The Story of Dark Matter

What is it?
Why do we care?
And how do we find it?

elusives
neutrinos, dark matter & dark energy physics

IFIC
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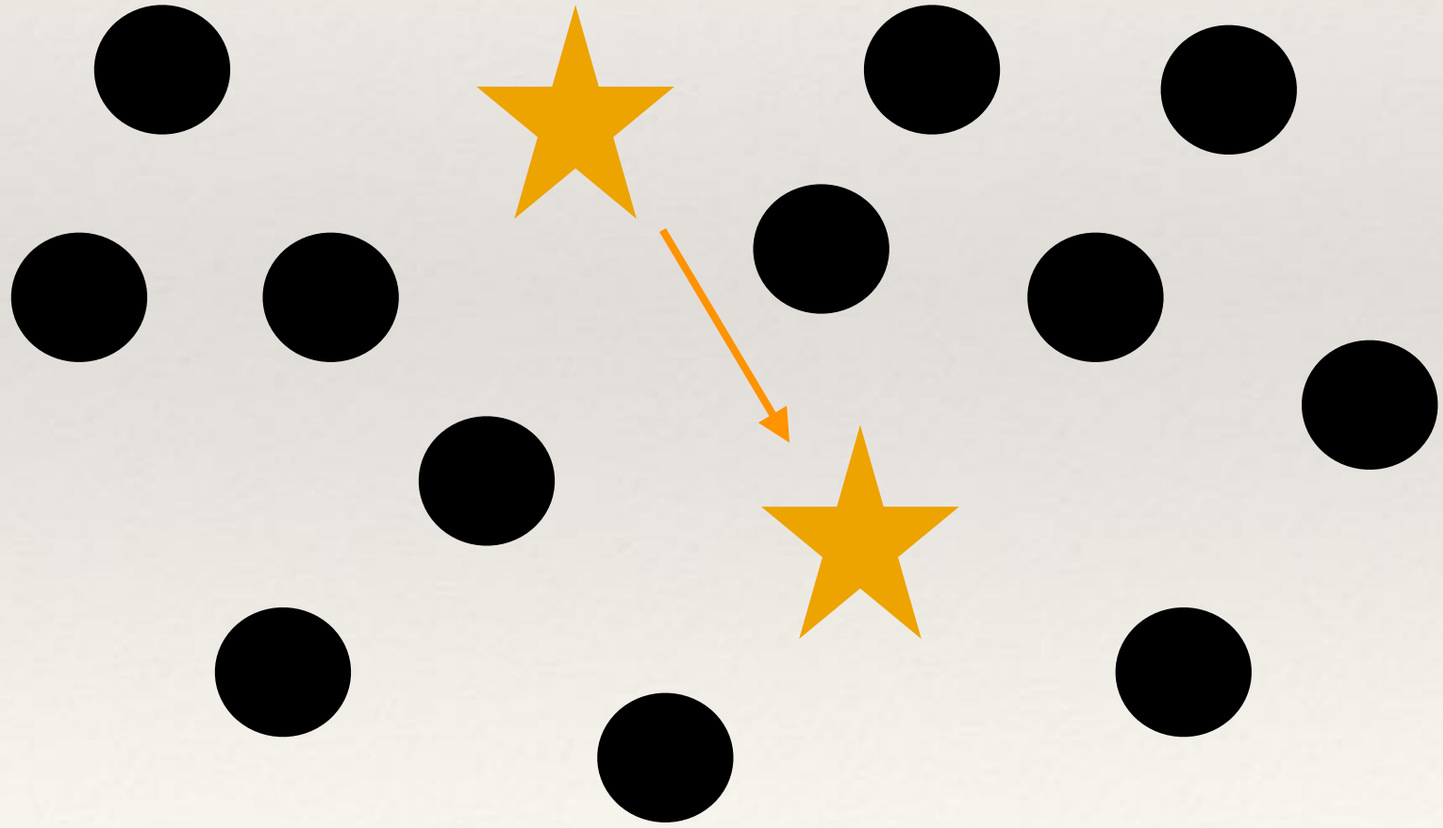
Origin of Dark Matter

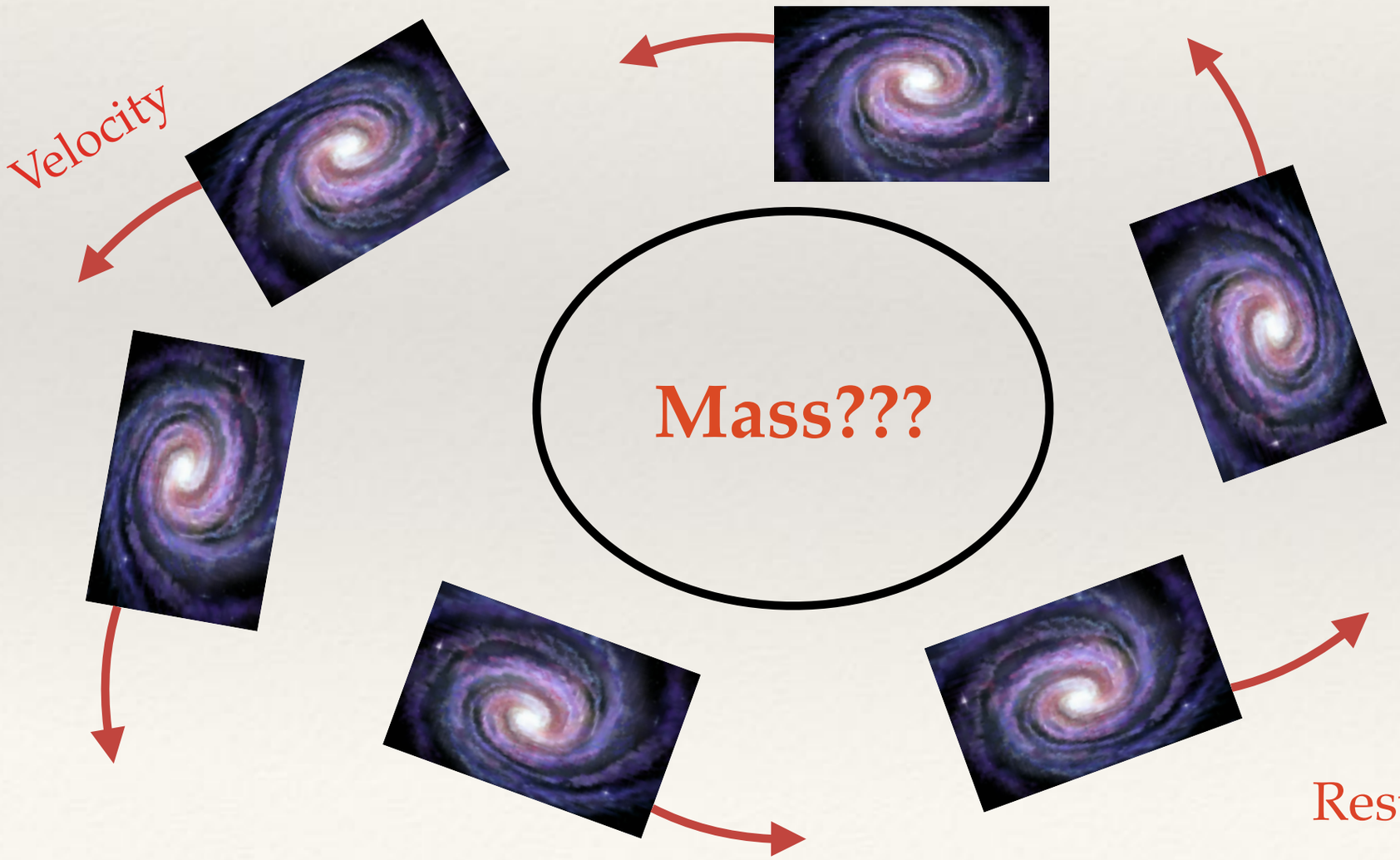
- ~1904: Lord Kelvin and Henri Poincaré began thinking about how much matter could reside in the galaxy that we cannot see
  - This could be because the objects do not emit light, like a black hole, or because the objects do not emit enough light for us to see here on Earth



There was no evidence, however, that dark matter *must* exist!

Early Evidence for Dark Matter

- ~1930s: Edwin Hubble and Milton Humason observe large velocities of galaxies
  - Franz Zwicky used this information to infer the amount of 'dark matter'



Determine total mass +
Estimate visible mass

↓

Calculate invisible mass

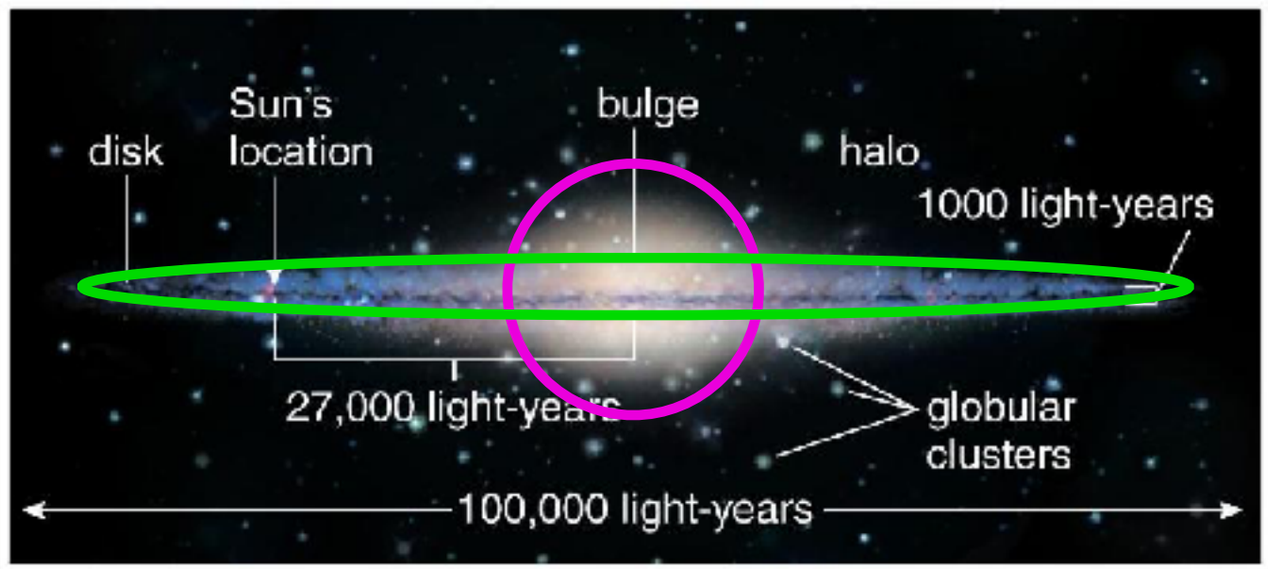
↓

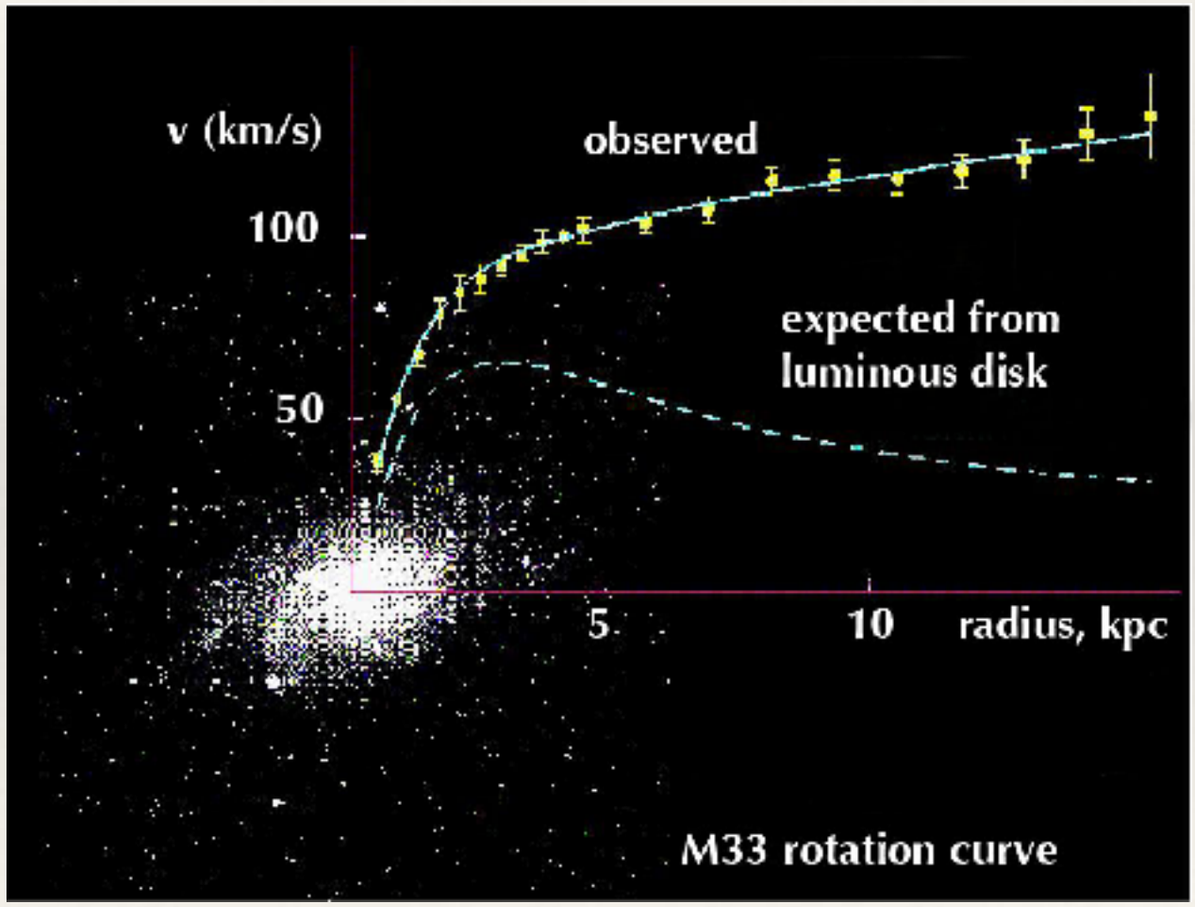
Conclusion:
Almost all mass is invisible

Result met with skepticism…

First Convincing Evidence

- ~1970s: Vera Rubin and Kent Ford observed the rotation velocity in galaxies
  - Not only is there mass missing, but the shape of visible mass is problematic



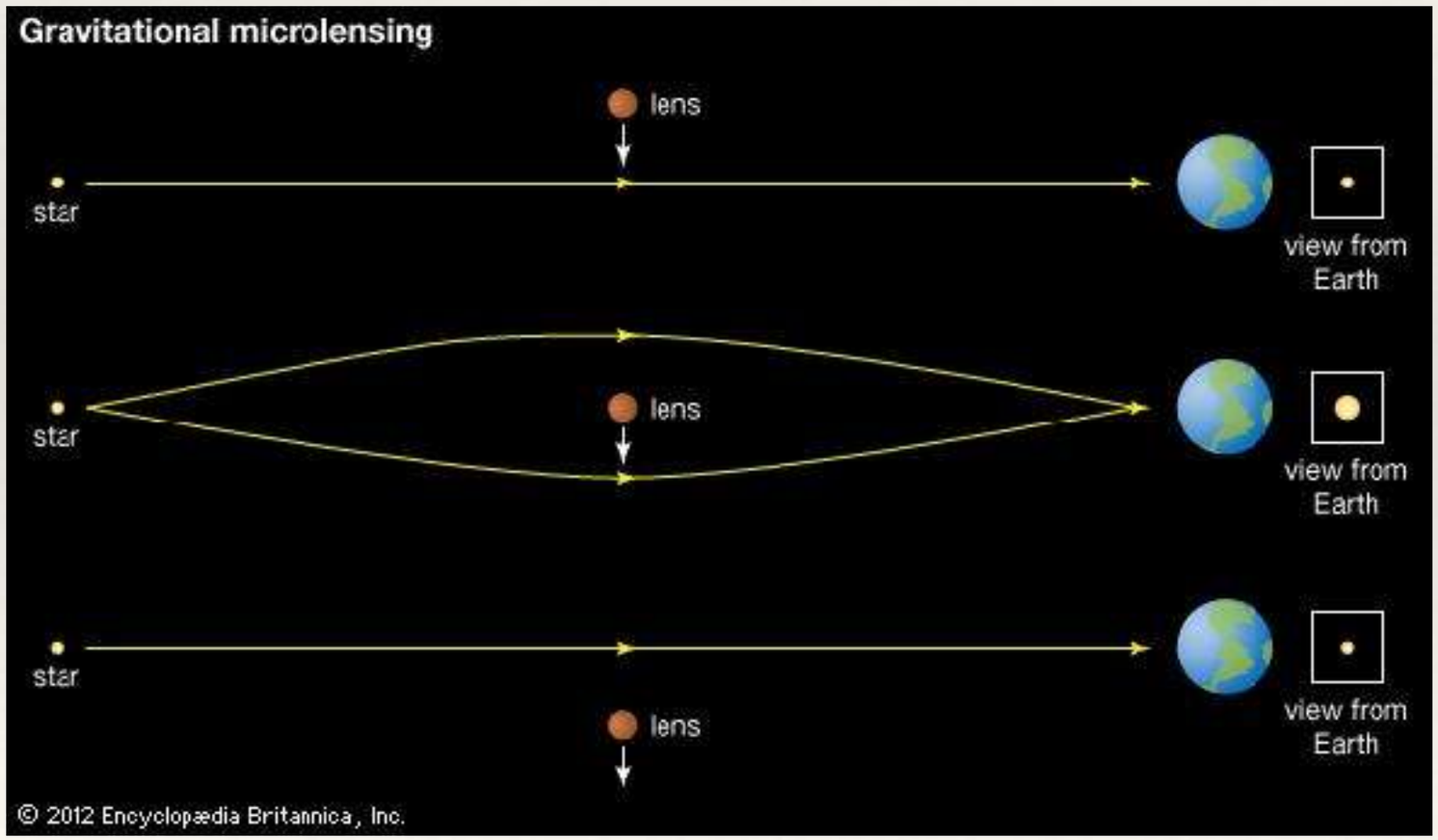


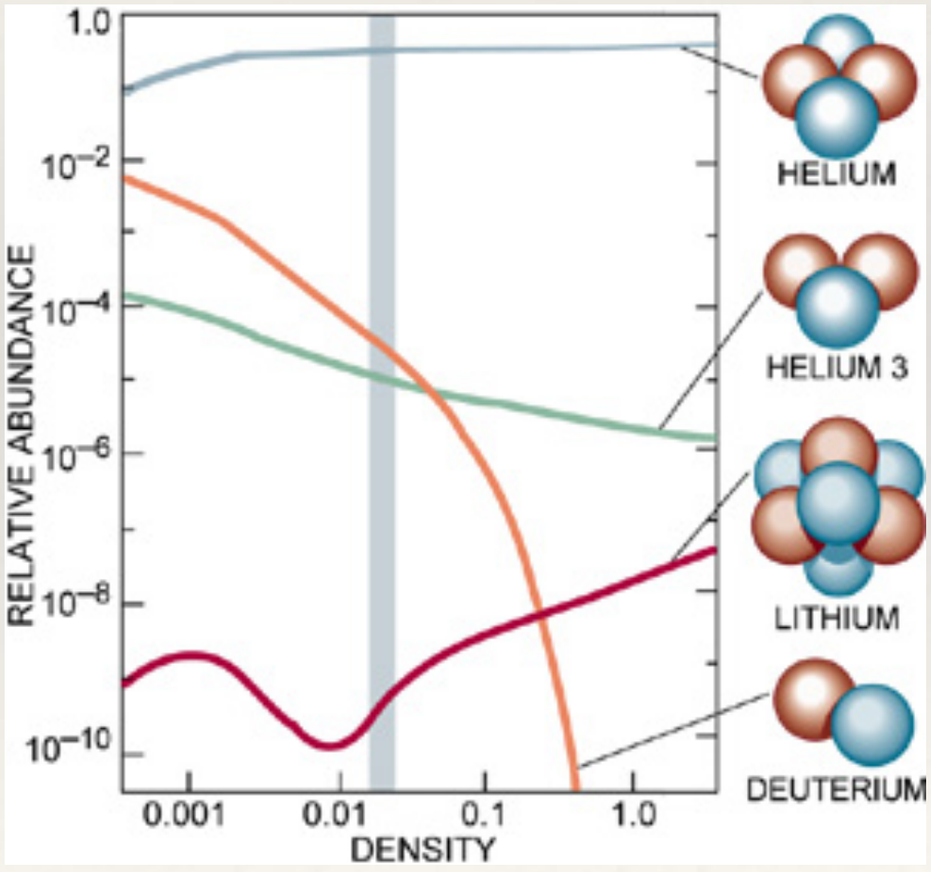
Conclusion:

Dark matter exists, it is spherically distributed in galaxies, and there is 5 times more dark matter than visible matter

Early Solutions

- General consensus around ~1980:
  - Dark matter must be dark astrophysical objects (for example stars that do not produce light, black holes, etc)
  - Problems: (1) gravitational microlensing, (2) big bang nucleosynthesis

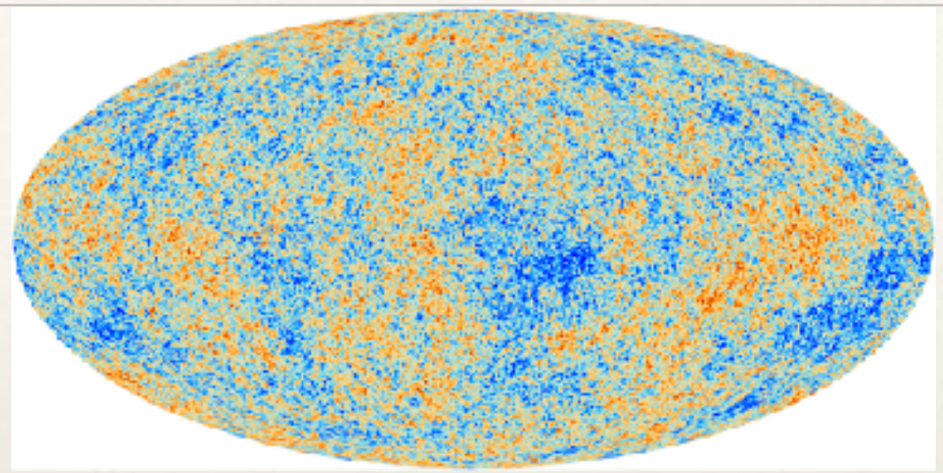


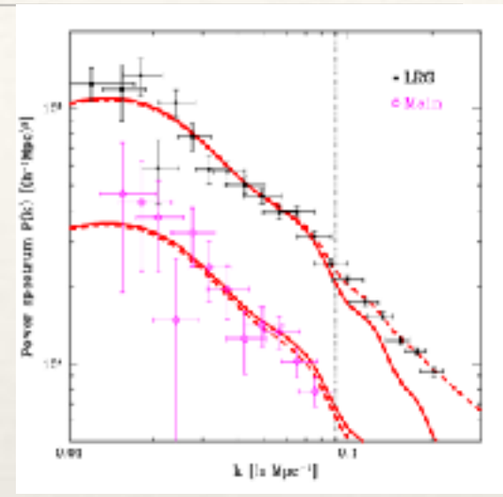


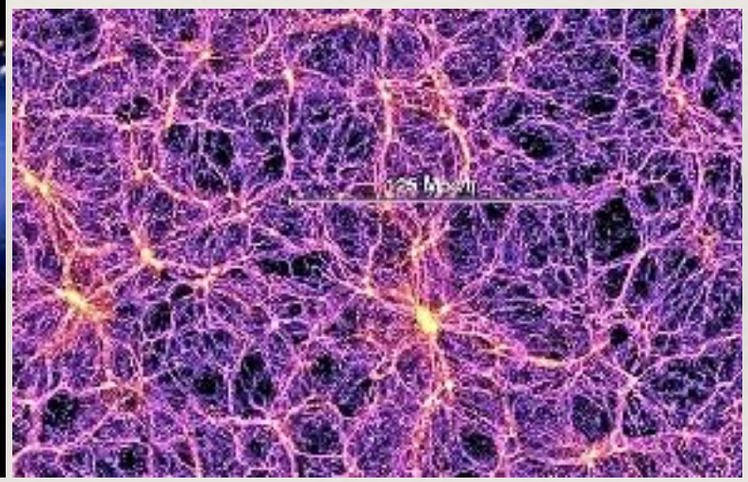
Conclusions: Dark matter should not be astrophysical, or made of protons or neutrons

Additional Evidence

- Cosmic Microwave Background
- Big Bang Nucleosynthesis
- N-body Simulations
- Galactic Rotation Curves
- Galaxy Cluster Rotation Curves
- Gravitational Lensing
- Large Scale Structure
- Type Ia Supernovae Measurements
- Baryonic Acoustic Oscillations
- Redshift Space Distortions
- Lyman-alpha Forest







Statistical confidence that dark matter does not exist is:

0.000000000000000000000000000000000000000…6%

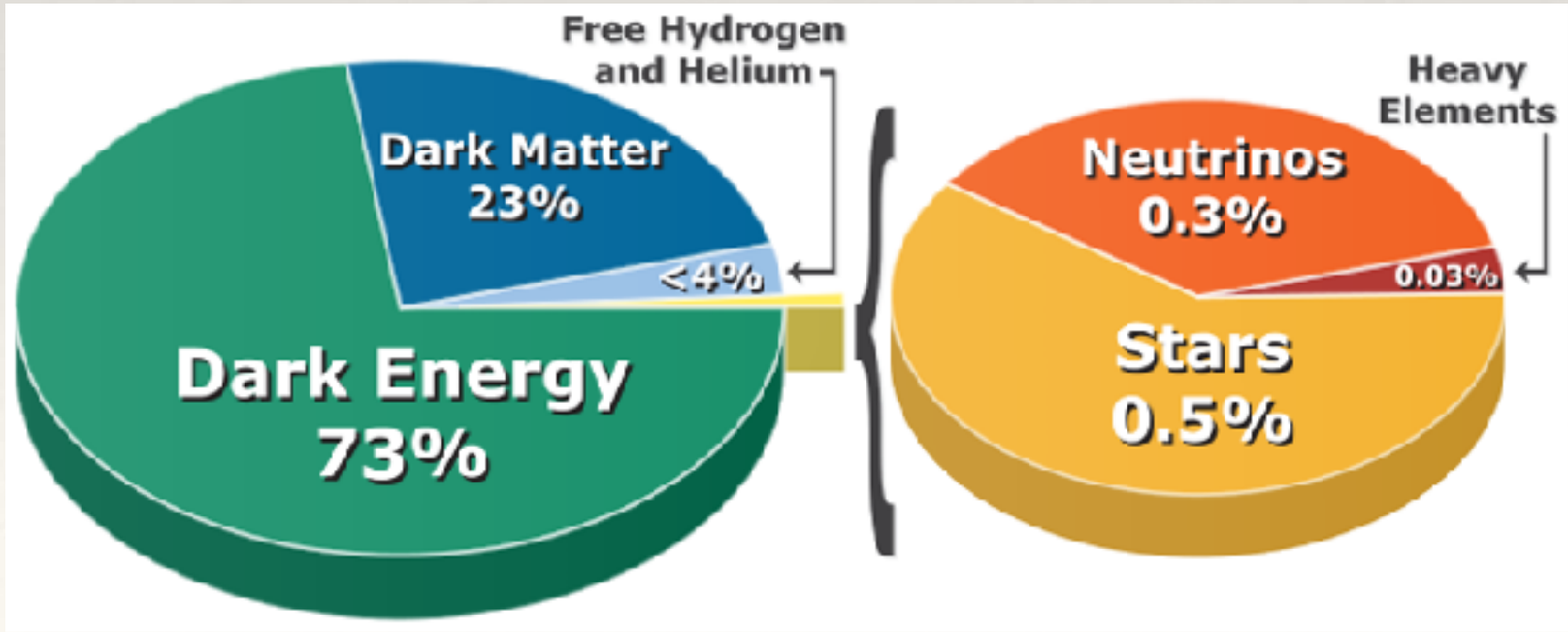
Many many 0s

So what do we actually know?

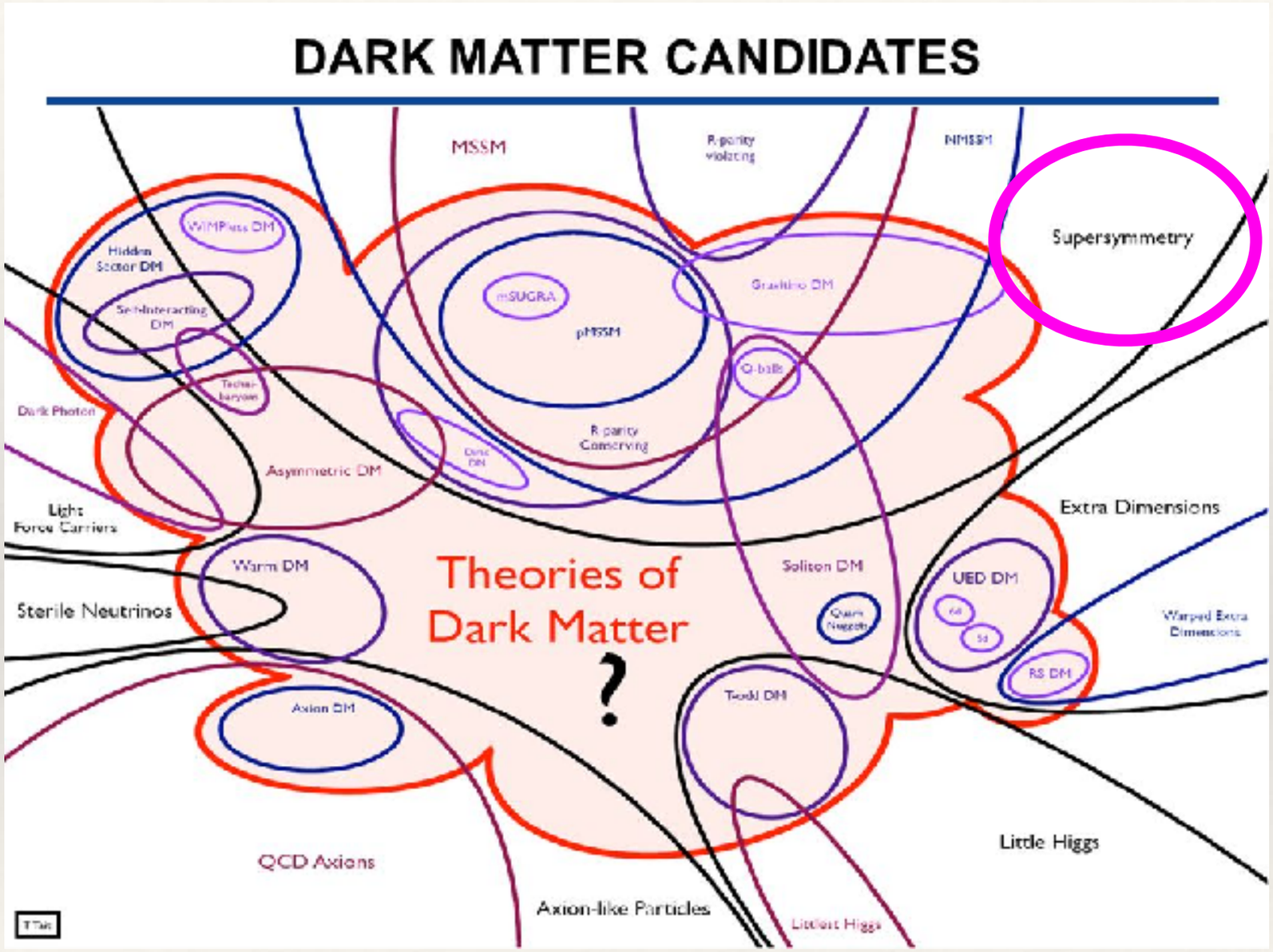
- Dark matter must:
  - Be ~5 times more abundant than visible matter
  - Not interact strongly with light
  - Not be in the form of compact astrophysical objects like stars or black holes

So what is it?

Perhaps some new particle that is yet to be discovered…



Dark Matter Candidates

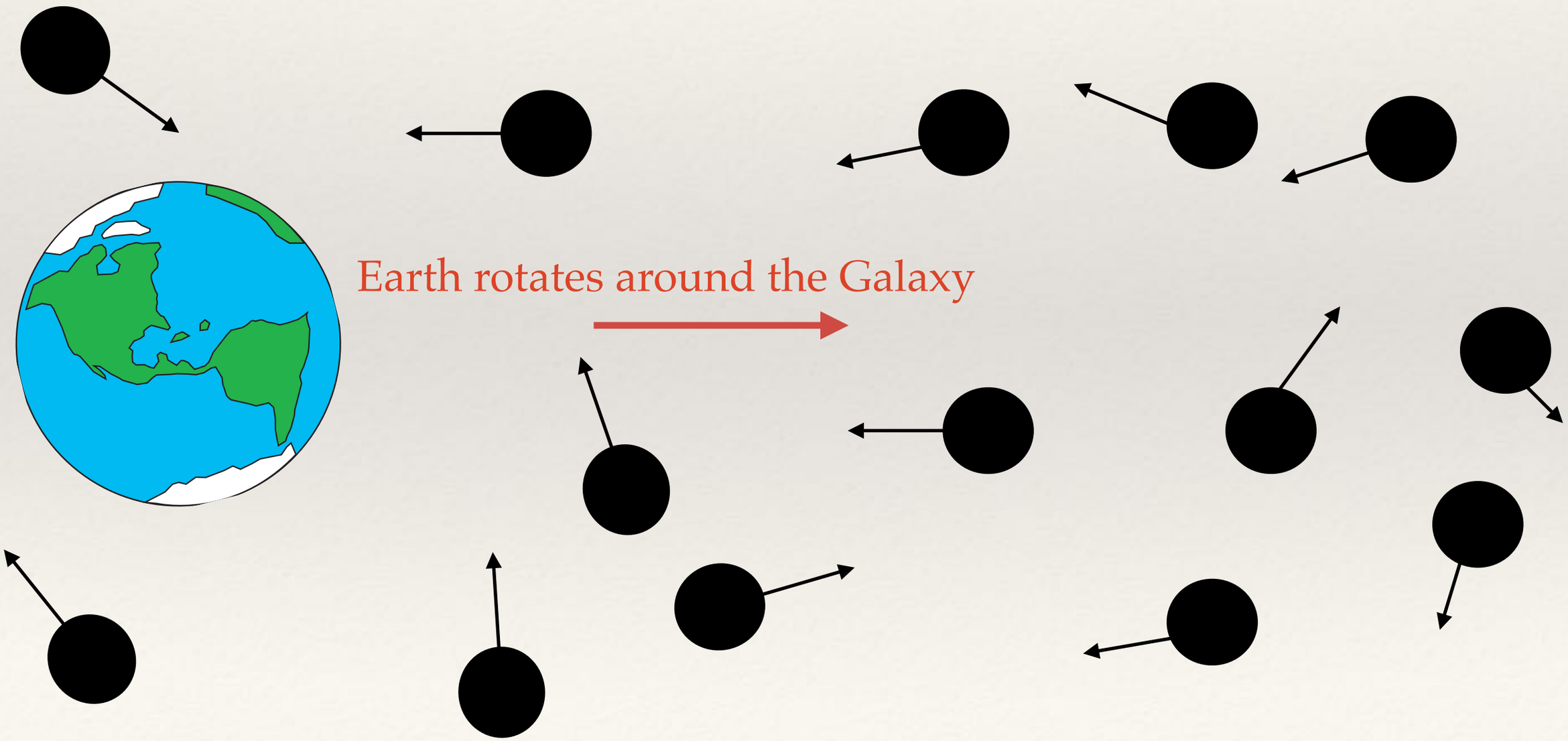


SUSY (supersymmetry) says dark matter most likely interacts through the "Weak Force" and is about 100 times more massive than a proton

For simplicity, I will only mention one of the most preferred candidates:
The Weakly Interacting Massive Particle (WIMP)

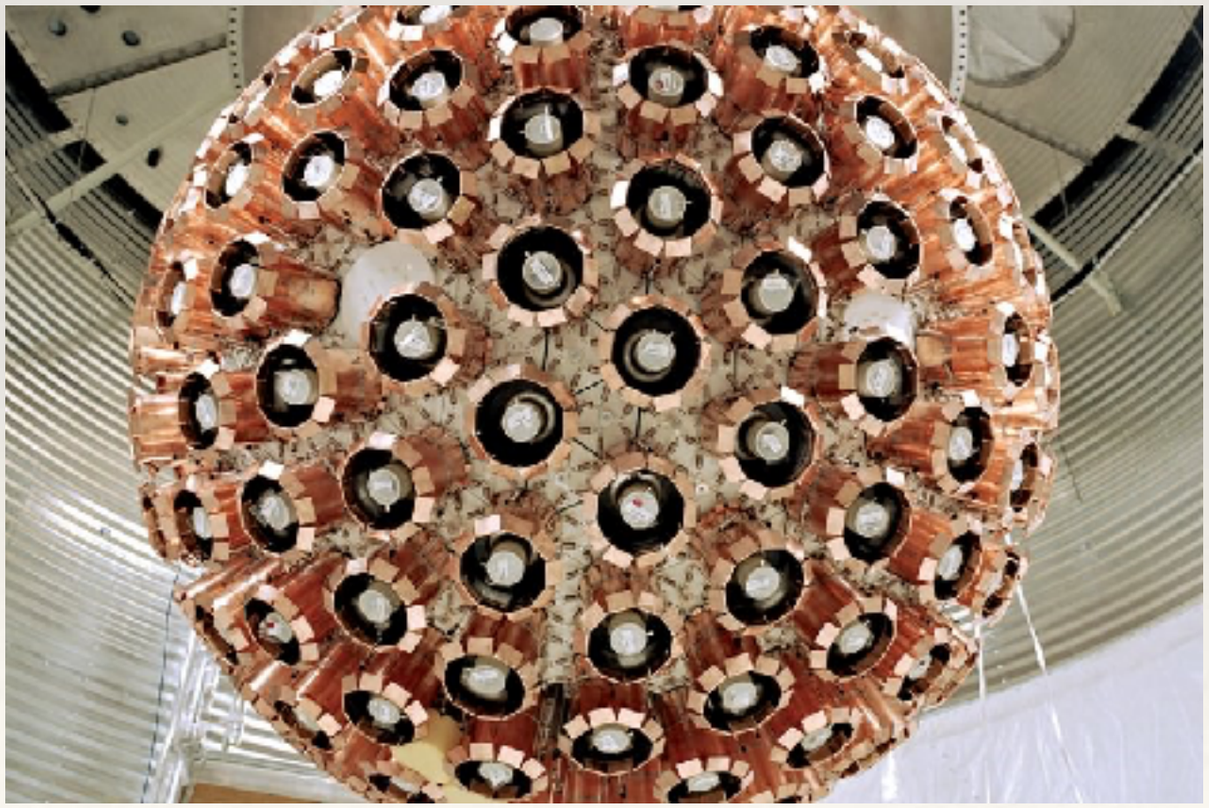
Using PMTs in WIMP detection

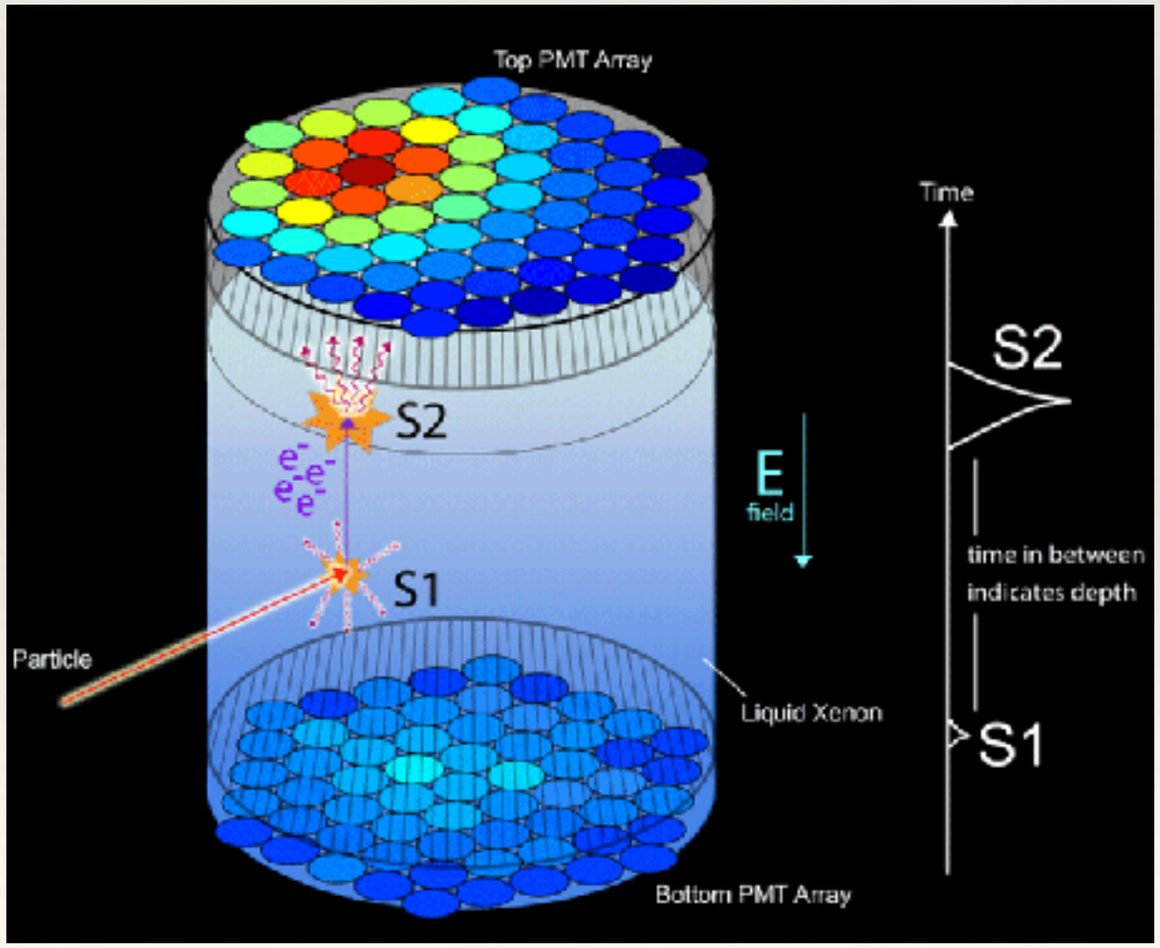
- Direct dark matter experiments look for rare interactions between nuclei in underground laboratories and dark matter in the galaxy
  - Today, the largest of these experiments expect as few as ~ 1 event / month



Using PMTs in WIMP detection

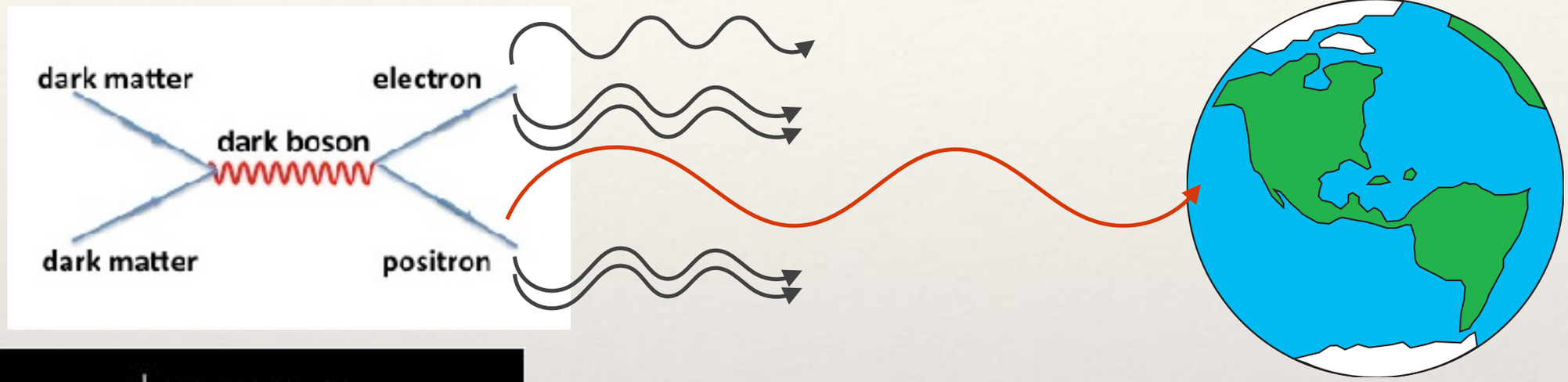
- Dark matter direct detection
  - WIMP hits nuclei, this produces (1) light that is detected with PMT and (2) electrons that are pushed with an electric field to the top, electrons pulled out of liquid into gas producing light that is detected with PMT
  - These 2 signals tell us: position of event, energy of event, and whether the interaction was with electron or nuclei

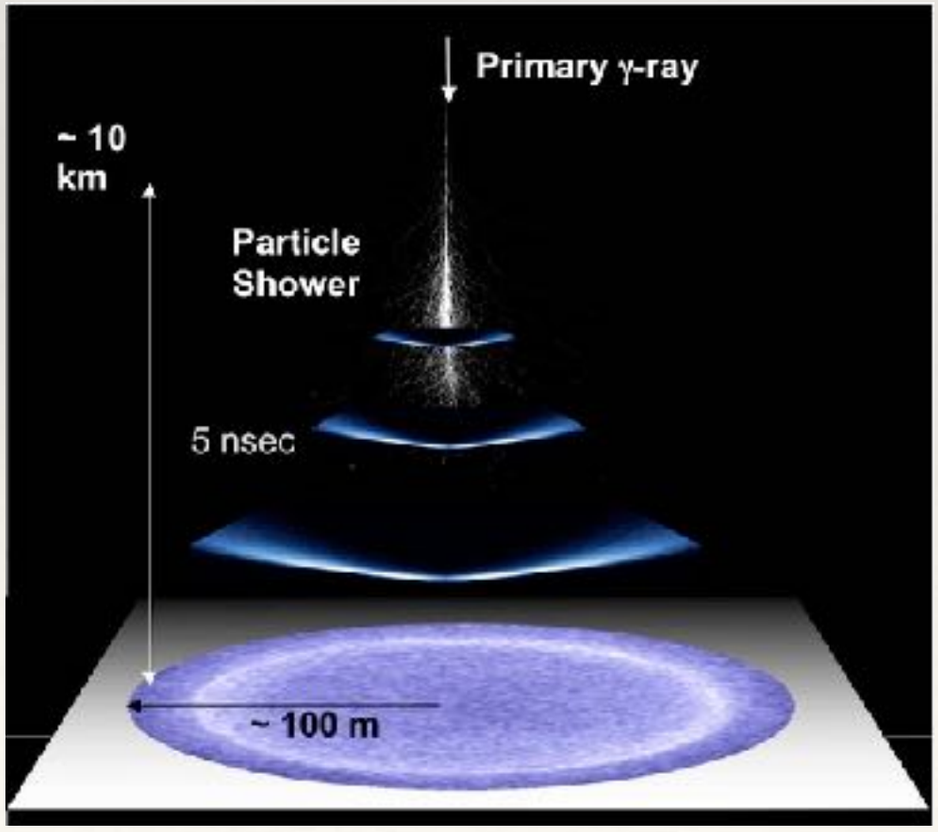


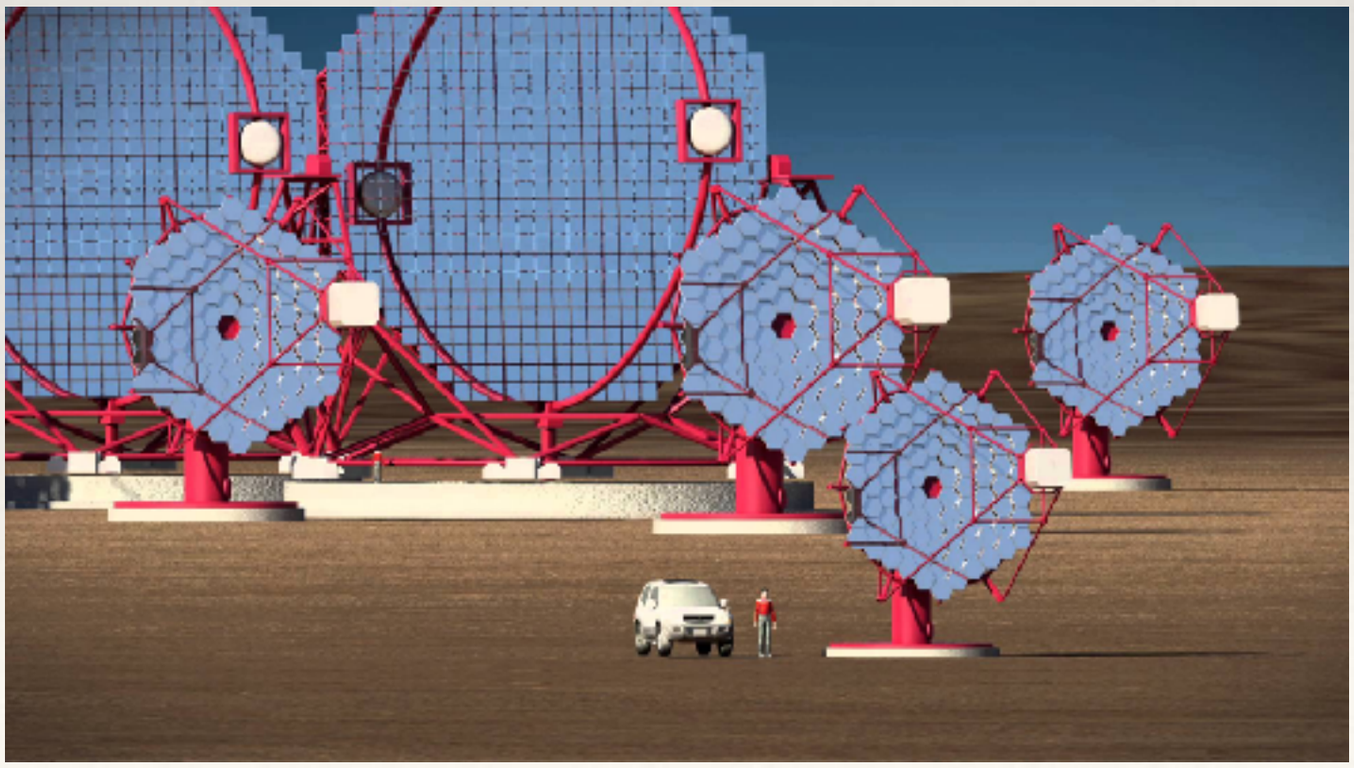


Using PMTs in WIMP detection

- Dark matter *in*direct detection
  - Two WIMPs can annihilate (destroy each other) and produce visible particles







Arigatougozaimasu

Back Up Slides

Cosmic Microwave Background (CMB)

- Measured first in 1964, the CMB is the oldest photograph in the world and captures what the Universe looked like ~13.8 billions years ago

What is a photograph:

A photograph contains information about where the photons last interacted

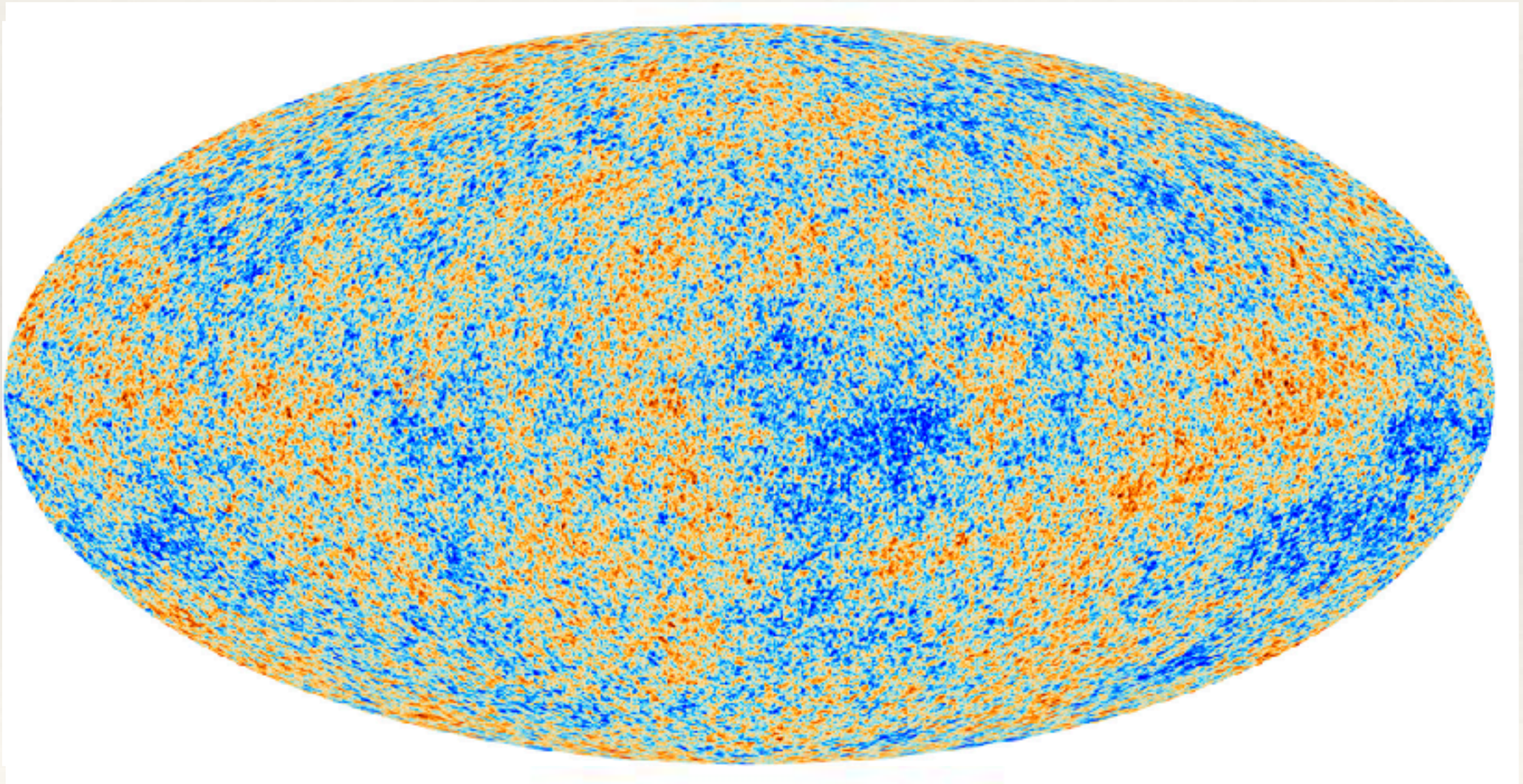
- The CMB photons last scattered ~13.8 billion years ago, and thus provide us information about the distribution and composition of matter at that time

Cosmic Microwave Background (CMB)

All photons have nearly the same energy

Temperature ~ 2.725 K

$$\frac{\delta T}{T} \sim 10^{-4}$$



CMB confirms that most of the universe is dark and does not have strong interactions