# Dark matter

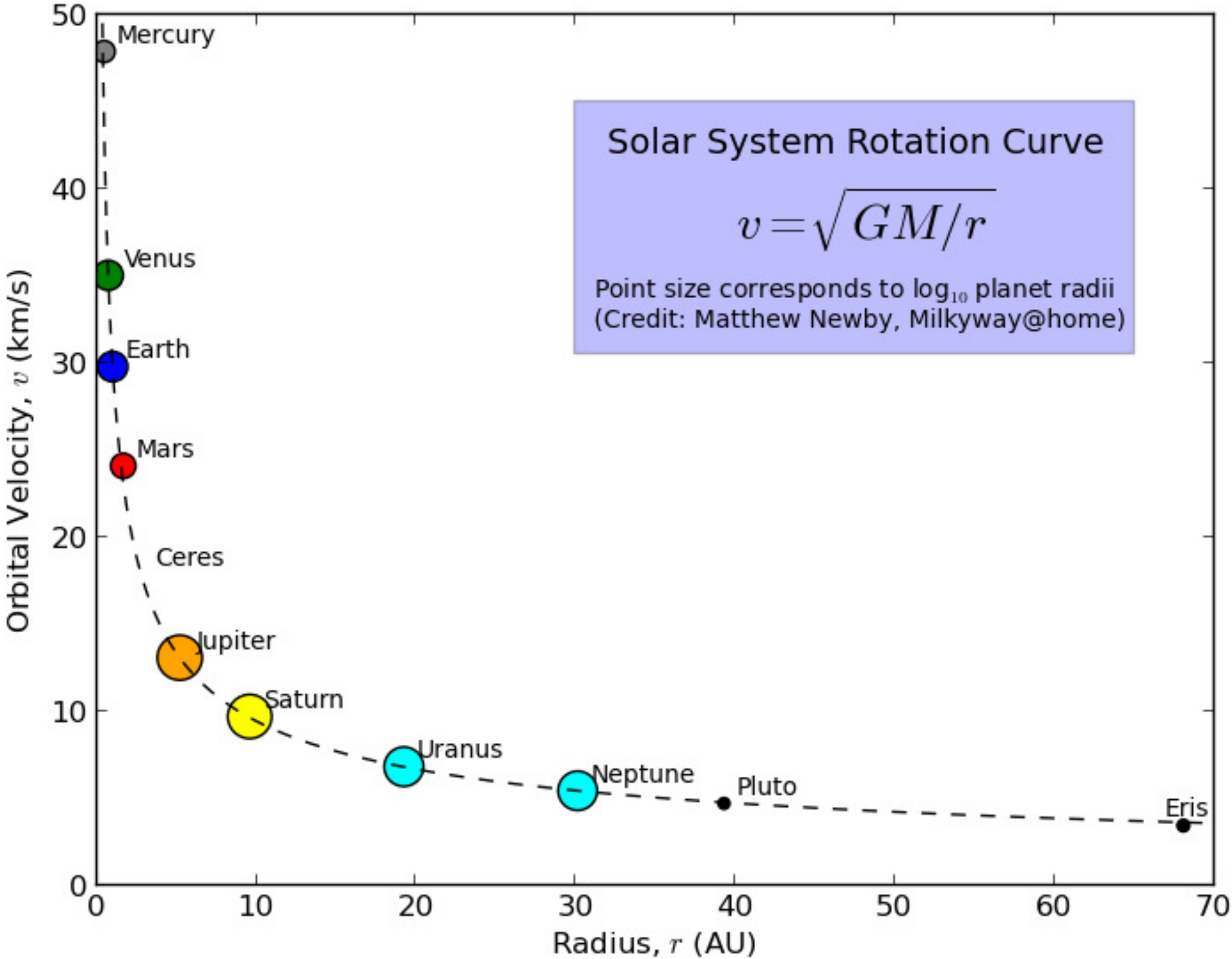
# Dark matter

Fritz Zwicky
California Institute of Technology

Coma Cluster: 1000 galaxies
321 million light years away

He measured the speed with which the galaxies in Coma move. To his surprise, he found enormous speeds—thousands of kilometers per second — **fast enough to rip the cluster apart.**

Why was the cluster not tearing itself up? Zwicky concluded that the cluster must be filled with additional unseen matter that holds the galaxies together with its gravitational force.

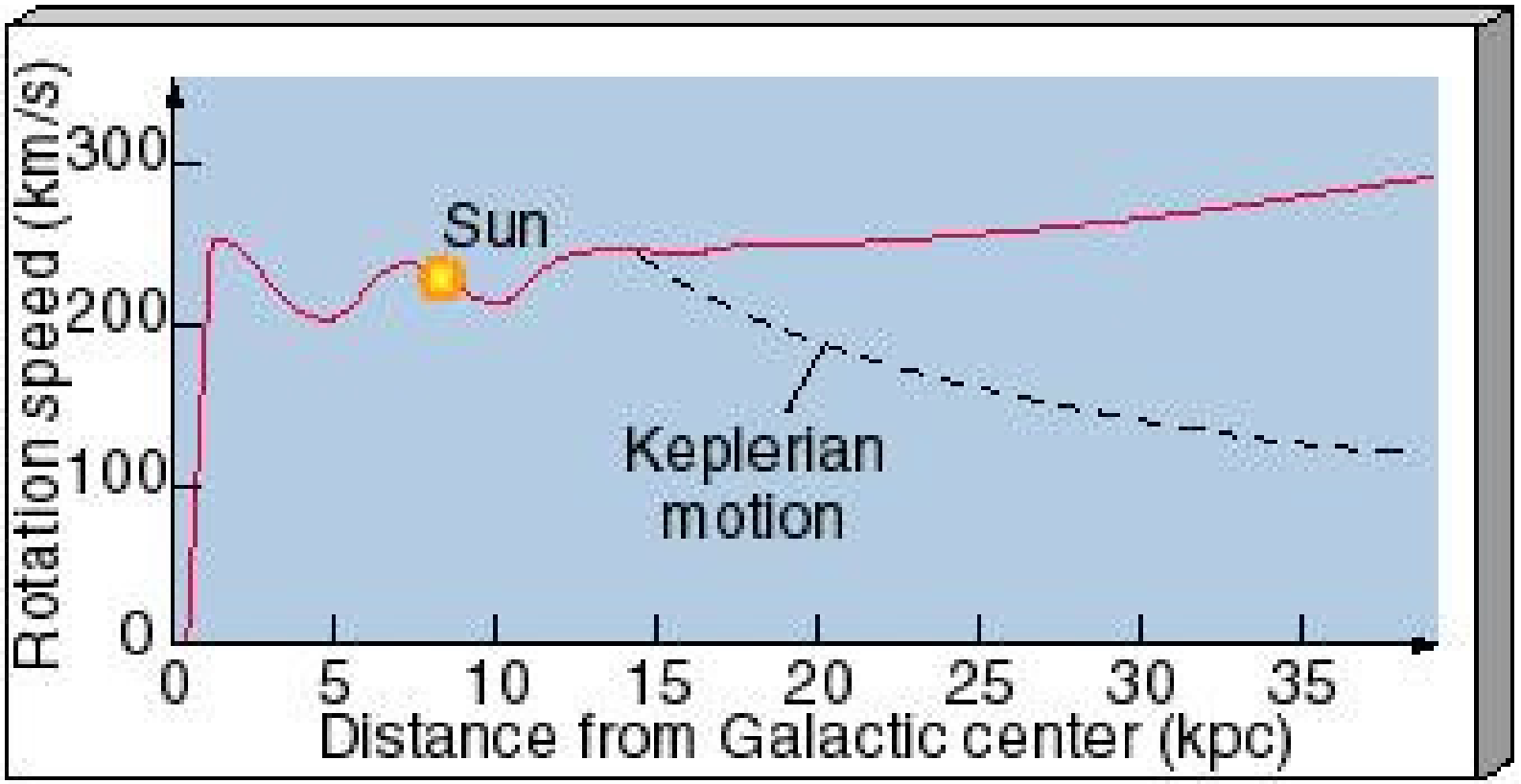



milkyway.cs.rpi.edu

# Problem with galaxy rotation curves

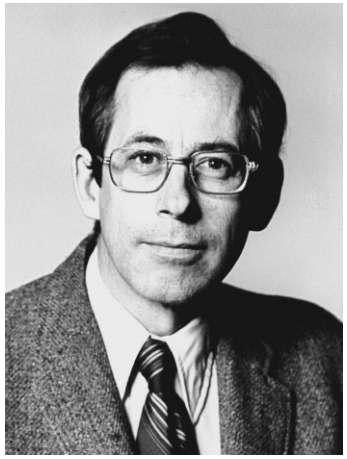
Outer stars in the galaxies do not rotate correctly! The outer stars should behave much like the planets of our solar system.

In galaxies, however, both inner and outer stars rotate at about the same speed.




http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt

# 1973: Further evidence for dark matter
# Problem with galactic simulations



James Peebles

Jeremiah Ostriker

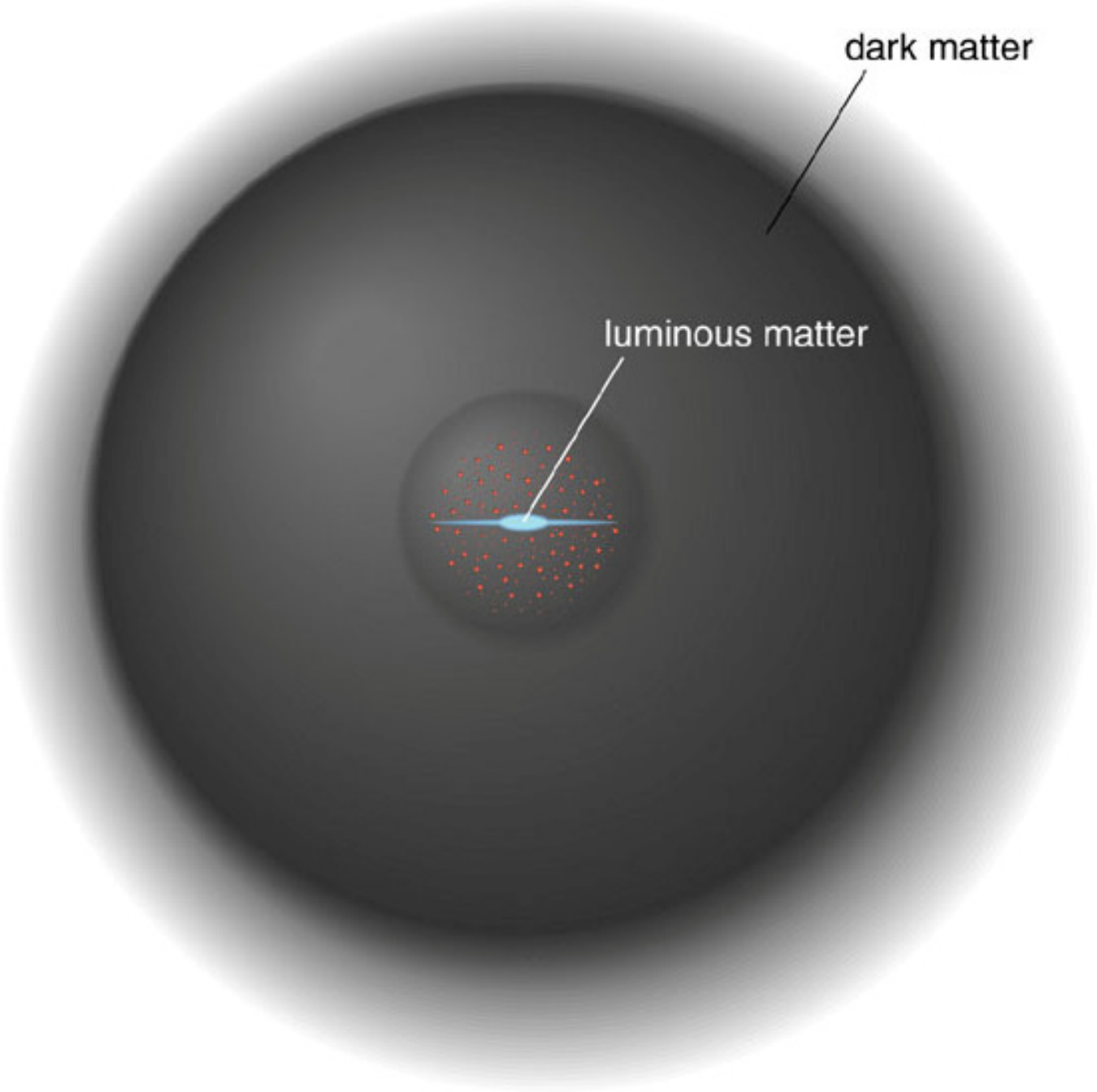
Princeton University

Jeremiah Ostriker and James Peebles used numerical simulation to study how galaxies evolve: they programmed 300 mass points into their computer to represent groups of stars in a galaxy rotating about a central point.

Ostriker and Peebles found that in a time less than an orbital period, most of the mass points would collapse to a bar-shaped, dense concentration close to the center of the galaxy with only a few mass points at larger radii.

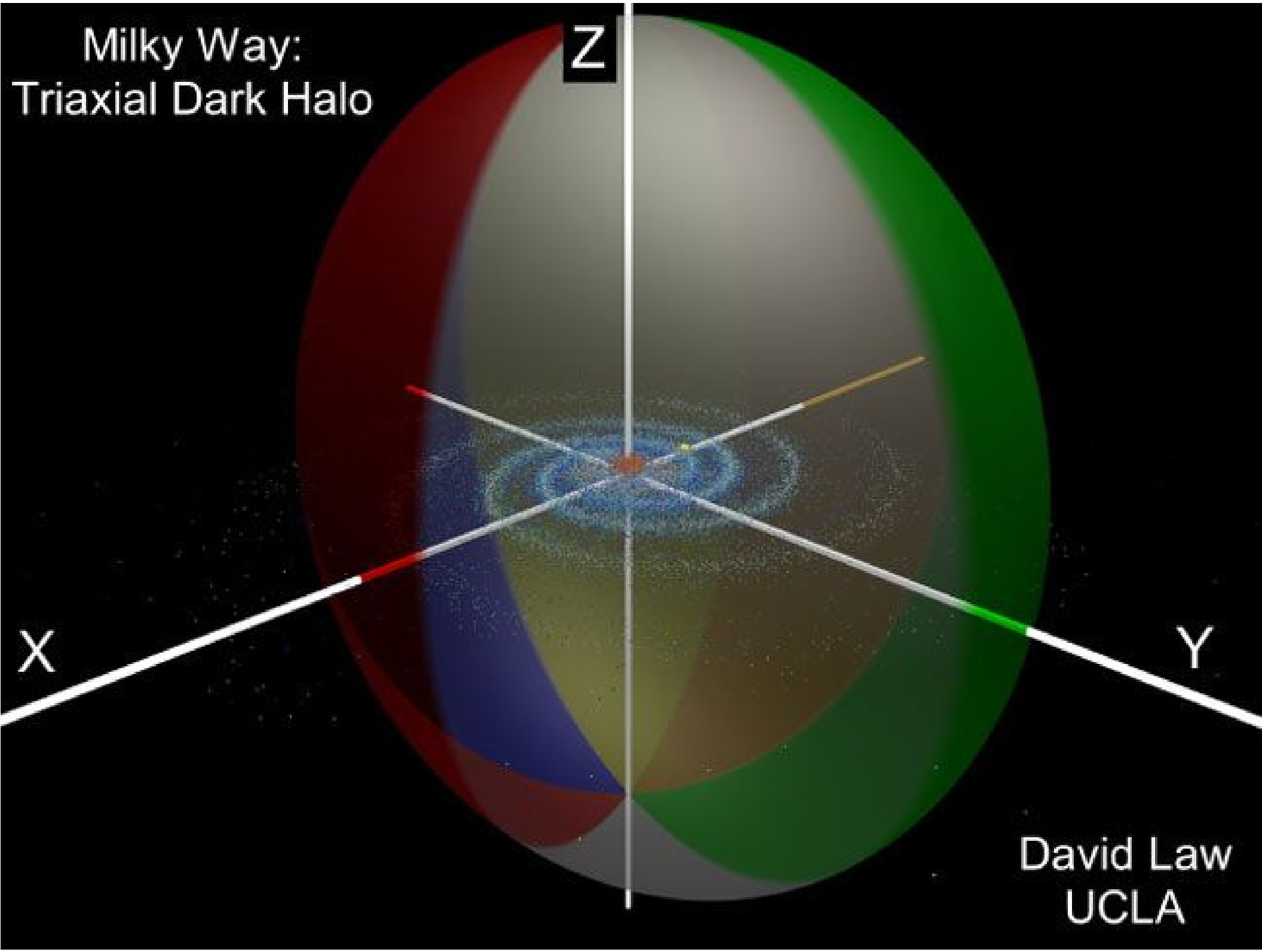
However, if they added a static, uniform distribution of mass three to 10 times the size of the total mass of the mass points, they found a more recognizable structure would emerge.

https://www.learner.org/courses/physics/unit/text.html?unit=10&secNum=2

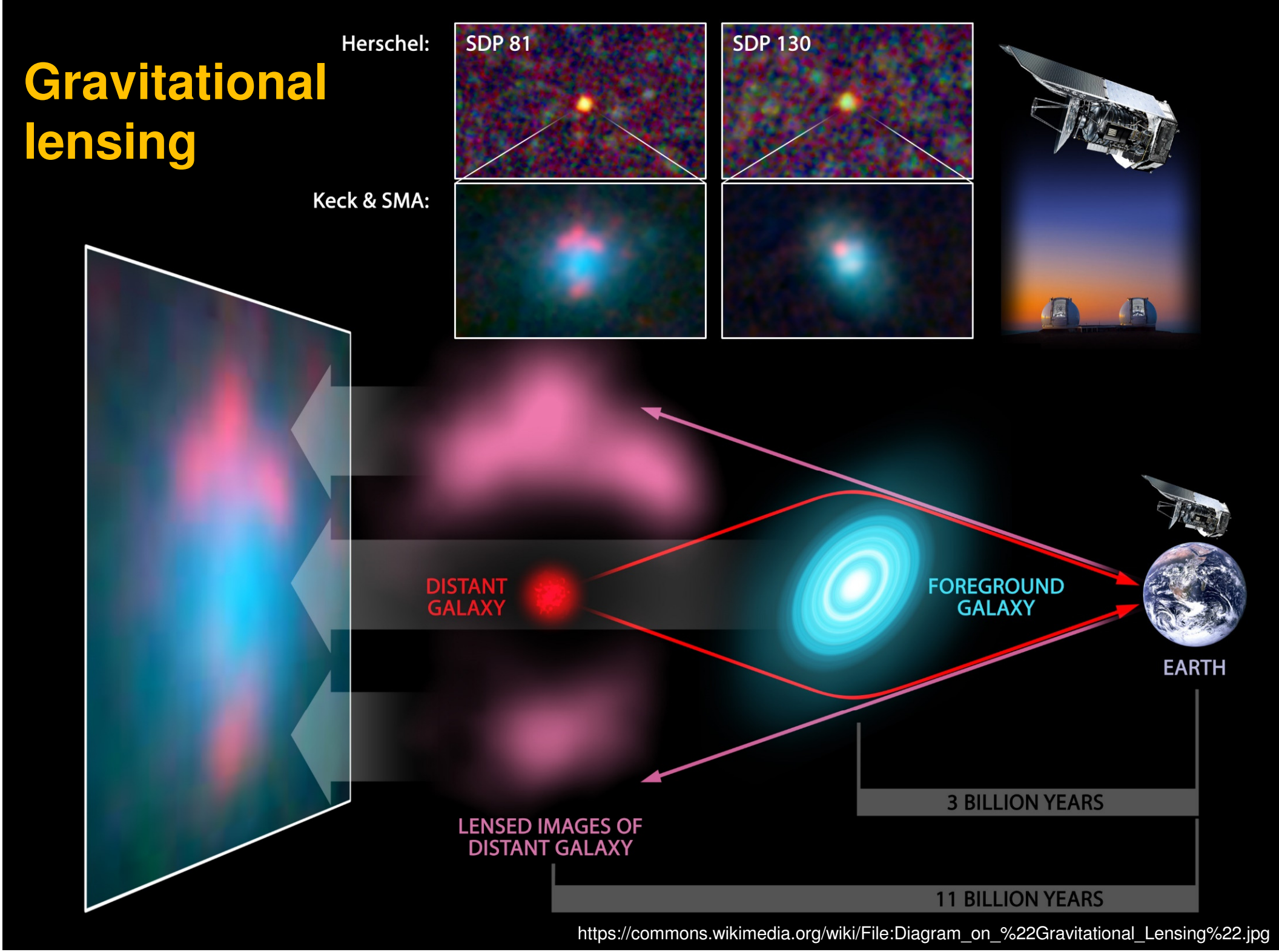



The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

http://www.sjsu.edu/people/monika.kress/courses/sci255/


Milky Way:
Triaxial Dark Halo
Z
X
Y
David Law
UCLA

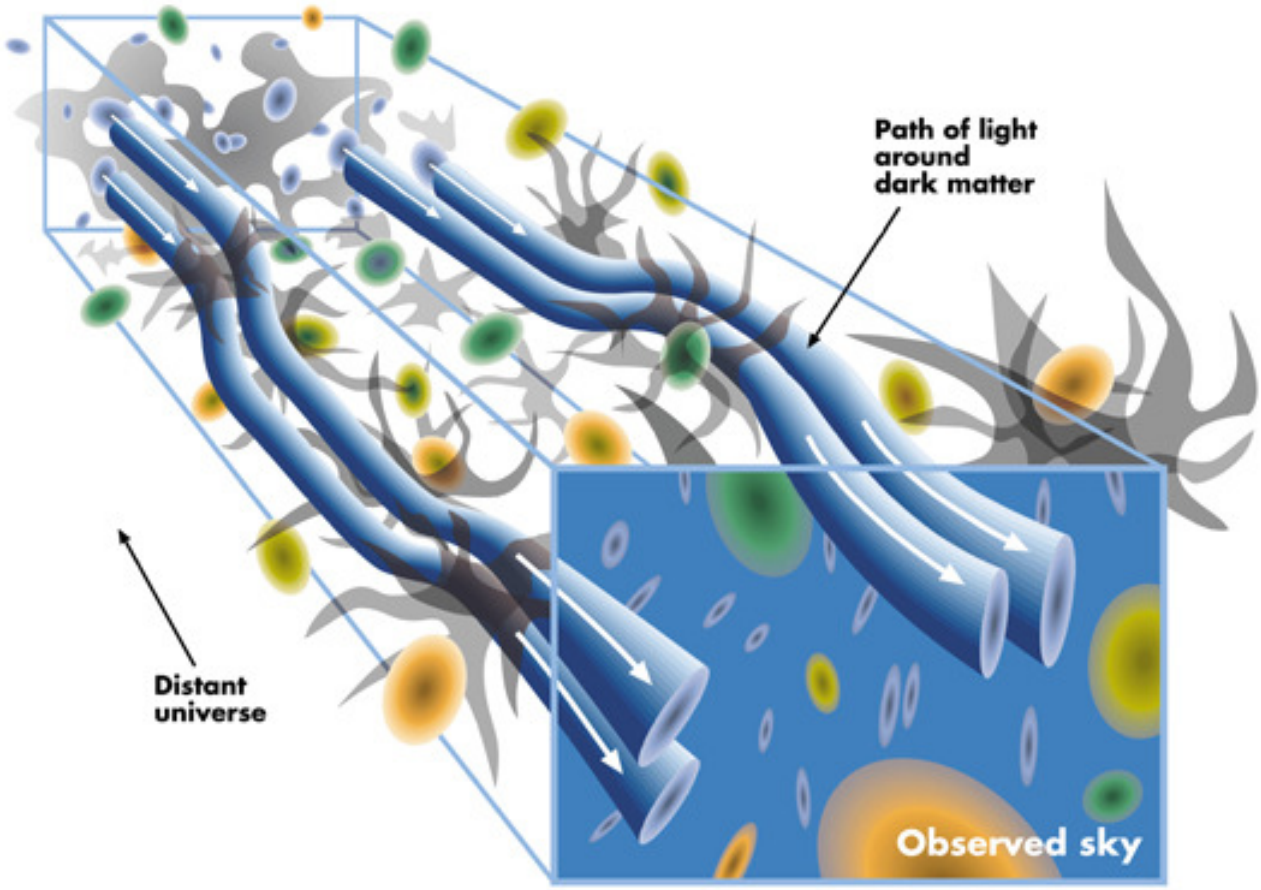
# Gravitational lensing




https://commons.wikimedia.org/wiki/File:Diagram_on_%22Gravitational_Lensing%22.jpg

# Gravitational lensing by dark matter

By measuring the distortion of the galaxies, one can “weigh” the dark matter. Result: dark matter accounts for 90% of the mass of the universe.

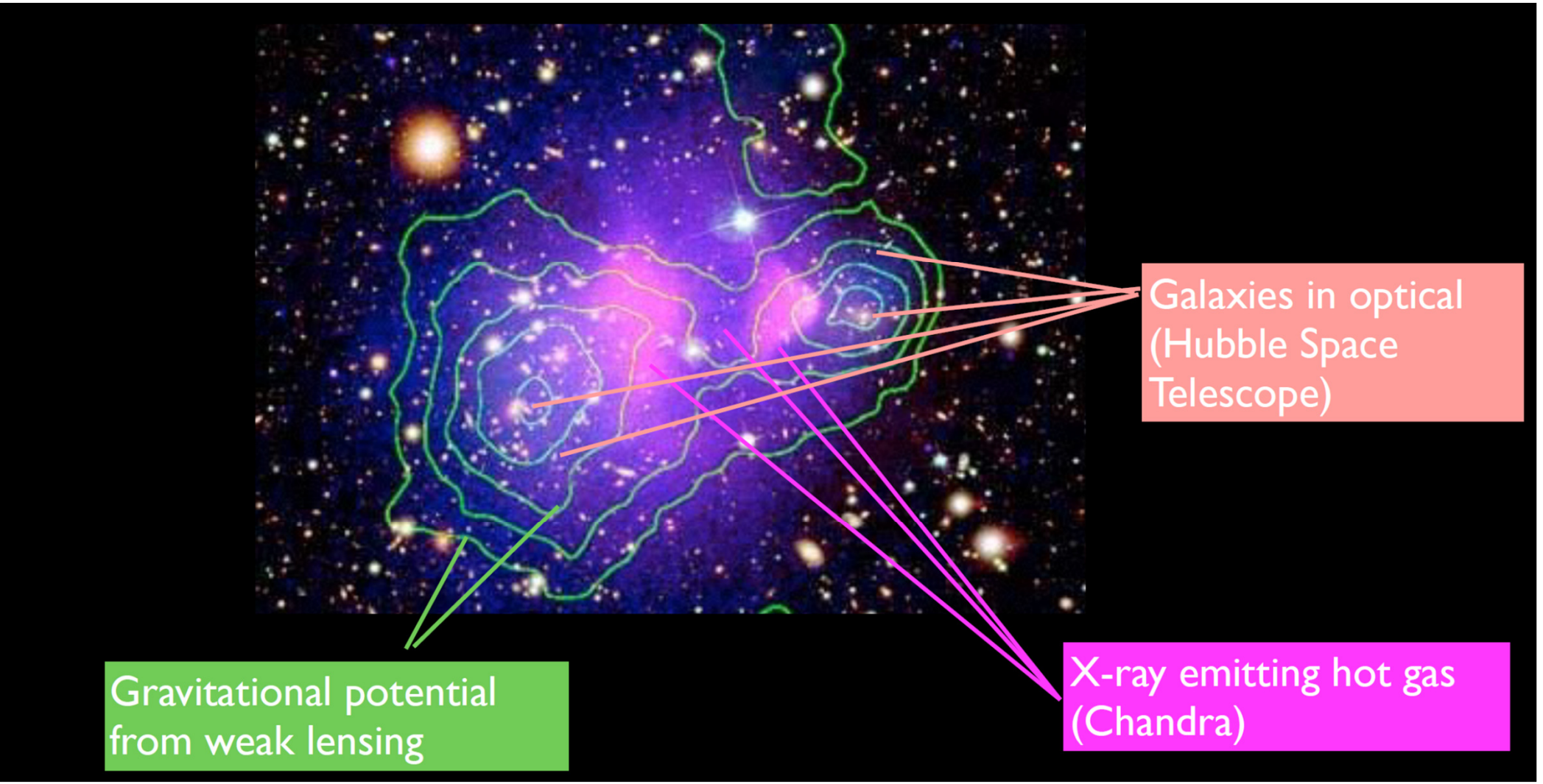



Cosmic shear: the light from distant galaxies is distorted by dark matter.

https://www.nsf.gov/od/lpa/news/press/00/pr0029.htm

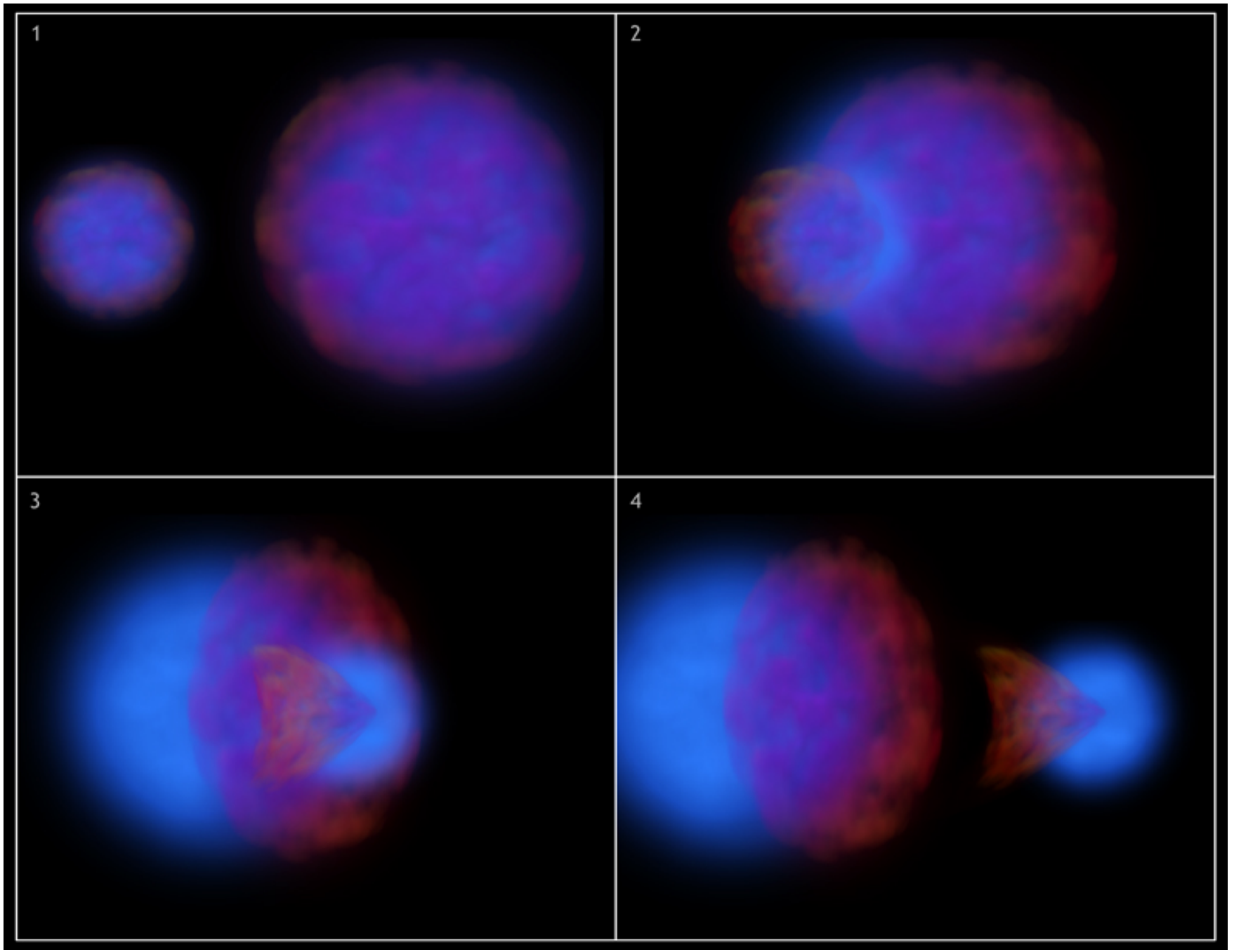
# 2006: Bullet cluster

The hot gas in each cluster was slowed by a drag force, similar to air resistance, during the collision. In contrast, the dark matter was not slowed by the impact because it does not interact directly with itself or the gas except through gravity.




Picture from: Paolo Gondolo, CosPA conference

# Bullet cluster collision




Pink clumps: "normal matter”  Blue clumps: dark matter

chandra.harvard.edu

# Cosmic Microwave Background (CMB)

**The photons started to travel freely through space rather than constantly being scattered by electrons and protons.**

**Universe expands and cools down**

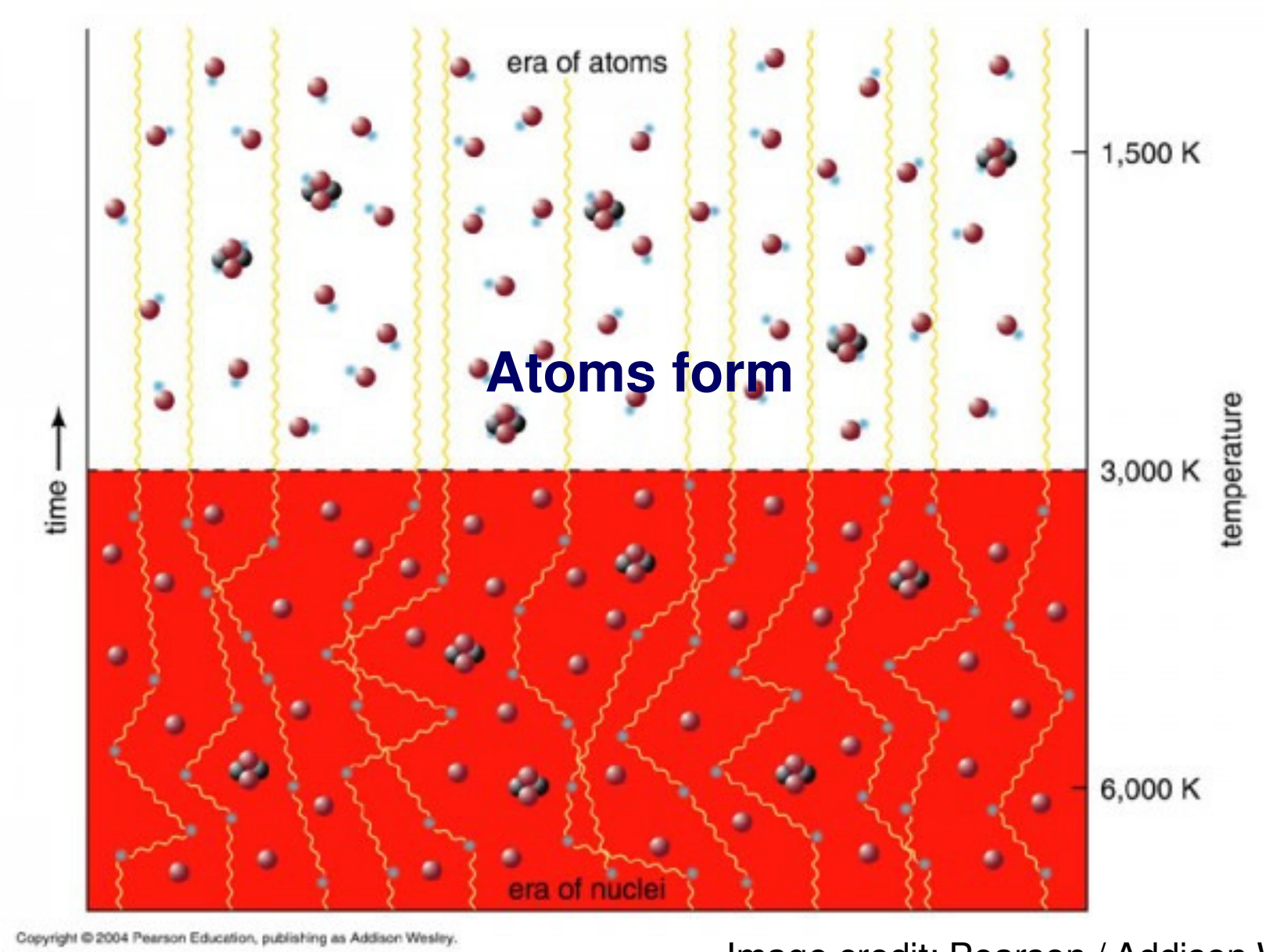
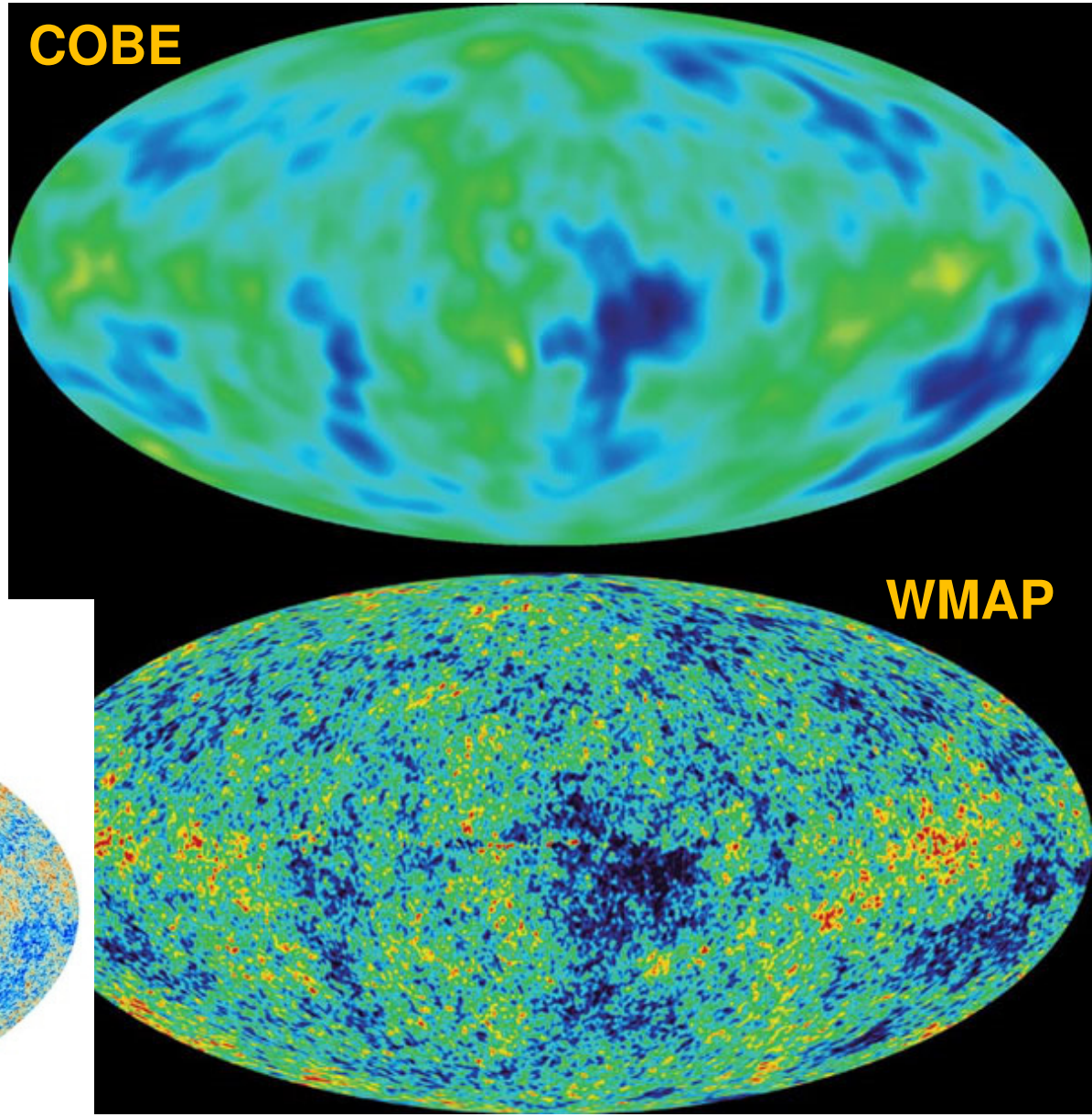


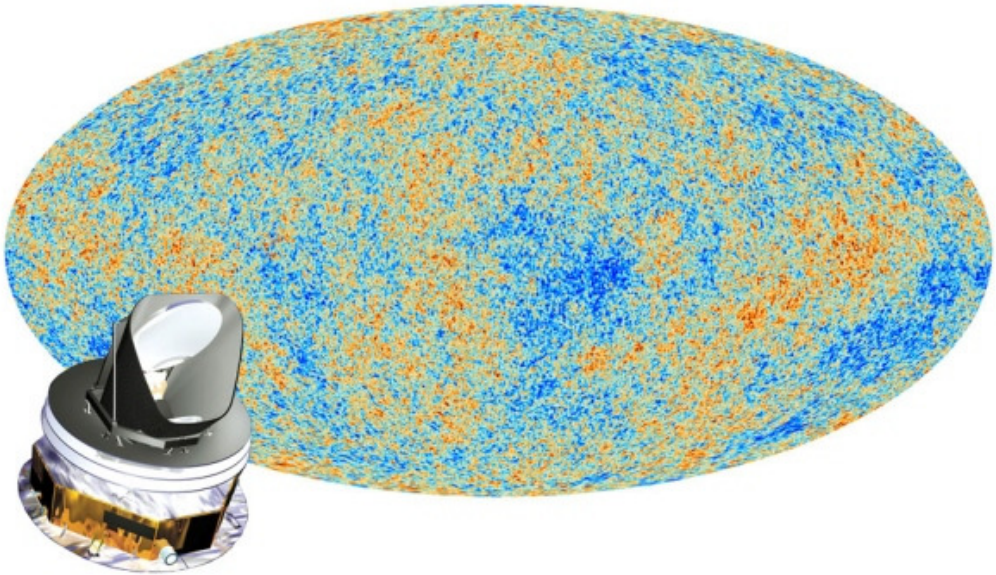

Image credit: Pearson / Addison Wesley

# CMB observations

PLANCK - a space observatory operated by the European Space Agency (ESA) from 2009 to 2013.




**PLANCK**



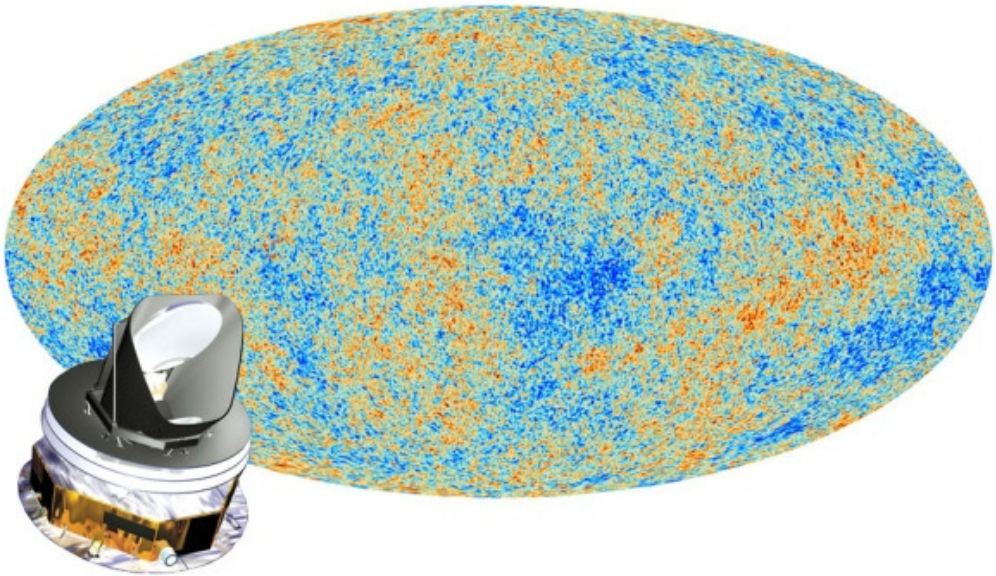
http://www.nature.com/news/planck-snaps-infant-universe-1.12671

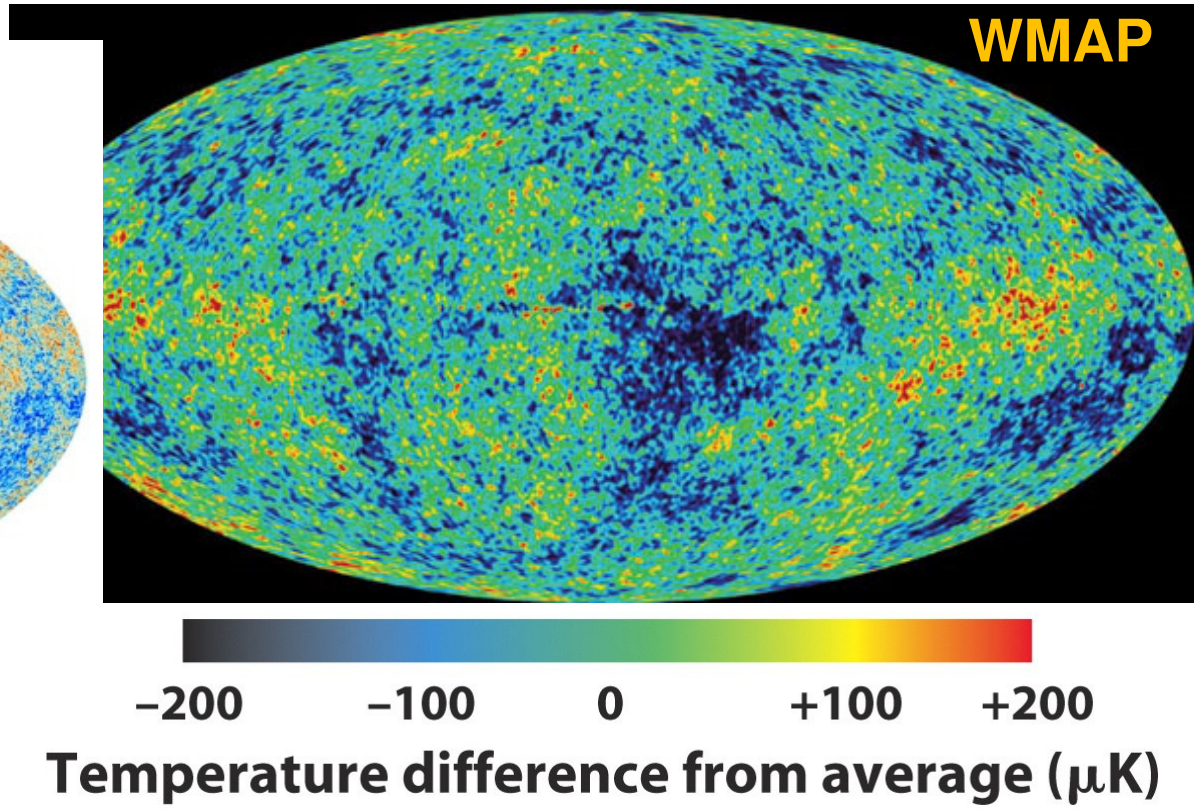
# CMB observations

**Without dark matter, fluctuations are too small to gravitationally grow into galaxies in the given 13 billion years.**

**Dark matter fluctuations, uncoupled to the plasma, start growing early and have enough time to grow into galaxies**

PLANCK





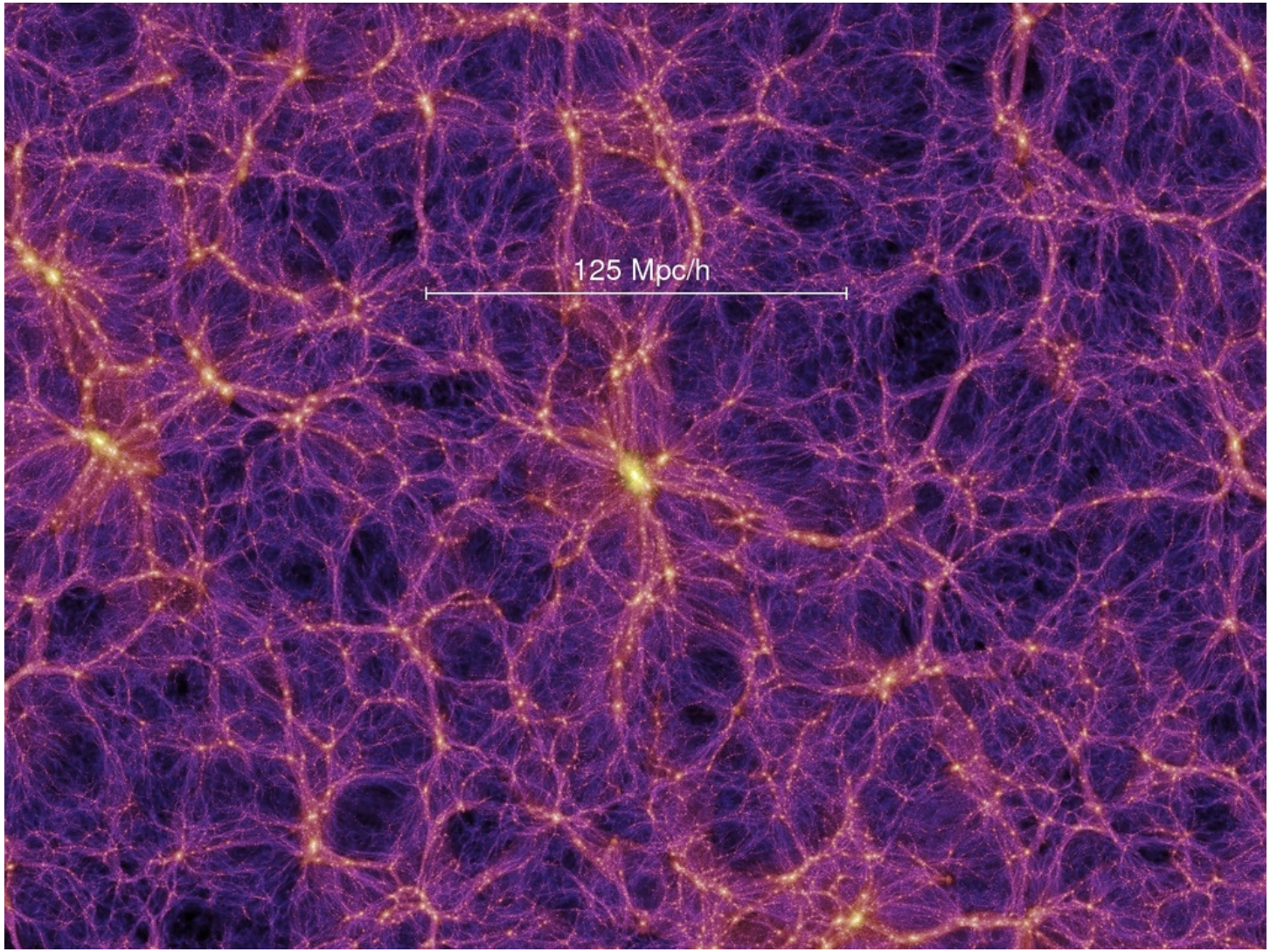

http://www.nature.com/news/planck-snaps-infant-universe-1.12671

# Dark Universe Planetarium Show: Dark Matter

https://www.slac.stanford.edu/~kaehler/homepage/visualizations/dark-matter.html

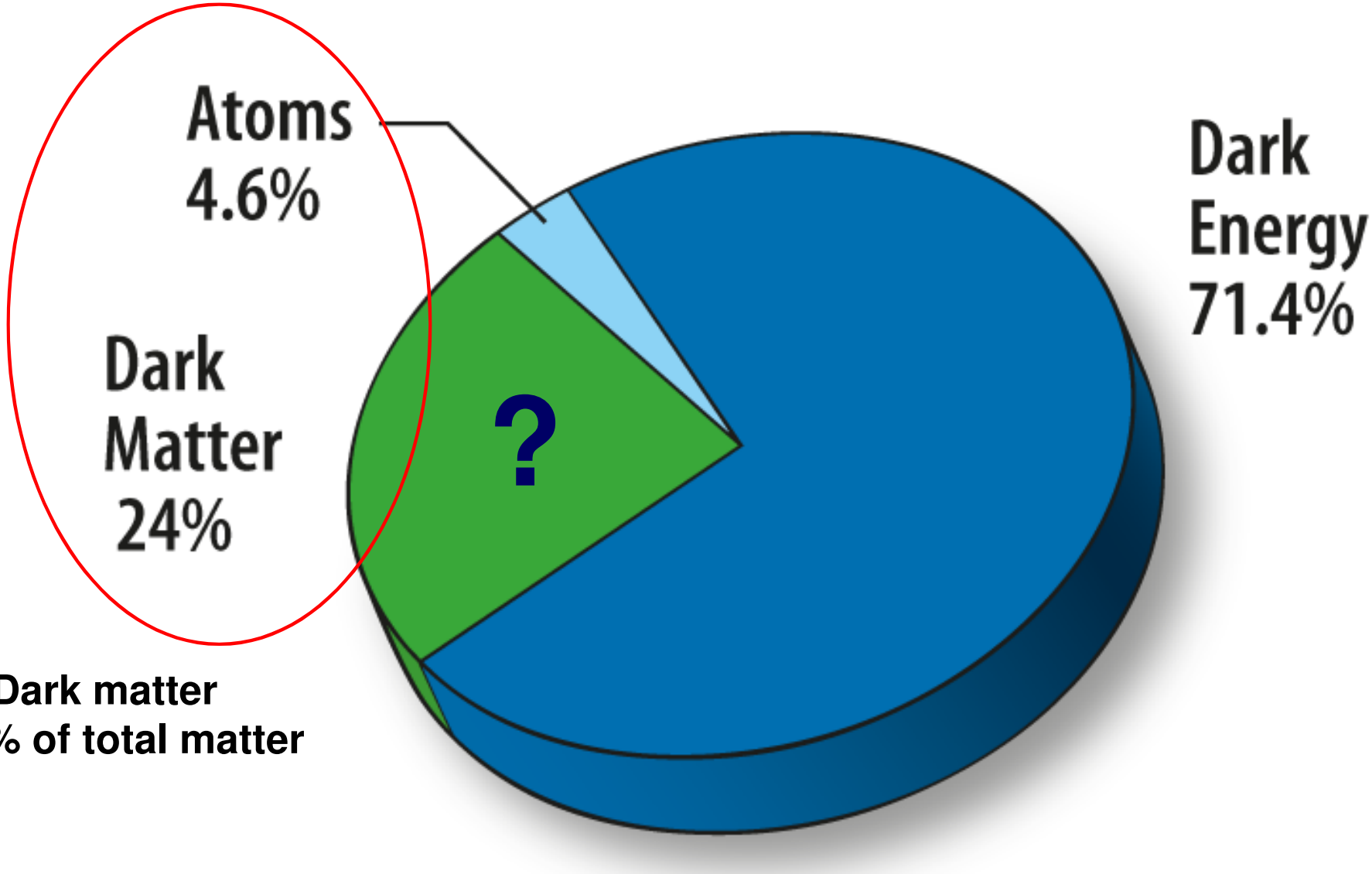
# Millennium Simulation

**http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/**
https://www.youtube.com/watch?v=Y9yQOb94yl0



# Summary of dark matter evidence:
# 85% of matter in the universe is of unknown nature

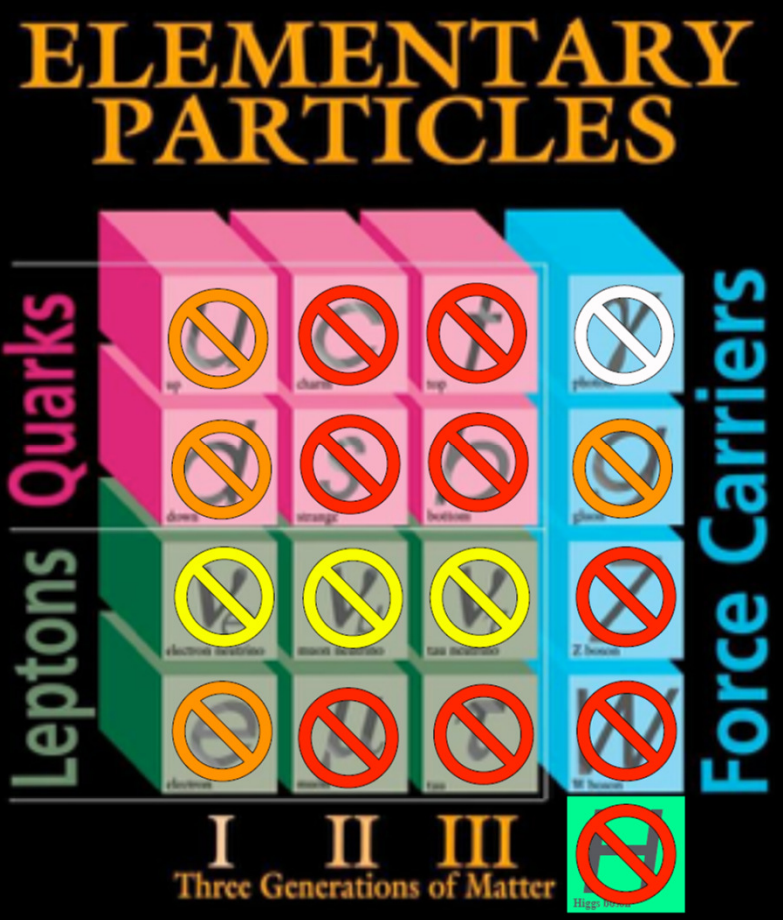
**Normal matter: ~15% of total matter**




**Dark matter**
**~85% of total matter**

**We know it is out there but we do not know what it is.**

# Is dark matter an elementary particle?




- ⊘ is the particle of light
- ⊘ couples to the plasma
- ⊘ disappears too quickly
- ⊘ is hot dark matter

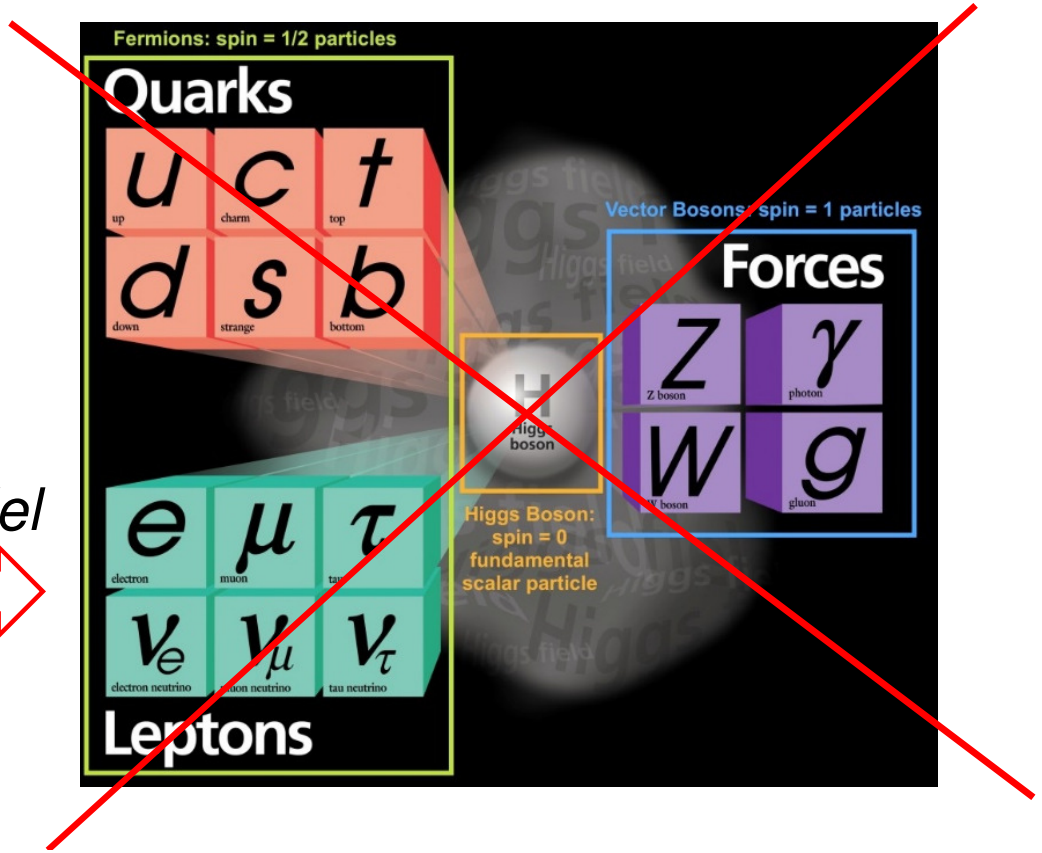
*No known particle can be nonbaryonic cold dark matter!*

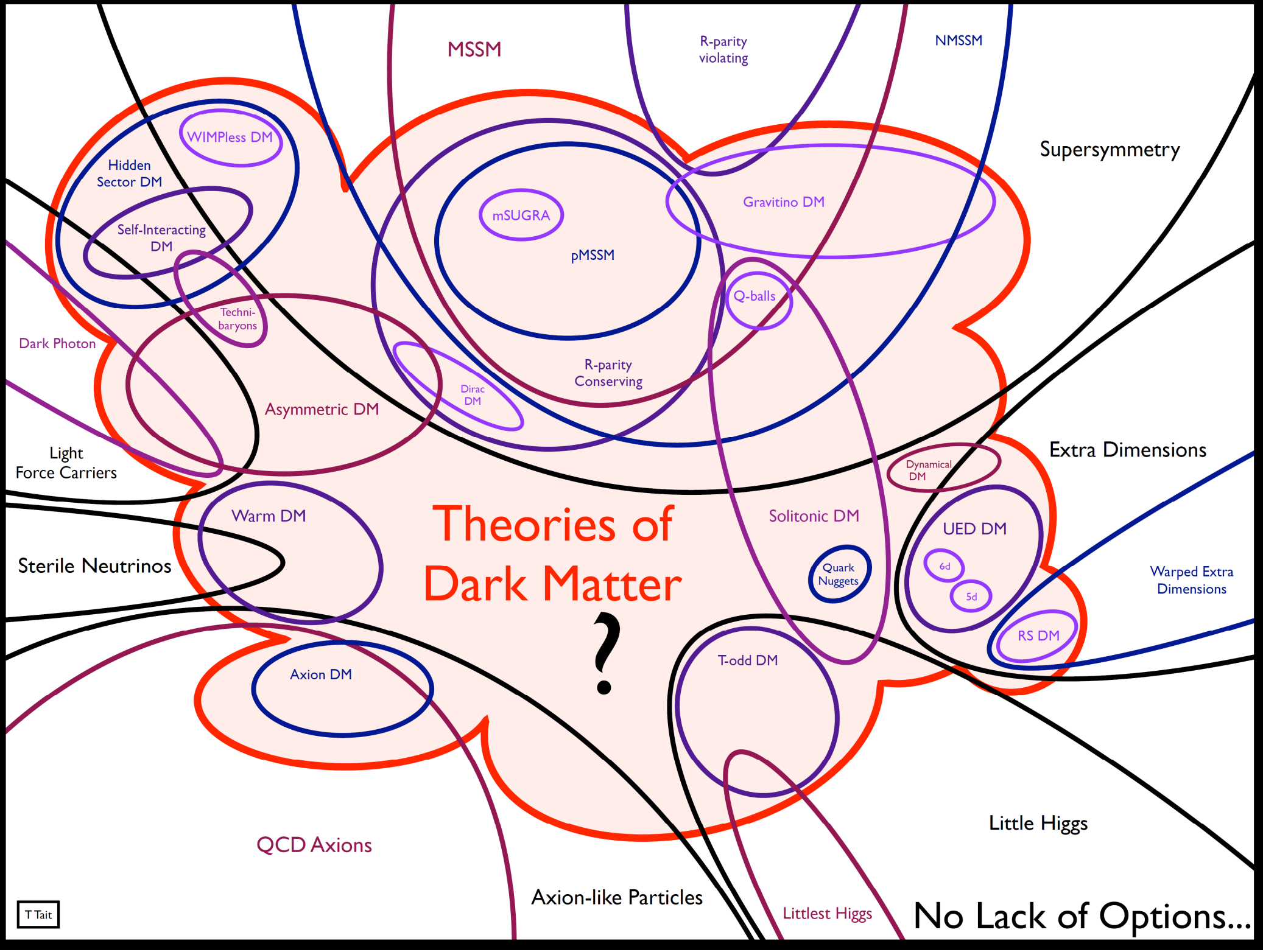
Slide from: Paolo Gondolo's talk, CosPA conference 2016

# What do we know about dark matter?

Mostly have "negative" information from astrophysics and searches for new particles:

- No electric charge
- No colour charge (property of quarks and gluons that is related to the particles' strong interactions)
- No strong self-interaction
- Does not seem to decay: stable, or very long-lived
- *Not a particle in the Standard Model of particle physics*




MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Sterile Neutrinos
Warped Extra Dimensions
RS DM
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
No Lack of Options...
T Tait

# Approaching dark matter theories

**Top down:**
Begin with theory motivation (hierarchy problem, strong CP problem.) develop model (SUSY [supersymmetry], axion) look for stable, neutral particle (LSP [light supersymmetric particle], axion)

**Bottom up:**
Motivated often by specific experimental anomalies, theories constructed. Implications for other experiments (and often SUSY)

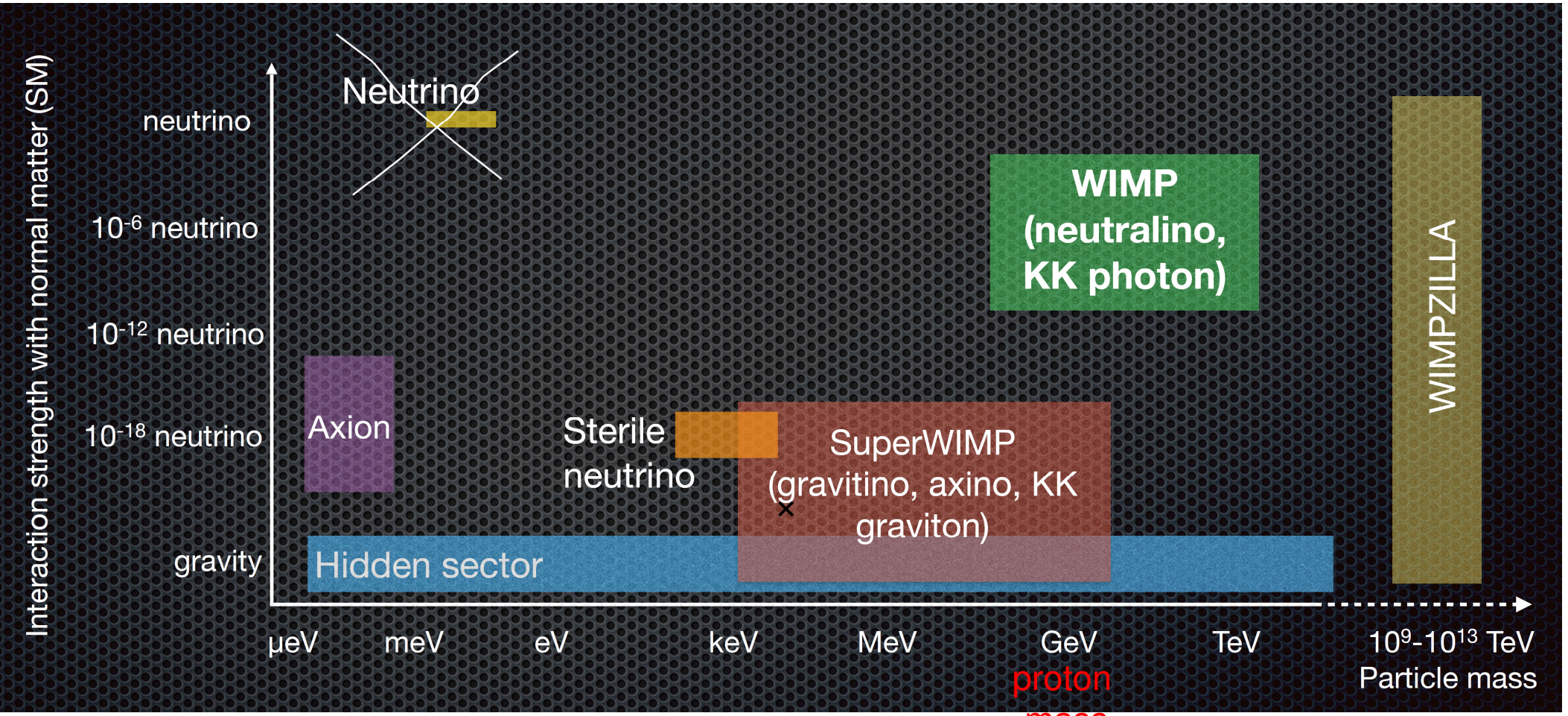
**Phenomenological:** Motivated by considering whether a viable and detectable model could exist of a certain type.

**Our most conservative idea for dark matter:**
**Some exotic particle that we have not yet detected**
**[note: it does not have to be just one particle]**

Two most important parameters of such particles

**(1) Mass** and **(2) Strength of interaction with normal matter**

# Dark matter candidate particle zoo




**WIMP: W**eakly **I**nteracting **M**assive **P**article

**SuperWIMPS:** superweakly-interacting massive particles produced in the late decays of other particles

**Axion,** Peccei–Quinn symmetry

**Kaluza-Klein (KK) photon and graviton** are from universal extra dimension models

**Neutralino and gravitino are particles of supersymmetric models**

**WIMPZILLA** (nonthermal dark matter)

https://indico.in2p3.fr/event/10162/session/5/contribution/10/material/slides/0.pdf

# THE ZOOLOGY OF DARK MATTER

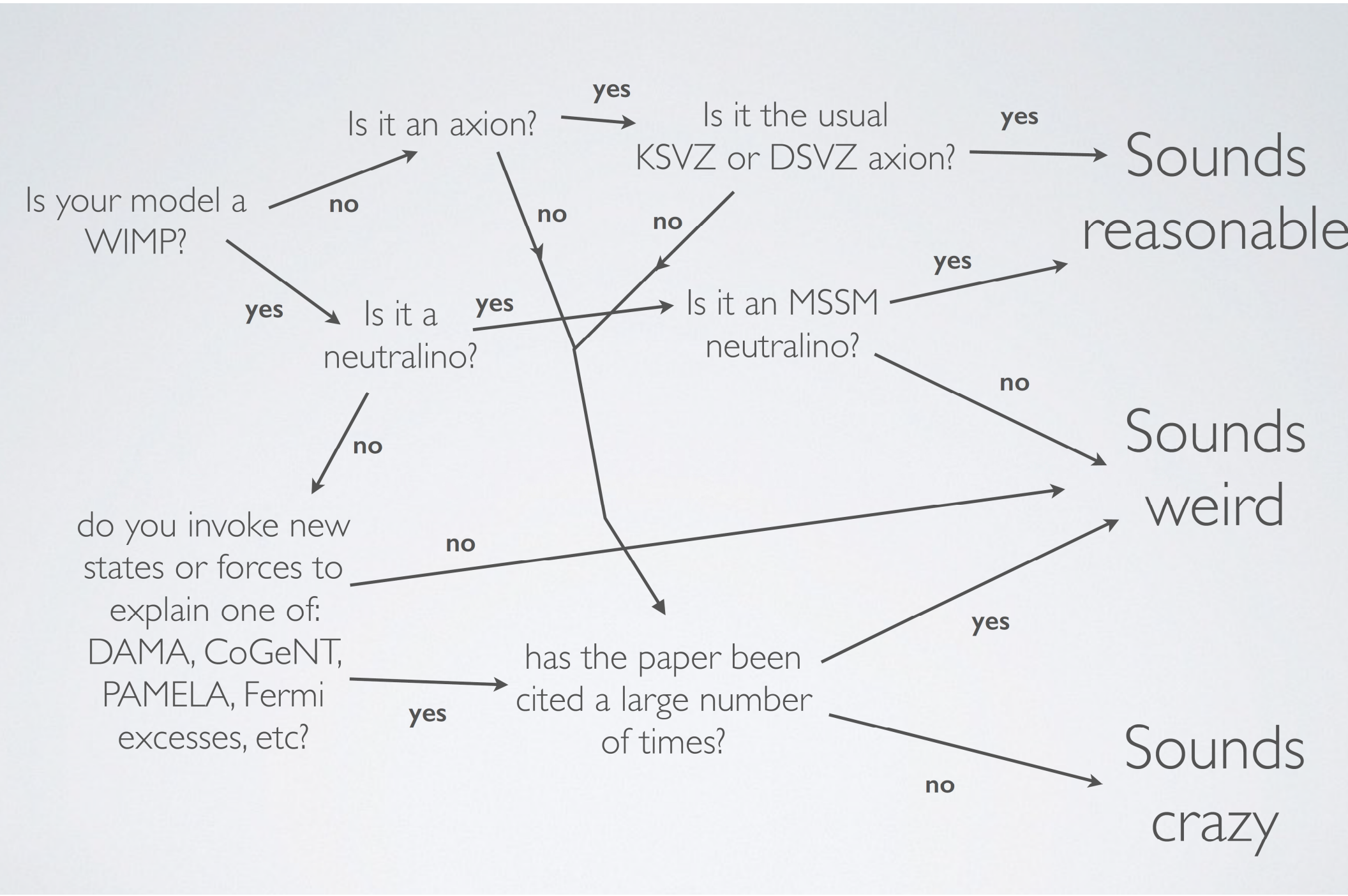
Three basic categories of dark matter:

Reasonable  Weird  Crazy

sometimes also called "normal"

(also "obviously wrong")

Slide from Neal Weiner's (New York University) review on dark matter at the 2015 Conference on the Intersections of Particle and Nuclear Physics




Neal Weiner, CIPANP 2015

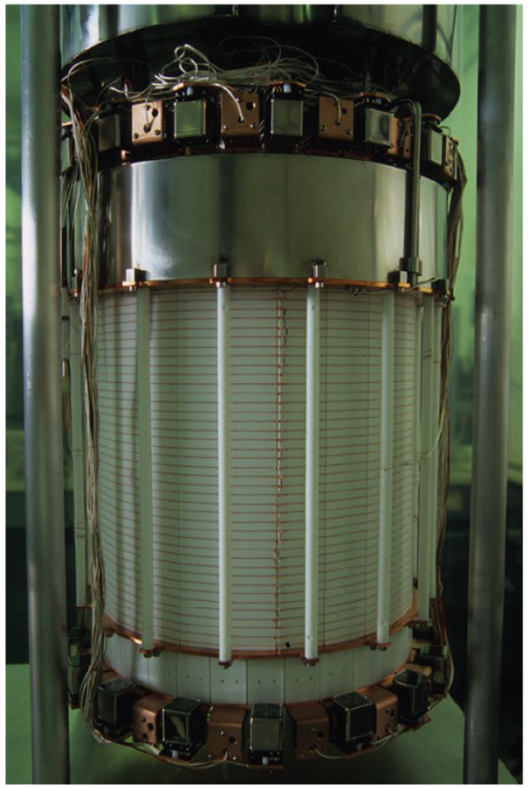
# How to search for dark matter particles

- Indirect detection

Search for things dark matter can decay to

$\chi\chi \rightarrow e^+e^-, p\overline{p}$

- Direct detection



Build a trap for dark matter

$\chi$ N $\rightarrow \chi$ N

- Production at LHC

Make dark matter particles

p + p $\rightarrow \chi$ + a lot

http://www.ippp.dur.ac.uk/~ross/invisibles13/talks/78-marrod_xe1n_undagoita/slides/78-0-Marrodan_Invis_Durham2013.pdf