Dark Matter: from the galaxies to deep mines

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4th Lisbon Mini-school on Particle and Astroparticle Physics

Contents

- Dark Matter
  - First hints from astronomical observations
  - More evidence: gravitational lensing
  - What is the Universe made of?
  - Possible explanations
- How to detect it
- Direct detection
  - The LUX & LZ detectors

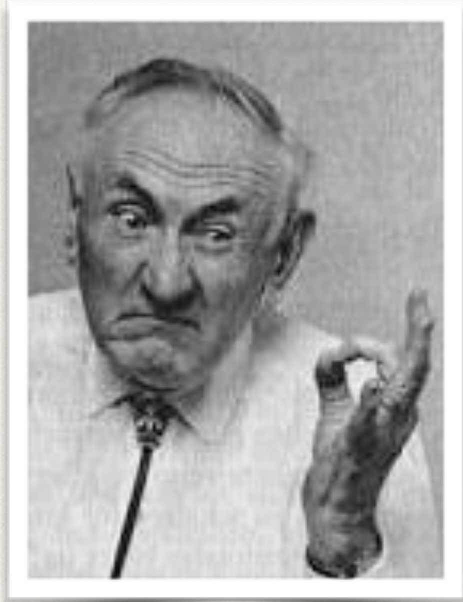
First hints:

gravitational effects in galaxies and clusters

First hints

1933 F. Zwicky: Compared the velocity distribution of galaxies in the Coma cluster to what would be expected given the observed mass (estimated from the luminosity)

- ➡ galaxies moved much faster than expected
- ➡ visible matter only 0.5 % of the total



Coma cluster (image from SDSS)

Virial theorem

$$\langle KE \rangle = -\frac{1}{2}\langle PE \rangle$$

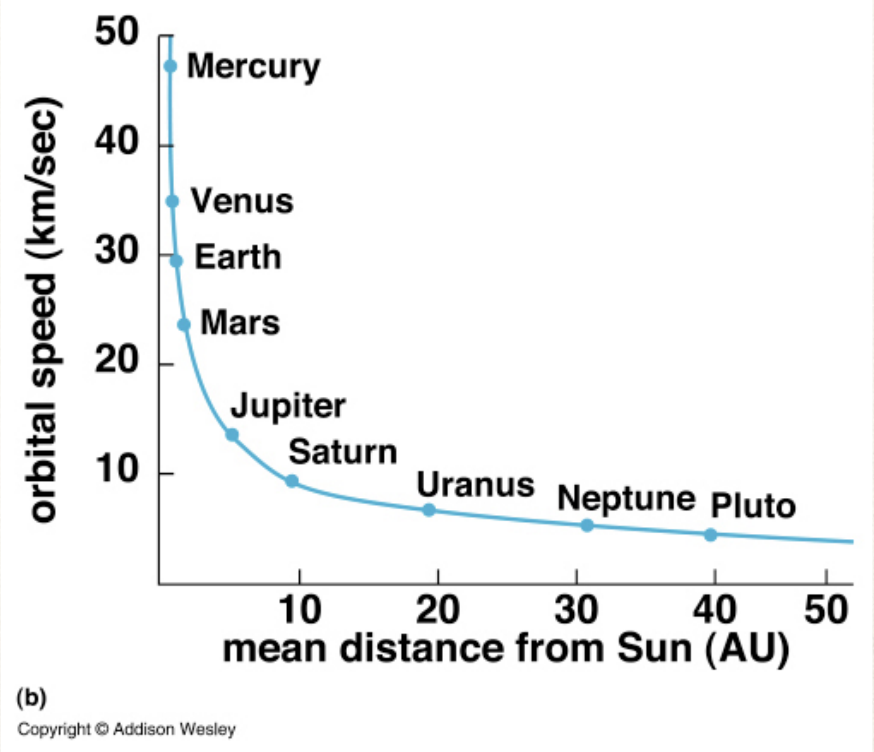
$$\frac{1}{2}Mv^2 \qquad\qquad G\frac{Mm}{R}$$

Galaxy rotation curves

1970s Vera Rubin measured the rotation velocities of stars in the outer regions of galaxies

- ➡ If we take the distribution of luminous matter, we expect the velocity to fall as we get further away from the center (as in the Solar System): $v \sim 1/\sqrt{r}$

Solar System

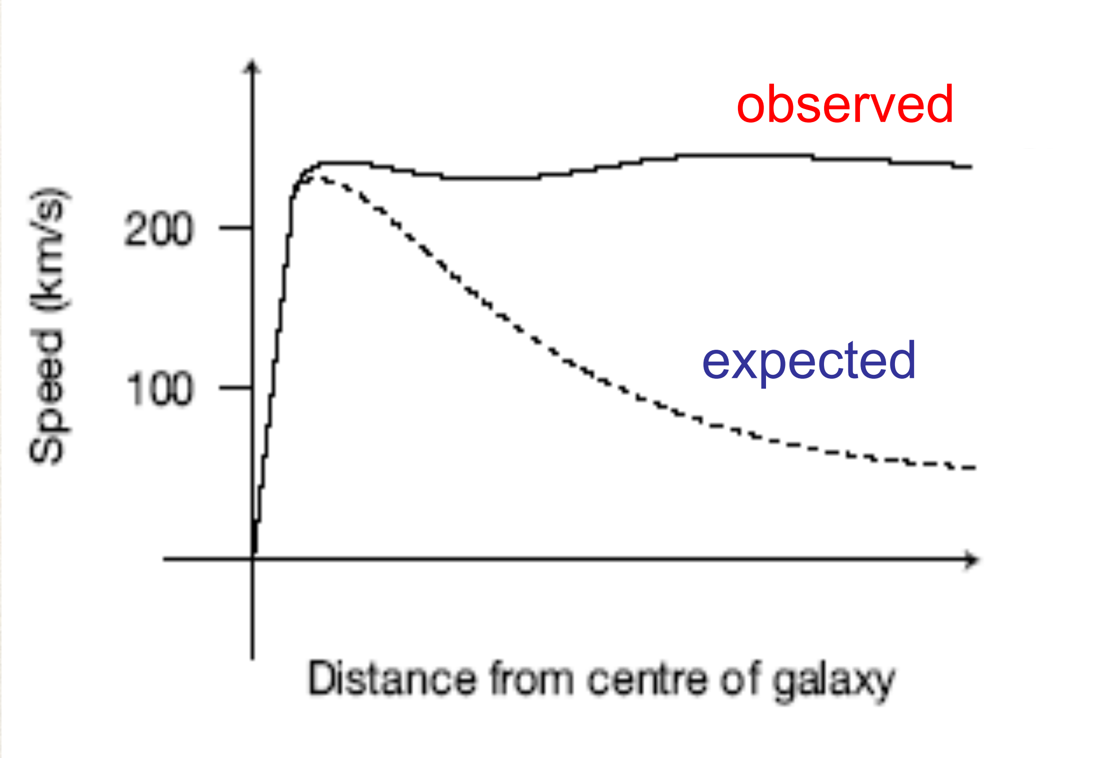


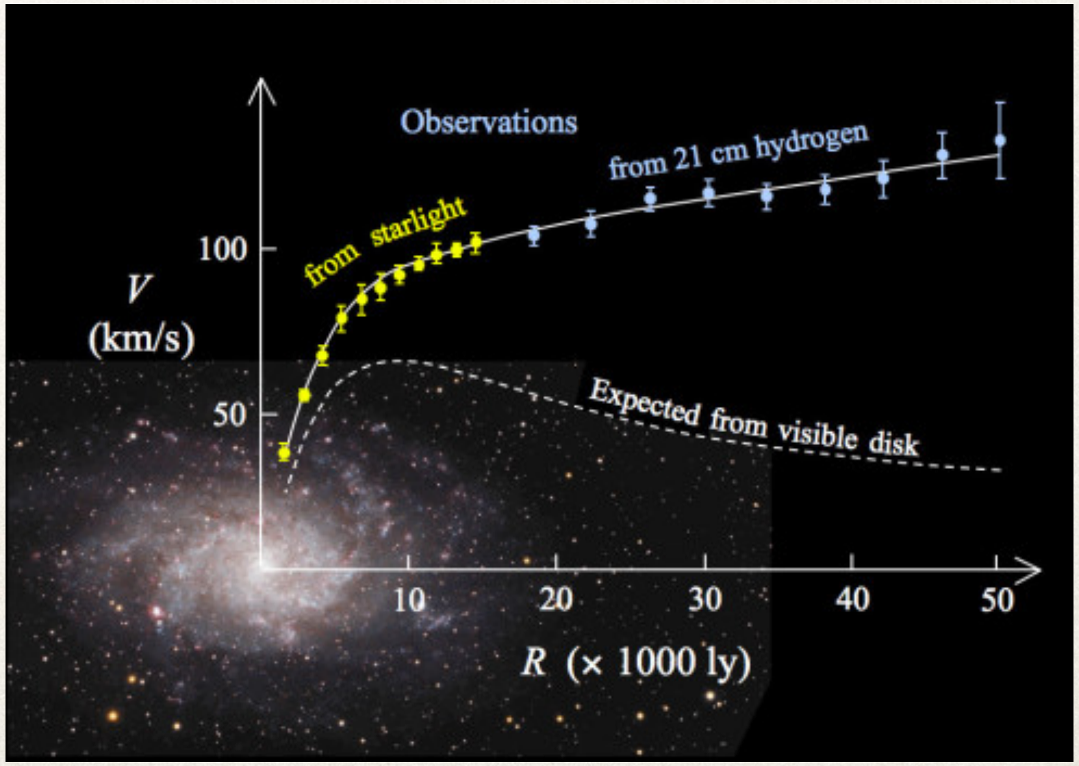
Galaxies

Galaxy rotation curves

1970s Vera Rubin measured the rotation velocities of stars in the outer regions of galaxies

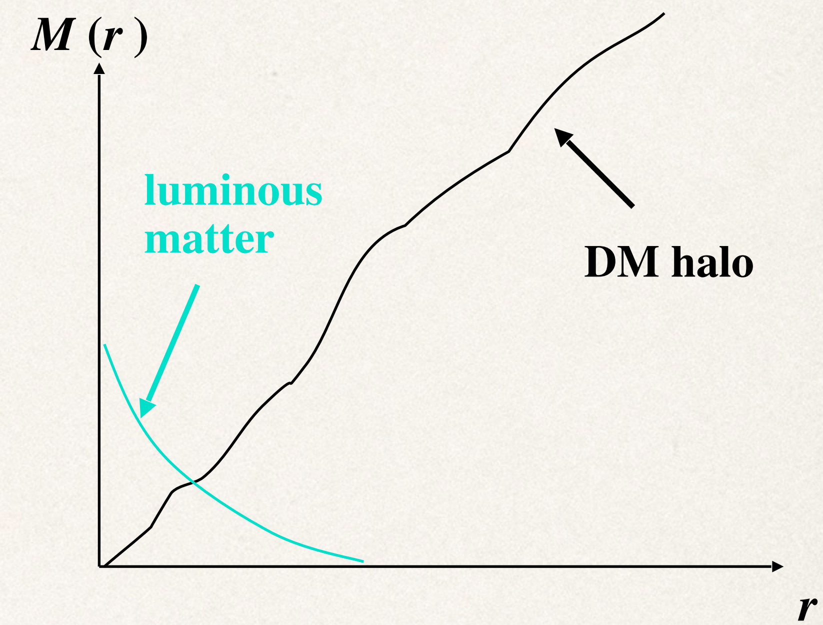
- ➡ If we take the distribution of luminous matter, we expect the velocity to fall as we get further away from the center (as in the Solar System): $v \sim 1/\sqrt{r}$
- ➡ **Stars in the outer regions move as fast as the inner ones!**

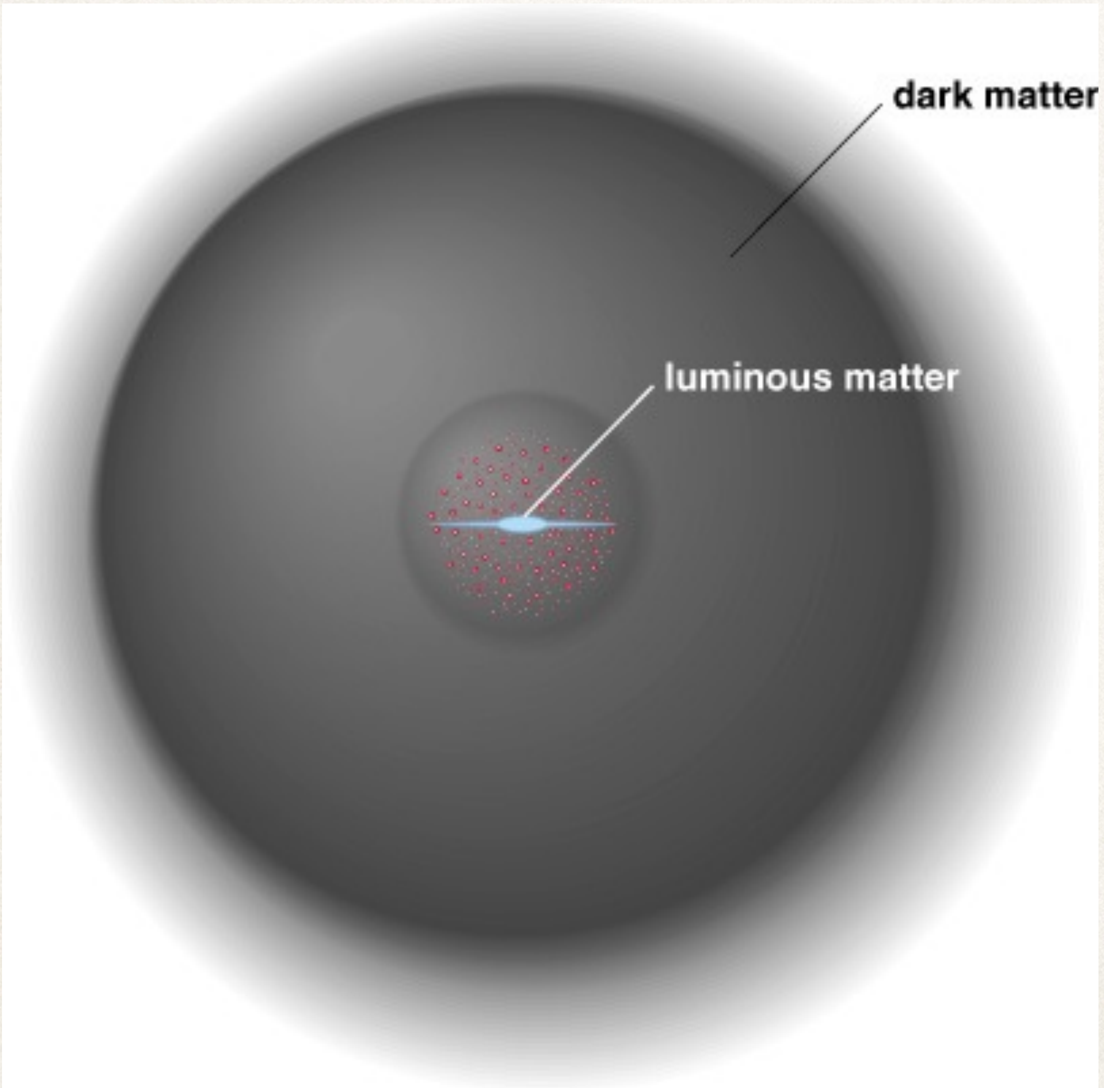


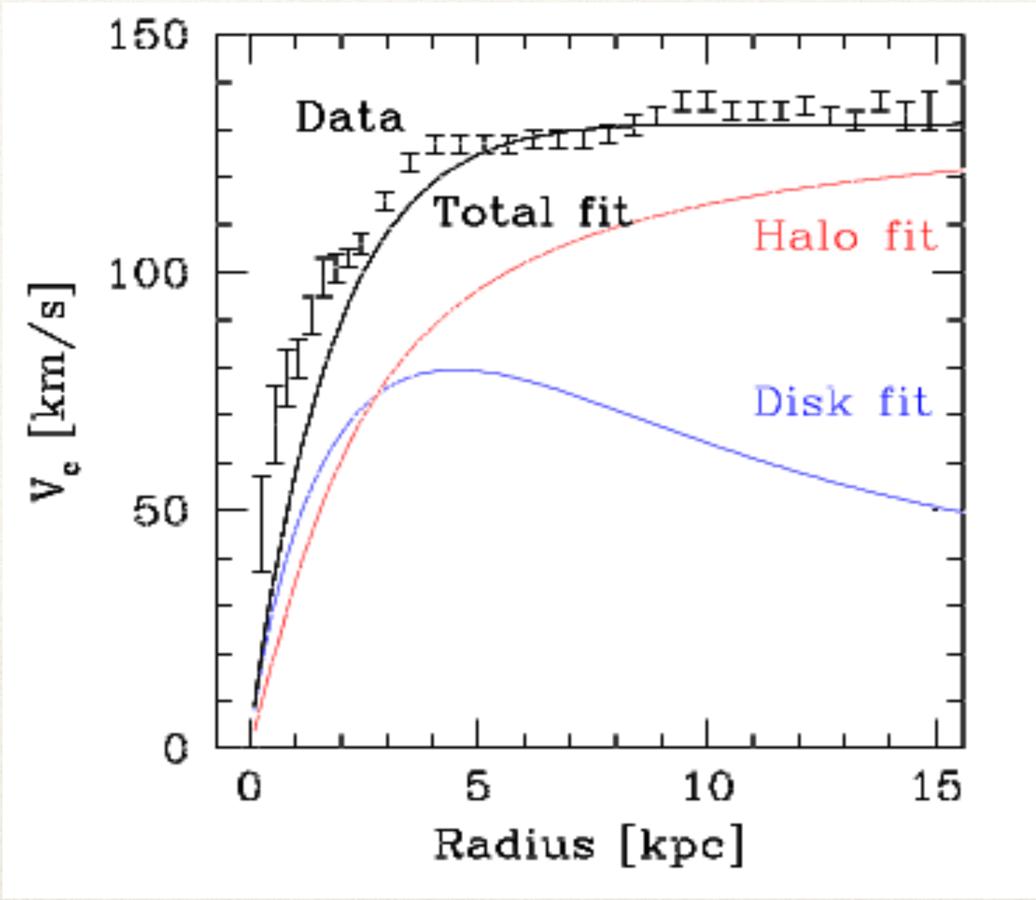


Galaxy rotation curves

- A halo of dark matter is required to explain the observations
- ~90% of the mass in galaxies is "dark"!

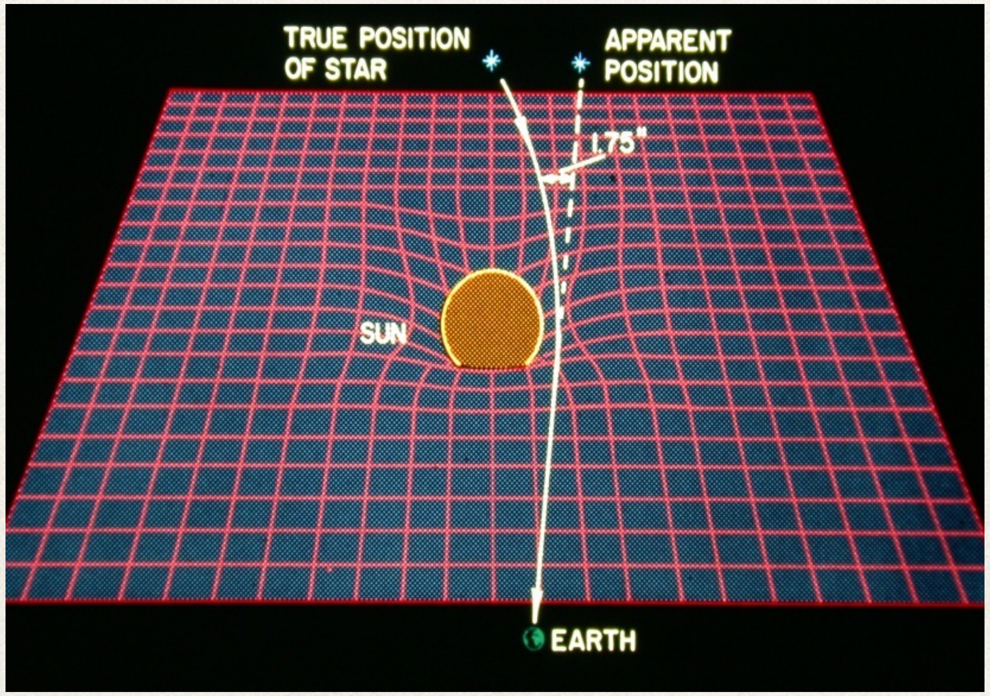


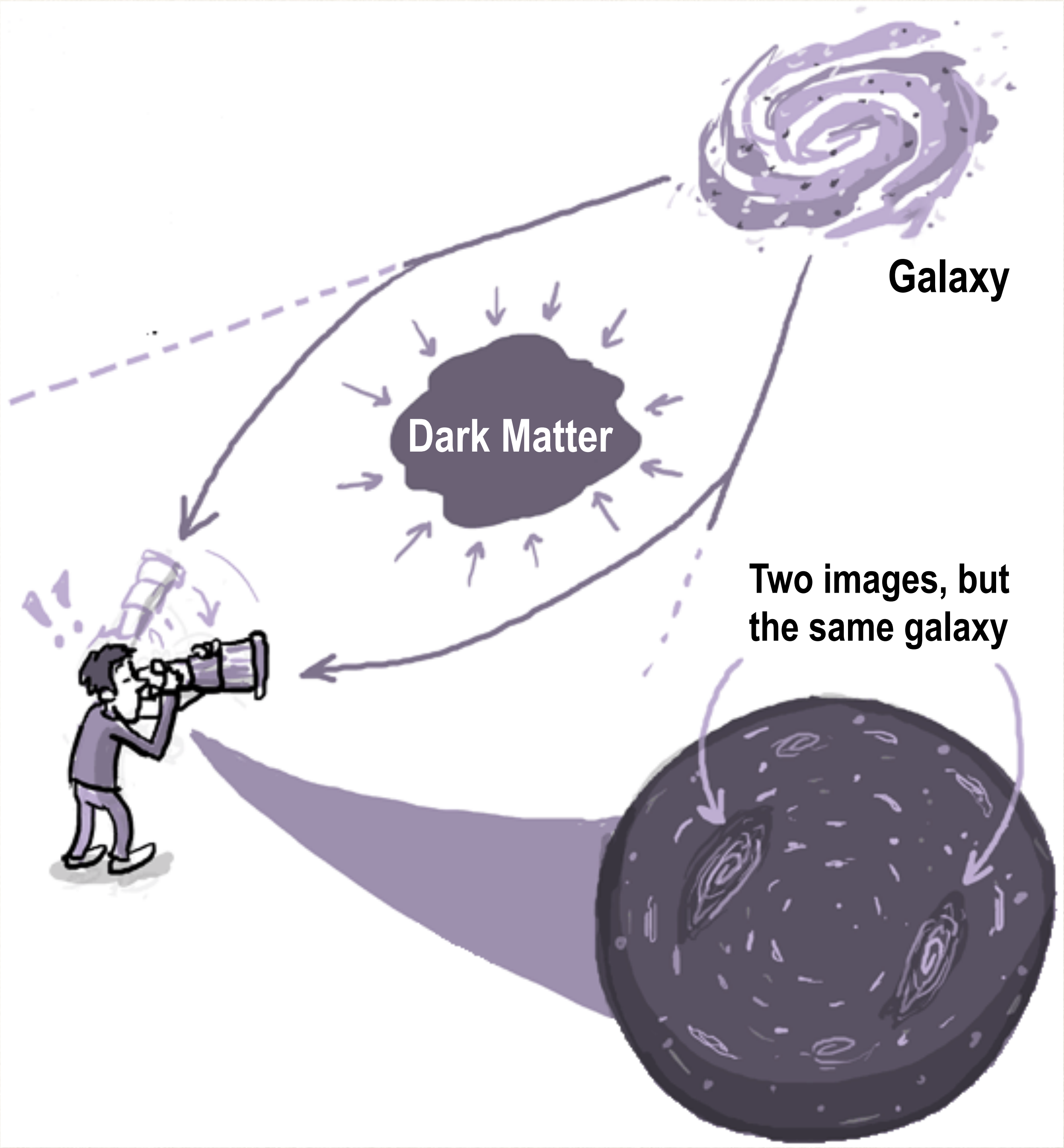




More evidence: gravitational lenses

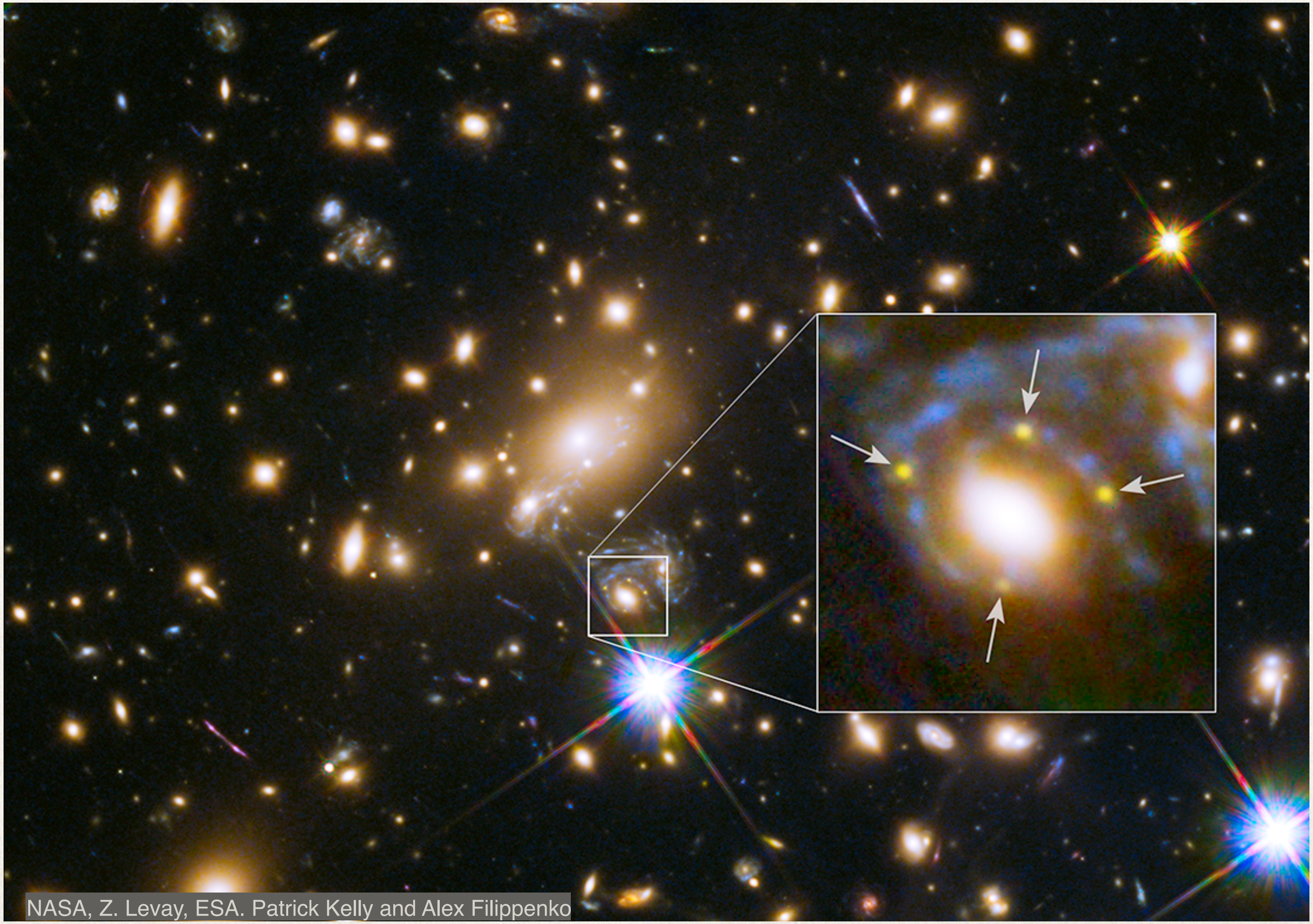
- **General relativity**
- Space-time is distorted by large masses: deflects the light path
  - <u>Weak lenses</u>: slight distortion of the image
  - <u>Strong lenses</u>: large distortion and multiple images





Gravitational lens example

Refsdal Supernova

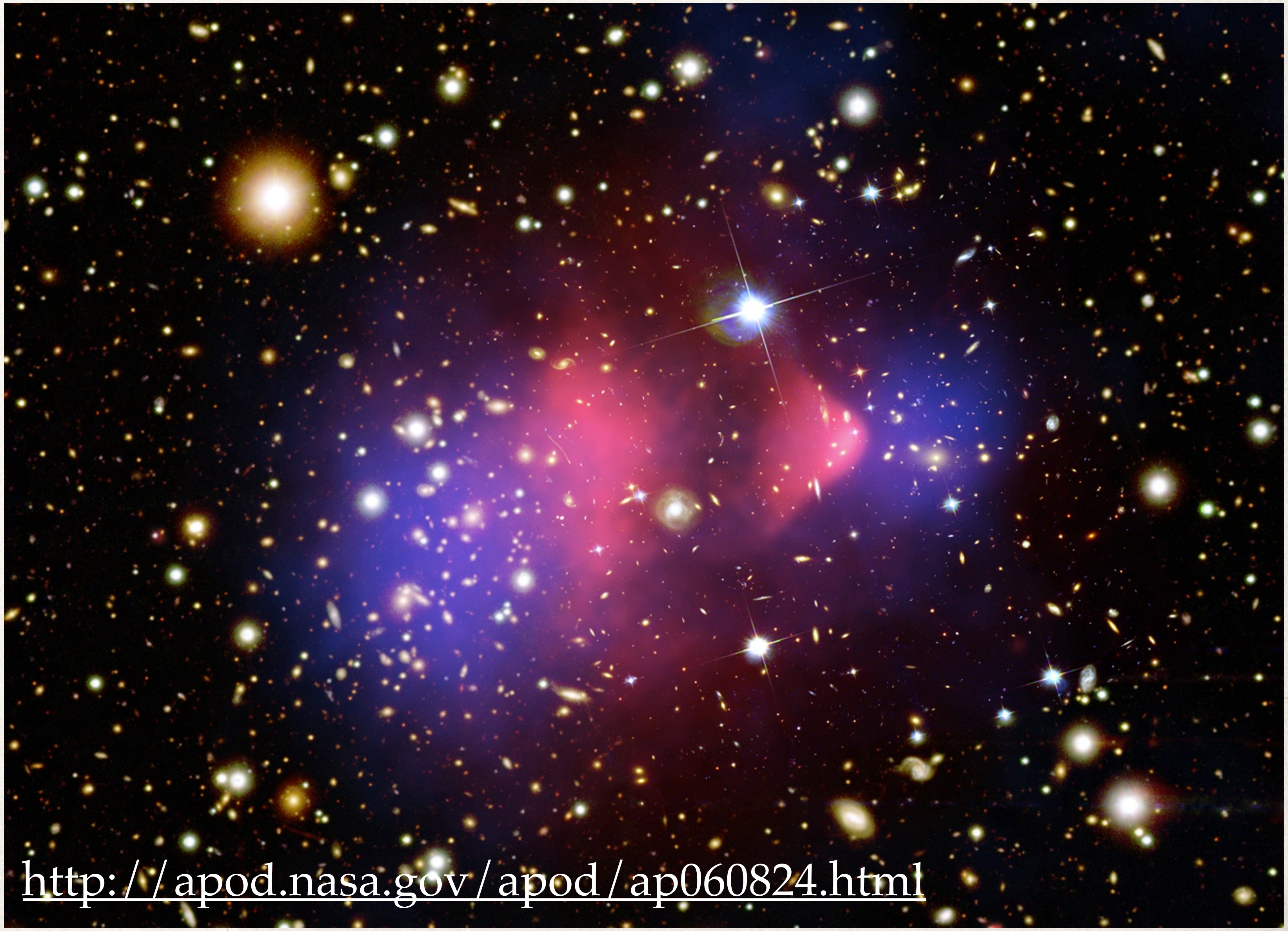


The Bullet cluster

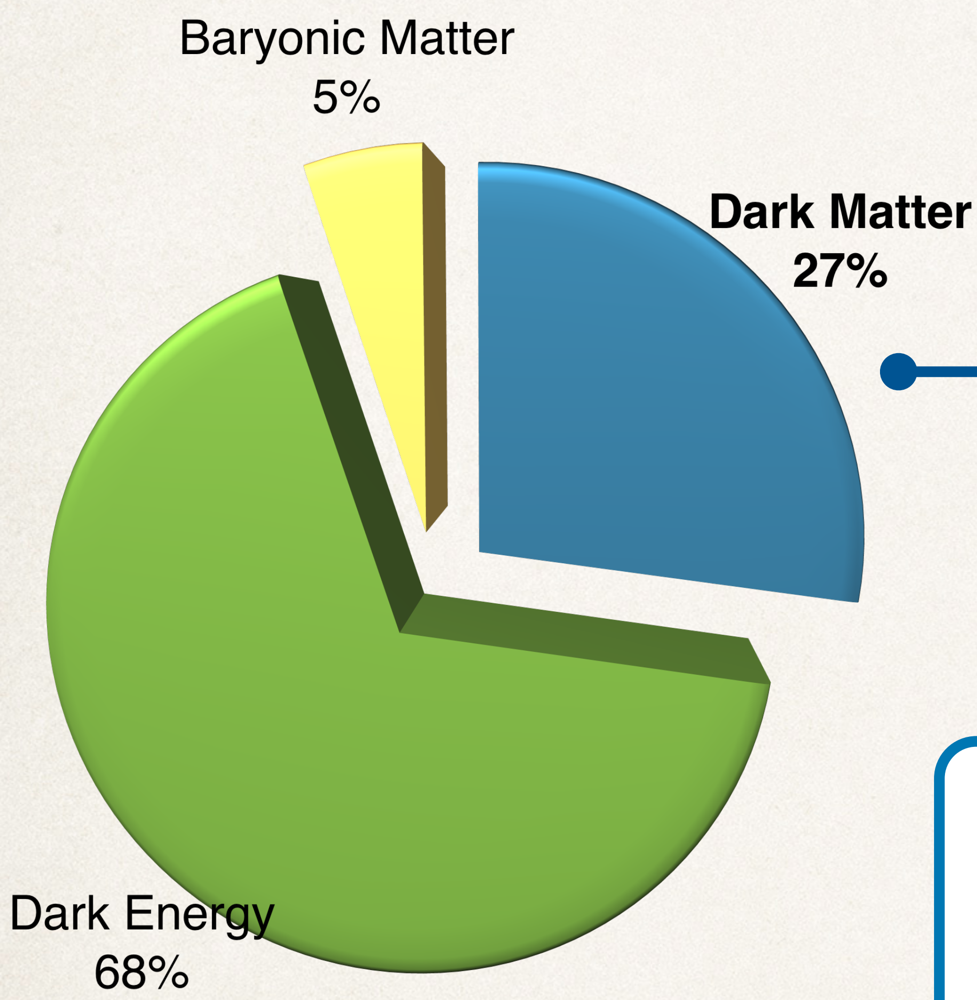
- Two galaxy clusters collided 100 million years ago
- While the dust clouds (red) interacted and got distorted during the collision, the dark matter halos (blue) just passed by each other

Gas distribution (red) measured using an X-ray telescope

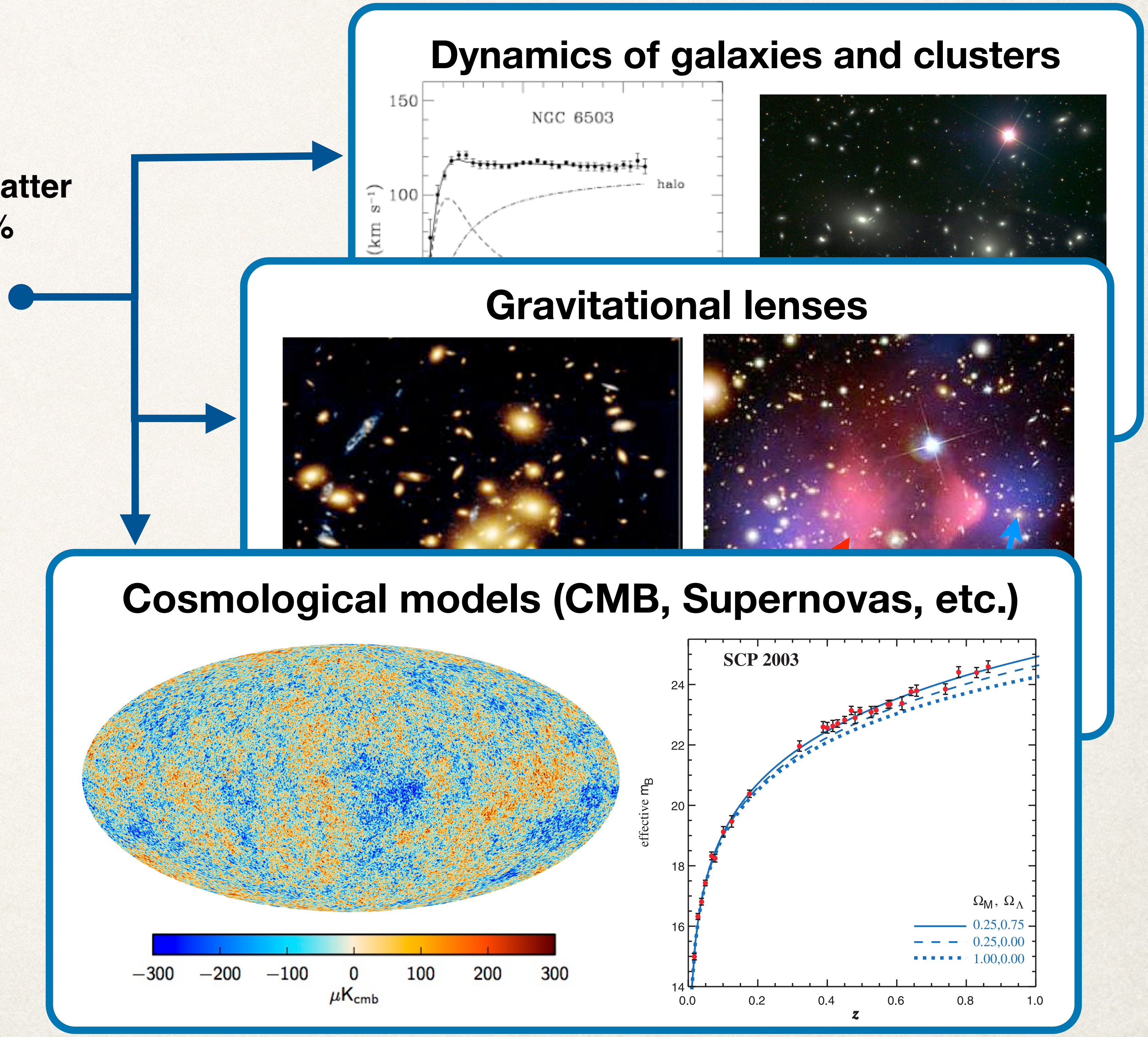
Mass distribution (blue) determined using the gravitational lens effect



What is the Universe made of?



Big Bang model

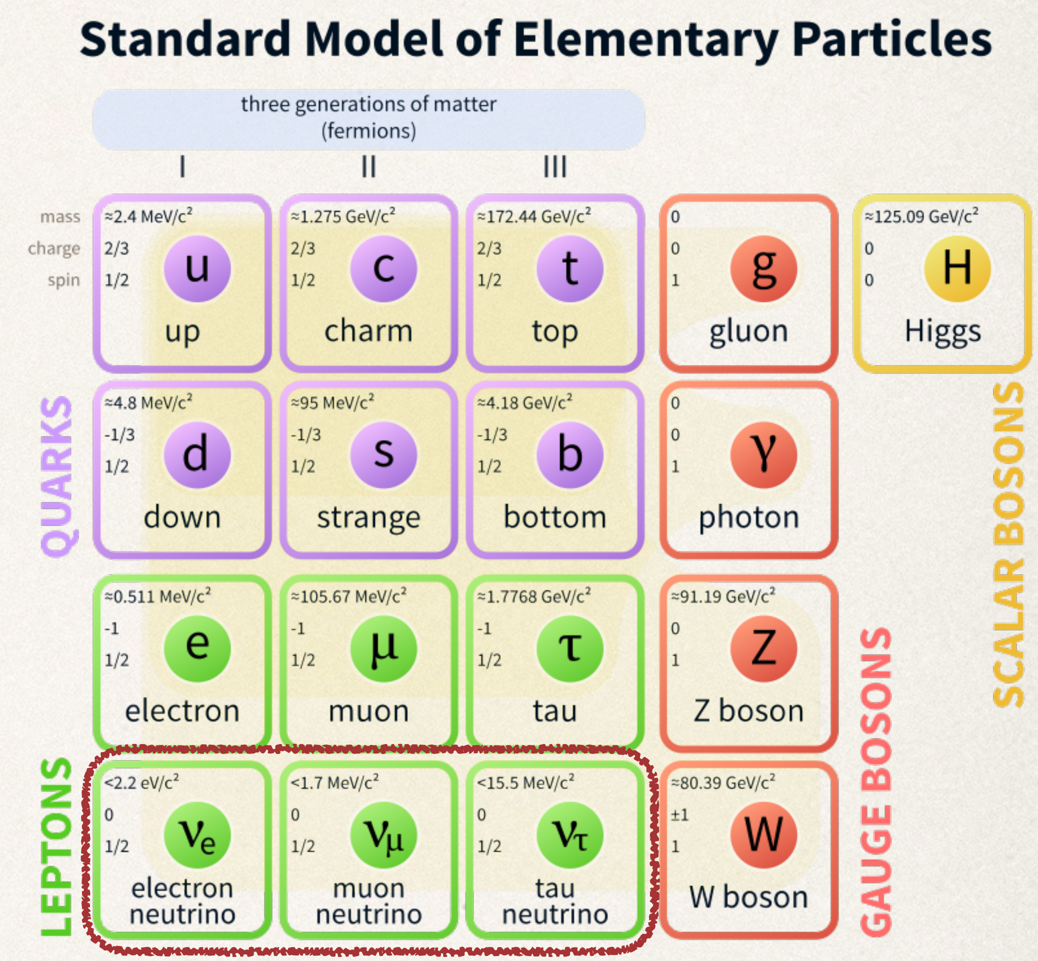


What can Dark Matter be?

- It does not exist! - modified gravity
  - MOND: *MOdified Newtonian Dynamics*
  - Assumes that gravity behaves differently at large distances (when the gravitational force is very small)
  - Explains galaxy and cluster dynamics, but not gravitational lenses or CMB
- Non luminous baryonic ("normal") matter
  - MACHOs: *Massive Astrophysical Compact Halo Objects*
  - Planets, brown dwarfs, neutron stars, etc.
  - Dedicated surveys using the gravitational lens effect, with little success
  - Total amount is limited by the CMB measurements

What can Dark Matter be?

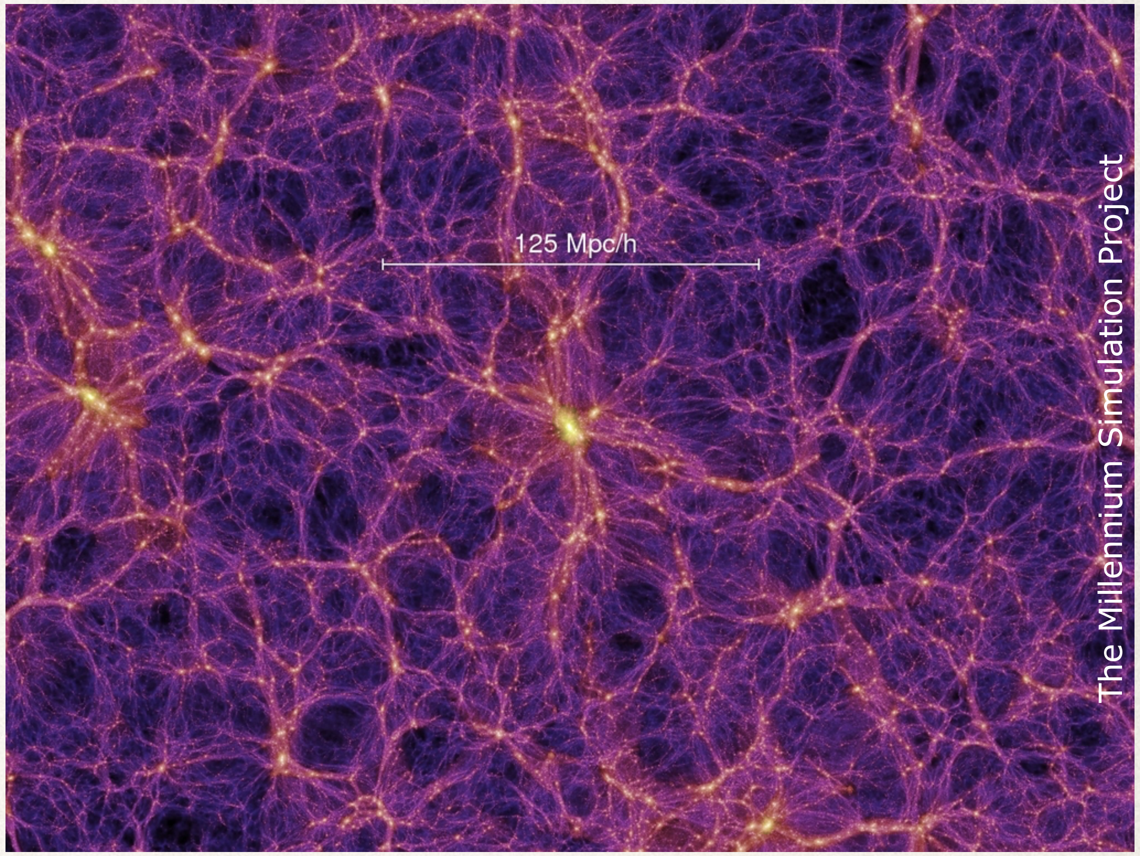
- Neutrinos
    - Sub-atomic particles with tiny masses
    - Generated in nuclear reactions inside the stars
    - We know there are plenty of them
    - Probability of interaction with normal matter is very small, but known



Due to their high velocity (close to the speed of light) they are "hot" dark matter: They would not form halos, so no galaxies or clusters would form in the Universe

It must be made of new particles!

- Required properties:
  - neutral
  - low energy ("cold" dark matter)
  - interaction with the "normal" matter only via gravity
    (and possibly a weak scale interaction)
  - high mass (~nuclei)
  - candidates from SUSY extensions of the SM

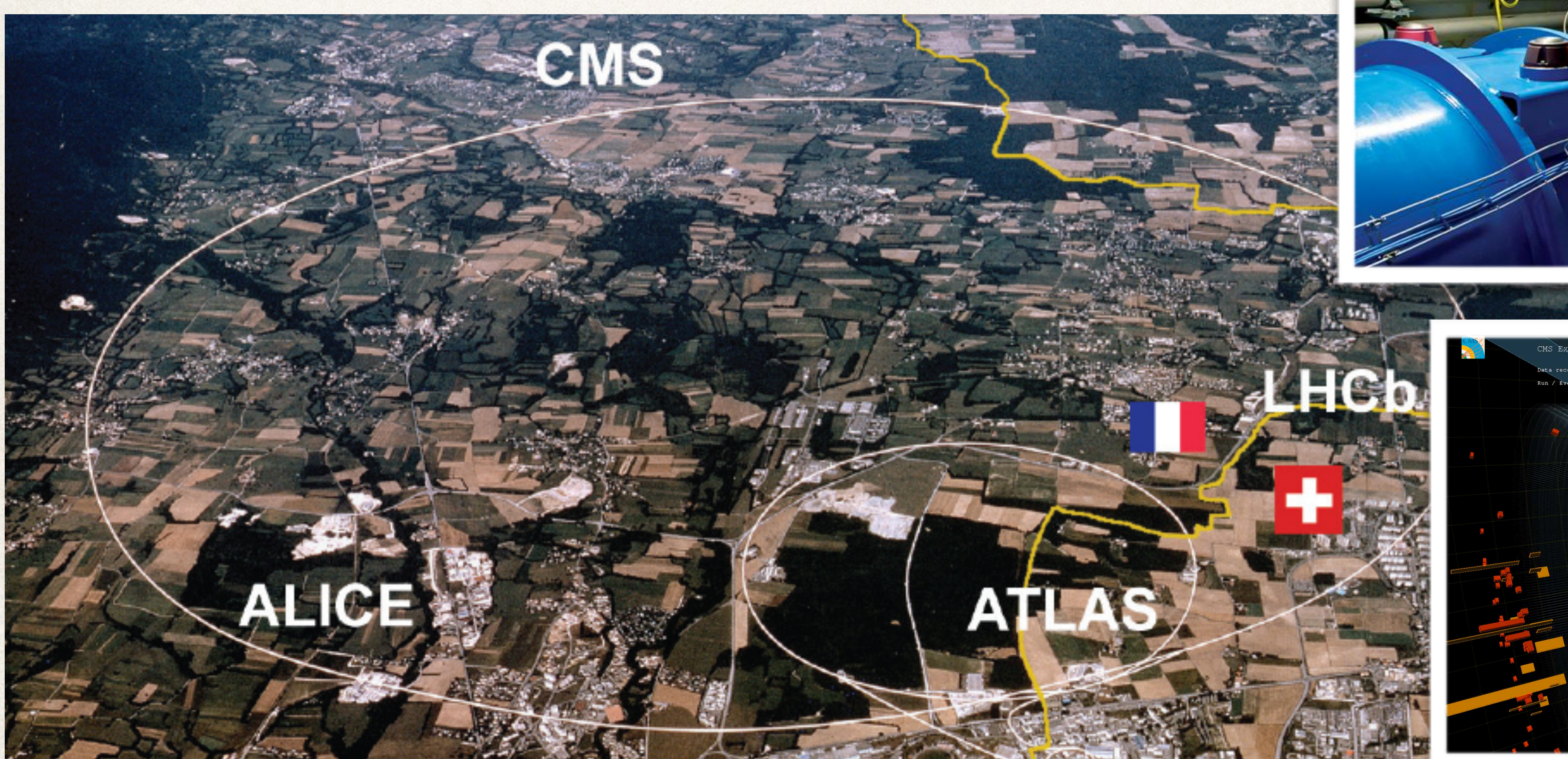


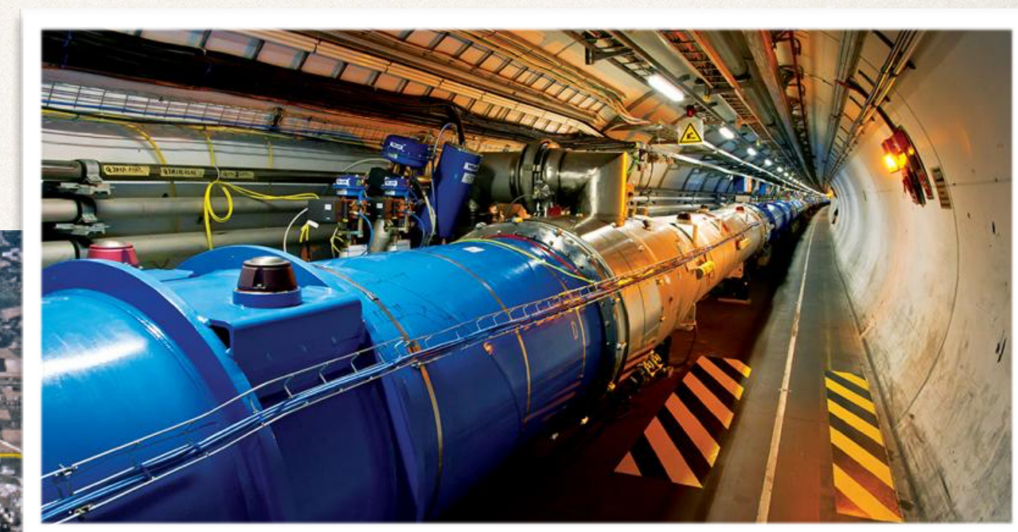
Computer simulation of large structure formation in the Universe using cold dark matter

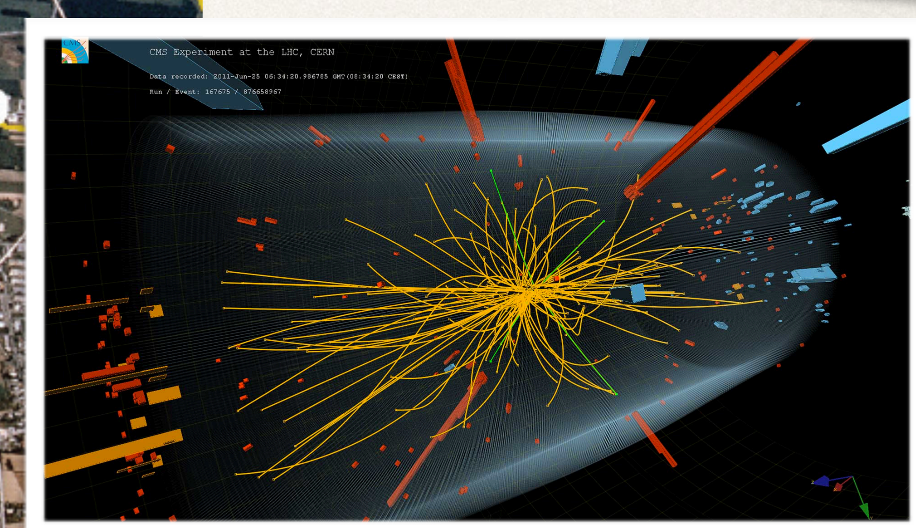
WIMPs (Weakly Interacting Massive Particles)

Production in particle accelerators (LHC)

- Protons are accelerated in a 27 km long tunnel
- Upon colliding, their energy(14 TeV*) becomes available to create new particles ($E = mc^2$)
- Some of these particles may be WIMPs (look for missing energy)



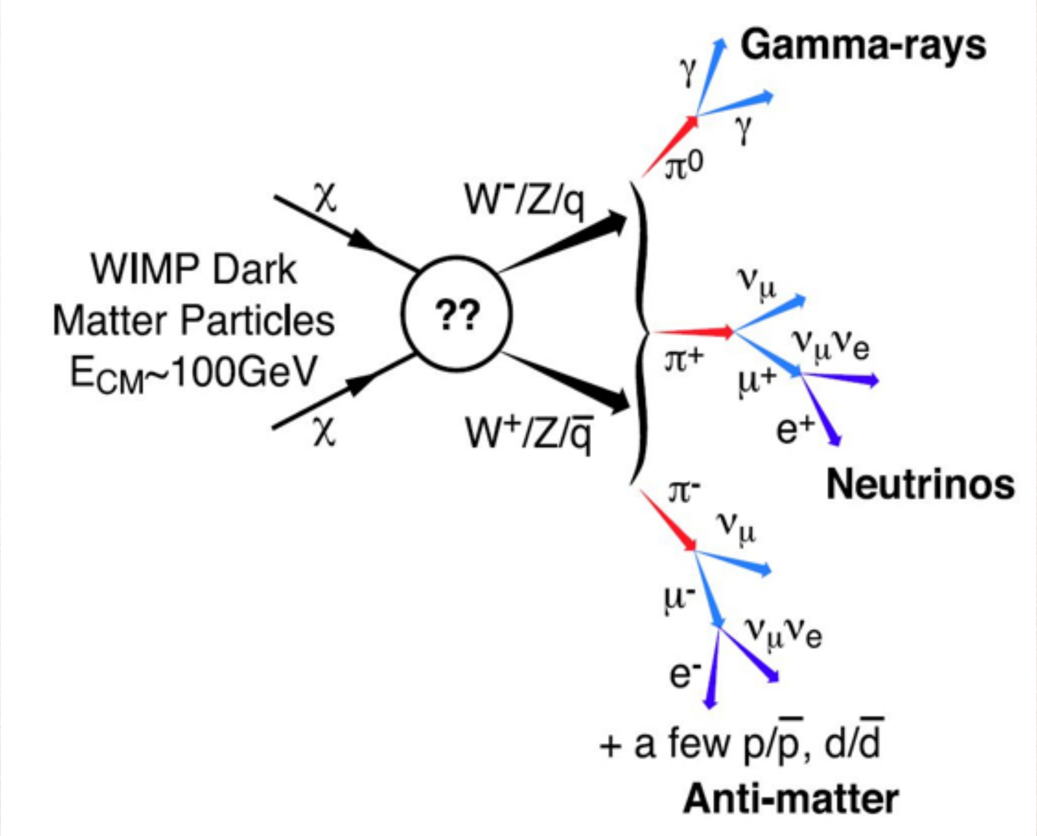




* Equivalent to the energy of a flying mosquito!

Indirect detection

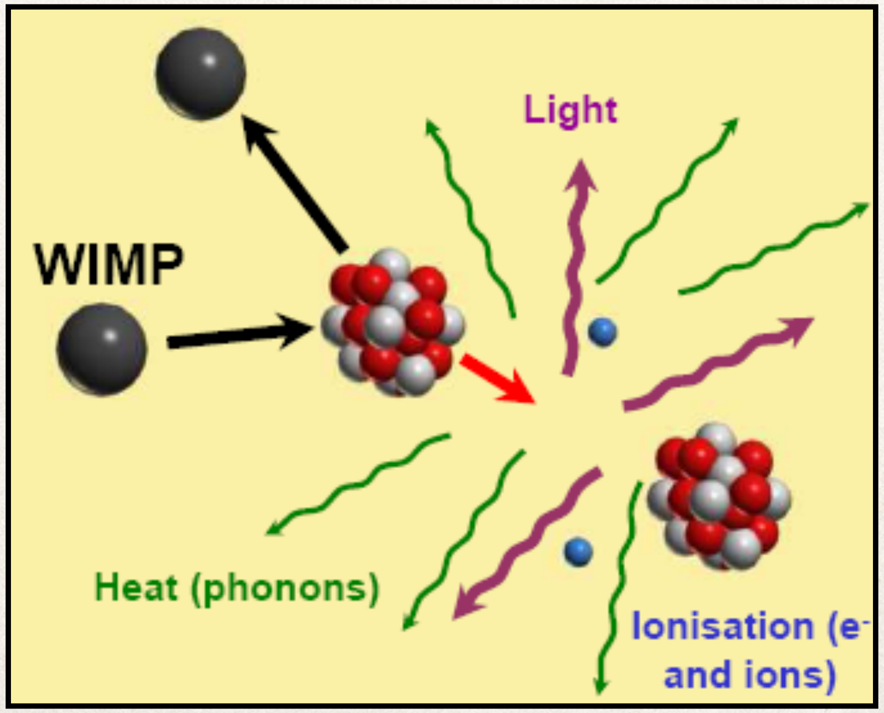
- Pairs of WIMPs may annihilate
- In this case, SM particles will be generated
- There are several experiments in orbit looking for sources of excess of these particles



This is similar to how PET scanners work: positrons annihilate with electrons and produce 2 back-to-back gammas

Direct detection

- The WIMP density in our region of the Milky Way is estimated to be 0.3 GeV/cm^3
  - This is ~3 WIMPs /litre
- Millions of WIMPs are crossing us at every second!
- Eventually, they may interact with normal matter…
- In direct detection, we try to observe the results of these interaction



Interactions produce:

- light
- charge (electrons and ions)
- heat

A couple of important details…

- The probability of WIMPs interacting with matter is **very (very!) low!**
  - Otherwise we would have found them already
  - The interaction rate is, at most 1 interaction/year/100 kg of matter
  - <u>We need detectors with large masses</u>
- The energy the WIMPs will deposit on the detectors is also **very (very!) low** (~10 keV*)
  - <u>We need very sensitive detectors</u>

Merging these two requirements is not a trivial feat!

*- 100 million times lower than the kinetic energy of a flying mosquito!

On the other hand…

- A very sensitive detector will also be sensitive to other interactions:
  - ✓ cosmic radiation
  - ✓ radioactivity in materials
  - ✓ even radioactivity in humans! (^{40}K)

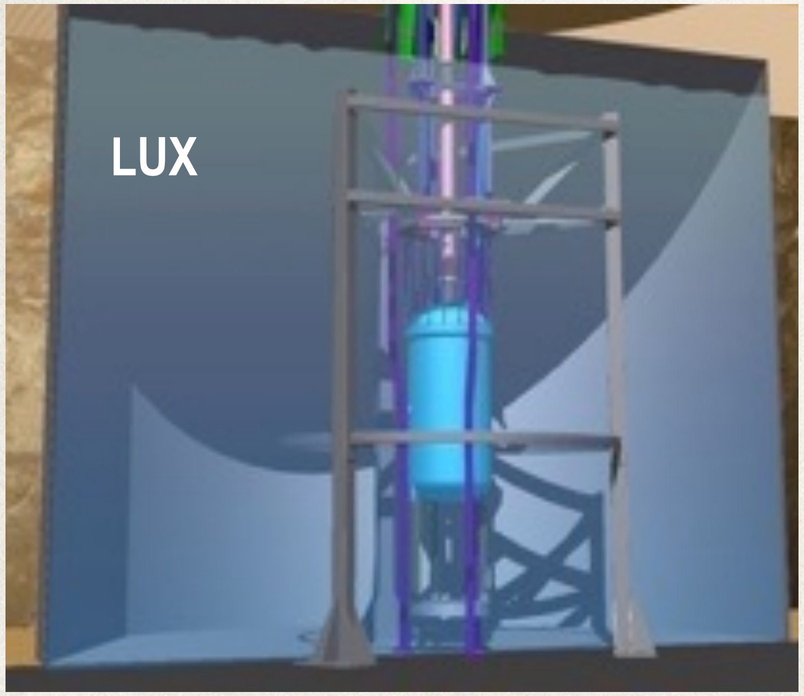
- We call **noise** to all these interaction (given that this is not what we're looking for)

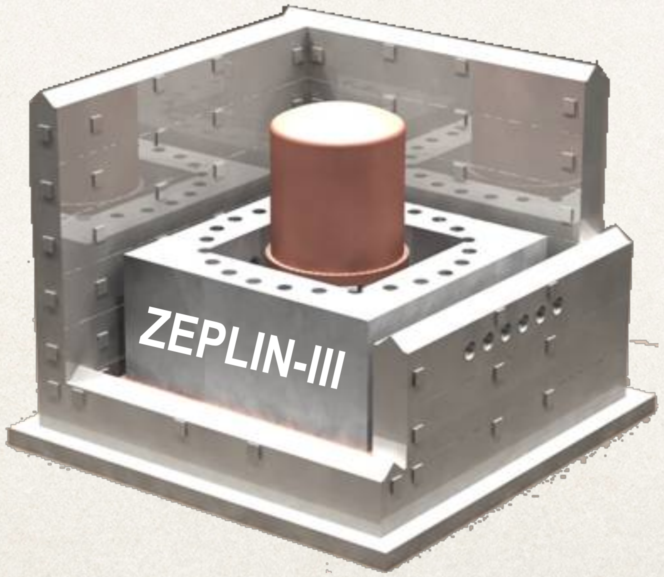
Signal vs Noise

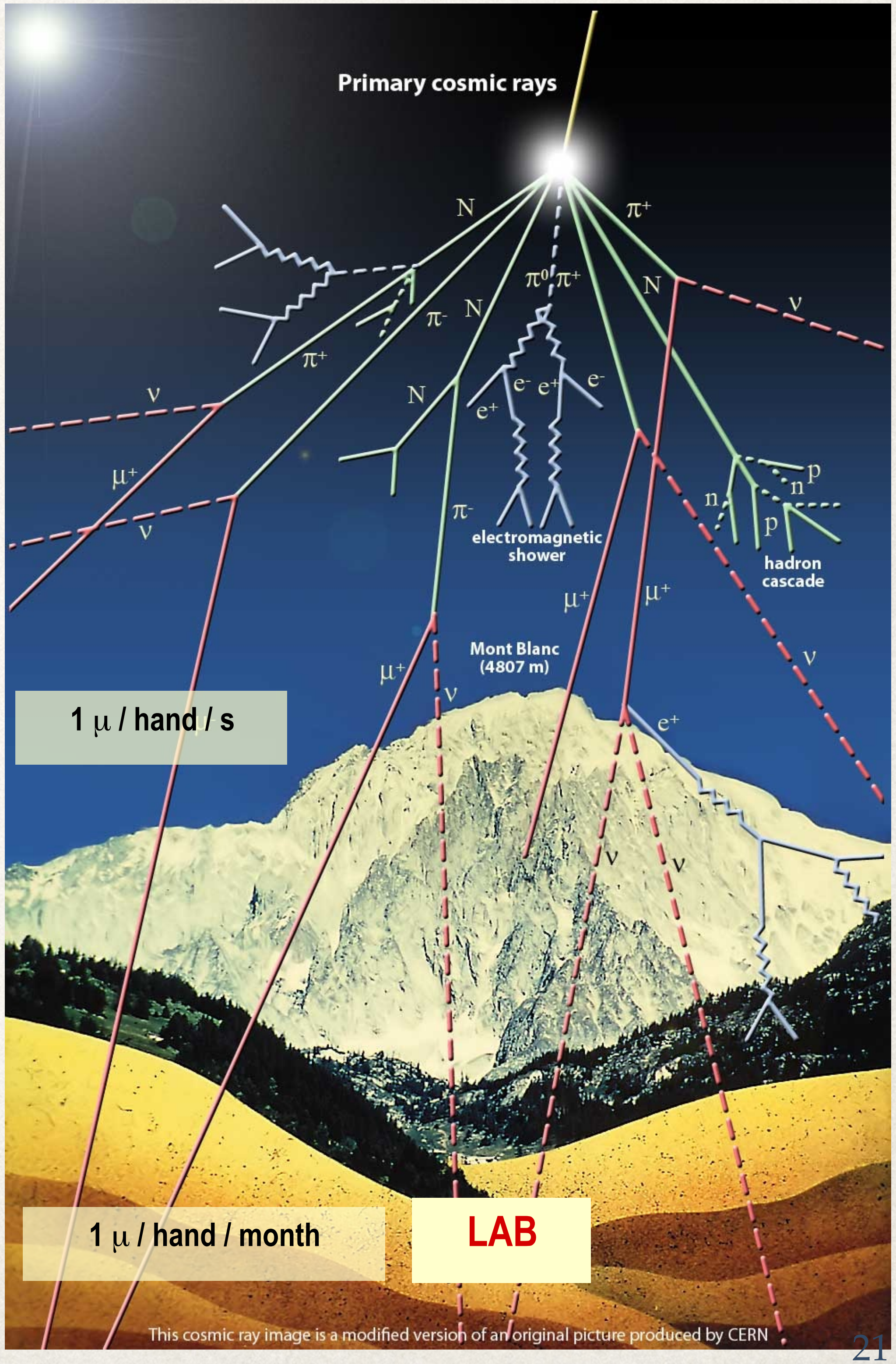
- Radioactivity from surrounding materials:
  ~100 decays/kg/sec
- Human radioactivity:
  ~1000 gamma-rays/person/sec
- Cosmic radiation:
  ~1 muon/hand/sec
- **WIMPs:**
  <1 interaction/100kg/year

How can we reduce the noise?

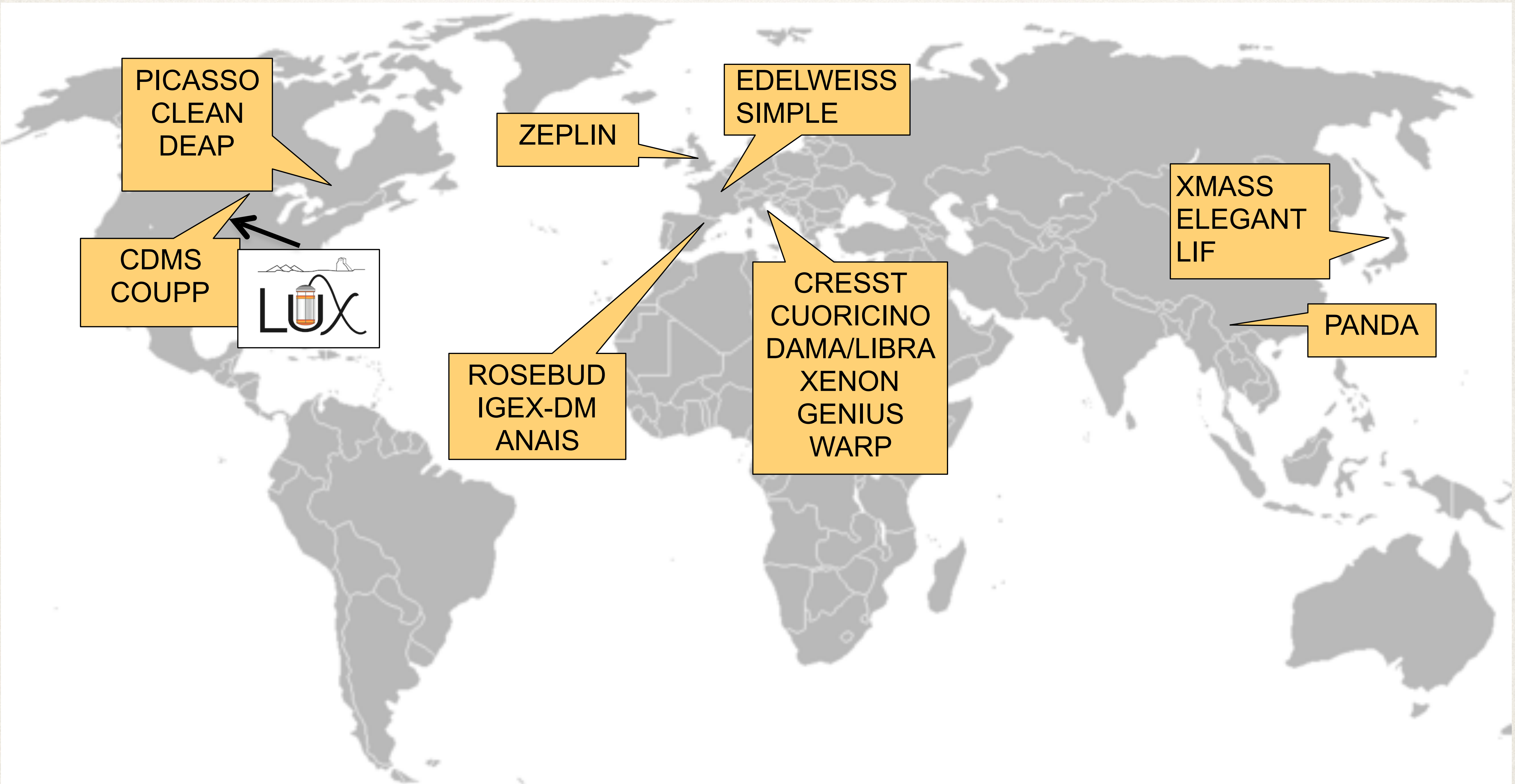
- Run the experiment in an underground laboratory
  - Reduces muon flux, but not the WIMPs
- Shield the detectors from surrounding radiation
  - Lead + H-rich plastic, water
- Carefully select building materials for low radioactivity







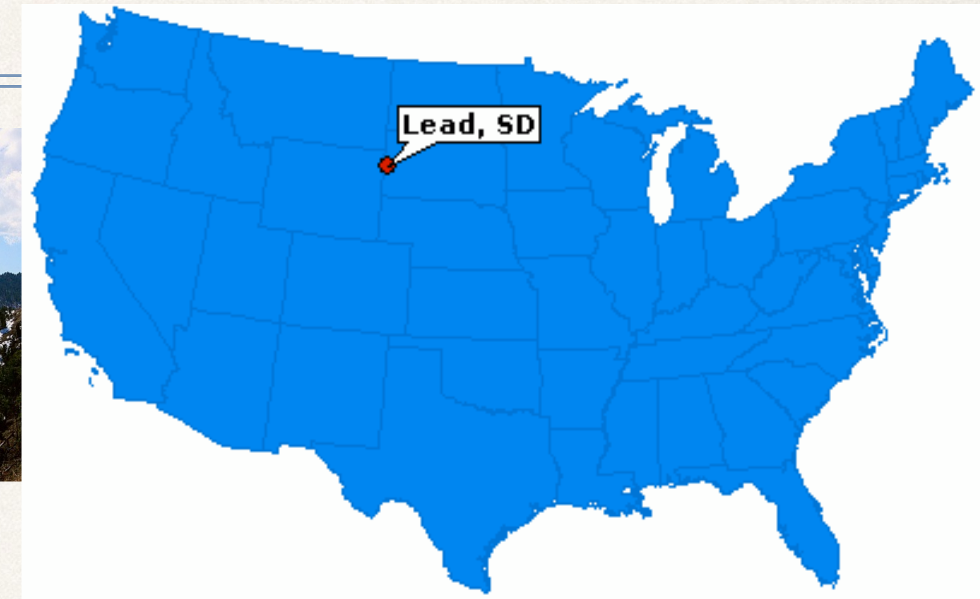
Direct detection experiments around the world

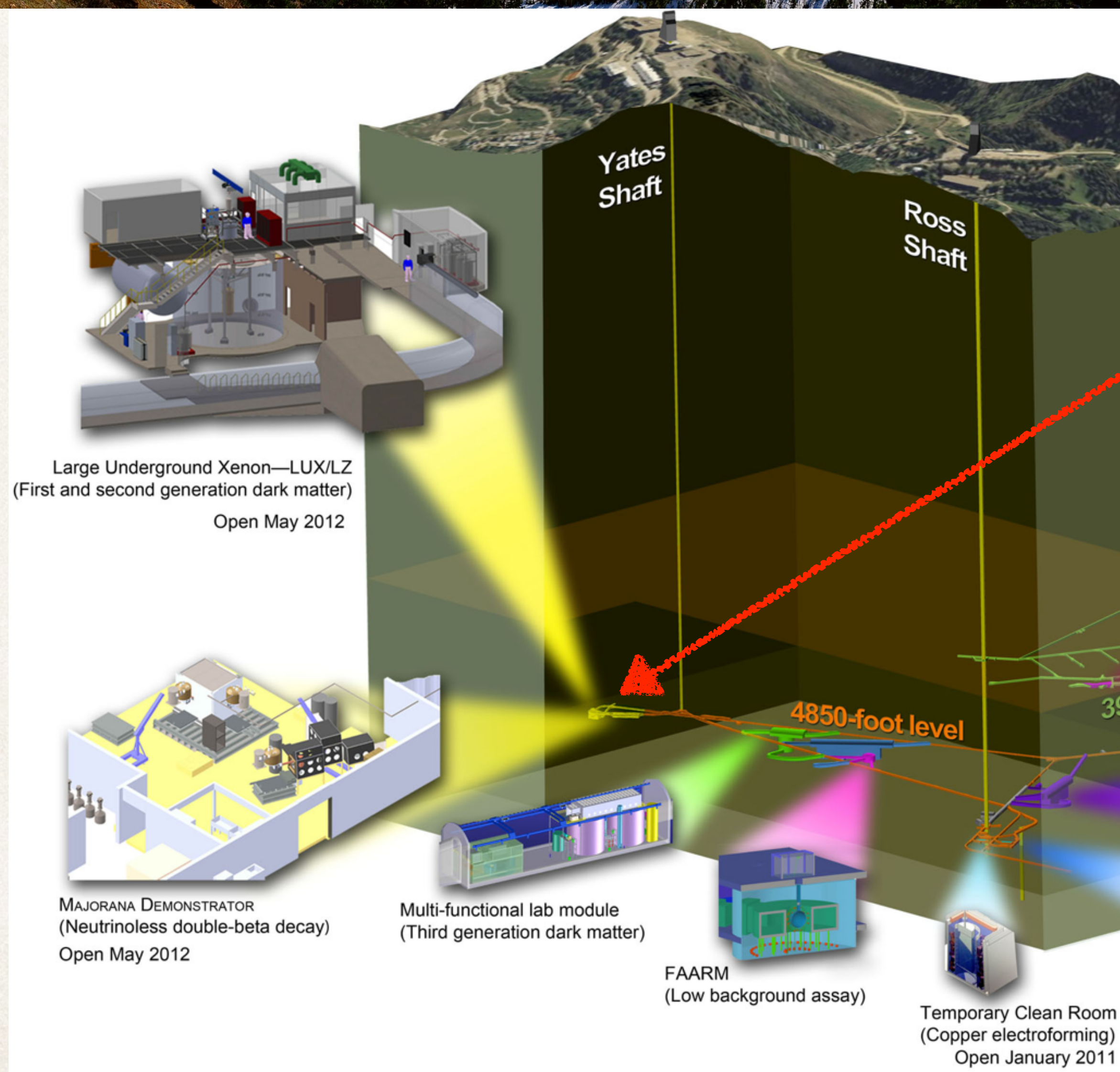


A specific example…

The Large Underground Xenon (LUX) Experiment

Sanford Underground Research Laboratory





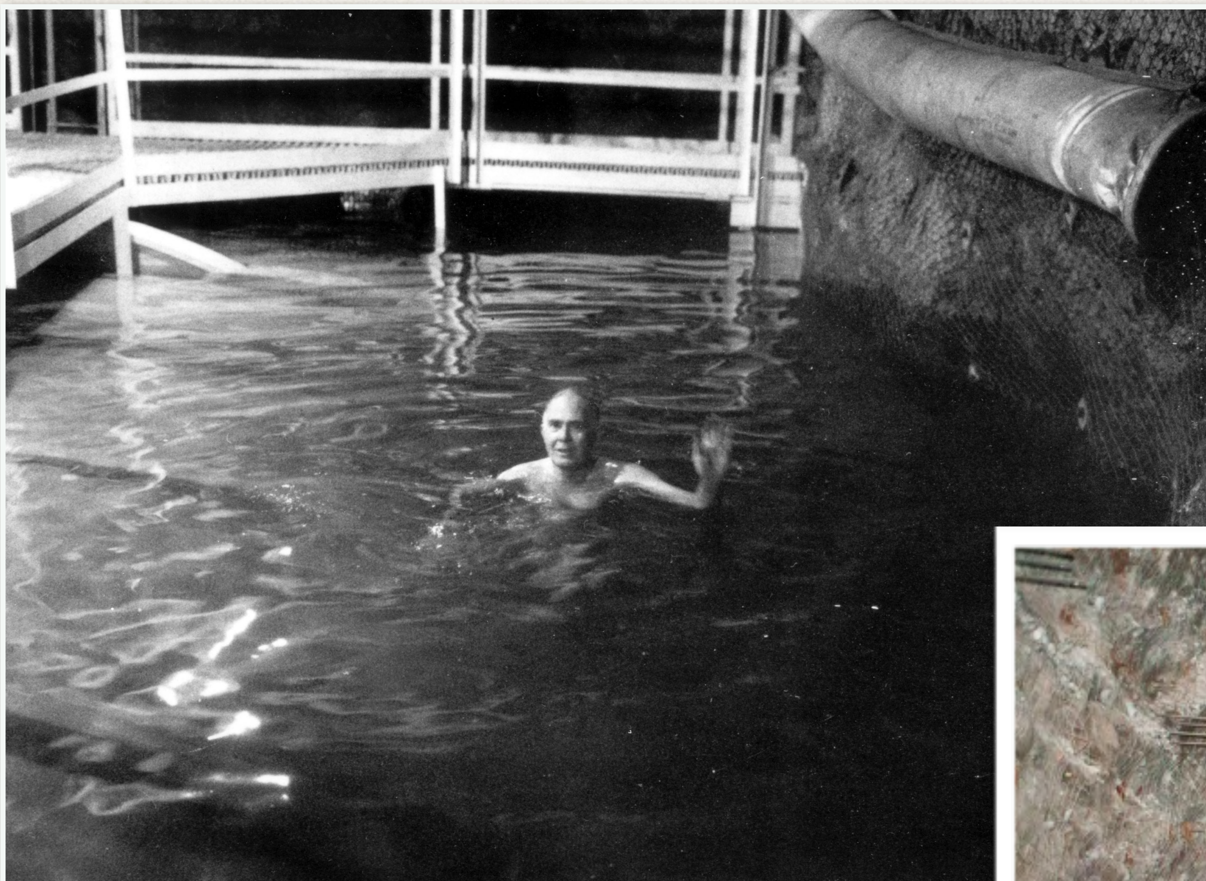
1478 m deep
(equivalent to 4.2 km of water)

Cosmic ray muon flux is reduced by a factor of 10 millions

1 muon/hand/3 months

Sanford Underground Research Facility

Building the underground lab…

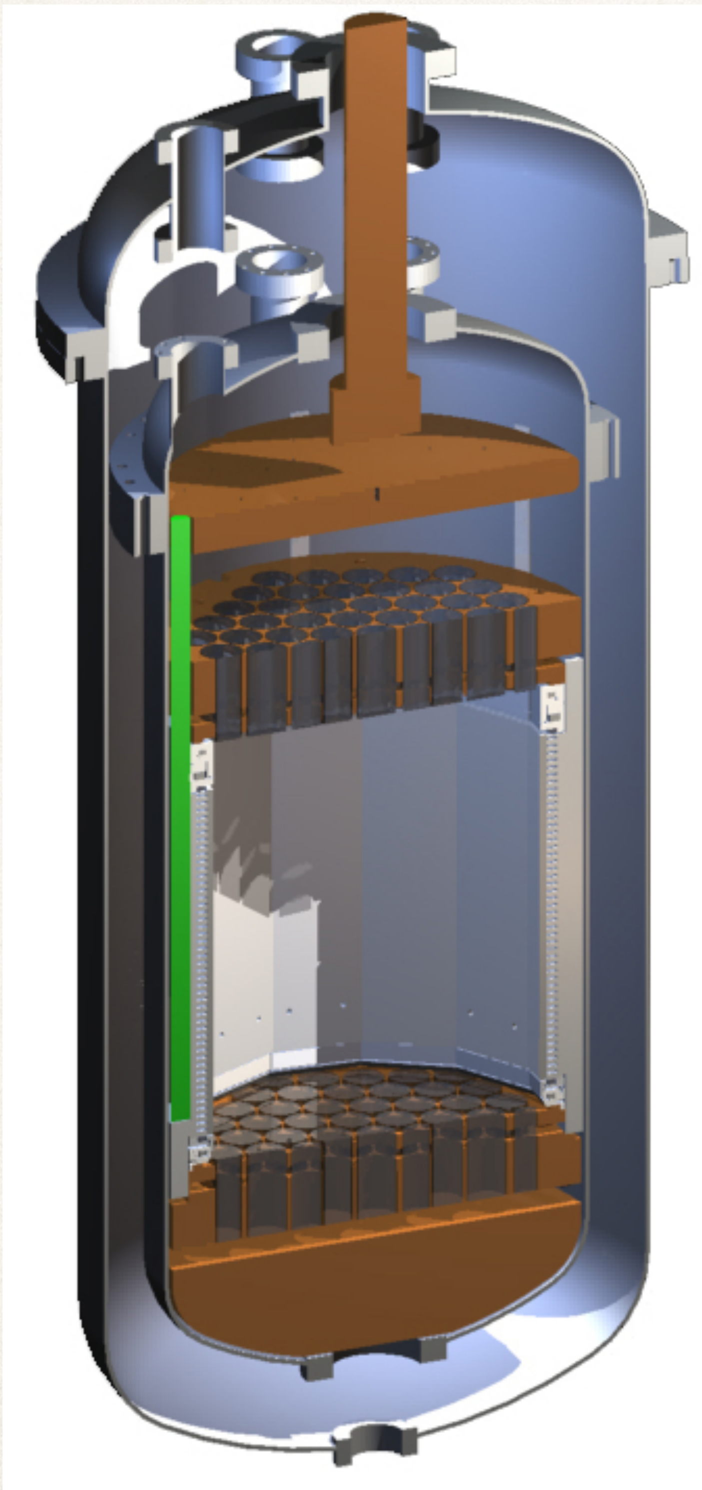


1960-80: Ray Davis installed the first solar neutrino experiment in this same cave

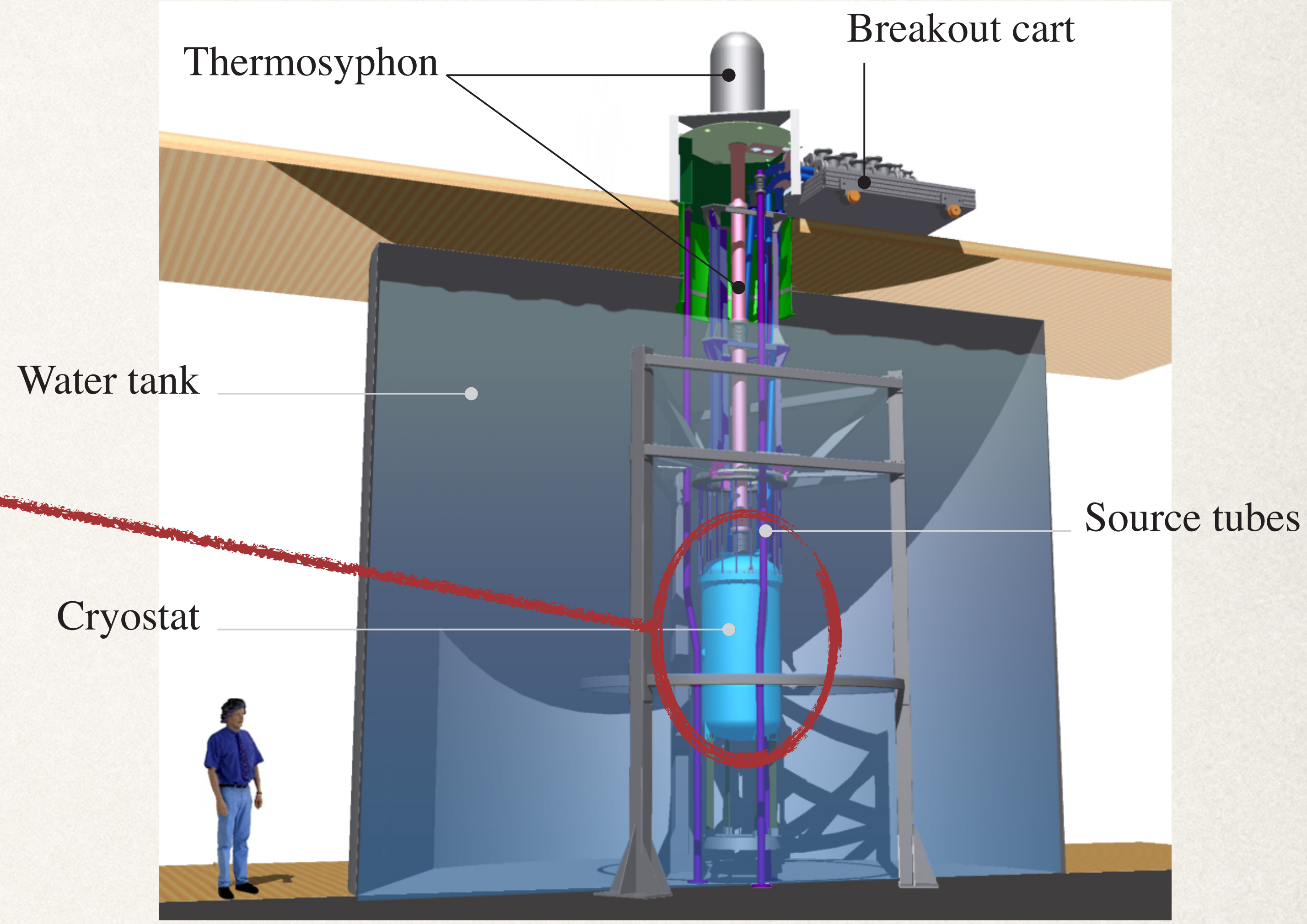
2010: Cavern clean and ready for the new laboratory

Current status…

The LUX detector (2013-2016)



370 kg of liquid xenon

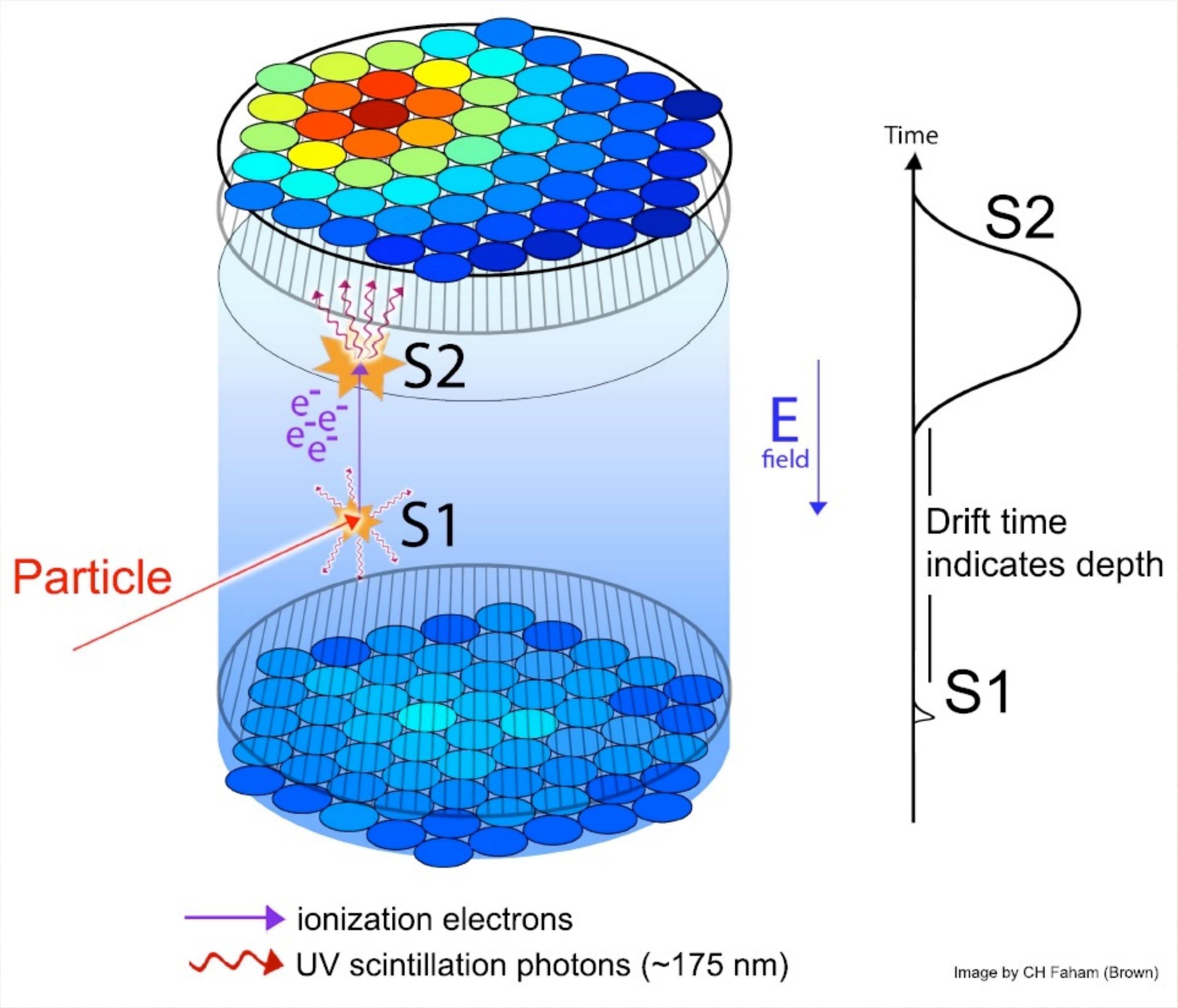


300 ton water tank

External radioactivity reduced to negligible levels

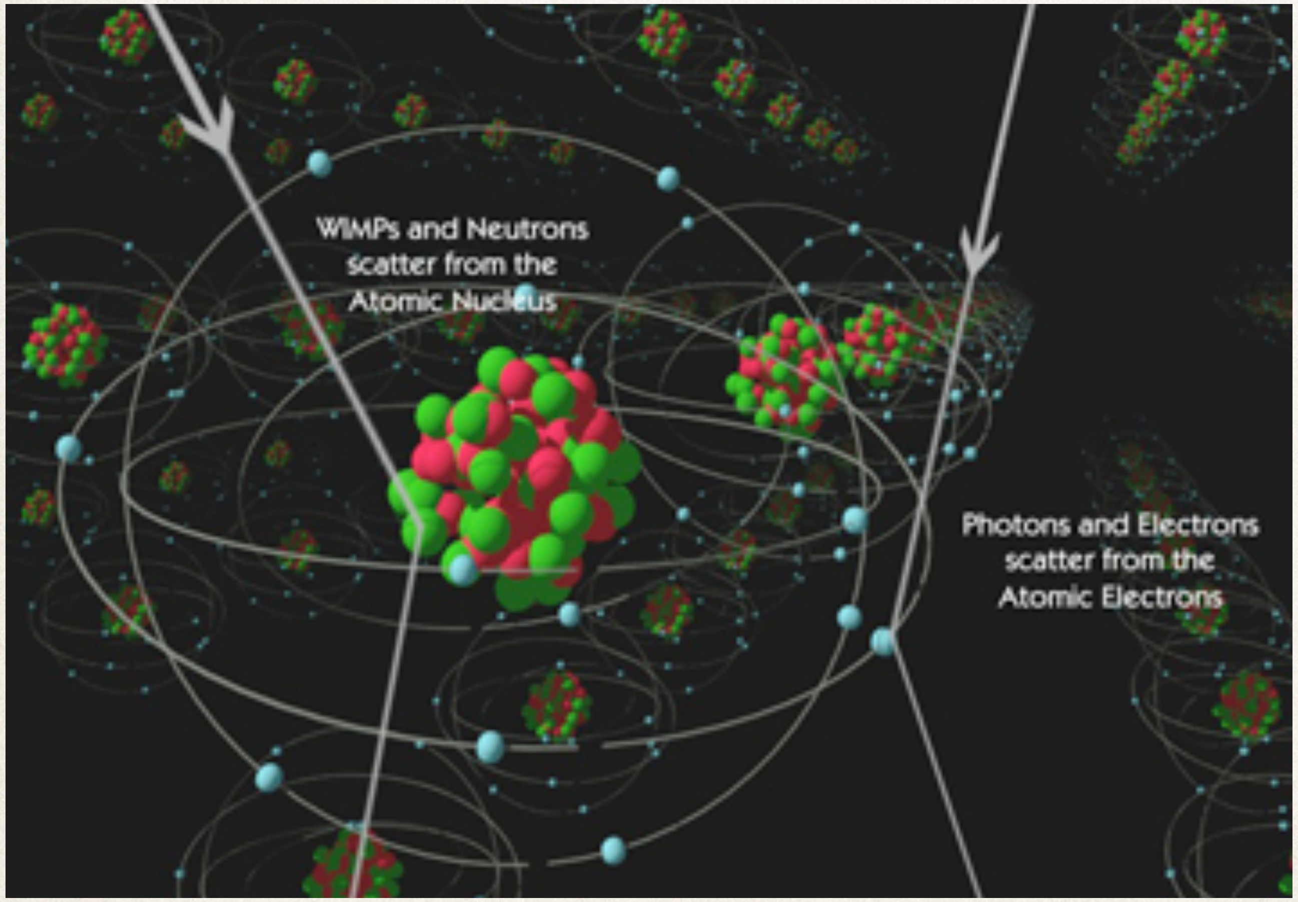
How a xenon detector works

- Xenon has high density (~3 g/cm^3) and high atomic number (A~130)
  - large interaction probability
- To liquify, we need to cool it (and maintain it stable) at ~ -100 ºC
- Small gas layer (~5 mm) above the liquid
- An electric field transports free electrons to the surface
- An interaction produces:
  - scintillation light (S1)
  - free electrons, which are extracted to the gas and produce a secondary light signal (S2)
- From these two signals we can reconstruct the energy and 3D position of the interaction

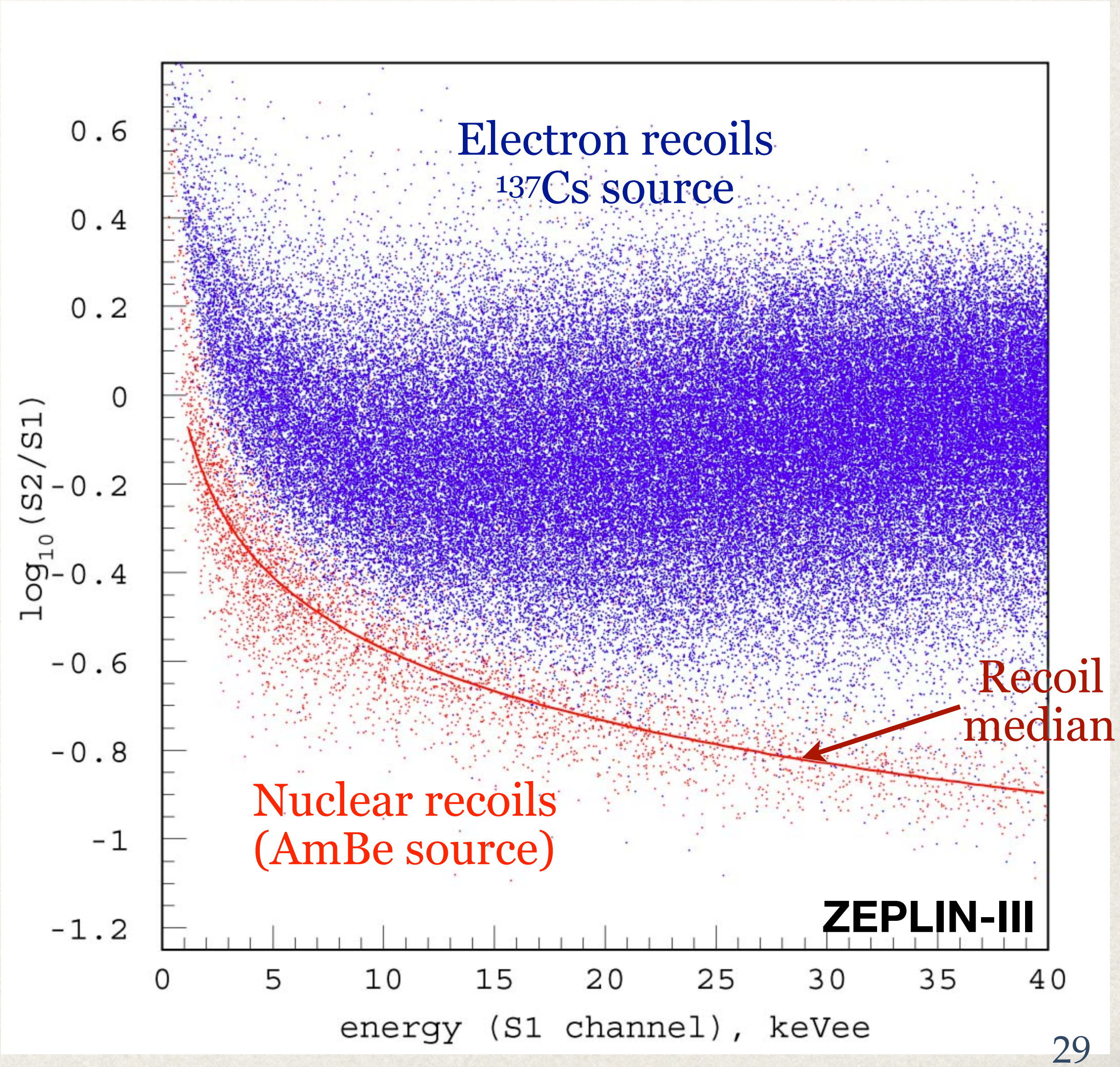


Discrimination in xenon TPCs

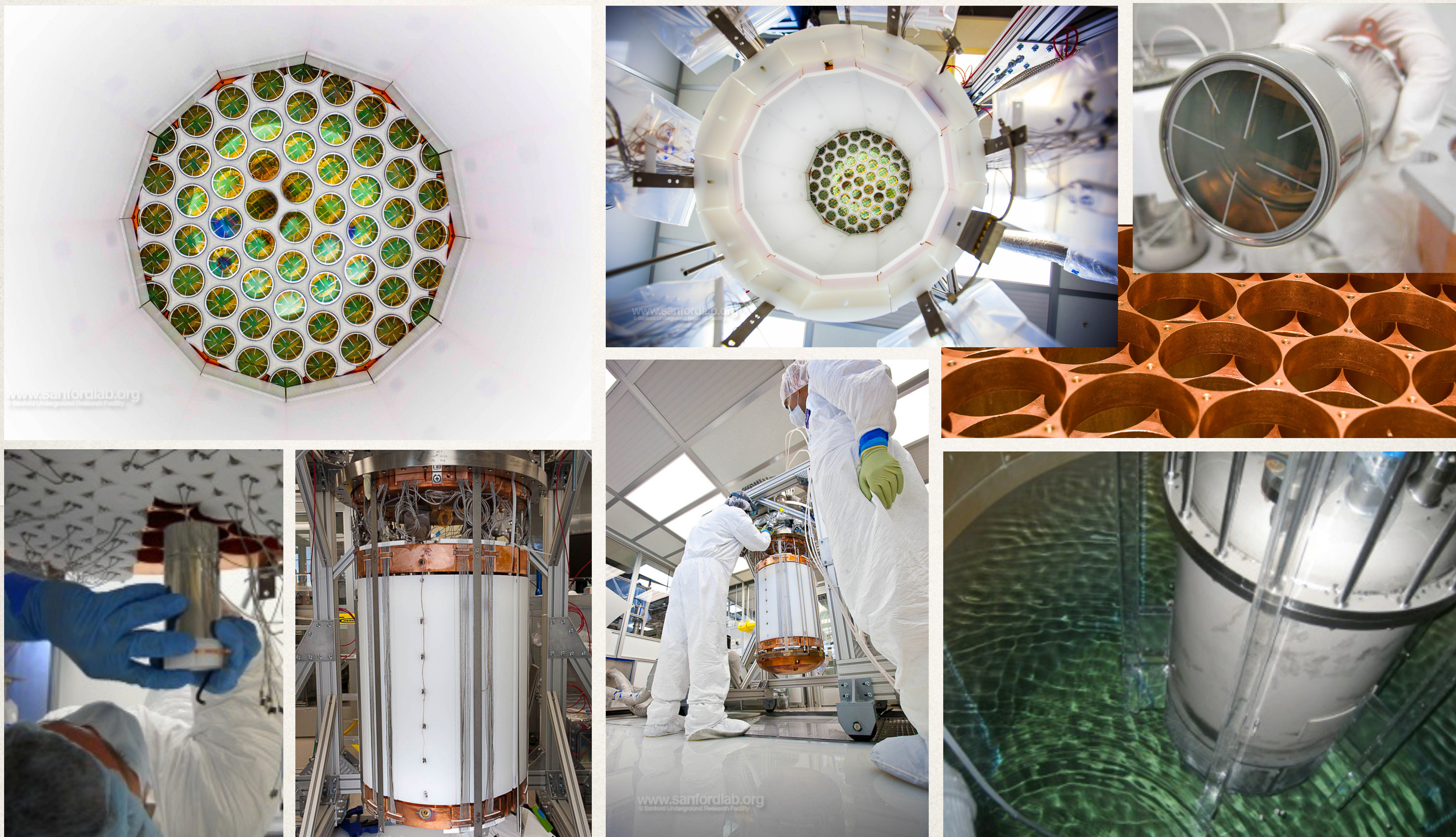
- The water tank provides great shielding against the external radioactivity, but there is still the radioactivity in the detector building materials
- Xenon detectors are very efficient at discriminating γ-ray and β interactions (interactions with the atomic electrons) from nuclear recoils (due to WIMPs or neutrons)



$(S2/S1)_{\gamma} > (S2/S1)_{WIMP}$

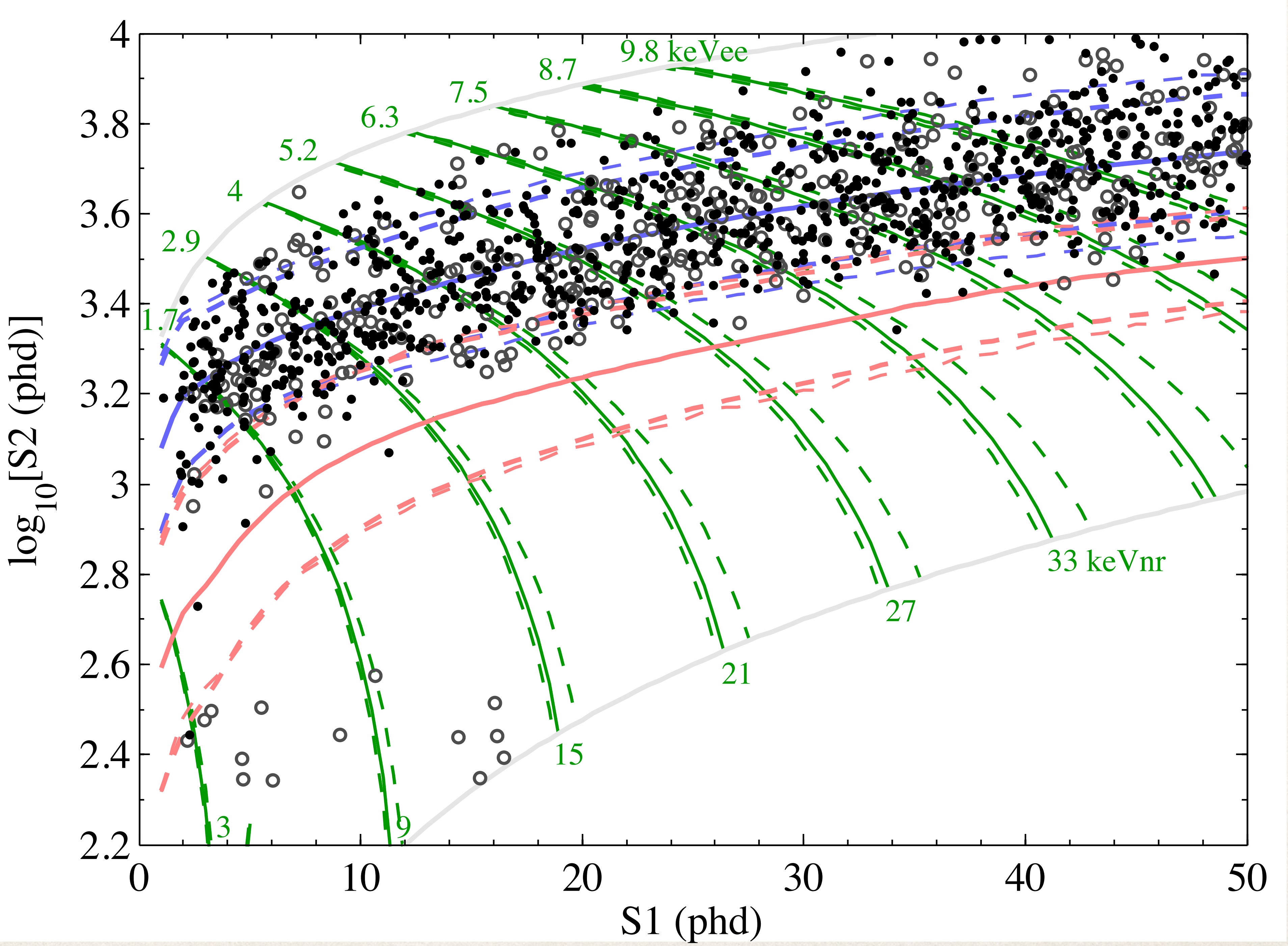


Assembling the LUX detector



LUX installed inside the water tank

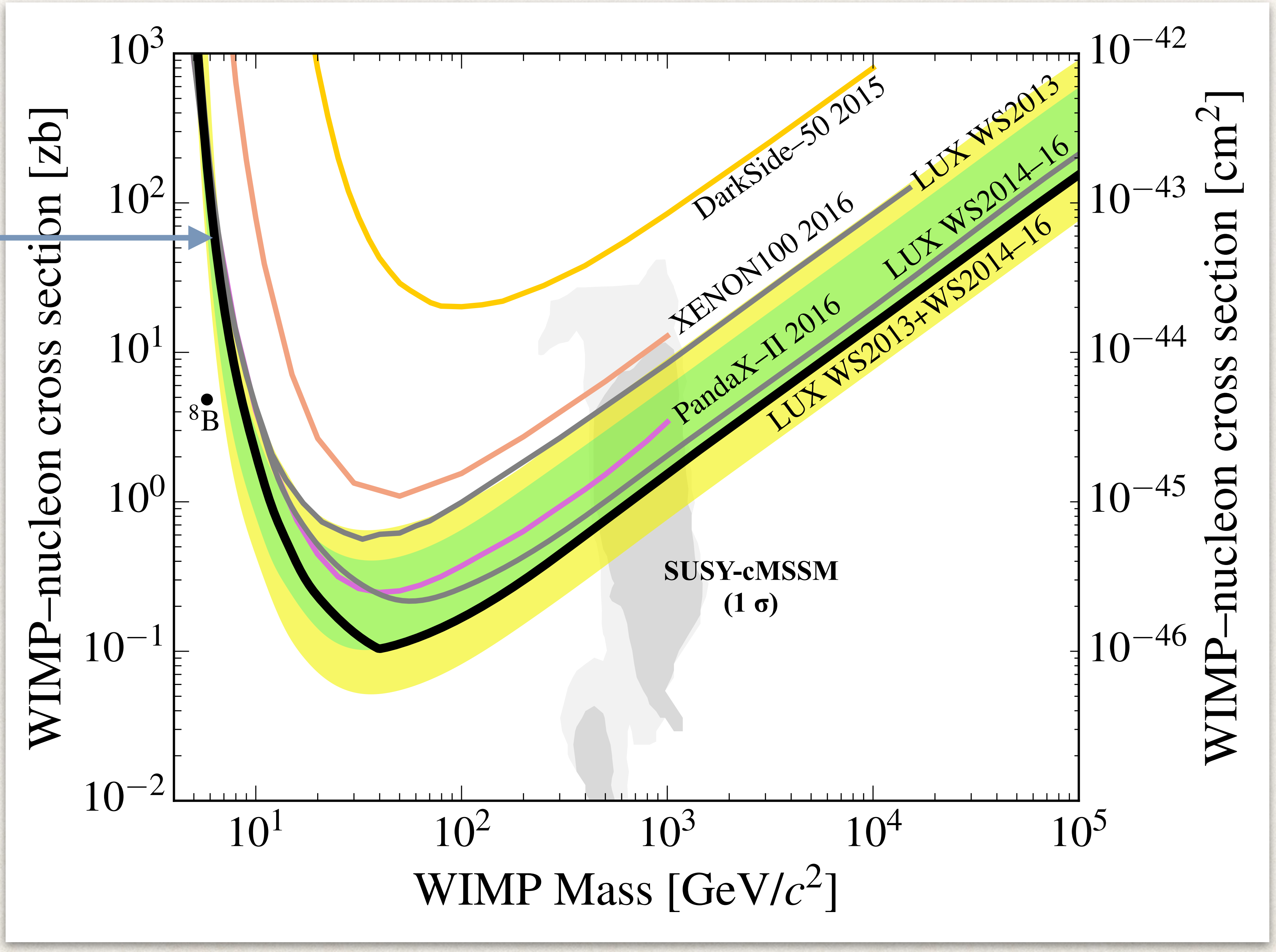
Latest LUX results (2017)



Latest LUX results (2017)

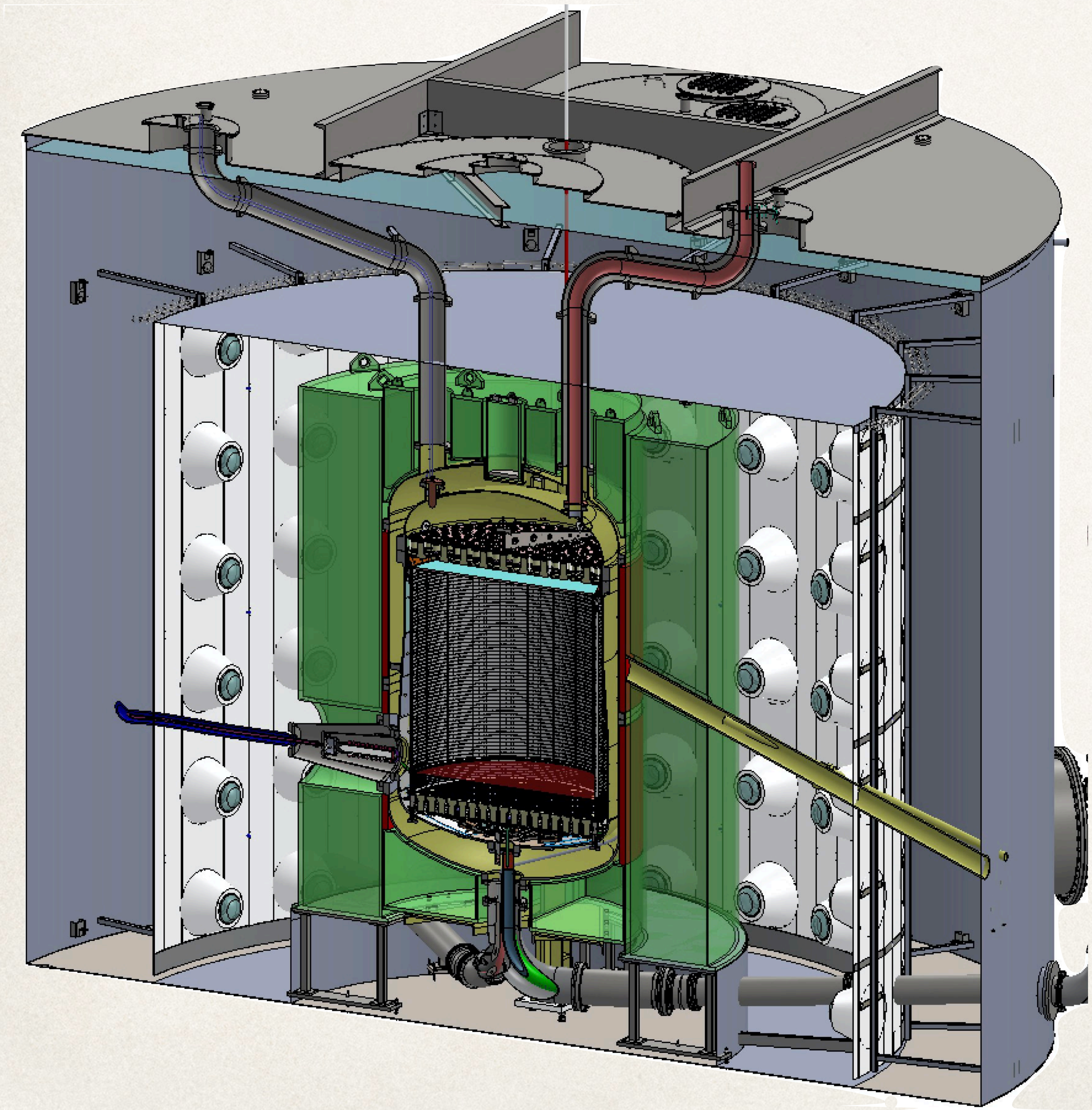
No WIMP detected after 3 years running

The entire space above this curve is excluded



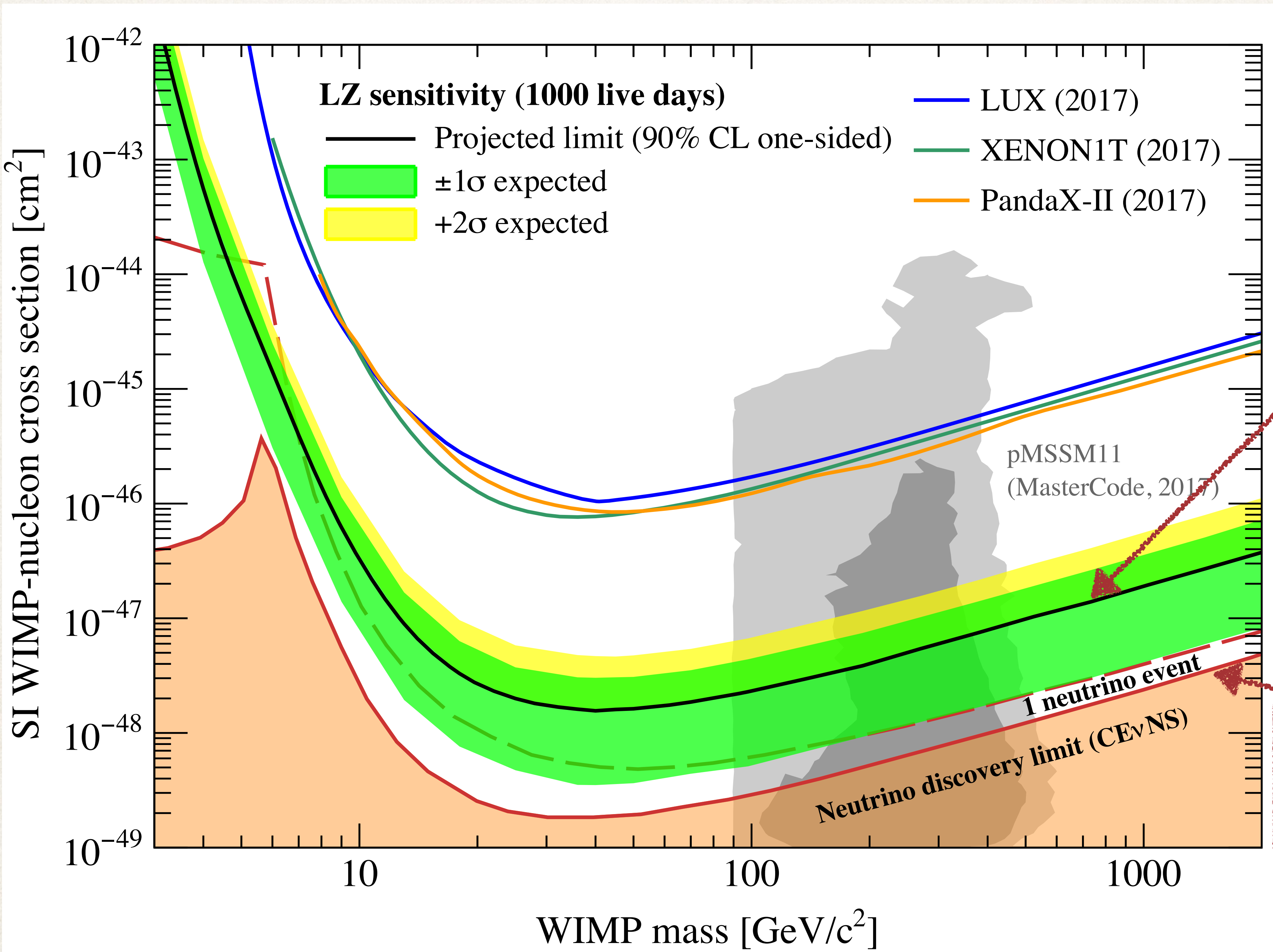
Most sensitive WIMP experiment in the world between 2013-17

The future: LUX-ZEPLIN (2020-25)



- Same technology as LUX
- 10 tonnes of xenon
- Installed in the same lab/tank
- Operation starts in 2020
- Duration: 4 - 5 years
  (but first results after just a couple of months)

The future: LUX-ZEPLIN

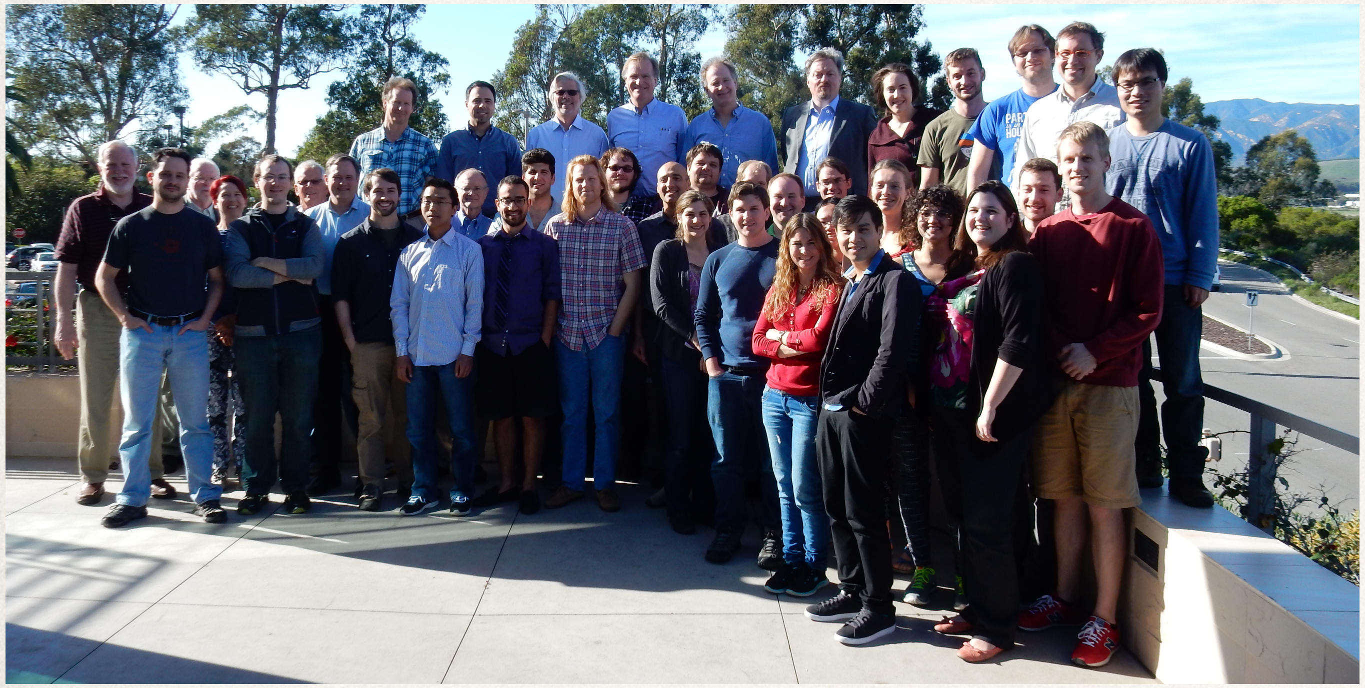


100x more sensitive than LUX

(this is the sensitivity, but we hope to find dark matter before getting there!)

Soon we will hit the "neutrino floor"

The LUX and LZ collaborations



LUX

20 institutions

~100 scientists

luxdarkmatter.org

LZ

36 institutions

~250 scientists,

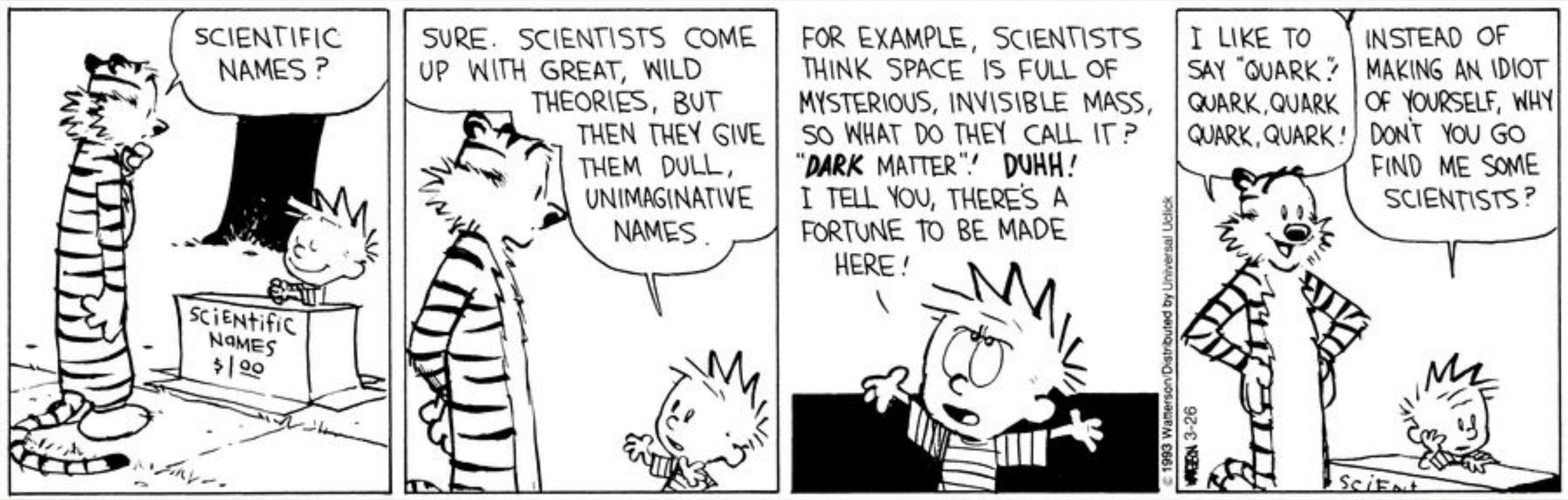
engineers and technicians

lzdarkmatter.org

The LIP Dark Matter group

LIP activities in LZ

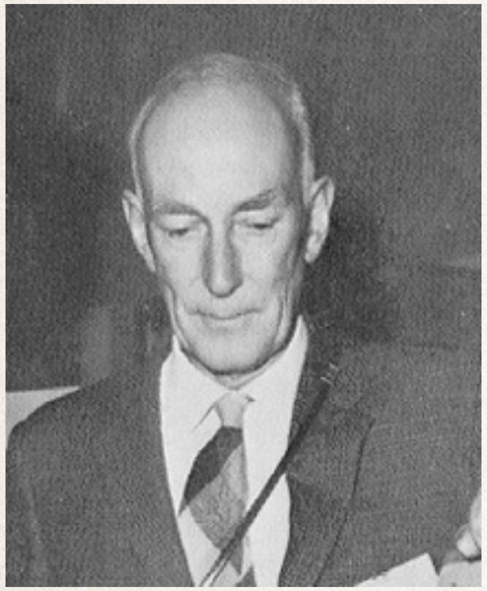
- Background studies and coordination
- Studies of rare physics (e.g. $0\nu2\beta$ decay)
- Software modules for data processing
- Experiment control system


SCIENTIFIC NAMES?
SCIENTIFIC NAMES $1 00
SURE. SCIENTISTS COME UP WITH GREAT, WILD THEORIES, BUT THEN THEY GIVE THEM DULL, UNIMAGINATIVE NAMES.
FOR EXAMPLE, SCIENTISTS THINK SPACE IS FULL OF MYSTERIOUS, INVISIBLE MASS, SO WHAT DO THEY CALL IT? "DARK MATTER"! DUHH! I TELL YOU, THERE'S A FORTUNE TO BE MADE HERE!
© 1993 Watterson/Distributed by Universal Uclick
I LIKE TO SAY "QUARK"! QUARK, QUARK QUARK, QUARK!
INSTEAD OF MAKING AN IDIOT OF YOURSELF, WHY DON'T YOU GO FIND ME SOME SCIENTISTS?

Thank you!

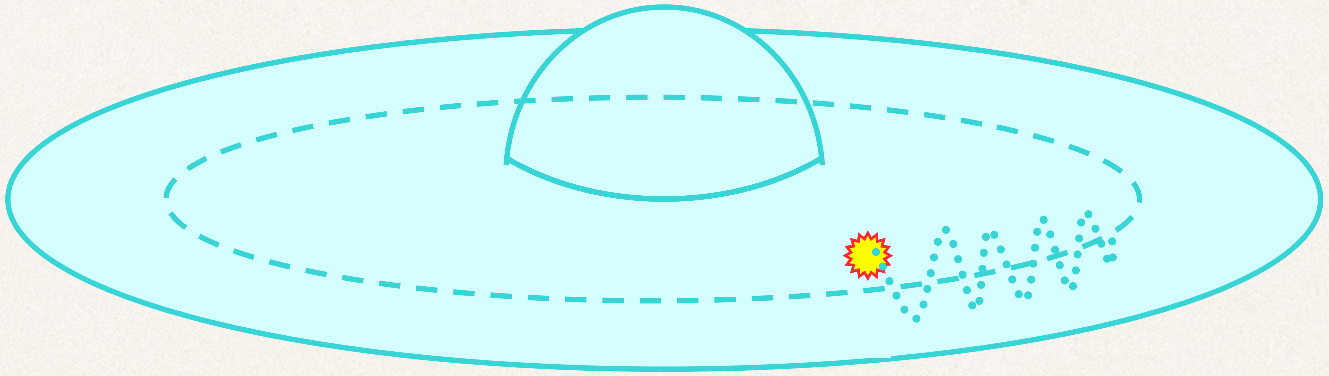
Extras

First hints



1932 Jan Oort: showed that our galaxy rotates (T_S ~225 Ma).

- Studied the movement of stars near the Sun, but outside the rotation plane (in the halo)
- Noticed that they move faster than expected given the visible mass in the galaxy disc (from the visible stars)
- He used the term "dark matter" to justify this difference

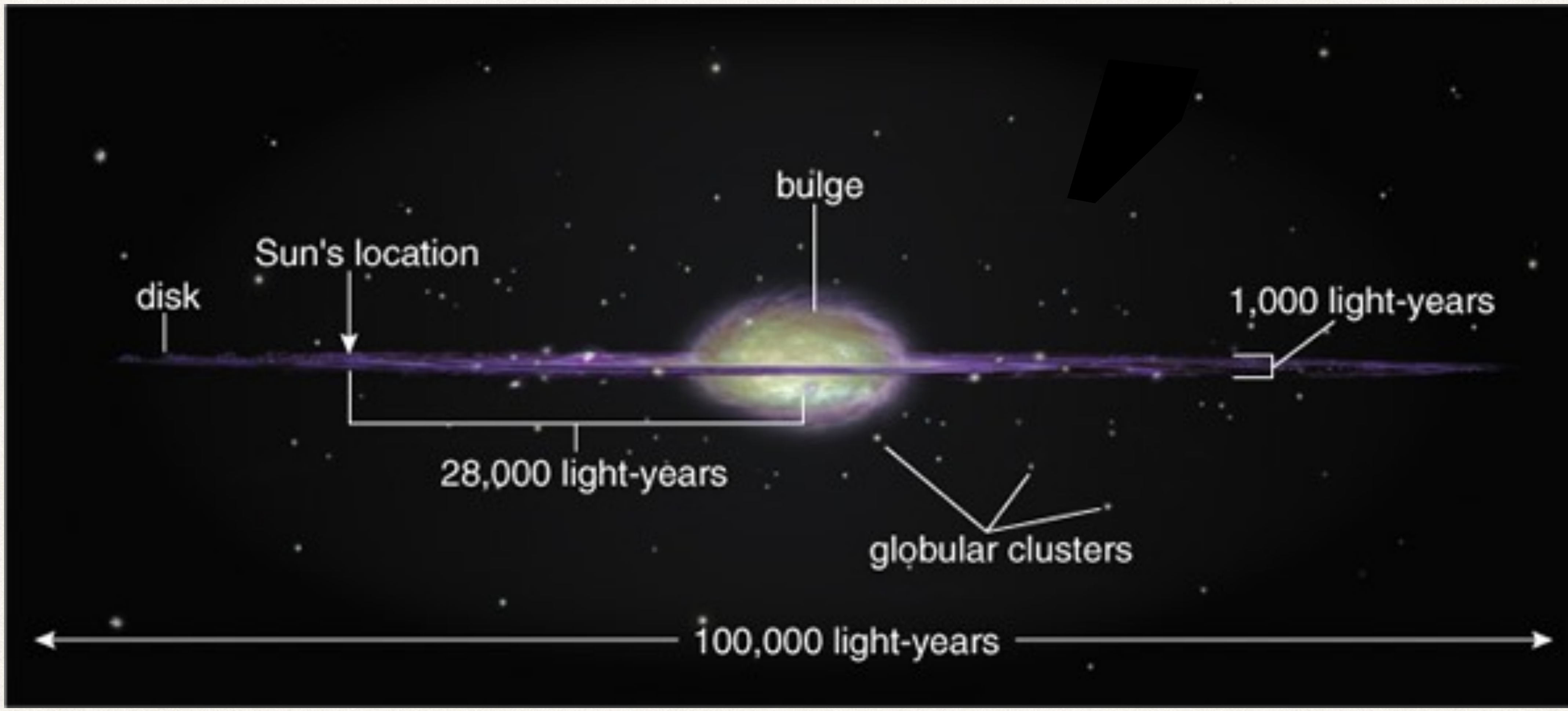


Estimated that the invisible mass could make up to 50% of the total, but would be in stars that were too dim to be observed.

First hints

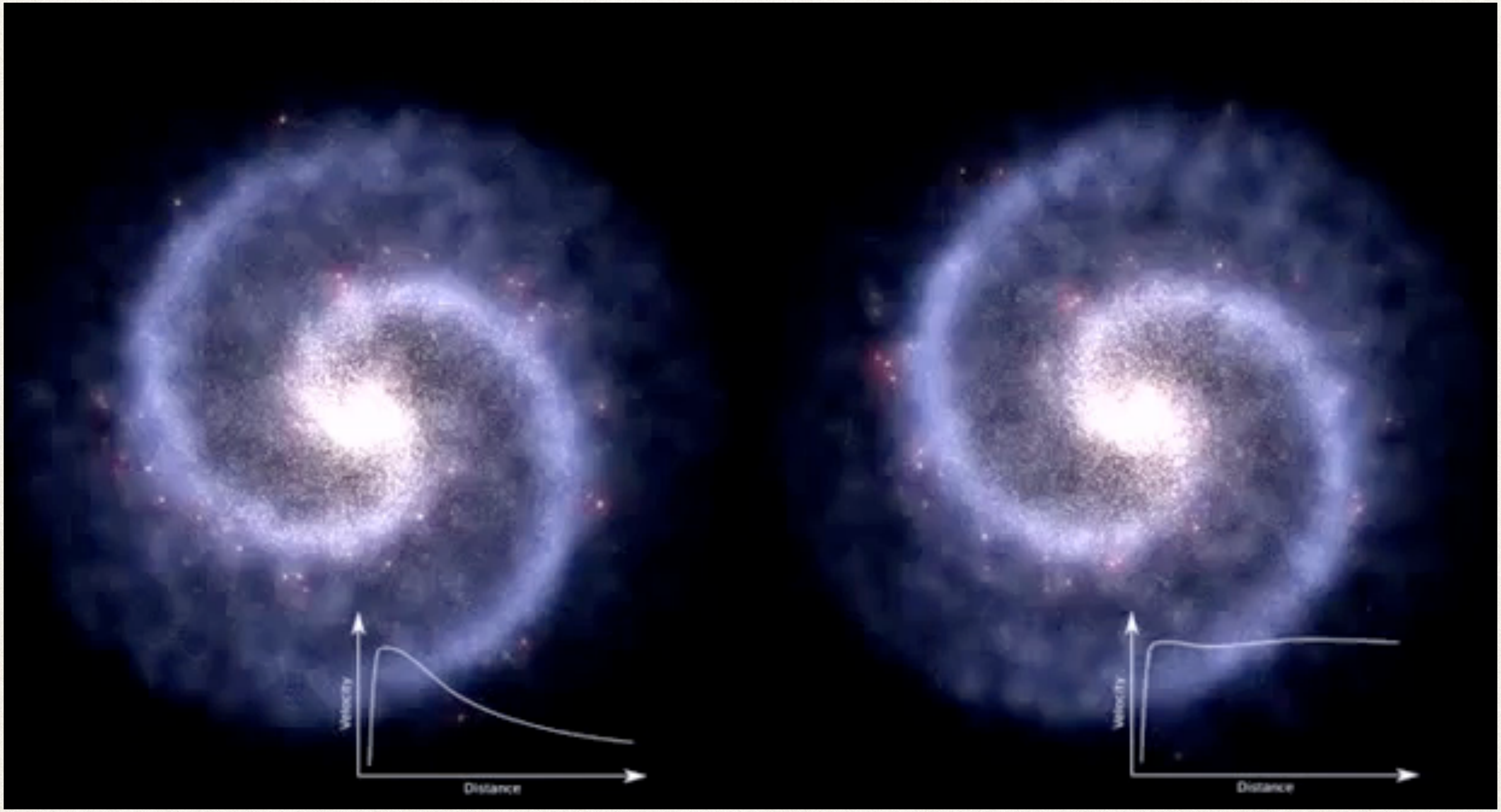
- Until the 70's, several estimates were done for other clusters
- The total mass obtained from the dynamics of the galaxies was always much larger than the visible matter
- Interstellar gas was studied as a possible explanation for this missing matter
  - At most, it should amount to less than 2% of the total mass
- Massive non-luminous objects were seen as the best candidates (*e.g.* dwarf of dead stars)

Milky Way



Most of the mass is in the central region of galaxies. What is expected is that the rotation velocity of stars and gas clouds decreases rapidly with the distance to the center.

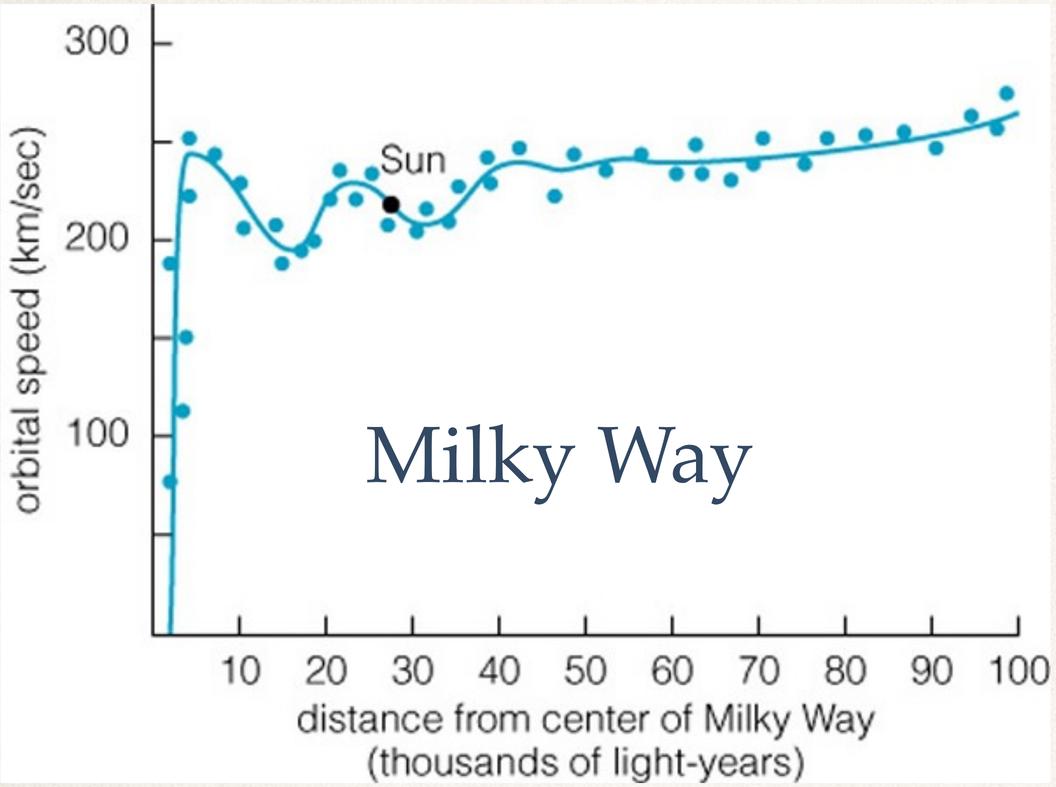
Galaxy rotation curves



Expected

Observed

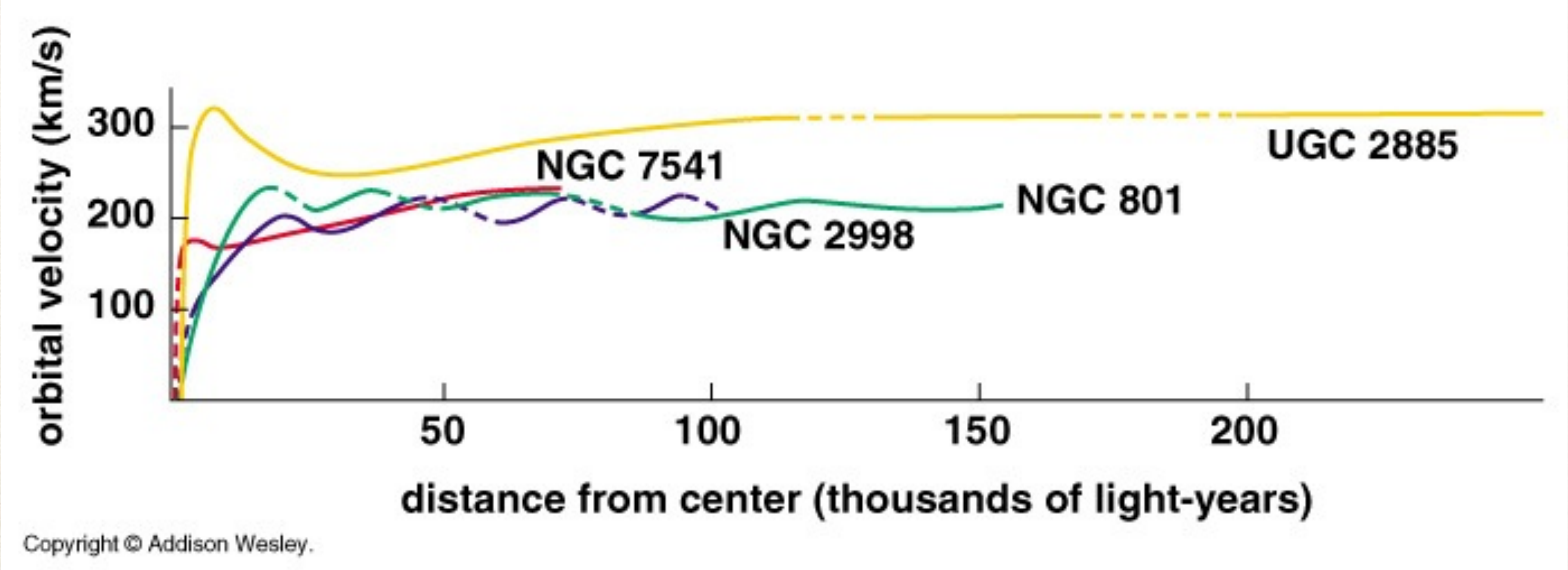
Galaxy rotation curves



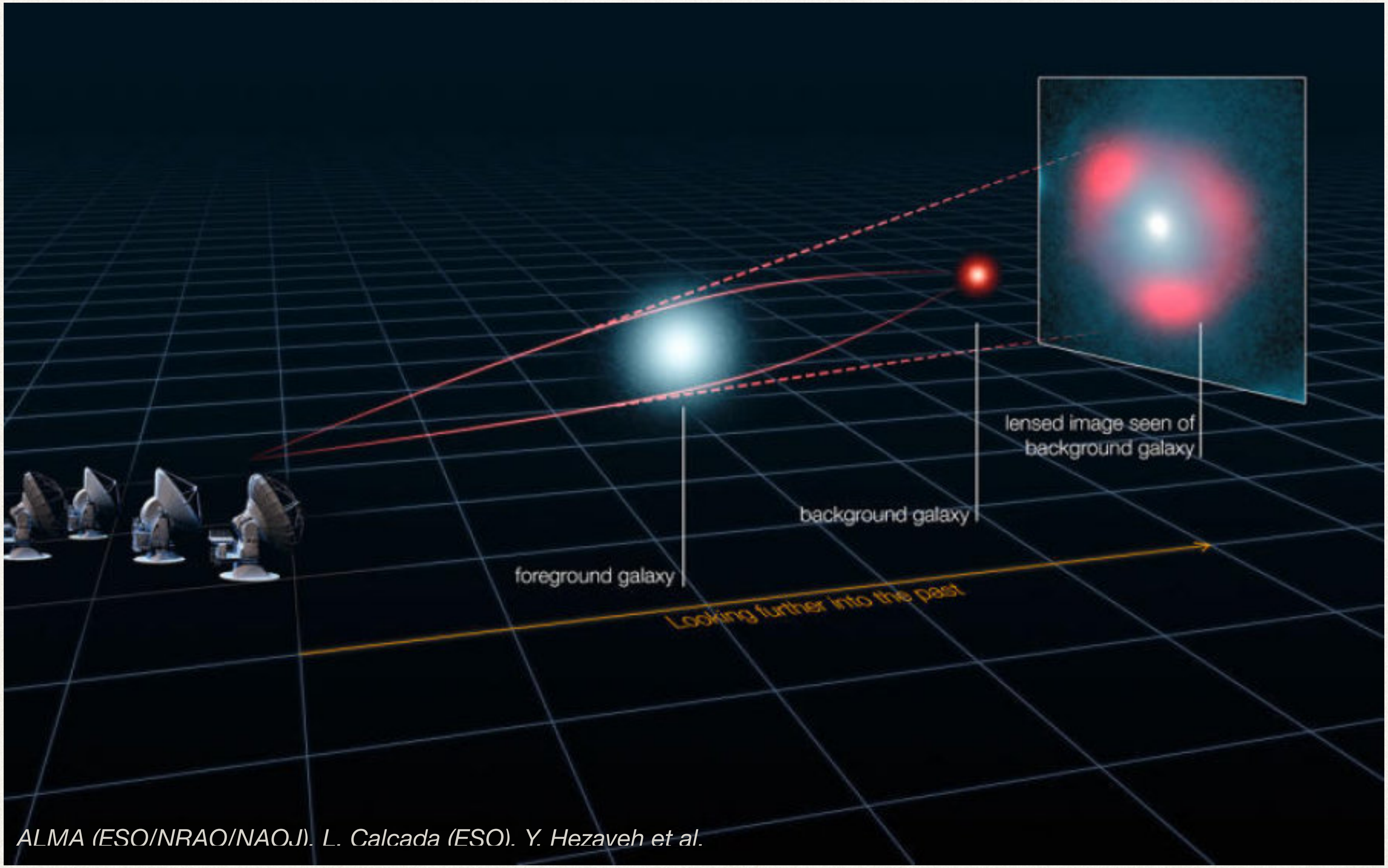
Even at very large distances from the center:

- rotation speed of the gas is constant
- evidence that there is a large amount of dark matter well beyond the limits of the galaxy disk

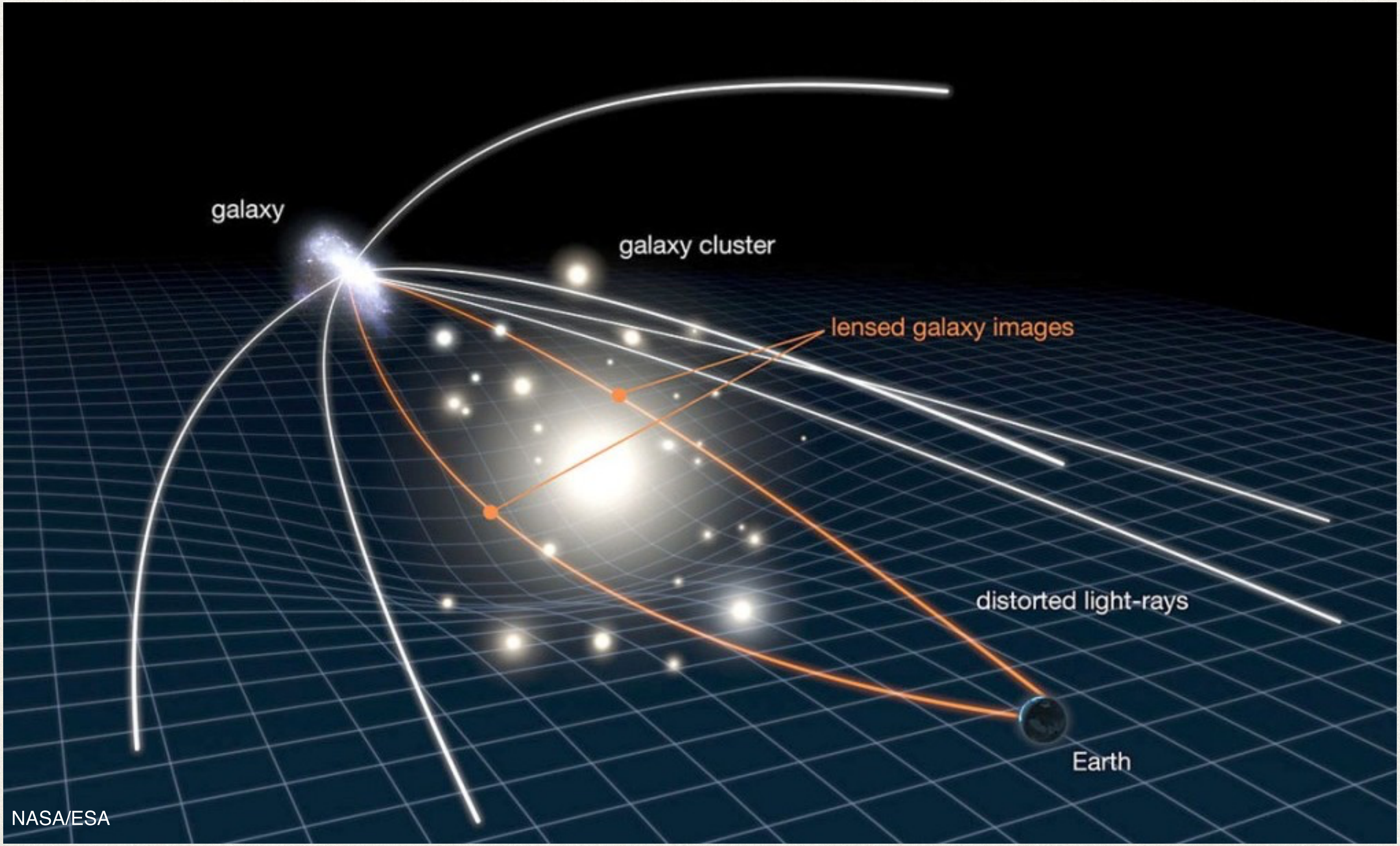
More examples



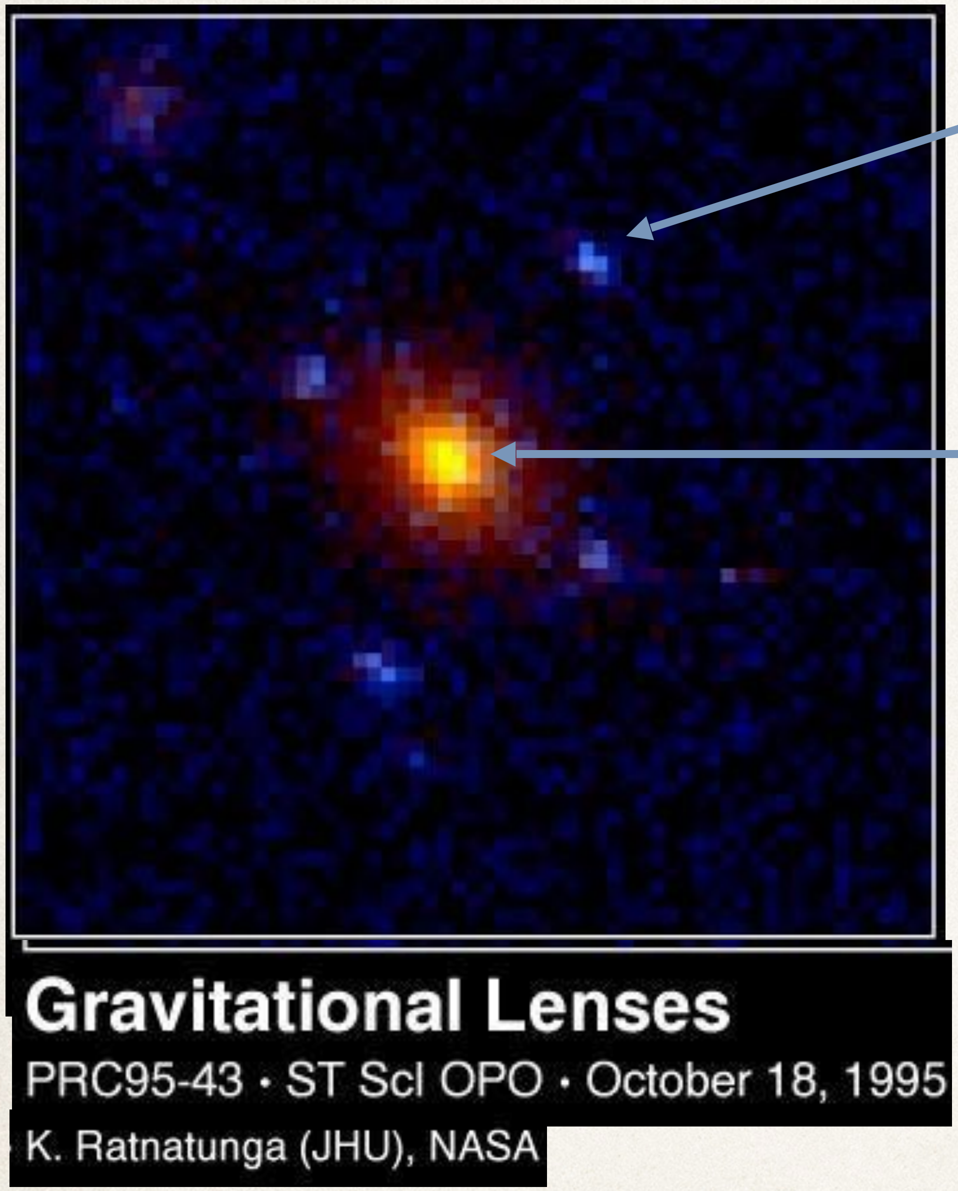
Efeito de lente gravitacional



Gravitational lenses



Gravitational lenses



One of four images created by the gravitational lens

Galaxy responsible for the lens effect

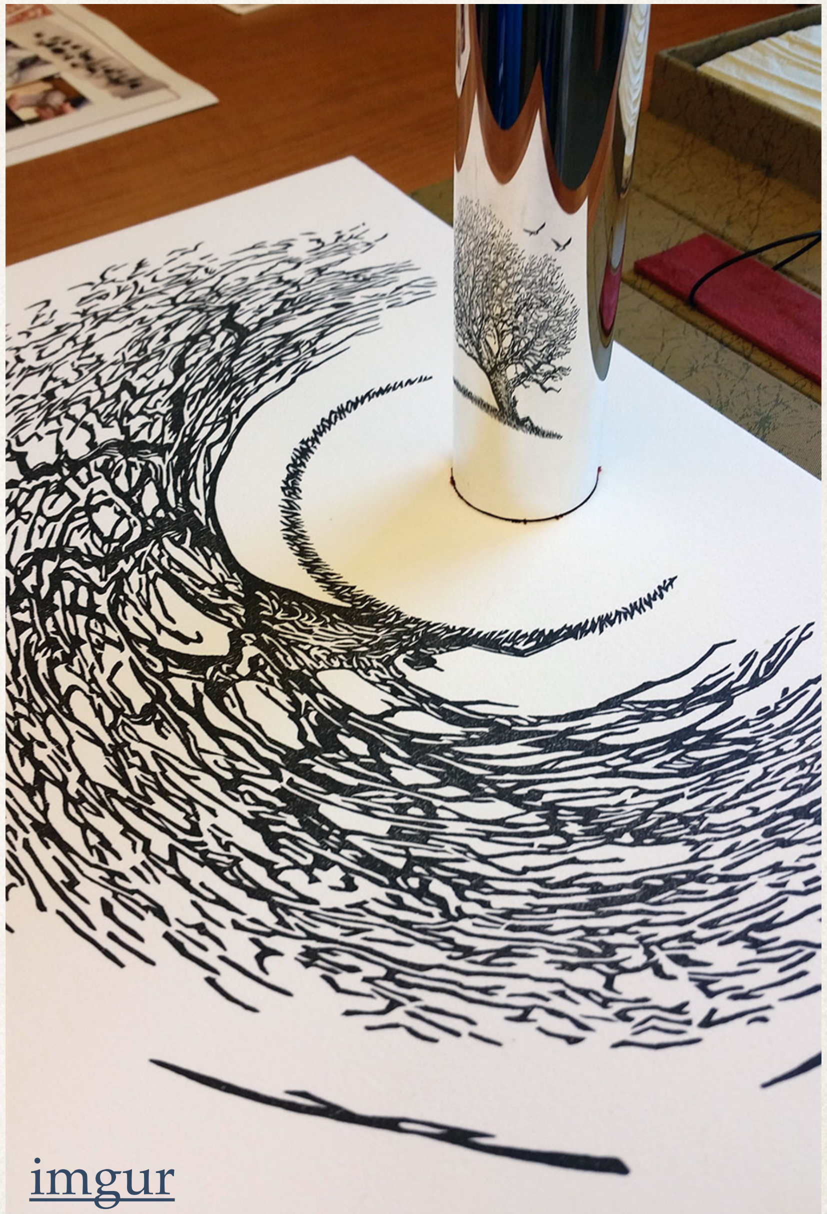
- Using the position and distortion of the four images it’s possible to estimate the mass of the galaxy
- Estimated mass >> visible mass!

Gravitational lenses

Einstein Ring around the LRG 3-757 galaxy

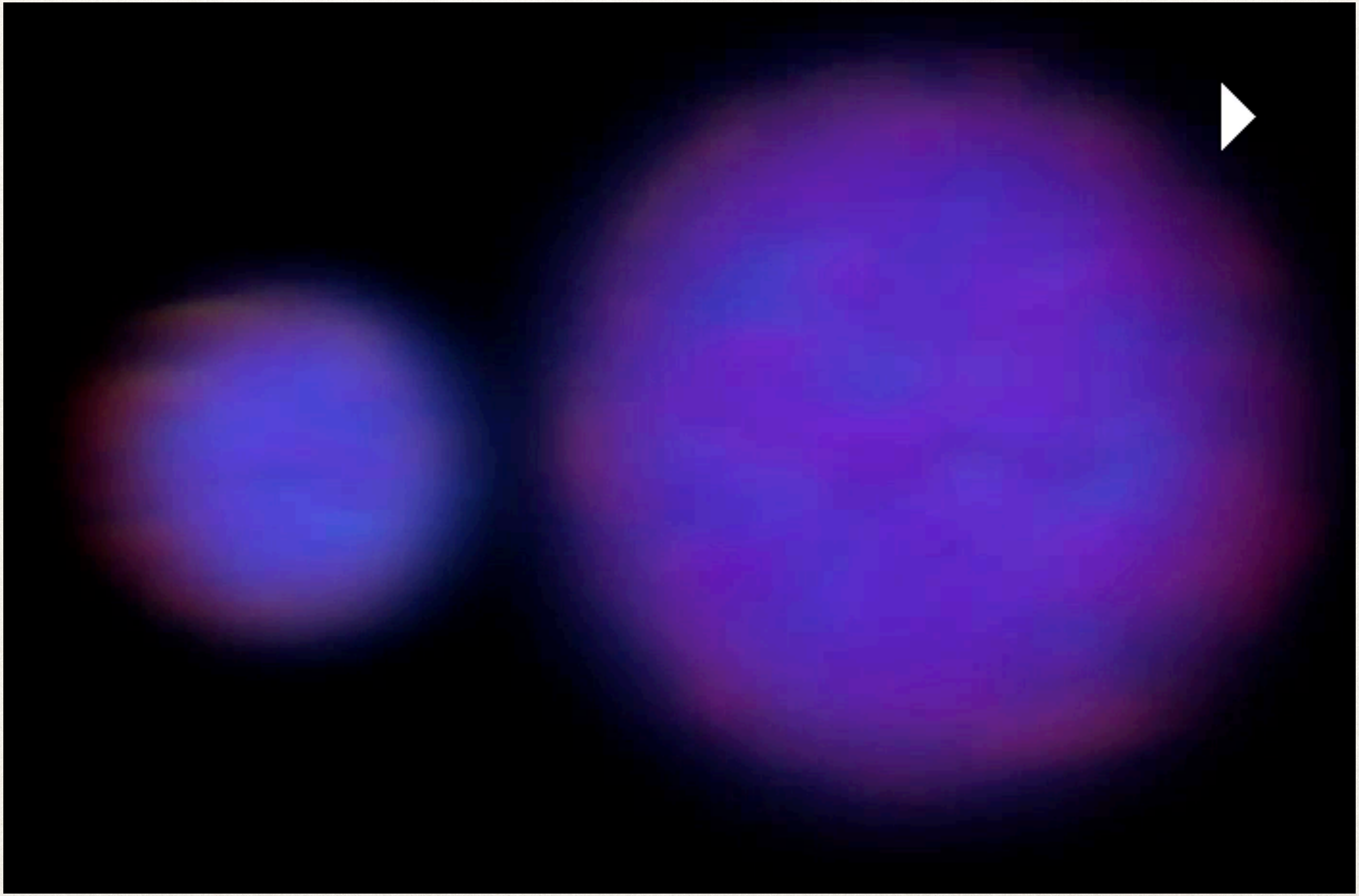
ESA/Hubble & NASA

Imagem anamórfica

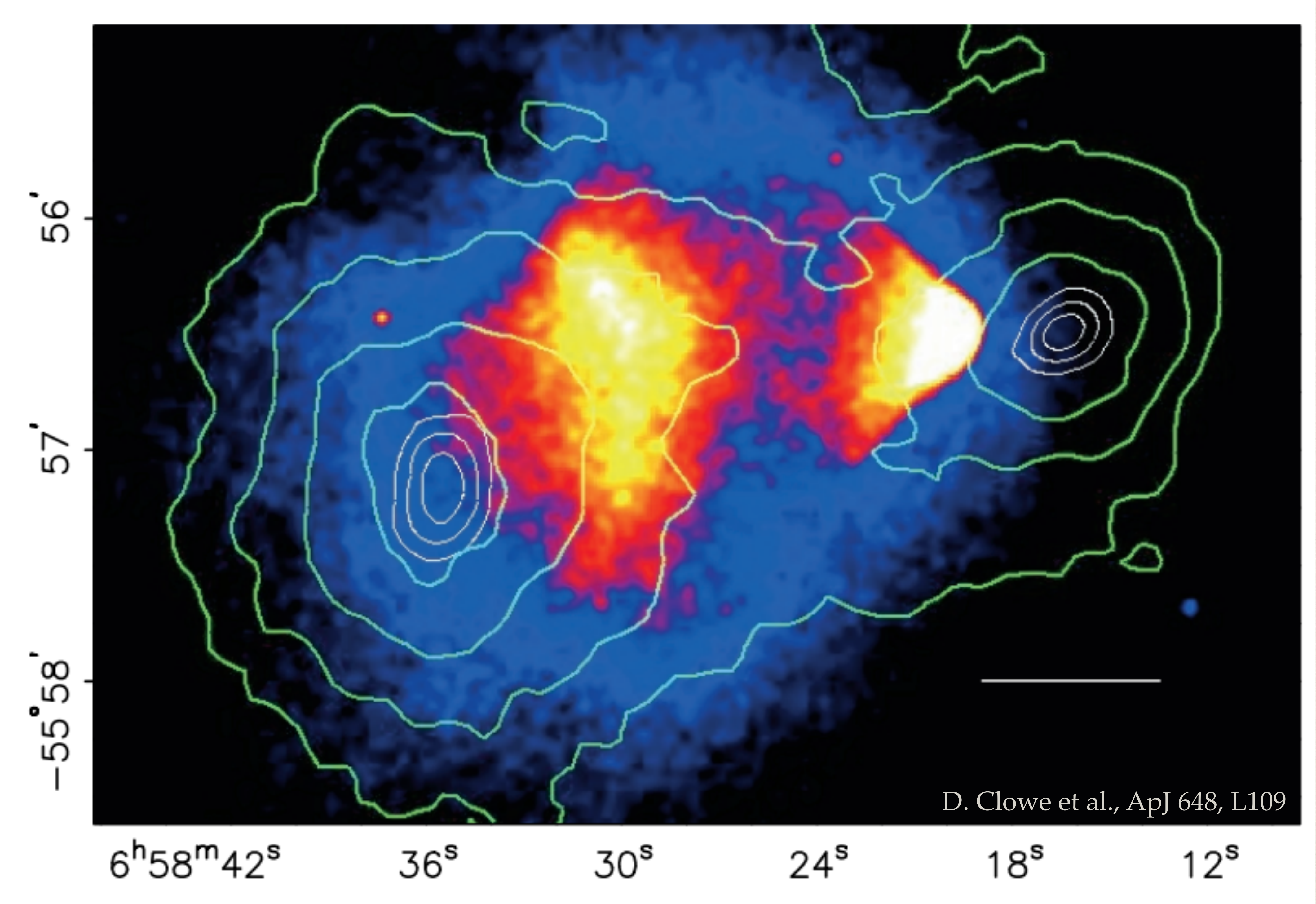


imgur

The Bullet cluster

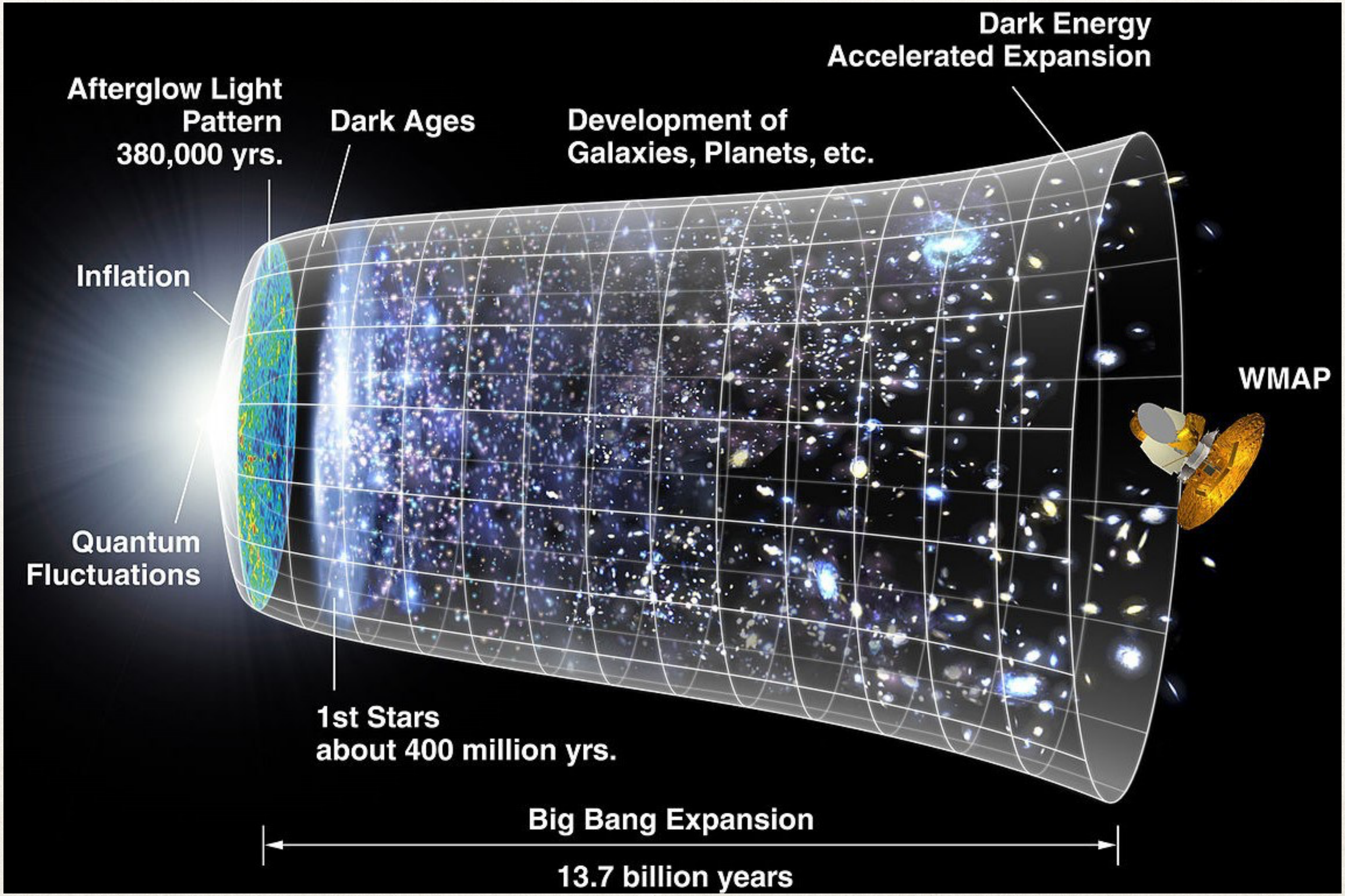


The Bullet cluster



Cosmological evidence

Big Bang Model



Cosmological evidence

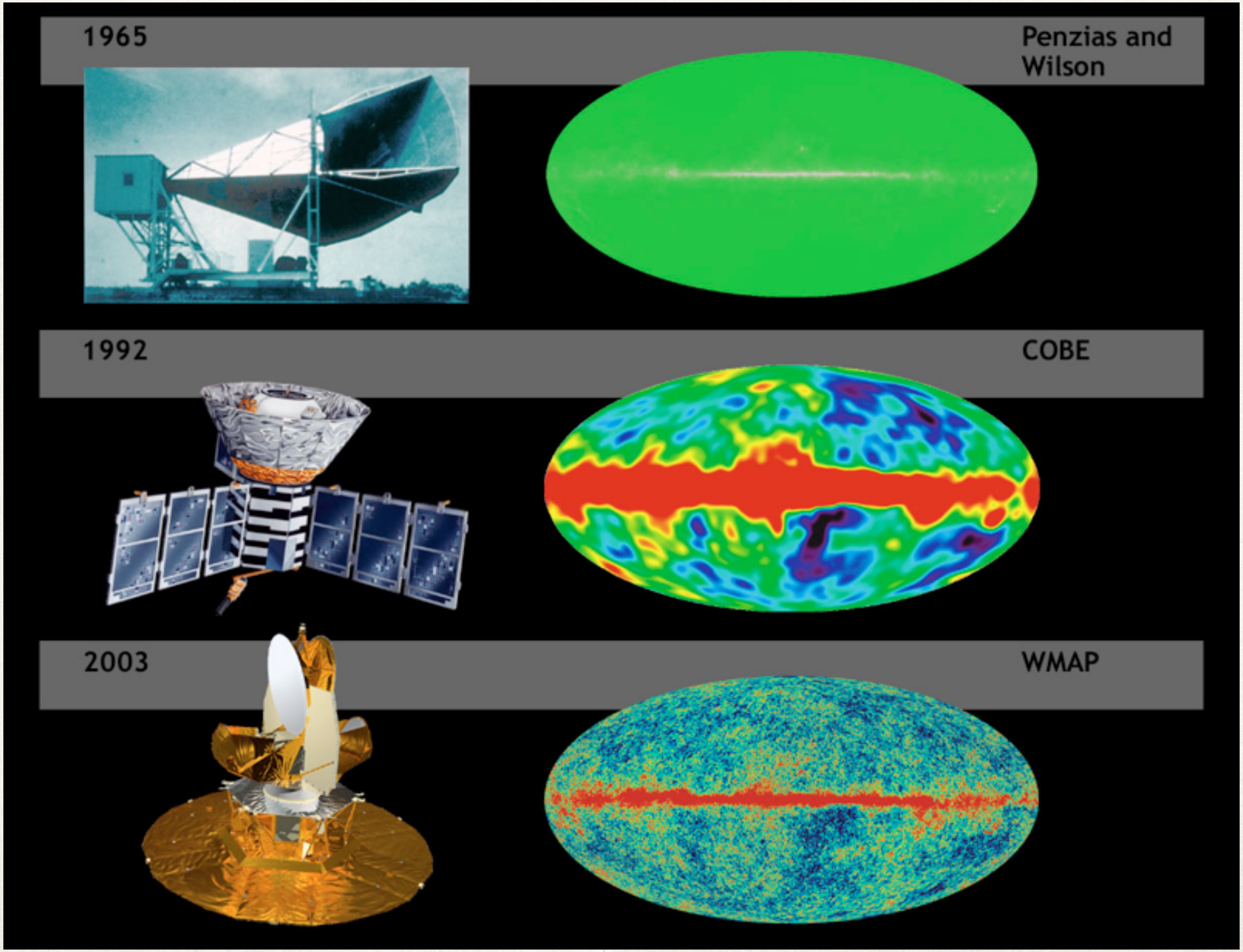
- Cosmic Background Radiation (CMB)
  - 380 thousand years after the Big Bang, the temperature gets too low for the radiation to have enough energy to ionise atoms
  - Protons and electrons combine, and make the first hydrogen atoms
  - Matter and radiation “decouple”
  - This radiation is a snapshot of the Universe at that age
  - As the Universe expands, the radiation gets colder (-270 °C)

1948 Predicted by
George Gamow

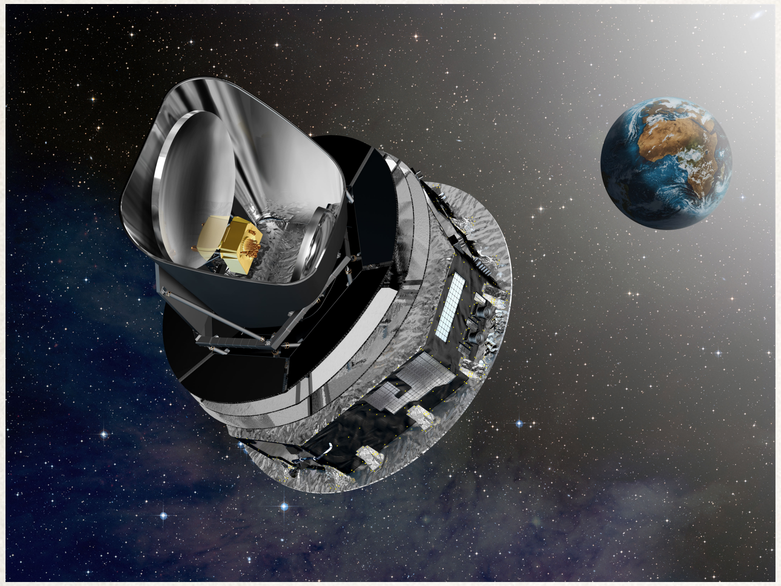
Did not win the Nobel prize…

1965 Accidentally discovered by
Penzias and Wilson
They thought it was just background noise
They won the Nobel prize!!!

Cosmic Background Radiation

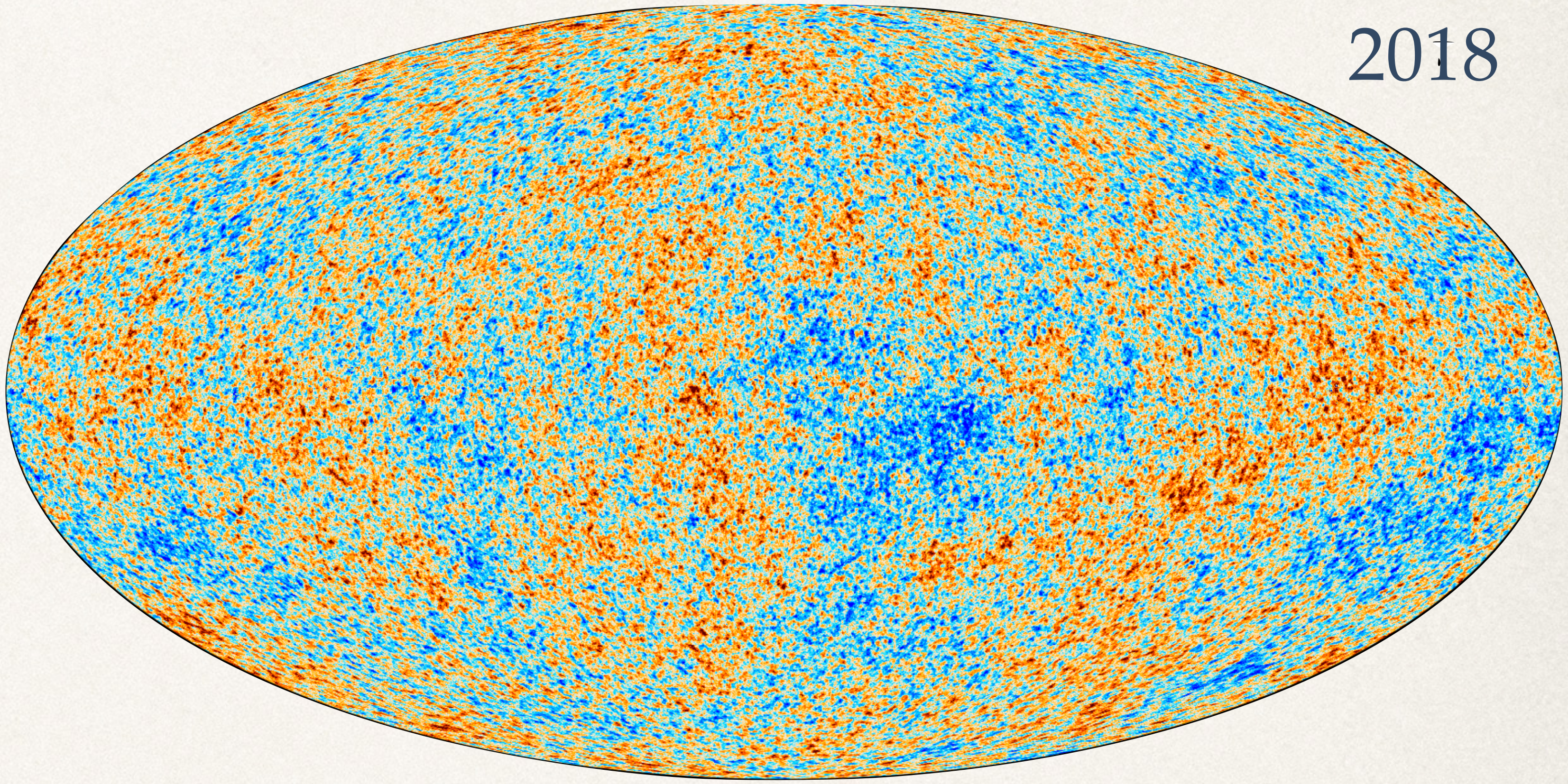


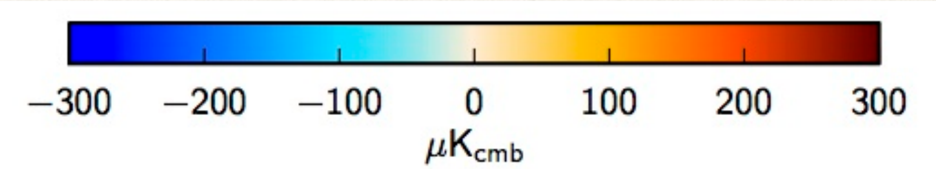
Cosmic Background Radiation



Planck satellite:
www.esa.int/Our_Activities/Space_Science/Planck

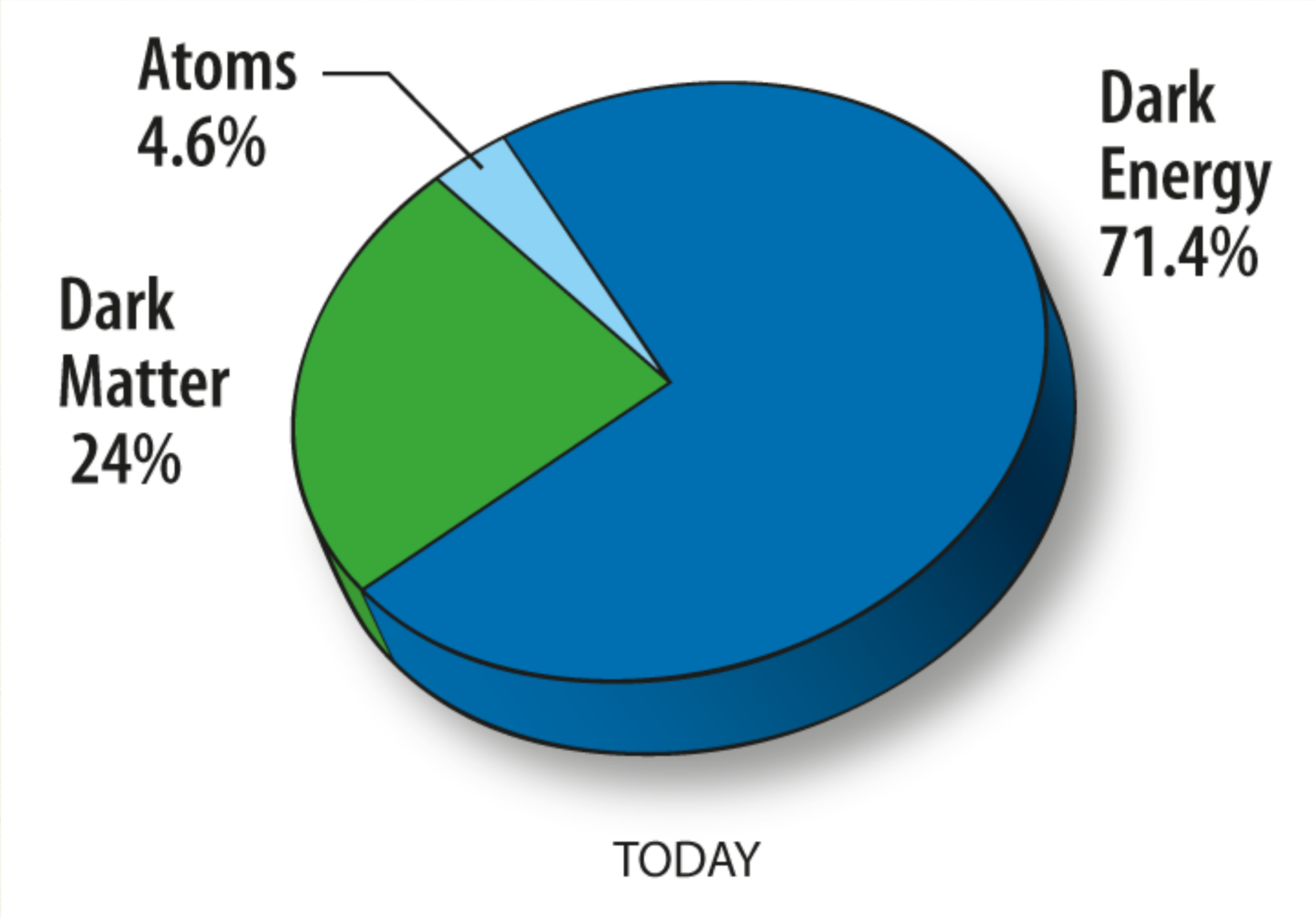
2018





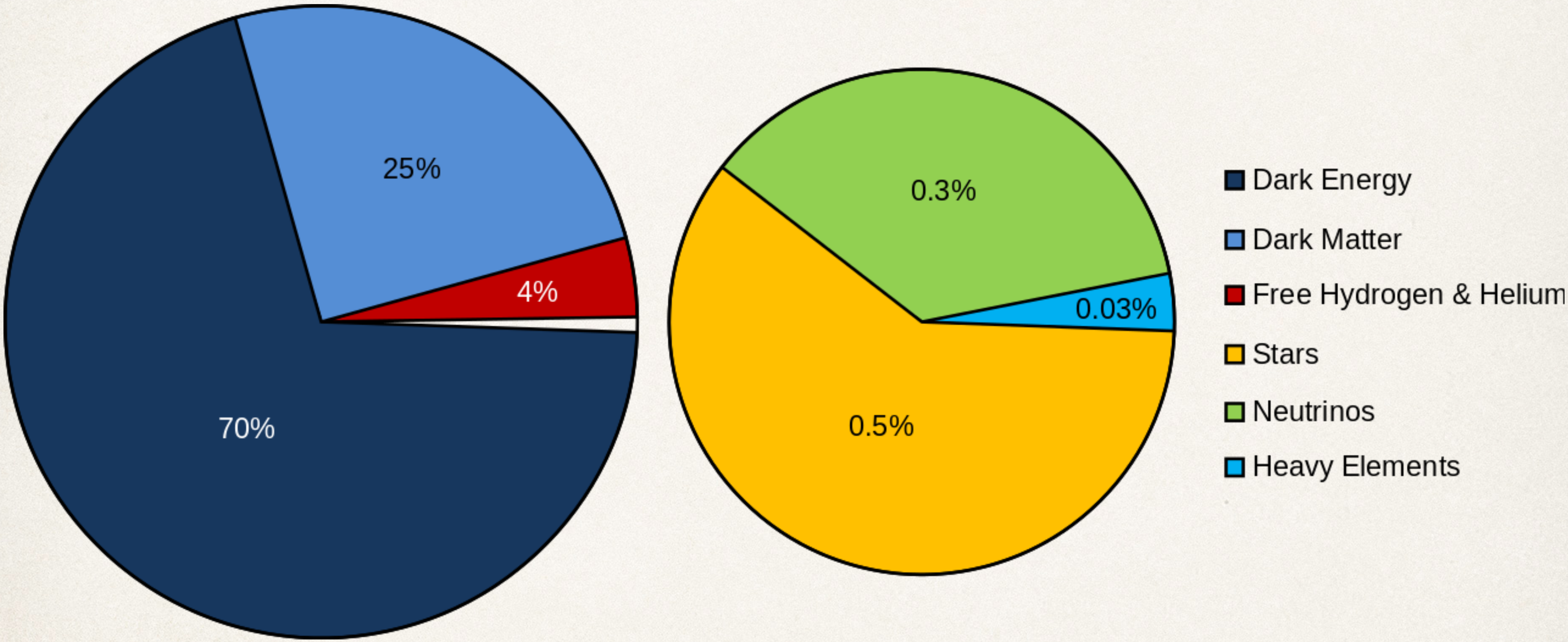
- Analysing this radiation, it's possible to determine several parameters of the Big Bang model, including:
  - density of baryonic ("normal") matter
  - density of dark matter

Big Bang Model



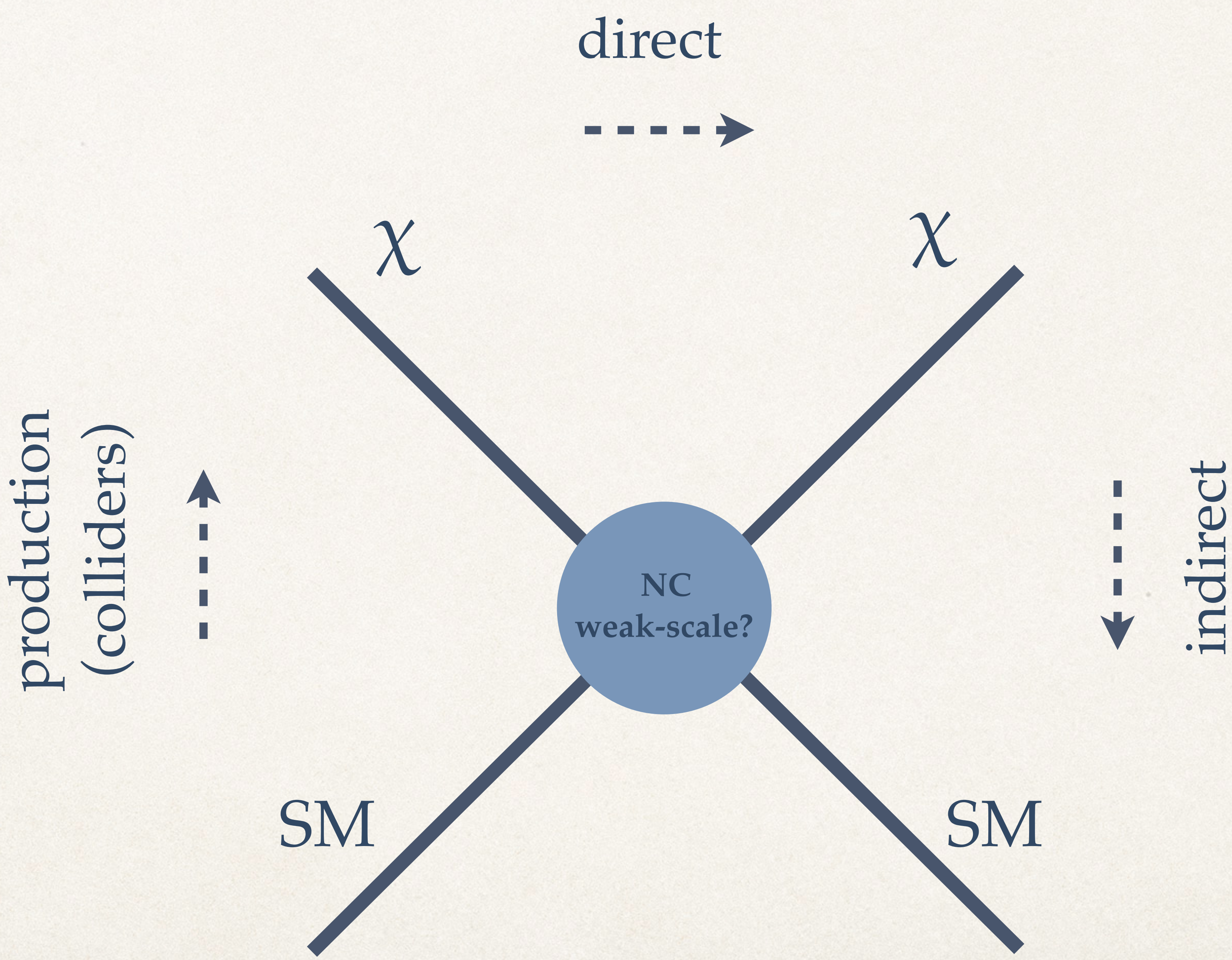
ΛCDM ("Lambda Cold Dark Matter")

Big Bang Model



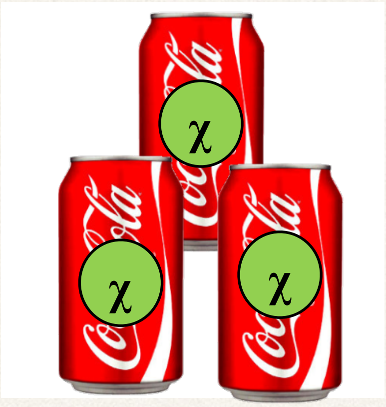
ΛCDM ("Lambda Cold Dark Matter")

How can we detect it?

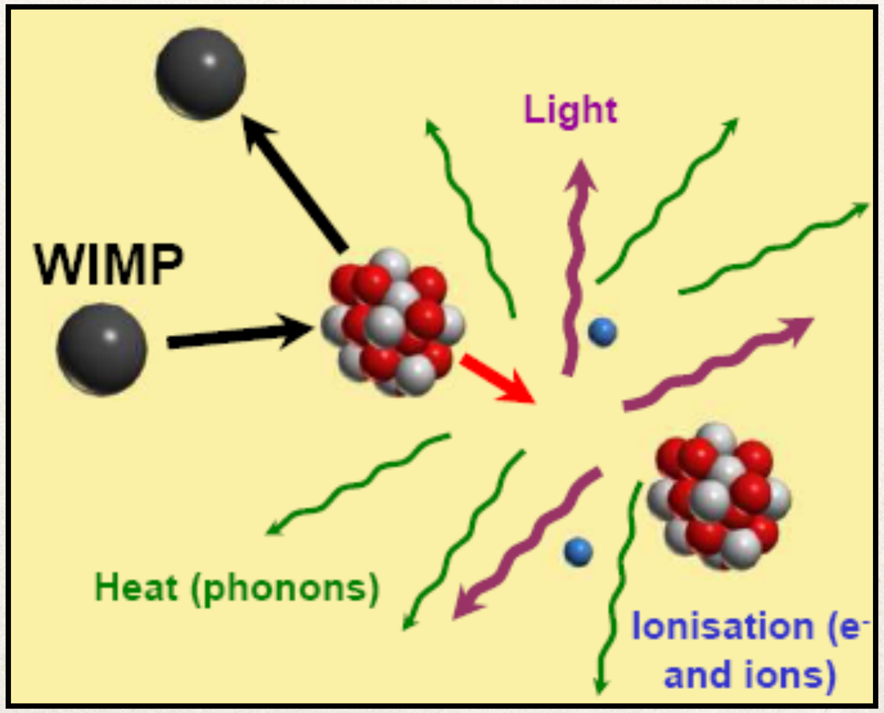


Detecção directa

- Espera-se que a densidade de WIMPs na nossa zona da Via Láctea seja de 0.3 GeV/cm3
  - Isto corresponde a ~3 WIMPs /litro



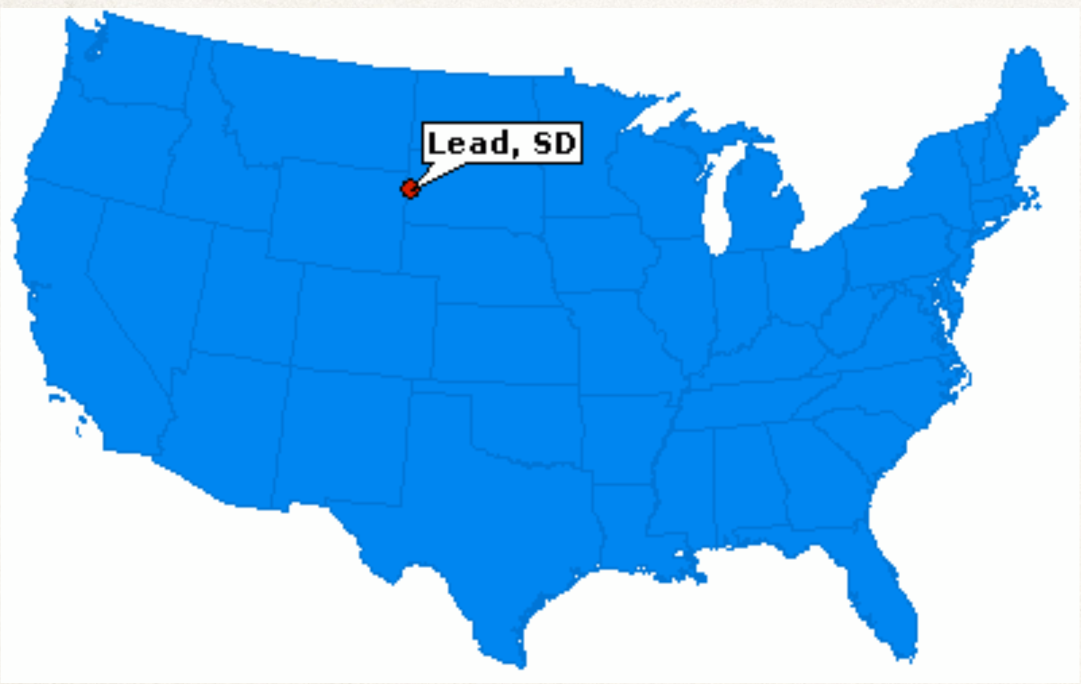
- 50 biliões de WIMPs atravessam uma pessoa a cada segundo!
- Ocasionalmente, deverão interagir com a matéria…
- Na detecção directa, tentamos observar o resultado destas interacções



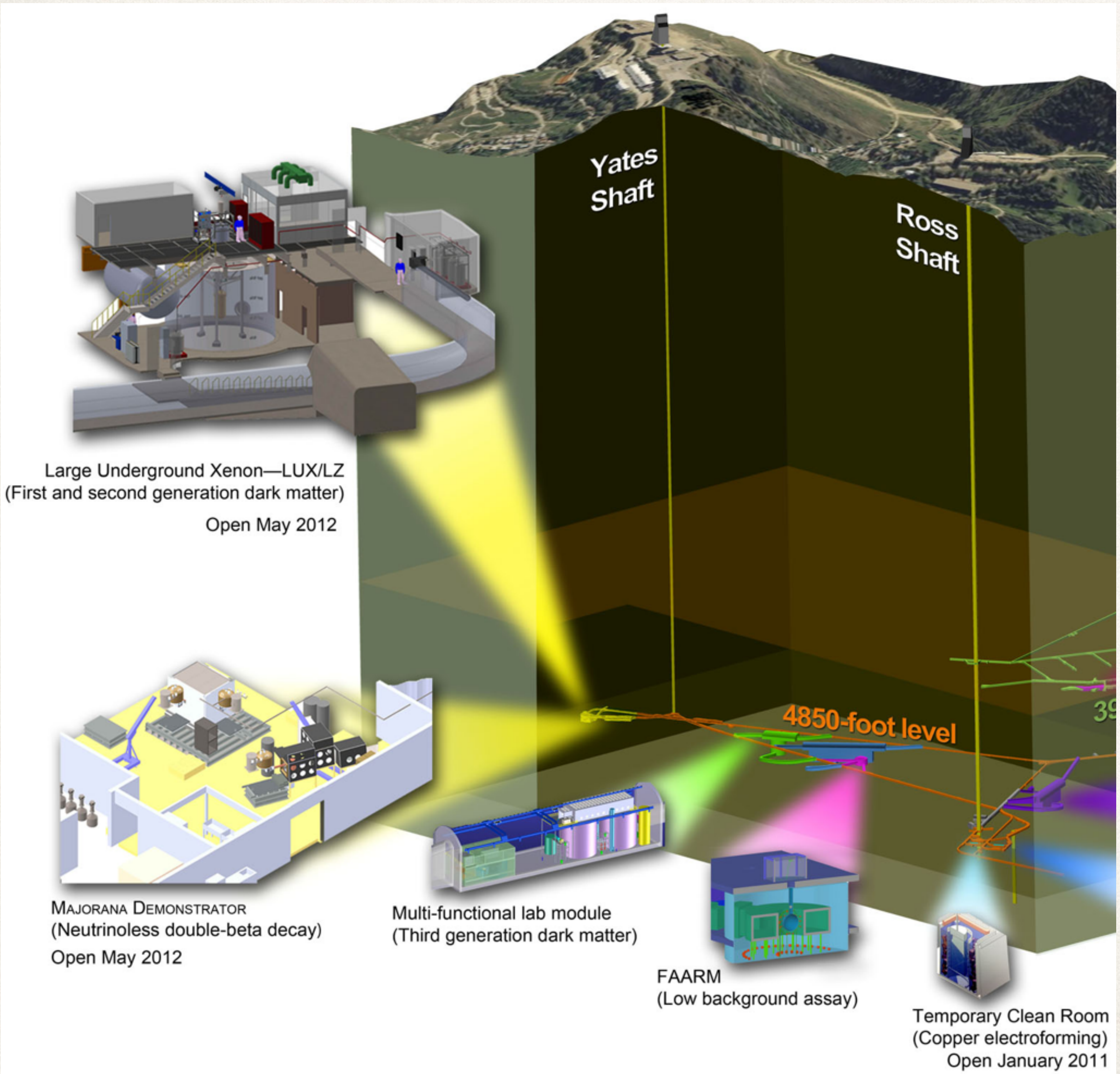
Esta interacção produz:
- luz
- carga (electrões e iões)
- calor

Sanford Underground Research Laboratory

- Largest and deepest gold mine in North America, abandoned in the late 90's
- A millionaire donated 70 million dollars to reconvert it to science



Sanford Underground Research Laboratory



1478 m deep
(equivalent to 4.2 km of water)

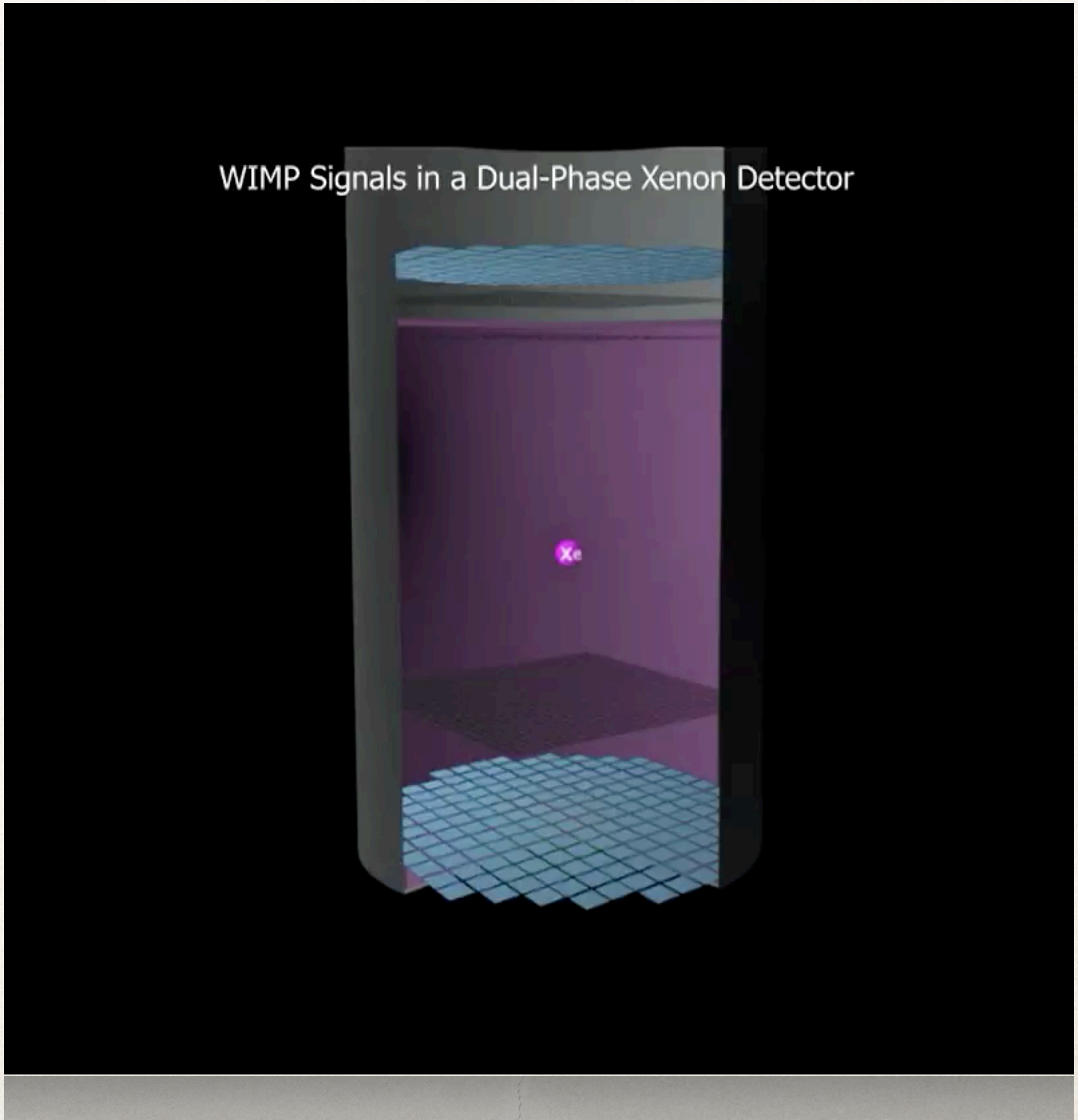
Cosmic ray muon flux is reduced by a factor of 10 millions

1 muon/hand/3 months

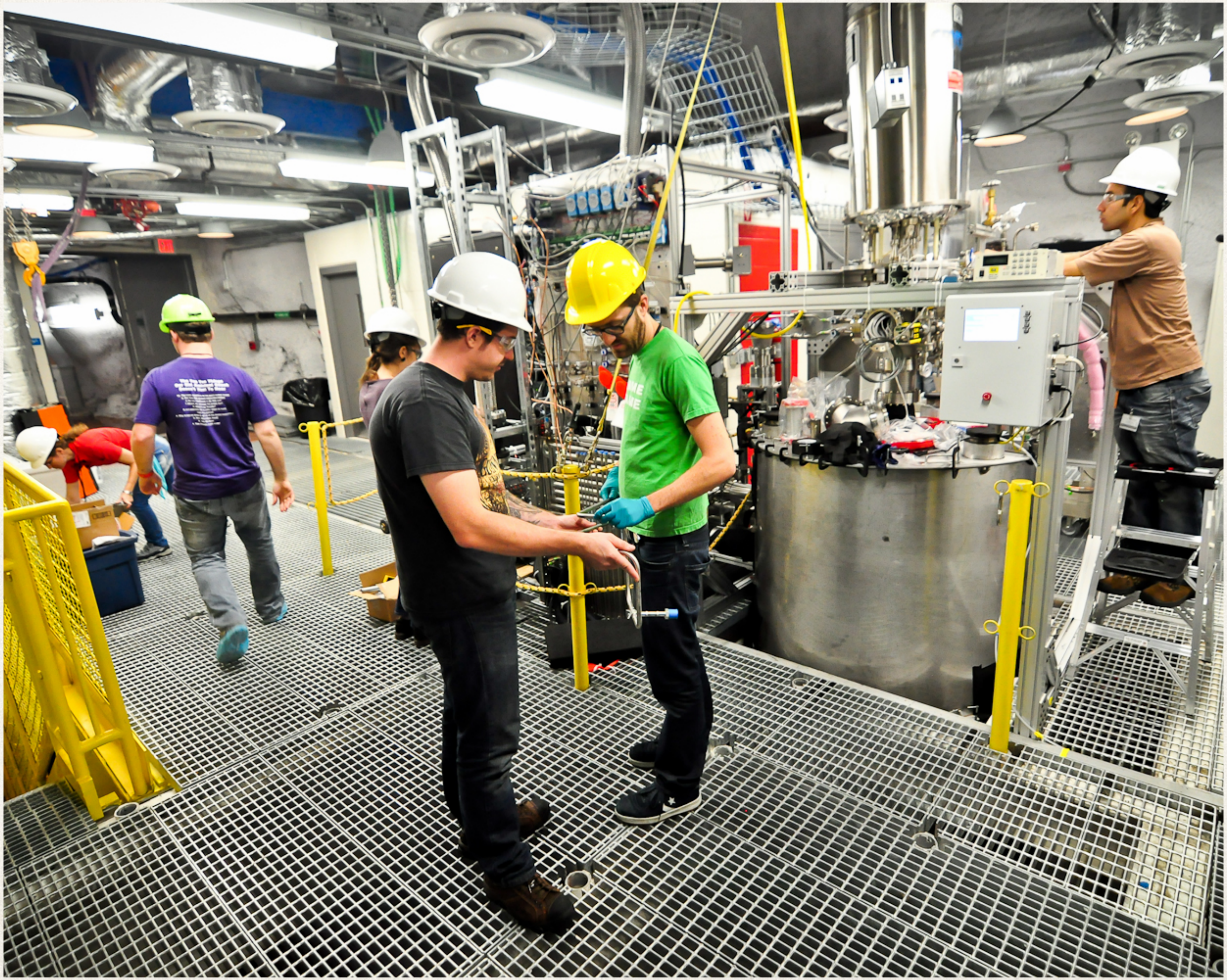
Building the underground lab…

Current status…

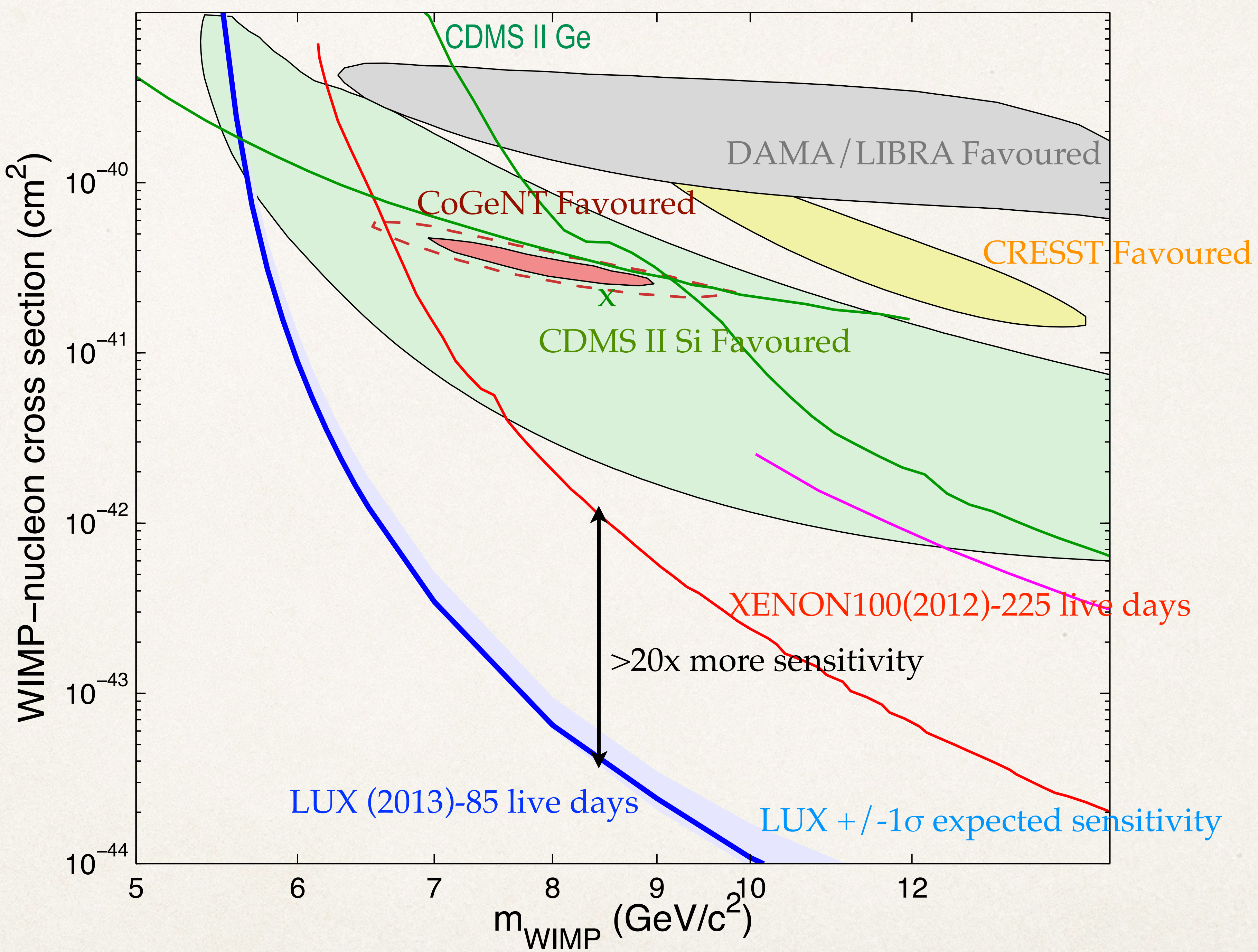
How a xenon detector works



Activity above the water tank…



LUX results for low-mass WIMPs



LUX completely excluded all the results from previous experiments claiming to have observed WIMP signals

Now a museum piece

LUX retired at the end of 2016

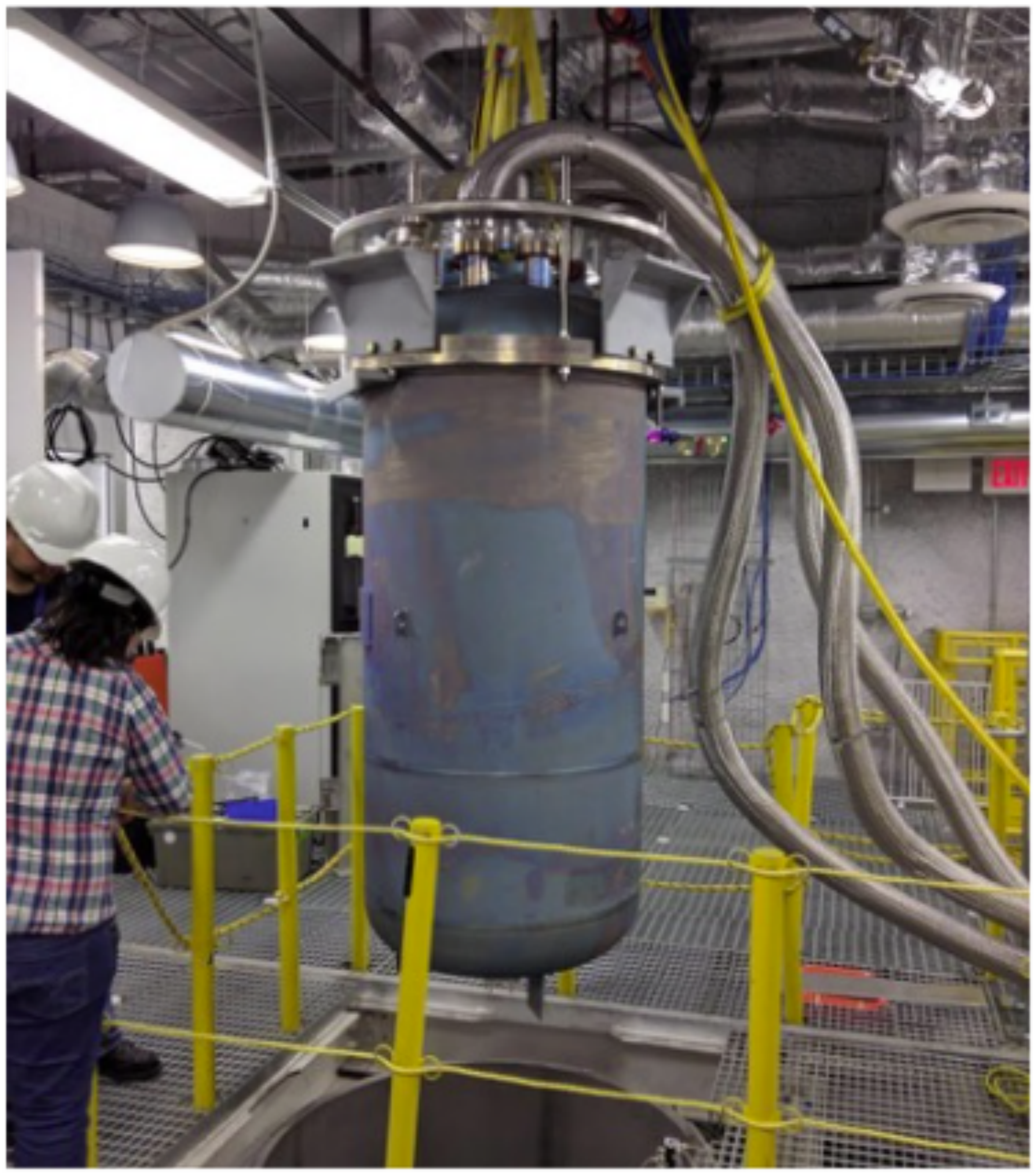
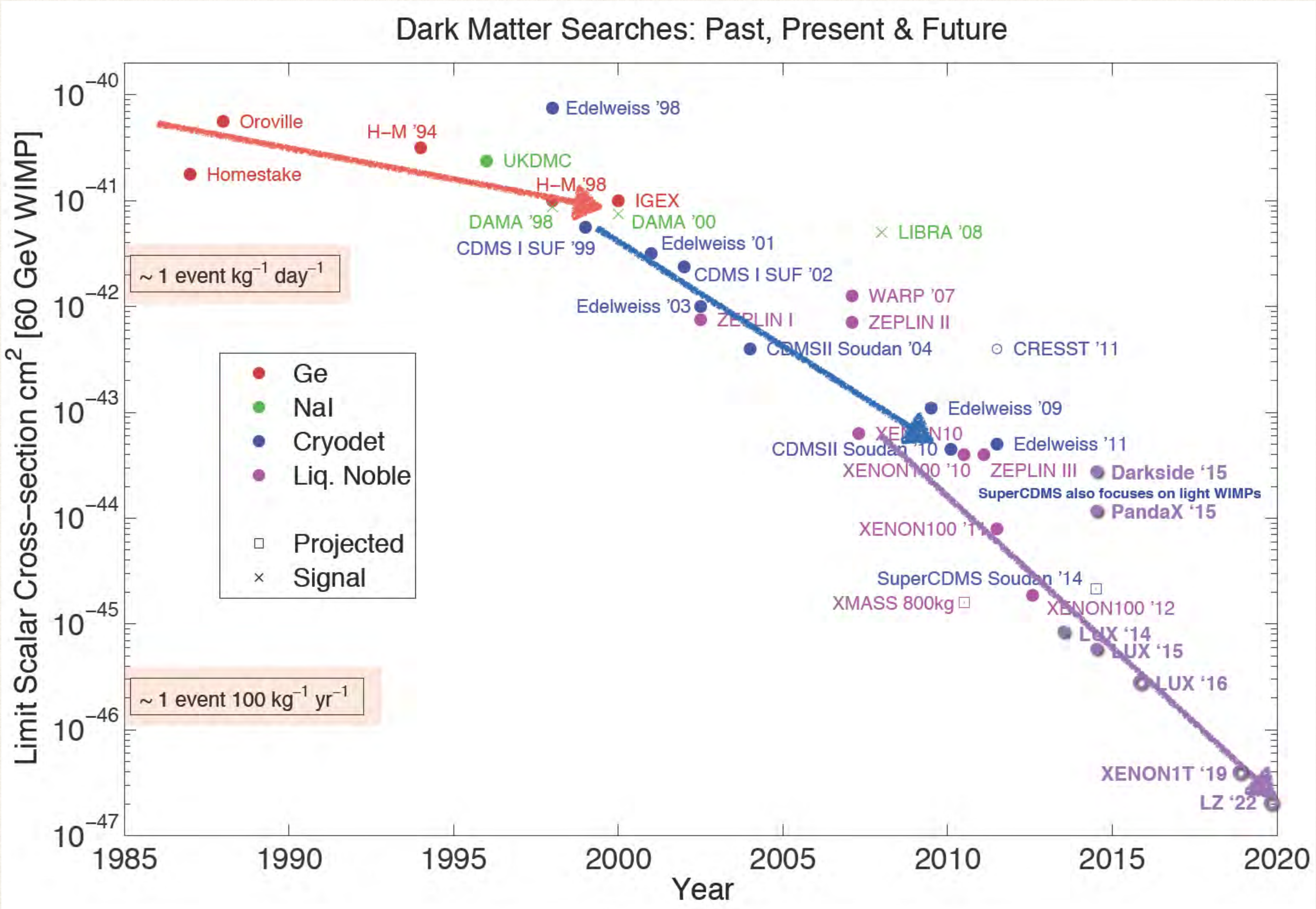


Exhibit (2017)

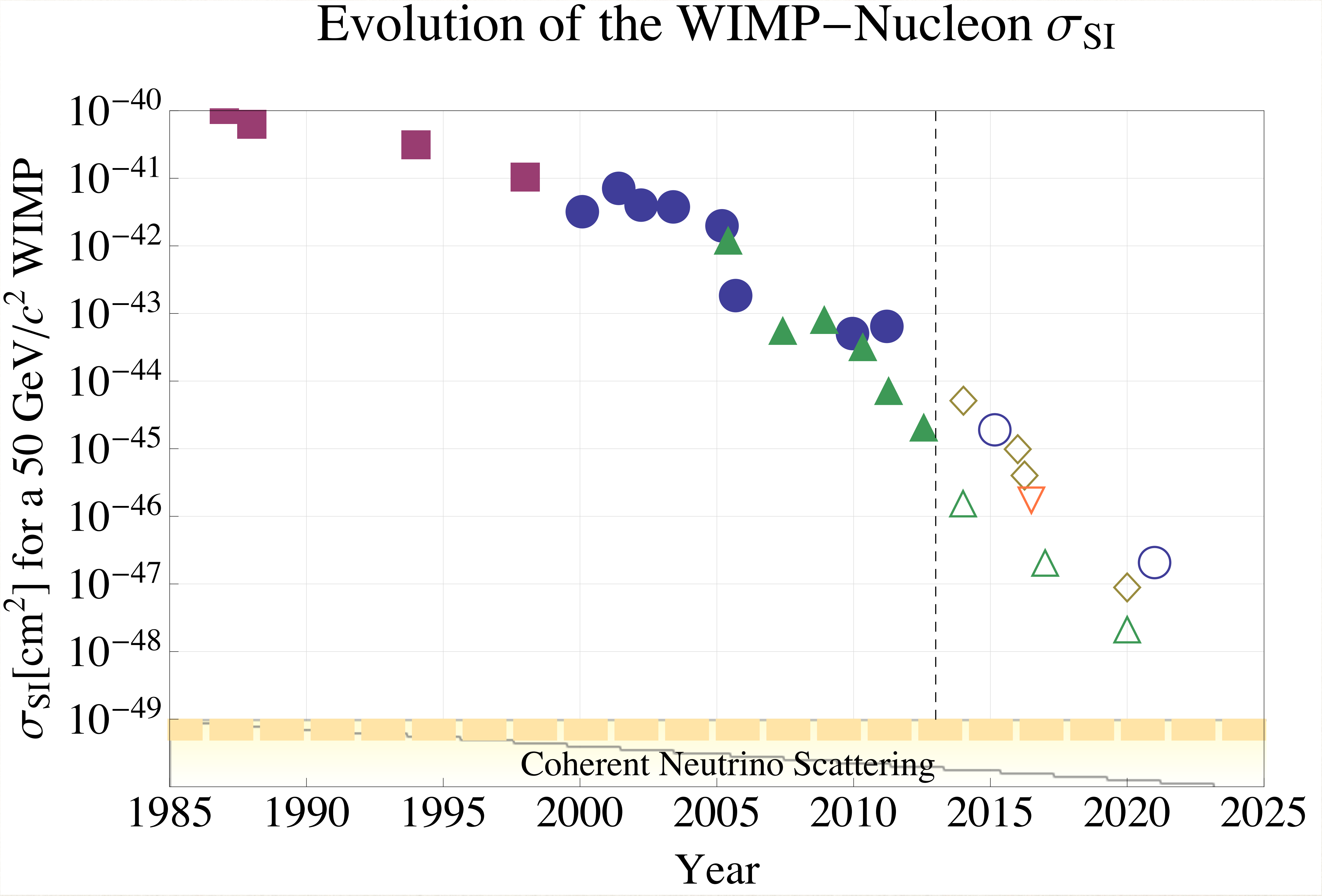
What we learned from LUX is now being used to build the next generation detector: LUX-ZEPLIN (LZ)

Sensitivity of direct dark matter experiments



Even faster then the computing power evolution: a factor of 10 every 5 years

Sensibilidade da detecção directa



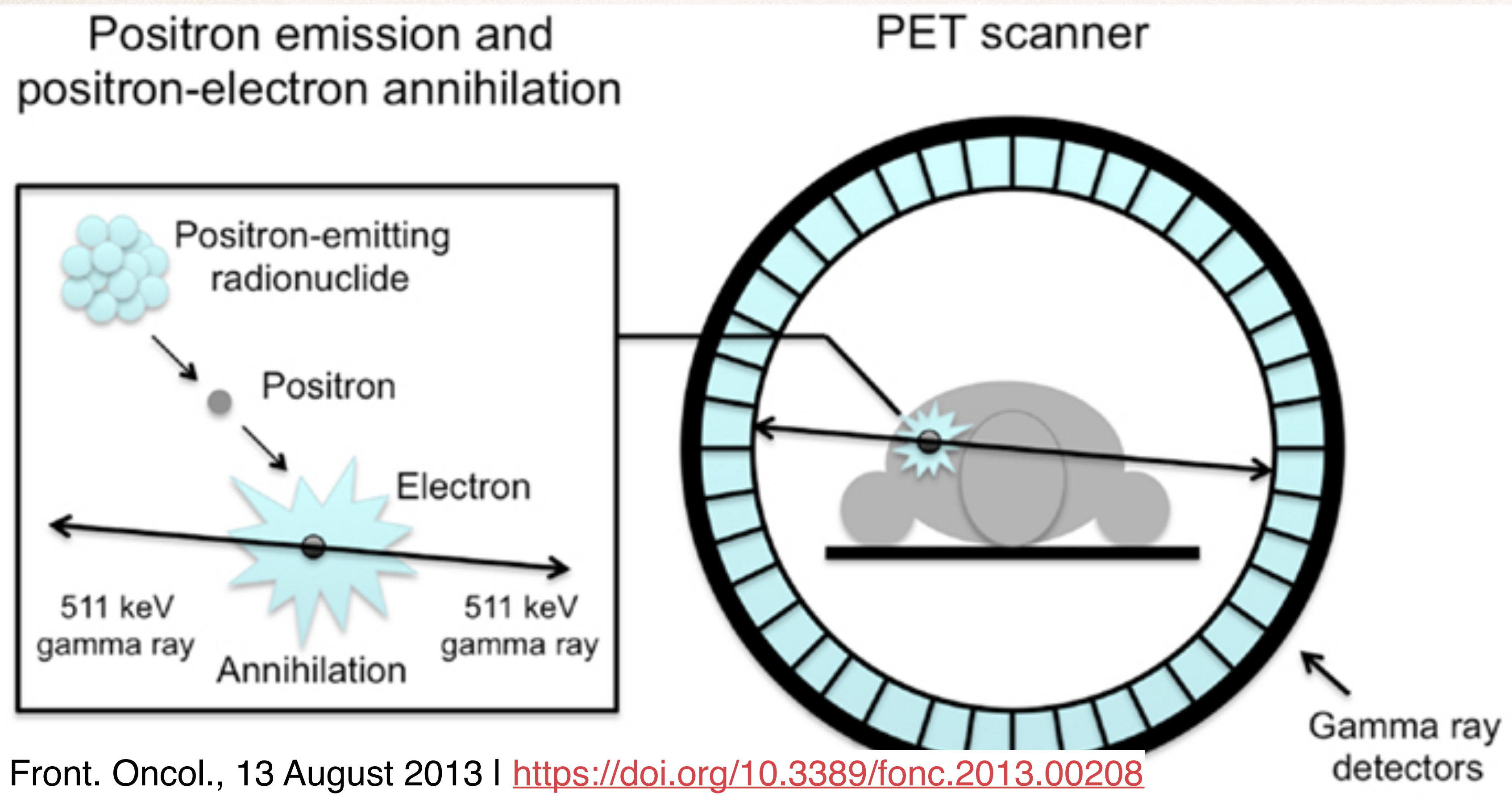
The flight of the mosquito

- Mosquito mass: 2 mg
- Reasonable flying velocity: 1.4 km/h
- Kinetic energy: $1/2\ mv^2 =$ **1.6×10^{-7} Joules**
- $1\ \text{eV} = 1.6 \times 10^{-19}$ J
- $1\ \text{TeV} = 1 \times 10^{12}\ \text{eV} =$ **1.6×10^{-7} Joules**

PET scanner

- The patient is injected with a drug containing a radioactive isotope which decays via positron emission

Positron: electron anti-particle



Front. Oncol., 13 August 2013 | https://doi.org/10.3389/fonc.2013.00208

Example of LUX S1 and S2 signals