Title: Observational Evidence for Dark Matter

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Abstract:

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Mike Hudson
U. Waterloo

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+ tiny amounts of radiation (photons)

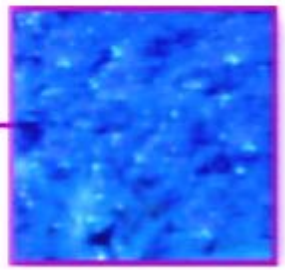
Cosmic Pie

Chemical Elements:
(other than H & He) 0.03%

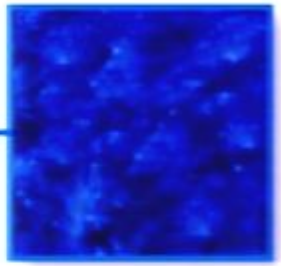
Neutrinos:
0.47%

Stars:
0.5%

Free H
& He:
4%



Dark Matter:
25% +/- 10 %



Dark Energy:
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mystery

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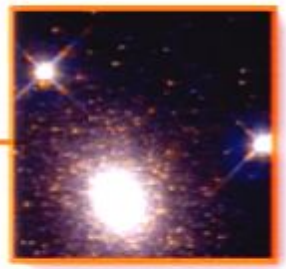

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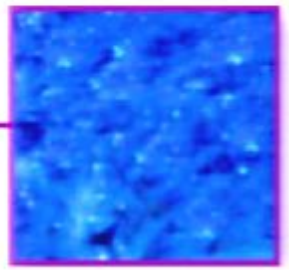

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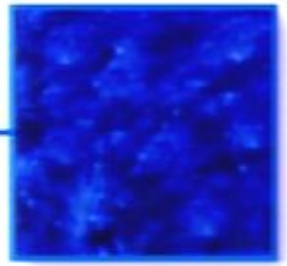

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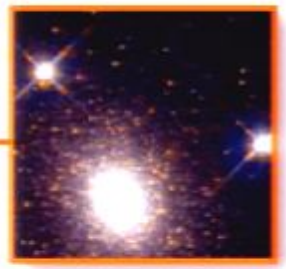

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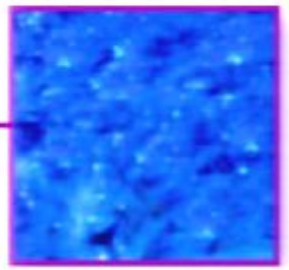

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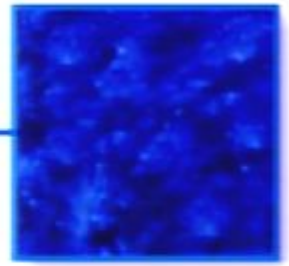

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95% mystery

Ω = density of matter or energy divided by critical density

Ω_b = density of baryons

Ω_m = density of matter

Ω_v = density of vacuum

Assumption: GR is valid

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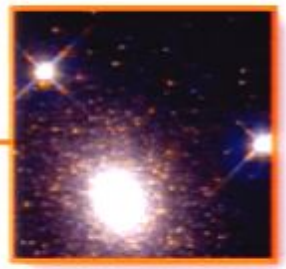

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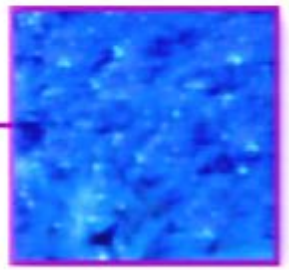

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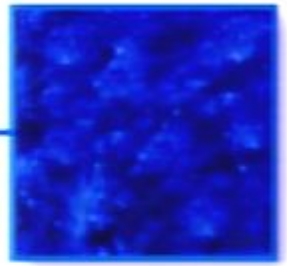

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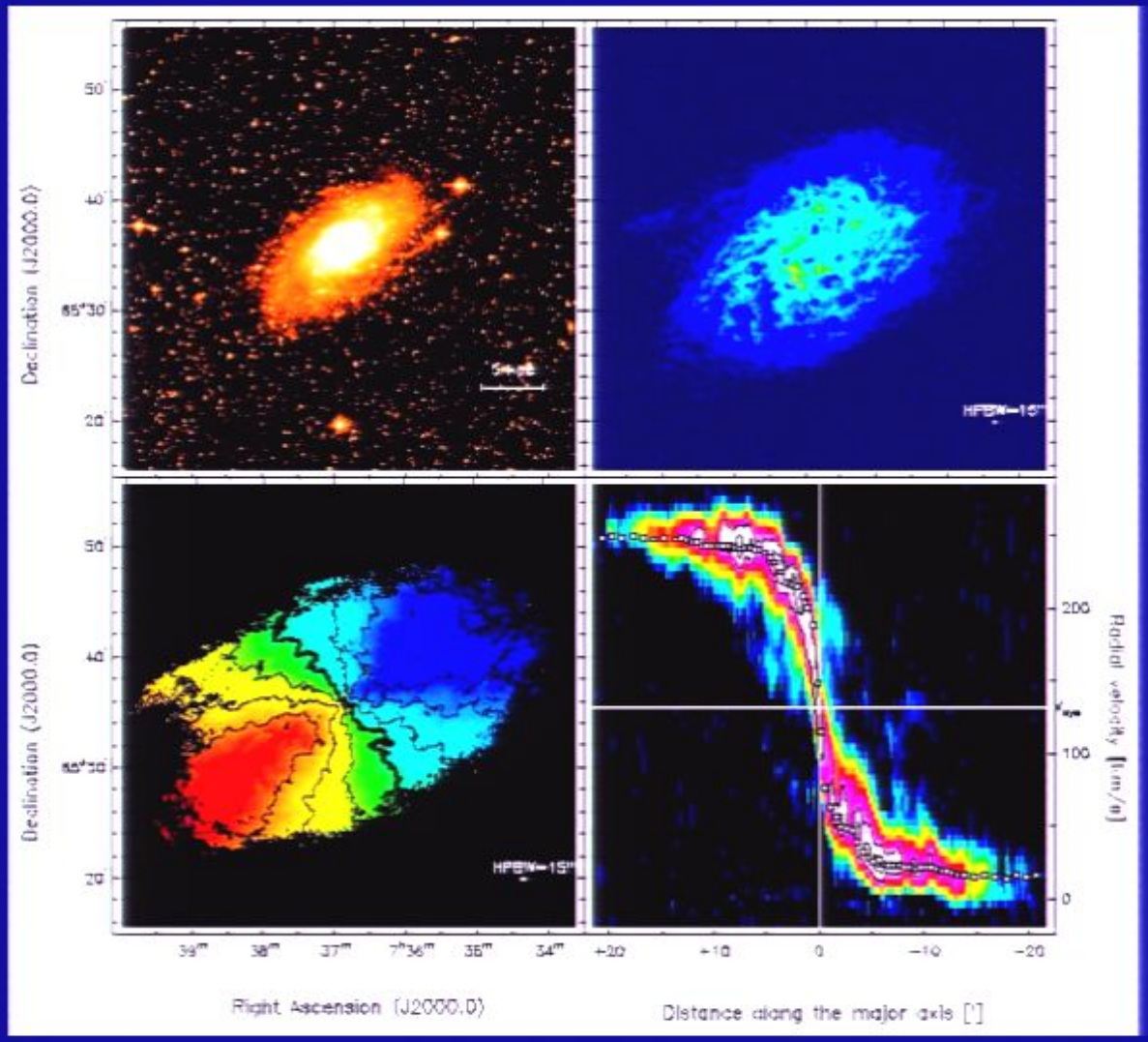
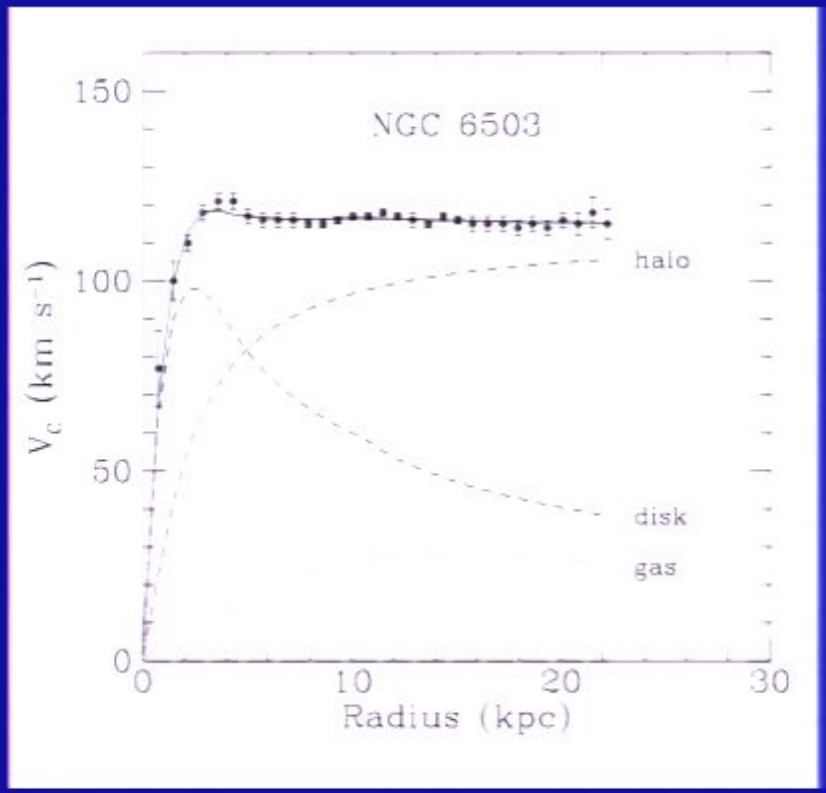
Outline

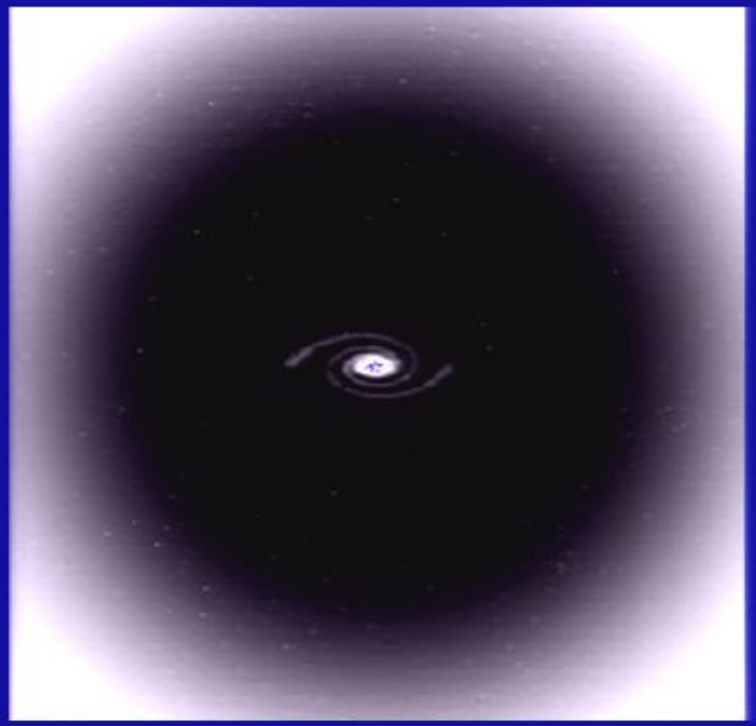
- Model-independent evidence for dark matter
  - Spiral galaxy rotation curves
  - Clusters of galaxies
  - Gravitational Lensing
  - Peculiar Velocities
- Model-dependent evidence
  - Cosmic Microwave background and large-scale structure

Spiral Galaxy Rotation Curves



Dark Matter Halo





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$$M(<R) \propto R$$

...lower limit on total mass

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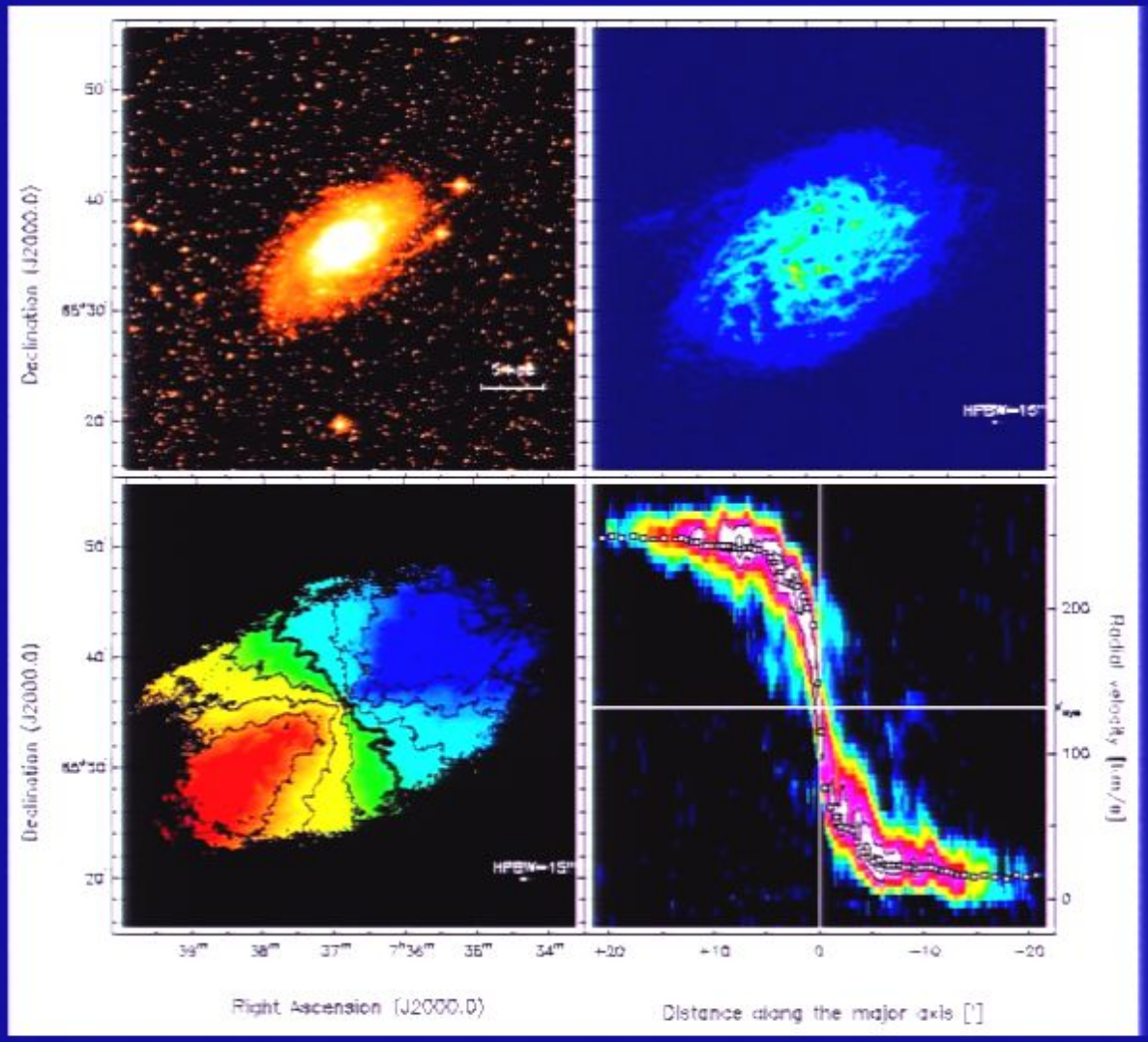

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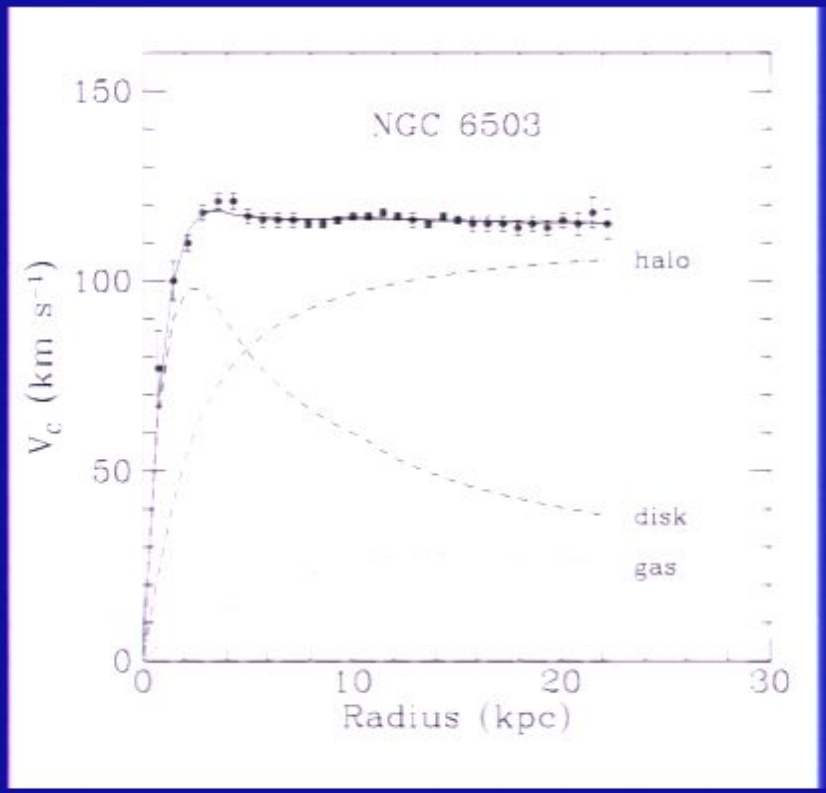

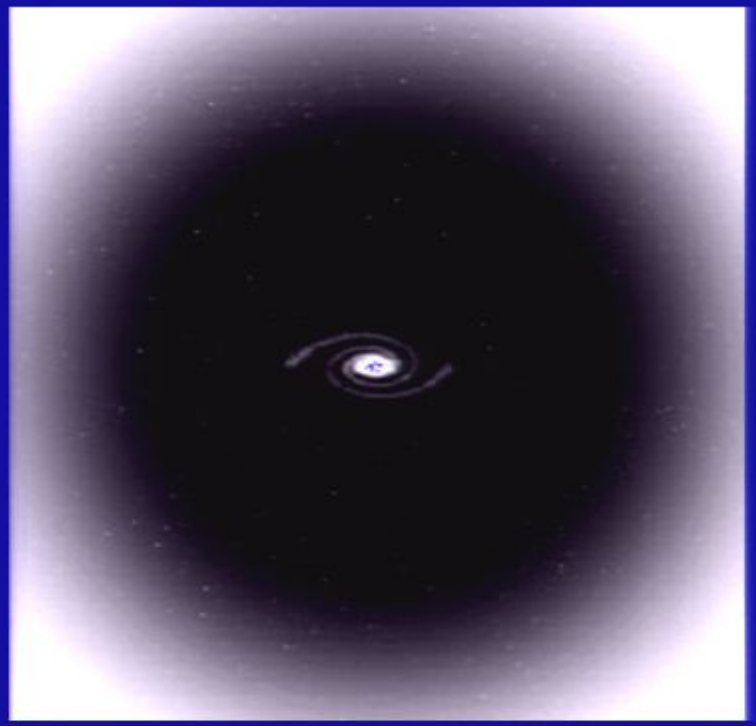

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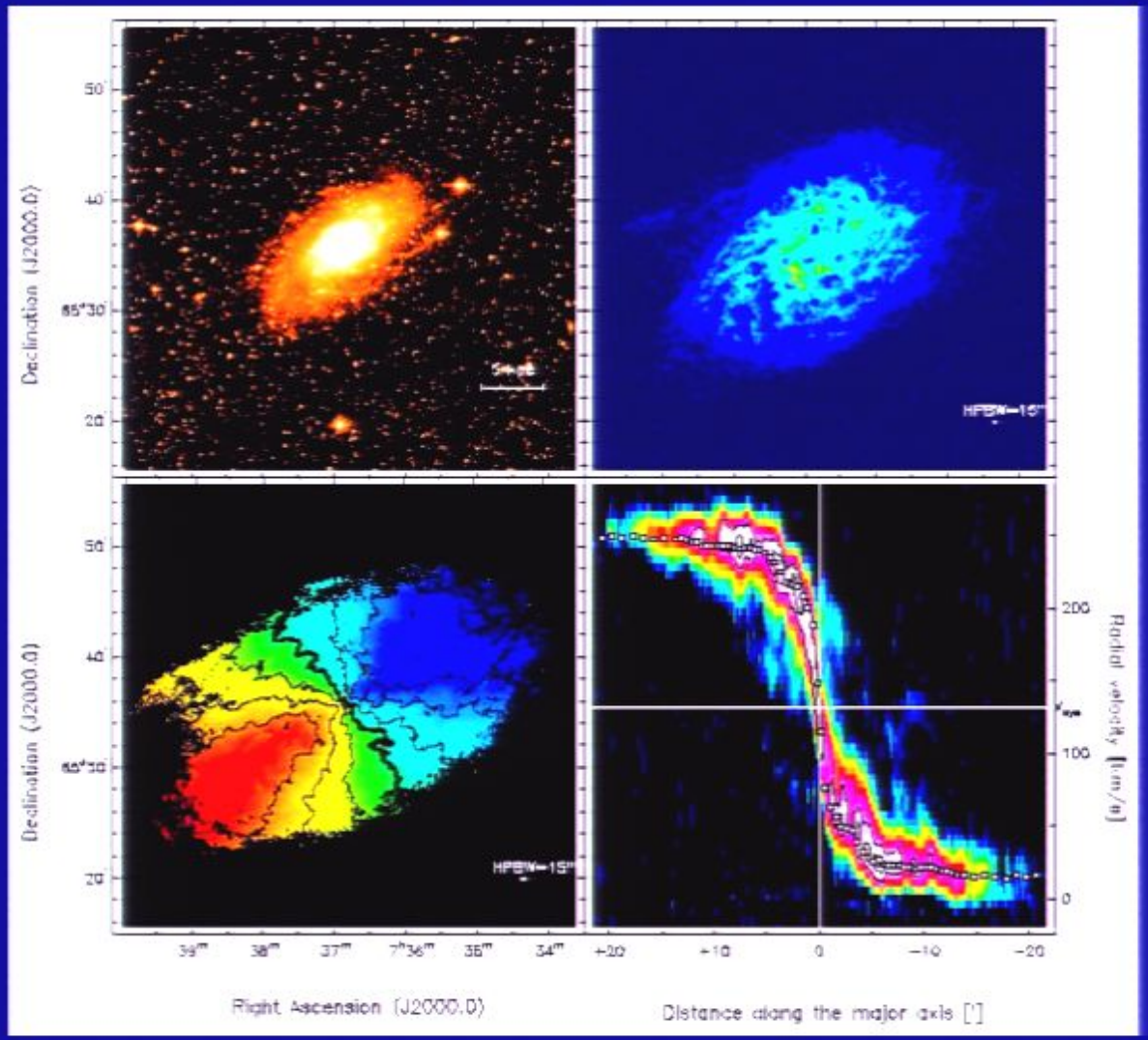

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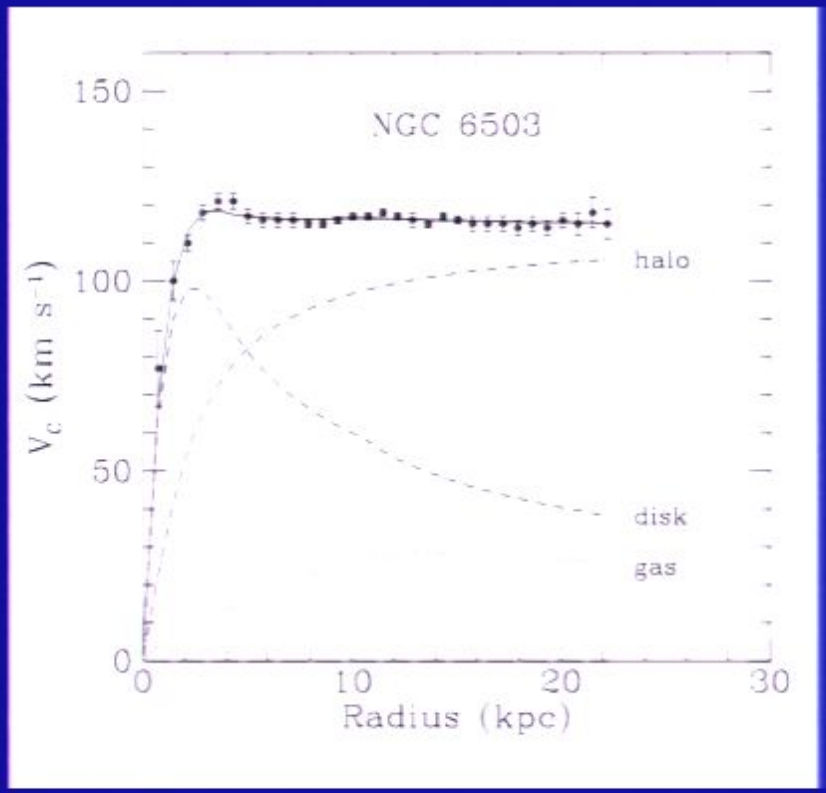

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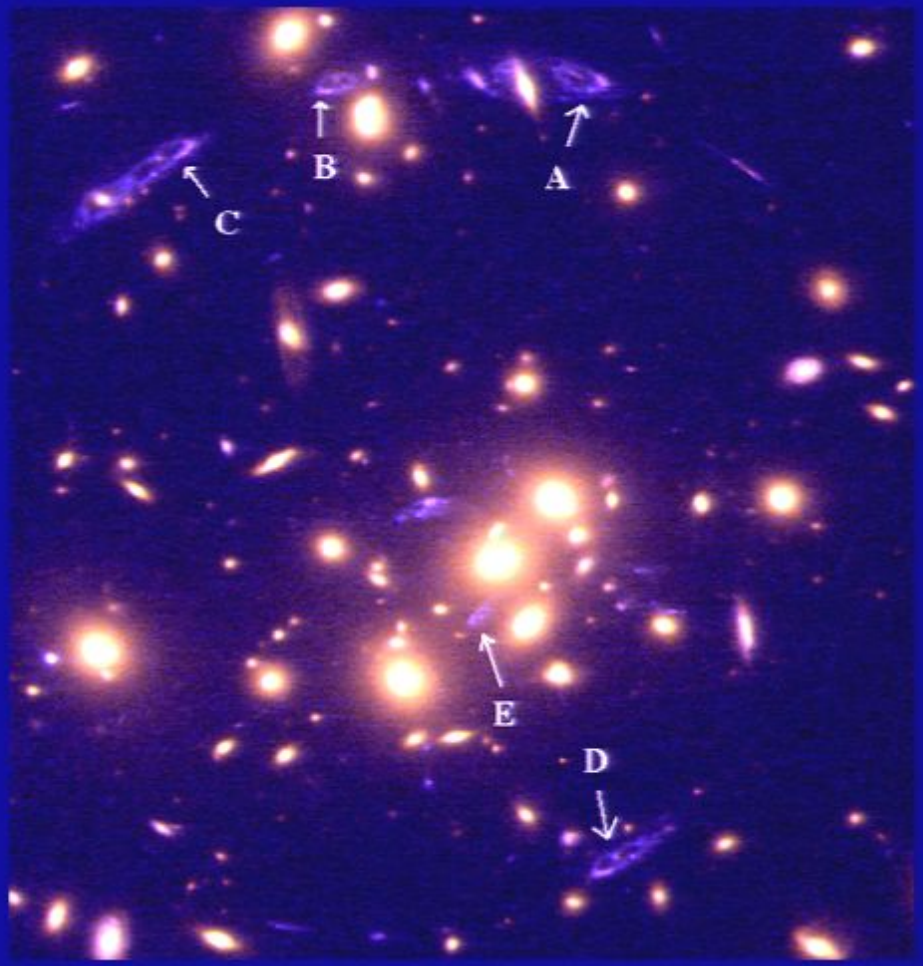
Clusters of Galaxies



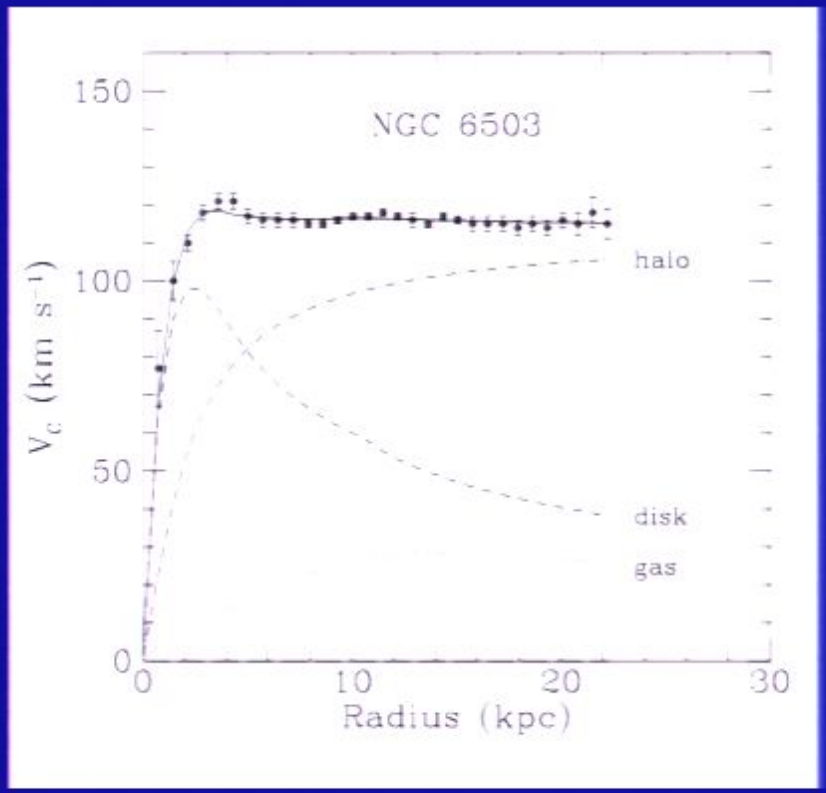
The largest virialized objects in the Universe

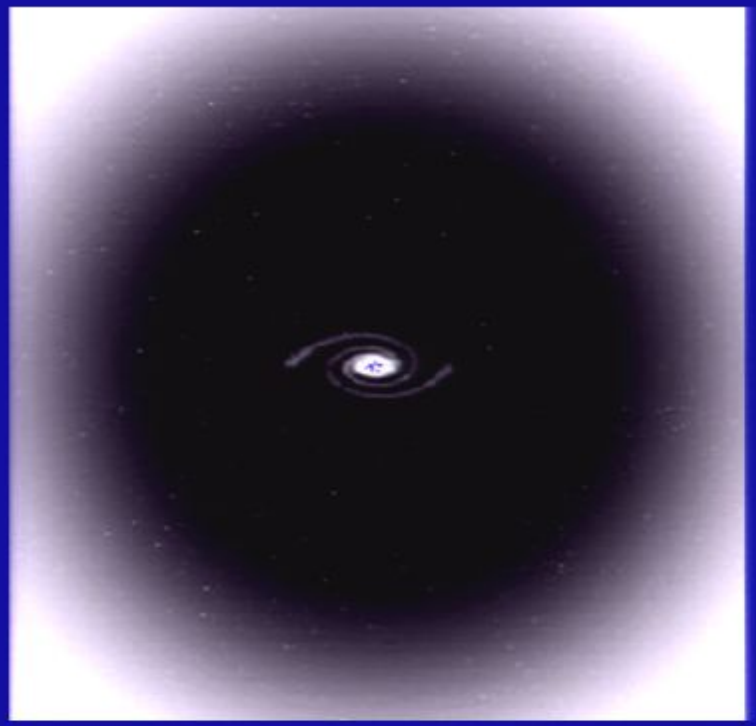
Masses can be obtained by three methods

- Dynamics of galaxies (virial theorem)
- X-ray emitting gas (hydrostatic equilibrium)
- Gravitational Lensing

Scale: ~1 Mpc

Dark Matter Halo





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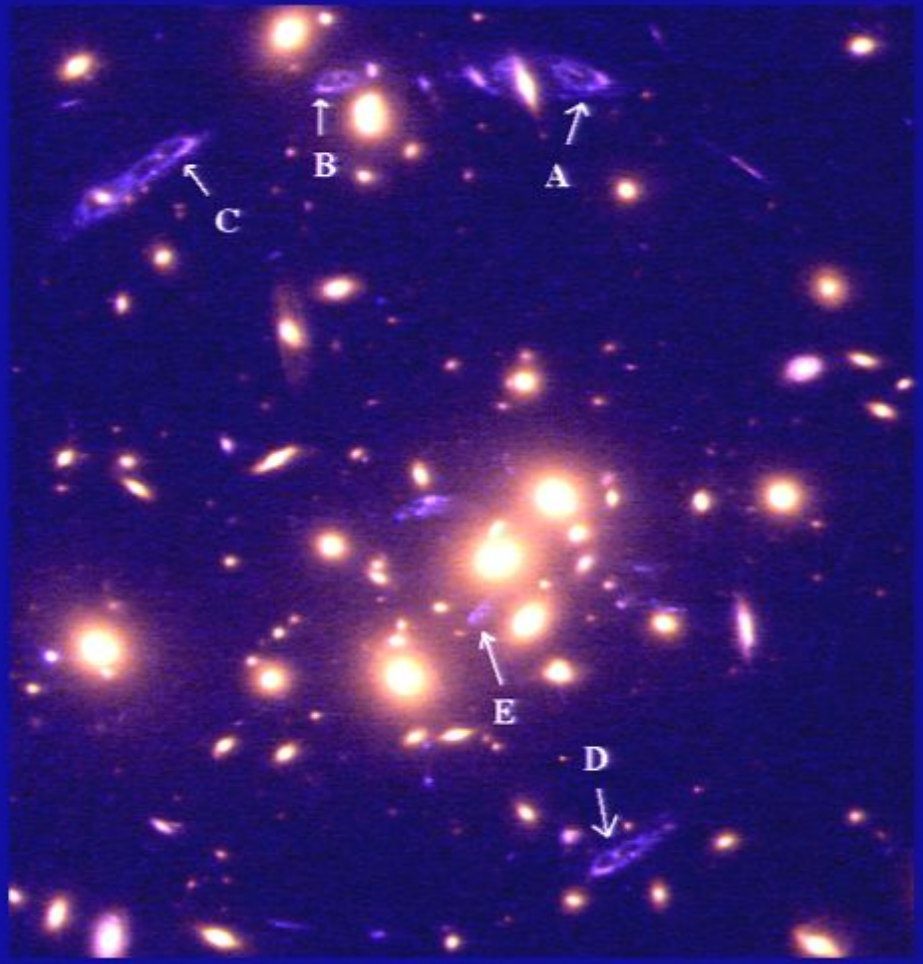

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- Virial theorem or Jean's equations applied to motions of galaxies with respect to cluster center yield cluster masses.

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$$\mathfrak{M} > 9 \times 10^{46}\,\mathrm{gr}\,. \qquad (35)$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43}\,\mathrm{gr} = 4.5 \times 10^{10}\,M_{\odot}\,. \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathfrak{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^{7} suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500\,. \qquad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several years ago, when the conclusion expressed in (36) was reached for the first time.[3]

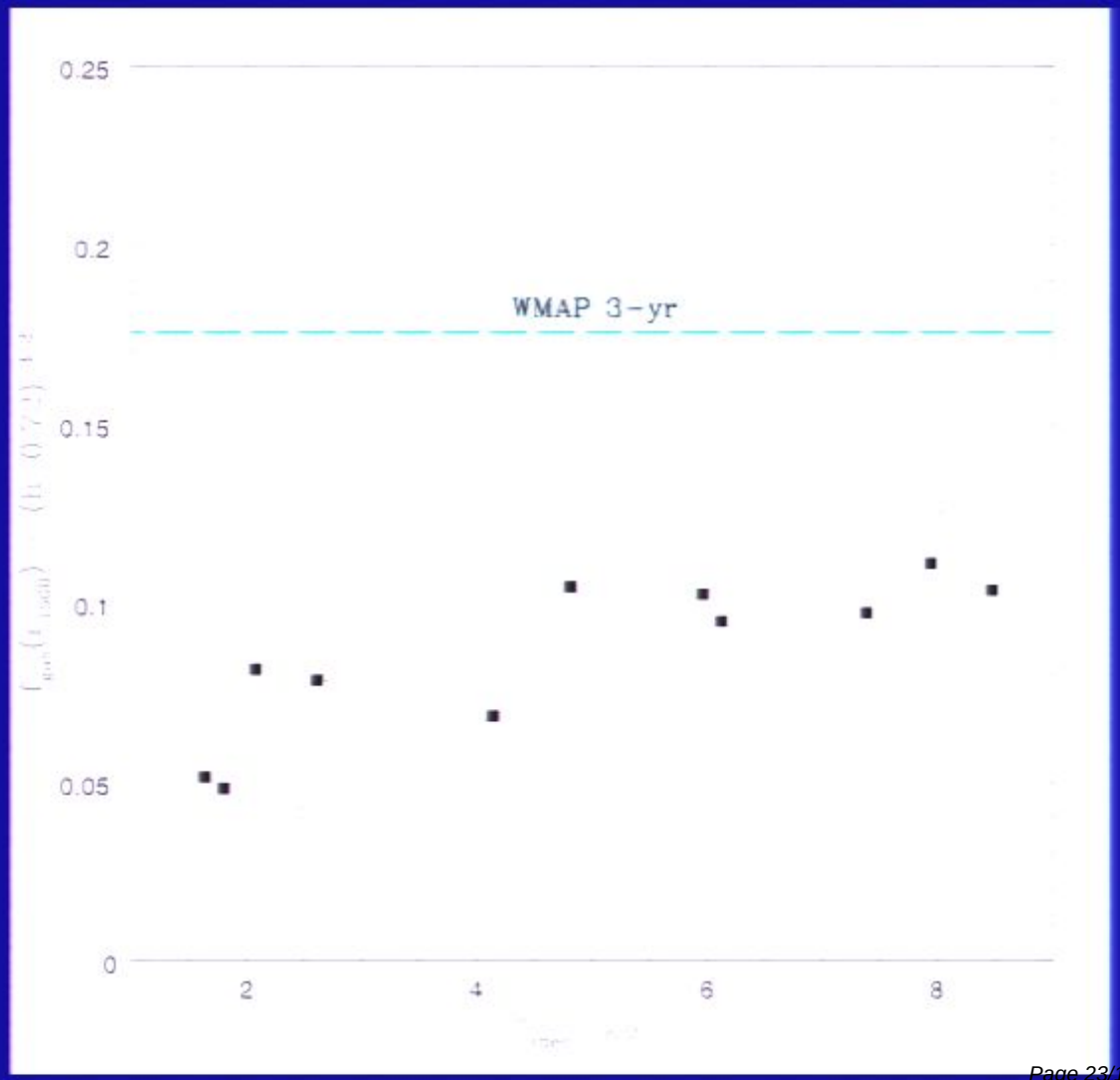
We inquire first what happens if the cluster considered is not st-a

Clusters masses from X-ray data

Ratio of gas mass to total (gas plus dark matter) mass

~ 0.12

(stars are negligible)



McCarthy, Balogh et al 07

Gravitational Lensing

$$\alpha = \frac{4GM}{b \cdot c^2}$$

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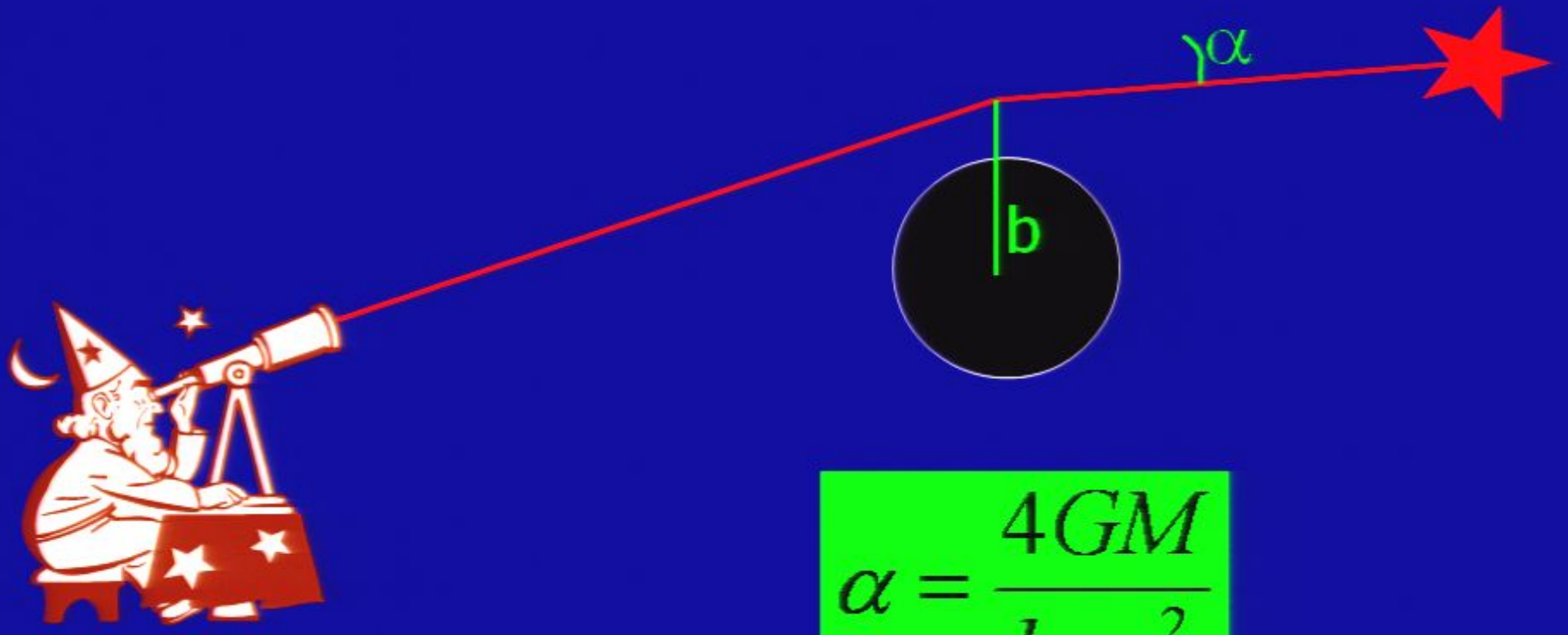

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Lensing in Cosmology

- Since the strength of the lensing effect depends on mass, use it to measure mass
- But the deflection is not directly observable, so use distortion and magnification

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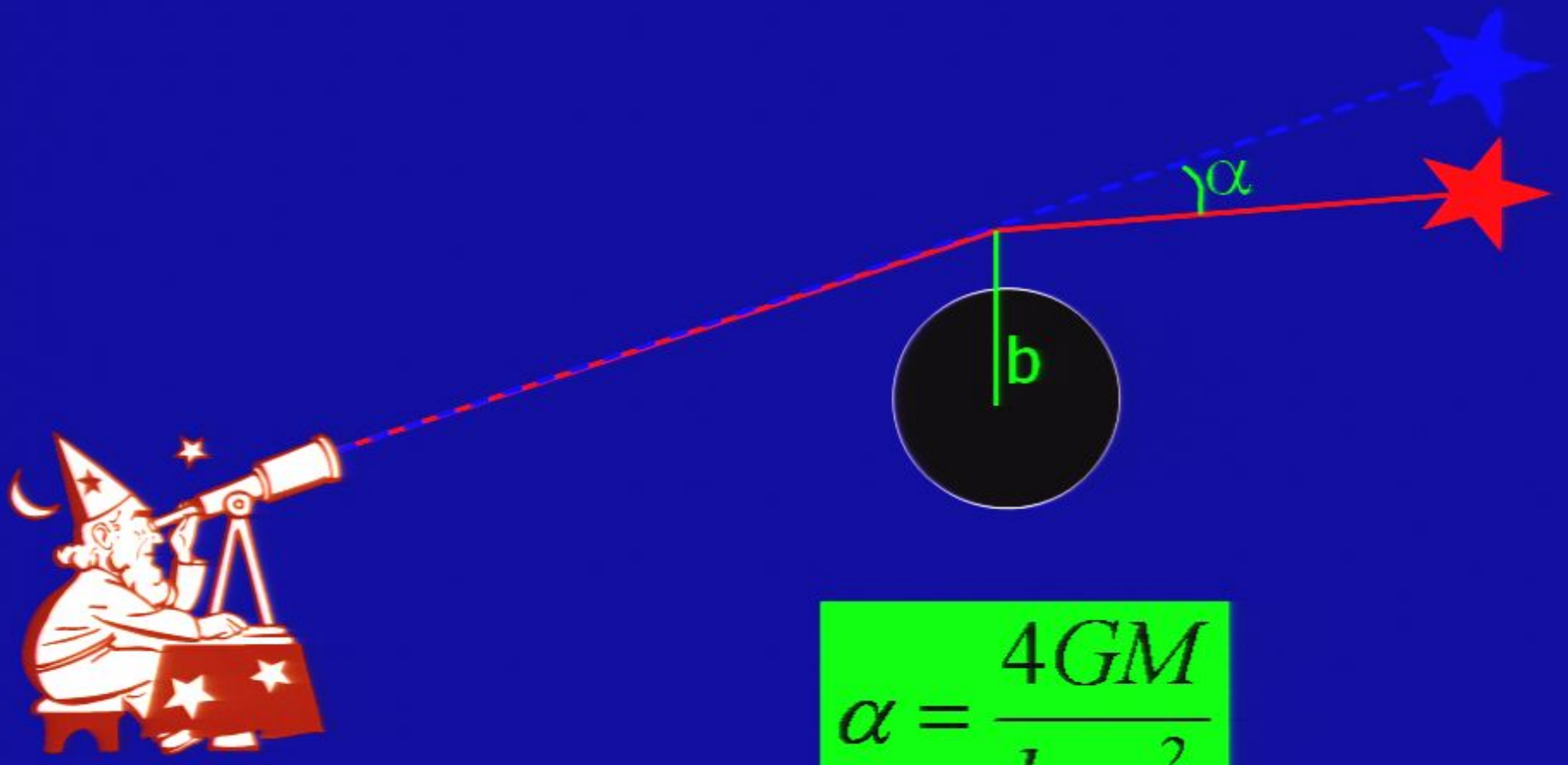

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Gravitational lensing ***magnifies*** and ***distorts***

Strong lensing (multiple imaging) in the center

Weak lensing at edges

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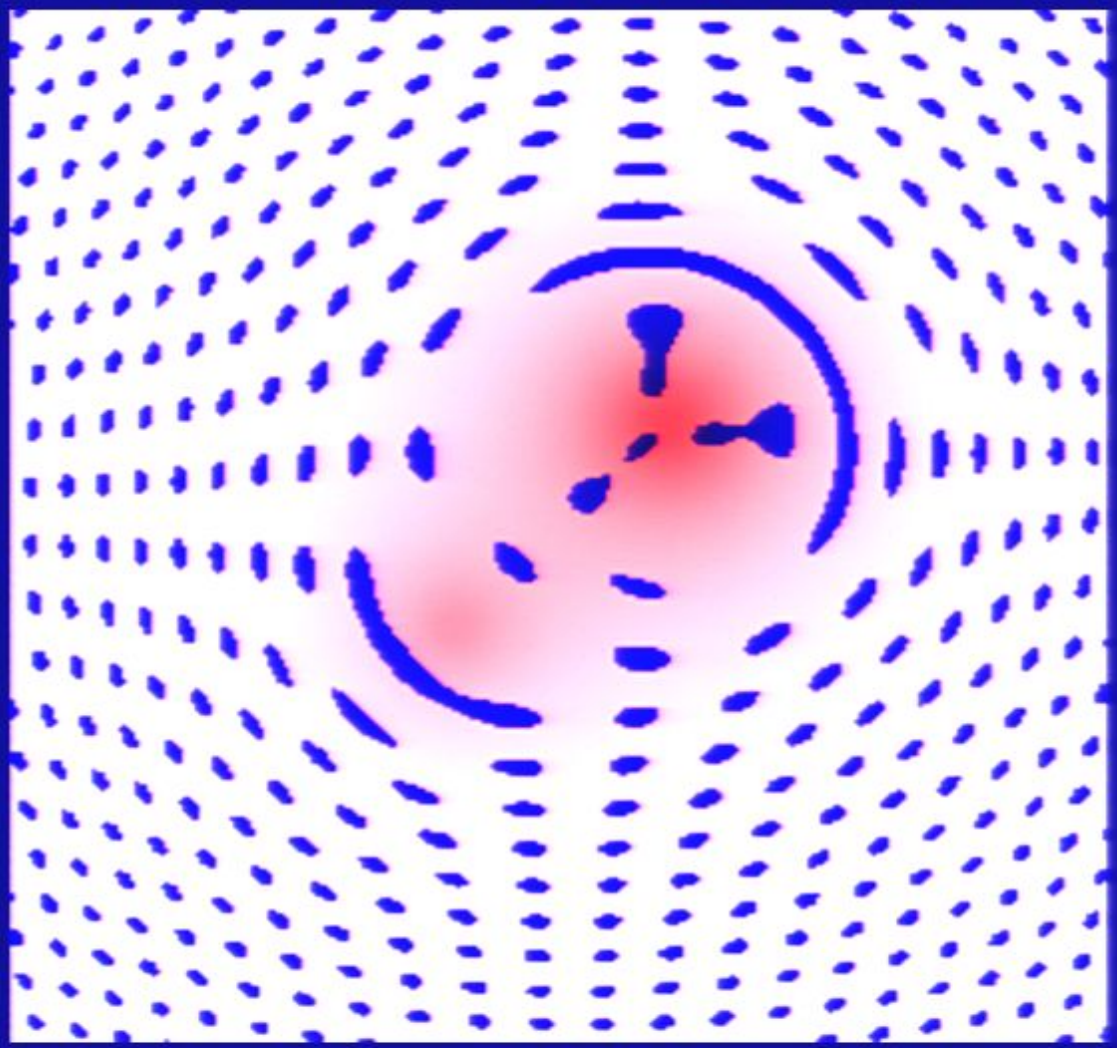

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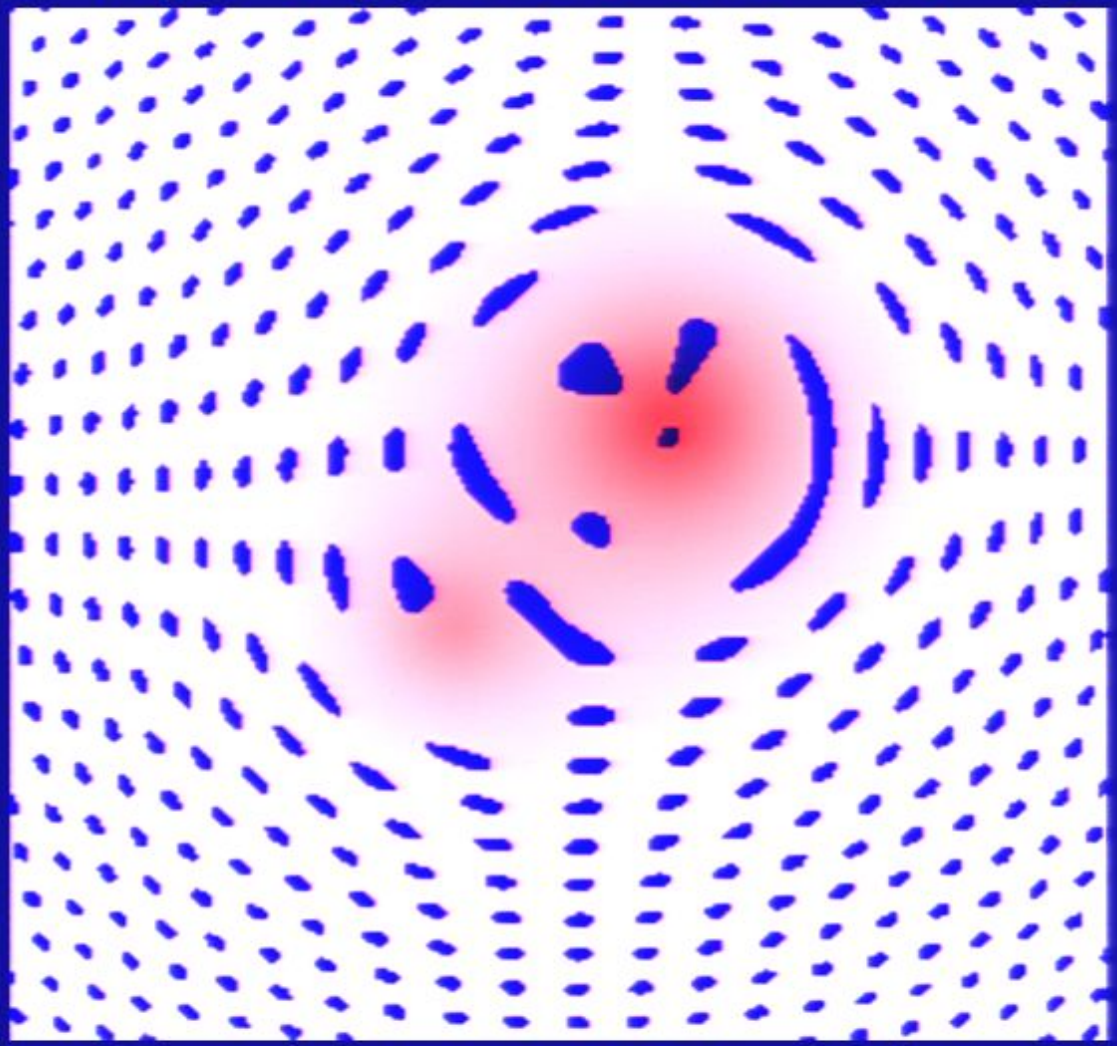

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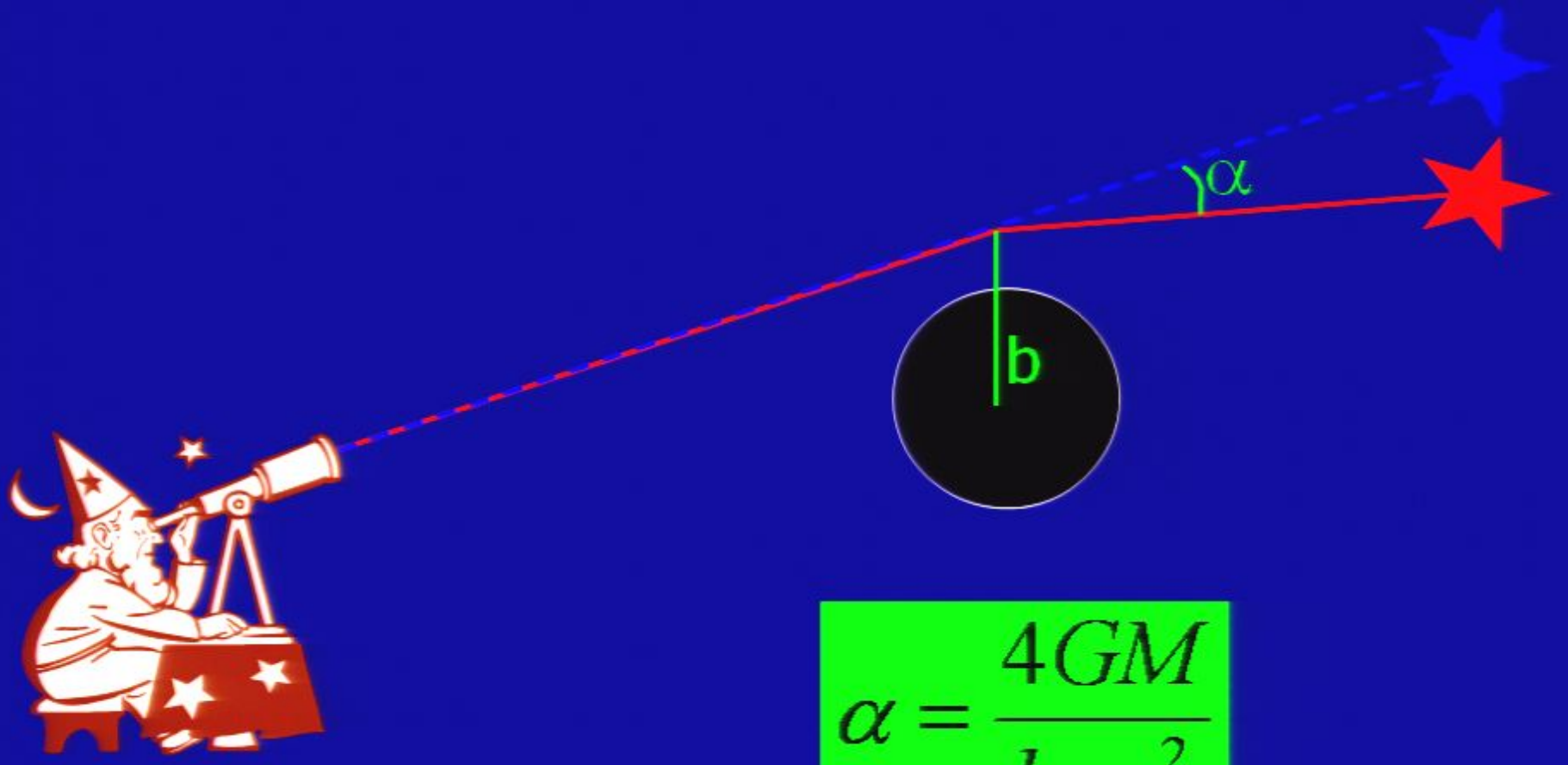

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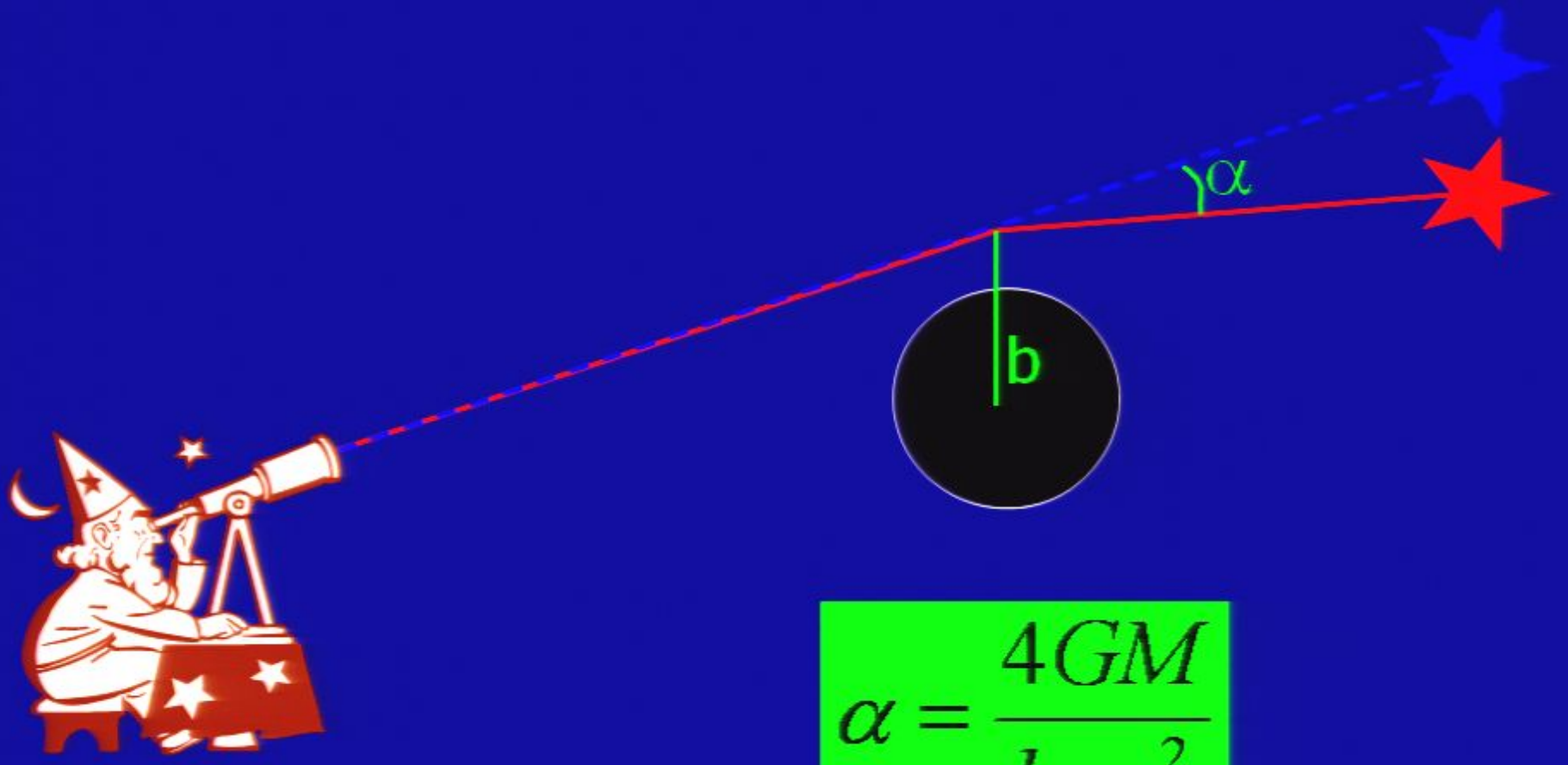

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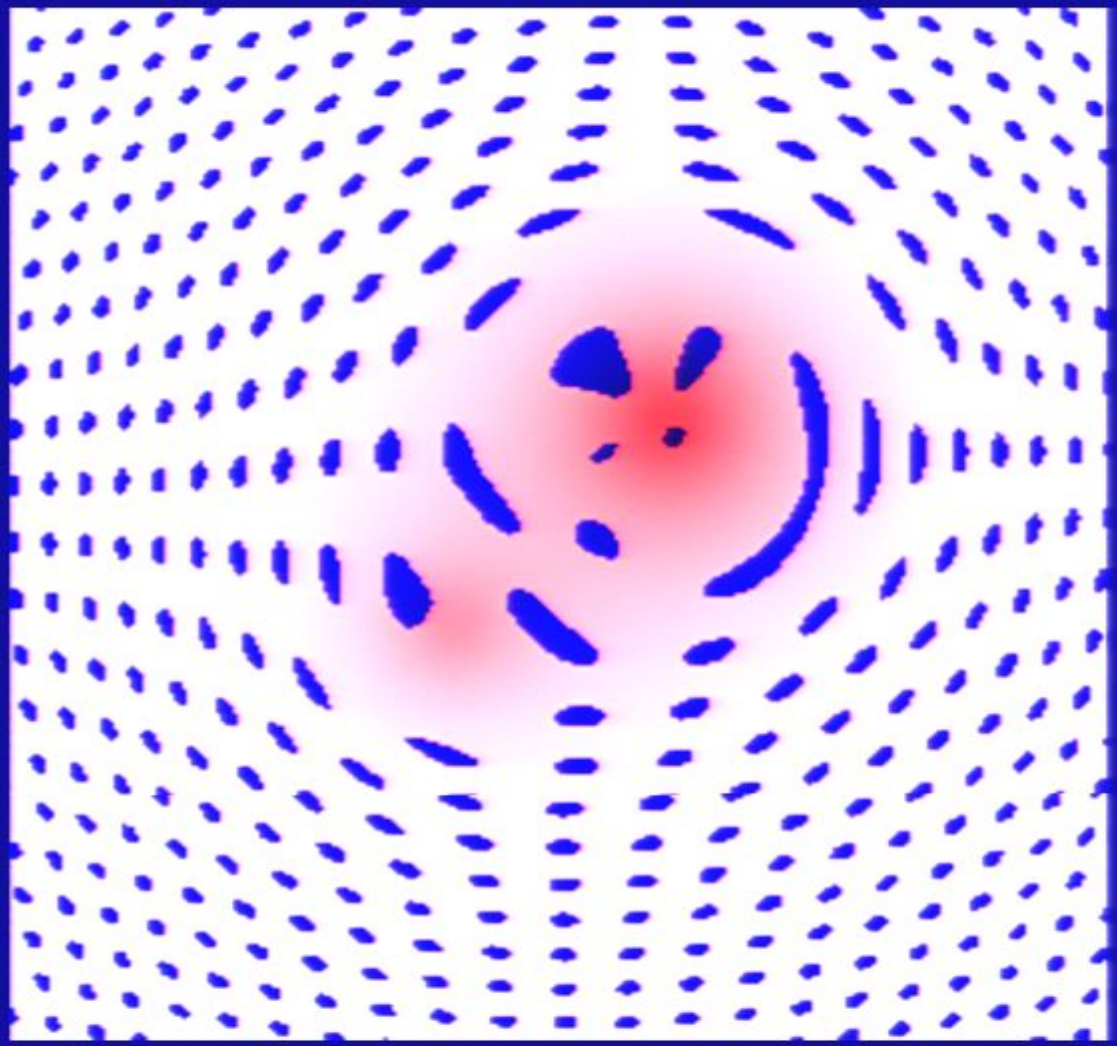

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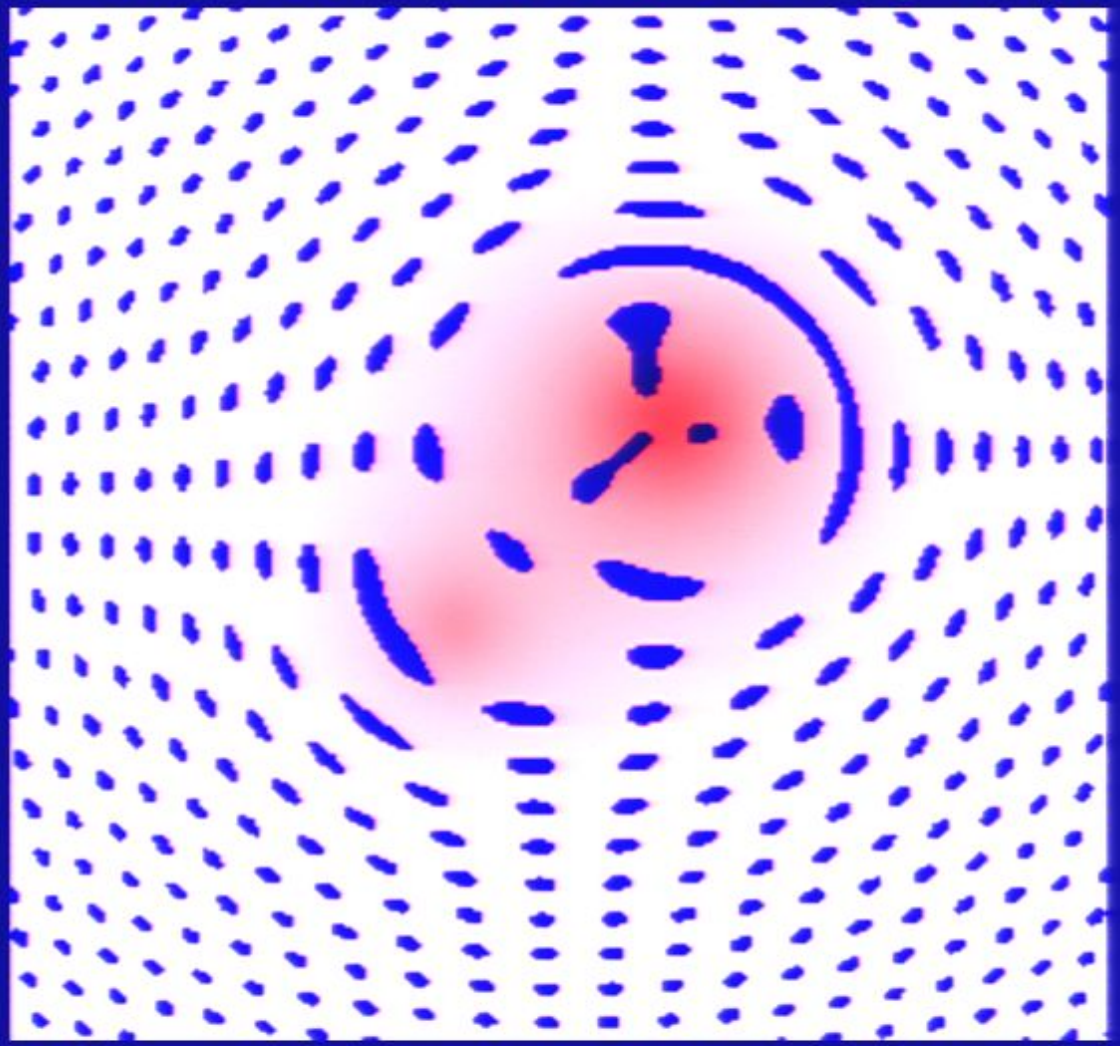

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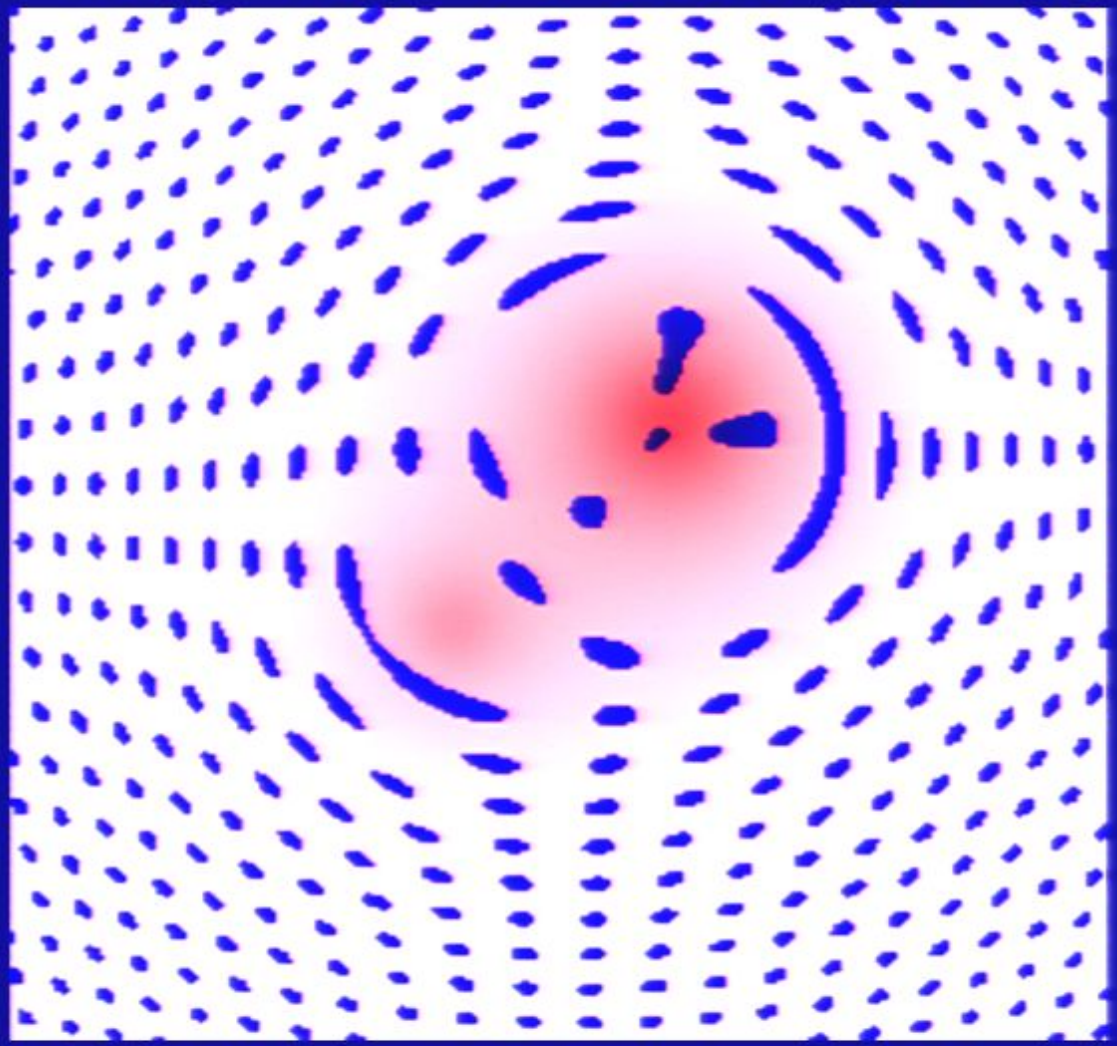

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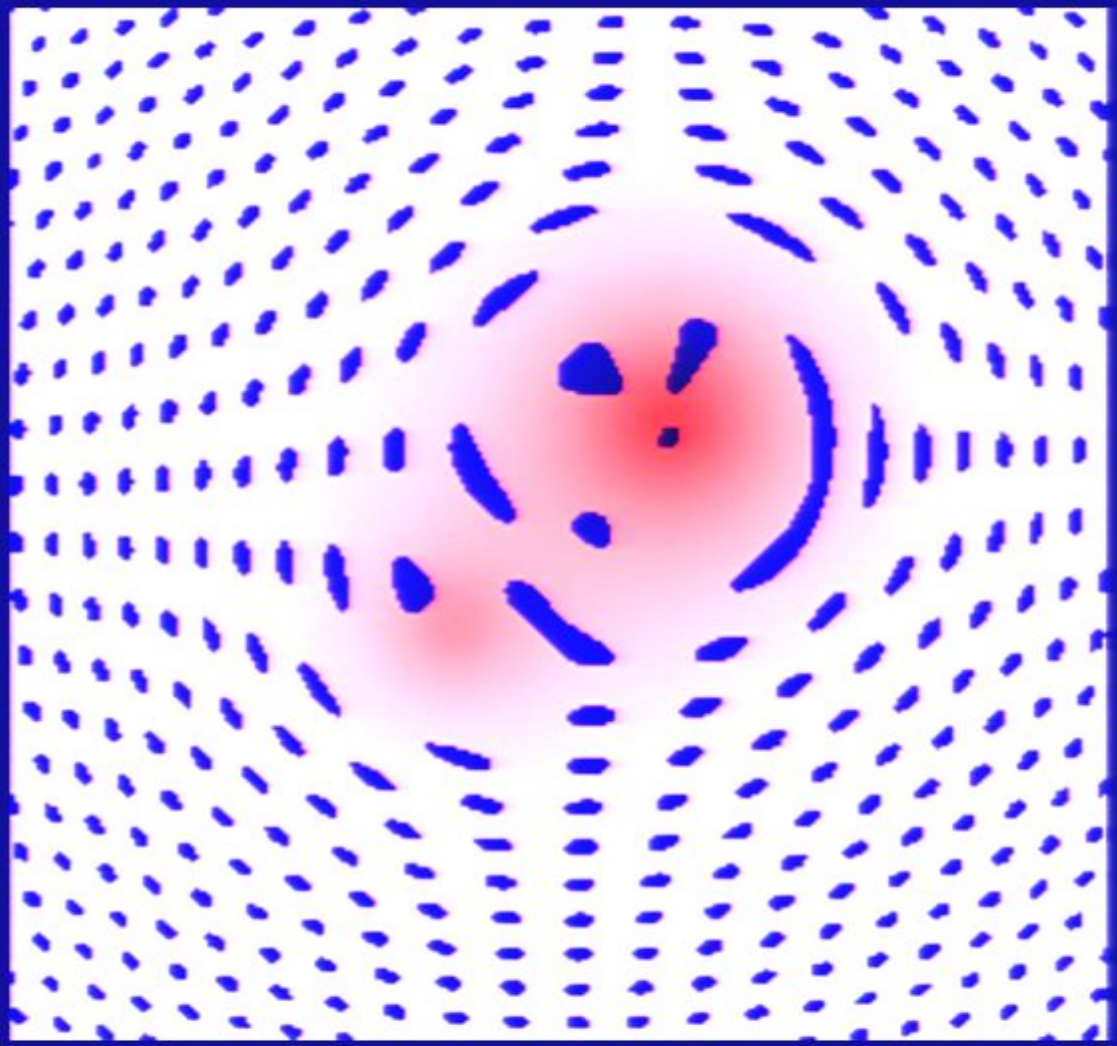

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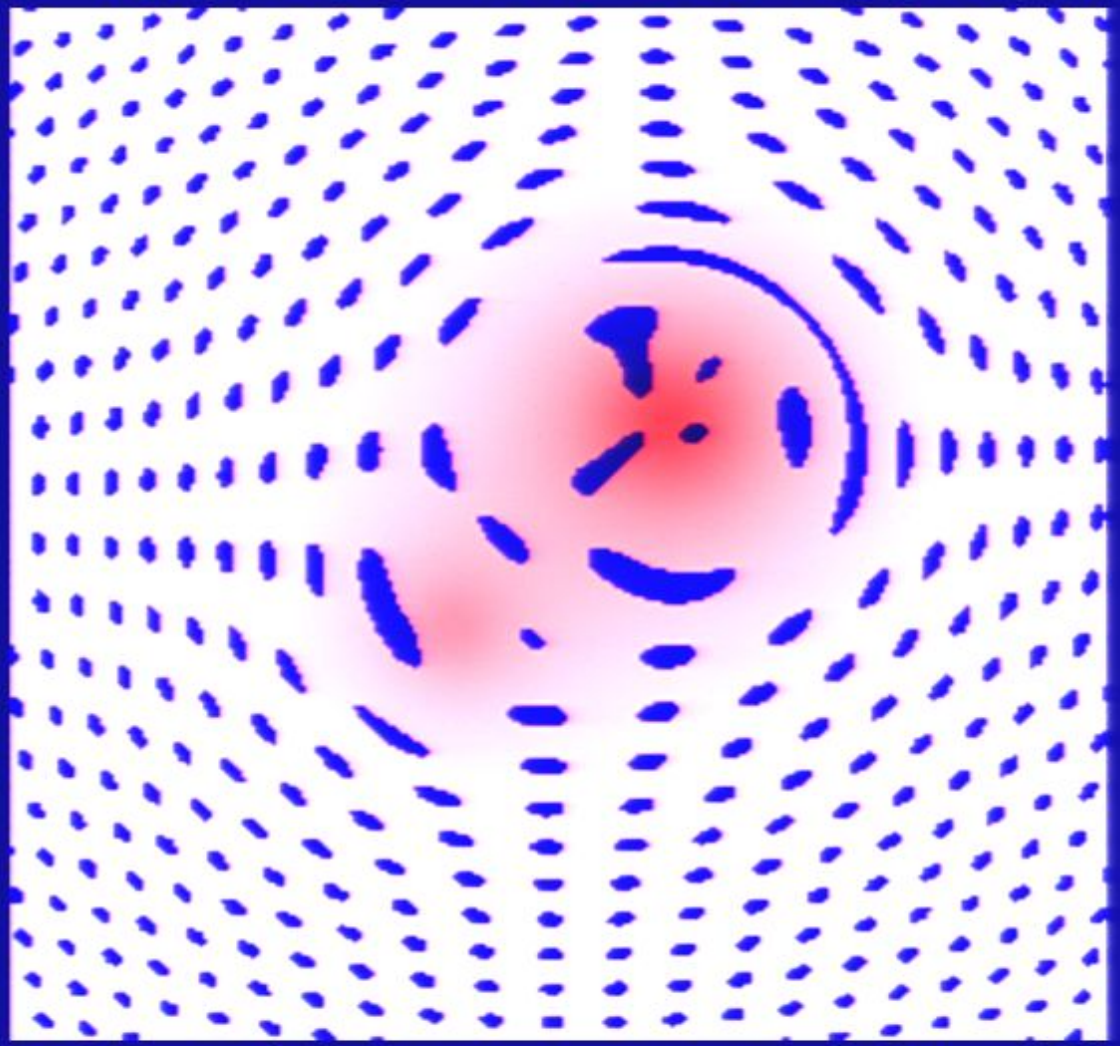

Zwicky, *Science*, 1937

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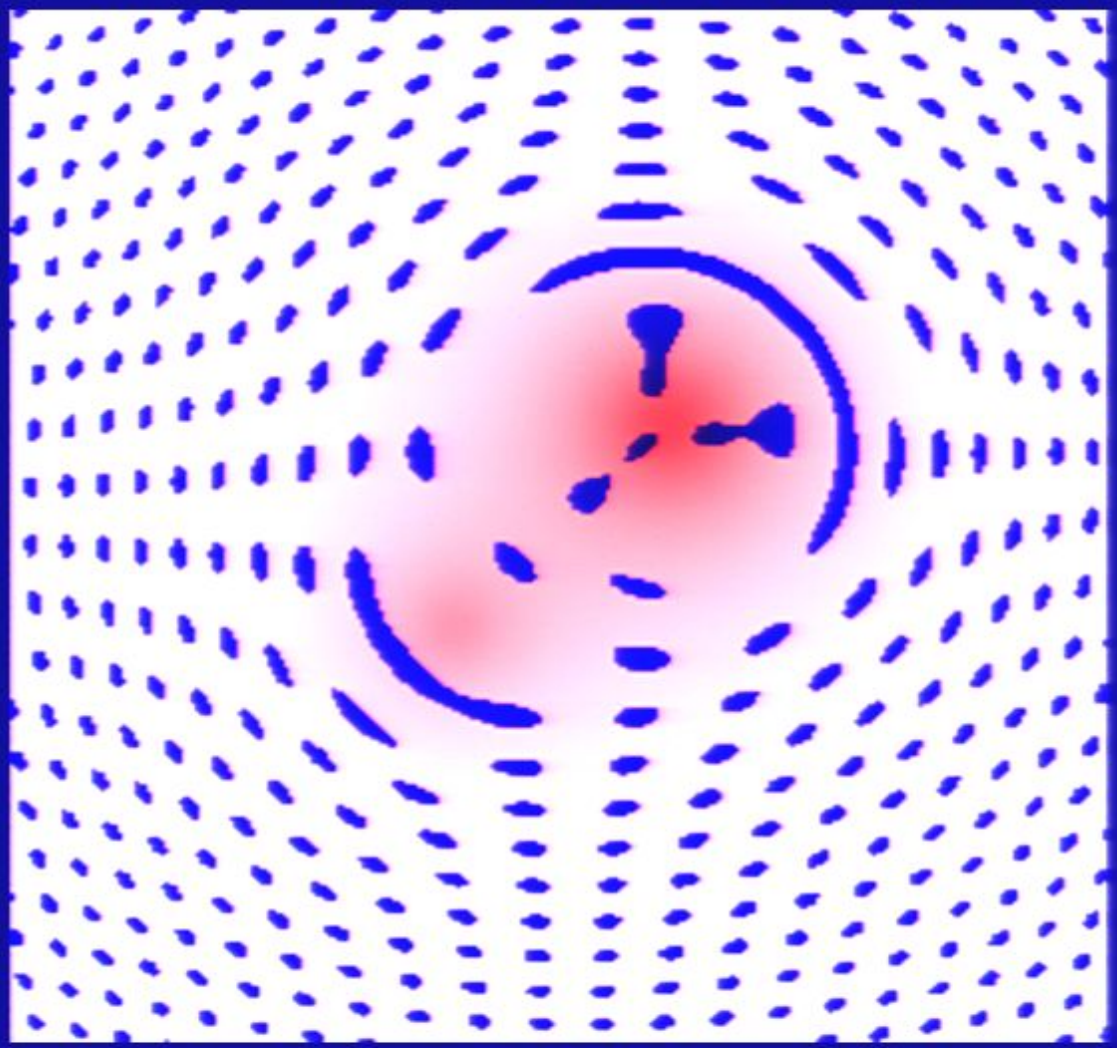

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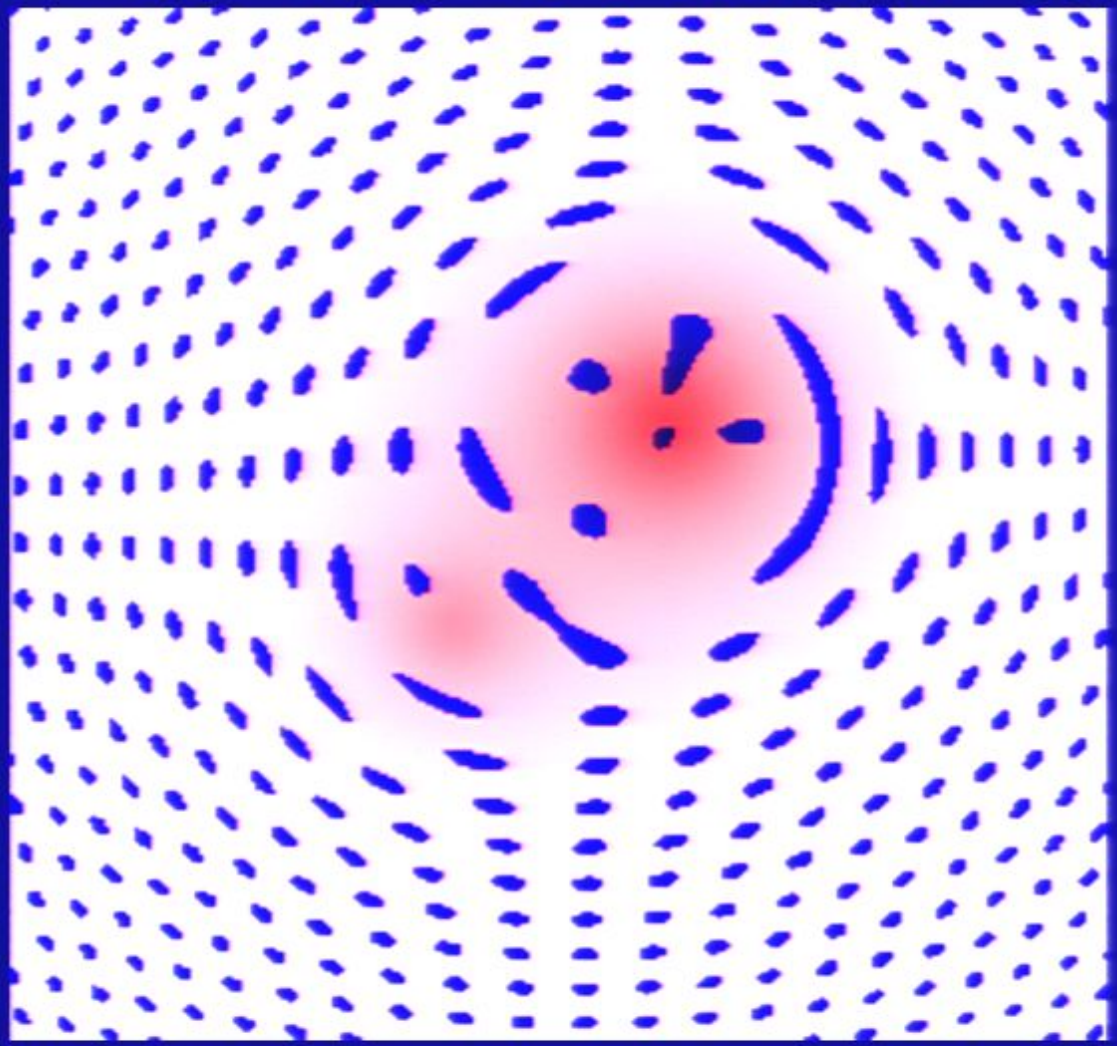

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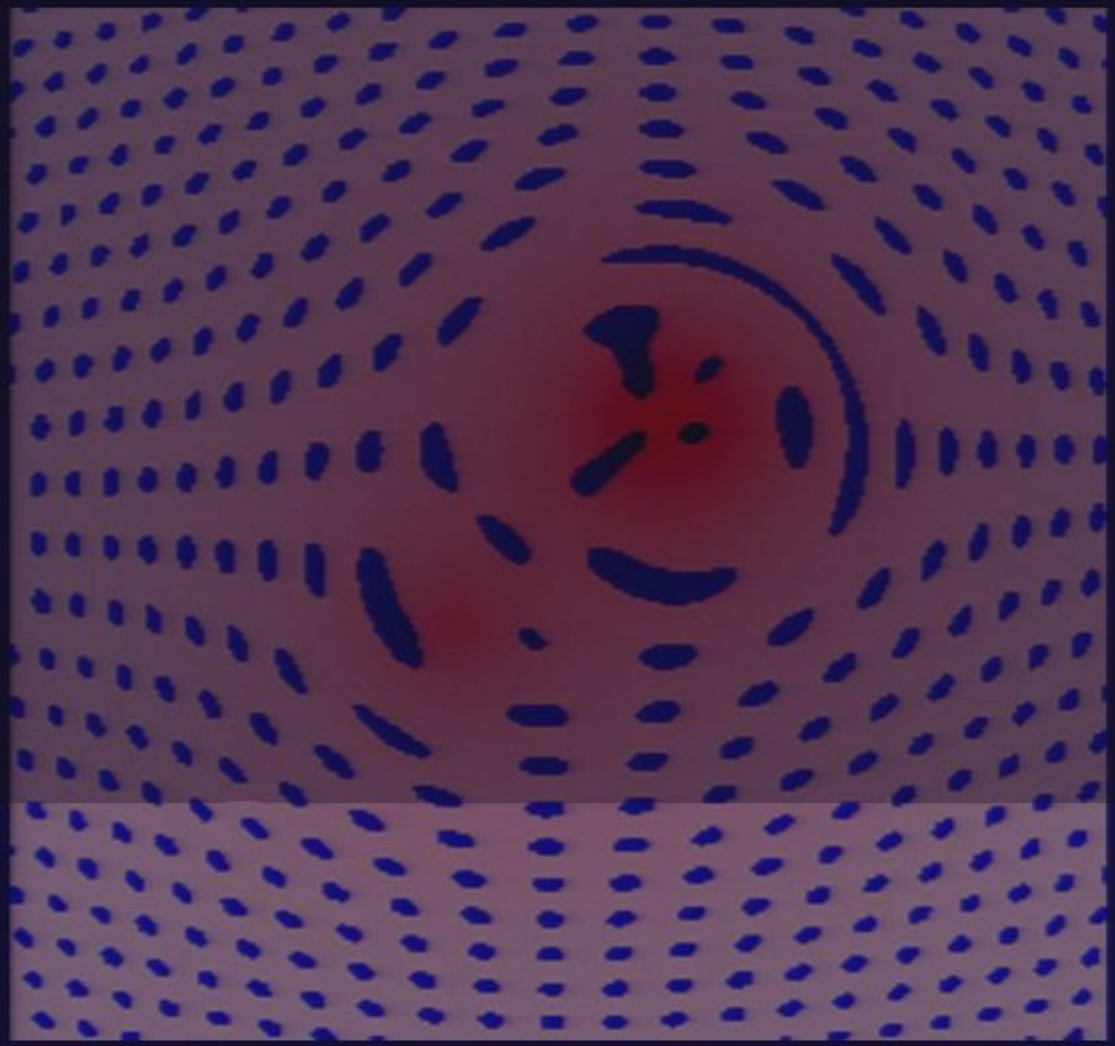

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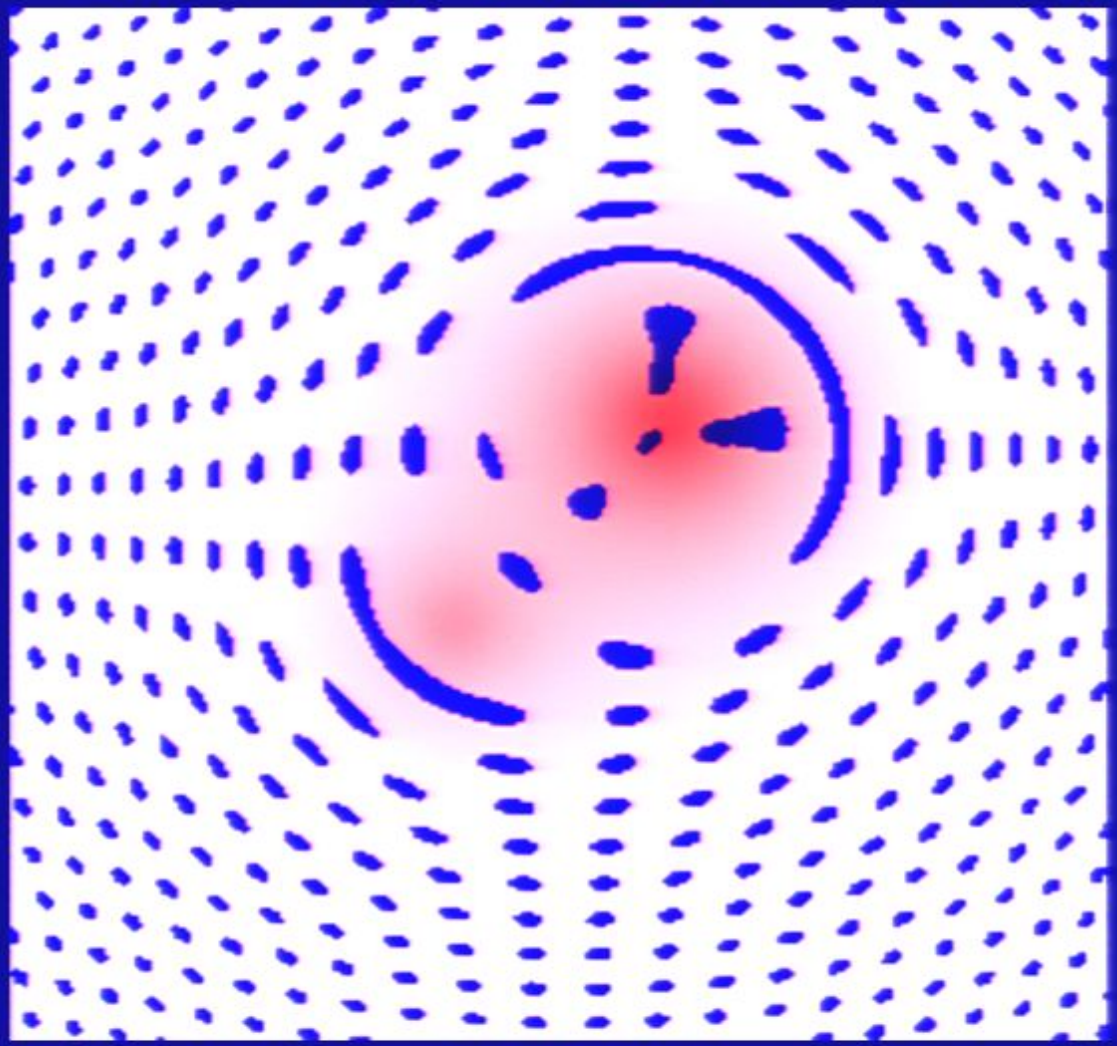

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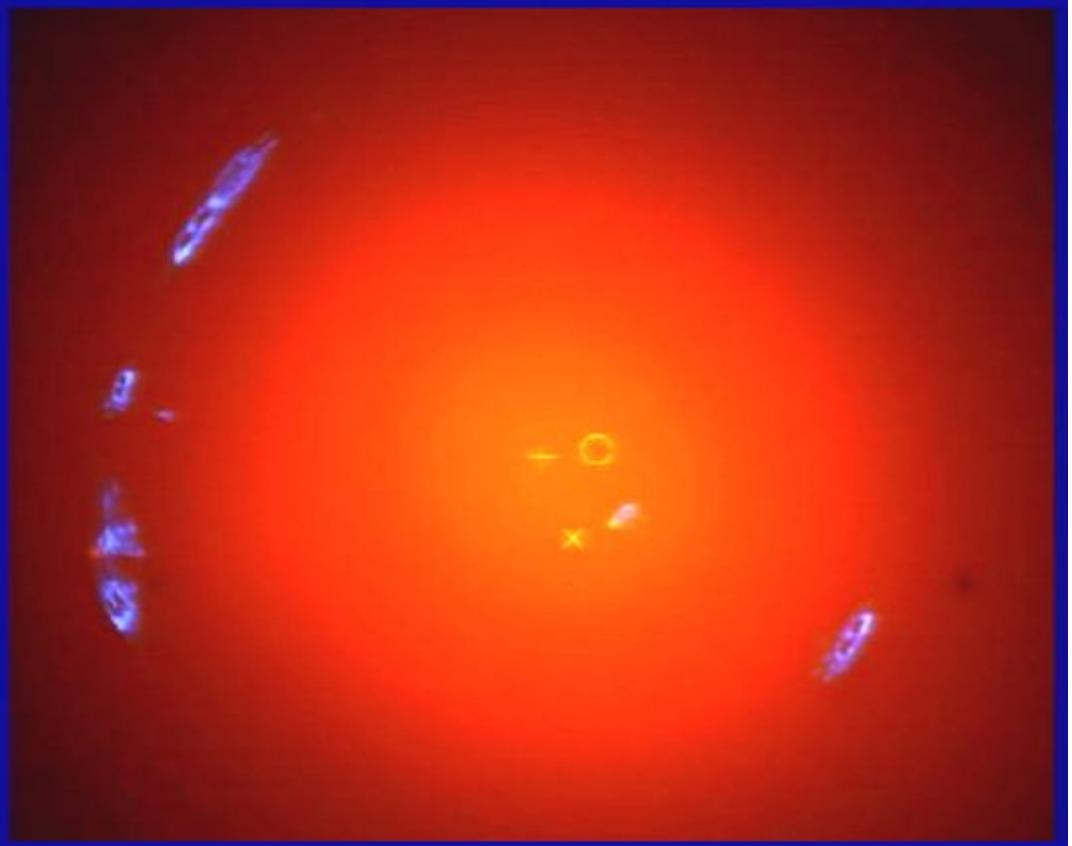
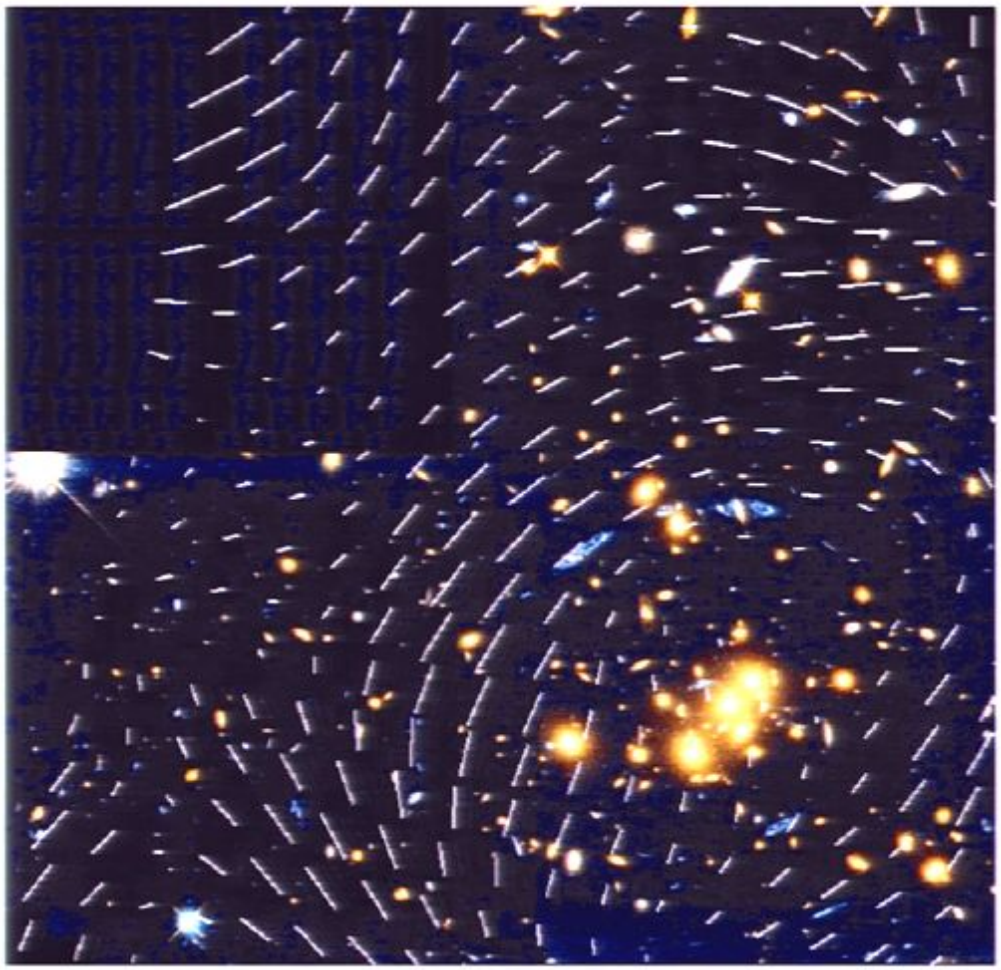
Strong lensing

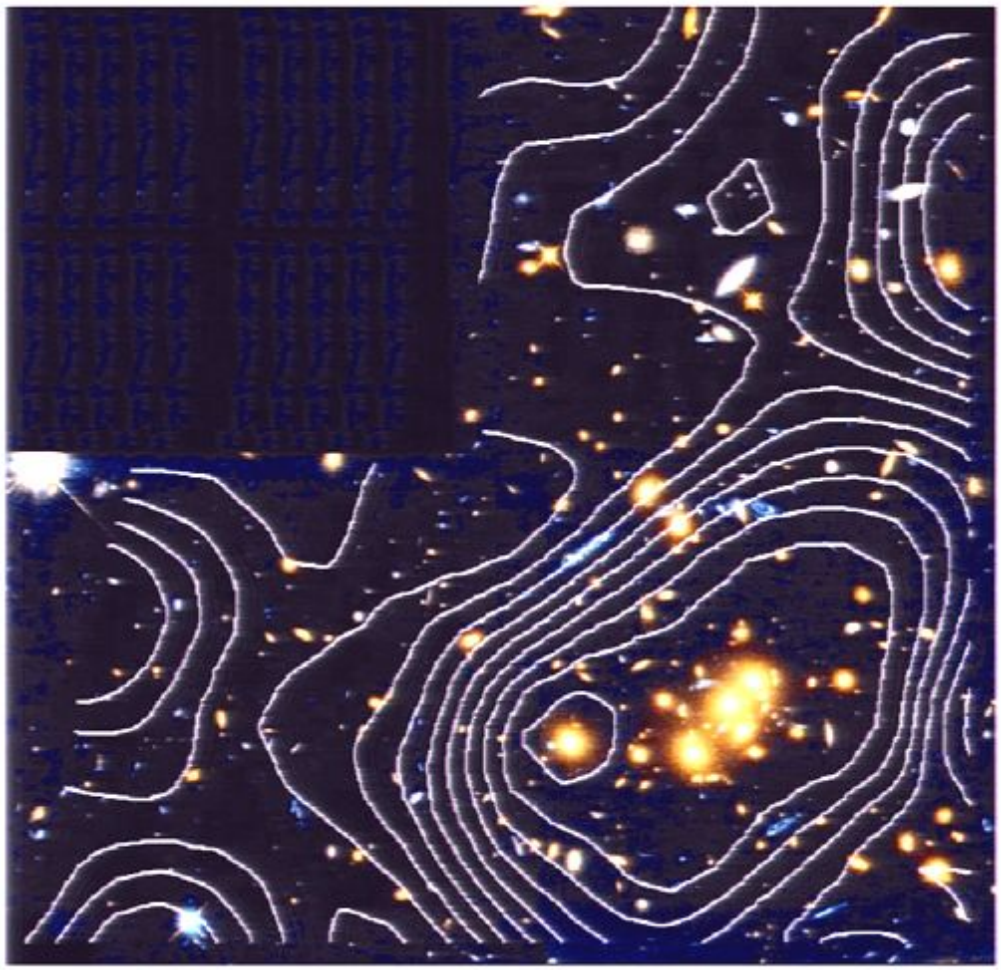
Gravitational Lens
Galaxy Cluster 0024+1654
HST · WFPC2
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University),
J.A. Tyson (AT&T Bell Labs) and NASA



Lensed images and model
(cluster at z=0.4, lensed source at z=0.7)

Weak lensing

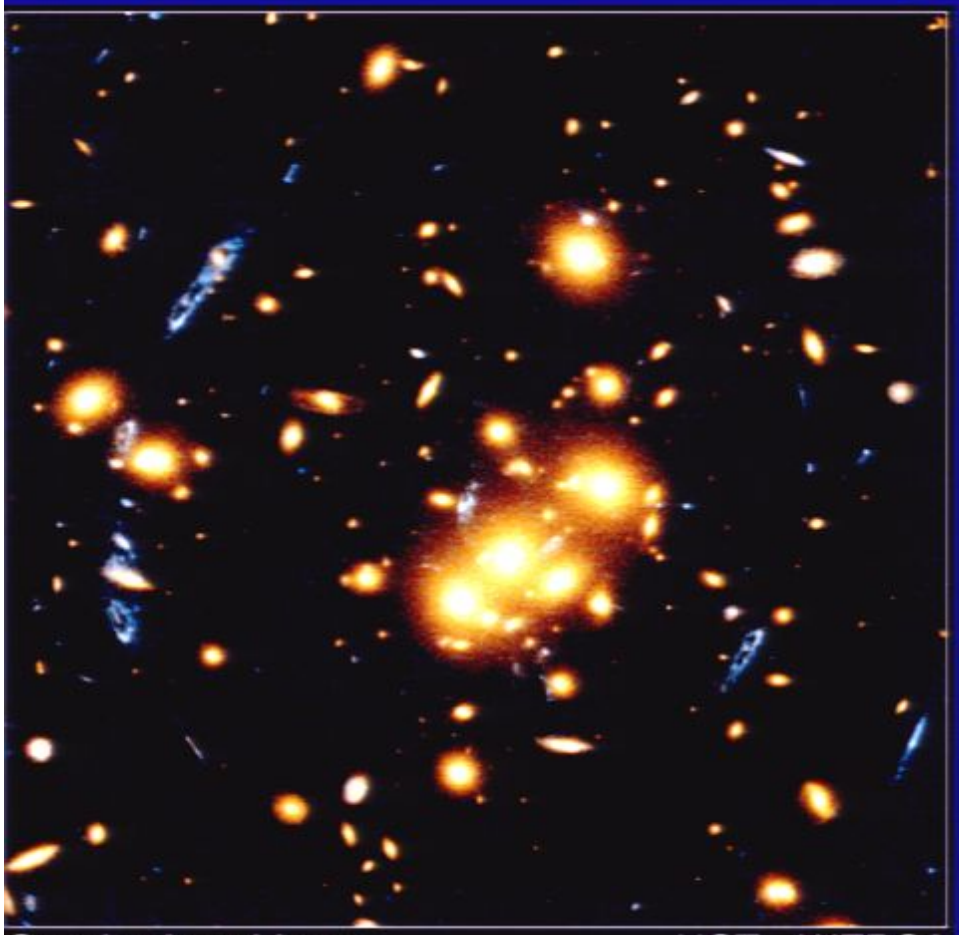




Observed "polarization"

Dark matter mass reconstruction

Strong lensing



Gravitational Lens
Galaxy Cluster 0024+1654
HST · WFPC2
PRC96-10 · ST ScI OPO · April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University),
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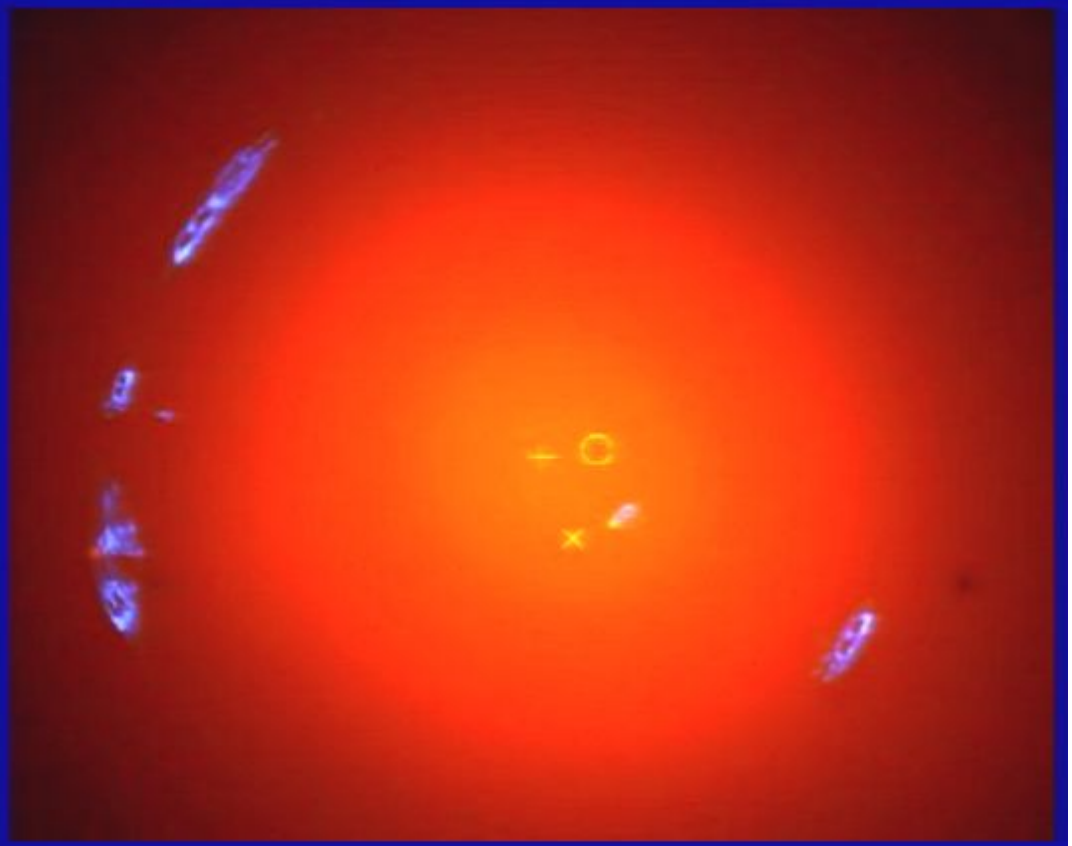

Lensed images and model
(cluster at z=0.4, lensed source at z=0.7)

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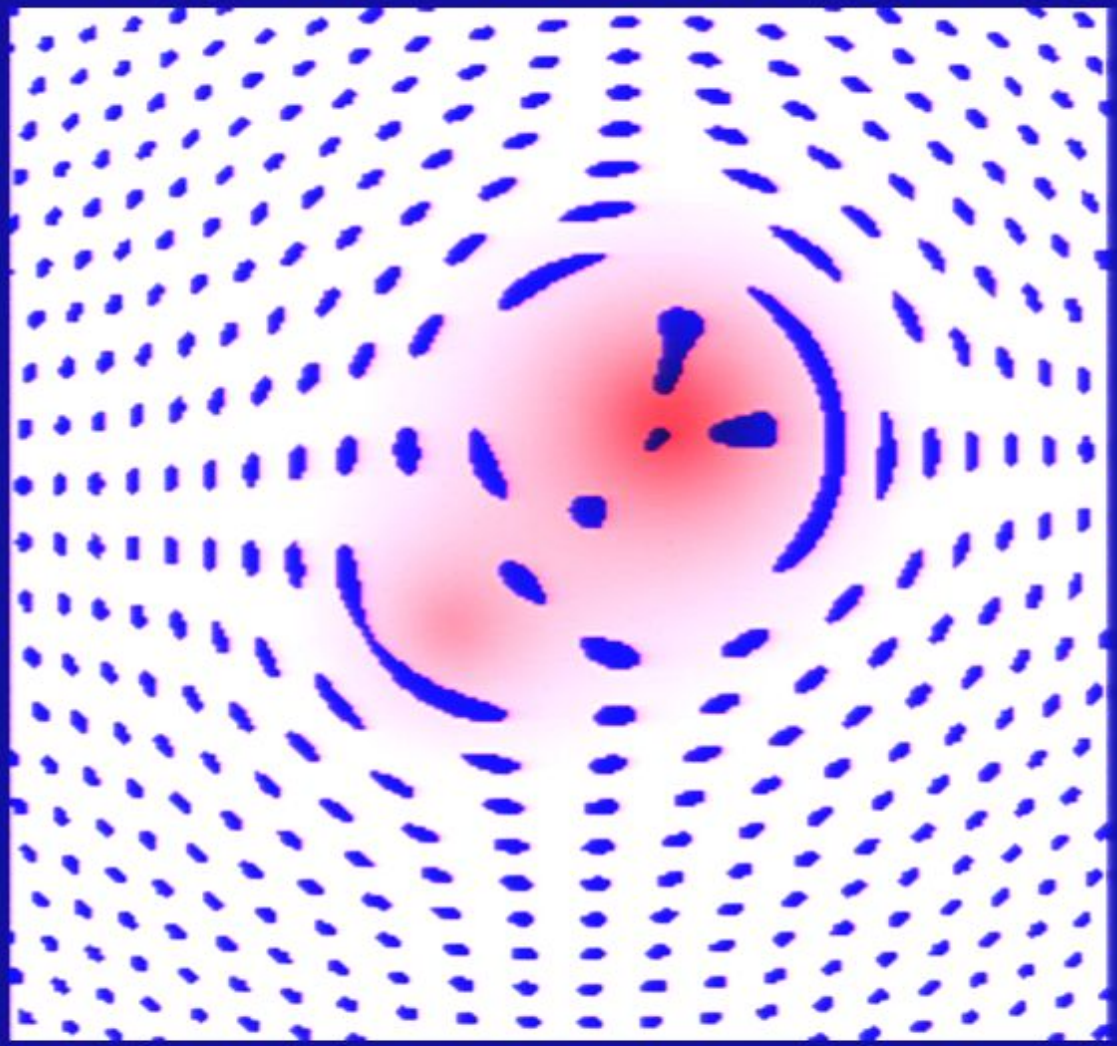
Gravitational lensing ***magnifies*** and ***distorts***

Strong lensing (multiple imaging) in the center

Weak lensing at edges



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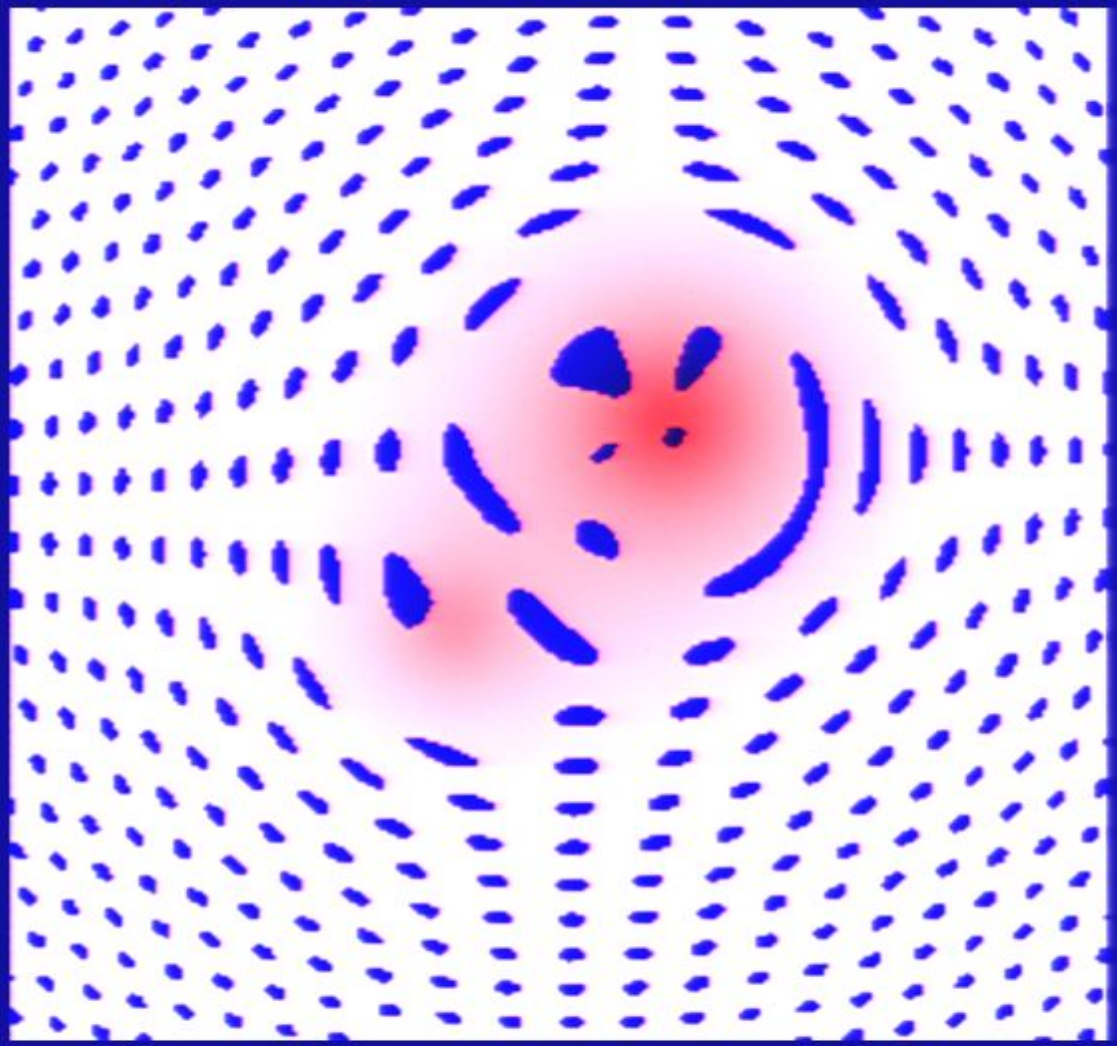

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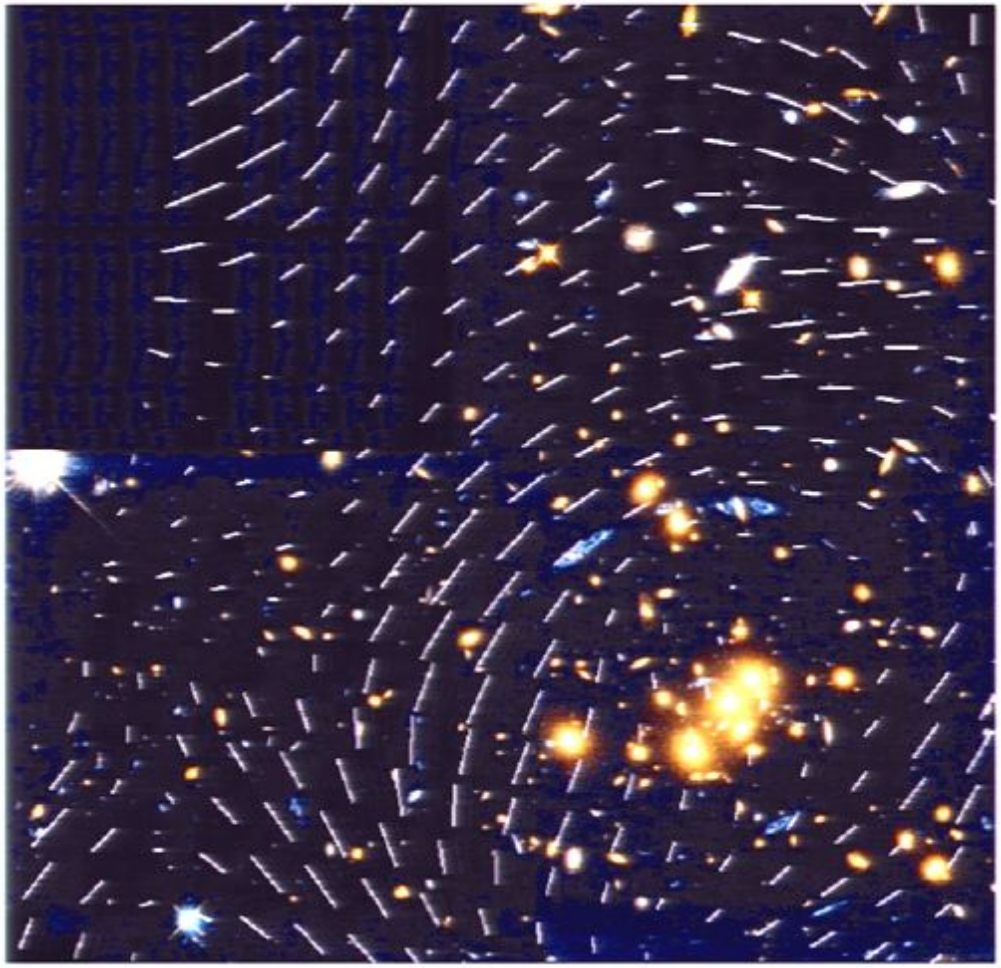

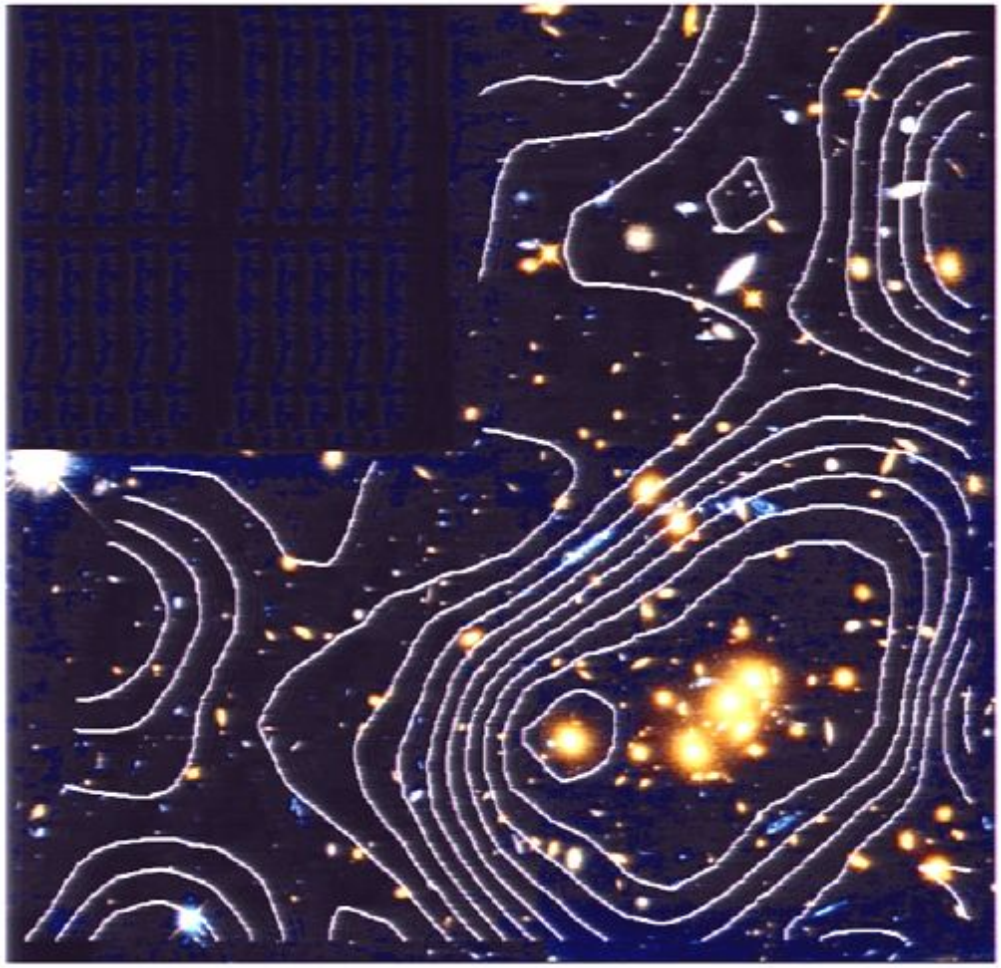

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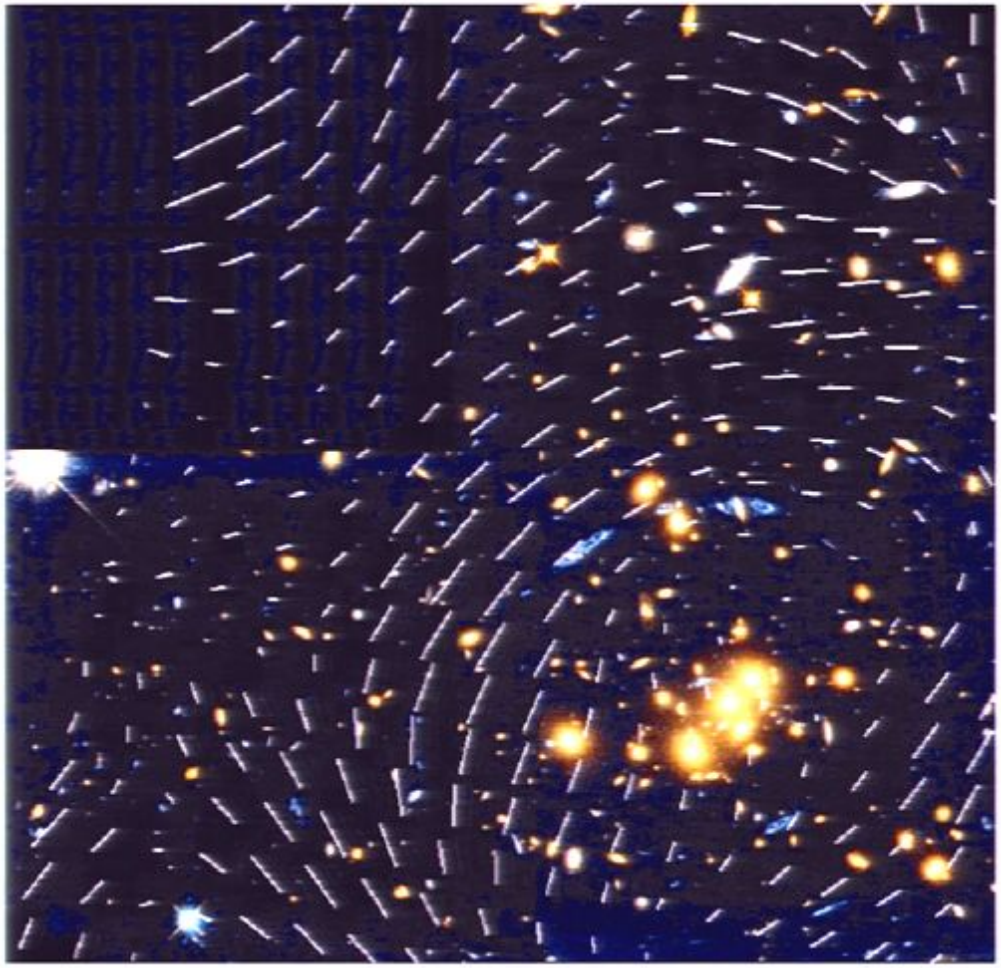
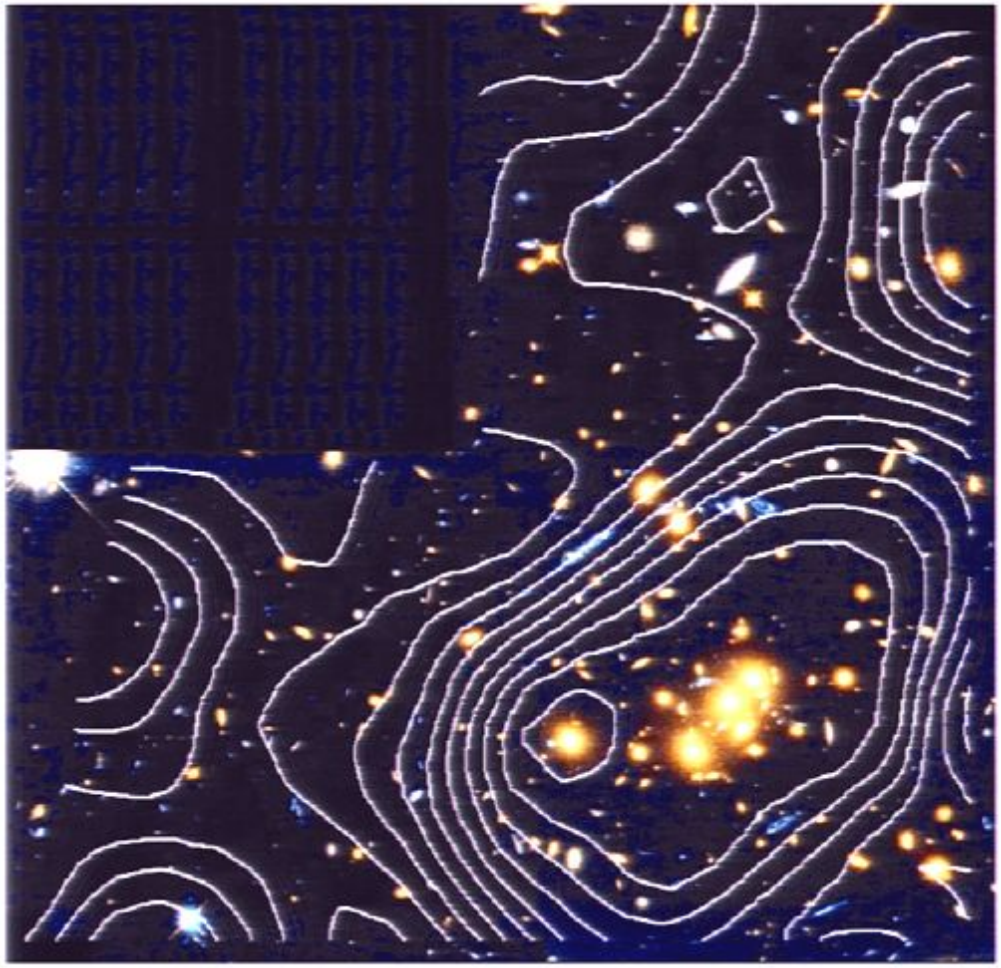
Dark matter mass reconstruction

Weak lensing





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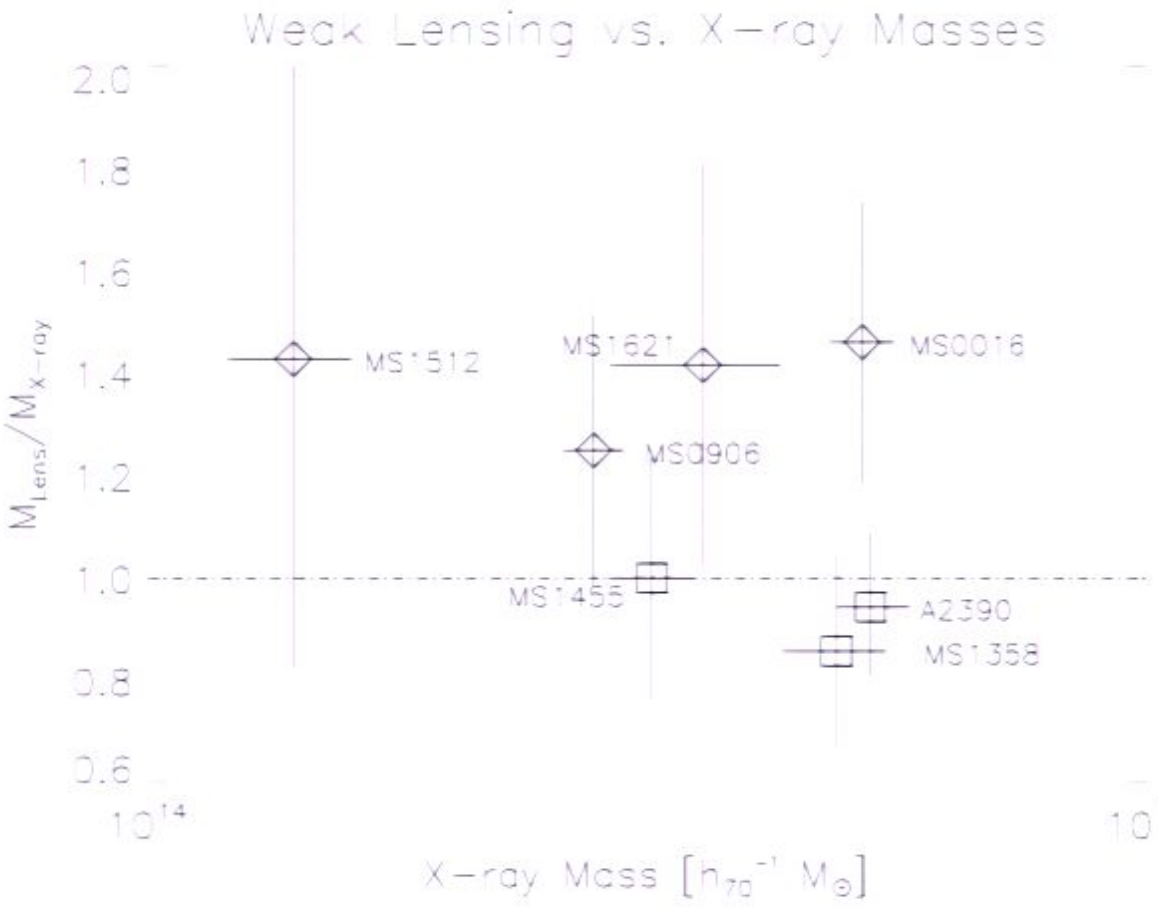

Fig. 6. — **Weak Lensing vs. X-ray Masses.** X-ray mass estimates are plotted against the ratio M_{Lens}/M_{X-ray}. The dot-dash line represents a mass ratio of 1.0. Squares indicate cooling core clusters, and error bars denote 68% confidence limits. Though the distribution appears assymmetric, it is not statistically significant.

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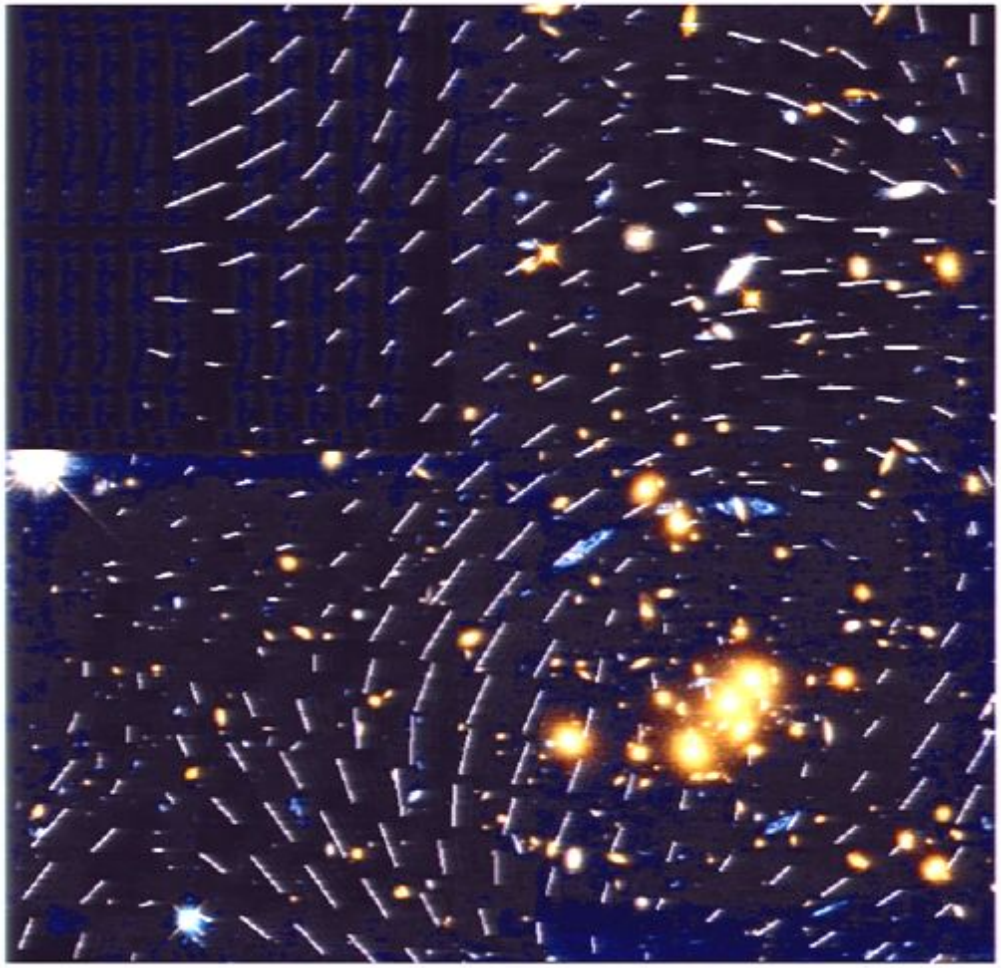

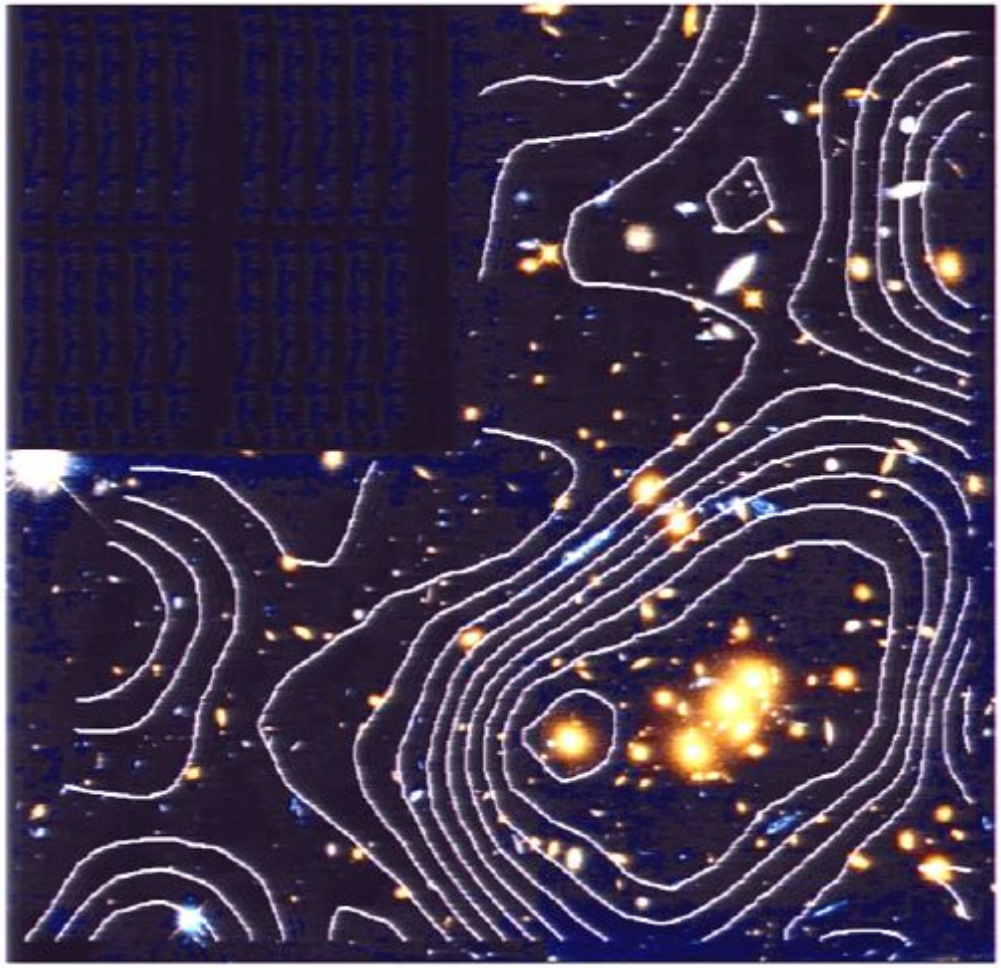

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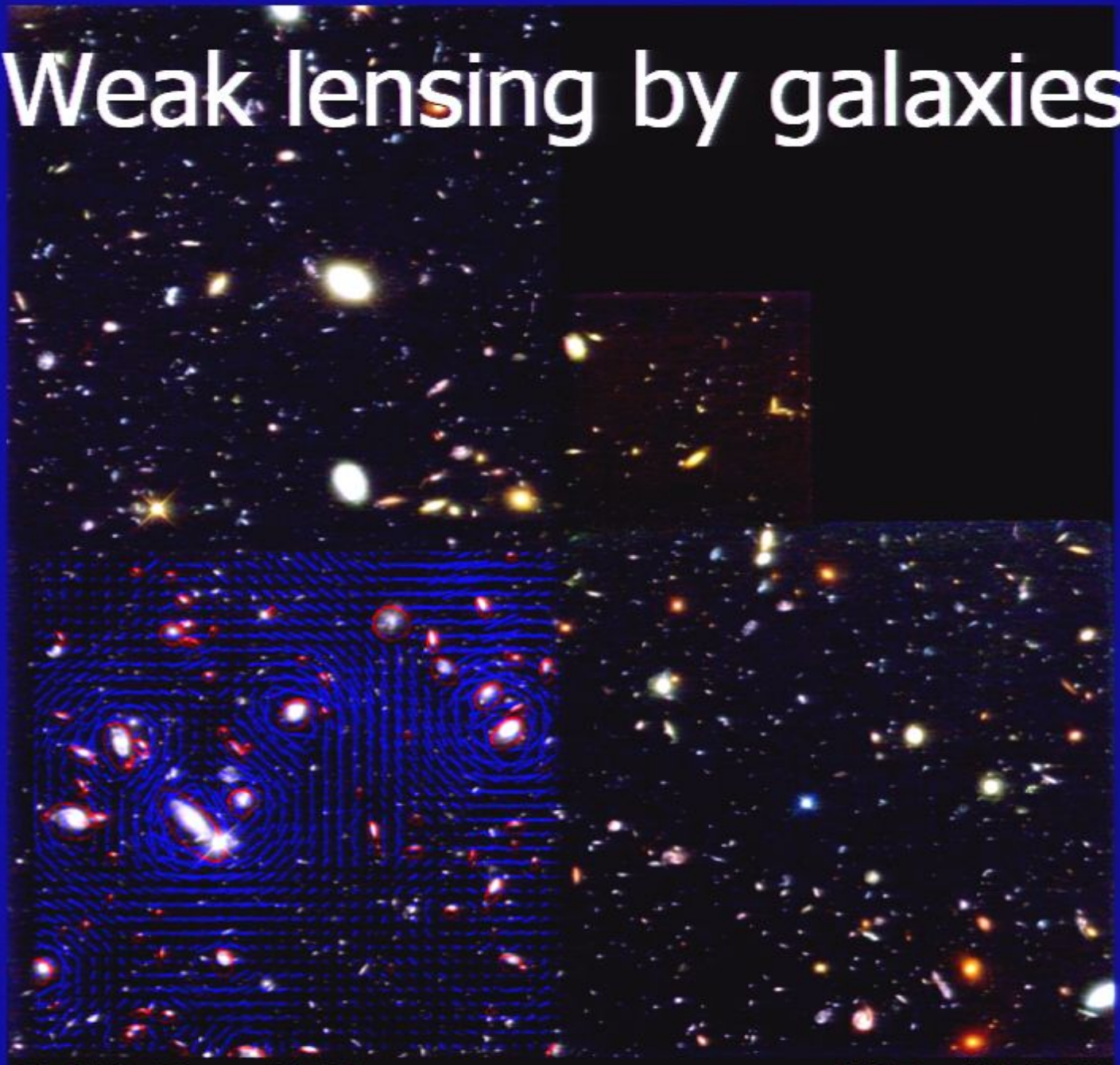
Dark matter mass reconstruction

Weak lensing by galaxies



Peculiar velocities

- Peculiar velocities are deviations from the uniform expansion of the Universe
- Caused by extra matter retards the expansion of the Universe locally
- In principle by measuring the former, one can deduce the latter.

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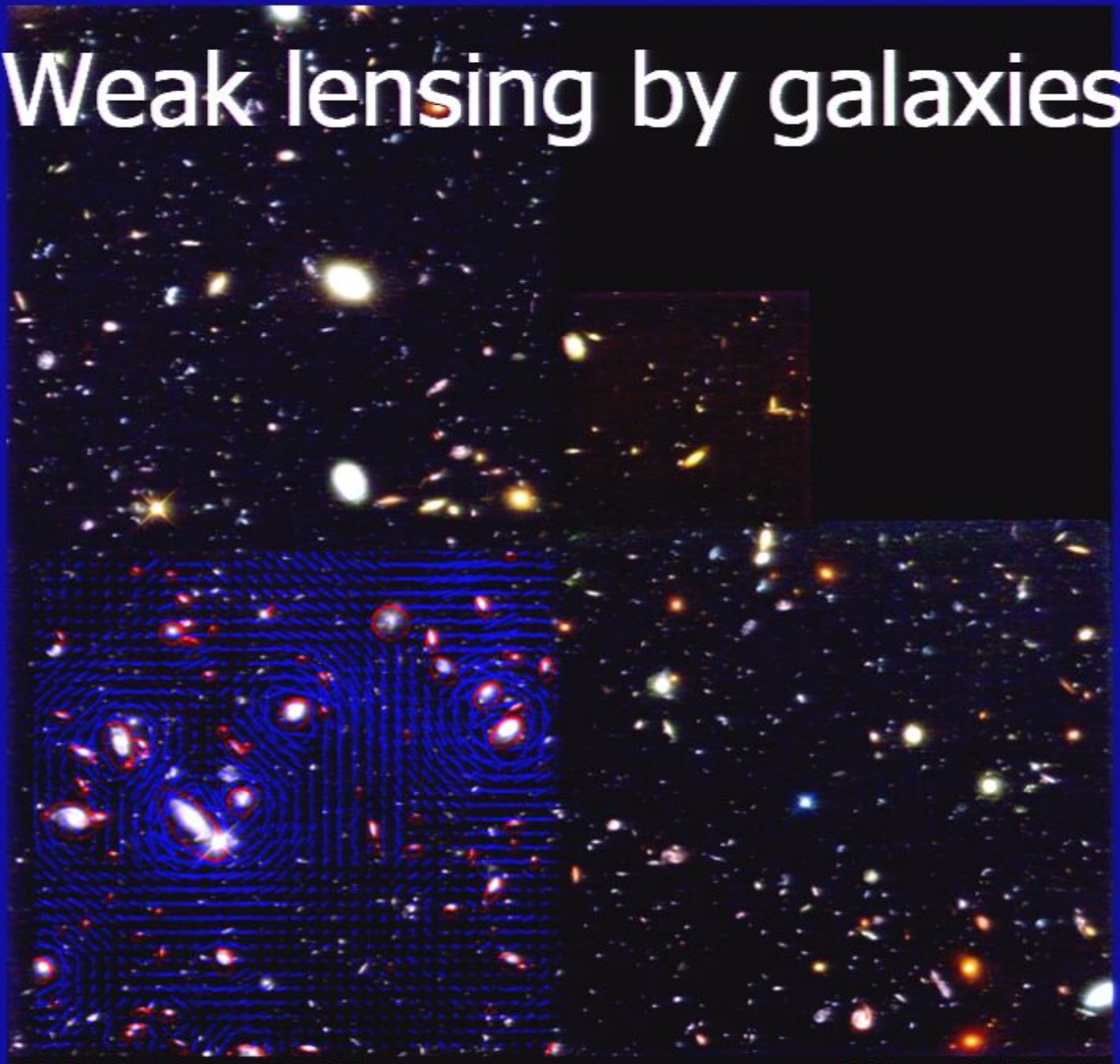

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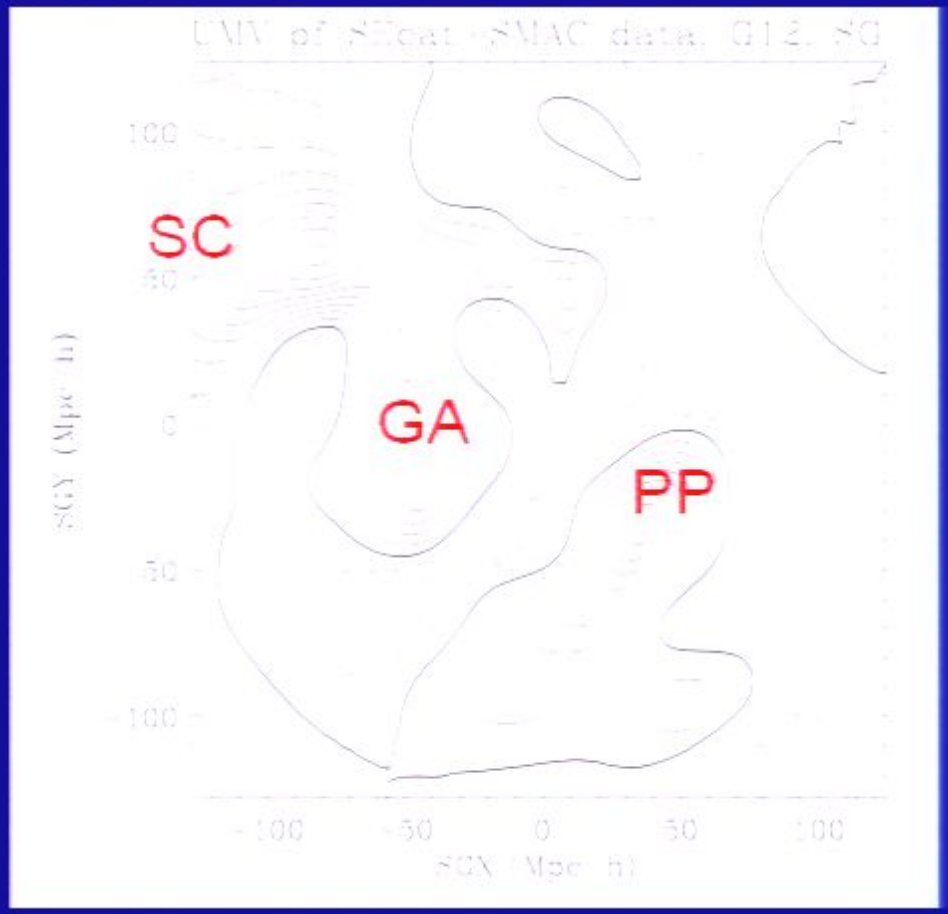

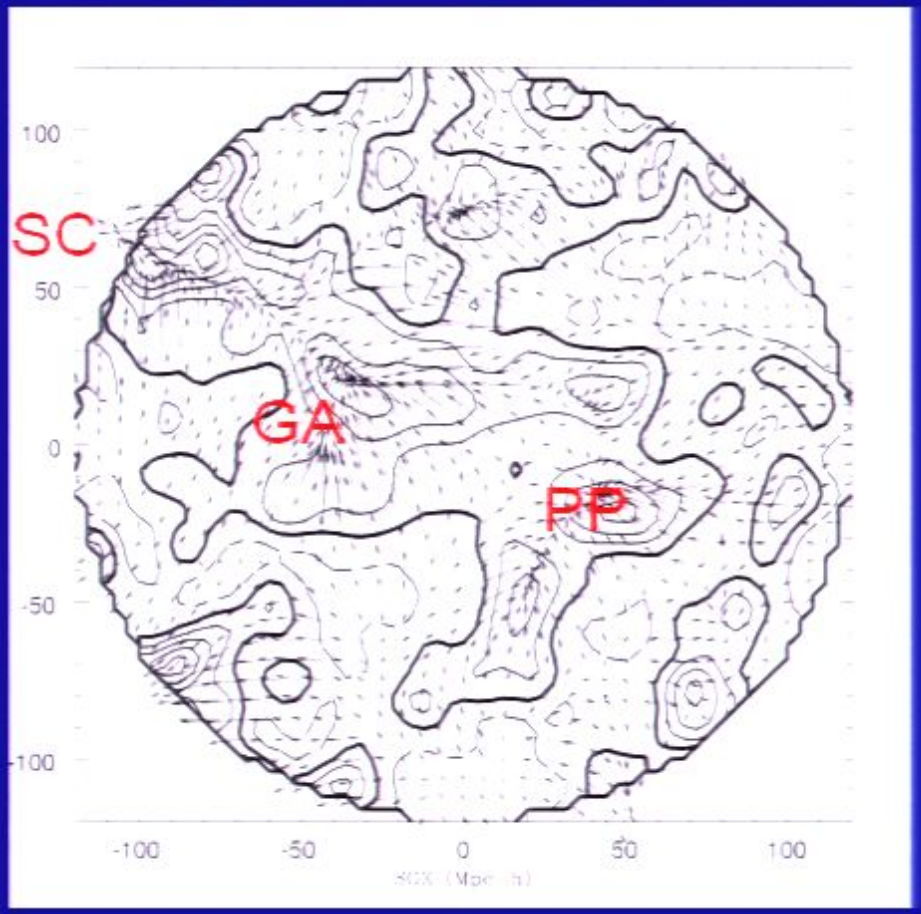

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The spectrum of mass fluctuations on large-scales and the angular spectrum of CMB fluctuations depends on the cosmological parameters.

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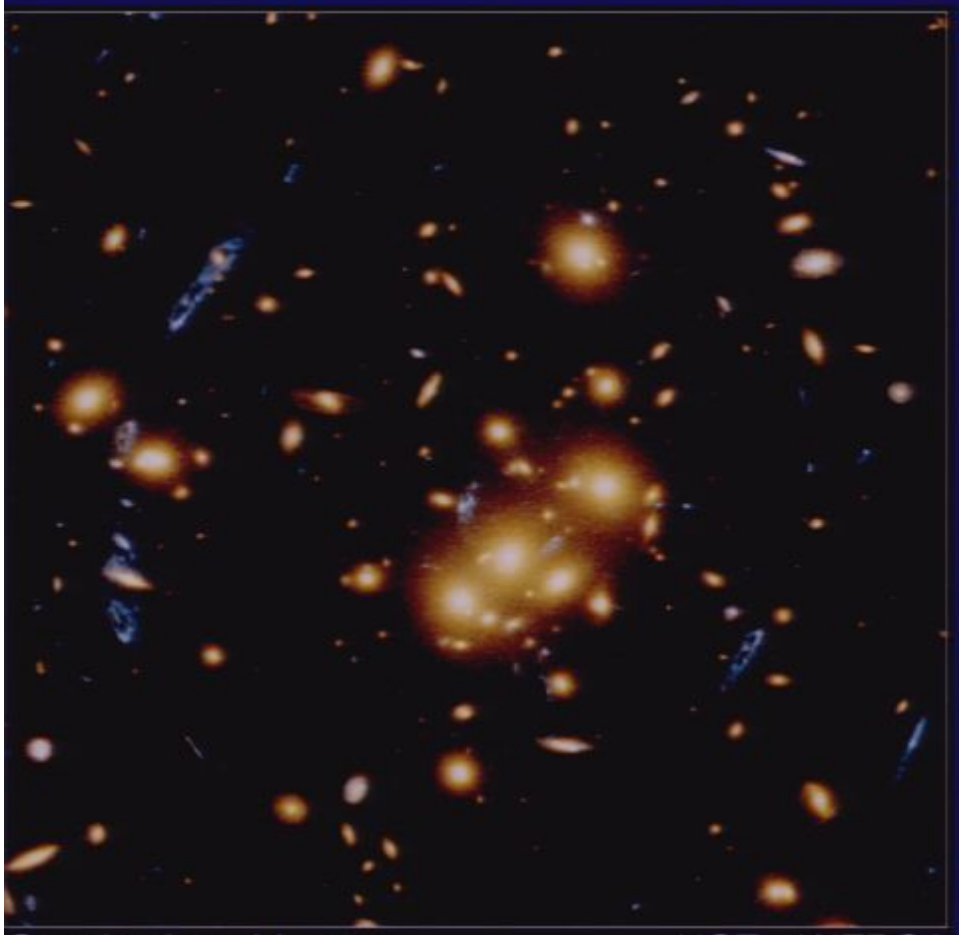

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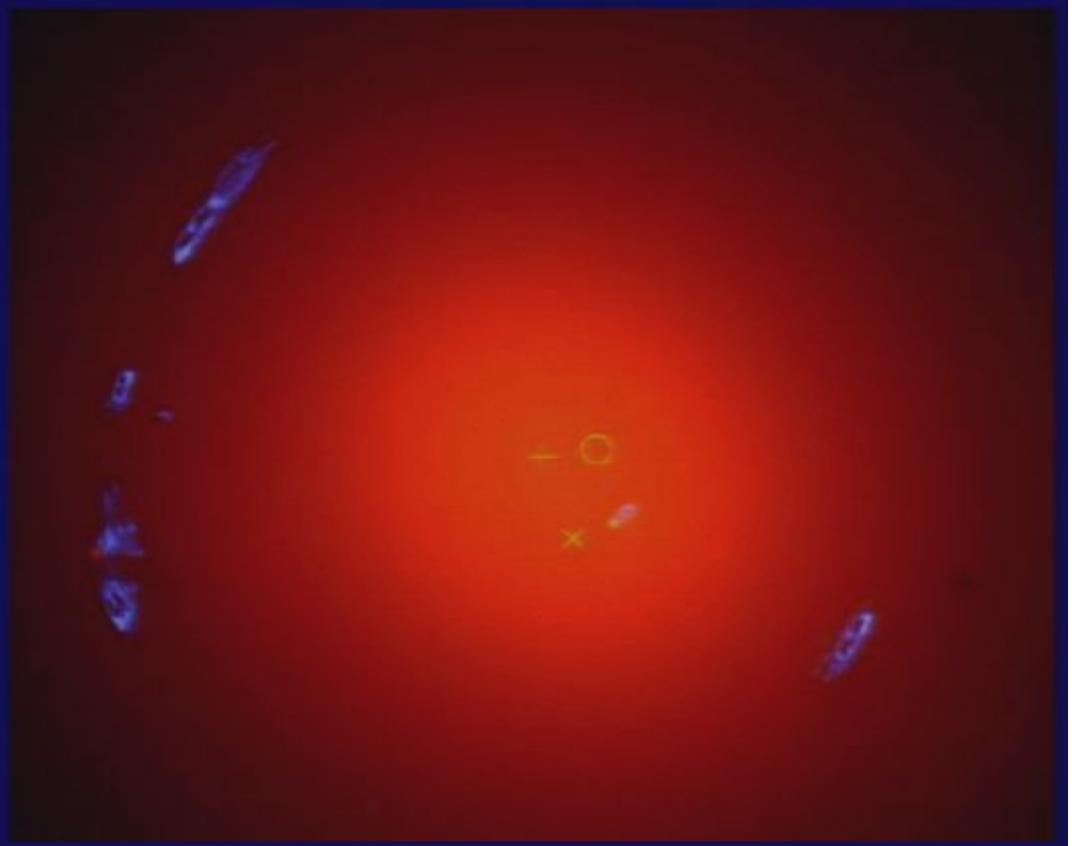

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$$\alpha = \frac{4GM}{b \cdot c^2}$$

Cluster Dynamics

- Virial theorem or Jean's equations applied to motions of galaxies with respect to cluster center yield cluster masses.
- Firs

$$\mathcal{M} > 9 \times 10^{46}\,\mathrm{gr}\,. \qquad (35)$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43}\,\mathrm{gr} = 4.5 \times 10^{10}\,M_{\odot}\,. \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathcal{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500\,. \qquad (37)$$

as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several years ago, when the conclusion expressed in (36) was reached for the first time.[5]

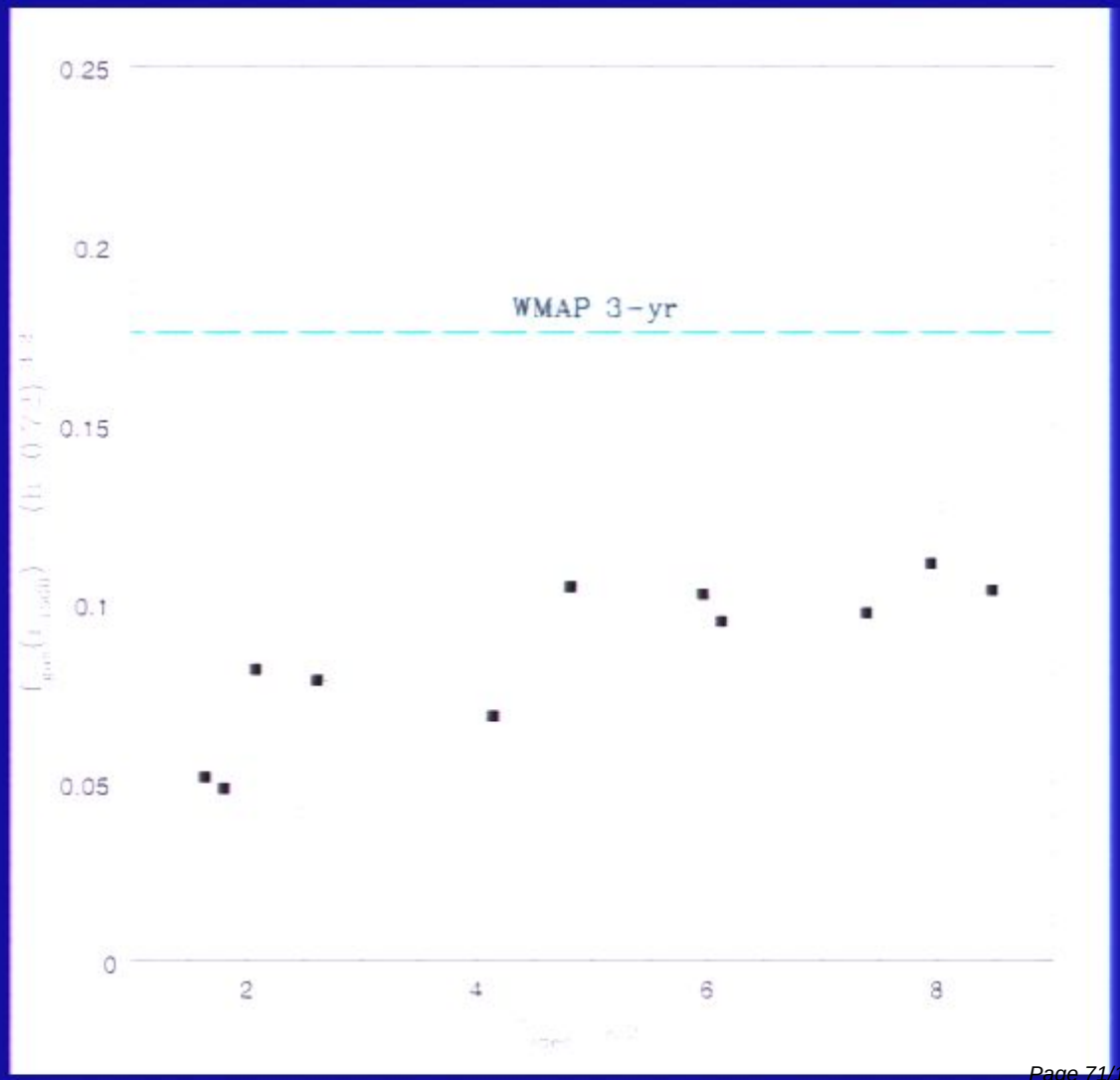
We inquire first what happens if the cluster considered is not st-a

Clusters masses from X-ray data

Ratio of gas mass to total (gas plus dark matter) mass

~ 0.12

(stars are negligible)



McCarthy, Balogh et al 07

Gravitational Lensing

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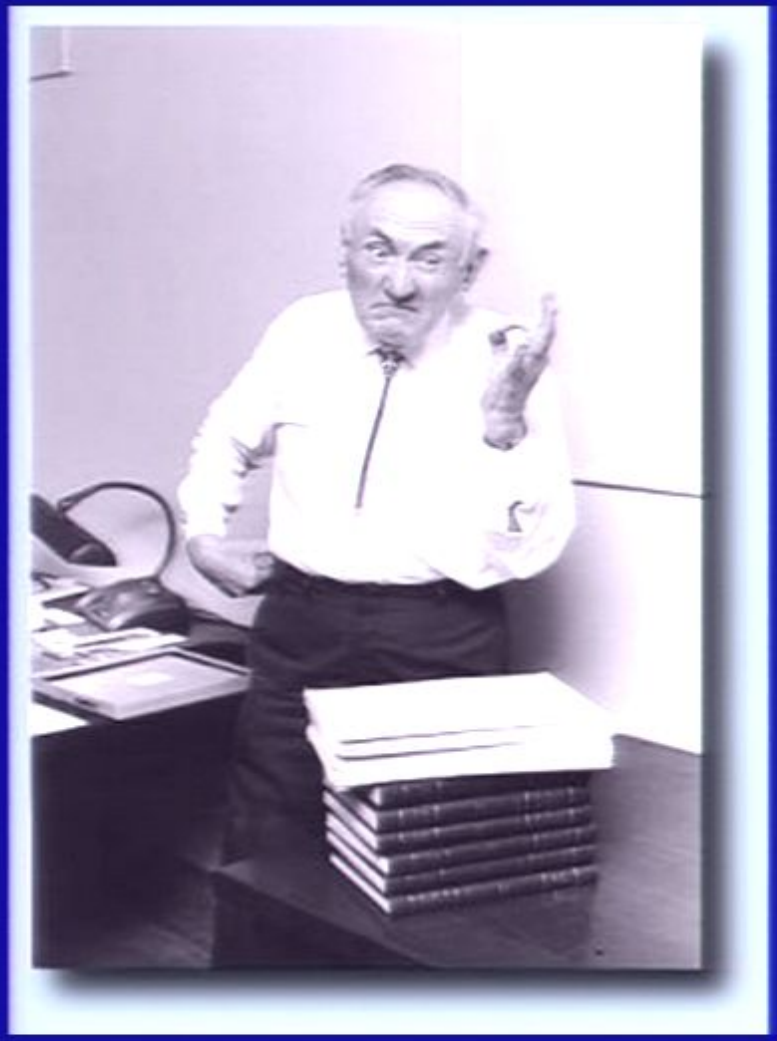
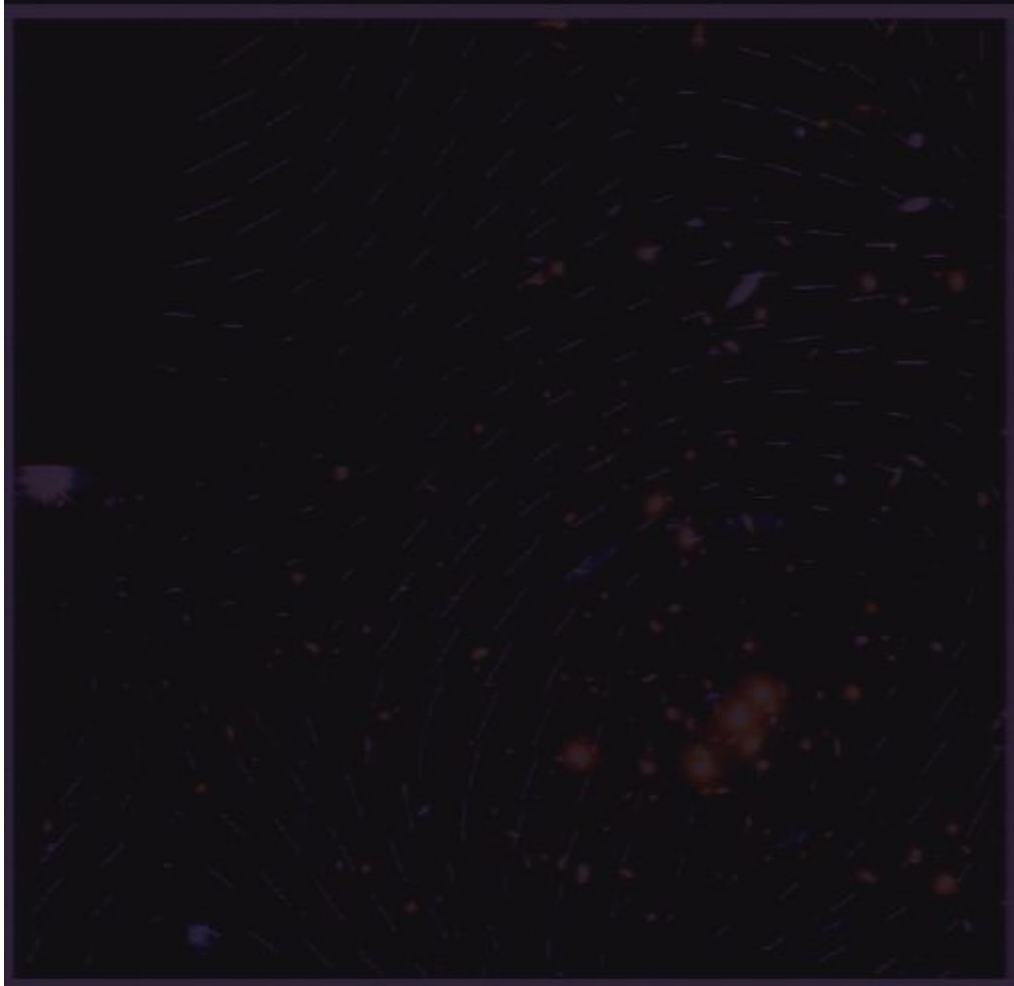
Fritz Zwicky



- Zwicky had a difficult personality:

He was fond of calling people *"spherical bastards"*, because they were bastards every way he looked at them.

Weak lensing



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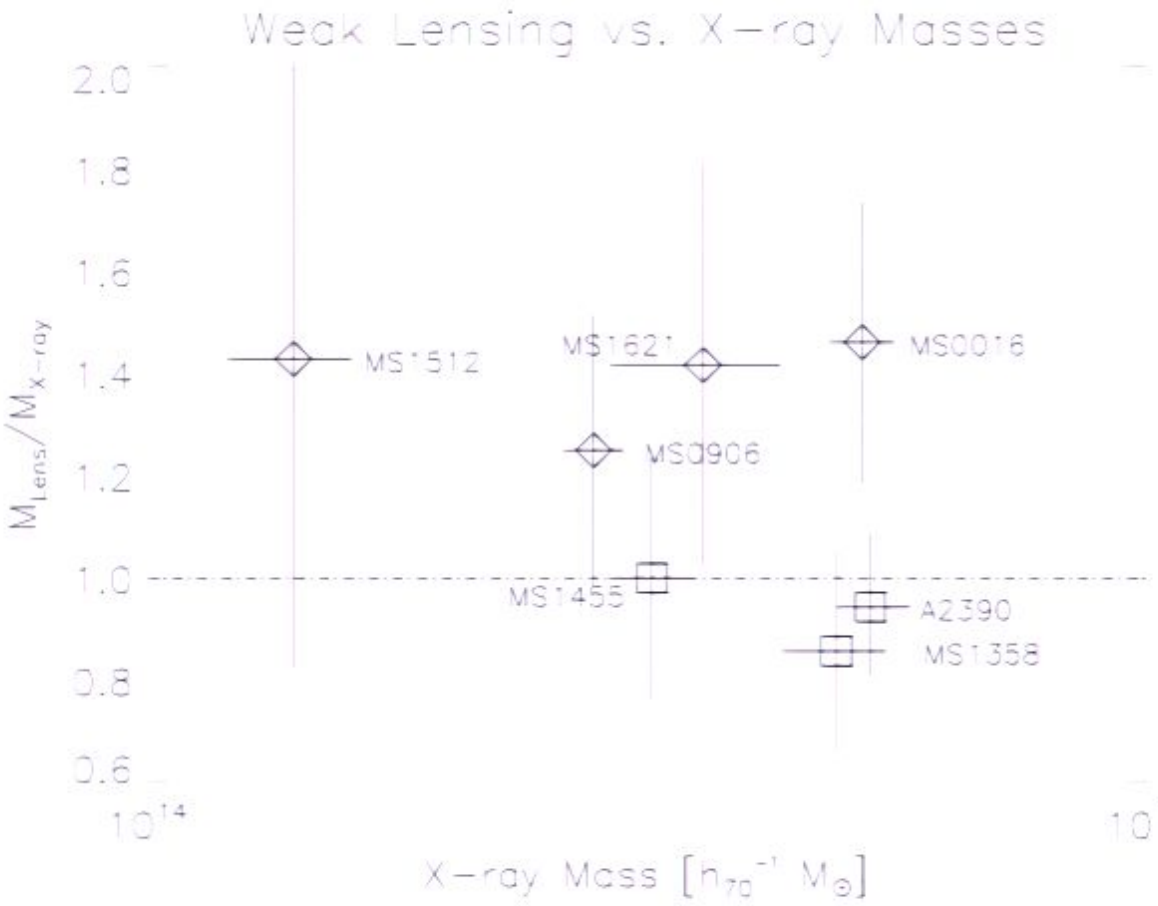

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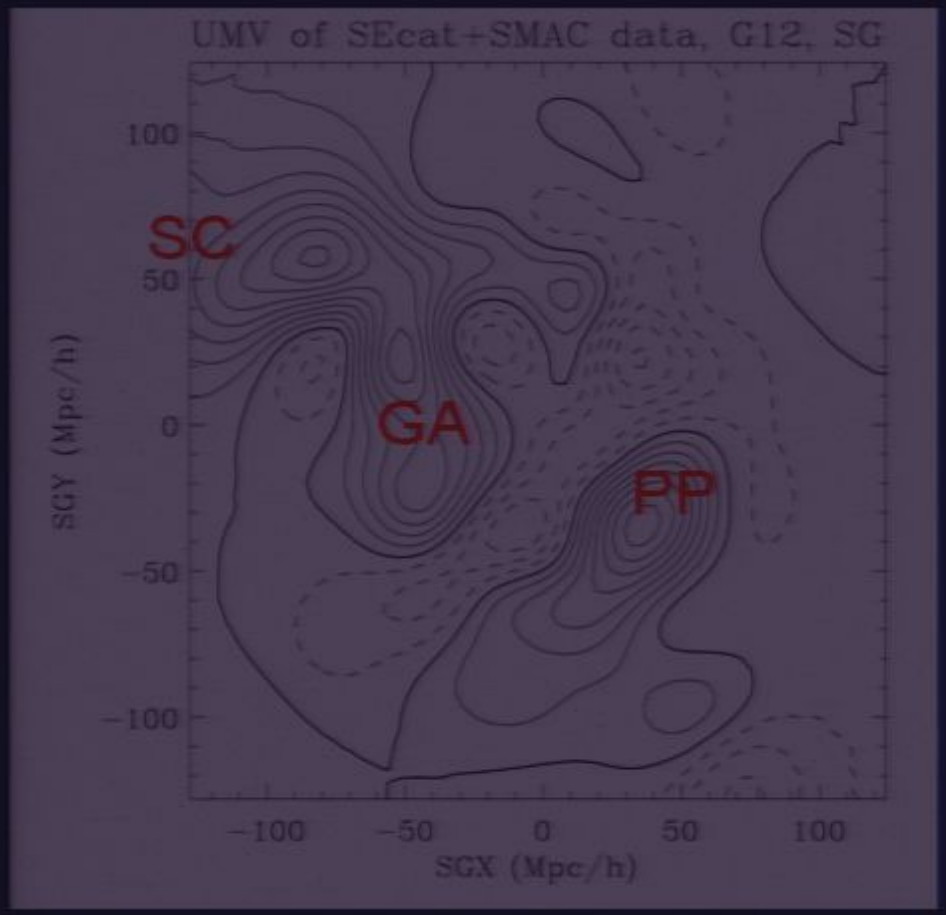

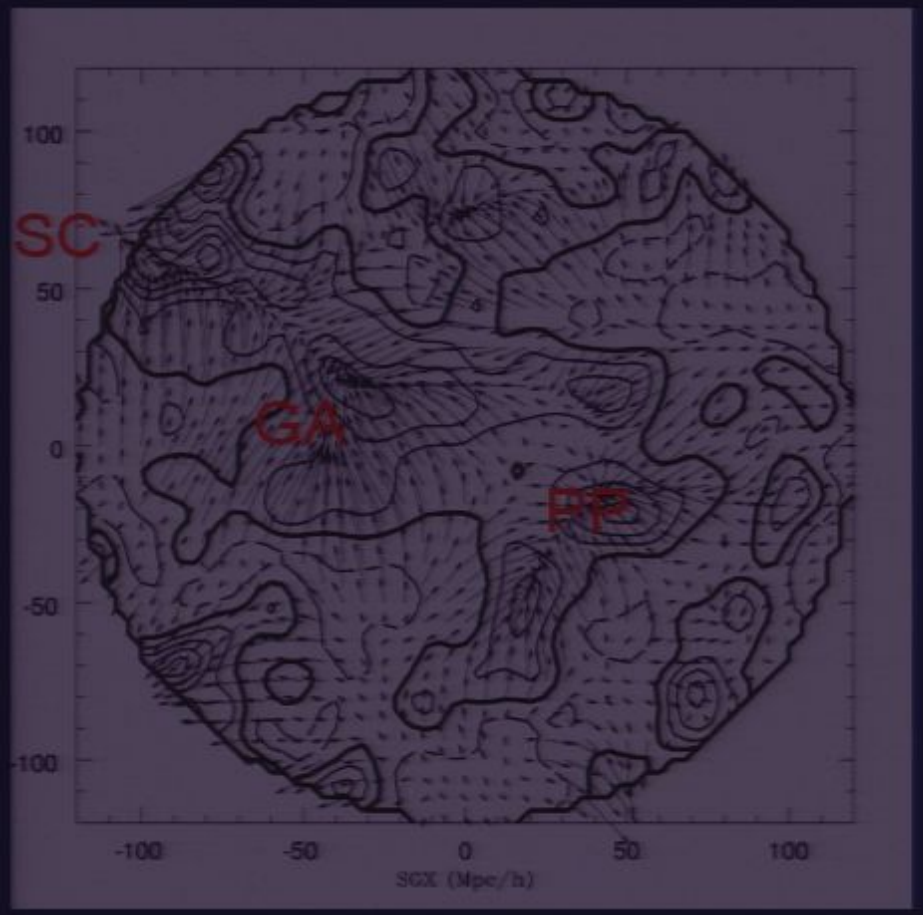

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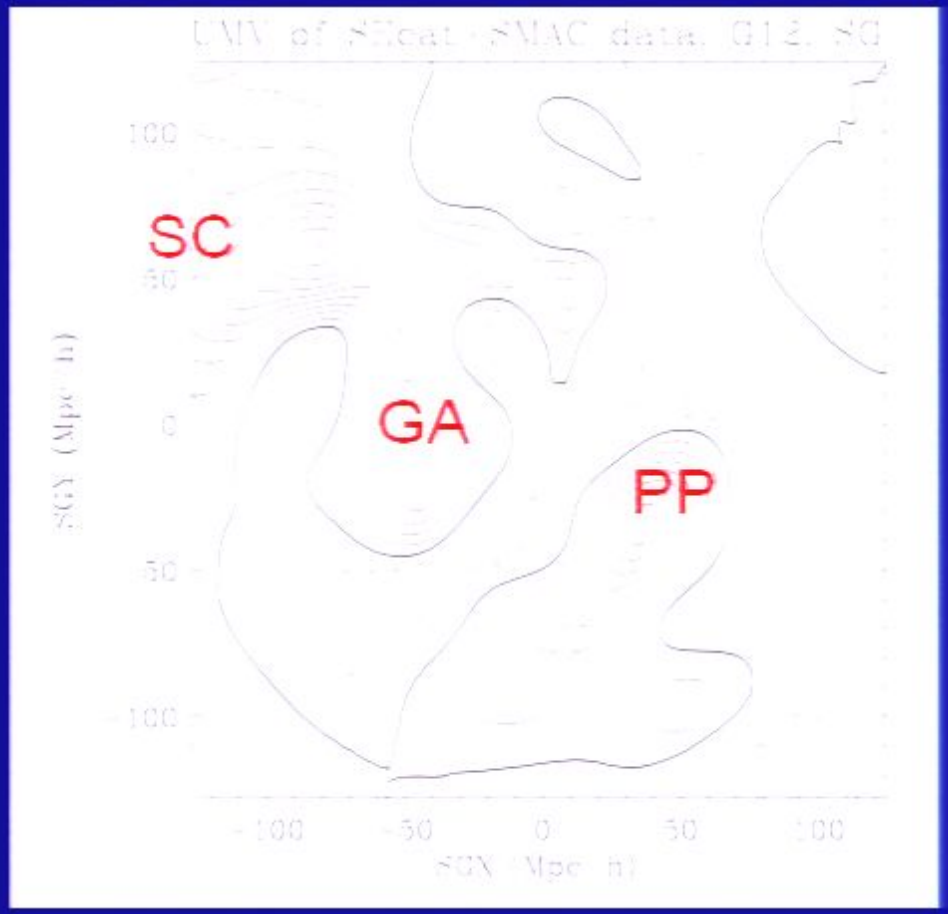

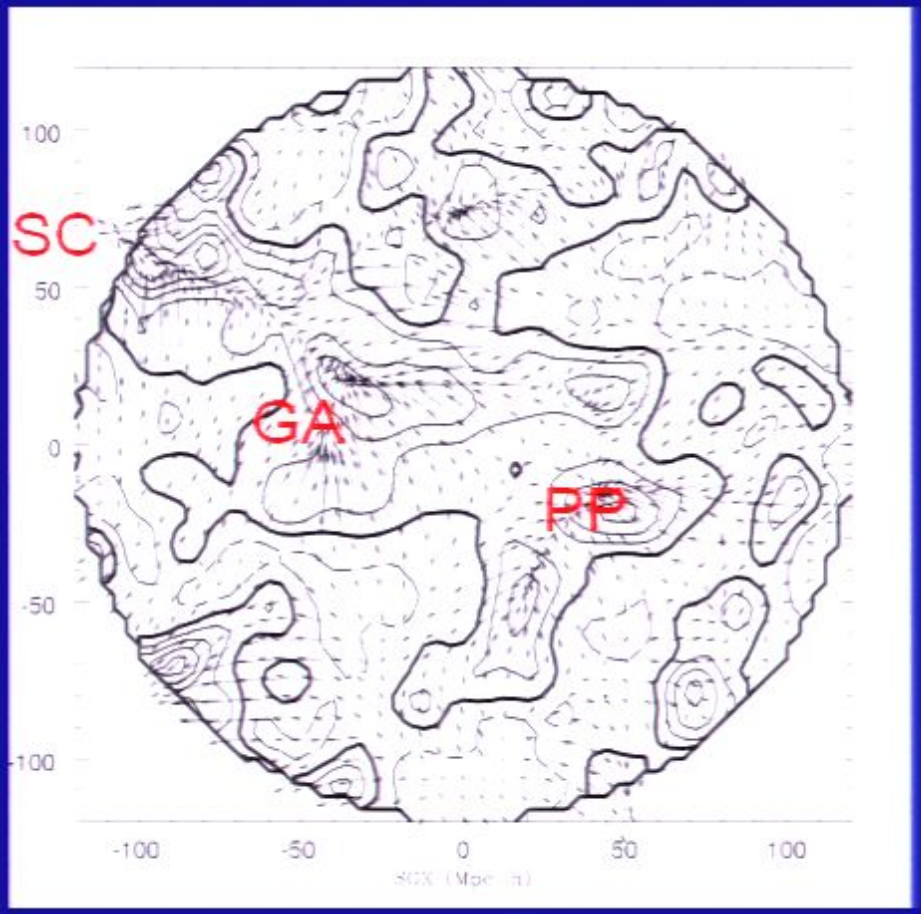

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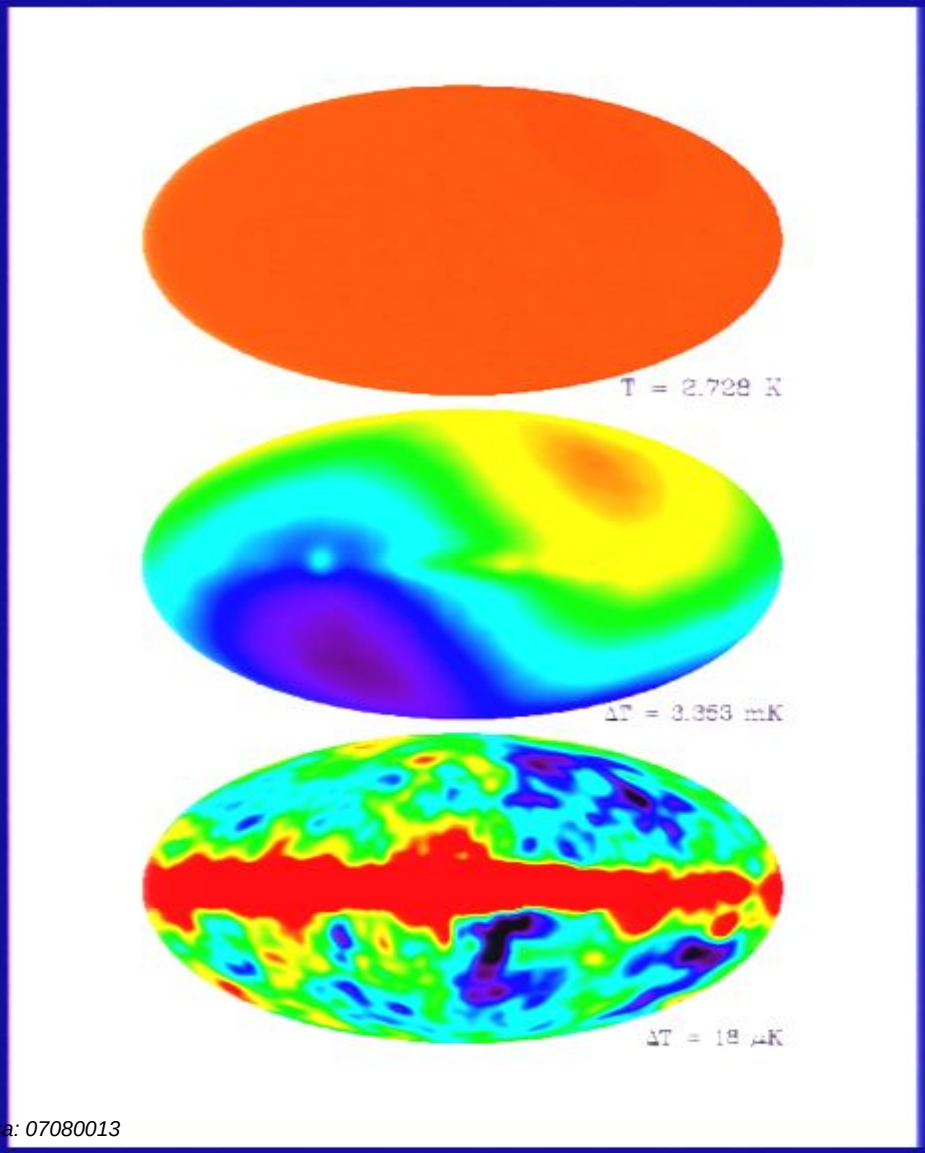
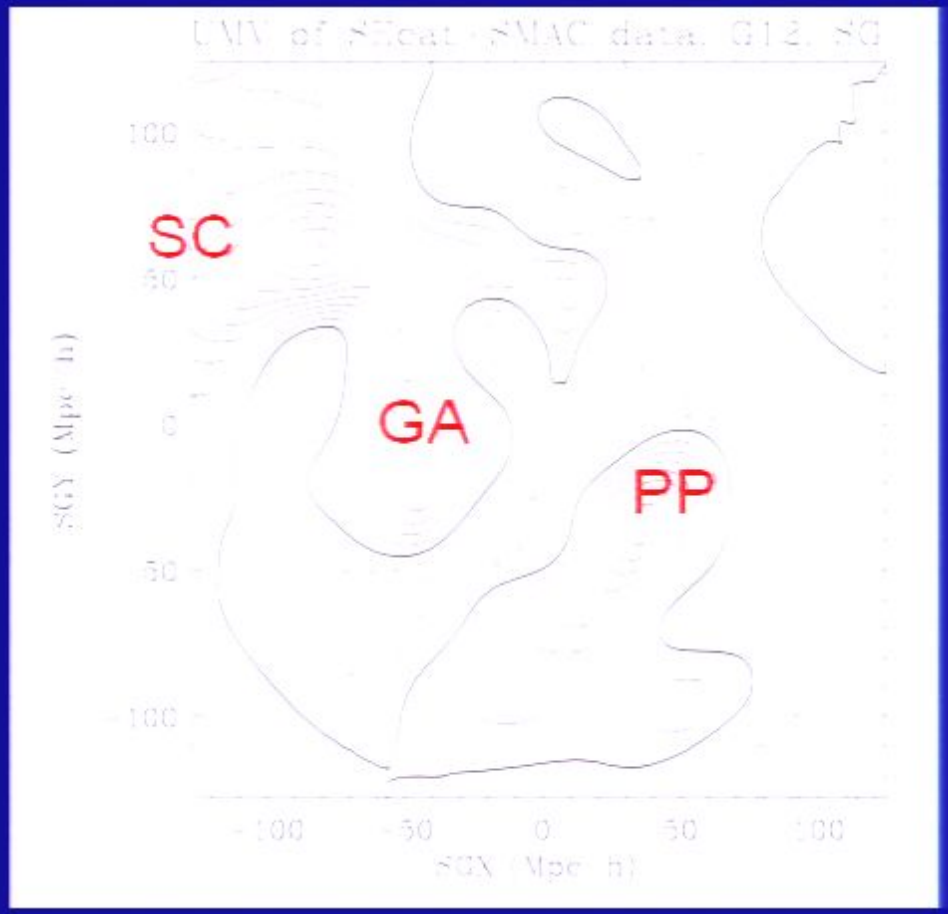
Cosmic Microwave Background

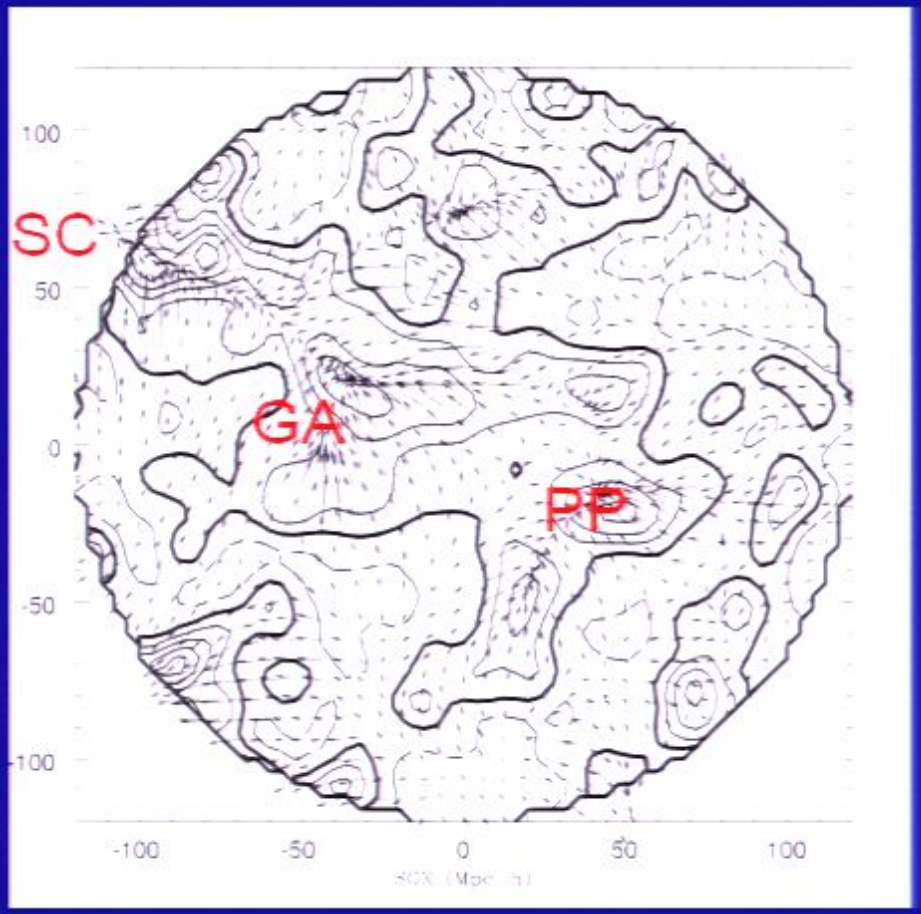


The primeval "fog" left over from when the Universe became transparent to radiation.

The micro-K ripples are due to redshifting from gravitational wells at z ~ 1000.

Mass vs Light





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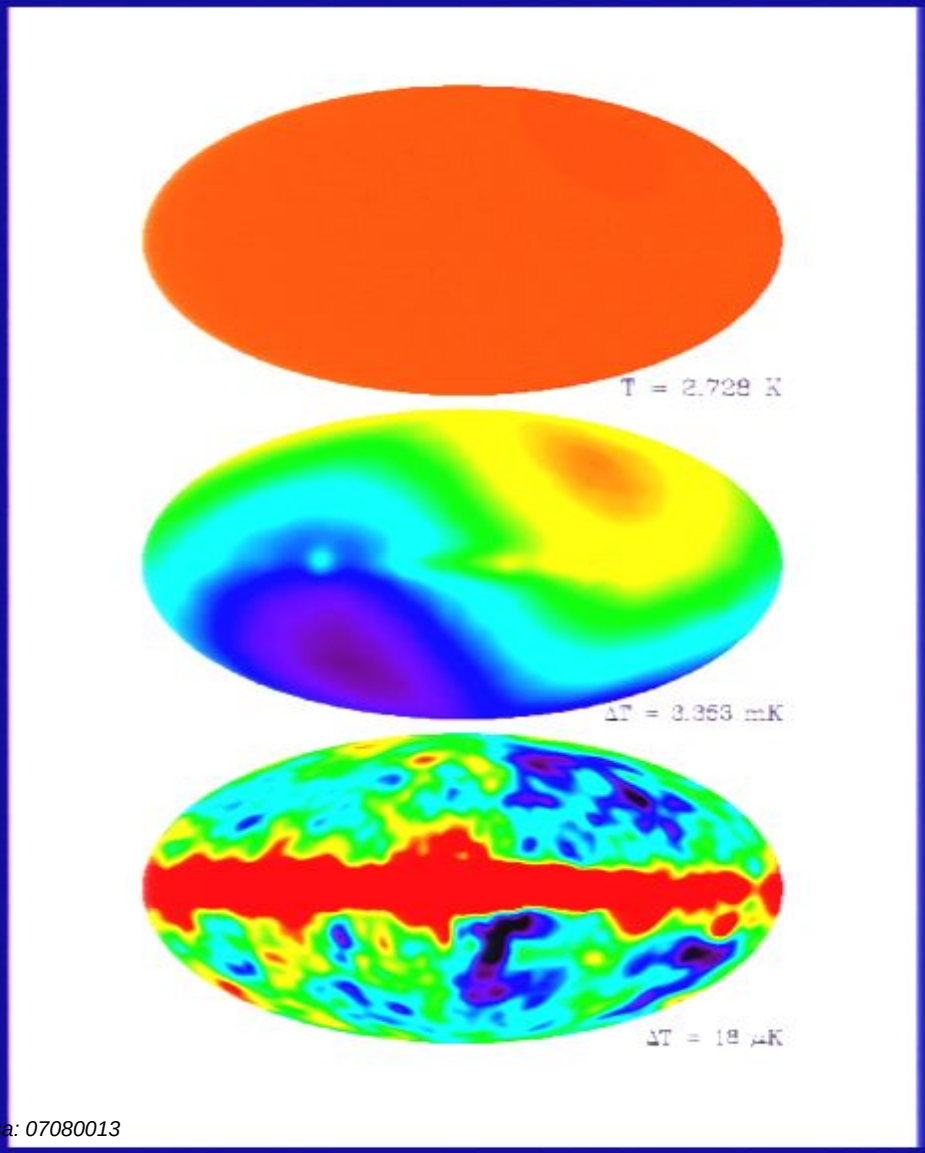

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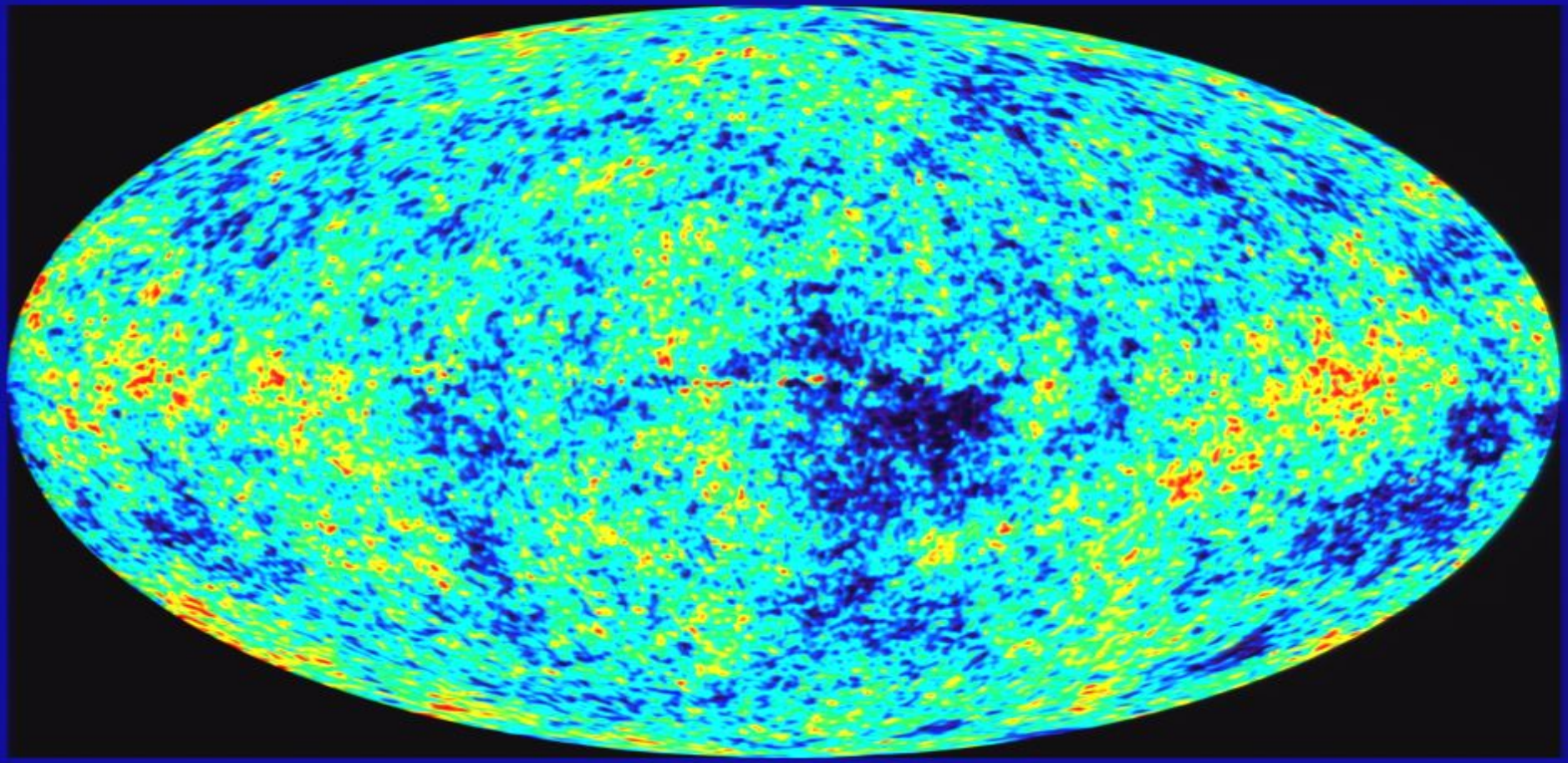

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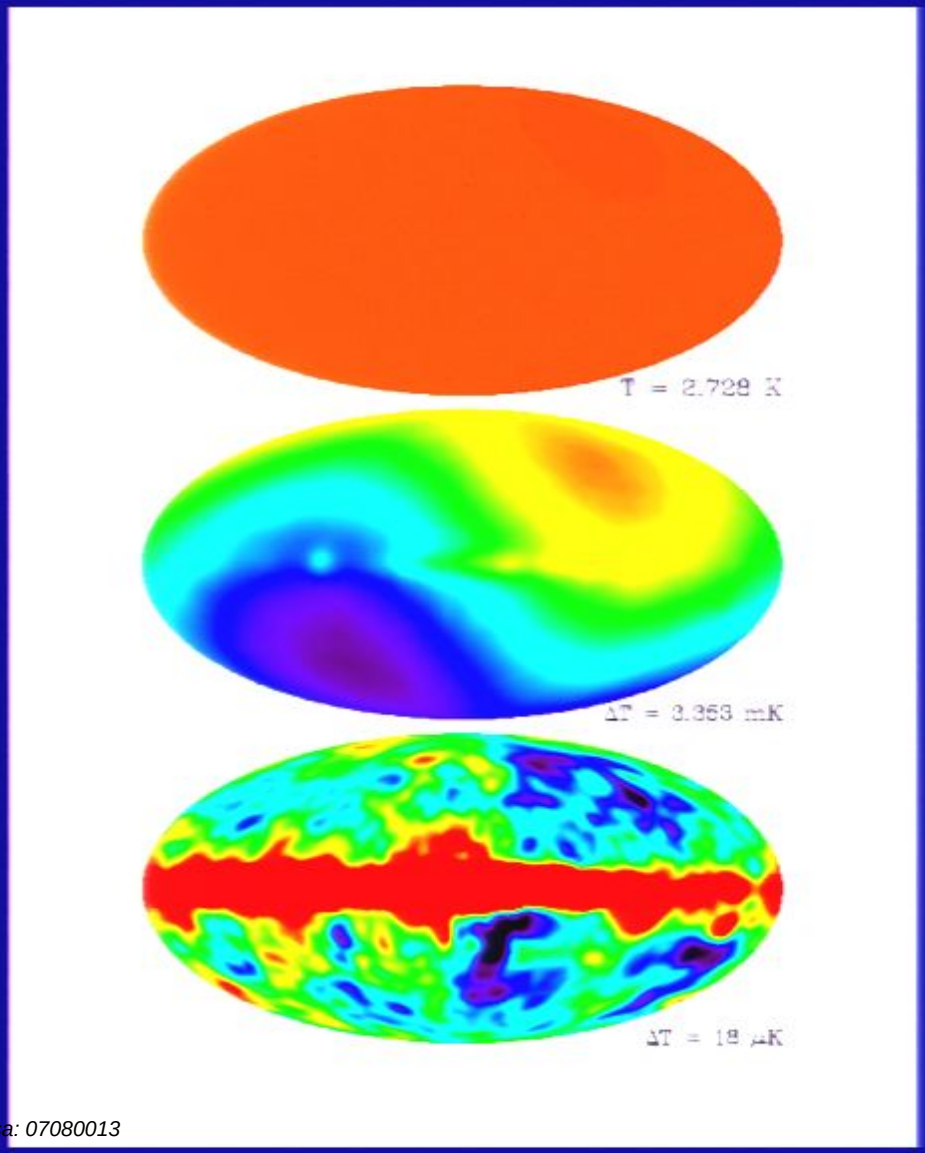

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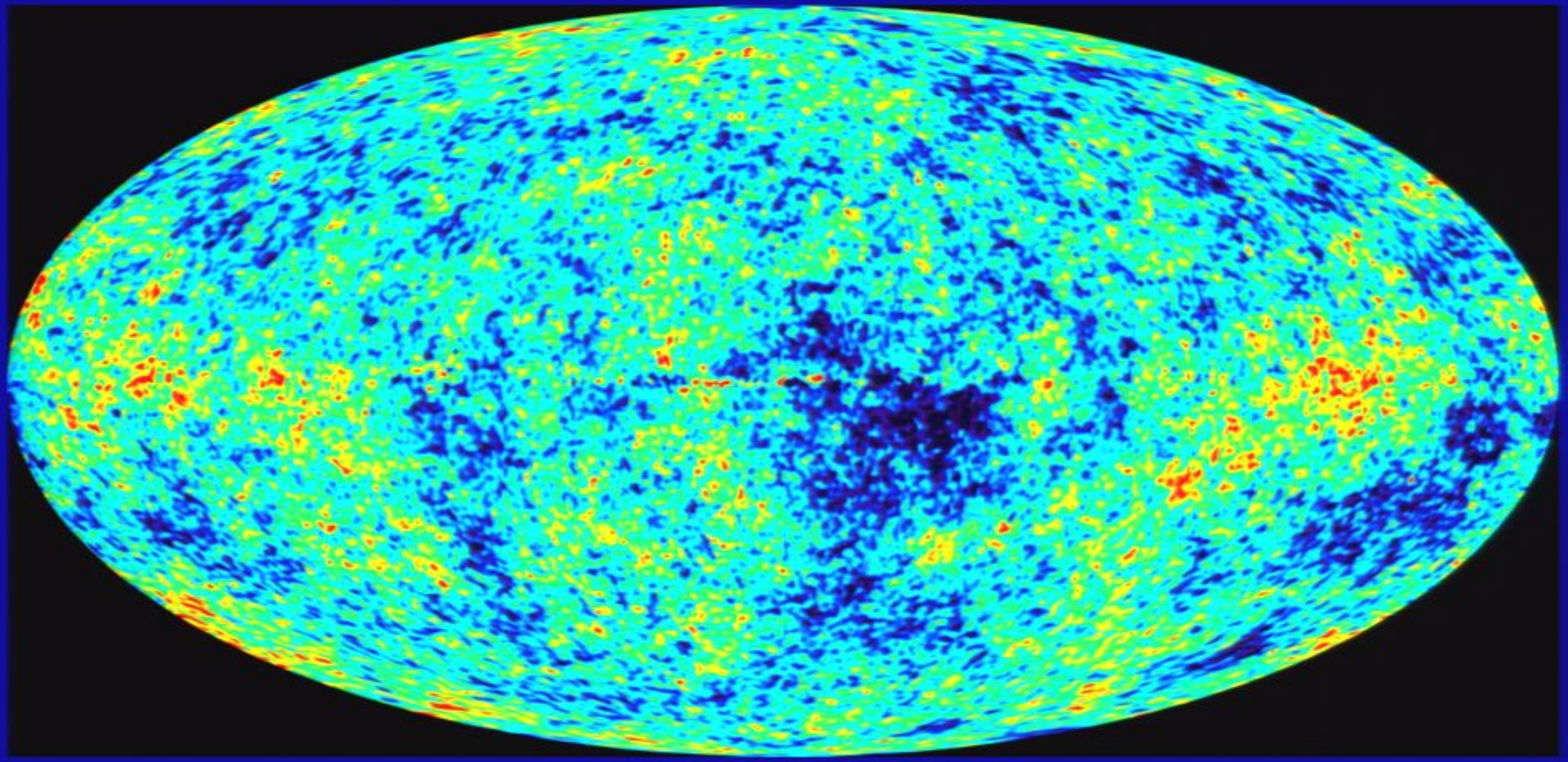

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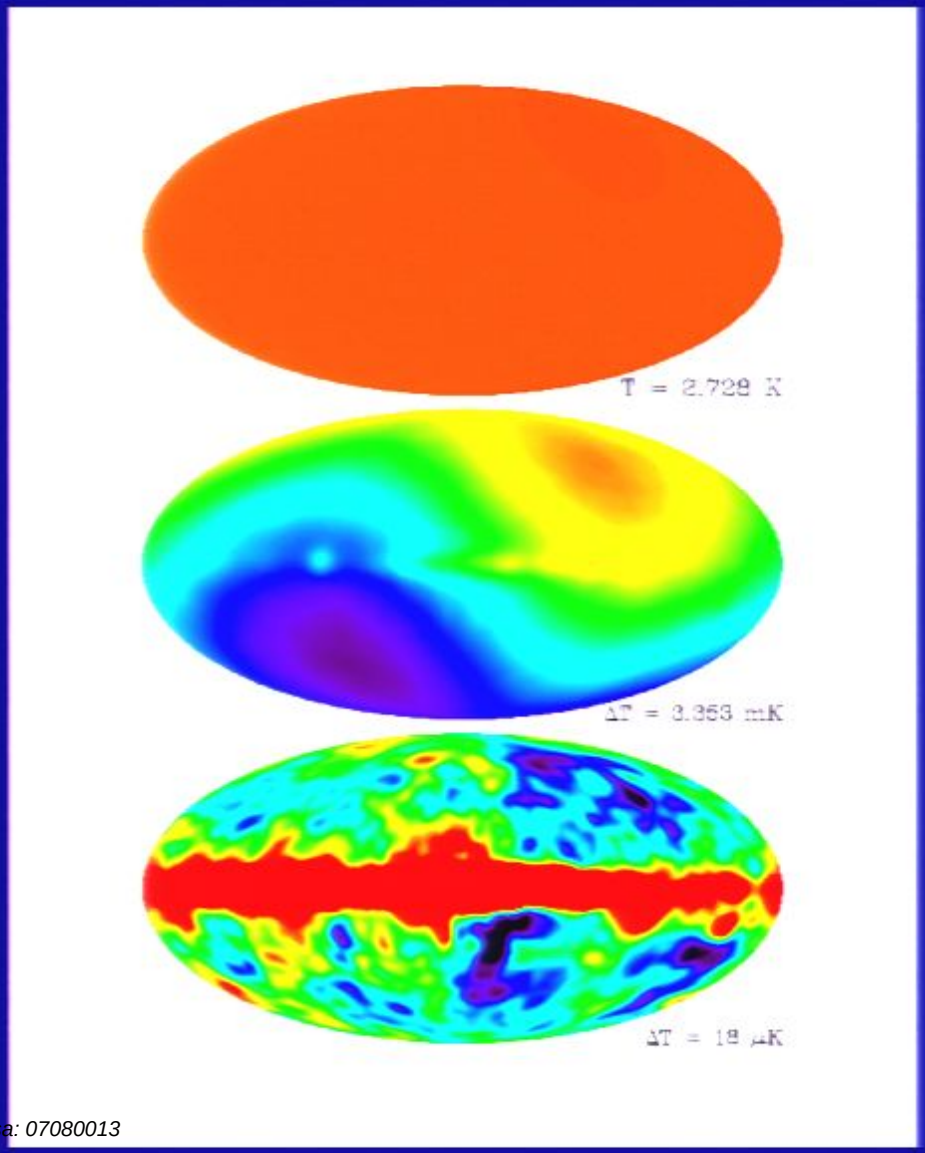

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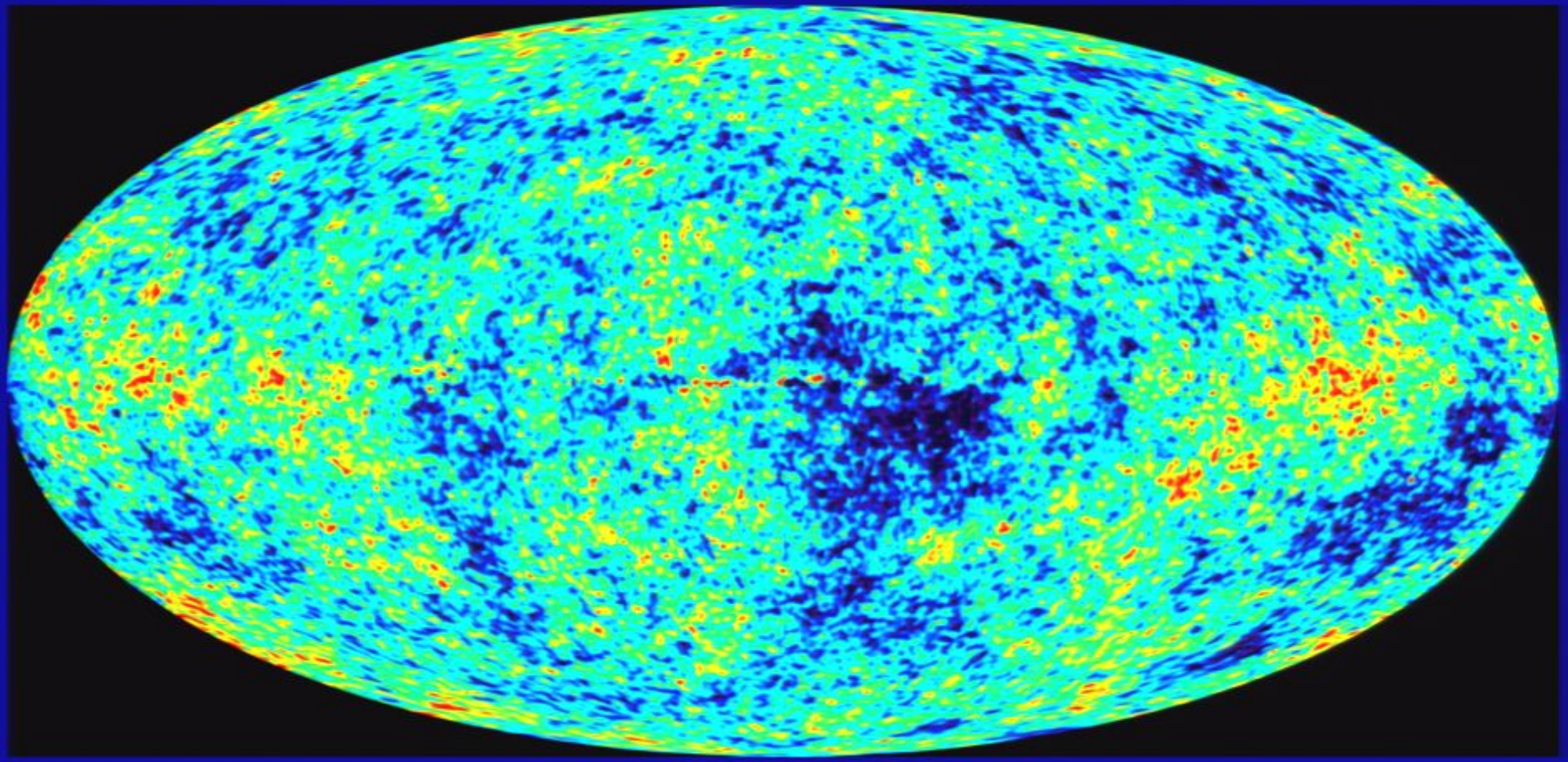

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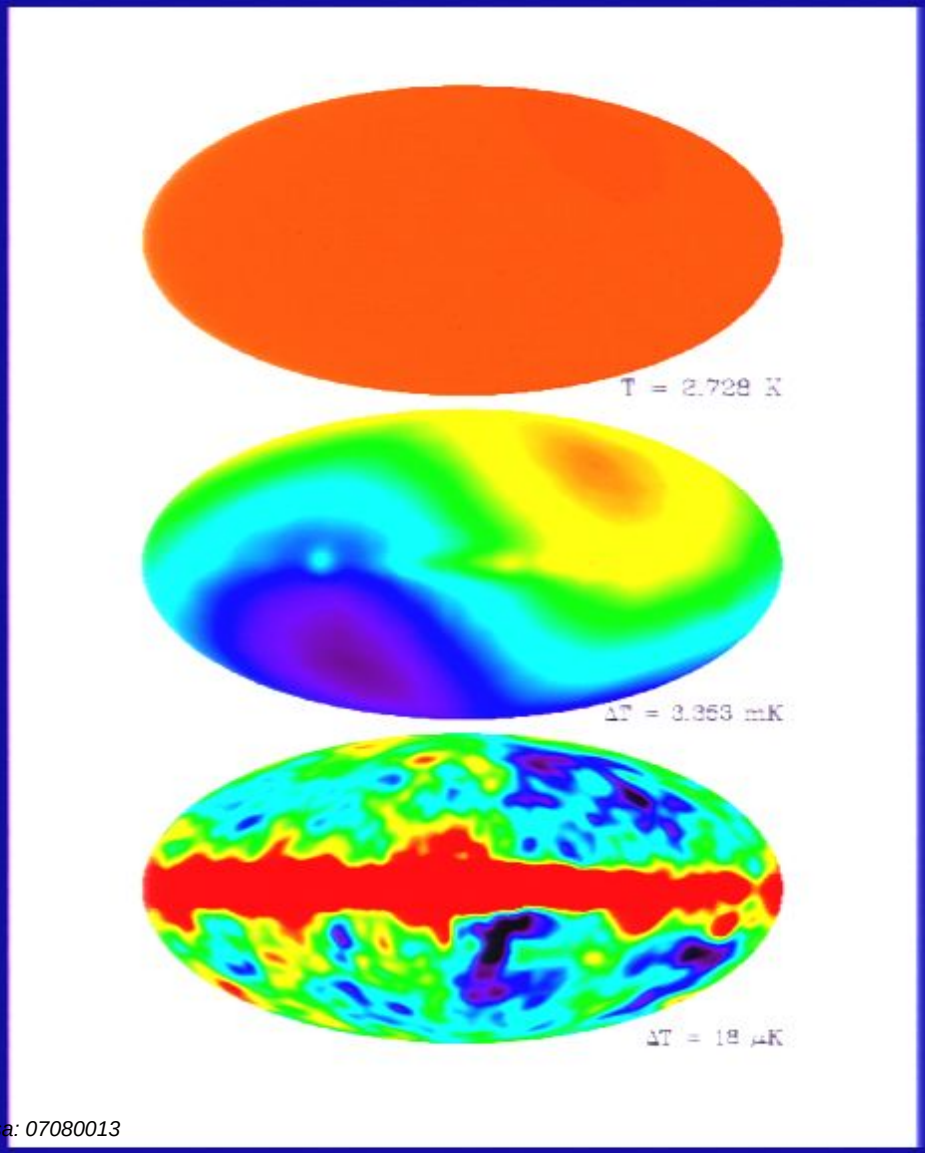

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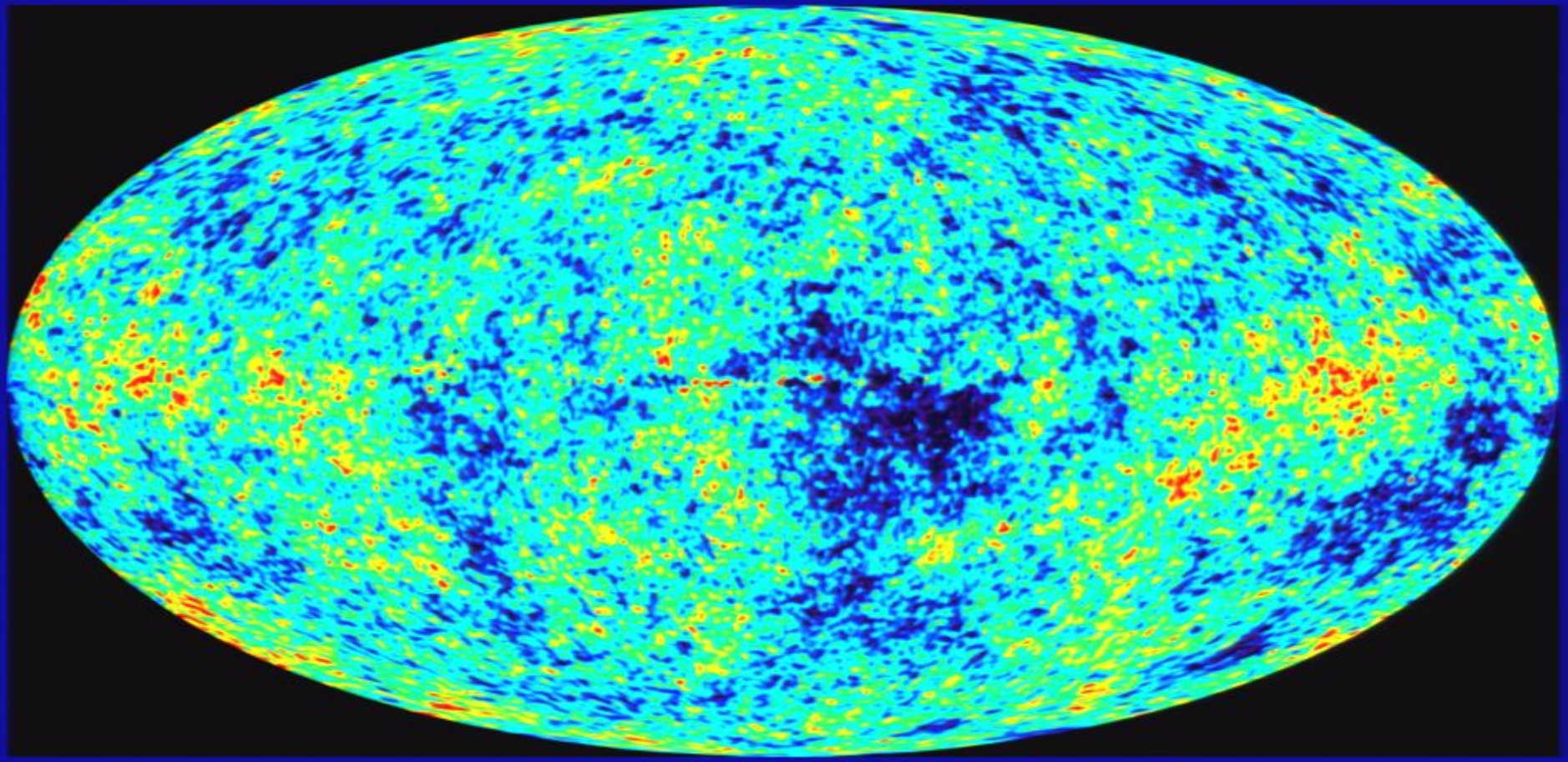

Very Large-scale Structure

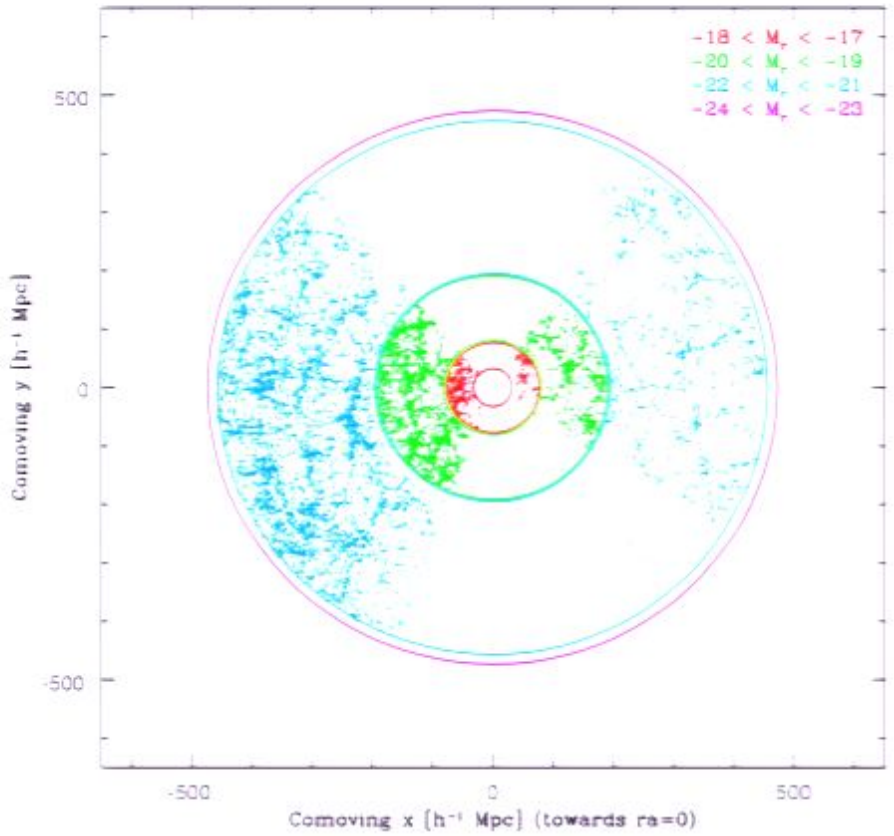

FIG. 5.— The distribution of galaxies within 5° of the equatorial plane is shown for the volume-limited subsamples L1, L3, L5 and L7 from Table 1.

Gradual transition to homogeneous Universe.

The structure that is visible on scales of 150 Mpc is the descendent of the 1 deg spots in the CMB!

(from SDSS)

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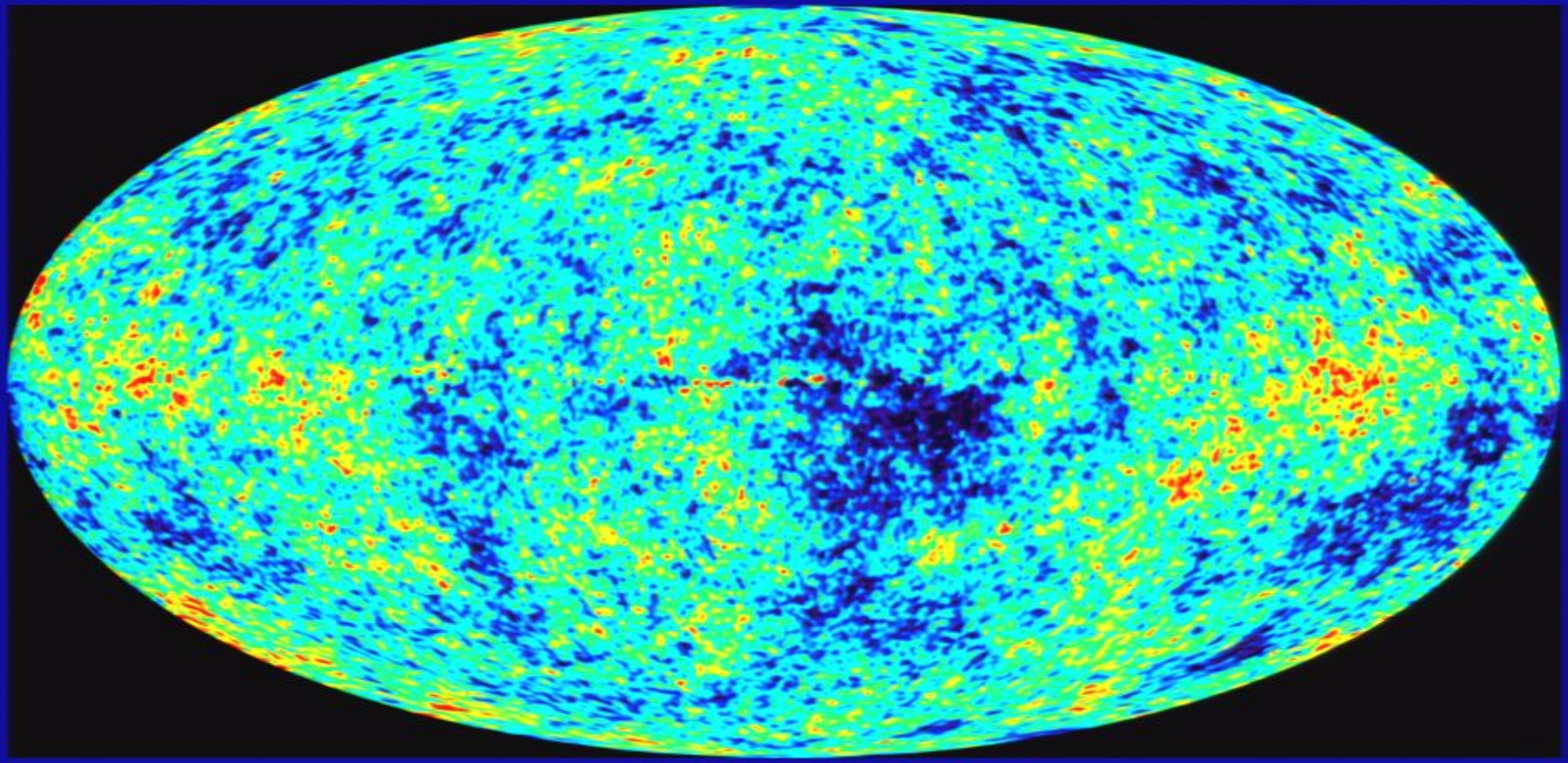

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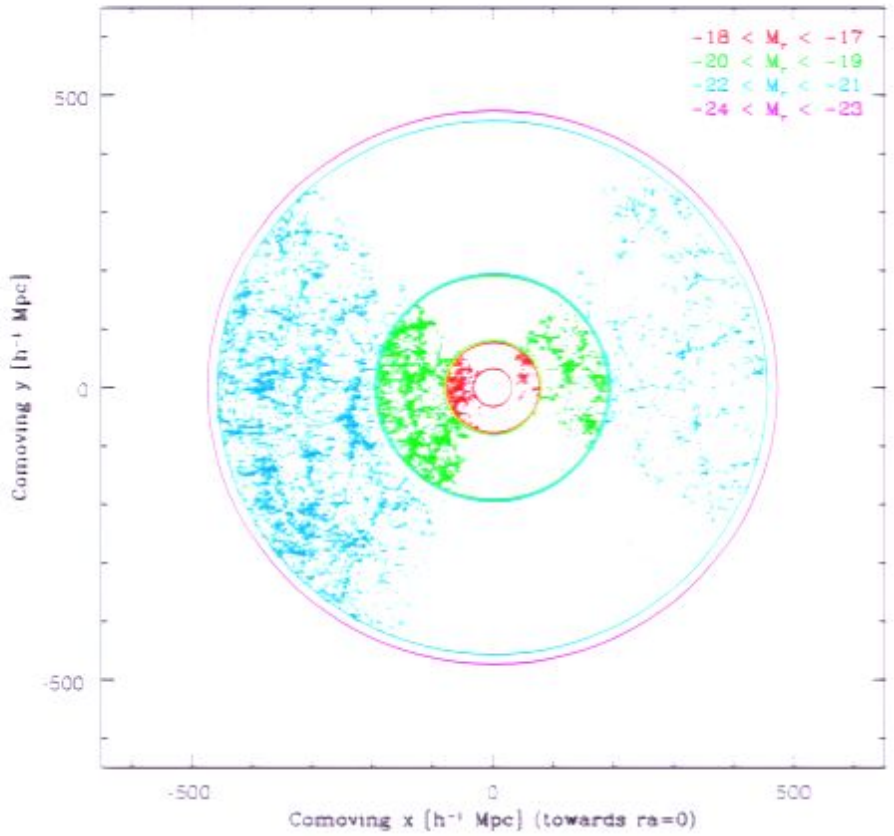

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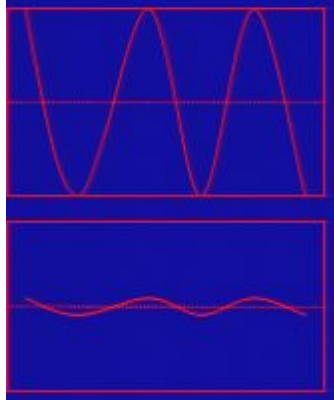

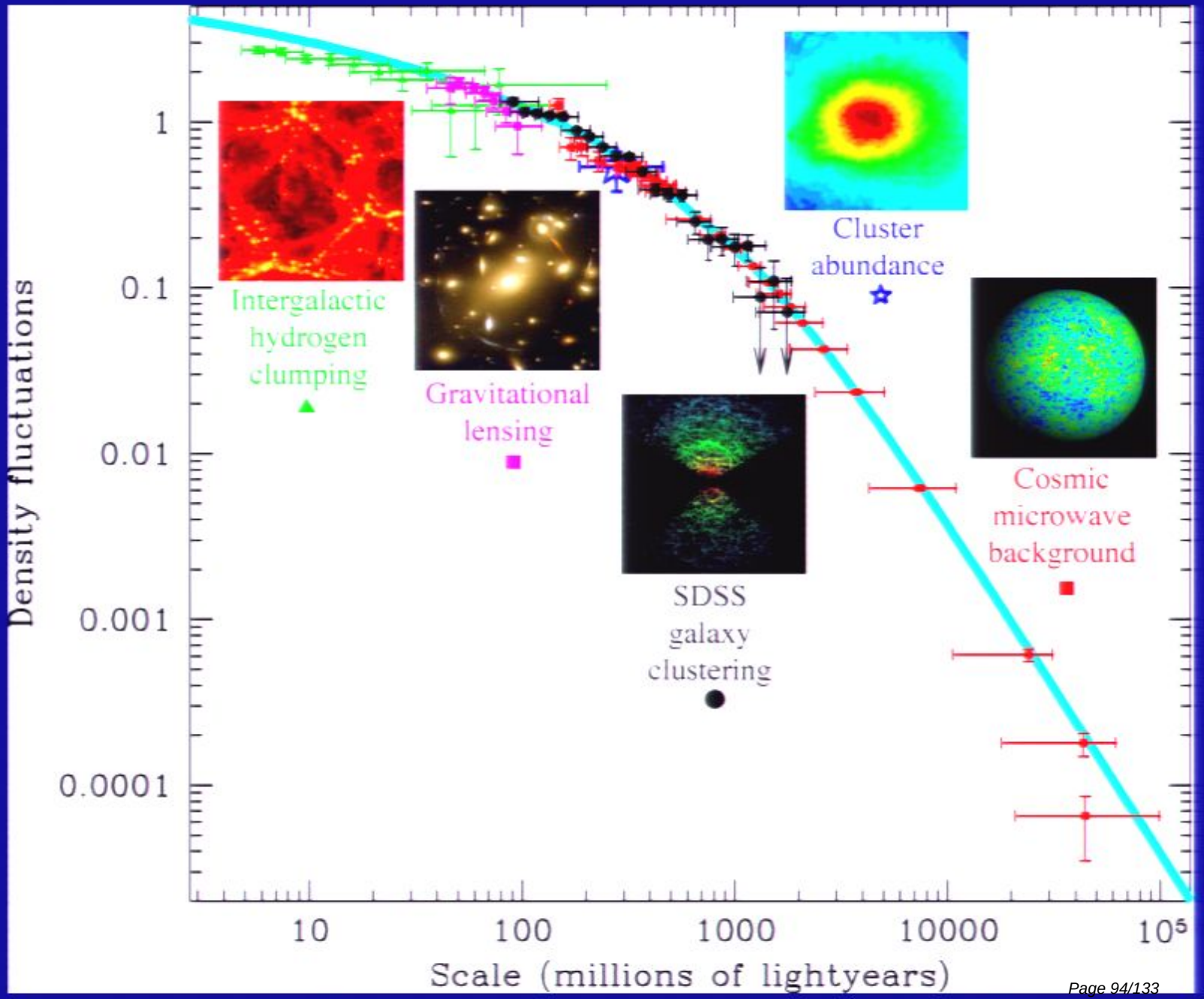

Wavelength of fluctuation

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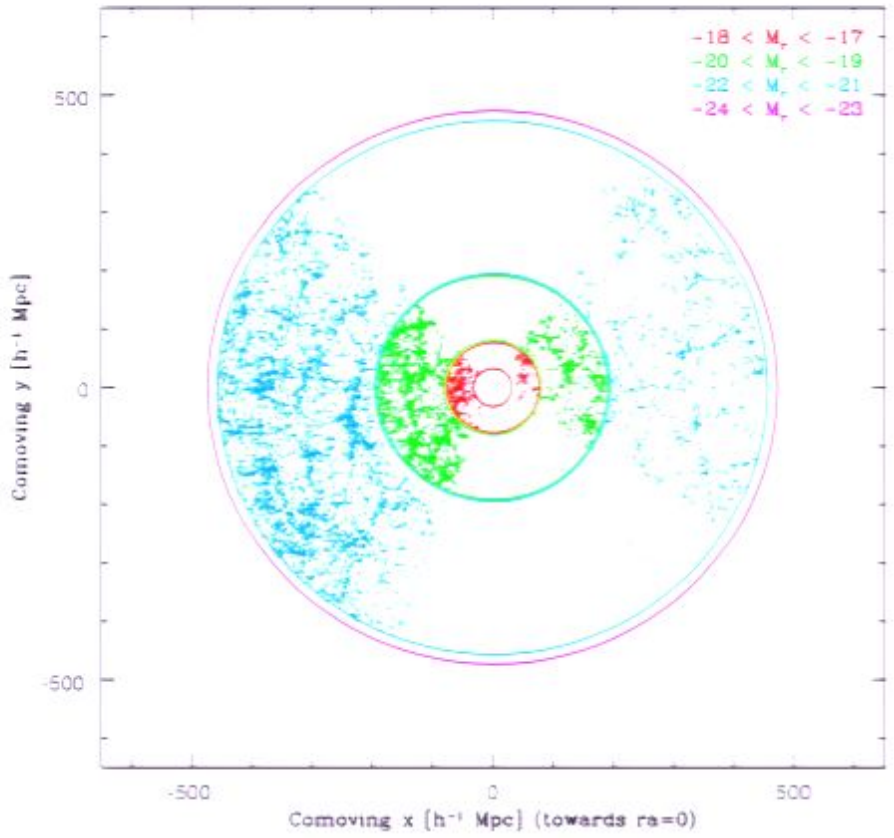

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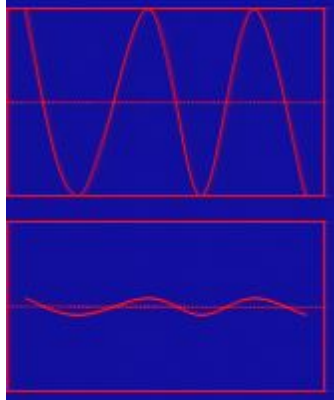
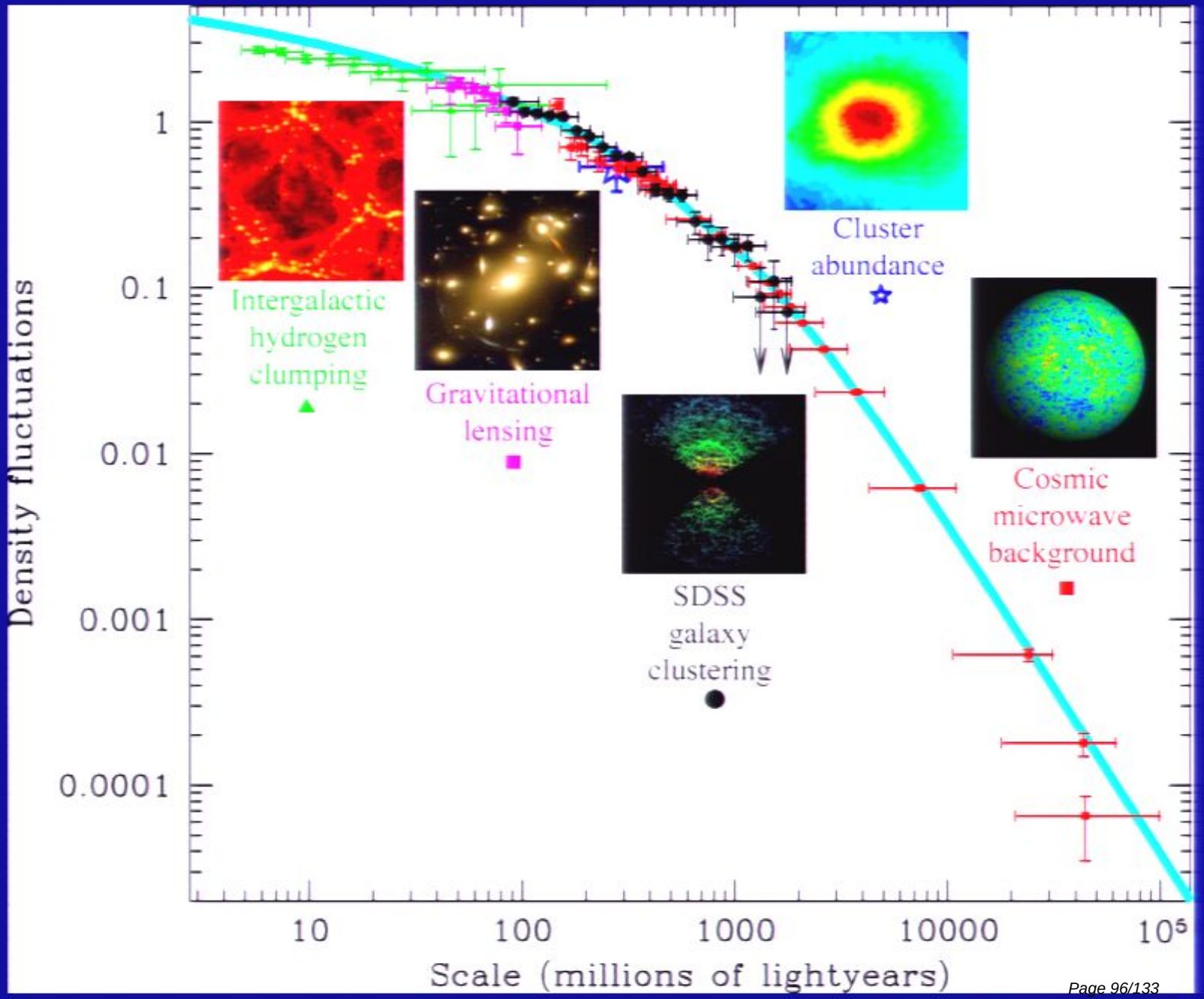
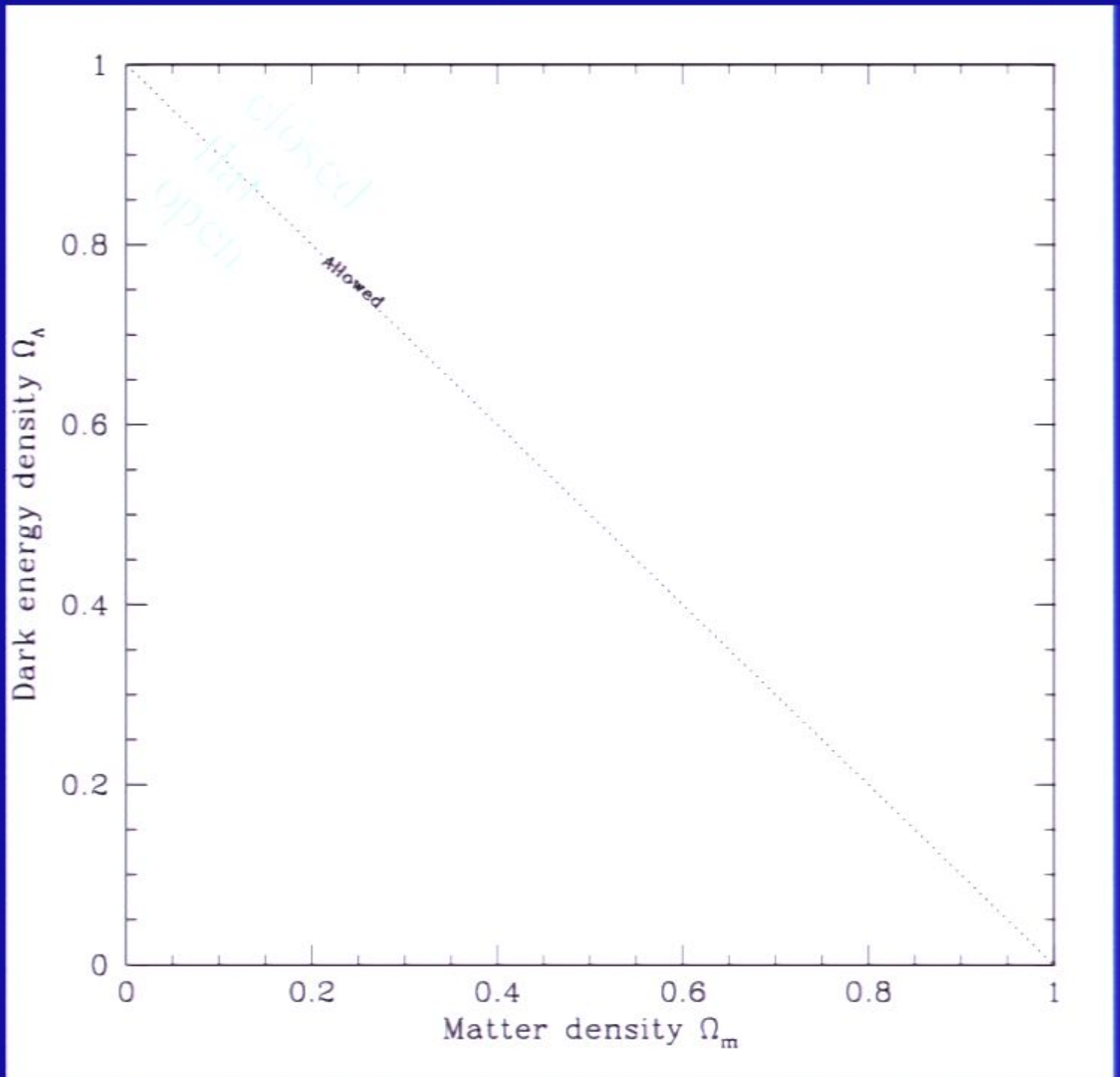
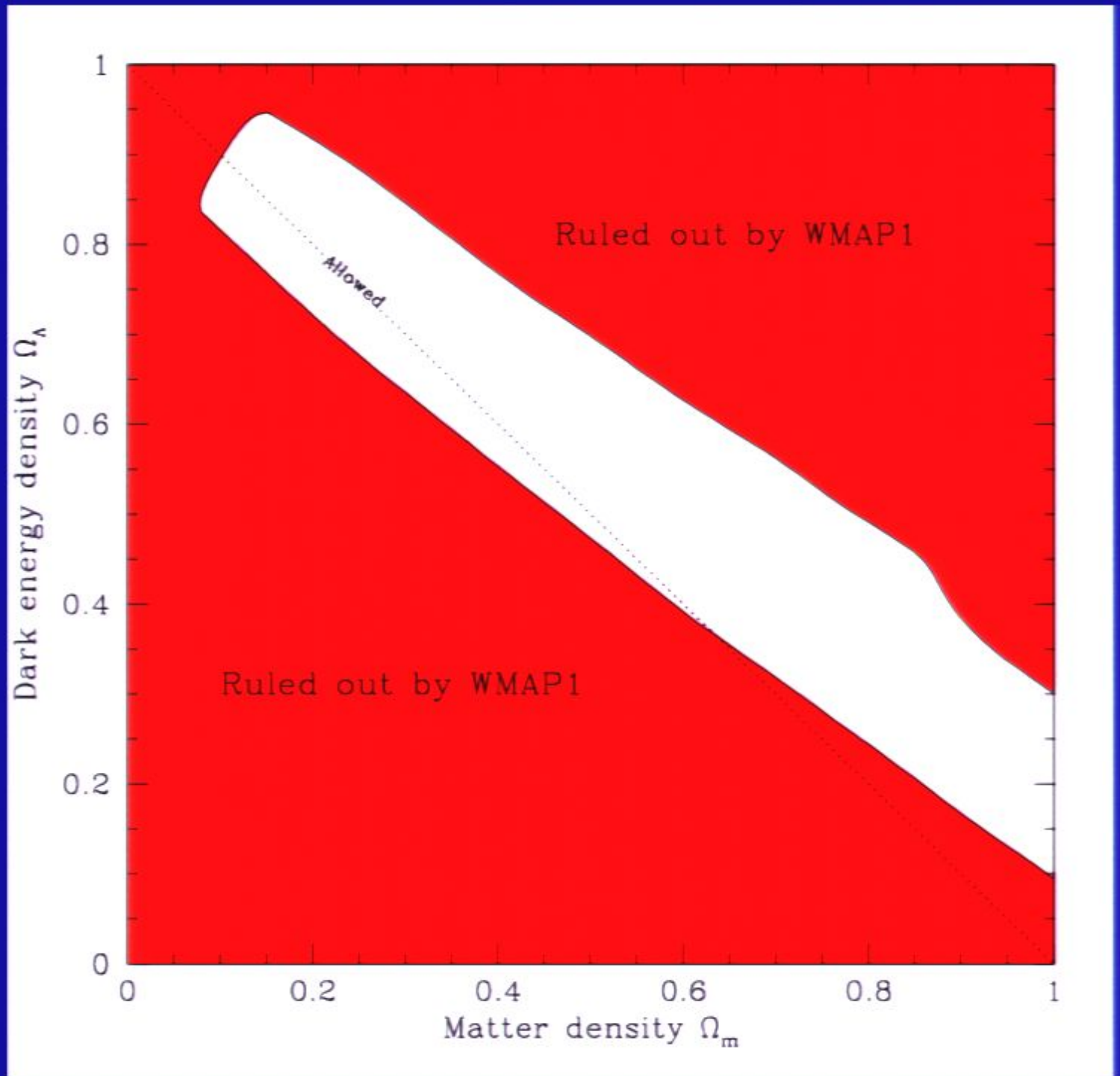




Wavelength of fluctuation

…. Skip hundreds of man-years of theoretical and observational work …


Allowed
Dark energy density Ω_Λ
Matter density Ω_m
0
0.2
0.4
0.6
0.8
1


Ruled out by WMAP1
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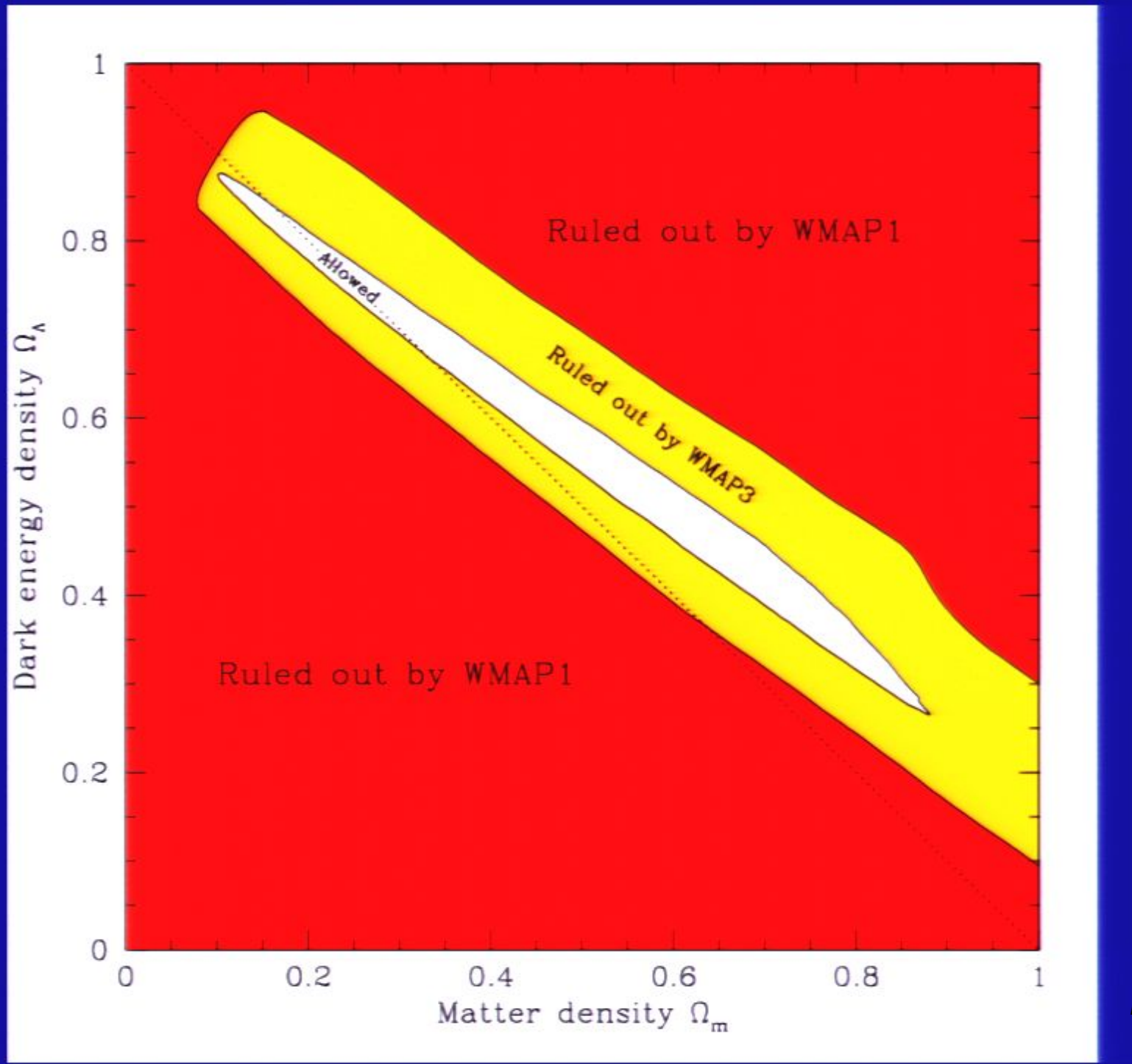
Ruled out by WMAP1
Allowed
Ruled out by WMAP3
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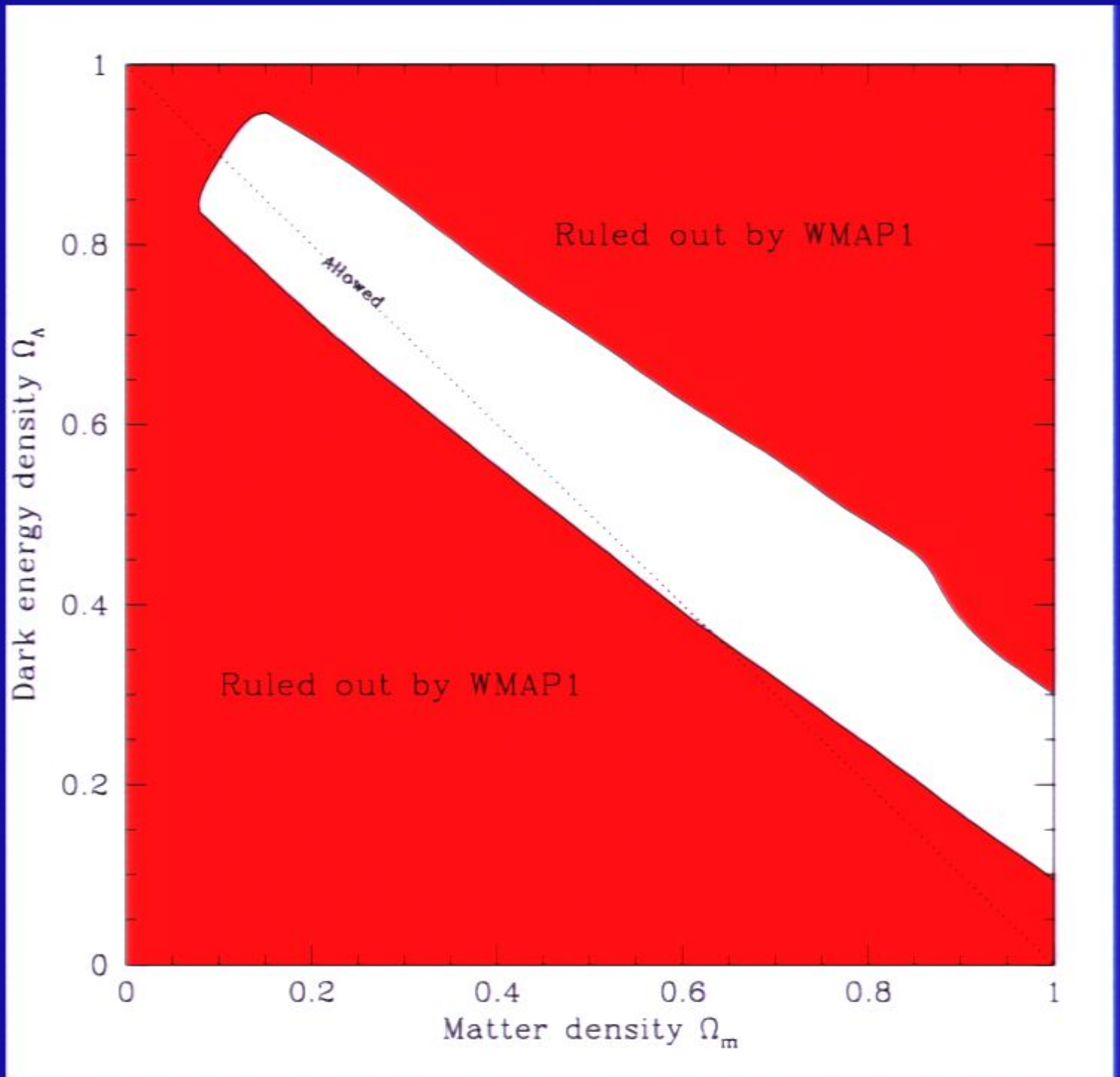
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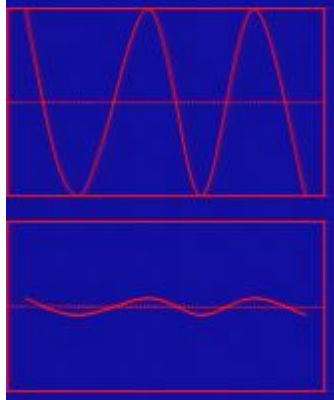

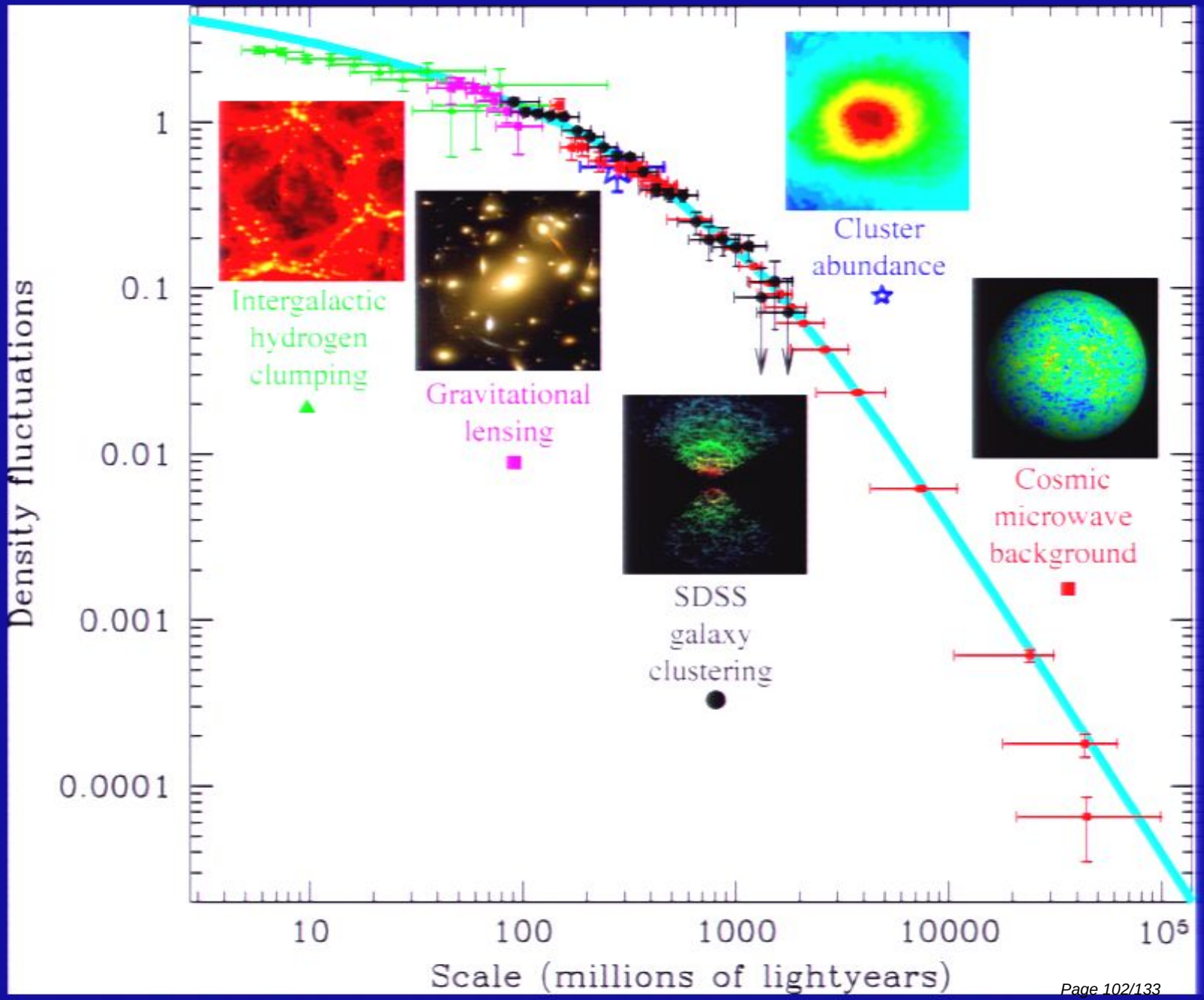

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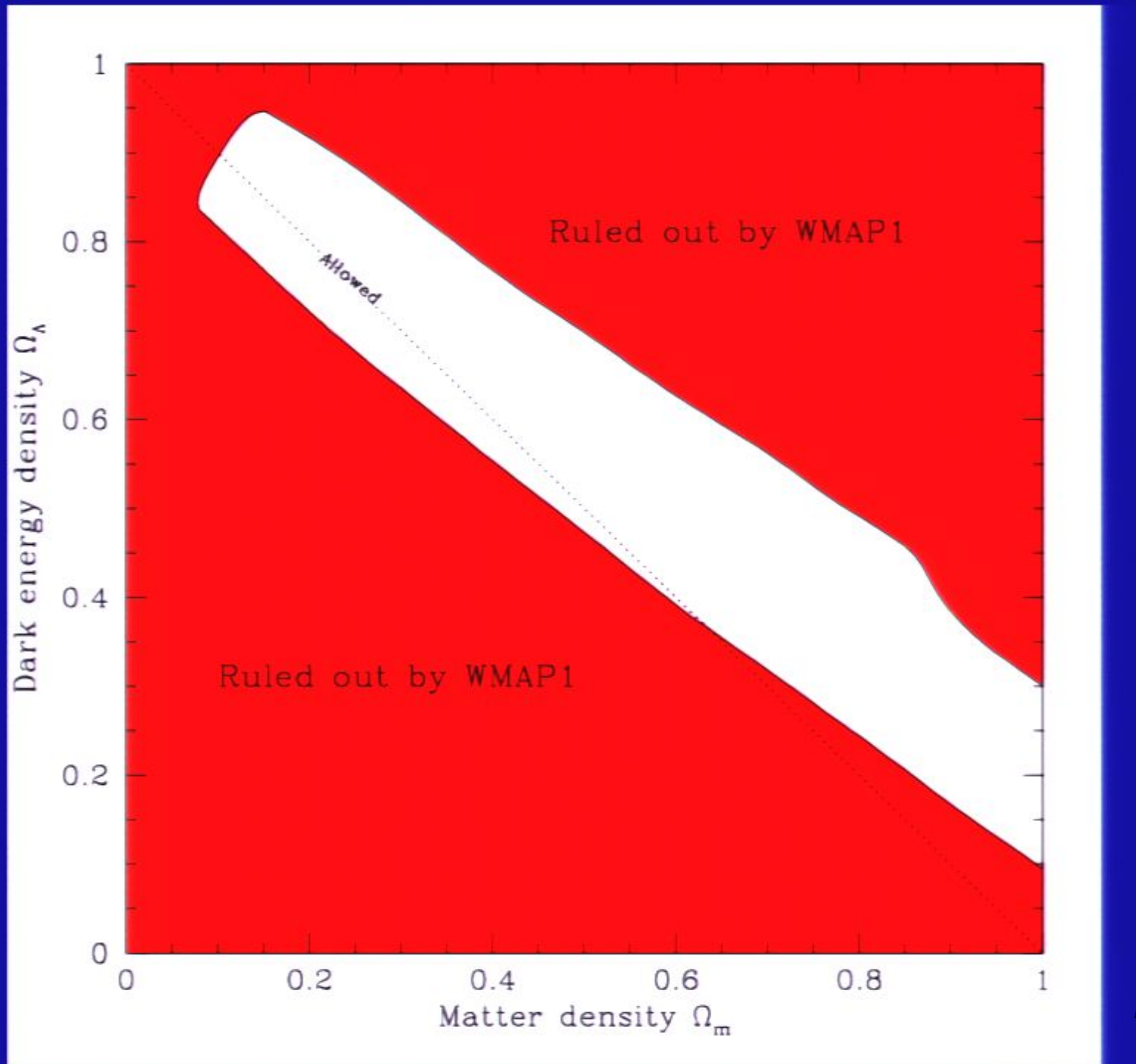
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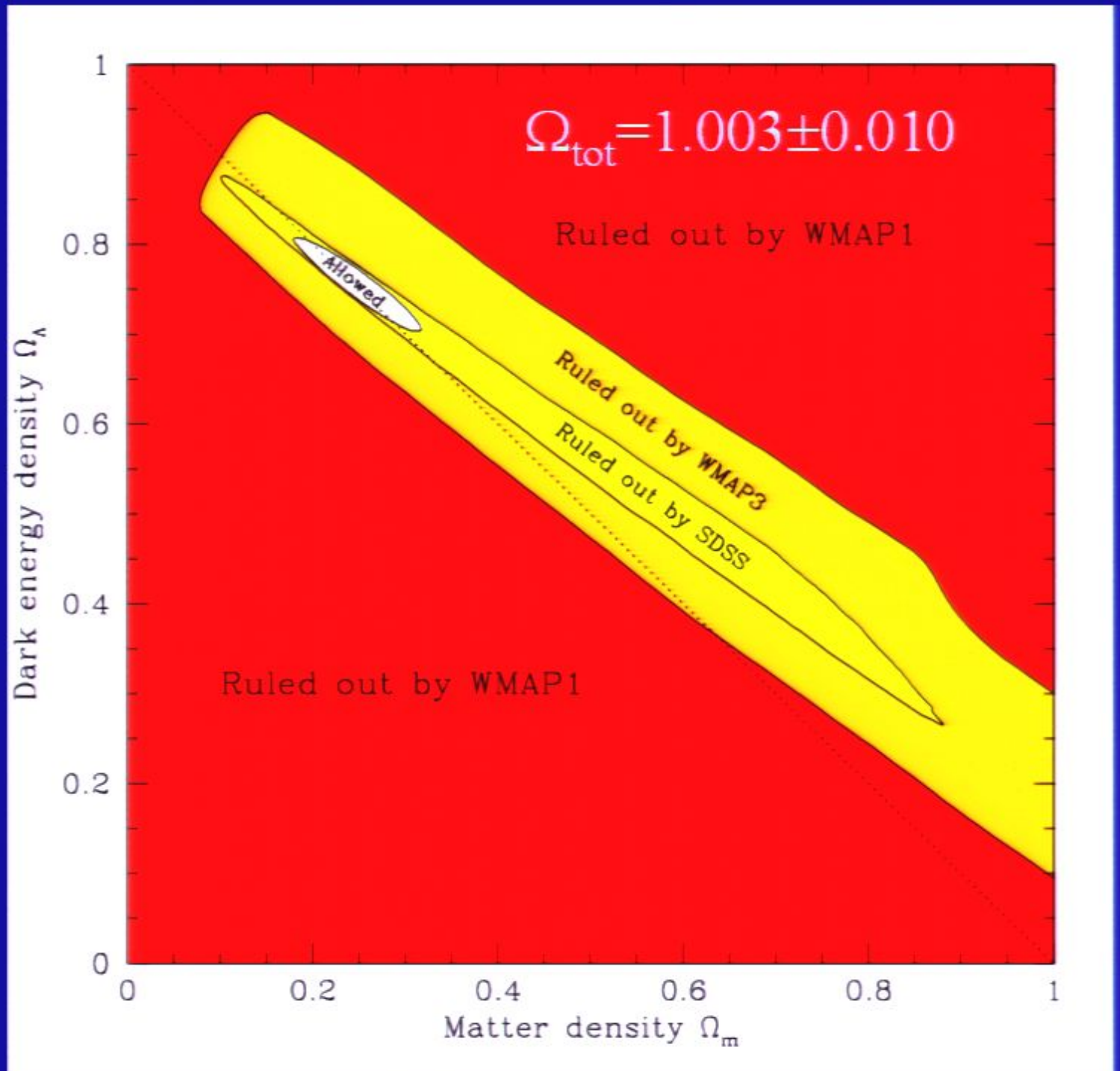
Ω_{tot}=1.003±0.010
Ruled out by WMAP1
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Ruled out by WMAP3
Ruled out by SDSS
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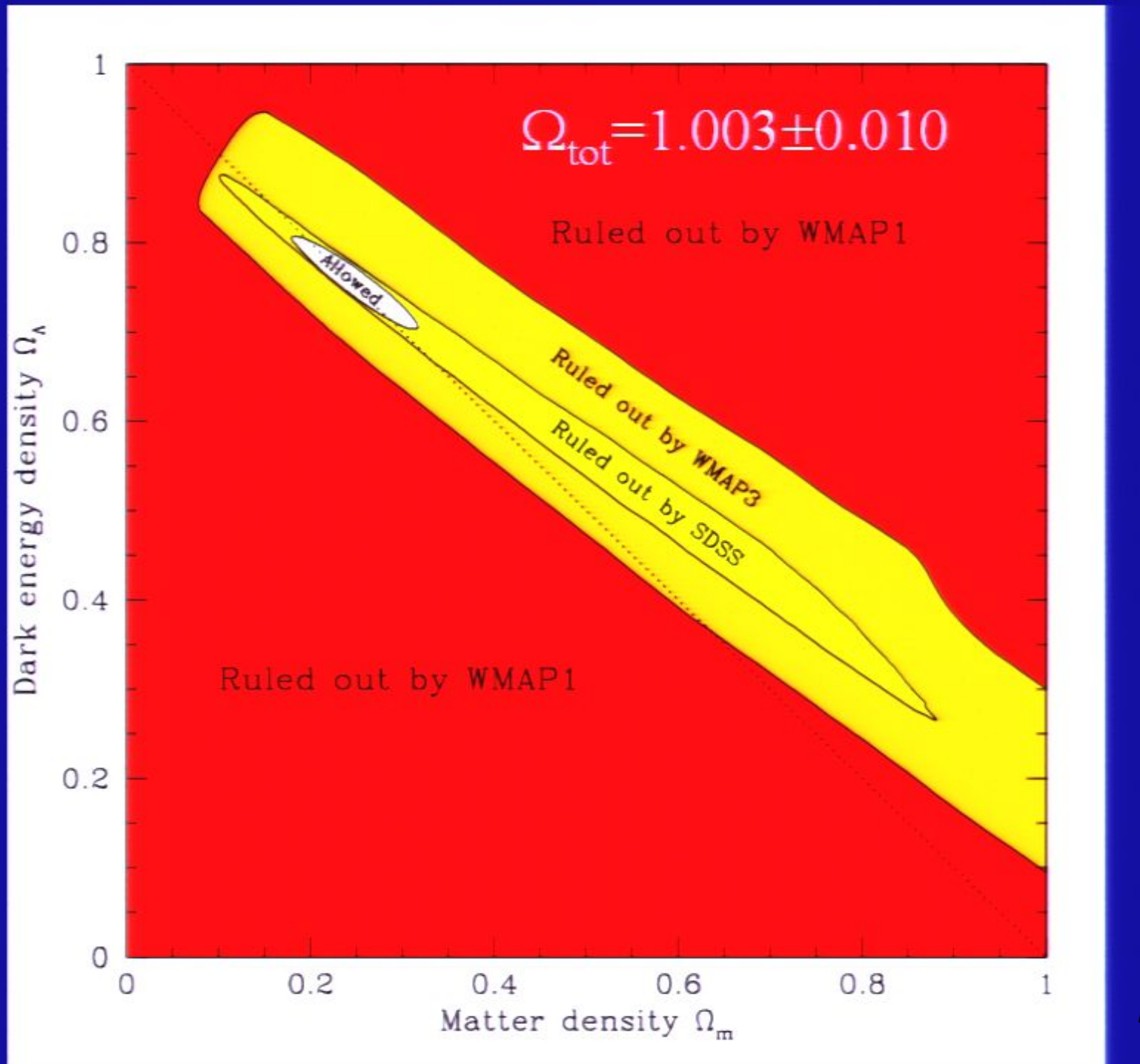
Consistency

- Clusters
  - Agreement amongst methods
  - All require 6-7x more matter than can be accounted for in gas and stars
- Peculiar velocities
- Large-scale structure and the CMB

Require dark matter (20-25%) and dark energy (70-75%) in addition to baryonic matter (~4%)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  - Jupiters
  - Bricks

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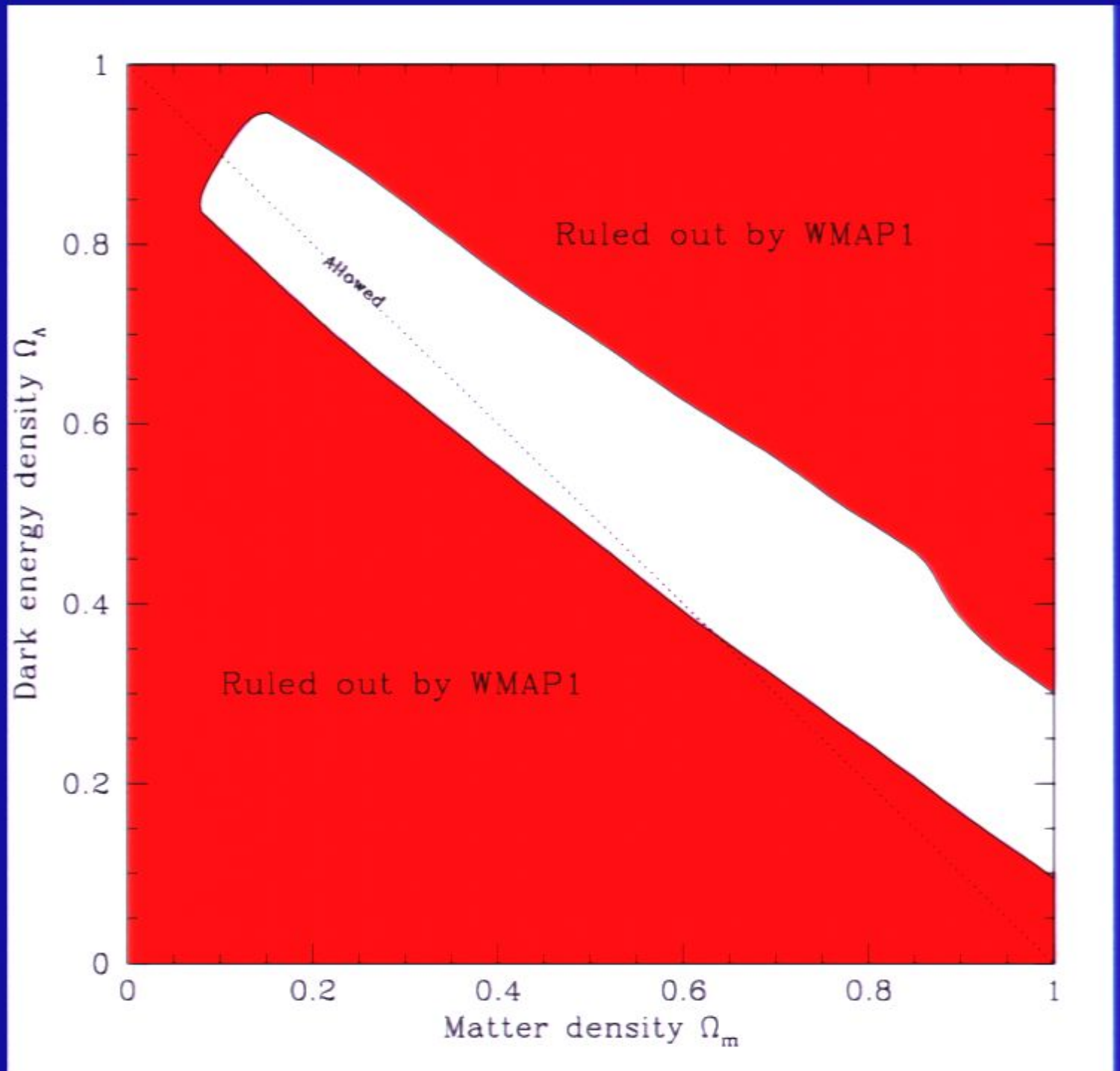
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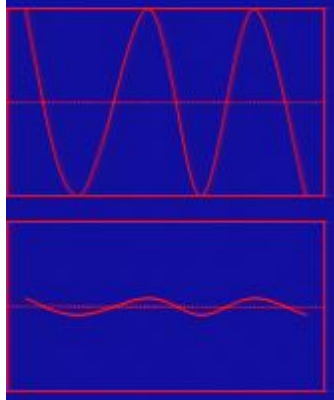

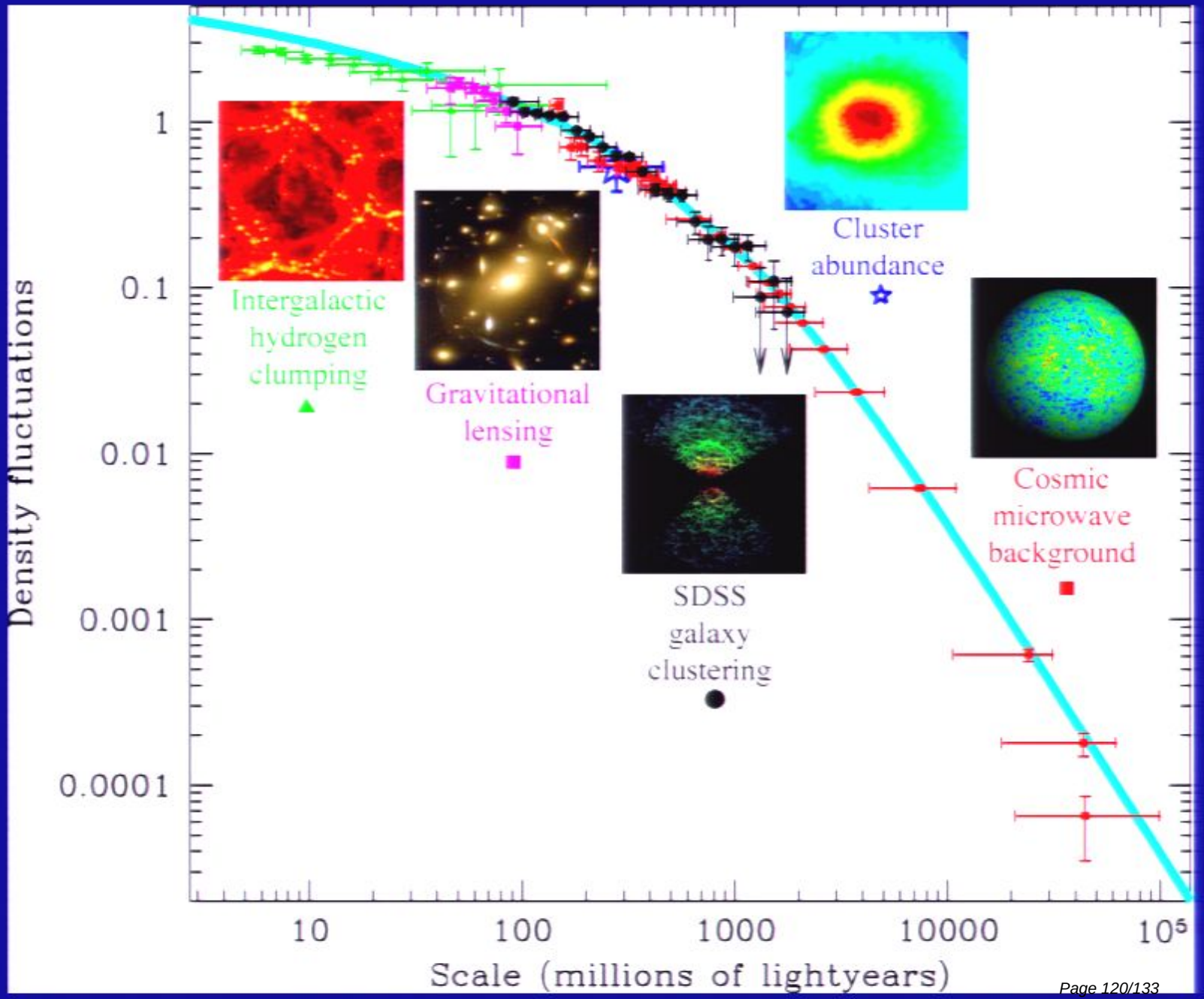

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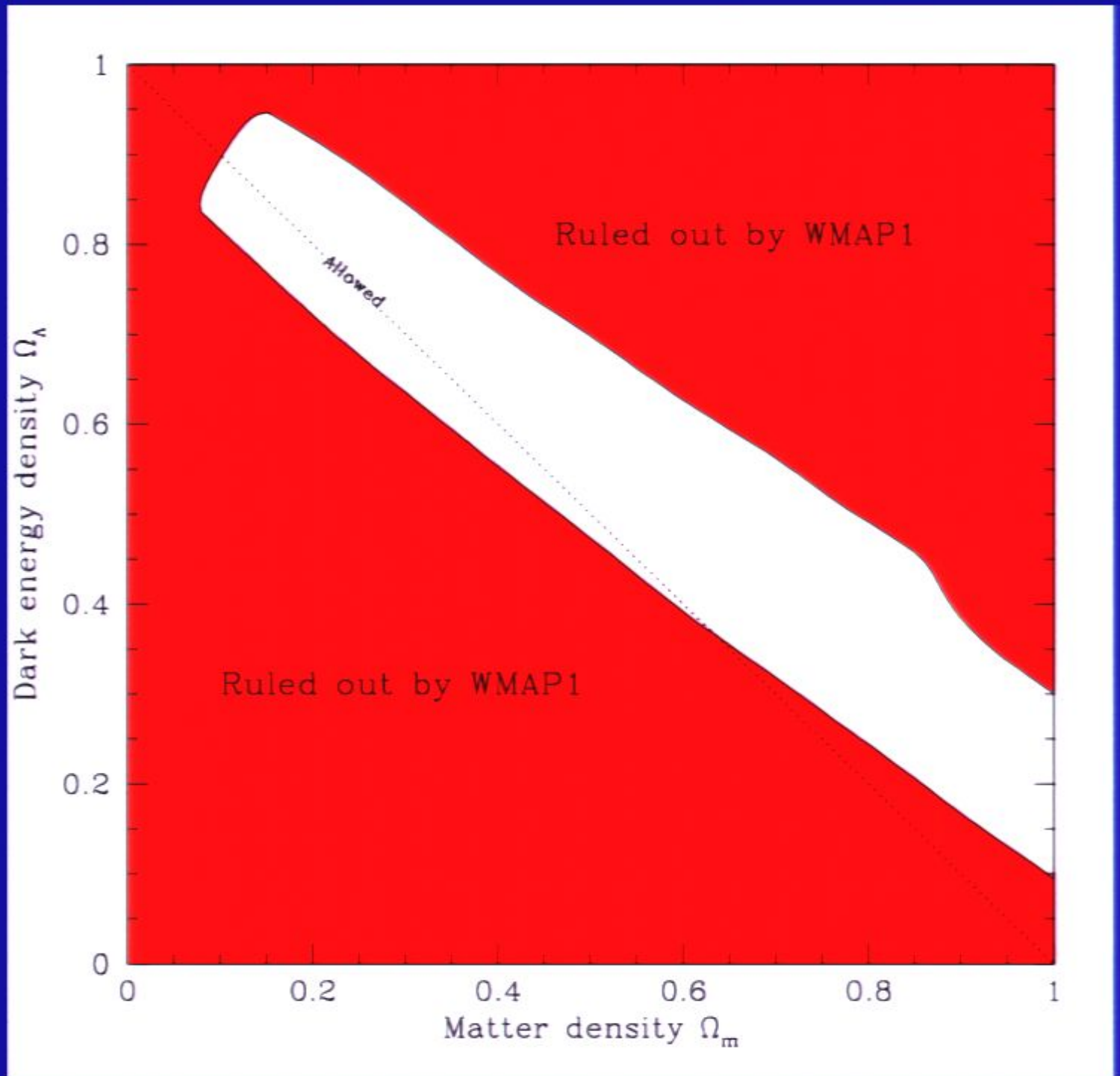
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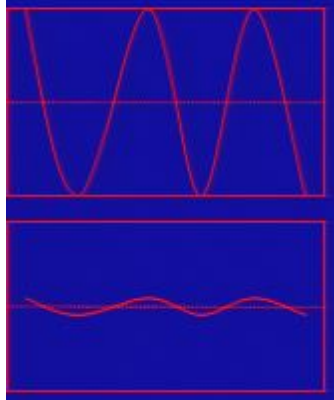

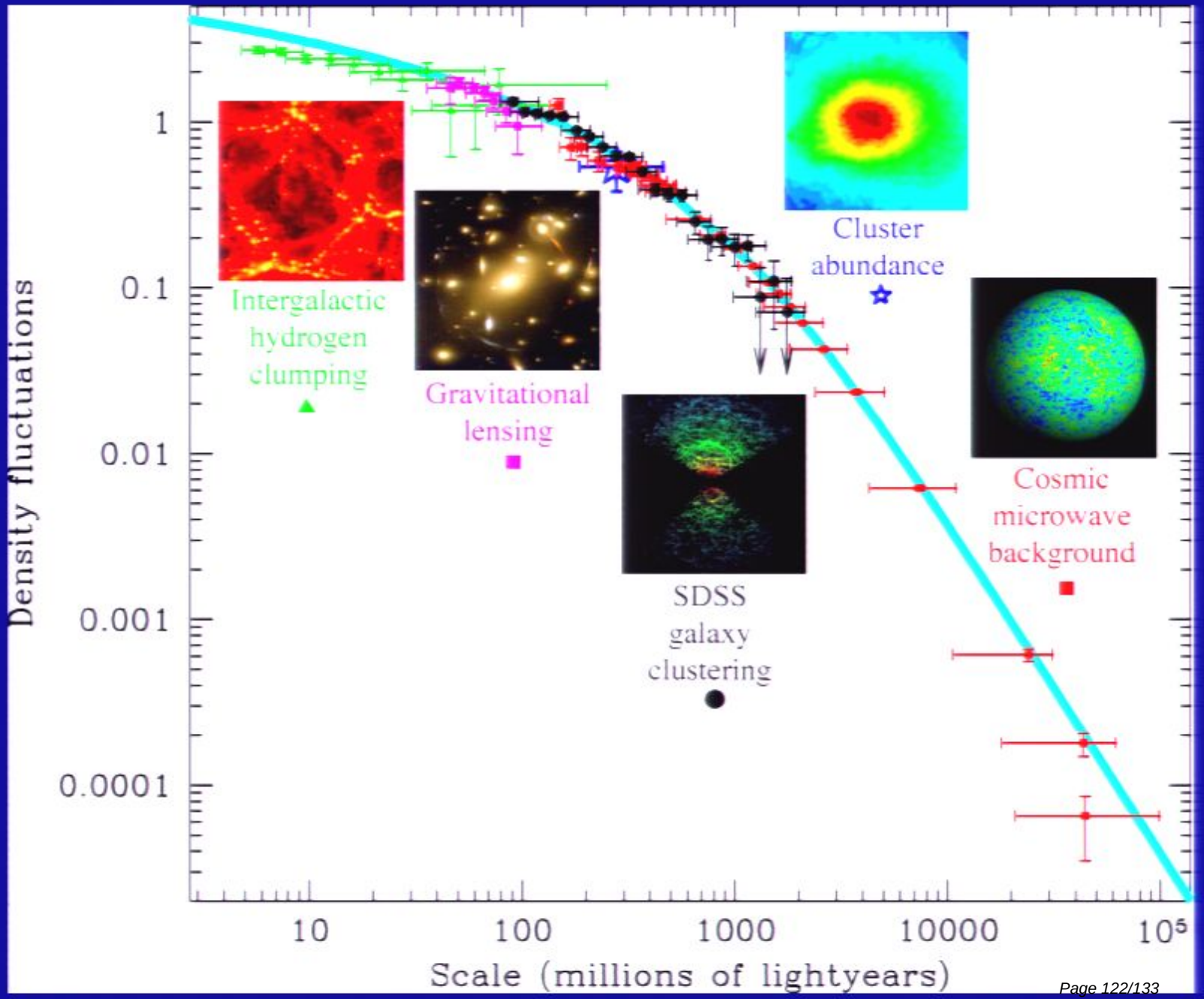

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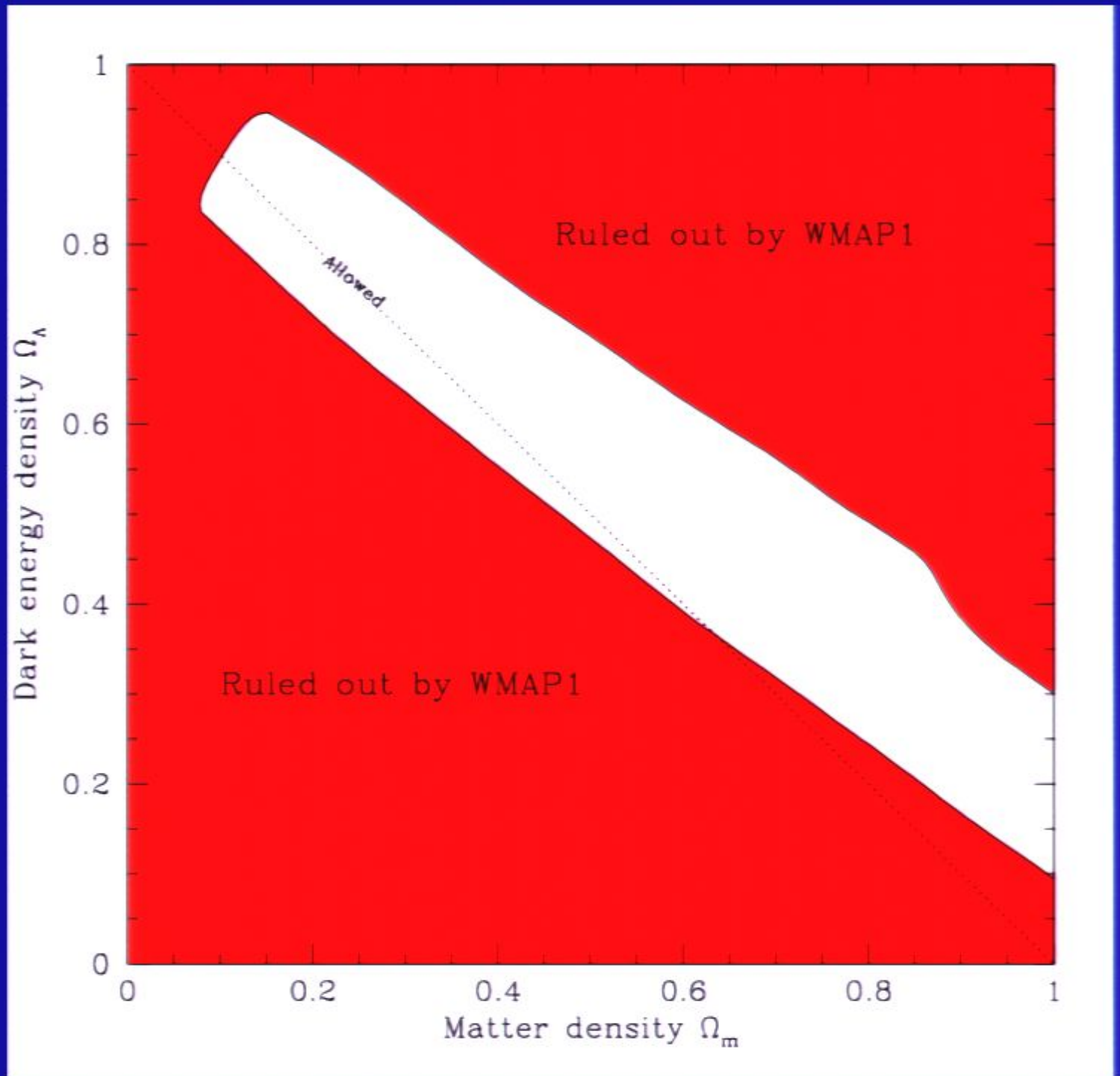
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- Q: What about modified gravity acting on baryons?
- A1: It is in general possible to modify gravity
  - MOND
  - TeVeS
  - etc

to explain individual spherical systems (e.g. galaxy rotation curves) by adjusting one or two parameters.

It is difficult to explain systems (clusters, large-scale structure) with very different masses using the *same* parameters.

A2: "Bullet" Cluster

collisionless
dark matter (blue) (from weak gravitational lensing)

gas (pink) (from X-ray emission)

collisionless
stars (yellow)

- The End