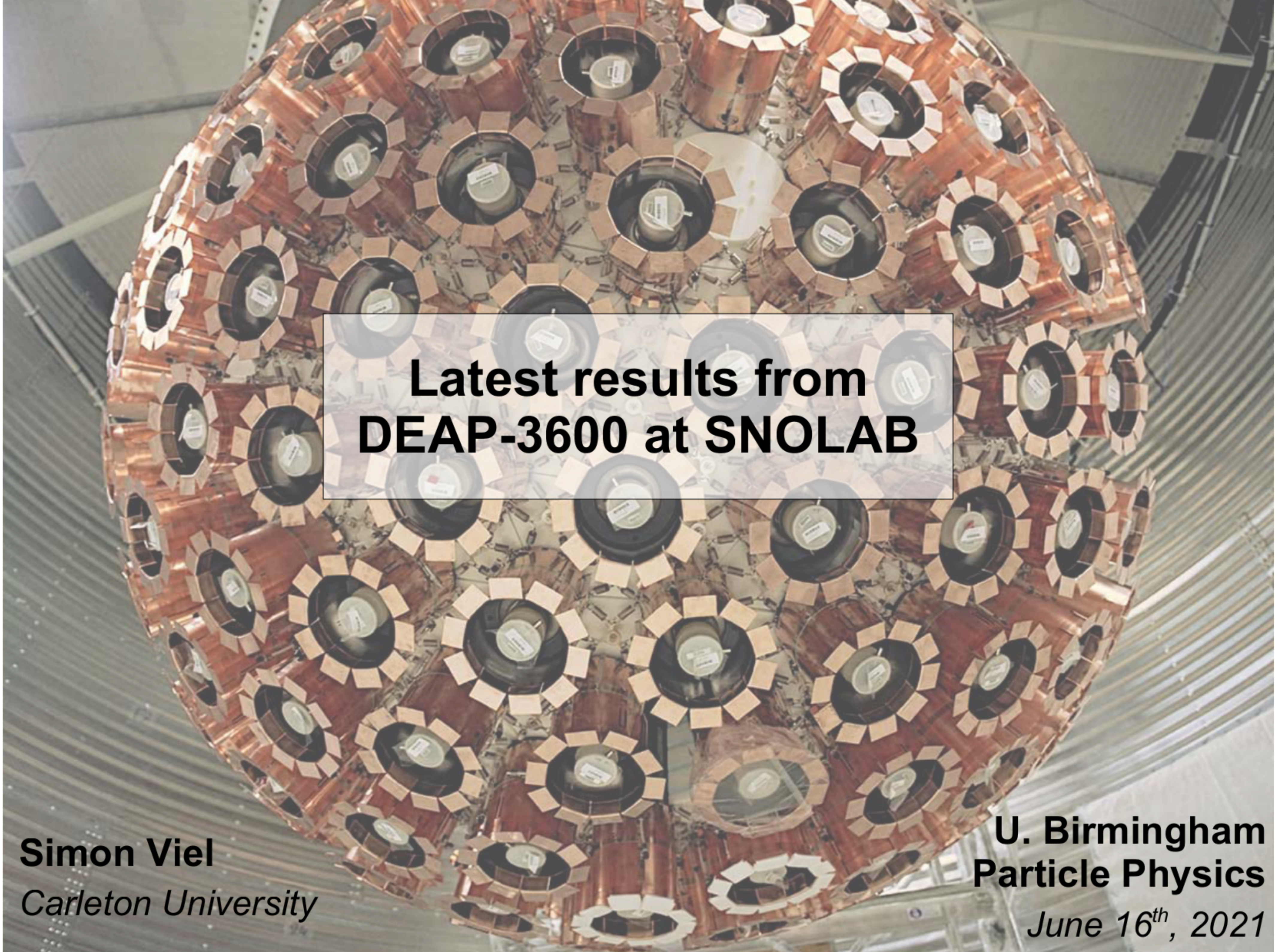
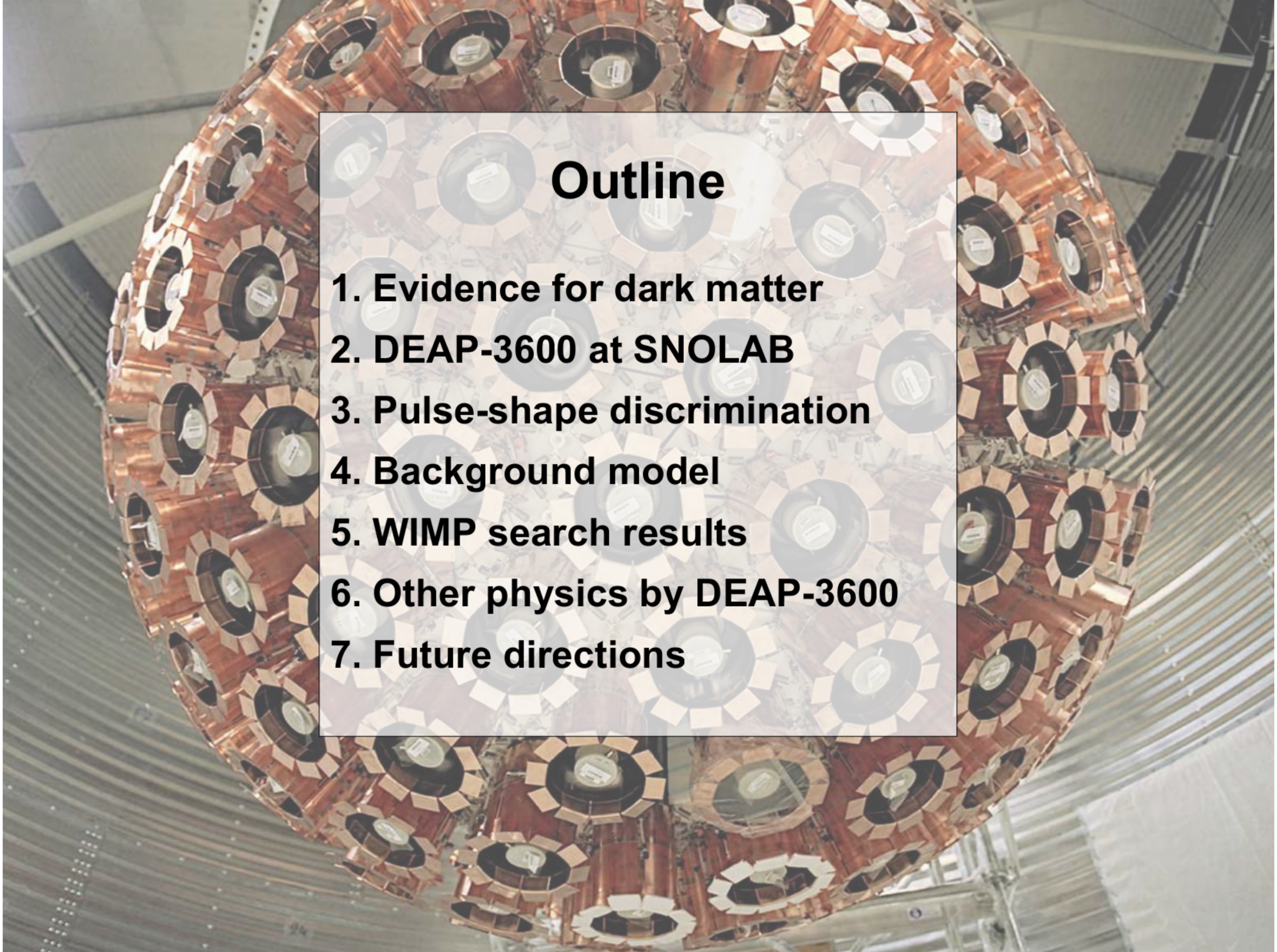


Latest results from DEAP-3600 at SNOLAB

Simon Viel
Carleton University

U. Birmingham Particle Physics
June 16th, 2021



Outline

1. Evidence for dark matter
2. DEAP-3600 at SNOLAB
3. Pulse-shape discrimination
4. Background model
5. WIMP search results
6. Other physics by DEAP-3600
7. Future directions

DEAP Collaboration:

95 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

LaurentianUniversity
UniversitéLaurentienne

Instituto de Física

INFN Istituto Nazionale di Fisica Nucleare

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

PRINCETON UNIVERSITY

Queen's UNIVERSITY

ROYAL HOLLOWAY UNIVERSITY OF LONDON

St. Petersburg Nuclear Physics Institute

SNOLAB

US University of Sussex

Technical University of Munich

TRIUMF

Particle Physics
Rutherford Appleton Laboratory

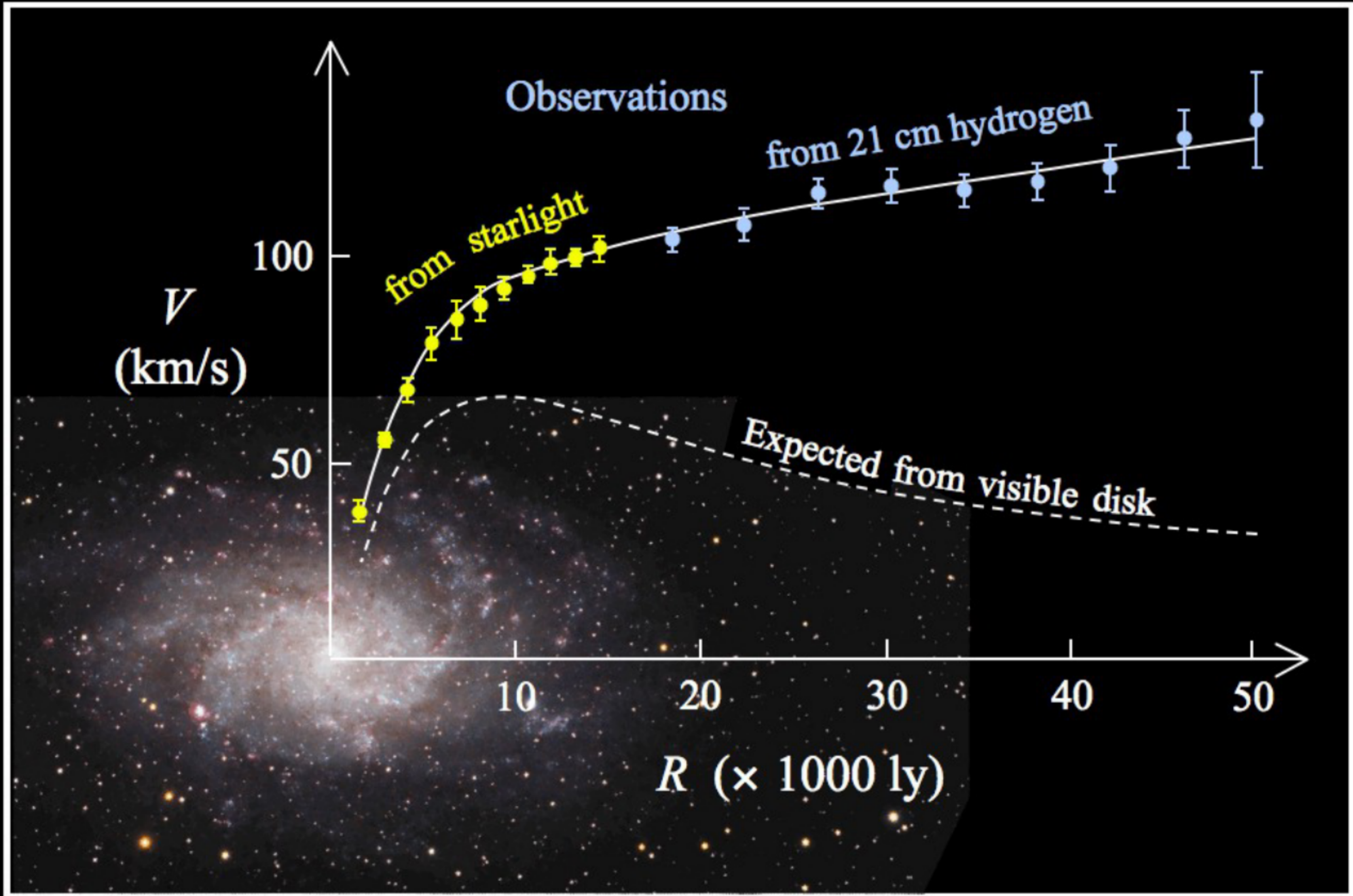
Thank you to funding agencies and partners for making this research possible!

The Whirlpool Galaxy (M51)

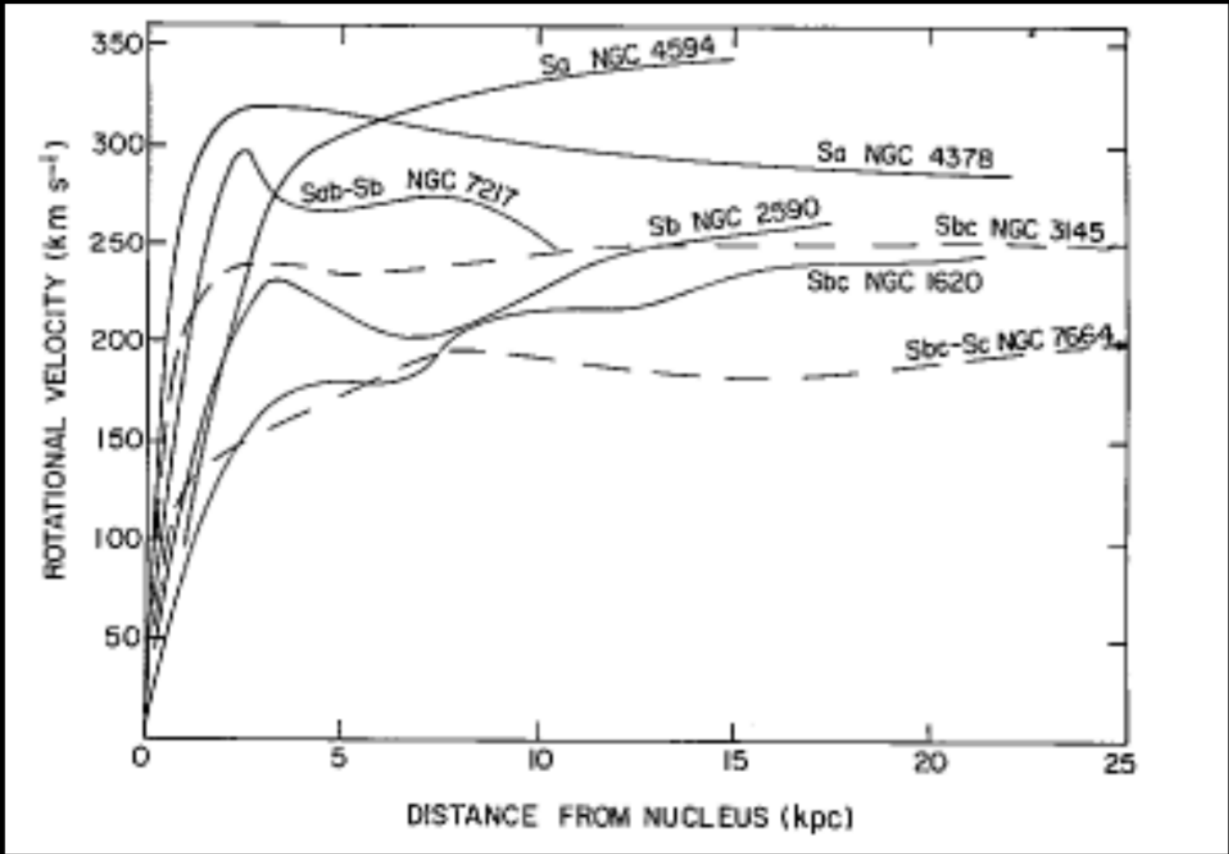
Figure credit: Chase Preuninger. Next slide: NASA / ESA, Hubble Space Telescope

The Mystery of Dark Matter

E. Corbelli and P. Salucci (2000), The extended rotation curve and the dark matter halo of M33
Figure by Stefania Deluca



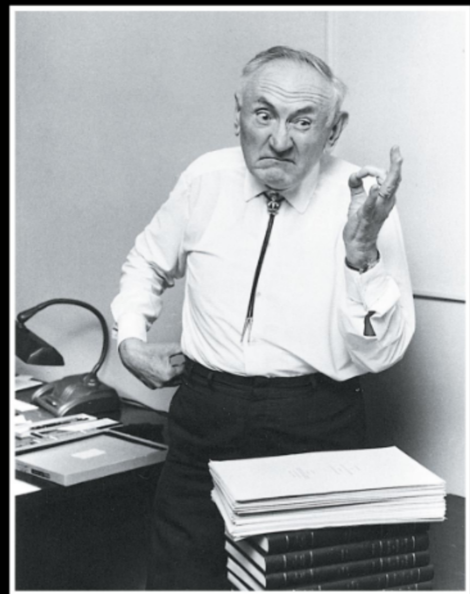
Velocity Profiles of Spiral Galaxies



V. Rubin, W. K. Ford Jr. and N. Thonnard (1978)
Astrophysical Journal, 225, L107-L111

Observation: Vera Rubin (1970)

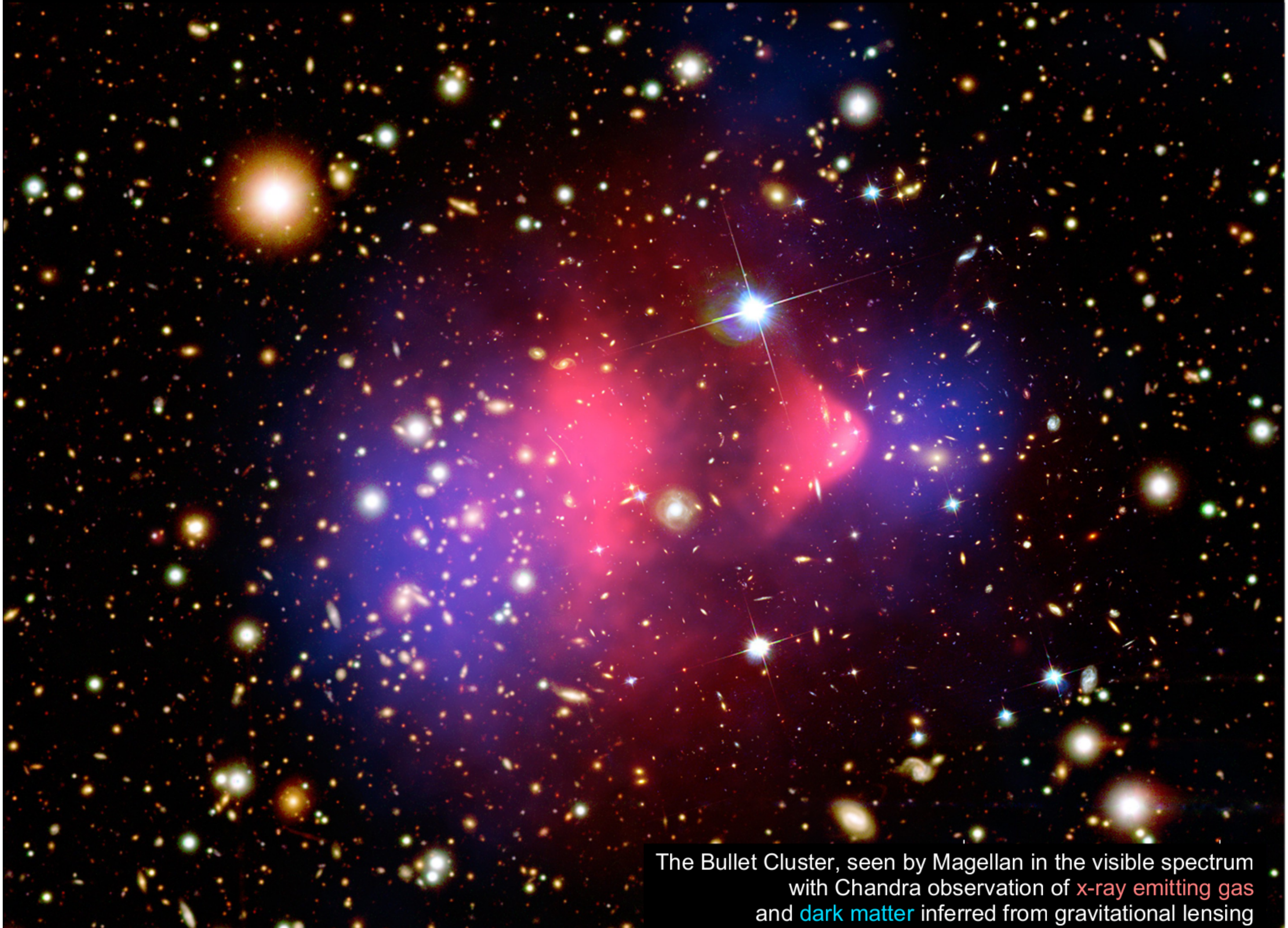
Theory: Fritz Zwicky (1933)



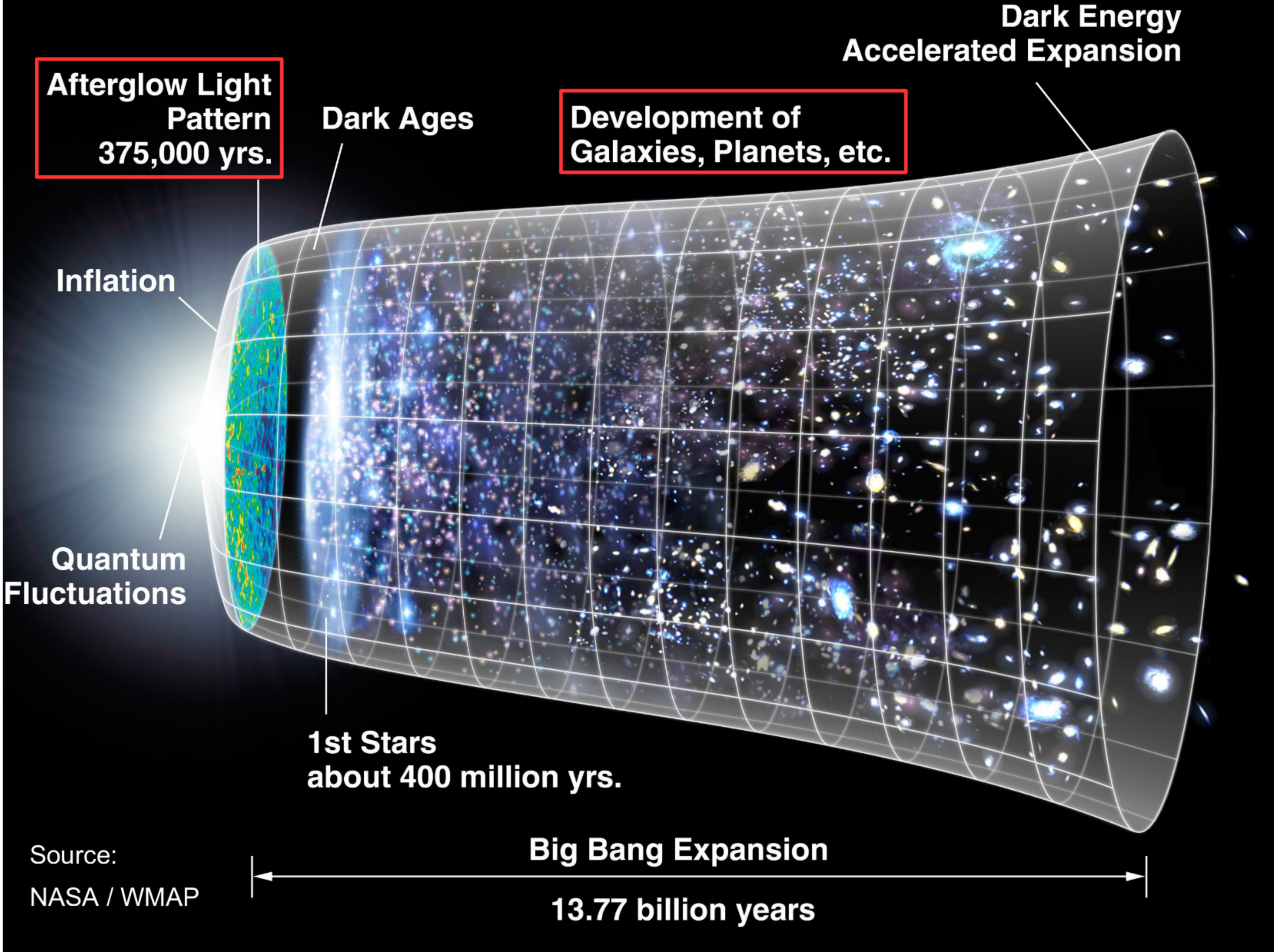
Most galaxies have “mass-to-light ratio” consistent with dark matter

→ Observed mass-to-light ratio values range from order 1 to 100

→ Supports dark matter hypothesis



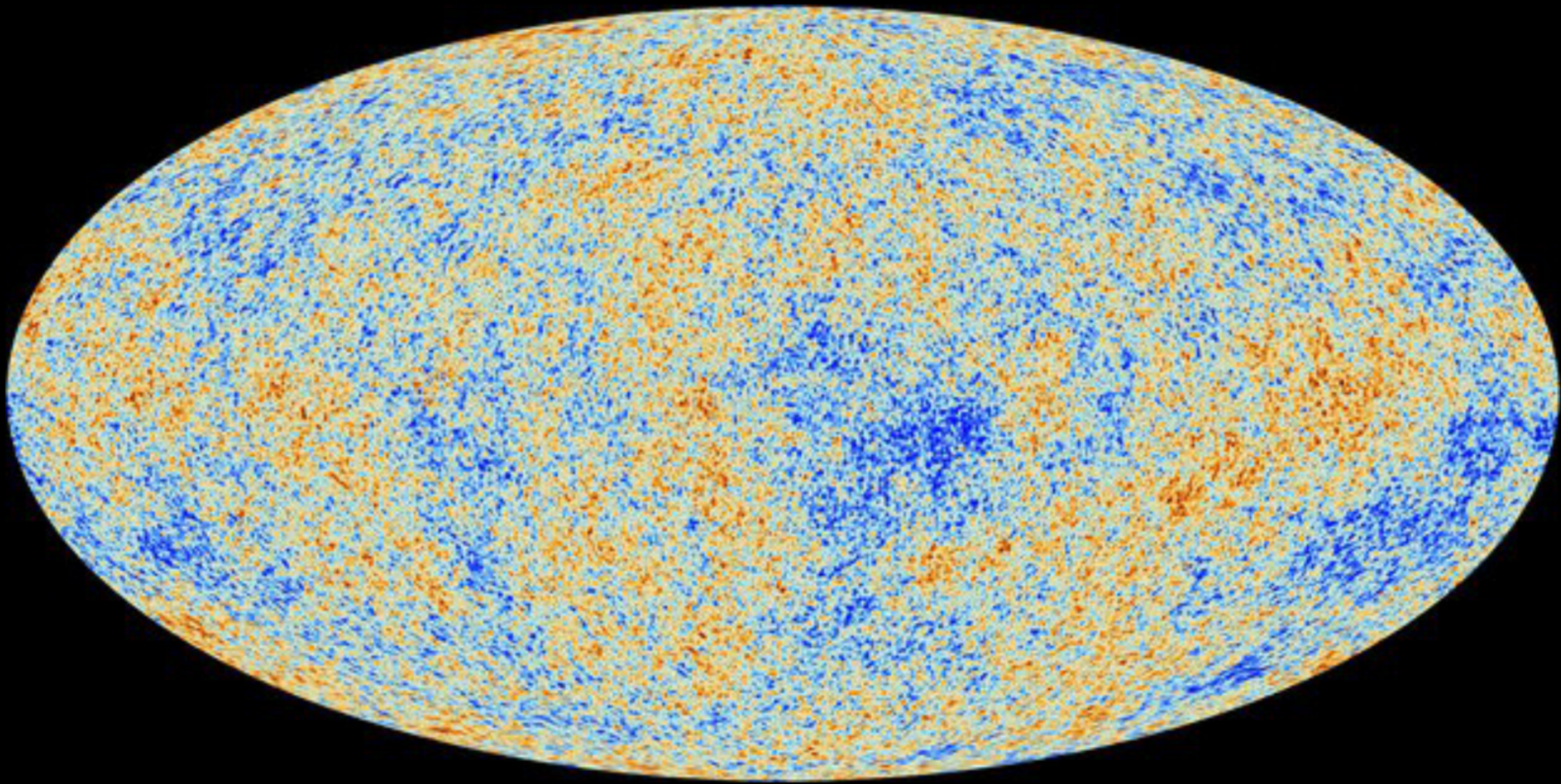
The Bullet Cluster, seen by Magellan in the visible spectrum
with Chandra observation of x-ray emitting gas
and dark matter inferred from gravitational lensing



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Source:
NASA / WMAP
Big Bang Expansion
13.77 billion years

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

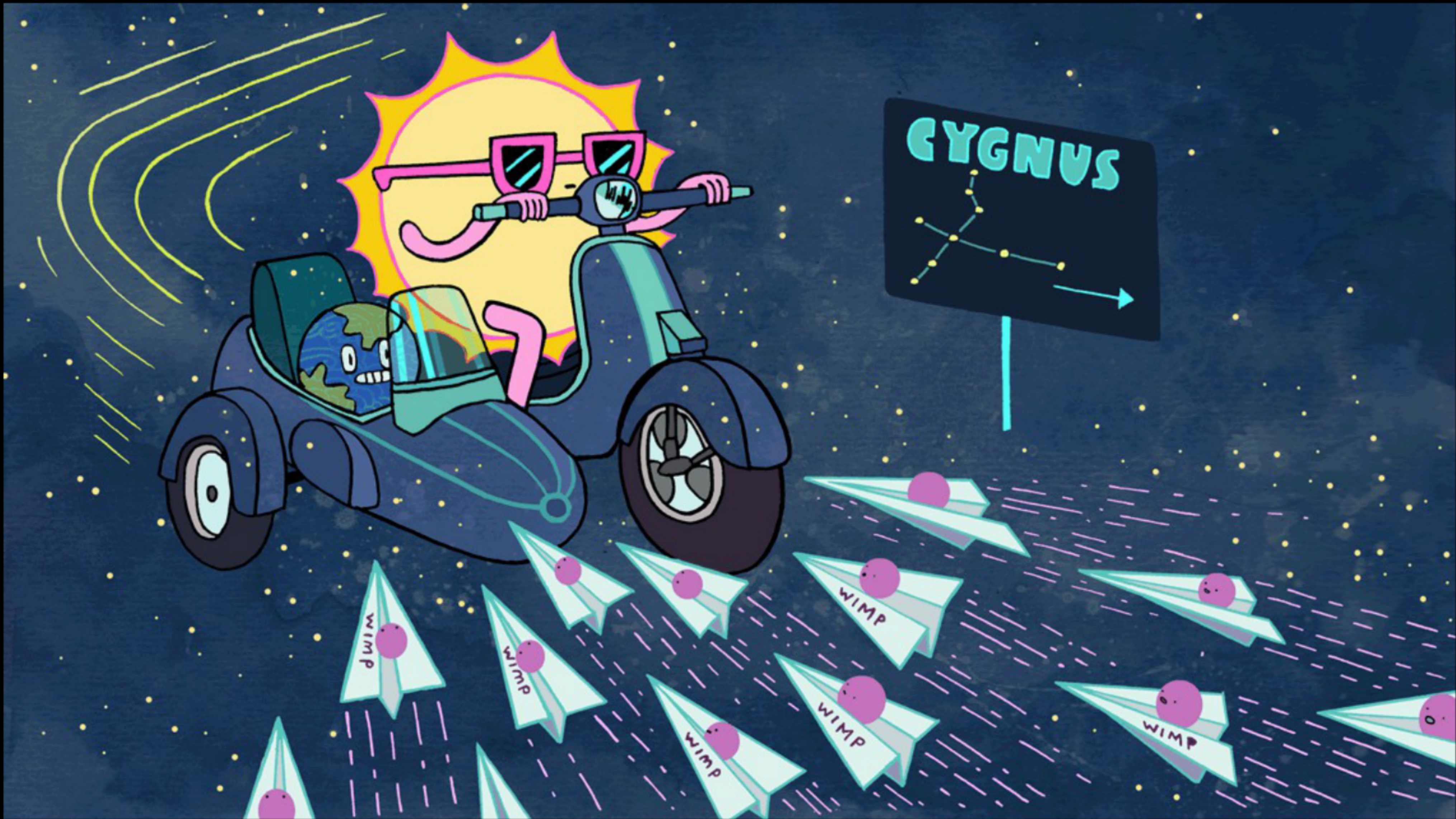


Temperature deviations from uniform blackbody with T = 2.726 K, shown on a ±300 μK scale

Source: European Space Agency / Planck collaboration

Riding in the Dark Matter Wind

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

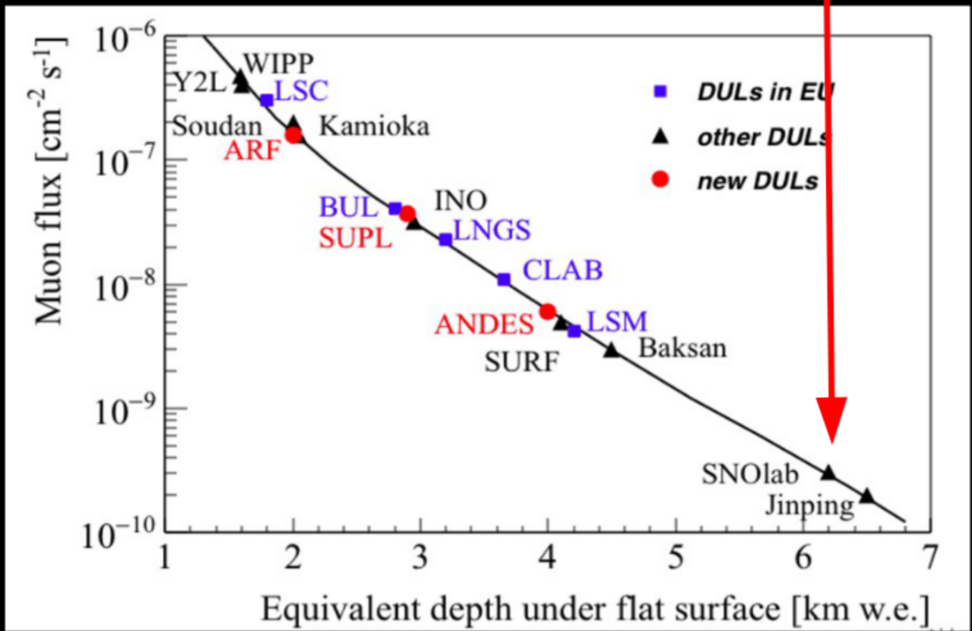


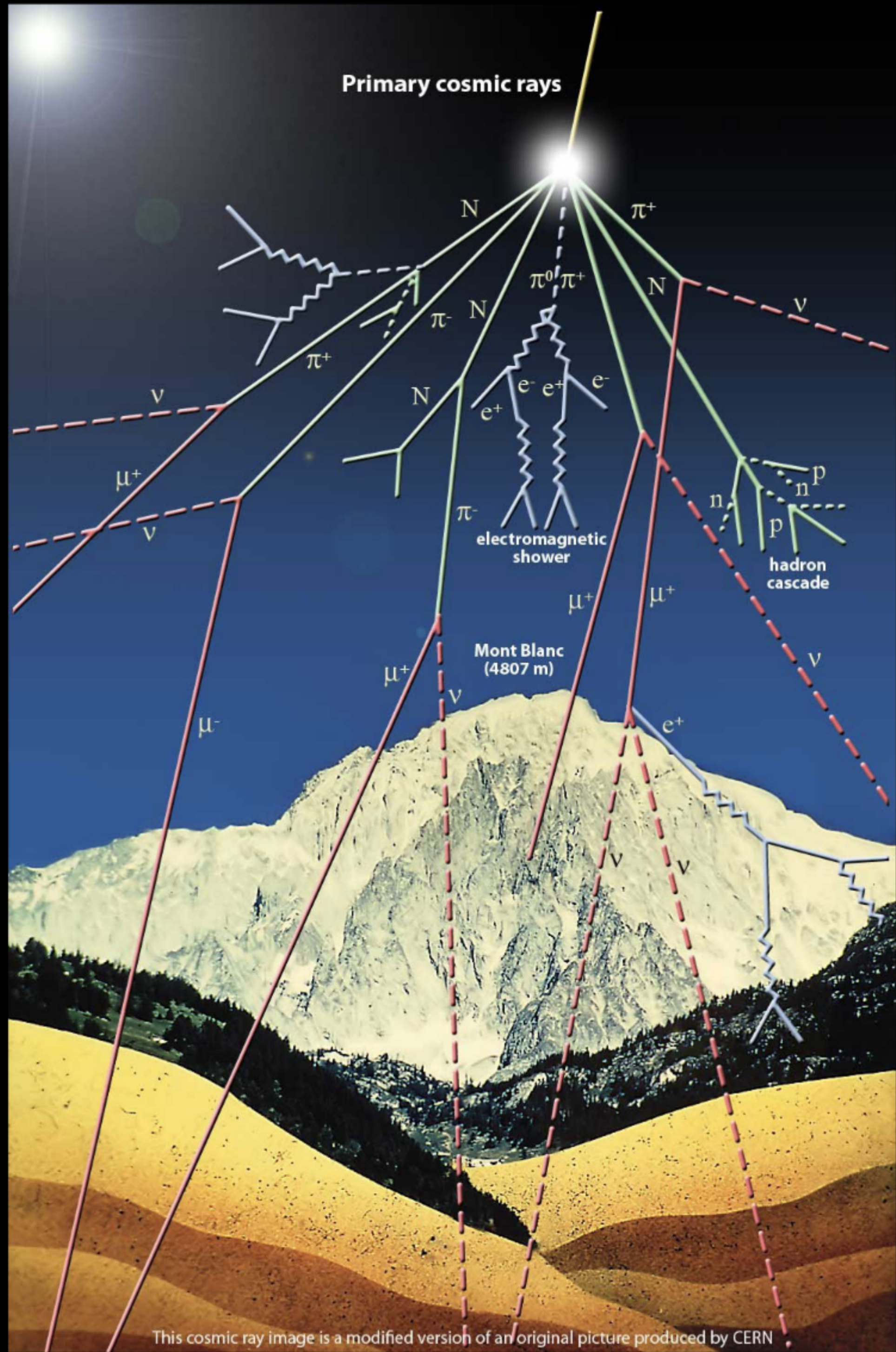
Why go underground?

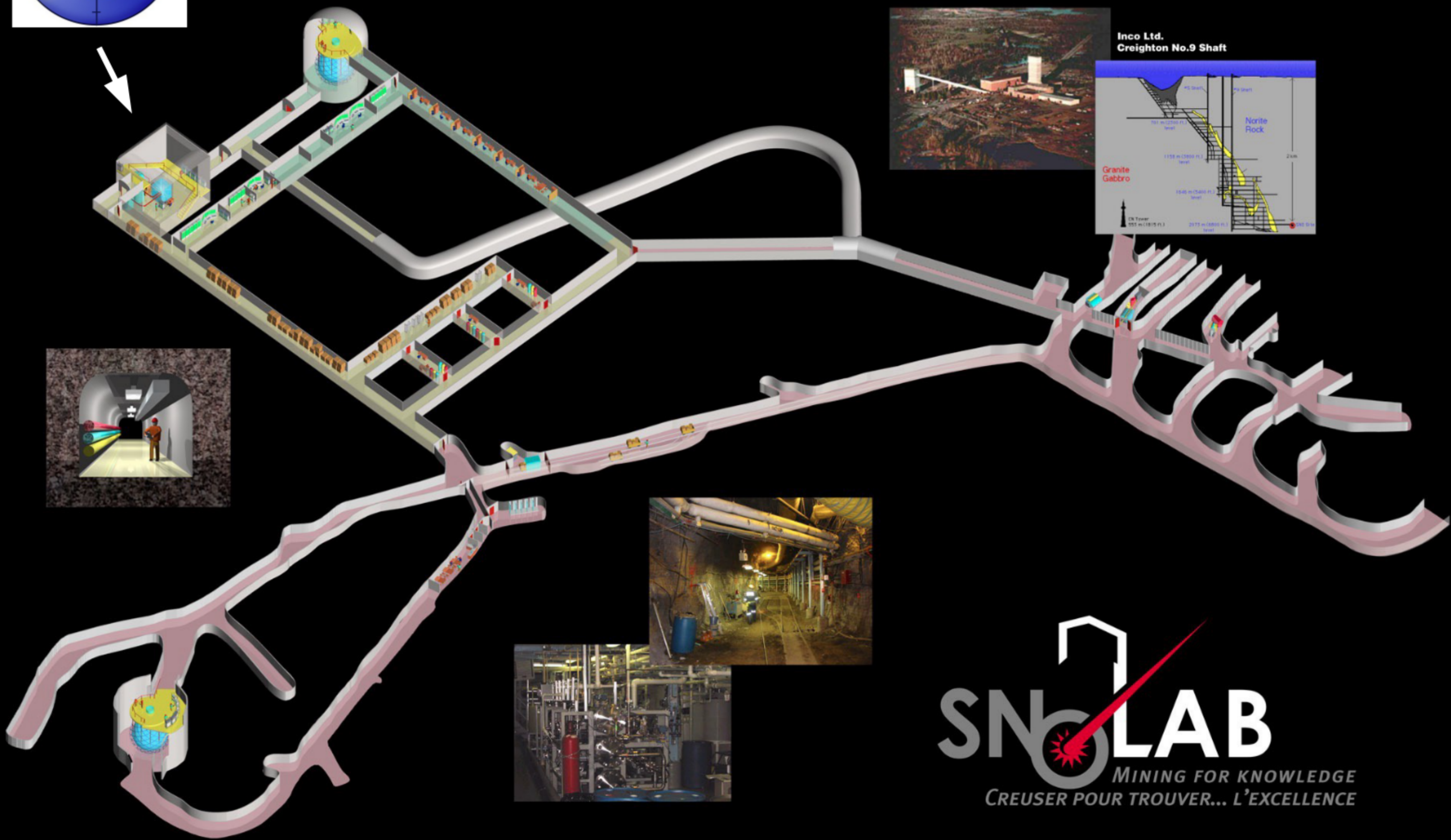
To shield detectors against cosmic rays

Surface:
~ 1 muon / cm^2 / minute
~ 14.4 million muons / m^2 / day

SNOLAB:
0.27 muons / m^2 / day







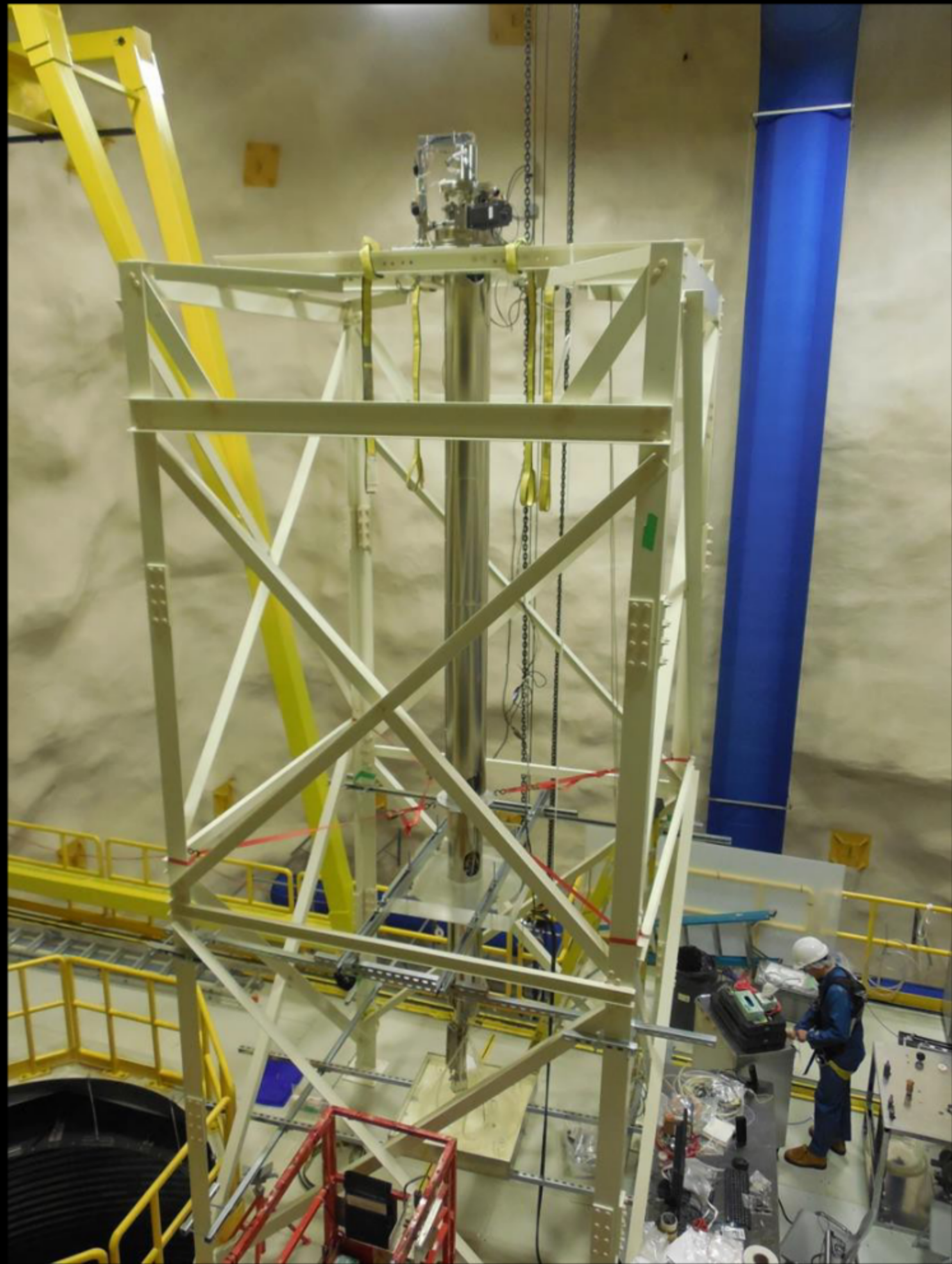
Video: A Day at SNOLAB
https://www.snolab.ca/outreach

2070 m underground

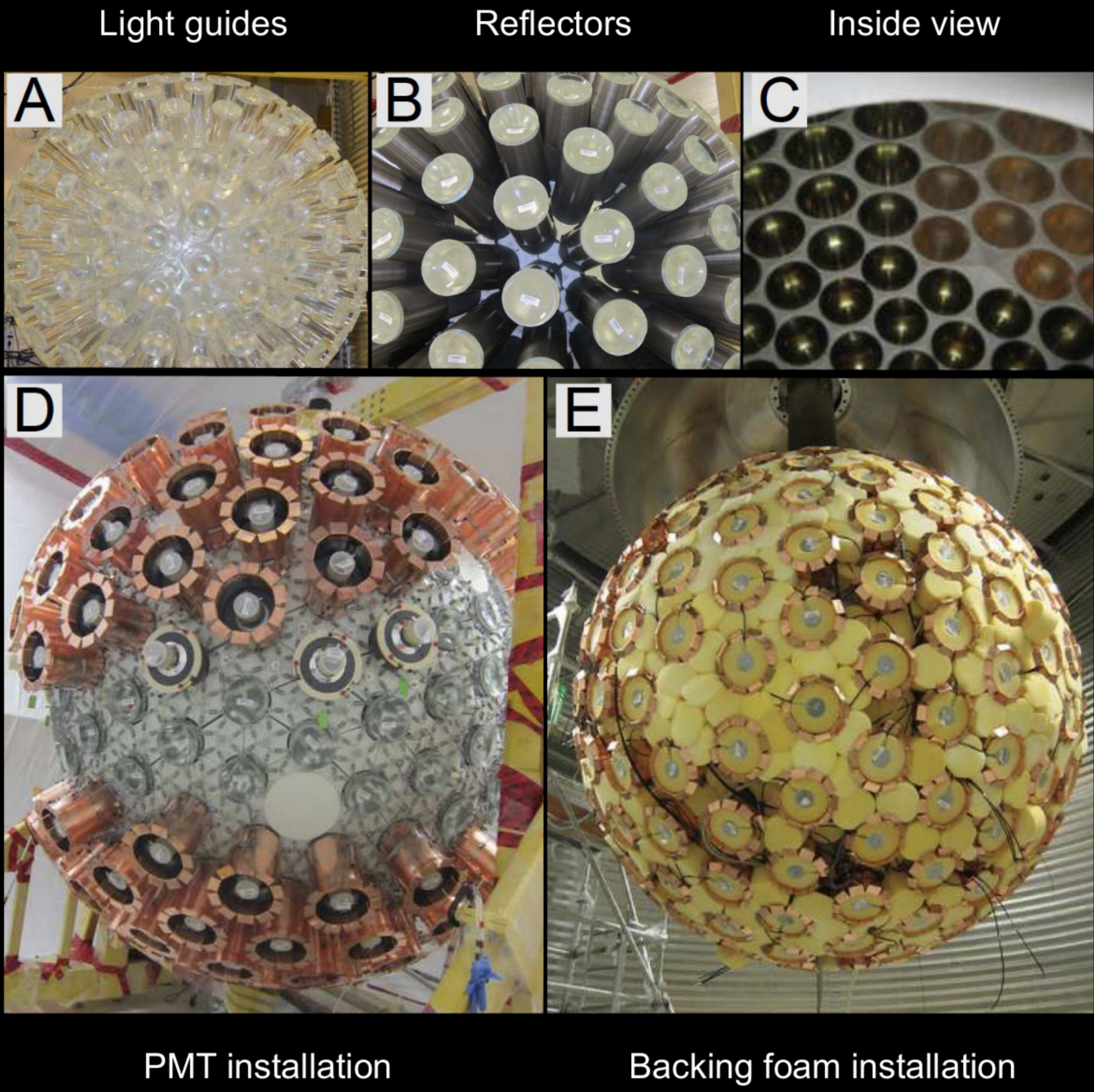
Acrylic vessel underground at SNOLAB

Acrylic vessel resurfacer

Mechanical sander to remove 0.5 mm off the inner surface



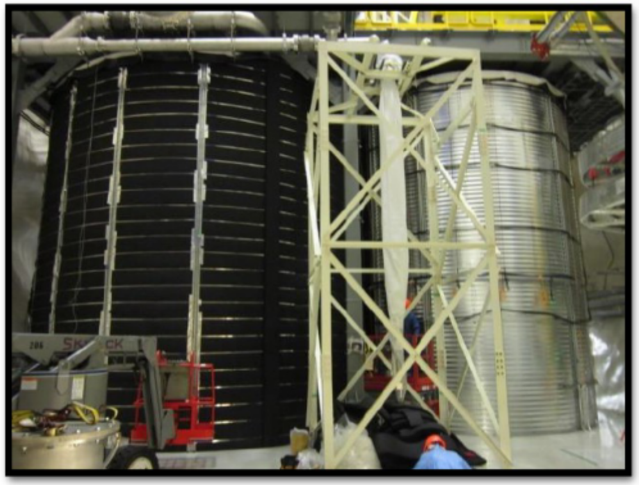
Bonding light guides underground at SNOLAB

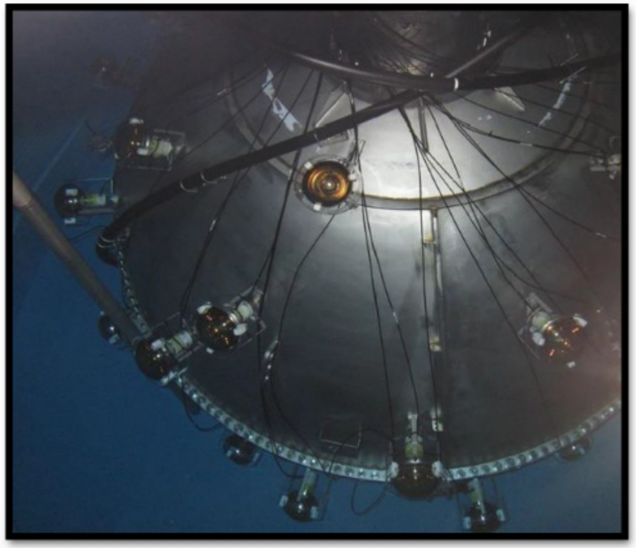


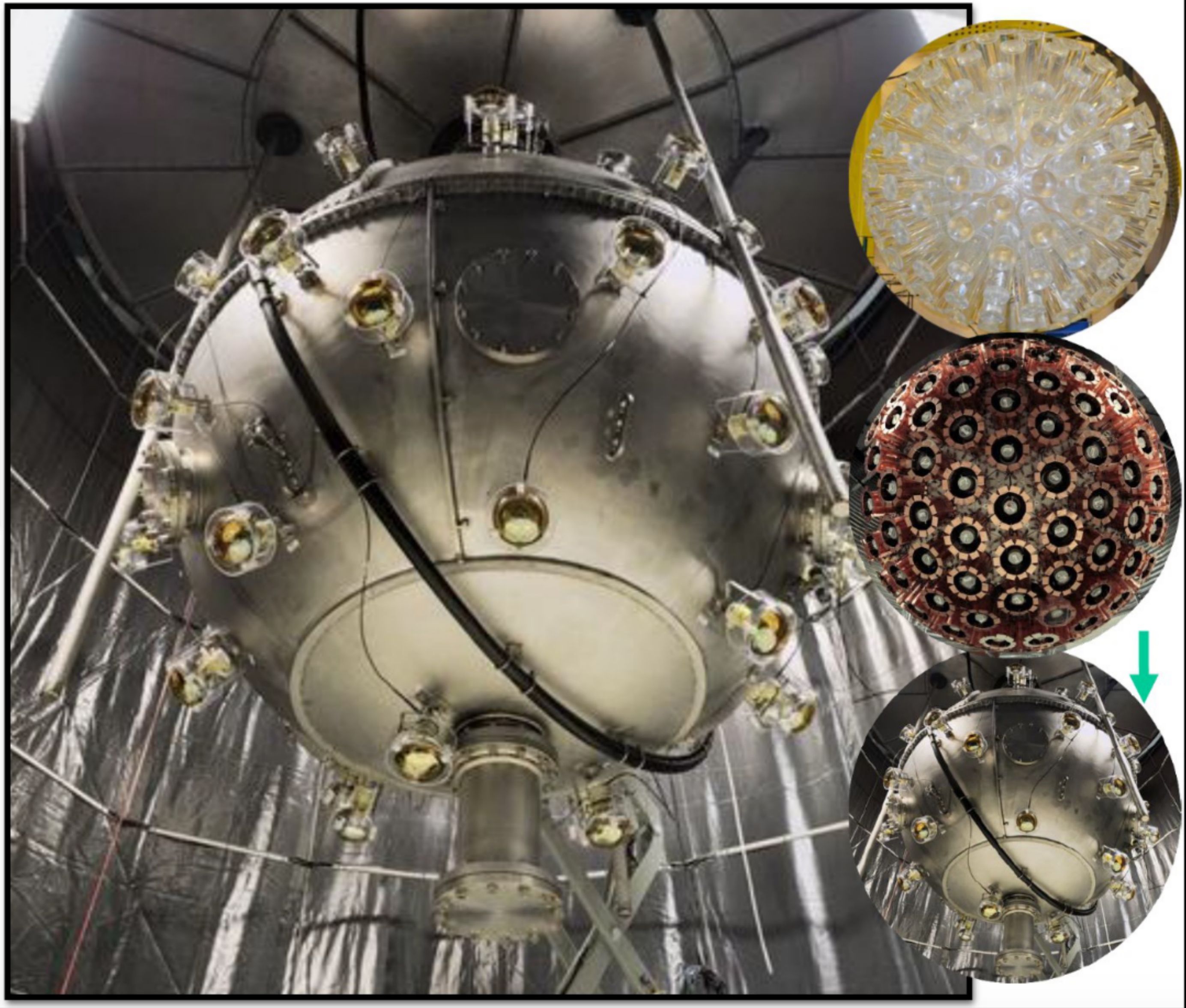
Light guides
Reflectors
Inside view
A
B
C
D
E
PMT installation
Backing foam installation

Steel shell, Veto PMTs

Water tanks in Cube Hall



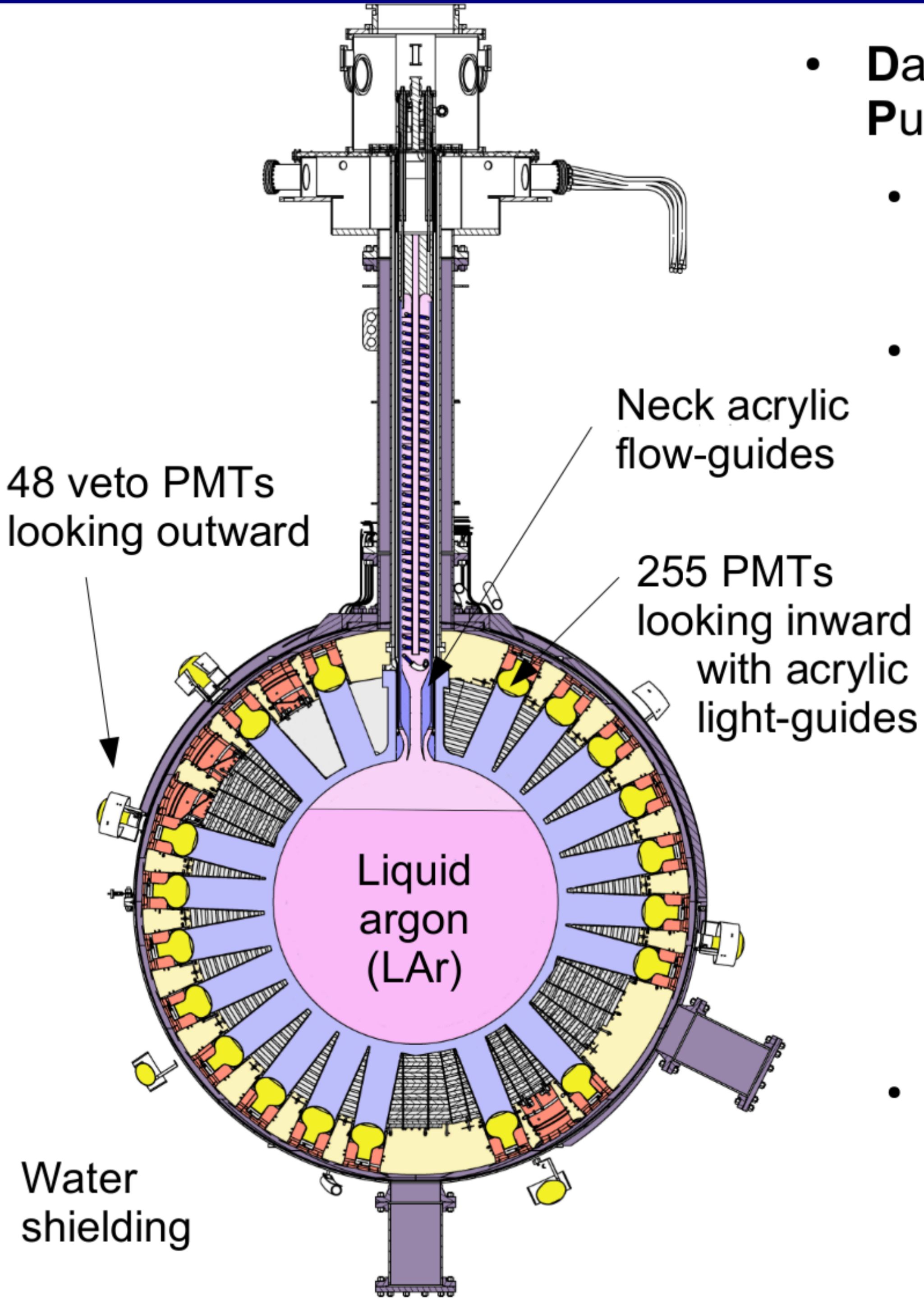




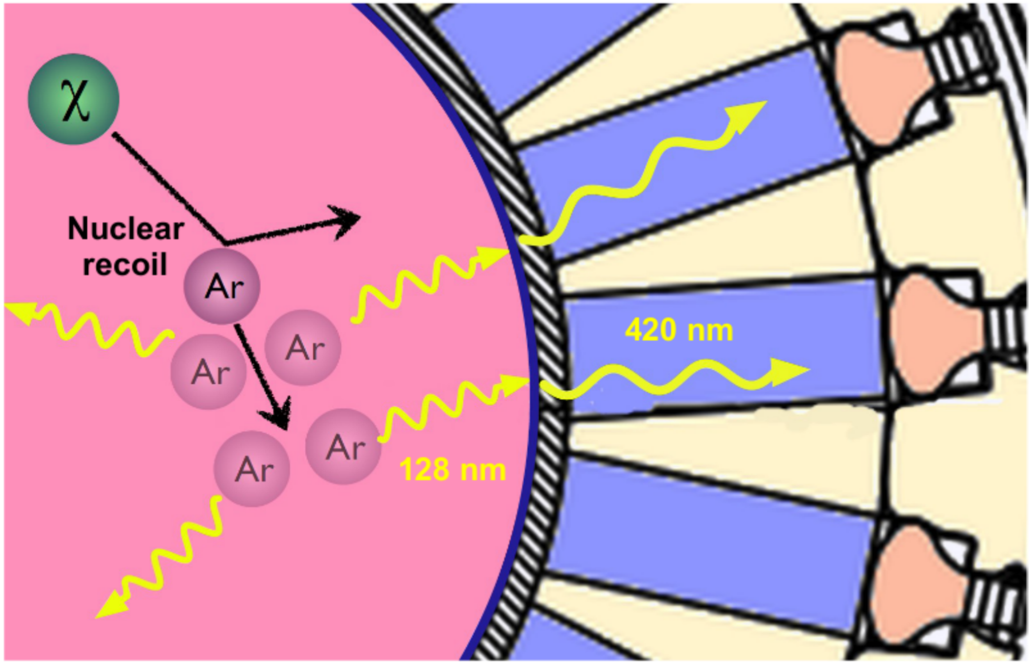
All details available in the DEAP-3600 detector publication!

Astroparticle Physics 108, 1-23 (2019) arXiv:1712.01982

DEAP-3600

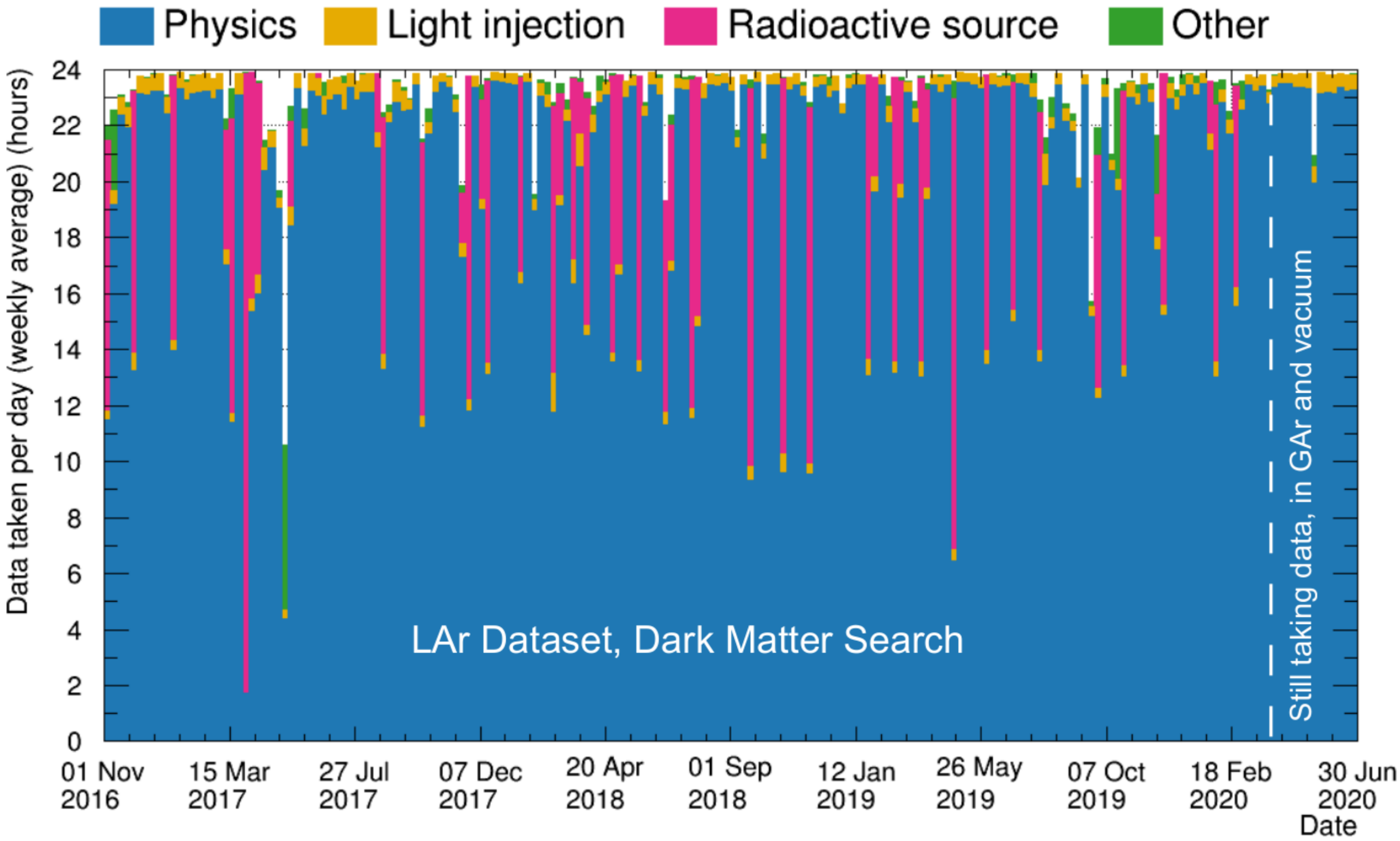


- **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination
  - Design mass: 3600 kg of liquid argon (LAr)
    - Largest acrylic cryostat ever built
  - Goal: Detect dark matter particles colliding with argon nuclei



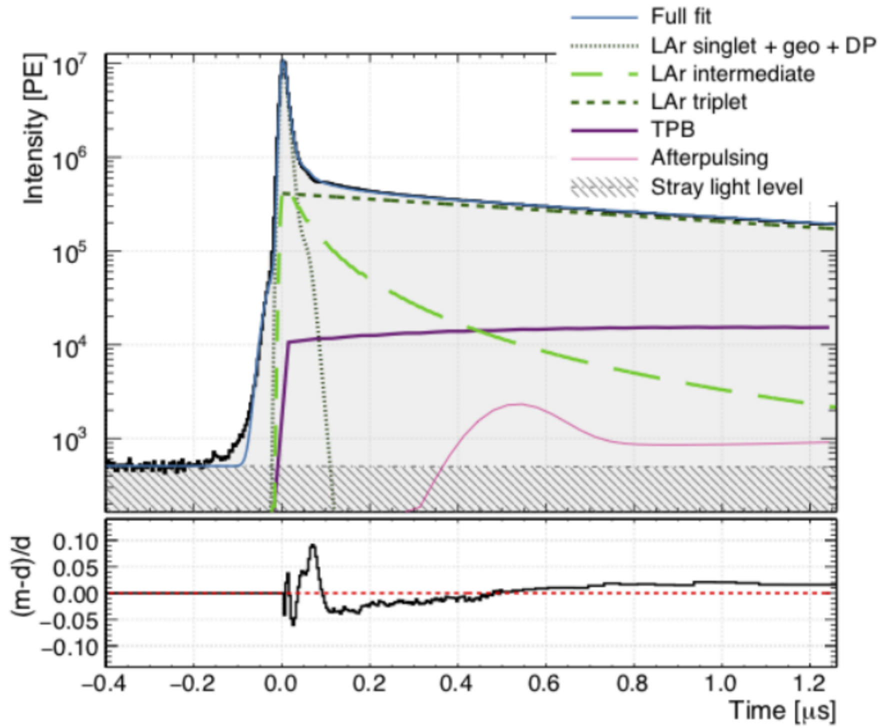
- **UV scintillation light** from LAr nuclear recoils is wavelength-shifted to visible at TPB layer, then collected by photomultiplier tubes (PMT)

DEAP-3600 Dataset



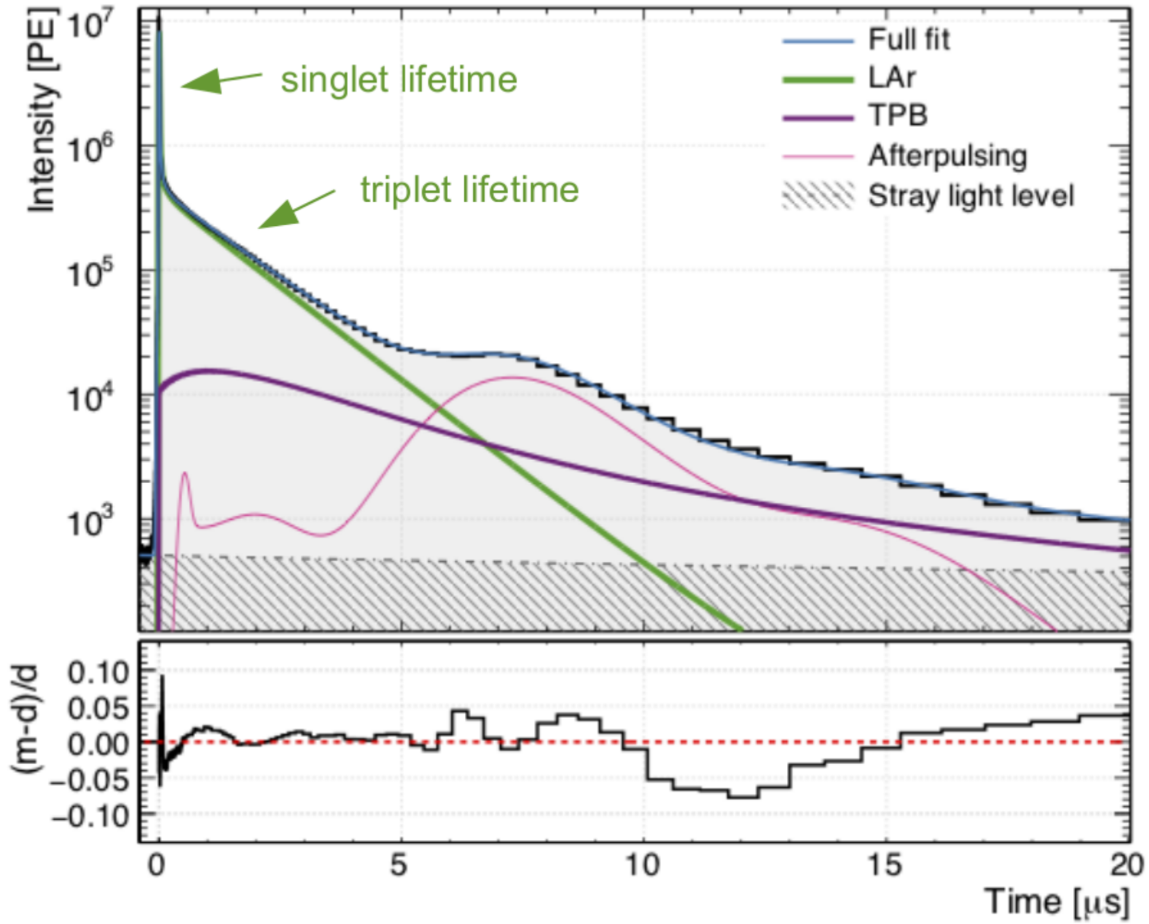
- Stable data collection for DM search: November 1st, 2016 – March 28th, 2020
  - 80% blind since January 1st, 2018

Liquid Argon Scintillation Pulse-Shape in DEAP-3600



Zoom at prompt times

Full event window →



Visible photons → Photoelectrons at PMT cathode → PMT pulses

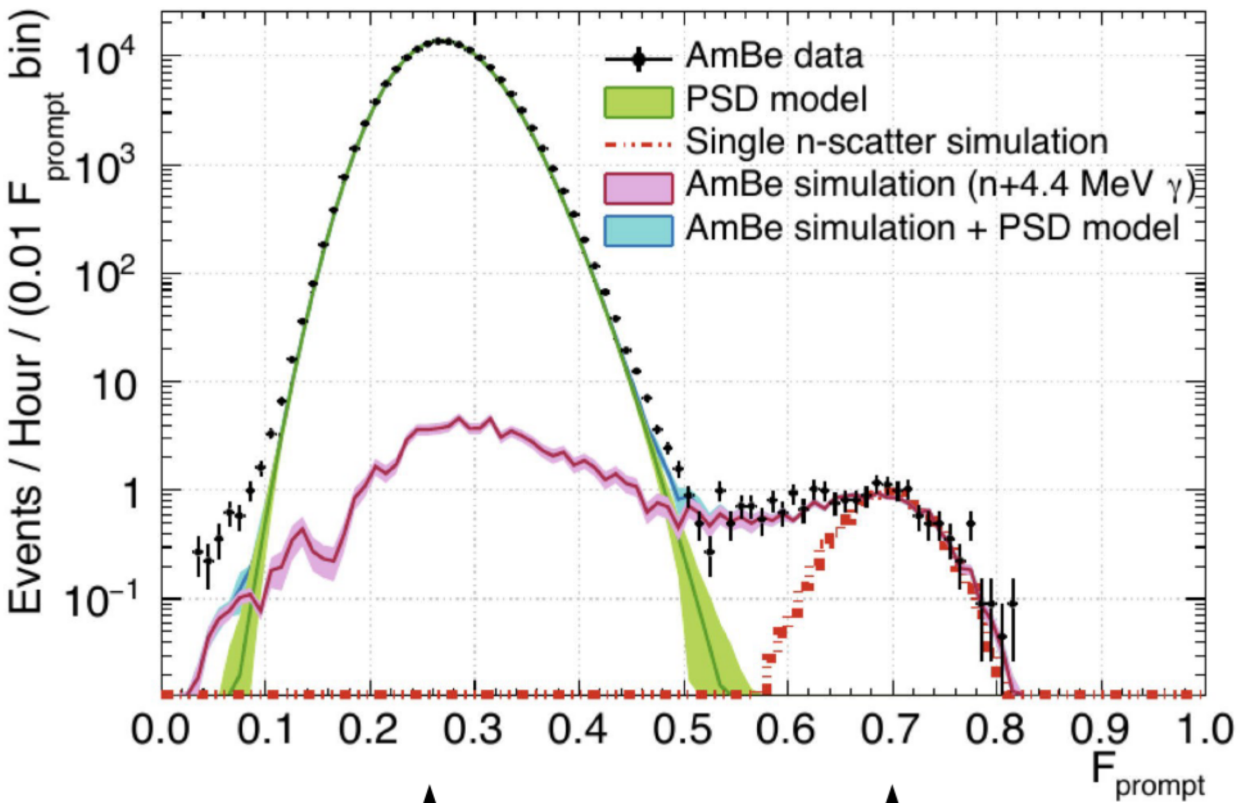
Pulse-shape model: European Physics Journal C, 80, 303 (2020) arXiv:2001.09855

Including intermediate time component of LAr scintillation, PMT response, and long TPB time constant

Pulse-Shape Discrimination (PSD)

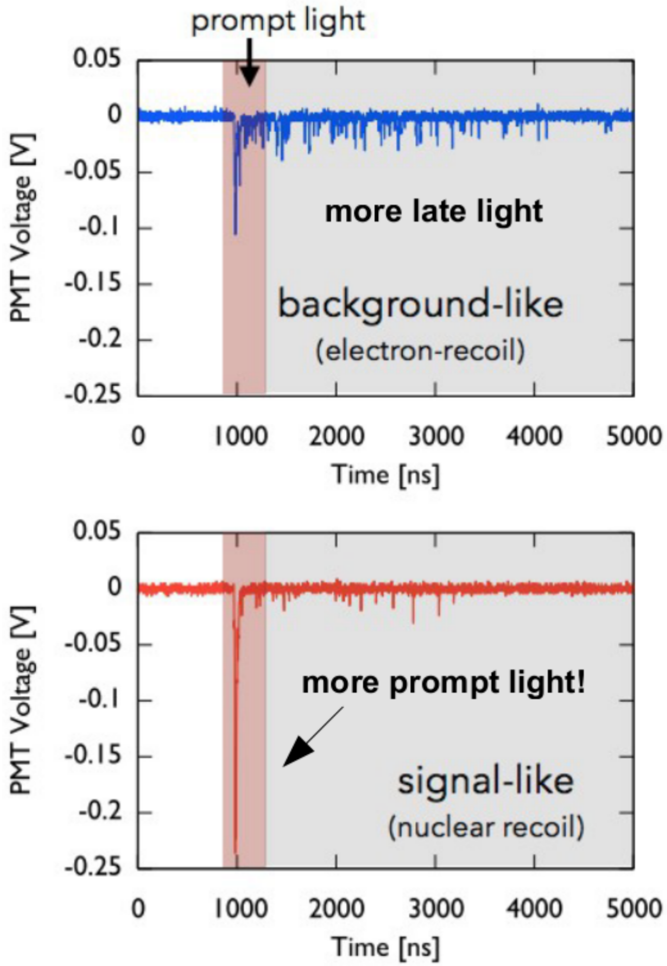
The goal is to **select dark matter signal events**, and reject background events

Example: Neutron source calibration data



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

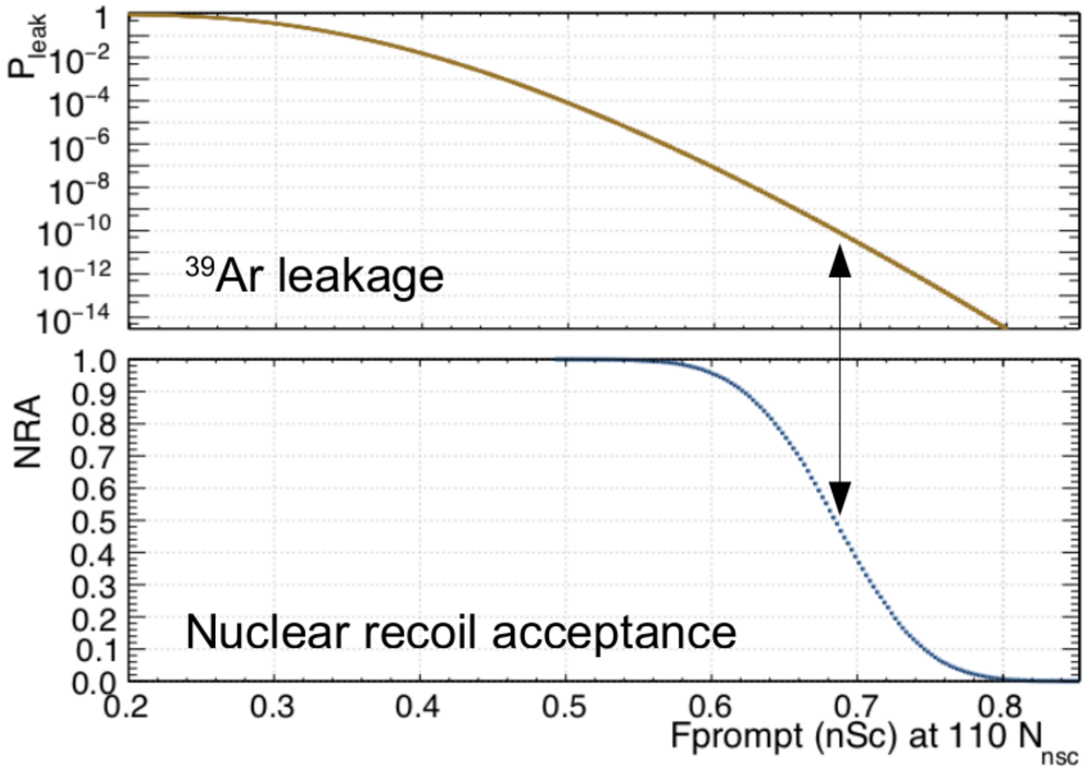
Signal-like
(nuclear recoils)

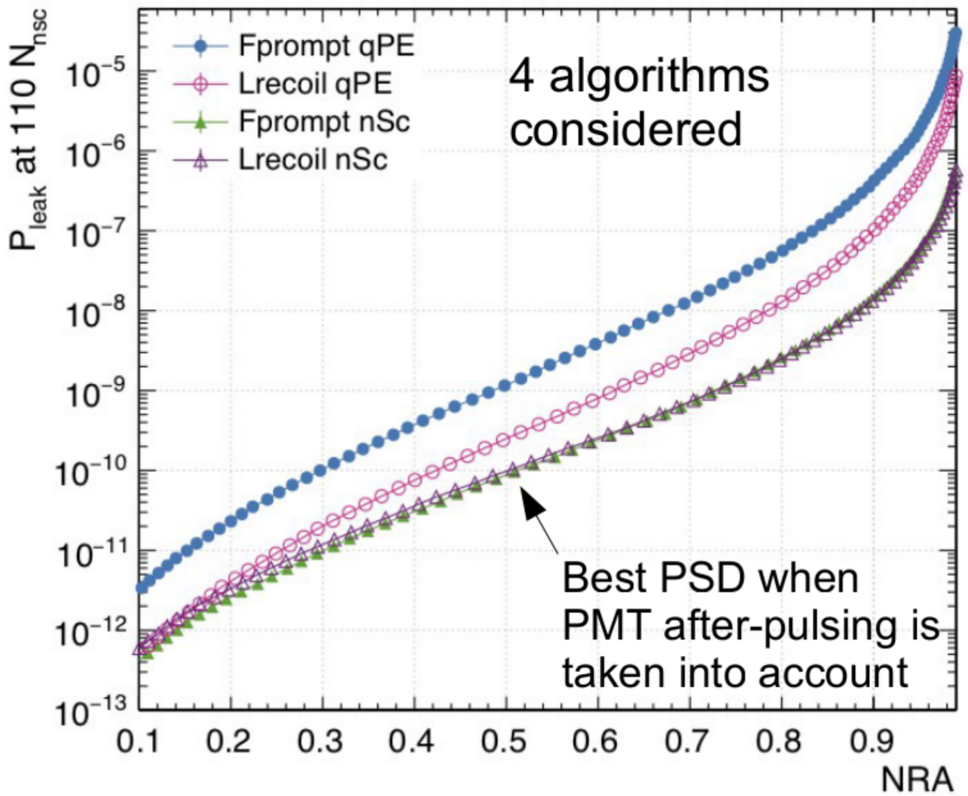


$$F_{prompt} = \frac{\sum_{t=-28\,\mathrm{ns}}^{60\,\mathrm{ns}} \mathrm{PE}(t)}{\sum_{t=-28\,\mathrm{ns}}^{10\,\mu\mathrm{s}} \mathrm{PE}(t)}$$

Pulse-Shape Discrimination (PSD)

World-leading PSD performance!



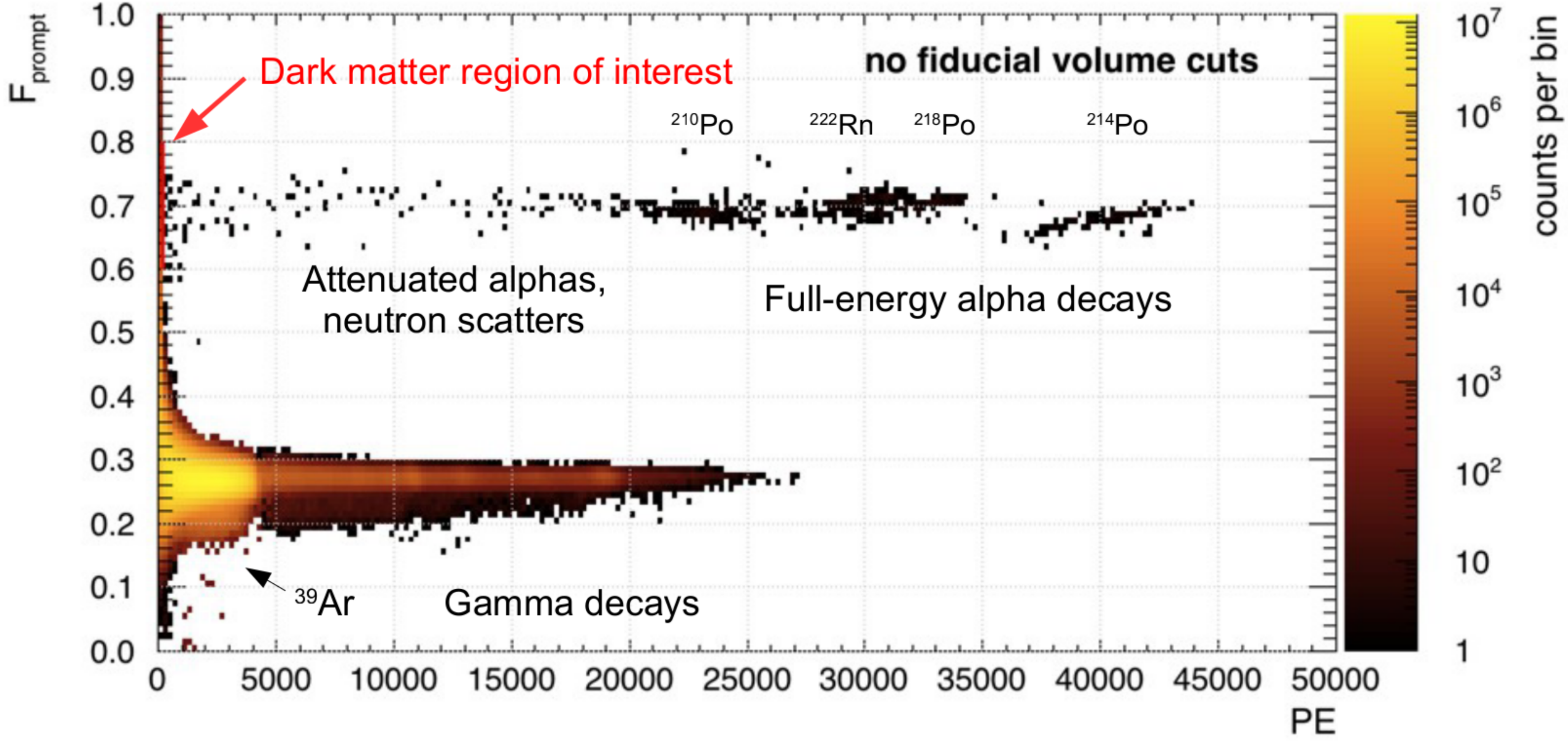


Using our best PSD algorithm:

Leakage probability at 110 PE (~ 17.5 keVee) is $\mathbf{10^{-10}}$ at 50% nuclear recoil acceptance

Detailed PSD paper: Submitted to European Physics Journal C (2021) arXiv:2103.12202

DEAP-3600: Early Physics Data



First DEAP-3600 dark matter search, with 4.4 live days

Phys. Rev. Lett. 121, 071801 (2018) arXiv:1707.08042

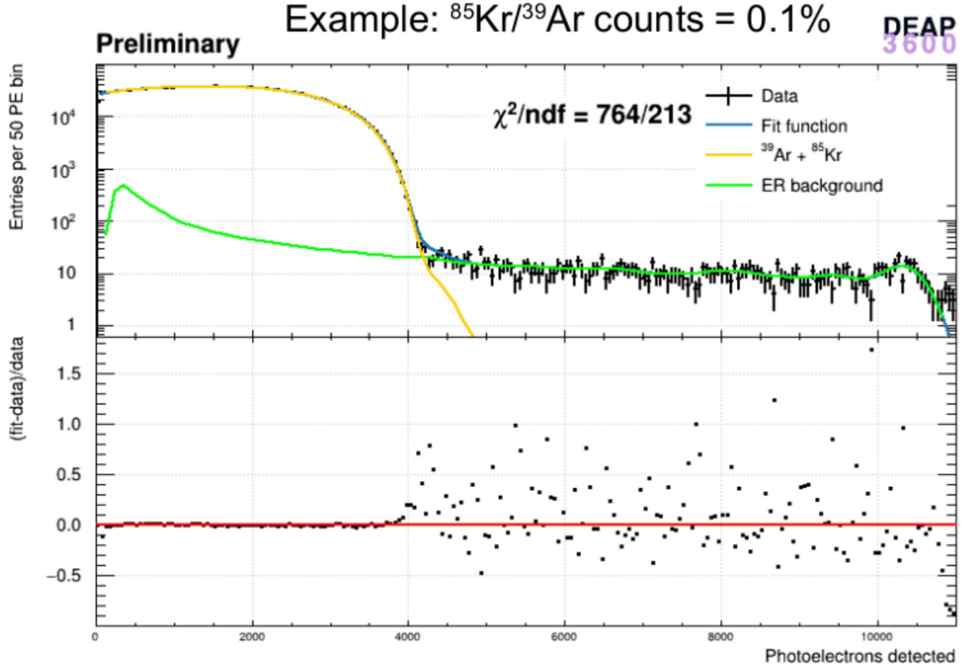
^{39}Ar Measurements

WORK IN PROGRESS

^{39}Ar specific activity

- Dominant systematic uncertainty: liquid argon mass
  - Latest published: 3279 ± 96 kg
  - Recent dedicated effort drastically **reduced this uncertainty**
- Constraint on ^{85}Kr contribution by including in the beta spectrum fit

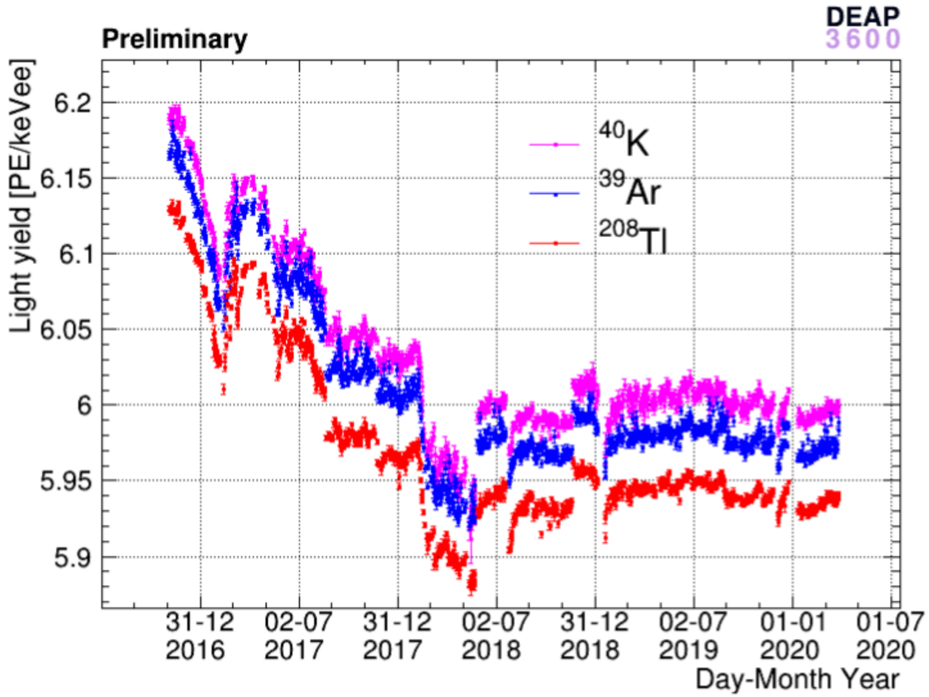
Example: ^{85}Kr/^{39}Ar counts = 0.1%



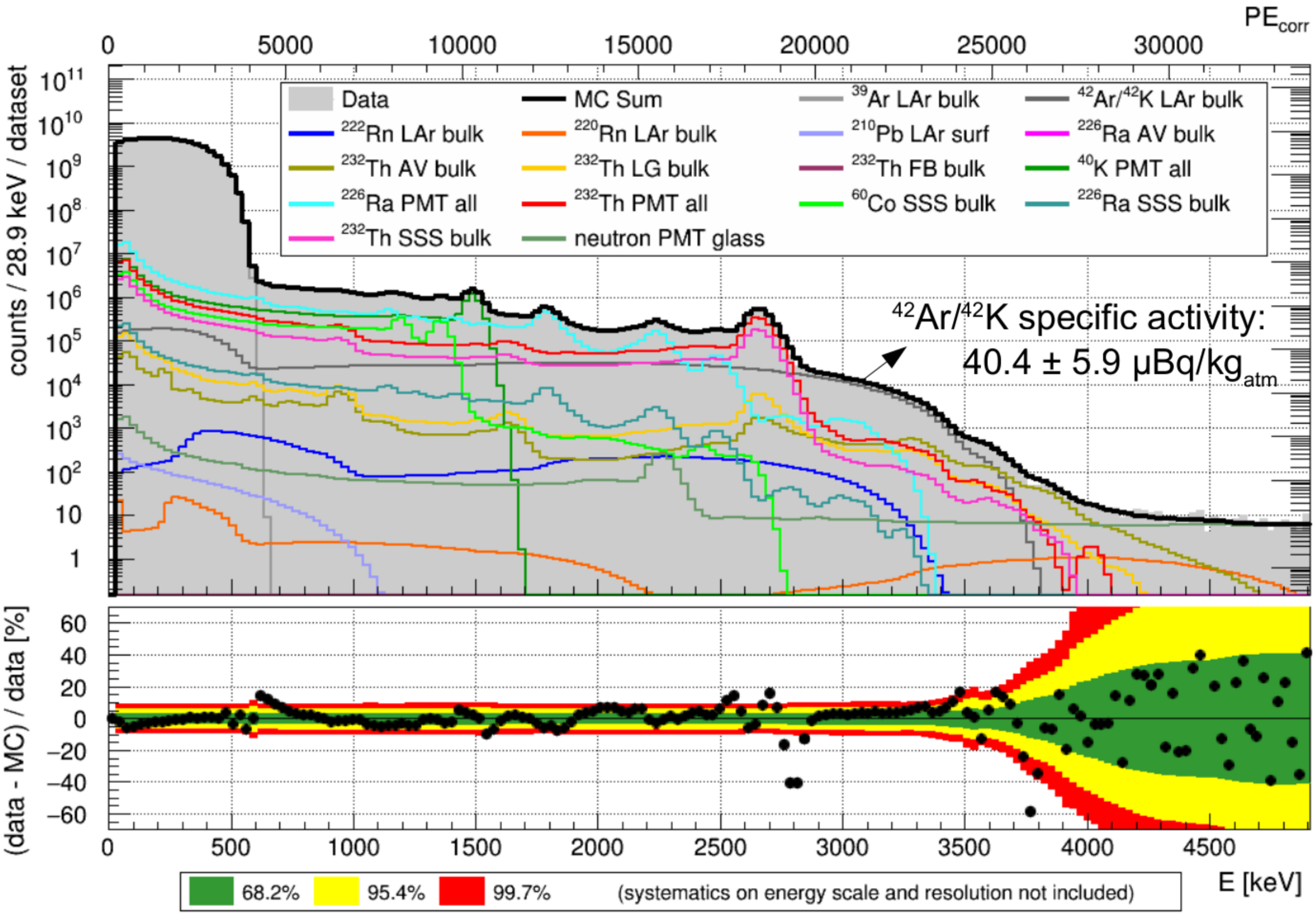
^{39}Ar half-life

- Requires very good understanding of detector conditions, **detector stability**
- Impact on radiometric dating
- Also planning annual modulation analysis

Shown here: Stability of light-yield (PE with after-pulsing removed) over the full dataset



Electromagnetic Backgrounds in First-Year Dataset

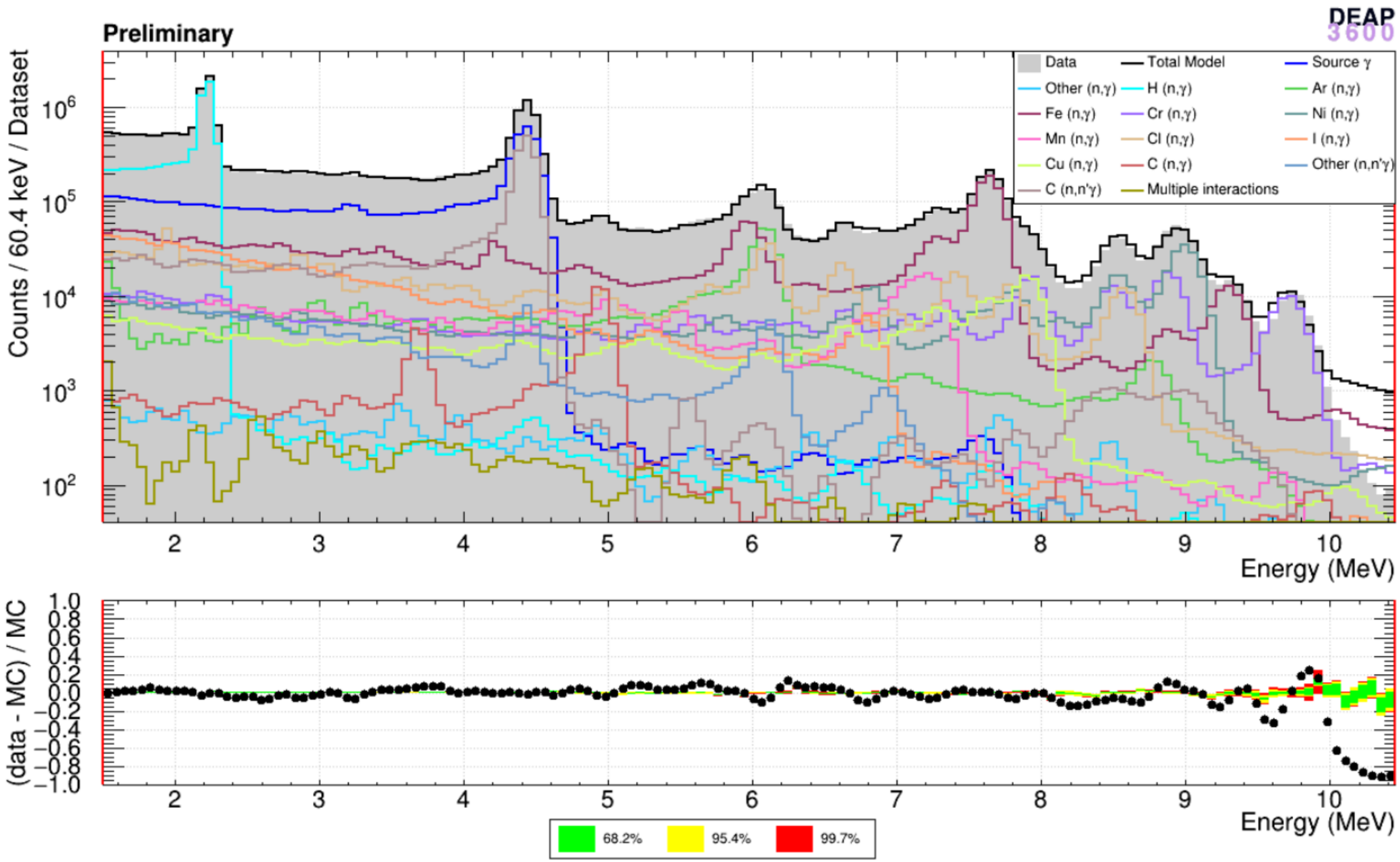


Physical Review D, 100, 072009 (2019) arXiv:1905.05811

5.5 MeV Solar Axion Search

WORK IN PROGRESS

- 5.5 MeV axions could be produced in the Sun's core: $p + d \rightarrow {}^{3}He + a$ (instead of γ)
- Search requires excellent understanding of gamma backgrounds at high energy
  - Shown here: Latest fit to AmBe neutron source calibration data



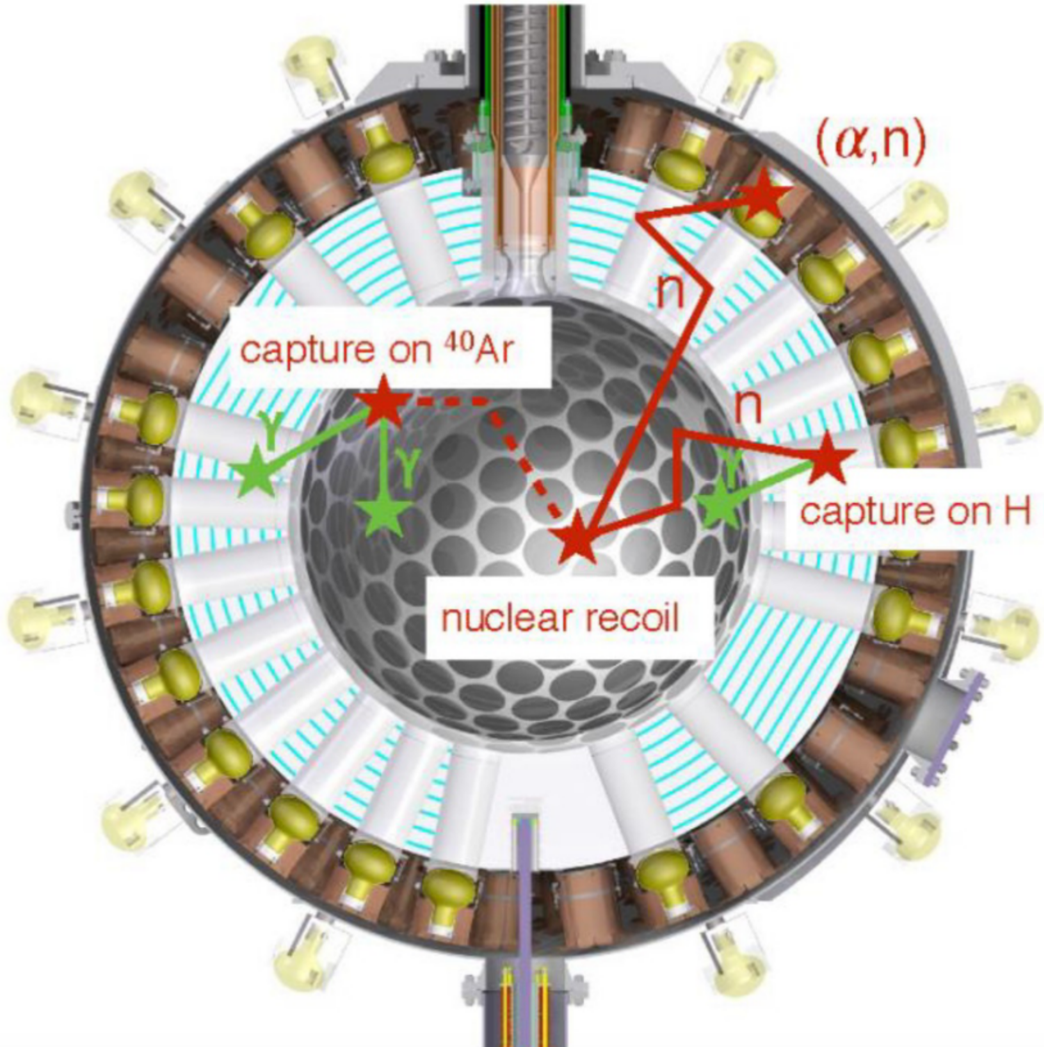
Neutron Backgrounds

Neutrons can cause multiple **nuclear recoils** in close succession, or result in γ-ray emission

→ Reject events consistent with multiple interactions

→ Estimate remaining neutron backgrounds using dedicated **data control region**

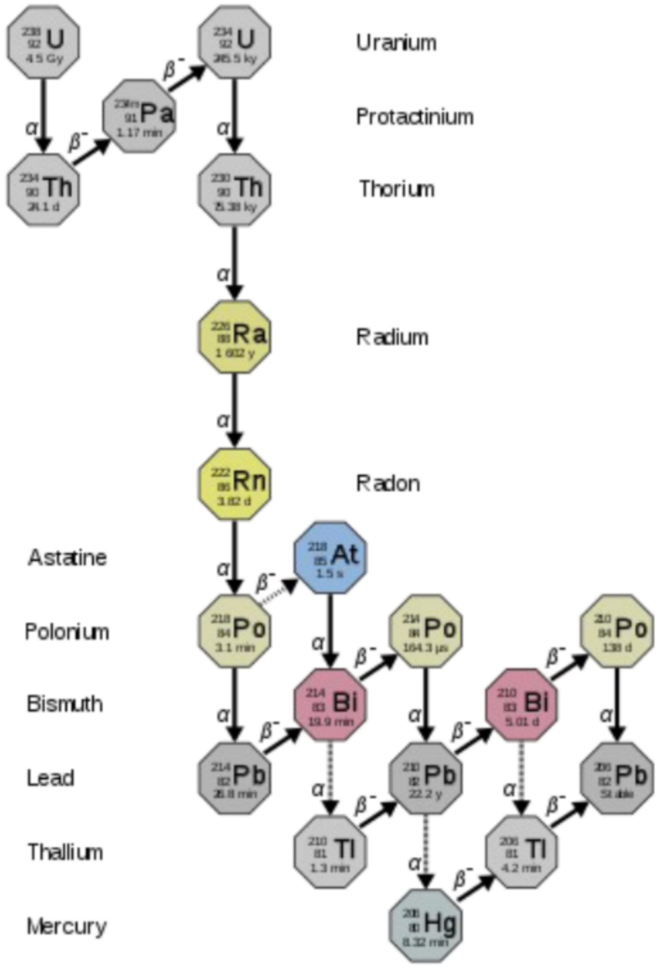
results in agreement with simulations taking material assays as input

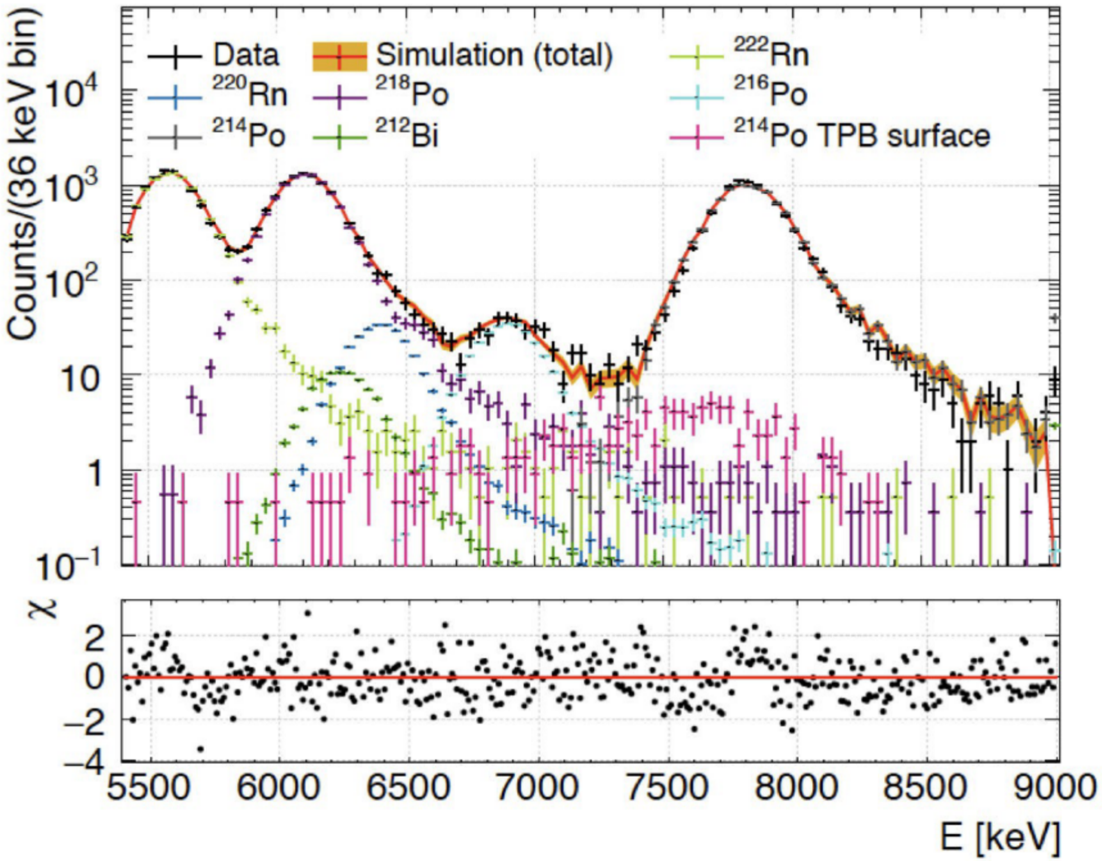


Alphas Decays in Liquid Argon Bulk

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

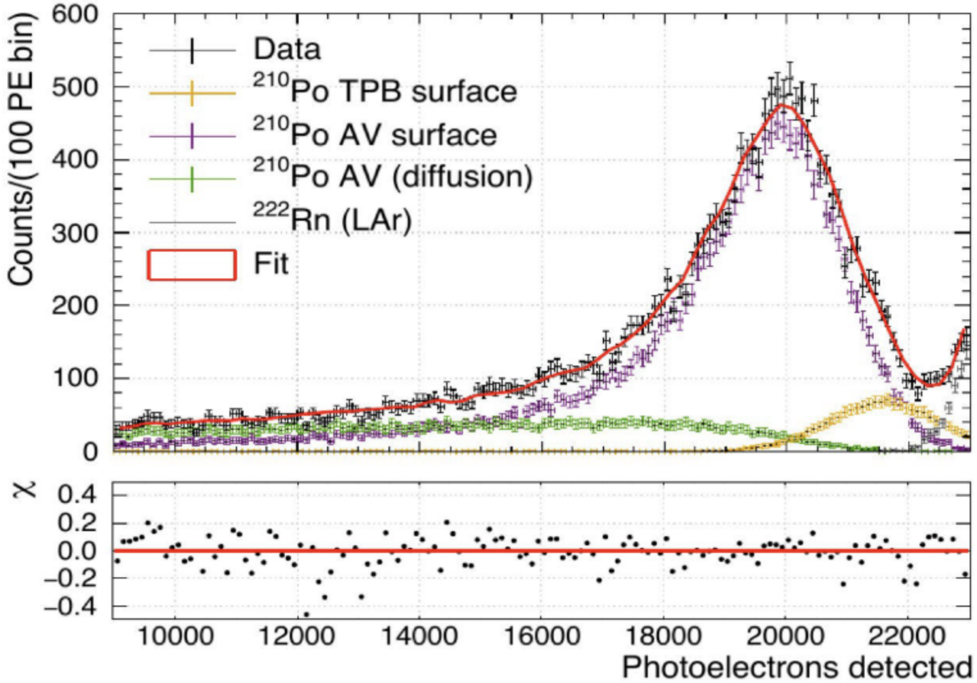


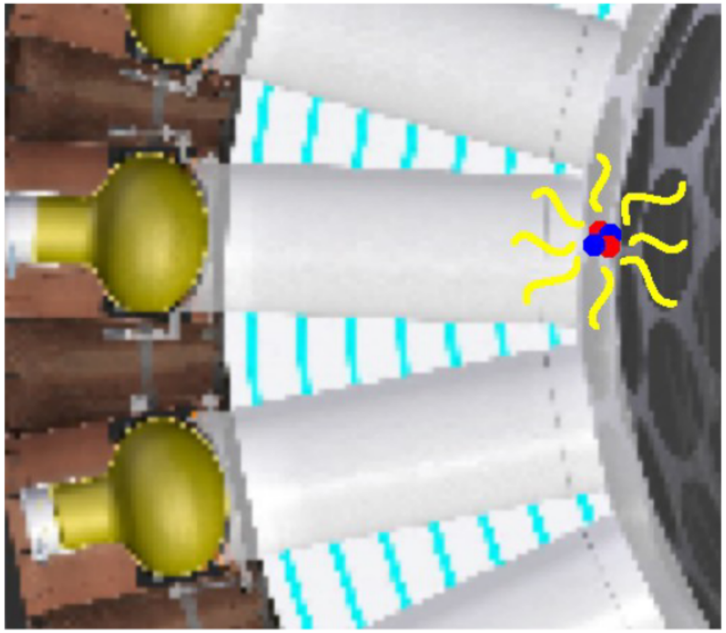


High-energy events observed from the liquid argon volume are well-explained by our background model

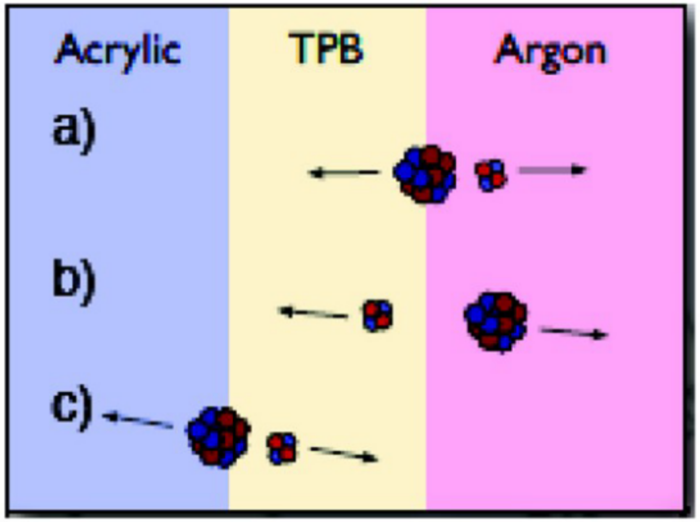
Surface Alpha Backgrounds

- **Alpha particles** emitted from **surface** impurities cause nuclear recoils
  - Mitigation:
    - Strict radon control
    - Resurfacing
    - Position reconstruction





Surface events send a high fraction of the light towards a single PMT

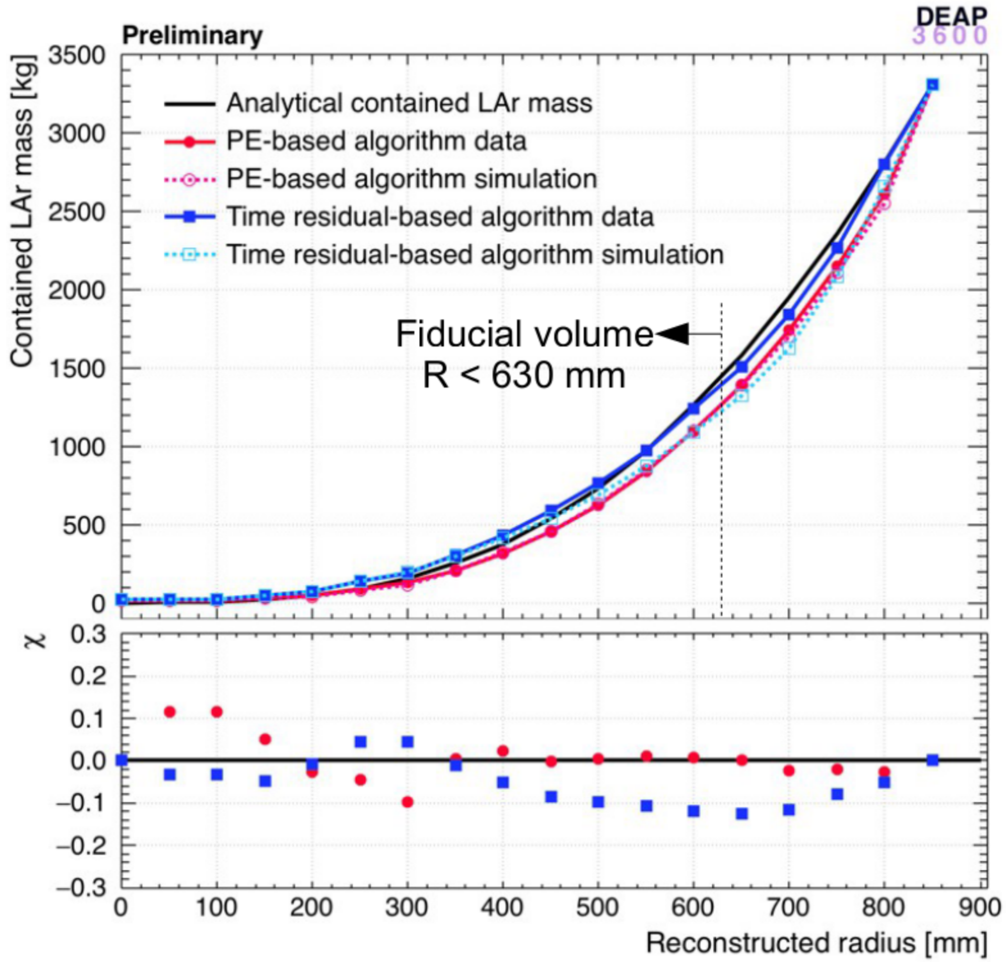


Possible surface event topologies

Position Reconstruction: Against Surface Alphas

Two main algorithms for position reconstruction

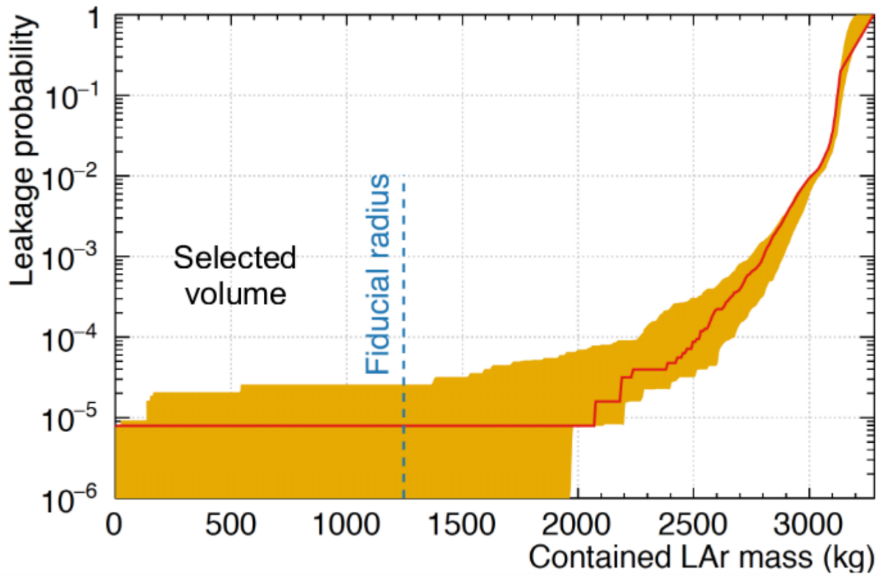
- "PE-based": **more PE are detected** closer to the event (use full 10 μs event window)
- "Time-based": **PE are detected earlier** closer to the event (use first 40 ns of event)



Data-driven measure of resolution:

30-45 mm at fiducial volume boundary for low-energy events (better at high-energy)

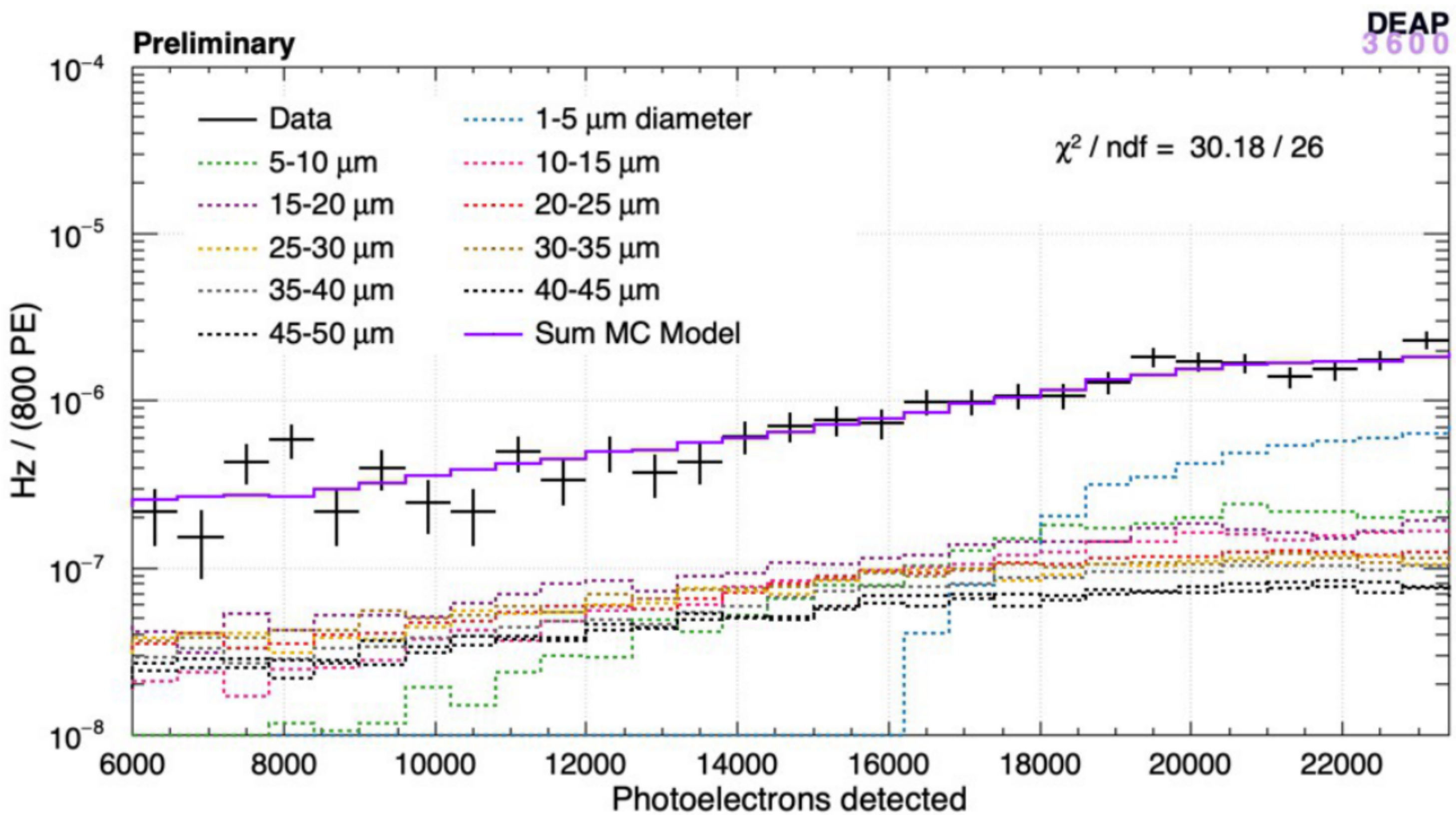
Very low surface alpha leakage

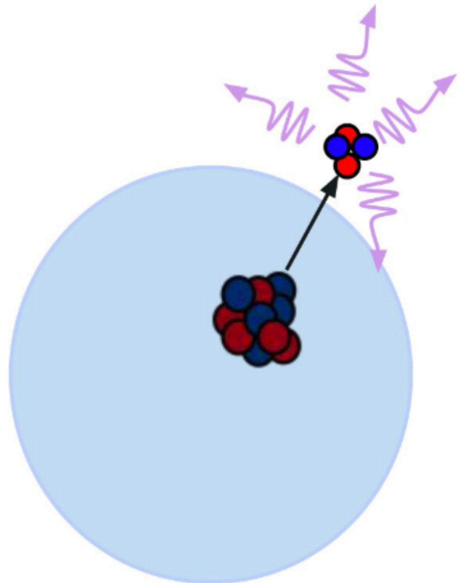


JINST 15, 05, C05061 (2020) arXiv:2004.02058

Dust Alpha Backgrounds

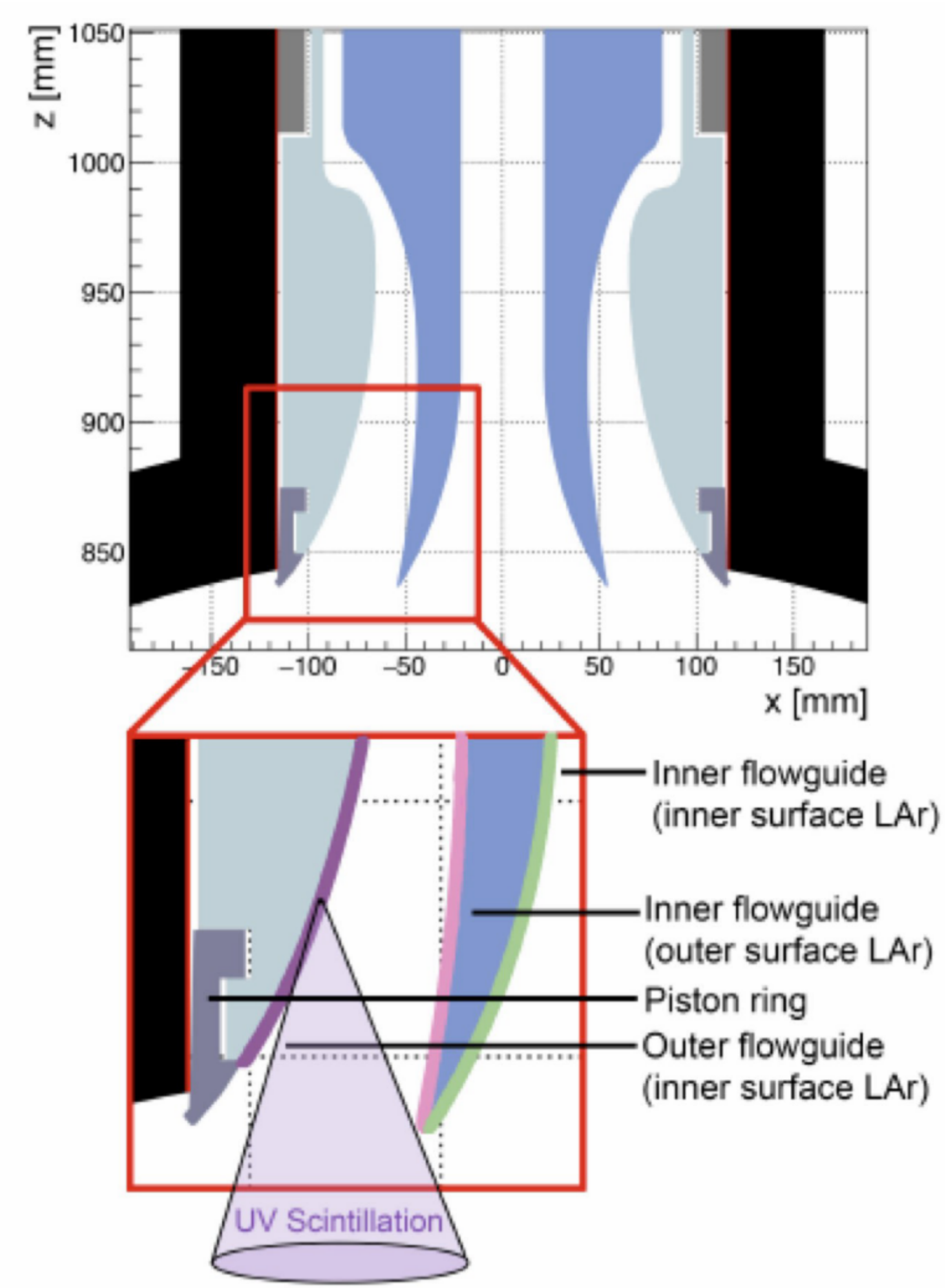
- **Alpha decays** from trace amounts of **dust particulates** in liquid argon create low-PE events originating from the LAr bulk volume
  - **Attenuation** before entering liquid argon, and scintillation light **shadowed**
  - Now included in background model
    - Pure control region defined at intermediate PE





Ex-situ measurements of metallic dust in liquid nitrogen support this hypothesis

Neck Alpha Backgrounds



Alpha decays in the detector bulk typically release many more photons than dark matter nuclear recoils.

Alpha decays in the **detector neck** can result in **shadowing of scintillation light**, such that only a small fraction of photons are detected by the PMTs.

Low number of photons → Signal-like!

This results in a particularly **challenging** source of background events

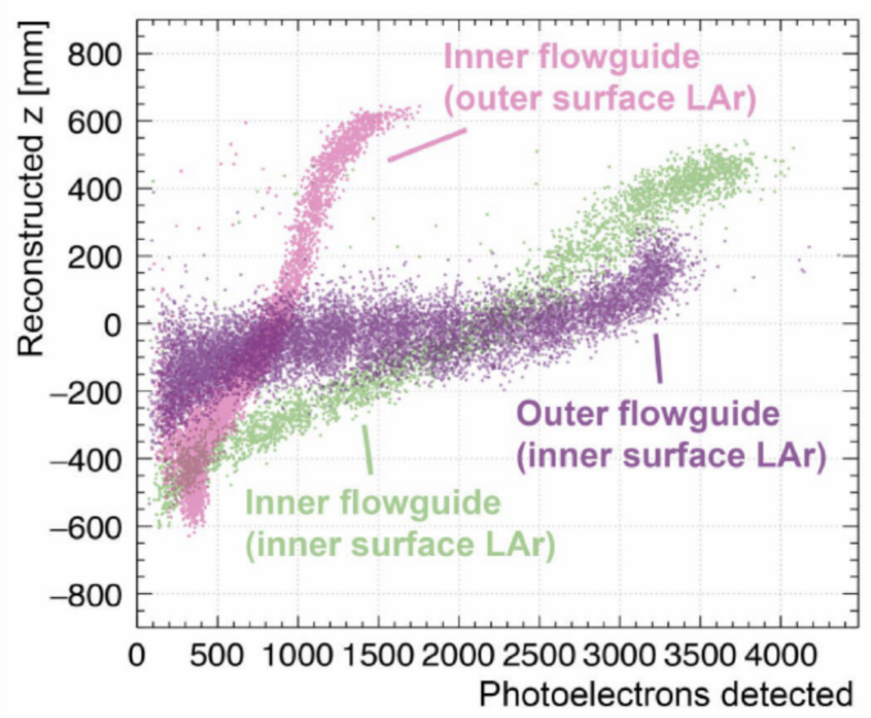
Colour code (this slide and next):

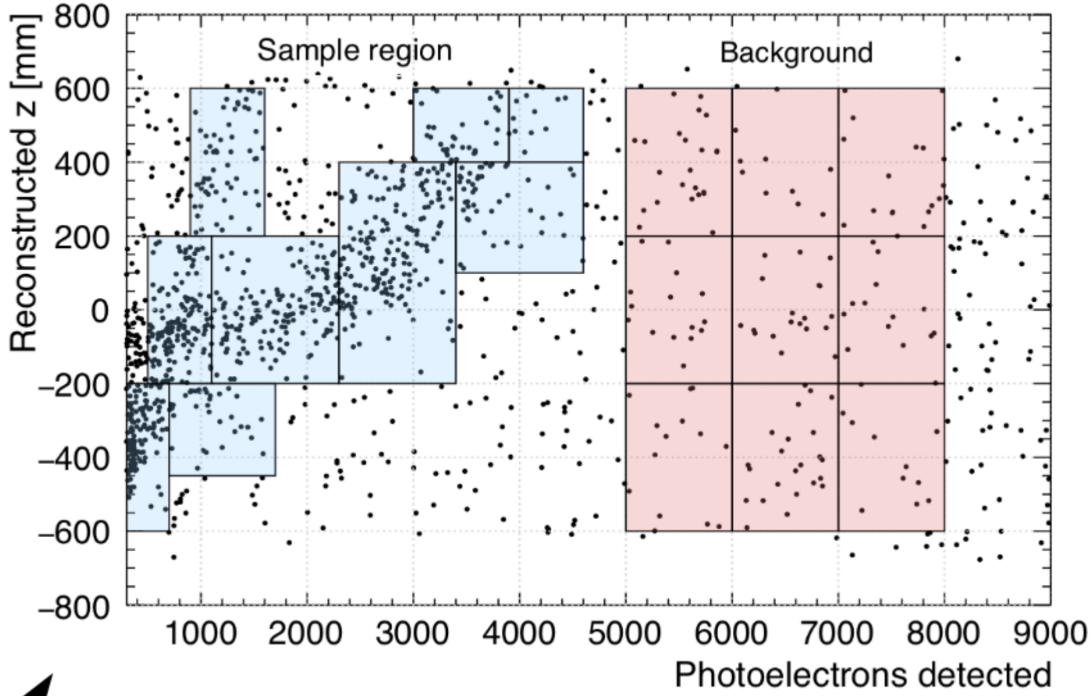
Outer flowguide, inner surface LAr

Inner flowguide, outer surface LAr

Inner flowguide, inner surface LAr

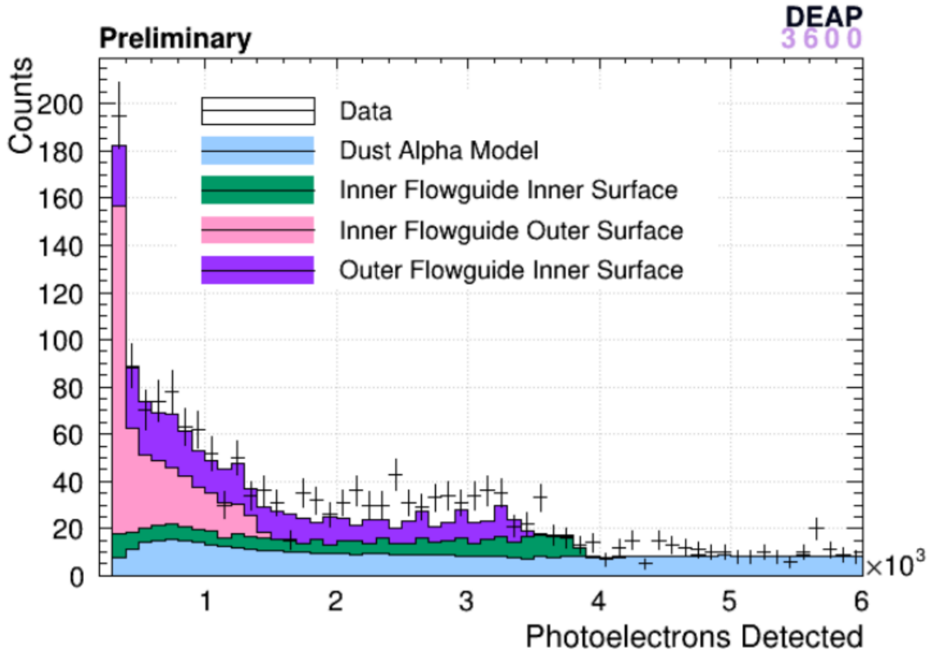
Neck Alpha Backgrounds: Event Rate Determination





Identification of features
from Monte Carlo **simulation**

... matching features seen in **data**

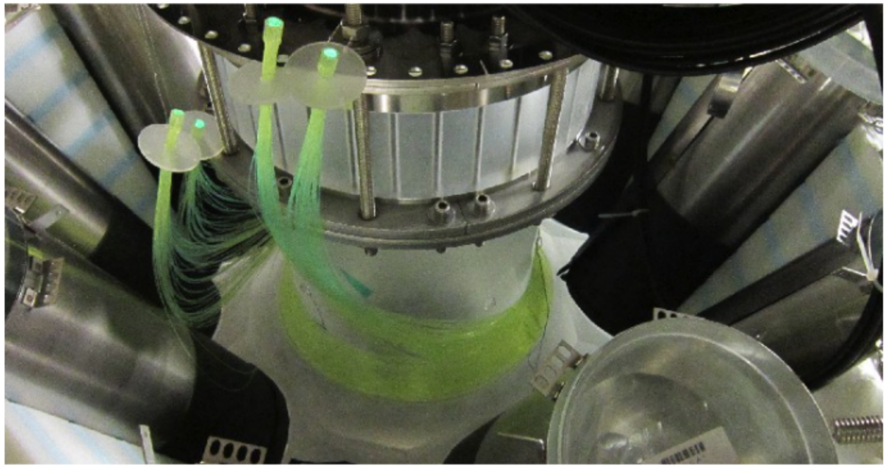


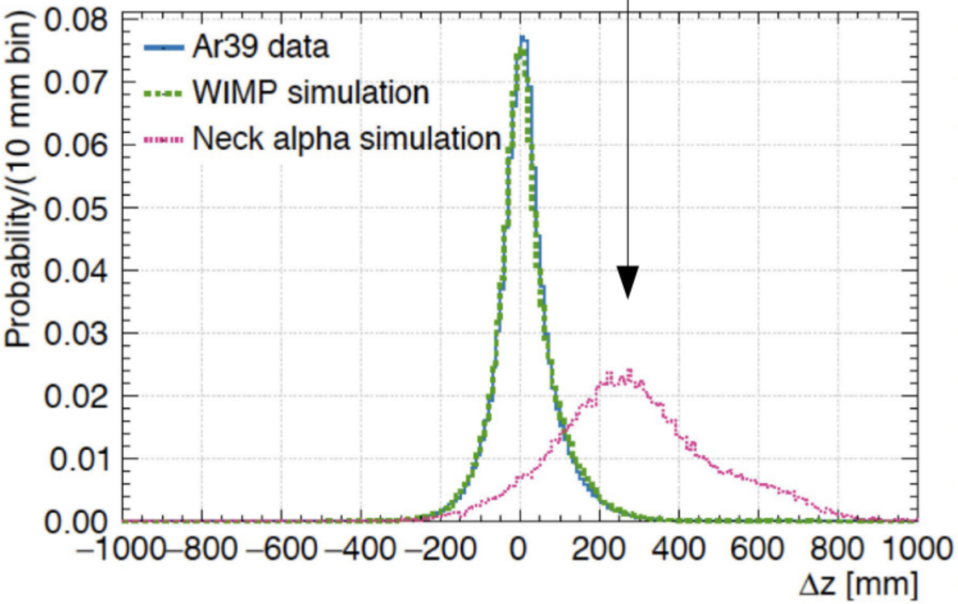
... allows a **template fit** using multiple
control regions, to figure out rates
of neck alpha events from all surfaces

New: Dust background considered in fit

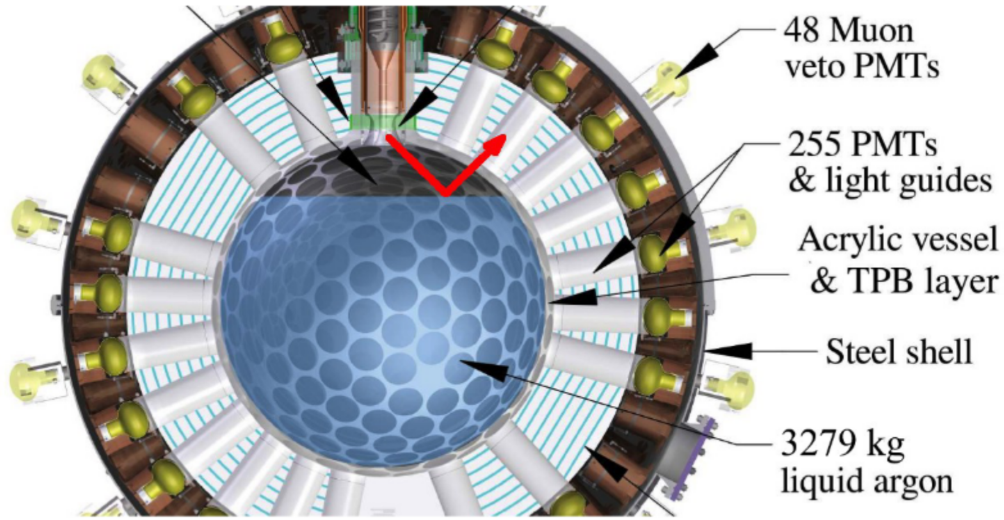
Known Handles Against Neck Alpha Backgrounds

- Developed a **dedicated event selection**, to reject background events
- In contrast to signal, neck alpha decays more frequently have:
  - light in the *neck veto fibres*
  - *excess* light in the top rows of PMTs
  - *early* light in the top rows of PMTs
  - PE-based position reconstruction disagrees with time-based method





Time-based vs. PE-based reconstructed vertical position

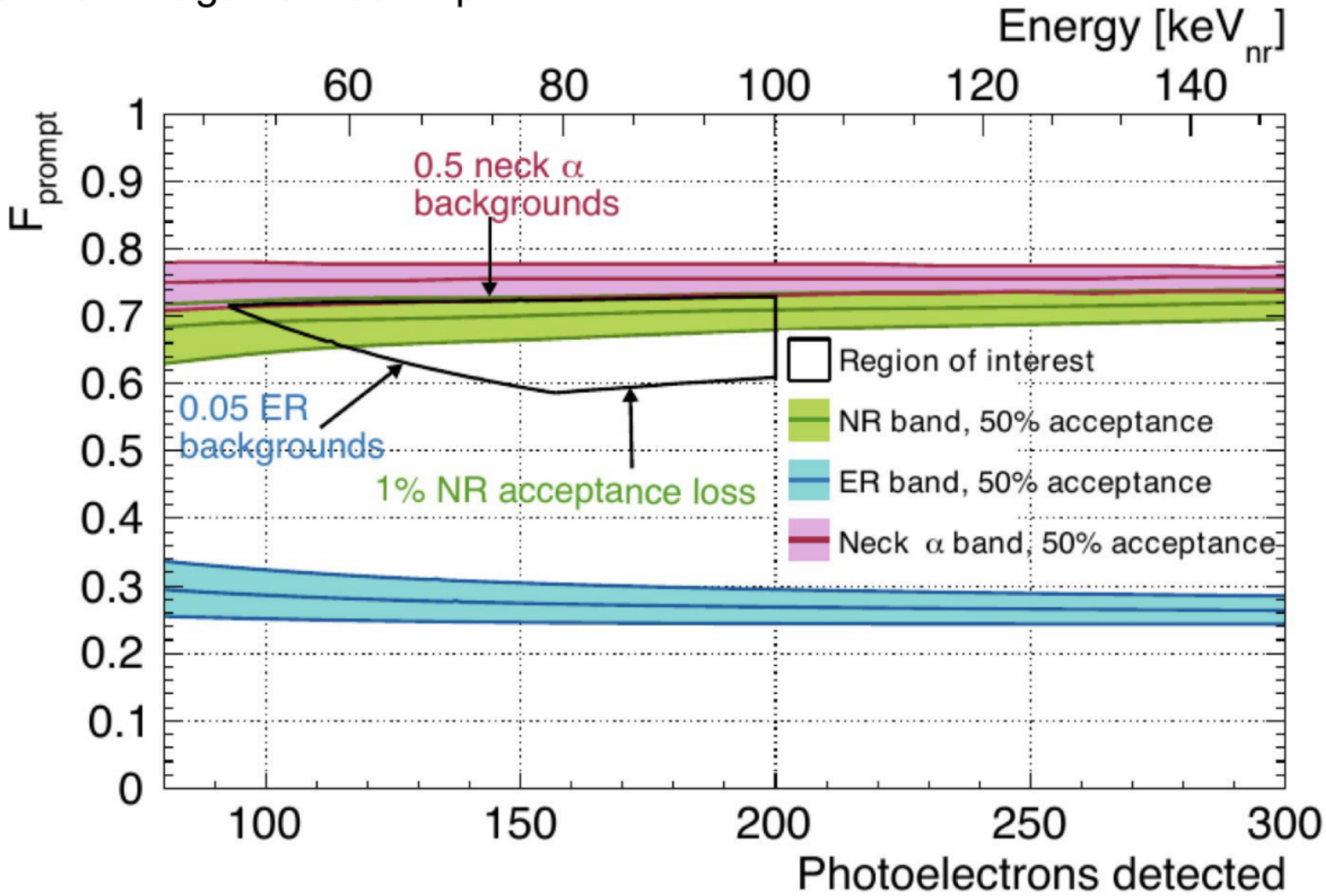


UV photon reflection at the liquid argon surface

WIMP Signal Region

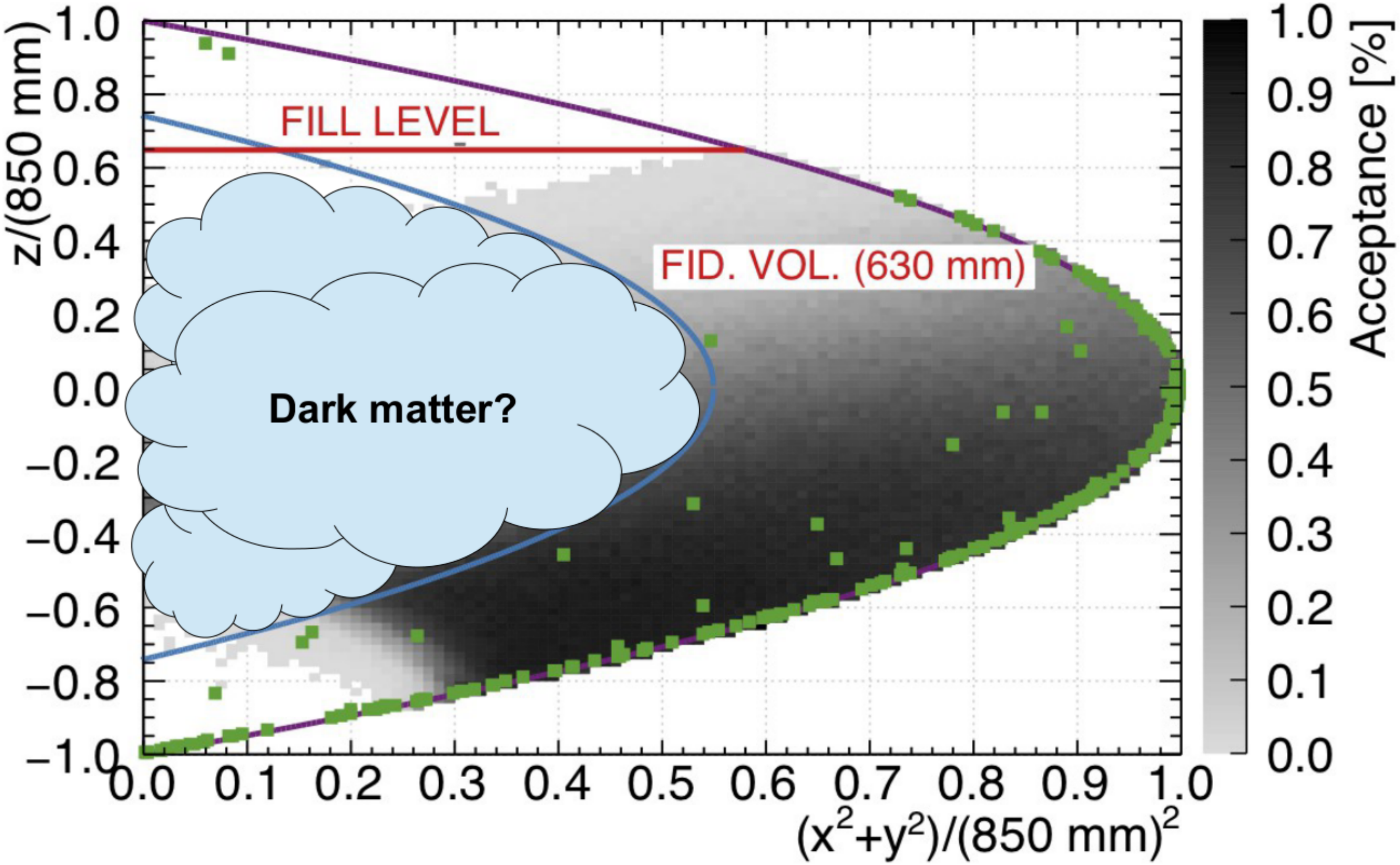
Event selection summary:
- Data quality selection, single-scatter events
- PSD against ^{39}Ar beta decays
- Energy and position cuts against alphas
- Dedicated cuts against neck alphas
- PSD is also useful against neck alphas

Final event selection in F_{prompt} and PE such that the total background expectation is **< 1 event** in 231 live-days



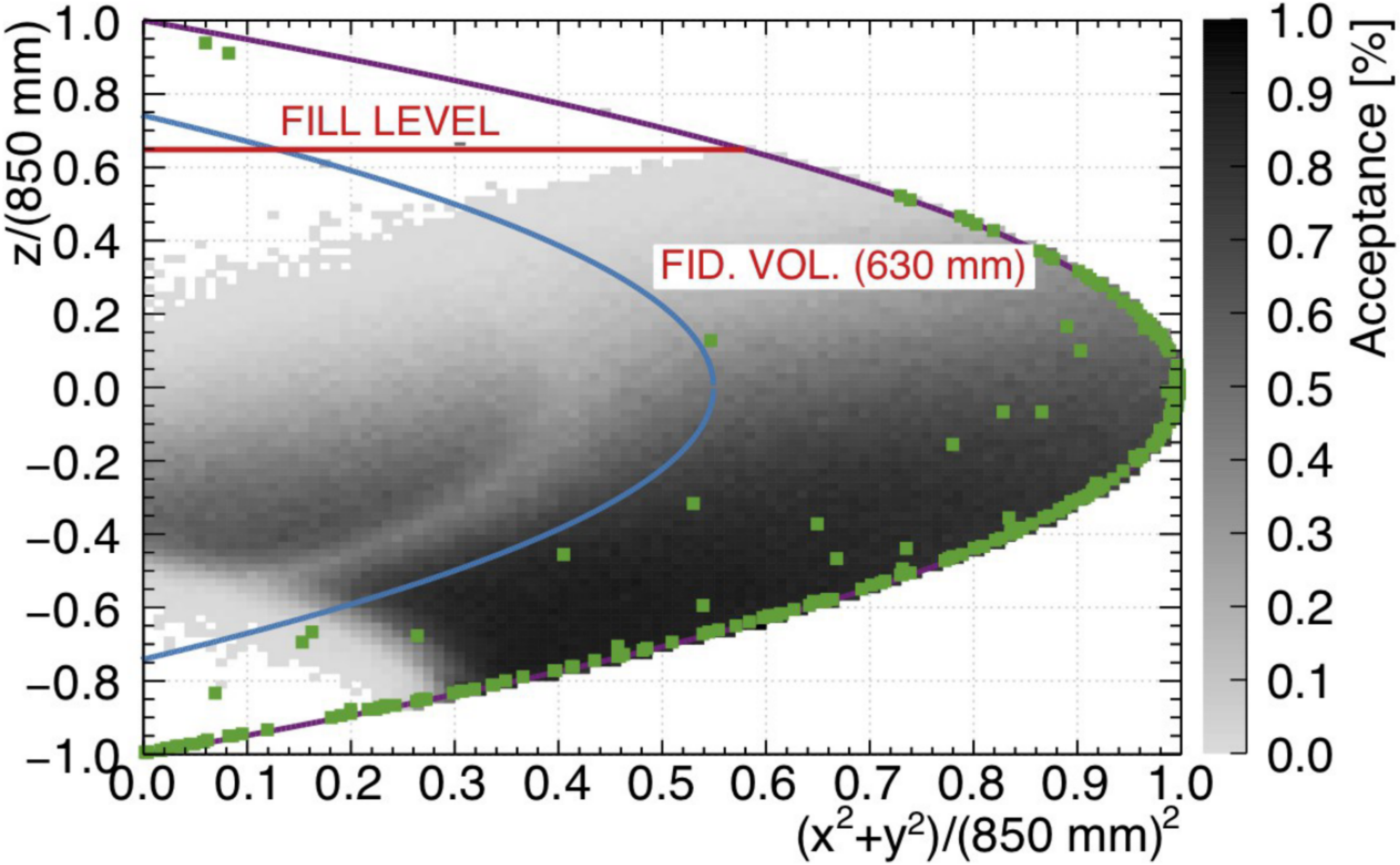
Dark Matter Search Results

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



Dark Matter Search Results

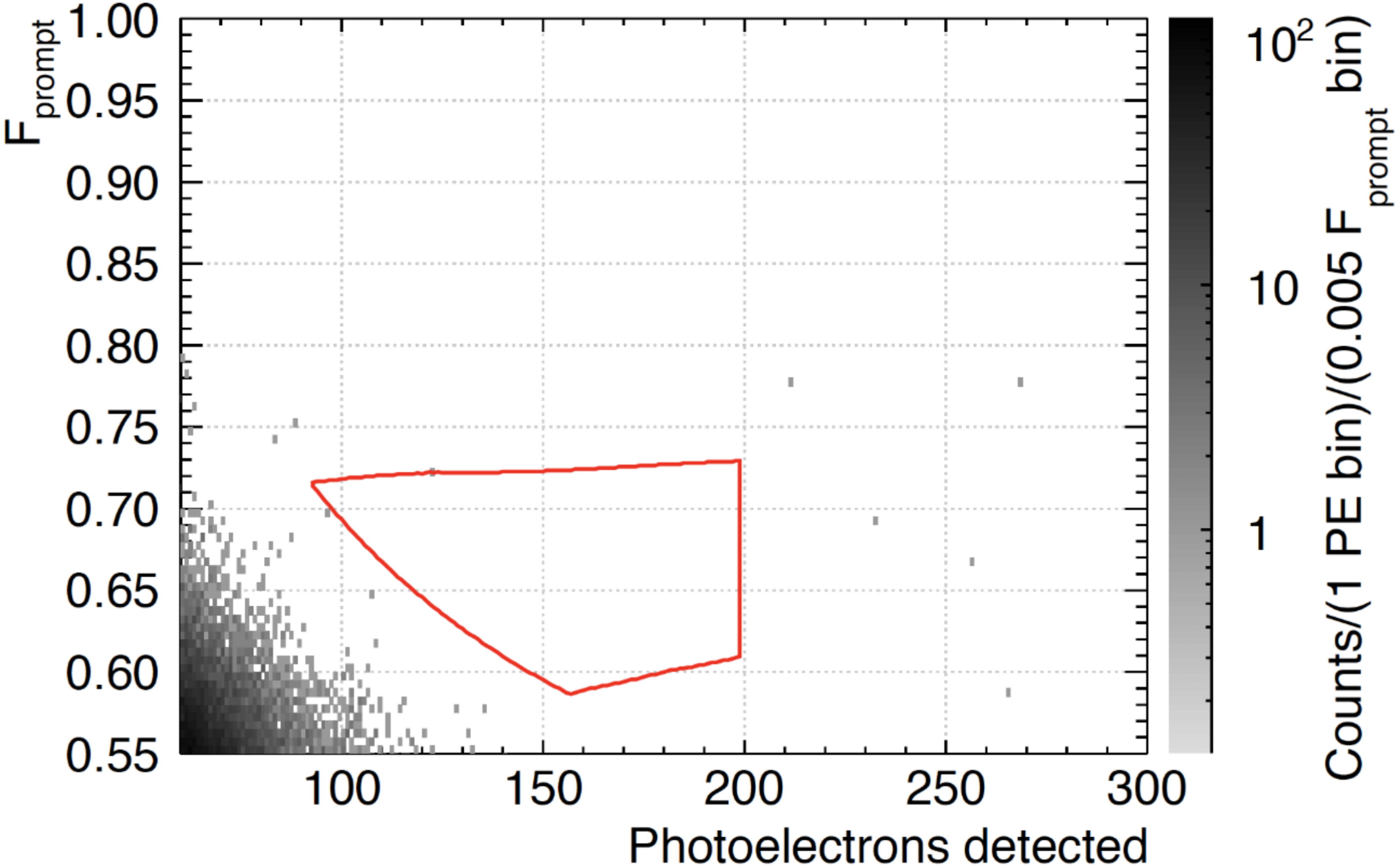
The detector is sensitive to dark matter, but no signal event was observed in our first-year dataset (November 2016 – October 2017)



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

Dark Matter Search Results

The detector is sensitive to dark matter, but no signal event was observed in our first-year dataset (November 2016 – October 2017)

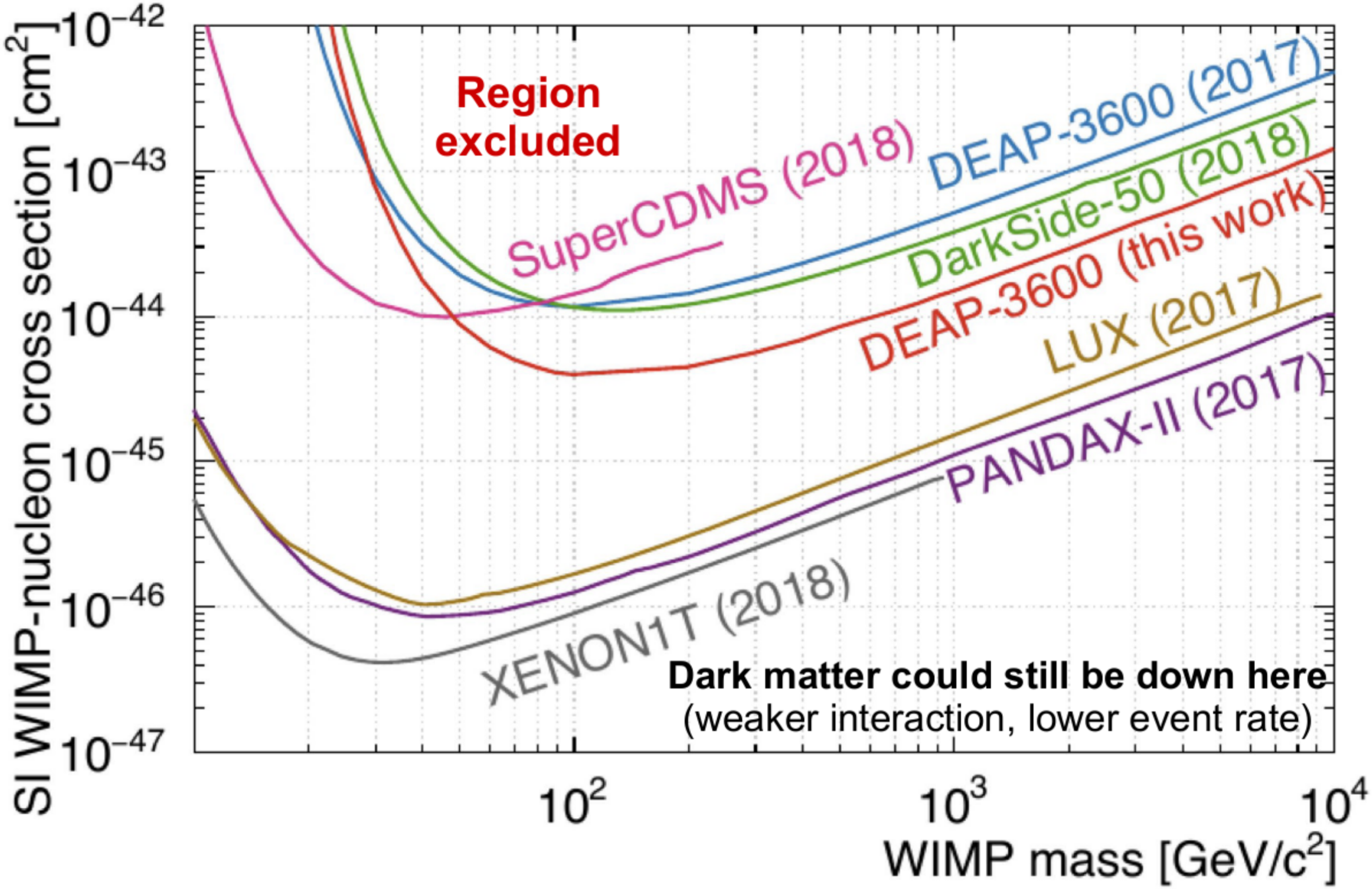


Physical Review D, 100, 022004 (2019) arXiv:1902.04048

Dark Matter Search Results

The detector is sensitive to dark matter, but no signal event was observed in our first-year dataset (November 2016 – October 2017)

Therefore we **exclude** certain dark matter hypotheses



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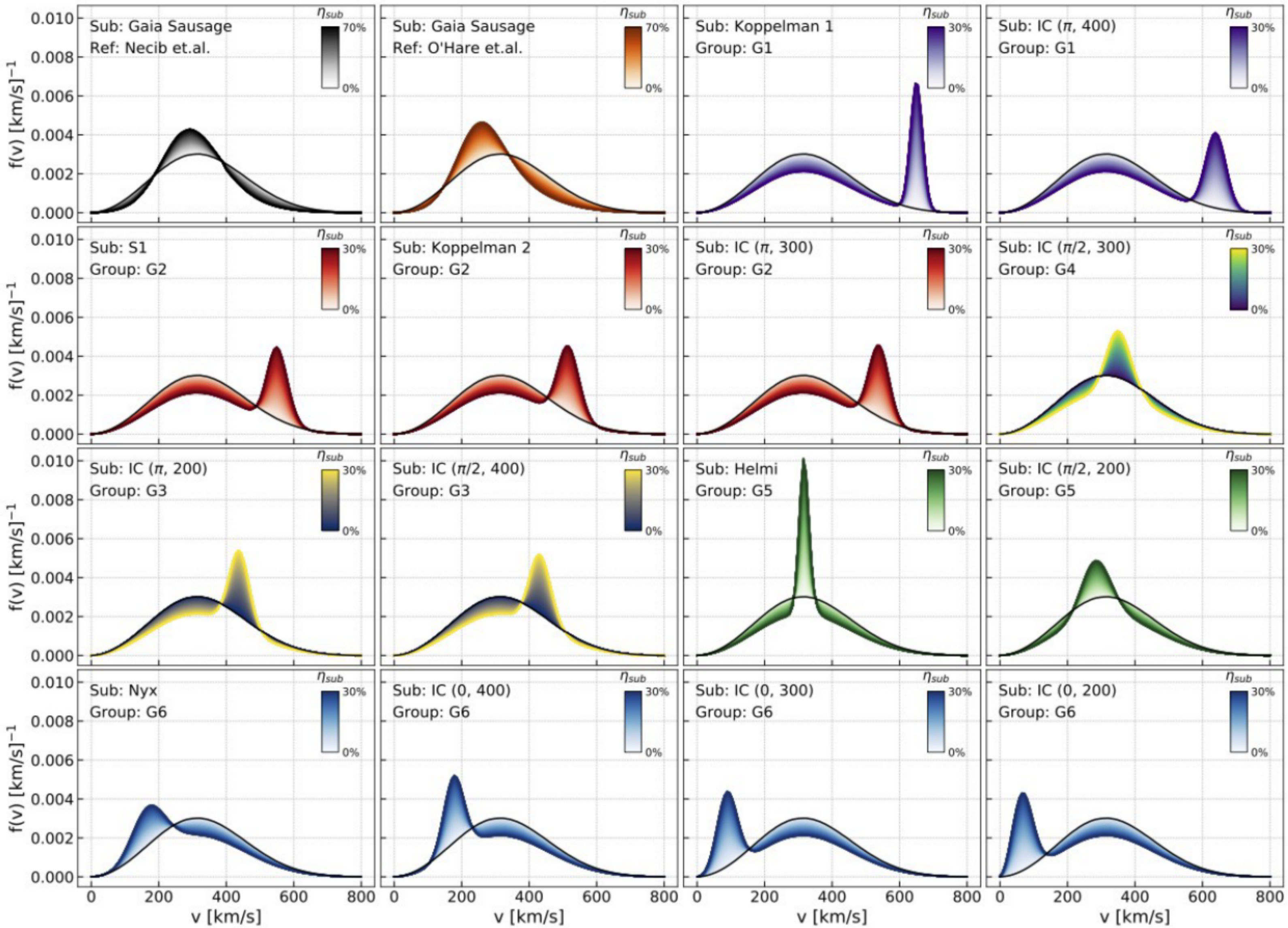
Further Constraints on Dark Matter

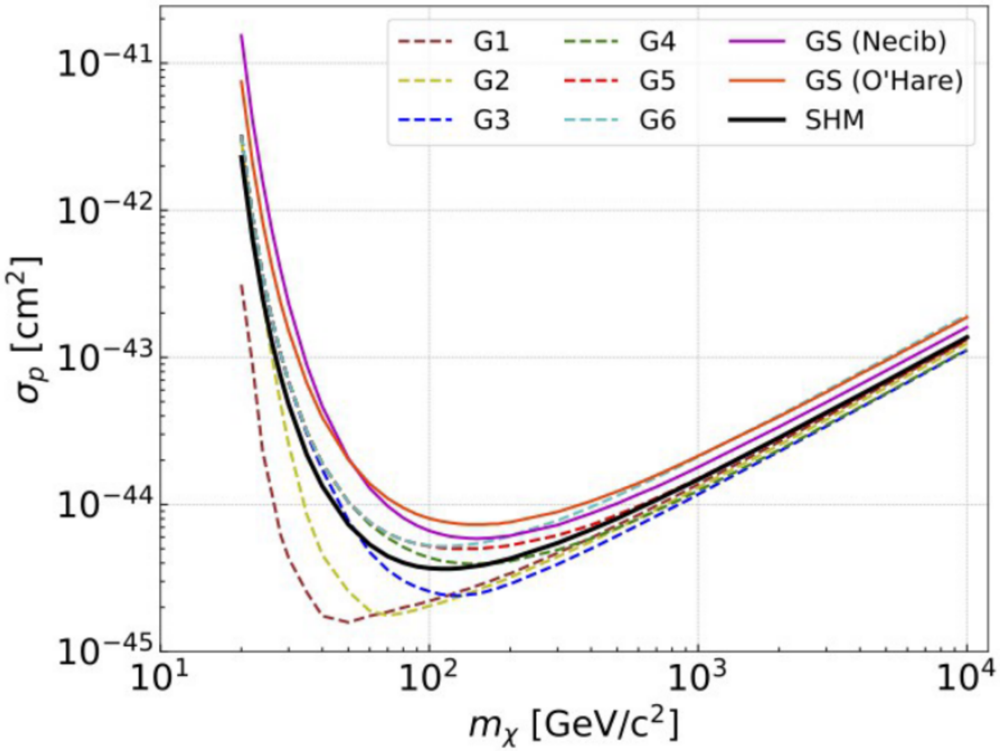
- Results are reinterpreted with a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints



Further Constraints on Dark Matter

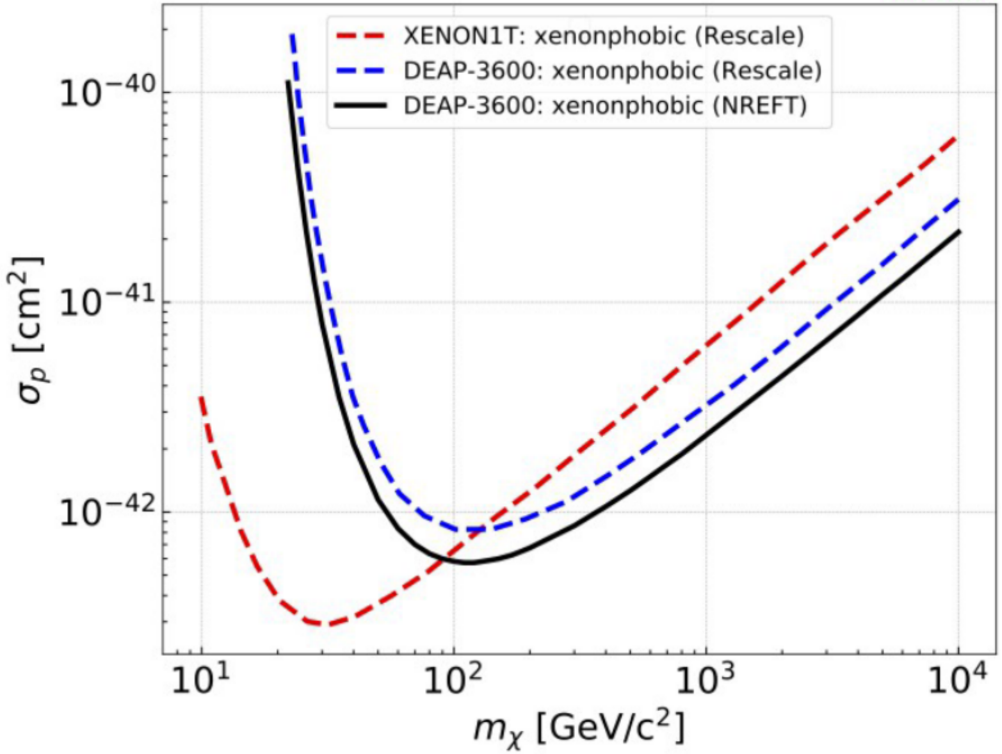
- Results are reinterpreted with a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints

Different DM halo structures result in variations from Standard Halo Model (SHM) benchmark



DEAP-3600 has **world-leading sensitivity** for a range of isospin-violating DM couplings

DEAP 3600

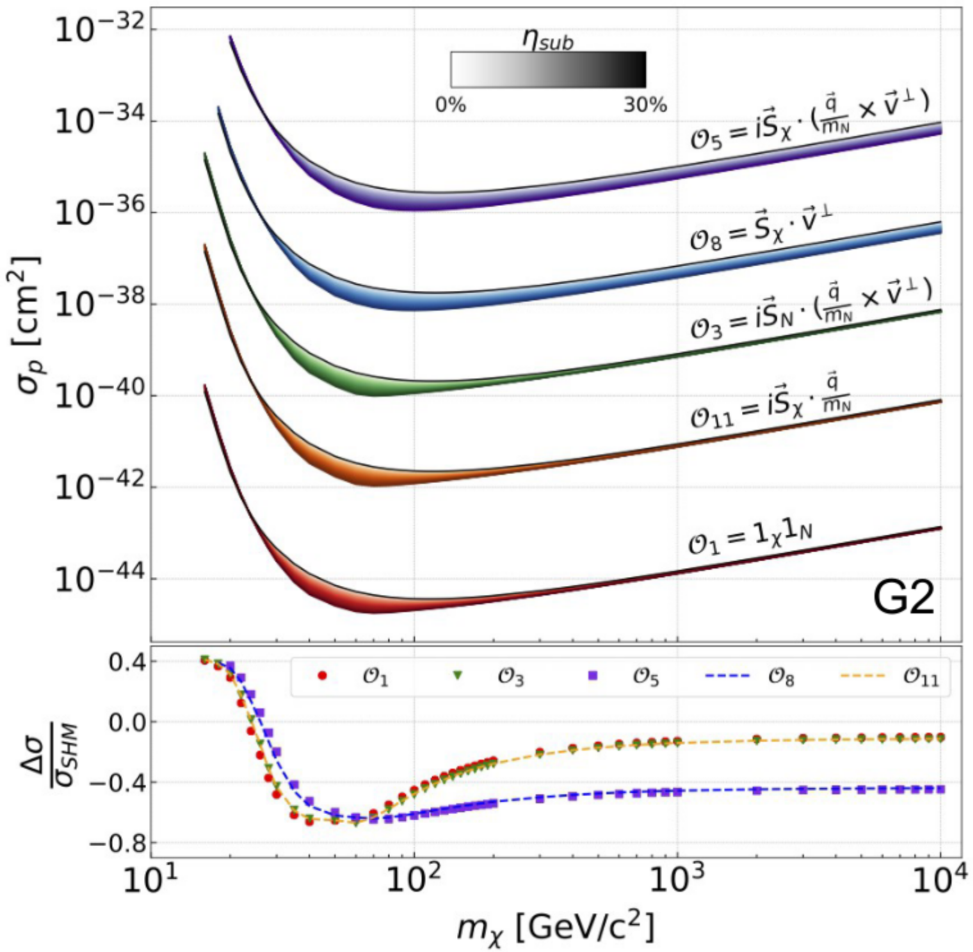


Physical Review D, 102, 082001 (2021) arXiv:2005.14667

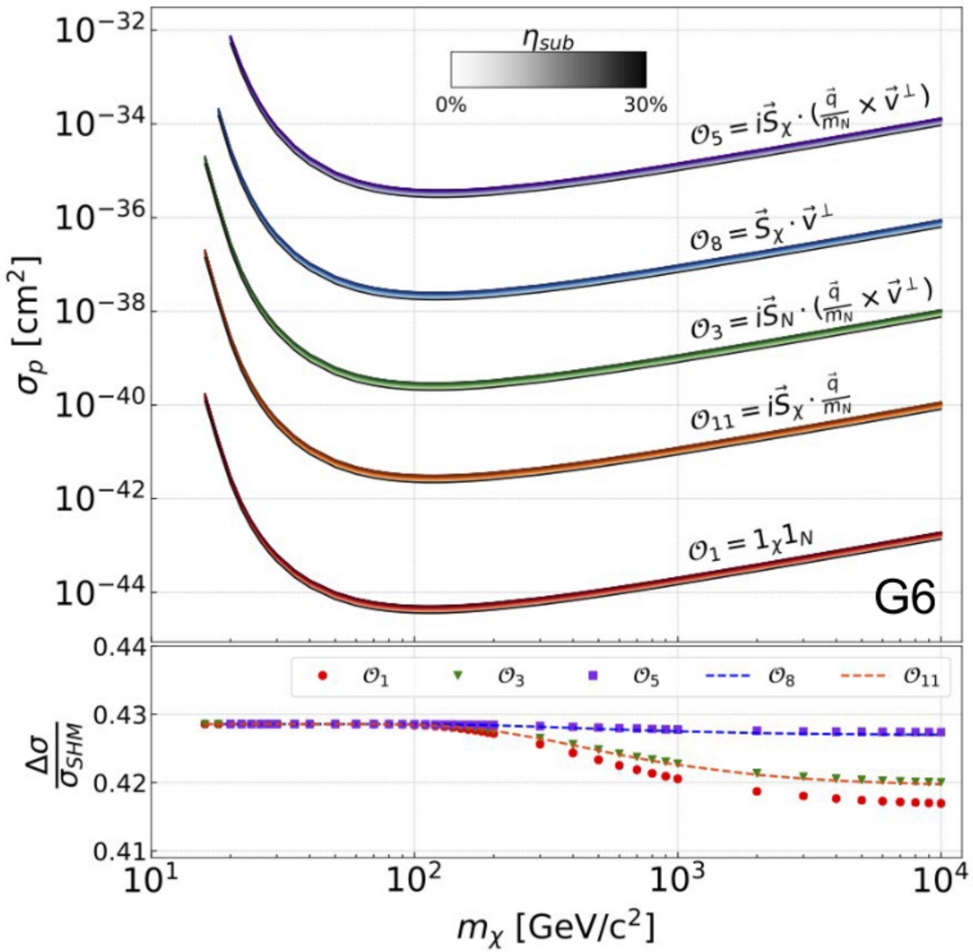
Further Constraints on Dark Matter

- Results are reinterpreted with a more general non-relativistic EFT framework, and exploring how possible substructures in DM halo affect these constraints

Example retrograde stellar stream, e.g. S1



Example prograde stellar stream, e.g. Nyx



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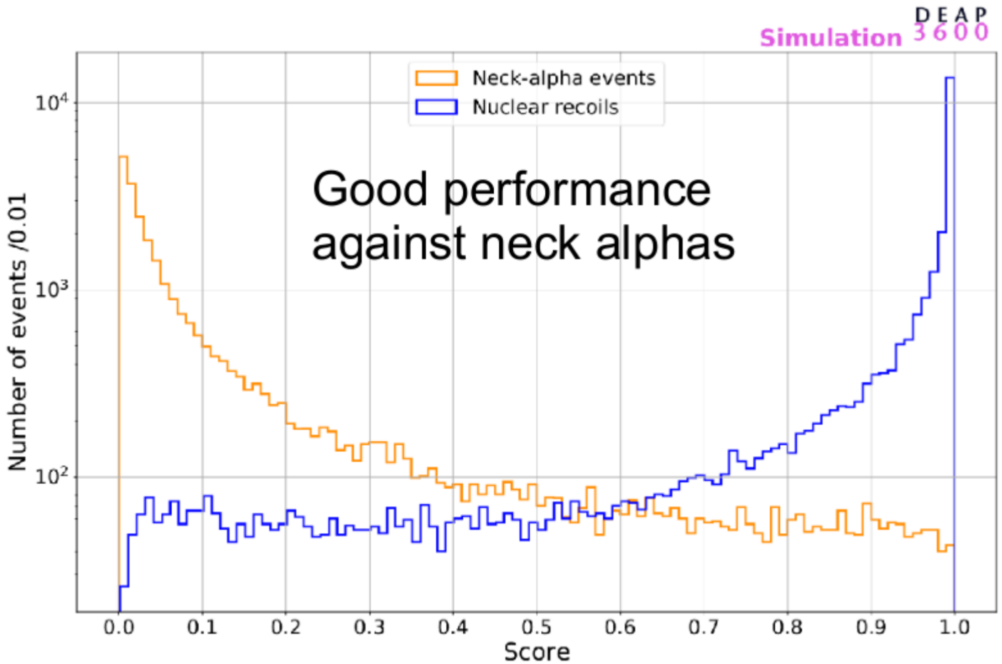
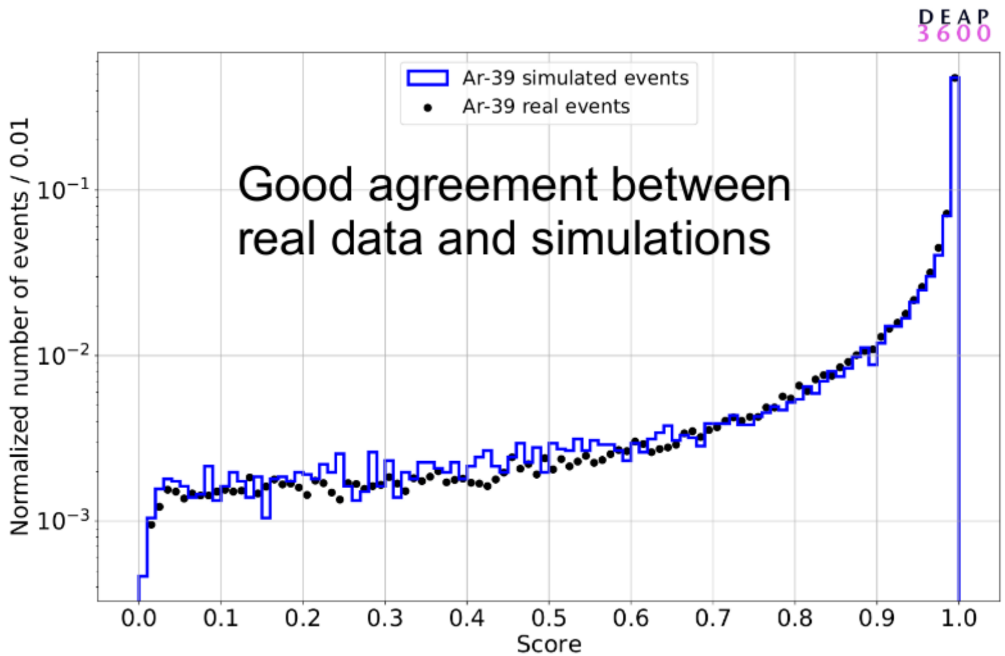
WIMP Search: Next steps

WORK IN PROGRESS

- Published DM search from first-year dataset November 2016 – October 2017
  - Working on **profile-likelihood ratio analysis** to extract full sensitivity on this dataset
- Main effort: Analyze full second-fill dataset to March 28th, 2020
- To improve sensitivity: three **MVA algorithms** trained against alpha backgrounds
  - Random Forest, Boosted Decision Trees, Neural Network (shown here)
  - Now **developing new observables**, validating background models, and re-optimizing our DM candidate event selection



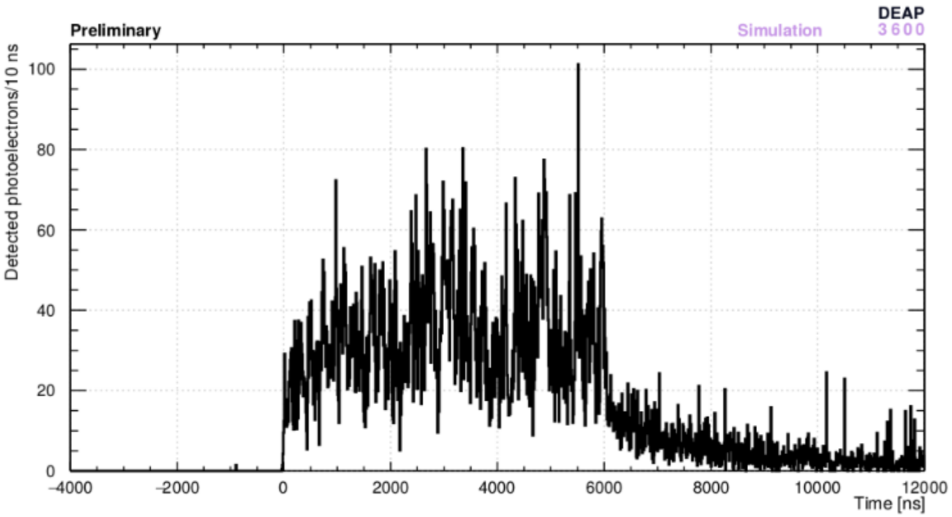


Other Searches

WORK IN PROGRESS

Multiply-interacting massive particles

- Distinct signature consistent with multiple recoils in succession
  - Pulse-shape inconsistent with coincidence backgrounds



- Size of DEAP-3600 gives great sensitivity
  - Search recently unblinded!
    Now writing up manuscript

Neutrino absorption search

- Look for ^{8}B solar neutrinos produced by

$$^{8}\mathrm{B} \rightarrow ^{8}\mathrm{Be} + e^{+} + \nu_e$$

- Detected via

$$\nu_e + ^{40}\mathrm{Ar} \rightarrow ^{40}\mathrm{K}^{*} + e^{-}$$

- Coincidence ROI: look for γ emission from ^{40}K with mean lifetime 480 ns
- High-energy ROI: look in ER spectrum above neutron capture gammas
- Expecting 17 ± 5 signal events in full dataset (before event selection)
  - 3σ expected sensitivity overall

Summary: DEAP-3600 Physics Programme

- Measurements
  - Pulse-shape [2001.09855], Pulse-shape discrimination [2103.12202]
  - ^{39}Ar specific activity
  - ^{39}Ar half-life
  - Electromagnetic backgrounds and ^{42}K activity [1905.05811]
  - Muon flux at SNOLAB

- WIMP dark matter search
  - Published search with 231 live-days [1902.04048]
    - Constraints on DM halo substructures and non-relativistic EFT [2005.14667]
    - Profile likelihood ratio analysis
  - Analysis in progress with 840 live-days
    - Limiting backgrounds: neck alphas, dust alphas
  - Background mitigation in hardware, data-taking to resume in 2022 [*next slide*]

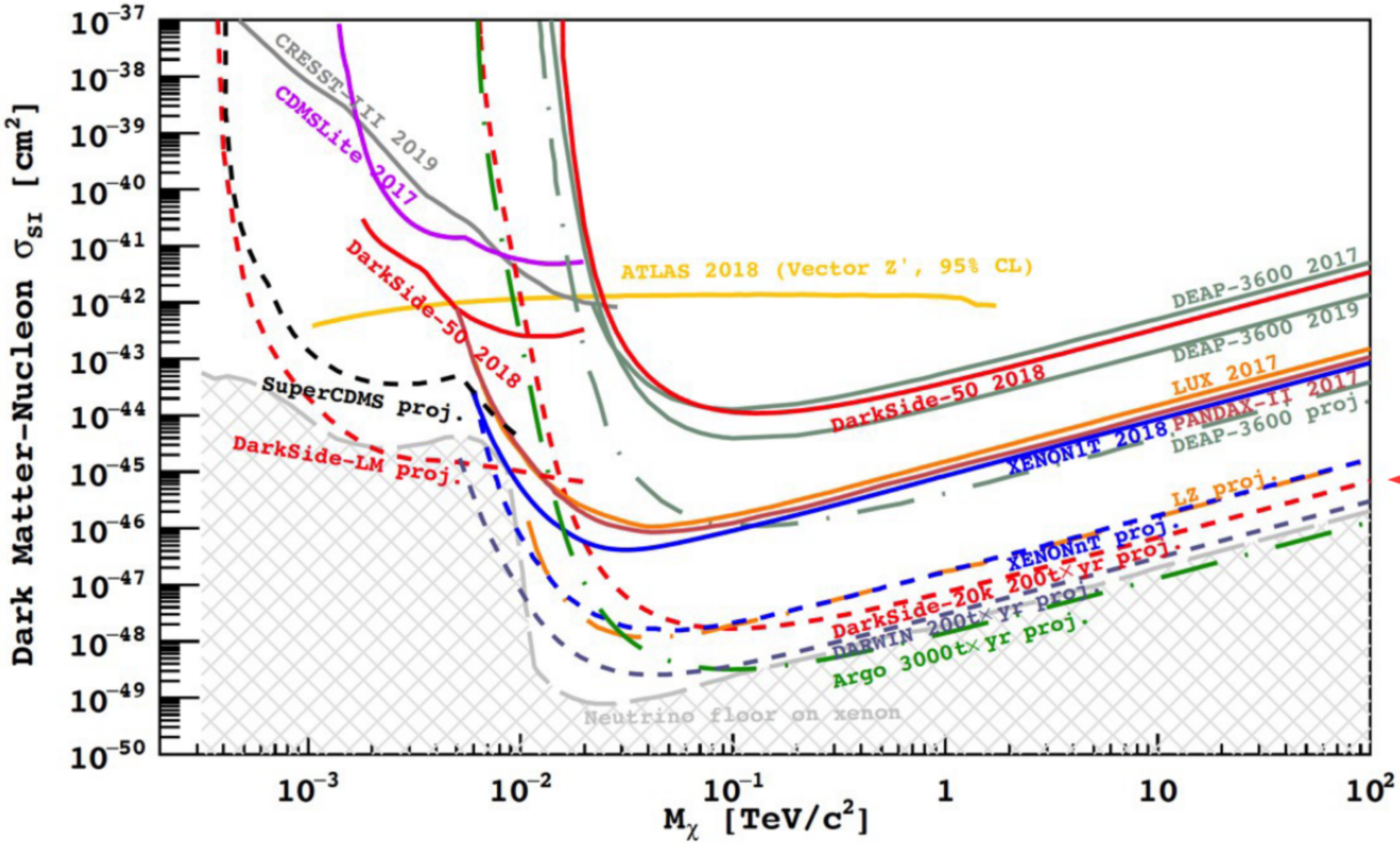
- Other searches
  - 5.5 MeV solar axions
  - Multiply-interacting massive particles (MIMP search)
  - Neutrino absorption (inverse beta decay)

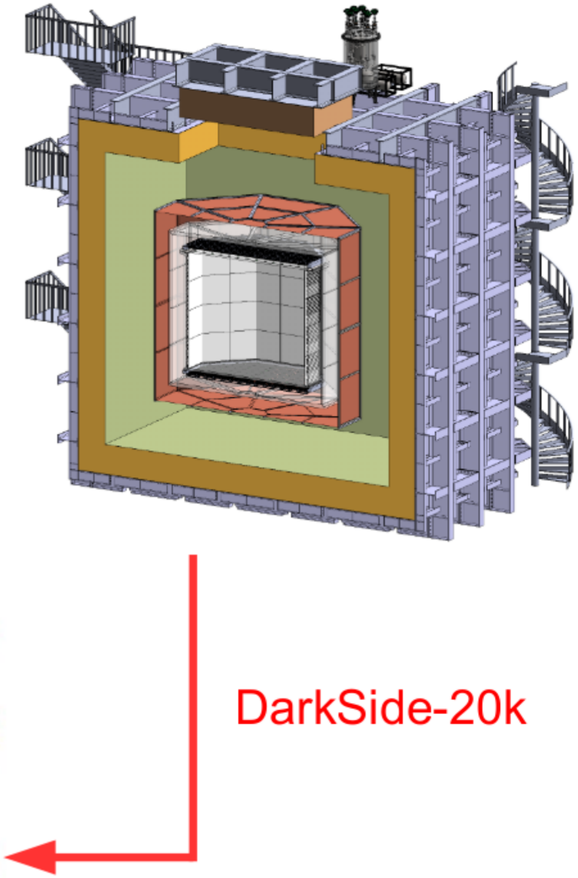
Next Steps: DEAP-3600 Hardware Upgrades

- **Hardware upgrade** program
  - Main objective: **Mitigate limiting background sources**
    - Neck seal replacement, allowing a complete fill with LAr
    - Pyrene: slow wavelength shifter on neck flowguides, to remove neck alpha background with PSD
    - Alternate cooling system, to filter out dust
    - Also perform maintenance on cryogenic systems
- Current status
  - Detector now empty of LAr
    - Still taking data in GAr and vacuum, with calibration sources
  - COVID delays: Plan to complete upgrades in the next 6 months
- New DM search data in upgraded detector expected in 2022
  - **Expecting improved sensitivity**
  - Inform design of next-generation liquid argon dark matter experiments

Next-Generation Liquid Argon Dark Matter Detectors

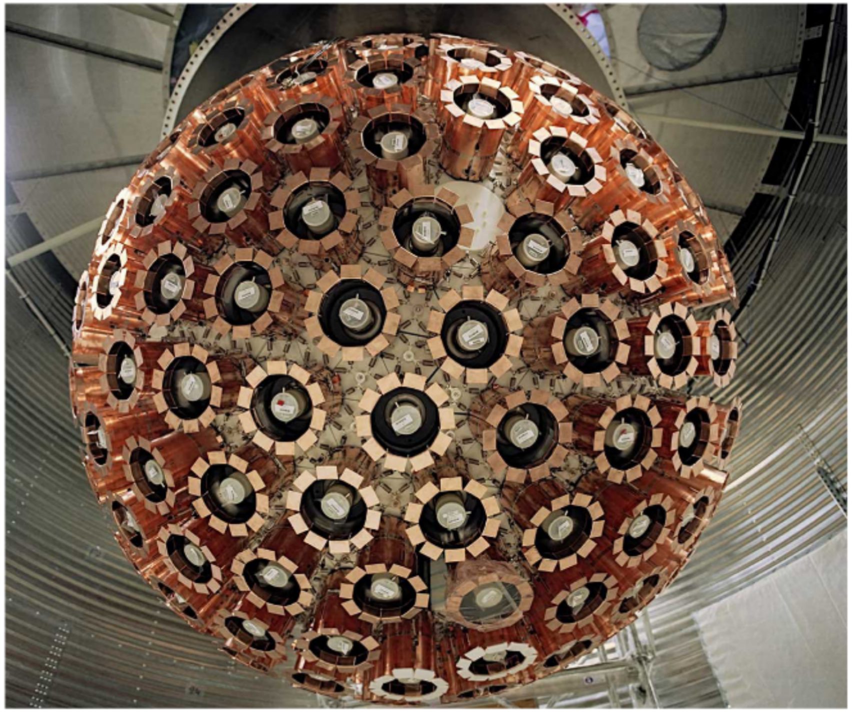
- To maximize sensitivity with next-generation experiments: **THINK BIG**
- **Global Argon Dark Matter Collaboration** formed!
  - Next objective: **DarkSide-20k** with underground argon
  - Objective: Neutrino floor sensitivity to spin-independent dark matter nucleon interactions with ARGO, a **multi-hundred tonnes** liquid argon detector





DarkSide-20k
Technical Design Report,
in preparation

Conclusion



- **Looking for dark matter** with **DEAP-3600**
  - Excellent detector performance!
    - Pulse-shape discrimination
    - Event reconstruction
    - Background rejection
    - Sensitivity to new physics
  - Stable data-taking continues
    - 80% blind since January 1^{st}, 2018
    - DM search data closed March 28^{th}, 2020
  - Work in progress:
    - **Multivariate analysis** to improve signal acceptance
    - **New searches and measurements**: stay tuned!
    - **Hardware upgrade**
- **Instrumentation** research and development for future particle detectors
  - Design and simulation for DarkSide-20k and ARGO
  - Silicon photomultipliers