

# **DATA INTENSIVE SEARCHES FOR DARK MATTER WITH FERMI AND LZ**

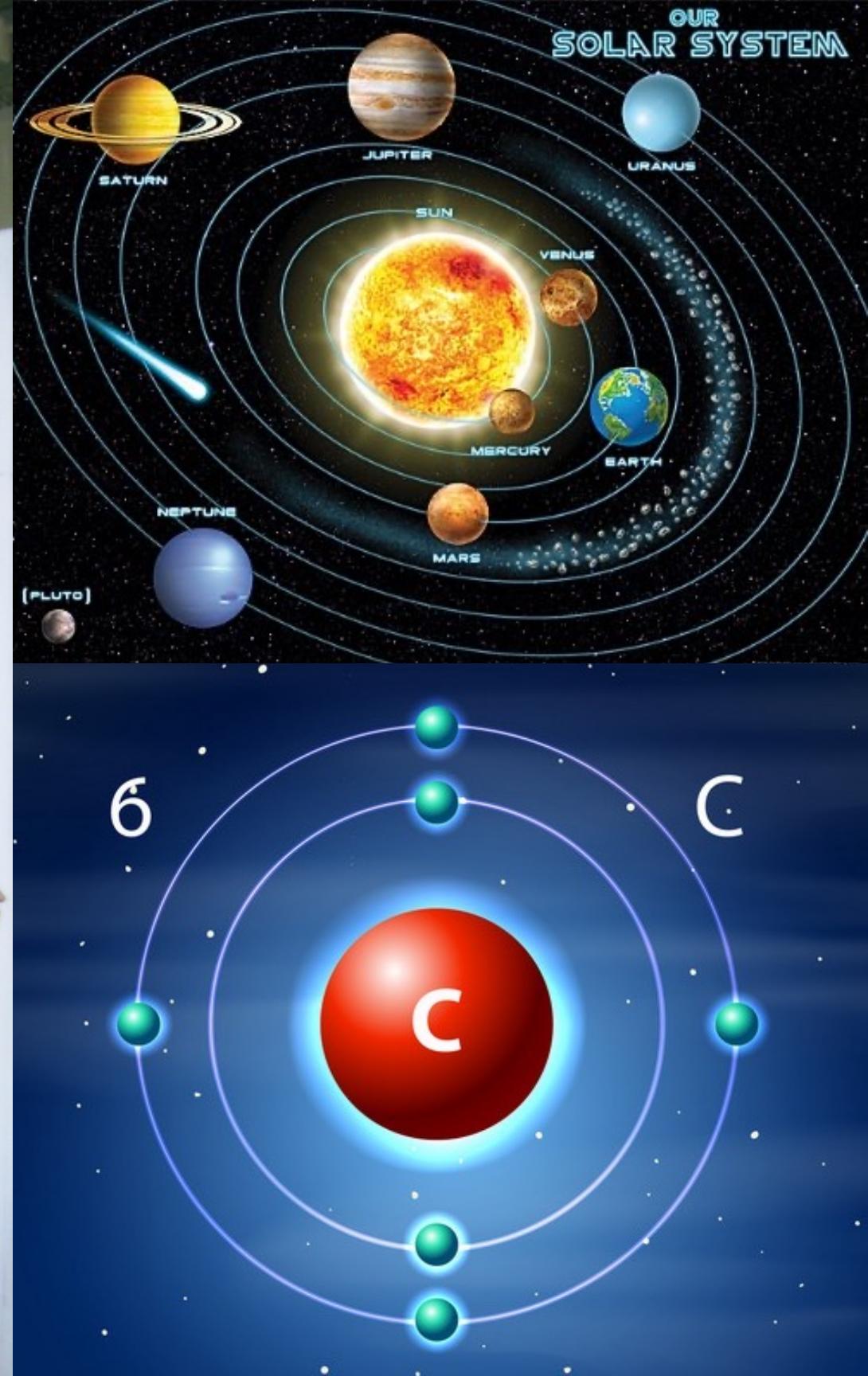


**MARIA ELENA MONZANI, SLAC/STANFORD,  
VATICAN OBSERVATORY, 13 JUNE 2023**





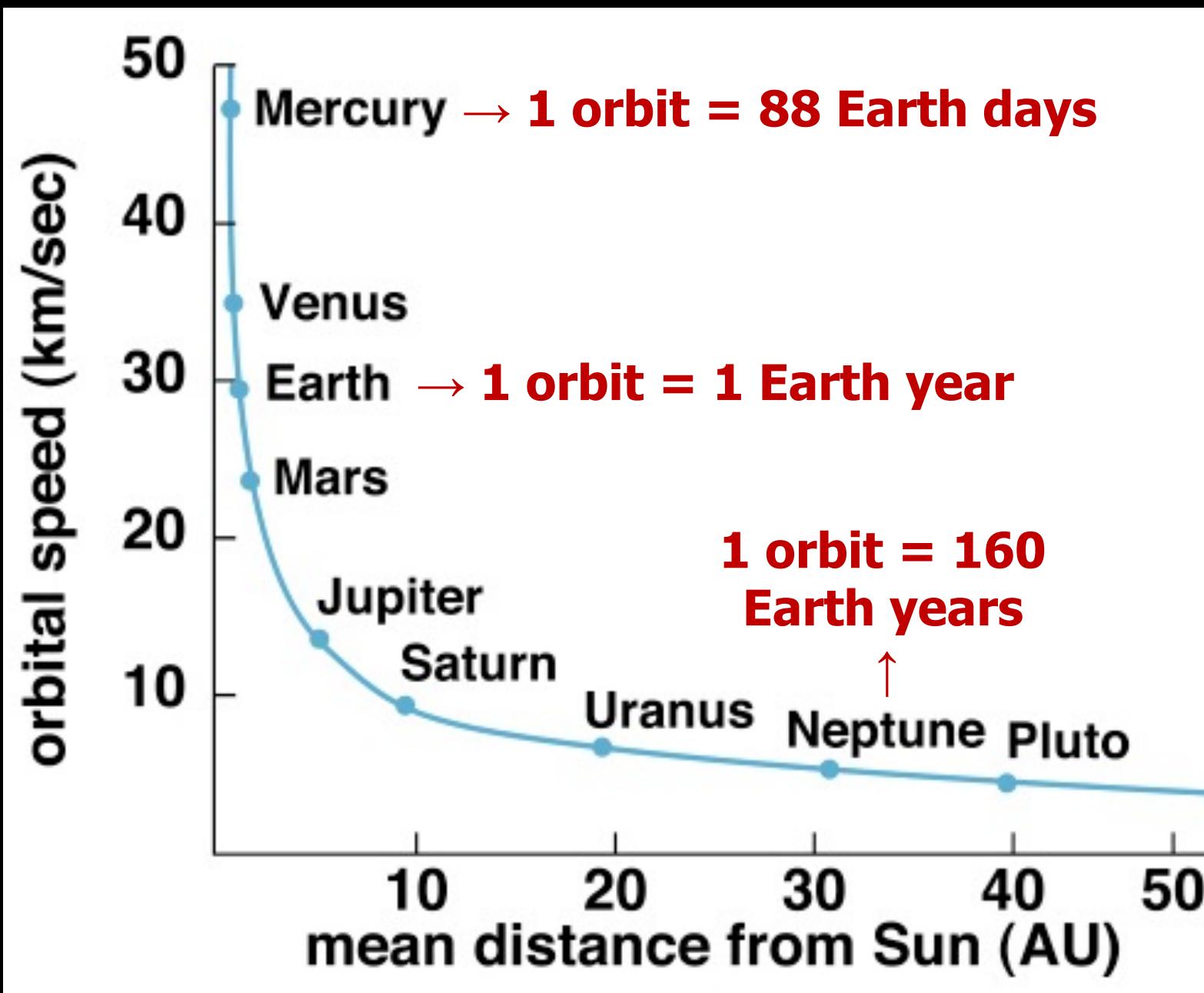




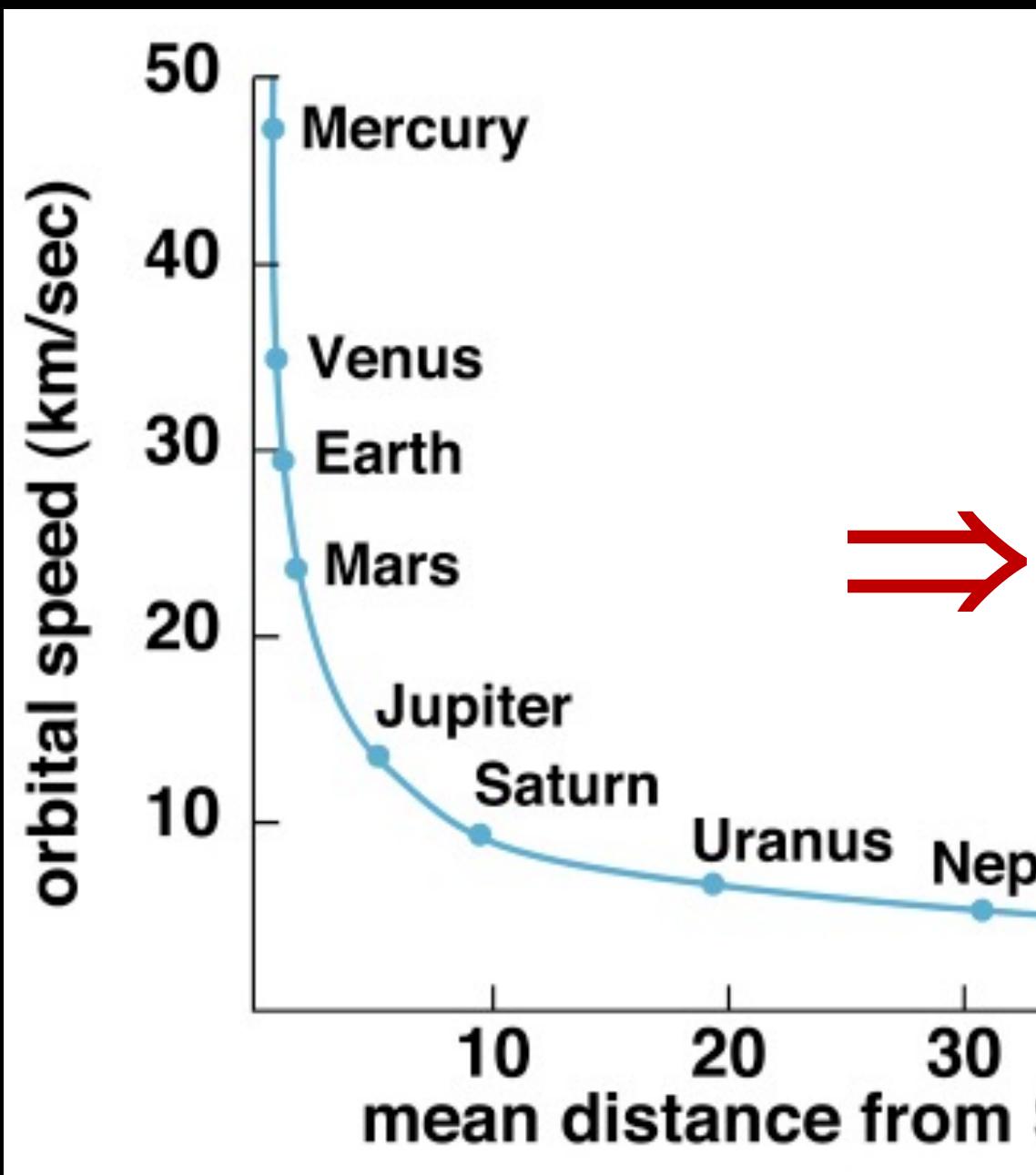


**WHAT IS DARK MATTER?  
HOW DO WE KNOW IT EXISTS?**

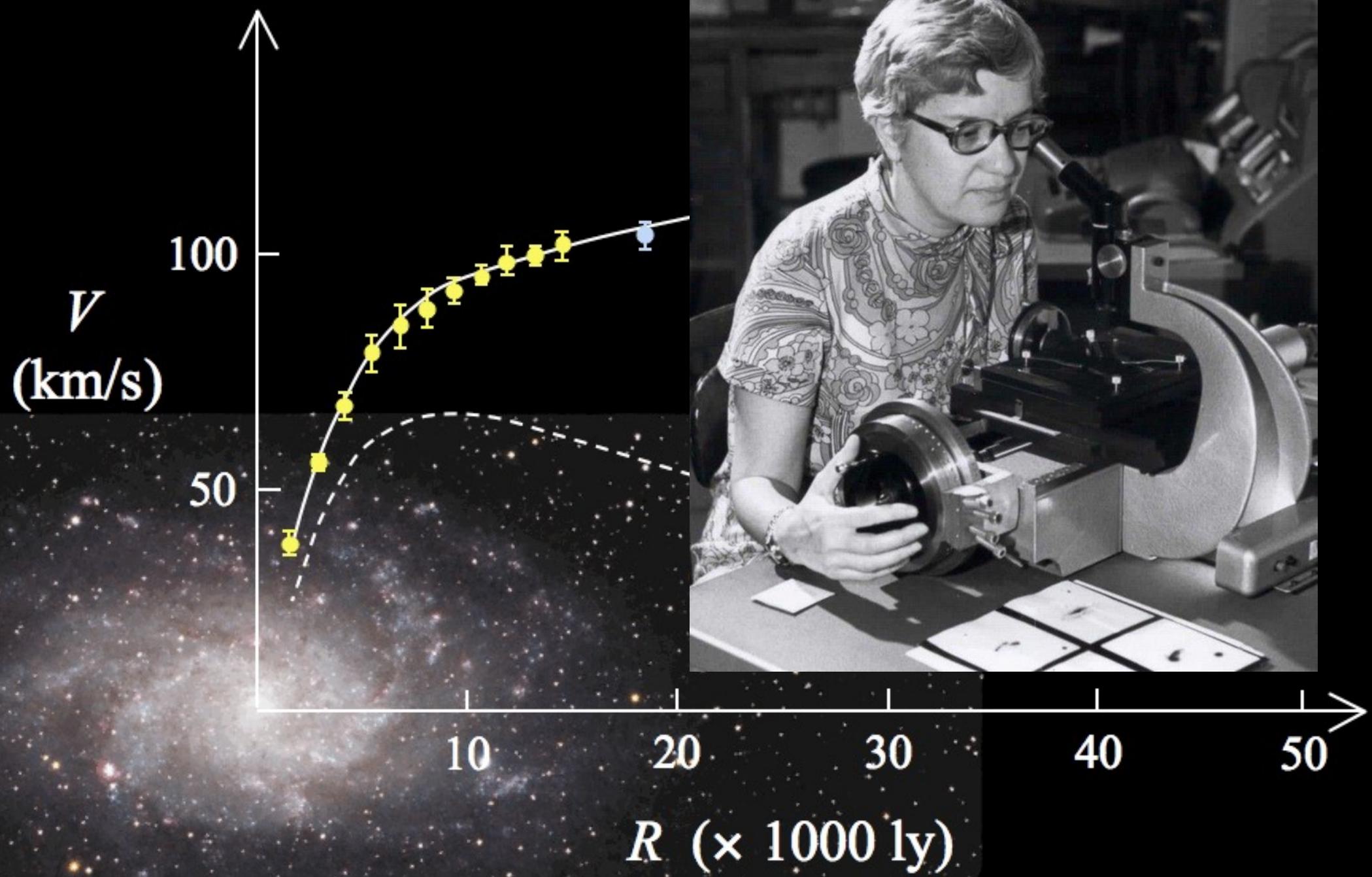
# ROTATIONAL VELOCITIES IN THE SOLAR SYSTEM



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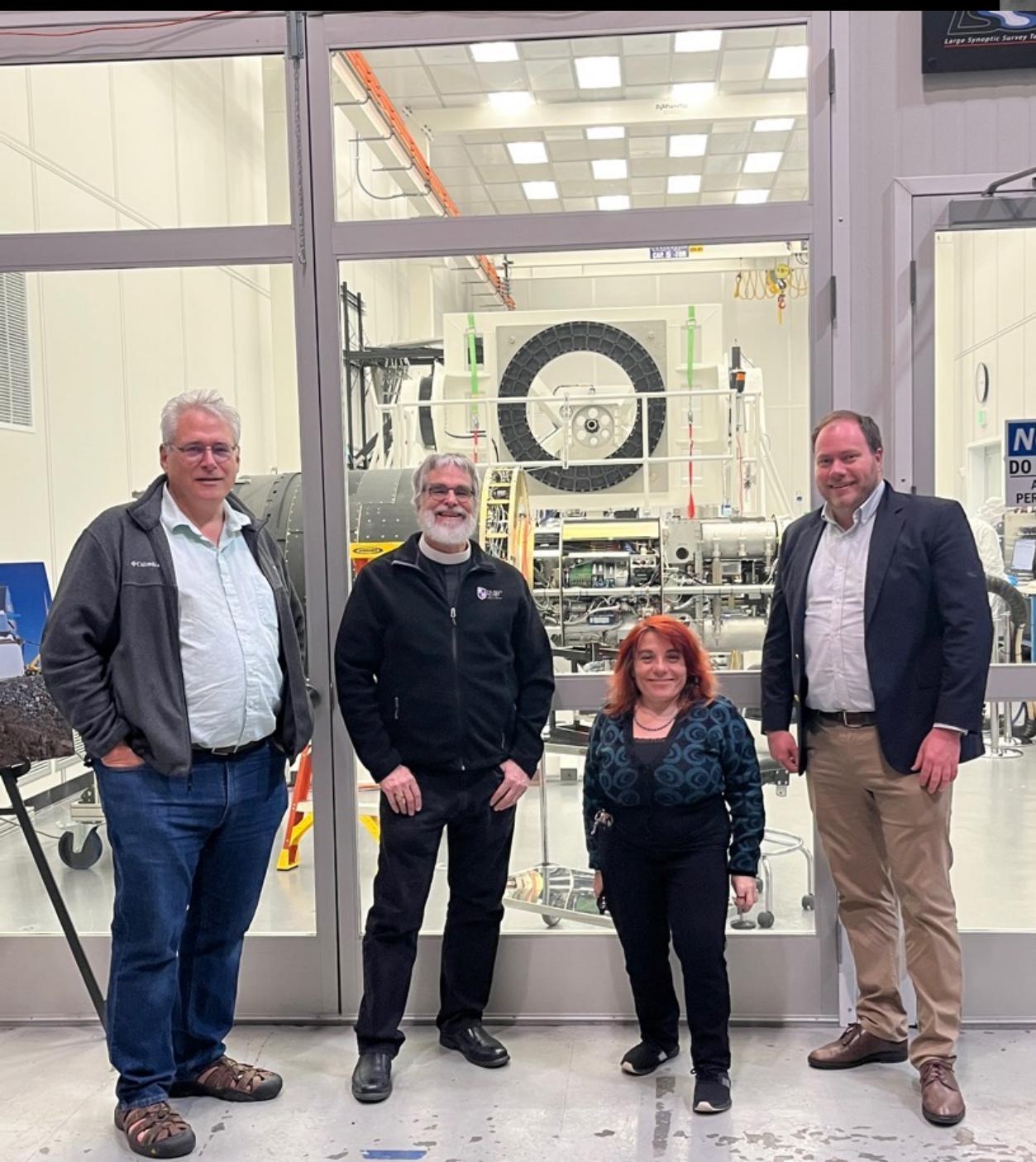


# MORE MATTER THAN MEETS THE EYE



**M33 GALAXY**

# MORE MATTER THAN MEETS THE EYE



**M33 GALAXY**

**THE MILKY WAY IS ESTIMATED TO HAVE ROUGHLY 10 TIMES AS MUCH DARK MATTER AS ORDINARY MATTER**

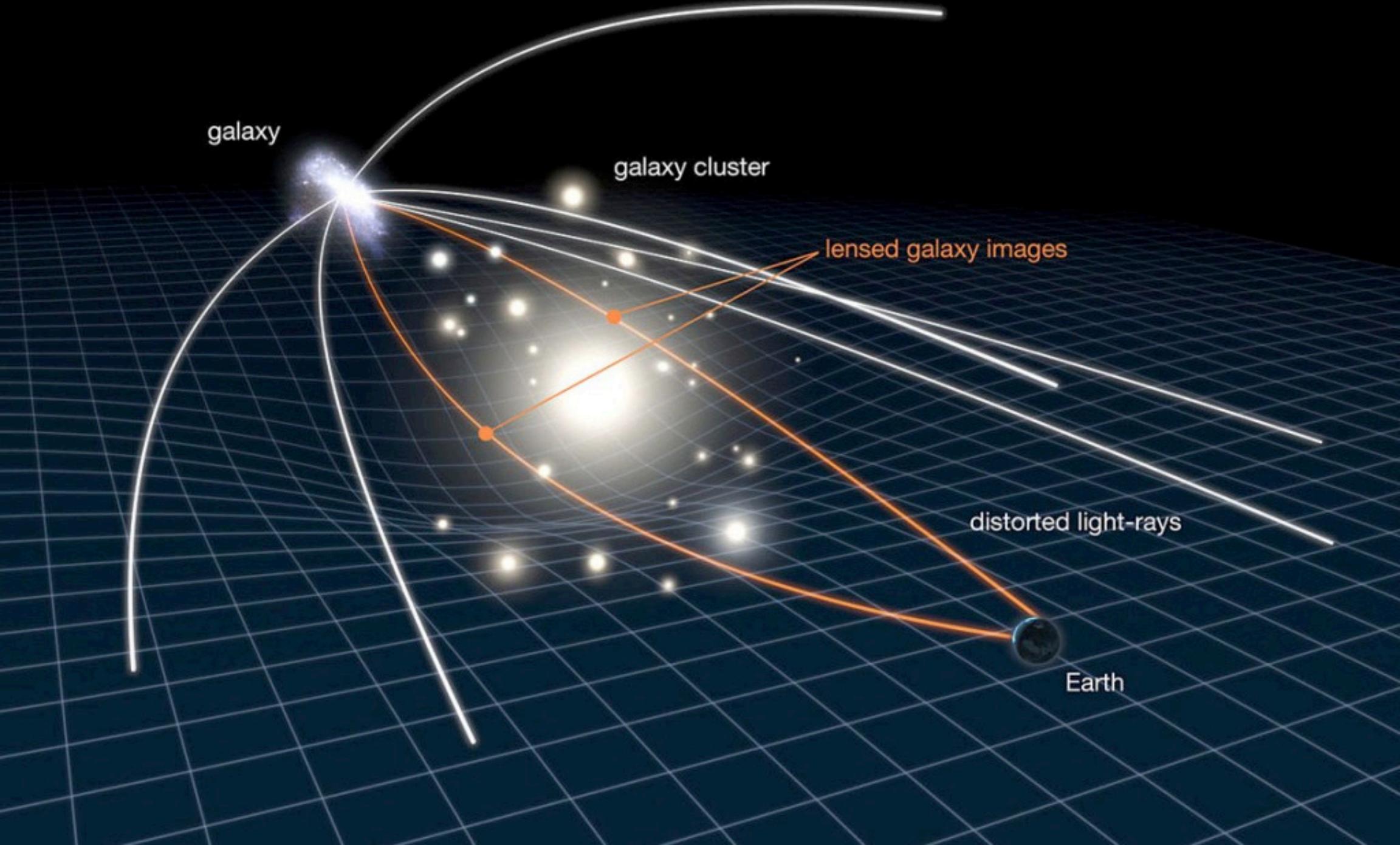


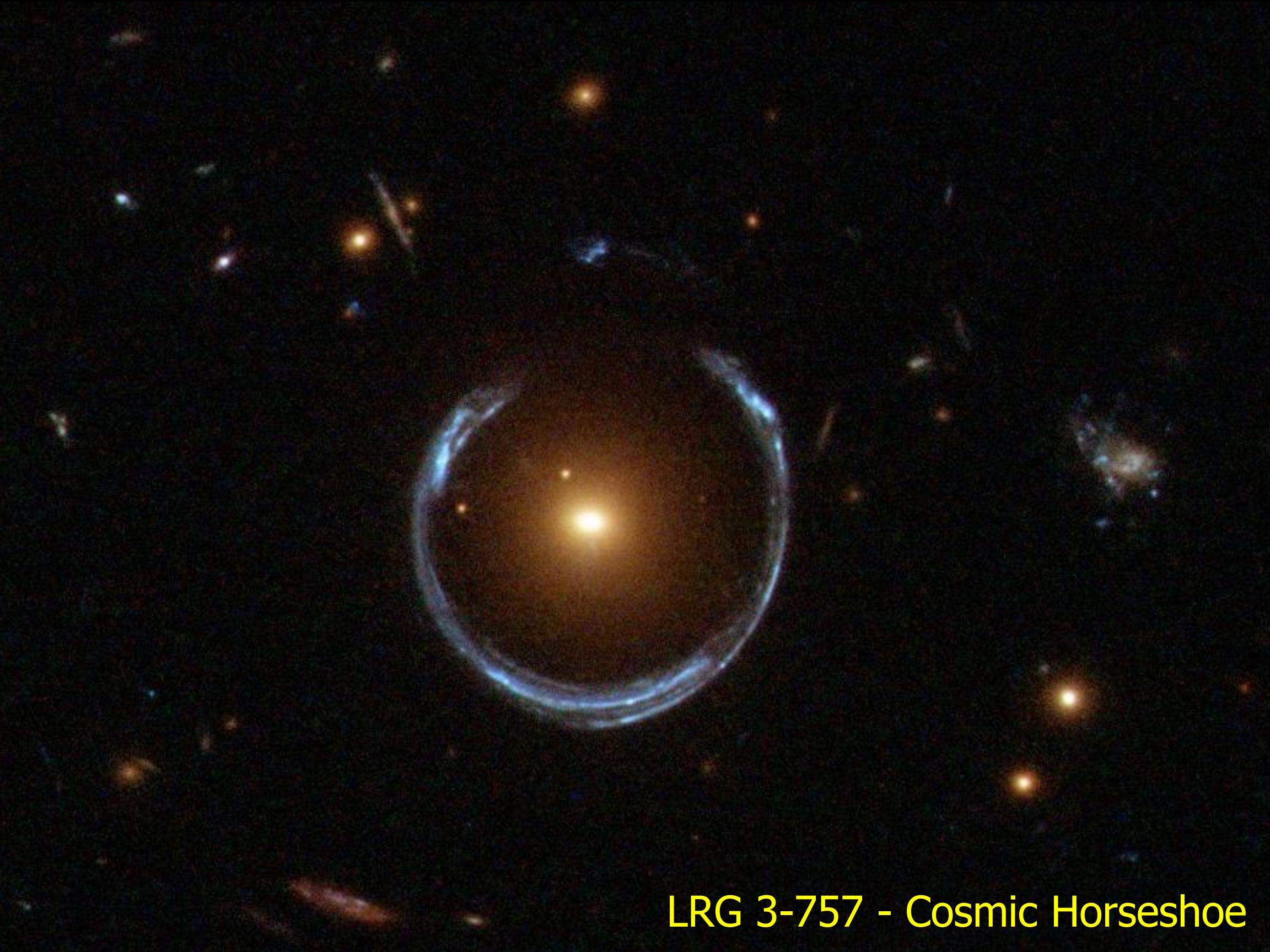
# WHAT ABOUT GALAXY CLUSTERS?



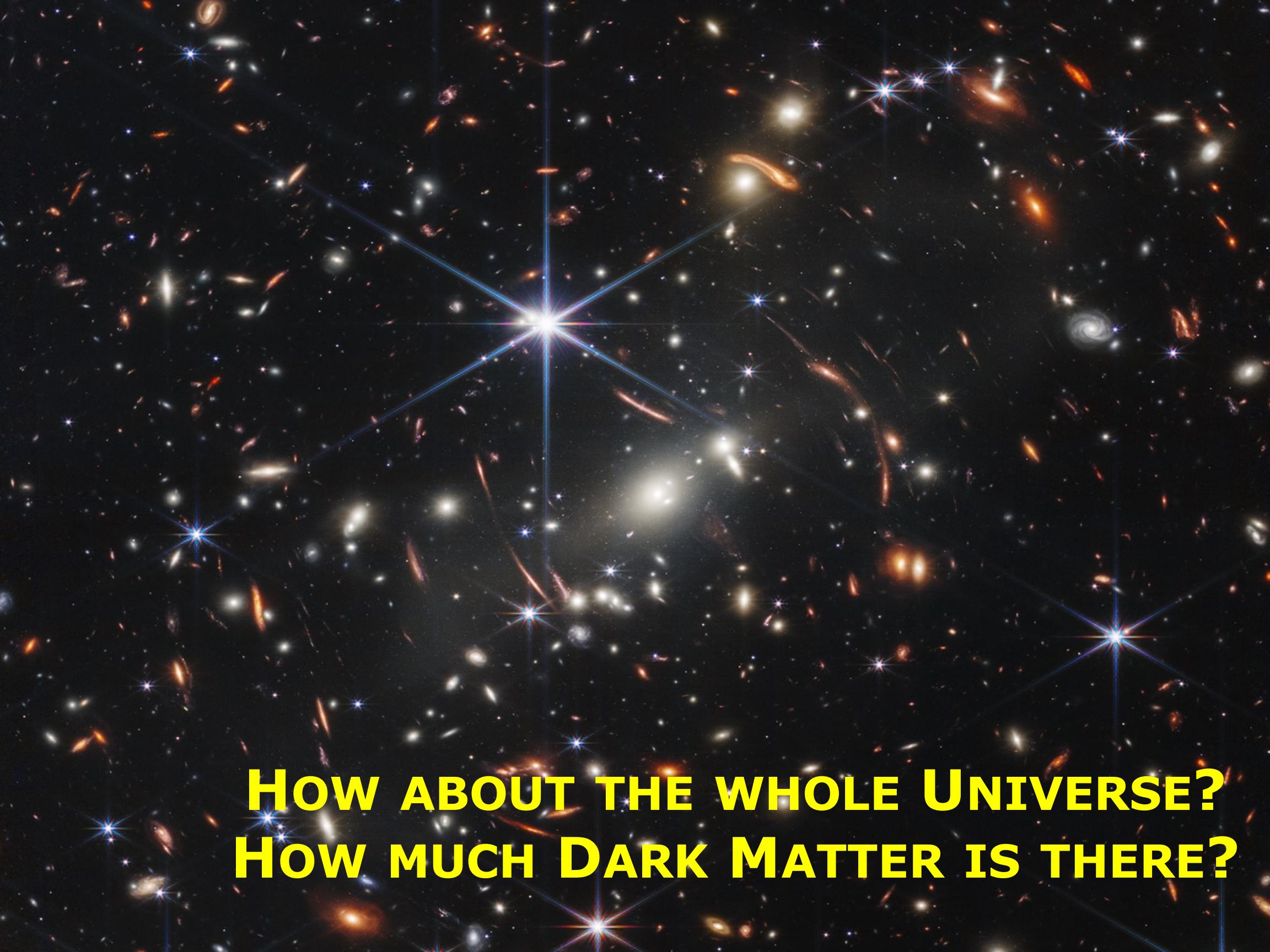
Galaxy cluster SDSS J1038+4849

# HOW ABOUT GALAXY CLUSTERS?

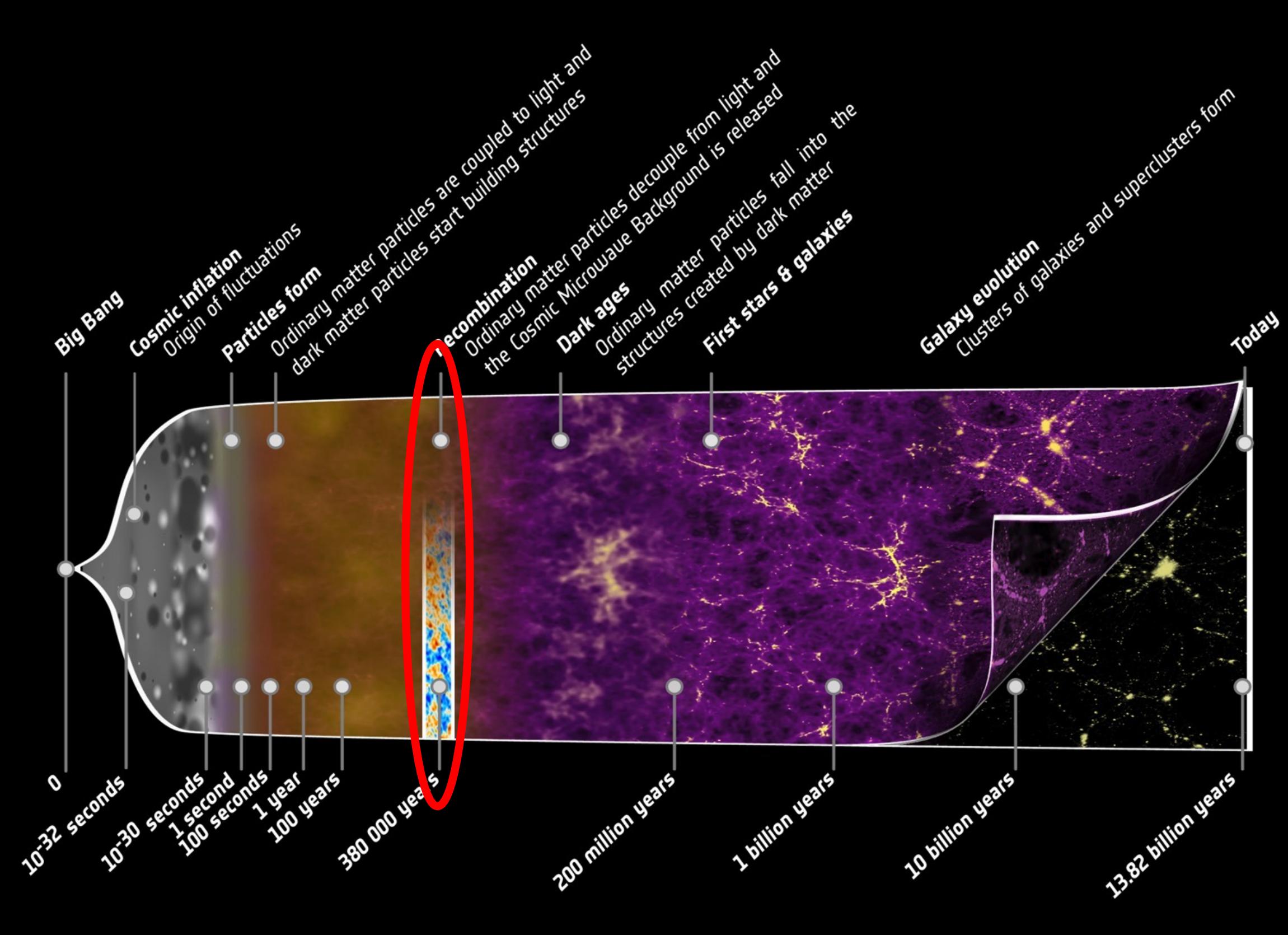




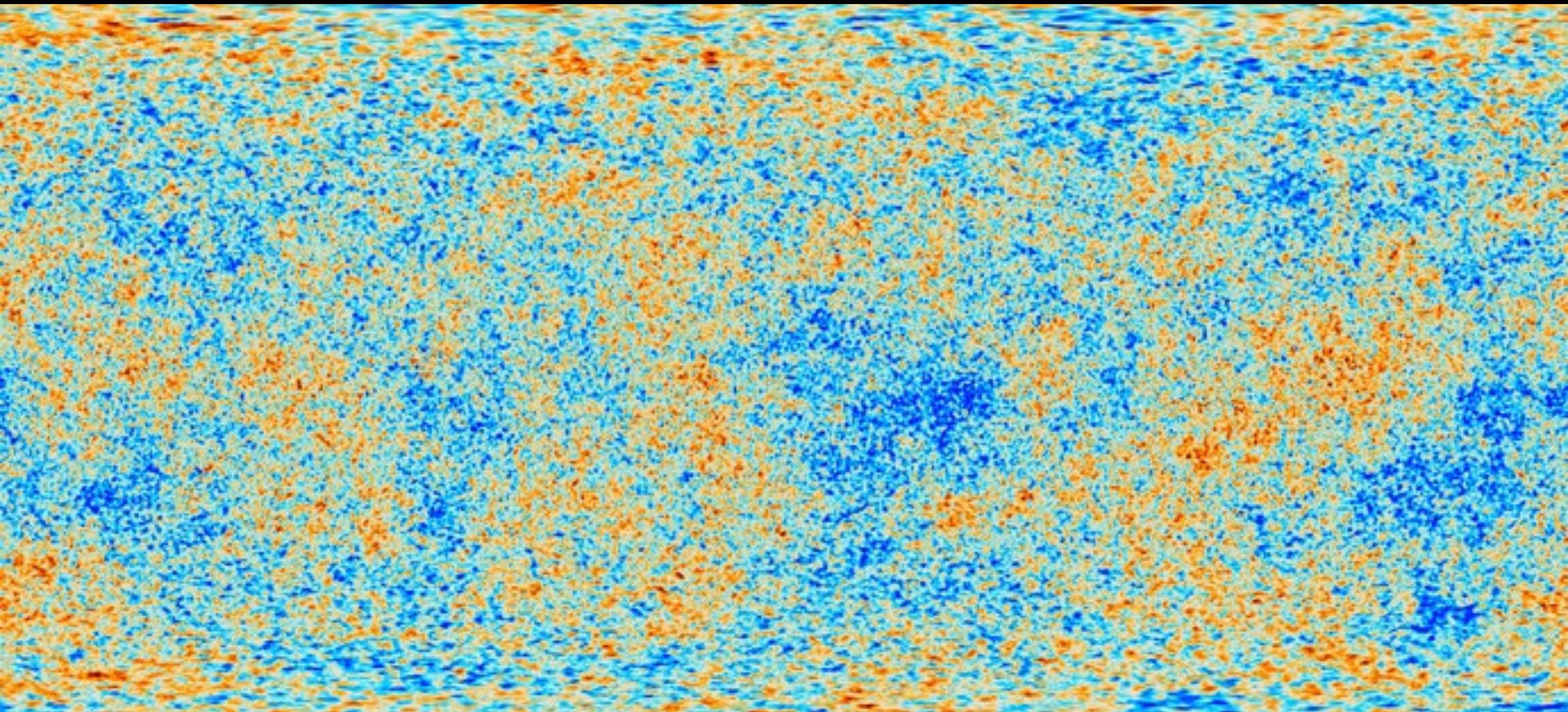
LRG 3-757 - Cosmic Horseshoe



**HOW ABOUT THE WHOLE UNIVERSE?  
HOW MUCH DARK MATTER IS THERE?**

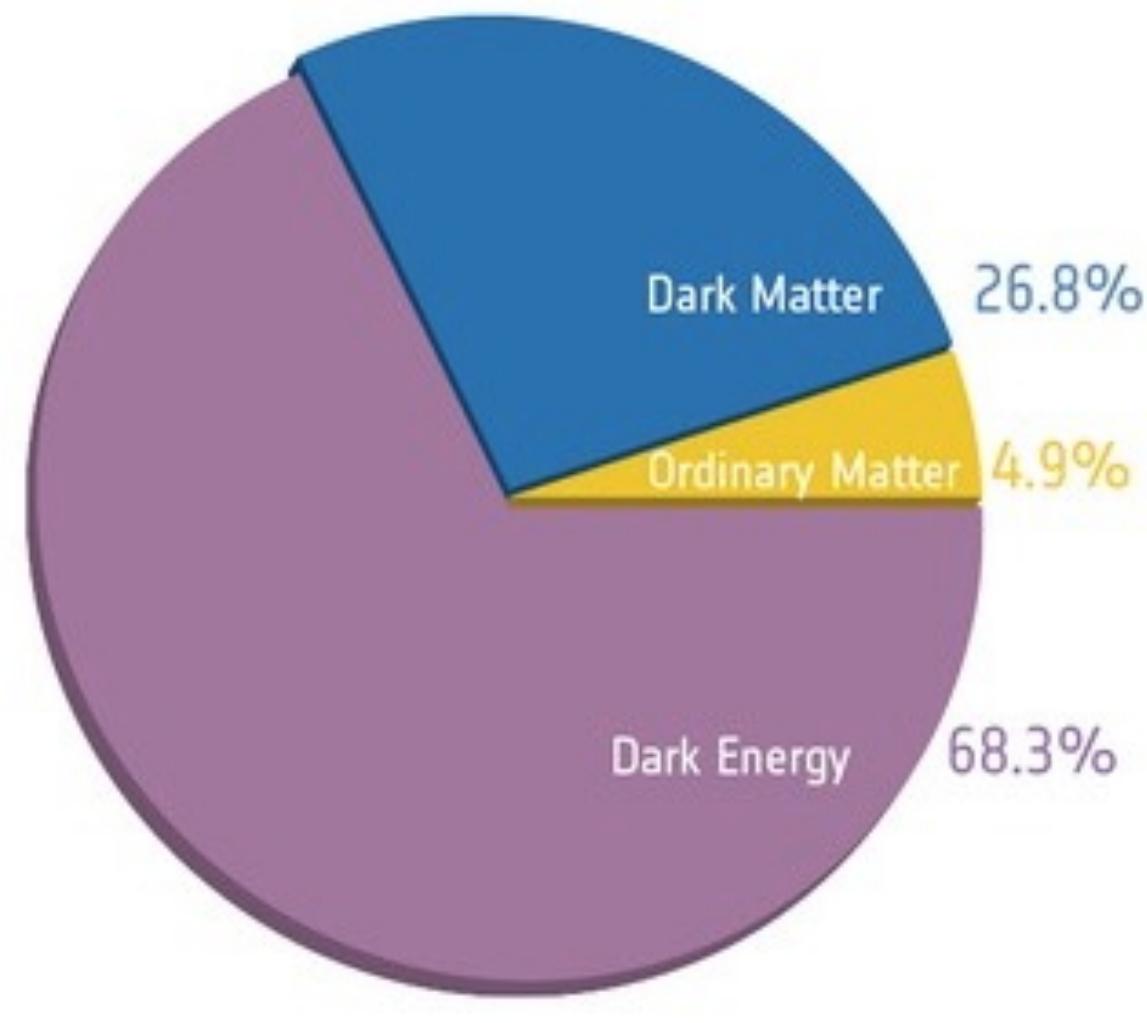


# A BABY PICTURE OF THE WHOLE UNIVERSE

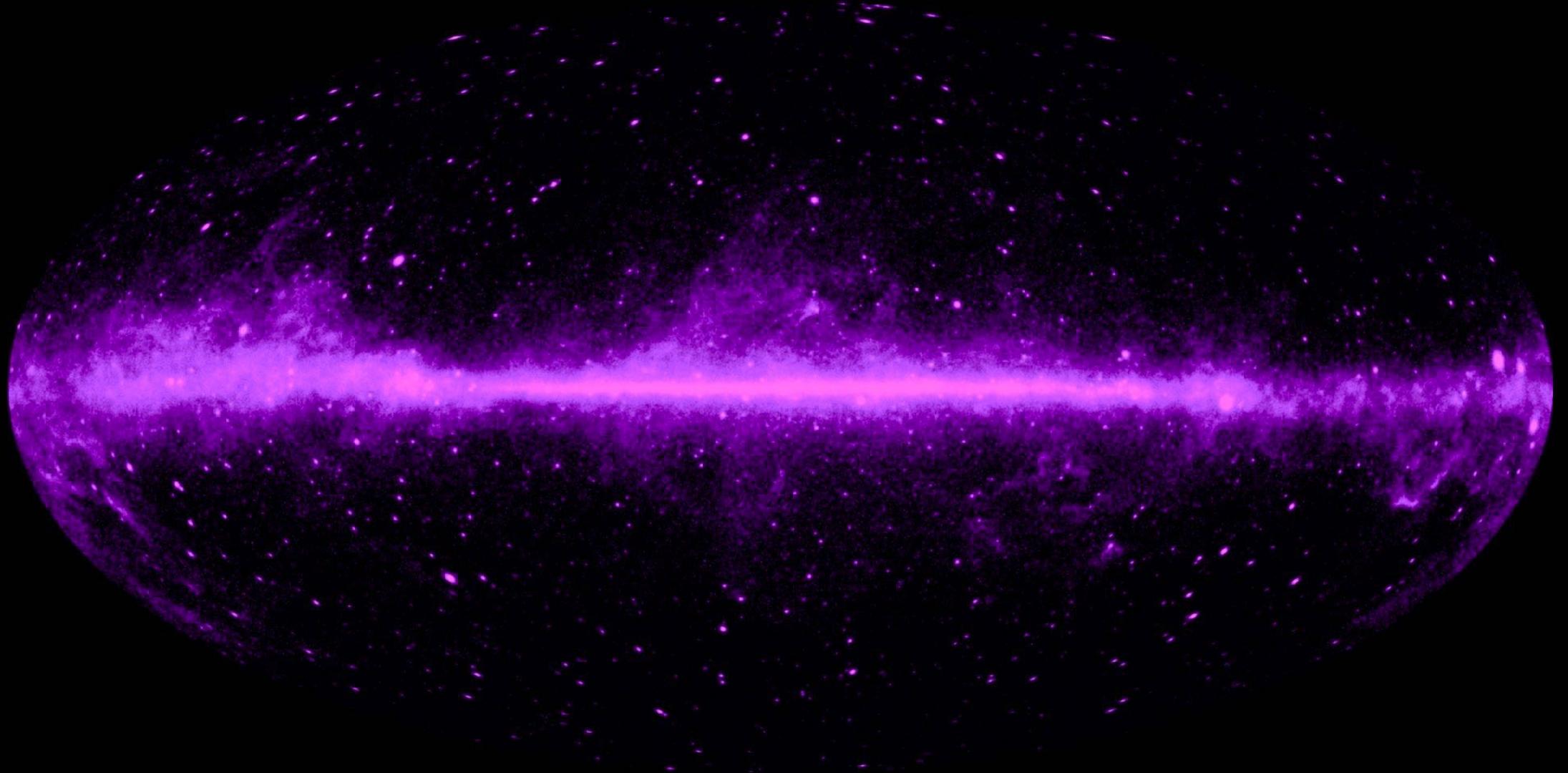


**This is the oldest light in the Universe  
Emitted 400,000 years after the Big Bang  
Observed by the Planck Telescope**

# LOTS OF WEIRD STUFF OUT THERE!



This is the oldest light in the Universe  
Emitted 400,000 years after the Big Bang  
Observed by the Planck Telescope



**OK, FINE, BUT WHAT IS DARK MATTER?**

# KNOWN DARK MATTER PROPERTIES



Fermions  
Matter {

Quarks

Lepton

Bosons  
Force Carriers {

Gauge Bosons

Higgs Boson

- Gravitationally interacting
- Not short-lived
- Not hot/light ("slippery")
- It doesn't emit or absorb light

## UNAMBIGUOUS EVIDENCE FOR NEW PARTICLES

# WHAT DO WE KNOW ABOUT DARK MATTER?



# WHAT DO WE KNOW ABOUT DARK MATTER?



- There is a LOT of it!
- It was formed during the Big Bang
- Back then, it may have interacted with regular matter

# WHAT DO WE KNOW ABOUT DARK MATTER?



- There is a LOT of it!
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- Back then, it may have interacted with regular matter
- Any chance it could interact with regular matter again?

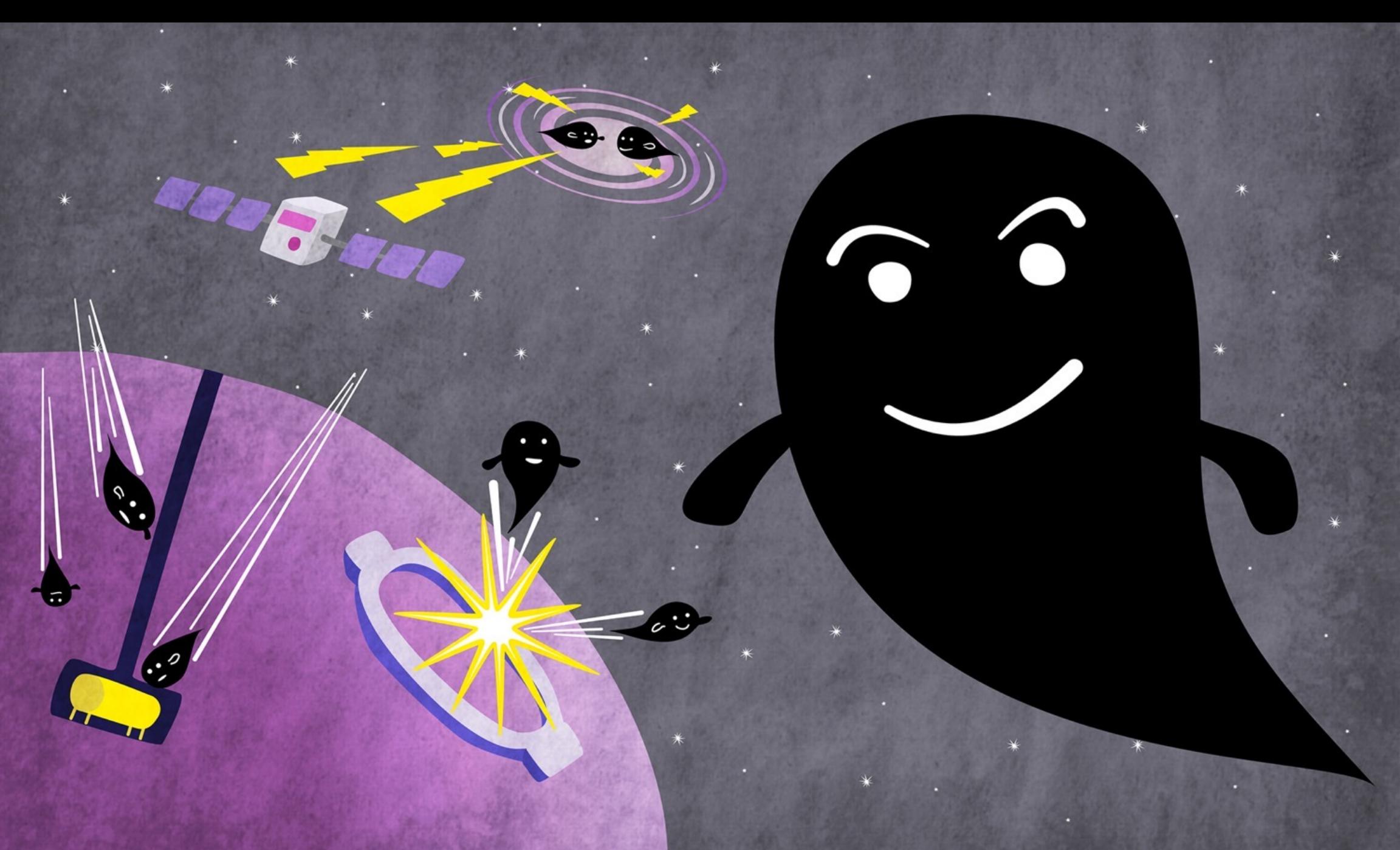
# WHAT DO WE KNOW ABOUT DARK MATTER?

BUT THEN HOW DID IT INTERACT  
WITH THE ORDINARY BARYONIC  
MATTER IN THE TITANIC'S HULL?



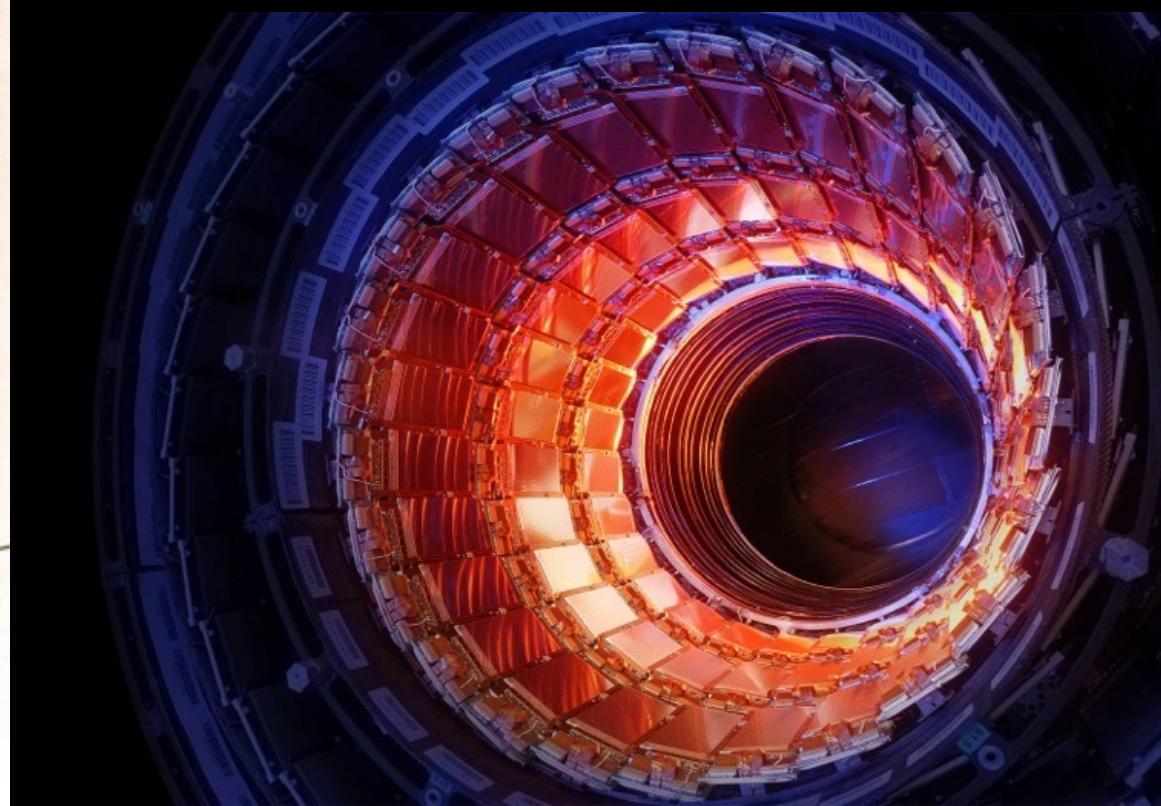
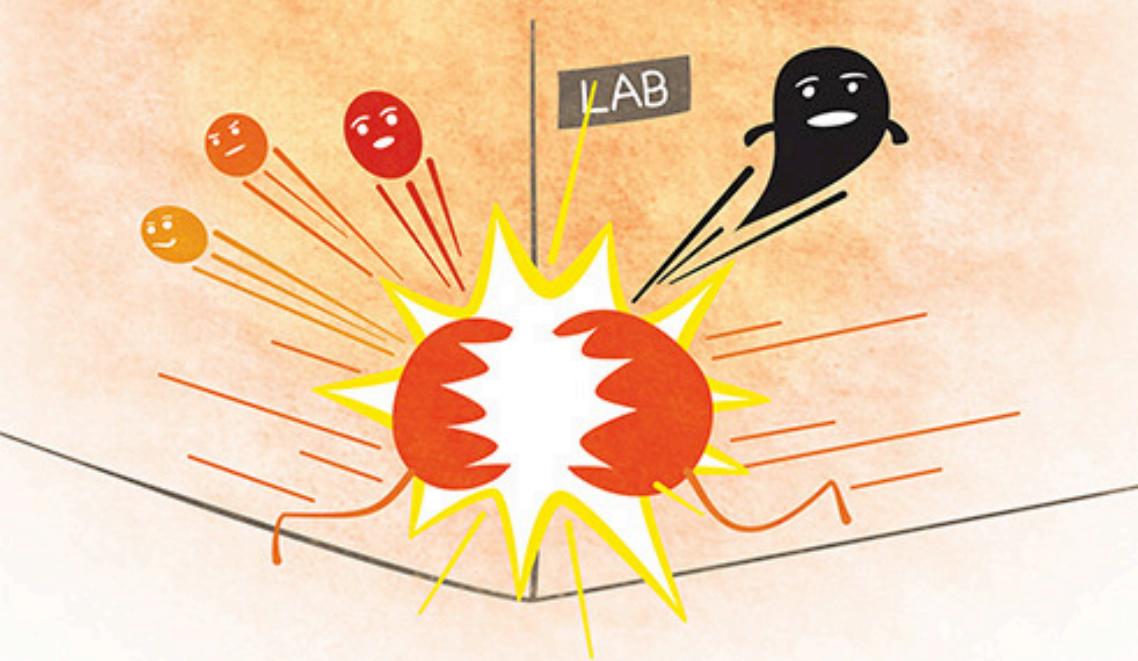
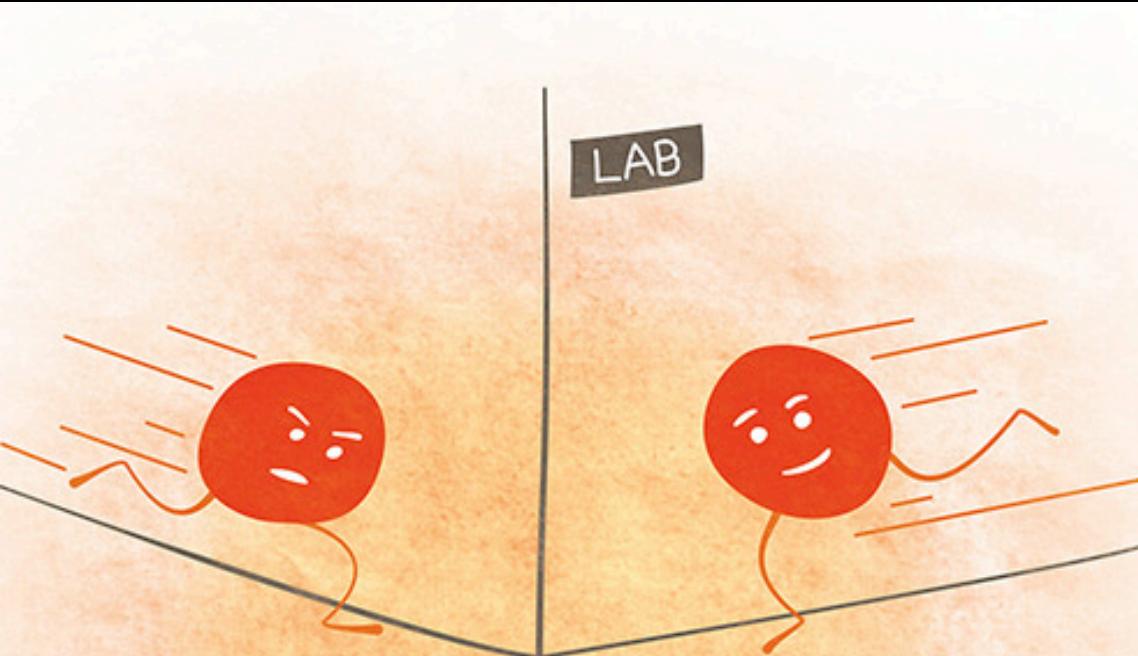
MY HOBBY:  
REFUSING TO UNDERSTAND  
THE ICEBERG METAPHOR

- There is a LOT of it!
- It was formed during the Big Bang
- Back then, it may have interacted with regular matter
- Any chance it could interact with regular matter again?

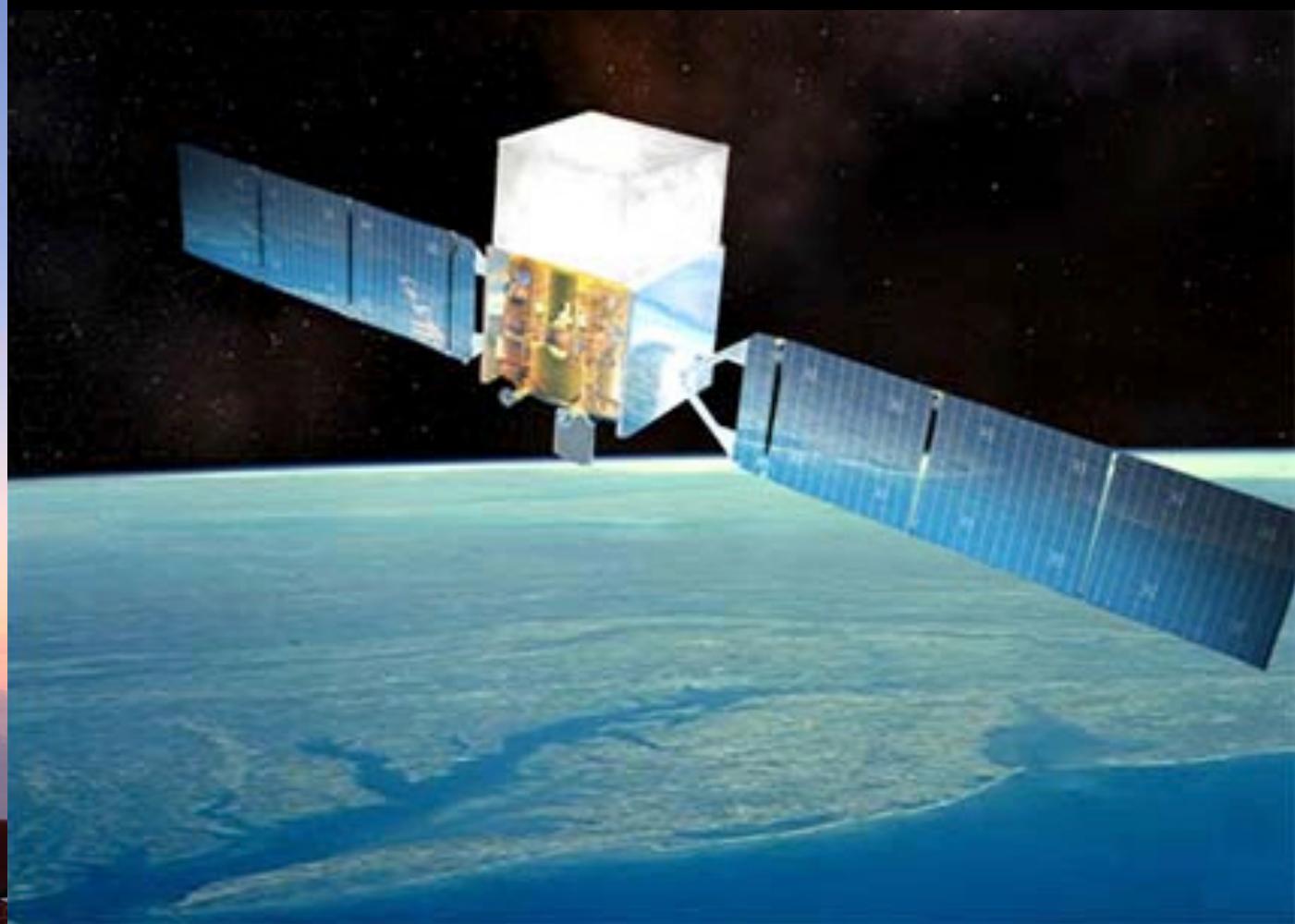


**THREE WAYS TO LOOK FOR DARK MATTER**

# 1. ENCOUNTERS IN THE LAB



## 2. TRACING KNOCKOUTS IN SPACE



# THE FERMI GAMMA-RAY SPACE TELESCOPE

Launched on June 11, 2008

- from Kennedy Space Center
- launch vehicle: Delta II Heavy
- circular orbit, 565 km altitude,  
25.6 degrees inclination

LAT milestones:

- 82,300 orbits to date
- 800 billion event triggers
- 179 billion evts downlinked
- 1.8 billion photons available  
in the public database

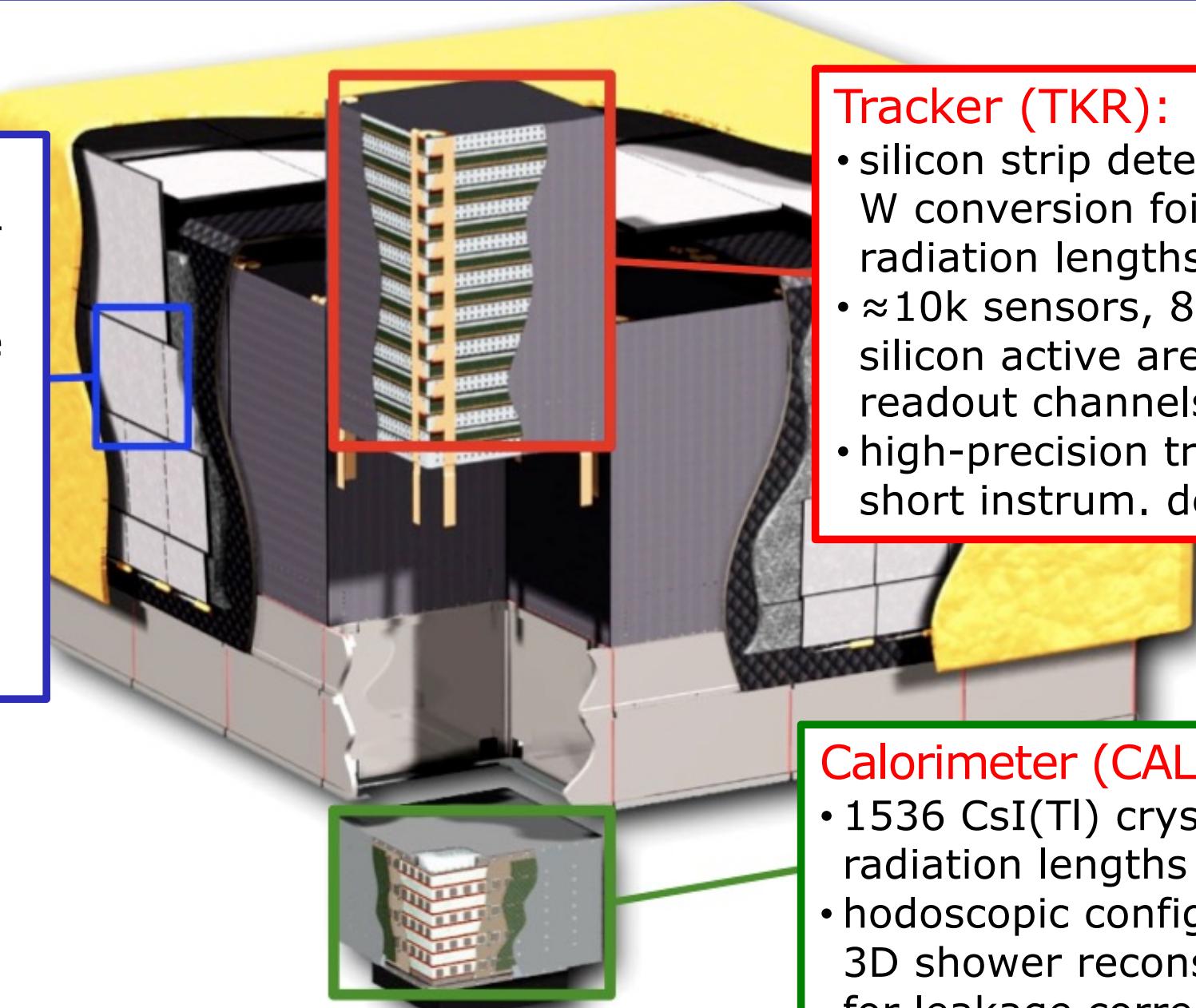


# THE FERMI LARGE AREA TELESCOPE (LAT)

Overall modular design:  $4 \times 4$  array of identical towers (each including a tracker and a calorimeter module); surrounded by an Anti-Coincidence Detector (ACD)

## ACD:

- plastic scintillator
- segmented (89 tiles) to minimize self-veto.
- 8 fiber ribbons covering gaps between tiles
- 99.97% average efficiency



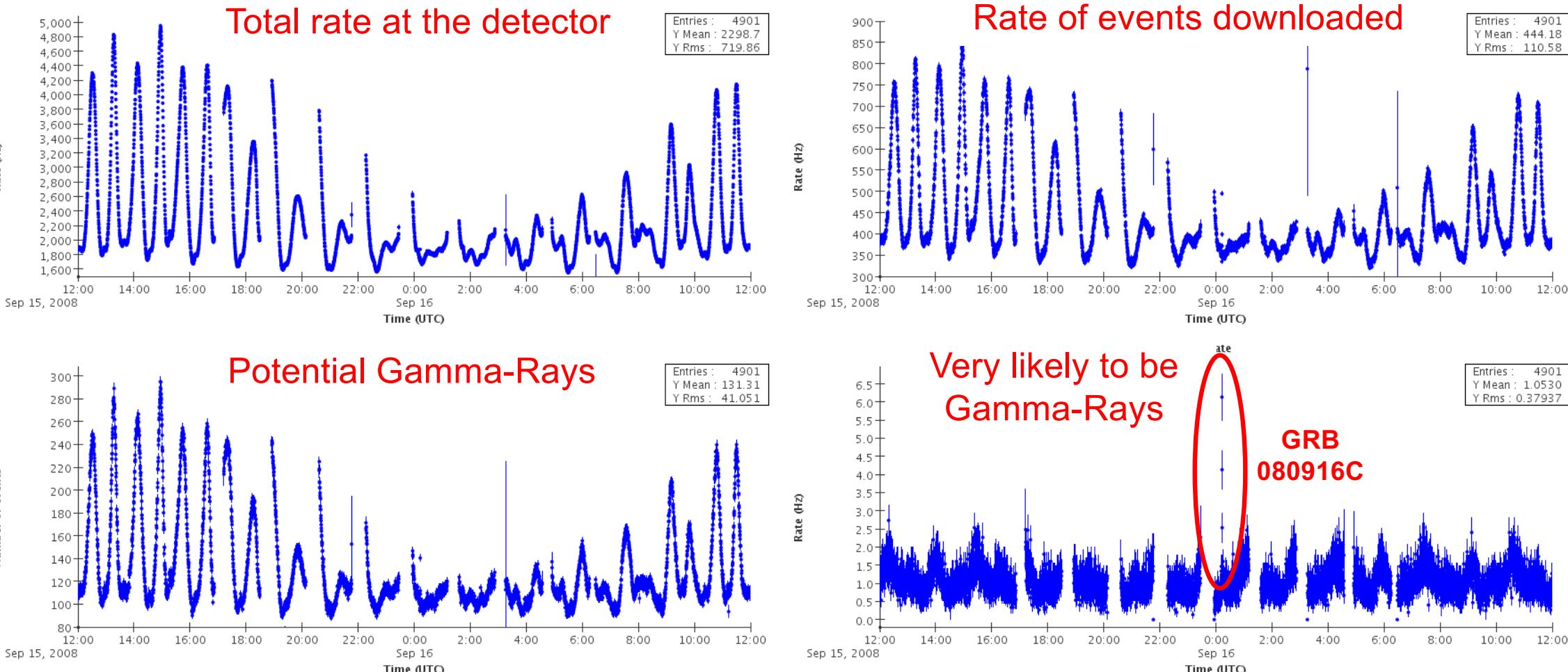
## Tracker (TKR):

- silicon strip detectors with W conversion foils (1.5 radiation lengths on-axis)
- $\approx 10k$  sensors,  $80 \text{ m}^2$  of silicon active area,  $\approx 1\text{M}$  readout channels
- high-precision tracking, short instrum. dead time

## Calorimeter (CAL):

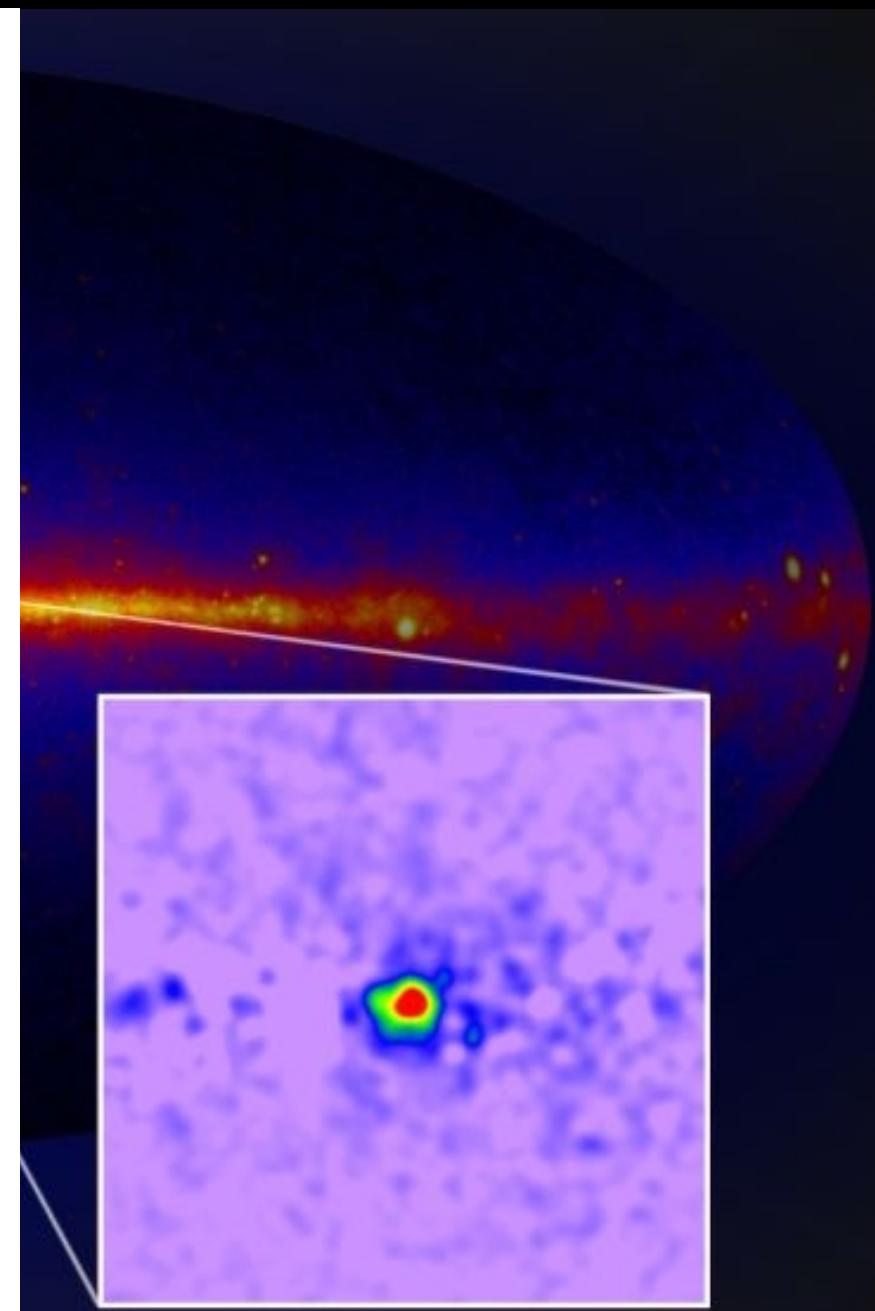
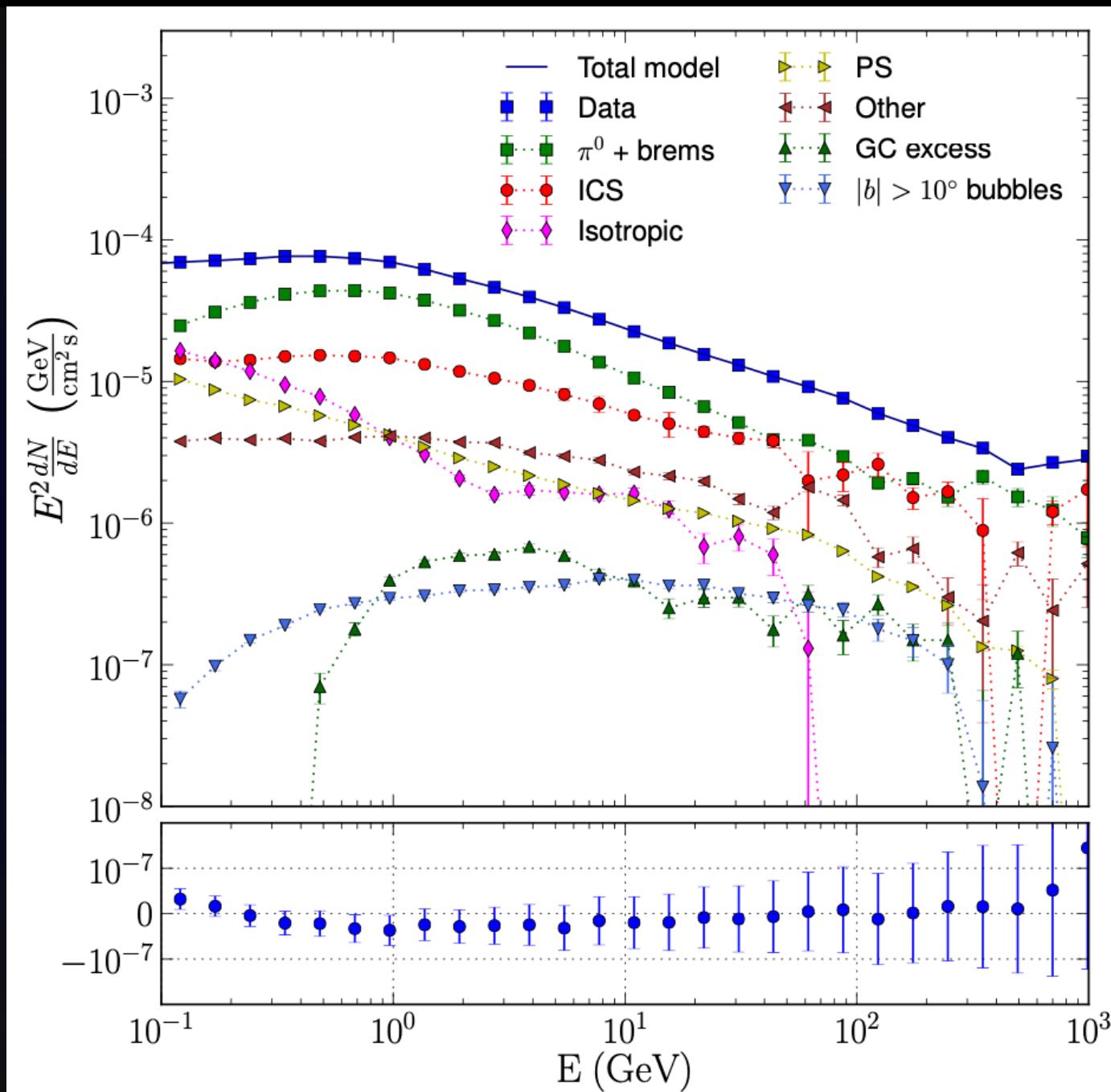
- 1536 CsI(Tl) crystals; 8.6 radiation lengths on-axis
- hodoscopic configuration, 3D shower reconstruction for leakage correction

# DATA RATES IN LOW EARTH ORBIT

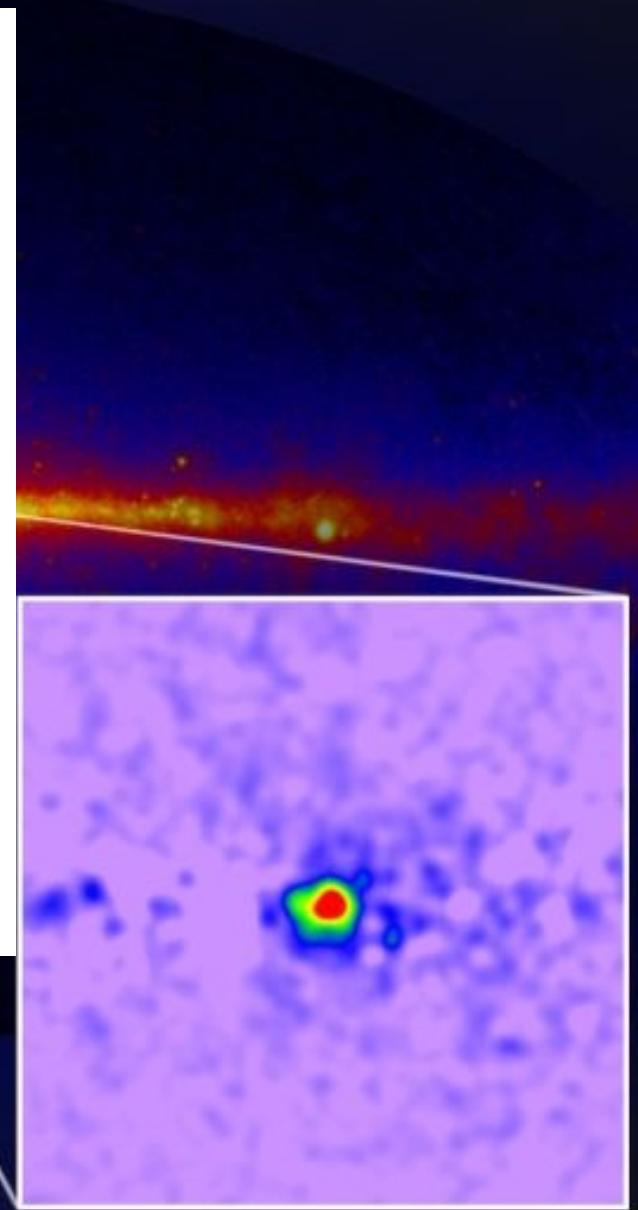
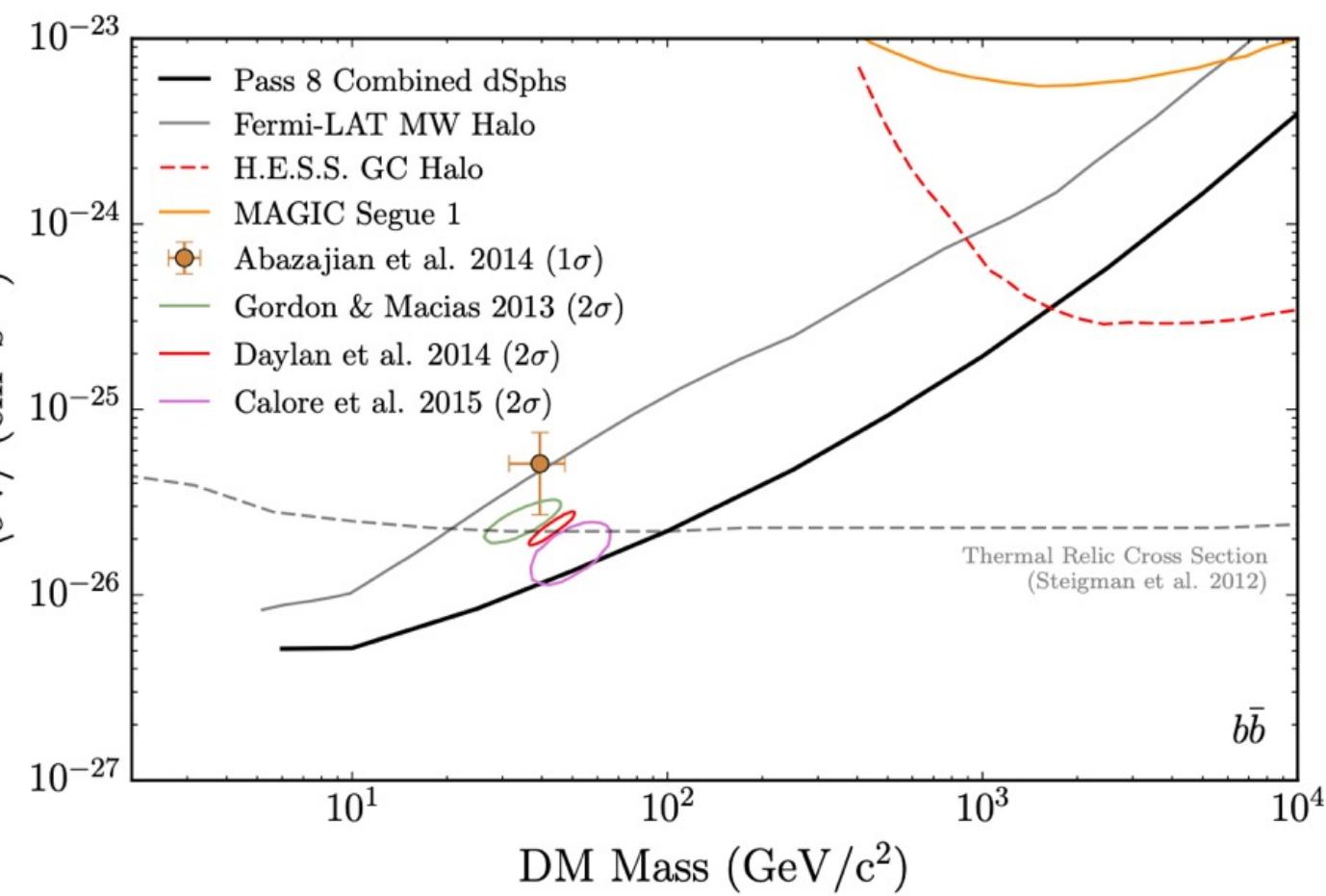


- **0.3 PB OF DATA EACH YEAR, OR 5 PB TOTAL SO FAR**
- **LESS THAN 1% OF THE DATA IS A LIKELY GAMMA-RAY**

# AND HOW MUCH OF THAT IS DARK MATTER?



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# A SUCCESSFUL OPEN SCIENCE EXPERIENCE!

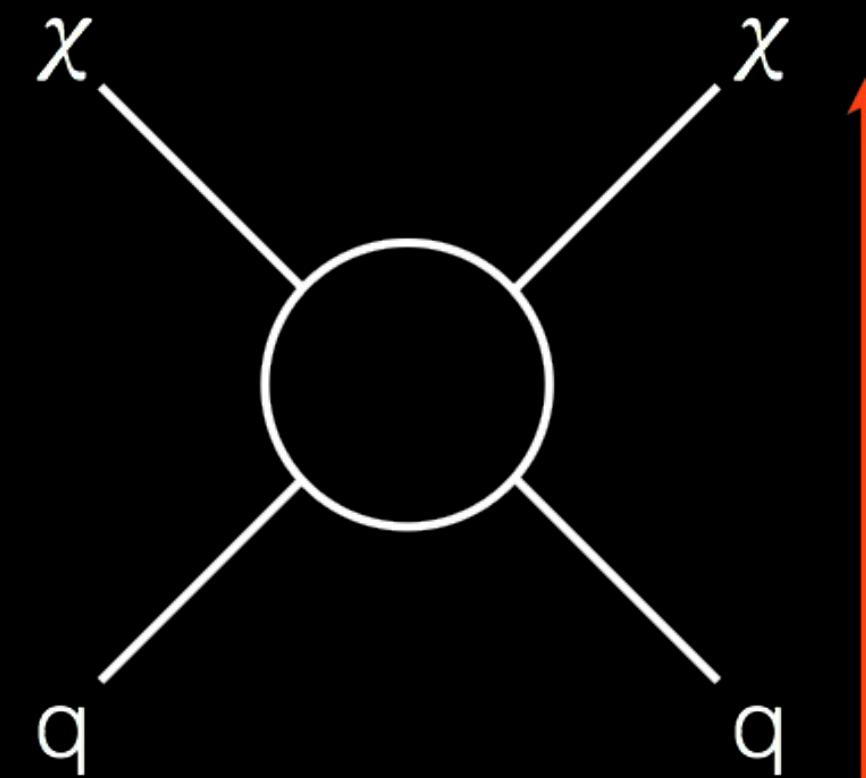
ALL FERMI DATA AND SOFTWARE ARE OPEN (SINCE 2009)



- HOSTED @NASA/HEASARC
- INCLUDES: DATA, ANALYSIS SOFTWARE, INSTRUMENT RESPONSE, BACKGROUND...
- TREMENDOUS COMMUNITY ENGAGEMENT WITH OUR DATA
- 90% OF SCIENTIFIC RETURN COMES FROM THE COMMUNITY
- REPRODUCIBILITY: QUALITY CONTROL OF ALL RESULTS

# THREE WAYS TO LOOK FOR WIMPS

Annihilation



Production



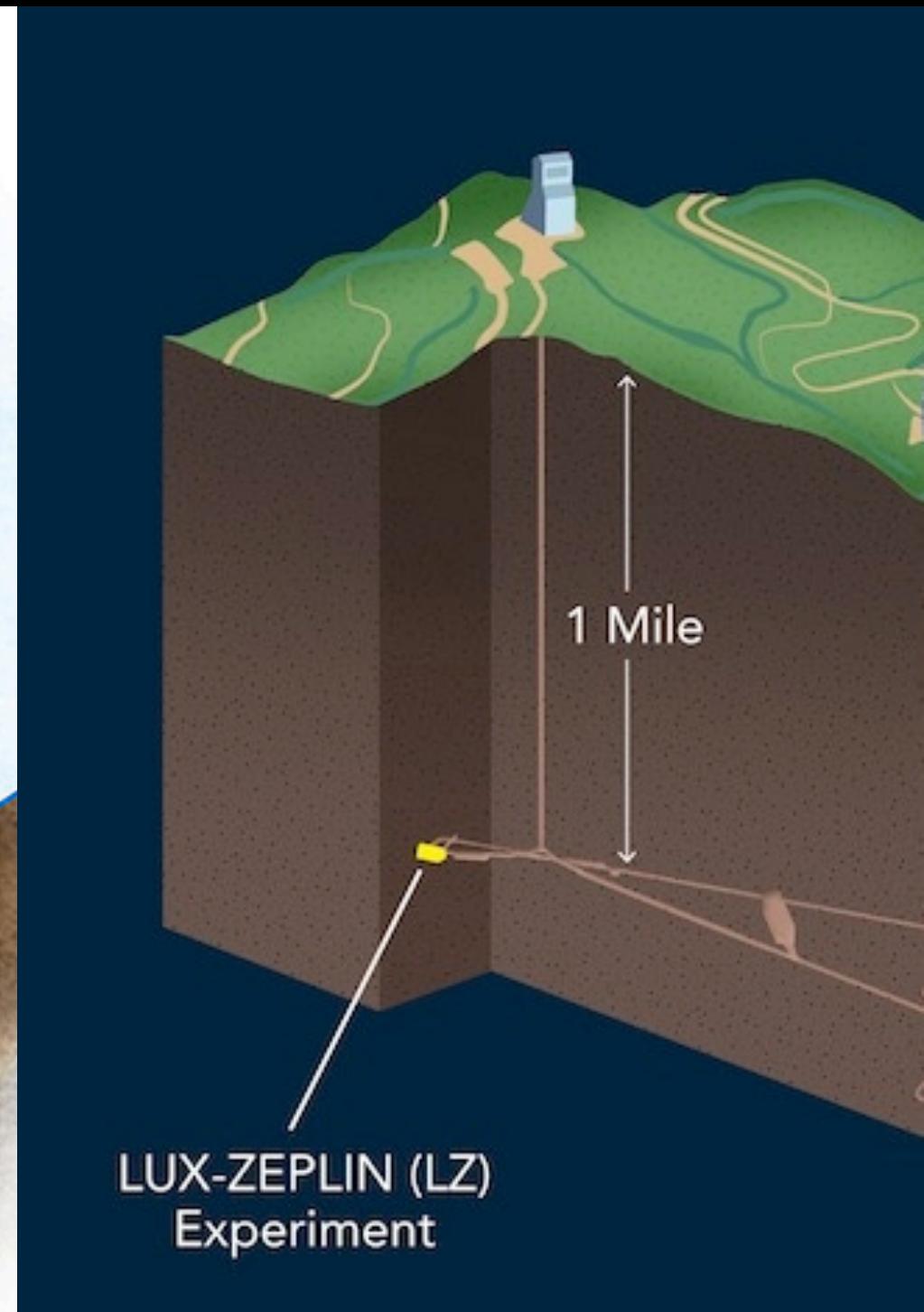
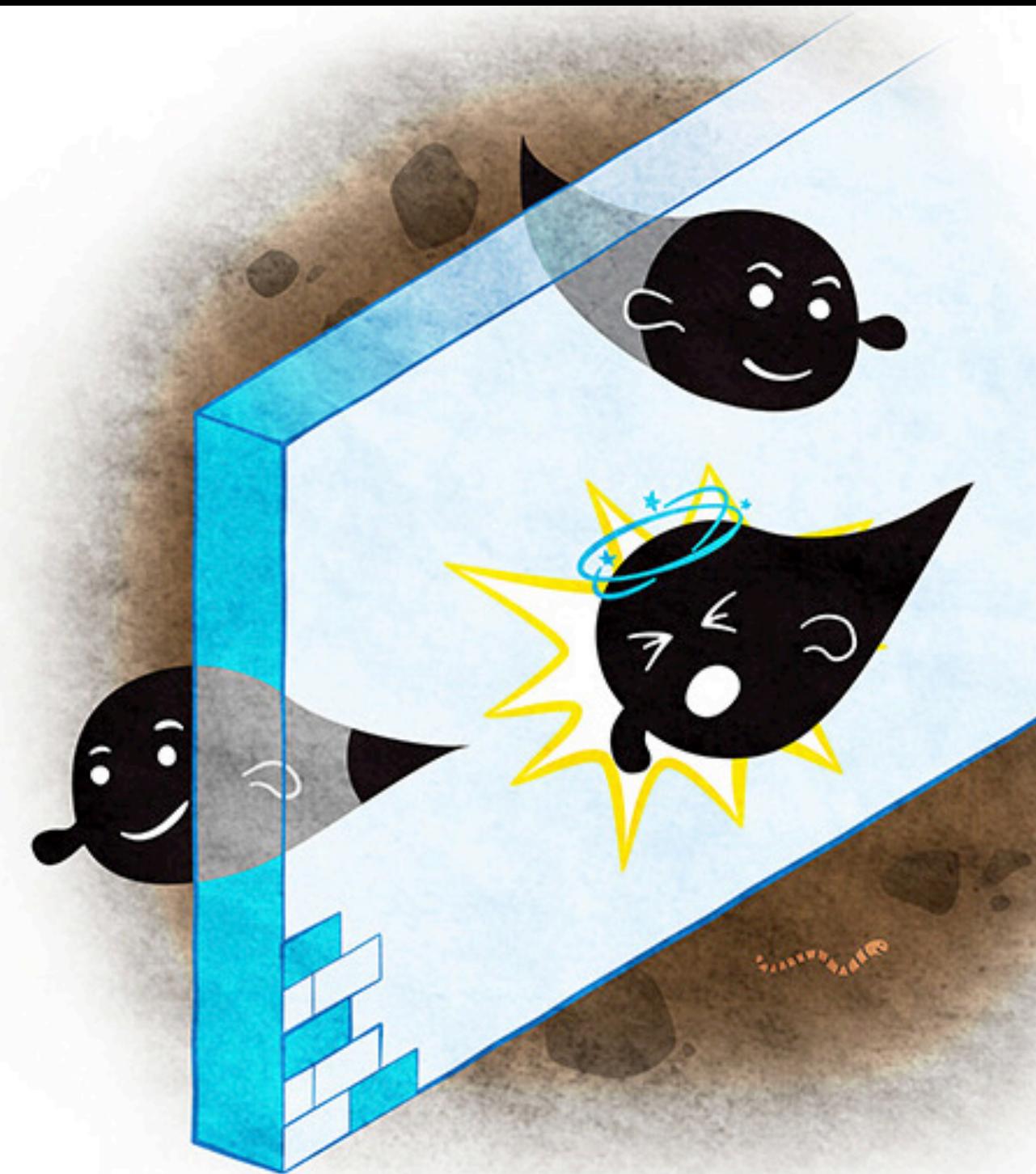
Indirect Detection



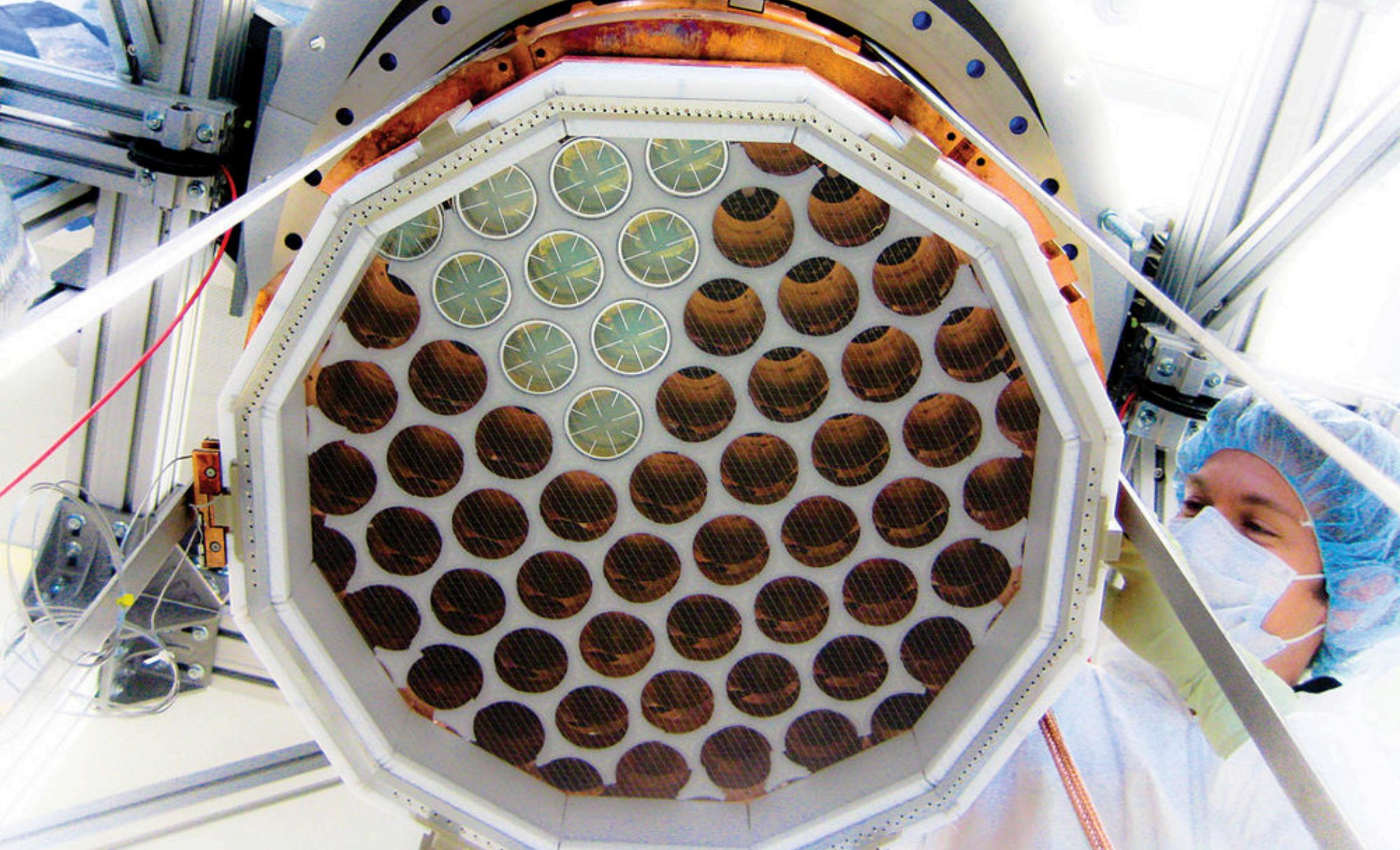
Scattering

Direct  
Detection

### 3. GOING BUMP UNDERGROUND!

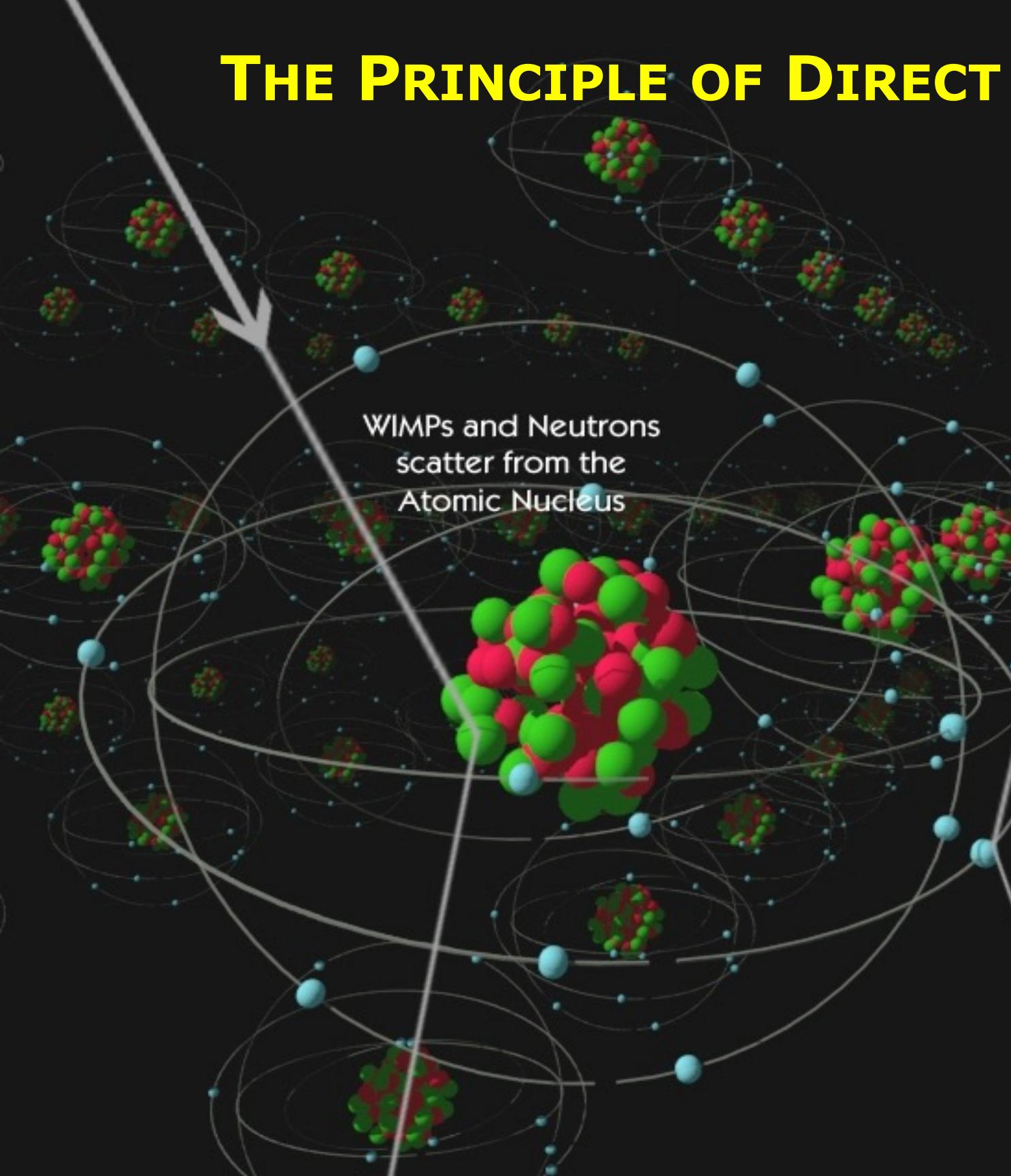


LUX-ZEPLIN (LZ)  
Experiment



**DIRECT DARK MATTER DETECTION**

# THE PRINCIPLE OF DIRECT DETECTION



BUILD A MASSIVE TANK (OR TOWER) OF NUCLEI

“HIDE” IT DEEP UNDERGROUND

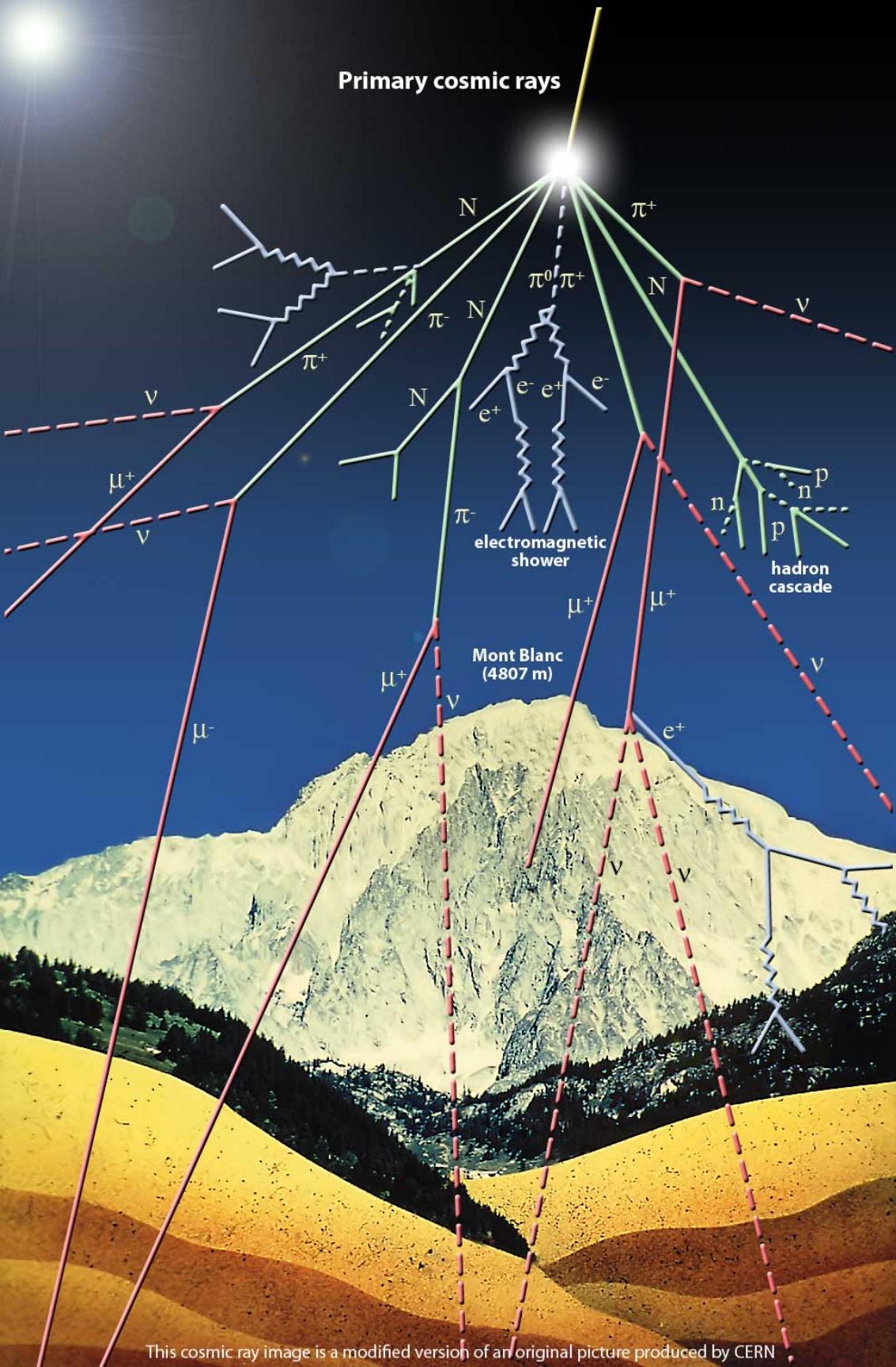
WAIT FOR DARK MATTER PARTICLES TO HIT THE NUCLEI

LOOK FOR TINY VIBRATIONS FROM NUCLEI THAT HAVE BEEN HIT BY DM

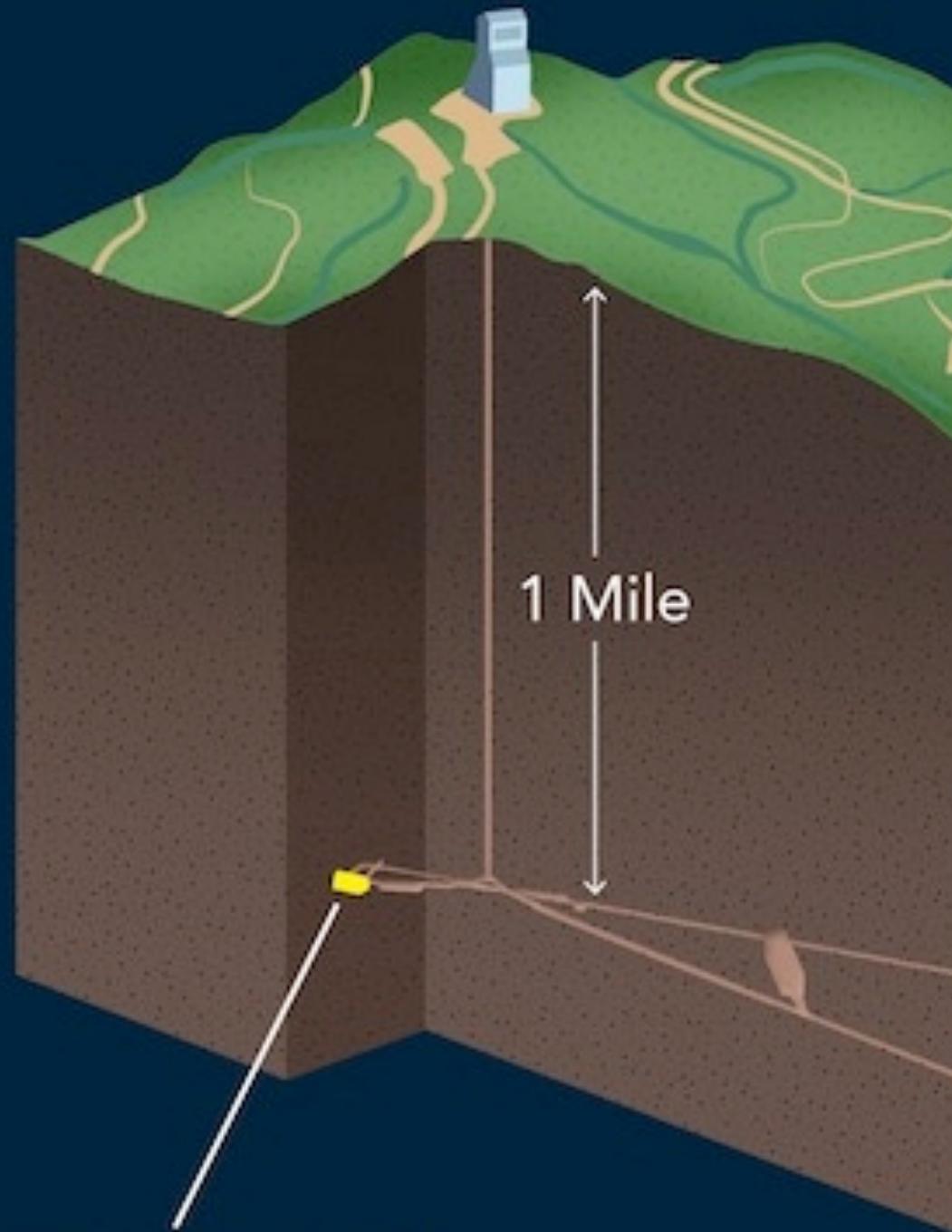
# **WAIT! DID YOU JUST SAY UNDERGROUND?**



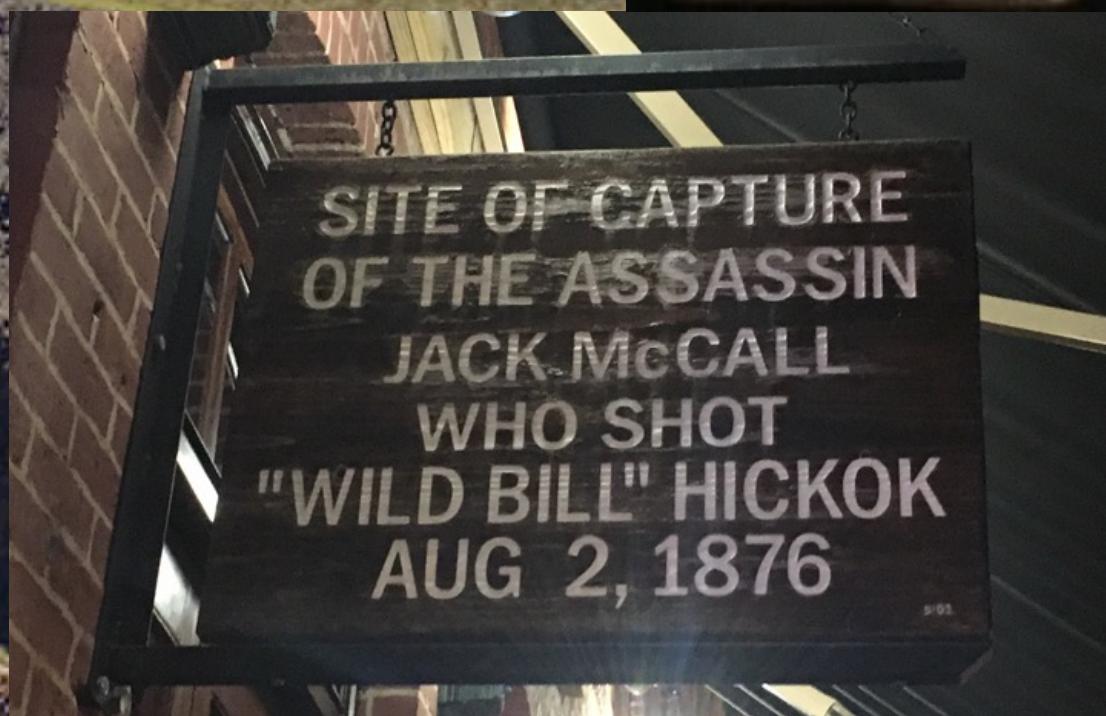
Image courtesy of  
the Earth Science and Remote Sensing Unit,  
NASA Johnson Space Center.  
Editing: Hirai Mamoru



This cosmic ray image is a modified version of an original picture produced by CERN.

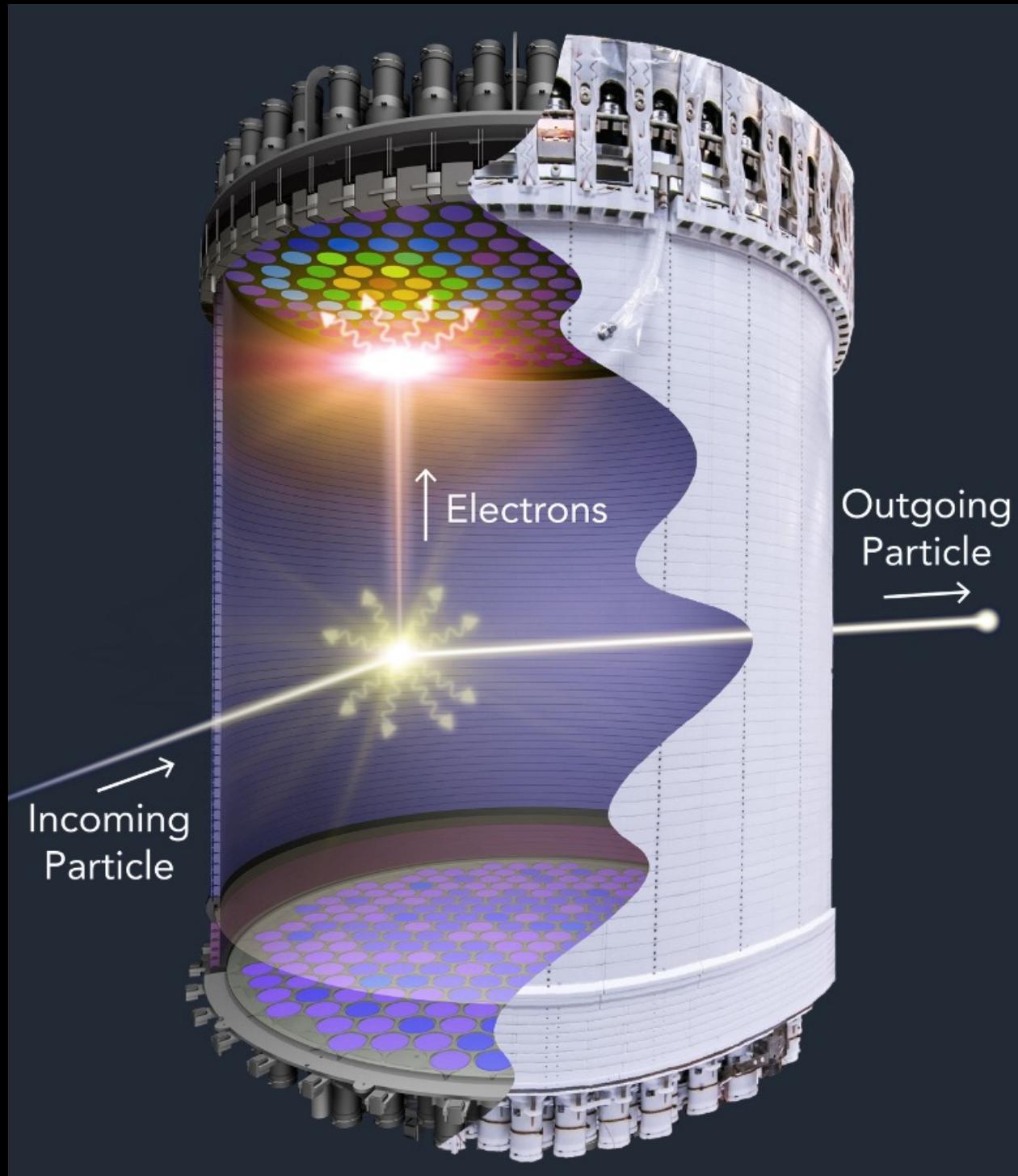


LUX-ZEPLIN (LZ)  
Experiment



**HOMESTAKE, SOUTH DAKOTA**

# THE LUX-ZEPLIN (LZ) DETECTOR



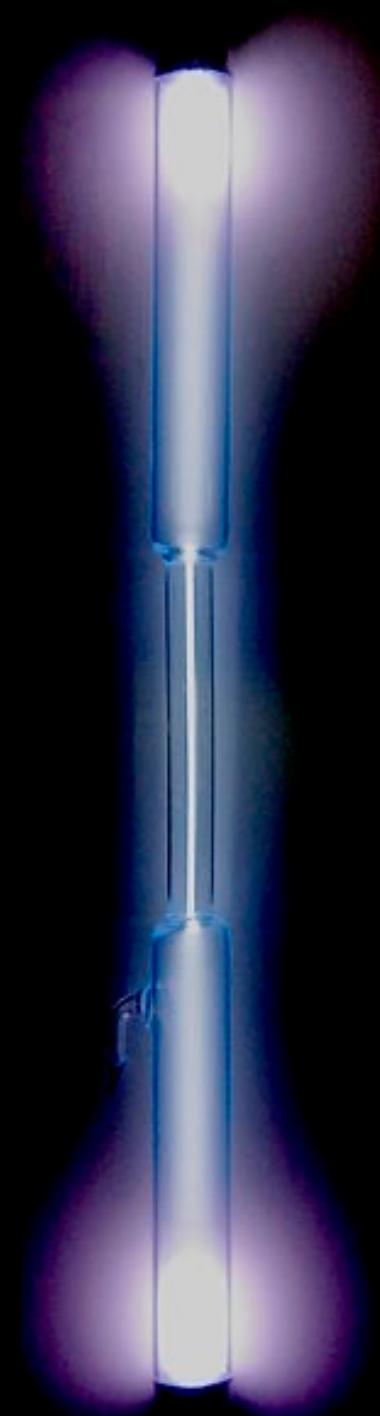
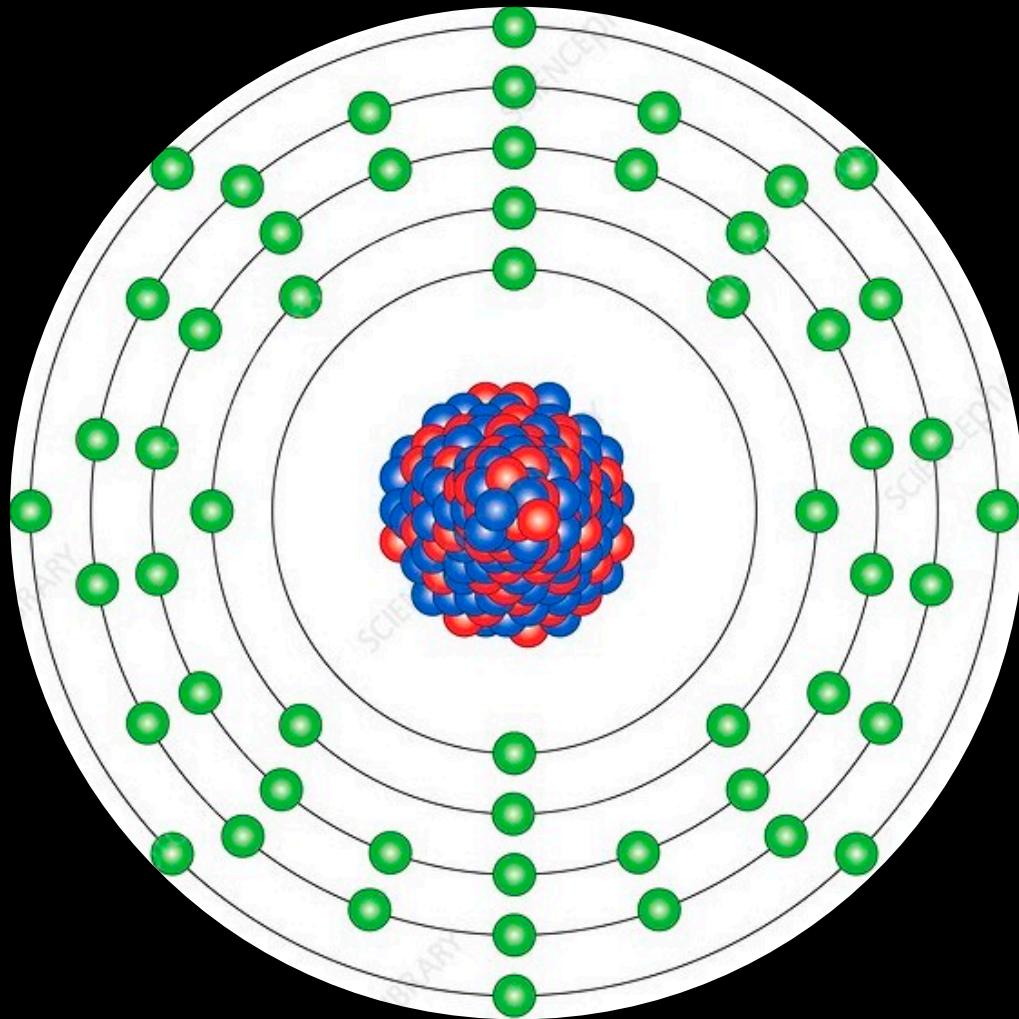
# WHY XENON? AND WHY A LIQUID?

- KINEMATIC MATCHING TO DM PARTICLE



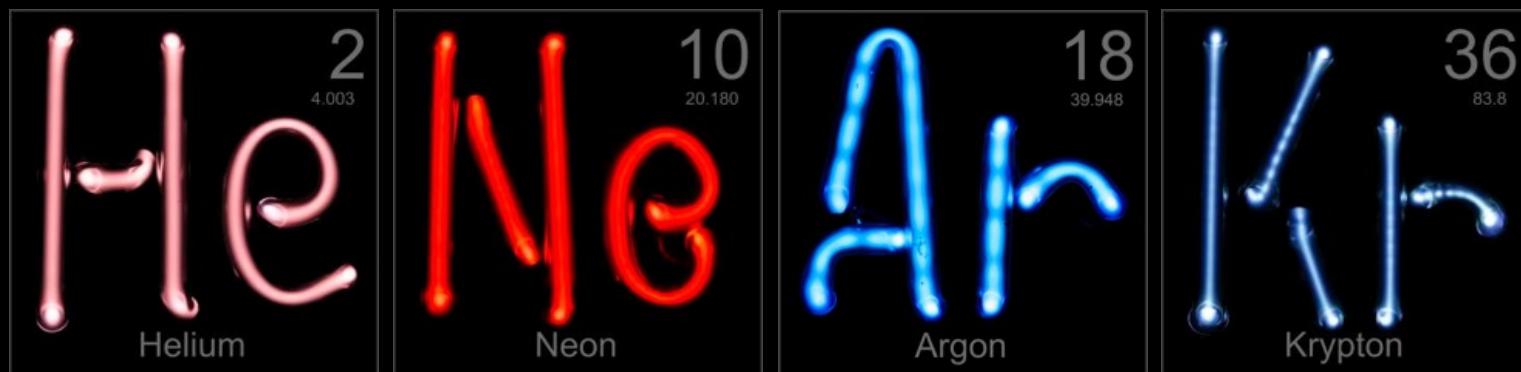
# WHY XENON? AND WHY A LIQUID?

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# WHY XENON? AND WHY A LIQUID?

- KINEMATIC MATCHING TO DM PARTICLE
- LOTS OF NUCLEONS PER ATOM
- TRANSPARENT TO ITS OWN LIGHT



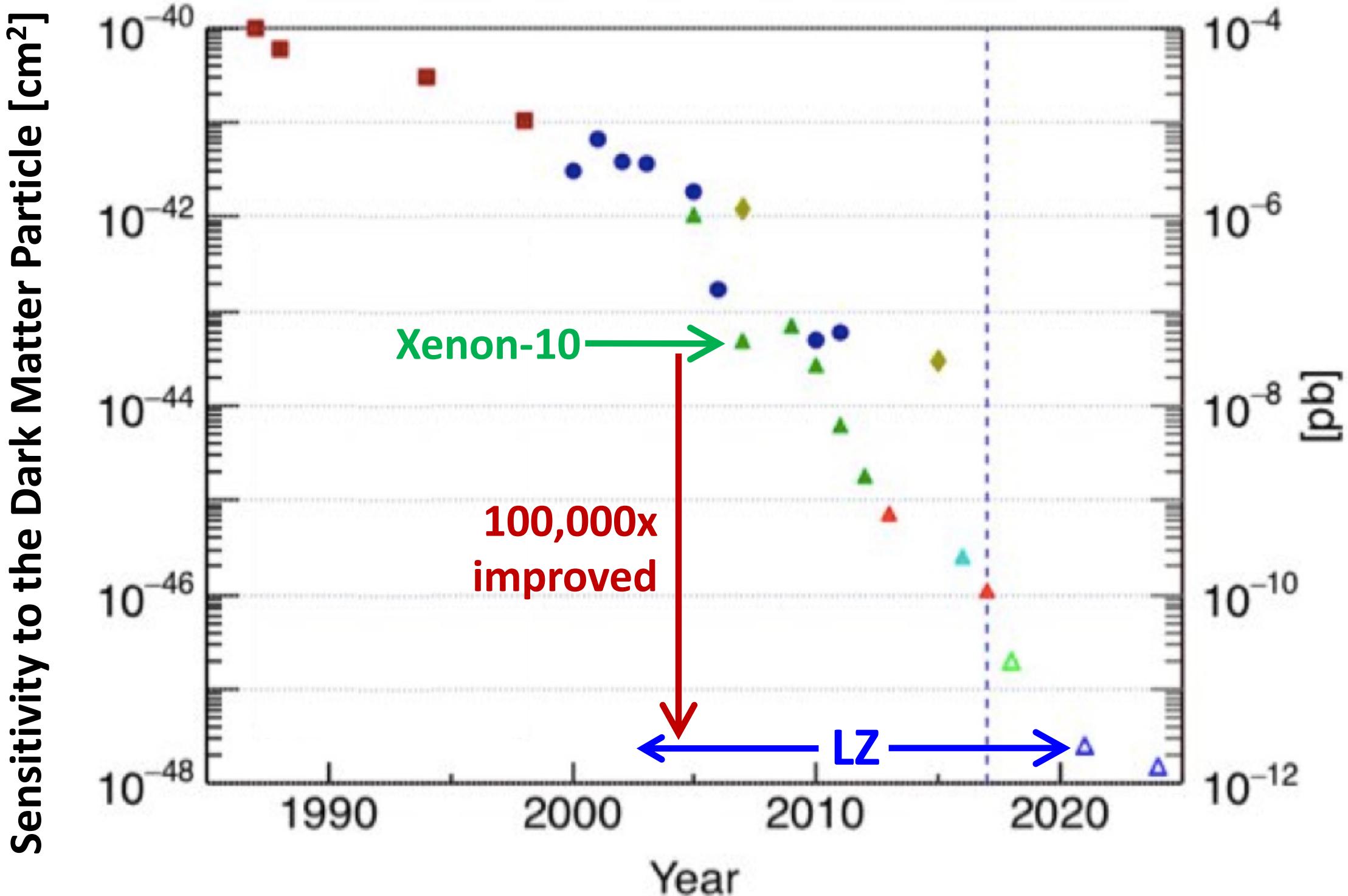
# WHY XENON? AND WHY A LIQUID?

- KINEMATIC MATCHING TO DM PARTICLE
- LOTS OF NUCLEONS PER ATOM
- TRANSPARENT TO ITS OWN LIGHT
- VERY DENSE (SELF-SHIELDING)
- BACKGROUND REJECTION (CHARGE)
- LIQUID: CAN BE PURIFIED IN A LOOP
- “EASY” TO MAKE A LARGER DETECTOR



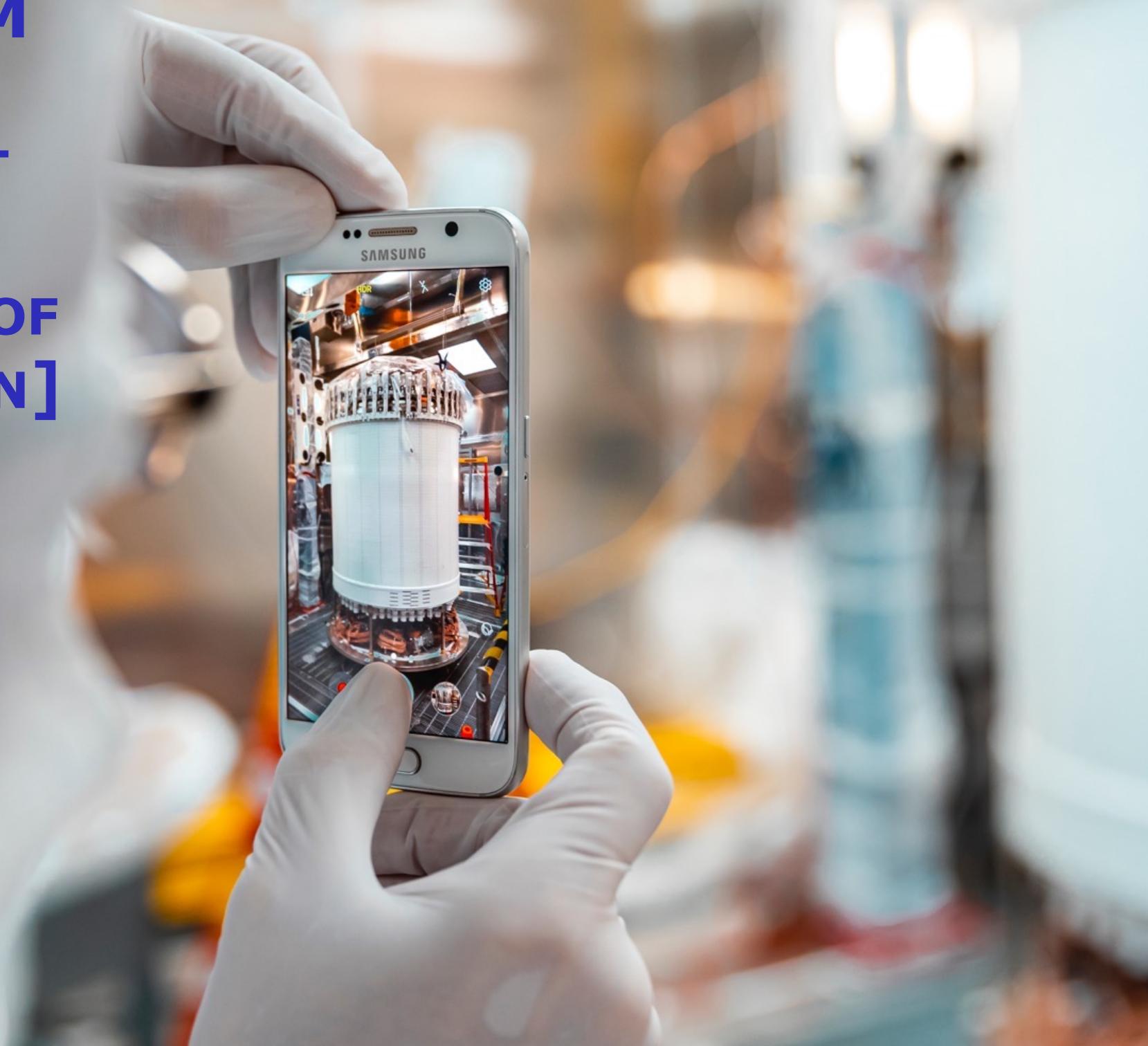


# MOORE'S LAW OF DARK MATTER DETECTION



# HOW TO BUILD A DIRECT DM DETECTION EXPERIMENT

[=A BUCKET OF  
LIQUID XENON]

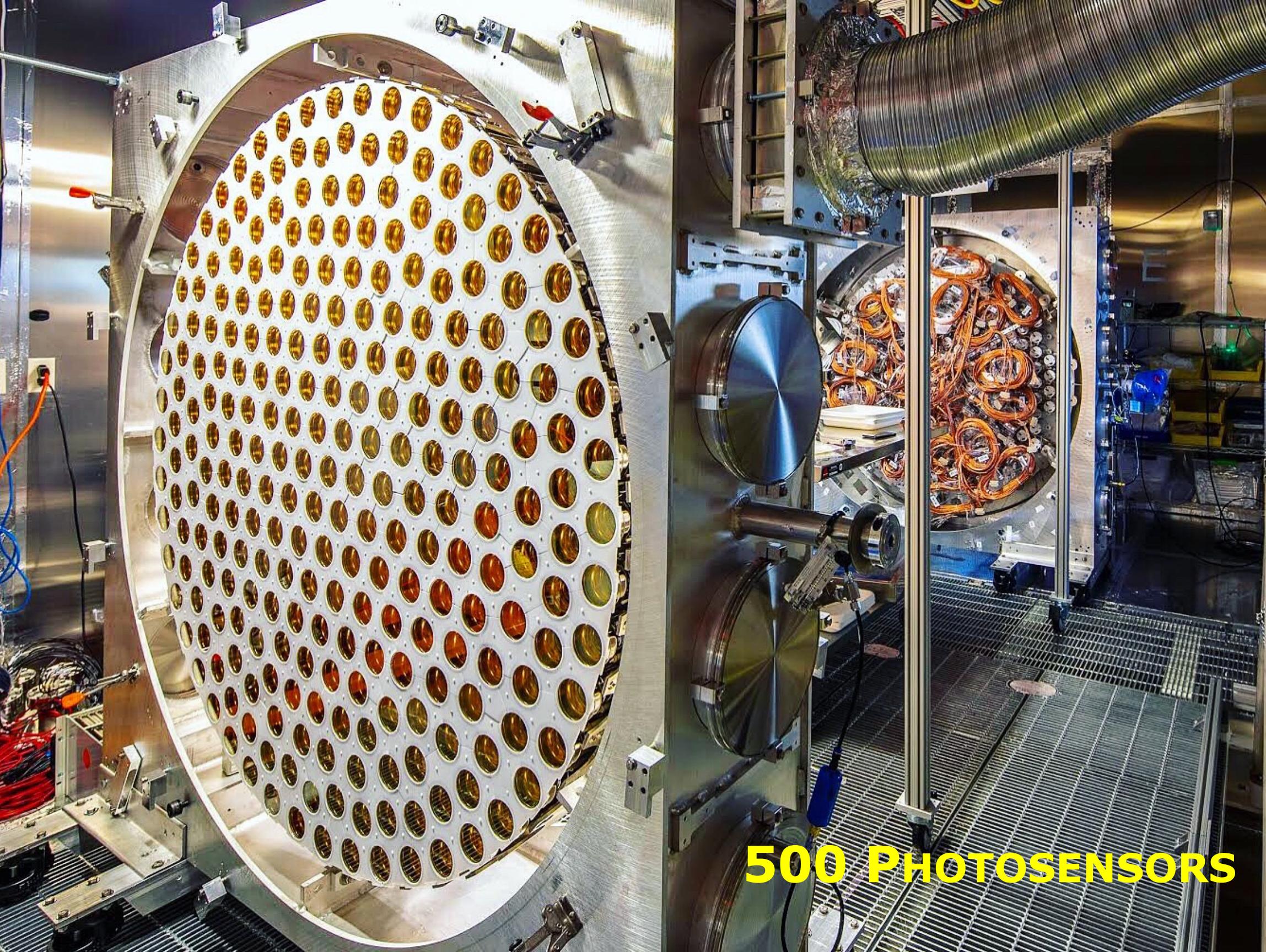




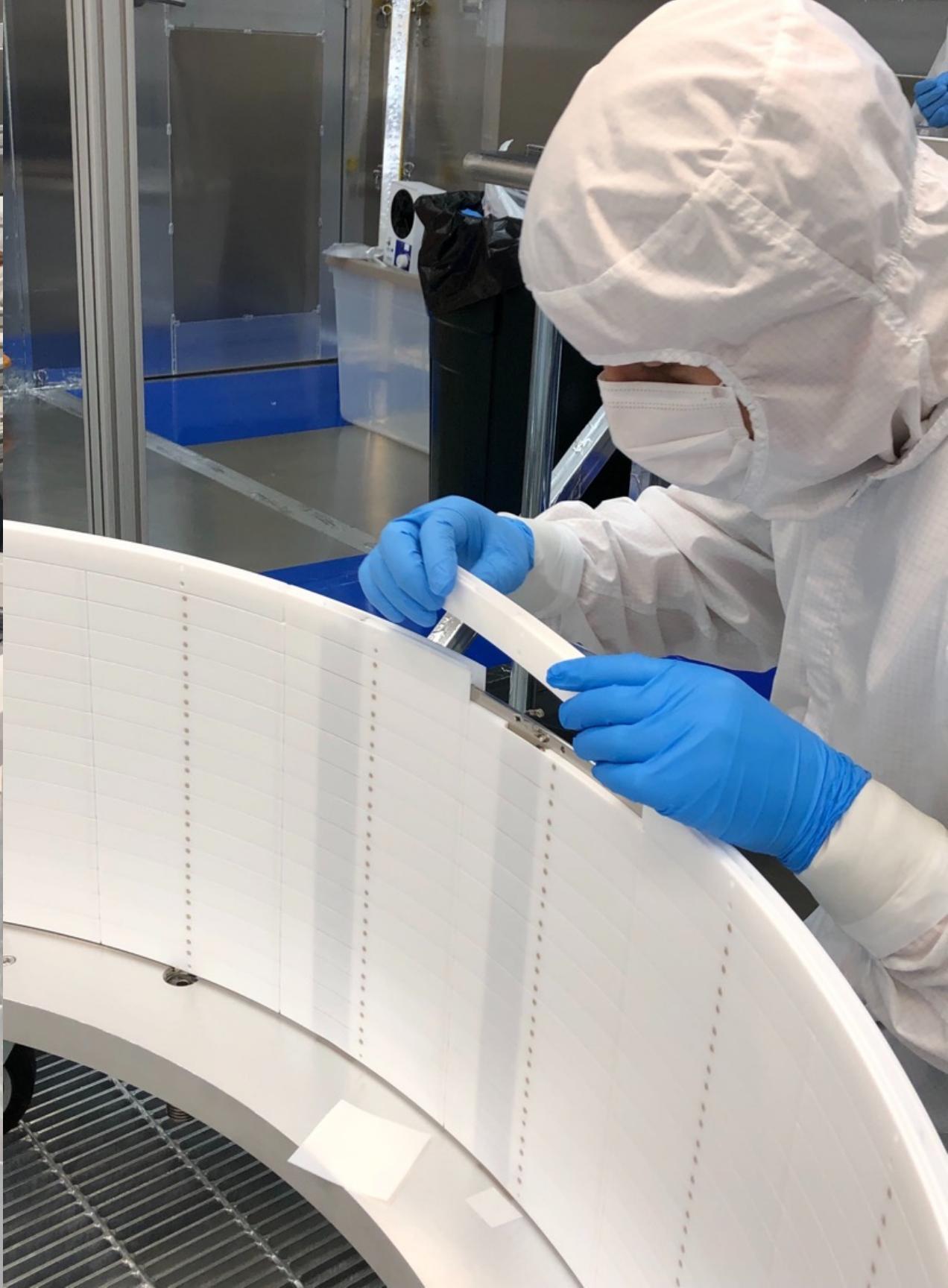
**PHOTONSENSORS**

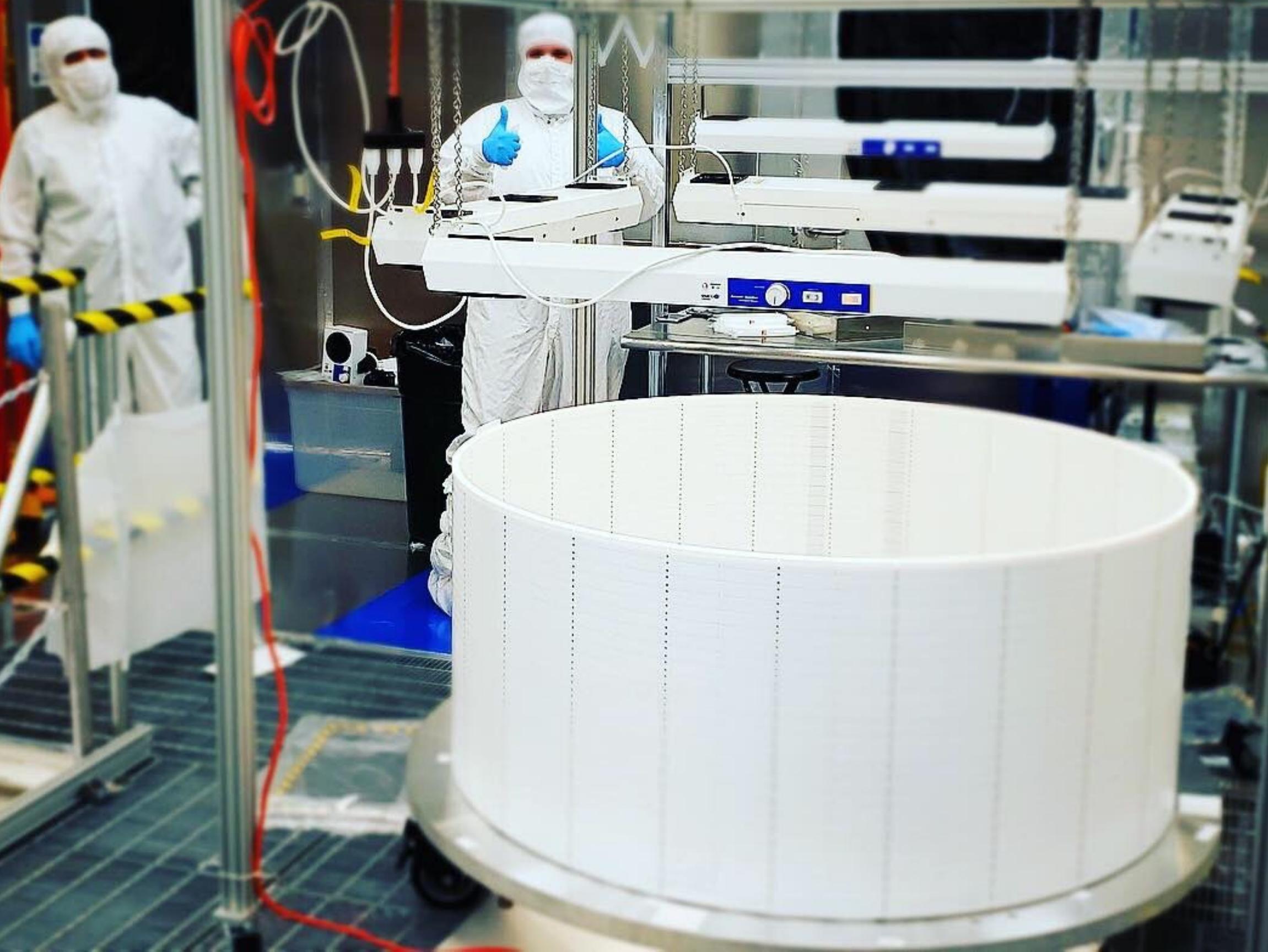


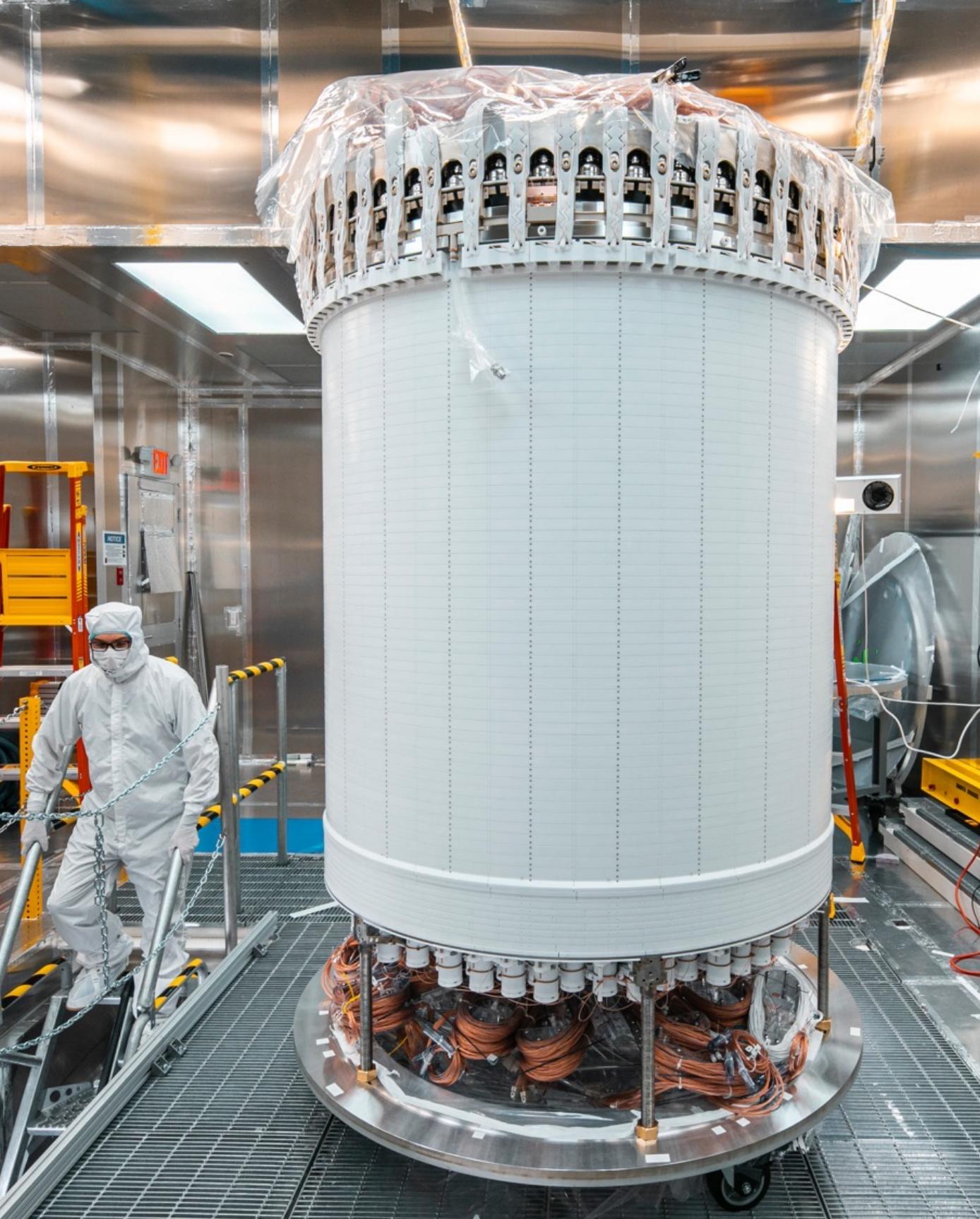


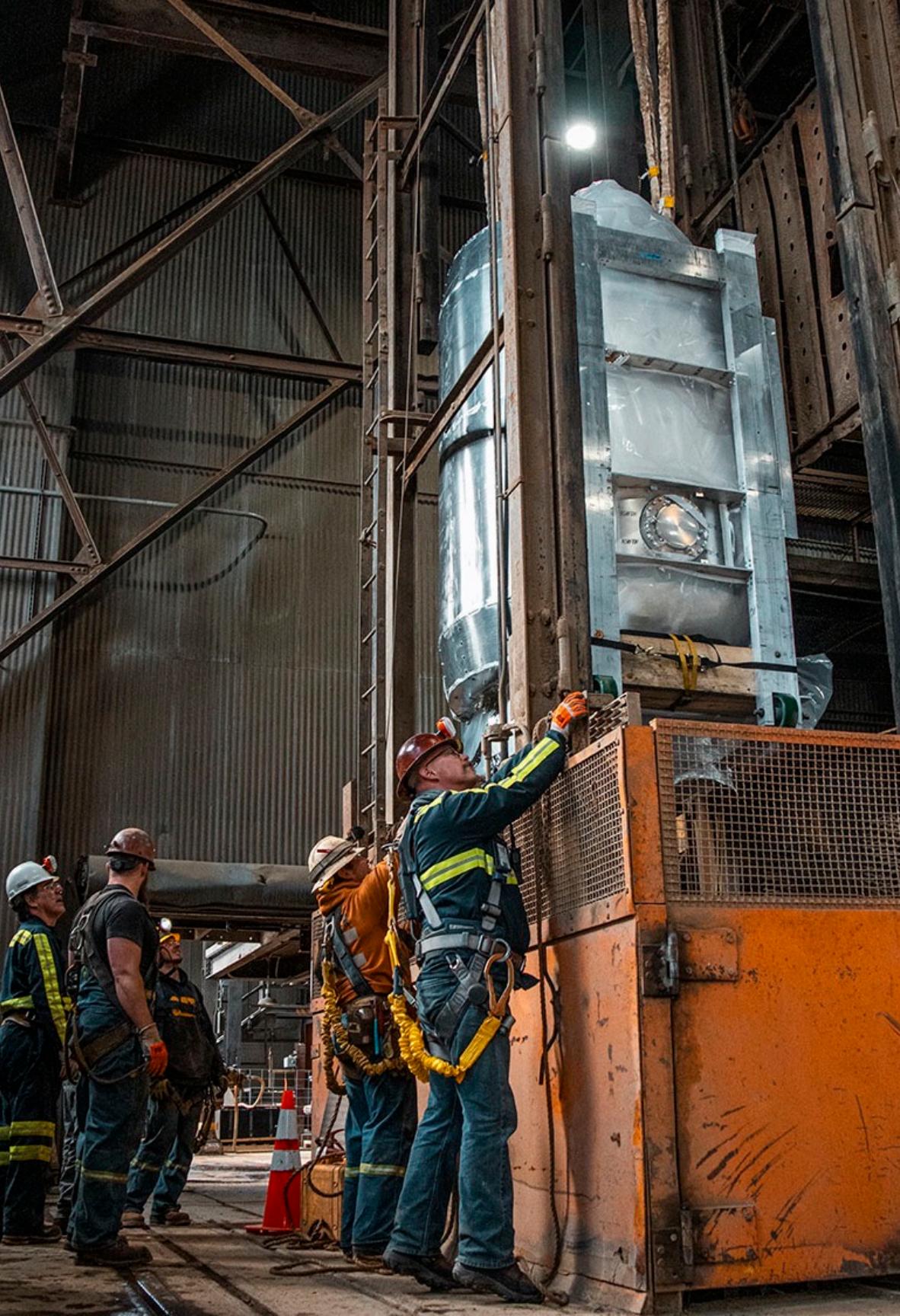


**500 PHOTOSENSORS**











# **EVERYTHING IS RADIOACTIVE!!!**



- **EVEN A MILE UNDERGROUND!**
- **WITH ULTRACLEAN MATERIALS [100,000 – 1 MILLION TIMES CLEANER THAN "REGULAR"]**
- **DATA RATE ~ 50 COUNTS/SEC (THIS IS "ALL" BACKGROUND)**
- **OR... 1 BILLION COUNTS/YEAR**
- **OR... 1 PB DATA/YEAR**
- **5 PB TOTAL EXPECTED DATA** 😱

# **DARK MATTER IS EXTREMELY ELUSIVE!**

- **THERE ARE ~3 DM PARTICLES PER LITER ON EARTH**
- **STREAMING THROUGH THE EARTH AT 150 MILES/SEC**
- **1 BILLION PARTICLES GO THROUGH LZ EVERY SECOND!**
- **OF THOSE DARK MATTER PARTICLES, WE ARE HOPING TO DETECT A HANDFUL PER YEAR (IF WE ARE LUCKY)!**
- **EXPECTED BACKGROUND INTERACTIONS: ~1 BILLION PER YEAR (OR 1 PB/YEAR OR 50/SECOND)!!!**

**HOW DO WE FIND THOSE FEW PARTICLES?!?**

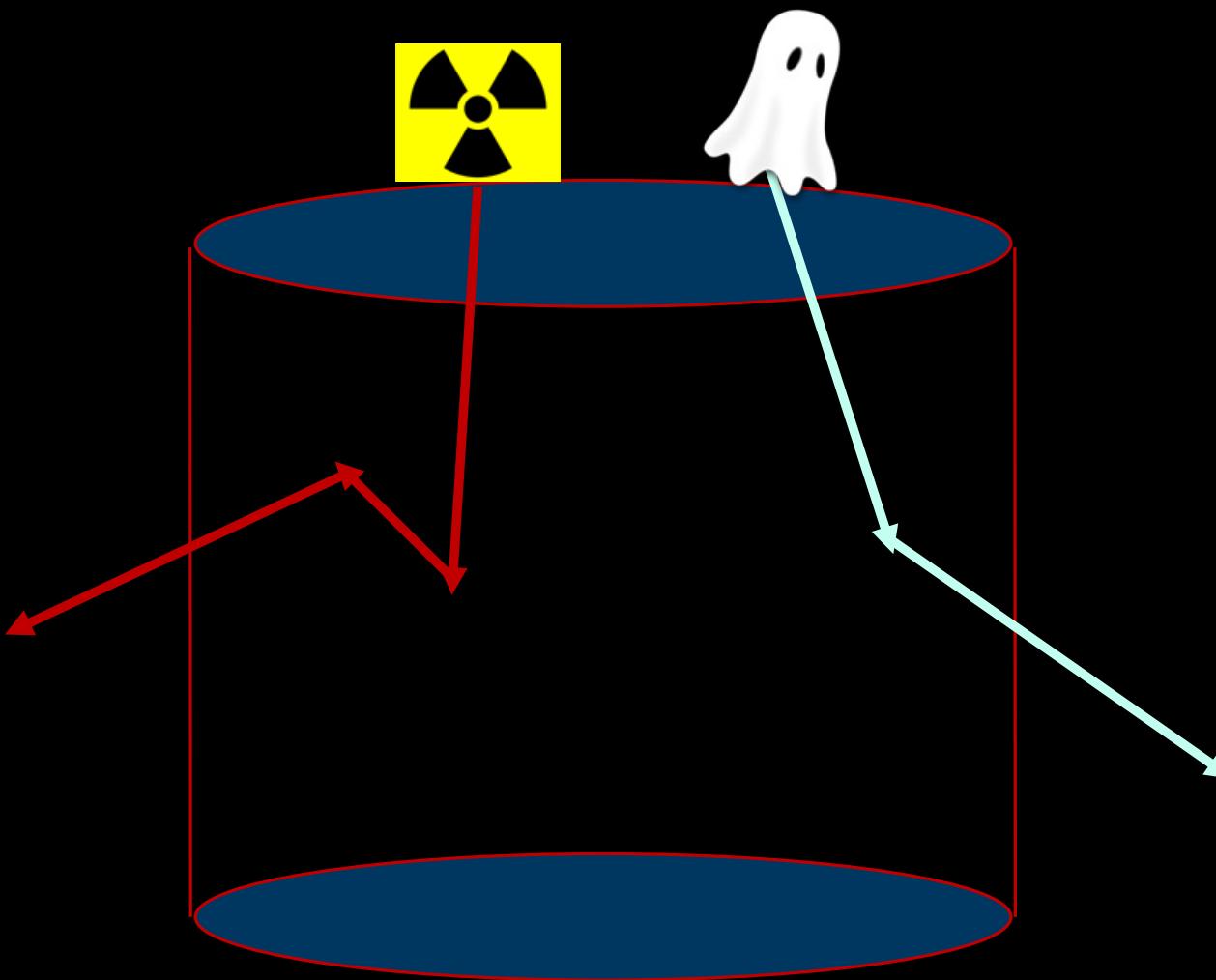
# **NEEDLE IN A HAYSTACK**



**HOW DO WE FIND THOSE FEW PARTICLES?!?**

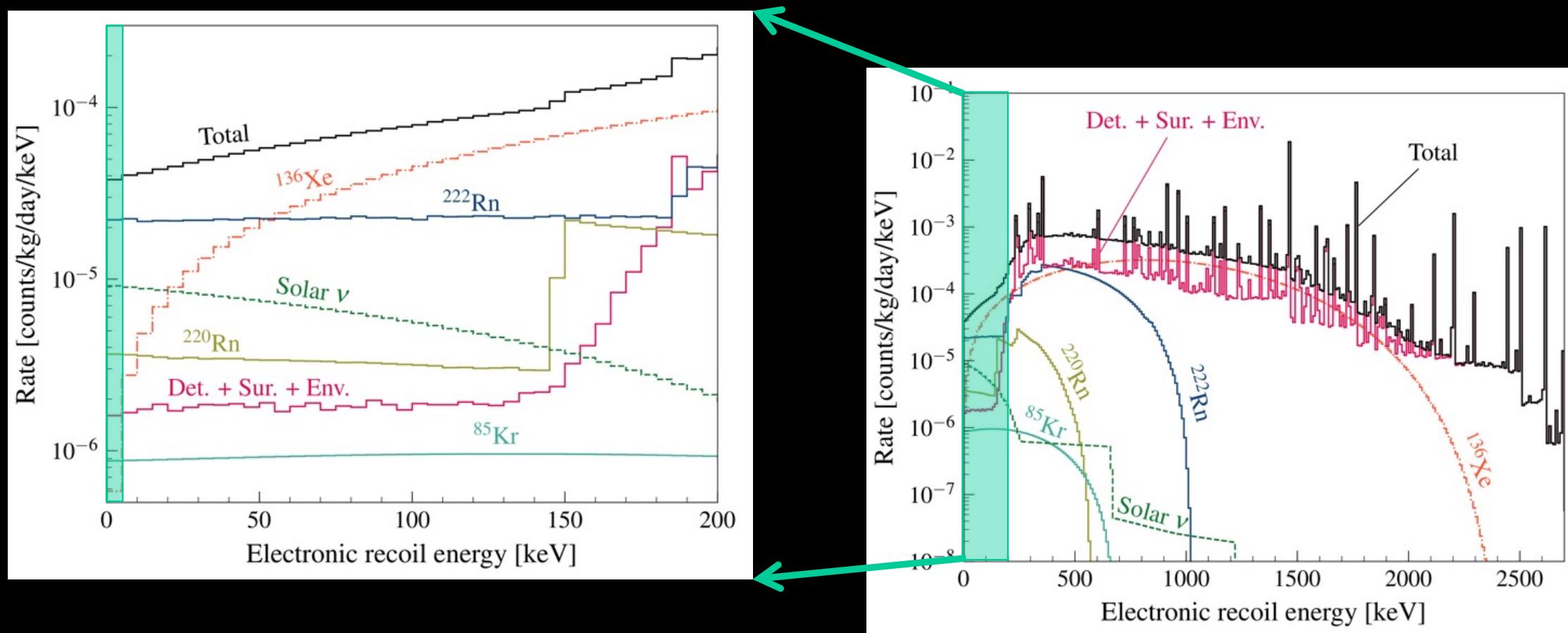
# NEEDLE IN A HAYSTACK

Total Collected Particles	100%	5 Billion
Single Site Interactions	5%	250 Million



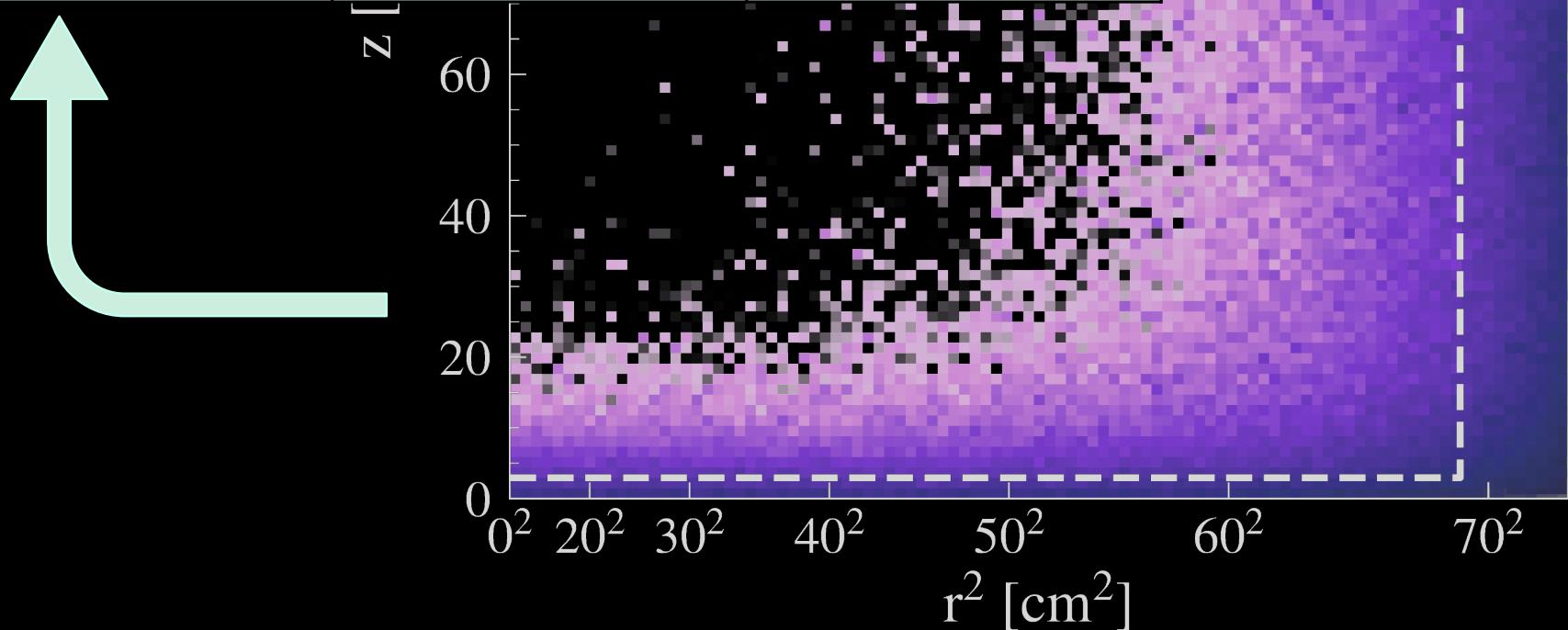
# NEEDLE IN A HAYSTACK

Total Collected Particles	100%	5 Billion
Single Site Interactions	5%	250 Million
Low Energy Transfer	0.4%	1 Million



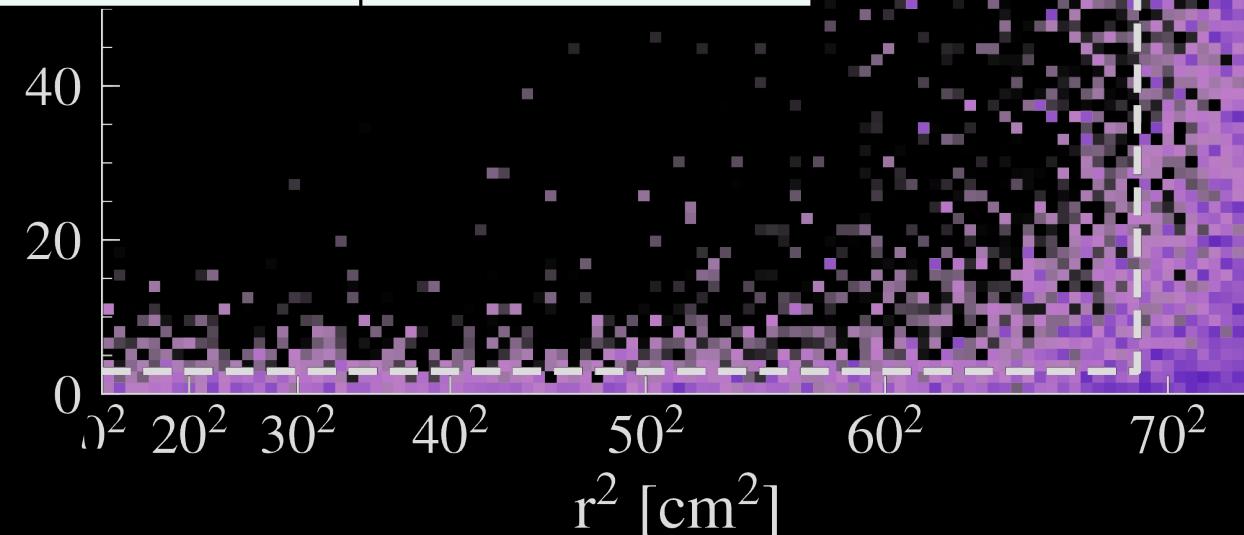
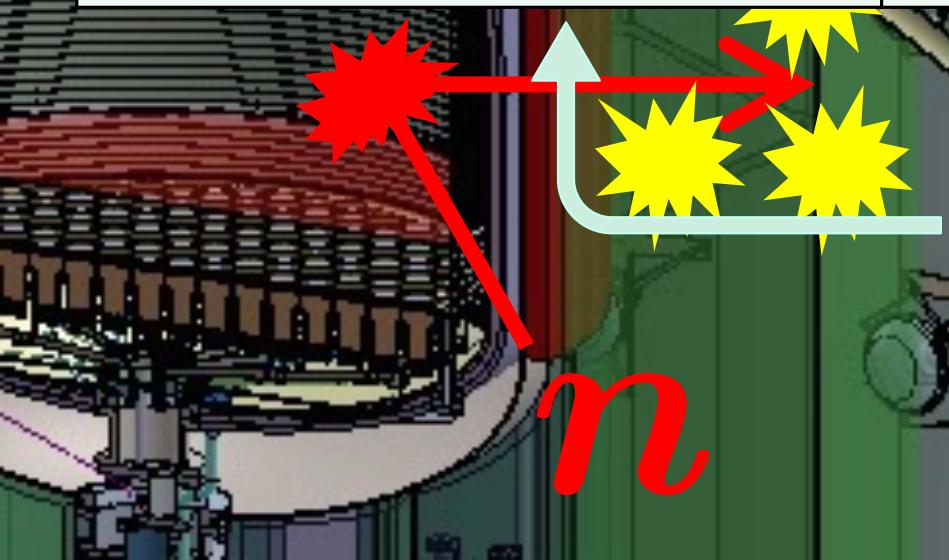
# NEEDLE IN A HAYSTACK

Total Collected Particles	100%	5 Billion
Single Site Interactions	5%	250 Million
Low Energy Transfer	0.4%	1 Million
Detectable Charge Level	10%	100,000
Use Inner Volume Only	5%	5,000

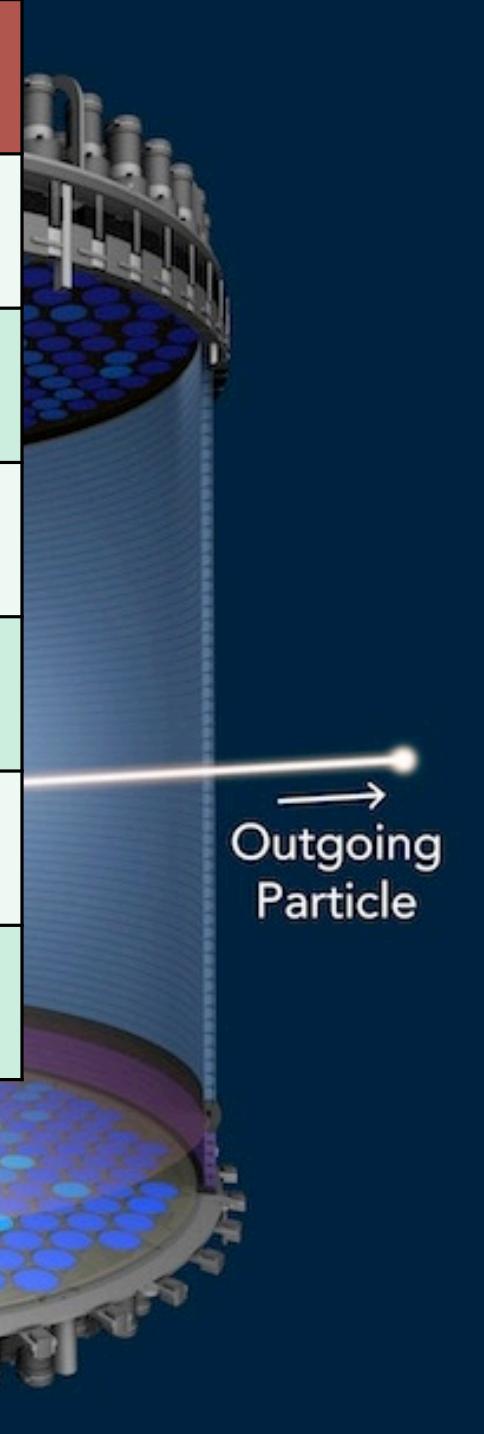


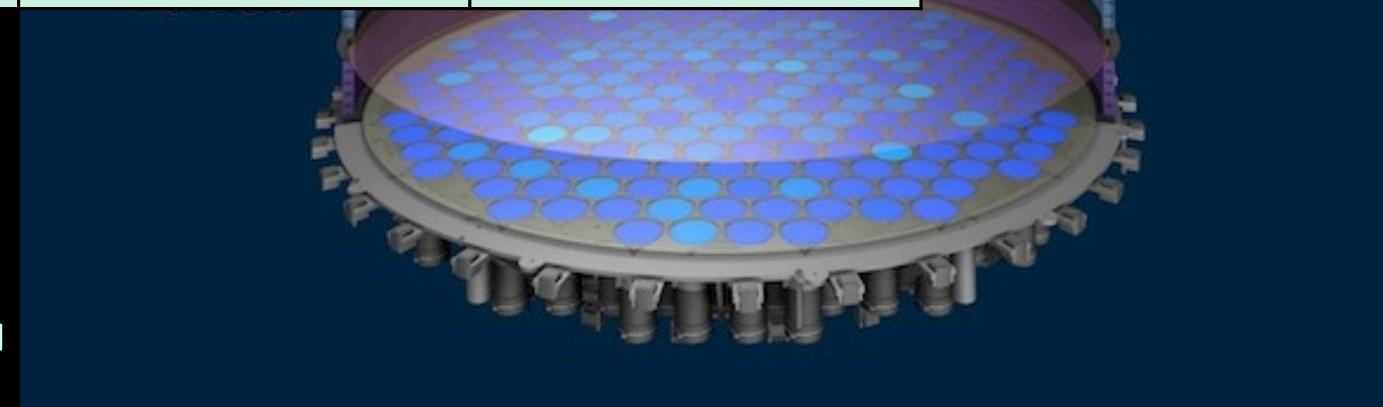
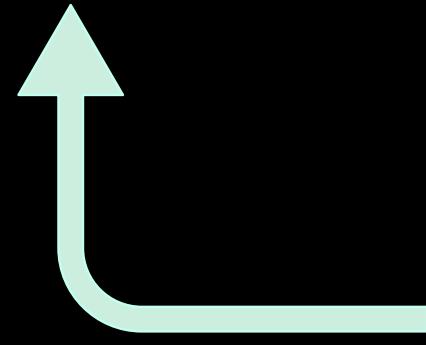
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Observed by Gadolinium	20%	1,000



# NEEDLE IN A HAYSTACK

Total Collected Particles	100%	5 Billion	
Single Site Interactions	5%	250 Million	
Low Energy Transfer	0.4%	1 Million	
Detectable Charge Level	10%	100,000	
Use Inner Volume Only	5%	5,000	
Observed by Gadolinium	20%	1,000	
Low Charge/Light Ratio	0.5%	5	

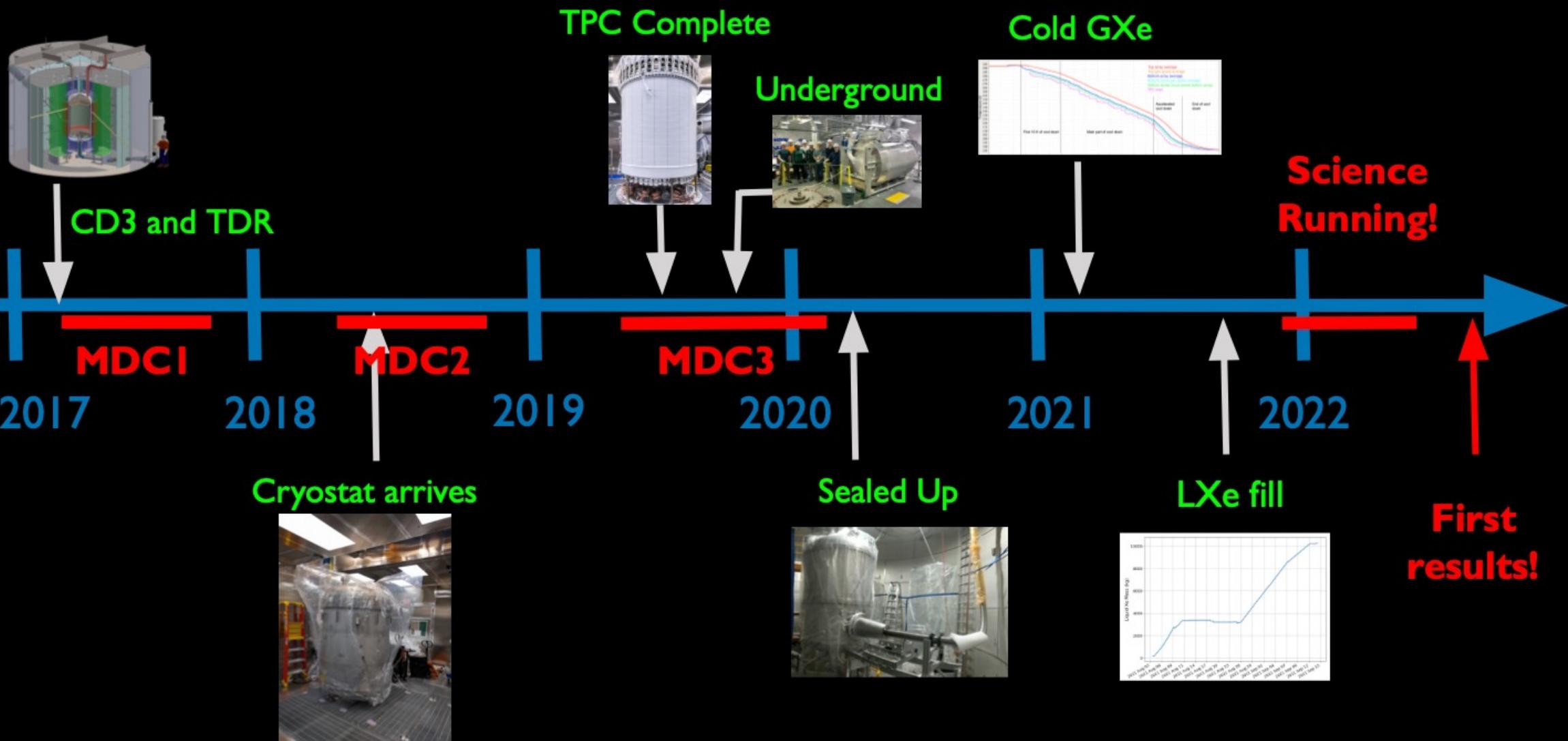


# NEEDLE IN A HAYSTACK: COMPUTING

- AUTOMATIC 24/7 PROCESSING OF ALL DETECTOR DATA
- LARGE-SCALE SIMULATIONS WITH DETAILED MODELING
- EXTENSIVE CAMPAIGN(x3) OF MOCK DATA CHALLENGES



# 5 WEEKS FROM DATA TAKING TO RESULTS!



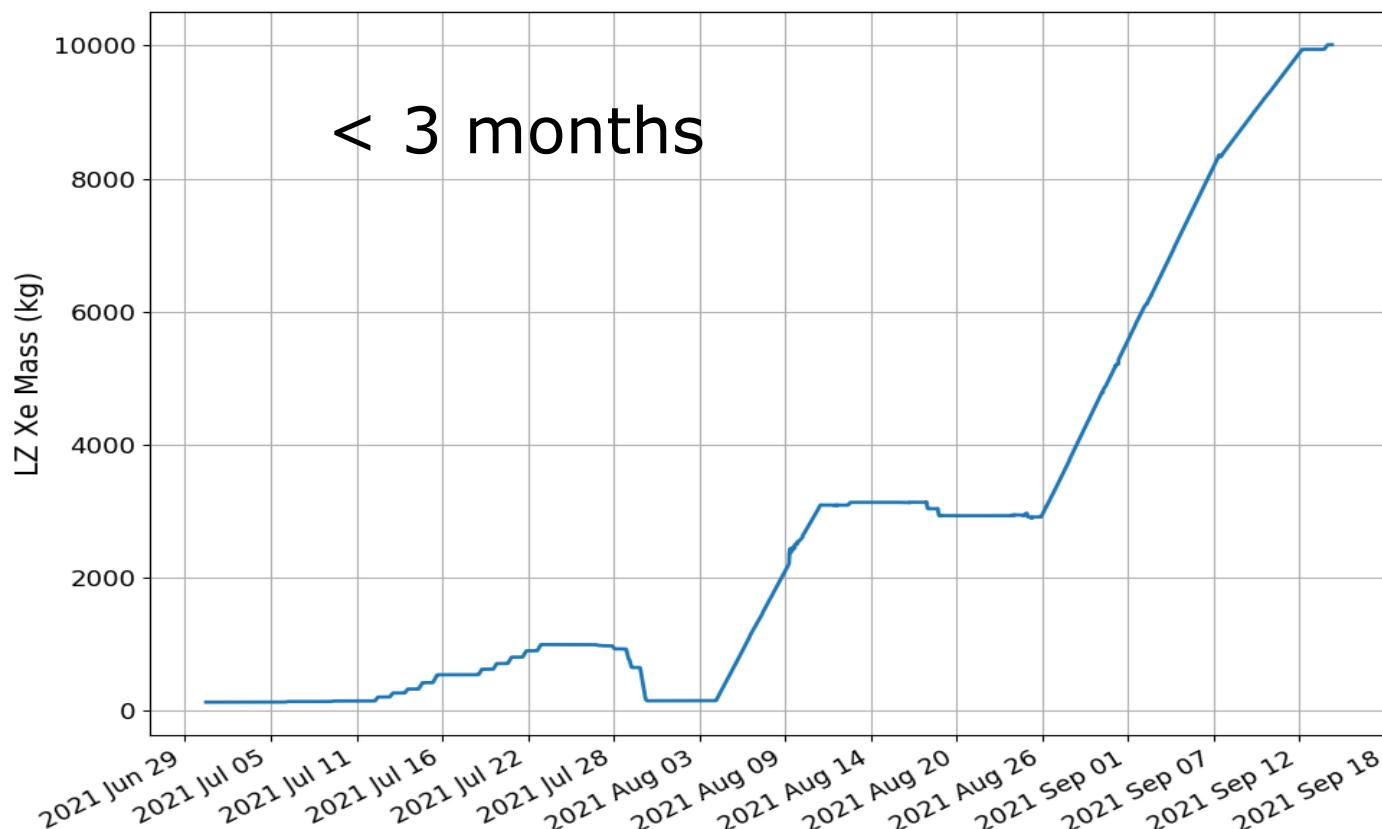
ENABLED BY AN EXTENSIVE CAMPAIGN  
OF MOCK DATA CHALLENGES (MDC)

# LZ COMMISSIONING: COOLDOWN & FILLING!

**COOLING!  
FEB 2021**



**< 3 months**



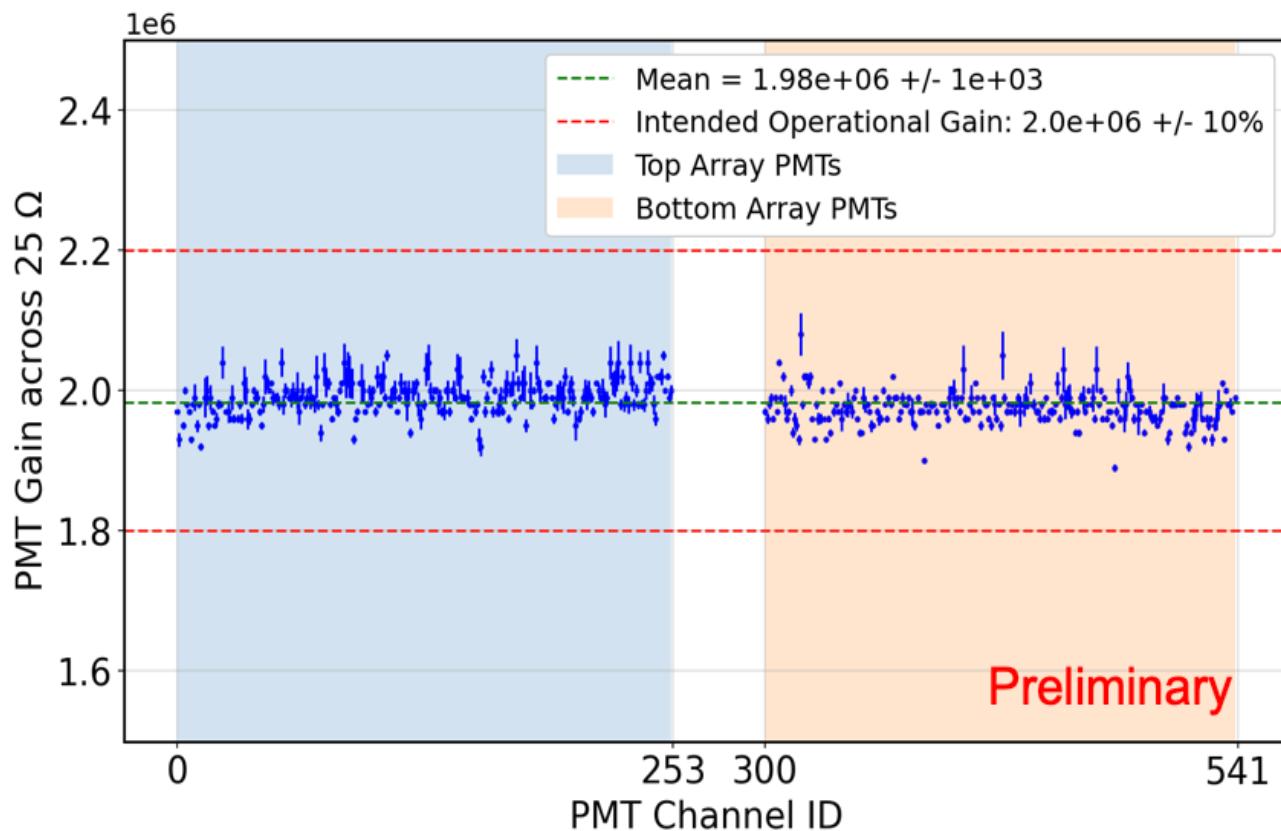
**CONDENSING  
(AND TESTING  
LXE RECOVERY)  
SUMMER 2021**

# FIRST LIGHT!

October 6th, 2021

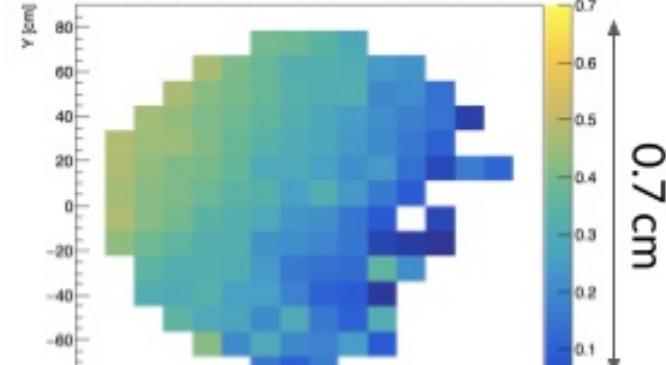
Alden Fan An S1+S2 pair with a real drift field (cathode at 20 kV, deltaV of 8 kV on the G/A)!!!!

image.png ▾

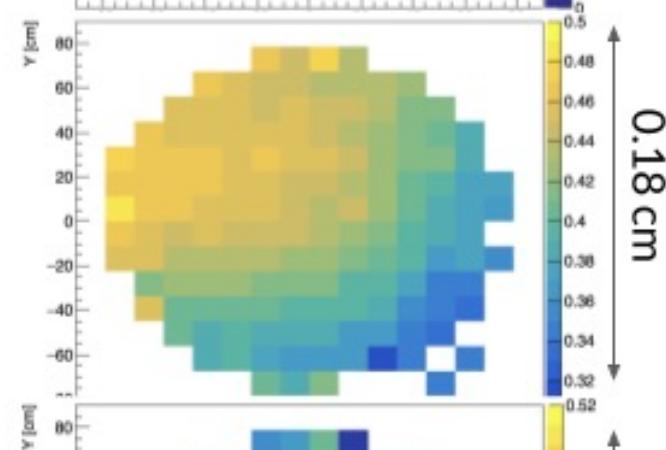


## TPC leveling campaign

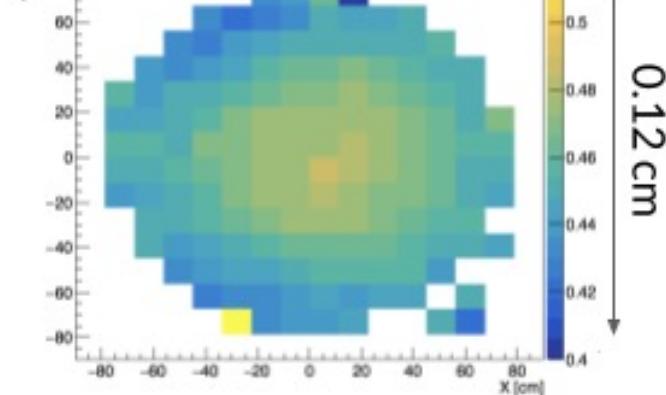
Liquid height above gate vs. xy



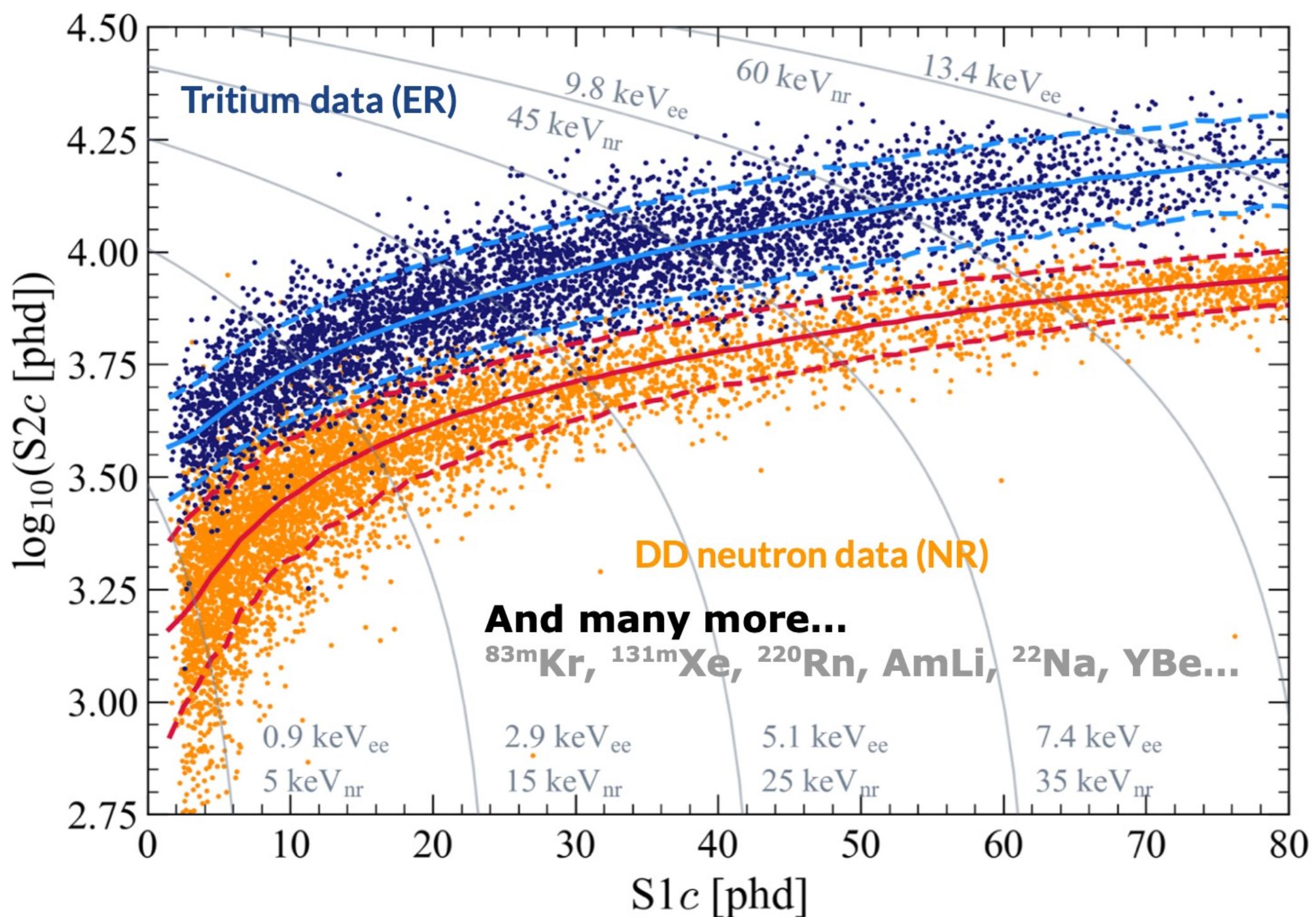
After coarse  
adjustment



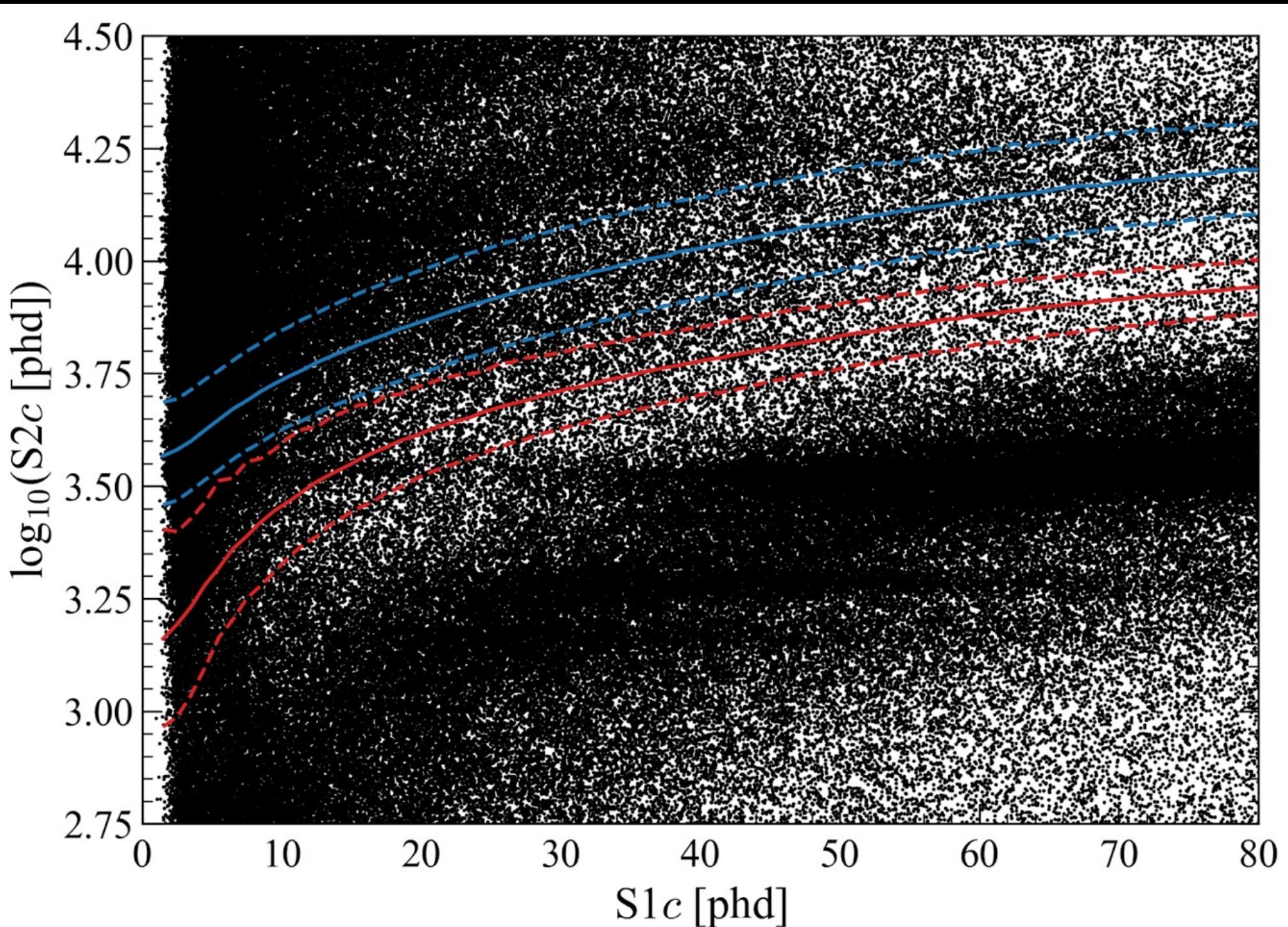
After fine  
adjustment



# LZ DATA TAKING: CALIBRATIONS!



# THE DATASET -> LZ: SCREAMS!!!



# THE DATASET: EVENT SELECTIONS

All triggers

Time hold-offs

high rates of spurious instrumental activity, dominated by post-S2 hold-off (70% live fraction)

Low energy single scatters

$3 < S1c < 80 \text{ phd}$ ,  $S2c > 600 \text{ phd}$  ( $10e^-$ )

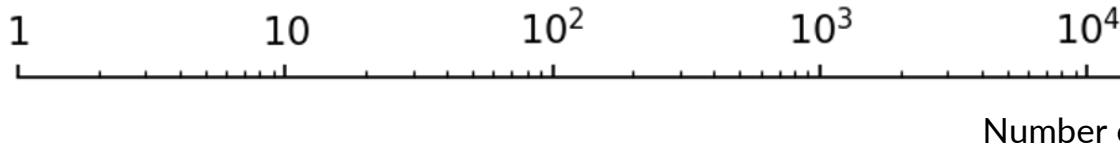
Pulse quality cuts

target accidental coincidence events

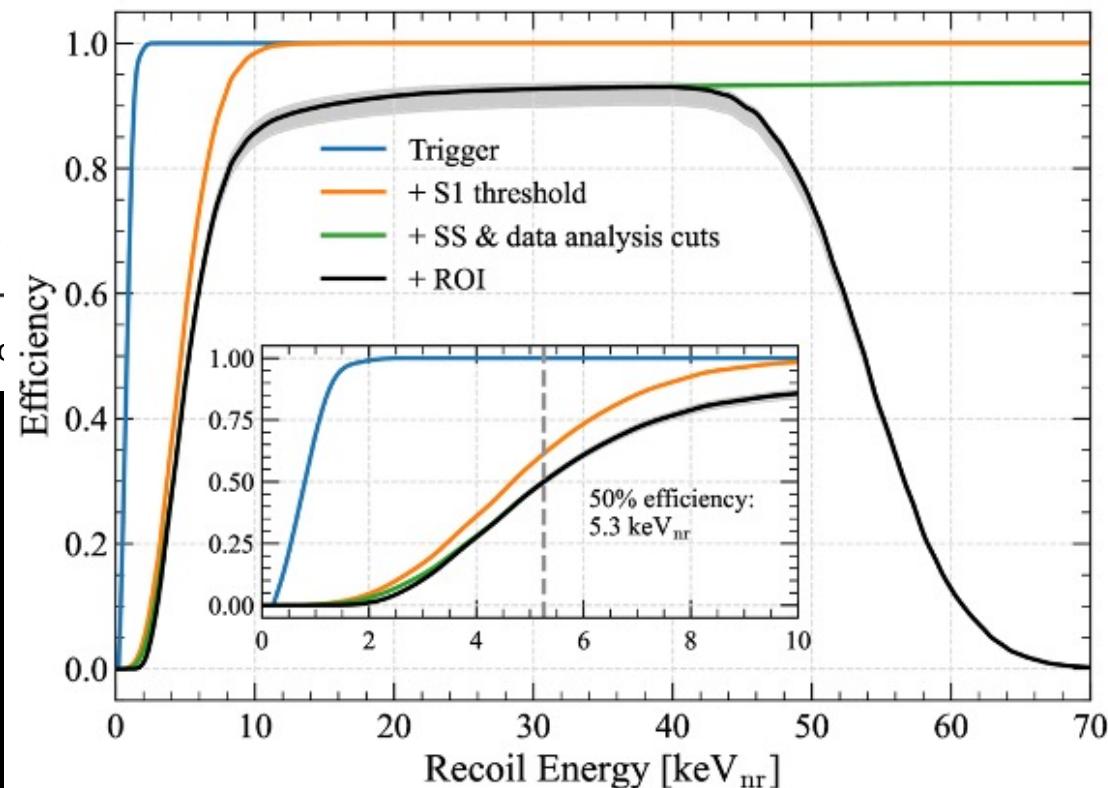
Fiducial volume

central 5.5 tonnes of LXe

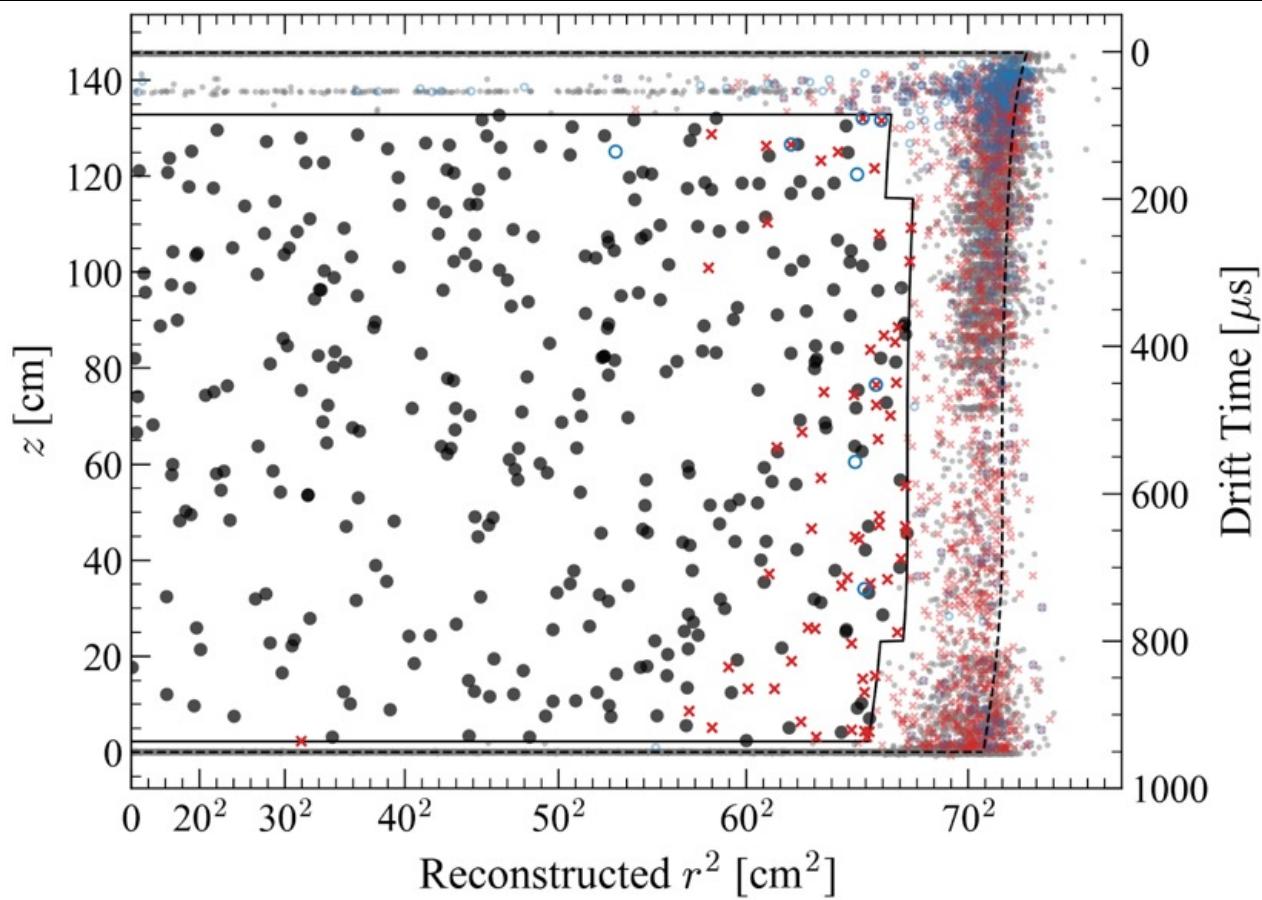
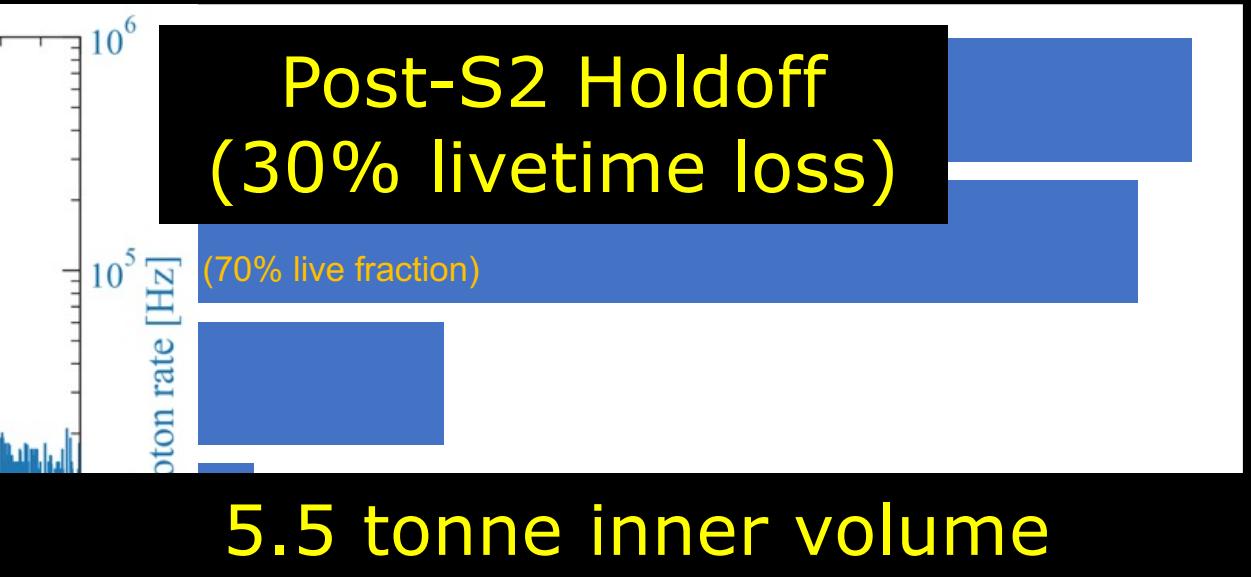
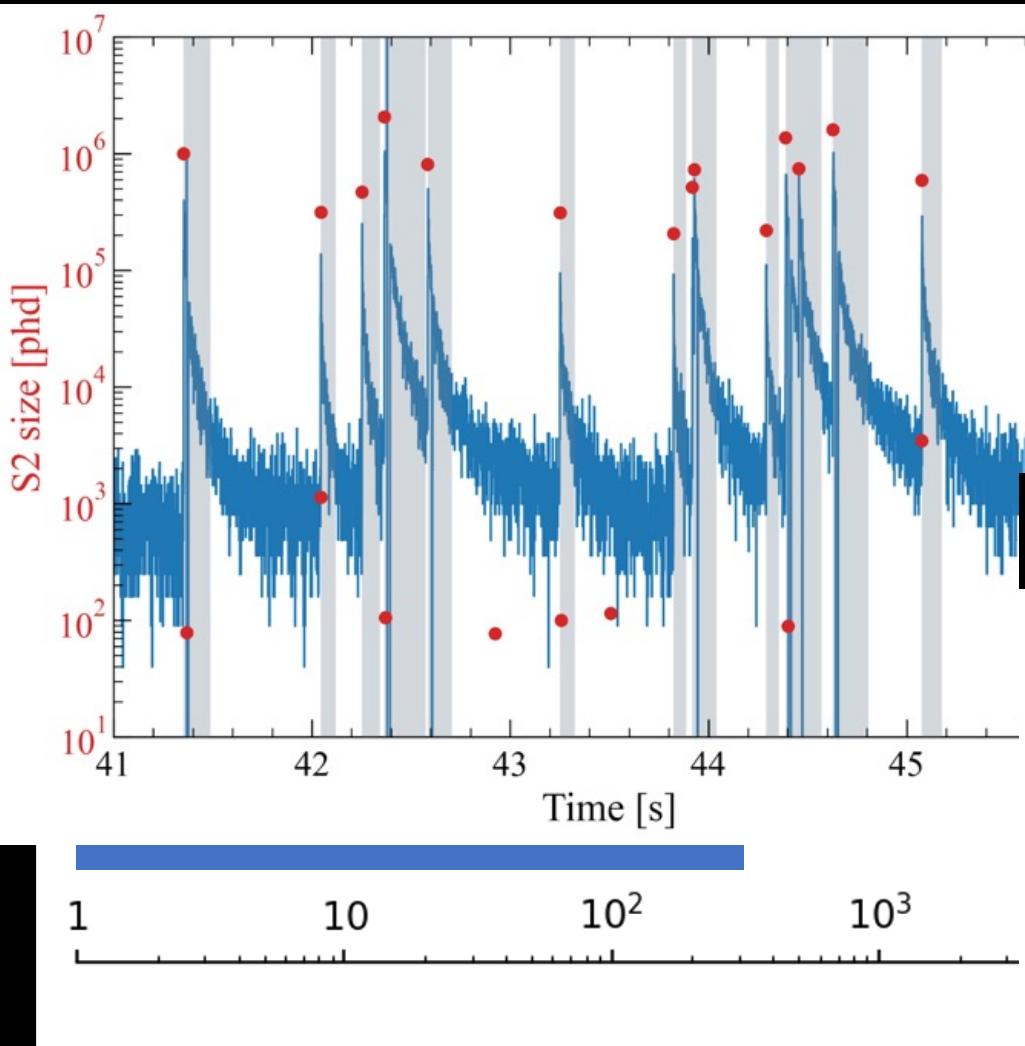
OD + Skin vetoes



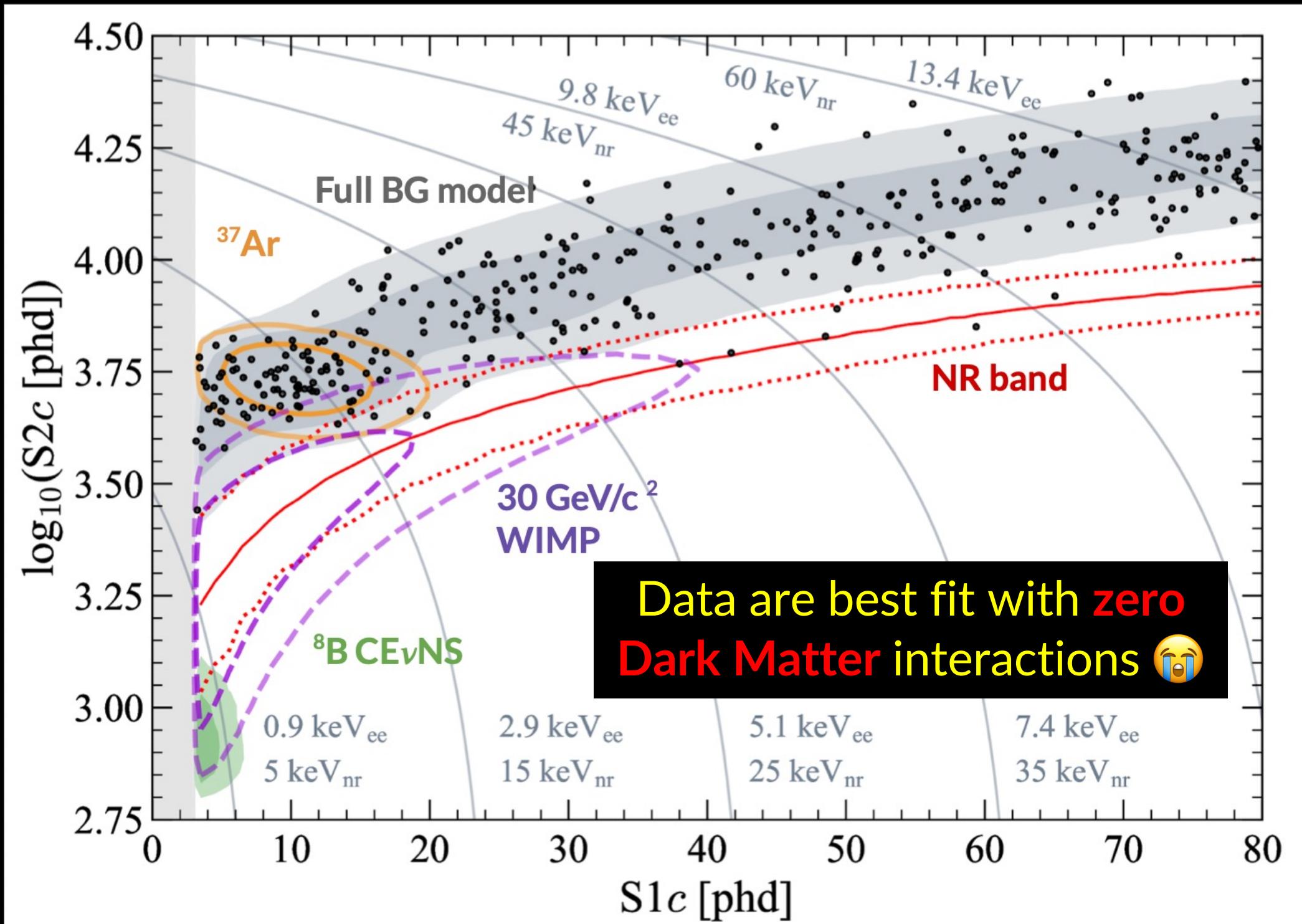
Signal efficiency evaluated using tritium and AmLi calibration data



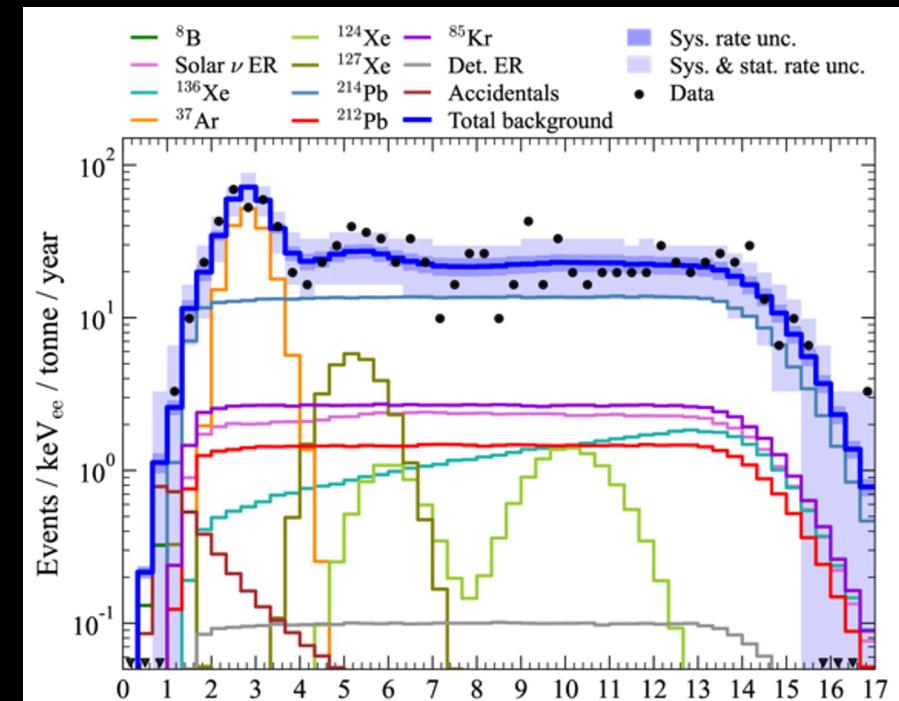
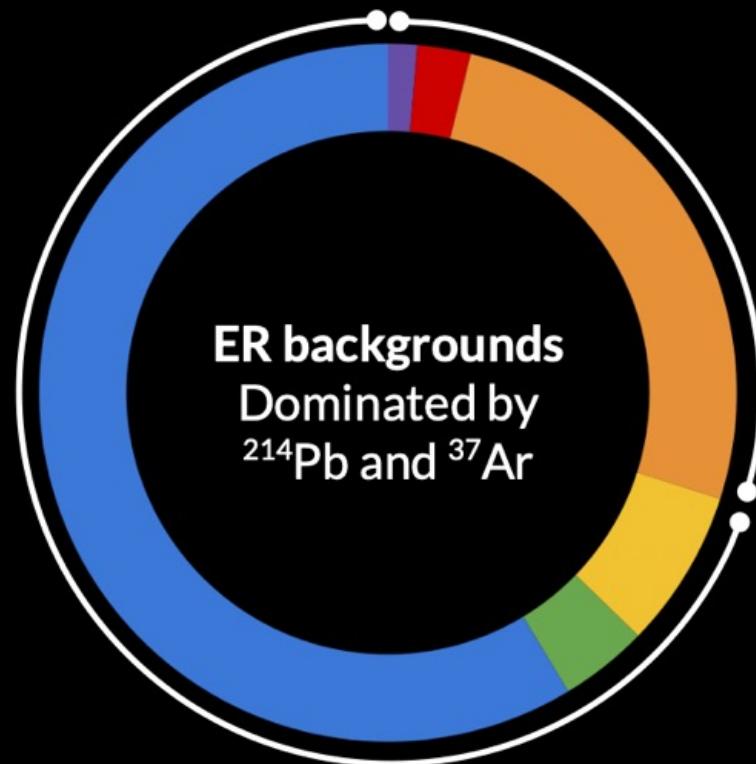
# THE DATASET: EVENT SELECTIONS



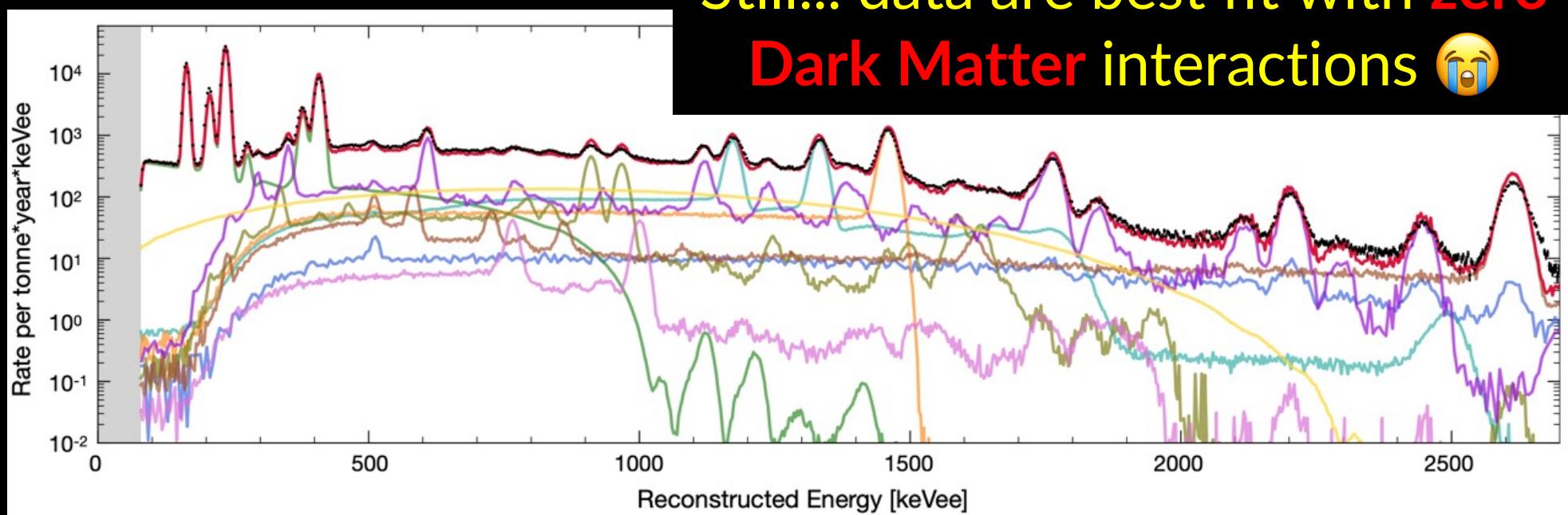
# HEY DATASET, YOU CLEAN UP REAL NICE 😜



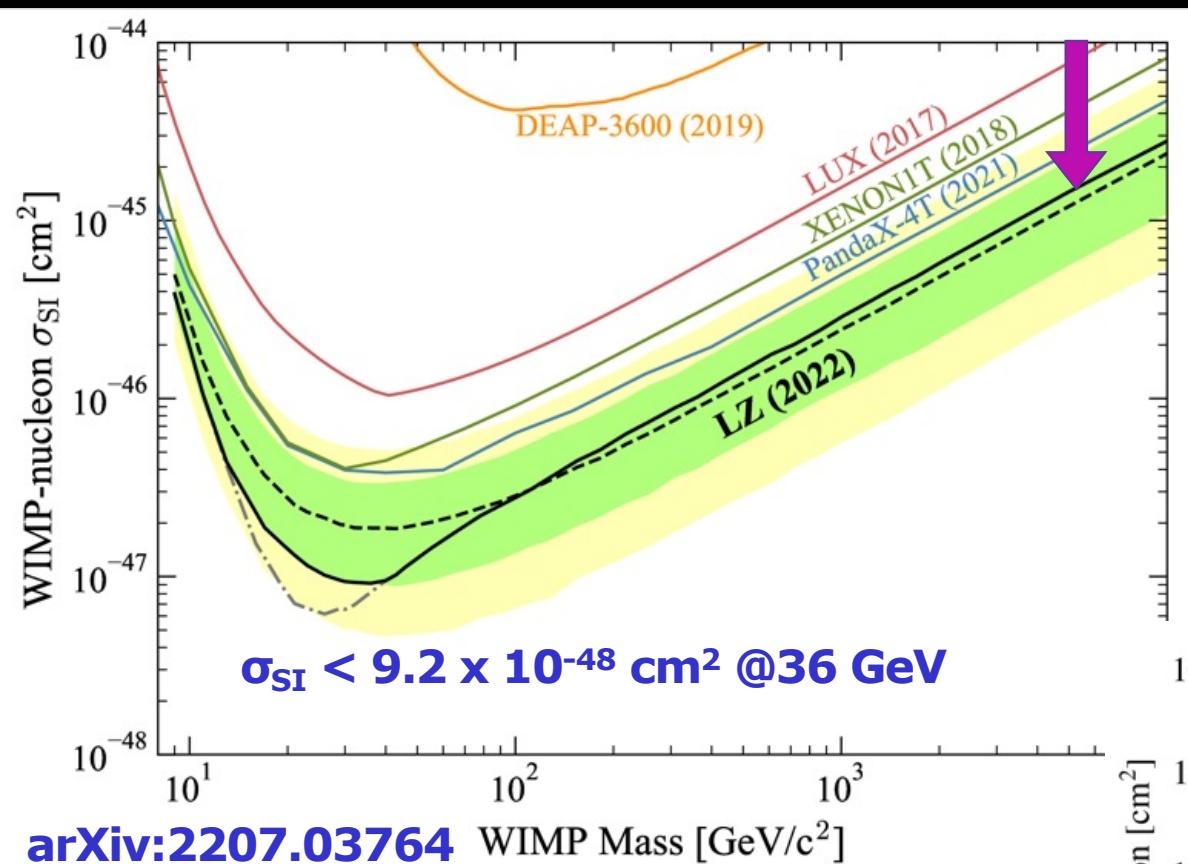
# EXTREMELY DETAILED BACKGROUND MODEL



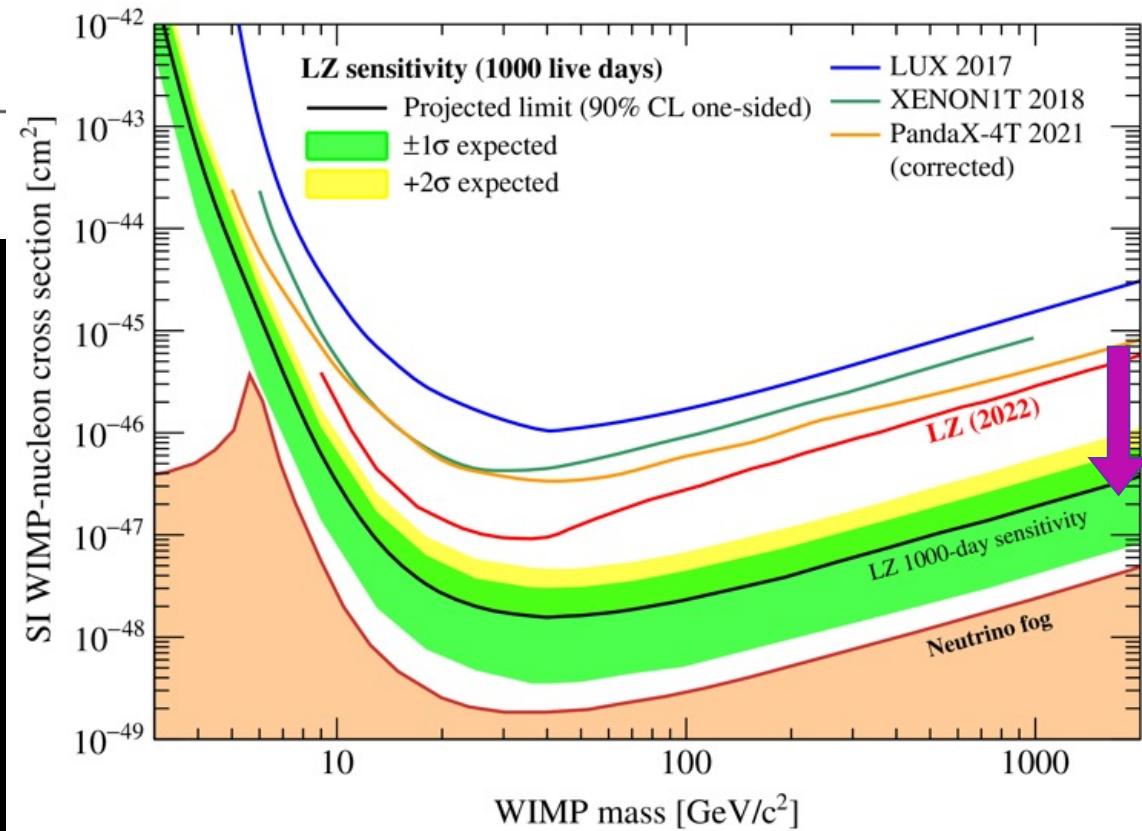
Still... data are best fit with zero  
Dark Matter interactions 😭



# FINDING NOTHING, BETTER THAN EVERYONE ELSE



NOT FINDING THE DARK MATTER PARTICLE TELLS US A LOT ABOUT THE DARK MATTER PARTICLE

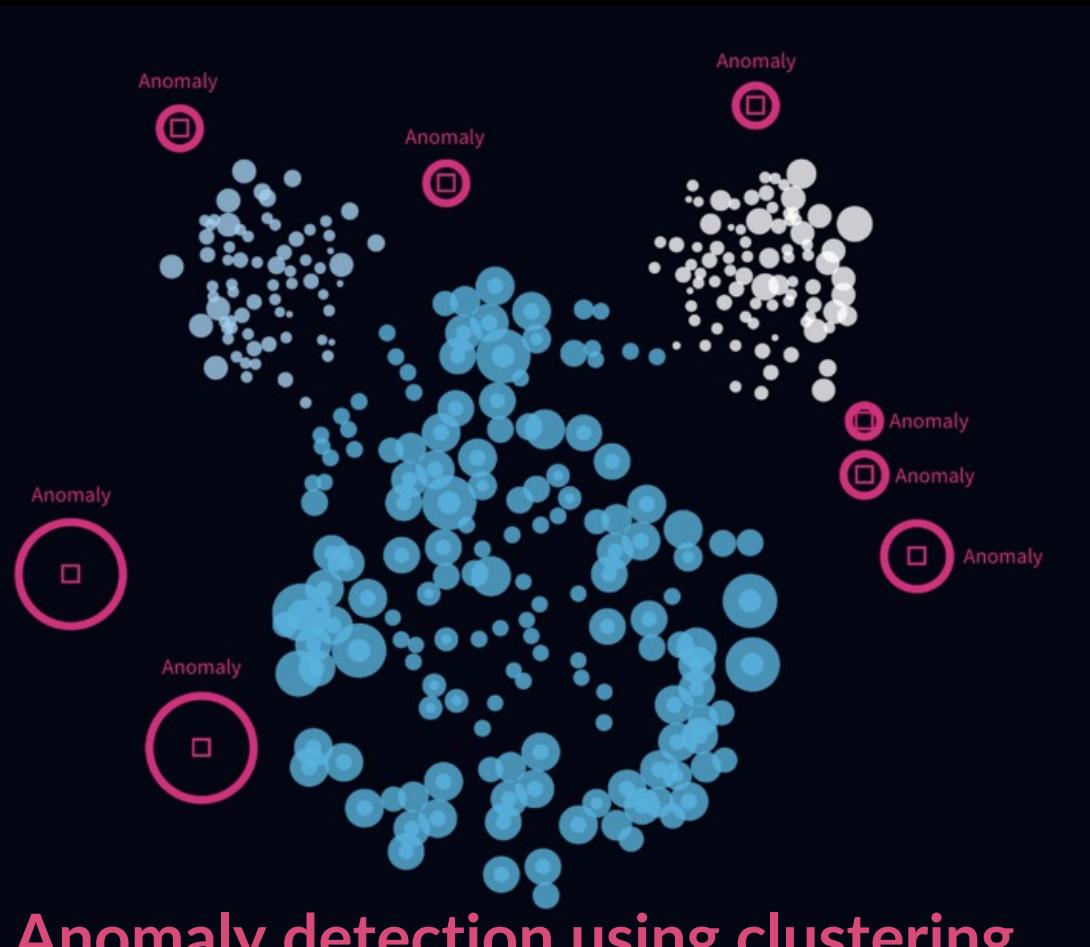


OK, WHAT'S NEXT?

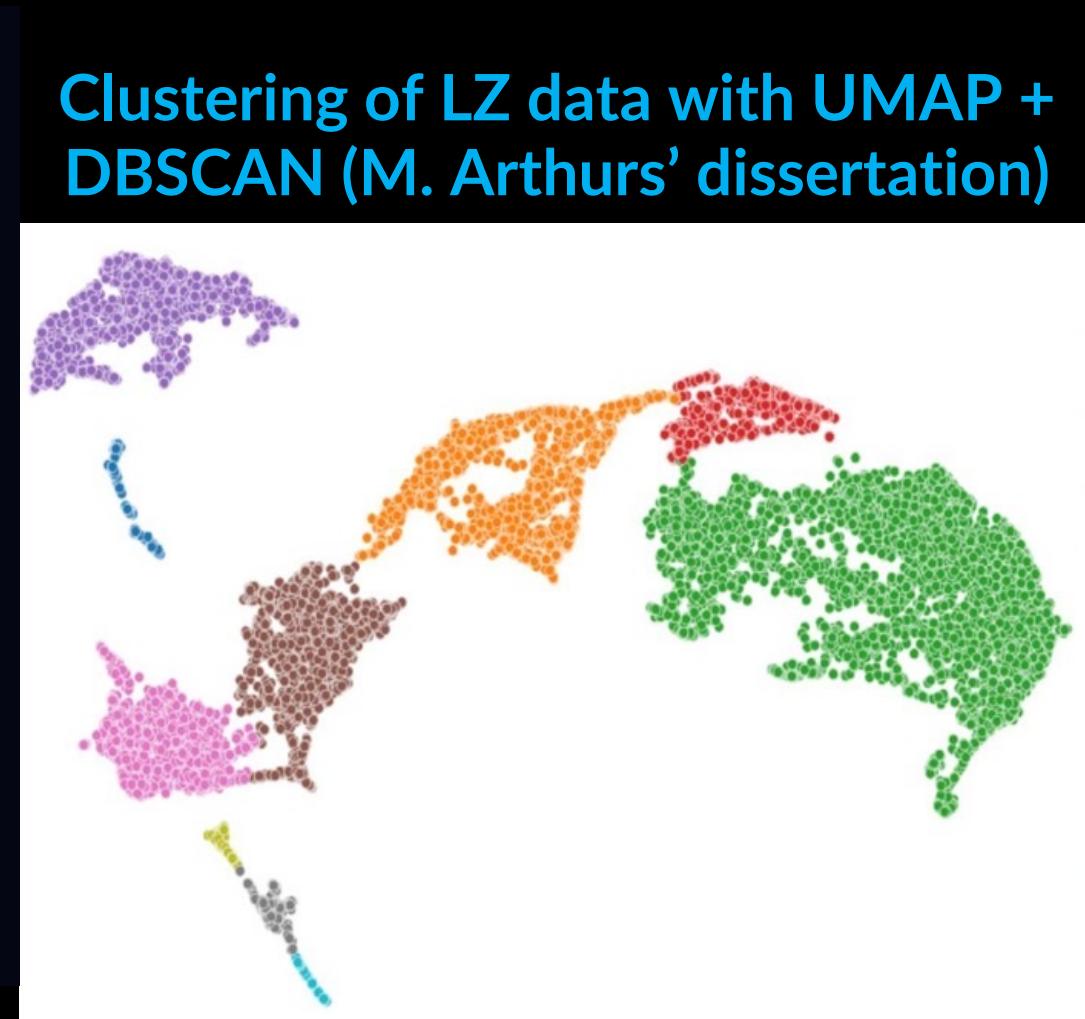
LET'S WAIT SOME MORE!  
AKA: LOTS. MORE. DATA

# CAN WE USE SOME FANCY ALGORITHMS?

- ISSUE: REJECT RARE/UNPHYSICAL DETECTOR EFFECTS
- APPROACH: ANOMALY DETECTION (CLUSTERING, VAE)
- [SEE ALSO: INTRUSION DETECTION @ DATA CENTERS]



Anomaly detection using clustering  
(diagram from Google Cloud blog)

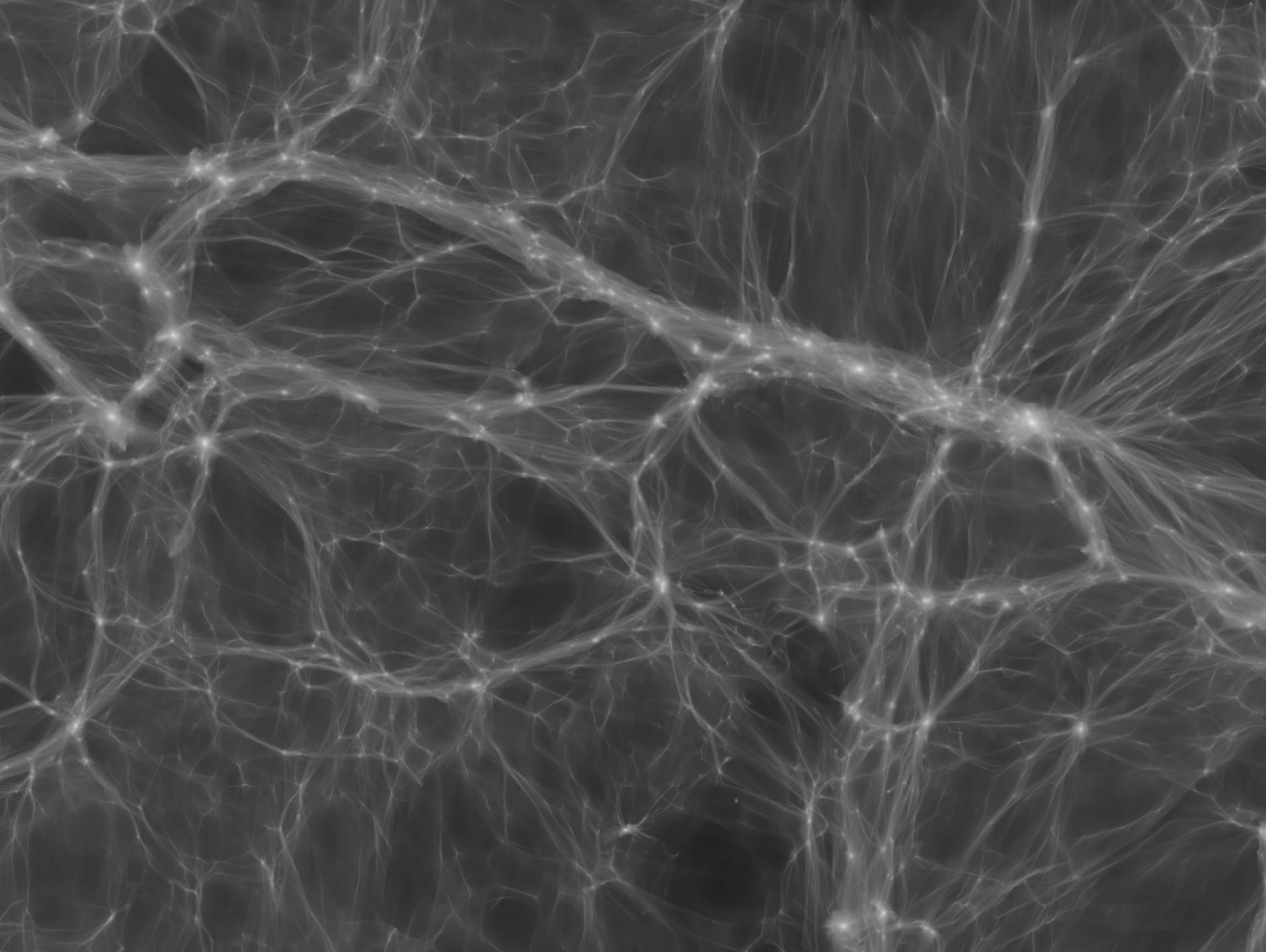


Clustering of LZ data with UMAP + DBSCAN (M. Arthurs' dissertation)

A wide-angle photograph of a dark night sky, densely packed with stars of various brightness. A prominent, glowing band of light, representing the Milky Way galaxy, stretches across the upper half of the frame. Below the horizon, a dark silhouette of hills or mountains is visible against the lighter sky. The overall atmosphere is one of a clear, dark night.

**DARK MATTER IS HIDING IN PLAIN SIGHT...**

**...OK, BUT WHO CARES!?**



# A TEAM EFFORT! THE LZ COLLABORATION (PRE-PANDEMIC PHOTO AT SURF)



Thanks to our  
sponsors and  
participating  
institutions!



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MINISTÉRIO DA EDUCAÇÃO E CIÉNCIA



South Dakota Science and Technology Authority



**Looking for Dark Matter at Underground Labs**  
**~50% Dark Matter Searches use Noble Liquids**





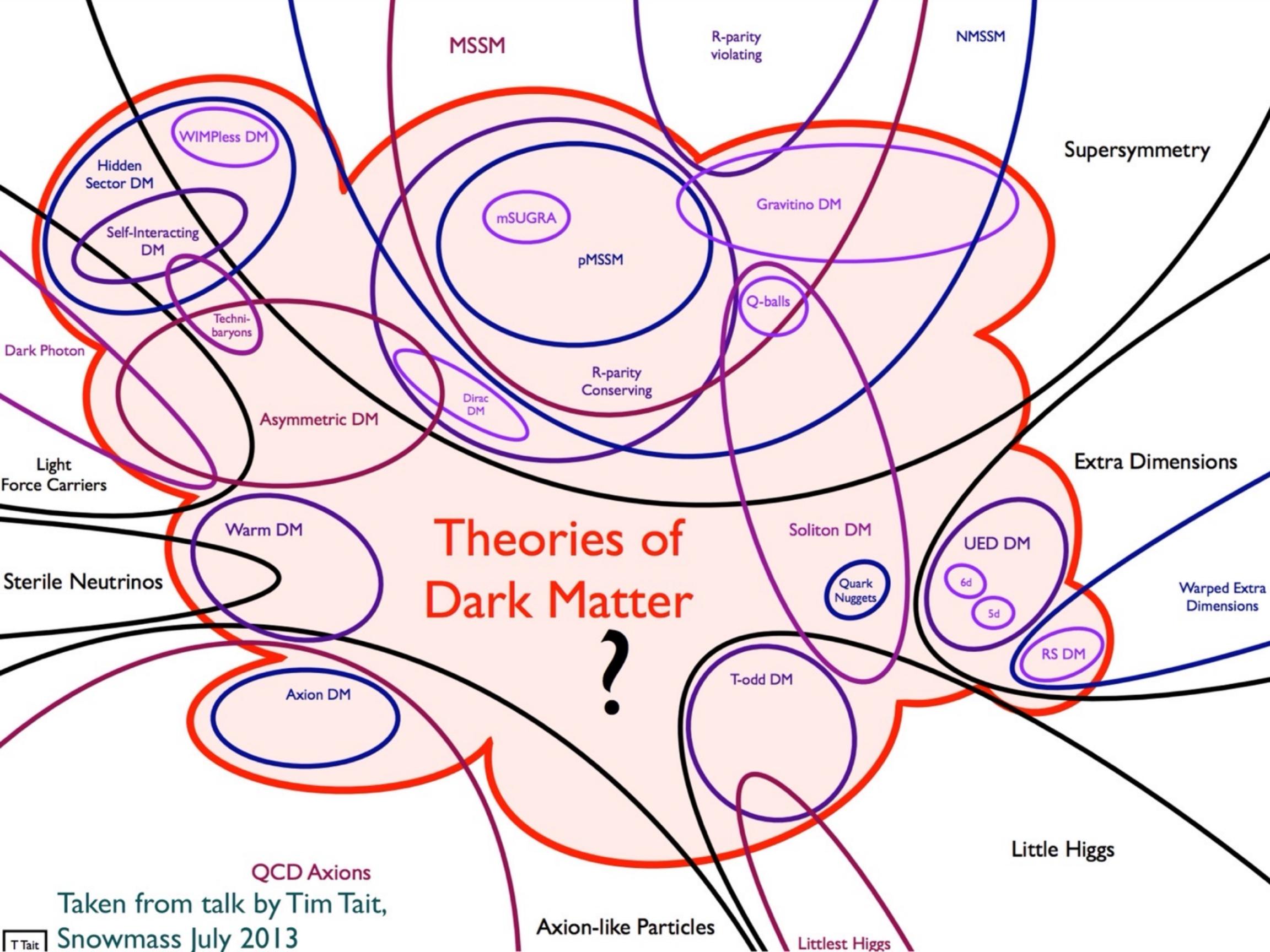
A surgeon in blue scrubs is shown from the side, focused on a procedure. They are wearing a surgical mask and glasses. The background is a dark, clinical setting with equipment visible.

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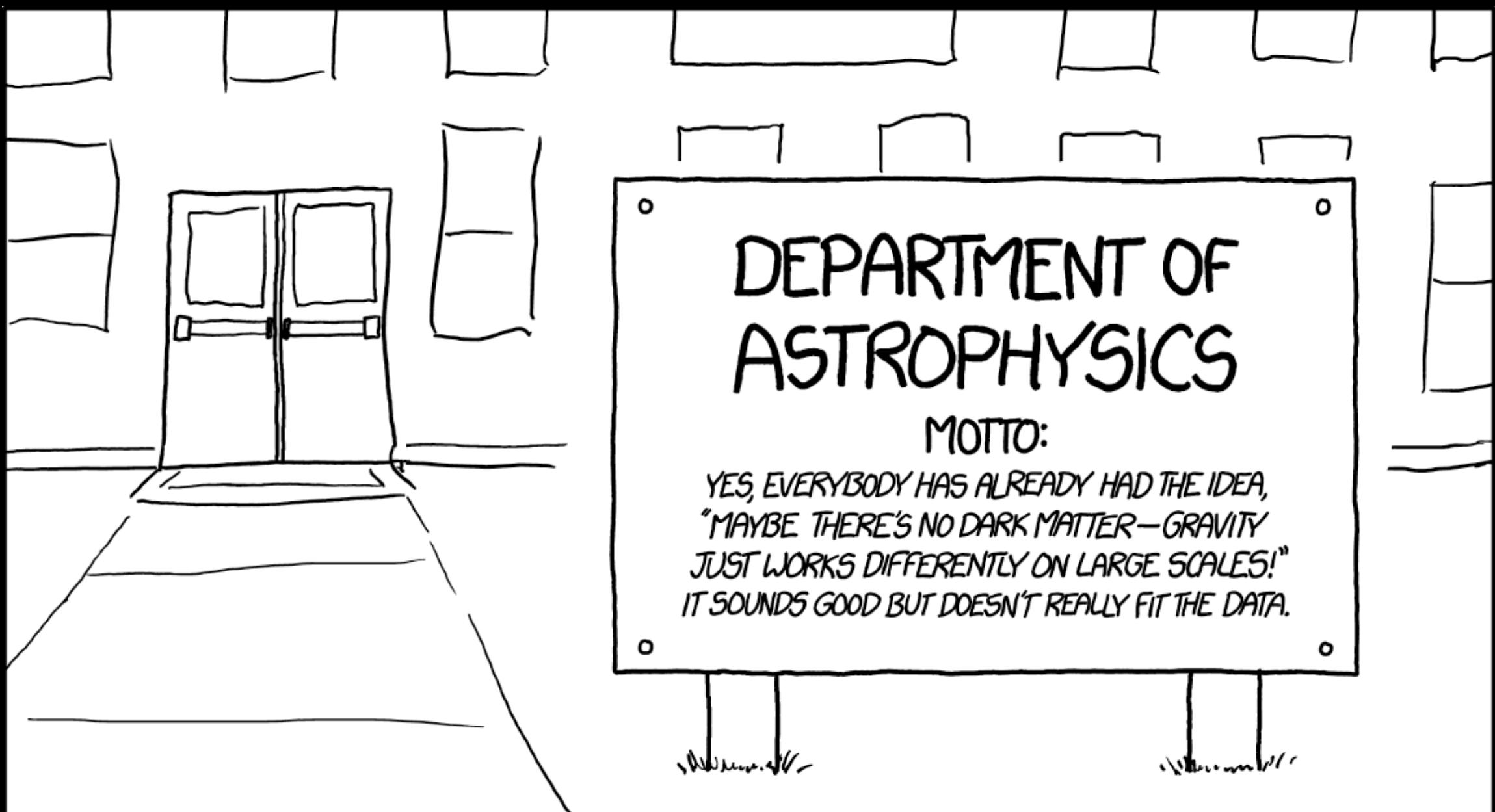
THANK YOU!

# Theories of Dark Matter

?



Taken from talk by Tim Tait,  
Snowmass July 2013



[HTTPS://XKCD.COM/1758/](https://xkcd.com/1758/)