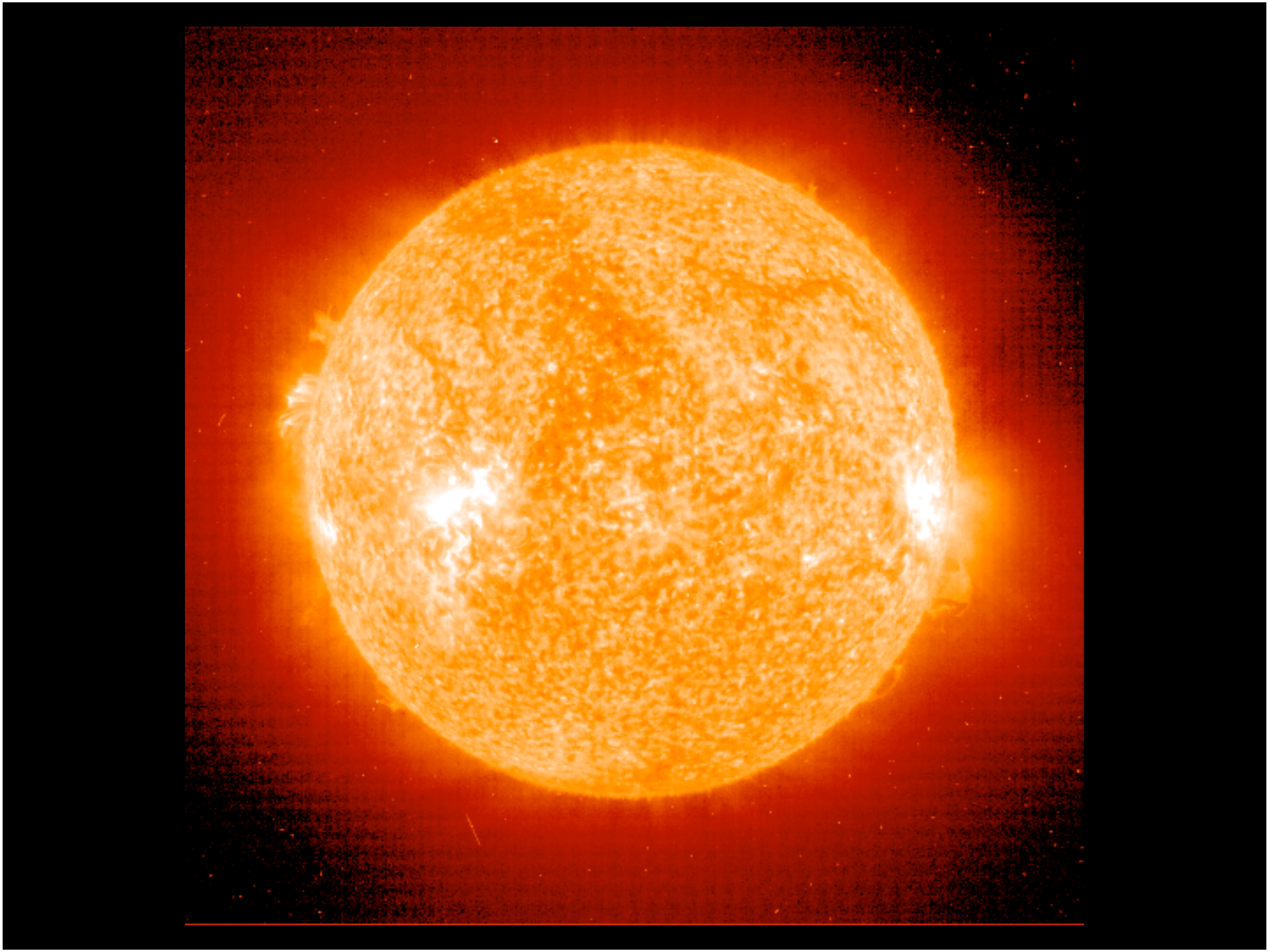
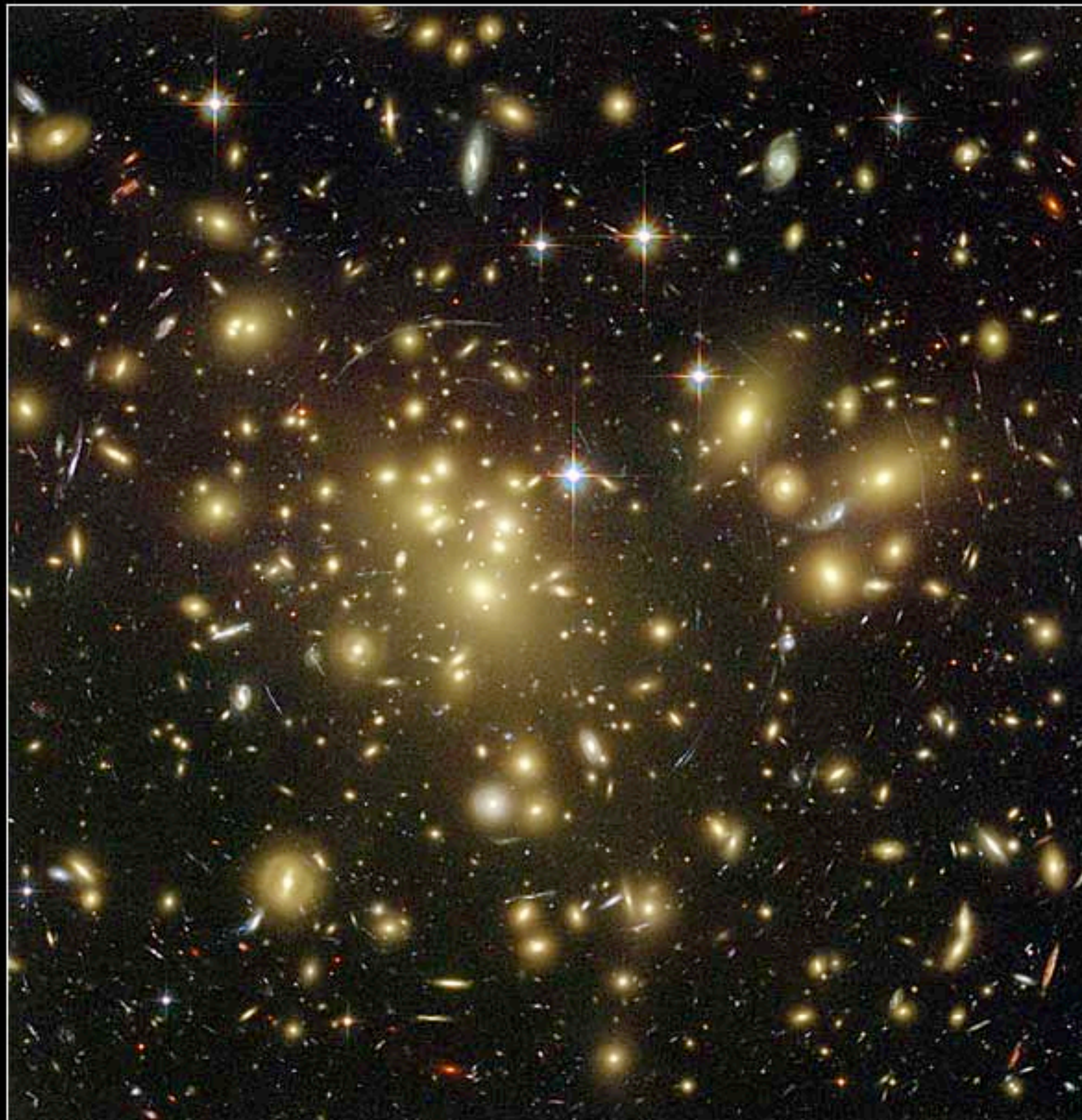
What is the Universe made of?

Dude – where’s my cosmos?



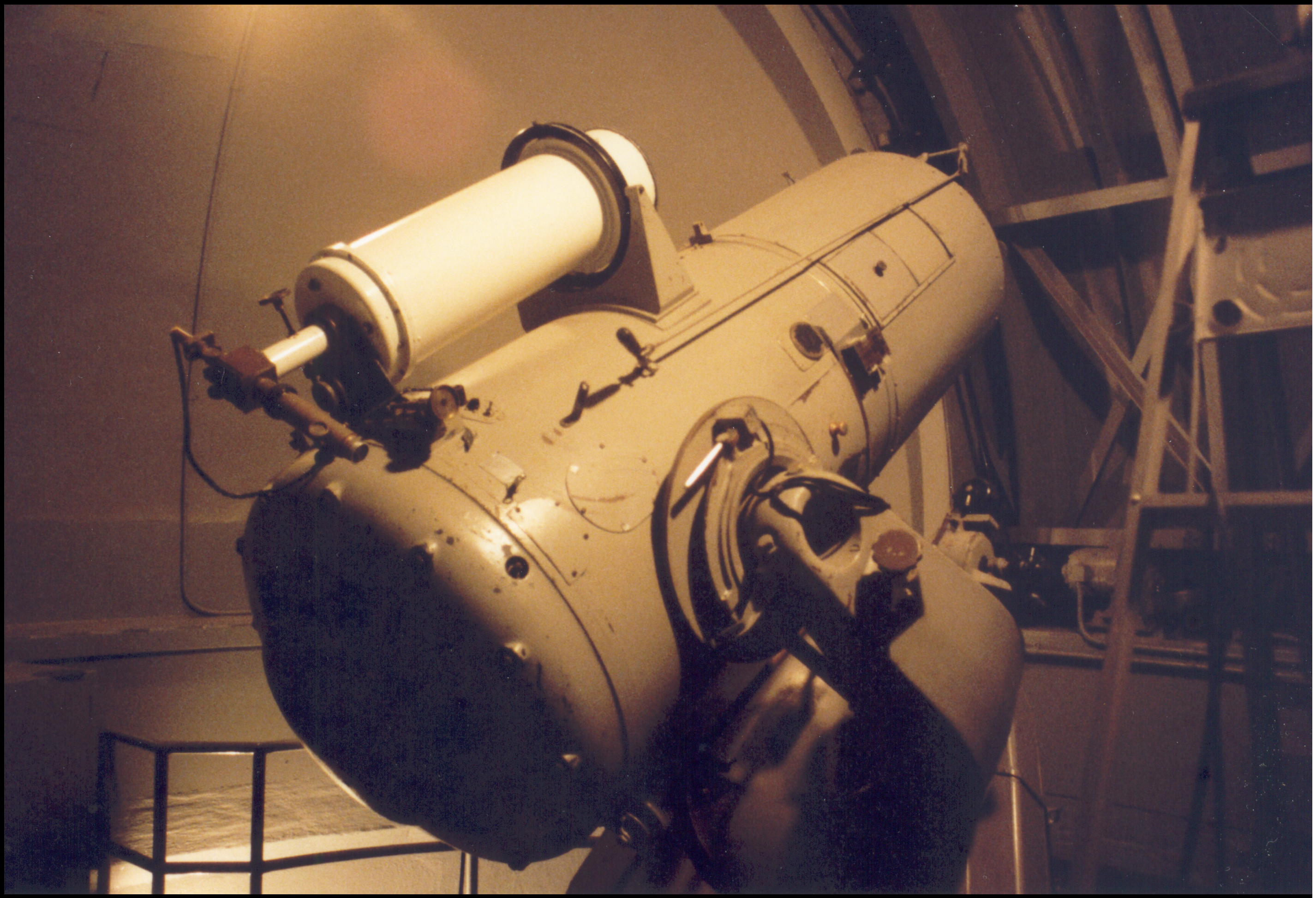
Cecilia Payne-Gaposchkin – stars are mostly hydrogen

Galaxy Cluster Abell 1689 **HST ▪ ACS**



NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

STScI-PRC03-01a



Fritz Zwicky – galaxies have dark matter.
Gravitational lensing happens among galaxies.
Other astronomers are stupid.

THE ASTROPHYSICAL JOURNAL

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ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

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.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

Combining (33) and (34), we find

$$\mathscr{M} > 9 \times 10^{46}\,\text{gr}\,. \tag{35}$$

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

$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_{\odot}\,. \tag{36}$$

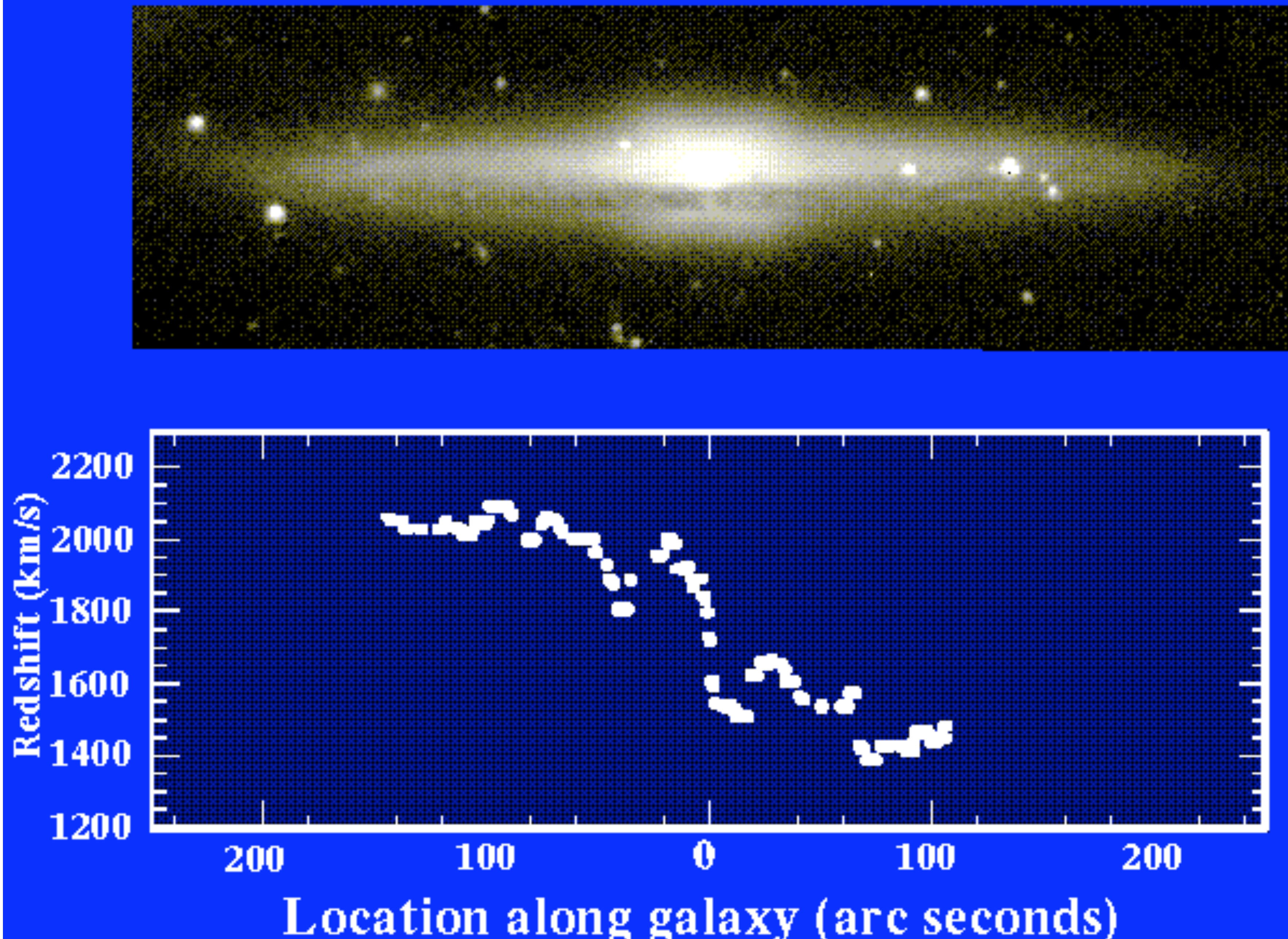
Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view 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

$$\gamma = 500\,, \tag{37}$$

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]

Vera Rubin – flat rotation curves are universal among spiral galaxies. This requires huge masses and extended structure.

NGC 5746


2200
2000
1800
1600
1400
1200
Redshift (km/s)
200
100
0
100
200
Location along galaxy (arc seconds)

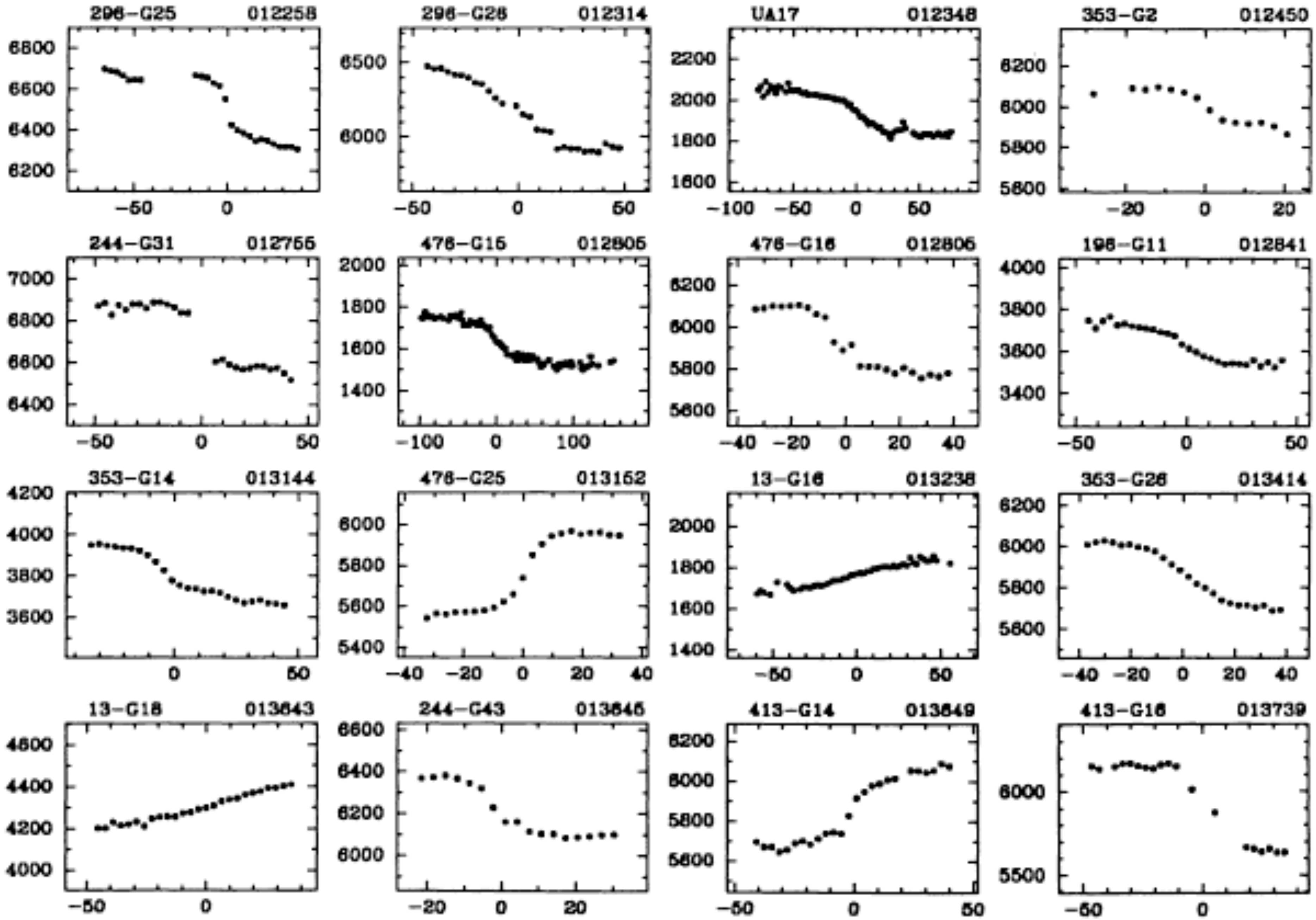
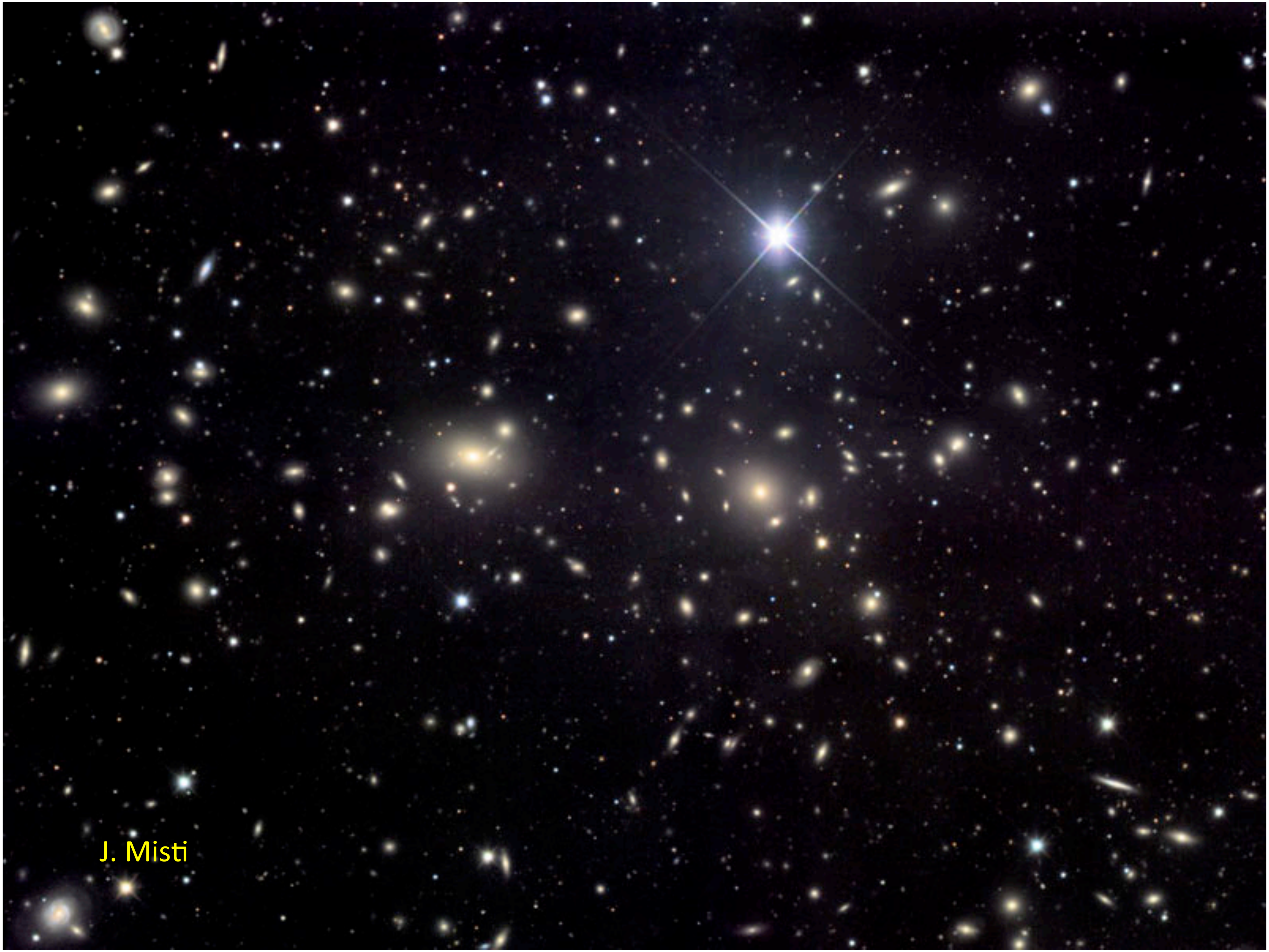
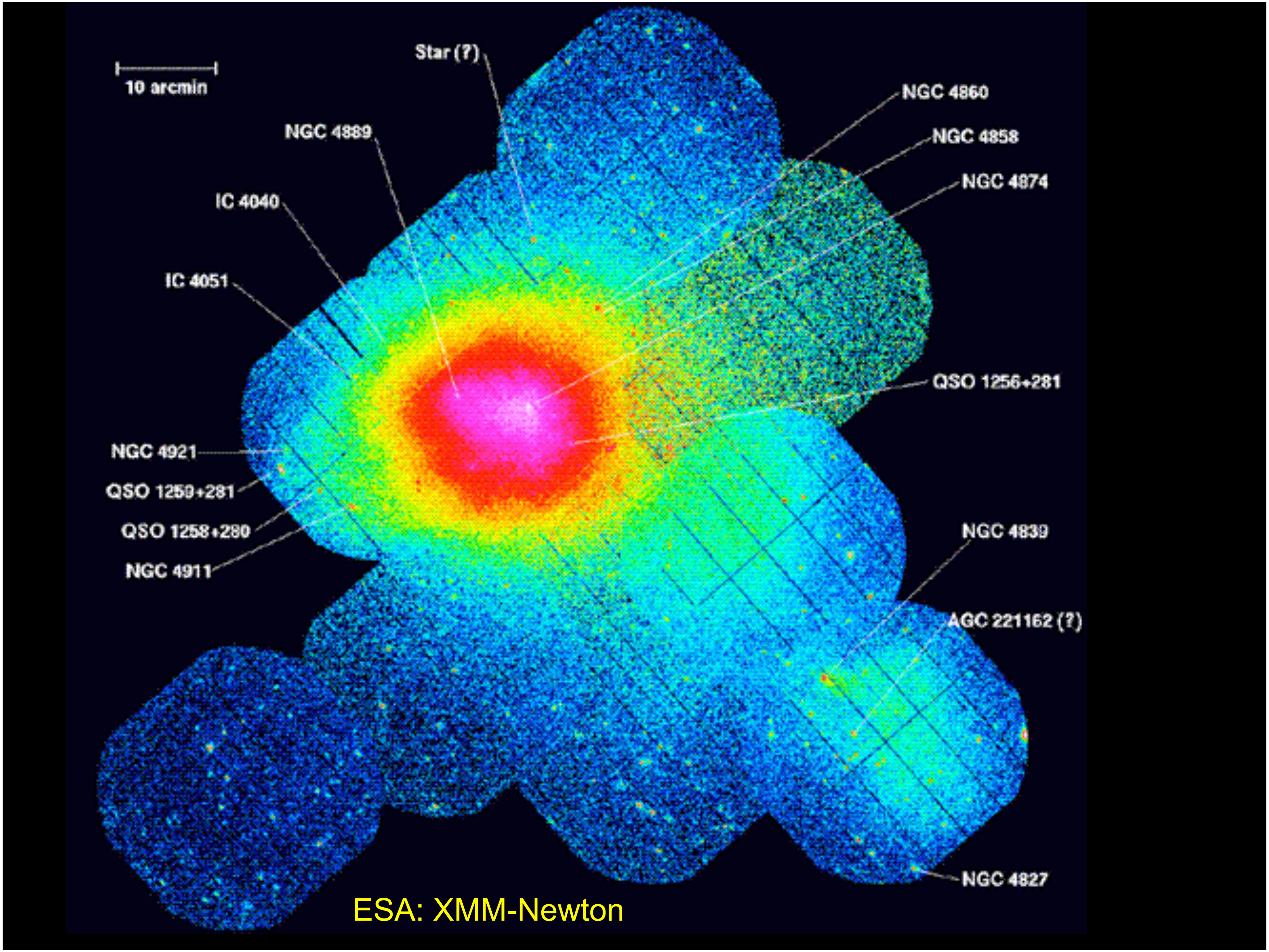
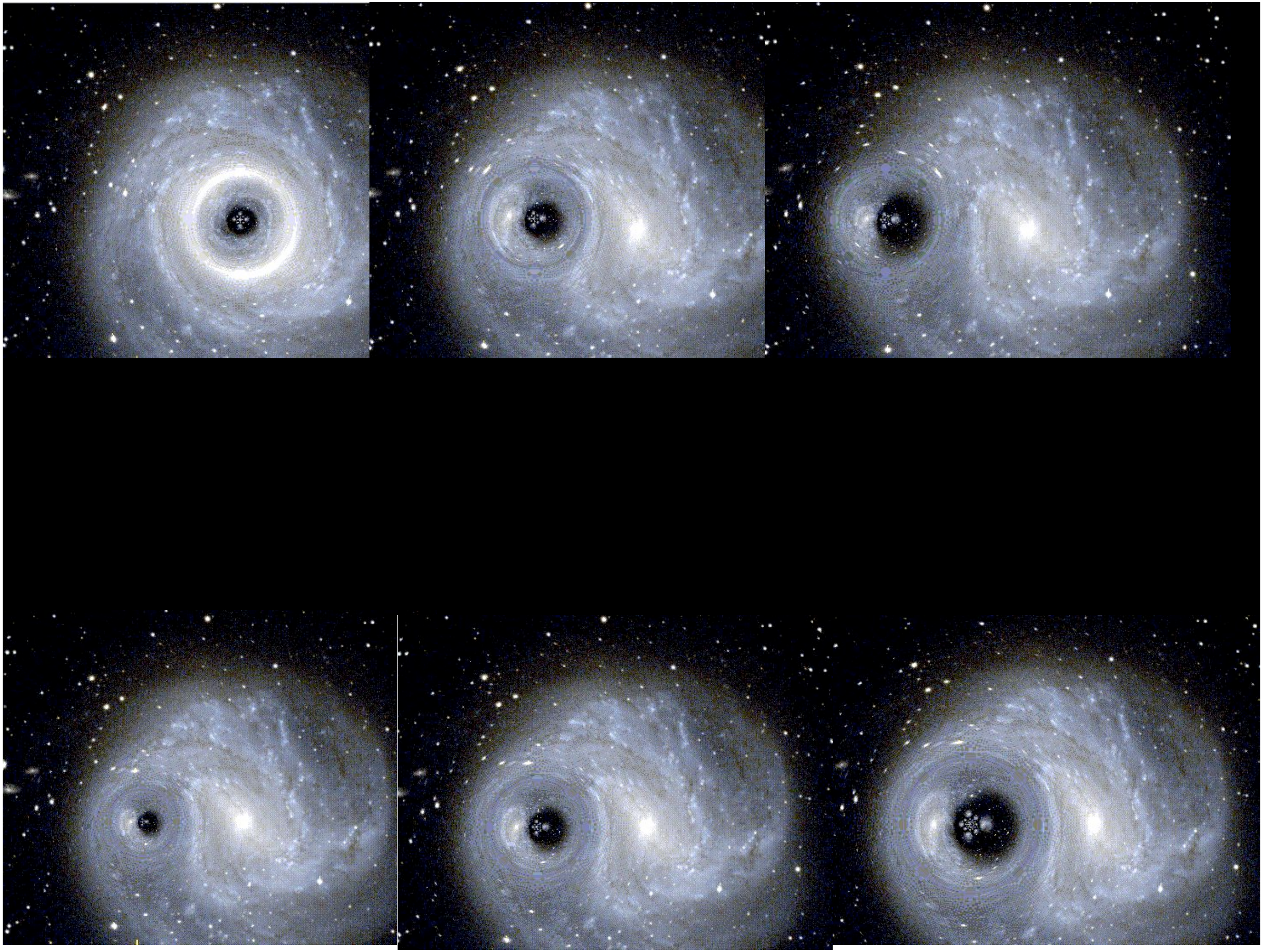


FIG. 2.—Continued.

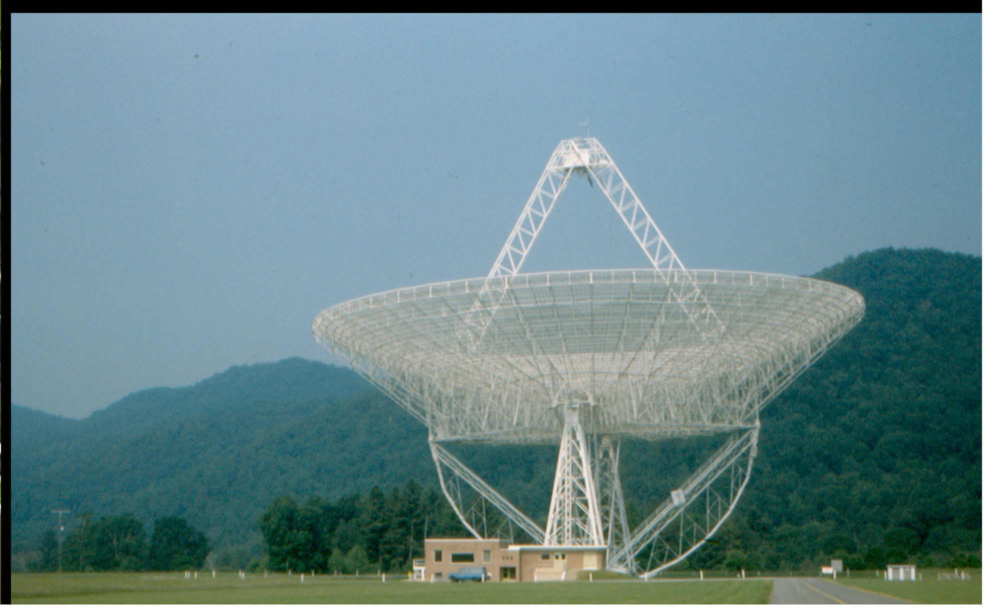

J. Misti

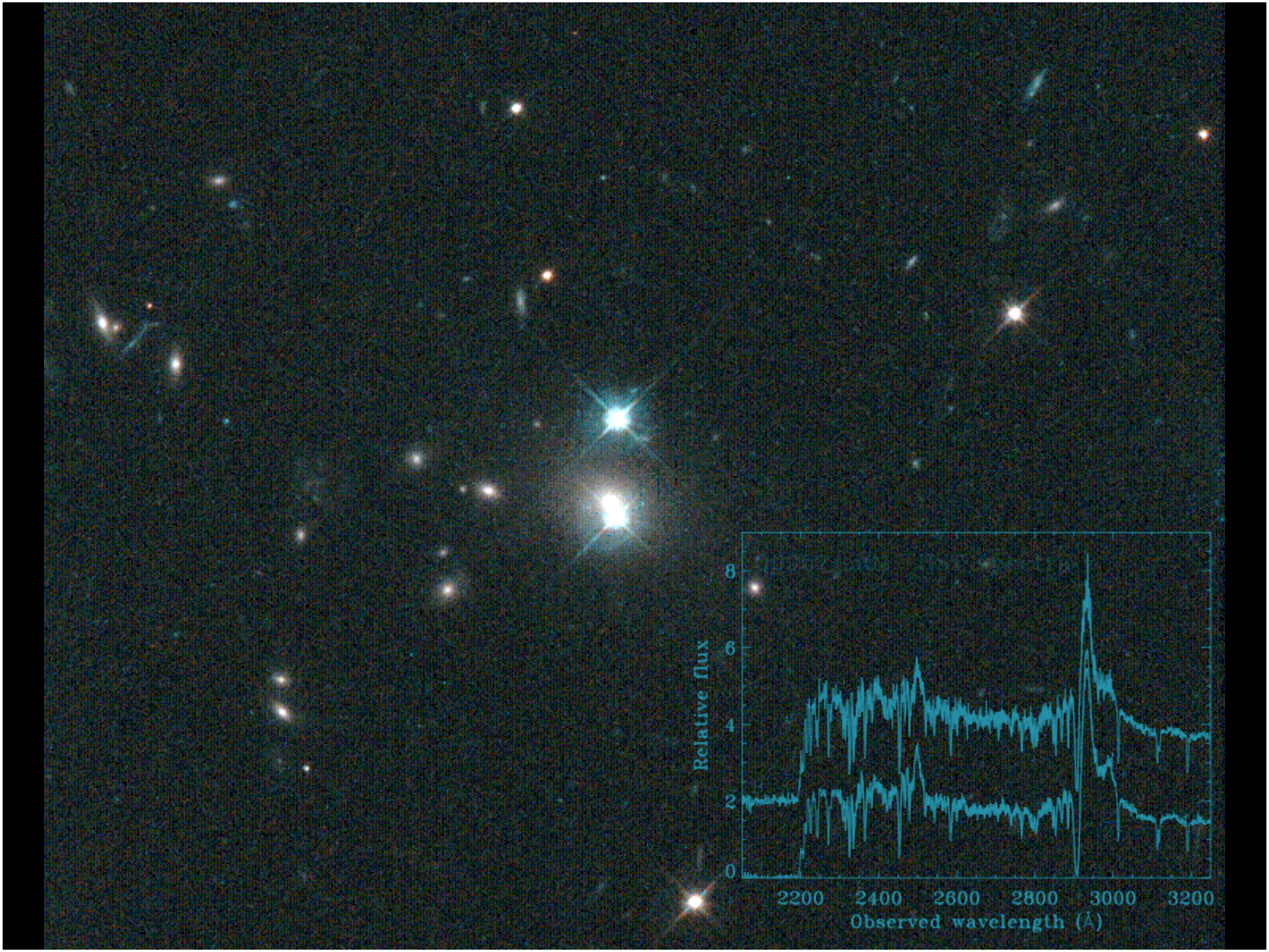

10 arcmin
Star (?)
NGC 4860
NGC 4858
NGC 4874
NGC 4889
IC 4040
IC 4051
QSO 1256+281
NGC 4921
QSO 1259+281
QSO 1258+280
NGC 4911
NGC 4839
AGC 221162 (?)
NGC 4827
ESA: XMM-Newton

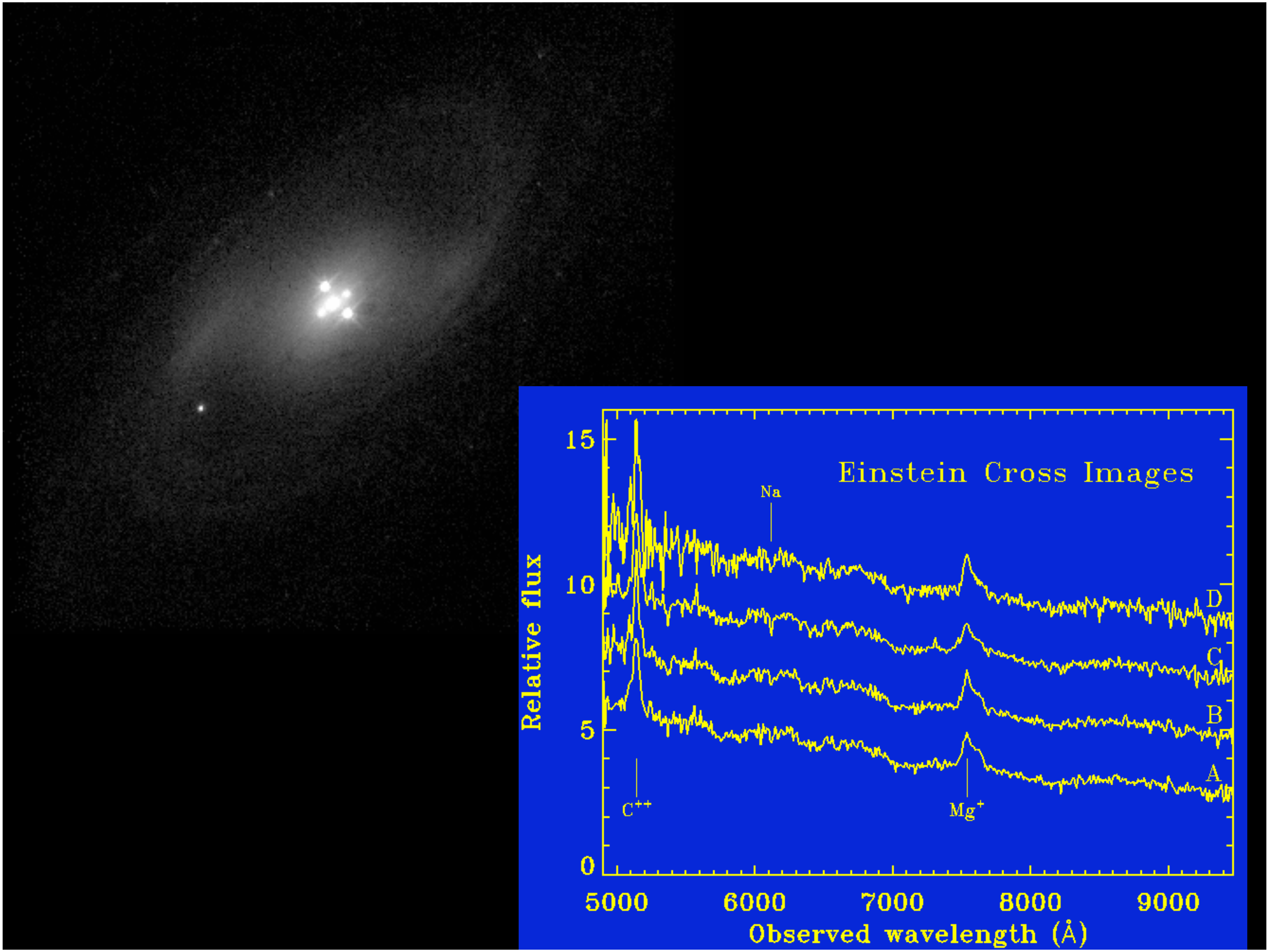

May 6 1921

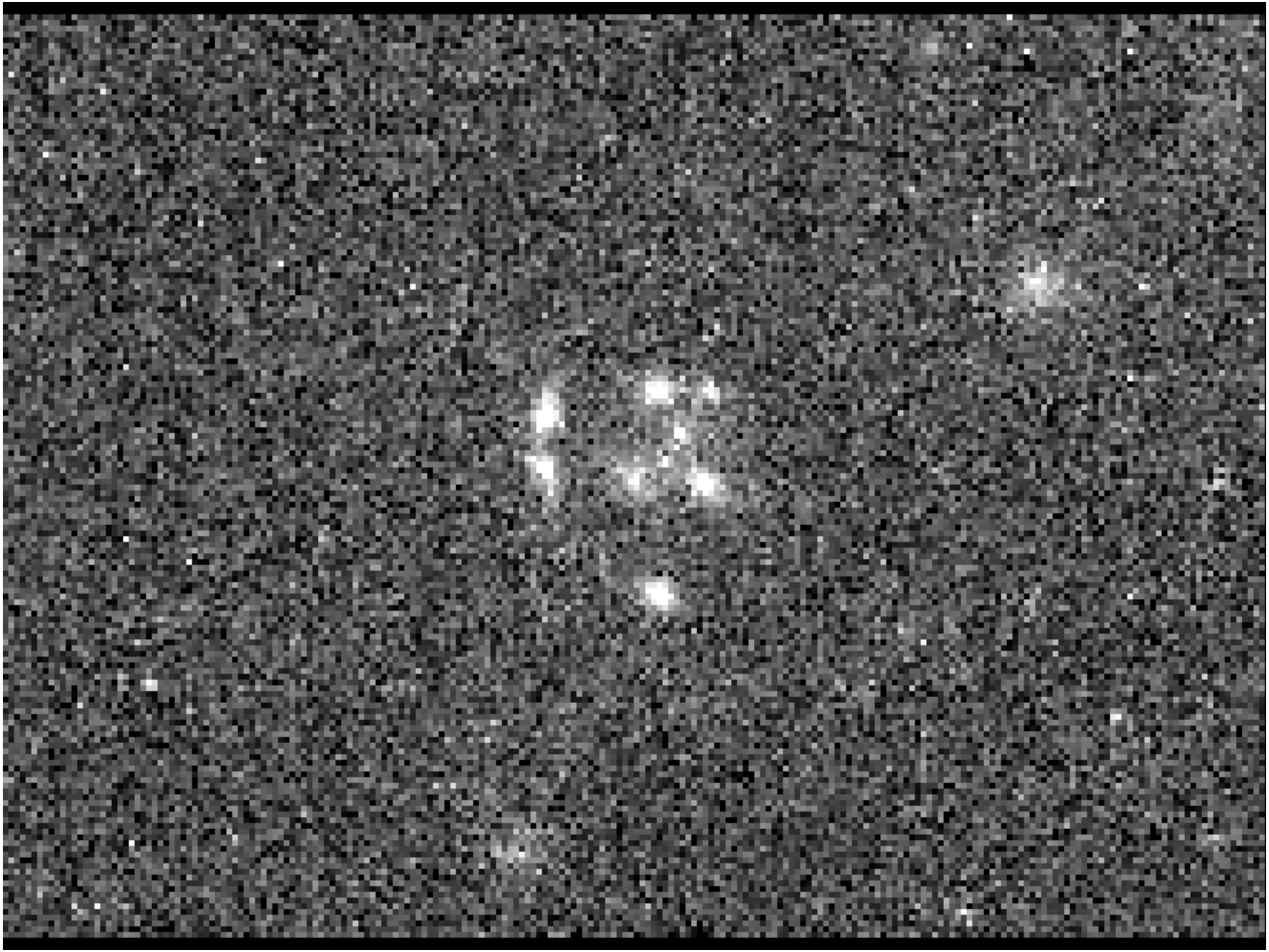


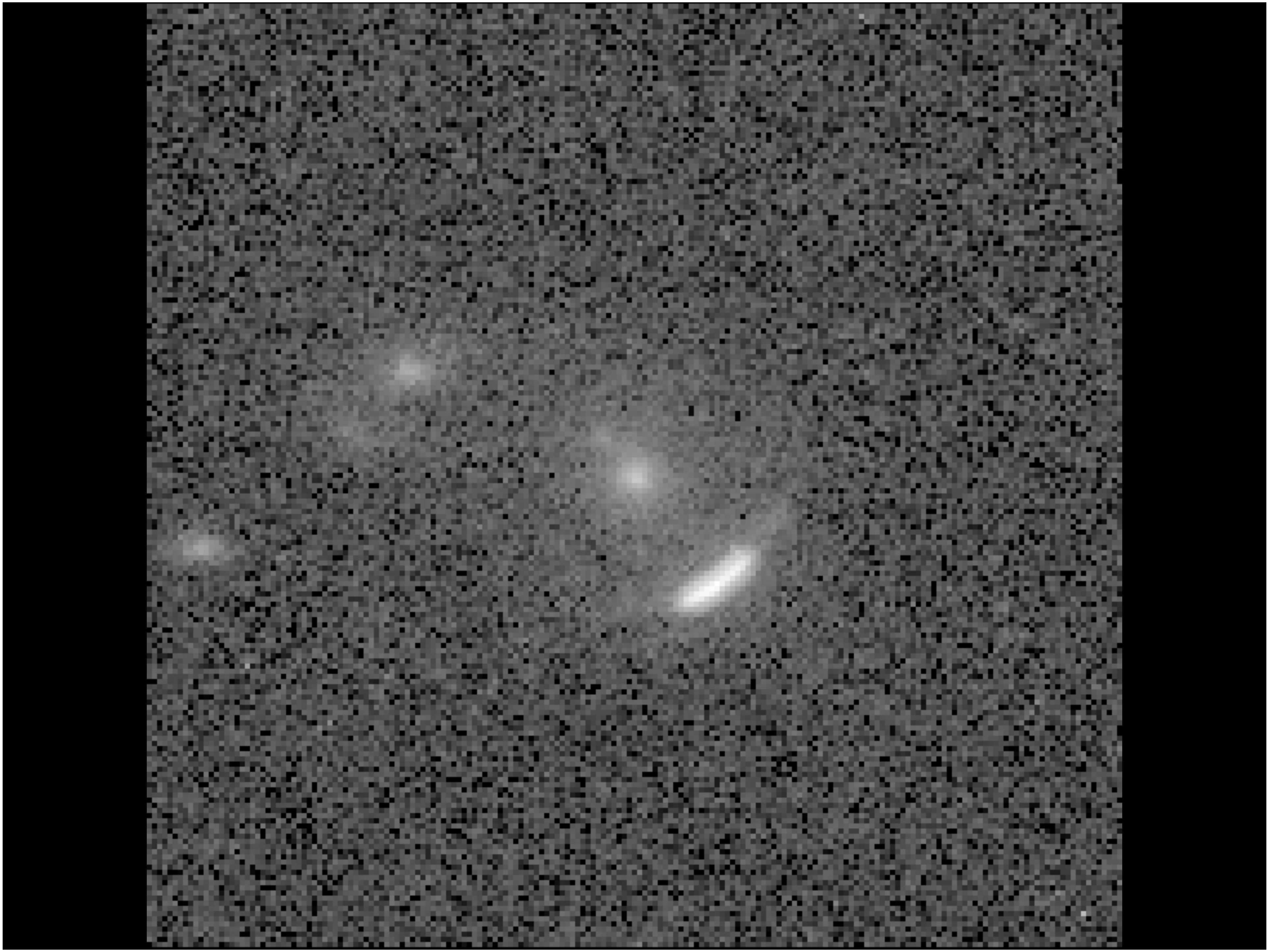


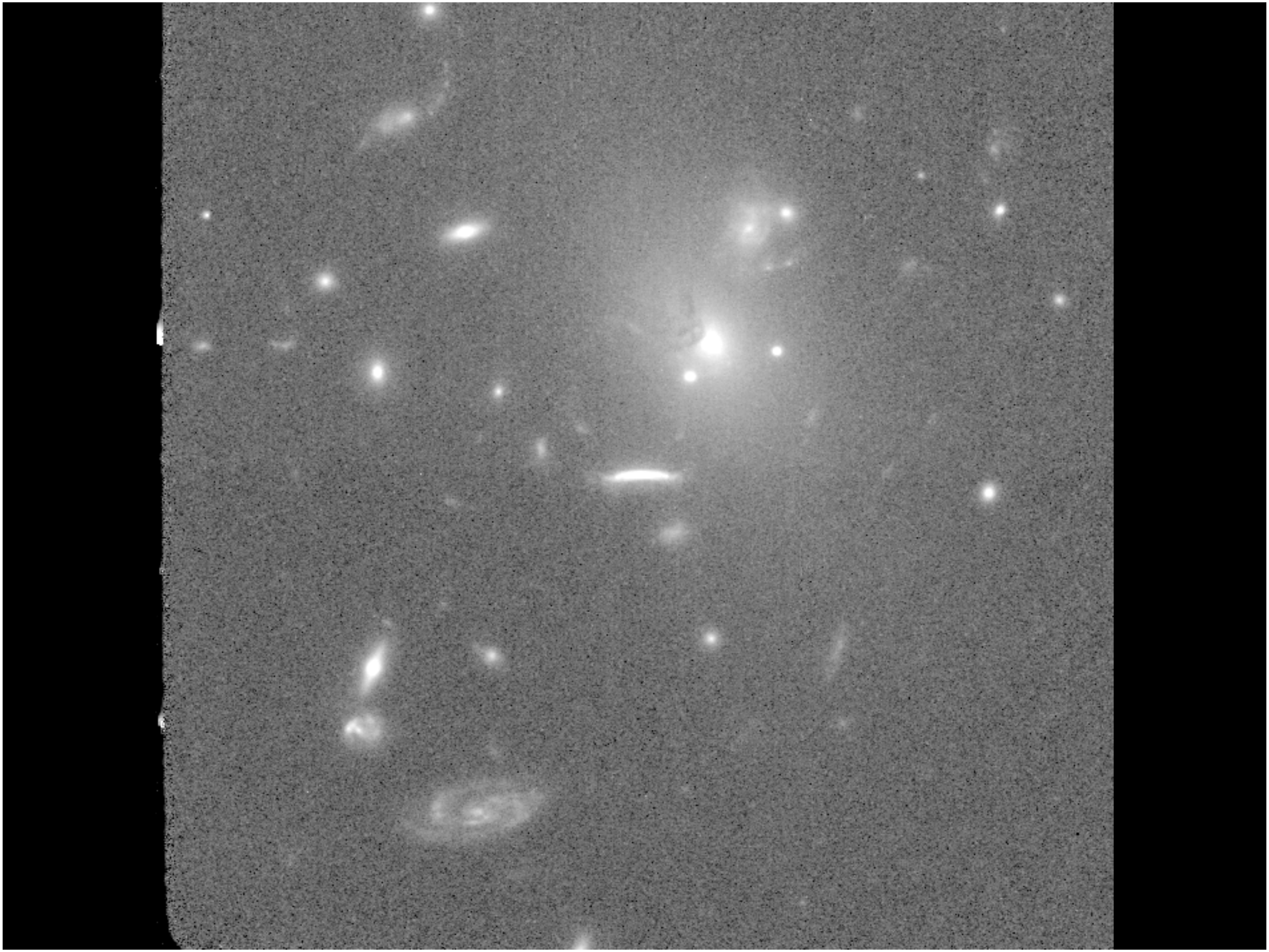



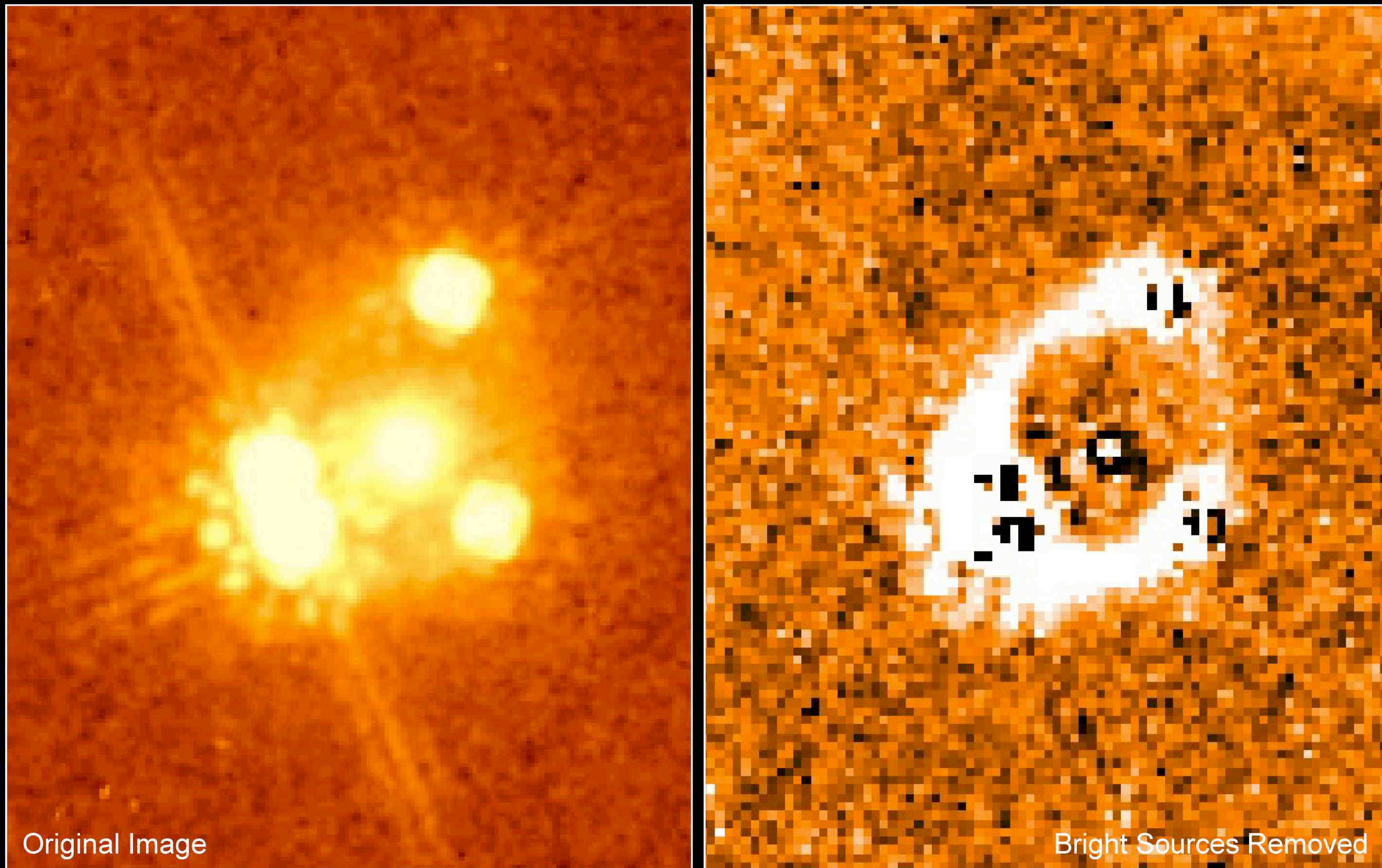

Relative flux
0
2
4
6
8
2200
2400
2600
2800
3000
3200
Observed wavelength (Å)


Einstein Cross Images
Na
C++
Mg+
D
C
B
A
Relative flux
15
10
5
0
5000
6000
7000
8000
9000
Observed wavelength (Å)









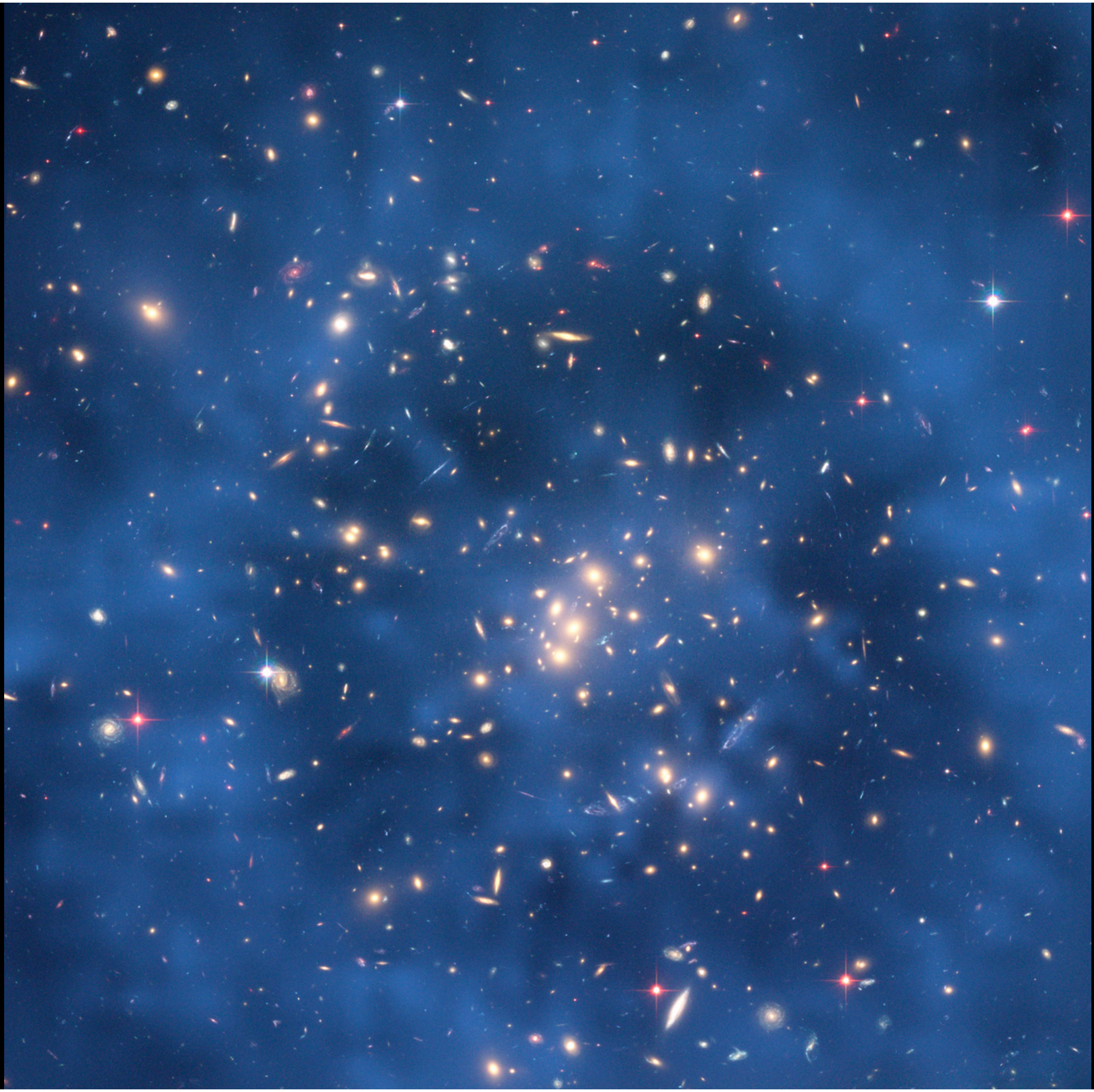
Gravitational Lens and Quasar PG 1115+080

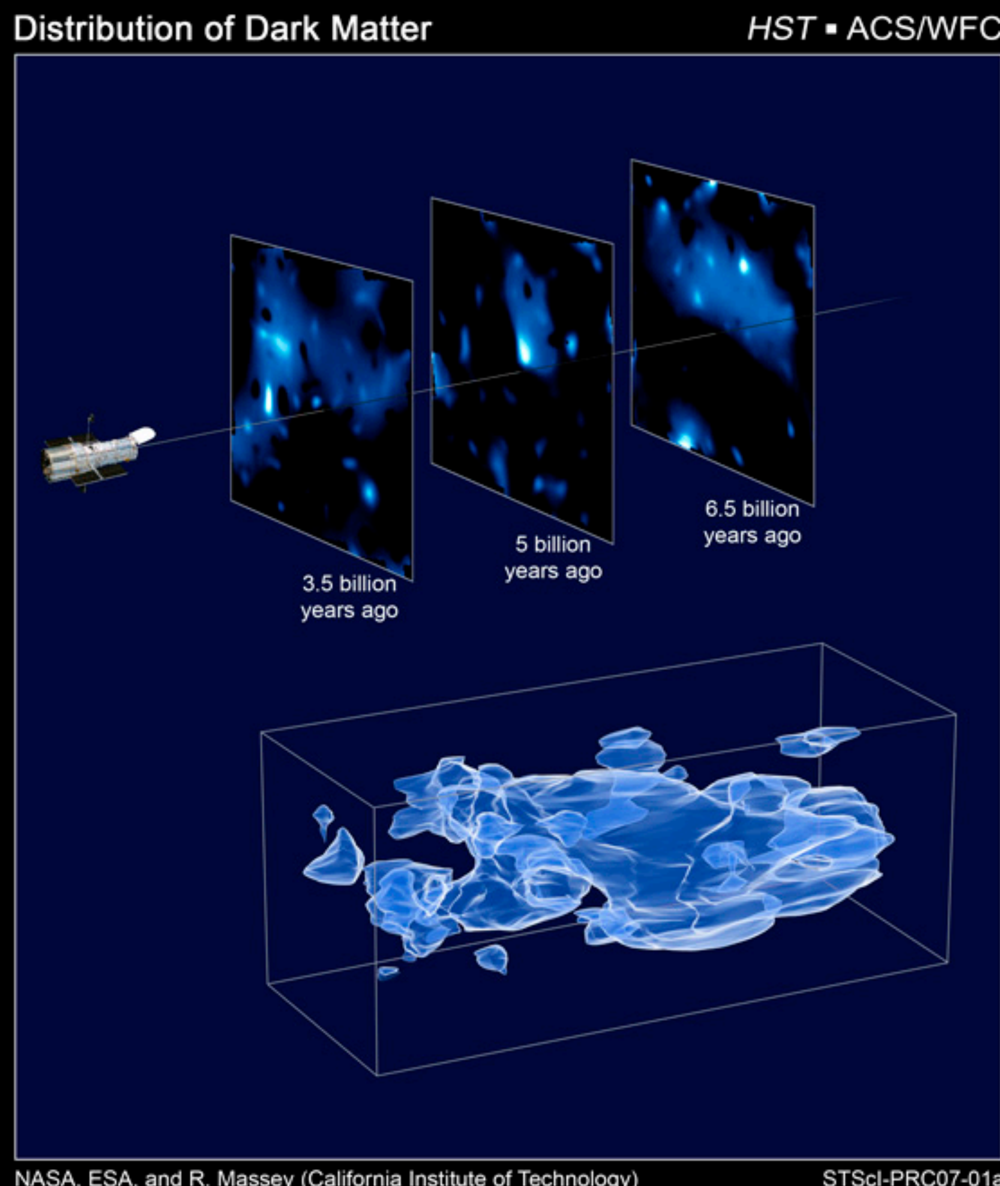
Hubble Space Telescope • NICMOS

PRC98-37 • STScI OPO • C. Impey (University of Arizona) and NASA

Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope • WFPC2

PRC96-10 • ST ScI OPO • April 24, 1996 • W. Colley (Princeton Univ.), NASA




Distribution of Dark Matter
HST ▪ ACS/WFC
3.5 billion
years ago
5 billion
years ago
6.5 billion
years ago
NASA, ESA, and R. Massey (California Institute of Technology)
STScI-PRC07-01a

What is all this stuff???

Ordinary matter?

Brown dwarfs?

Cold gas?

Hot gas?

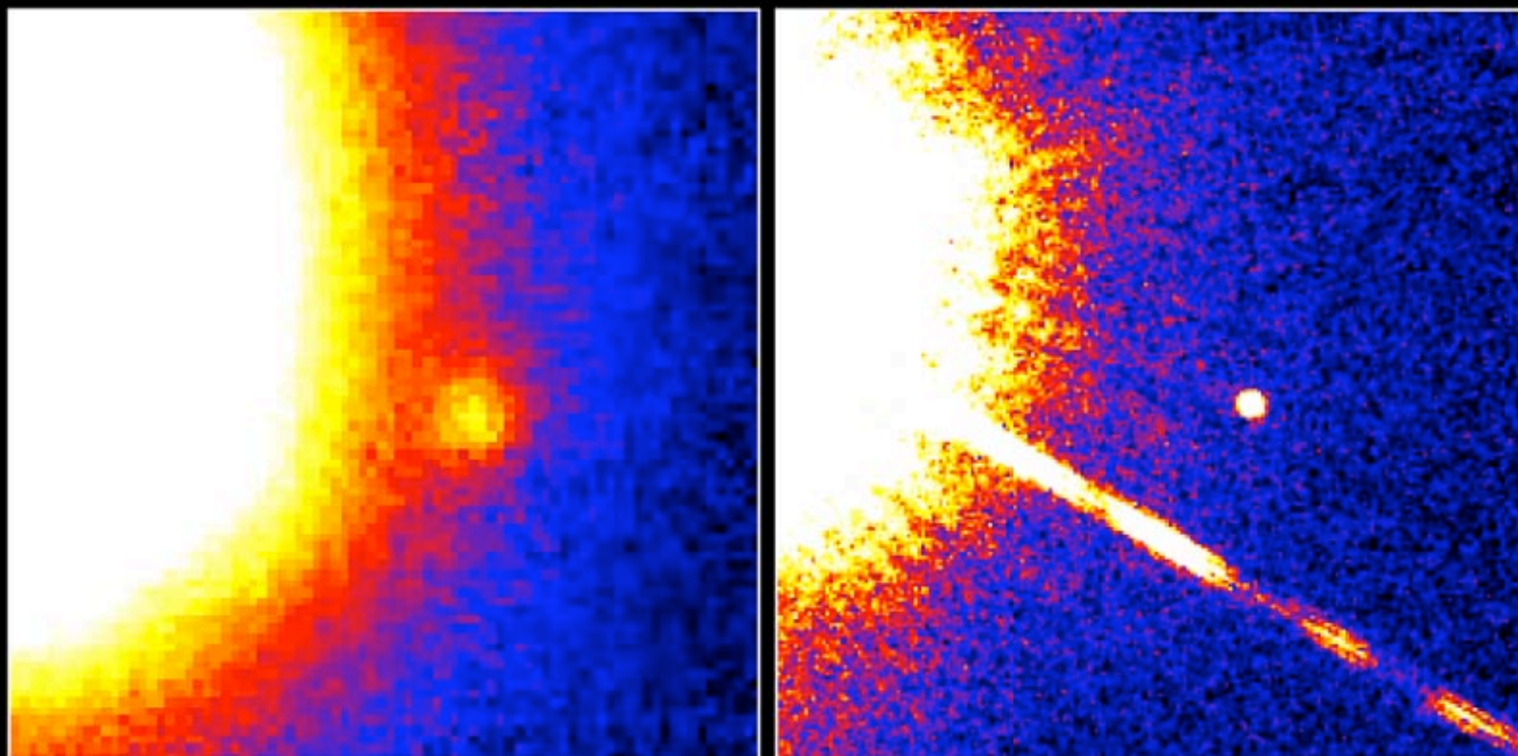
Black holes?

Exotic elementary particles?

WIMPS? MACHOS?

Misunderstanding large-scale gravity?

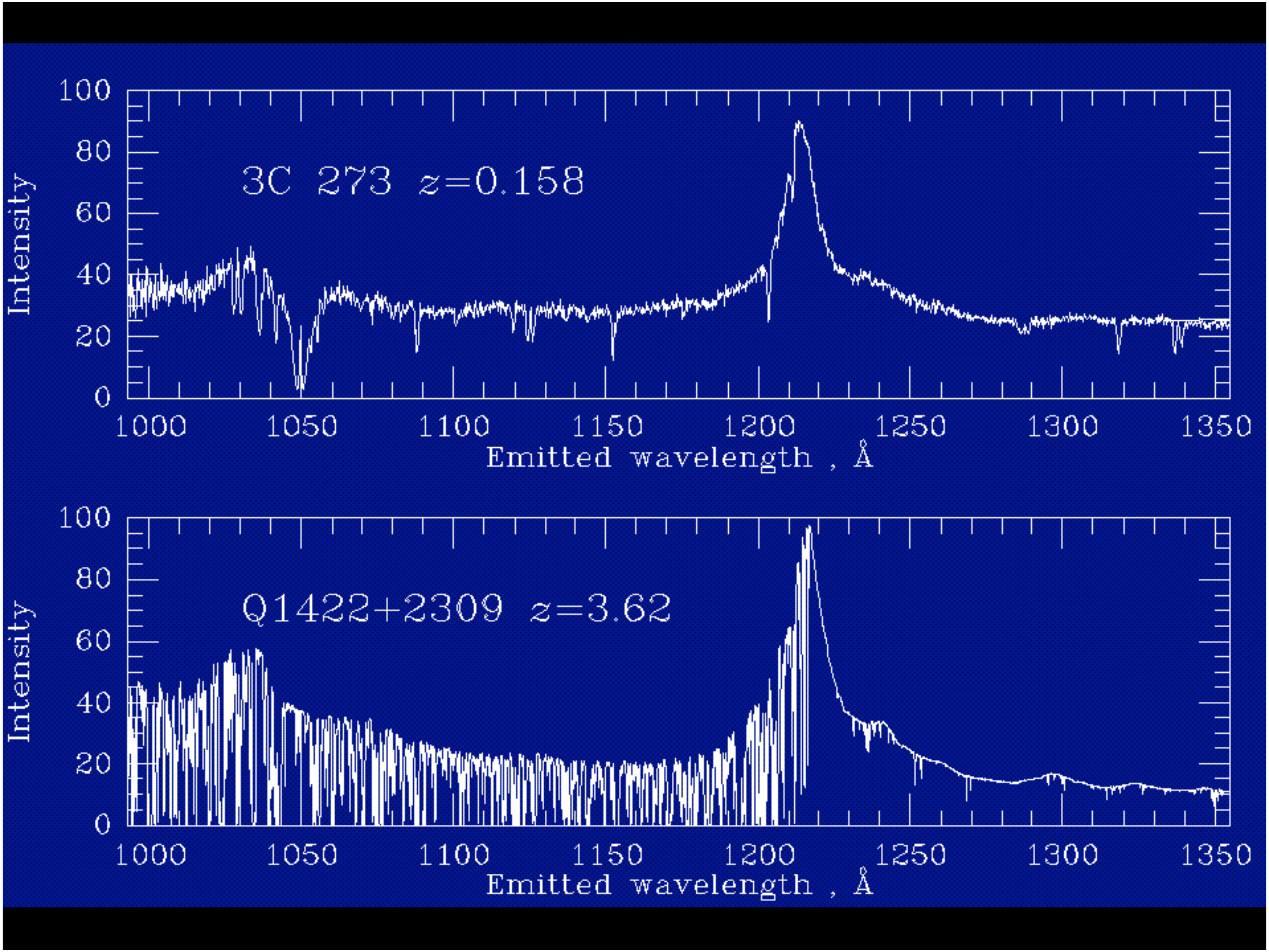
Brown Dwarf Gliese 229B

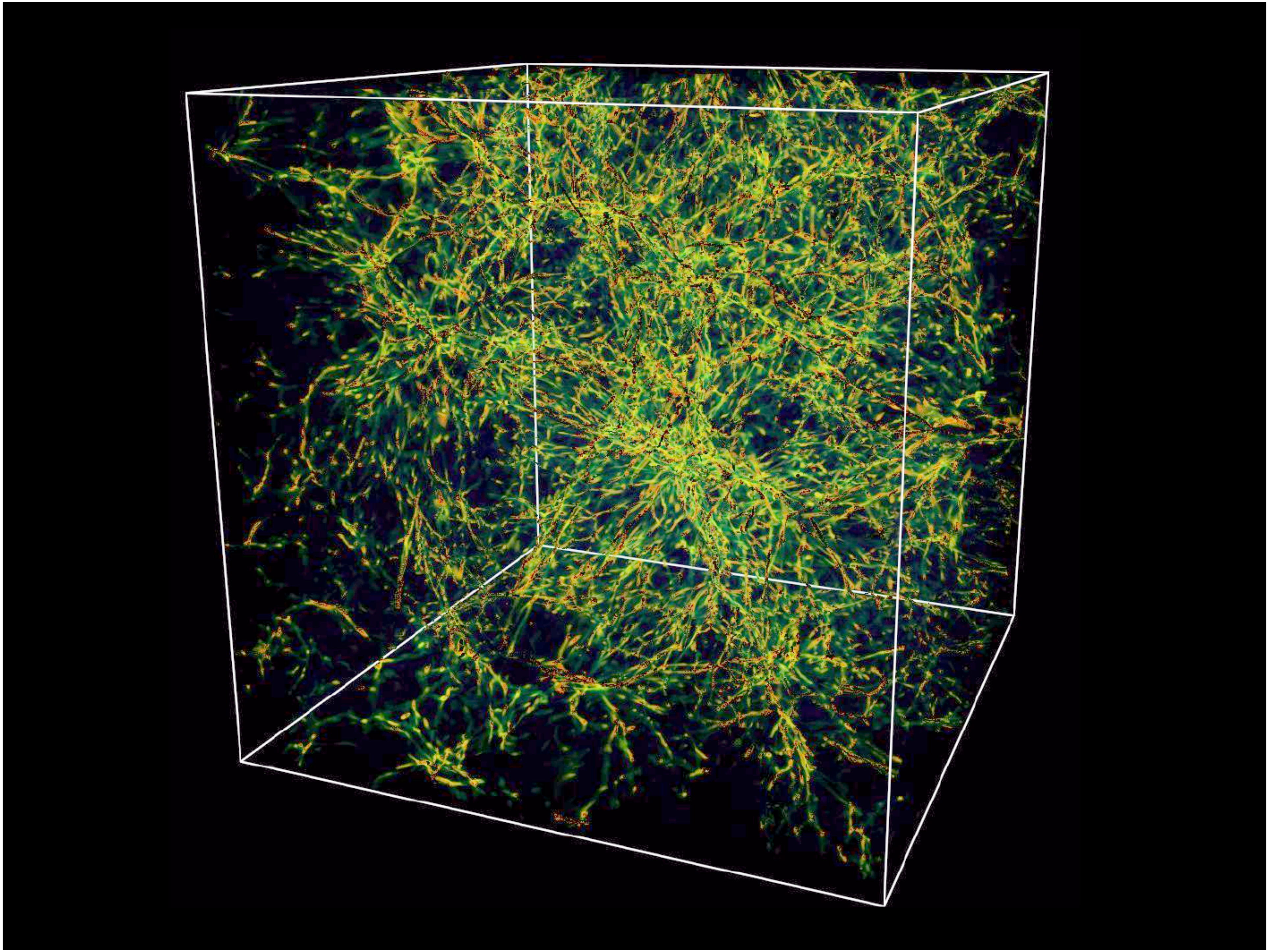


Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

PRC95-48 • ST ScI OPO • November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA


3C 273 z=0.158
Intensity
Emitted wavelength , Å
Q1422+2309 z=3.62
Intensity
Emitted wavelength , Å



Primordial nucleosynthesis

$$p + n \rightarrow D$$

$$D + D \rightarrow {}^3He + n$$

$$D + D \rightarrow {}^3H + p$$

$${}^4He + {}^3H \rightarrow {}^7Li + \gamma$$

$${}^7Li + p \rightarrow {}^4He + {}^4He$$

$${}^7Be + n \rightarrow {}^7Li + p.$$

+

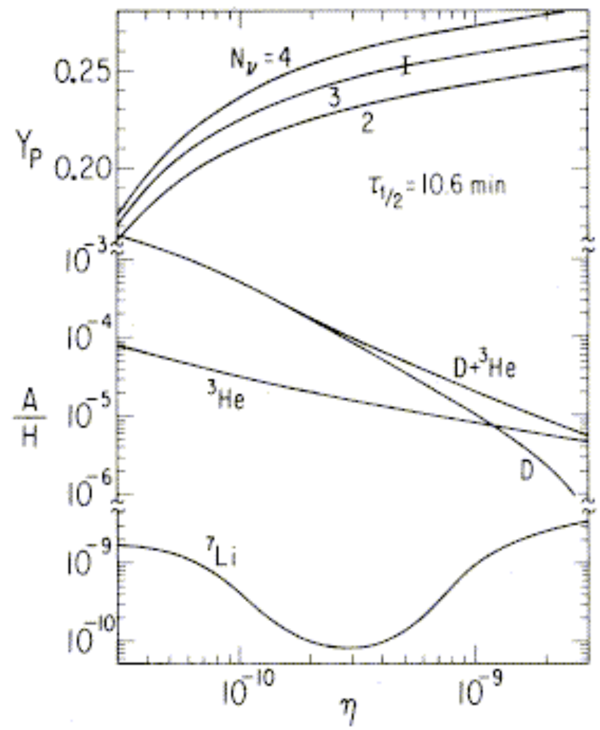


FIG. 5.—The predicted primordial abundances of ^4He (by mass), D, ^3He, and ^7Li (by number relative to H) as a function of η for $\tau_{1/2} = 10.6$ minutes; for ^4He the predictions for $N_\nu = 2, 3, 4$ are shown, and the size of the "error" bar shows the range in Y_p which corresponds to $10.4 < \tau_{1/2} < 10.8$ minutes. Note the changes in the abundance scales.

Light-element ratios in cosmic boondocks fit with only about 4% of the Mass density being in baryons. Black holes are included if formed from stars.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Particle Zoo ♥ CERN & LHC
The PARTICLE ZOO
Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!
QUARKS
UP QUARK
A teeny little point inside the proton and neutron, it is friends forever with the down quark.
CHARM QUARK
A second generation quark, he is charmed, indeed.
TOP QUARK
This heavyweight champion doesn't live long enough to make friends with anyone.
DOWN QUARK
A tiny little point inside the proton and neutron, it is friends forever with the up quark.
STRANGE QUARK
What's so strange about this second generation quark?
BOTTOM QUARK
This third generation quark is puttin' on the pounds.
FORCE CARRIERS
PHOTON
The massless wavicle we know and love.
GLUON
The "glue" of the strong nuclear force.
W BOSON
Z BOSON
As the carrier particles of the weak nuclear force, they're downright obese.
LEPTONS
ELECTRON-NEUTRINO
These minuscule bandits like to steal away energy and escape detection.
MUON-NEUTRINO
A slightly heavier bandit than his sibling to the left.
TAU-NEUTRINO
Wily and sneaky, this bandit is the newest particle to arrive at the Zoo.
ELECTRON
A familiar friend, this negatively charged, busy li'l guy likes to bond.
MUON
A "heavy electron" who lives fast and dies young.
TAU
A "heavy muon" who could stand to lose a little weight.
THEORETICALS
HIGGS BOSON
He's the one everyone wants to meet, but for now he's playing hard to get. You'd be smiling too if everyone was looking to interview you.
GRAVITON
Still unobserved, yet theoretically everywhere, he's got big legs for jumping branes.
TACHYON
Can this devious and clever particle really travel faster than light?
DARK MATTER
The mysterious missing mass. Difficult to see because he's so dark.
NUCLEONS
PROTON
We would not be here without her positivity.
NEUTRON
He insists on remaining neutral.
Visit the
ANTIPARTICLE ANNEX
You can now buy antimatter on the web!
Toys are weighted according to mass:
light, medium, heavy
see chart
STAMPSHEET
Twenty-three particles on one 8.5x11" sheet of perforated "stamps"


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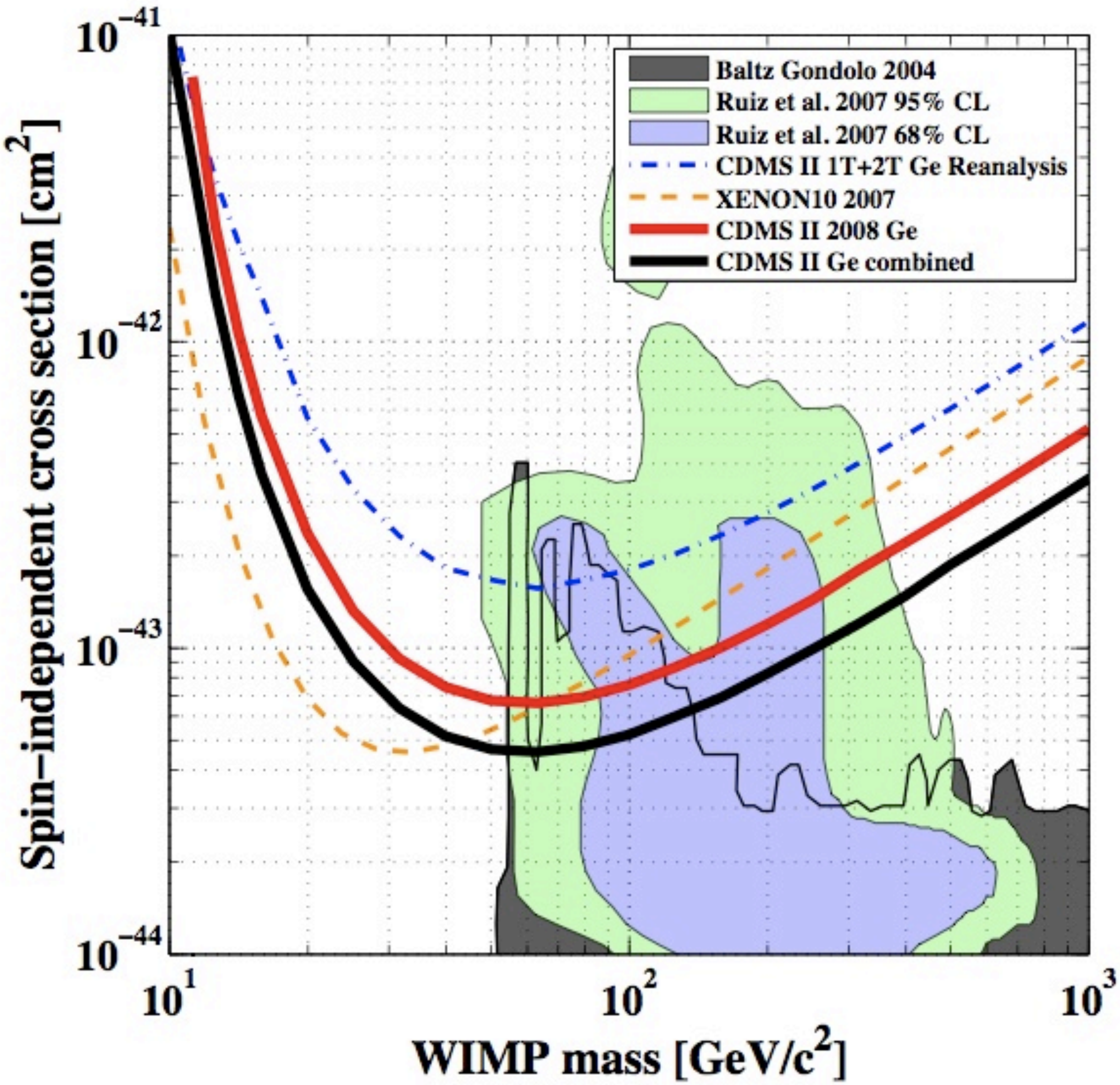
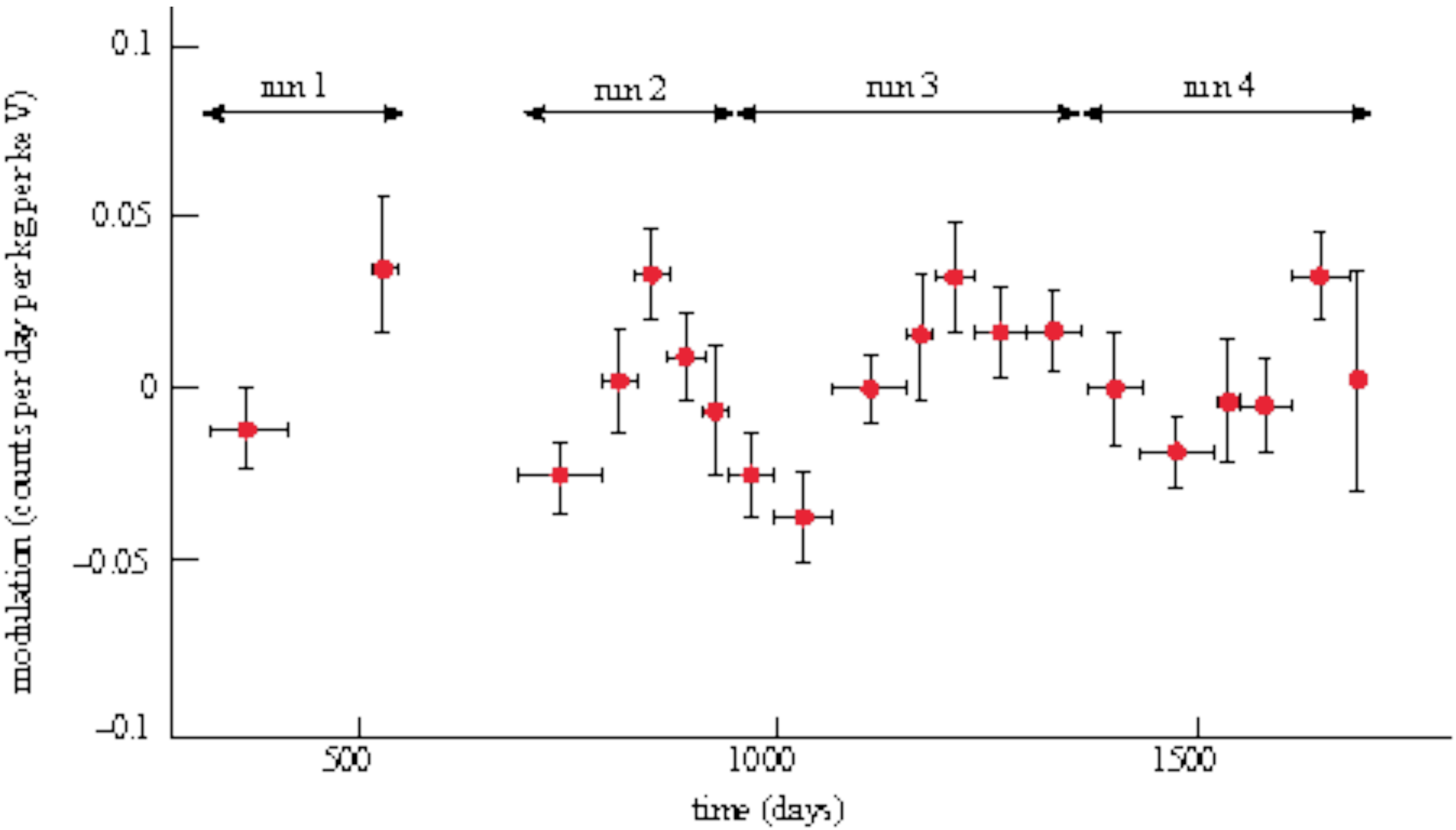
Can this devious and clever particle really travel faster than light?
DARK MATTER
The mysterious missing mass. Difficult to see because he's so *dark*.

Cryogenic Dark Matter Search (CDMS)
Soudan underground lab; photon recoil+ionization
No detection yet:



DAMA
Gran Sasso lab (Alps)
See an annual modulation of signal!



DAMA, CDMS results inconsistent at 99.8% confidence – there's something to learn.

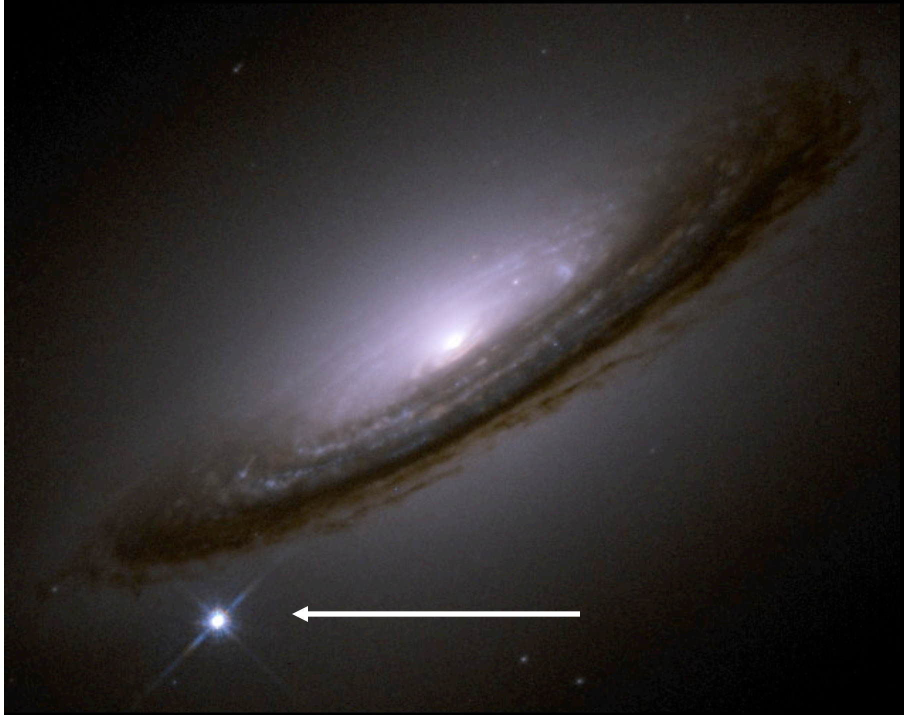
Who ordered this?

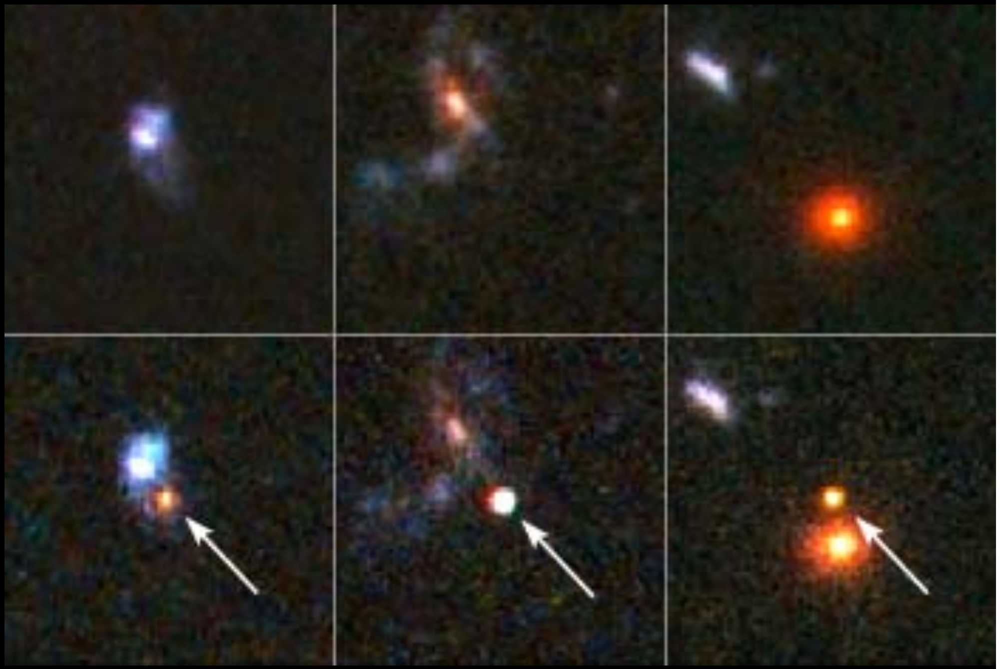
Cosmological constant Λ

Quintessence

Dark energy

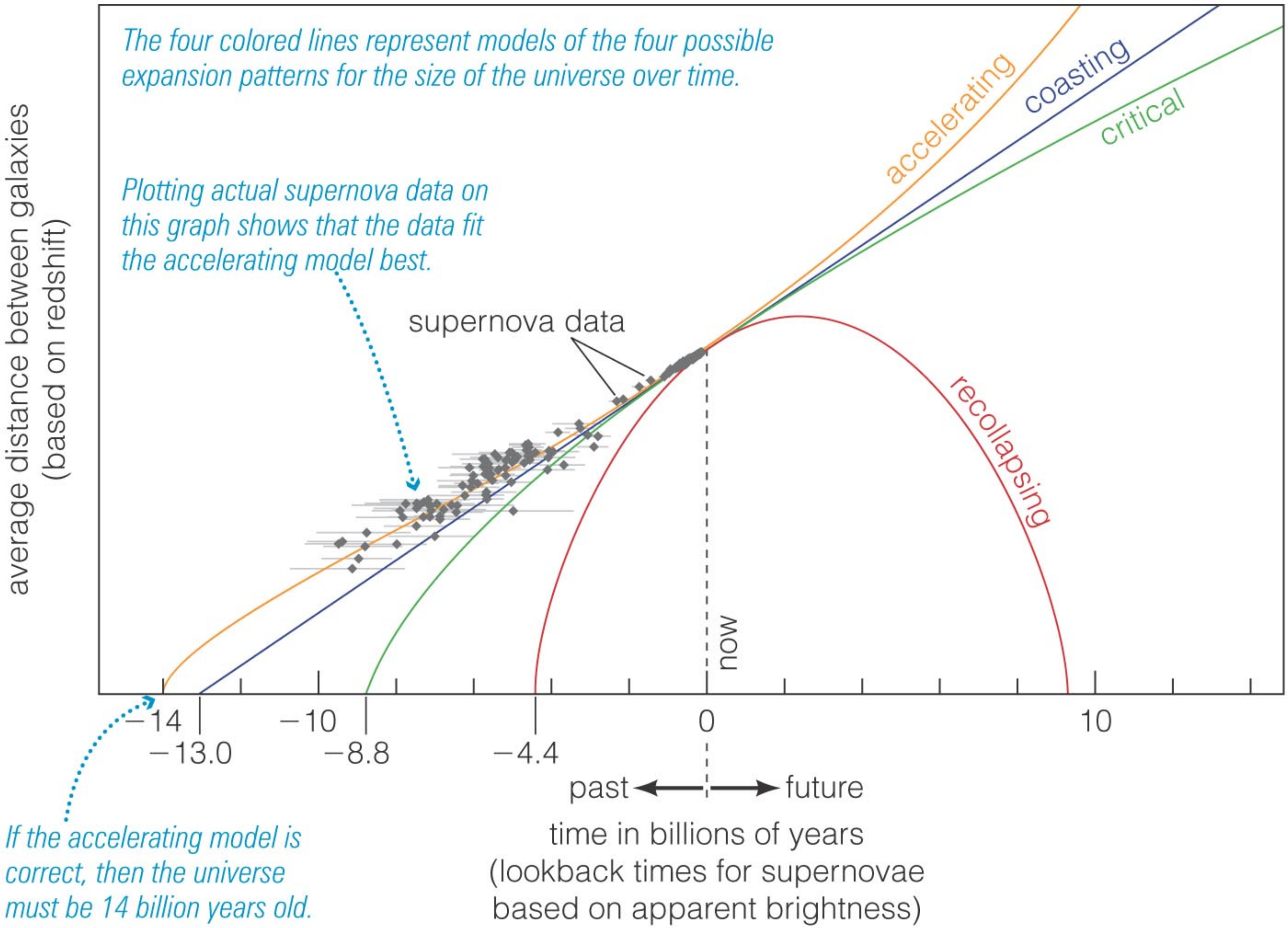
Supernovae point to cosmic acceleration

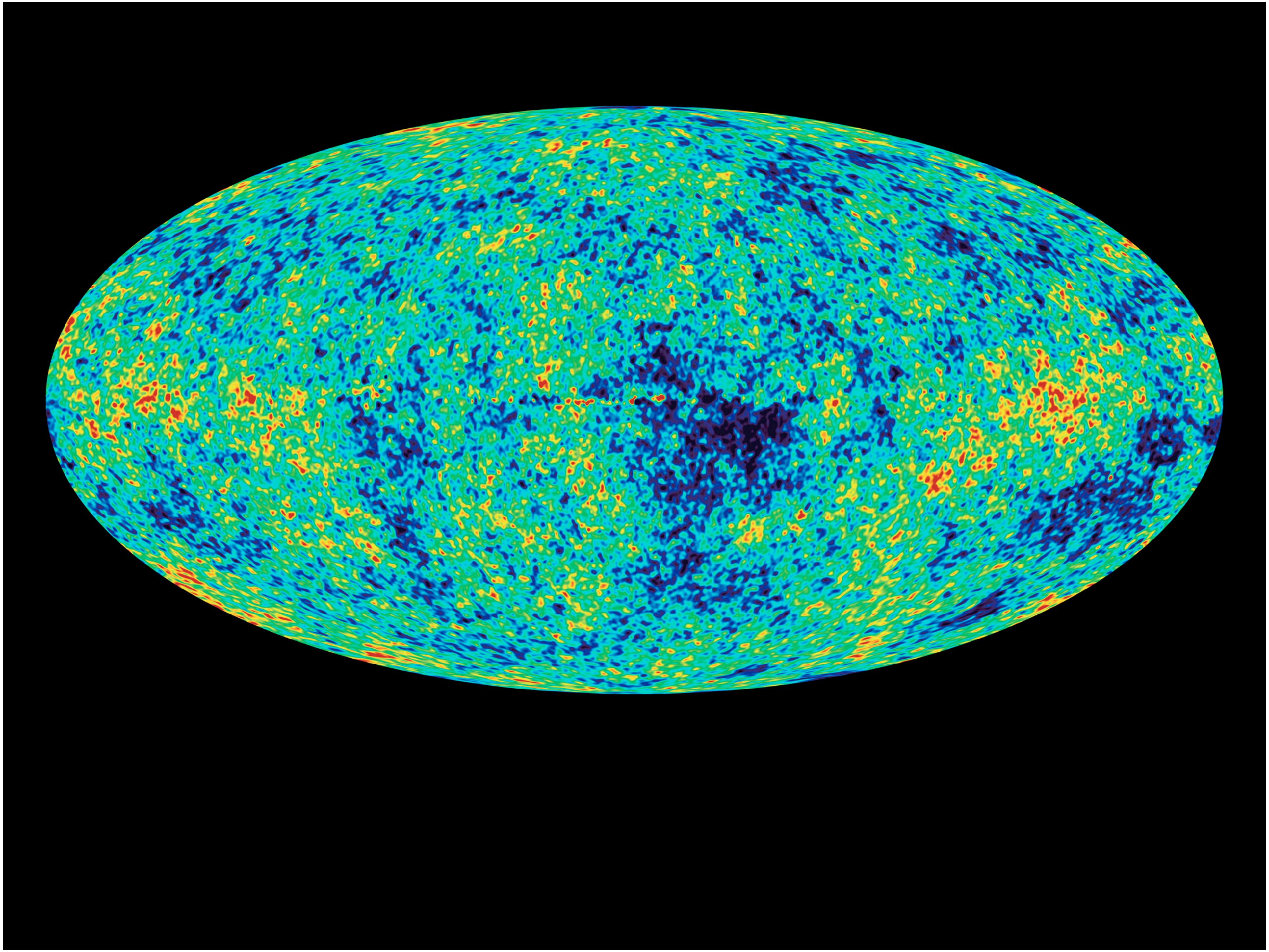


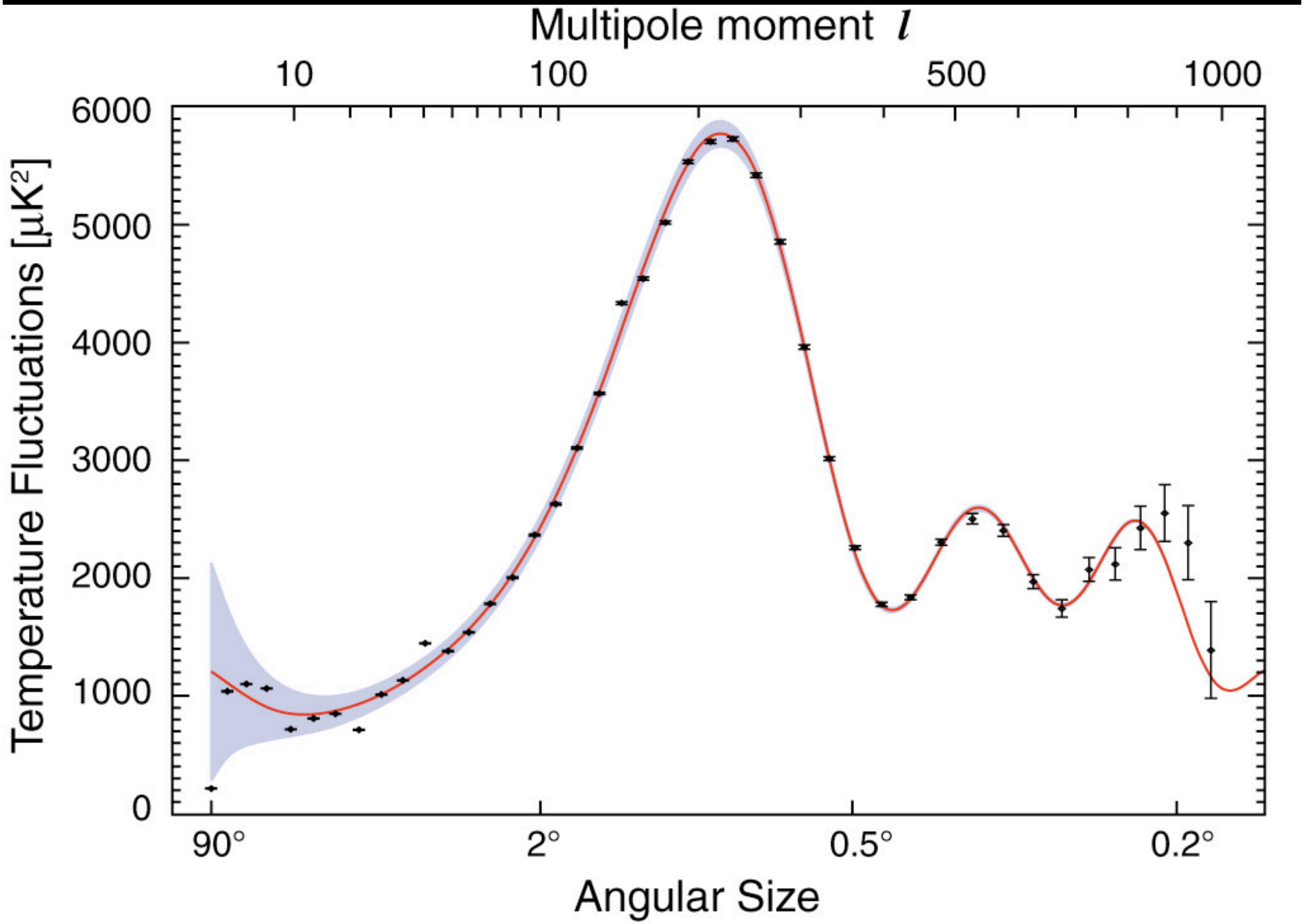


Who ordered that? Einstein may have been right the first time…

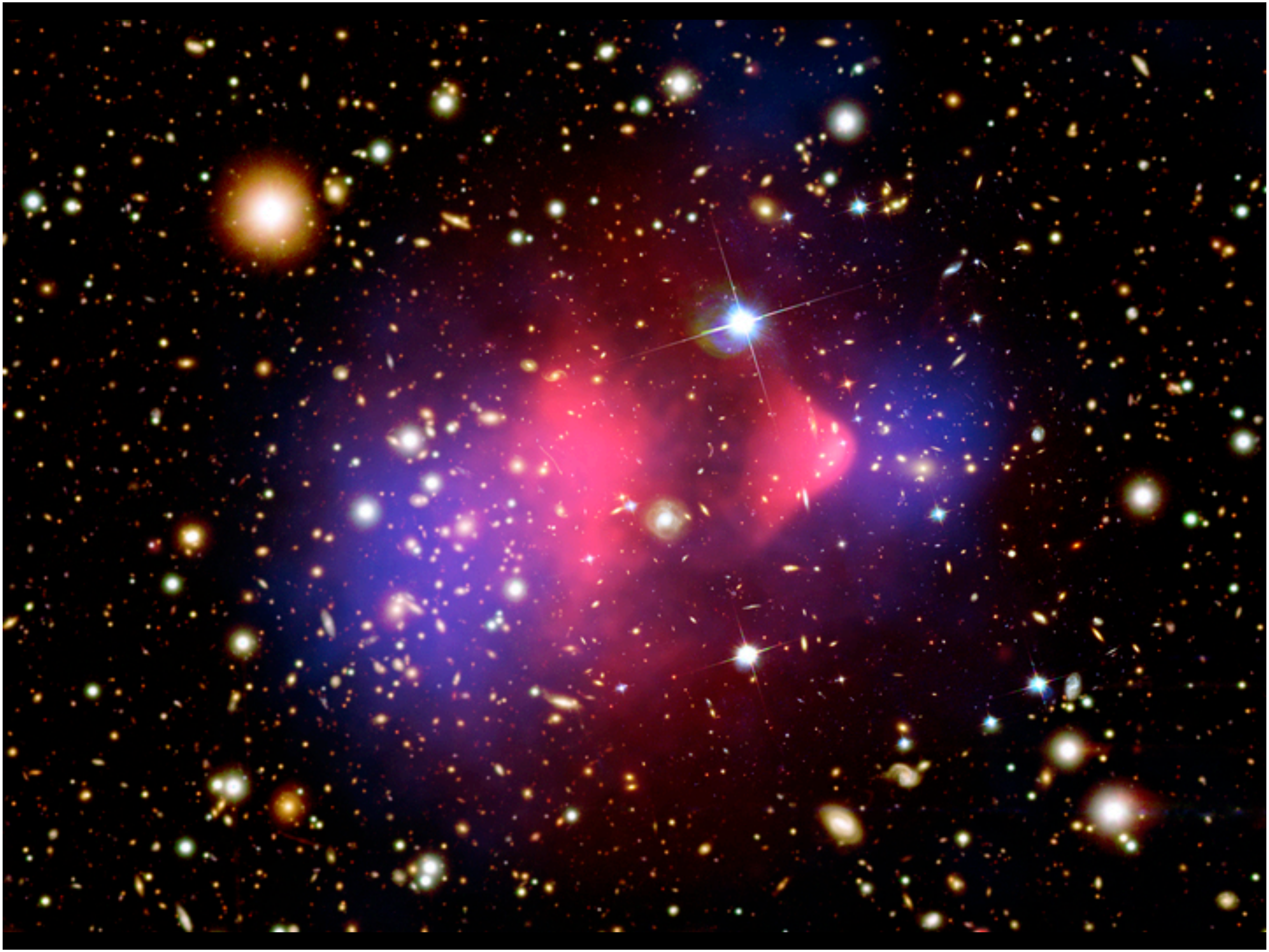
(HST)


The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.
accelerating
coasting
critical
Plotting actual supernova data on this graph shows that the data fit the accelerating model best.
supernova data
recollapsing
now
average distance between galaxies (based on redshift)
−14
−13.0
−10
−8.8
−4.4
0
10
past
future
time in billions of years (lookback times for supernovae based on apparent brightness)
If the accelerating model is correct, then the universe must be 14 billion years old.





Multipole moment l
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
Temperature Fluctuations [μK²]
90°
2°
0.5°
0.2°
Angular Size



DARK MATTER

Most of the universe can't even be bothered to interact with you.