Structure Formation

Tom Abel

Outline

- What Structure?
- Gravitational instability forms structure in the Universe
- Vlasov-Poisson and N-body
- Numerical Techniques & Codes
- Cold, warm & hot Dark Matter models
- DM Halo properties and other select Simulation results


today


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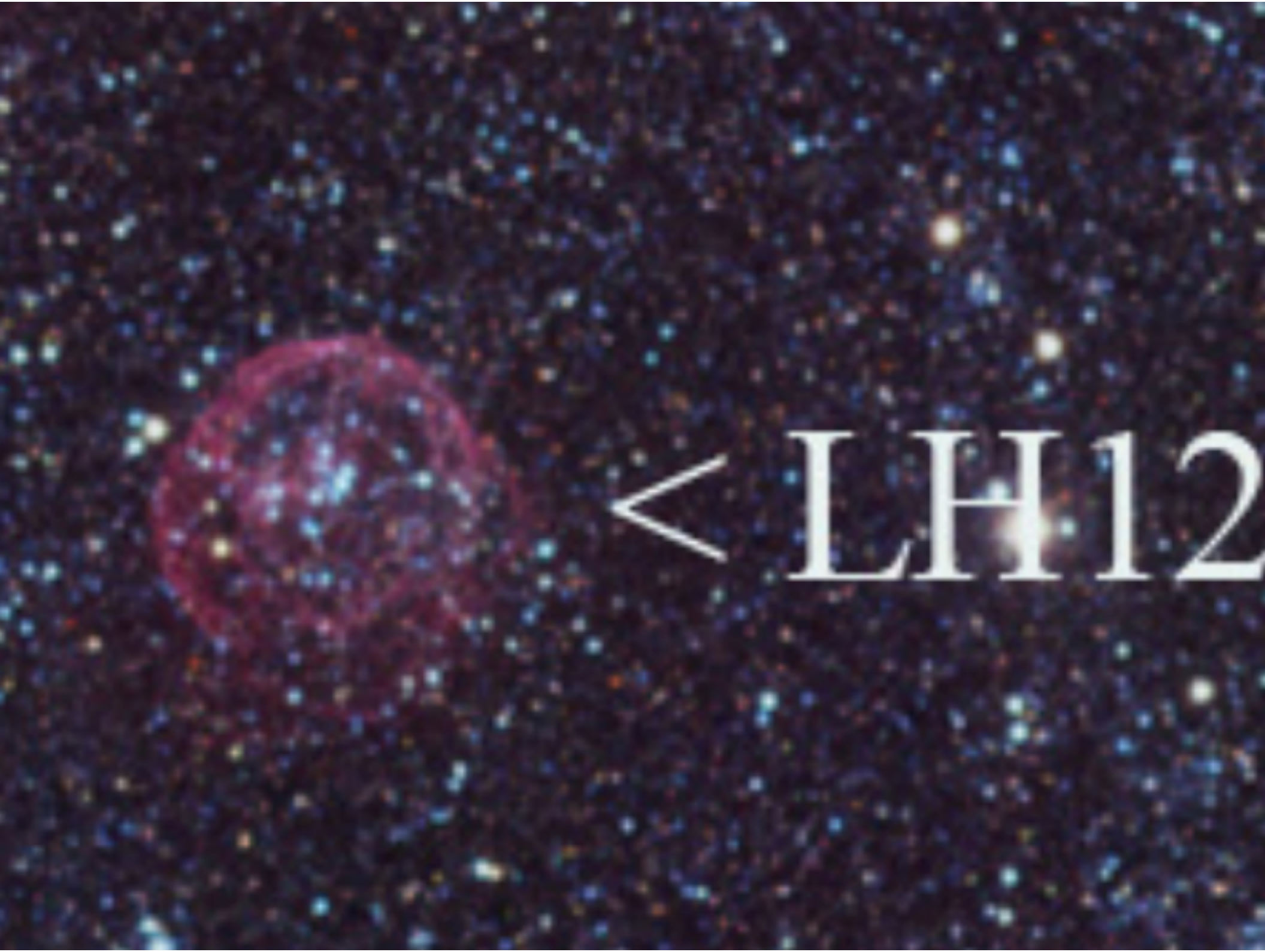
N
(The Bean Nebula)
N 11
N 185
N 44
N 51
N 144
N 200
N 206
N 198
The Tarantula Nebula
(NGC 2070)
(Dragon's Head)
N 64 A & C
160,000 light years
from here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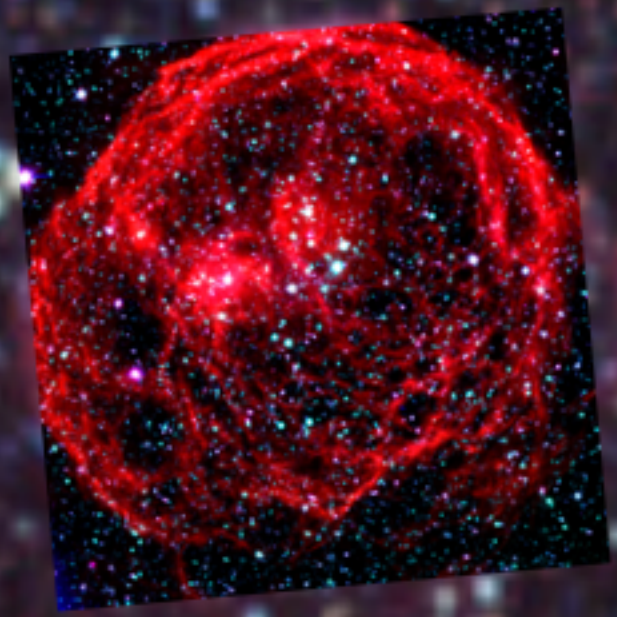

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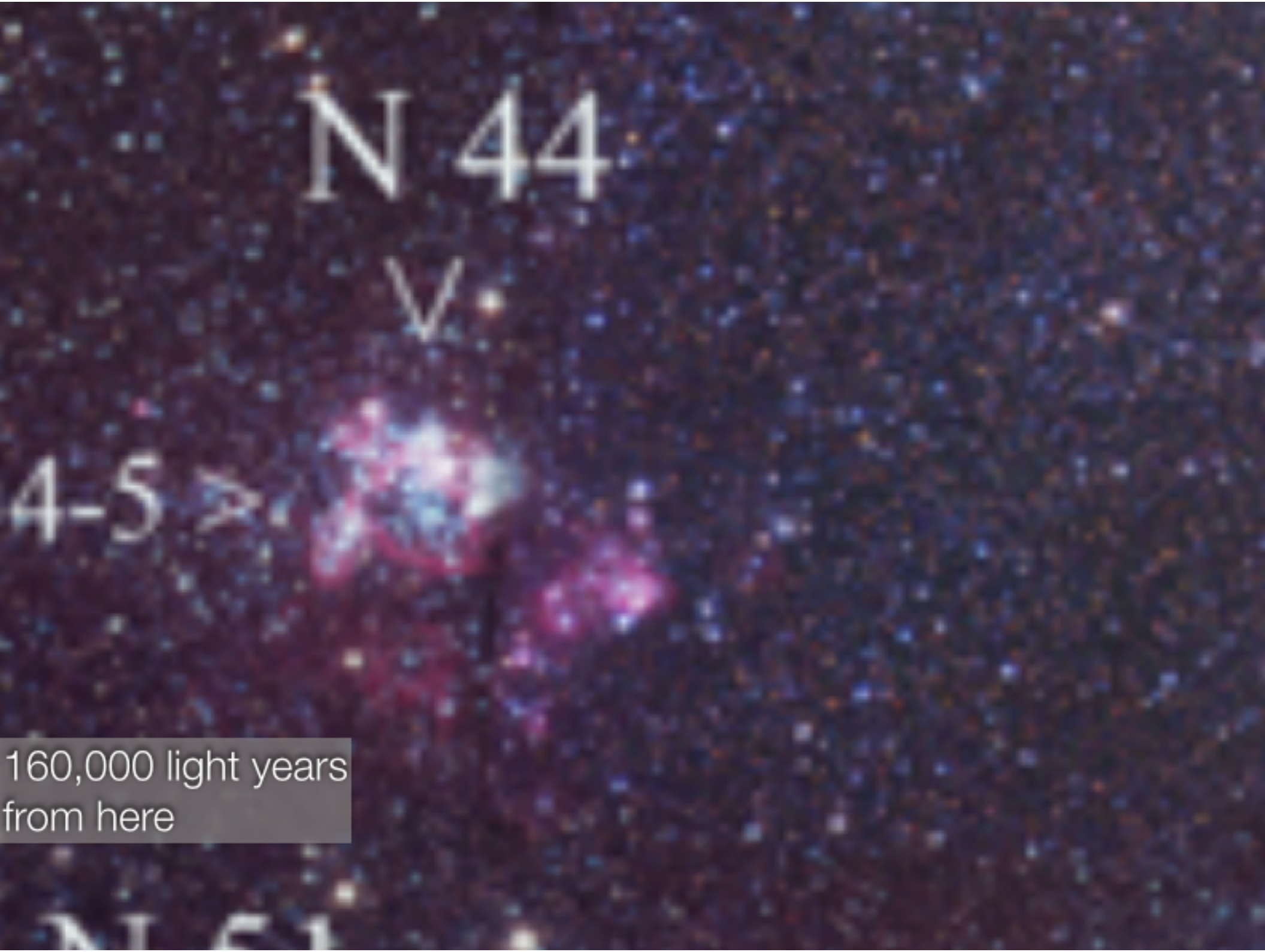
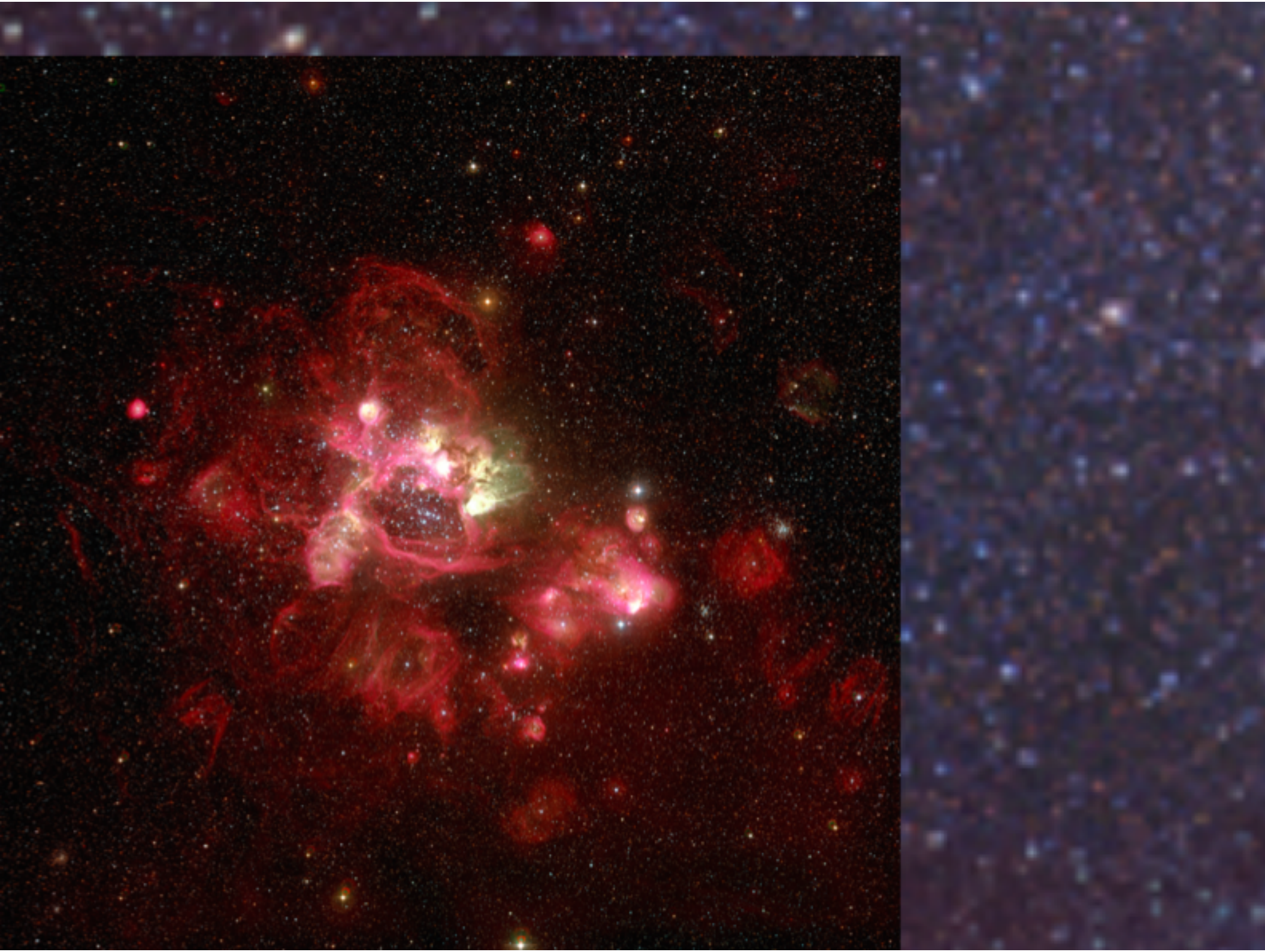
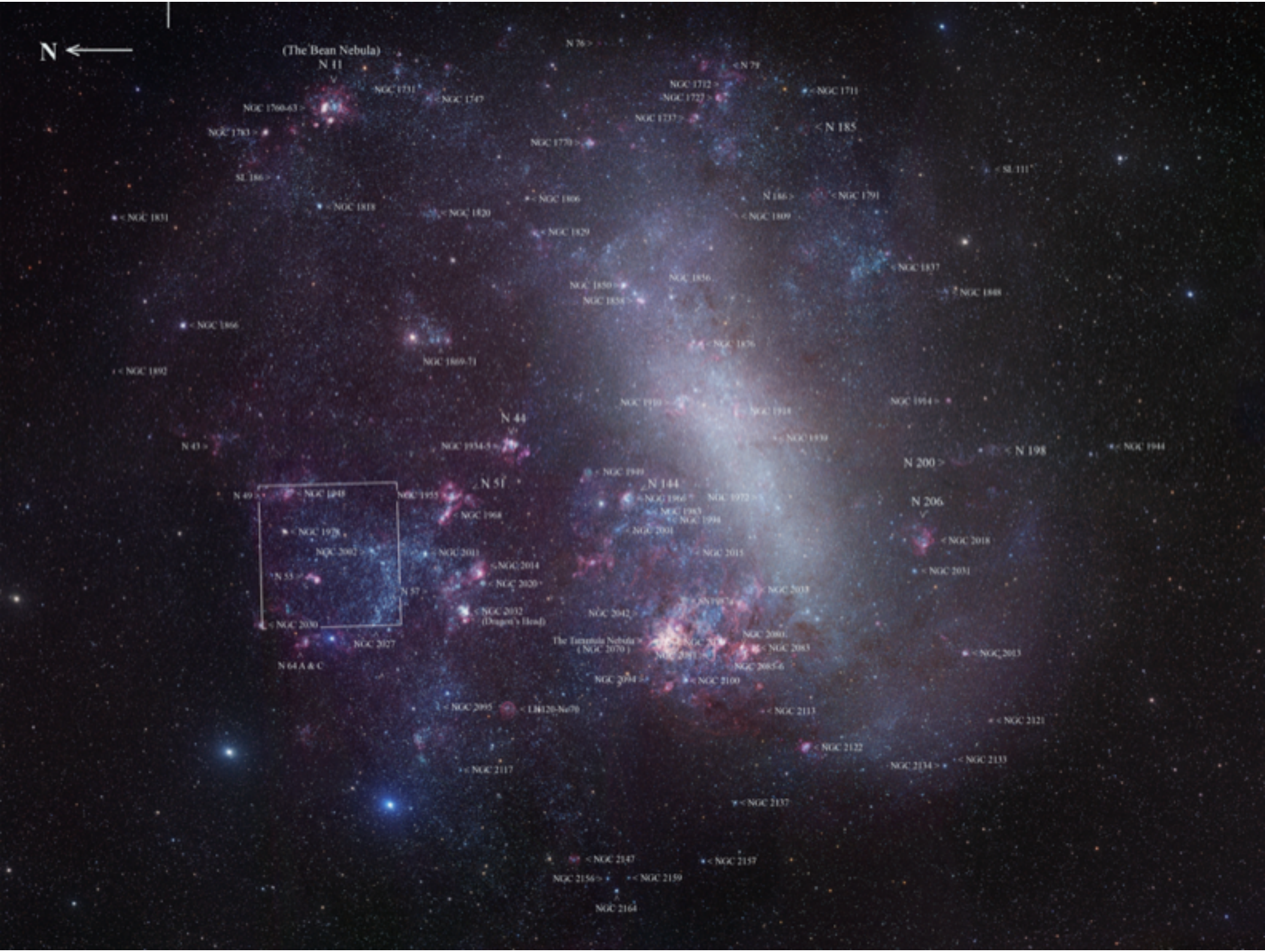

N 44
V
4-5
160,000 light years
from here

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NGC 1760-63 >
NGC 1783 >
NGC 1712 >
NGC 1722 >
< NGC 1711
NGC 1737 >
< N 185
NGC 1770 >
SL 186 >
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< NGC 1806
N 186 >
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< NGC 1818
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NGC 1850 >
NGC 1856
NGC 1858 >
? NGC 1848
< NGC 1866
< NGC 1876
NGC 1869-71
< NGC 1892
NGC 1910 >
NGC 1918
NGC 1954 >
N 44
NGC 1934-5 >
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N 43 >
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NGC 2002 >
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N 55 >
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N 57
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(Dragon's Head)
NGC 2042
< NGC 2030
NGC 2027
The Tarantula Nebula
(NGC 2070)
NGC 2081
< NGC 2083
< NGC 2013
N 64 A & C
NGC 2085-6
NGC 2094 >
< NGC 2100
< NGC 2095
< LH120-Na70
< NGC 2113
< NGC 2121
< NGC 2122
NGC 2134 >
< NGC 2133
< NGC 2117
< NGC 2137
< NGC 2147
< NGC 2157
NGC 2156 >
< NGC 2159
NGC 2164


N
NGC 2164

Magellanic Cloud

Spitzer Space Tel

ch / M. Meixner (STScI) & the SAGE Legacy Team

N
Magellanic Cloud
Spitzer Space Te
M. Meixner (STScI) & the SAGE Legacy Team

DM in Galaxy Clusters

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Fritz Zwicky
Born: 14-Feb-1898
Birthplace: Varna, Bulgaria
Died: 8-Feb-1974
in: Pasadena, CA
Cause of death: Heart Failure
Remains: Buried, Mollis Cemetery, Glarus, Switzerland

Zwicky (1933)

Coma Cluster from the Coma Cluster Treasury Survey (HST)
Distance: ~320 Mlyr,

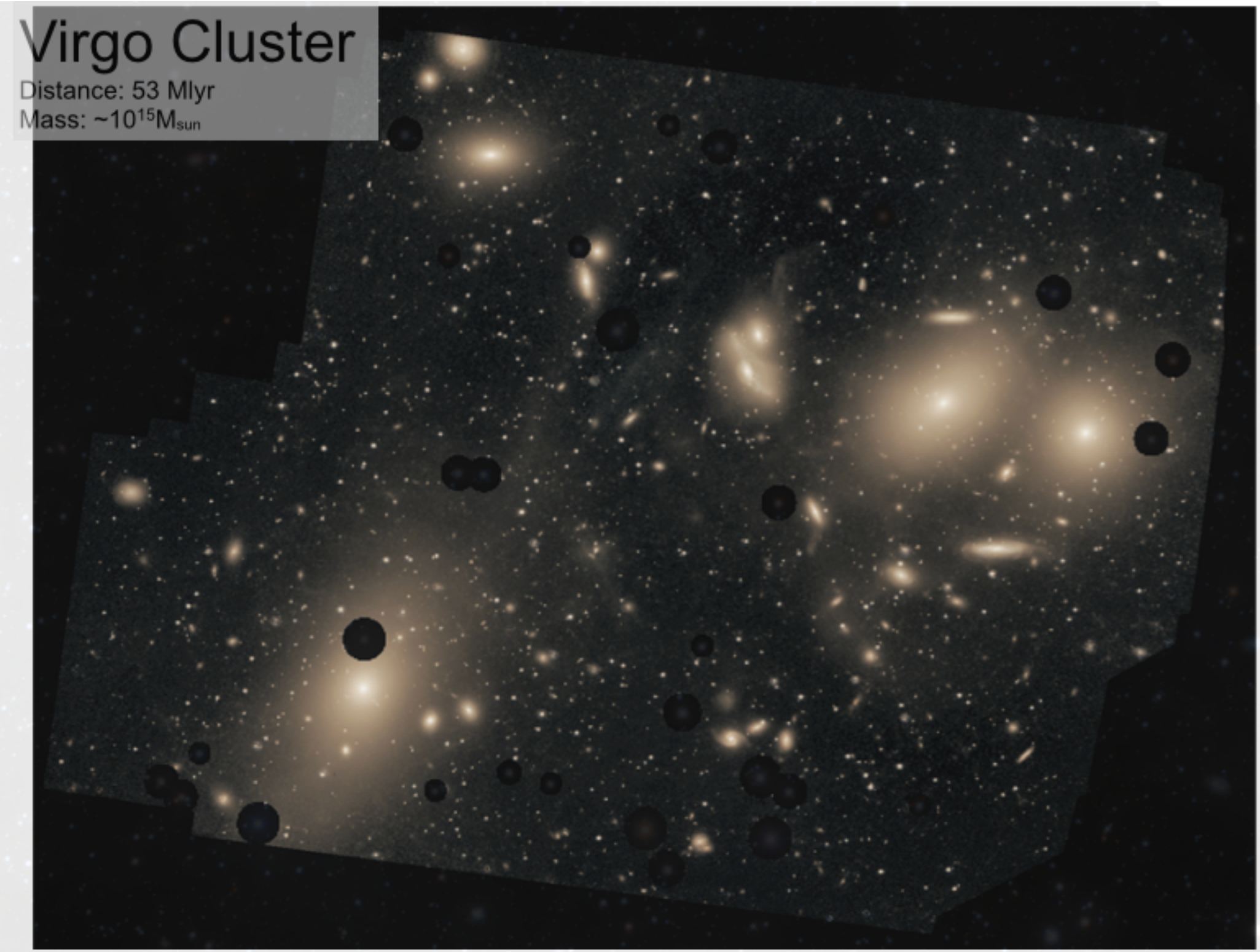
In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Zwicky (1937)


Virgo Cluster
Distance: 53 Mlyr
Mass: ~$10^{15}M_{sun}$


Virgo Cluster
Distance: 53 Mlyr
Mass: ~$10^{15}M_{sun}$

Checklist:
✓Dark Matter exists on Mlyr scale
✓Distributed differently from stars
✓Also exists in galaxies
✓Many accurate measures of DM

1986BAAS...18R1014L

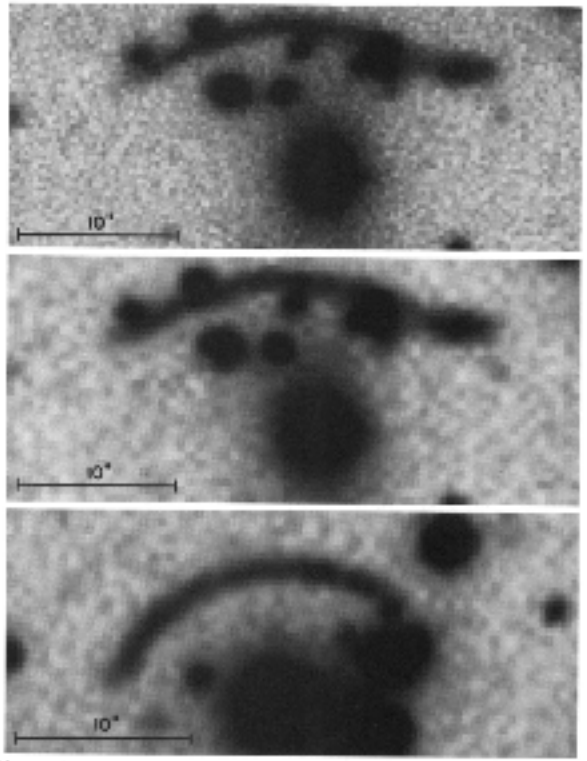
68.01

Giant Luminous Arcs in Galaxy Clusters

R. Lynds (KPNO/NOAO), V. Petrosian (Stanford U.)

We announce the existence of a hitherto unknown type of spatially coherent extragalactic structure having, in the two most compelling known examples, the common properties: location in clusters of galaxies, narrow arc-like shape, enormous length, and situation of center of curvature toward both a cD galaxy and the apparent center of gravity of the cluster. The arcs are in excess of 100 Kpc in length, have luminosities roughly comparable with those of giant E galaxies, and are distinctly bluer than E galaxies - especially so in one case. Interpretations of the nature of the arcs are discussed within the framework of available data.

Gravitational Lensing



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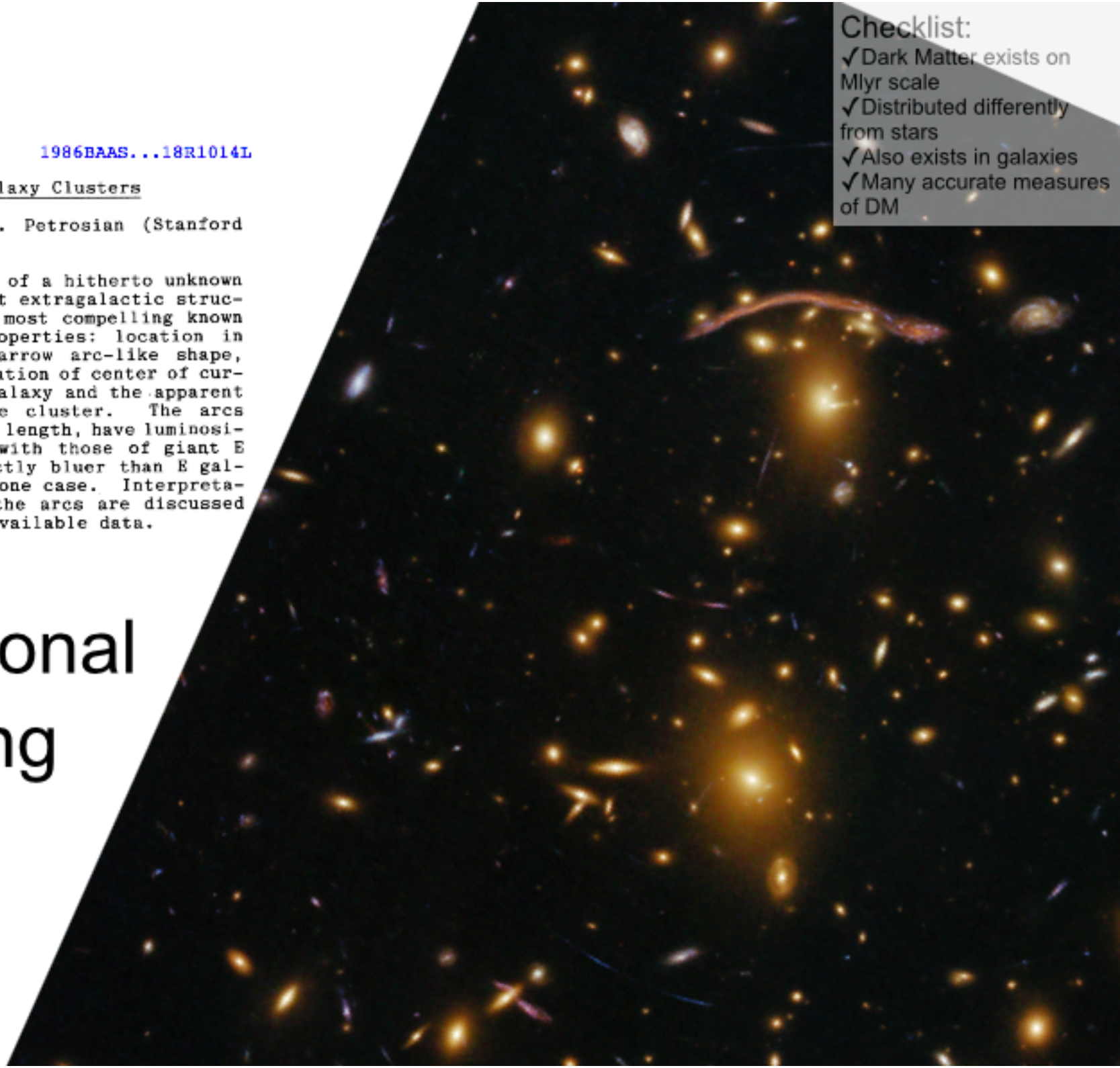

Checklist:

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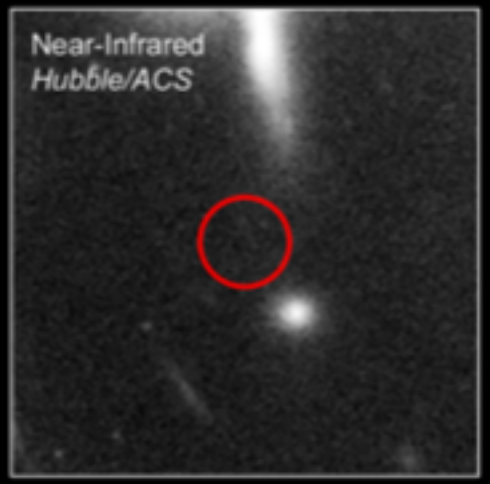
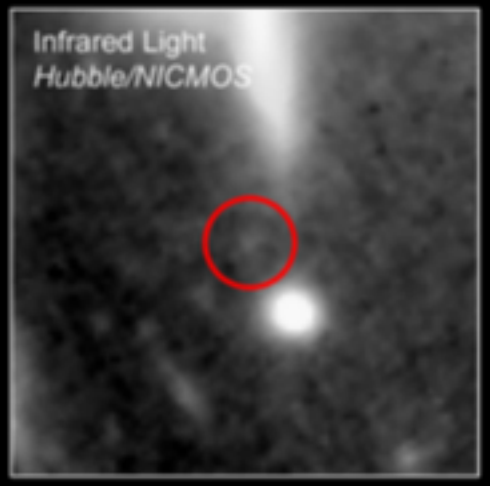
✓Also exists in galaxies

✓Many accurate measures of DM

Dark Matter "seen" with your naked eye





Abell 2218
Distance:
2,3Glyr
Redshift: 0.18

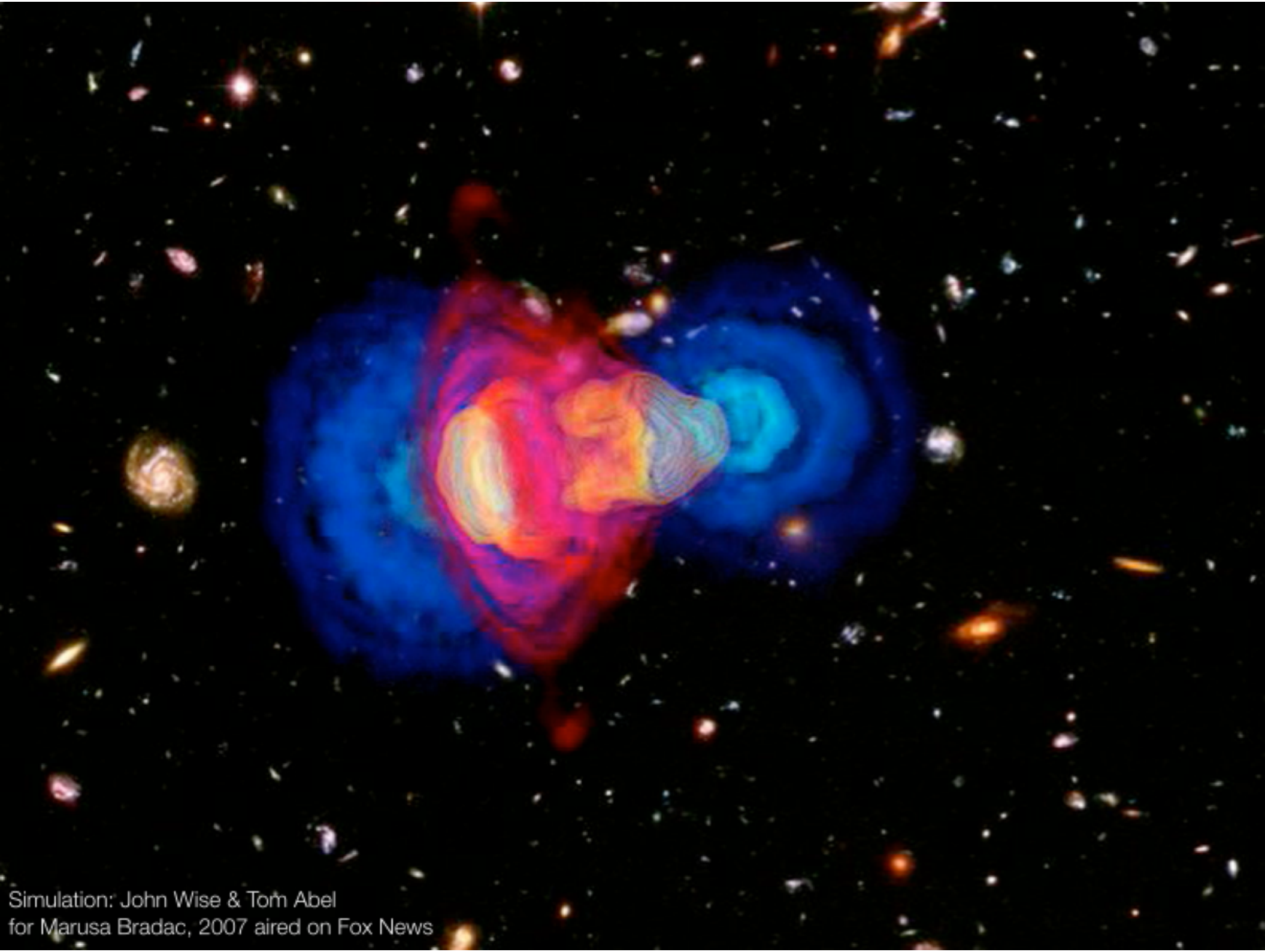
Strong
Gravitational
Lensing

Dark matter & Gravity dominate on large scales

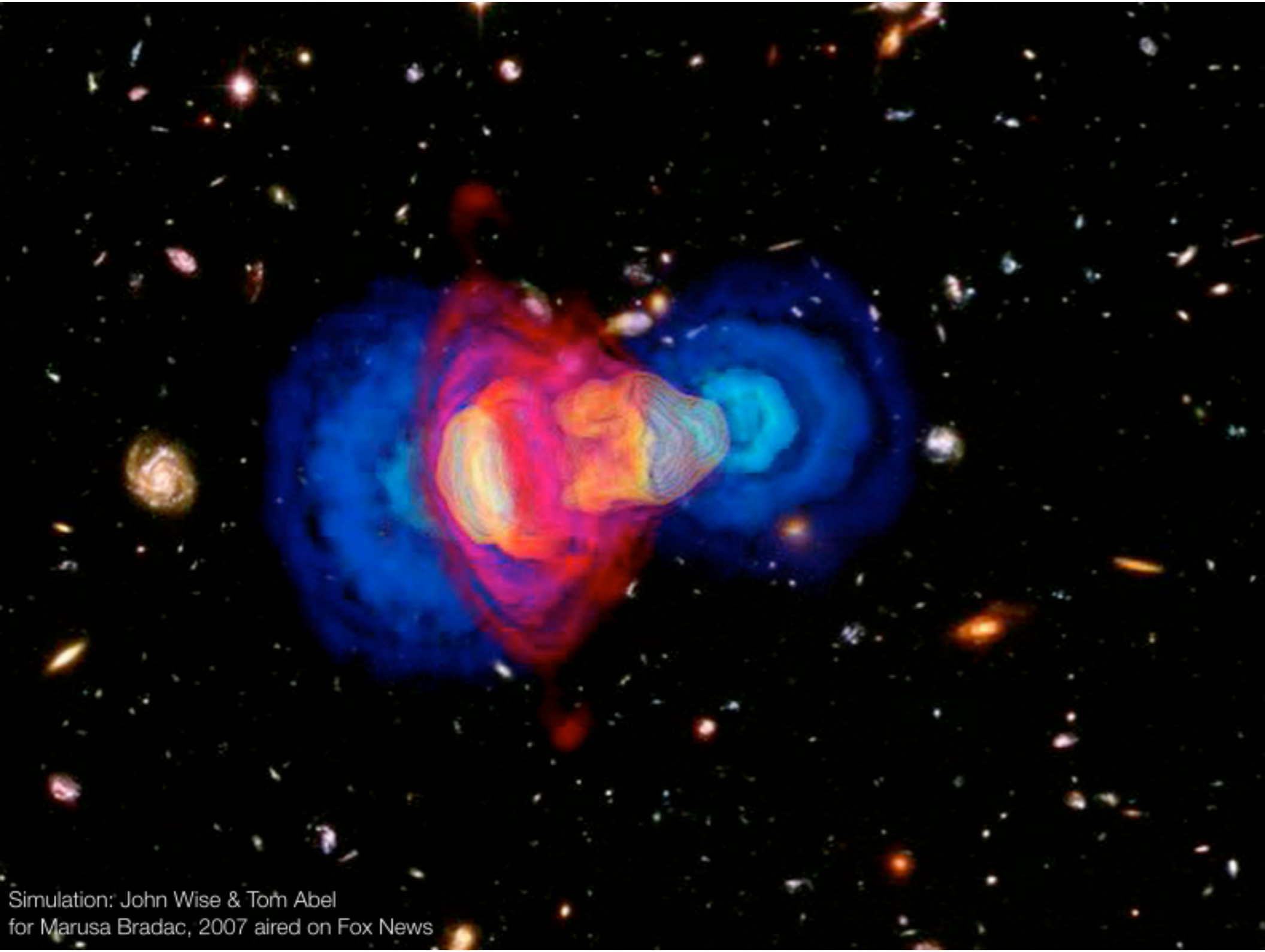
Checklist:
✓Dark Matter exists on Mlyr scale
✓Distributed differently from stars
✓Also exists in galaxies
✓Many accurate measures of DM
✓DM interacts weakly with gas and itself. Collisionless?

Bullet Cluster
collision speed 2600 km/s
mass ratio ~1/10
Cluster: 1E0657-56
~ 10 million lyrs across
~ 10 billion lyrs from earth

Clowe, Bradac, et al. 2007



Simulation: John Wise & Tom Abel
for Marusa Bradac, 2007 aired on Fox News



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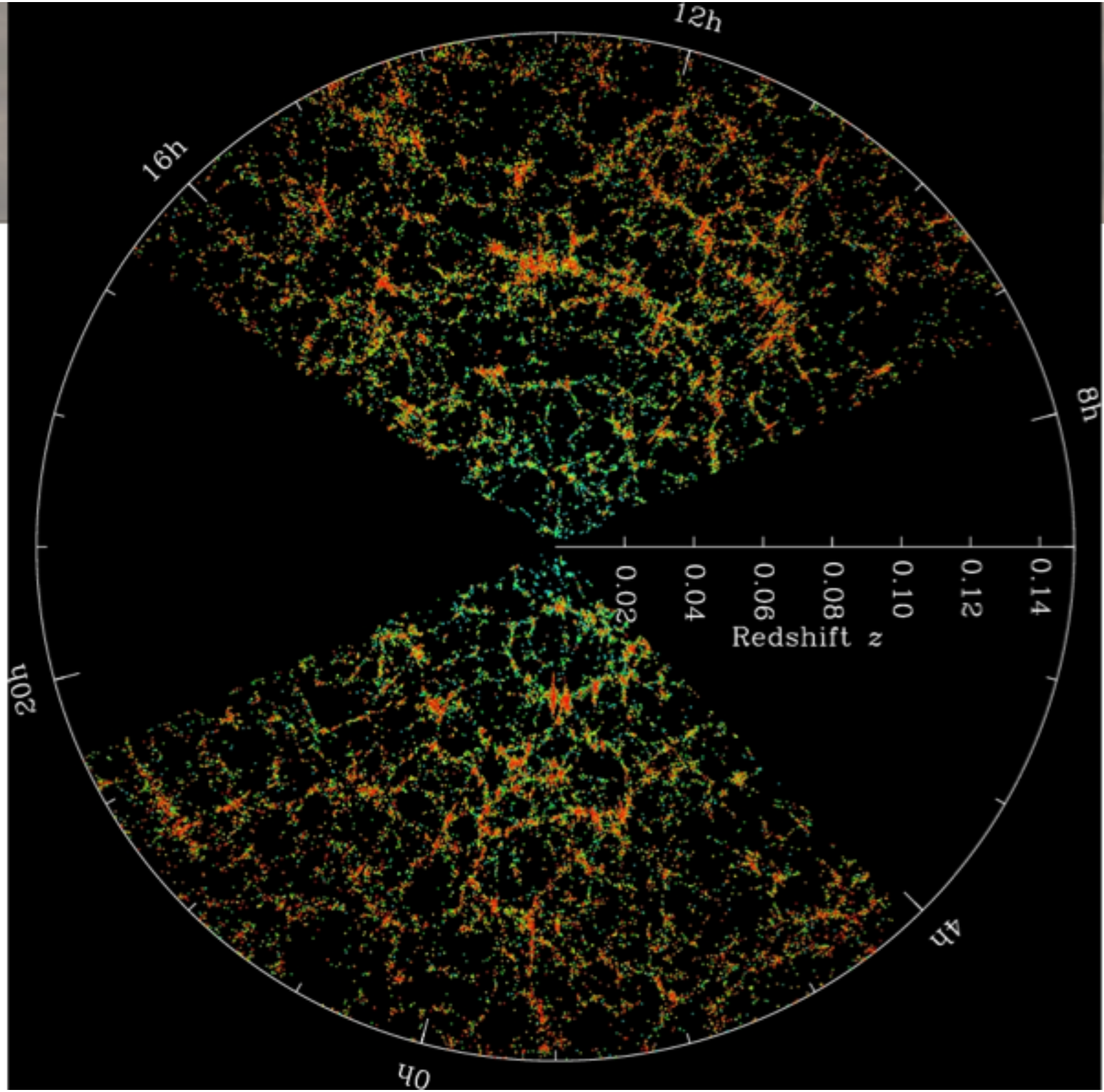
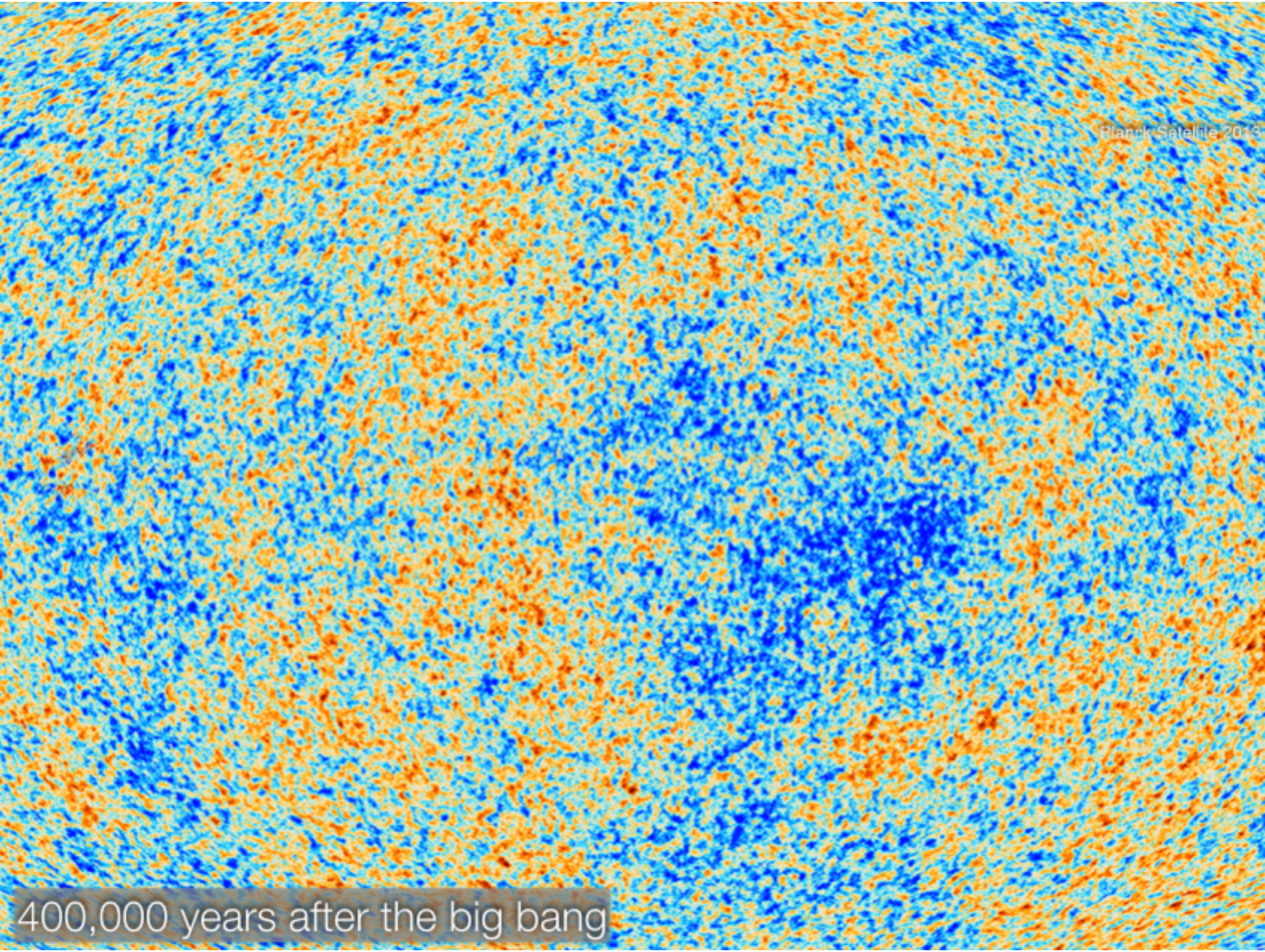
SDSS



Slices through the SDSS 3-dimensional map of the distribution of galaxies. Earth is at the center, and each point represents a galaxy, typically containing about 100 billion stars. Galaxies are colored according to the ages of their stars, with the redder, more strongly clustered points showing galaxies that are made of older stars. The outer circle is at a distance of two billion light years. The region between the wedges was not mapped by the SDSS because dust in our own Galaxy obscures the view of the distant universe in these directions. Both slices contain all galaxies within -1.25 and 1.25 degrees declination.

Credit: M. Blanton and the Sloan Digital Sky Survey.

13.8 billion years ago


Planck Satellite 2013
400,000 years after the big bang

Viz: Ralf Kaehler & Tom Abel
For "Dark Universe" planetarium show

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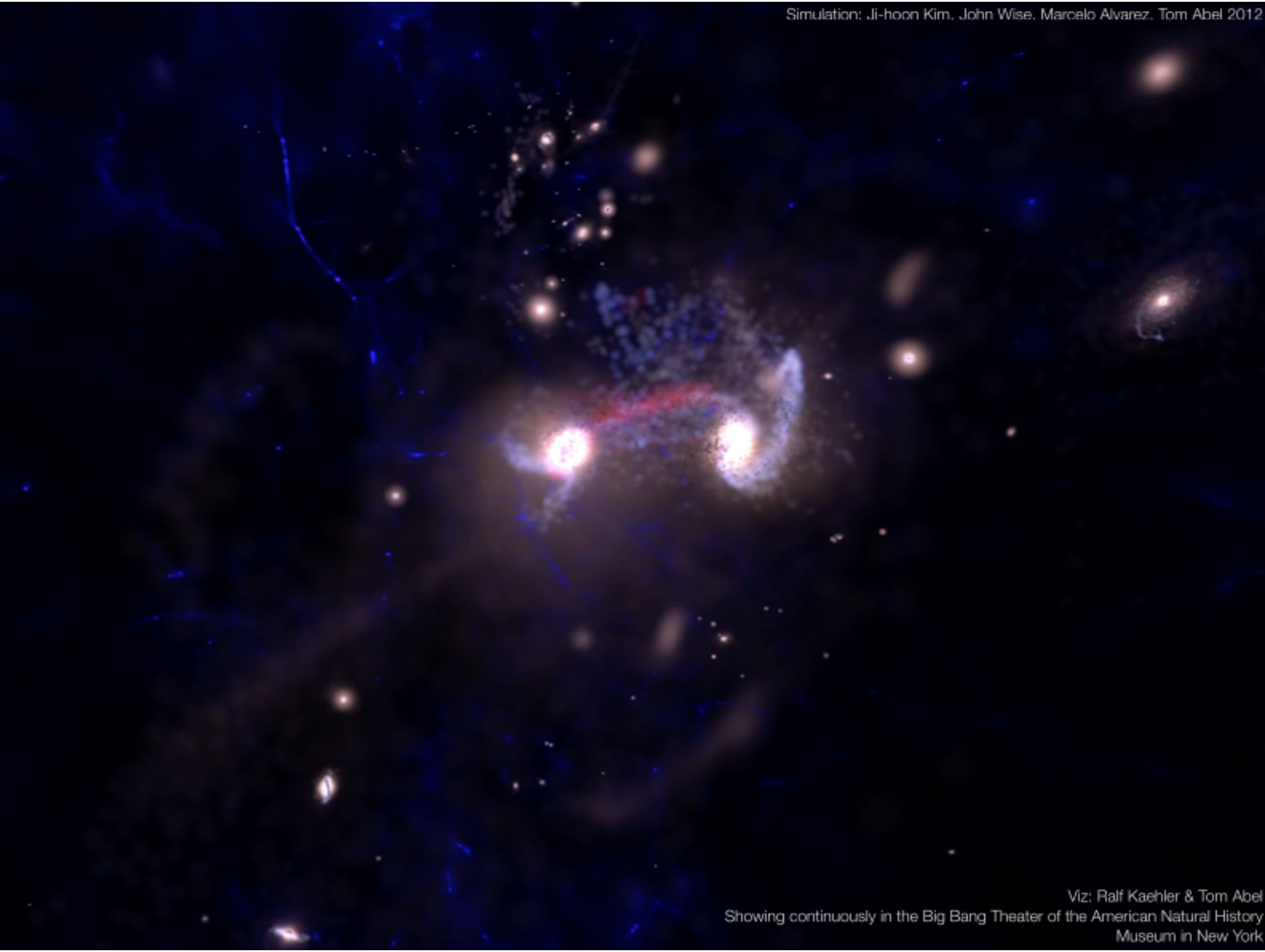
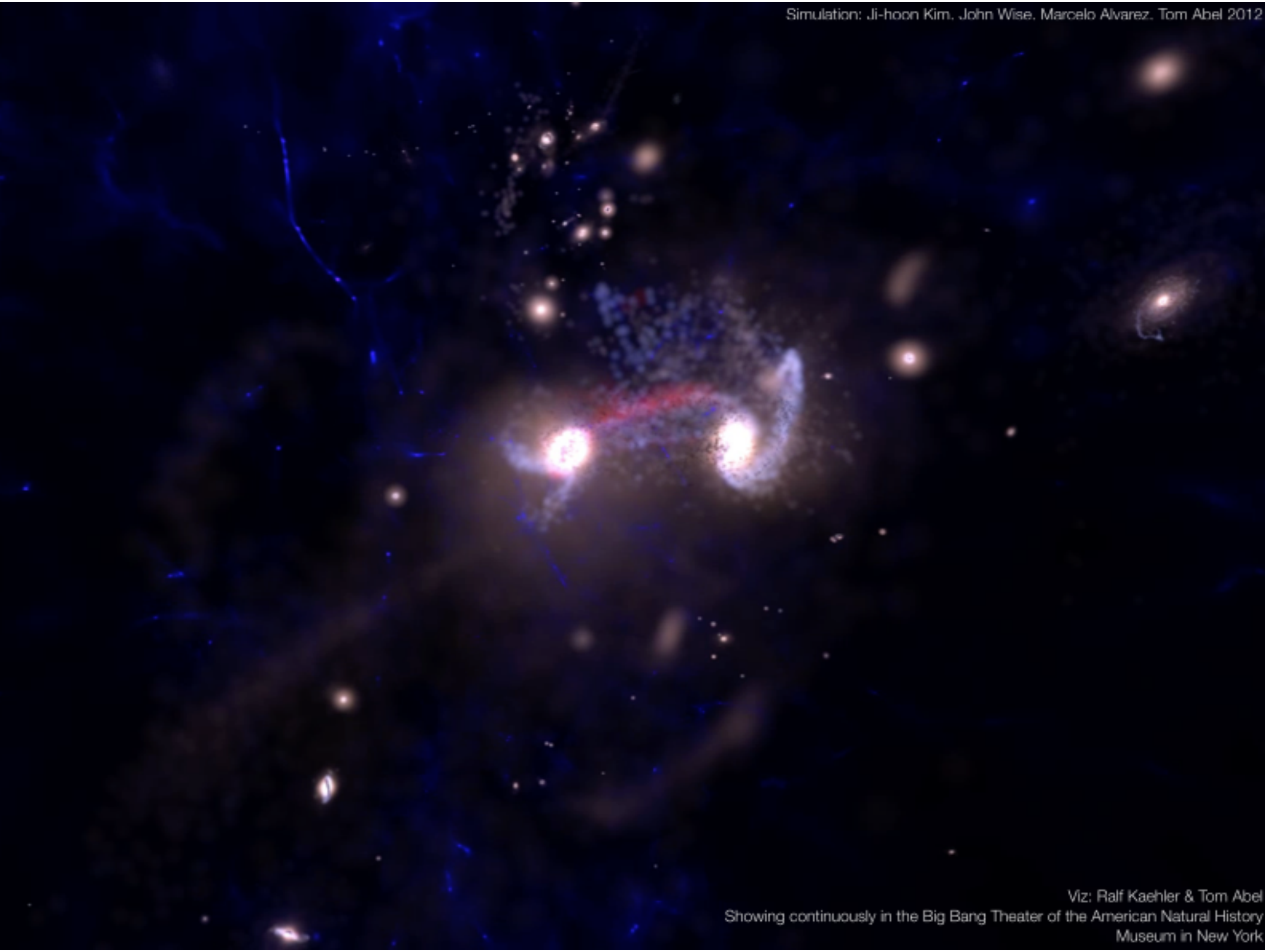

Simulation: Ji-hoon Kim, John Wise, Marcelo Alvarez, Tom Abel 2012
Viz: Ralf Kaehler & Tom Abel
Showing continuously in the Big Bang Theater of the American Natural History
Museum in New York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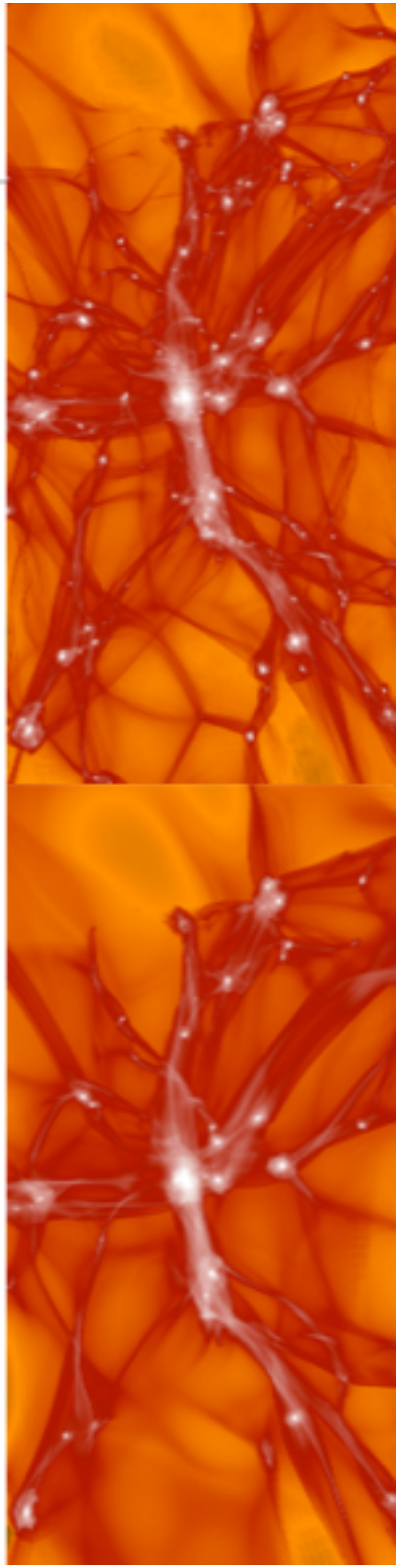
Cosmological N-body simulations

- Used to make predictions about the distribution of dark matter in the Universe
- Key results
  - Galaxies are arranged in cosmic web of voids/sheets/filaments/halos
  - Universal spherical Dark Matter density profile (NFW) [not understood from analytical arguments]
  - Predicted mass functions of halos and their clustering and velocity statistics
- Primary tool to study observational consequences of LCDM
  - initial conditions: warm vs cold DM, Gaussian vs non-Gaussian
  - sensitivity on global cosmological parameters such as the total matter content and amount of dark energy, etc.
  - Gravitational Lensing signatures

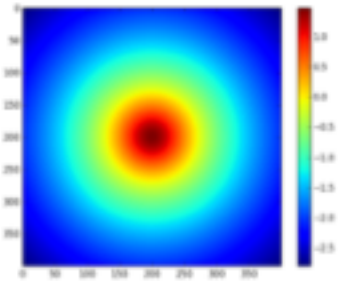


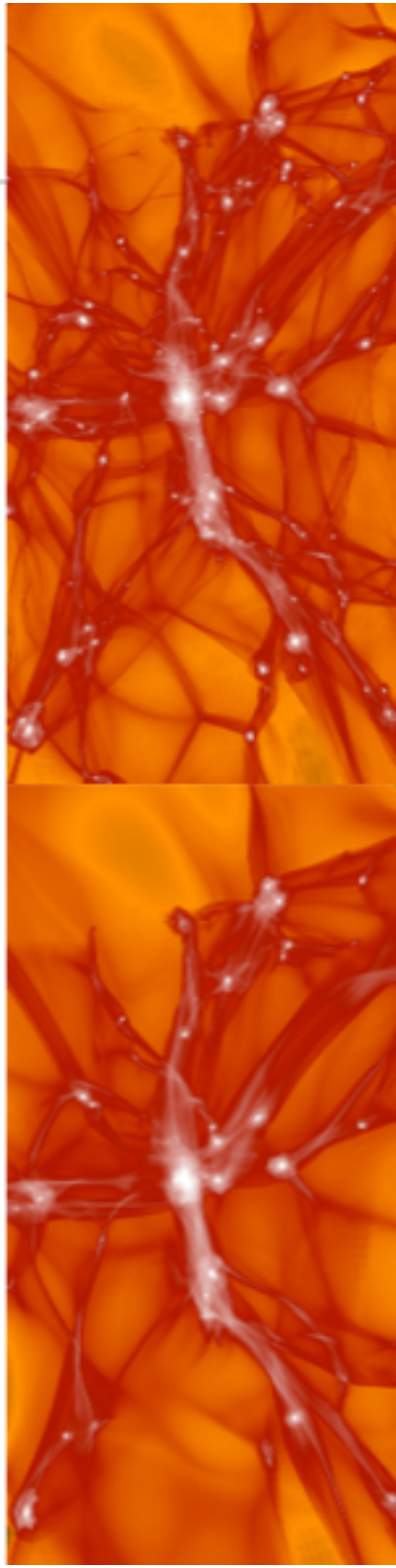
Cosmological N-body simulations

$$\dot{\mathbf{x}} = \mathbf{v}(t) \qquad \dot{\mathbf{v}}_\mathbf{i} = -\sum_{i \neq j}^{N} G m_i m_j \frac{(\mathbf{x_j} - \mathbf{x_i})}{|\mathbf{x_j} - \mathbf{x_i}|^3}$$

- All modern cosmological simulation codes only differ in how they accelerate the computation of the sum over all particles to obtain the net force
- End result are simply the positions and velocities of all particles
- Limit N goes to infinity must give correct answer, right?
- Softening of forces (add epsilon^2 in denominator) avoids singularities.

$$\dot{\mathbf{v}}_i = -\sum_{i \neq j}^{N} G\, m_i\, m_j \frac{(\mathbf{x}_j - \mathbf{x}_i)}{\left(|\mathbf{x}_j - \mathbf{x}_i|^2 + \epsilon^2\right)^{3/2}}$$





Some public Cosmological N-body codes

- Enzo: Adaptive mesh DM+Hydro+MHD+Radiation etc.
  http://enzo-project.org

- Gadget: Popular DM only code and SPH hydro:
  http://www.mpa-garching.mpg.de/gadget/

- Ramses: Adaptive mesh cosmology code
  http://www.ics.uzh.ch/~teyssier/ramses/RAMSES.html

- Initial conditions generator:
  http://www.phys.ethz.ch/~hahn/MUSIC/

- Yt: Simulation output analysis
  http://yt-project.org

Summary

- We have now an appreciation of
  - how gravitational instability forms structure in the Universe
  - rough idea how cosmological N-body codes work
  - some of the challenges in studying the fully non-linear dynamics of a self-gravitating collisionless fluid