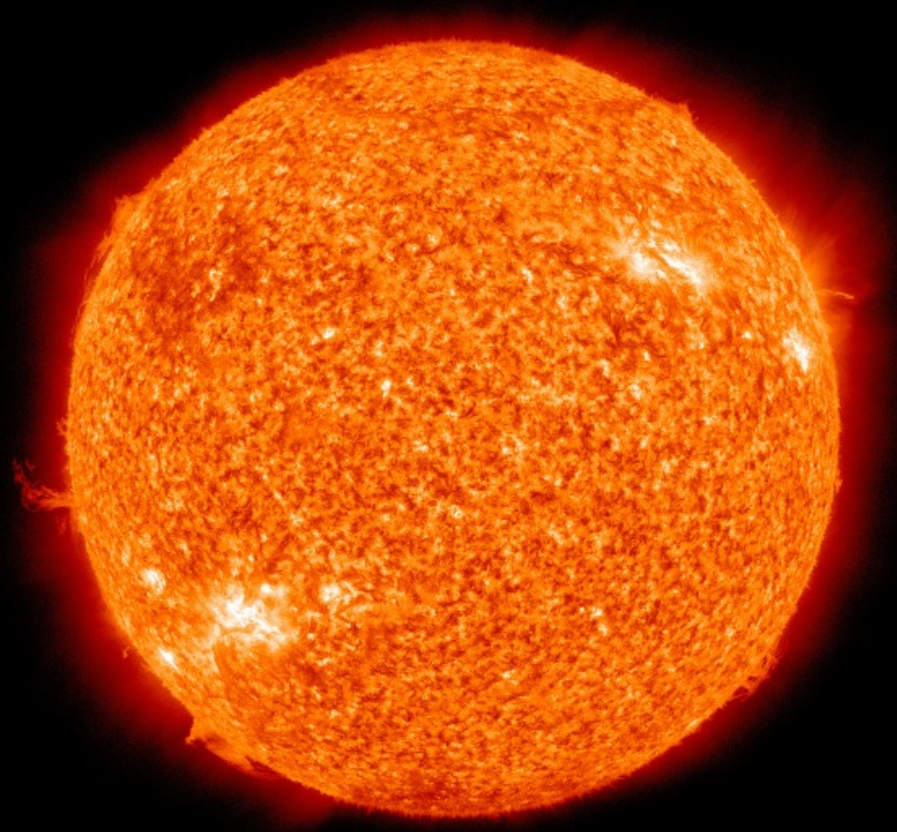
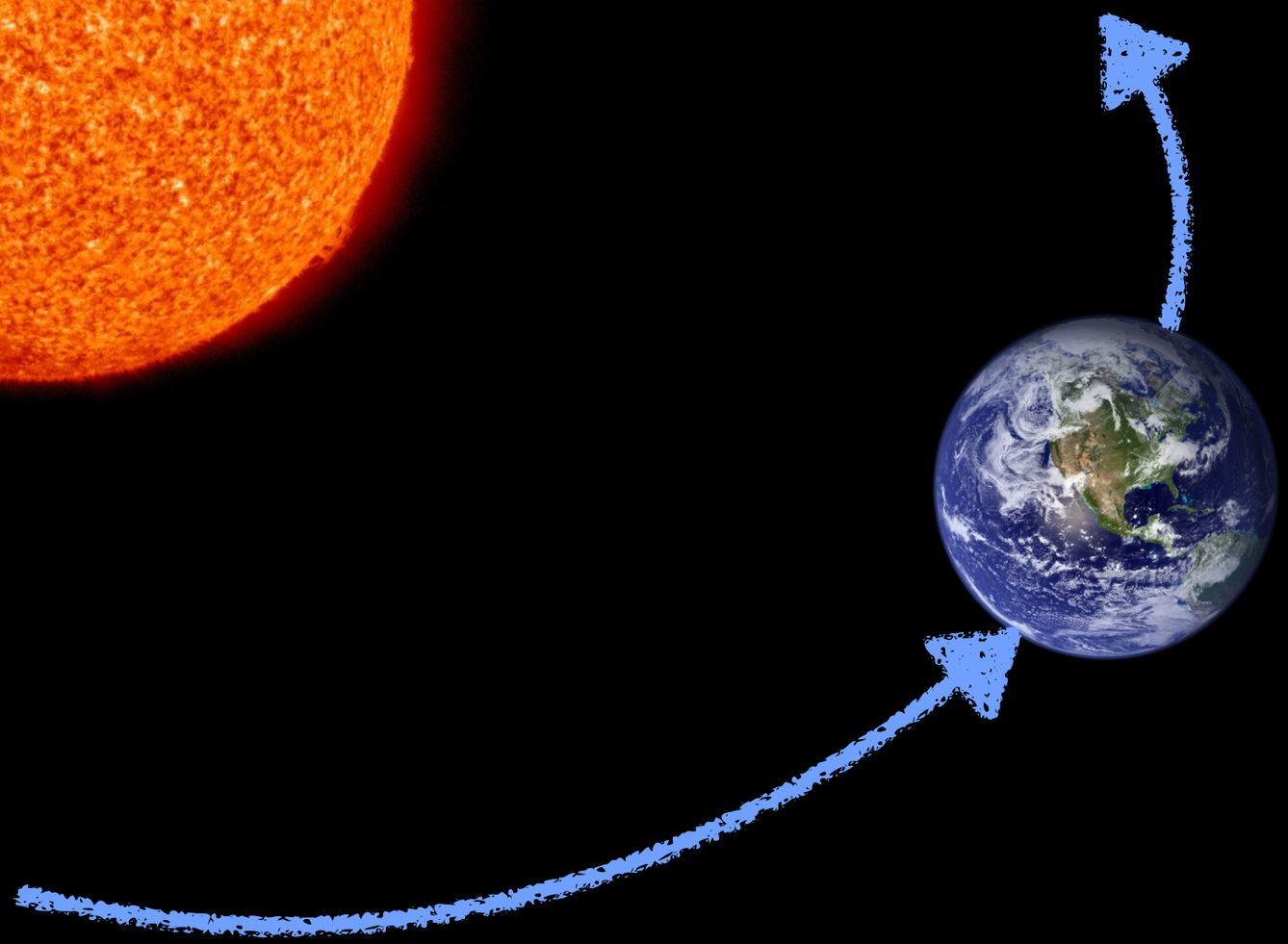
The Dark Universe

Tongyan Lin/Hugh Lippincott
University of Chicago/FermiLab



Gravity accurately describes the motions of the planets around the sun.



If the sun were **more massive** the planets would rotate **faster** around it.

Pinwheel galaxy, an “Island Universe” of stars:

Does gravity also explain the motions of stars in galaxies?

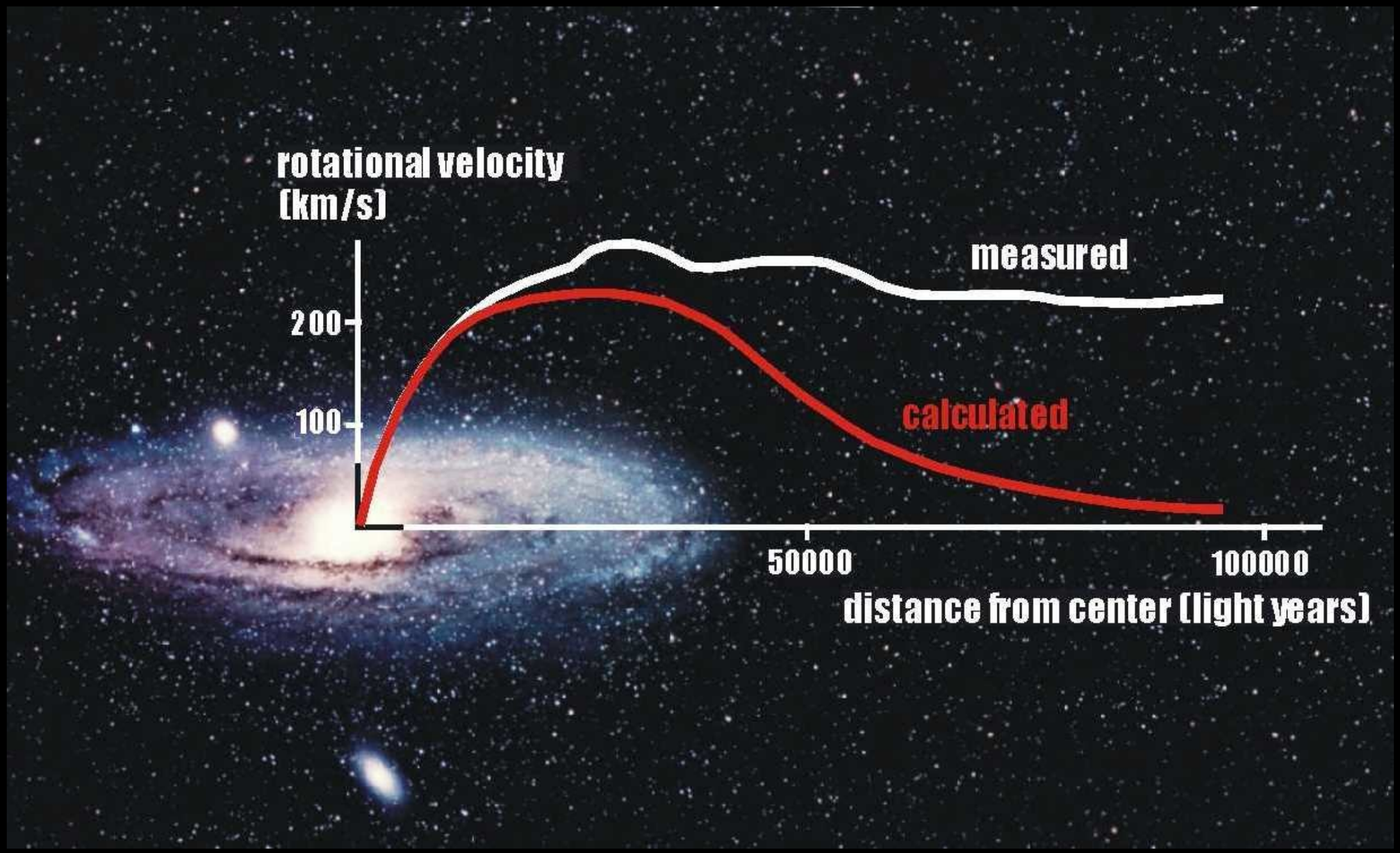
The Galaxy Rotation Problem

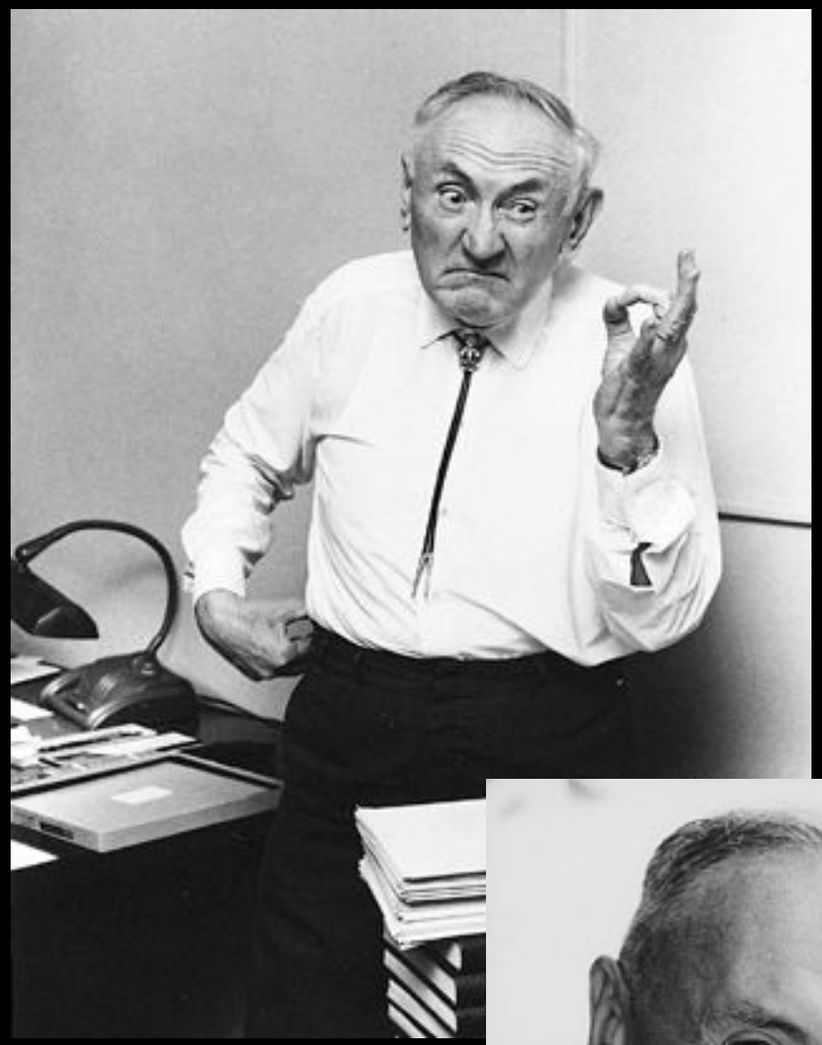
Vera Rubin ca. 1970

Rubin measured velocities of stars in spiral galaxies.

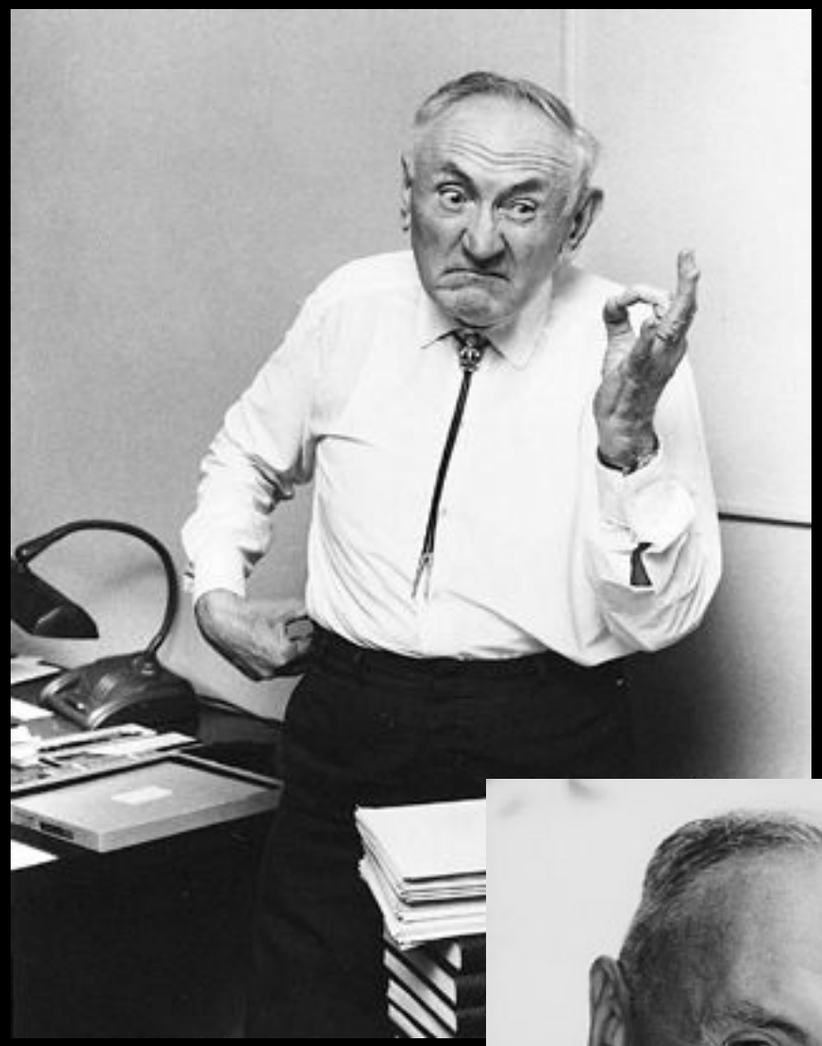
They were moving far too fast - something was needed to keep those stars bound.

Evidence from Galaxy Rotation Curves





In the 1930s, Fritz Zwicky observed that the gravitational mass of the Coma galaxy cluster far exceeded the mass of the observed stars.



In the 1930s, Fritz Zwicky observed that the gravitational mass of the Coma galaxy cluster far exceeded the mass of the observed stars.

He inferred the existence of some form of invisible matter, which he called dark matter

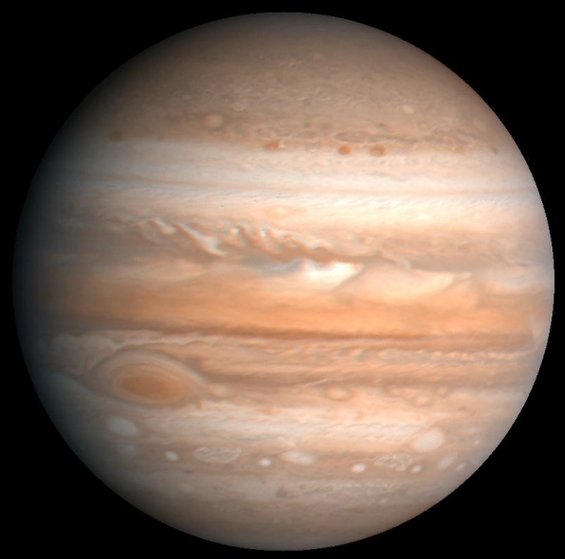
Gravity seemed **stronger** than expected in the outer parts of galaxies.

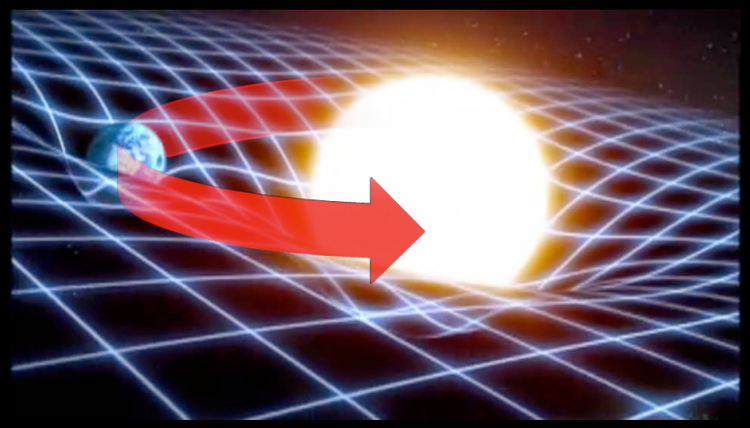
What could explain this?

Incomplete theory of gravity?

“Invisible” matter?

Something else?



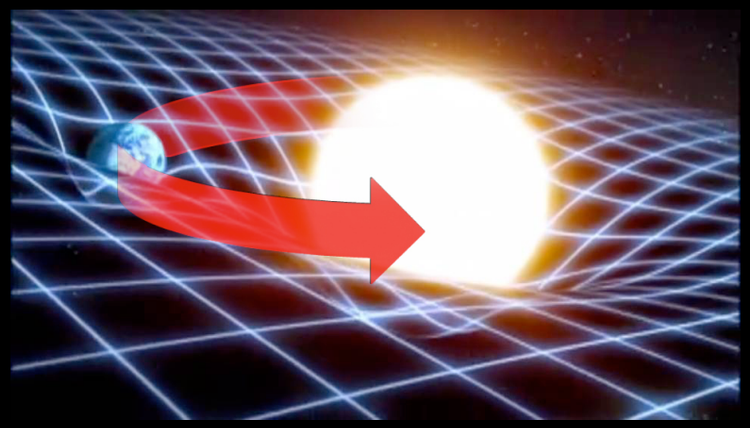


Jupiter-like objects

Modified Gravity

New Particle

Jupiter-like objects



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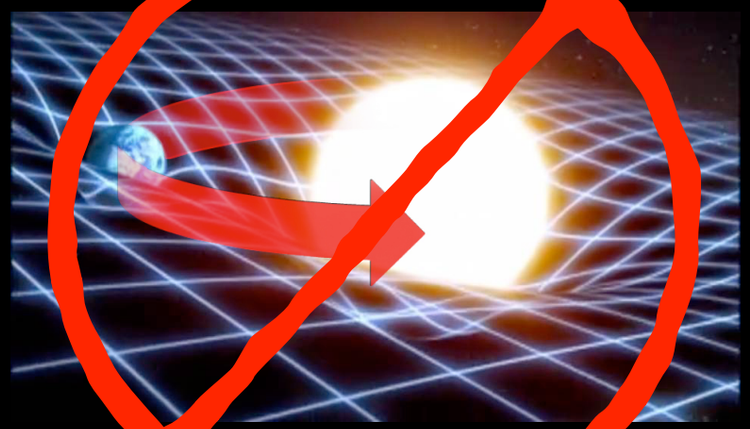

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??

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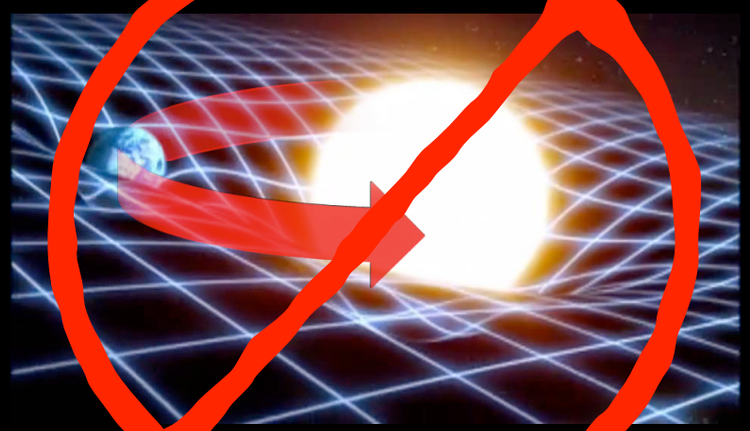


Modified Gravity

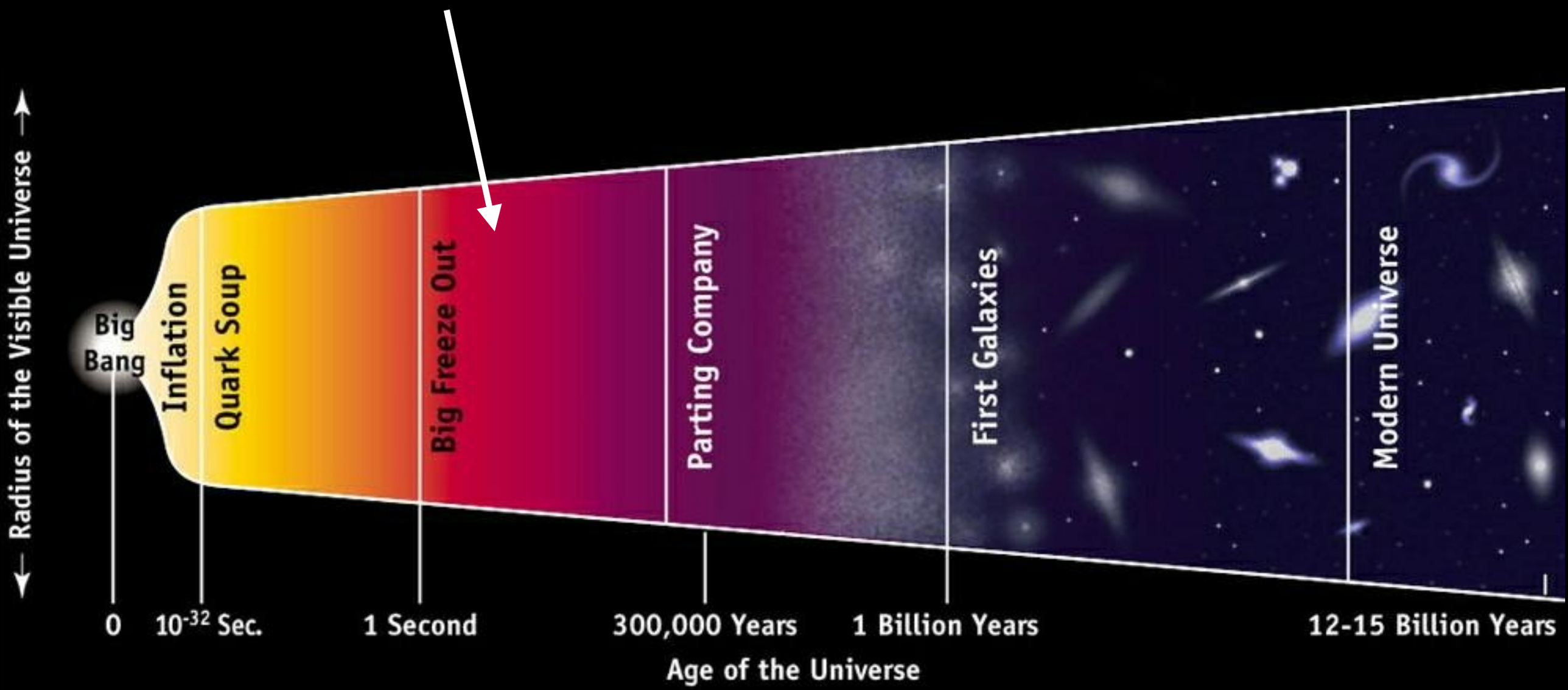
??

New Particle

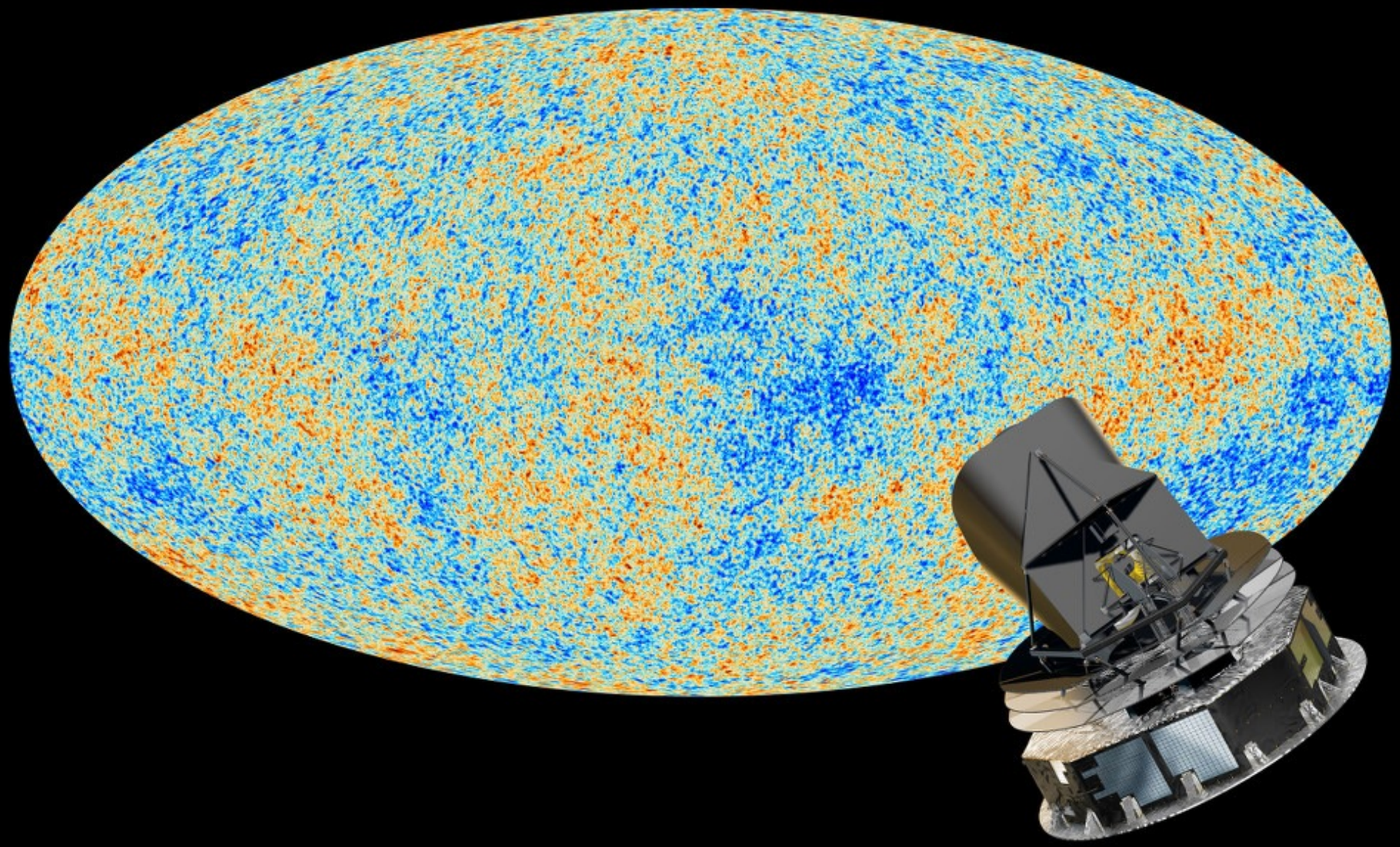
The “simplest” explanation seems to be:

dark matter is a **new subatomic particle**

Dark matter has been around since the very beginning of the universe, earlier than the first few minutes.



There is on average **6 times more mass in dark matter** than in protons and neutrons.



Cosmic Microwave Background Radiation observed by Planck satellite

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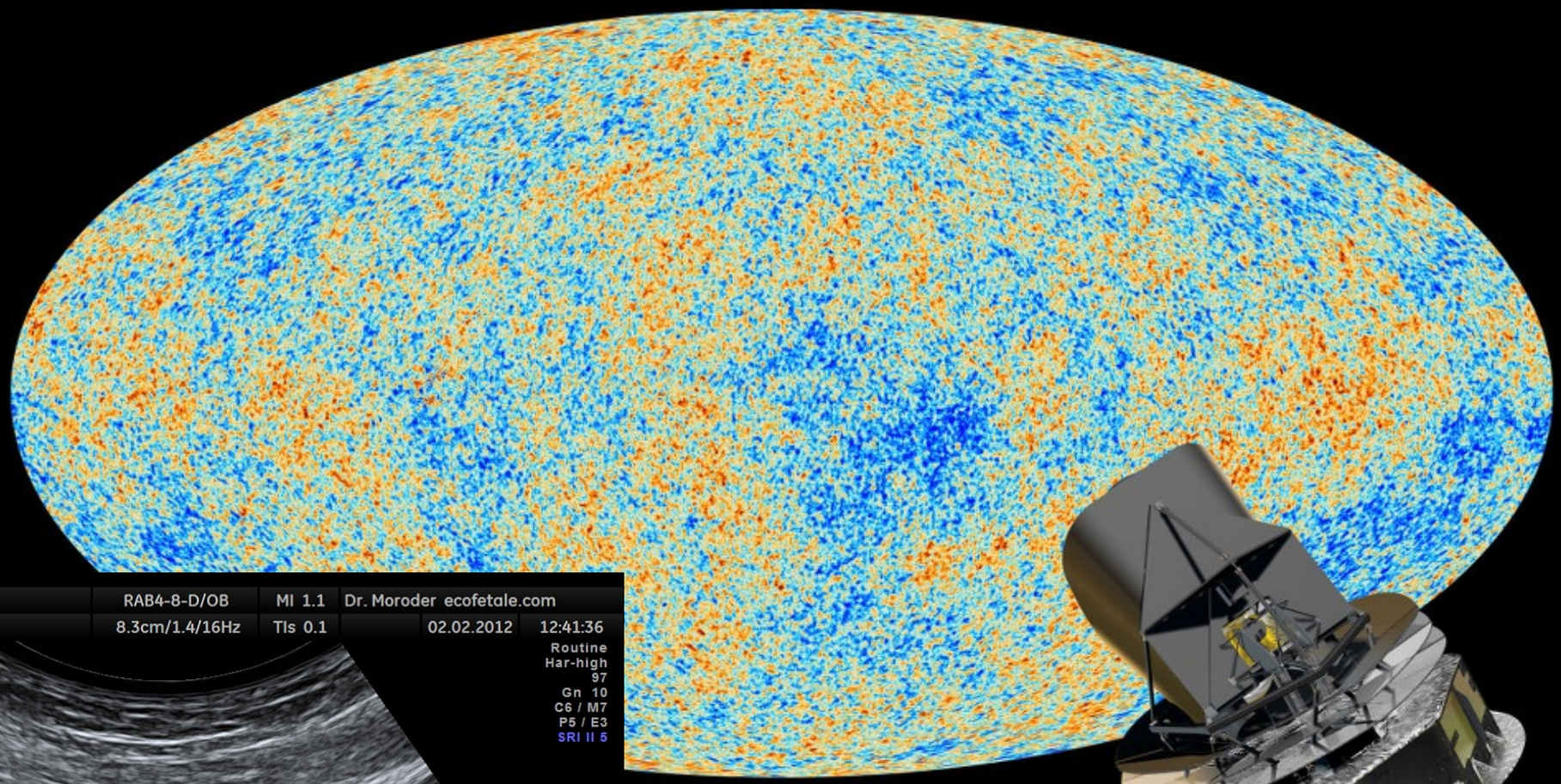
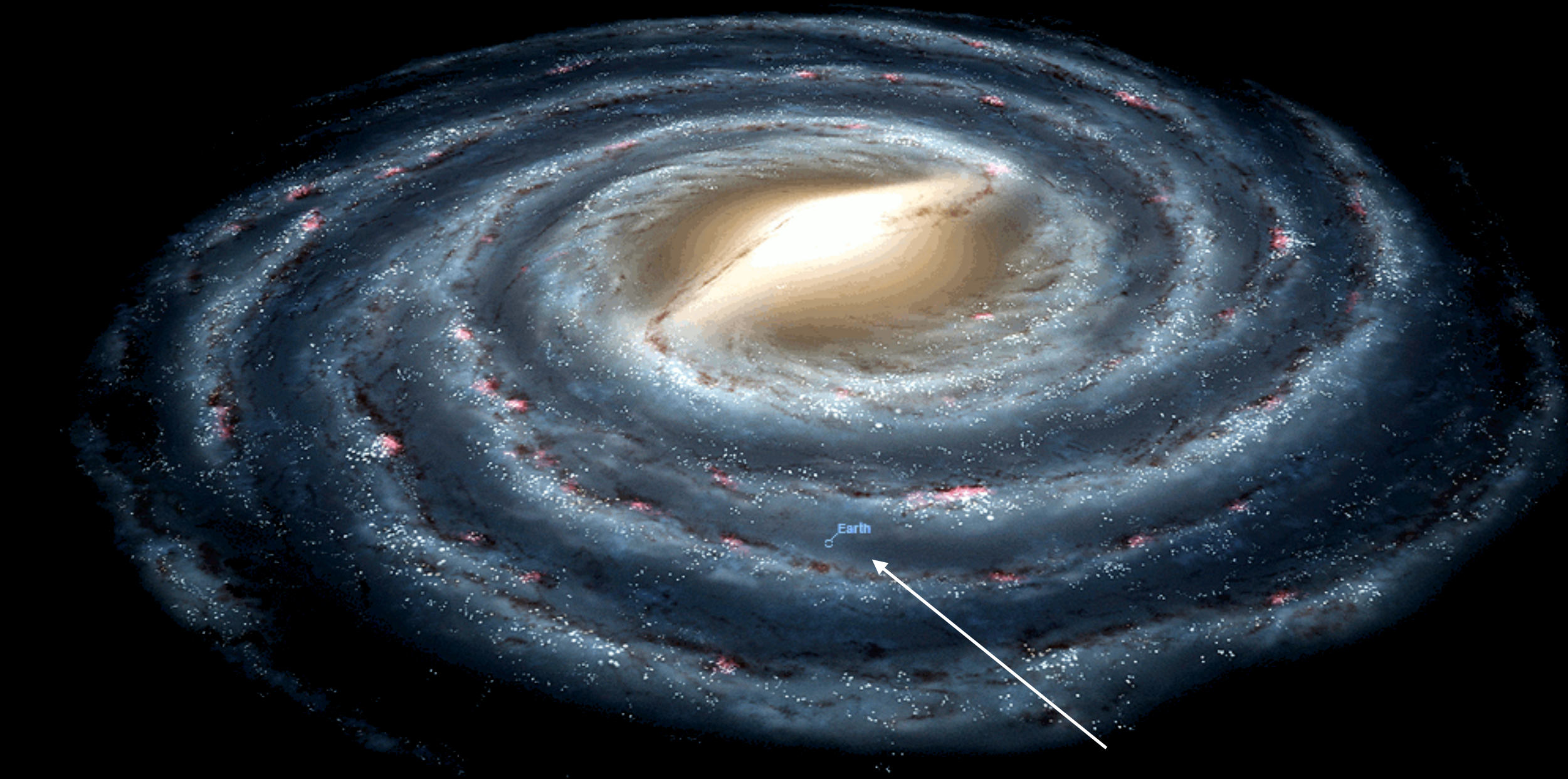


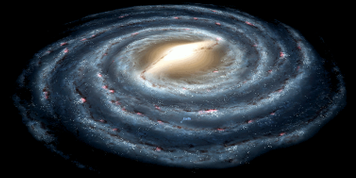
Cosmic Microwave Background Radiation observed by Planck satellite

Dark matter is responsible for the structures (galaxies) we see today.

Milky Way (Artist's Rendition):



Galaxies sit inside much larger **dark matter halos**



Aquarius simulation

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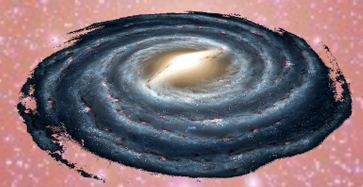


Aquarius simulation

Dark matter has mass and influences us through gravity.

- Does dark matter do anything else?
- Where did the dark matter come from?

These are questions we hope to answer within the framework of fundamental particle physics.

Properties of particles

- **Mass**

  A proton is about 2000 times heavier than an electron

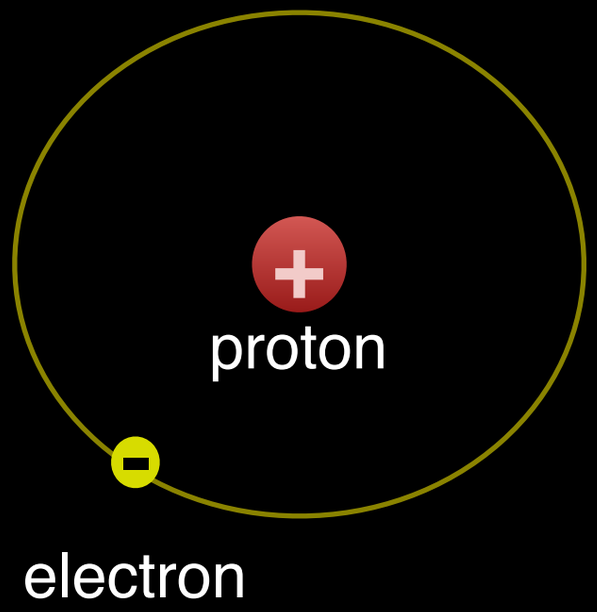
- **Interactions with other particles**

  Protons and electrons have opposite charge

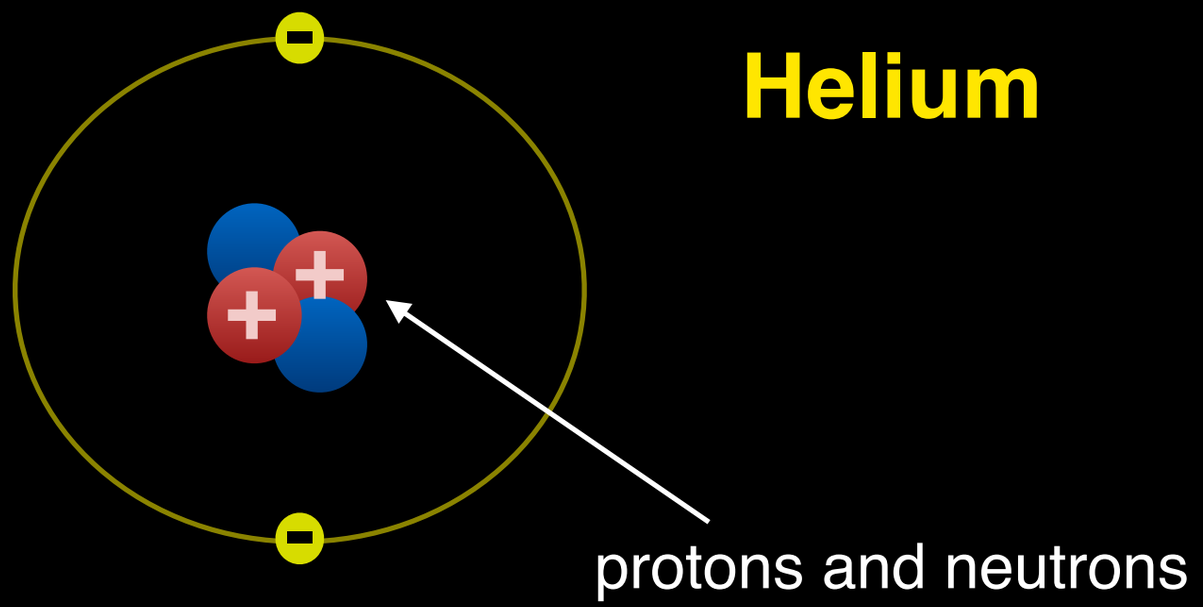
- **Spin**

  A proton has different spin from a photon (light)

Hydrogen atom



Helium



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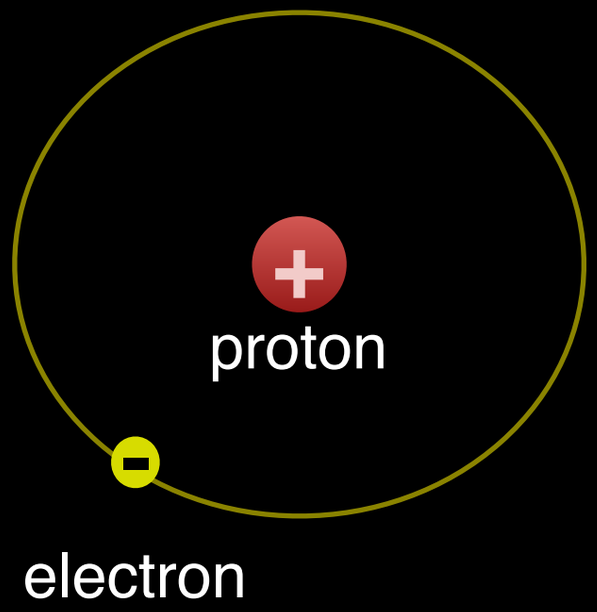

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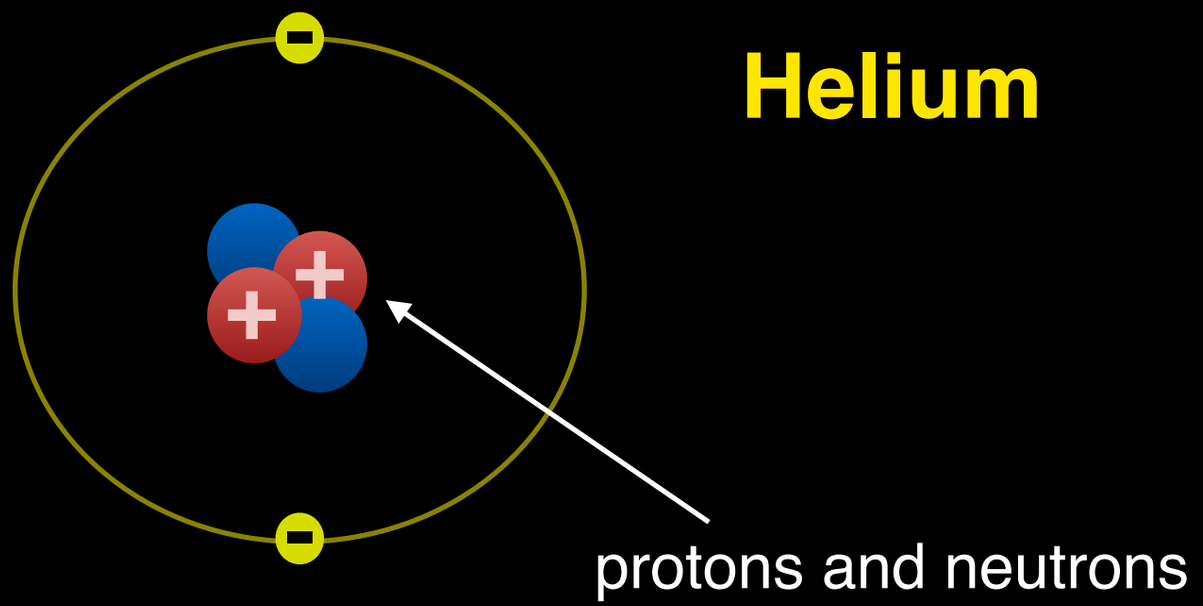
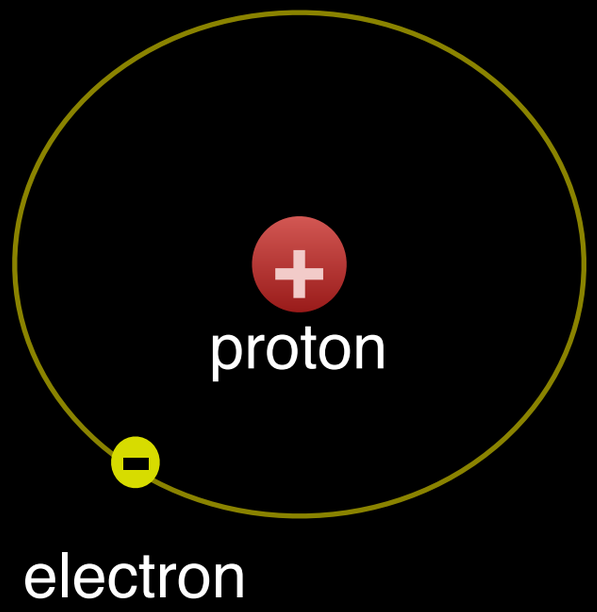


There is even more structure inside protons and neutrons:

Hydrogen atom



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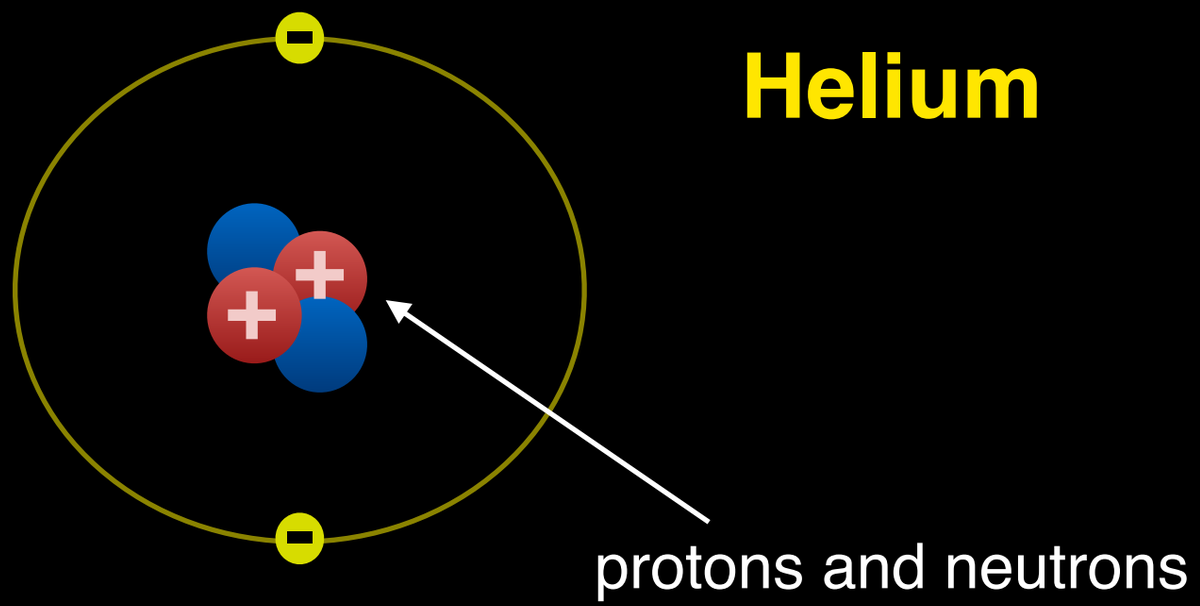

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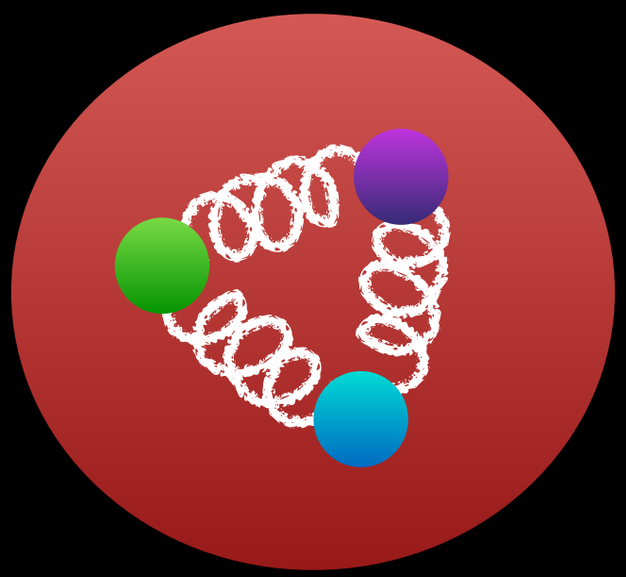

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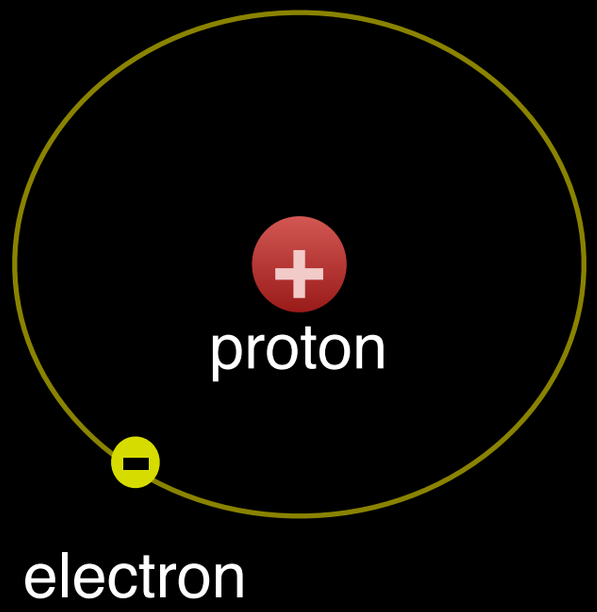

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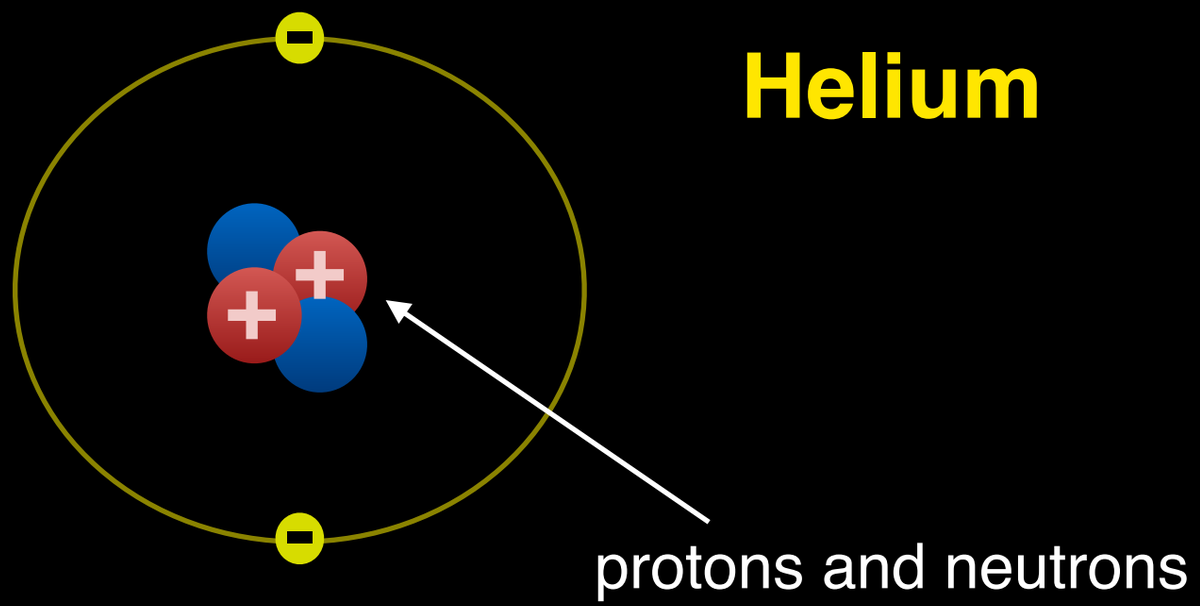

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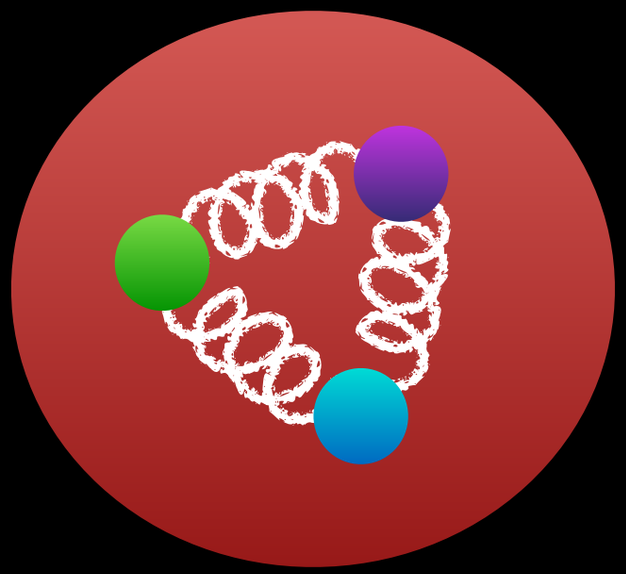
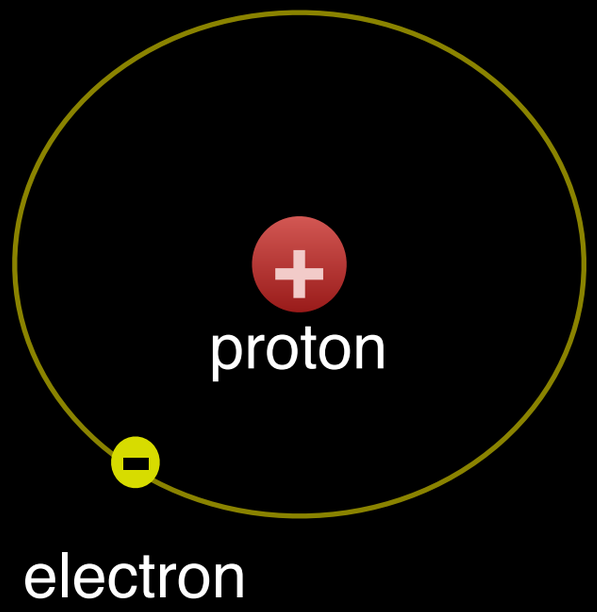


New particles: QUARKS

Hydrogen atom



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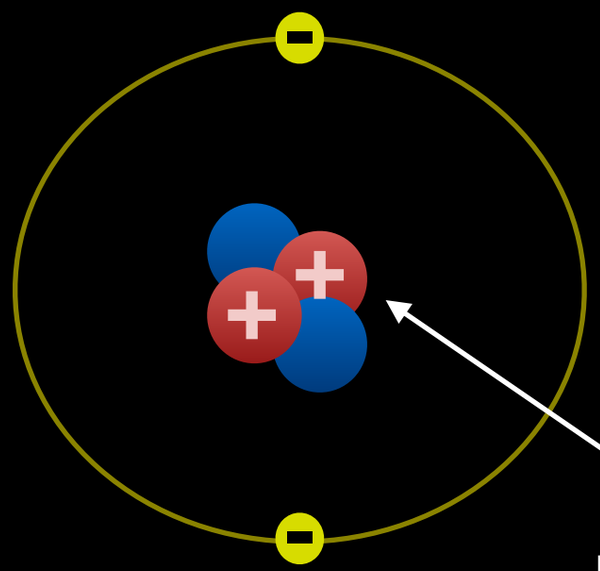

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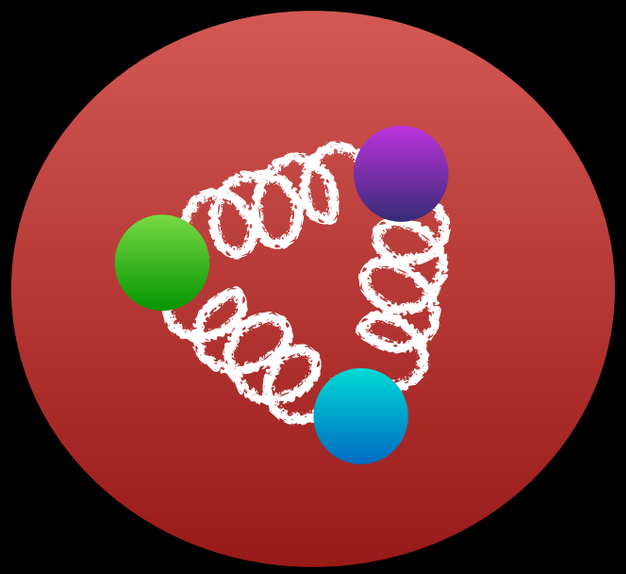


New particles: QUARKS

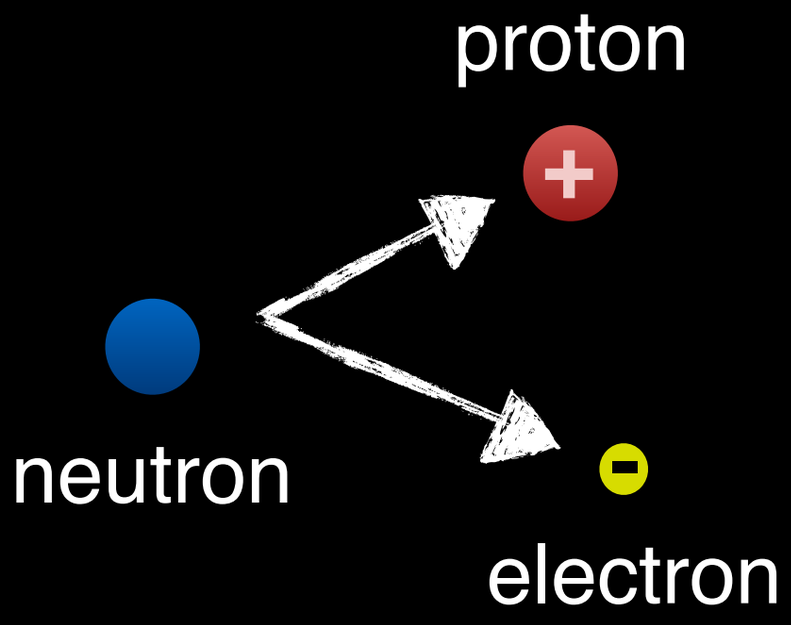
New forces: STRONG FORCE

Only two kinds of quarks are found in protons and neutrons.

We have found FOUR other quarks
at particle accelerators.

Electrons also have heavier cousins:

Another class of particles, **neutrinos**, was proposed by Enrico Fermi to solve a different “missing matter” problem.



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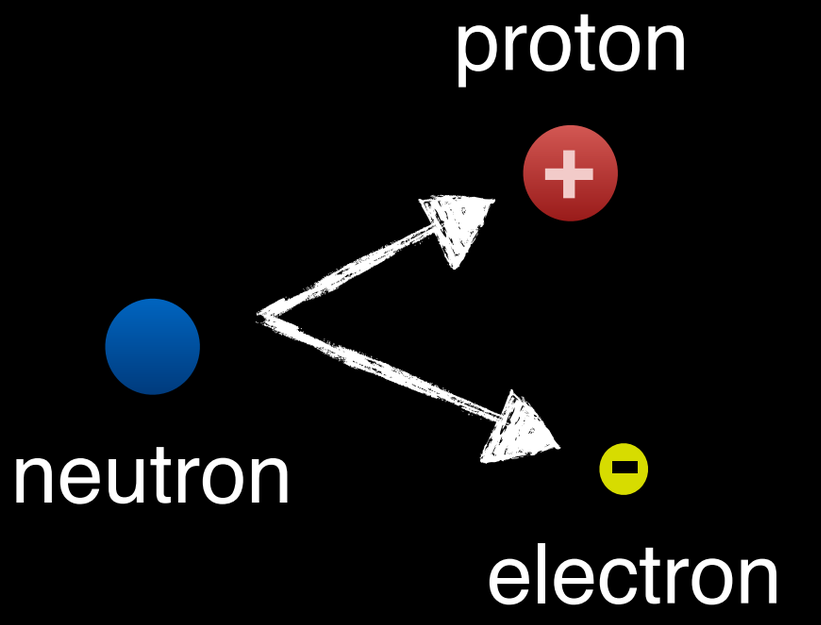

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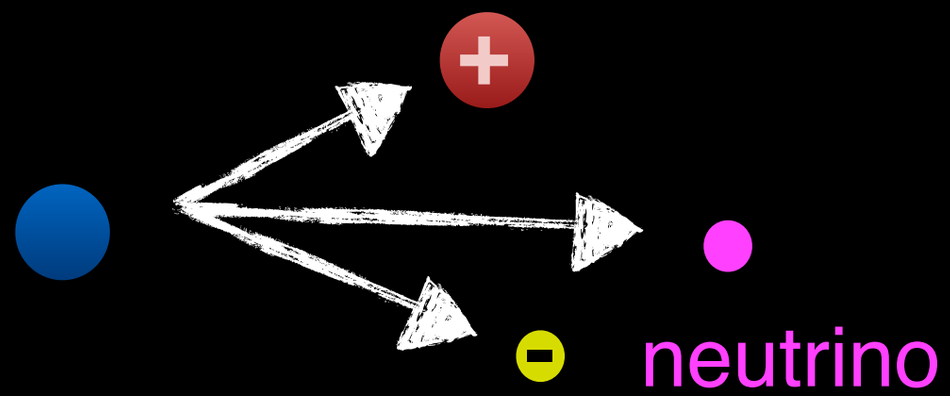


Solution: “Extra” energy carried off by new particle, the neutrino

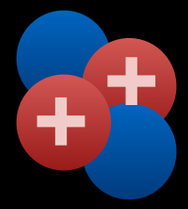
Forces

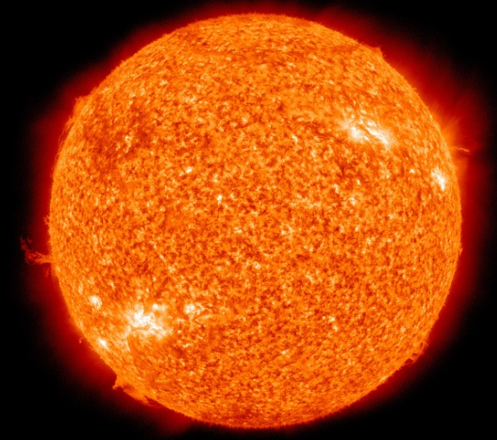
ELECTROMAGNETISM

GRAVITY

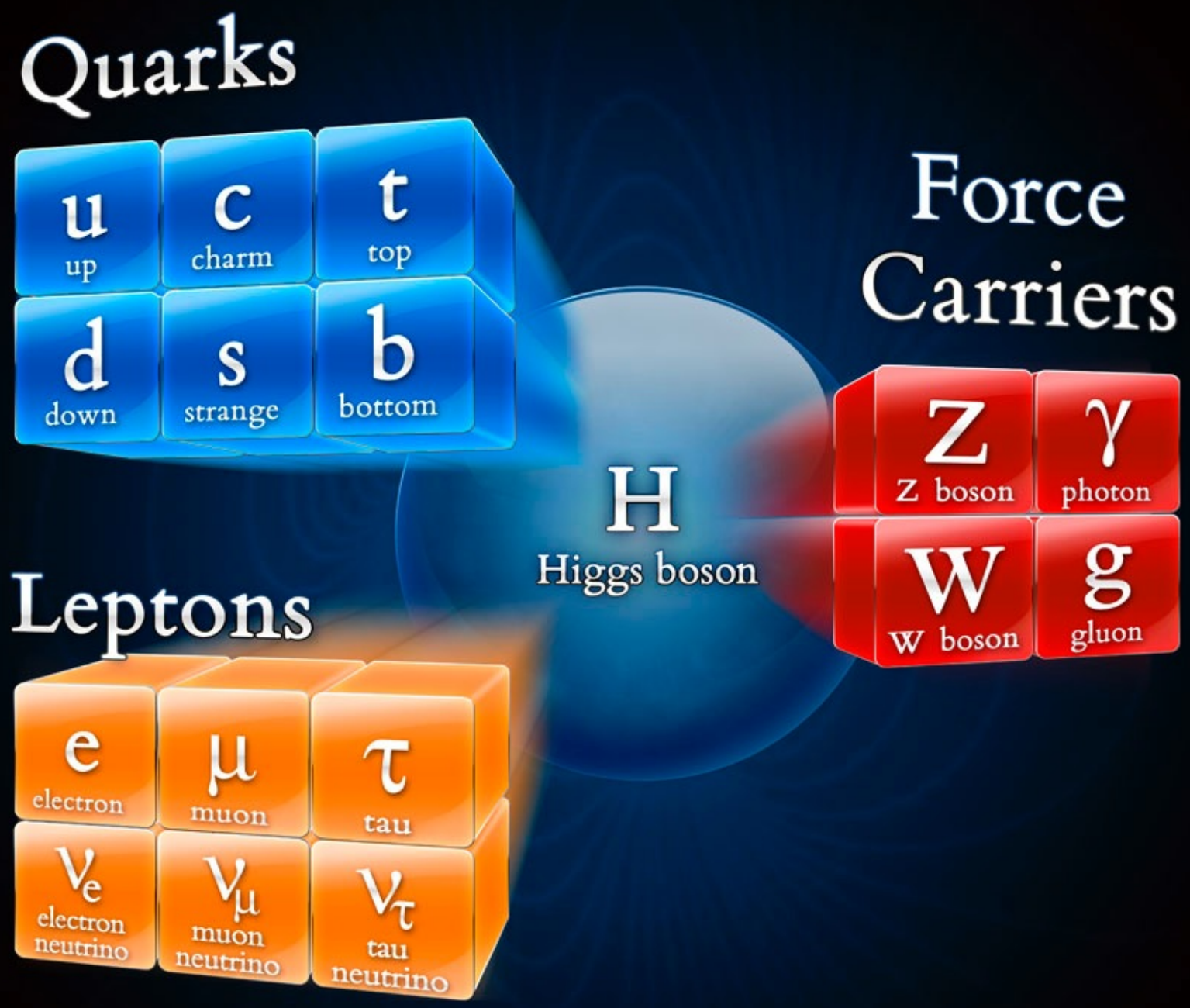
STRONG

WEAK
(NUCLEAR)





The Standard Model of Particle Physics



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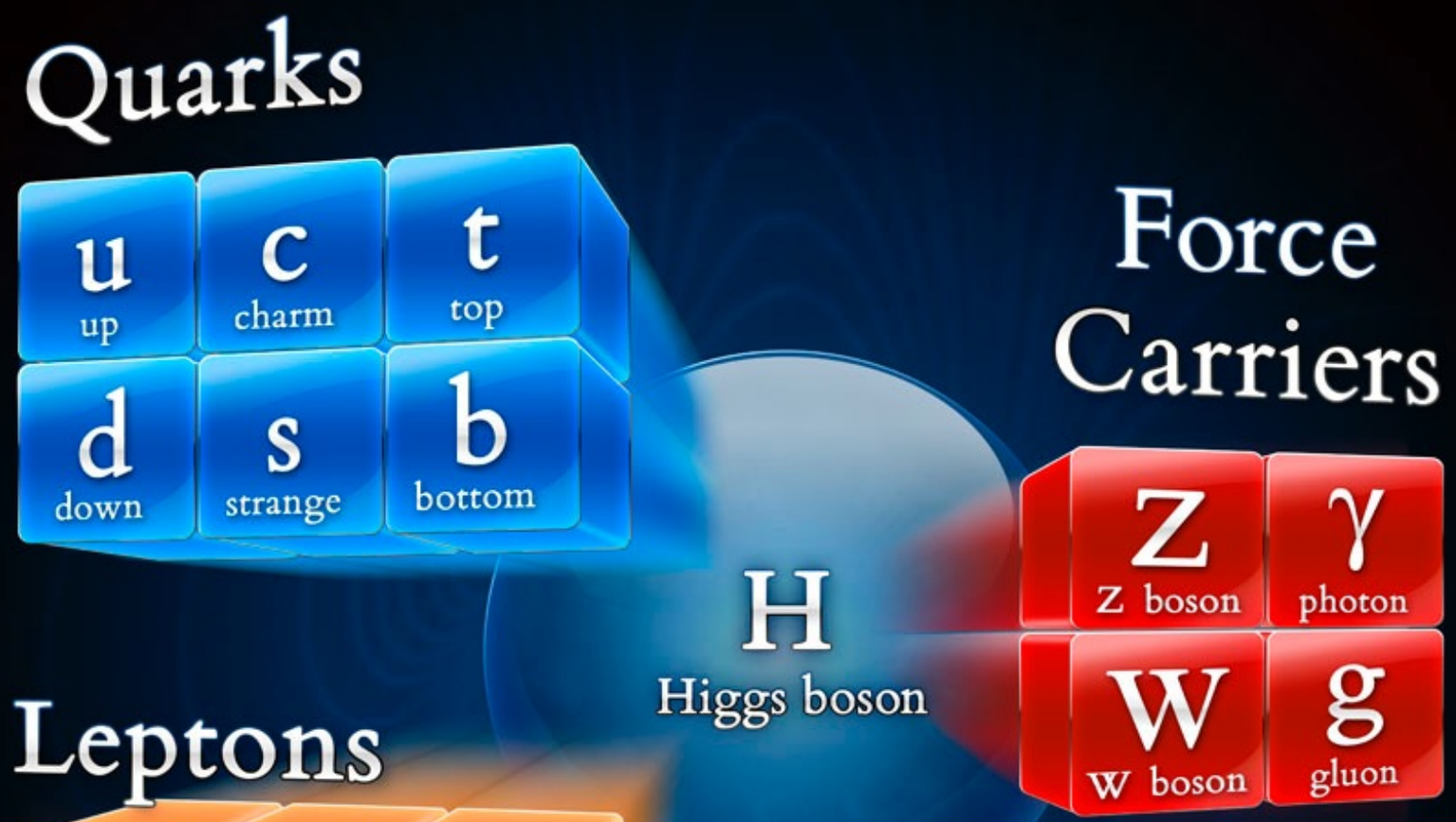


(plus Gravity)

Higgs

Englert

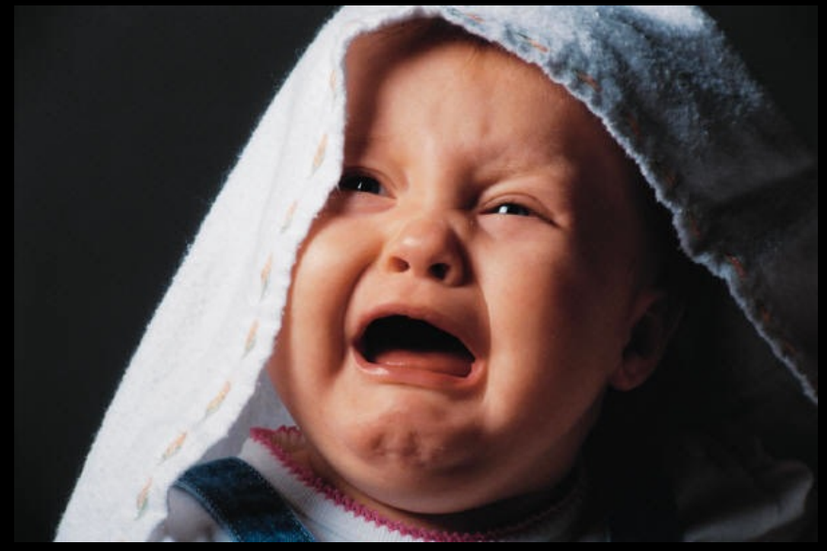
Dark Matter Candidates

- One of the leading candidates is a

WIMP - Weakly Interacting Massive Particle

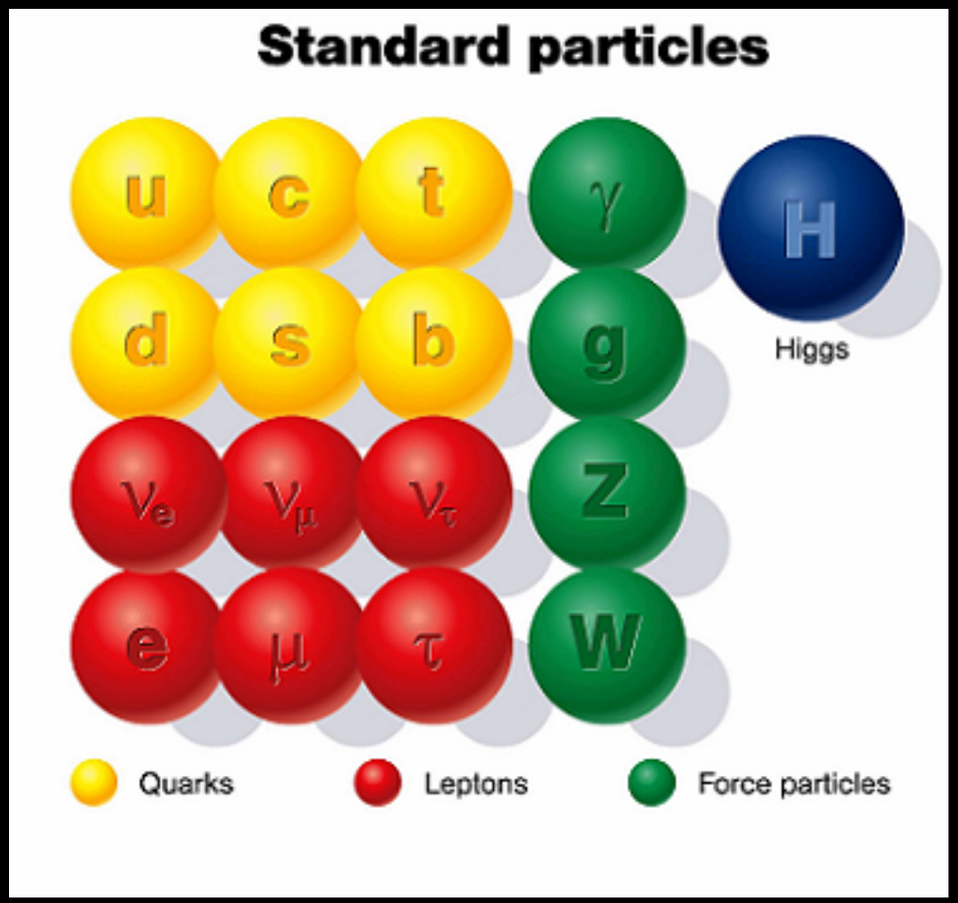
- MANY others:

— Axion
— Sterile Neutrino
— Gravitino
— CHAMPs, SuperWIMPs, WIMPzillas, SuperWIMPzilla??!!!



Supersymmetry

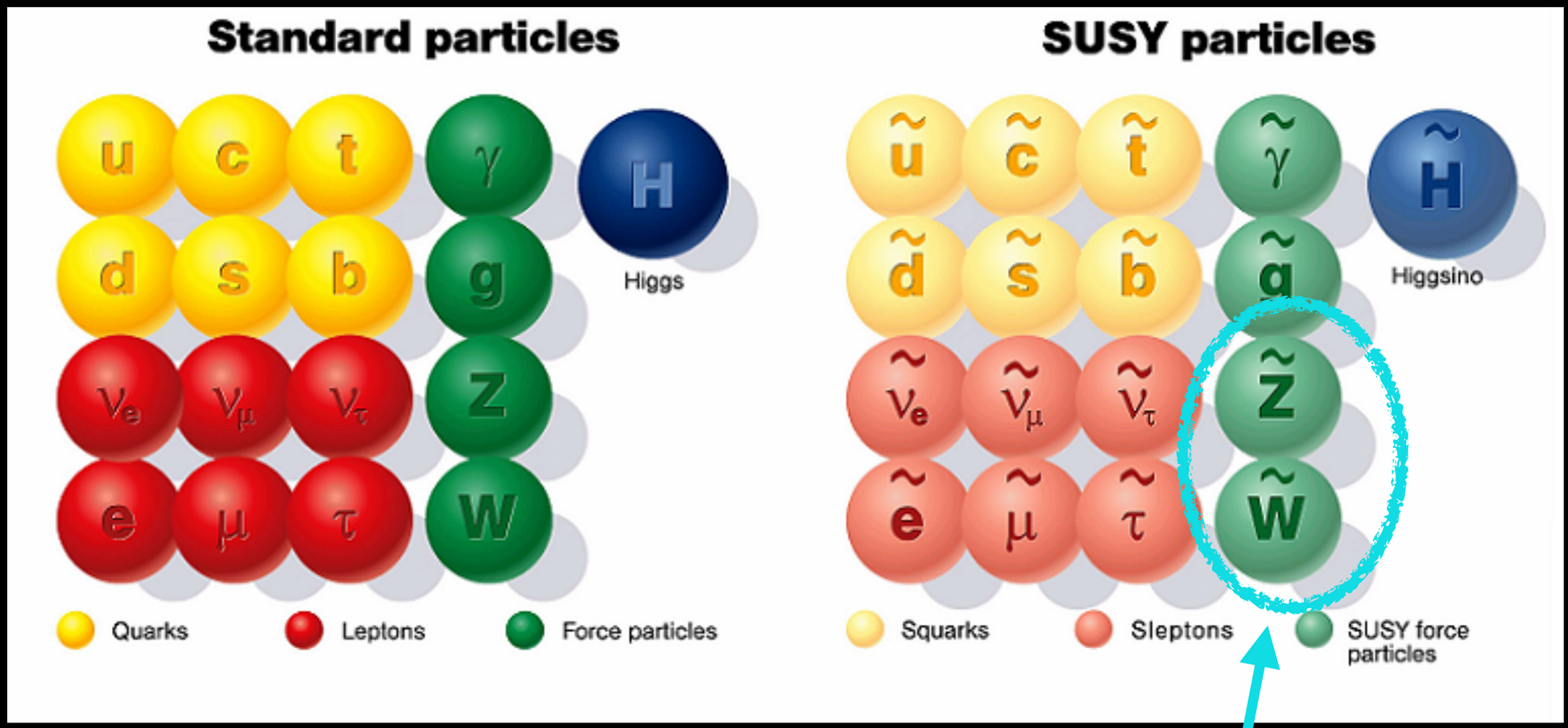
Known particles



Supersymmetry

Known particles

New supersymmetric particles



WIMP candidates

So we look for WIMPs

- A few billion just passed through us, and we might expect a handful of counts in a detector per year

- The problem is that low level radioactivity is everywhere!

100 events/second/kg =
3,000,000,000,000 events/year
in a ton-scale experiment

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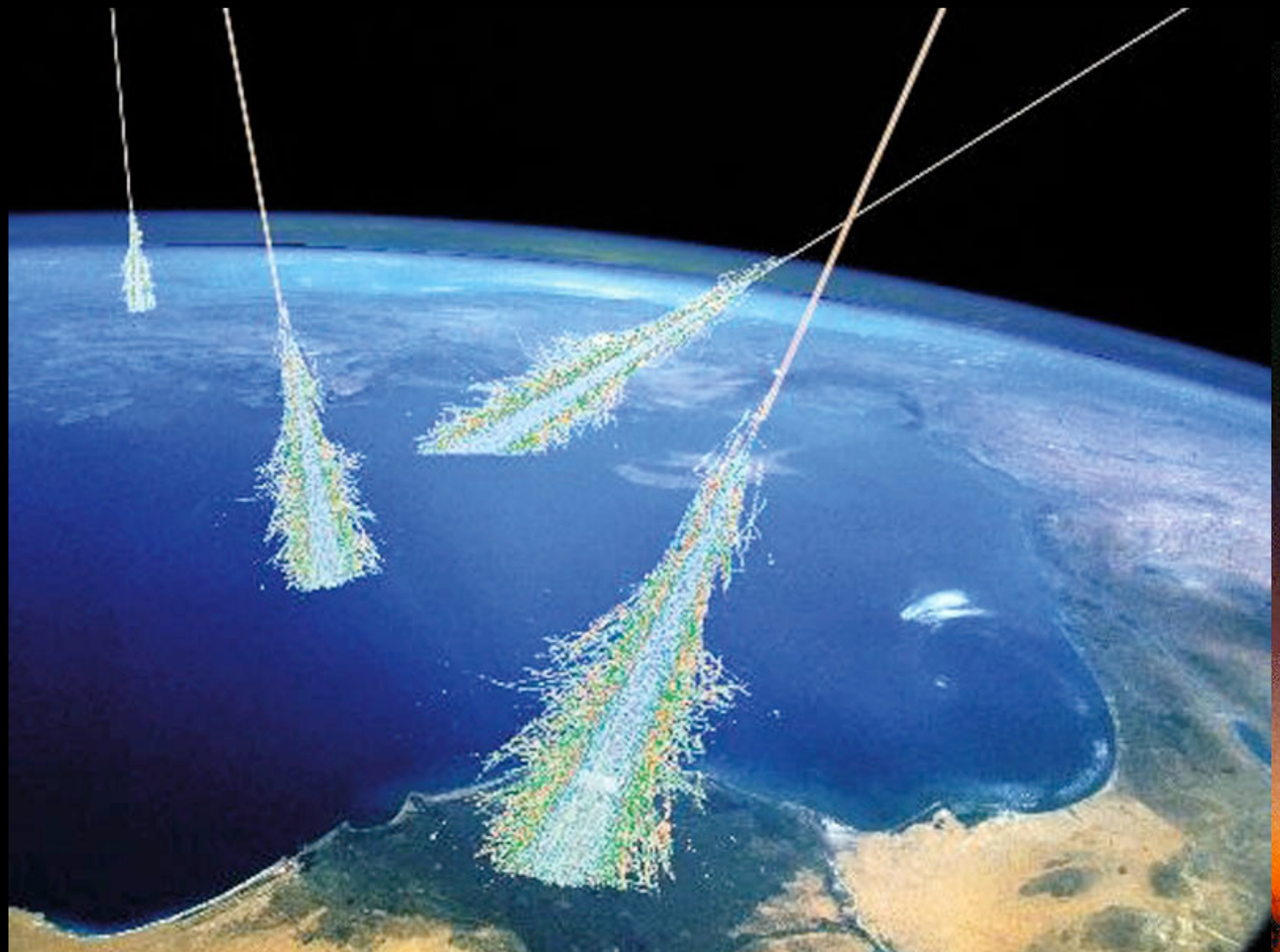
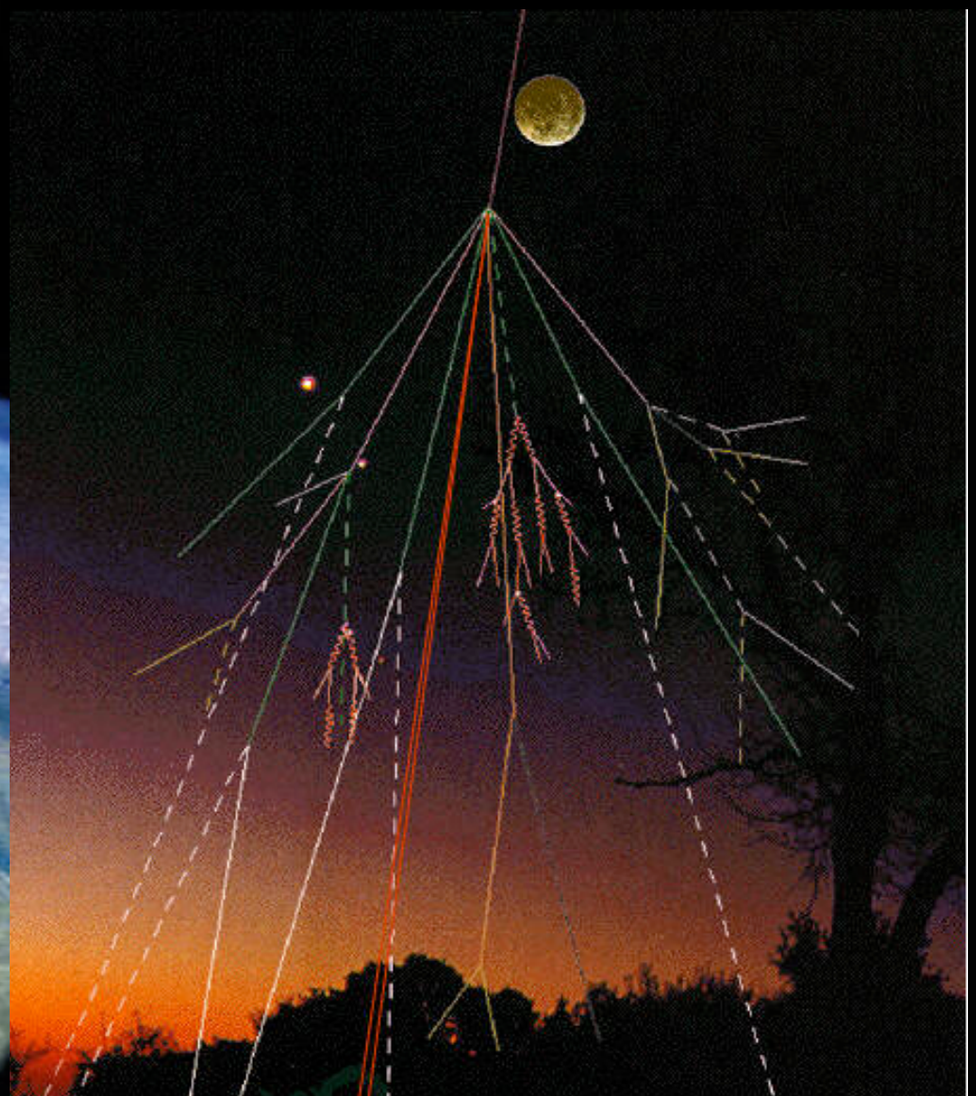
Backgrounds!

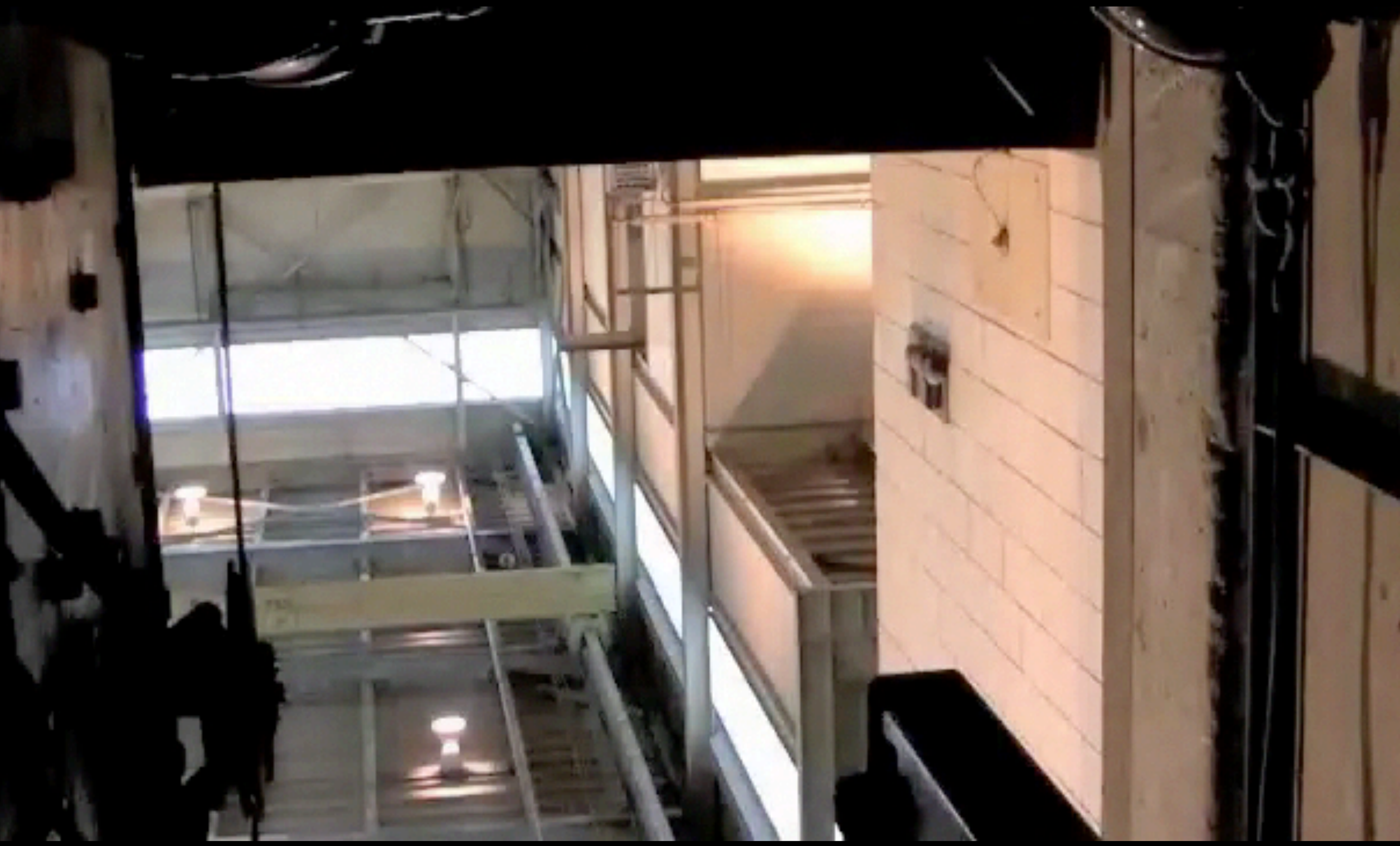
Background sources

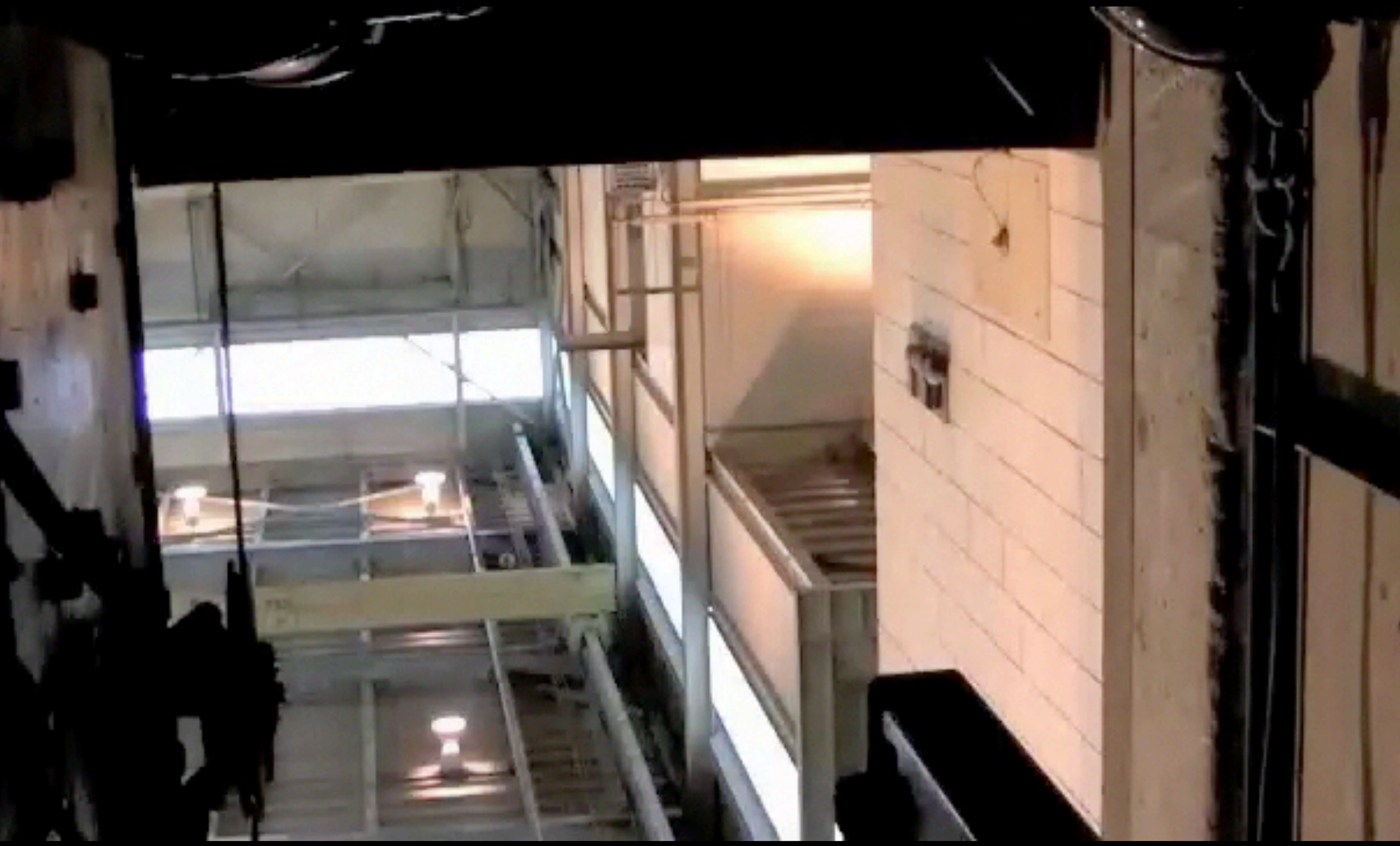
- Cosmic rays are highly energetic particles coming from space that are always streaming through

  - All experiments are underground







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Background sources

- Radioactive contaminants - rock, radon in air, impurities
- Emphasis on purification, everything must be clean

Background sources

- The detector itself - steel, glass, detector components
  - Can you use the signal you observe in the detector to separate dark matter from backgrounds?

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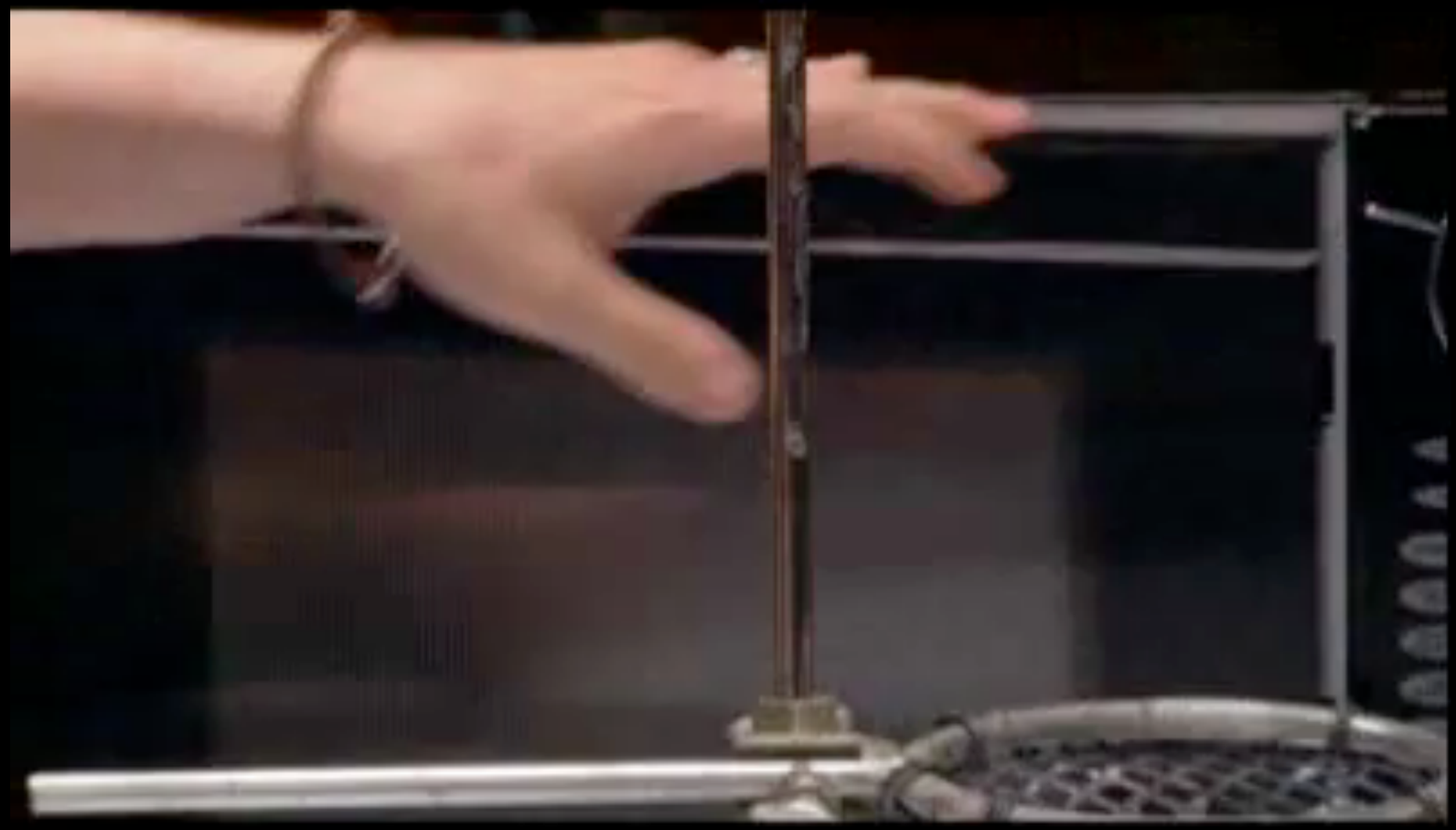
Bubble Chambers!

Bubble chambers

- "Superheated" fluid that wants to boil but has no place to form bubbles



- Radiation can give the fluid the energy needed to make those bubbles

Bubble chambers

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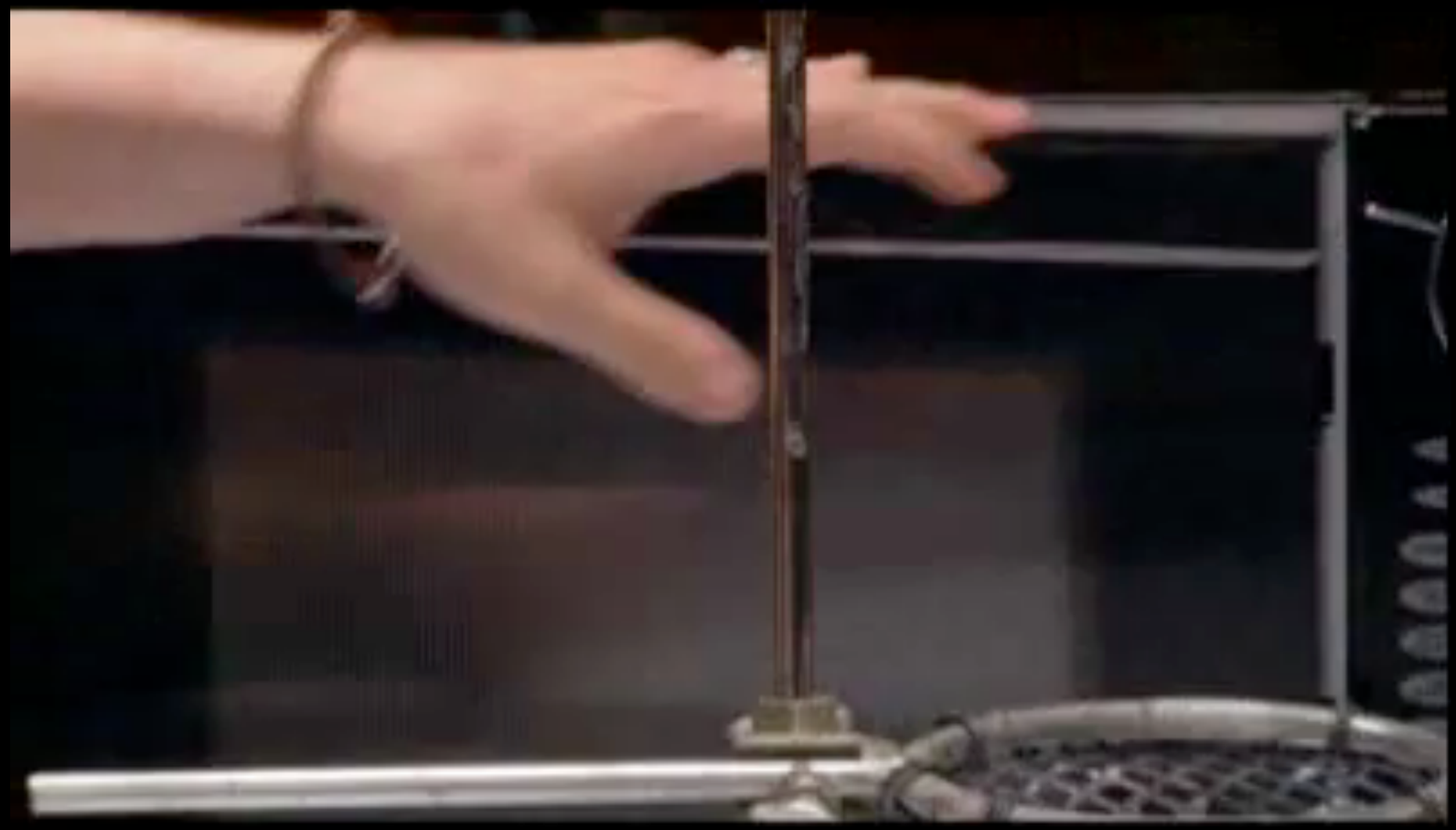
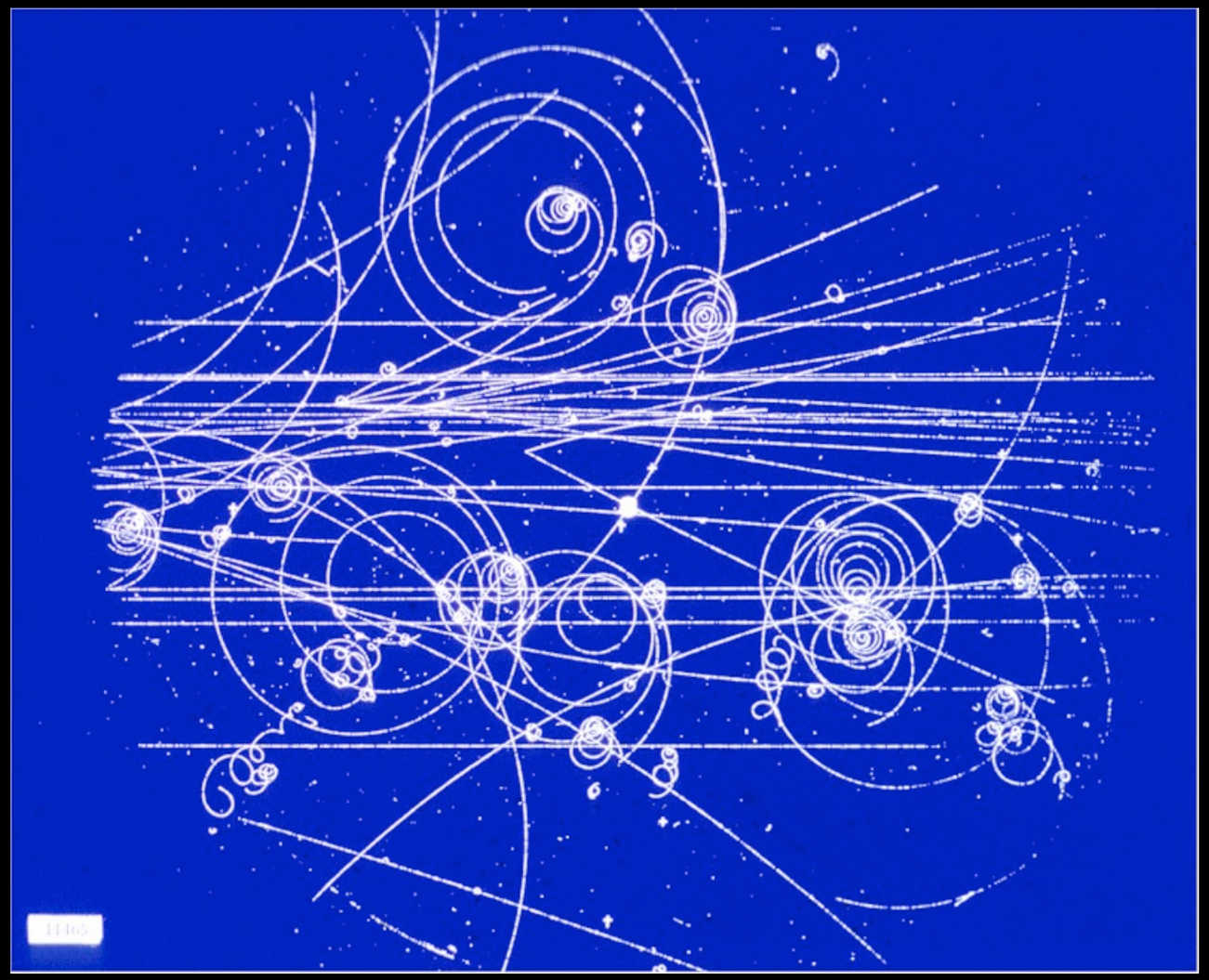


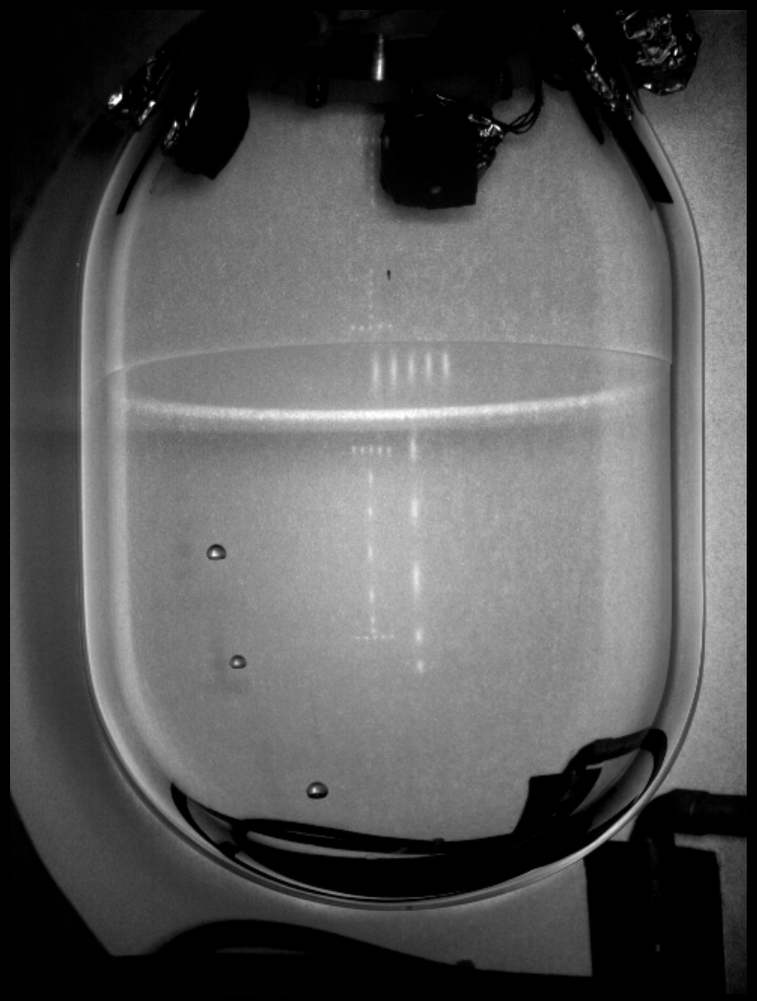
- Radiation can give the fluid the energy needed to make those bubbles

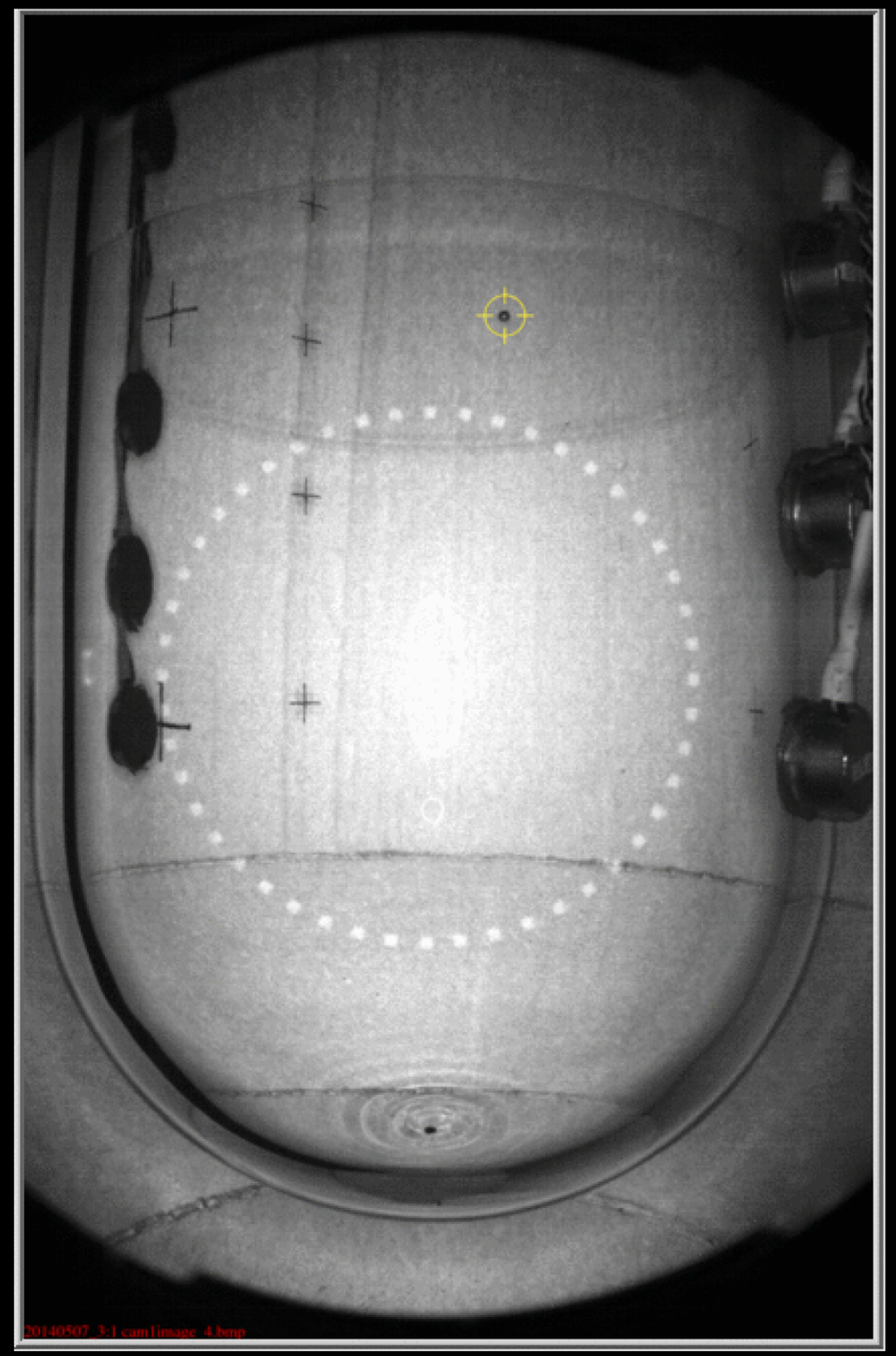
Bubble chambers have an illustrious history in particle physics and at Fermilab



The PICO Collaboration

Project In CAnada to Search for Supersymmetric Objects (PICASSO) +
Chicagoland Observatory for Underground Particle Physics (COUPP) = PICO

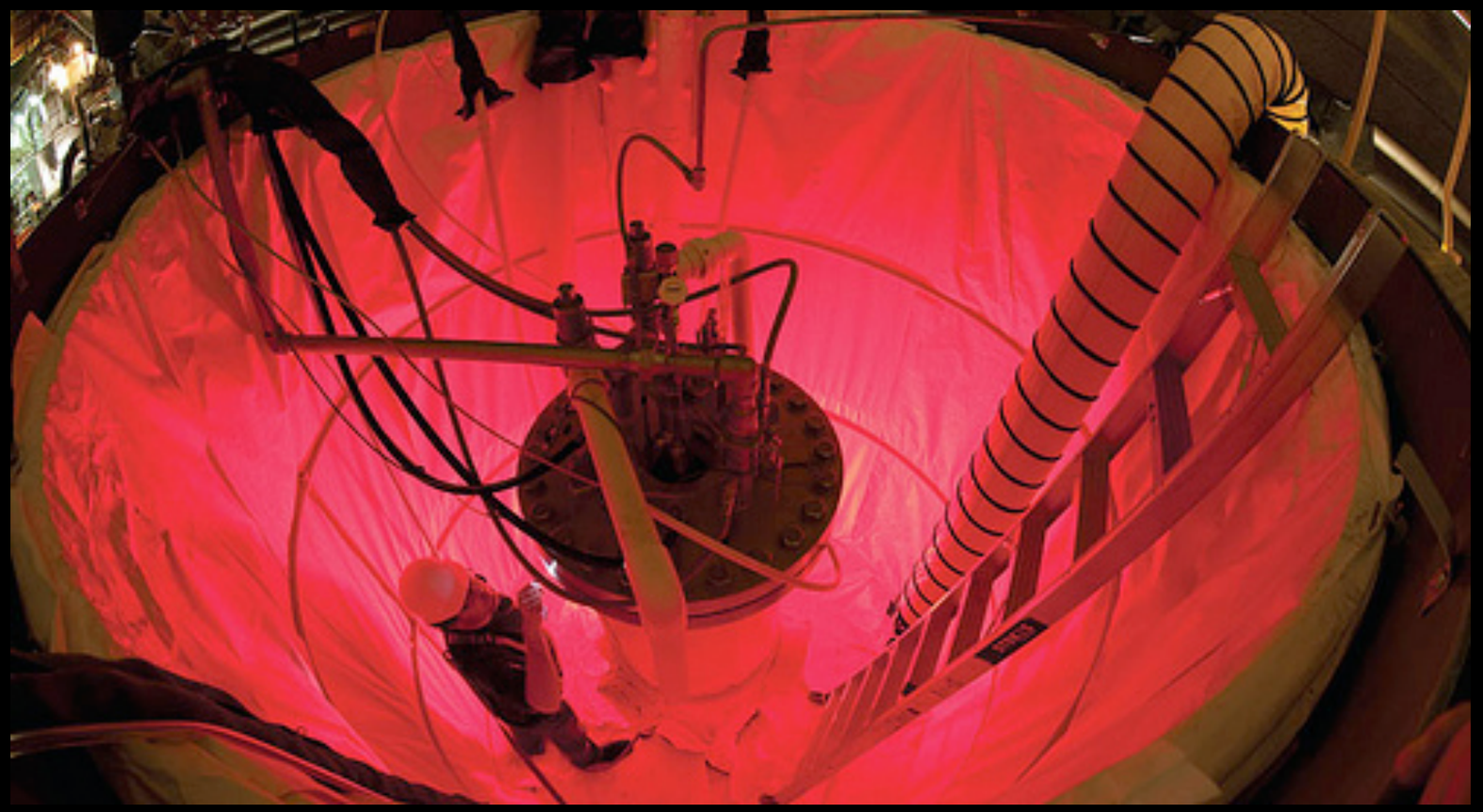




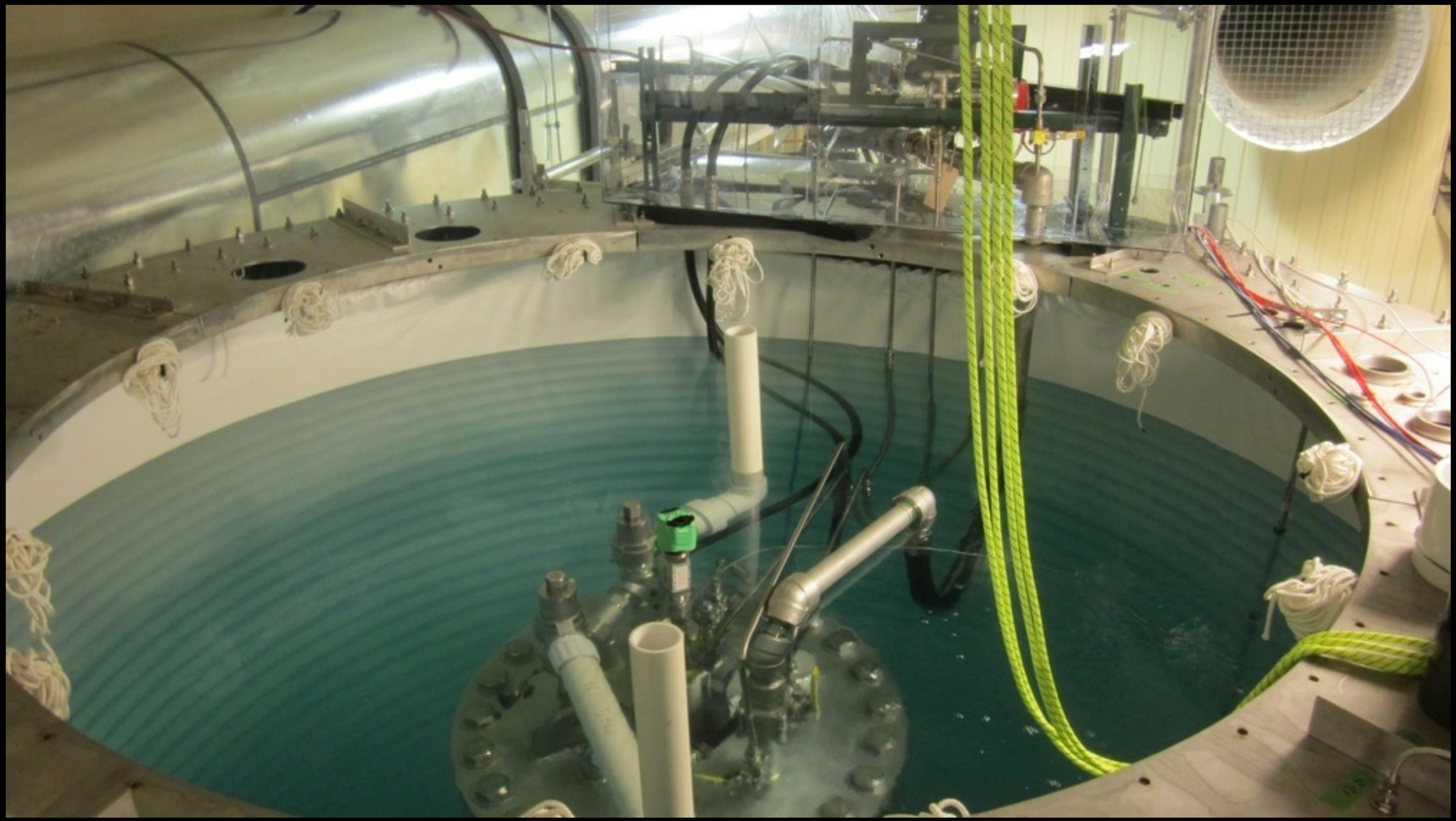
Why bubble chambers for dark matter

- The physics of bubble chambers means that the biggest source of background (after going underground and getting clean) don't make events

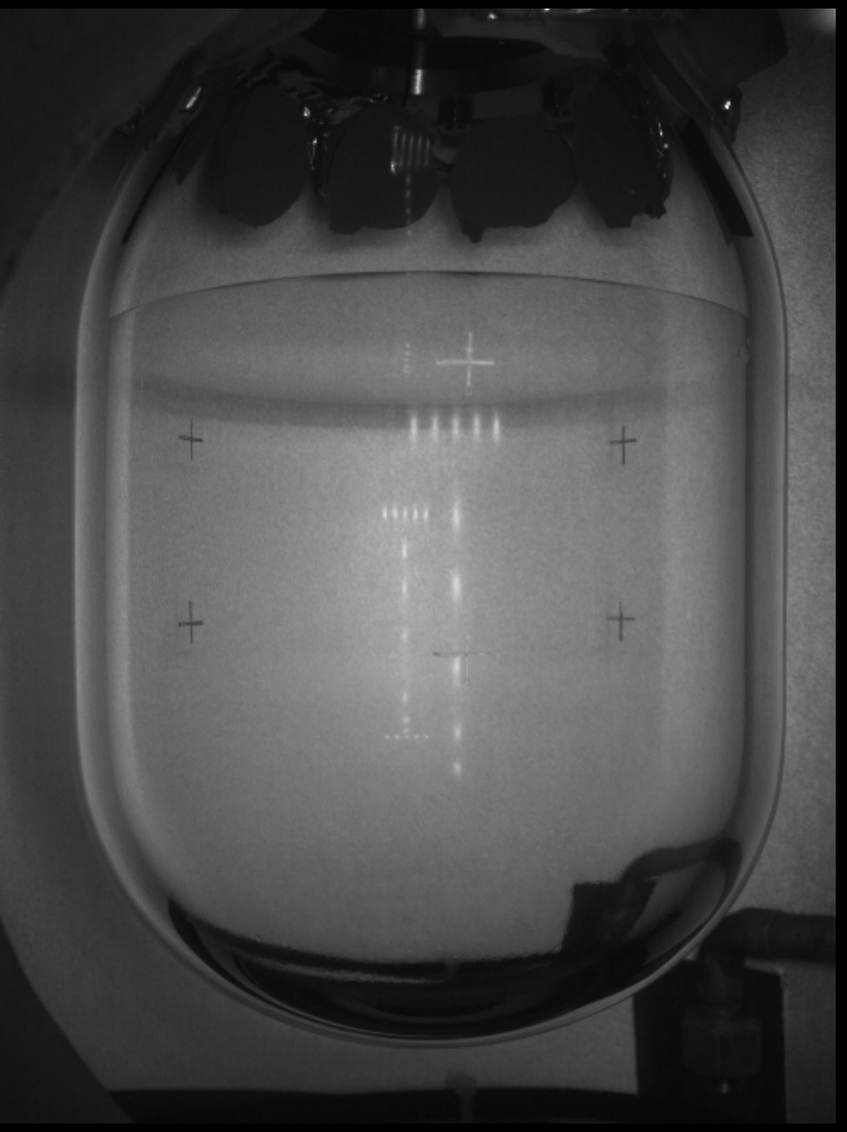
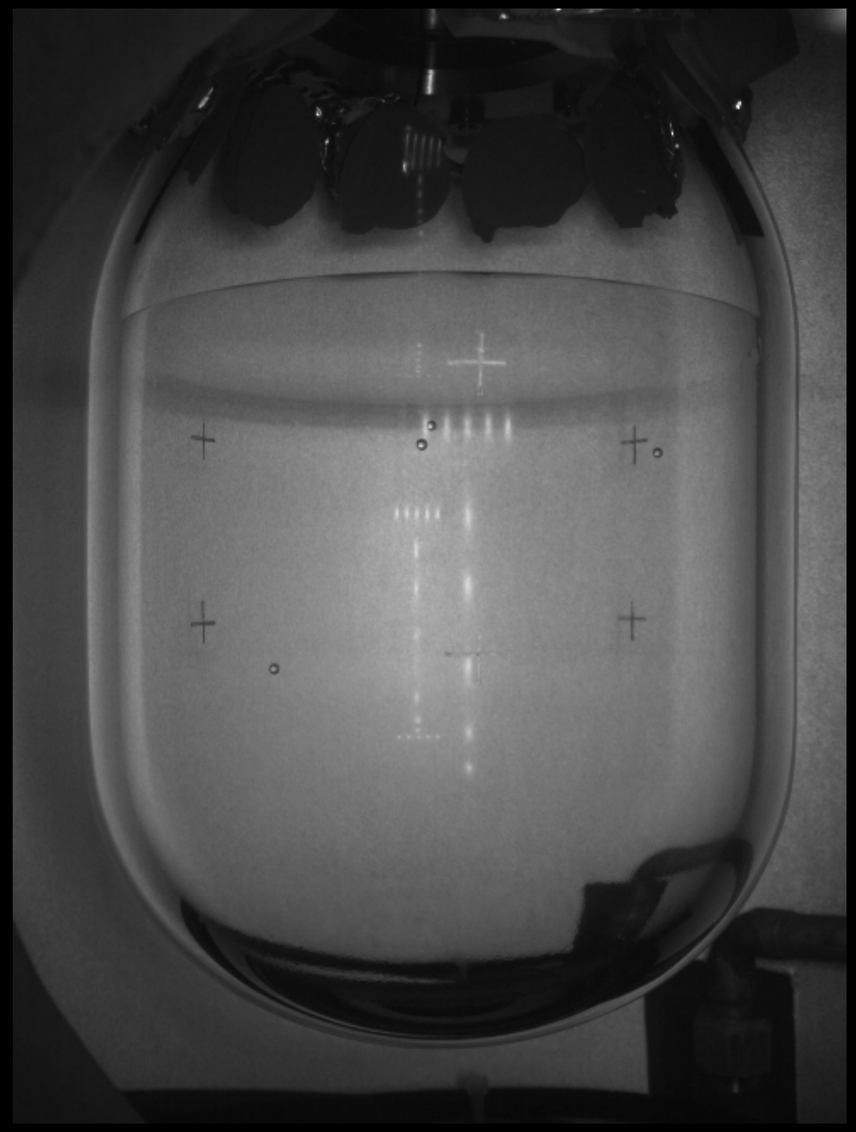
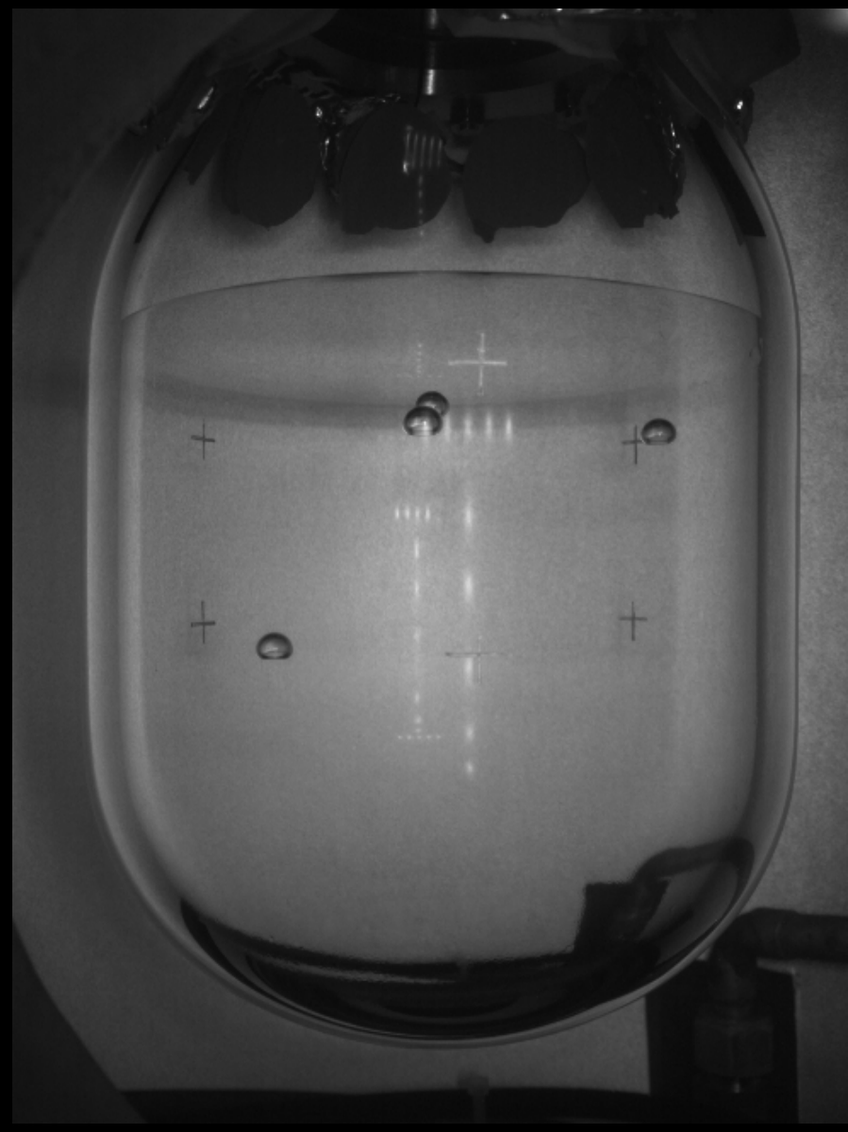
We do not even see the biggest background to most dark matter detectors!

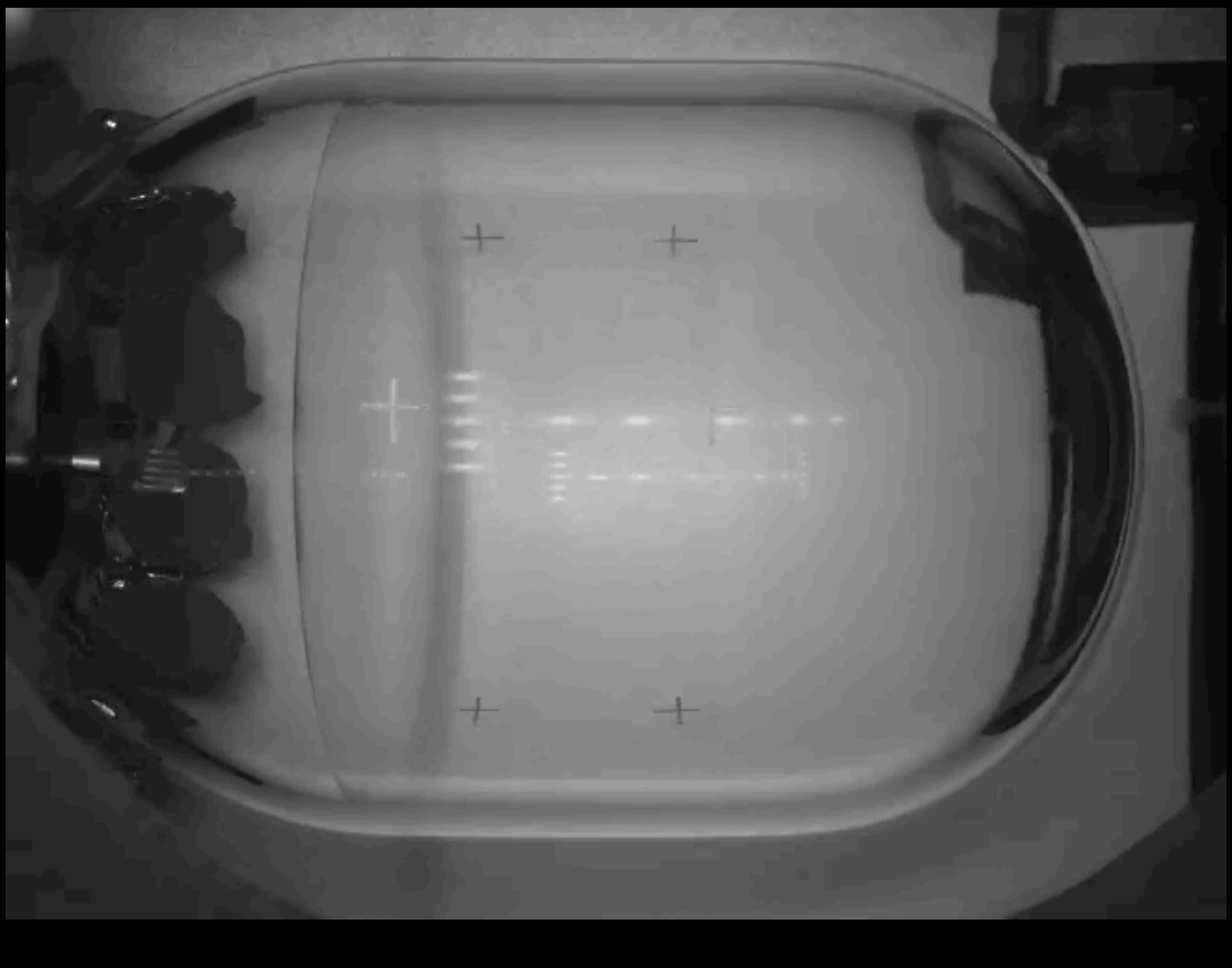


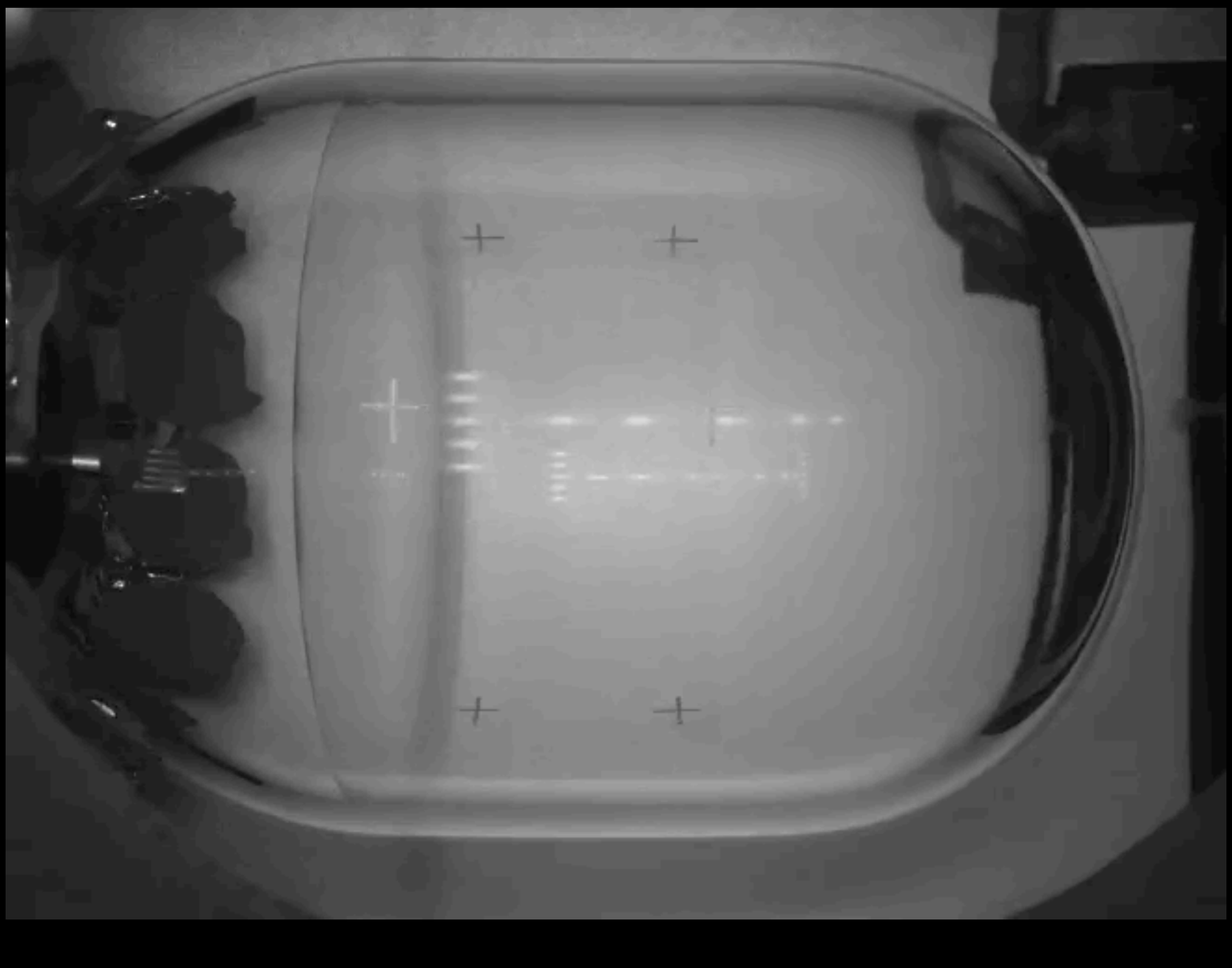

Bell jar



We take pictures

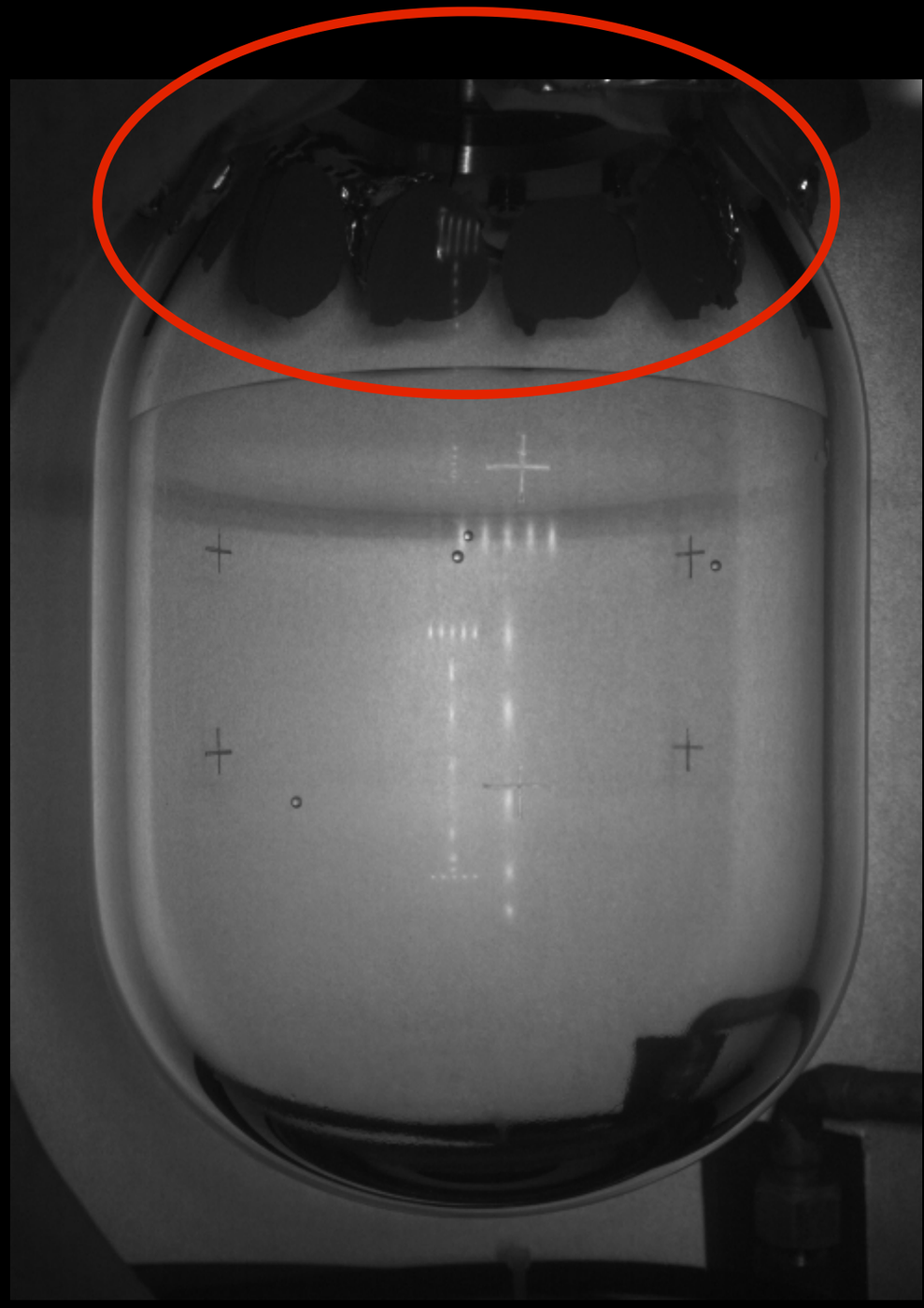








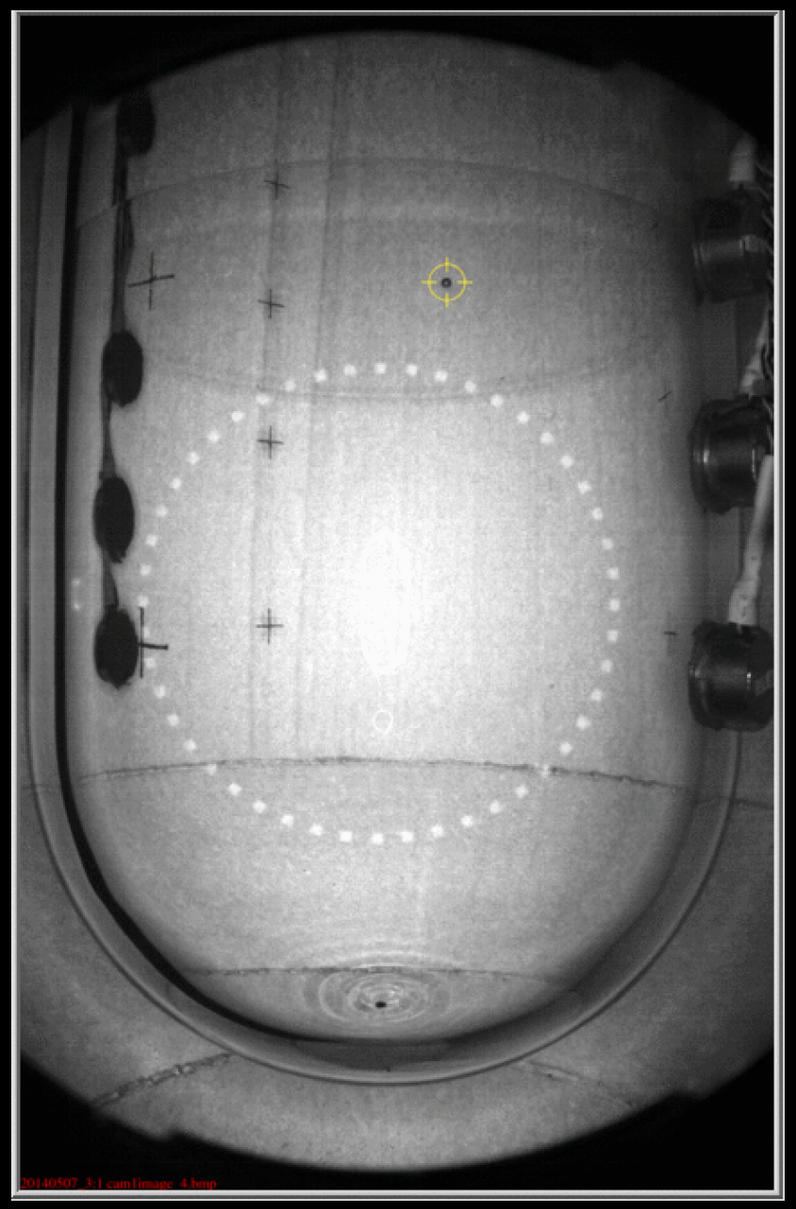
So we're ready to see dark matter?

- Alas, no
- We now see some events that sound like dark matter might
- Radioactive dust?

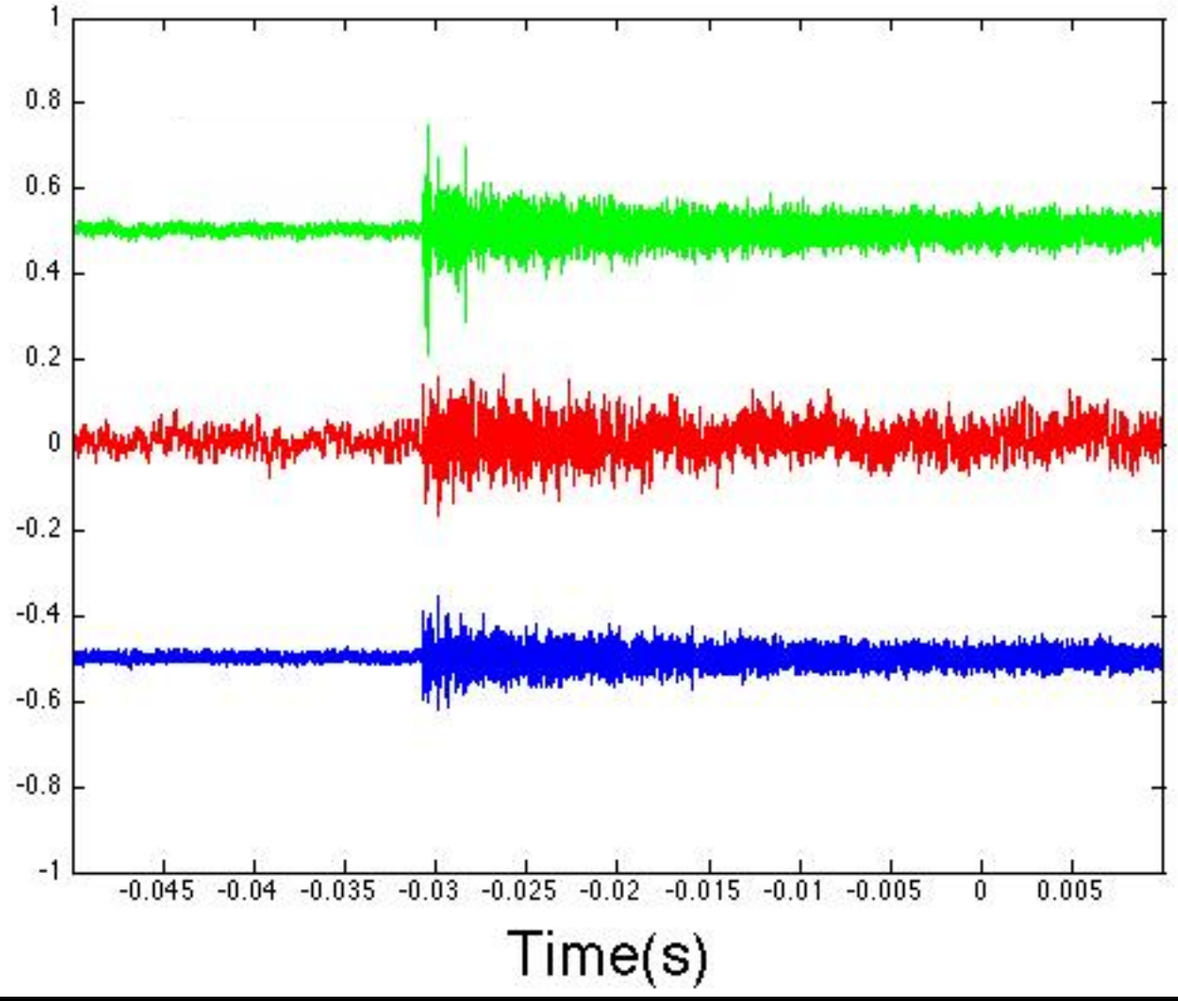


The history of dark matter is digging down into the next level of backgrounds until we see a signal

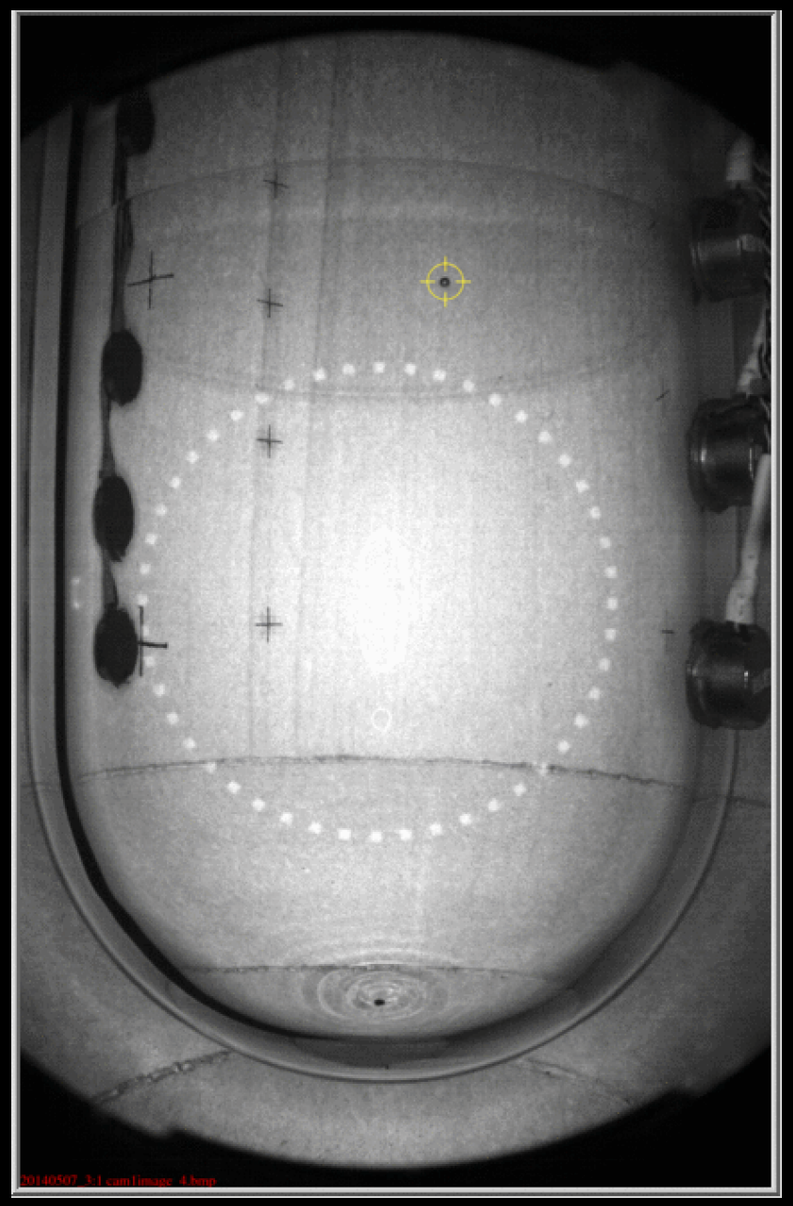
We also listen to the events (some background sources are loud!)

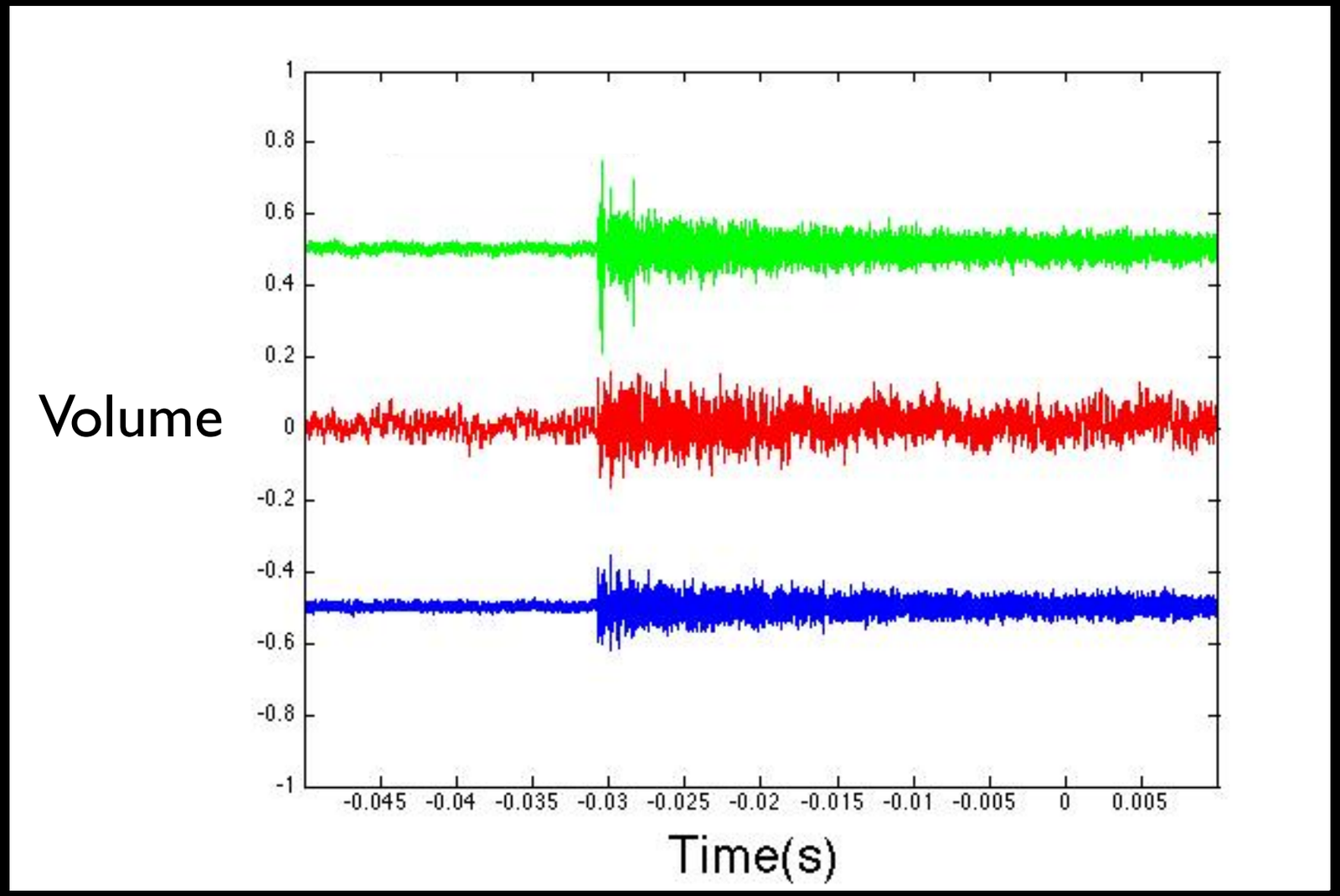


Volume



This is what dark matter would sound like





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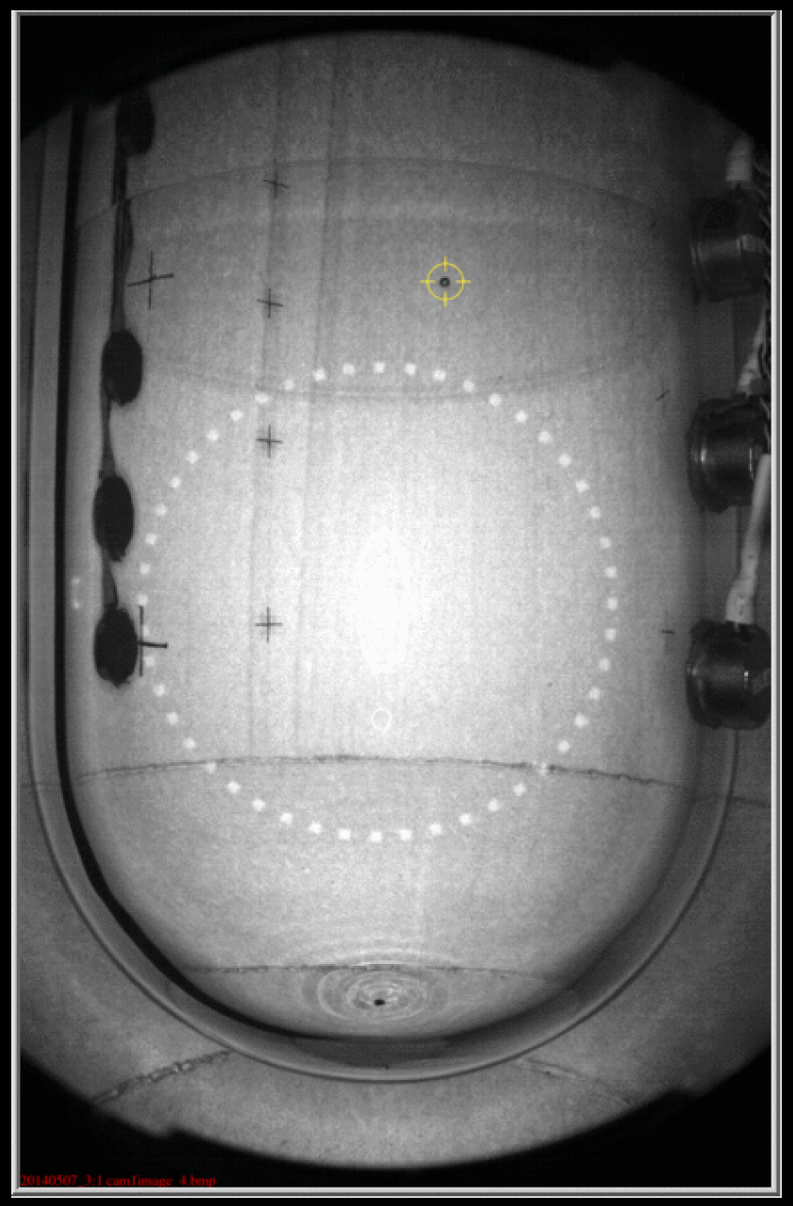
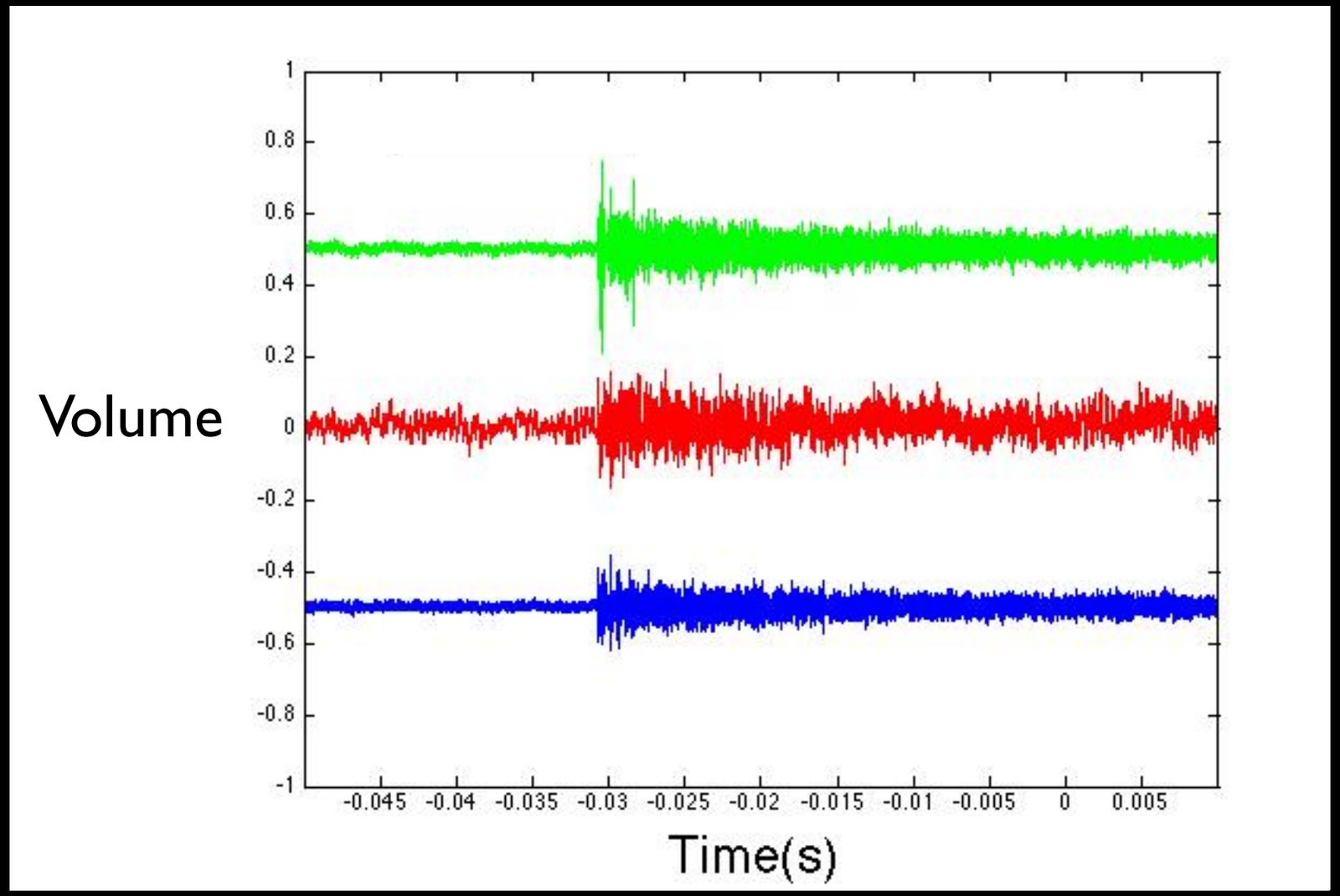
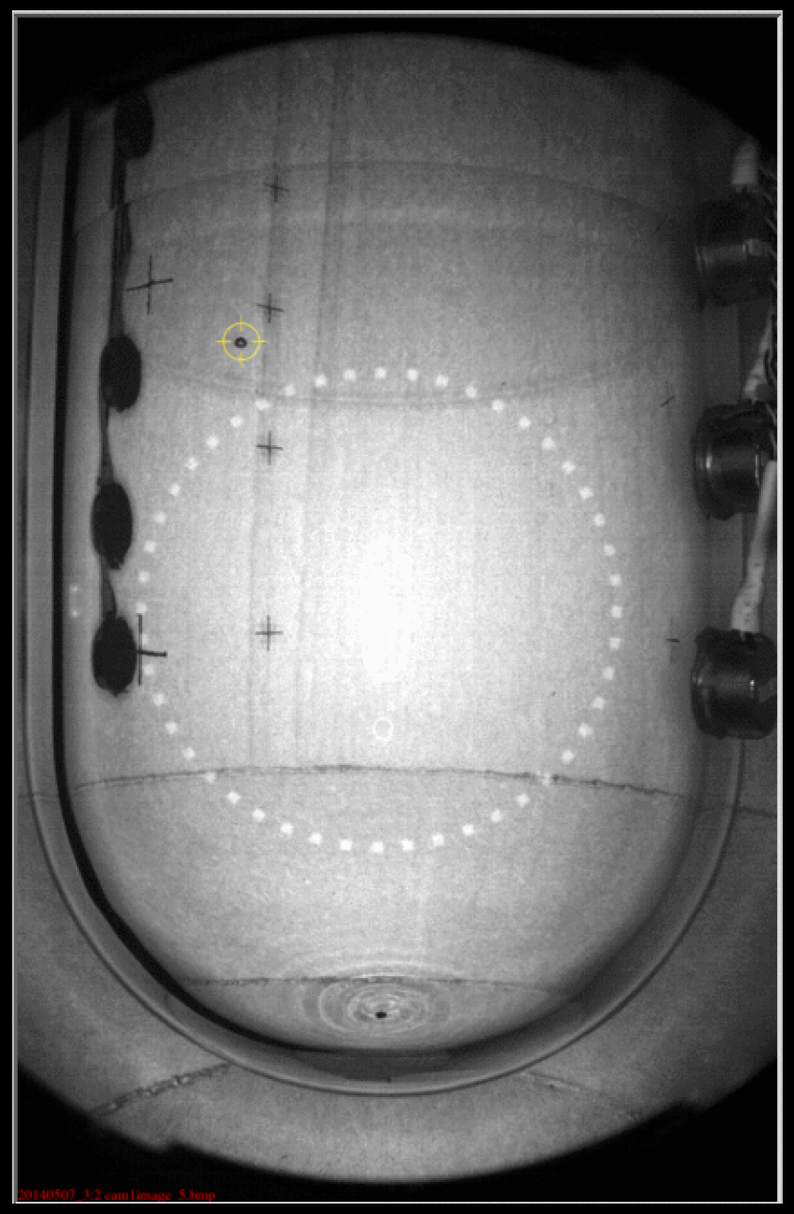
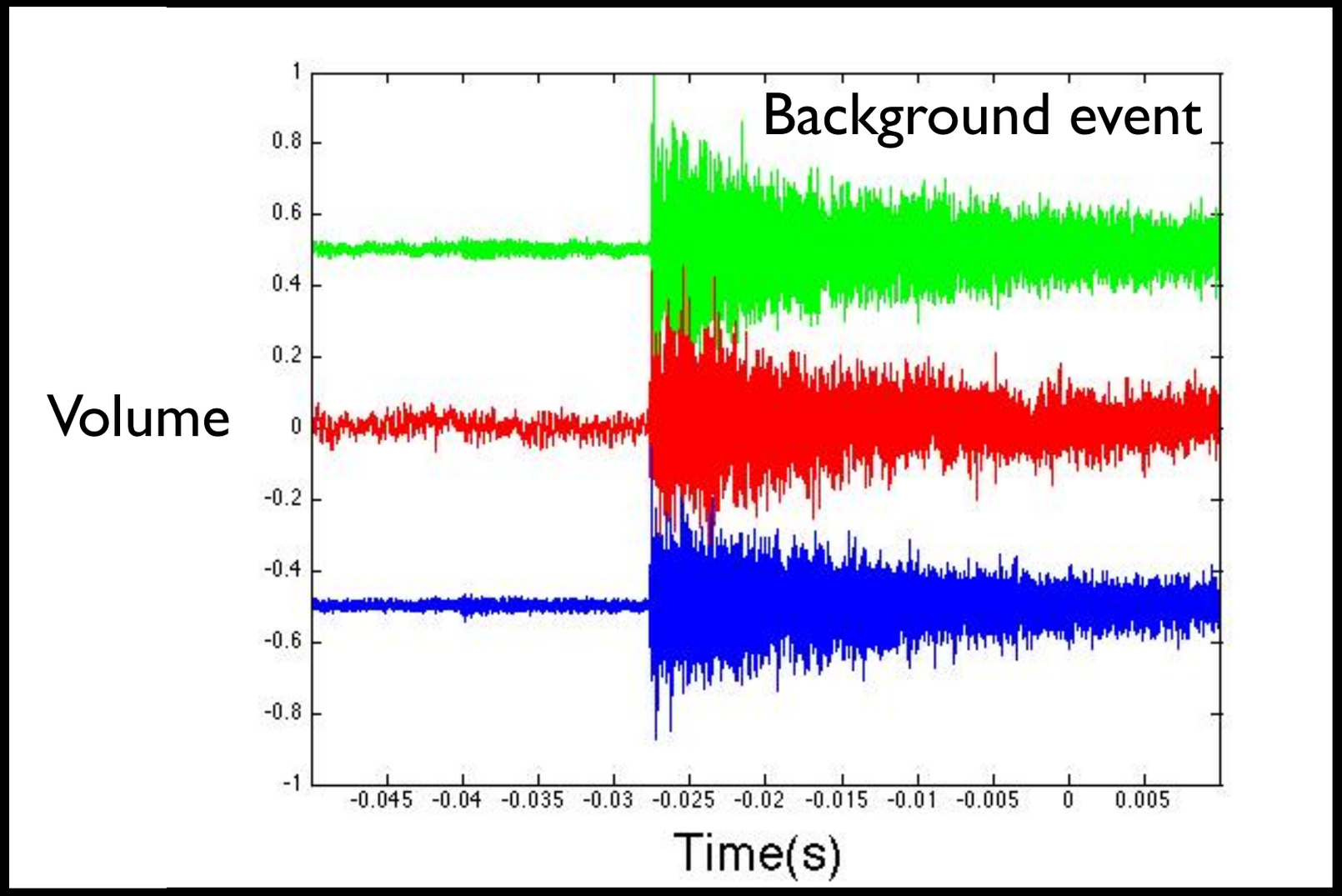




This is what a background event sounds like





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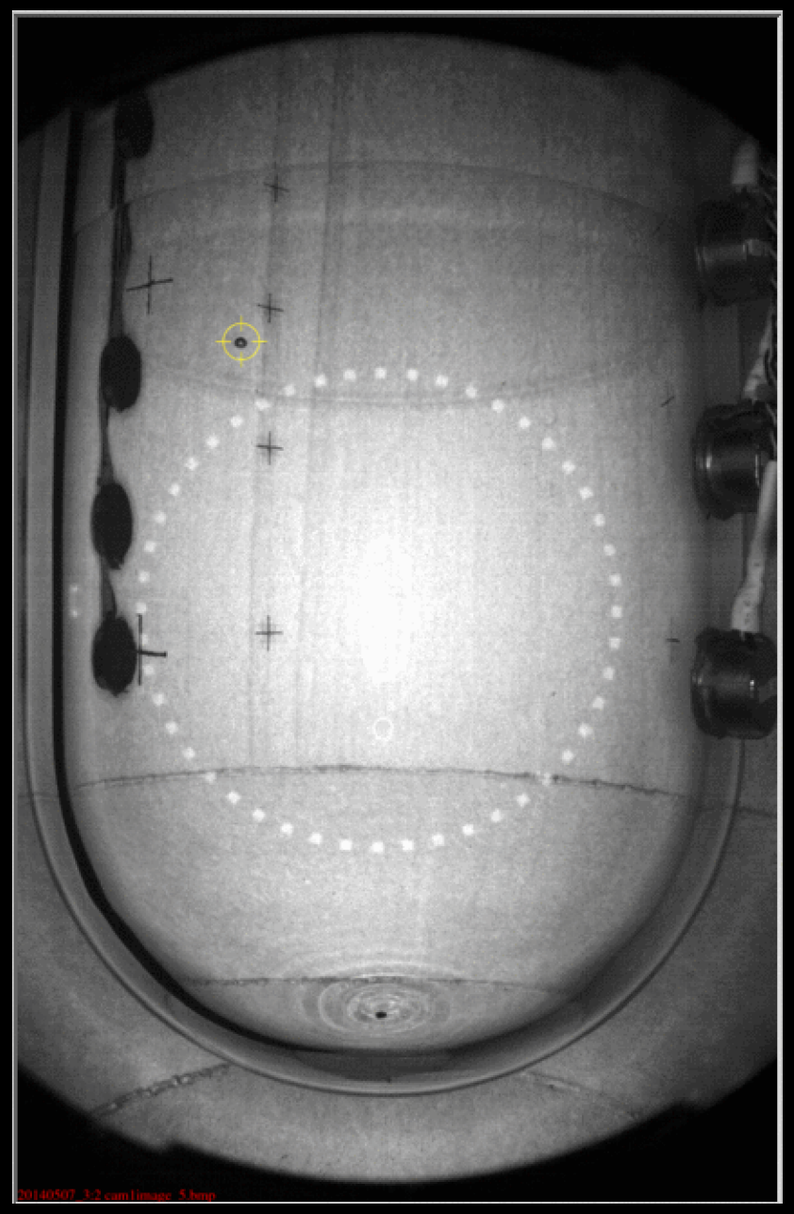

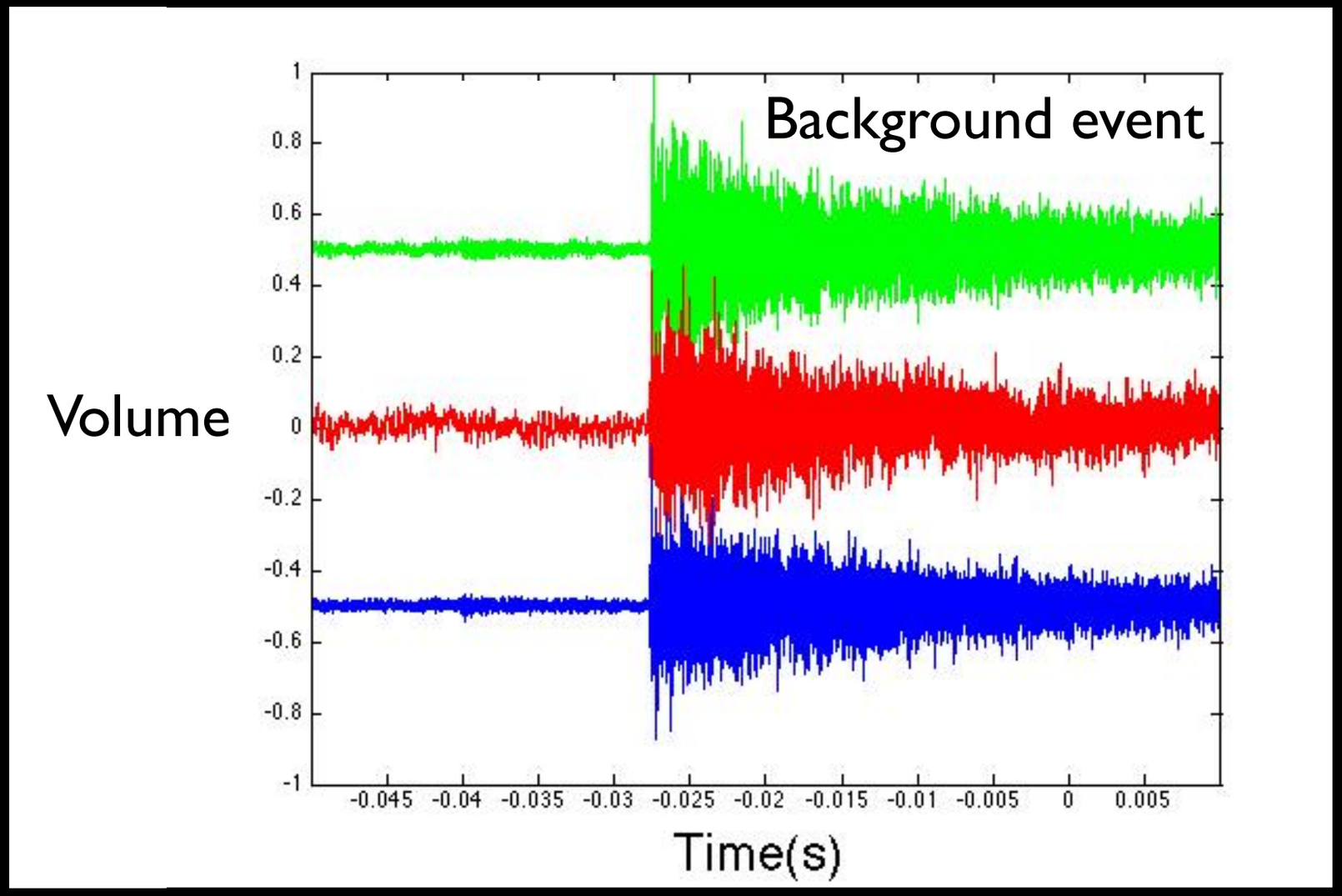

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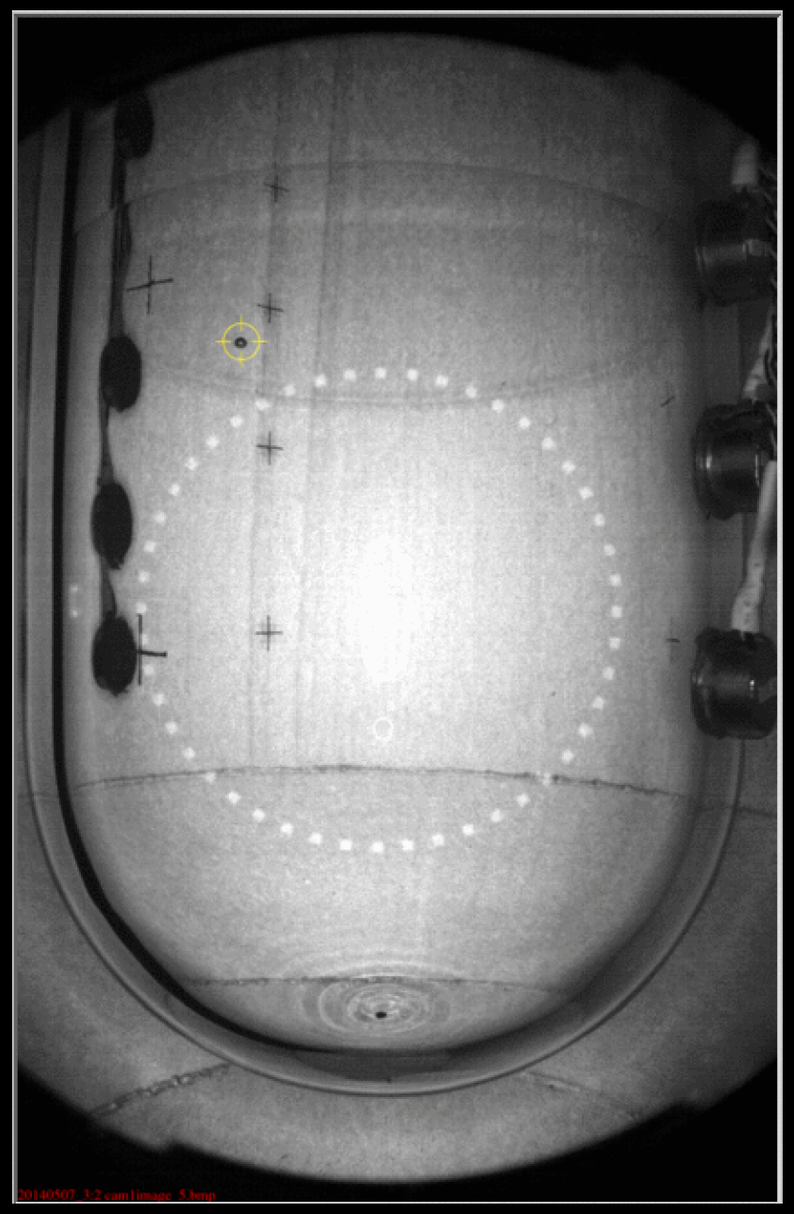
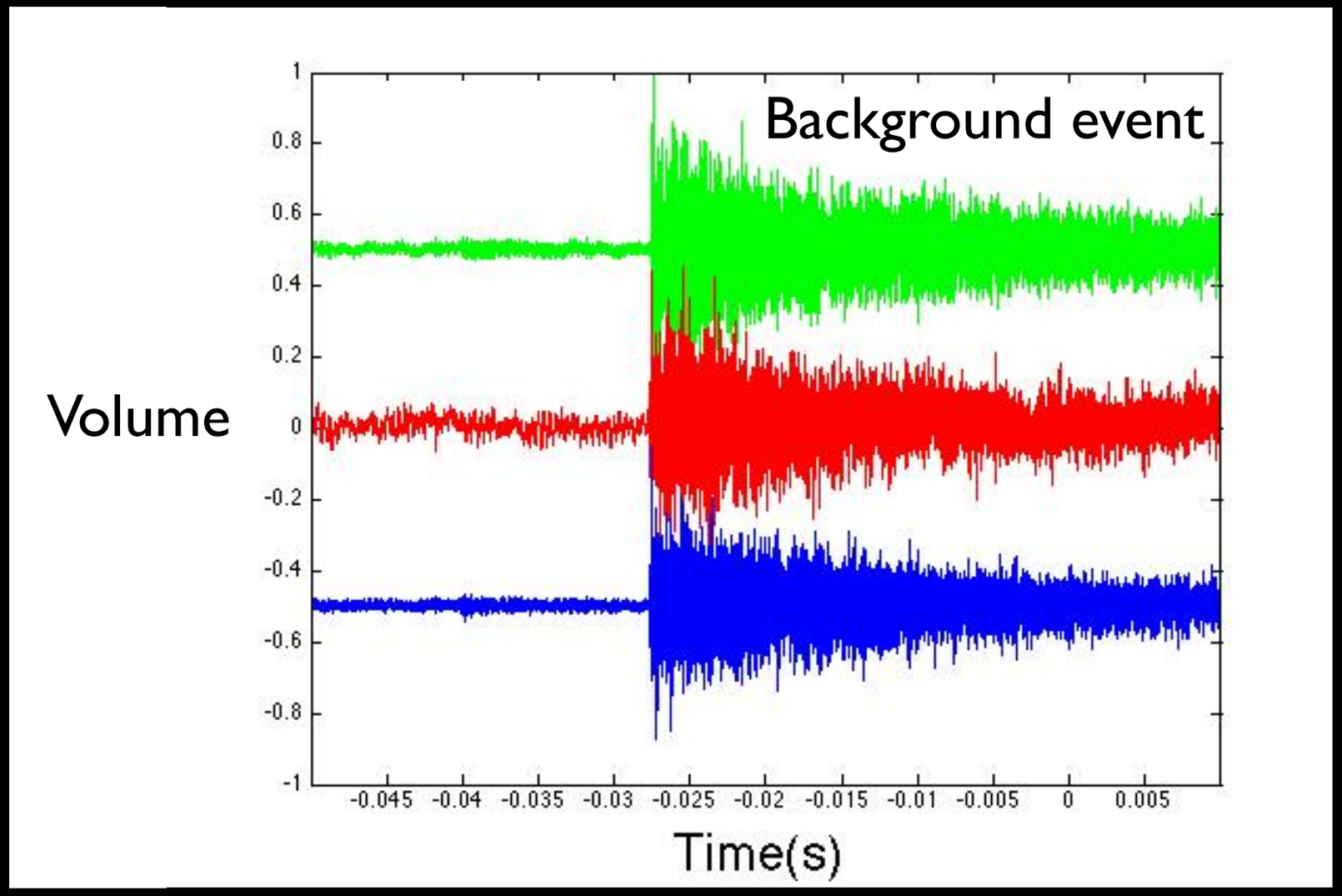


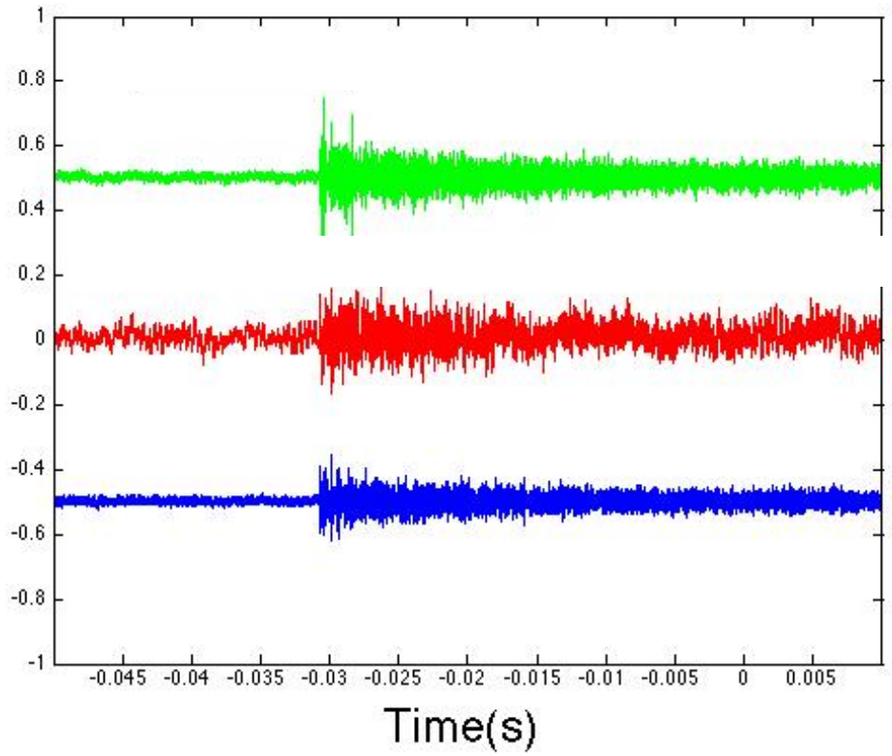


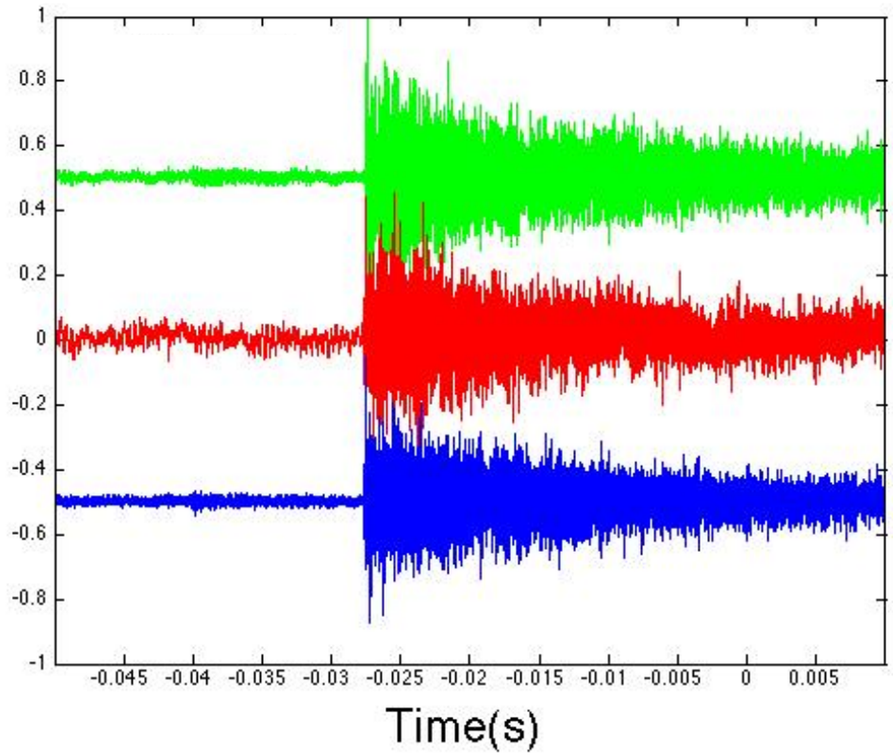
Both together, just to hear the difference

Dark Matter

Background

Volume





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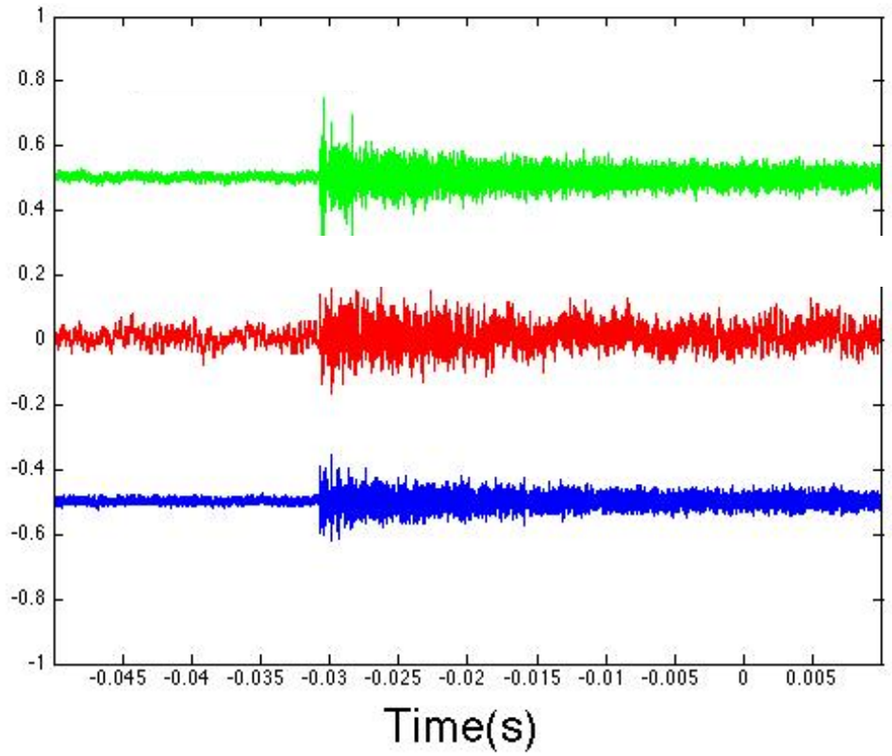
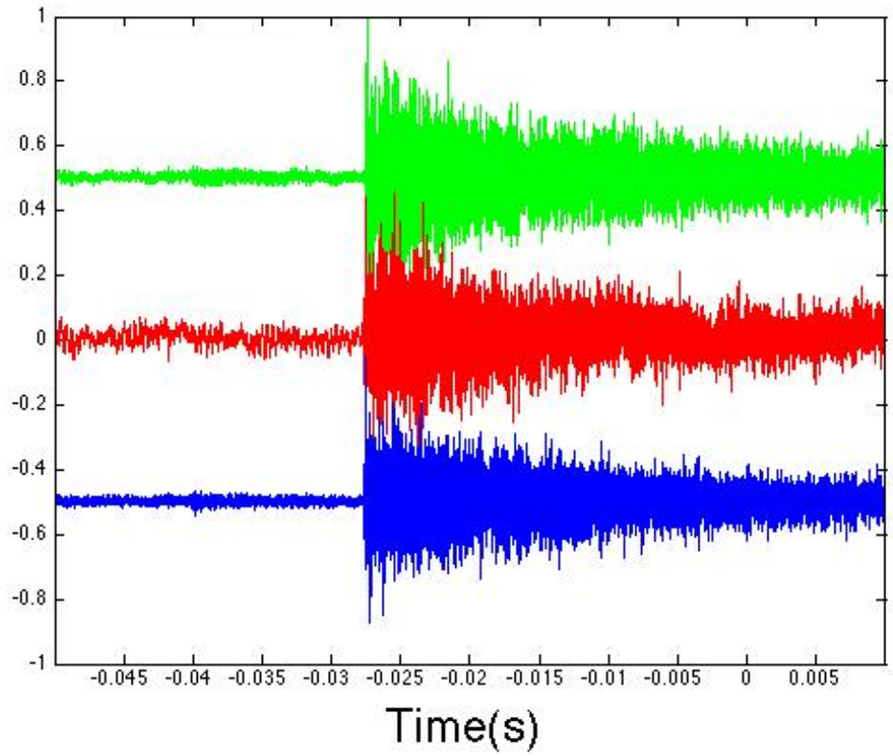
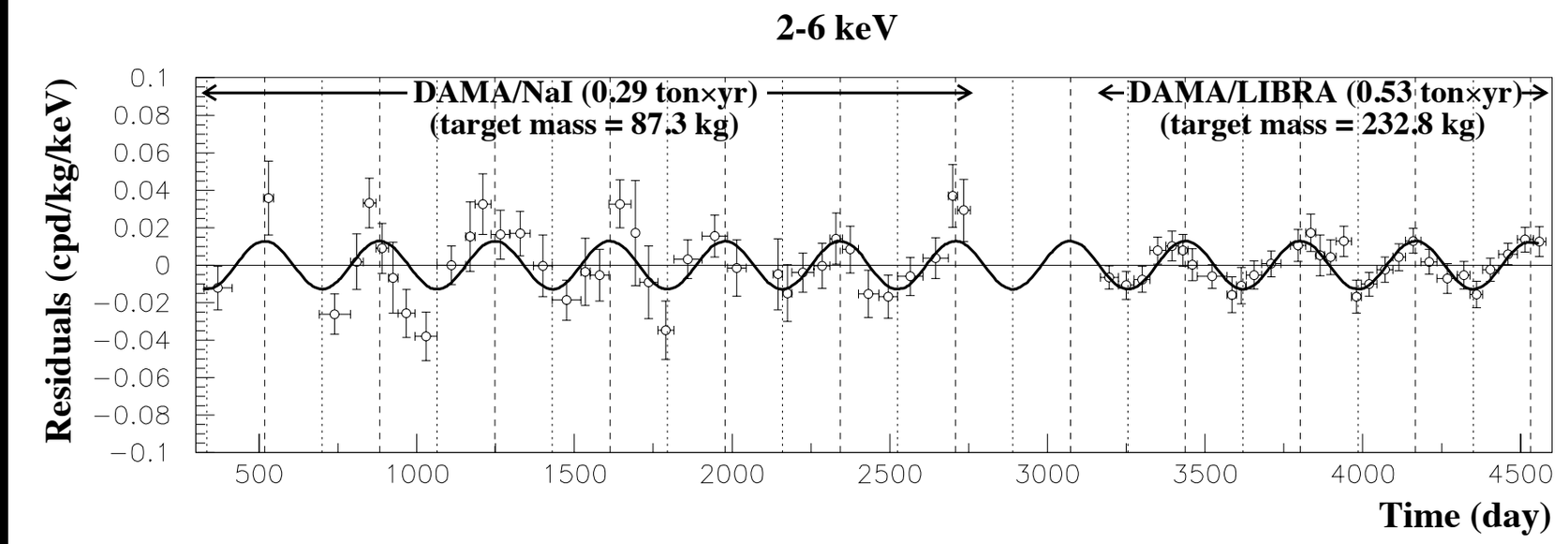




Dark matter controversies

DAMA - positive claim for 10 years!



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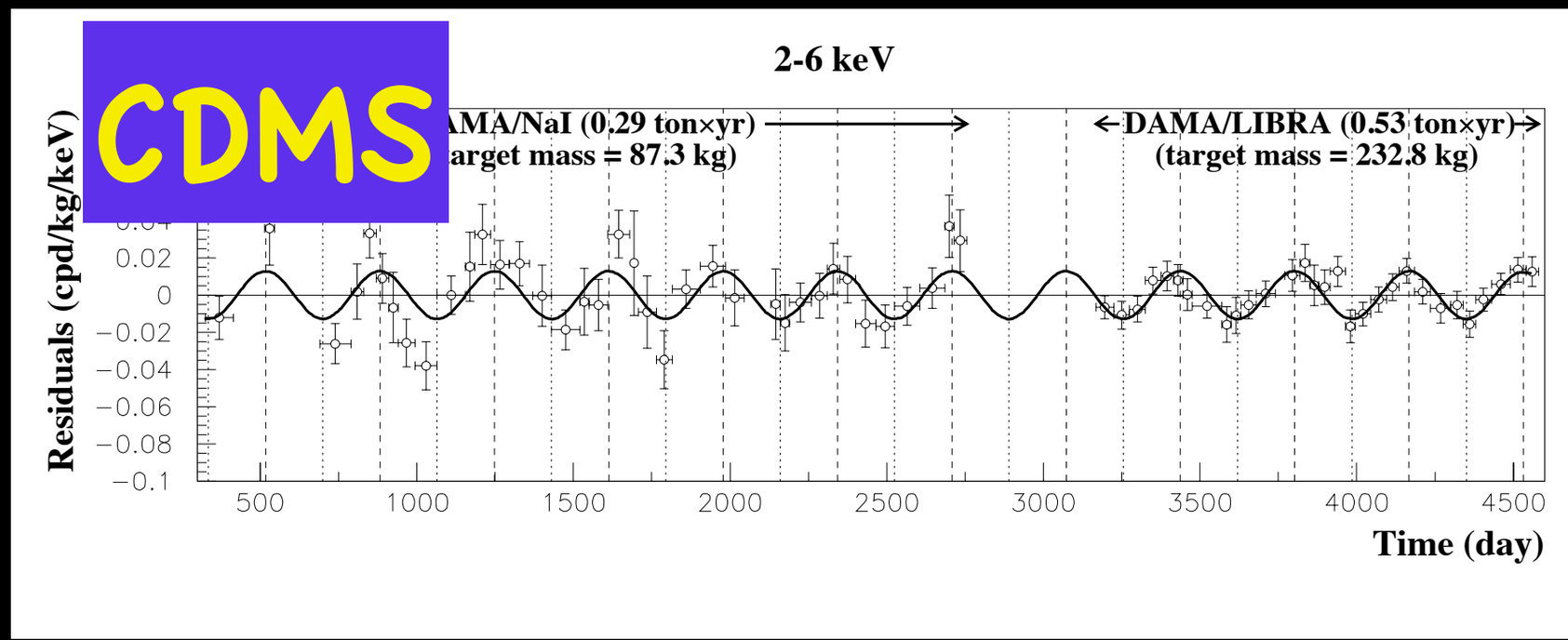

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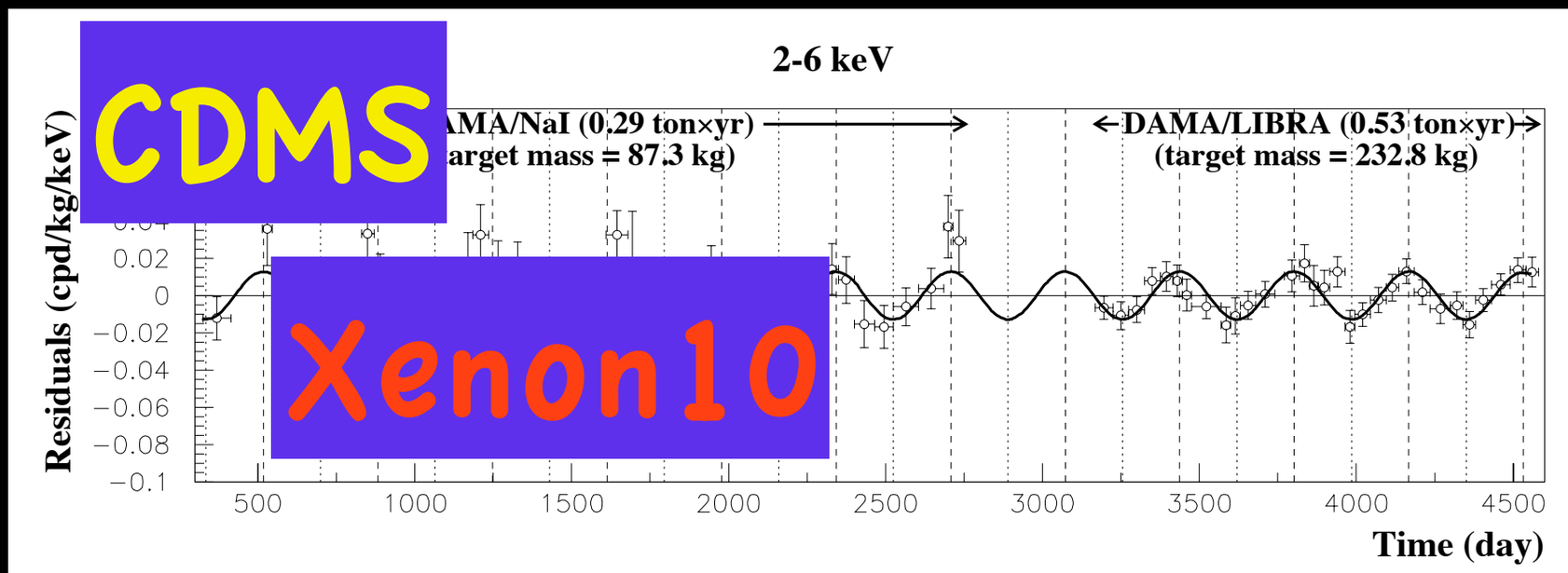

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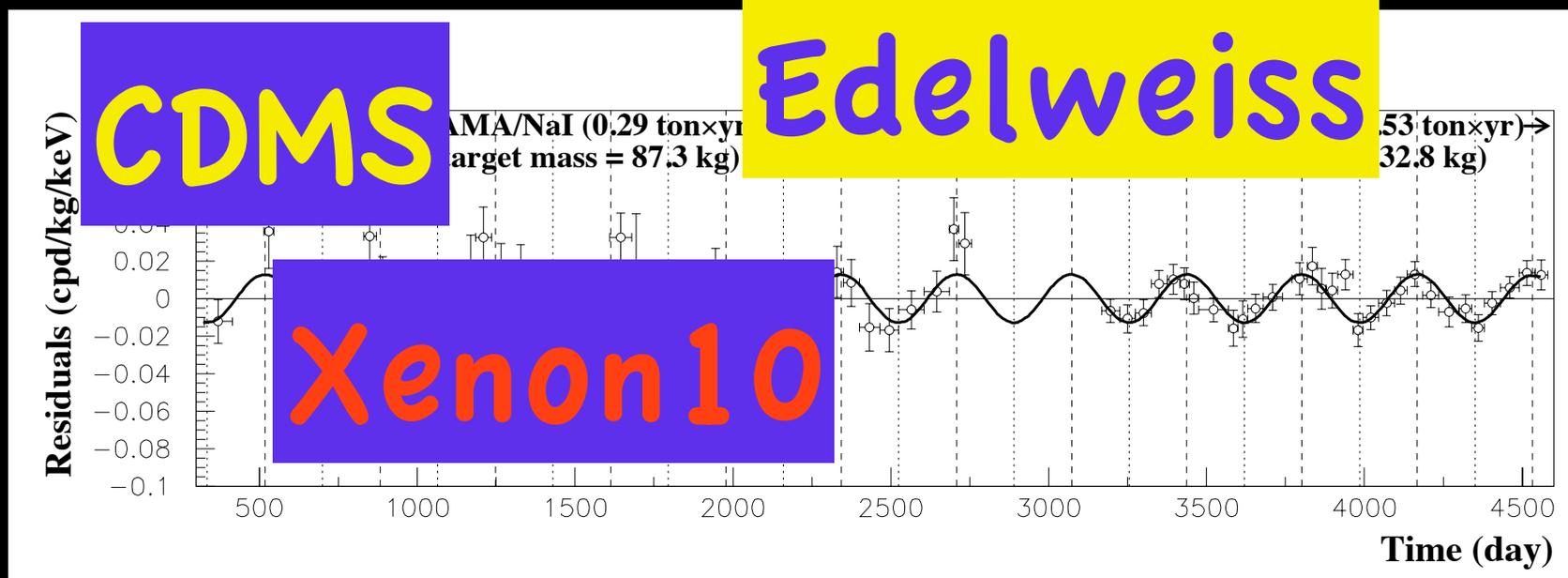

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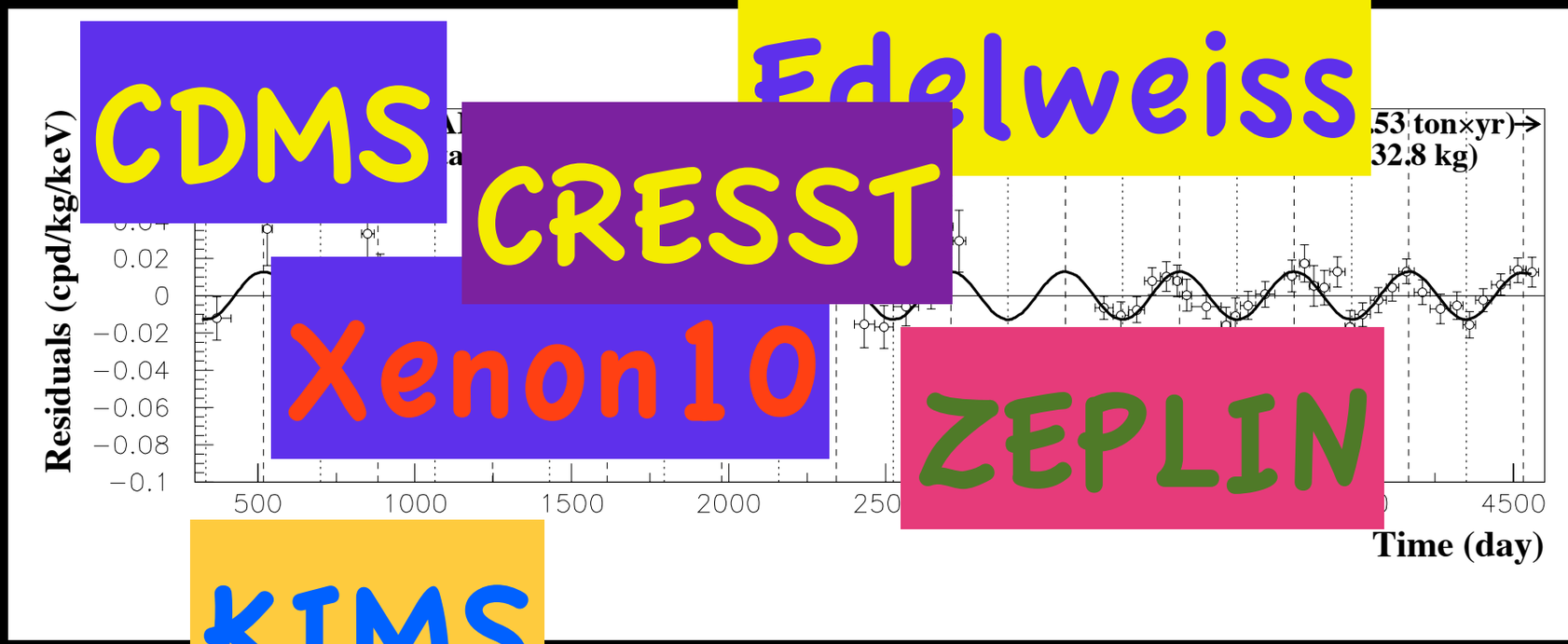

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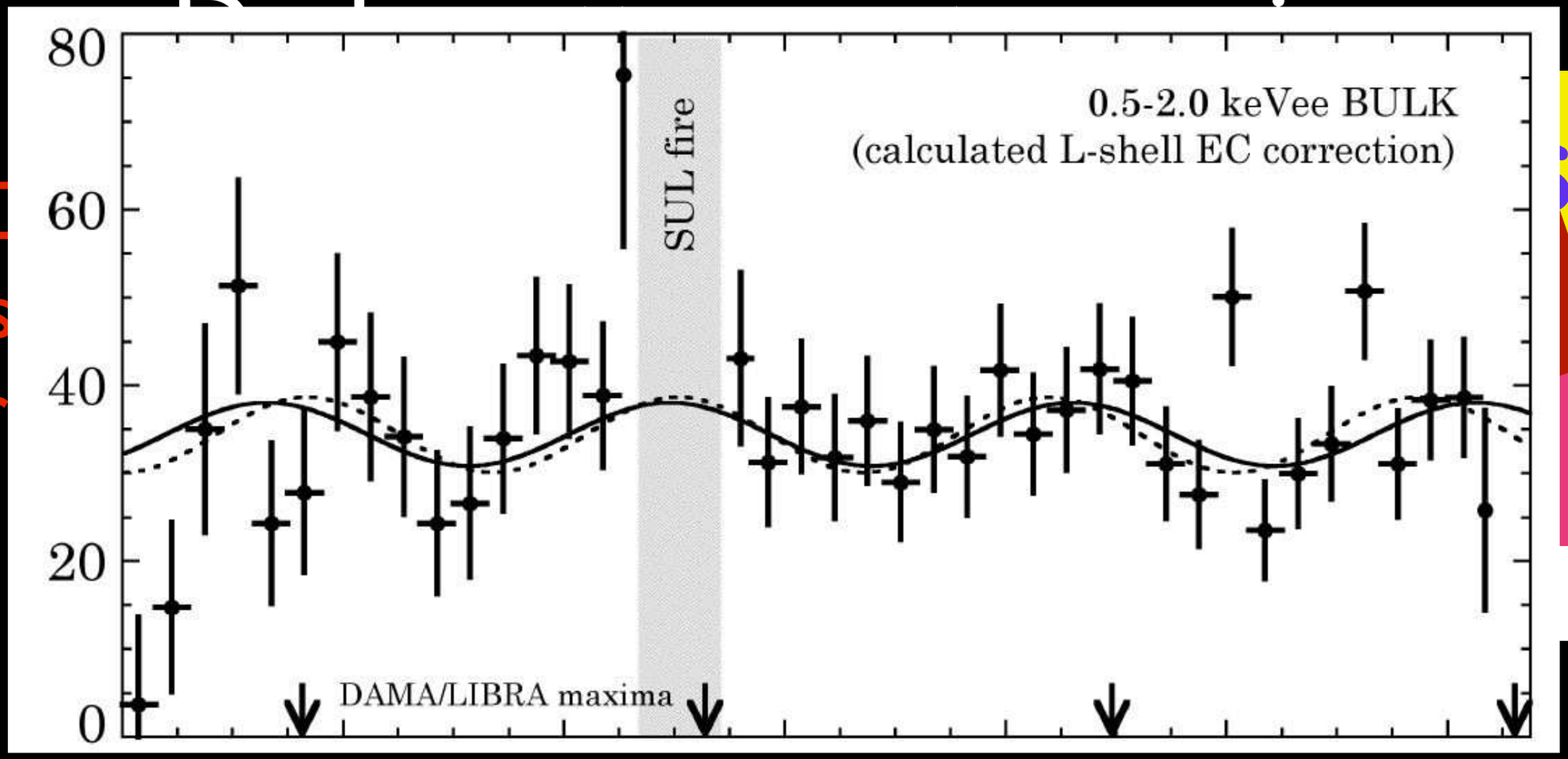

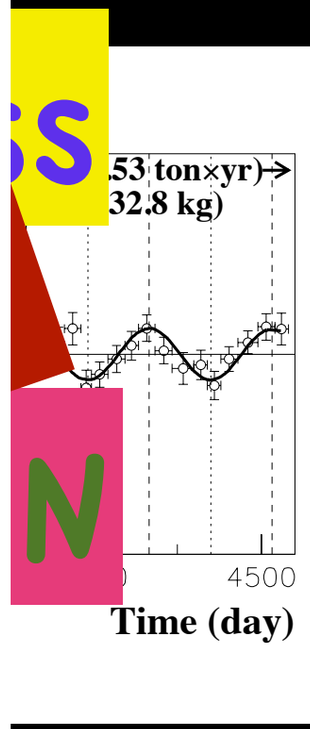

Recently, a second experiment (run by my former boss) saw a signal

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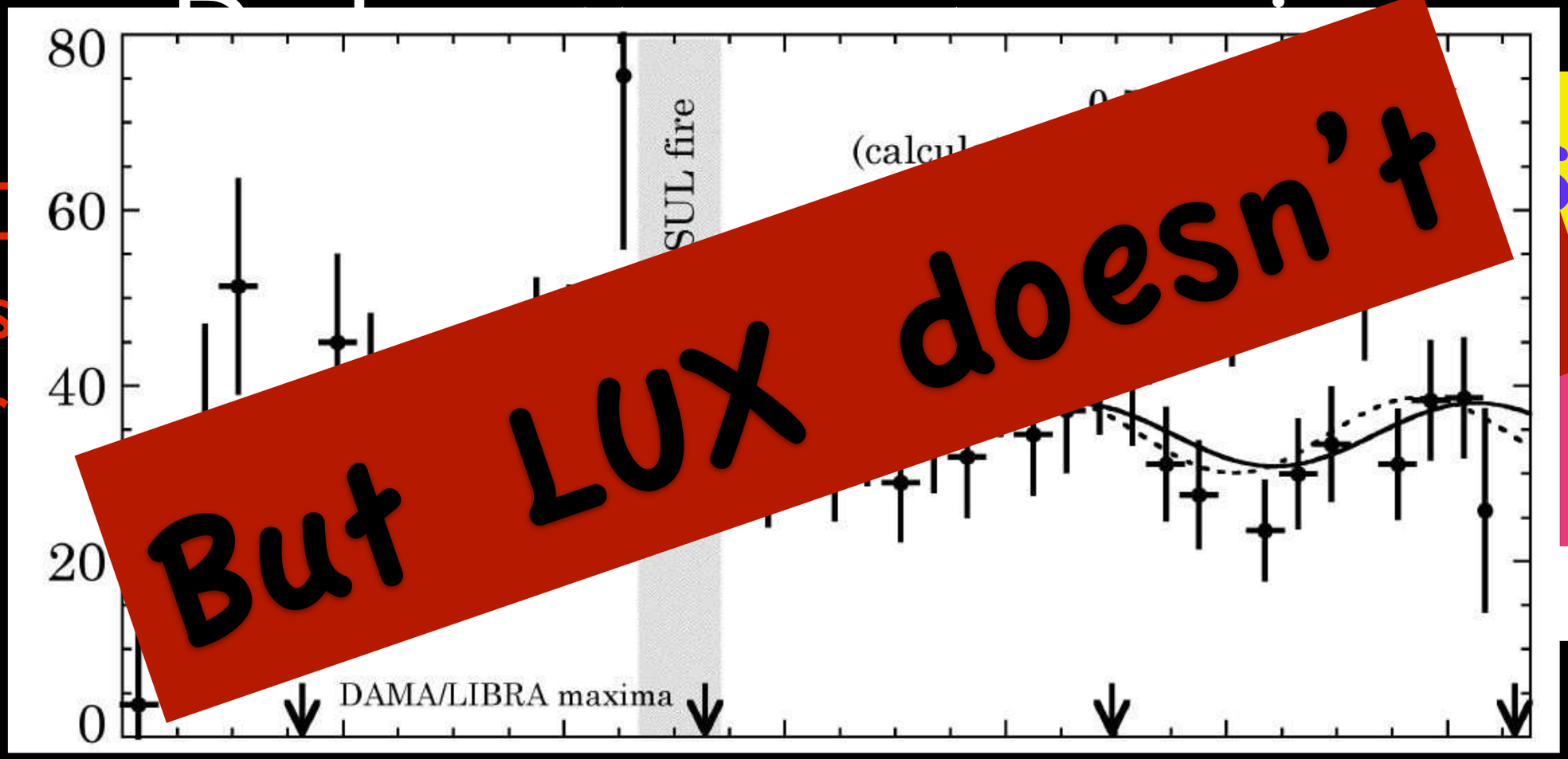
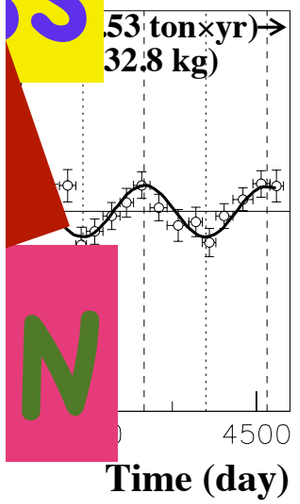


But LUX doesn't

ss

N



Recently, a second experiment (run by my former boss) saw a signal

Dark Matter

- This is hard!
- One positive claim, one “excess”, but lots of null results
- I didn’t even mention the possible signals in the Fermi satellite
- We’ll keep pushing and hopefully someday we’ll get there

Dark Matter

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- One positive claim, one "ex
results
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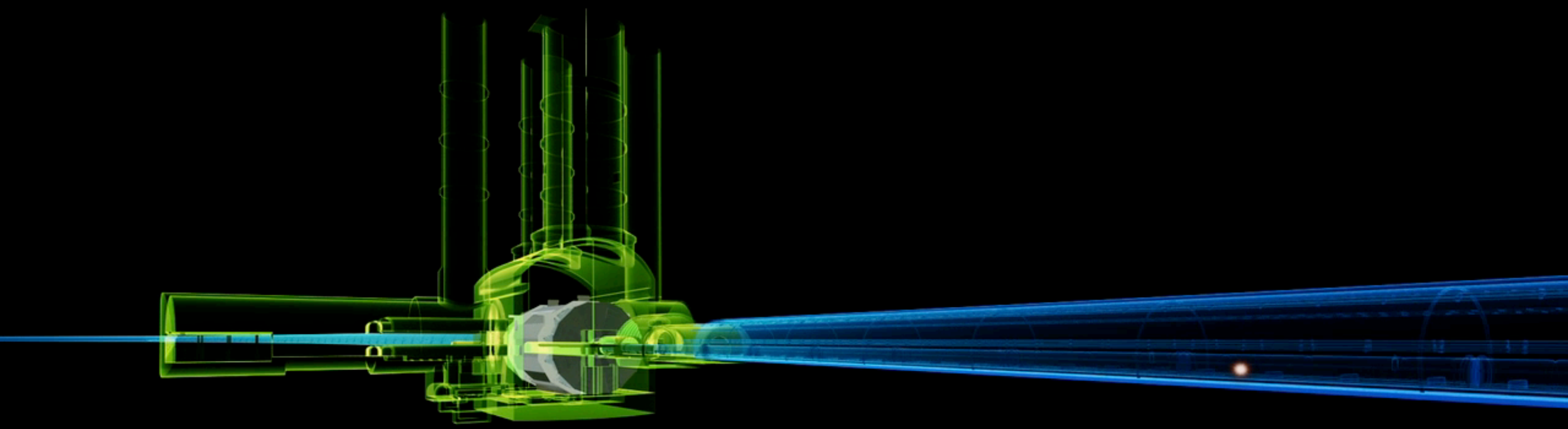
Summary

- We know there is dark matter because gravity looks **stronger** than expected in galaxies
- There is ~6 times more mass in dark matter than in atoms
- We think dark matter could be a new subatomic particle
- Many exciting efforts to **detect** dark matter in particle accelerators and measure its properties

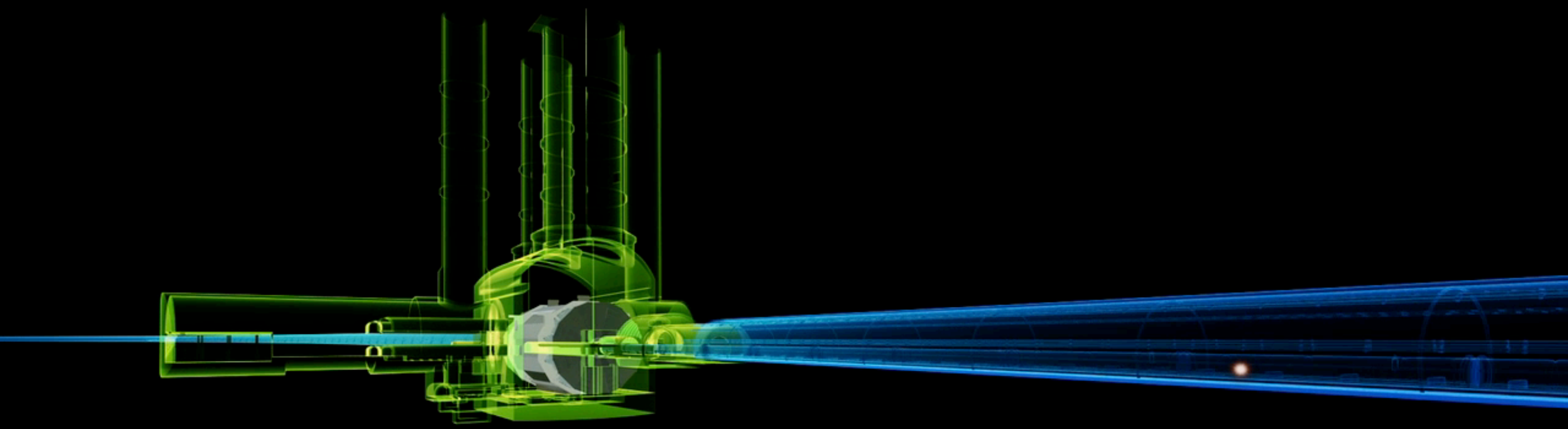
Exciting times, thanks for listening!

Backup

Atom Smashing



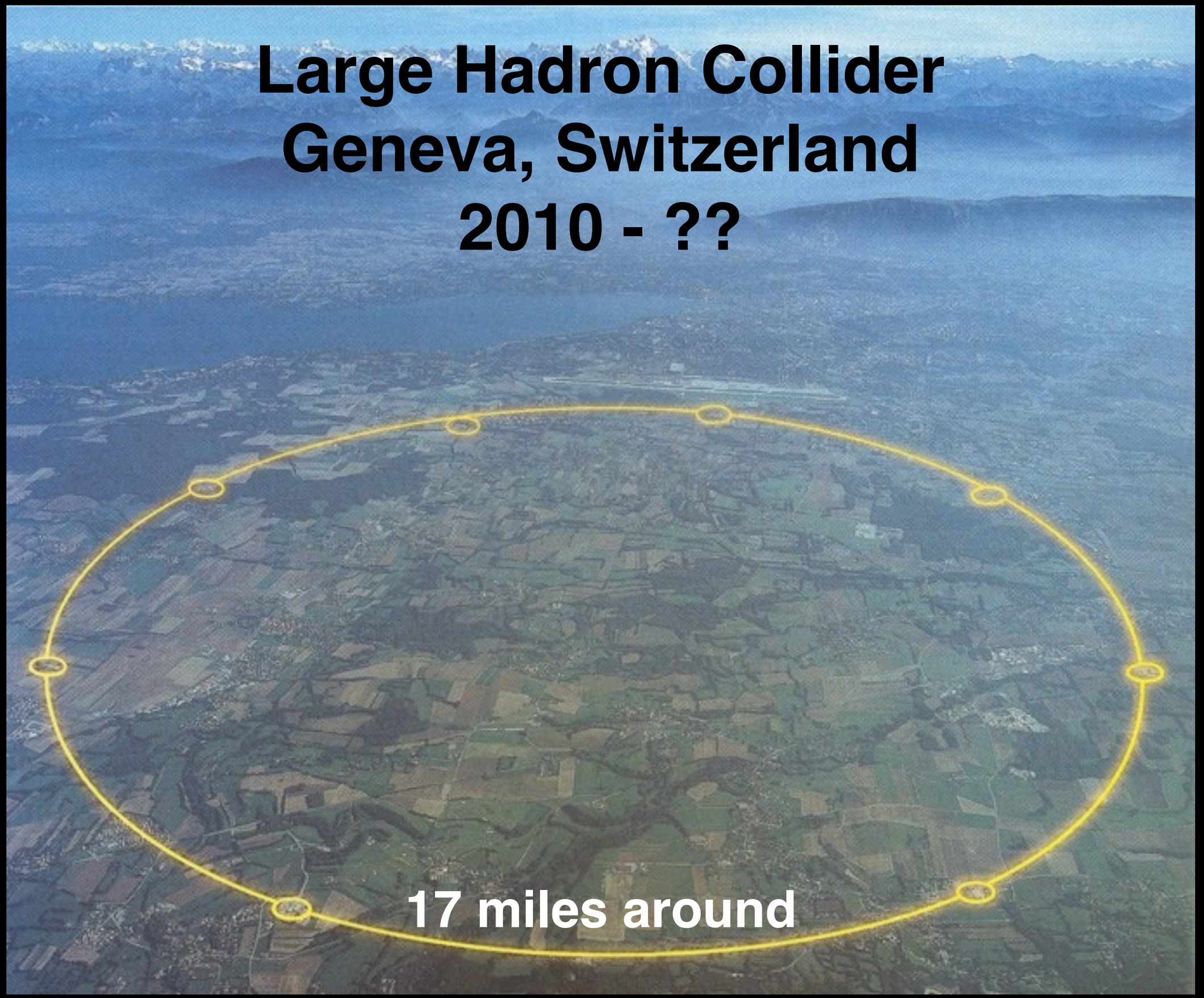
Atom Smashing



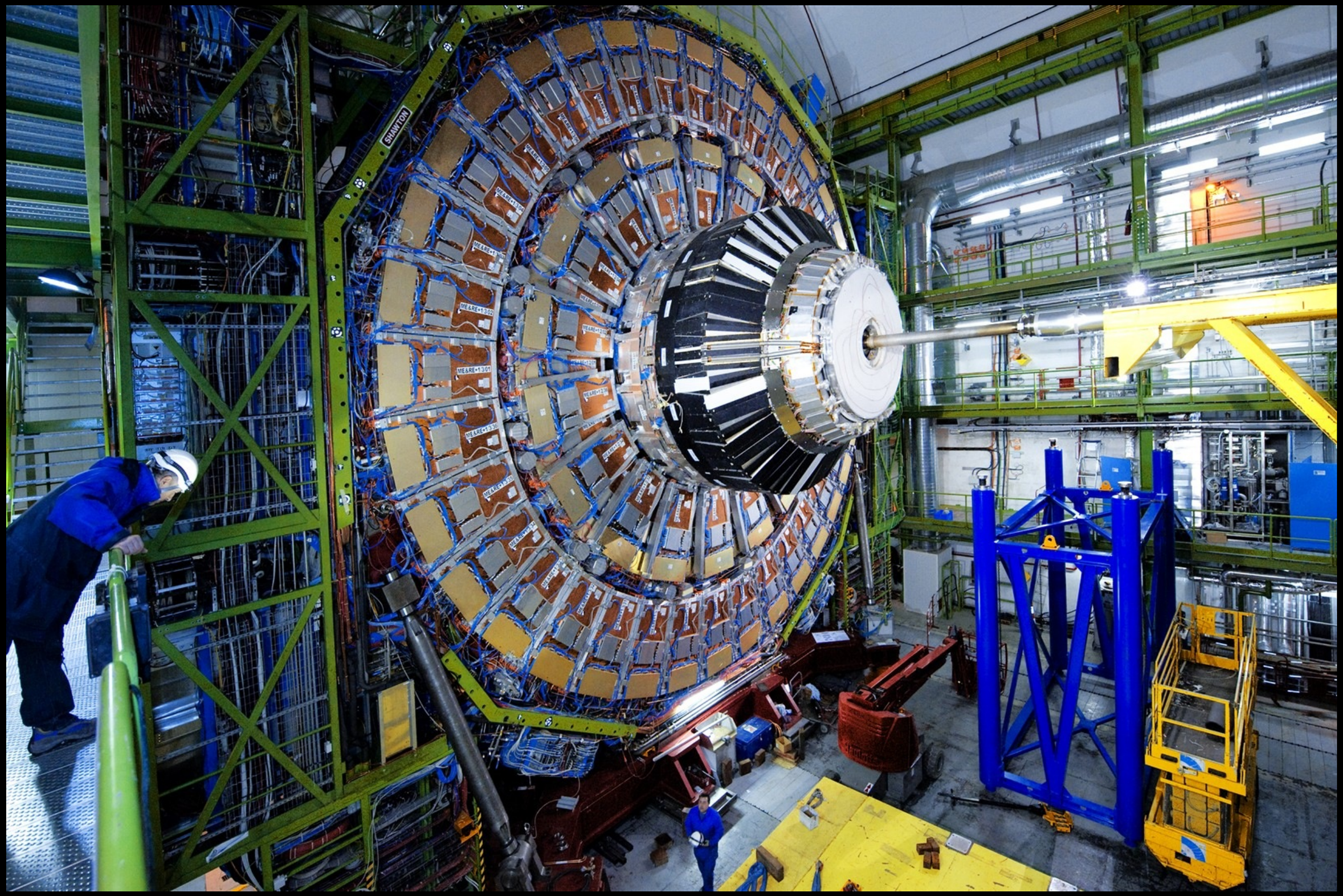
Tevatron, 1983-2011

Protons are accelerated to 99.999999% the speed of light in a tunnel underground

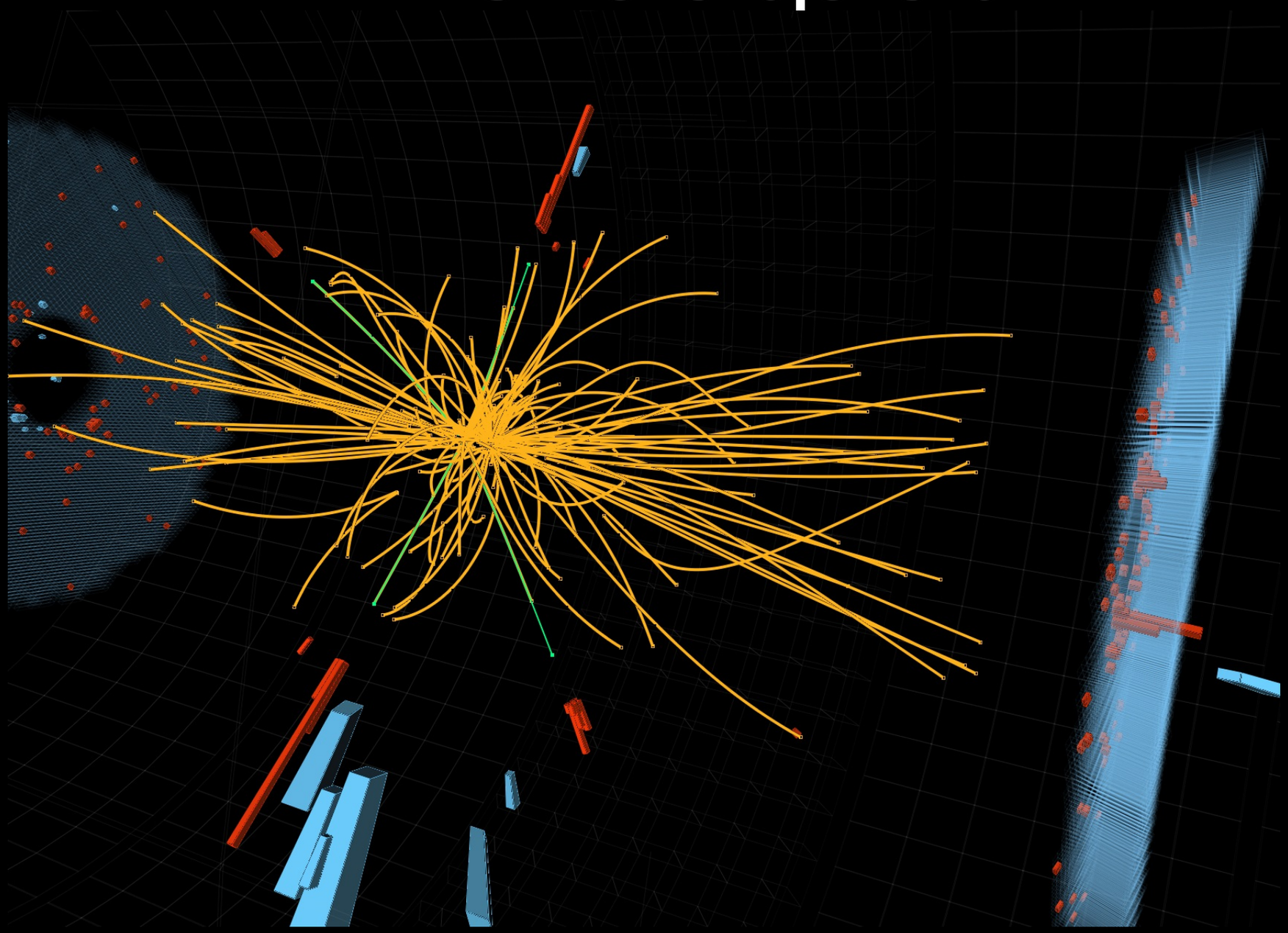
Large Hadron Collider
Geneva, Switzerland
2010 - ??



Big detectors to study big collisions:



The output



Hundreds of millions of collisions per **second**

SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
SuperCDMS SNOLAB
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos

WIMP–nucleon cross section [cm^2]

10^{-39} 10^{-40} 10^{-41} 10^{-42} 10^{-43} 10^{-44} 10^{-45} 10^{-46} 10^{-47} 10^{-48} 10^{-49} 10^{-50}

10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14}

1 10 100 1000 10^{4}

WIMP Mass [GeV/c^2]