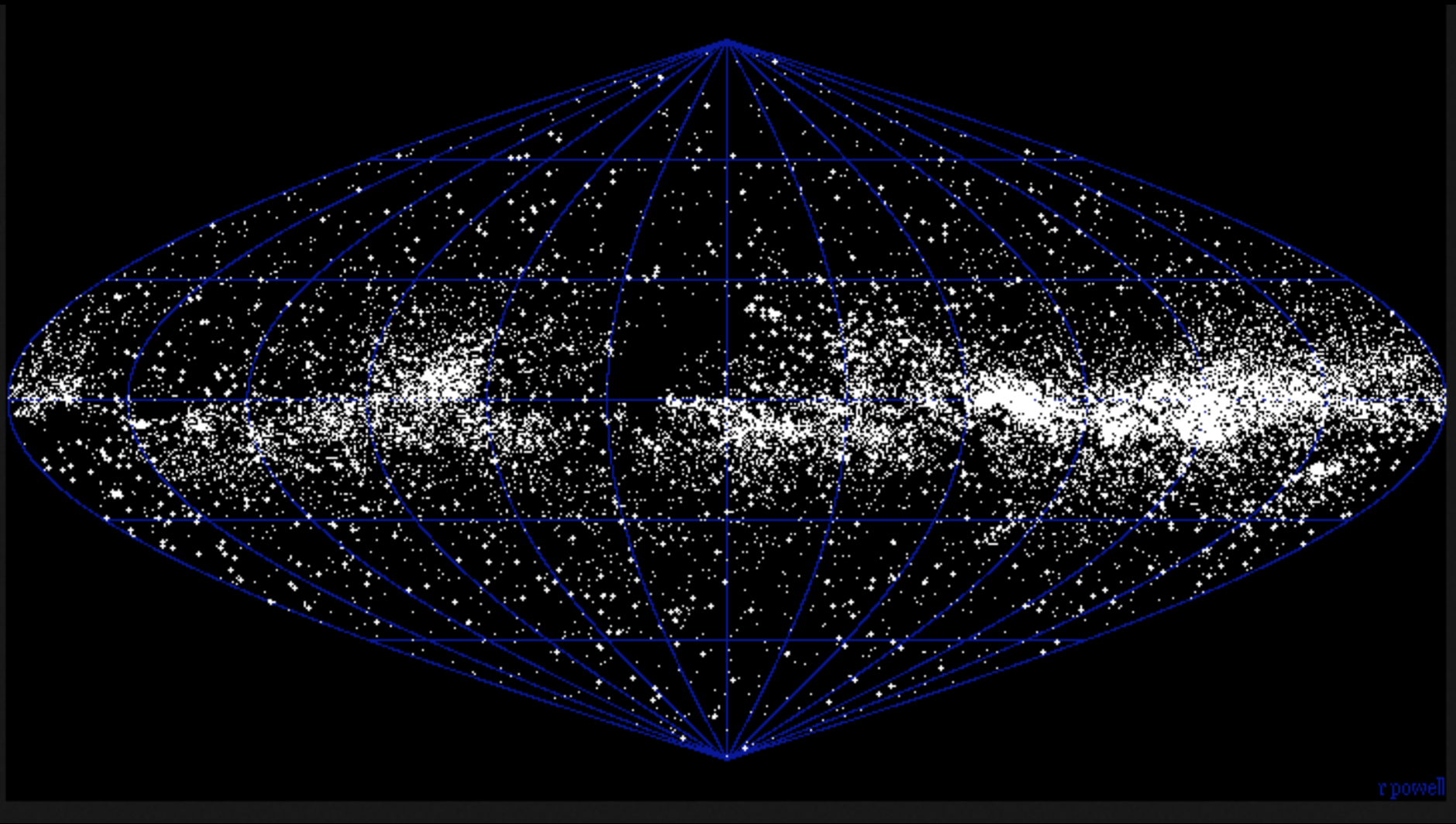
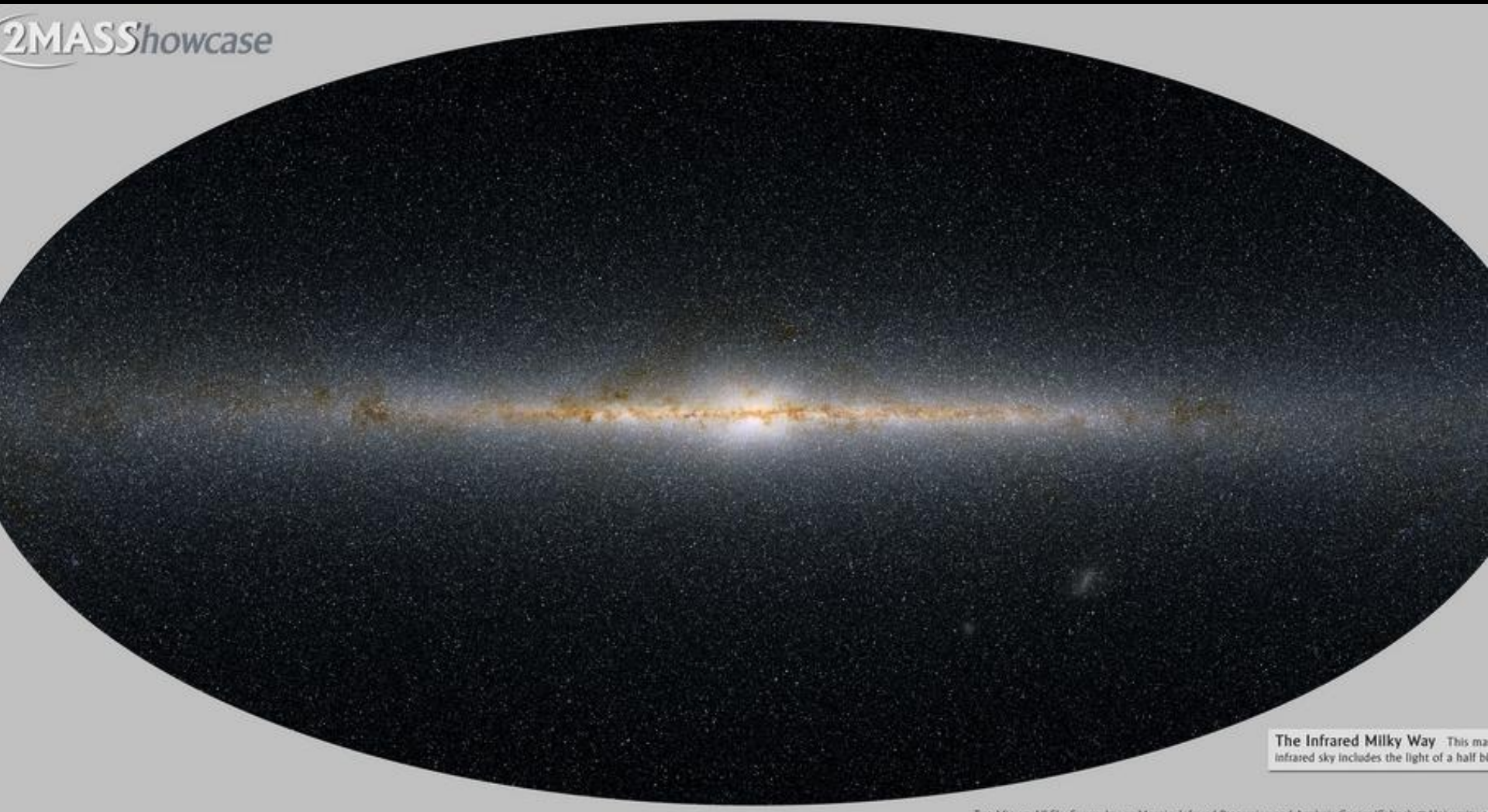
Formation of our Galaxy

Joseph Silk

4th Gresham Lecture: 3 February 2016


r powell

2MASS Showcase

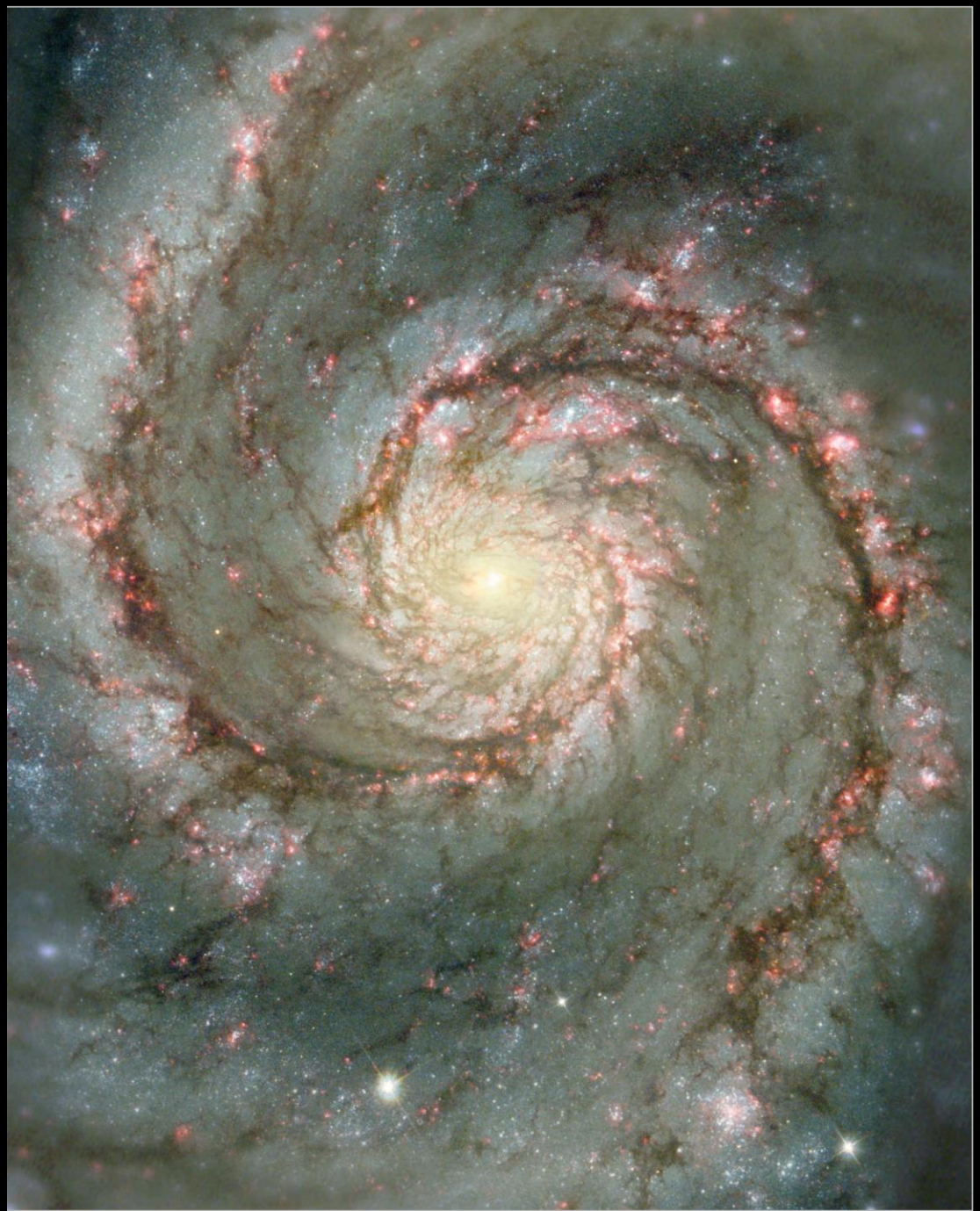


The Infrared Milky Way This ma
infrared sky includes the light of a half bi

Two Micron All Sky Survey Image Mosaic; Infrared Processing and Analysis Center/Caltech & University o


Infrared
Infrared (24 m
Visible

Whirlpool Galaxy • M51



SOME GALAXIES ARE PURE SPHEROID

SOME GALAXIES ARE PURE DISKS

if the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space.And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.

Isaac Newton, letter to Richard Bentley, December 10, 1692

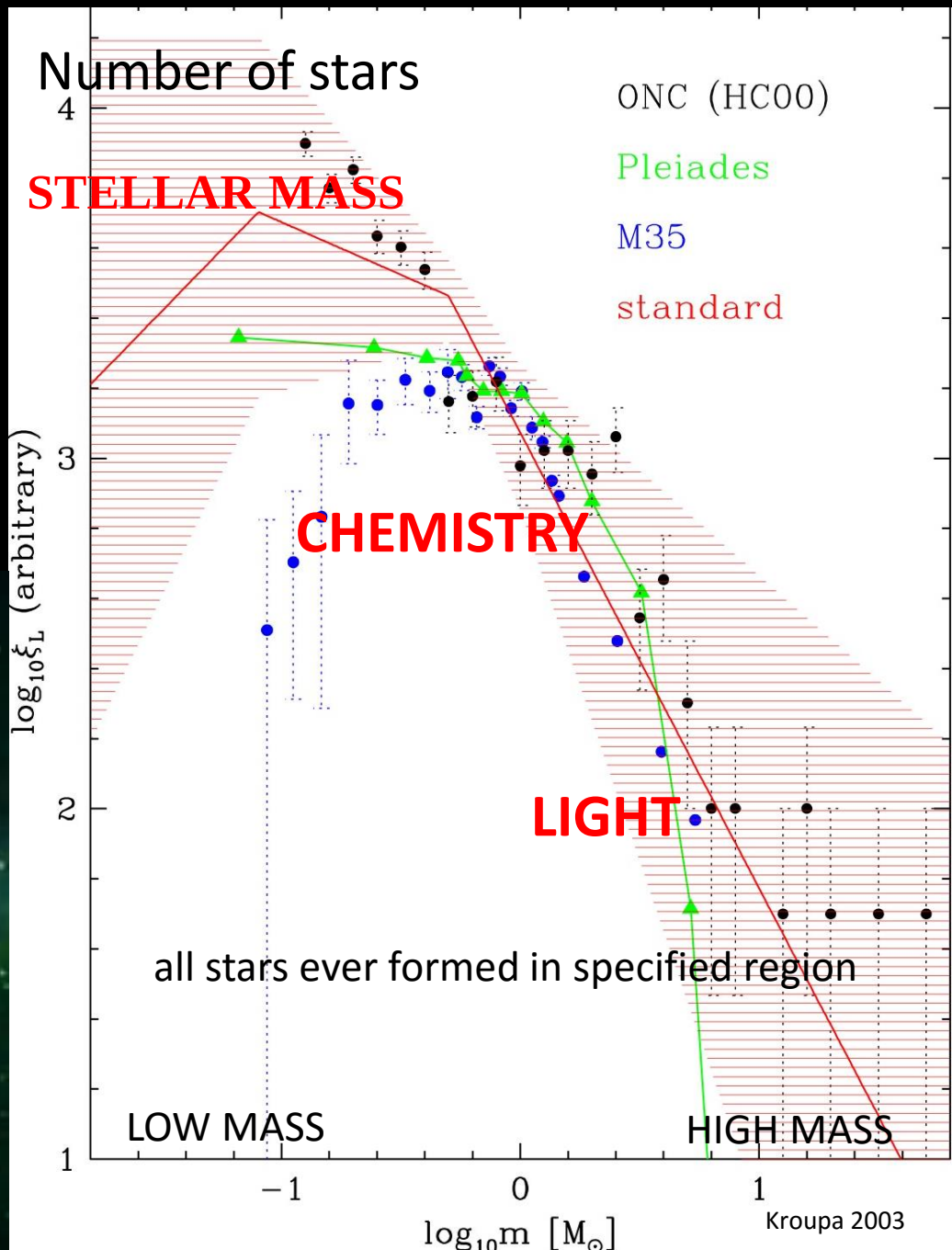
if the sun at rest were an opaque body like the planets or the planets lucid bodies like the sun, how he alone should be changed into a shining body whilst all they continue opaque, or all they be changed into opaque ones whilst he remains unchanged,
by mere natural causes, but am forced to ascribe it to the counsel and contrivance of a voluntary Agent.

THE HOLY GRAIL OF STAR FORMATION

- Can we predict the masses of stars? No
- Can we account for the efficiency of star formation? No
- Can we account for the rate No

We still need a robust theory of star formation but there are many empirical clues obtained with a wide variety of telescopes. This allows astronomers to model how stars form.

The mass distribution of stars is a key ingredient



Kroupa 2003

What's a star?

A gigantic ball of hydrogen gas weighing about
ten trillion trillion trillion tons
with a diameter of a million kilometers

A star is precariously balanced by the struggle
between gravity and hot gas pressure

A star is born

Recipe for a star

A giant cloud of diffuse hydrogen gas

Helium 30%

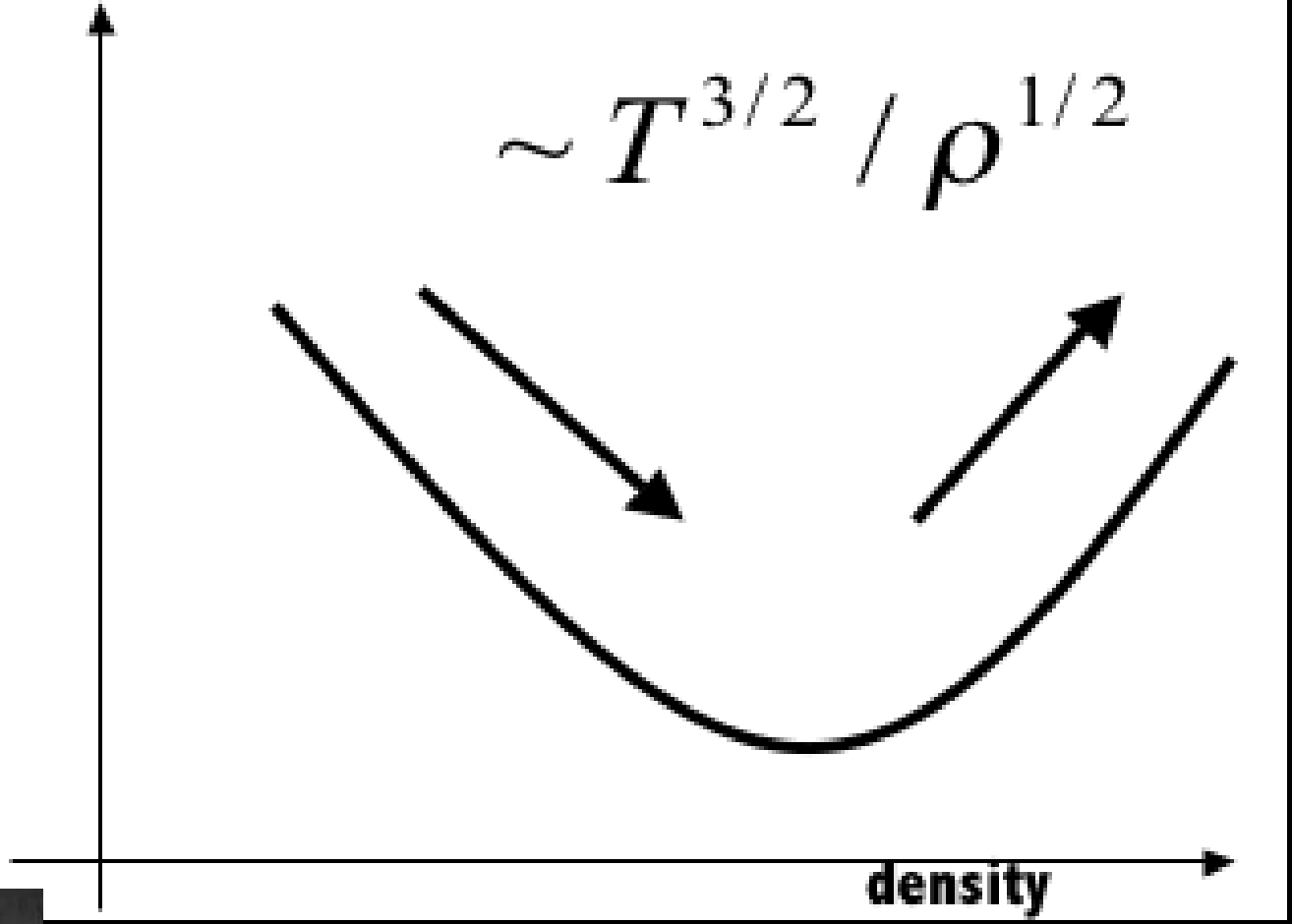
About 2% heavier stuff, such as carbon, oxygen, iron

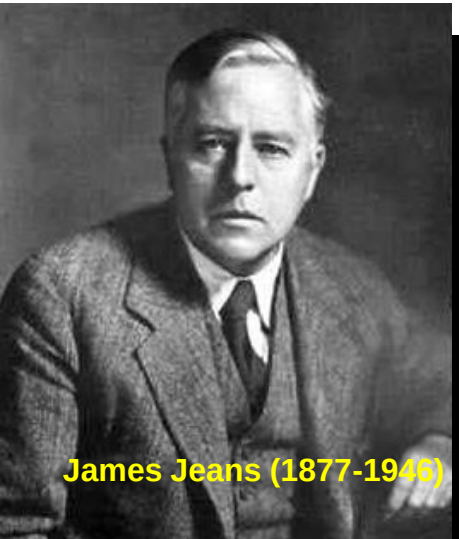
The compressive force of gravity

Spin it up and mix it well

Jeans mass

$$\sim T^{3/2} / \rho^{1/2}$$

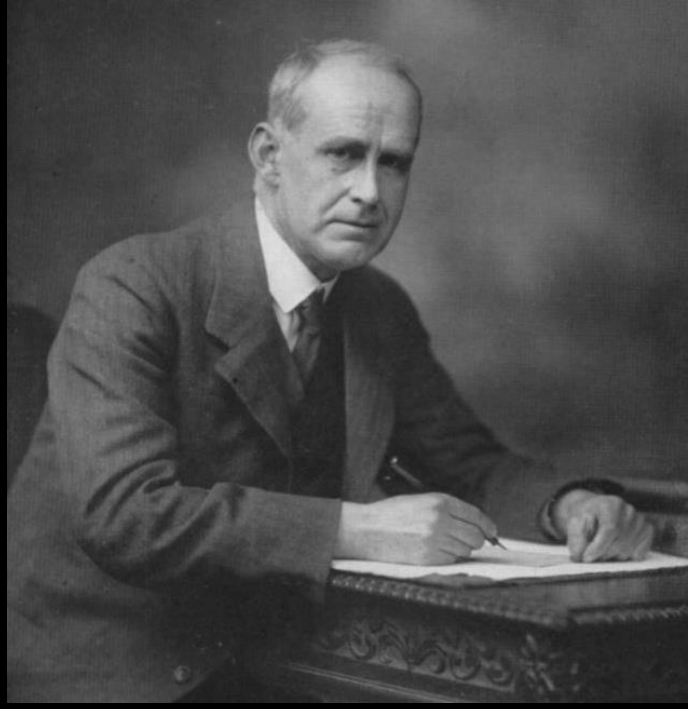




James Jeans (1877-1946)

gas pressure opposes gravitational collapse

imagine a physicist calculating on a cloud-bound planet
and ending with the dramatic conclusion,
"What 'happens' is the stars."



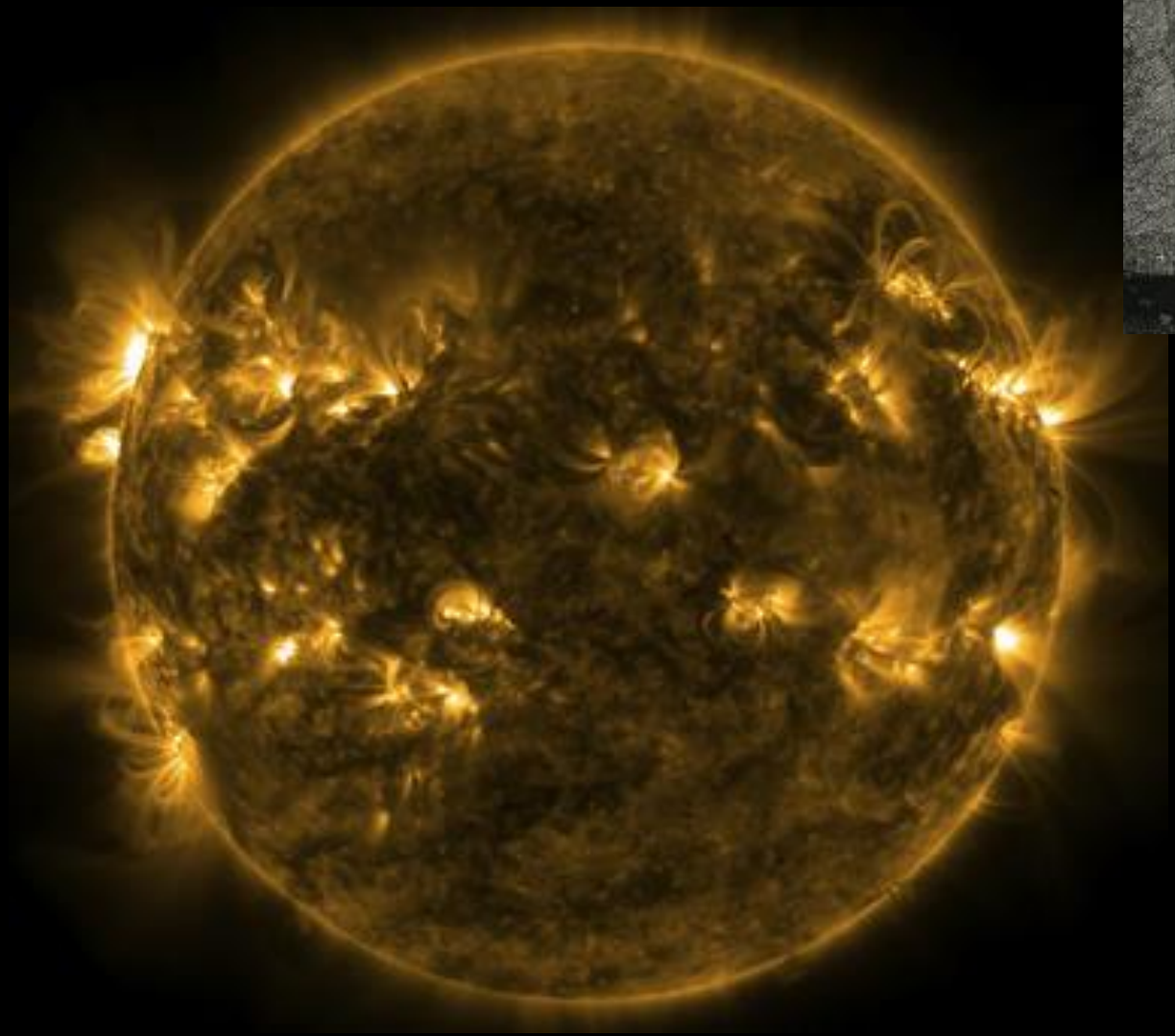
Sir Arthur Eddington (1882-1946)

He reasoned that too big a gas globe
would be so hot and full of radiation that it would blow itself up
and that too small a gas globe would be too cold to be luminous

This left him with the range between 0.5 and 50 solar masses

An amazing prediction:
he didn't know in 1926 that the source of stellar light is thermonuclear energy!

Double, double toil and trouble;
Fire burn and cauldron bubble.

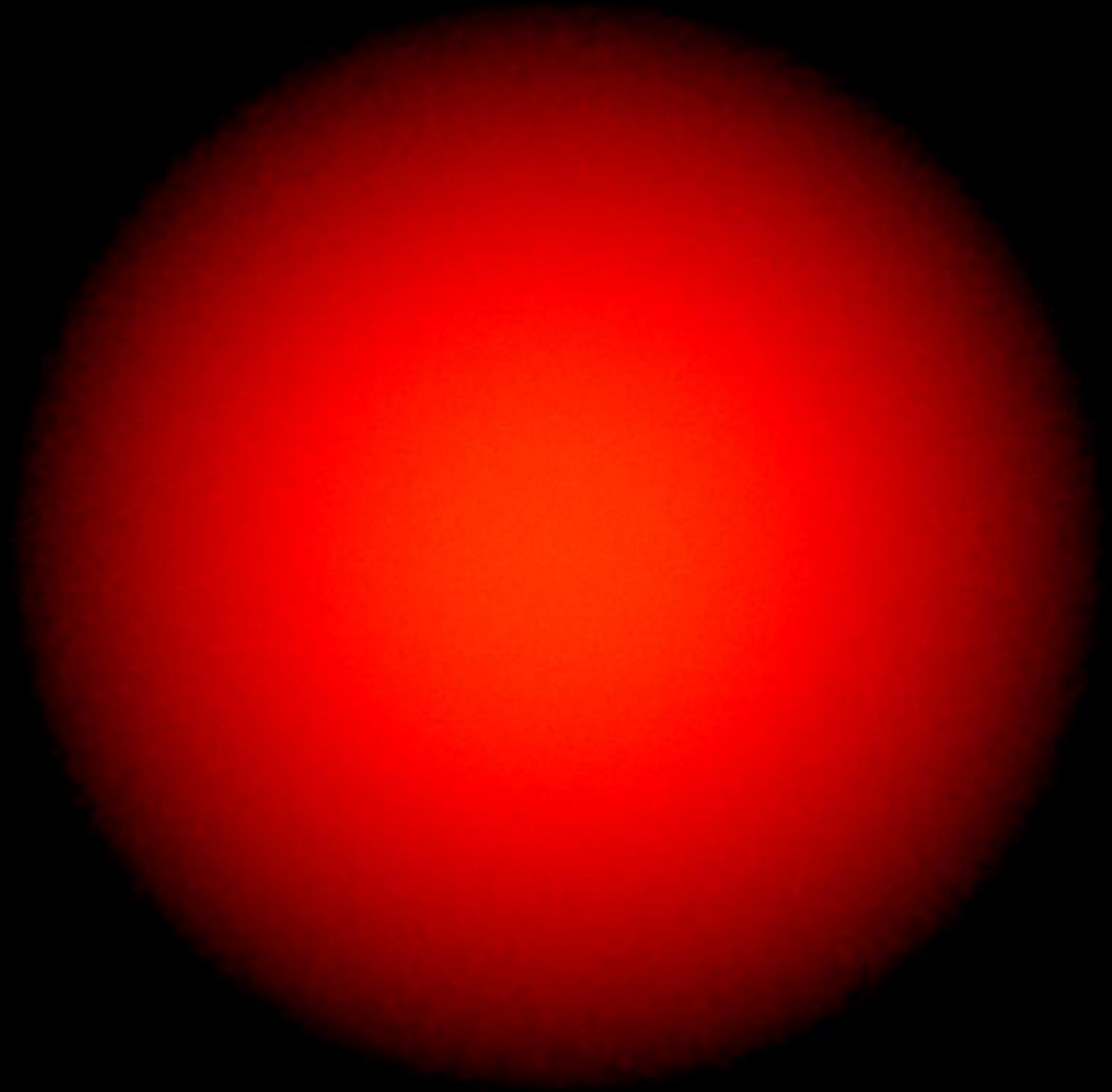


What is it that breathes fire into the equations and makes a universe for them to describe?

Stephen Hawking, in *A Brief History of Time (1998)*

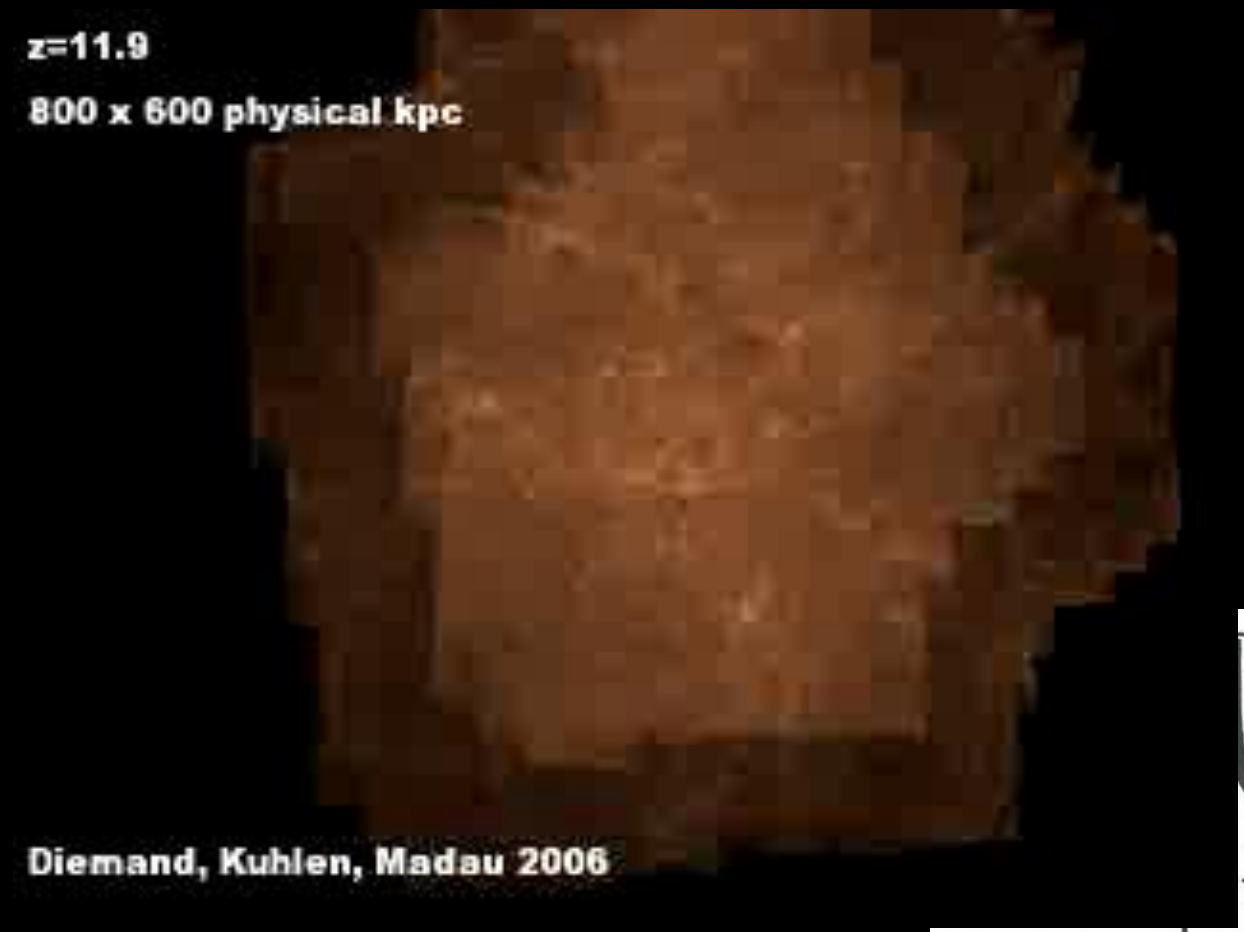
Stars don’t form alone but in clusters

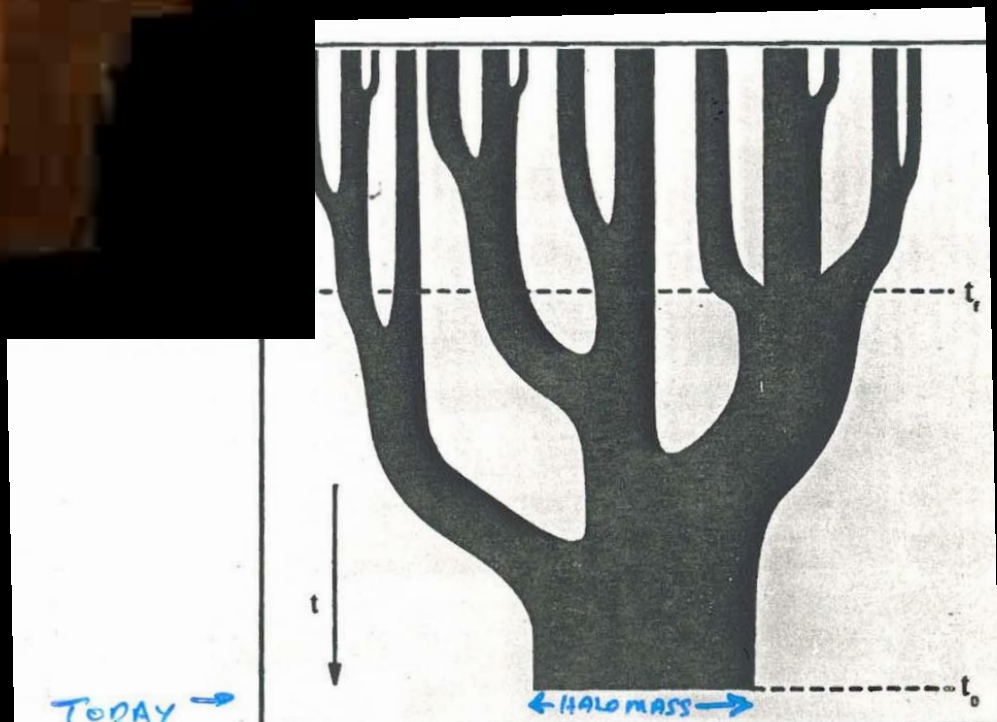
BIRTH OF A STAR CLUSTER



Ian Bonnell

THE MERGER TREE OF STRUCTURE EVOLUTION





Quantum fluctuations

Vacuum energy is what accelerates the universe: we call it dark energy

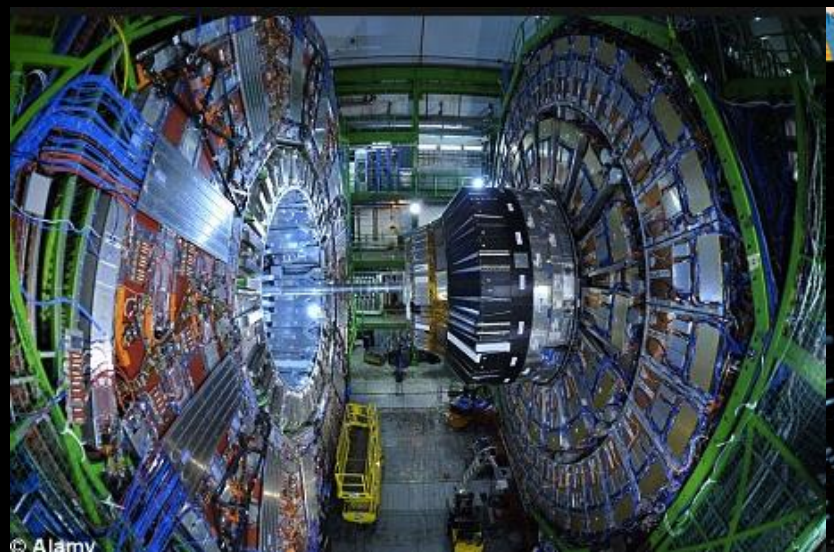
It generates wrinkles in space-time that come and ago in no time at all

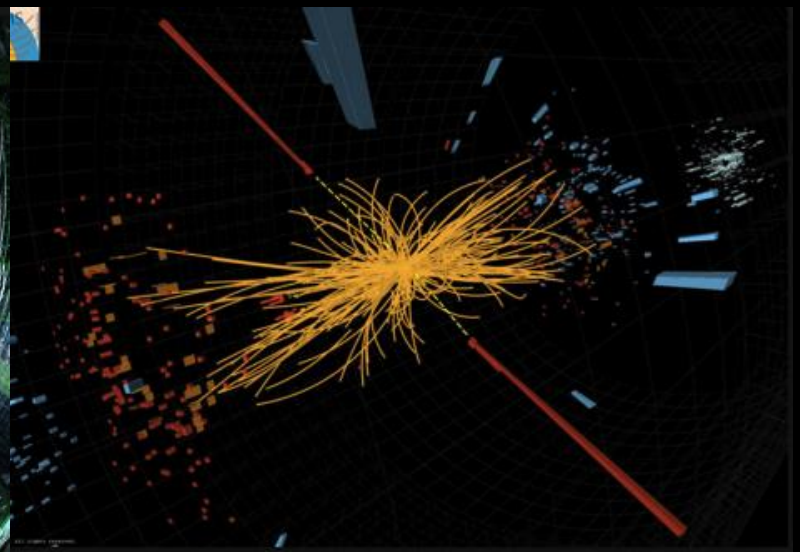
Predicted by Heisenberg's uncertainty principle

The wierdest things can exist if sufficiently short-lived

Higgs bosons were discovered in the Large Hadron Collider but really are everywhere:
It's just that they come and go so rapidly that we cannot detect them

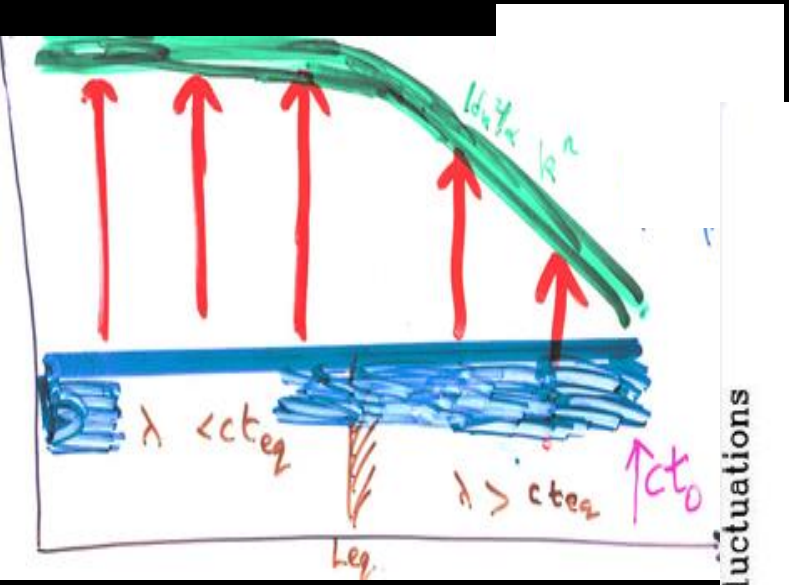
All this coming and going produces fluctuations in energy

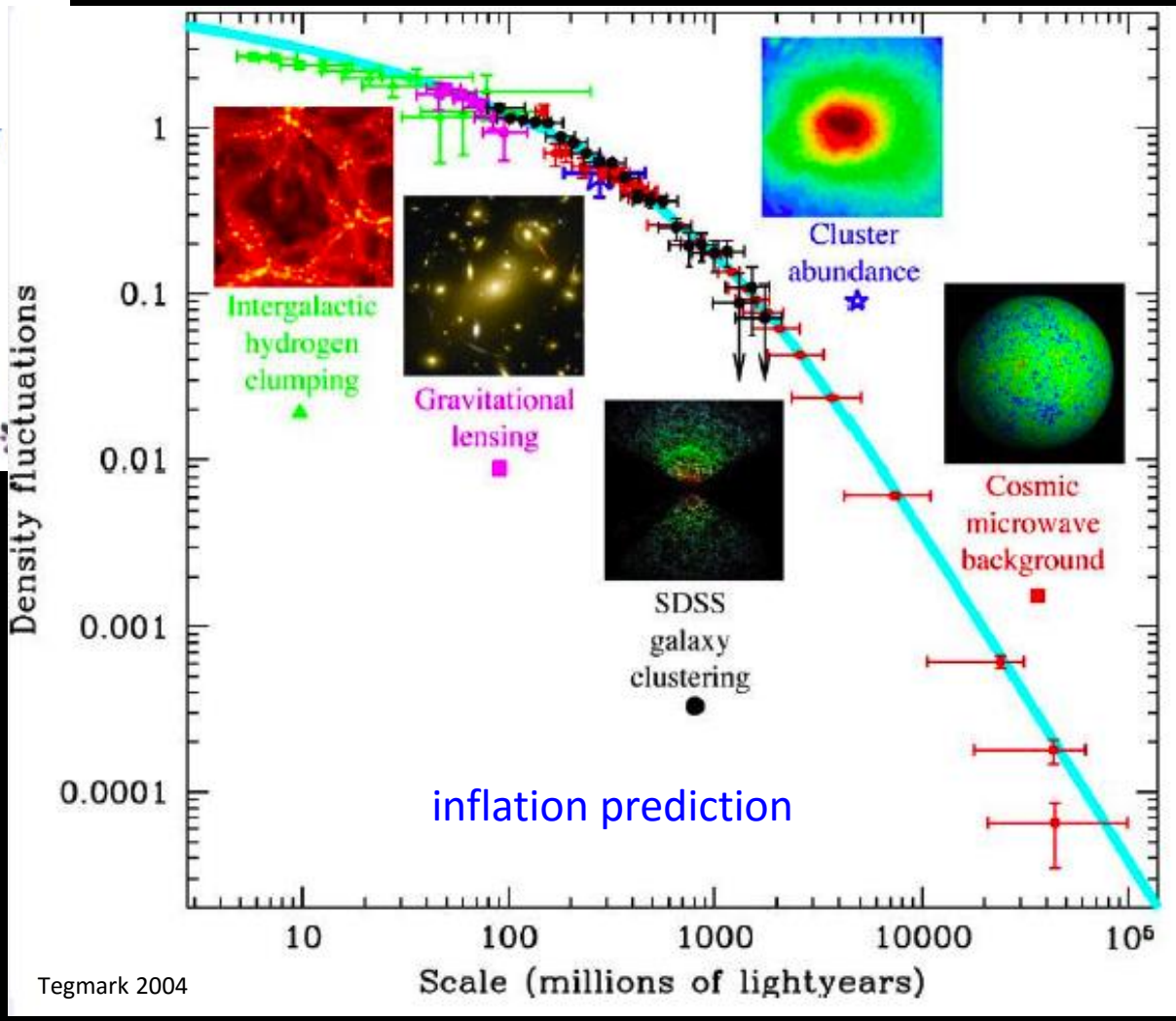




FROM DENSITY FLUCTUATIONS TO GALAXIES

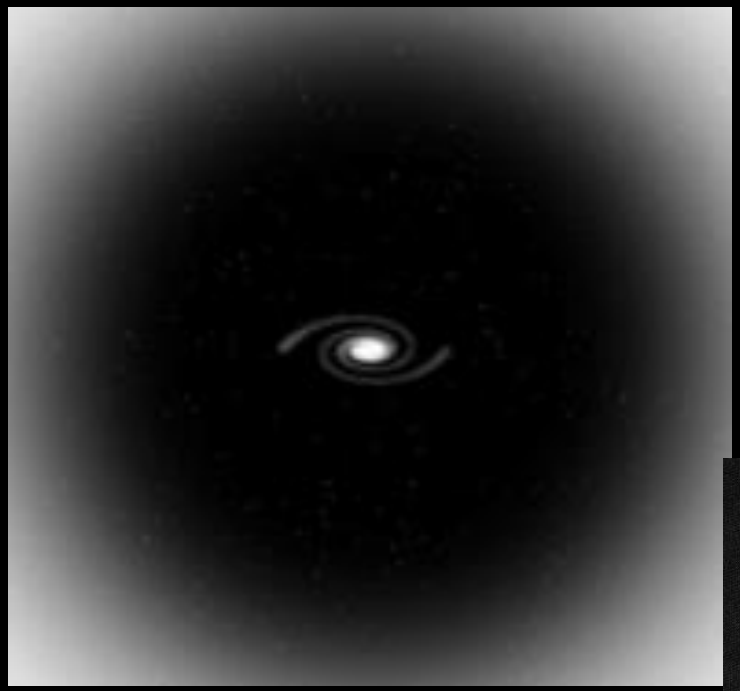
Cosmic microwave background and large-scale structure constraints overlap





prediction for dark matter

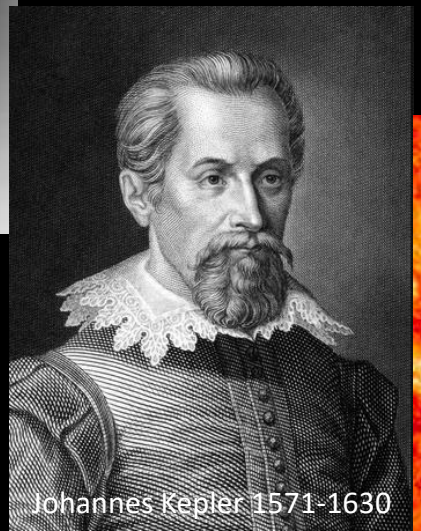
orbital velocities of stars in a galaxy dominated by dark matter should not decrease at large radii



$V^2 = \frac{GM(r)}{r} \sim$ constant

if M increases with r

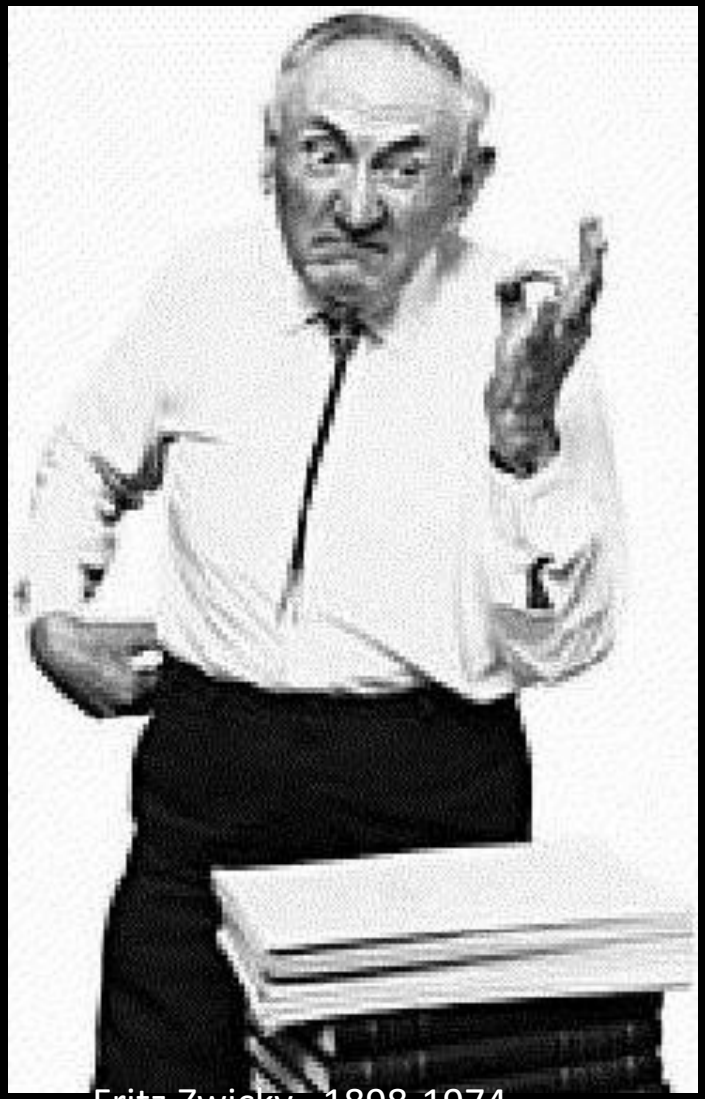
Unlike Kepler's Law for the planets:
with increasing distance from Sun, $V \sim r^{-1/2}$



Johannes Kepler 1571-1630

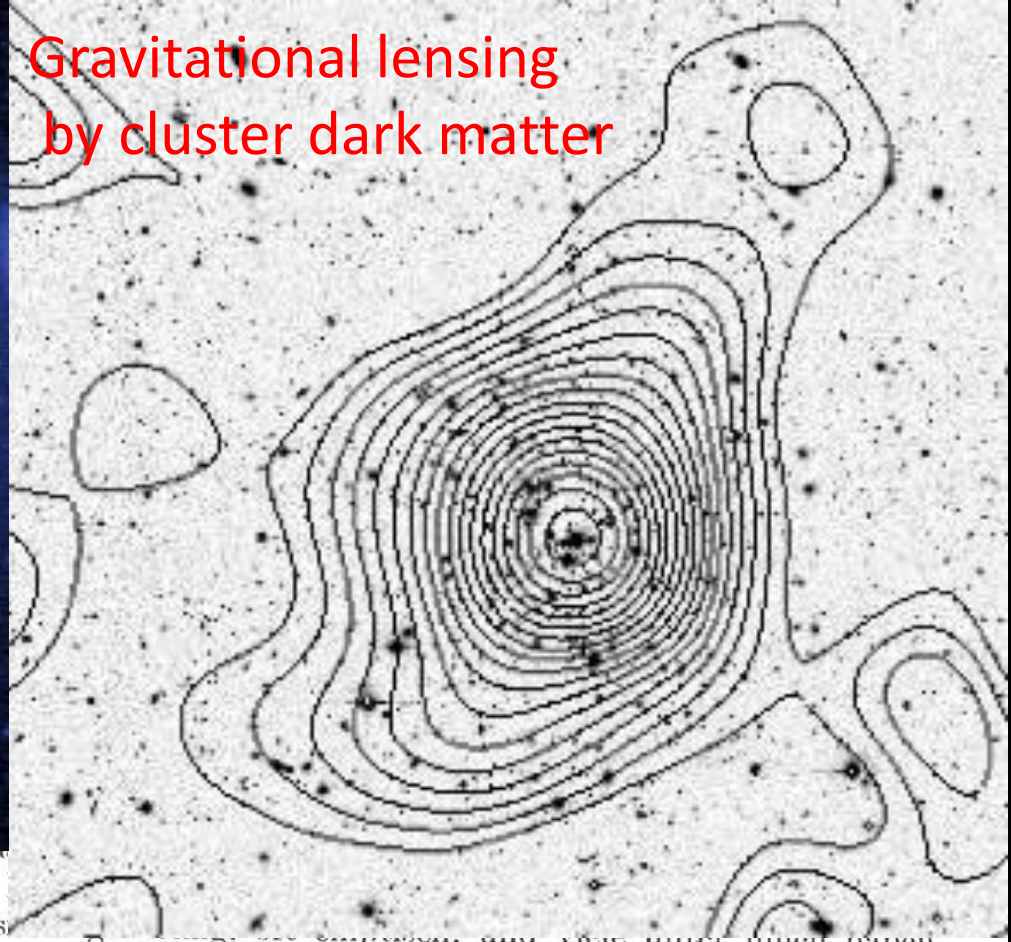
HE PREDICTED DARK MATTER

Pioneered supernovae, neutron stars, gravitational lensing by clusters and dark matter



Fritz Zwicky 1898-1974

Gravitational lensing
by cluster dark matter



Fritz Zwicky

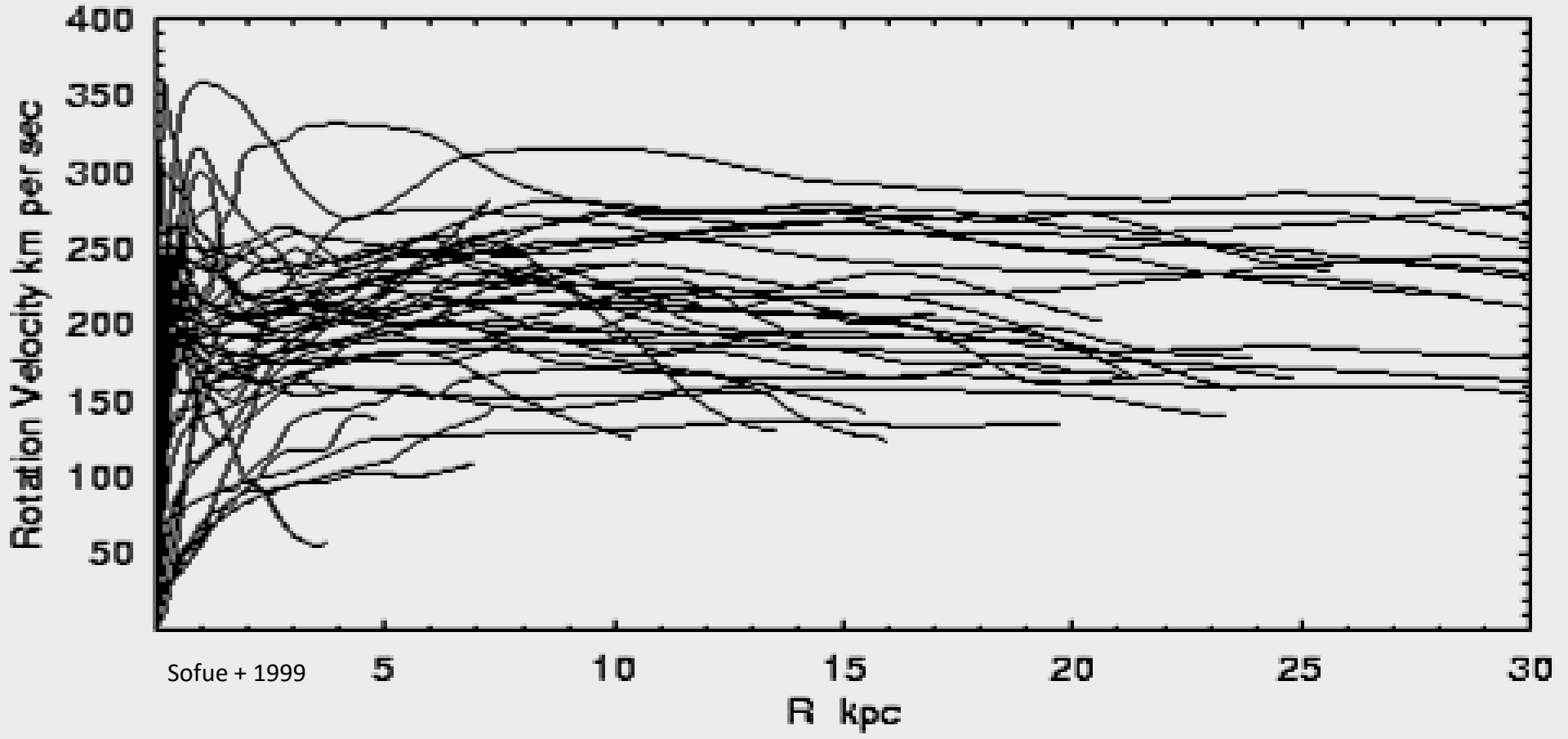
nen.
sind s

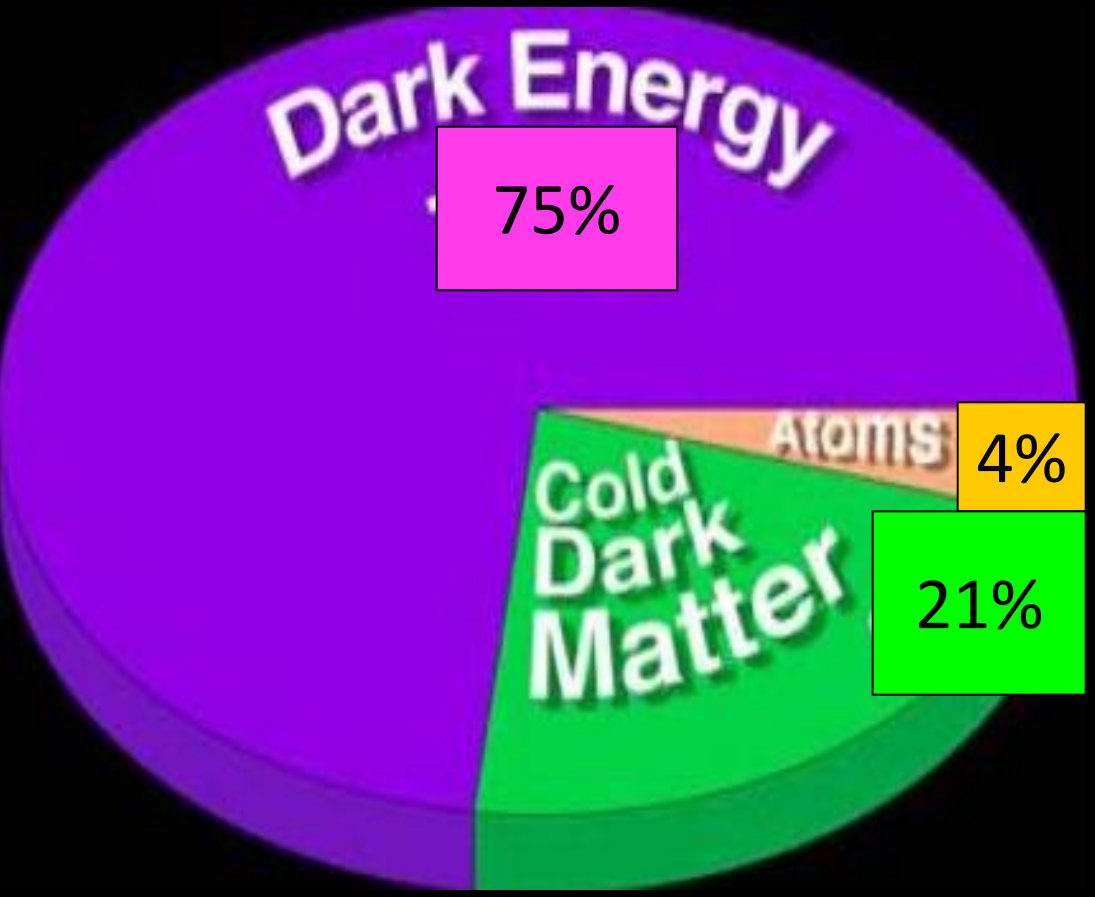
Rotverschiebung extragalaktischer Nebel.

wie beobachtet, einen mittleren Dopplereffekt von
k oder mehr zu erhalten, müsste also die mittlere
masystem mindestens 400 mal grösser sein als die auf
Beobachtungen an leuchtender Materie abgeleitete[1]).
lies bewahrheiten sollte, würde sich also das überras
tat ergeben, dass dunkle Materie in sehr viel grösserer
nden ist als leuchtende Materie.


Vera Rubin

M 31
Babcock
140 foot
HI data points from Roberts
400
300
200
100
DISTANCE TO CENTER (ARC MINUTES)

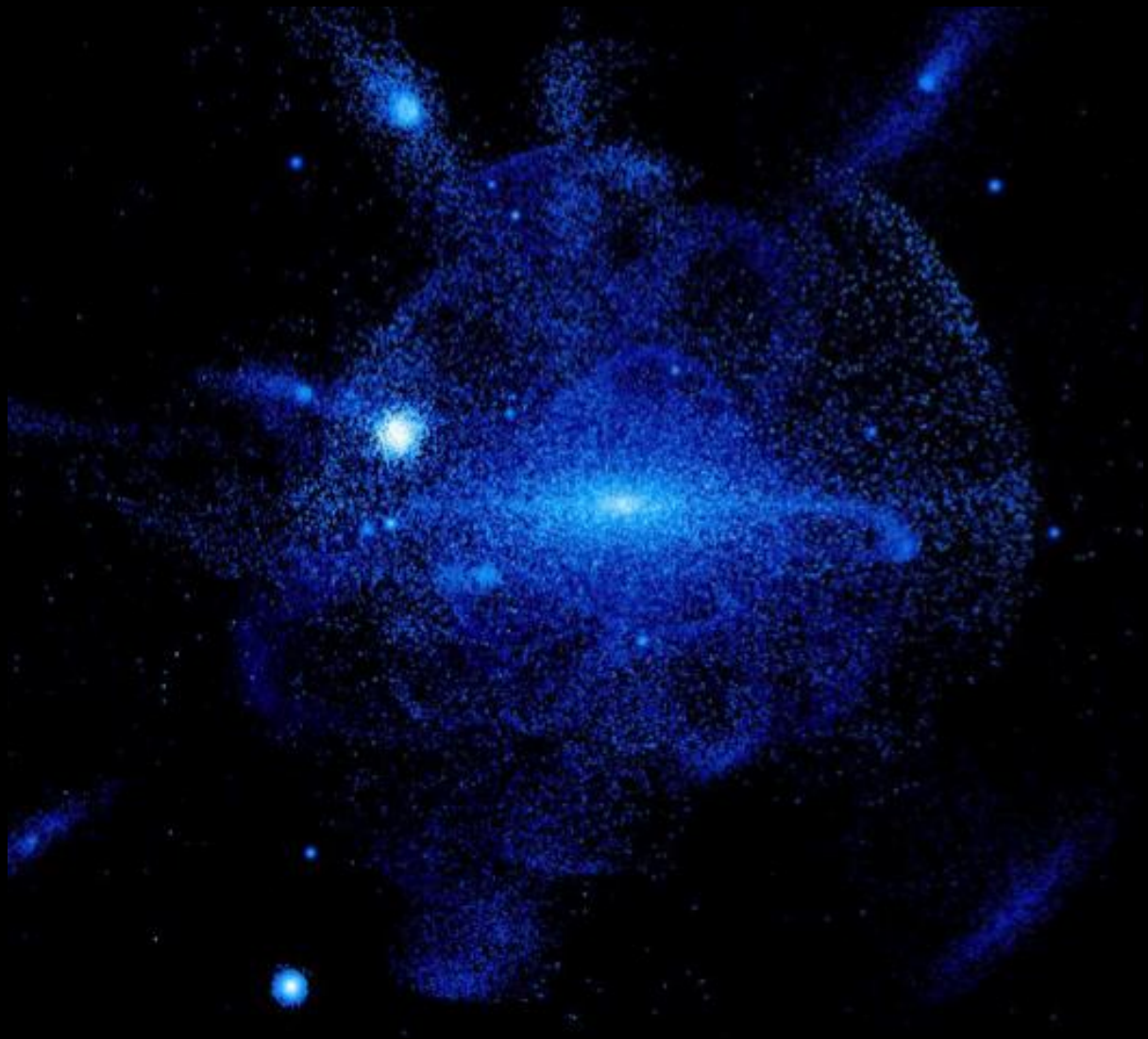

Rotation Velocity km per sec
400
350
300
250
200
150
100
50
5
10
15
20
25
30
R kpc
Sofue + 1999



We still do not know what the dark matter is, but there is a lot of it!

Before the numerical simulations
this is how a dark halo was imagined to be

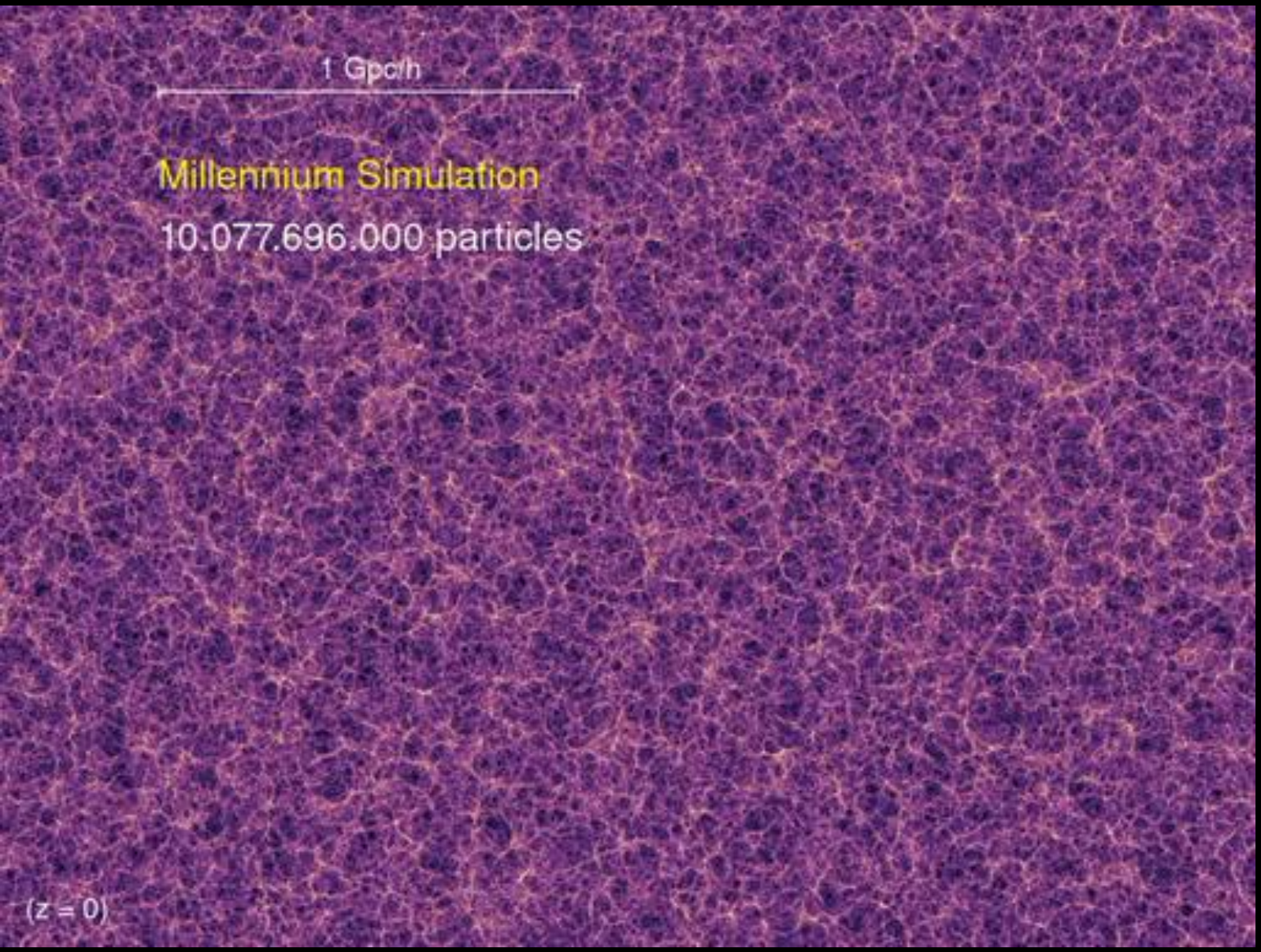
The new reality



Bullock & Johnston 2005

THE DARK SIDE OF STRUCTURE EVOLUTION

FROM THE BEGINNING



Volker Springel


Simulation of a dark halo
Galaxy
© ESA &

THE LUMINOUS SIDE OF STRUCTURE EVOLUTION: THE BIG PICTURE

THE BIG PICTURE, FROM OXFORD

Julien Devriendt et al

THE LUMINOUS SIDE OF STRUCTURE EVOLUTION: TOWARDS OUR GALAXY

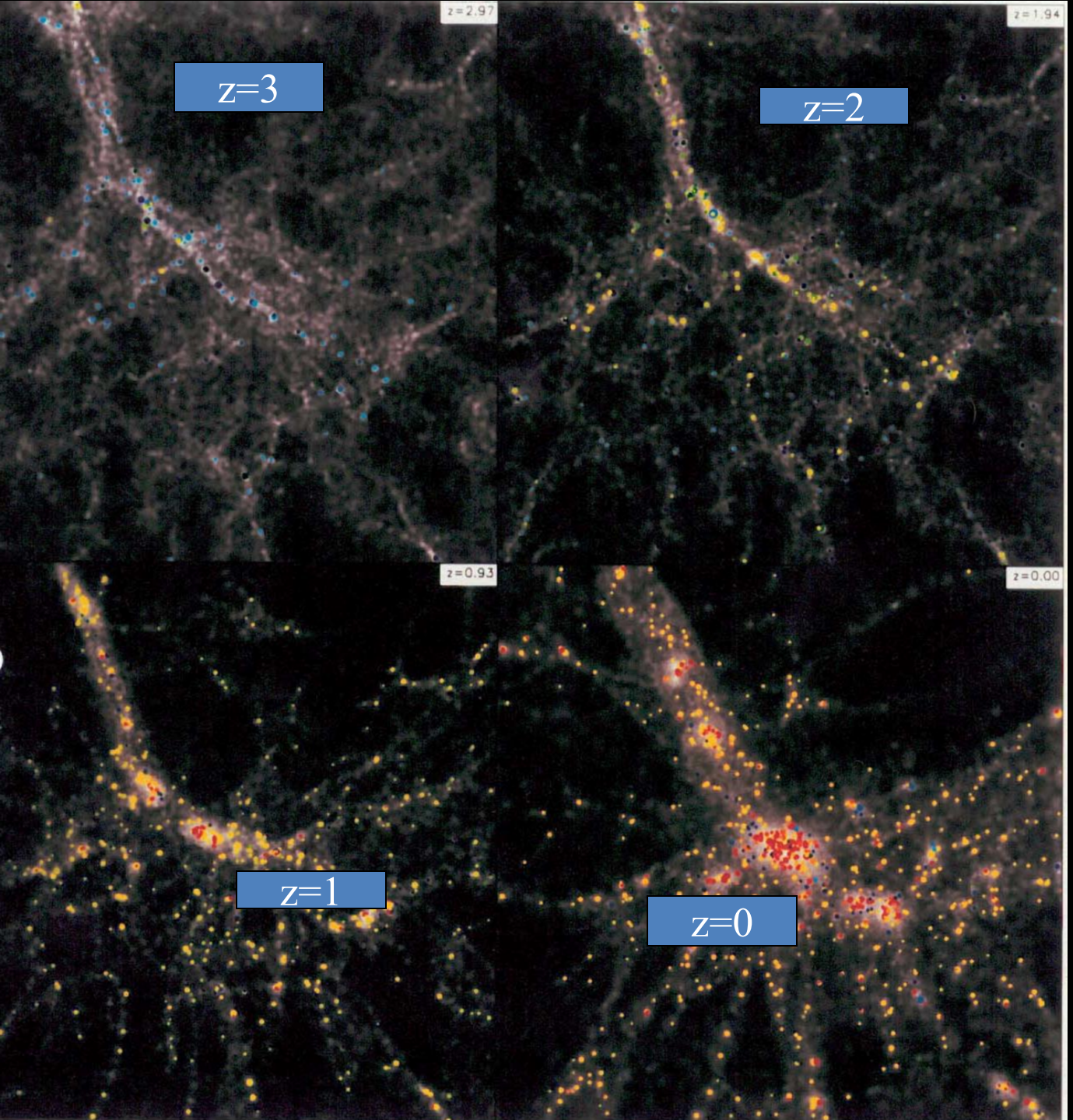
THE BIG PICTURE, FROM AMSTERDAM

Joop Schaye et al

BIRTH OF THE MILKY WAY

THE VIEW FROM UCL

Andrew Pontzen et al



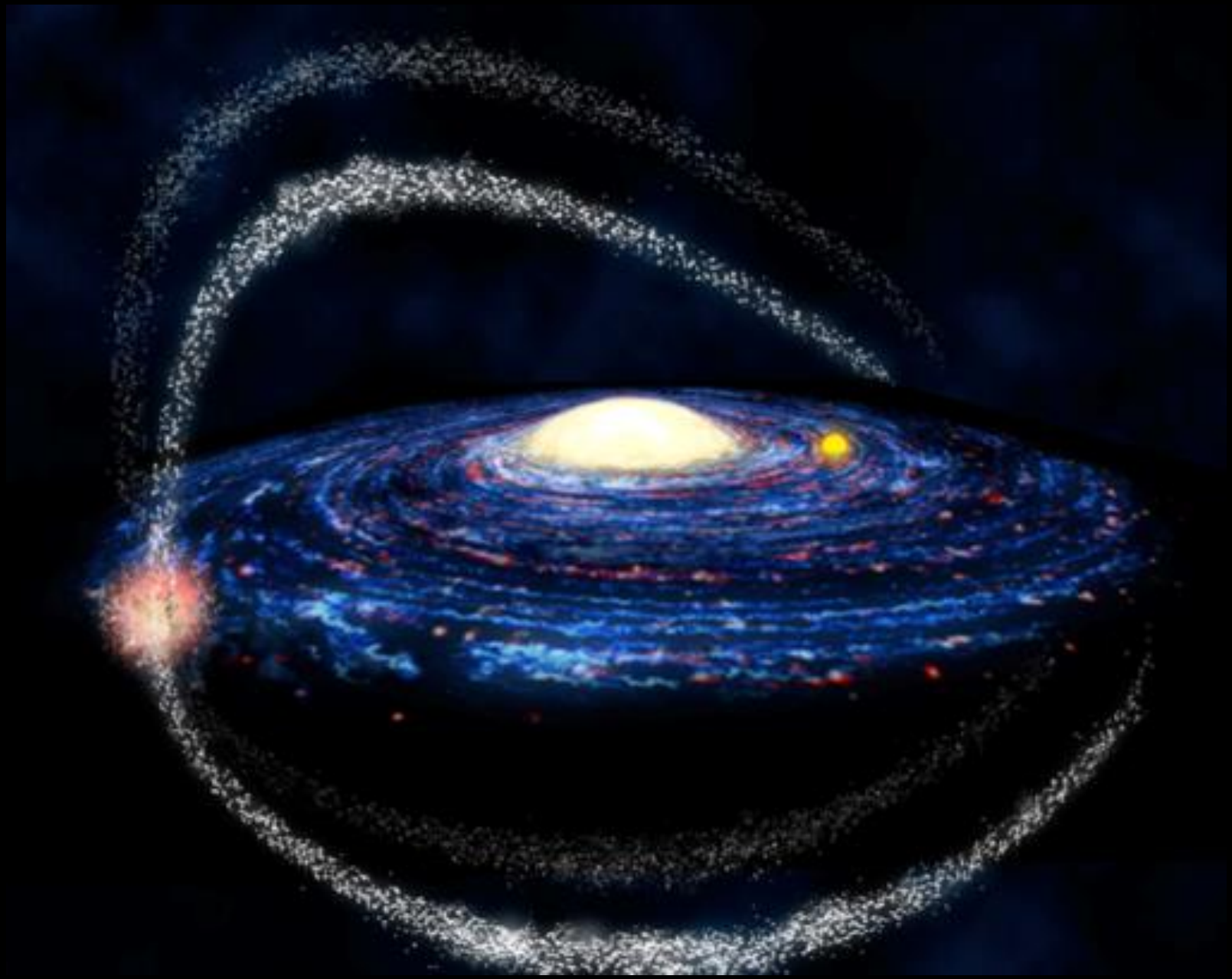
Red galaxies are older,
Formed in denser regions

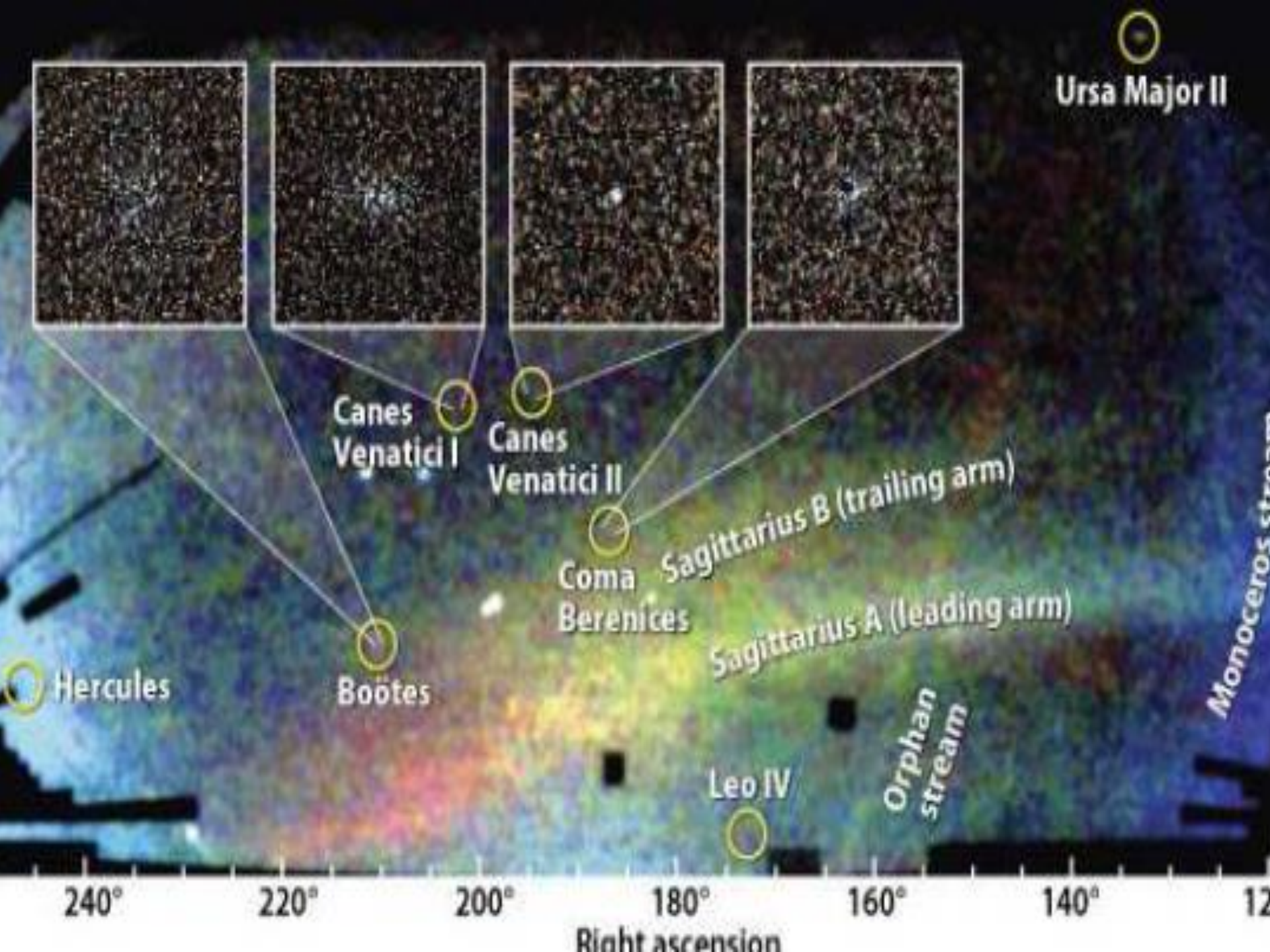
Blue galaxies are young,
formed in low density
regions

G, Kauffmann 2008

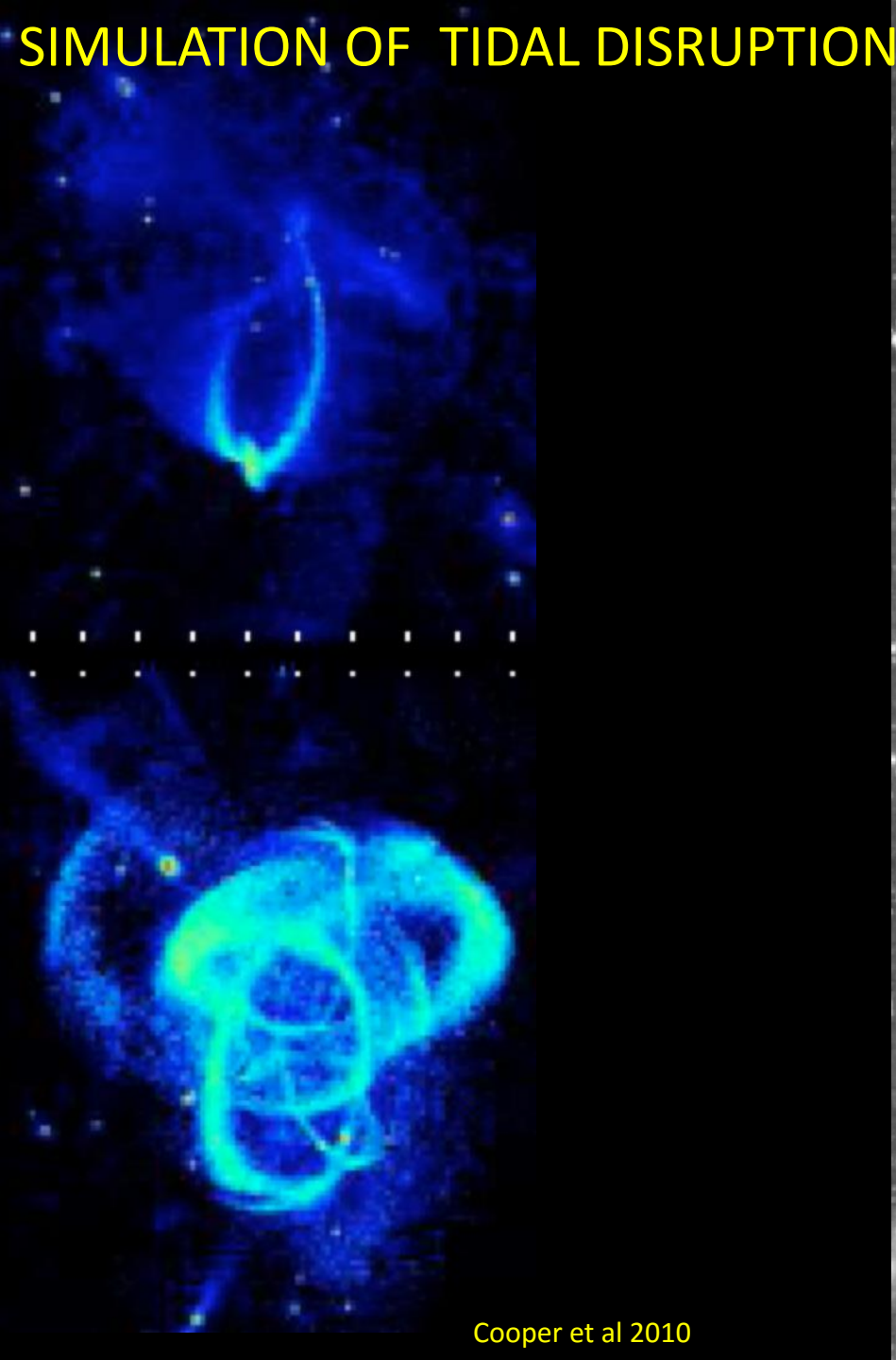
Searching for fossils from the assembly of the Milky Way

A reconstruction of how our galaxy was assembled




Ursa Major II
Canes Venatici I
Canes Venatici II
Coma Berenices
Sagittarius B (trailing arm)
Sagittarius A (leading arm)
Hercules
Boötes
Leo IV
Orphan stream
Monoceros stream
240°
220°
200°
180°
160°
140°
Right ascension

SIMULATION OF TIDAL DISRUPTION



Cooper et al 2010

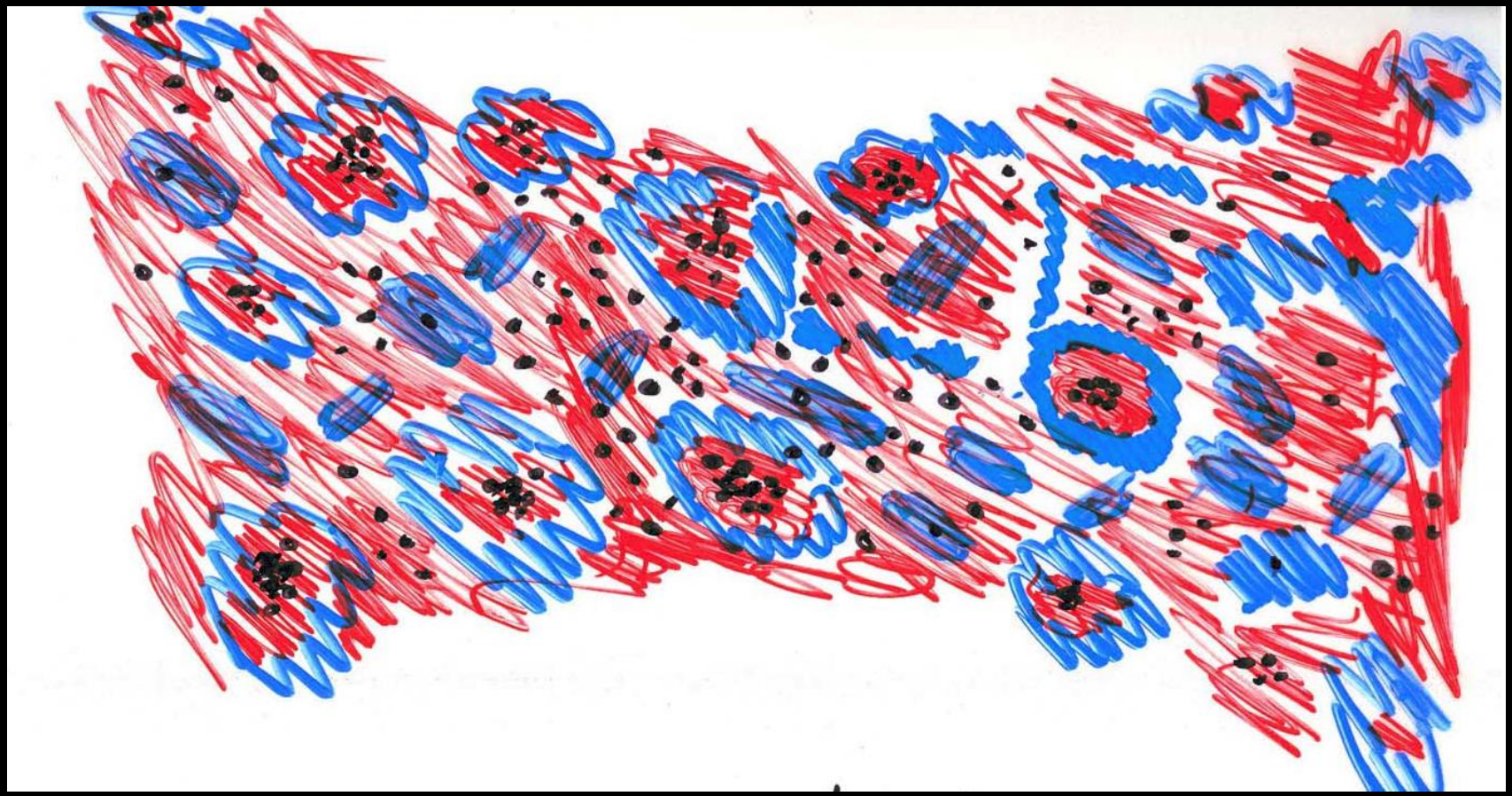
OBSERVATION

Martinez-Delgado et al 2008

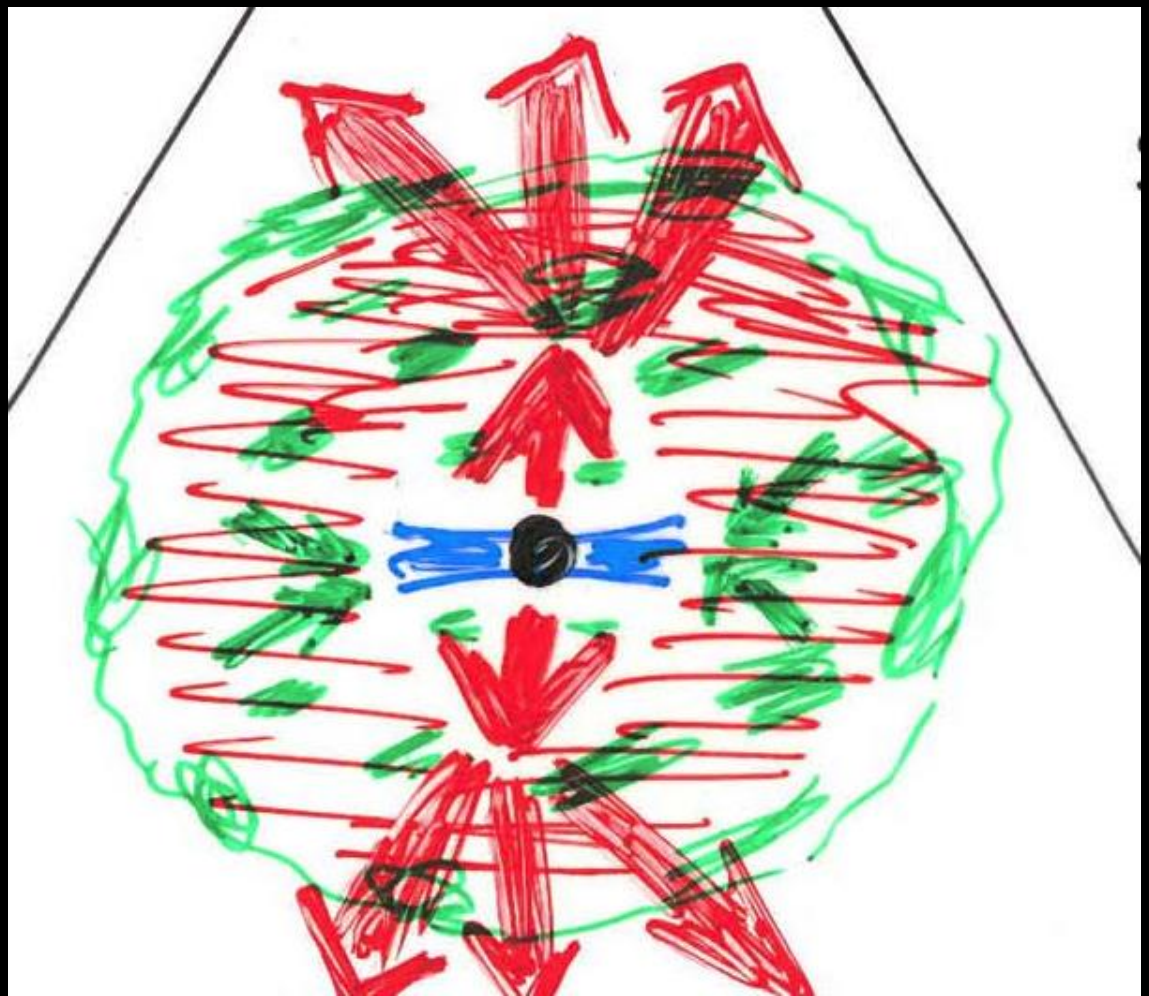
An ultrafaint dwarf galaxy

Leo T

Our Milky Way galaxy is a complex mixture of stars and cold gas clouds and hot diffuse gas



And in our galactic centre there lurks a massive black hole which springs into explosive activity every million years or so

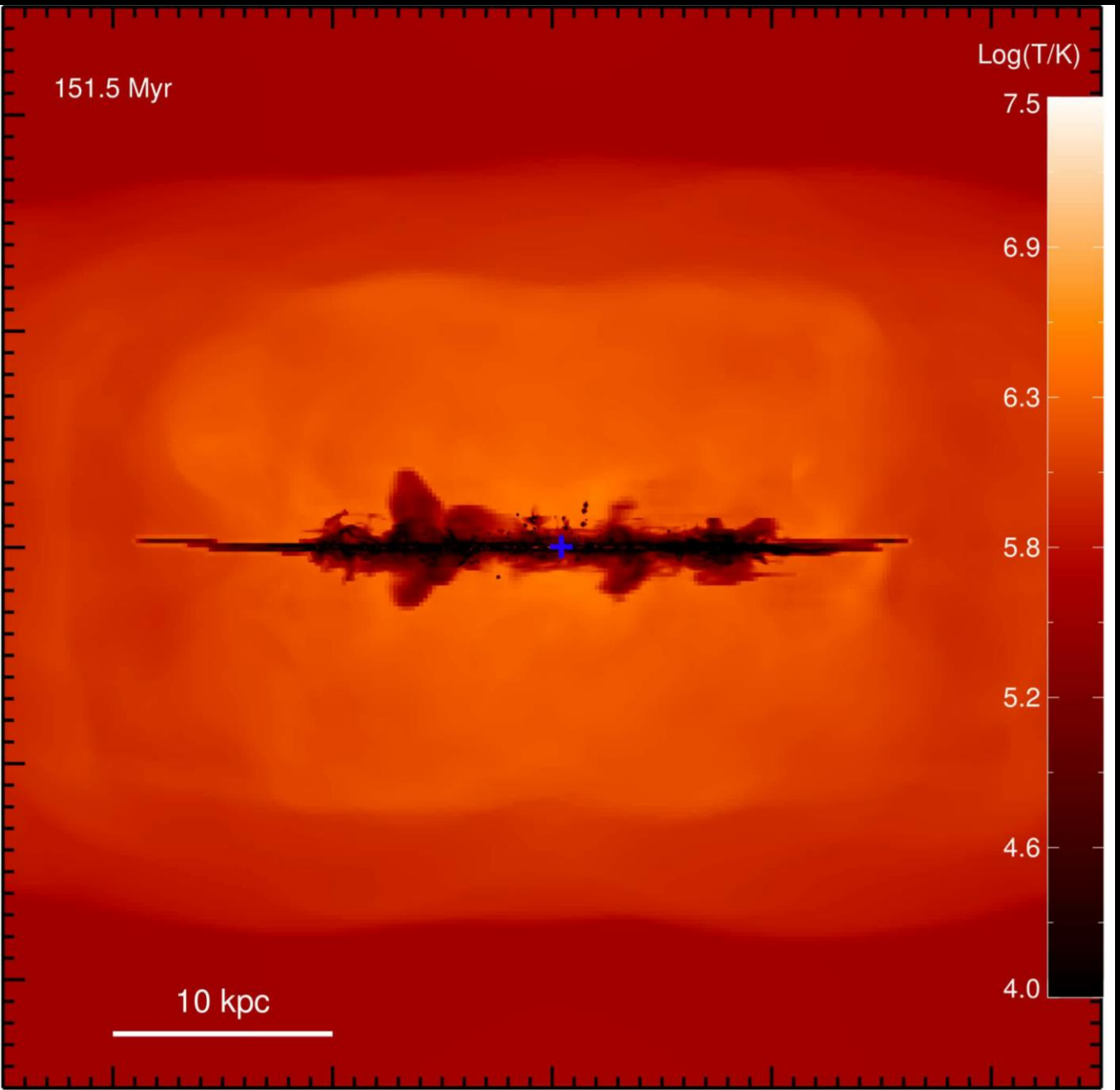


THE VIOLENT SIDE OF STRUCTURE EVOLUTION: LONG AGO

THE VIOLENCE OF BLACK HOLES

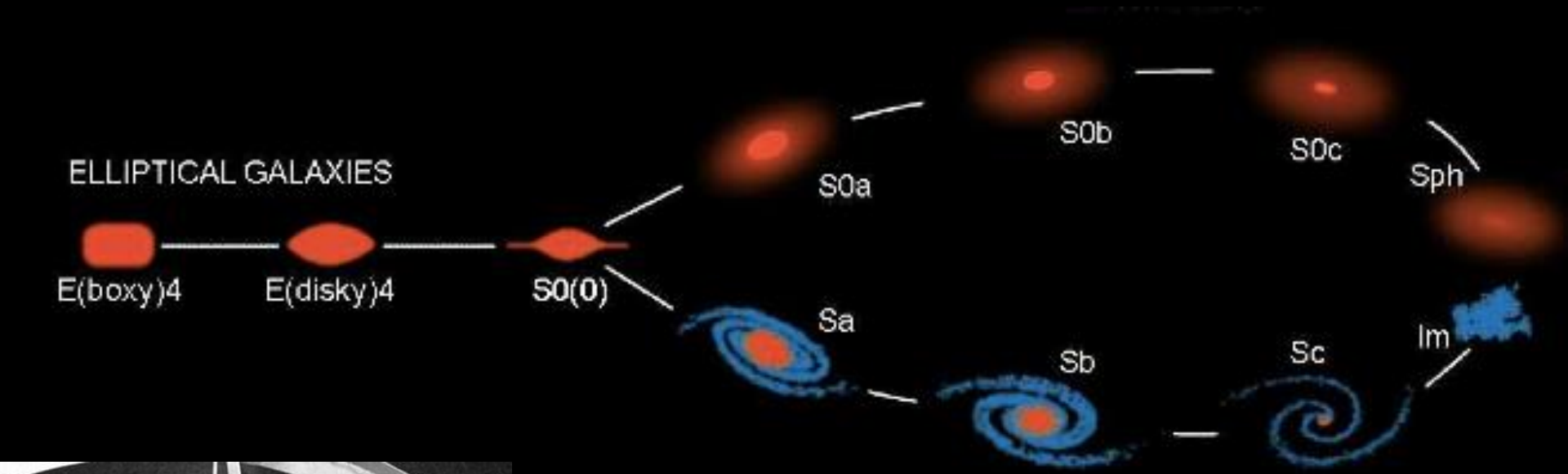
Tiago Costa et al

SURVIVAL IS AN OPTION

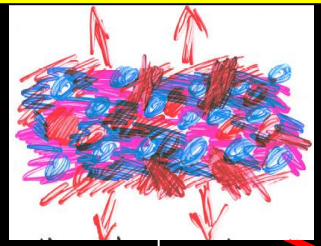


Jared Gabor

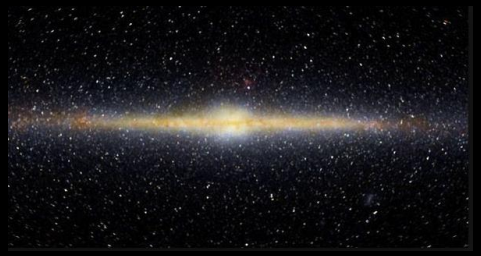
The Hubble sequence of galaxies



FEEDBACK IS CRUCIAL



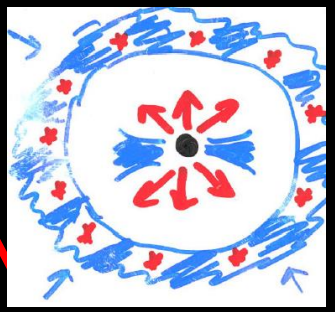
theory



Model matches data

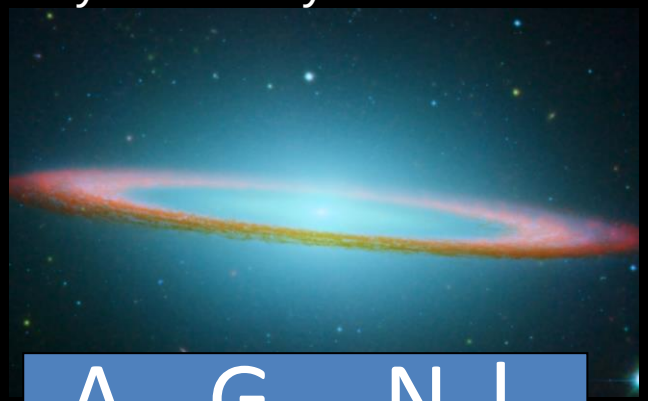
observations

Number of galaxies



SuperNovae

Galaxy luminosity/mass



ActiveGalacticNuclei

We are nothing special:

"our galaxy is only one of millions of billions in this amazing and expanding universe"

The Galaxy Song, Monty Python