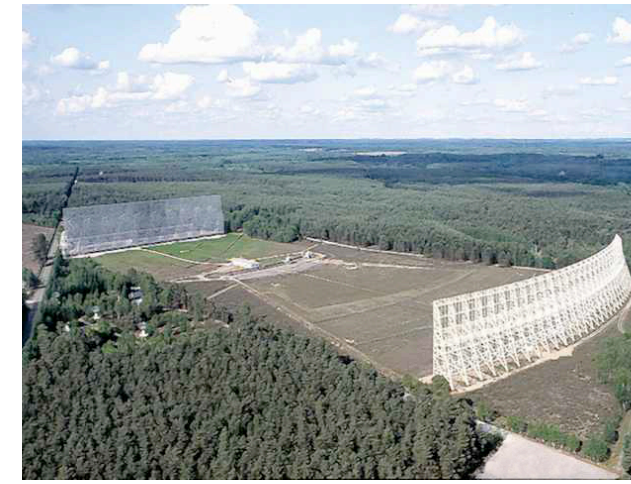


Radio Astronomy

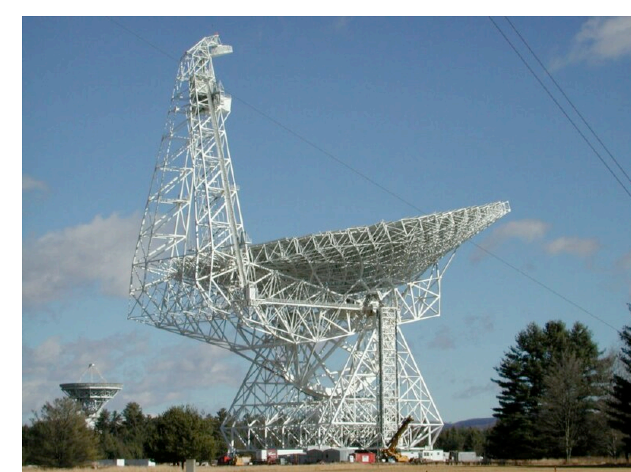
Lecture 2

The Science of Radio Astronomy: Extragalactic

Lecturer: Michael Wise (wise@astron.nl)

April 4th, 2013



Outline

- Radio Astronomy for Extragalactic Science
- Nearby Galaxies, Astrometry, SNR, GRBs, Mapping HI, Dynamics, Star Formation, FIR-Radio Correlation Magnetic Fields, Lensing
- Radio Galaxies, AGN, Jets, Quasars, Black Hole Growth, Feedback, Gas Flows, and Radio Source Evolution
- Groups and Clusters, Feedback, Relics, Halos, Shocks and Turbulence
- Cosmic Microwave Background, S-Z Effect, EoR, Cosmology and Large-scale Structure

Extragalactic Science

How do galaxies form and evolve?
What part do black holes play?
How do black holes form and grow?
What governs large-scale structure growth?
What is dark matter and where is it?
What were the early phases of the universe?

⇒ *Gives us the big picture*

Why Radio Observations?

⇒ *Probes a wide range of physics*

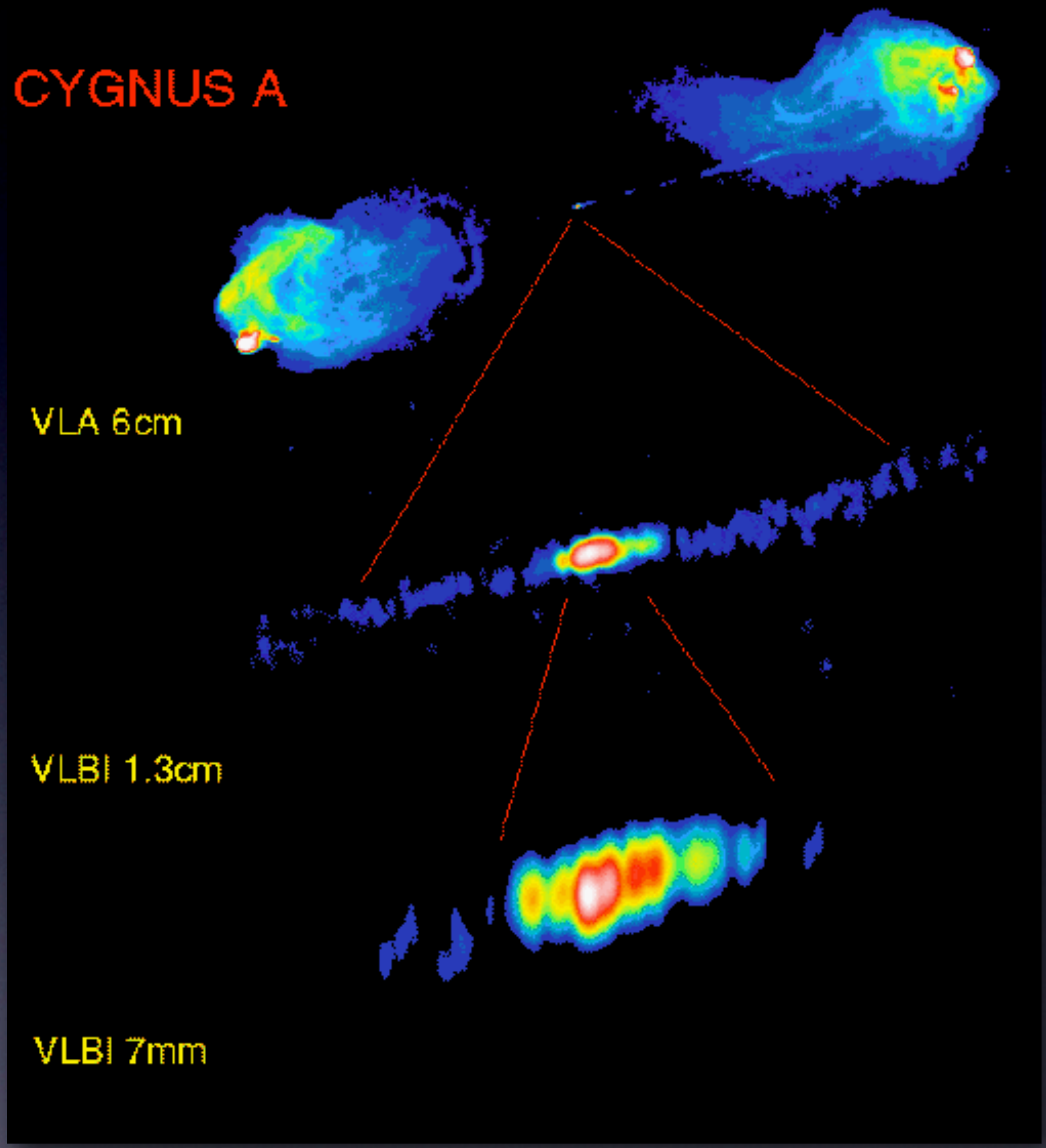
- Dark Ages (spin decoupling)
- Epoch of Reionization (highly redshifted 21 cm lines)
- Early Structure Formation (high z RG)
- Large Scale Structure Evolution (diffuse emission)
- Evolution of Dark Matter & Dark Energy (Clusters)
- Energy Feedback into the Intracluster Medium (AGN)
- Black Hole Formation and Growth (AGN, jets)
- Particle Acceleration (AGN, cluster merger/accretions shocks)
- Star Formation and Galaxy Evolution (distant starburst galaxies)
- Formation of Magnetic Fields (nearby galaxies)
- Source populations (large, all-sky surveys)

Why Radio Observations?

Why Synthesis Imaging?
⇒ Resolution

Angular resolution can be tuned by the observer by selecting baselines (but trade sensitivity to emission on different scales)

Reduce source "confusion" problem
Match resolutions at other wavelengths
Extremely accurate absolute astrometry
High angular resolution (10^{-3} arcsec)



Carilli & Harris (1996)

Bright radio AGN Cygnus A at a variety of frequencies and angular resolutions from VLA to VLBI baselines

Why Radio Observations?

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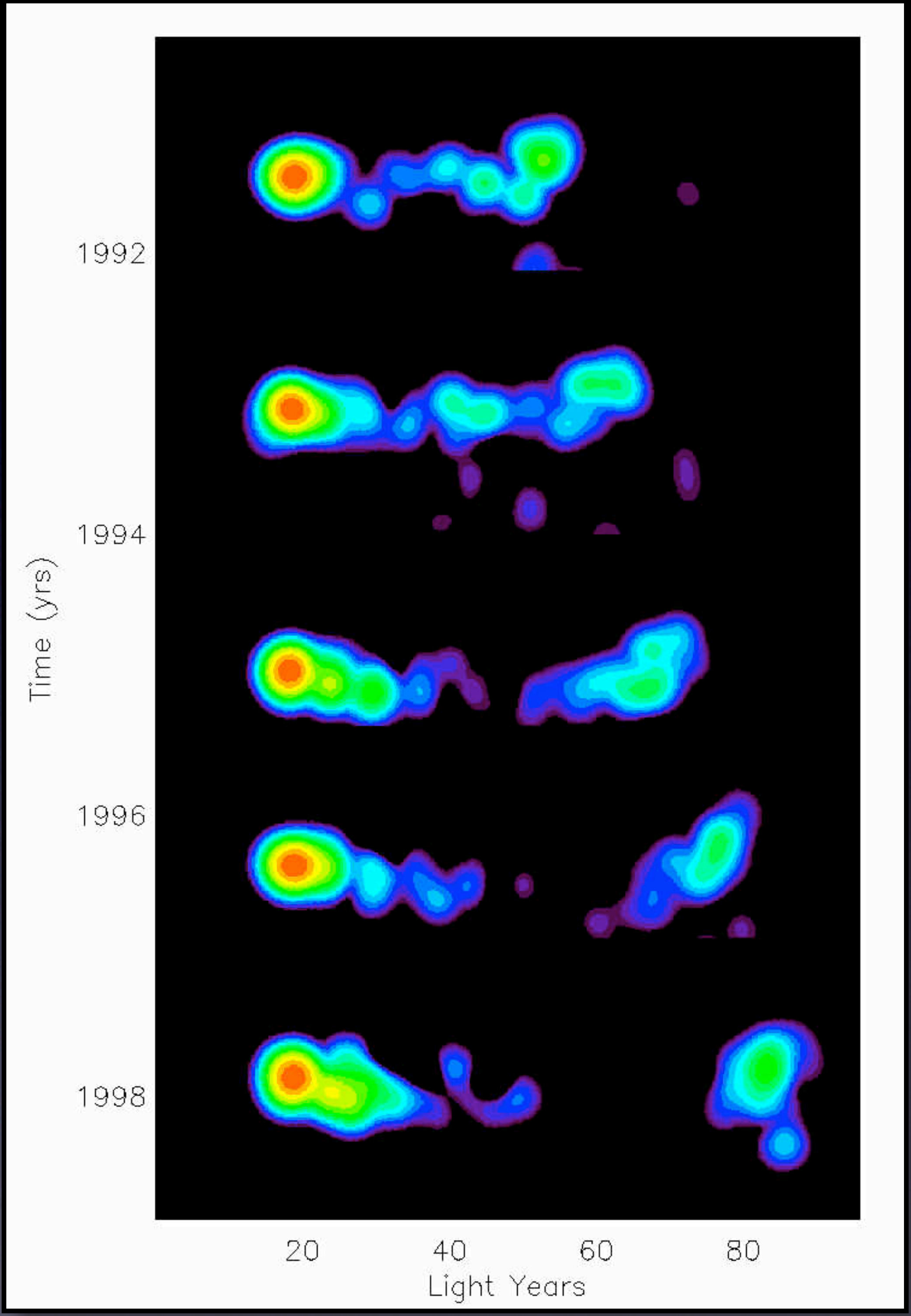


Apparent superluminal motion in quasar 3C279 is shown as mosaic of five VLBA radio images made over seven years at 22 GHz with resolution of 0.001 arcseconds

Wehrle et al. (2001)

Why Radio Observations?

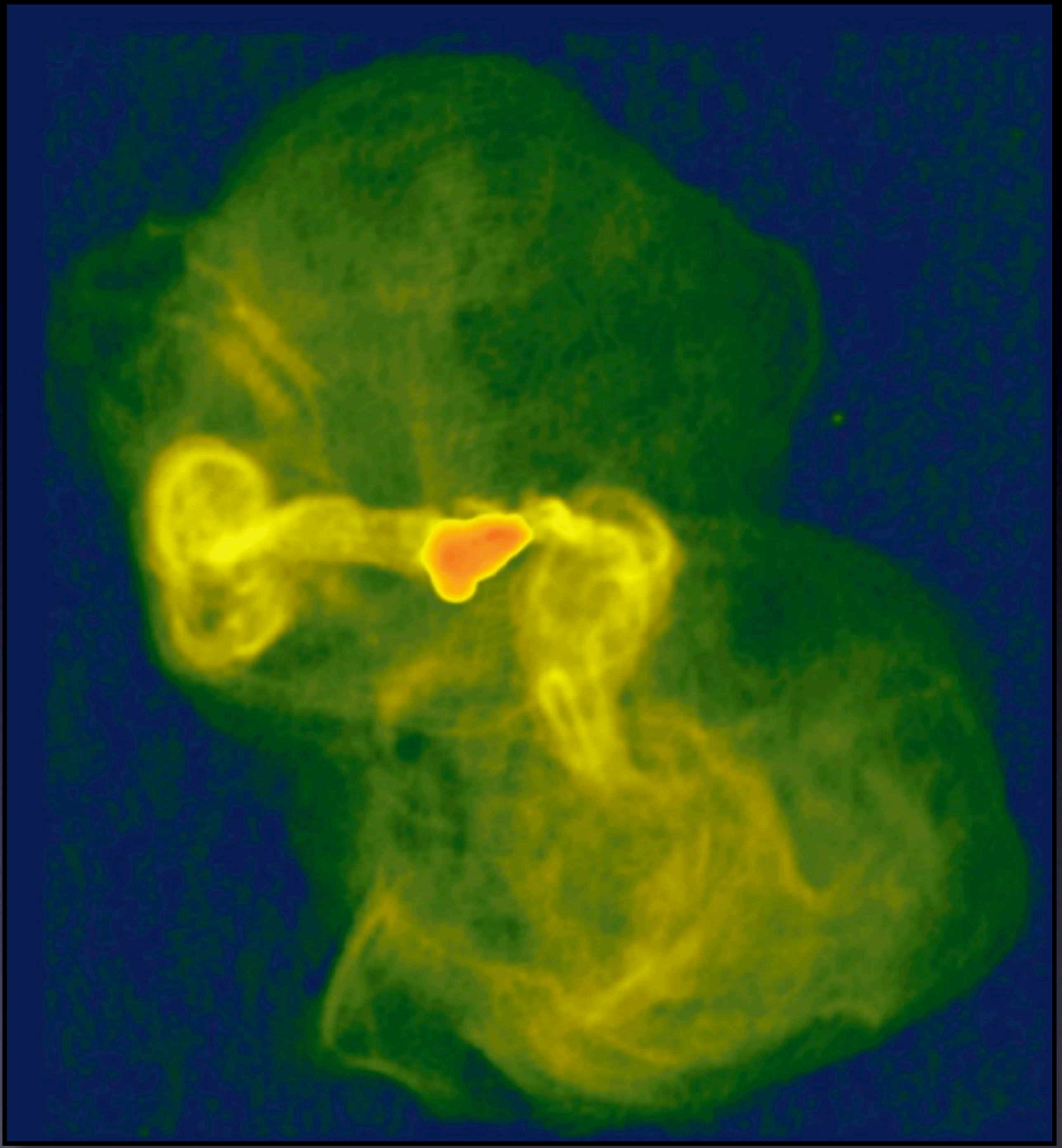
Why Synthesis Imaging?
⇒ Dynamic Range

High dynamic range achieved via deconvolution and self-calibration (1,000,000:1 in some cases!)

High sensitivity via long exposures

Resolve diffuse emission in the presence of bright sources

Detect faint sources and resolve "confusion" limitations



Owen, Eilek, & Kassim (1999)

VLA 330 MHz image of the galaxy M87, showing details of the large-scale, radio-emitting "bubbles" believed to be powered by the central black hole

Why Radio Observations?

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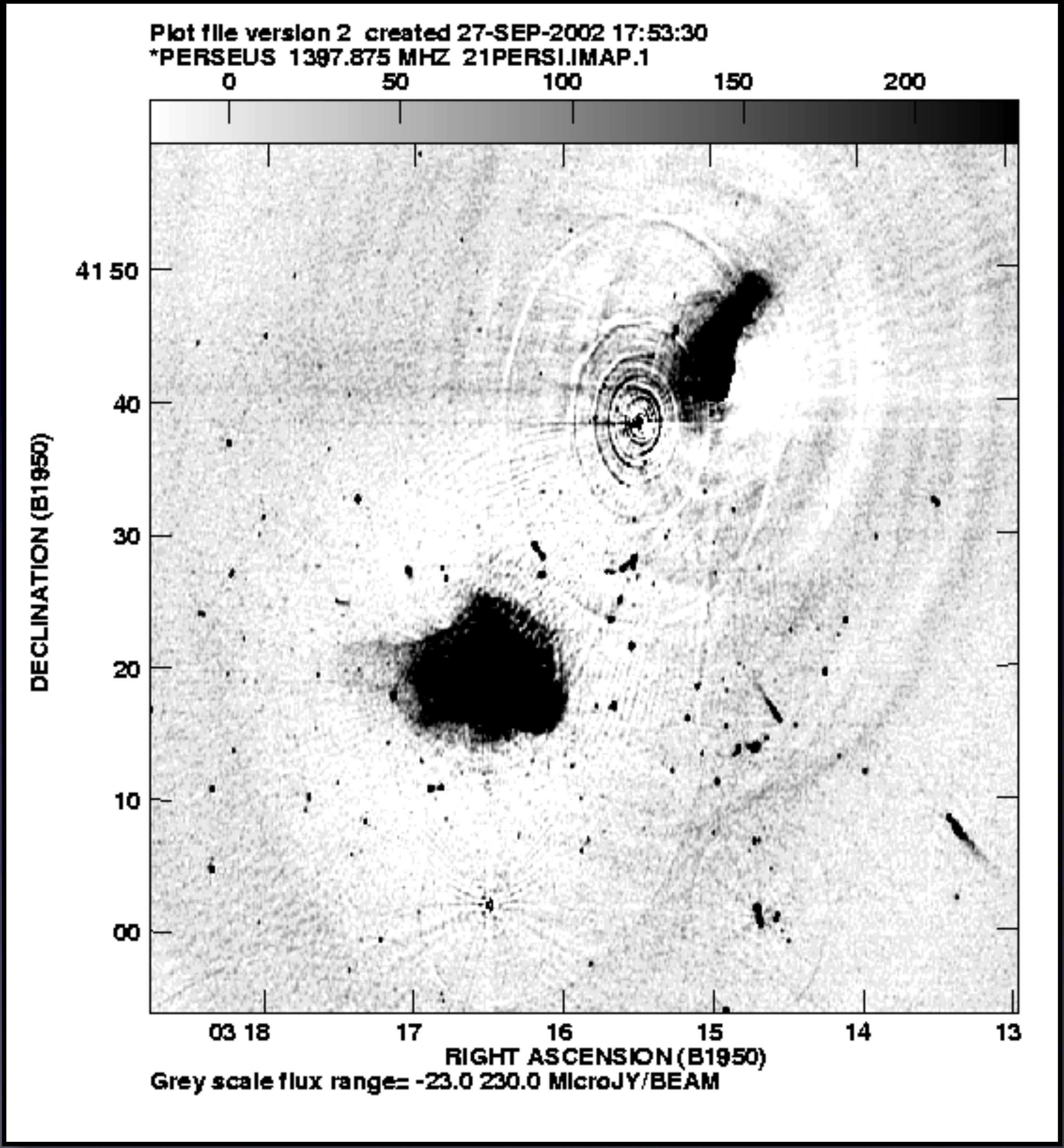
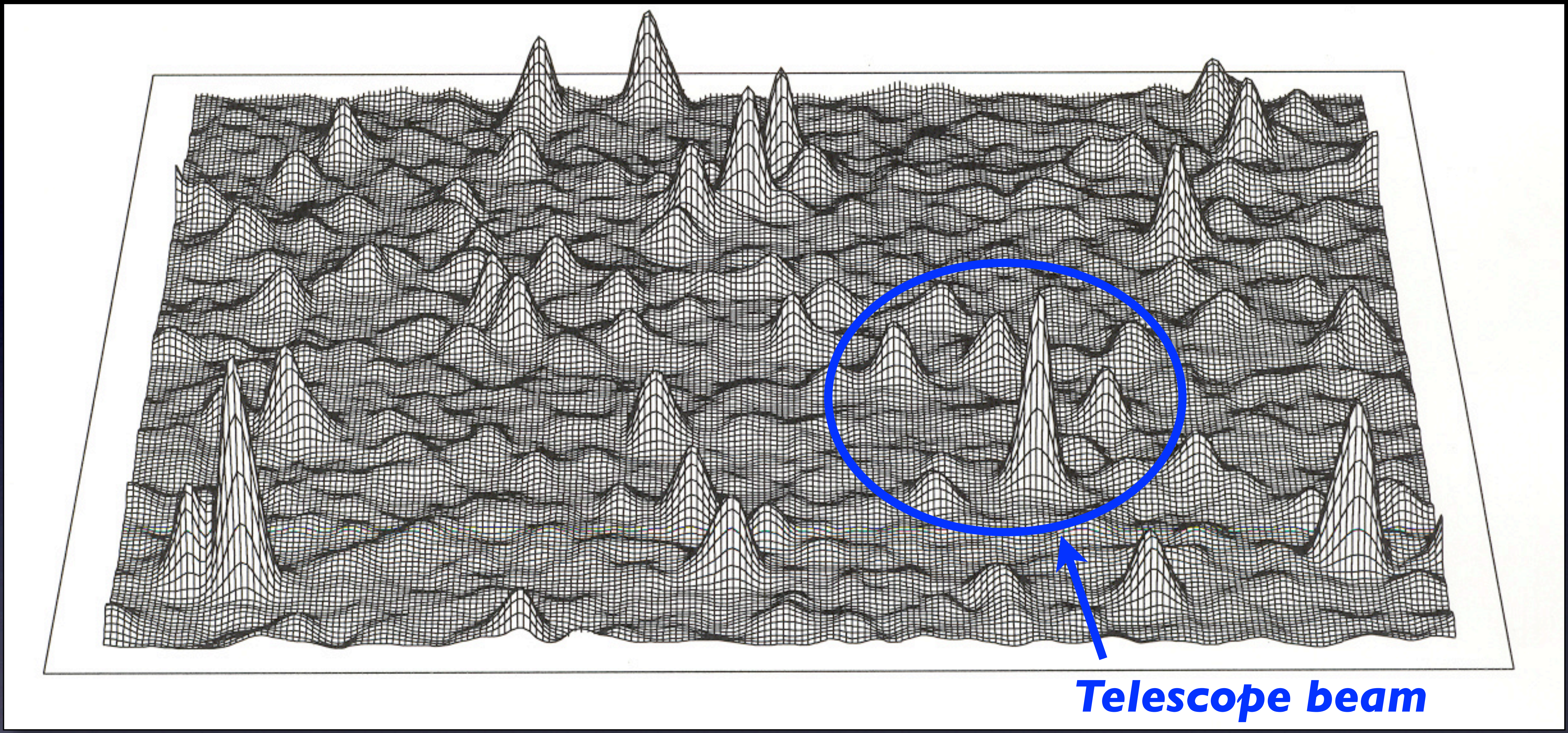


de Bruyn & Brentjens (2010)

WSRT 1.4 GHz image of the Perseus cluster showing details of the large-scale, radio halo exposed at a dynamic range of 1,000,000:1

Beating Confusion



Un-resolved sources in beam limit achievable sensitivity
Function of resolution, frequency, and source density

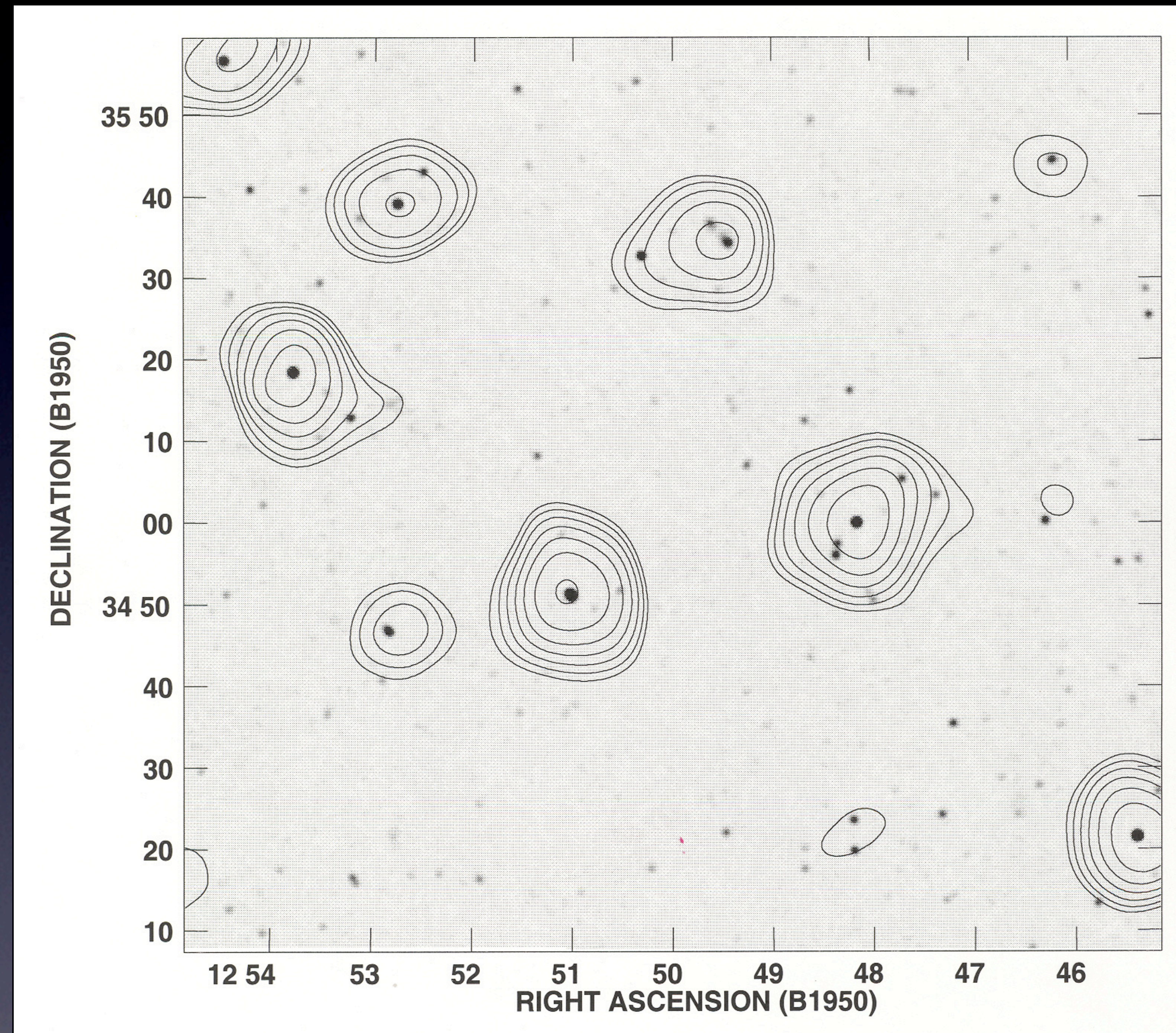
Beating Confusion

"RMS" confusion:

$\sigma_c \approx 0.2\ \nu^{-0.7}\ \theta^2$

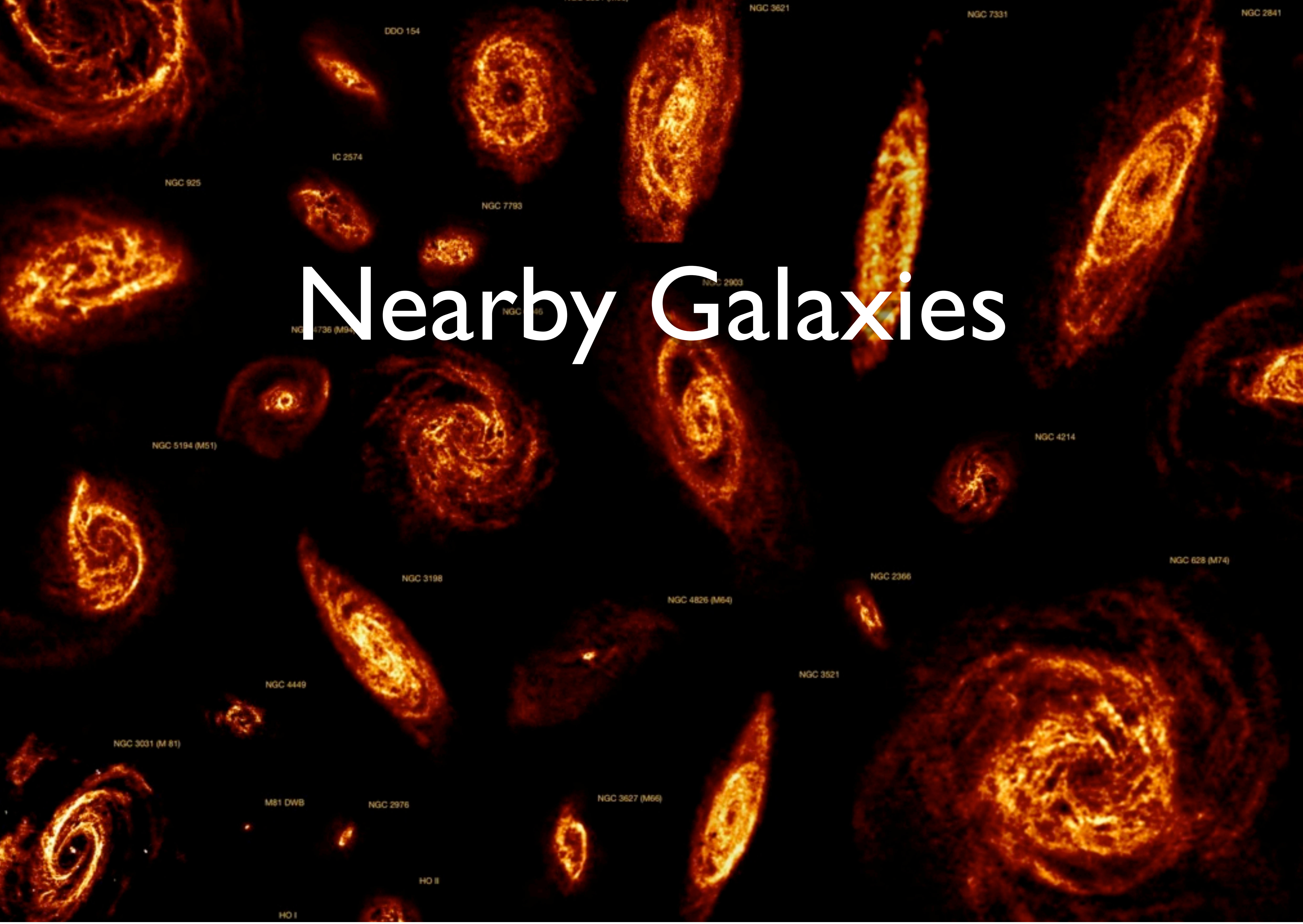
where

σ is in mJy/beam
ν is in GHz
θ is in arcmin

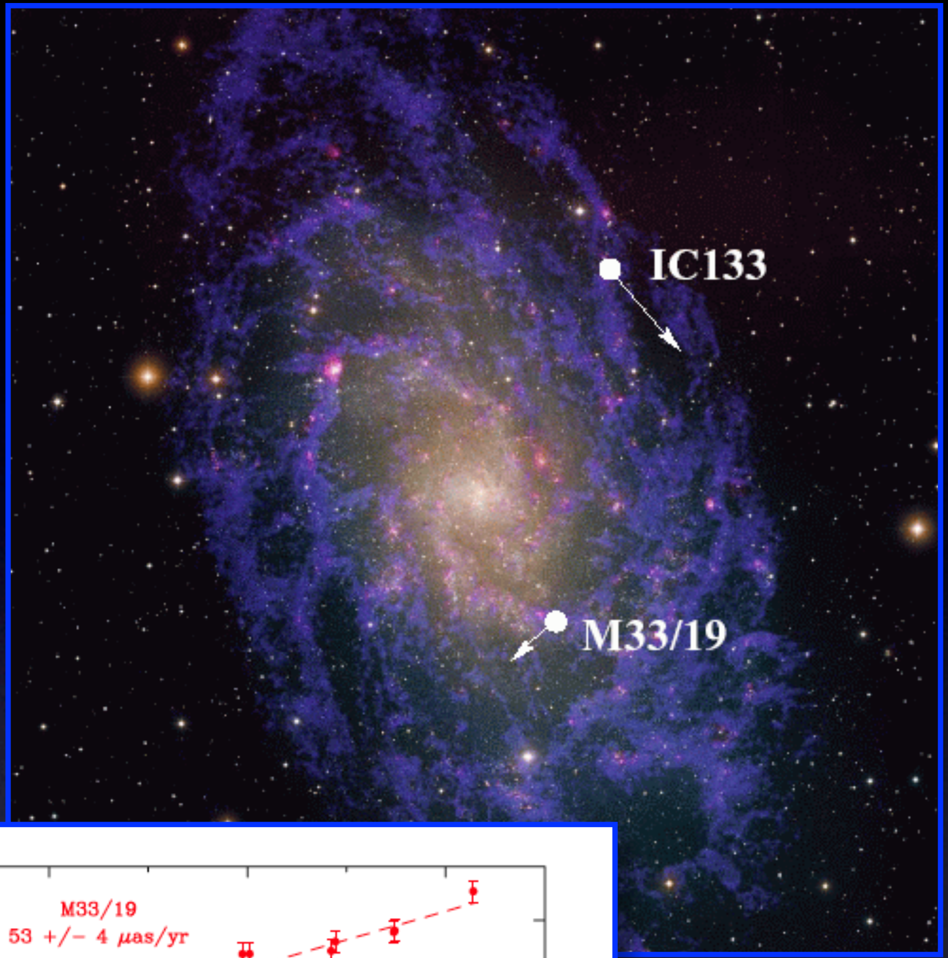


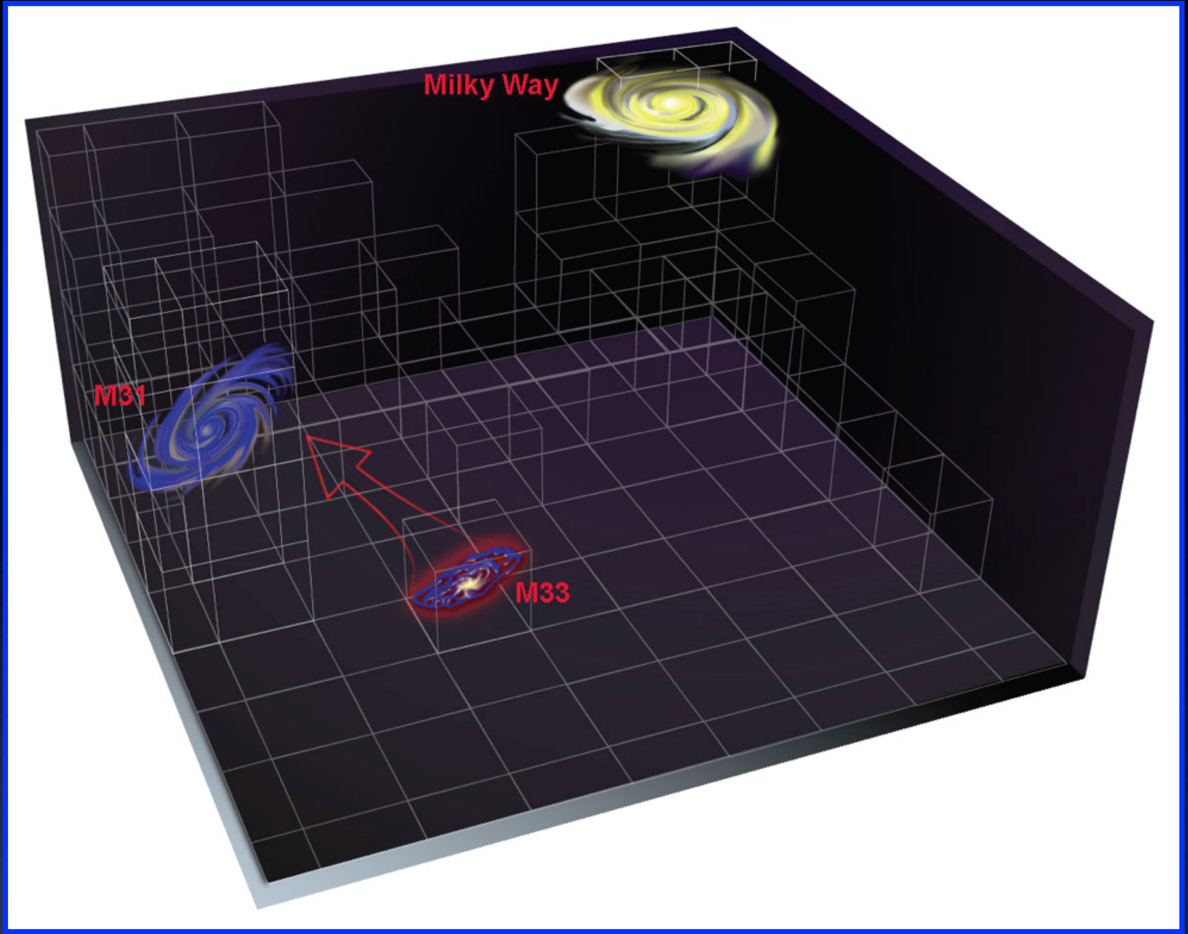
NVSS (45 arcsec) grayscale under GBT (12 arcmin) contours

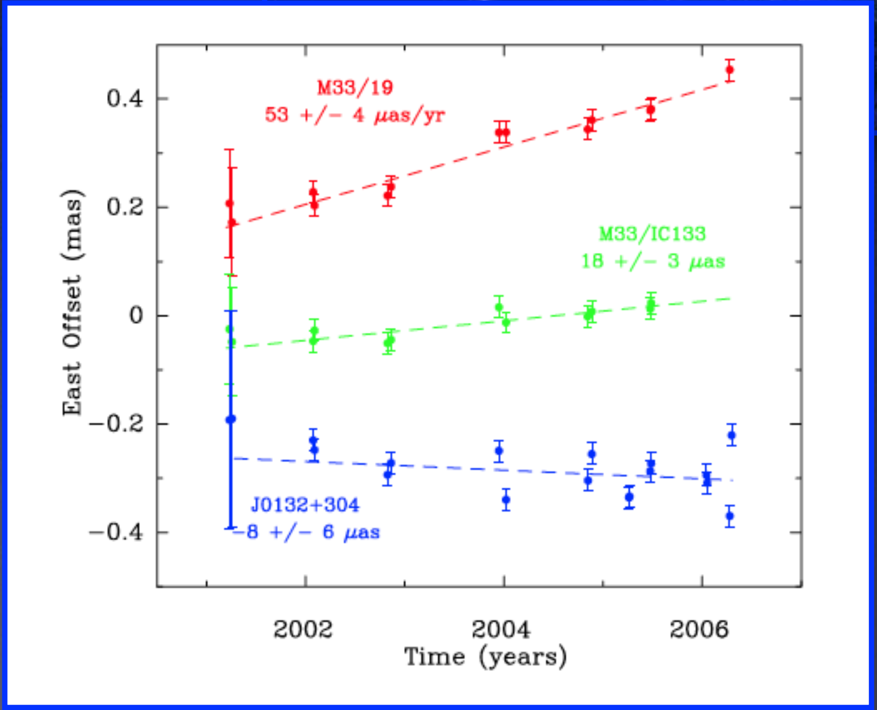
Nearby Galaxies



Radio Astrometry





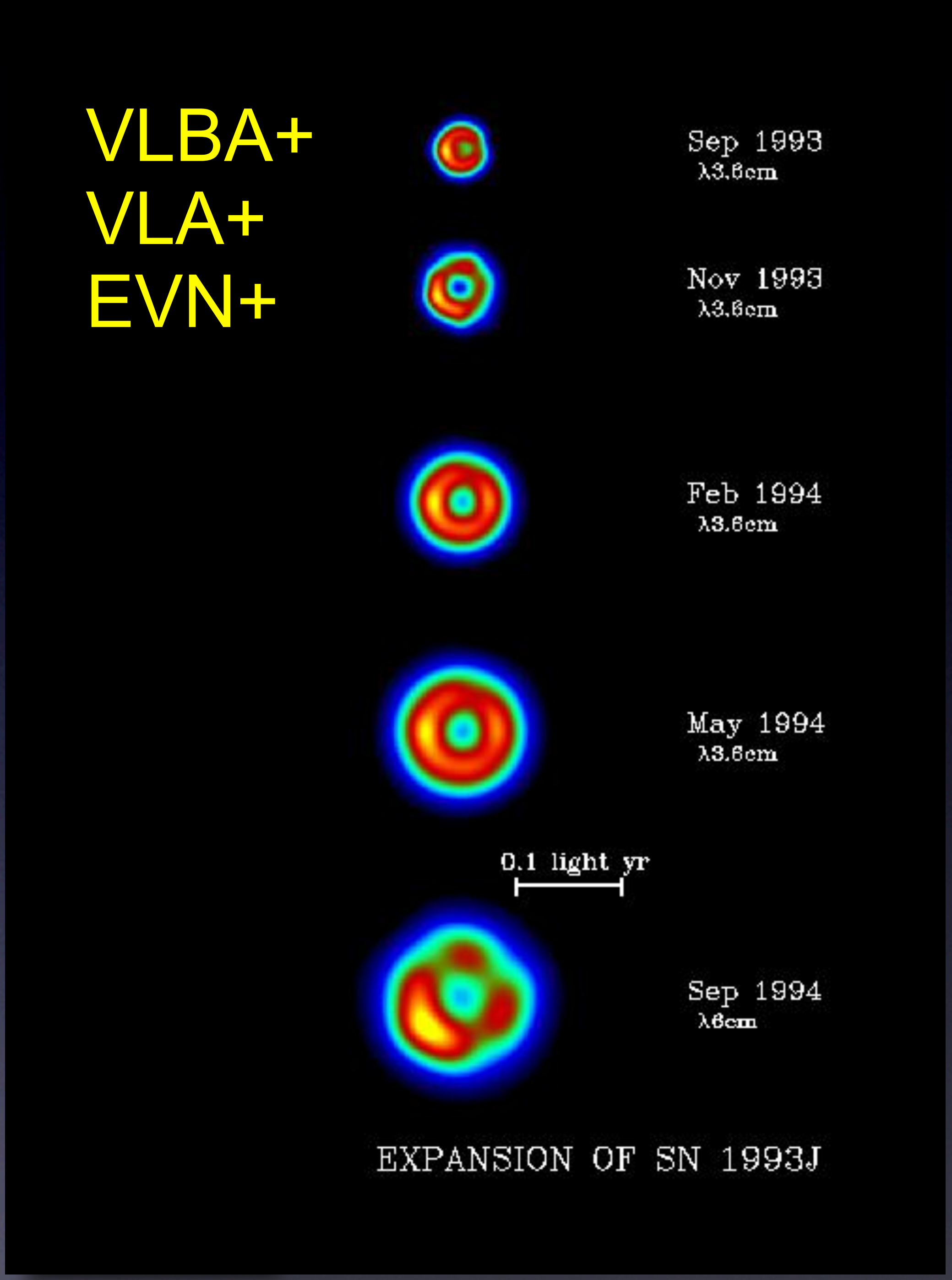


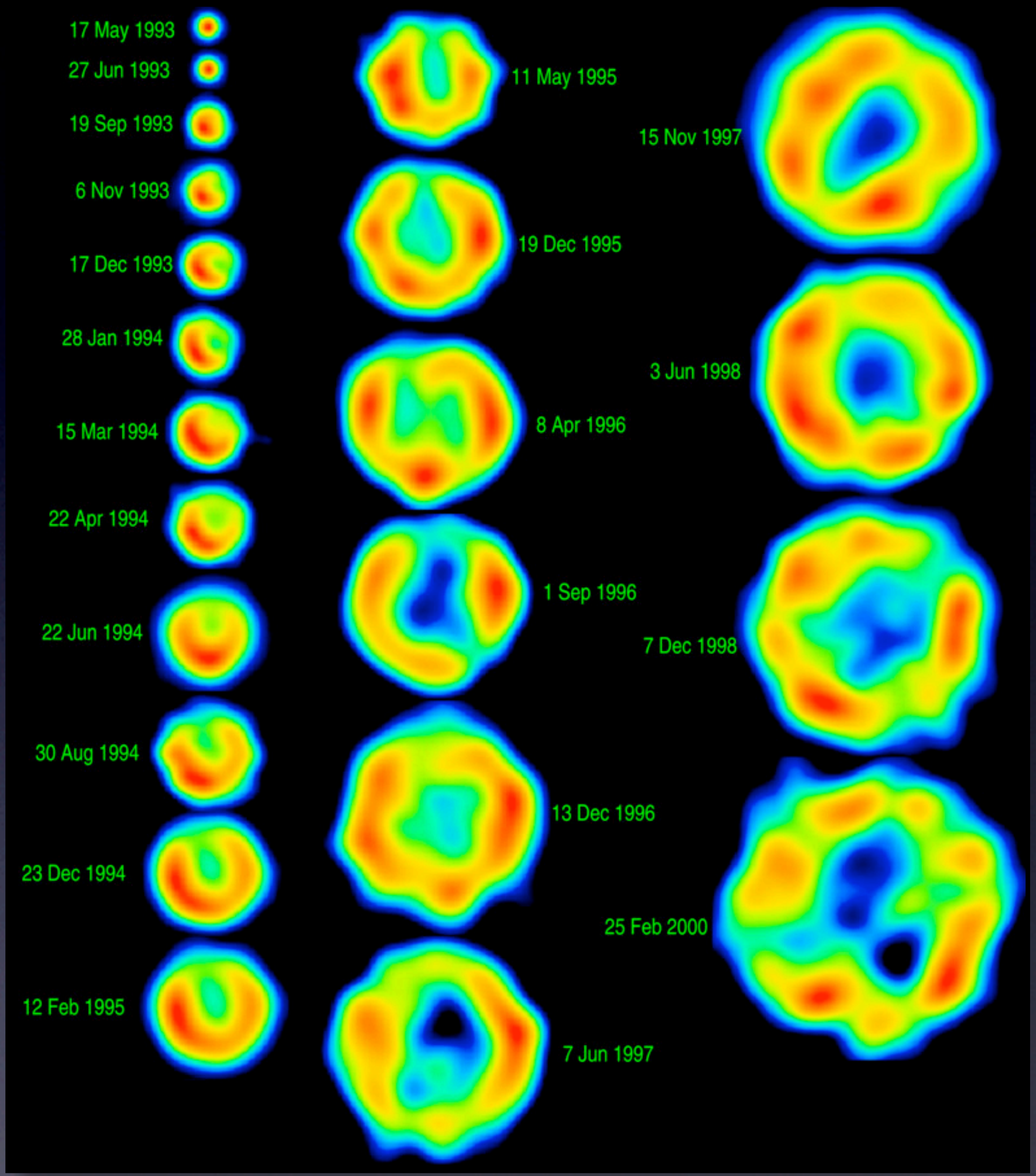
Brunthaler et al. (2000)

- VLBA astrometry of H_2O masers in M33
- Angular rotation + proper motion
- Distribution of dark matter in the Local Group
- History and fate of Local Group galaxies
- Distribution of dark matter in nearby galaxies

Supernova Remnants

VLBA+
VLA+
EVN+

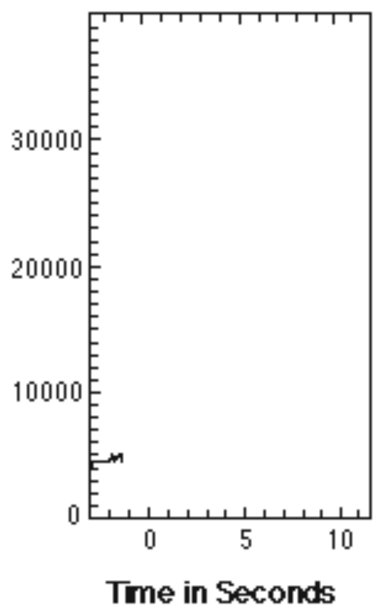


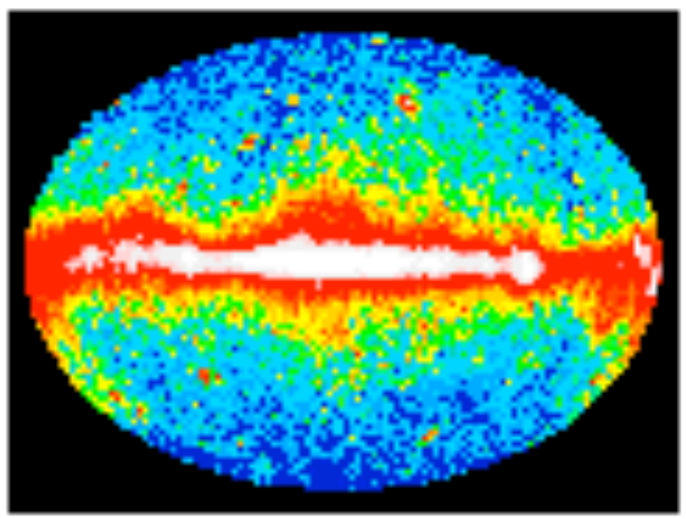


Radio monitoring of the supernova remnant from SN 1993J located in M81, a spiral galaxy in the constellation Ursa Major, from May 1993 to Feb 2000.

Gamma-ray bursts

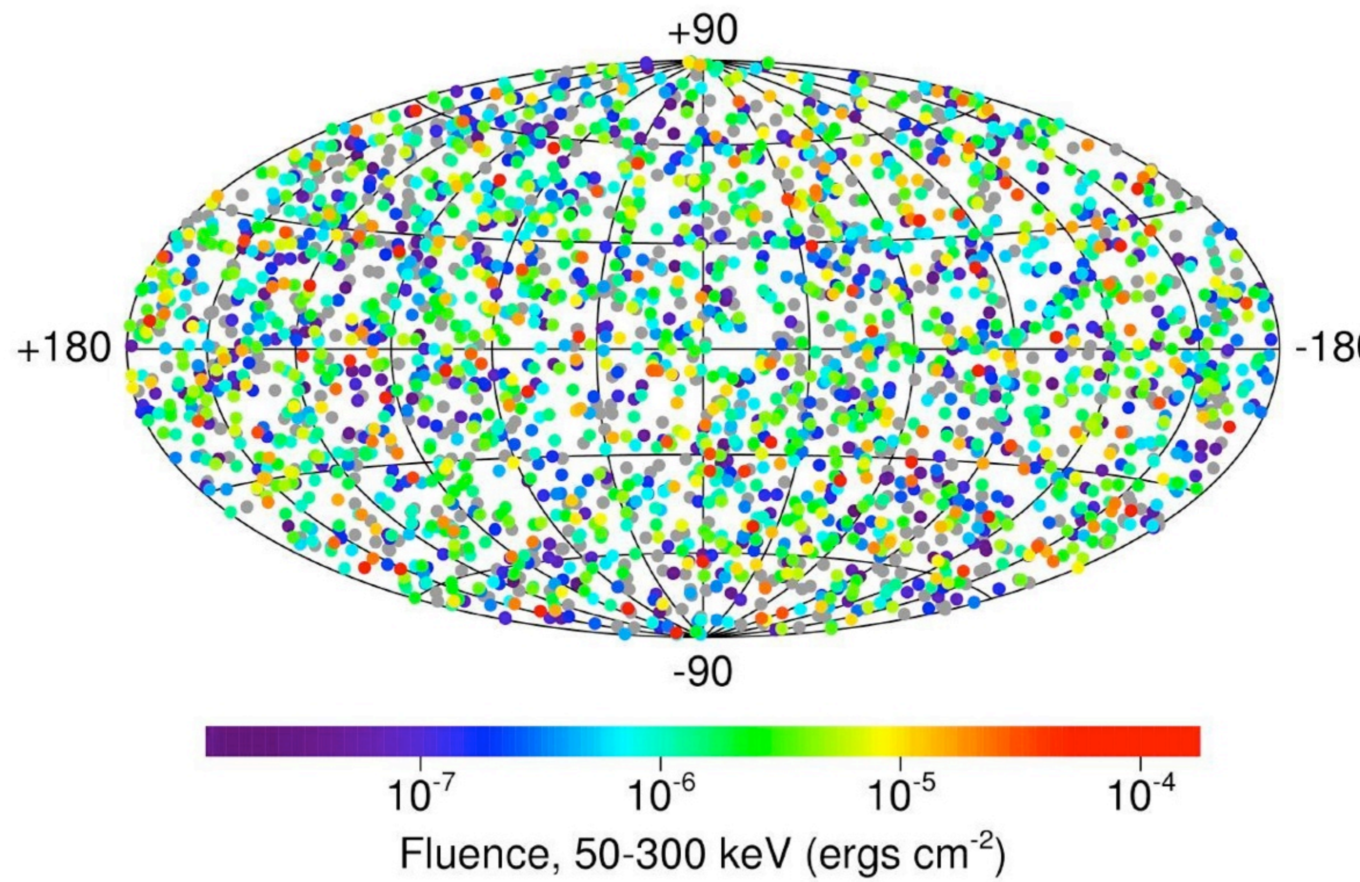
⇒ Most luminous explosions in the universe
Each burst may emit up to ~10^{54} erg





A GRB detected by [BATSE](), the Burst And Transient Source Experiment, on-board the Compton Gamma-Ray Observatory (CGRO)

Spatial distribution of GRBs detected by [BATSE]()



Distribution implies extragalactic origin
Confirmed using host galaxy emission lines

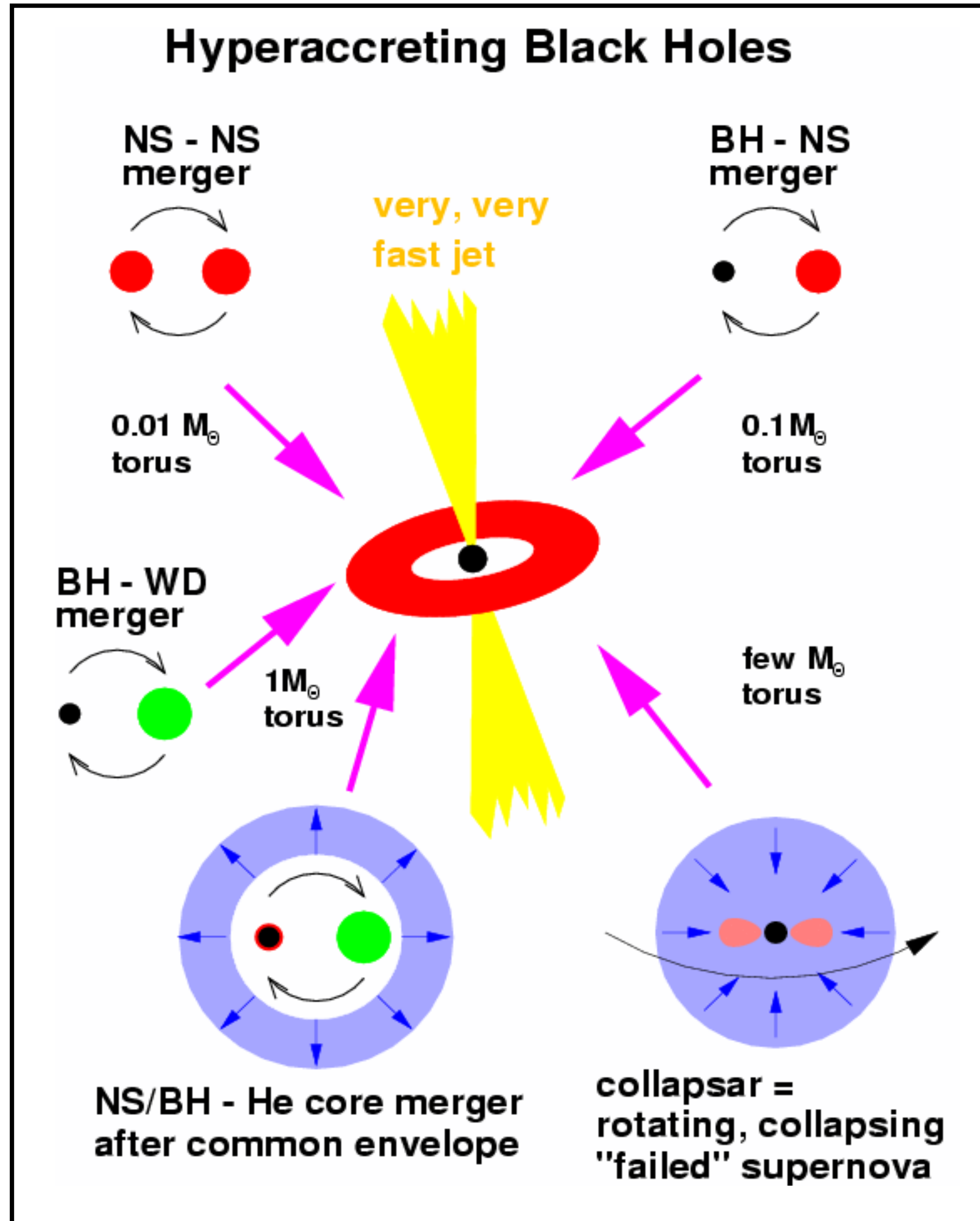
Gamma-ray bursts

Principal GRB Models

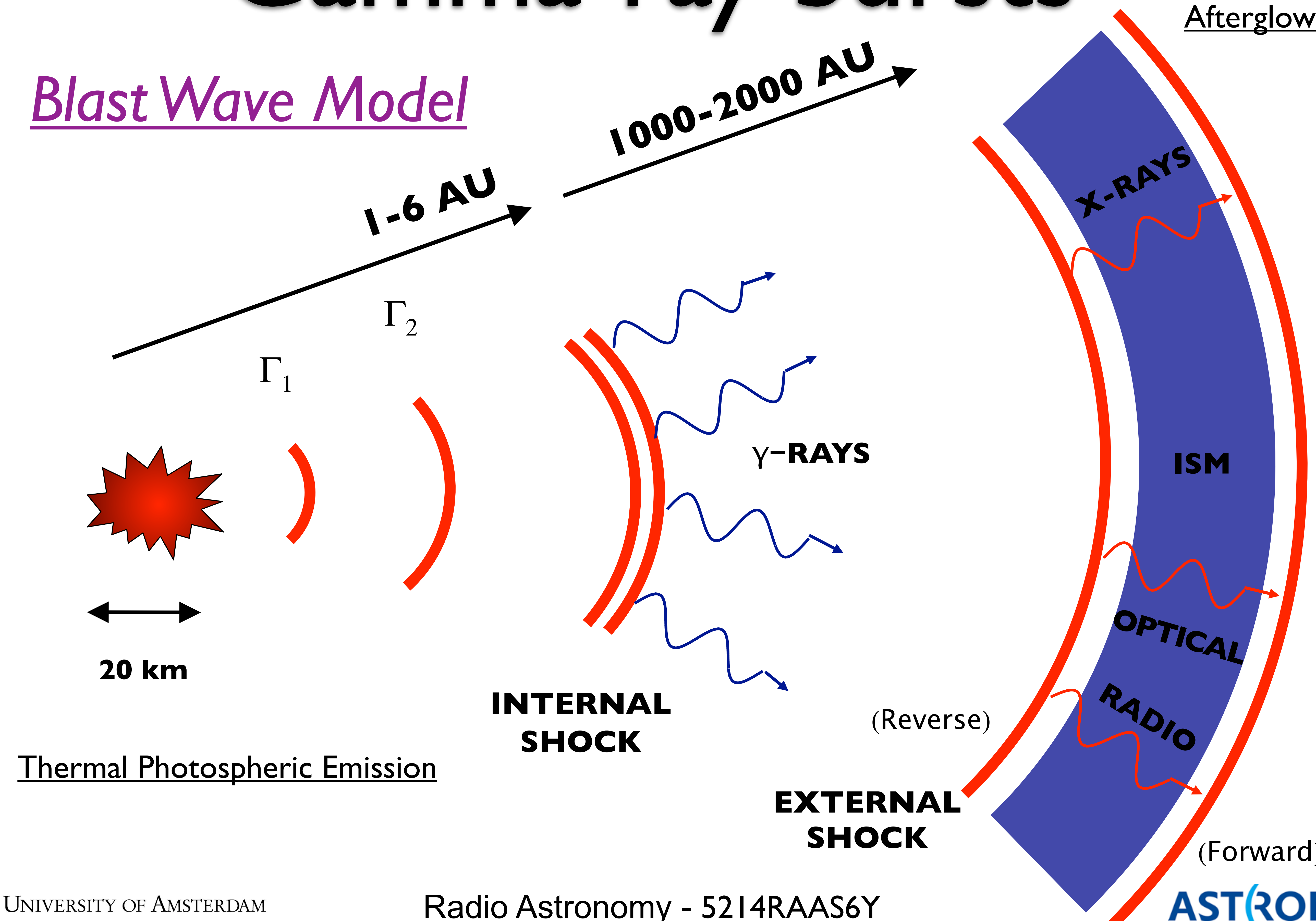
- Collapse of a rotating massive star
- Neutron Star – Neutron Star Mergers
- Black Hole – Neutron Star (He star) Mergers
- Black Hole – Neutron Star Mergers
- Black Hole – White Dwarf Mergers

Science Drivers

- Stellar Collapse, Black Holes
- Jet and Fireball Physics
- UHE cosmic ray acceleration , ν
- Gravitational radiation
- Early universe, star formation, reionization

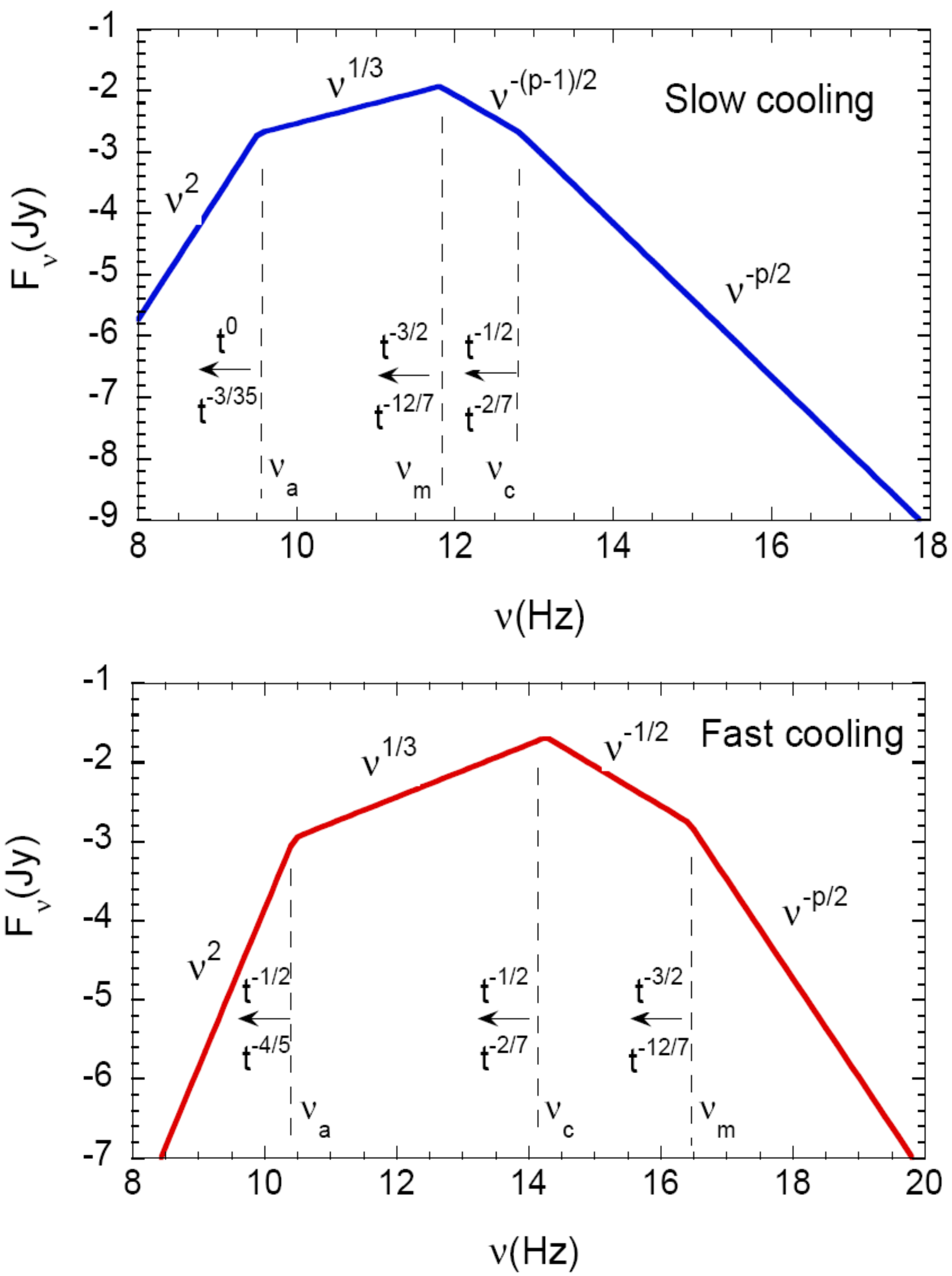


Gamma-ray bursts



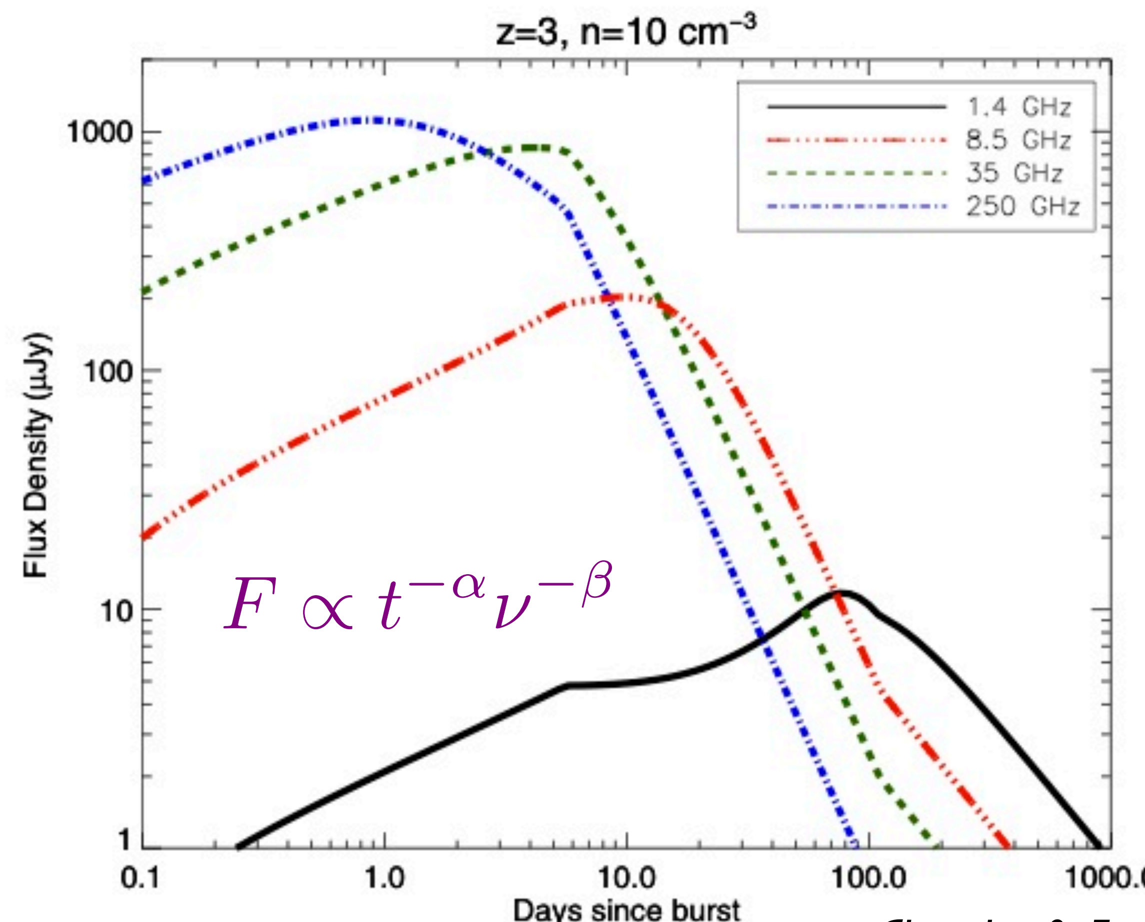
Gamma-ray bursts

Synchrotron Afterglow Spectrum



Sari, Piran, and Narayan (1998)

Radio Emission from Forward Shock



Chandra & Frail (2012)

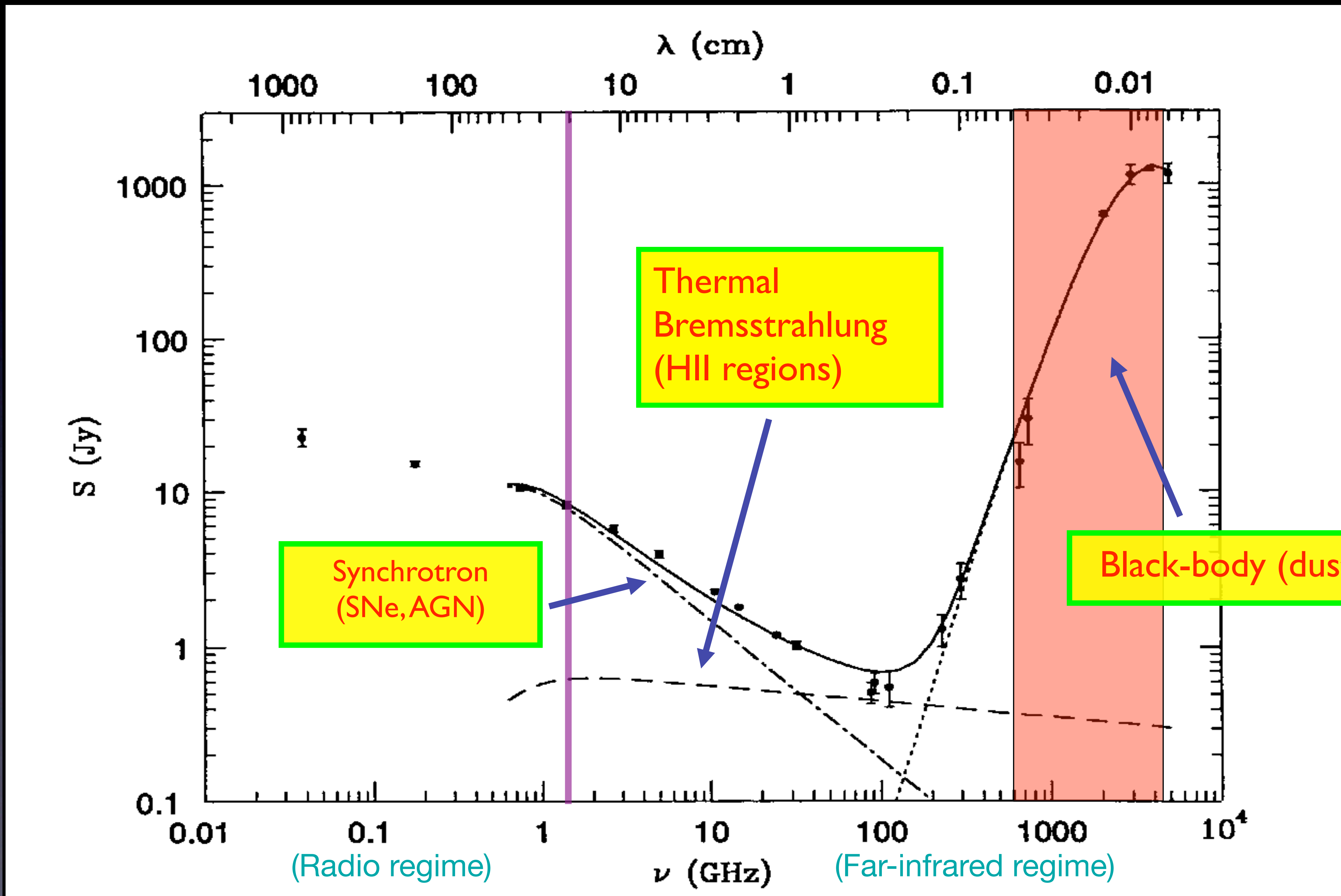
- 50% of all bursts show radio afterglows
- Radio positions accurate to 0.01”
- Good for location in host galaxy (galaxy size 1-3”)
- No simple power law decline
- Can monitor the source for years
- Prompt, short-lived radio flares have been detected
- Beginning of afterglows show strong ISM scintillation

Starburst Galaxies

- Starburst galaxies have star-formation intensities of 1-100 $M_\odot$ yr^{-1} kpc^{-2} (x10^3 Milky Way)
- Starbursts often are stimulated by galaxy mergers or close passages
- Radio emission is thermal emission from HII regions ("super star clusters") or nonthermal emission from supernova remnants
- Correlated with Far-Infrared emission
- Starbursts younger than a few Myr are dominated by thermal radio emission

Image of starburst galaxy M82 (D ~ 3 Mpc) showing the stellar disk of the galaxy, which harbors its active star formation, and a perpendicular supergalactic wind of ionized gas powered by the starburst (HST+WIYN).

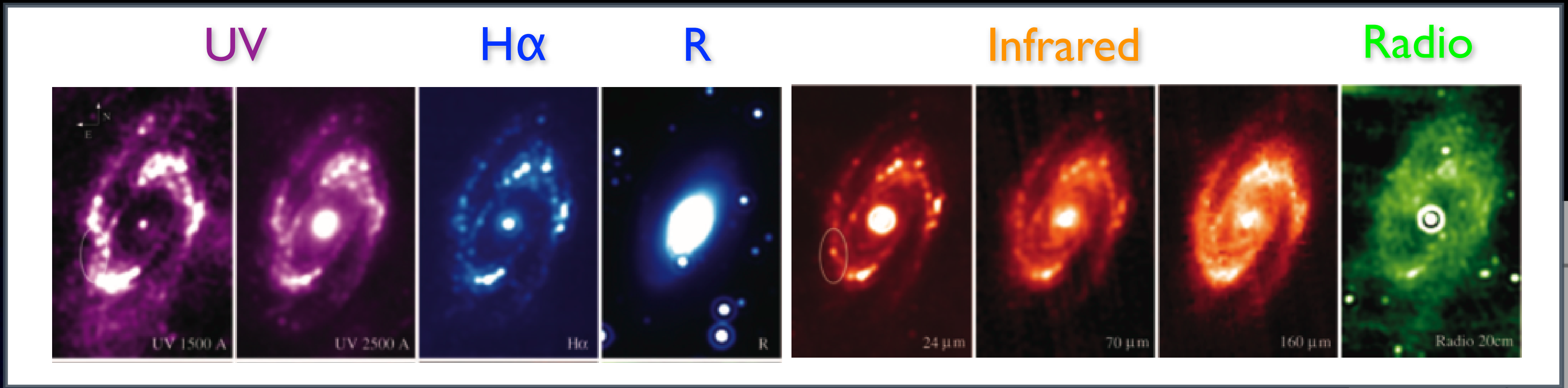
Typical Spectrum (M82)



Condon (1992)

L_{FIR} - L_{Radio} Correlation

M81

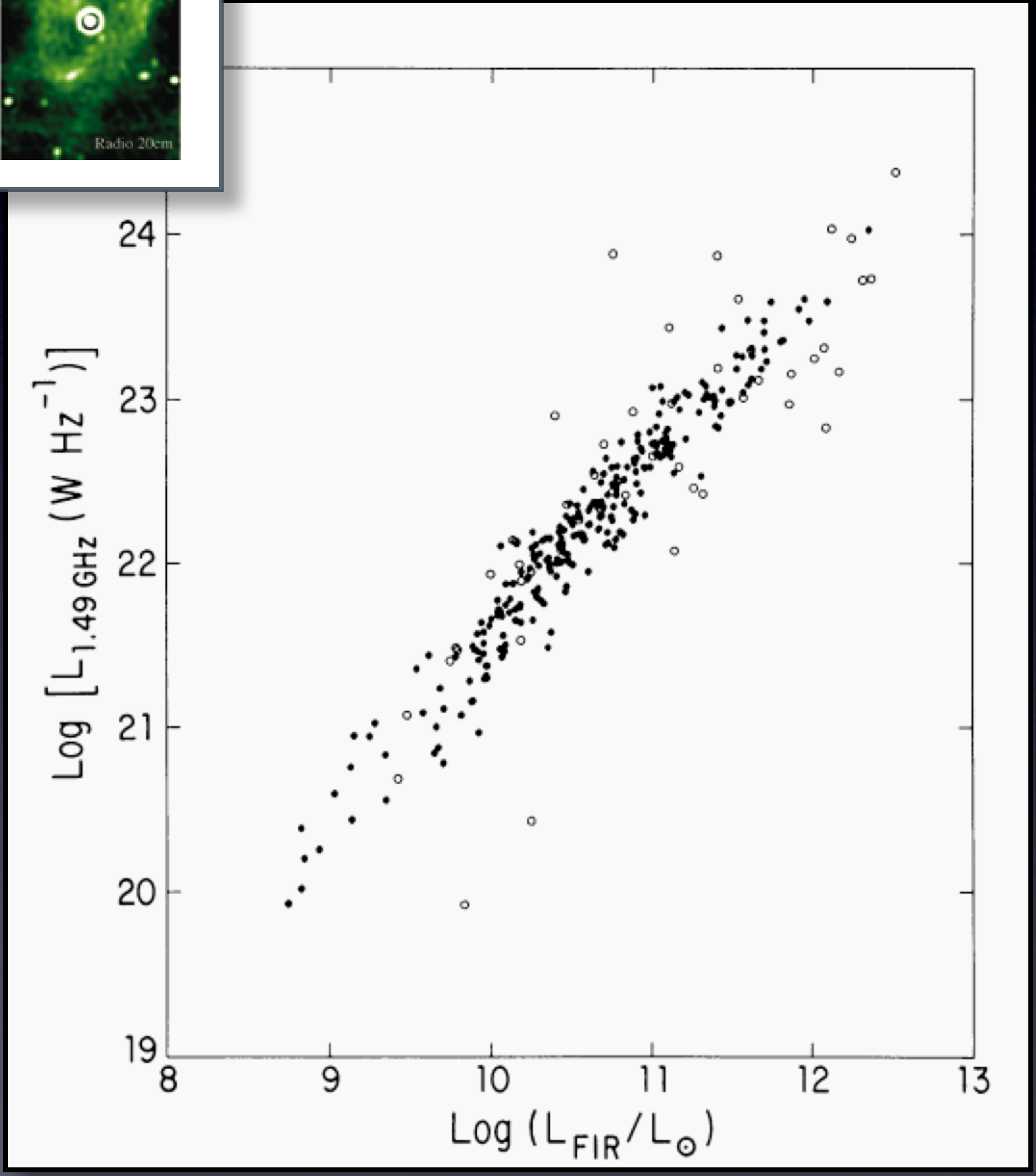


Gordon et al. (2004)

- Driven by star formation of massive stars
- Form in dusty giant molecular clouds; nearly all their luminosity emerges in FIR
- SNR accelerate free electrons which escape into the galaxy and emit synchrotron
- Assume starburst history, adopt IMF:

$$SFR\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (ergs\ s^{-1})$$

- Can use radio to measure SFR at high z!

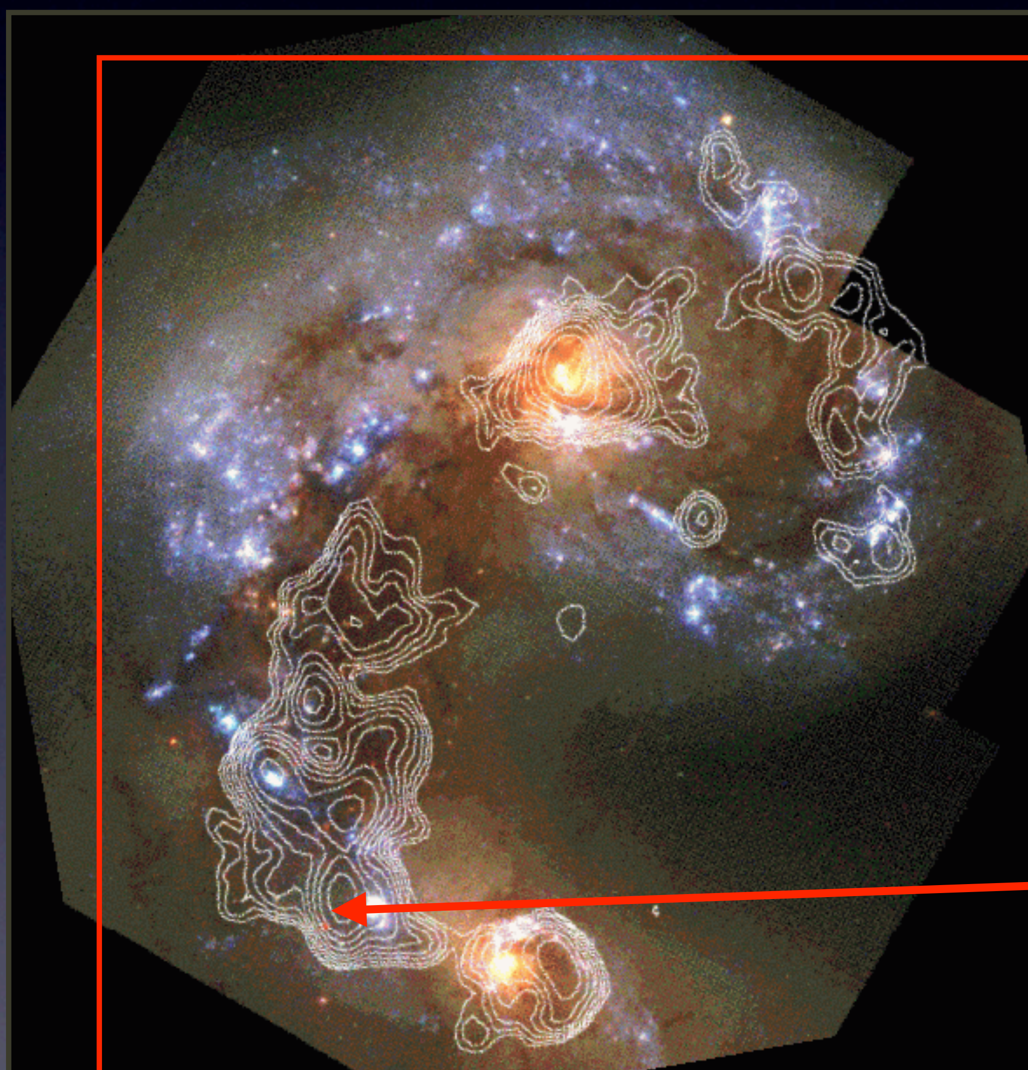


Kennicutt (1998)

Merger Induced Starbursts

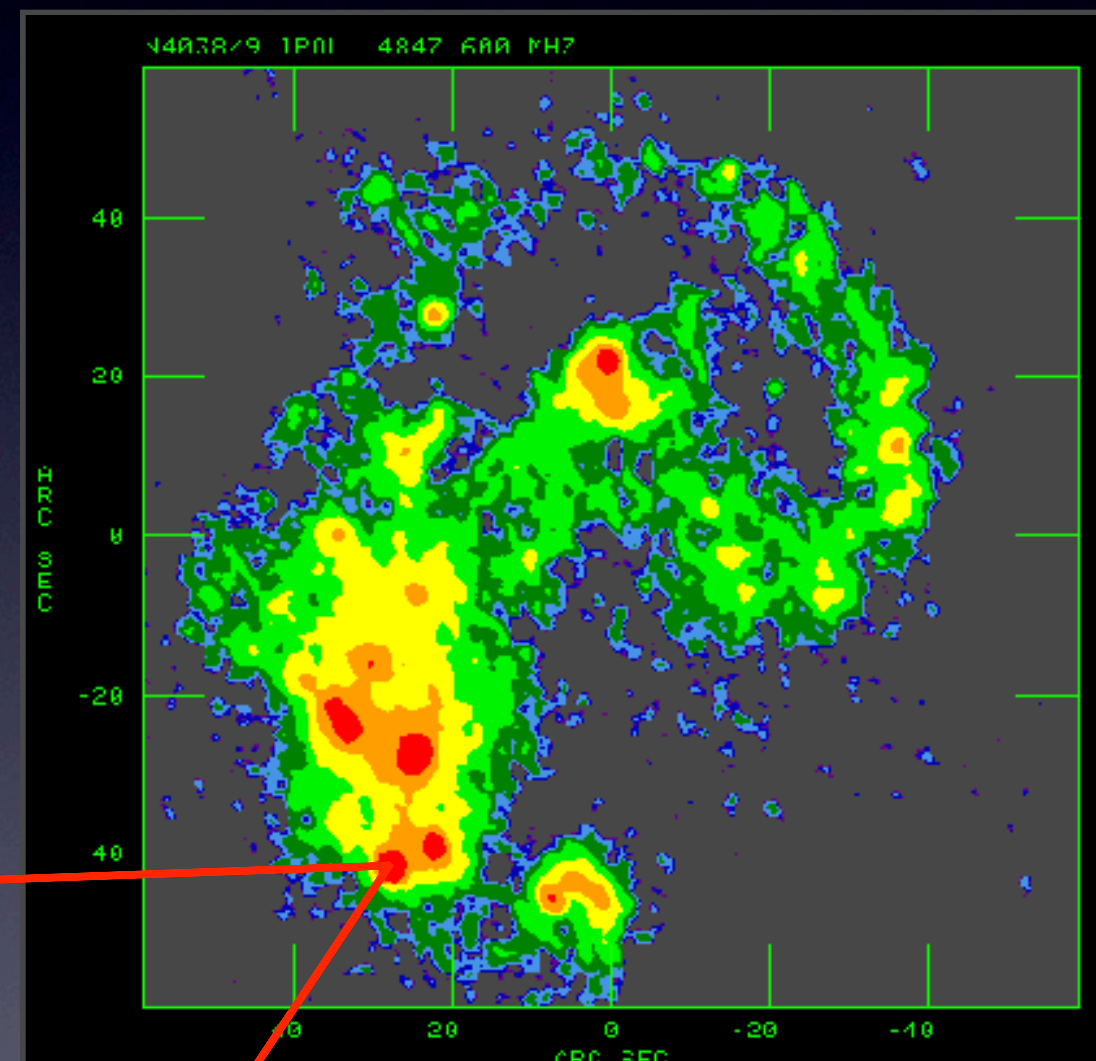
⇒ *Nearest Merger - The "Antennae"*

WFPC2 with CO overlay



Whitmore et al. (1999); Wilson et al. (2000)

VLA 5 GHz image

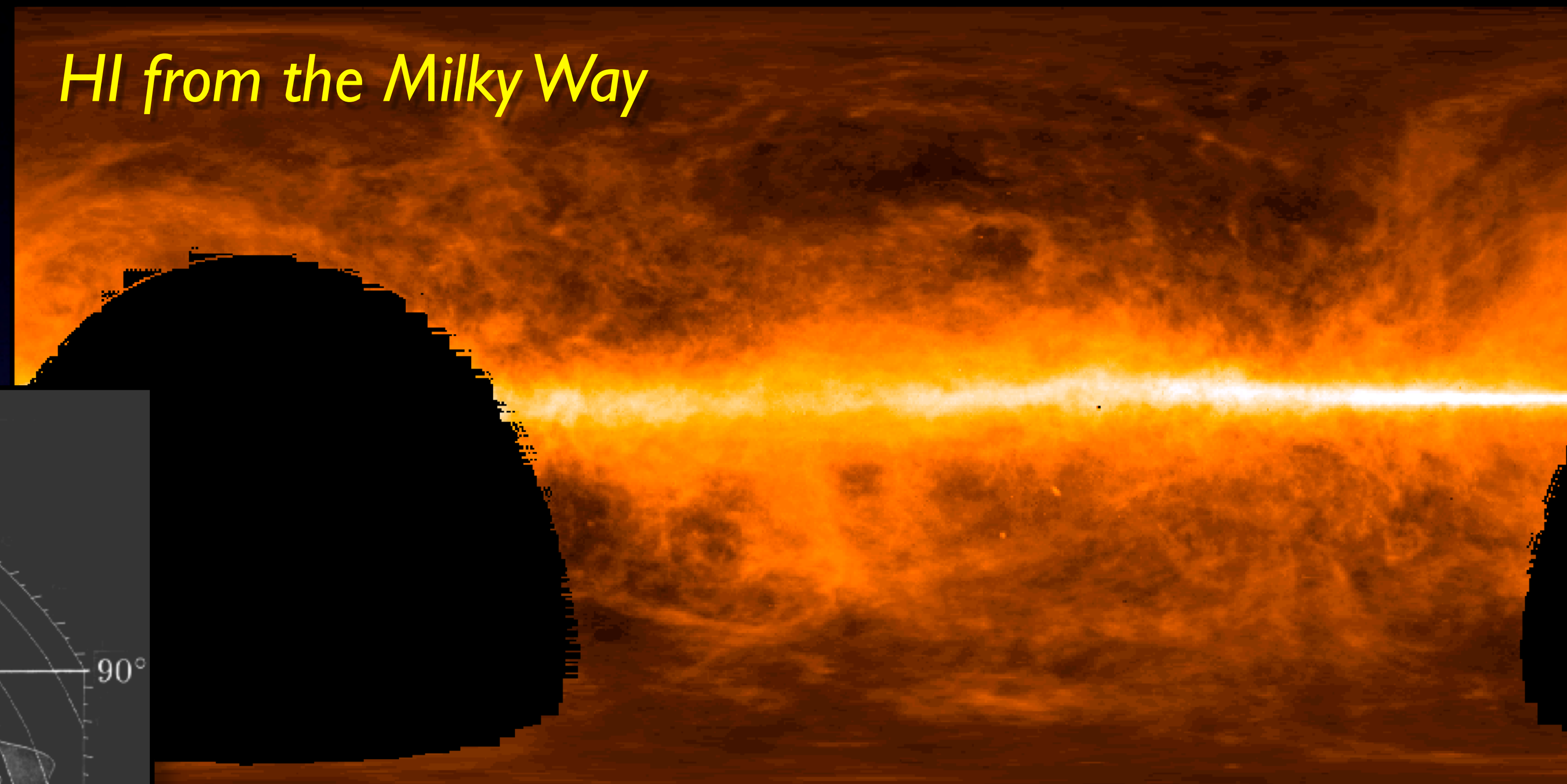


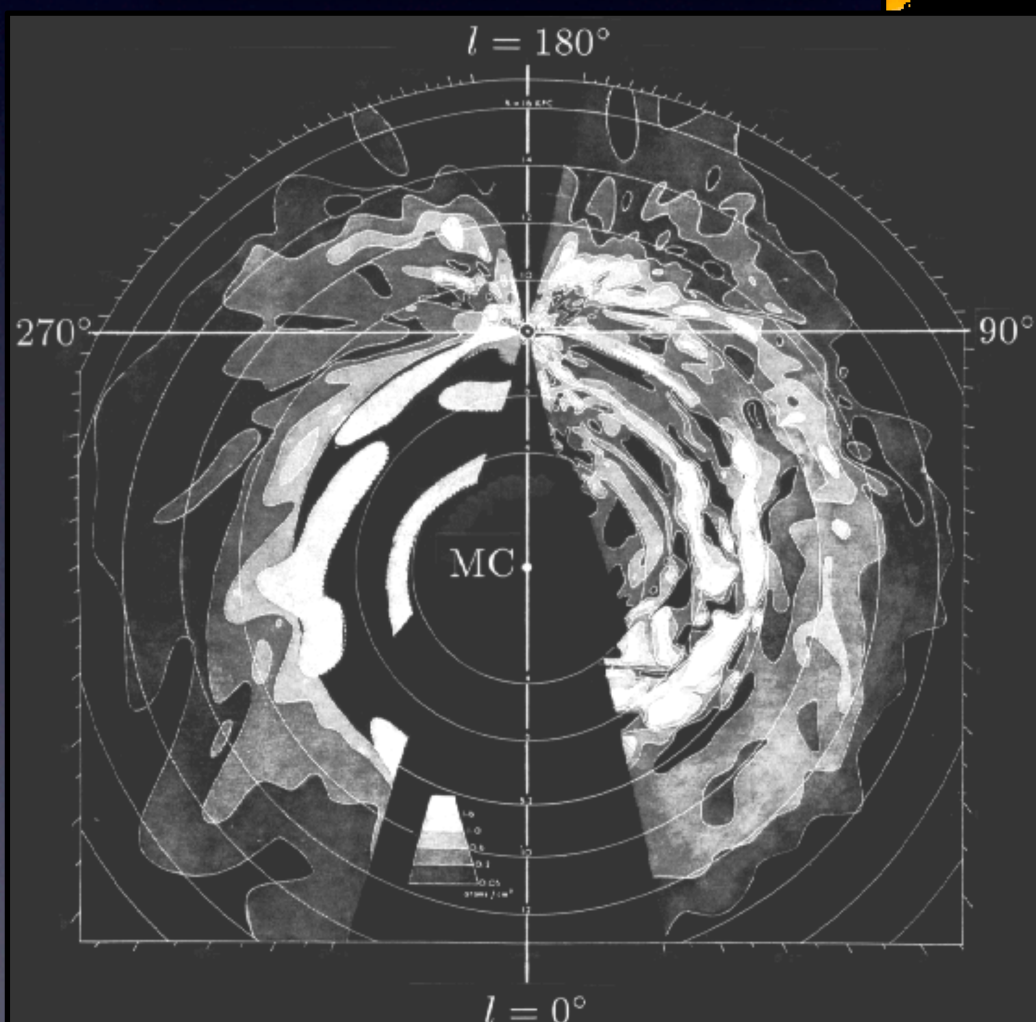
Neff & Ulvestad (2000)

5 mJy ~ 30,000 O7-equivalent stars

HI Galaxy Structure Studies

All-sky image of the HI column density in the Milky Way - from the Dwingeloo- Leiden survey



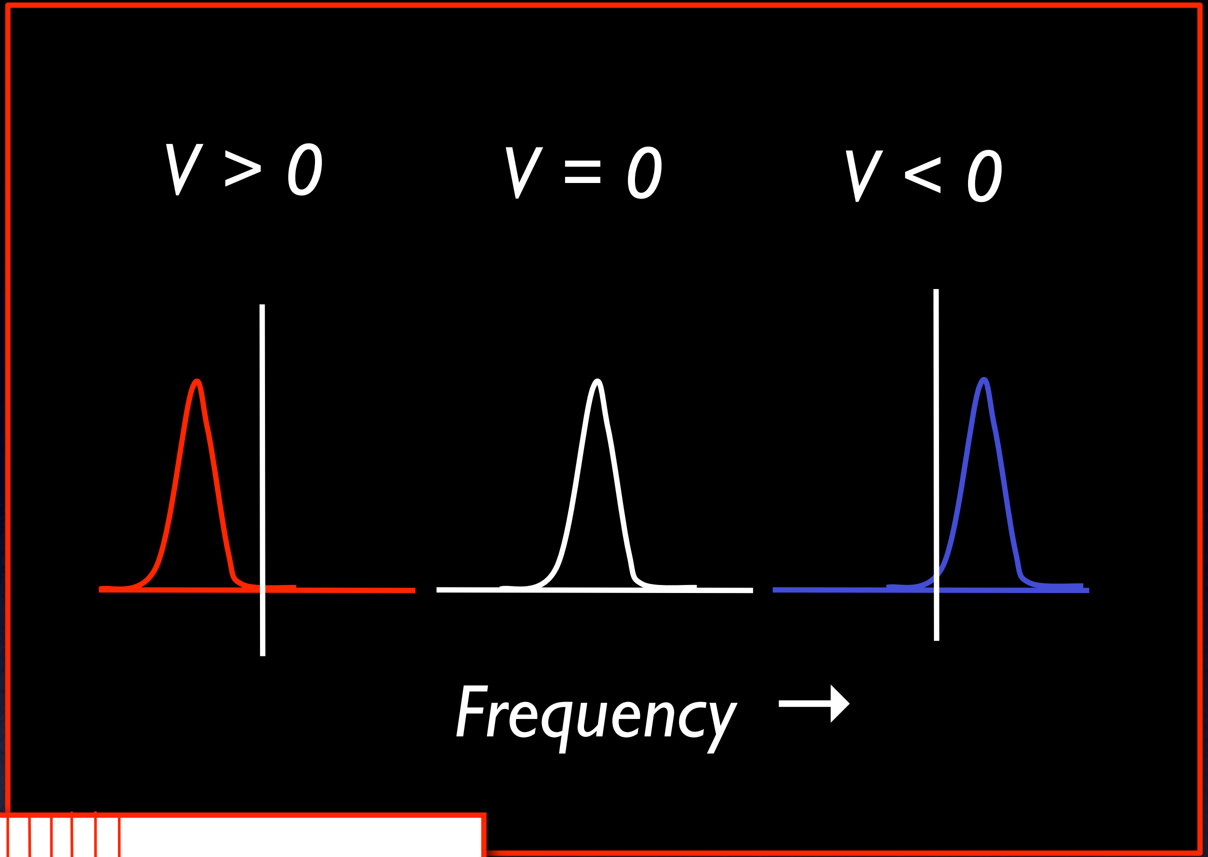


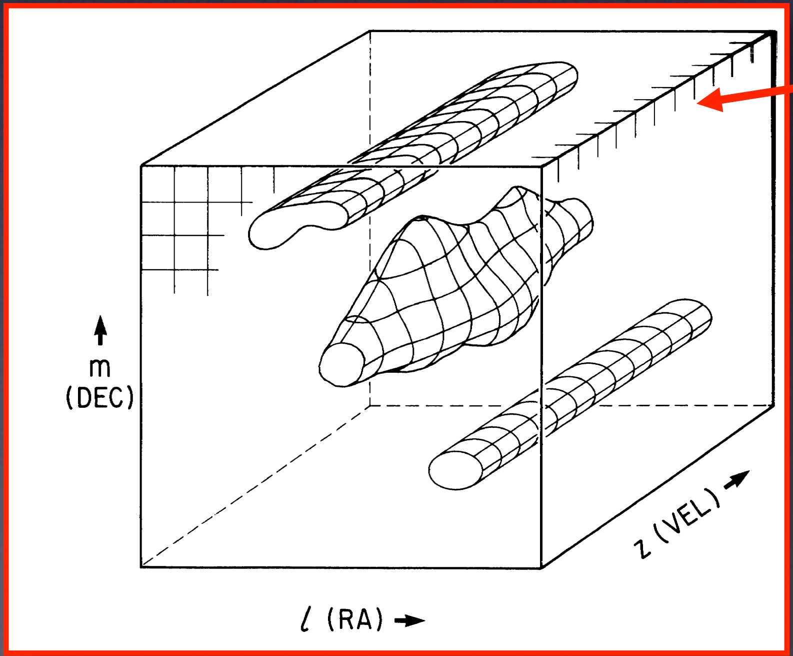
Oort, Kerr & Westerhout (1958)

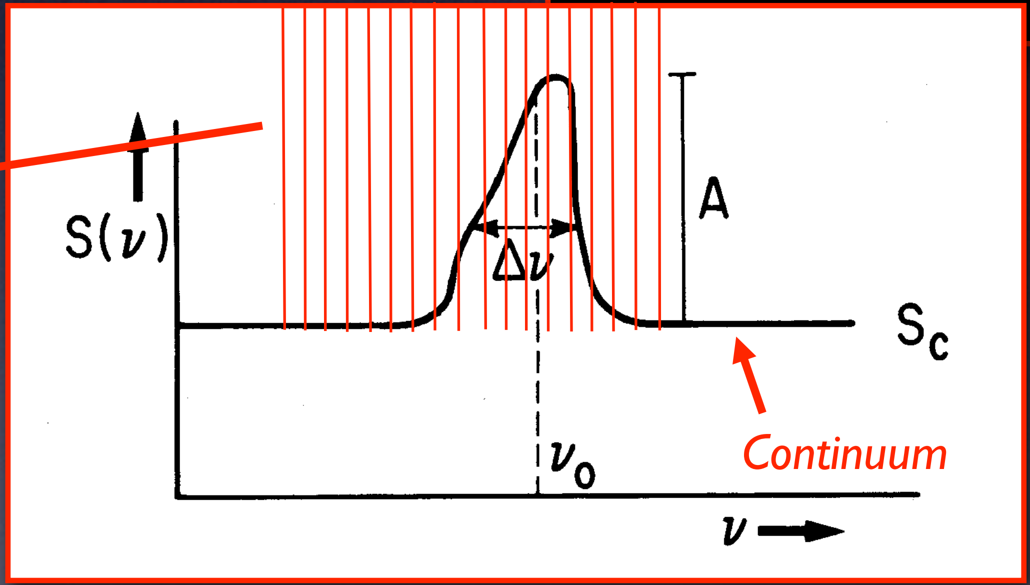
- HI comprises 5-10% mass in the Milky Way
- HI traces the "warm" interstellar medium
- Organized into diffuse clouds of gas and dust
- Traces structure and kinematics
- Traces streams and high velocity clouds
- Traces accretion and mergers
- Probe of dark matter
- Evolution of gas content with redshift

Why Neutral Hydrogen (HI) ?

- Hydrogen most common element in the universe ⇒ present "everywhere"!
- Narrow spectral line (for T ~ 100 K, Δv ~ 1 km/s)
- Systemic shifts are always much larger
- Doppler effect ⇒ kinematics!
- Optically thin



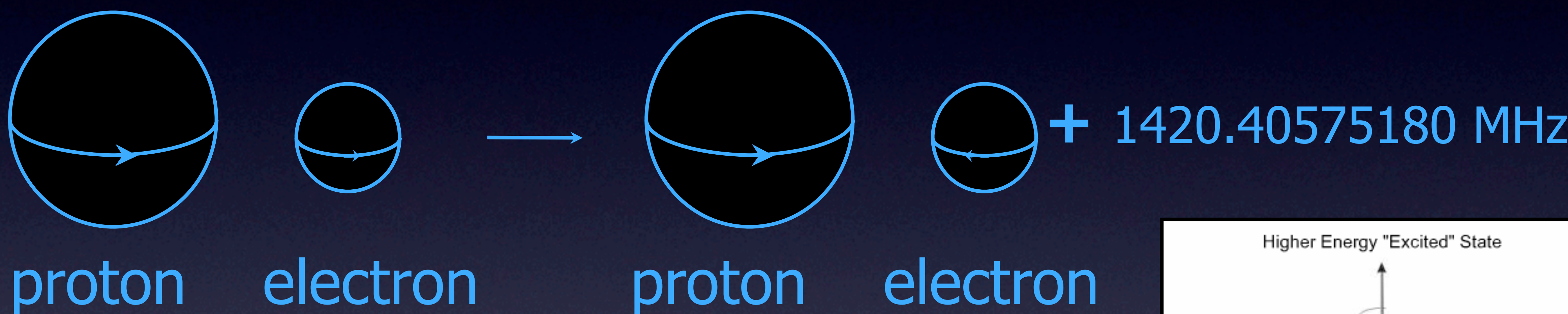


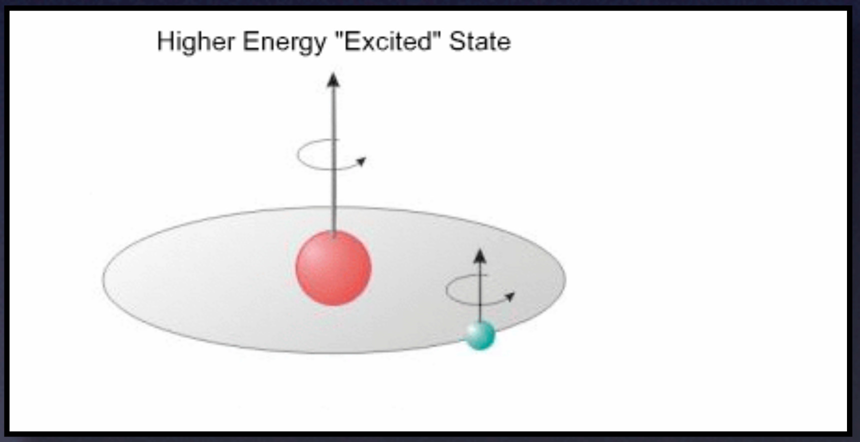


Every channel is one plane of the cube

21-cm line of Neutral Hydrogen

- The ground state of HI can undergo a hyperfine transition
- Spin of electron reverses (higher energy state when the spins are parallel)
- Difference corresponds to $E = 6 \times 10^{-6}$ eV)

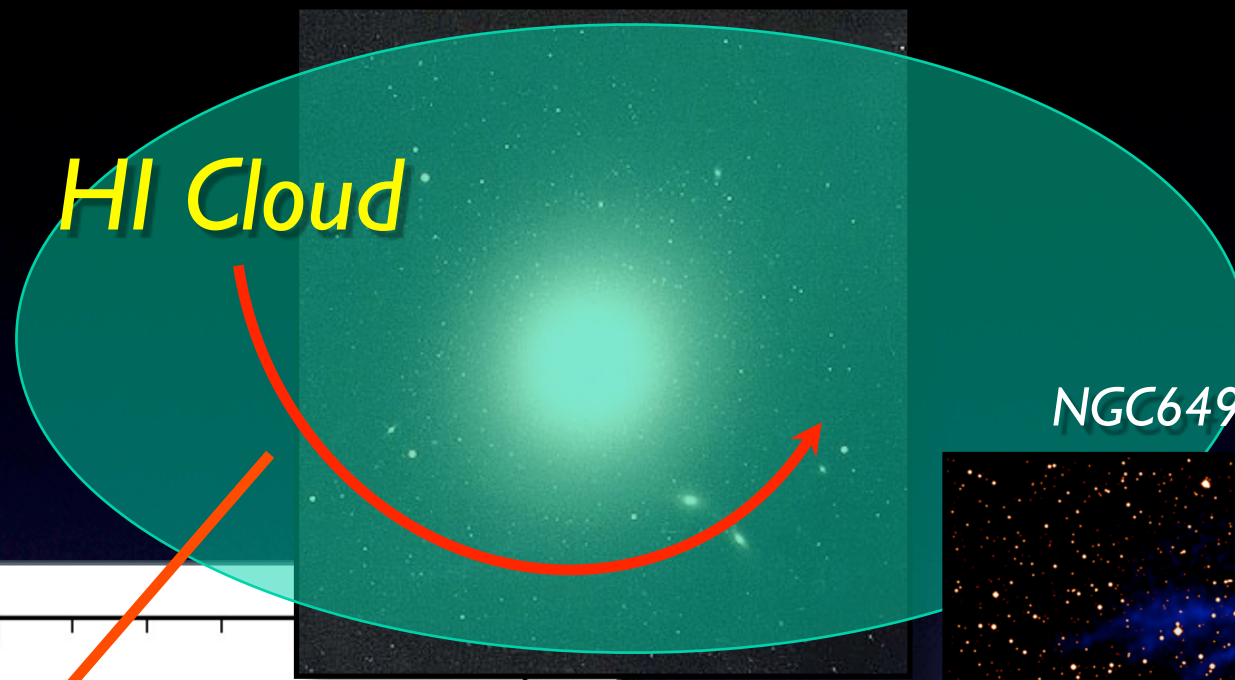




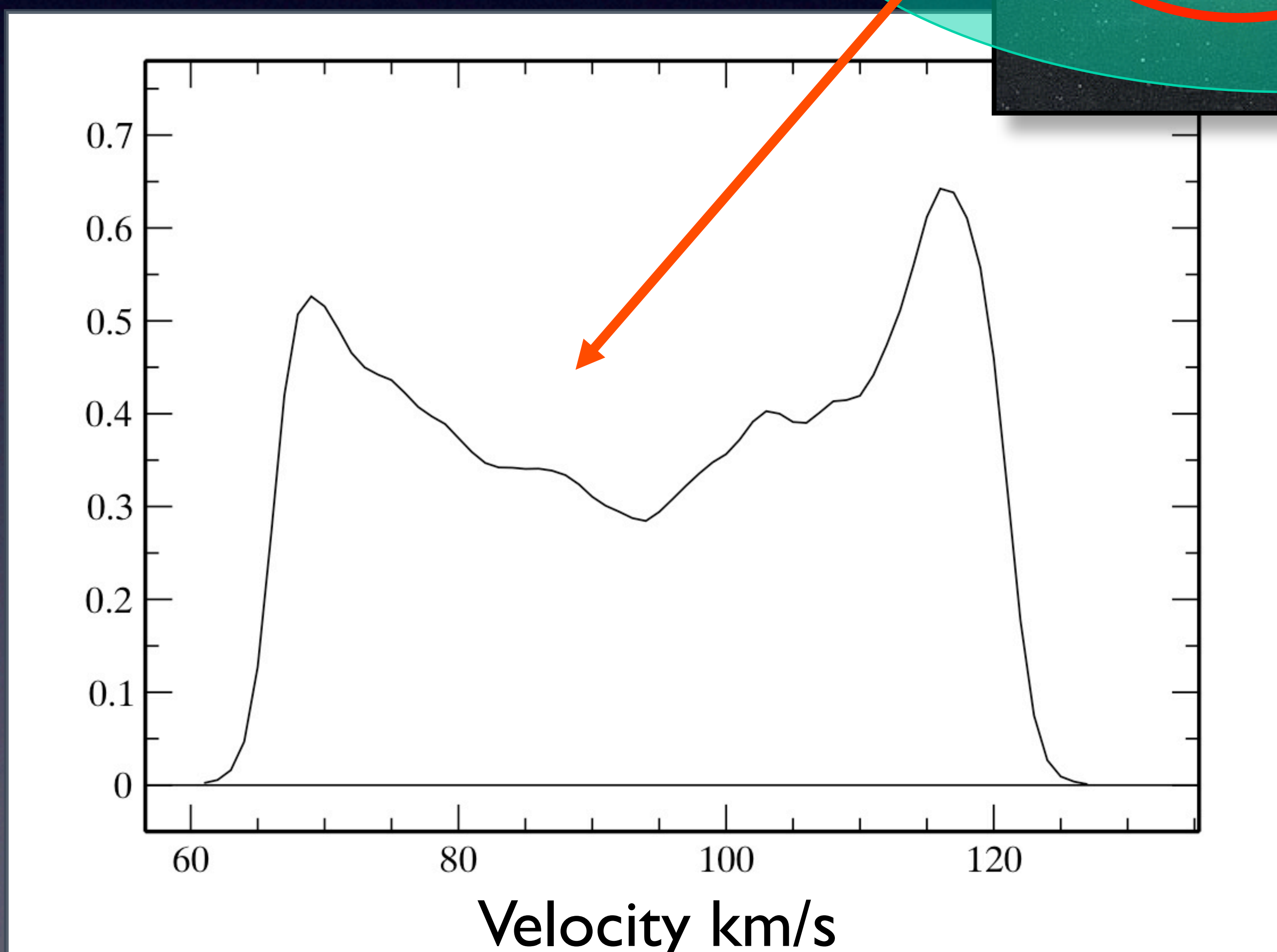
Frequency of the transition:
1420.405752 MHz (21.105 cm)

Population of the two states is determined primarily by collisions between atoms ⇒ T_s equal to the kinetic temperature

HI Detected in Emission



HI Emission

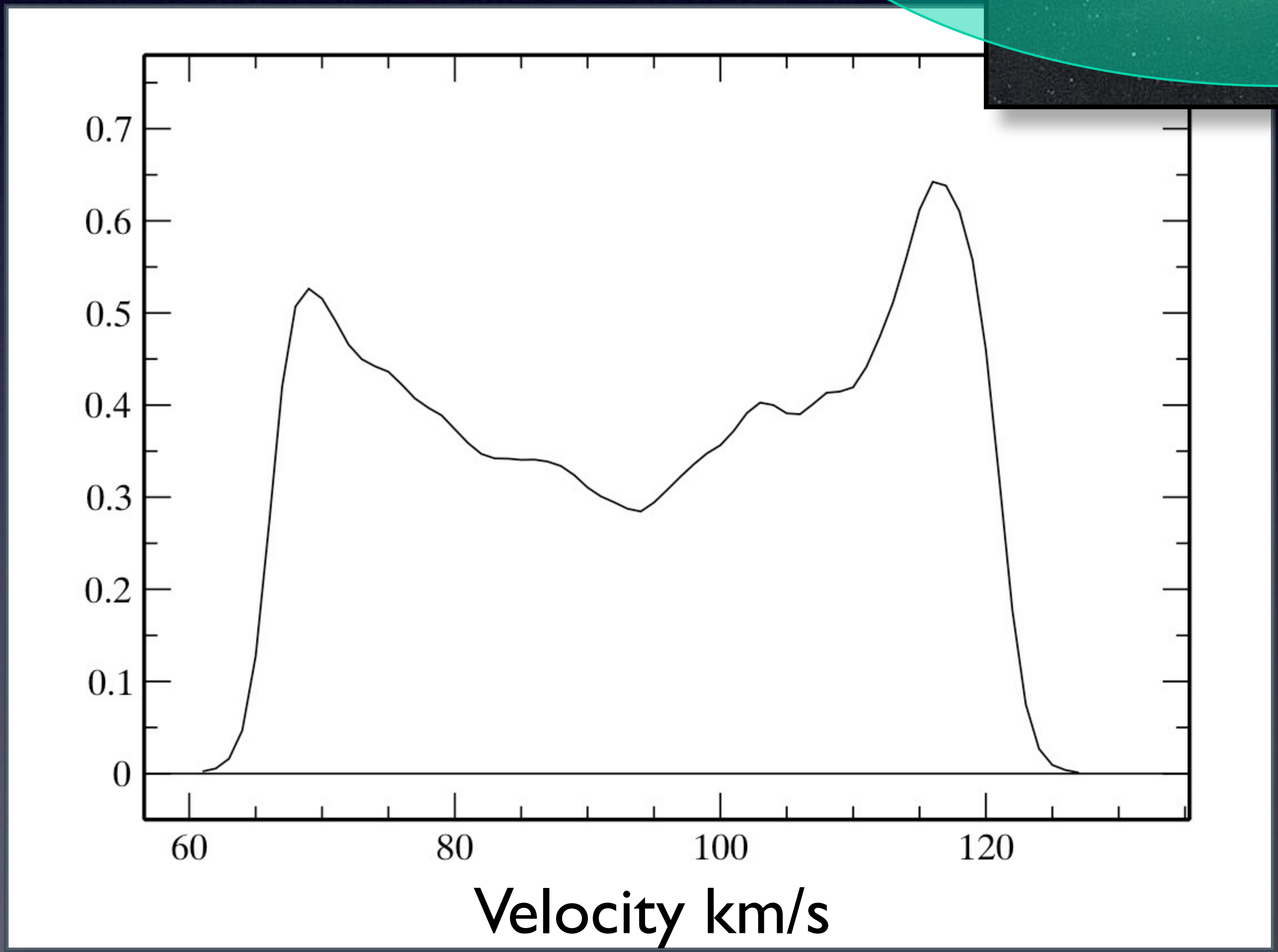


NGC6496 - HI WSRT + optical

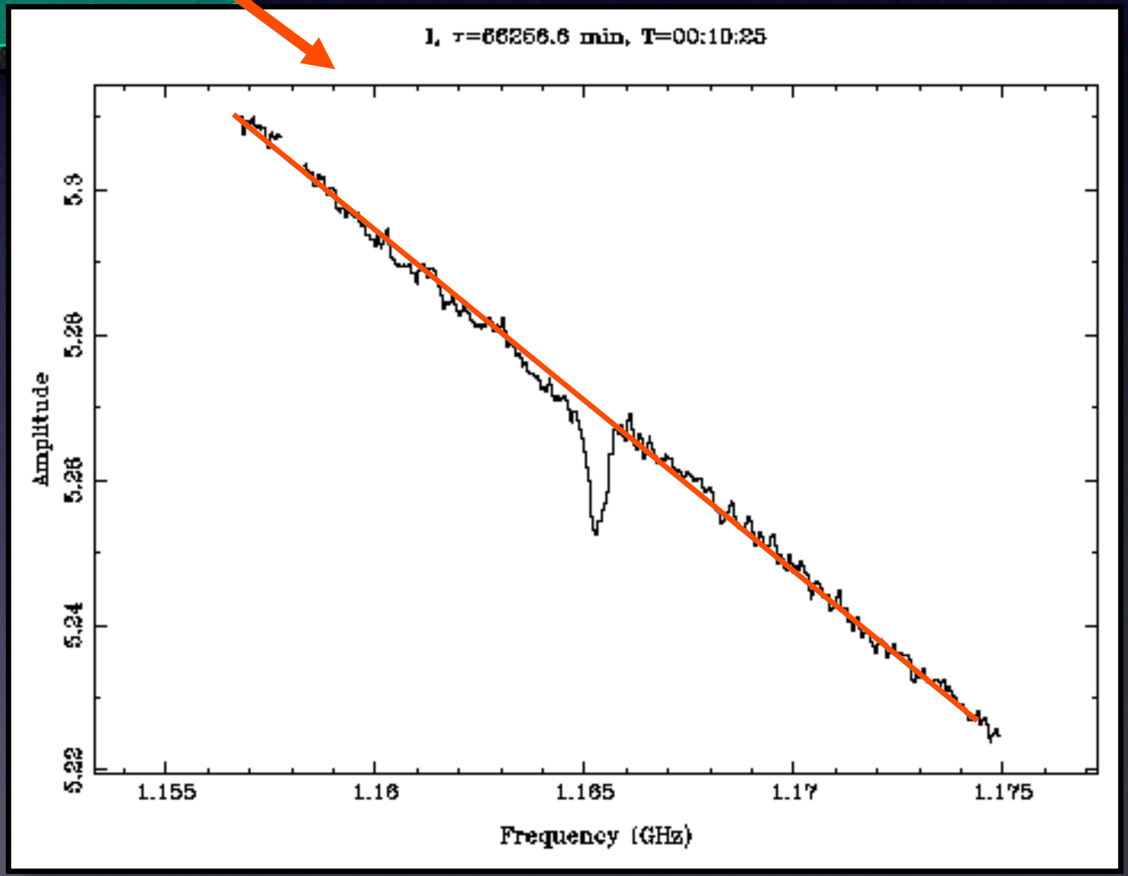
Boomsma, Oosterloo et al. (2004)

HI Detected in Absorption

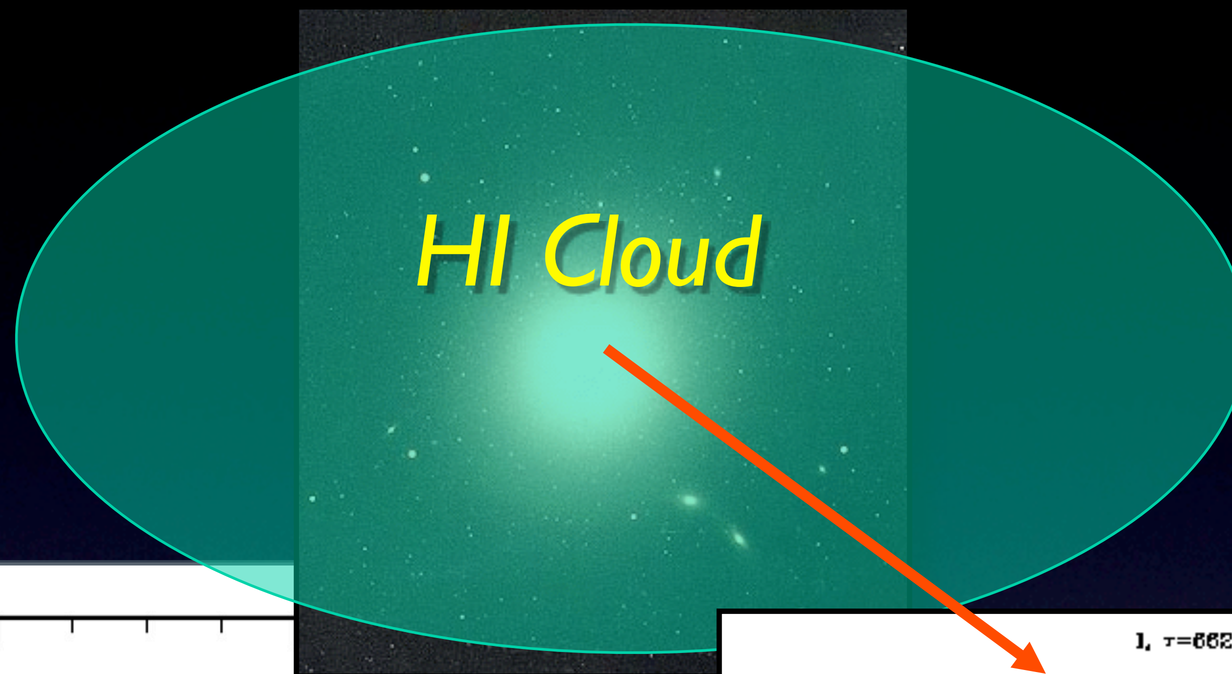
HI Emission



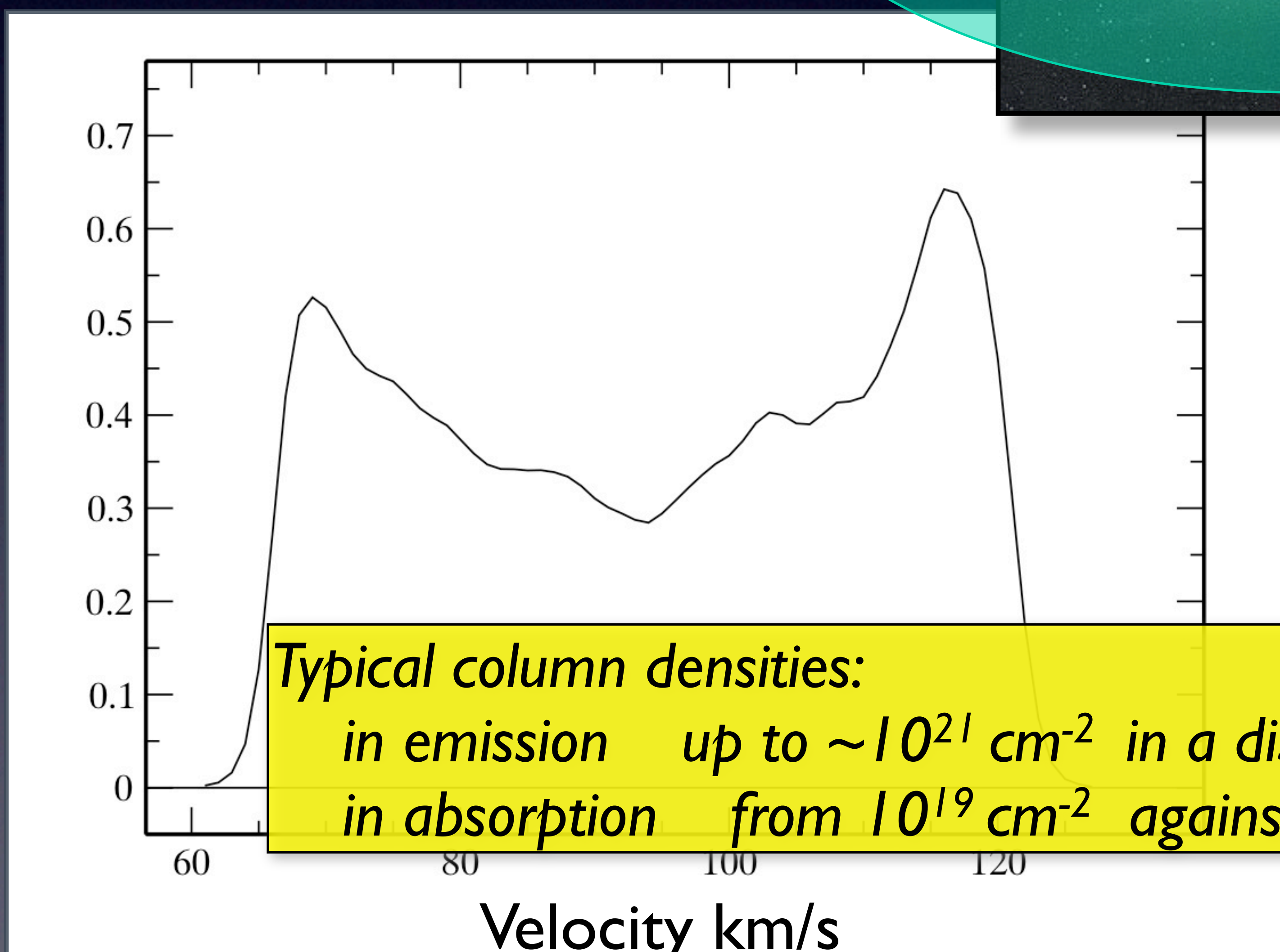
HI Absorption



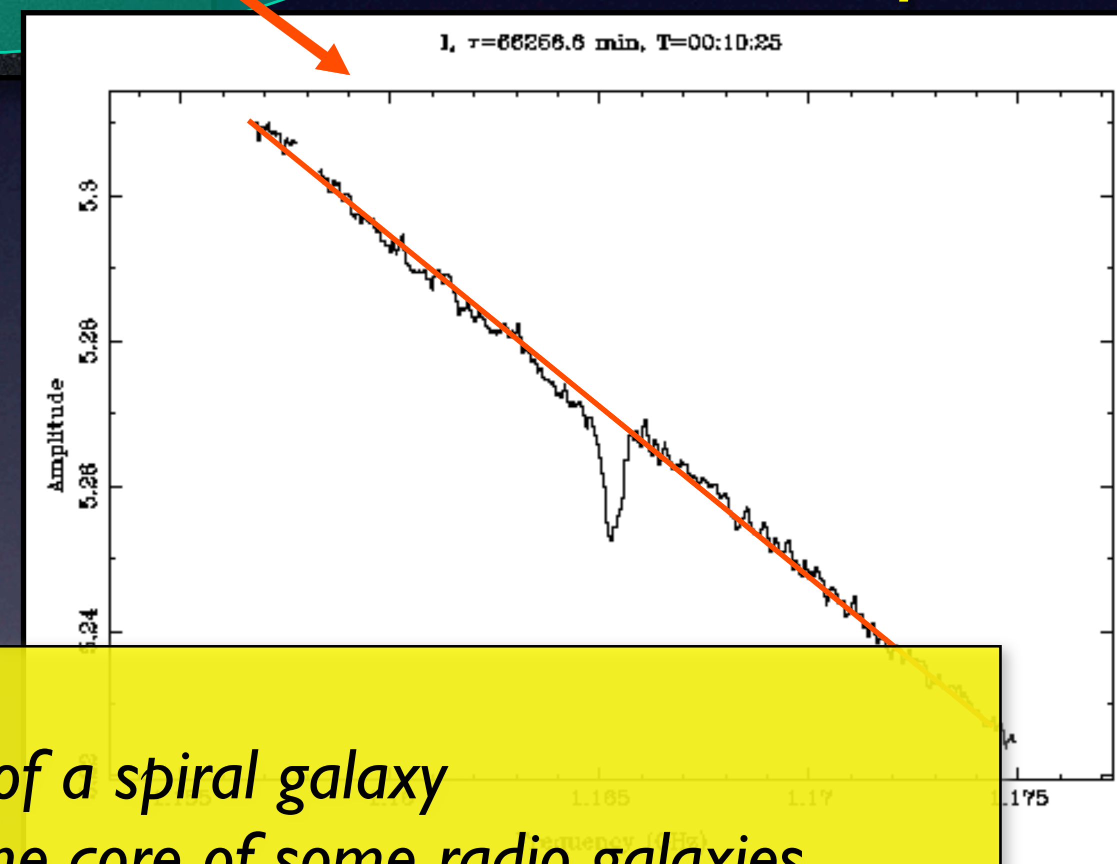
HI Detected in Absorption



HI Emission



HI Absorption

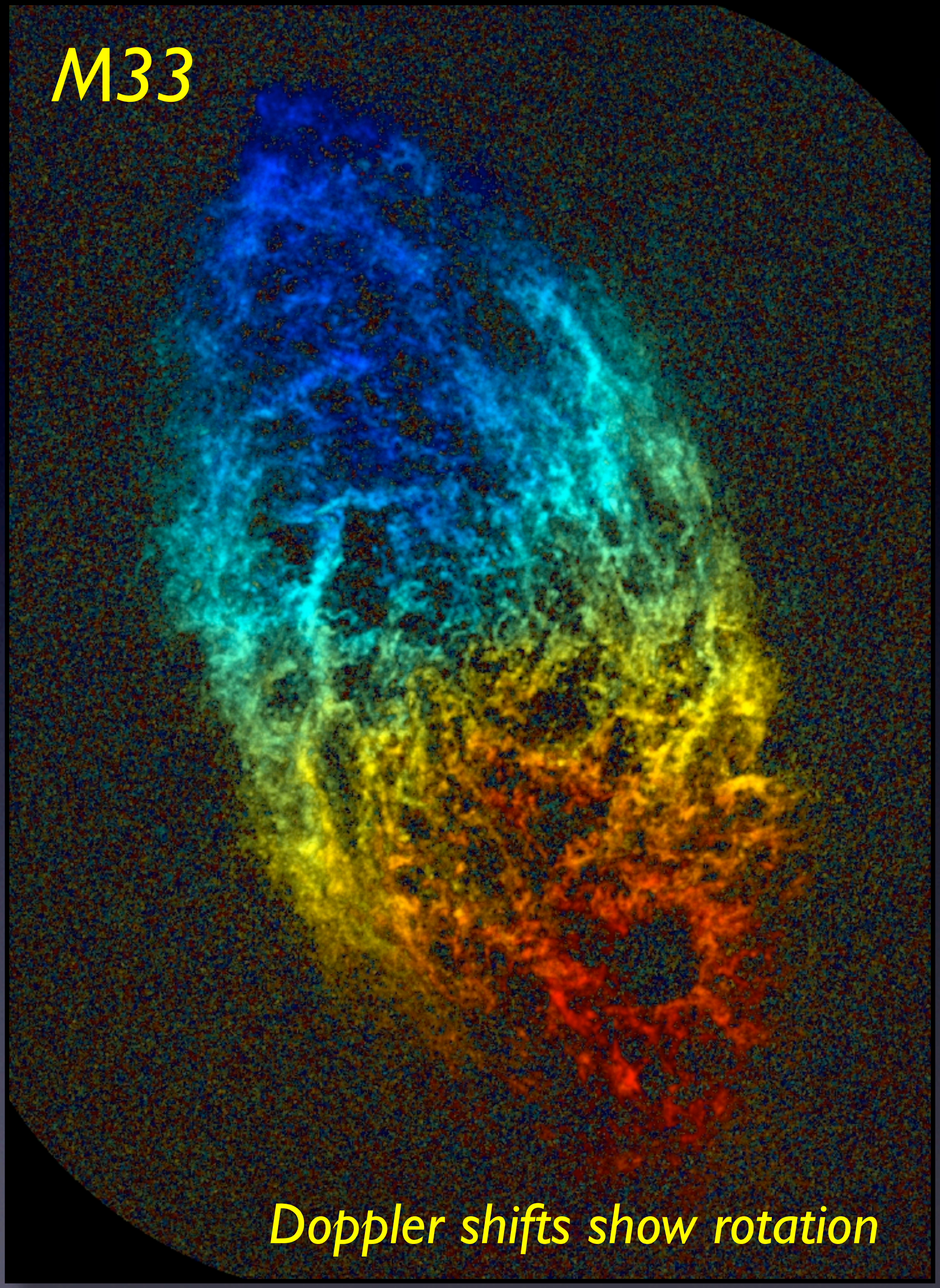


Typical column densities:

in emission up to ~10^{21} cm^{-2} in a disk of a spiral galaxy

in absorption from 10^{19} cm^{-2} against the core of some radio galaxies

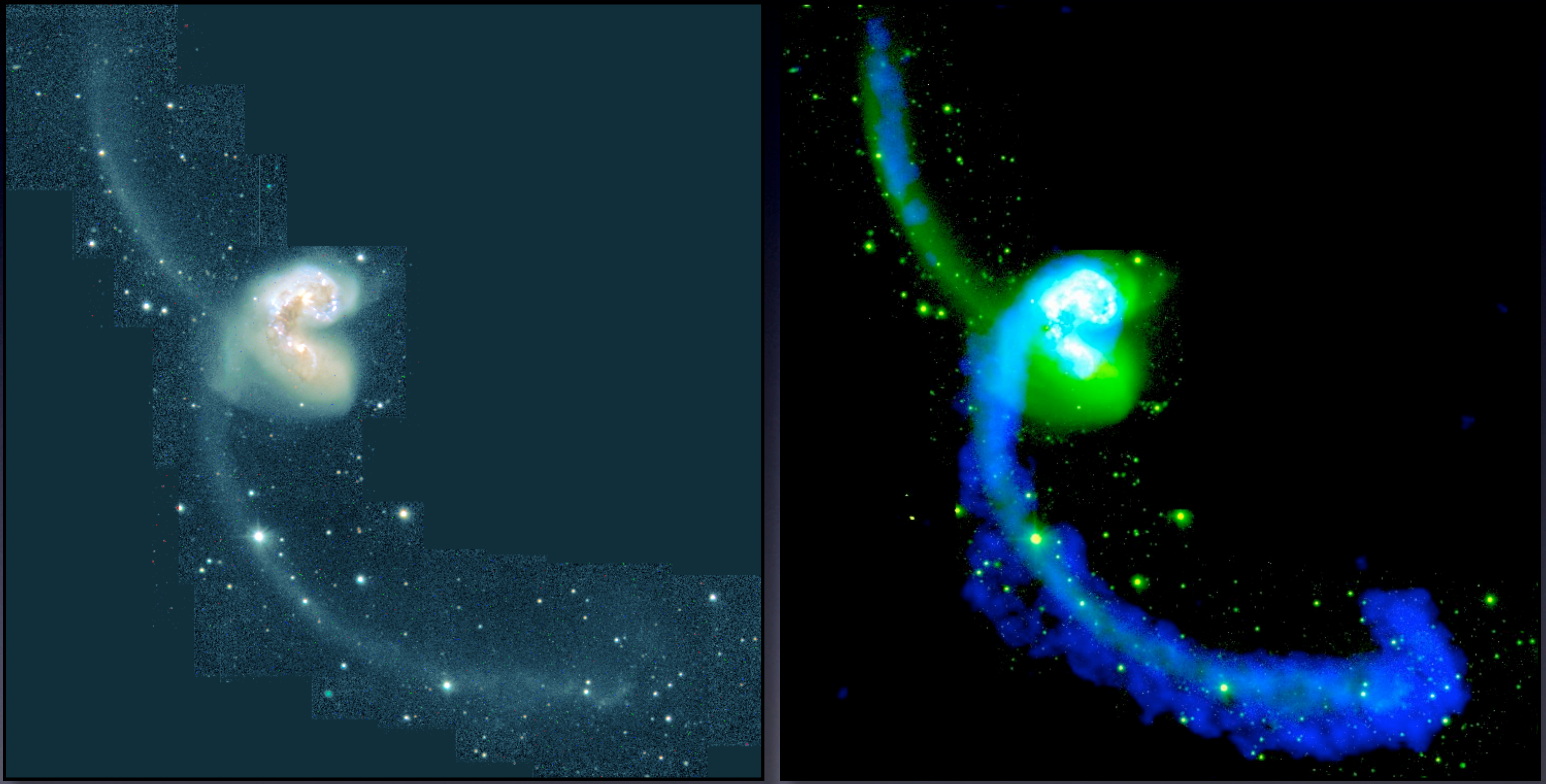
Examples of HI studies



- Galactic studies , high velocity clouds, satellites of the Milky Way.....
- Nearby galaxies and gas accretion
- Dark matter studies
- Interacting systems (including the stream in our own Galaxy)
- Effects of dense cluster IGM on cluster member galaxies (e.g. stripping etc.)
- Gas and Active Galactic Nuclei (AGN) ⇒ HI absorption tracing circumnuclear gas outflows
- Intervening HI => neutral hydrogen located between us and a radio source

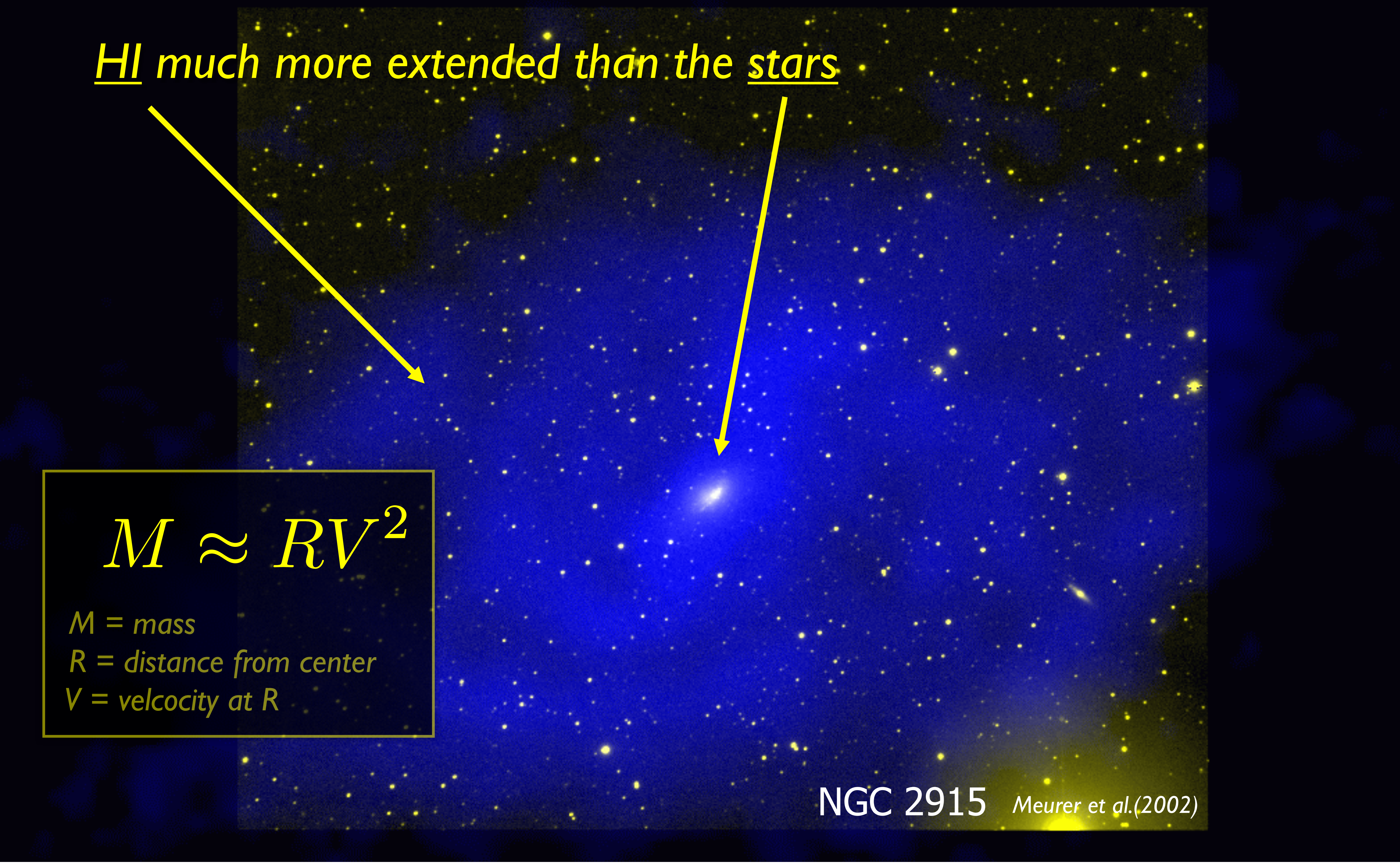
Interacting systems

VLA C+D-array observations of NGC 4038/9 - "The Antennae"



Hibbard et al. (2001)

Dark matter studies

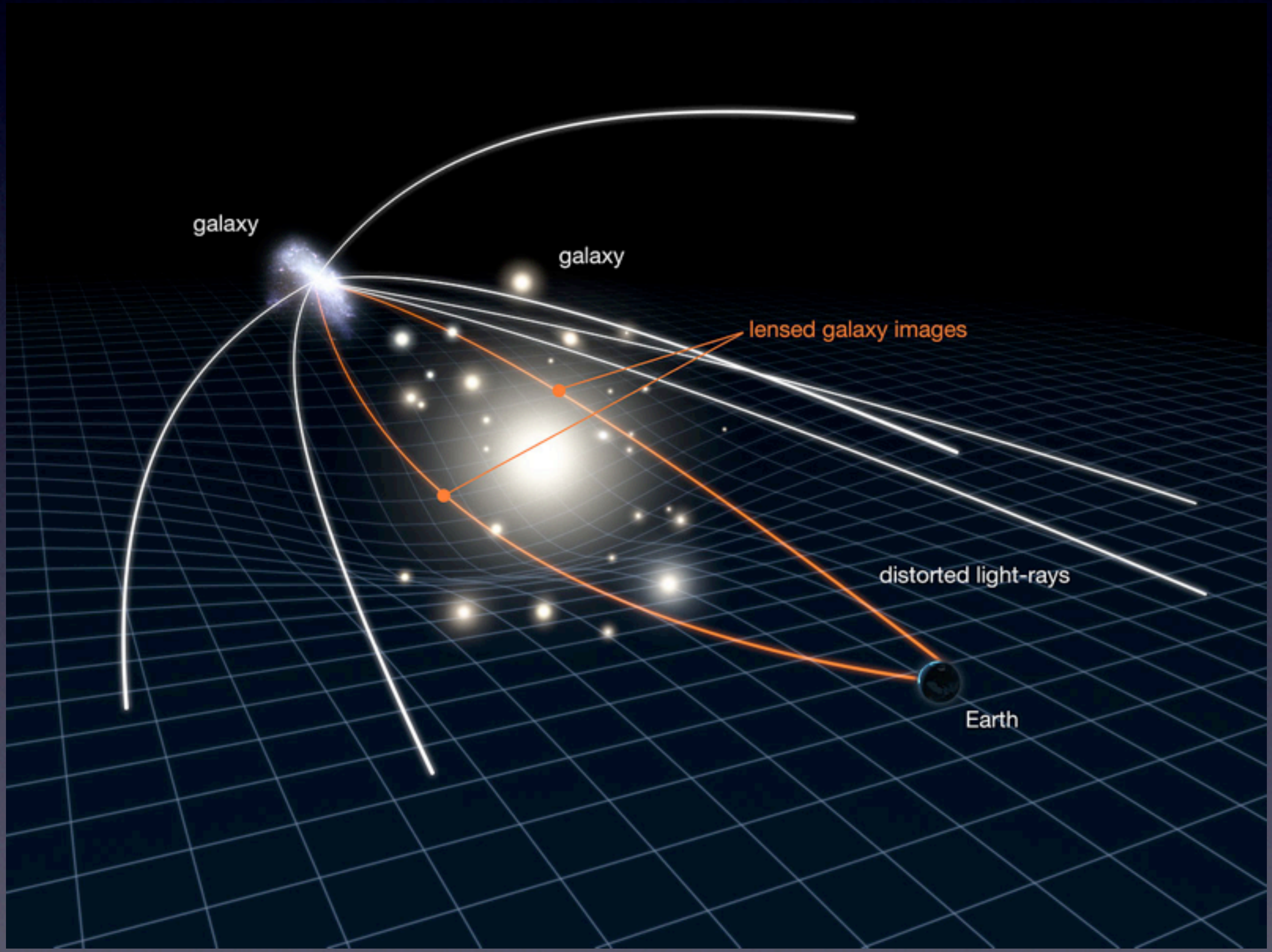


$$M \approx RV^2$$

M = mass
R = distance from center
V = velcocity at R

Gravitational Lensing

Gravitational lensing is the deflection of light by mass along the line of sight to the background source.



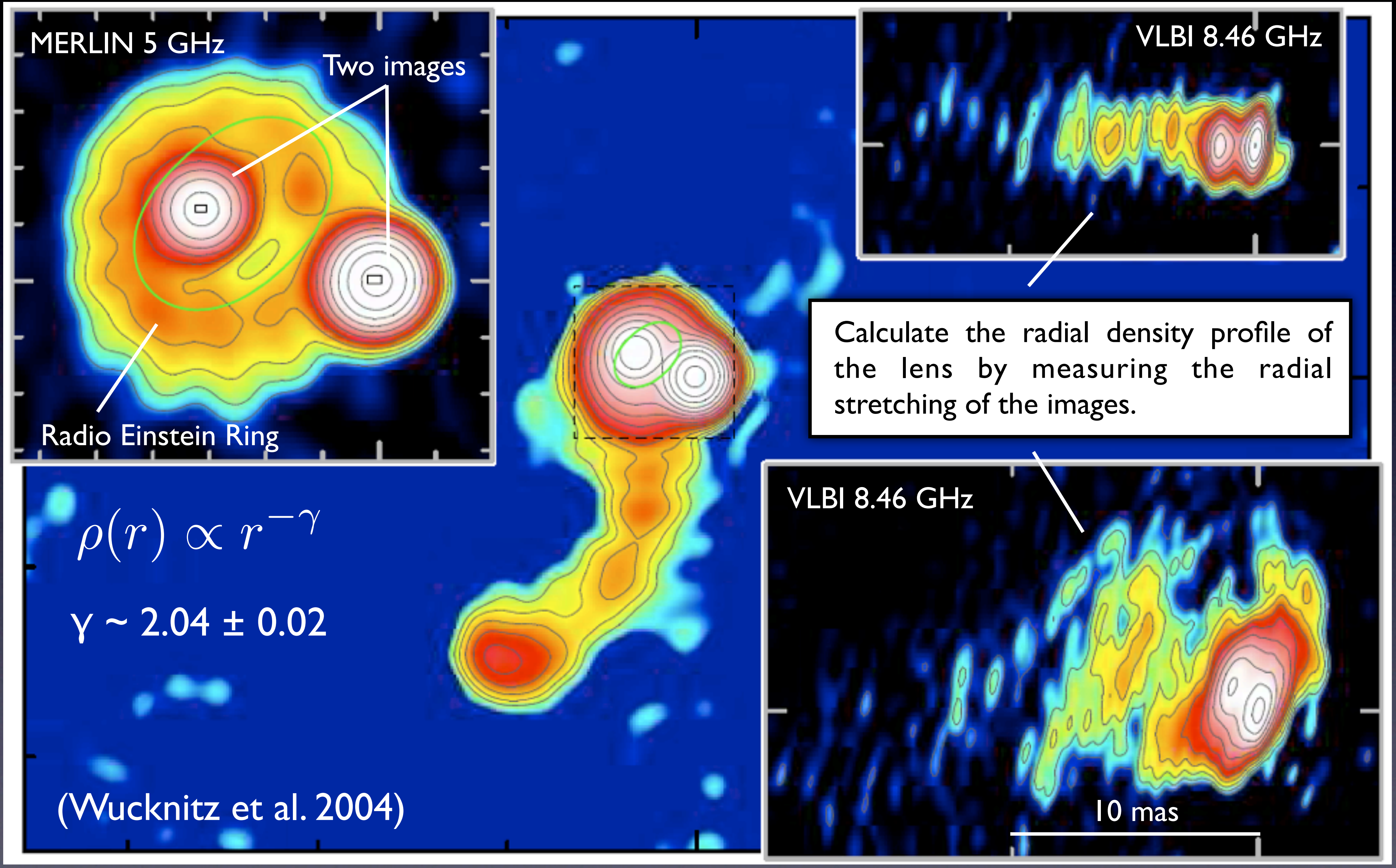
Can be used to:

i) Study the mass distribution of the lens -- test galaxy formation and models for dark matter.

ii) Study the high redshift Universe as a cosmic telescope.

iii) Measure the cosmological parameters through the lensing statistics.

Mass Structure of Galaxies

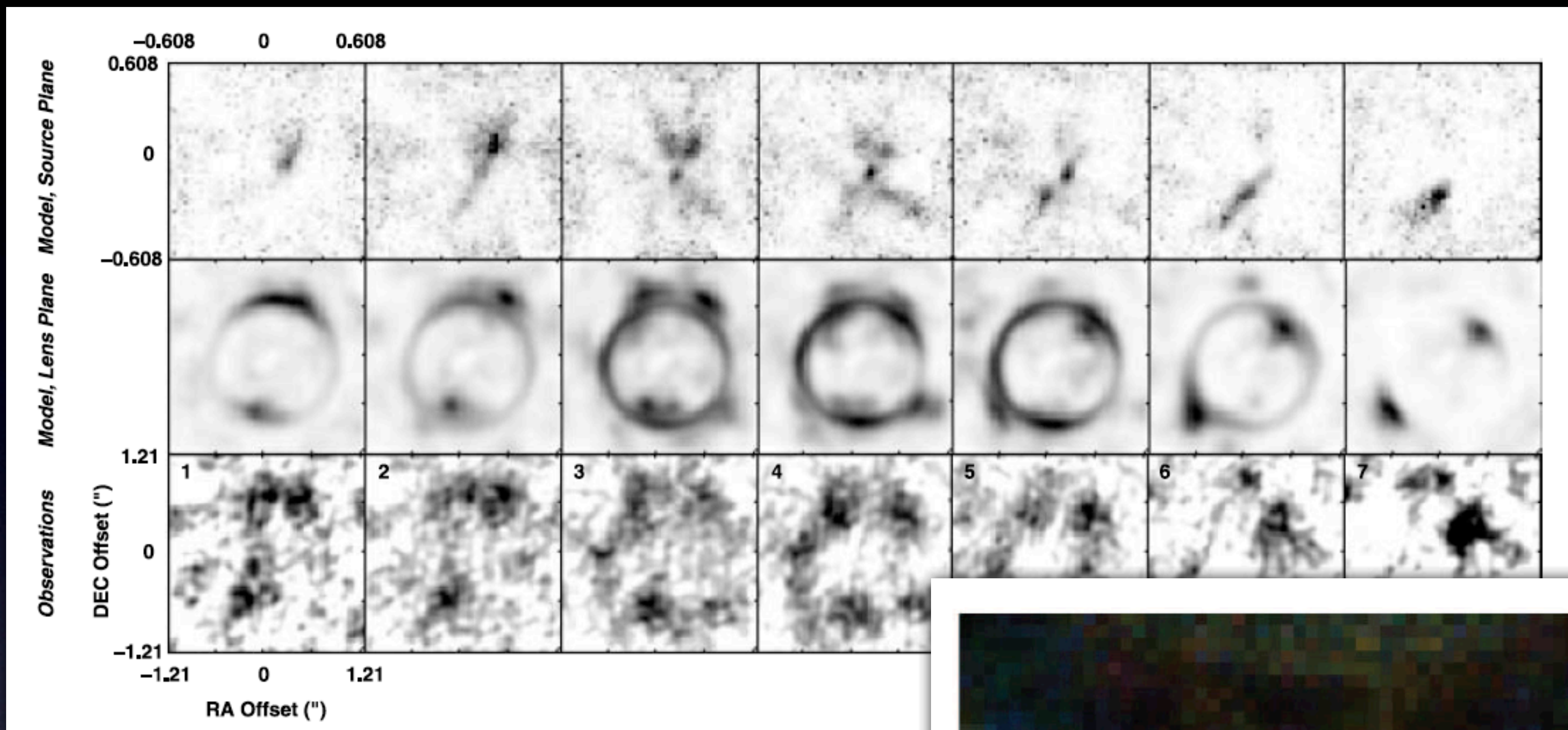


$$\rho(r) \propto r^{-\gamma}$$

$\gamma \sim 2.04 \pm 0.02$

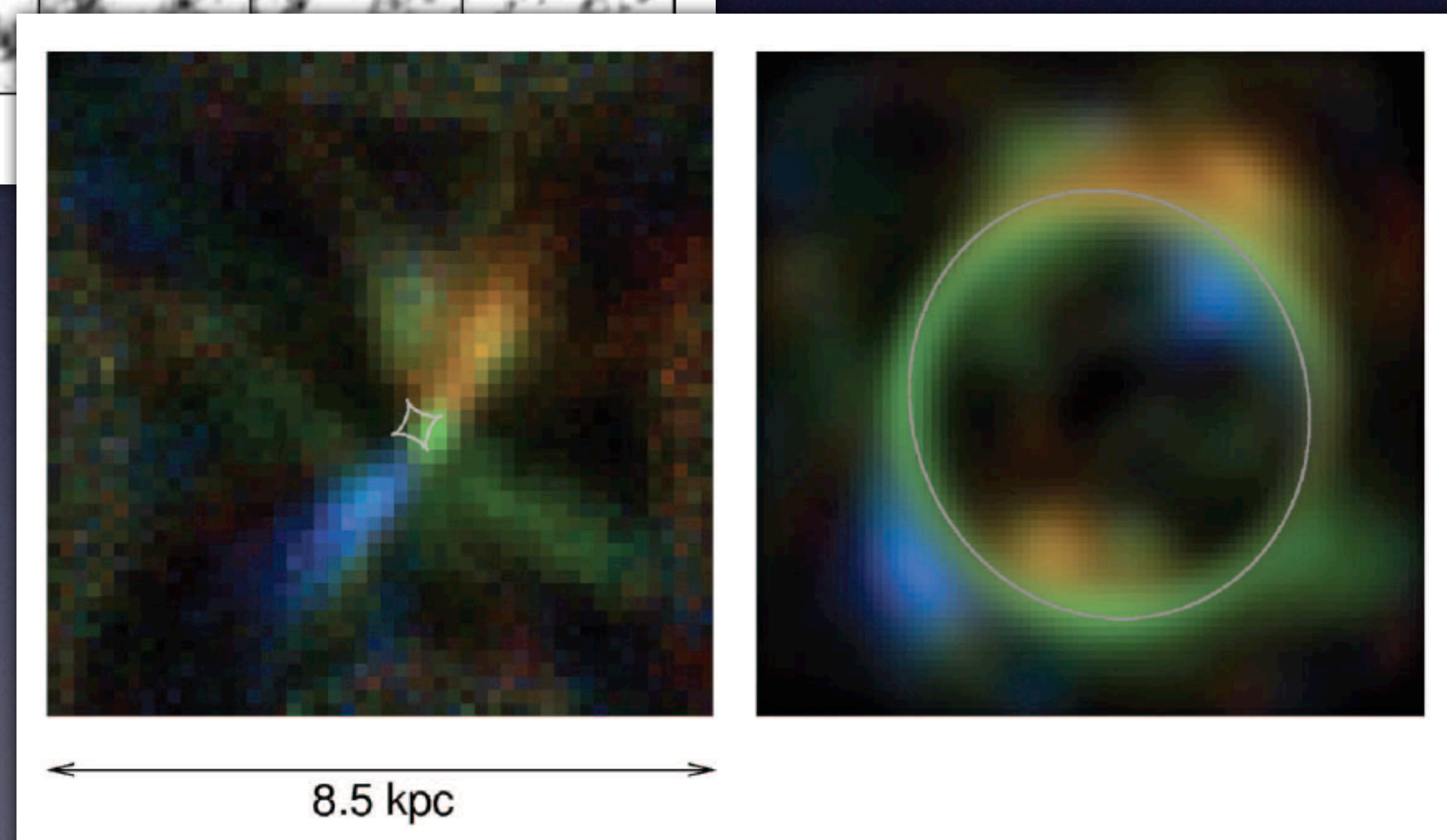
(Wucknitz et al. 2004)

The Magnified Universe



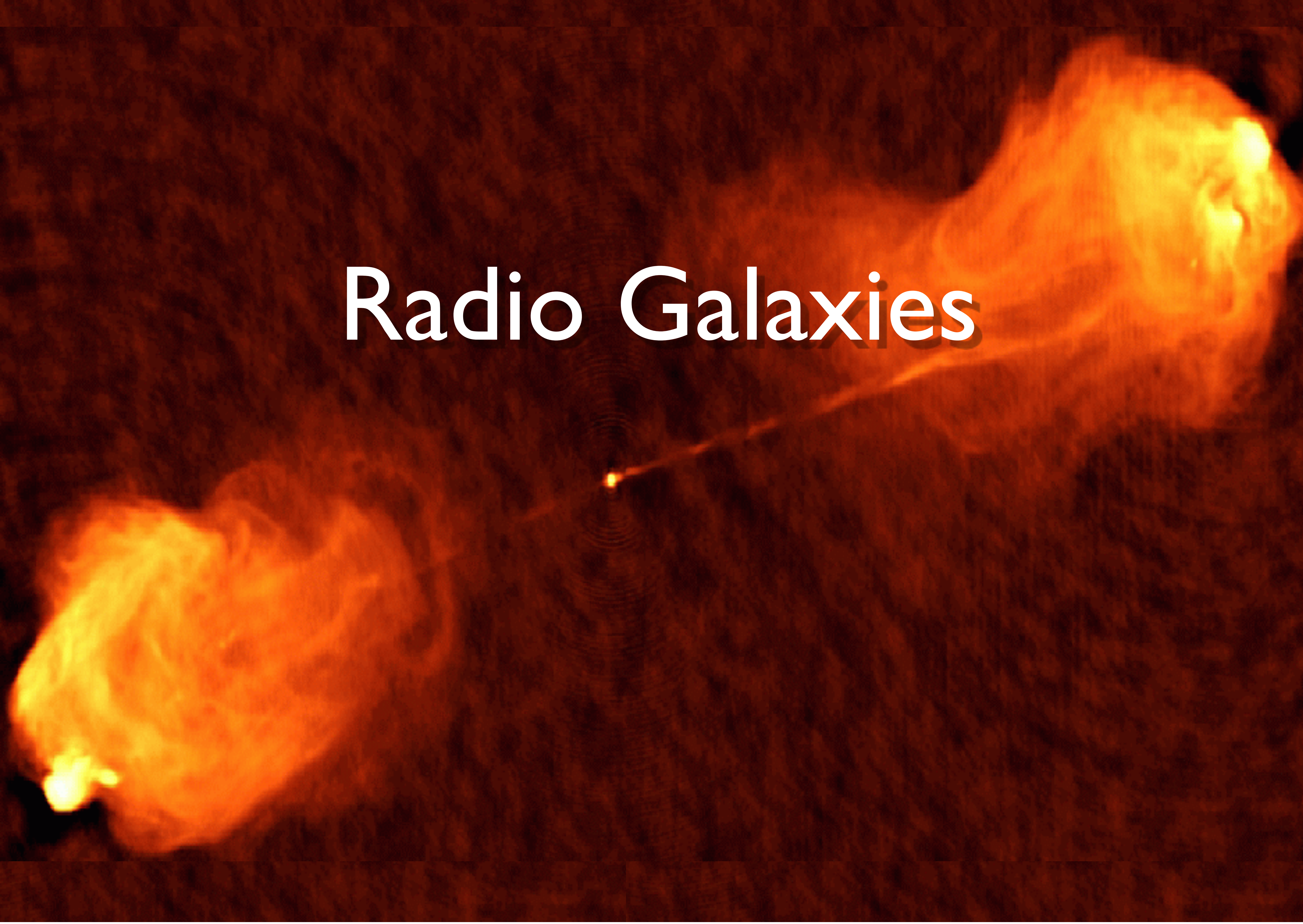
VLA imaging of CO (2-1) molecular gas at 0.3 arcsec resolution.

Lens modelling detects a rotating disk of gas around a z = 4.12 quasar.



(Riechers et al. 2008)

Radio Galaxies



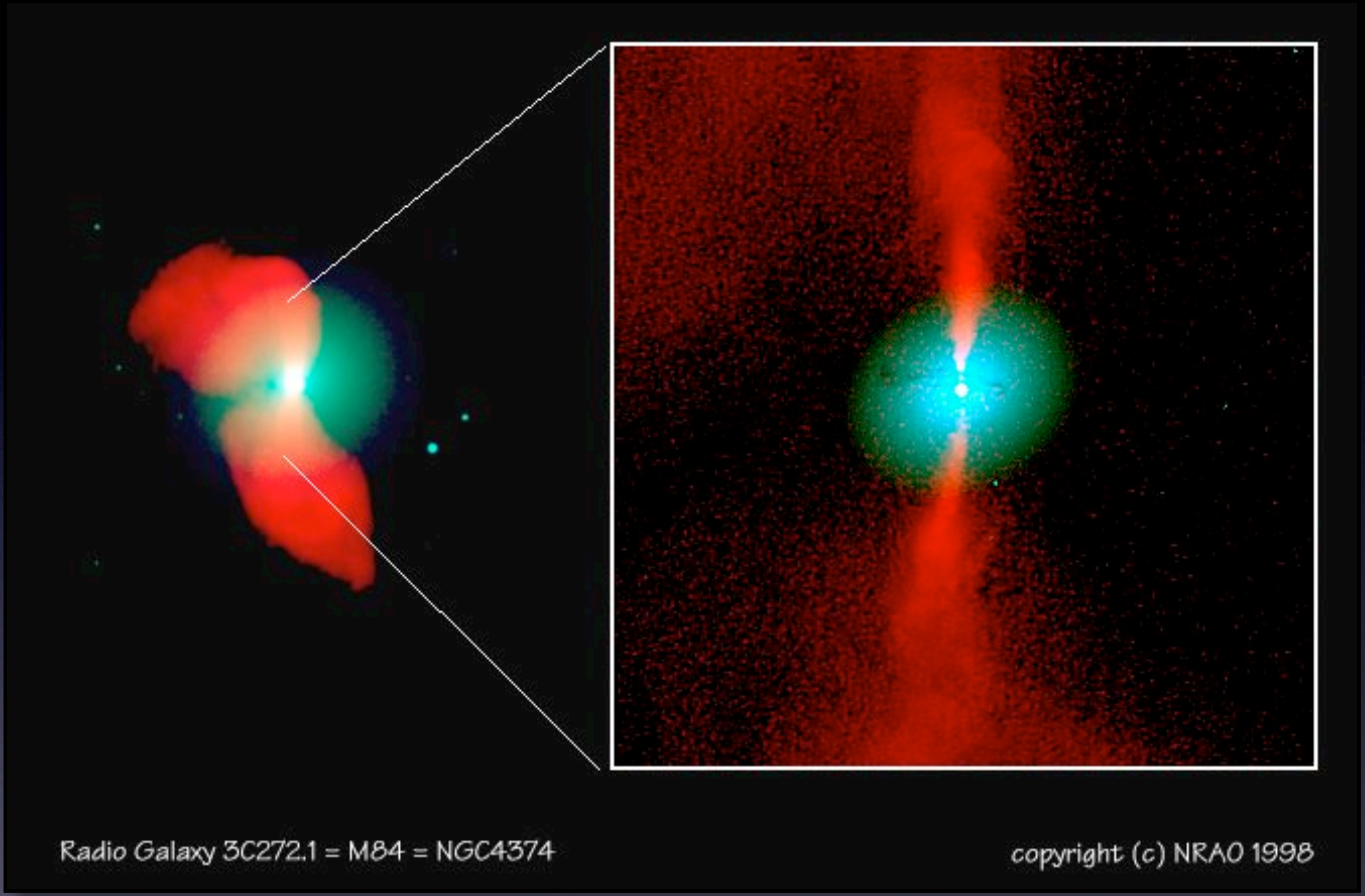
AGN Terminology

- Supermassive Black Hole (SMBH)
- Active Galactic Nucleus (AGN)
  - Technically any accreting SMBH, but generally used for low-luminosity (or similarly low-accretion rate)
- Quasar - short for quasi-stellar radio source
  - Usually luminous AGN (>1043-44 erg/s), regardless of radio emission (a better name is quasi-stellar object or QSO)
- Standard Review Papers
  - Canonical Paradigm: Antonucci 1993 (Radio-quiet AGN); Urry & Padovani 1995 (Radio-loud AGN)
  - More Recently: Ho et al. (2008); Antonucci (2011); Elitzur (2012)
  - Also see Boroson & Green (1992); Elvis (2000); Richards et al. (2011)

The Radio Galaxy Zoo

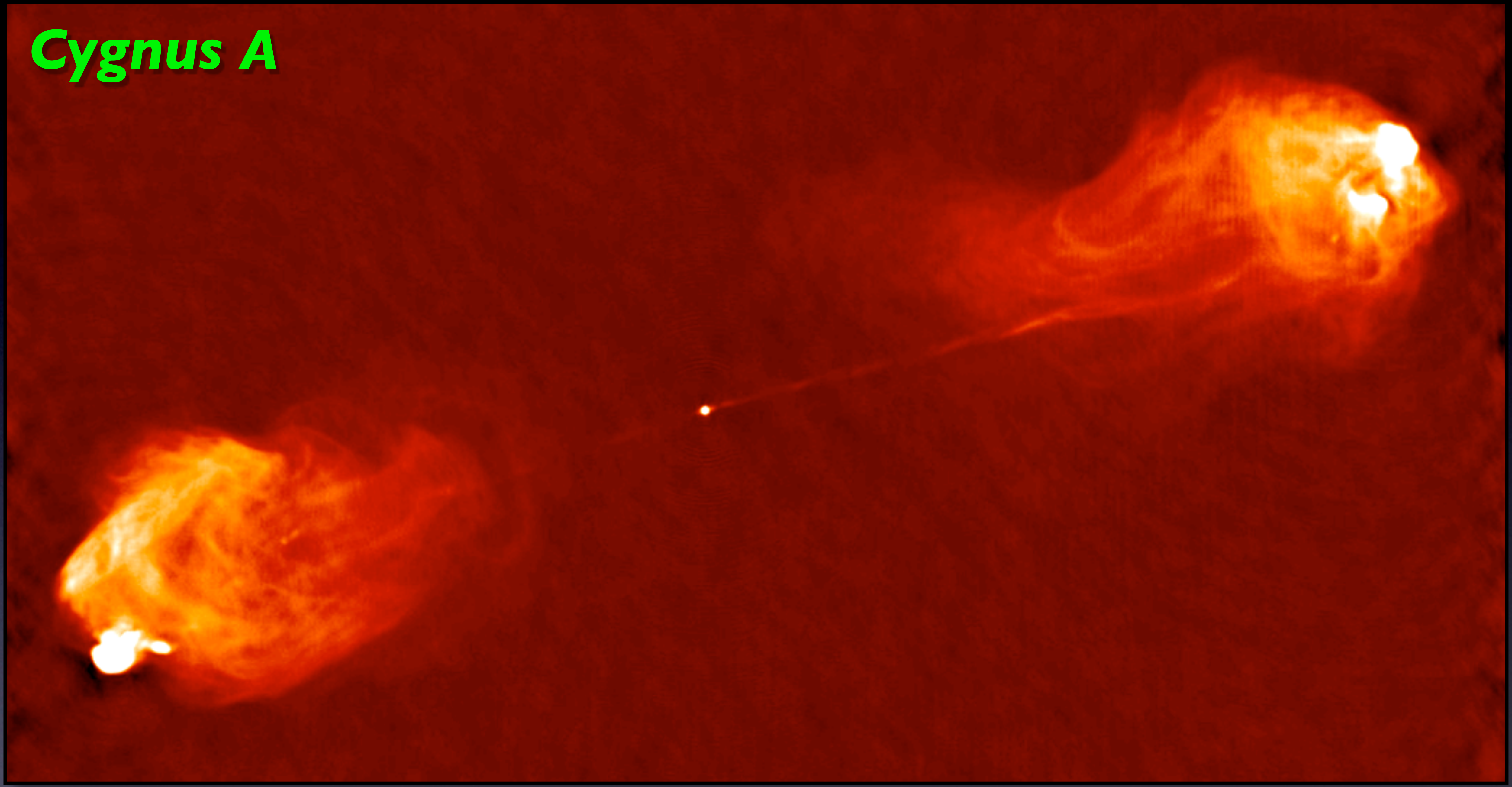
- **Radio Galaxies**
  - **Strong extended radio emission but rather weak nucleus. Can display either narrow optical emission lines (NLRG) or broad optical emission lines (BLRG)**
- **Radio Loud Quasars**
  - **Strong extended radio emission *and* a strong/variable nucleus showing broad optical emission lines**
- **Blazars**
  - **Strong and variable emission across the whole spectrum; no emission lines; highly polarized, nonthermally dominated**

Faranoff-Riley Type I & II



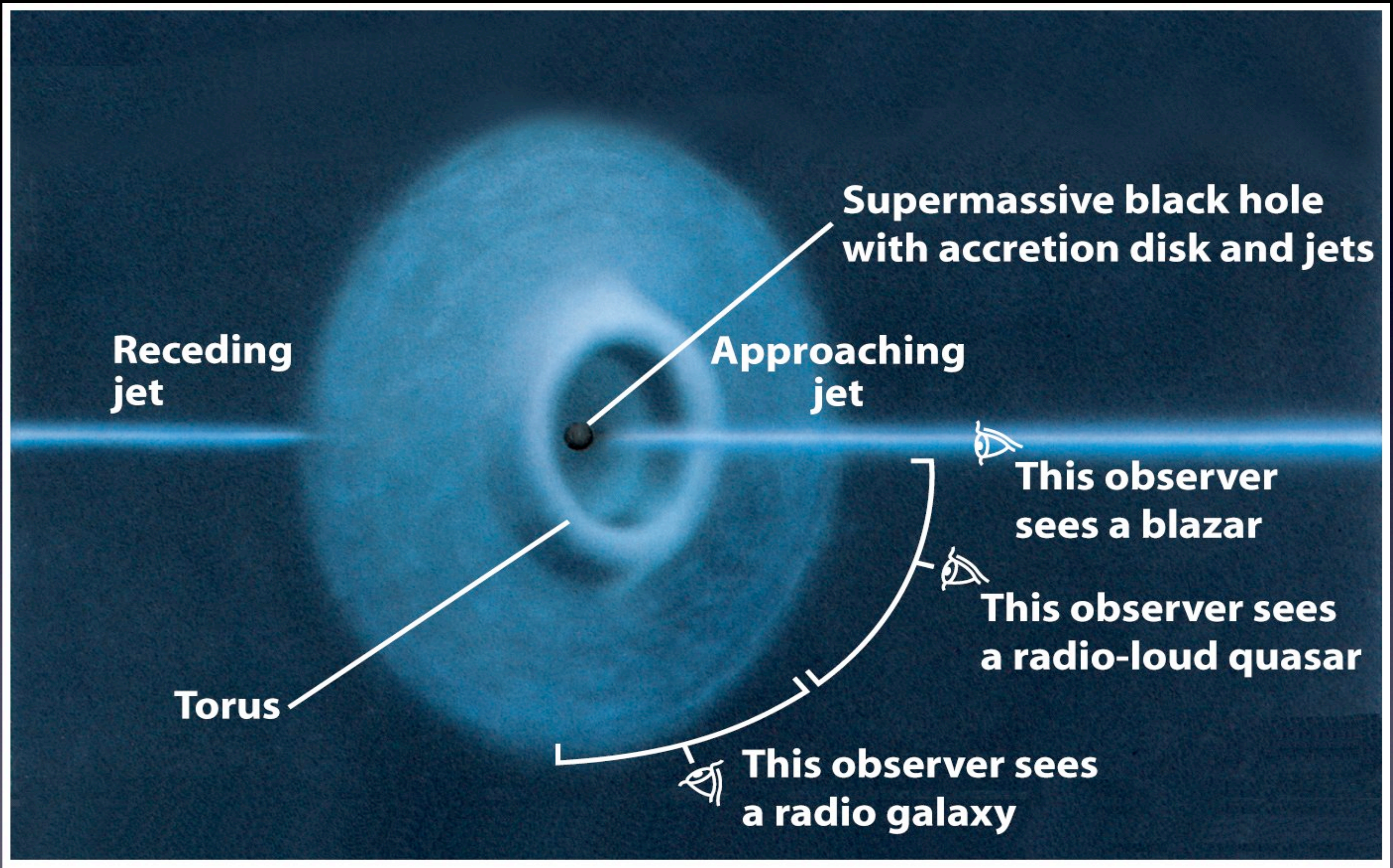
⇒ *FR-I : low power systems that are bright in the center and then fade off at the edges, i.e., "edge darkened". Look like smoke-stacks.*

Faranoff-Riley Type I & II



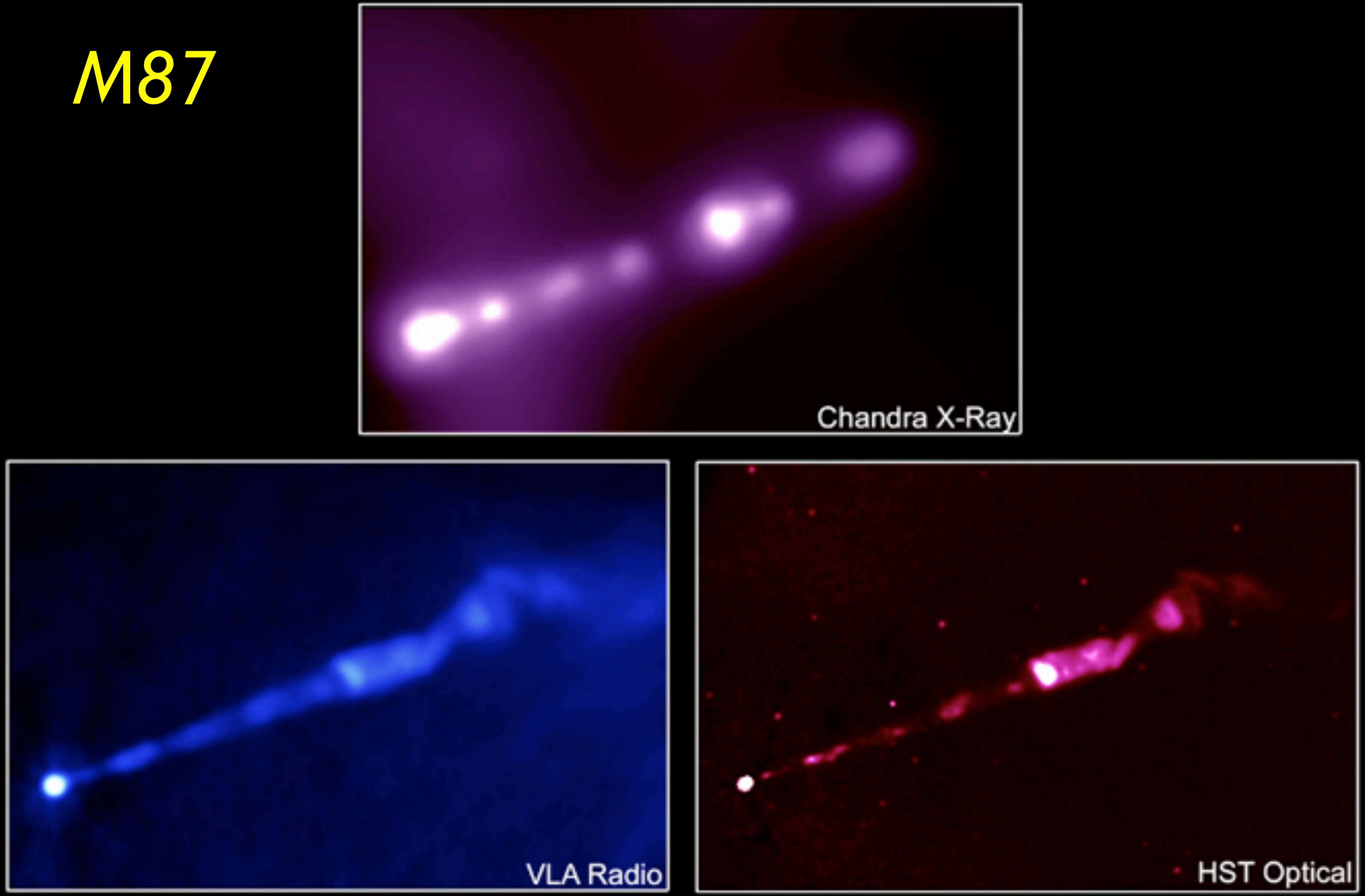
⇒ *FR-II : high power systems that brighten at the edges (edge-brightened). Often look like directed "explosions".*

AGN Unification Schemes

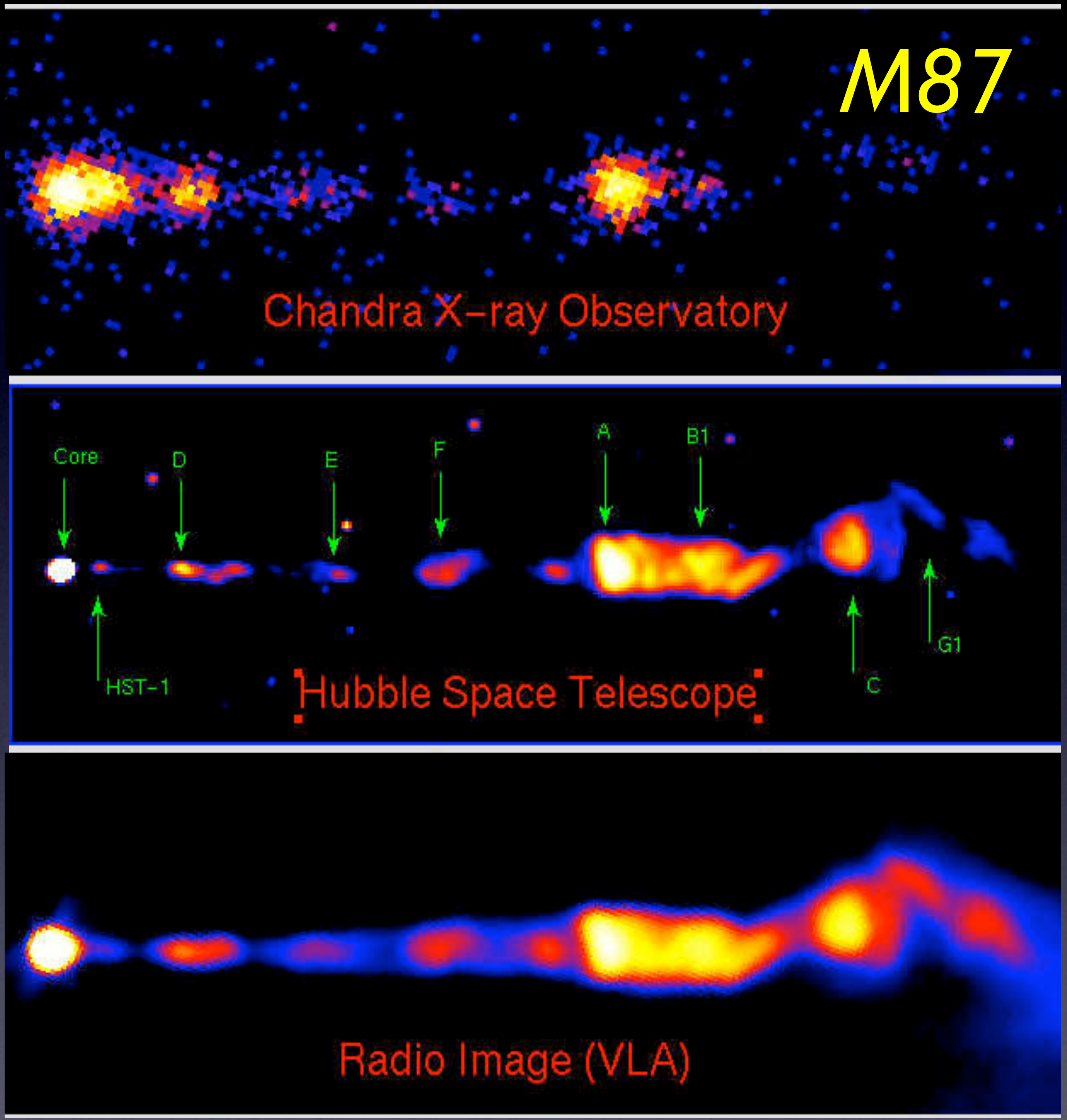


Jet Propagation

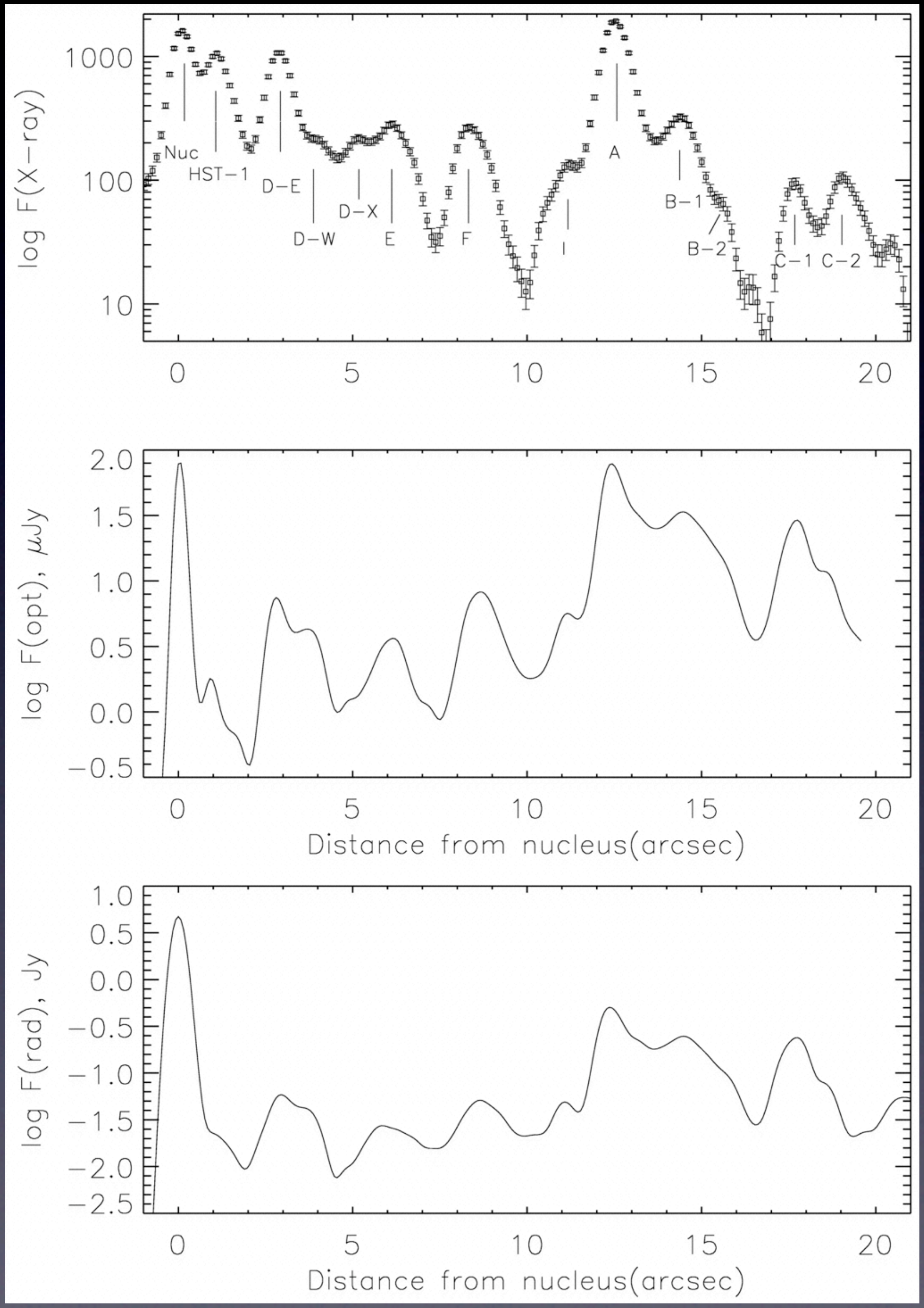
M87



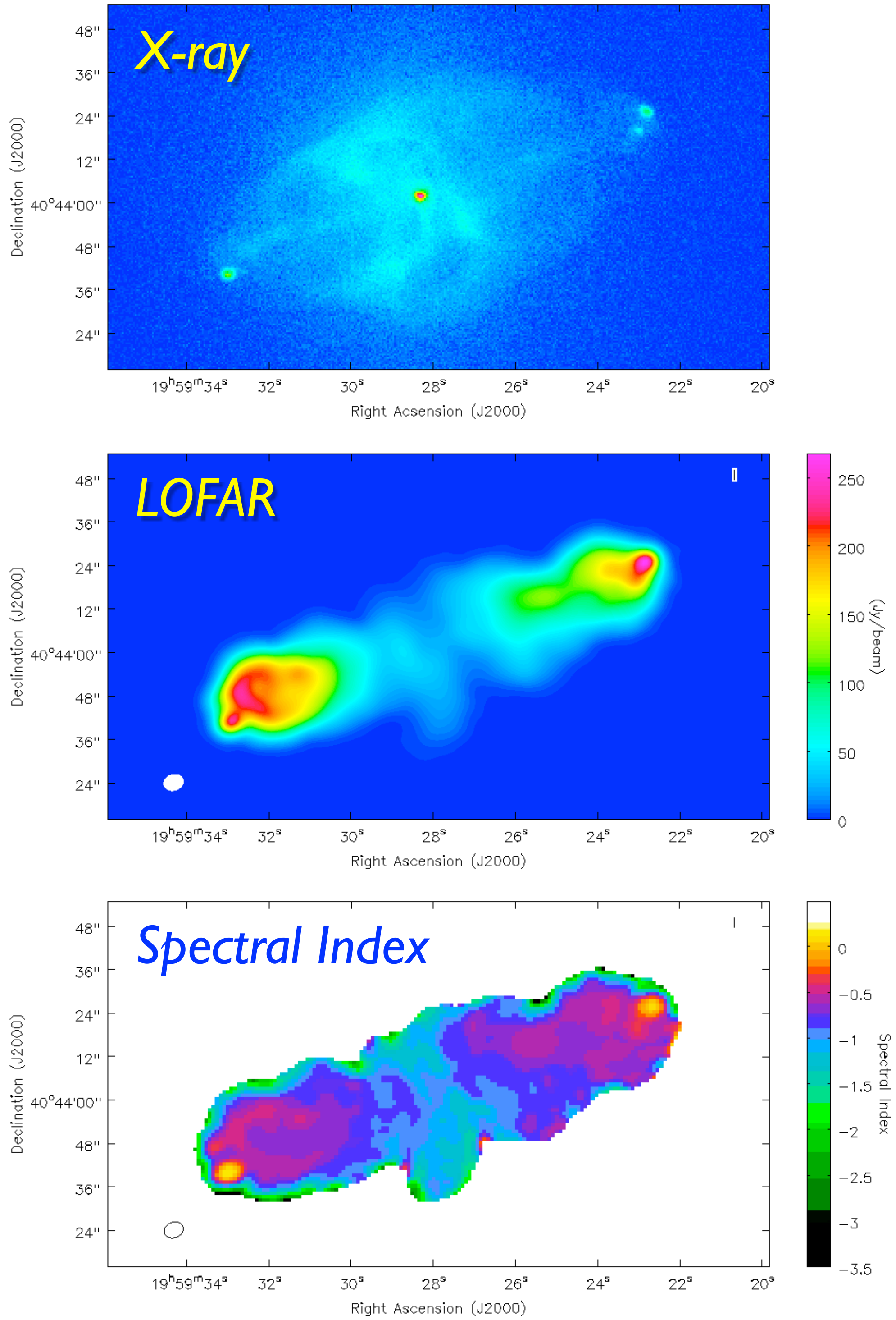
Jet Propagation



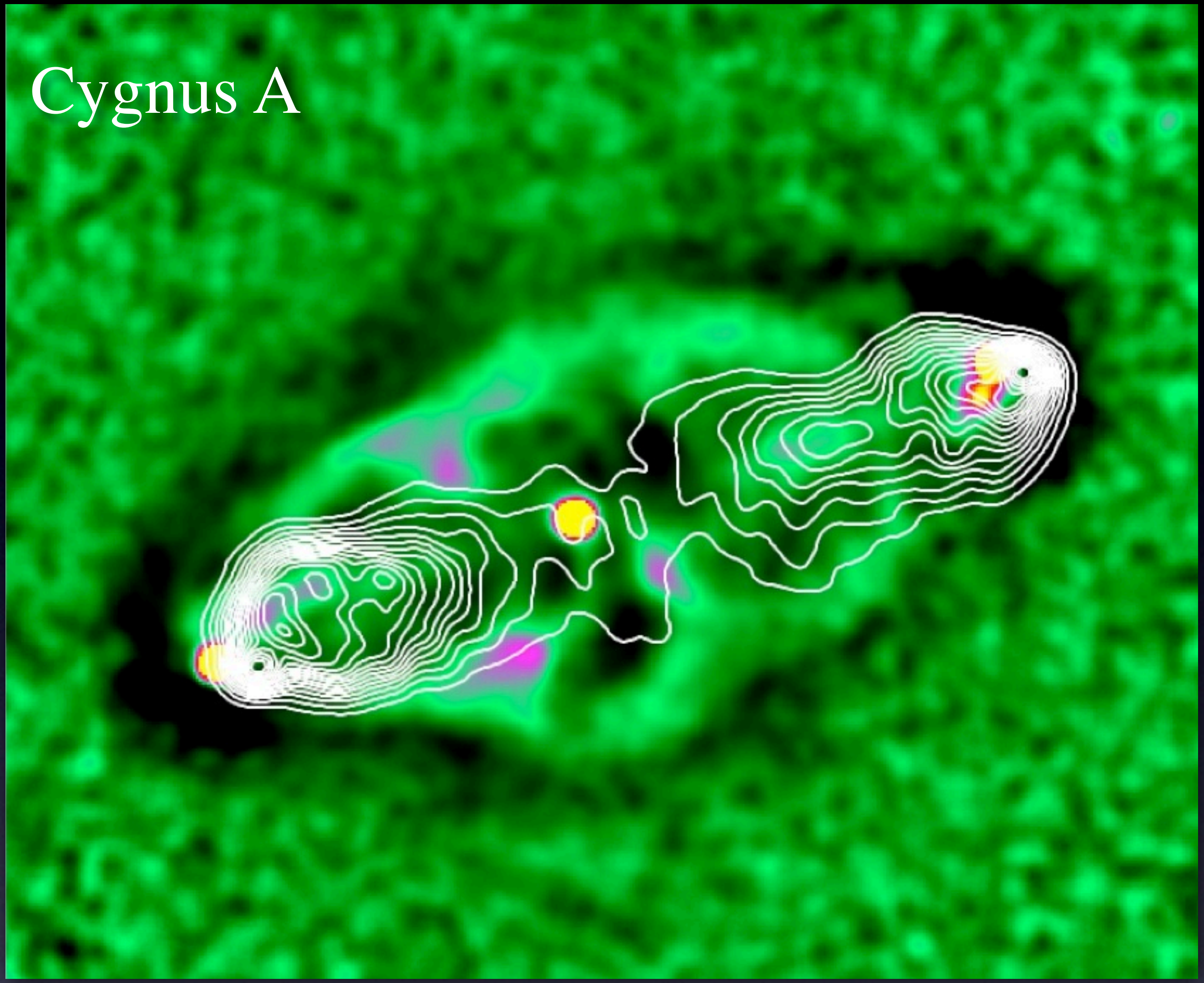
Perlman & Wilson (2005)



Radio Source Diagnostics



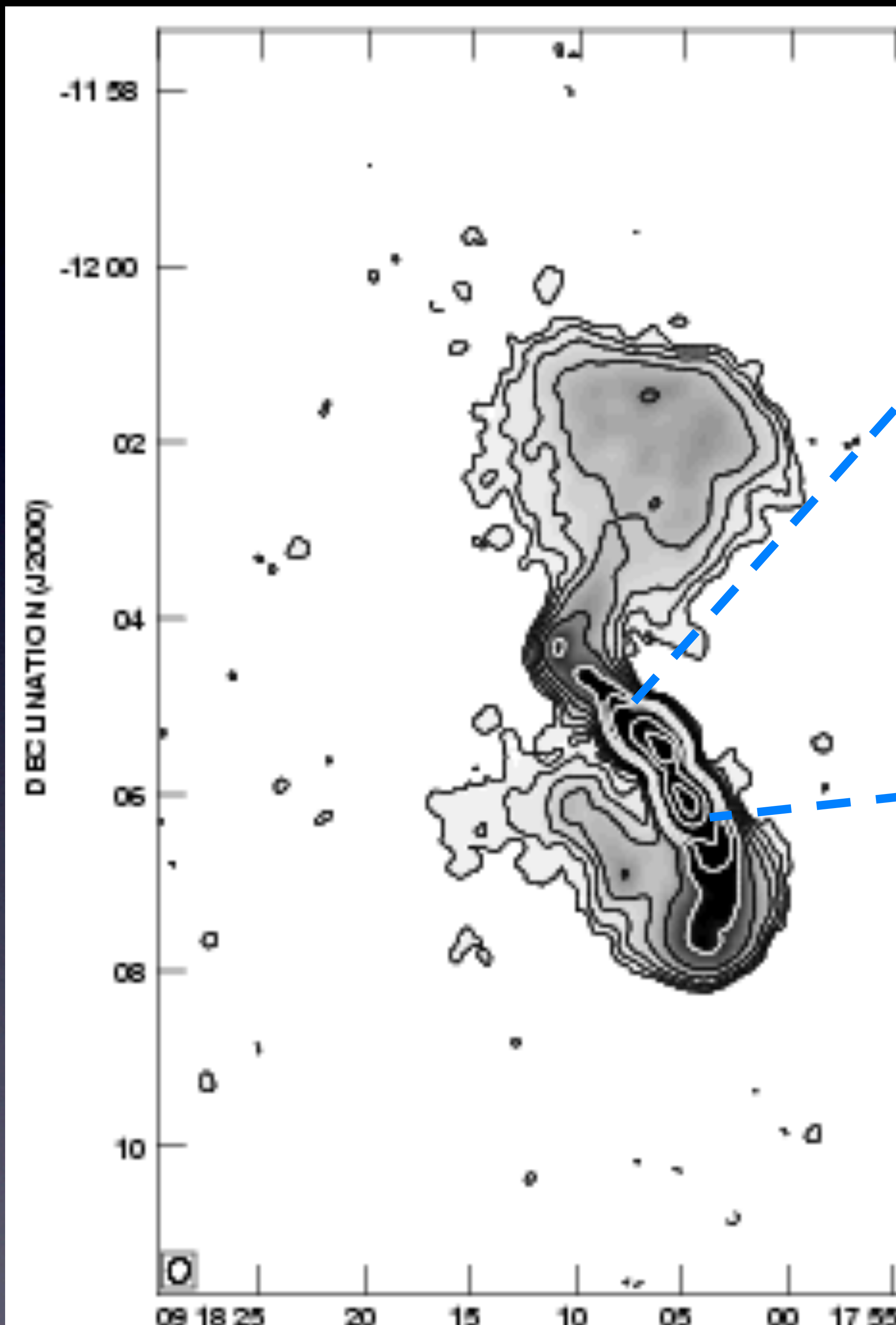
McKean et al. (2013)



Wise et al. (2013)

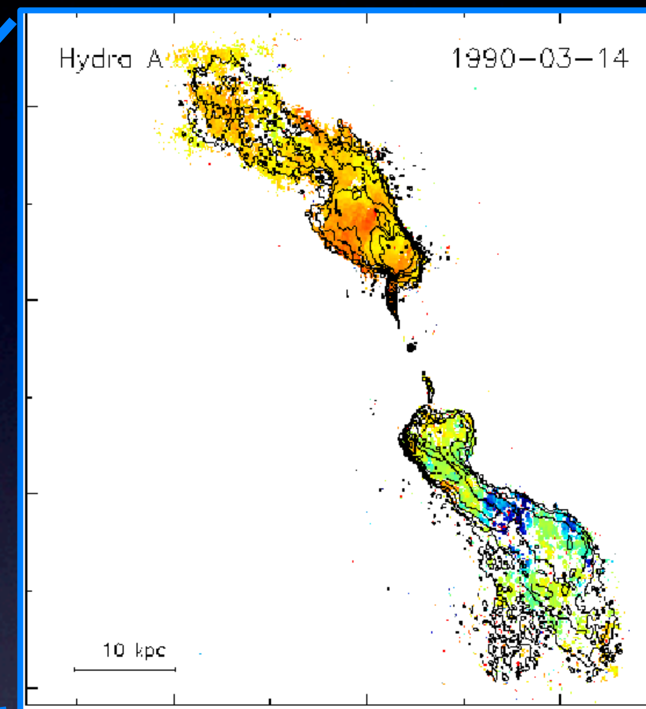
- Spectral index maps over broad frequency range
- Determine spectral ageing of e- population
- Determine jet and lobe particle content
- Constrain strength and topology of B fields

Radio Galaxies: Outburst Lifecycle



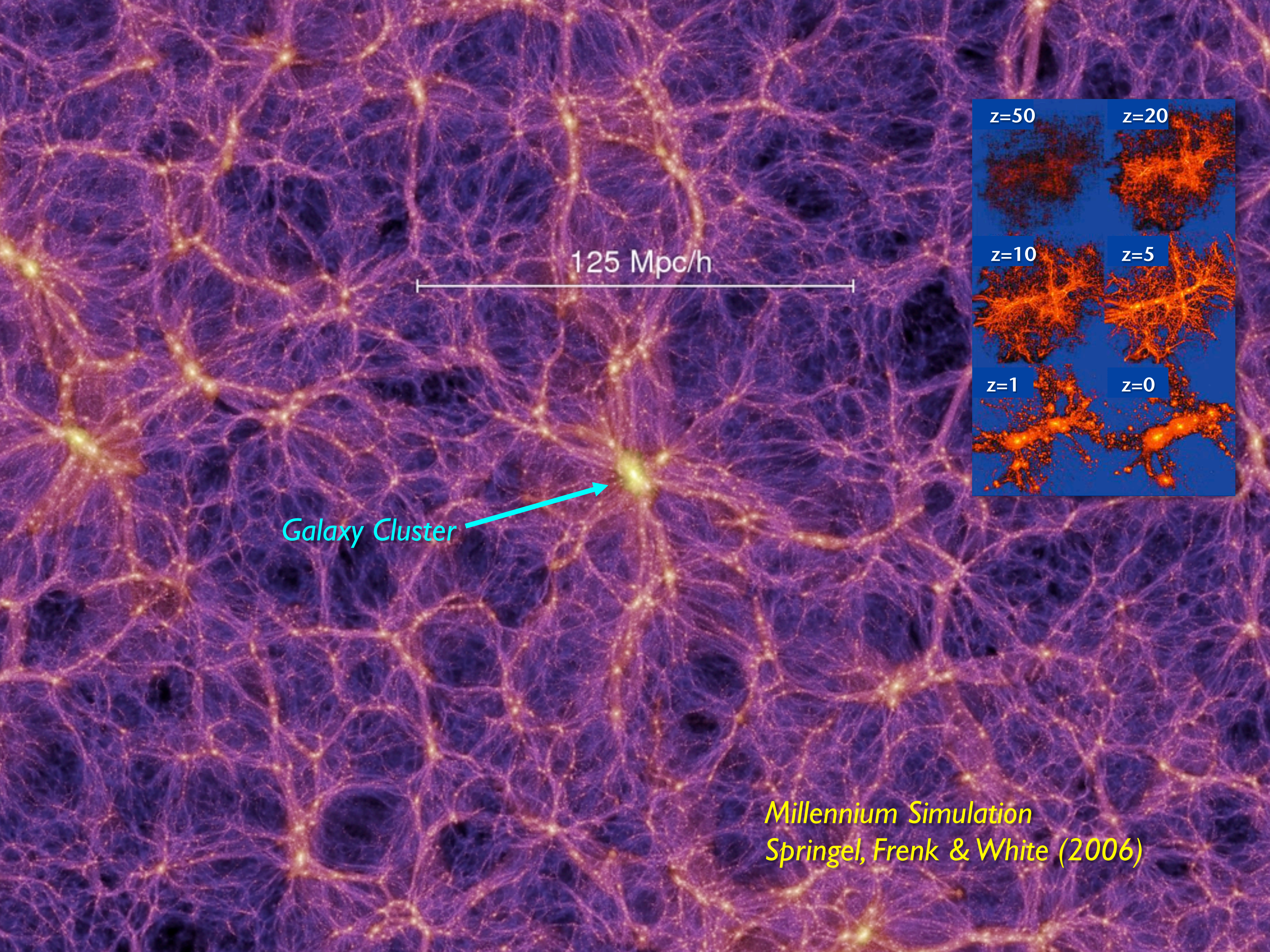
Lane et al. (2004)

- Hydra A at 4500 MHz (inset) shows an FR-I morphology on scales of <1.5' (100 kpc)



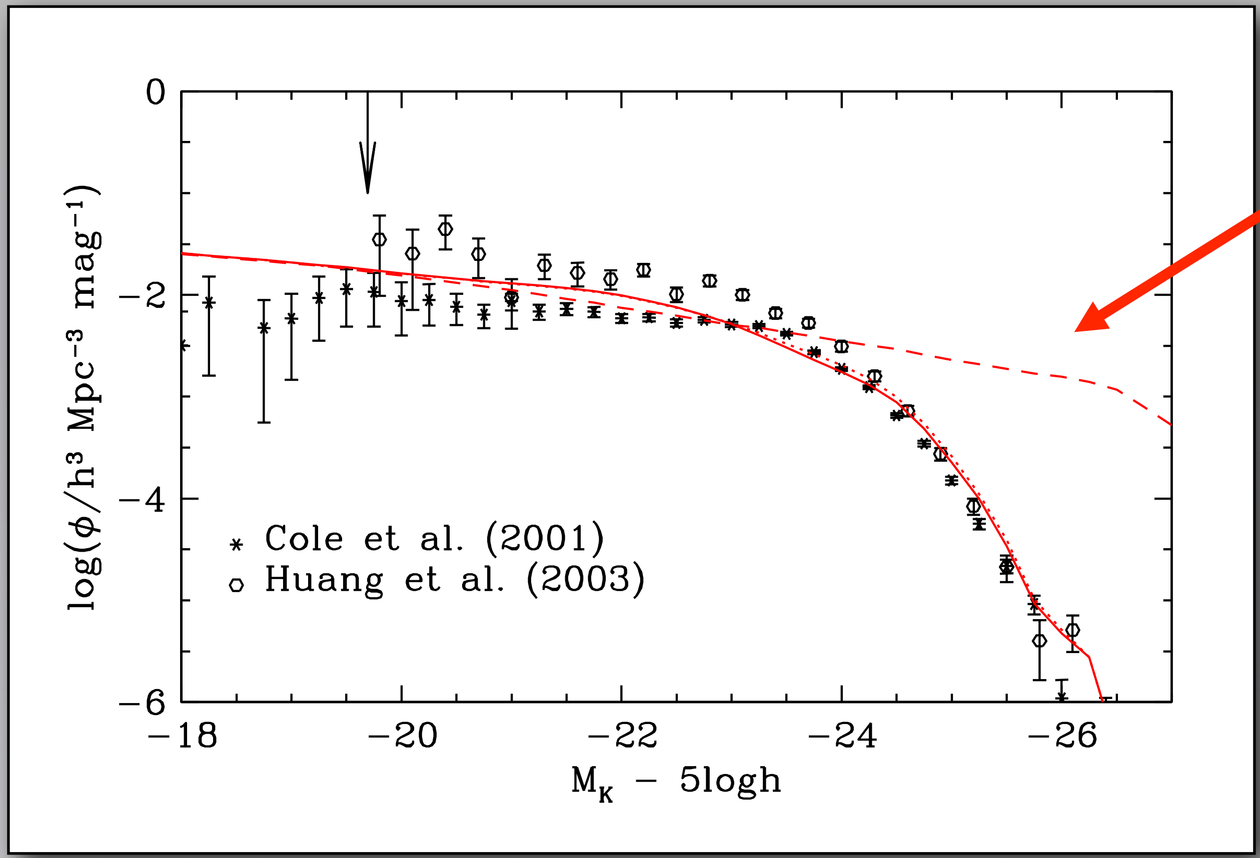
- New 74 and 330 MHz data show Hydra A is > 8' (530 kpc) in extent with large outer lobes surrounding the high frequency source
- Outer lobes have important implications for the radio source lifecycle and energy budget

Clusters of Galaxies

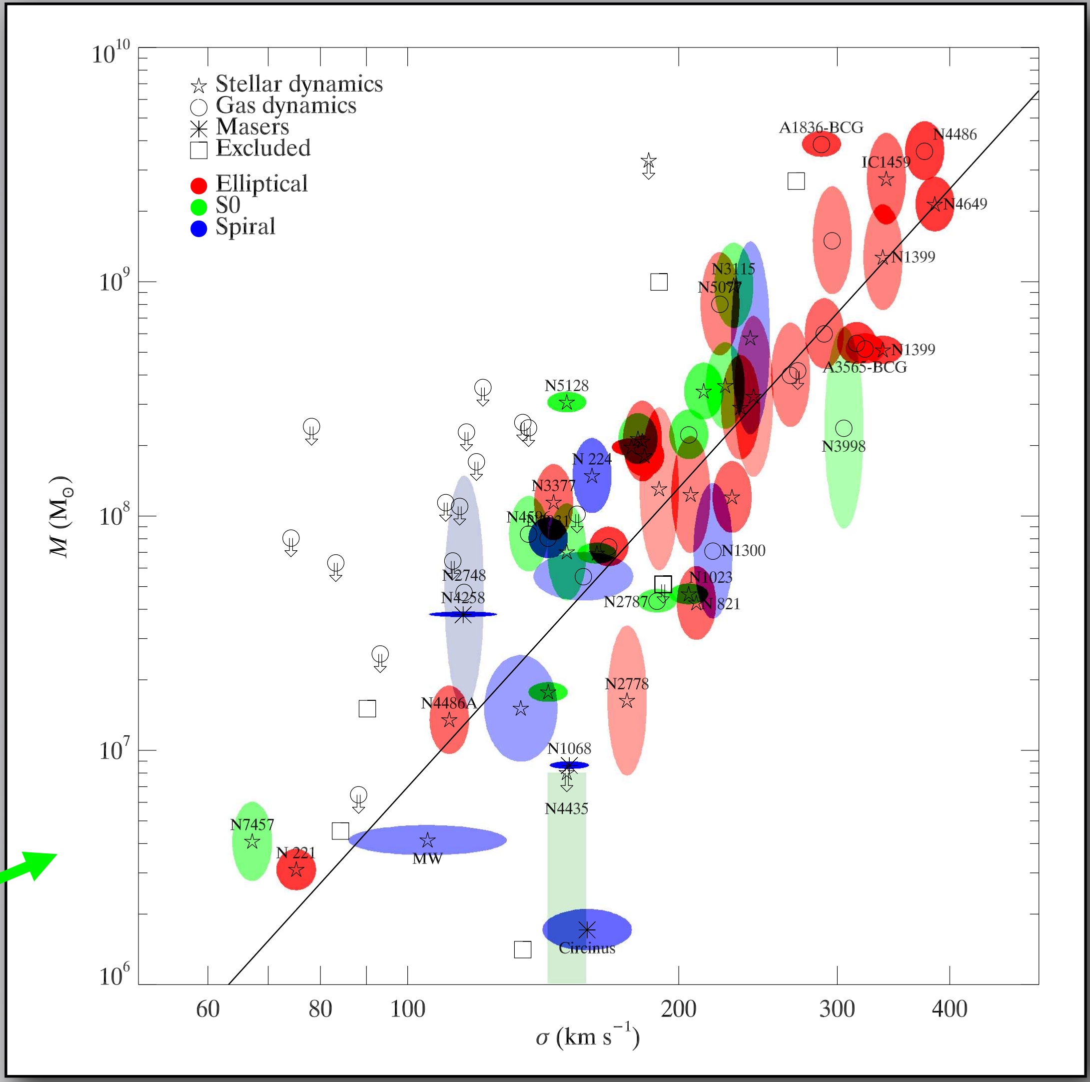

125 Mpc/h
z=50
z=20
z=10
z=5
z=1
z=0
Galaxy Cluster
Millennium Simulation
Springel, Frenk & White (2006)

Evidence for AGN Feedback

Over-predict high-mass systems
Missing physics, suppressed cooling



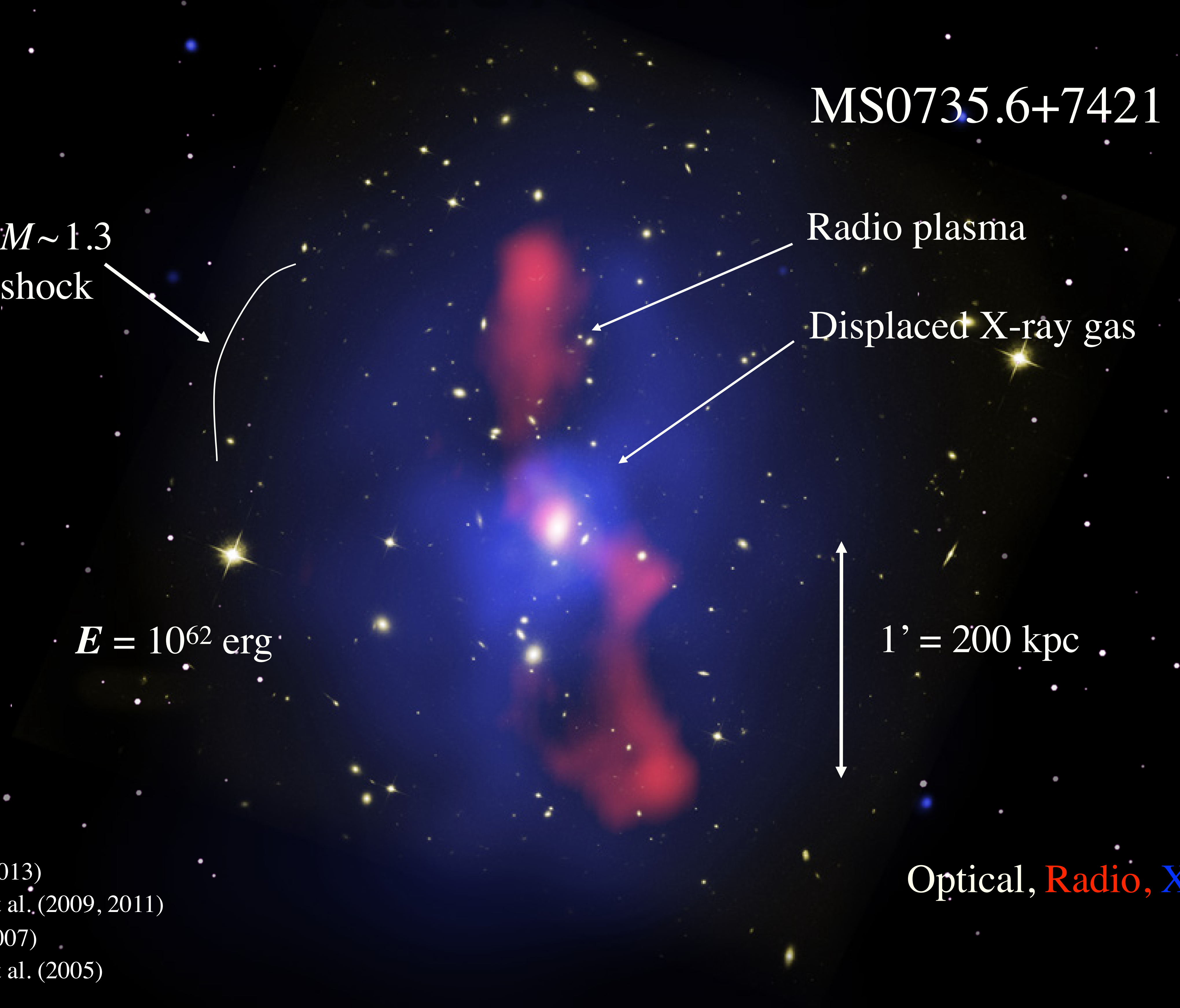
Bower et al. (2006)



Gültekin et al. (2009)

Connection between BH growth and Bulge assembly

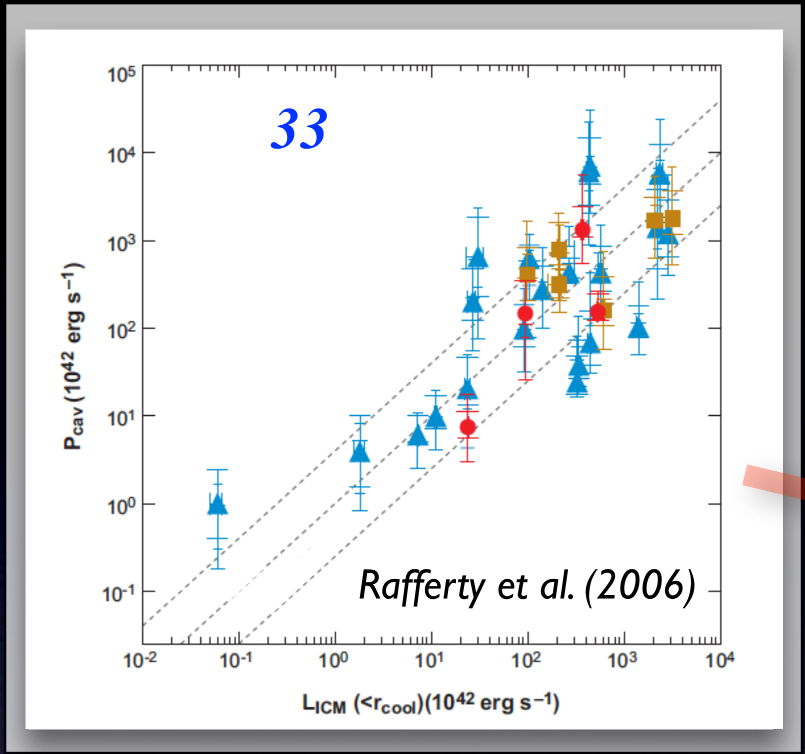
Cluster-scale AGN Outbursts

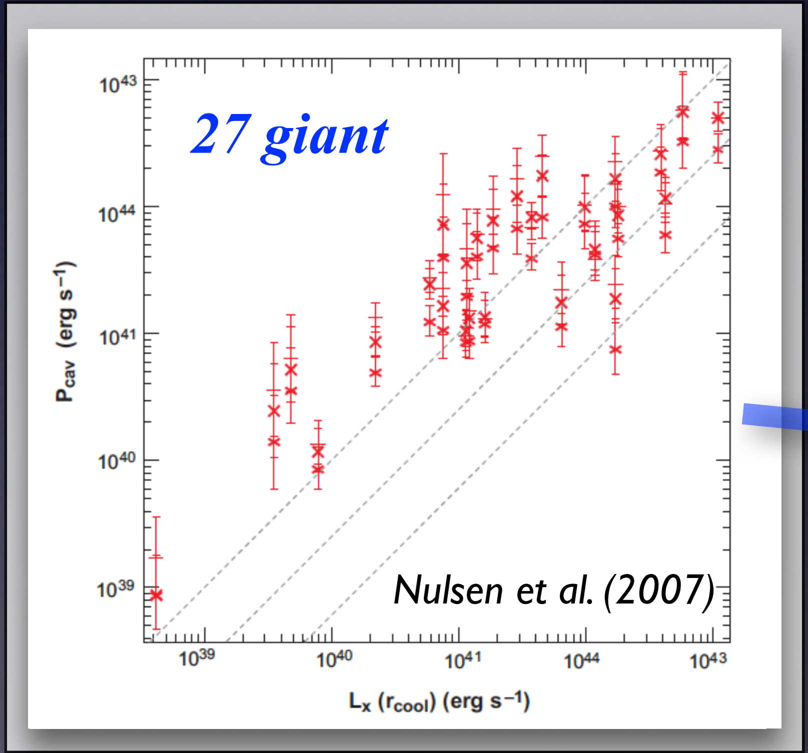


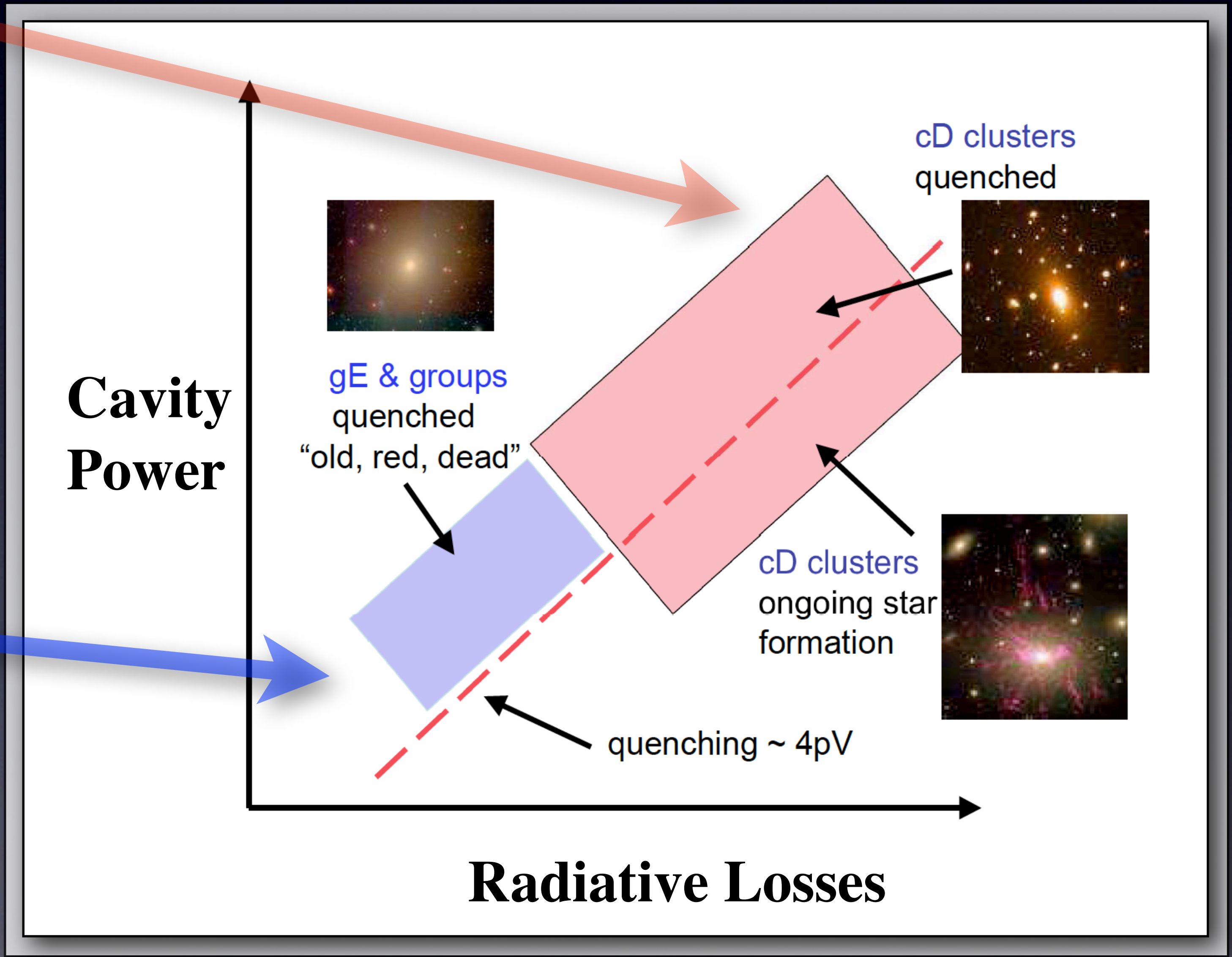
Wise et al. (2013)
McNamara et al. (2009, 2011)
Gitti et al. (2007)
McNamara et al. (2005)

The Feedback Sequence

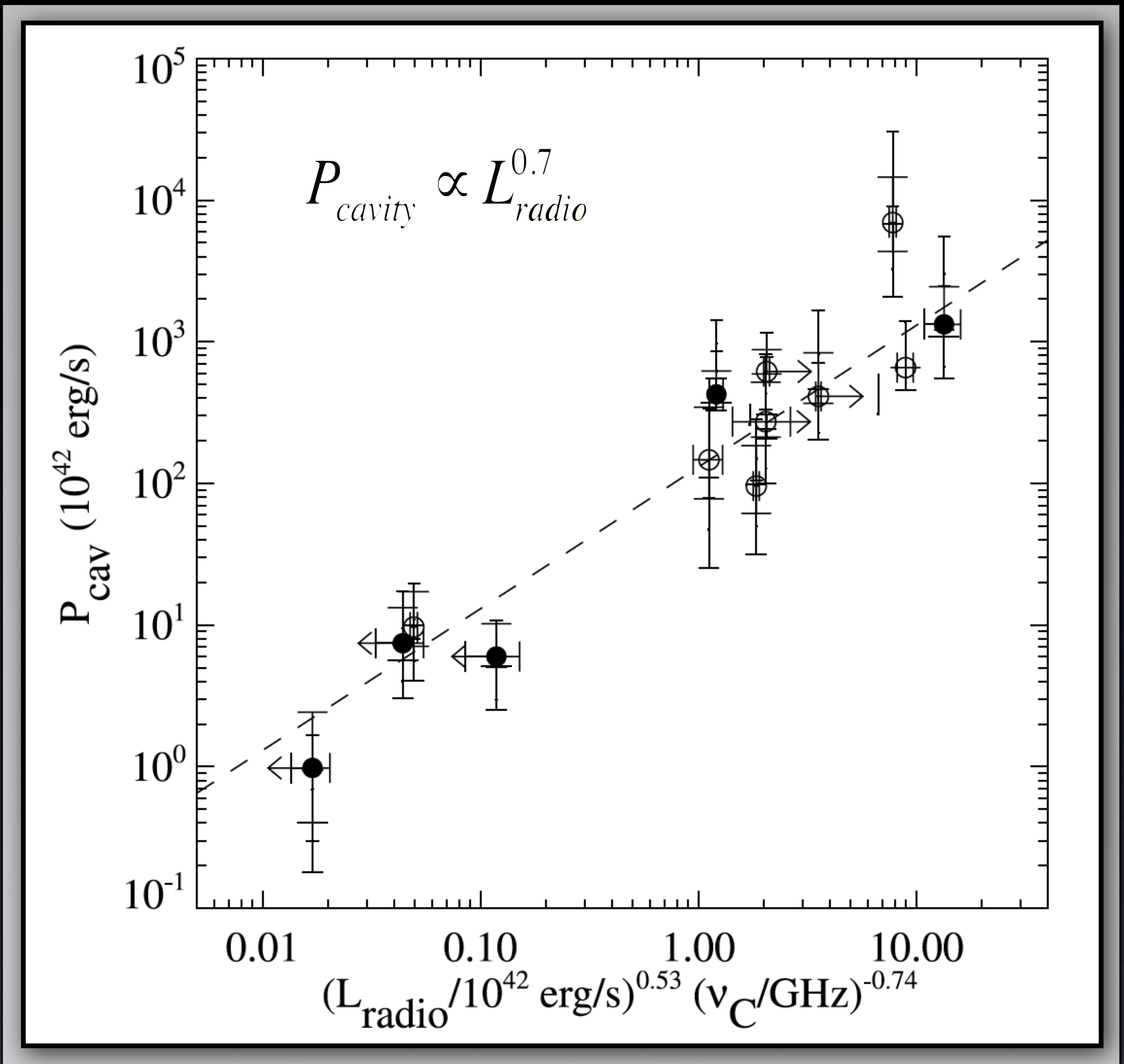
What produces the observed scatter?
How do we extend this to high z?



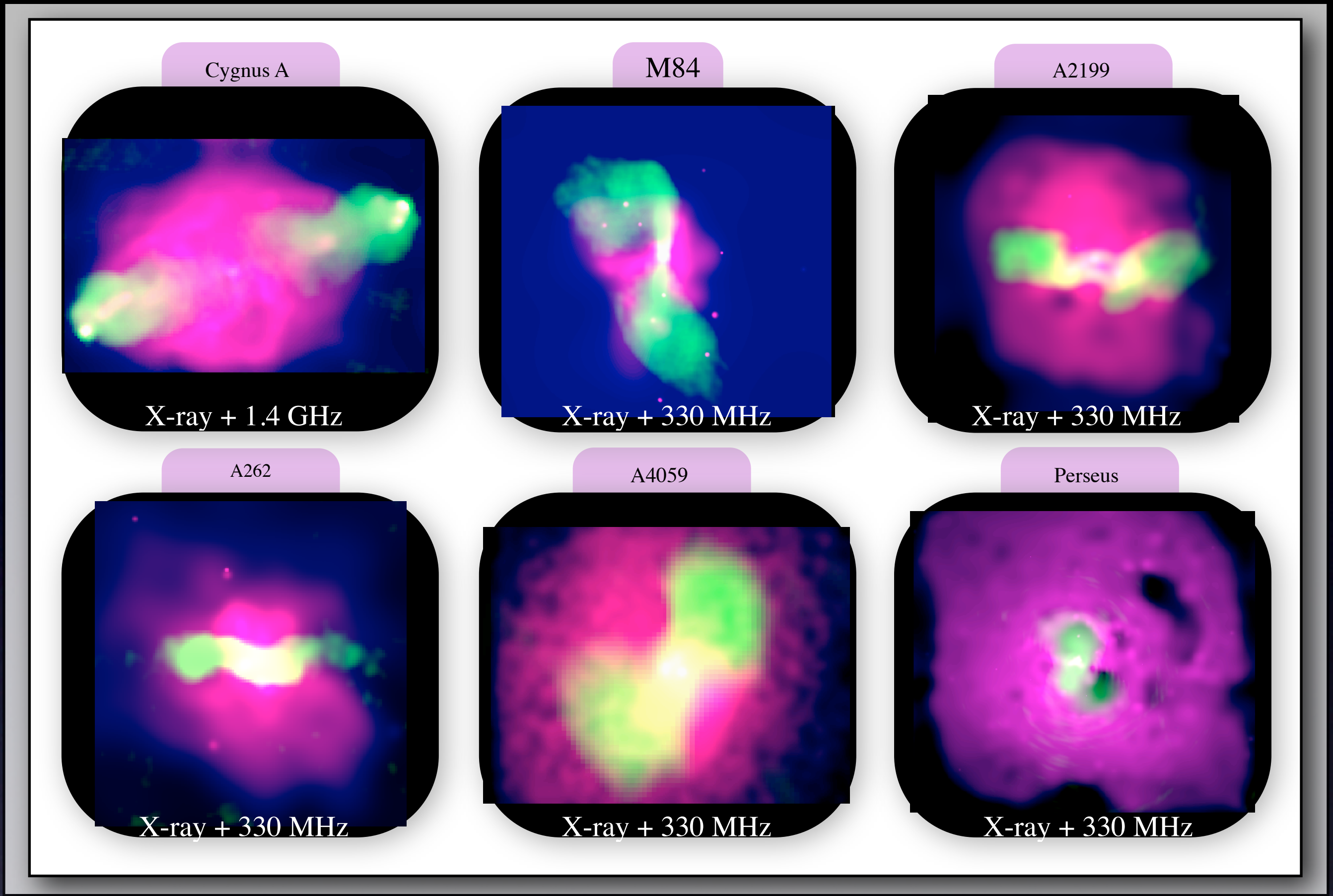




L_{radio} as proxy for P_{cavity}



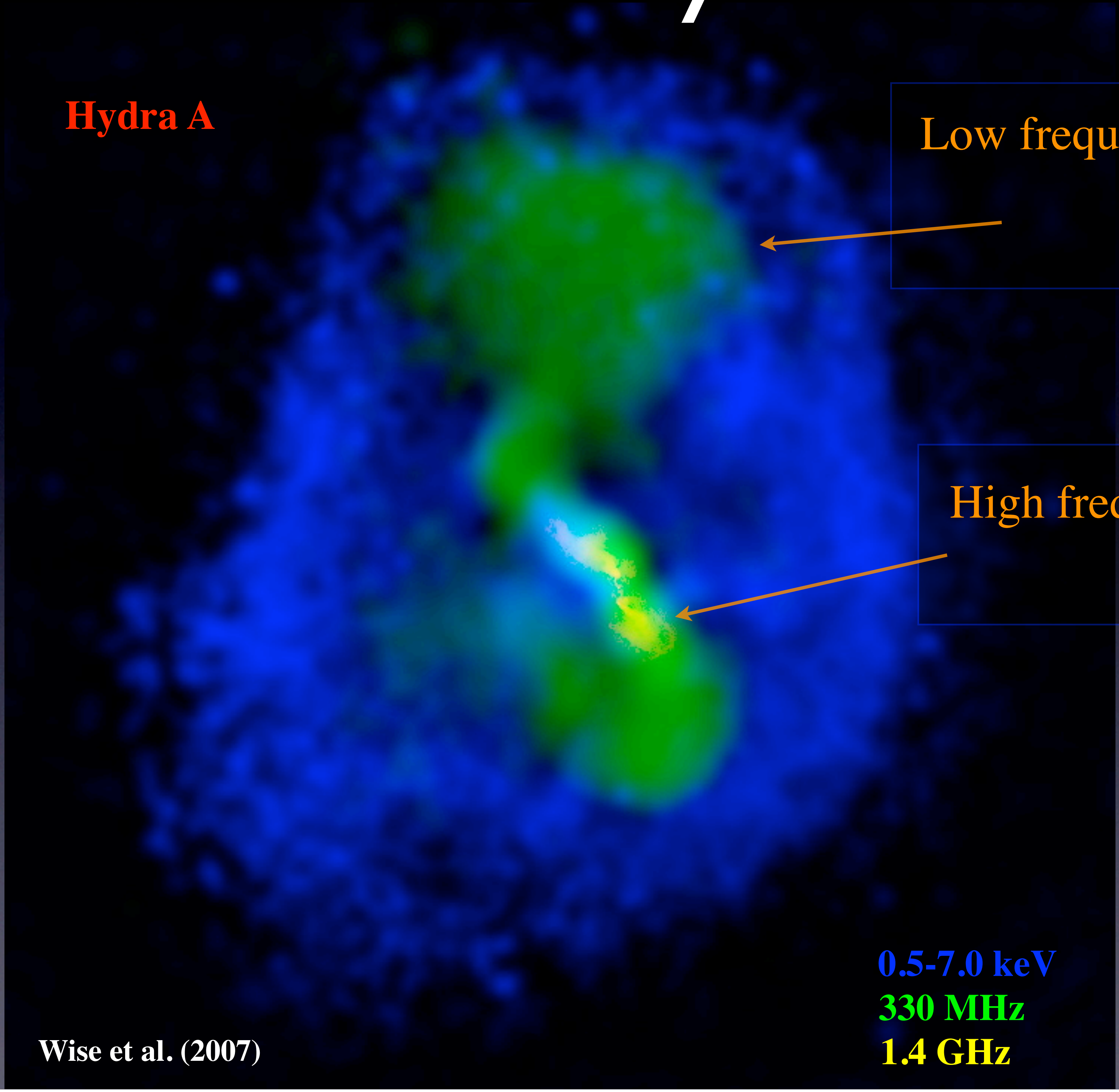
Bîrzan et al. (2008)



- 24 cavity systems from Chandra Archive
- Low to moderate redshift (0.0035 < z < 0.545)
- VLA data: 330 MHz, 1.4, 4.5, and 8.5 GHz
- Combine X-ray + Radio
- Depends on source extent

Calibrate at low-z ⇒ Extrapolate to high z

Trace History of AGN Output



Low frequency ⇒ integrated history
$t > 200$ Myr

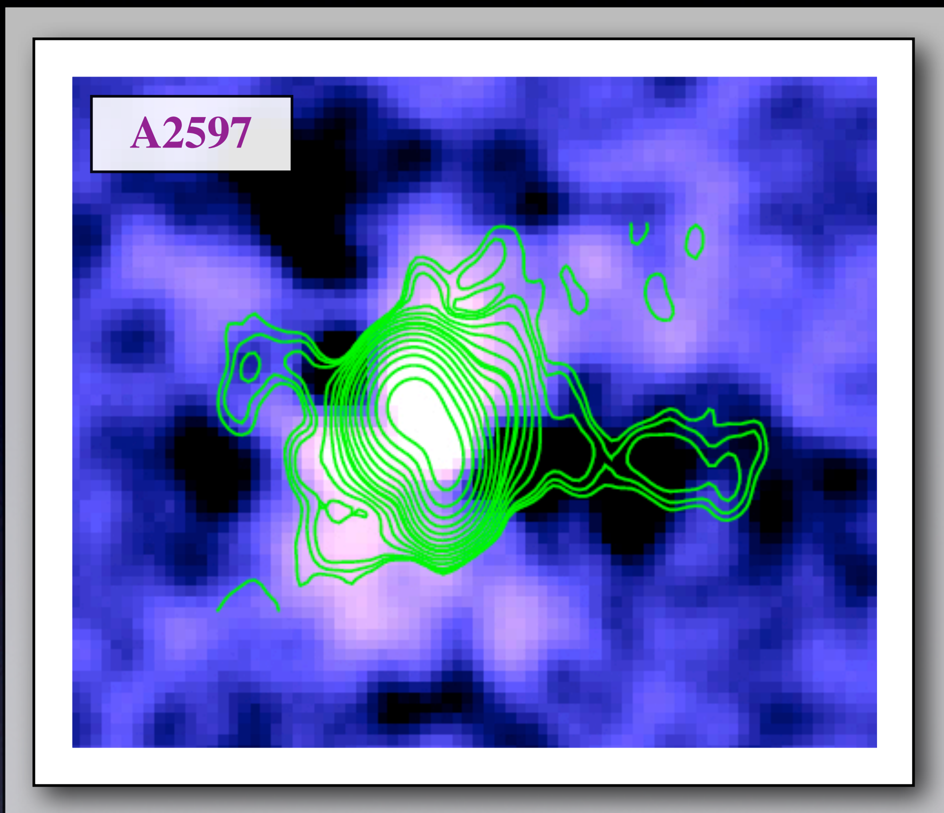
High frequency ⇒ recent activity
$t \sim 50$ Myr

Diffuse emission

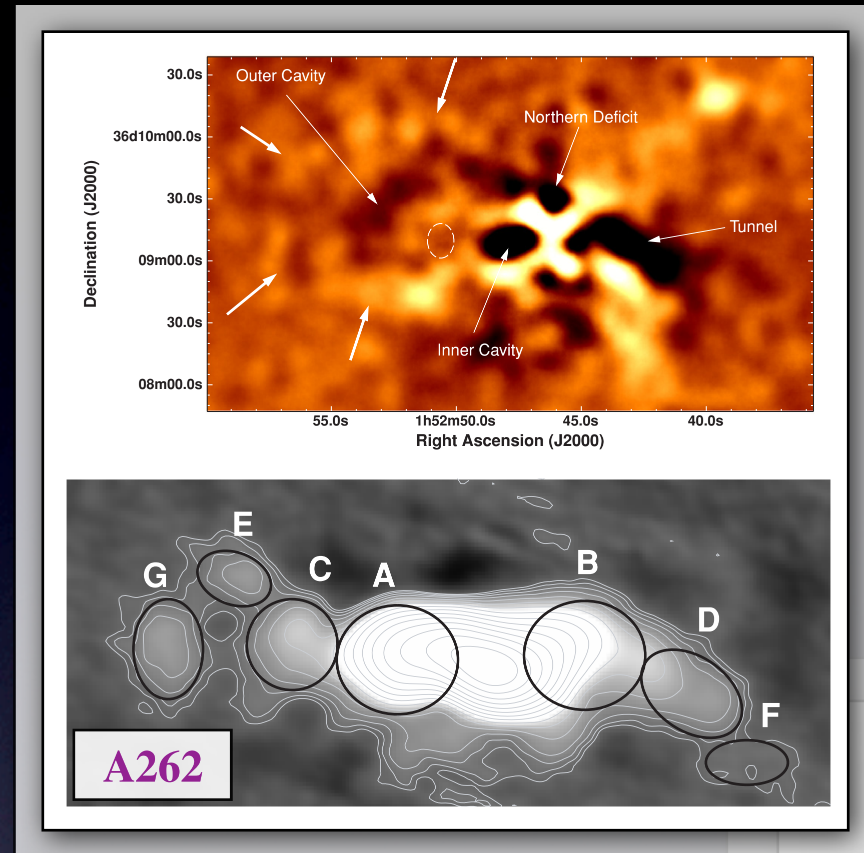
Steep spectrum

Traces integrated AGN output

AGN Duty Cycle and SMBH Growth

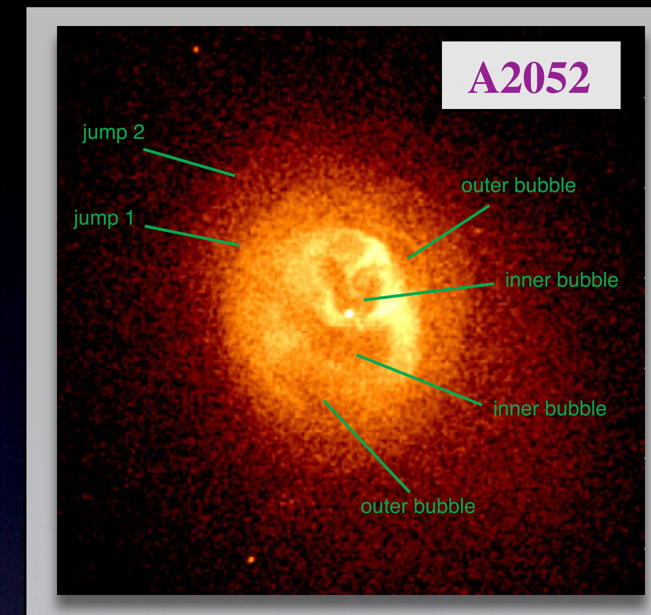


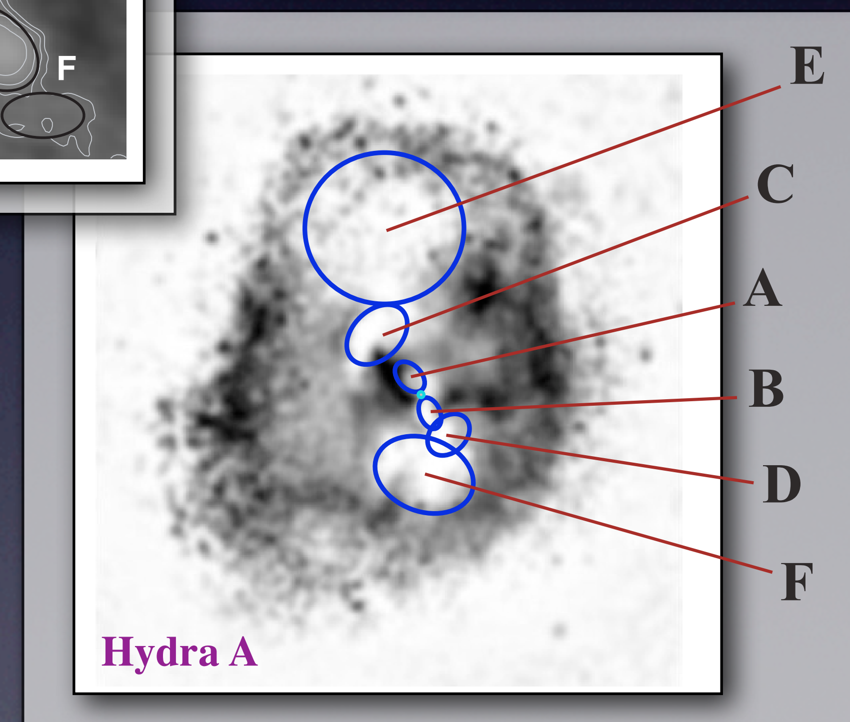
Clarke et al. (2007)



Clarke et al. (2009)

Blanton et al. (2007)



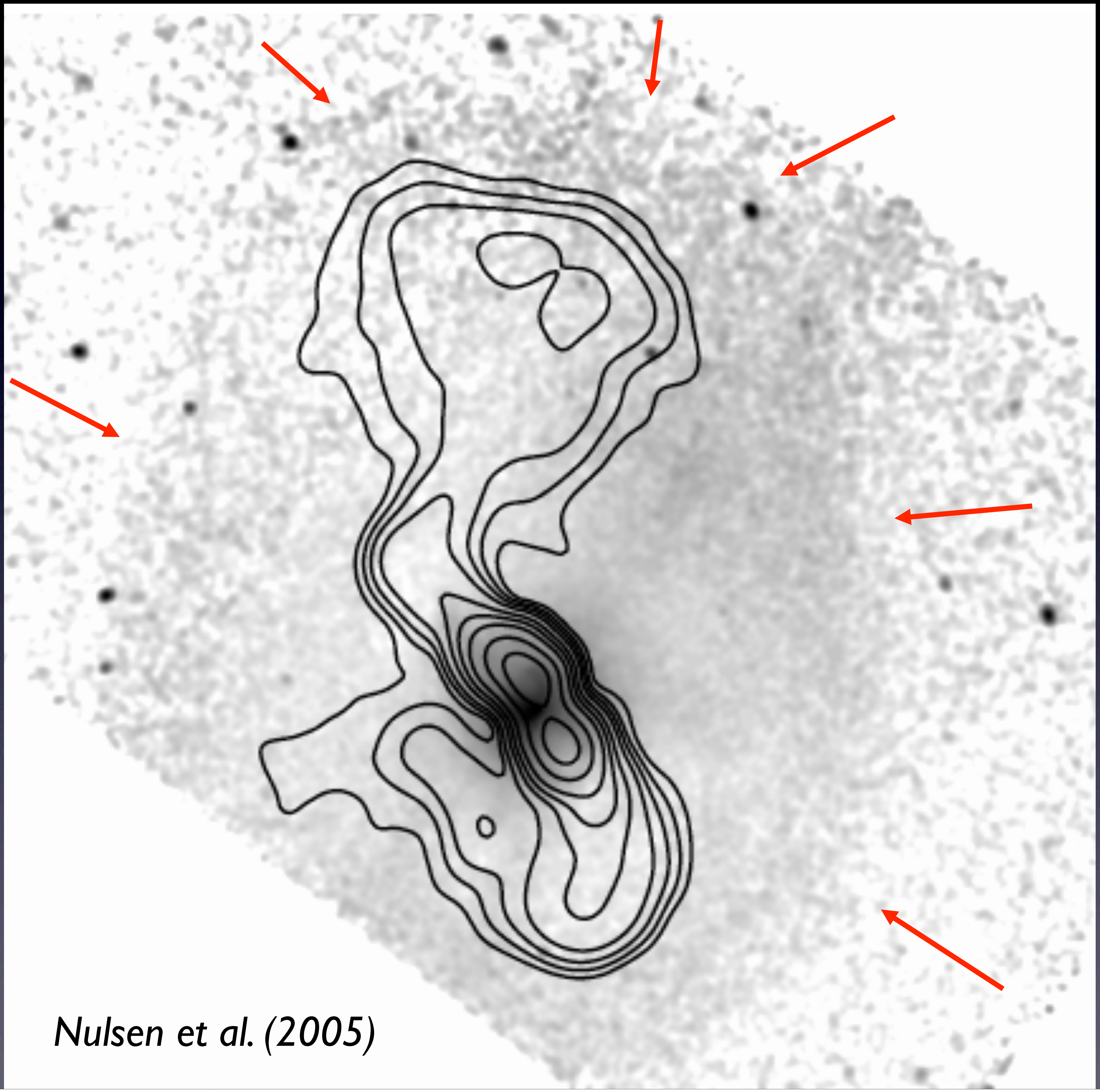


Wise et al. (2007)

- Multiple cavities detected in X-ray maps
- Imply multiple AGN outbursts over ~200 Myr
- Limits on rate of BH growth:

$$M_{acc} = \frac{E_{cav}}{\epsilon c^2} \qquad \Delta M_{BH} = (1-\epsilon) M_{acc}$$

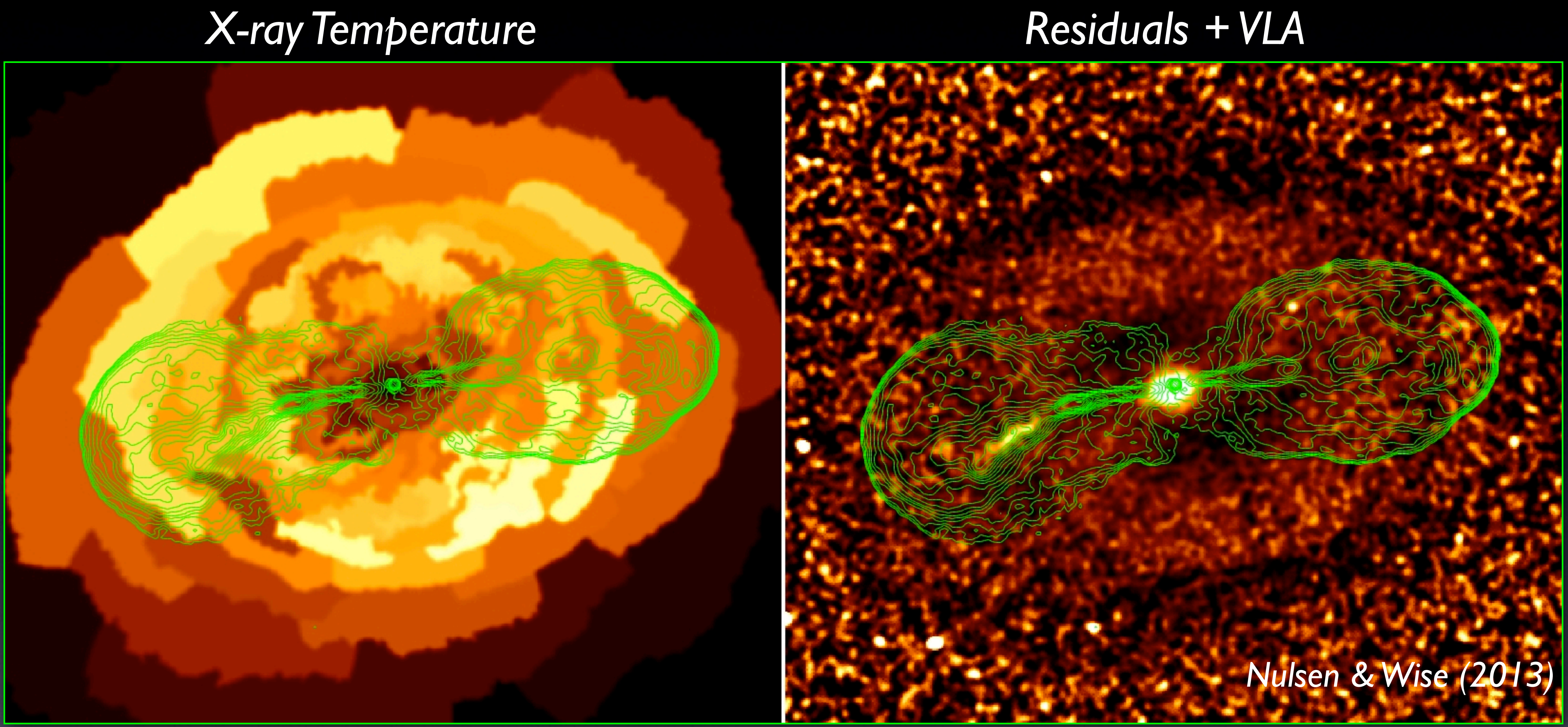
Driving Shocks into ICM



Nulsen et al. (2005)

- Chandra X-ray emission detects shock front surrounding low frequency radio contours
- Expanding radio lobes drive the shock over last ~1.4×10^8 yr
- Total energy input significantly exceeds requirements to offset X-ray cooling in cluster

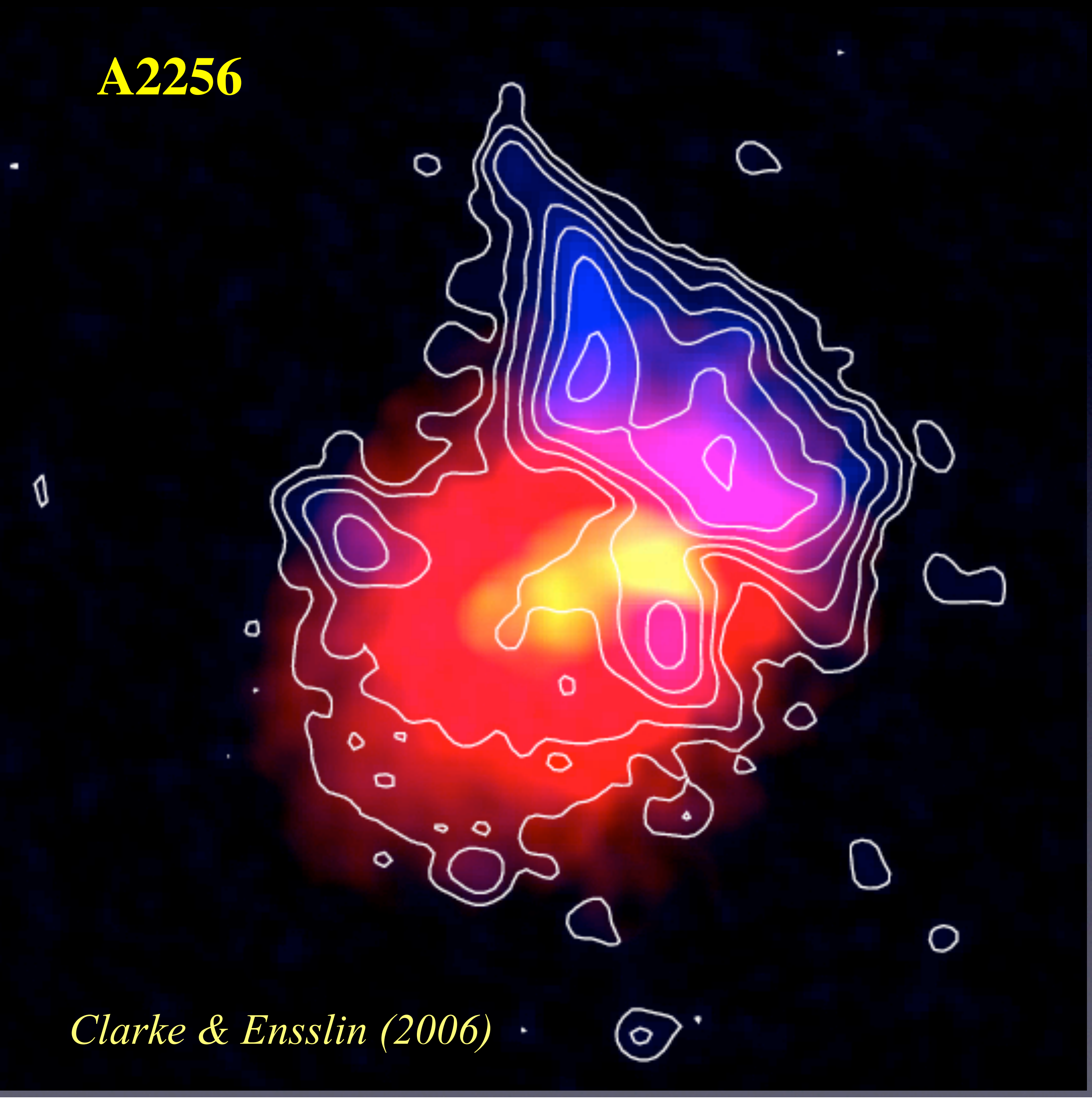
Driving Shocks into ICM



Hercules A

- Second most powerful AGN outburst known ($E_{tot} > 10^{61}$ erg)
- Synchrotron power on par with Cygnus A, FRII-like
- Radio morphology is jet-dominated, no hotspots, FRI-like
- Spherical, M~1.6 shock surrounding the cavities

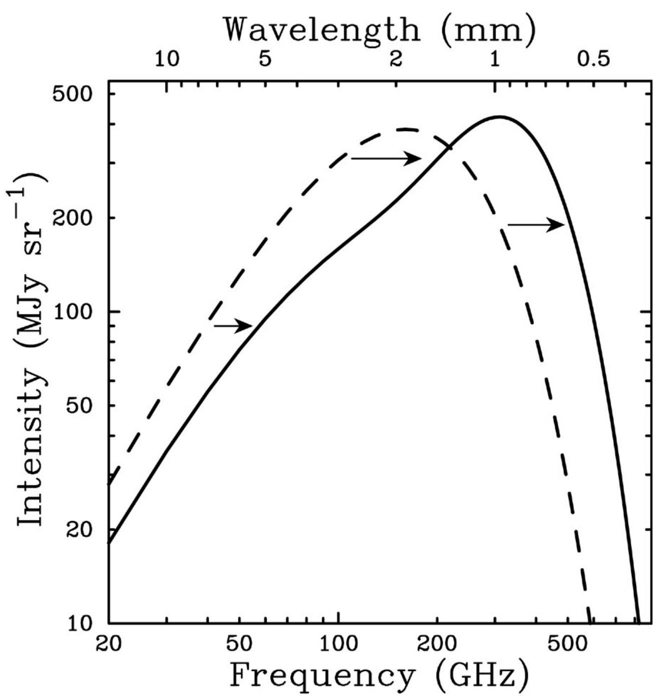
Merger Calorimetry

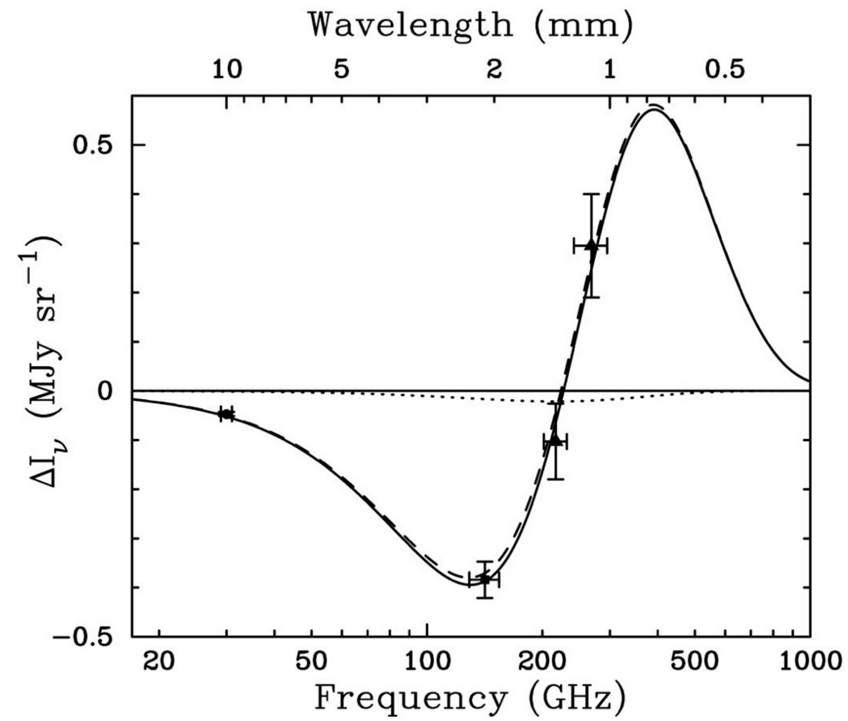


Several clusters display large regions of diffuse synchrotron:

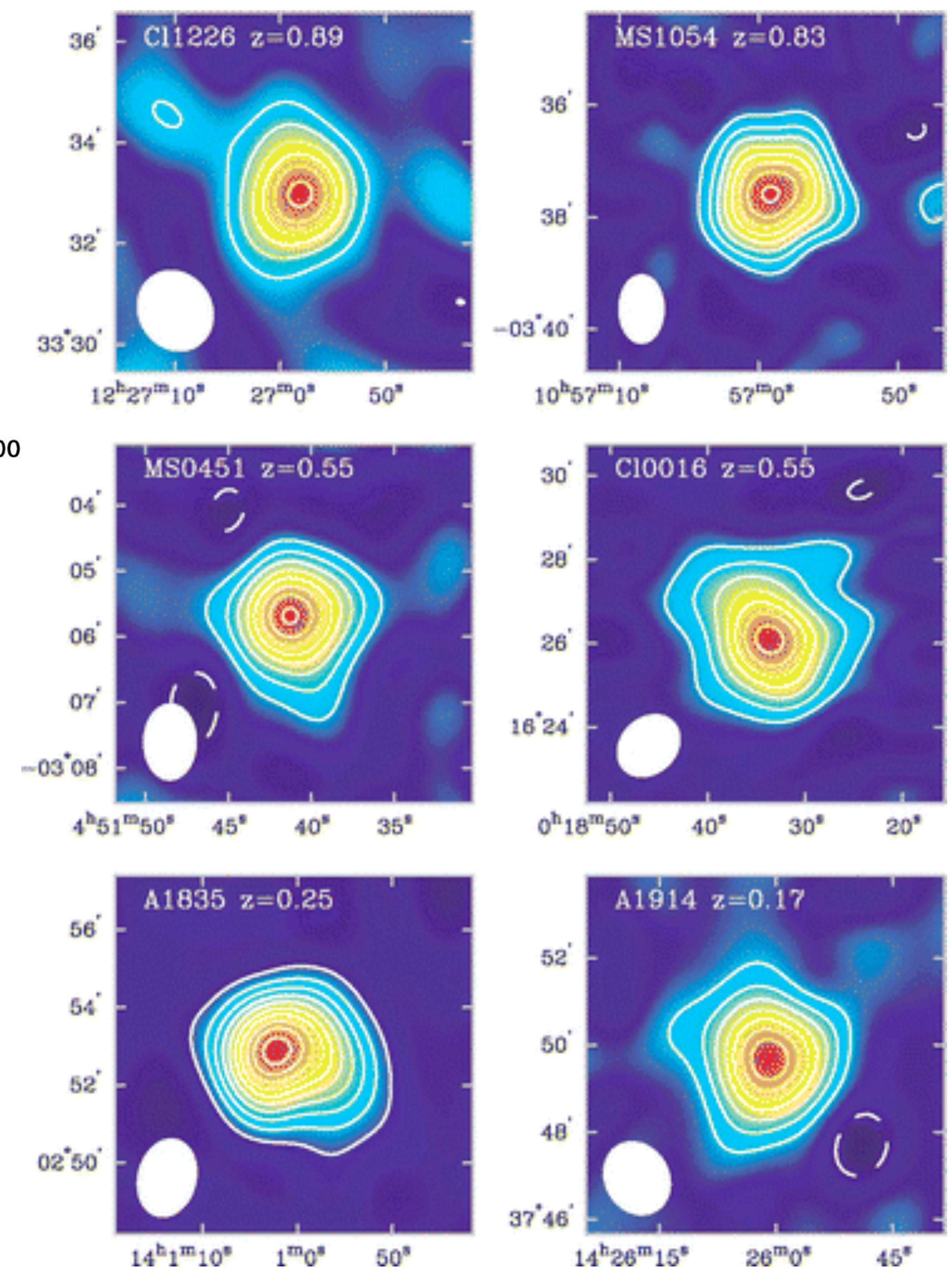
- 'Halos' & 'relics' associated with merging clusters
- Radio emission is generally steep spectrum
- RADIO RELICS: cluster outskirts, elongated morphology, polarized at the ~30% level
- RADIO HALOS: centrally located, regular structure similar to the X-ray morphology, unpolarized
- Location, morphology, spectral properties, etc... can be used to understand merger geometry and energetics

Sunyaev-Zel'dovitch Effect





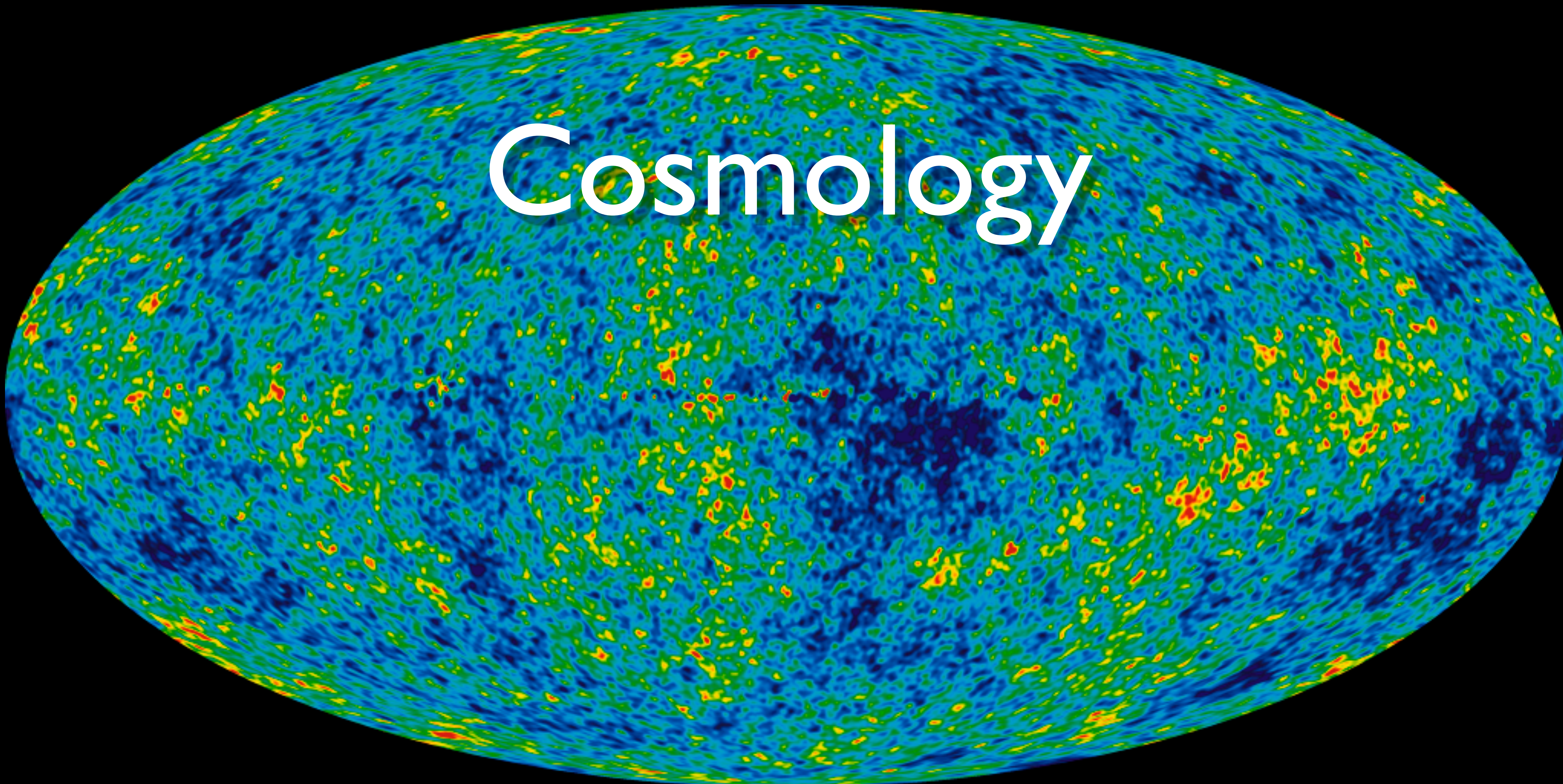
OVRO 30 GHz



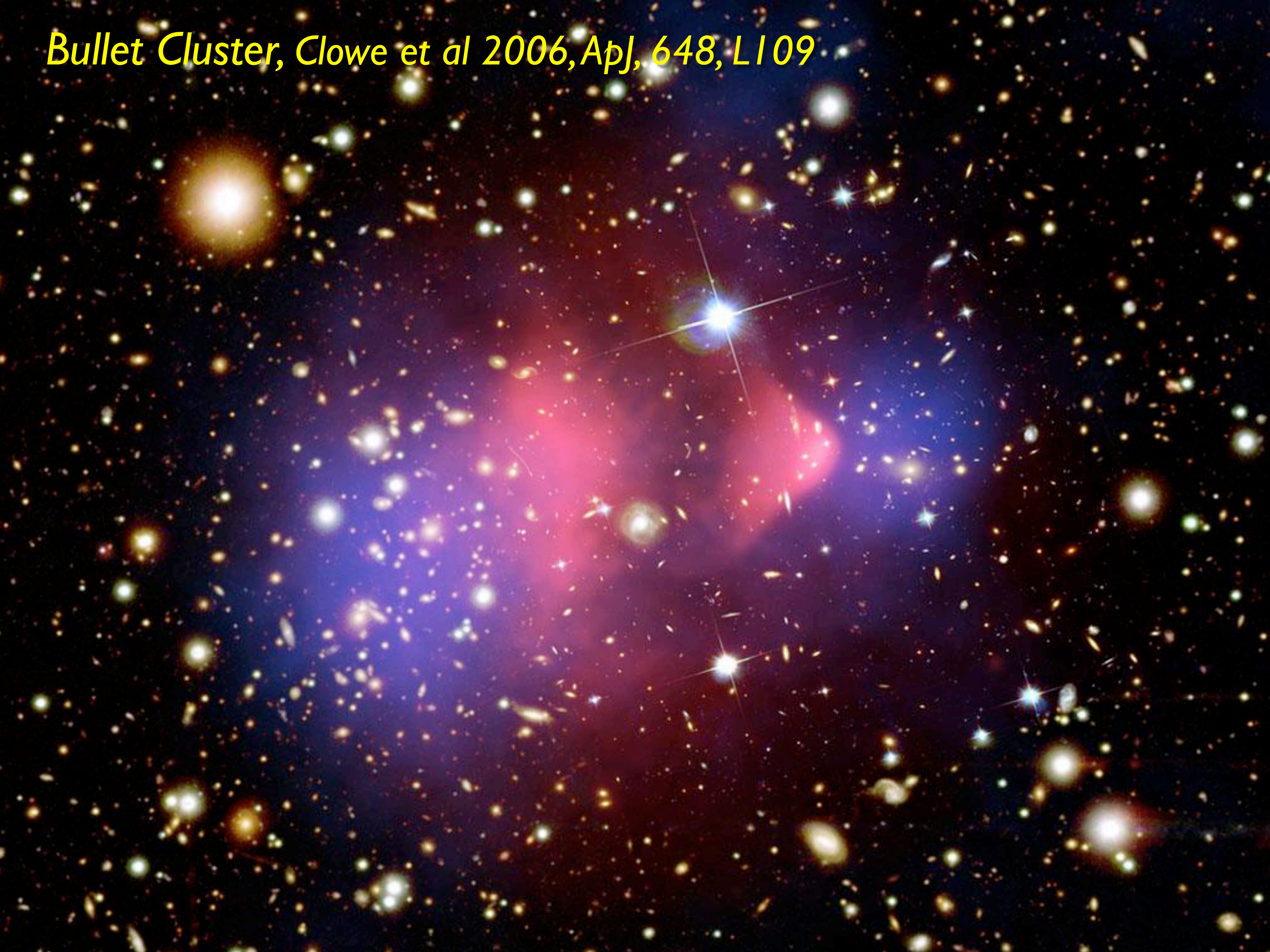
- Temperature shift proportional to gas pressure,
- CMB photon energies boosted by ~$kT_e/(m_ec^2)$
- kTe ~ 10 keV, Te ~ 108 K relativistic
- x = h/(kT_e)
- f(x) is the spectral dependence
- Notice that the T shift is redshift independent
- Unbiased surveys for clusters

$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,$$

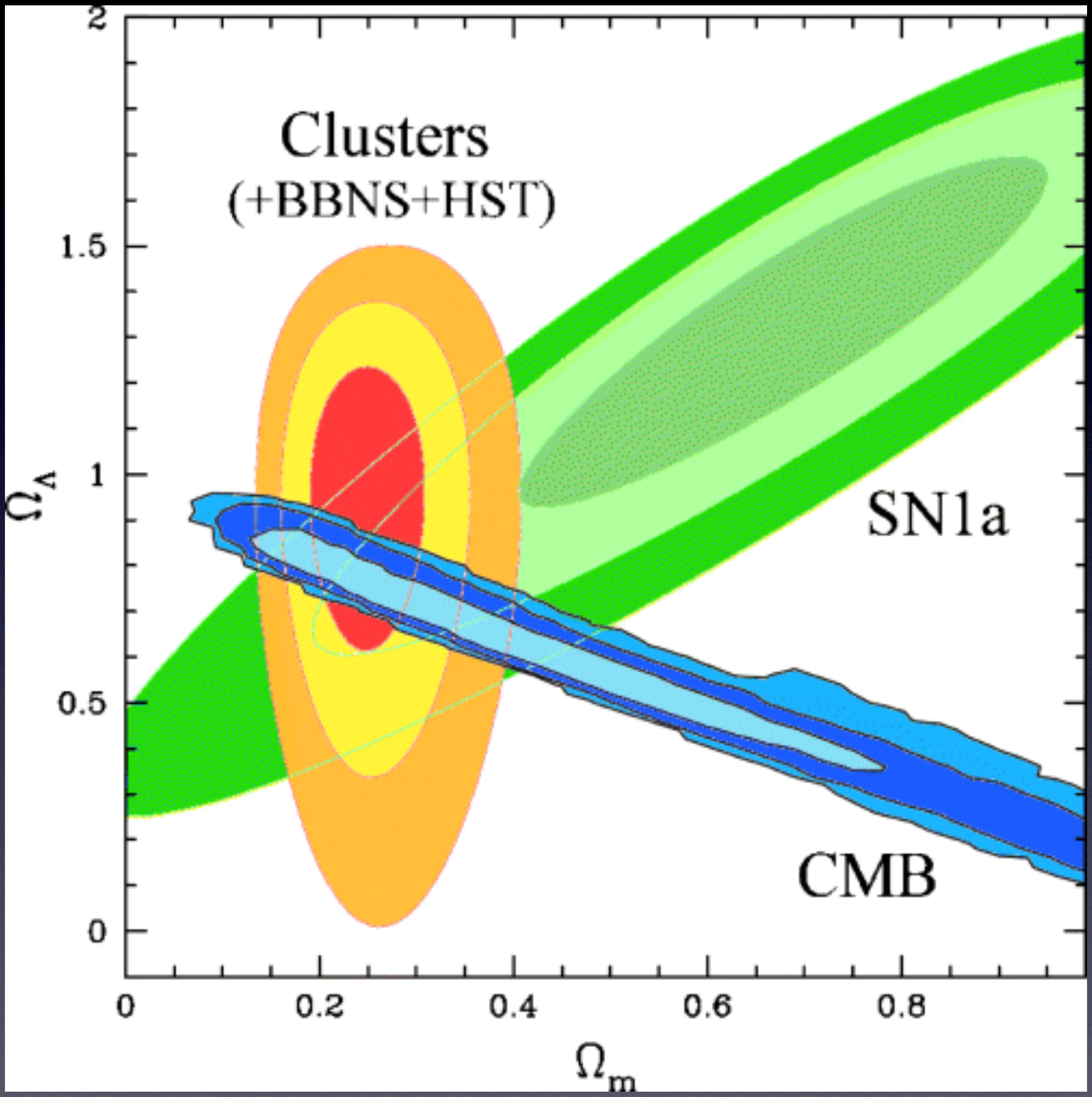
Cosmology



Bullet Cluster, Clowe et al 2006, ApJ, 648, L109



Tracing Dark Energy



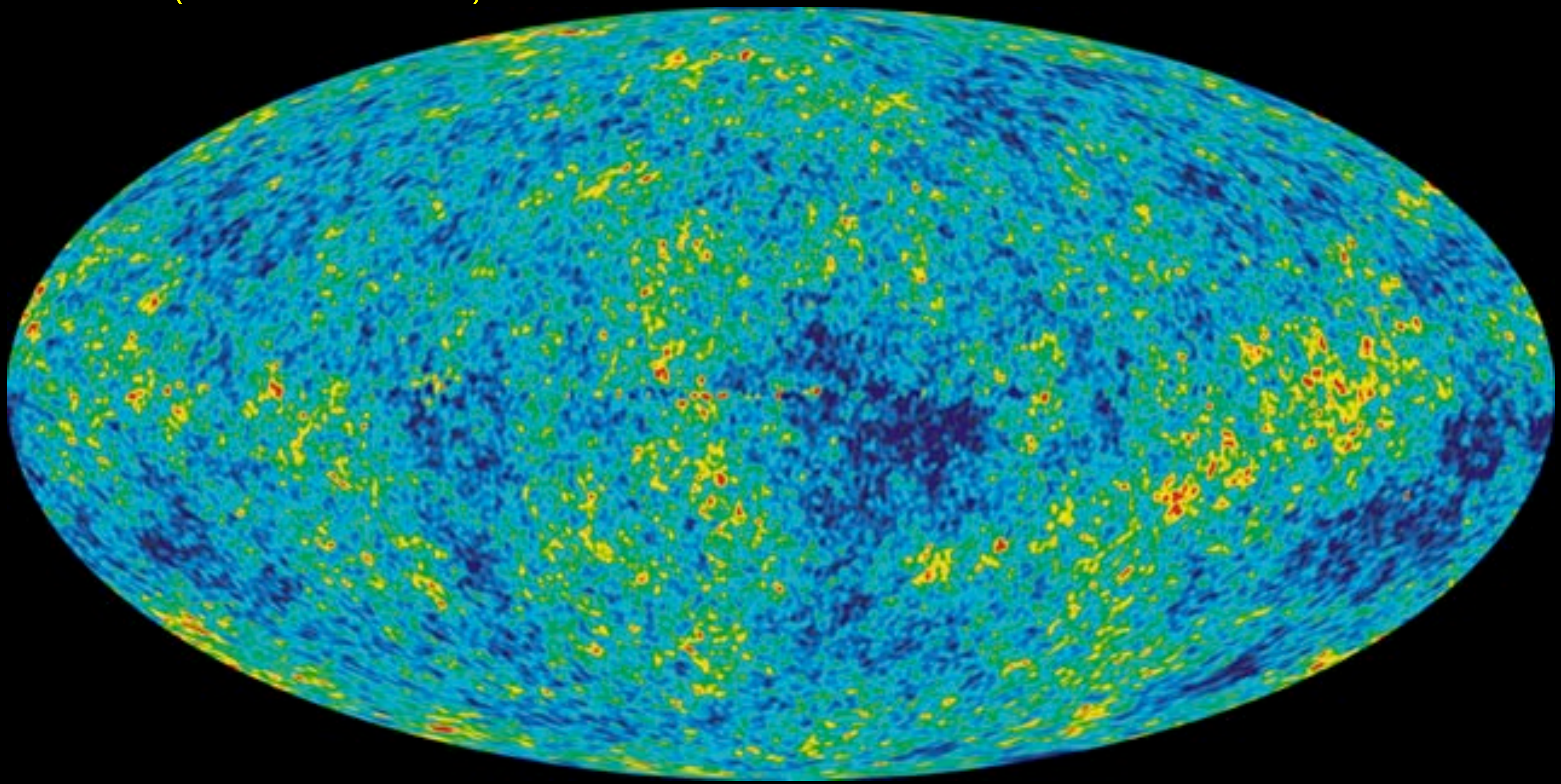
Allen et al. (2004)

Observations of cosmic acceleration have led to studies of Dark Energy:

- Clusters should be representative samples of the matter density in the Universe
- Study DE through various methods including the 'baryonic mass fraction'
- Requires assumption of hydrostatic equilibrium
- Merging cluster can be identified and removed using low frequency detections of halos and relics (Clarke et al. 2005)

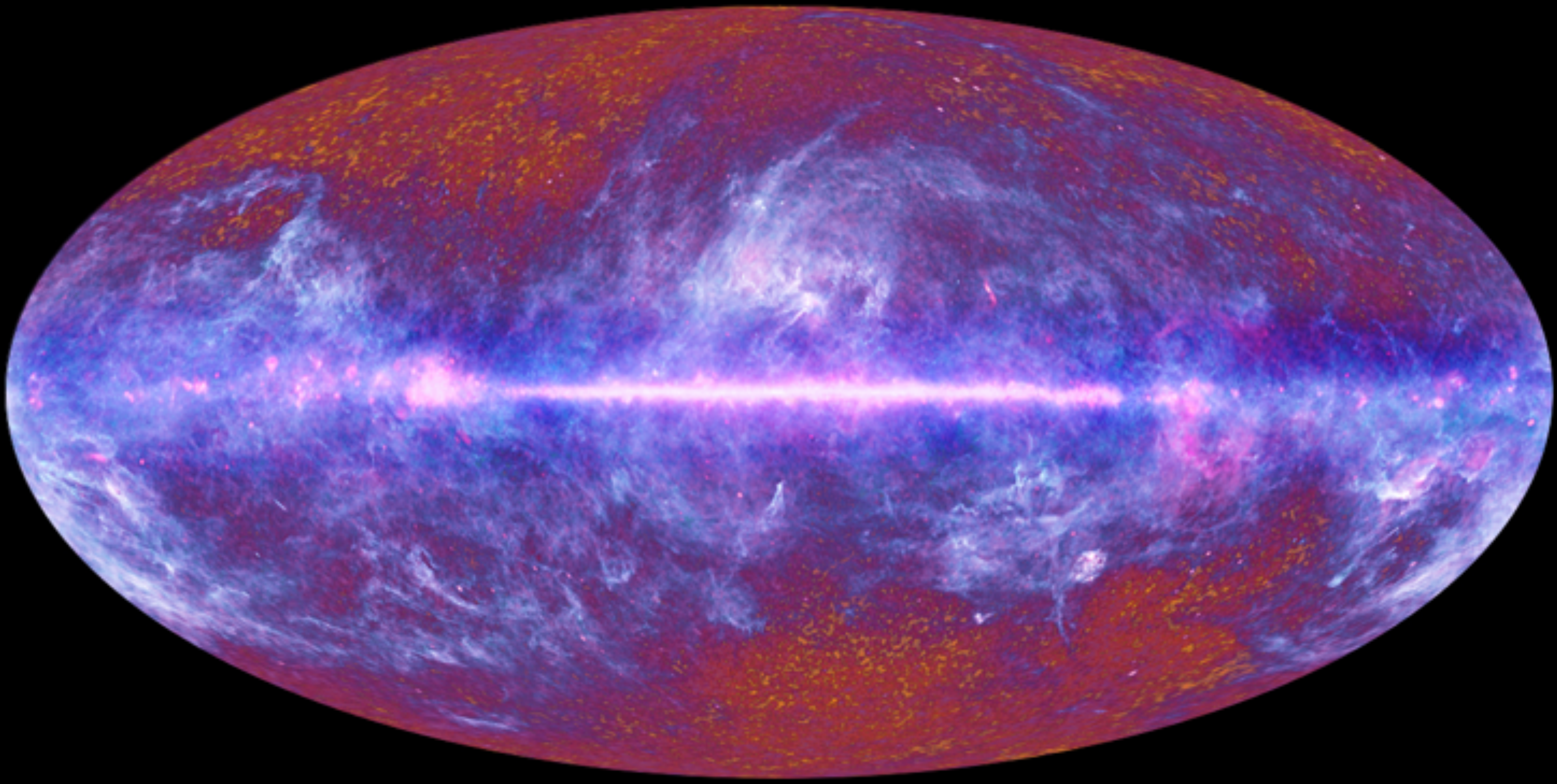
Cosmic Microwave Background

WMAP (20 - 100 GHz)



- **After subtracting off the emission from all the "foregrounds", find fluctuations of ~10^{-6} K at ~0.25° resolution**

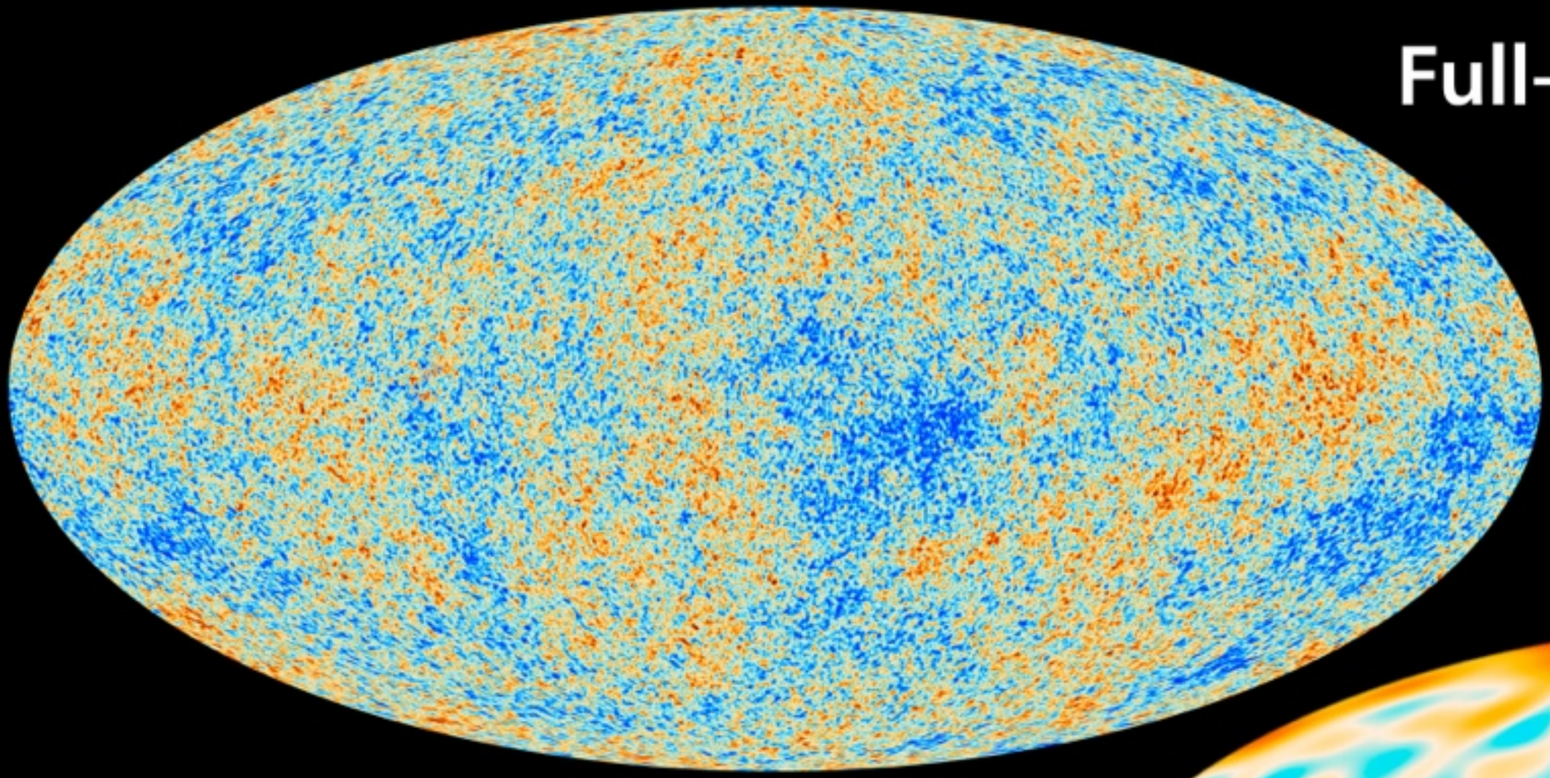
Planck Mission

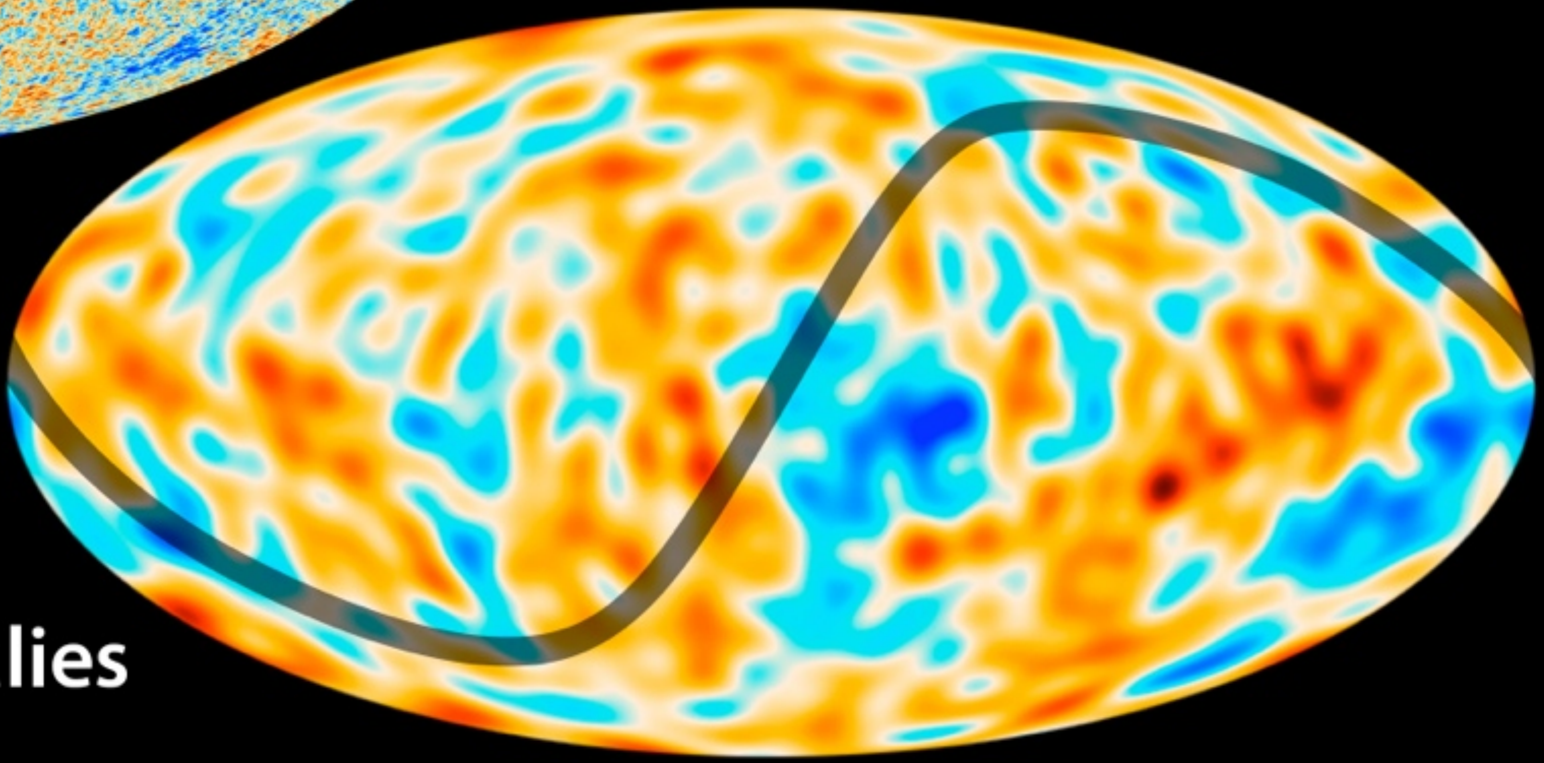


(30 - 857 GHz)

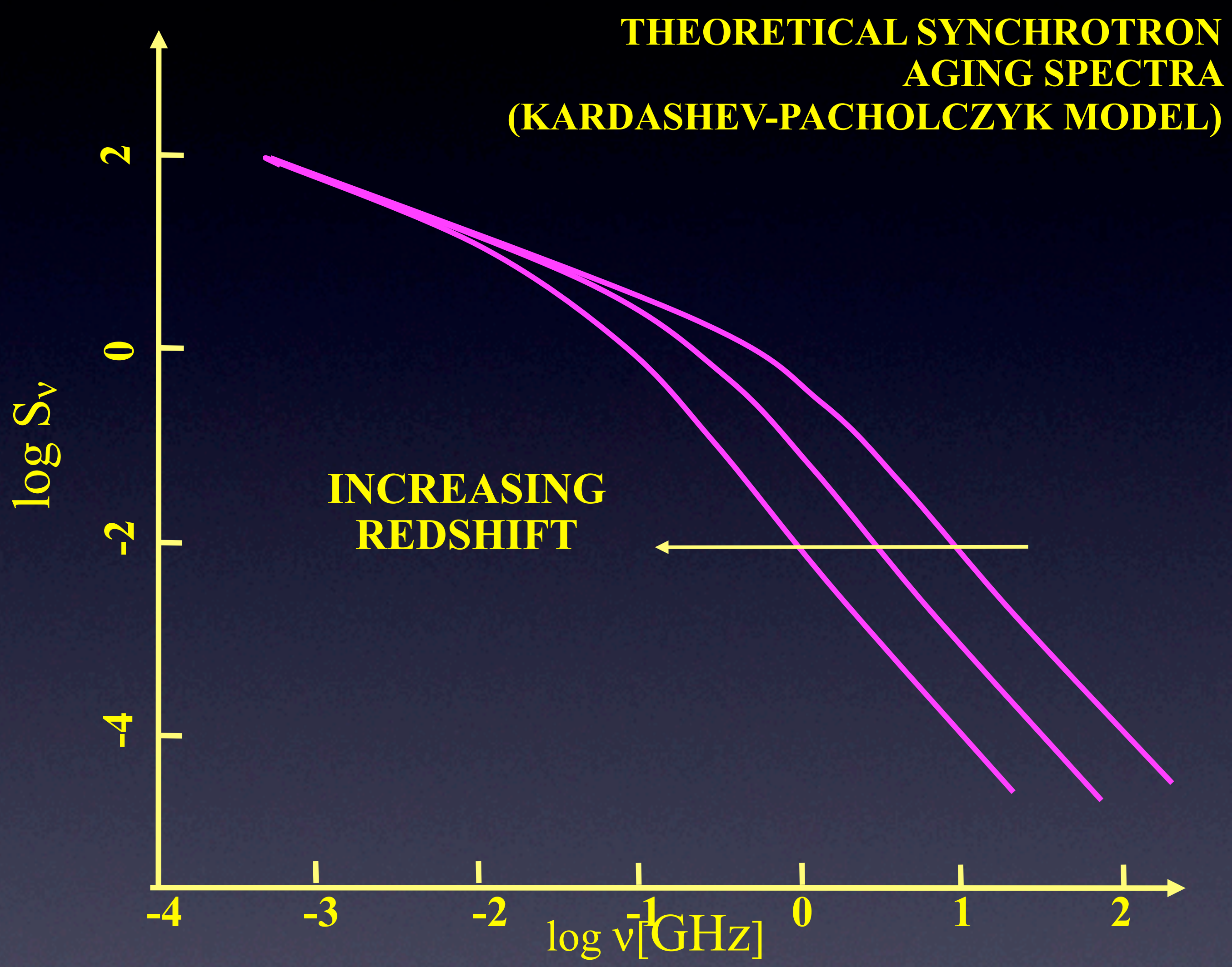
Resolution ~ x5 better

Planck Mission





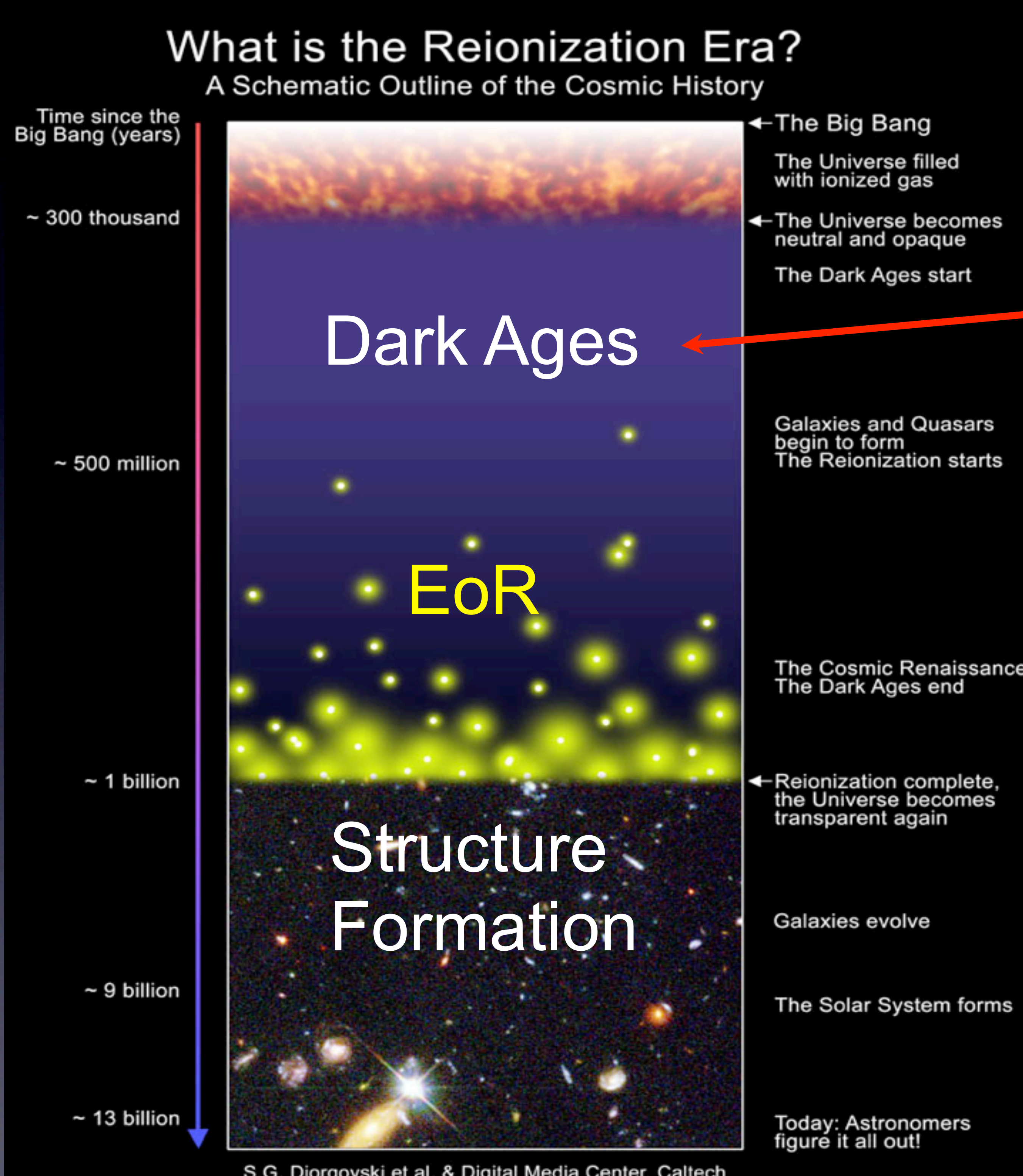
High Redshift Galaxies

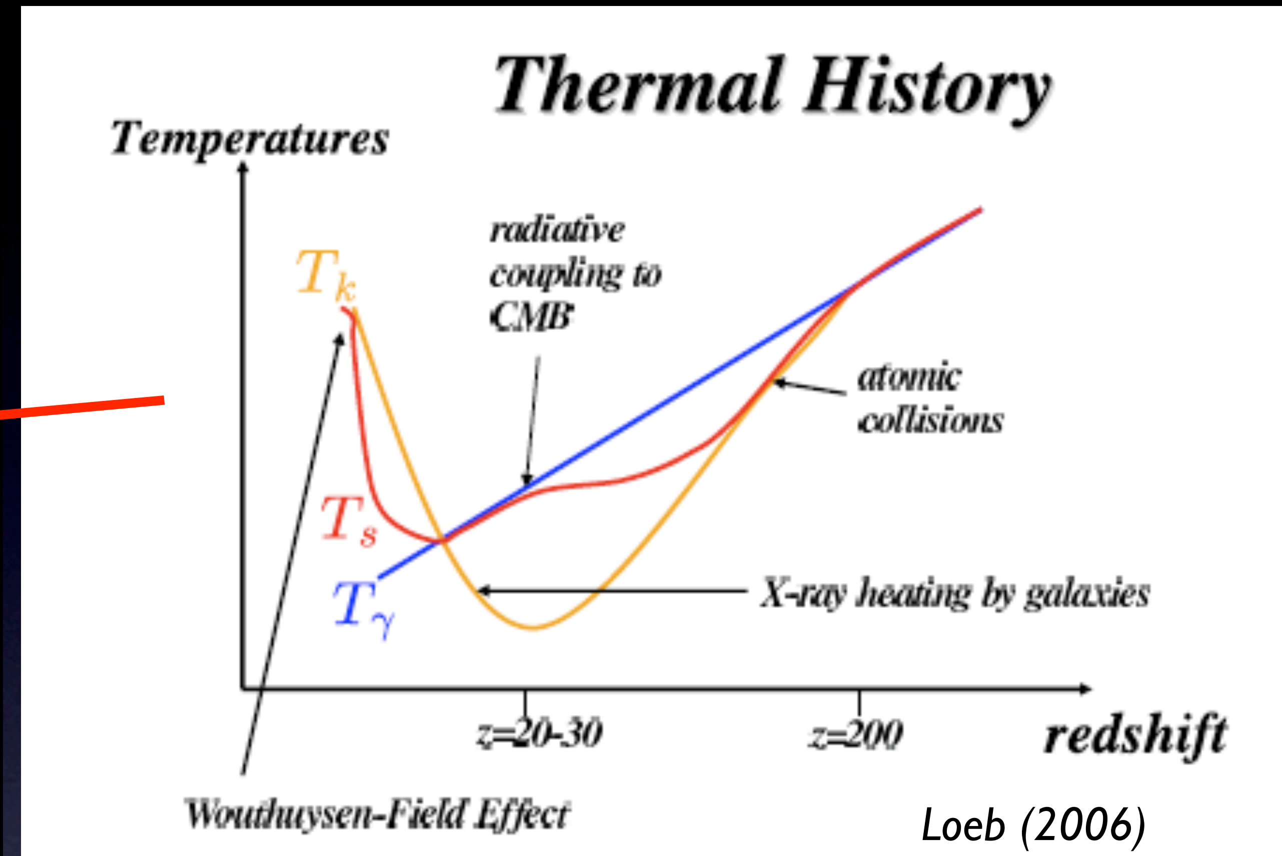


Observations of cosmic acceleration have led to studies of Dark Energy:

- Synchrotron losses steepen the spectrum of radio galaxies at high z
- Inverse Compton losses act similarly to steepen the spectrum, especially at high *z* since IC losses scale as z^4.
- Spectrum is also red shifted to lower frequencies so that the entire *observed* spectrum is steep.

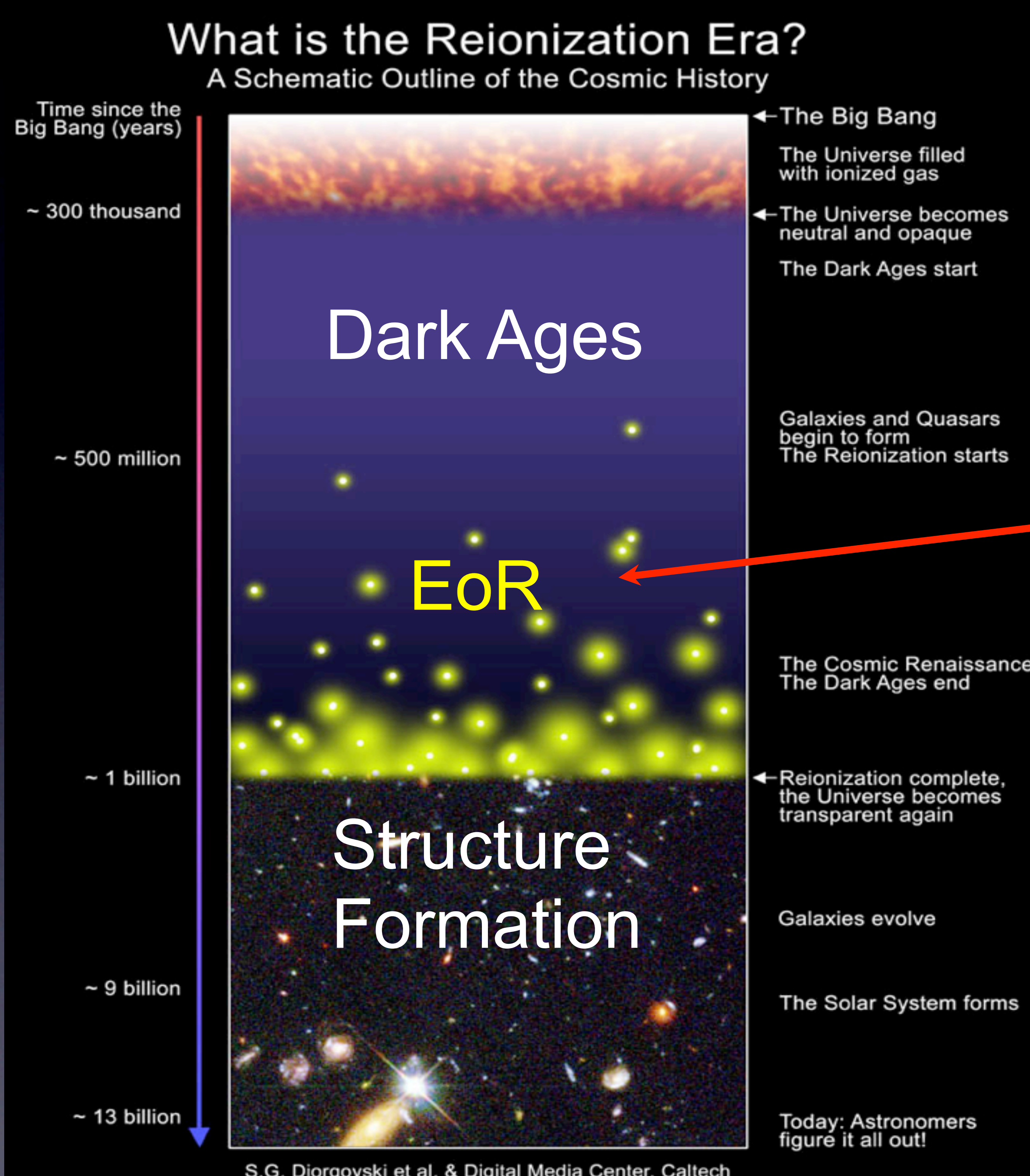
Dark Ages

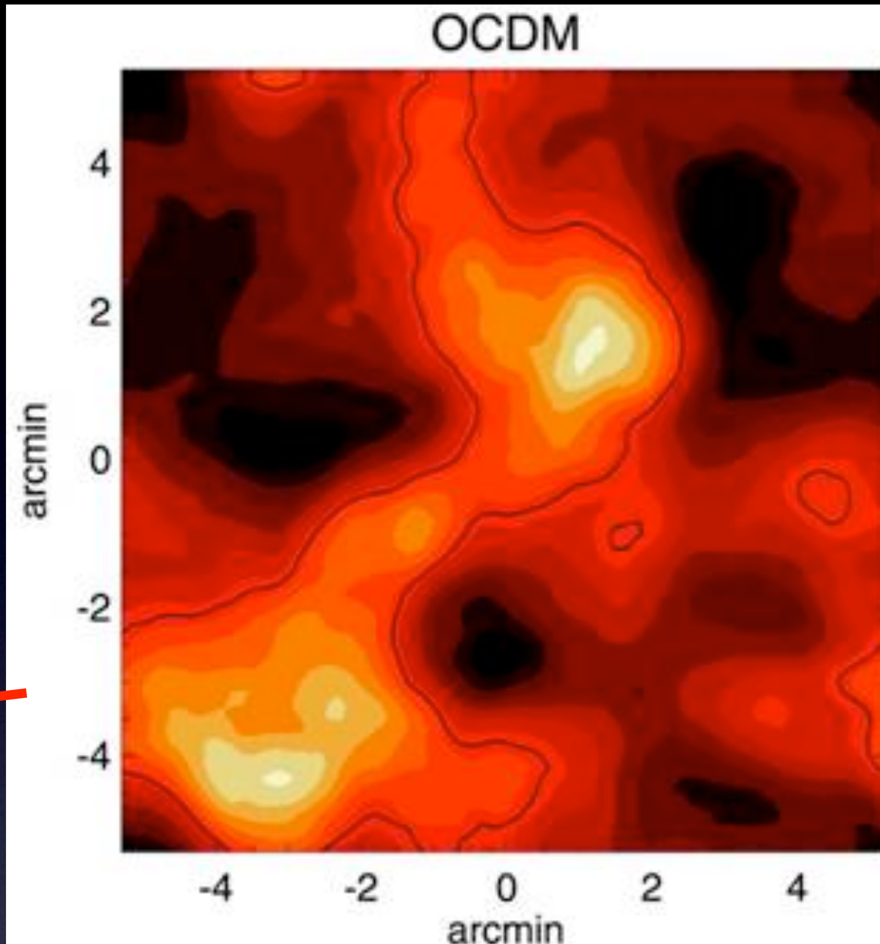




- Spin temperature decouples from CMB at z~200 (ν =7 MHz) and remains below until z~30 (ν =45 MHz)
- Neutral hydrogen absorbs CMB and imprints inhomogeneities

Epoch of Reionization



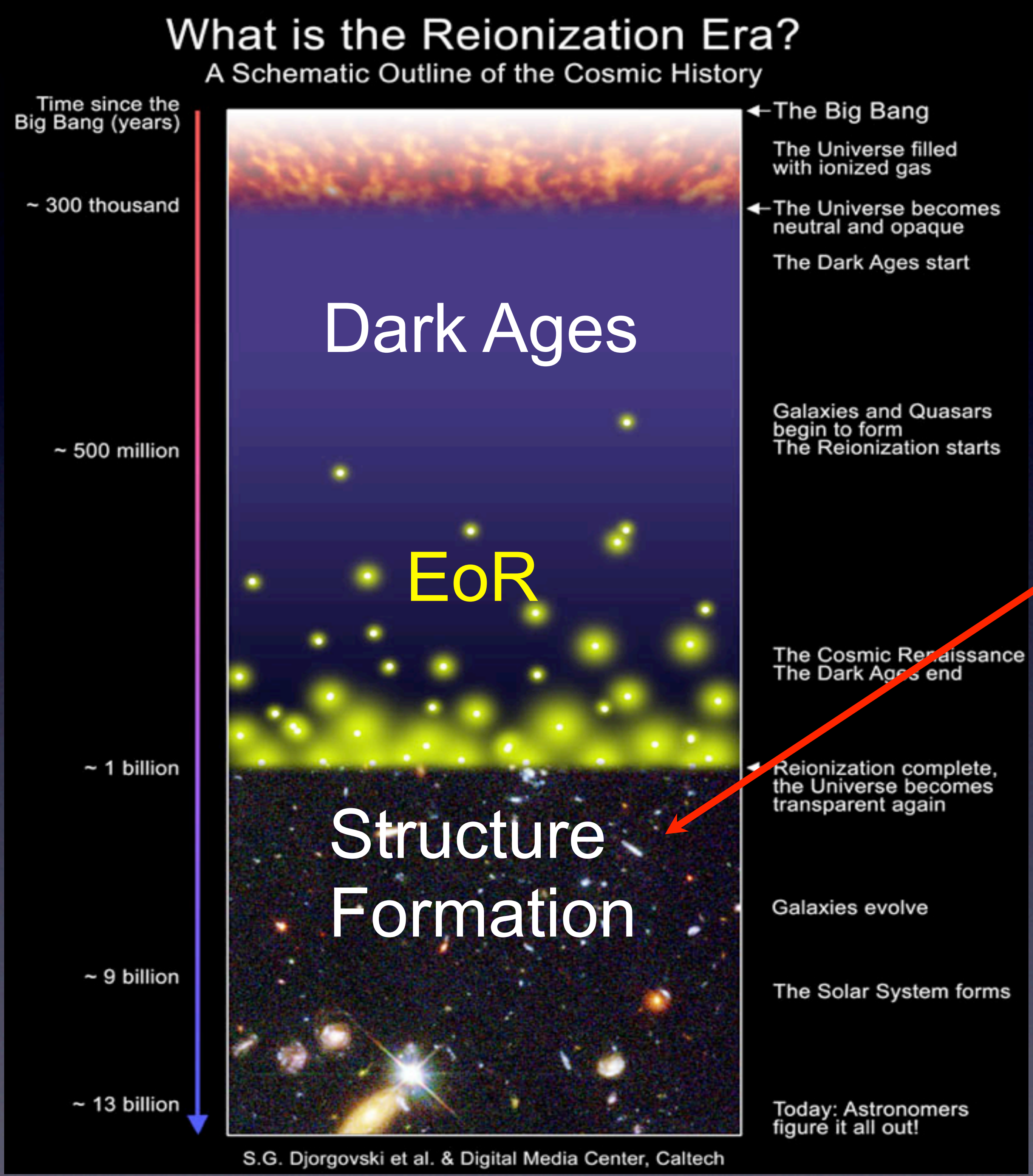


Tozzi et al. (2000)

- Hydrogen 21 cm line during EoR between z~6 (ν ~ 200 MHz) and z~11 (ν ~ 115 MHz)

EoR Intruments: MWA, LOFAR, 21CMA, PAPER, SKA

Structure Formation



Clarke & Ensslin (2006)

- Galaxy clusters form through mergers and are identified by large regions of diffuse synchrotron emission (halos and relics)
- Important for study of plasma microphysics, dark matter and dark energy

Questions?