# Shedding Light

# On The Dark Universe

Summer Lectures Club - Guelph
May 10TH, 2021

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# Outline

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

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

# First Evidence for Dark Matter

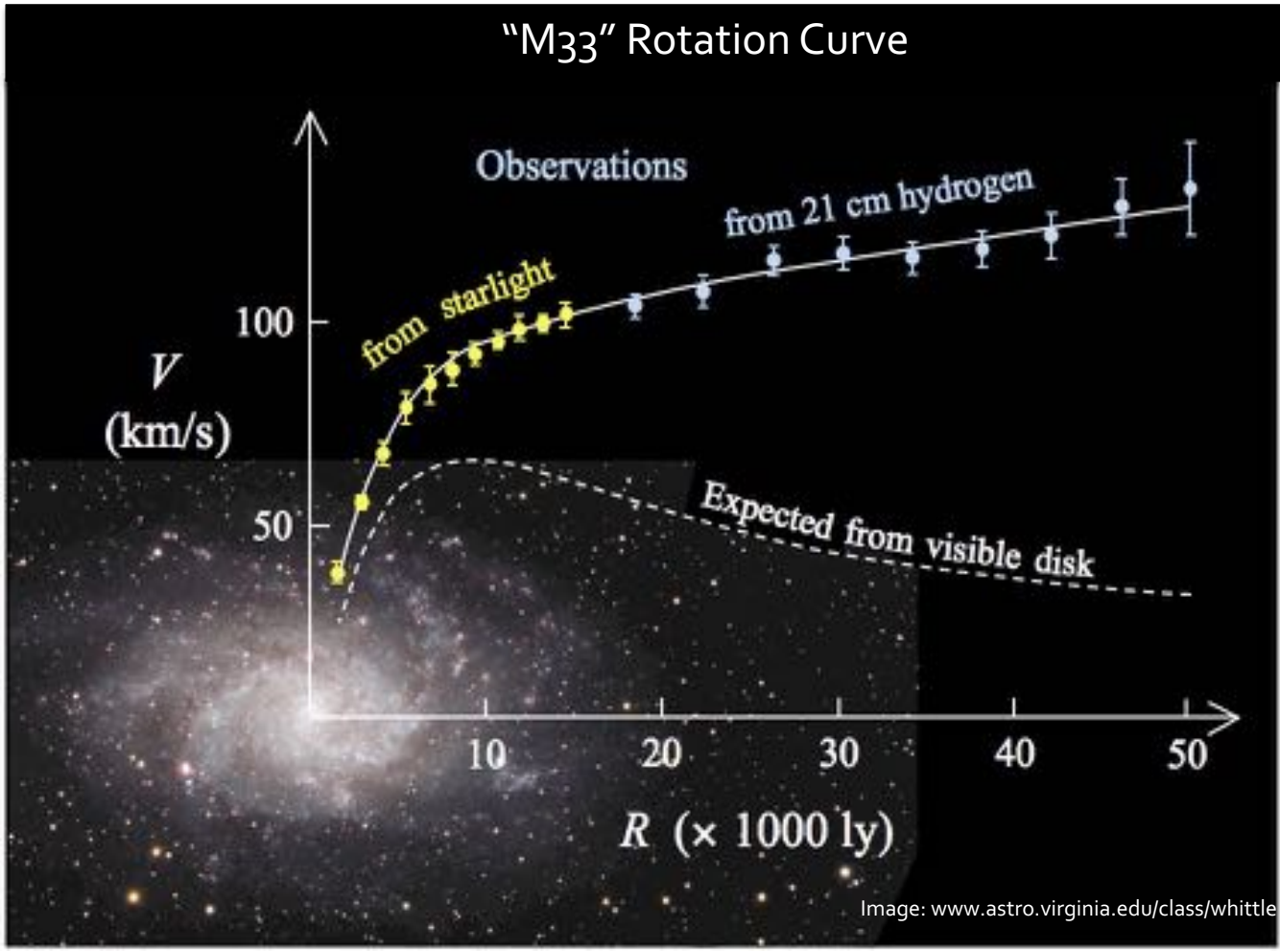
In 1933 Fritz Zwicky used the relative motions of the galaxies in the Coma Cluster to infer the cluster mass

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

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

# "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 ≈ 0.3 GeV/$c^2$/$cm^3$
  - 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 $v_{orbit}$ ≈ 220 km/s

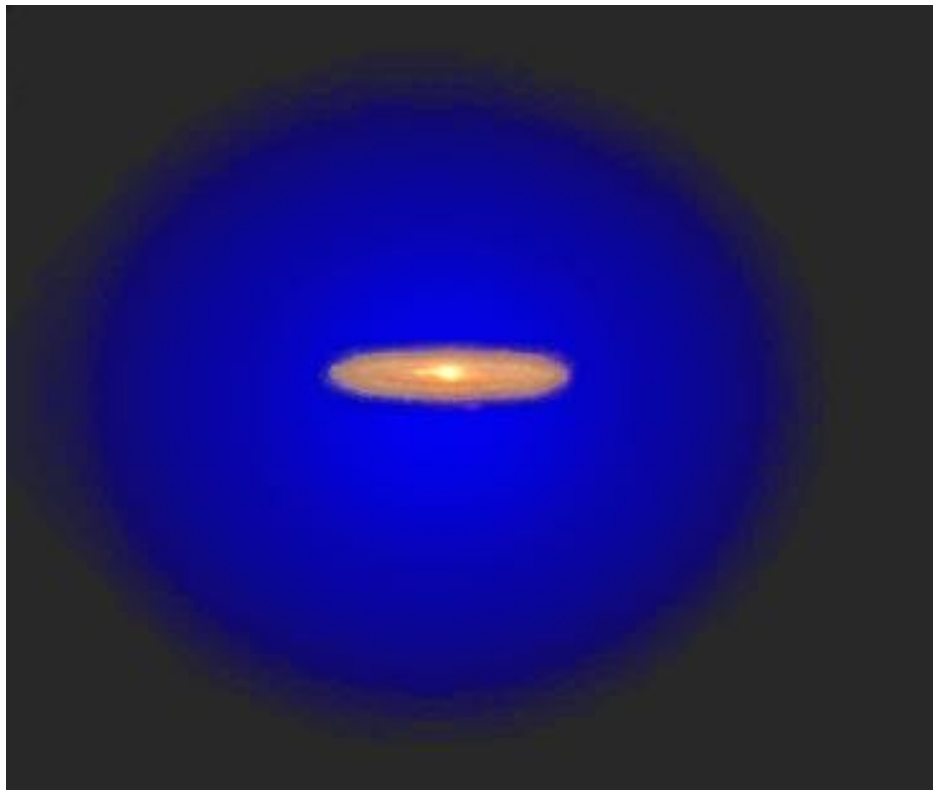


Image credit: J. Kormendy, chandra.as.utexas.edu/~kormendy

# 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

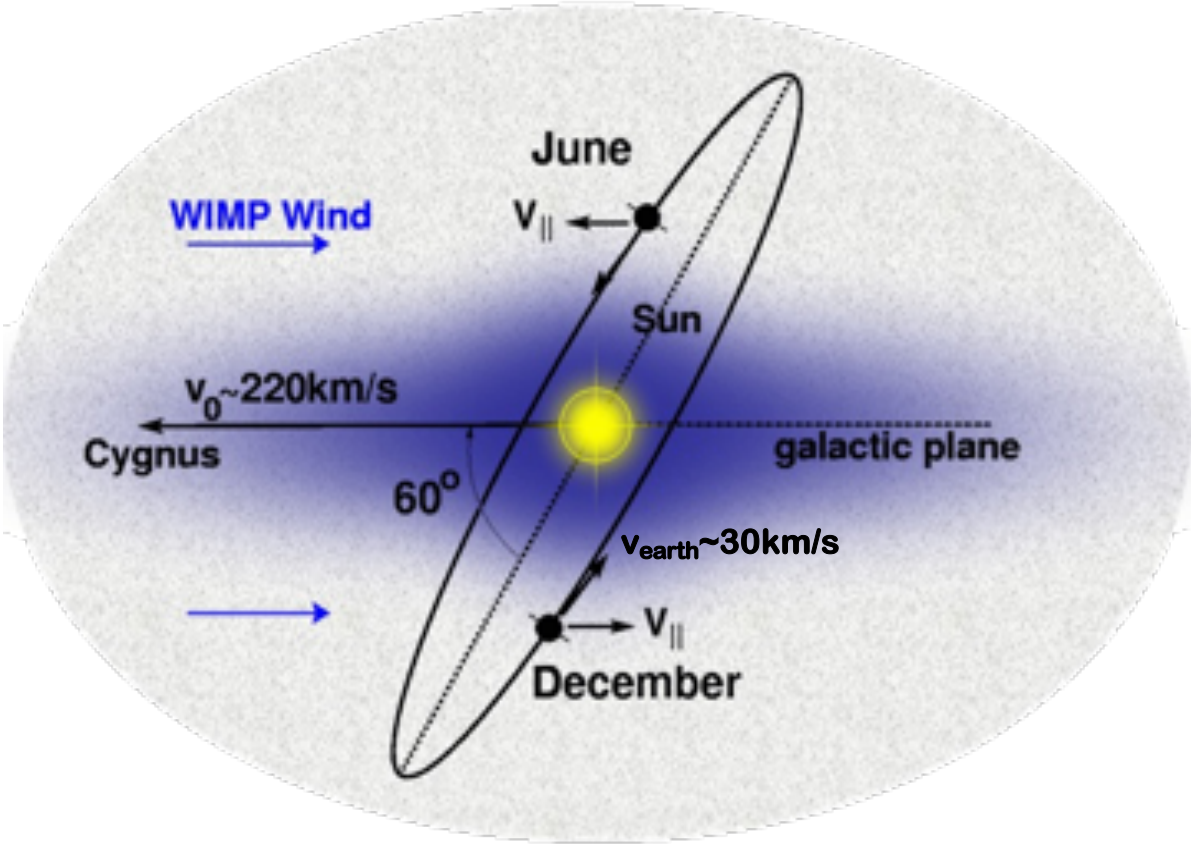
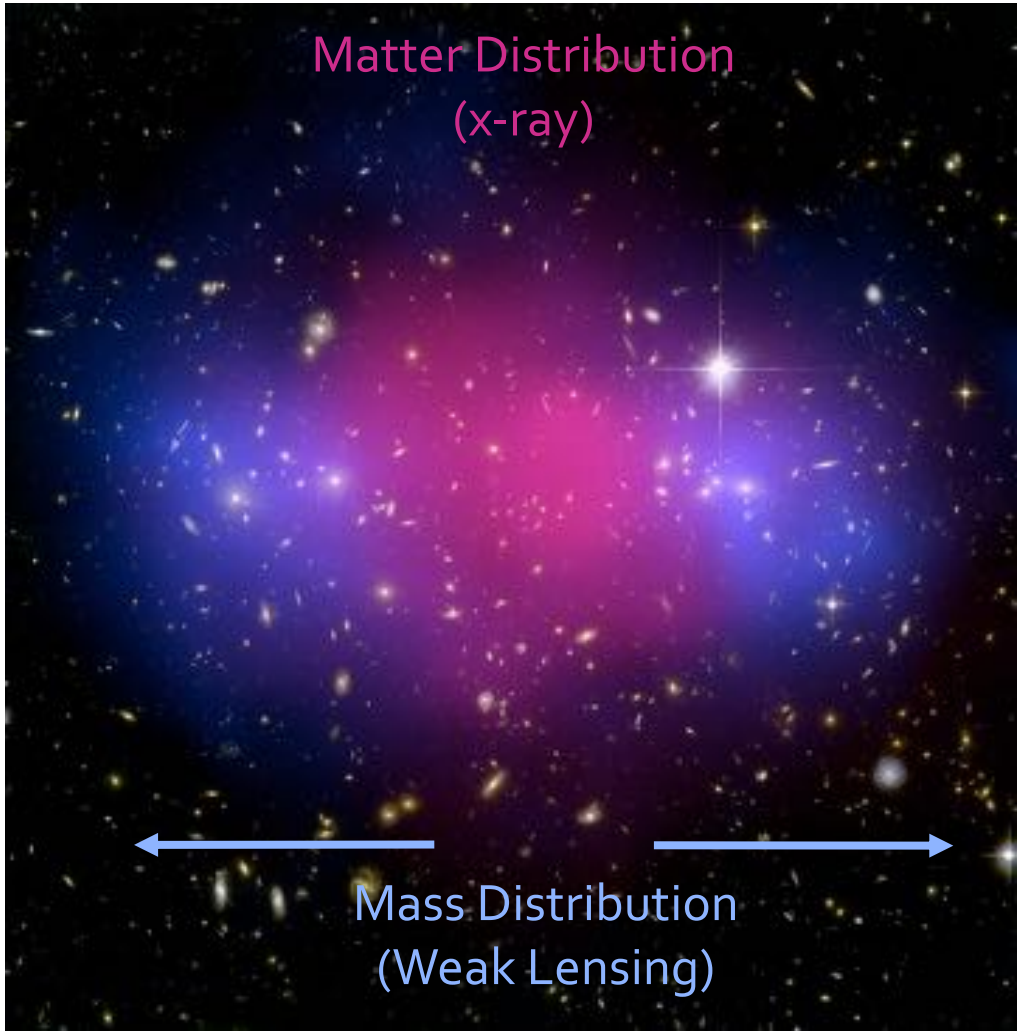



Image credit: www.hep.shef.ca.uk/research/dm/intro.php

# 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

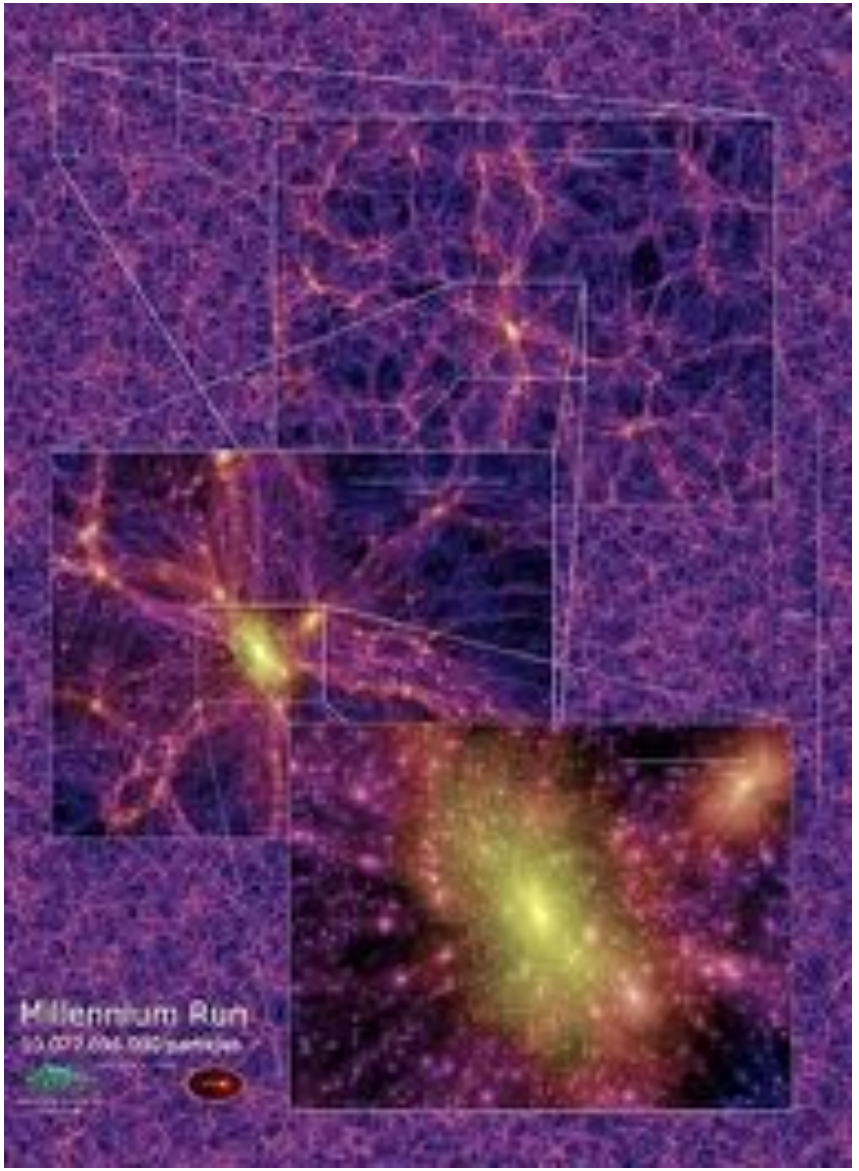
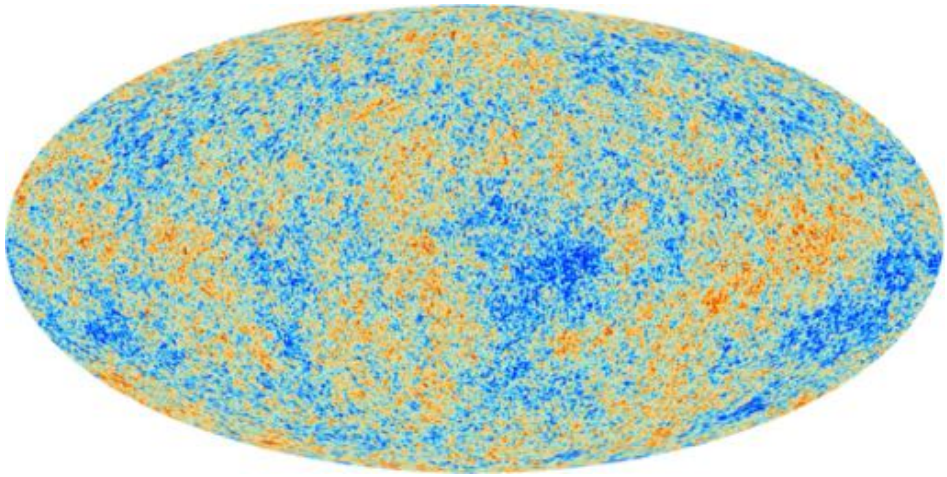
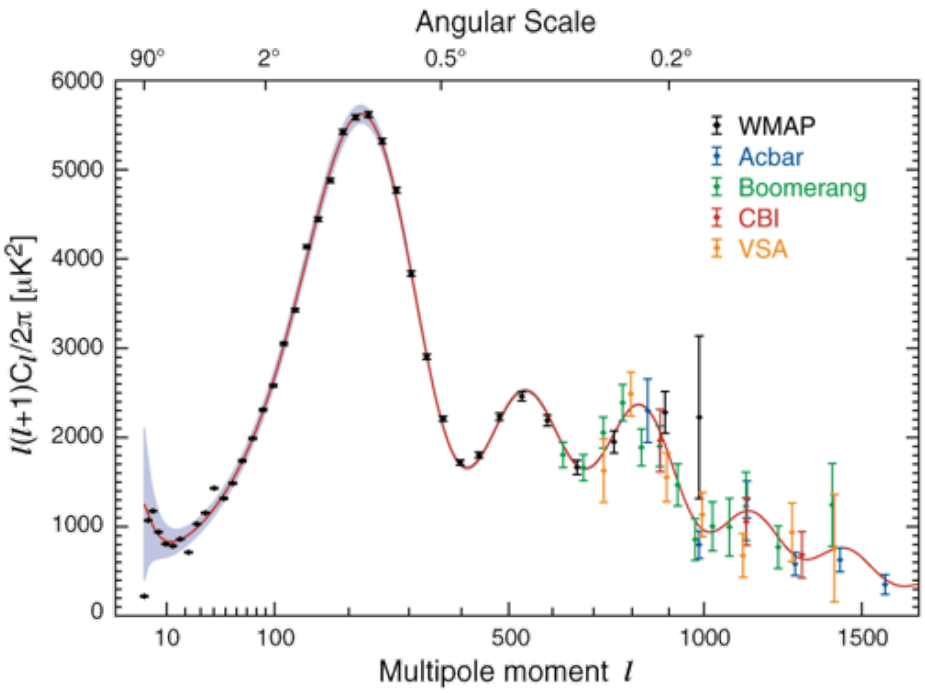



Image credit: http://www.mpa-garching.mpg.de/galform/millennium/, astro-ph/0504097

# The Cosmic Microwave Background Radiation





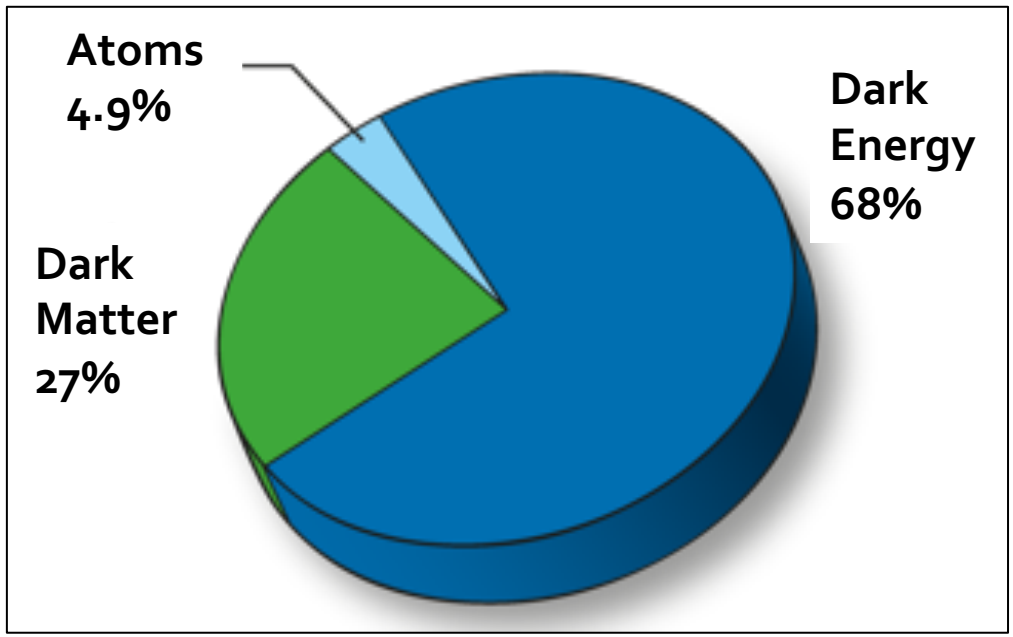
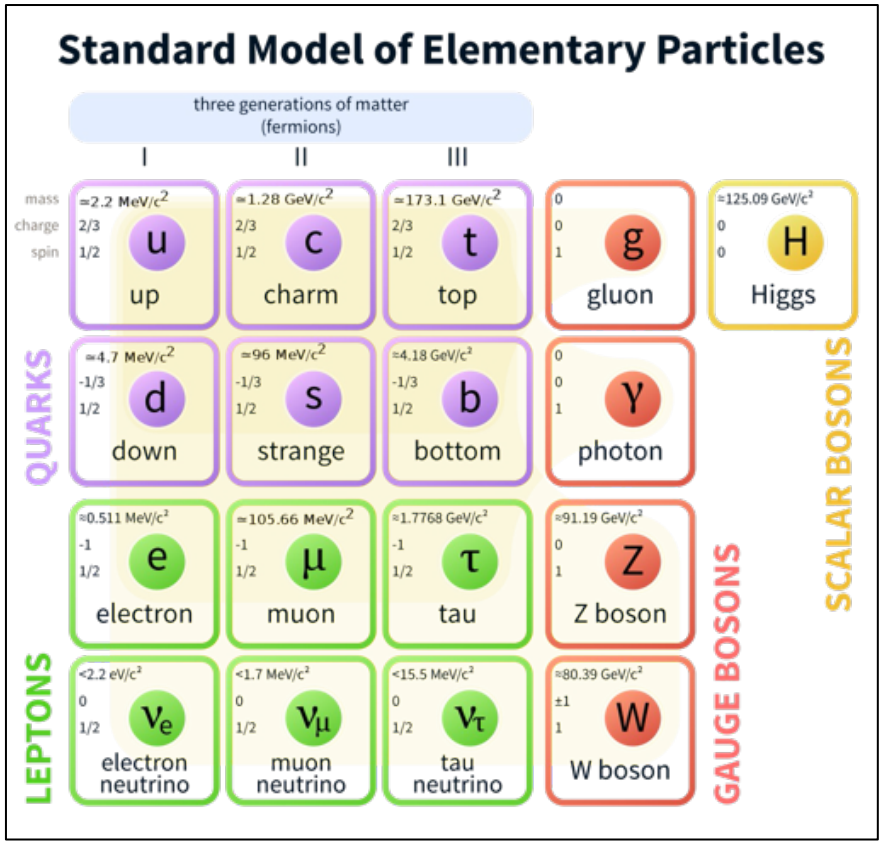




Image credits: WMAP Science Team, NASA, ESA AND THE PLANCK COLLABORATION

# 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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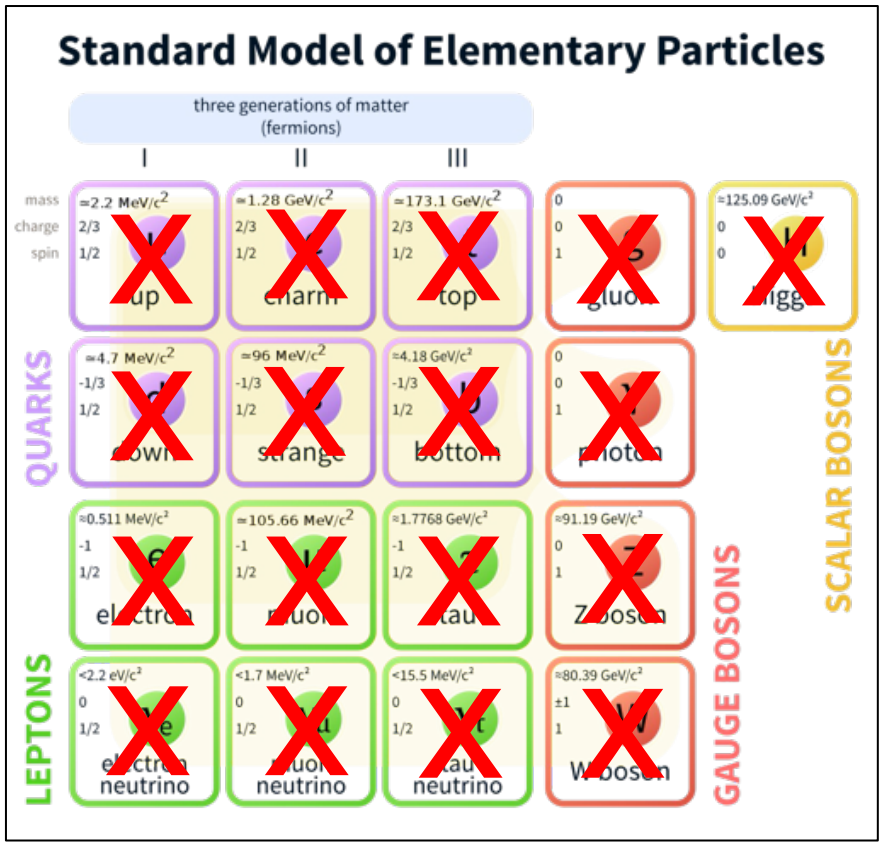



***This excludes all known elementary particles: most of the Universe is made of something entirely new!***

# Dark Matter Candidates

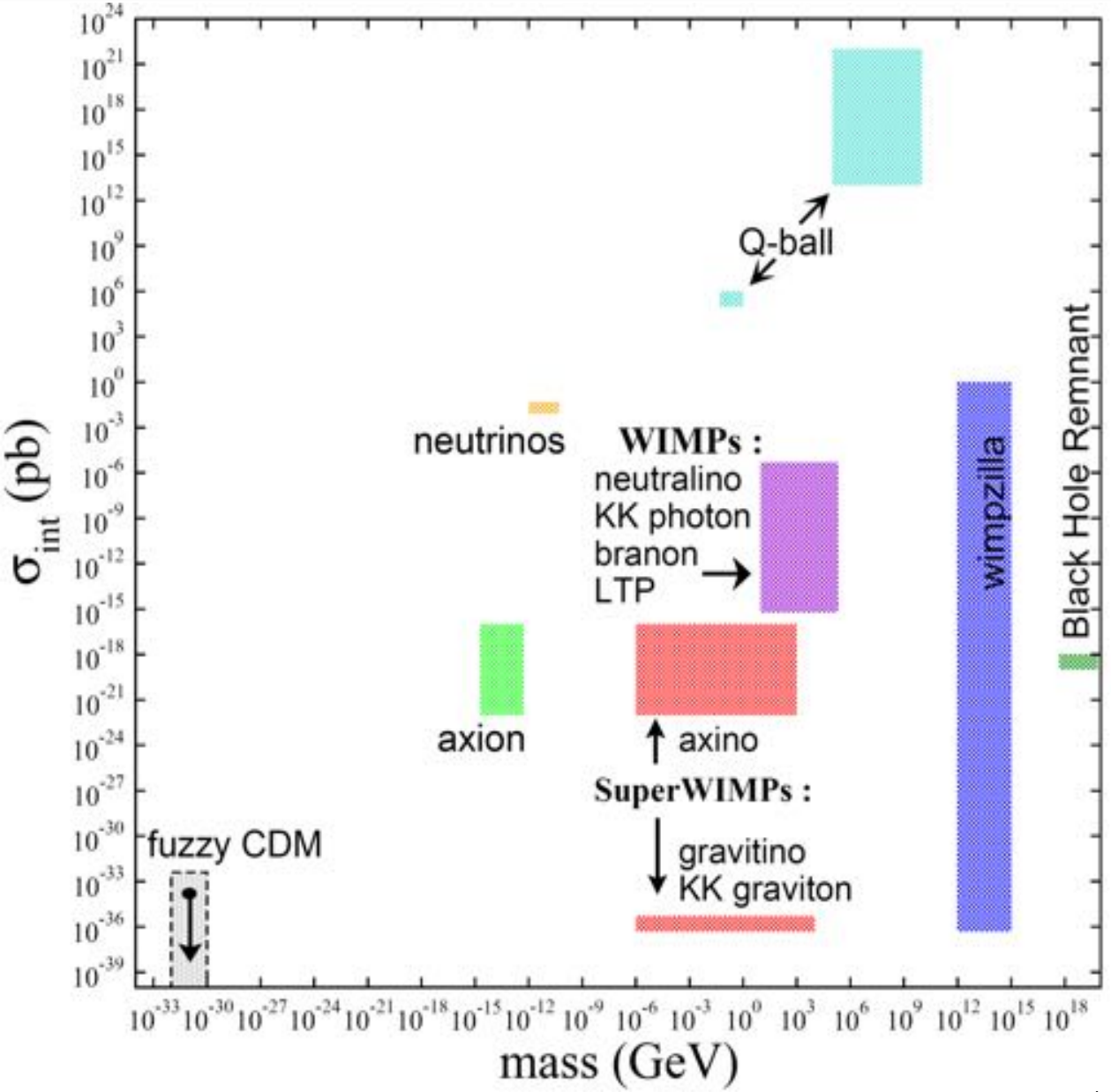
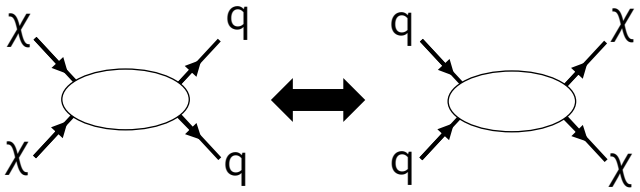


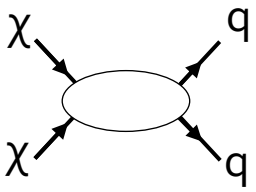

Image credit: HEPAP/AAAC DMSAG Subpanel (2007)

# "Weakly Interacting Massive Particles" - Thermal Relics

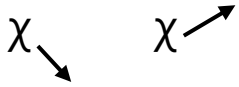
1) WIMPs are produced in thermal equilibrium

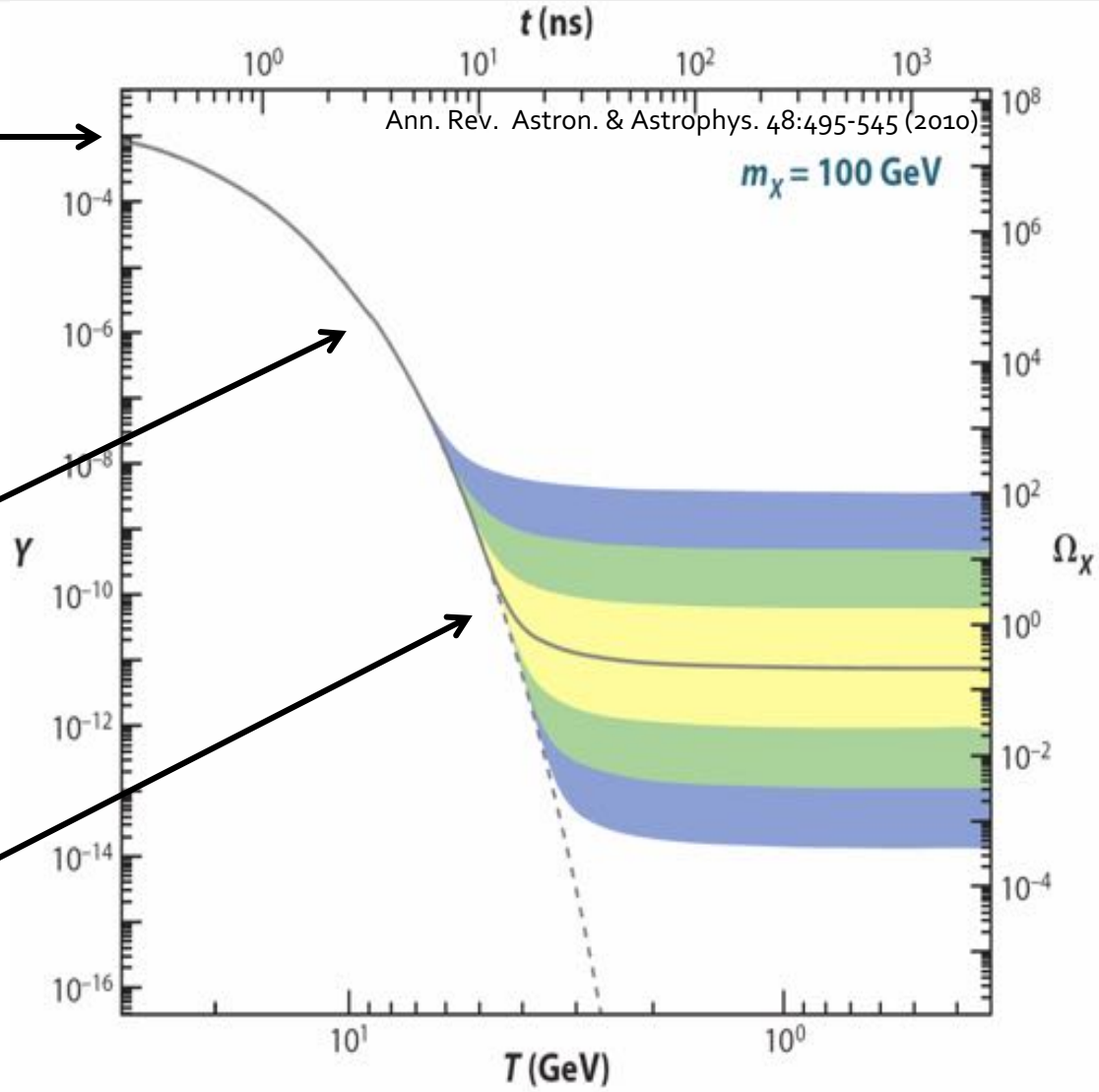



2) WIMP density decays as the universe cools



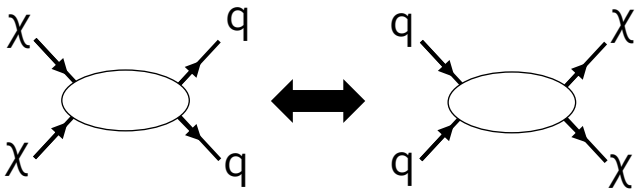

3) WIMP density "freezes out" based on coupling strength



# The "WIMP Miracle"

1) WIMPs are produced in thermal equilibrium

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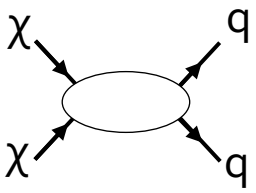


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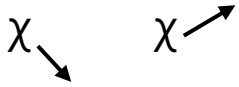
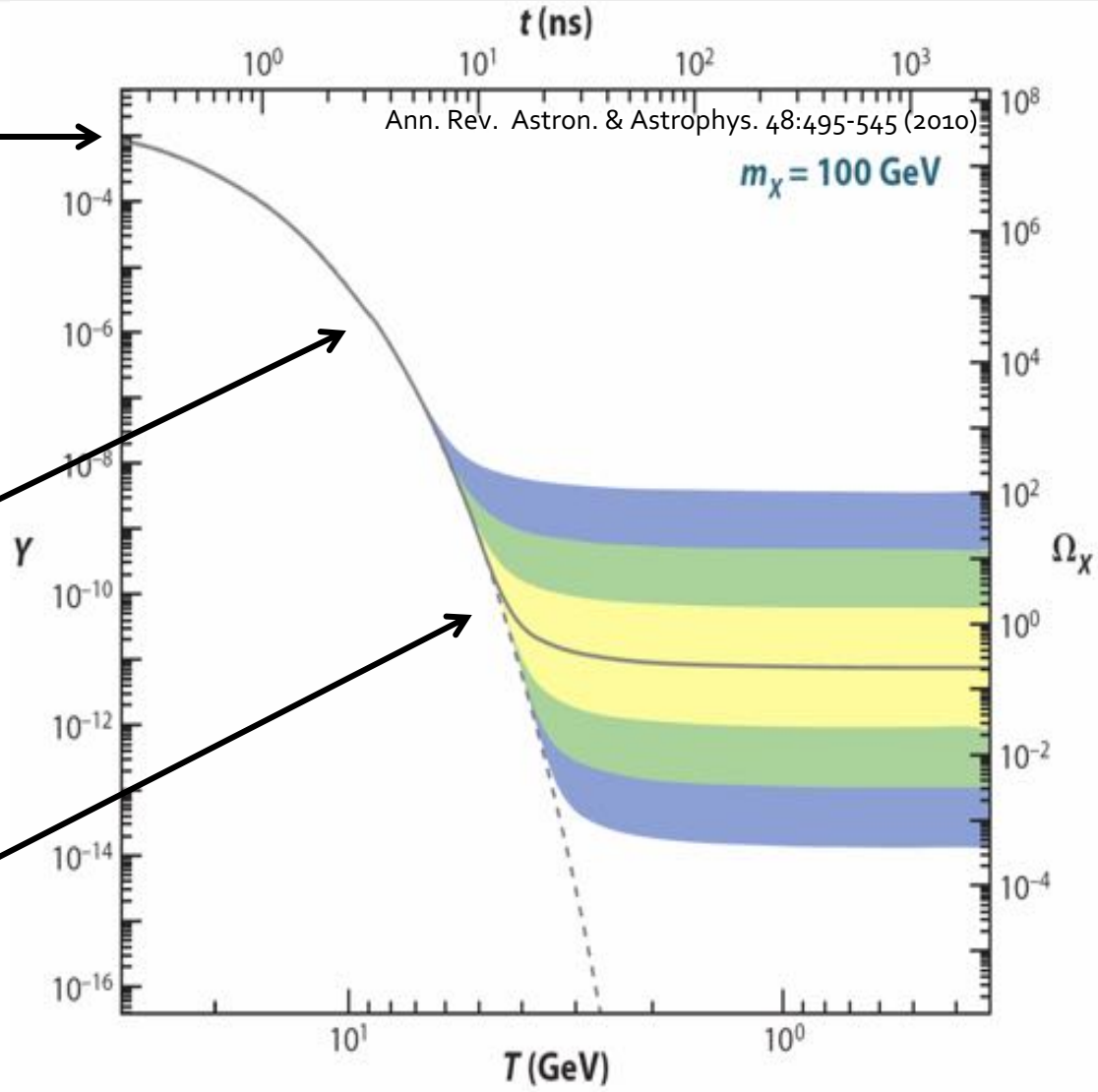
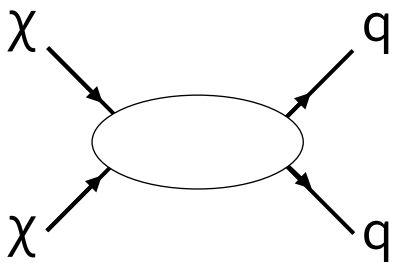


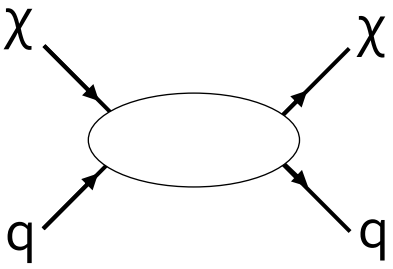

***Weak mass & coupling give just the right relic density for dark matter!***

# Searching for Dark Matter

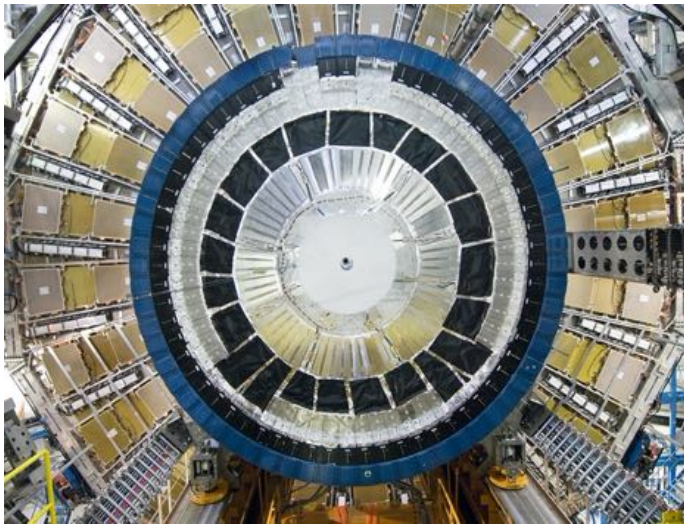
Aboveground




Underground




At Accelerators



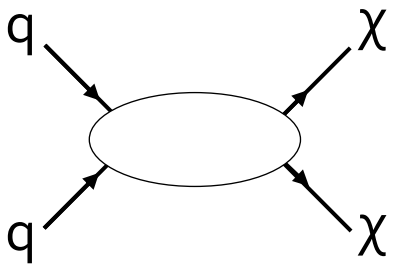
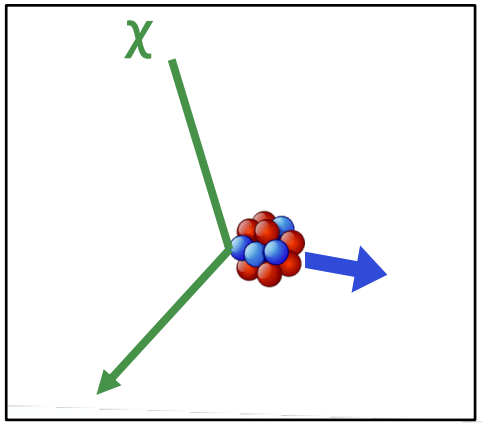



Image credits: NASA, discovermagazine.com, atlas.ch

# 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 (<~100 keV) nuclear recoils
- Current experiments are searching for at the level of ~1 interaction/tonne/yr



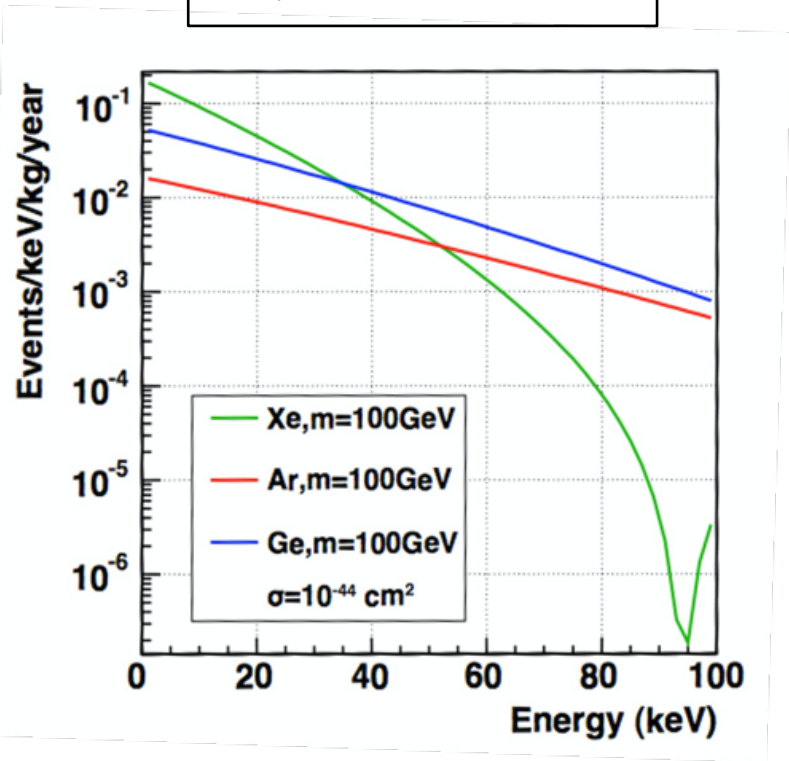
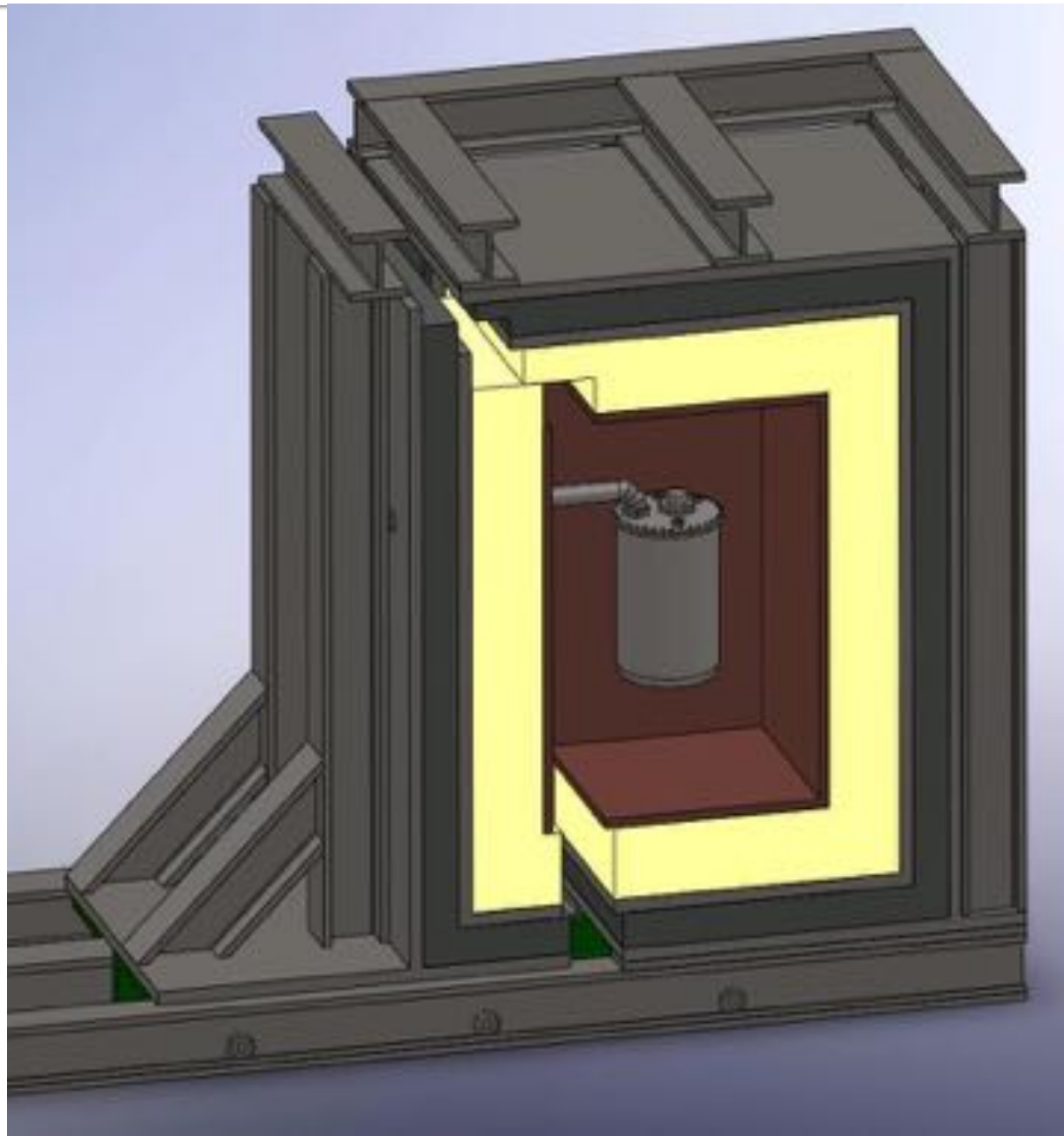



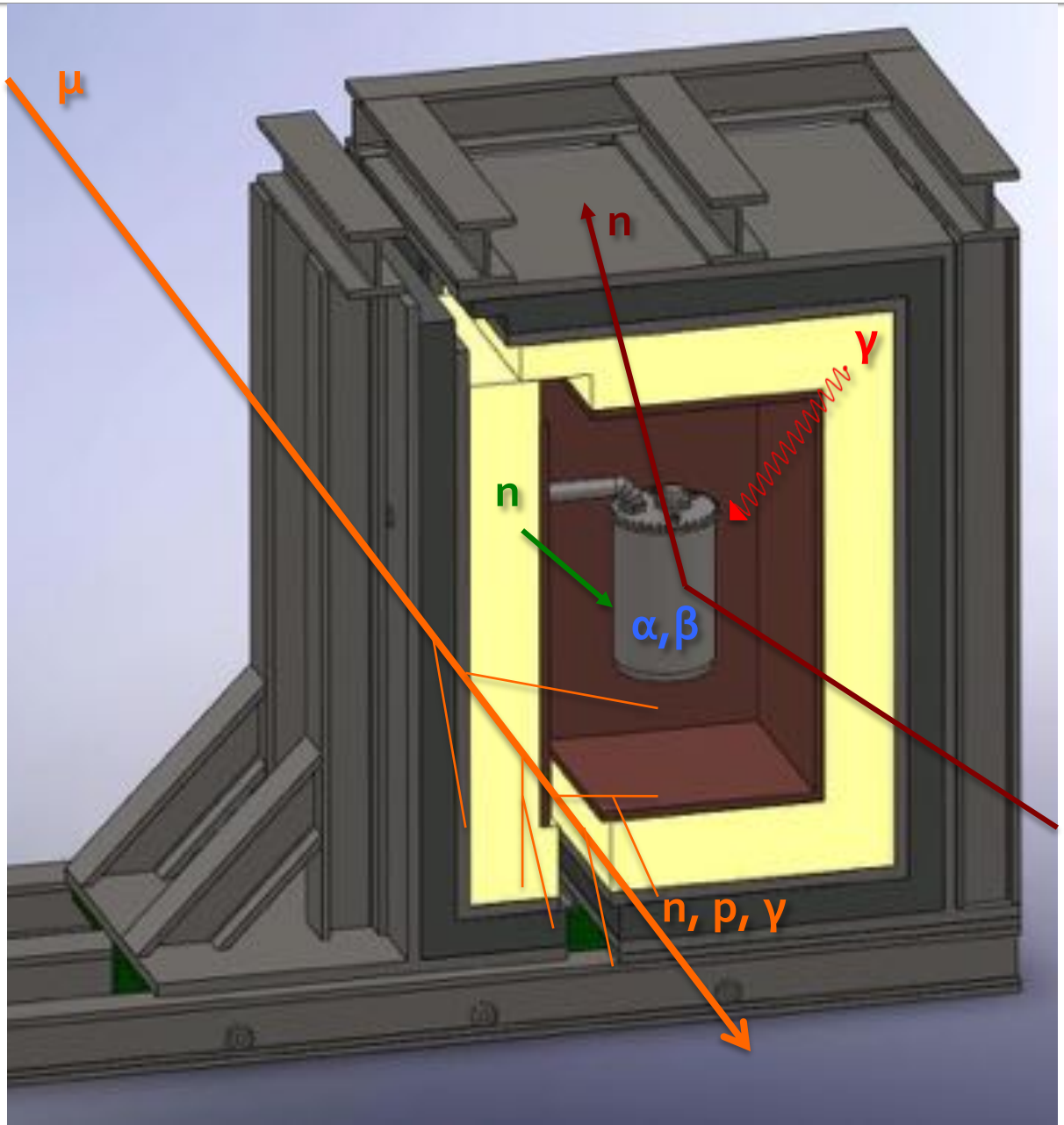

Image credit:777icons.com

# 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

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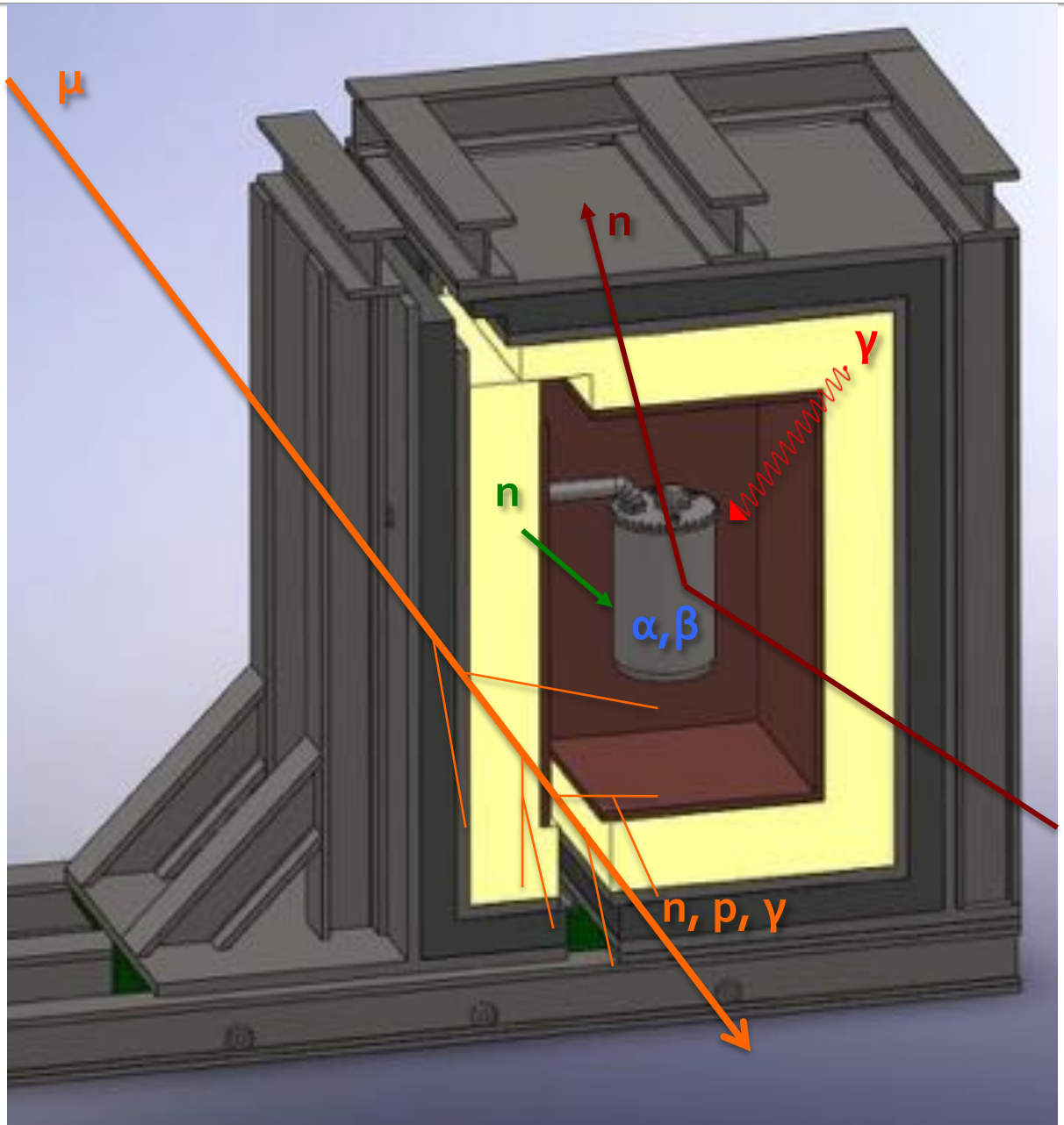


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WIMP signal: <1 ev/T-yr

Dust: ~7000 signals/mg-yr

Air: >300 signals/mL-yr

Fingerprint: ~10 signals/yr

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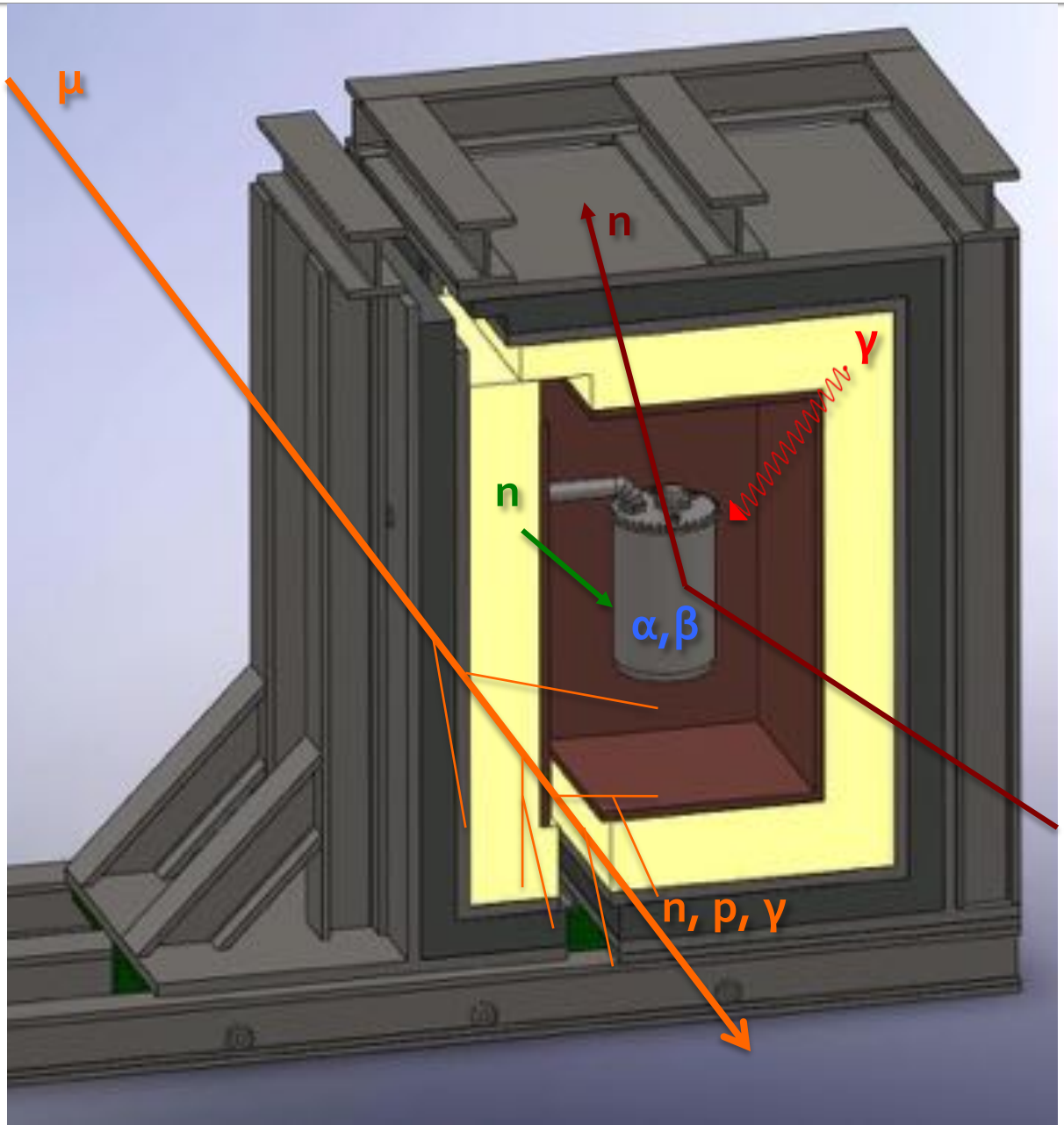


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Image from https://astro.fnal.gov/science/dark-matter/supercdms/

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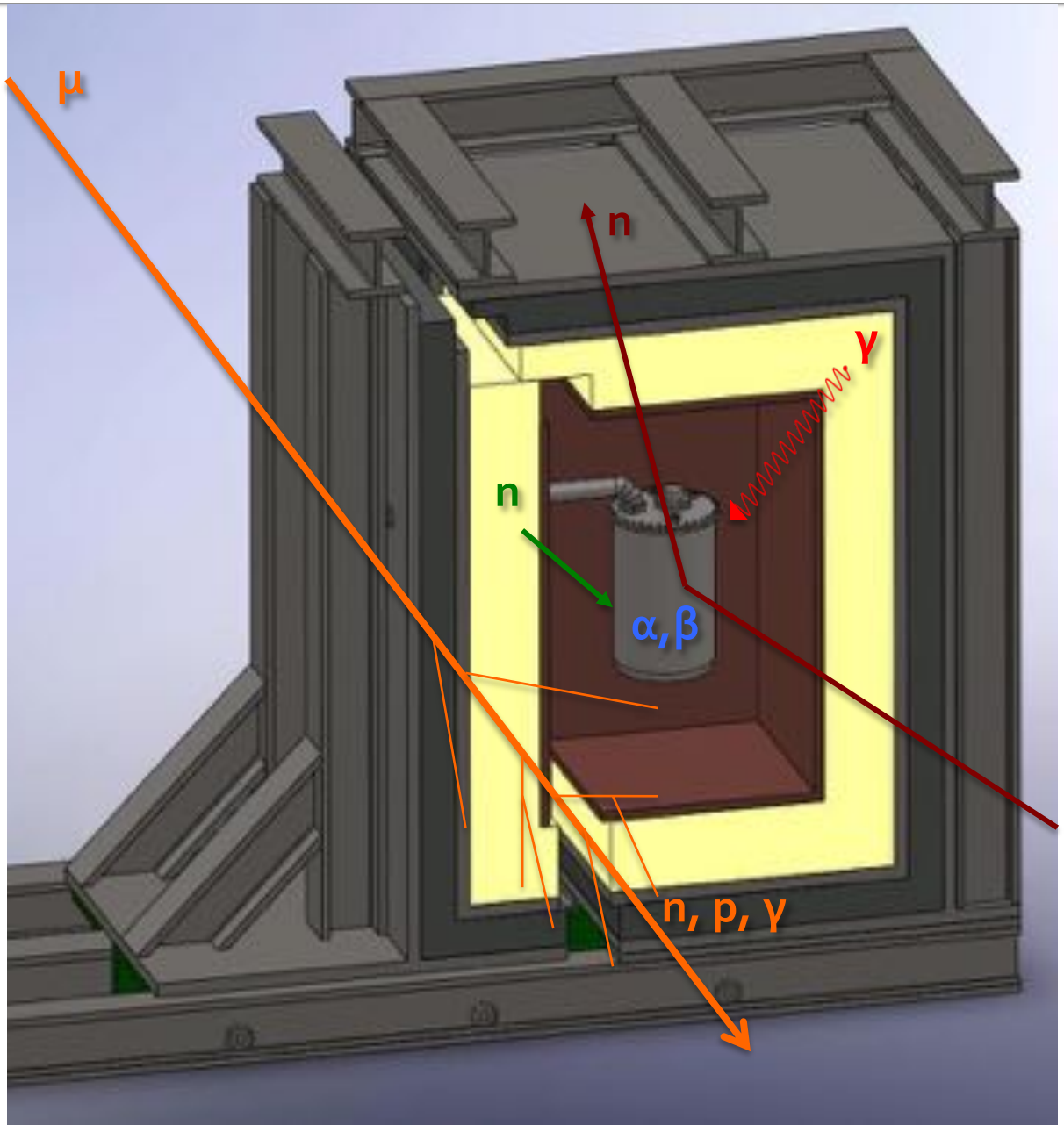


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from spontaneous fission and (α,n), externally and in shielding

Cosmic Muons

Fast Neutrons

from muons in the shield and beyond

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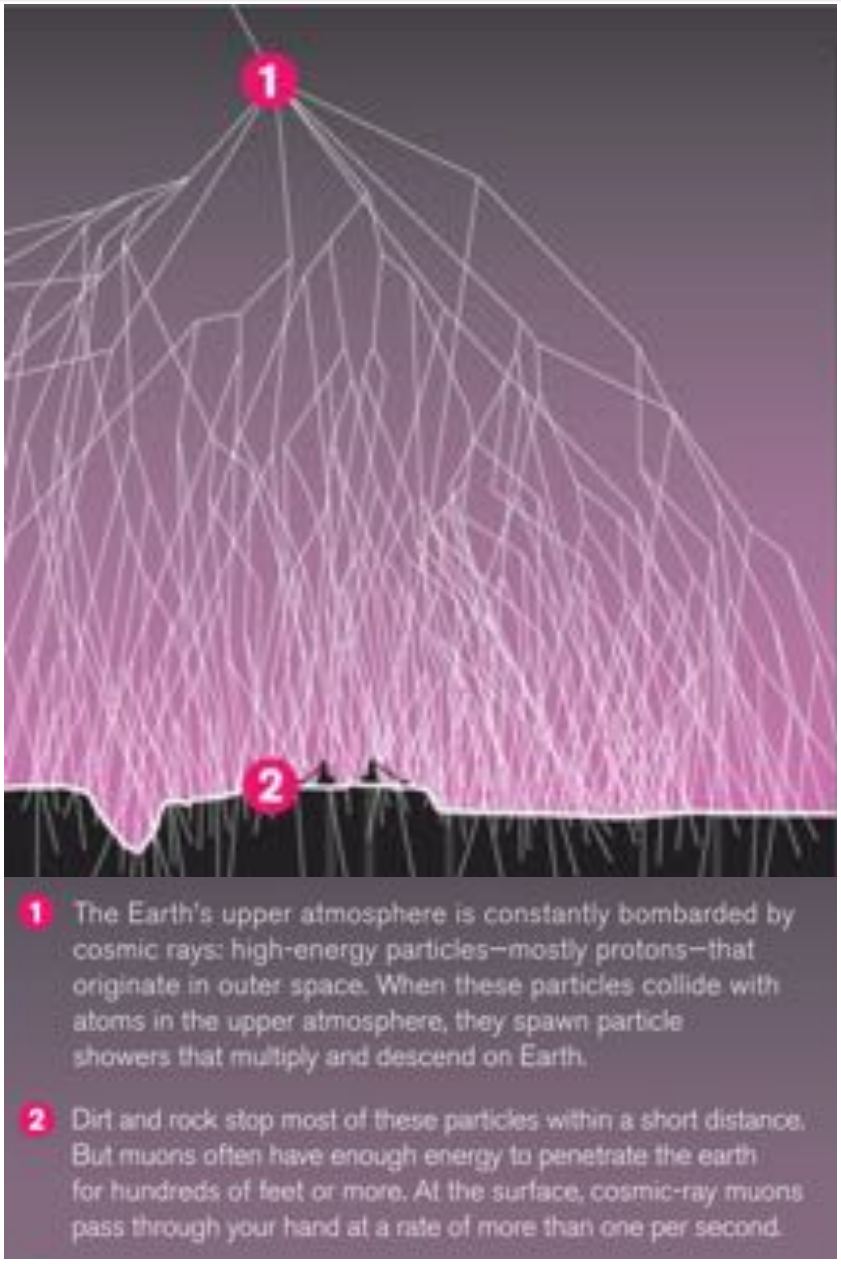


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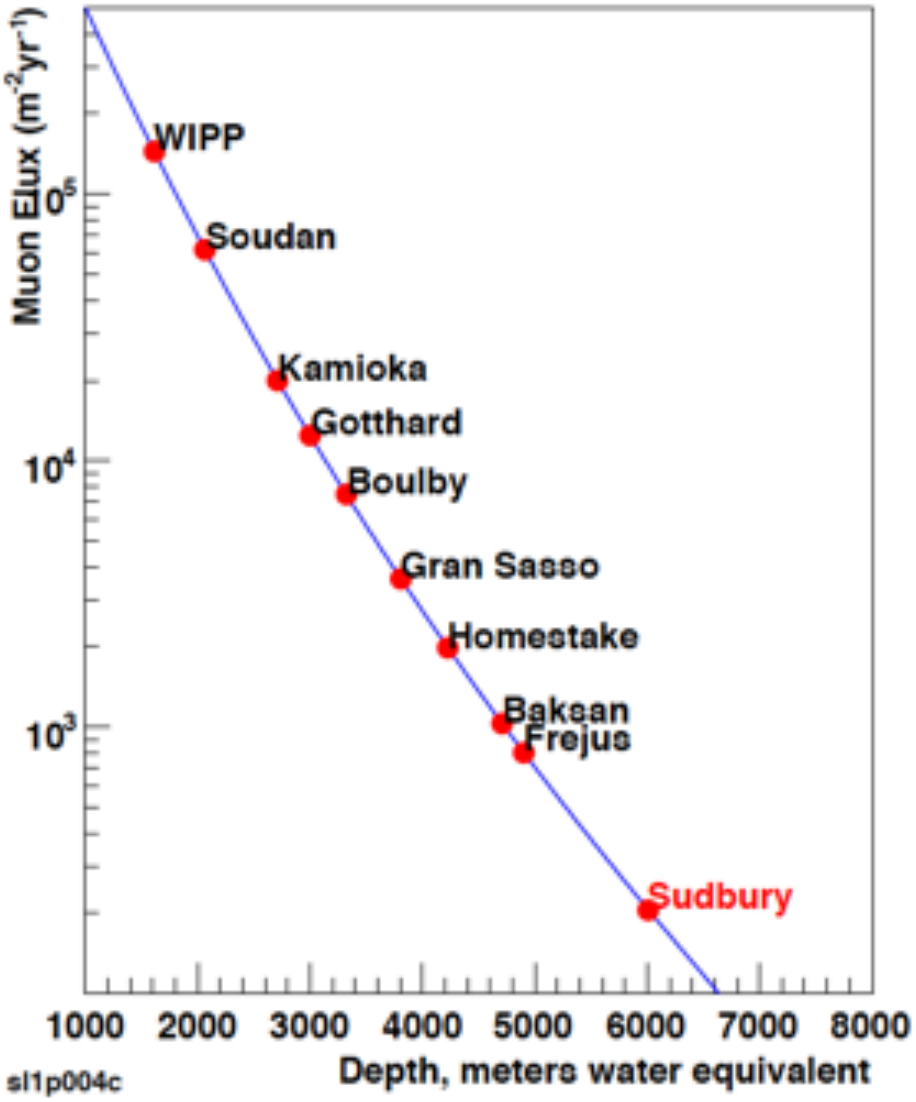
Image by Sanford Laboratory, www.symmetrymagazine.org

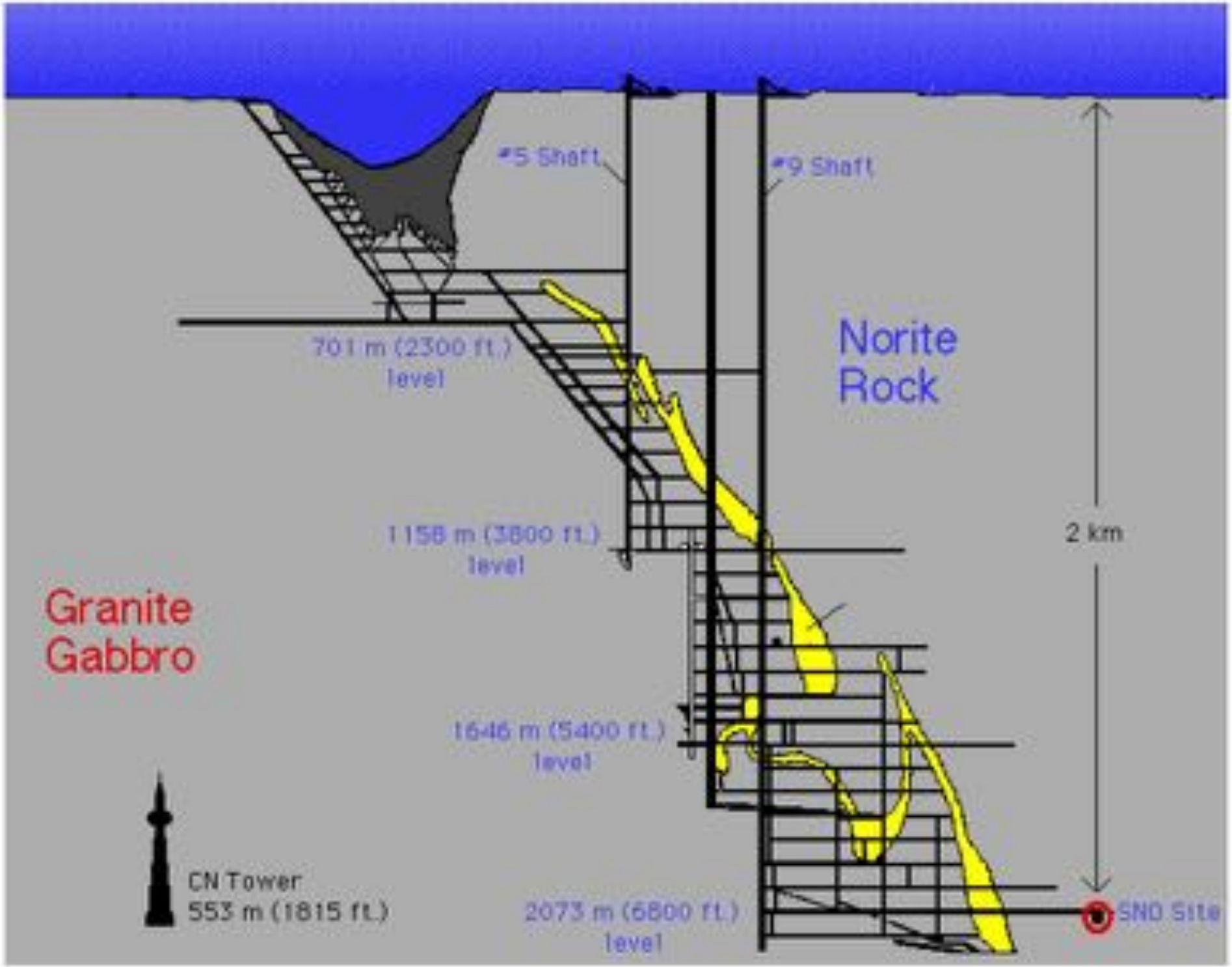
# Why an Underground Lab?

- 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!***


SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence


#5 Shaft
#9 Shaft
701 m (2300 ft.) level
1158 m (3800 ft.) level
1646 m (5400 ft.) level
2073 m (6800 ft.) level
Norite Rock
Granite Gabbro
2 km
CN Tower
553 m (1815 ft.)
SNO Site


SNO
LAB

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


SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

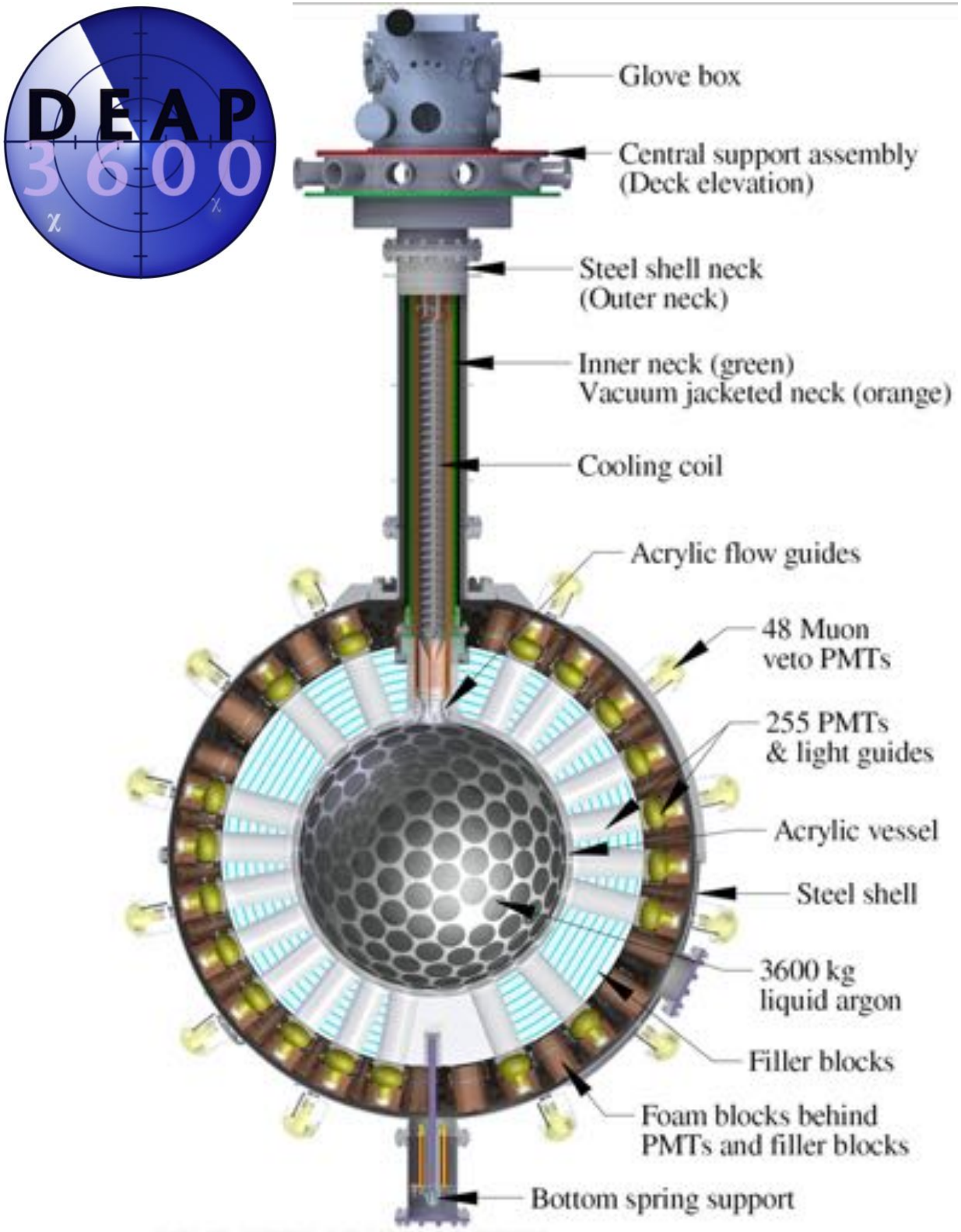

SNOLAB


CUBE HALL
DEAP-3600
MiniClean
NEWS-G


CORROSIVES

# Searching for Dark Matter at SNOLAB



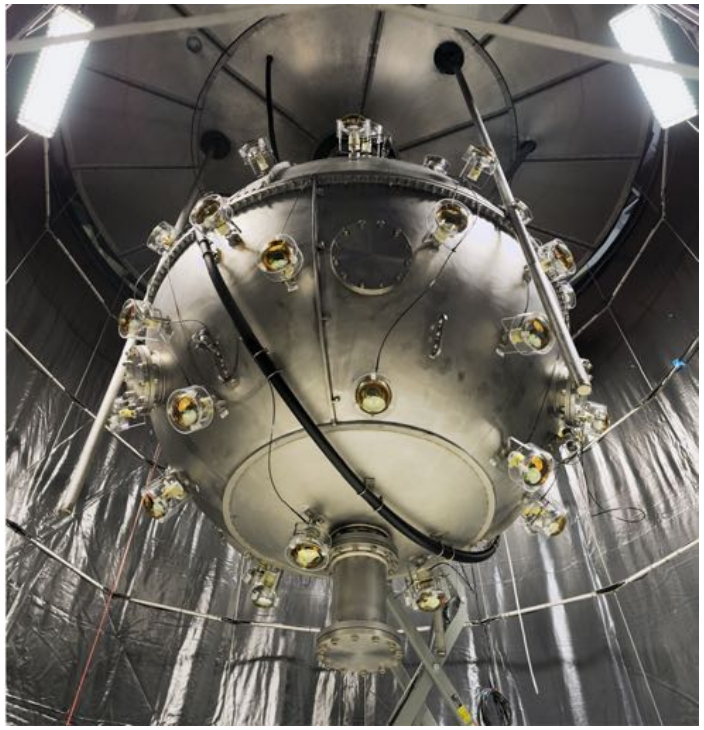
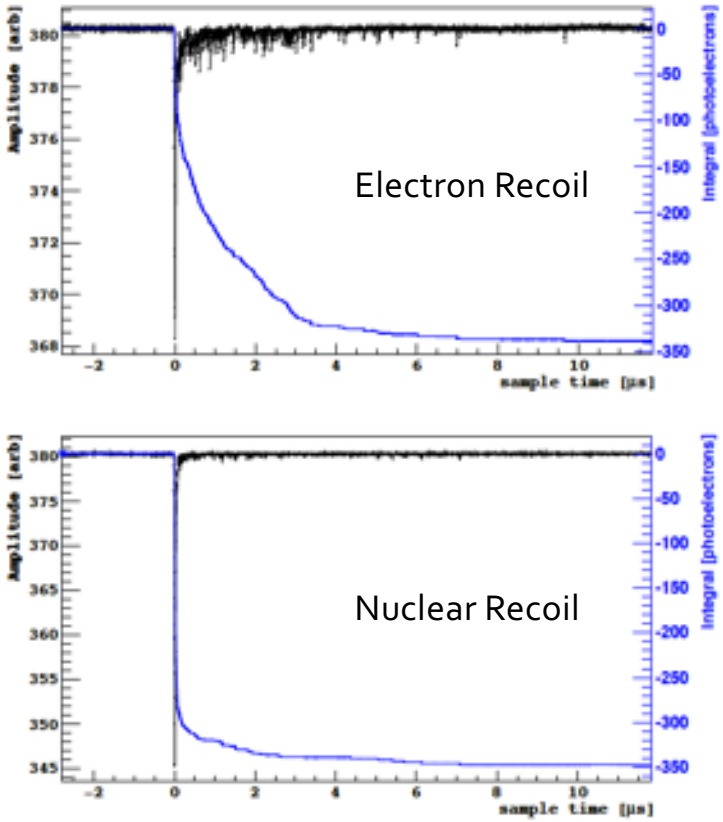
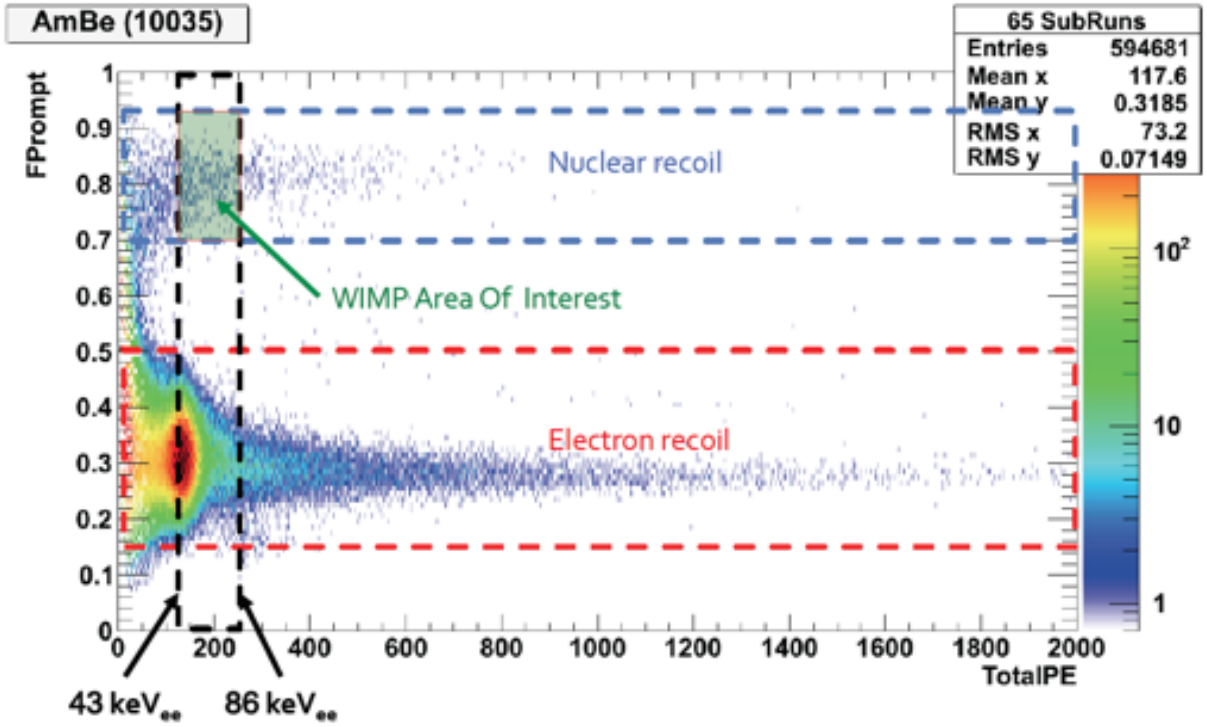



Image credit: deap3600.ca

# "Pulse Shape Discrimination"

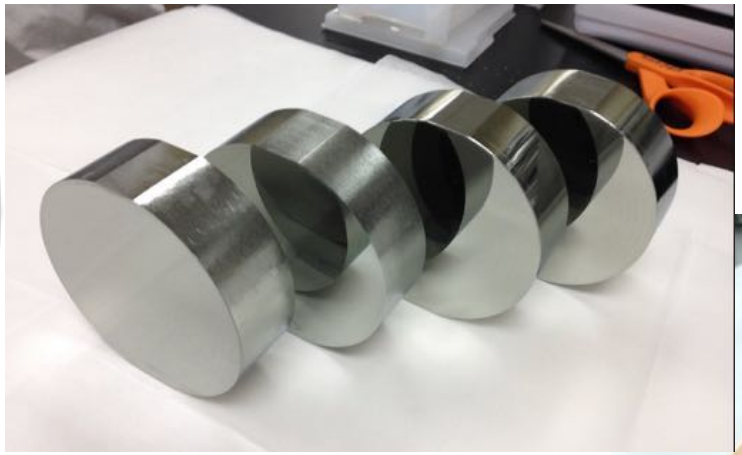


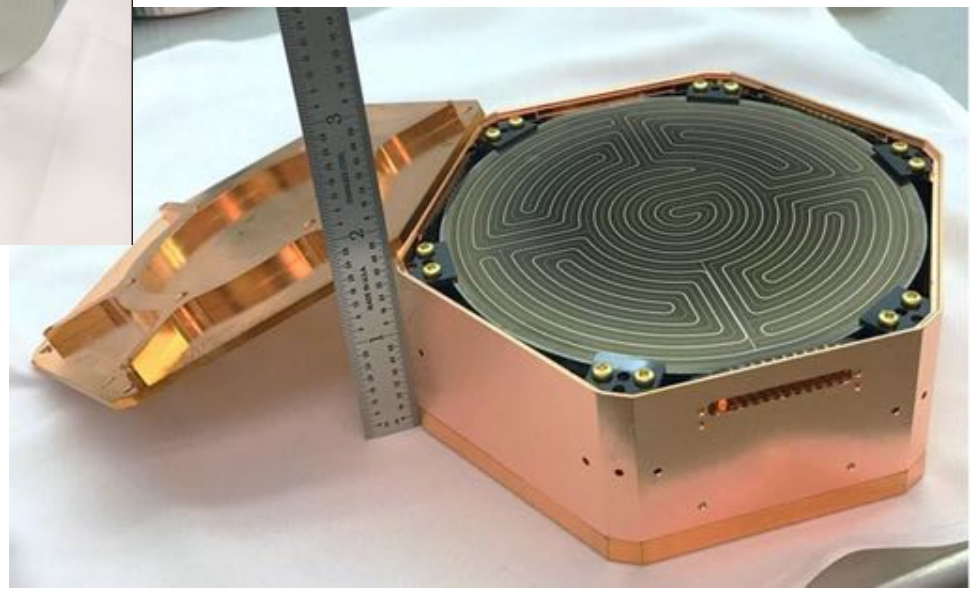



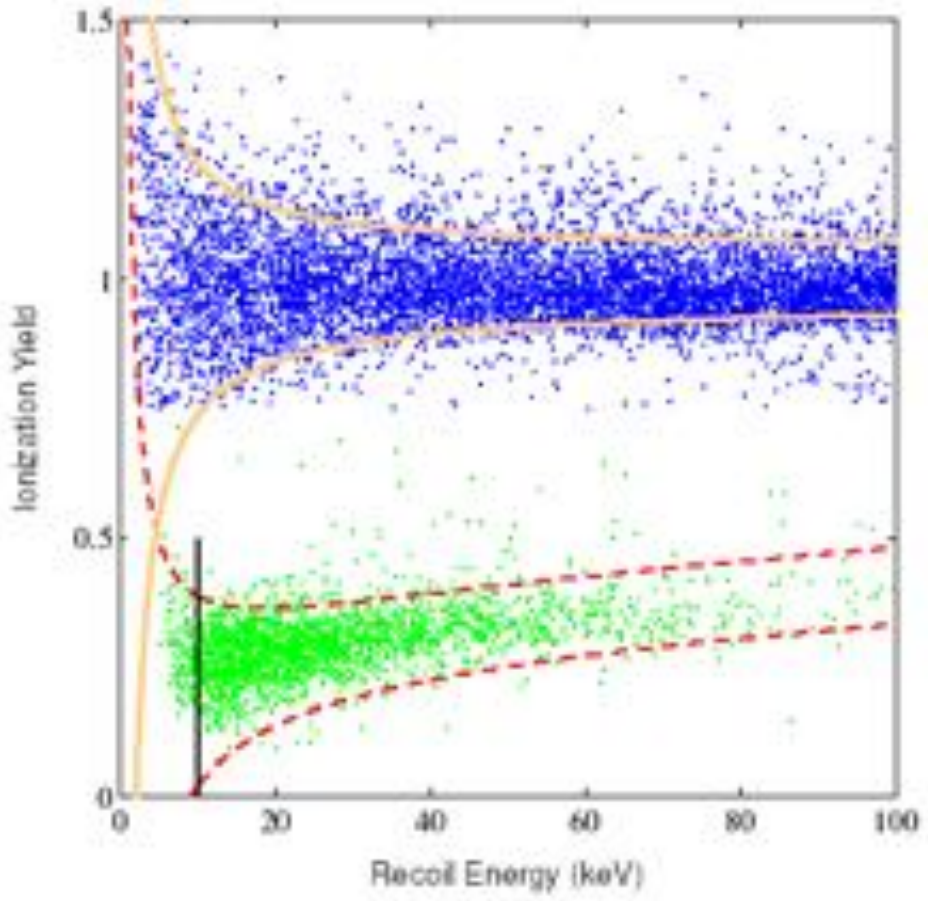

- The ratio of light from singlet (~7 ns decay time) and triplet (1.6 μs decay time) depends on particle type

  ➡ *>$10^8$ electron/nuclear recoil discrimination*

Image credit: deap3600.ca





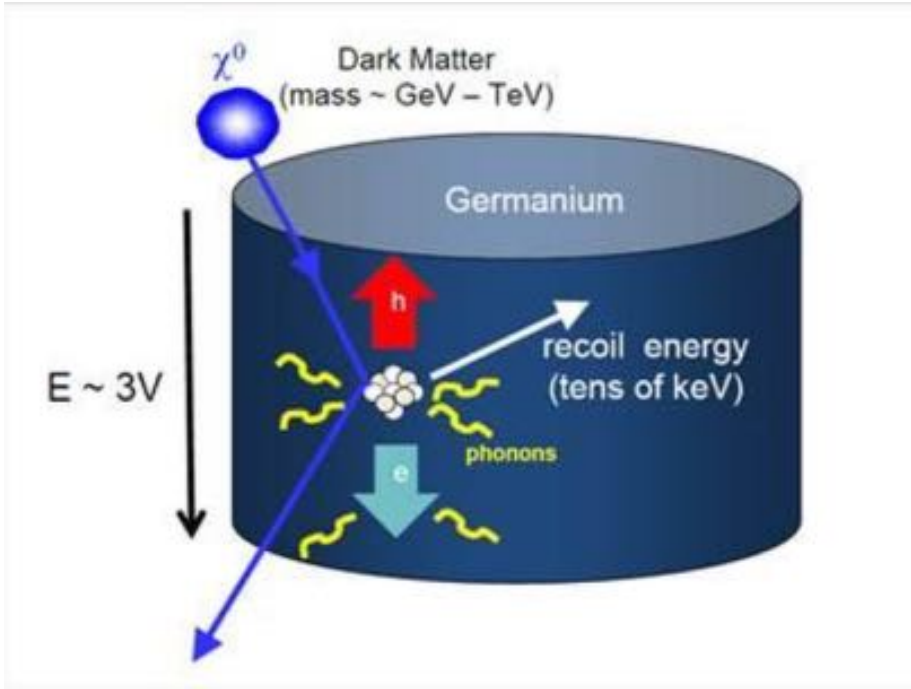
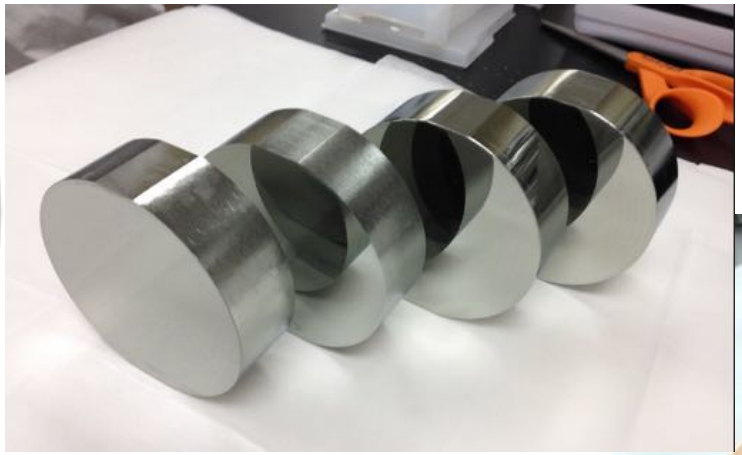
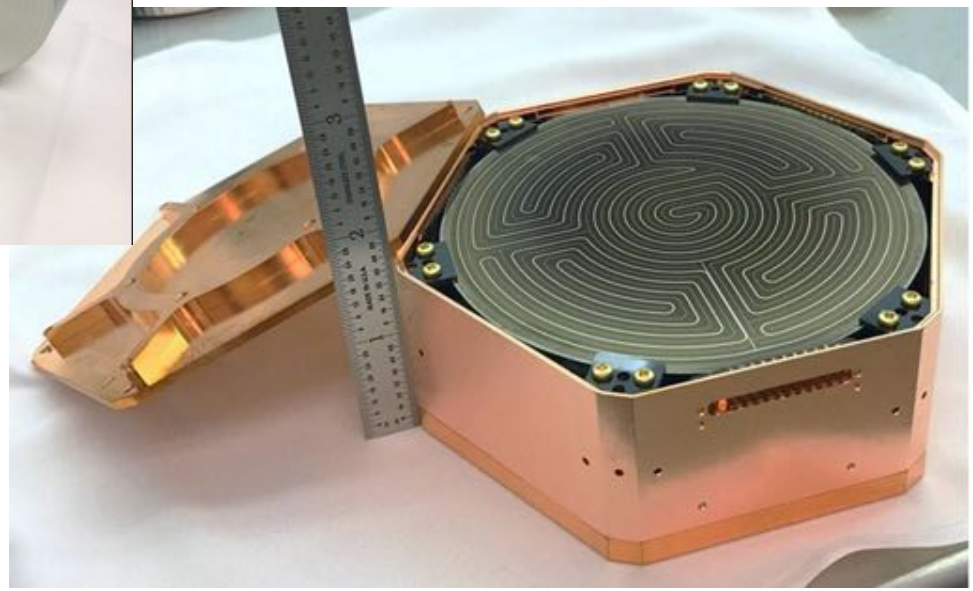
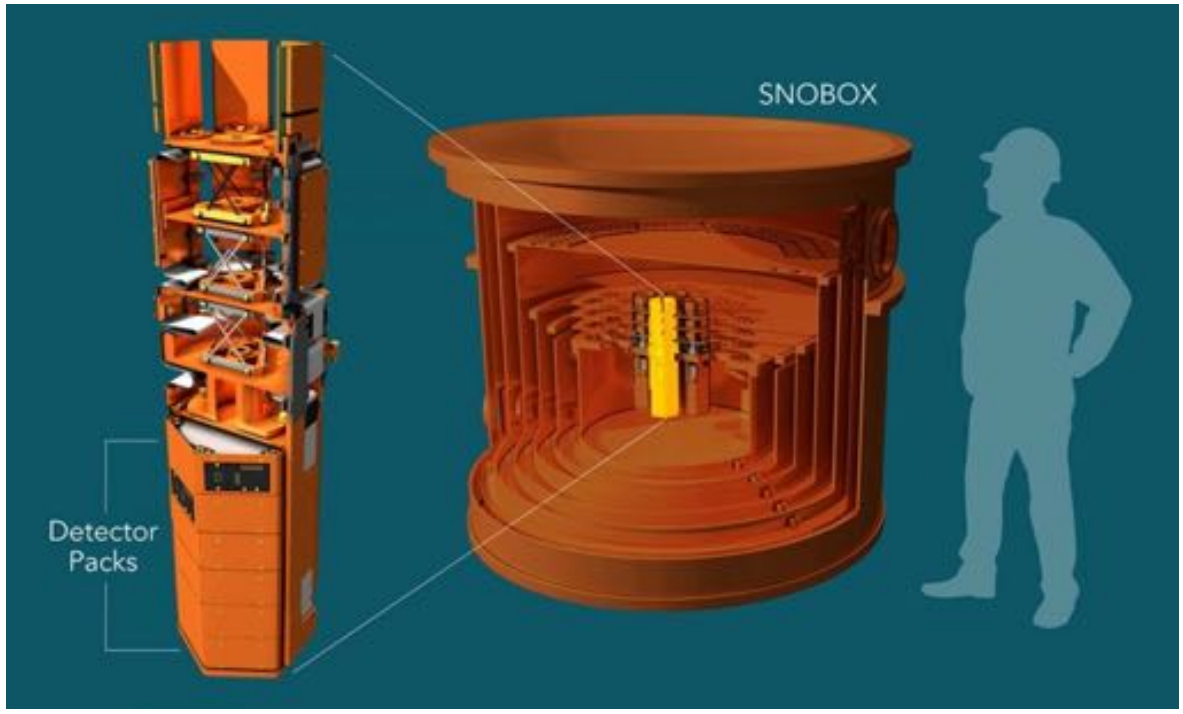




Image credit: supercdms.slac.stanford.edu



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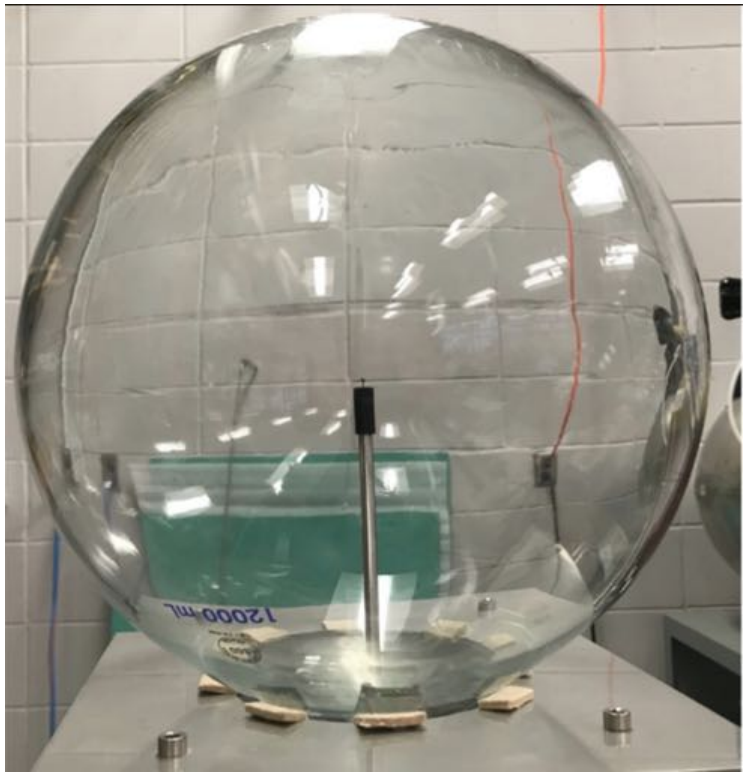


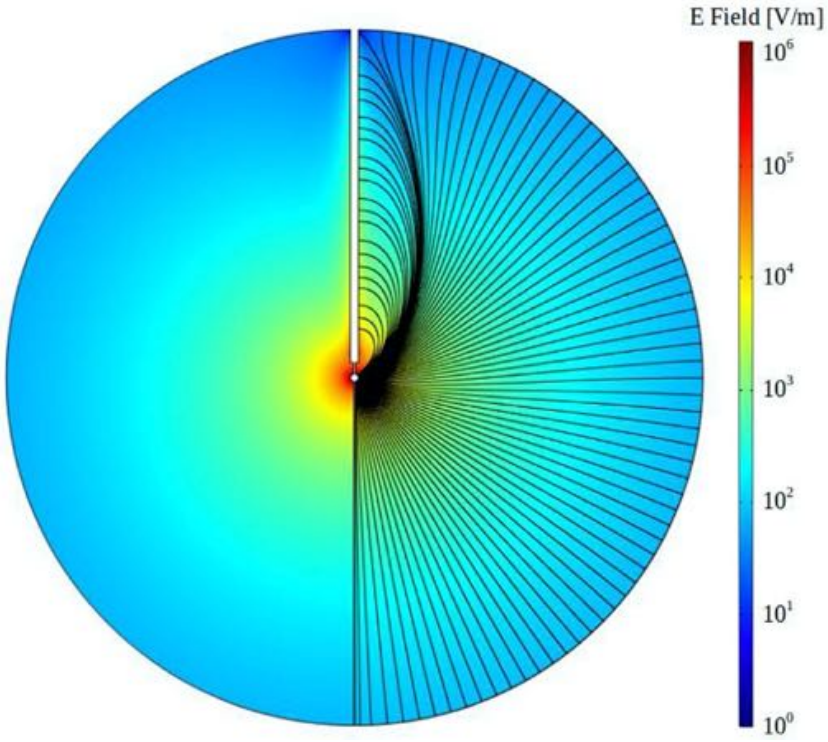
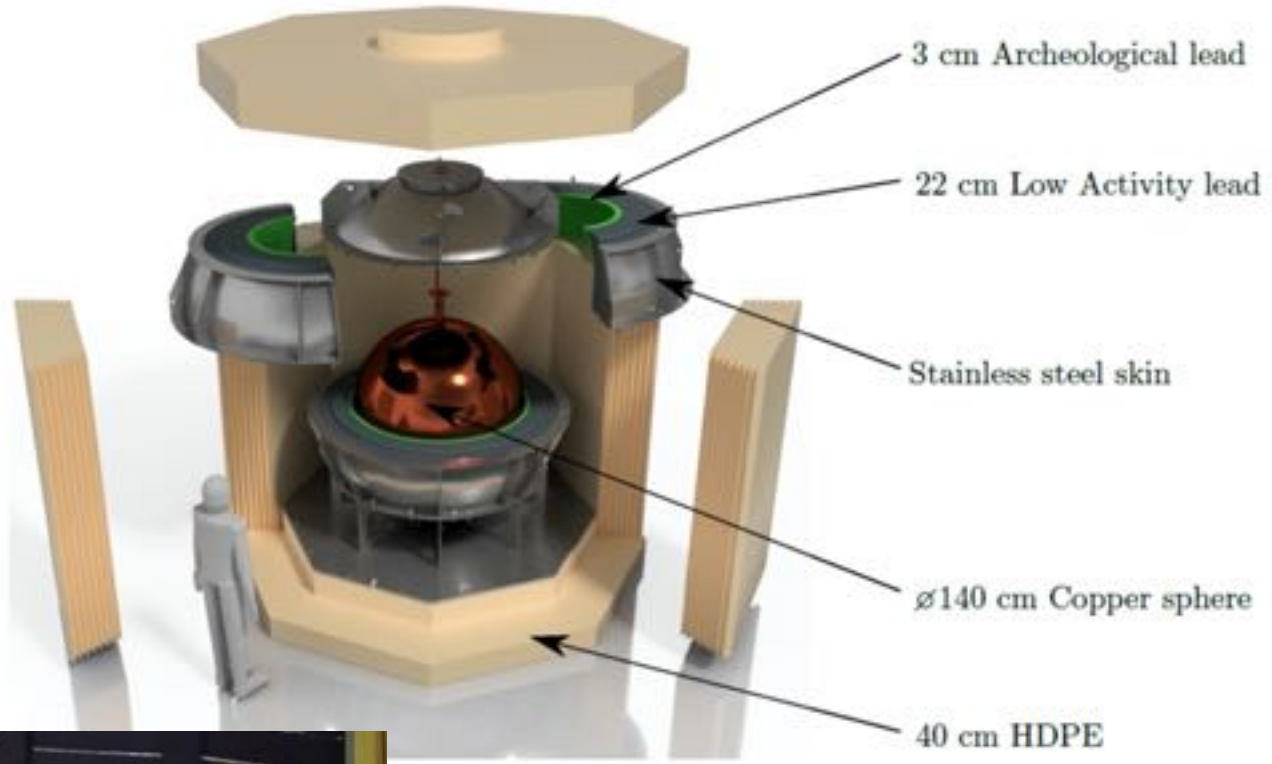



Image credit: news-g.org



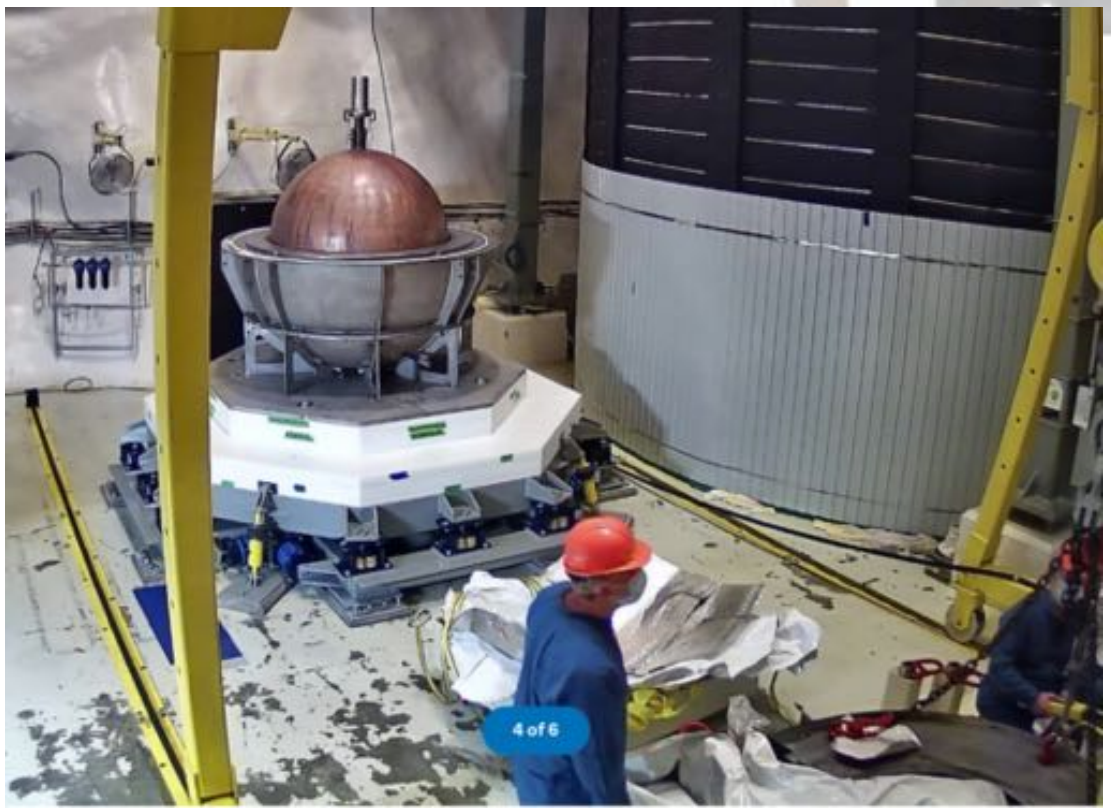




Image credit: news-g.org

PICO

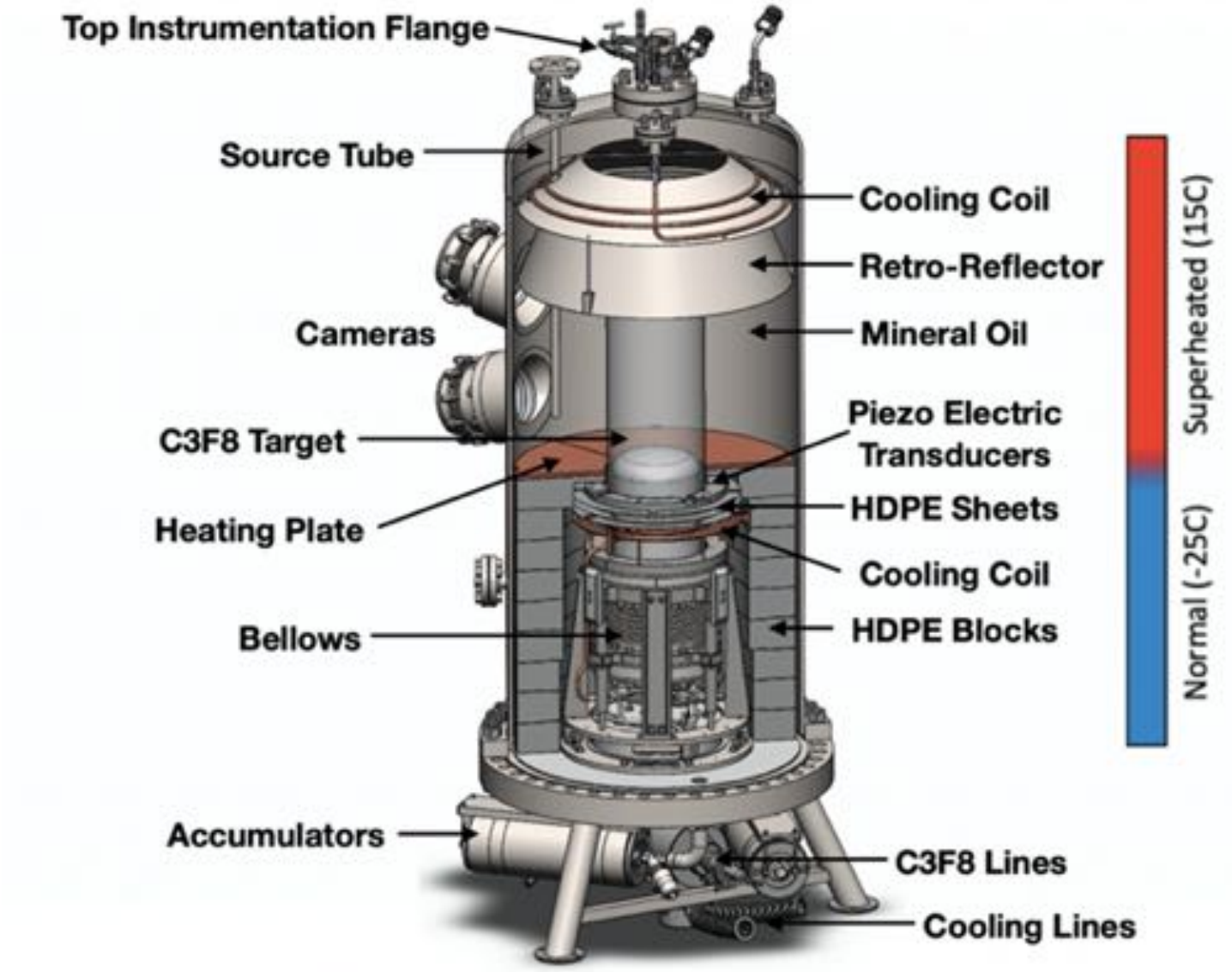



Image credit: picoexperiment.com

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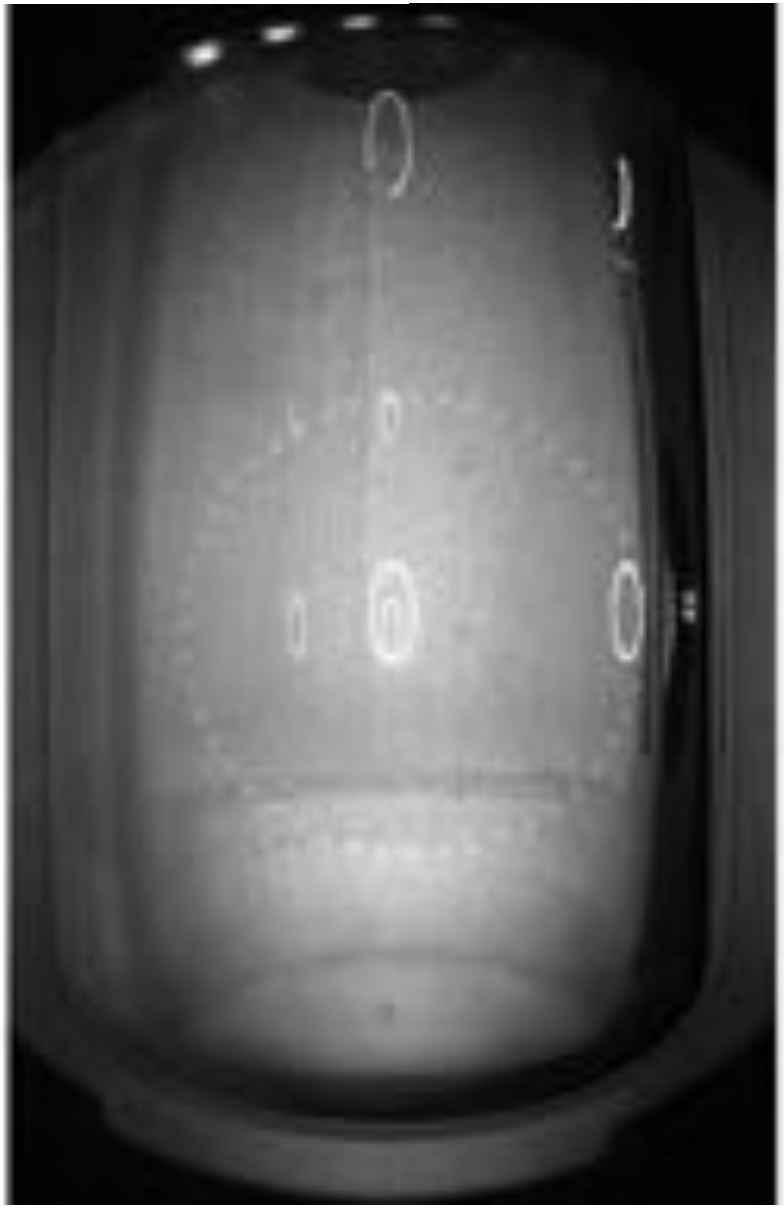

Image credit: picoexperiment.com

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Image credit: picoexperiment.com

# 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