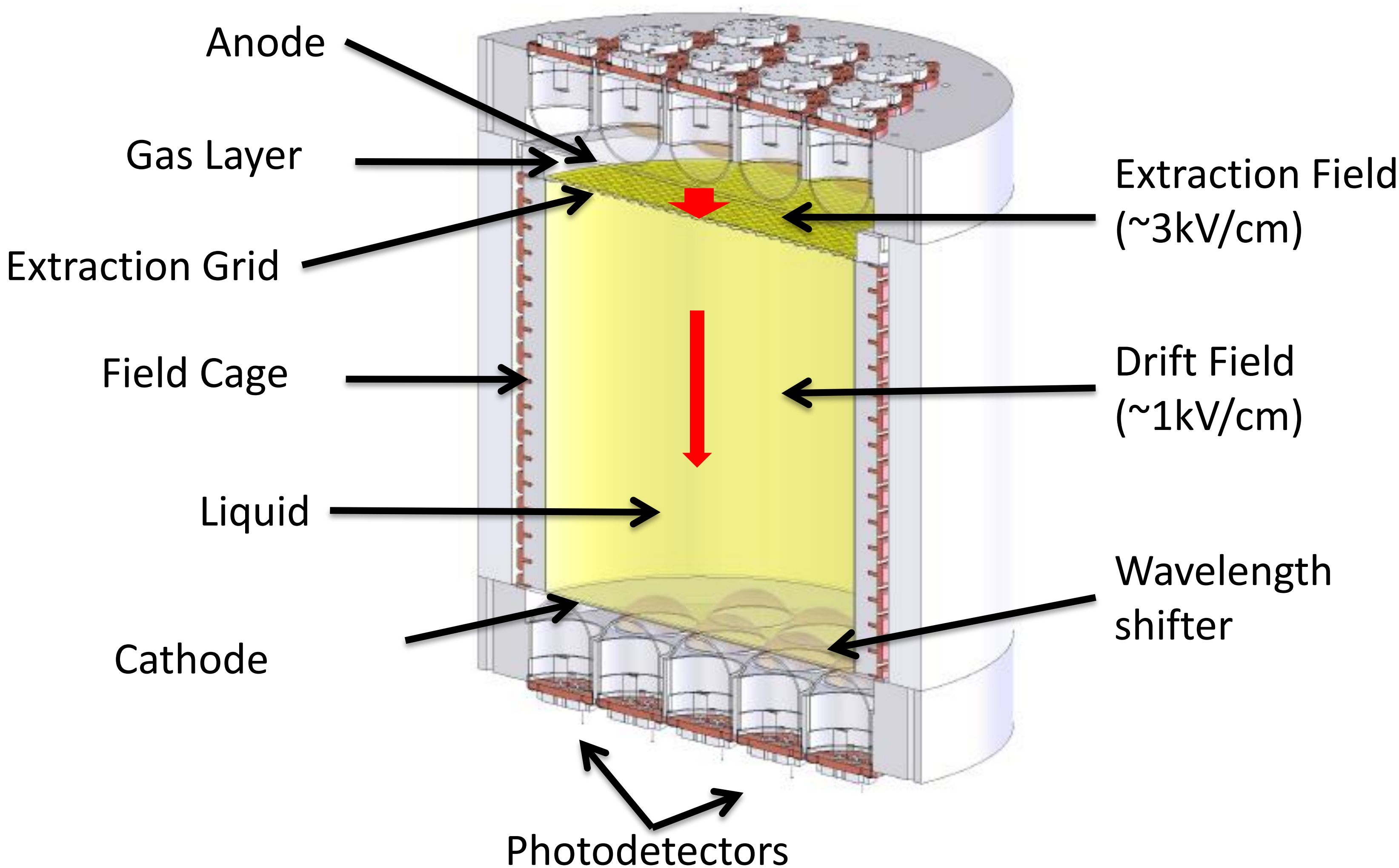
- Primary scintillation occurs in the liquid (S1)
- Free electrons from ionization are drifted to a gas region where a secondary scintillation pulse measures ionization (S2)
- Eliminating surface events (Fiducial volume)
  - PMT hit pattern provides X-Y position
  - Drift time provides Z position

Pulse shape discrimination

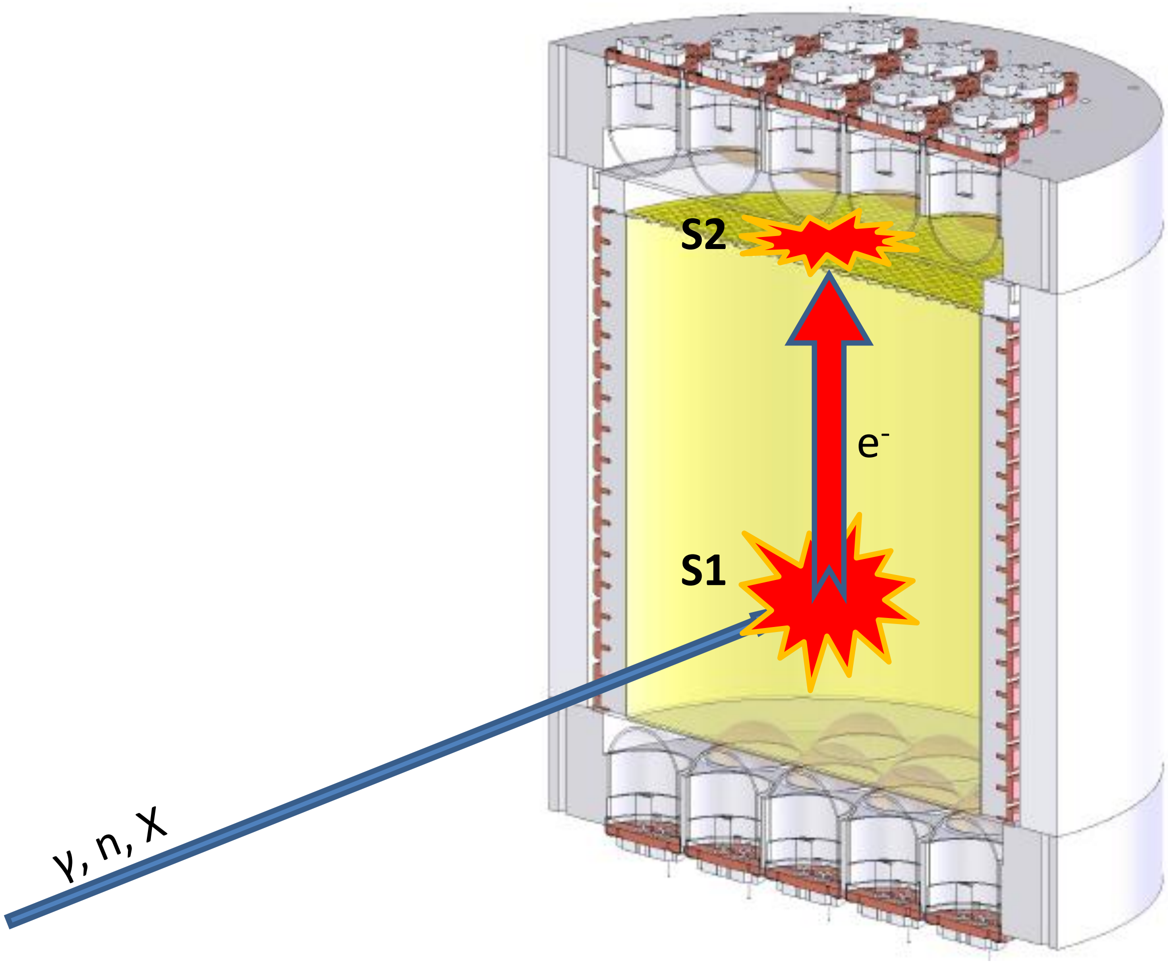
Ionization:Scintillation discrimination (S2/S1)



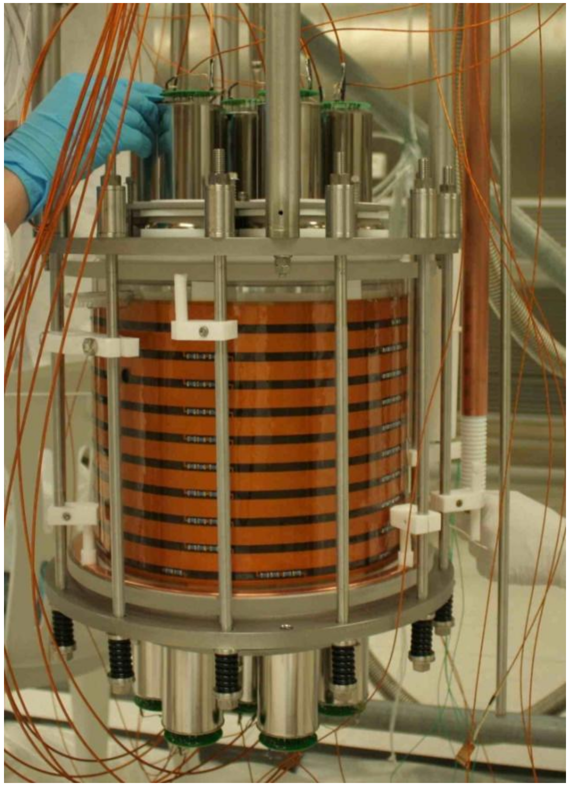
DarkSide design



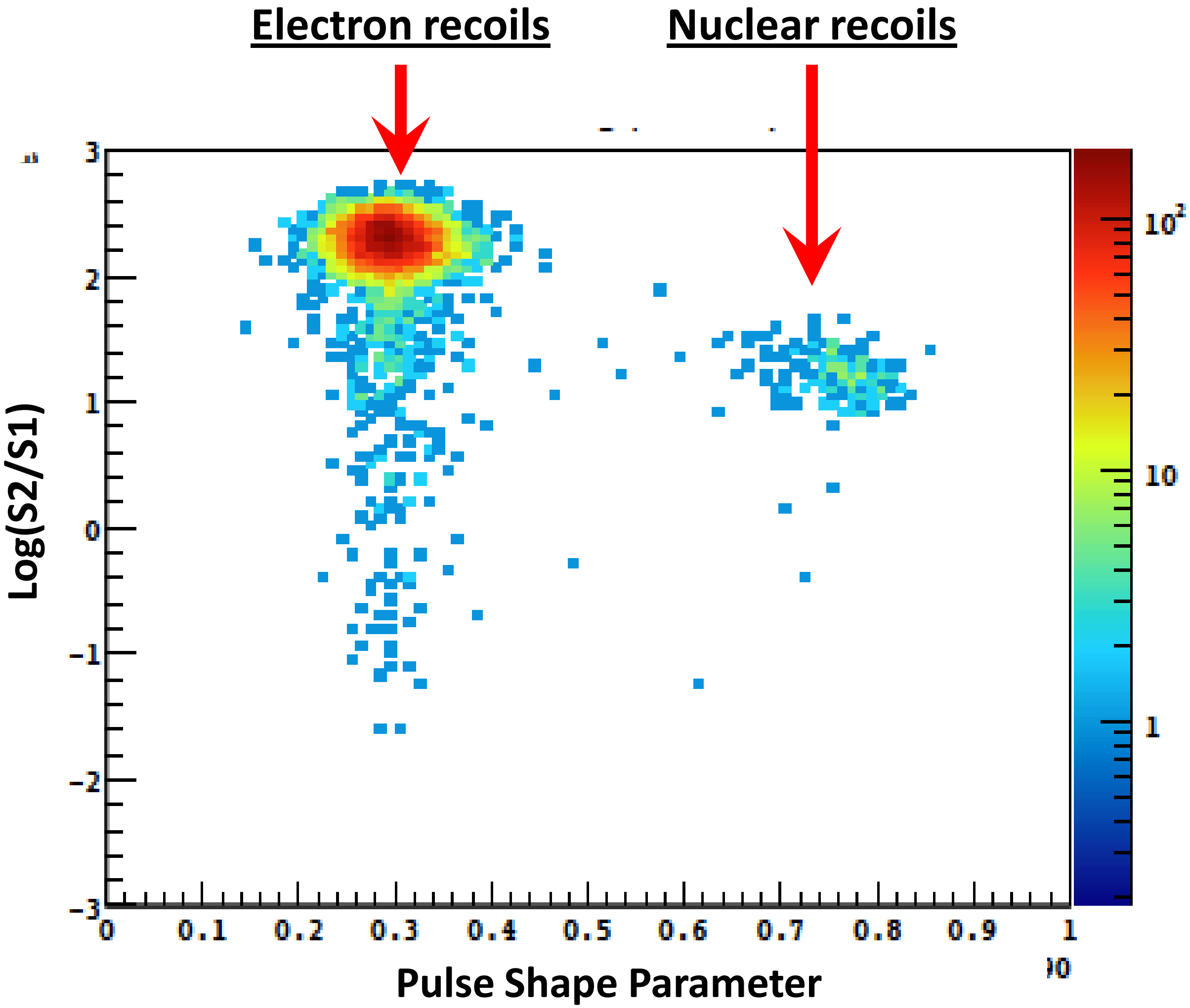
DarkSide events



DarkSide-10 results

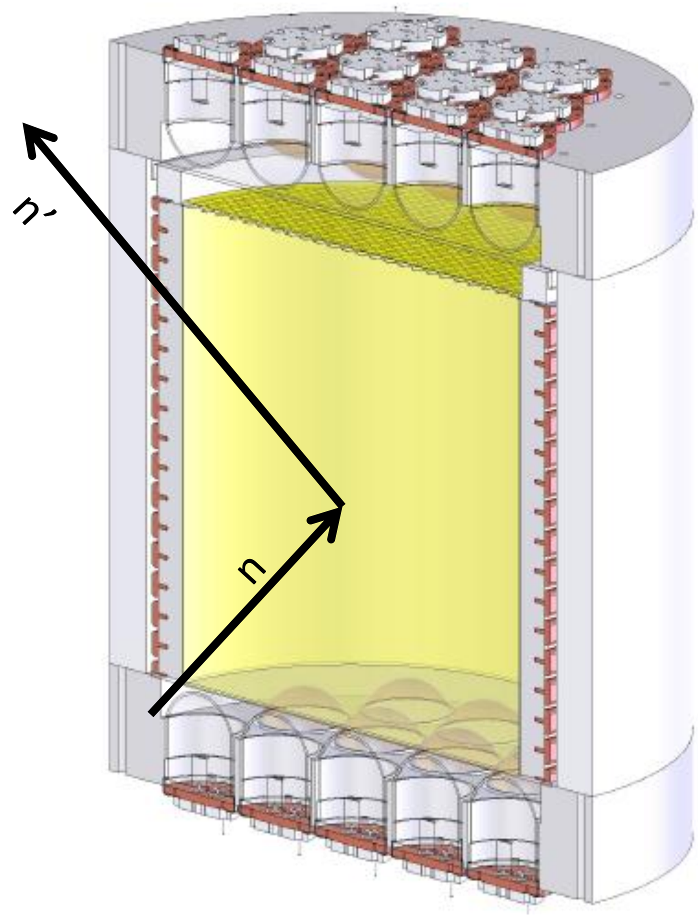


DarkSide-10



High efficiency neutron veto

- Boron-loaded liquid scintillator
  - (^{10}Bo + n → ^{7}Li + α)
- Tag nuclear recoils events
  - A neutron can produce a nuclear recoil in TPC
  - Neutron is then captured in veto and event is tagged
- Efficiency
  - >99.5% efficiency for radiogenic neutrons
  - >95% efficiency for cosmogenic neutrons



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

Pure argon target

- Generally:
  - Readily available
  - Easily purified

But…

We will discuss this in more detail later

Clean detector materials

Detector materials

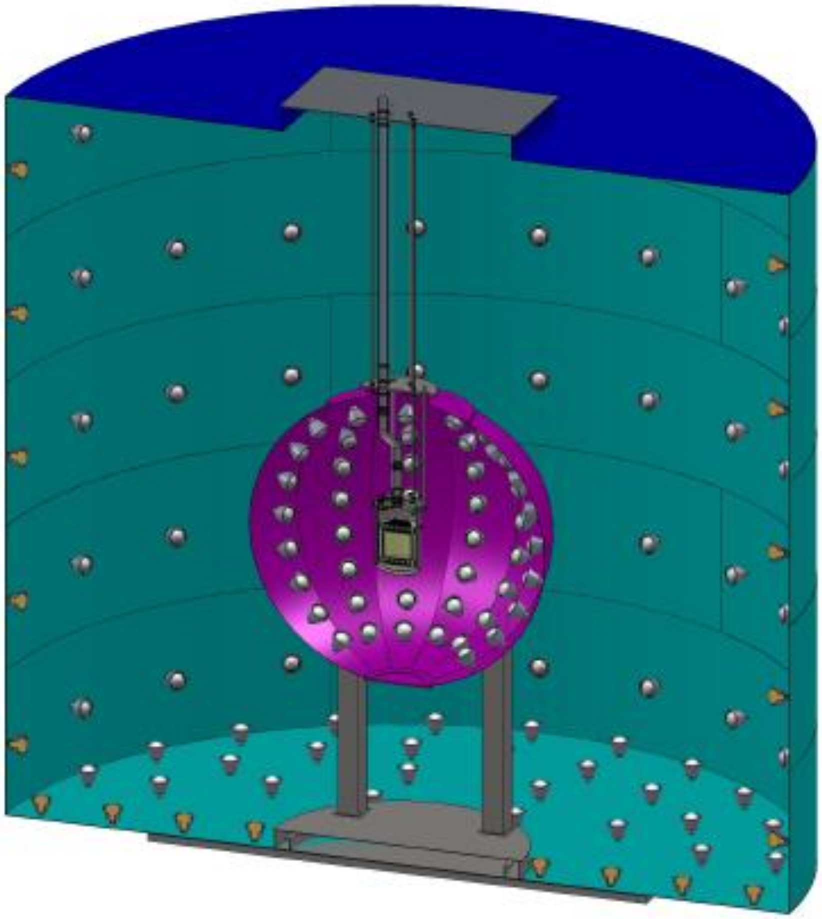
- All are generally low in Uranium and Thorium
  - Stainless steel
  - Teflon
  - Copper
  - Etc.
- All materials are being screened
  - Direct gamma assay
  - Neutron Activation Analysis
  - ICP-MS

Photodetectors

- Quartz Photo Intensifying Device (QUPID)
- Limited material (No dynodes)
- Quartz = No ^{40}K (1.46 MeV γ)

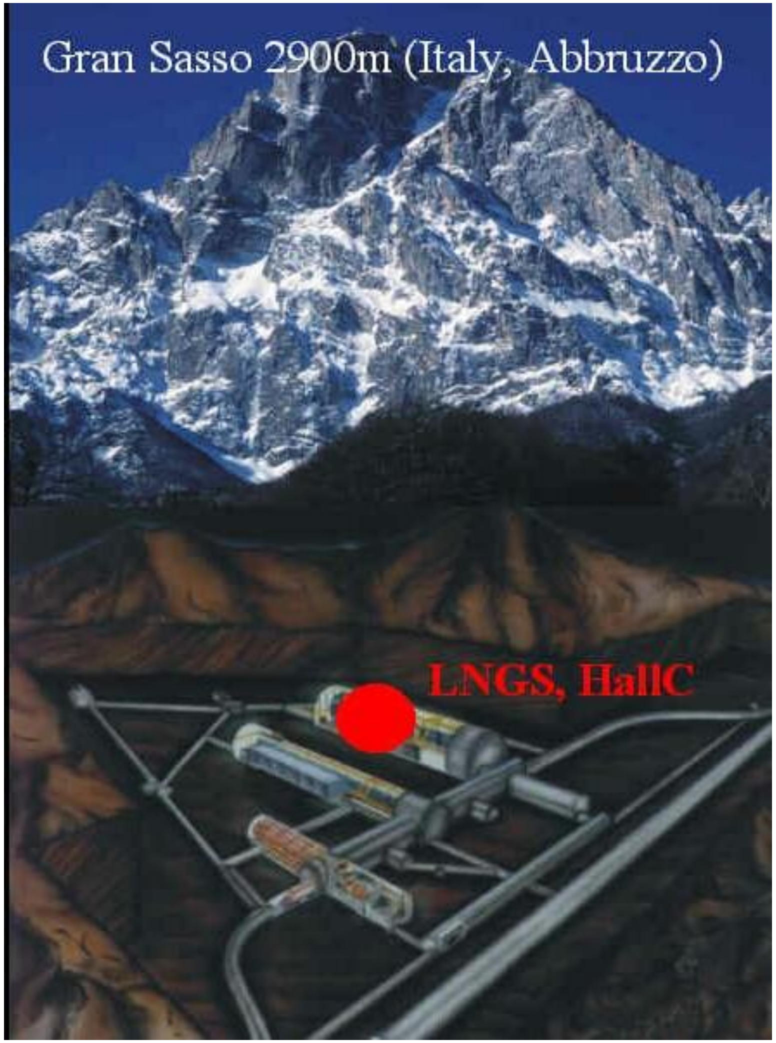
CTF water tank

- Counting Test Facility was Borexino's prototype
- DarkSide will use the CTF water tank
- Provides shielding from cavern walls, etc.
- Water is also instrumented for muon veto
- Dimensions
  - 11m tall
  - 10m diameter



Laboratori Nazionale del Gran Sasso (LNGS)

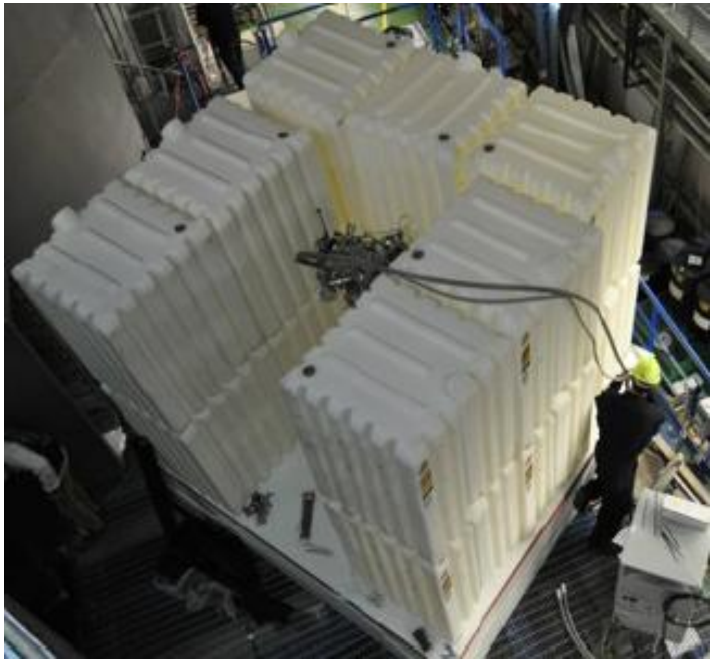
- 5000 meter H_2O equivalent



Detector Status

DarkSide 10

- 10 kg active mass
- Installed at LNGS
- Includes water shield



DarkSide 50

- 50 kg active mass
- CTF water tank is being drained
- Neutron veto sphere panels are being fabricated
- TPC construction beginning at Princeton
- Argon target → next topic

THE DARKSIDE ARGON

Pure low radioactive underground argon

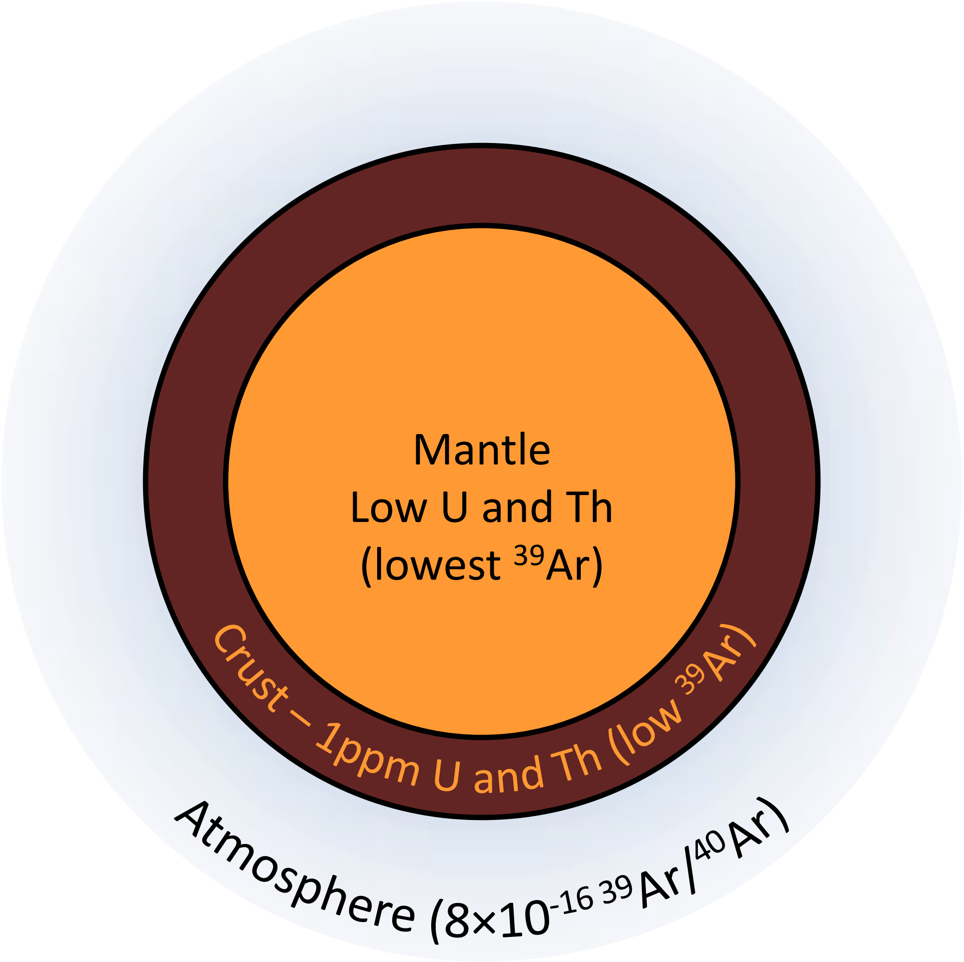
Atmospheric argon limits

- Argon-39
  - Beta emitter (q = 565 keV, $t_{1/2}$ = 269 years)
  - Produced in the atmosphere through cosmic ray interactions (eg, ^{40}Ar(n, 2n)→^{39}Ar)
  - Atmospheric abundance
    - ^{39}Ar/^{40}Ar is 8×10^{-16} (0.8 ppq)
    - Specific activity = **1 Bq/kg**
  - Is the limiting factor in size and sensitivity for argon detectors
    - Limits detector size due to ^{39}Ar event pile-up
    - One ton detector
      - Electron drift time across 1 ton detector (1m)= order 500μs (minimum time between events, equivalent to 2kHz)
      - Atmospheric ^{39}Ar decay rate = 1kHz/ton

Terrestrial argon sources

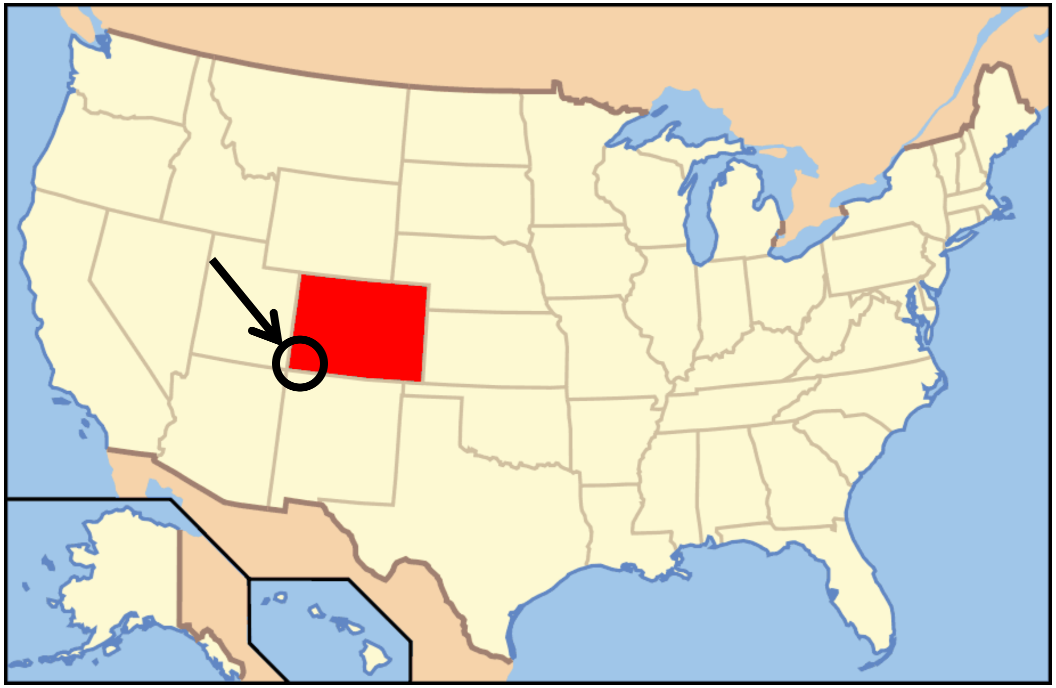
As I understand them

- ^{40}Ar comes from ^{40}K decay
- Atmosphere
  - ^{39}Ar produced by cosmic ray neutrons
- Crust
  - No cosmic ray
  - Neutrons from U and Th
- Mantle
  - Very low U and Th
  - Lowest ^{39}Ar levels

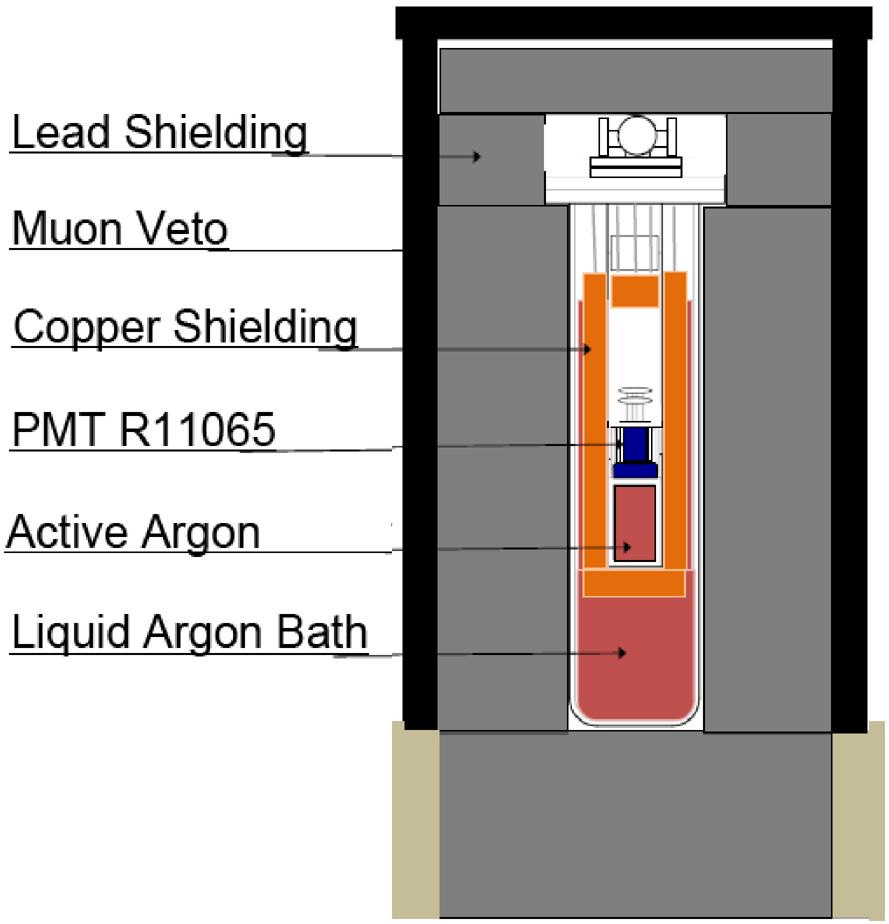


CO_2 well is SW Colorado

- There are geological formations that trap gases underground
- We found CO_2 well in SW Colorado (near Cortez)
- Contains 600 ppm Argon



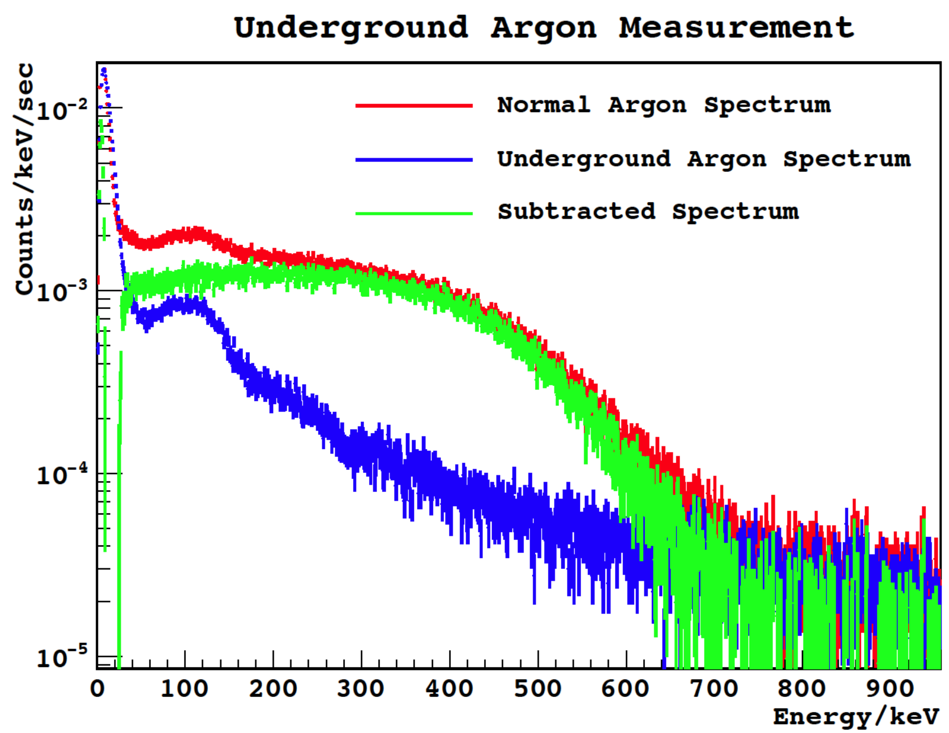
Depleted Argon Counting



- Dedicated "low background detector"
- ~0.56 kg liquid Ar active mass
- Cryogenic, low background 3'' PMT
- 2'' Cu, 8'' Pb shielding
- Muon veto

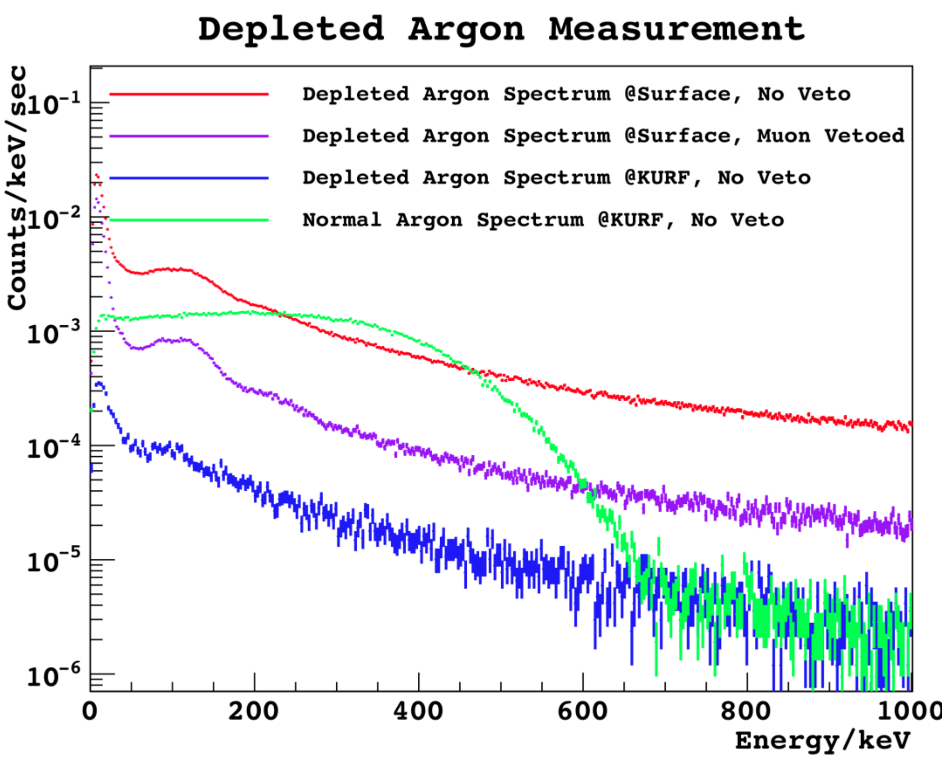
Depleted Argon Counting

- At Princeton, background in the ^{39}Ar region is 0.05 Bq in (200,800 keV)
- ^{39}Ar depletion factor of >10 from direct counting, >~50 from spectral fit



Depleted Argon Counting

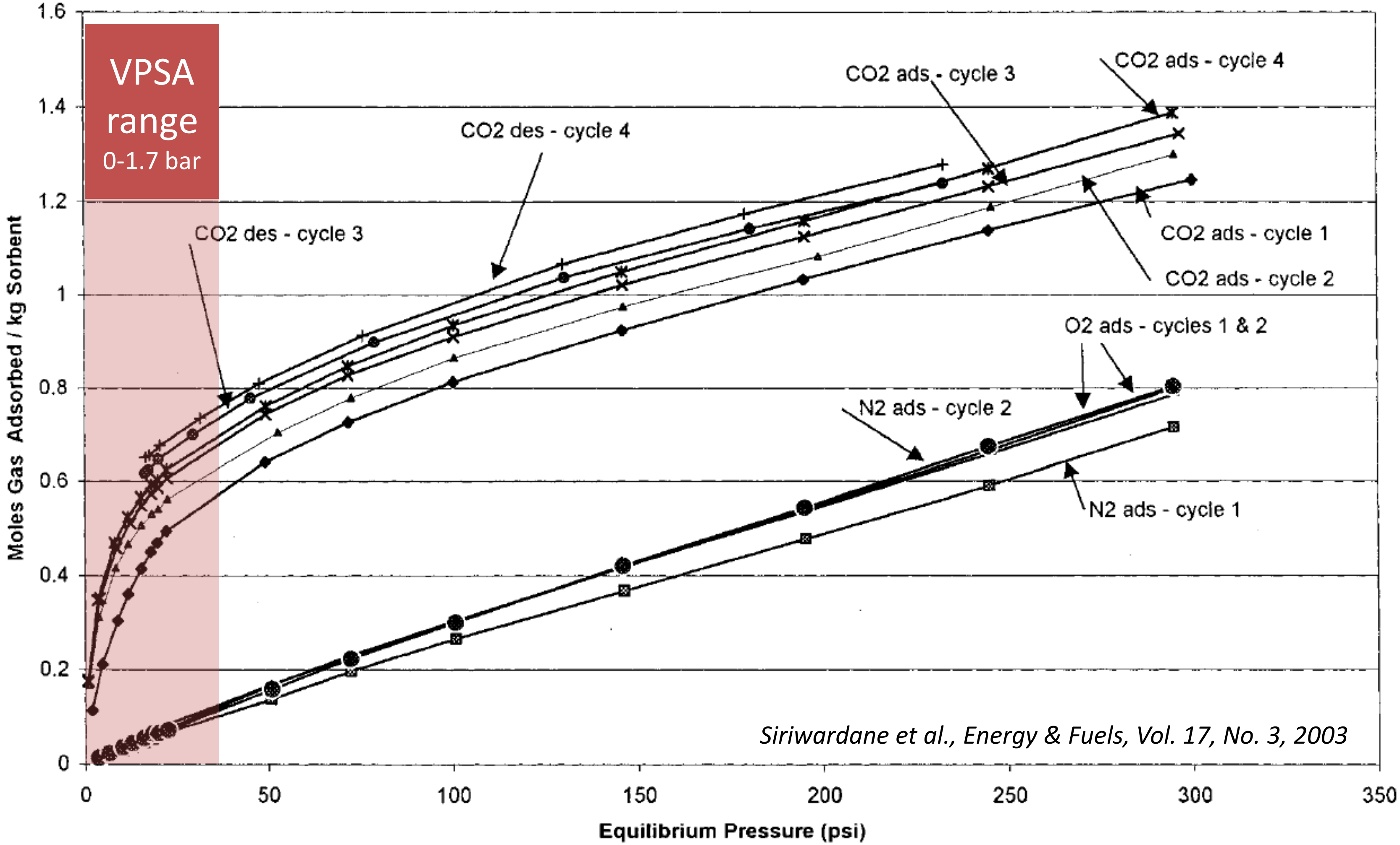
- At KURF (1400 m.w.e.) background reduced to 0.002 Bq in 300-400 keV
- **Depletion factor of >50 from counting**
  - Spectral fit in progress



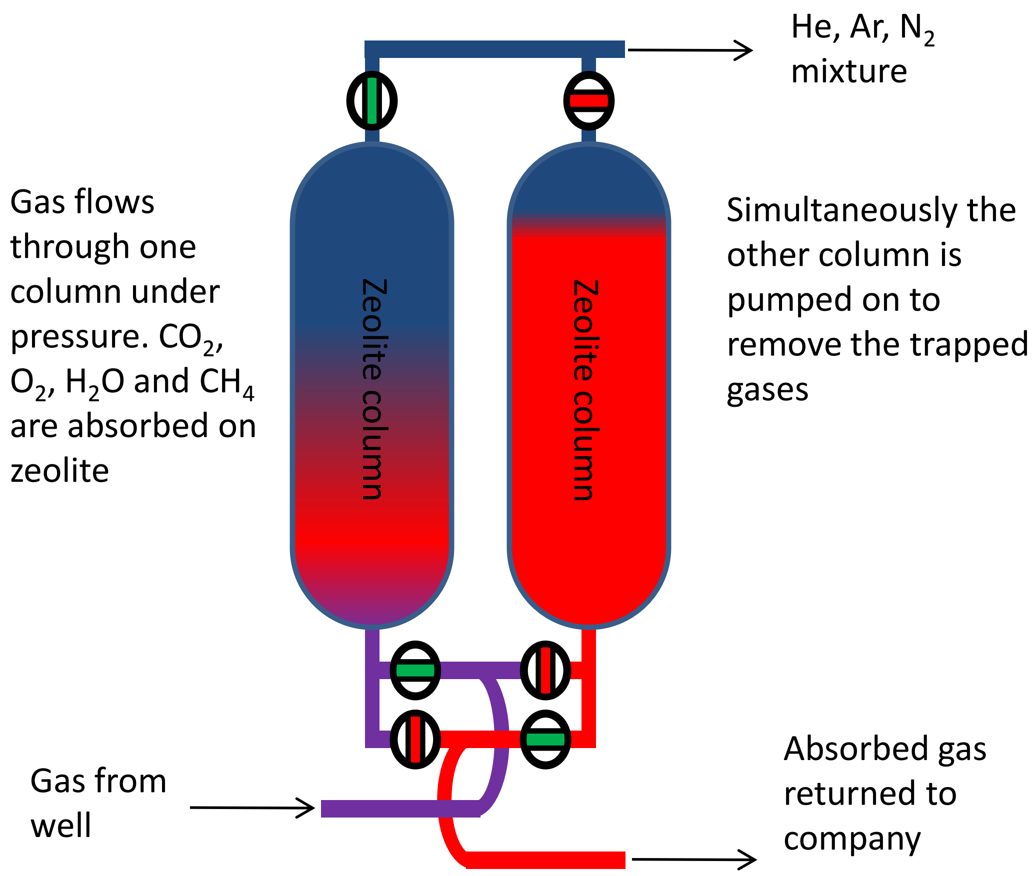
Getting to the argon

- Extraction
  - In Colorado we extract a crude argon gas mixture (Ar, N_2, and He)
- Purification
  - The gas from Cortez is then sent to Fermilab for further purification

Absorption of CO2 on 4A zeolite

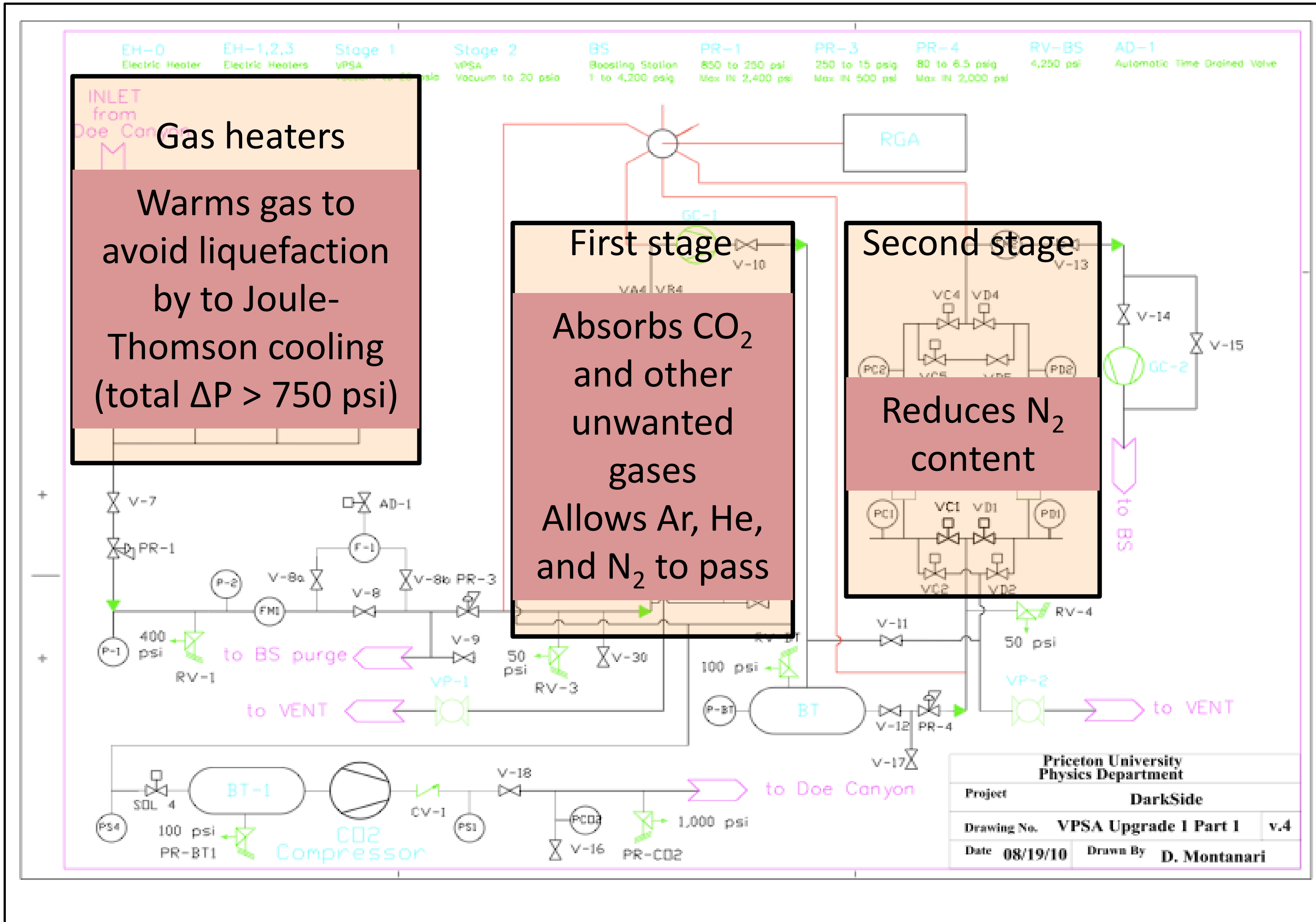


Vacuum Pressure Swing Absorption (VPSA)



- Capitalize on pressure dependence of absorption
- Absorb CO_2 under pressure
- Regenerate column under vacuum
- Use 2 columns for (near) continuous operation

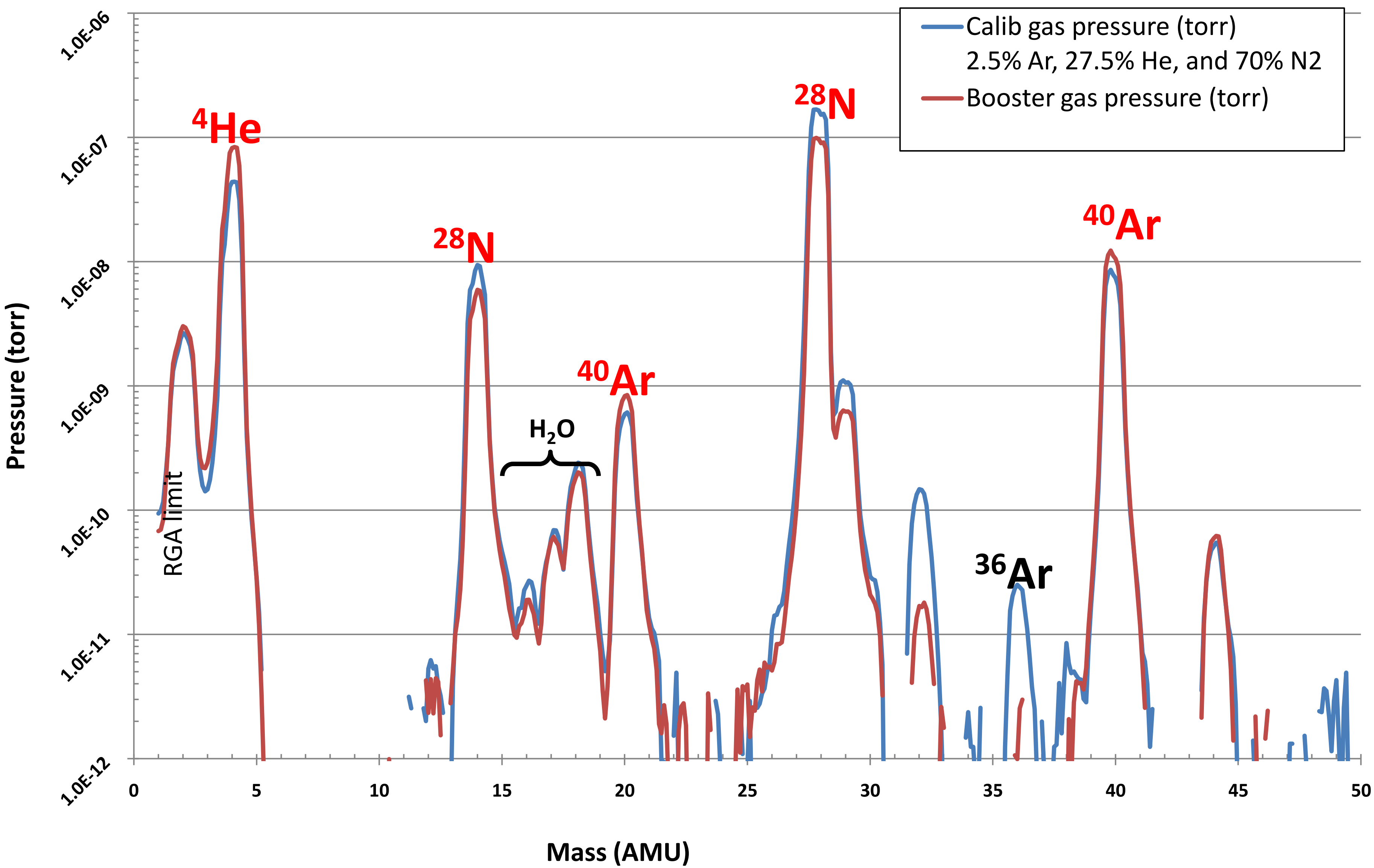
Our plant


Gas heaters
Warms gas to avoid liquefaction by to Joule-Thomson cooling (total ΔP > 750 psi)
First stage
Absorbs CO_2 and other unwanted gases
Allows Ar, He, and N_2 to pass
Second stage
Reduces N_2 content
EH-0
Electric Heater
EH-1,2,3
Electric Heaters
Stage 1
Stage 2
BS
Boosting Station
PR-1
PR-3
PR-4
RV-BS
AD-1
Automatic Time Drained Valve
RGA
V-7
PR-1
AD-1
V-8a
V-8b
V-8
PR-3
V-9
400 psi
RV-1
to BS purge
VP-1
to VENT
50 psi
RV-3
V-30
100 psi
BT
V-11
V-12
PR-4
RV-4
50 psi
VP-2
to VENT
V-14
V-15
GC-2
to BS
V-17
V-18
BT-1
SOL 4
100 psi
PR-BT1
CO2 Compressor
CV-1
to Doe Canyon
1,000 psi
V-16
PR-CO2
Priceton University
Physics Department
Project DarkSide
Drawing No. VPSA Upgrade 1 Part 1 v.4
Date 08/19/10
Drawn By D. Montanari

VPSA plant

Operated locally by technician Chris Condon – Managed by H. Back

Calibration gas versus VPSA stage 2 output



Results and status

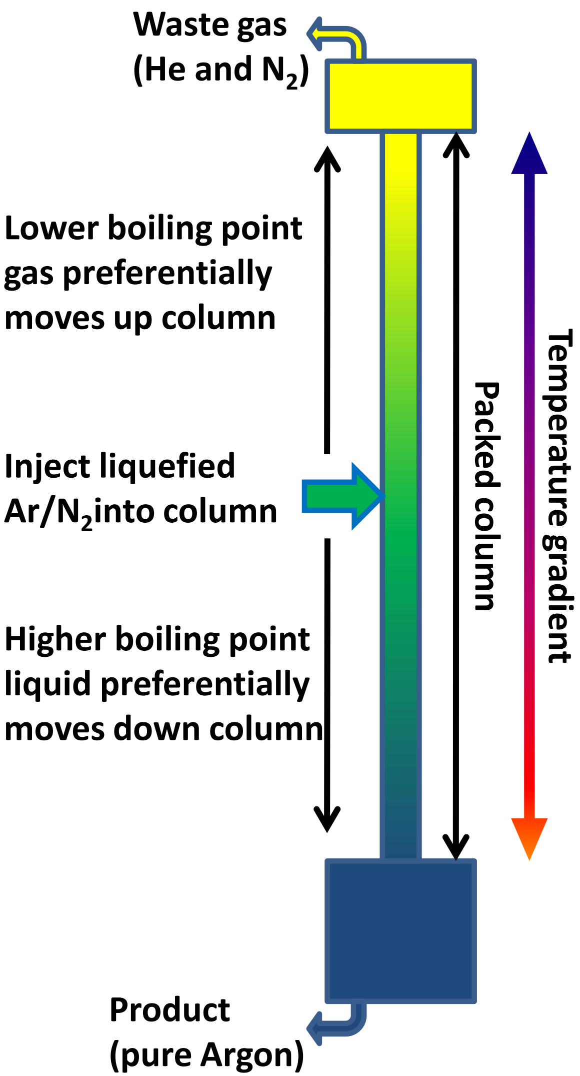
- Final output of plant is a gas mixture
  - Argon
  - Helium
  - Nitrogen
- Gas is compressed into high pressure cylinders and shipped to Fermilab
- From lessons learned:
  - Plant operations continue to improve – moving from R&D to production
  - Plant efficiency has increased

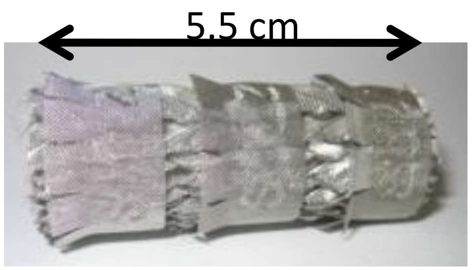
- 2010
  - Output
    - 2.5% argon
    - 70% nitrogen
    - 27.5% helium
  - Production
    - 23kg argon
- 2011
  - Output
    - ~5% argon
  - Production
    - 53kg argon
    - Continuous operation: May-June & July - October
- 2012
  - Plant starting up this week

Total underground argon collected to date = 76kg

Purification at Fermilab

The Cryogenic Distillation Column

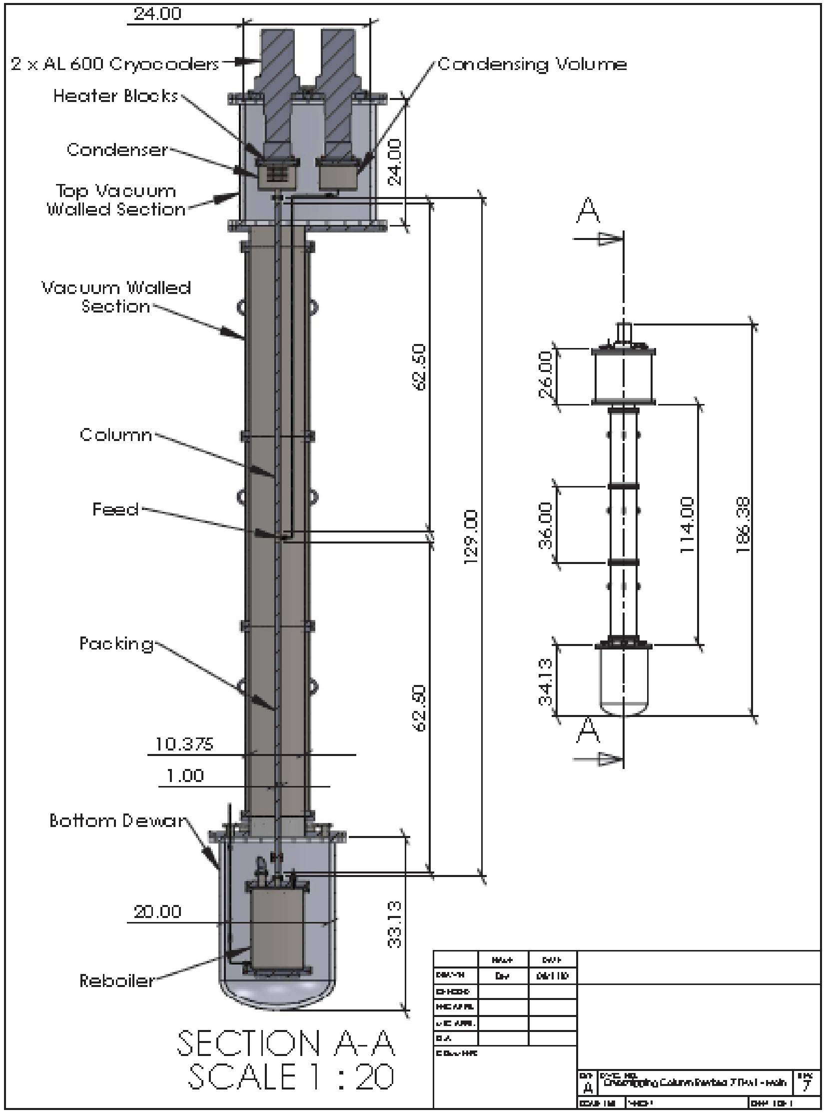




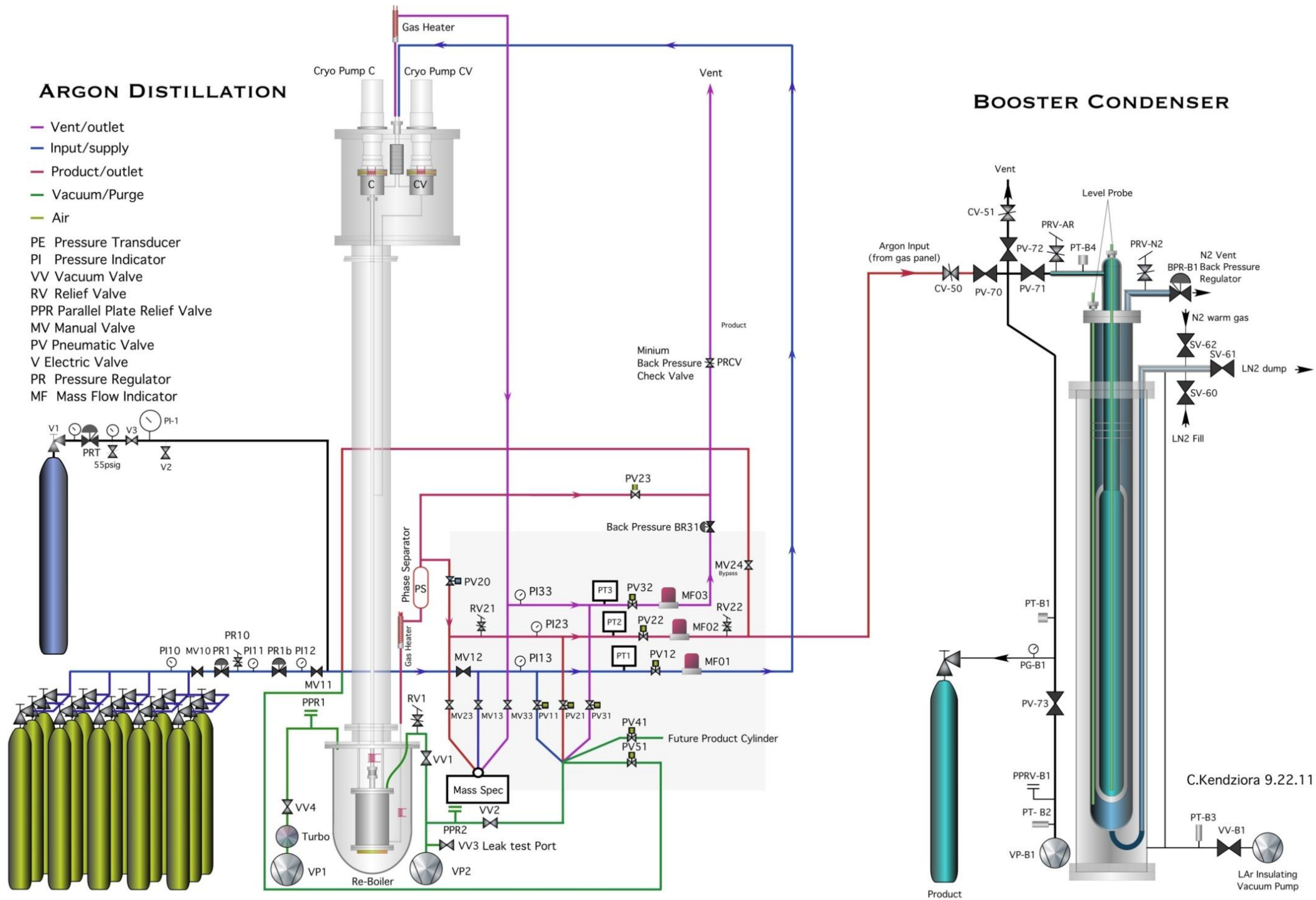
Column packing material

- Column is filled with high surface area material
- Boiling and condensation happens on the surface of column packing material
- Controlling temperature and gas/liquid flows allows for continuous purification

Distillation Column



- 2 – 600W cryocoolers
  - Balanced with 700W heaters for temperature control
- Reboiler cooled by liquid from column
  - Temperature controlled with 700W heater
- Active PID temperature control
- Active mass flow control
- Pressure and temperature monitoring throughout
- Multiple input RGA measures gas at three points
  - Input
  - Waste
  - **Product**

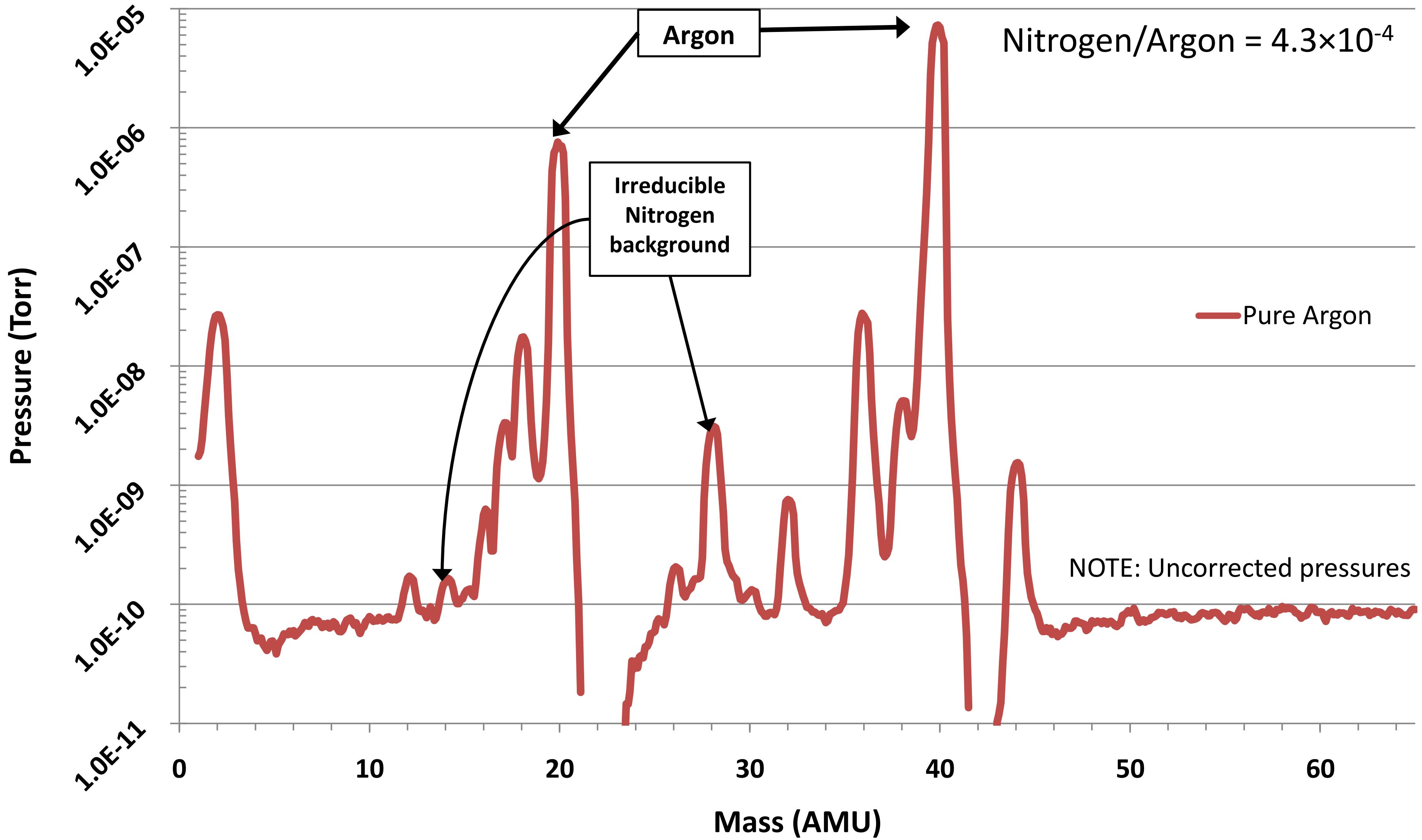

ARGON DISTILLATION
Vent/outlet
Input/supply
Product/outlet
Vacuum/Purge
Air
PE Pressure Transducer
PI Pressure Indicator
VV Vacuum Valve
RV Relief Valve
PPR Parallel Plate Relief Valve
MV Manual Valve
PV Pneumatic Valve
V Electric Valve
PR Pressure Regulator
MF Mass Flow Indicator
Gas Heater
Cryo Pump C
Cryo Pump CV
C
CV
Vent
Product
Minium
Back Pressure
Check Valve
PRCV
PI-1
V1
V3
PRT
55psig
V2
PV23
Back Pressure BR31
MV24
Bypass
Phase Separator
PS
PV20
PI33
PT3
PV32
MF03
RV21
PI23
PT2
PV22
MF02
RV22
Gas Heater
MV12
PI13
PT1
PV12
MF01
PR10
PI10
MV10
PR1
PI11
PR1b
PI12
MV11
PPR1
RV1
MV23
MV13
MV33
PV11
PV21
PV31
PV41
PV51
Future Product Cylinder
VV1
Mass Spec
VV4
Turbo
VV2
PPR2
VV3 Leak test Port
VP1
Re-Boiler
VP2
BOOSTER CONDENSER
Vent
Level Probe
CV-51
PRV-AR
Argon Input
(from gas panel)
PV-72
PT-B4
PRV-N2
N2 Vent
BPR-B1 Back Pressure
Regulator
CV-50
PV-70
PV-71
N2 warm gas
SV-62
SV-61
LN2 dump
SV-60
LN2 Fill
PT-B1
PG-B1
PV-73
PPRV-B1
PT- B2
VP-B1
C.Kendziora 9.22.11
PT-B3
VV-B1
LAr Insulating
Vacuum Pump
Product

RGA quantitative gas analysis

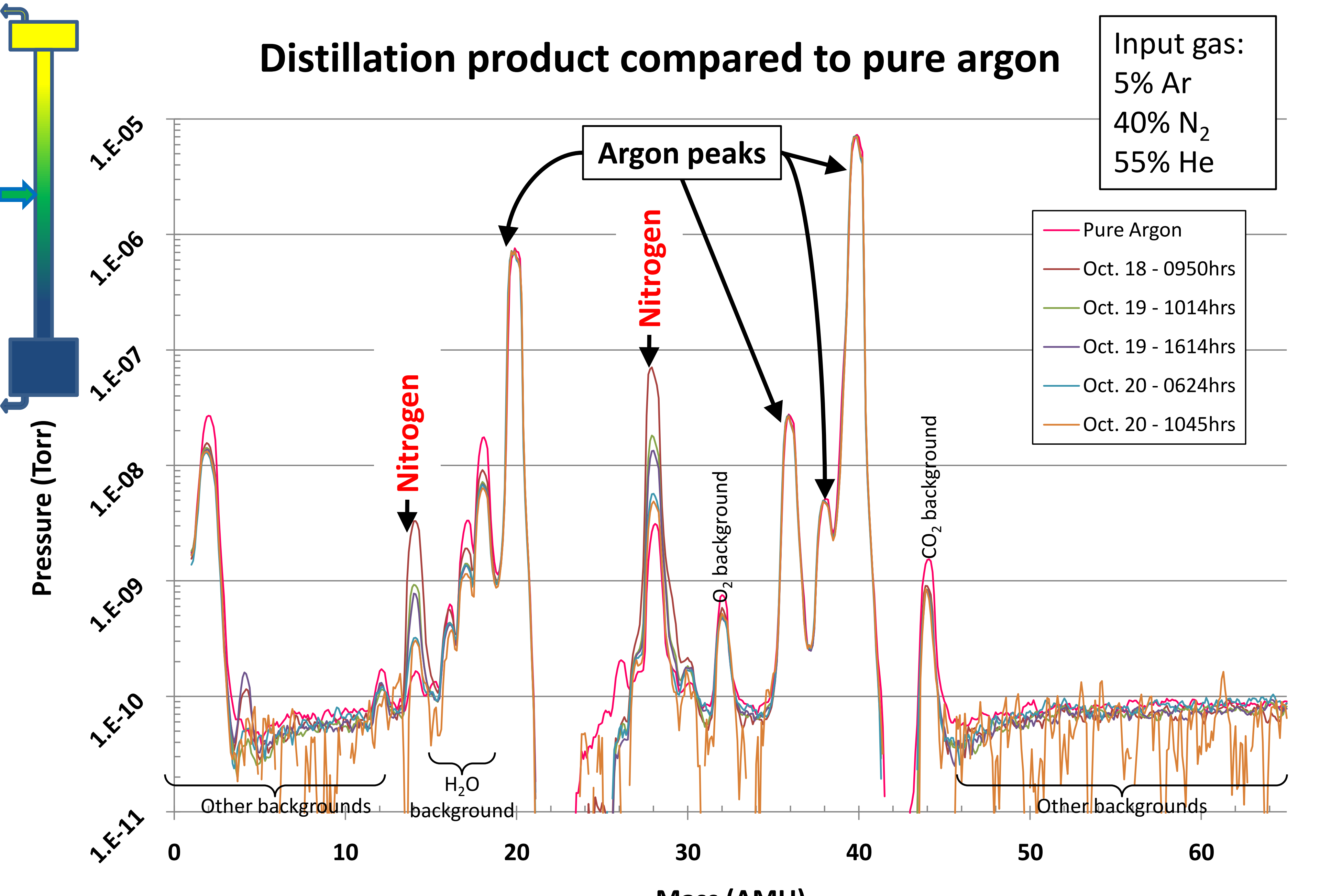
- An RGA measures the partial pressure of component gases
- Generally calibrated for nitrogen (N_2 pressure is correct)
- Correction factor for other components needs to be calculated using known calibration gas
- Correction factor is gas mixture dependent
- For our analysis here we assume correction factors below are correct

Gas	Known mixture	Measured RGA pressures (Torr)	Expected pressure Total pressure calculated from N_2 pressure ($P_T = 2.15\times10^{-6}$ / 40%)	Correction factors for this mixture
Nitrogen	40%	2.15×10^{-6}	2.15×10^{-6}	1.0
Argon	5%	3.90×10^{-7}	2.69×10^{-7}	0.69
Helium	55%	2.16×10^{-6}	2.96×10^{-6}	1.37

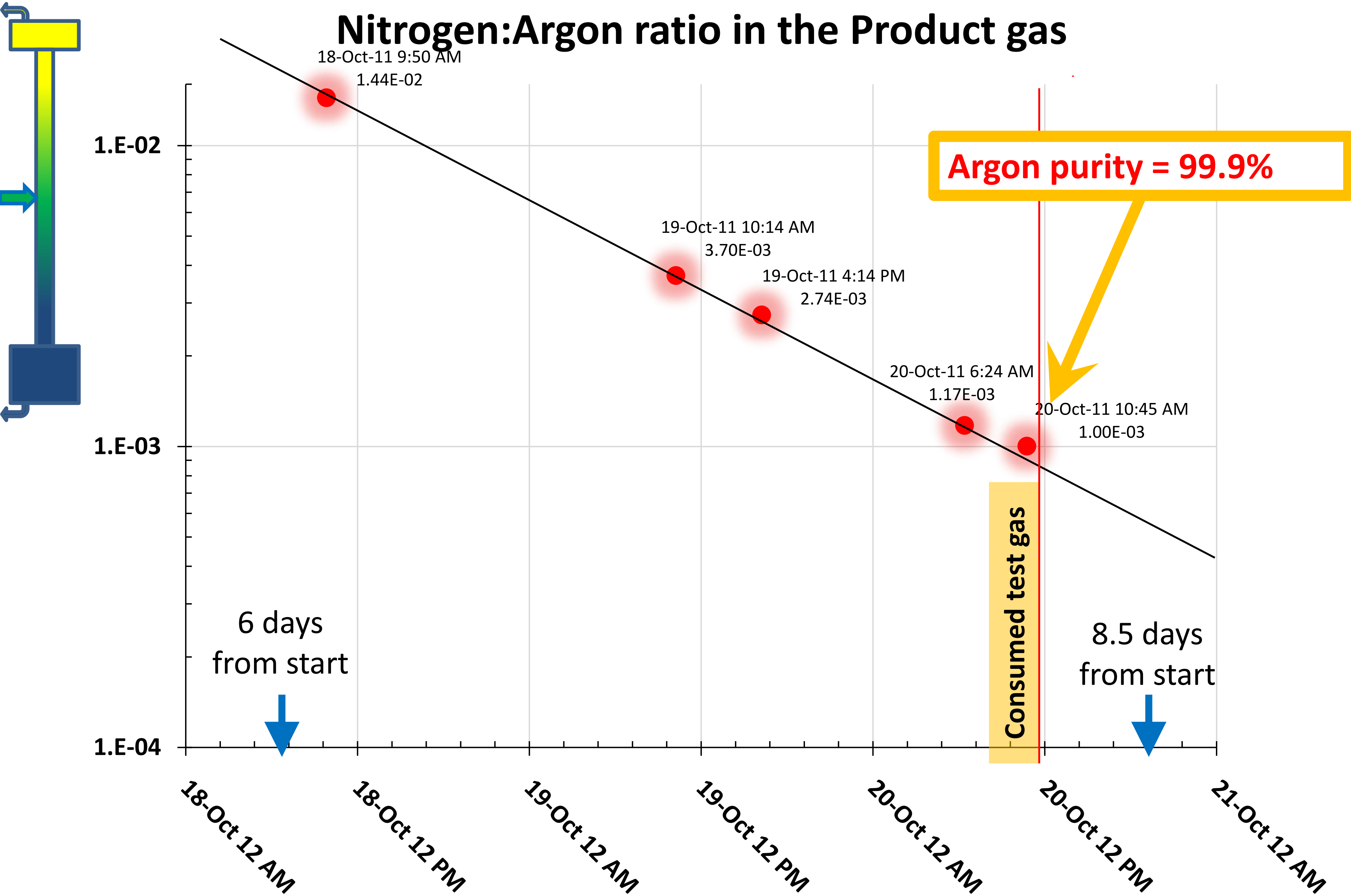
Pure Argon RGA Spectrum



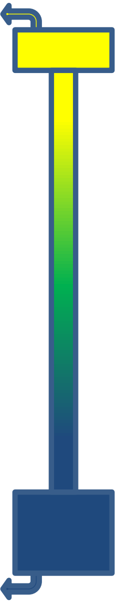
Distillation product compared to pure argon

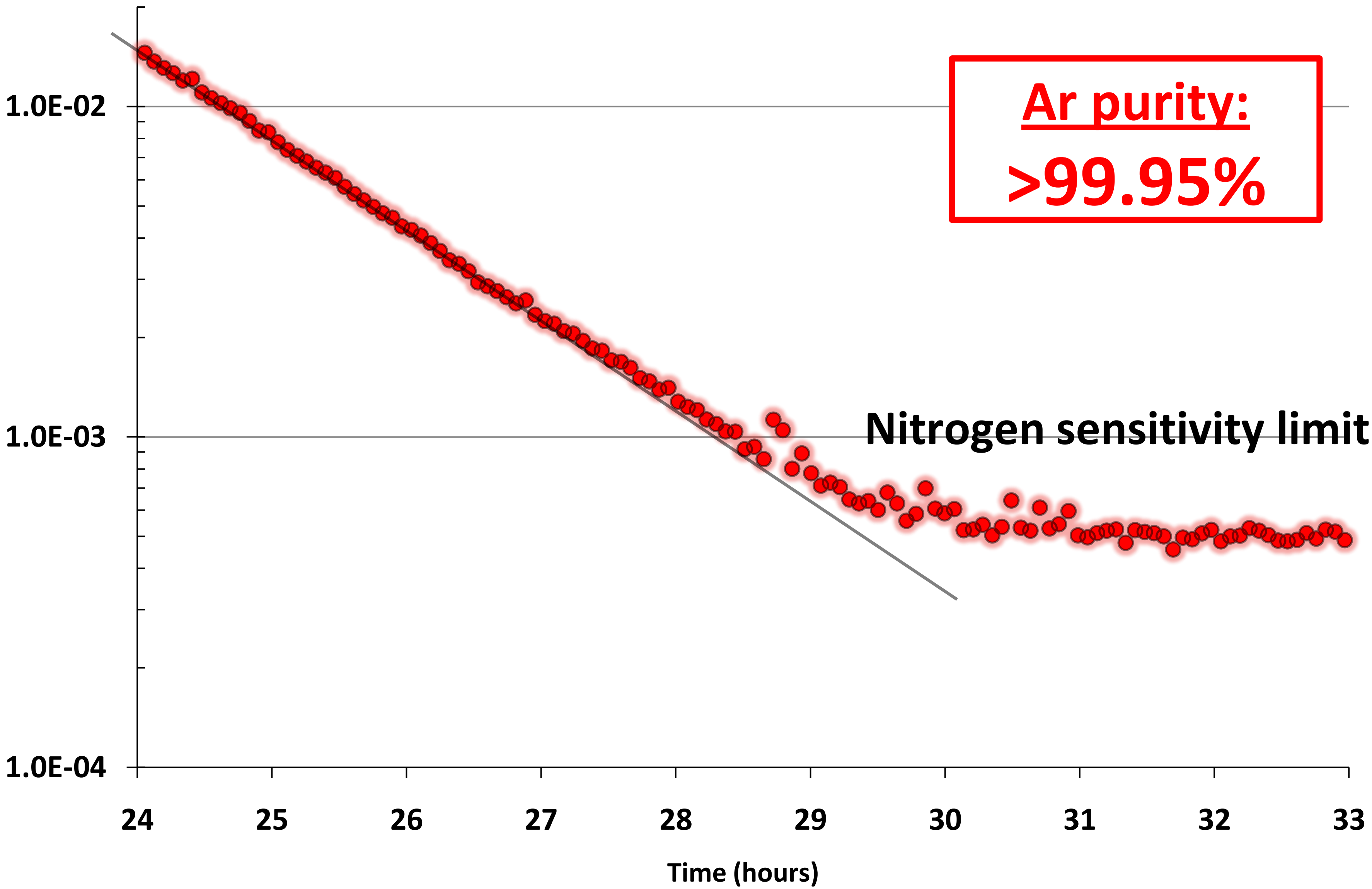


Nitrogen:Argon ratio in the Product gas



Nitrogen:Argon ratio in the product gas





Tested gas samples

Sample #1

- Our RGA measurement:
  - N_2 = 1000 ppm
- Atlantic Analytical:
  - N_2 = 700 ppm
  - O_2 = 40 ppm
- Pacific Northwest National Lab
  - N_2 = 920 ppm
  - O_2 < 10 ppm

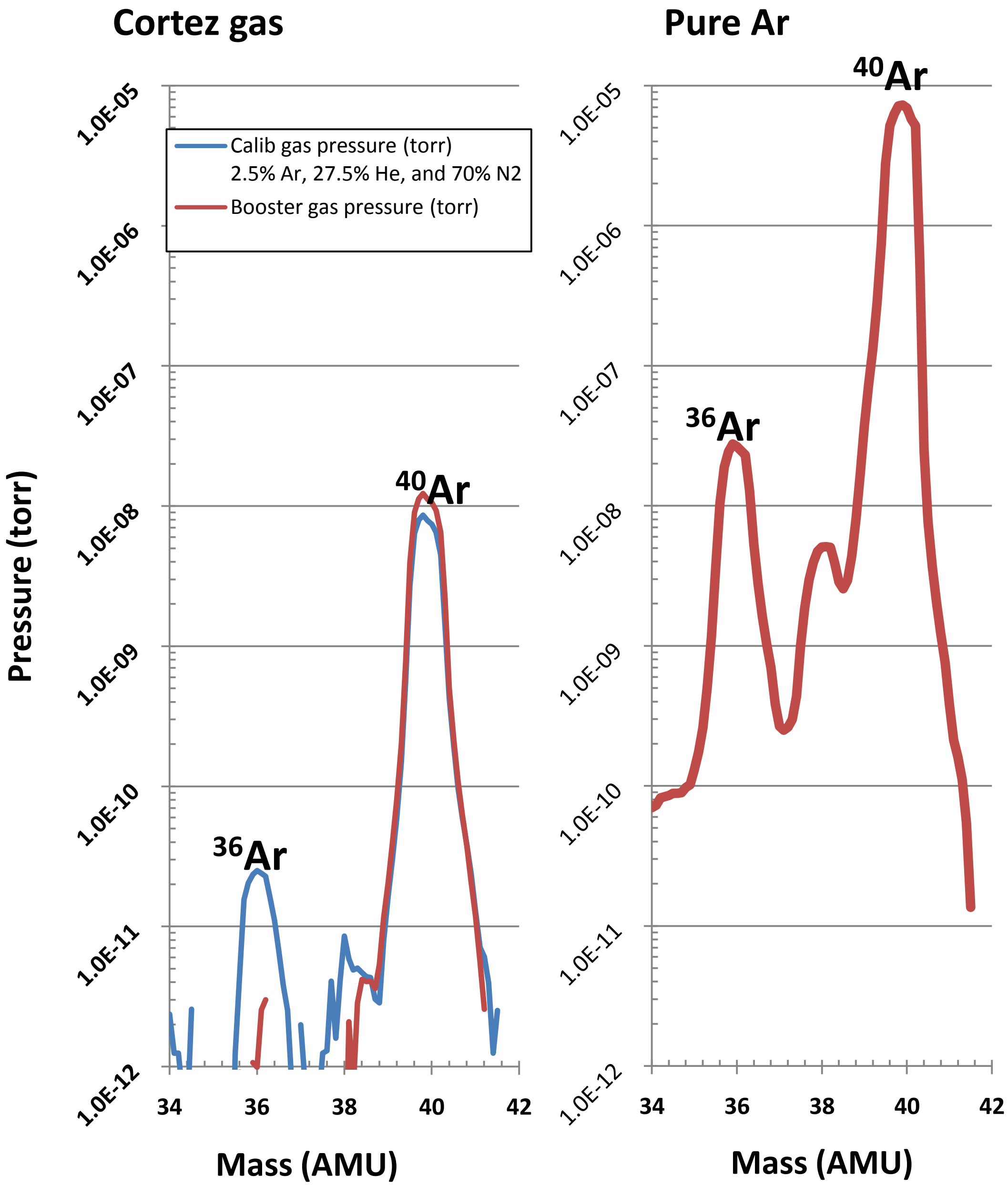
Sample #2

- Our RGA measurement:
  - N_2 < 500 ppm
- Atlantic Analytical:
  - N_2 = 4100 ppm
  - O_2 = 810 ppm
- Pacific Northwest National Lab (2 runs)
  - N_2 = 4250 and 4000 ppm
  - O_2 = 430 and 600 ppm

- We believe there was air contamination

Argon recovery efficiency

- Consumed 24 high pressure cylinders with 262 scf of gas each (7419 liters)
  - 662g of Argon / cylinder
  - 14.9 kg of Argon total in 24 cylinders
- Accumulated mass (rough estimate)
  - Mass lost through product line – 50scc/m for ~10days = 1.2kg
  - Mass from liquid level
    - 16 cm of liquid = 10.8 kg
    - **Total = 10.8 + 1.2 = 12 kg**
  - Mass from measuring flow out of reboiler during warm up
    - Integral volume out of product – 5521liters = 9.3 kg
    - **Total = 9.3 + 1.2 = 10.5kg**
- Collection efficiency
  - Overall 70-80%
  - During continuous distillation = 80%
  - Residual loss during cool down, tuning, etc.



^{36}Ar as a diagnostic tool

- ^{36}Ar natural atmospheric isotopic abundance = 0.34%
- Cortez gas does not show any ^{36}Ar
- What is the background at mass 36?
  - What is the ^{36}Ar reduction factor?
  - Need pure underground argon mass spectrum
- Underground argon ^{39}Ar reduction factor >50
- Might be able to measure atmospheric argon contamination at a level where the ^{39}Ar level is still acceptable.

Distillation Column

- Argon purity achieved
  - Continuous distillation – 99.90%
  - Batch purification > 99.95%
- Argon collection efficiency
  - 80% for gas with 55% helium content
  - Probably better with less helium
- Production rate in continuous distillation ~1kg/day
- Distillation of underground argon begins this week (tomorrow)
- Underground argon mass required – 200kg

Conclusion

- Argon is a powerful scintillator and excellent medium for detection of ionization
- Argon's discrimination power make is attractive for WIMP dark matter detector
- Although ^{39}Ar is a limiting factor with atmospheric argon, we have found a source of underground argon whose ^{39}Ar concentration is at least 50 times less than atmospheric argon
- Extraction and purification of this underground argon is underway, and approaching a production mode