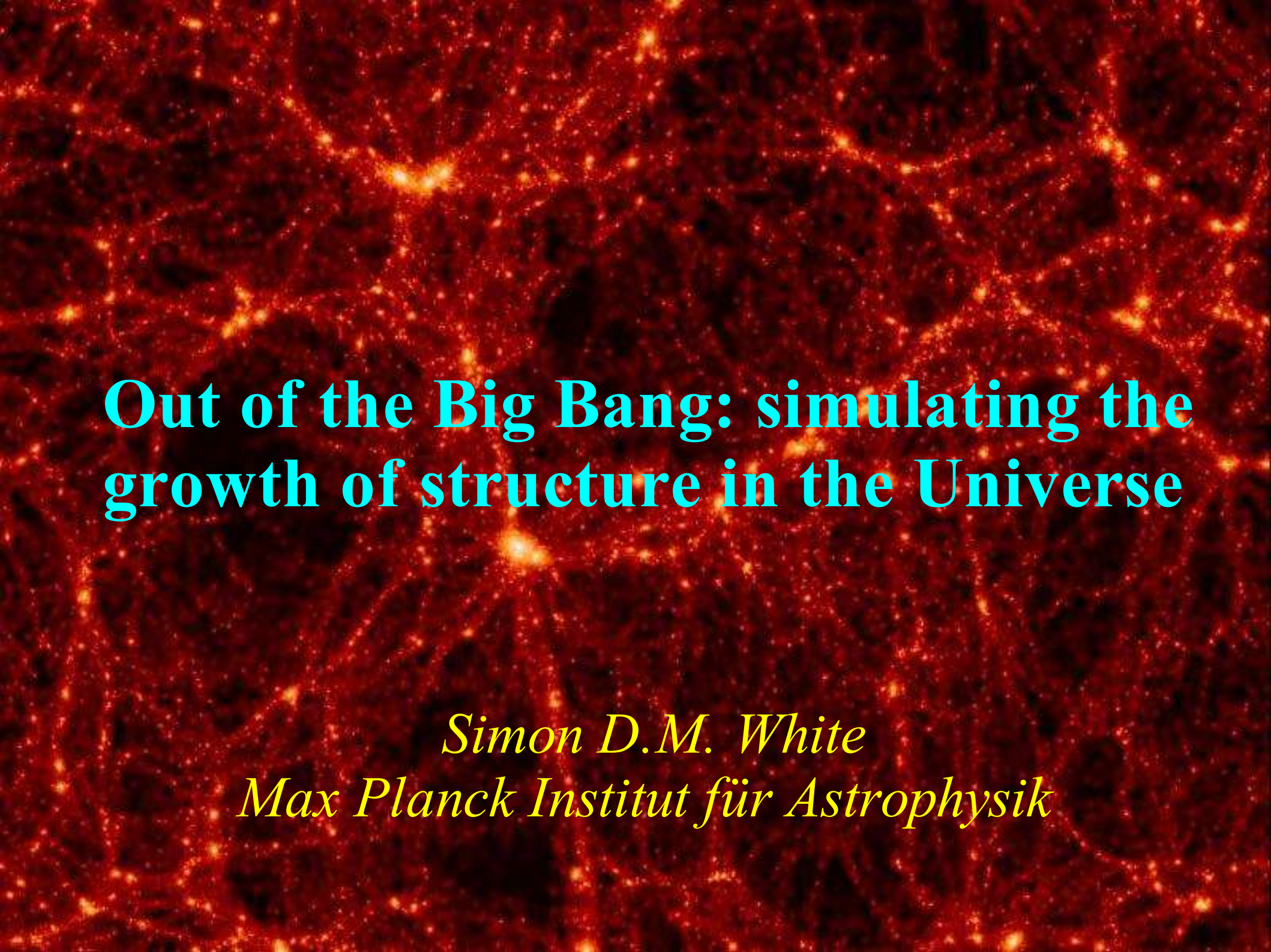


Out of the Big Bang: simulating the growth of structure in the Universe

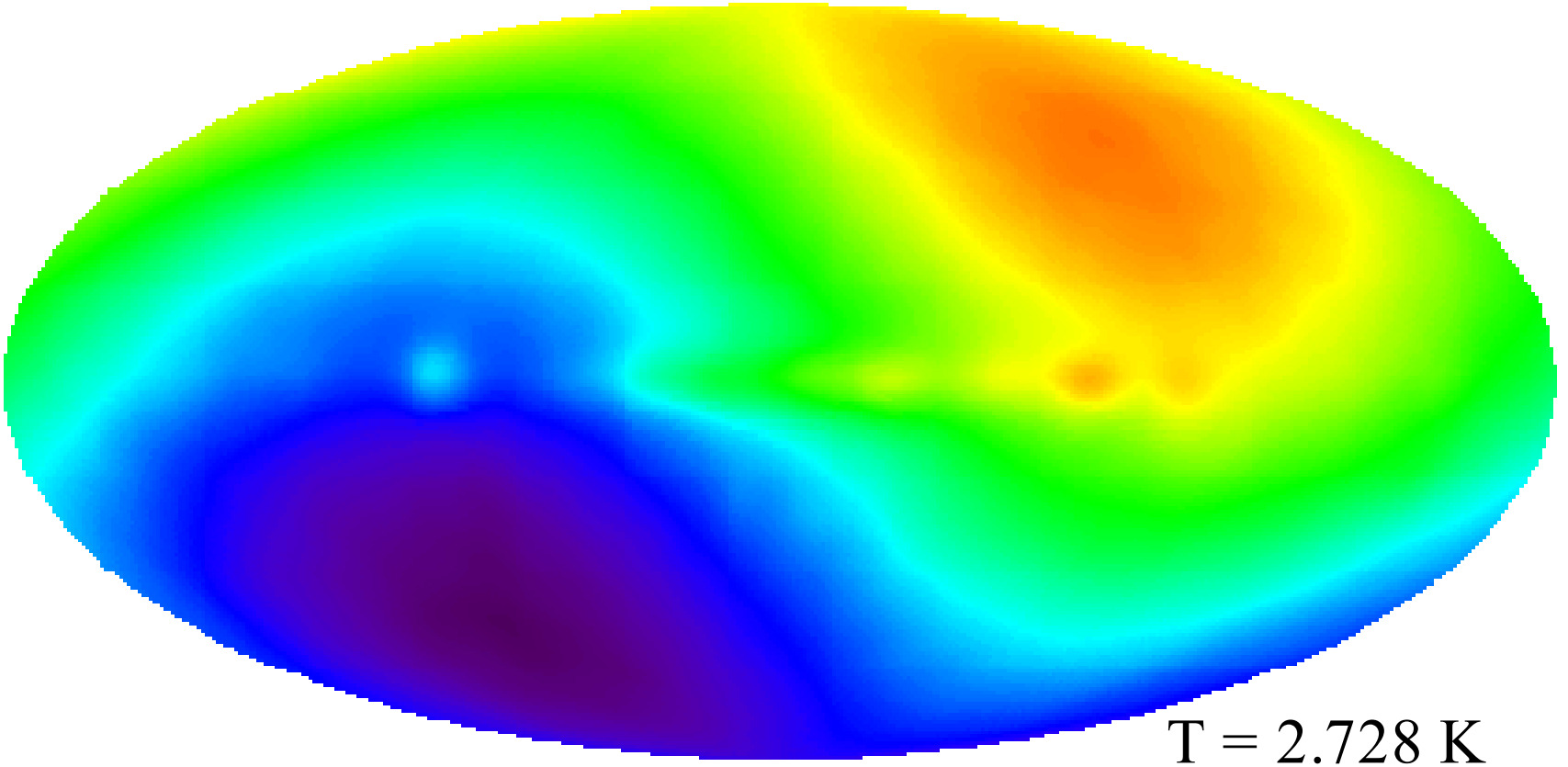
Simon D.M. White
Max Planck Institut für Astrophysik

COBE's microwave map of the entire sky

T = 2.728 K

ΔT = 0.1 K

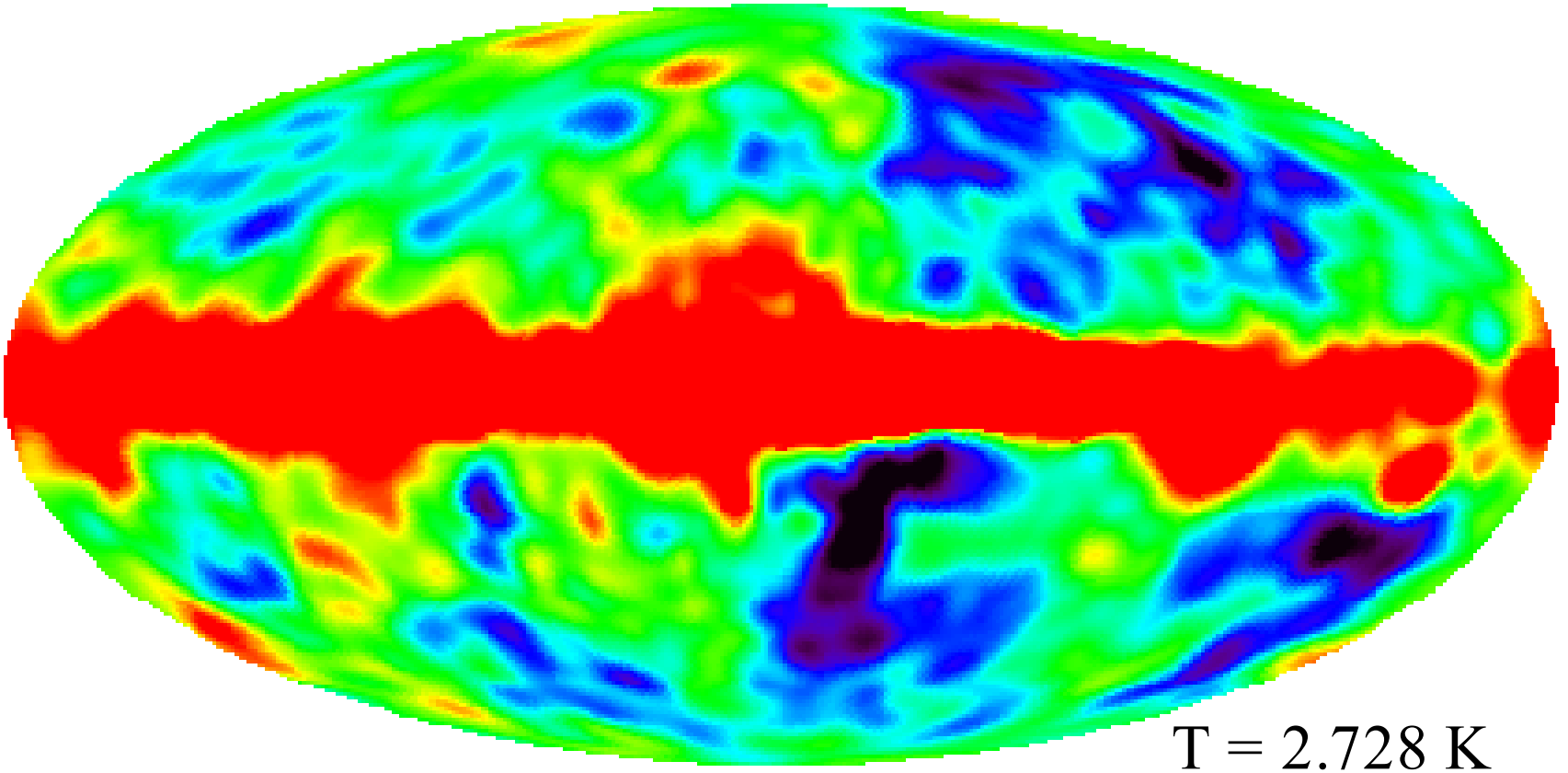
COBE's microwave map of the entire sky



T = 2.728 K

ΔT = 0.0034 K

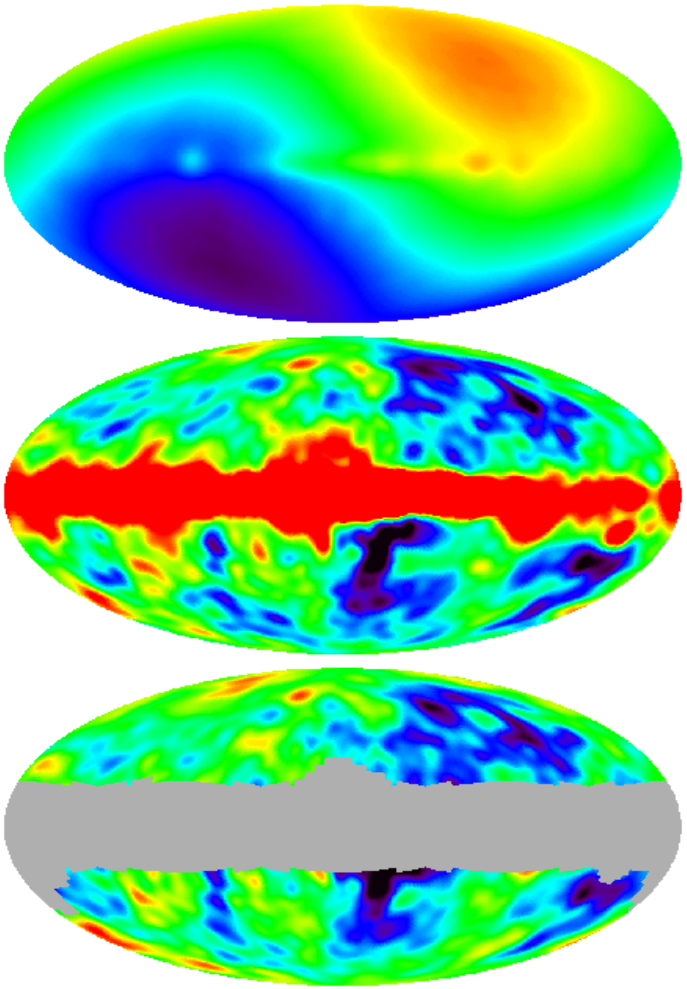
COBE's microwave map of the entire sky



T = 2.728 K

ΔT = 0.00002 K

Structure in the COBE map



- One side of the sky is `hot', the other is `cold'

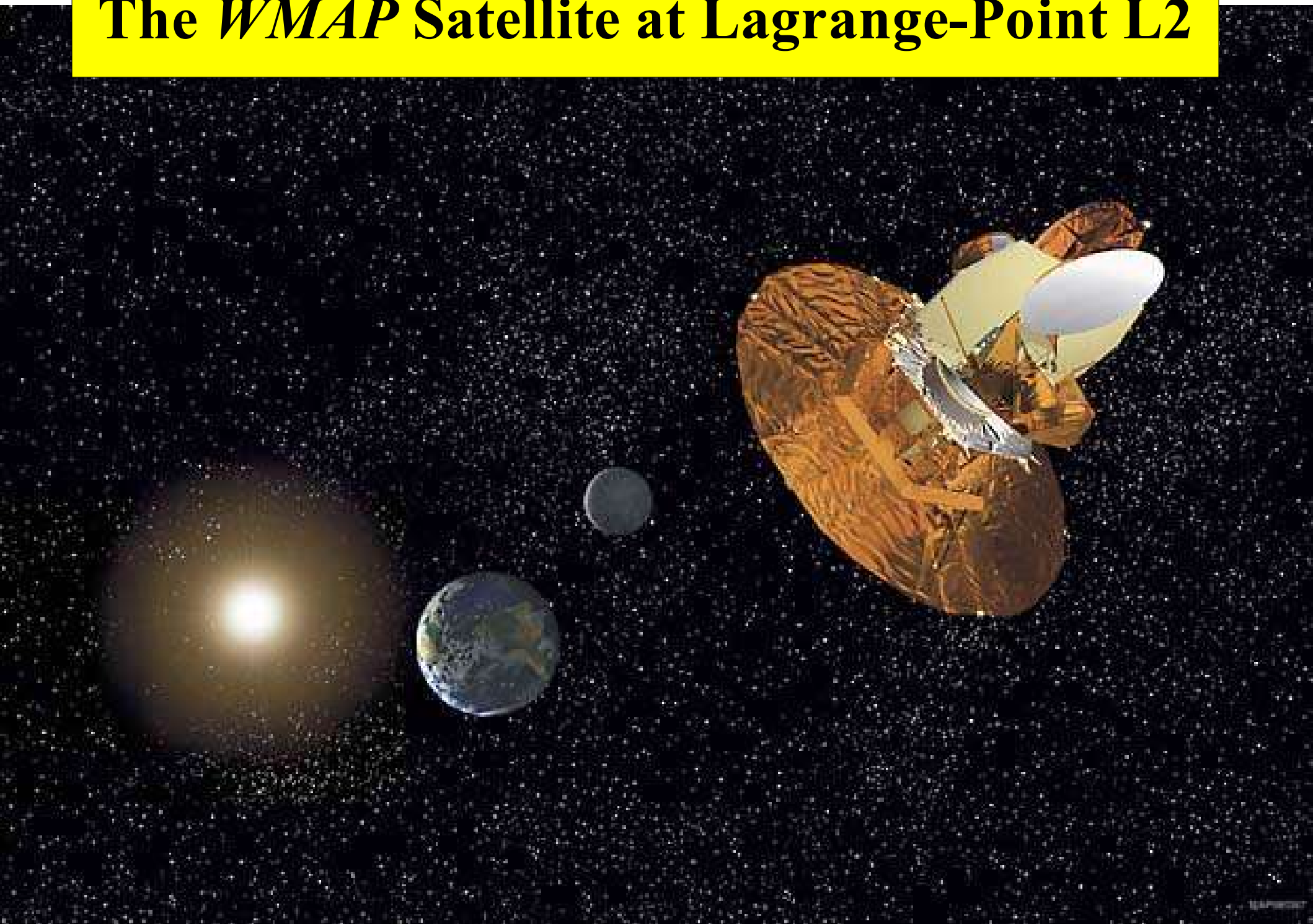
→ the Earth's motion through the Cosmos

$V_{\text{Milky Way}} = 600$ km/s

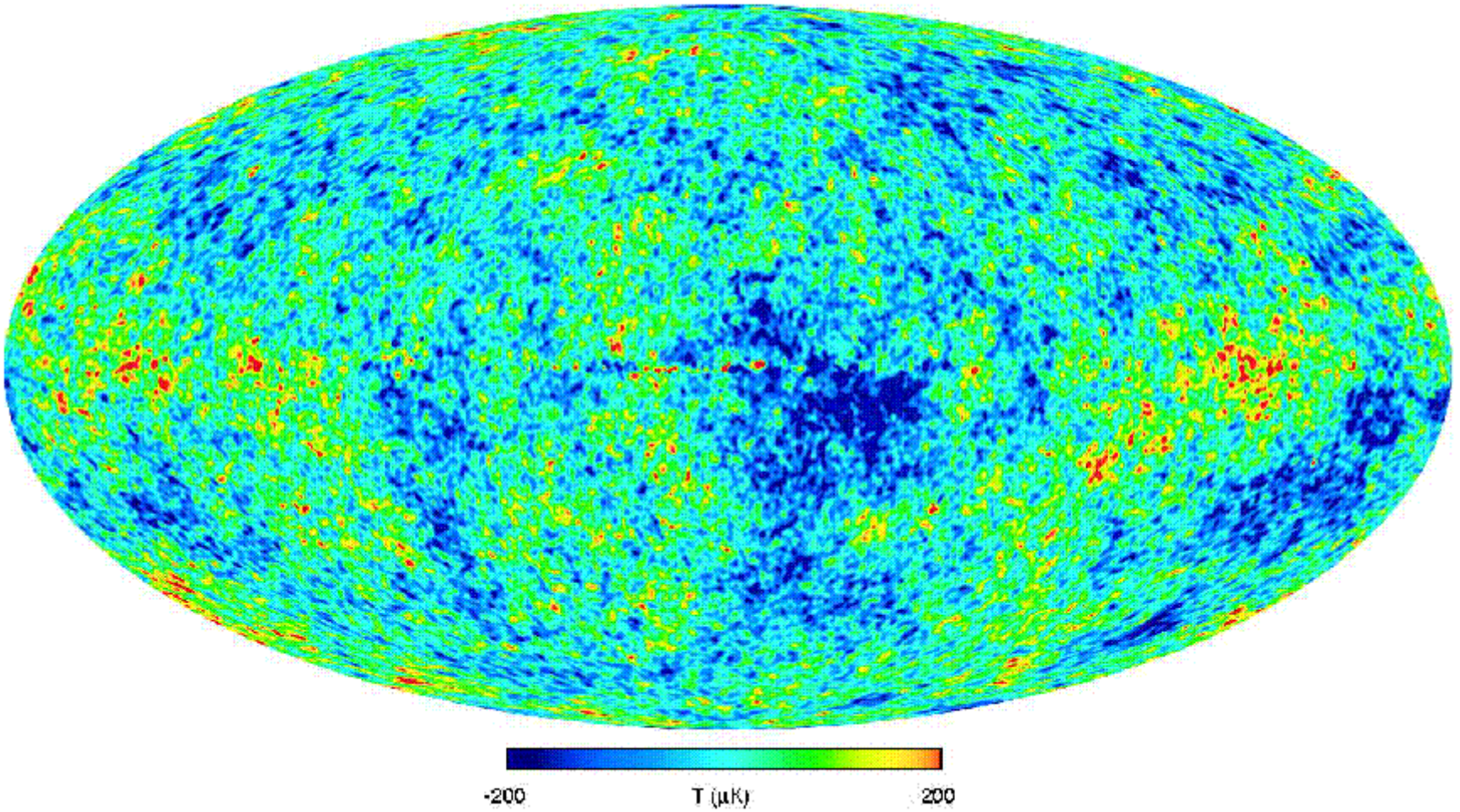
- Radiation from hot gas and dust in our own Milky Way

- Structure in the Microwave Background itself
  An image of structure in the `cosmic fog bank' at a distance of 40 billion light-years when the Universe was 400,000 years old

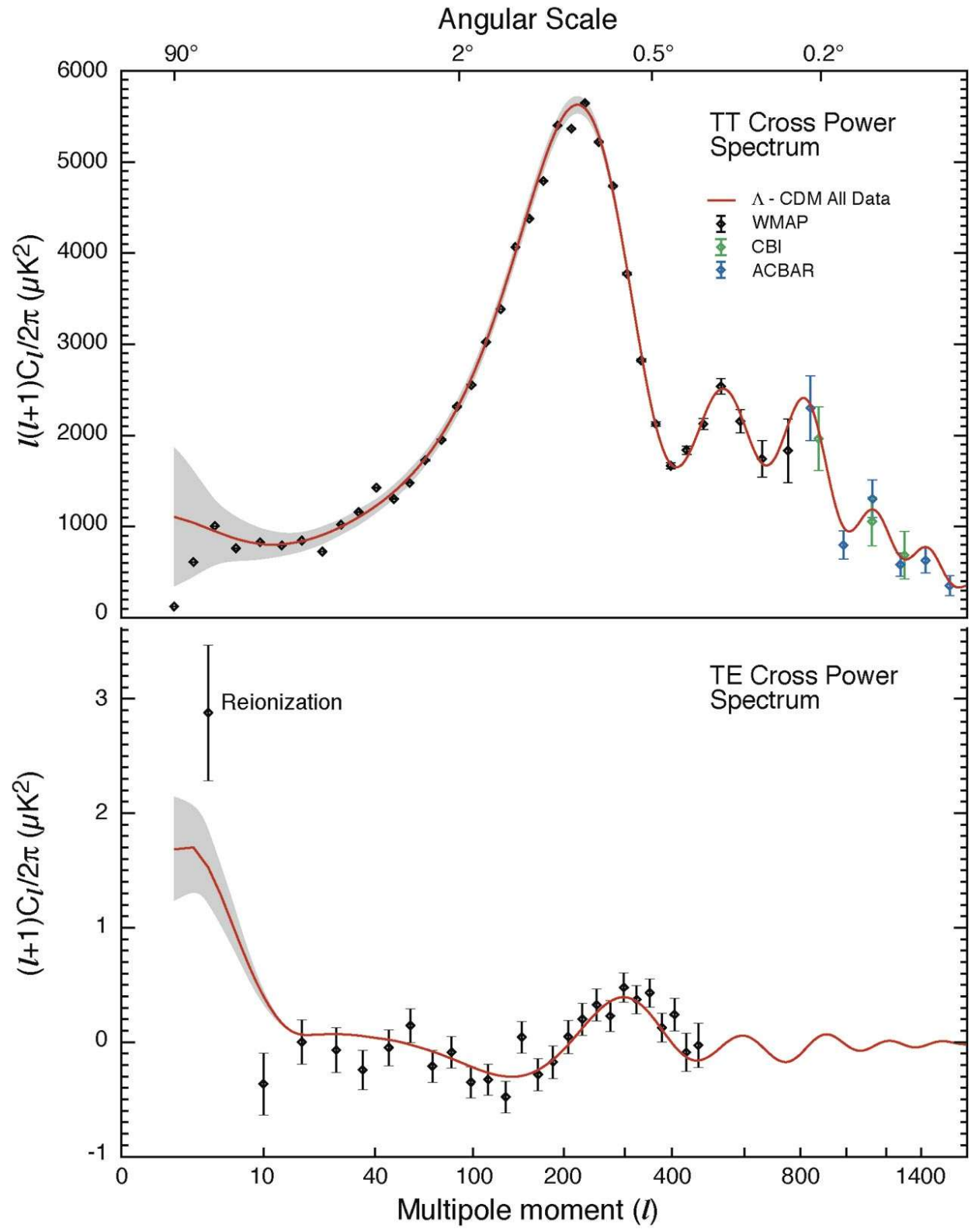
The *WMAP* Satellite at Lagrange-Point L2



WMAP map of the Universe when it was only 400,000 years old



Bennett et al 2003



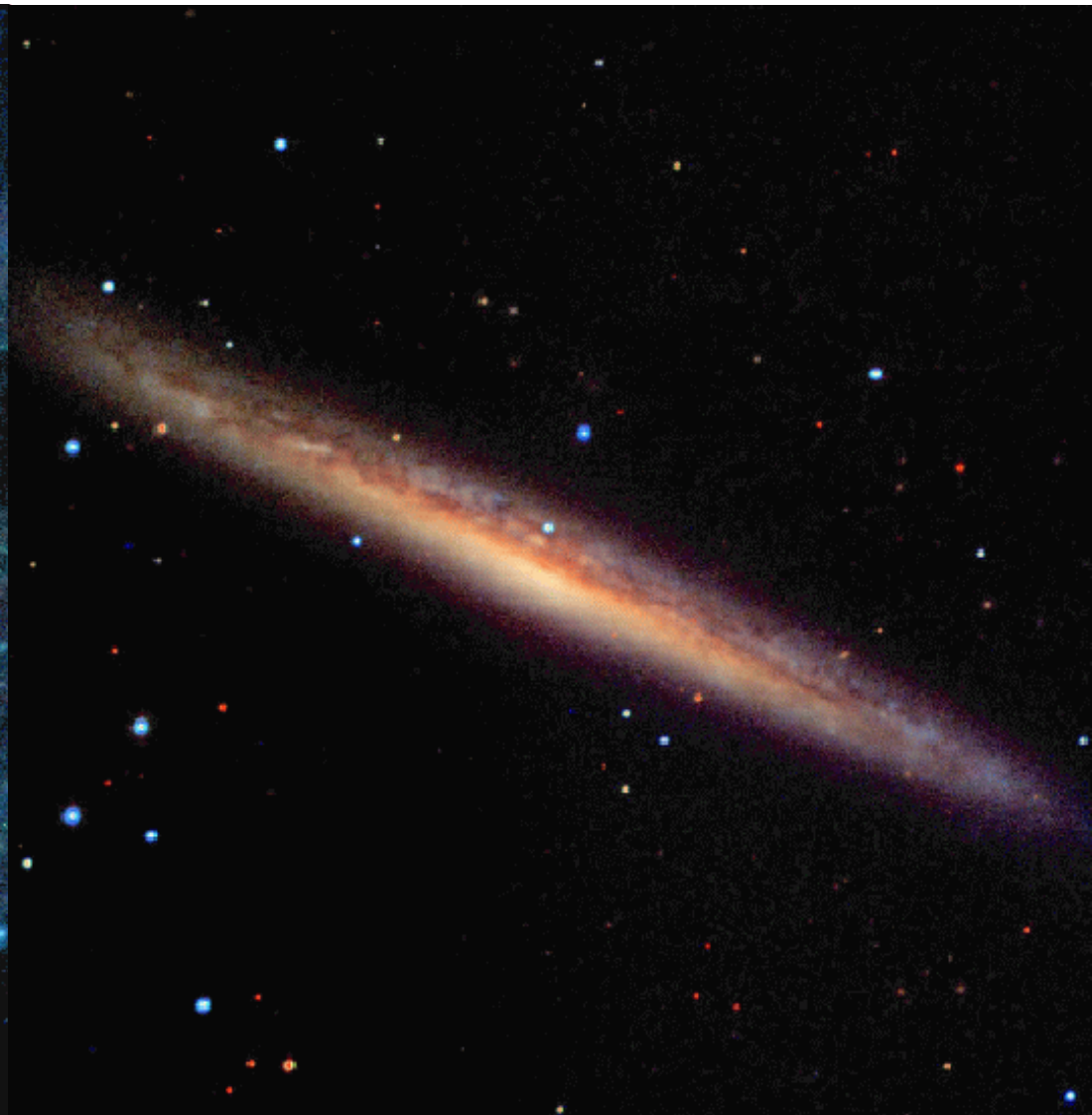
Initial conditions for the formation of all structure

- Our Universe is flat
- It is 13.7 ± 0.2 billion years old.
- It is made of 70% dark energy, 26% cold dark matter and only 4% normal baryonic matter
- 400,000 years after the Big Bang it was nearly uniform
- All structure was imprinted in the first 10^{-30}s by quantum fluctuations of the vacuum

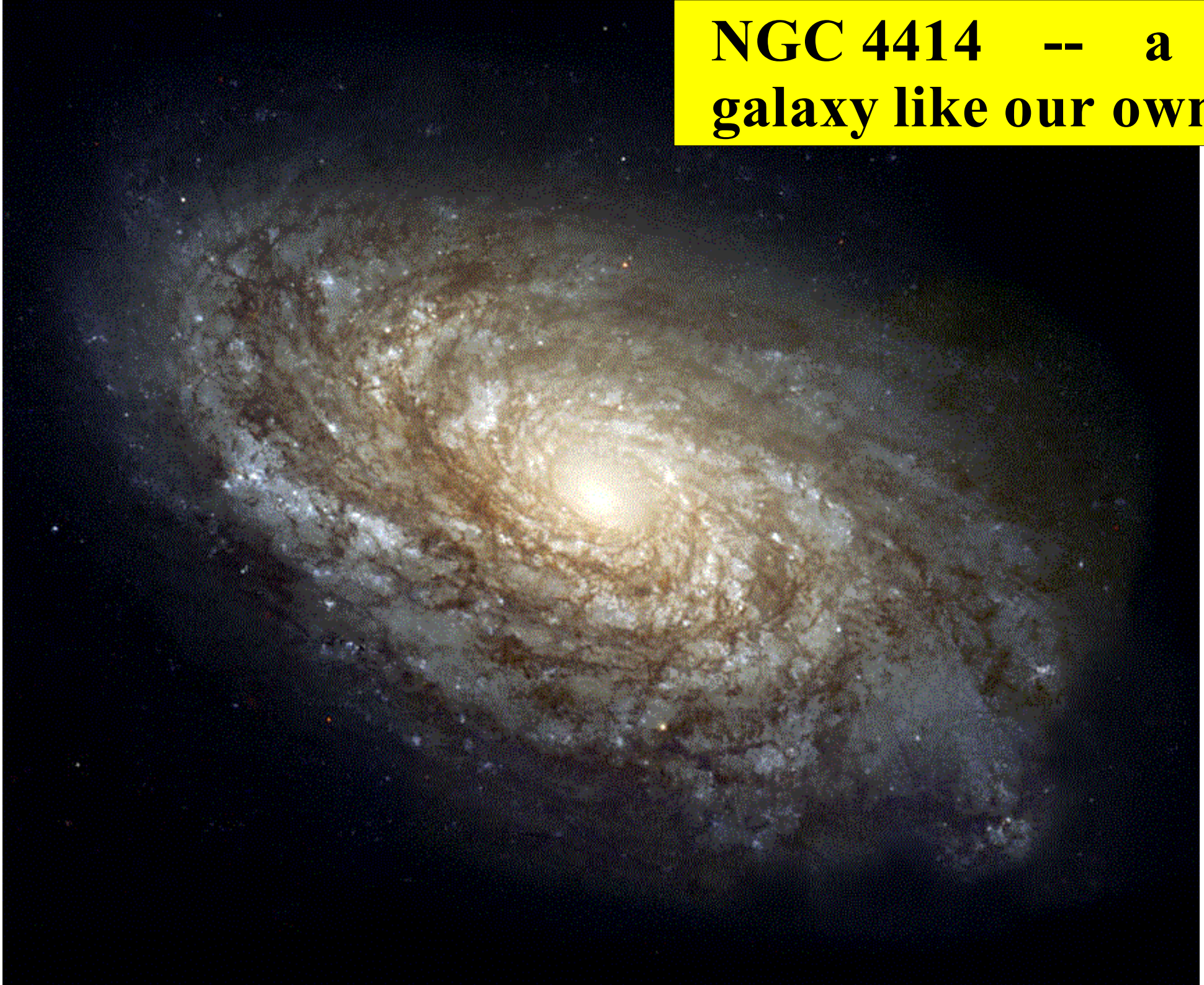
Spiral galaxies

M101

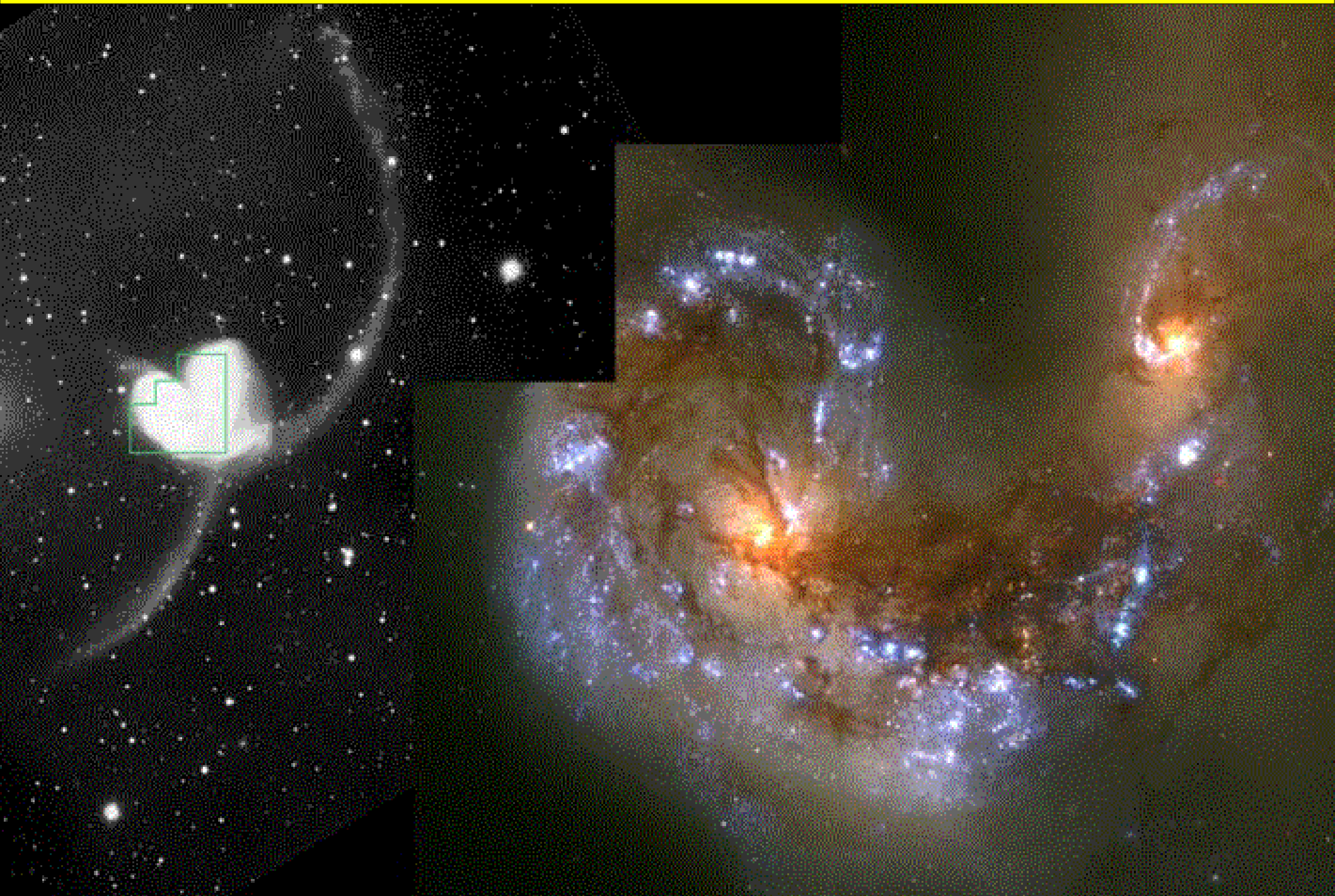
NGC 5907

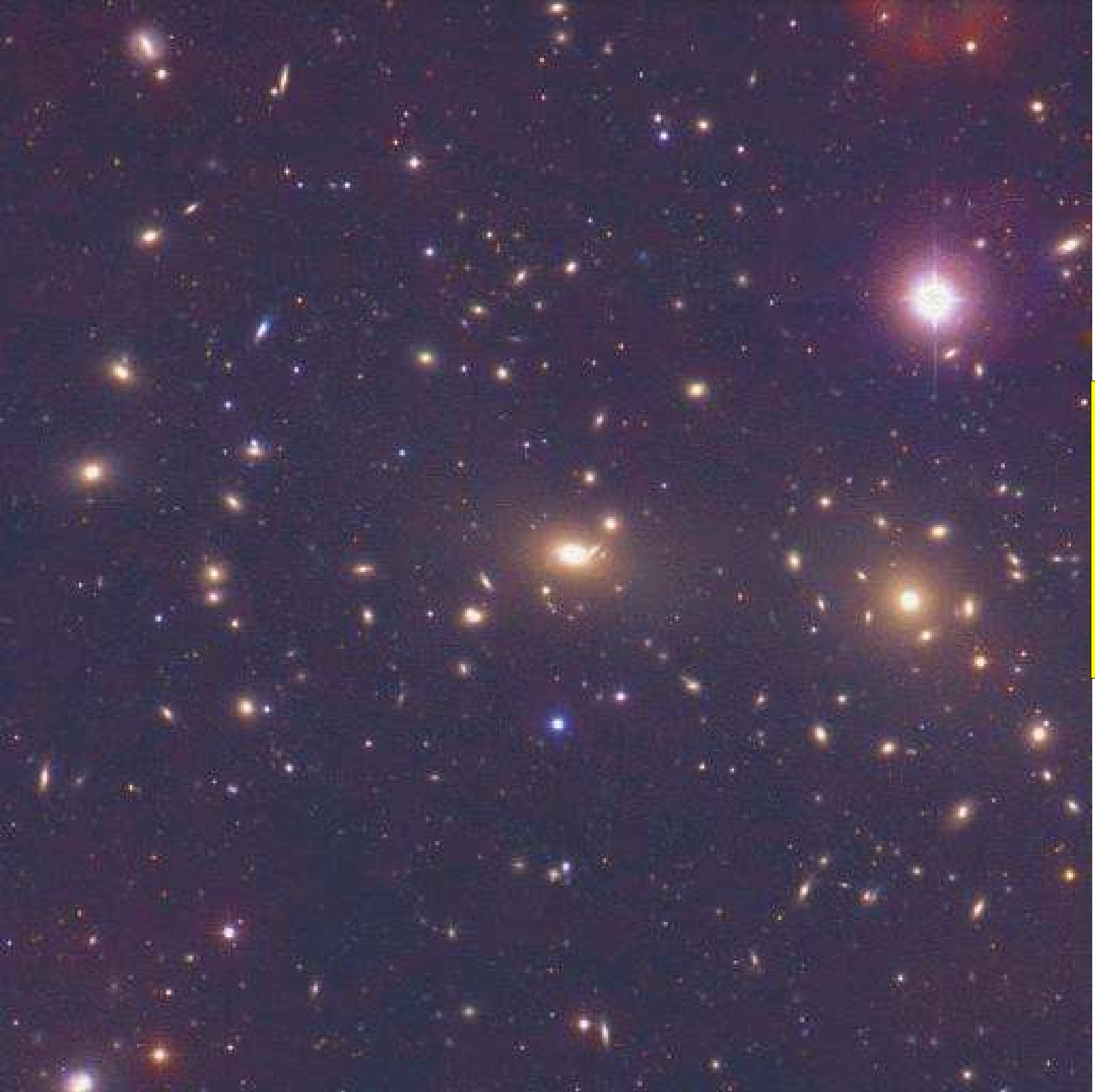


NGC 4414 -- a galaxy like our own



NGC 4038/4039 -- a galactic traffic accident

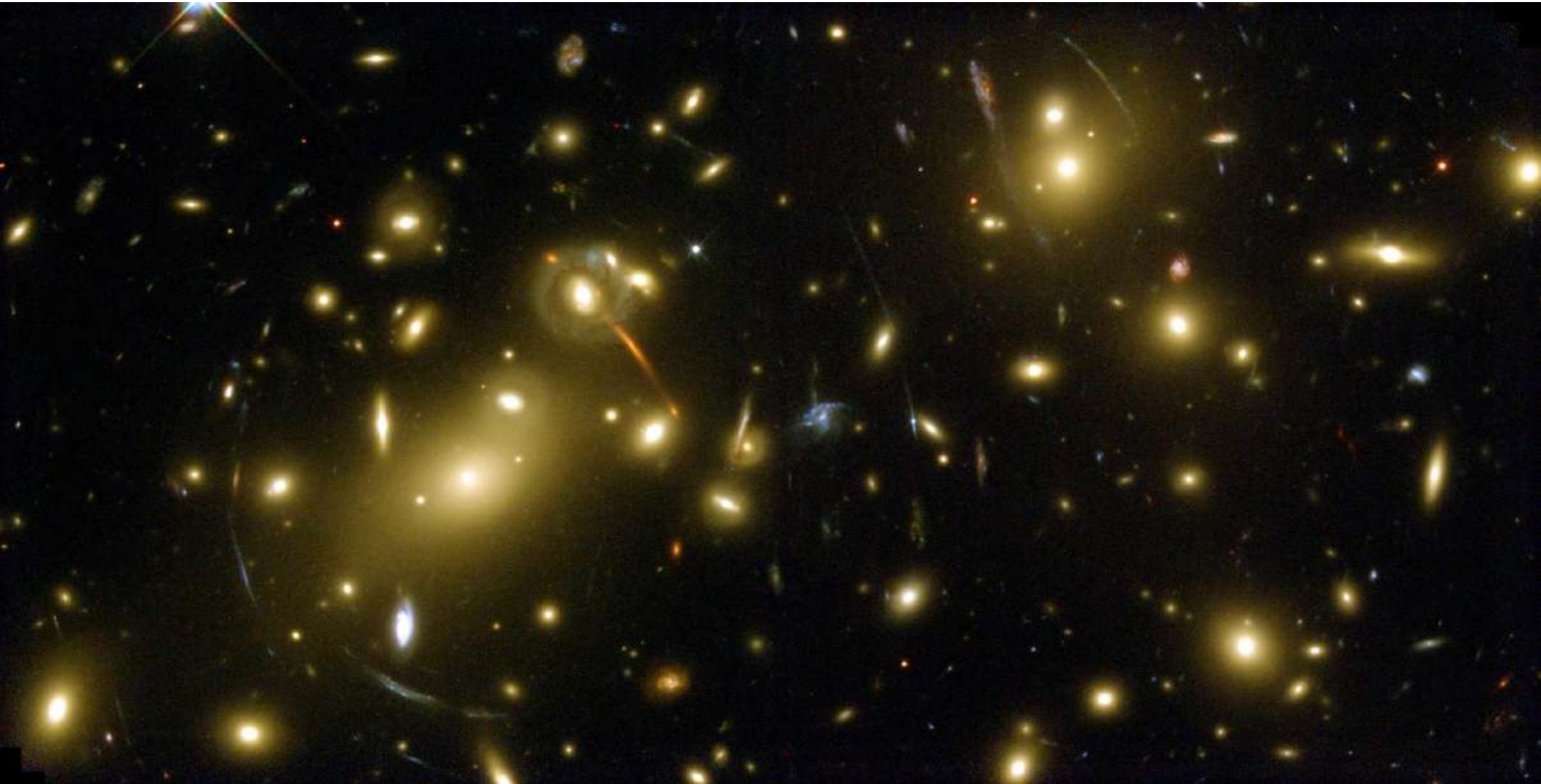




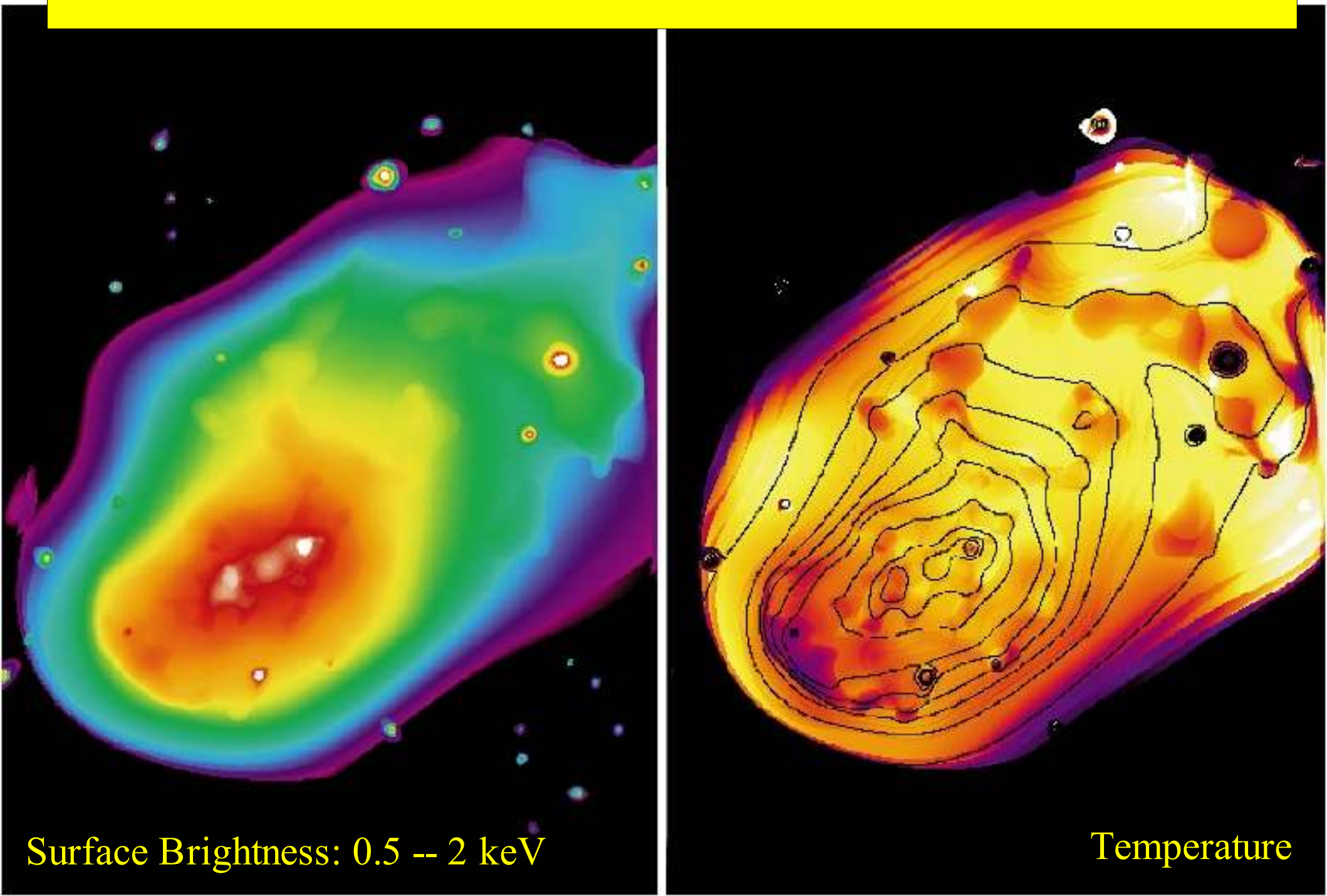
Elliptical galaxies in a cluster

Gravitation lens effects: the dark matter in a cluster becomes visible

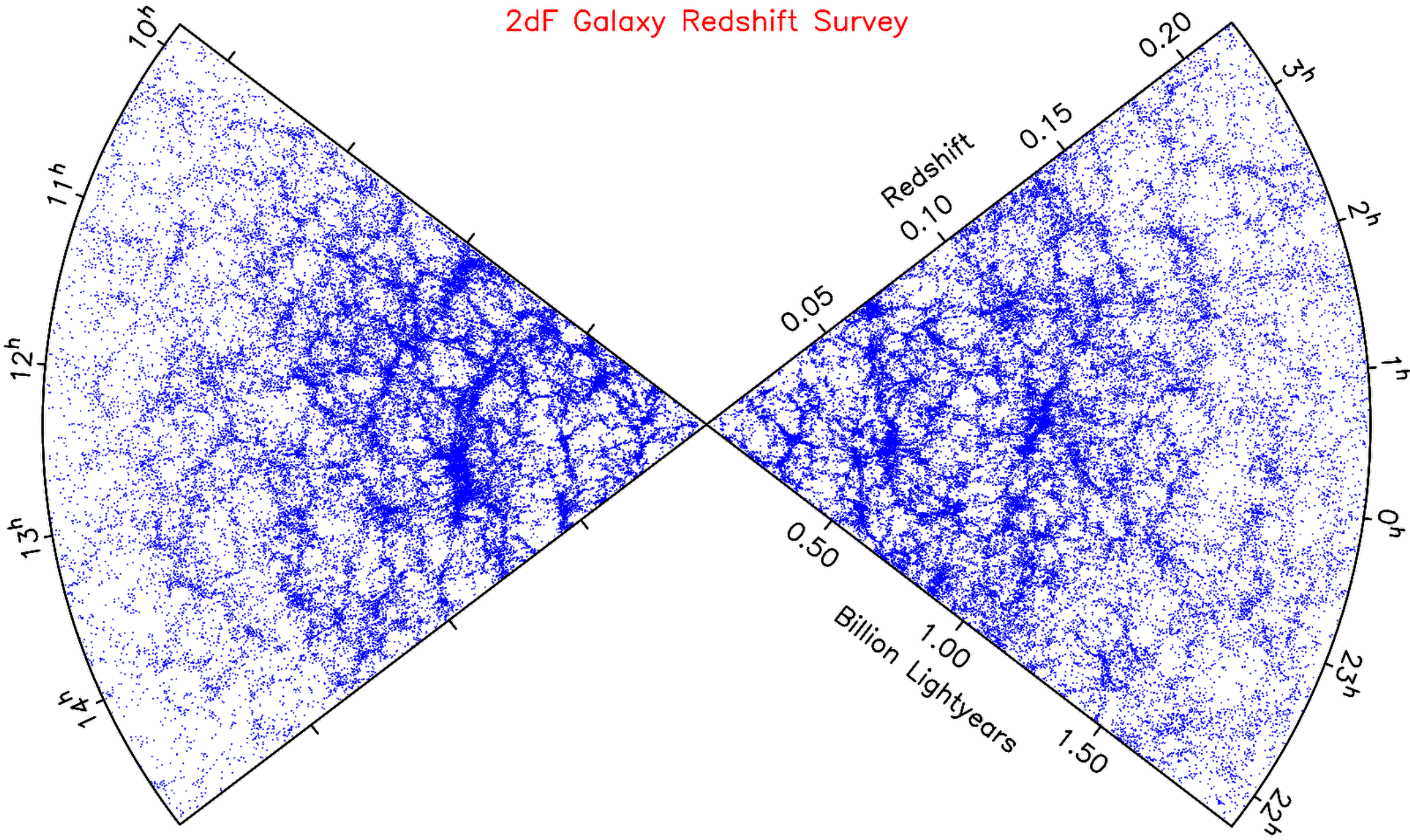
Abell 2218 z=0.17



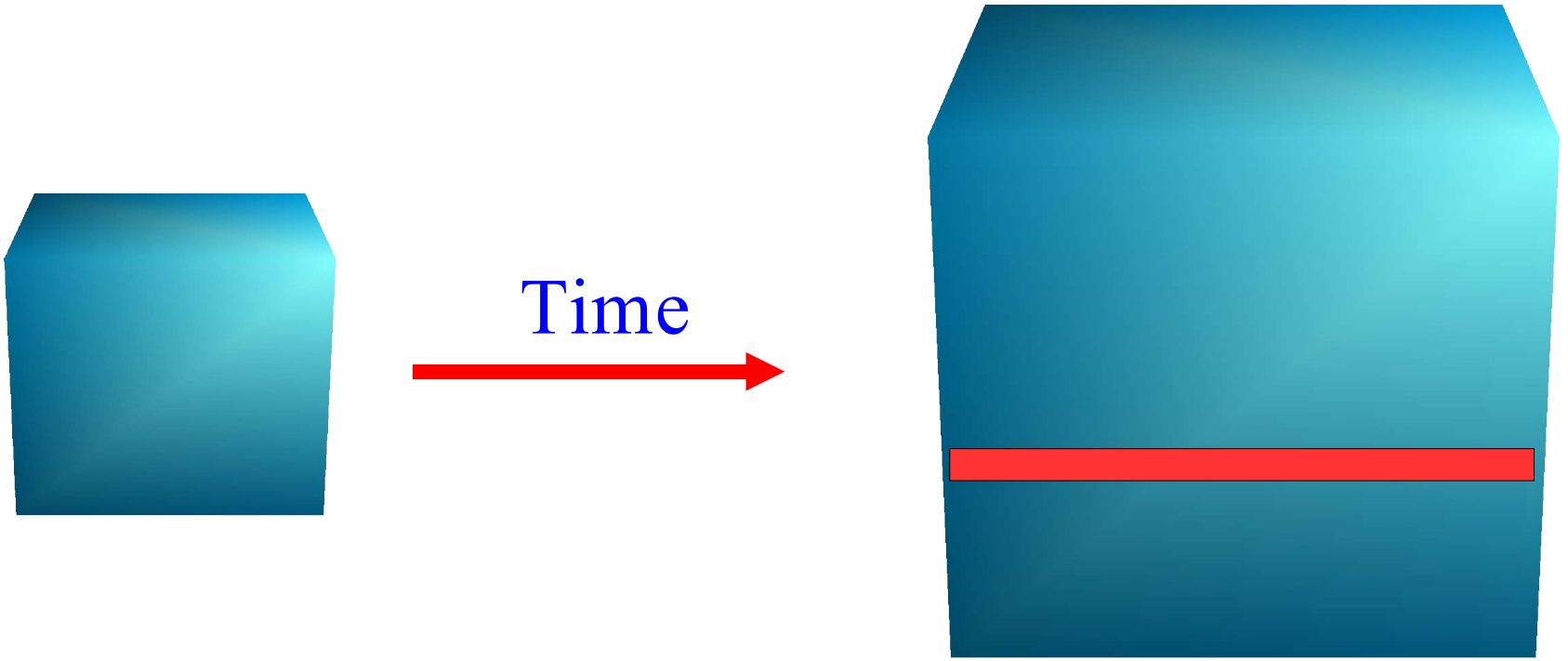
X-ray image of the cluster Abell 3667



Structure on large scales

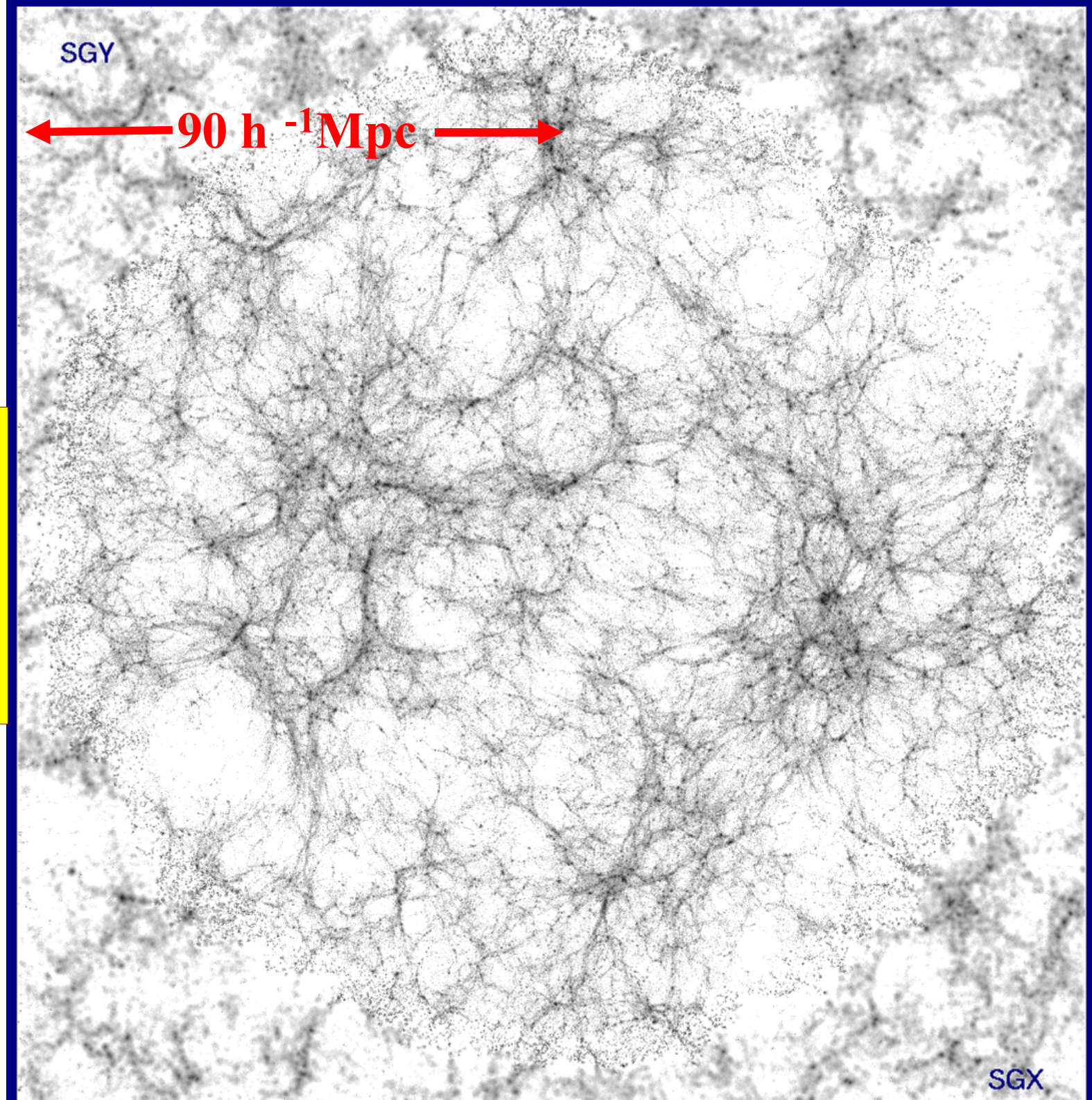


How to follow the evolution of the Universe on a supercomputer



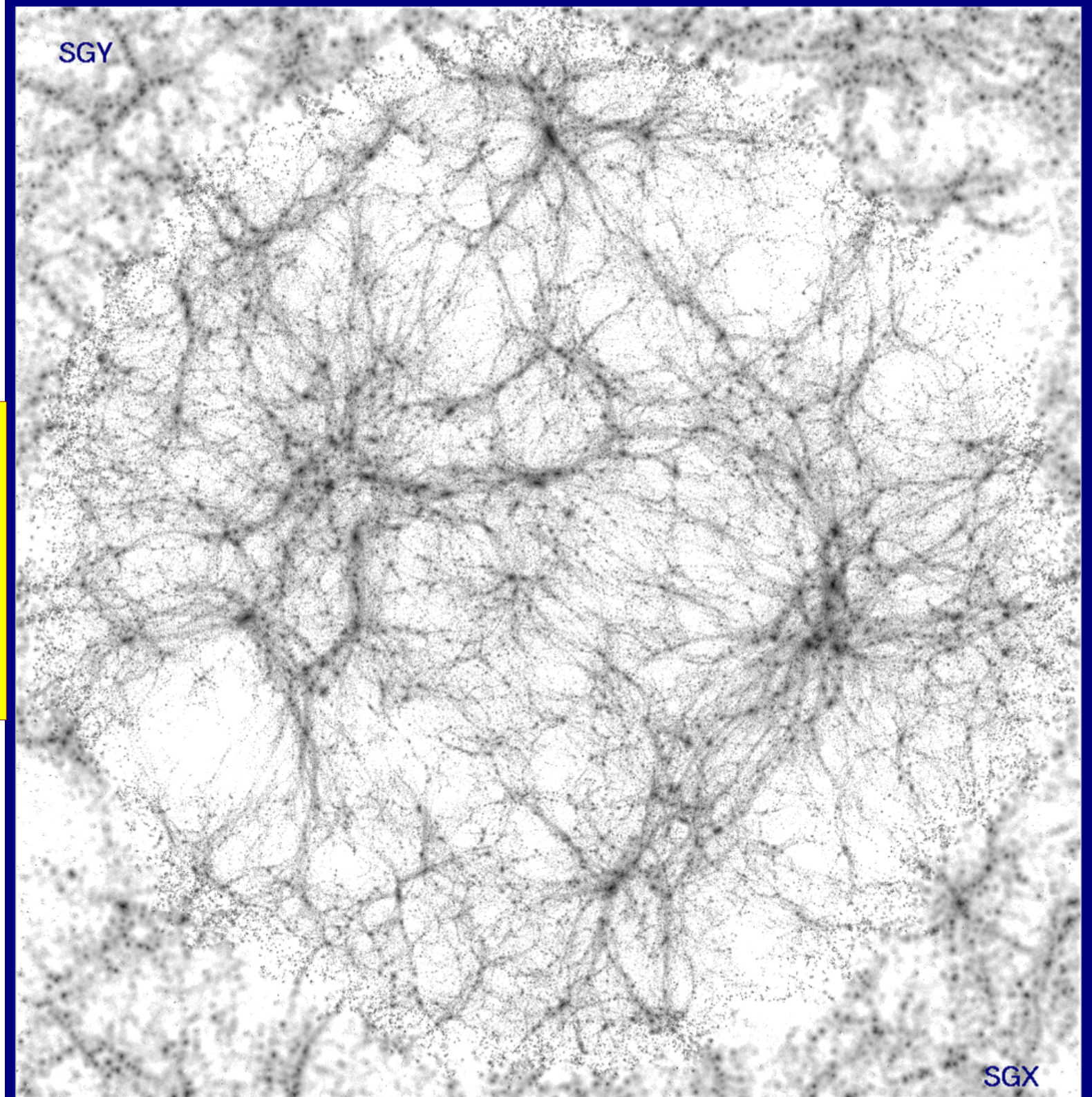
- Follow the material in an expanding cube
- Start 400,000 years after the Big Bang
- Choose initial conditions to match the microwave background
- Calculate forwards to the present day

Our cosmic neighborhood at redshift z=2.4

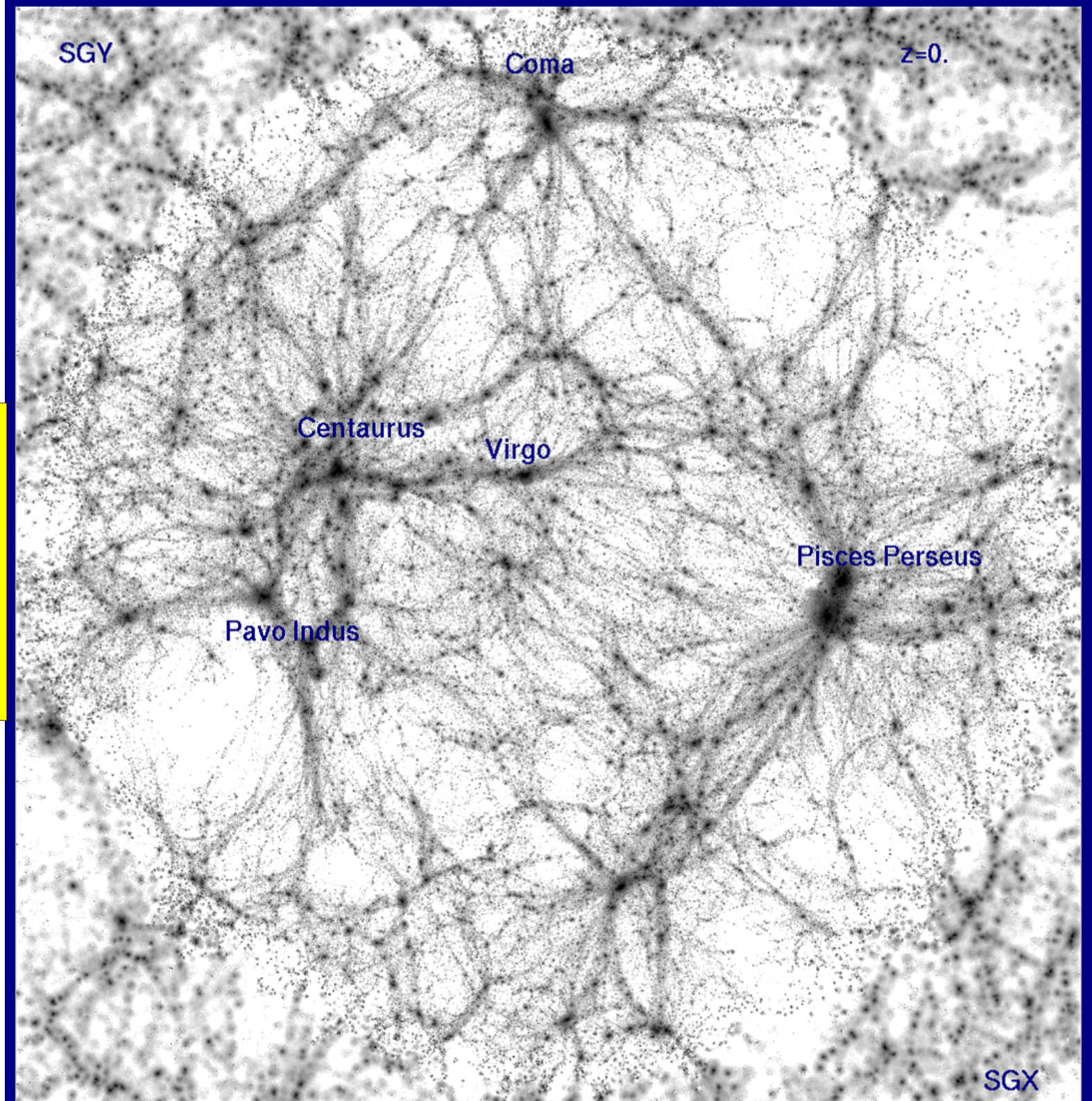


Mathis et al 2001

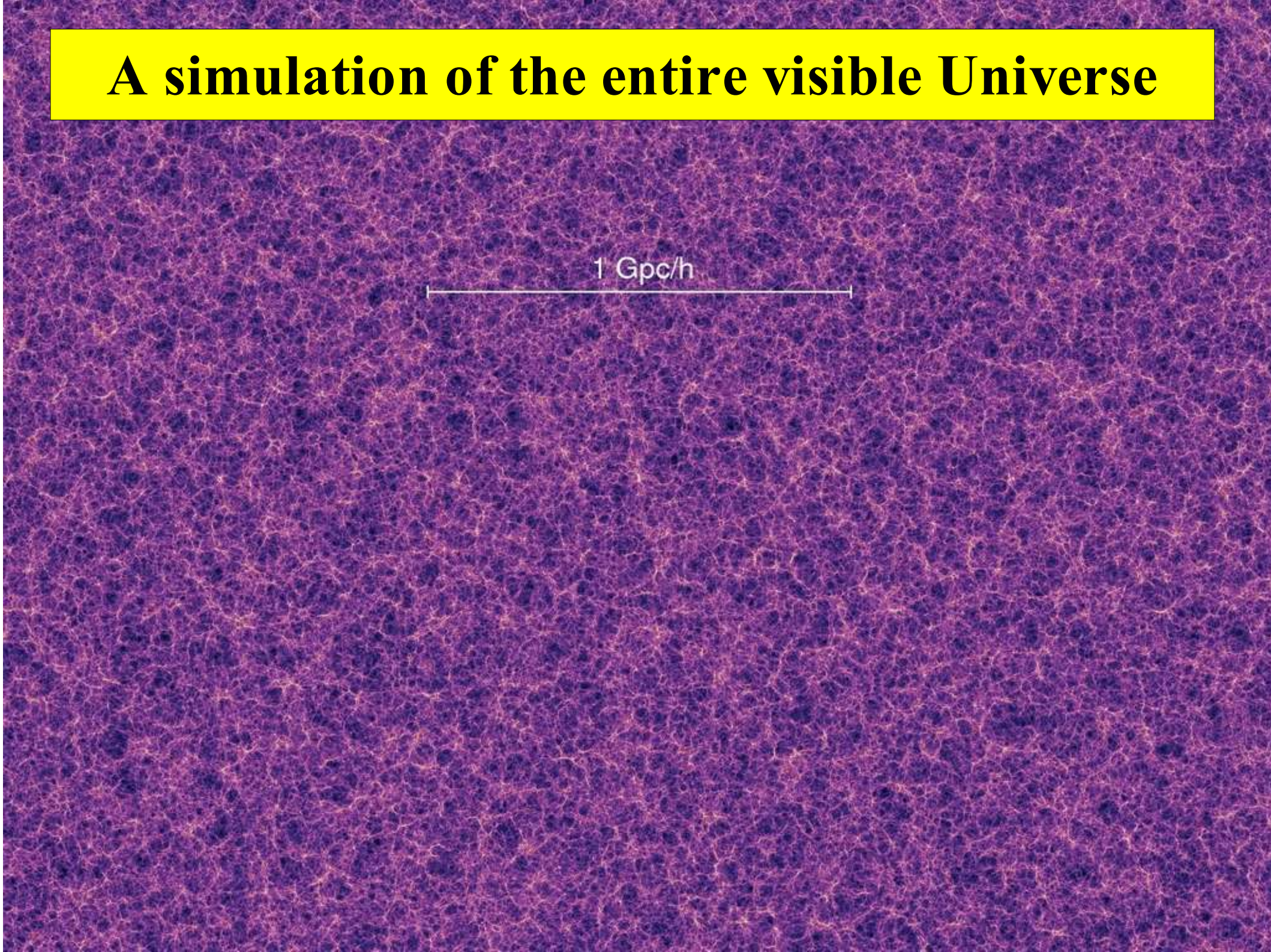
Our cosmic neighborhood at redshift z = 0.8



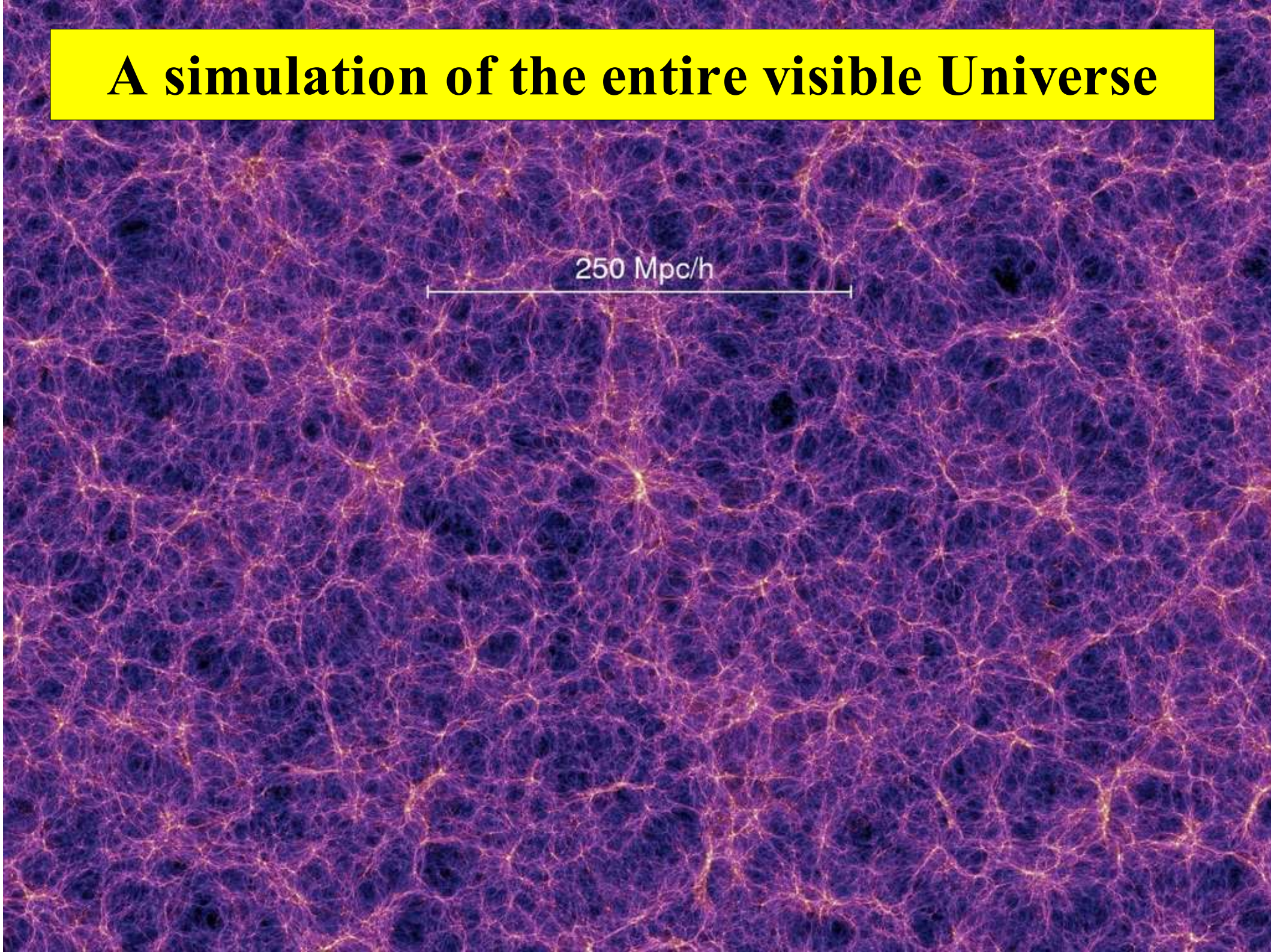
Our cosmic neighborhood today



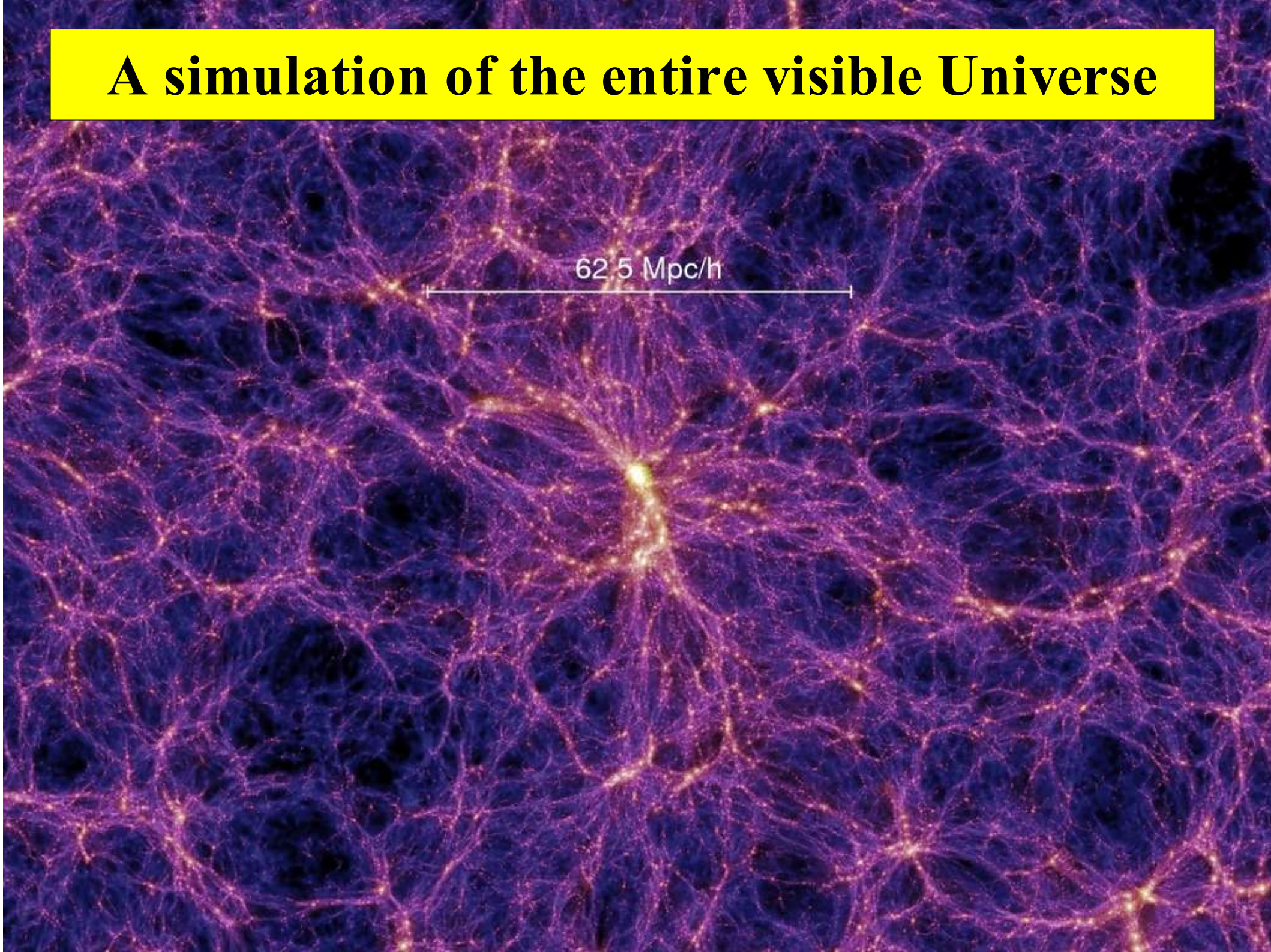
A simulation of the entire visible Universe



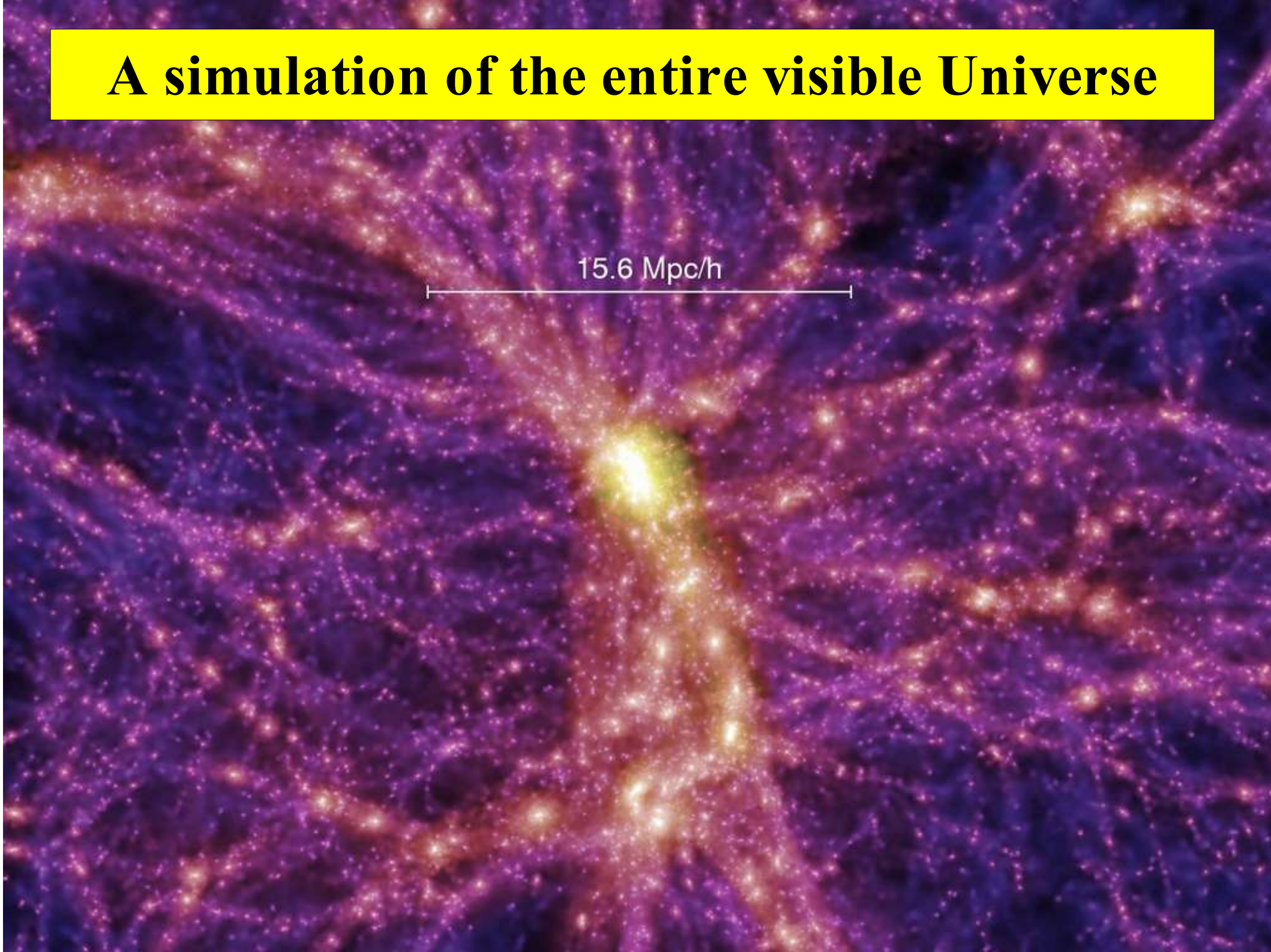
A simulation of the entire visible Universe



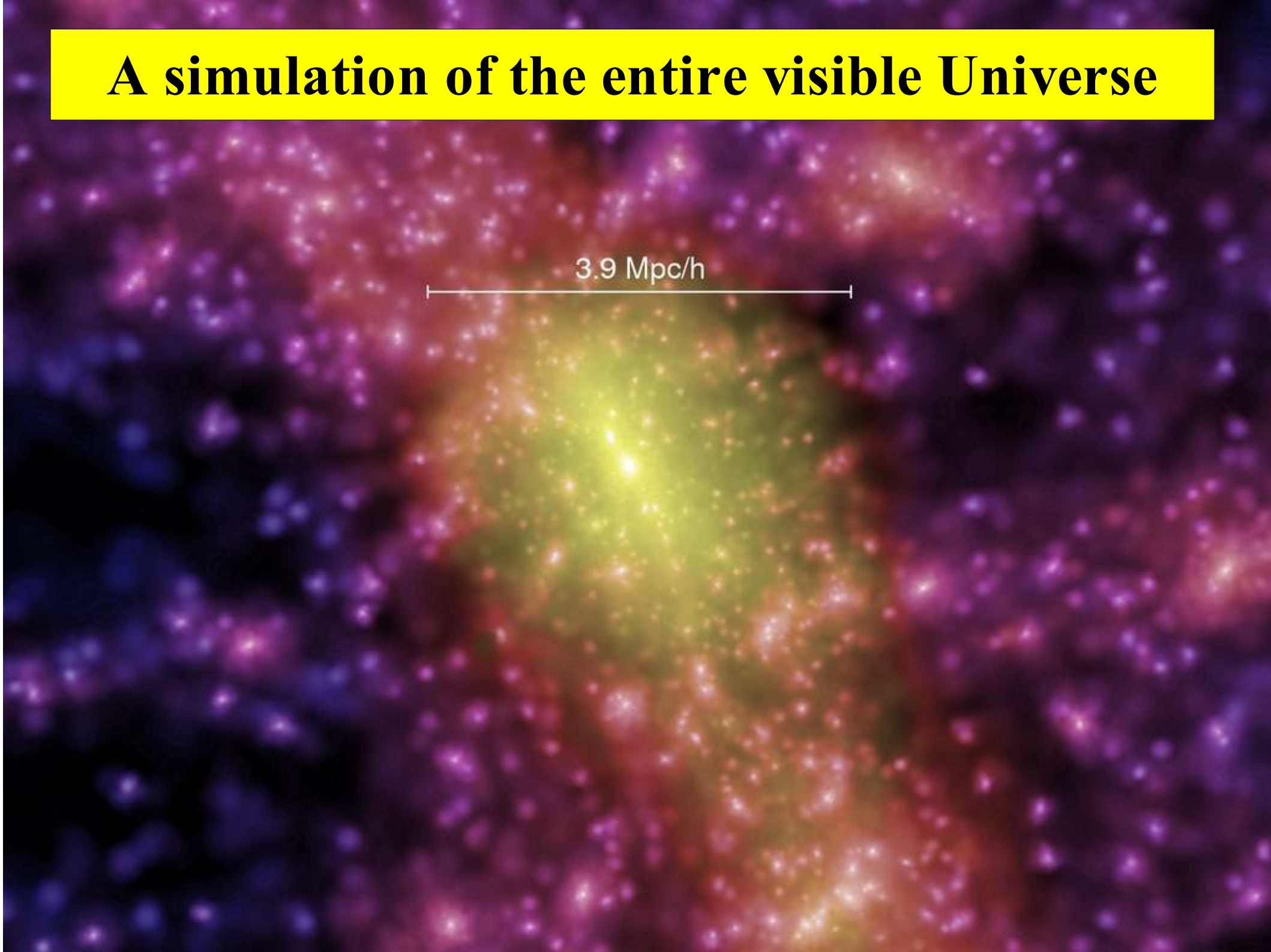
A simulation of the entire visible Universe



A simulation of the entire visible Universe



A simulation of the entire visible Universe

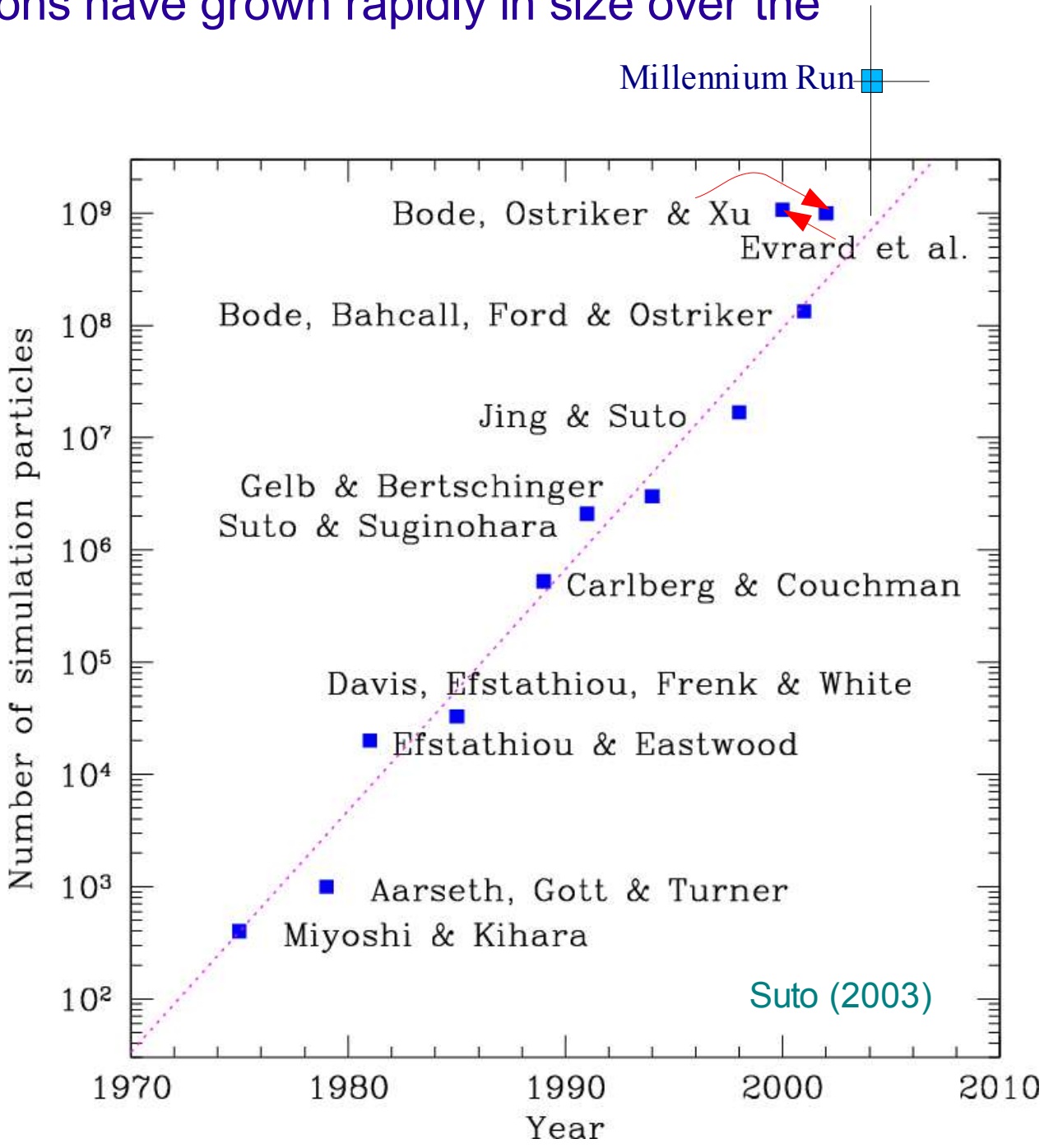


Cosmological N-body simulations have grown rapidly in size over the last three decades

"**N**" AS A FUNCTION OF TIME

$$N = 400 \times 10^{0.215(\mathrm{Year}-1975)}$$

- Computers double their speed every 18 months (Moore's law)
- N-body simulations have doubled their size every 17 months even though naïve force calculation needs N^2 operations
- Recently, growth has accelerated further.
  The Millennium Run should have become possible in 2010 . It finishes in 2004 !



Computational challenges of very large cosmological simulations

- Efficient algorithms to calculate self-consistent forces between a large number of particles ($N = 10^{10}$) and over a large dynamic range ($L_{max}/L_{min} = 10^5$)
- Efficient and conservative (symplectic) time integration
- Efficient load-balancing across many processors on distributed memory machines (16 x 32 Regatta processors)
- Adaptive domain decomposition of simulated volume
- On-the-fly estimation of statistics requiring global data
- Efficient output and storage strategies for results (27 Tbyte)
- Globally accessible post-processing pipelines to be run remotely on serial machines · the Global Virtual Observatory

The Millennium simulation was run on the *Regatta* supercomputer of the RechenZentrum Garching

REQUIRED RESOURCES

1 TByte RAM needed

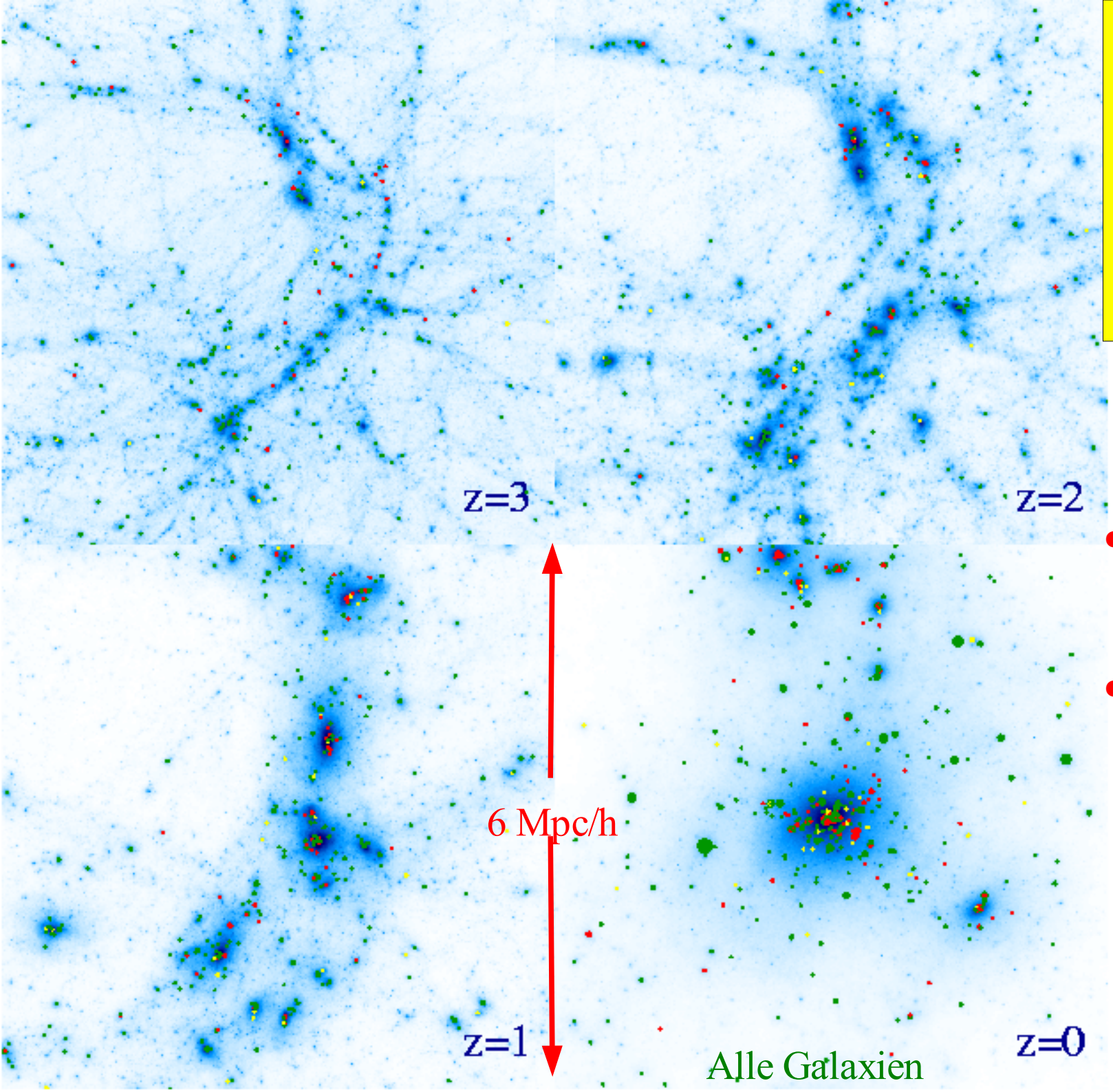
16 x 32-way Regatta Node
64 GByte RAM
512 CPU total

CPU time requirement

330.000 processor hours

- 27 days on 512 CPUs/16 nodes
- 38 years in serial
- ~ 6% of annual time on total Regatta system

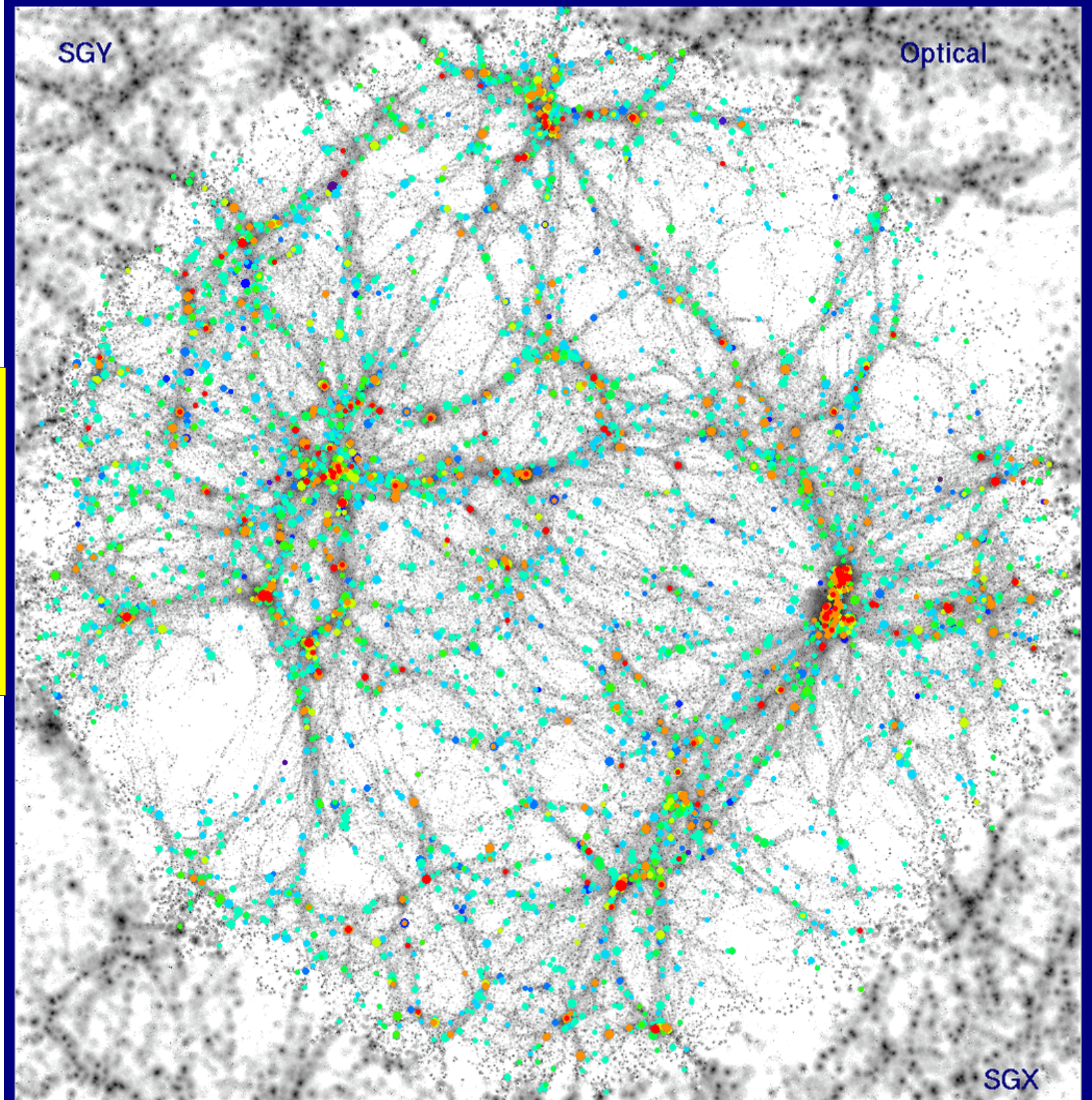
Evolution of the galaxies in a cluster



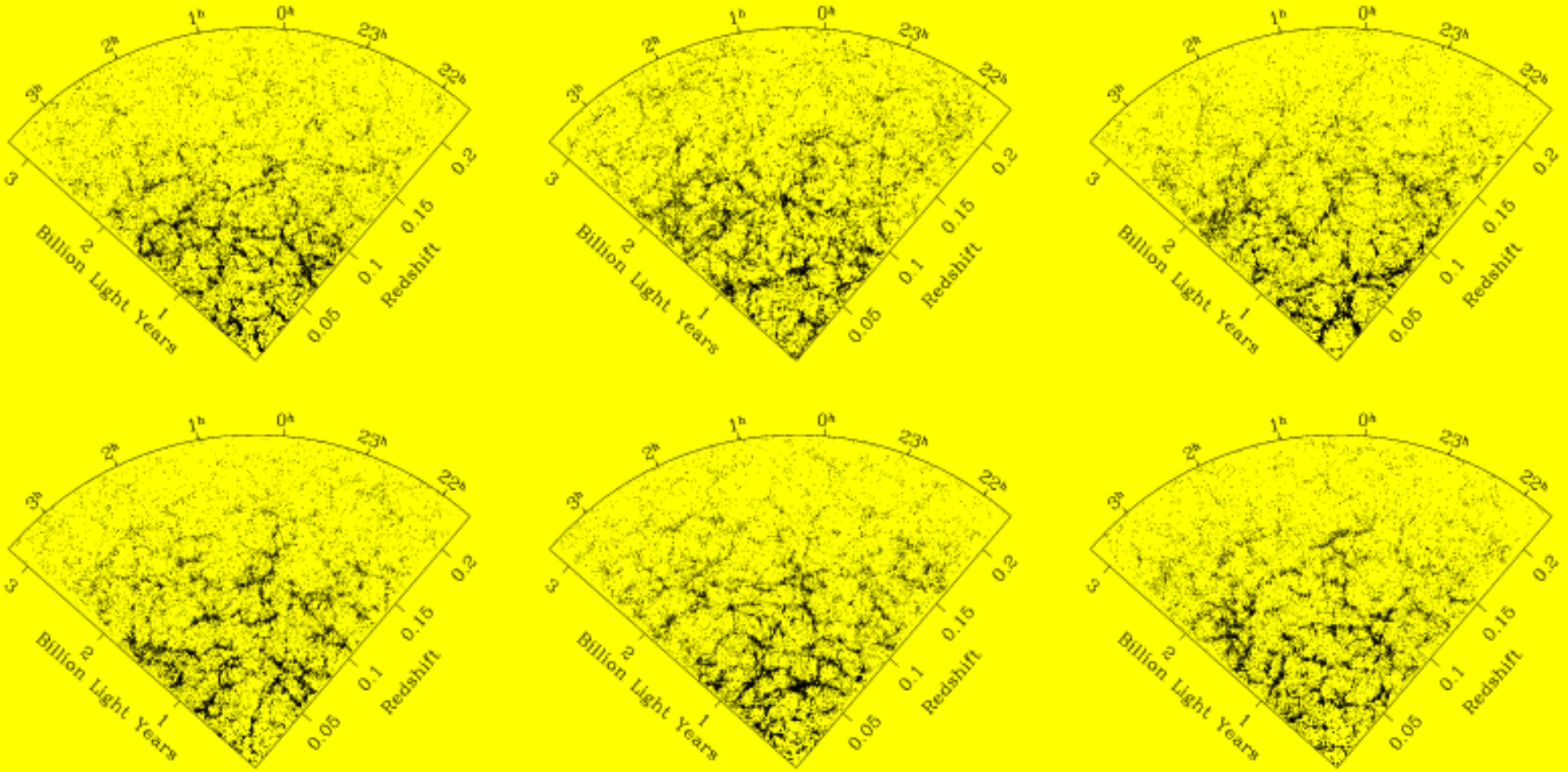
Springel et al 2001

- The dark matter is shown in blue
- Colored points represent the galaxies

Our cosmic neighborhood *with* galaxies

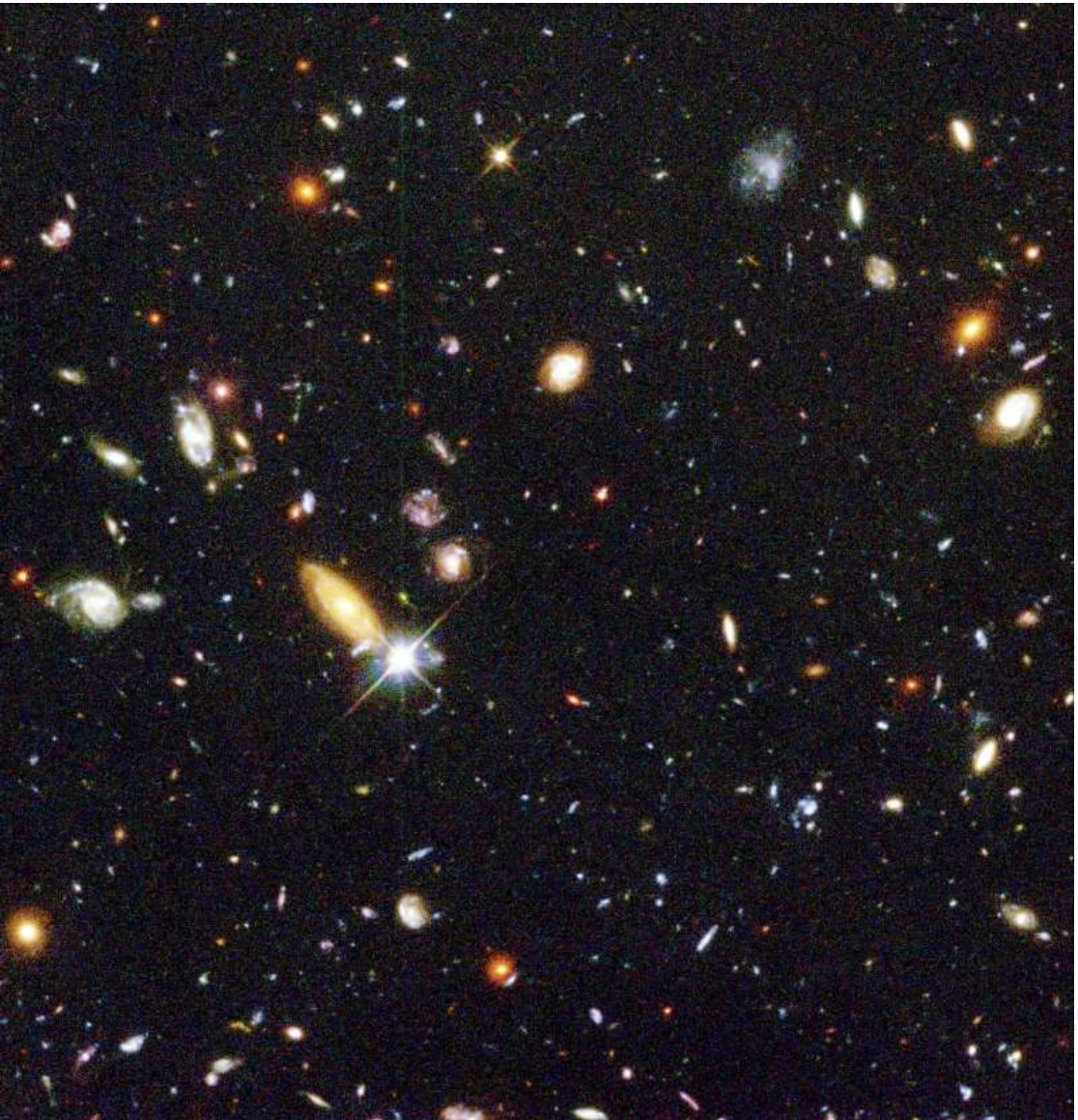


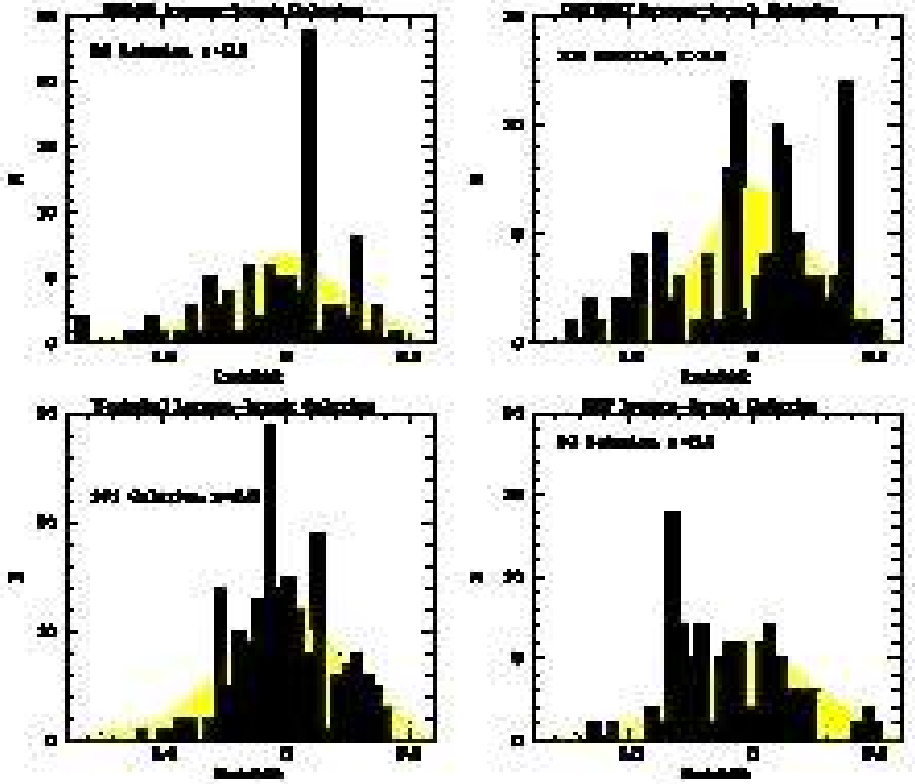
VIRTUAL vs REAL UNIVERSES II

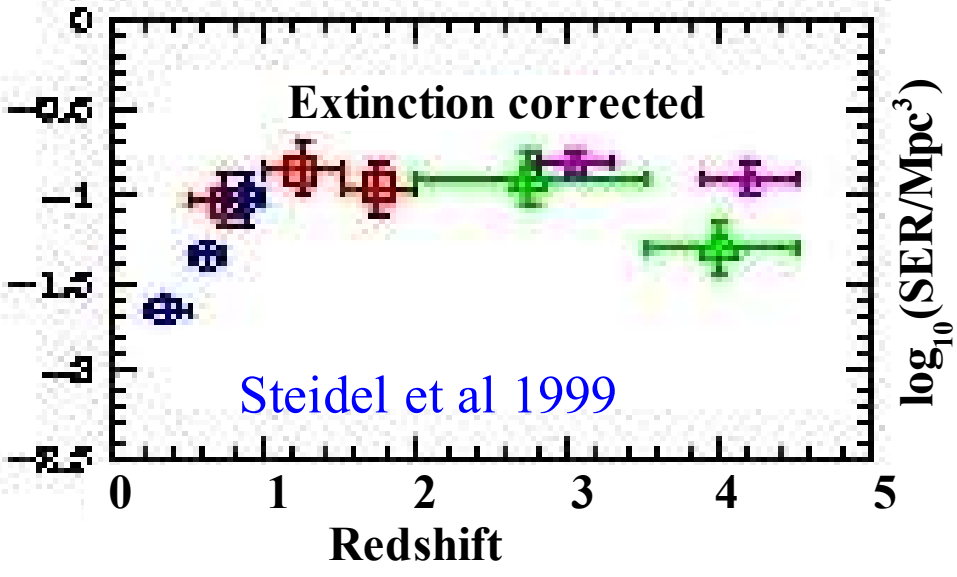


Telescopes as time machines: glimpses of the past

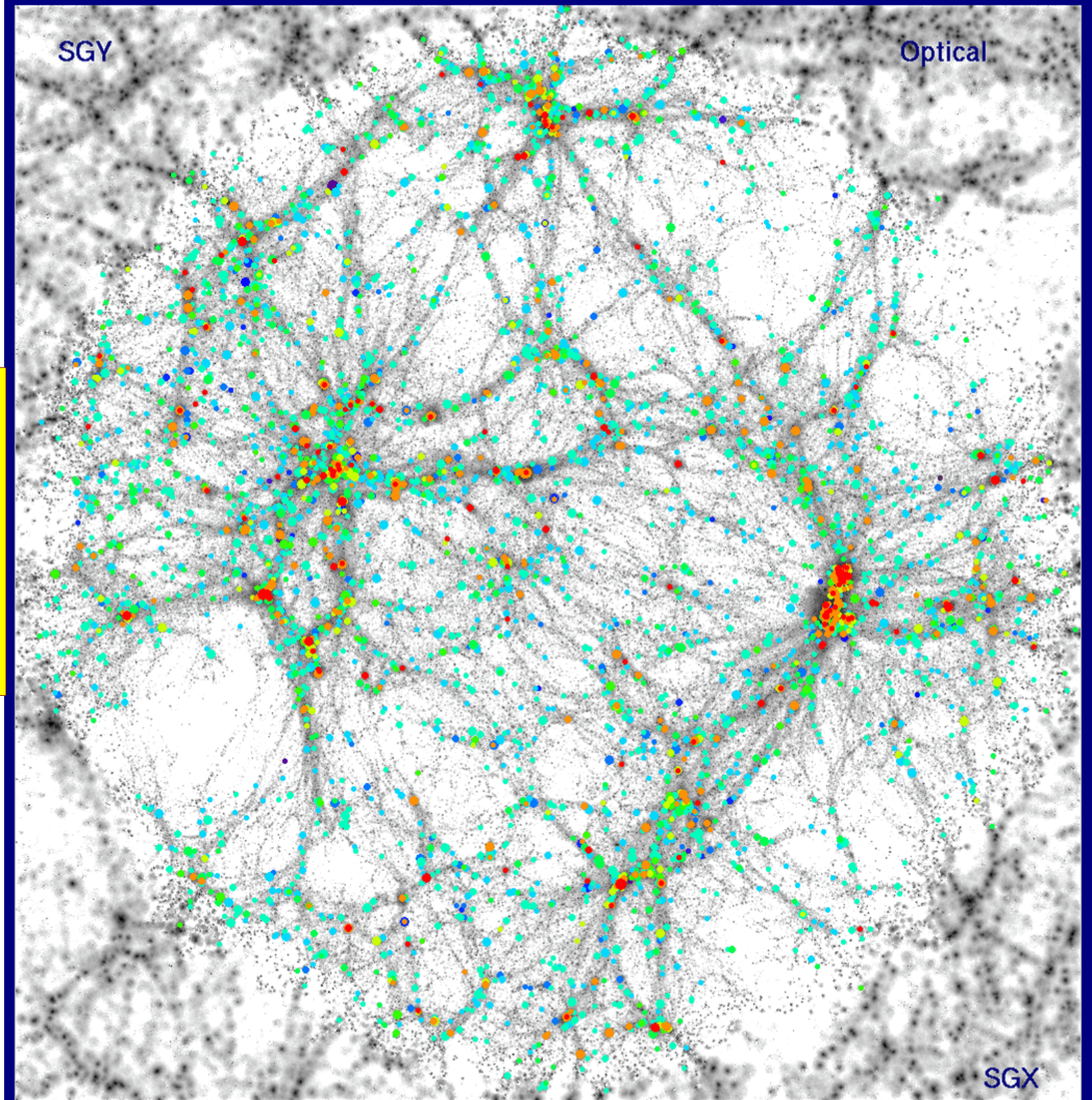
The Hubble Deep Field





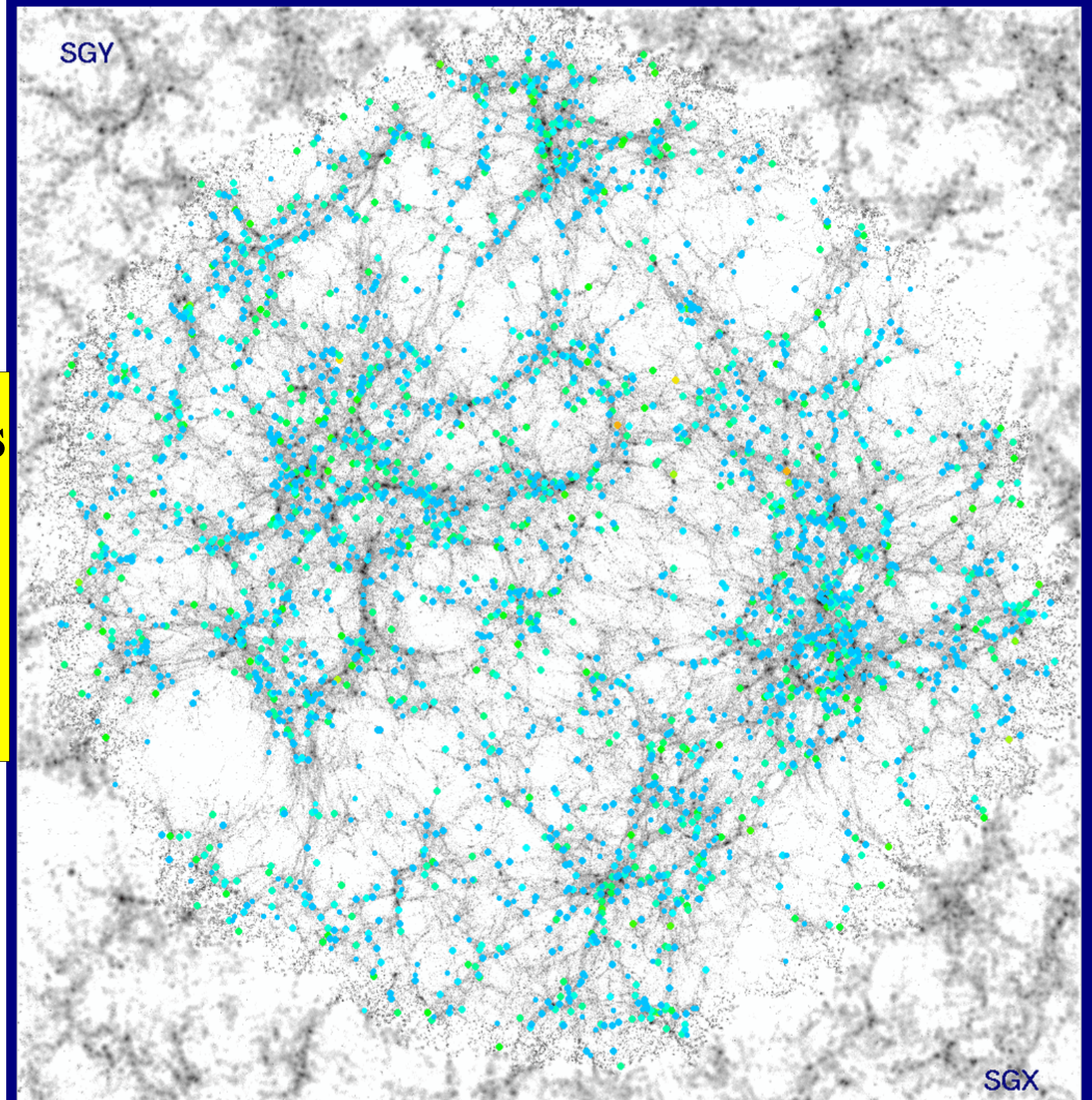


Our cosmic neighborhood *with* galaxies

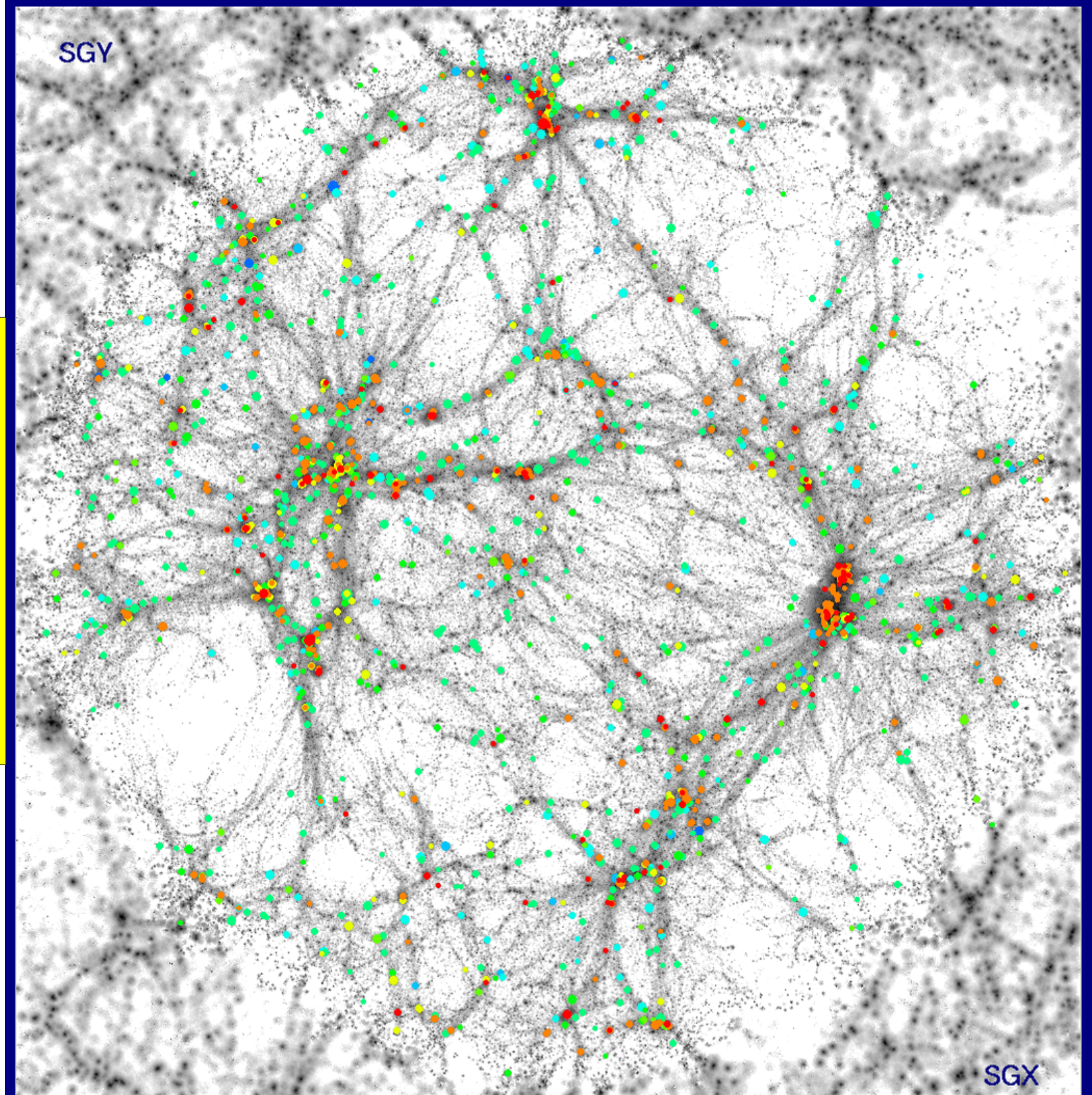


Bright galaxies at redshift z=2.4

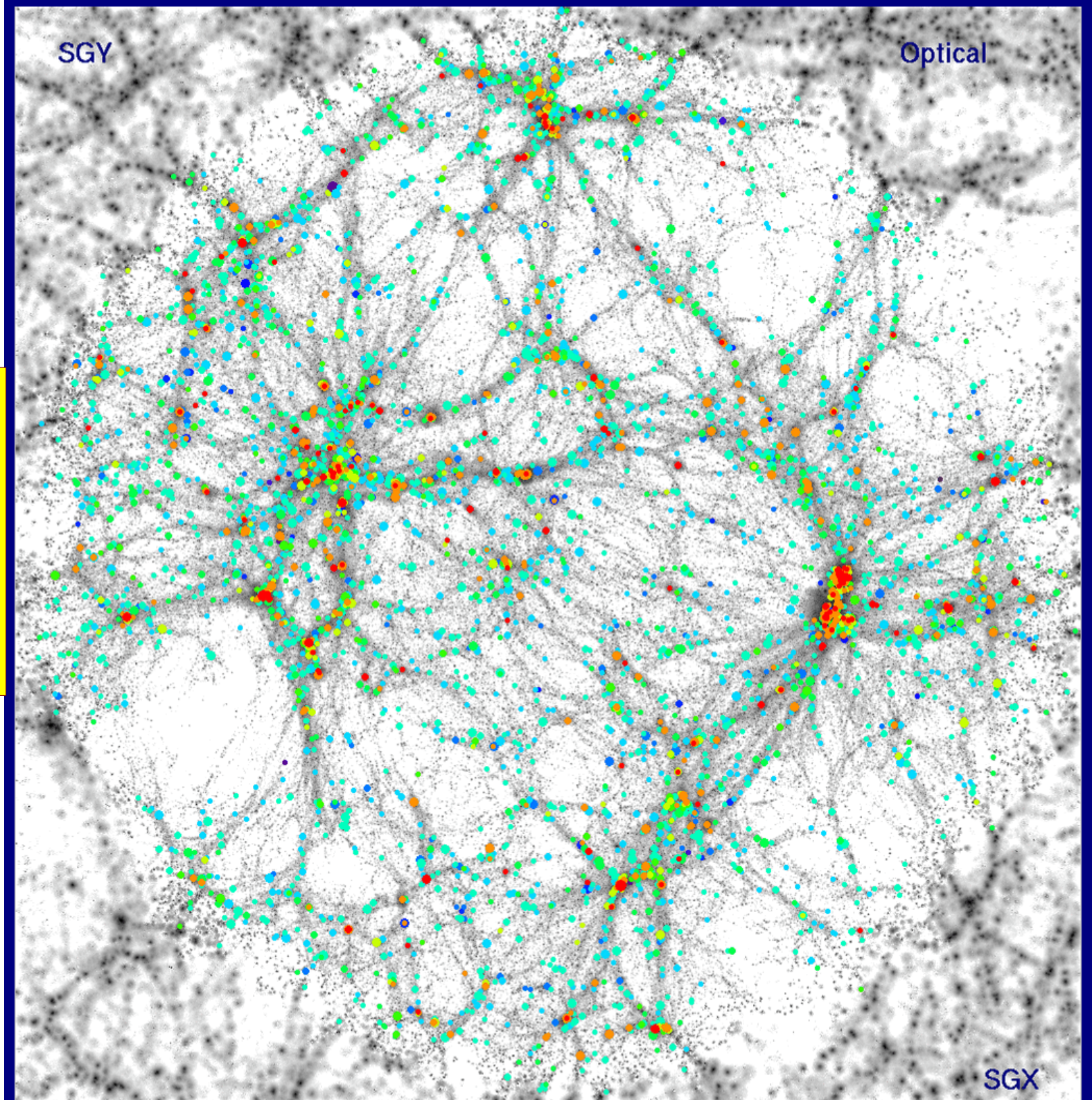
SFR>5.0



Present-day descendents of bright galaxies from redshift z=2.4



Our cosmic neighborhood *with* galaxies



To conclude.....

- In the beginning the Universe was hot, dense and almost uniform
- All structure has grown from quantum fluctuations of the vacuum
- Normal material is only 4% of the content of the Universe
- About 25% is made of as yet unidentified elementary particles
- About 70% consists of a new and as yet unidentified form of dark energy which is accelerating the expansion of the Universe.
- Galaxies, galaxy clusters and larger structures, as well as stars and planets formed from primordial gas through the effects of gravity
- Supercomputing is indispensible to compare theory with reality