

SHEDDING LIGHT

ON THE DARK UNIVERSE

SUMMER LECTURES CLUB - GUELPH

MAY 10TH, 2021

ALEX WRIGHT

INSTITUTE OF PARTICLE PHYSICS & QUEEN'S UNIVERSITY

Outline

- What is Dark Matter?
- How to search for Dark Matter
- Searching for Dark Matter at SNOLAB

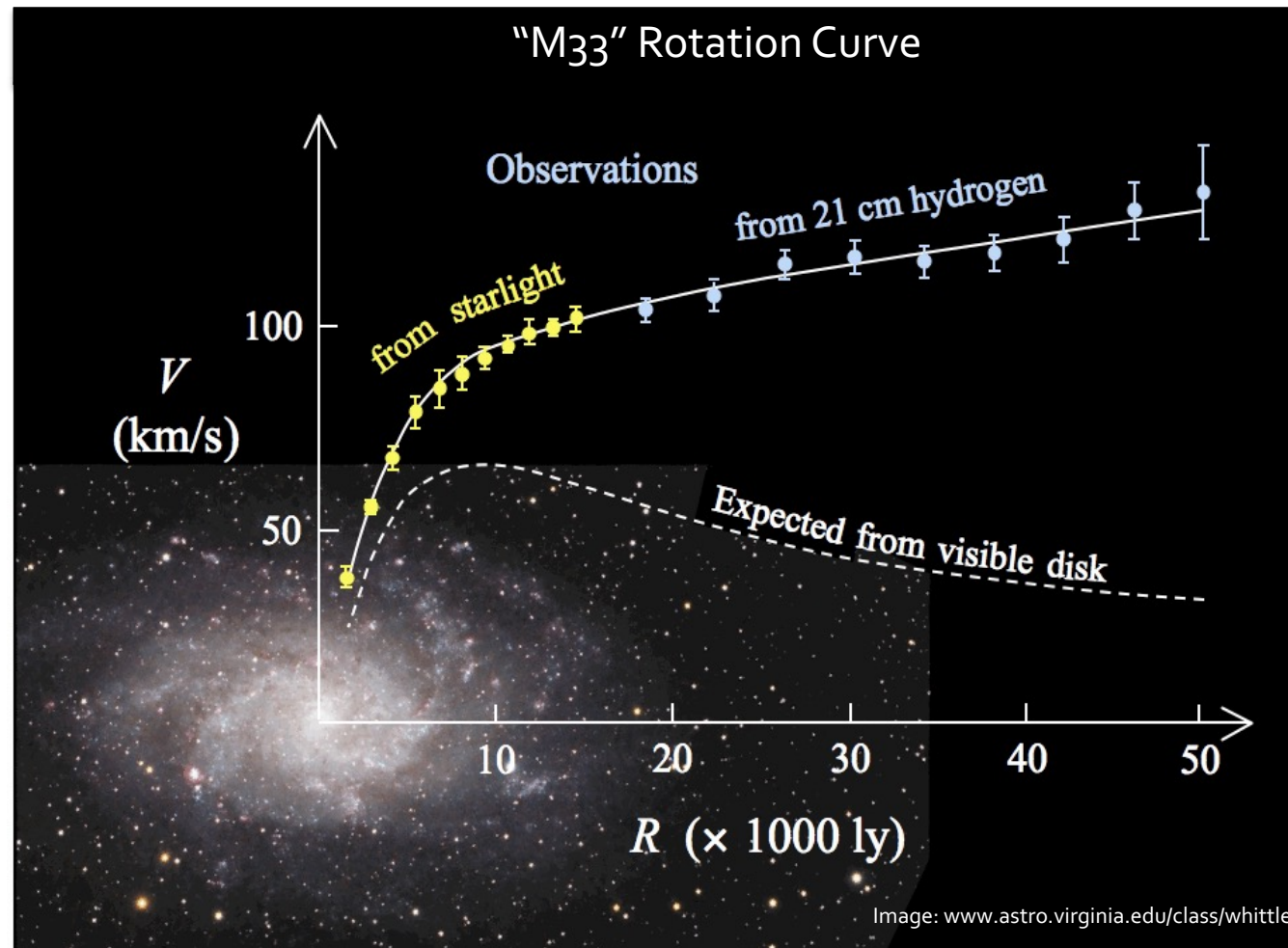
First Evidence for Dark Matter

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!

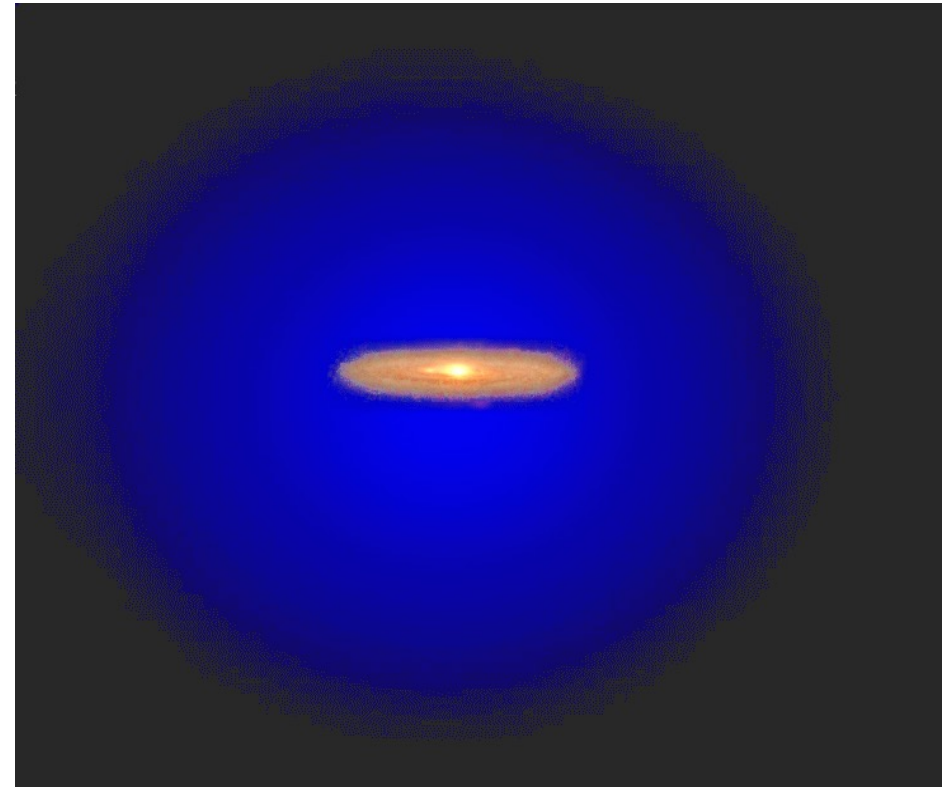
"Galaxy Rotation Curves"

- The rotation speed of stars in galaxies, and galaxies in clusters, is related to the mass which gravitationally binds them
- Observed rotation speeds do not agree with predictions based on the observable matter
- Adding a spherical dark matter "halo" around the galaxies at ~20 times the mass of the stars gives good agreement with the observed rotation speed



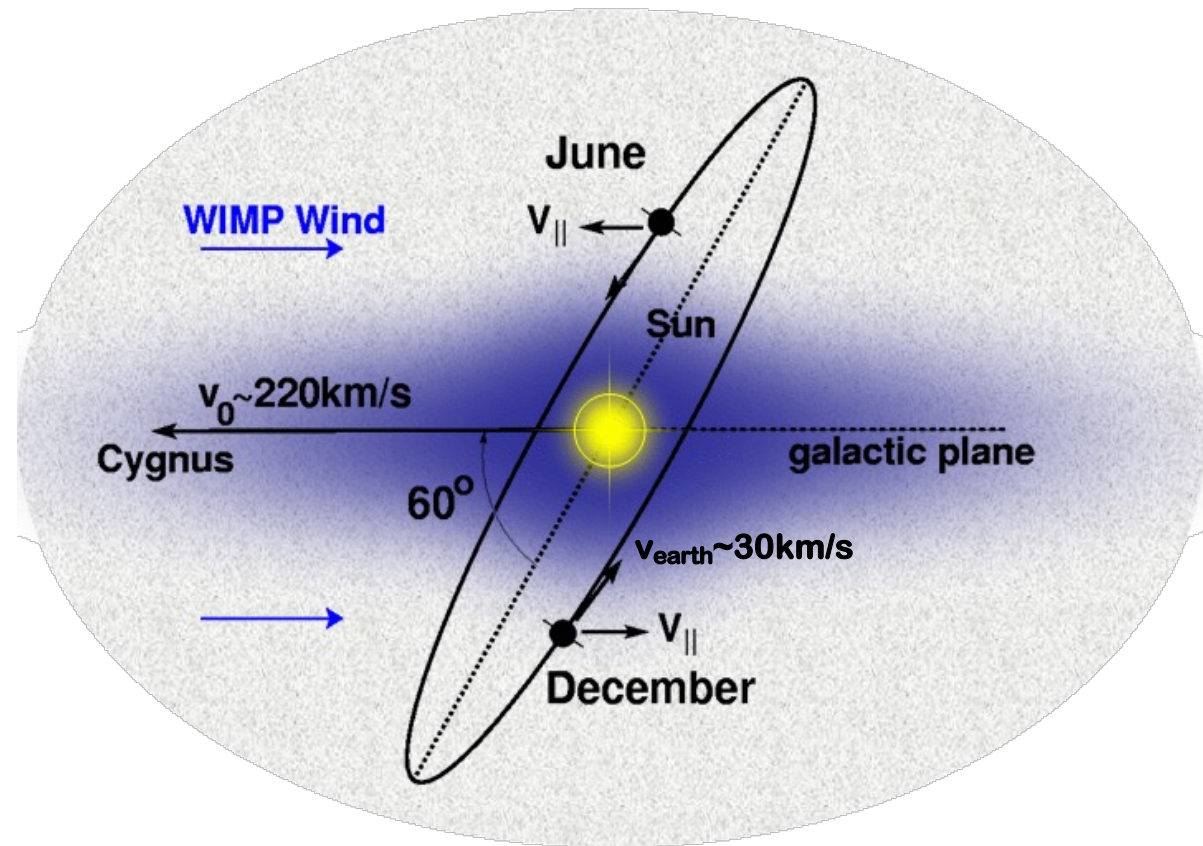
"Galaxy Rotation Curves"

- The dark matter "halo" is considerably larger than the region of the galaxy that contains the visible stars
- Local dark matter density $\approx 0.3 \text{ GeV}/c^2/\text{cm}^3$
 - For the types of dark matter we look for, this means a few dark matter particles per litre
- As dark matter particles essentially don't collide, they all independently orbit the galaxy
 - Typical $v_{\text{orbit}} \approx 220 \text{ km/s}$



Dark Matter “Wind”

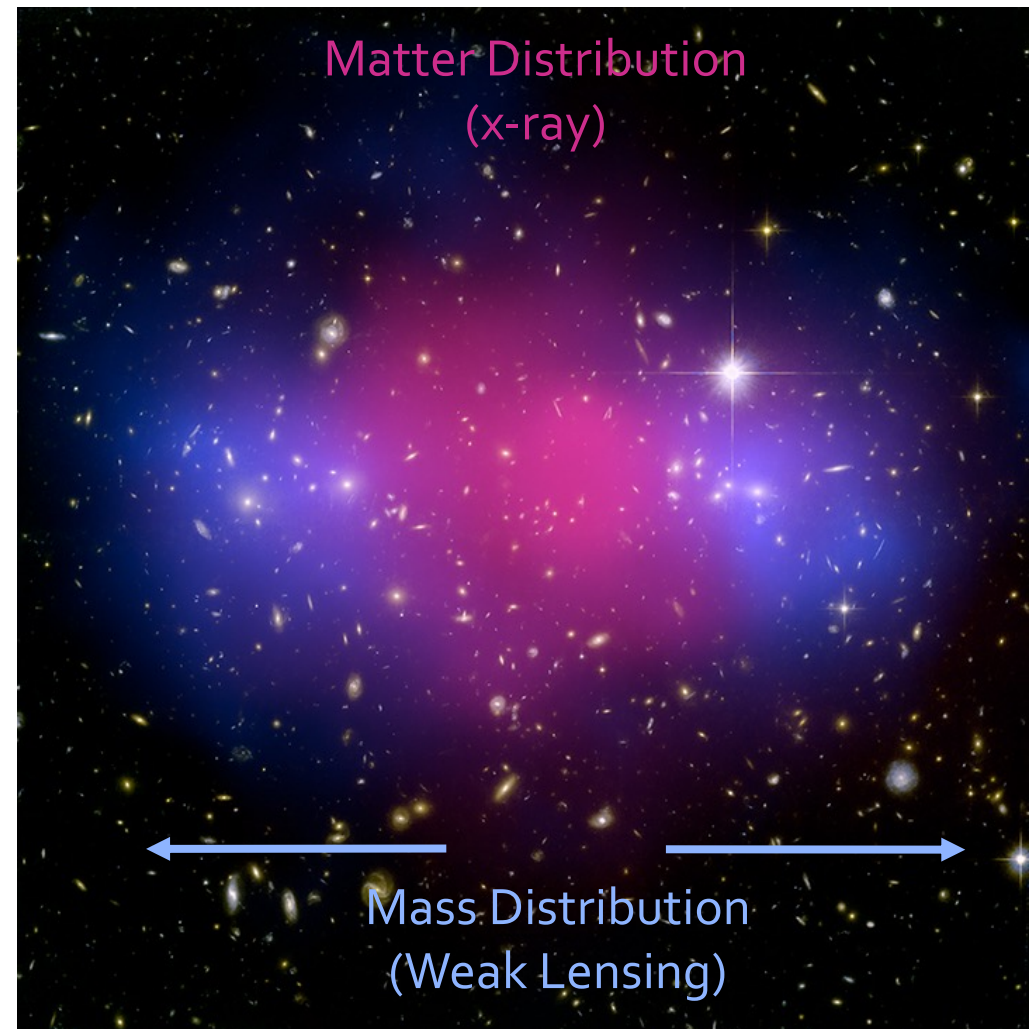
- Motion of the sun around the galaxy induces a dark matter “wind”
- Rotation of the earth about the sun produces a seasonal modulation in the velocity of the wind



Galaxy Collisions

- Because gravity bends light, we can study the mass of astronomical objects using “weak gravitational lensing”
 - Distortions in the appearance of background galaxies can be used to measure the mass and mass distribution of foreground objects
- Confirms that galaxies are much heavier than their stars
- Observe mass distributions after galaxy collisions

MACS J0024.4-1222



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

The Large-Scale Structure of the Universe

- At very large scales, the Universe has a characteristic level of “clumpiness”
- We can model the development of the “clumpiness” from simulations
- The observed baryonic matter alone would not result in the large-scale structure we observe
 - Need dark matter to encourage “clumping” of baryons in the early Universe

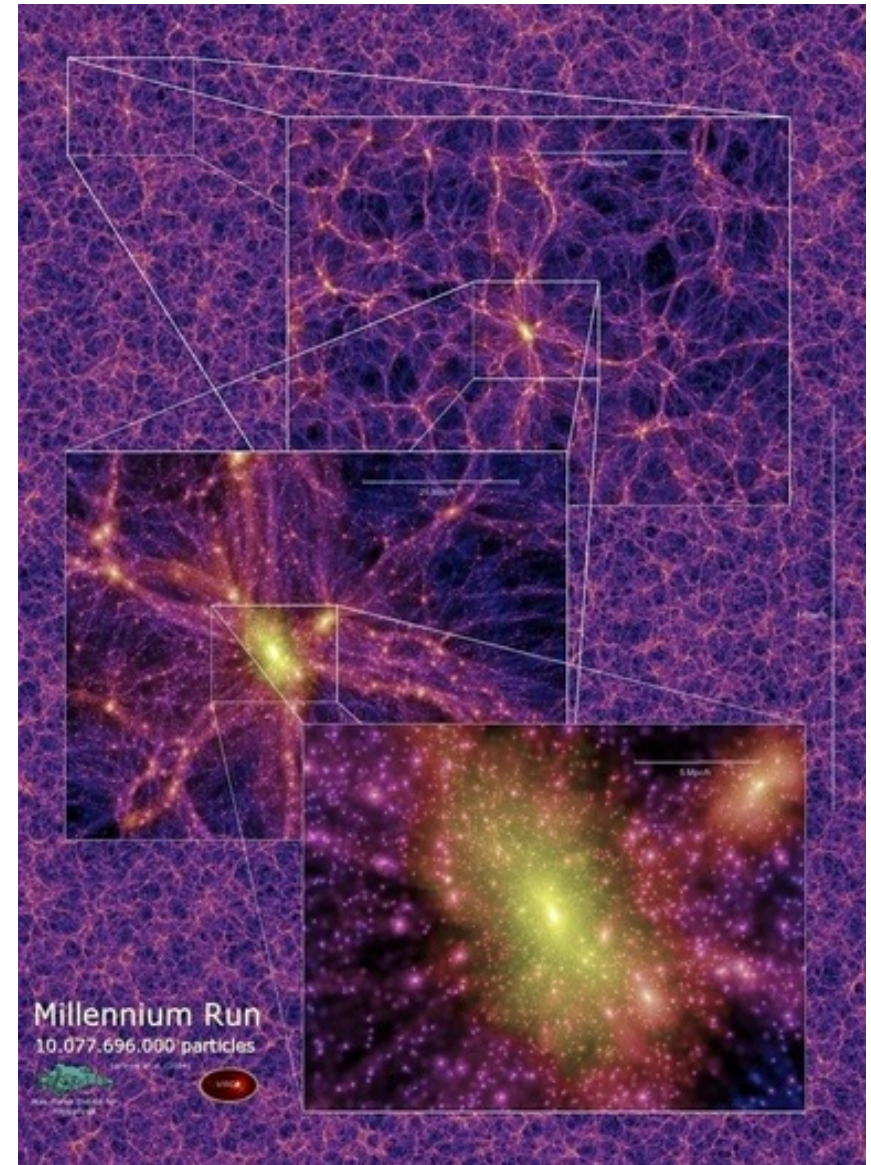
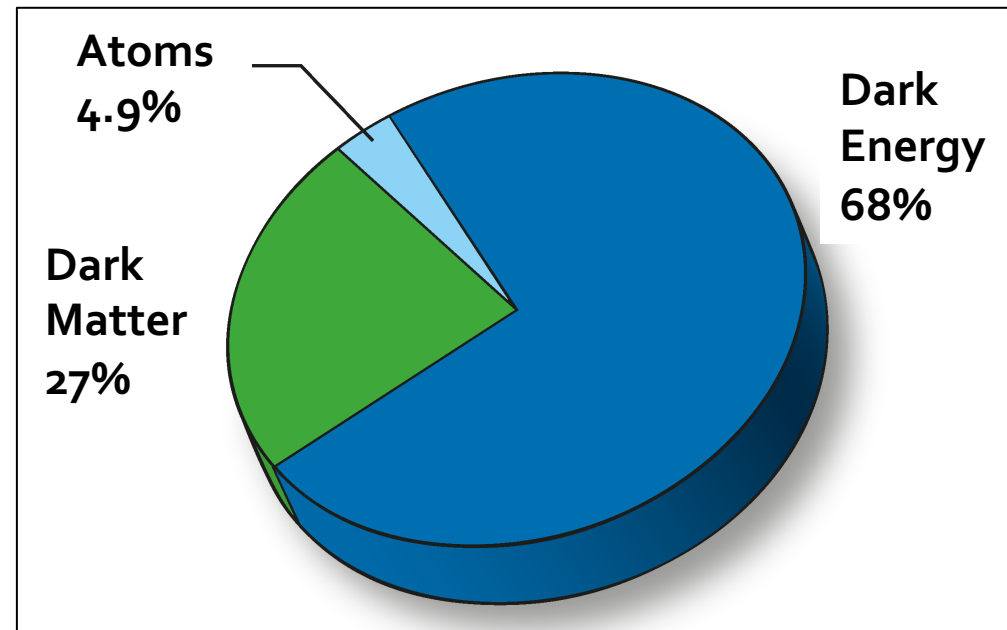
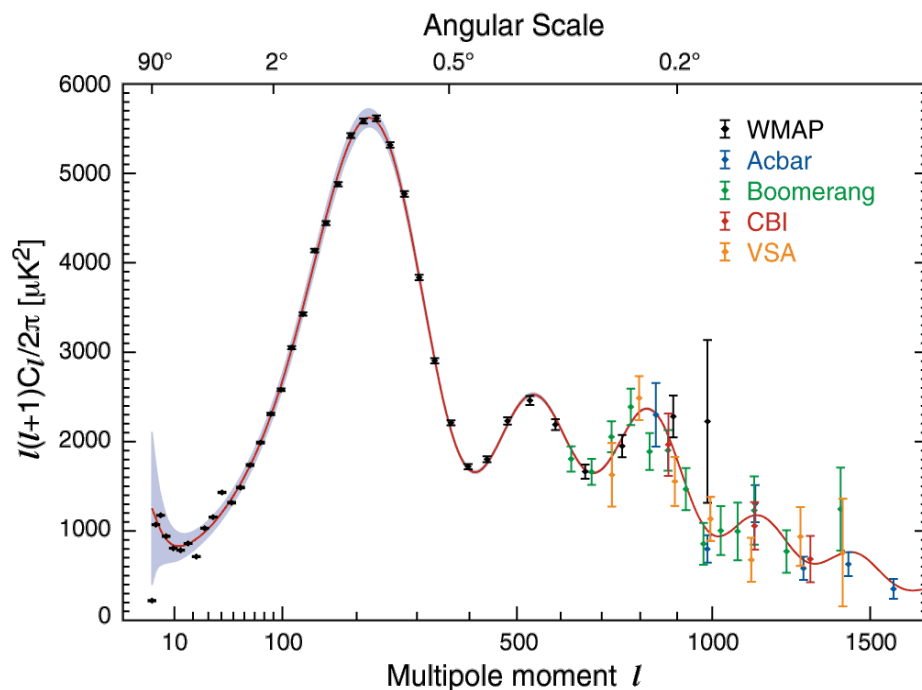
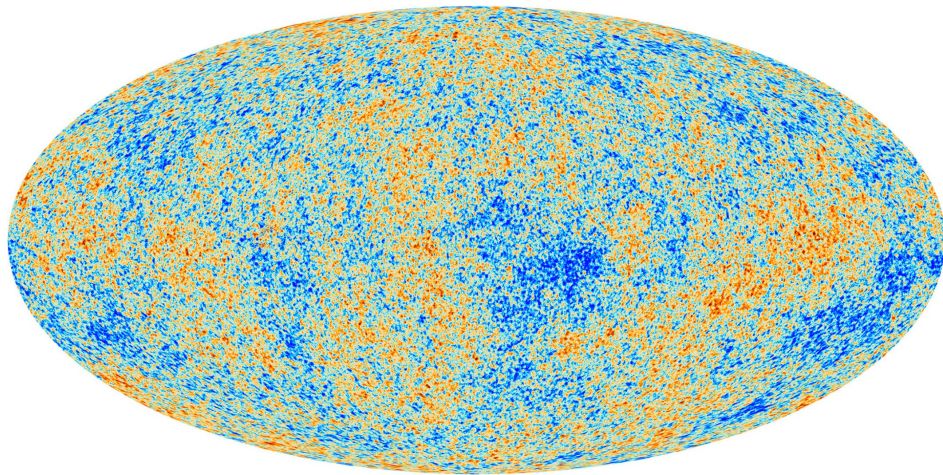


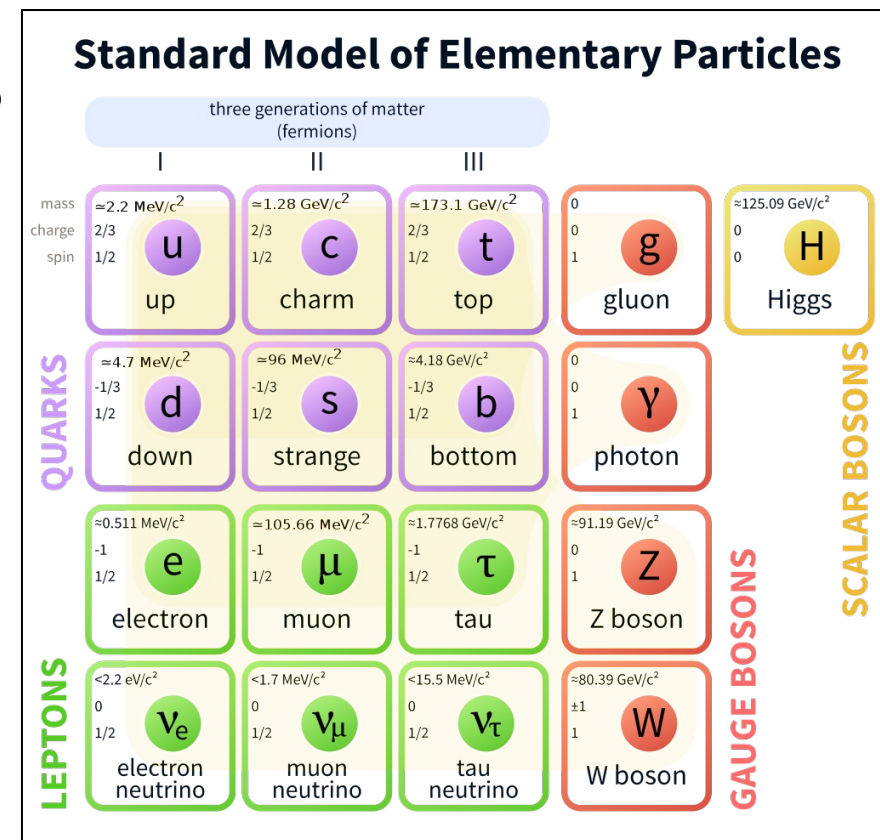
Image credit: <http://www.mpa-garching.mpg.de/galform/millennium/>, astro-ph/0504097

The Cosmic Microwave Background Radiation



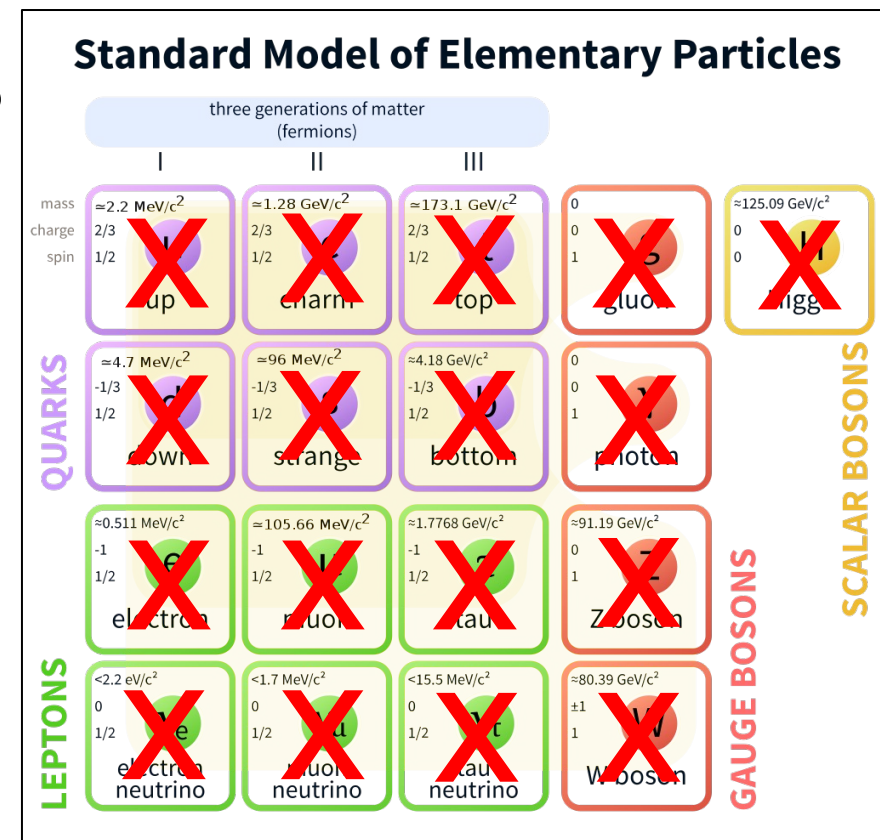
Dark Matter Properties

- ~27% 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)



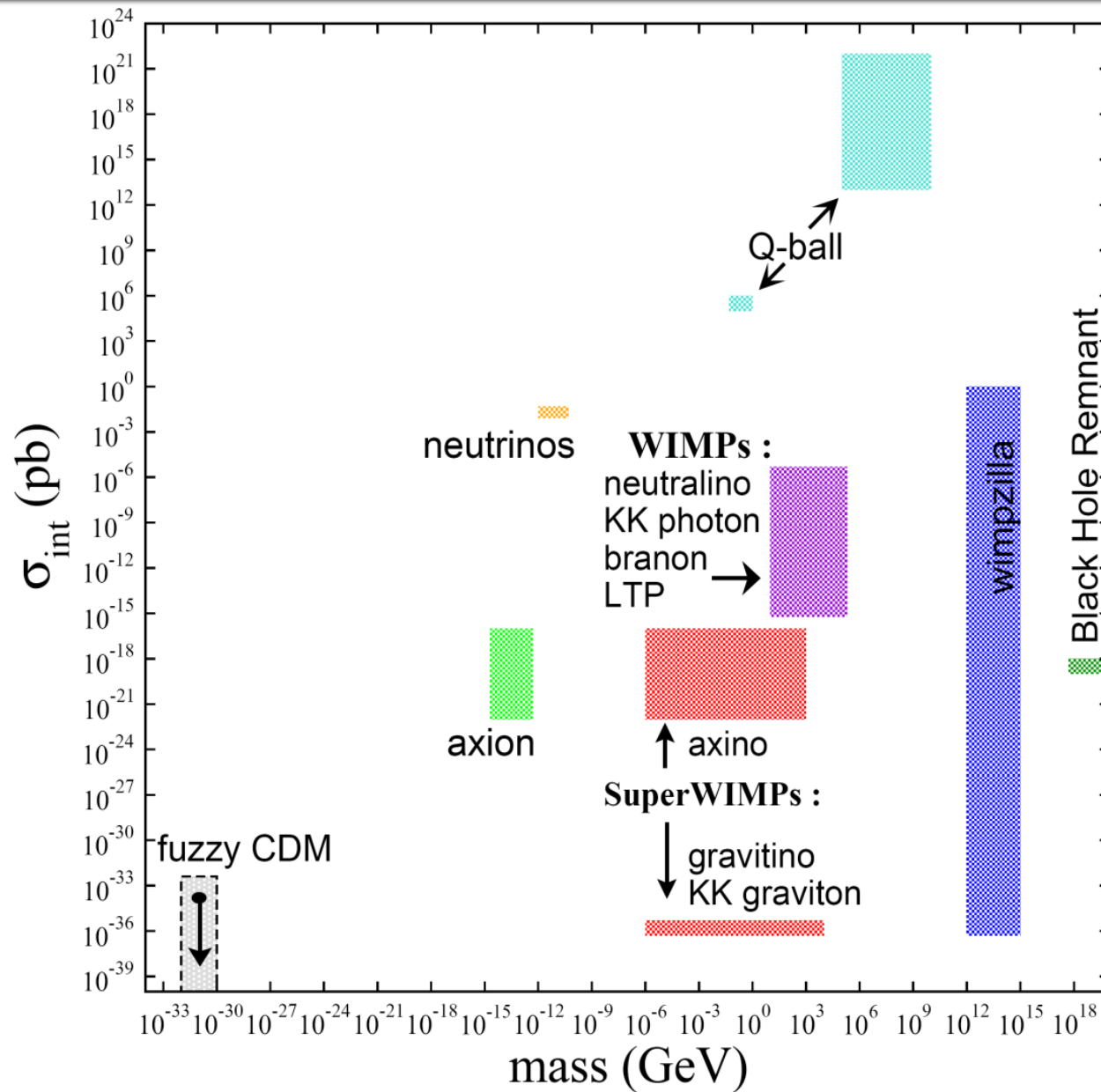
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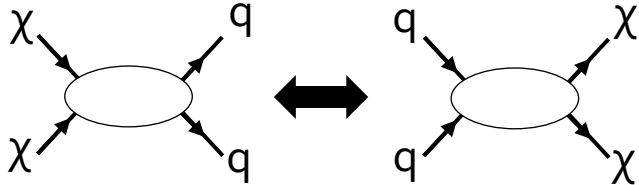
***This excludes all known elementary particles:
most of the Universe is made of something entirely new!***

Dark Matter Candidates

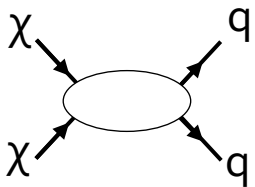


“Weakly Interacting Massive Particles” - Thermal Relics

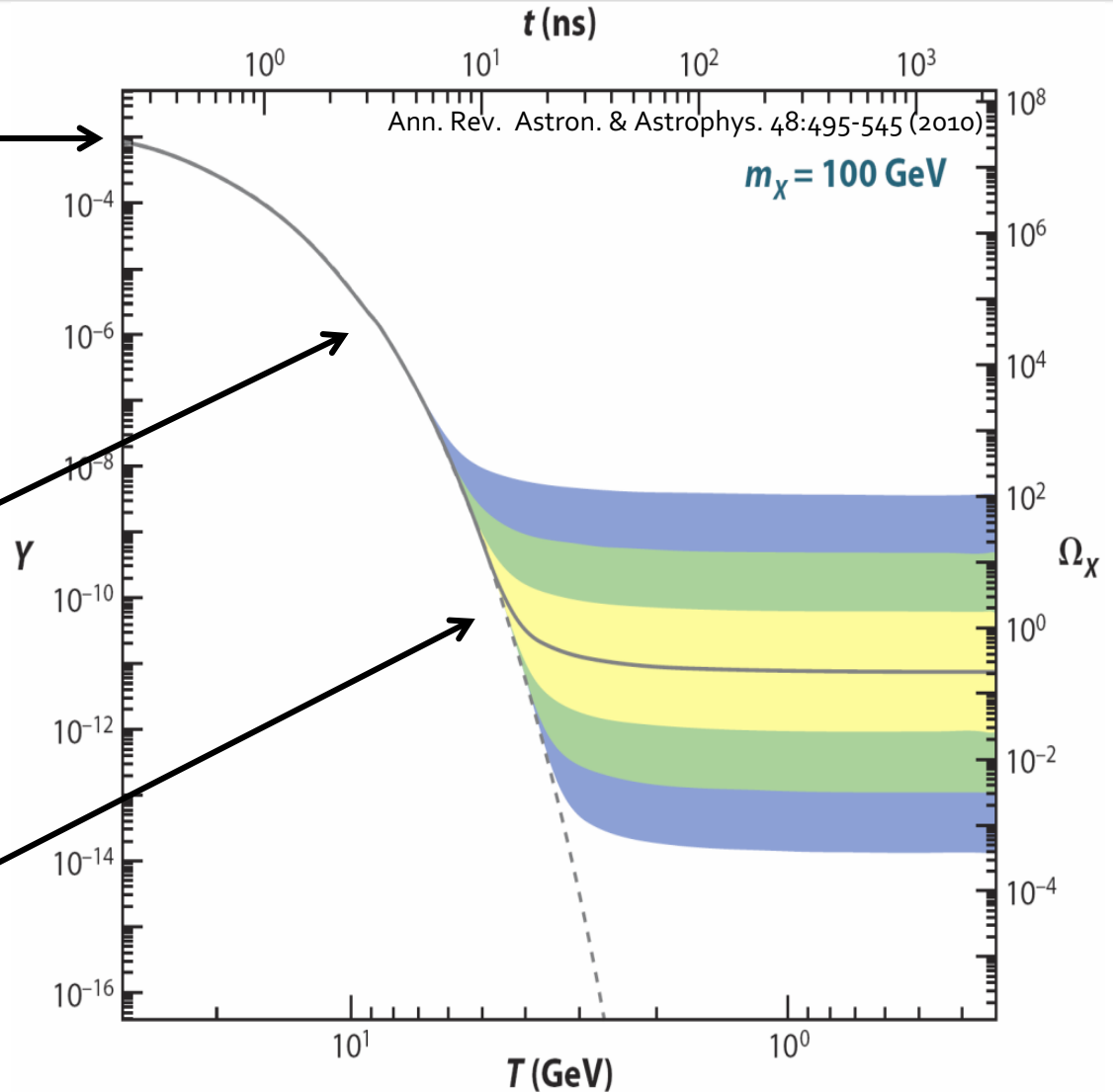
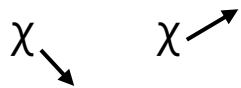
1) WIMPs are produced in thermal equilibrium



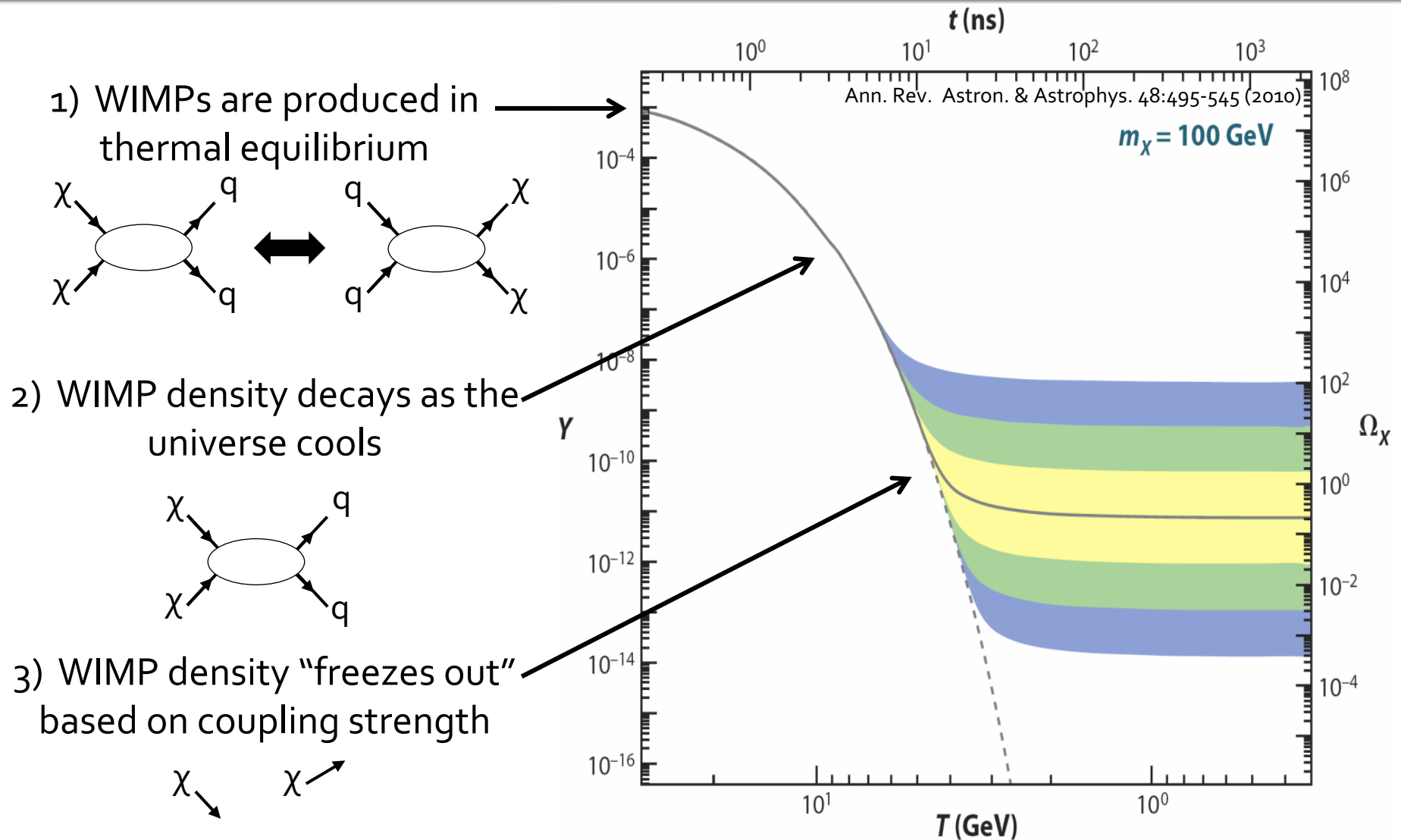
2) WIMP density decays as the universe cools



3) WIMP density “freezes out” based on coupling strength



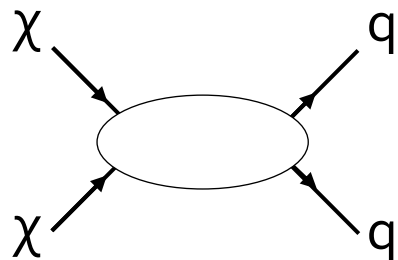
The "WIMP Miracle"



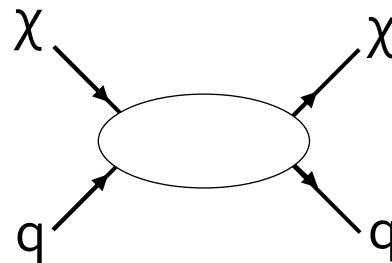
Weak mass & coupling give just the right relic density for dark matter!

Searching for Dark Matter

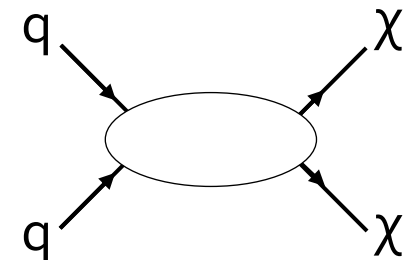
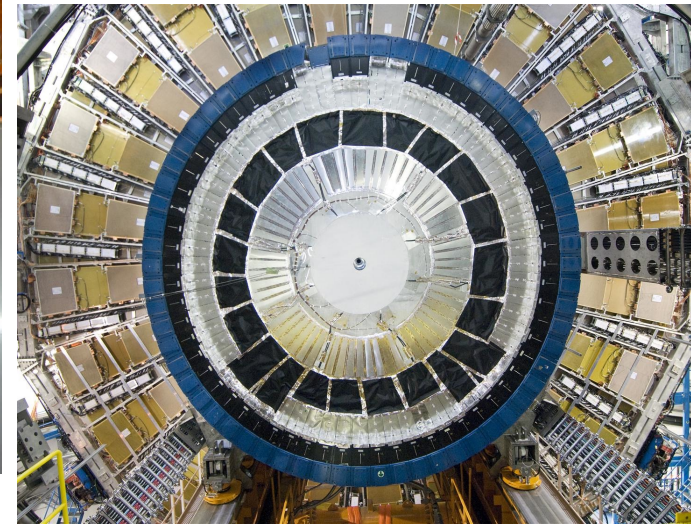
Aboveground



Underground

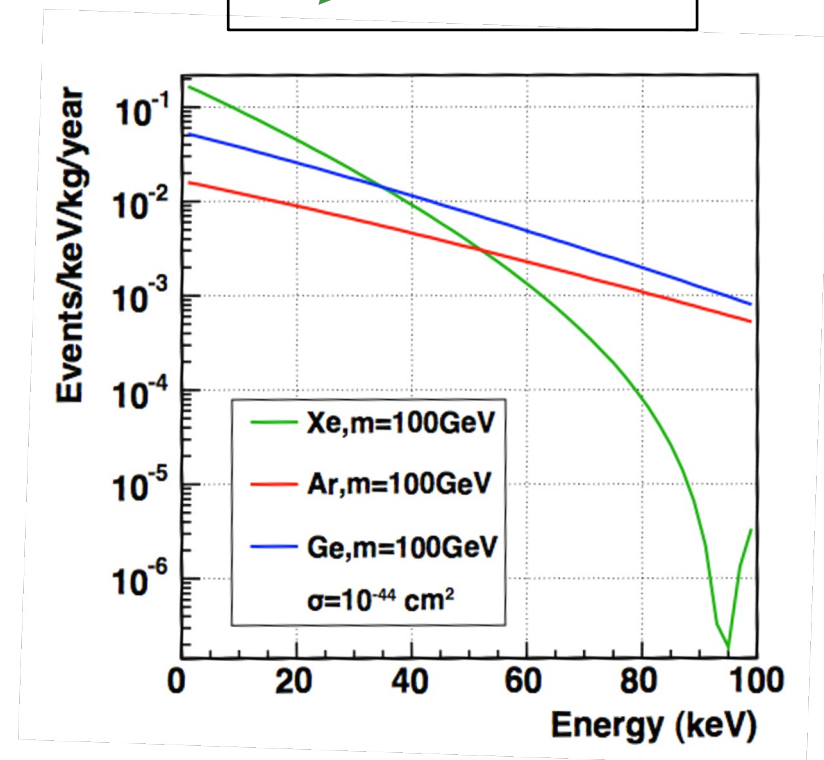
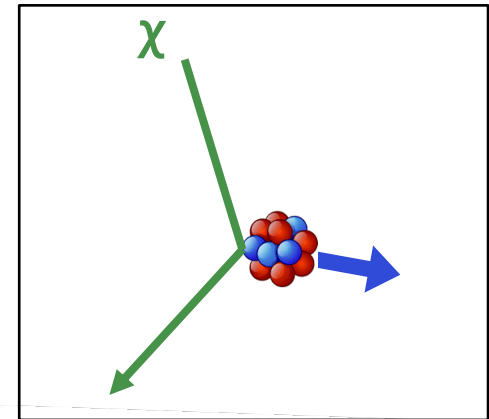


At Accelerators



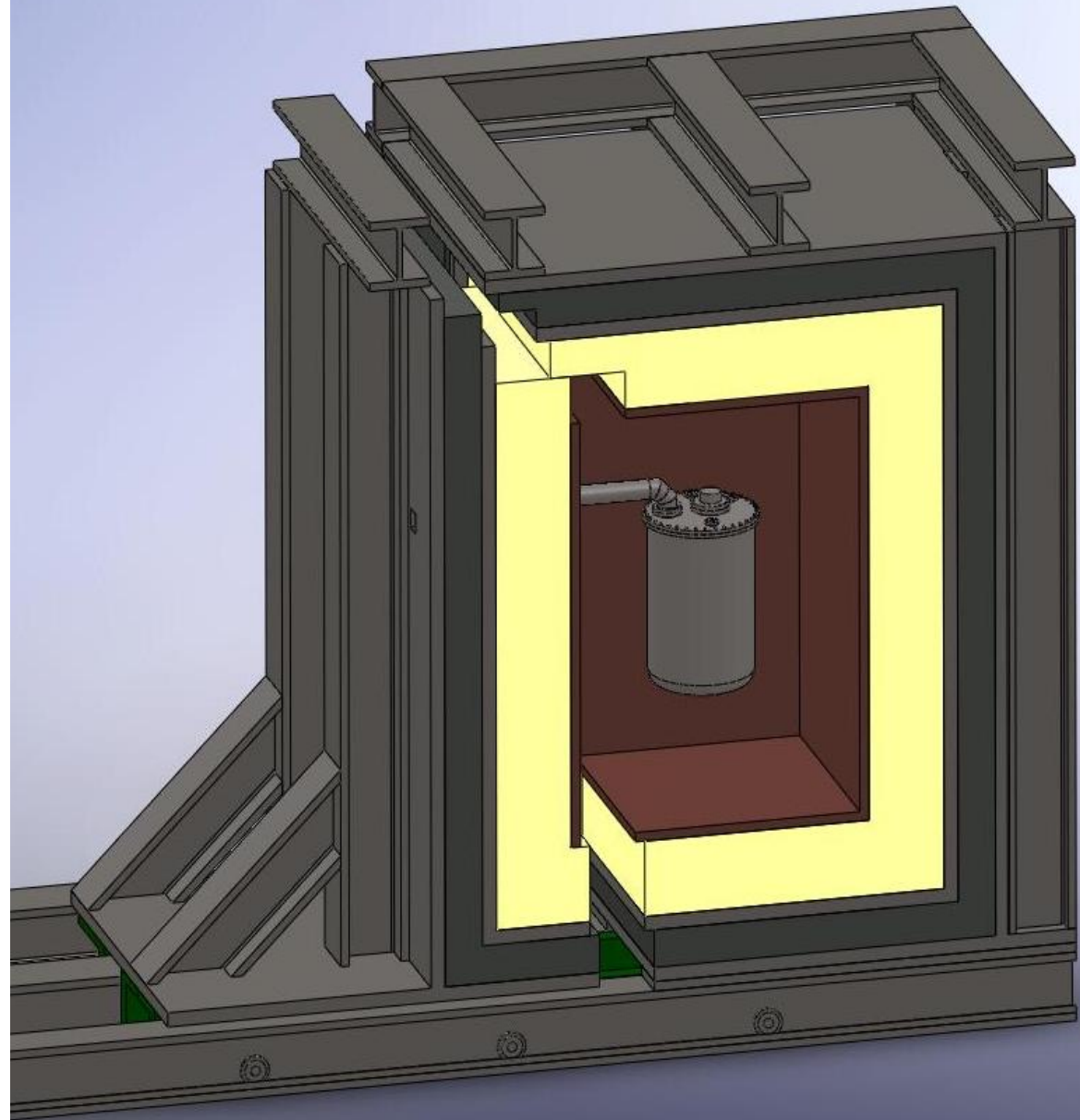
Dark Matter “Direct Detection”

- Heavy dark matter particles can scatter elastically from nuclei, inducing low energy nuclear recoils
 - We are looking for very low energy ($< \sim 100$ keV) nuclear recoils
- Current experiments are searching for at the level of ~ 1 interaction/tonne/yr

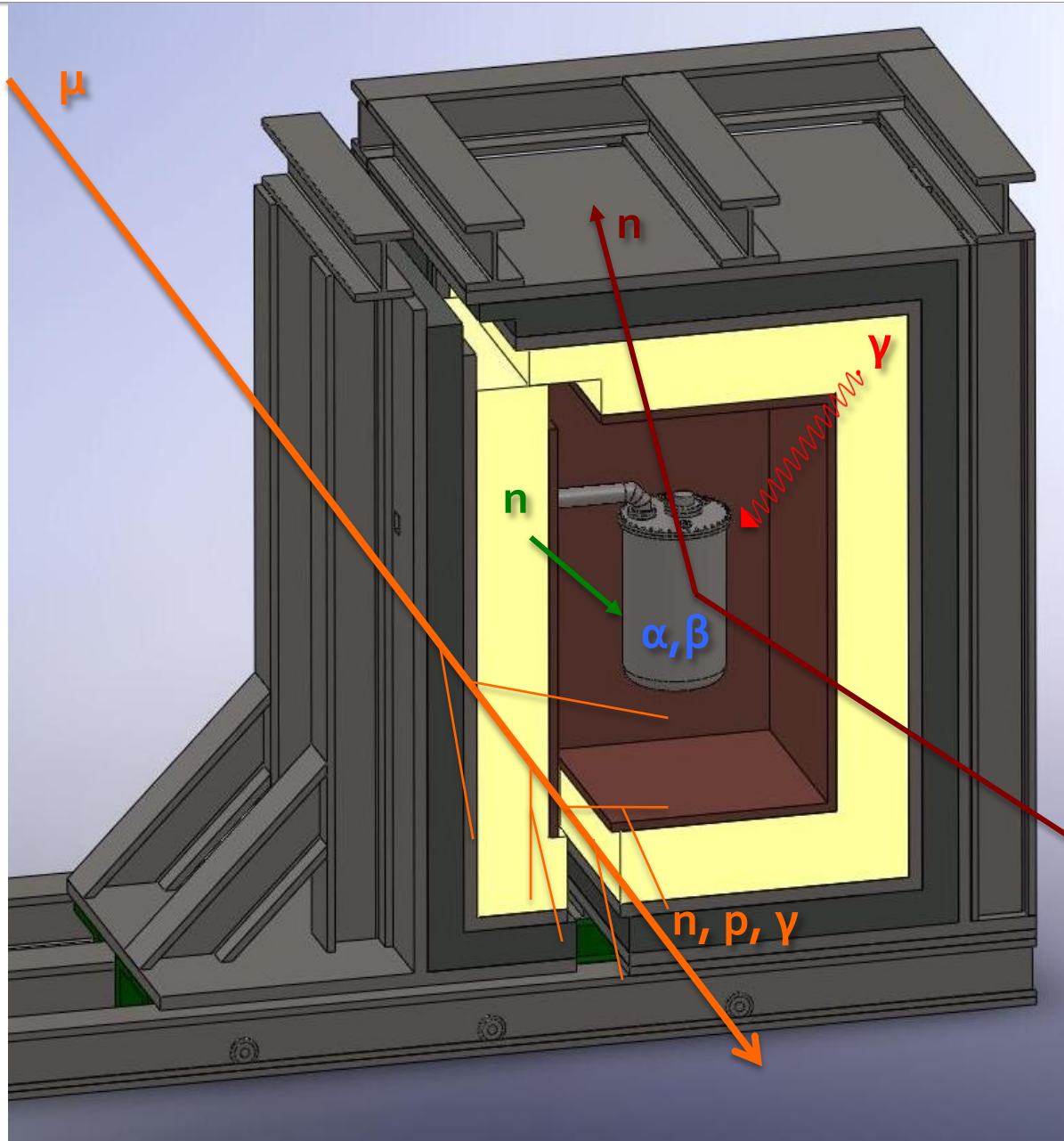


Ideal WIMP Detector

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



Central Challenge: Background



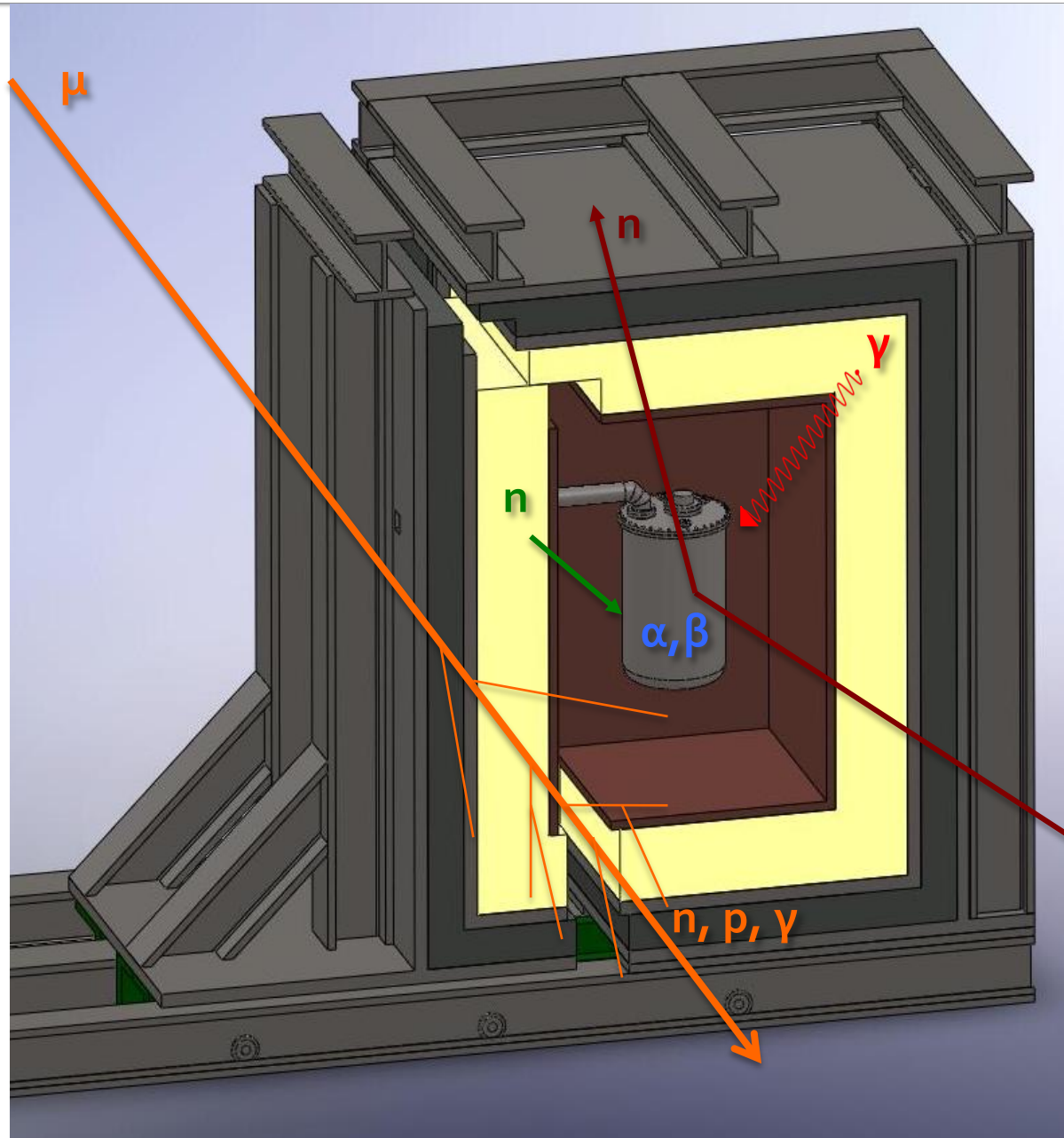
Internal Radioactivity

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

Gamma Rays

external and from
shielding

Central Challenge: Background



Internal Radioactivity

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

Gamma Rays

external and from shielding

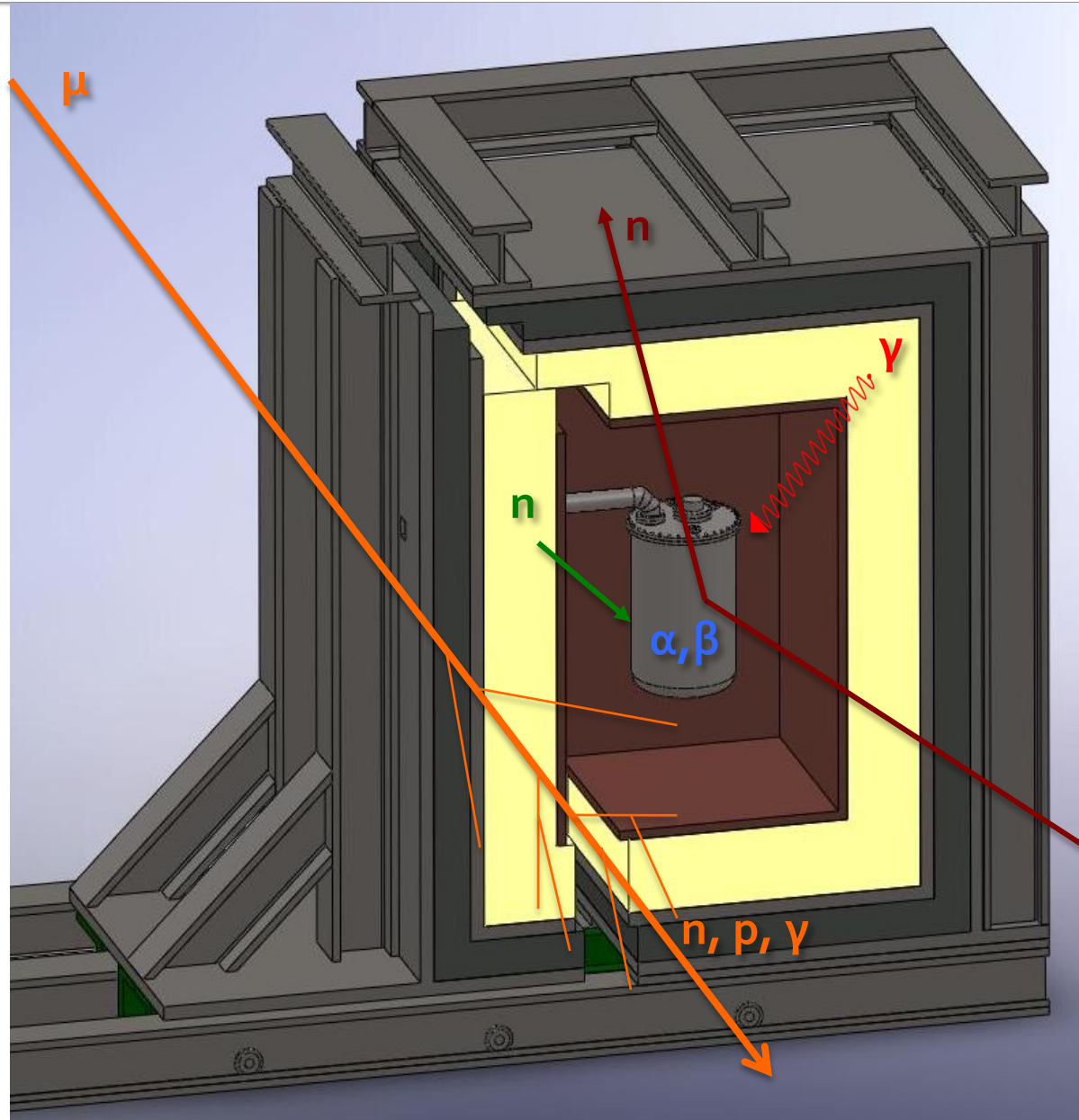
WIMP signal: $< 1 \text{ ev/T-yr}$

Dust: $\sim 7000 \text{ signals/mg-yr}$

Air: $> 300 \text{ signals/mL-yr}$

Fingerprint: $\sim 10 \text{ signals/yr}$

Central Challenge: Background



Internal Radioactivity

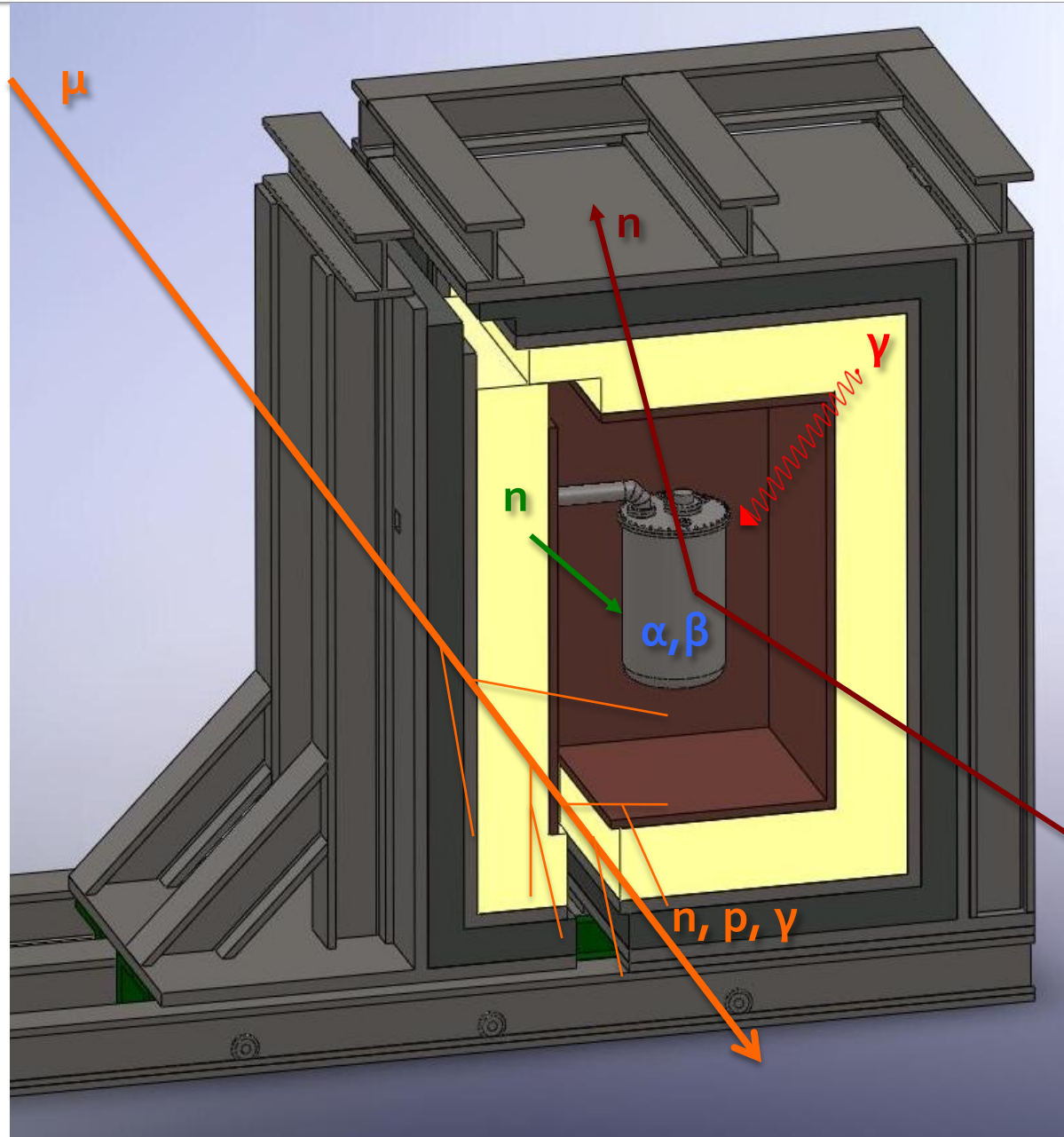
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Gamma Rays

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Central Challenge: Background



Internal Radioactivity

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Gamma Rays

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Radiogenic Neutrons

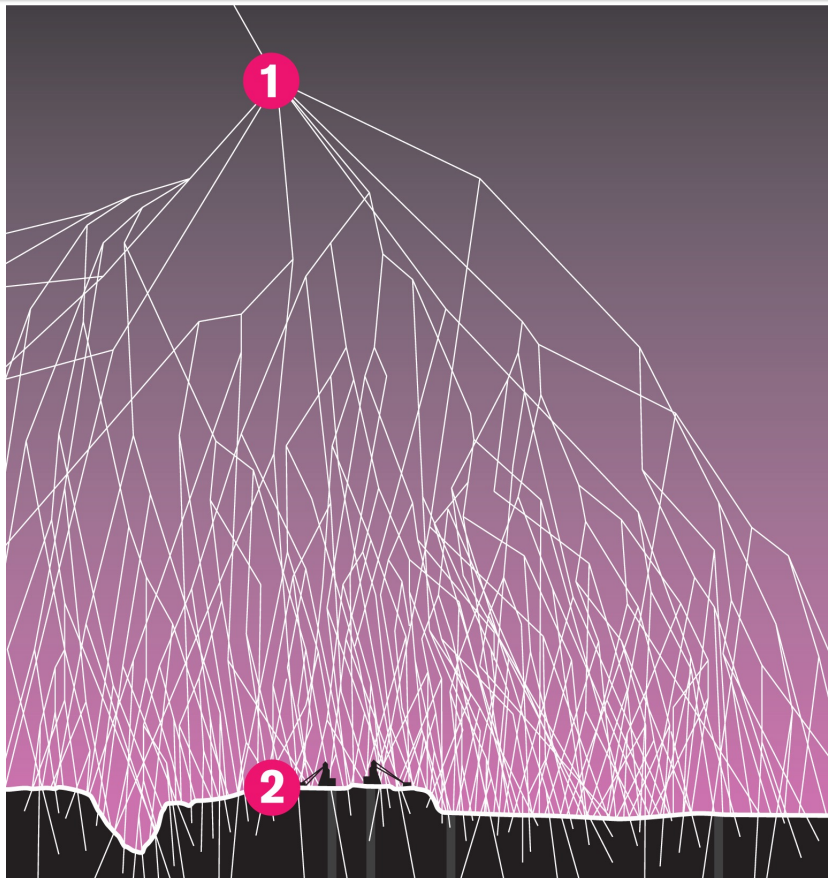
from spontaneous fission and (α, n) , externally and in shielding

Cosmic Muons

Fast Neutrons

from muons in the shield and beyond

Central Challenge: Background



1 The Earth's upper atmosphere is constantly bombarded by cosmic rays: high-energy particles—mostly protons—that originate in outer space. When these particles collide with atoms in the upper atmosphere, they spawn particle showers that multiply and descend on Earth.

2 Dirt and rock stop most of these particles within a short distance. But muons often have enough energy to penetrate the earth for hundreds of feet or more. At the surface, cosmic-ray muons pass through your hand at a rate of more than one per second.

Internal Radioactivity

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

Gamma Rays

external and from shielding

Radiogenic Neutrons

from spontaneous fission and (α, n) , externally and in shielding

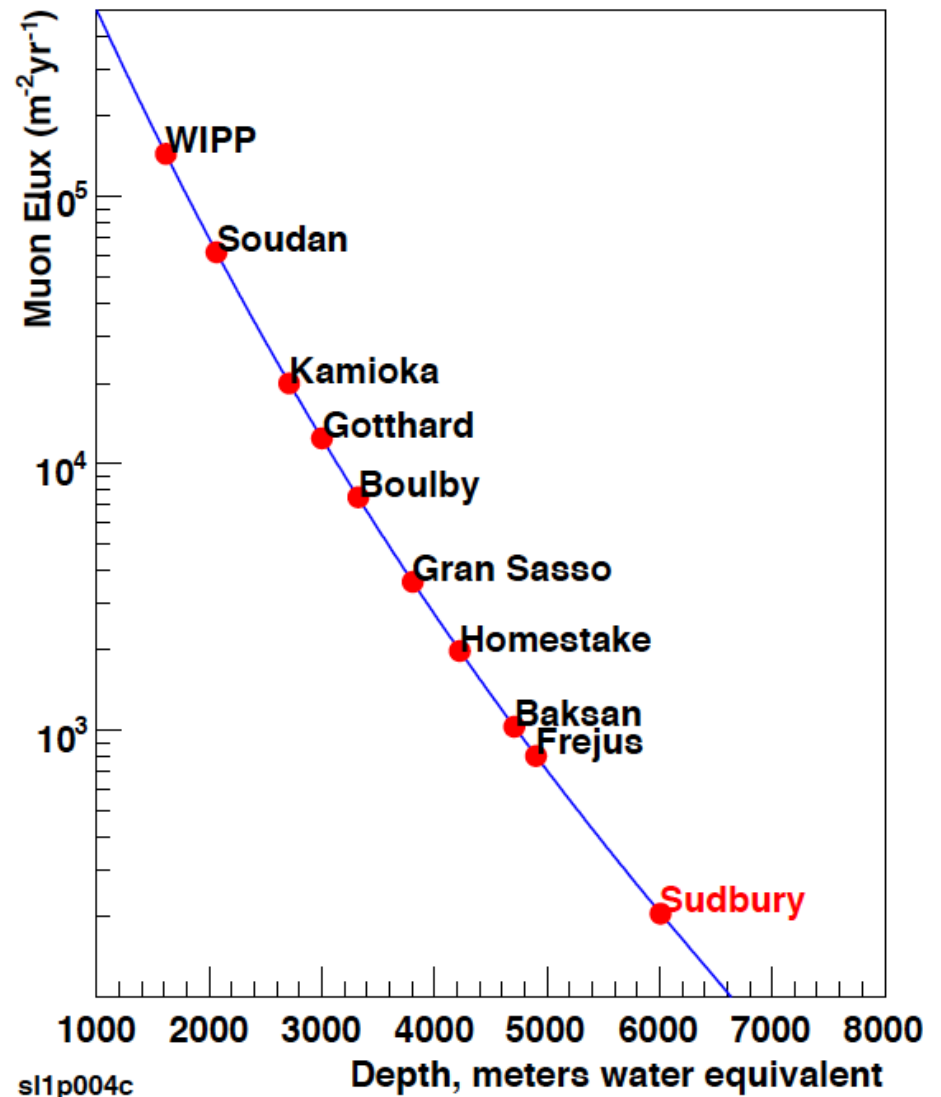
Cosmic Muons

Fast Neutrons

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Why an Underground Lab?

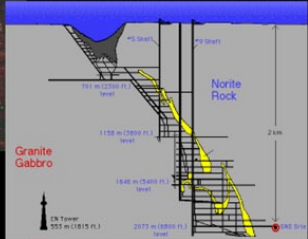
- The most pernicious backgrounds in astroparticle experiments are cosmogenic
- The muons are (slowly) filtered by rock – deeper labs allow lower background



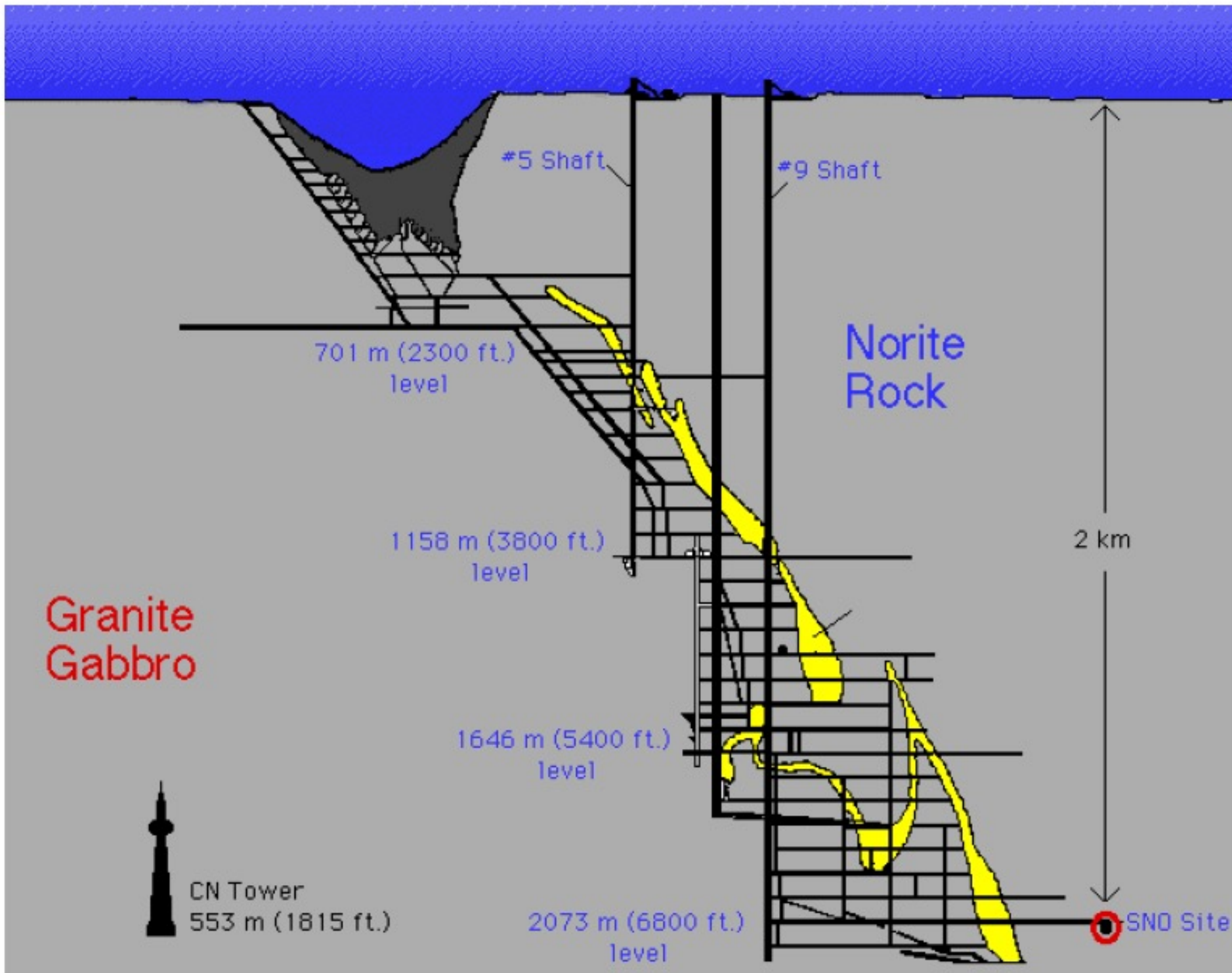
SNOLAB has the lowest muon flux!



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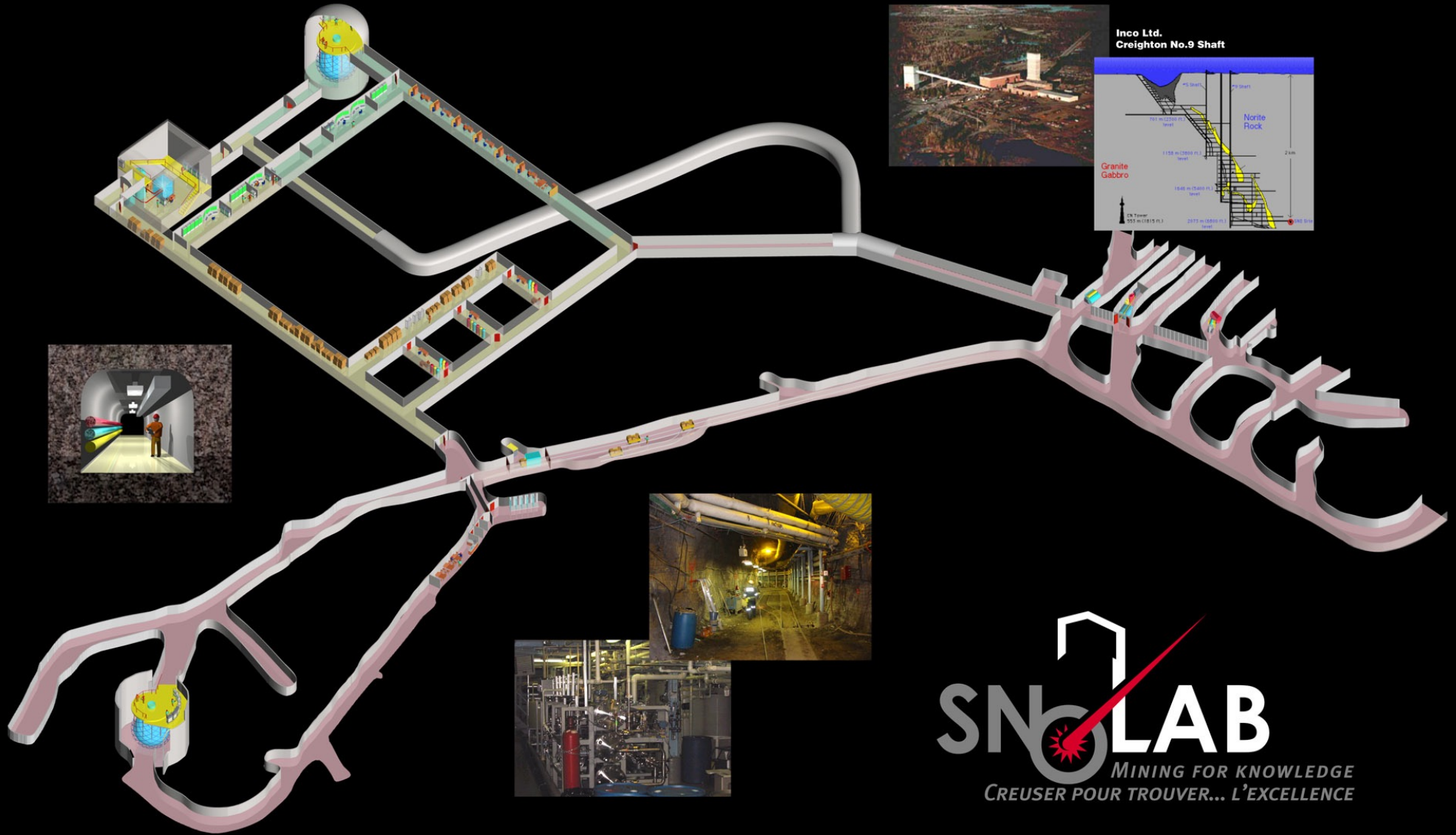




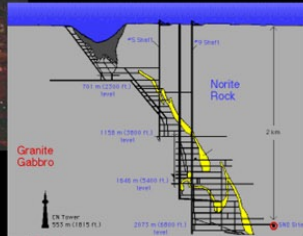


The entire underground laboratory is a clean room, to assist experiments in achieving ultra-low backgrounds.

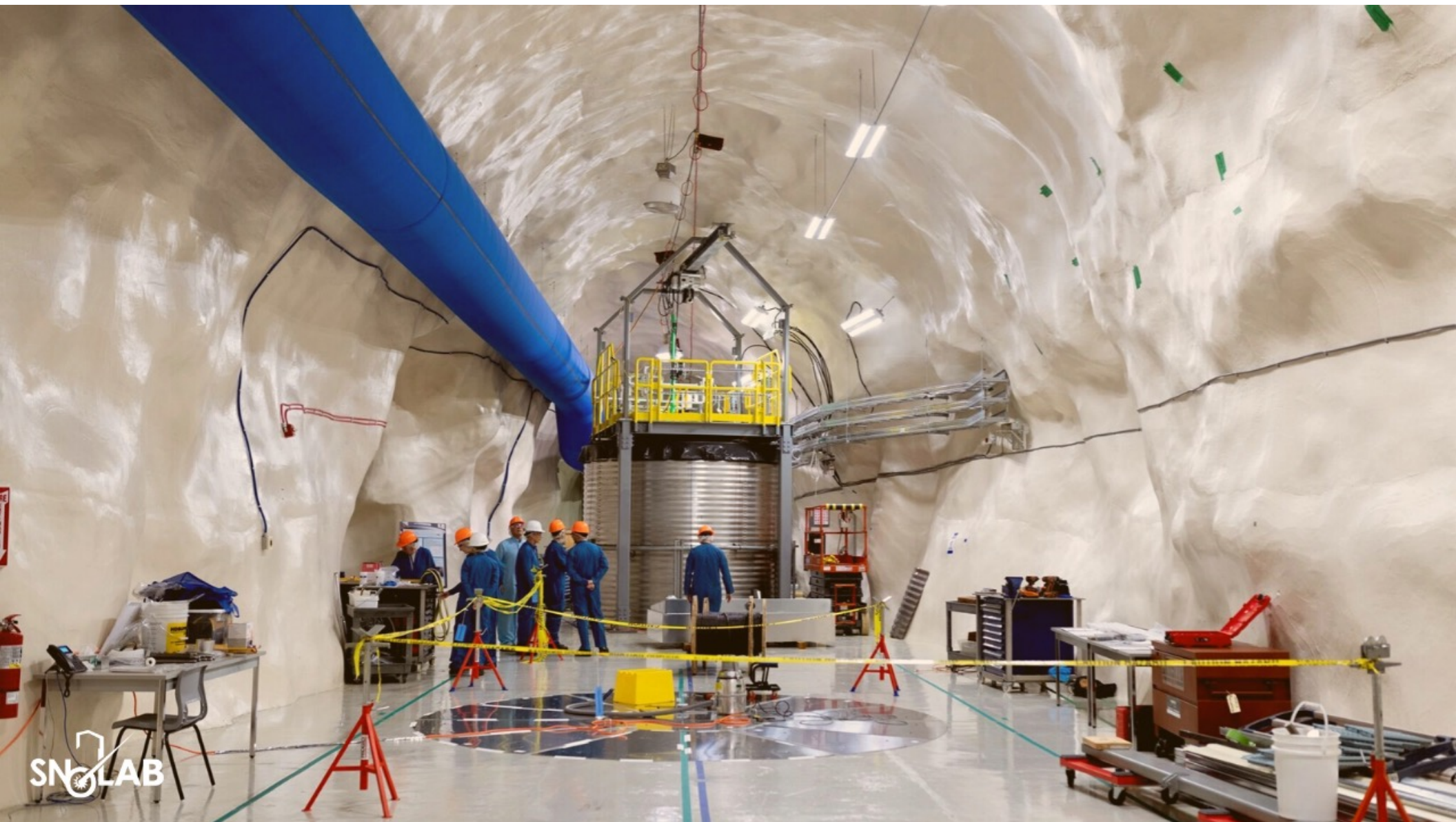




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SNOLAB



CUBE HALL

An aerial view of the interior of the CUBE HALL. The space is filled with industrial equipment, including a large cylindrical tank in the center, various workbenches, and scaffolding. Yellow overhead cranes are visible. The floor is light-colored, and the walls are a light grey. A blue structure is visible in the bottom left corner. The text 'CUBE HALL' is at the top left. 'DEAP-3600' is on the left side, 'MiniClean' is on the right side, and 'NEWS-G' is at the bottom, circled in red.

DEAP-3600

MiniClean

NEWS-G

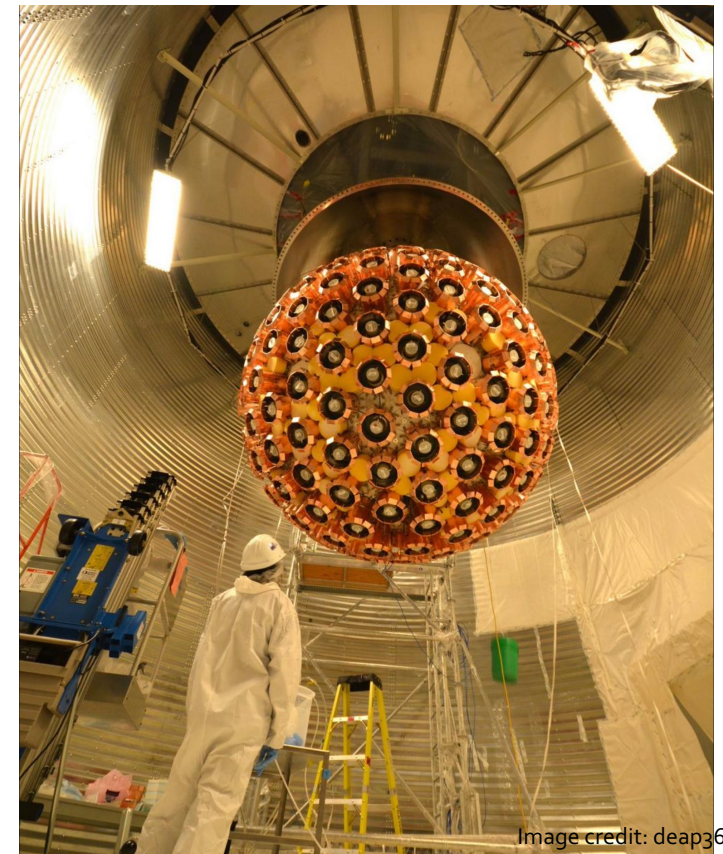
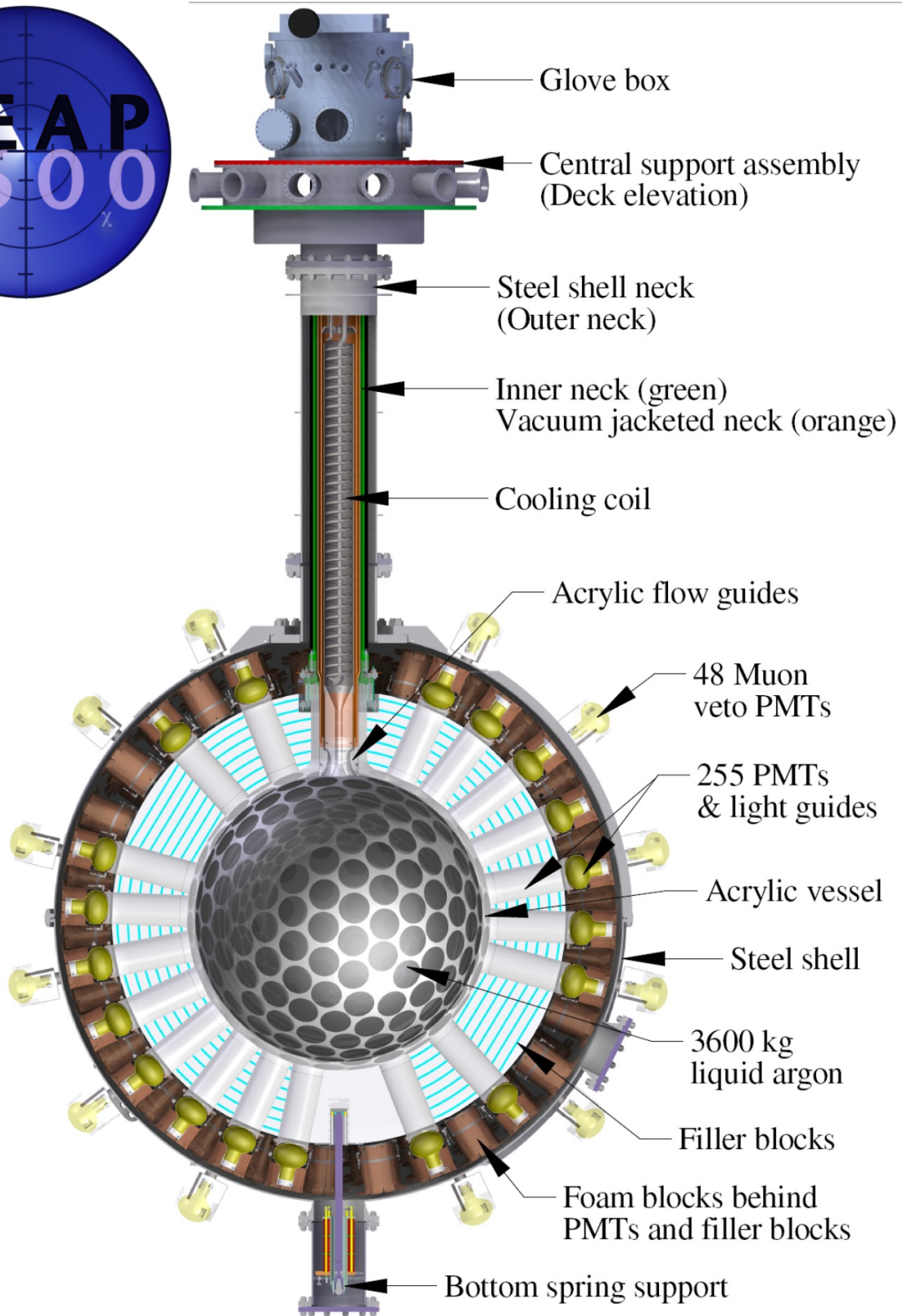






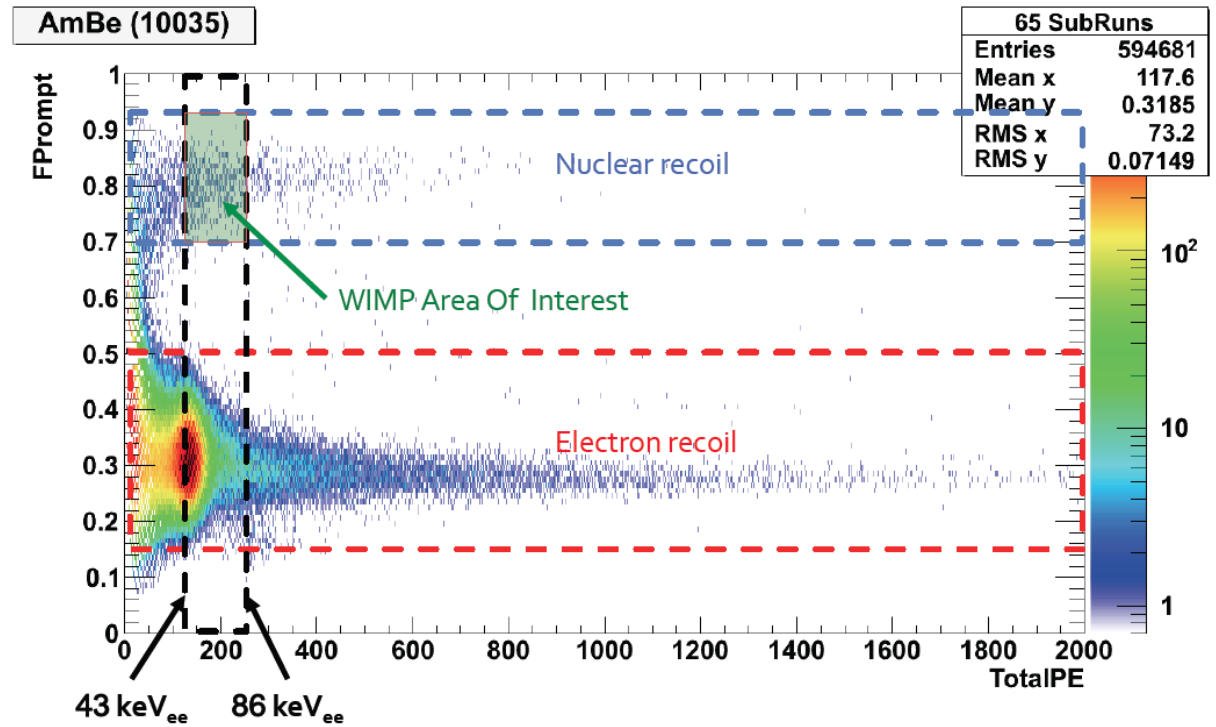
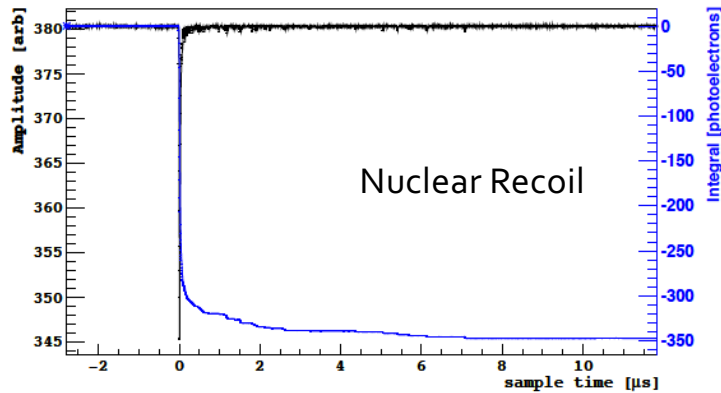
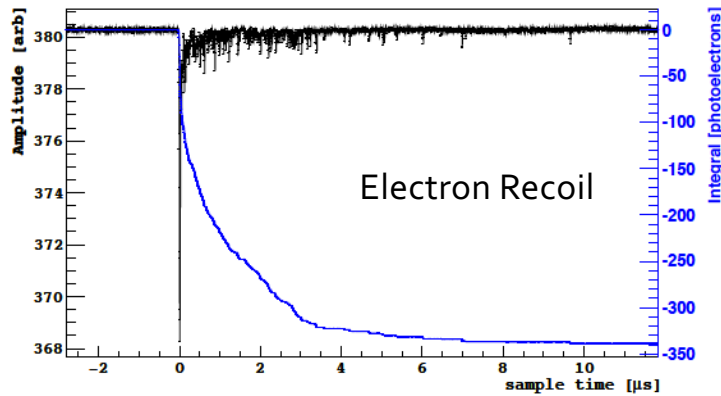
Searching for Dark Matter at SNOLAB



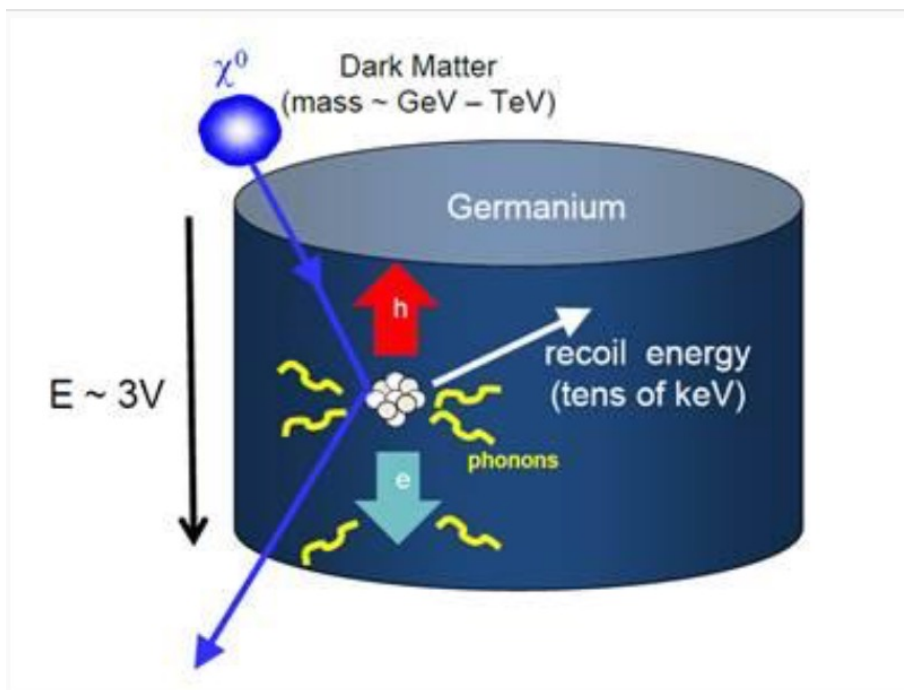
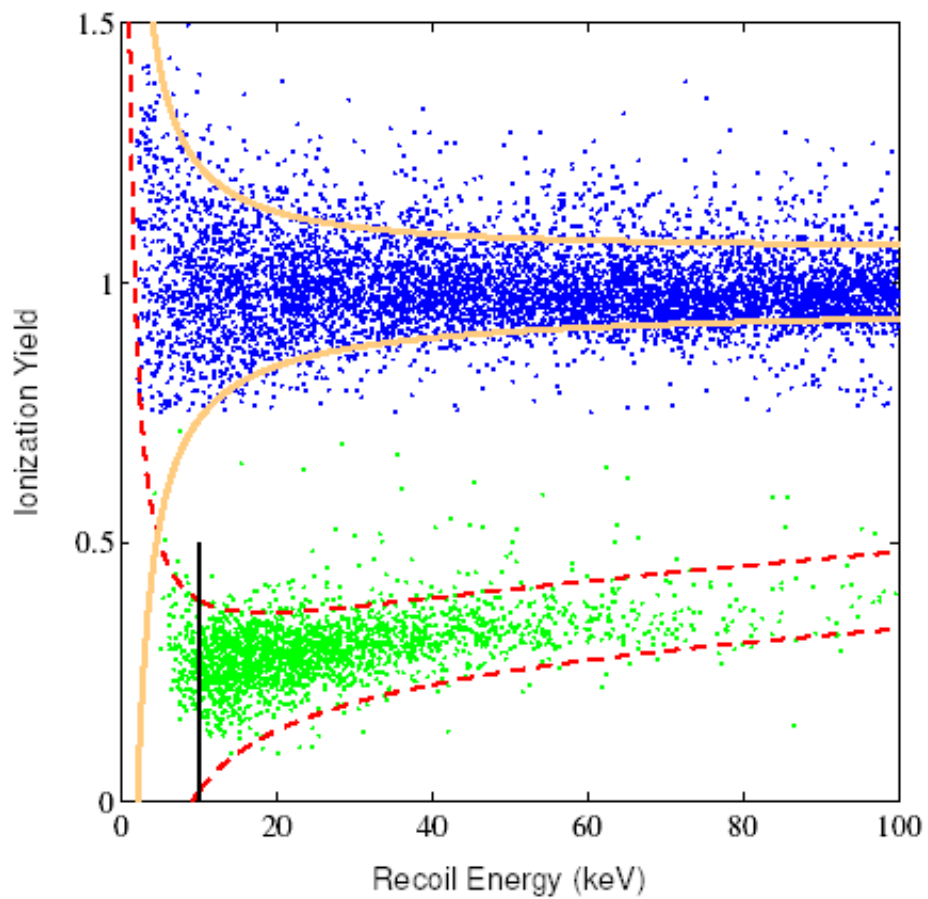
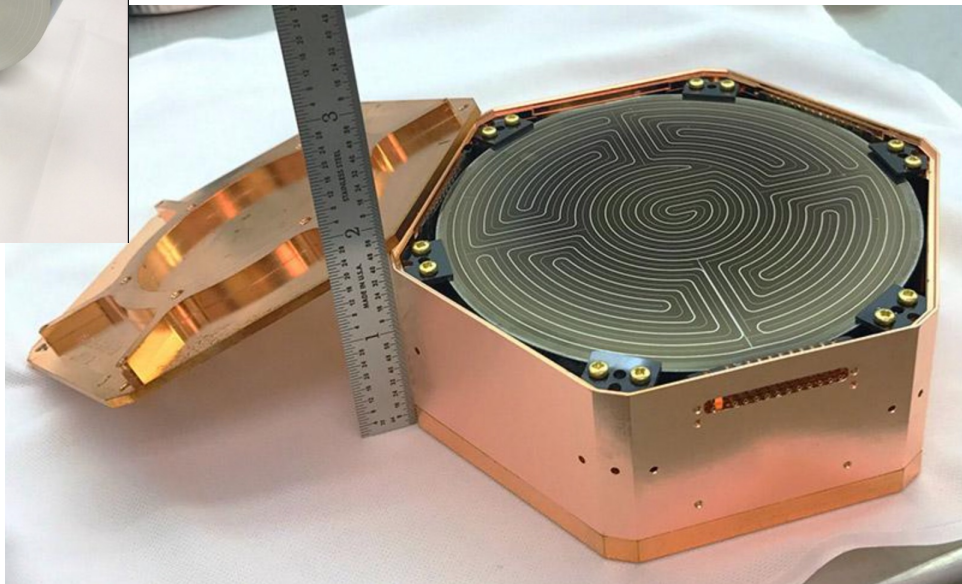
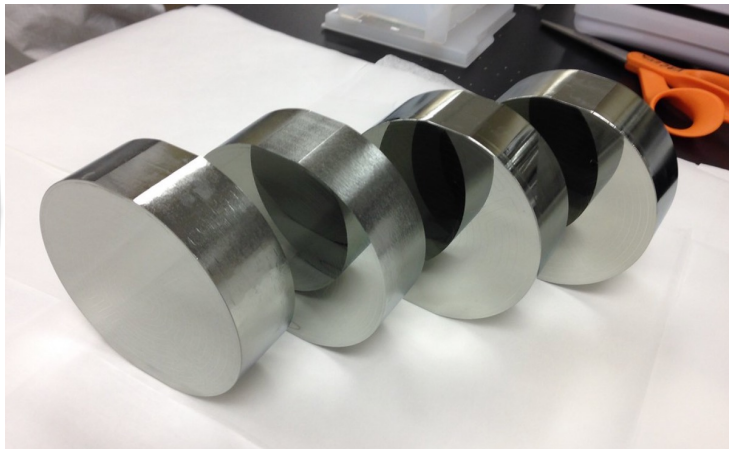


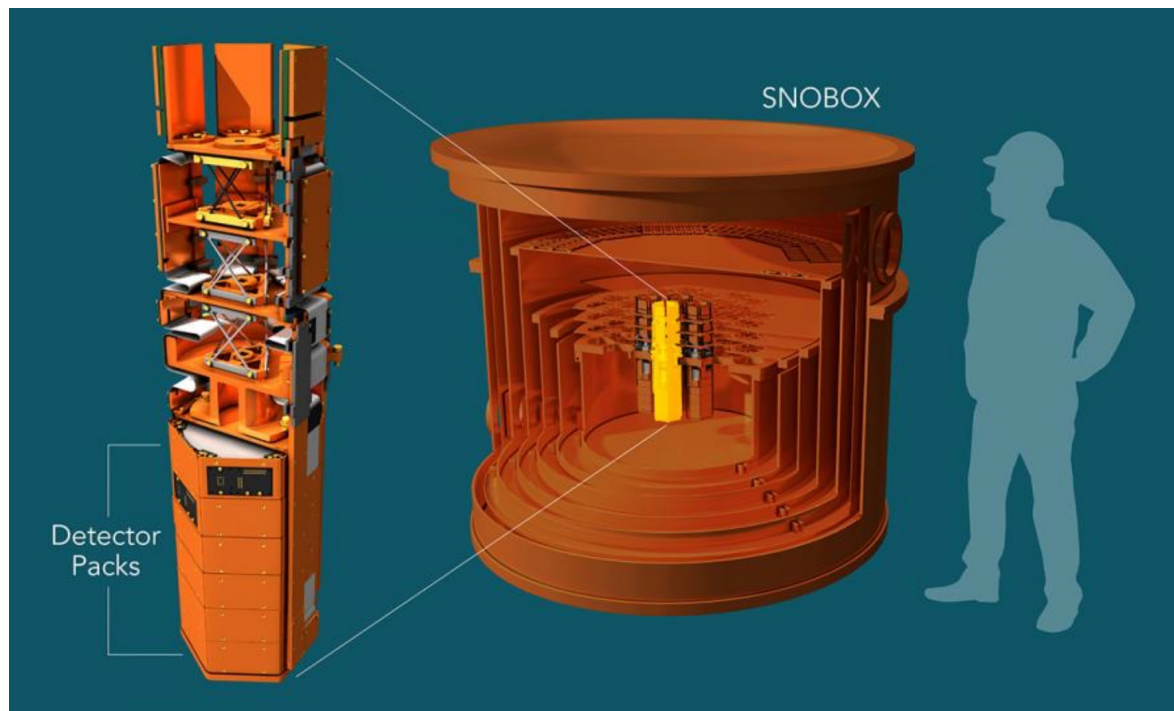
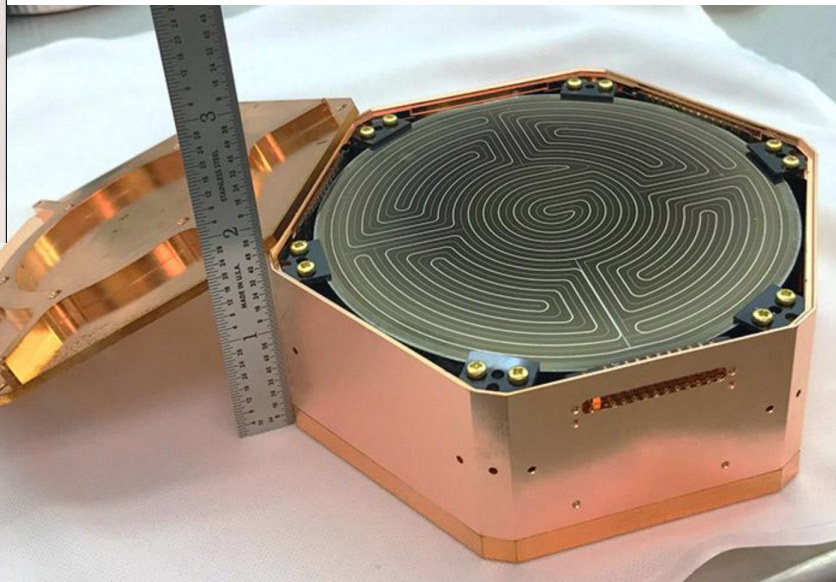
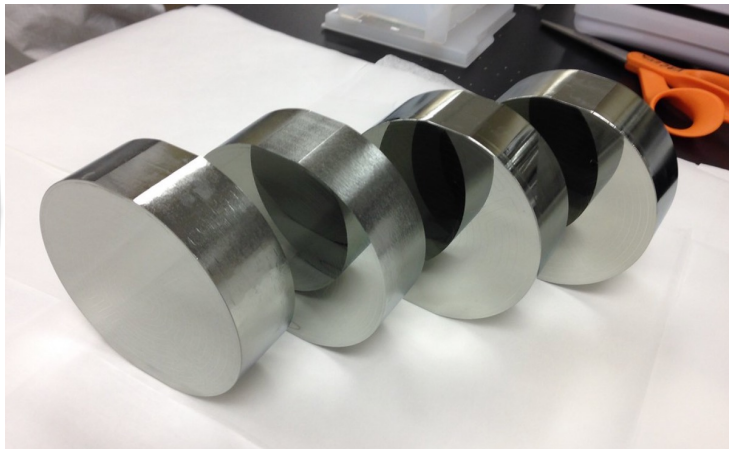


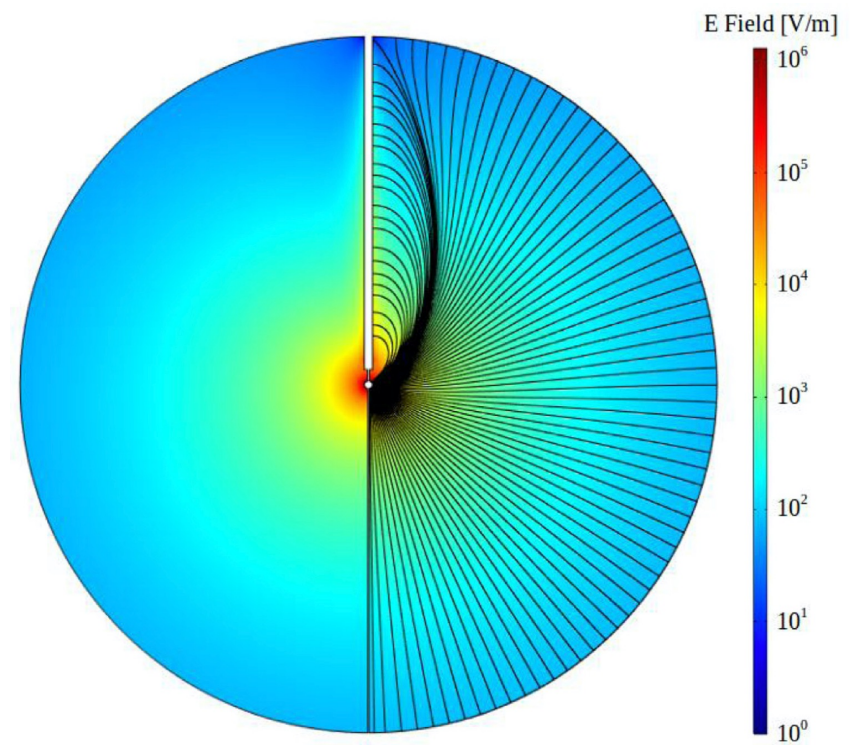
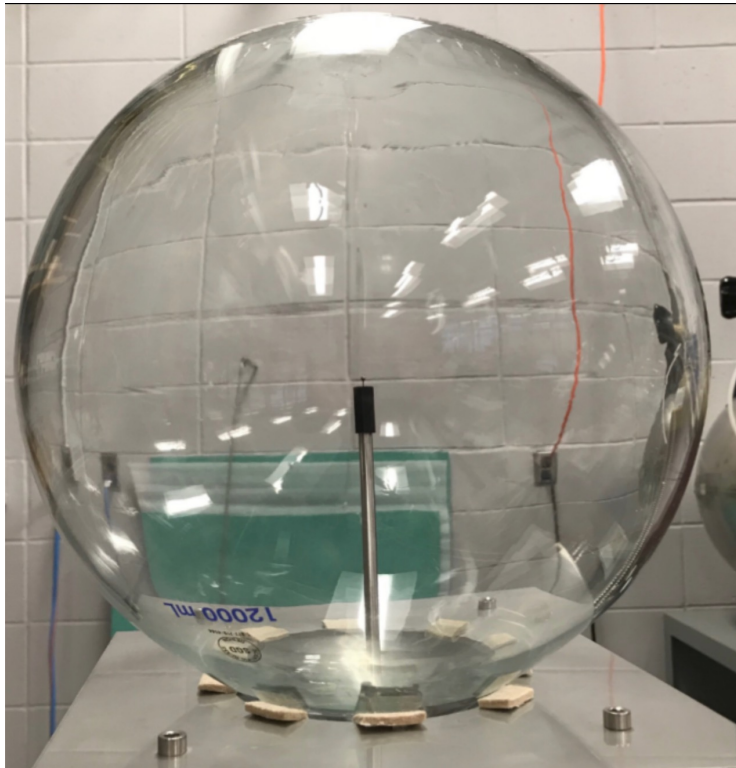
"Pulse Shape Discrimination"

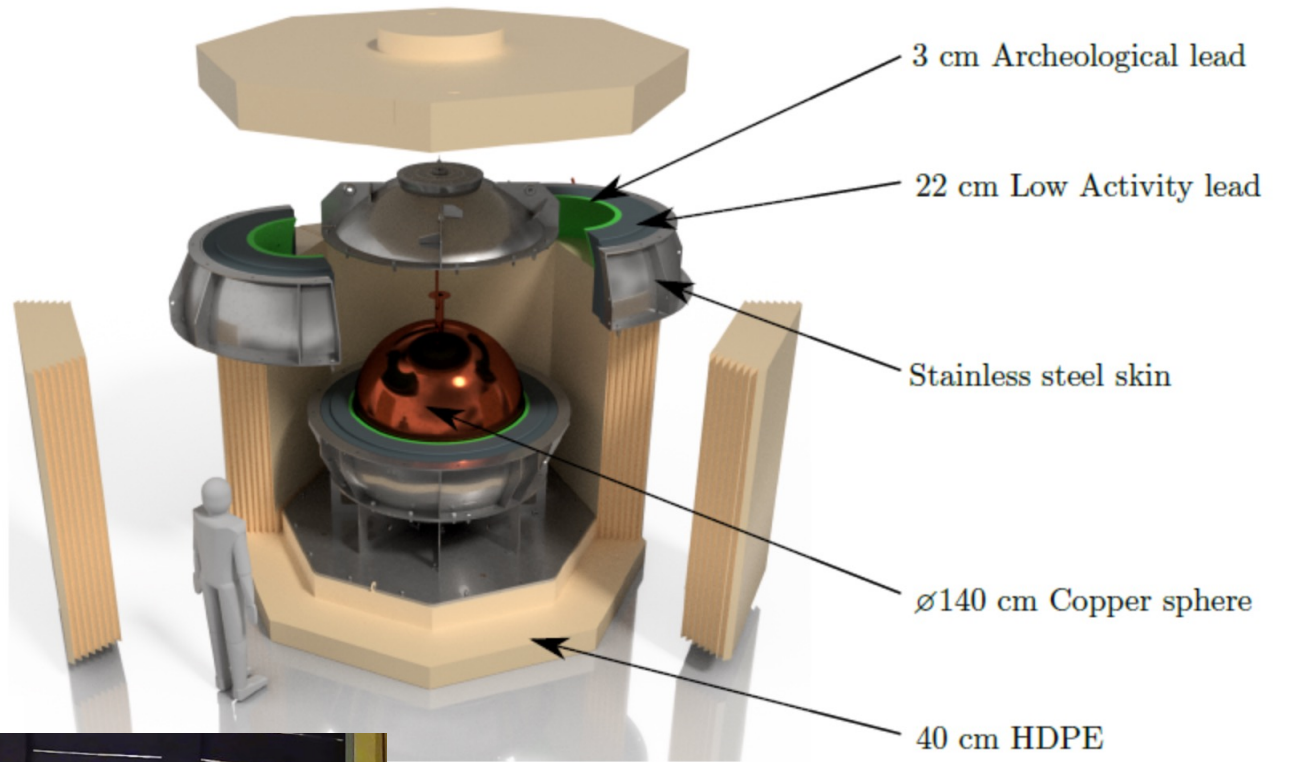


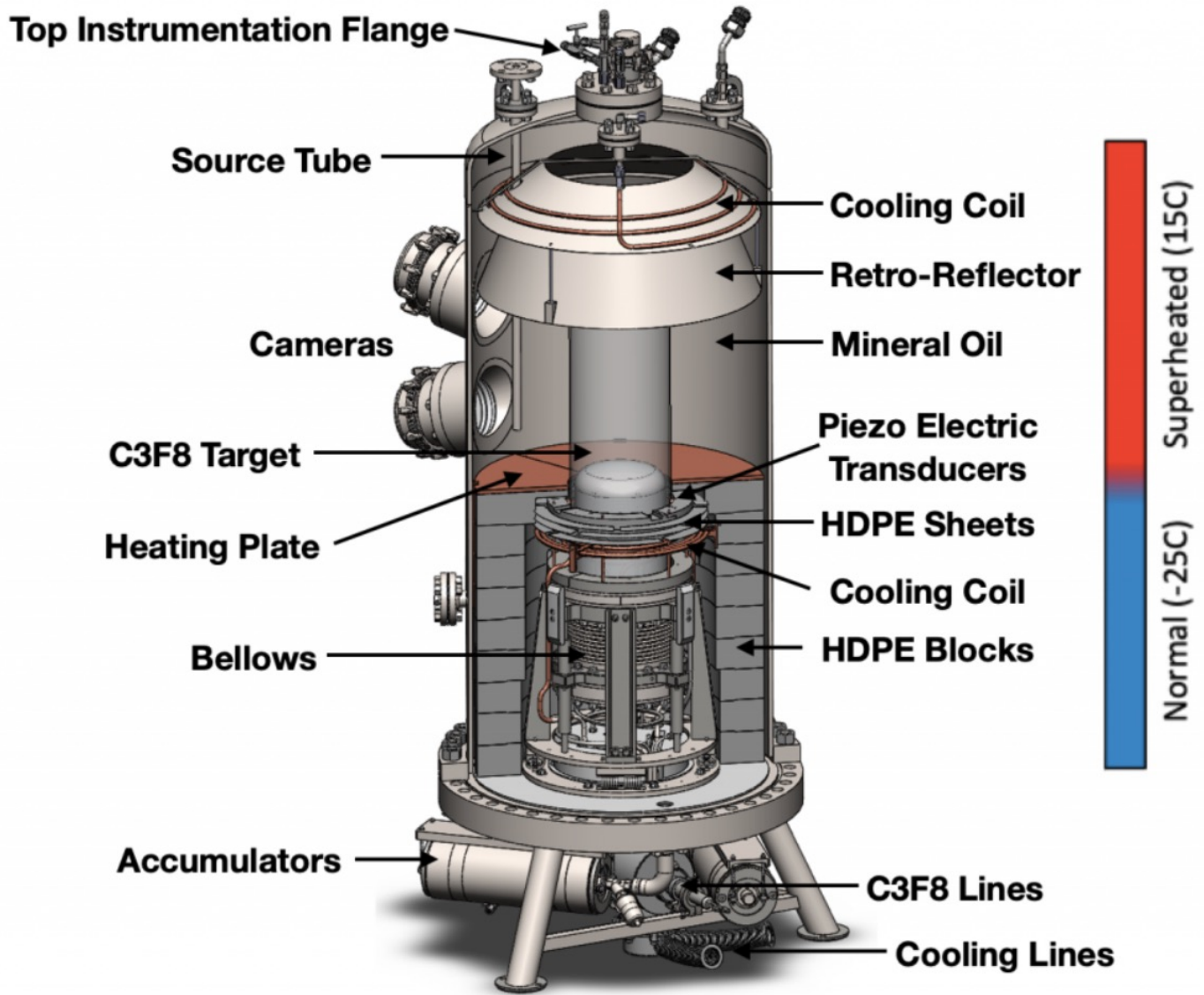
- The ratio of light from singlet (~ 7 ns decay time) and triplet ($1.6 \mu\text{s}$ decay time) depends on particle type
 → $>10^8$ electron/nuclear recoil discrimination





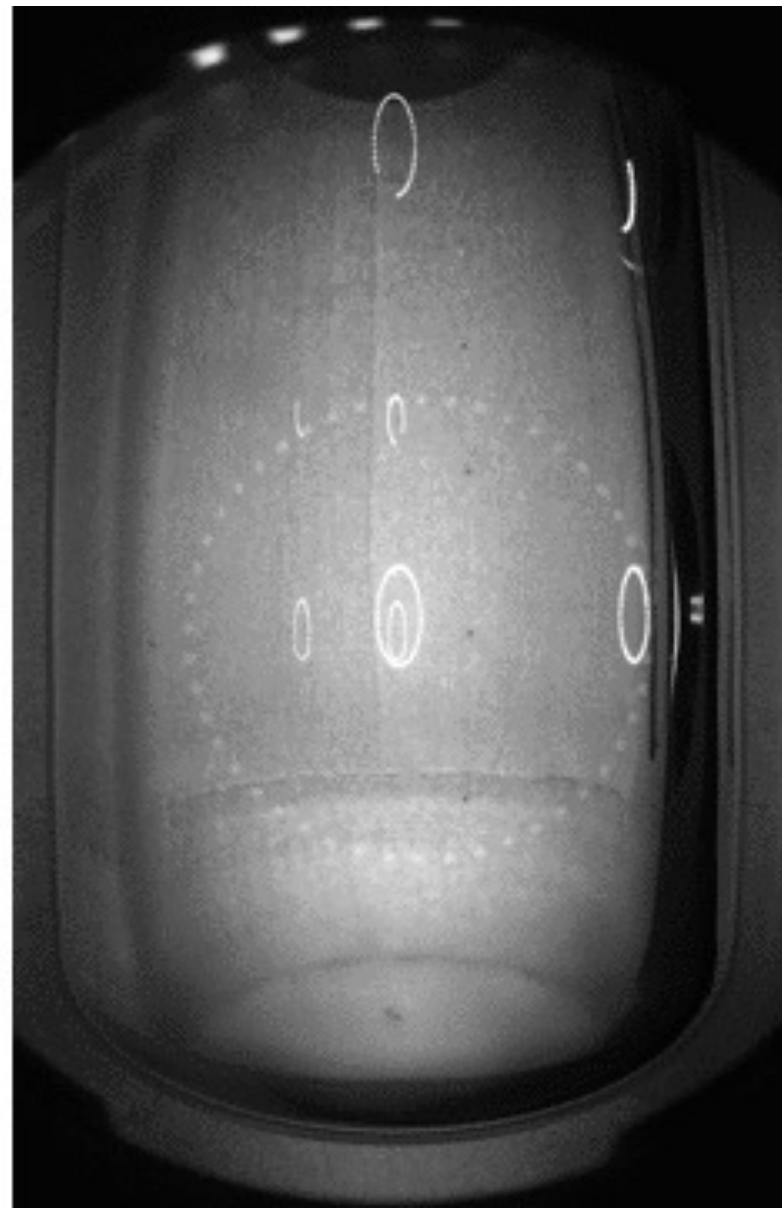
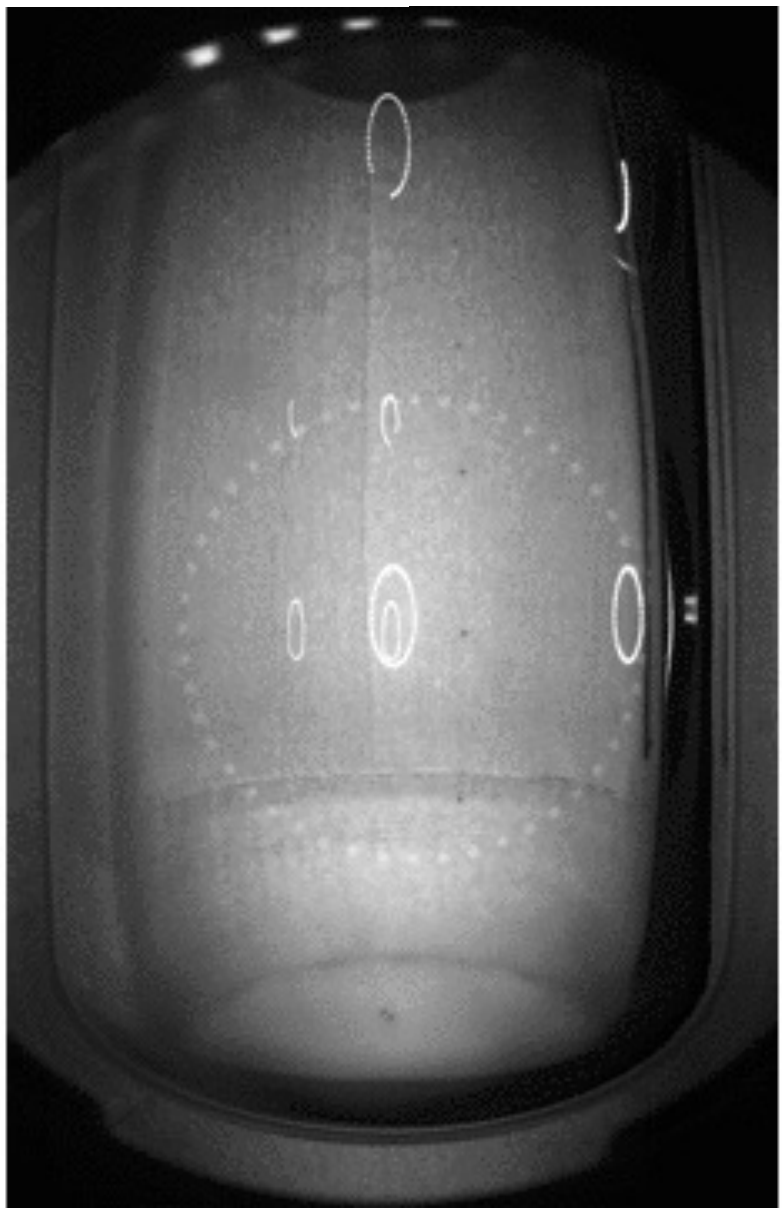




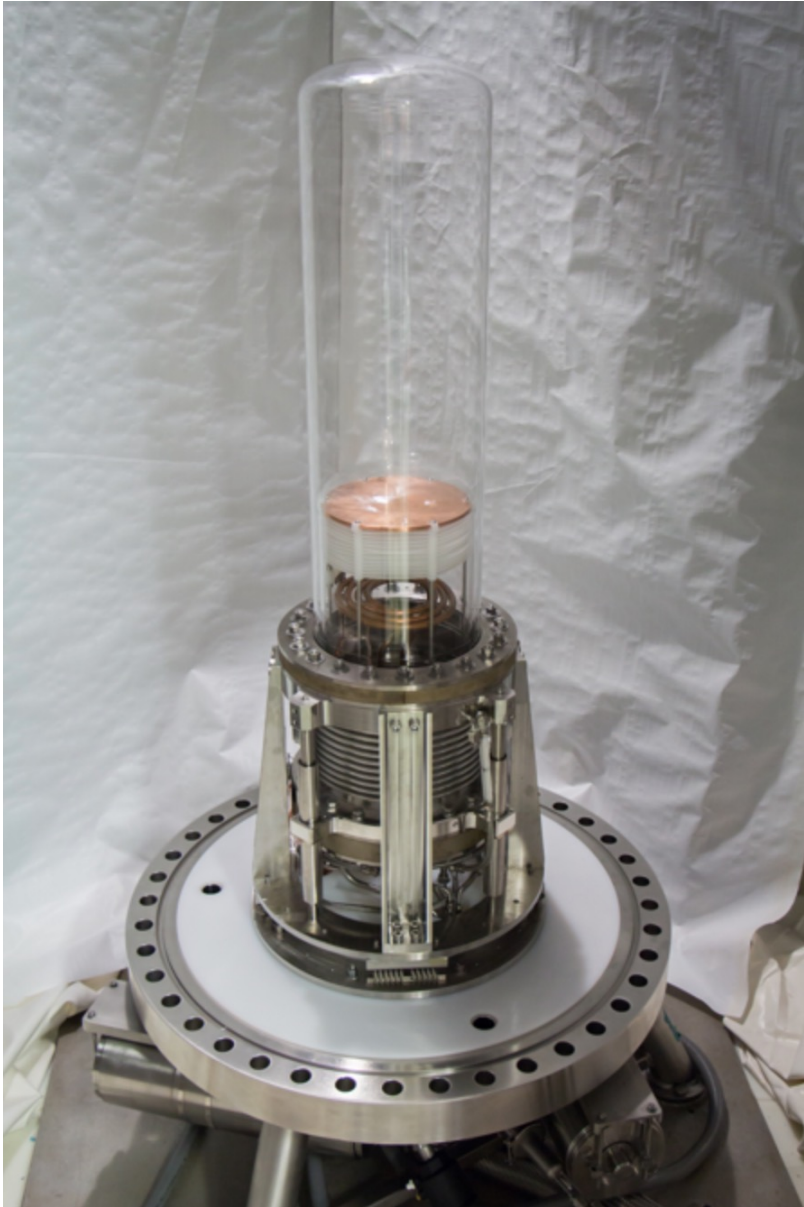




PICO



PICO



Summary

- Dark Matter is one of the great mysteries of our time
- Attempting to detect dark matter requires specialized experiments in dedicated underground laboratories
- Canada's SNOLAB hosts a number of leading dark matter search experiments