

Galaxies & Galaxy Clusters

Chiara Ferrari



Observatoire
de la CÔTE d'AZUR



The galaxy cluster Abell 520

<http://chandra.harvard.edu/>

Credits: NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), and A. Mahdavi (San Francisco State University)

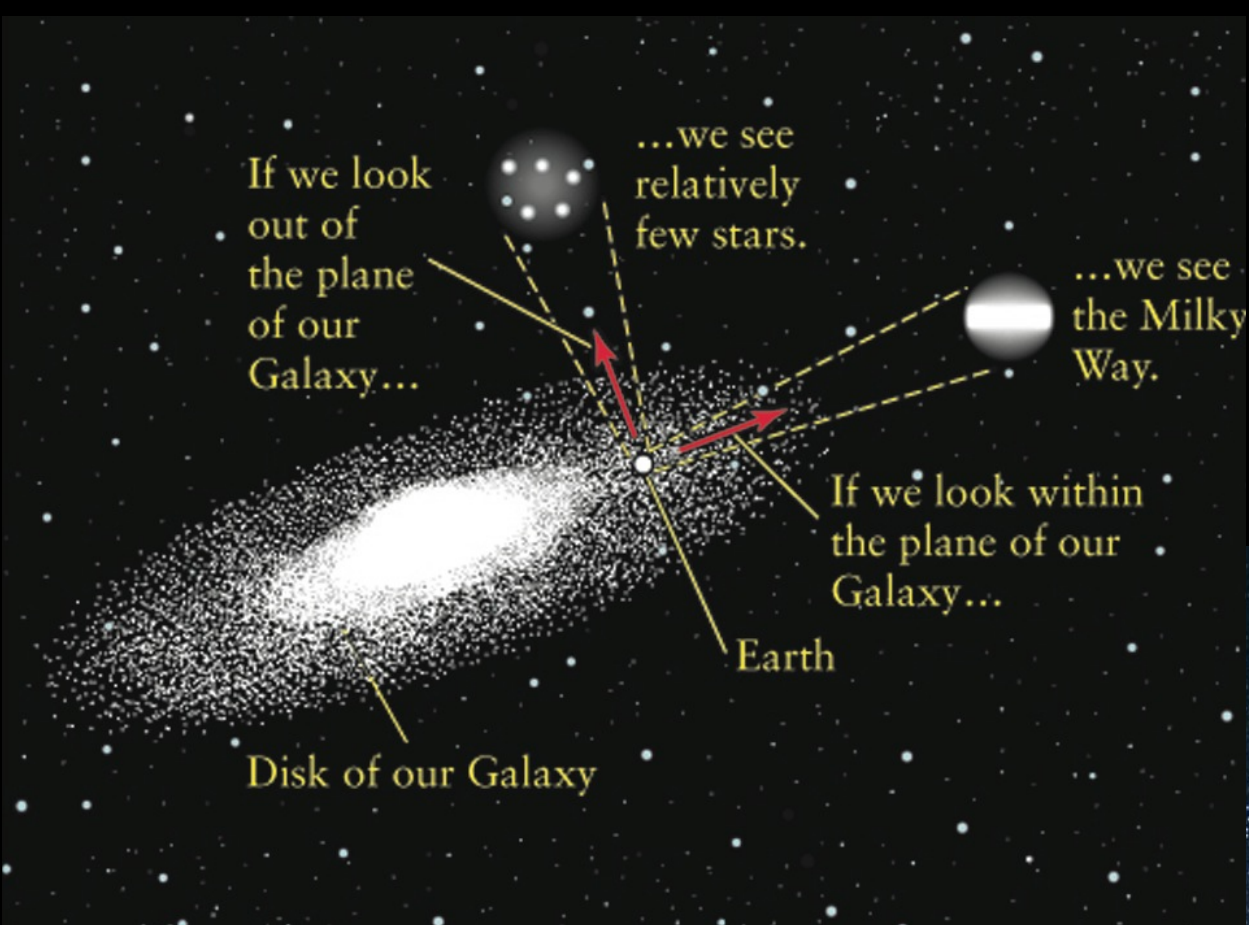
The galaxy cluster Abell 520: visible light



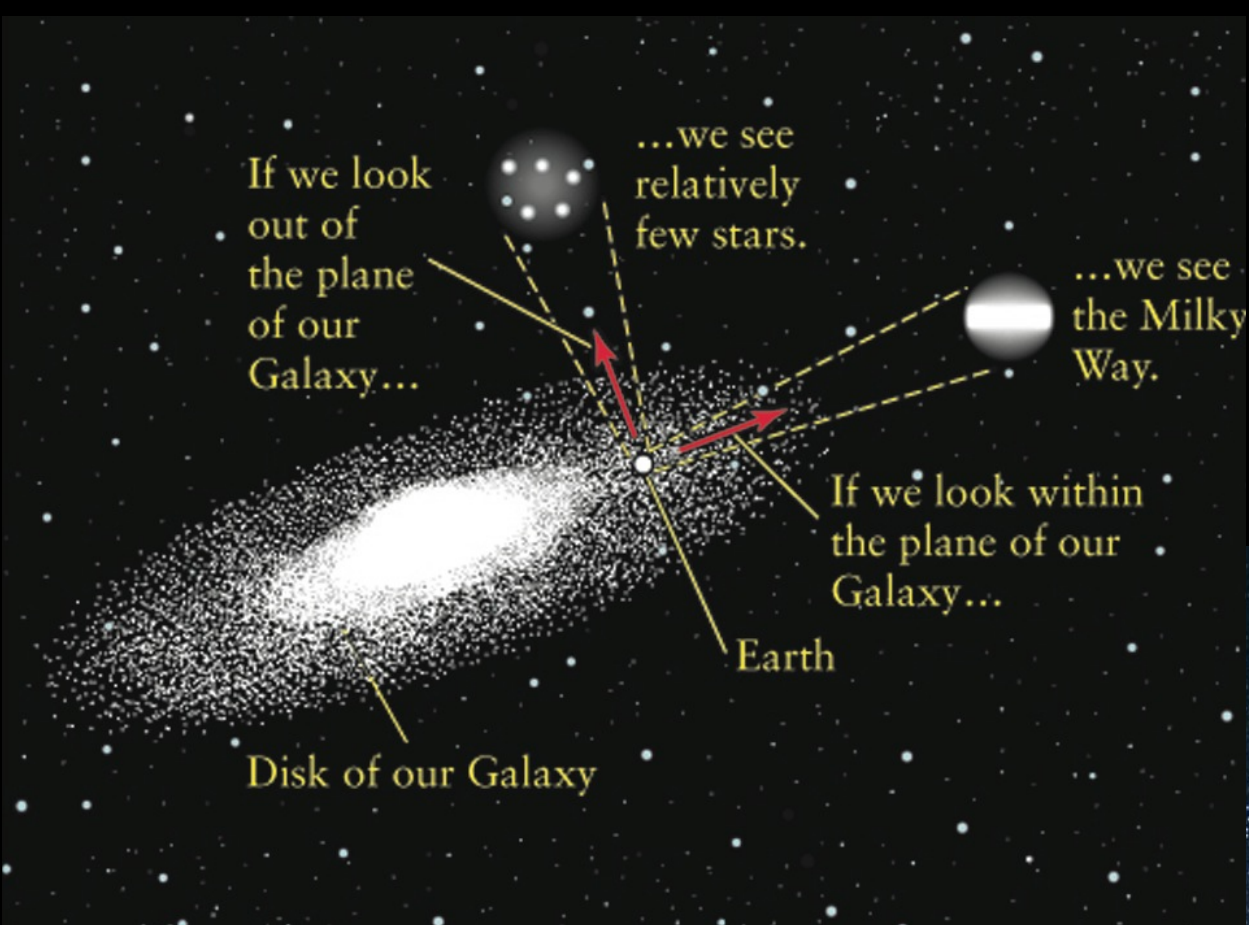
<http://chandra.harvard.edu/>

Credits: CFHT, A.Mahdavi (UVic.)

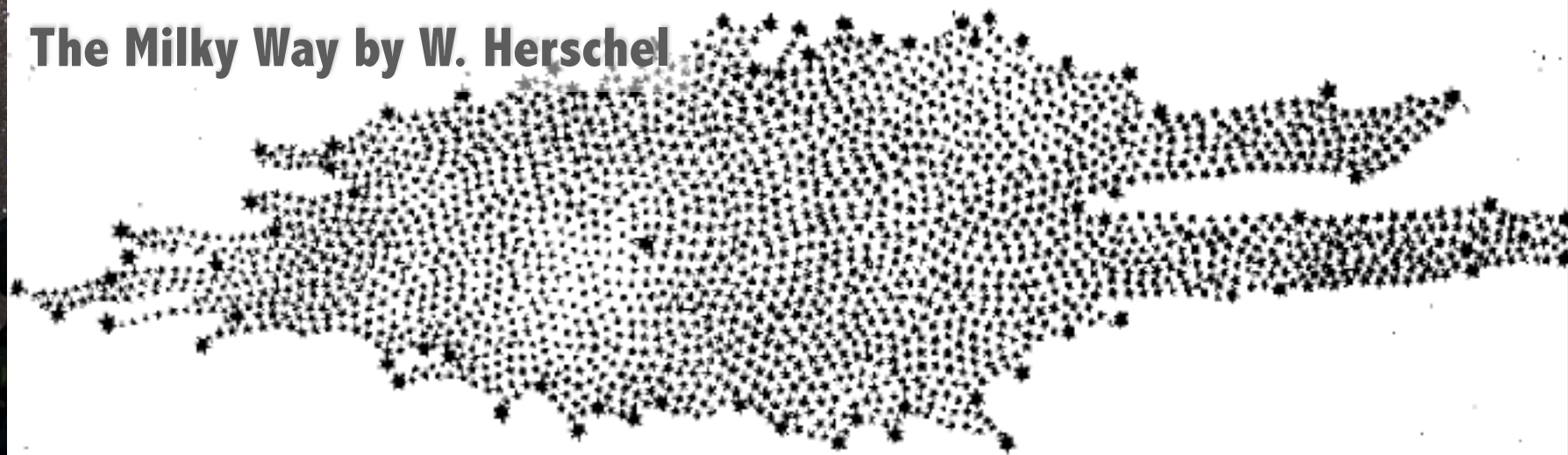
What is a galaxy?



What is a galaxy?



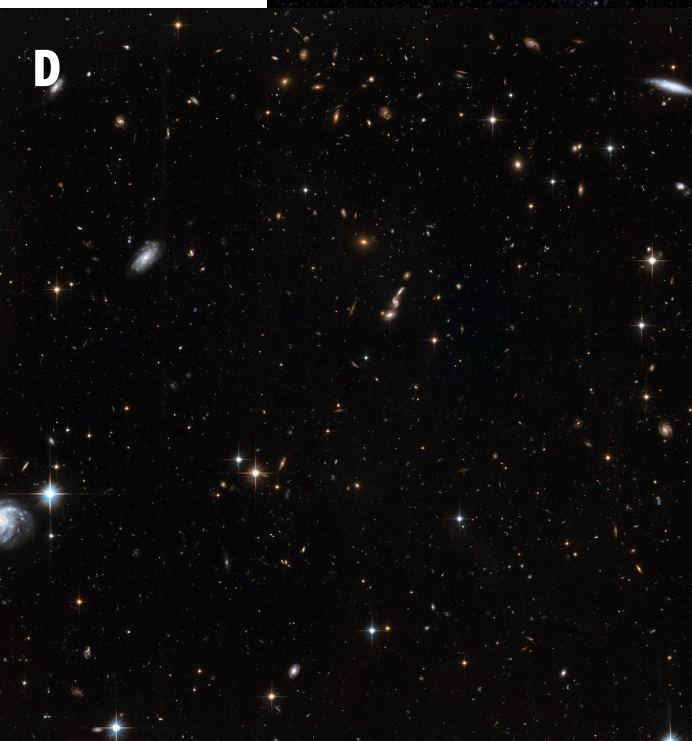
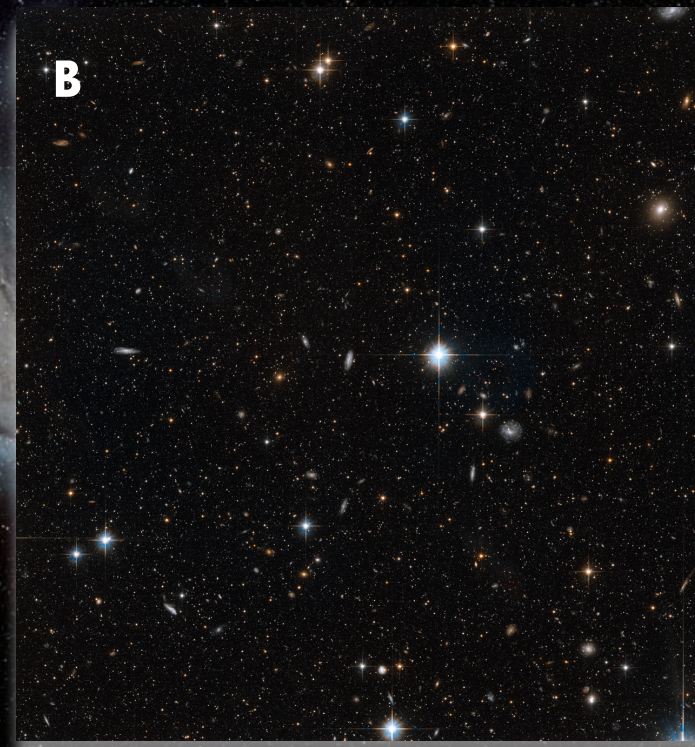
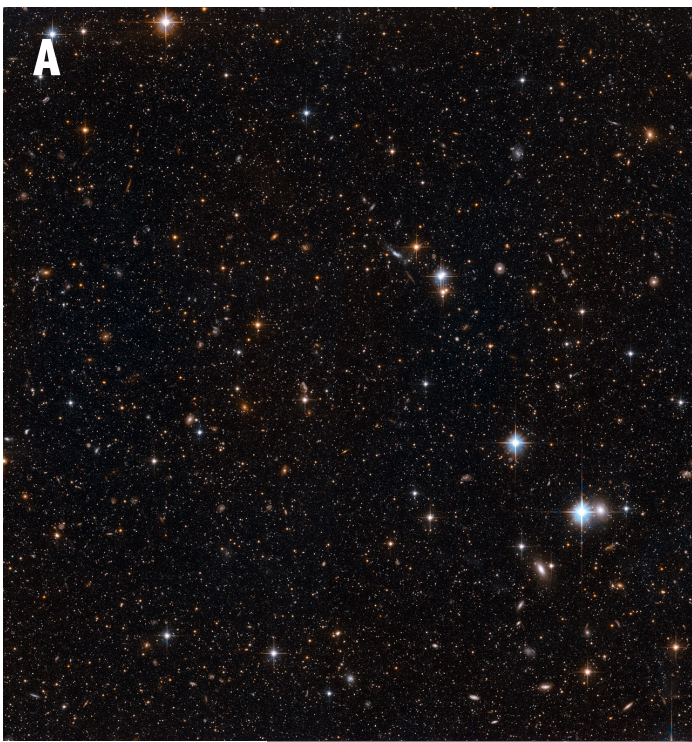
The Milky Way by W. Herschel



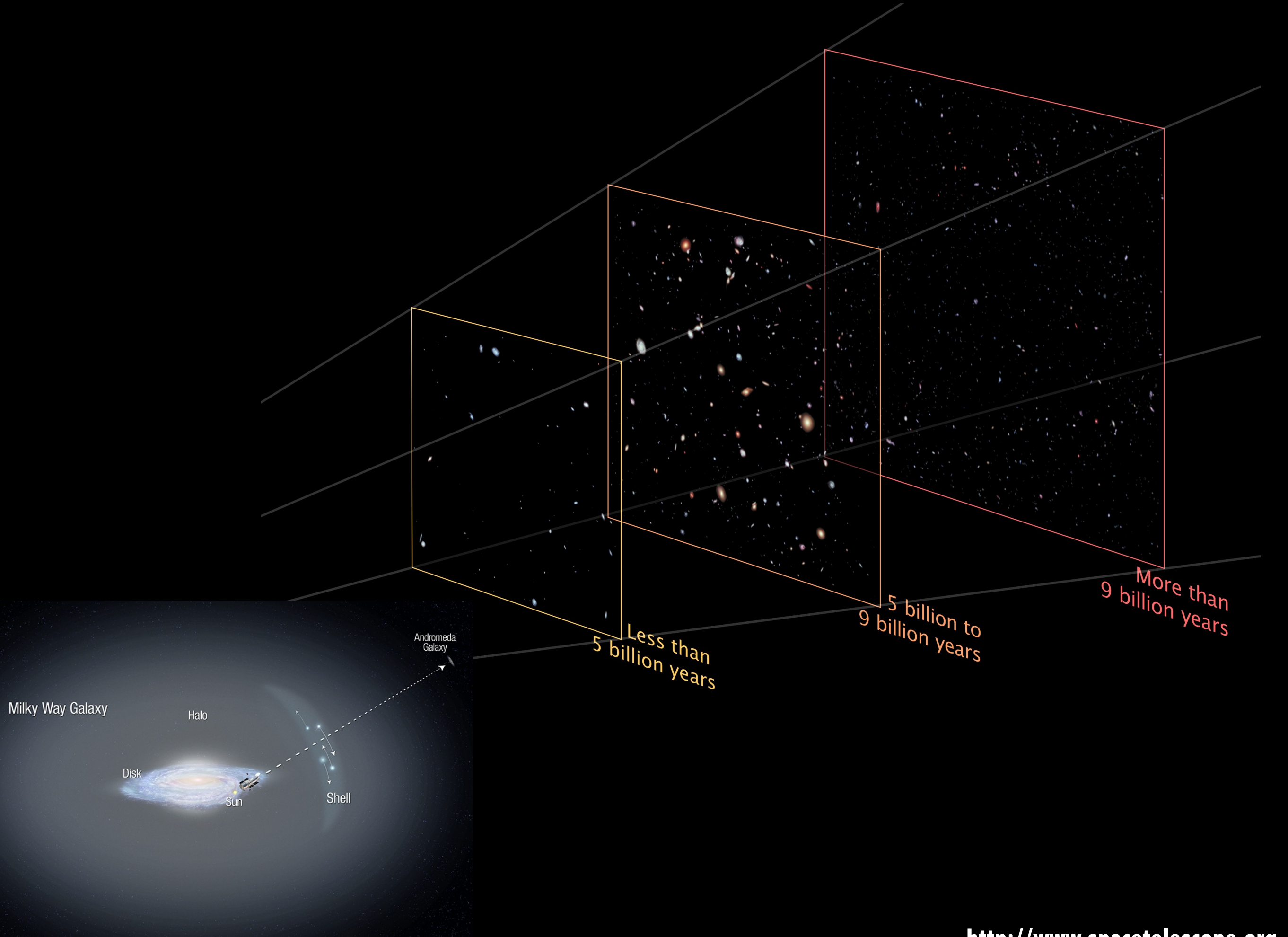
What is a galaxy?



What is a galaxy?

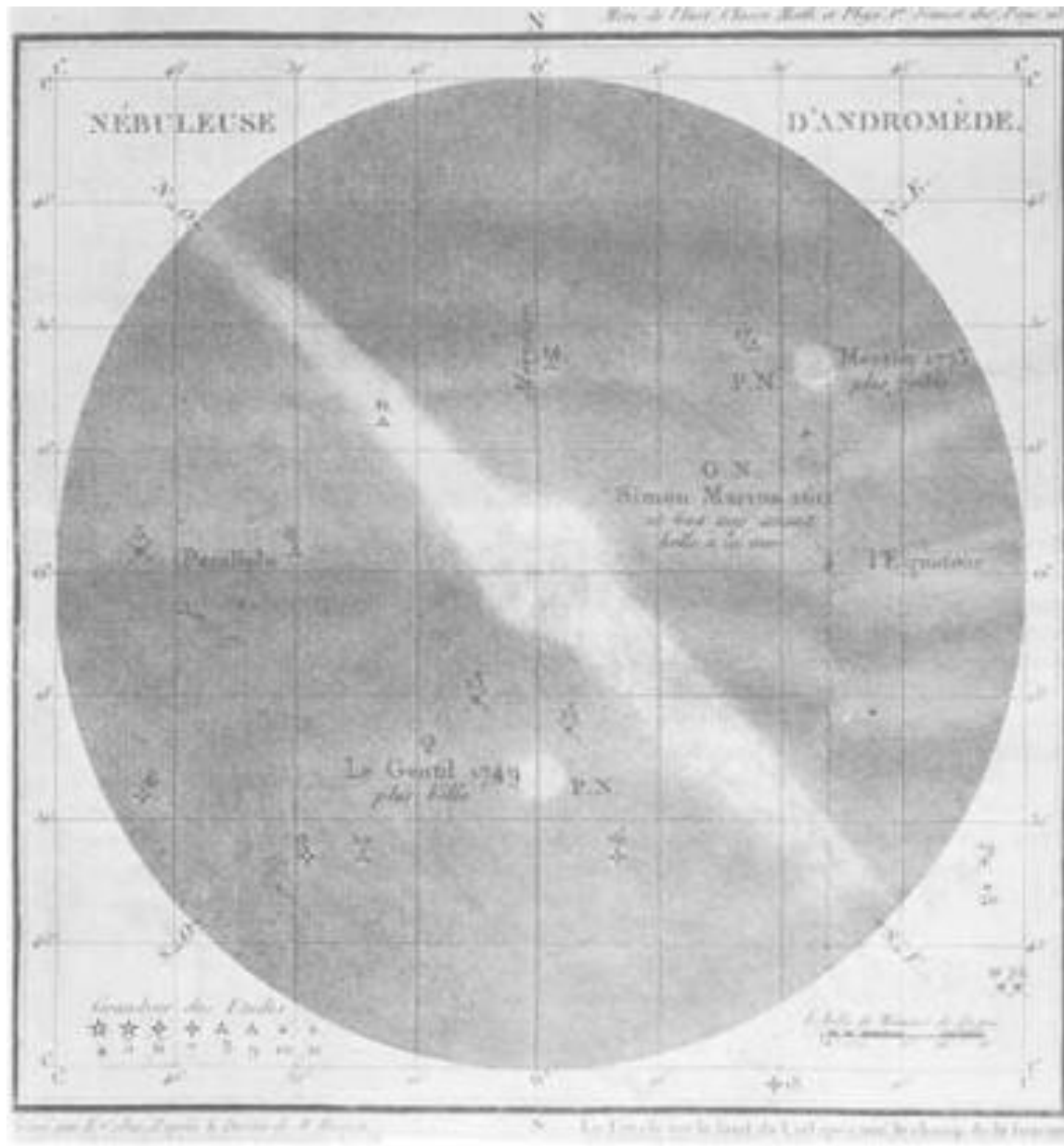


ESA/Hubble & Digitized Sky Survey 2. Acknowledgment: Davide De Martin (ESA/Hubble)





The Andromeda “nebula” (M31)



As seen by Messier in the XVIII century...



... and by the Hubble Space Telescope

What is a “nebula”?



XVIII century: Messier and Herschel point out the existence of “nebulae” in the sky

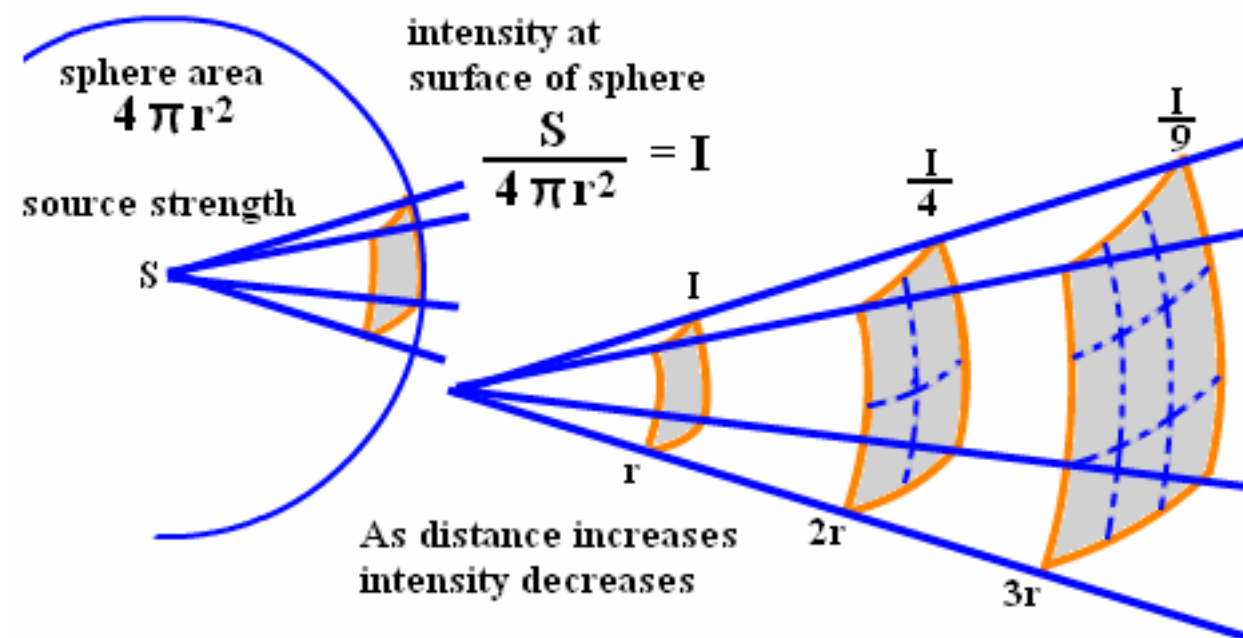


1920: “Great debate” by Curtis and Shapley

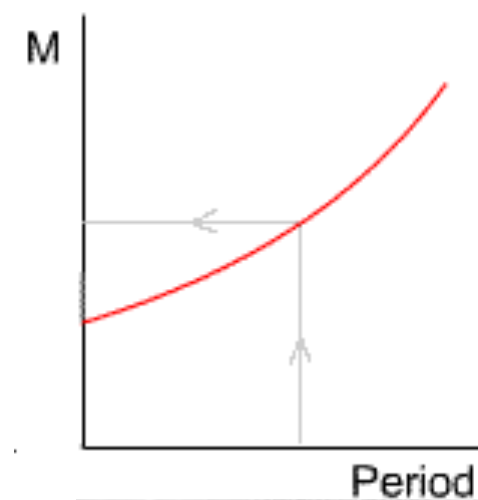
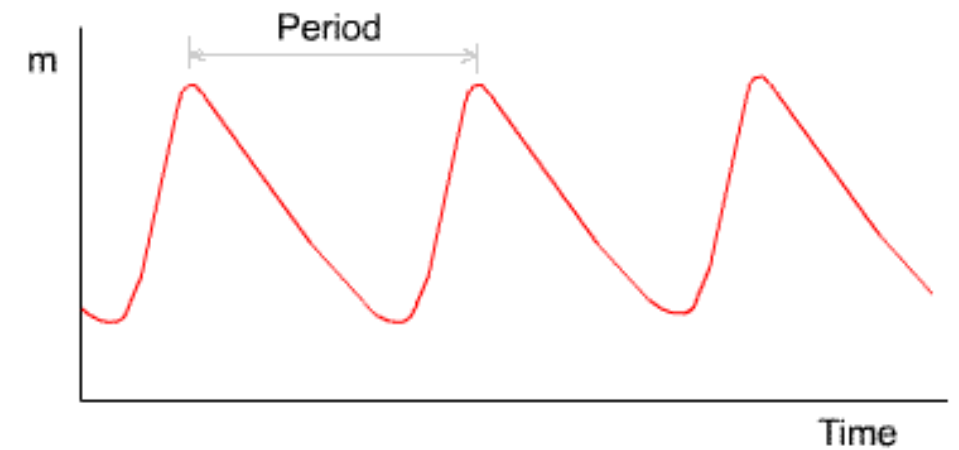
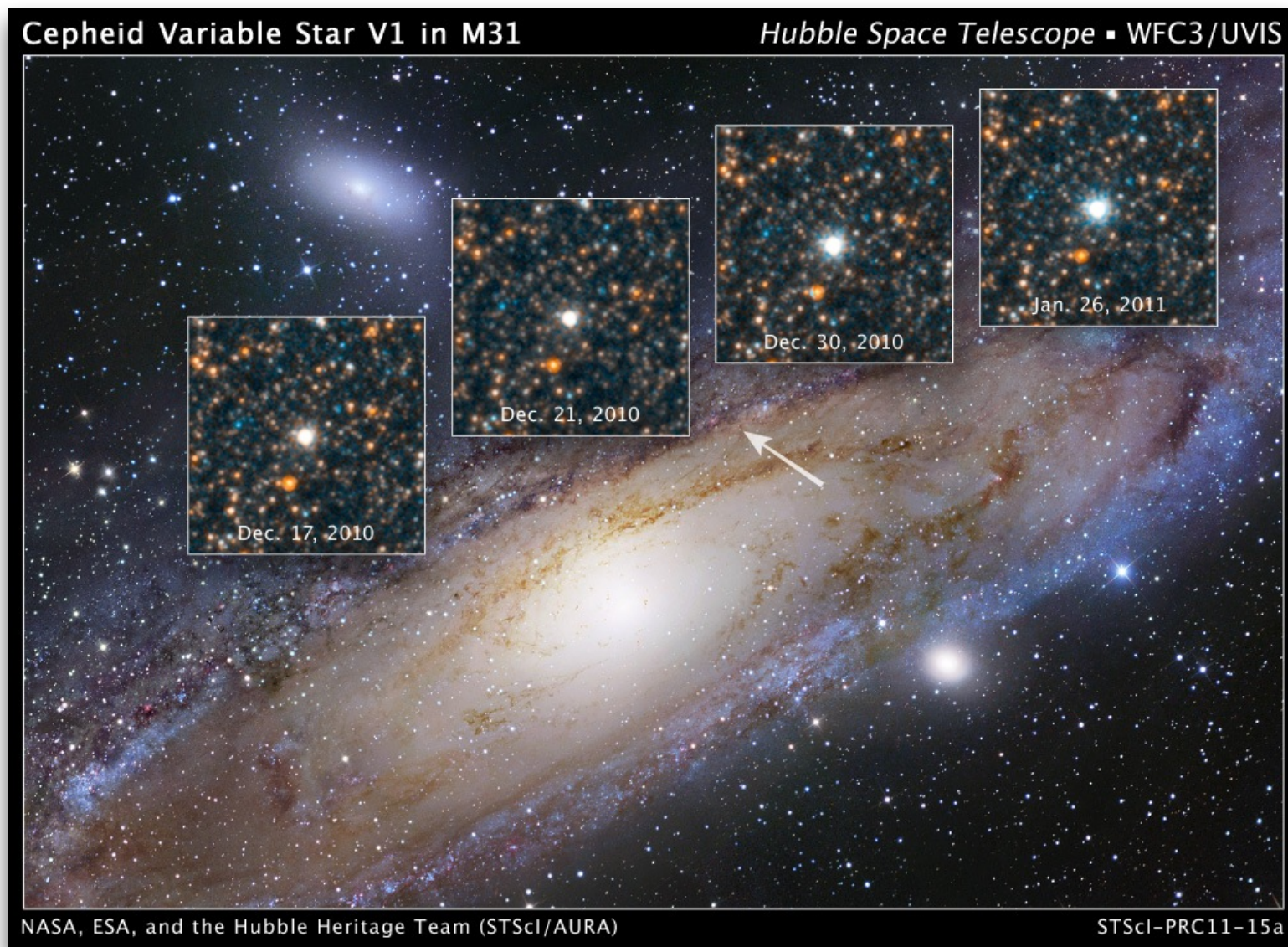
Measuring distances ...



S = luminosity
 I = flux

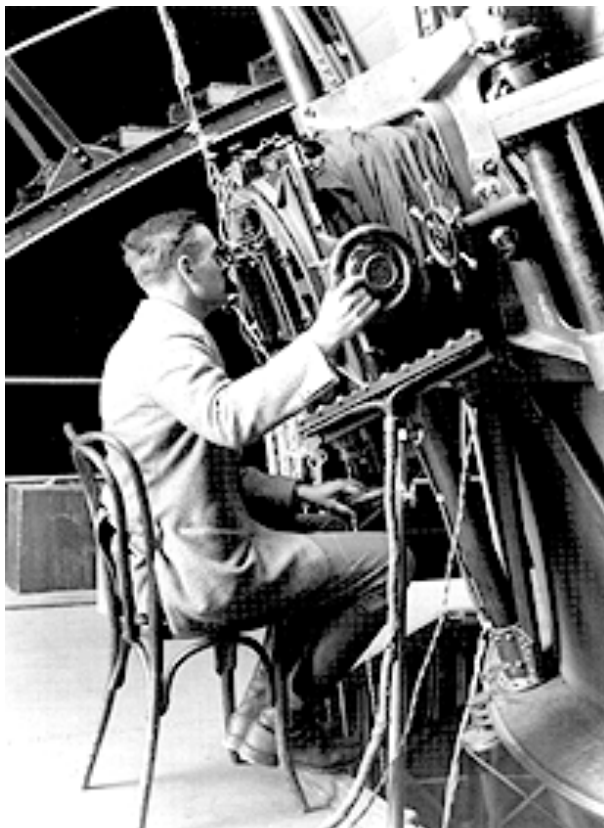


Measuring distances to galaxies

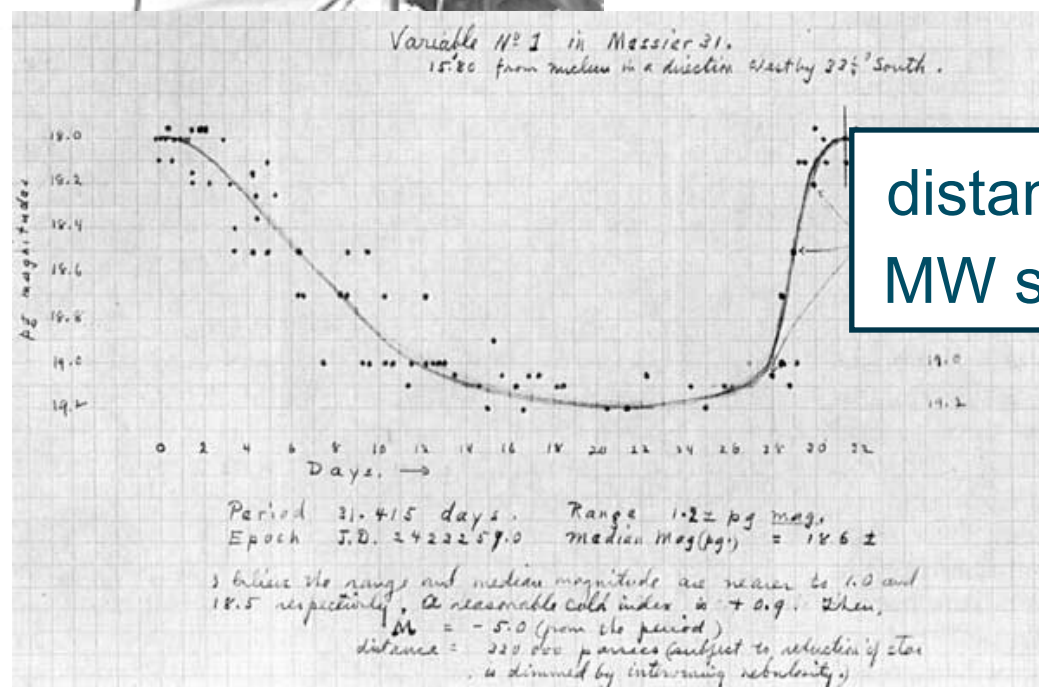


H. Leavitt

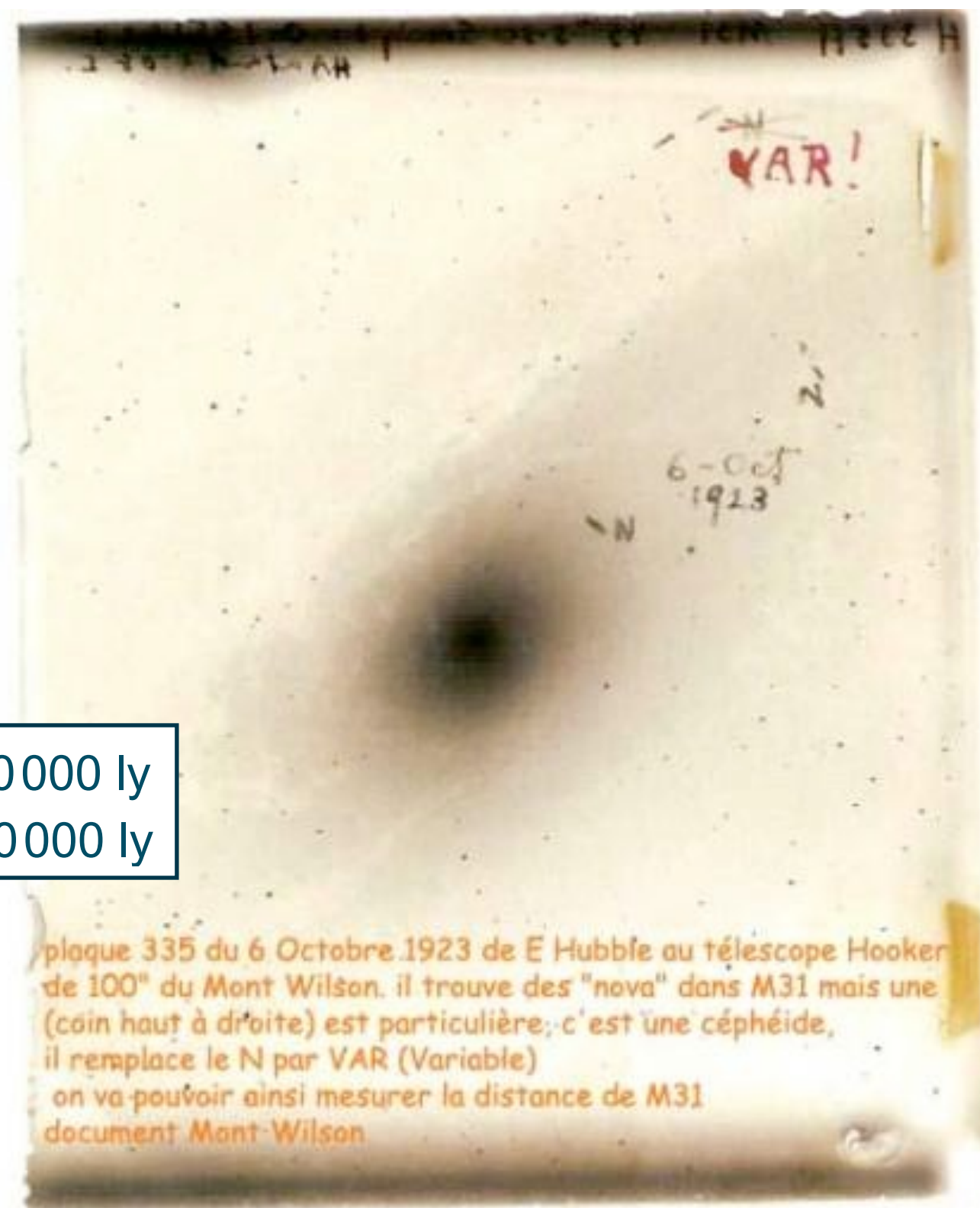
Our Galaxy is not Unique!



E. Hubble

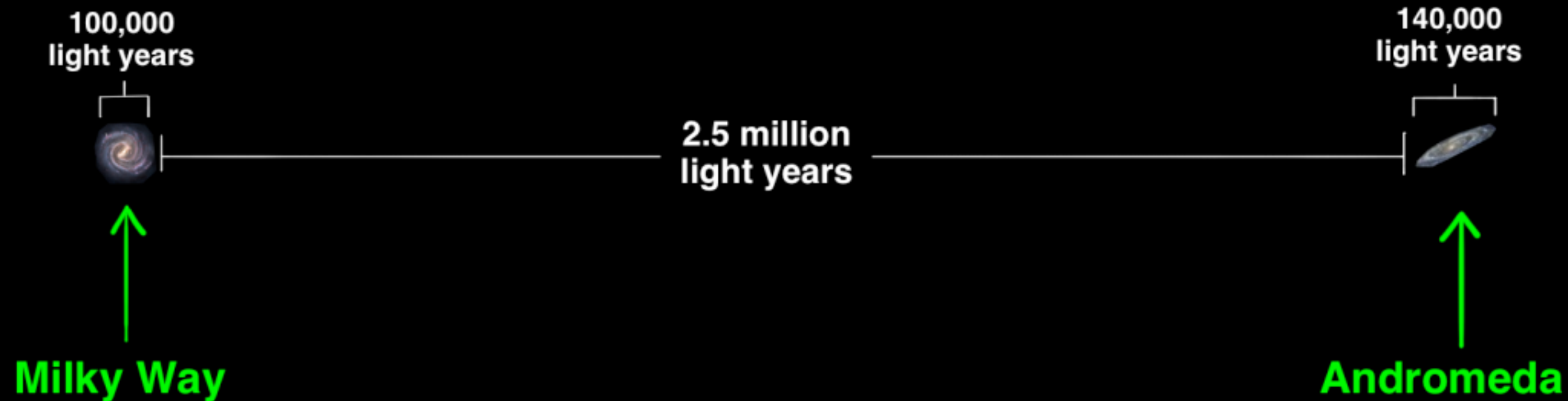


distance ~ 900 000 ly
MW size ~ 100 000 ly



Our Galaxy is not Unique!

Andromeda's Distance From Us (to Scale)



www.waitbutwhy.com

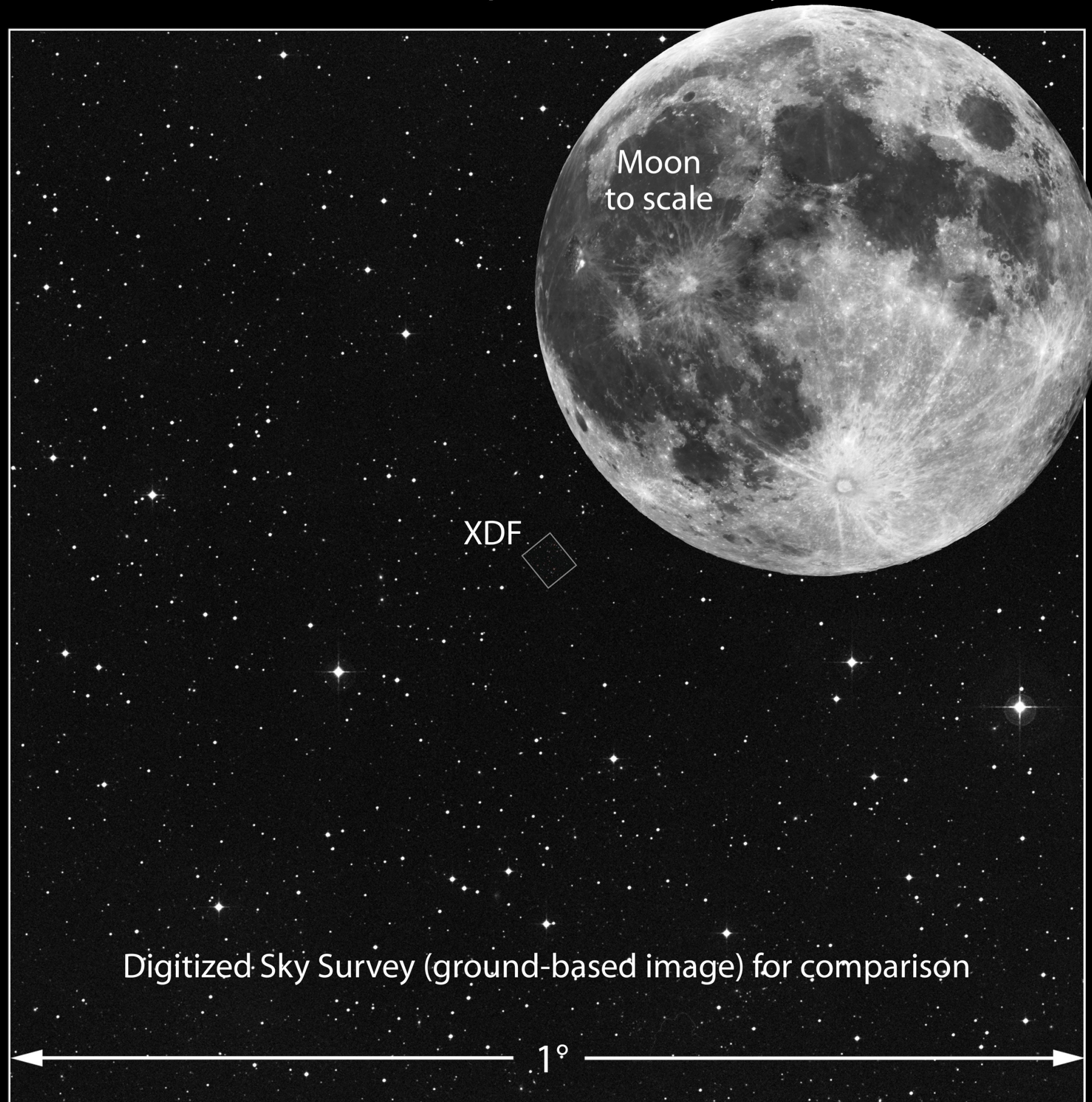
1 parsec = 3.26 light years = 3.0857×10^{16} m

We use kpc and Mpc in extra-galactic astrophysics

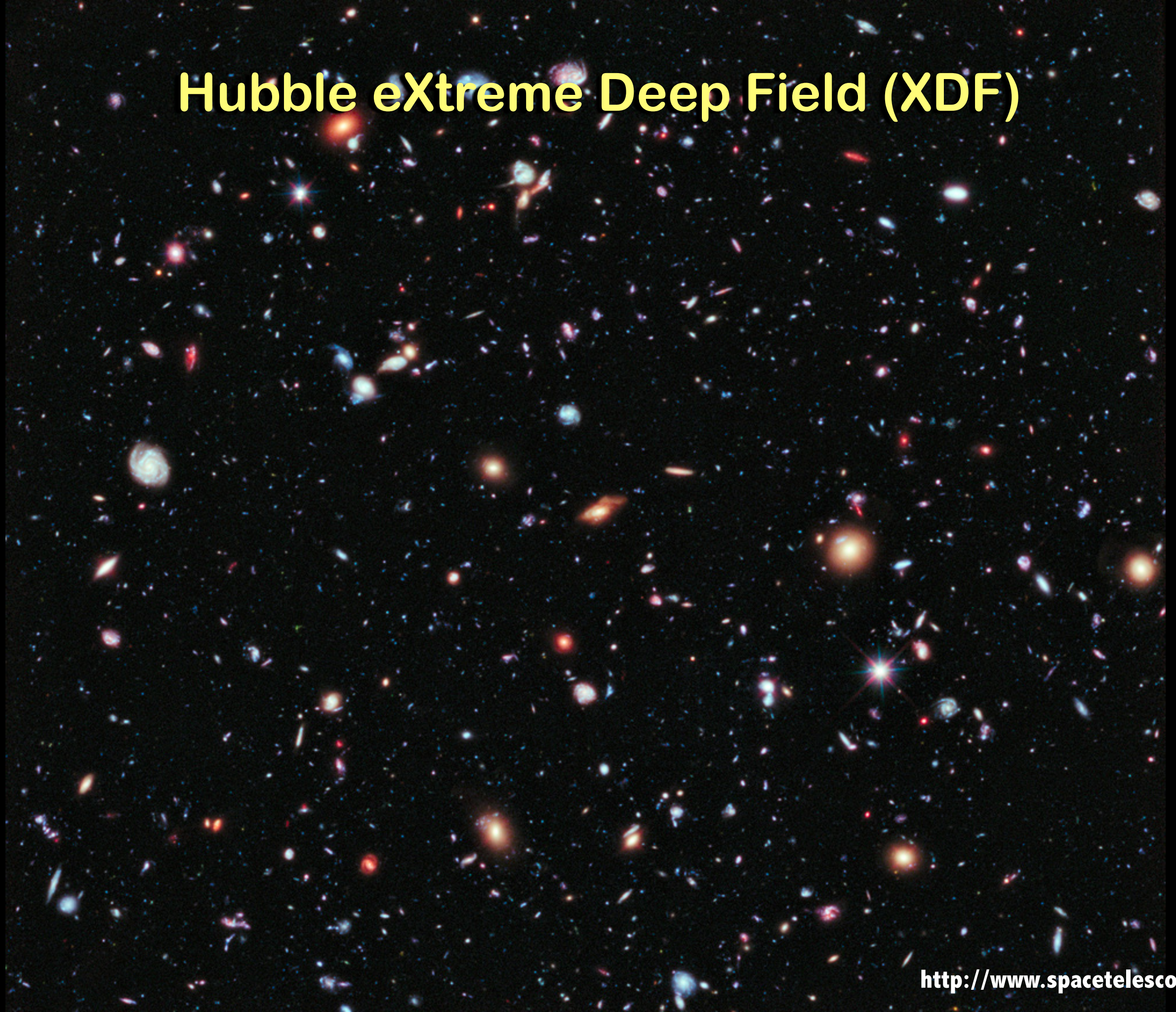




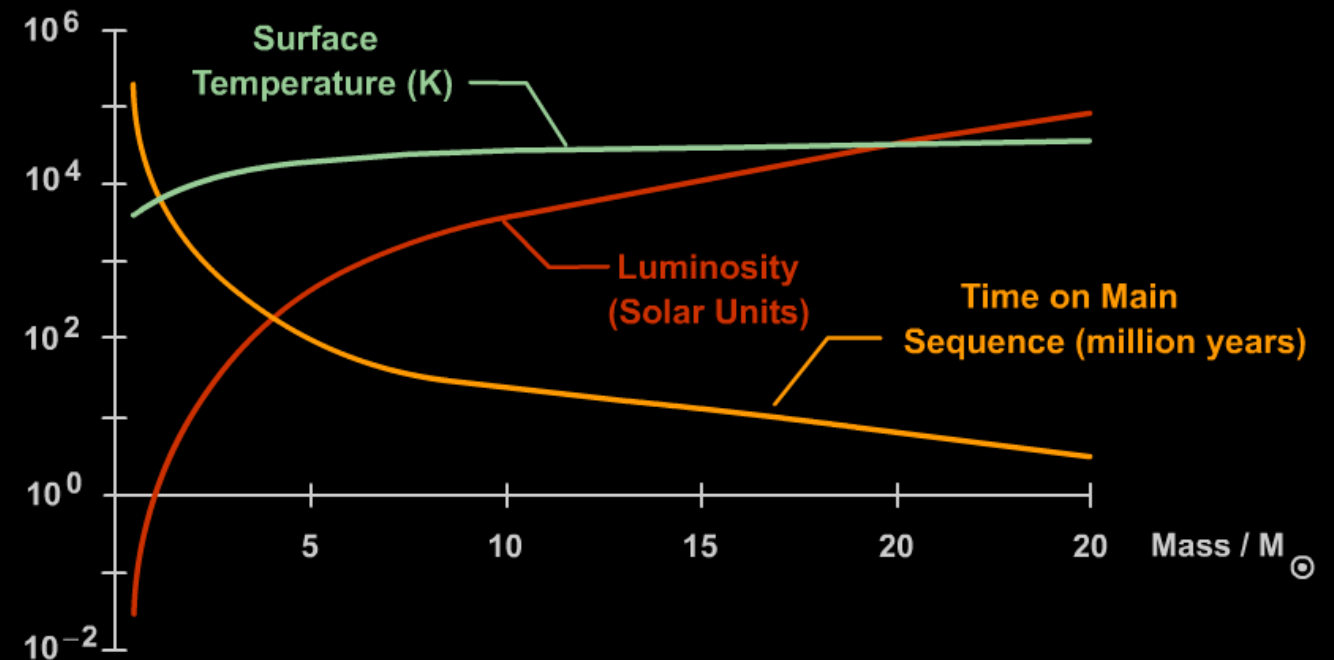
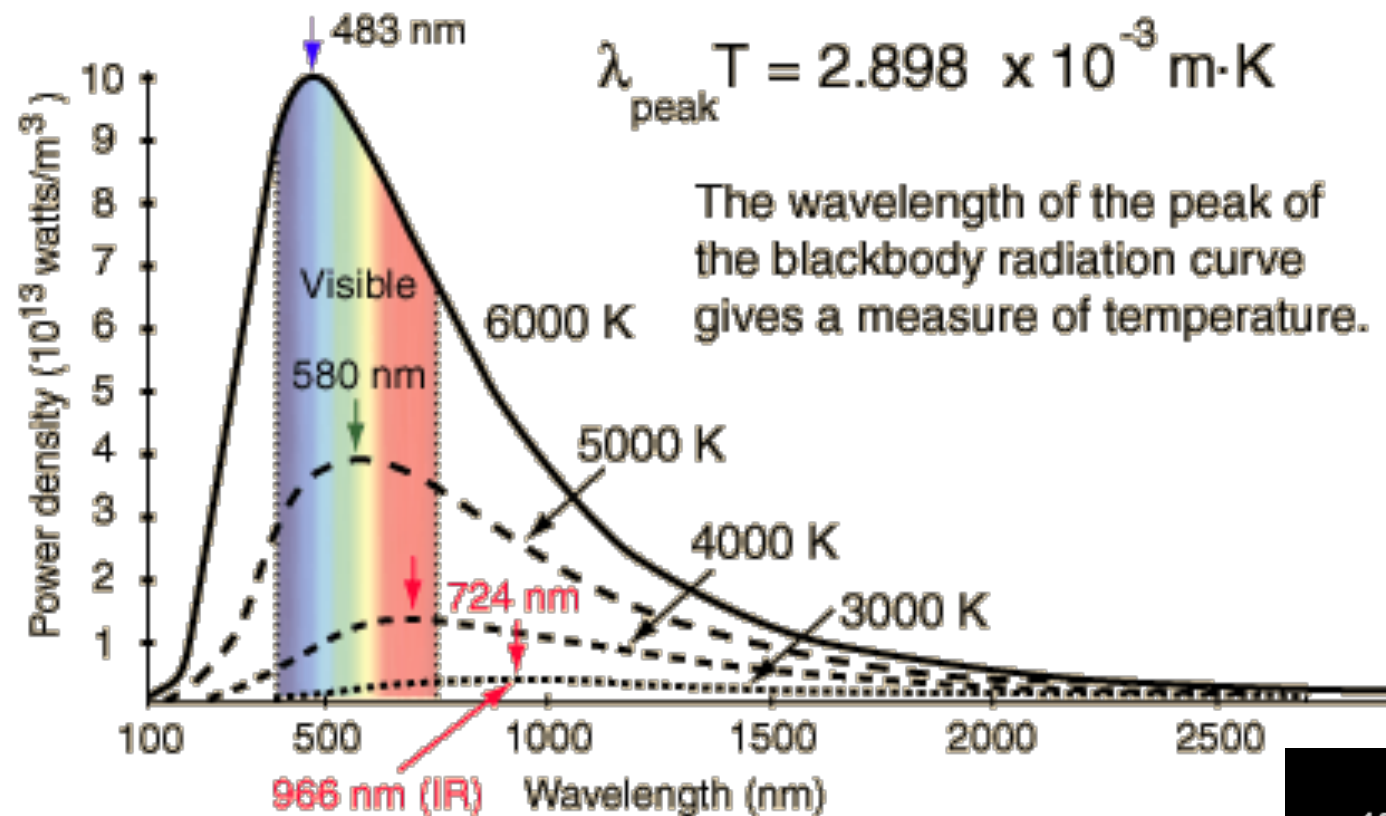
Size of Hubble eXtreme Deep Field on the Sky



Hubble eXtreme Deep Field (XDF)



Galaxy and stars colors



Galaxy colors

Elliptical galaxy



Spiral galaxy

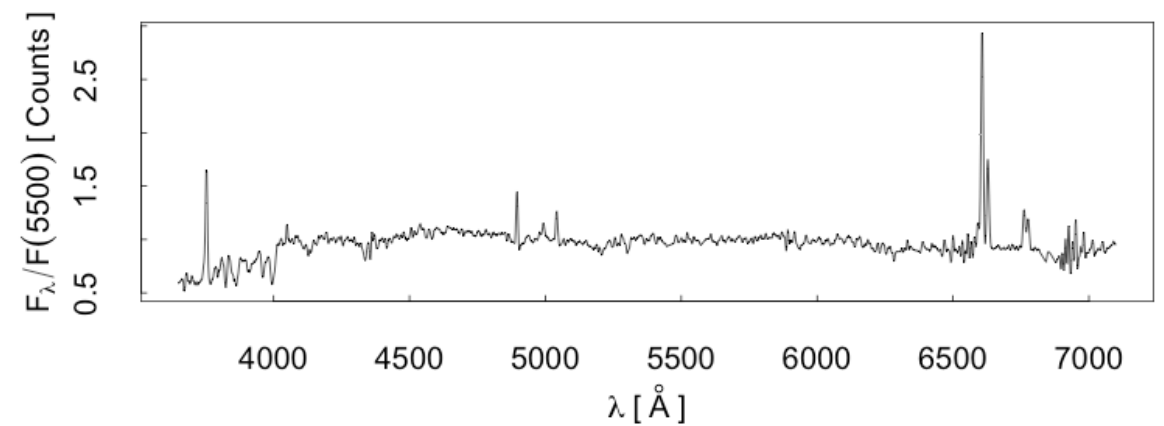
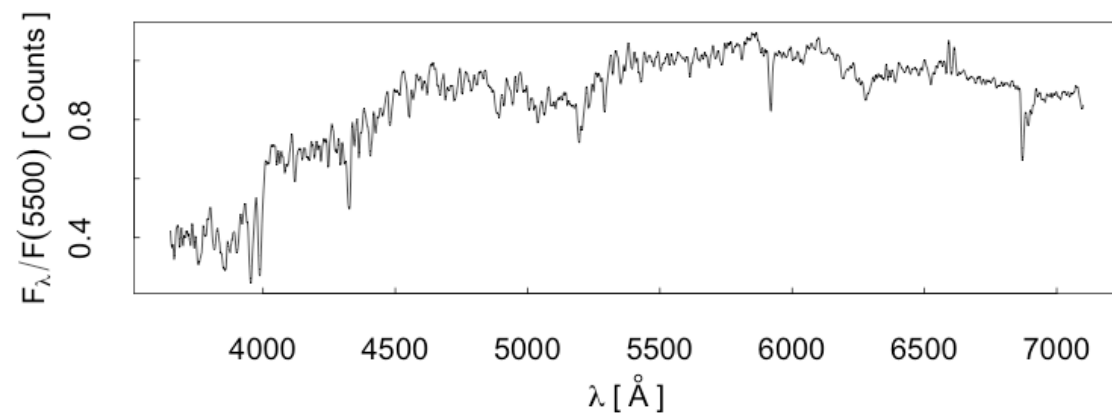


Galaxy colors

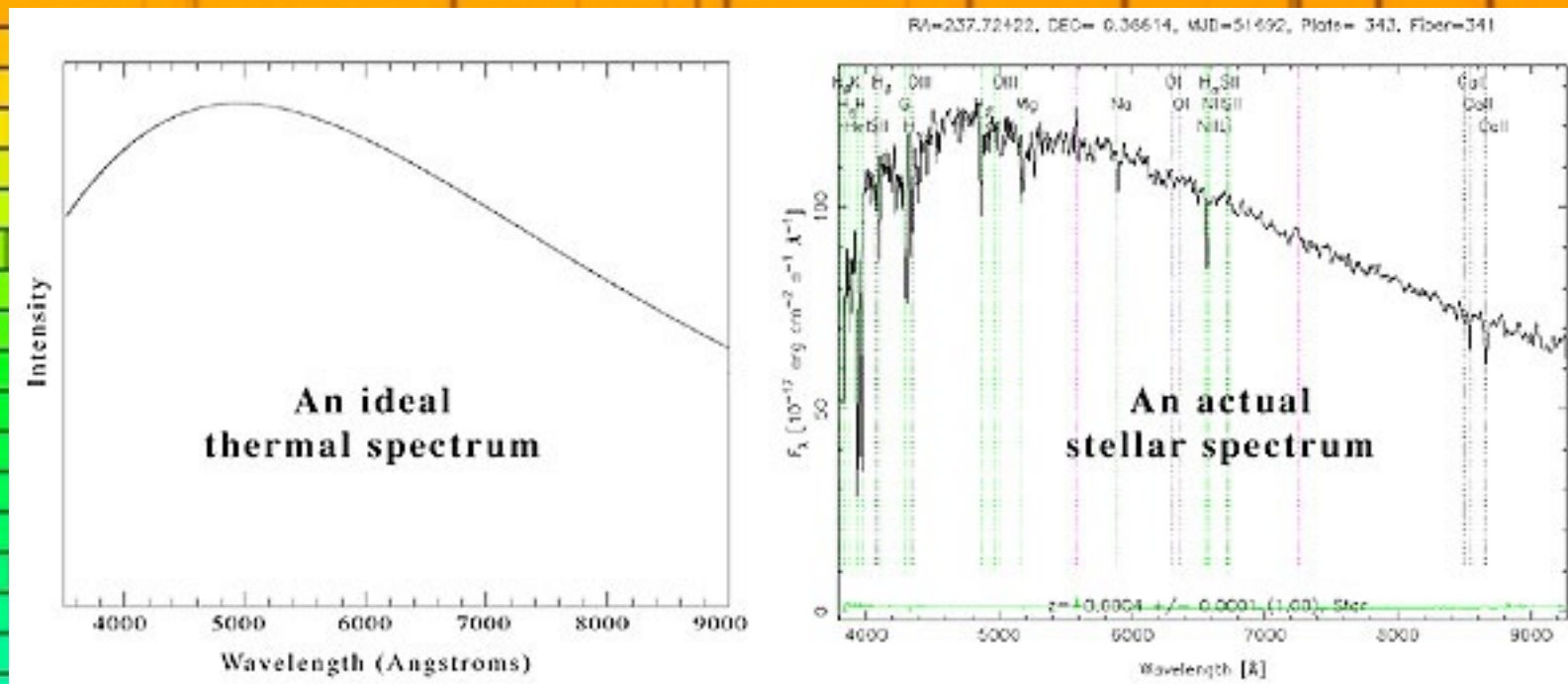
Elliptical galaxy

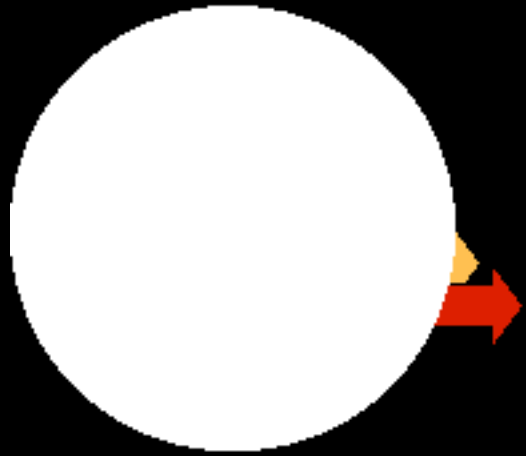


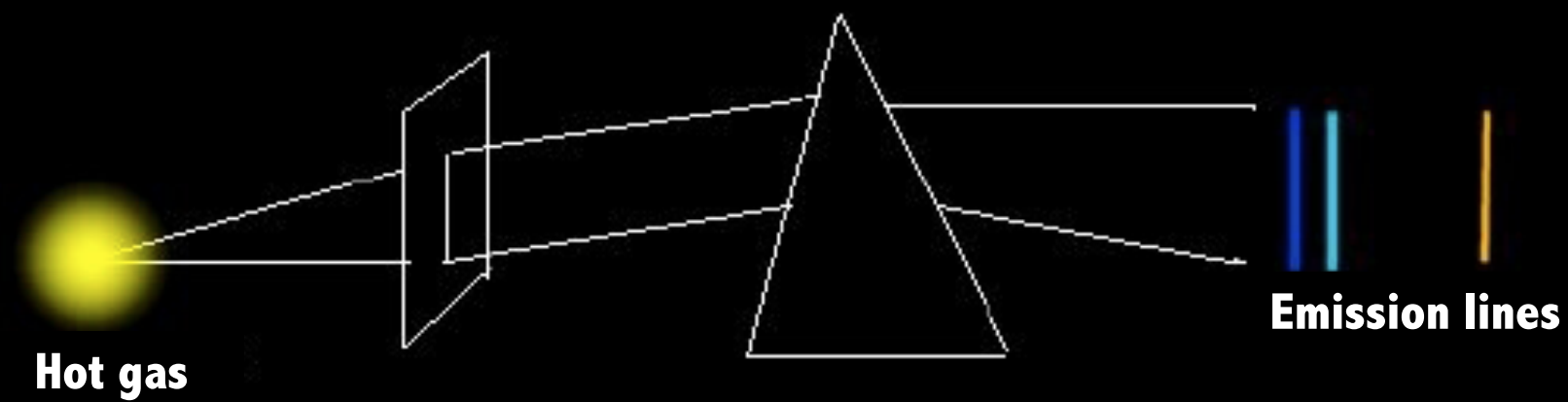
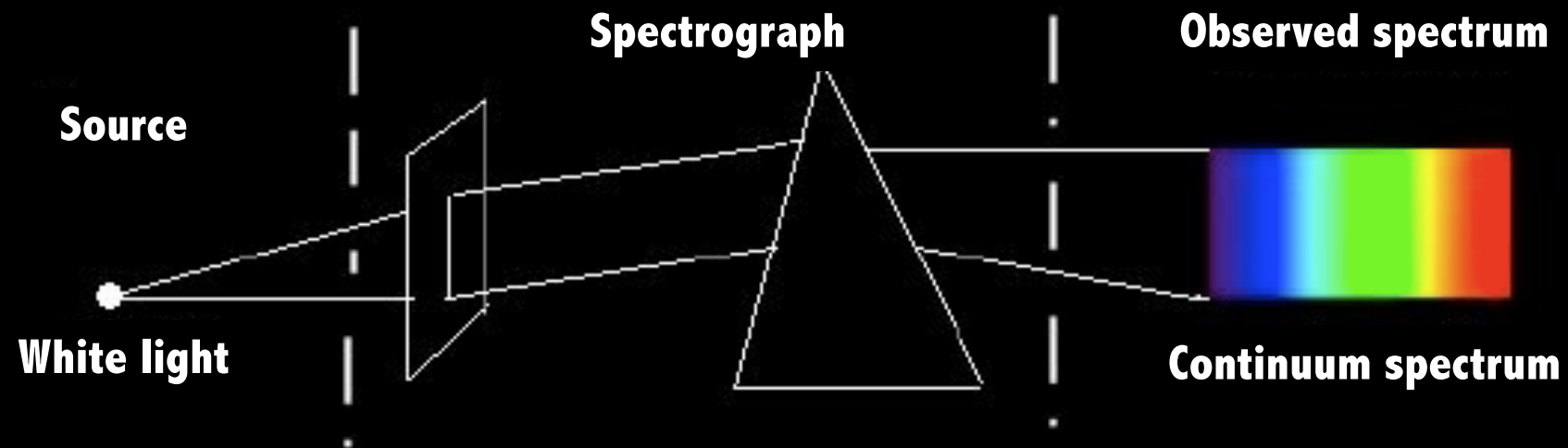
Spiral galaxy

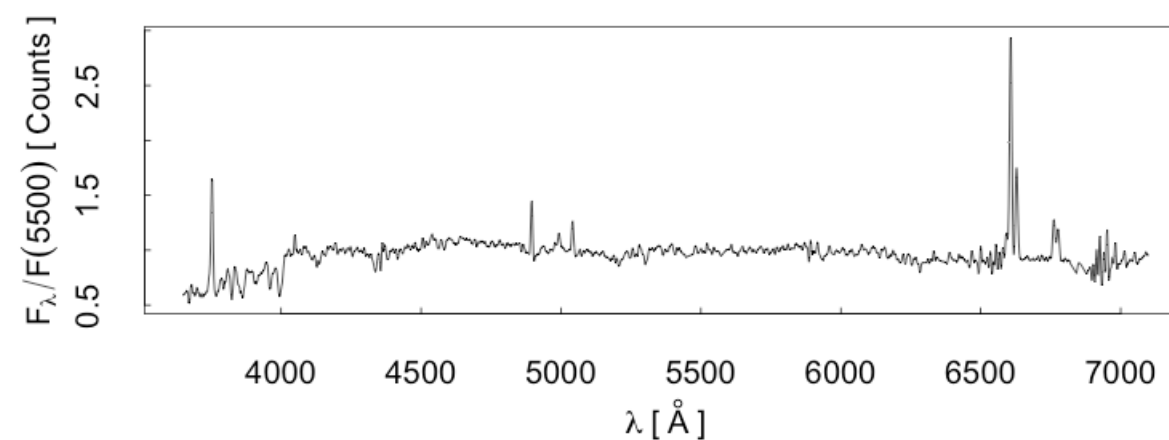
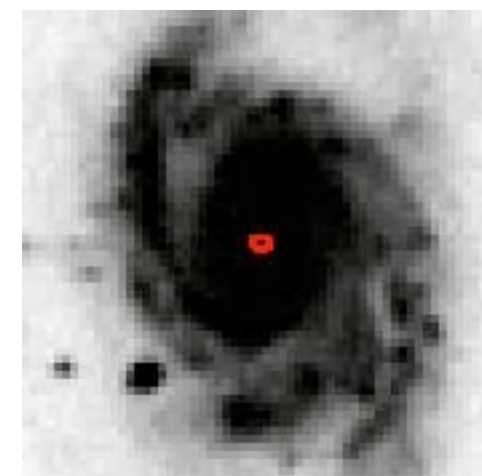
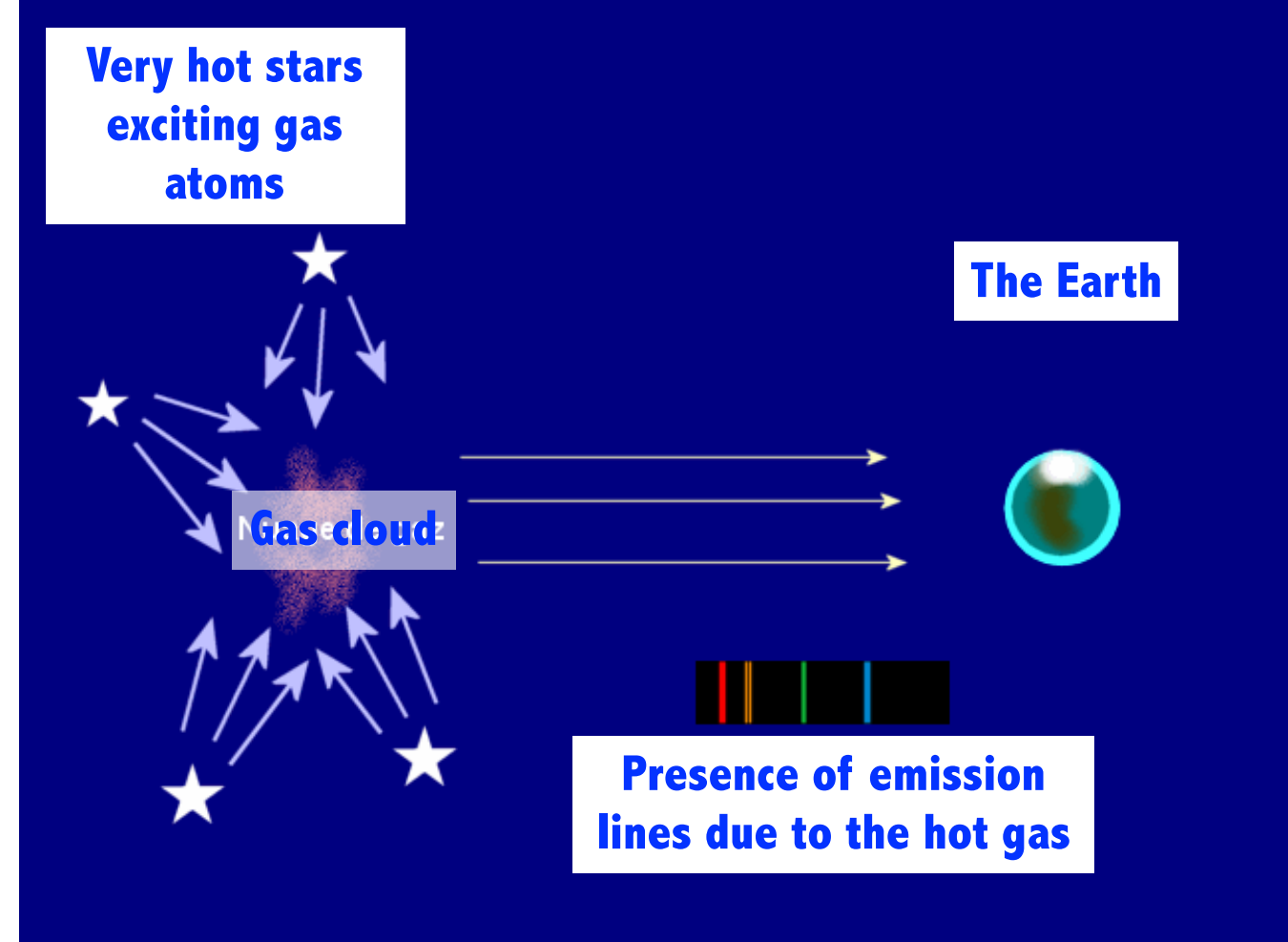
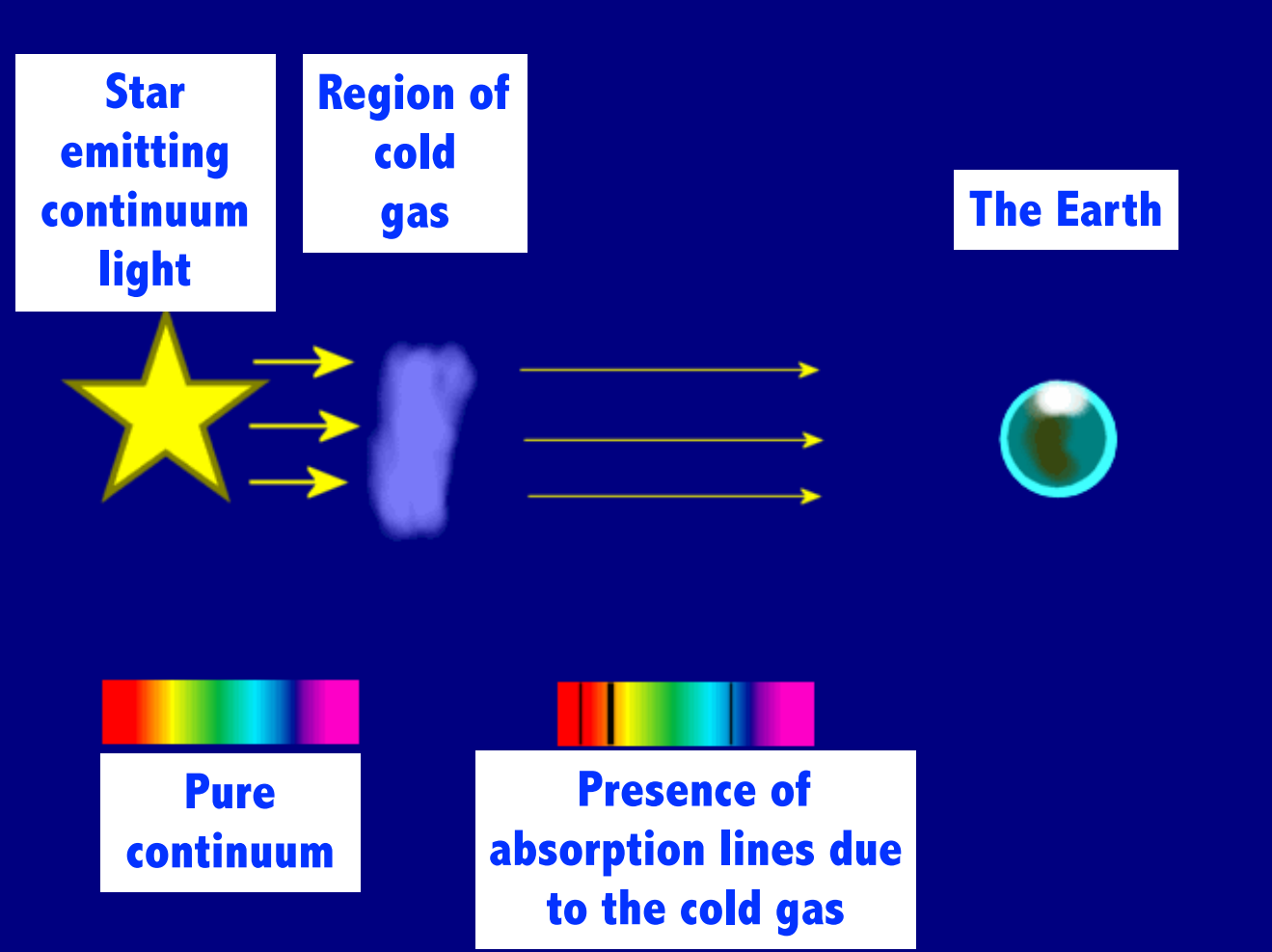


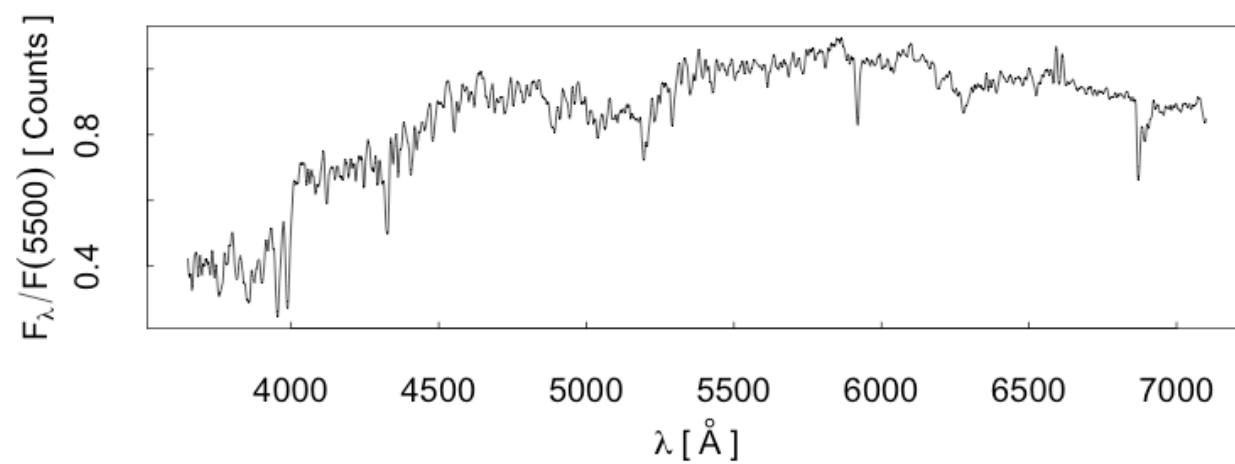
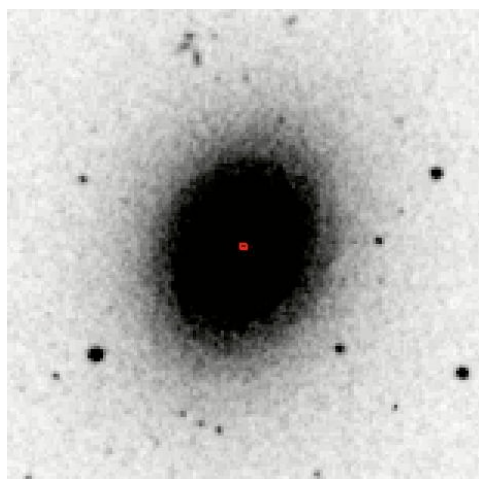
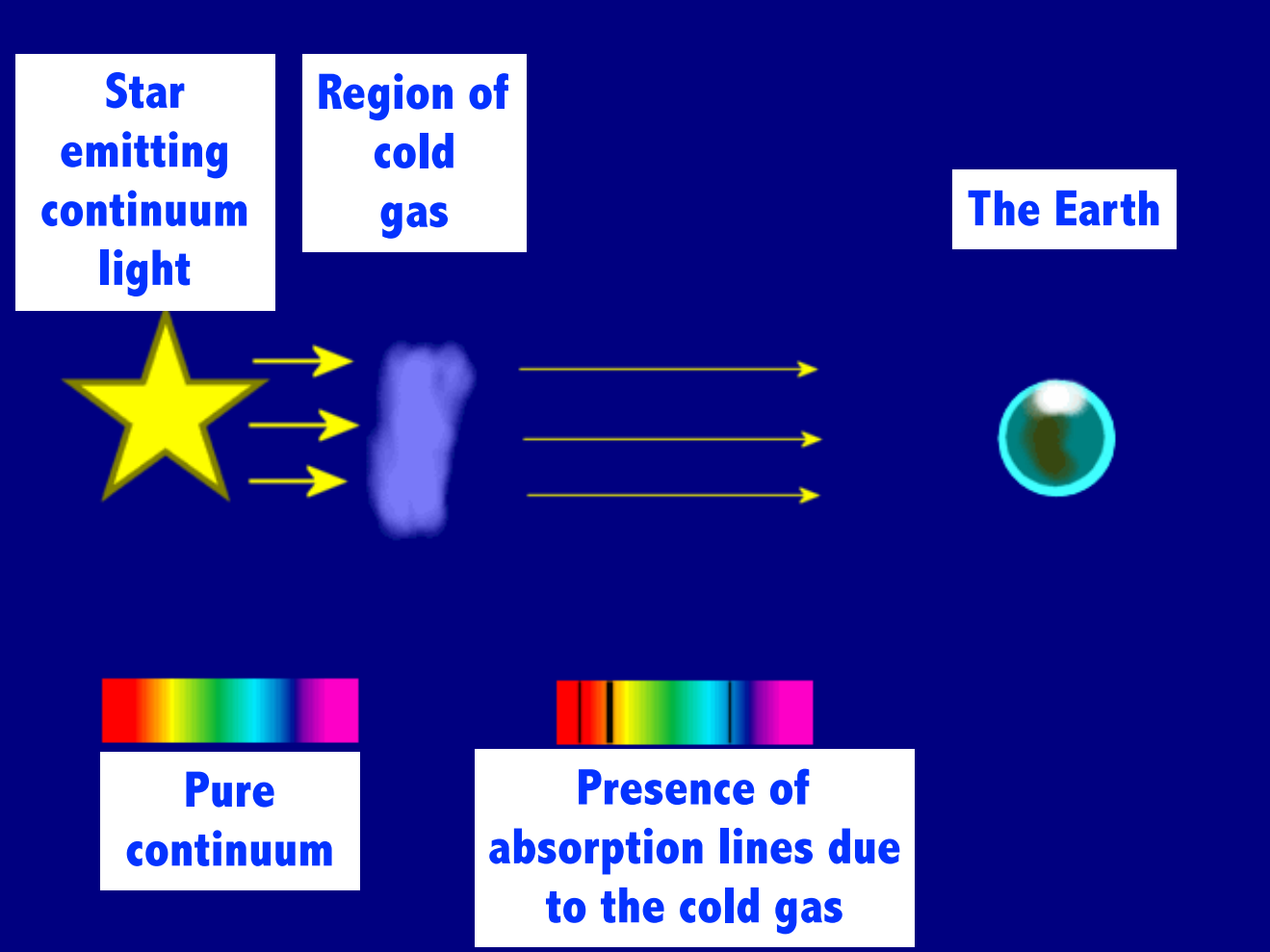
Stars spectra



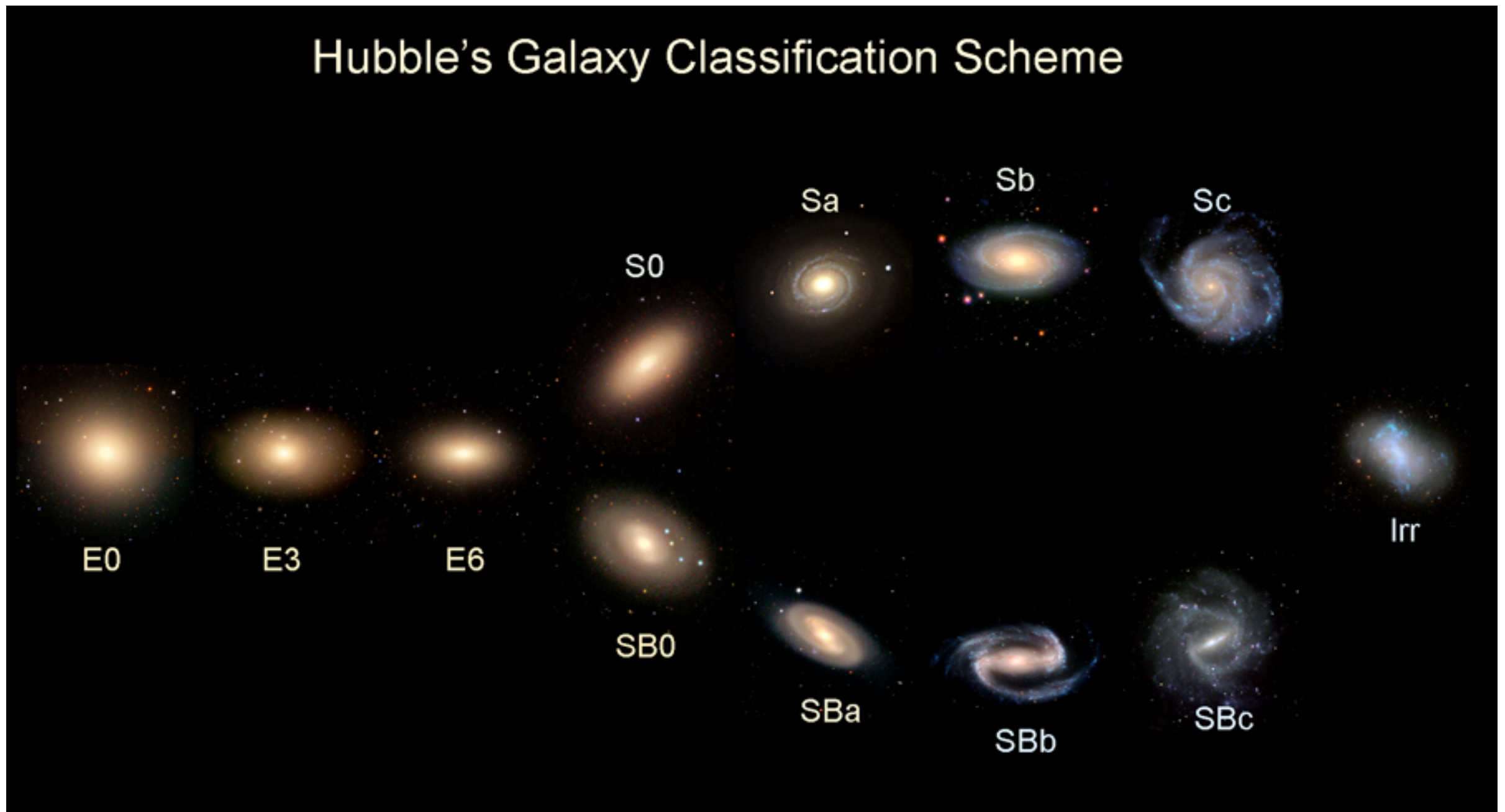








Galaxy morphologies



Galaxy morphologies



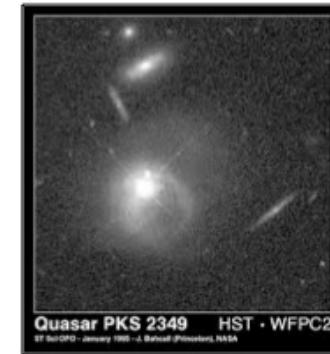
<http://www.spacetelescope.org>

Morphological evolution

The Evolutionary Merger Scenario



Spiral Galaxies



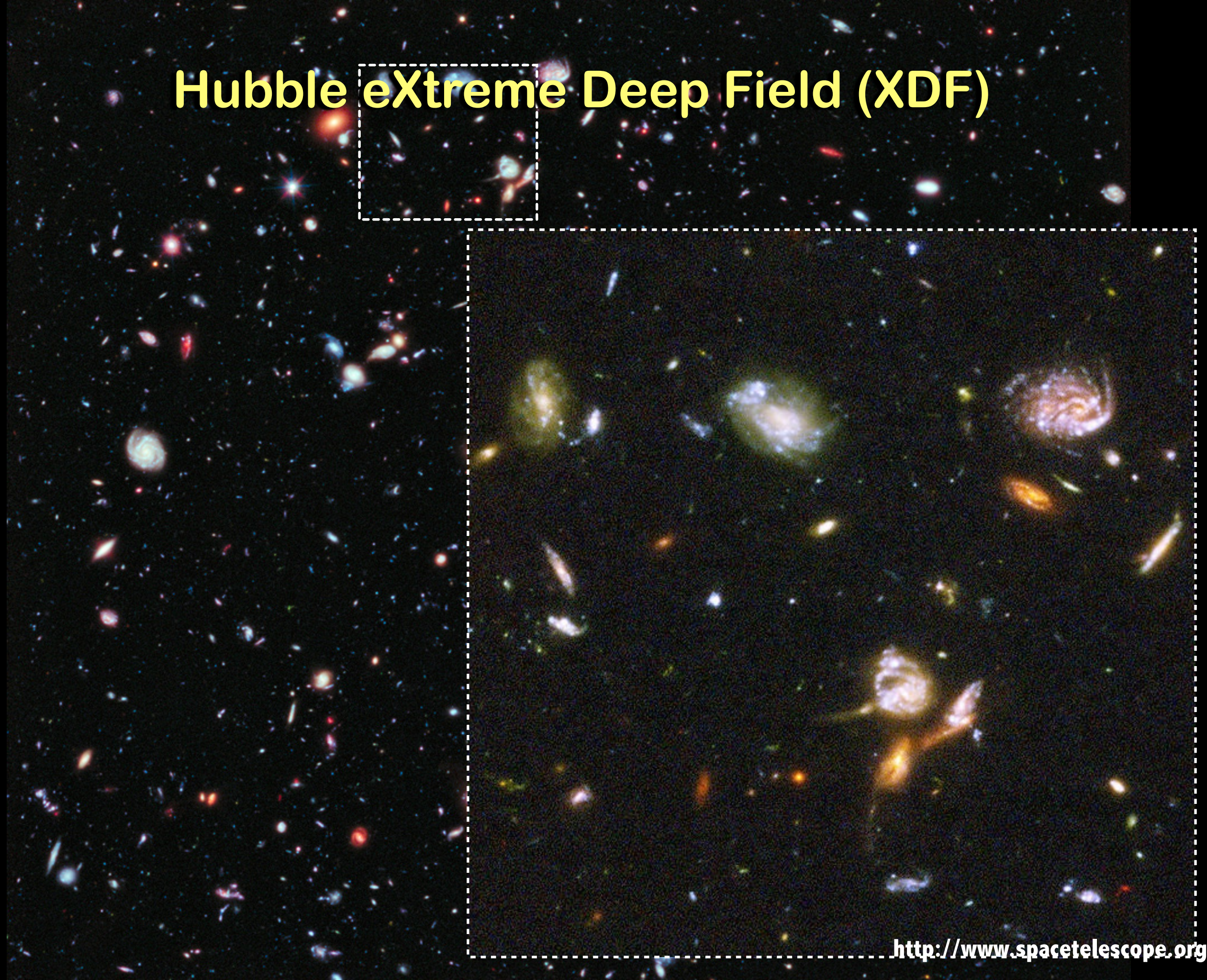
Elliptical Galaxy



Morphological evolution

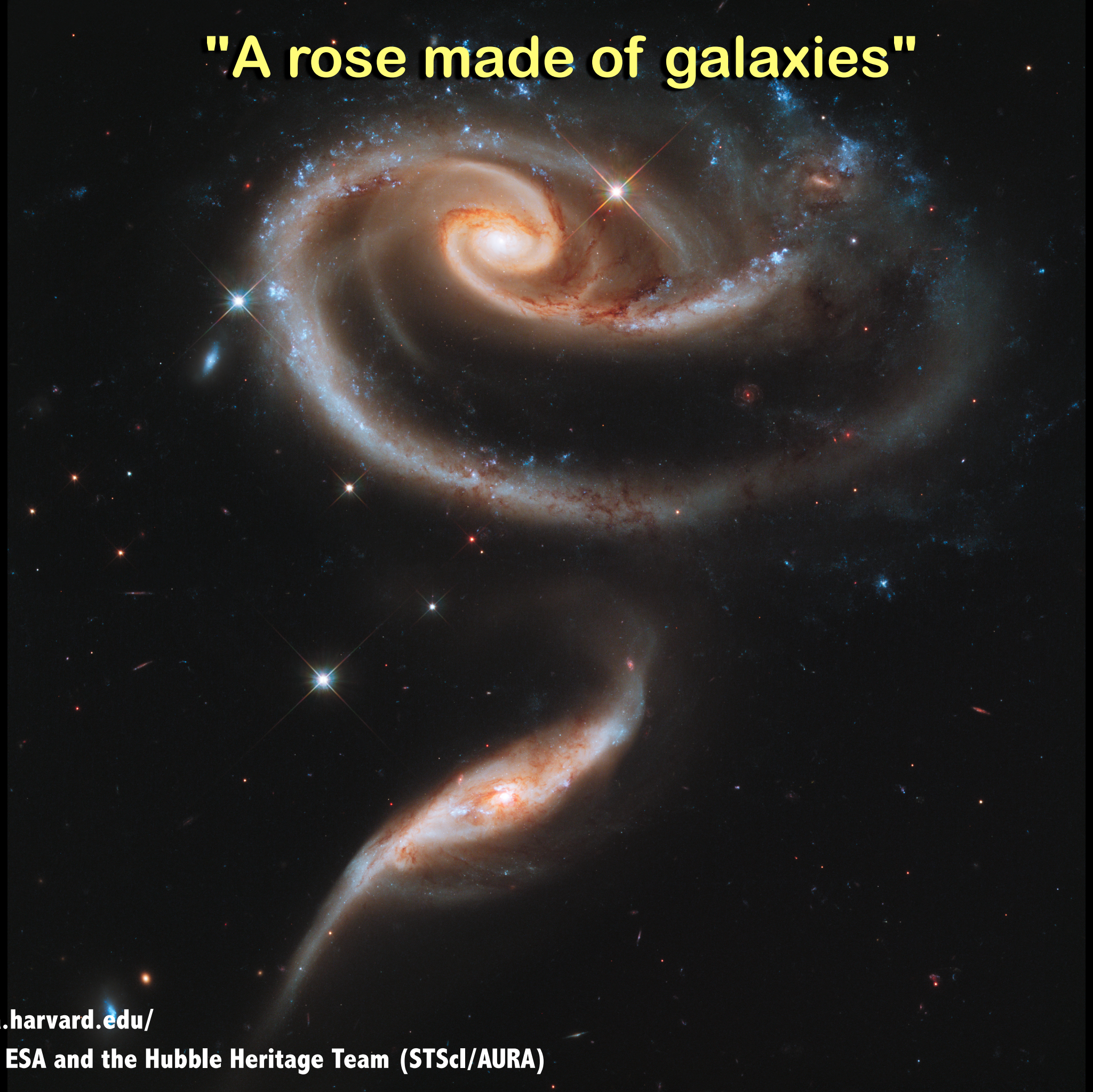


Hubble eXtreme Deep Field (XDF)



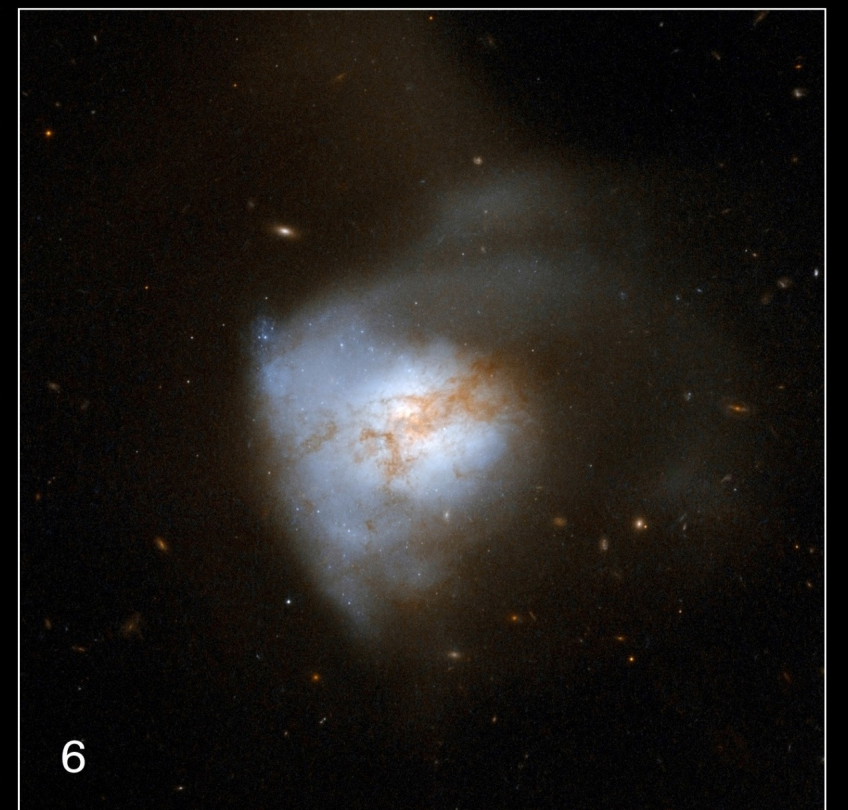
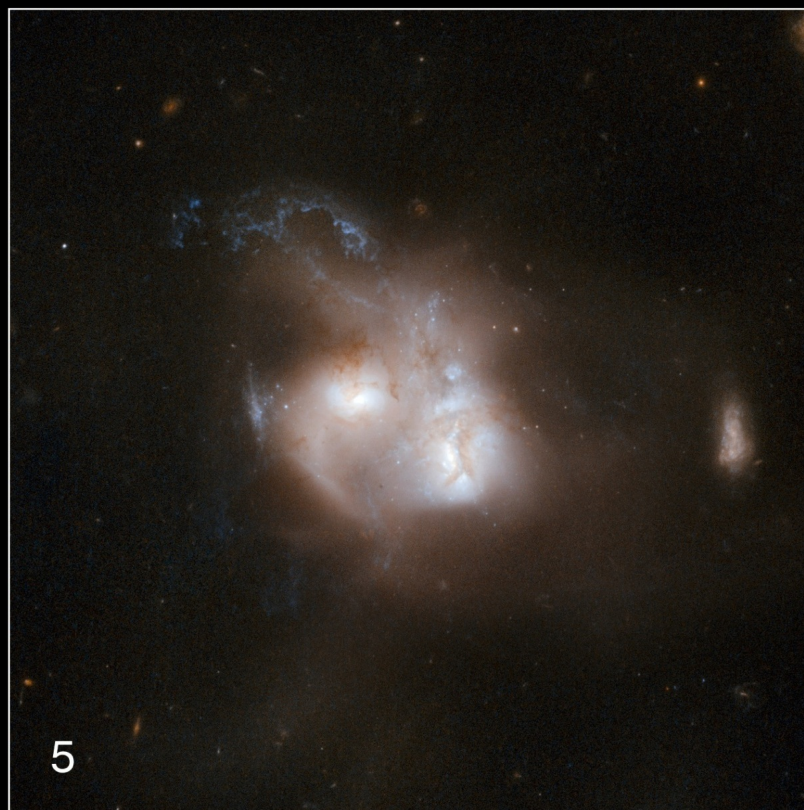
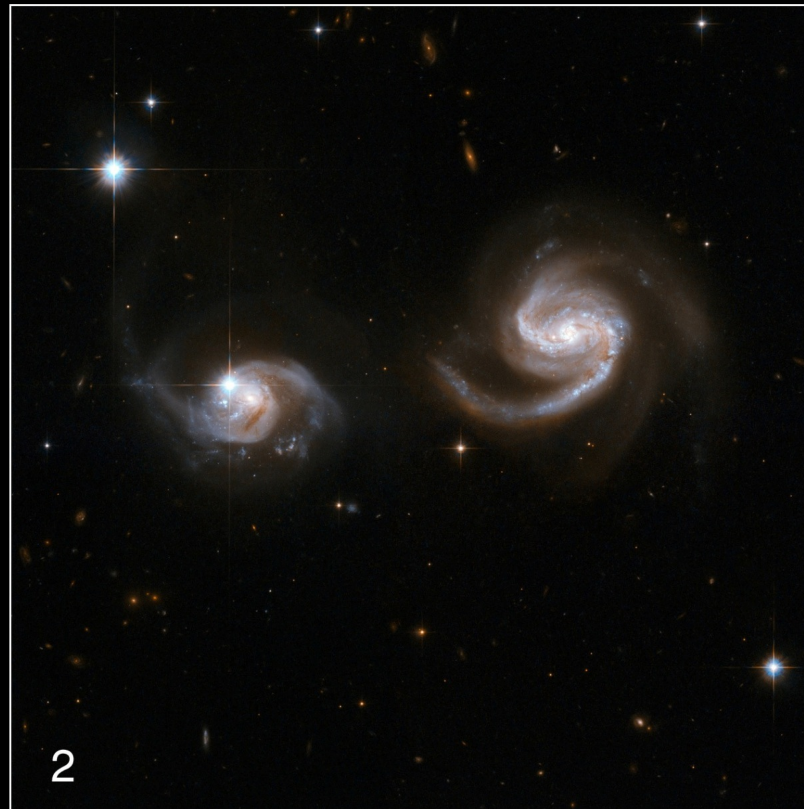


"A rose made of galaxies"



<http://chandra.harvard.edu/>

Credits: NASA, ESA and the Hubble Heritage Team (STScI/AURA)



<http://chandra.harvard.edu/>

Credits: NASA, ESA, the Hubble Heritage Team (STScI/AURA) -ESA/Hubble Collaboration and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University), K. Noll (STScI), and J. Westphal (Caltech)



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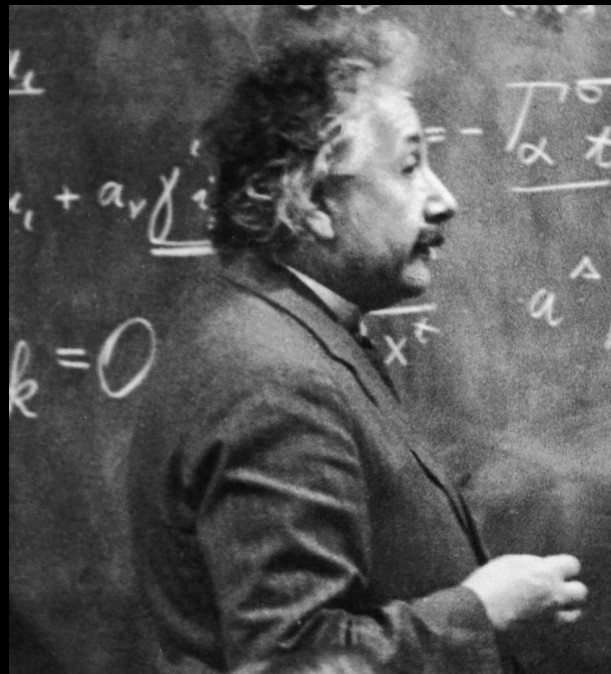
One or more telescopes (powerful...)

The sky (without clouds...)

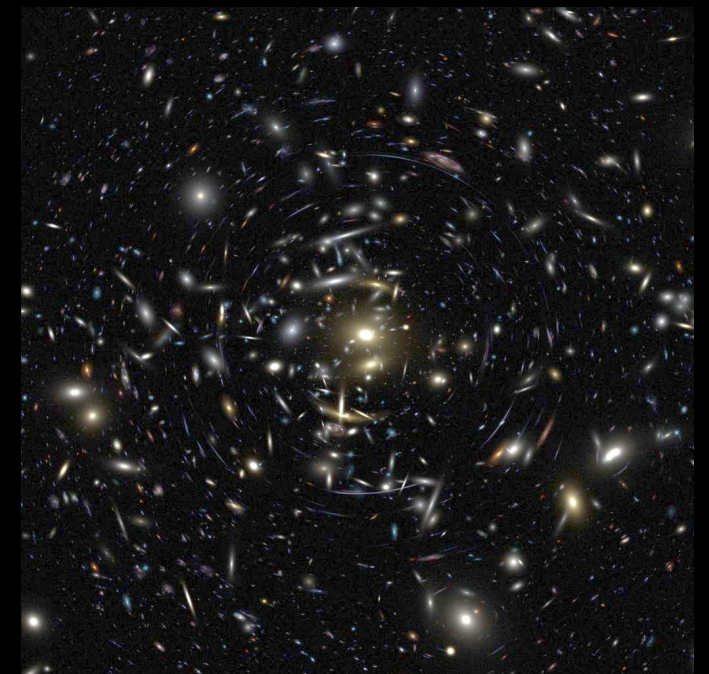
Wonderful images of the sky !



+



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**One or more computers
(powerful...)**

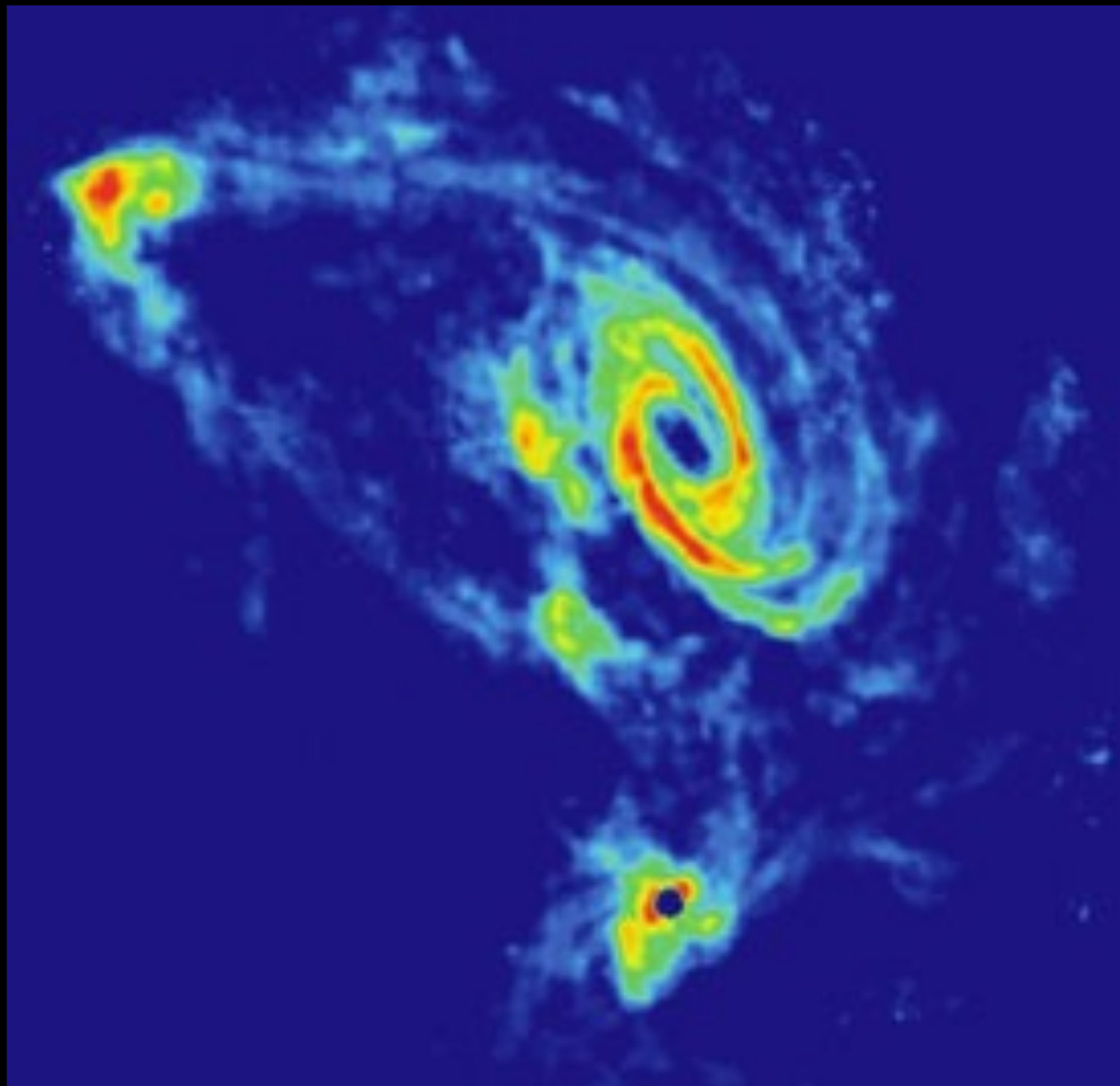
**Some physics
(more or less complicate..)**

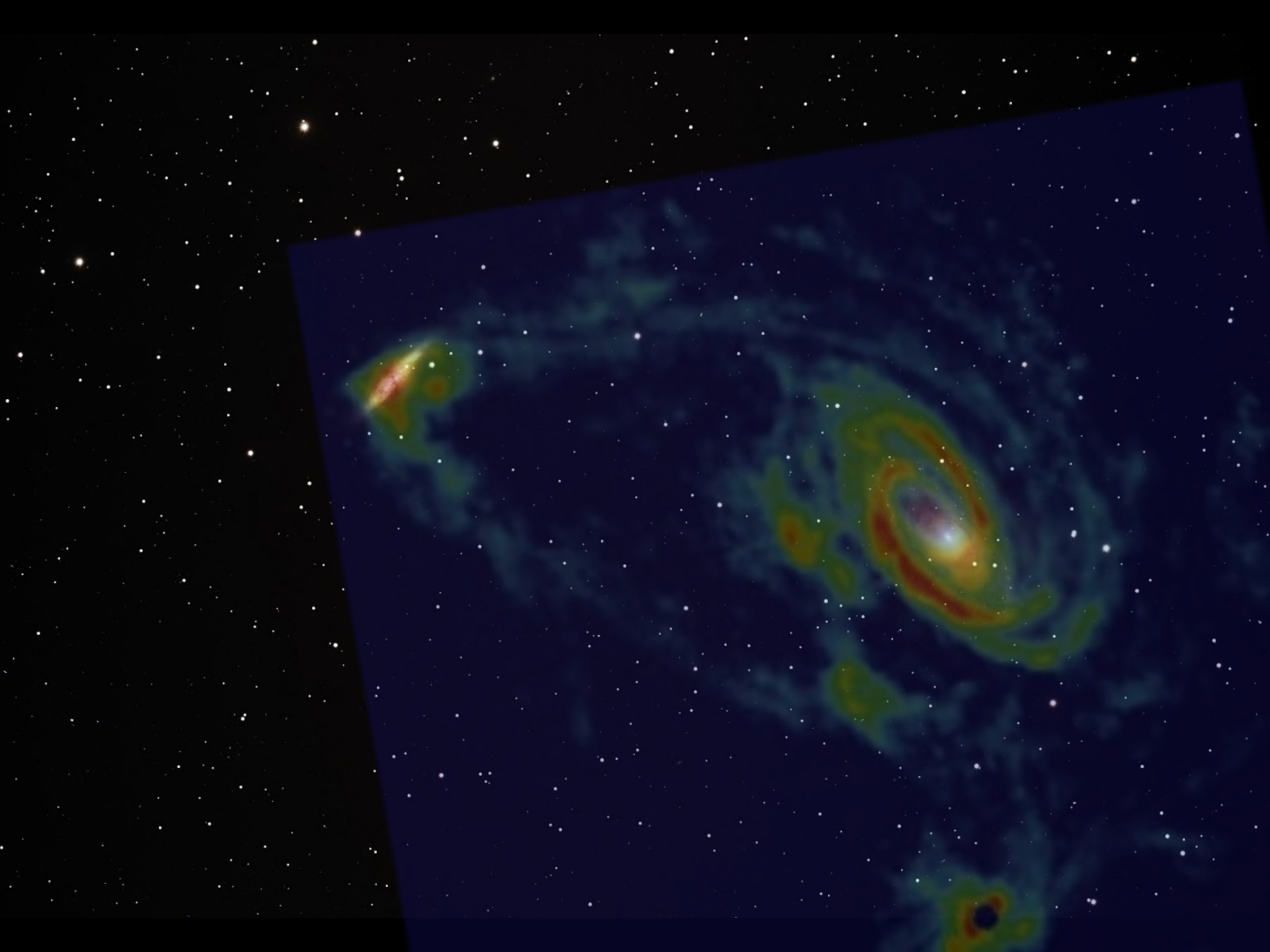
Wonderful images of the “sky” !

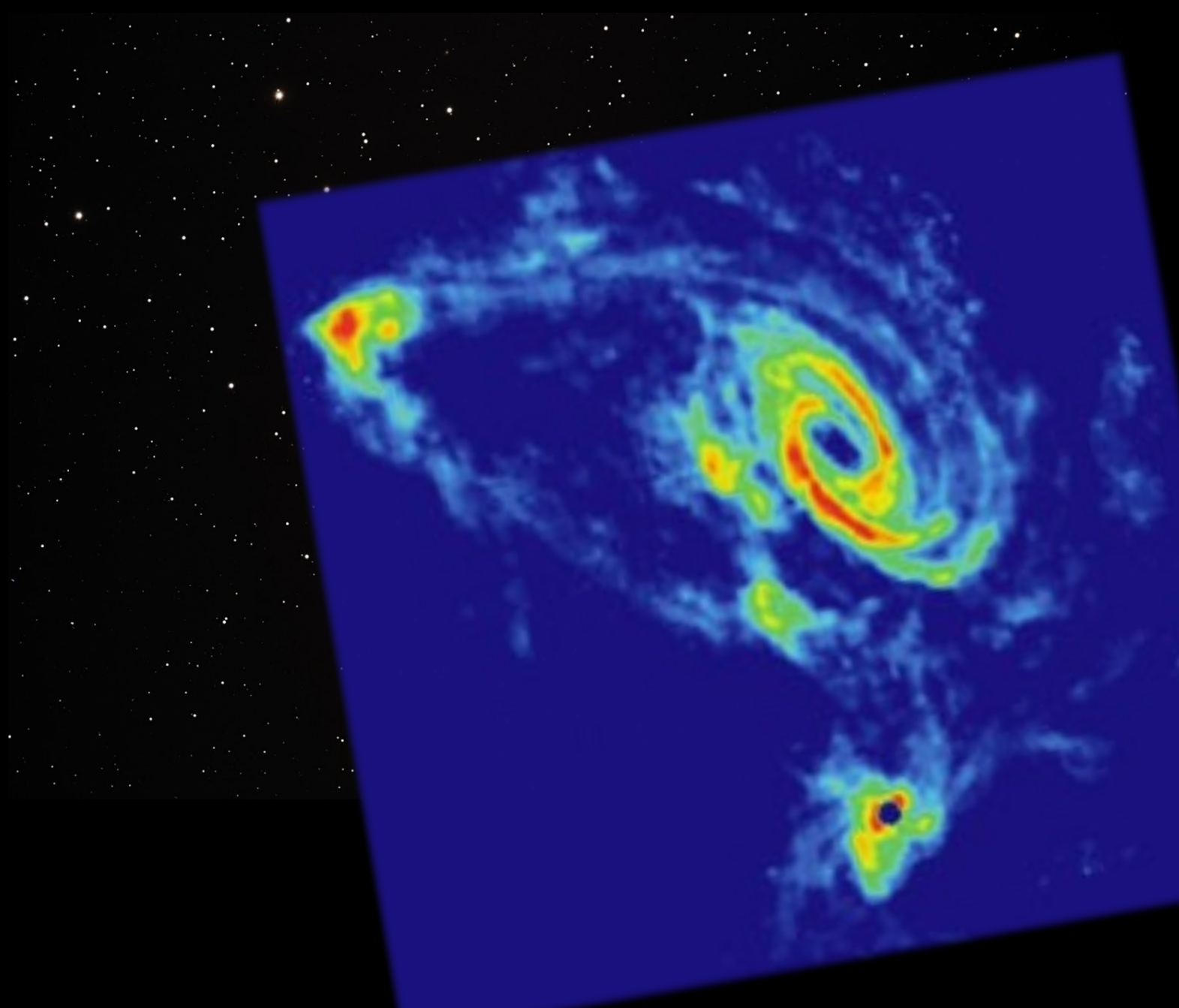
<http://hubblesite.org/videos/>

Credits: Visualization: F. Summers (STScI) - Simulation: C. Mihos (CWRU) & L. Hernquist (Harvard)



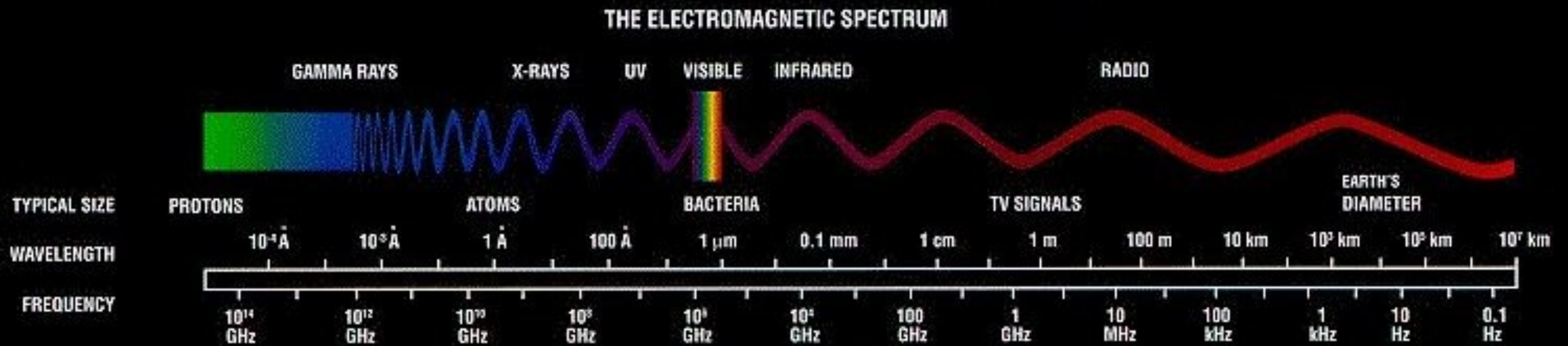






The Very Large Array (VLA)





A different view of the sky: radio observations

The Very Large Array (VLA)



The atomic gas content of galaxies



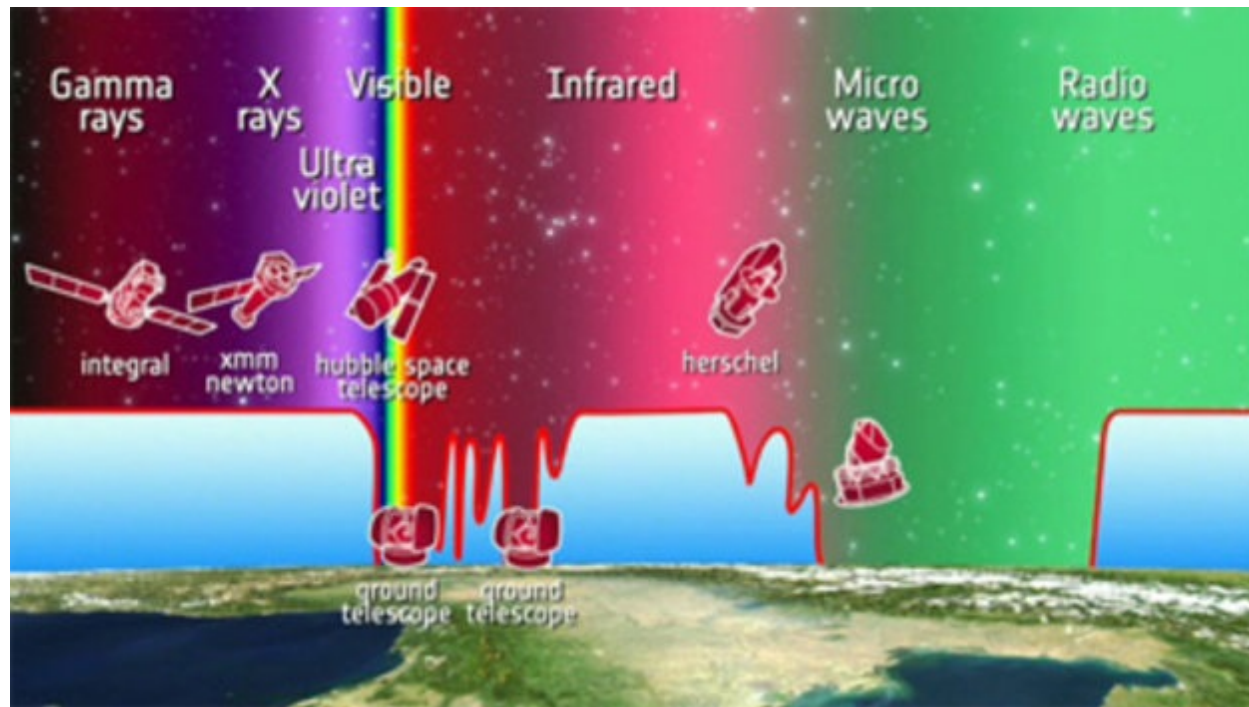
Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting).
(By courtesy of H. C. van de Hulst, Leiden)

Predicted by Van de Hulst in 1945 ...



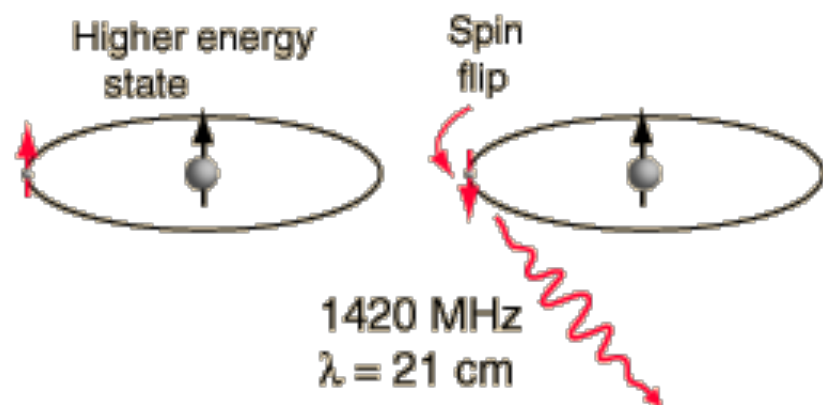
... and detected by Ewen & Purcell in 1951

The atomic gas content of galaxies

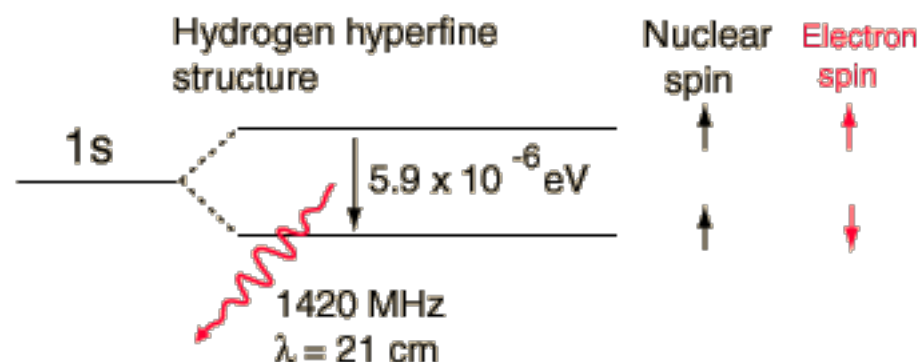


... and detected by Ewen & Purcell in 1951

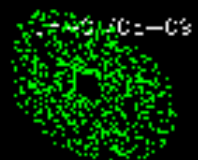
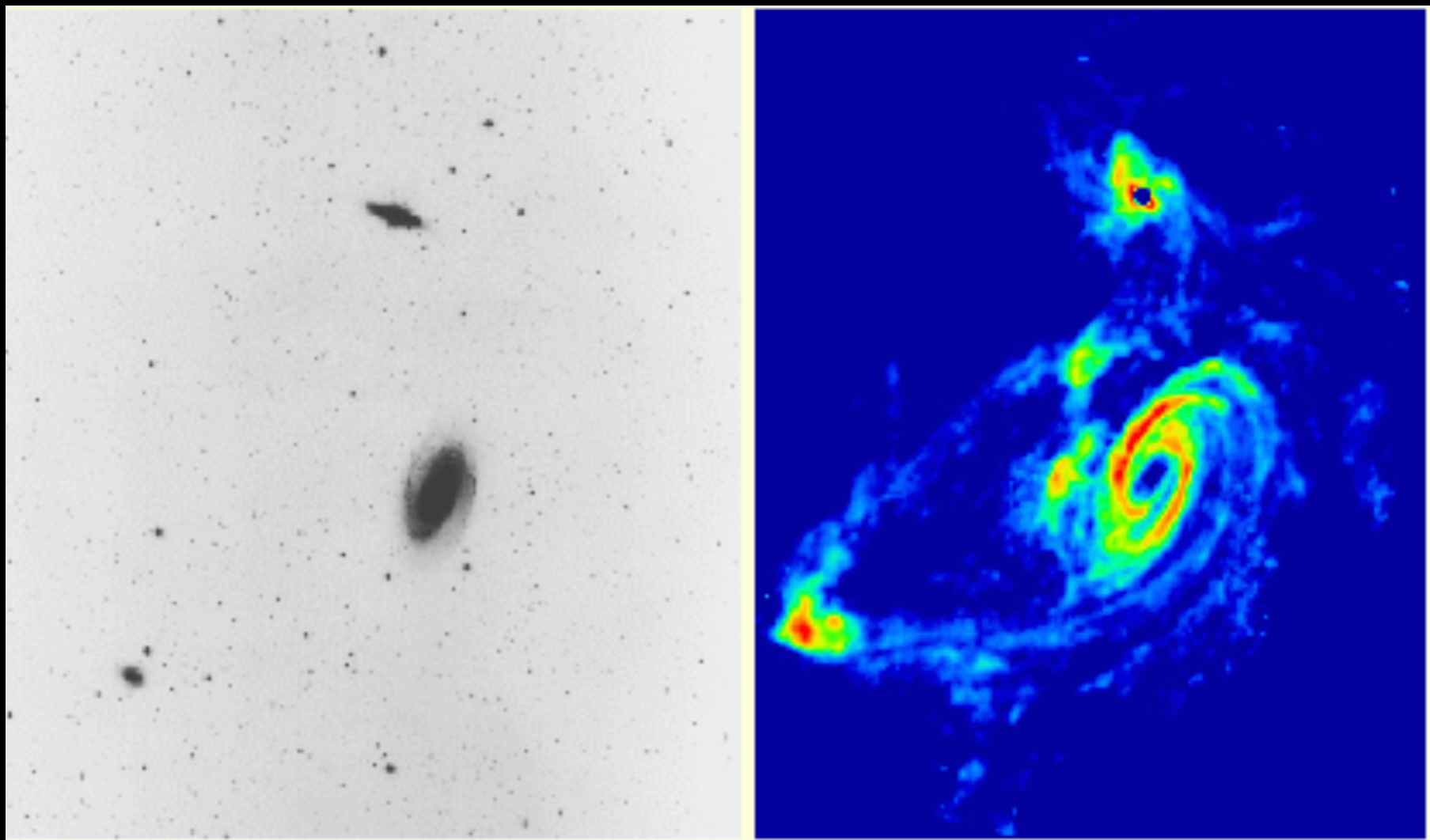
The atomic gas content of galaxies



$$\underline{n = 1, {}^2S} \quad \underline{J = 1/2} \quad \begin{array}{c} \underline{F = 1} \\ \underline{F = 0} \end{array} \updownarrow$$



- During low energy collisions, electrons flip their spin (from anti-parallel to parallel). **Collisional excitation**
- A longer time later, electrons flip back (average time = 10 000 yrs)
- 21 cm radiation is emitted
- It happens in galaxies due to:
 - i. huge amount of gas: 10^9 - $10^{10} M_{\odot}$
 - ii. very low density: $<1 \text{ atom/cm}^3$

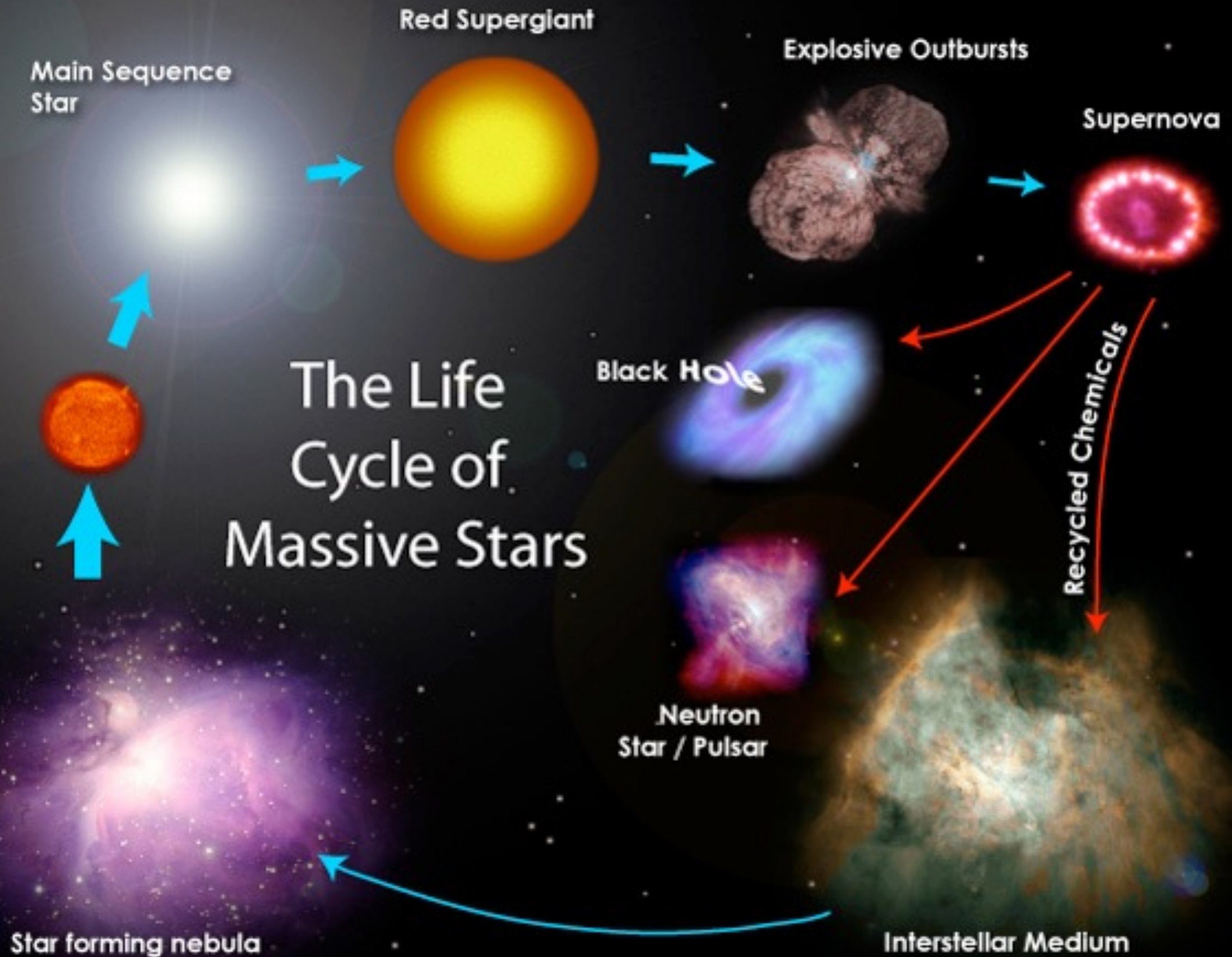


Interacting Galaxies Arp 194

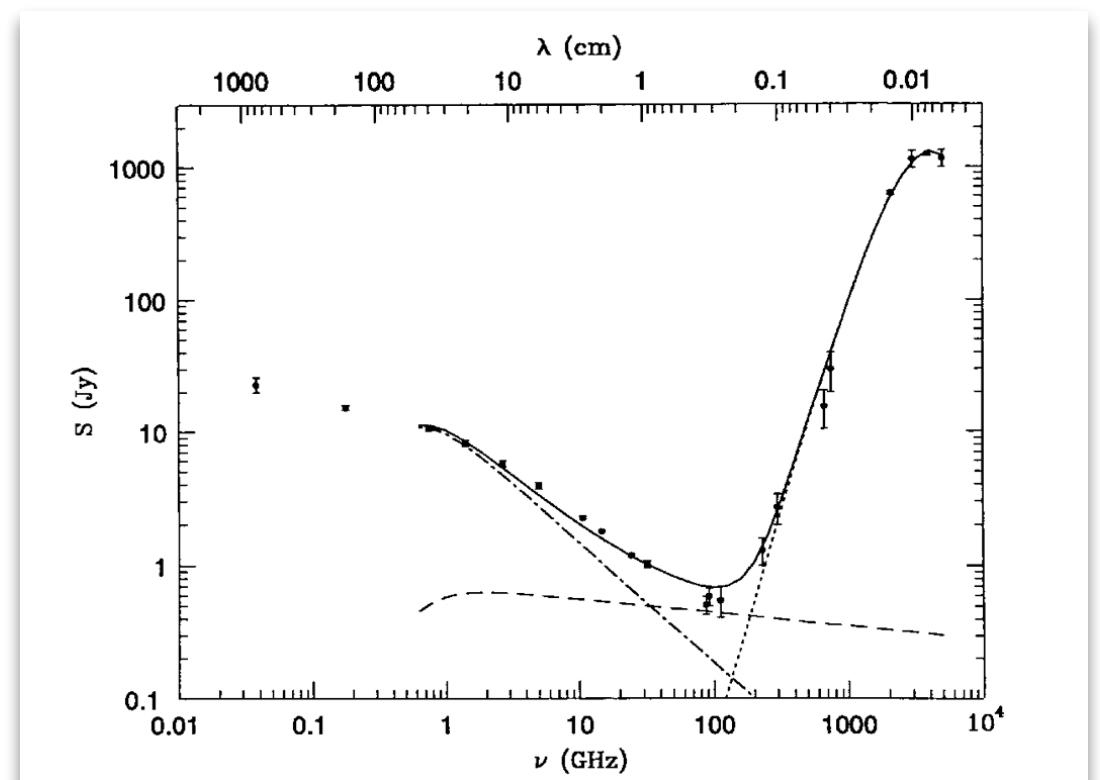
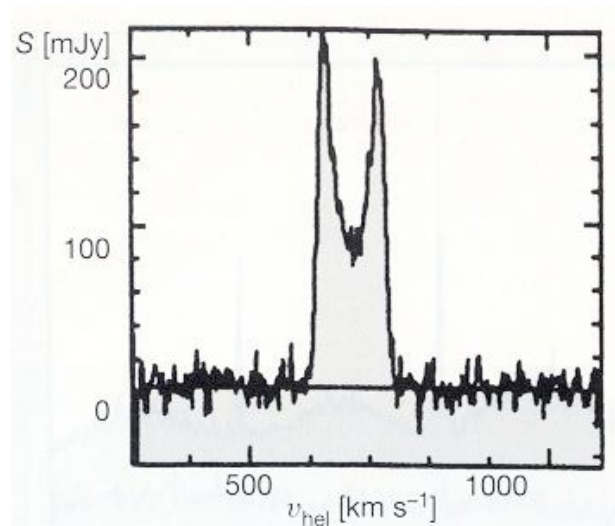
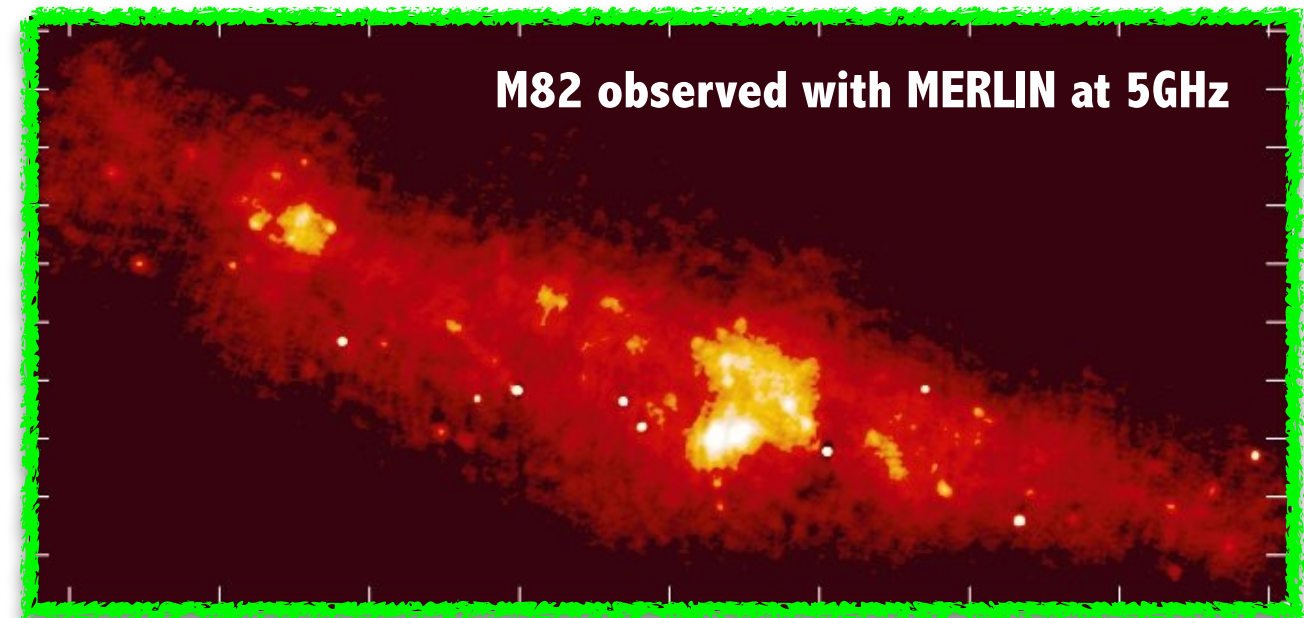
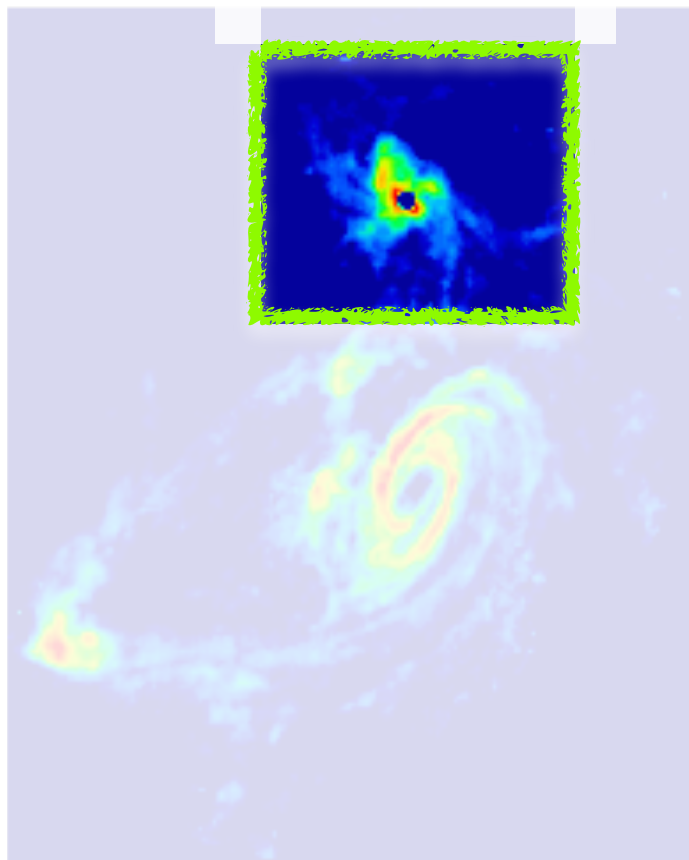


Hubble
Heritage

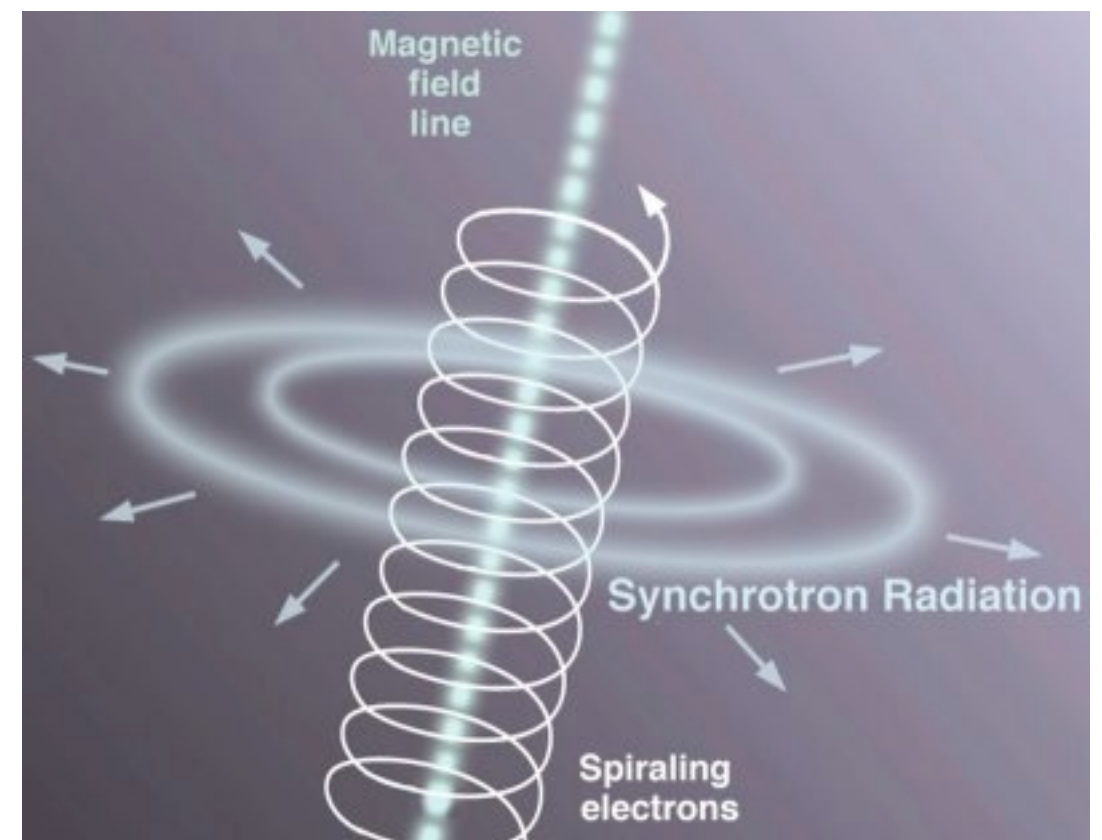
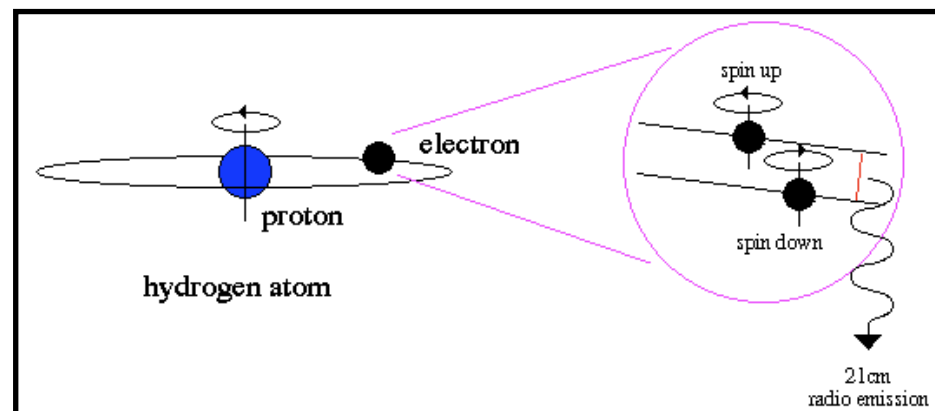
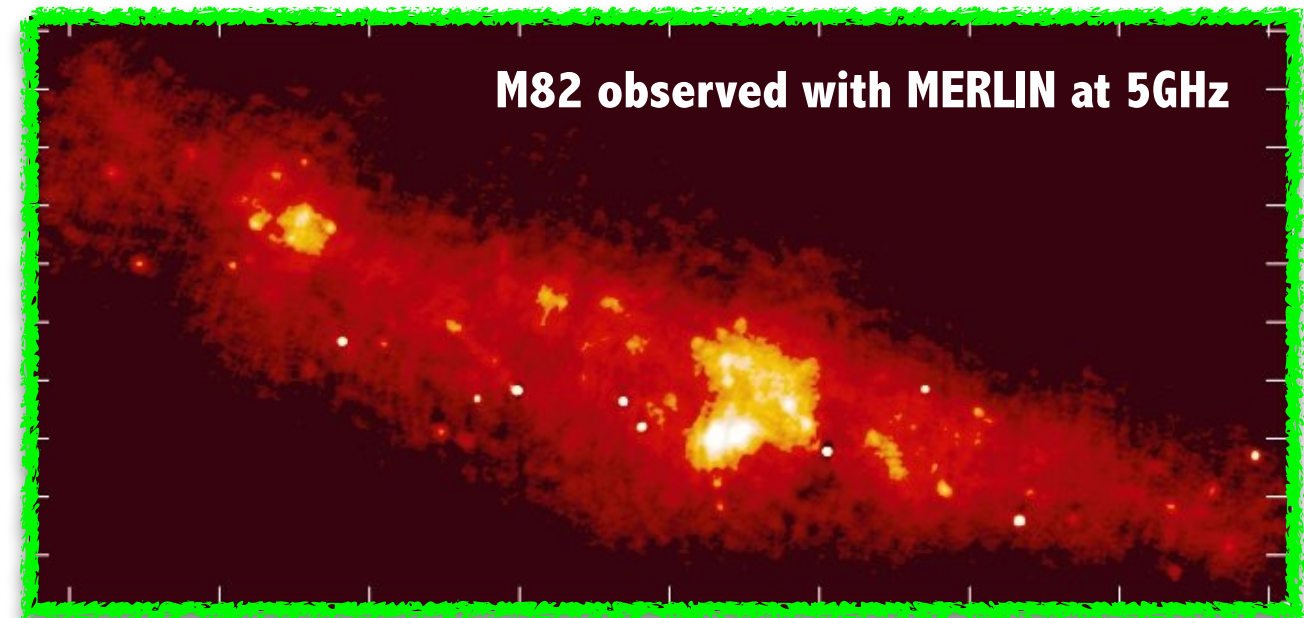
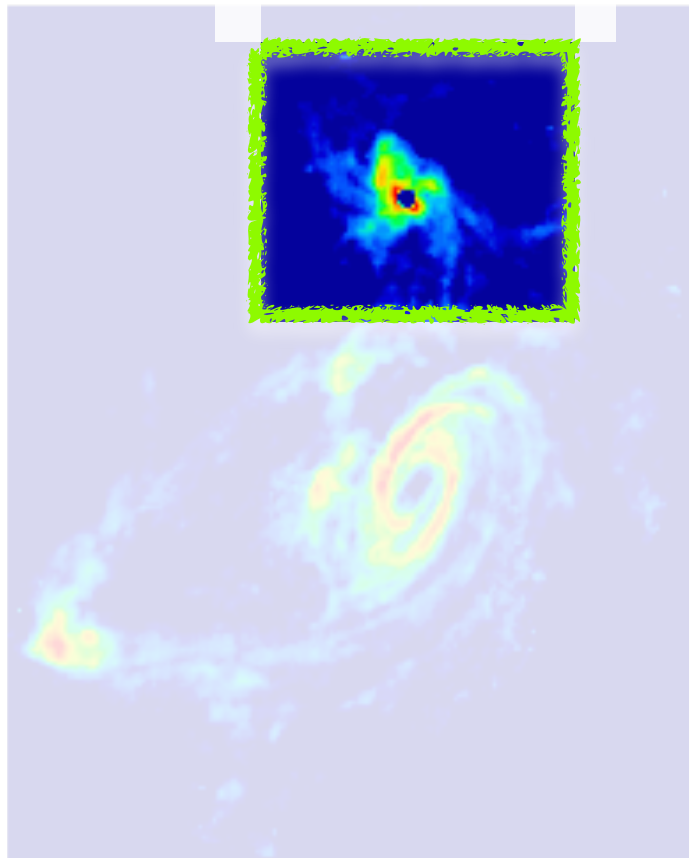
The Life Cycle of Massive Stars



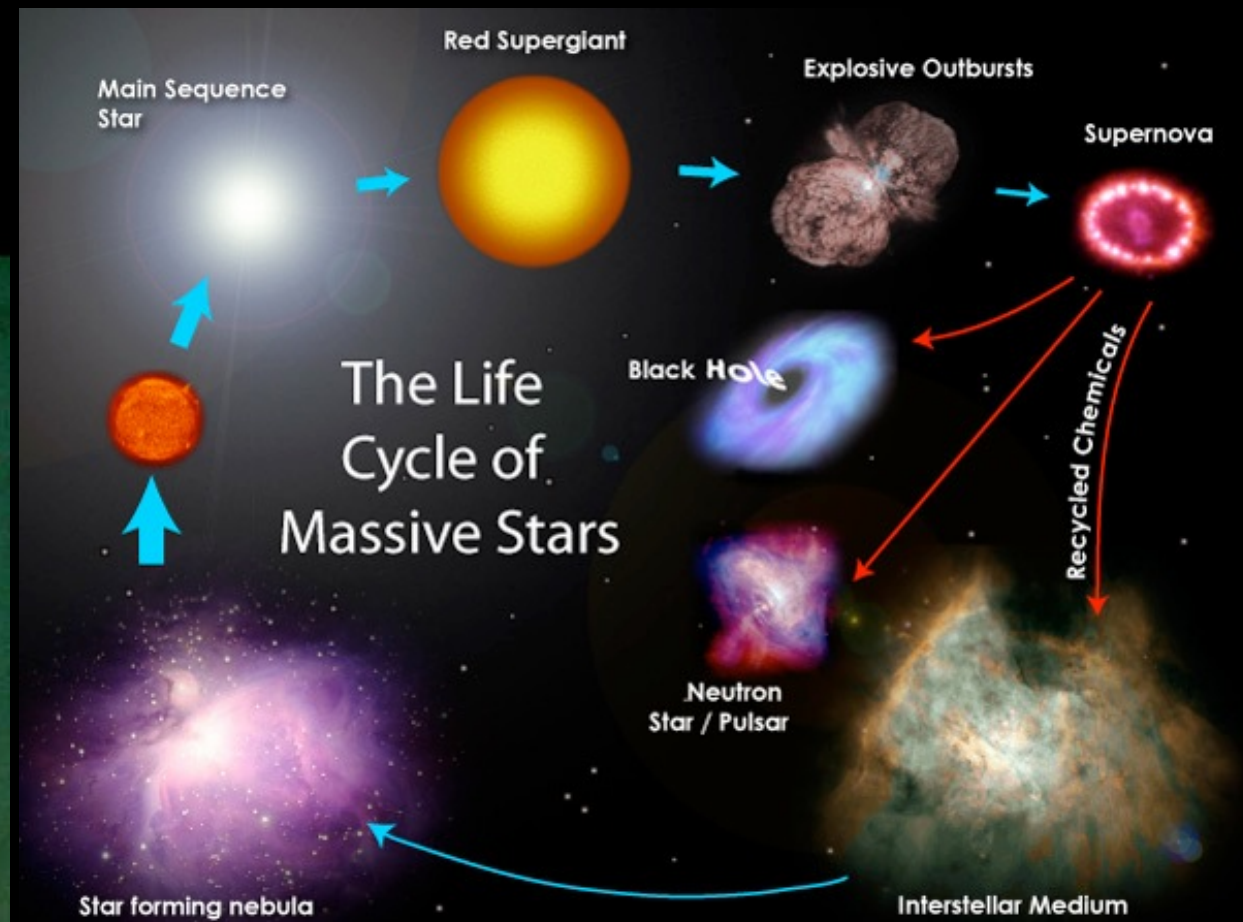
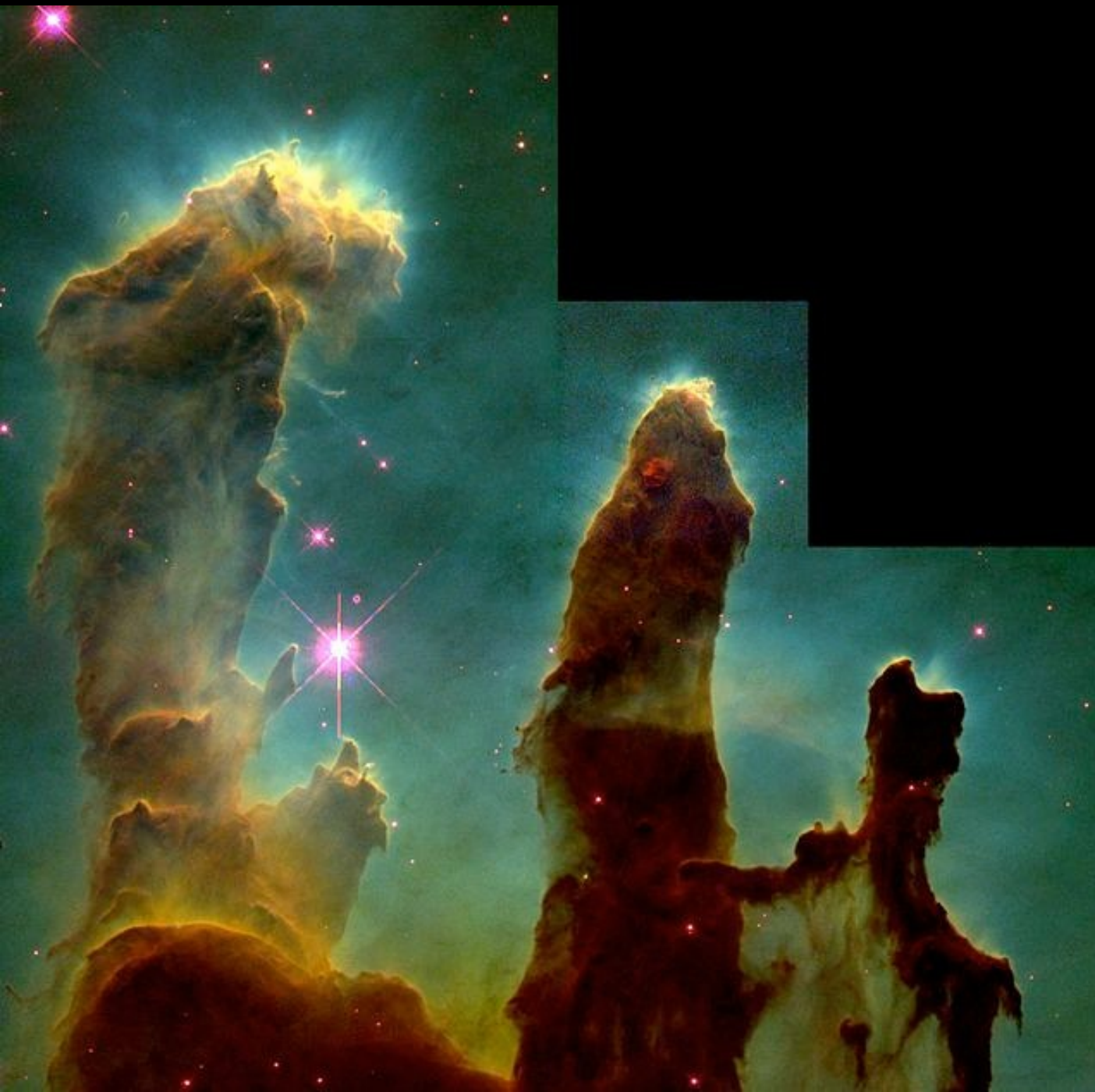
Radio emission from galaxies



Radio emission from galaxies

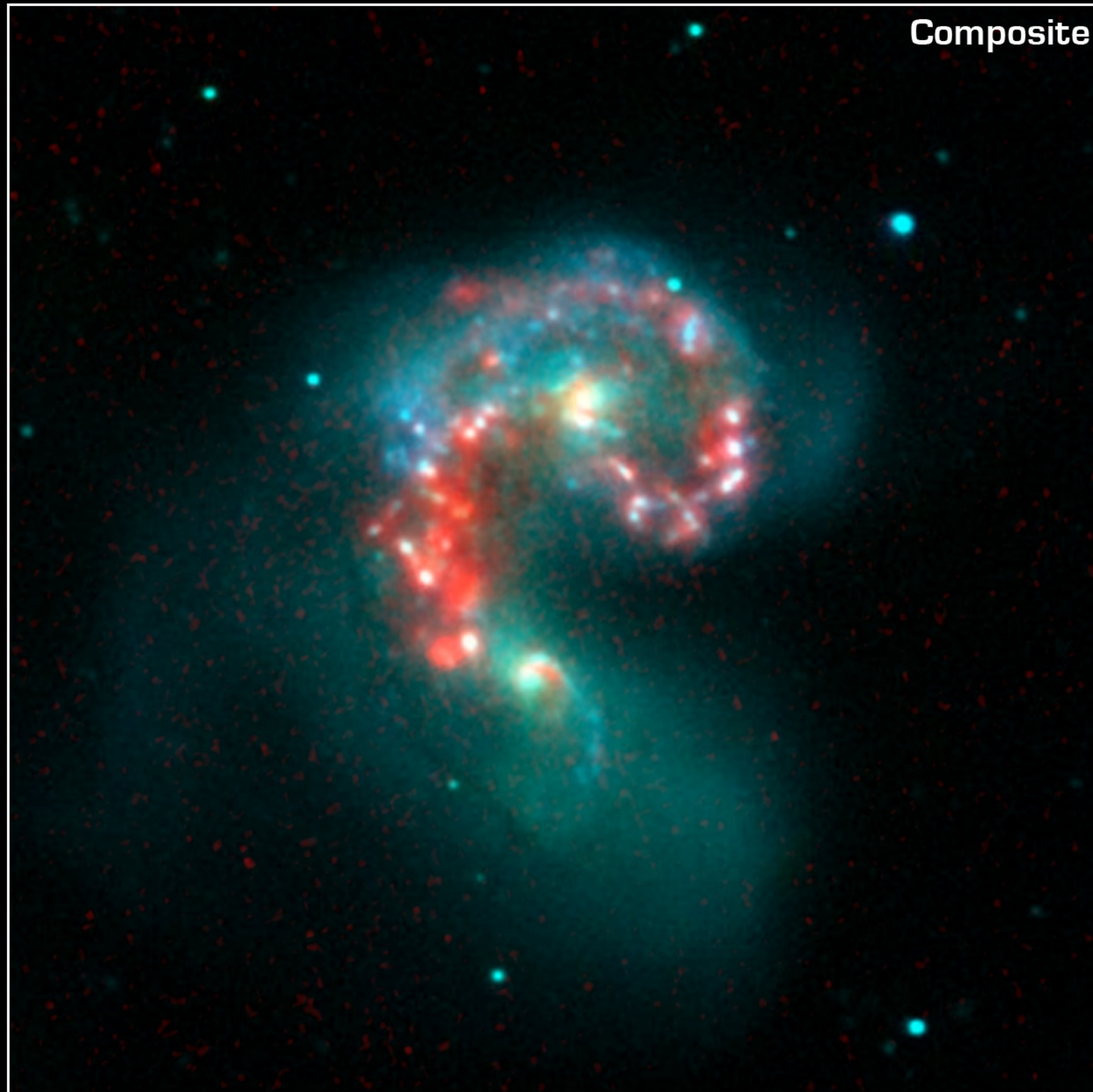


Birth and death of stars

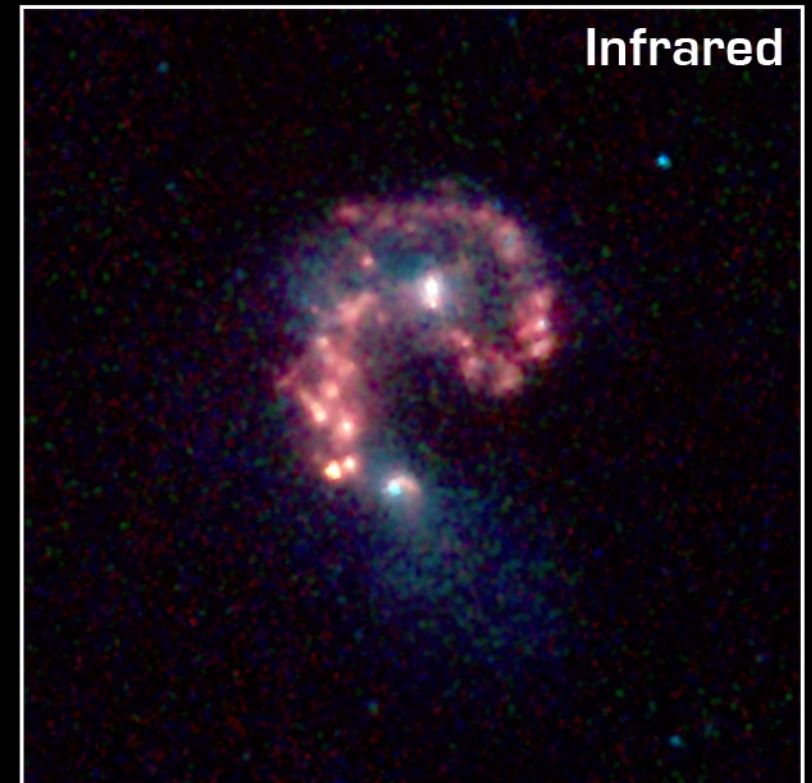




Credit: NASA, ESA, and the Hubble Heritage Team STScI/AURA)-ESA/Hubble Collaboration. Acknowledgement: B. Whitmore (Space Telescope Science Institute) and James Long (ESA/Hubble)



Composite



Infrared



Visible

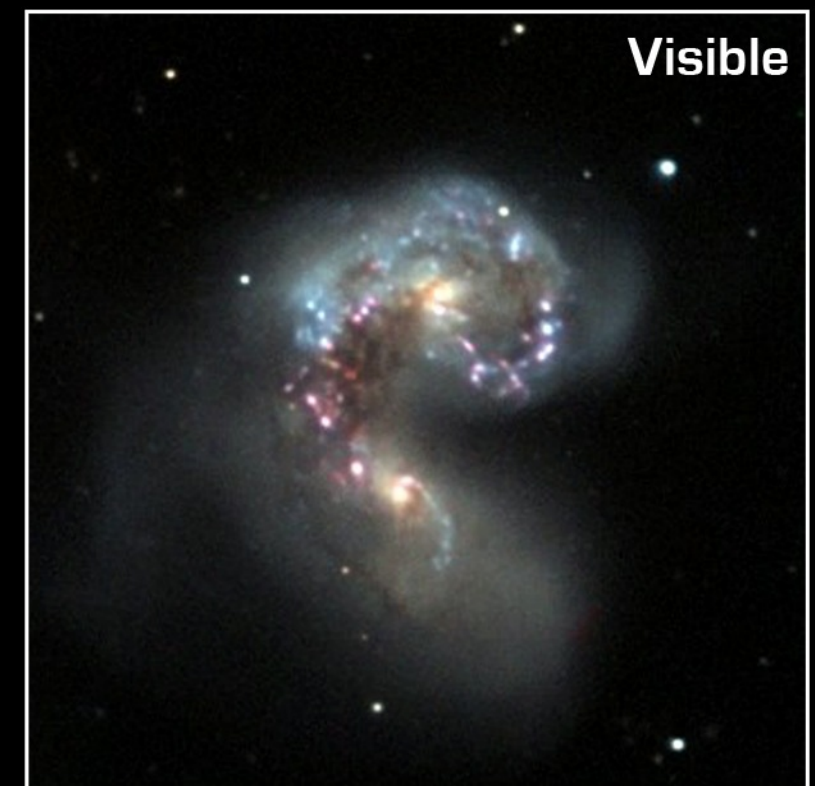
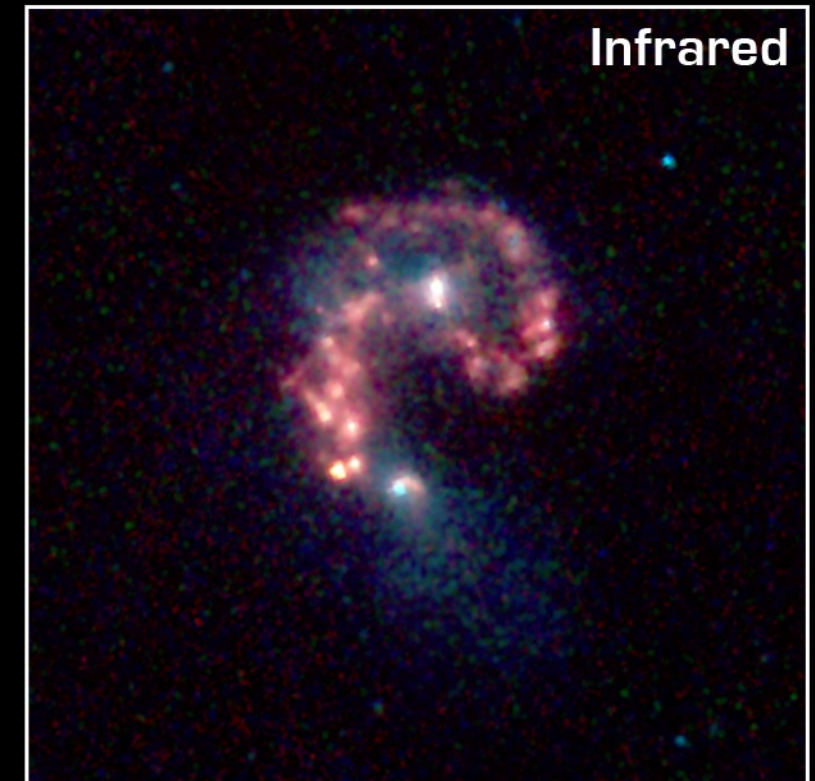
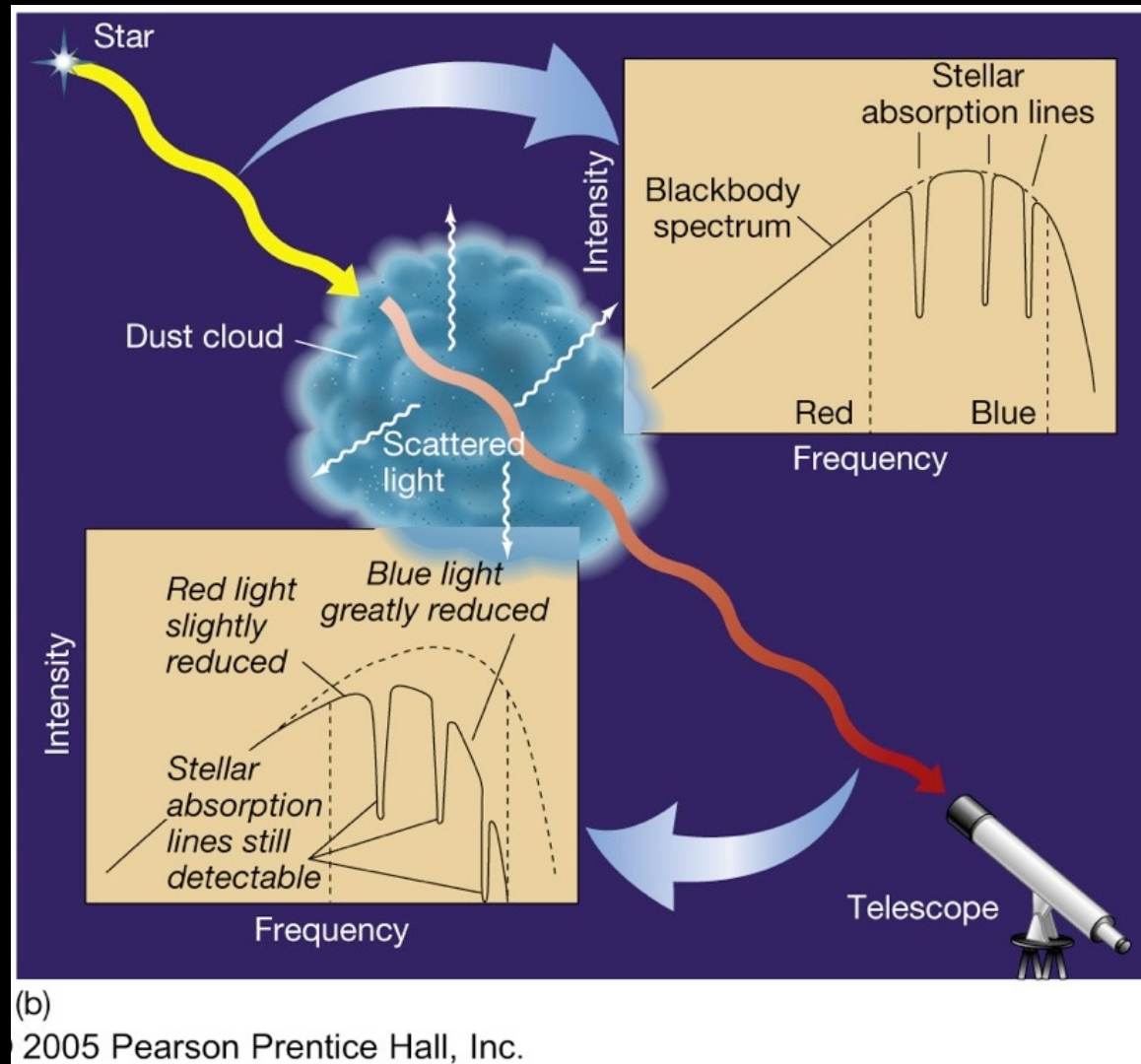
Interacting Antennae Galaxies

NASA / JPL-Caltech / Z. Wang (Harvard-Smithsonian CfA)

Spitzer Space Telescope • IRAC

Visible: M. Rushing / NOAO

ssc2004-14a



Interacting Antennae Galaxies

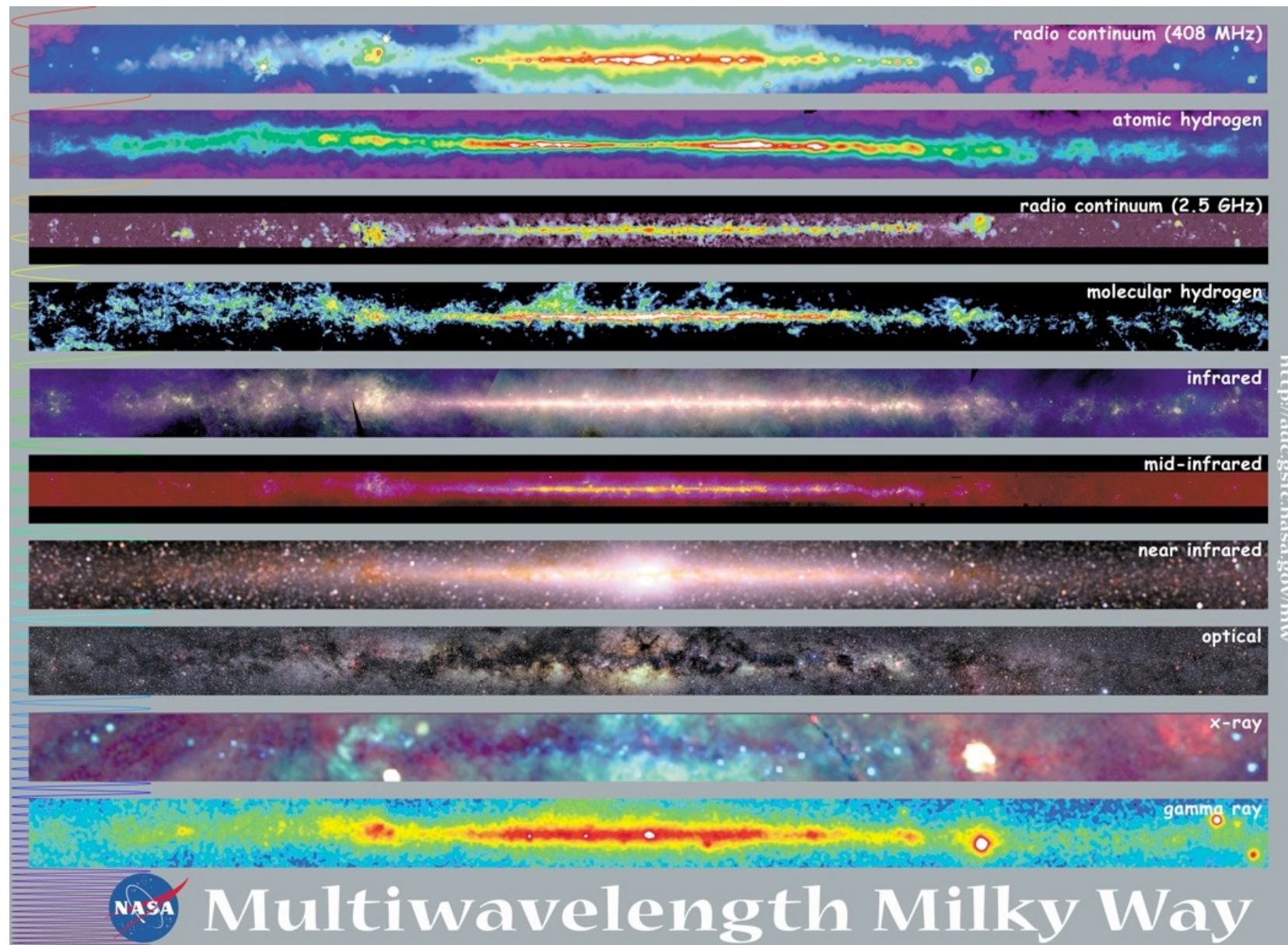
NASA / JPL-Caltech / Z. Wang (Harvard-Smithsonian CfA)

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ssc2004-14a

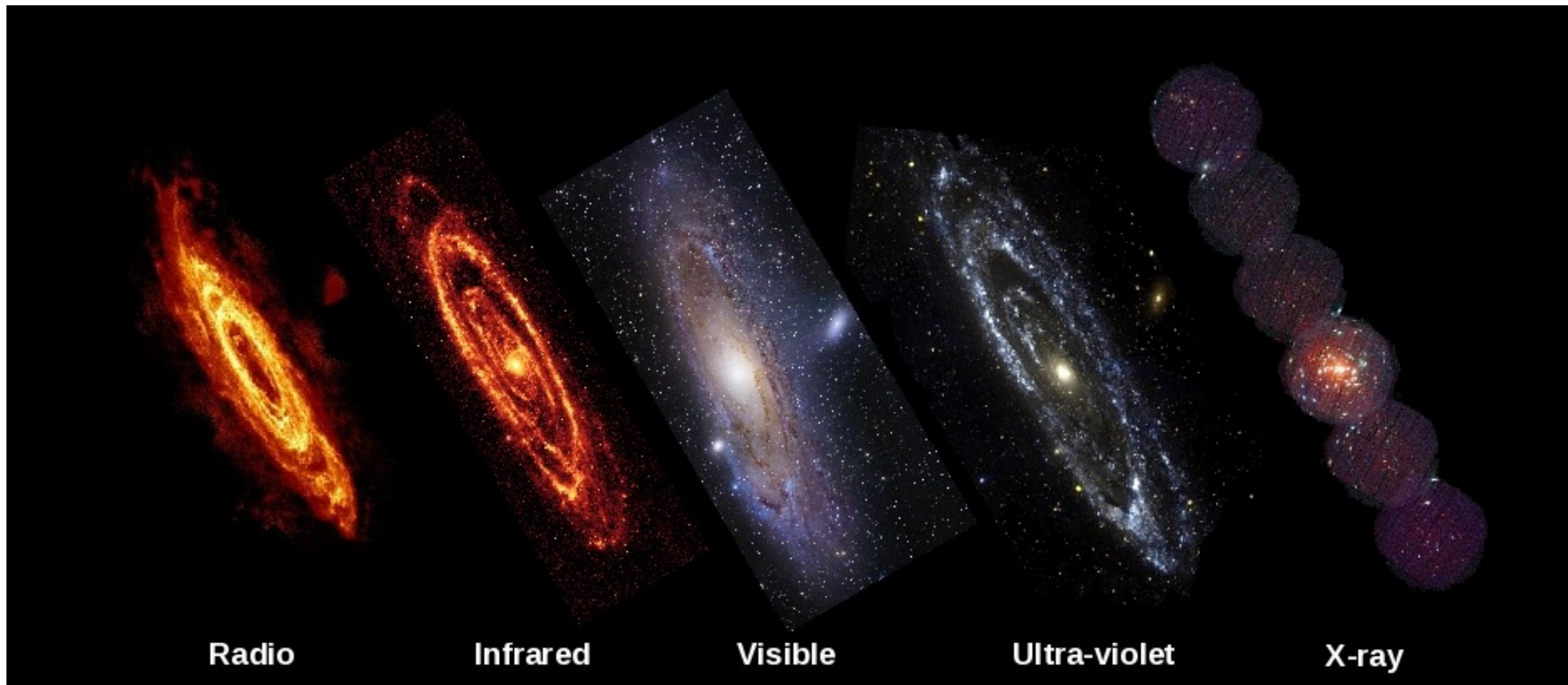
A multi-wavelength view of the Milky Way



- Mass in stars $\sim 10^{11} M_{\odot}$
- Mass in gas $\sim 10^{10} M_{\odot}$
- Mass in dust $\sim 10^8 M_{\odot}$
- Total mass $\sim 10^{12} M_{\odot}$

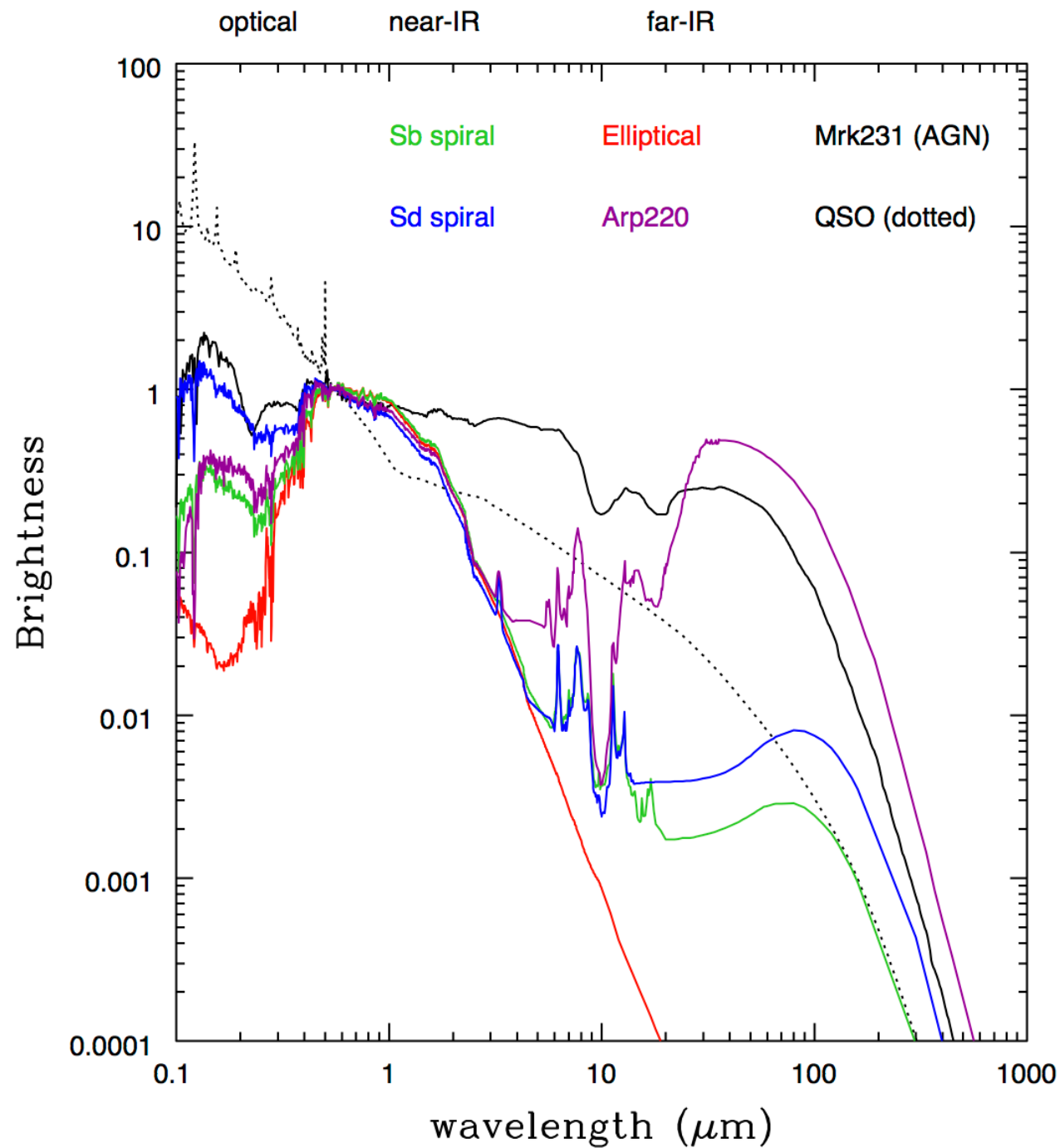


A multi-wavelength view of galaxies



Credits: Radio: WSRT/R. Braun; Infrared: NASA/Spitzer/K. Gordon; Visible: Robert Gendler; Ultraviolet: NASA/GALEX; X-ray: ESA/XMM/W. Pietsch

Spectral Energy Distribution (SED)

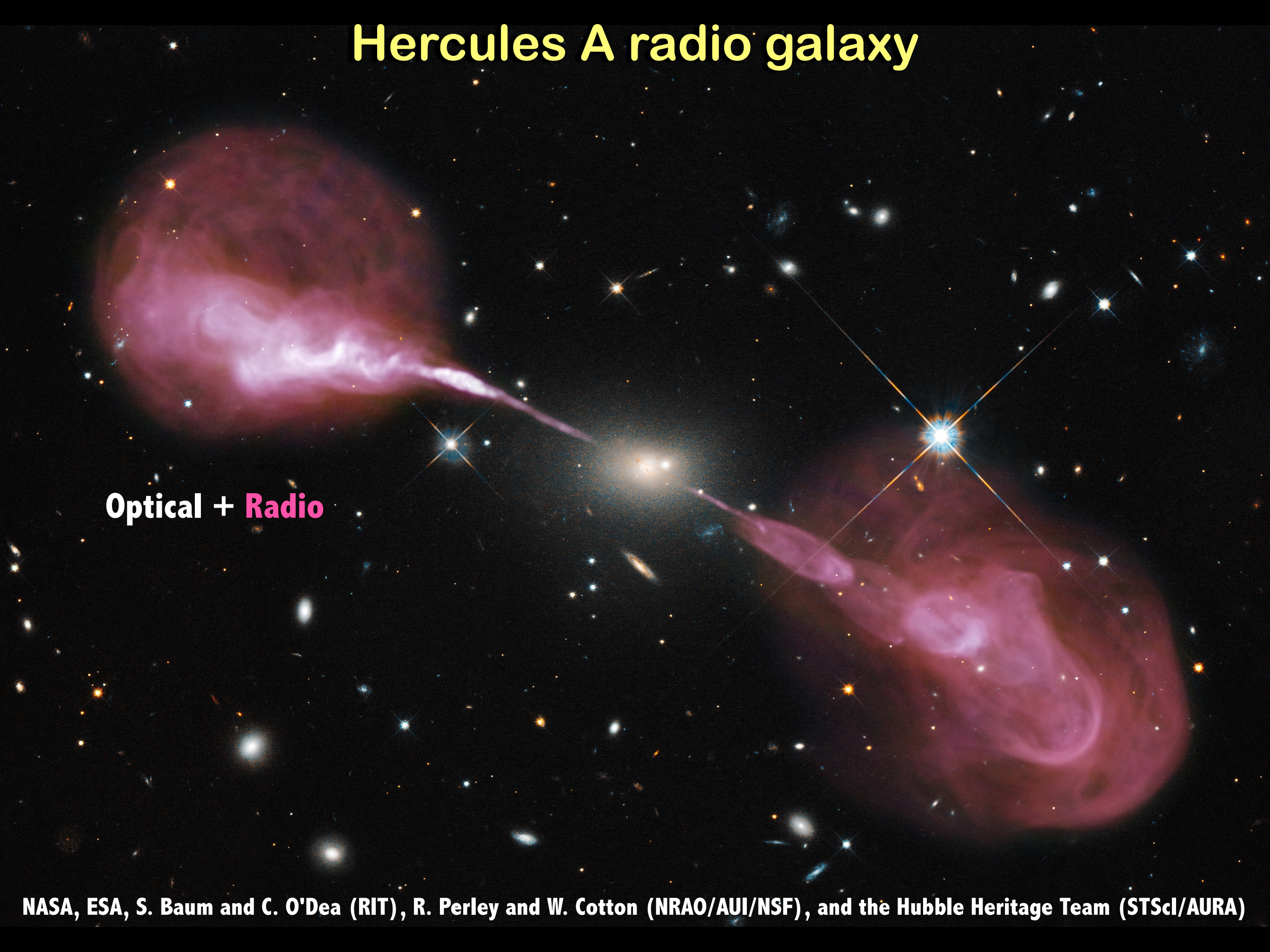


Courtesy: CANDELS

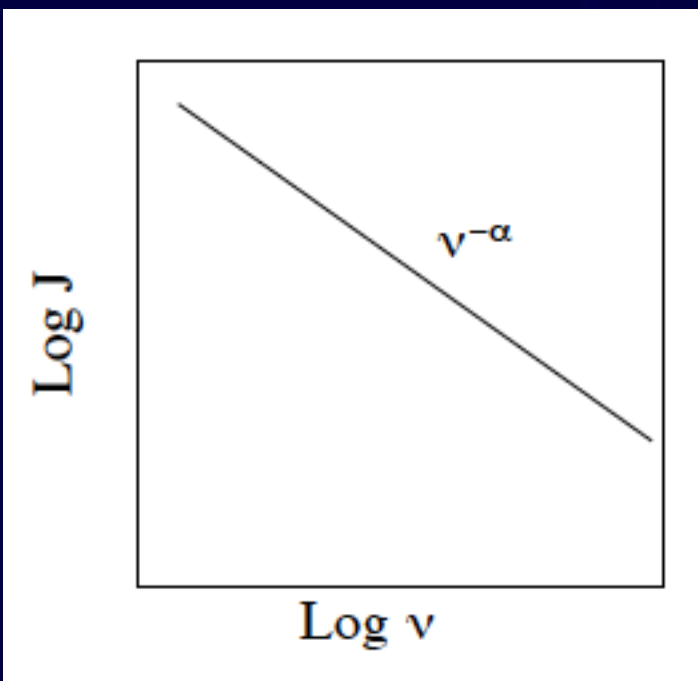
(Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey)

Hercules A radio galaxy

Optical + Radio



Examples of radio galaxies



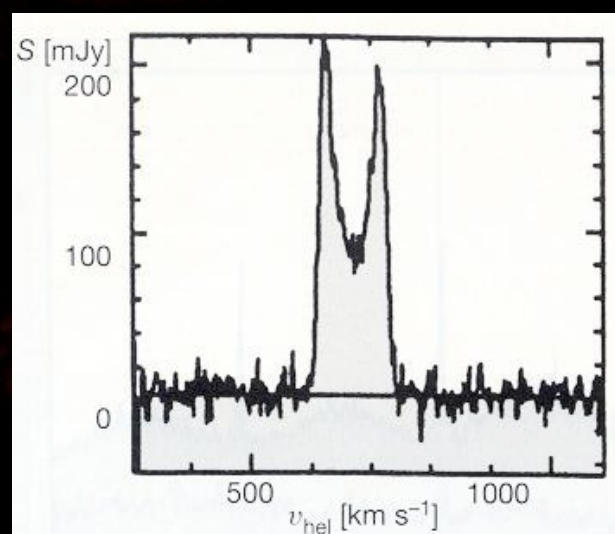
COSMO in the MED

Chiara Ferrari
Courtesy: G. B. Taylor, VLA

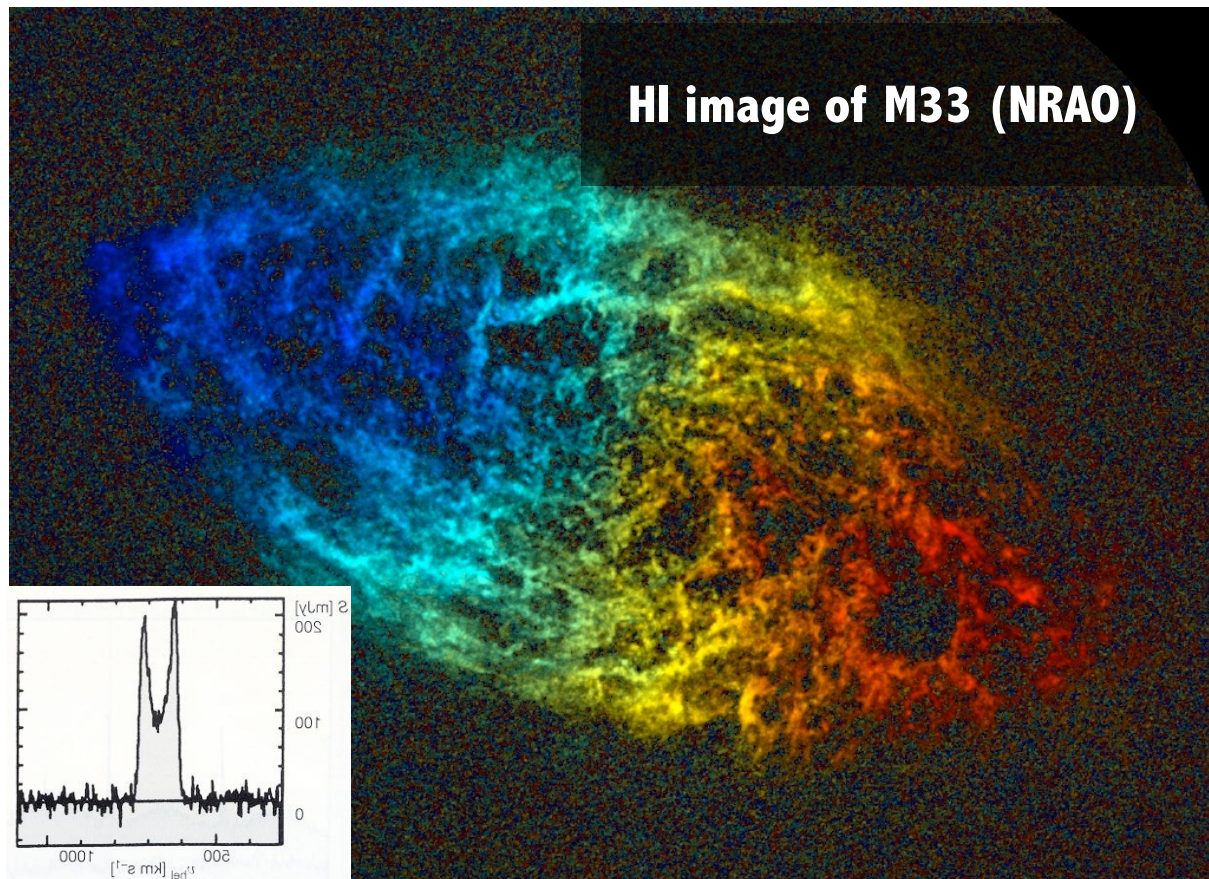


The *H*I Nearby Galaxy Survey (THINGS)

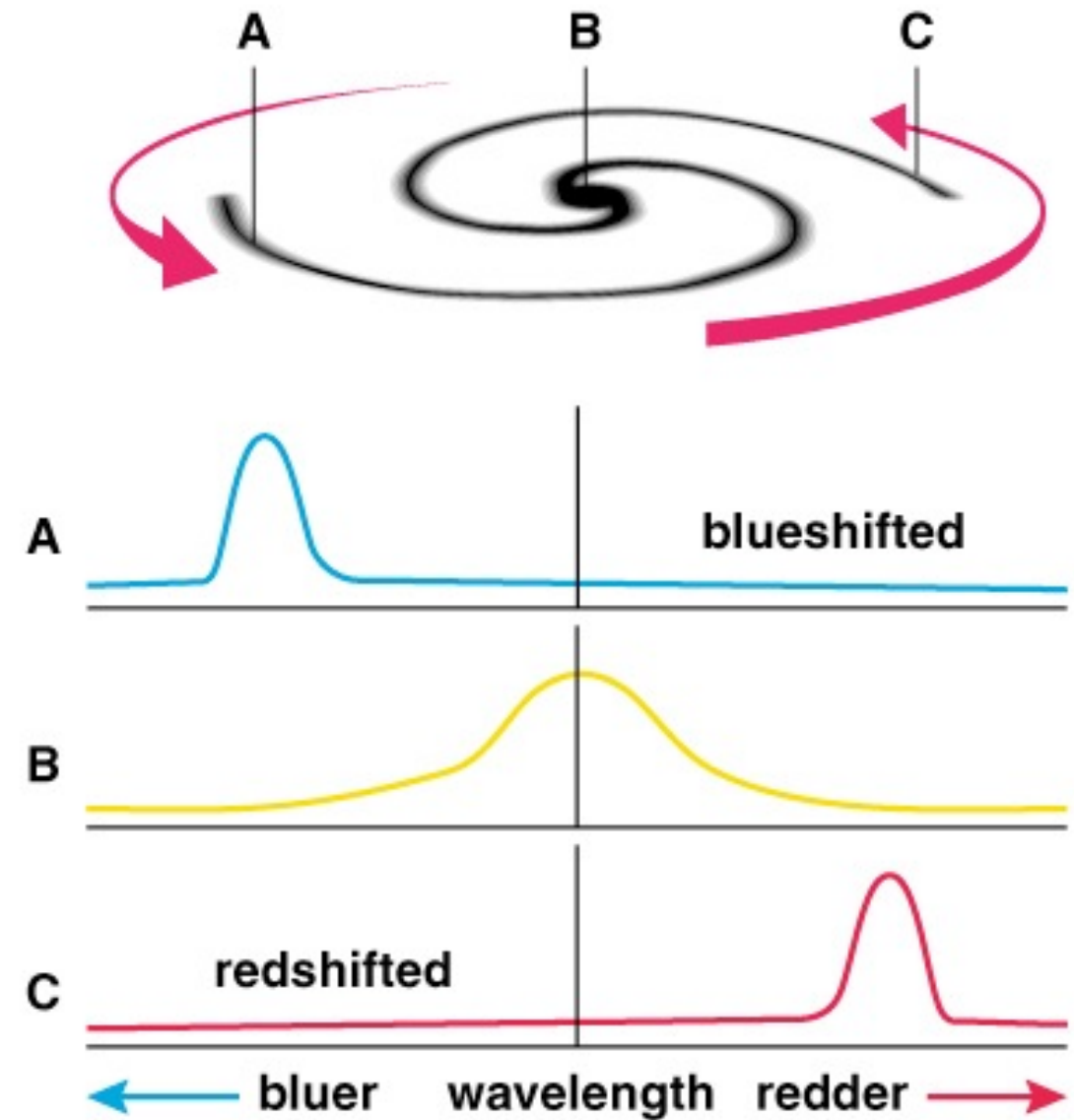
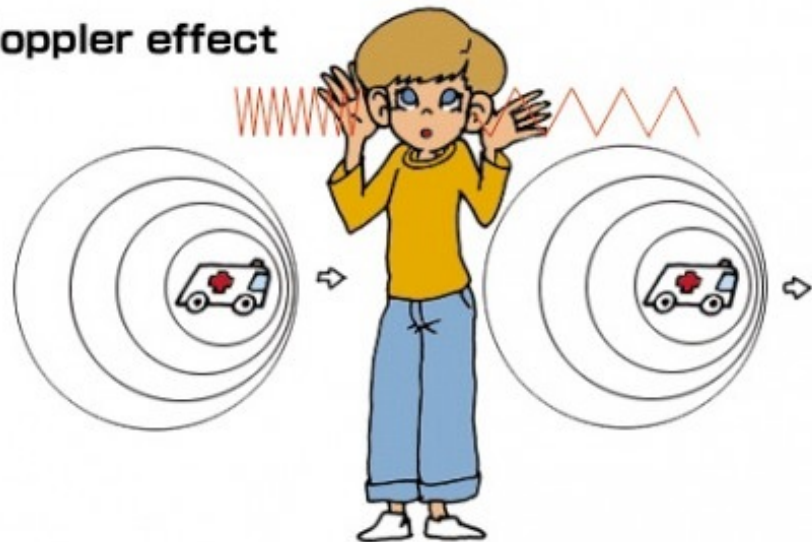
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt



Galaxy rotation curves

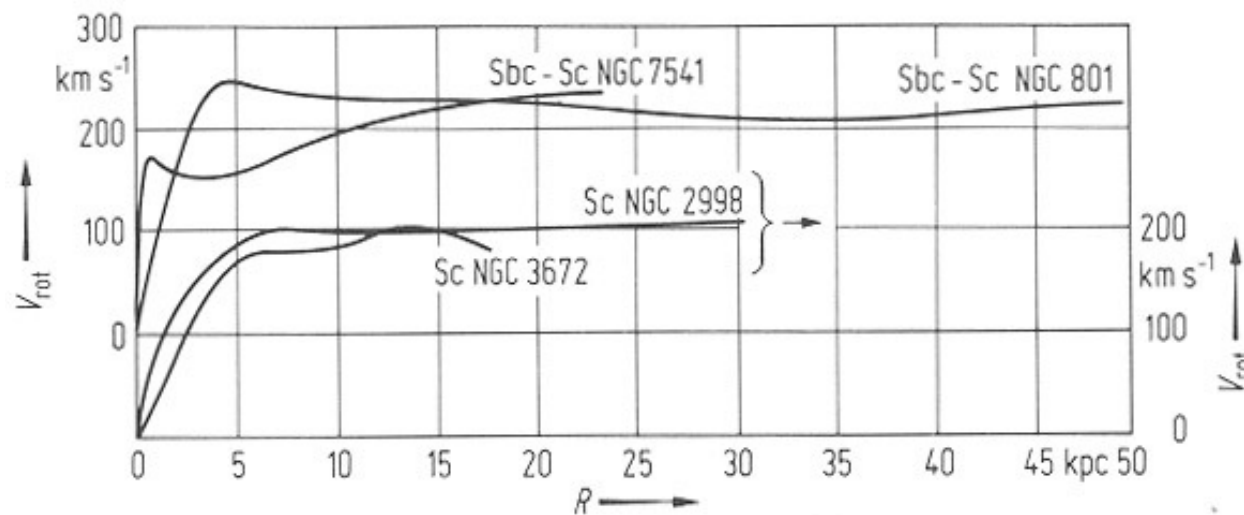


Doppler effect

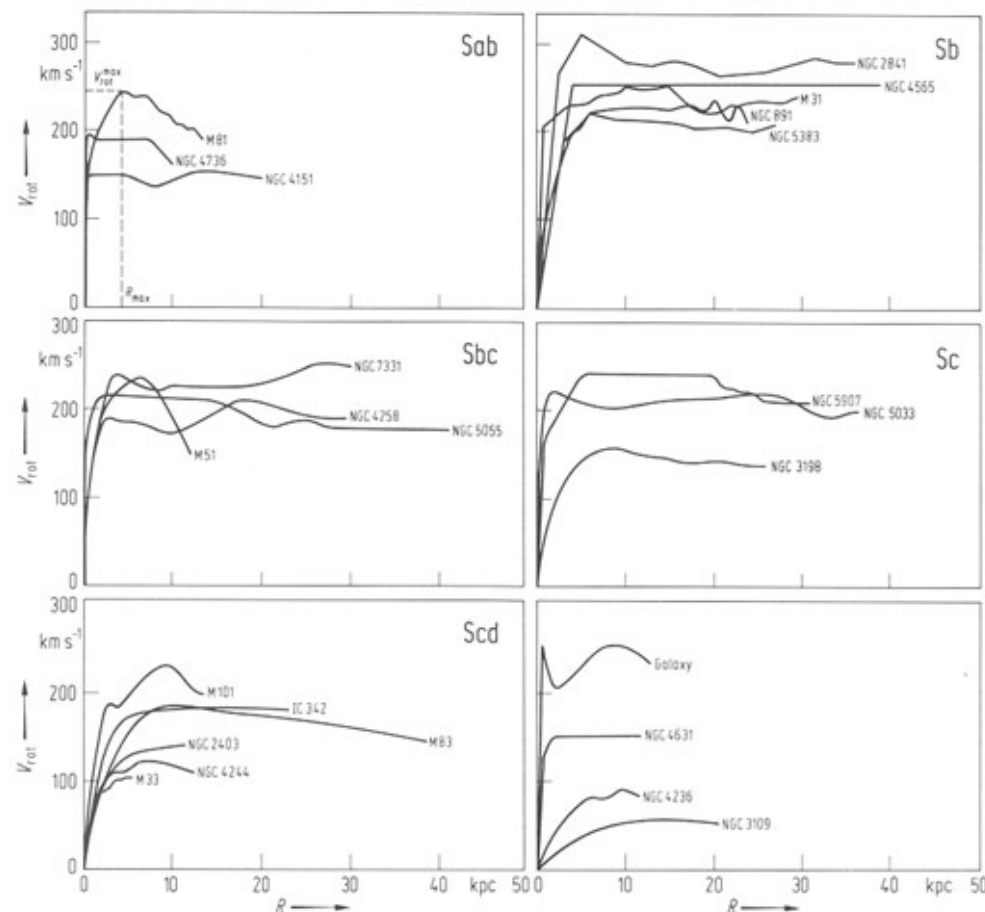


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Galaxy rotation curves

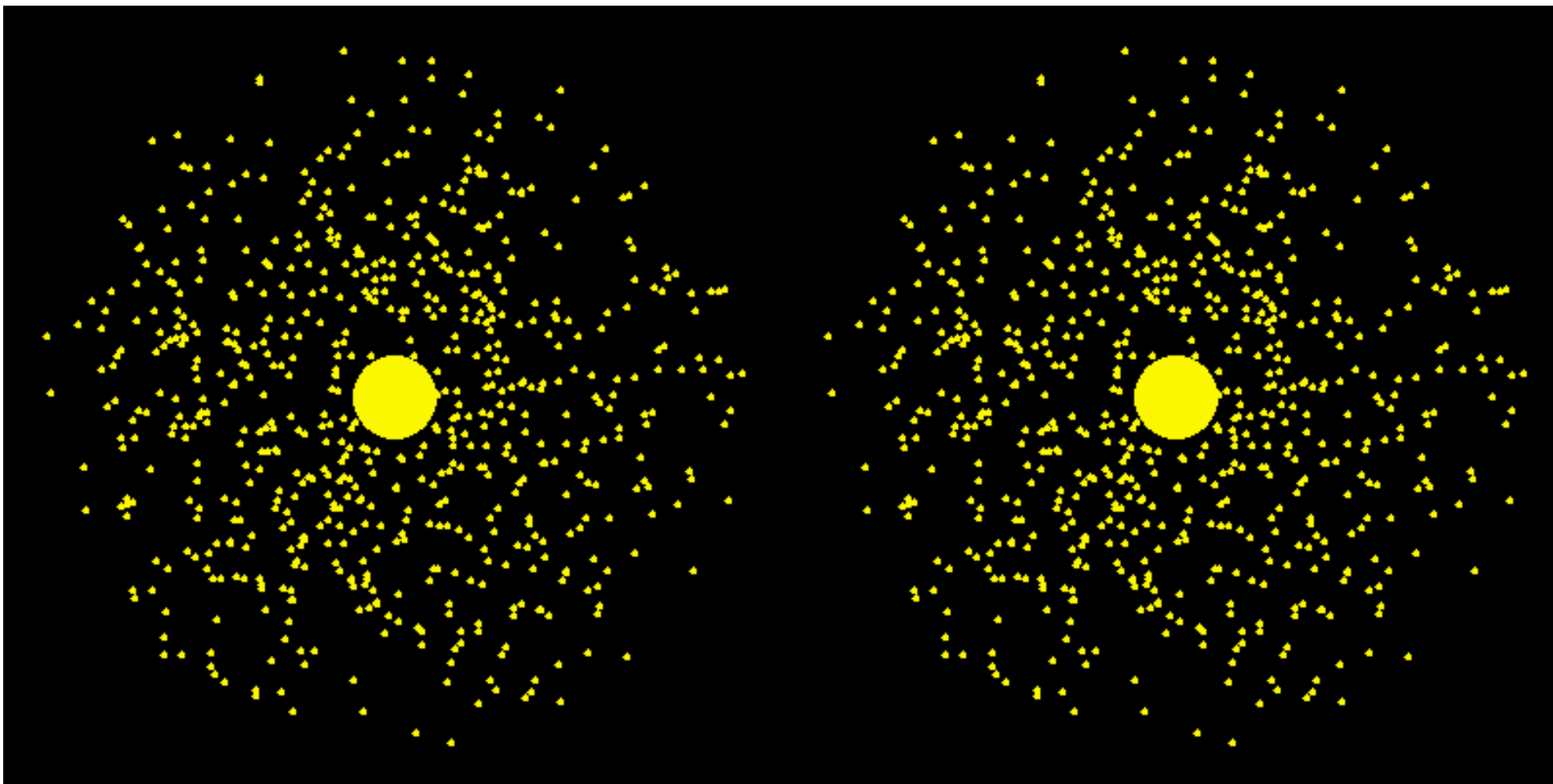


Rubin et al. 1978
(from rotational velocity of stars)



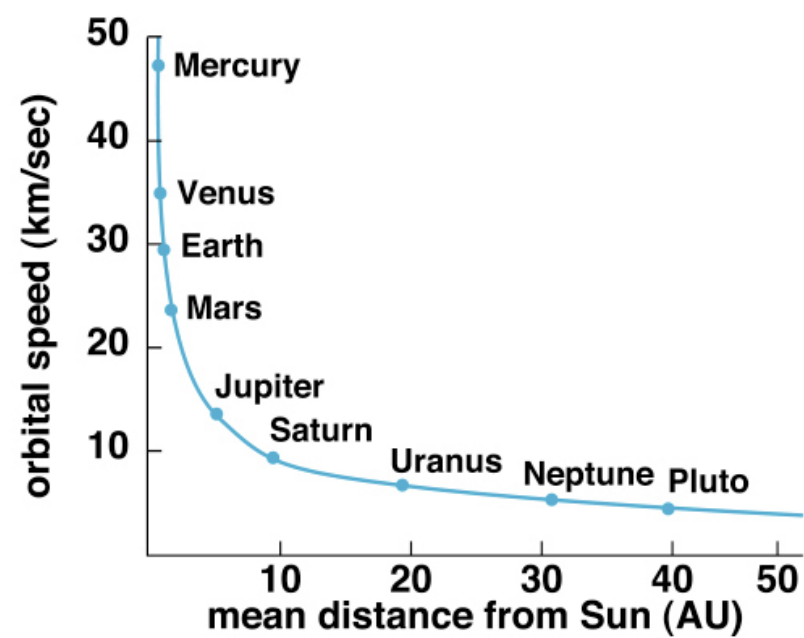
Bosma 1978
(from HI measurements)

See e.g. Faber & Gallagher (1979)
for a review of this very active field
in the 70's

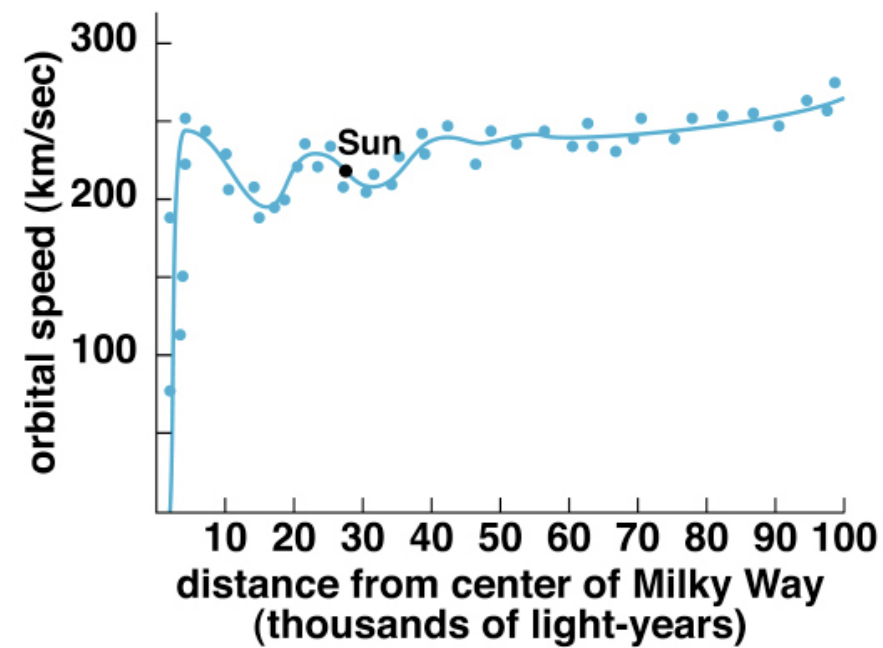


$$M(r) = M \rightarrow v(r) = (GM/r)^{1/2} = \text{const} \times r^{-1/2}$$

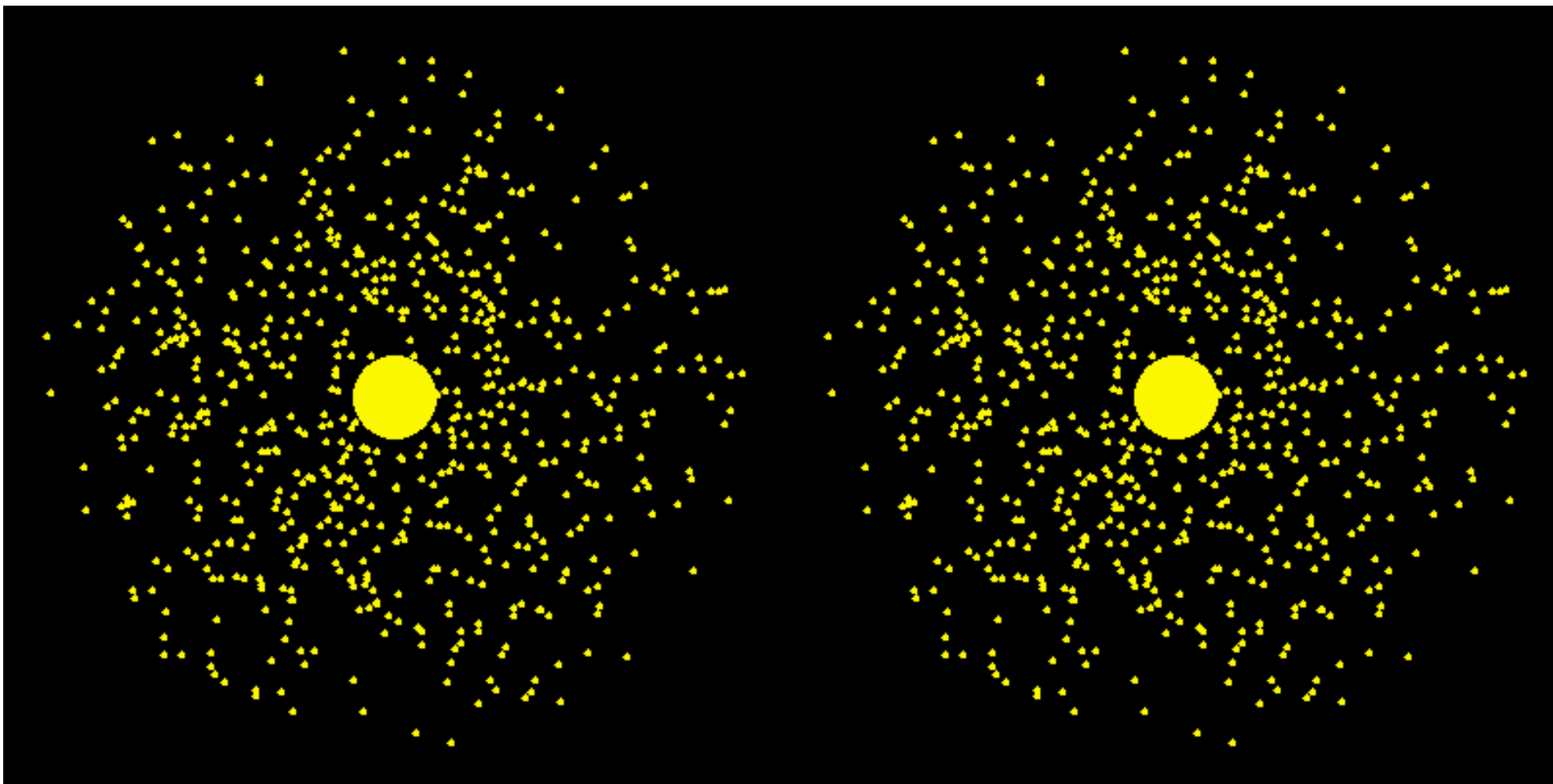
$$M(r) = kr \rightarrow v(r) = (GM/r)^{1/2} = \text{const}$$



(b)
Copyright © Addison Wesley

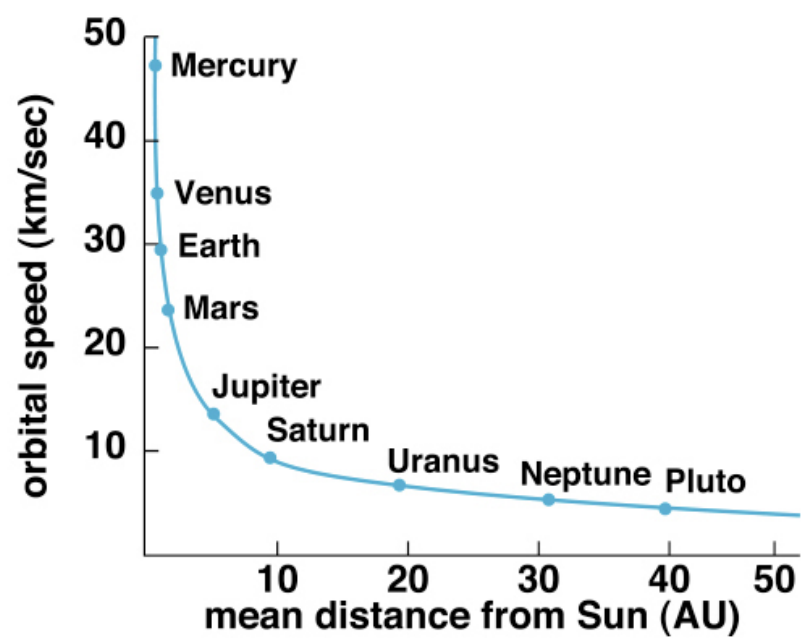


(c)
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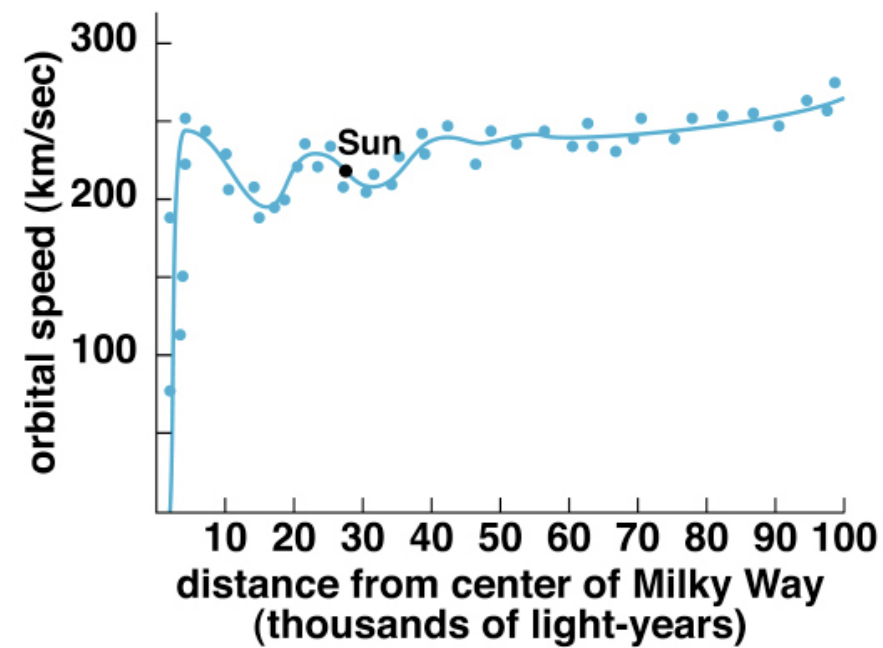


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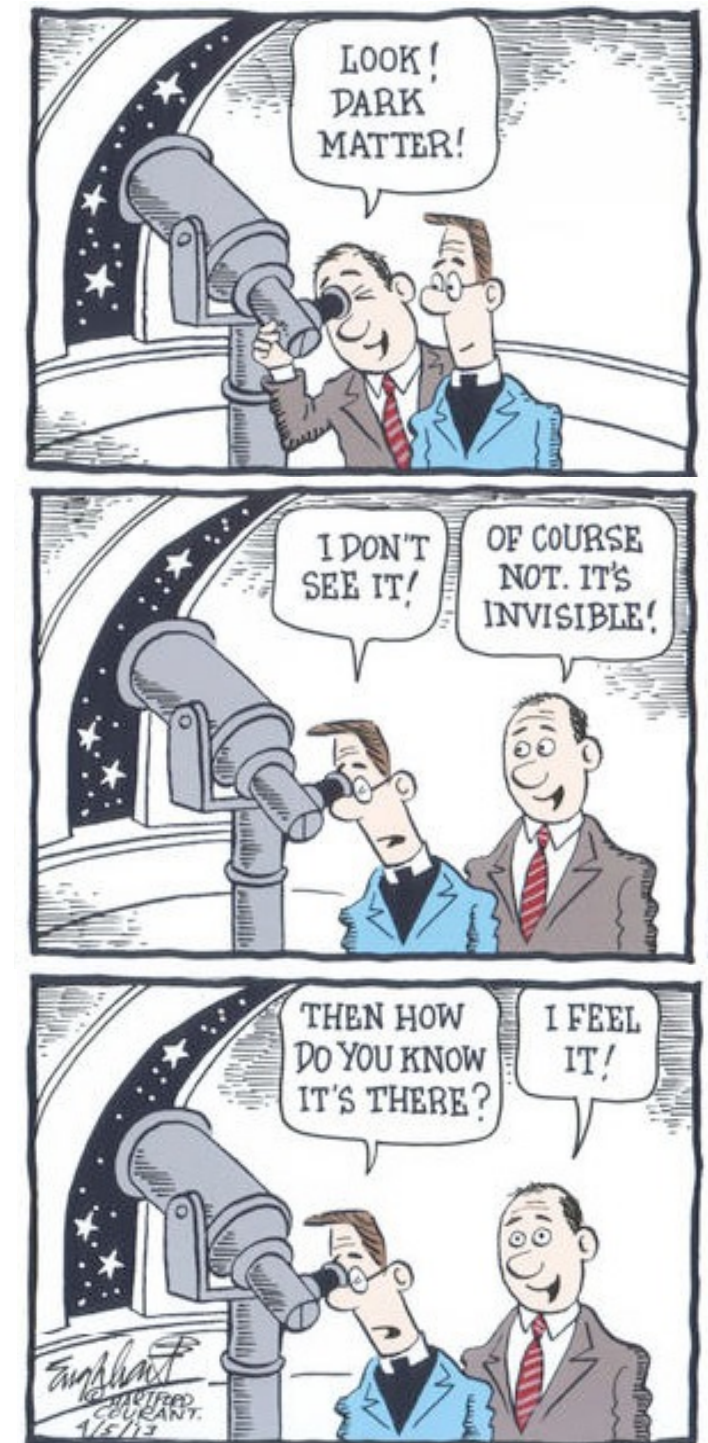
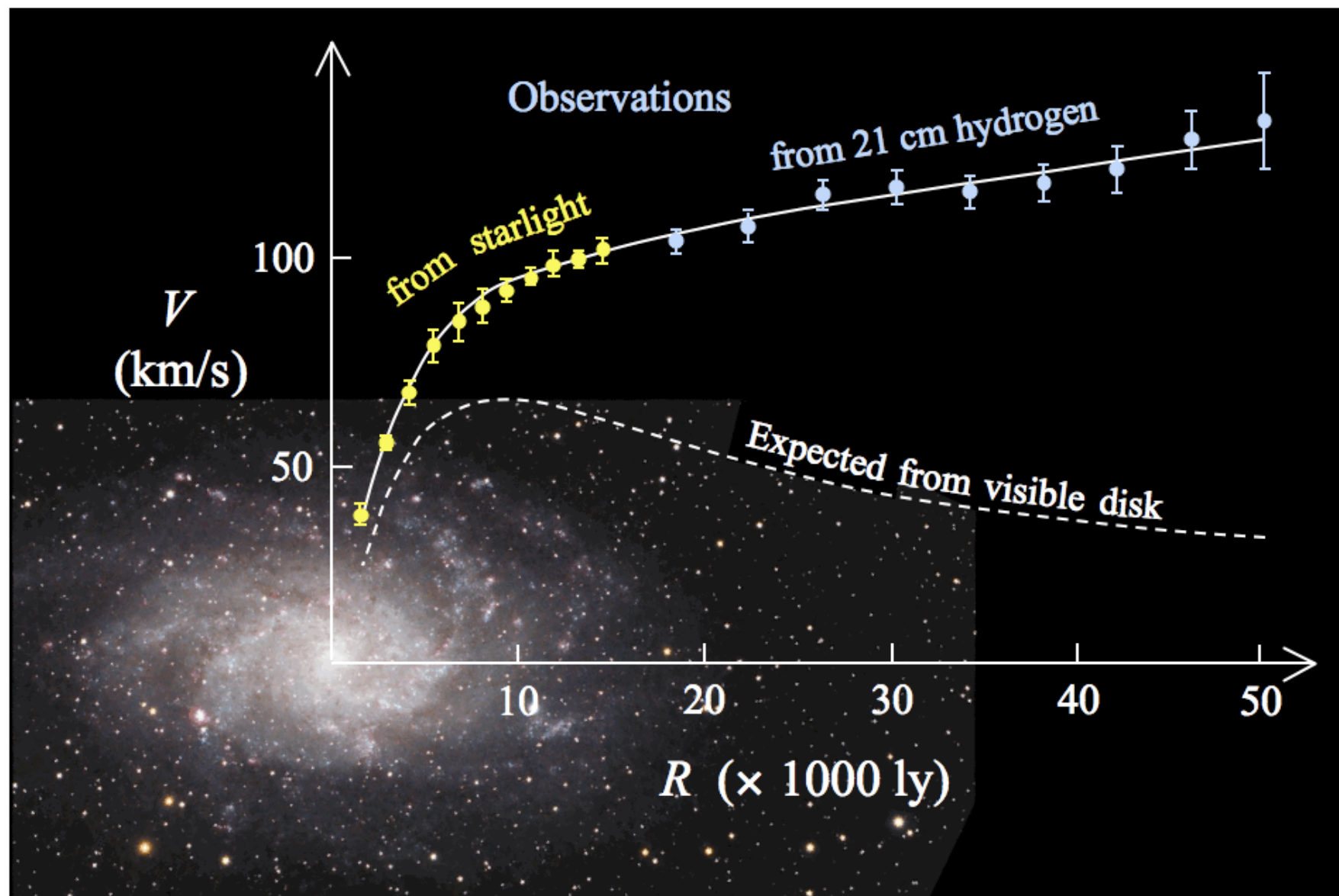


(b)
Copyright © Addison Wesley



(c)
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Dark matter evidence in galaxies



Dark matter evidence through galaxies

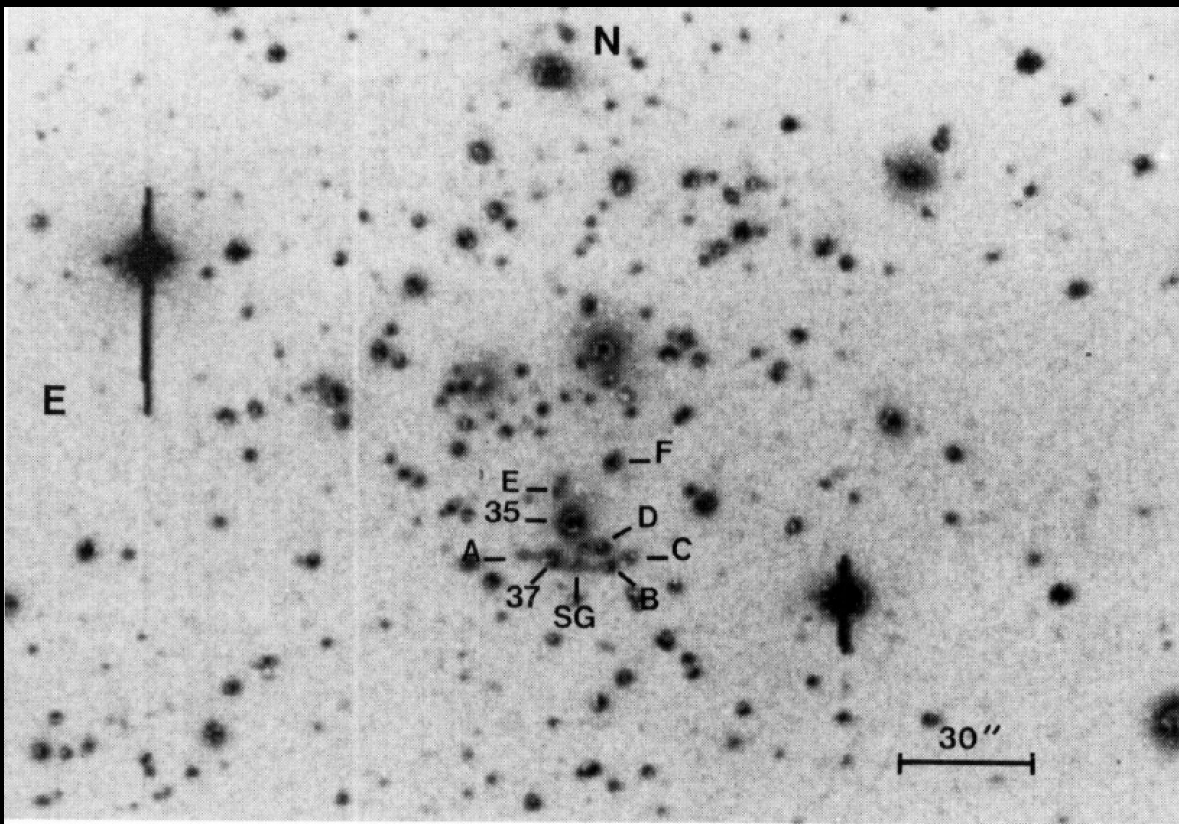
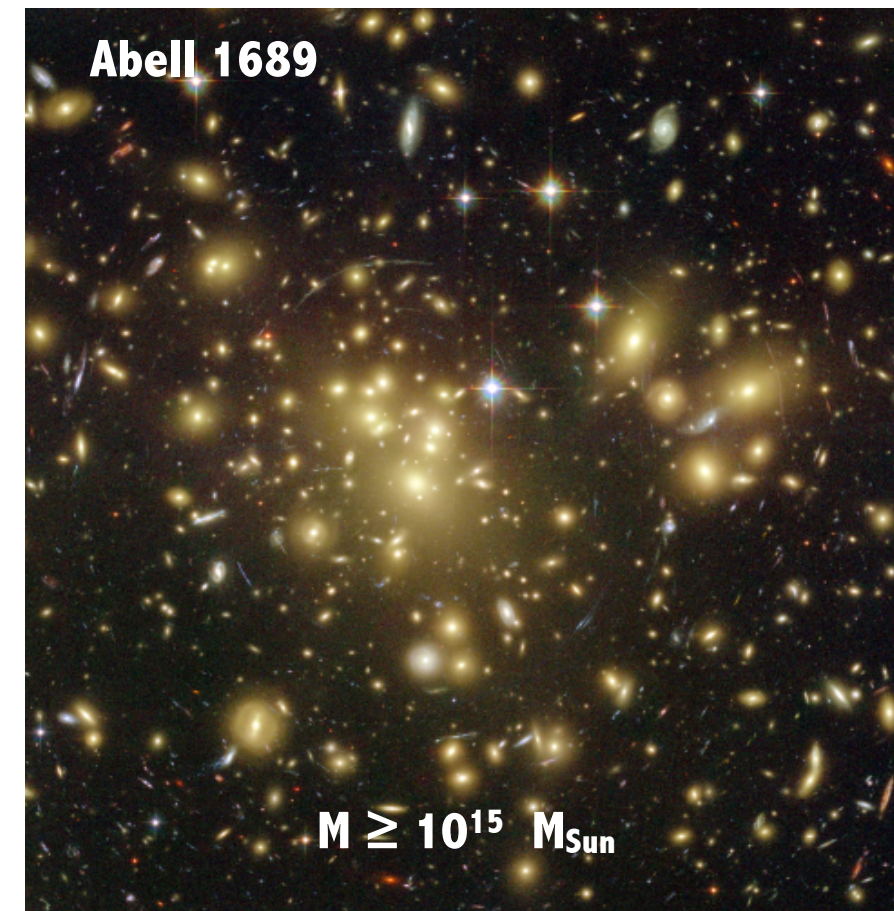
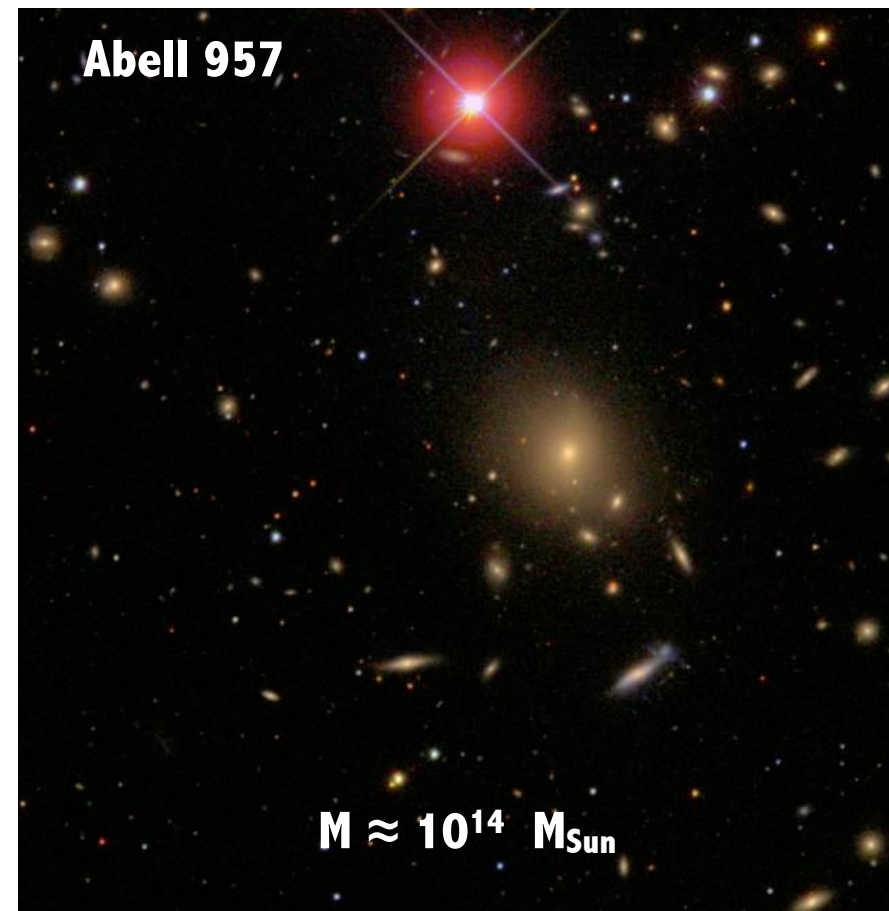
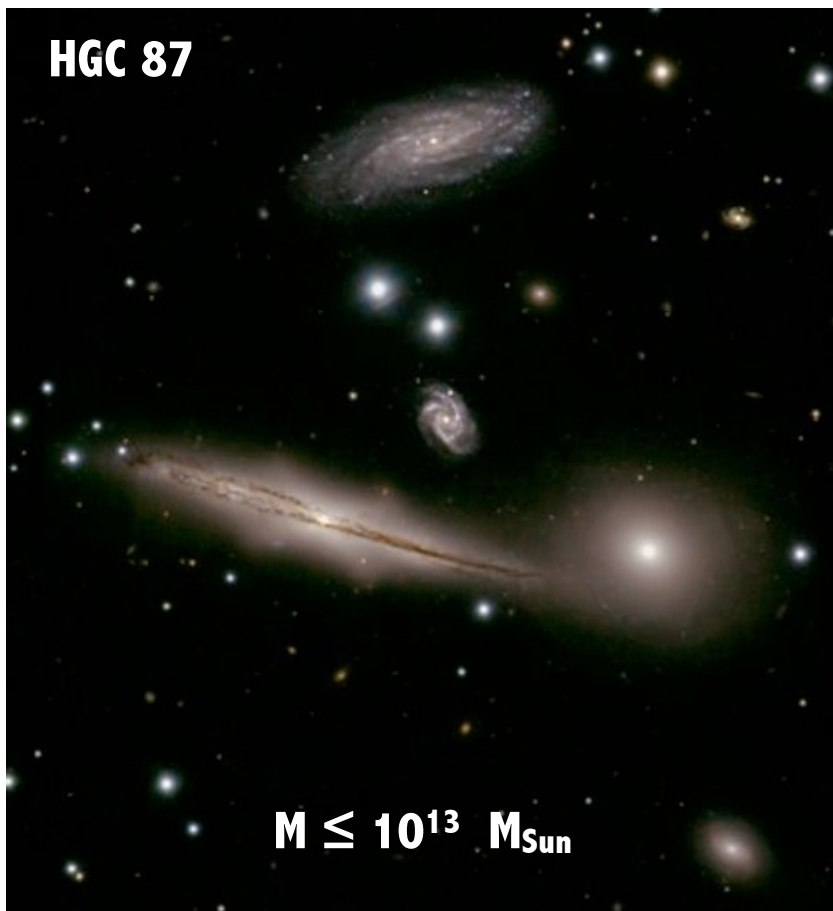


Fig. 1 : CCD image of the A370 center with a R filter at the F/2 C.F.H.T. focal reducer (exposure time 10 mn)

From groups to rich clusters



Most galaxies are not isolated in the Universe.
They are bound together by their mutual gravity in structures containing from a few galaxies,
to hundreds or even thousands galaxies

Soucail et al . 1987

Dark matter evidence through galaxies

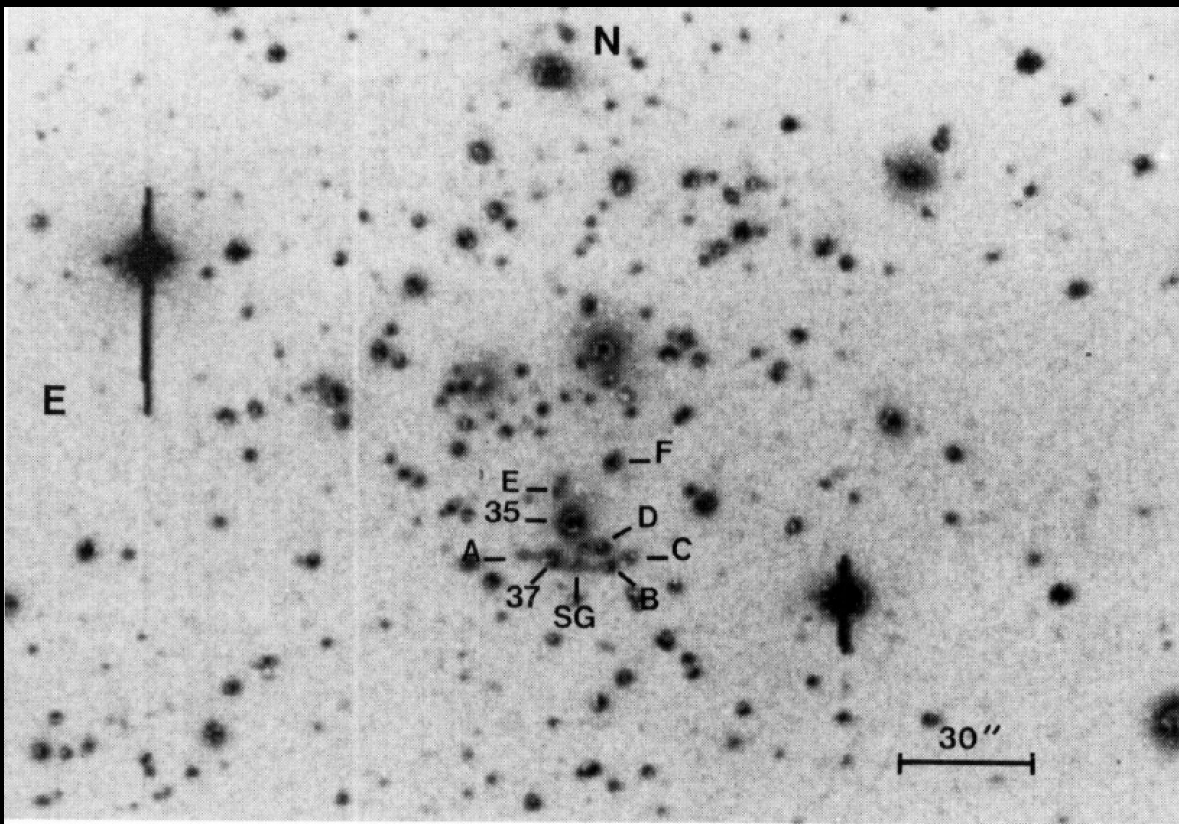
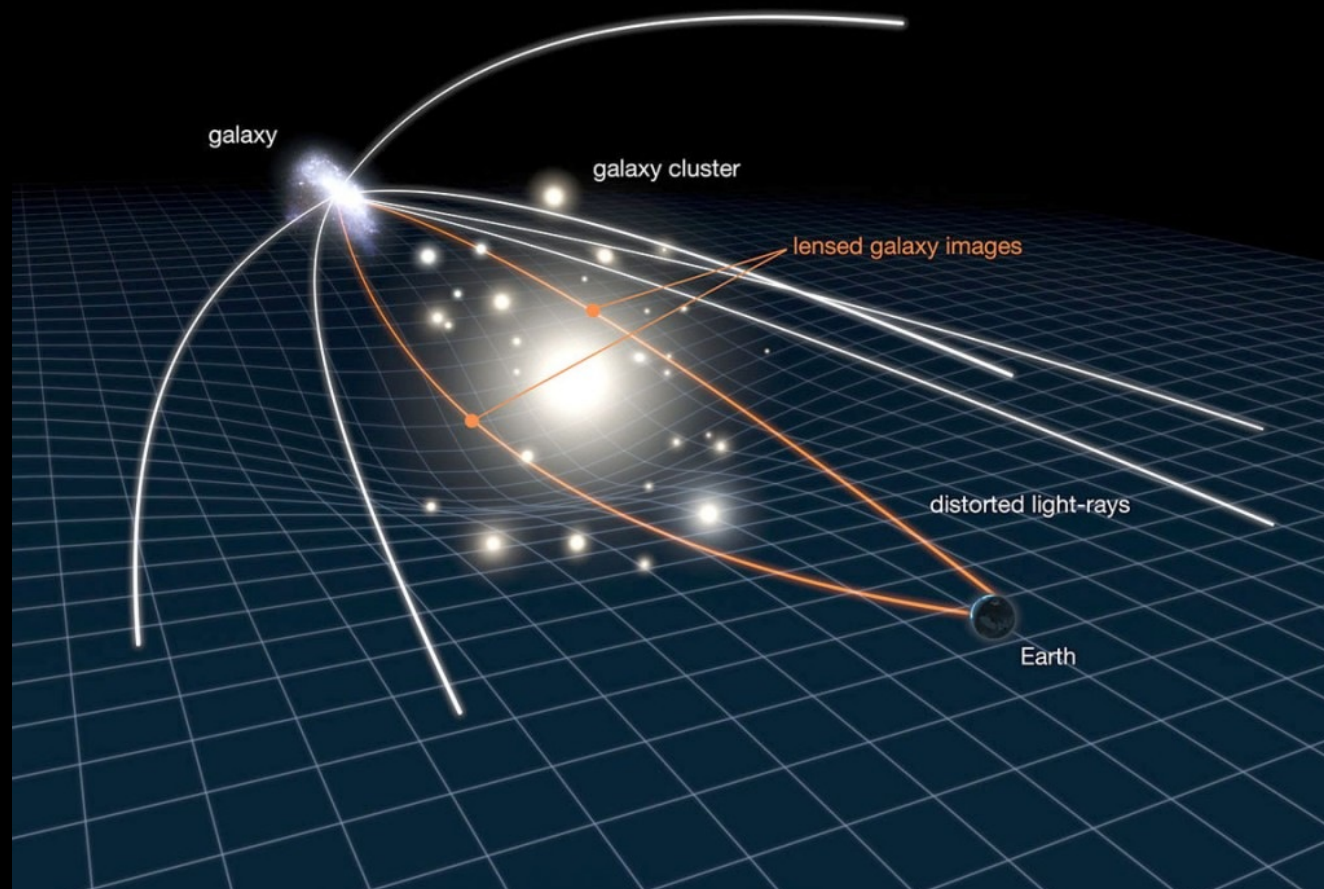


Fig. 1 : CCD image of the A370 center with a R filter at the F/2 C.F.H.T. focal reducer (exposure time 10 mn)



Credit: NASA, ESA, the Hubble SM4 ERO Team, and ST-ECF



Galaxy Cluster Abell 370
Hubble Space Telescope ■ ACS/WFC

Dark matter evidence through galaxies



$$M_{\text{cluster}} \approx 400 \sum M_{\text{Galaxies}}$$

Radial velocity measurements

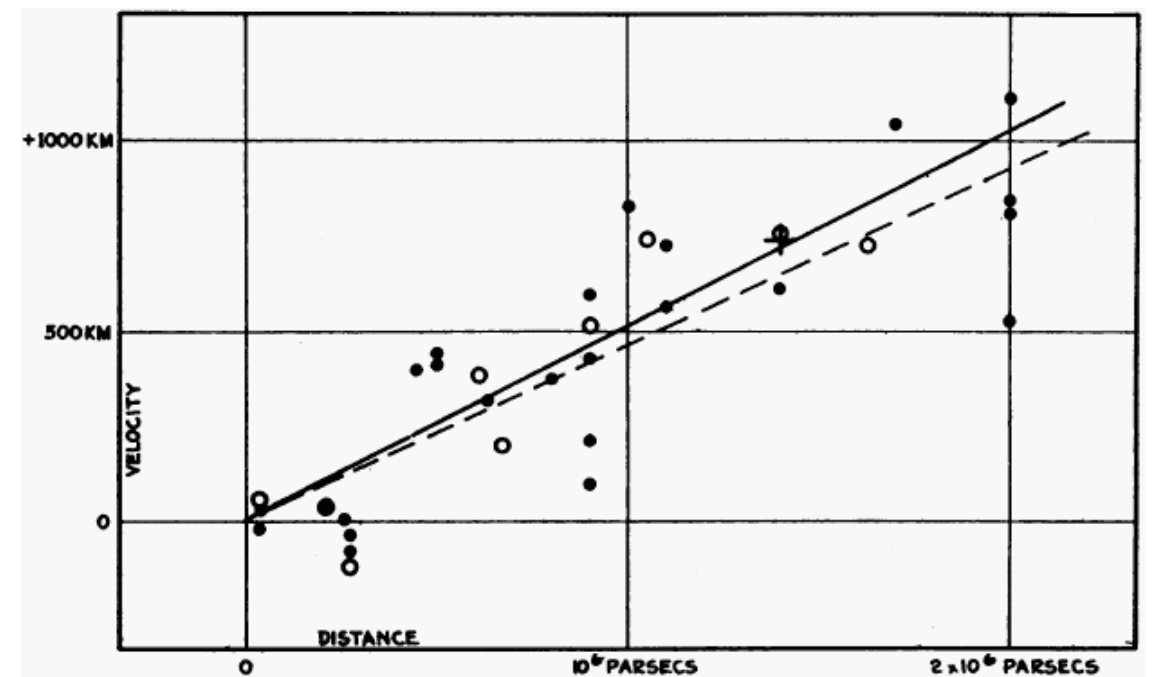
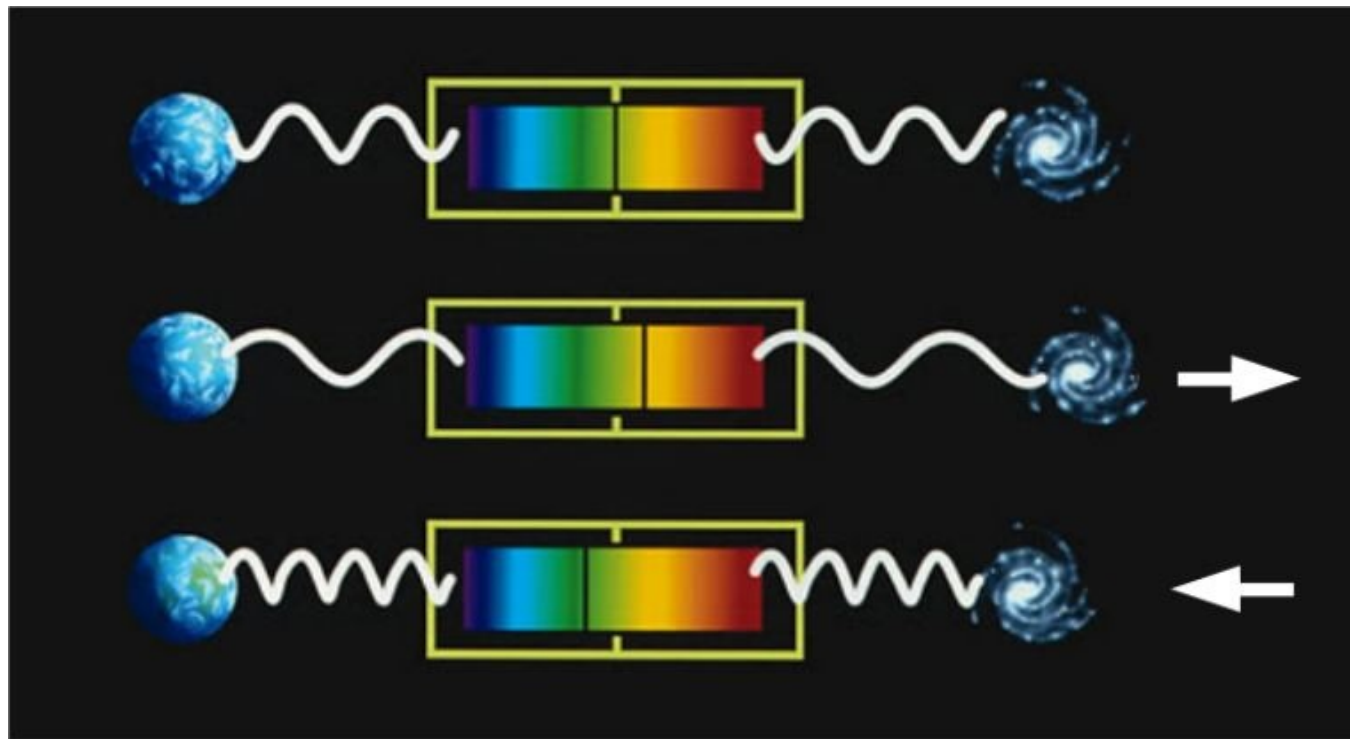


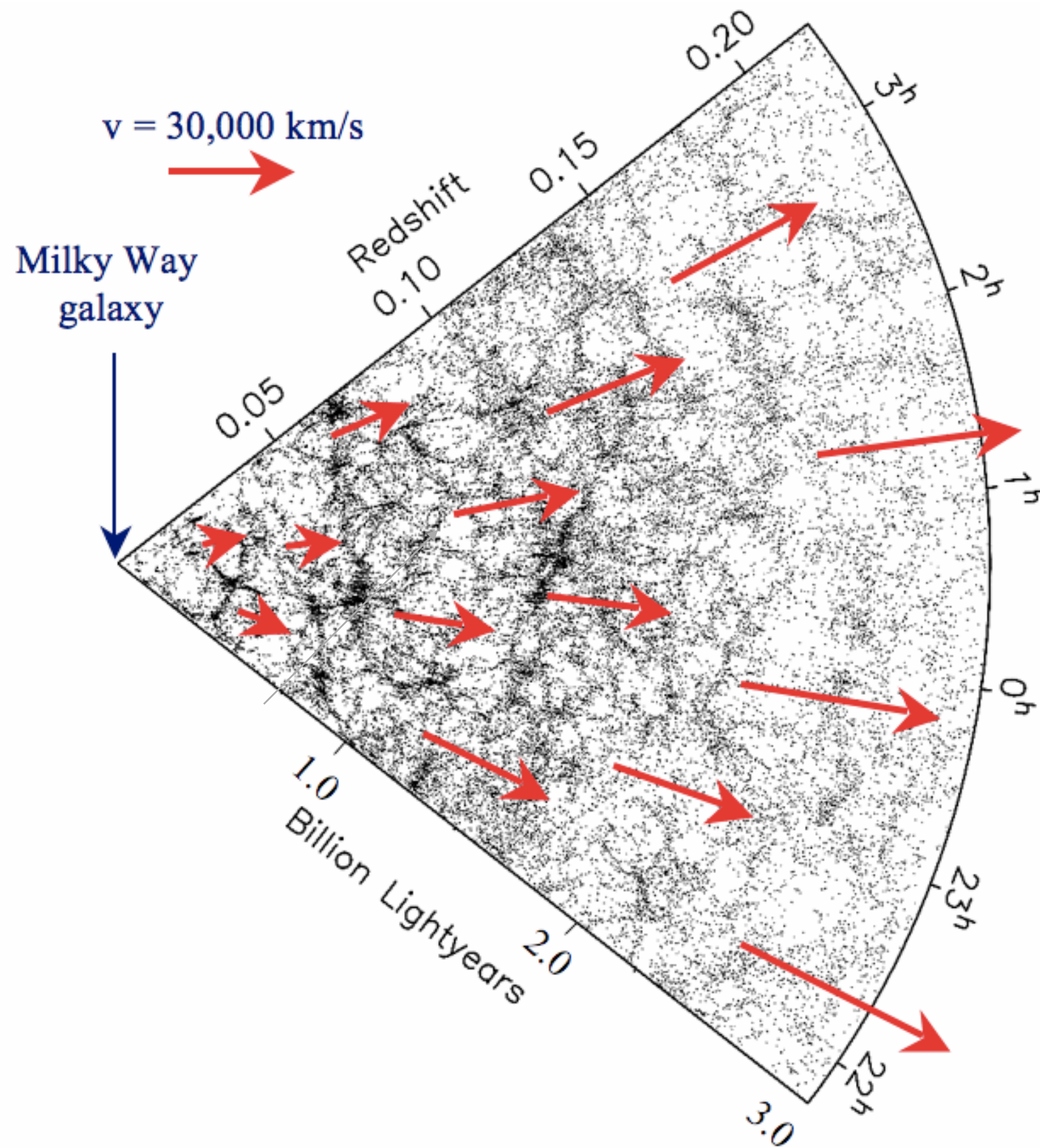
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

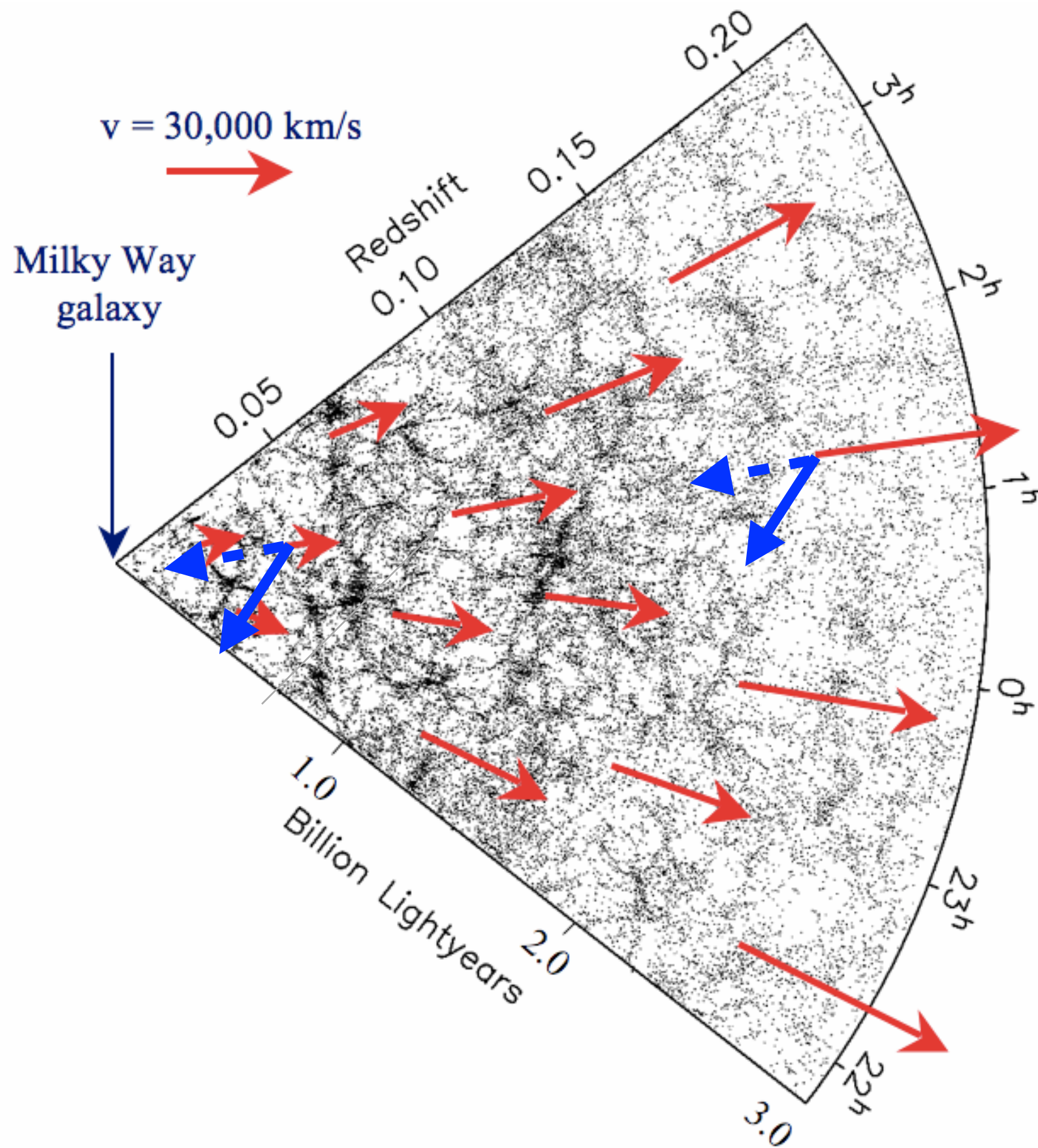
Hubble original diagram (1929)

$$z = \frac{\lambda_{\text{obsv}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$$

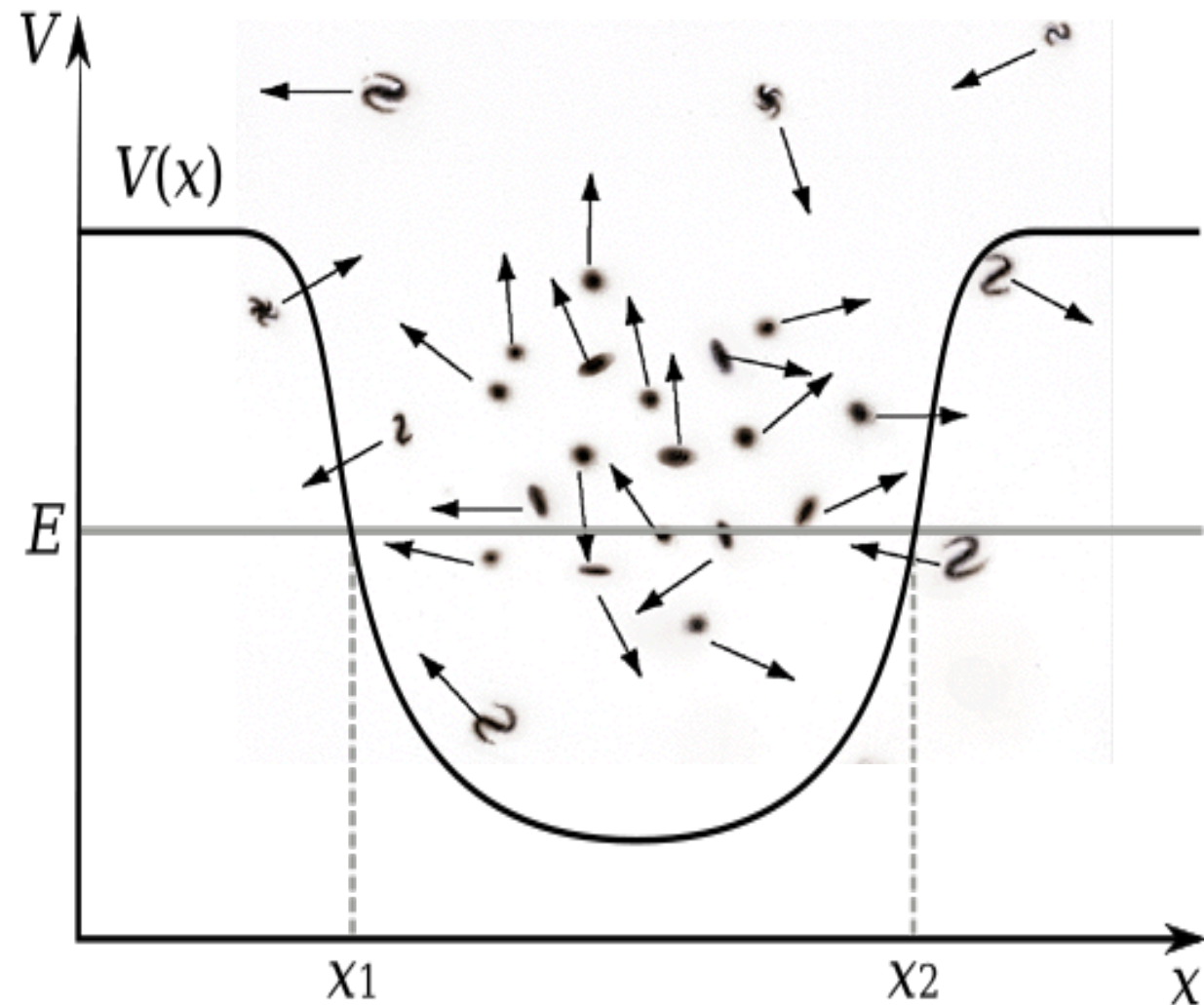
$$z \approx \frac{v_{\parallel}}{c}$$

$$cz \approx H_0 D$$



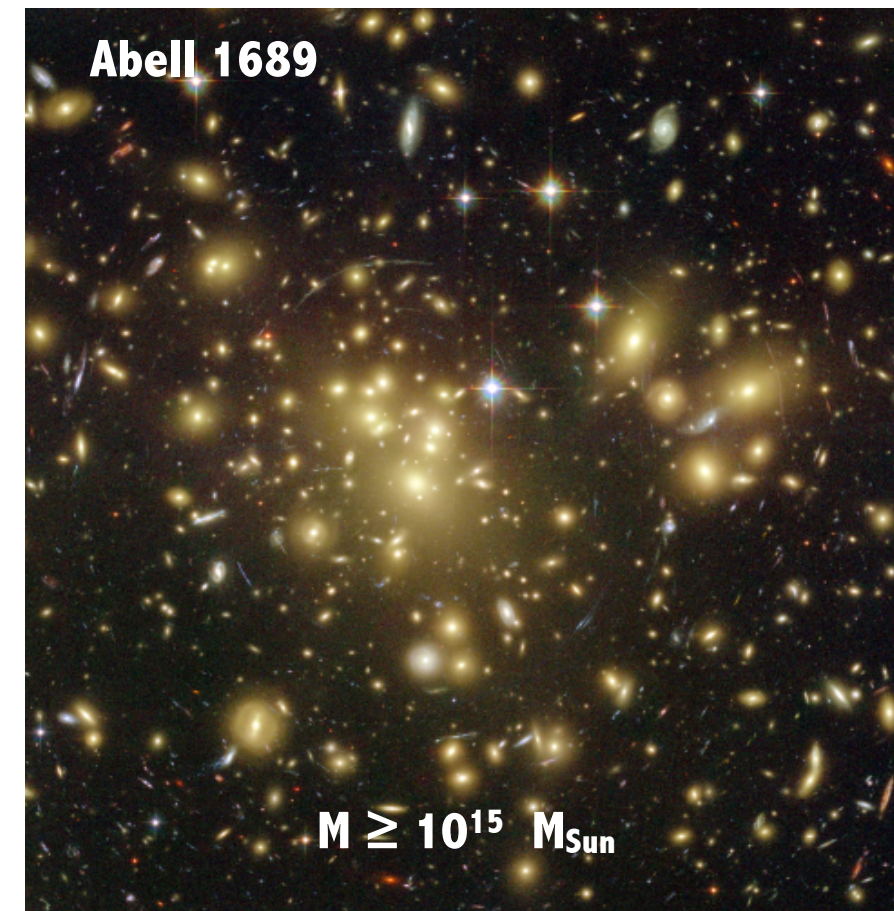
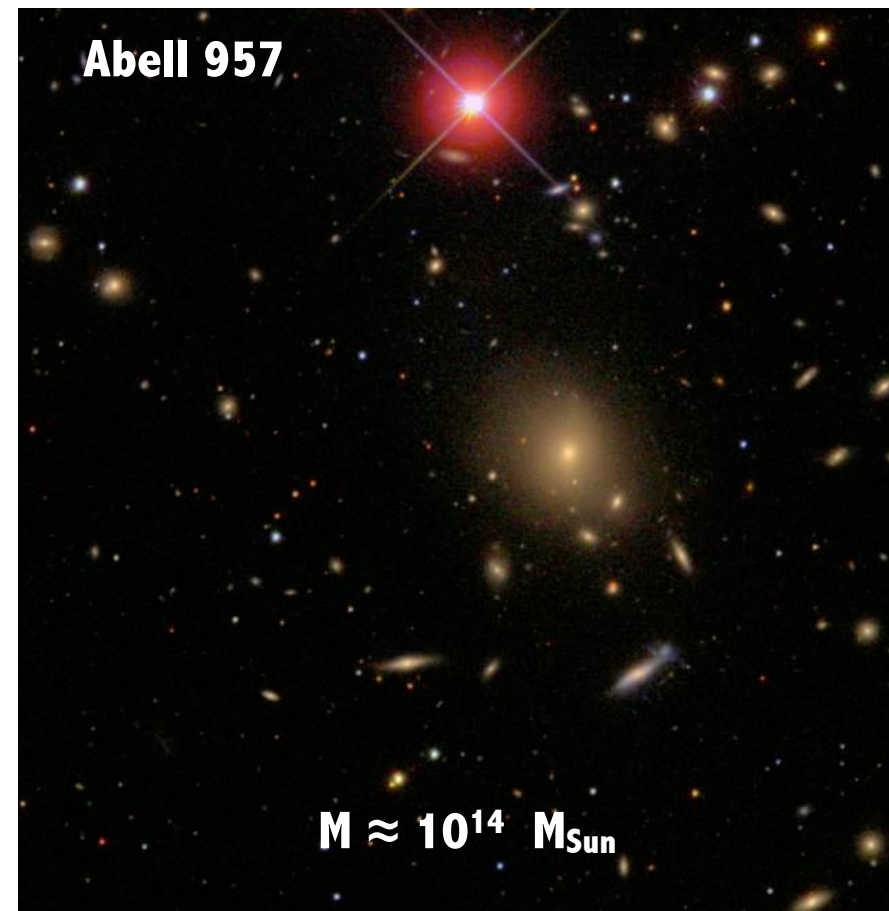
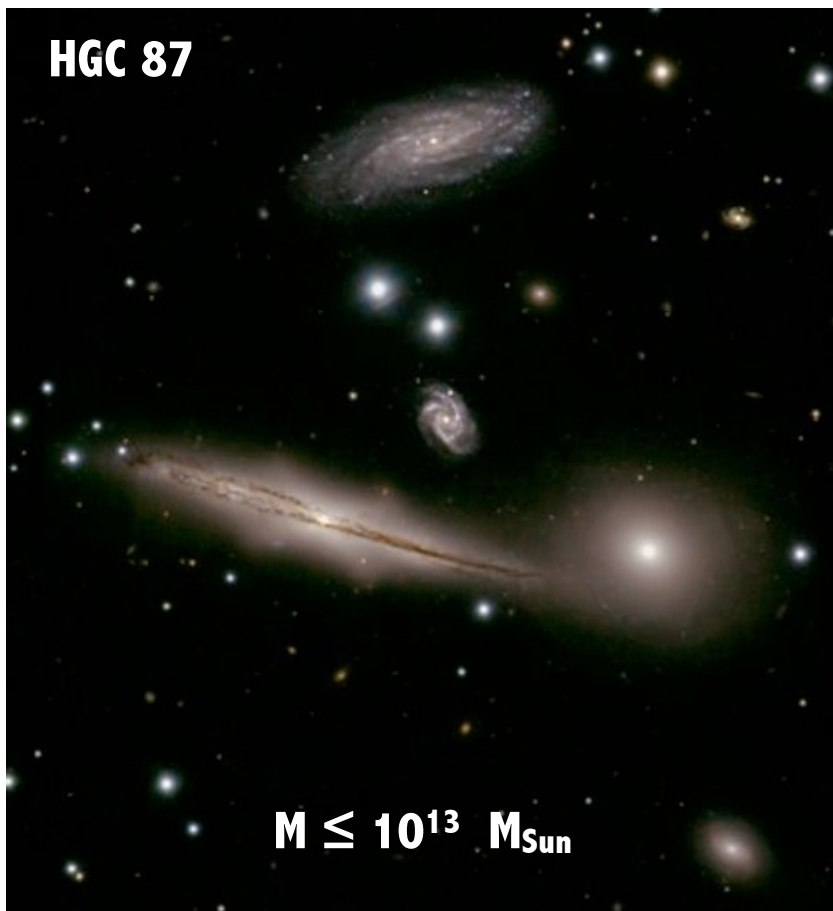


Dark matter evidence through galaxies



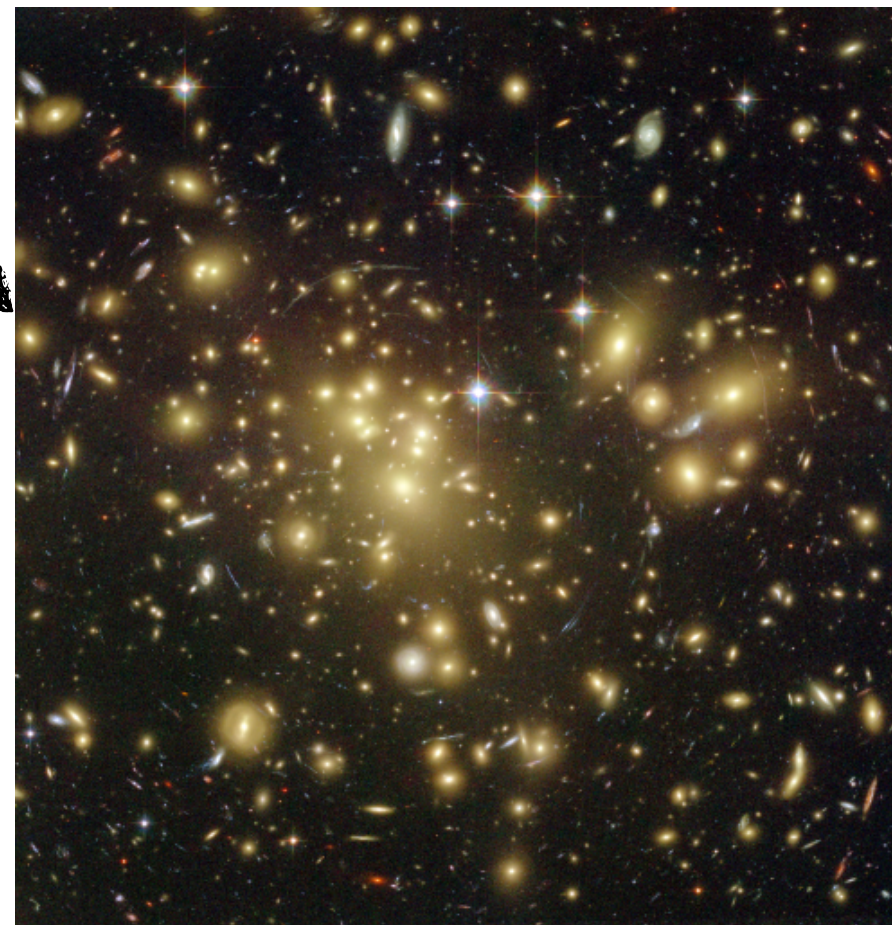
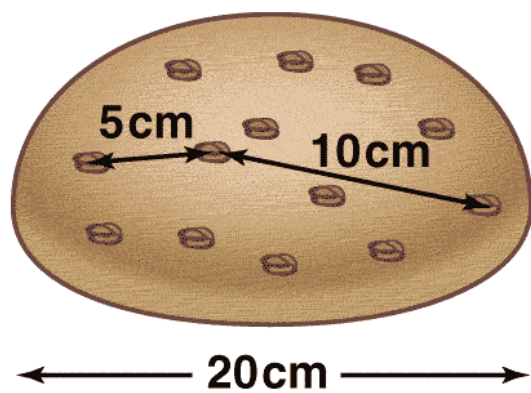
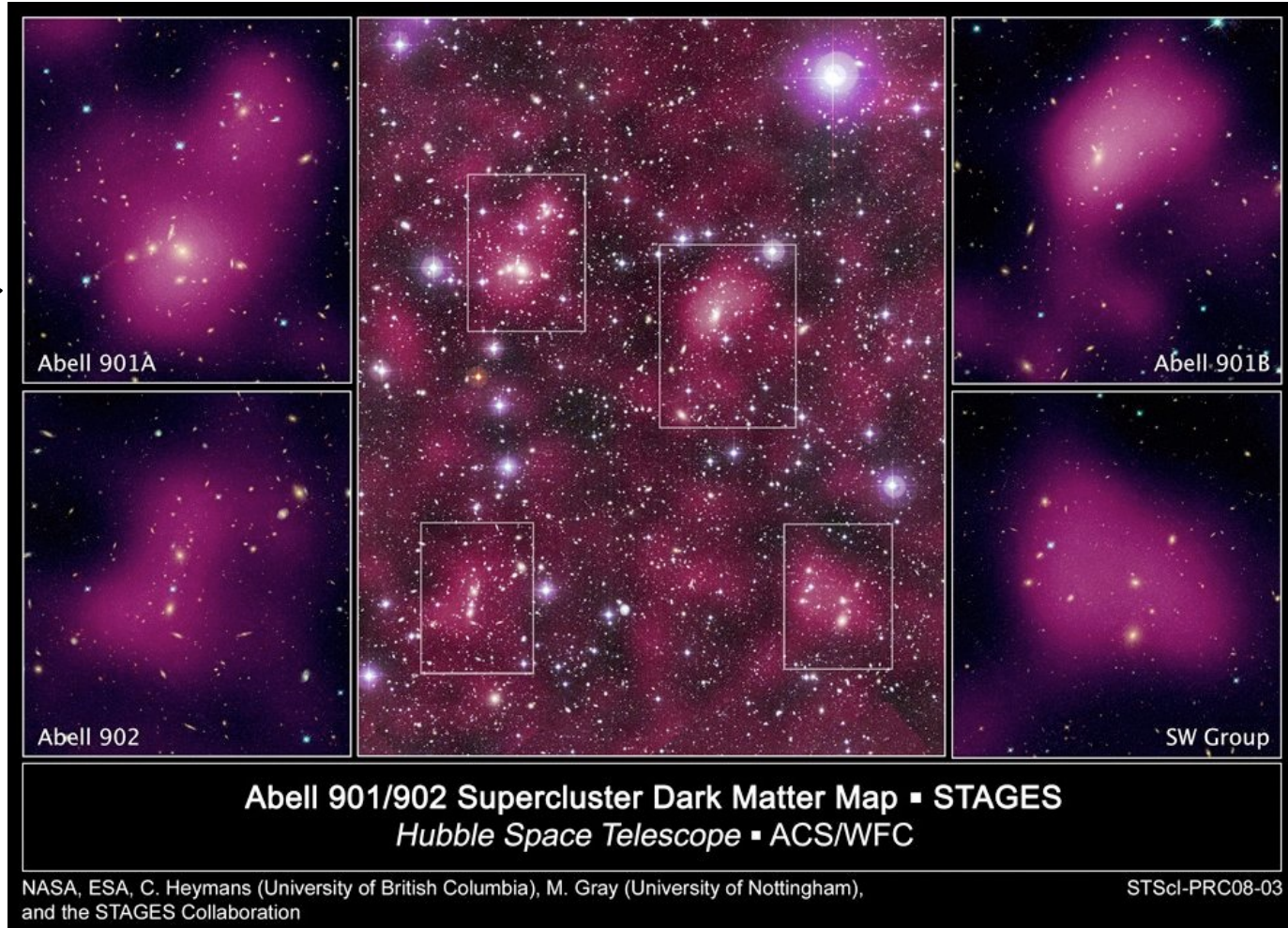
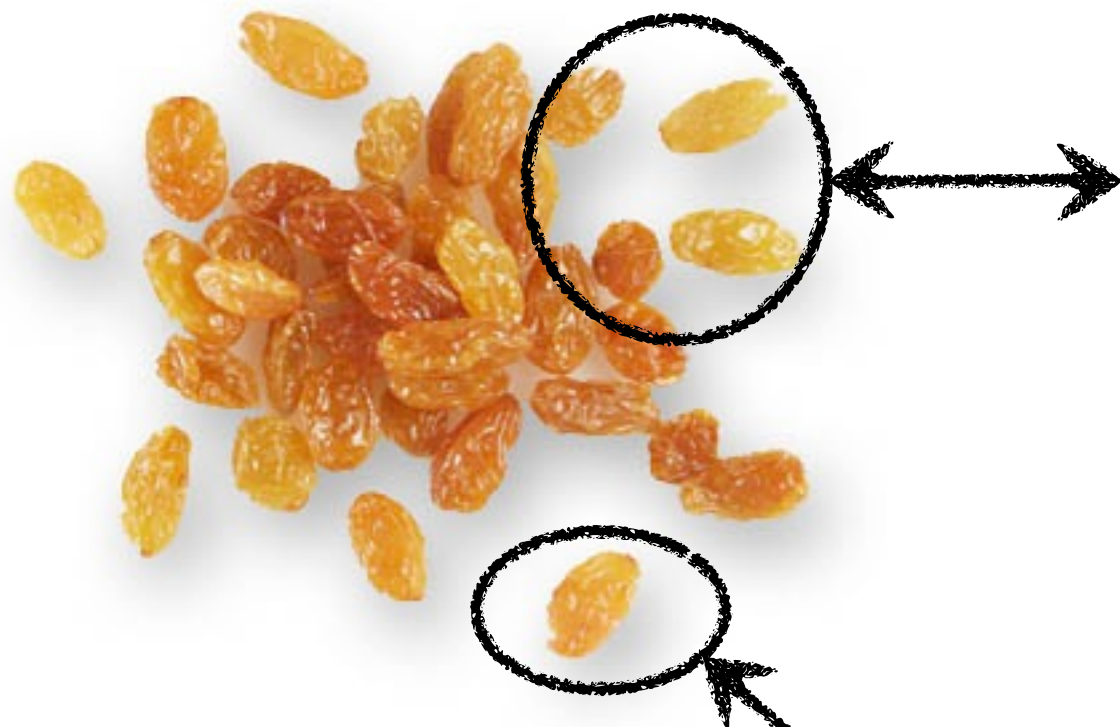
$$M_{\text{cluster}} \approx 400 \sum M_{\text{Galaxies}}$$

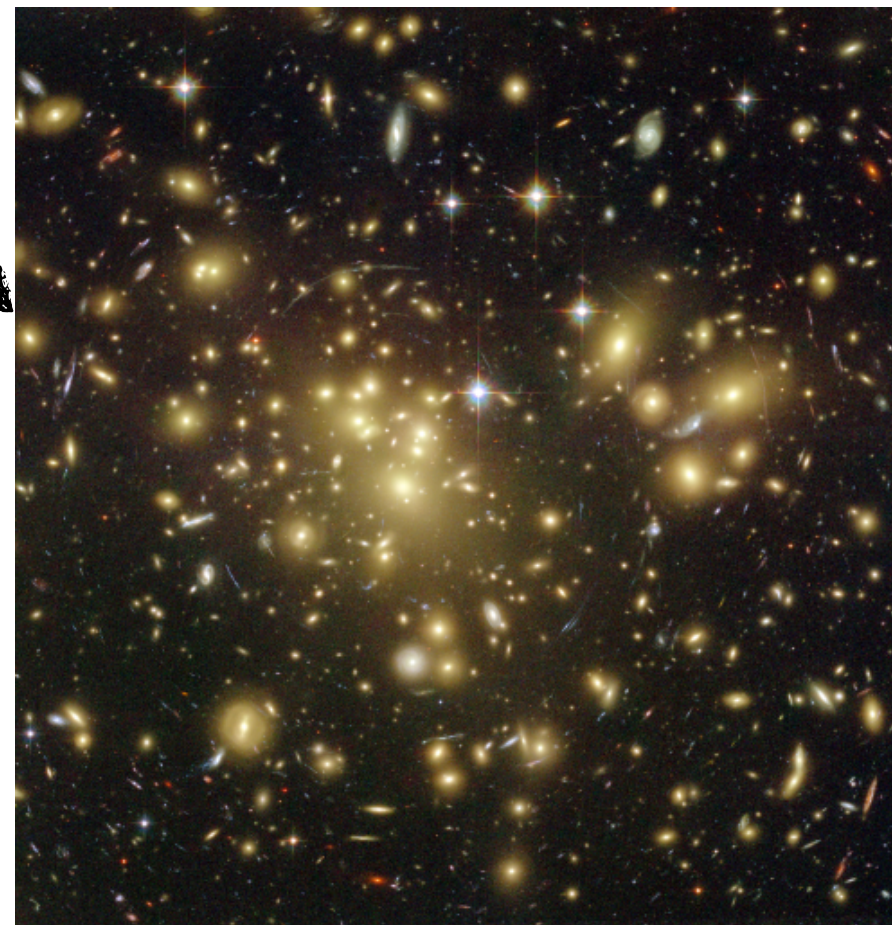
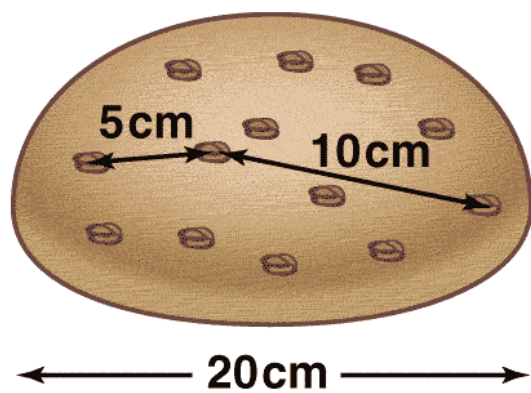
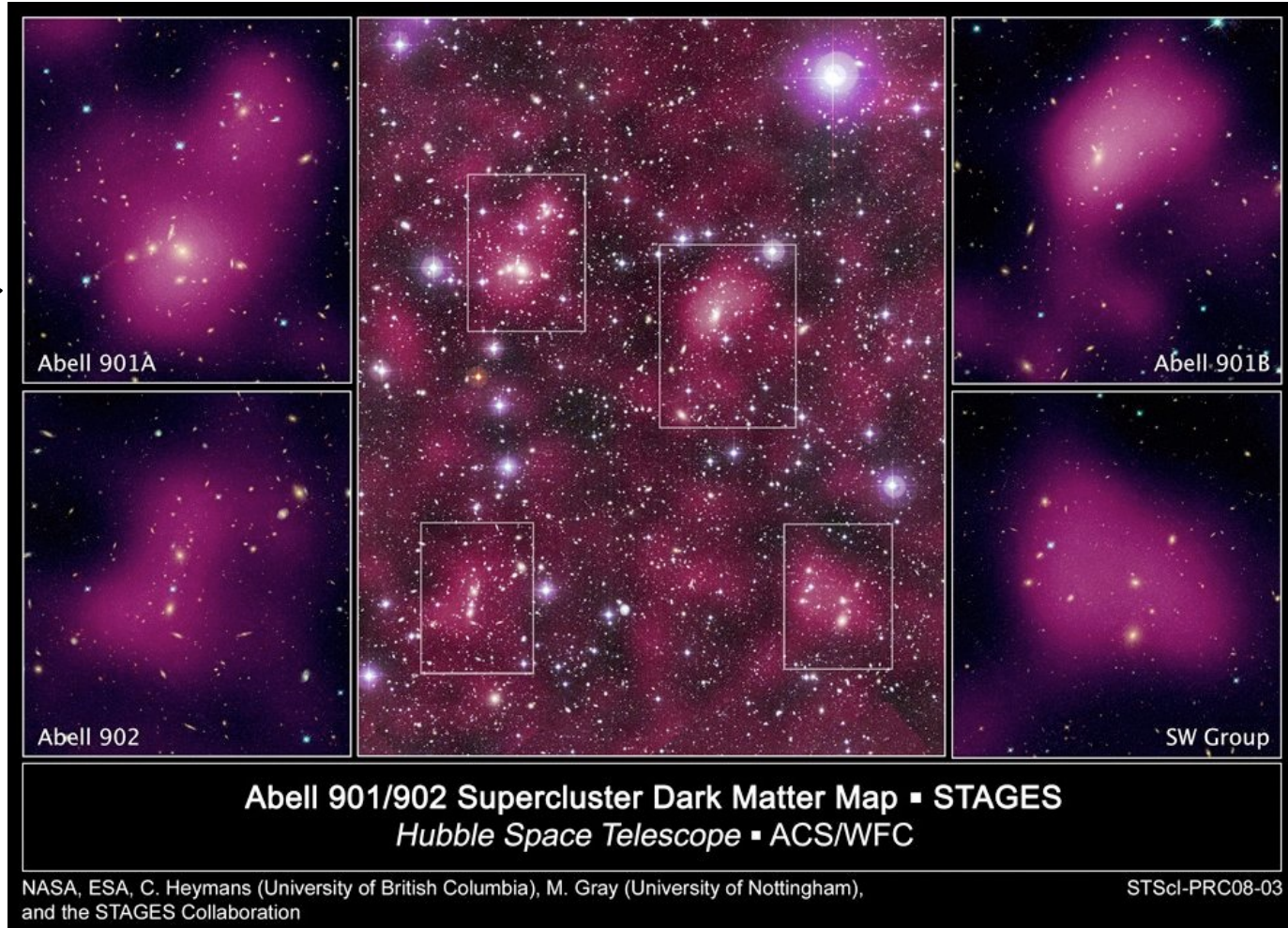
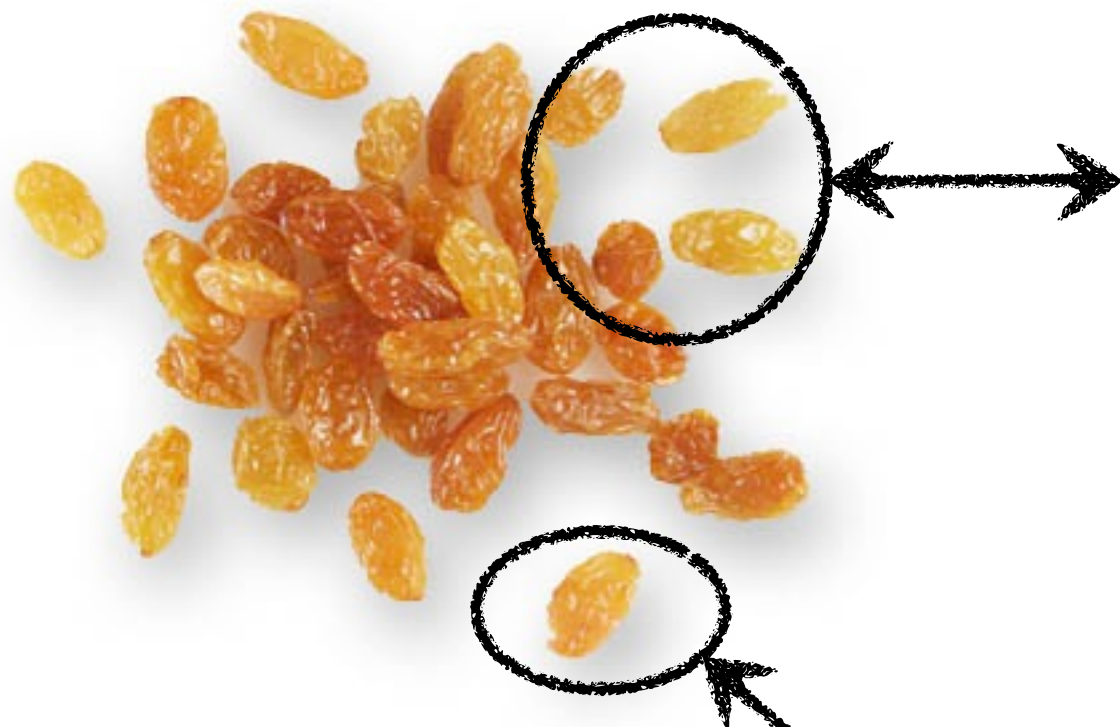
From groups to rich clusters

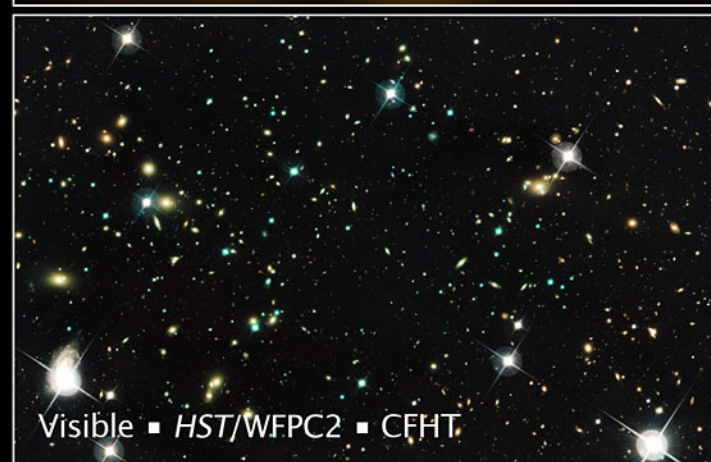
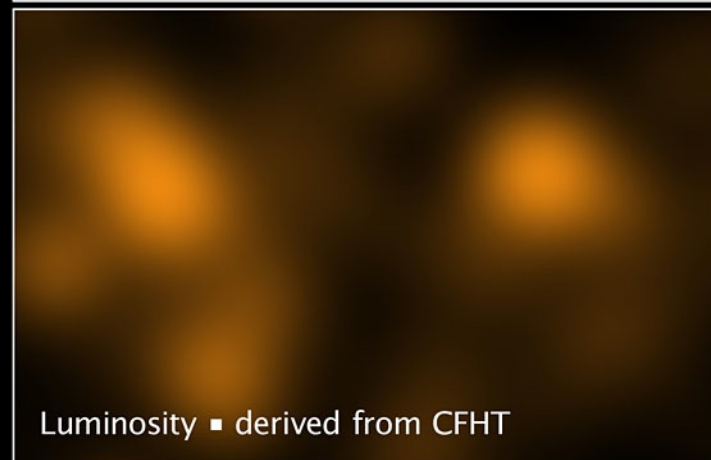


Most galaxies are not isolated in the Universe.
They are bound together by their mutual gravity in structures containing from a few galaxies,
to hundreds or even thousands galaxies

Rich clusters are the largest gravitationally bound virialized systems in the Universe

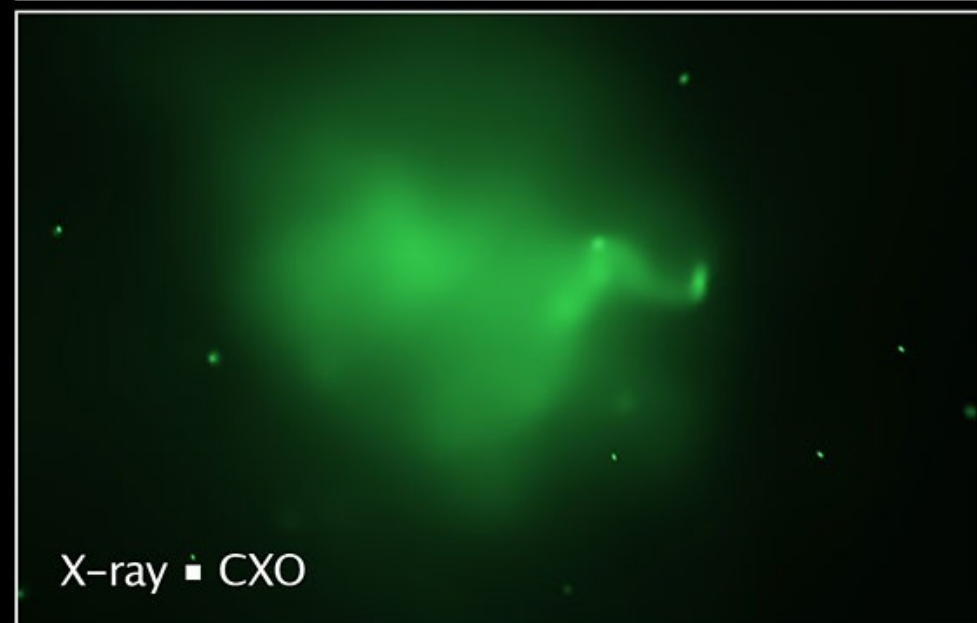




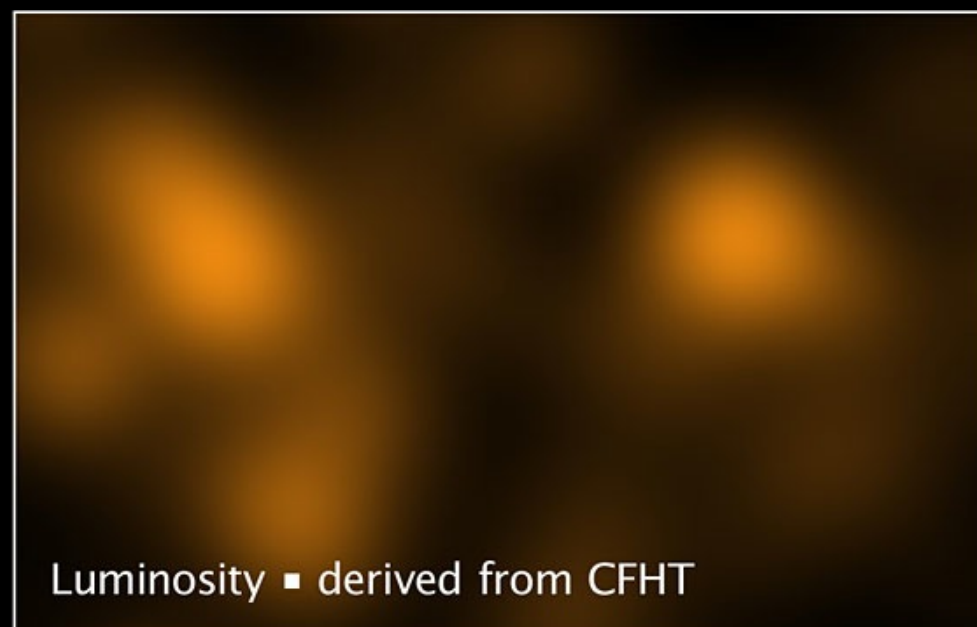




Why elliptical galaxies dominate in clusters ?



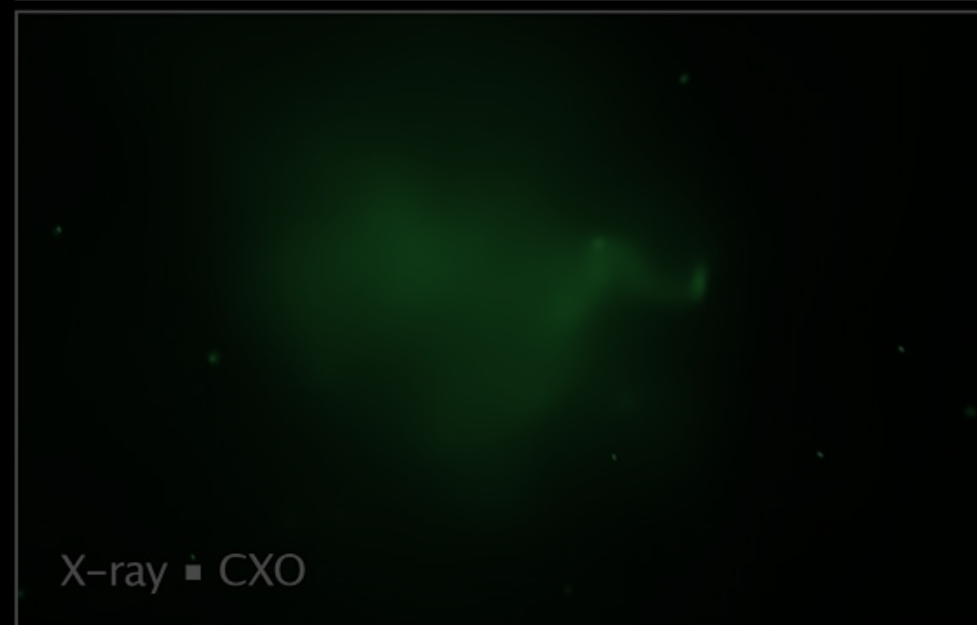
What is this component that we observe in X-rays ?



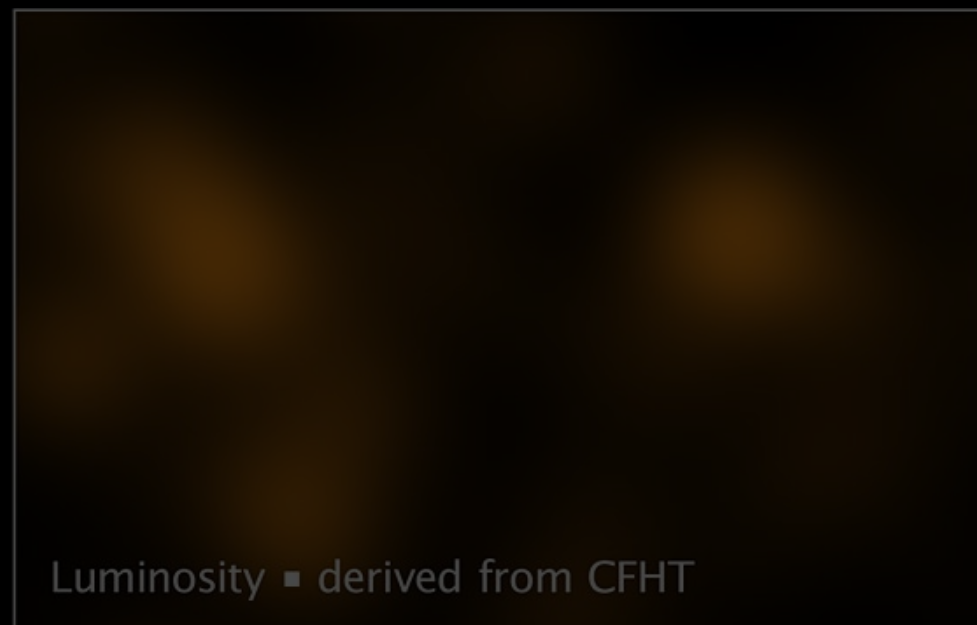
Why galaxies are not distributed in a nearly spherical way ?



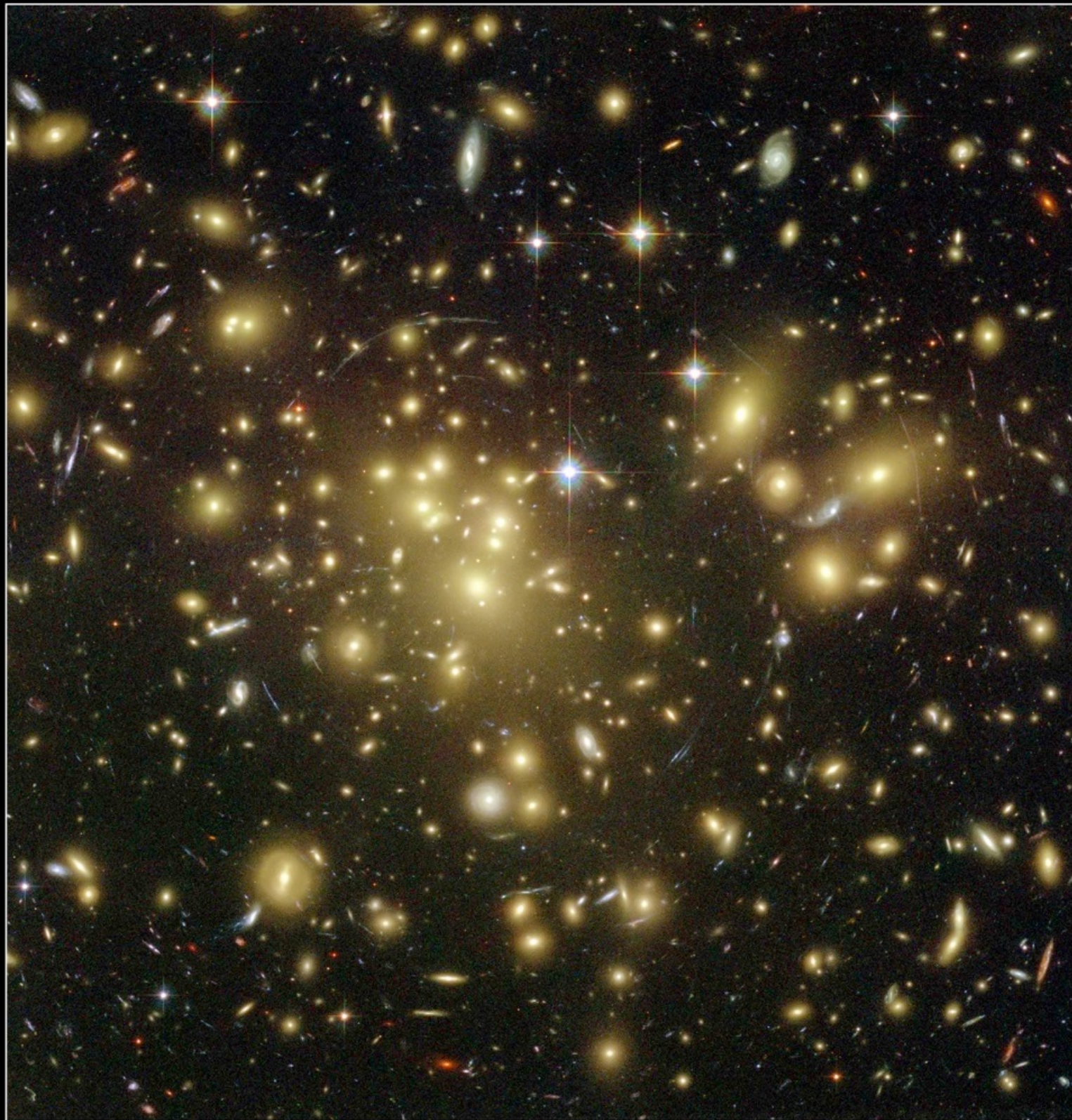
Why elliptical galaxies dominate in clusters ?



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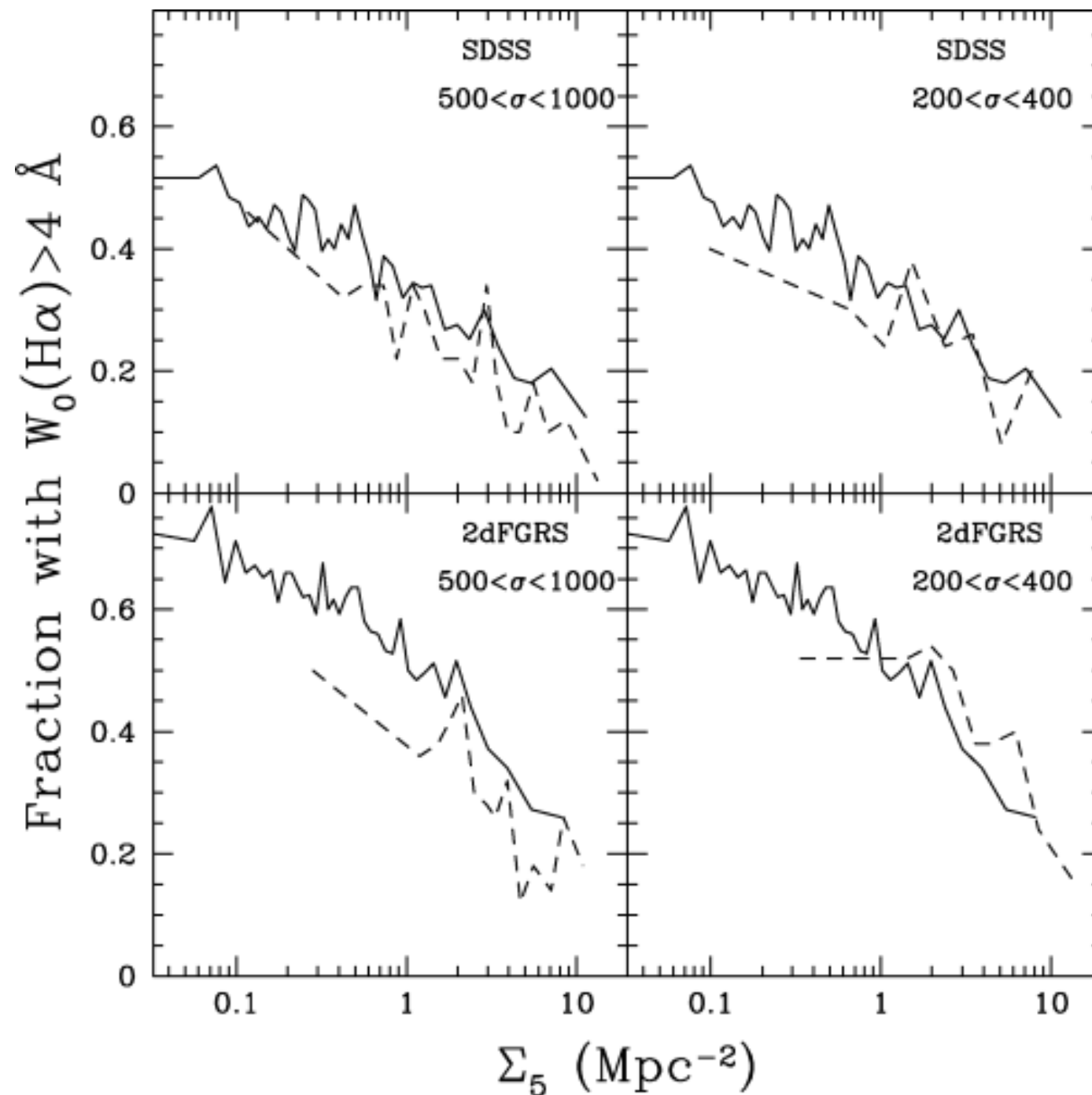
Why galaxies are not distributed in a nearly spherical way ?



Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Cluster environment hostile to star formation

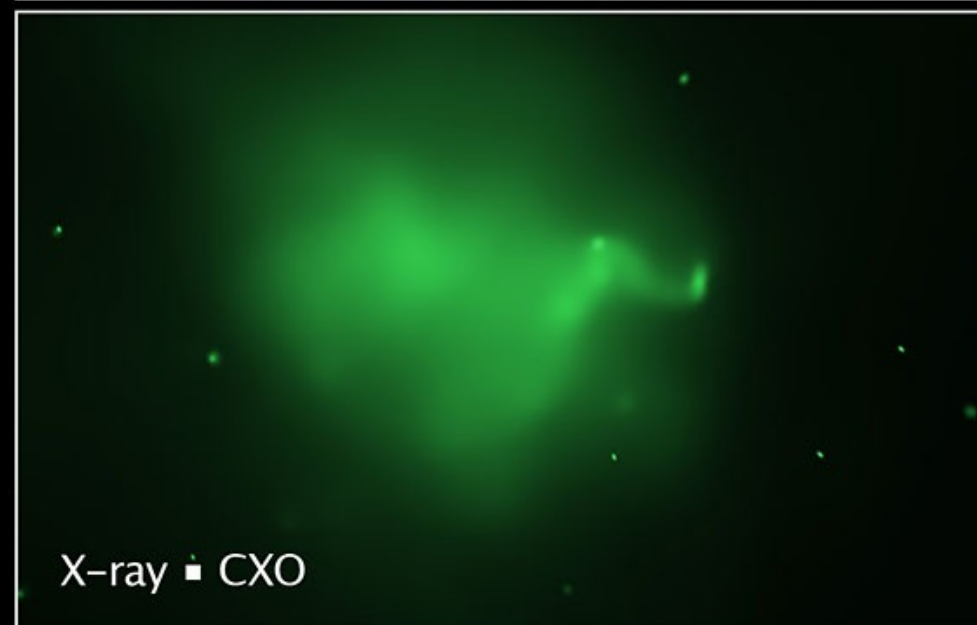


$W_0(\text{H}\alpha) > 4 \text{ \AA} \equiv$ Star forming galaxies

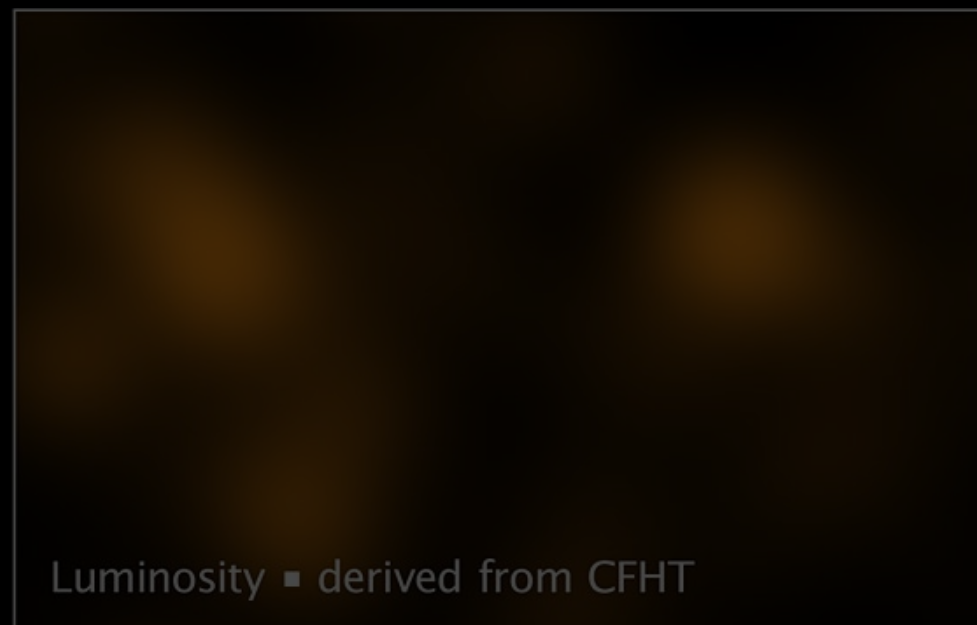
Balogh et al. 04



Why elliptical galaxies dominate in clusters ?



What is this component that we observe in X-rays ?



Why galaxies are not distributed in a nearly spherical way ?

The Intra-Cluster Medium (ICM)

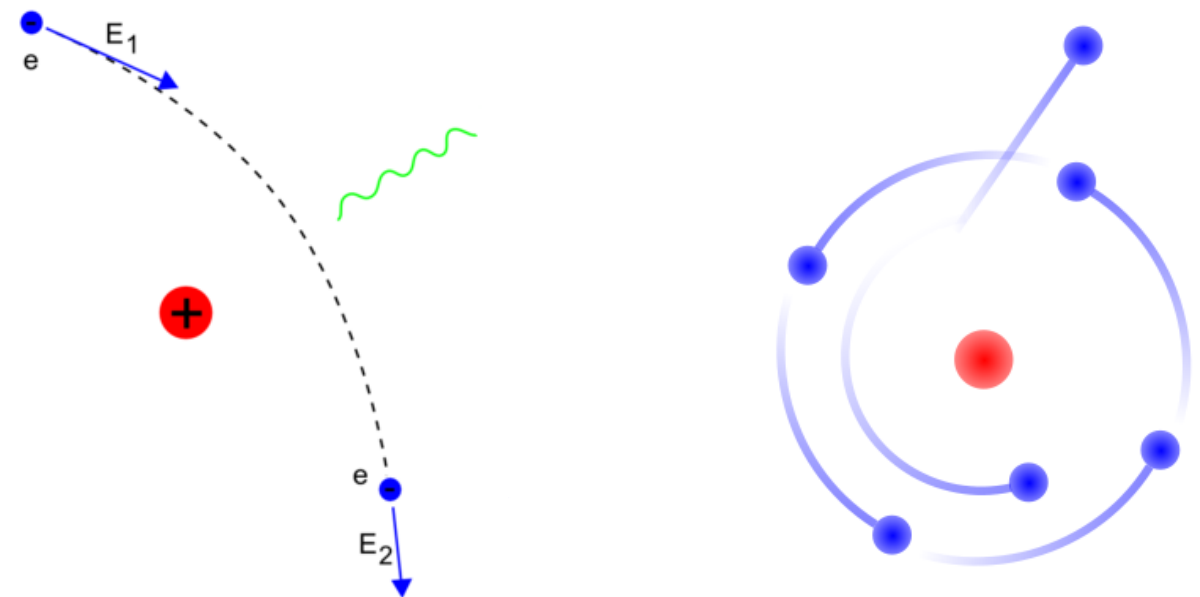
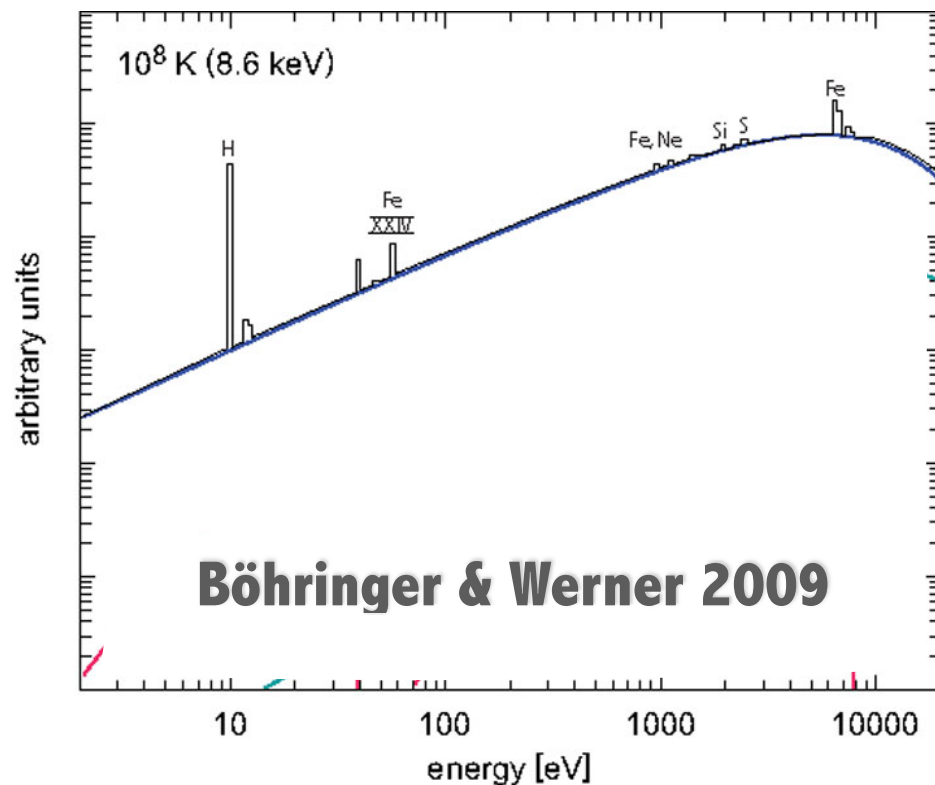
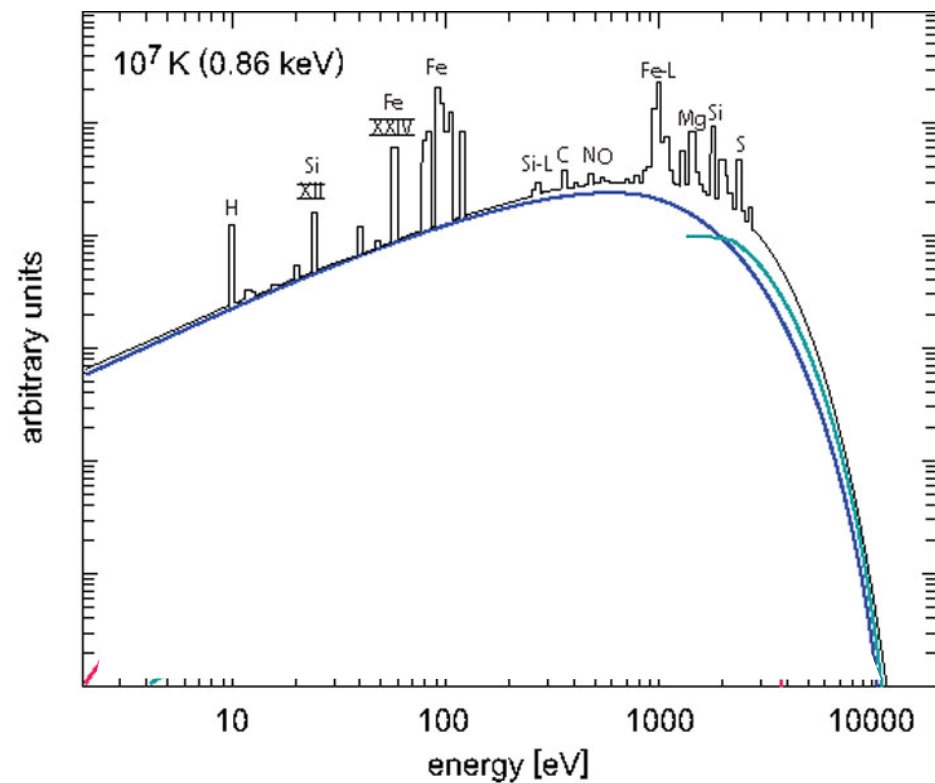


Optical: NASA/STScI, ESO/VLT, SDSS



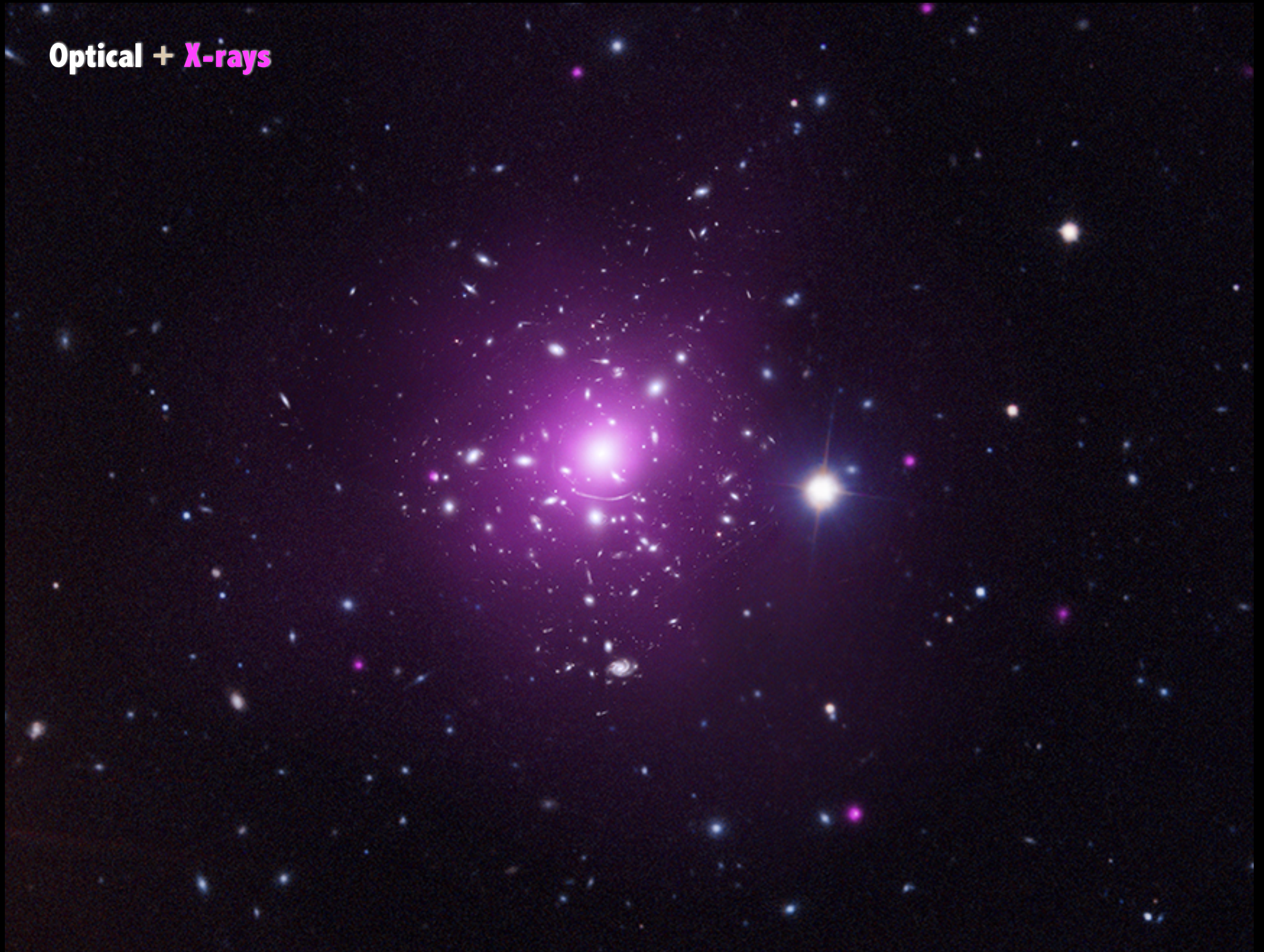
**X-ray: NASA/CXC/Caltech/A.Newman et al/
Tel Aviv/A.Morandi & M.Limousin**

Thermal bremsstrahlung emission



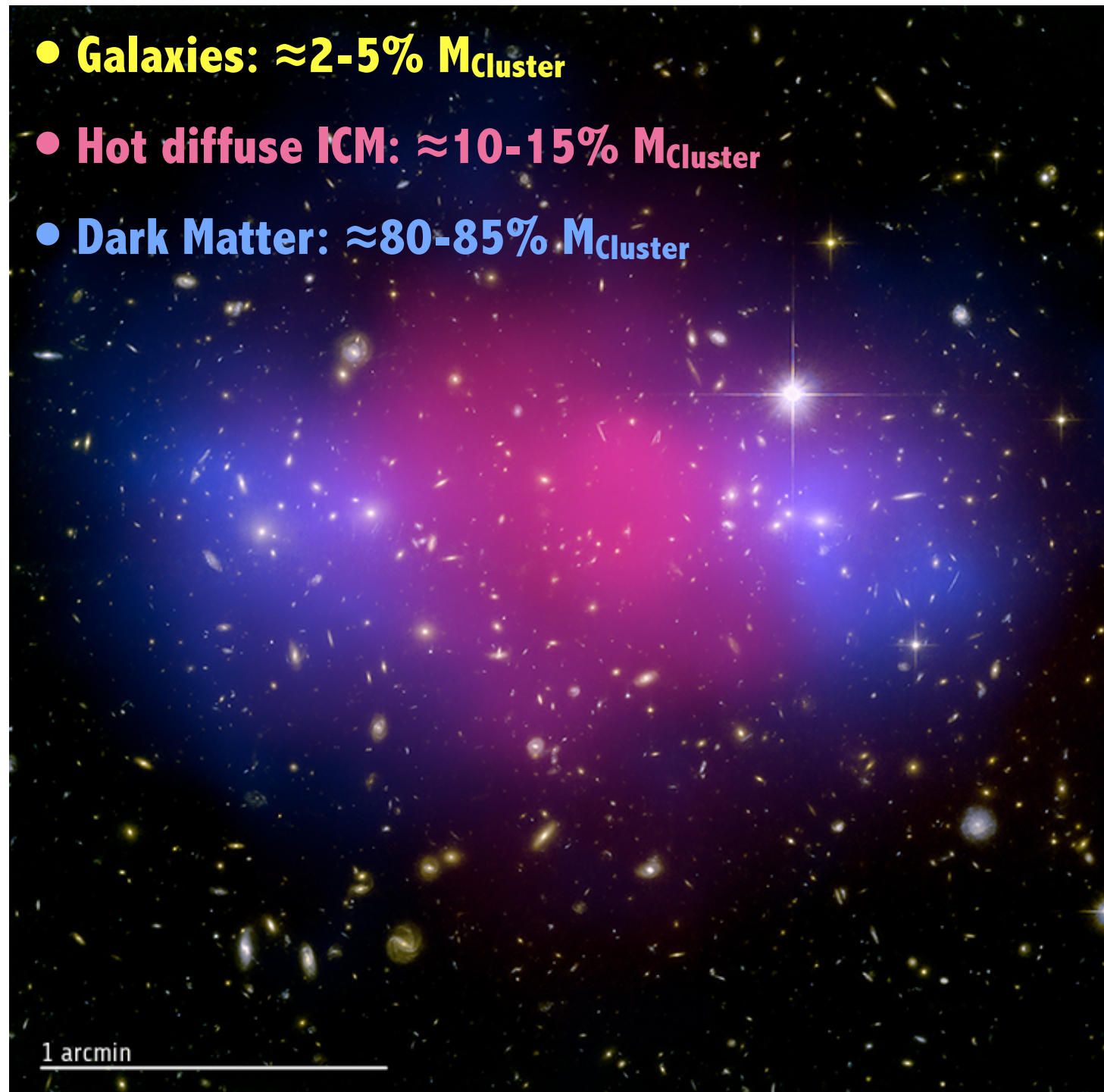
Diffuse ($10^{-5} - 10^{-1}$ atoms/cm³)
and very hot ($10^7 - 10^8$ K!!!)
ionised intra-cluster gas

Optical + X-rays

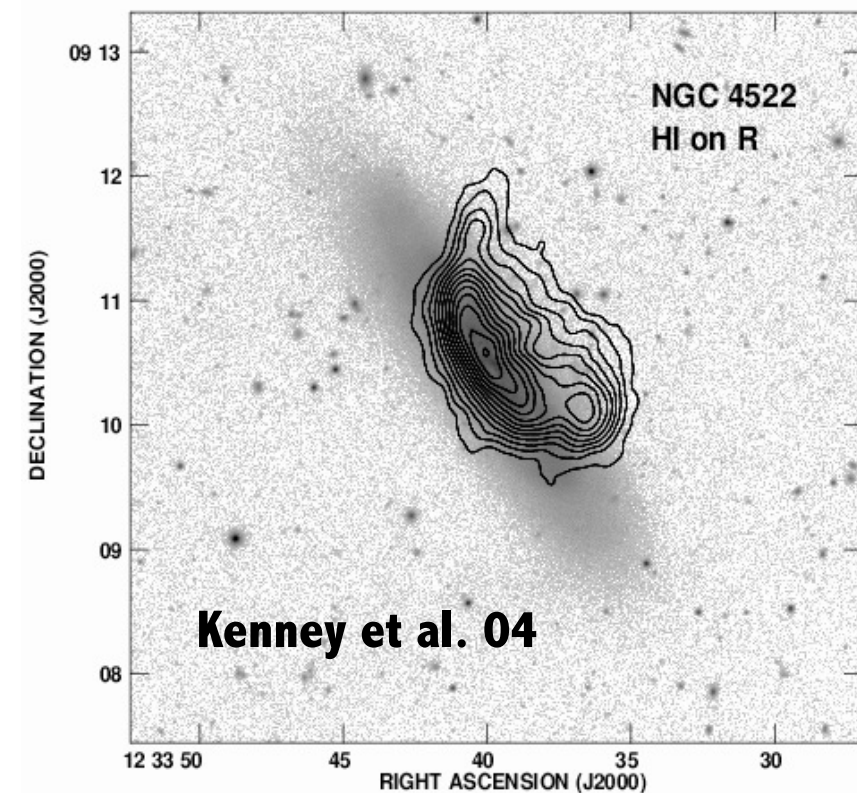


The massive components of galaxy clusters

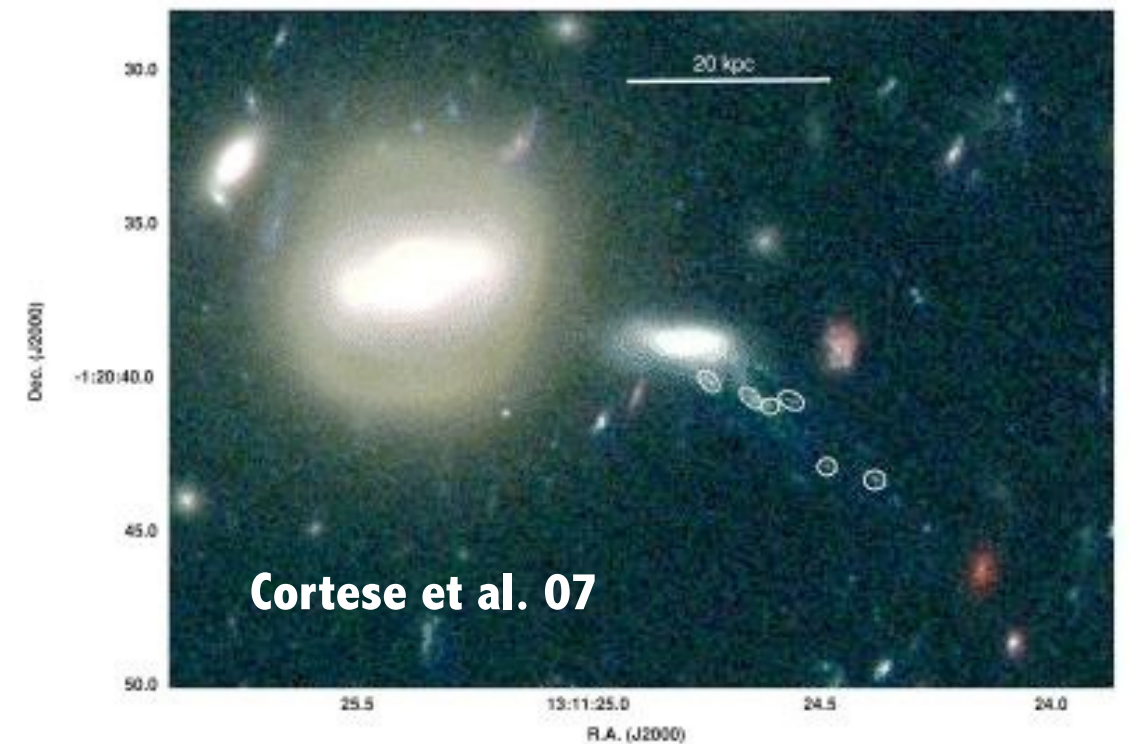
- **Galaxies:** $\approx 2-5\% M_{\text{cluster}}$
- **Hot diffuse ICM:** $\approx 10-15\% M_{\text{cluster}}$
- **Dark Matter:** $\approx 80-85\% M_{\text{cluster}}$



Ram-pressure stripping (and compression)



- Ram-pressure
($\propto \rho_{\text{ICM}} \times v^2$)
- Gas stripping
- Gas compression

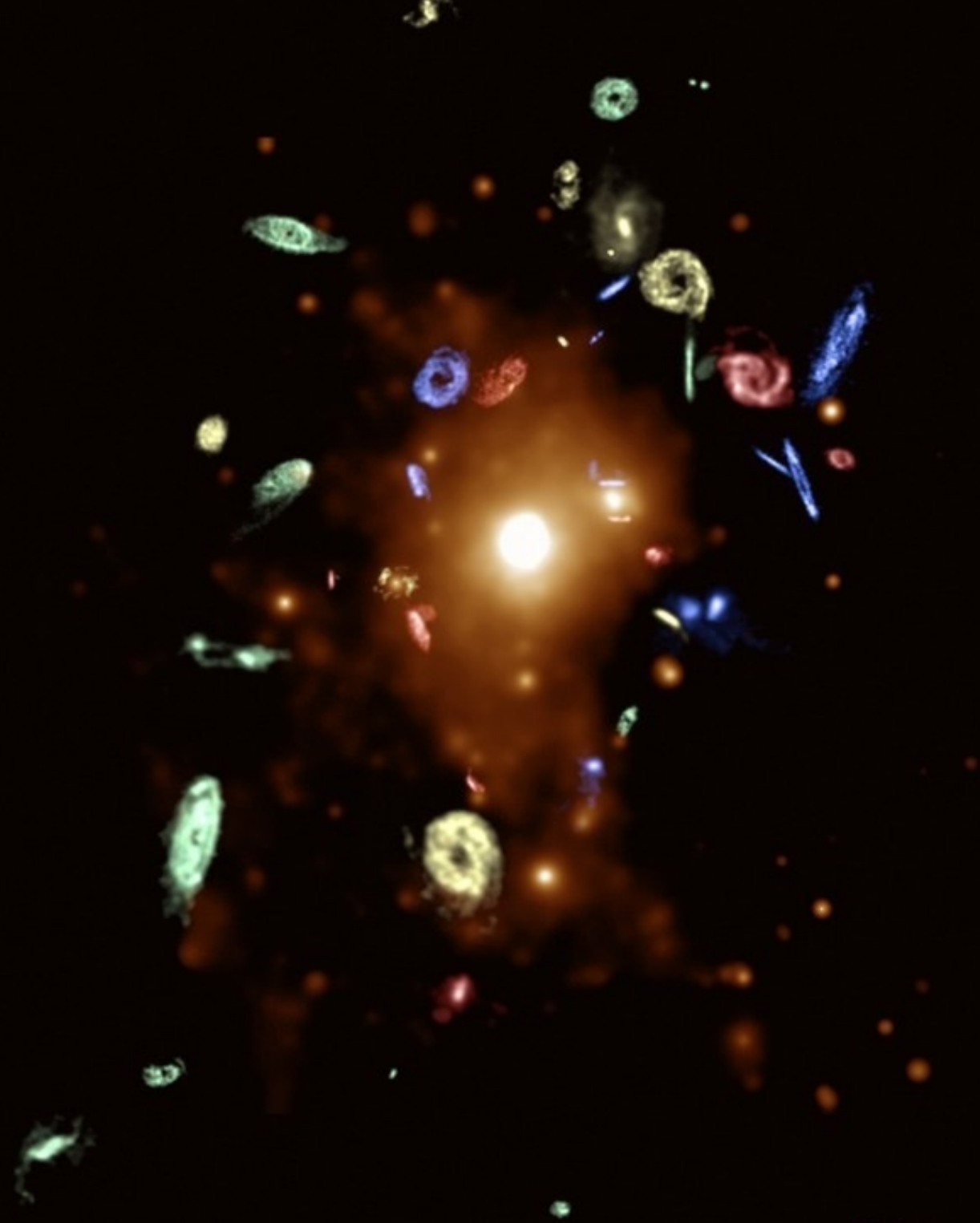


Kapferer et al. 09

Newly formed stars

Stripped Interstellar Medium

Virgo, A Laboratory for Studying Galaxy Evolution

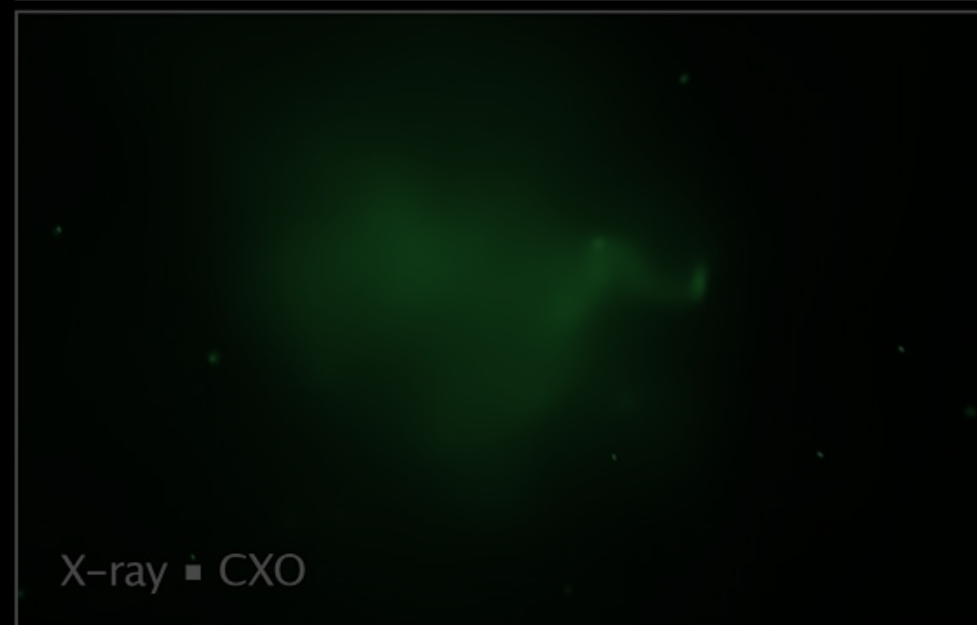


The VIVA Survey (VLA Imaging of Virgo in Atomic gas)
Imaging survey in HI

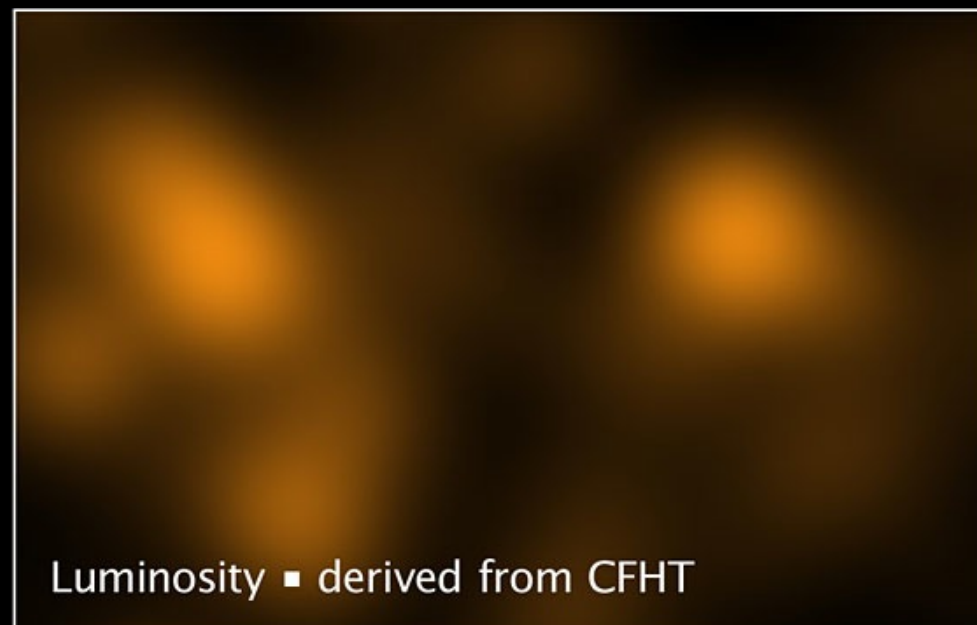
- $\mathcal{V} < 500 \text{ km/s}$
- $600 \text{ km/s} < \mathcal{V} < 1300 \text{ km/s}$
- $1400 \text{ km/s} < \mathcal{V} < 2000 \text{ km/s}$
- $\mathcal{V} > 2000 \text{ km/s}$



Why elliptical galaxies dominate in clusters ?



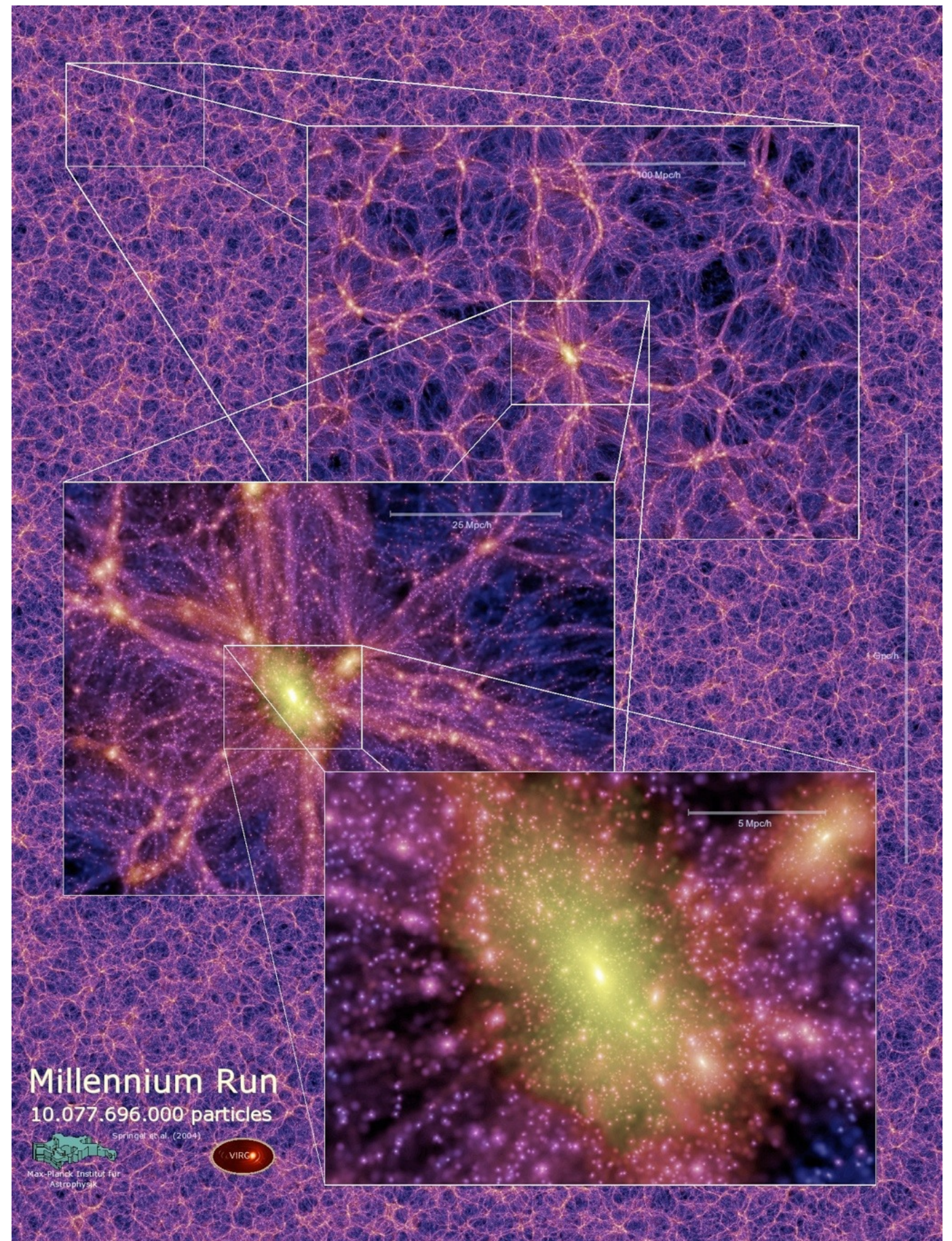
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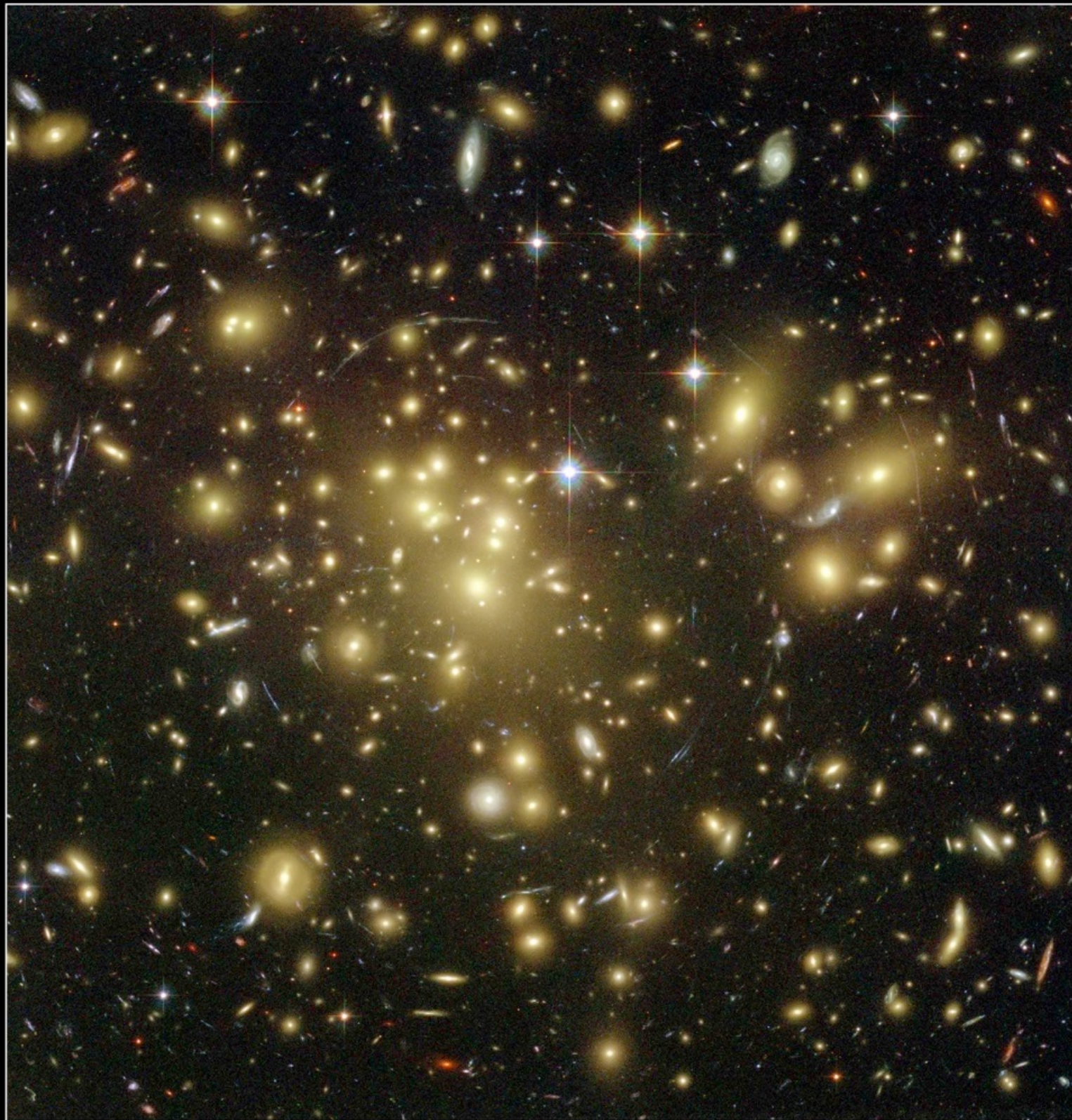


Why galaxies are not distributed in a nearly spherical way ?

Hierarchical structure formation

- Galaxy clusters form through merging of less massive clusters and/or accretion of field galaxies or small groups
- Huge gravitational binding energies ($\geq 10^{64}$ ergs) are realised during major cluster mergers
- Complex evolutionary physics of clusters





Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

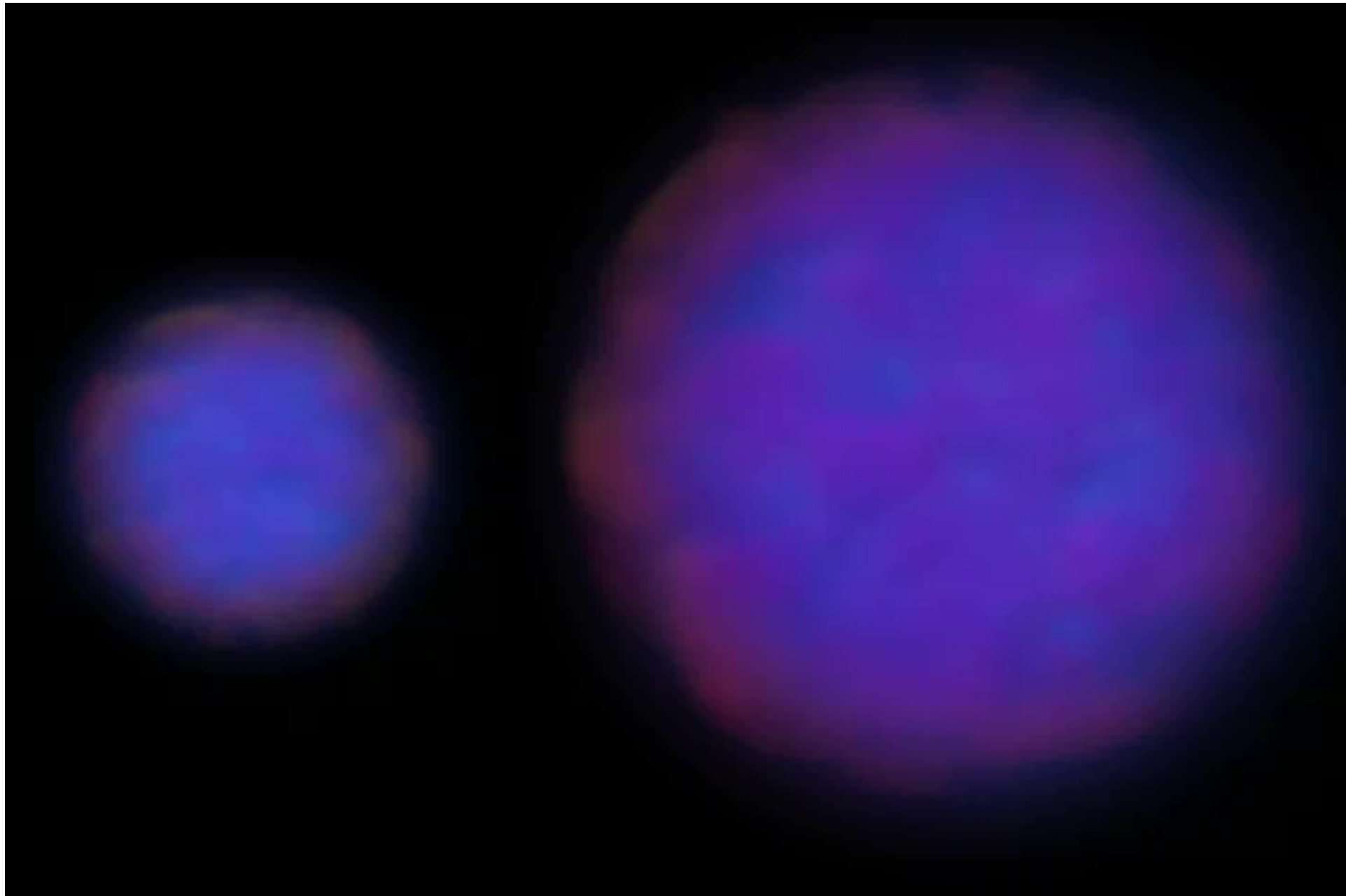
The “Bullet Cluster”



The “Bullet Cluster”

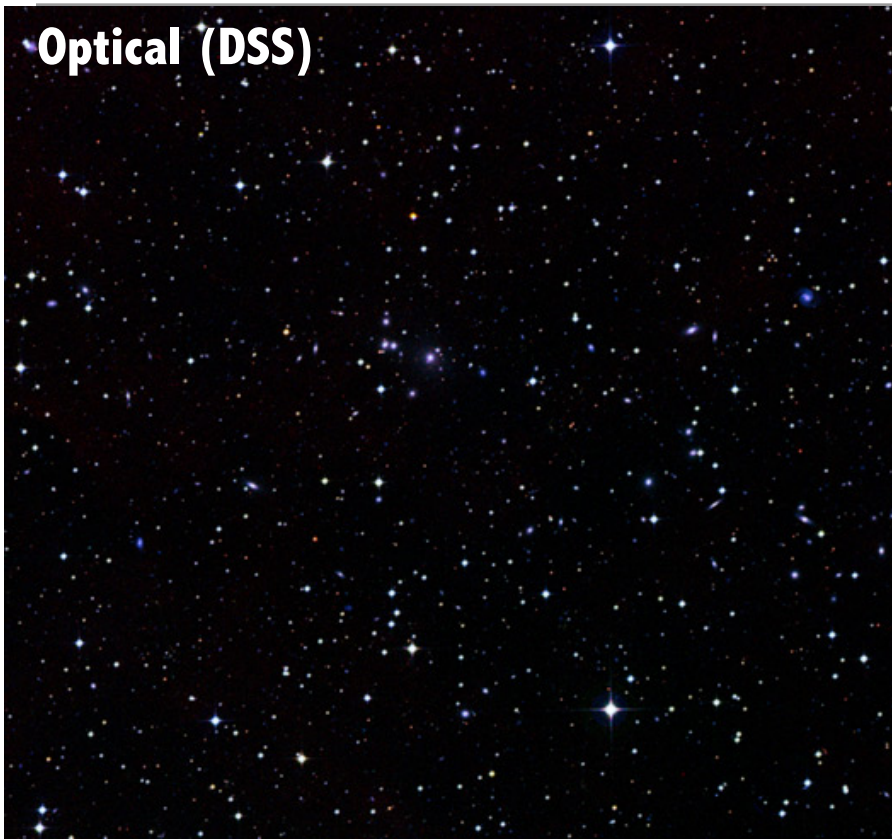


Numerical simulations of the Bullett cluster



A new window on galaxy cluster studies

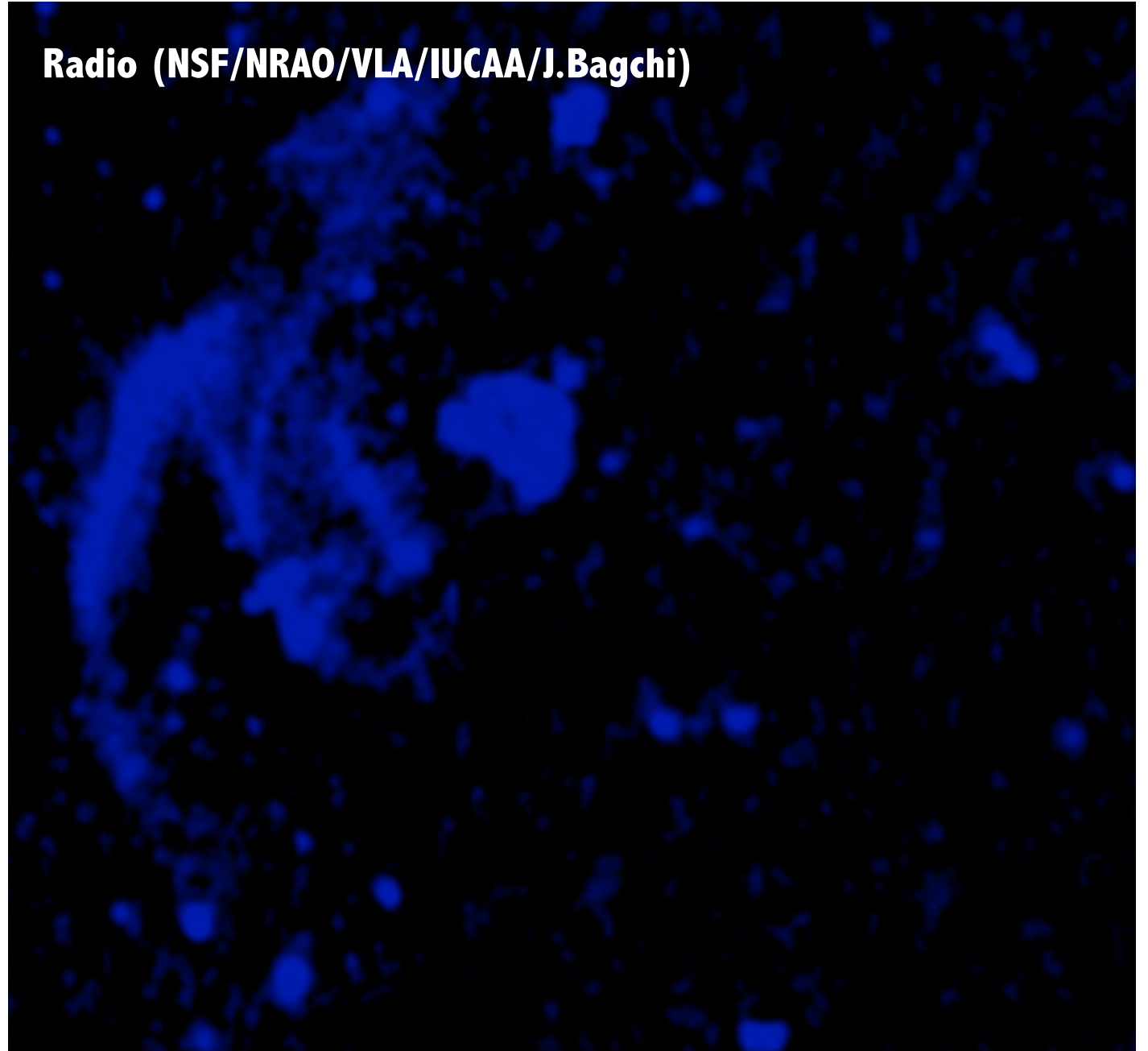
Optical (DSS)



X-ray (NASA/CXC/SAO/Vikhlinin; ROSAT)

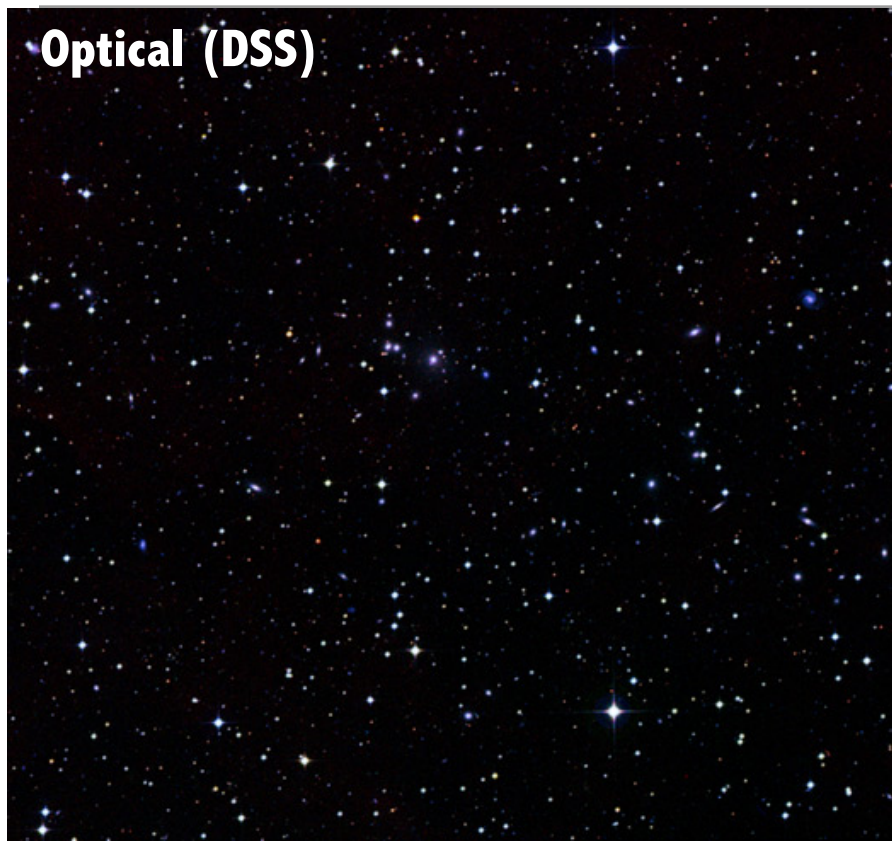


Radio (NSF/NRAO/VLA/IUCAA/J.Bagchi)



A new window on galaxy cluster studies

Optical (DSS)

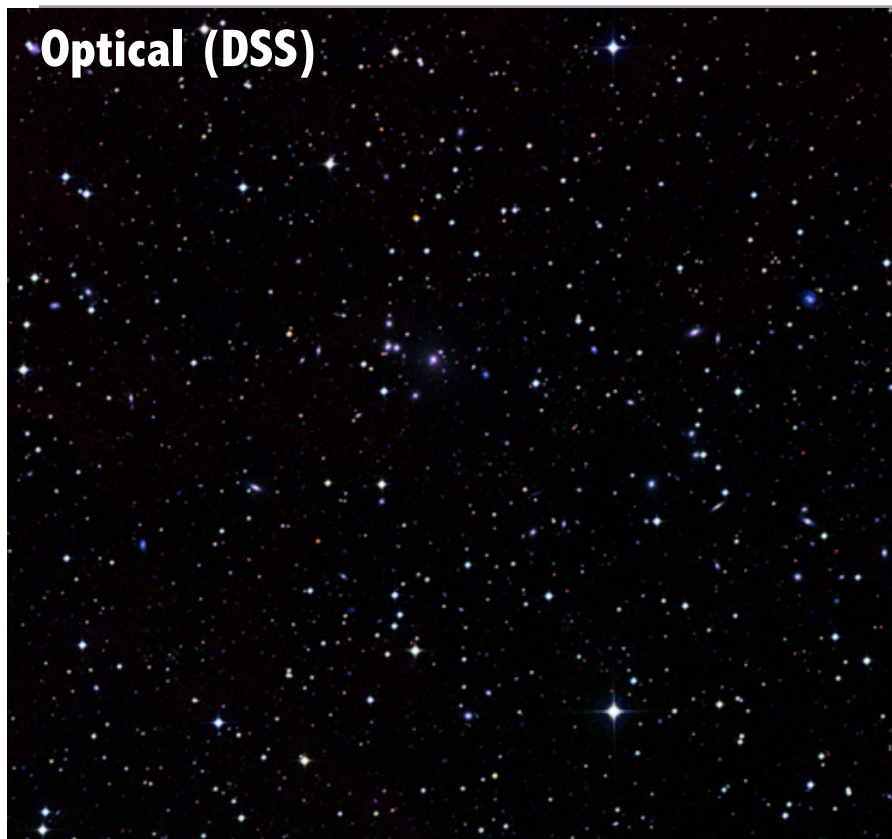


X-ray (NASA/CXC/SAO/Vikhlinin; ROSAT)

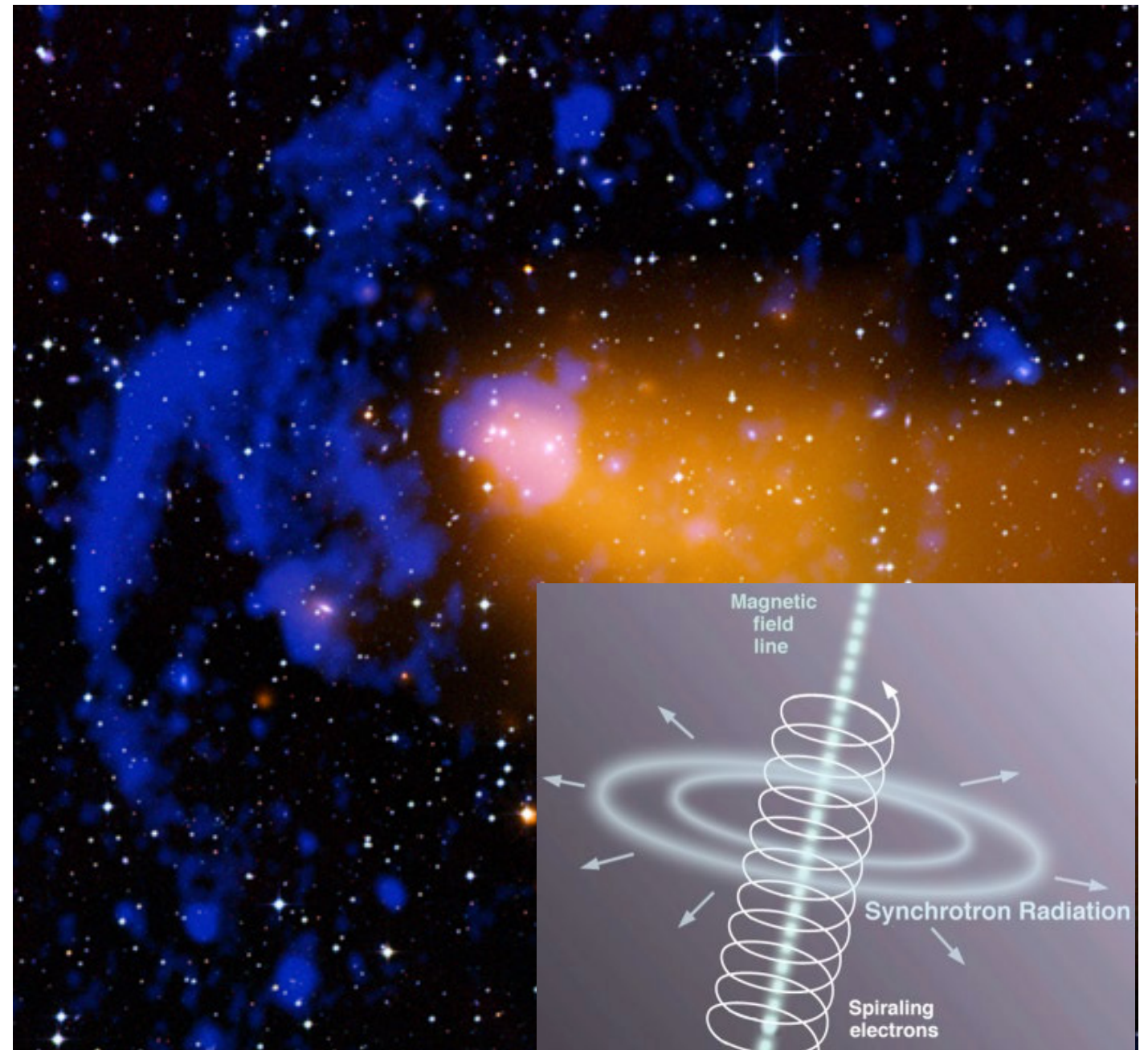


A new window on galaxy cluster studies

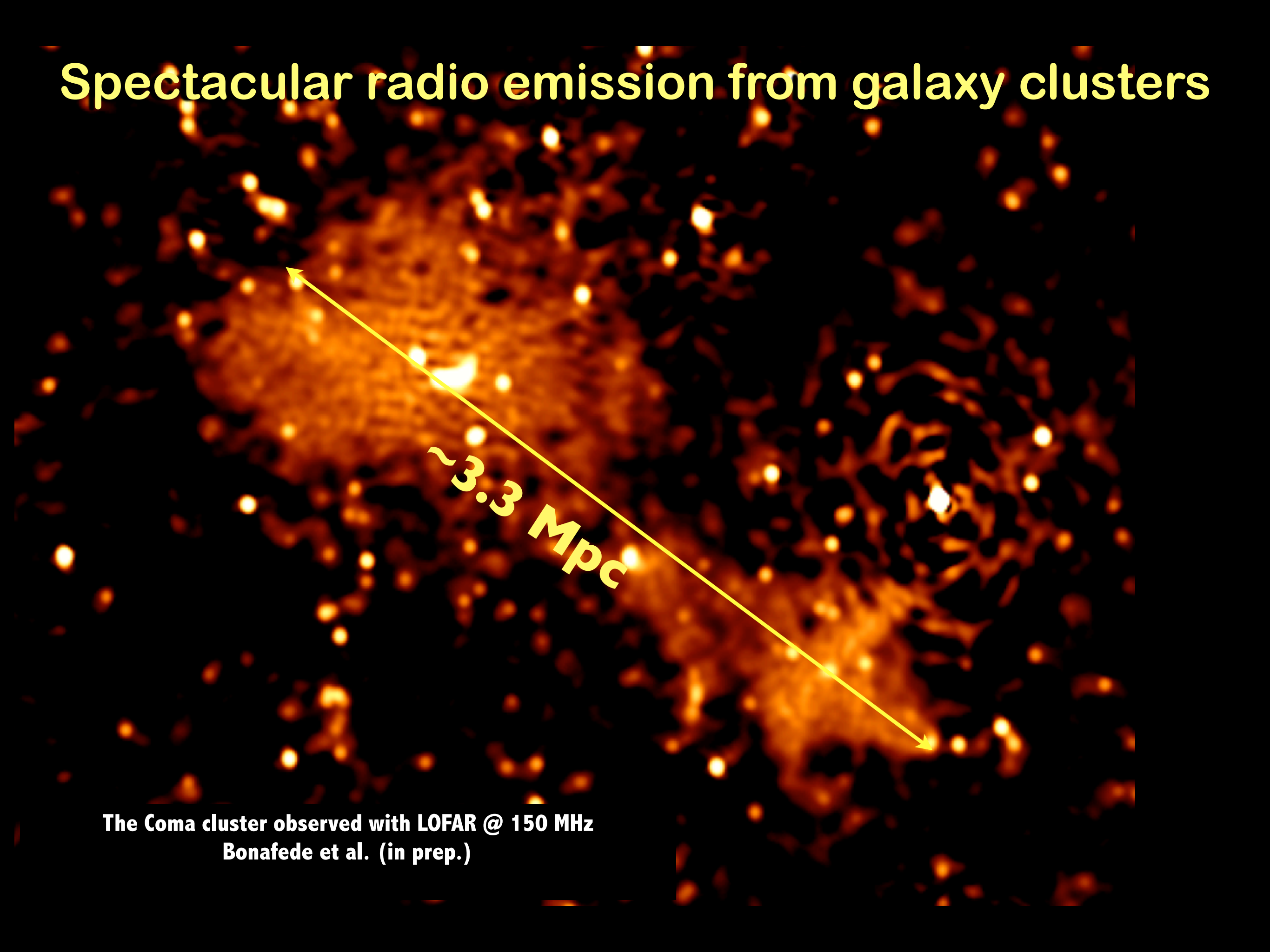
Optical (DSS)



X-ray (NASA/CXC/SAO/Vikhlinin; ROSAT)



Spectacular radio emission from galaxy clusters

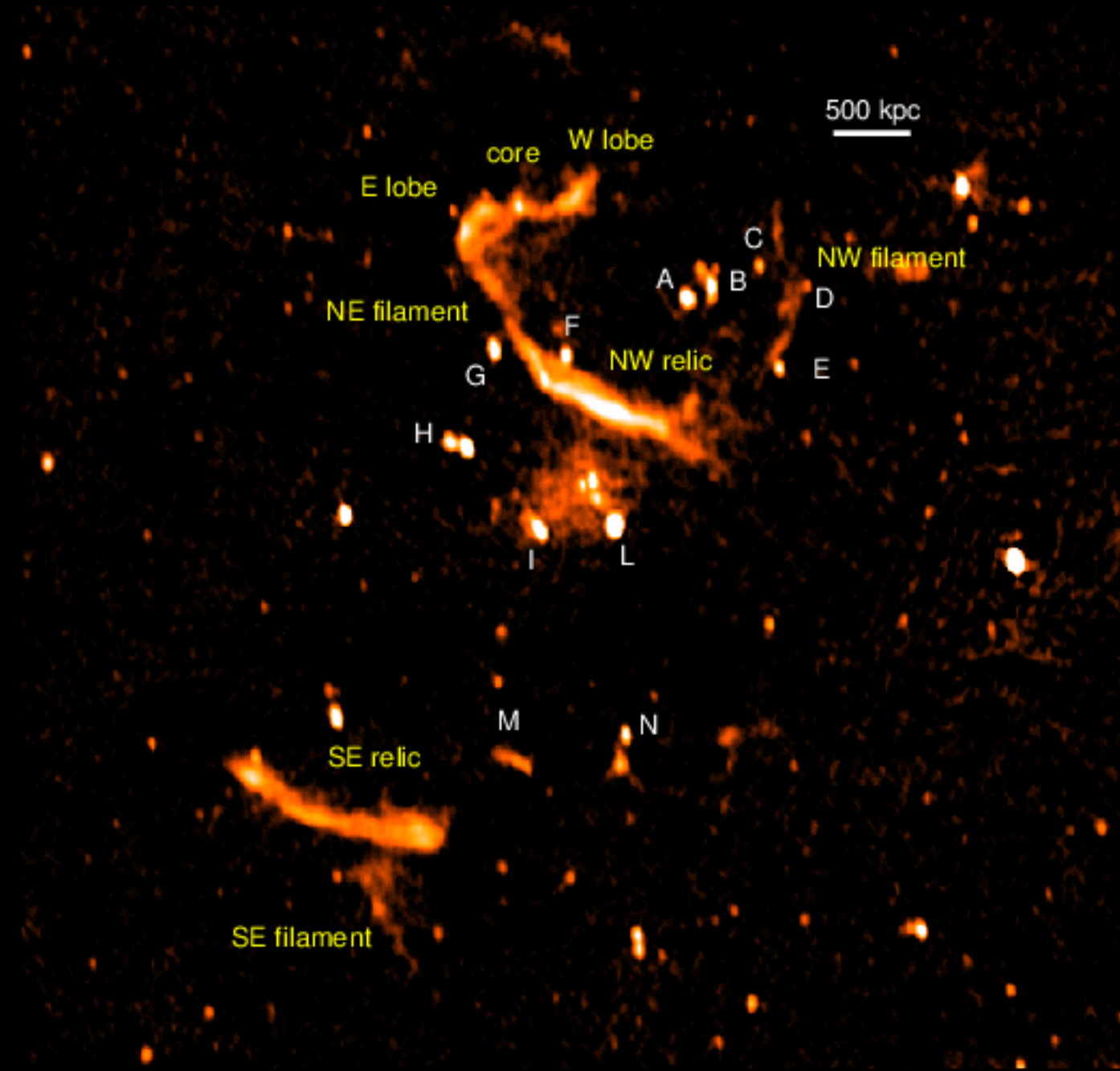
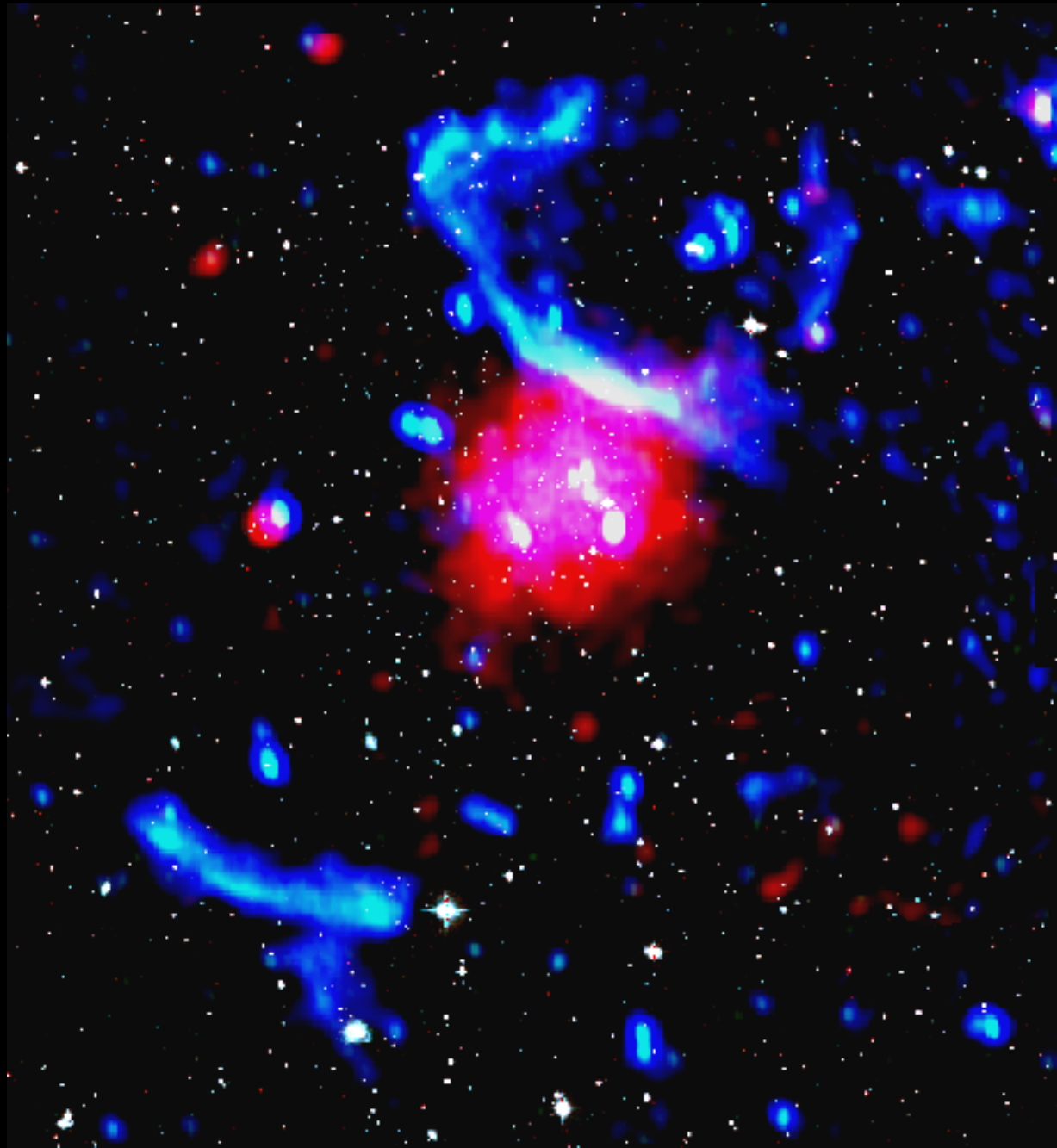


The image shows a radio emission map of the Coma galaxy cluster. The background is a dense field of orange and yellow spots, representing individual galaxies and their radio emission. A prominent, bright, and diffuse radio emission region is visible in the upper left quadrant, indicating the cluster's core. A yellow double-headed arrow spans a distance of approximately 3.3 Mpc across the image, providing a scale for the size of the cluster.

~3.3 Mpc

The Coma cluster observed with LOFAR @ 150 MHz
Bonafede et al. (in prep.)

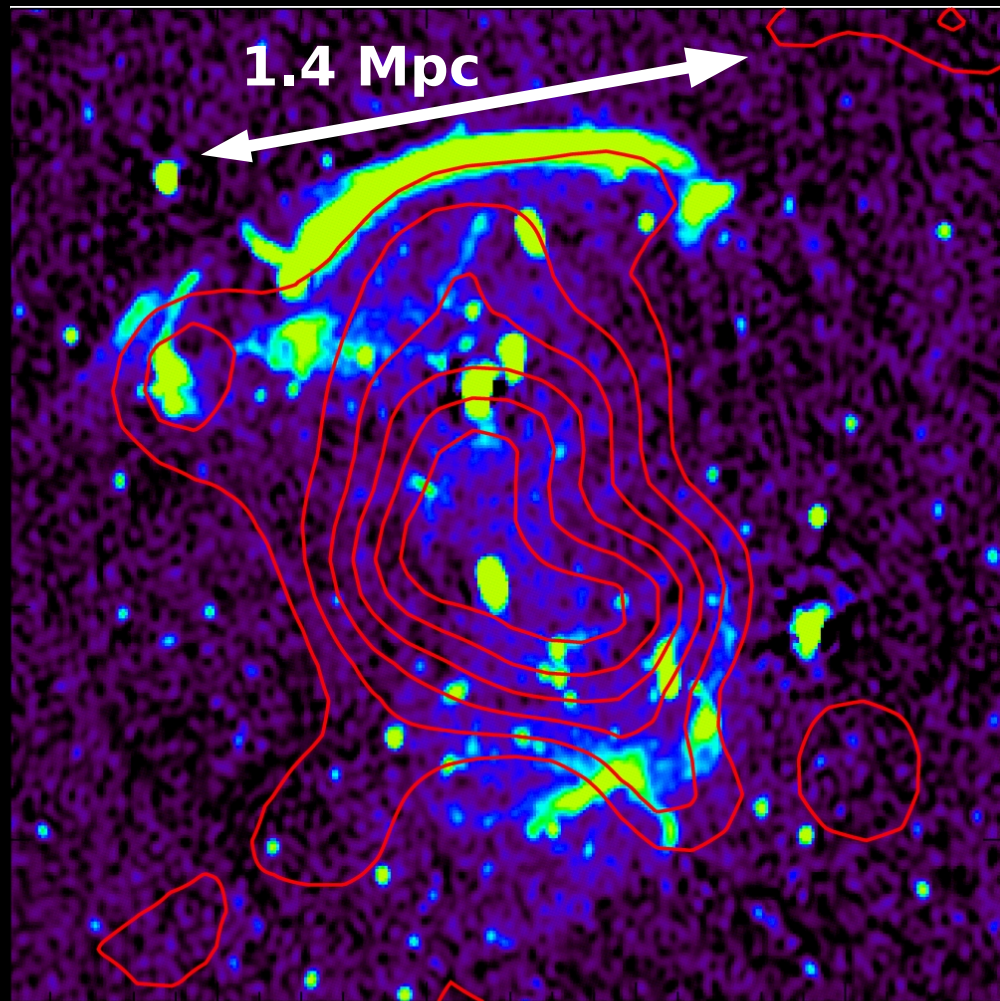
Spectacular radio emission from galaxy clusters



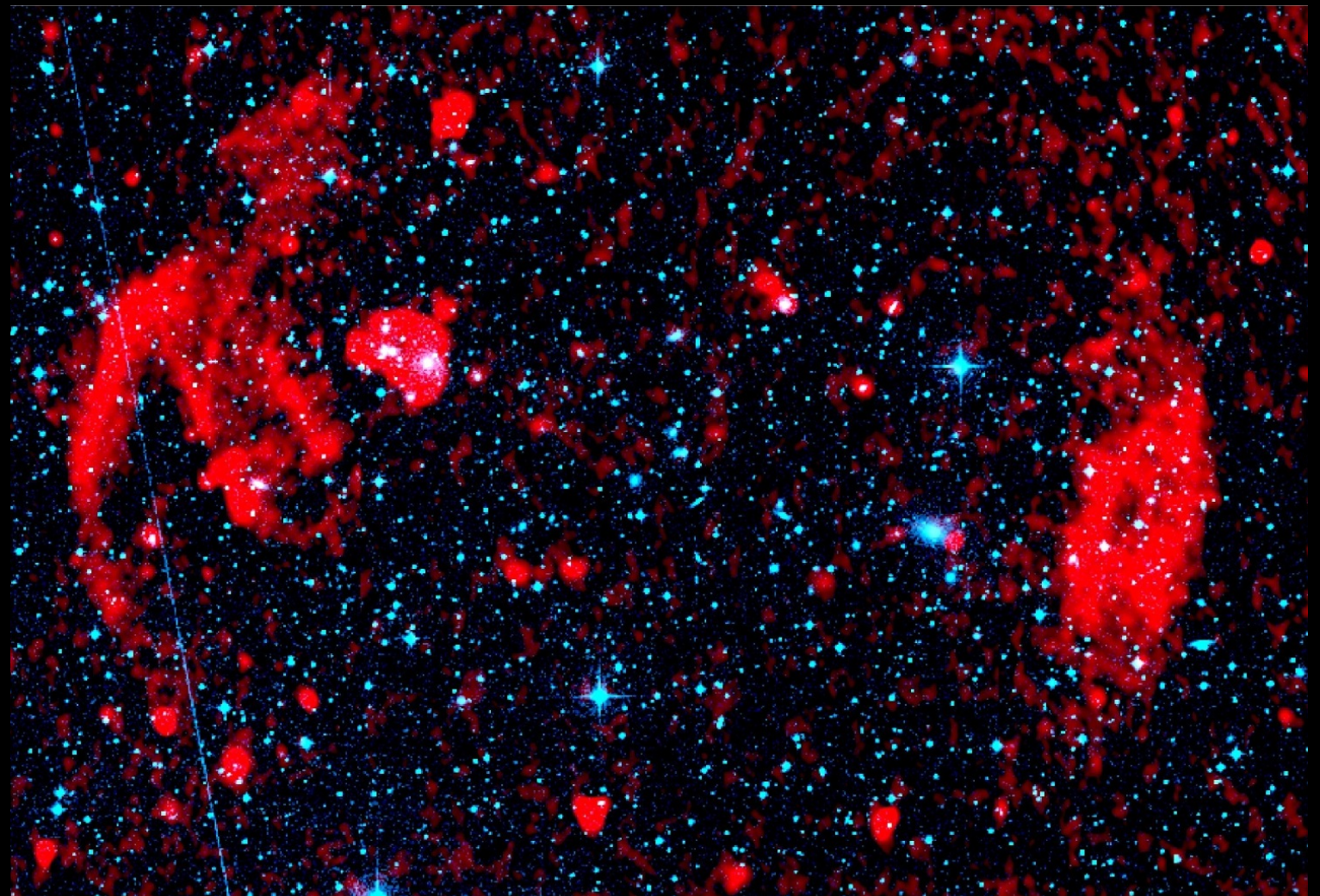
PLCKG287 observed with the GMRT @ 325 MHz and 610 MHz

Bonafede et al. 2014

Spectacular radio emission from galaxy clusters



CIZA 2242 observed with the WSRT@1.4 GHz
van Weeren et al. 2010

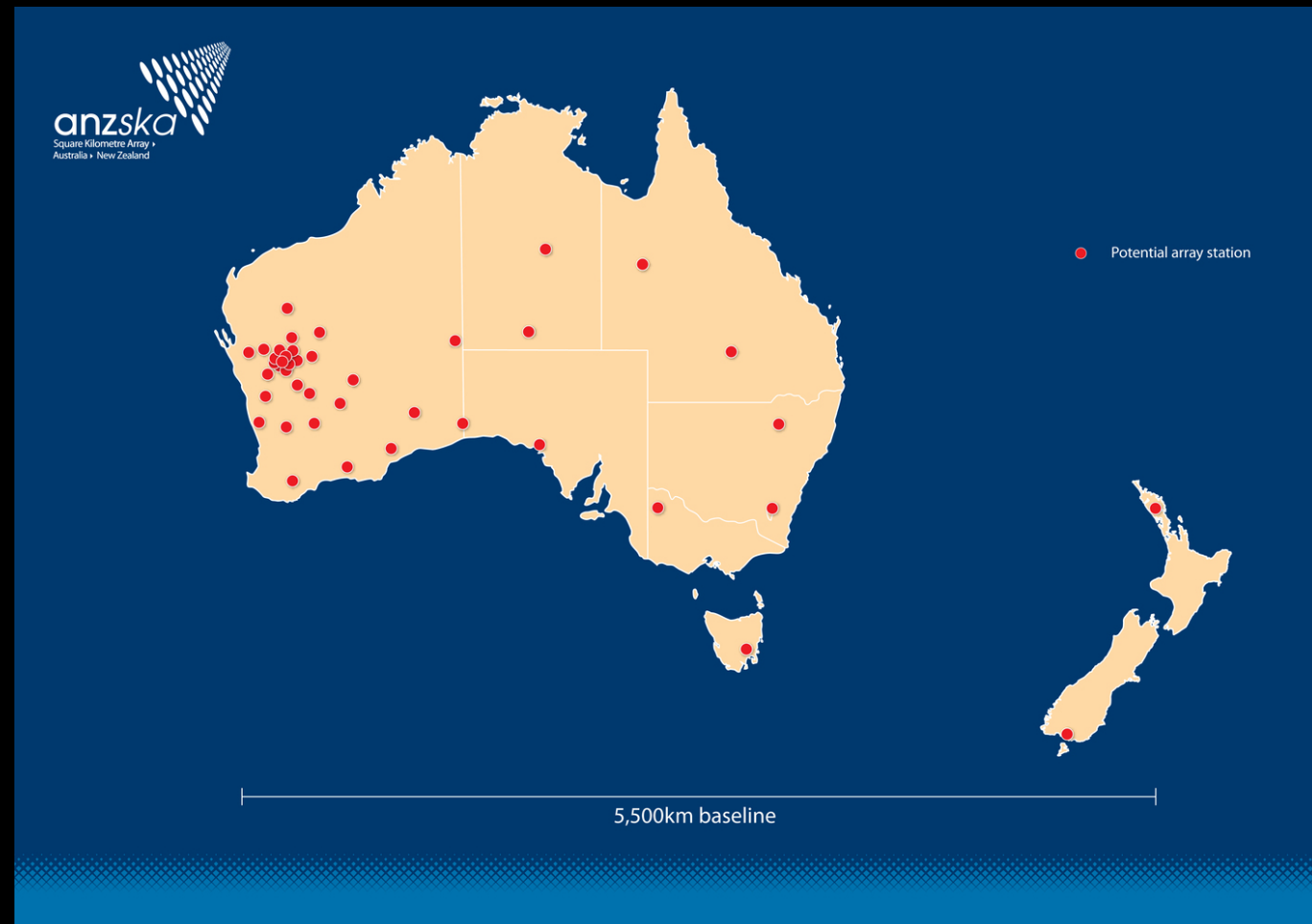
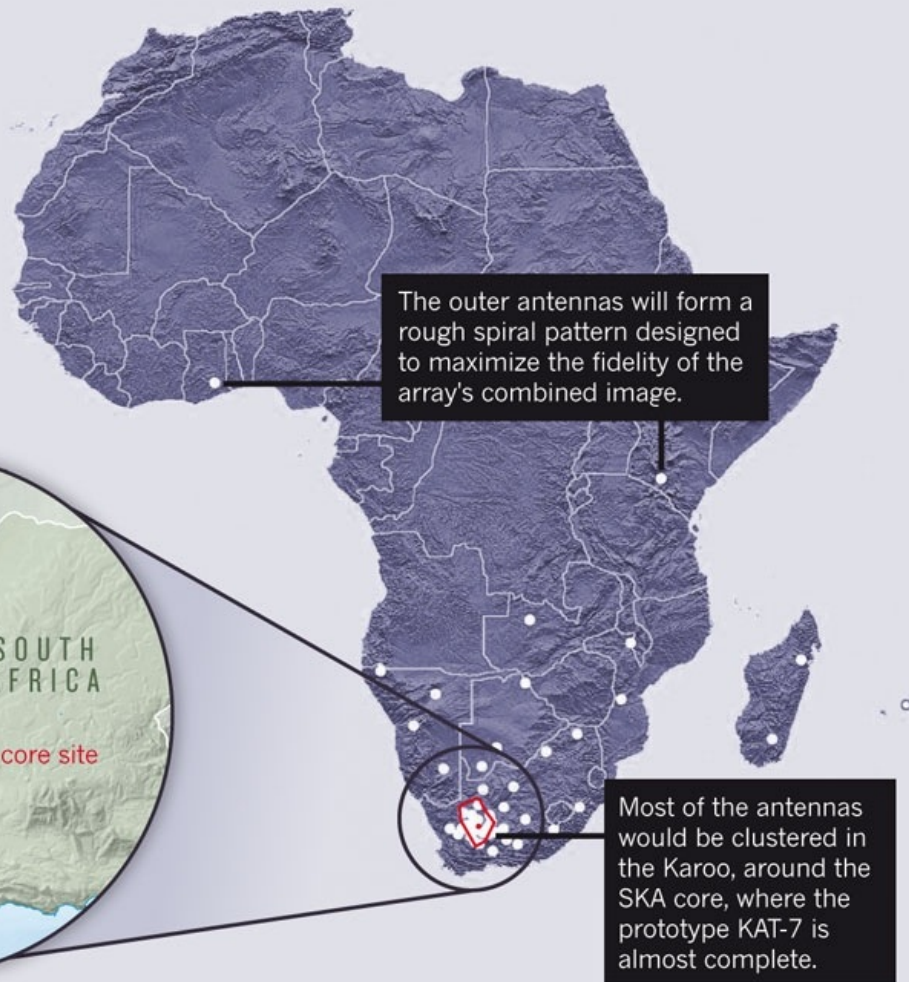


Abell 3376 observed with the VLA@1.4 GHz
Bagchi et al. 2006

The Square Kilometre Array

THE BIGGEST ARRAY

South Africa's plan for the Square Kilometre Array (SKA) calls for some 3,000 antennas spaced over half the continent.



The biggest radio telescope in the world
1 km² = 140 football pitches !!!

The Square Kilometre Array

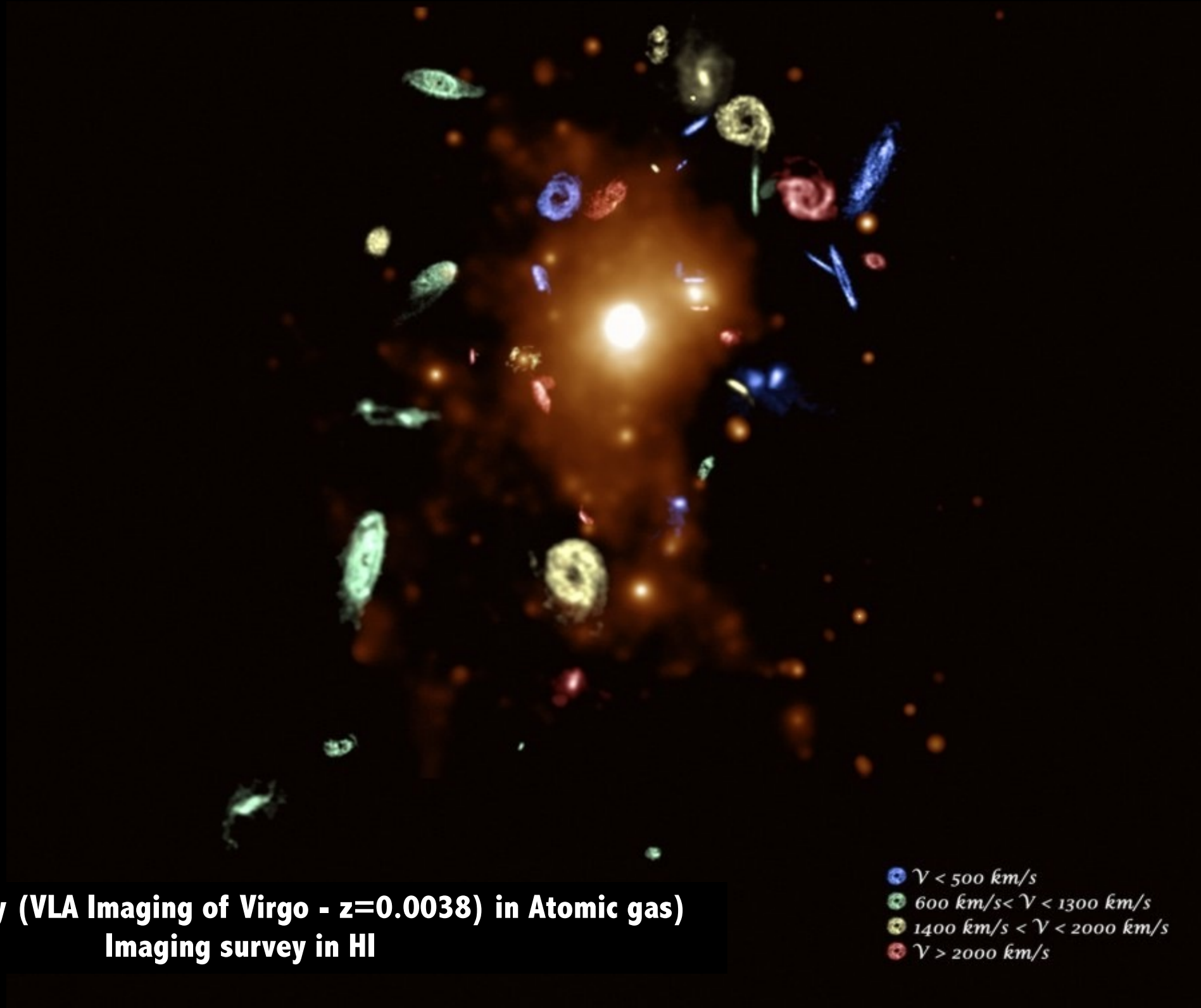


The Square Kilometre Array



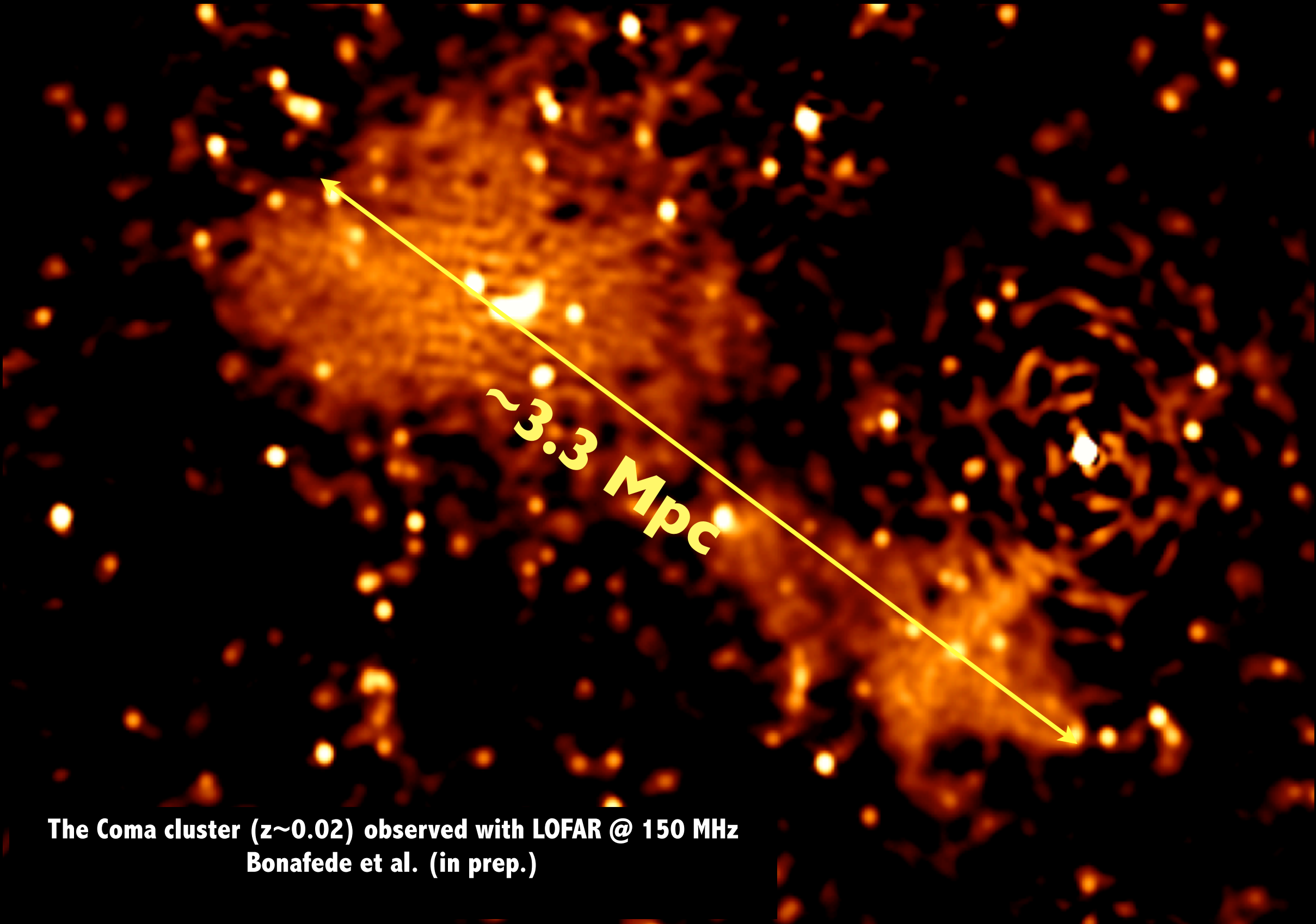
Not only for the local universe, but out to $z \sim 0.8$ (resolved) and $z \sim 2$ (unresolved)

(see e.g. van der Hulst et al. 2014)



Not only for the local universe, but out to $z \sim 1.0$

(see e.g. Ferrari et al. 2014)



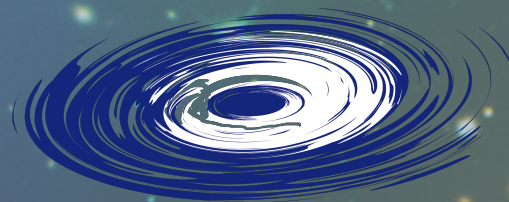
The Coma cluster ($z \sim 0.02$) observed with LOFAR @ 150 MHz
Bonafede et al. (in prep.)

Thank you !

Chiara Ferrari



Observatoire
de la CÔTE d'AZUR



LAGRANGE



Université
Nice
Sophia Antipolis