# Shining light on dark matter


Luca Pagani - 13th May 2021

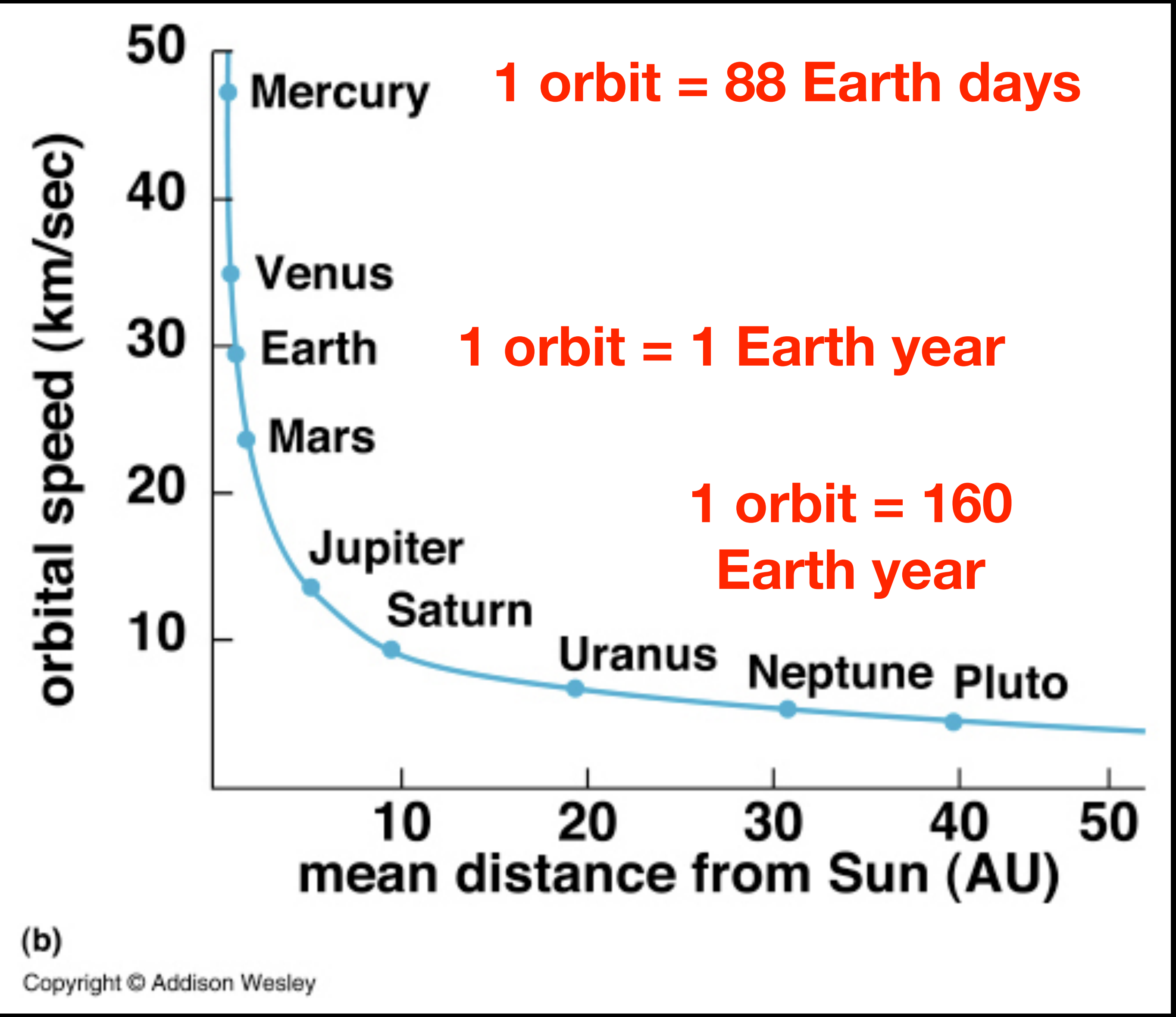
# Dark matter
## Glossary

- **Dark:** cannot see it / it does not shine

- **Matter:** do not have a better word to describe it (but gravity does affect it!)

# Galaxies are missing some matter

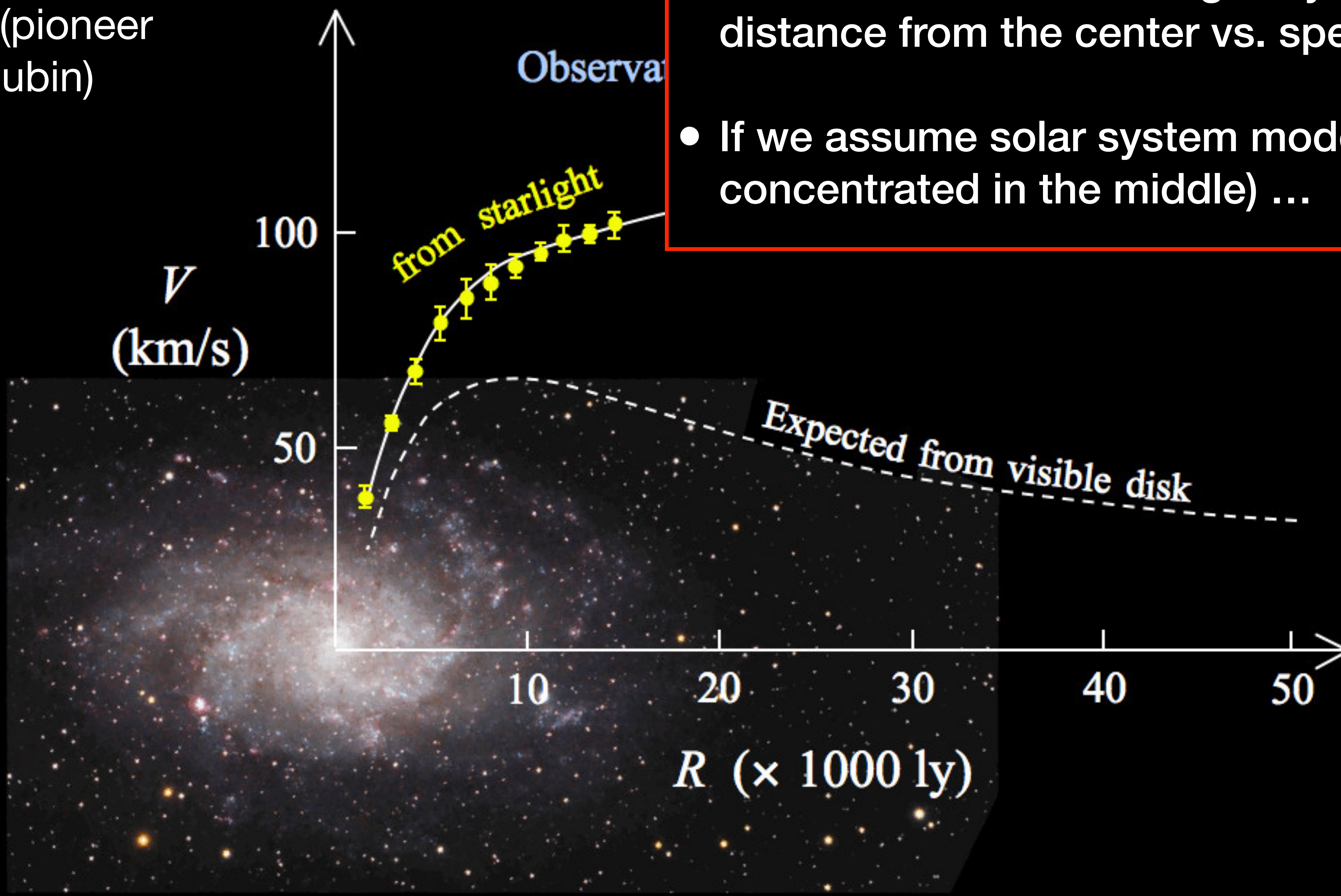
- Galaxies are the smallest cosmological scale where we can observe dm
- **Rotation curve:** mean distance from the Sun of a planet vs. average velocity
- Look at solar system where all the mass is located in the center



# Galaxies are missing some matter

## Spiral galaxies: more matter than meets the eye

Galaxies rotation curves measured since 1970 (pioneer was V. Rubin)




- Look at all the stars in a galaxy and measure distance from the center vs. speed
- If we assume solar system model (mass concentrated in the middle) …

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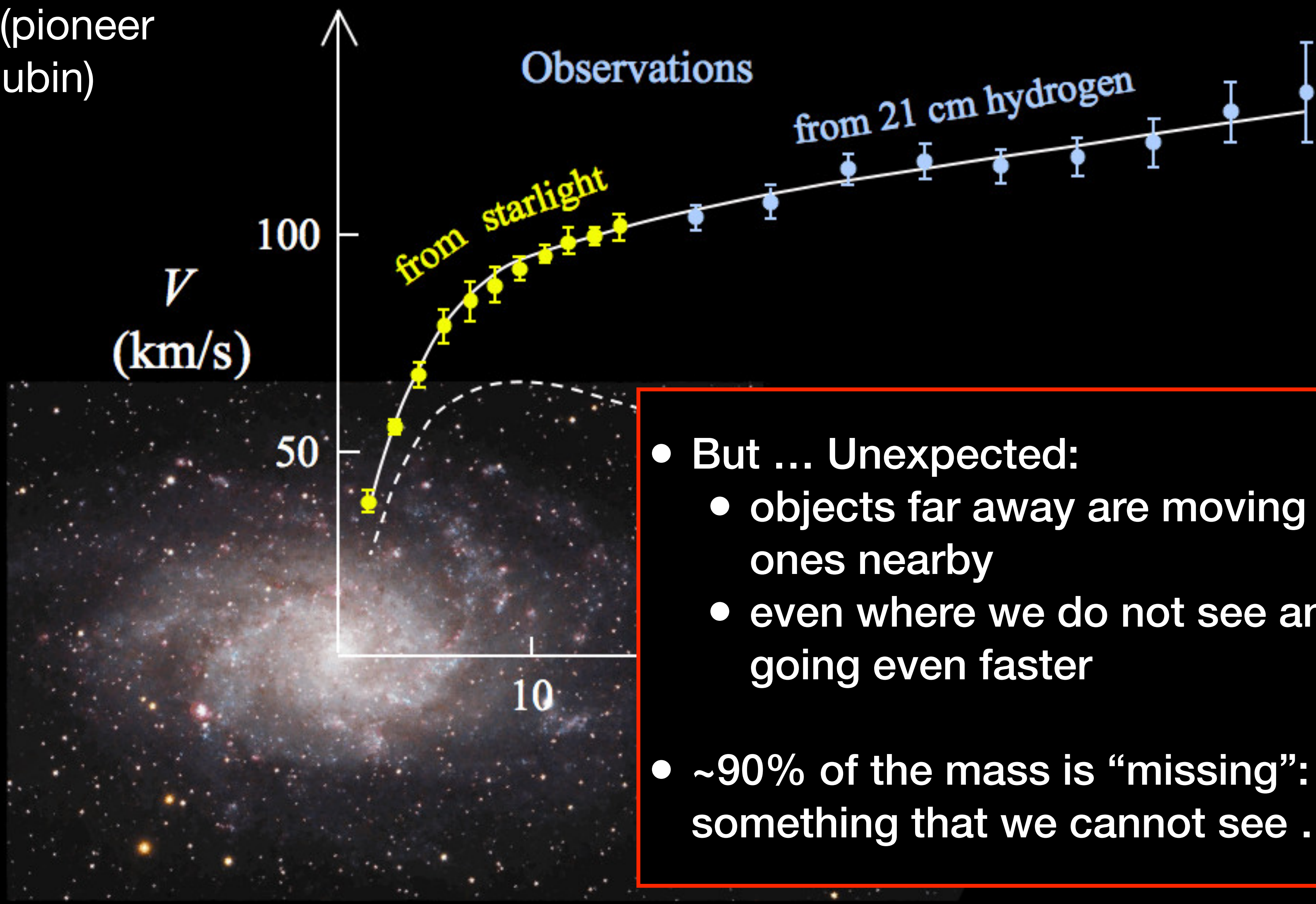
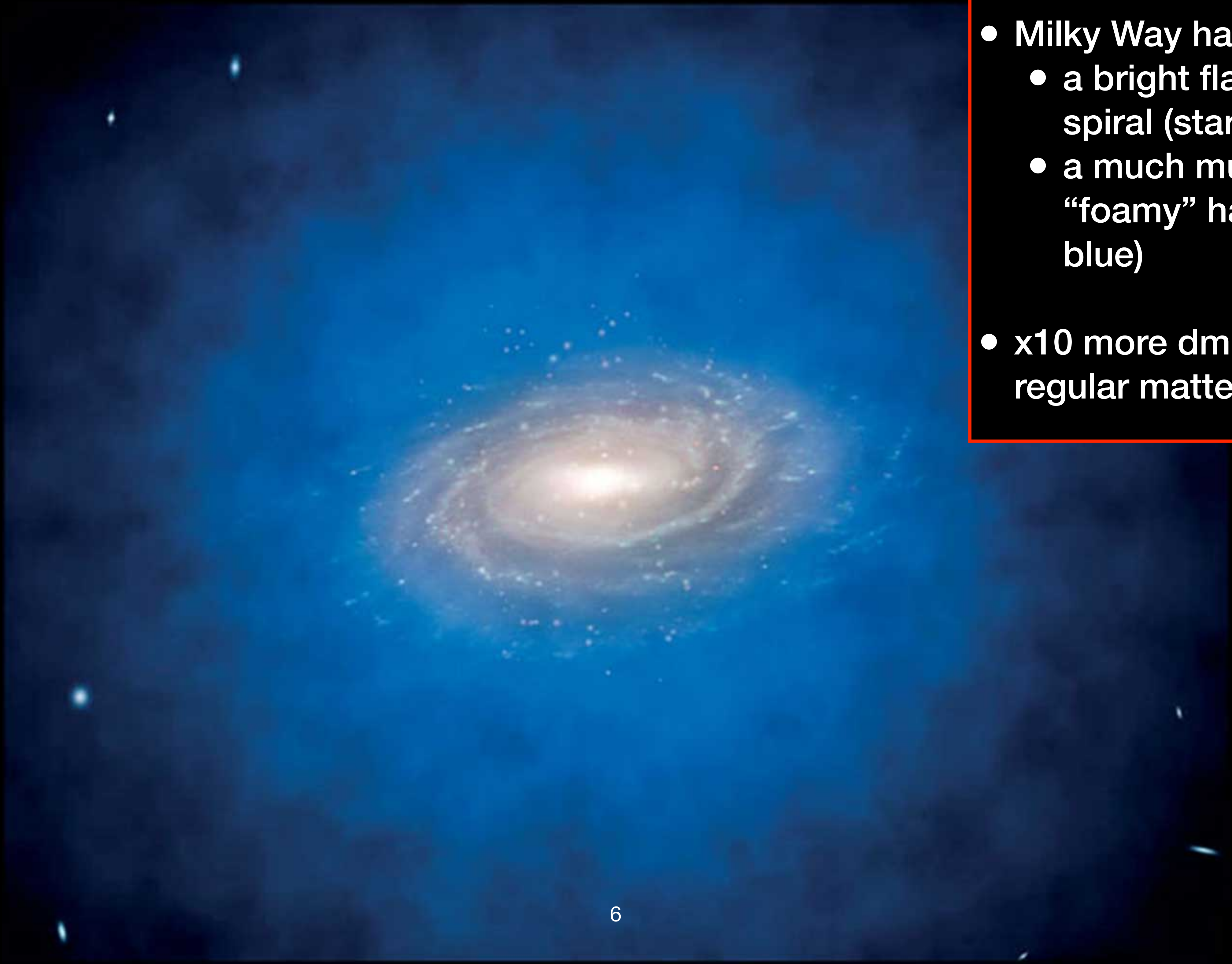



- But … Unexpected:
  - objects far away are moving faster than the ones nearby
  - even where we do not see any stars they are going even faster
- ~90% of the mass is “missing”: there is something that we cannot see …

# Galaxies are missing some matter

## The milky way seen with dm glasses



- Milky Way has
  - a bright flat circle/ spiral (stars)
  - a much much larger “foamy” halo (in blue)
- x10 more dm than regular matter

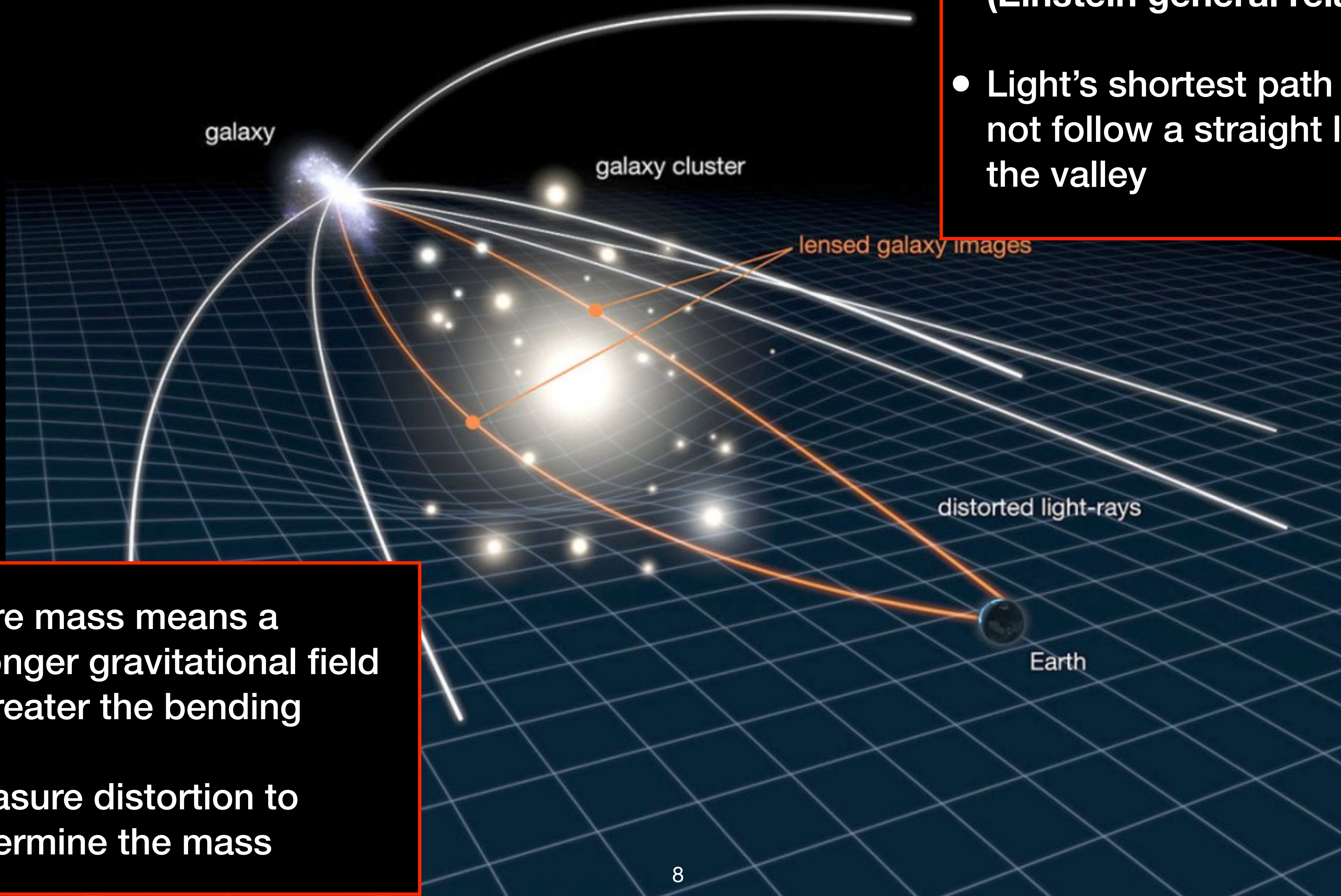
# Galaxy clusters are missing some matter too

- Increasing the scale to cluster of galaxies
- A cluster contains 100 of thousands galaxies
- How do we see dm?

# Galaxy clusters are missing some matter too

## Gravitational lensing

- Massive object deforms the space time **(Einstein general relativity)**
- Light's shortest path does not follow a straight line but the valley




- More mass means a stronger gravitational field = greater the bending
- Measure distortion to determine the mass

# Galaxy clusters are missing some matter too

- Measuring the Einstein ring / deformation of the galaxy image, we find the mass is x10 bigger than just the stars

# What about the whole Universe?

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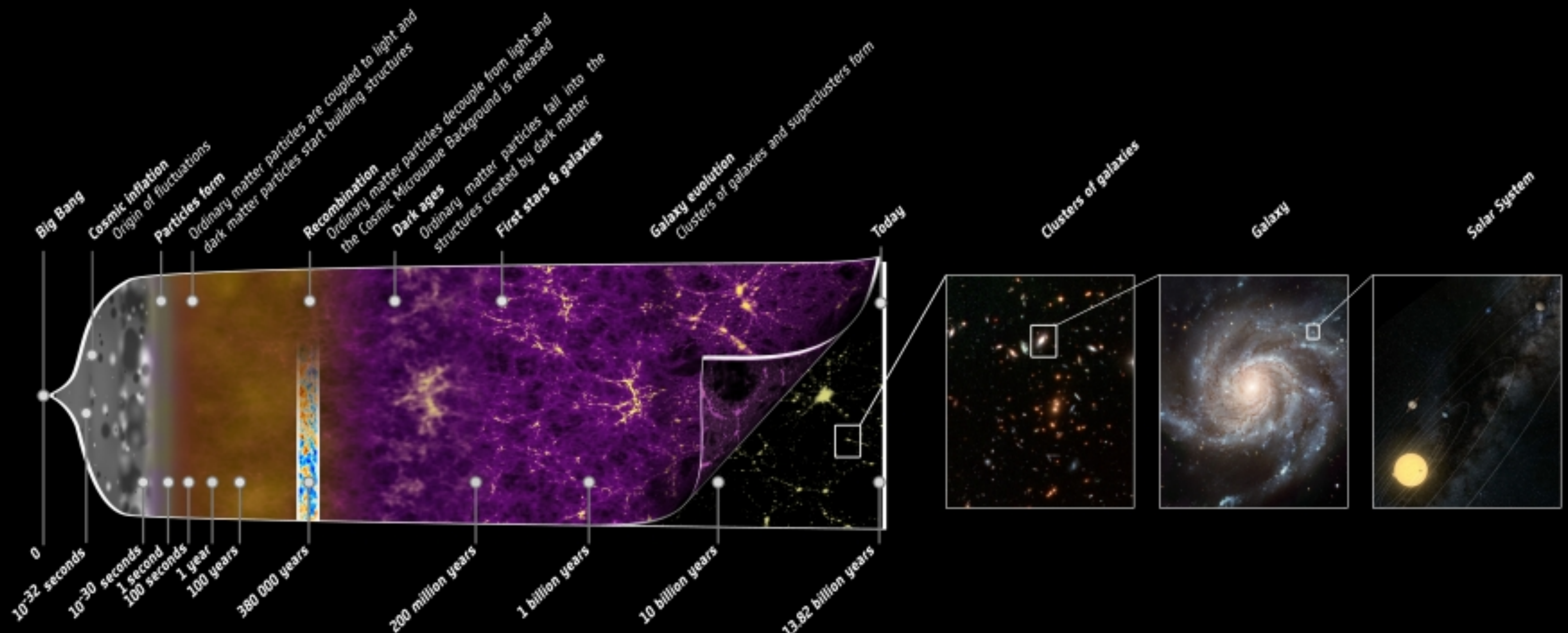
## Brief history of the Universe



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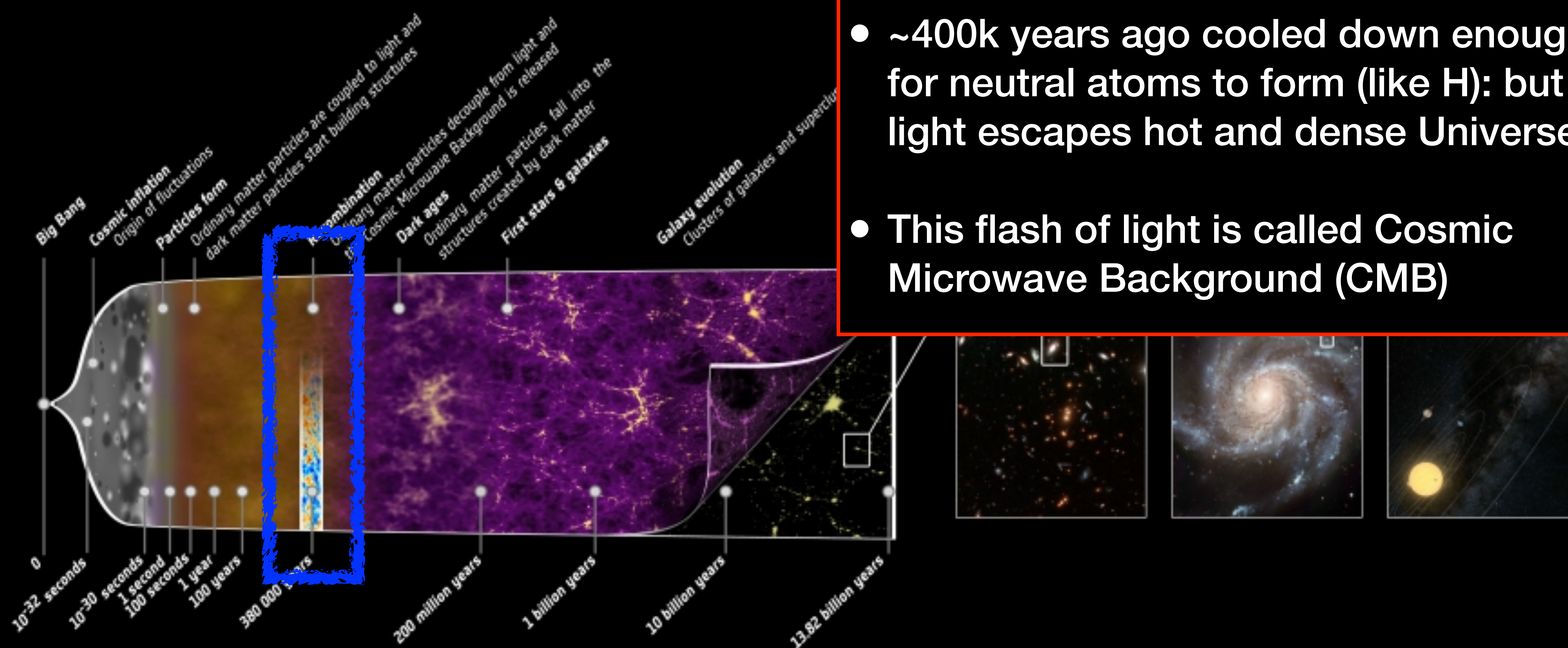


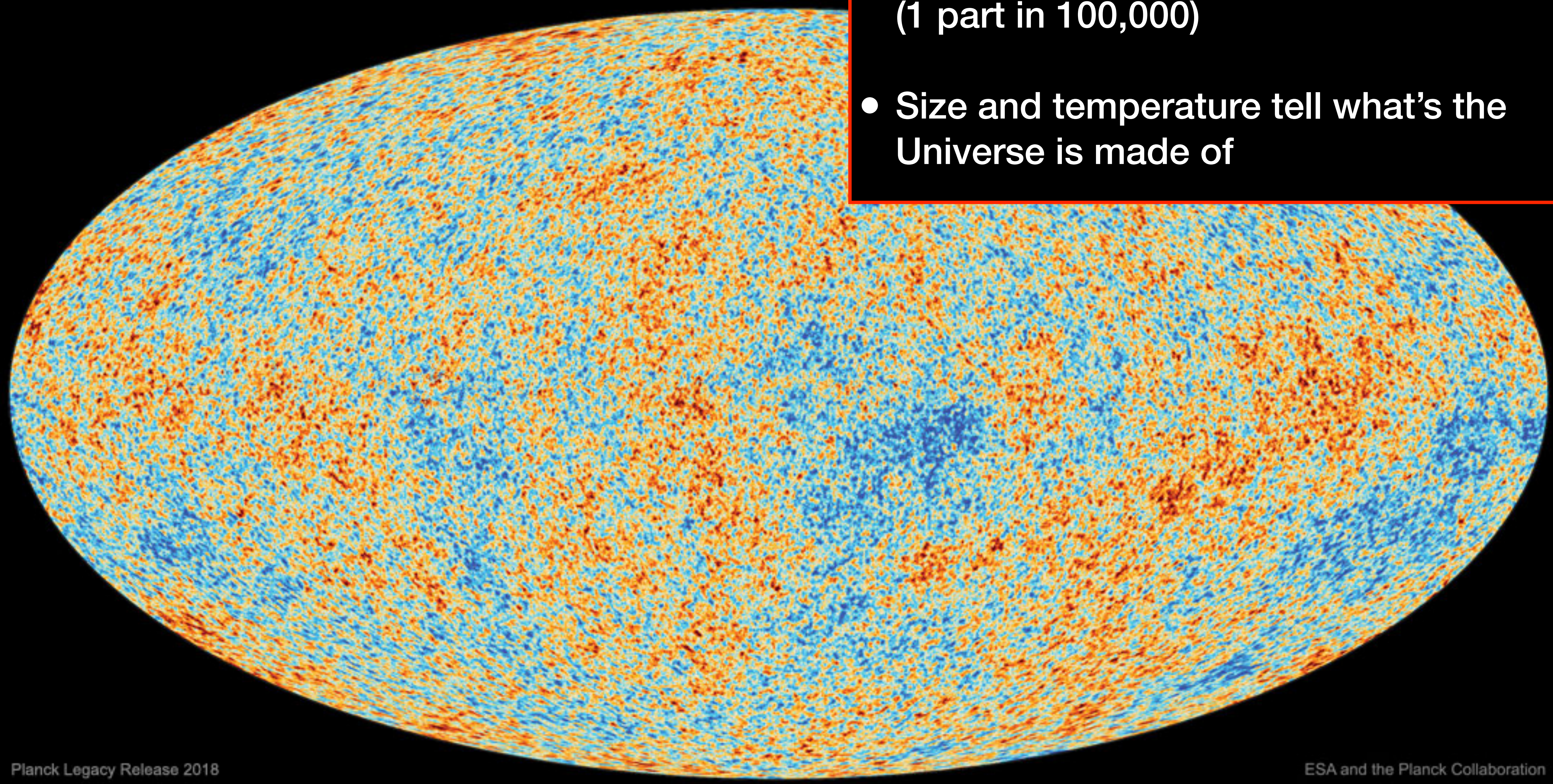

- ~400k years ago cooled down enough for neutral atoms to form (like H): but light escapes hot and dense Universe
- This flash of light is called Cosmic Microwave Background (CMB)

- During the Big Bang, Universe expanded faster than the speed of light and then started to cool down

# What about the whole Universe?

## Brief history of the Universe

- Regions slightly colder or slight warmer (1 part in 100,000)
- Size and temperature tell what's the Universe is made of



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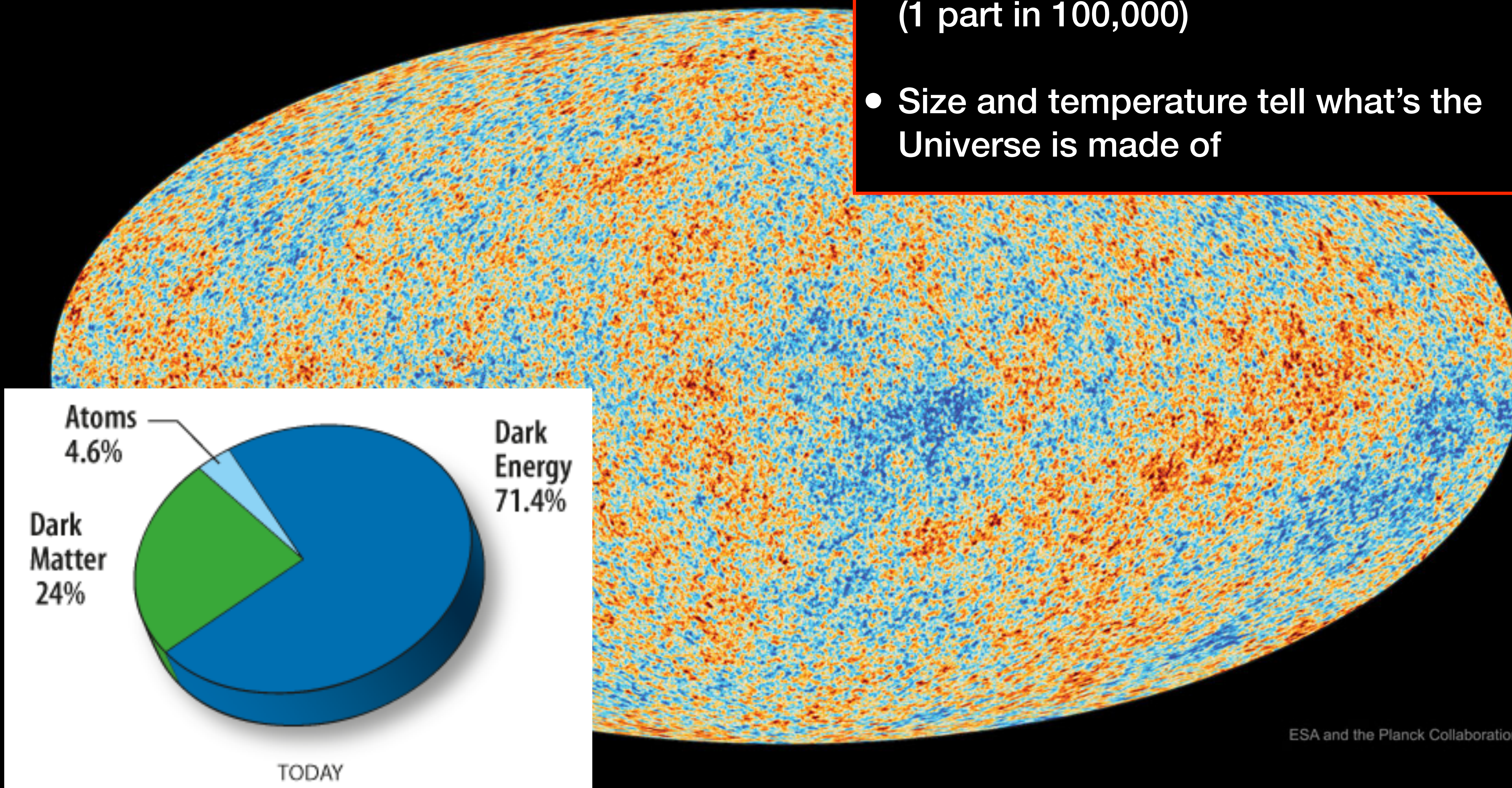
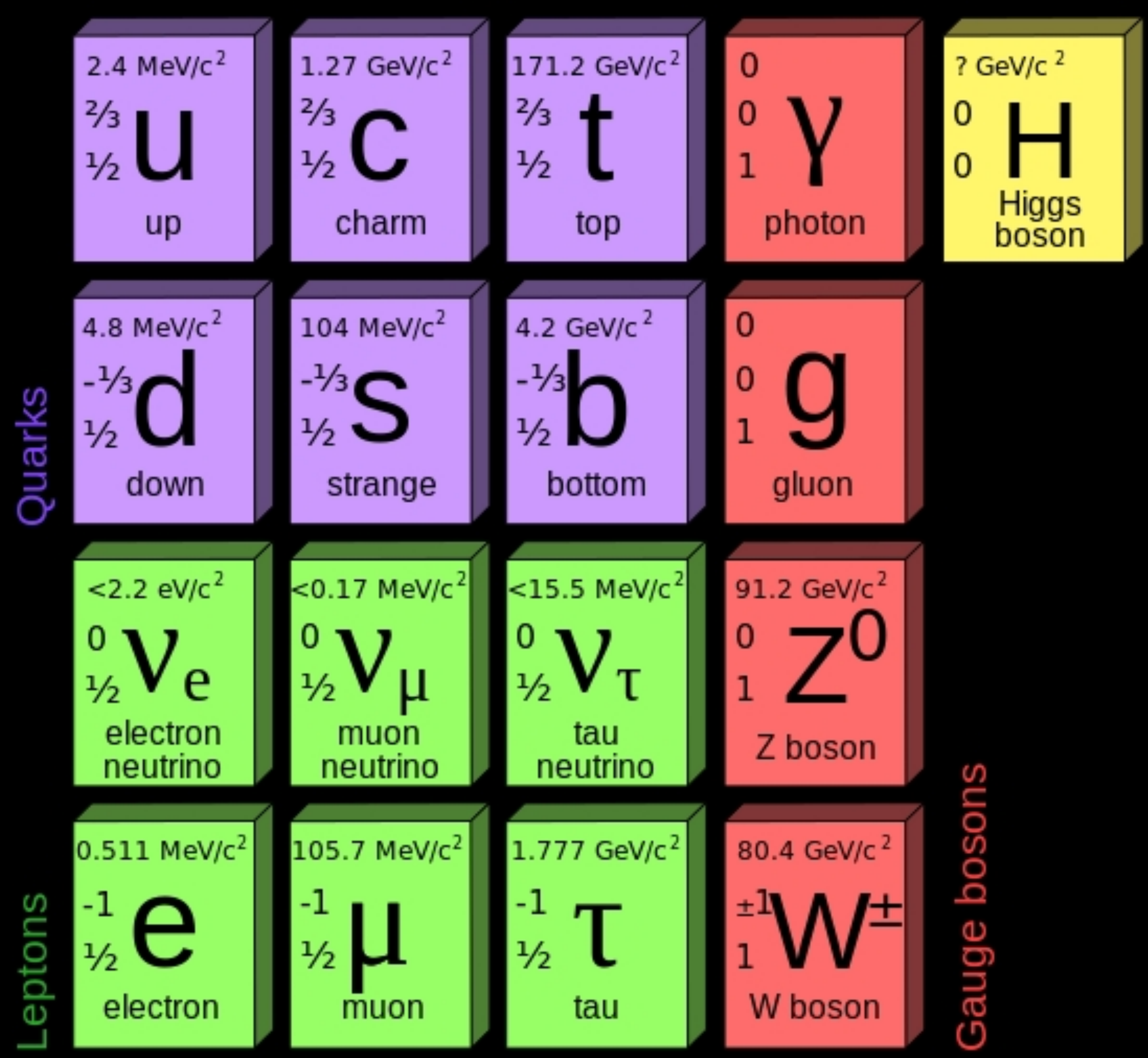


# What is dark matter?

## Let’s start from what it is NOT

**Standard model of particle**




- Gravitationally interactive

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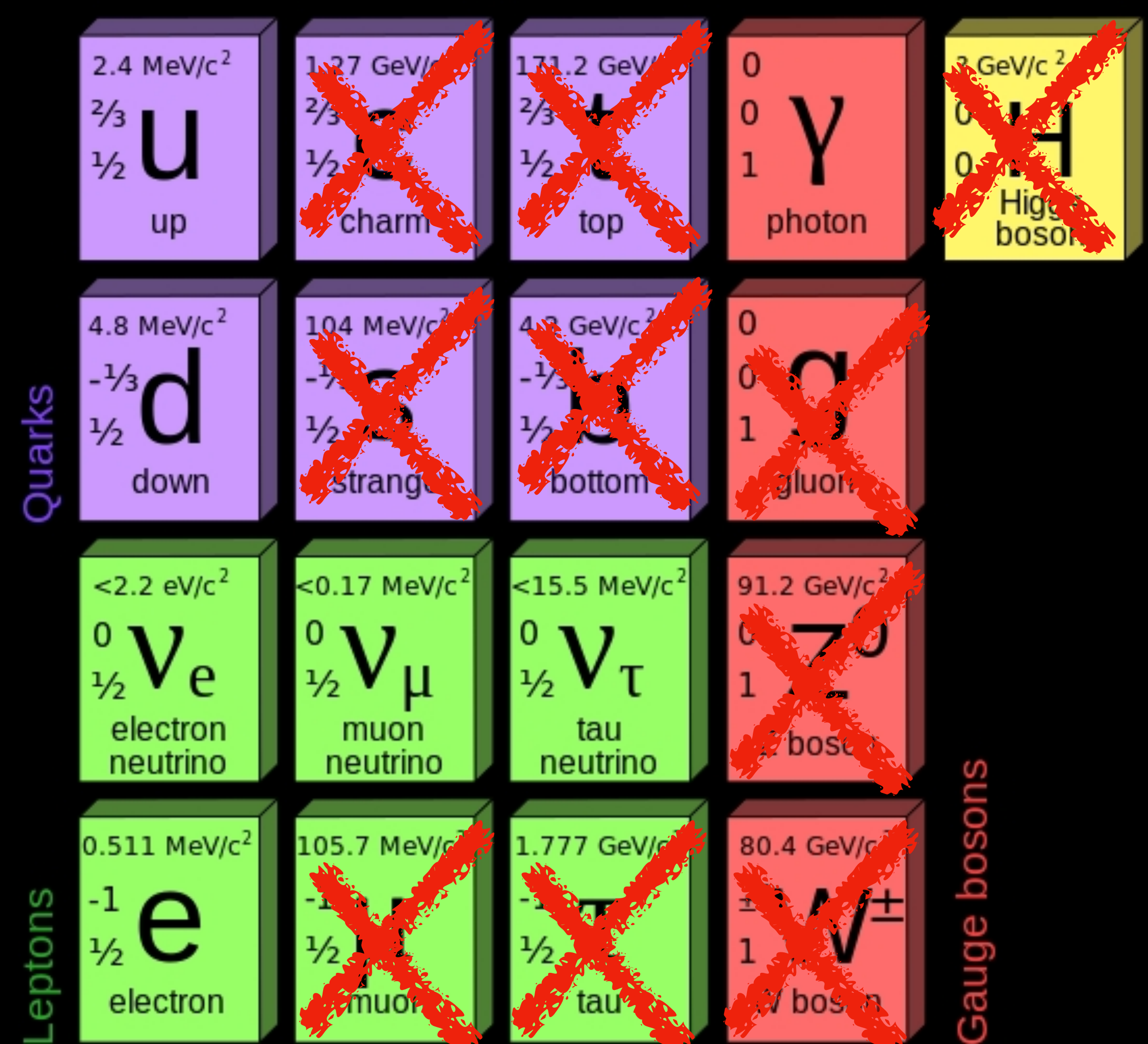


- Gravitationally interactive
- Not short lived

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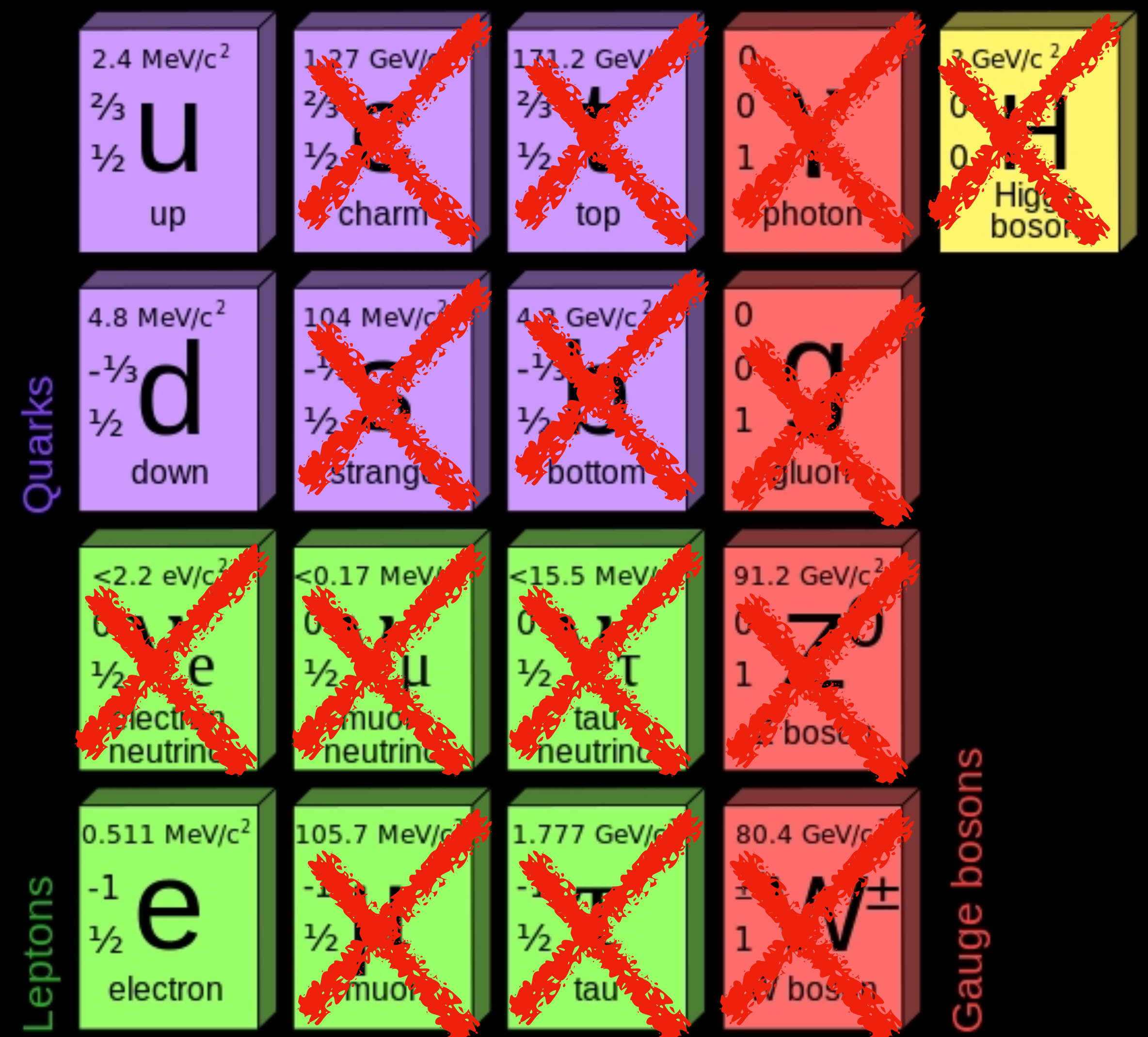


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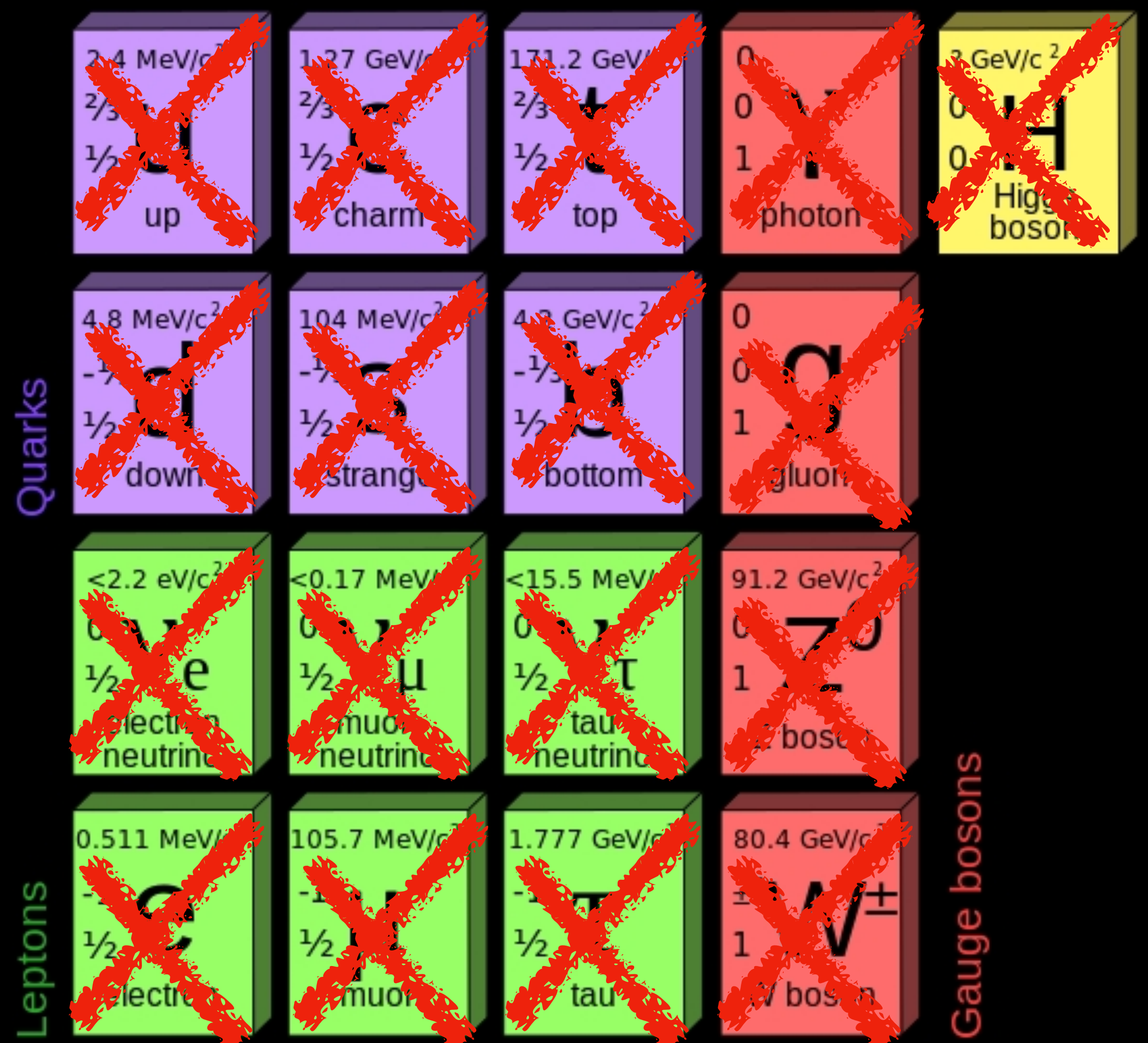
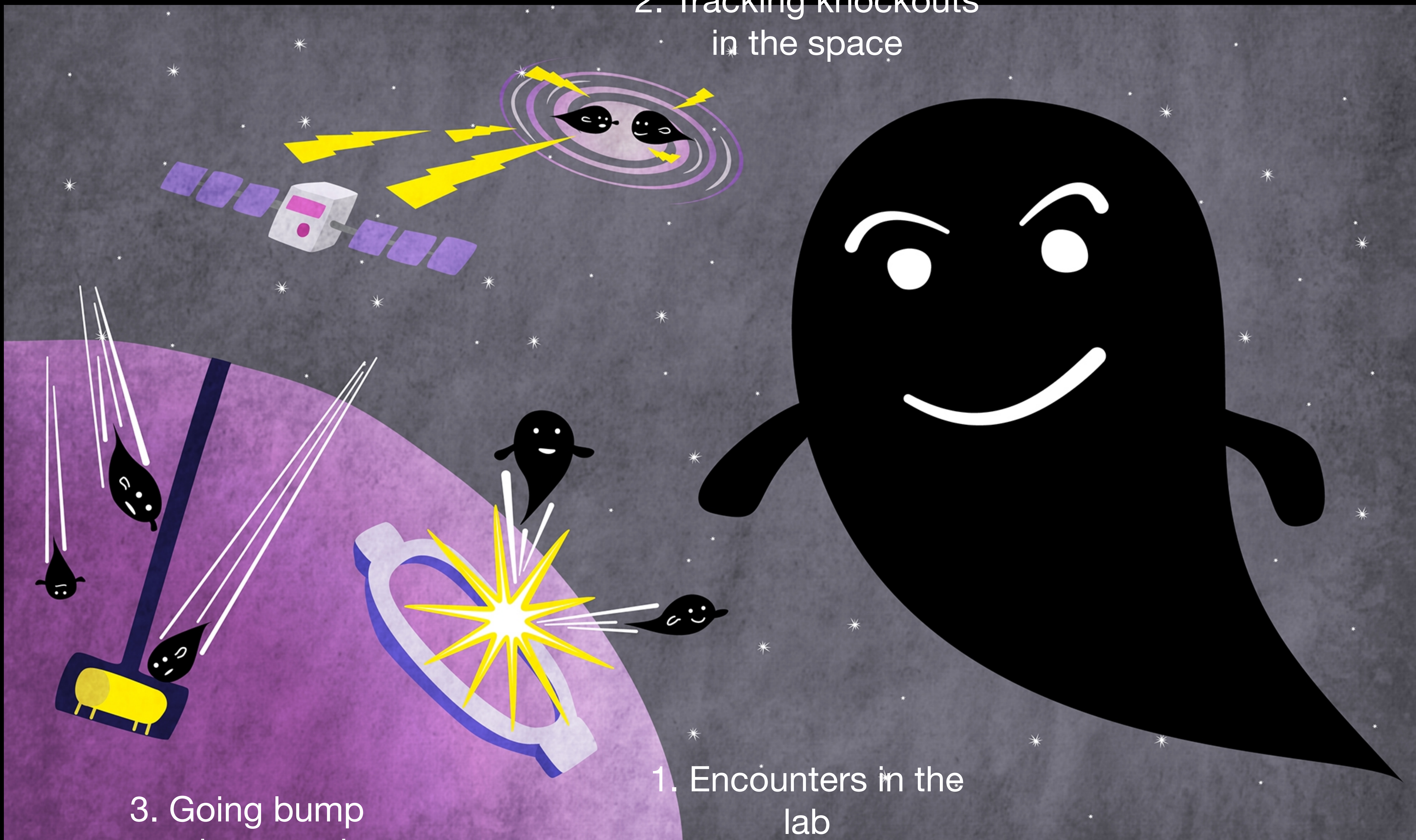



- Gravitationally interactive
- Not short lived
- Not light mass/hot
- Do not emit/absorb light (dark)
- It must be a **NEW PARTICLE,** maybe a WIMP (Weakly Interacting Massive Particle)

# Recap: so what do we know about dm?

- There's lot of dm (x10 more than regular matter)
- It formed during the Big Bang: a lot of energy created a lot of particles
- If we rewind the Universe's story, dm was interacting with ordinary matter (dm ↔ regular matter)
    - Any chance dm could interact again with regular matter? Maybe

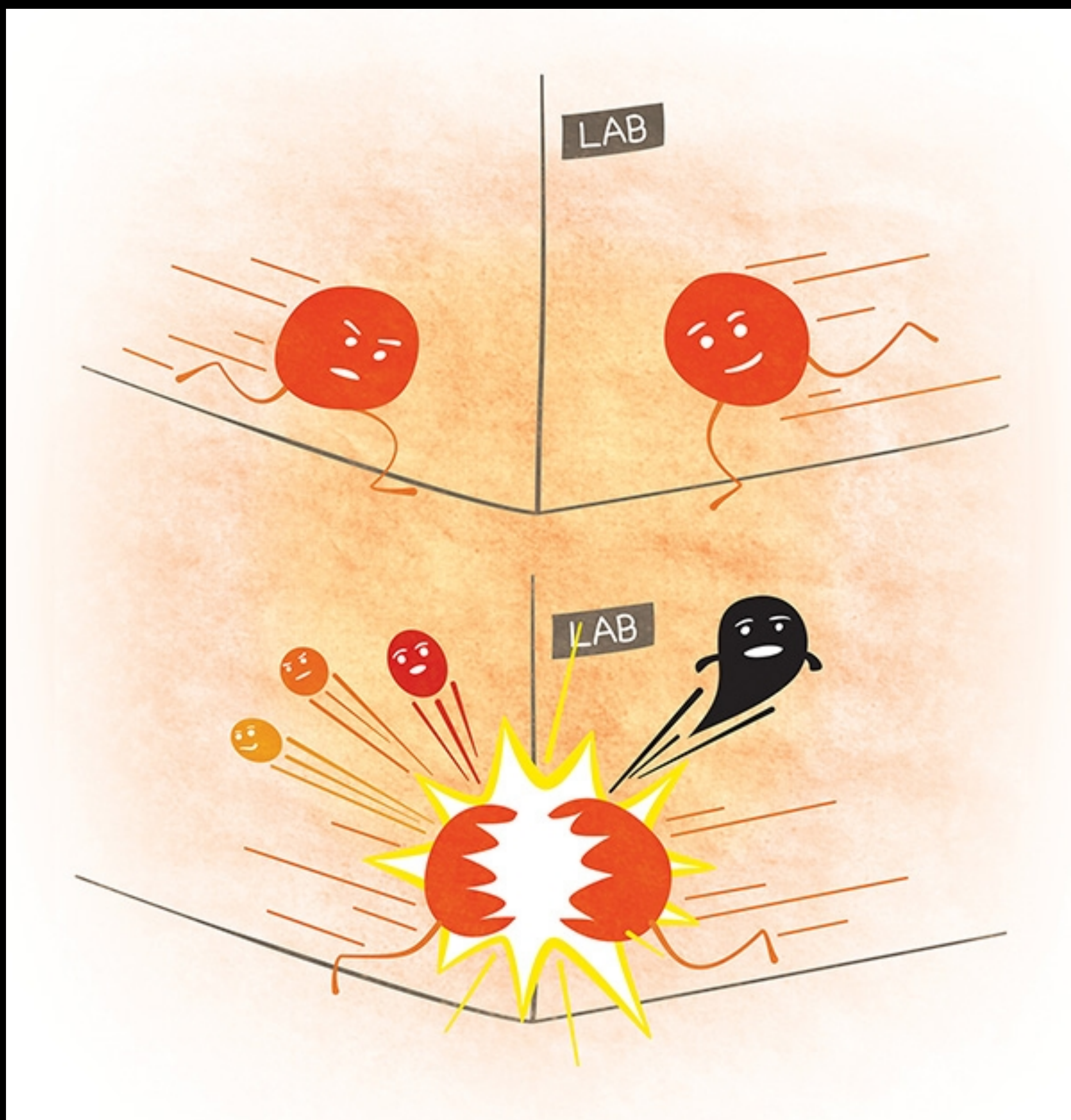
# Three ways to look for dm




Pics from https://www.symmetrymagazine.org/

# Encounters in the lab

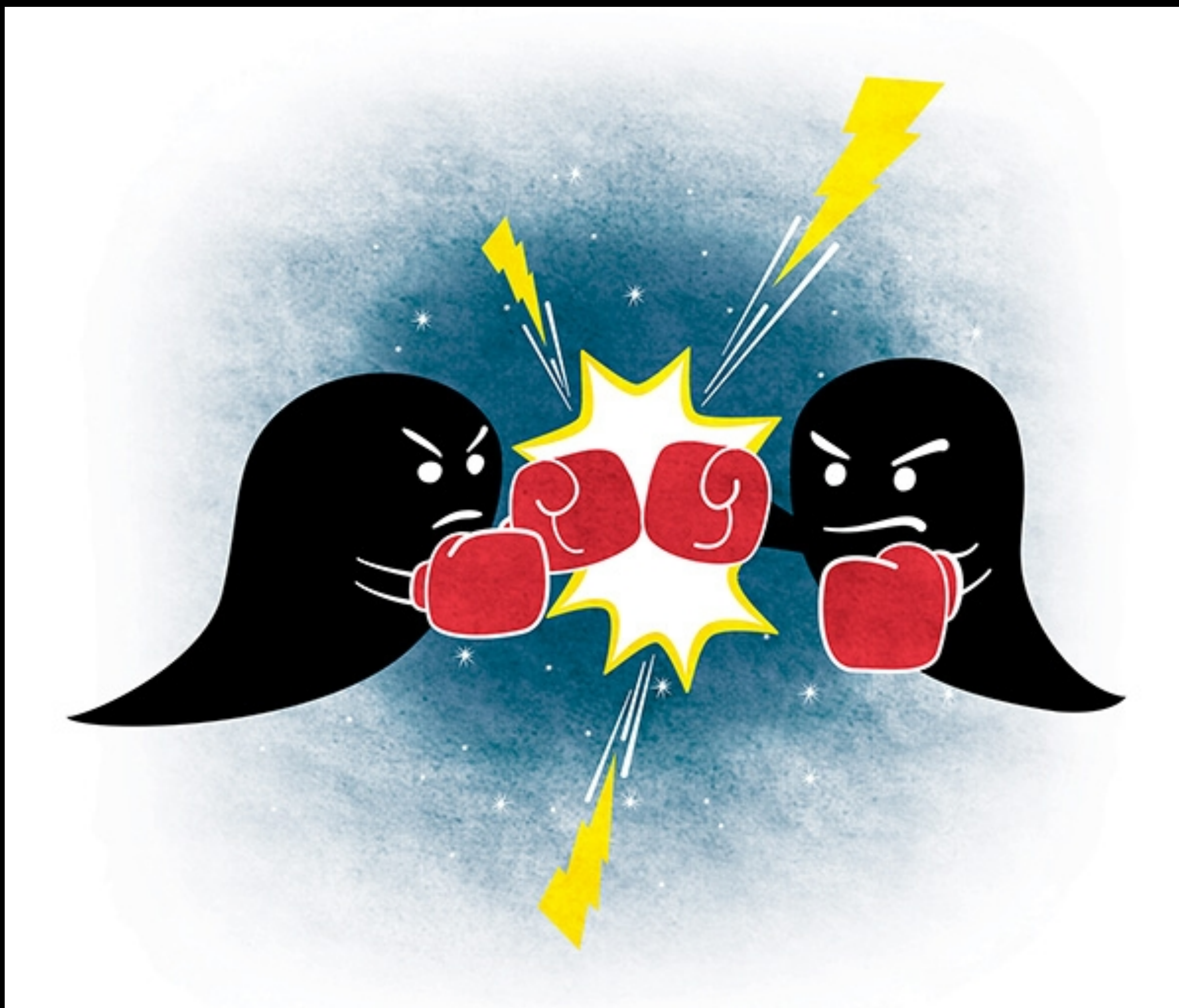
## Particle accelerators




- Particle accellerator (like at CERN) can produce dm by smashing ordinary matter (like protons)
- How to see dm?
  - As unbalanced energy in the collision

# Tracking knockouts in the space

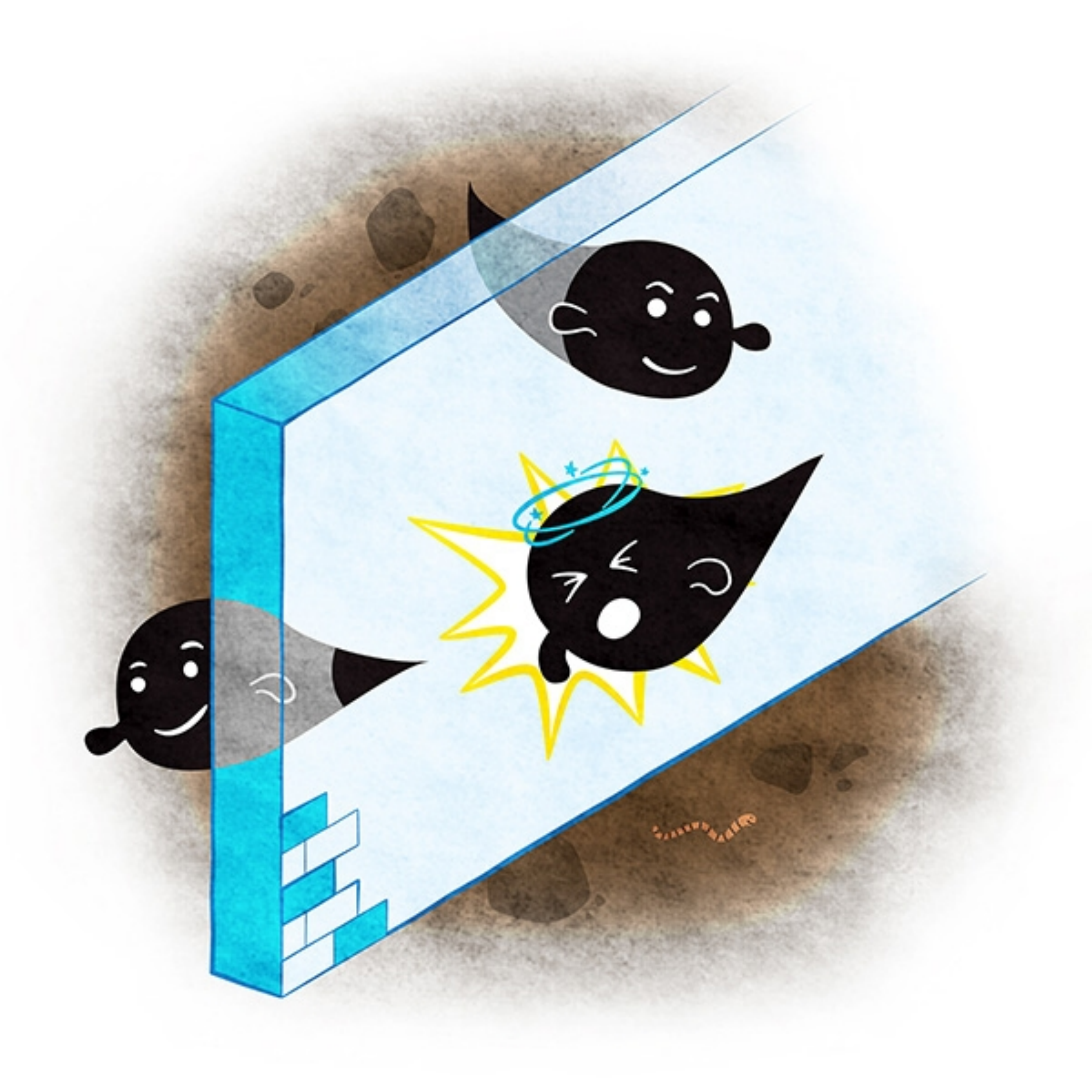
## Satellite



- Use Universe as particle accelerator, and look for the remains of dm collision
- Two dm particles annihilate in gamma rays
- How to see dm?
  - Look for excess

# Going bump underground

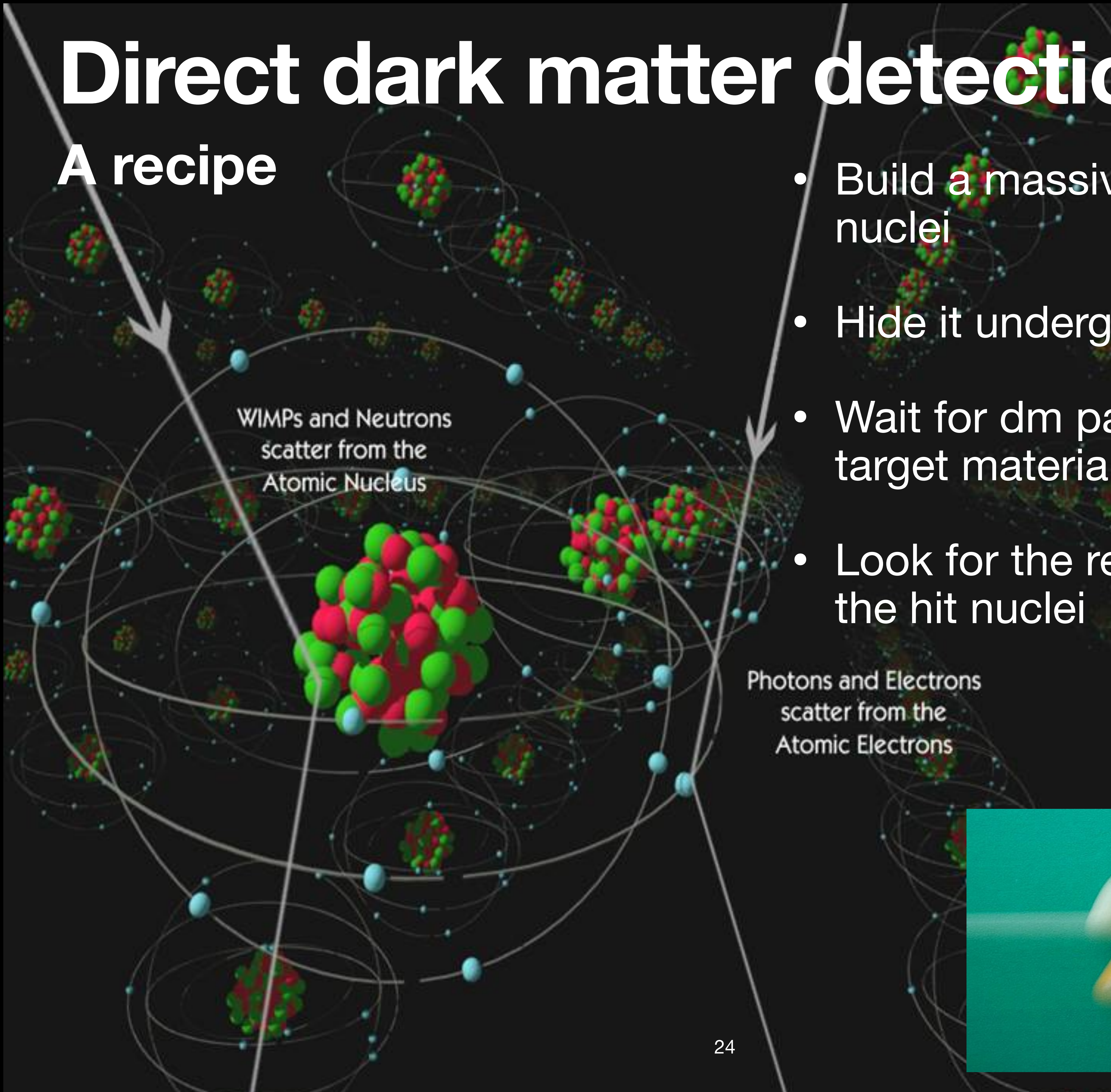
## Underground lab



- Dm could bump into ordinary matter in lab
- Very unlike event: need to suppress any unrelated signal which can mask/ mimic
- Need extremely sensitive detector located underground
- Earth's surface can be a filter to suppress all unwanted signals

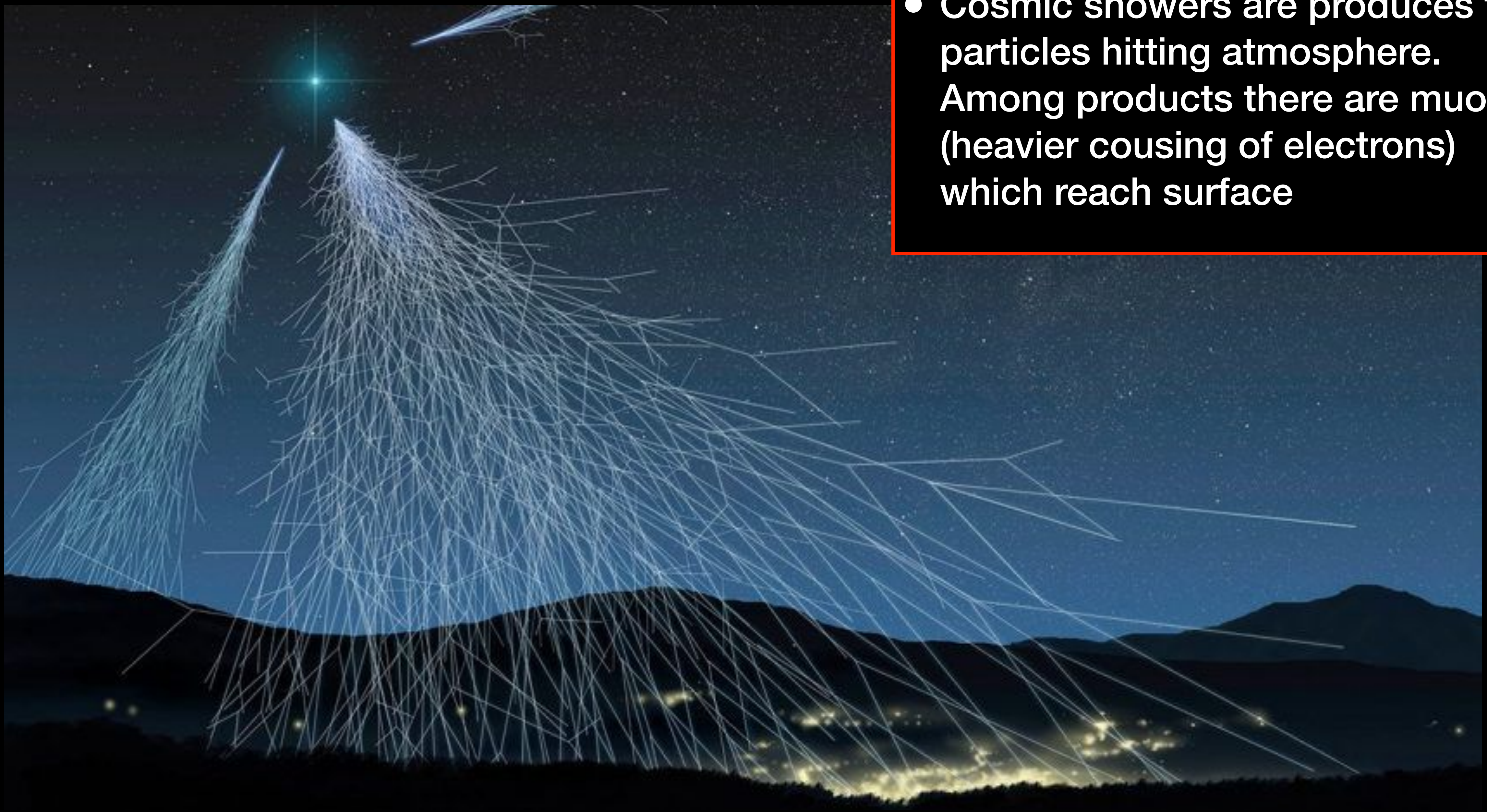
# Direct dark matter detection

## A recipe




- Build a massive “tank” of nuclei
- Hide it underground
- Wait for dm particle to hit the target material
- Look for the response from the hit nuclei

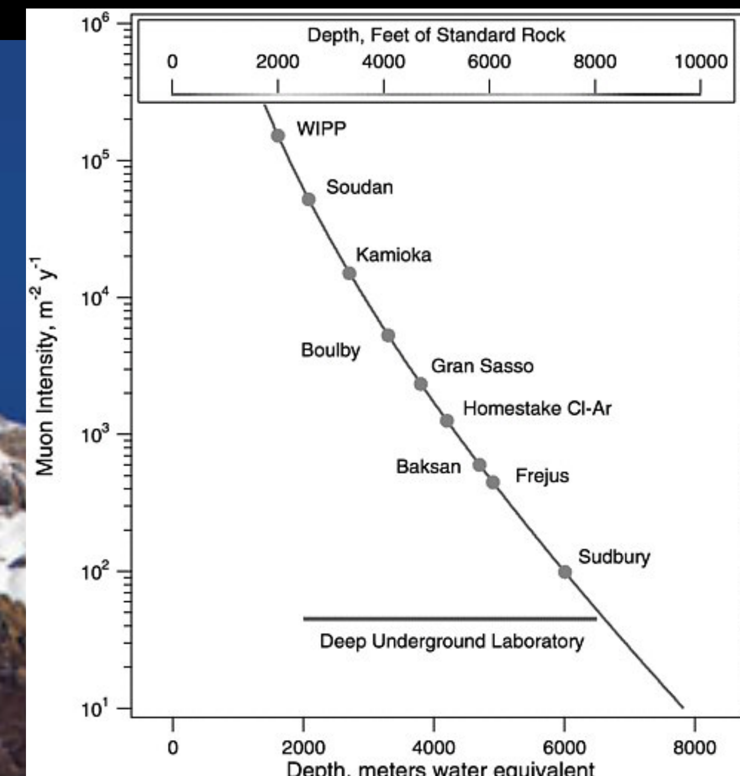
# Why underground?
## Cosmic rays



- Atmosphere is extremely alive with particles
- Cosmic showers are produces from particles hitting atmosphere. Among products there are muons (heavier cousing of electrons) which reach surface

# An underground lab in Italy

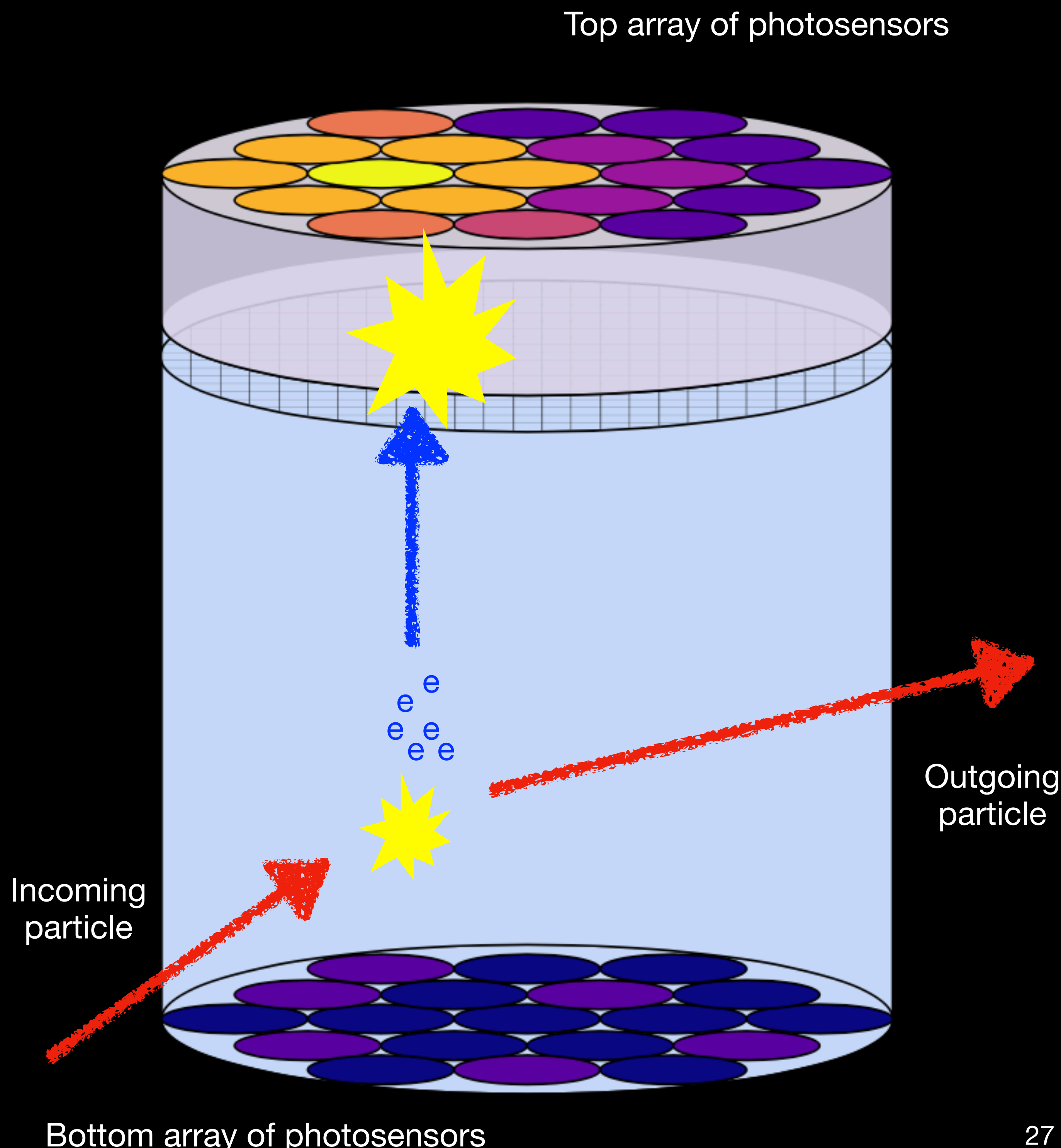
## Laboratori Nazionali del Gran Sasso


- Place experiment under a mountain: natural filters for all the muons to have a “quite” environment
- Note: dm is very elusive (do not care for a mountain or even a planet!)

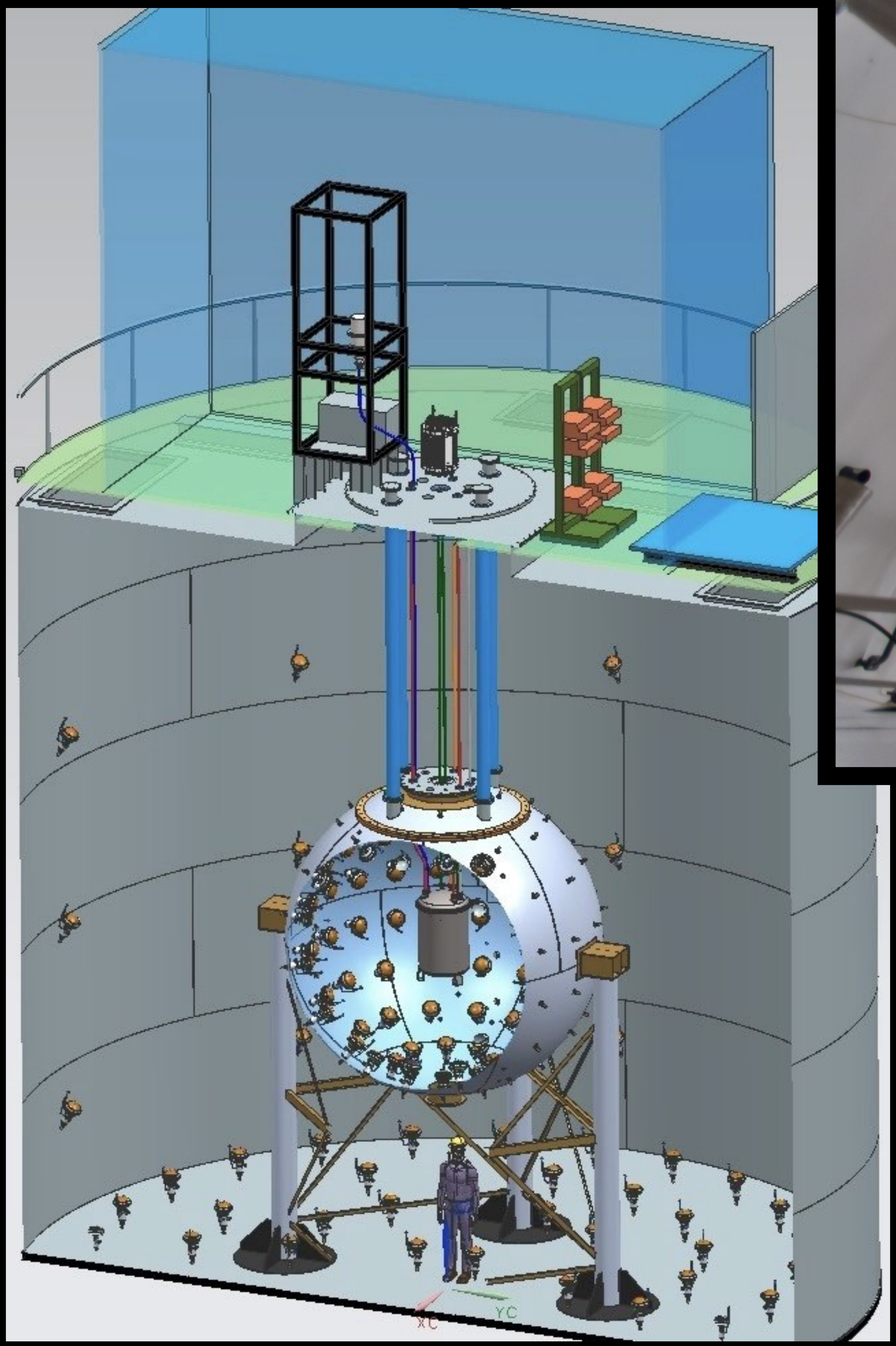
# An example: The DarkSide-50 detector

## How to detect dm




- Housed in LNGS lives the DarkSide-50 detector
- Bucket of liquid argon (~50kg) which detect dm by seeing light
- Incoming particles bump argon atoms producing direct light and electrons
- Electron drifted (by electric field) into gas region producing secondary light
- Very sensitive detector because:
  - Can discriminate among particles
  - Can 3D reconstruct the interaction (time difference between light signals + light pattern on top)

# An example: The DarkSide-50 detector



- Muon detector/veto to identify muons deep underground
- 1000L water tank acts as passive shild against radiation,  and muons

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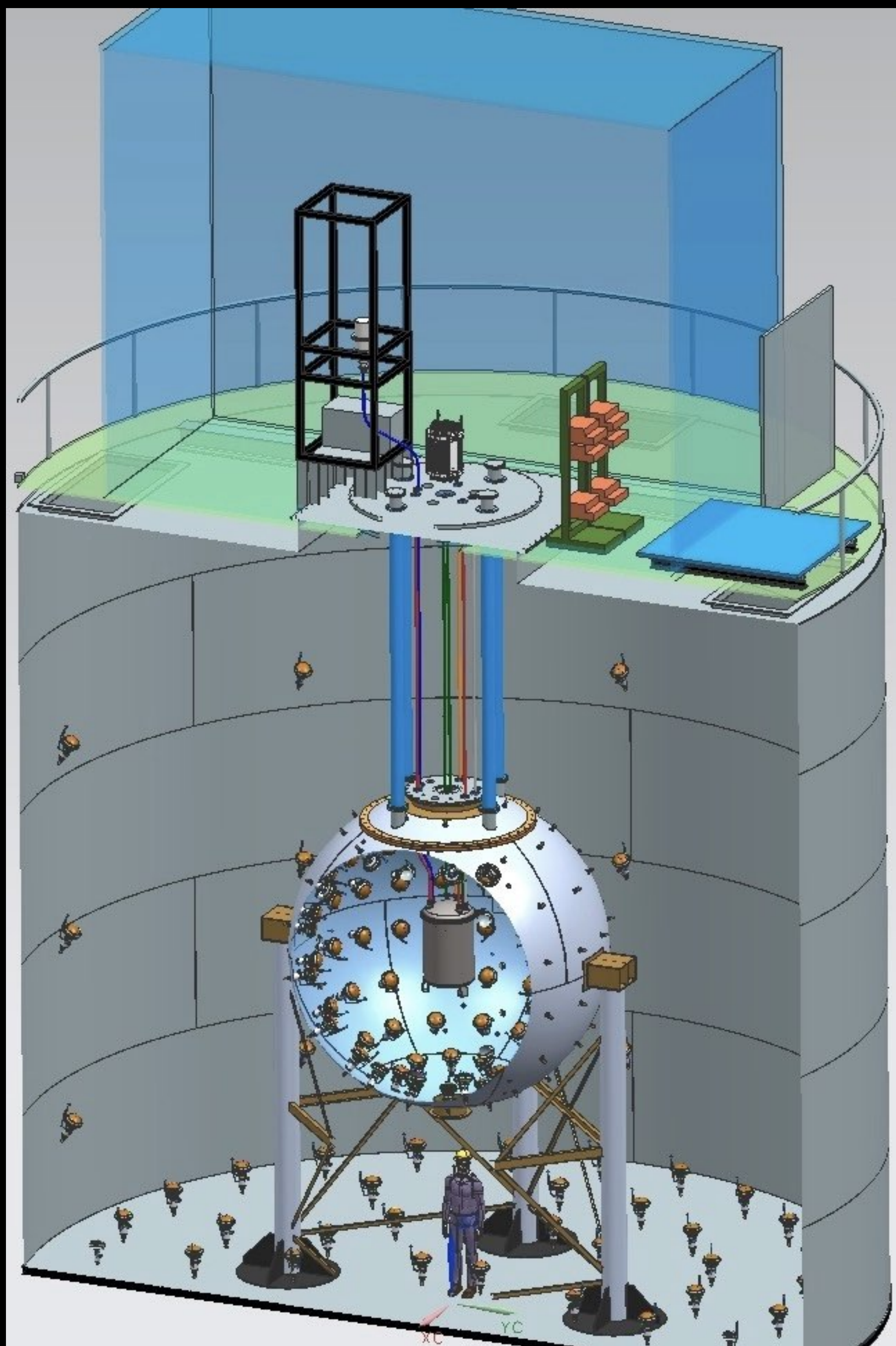
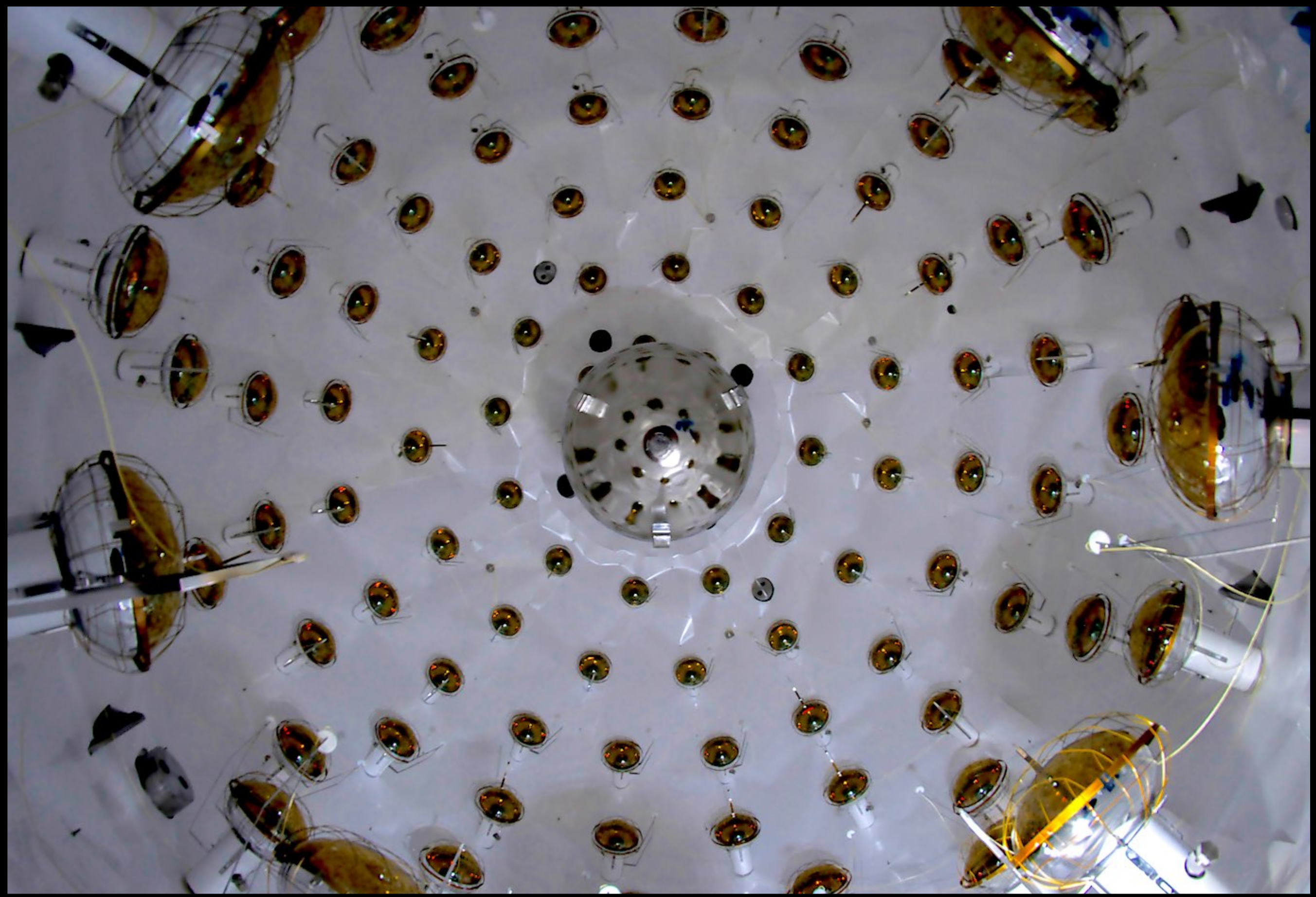
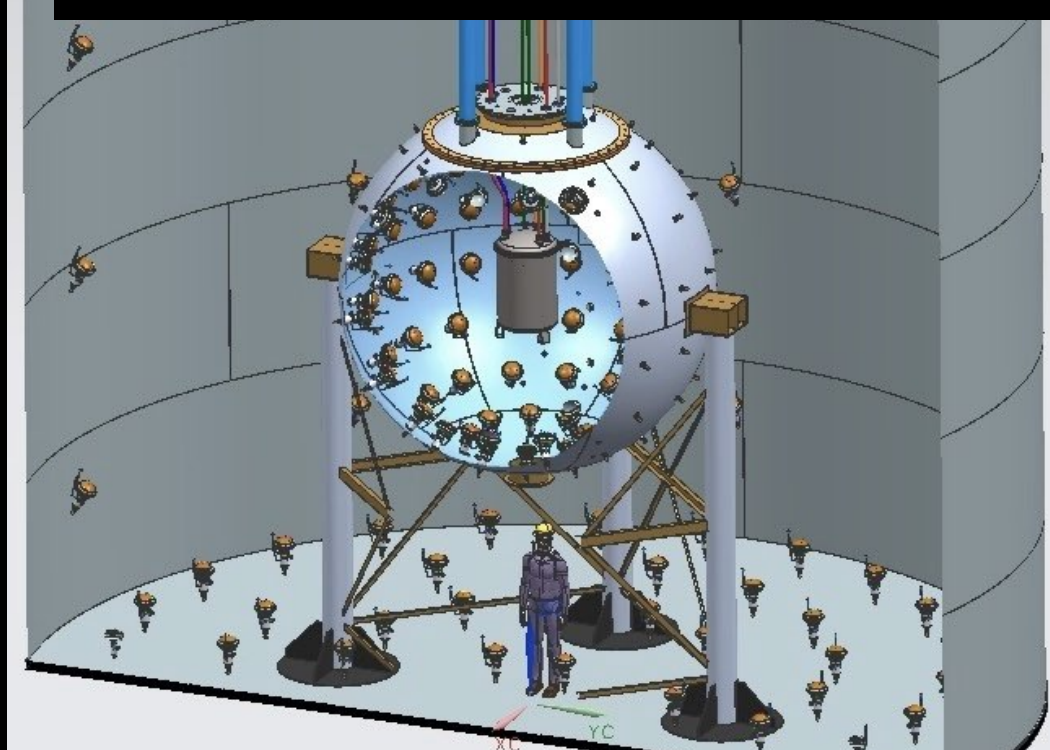




- Neutron detector/veto to identify neutrons which can mimic dm
- 30 ton liquid scintillator doped with boron ("likes" to capture neutrons)

# An example: The DarkSide-50 detector



- 50kg liquid argon bucket seen by top and bottom light sensors. It is the dm detector
- Some numbers: on Earth there are ~3 dm particles per liter which streams through Earth at ~150 miles/s. ~1 billion dm particles every year, but dm is very elusive

# Take home messages

- We know dark matter exist because we see its effect in galaxies, clusters of galaxy, and in the Universe itself
- But …
  - we do not really see it directly
  - we do not know much about it
  - and we haven’t discovered it directly yet (maybe in the next 20 years).
- The little we know is that it is extremely elusive and we need big and quite detectors to record such a faint blip

# Galaxies are missing some matter

## Rotation curve measurements: a little history

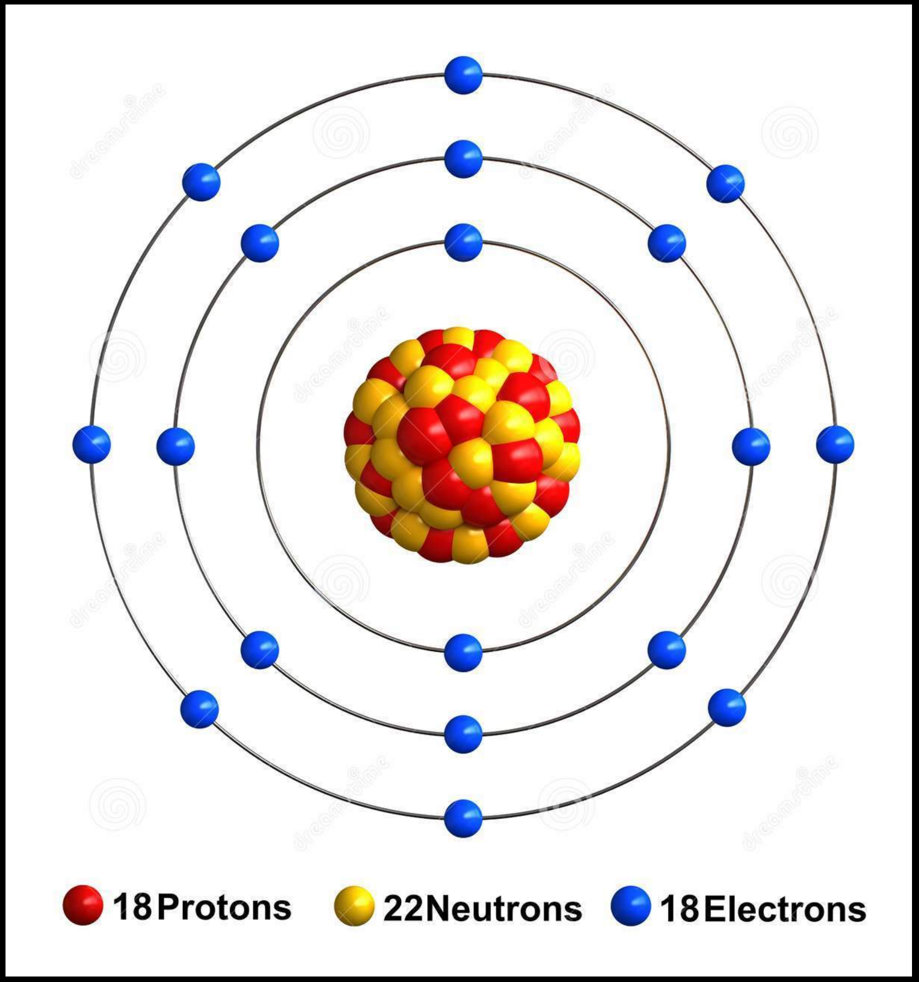
- In 1970s Vera Rubin observed Andromeda galaxy stars were rotating too fast
- Not taken seriously for decades but she made the original measurements of dm

# Why argon? And why a liquid?

- Kinematic matching with dm
  - Study an object you cannot see by “throwing” stuff at it: projectile needs to be same size as the object

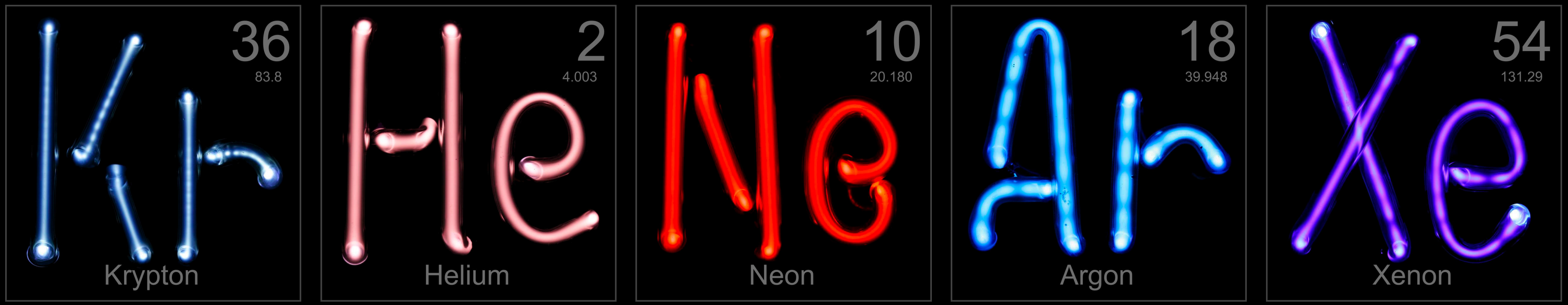
# Why argon? And why a liquid?

- Kinematic matching with dm
- Decent amount of nucleons (proton+neutron)
  - Dm interactions via Nuclear Weak Interactions
  - The more targets (nucleons) the better



# Why argon? And why a liquid?

- Kinematic matching with dm
- Decent amount of nucleons (proton+neutron)
- Transparent to its own light
  - Excited noble gases emit (UV) light which can escape and be detected by a light sensor



# Why argon? And why a liquid?

- Kinematic matching with dm
- Decent amount of nucleons (proton+neutron)
- Transparent to its own light
- Can be a liquid (at -303F or -186C) so it “easy”
  - To purify: the purer the better
  - To scale: to make a bigger detector just use a bigger bucket (easier said than done)

# Dark matter numbers

## Dark matter is very very elusive

- Onion-like DarkSide-50 design to detect dm
- Some numbers:
  - ~3 dm particles per liter on Earth
  - dm streams through Earth at ~150 miles/s
  - ~10,000 dm particles at anytime crossing detector volume in ~10 miscroseconds
  - ~1 billion dm particles every year
    - We hope to detect ~1 per year (if we are very lucky) … but we did not do it yet!

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