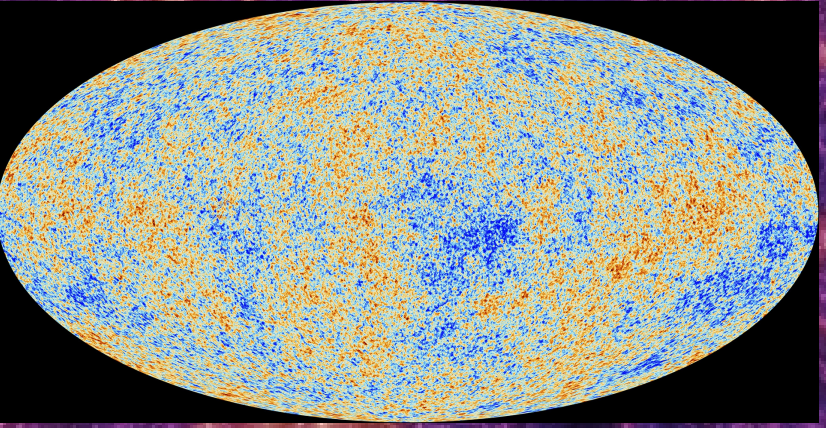
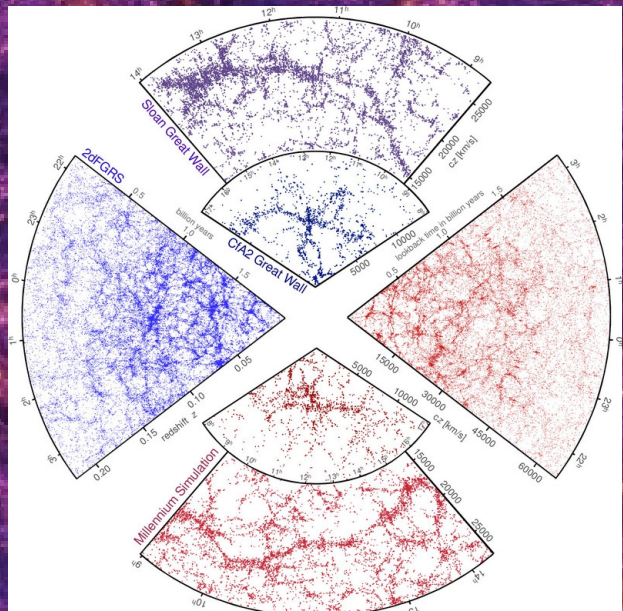


The Shaw Prize Lecture in Astronomy
2017

Computer Reconstruction of Cosmic History

Simon White
Max Planck Institute for Astrophysics



Aristotle

Greece, 384 – 322 B.C.

Student of Plato

Tutor to Alexander the Great

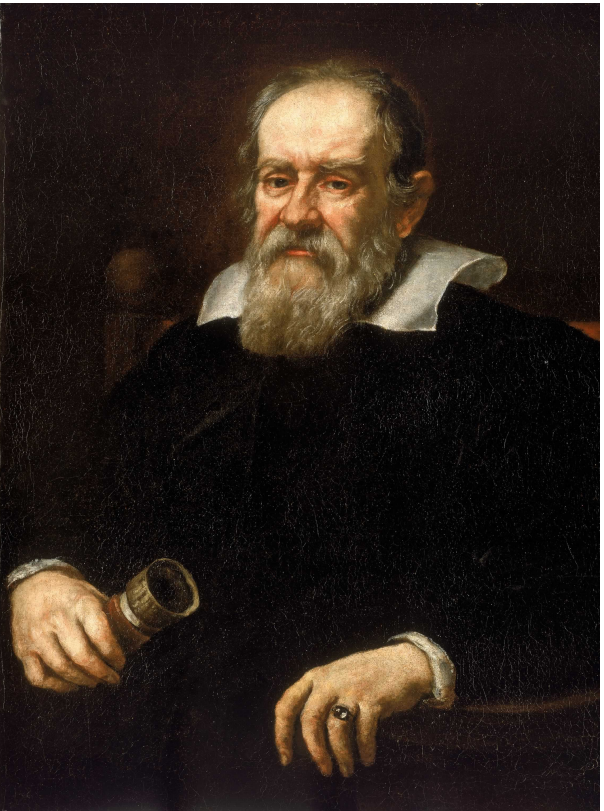
The authoritative scientist in Europe for 1800 years

"The speed at which an object falls is directly proportional to its weight"

Simon Stevin

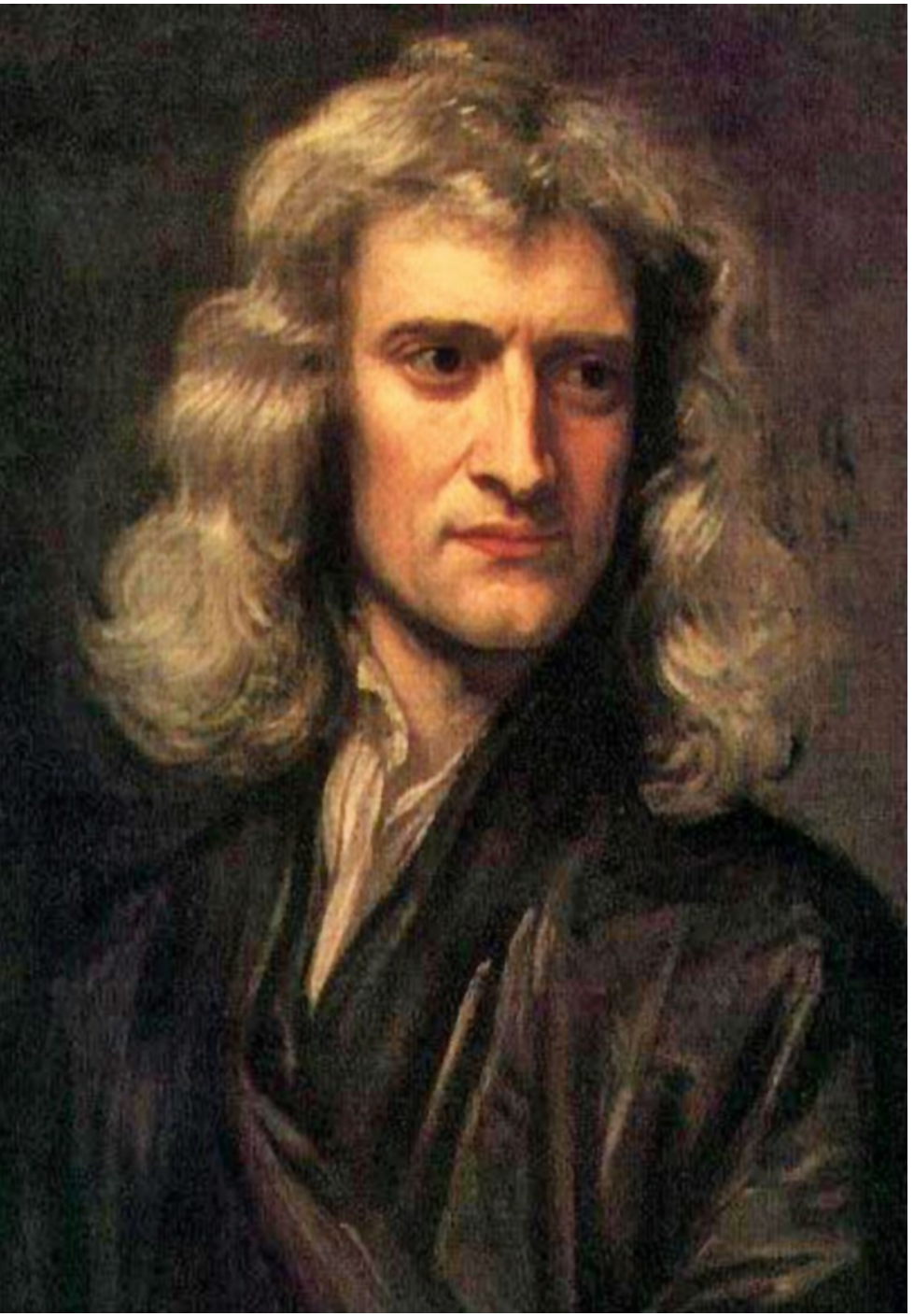
Holland, 1548 – 1620

Experiment shows all objects fall at the same rate



Galileo Galilei

Italy, 1564 – 1642



Isaac Newton

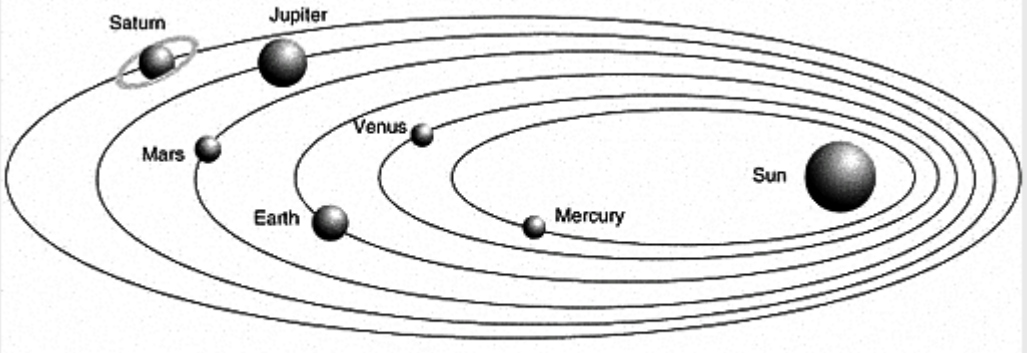
England, 1643 – 1727

$F = m\,a$ Law of Motion

$F_{grav} = G\,m\,M_{\oplus} / R_{\oplus}^{2}$ Law of Gravity

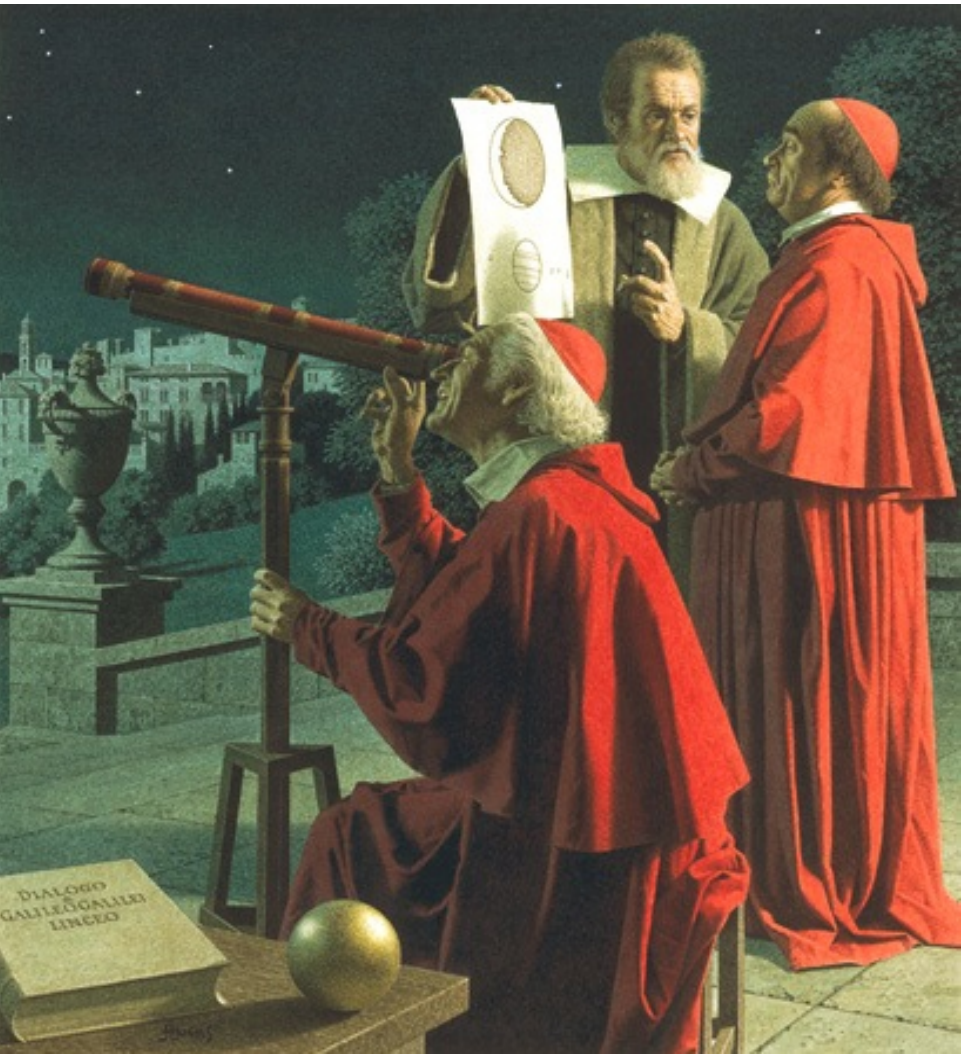
$\rightarrow \quad a_{grav} = G\,M_{\oplus} / R_{\oplus}^{2}$

Mathematics links the motion of the Moon and planets to the falling of objects



Kepler's Laws

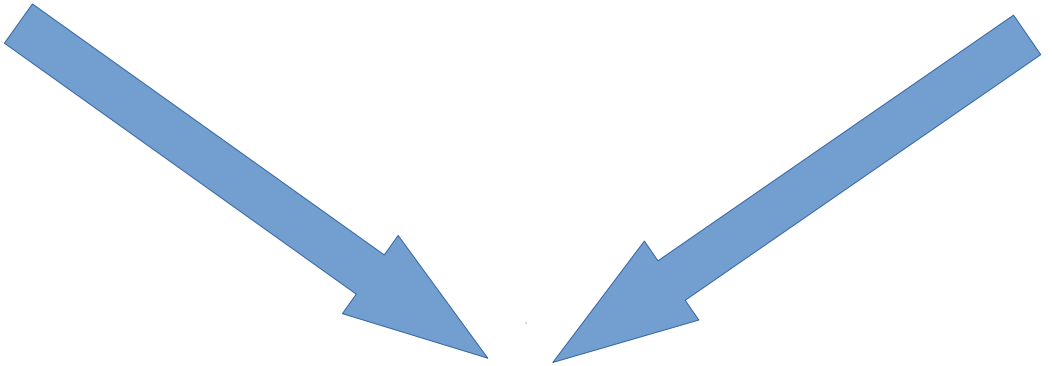
Astronomers cannot experiment with the stars – they can only **observe** them



Galileo using his telescope to show the mountains of the Moon to two cardinals

The scientific route to “Truth”

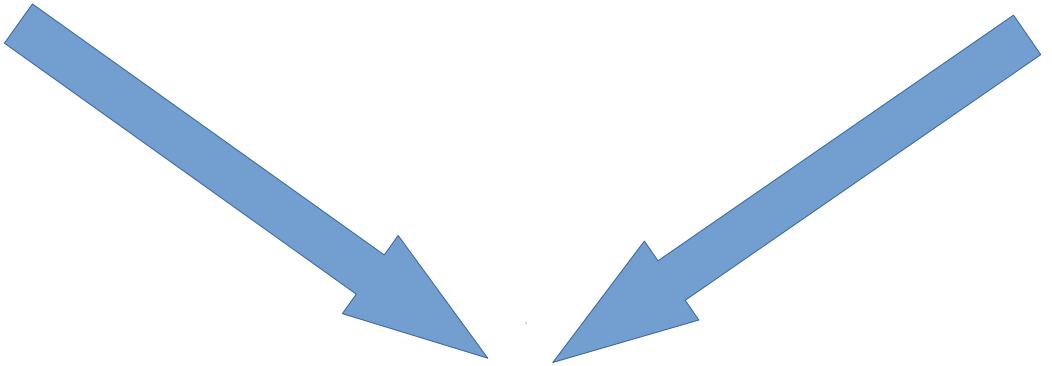
Experiment/Observation ⟷ **Mathematical modelling**



Physical understanding

The scientific route to "Truth"

Experiment/Observation ⟷ **Mathematical modelling**

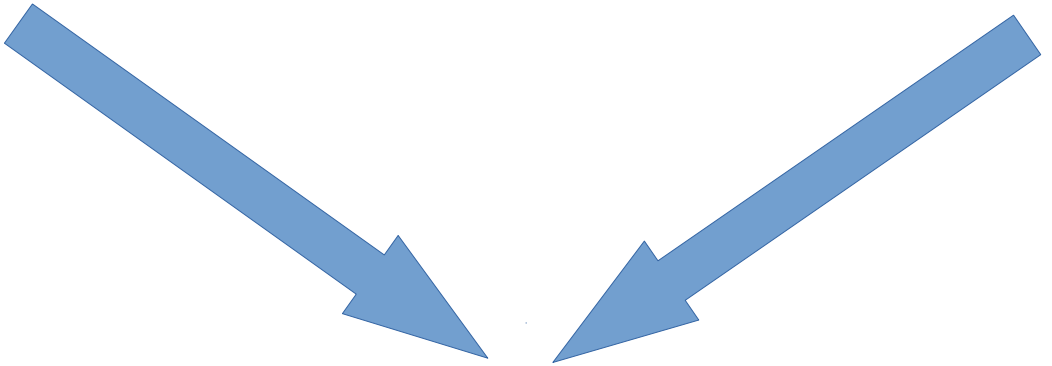


Physical understanding

- *Why* is the physical world describable by mathematical laws?

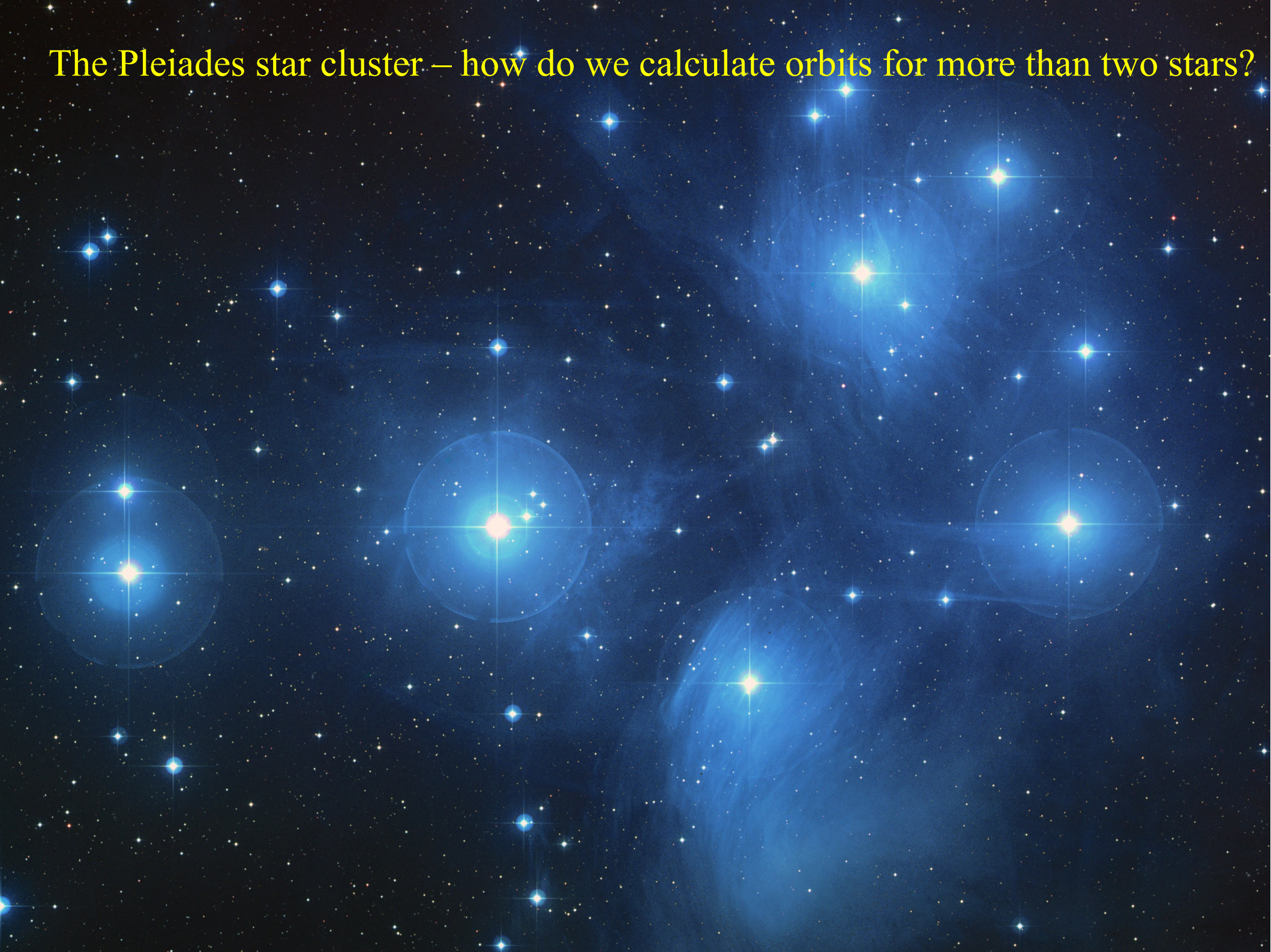
The scientific route to "Truth"

Experiment/Observation ⟷ **Mathematical modelling**



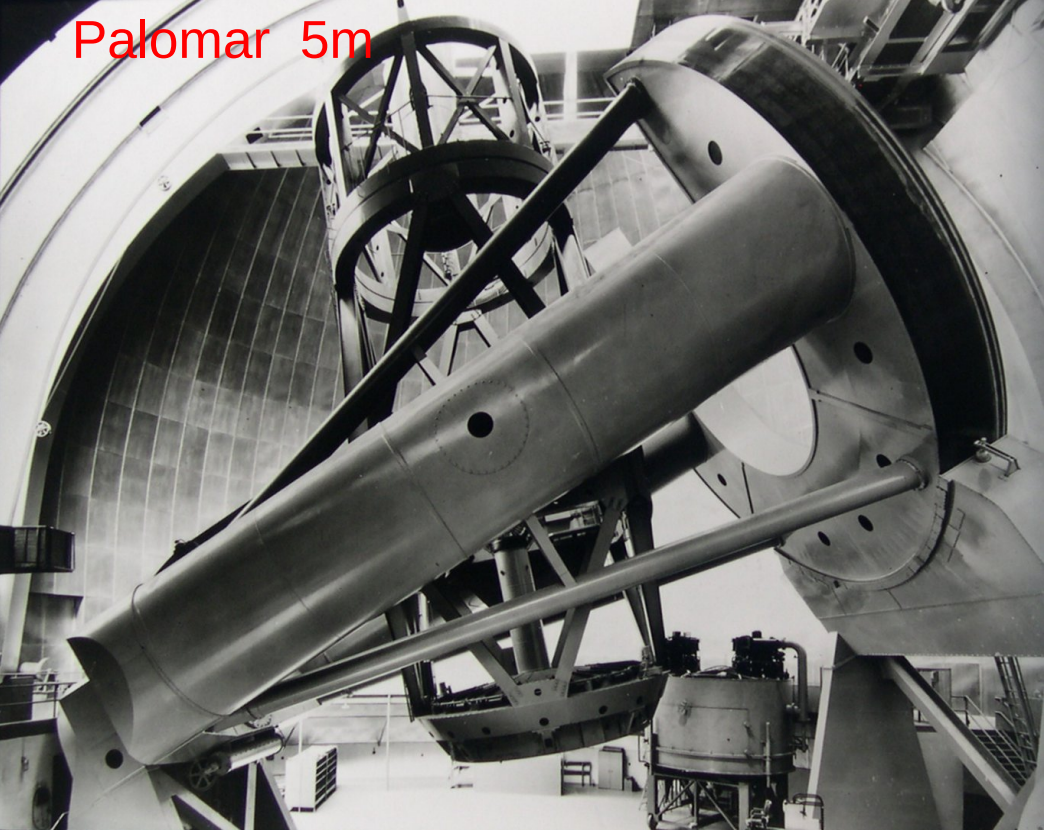
Physical understanding

- *Why* is the physical world describable by mathematical laws?
- Is experiment/observation the only route to understanding new aspects of the behaviour of natural systems?

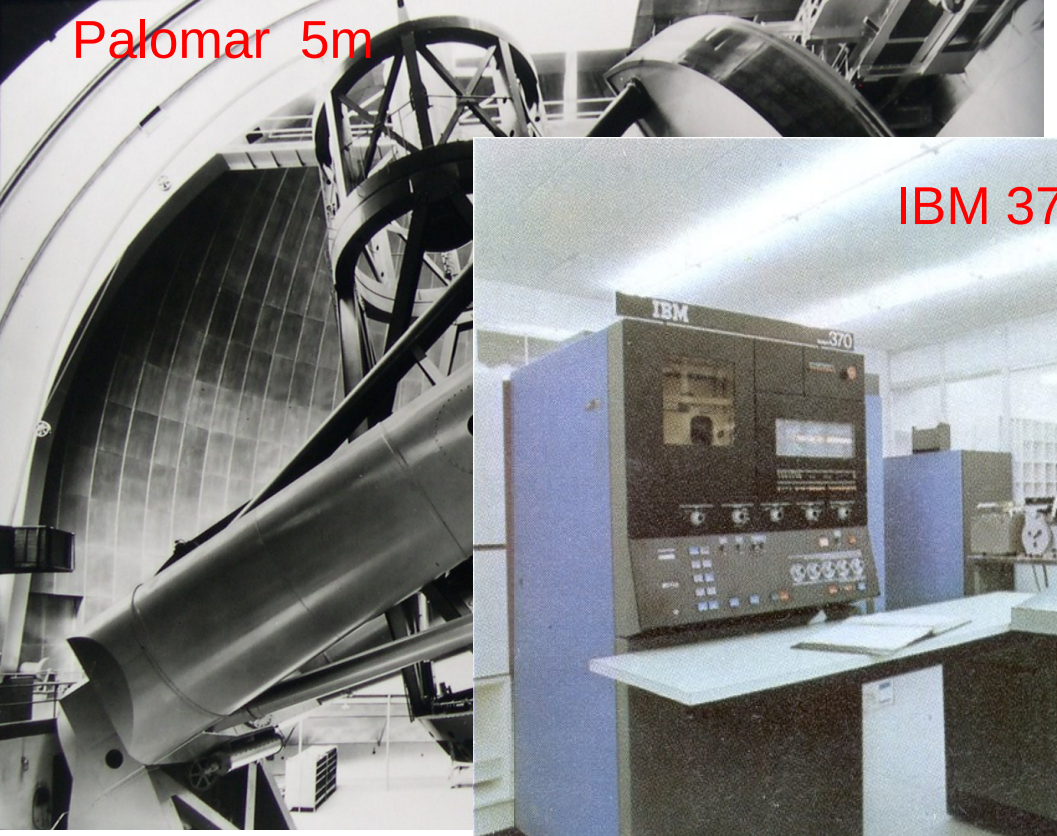

The Pleiades star cluster – how do we calculate orbits for more than two stars?

The Coma galaxy cluster – mostly unseen “dark matter” ?

Zwicky 1933

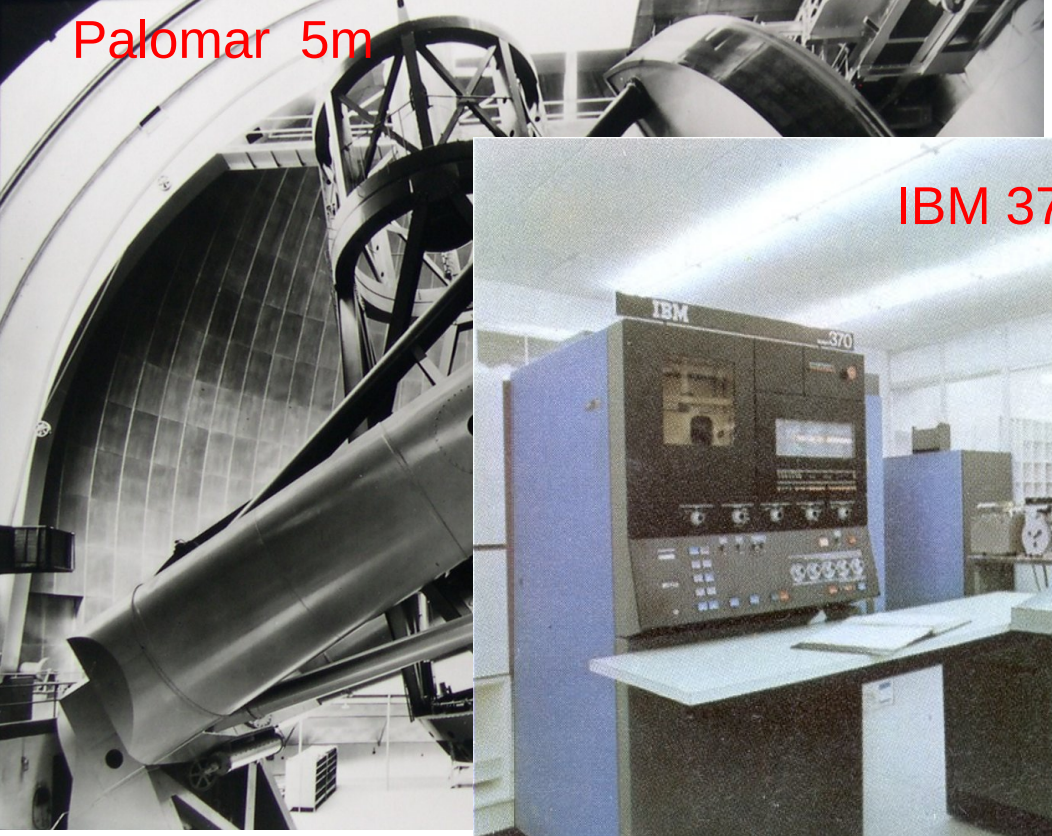

Palomar 5m

Palomar 5m



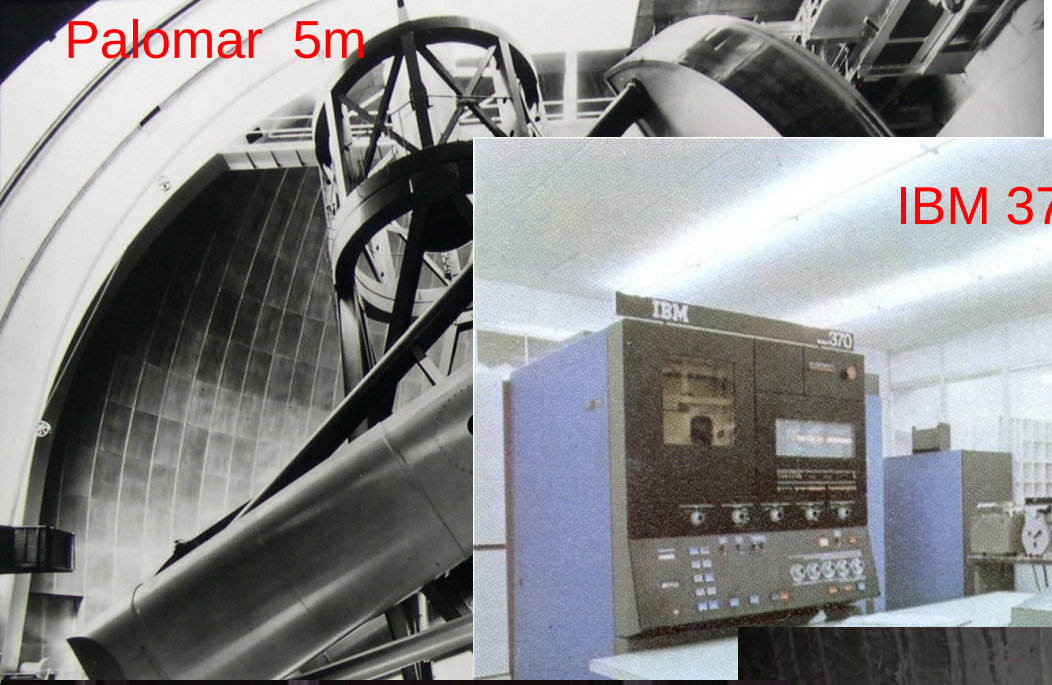
IBM 370

Palomar 5m



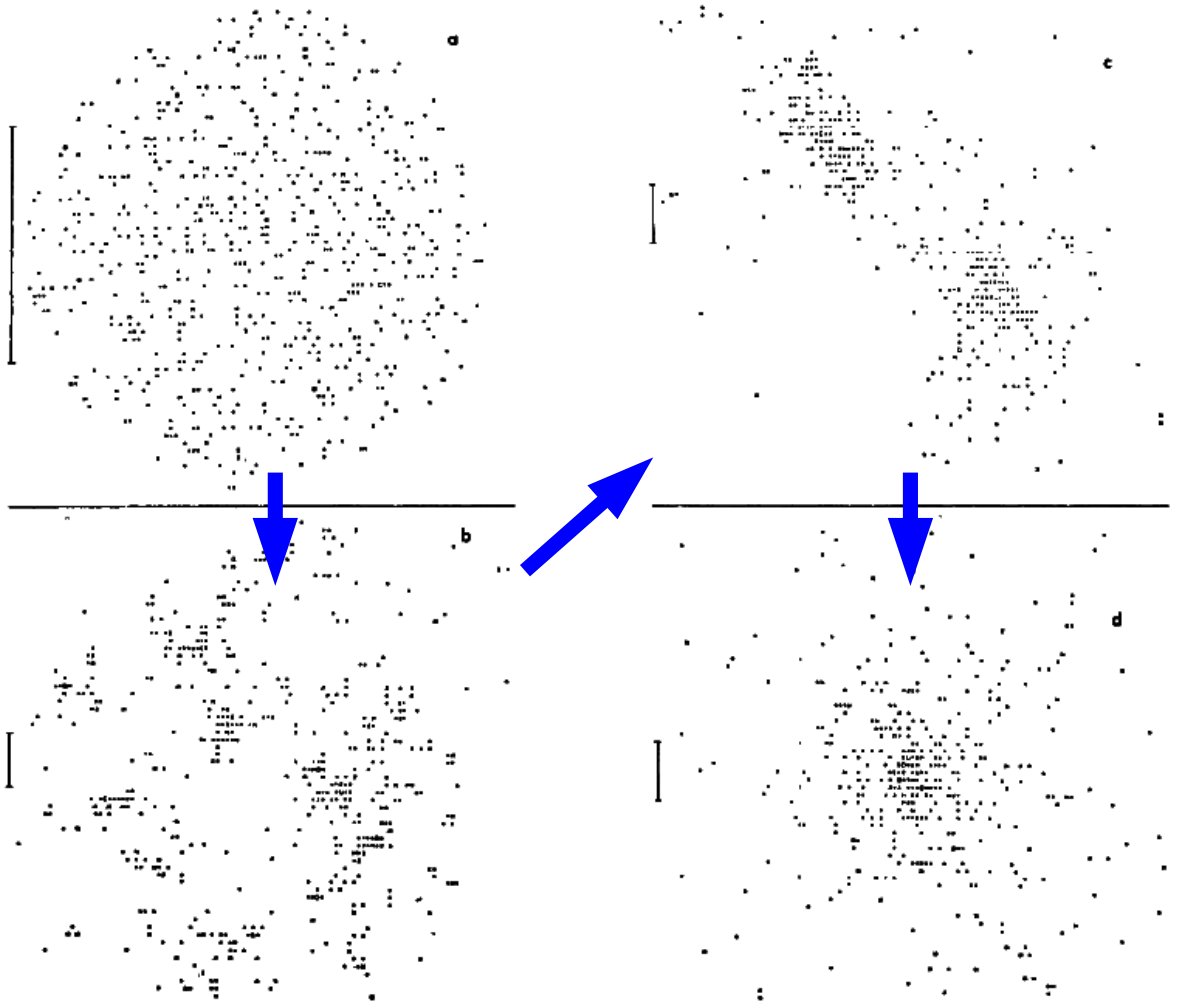
IBM 370

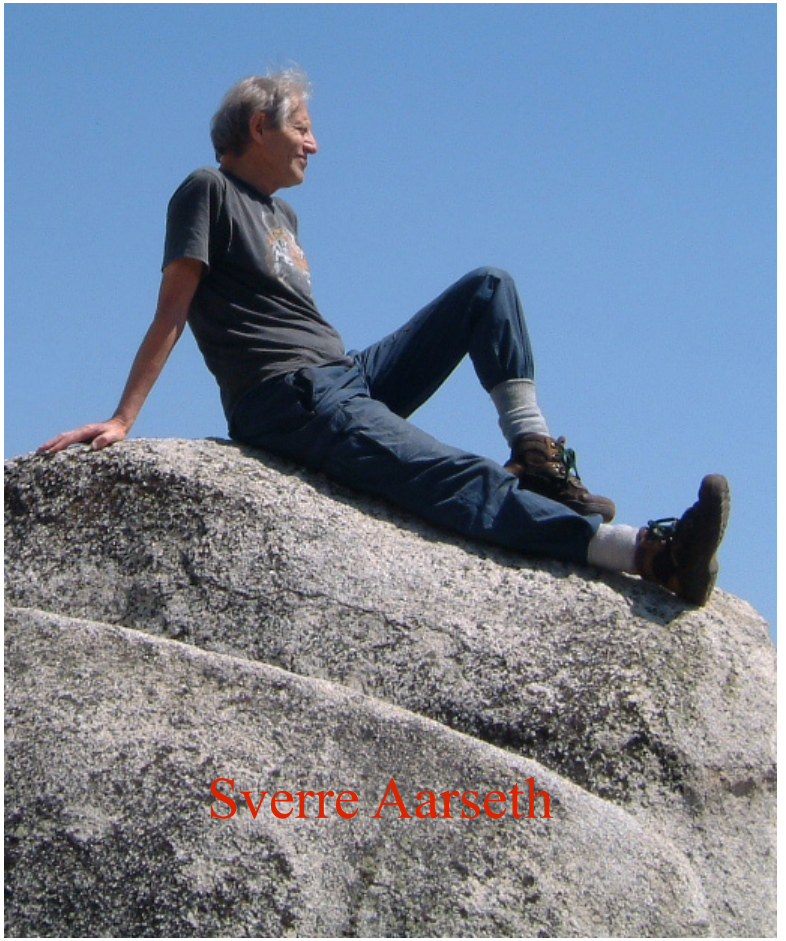
Palomar 5m



IBM 370

White 1976



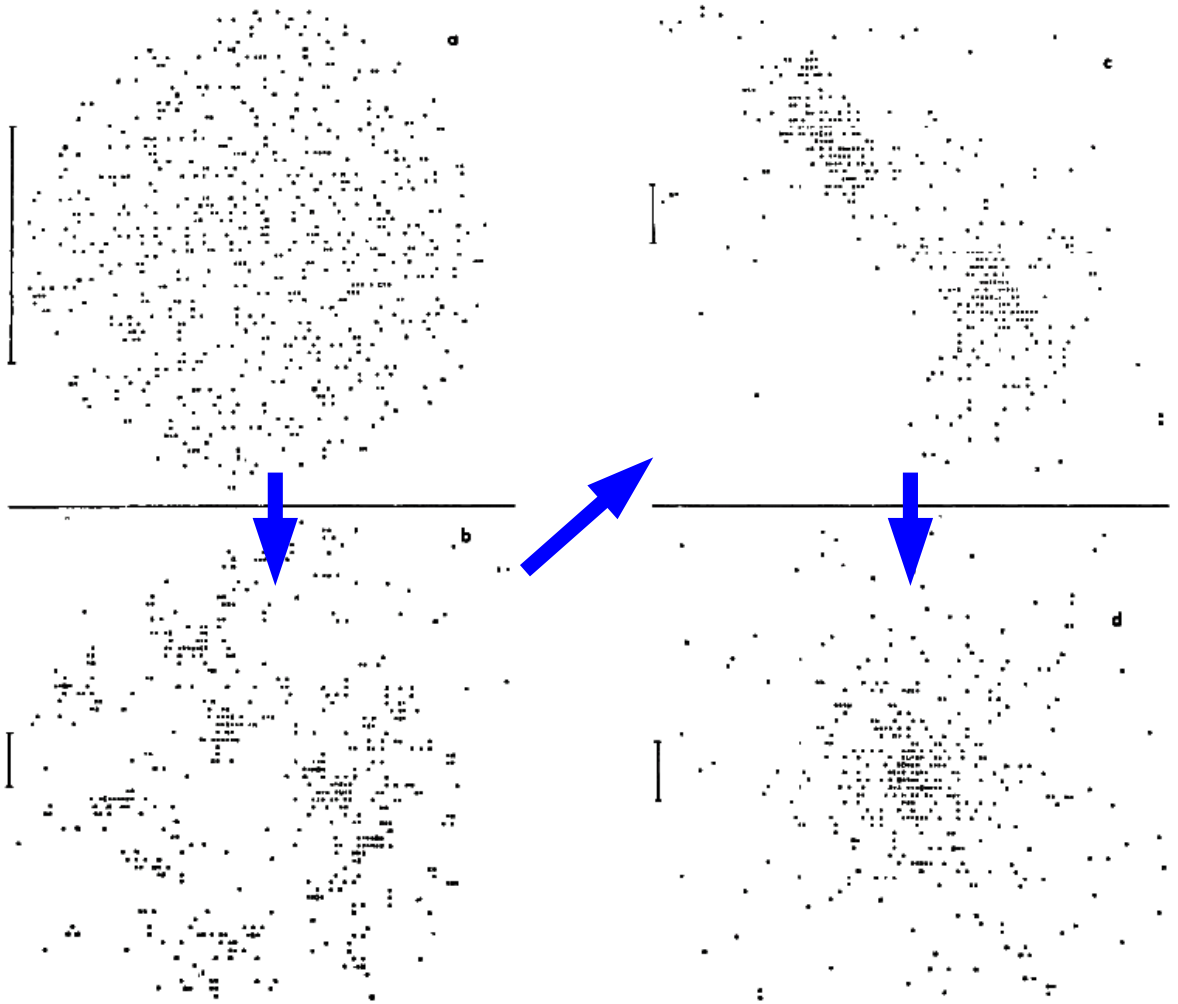


cluster simulation 1976

N = 700

An experiment? On what?

White 1976



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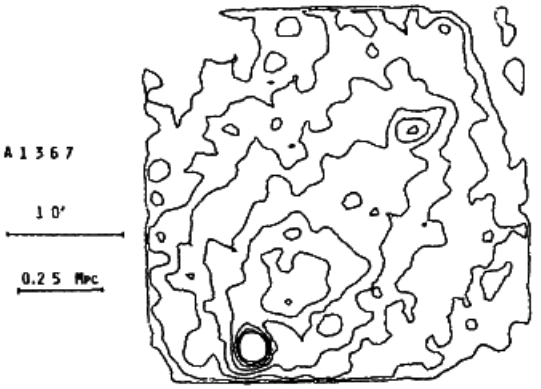
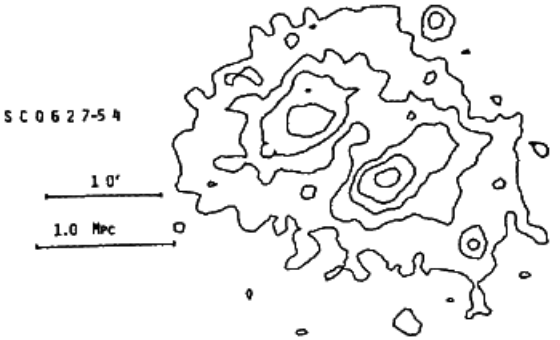
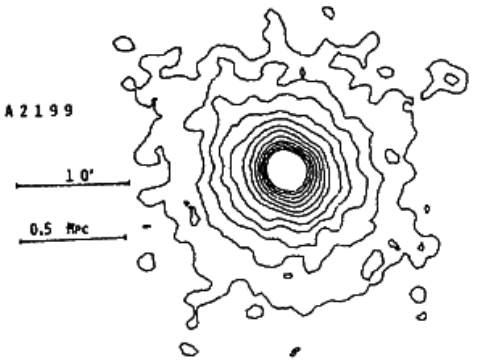


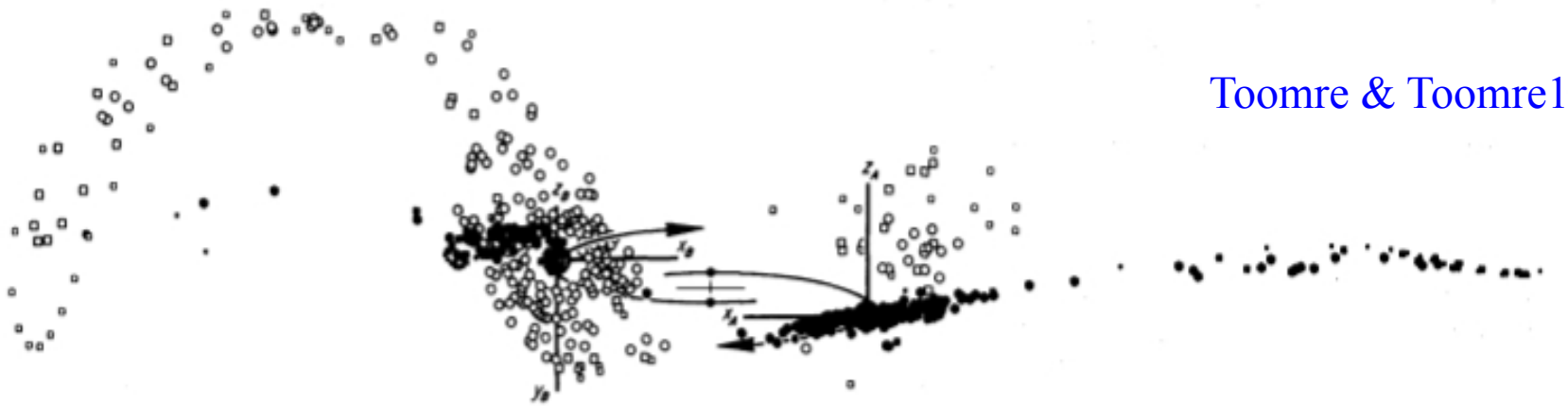




images of real clusters 1980

Springel et al 2008

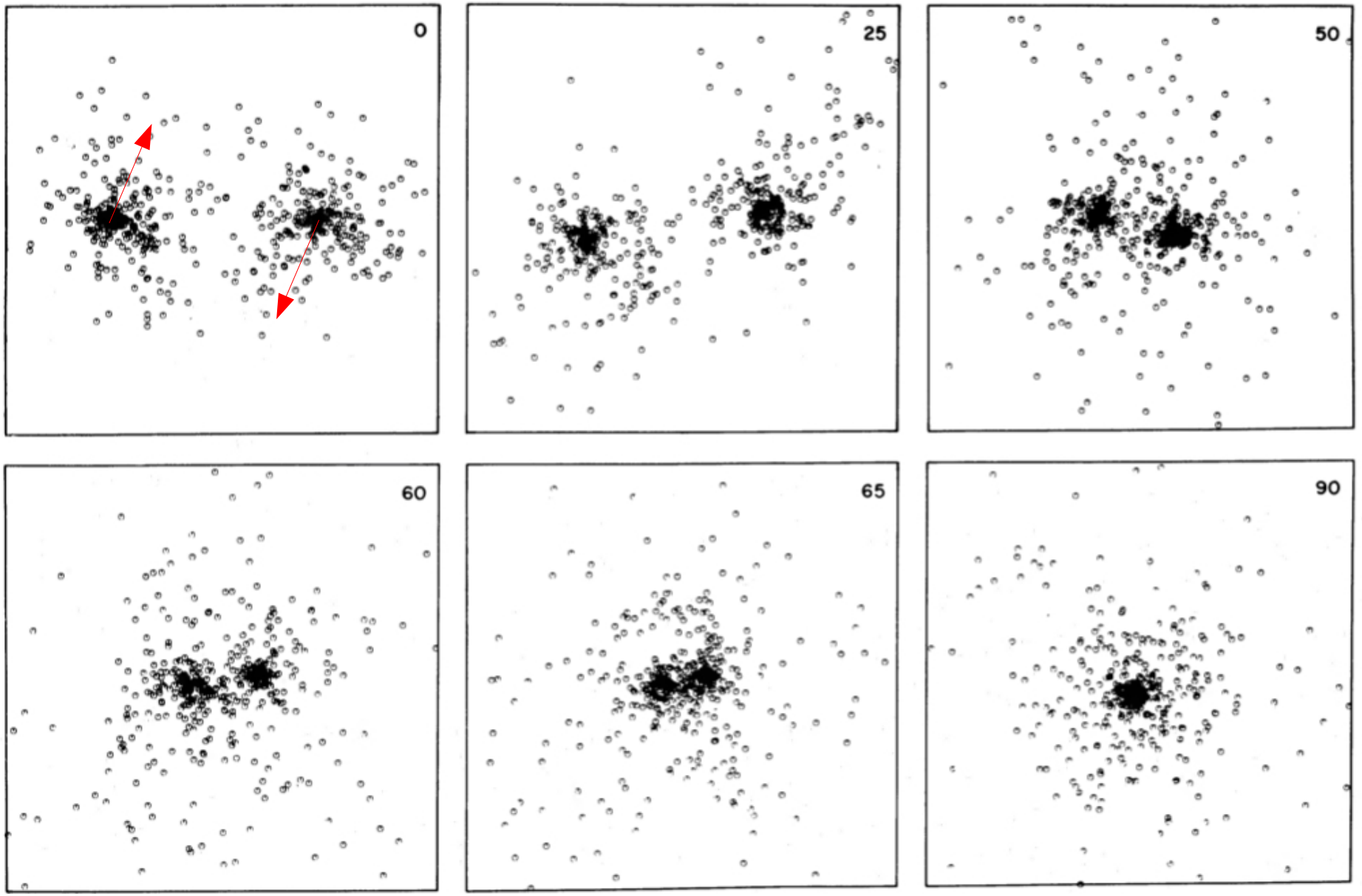
Newtonian “experiment” with 100 million bodies – forming a dark matter halo



Toomre & Toomre1972

What will the “Mice” look like in a few billion years time? An elliptical galaxy?

White 1978

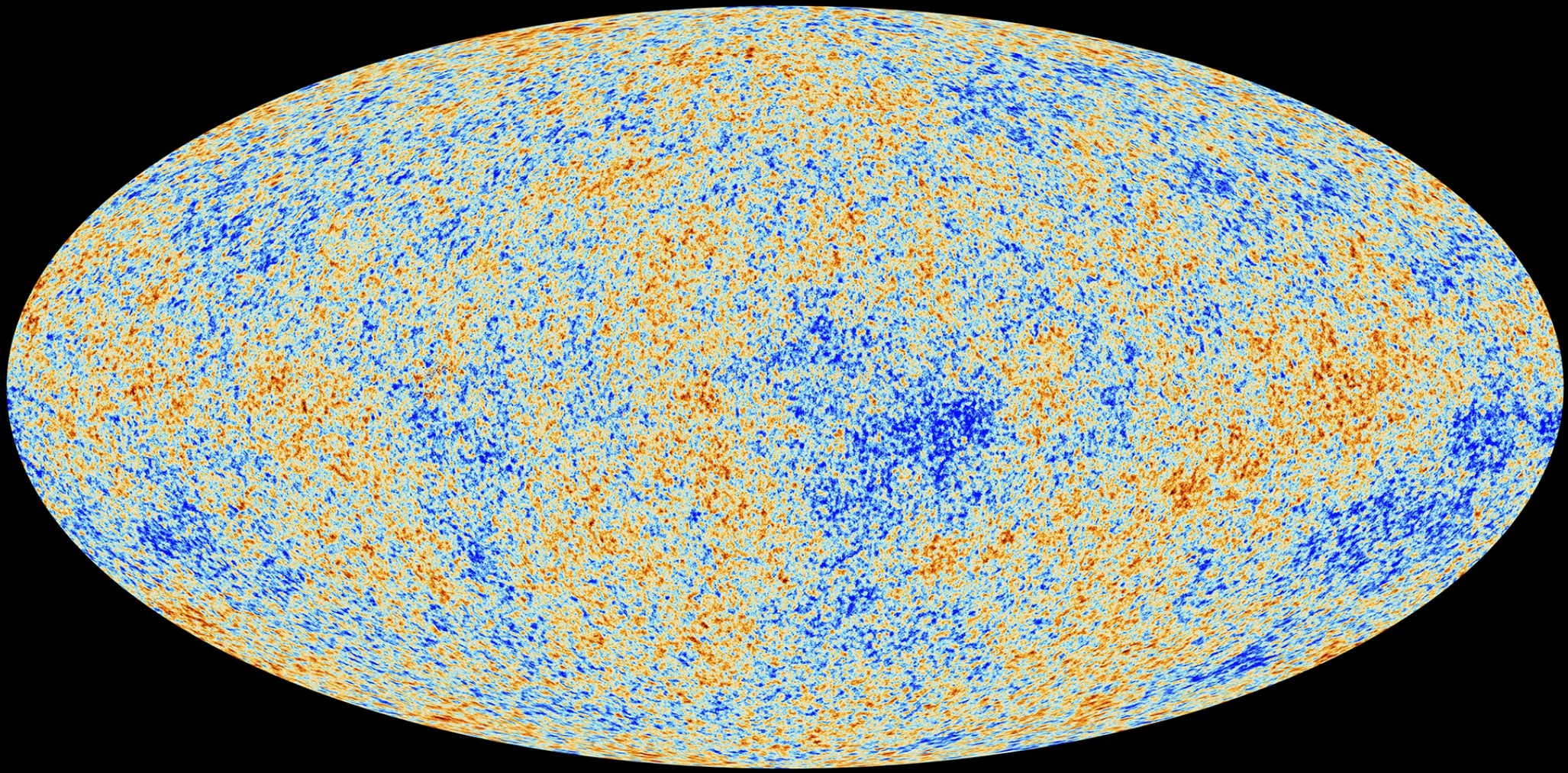


Merger simulation 1978

Springel et al 2005

Merger simulation 2005 – with gas, stars, dark matter and central black holes

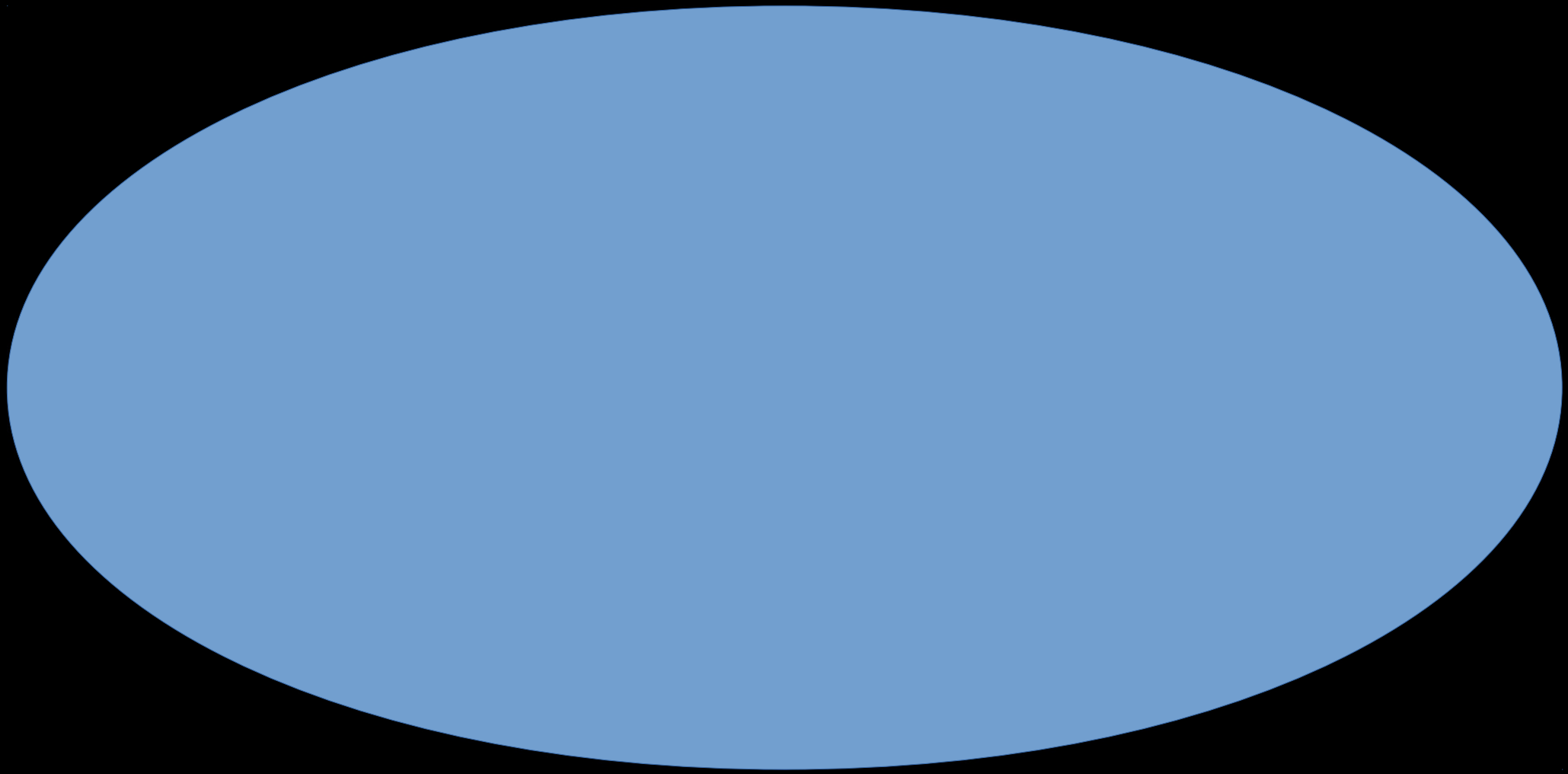
The Cosmic Microwave Background as seen by Planck (2015)



An image of the Universe when it was just 400,000 years old!

The largest temperature variations are about ± 0.0003 around the mean of 2.73

The Cosmic Microwave Background as measured in 1980



No temperature variations yet seen, but the CMB known to be so smooth that galaxies could not have formed in a Universe containing ordinary matter alone

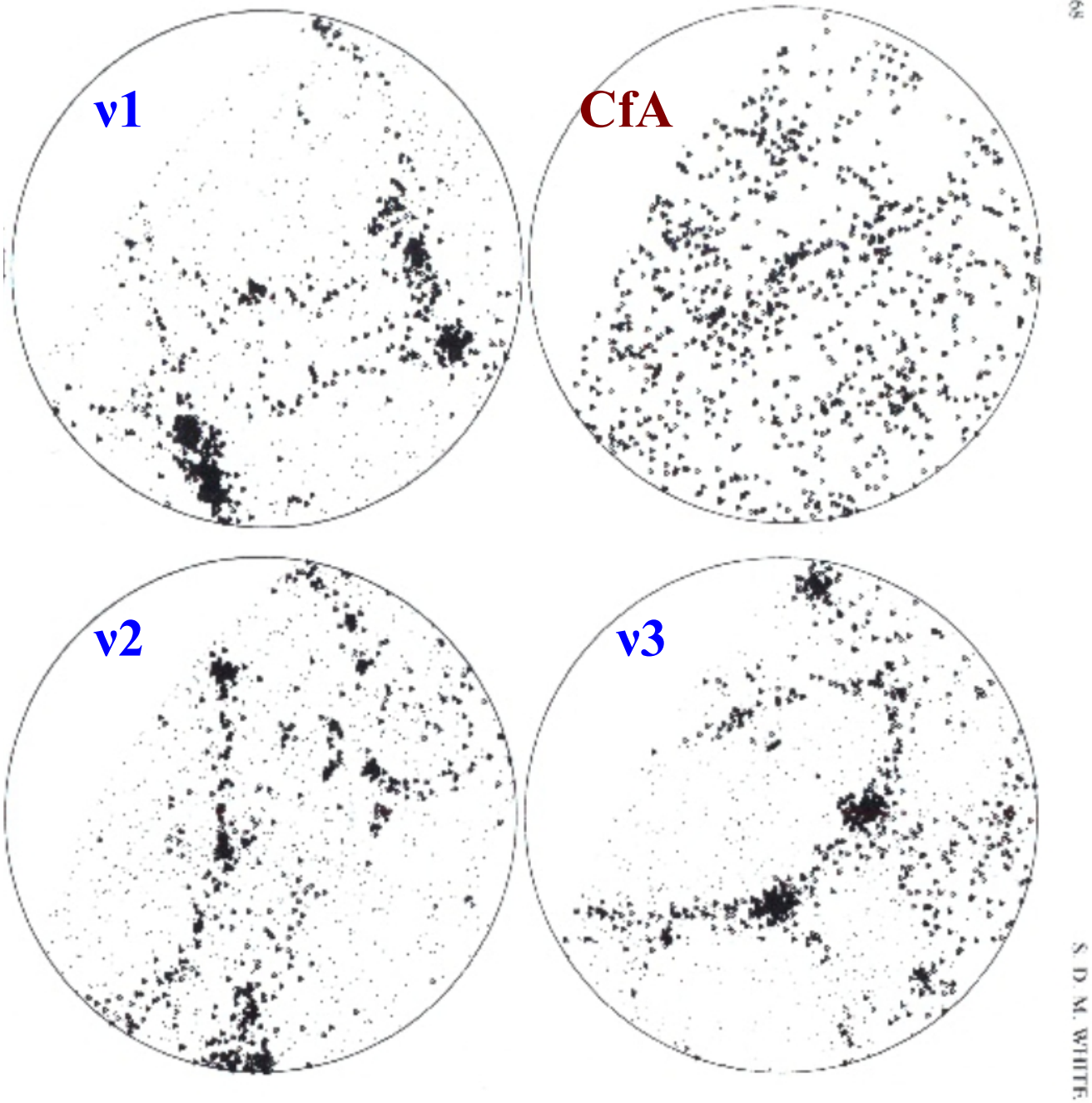
→ need to add Dark Matter made of some different kind of stuff ?

Could massive neutrinos be the Dark Matter?

White, Frenk & Davis 1983

Simulations assuming the dark matter to be made of massive neutrinos led to much larger cosmic structures than observed.

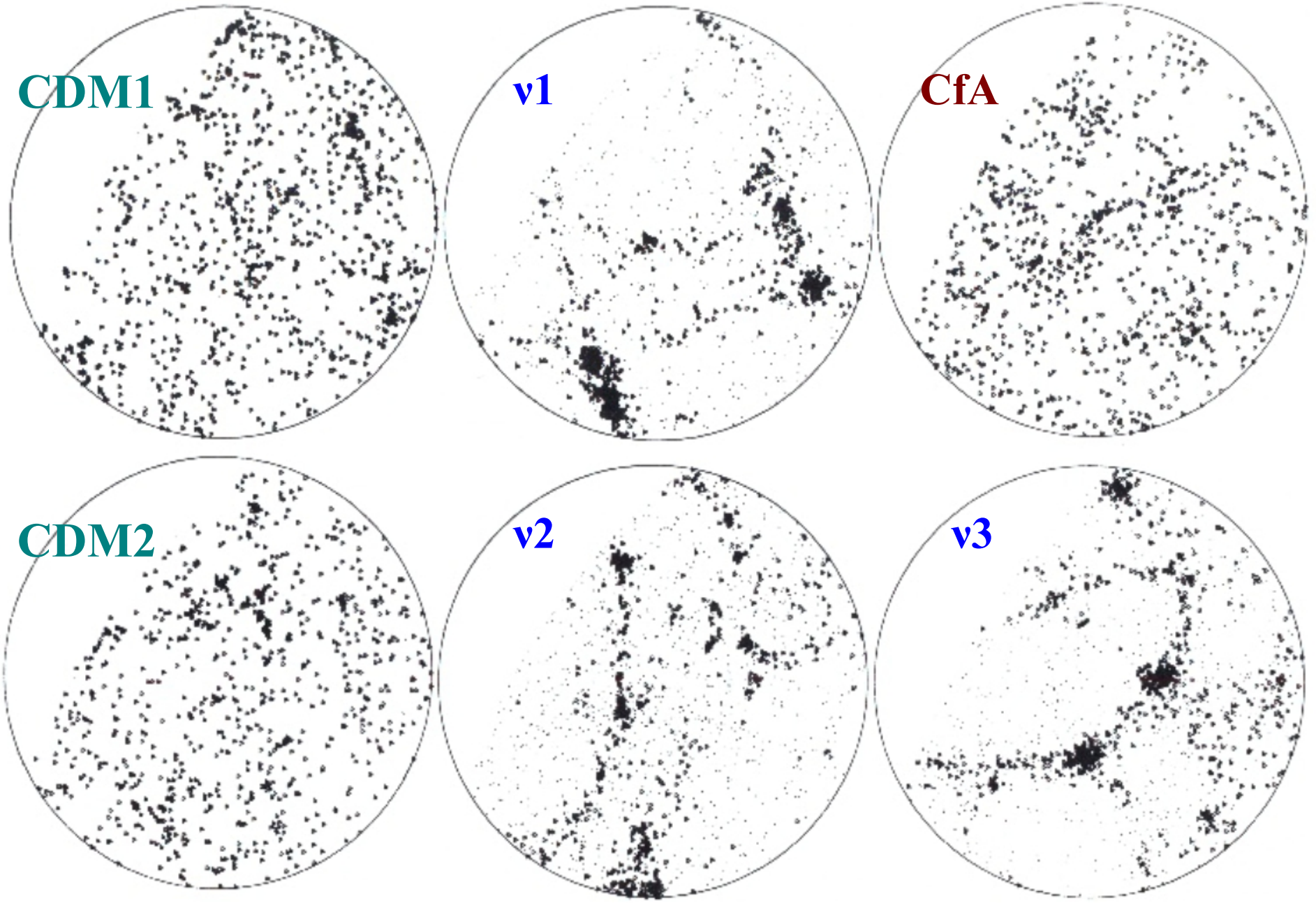
Computer "experiments" thus showed that the dark matter cannot be made of *any* known particle!



A new kind of particle, Cold Dark Matter, **is** possible

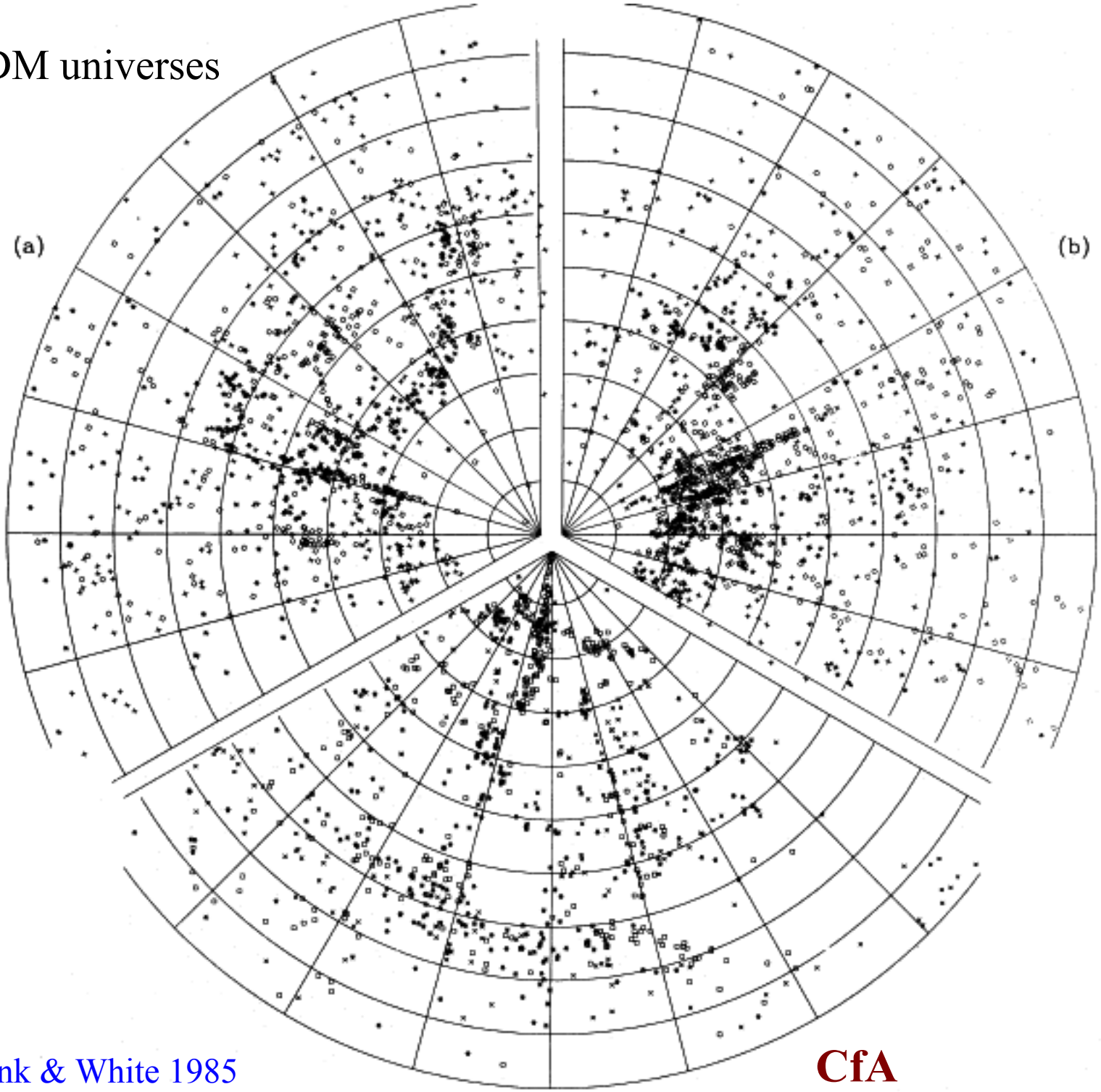
Davis, Efstathiou, Frenk & White 1985

White, Frenk & Davis 1983



Low density CDM universes

$\Omega = 0.2$



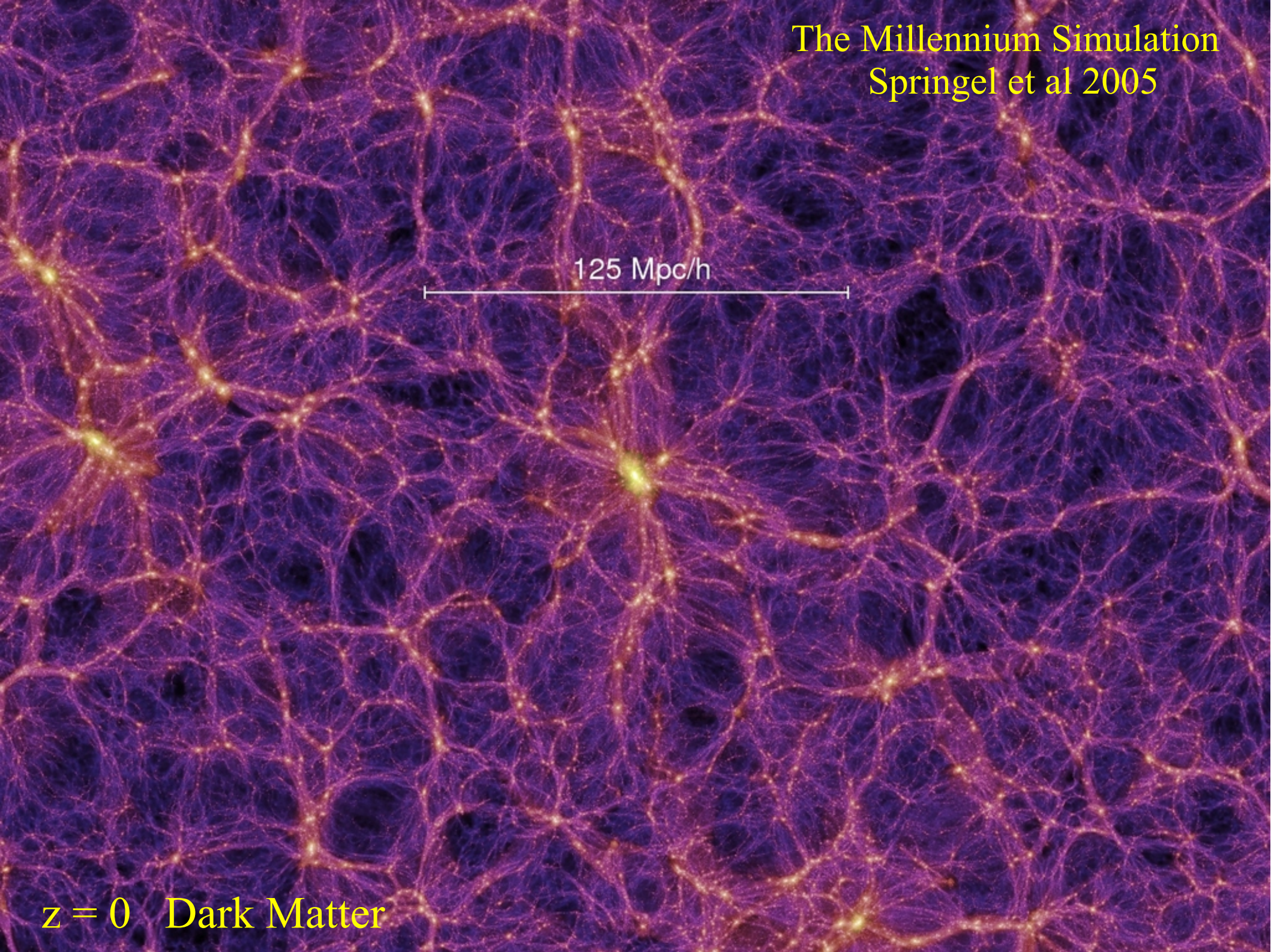
Davis, Efstathiou, Frenk & White 1985

CfA

Davis, Efstathiou, White & Frenk around 1983

...and thirty years later at the Gruber Cosmology Prize ceremony

White & Springel around 2005


The Millennium Simulation
Springel et al 2005
125 Mpc/h
z = 0 Dark Matter

Following the formation of the galaxies

The gravity of dark matter controls structure formation but the observable properties of galaxies also depend strongly on

The cooling and condensation of gas within lumps of dark matter — the dark matter "halos" of galaxies

The formation of stars from this dense gas

The formation of massive black holes in galaxy centres

The energy output from evolving stars and black holes

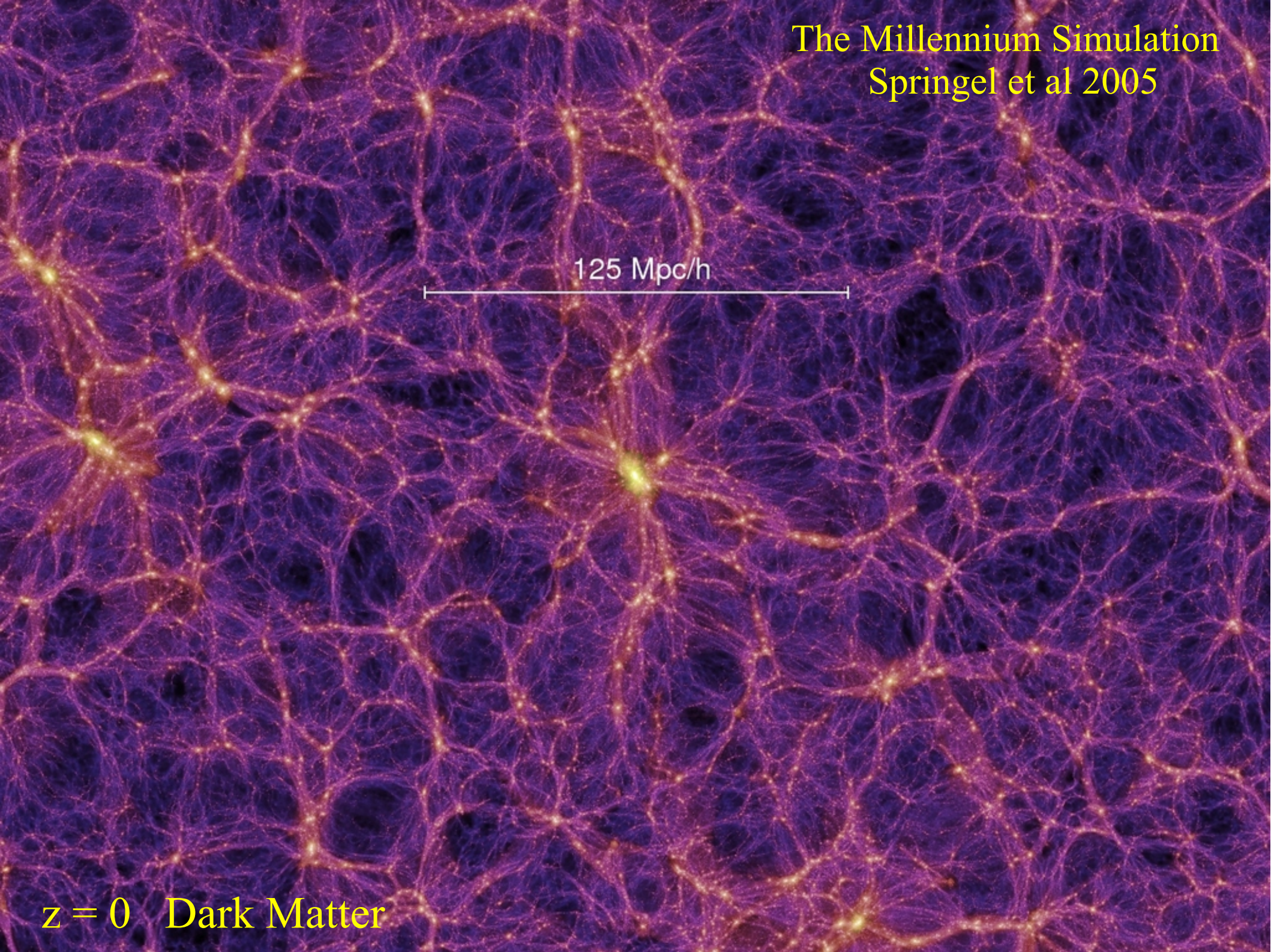
The merging of galaxies and their dark halos

To compare properly with observation requires simulations that treat **all** these processes simultaneously

→ Semianalytic "experimentation"

White & Rees 1978
White & Frenk 1991,
Kauffmann et al 1993, 1999

Kauffmann & White around 2003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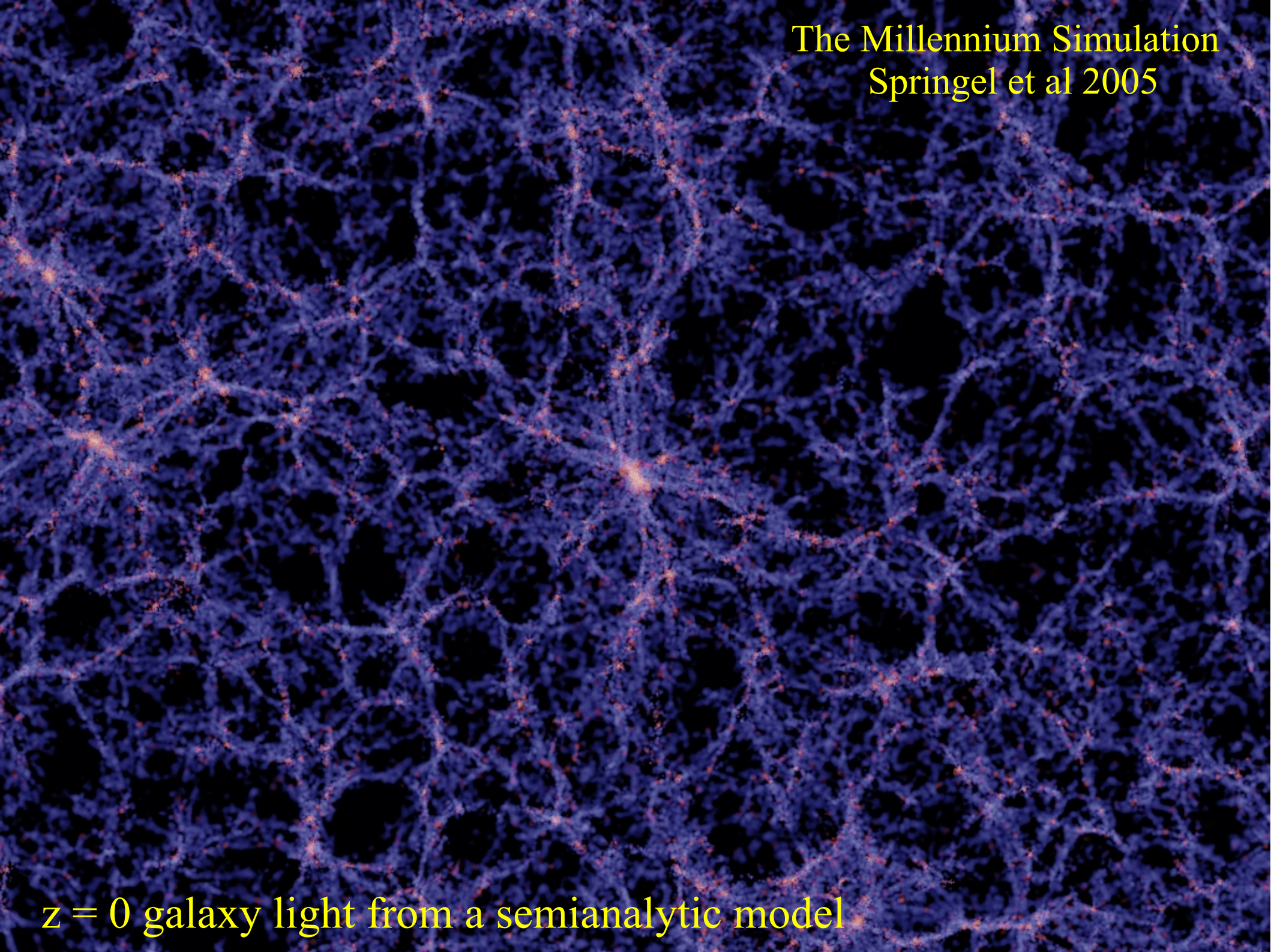
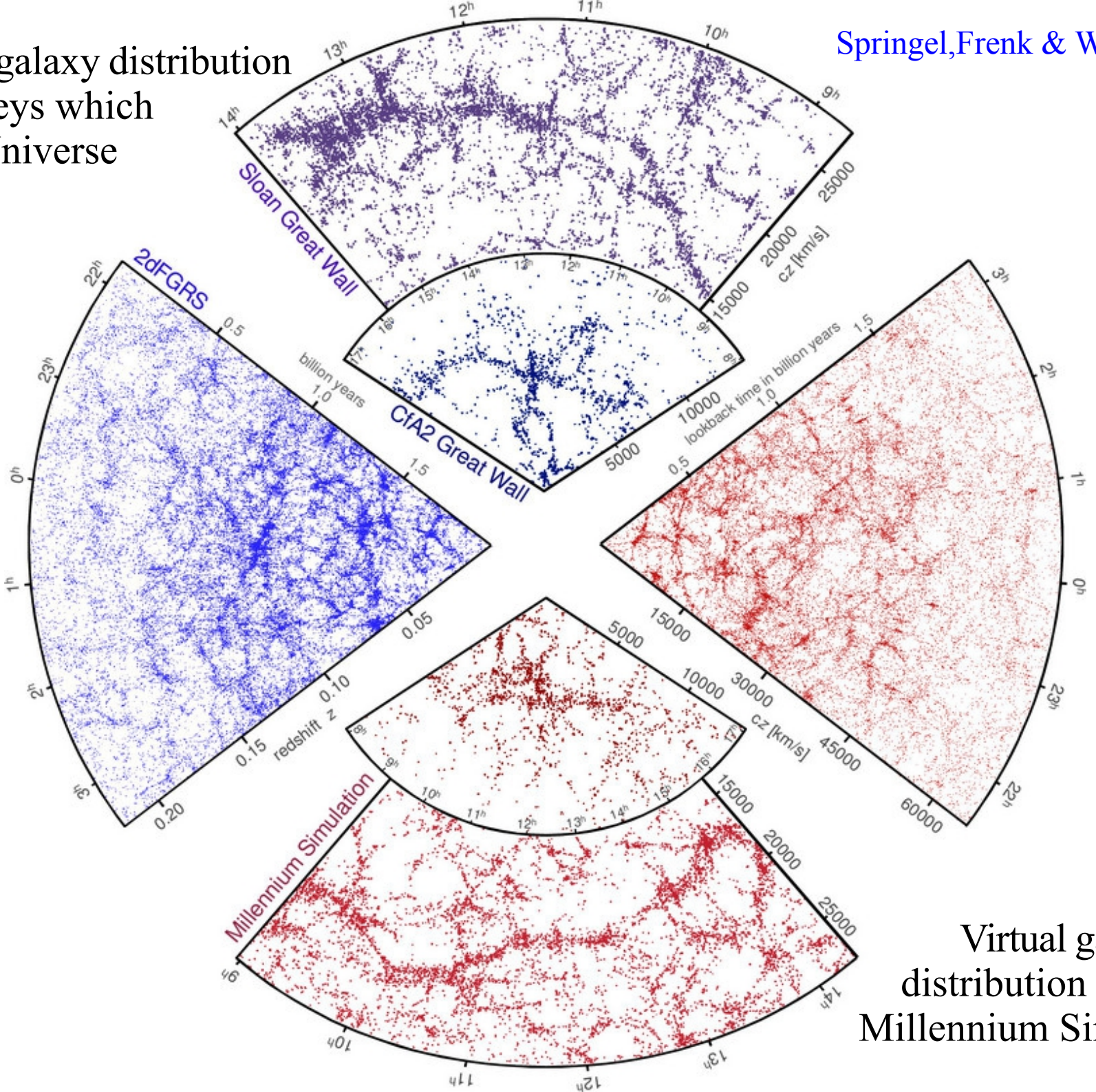

The Millennium Simulation
Springel et al 2005
z = 0 galaxy light from a semianalytic model

Observed galaxy distribution from surveys which map the Universe

Springel,Frenk & White 2006



Virtual galaxy distribution from the Millennium Simulation

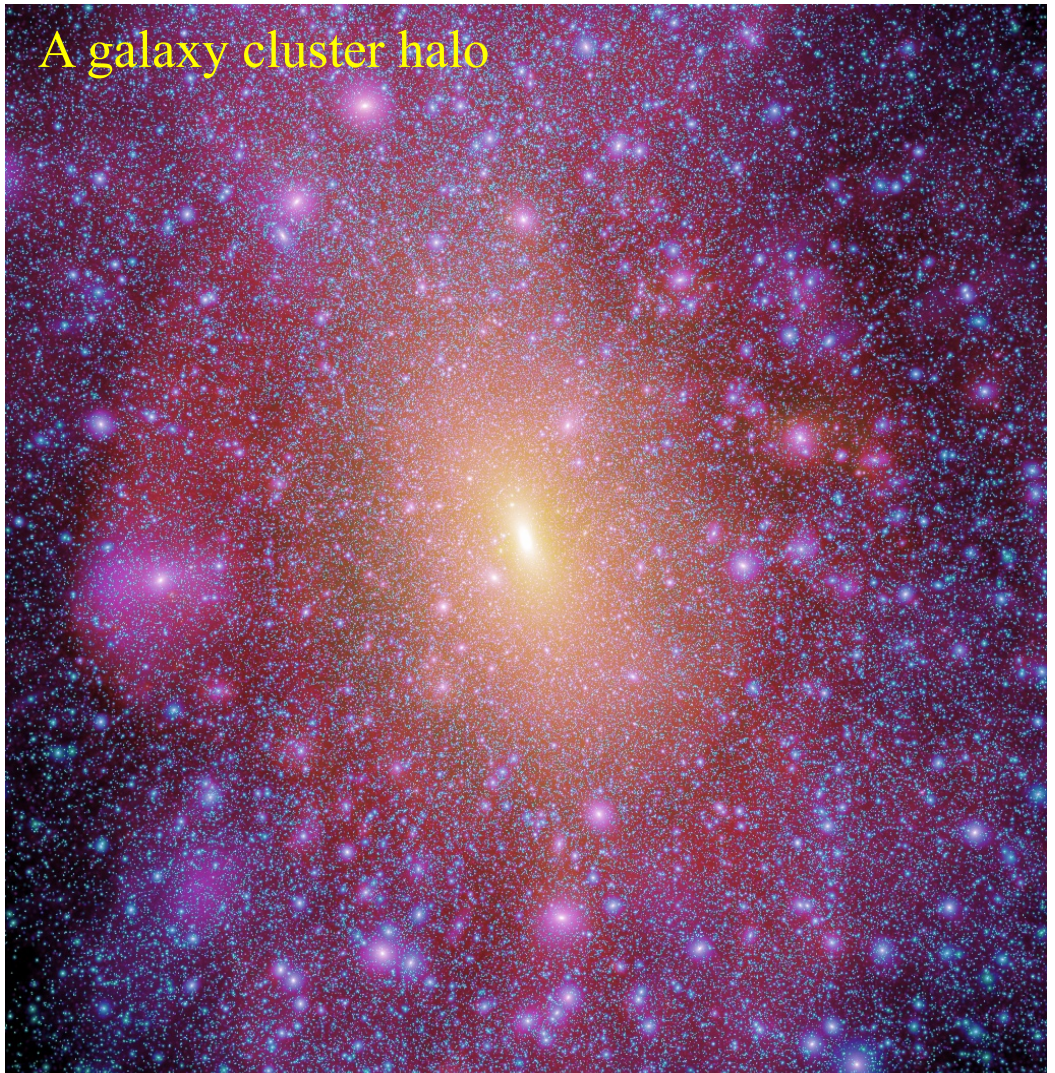
All dark matter halos look similar...

A "universal" density profile

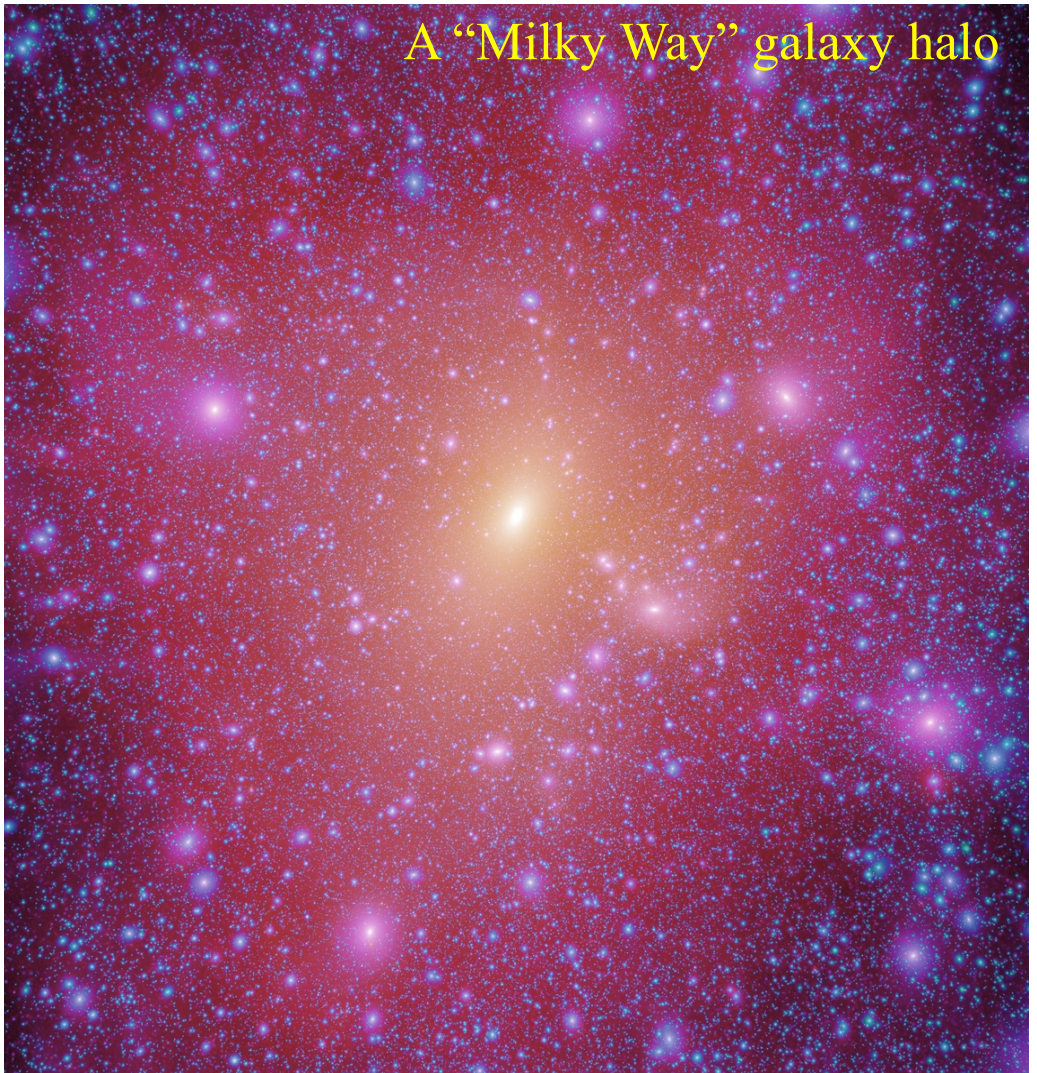
$$\rho(r) / \langle\rho\rangle = \delta\, r_s / r\,(1 + r / r_s)^2$$

The "NFW profile" Navarro, Frenk & White 1996 1997

5 Mpc



0.5 Mpc



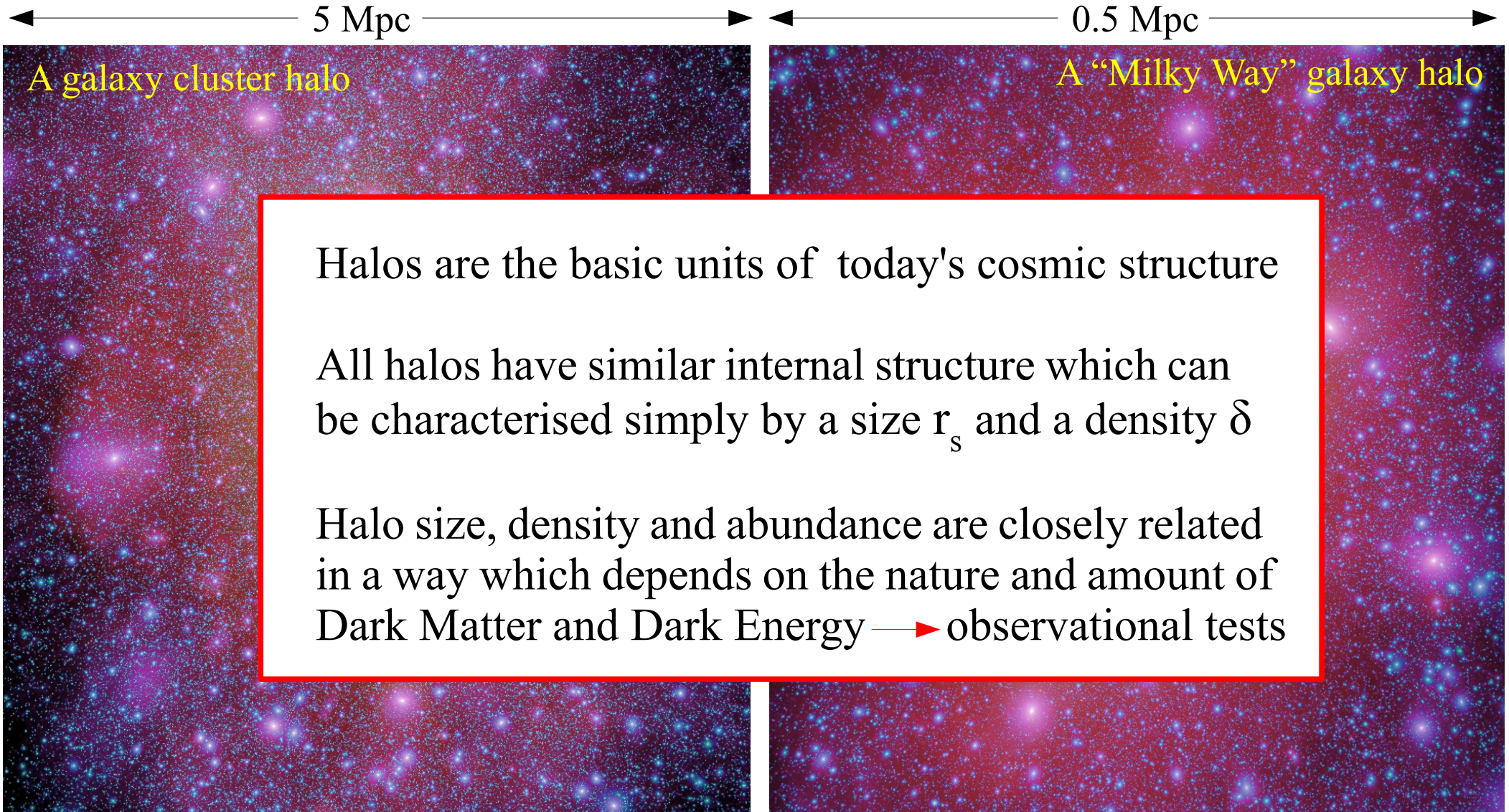
NFW profiles in everyday life around 2011

All dark matter halos look similar...

A "universal" density profile

$$\rho(r) / \langle\rho\rangle = \delta\, r_s / r\,(1 + r / r_s)^2$$

The "NFW profile"
Navarro, Frenk & White 1996 1997

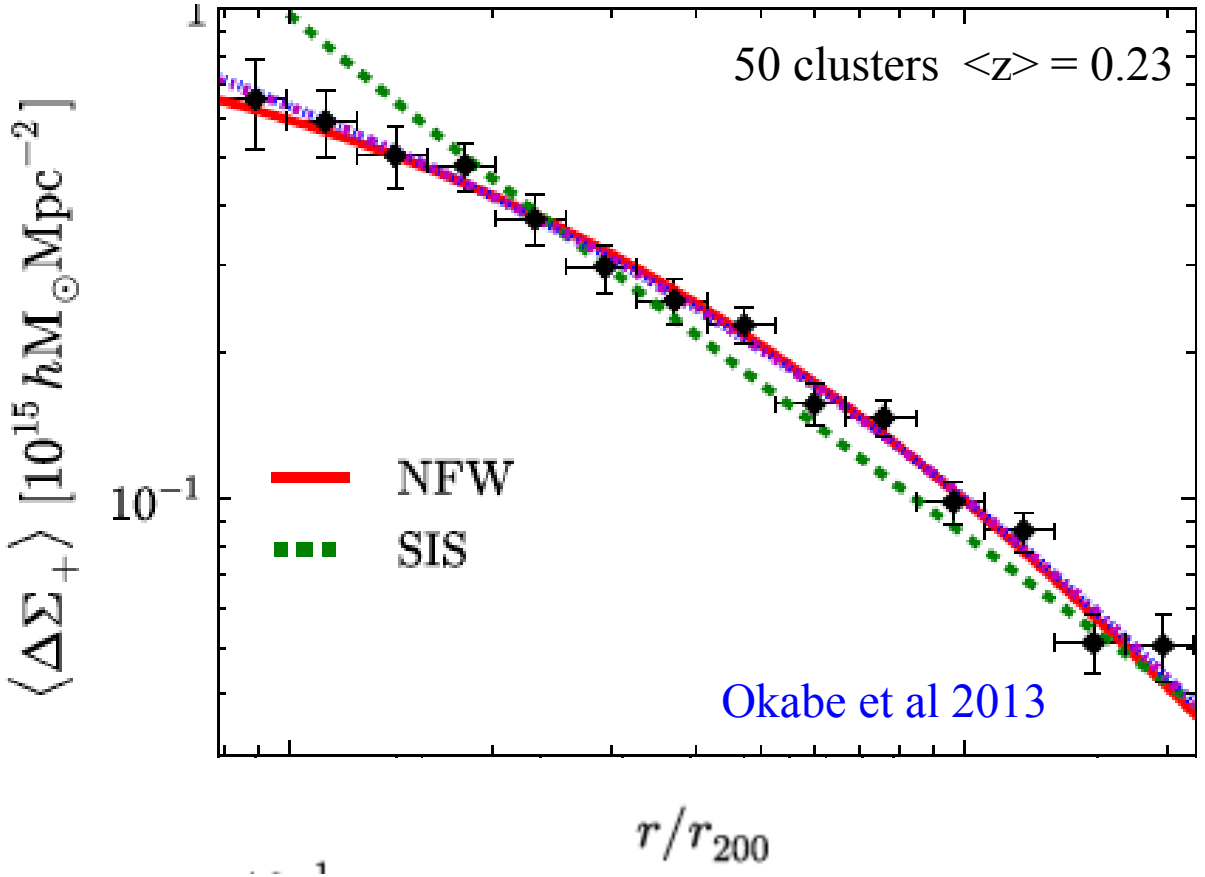


Halos are the basic units of today's cosmic structure

All halos have similar internal structure which can be characterised simply by a size r_s and a density δ

Halo size, density and abundance are closely related in a way which depends on the nature and amount of Dark Matter and Dark Energy → observational tests

The observed mass profile of galaxy clusters

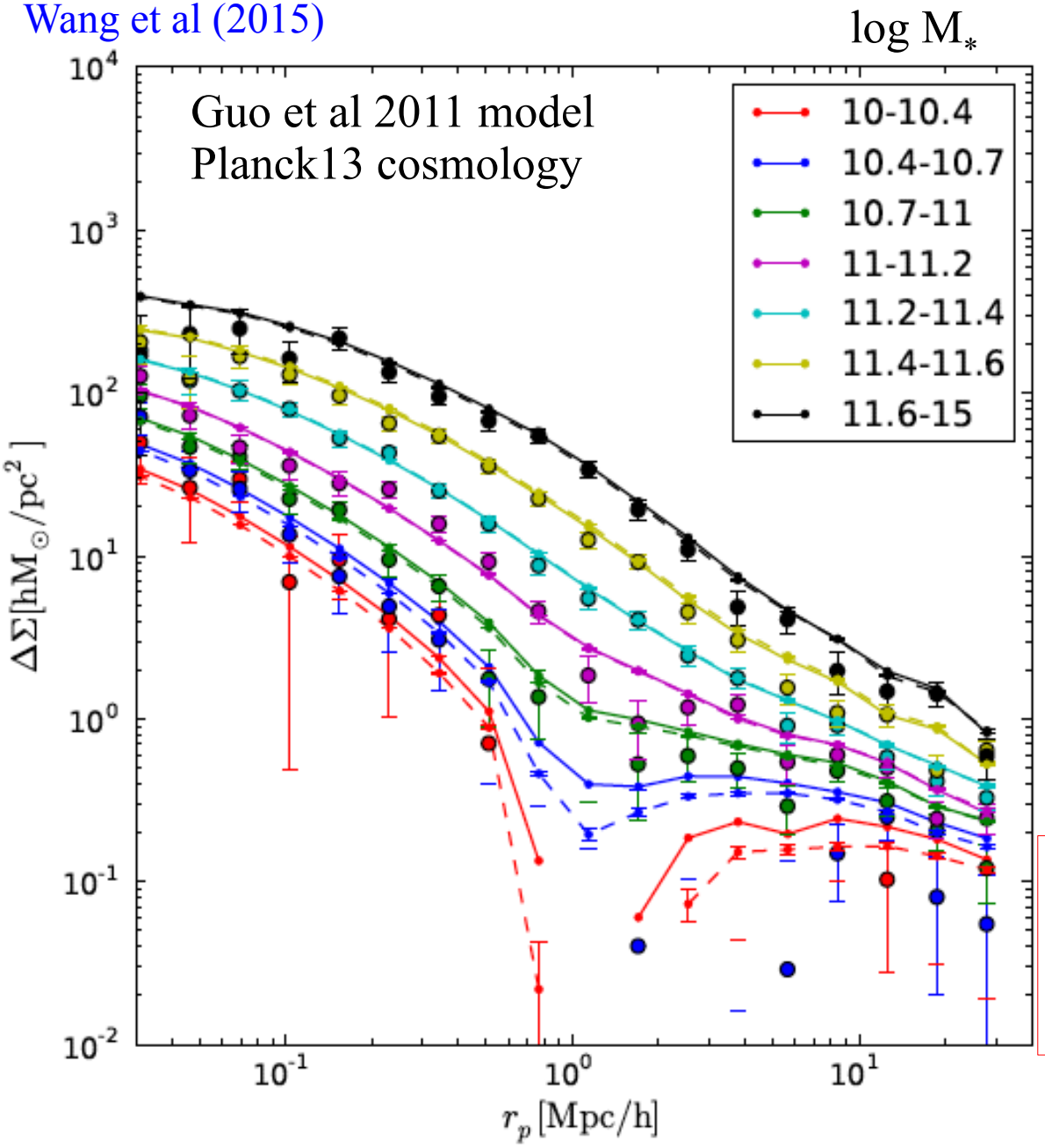


The mass distribution in galaxy clusters can be measured using the effects of gravitational lensing on background galaxies

- The observed mass profile matches that predicted. This tests
  - – that cosmic structure grows as expected for ΛCDM
  - – that the amounts of dark matter and dark energy assumed by the simulation are approximately right

Average mass profiles around bright galaxies

Wang et al (2015)



The points are measured mass profiles around the central galaxies of galaxy groups

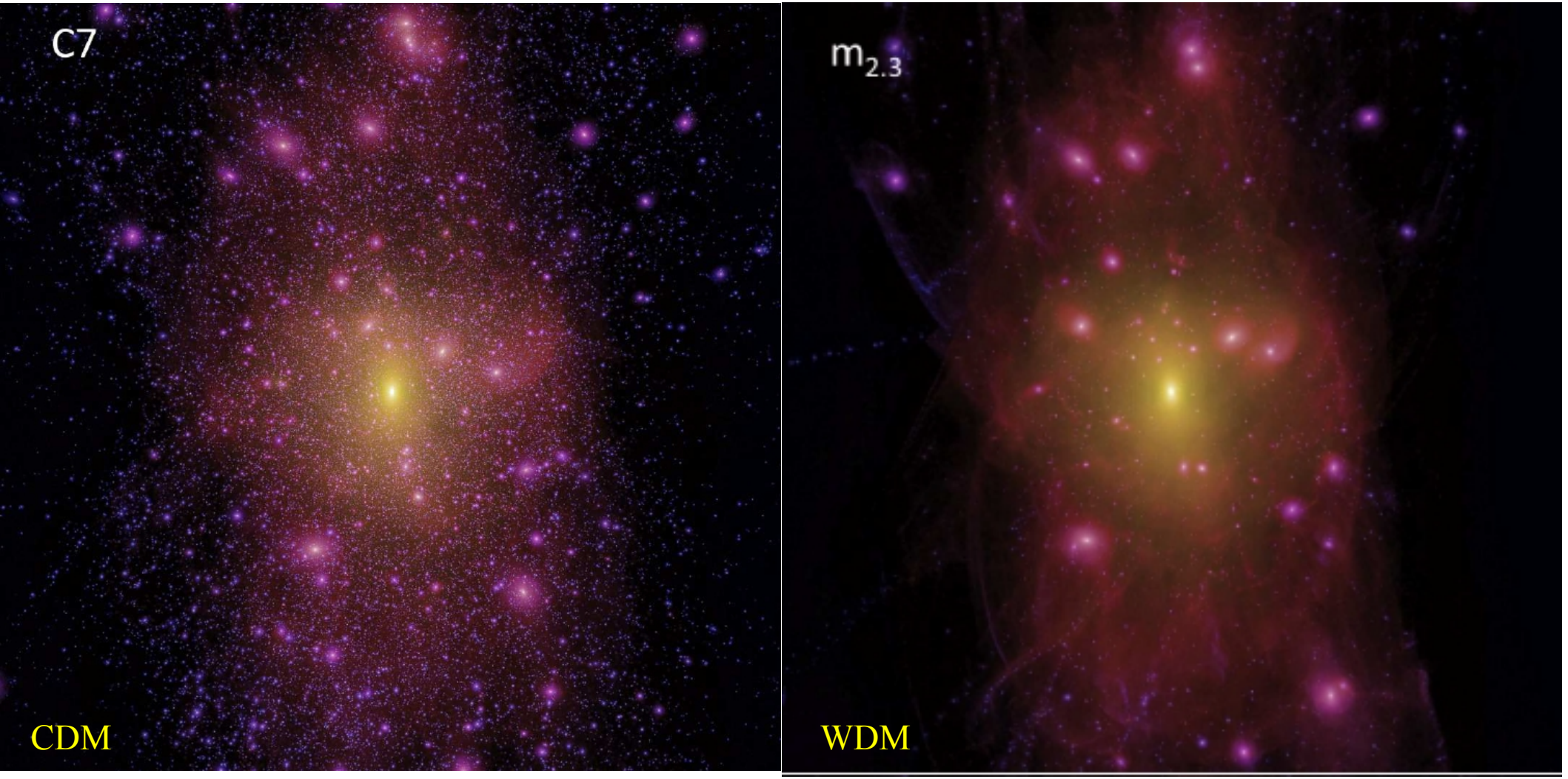
Top to bottom goes from rich galaxy clusters to poor groups

The lines are the predicted mass profiles about such groups in the Millennium Simulation

The simulation matches the mass distribution around galaxies even in regions where no light is seen!

How to figure out what the dark matter is?

Lovell et al 2014.

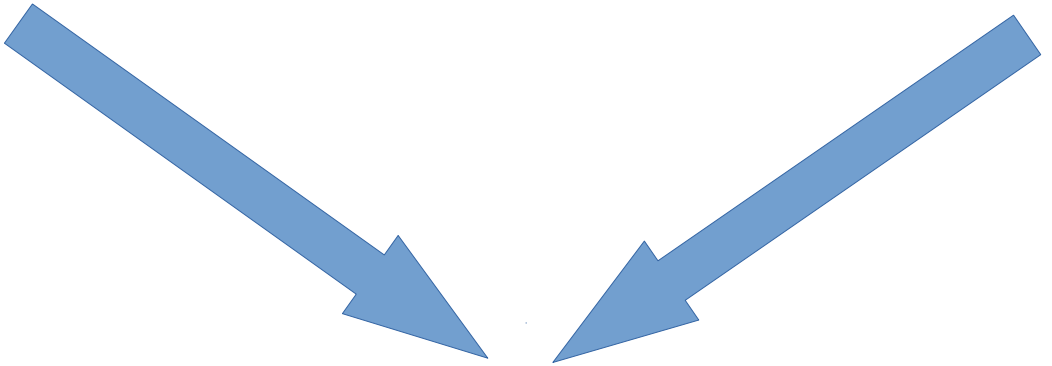


The same "Milky Way" halo simulated assuming the dark matter is cold (left) and warm (right). Small lumps are missing in WDM

Gravitational lensing may be able to measure this difference

The scientific route to “Truth”

Experiment/Observation ⟷ **Mathematical modelling**



Physical understanding

The scientific route to “Truth”