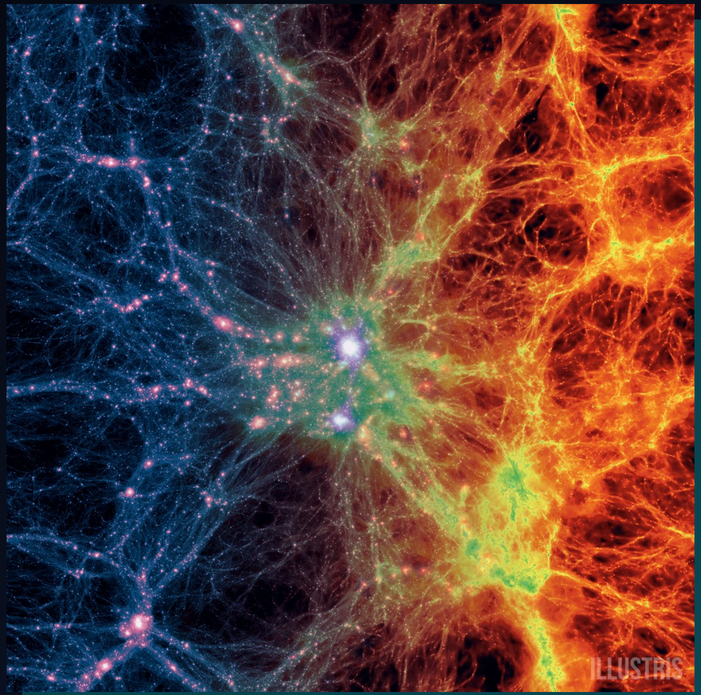
DARK MATTER THEORY I

REBECCA LEANE
SLAC NATIONAL ACCELERATOR LABORATORY

SLAC SSI LECTURES
AUG 15-16th 2022

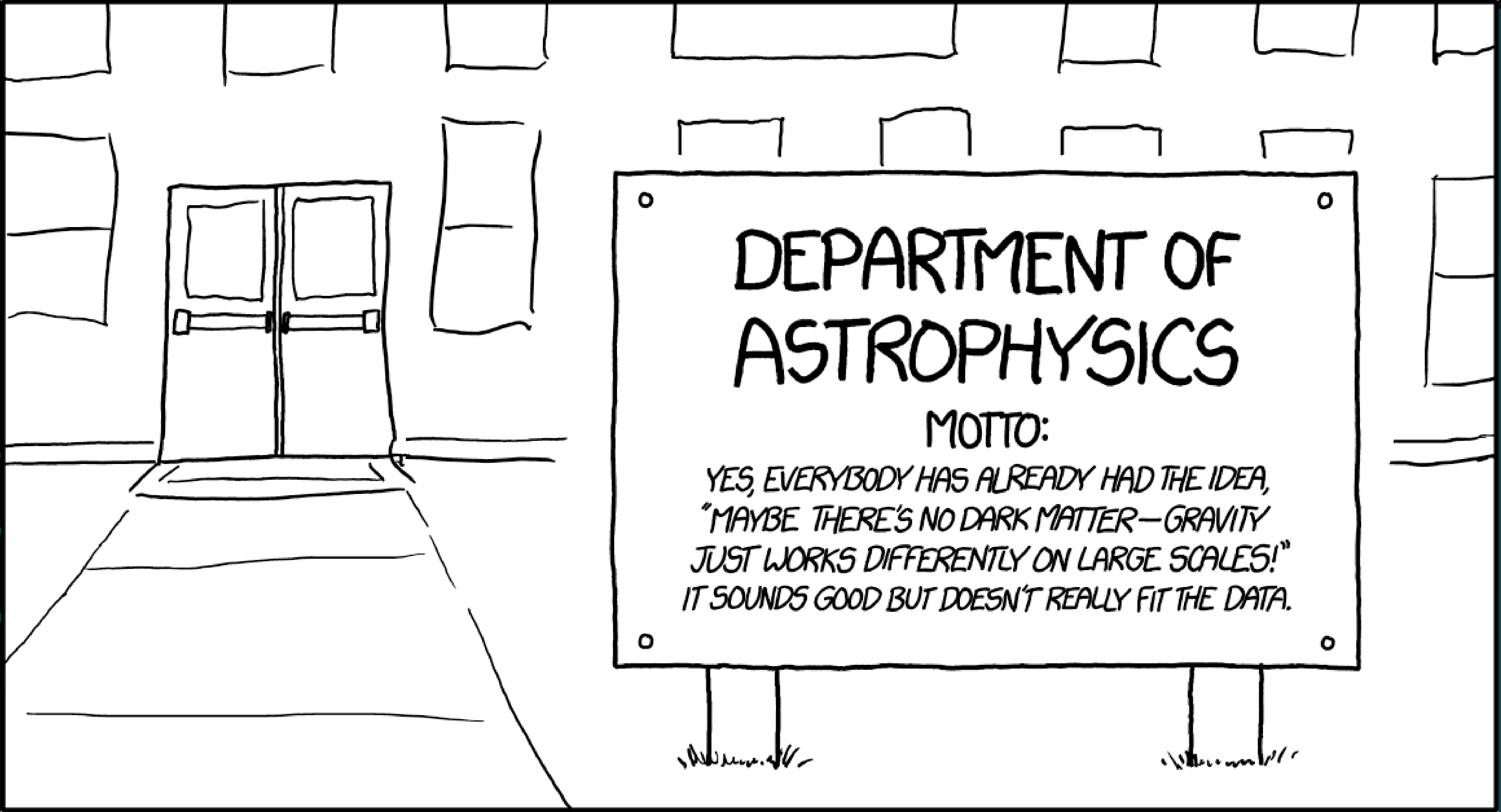
Dark matter lectures

- Today:
  - Dark Matter Theory I (R. Leane)
    - Evidence, weak-scale particle dark matter
  - Dark Matter Experiment I (M.E. Monzani)
    - Heavy DM detection
- Tomorrow:
  - Dark Matter Theory II (R. Leane)
    - Range of theories (e.g. Axions, PBHs) and production mechanisms, future developments
  - Dark Matter Experiment II (B. von Krosigk)
    - Light DM detection



Illustris Simulation

JWST 2022


DEPARTMENT OF ASTROPHYSICS
MOTTO:
YES, EVERYBODY HAS ALREADY HAD THE IDEA, "MAYBE THERE'S NO DARK MATTER—GRAVITY JUST WORKS DIFFERENTLY ON LARGE SCALES!" IT SOUNDS GOOD BUT DOESN'T REALLY FIT THE DATA.

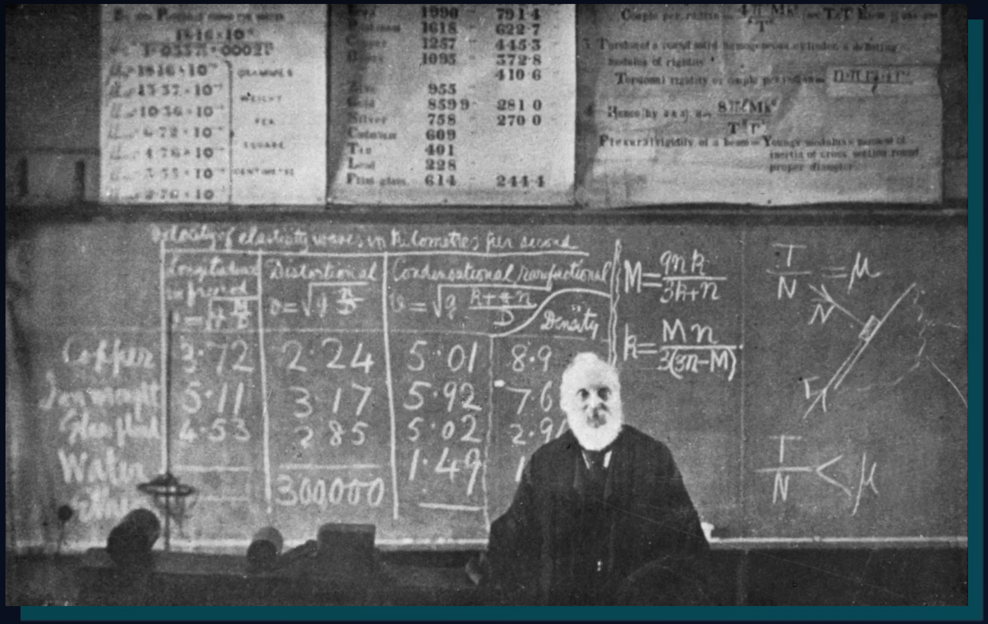
xkcd

1884:
FIRST DYNAMICAL ESTIMATE

Rebecca Leane

First dynamical estimate for DM

Stars modeled as gas of particles influenced by gravity, then the size of the system and the velocity dispersion of the stars should be related



William Thomson (Lord Kelvin), 1899

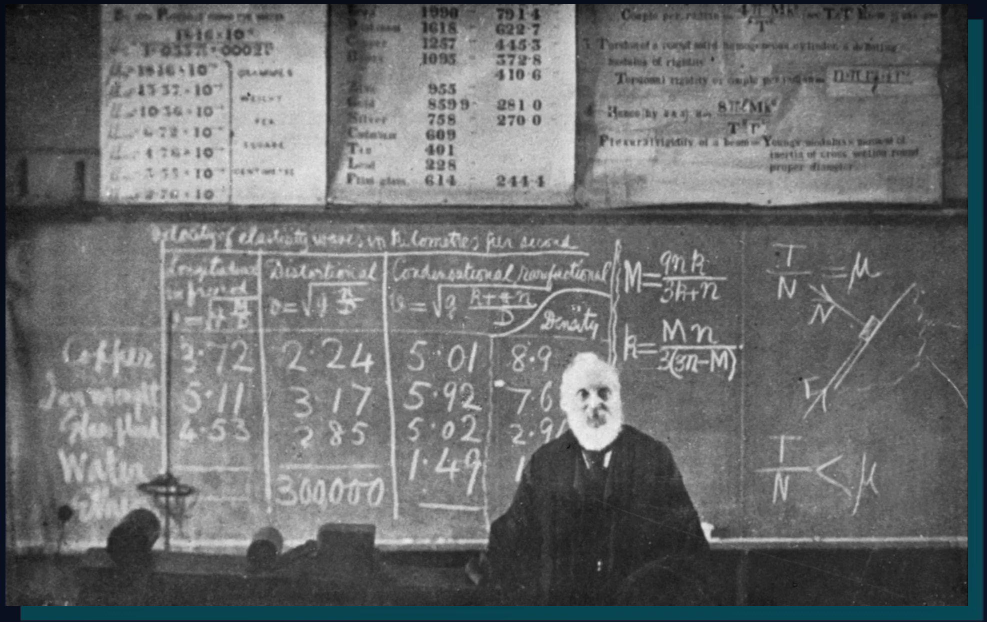
Source: National Museums of Scotland

First dynamical estimate for DM

Stars modeled as gas of particles influenced by gravity, then the size of the system and the velocity dispersion of the stars should be related

“It is nevertheless probable that there may be as many as 10^9 stars [..] but many of them may be extinct and dark, and nine-tenths of them though not all dark may be not bright enough to be seen by us at their actual distances…

Many of our stars, perhaps a great majority of them, may be dark bodies.”



William Thomson (Lord Kelvin), 1899

Source: National Museums of Scotland

Kelvin, B. (1904), Baltimore lectures on molecular dynamics and the wave theory of light, https://archive.org/details/baltimorelecture00kelviala

1906-1930:

EARLY ABUNDANCE ESTIMATES

Rebecca Leane

DM Abundance Estimates

- 1906: Poincaré used “dark matter”, argued that DM must be comparable to the amount of visible matter, due to Kelvin’s velocity dispersion estimate
- 1915: Öpik modeled the motion of stars in the Galaxy, also concluded that lots of DM wasn’t unlikely

DM Abundance Estimates

- 1906: Poincaré used “dark matter”, argued that DM must be comparable to the amount of visible matter, due to Kelvin’s velocity dispersion estimate
- 1915: Öpik modeled the motion of stars in the Galaxy, also concluded that lots of DM wasn’t unlikely
- 1922: Kapteyn expressed the local density in terms of an effective stellar mass, included faint stars through an extrapolation of the luminosity function, considered DM:

“We therefore have the means of estimating the mass of the dark matter in the universe. As matters stand at present, it appears at once that this mass cannot be excessive. If it were otherwise, the average mass as derived from binary stars would have been very much lower than what has been found for the effective mass.”

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- Jeans (1922), Lindblad (1926), Oort (1932) further estimated the local DM density

1930s:

EVIDENCE FROM CLUSTERS

Rebecca Leane

Evidence from the Coma Cluster

- By 1931, Hubble + Humason measured redshifts of galaxies in the Coma Cluster, finding large velocities

- In 1933-37, Zwicky related kinetic energy to the gravitational potential (virial theorem to estimate mass)
  - Found luminosity observed could NOT explain motion

Sloan/Spitzer. NASA / JPL-Caltech / L. Jenkins (GSFC)

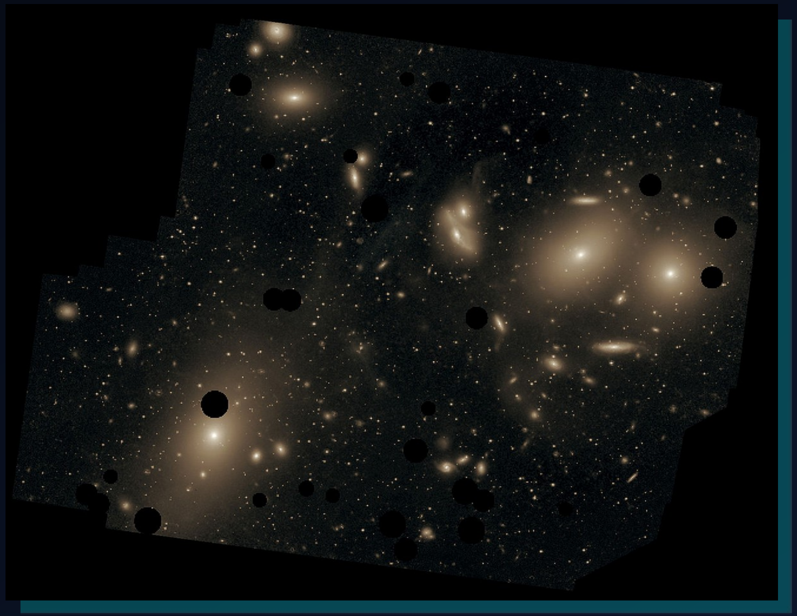
If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.

Zwicky, F. (1937), Astrophys. J. 86, 217.

Evidence from the Virgo Cluster

- In 1936, Smith studied Virgo Cluster, finding qualitatively similar results:

> *"the difference represents internebular material, either uniformly distributed or in the form of great clouds of low luminosity surrounding the [galaxies]."*



Burell Schmit Telescope, Chris Mihos /ESO

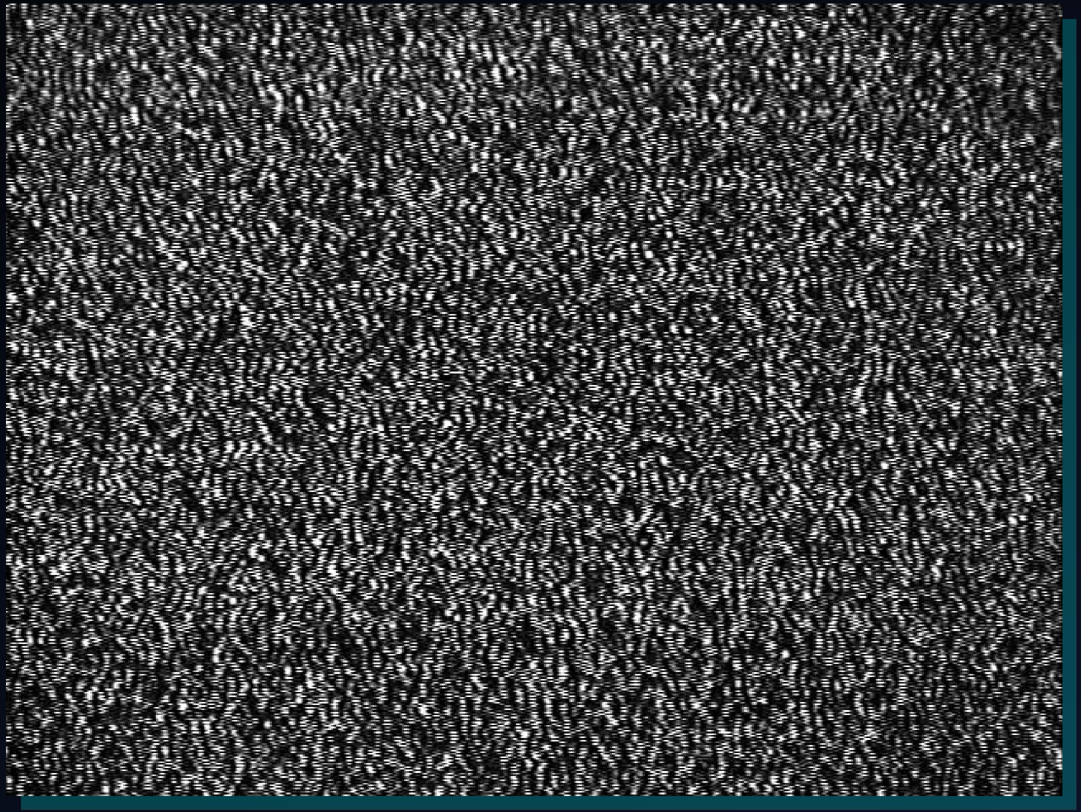
Zwicky, F. (1937), Astrophys. J. 86, 217.

1940-1970:

????

Rebecca Leane

TVs BEGIN TO TURN ON…



Penzias, A. A.; Wilson, R. W. (1965). "A Measurement of Excess Antenna Temperature at 4080 Mc/s". The Astrophysical Journal.

1970-1980:

EVIDENCE FROM ROTATION CURVES

Rebecca Leane

Galactic Rotation Curves

- Find rotational velocity:

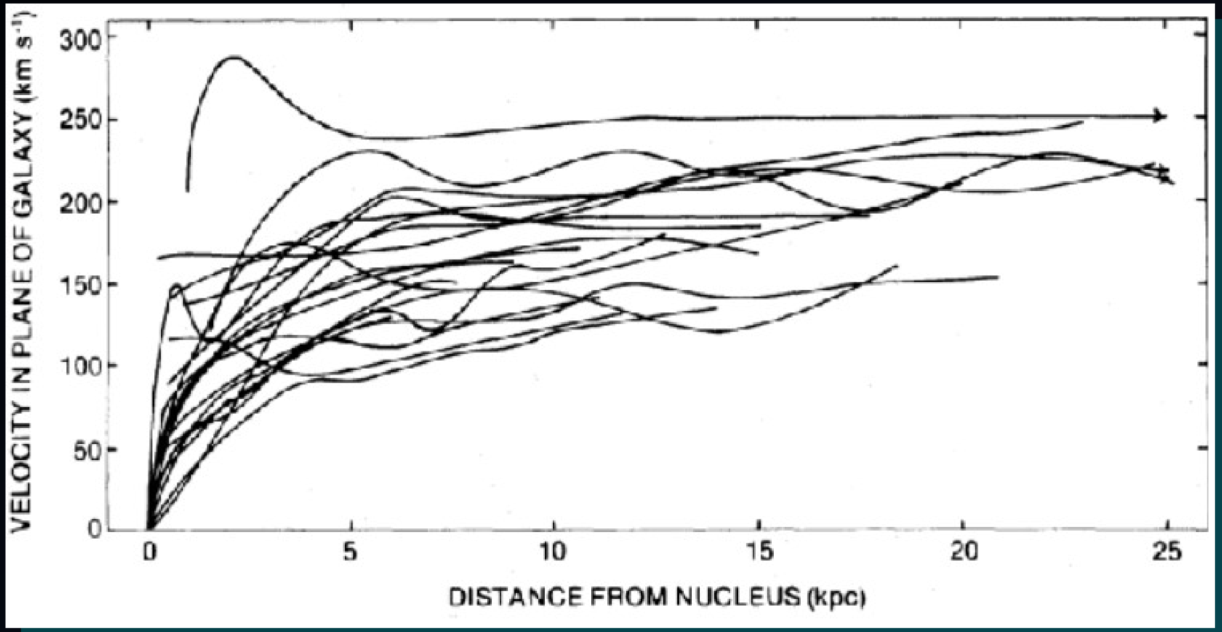
$$F = m\,a \;\rightarrow\; \frac{GMm}{r^2} = \frac{mv_{\rm rot}^2}{r} \;\rightarrow\; v_{\rm rot} = \sqrt{\frac{GM(r)}{r}}$$

- For r > R where R is edge of visible matter, if M(r) = M(R) covers all matter, expect

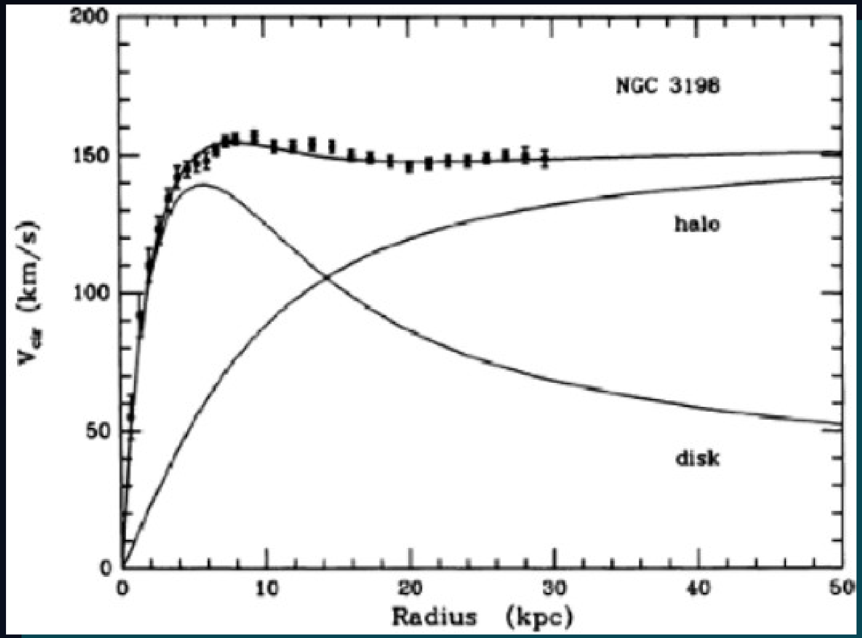
$$v_{\rm rot} = \sqrt{\frac{GM(R)}{r}} \approx r^{-1/2}$$

Is this what we observe in galaxies?

Evidence from Rotation Curves



Rubin, Ford, Thonnard 1980



Albada, Bahcall, Begeman, Sancisi, 1985

Galaxies rotate too fast out at large radii!
How can we explain it?

Evidence from Rotation Curves

- We observe constant velocities for r>R

$$v_{\rm rot} = \sqrt{\frac{GM(r)}{r}} \propto \text{constant}$$

which implies

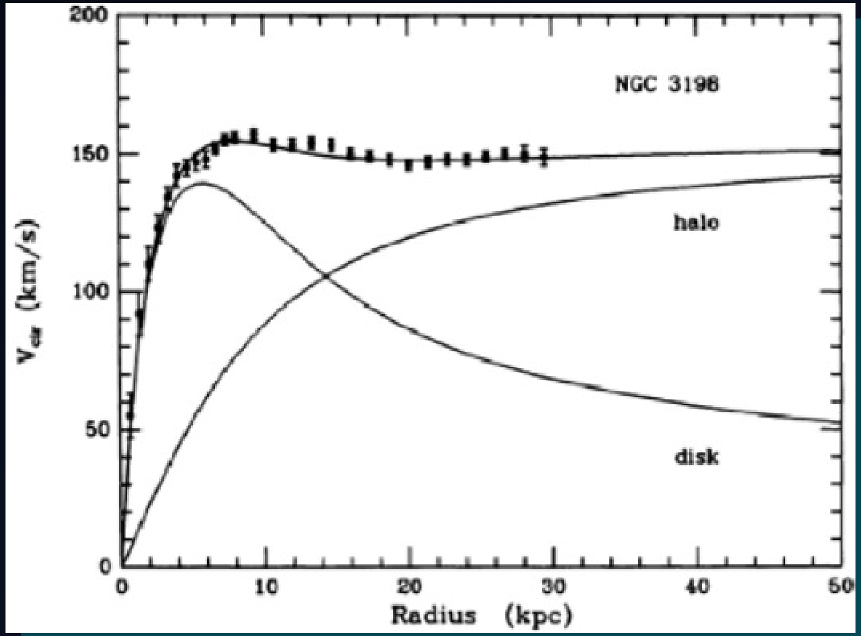
$$M(r) \propto r$$

- Now,

$$M(r) = 4\pi \int r^2 \rho(r)\, dr$$

which implies

$$\rho(r) \propto \frac{1}{r^2}$$



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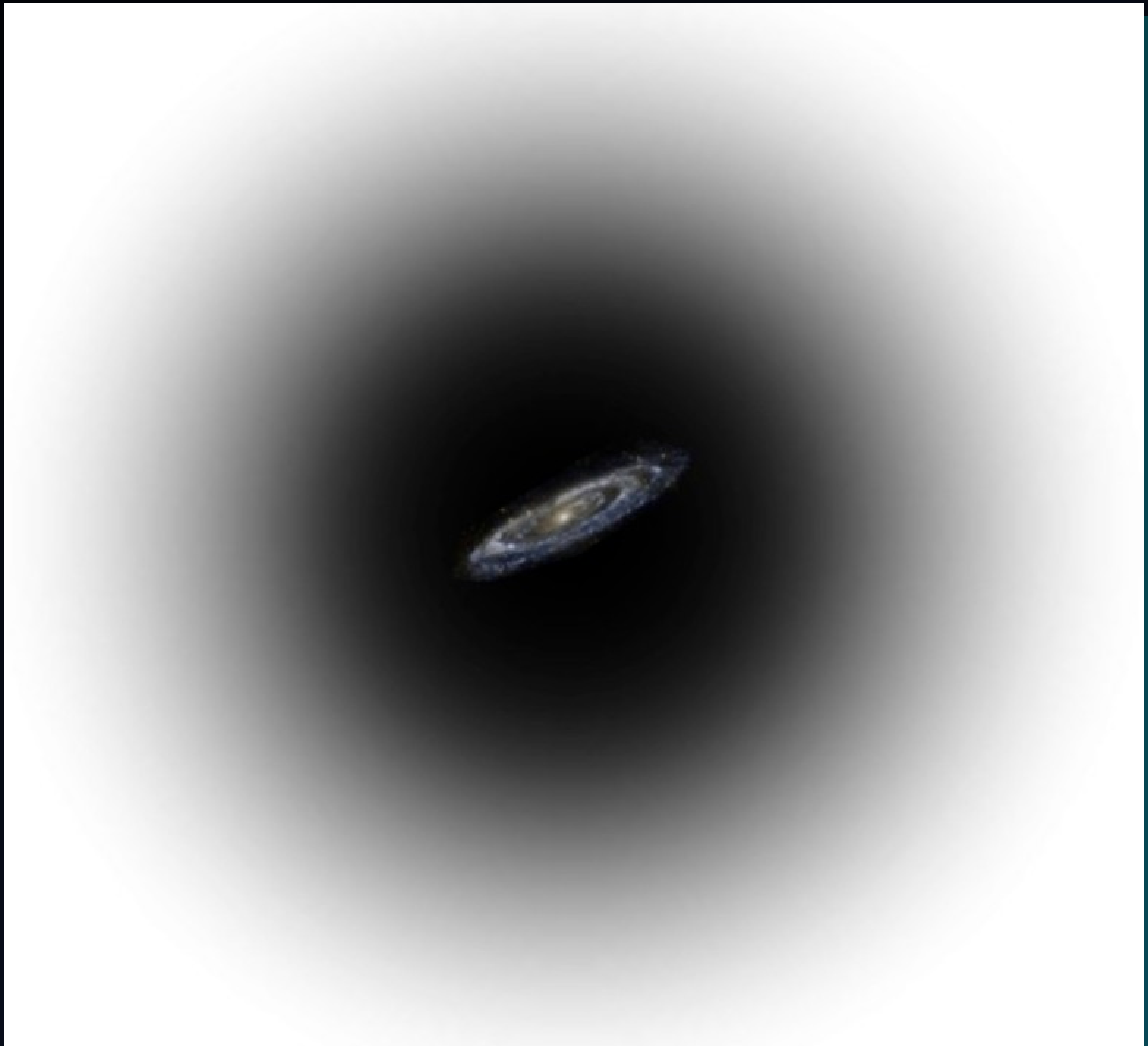


Source: dark matter: K. Mack; Andromeda Galaxy: GALEX, JPL-Caltech, NASA

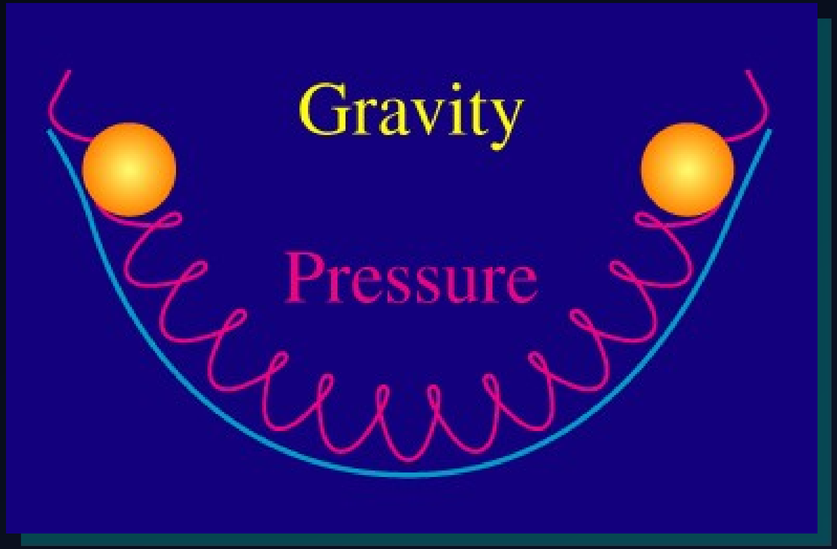
1990s-2000s:

EVIDENCE FROM THE COSMIC MICROWAVE BACKGROUND

Rebecca Leane

The Cosmic Microwave Background (CMB)

- After ~380,000 years, the Universe was a nearly homogeneous soup of photons, electrons, protons and dark matter
- Competition of gravity and radiation pressure → density/temperature oscillations
- Universe cooled, neutral hydrogen could form (recombination), matter and radiation decoupled, and the pattern of acoustic oscillations became frozen into the CMB
- The cosmic microwave background is the “relic radiation” of photons that last scattered at this time
- Afterwards, the Universe is neutral and transparent



Wayne Hu, http://background.uchicago.edu/~whu/

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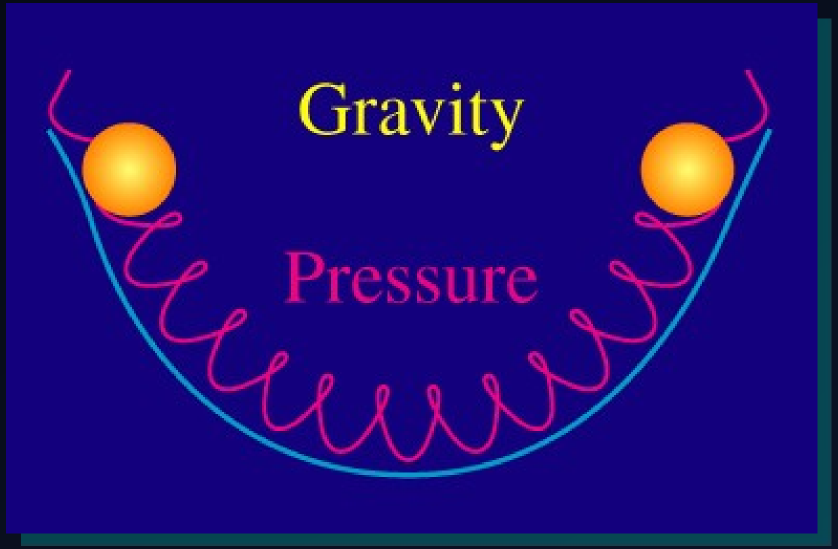

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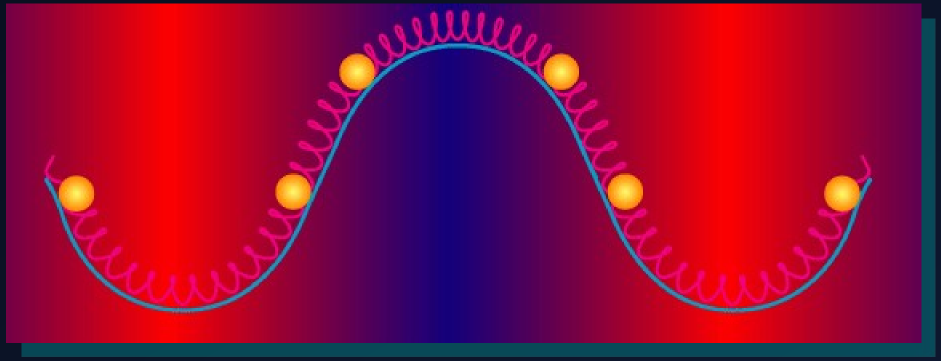
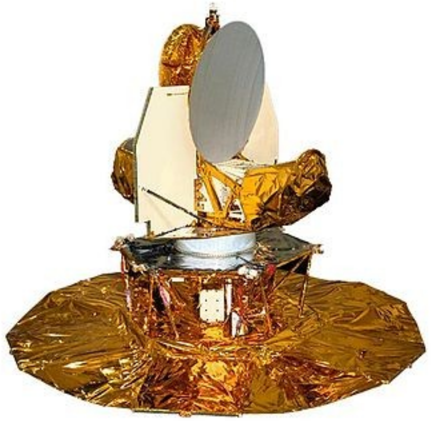
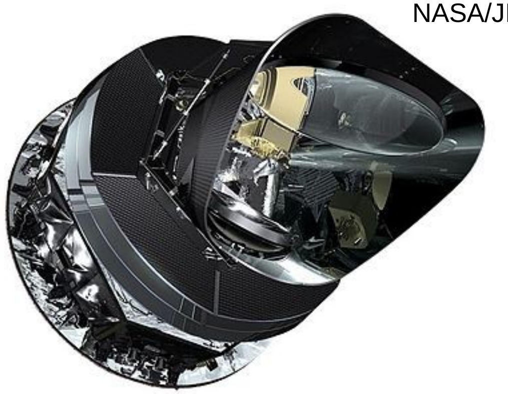
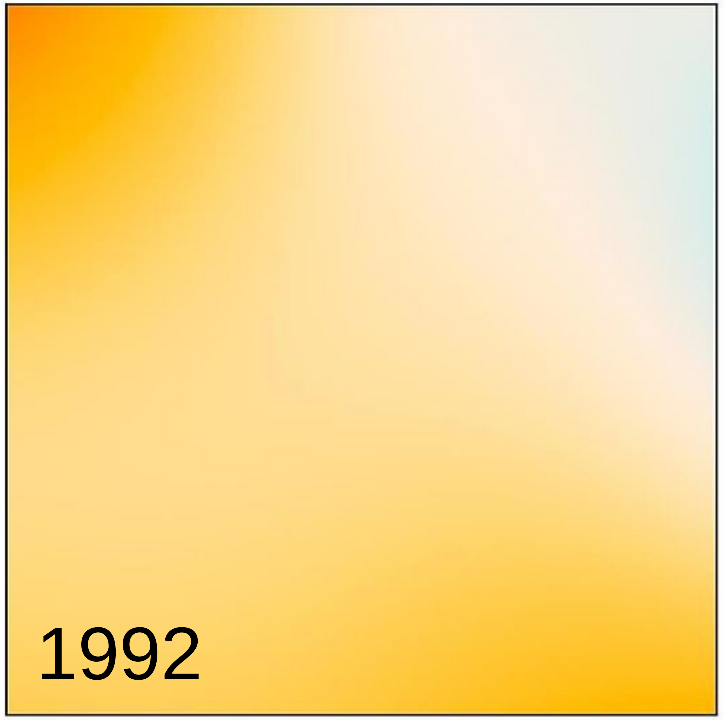
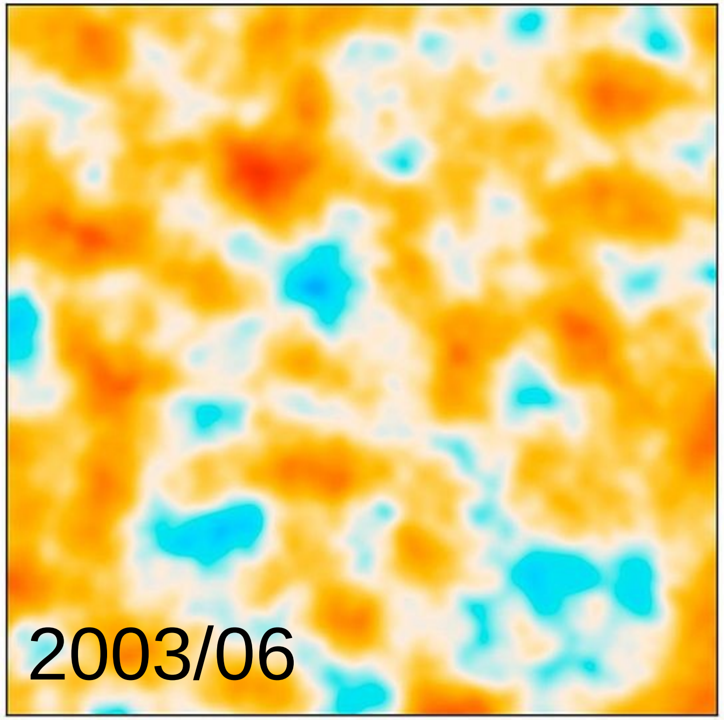


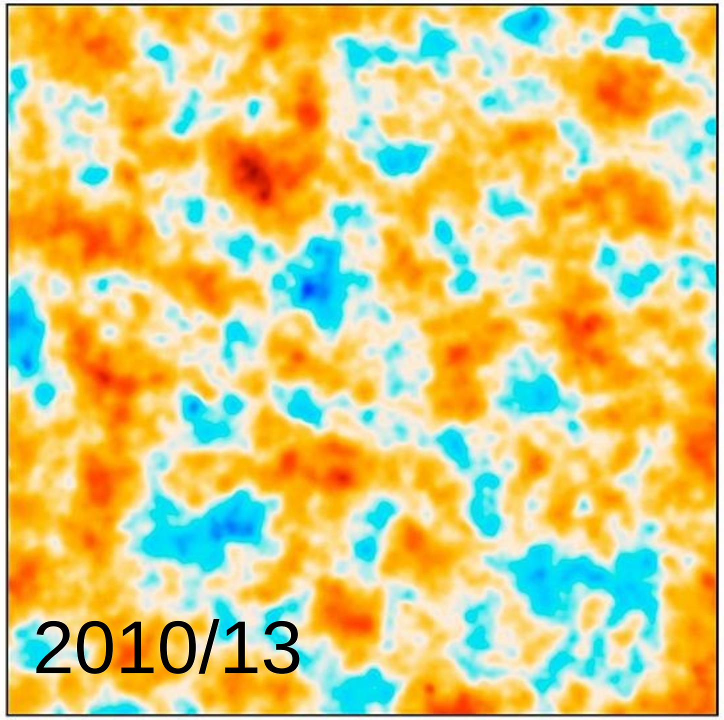
NASA/JPL-Caltech/ESA









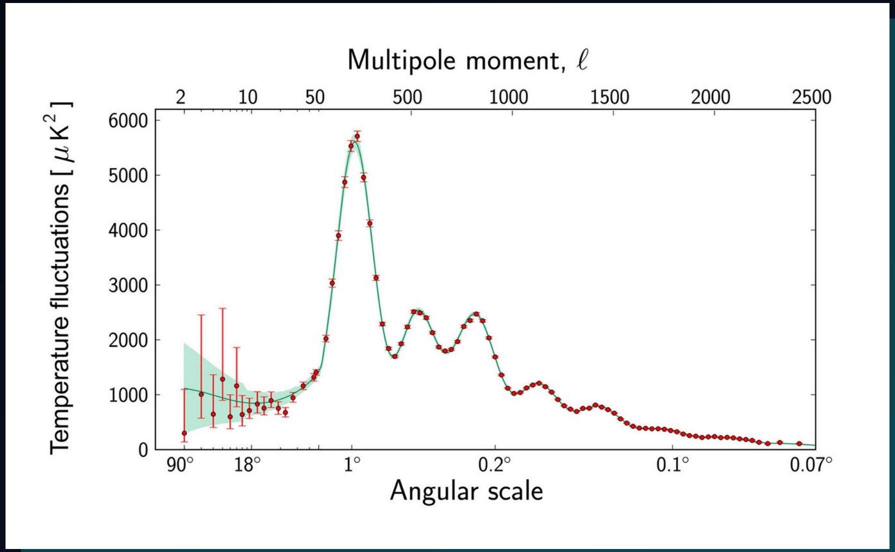


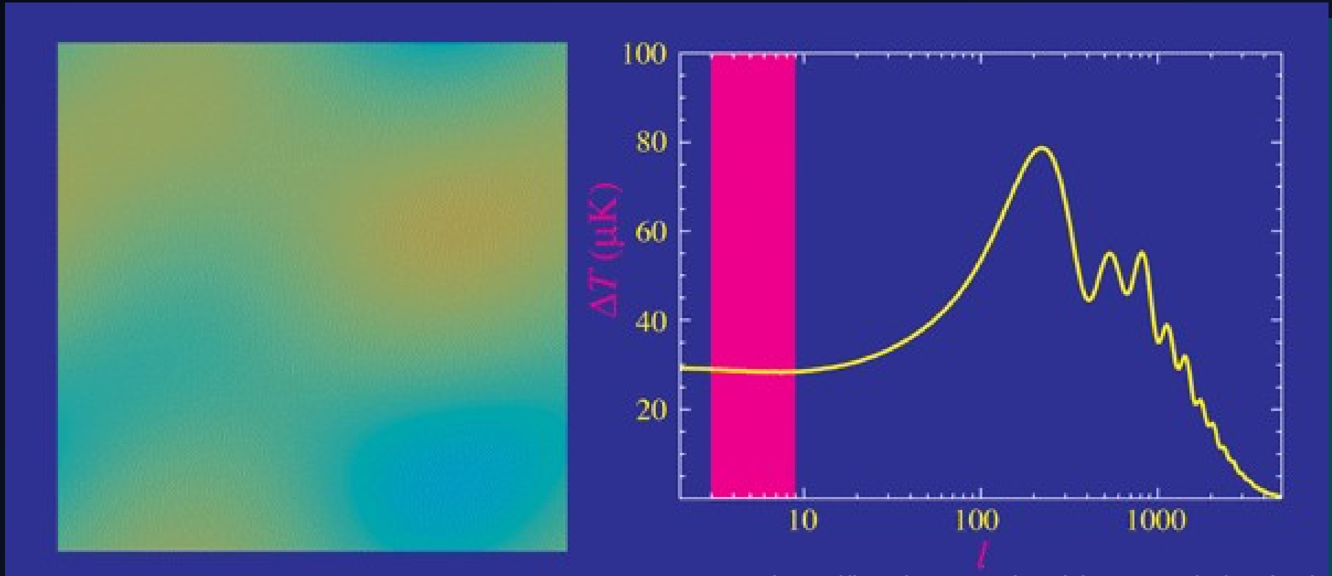
COBE WMAP Planck

CMB Anisotropies

- Photon temperature anisotropies today provide a snapshot of the inhomogeneities at recombination
- Today, we detect the evidence of the sound waves (regions of higher and lower density) via CMB anisotropies
- Peaks occur at angular scales corresponding to a harmonic series based on the sound horizon at recombination

Planck (2013)





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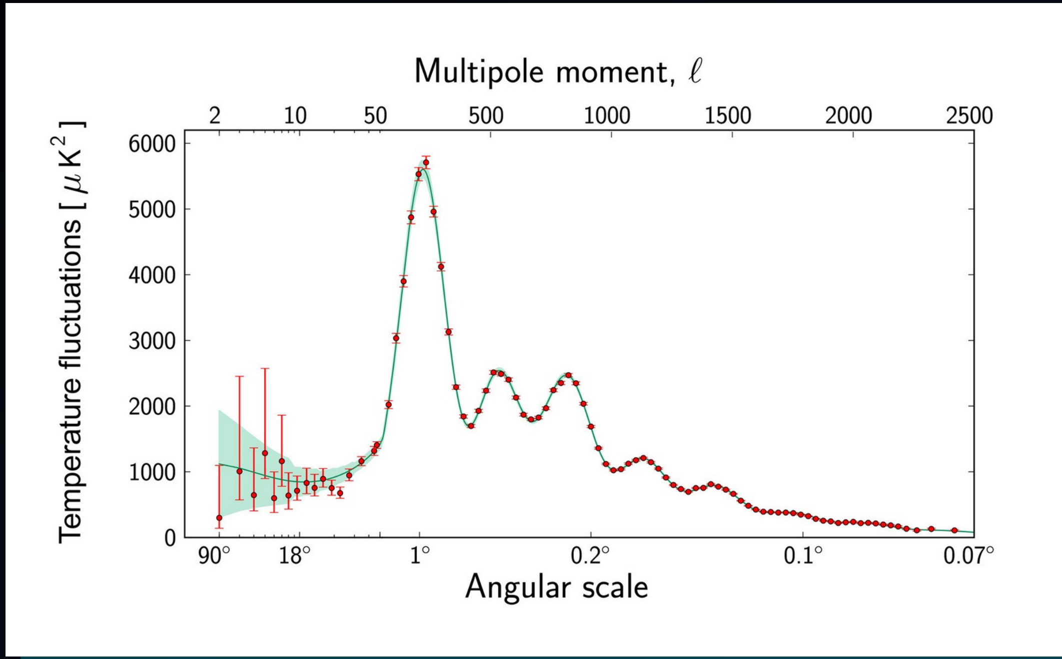
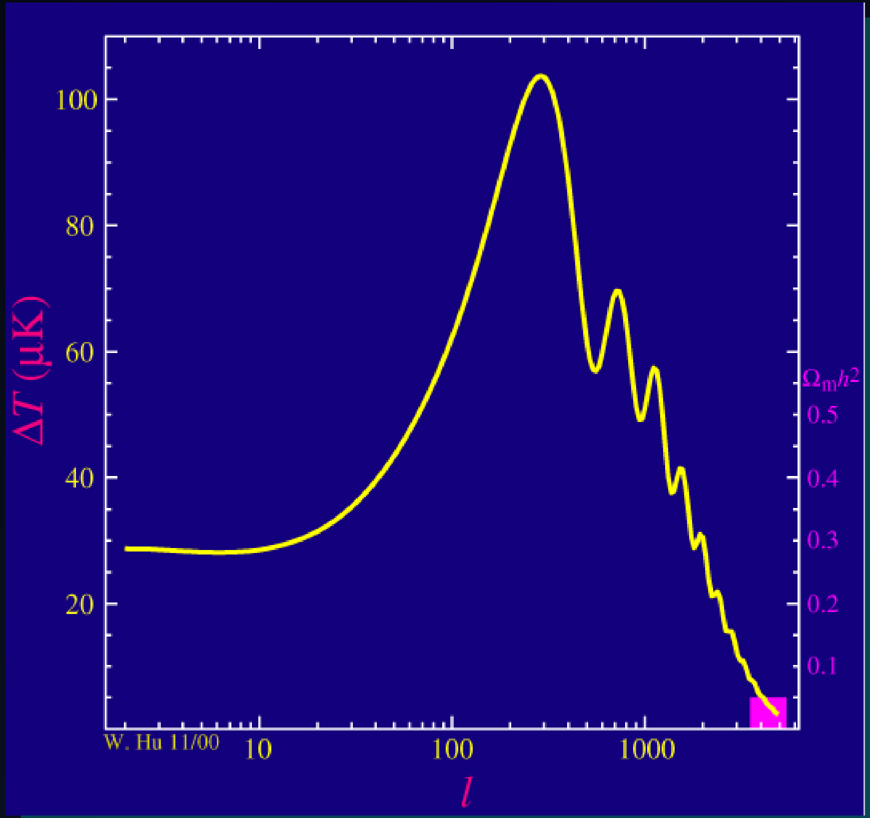
CMB: Dark Matter Evidence



Planck (2013)



Wayne Hu, http://background.uchicago.edu/~whu/

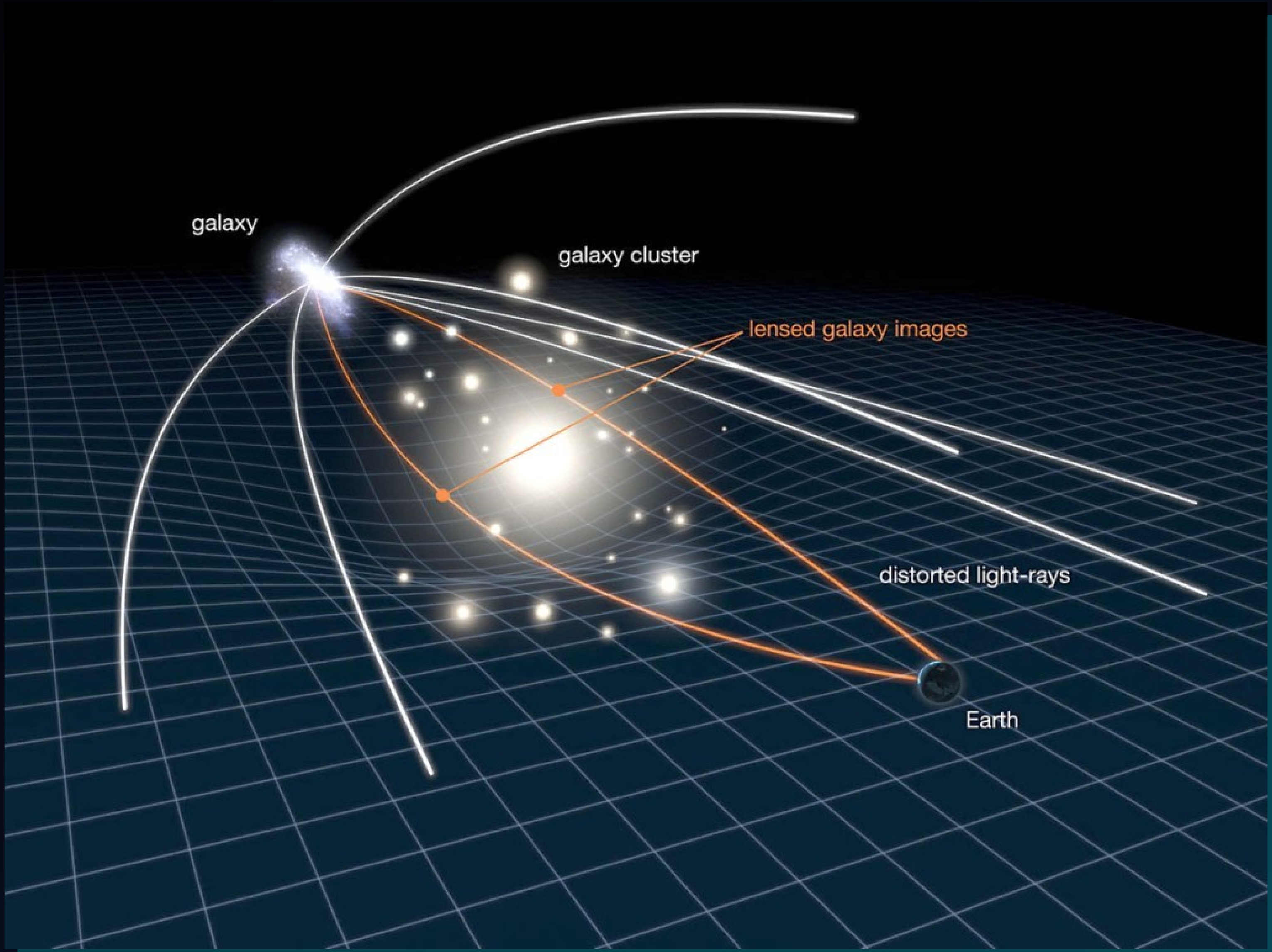
- To match data, need a DM component with ~5x more total mass
- DM does not experience radiation pressure, only gravity
- Big bang nucleosynthesis (BBN) constrains baryon to photon ratio

1990s-2000s:

EVIDENCE FROM GRAVITATIONAL LENSING

Rebecca Leane

Gravitational Lensing



NASA, ESA & L. Calcada

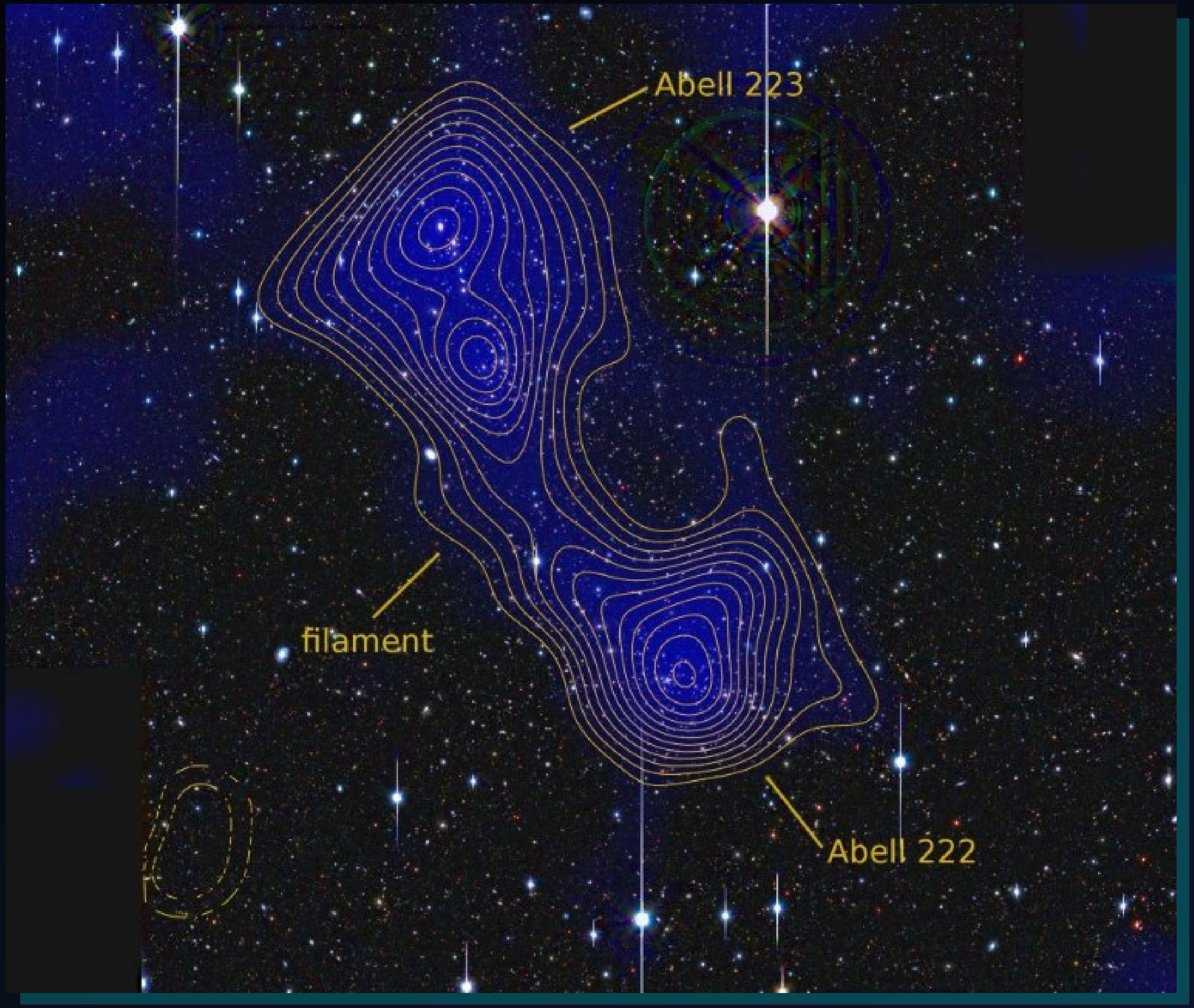
Evidence from Strong Gravitational Lensing

JWST 2022

Evidence from Strong Gravitational Lensing

Hubble, NASA/ESA

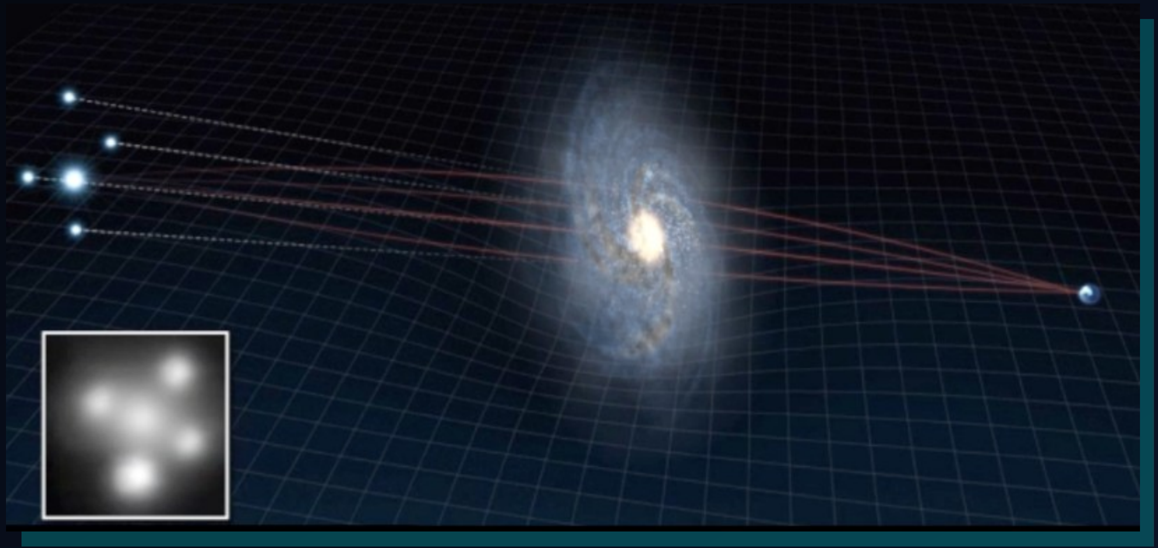
Evidence from Weak Gravitational Lensing



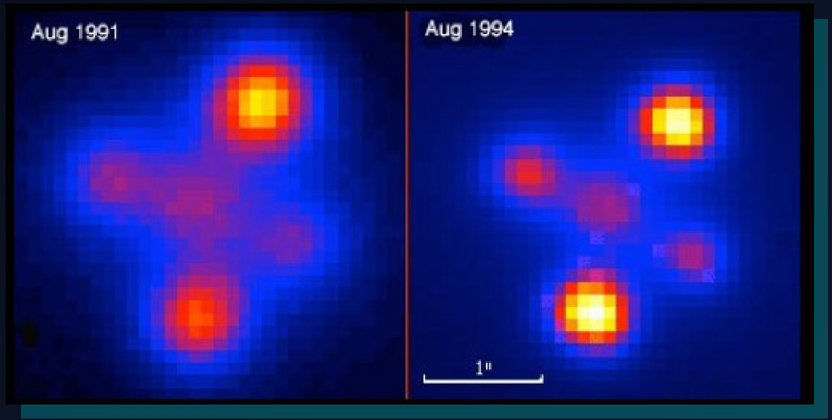
Dietrich et al. 2016

Evidence from Cosmological Microlensing

- Also known as “quasar microlensing”
- Galaxy acts as strong lens, makes multiple images of the quasar
- Objects like black holes, stars within the galaxy can act as microlens for the light paths
- Brightness of quasar images all vary



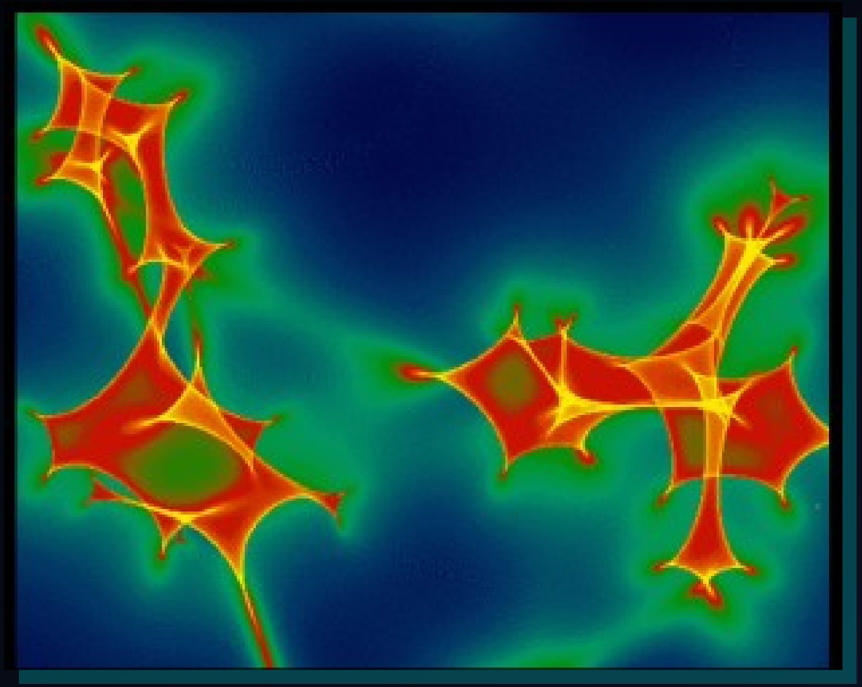
Lewis & Irwin 1996



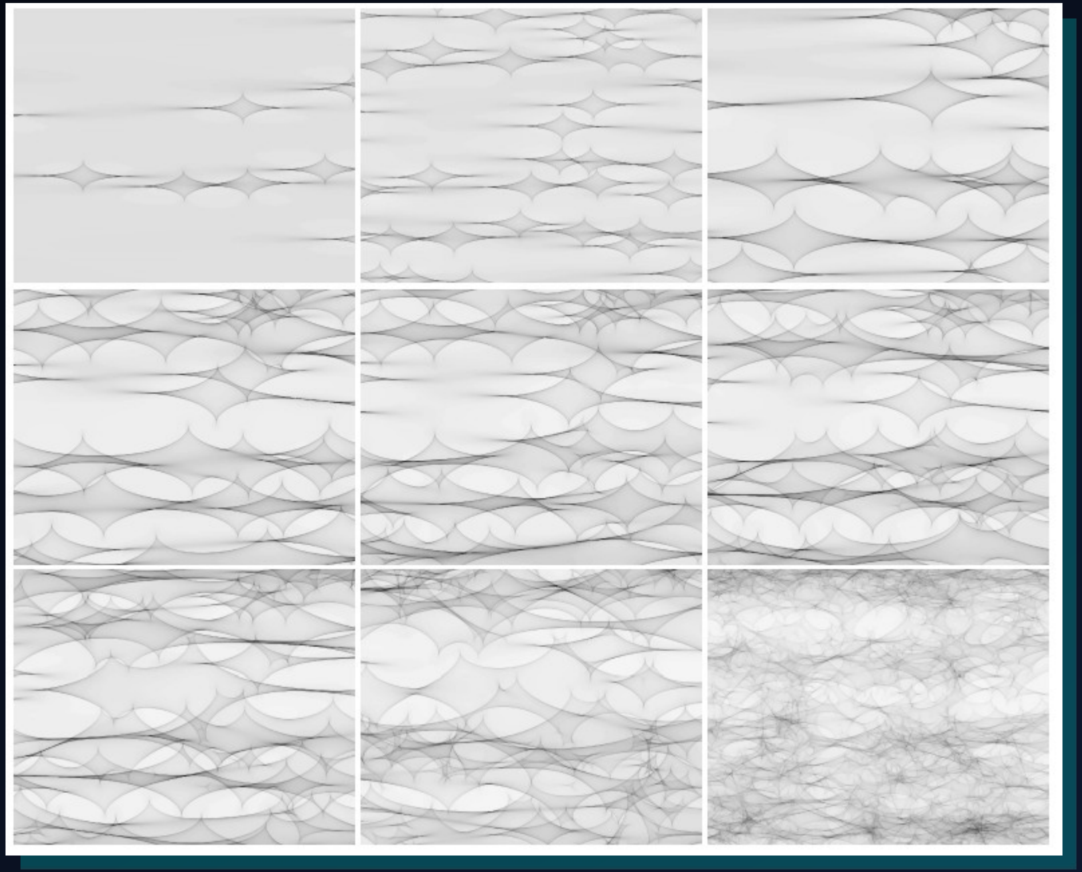
Evidence from Cosmological Microlensing

Builds a “magnification map”

How much matter is there, and is it “clumpy” or is it mostly smooth?



Wambsganss 2006



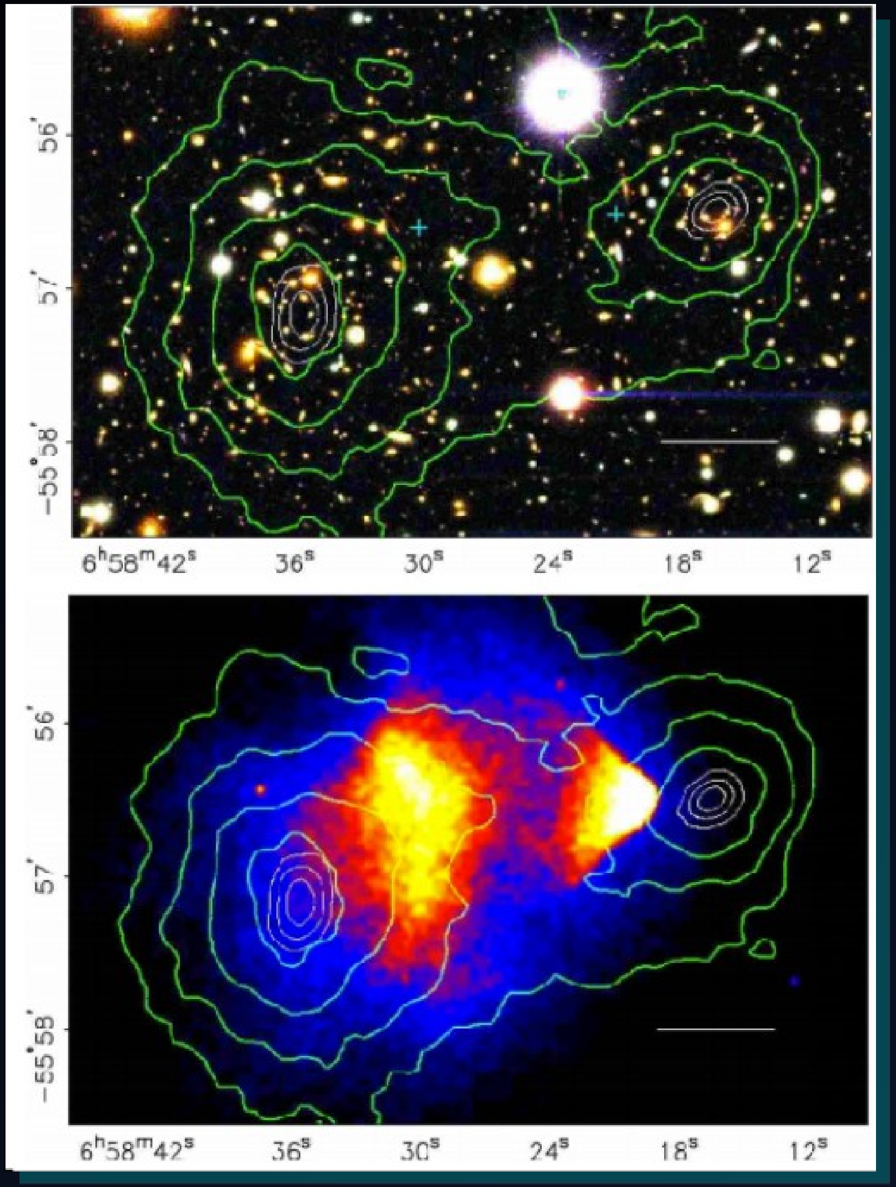
Mediavilla et al. 2009

Bulk of matter is fairly smooth.

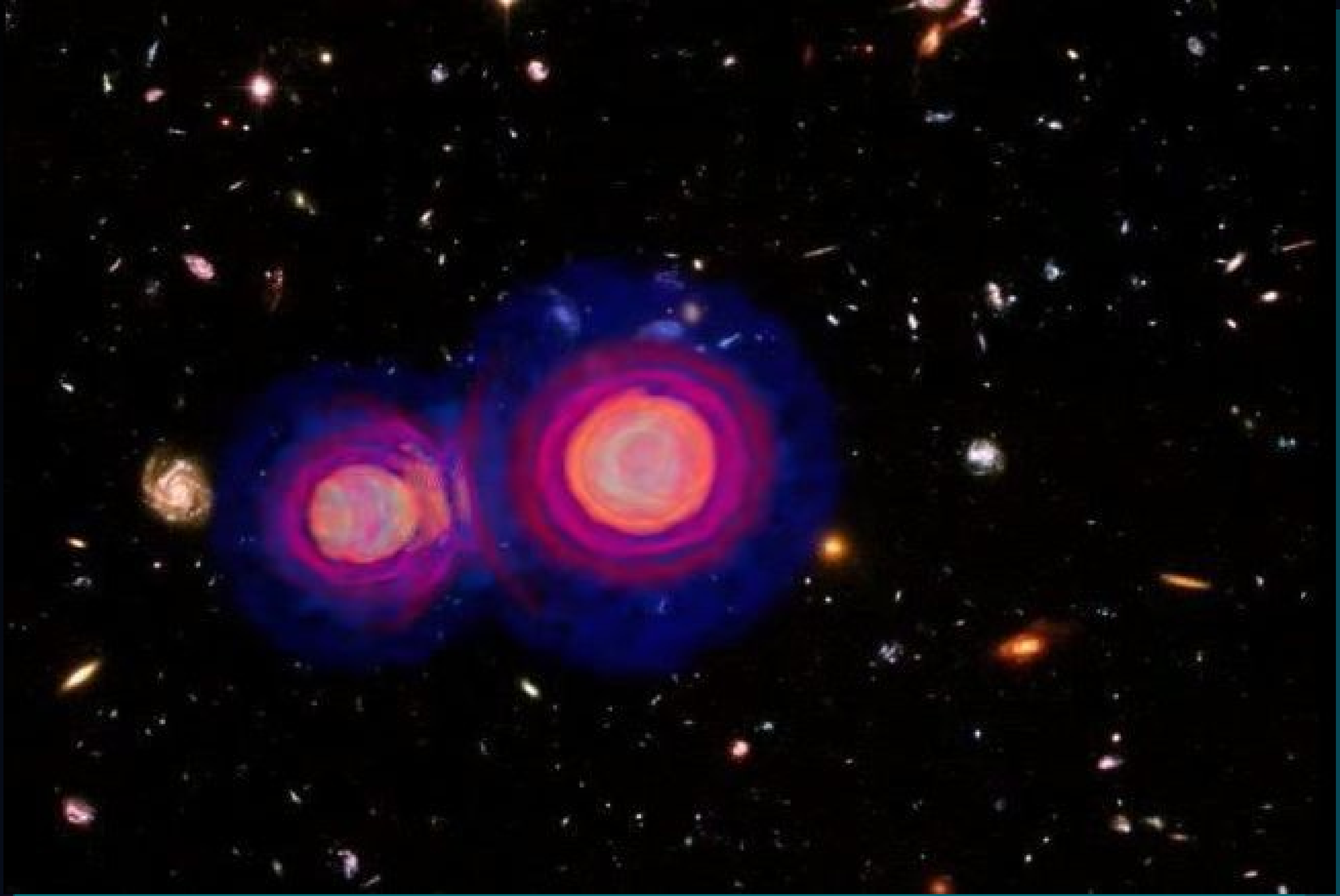
2006:

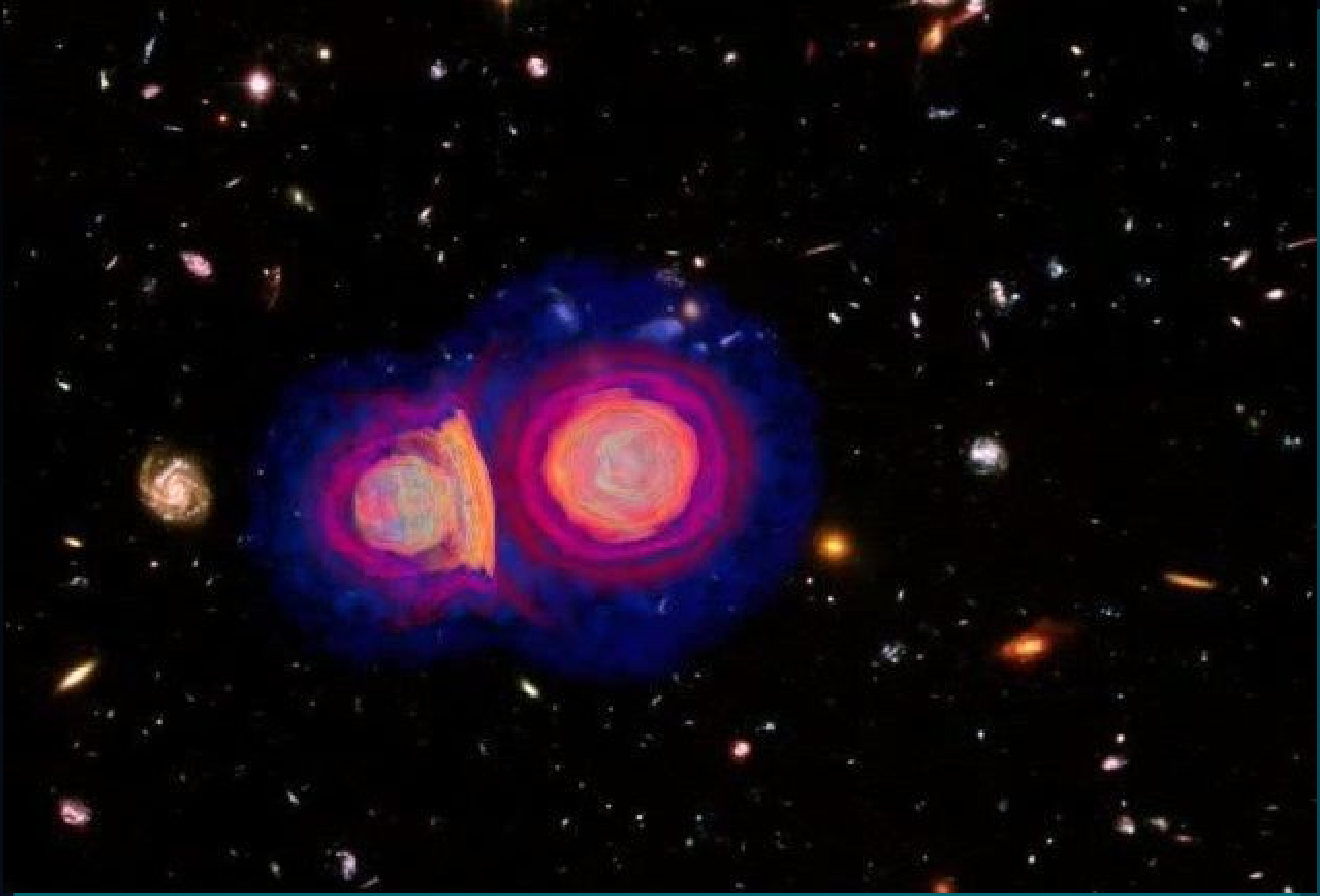
EVIDENCE FROM THE BULLET CLUSTER

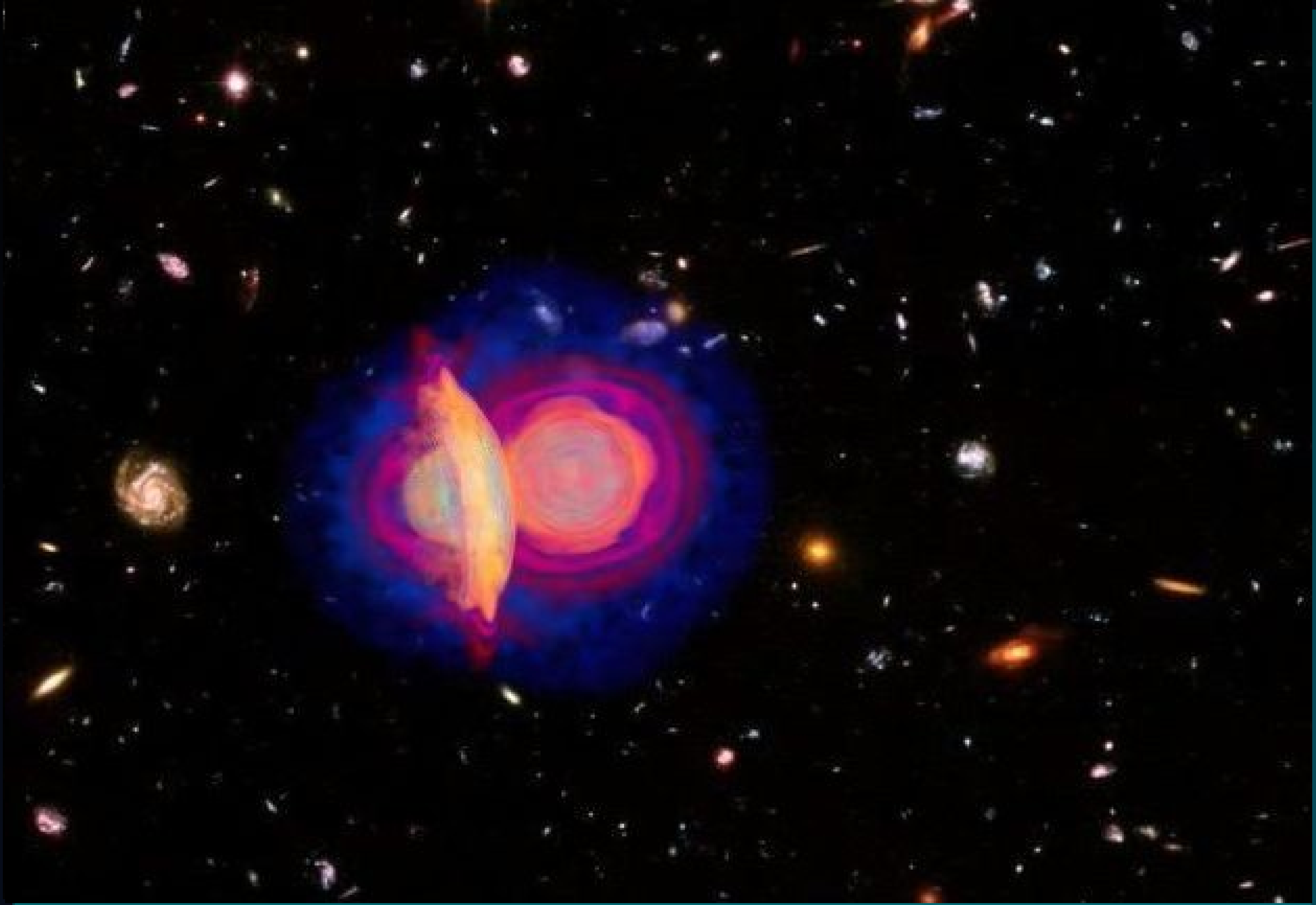
Rebecca Leane

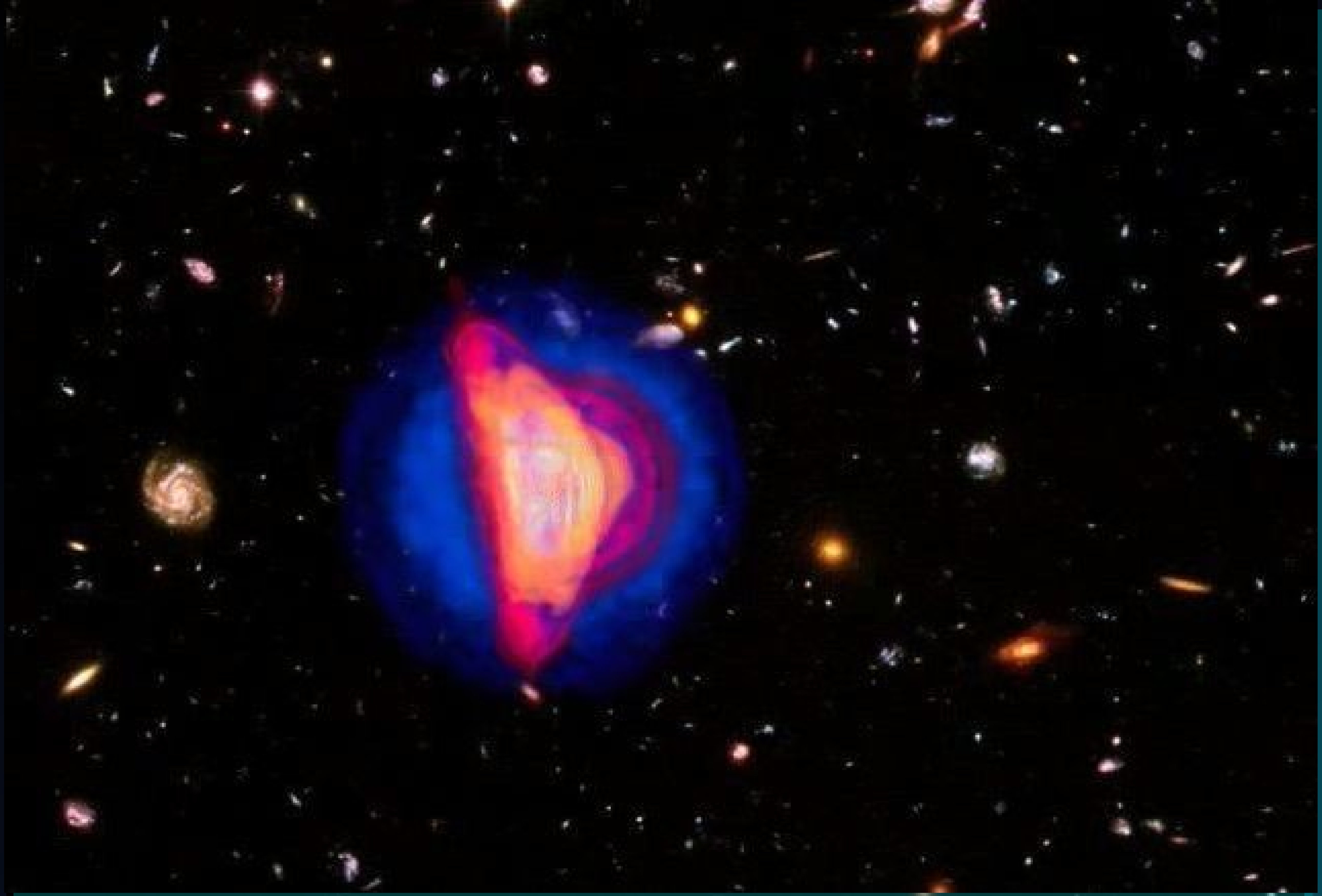


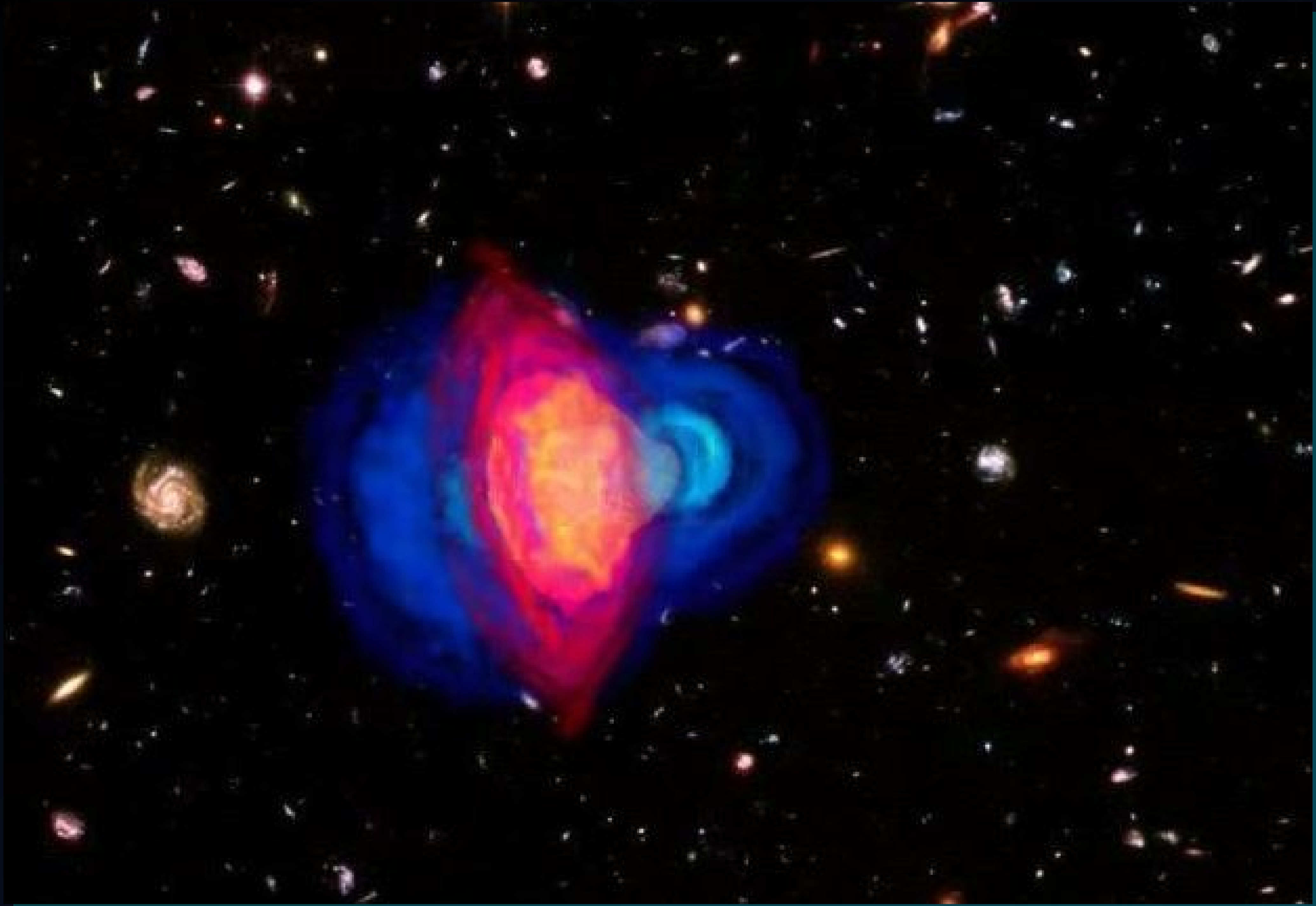
NASA/Clowe et al. 2006

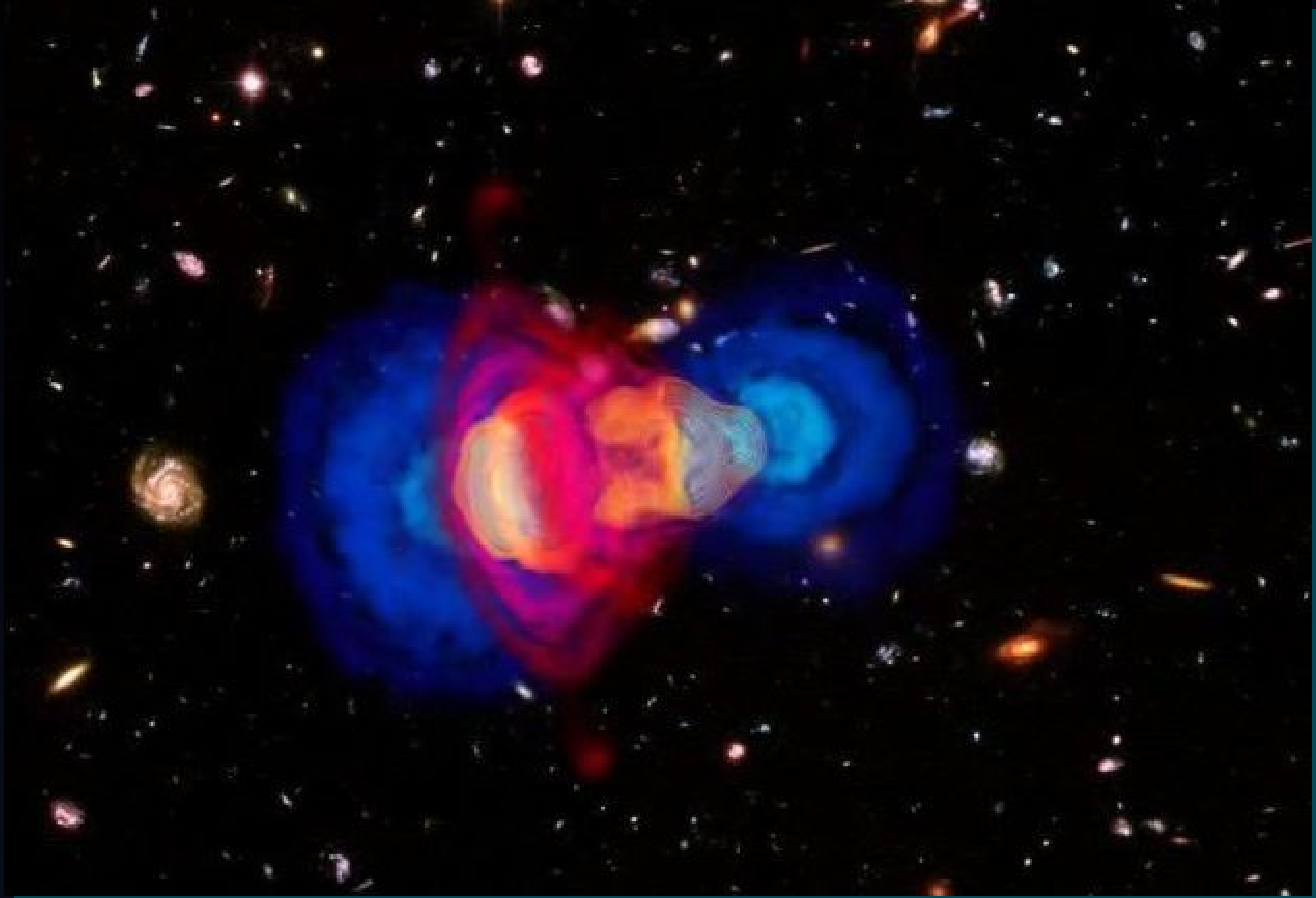


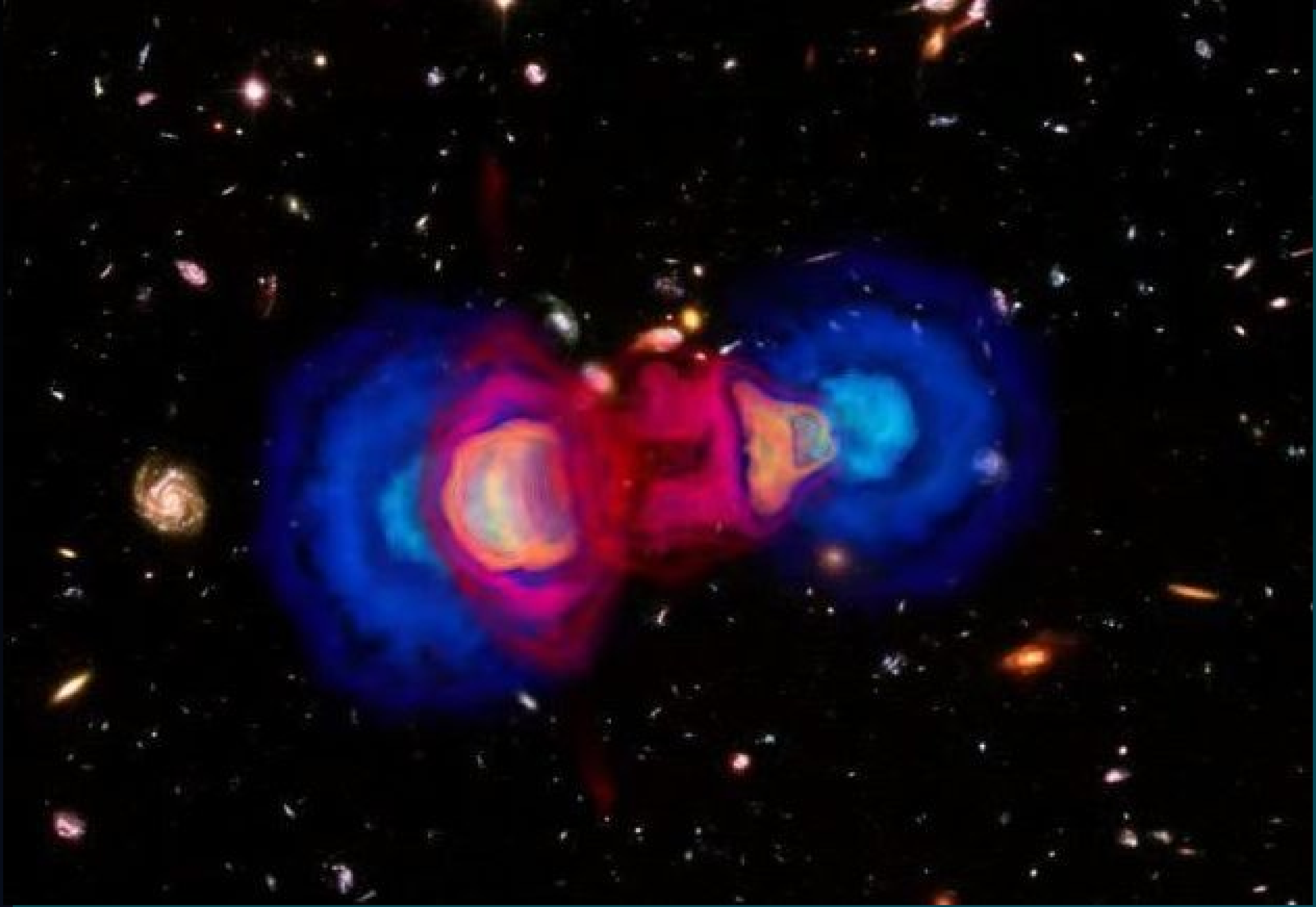


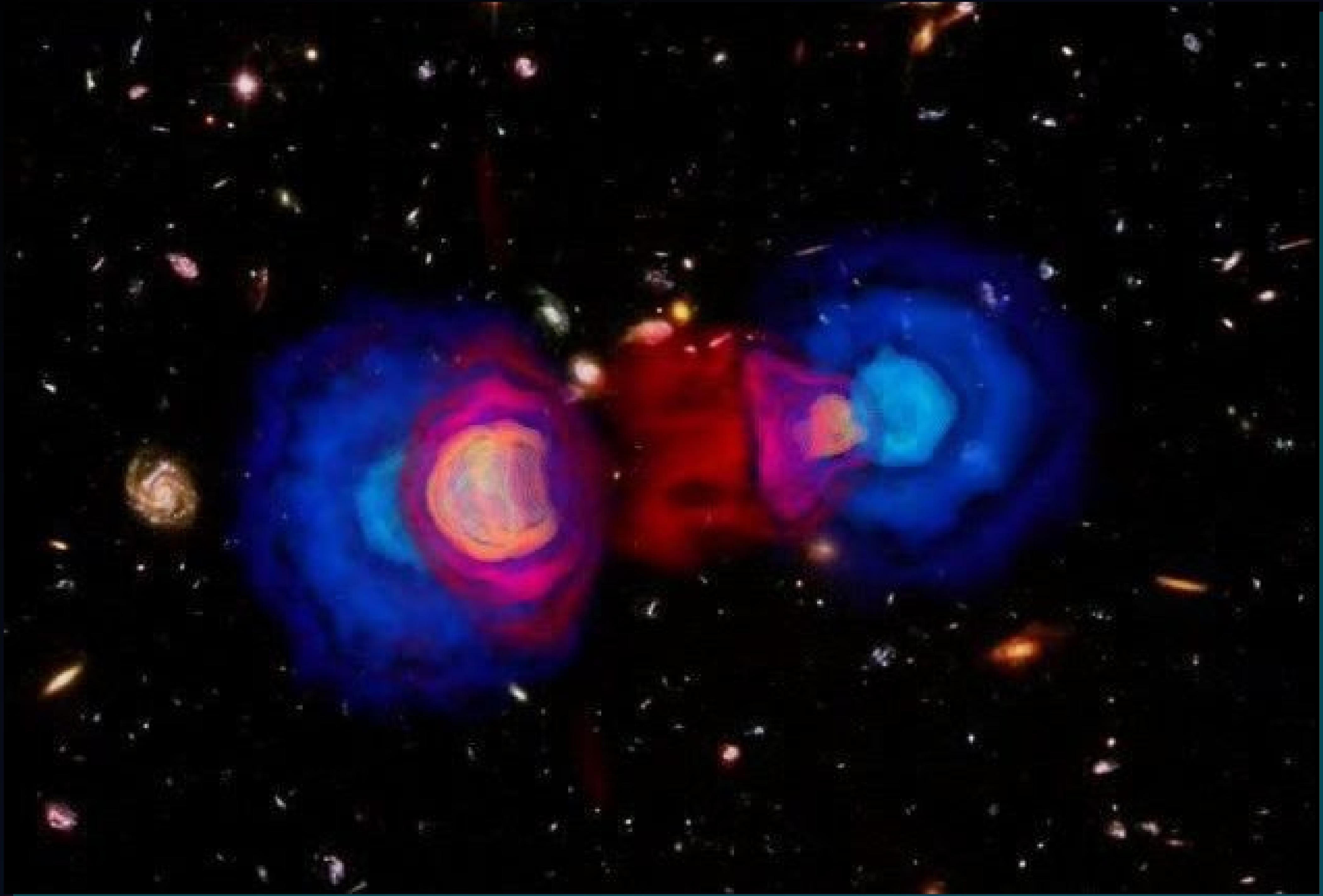












Hard to explain
Without new
collisionless matter

Constrains self-
interactions

2000-2010s:

LARGE SCALE STRUCTURE

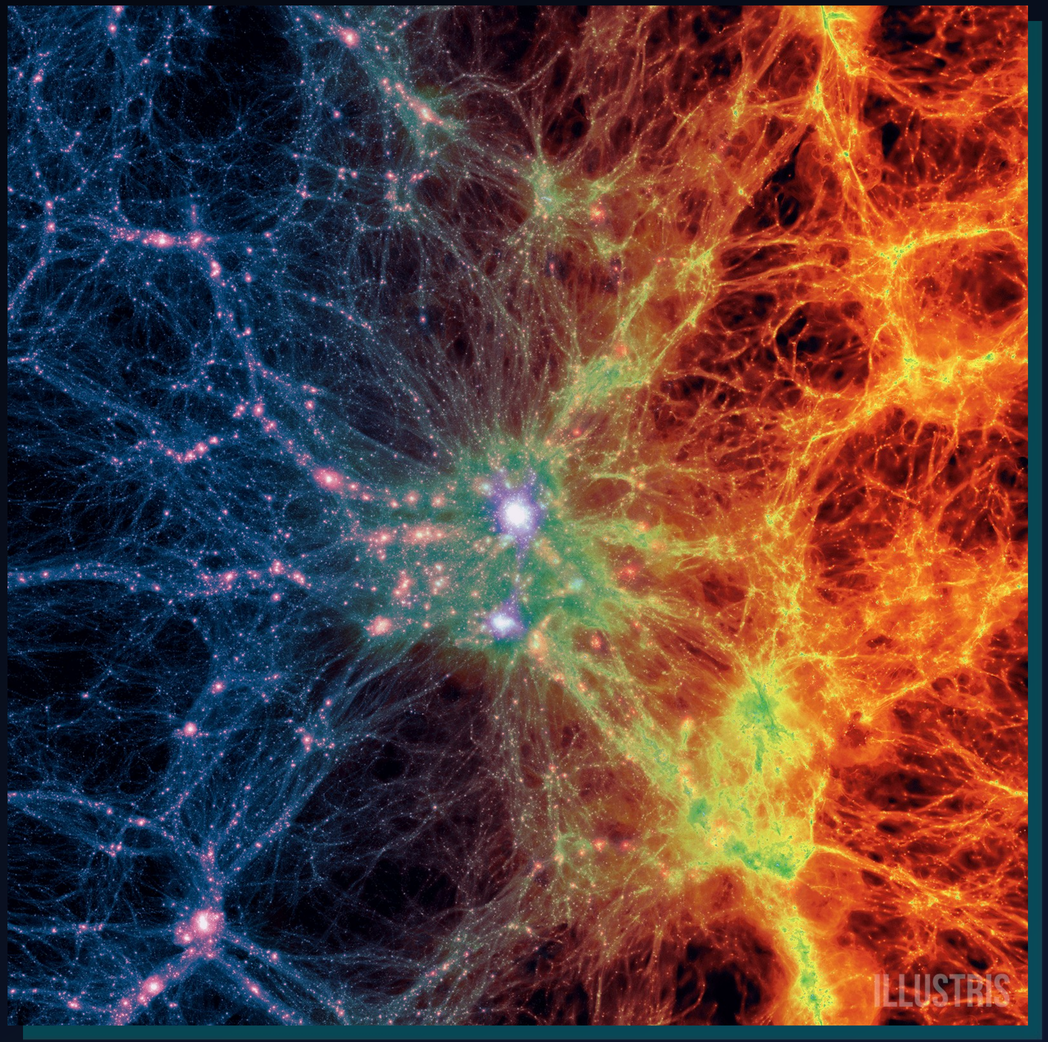
Rebecca Leane

Evidence from Large Scale Structure

- Evolution of the Universe seeded by anisotropies of CMB: gives initial conditions for cosmic structure formation

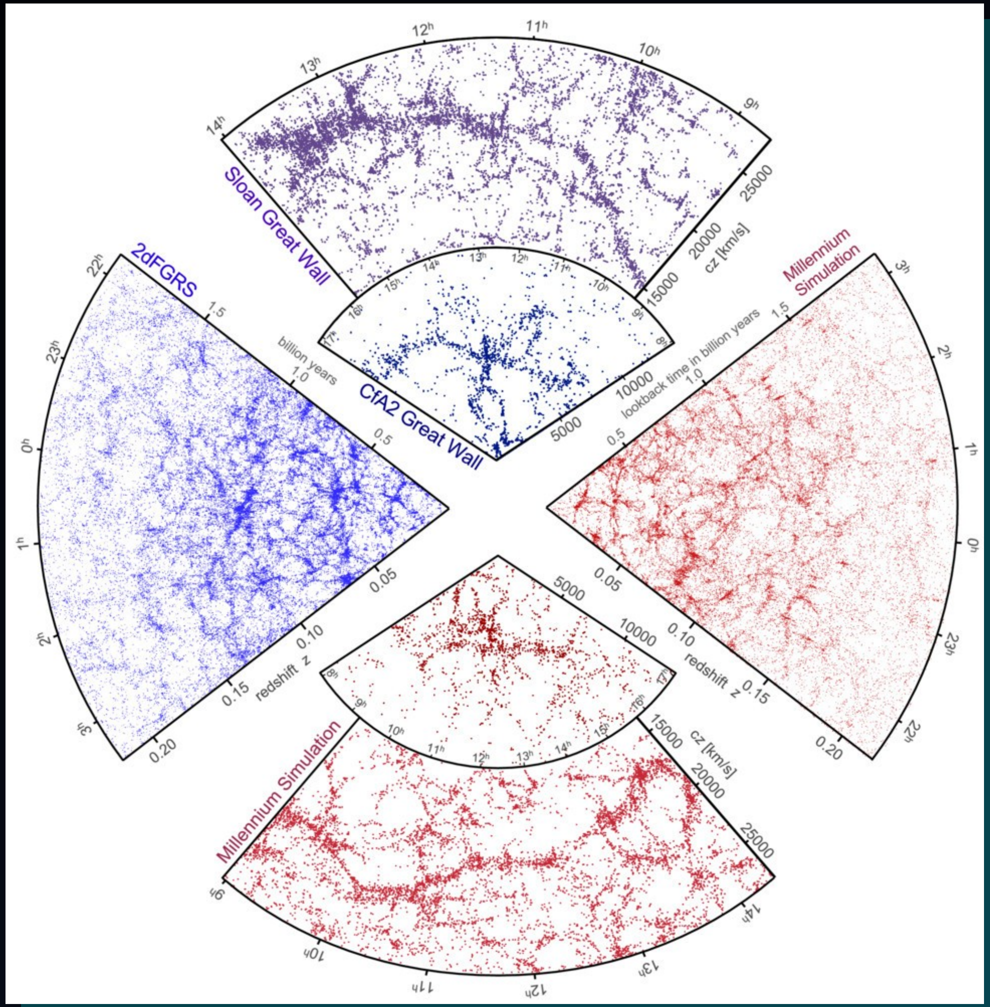
- After the photons decouple from the baryons, overdensities continue to grow under gravity

- Eventually collapse into virialized structures; backbone of cosmic structure

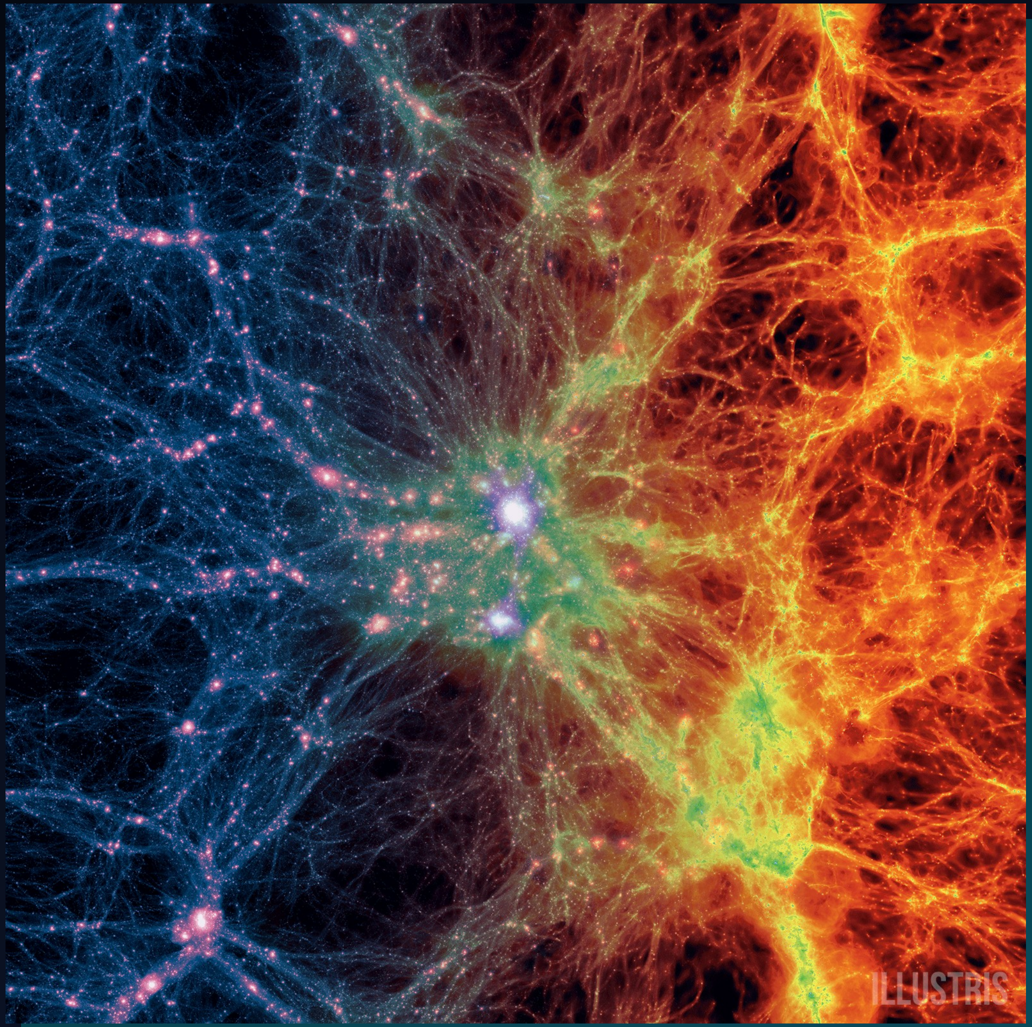


Illustris Simulation

Evidence from Large Scale Structure



Millenium Simulation, Frenk & White 2012



Illustris Simulation

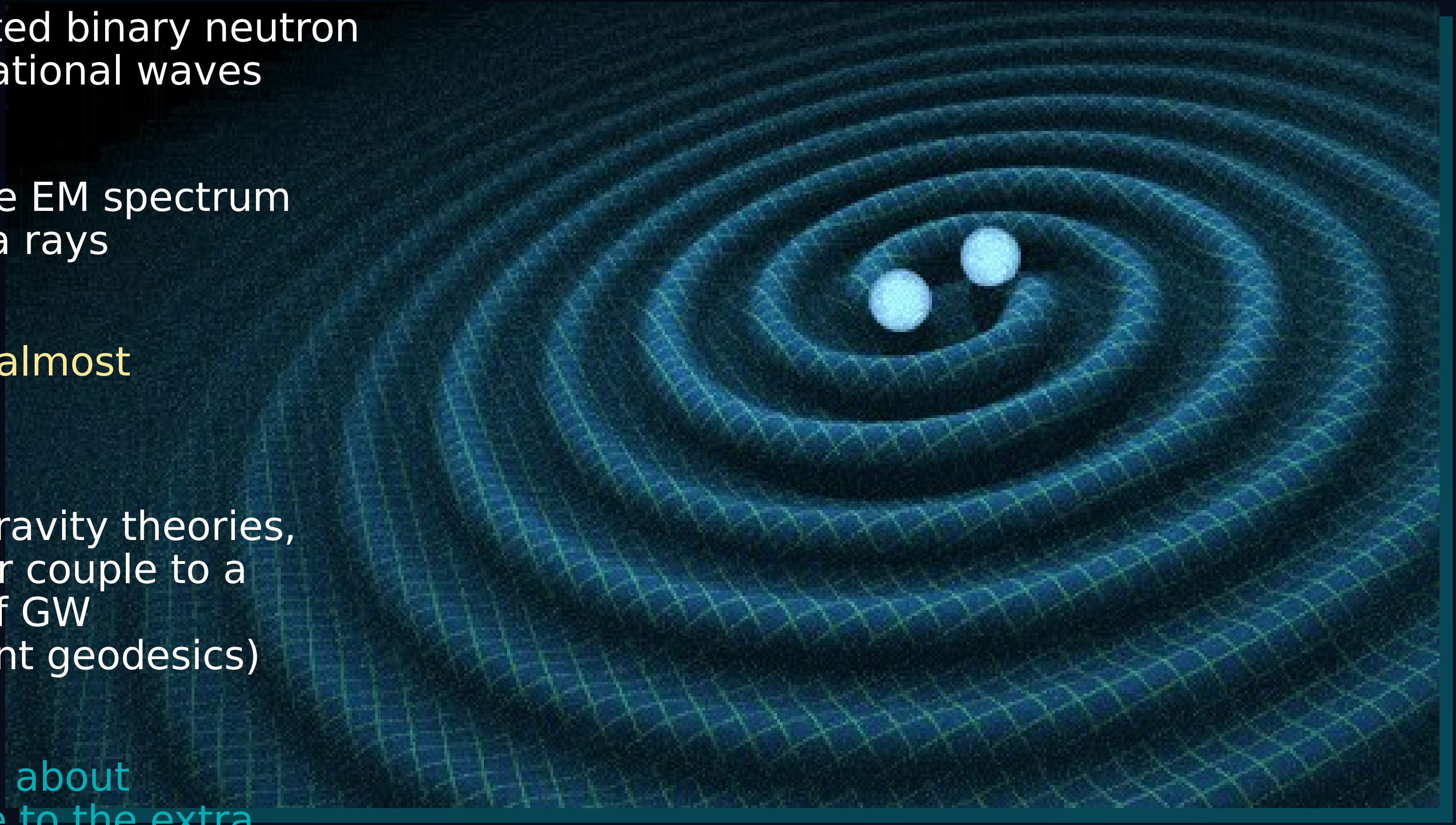
2018:

GRAVITATIONAL WAVES

Rebecca Leane

Gravitational Waves

- In 2017, LIGO/VIRGO detected binary neutron star merger event in gravitational waves
- Merger was measured in the EM spectrum from radio waves to gamma rays
- GW and EM signals arrived almost simulaneously
- There is class of modified gravity theories, which make ordinary matter couple to a different metric from that of GW (light and GW follow different geodesics)
- Photons would have arrived about 400 days after the GWs due to the extra Shapiro delay w/ MOND, so ruled out

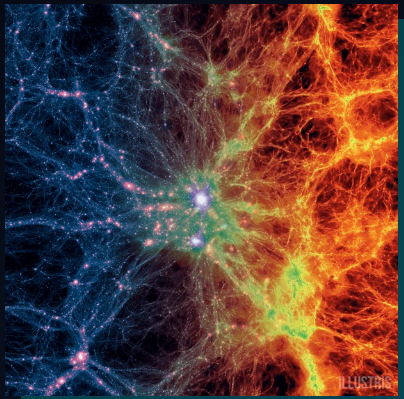


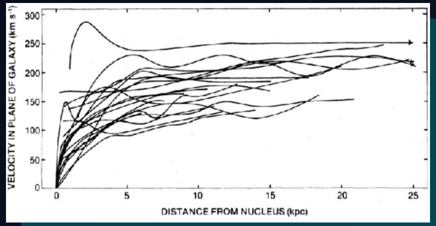
Boran et al 2018

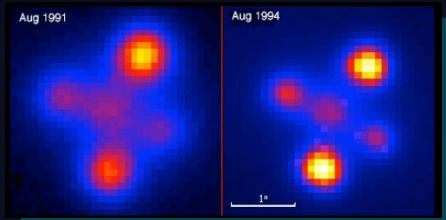
Overwhelming evidence!

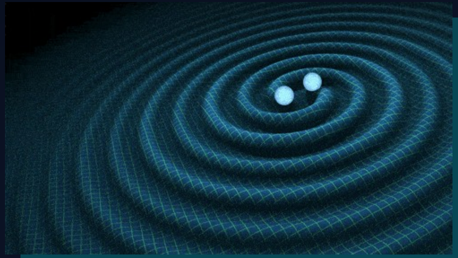
- Includes:
  - Cluster velocities
  - Rotation curves
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis
  - Weak and Strong Lensing
  - Quasar Microlensing
  - Galaxy mergers
  - Large scale structure
  - Gravitational Waves

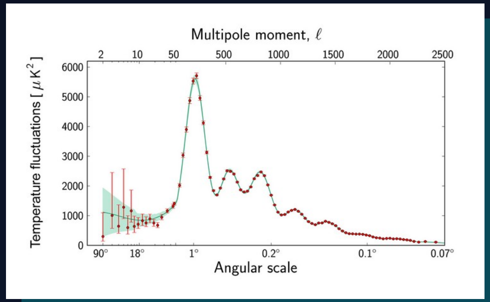
This picture of evidence tells us what dark matter can / can’t be





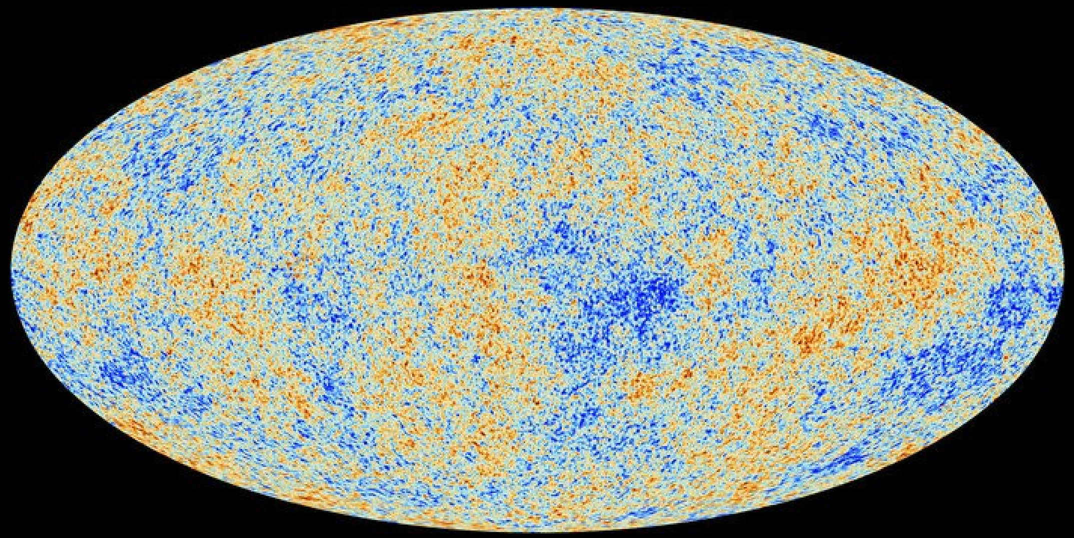






What we know about Dark Matter

- Makes up about 85% of matter in the Universe (~5x more mass than SM)
- Doesn’t interact too much with light (or itself)



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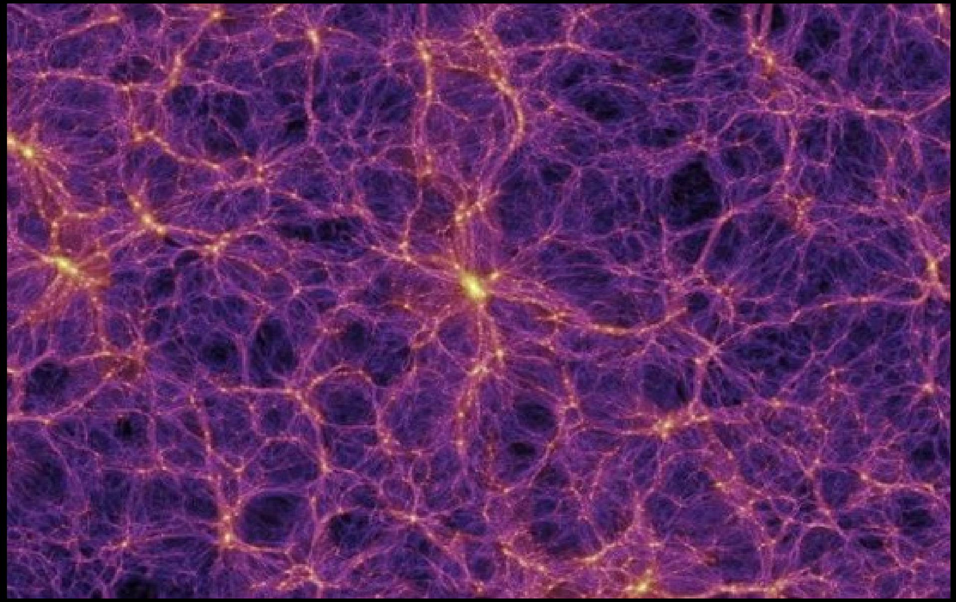

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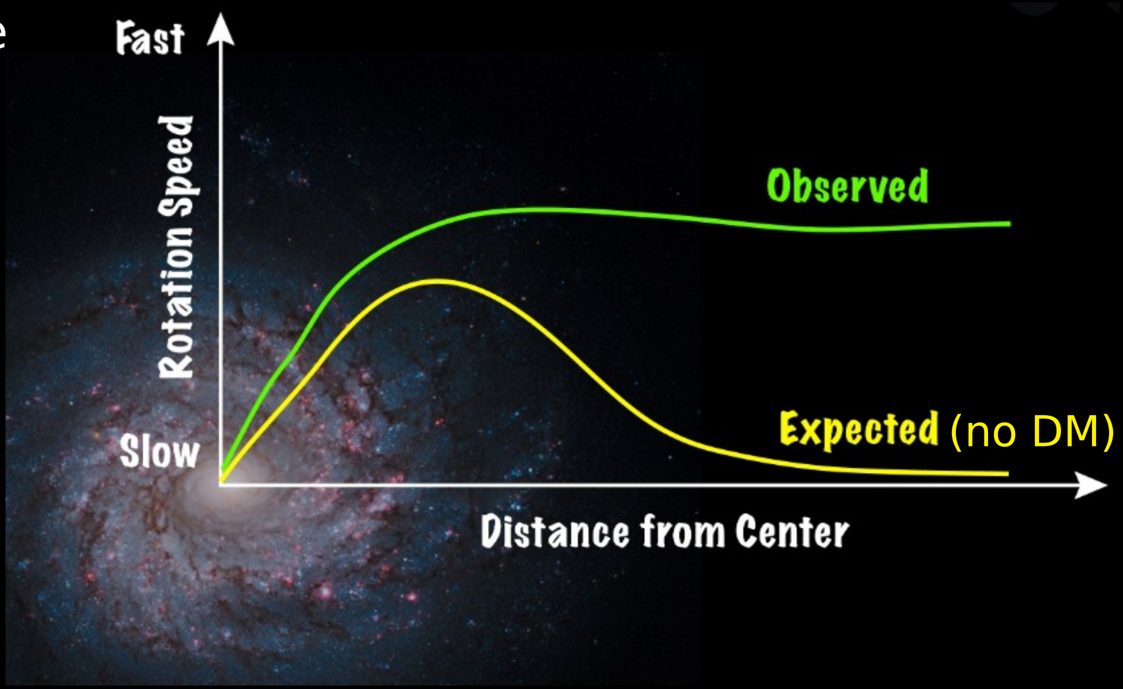
- Forms halos around Galaxies
- Stable on cosmological timescales



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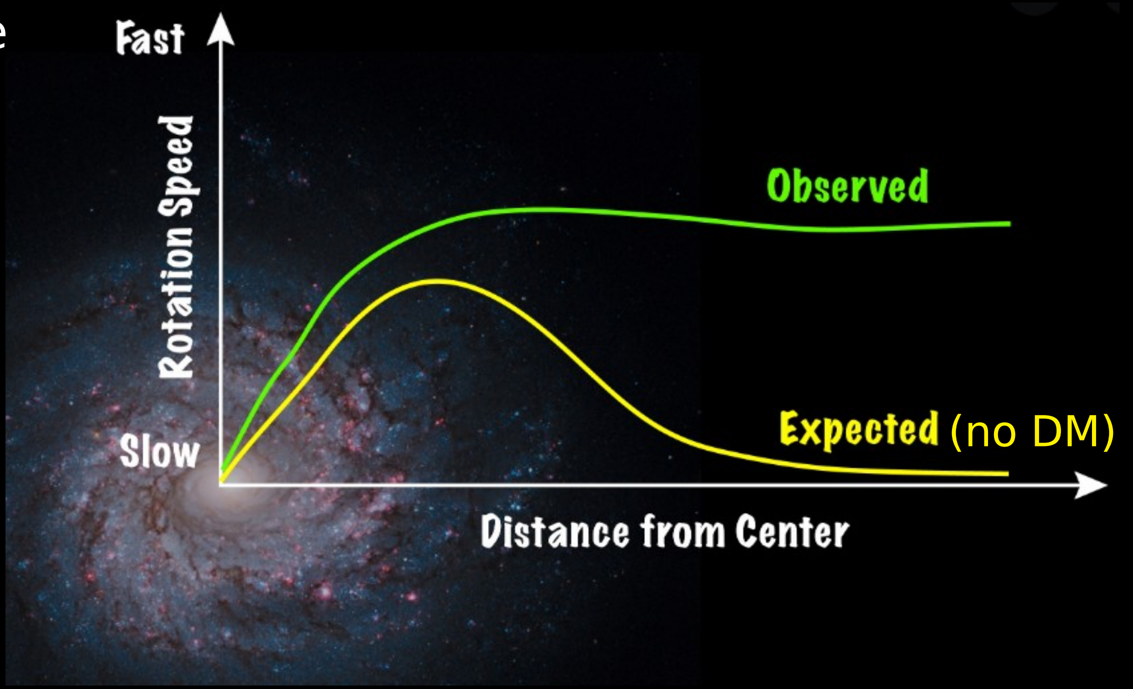
- Doesn't interact too much with light (or itself)
- Provides large scale structure of the Universe
- Structure tells us non-relativistic
- Forms halos around Galaxies
- Stable on cosmological timescales



Cannot be explained by any known particles!

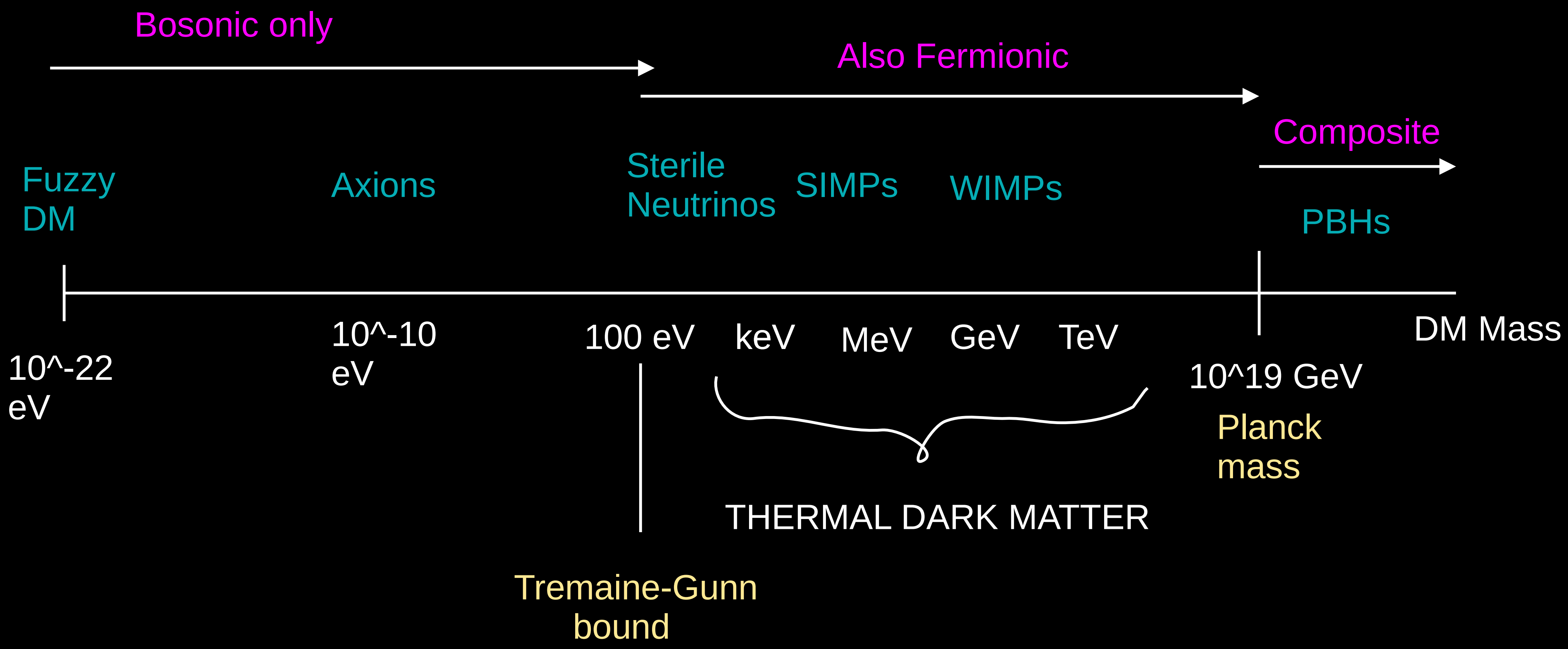
What we *don't* know about Dark Matter

What is it made of?

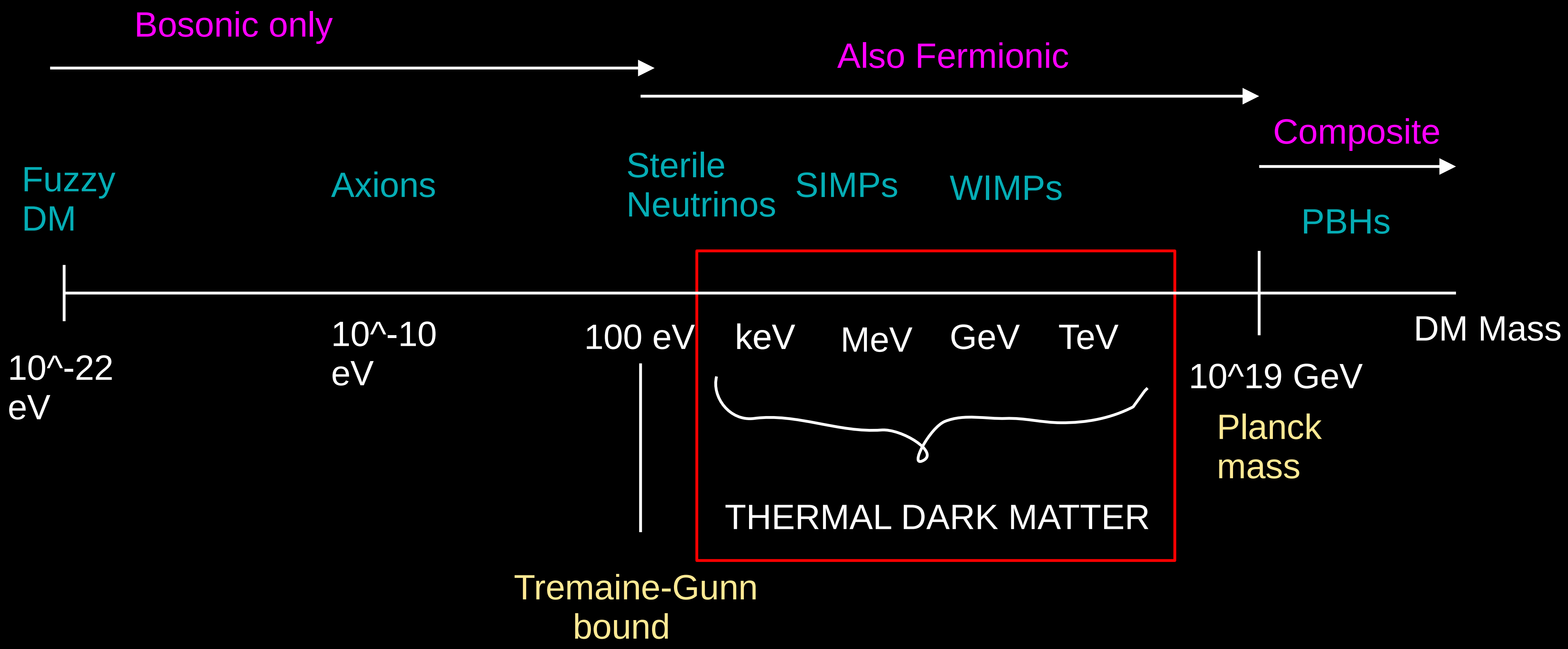
Where did it come from?

Does it interact with regular matter?

The Theory Space

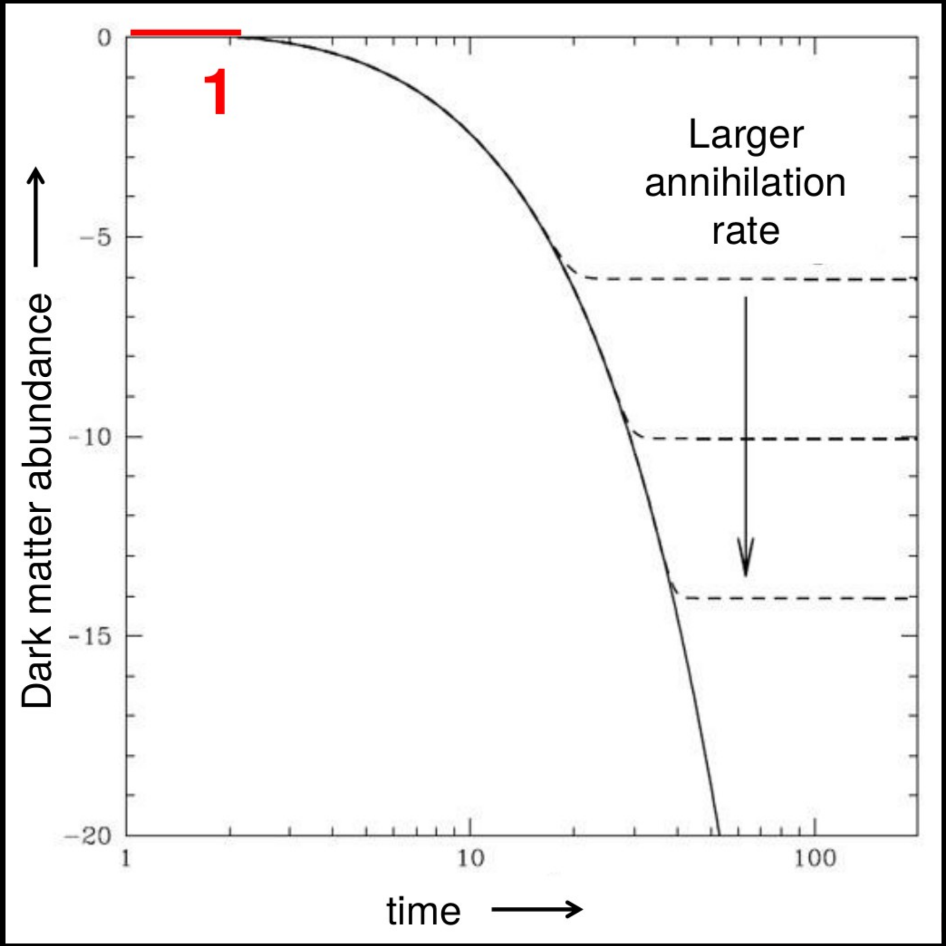


The Theory Space



Dark Matter Abundance: WIMPs

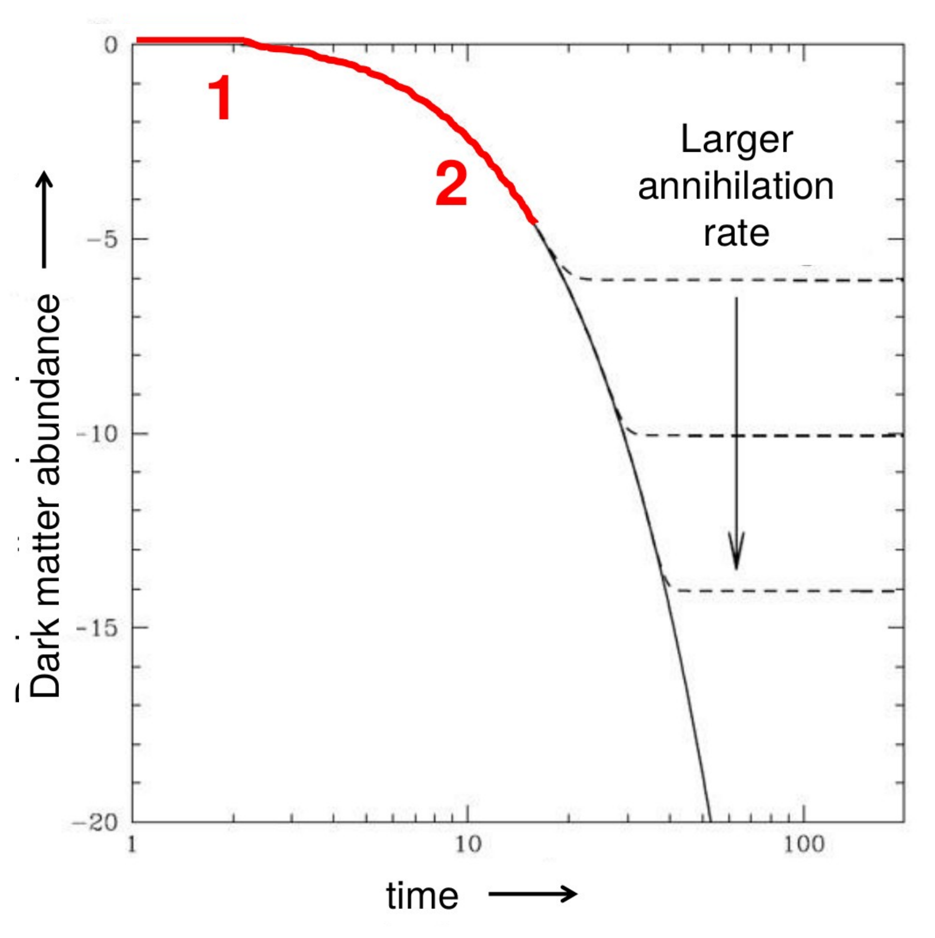
1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM



Dark Matter Abundance: WIMPs

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

2) Universe cools, only
DM + DM ⇒ visible particles

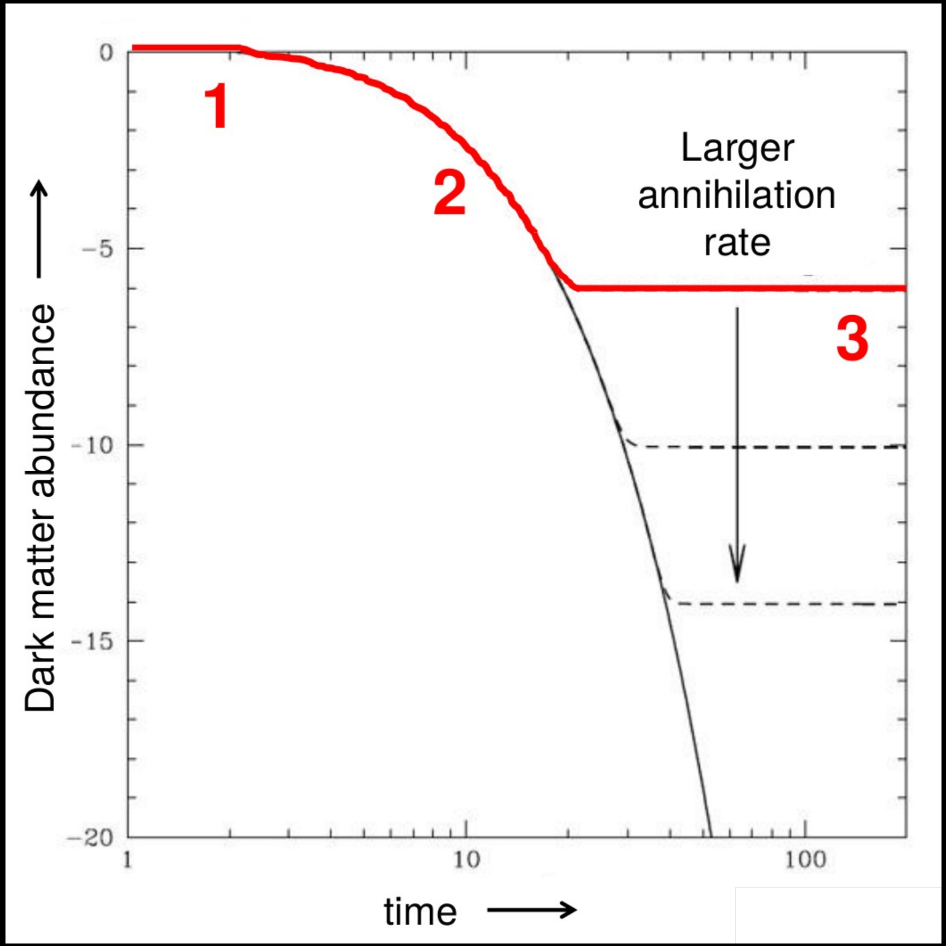


Dark Matter Abundance: WIMPs

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

2) Universe cools, only
DM + DM ⇒ visible particles

3) Universe expands too fast.
No more annihilations.
DM abundance is set.



Predicts a particular annihilation rate for dark matter.

Dark Matter Abundance: WIMPs

The evolution of the DM densty between annihilation, production, and expansion of the Universe is described by the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$

Can solve this for “n”, and compare the cross section predictions for the correct relic abundance of DM

Dark Matter Abundance: WIMPs

Can write the DM contribution to the matter density as

$$\Omega_\chi h^2 \approx 0.1 \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

From WMAP and Planck, DM contribution to matter is

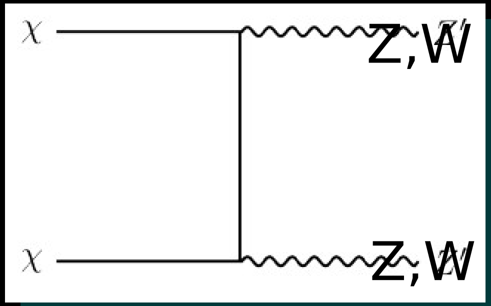
$$\Omega_\chi h^2 \approx 0.12$$

Therefore we need roughly alpha~0.01, mDM~100 GeV, to get correct relic abundance of DM.

This is right at the weak scale! → “WIMP miracle”

Dark Matter Abundance: WIMPs

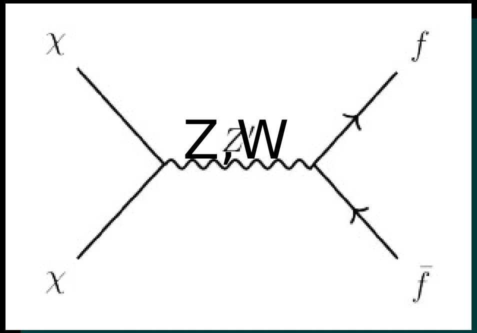
Case where DM mass > W,Z mass:



$$\langle \sigma v \rangle \sim \frac{\alpha_w^2}{m_\chi^2}$$

$$= 1 \text{ pb} \left(\frac{\alpha_w}{1/30} \right)^2 \left(\frac{\text{TeV}}{m_\chi} \right)^2$$

Case where DM mass < W,Z mass:



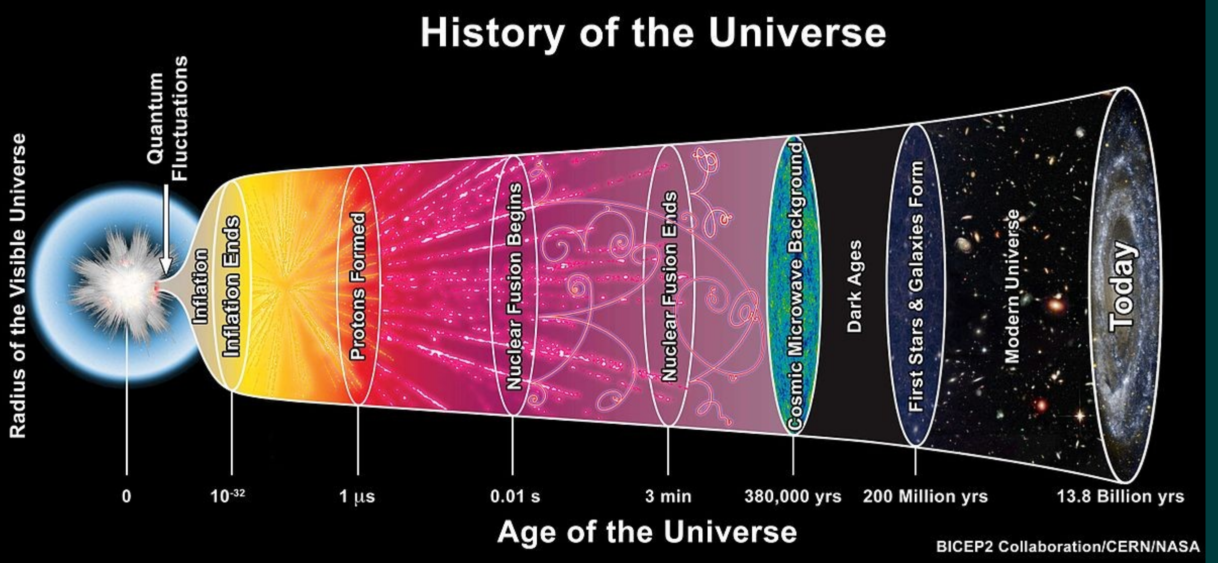
$$\langle \sigma v \rangle \sim 1 \text{ pb} \left(\frac{m_\chi}{5 \text{ GeV}} \right)^2$$

Lee-Weinberg bound is DM mass > about 2 GeV for WIMPs.

Experimentally, this simple picture is fairly ruled out.

Uncertainties for the early Universe?

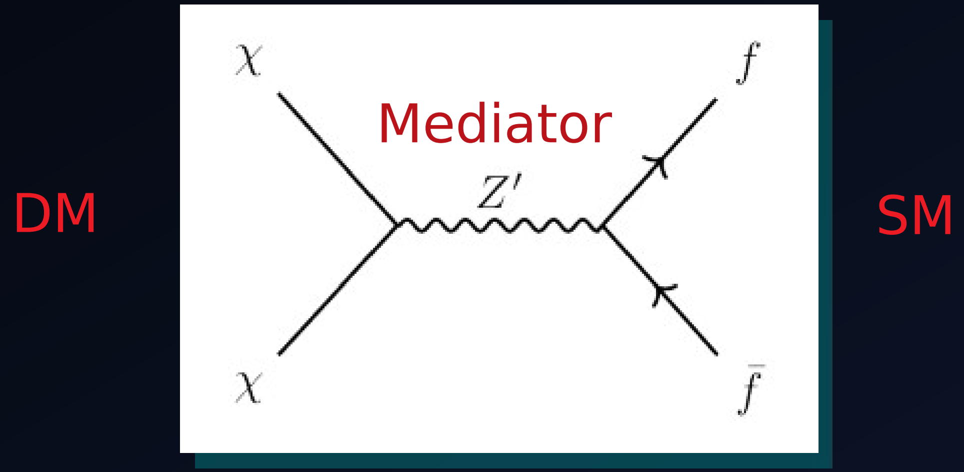
- WIMP freezes out before BBN and CMB
  - A lot could happen between these times!
- Some particle could decay into DM
- Some particle could decay into visible matter, diluting the original amount of DM



- Maybe physics was just different to what we expect! Hard to know.
  - Finding DM may give us a new window further back into the Universe

Dark Sectors

- Standard Model (SM) mediated WIMP processes, e.g. with Z bosons, extremely constrained
- Need new fields beyond the SM!
- These can mediate interactions between the dark sector, and the SM



Dark Sectors

- Need new fields beyond the SM, consider extensions:
  - New scalar, pseudoscalar, fermion, or vector
- Symmetries of SM restrict how these fields interact with the SM

$$-\lambda_{HS}(S^\dagger S)(H^\dagger H)$$ Higgs Portal

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$ Axion Portal

$$-\frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu}$$ Hypercharge Portal

$$y_n L H N$$ Fermion Portal

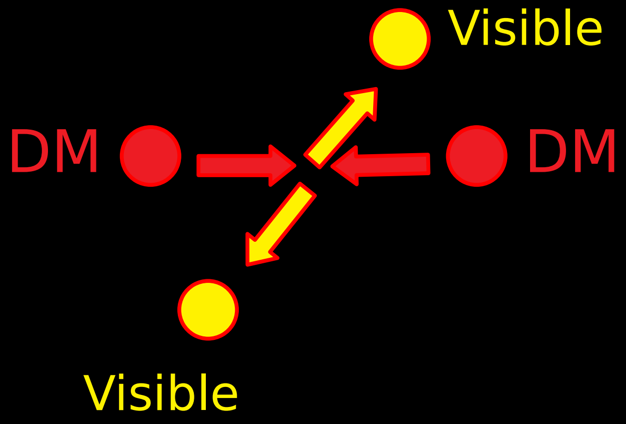
Generally easiest to parameterize searches by generic masses and couplings

WIMP Dark Matter Search Program

Annihilation

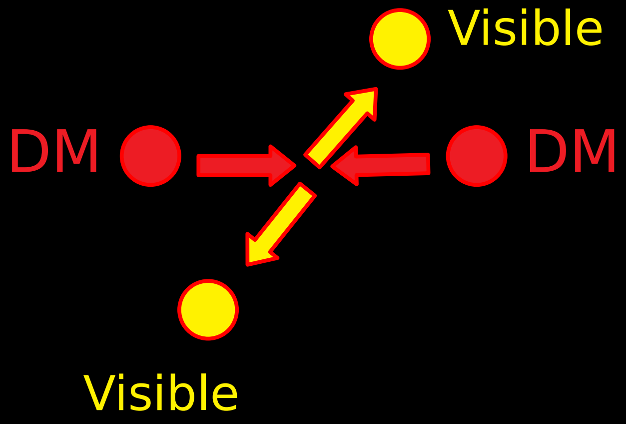
Scattering

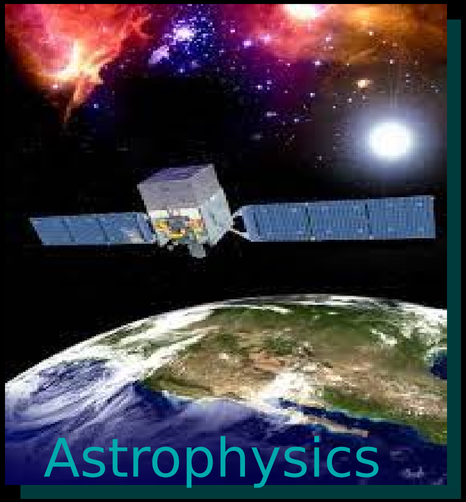
Production



WIMP Dark Matter Search Program

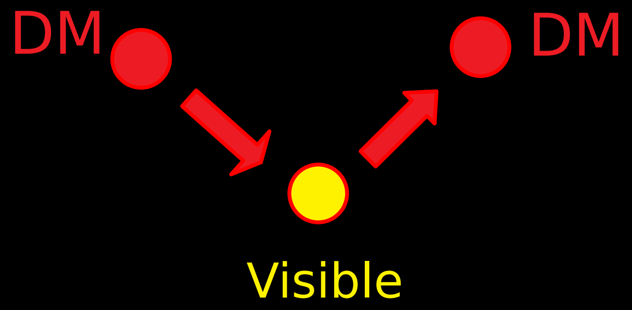
Annihilation





Astrophysics

Scattering

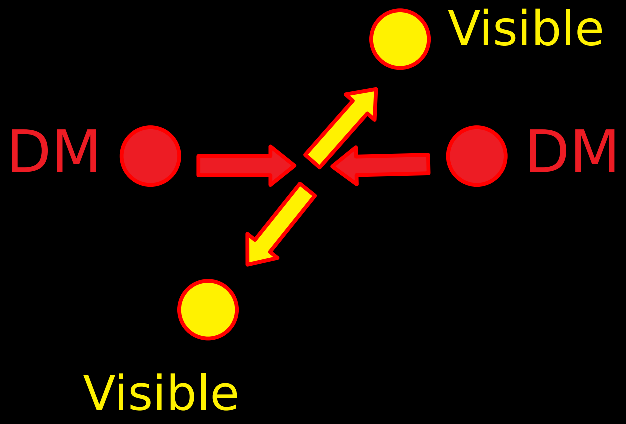


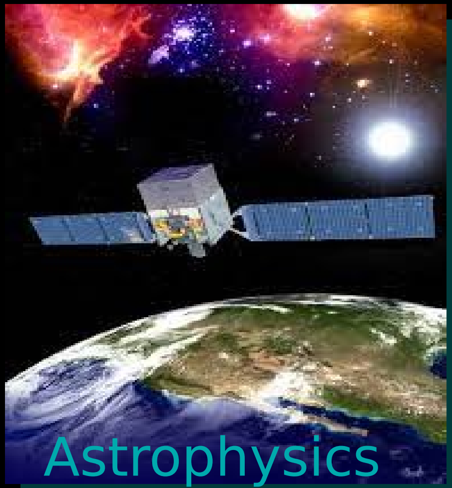
Direct detection
+ Astrophysics

Production

WIMP Dark Matter Search Program

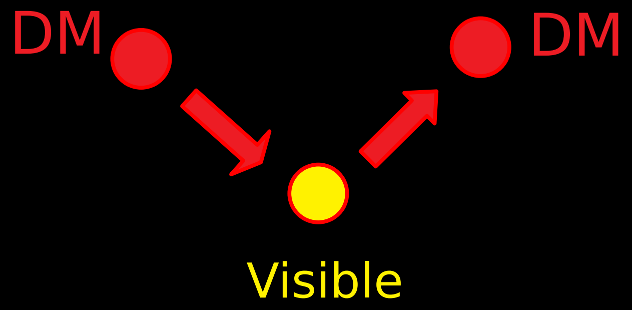
Annihilation





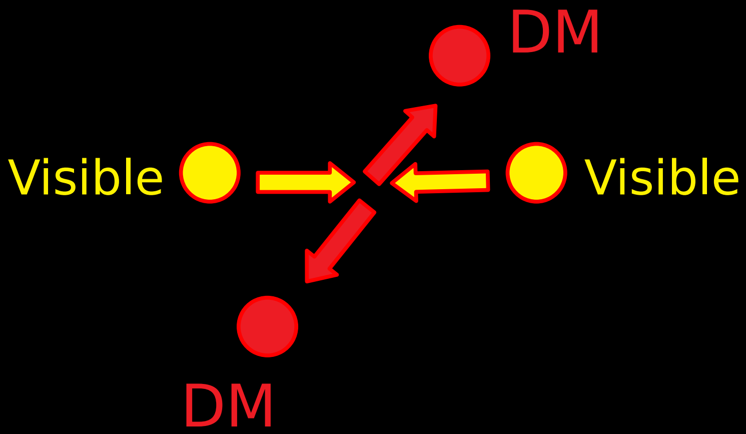
Astrophysics

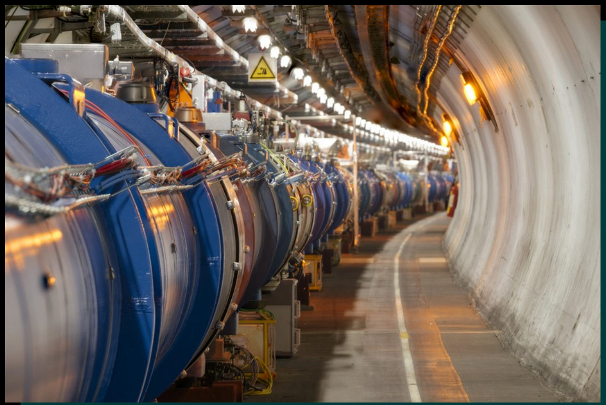
Scattering



Direct detection
+ Astrophysics

Production



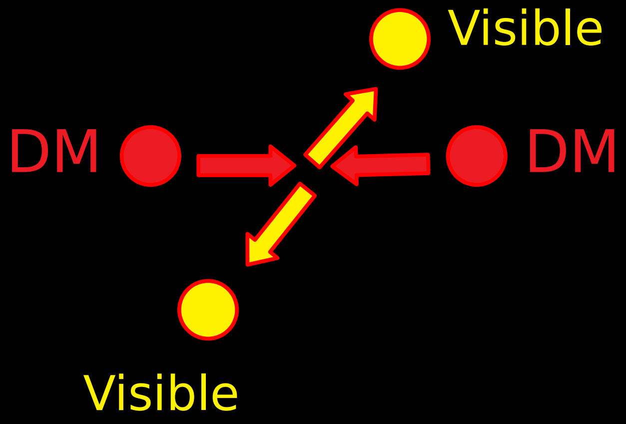


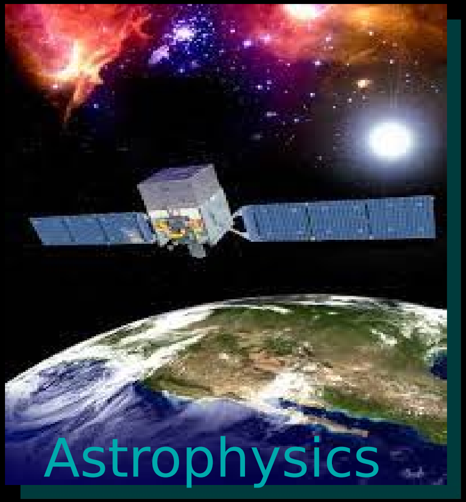
Colliders
+ Astrophysics

WIMP Dark Matter Search Program

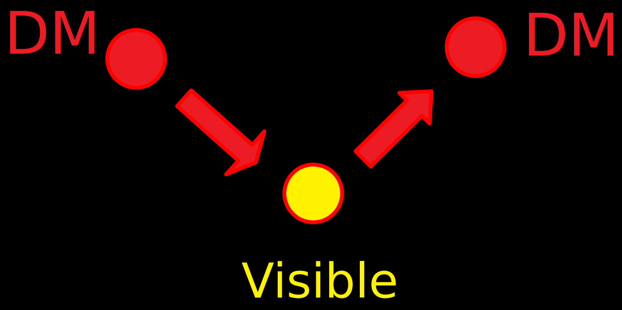
M.E. Mozani's lecture next

Annihilation



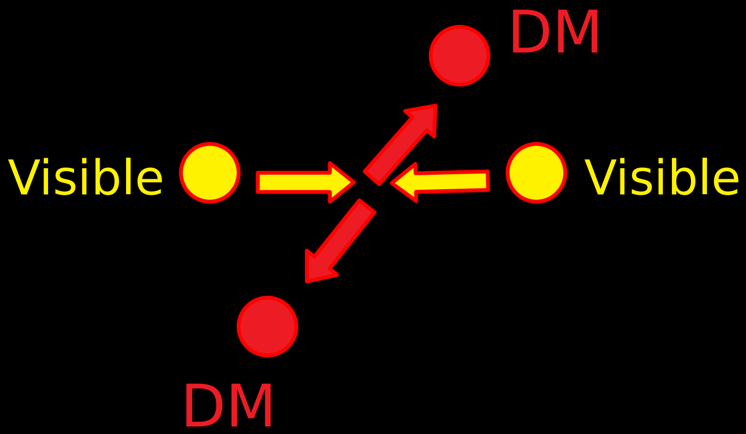


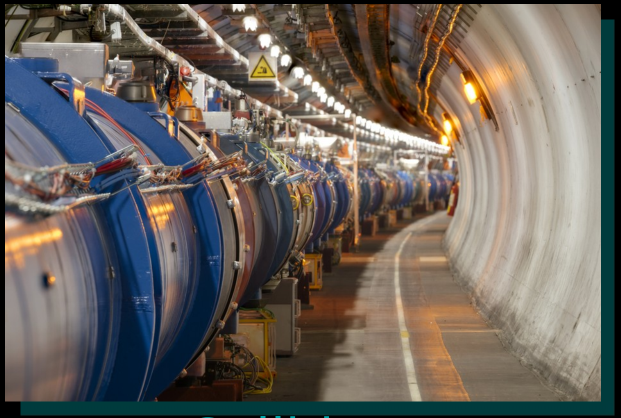
Scattering



Direct detection
+ Astrophysics

Production





Colliders
+ Astrophysics

Summary

- Dark matter exists! Diverse range of evidence across many length scales
  - Finding its nature is a key goal of our community
- WIMPs are a popular candidate, can be produced through freeze-out mechanism in the early Universe, provide right DM abundance with weak-scale interactions
  - Need richer dark sector than just one DM particle
- Next lecture: are WIMPs dead? What other models do people think about? How do we find DM going forward?