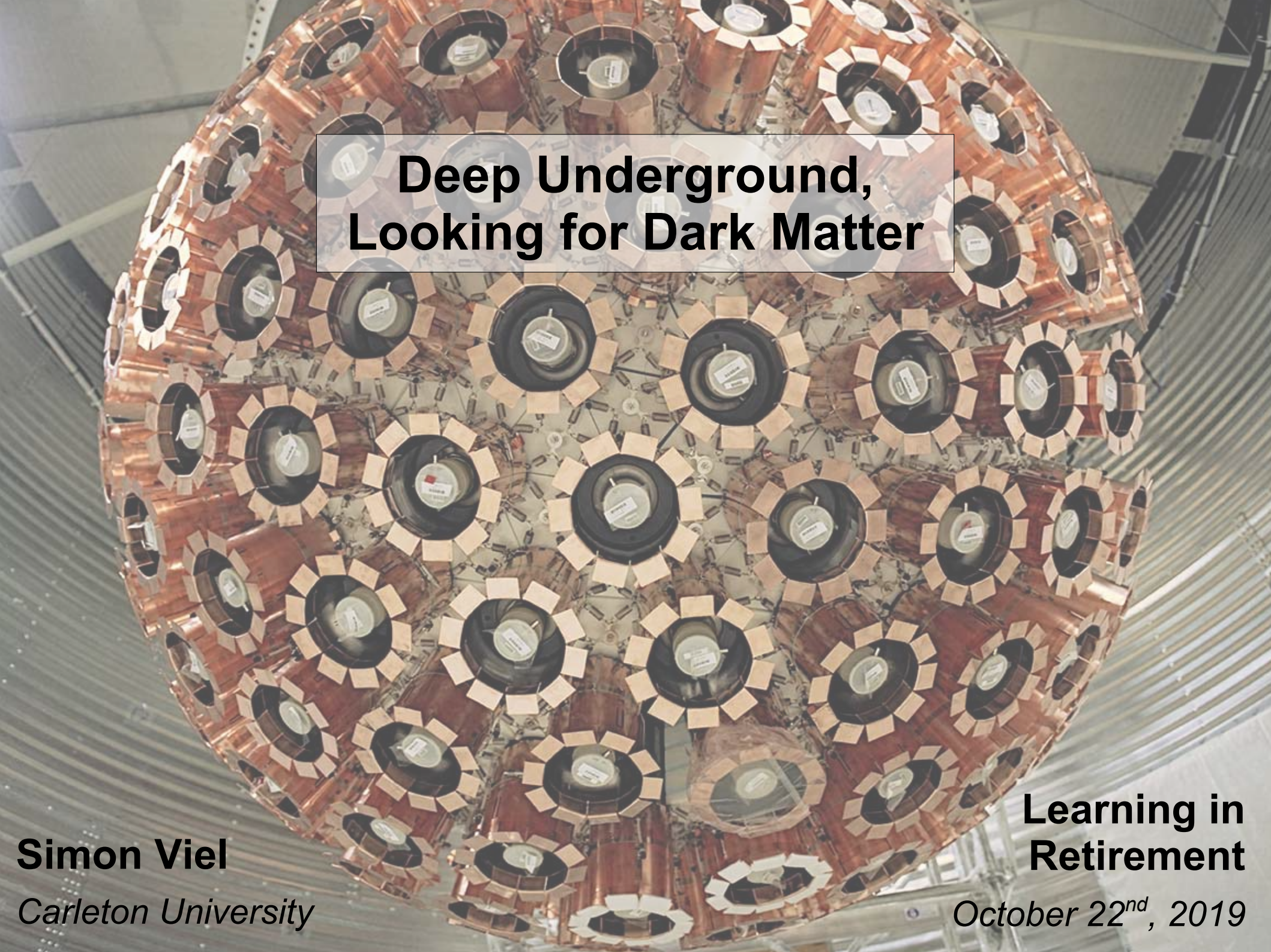


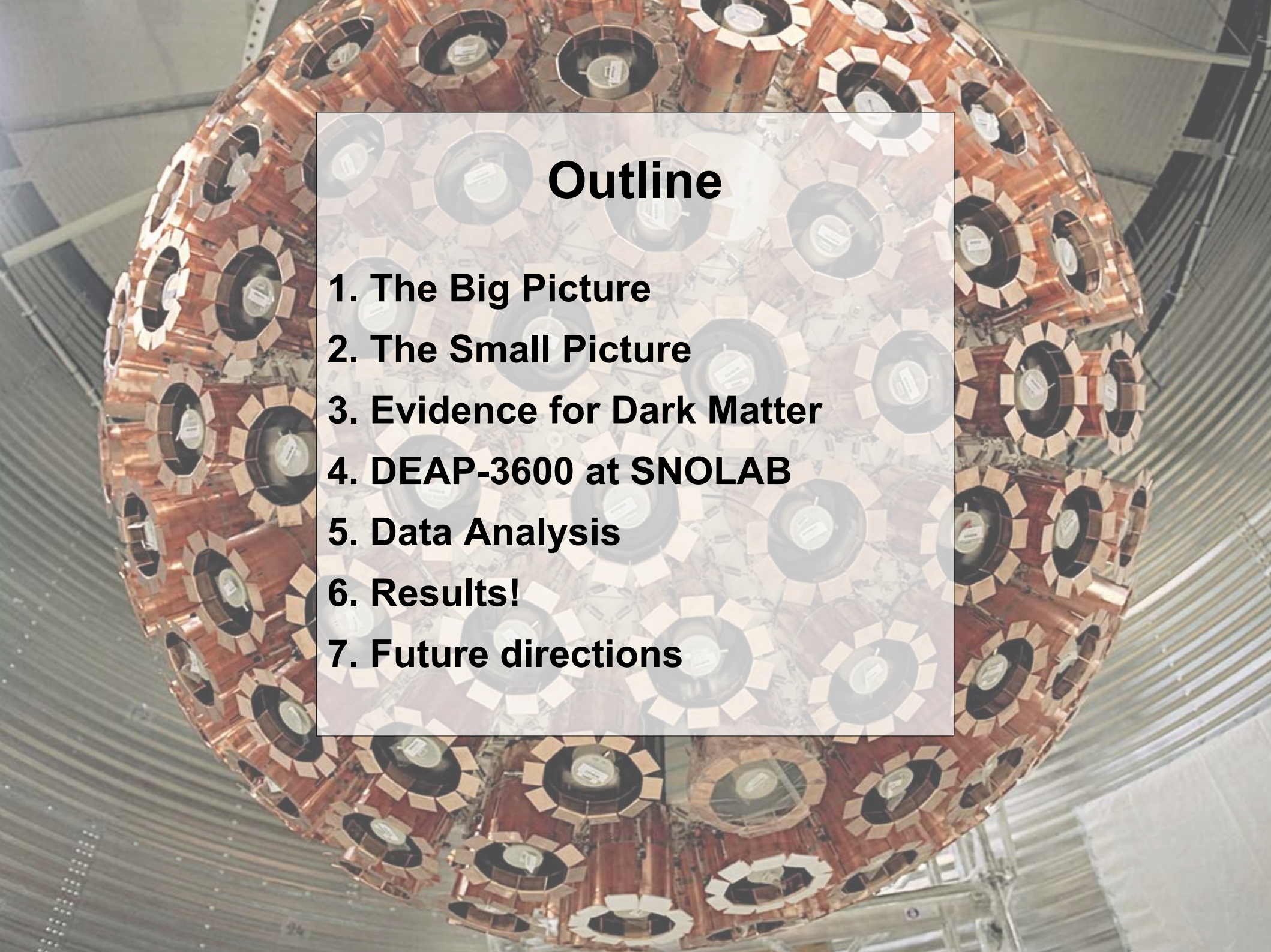
Deep Underground, Looking for Dark Matter

Simon Viel

Carleton University

Learning in Retirement

October 22nd, 2019



Outline

1. The Big Picture
2. The Small Picture
3. Evidence for Dark Matter
4. DEAP-3600 at SNOLAB
5. Data Analysis
6. Results!
7. Future directions

DEAP Collaboration:

80 researchers in **Canada**, Germany, Italy, Mexico, Poland, Russia, Spain, UK, USA

University of Alberta
AstroCeNT Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carleton University
Ciemat
Laurentian University / Université Laurentienne
Instituto de Física
INFN Istituto Nazionale di Fisica Nucleare
National Research Center "Kurchatov Institute"
Princeton University
Queen's University
Royal Holloway University of London
Particle Physics Rutherford Appleton Laboratory
St. Petersburg Nuclear Physics Institute
SNOLAB
University of Sussex
Technical University of Munich
TRIUMF

NSERC CRSNG

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CANADA FIRST
RESEARCH EXCELLENCE FUND

APOGÉE CANADA
FONDS D'EXCELLENCE EN RECHERCHE

Alberta Advanced Education

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VALE

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

UNIVERSITY OF ALBERTA

Carleton UNIVERSITY

Queen's UNIVERSITY

Science & Technology Facilities Council

SNOLAB

CONACYT
Consejo Nacional de Ciencia y Tecnología

Particle Physics
Rutherford Appleton Laboratory

Thank you to funding agencies and partners for making this research possible!

iF Instituto de Física

compute canada | calcul canada

Calcul Québec

Centre for Advanced Computing

erc
European Research Council
Established by the European Commission

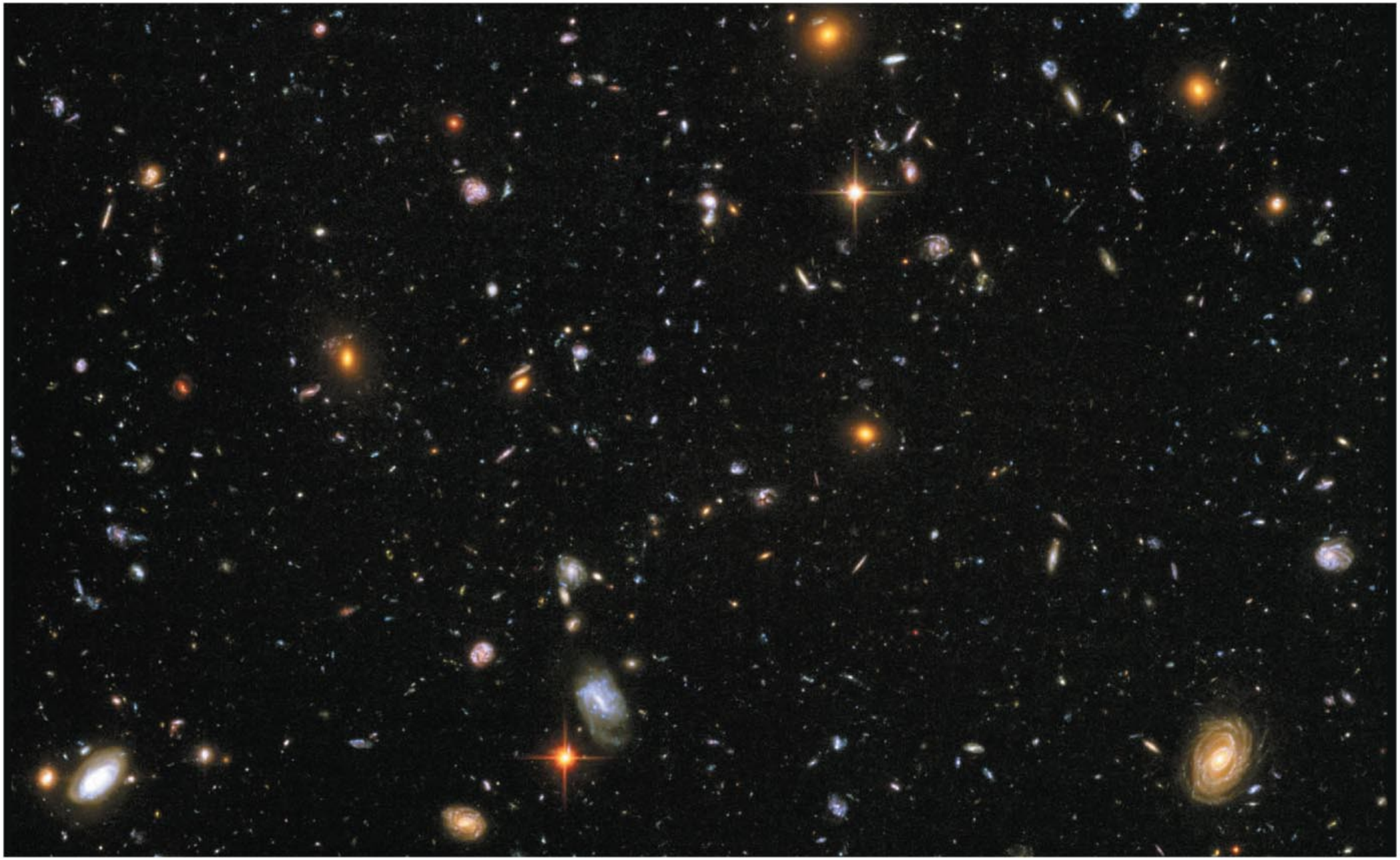
LEVERHULME TRUST

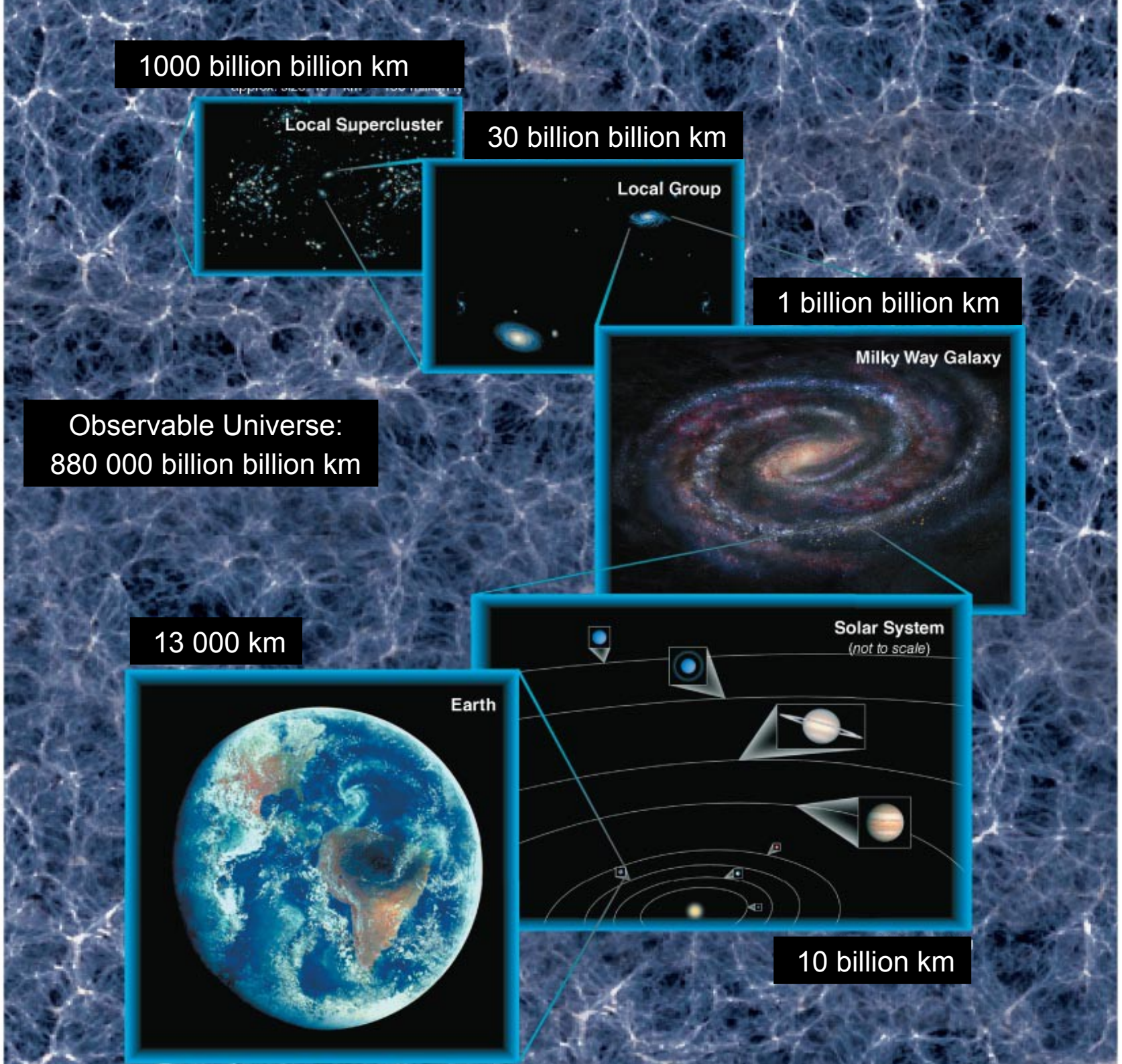
lrz Leibniz Supercomputing Centre
of the Bavarian Academy of Sciences and Humanities

SEPnet
South East Physics Network

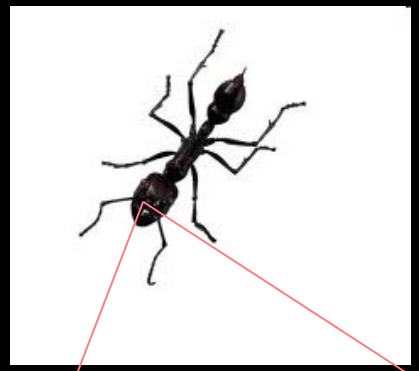
Hubble Space Telescope Ultra Deep Field: Thousands of galaxies

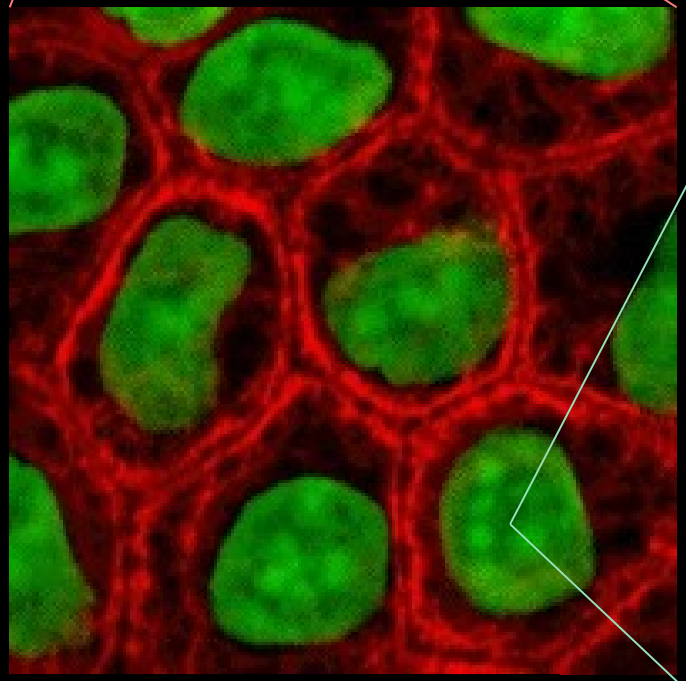
(angular size of one grain of sand held at arm's length)



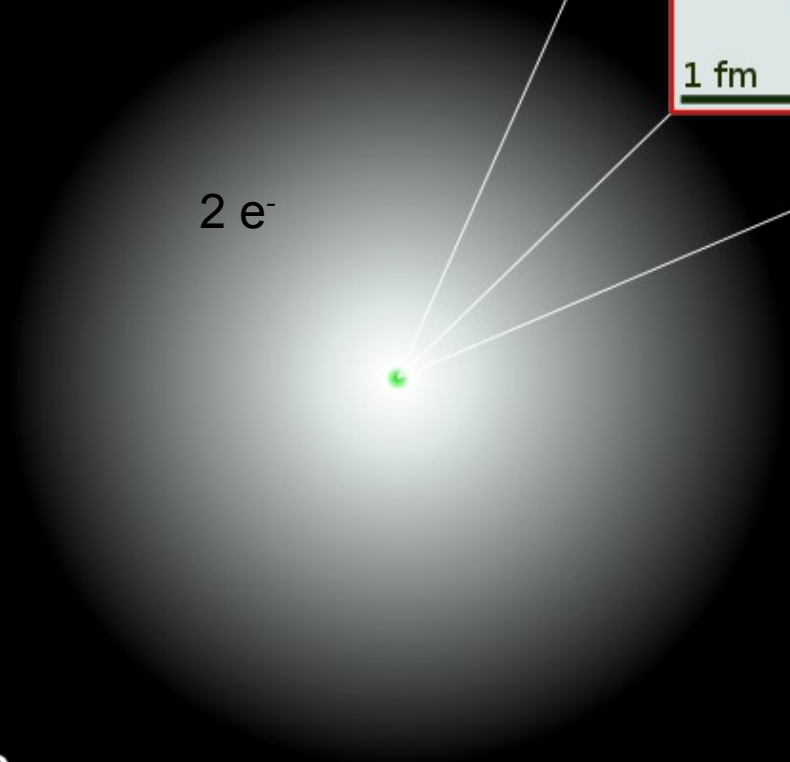

1000 billion billion km
Local Supercluster
30 billion billion km
Local Group
1 billion billion km
Milky Way Galaxy
Observable Universe:
880 000 billion billion km
13 000 km
Earth
Solar System
(not to scale)
10 billion km

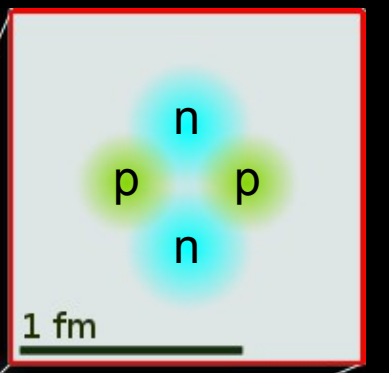
10 mm = 10 000 µm





10 µm = 100 000 Å





1 Ångström (=100,000 fm)

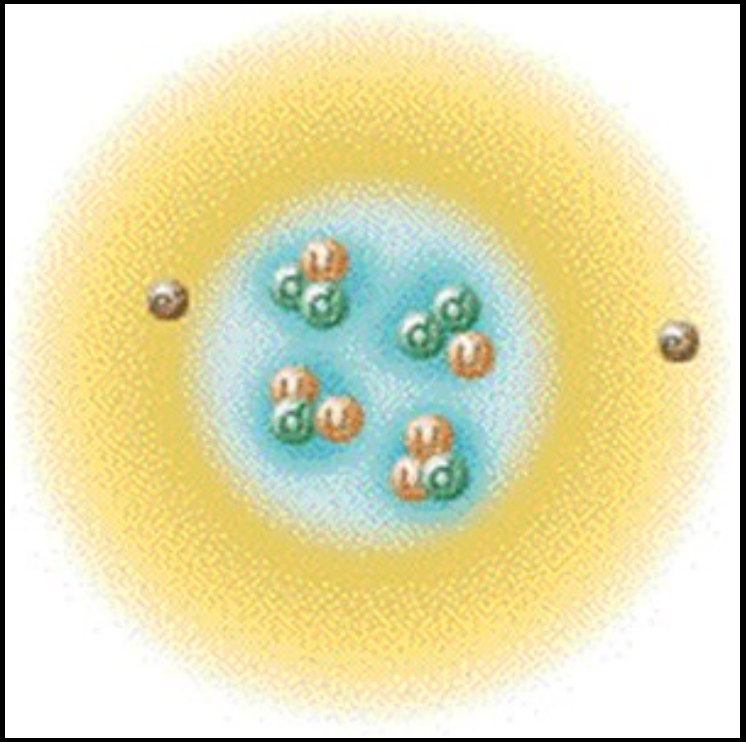


Figure credit: Fermilab

The Standard Model of particle physics

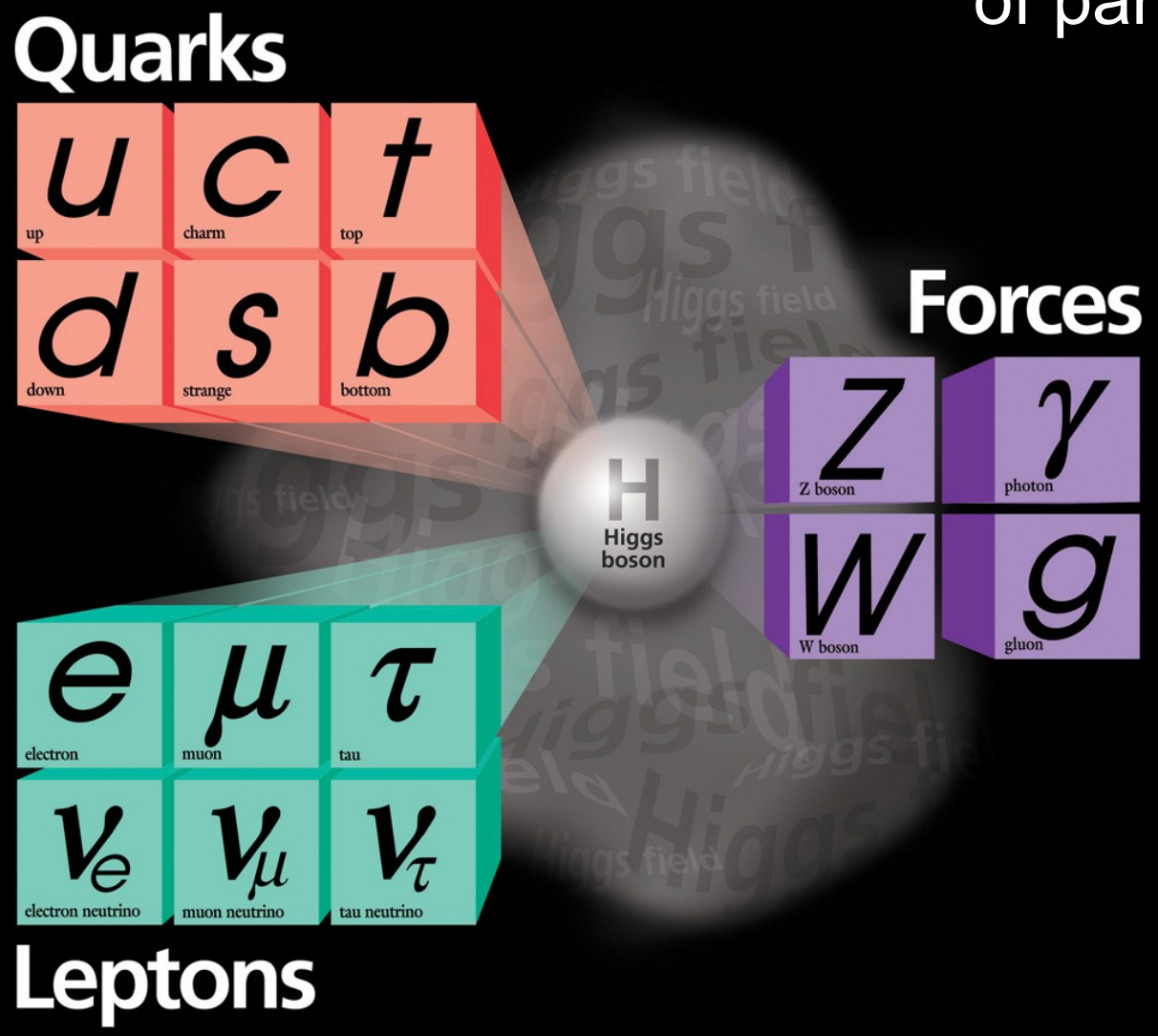
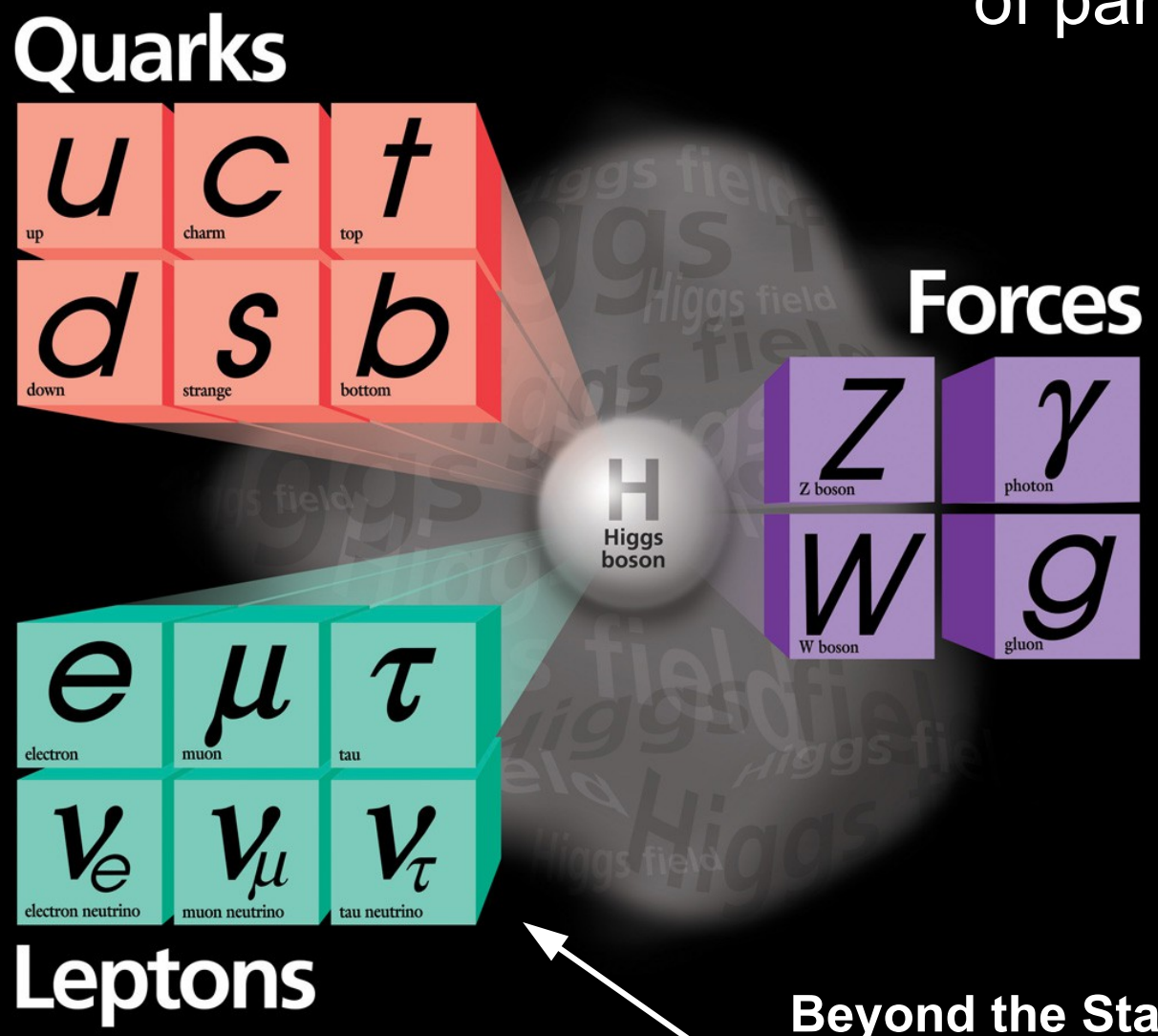


Figure credit: Fermilab

The Standard Model of particle physics

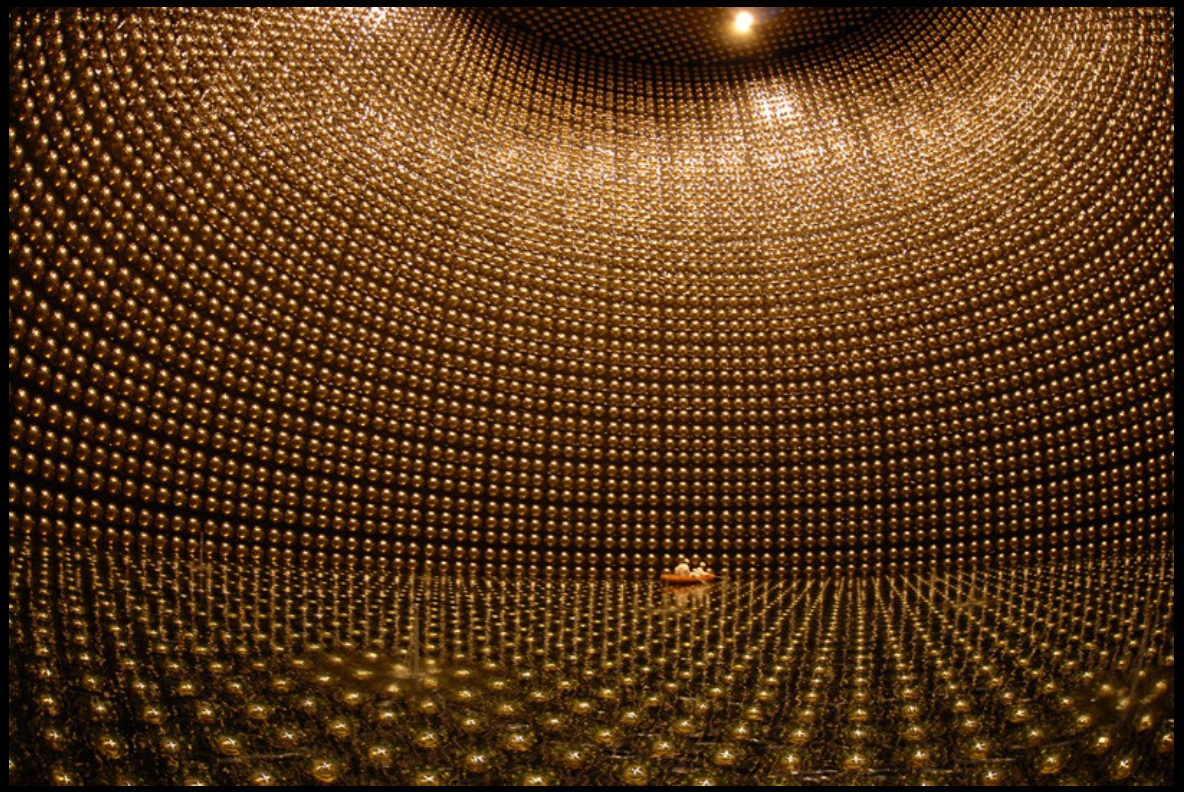


Beyond the Standard Model:

Do neutrinos have a mass? Yes!

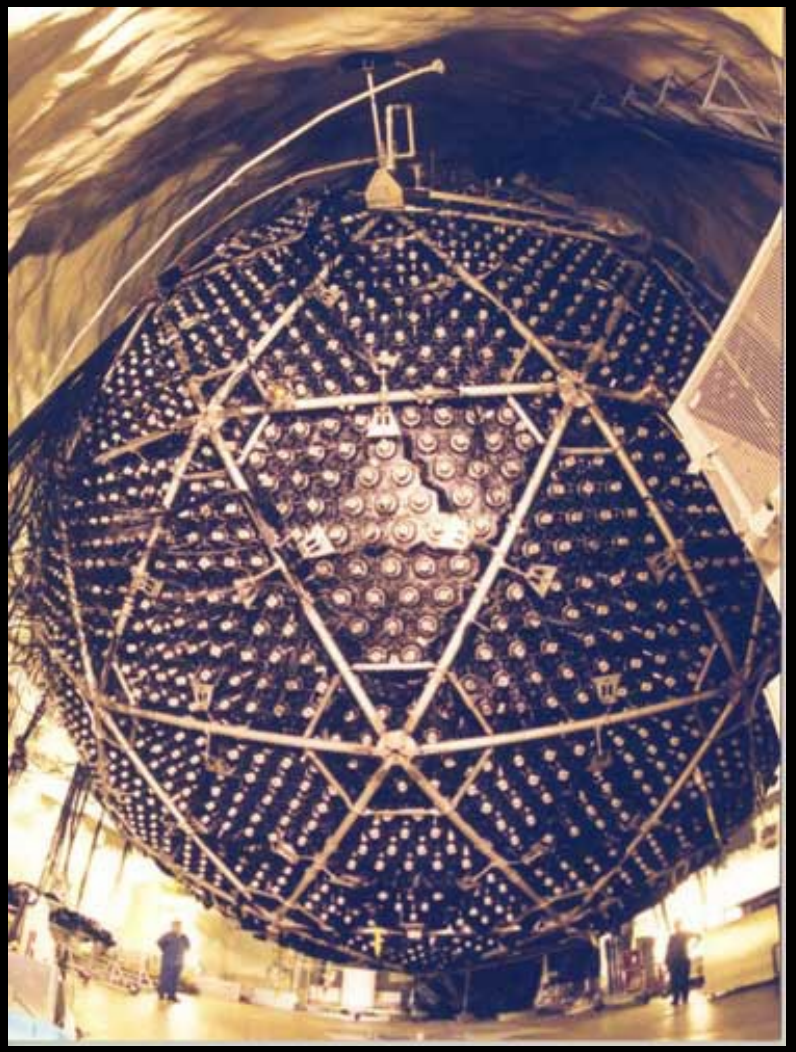
How do neutrinos acquire their mass?

Are neutrinos their own antiparticles?

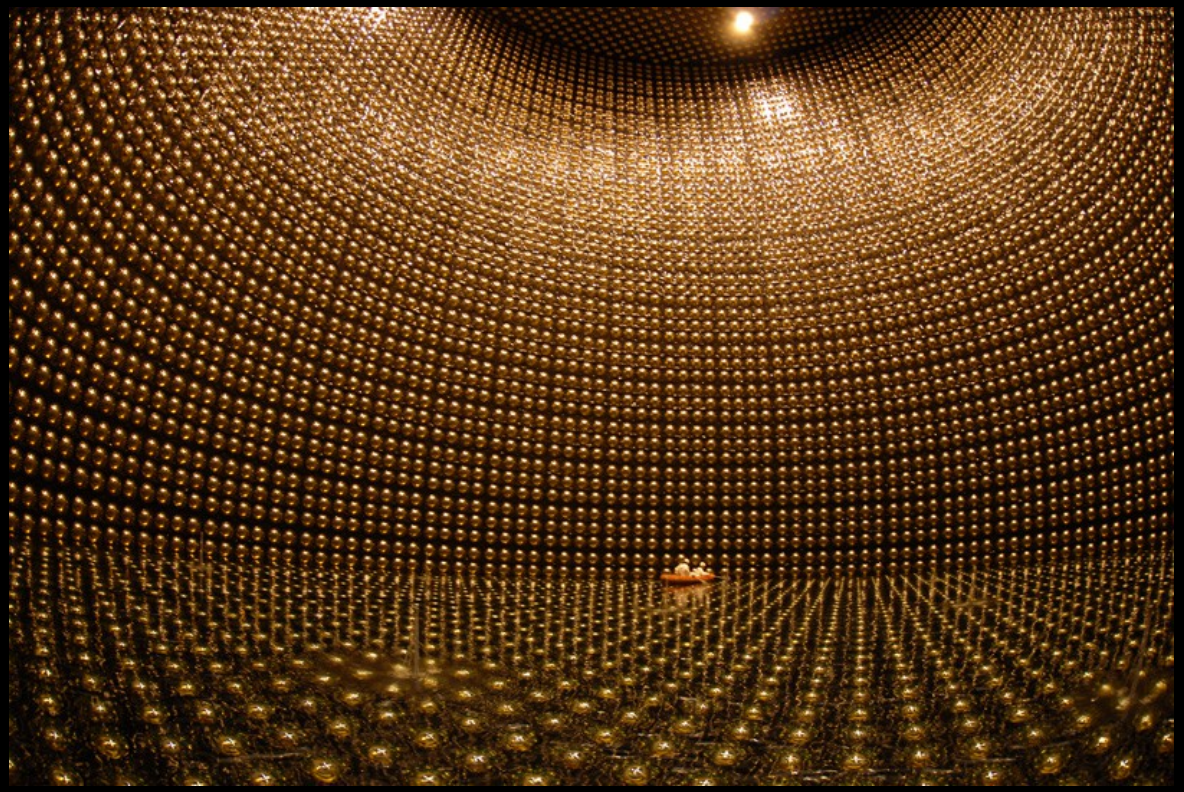


Super-Kamiokande

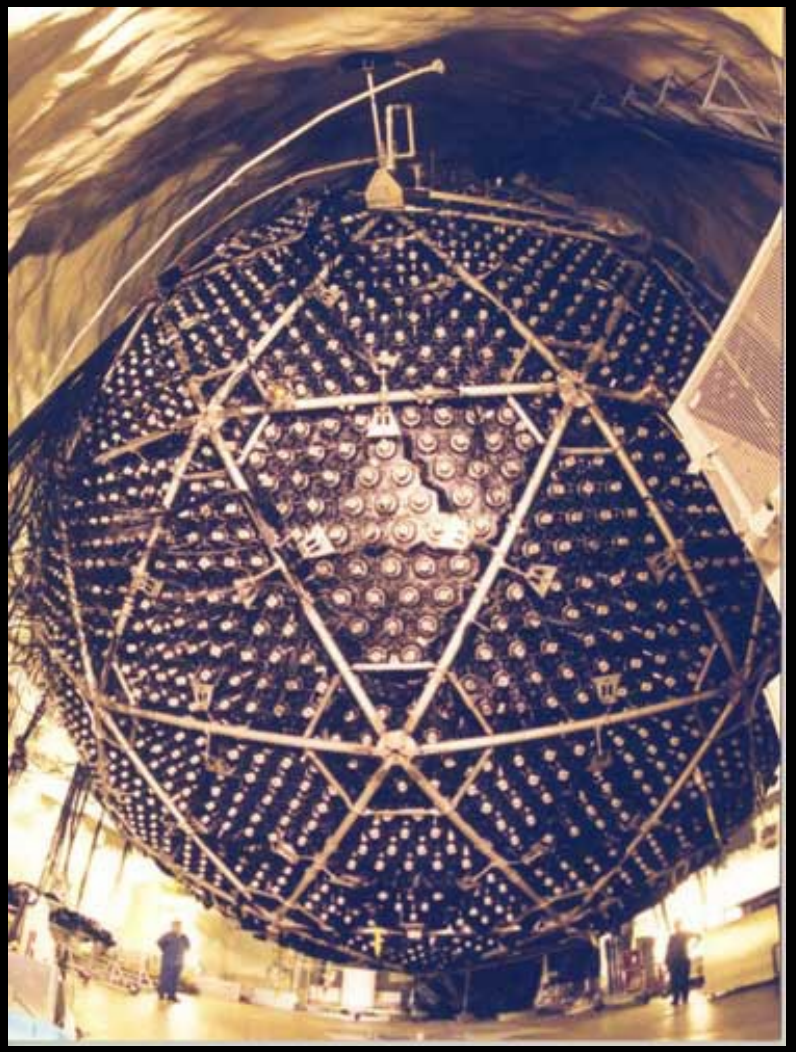
Discovery of neutrino flavour oscillations
implies that neutrinos must have a small mass



Sudbury Neutrino Observatory



Super-Kamiokande



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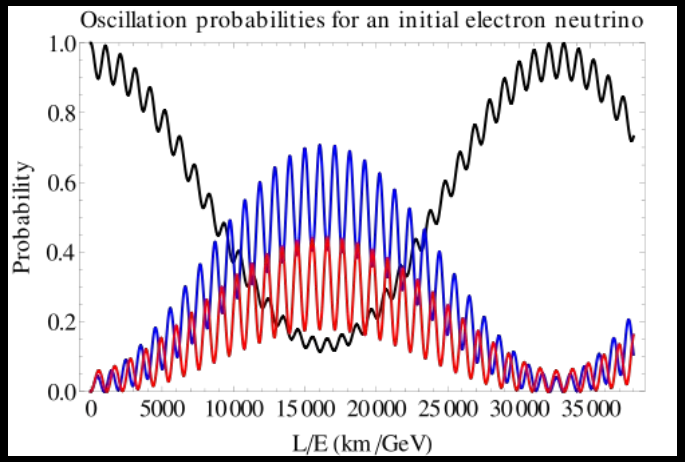
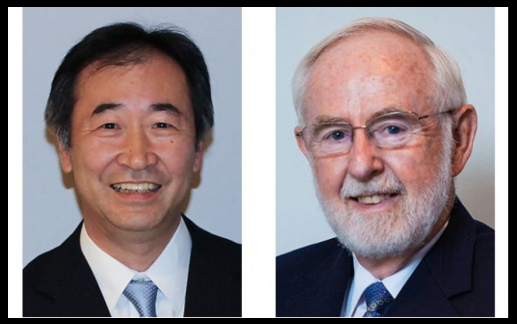


Nobel Prize 2015



Back to the largest scale

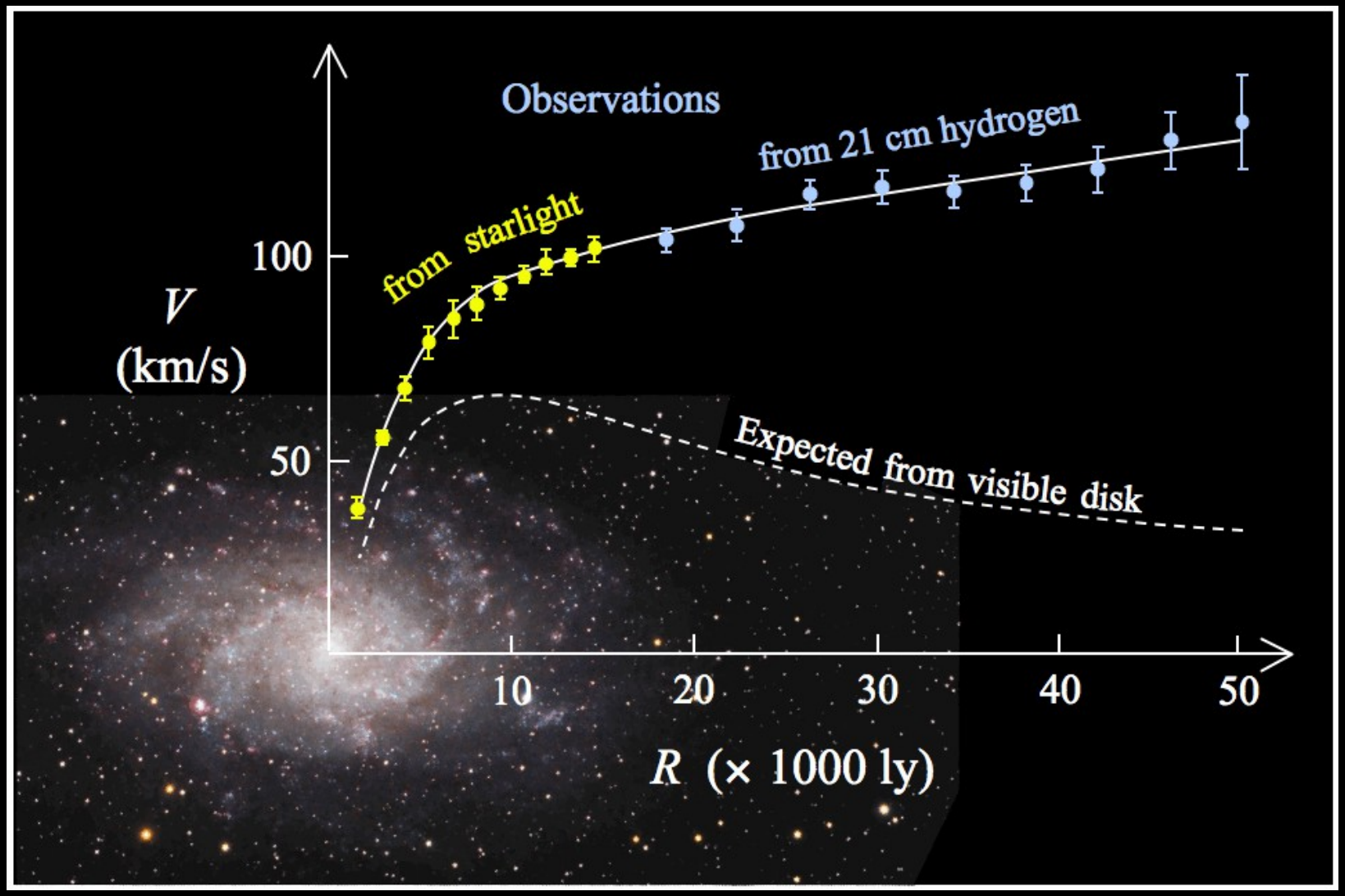
The evidence for dark matter

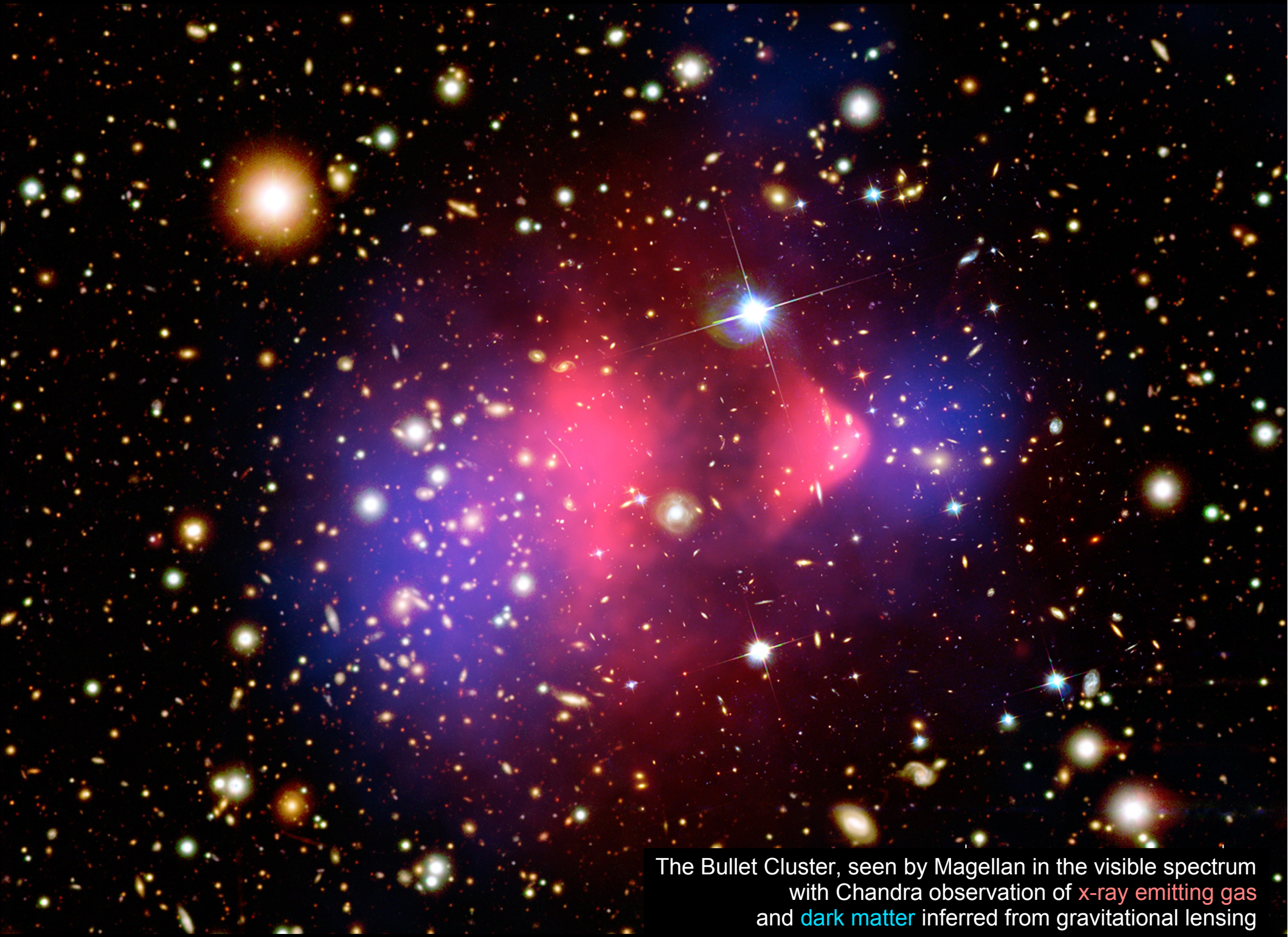
The Whirlpool Galaxy (M51)

Figure credit: Chase Preuninger. Next slide: NASA / ESA, Hubble Space Telescope

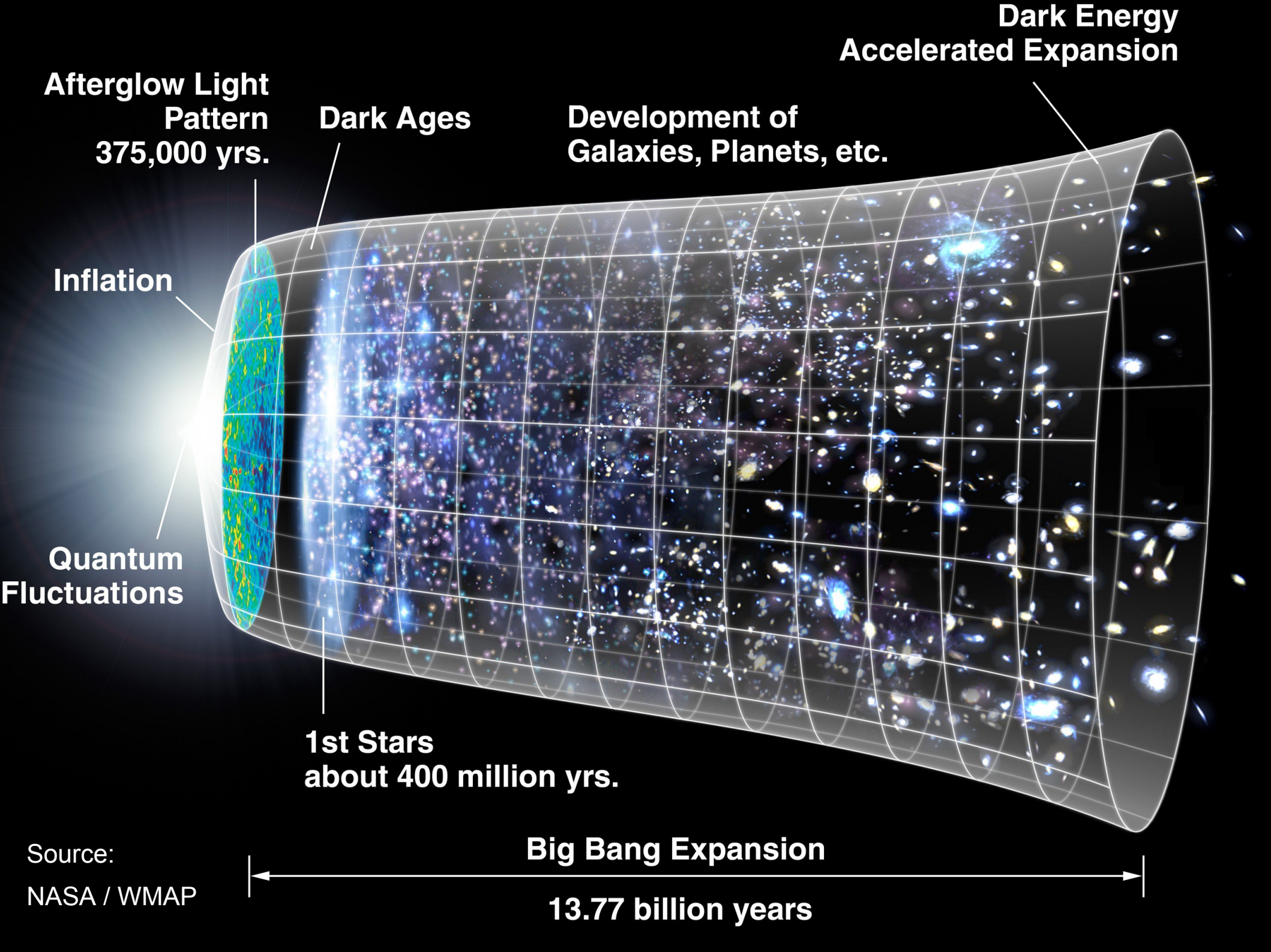
The Mystery of Dark Matter

E. Corbelli and P. Salucci, The extended rotation curve and the dark matter halo of M33
Figure by Stefania Deluca





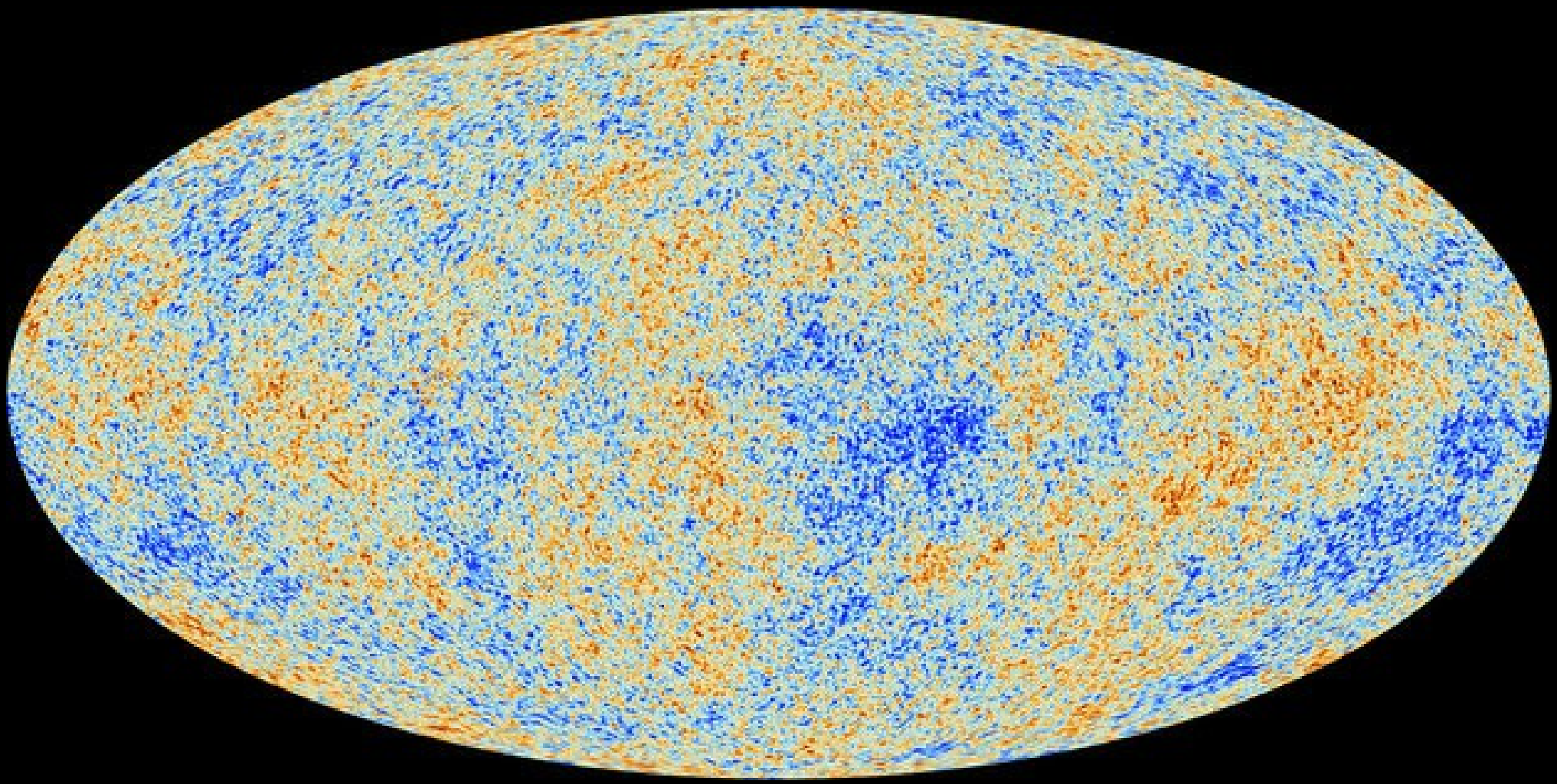
The Bullet Cluster, seen by Magellan in the visible spectrum
with Chandra observation of x-ray emitting gas
and dark matter inferred from gravitational lensing



Source:
NASA / WMAP

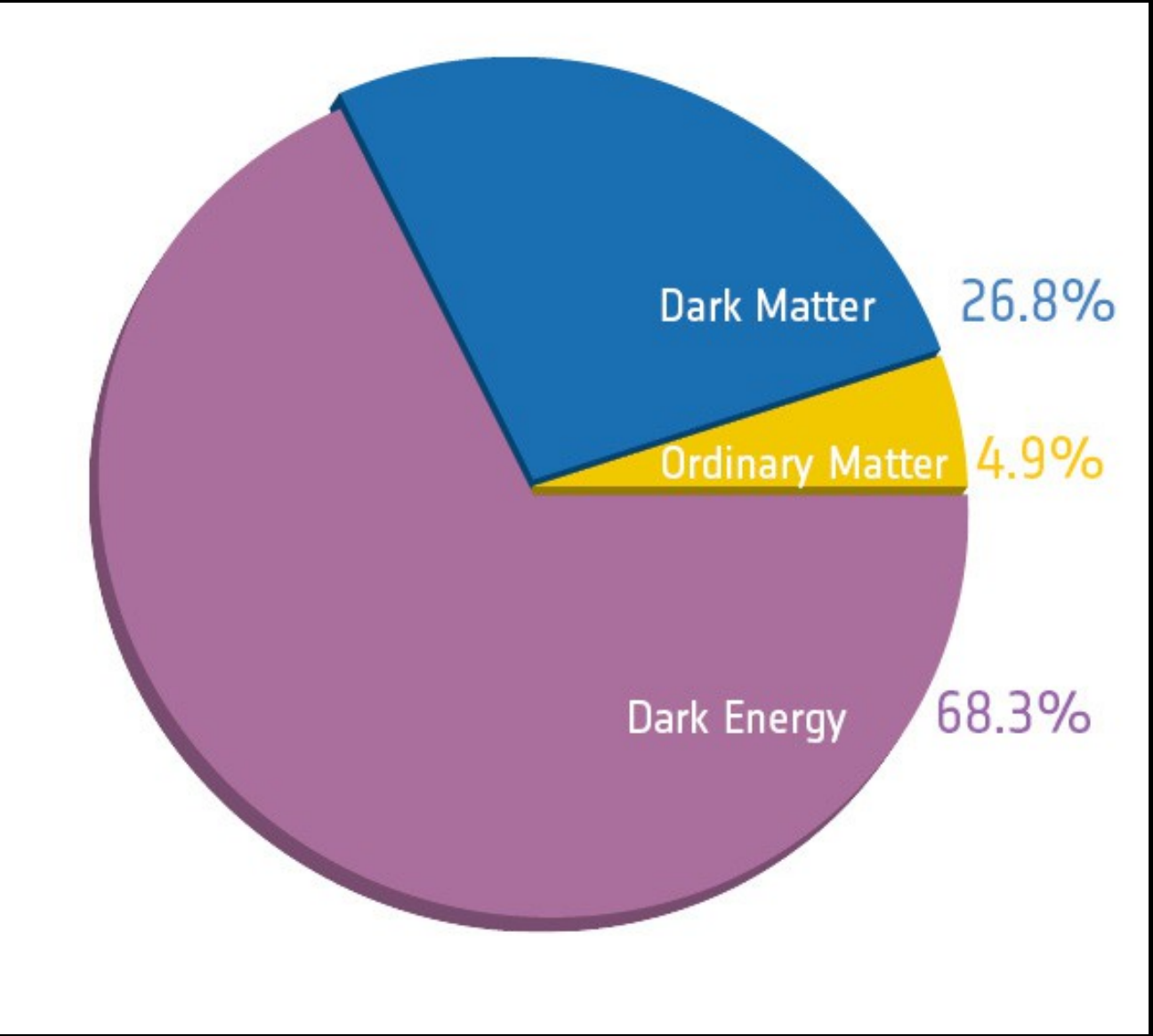
Full-sky map of the cosmic microwave background by the Planck collaboration

Mass-energy density (ΛCDM model): 5% ordinary matter, 27% dark matter, 68% dark energy



Relative amounts of the constituents of the Universe (aka the “cosmic pie chart”)

Source: European Space Agency / Planck collaboration

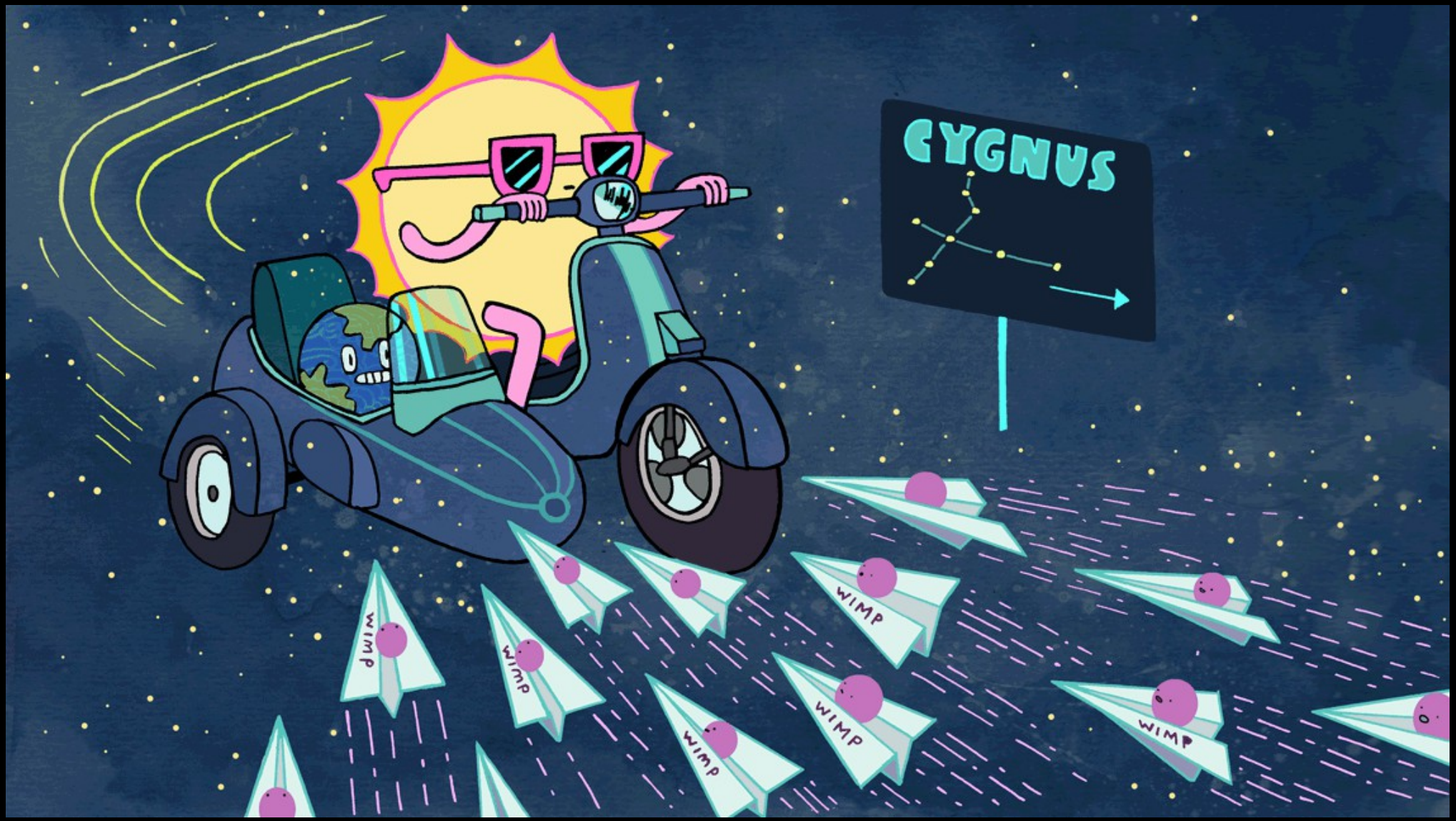


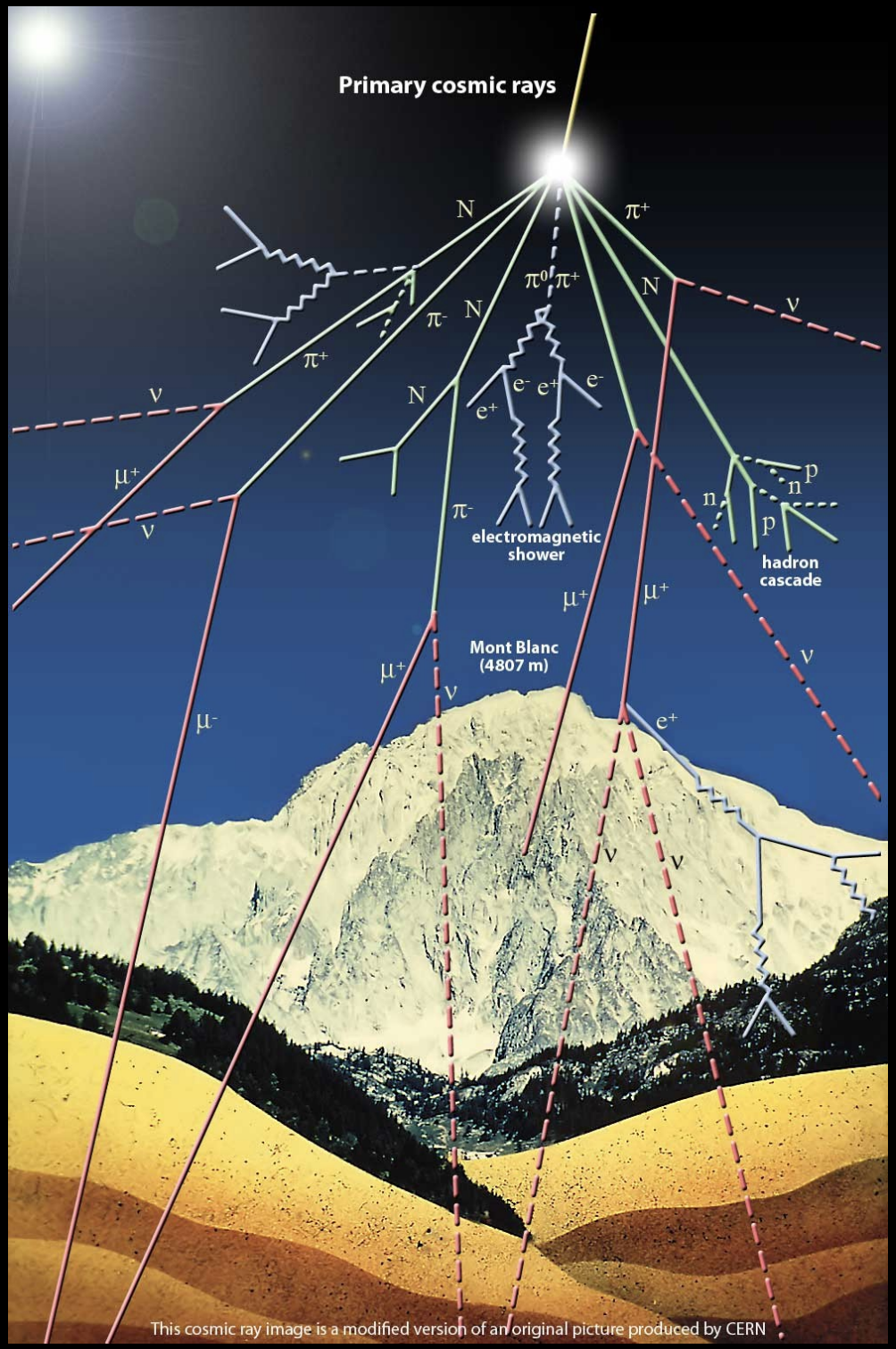
15-minute break!

Coming up:
Searching for dark matter at SNOLAB

Riding in the Dark Matter Wind

Source: Symmetry Magazine – Artwork by Sandbox Studio, Chicago with Corinne Mucha



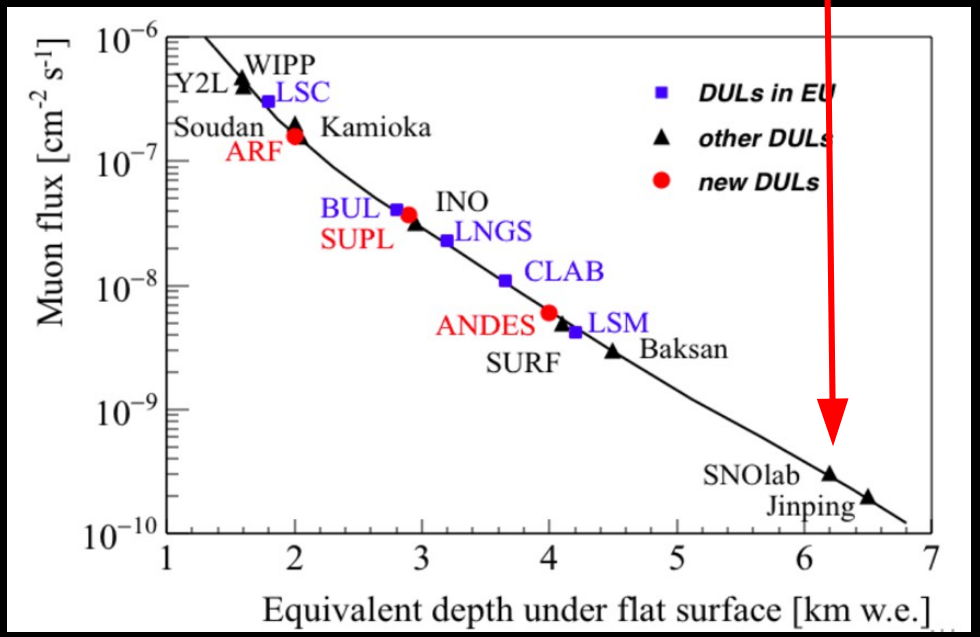


Why go underground?

To shield detectors against cosmic rays

- Surface:
  ~ 1 muon / cm² / minute
  ~ 14.4 million muons / m² / day

SNOLAB:
0.27 muons / m² / day

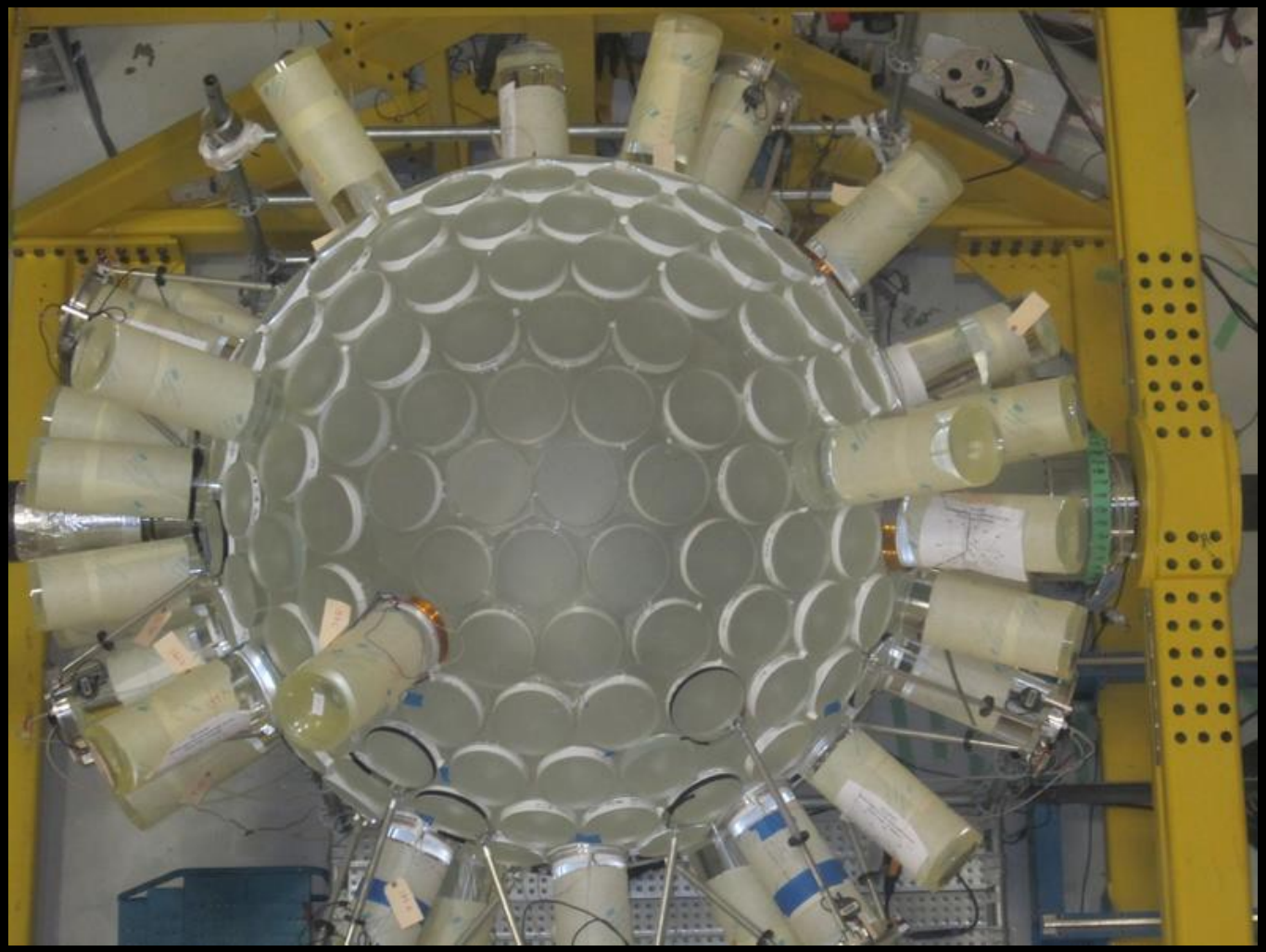


Video: A Day at SNOLAB
https://www.snolab.ca/outreach

2070 m underground

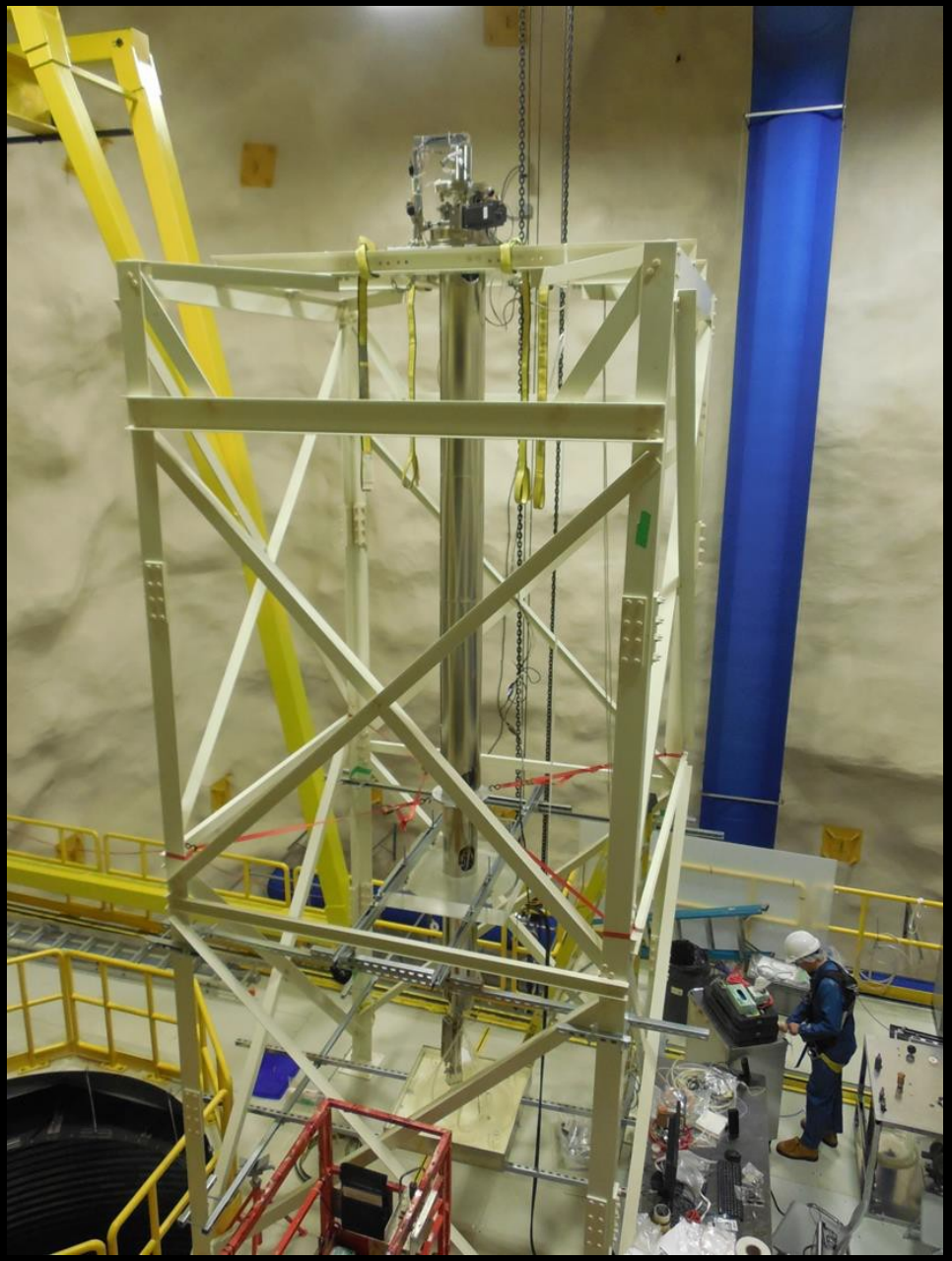
Acrylic vessel underground at SNOLAB

Bonding light guides underground at SNOLAB

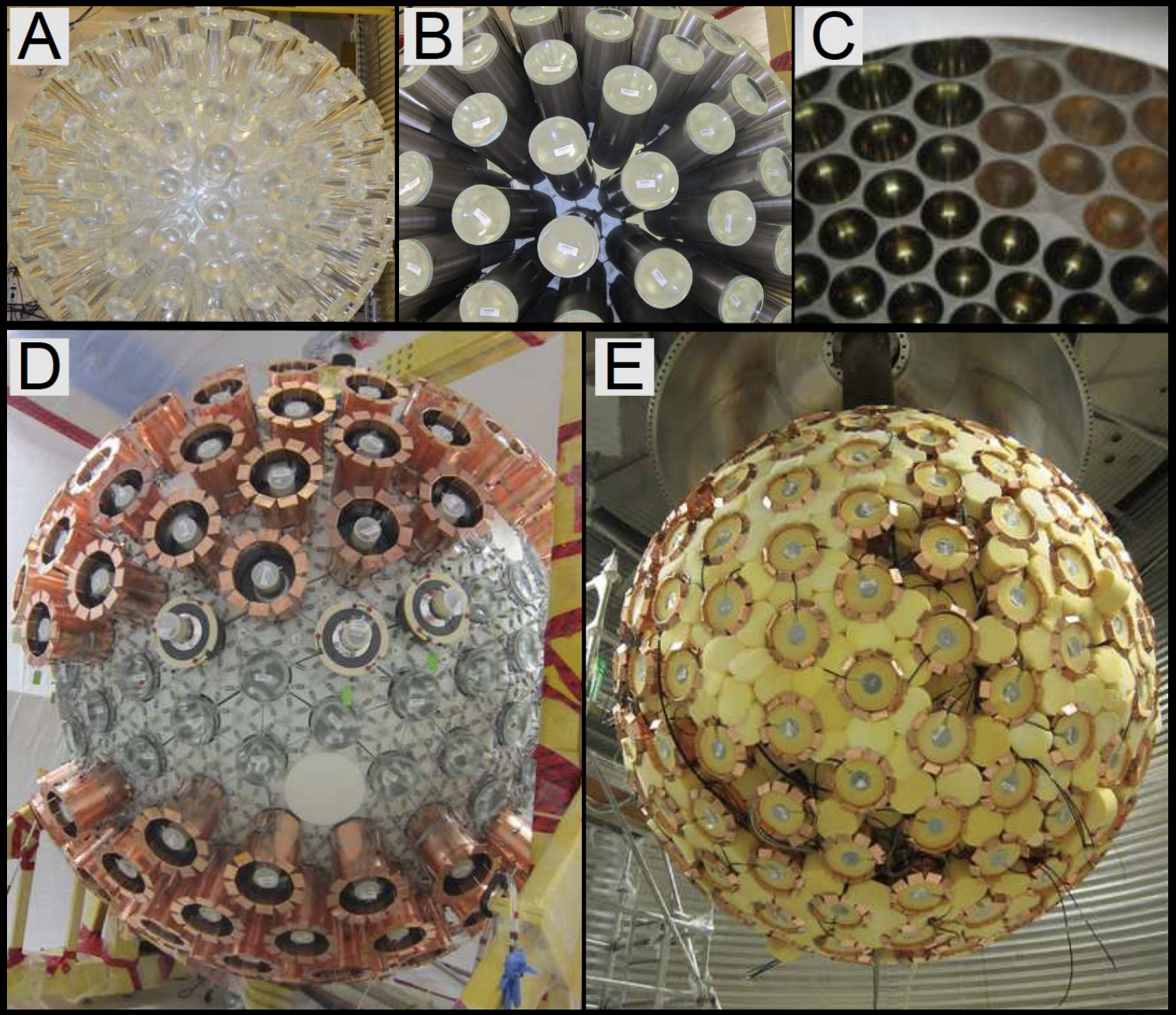


Acrylic vessel resurfacer

Mechanical sander to remove 0.5 mm off the inner surface



Light guides Reflectors Inside view

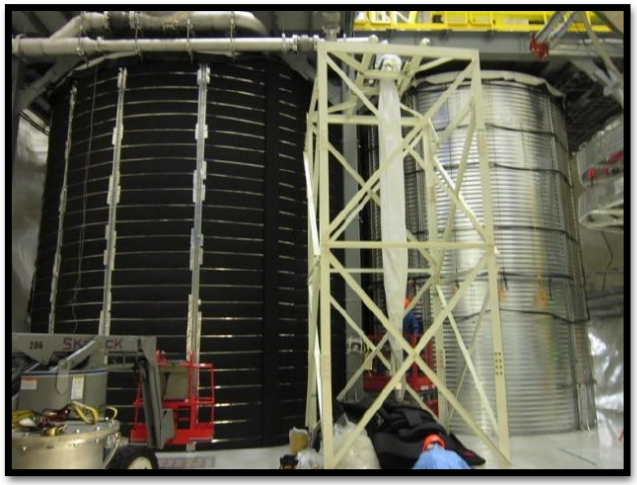


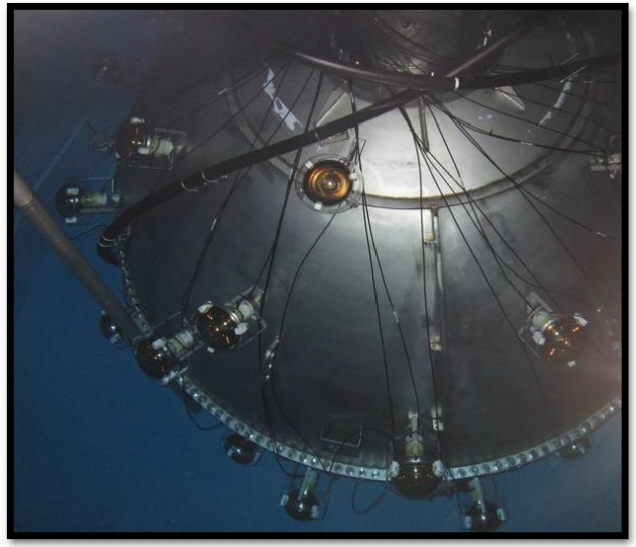
PMT installation Backing foam installation

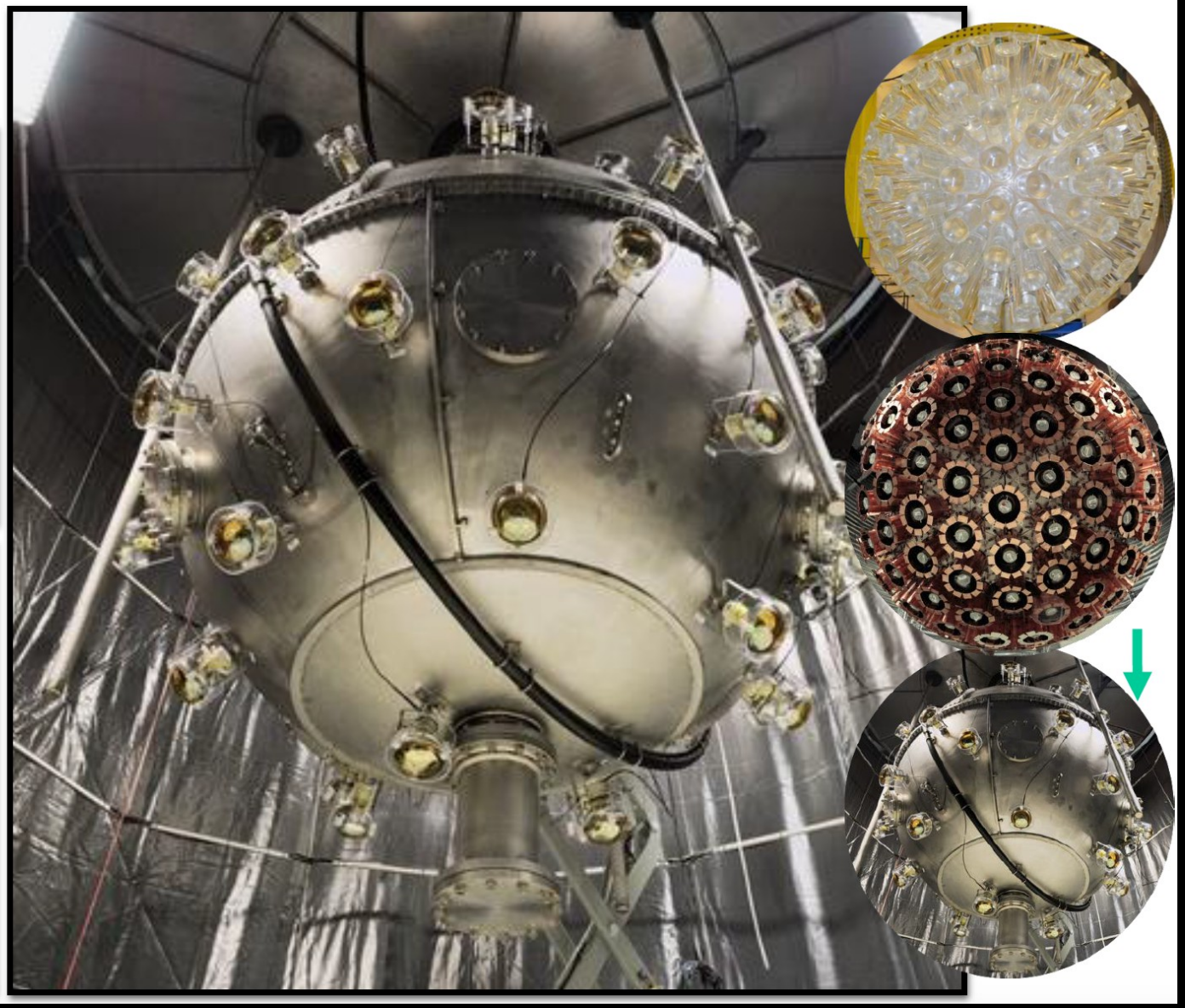
All details available in the DEAP-3600 detector publication! arXiv:1712.01982

Steel shell, Veto PMTs

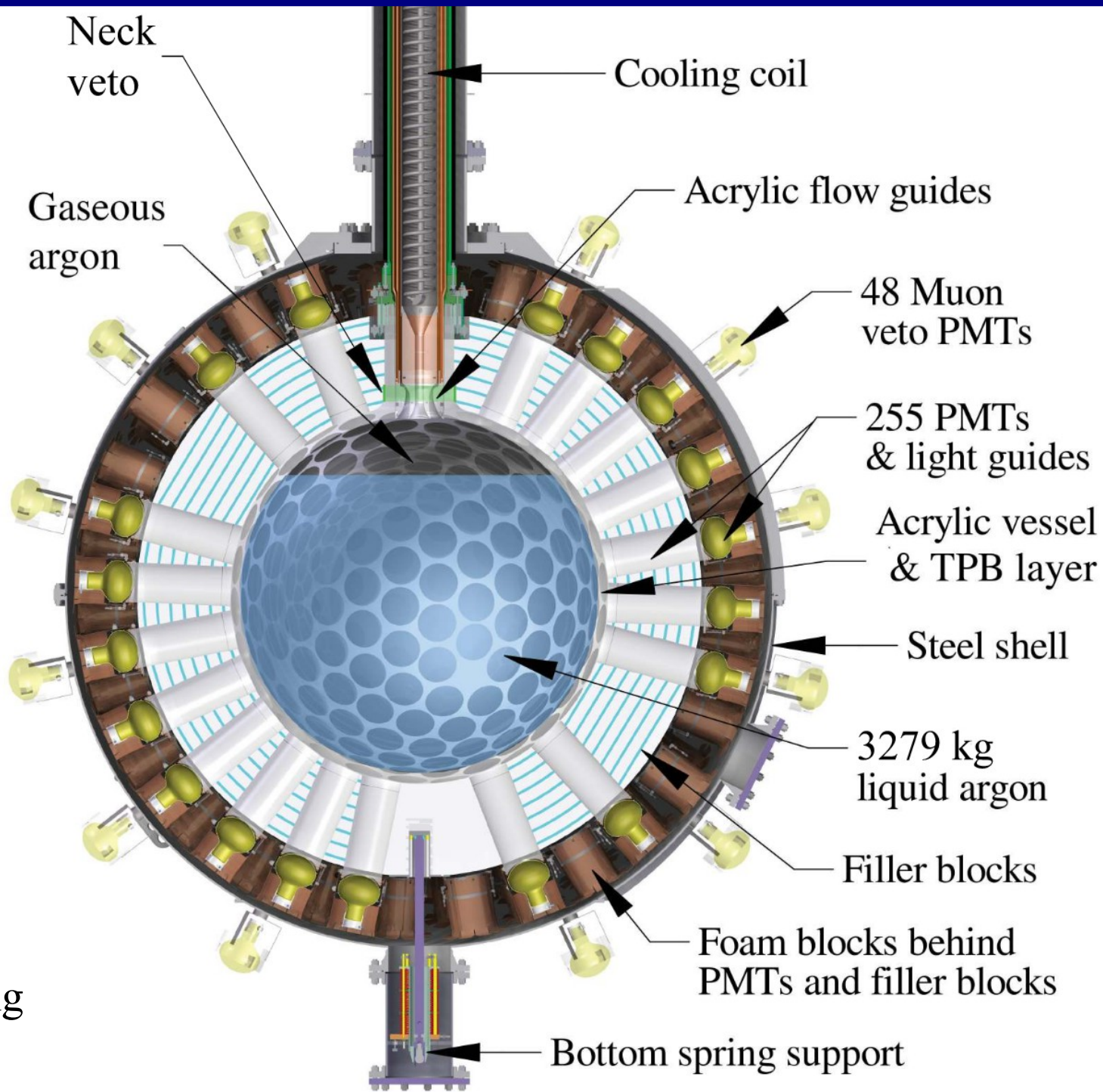
Water tanks in Cube Hall



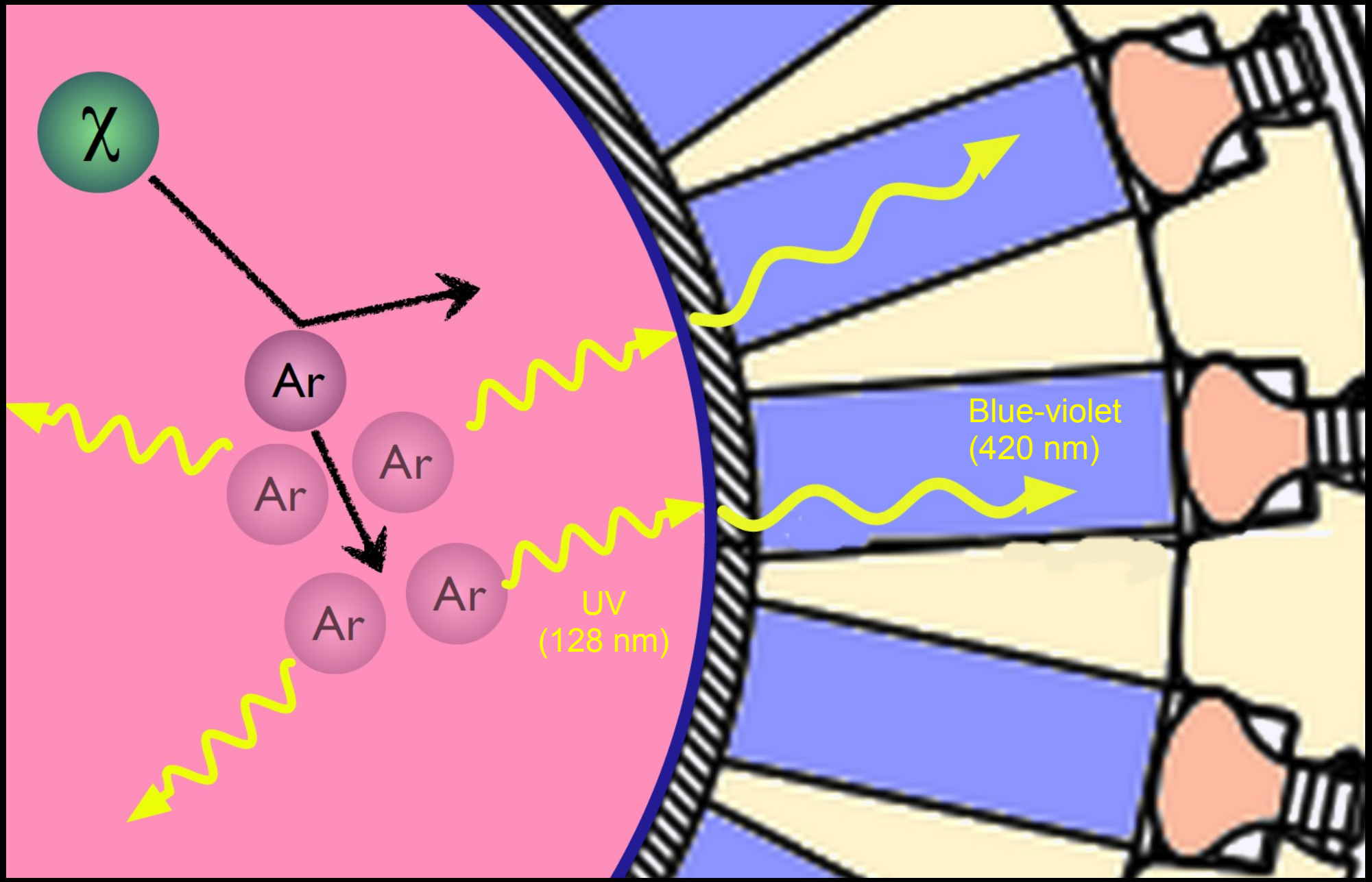




Dark matter Experiment using Argon Pulse-shape discrimination



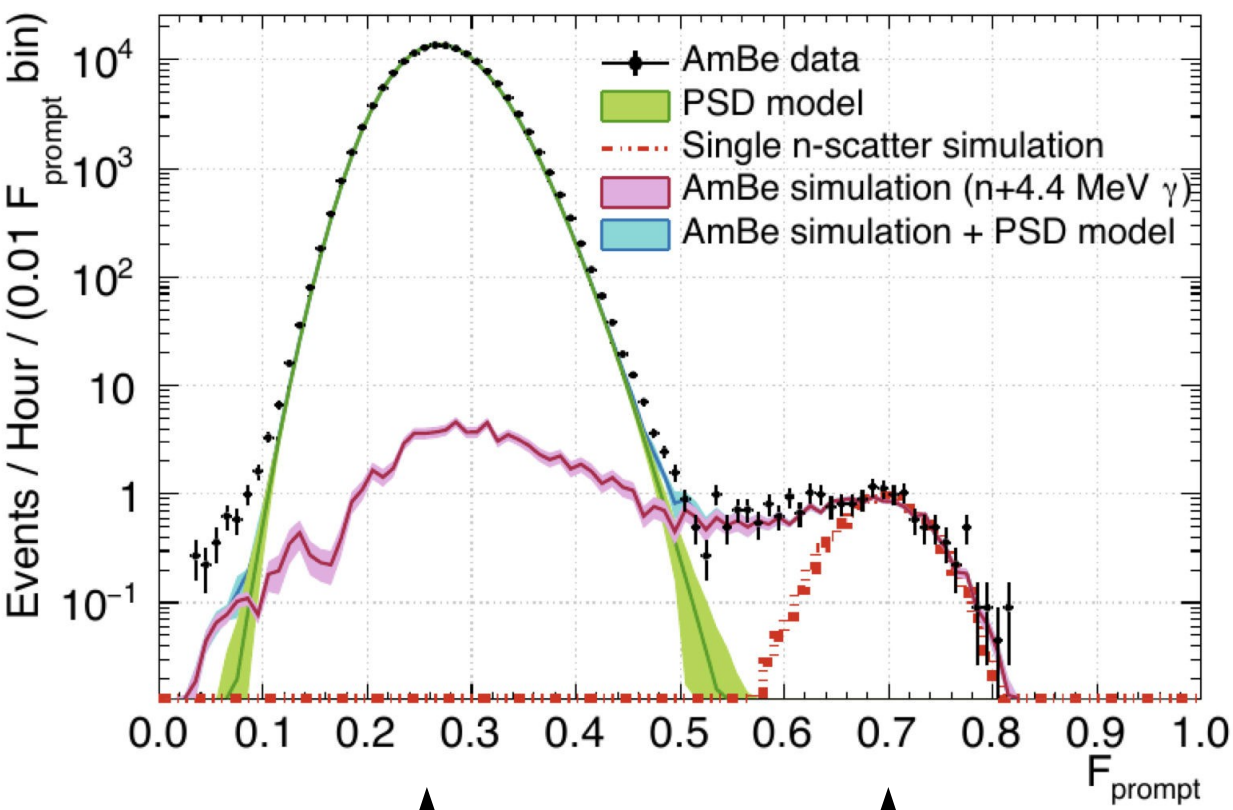
Water shielding


χ
Ar
Ar
Ar
Ar
Ar
UV
(128 nm)
Blue-violet
(420 nm)

Did you say “pulse-shape discrimination”?

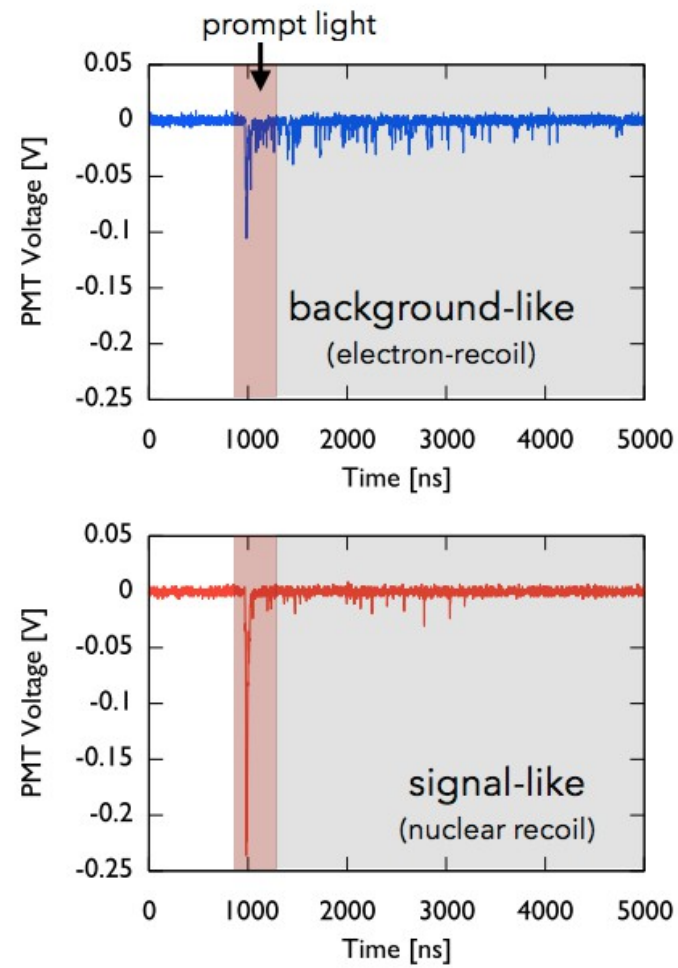
The goal is to **select dark matter signal events**, and <u>reject background events</u>

Example: Neutron source calibration data



Background-like
(electron recoils, ^{39}Ar)

Signal-like
(nuclear recoils)

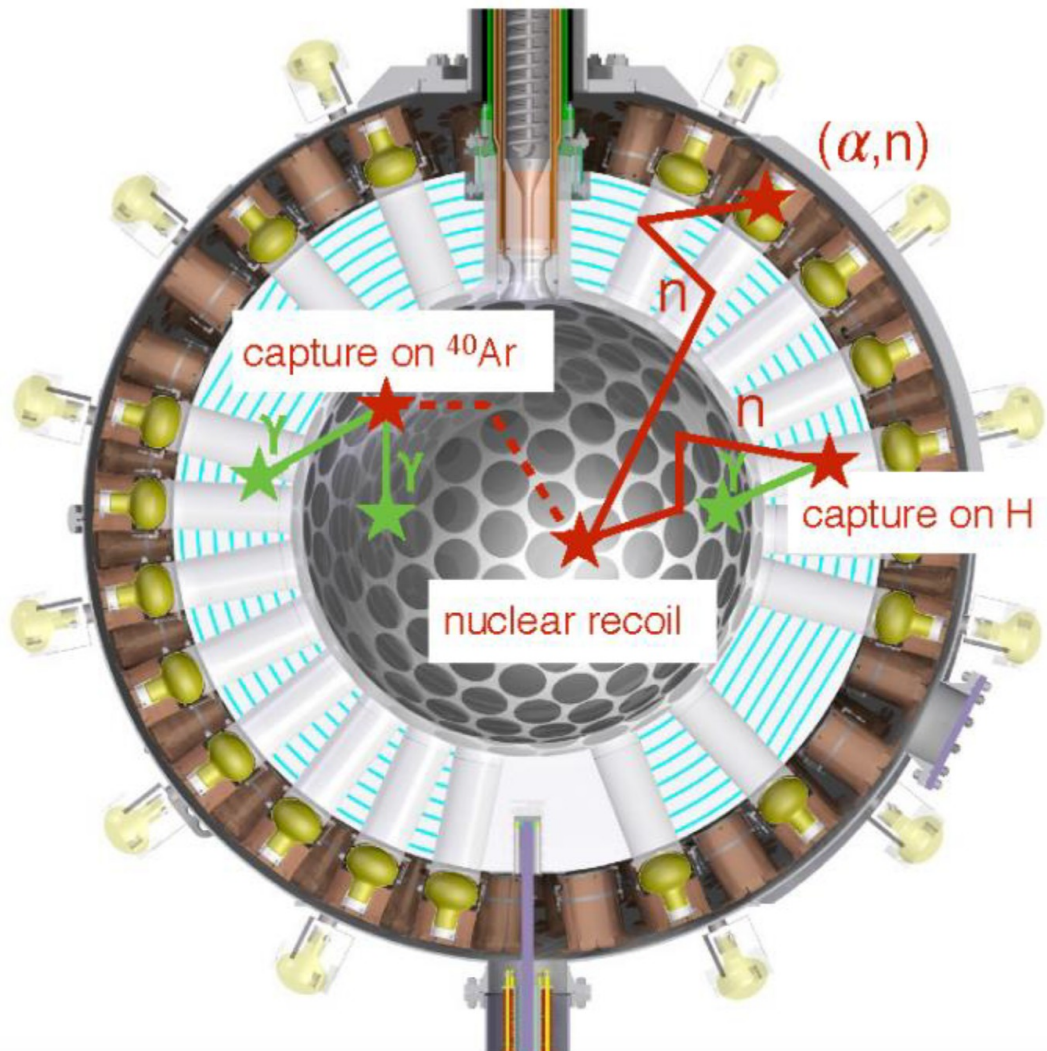


$$F_{prompt} = \frac{\text{PE prompt}}{\text{PE total}}$$

Nuclear recoil backgrounds: Neutrons

Signal-like events can be produced by **neutrons** wandering into the detector

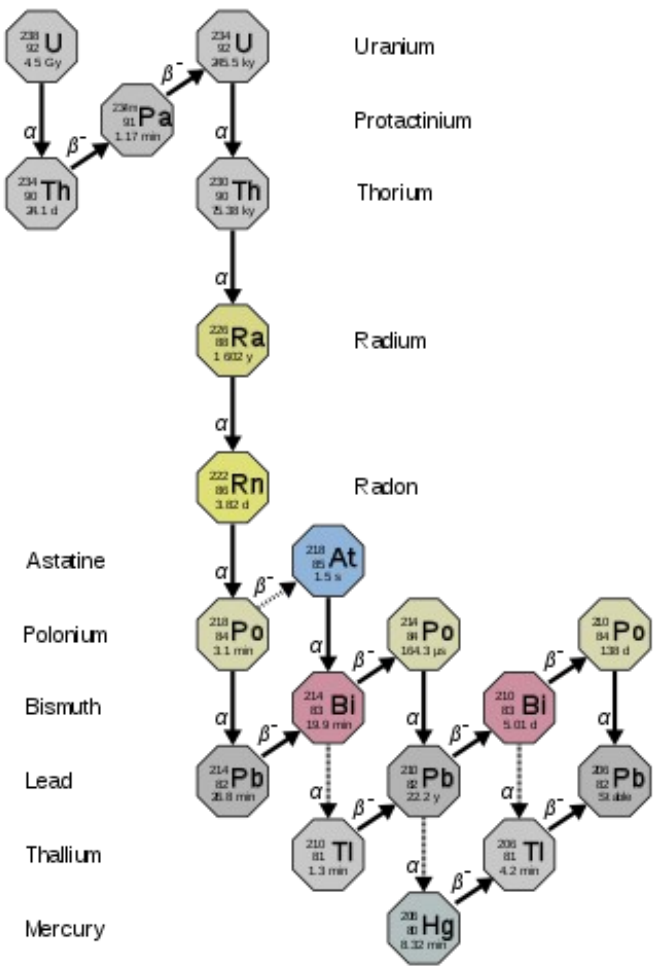
These events can cause multiple nuclear recoils in close succession,
or result in gamma-ray emission → **Reject** events observed with these properties

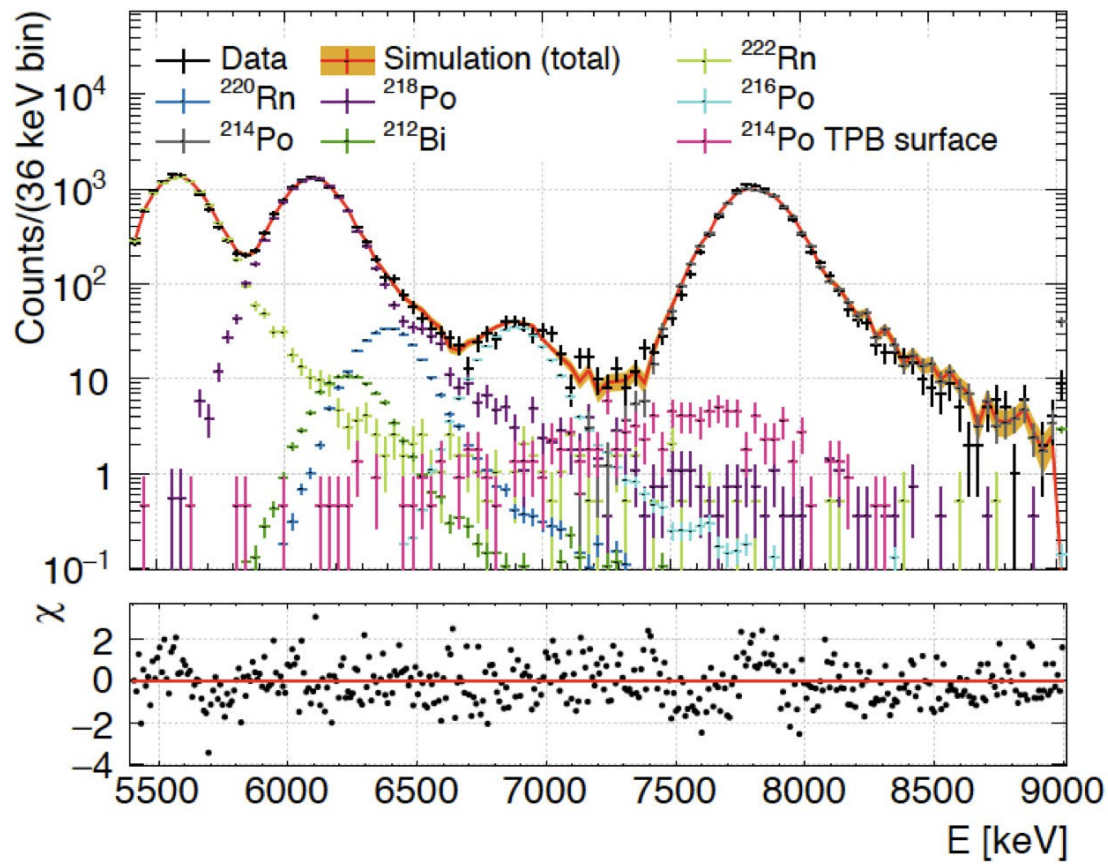


Nuclear recoil backgrounds: Alphas from liquid argon bulk

Signal-like events can be produced by radioactive decays **in the liquid argon**

These events deposit **much more energy** than dark matter interactions (50-100 keV)
→ Much more light detected → No impact on the dark matter search



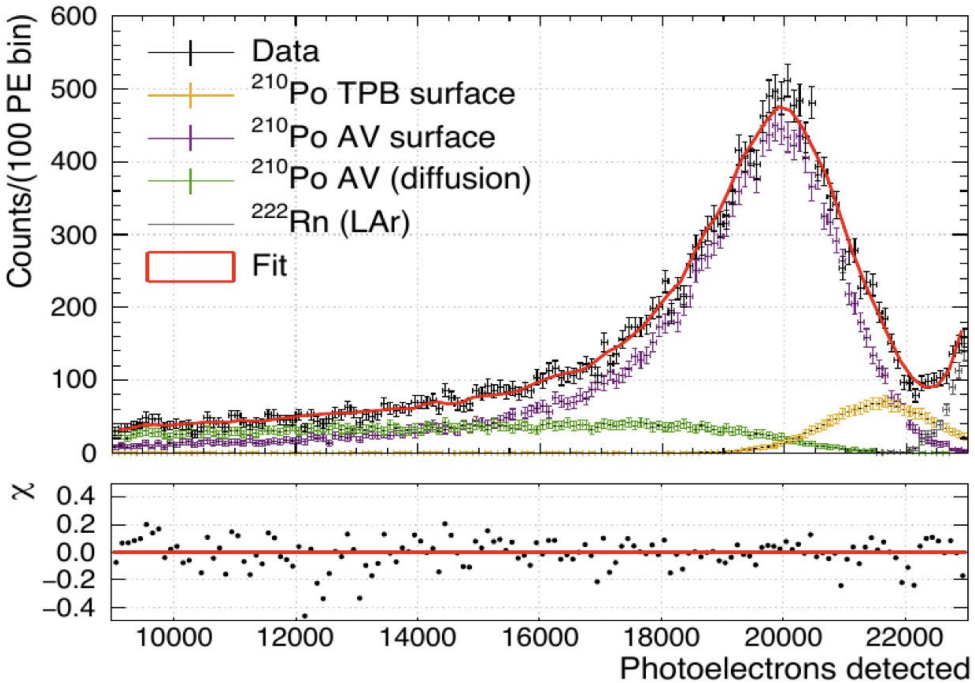


High-energy events observed from the liquid argon volume are well-explained by our background model

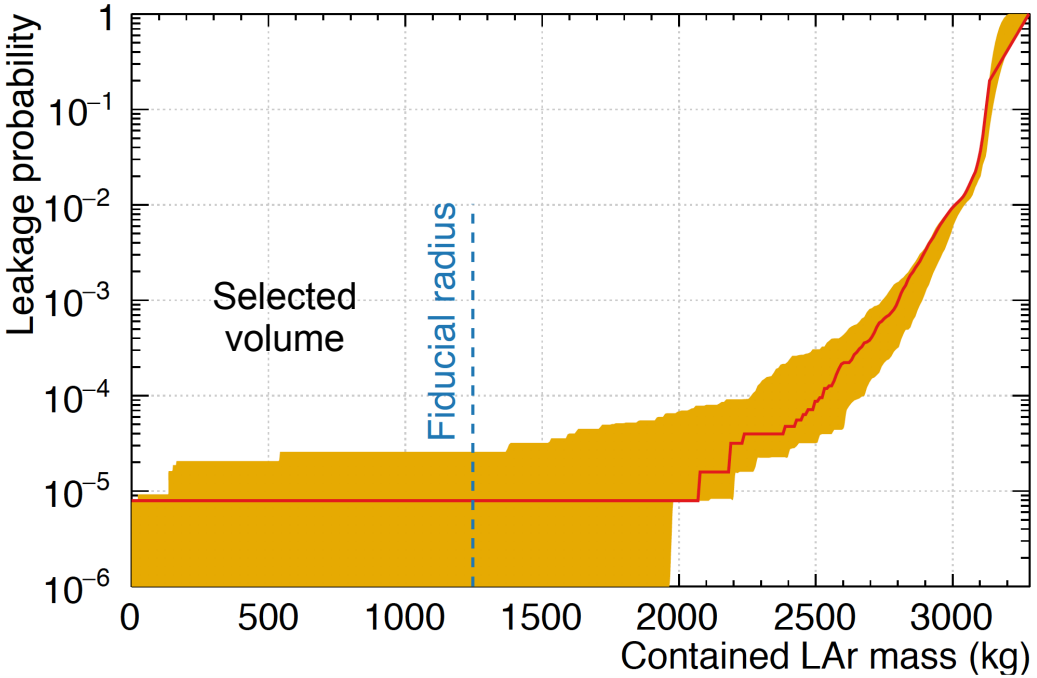
Nuclear recoil backgrounds: Alphas from detector surface

Signal-like events can be produced by radioactive decays **at the detector surface**

Position reconstruction algorithms are able to reject these backgrounds effectively



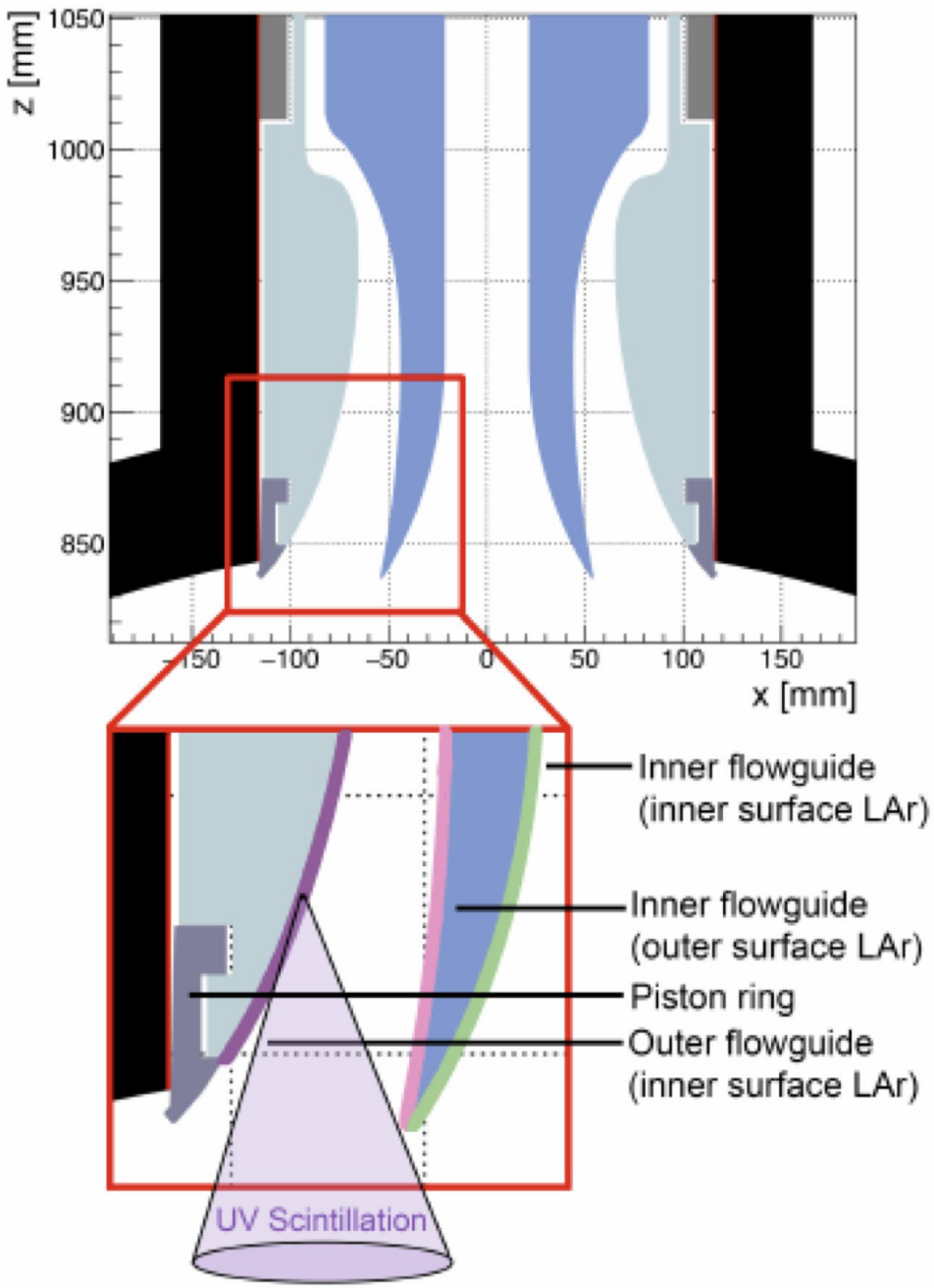
High-energy events observed from the detector surface are well-explained by our background model



Select events from the **innermost part** of the liquid argon vessel

Excellent performance of position reconstruction for rejecting simulated alpha-decays from the detector surface

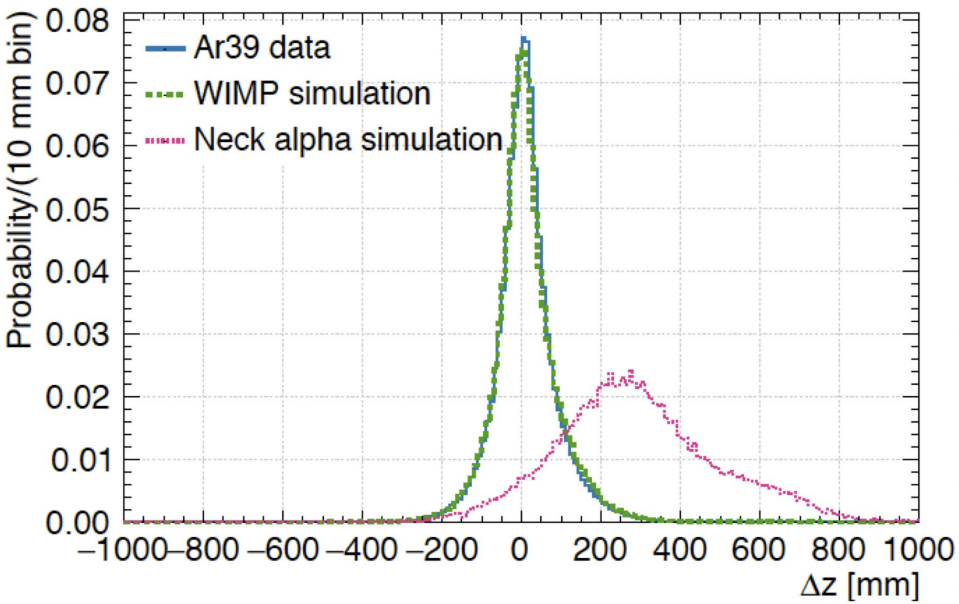
Nuclear recoil backgrounds: Alphas from detector neck



Signal-like events can be produced by radioactive decays **at the detector neck**

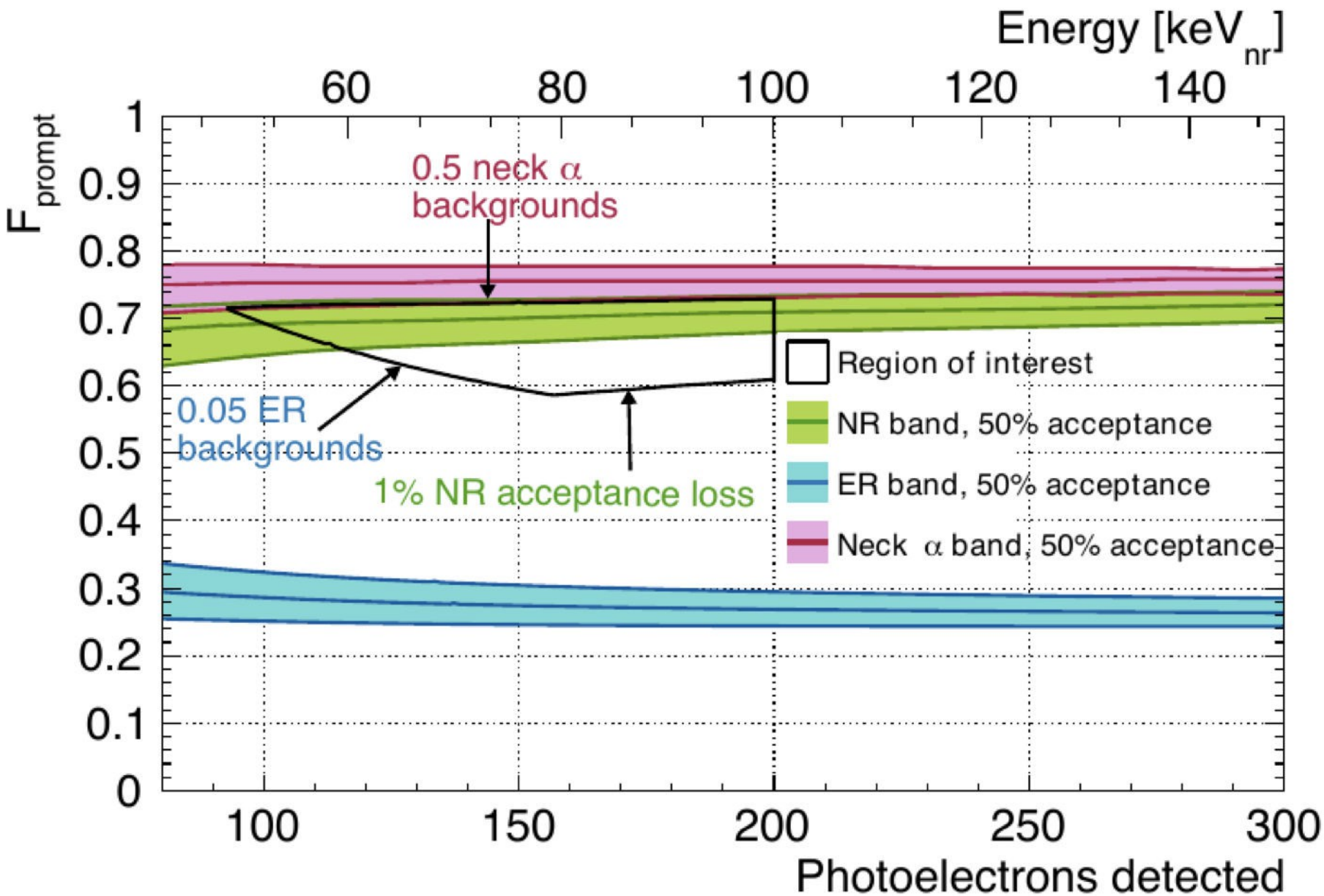
These background events can be particularly **challenging**, because the scintillation light can be blocked

Dedicated event selection and **position reconstruction** are able to reject these backgrounds effectively



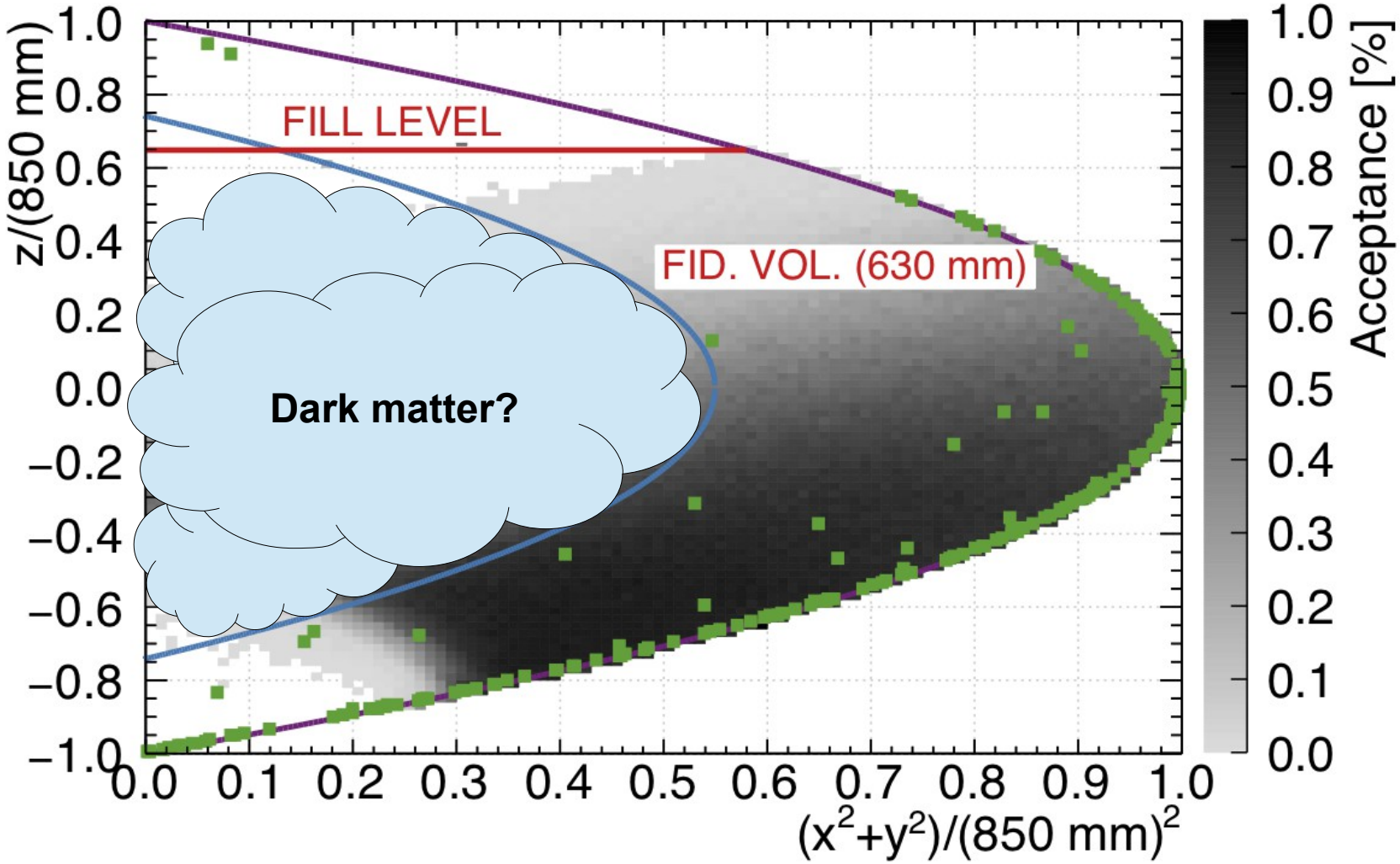
Time-based vs. pattern-based reconstructed position

Definition of the Signal Region



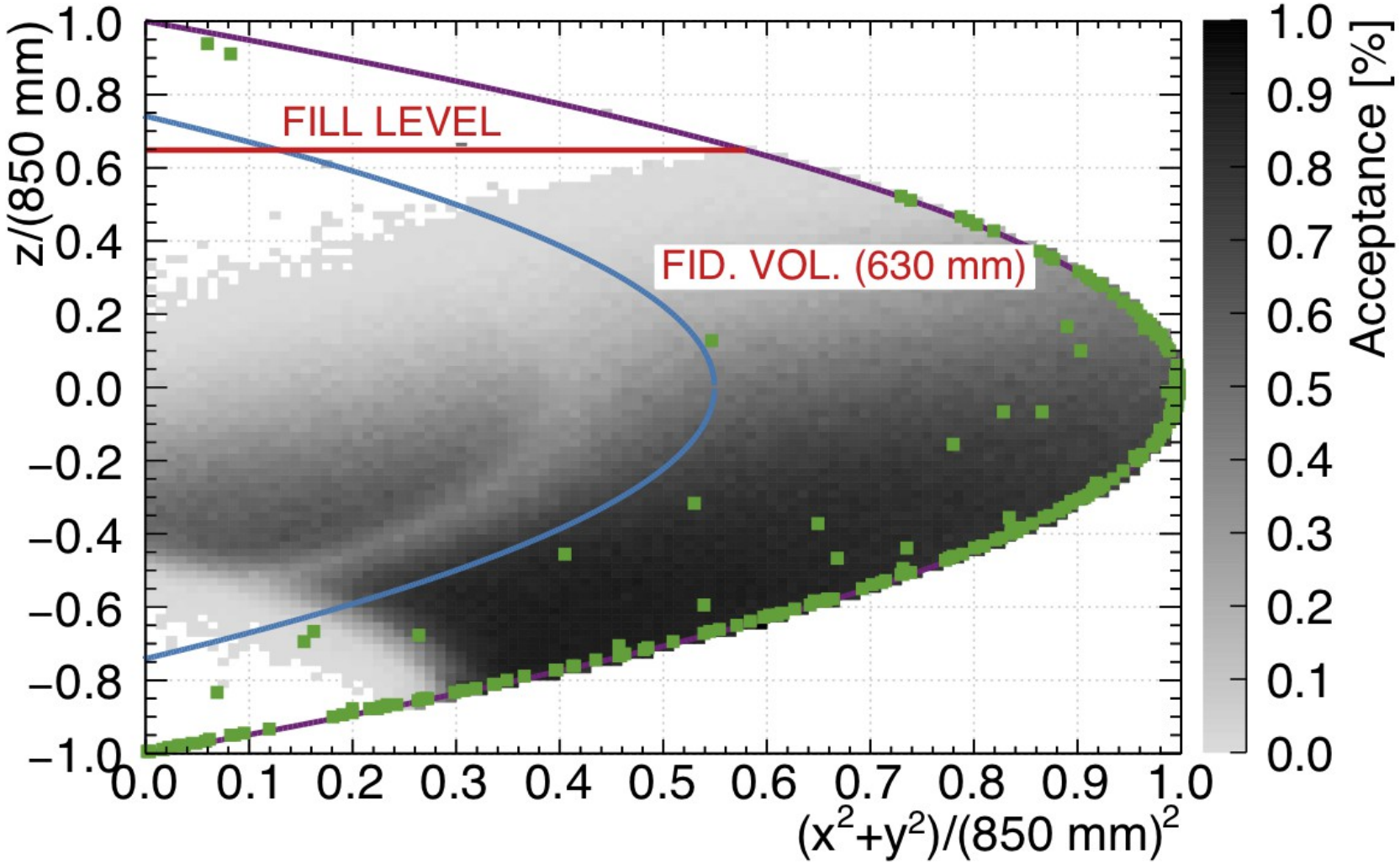
After event selection, the result is ...

Was dark matter observed in the first year of DEAP-3600 data?



After event selection, the result is ...

The detector is sensitive to dark matter, but no signal event was observed!



DEAP Collaboration (2019) Physical Review D, 100, 022004 arXiv:1902.04048

After event selection, the result is ...

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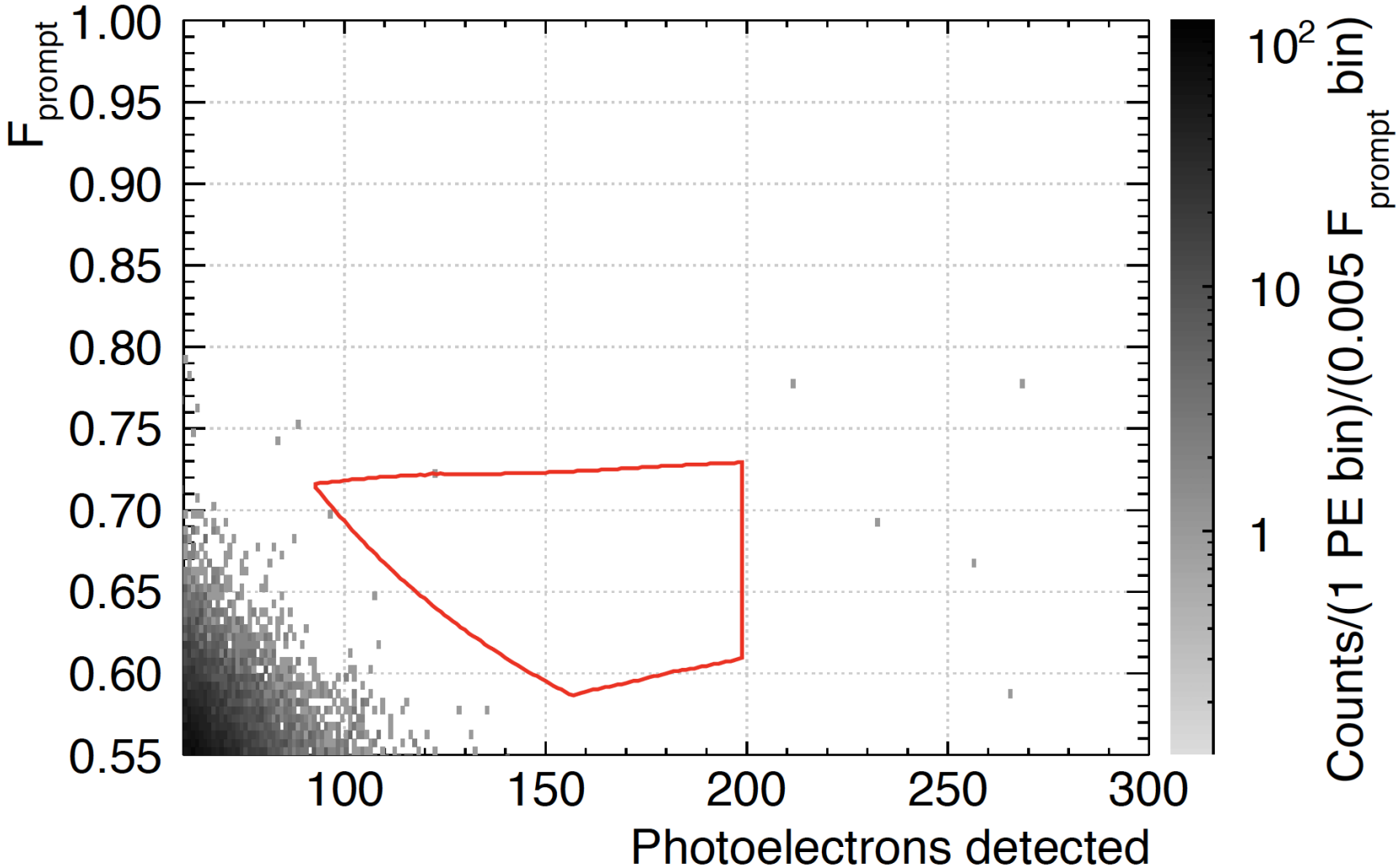
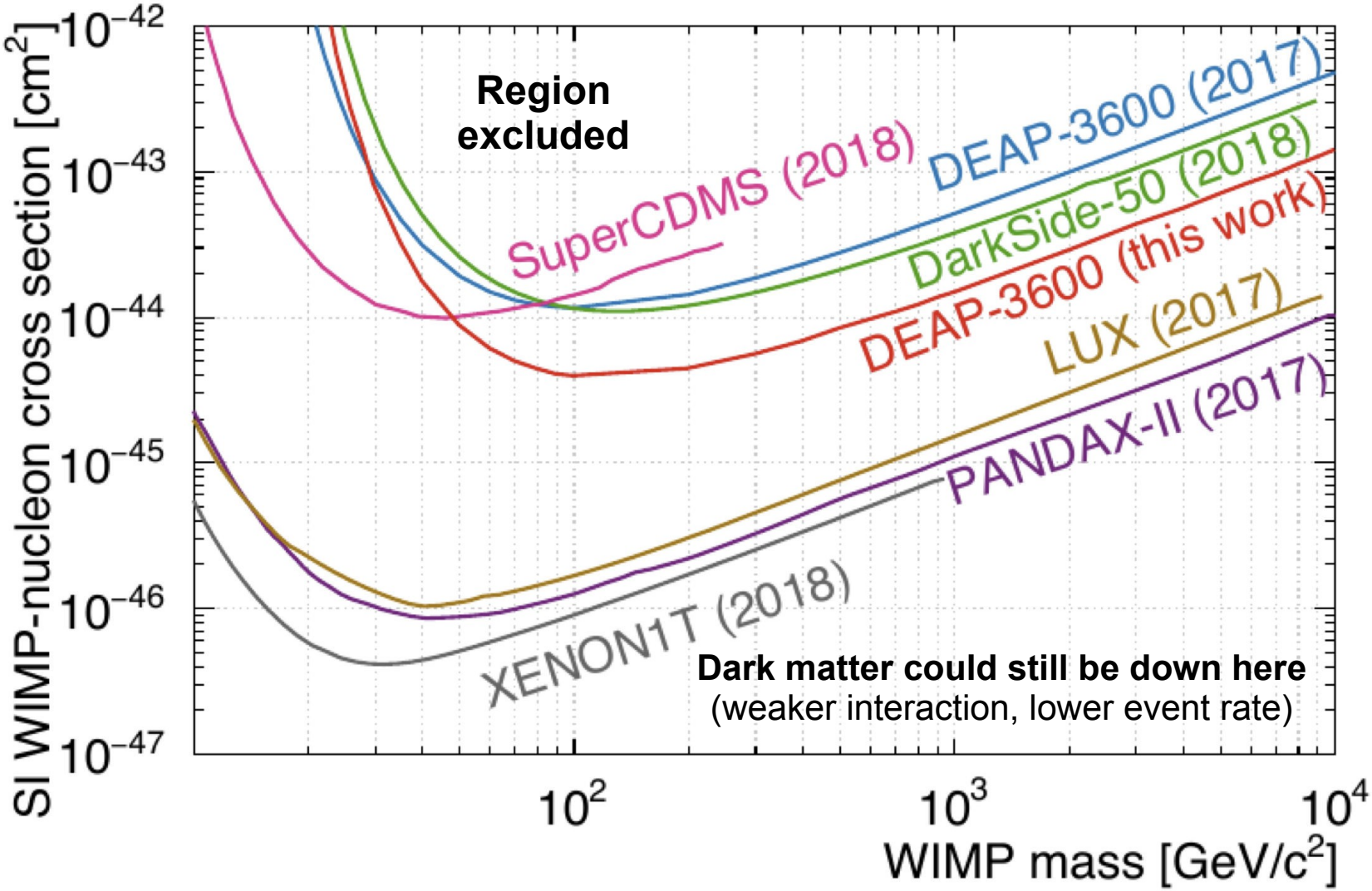


DEAP Collaboration (2019) Physical Review D, 100, 022004 arXiv:1902.04048

Dark matter search results

The detector is sensitive to dark matter, but no signal event was observed!

Therefore we **rule out** certain dark matter hypotheses



Sensitivity of future dark matter searches

- How to maximize sensitivity with next-generation experiments? **Think BIG!**
- **Global Argon Dark Matter Collaboration** formed!
  - Objective: to reach ultimate sensitivity to spin-independent nuclear interactions with high-mass dark matter, with a **multi-hundred tonnes** liquid argon detector

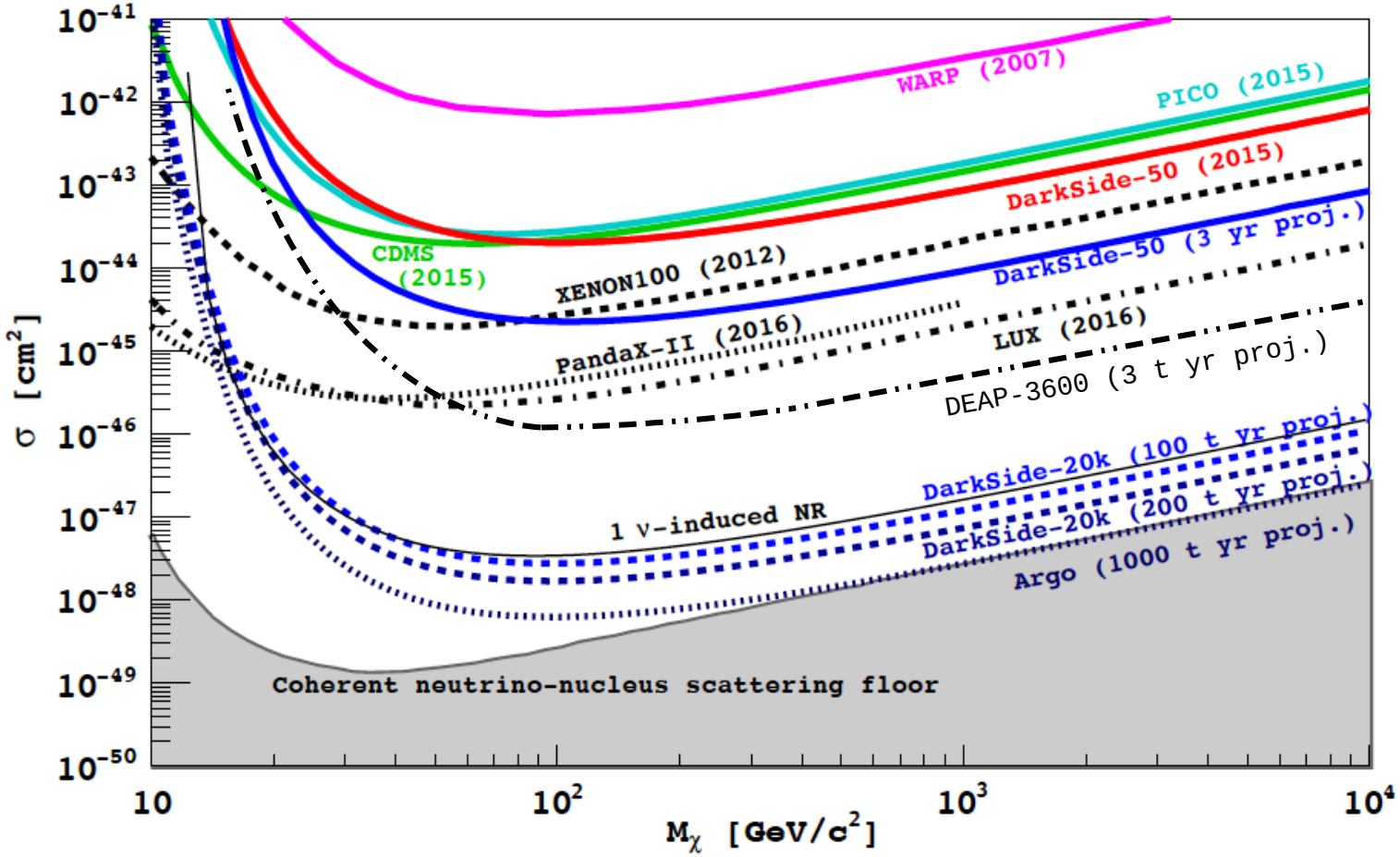
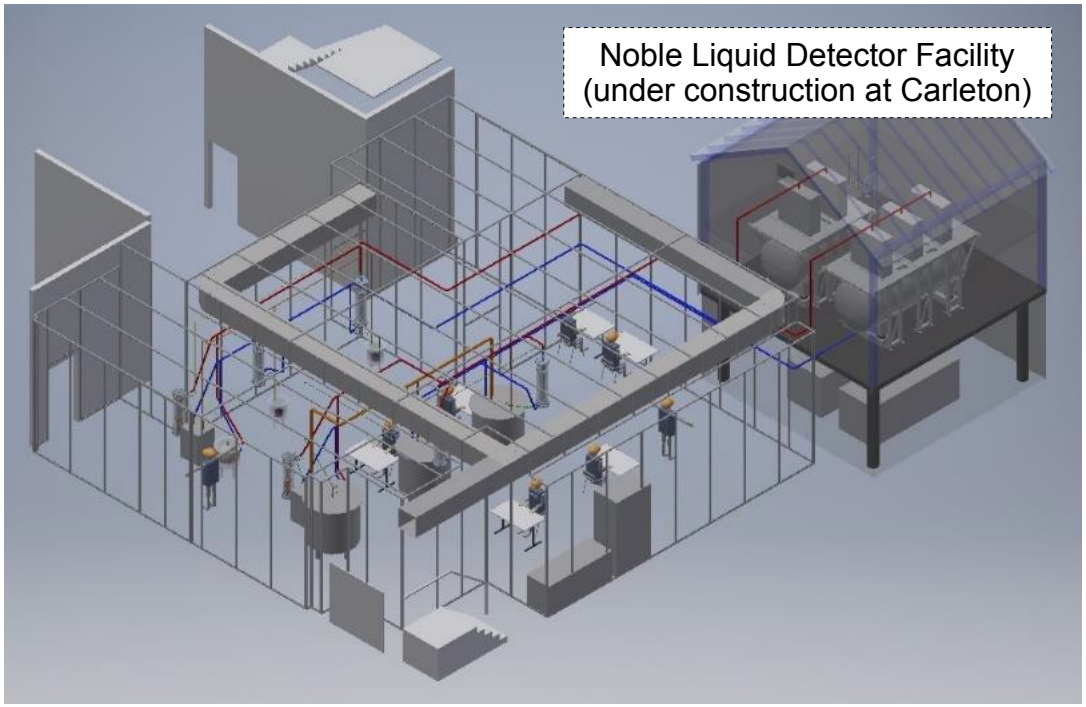
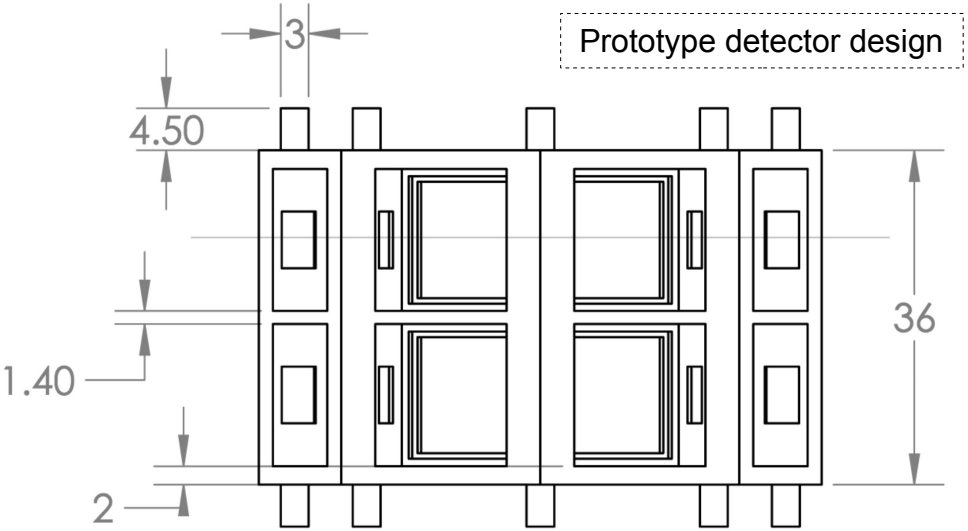


Figure credit: DarkSide-20k, arXiv:1707.08145 (DEAP-3600 expected limit added by hand)

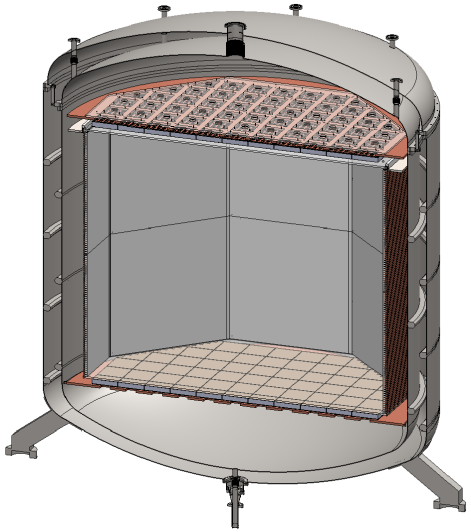
Experiment design, research and development



Noble Liquid Detector Facility
(under construction at Carleton)

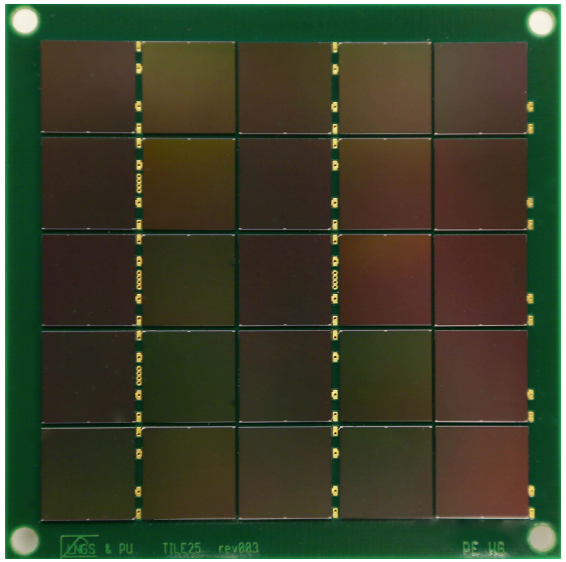


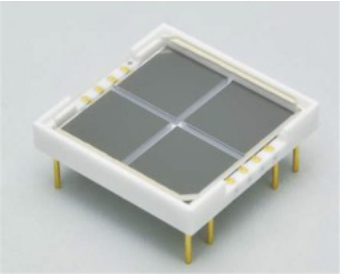
Prototype detector design



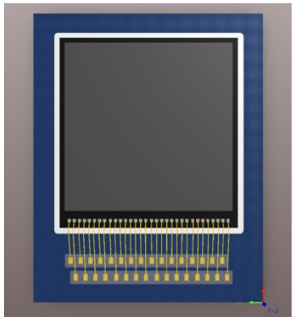
DarkSide-20k simulation

DarkSide-20k prototype SiPM tile

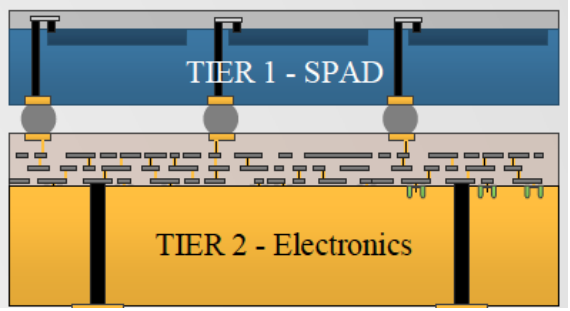




Hamamatsu VUV4



3DdSiPM, top view



3DdSiPM, side view

Conclusions

- **Dark matter** is one of the most fundamental questions of our time
  - Has to exist in abundant quantities
    - Interacts so weakly with ordinary matter, that it has not been discovered yet
  - Looking for dark matter directly with the **DEAP-3600** experiment at **SNOLAB**
    - Found no dark matter signal event → Excluded some hypotheses
    - Experiment is still taking data!
      - More and more sensitive to very rare events in the detector
- **Instrumentation** research and development for future particle detectors
  - Design and simulation for DarkSide-20k and ARGO
  - Silicon photomultipliers, with applications within and outside particle physics (e.g. medical physics: imaging devices, positron emission tomography, etc.)
- Why study **particle physics**?
  - Understand the world around us with a deep, fundamental perspective
  - "The kinds of beauty that are most embodied in physics are symmetry on the one hand, and exuberance on the other." – Frank Wilczek

Stay curious!