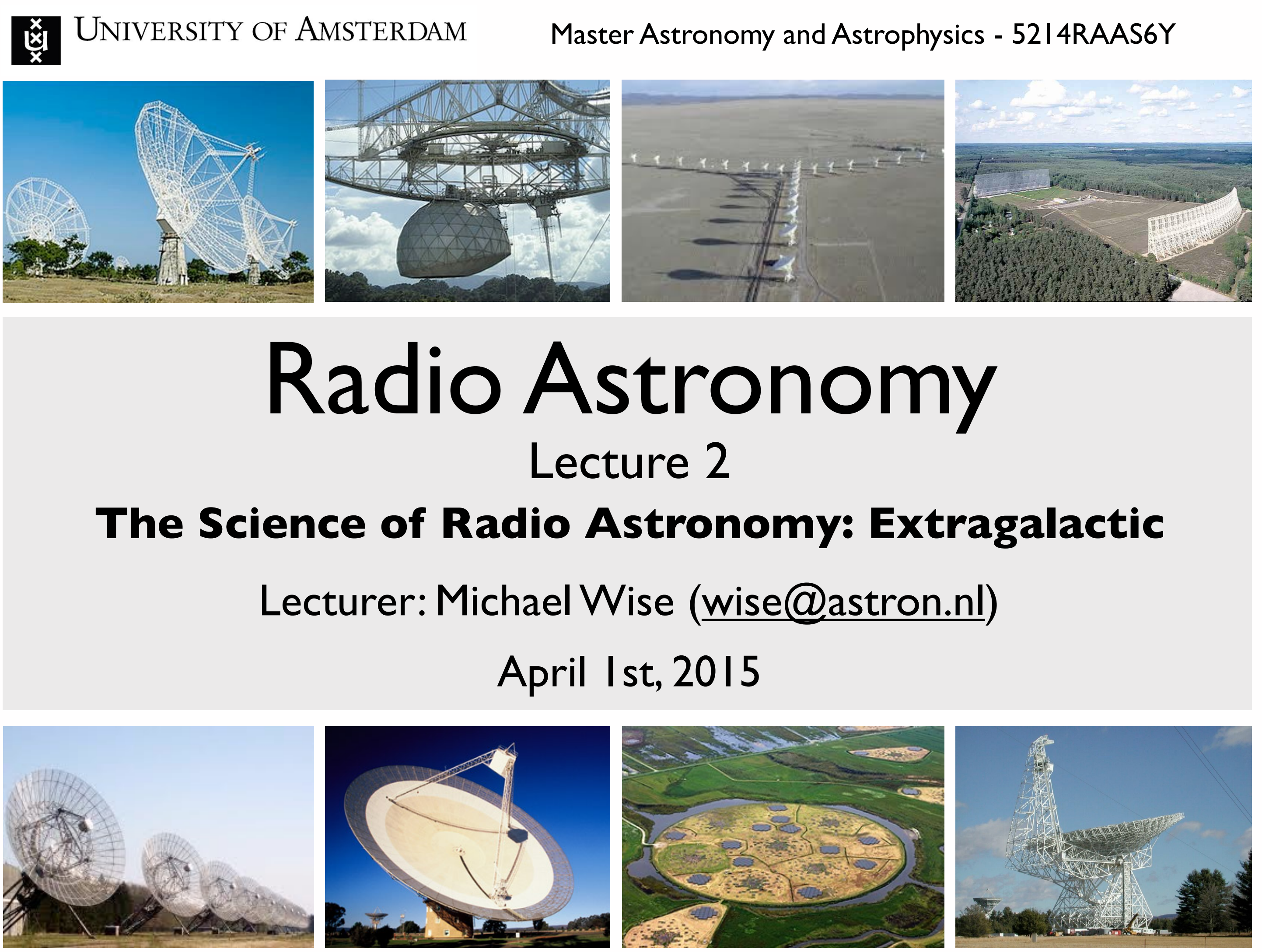


I’m an extragalactic astronomer. I study large scale structures like galaxies and clusters of galaxies.
I use multi wavelength data (mostly radio and X-ray) to study these objects.
To really understand the full picture of what’s going on in these objects you need a wide range of data.
Radio astronomy has a number of unique advantages for extragalactic studies however.

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

“Extragalactic” is a somewhat artificial division. For our purposes, we mainly mean studies of objects and phenomena on the scale of galaxies or bigger. This definition can include our own Galaxy or other galaxies.

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)

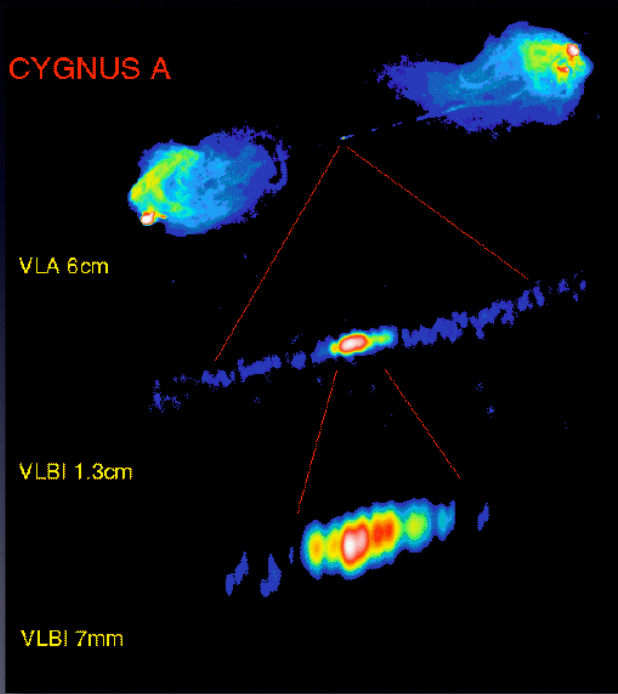
When we observe in different parts of the EM spectrum, we see different physics at work.
Radio observations probe a wide range of physics.
A wide range of physics translates into the ability to answer a wider range of scientific questions.

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

The highest angular resolution images currently possible are radio observations (down to milli-arcseconds).
Extragalactic sources by definition are very far away and very faint.
Studying their structure invariably requires high angular resolution and sensitivity to faint sources.
Radio observations are very good at both.

Why Radio Observations?

Why Synthesis Imaging?
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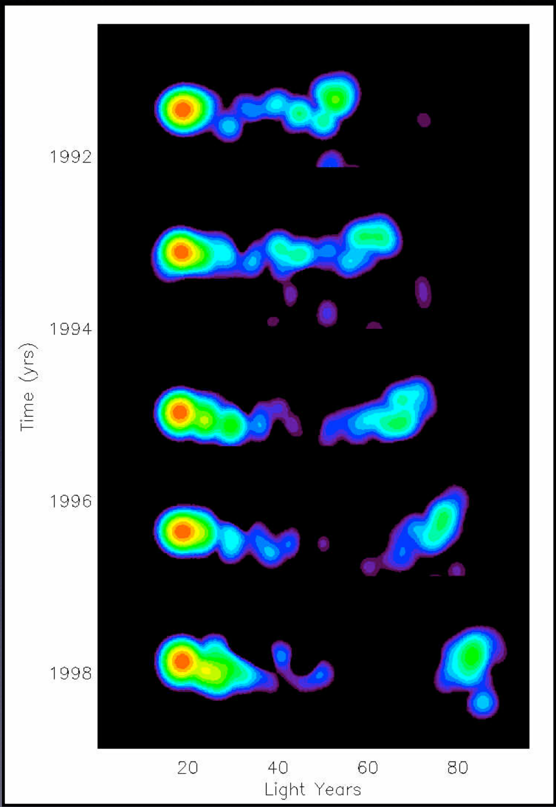
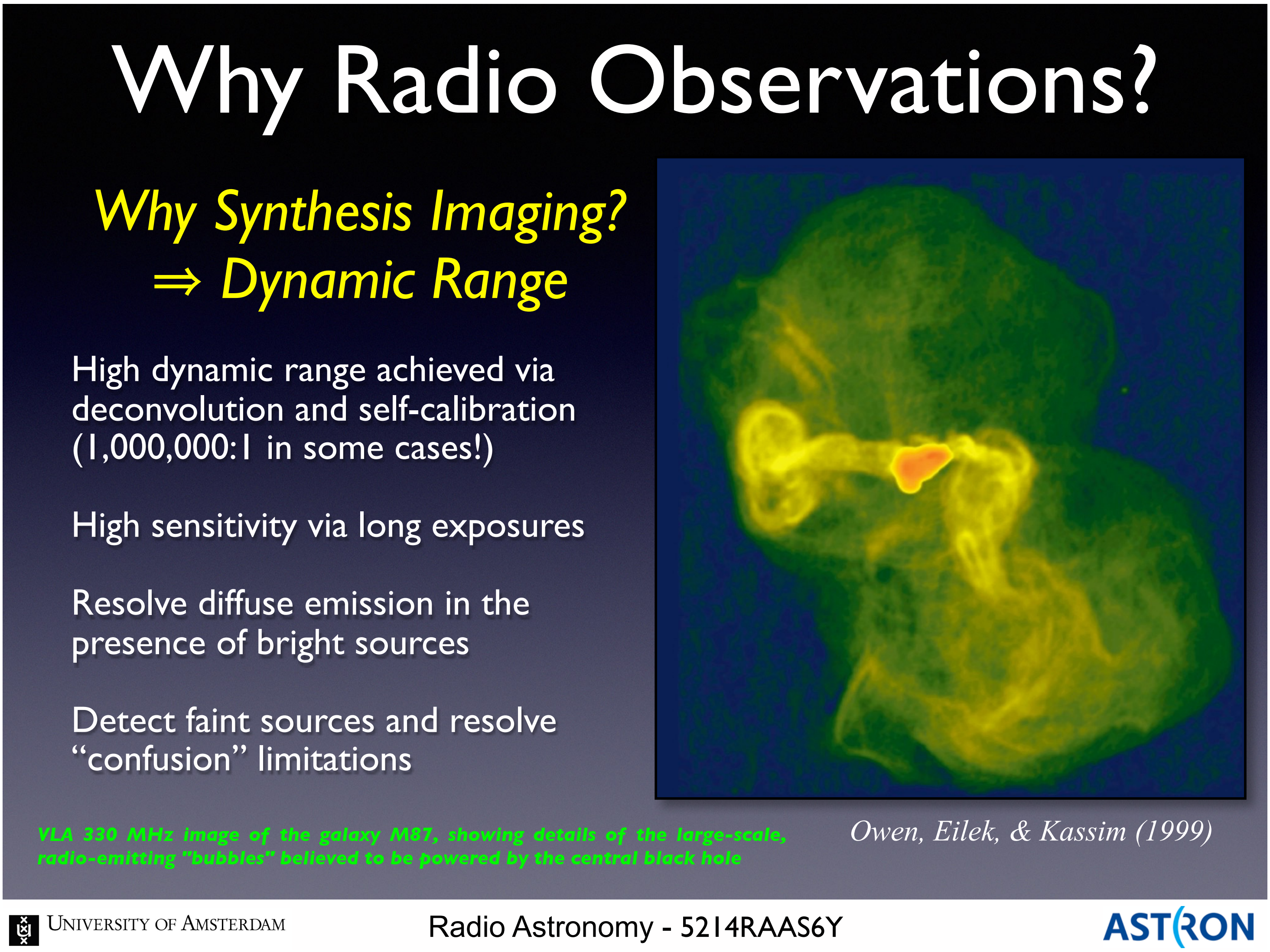


Apparent superluminal motion in quasar 3C279 is shown as mosaic of five VLBA radio images made over seven years at 22 GHz with resolution of 0.001 arcseconds

Wehrle et al. (2001)



Dynamic range is defined as the ratio of the brightest part of an image to the faintest ("contrast ratio").
Its a measure of how well we can detect very faint objects or diffuse emission (more in Lecture 8).
Radio observations can achieve DR > 1,000,000:1 (but not easy!).
For comparison, optical CCDs can achieve DR ~10,000 and X-ray images rarely have DR > 1000.

Why Radio Observations?

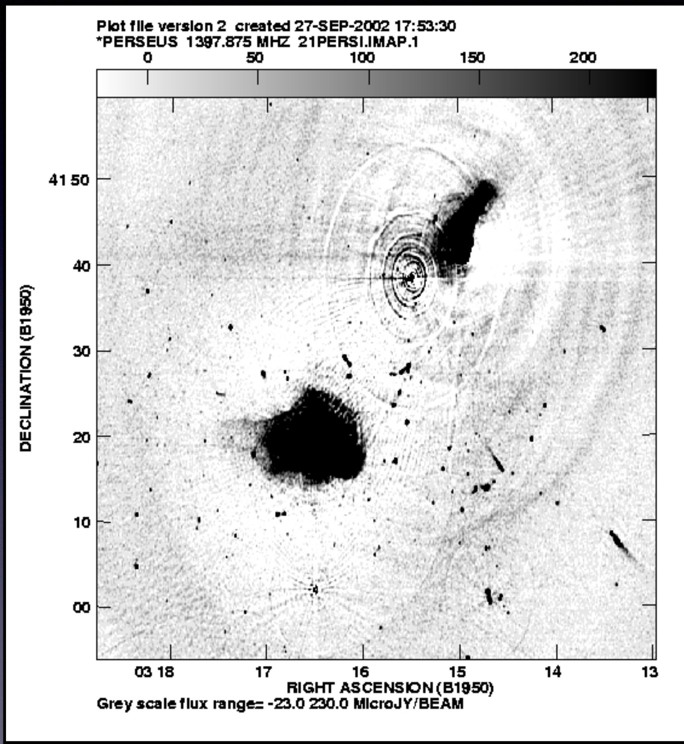
Why Synthesis Imaging?
⇒ Dynamic Range

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

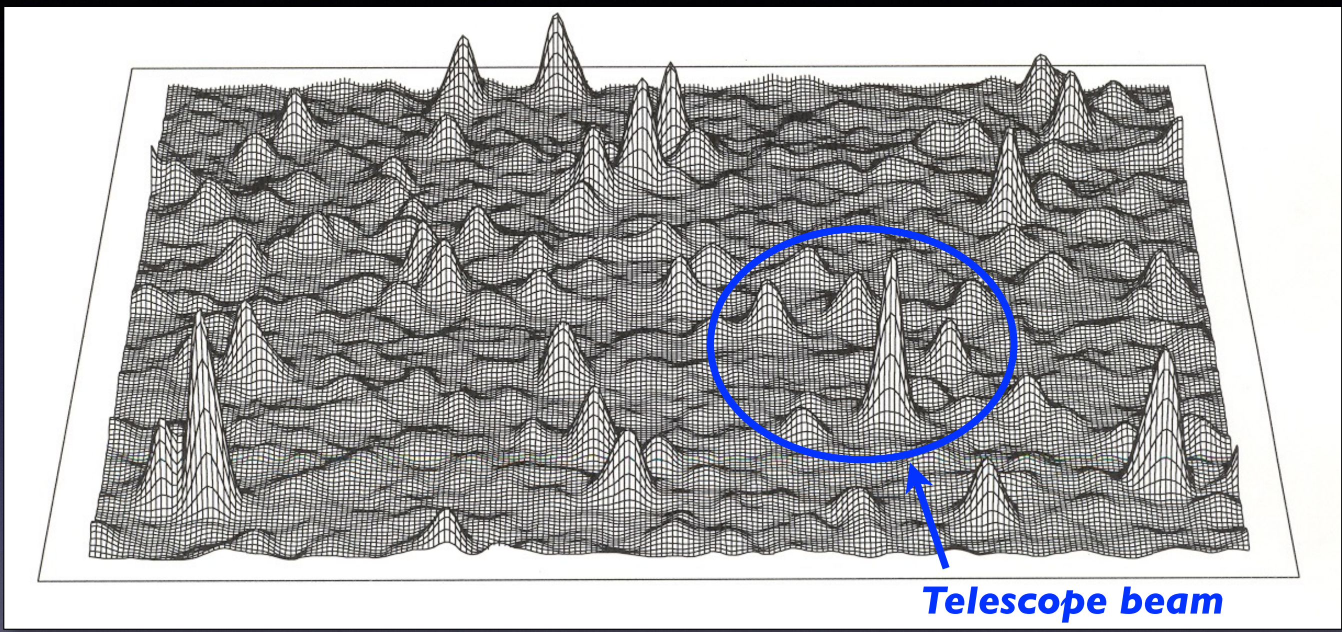
Detect faint sources and resolve "confusion" limitations



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

de Bruyn & Brentjens (2010)

Beating Confusion



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

The sky is filled with a distribution of sources, some bright, some faint.
The unresolved, faint ones produce a combined signal.
This signal limits the ultimate sensitivity of any radio telescope.

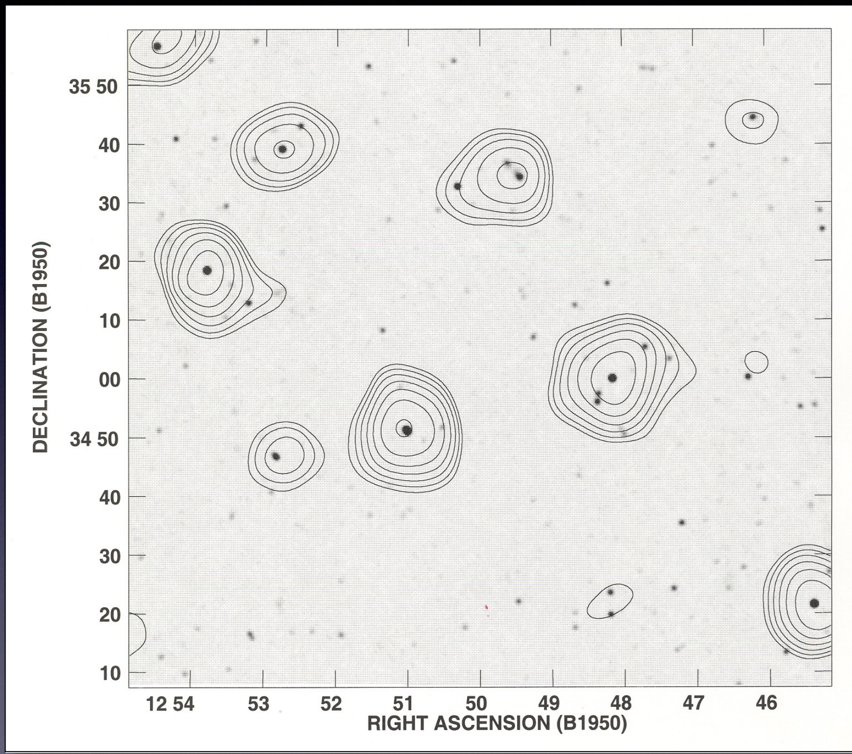
Beating Confusion

"RMS" confusion:

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

where

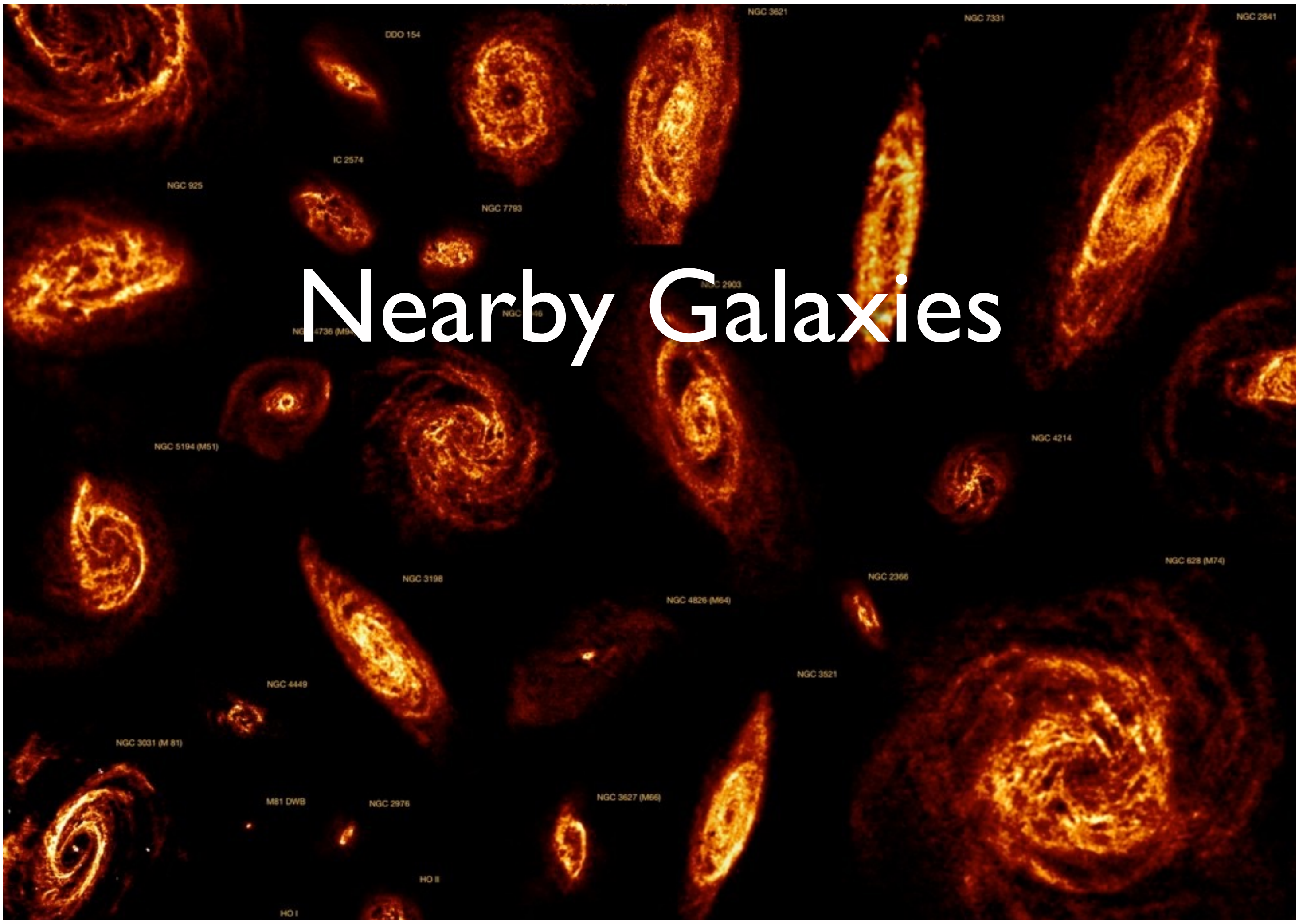
σ is in mJy/beam
ν is in GHz
θ is in arcmin



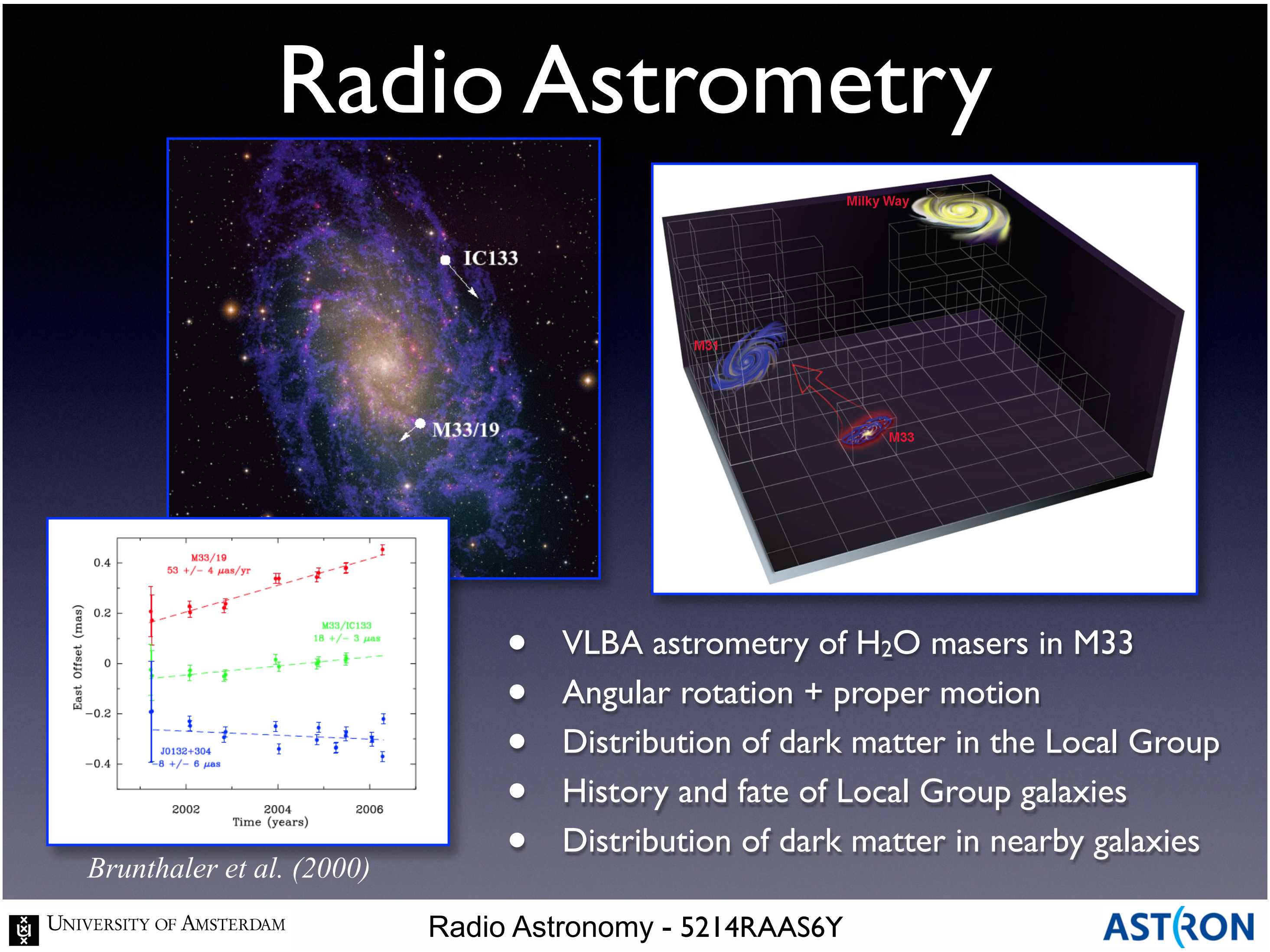
NVSS (45 arcsec) grayscale under GBT (12 arcmin) contours

The best way to beat confusion and achieve greater sensitivity is to increase the resolution.
High angular resolution means we can separate all those fainter sources and get closer to the "true" noise.
Radio telescopes are great for high angular resolution.
We can increase the resolution *and* the sensitivity by going to longer baselines.
Longer baselines -> high angular resolution.

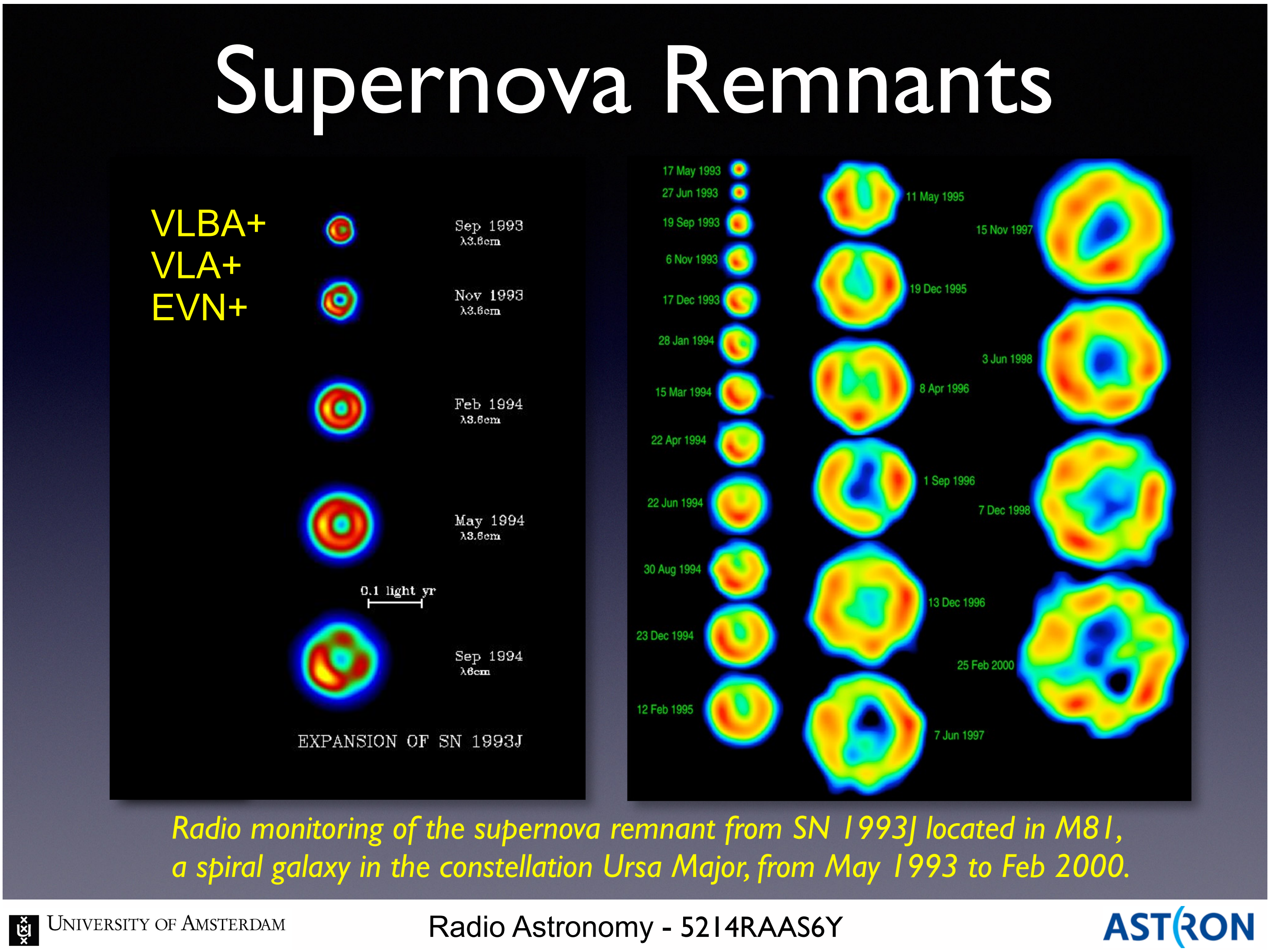
Nearby Galaxies



An atlas of HI maps for a sample of nearby galaxies created with the WRST.
“Nearby” is another poorly defined term, but basically we mean galaxies that are close enough to resolve their internal structures.



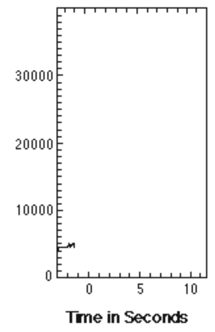
Similar to optical astrometry.
High angular resolution can give us very accurate positions even in other galaxies.
Long baseline interferometry can detect angular motions in external galaxies.
Can infer actual dynamical motion like the rotation of the spiral arms in spiral galaxies.

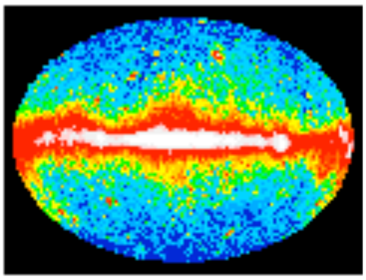


For nearby galaxies, we can trace the evolution of supernova remnants following a supernova.
High angular resolution in the radio lets us see and measure the velocity of the expansion.
Spectral resolution can separate thermal and non-thermal emission.
These sorts of observations can provide constraints on the energy of the explosion, density of the surrounding medium, etc.

Gamma-ray bursts

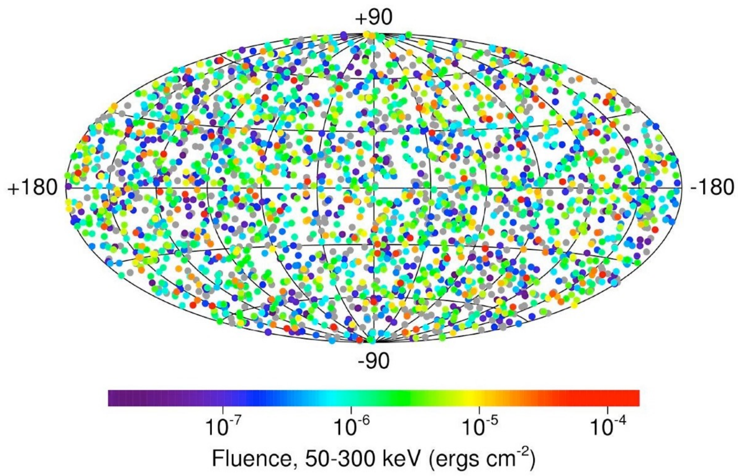
⇒ *Most luminous explosions in the universe*
Each burst may emit up to ~10^{54} erg





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 are believed to originate from very energetic events occurring at extragalactic distances.
The physical mechanism producing these bursts is still unknown.
The spatial resolution of gamma ray telescopes is not great, so its hard to identify the source of the burst.
Also the bursts themselves last for seconds typically making it hard to followup with telescopes at other wavelengths.

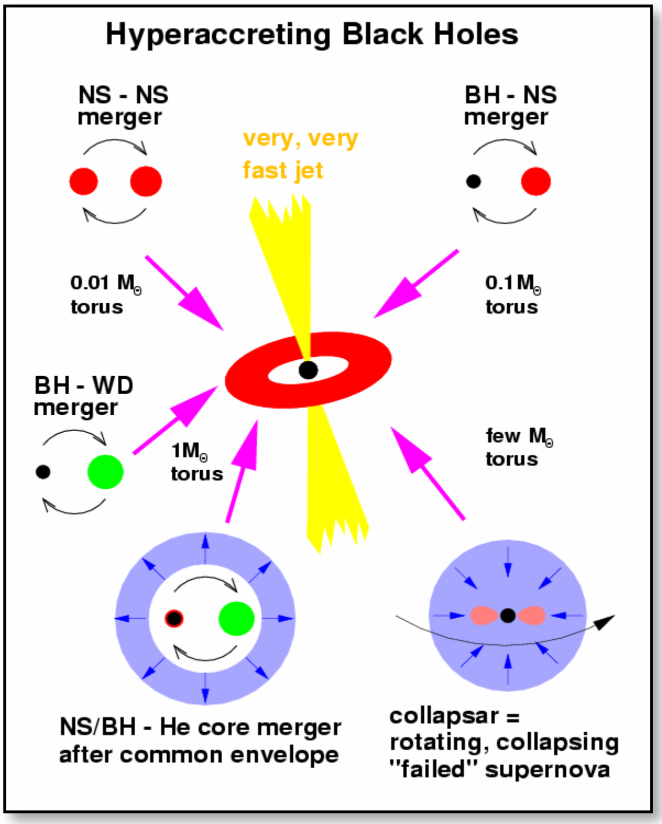
Gamma-ray bursts

Principal GRB Models

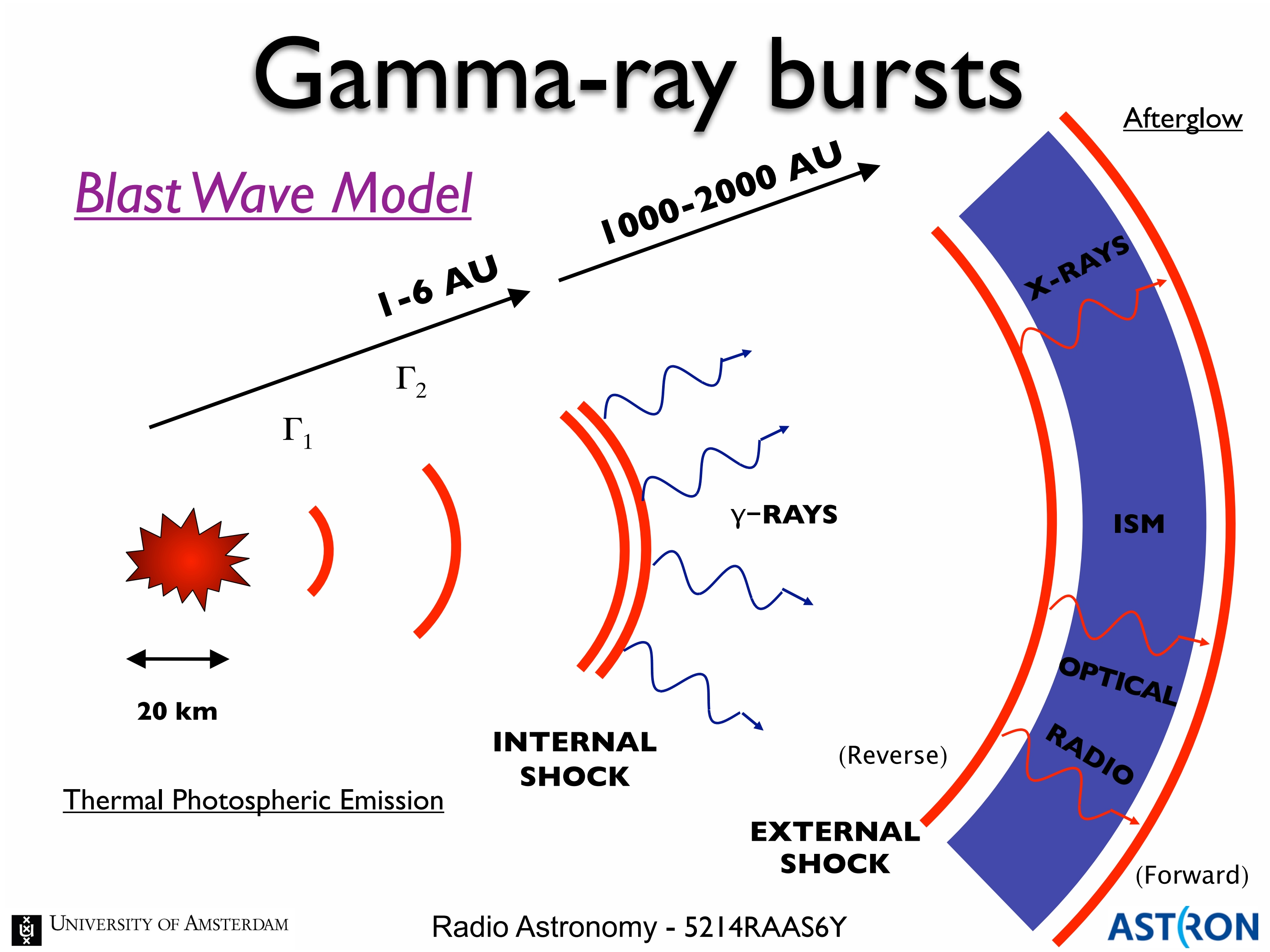
- Collapse of a rotating massive star
- Neutron Star – Neutron Star Mergers
- Black Hole – Neutron Star (He star) Mergers
- Black Hole – Neutron Star Mergers
- Black Hole – White Dwarf Mergers

Science Drivers

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



There are a variety of different models for what produces the bursts.
The trick is distinguishing one model from the other.
Depending on which model is correct, we can potentially gain insight into various interesting scientific questions, i.e. how do black holes grow?

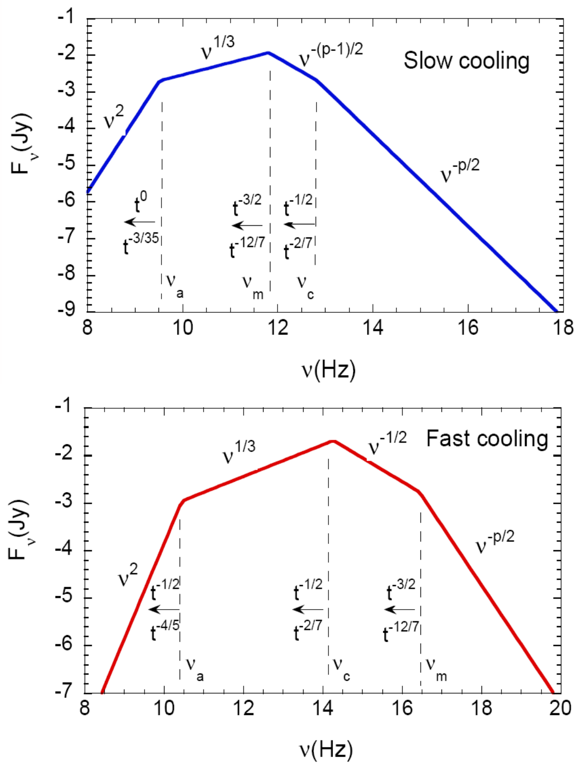


The emission from a gamma ray burst is believed to originate from a blast wave propagating outward. Emission at different wavelengths can occur at much later times than the immediate gamma ray burst itself.

Can be easier to localize the source of the burst at other wavelengths (like radio).

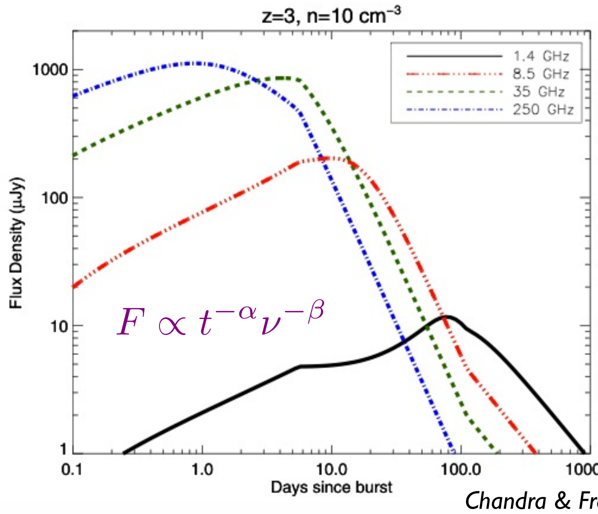
Gamma-ray bursts

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

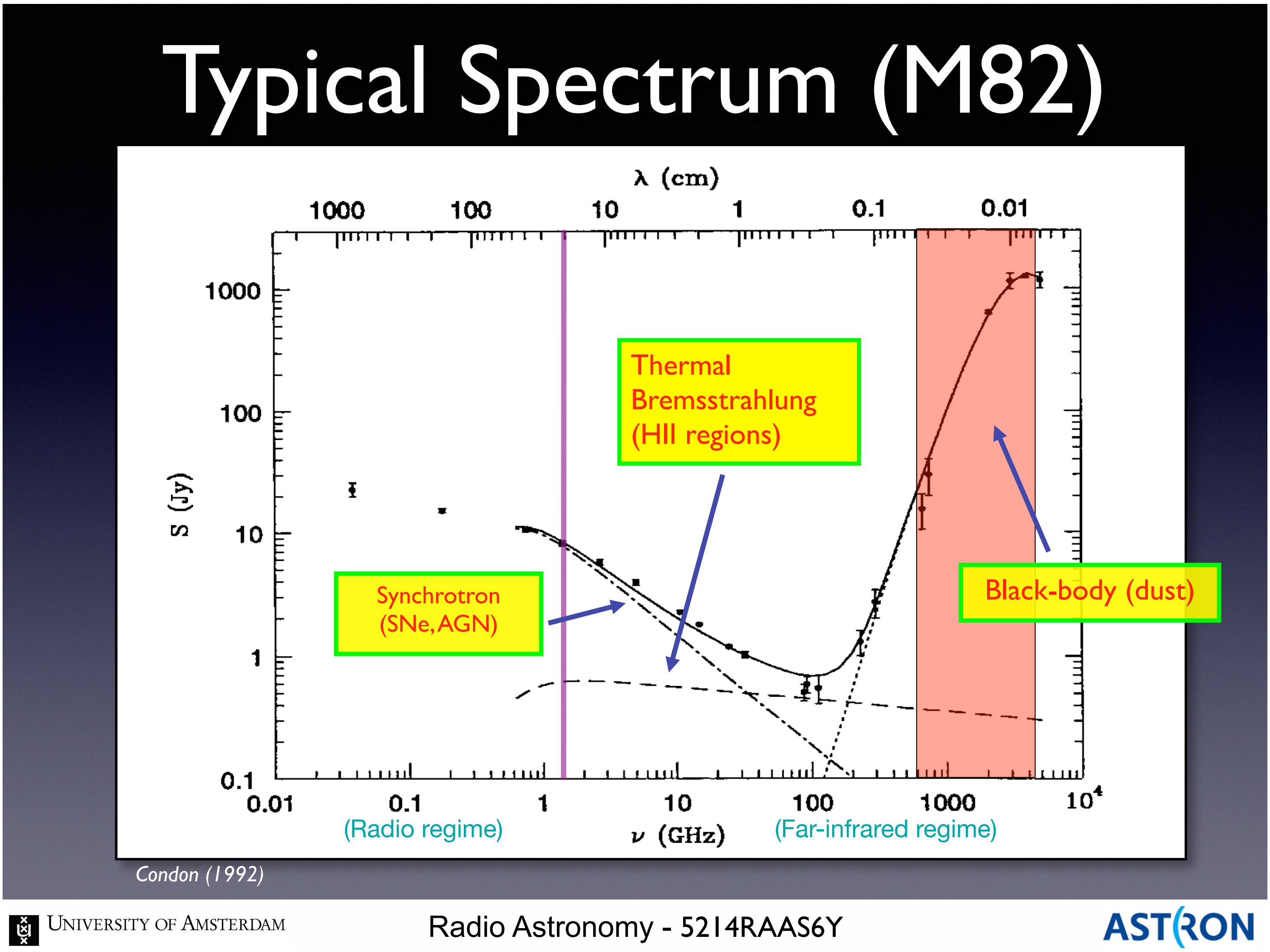
Differences in the shape of the spectrum can sometimes distinguish between physical models. In a general sense, this statement is true at all wavelengths.
The radio spectrum is particularly sensitive to different models for gamma ray bursts.
The radio emission associated with the shock also appears at later times for lower frequencies.
Can potentially identify the source of the bursts days after the gamma ray flash instead of seconds.

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).

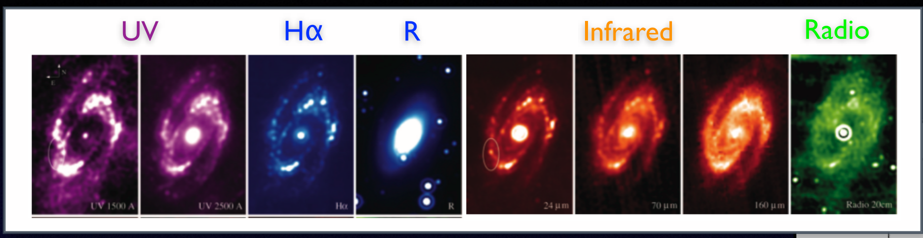
Starburst galaxies are descriptively named since these are galaxies seem to be undergoing a large, recent burst of star formation.
Understanding what causes these big episodes of star formation can tell us about how galaxies grow and evolve.



Typical broadband radio spectrum for a galaxy. Different parts of the spectrum are dominated by different sources and different physics. Typically break the spectrum down into two components: thermal and non-thermal.

L_{FIR} - L_{Radio} Correlation

M81

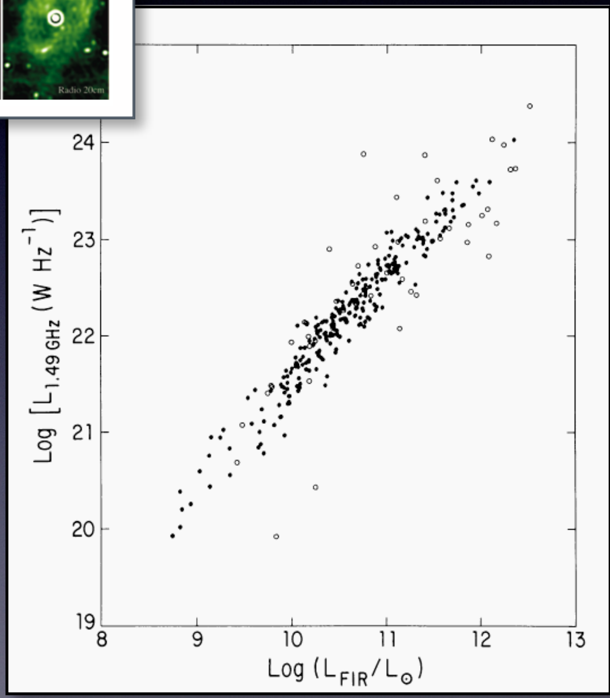


Gordon et al. (2004)

- 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:

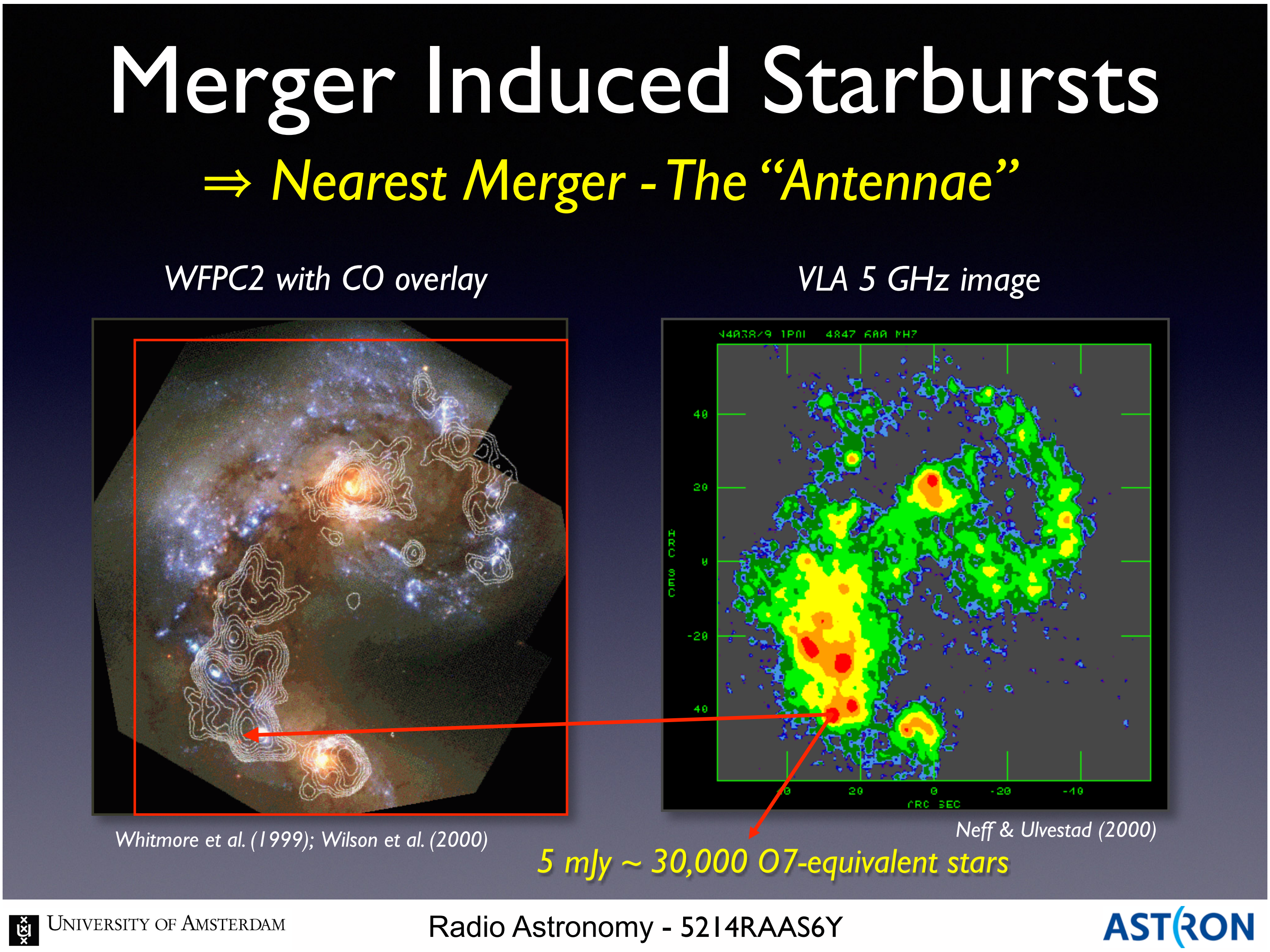
  $SFR\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (ergs\ s^{-1})$

- Can use radio to measure SFR at high z!



Kennicutt (1998)

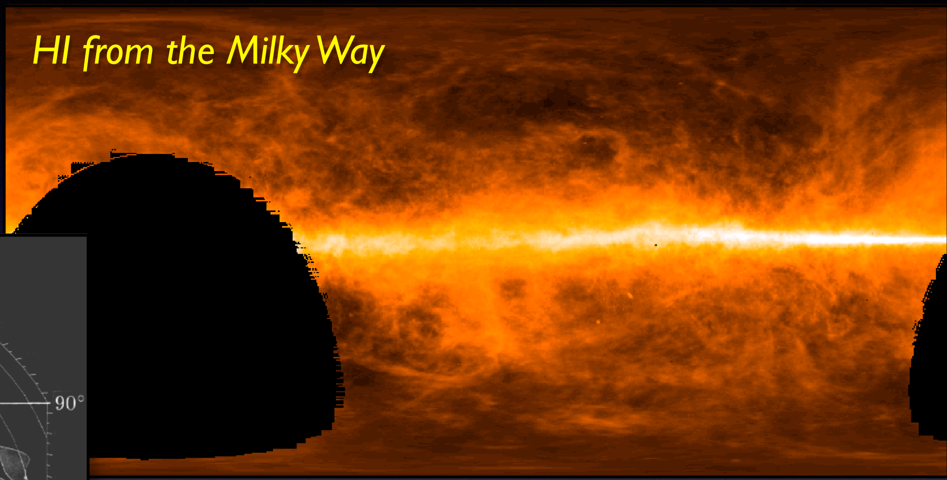
Well-established correlation between infrared luminosity and radio luminosity.
Can use radio observations as a proxy for star formation.
Since radio emission can be easily detected to greater distances than say IR, radio data provides an easier way to search for star formation at high redshifts.
Must assume something about the star formation history to use this method.

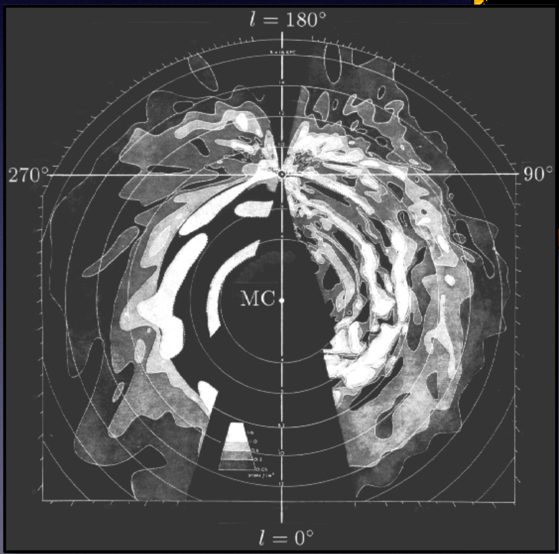


Comparison between optical+CO maps and radio image for a nearby merging galaxy.
Optical shows current distribution of stars, while CO shows cold material out of which the stars formed.
Images show how well radio emission traces the cold, star forming material.
Mergers are believed to be an important mechanism for how stars form.

HI Galaxy Structure Studies

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

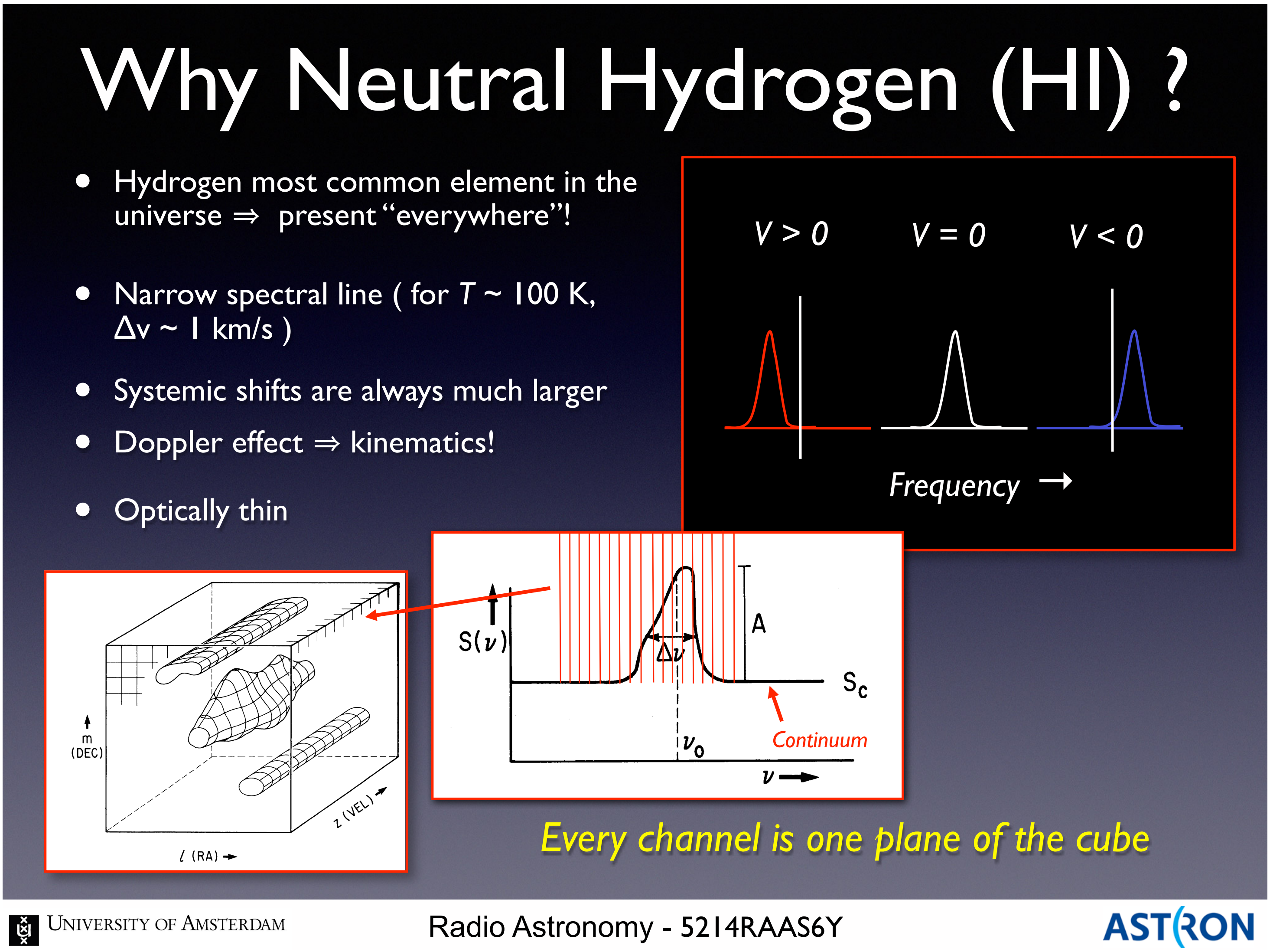




Oort, Kerr & Westerhout (1958)

- 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

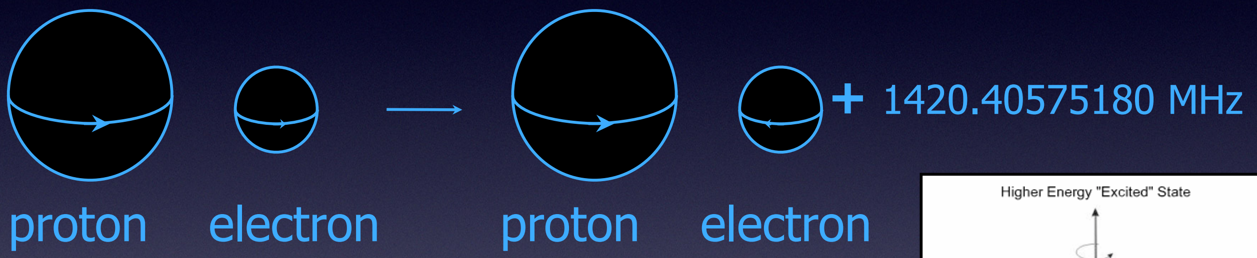
Radio emission from neutral hydrogen, HI (pronounced "H-1"), is one of the primary ways to study the evolution of mass in the universe.
Can use it to study mass distribution in our own galaxy and in others.

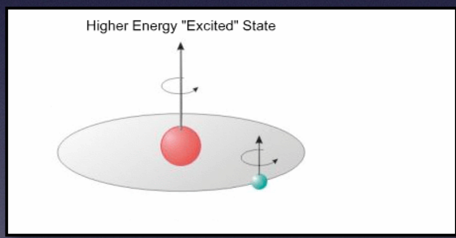


Radio observations of HI are based on detected an emission line from hydrogen.
HI line emission has a narrow intrinsic width which means we can more easily detect shifts due to gas motions.
Red and blue doppler shifts in the observed line translate into velocity motion away and towards us.
HI line emission also tends to be optically thin so the strength of the line scales directly with the amount of HI gas.

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)

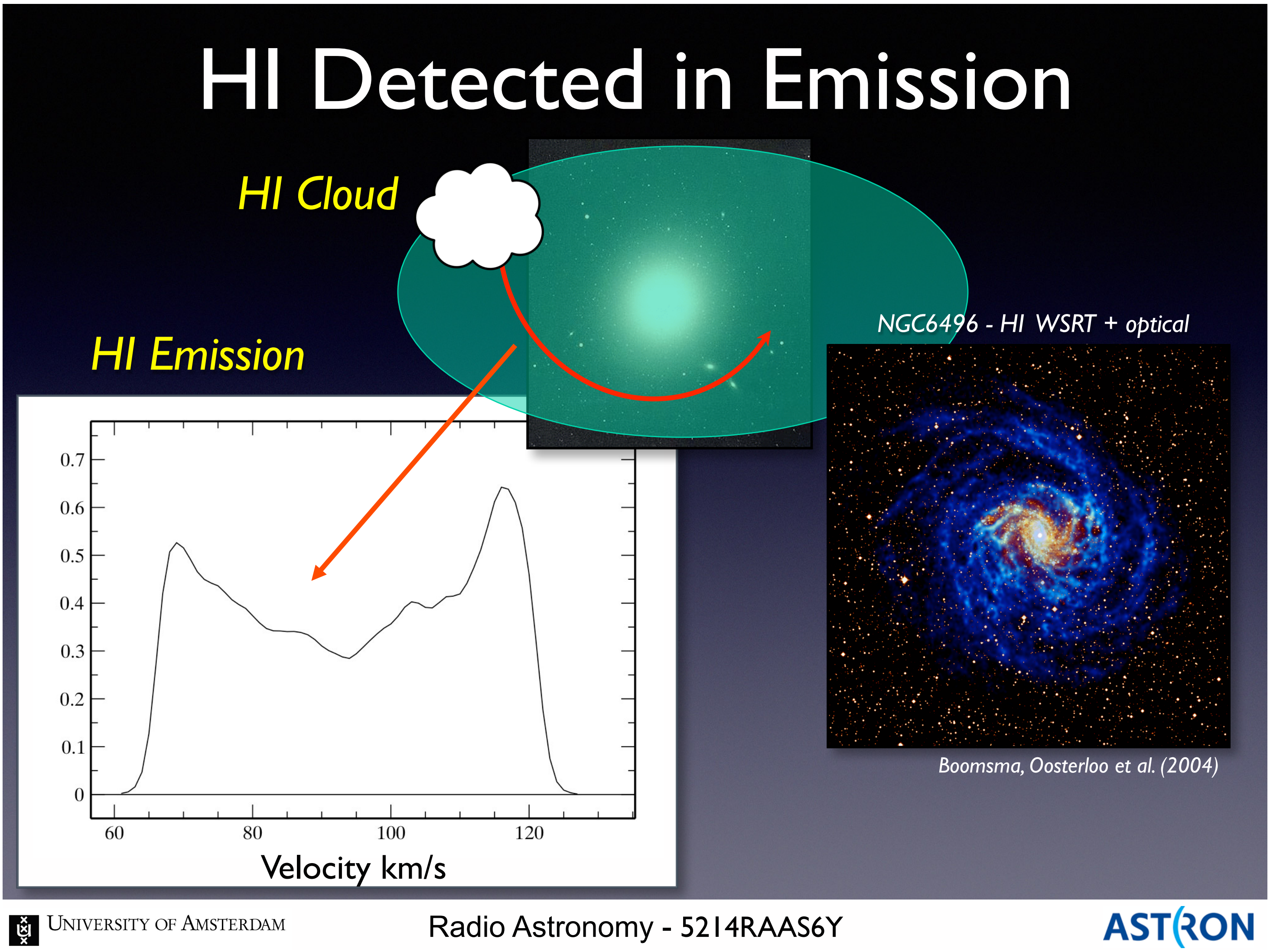




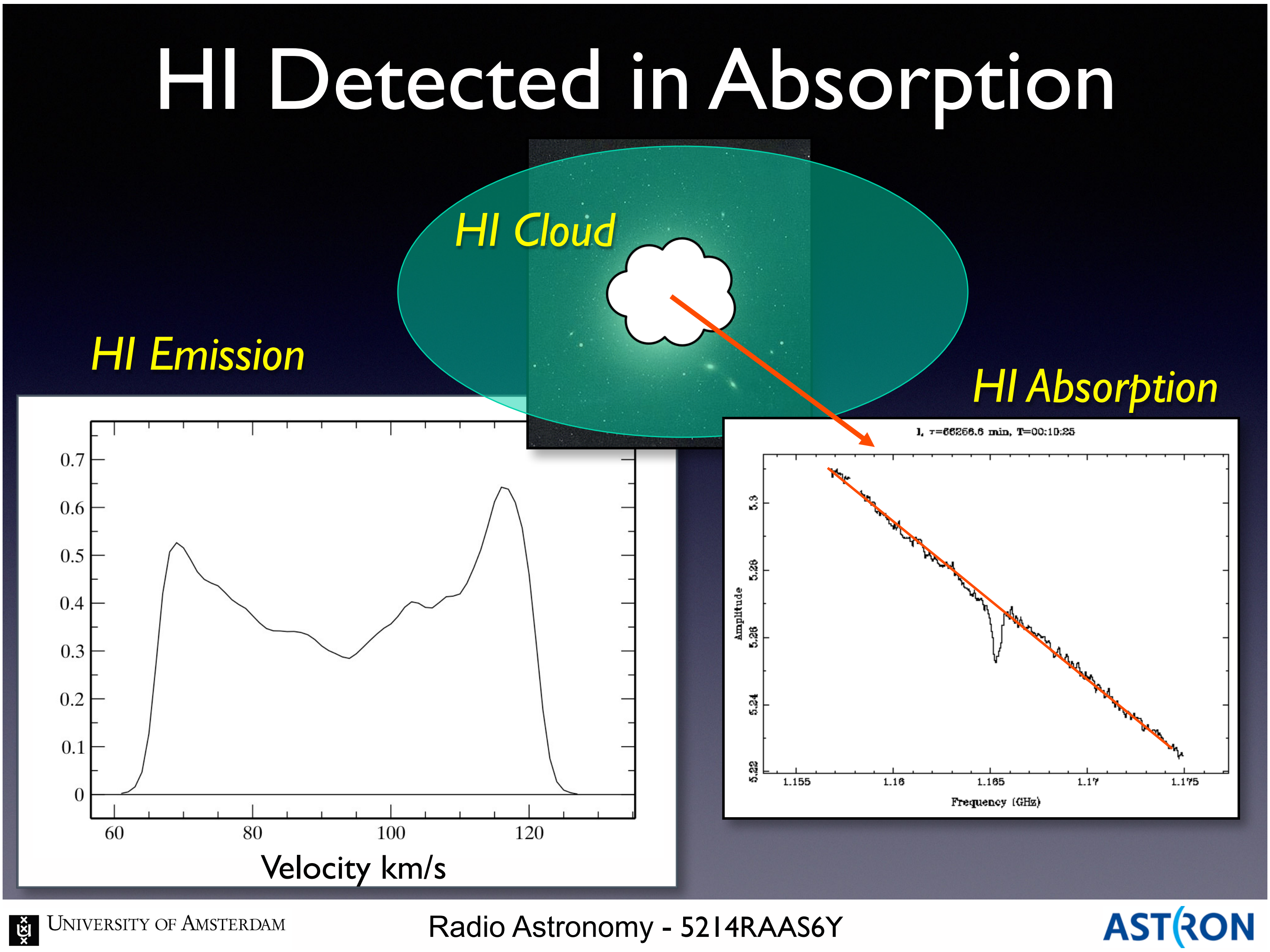
Frequency of the transition:
1420.405752 MHz (21.105 cm)
(Hendrik van de Hulst, 1944)

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

21 cm line emission from HI first predicted by a Dutchman in 1944. Hup Holland hup!

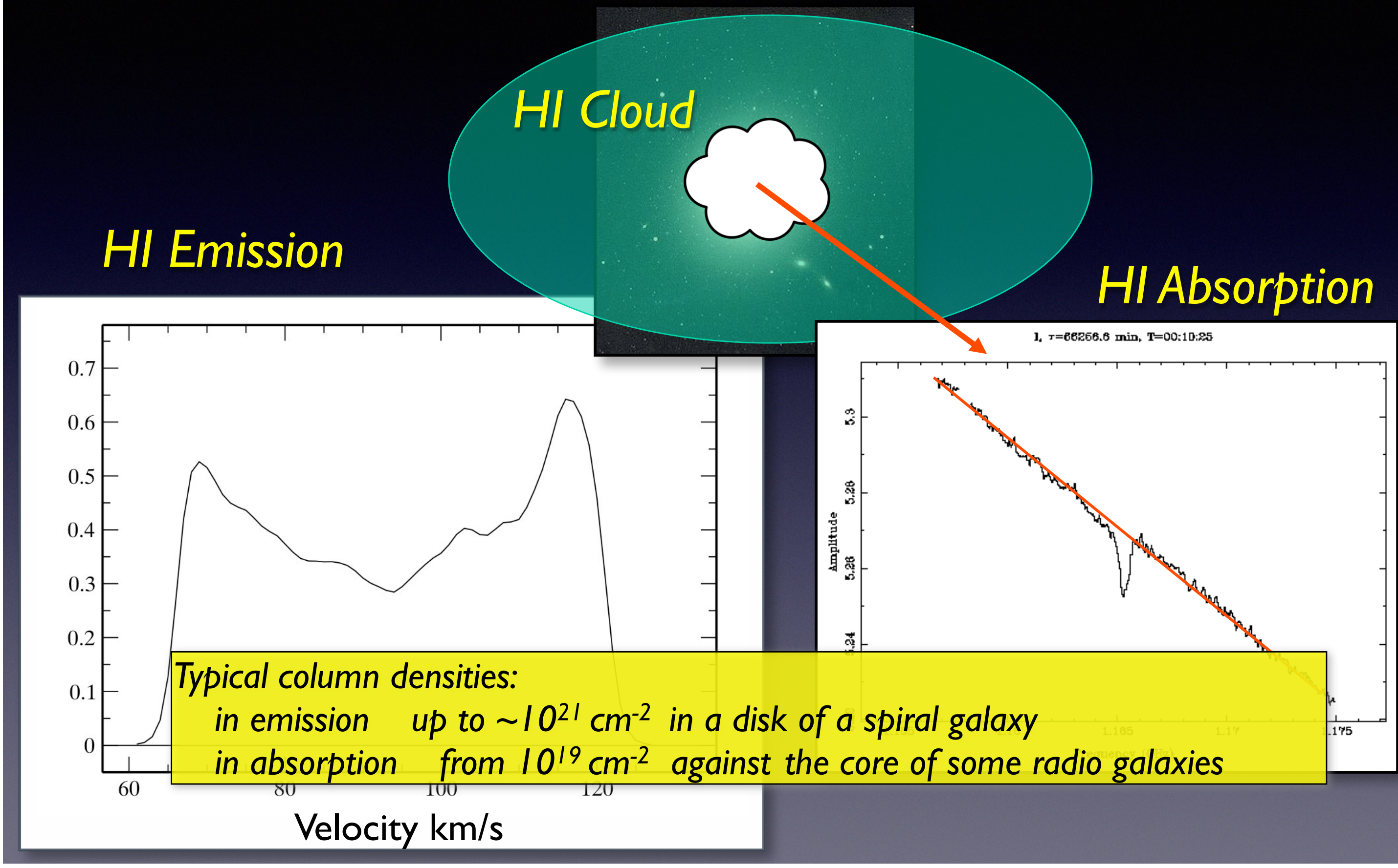


We can detect HI lines in both emission and absorption.
In emission, the shape of the line profile contains velocity information about the orbit of the HI cloud that emitted it.
The orbital velocity also contains information about the mass of the galaxy the HI cloud is orbiting.



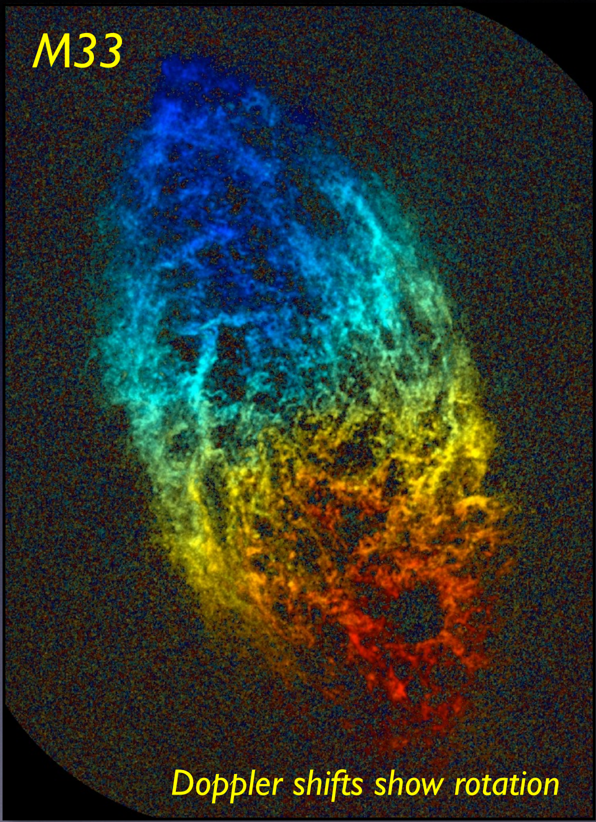
In absorption, the HI cloud blocks photons from a source behind the cloud.
The decrement in the observed spectrum is basically related to the amount of HI in the cloud.
Requires a bright background source.

HI Detected in 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

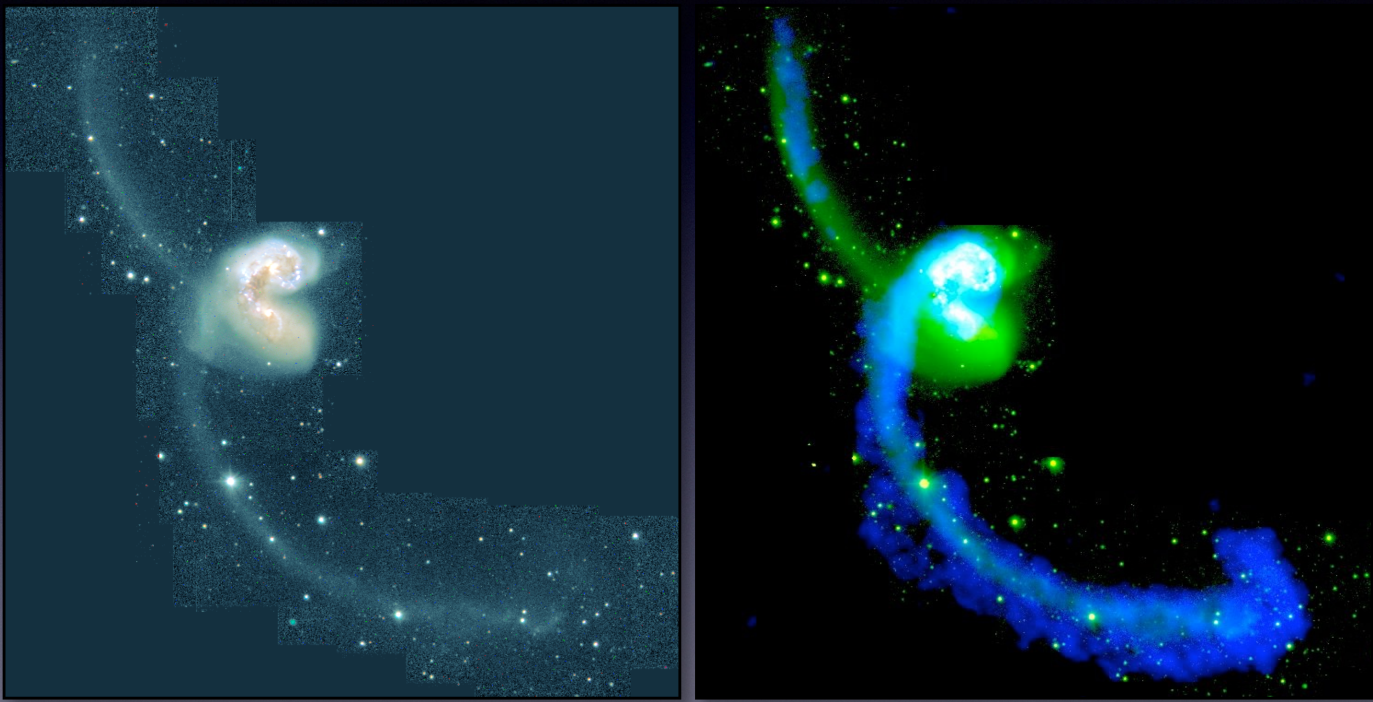


- Galactic studies , high velocity clouds, satellites of the Milky Way.....
- Nearby galaxies and gas accretion
- Dark matter studies
- Interacting systems (including the stream in our own Galaxy)
- Effects of dense cluster IGM on cluster member galaxies (e.g. stripping etc.)
- Gas and Active Galactic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

An example of the sort of detailed velocity maps we can make for nearby galaxies using HI studies.

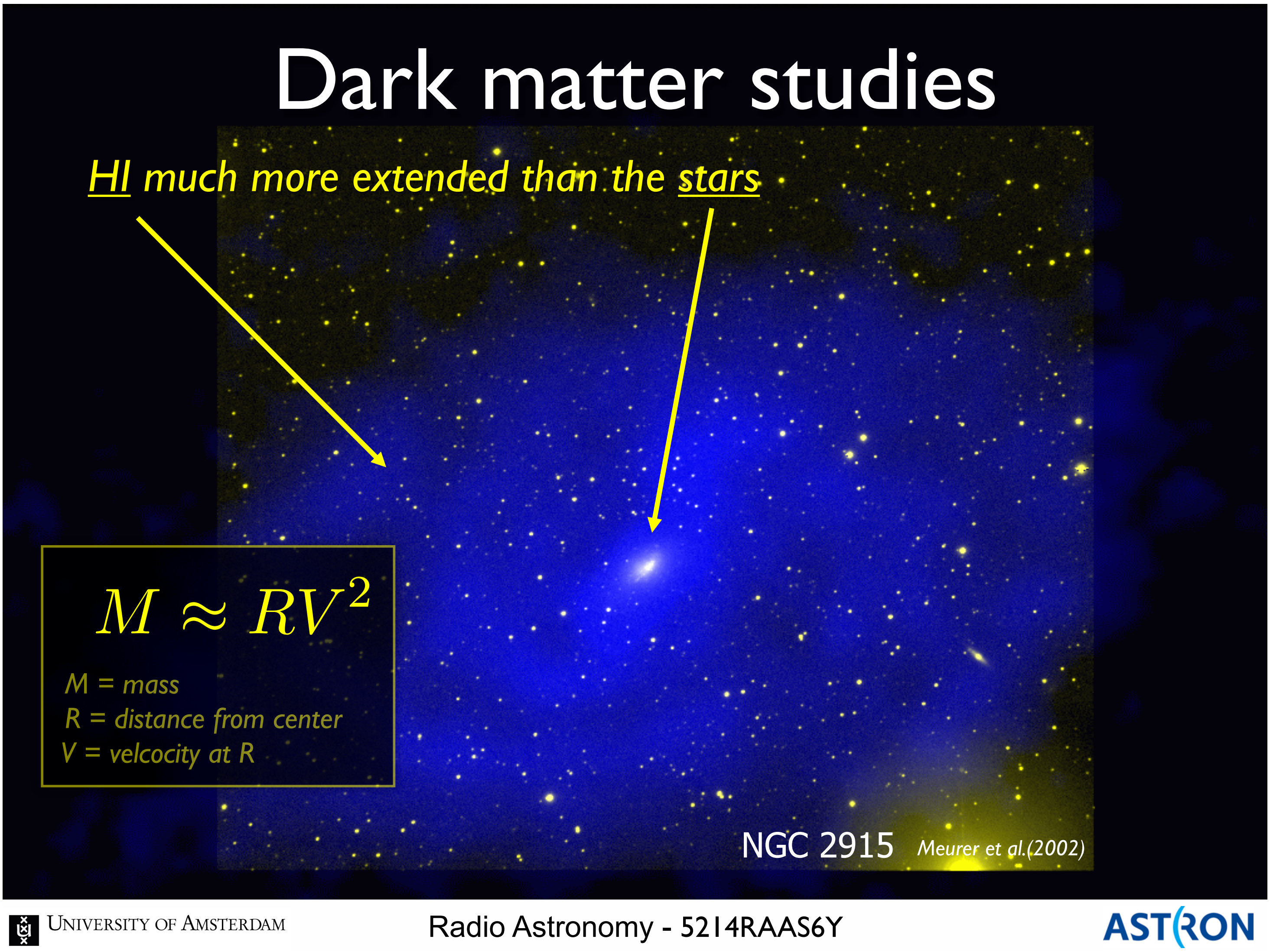
Interacting systems

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



Hibbard et al. (2001)

An example of using HI maps to trace the gas stripped out of two interacting galaxies.

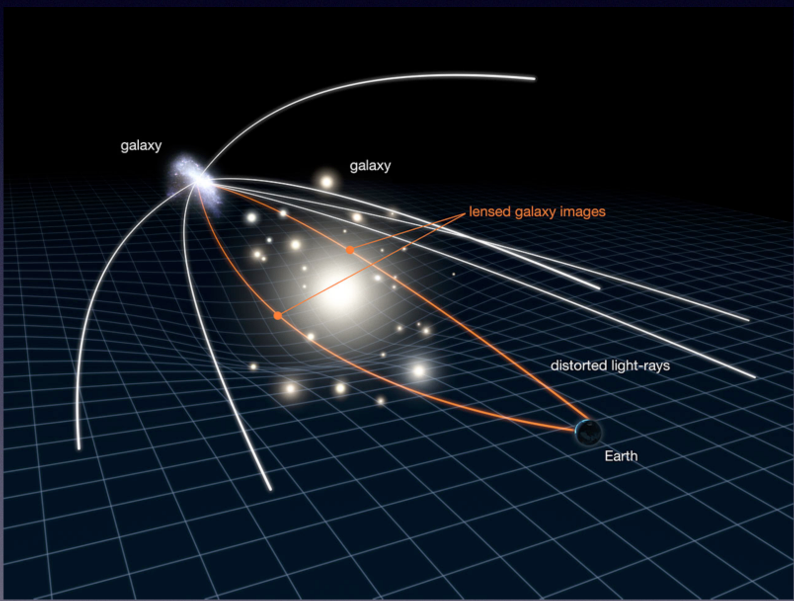


HI studies can allow us to study the rotation curves for gas in galaxies out to much larger radii.
The rotation velocity as a function of radius is related to the total mass inside that radius.
Total mass includes matter we see and also dark matter.
Measuring the HI velocity curve allows us to constrain the dark matter in galaxies.
This technique is how “dark matter” was first discovered.

Intermission

Gravitational Lensing

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



Can be used to:

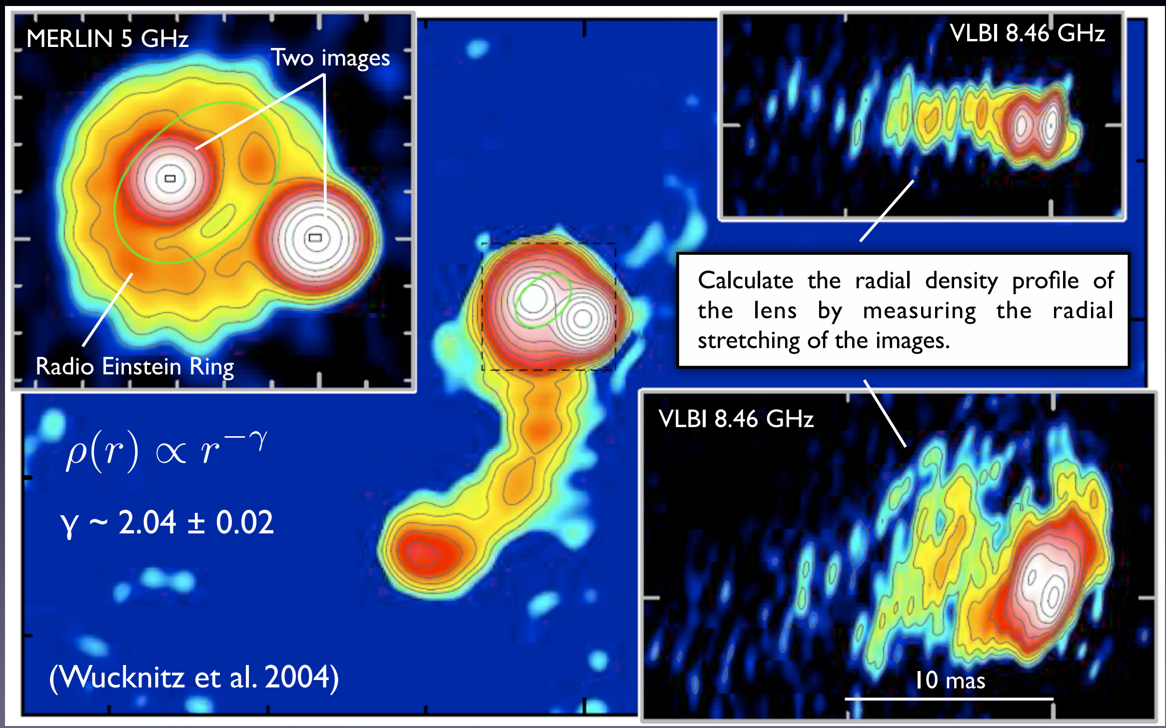
i) Study the mass distribution of the lens -- test galaxy formation and models for dark matter.

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

iii) Measure the cosmological parameters through the lensing statistics.

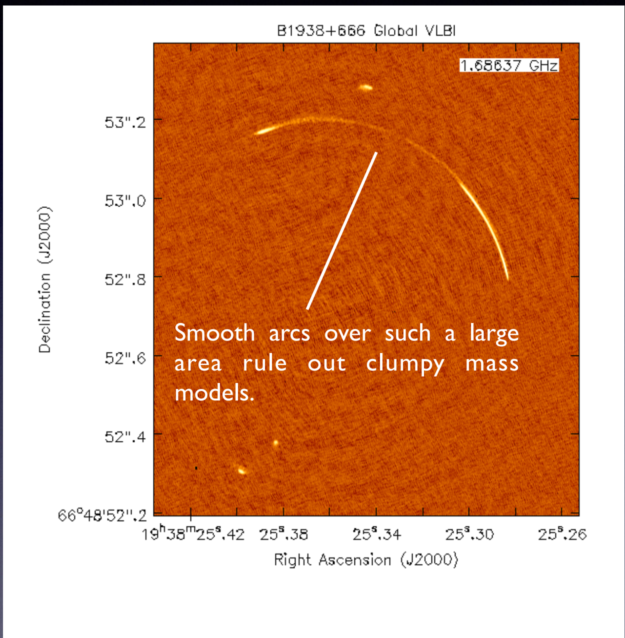
Gravitational lensing is a technique that can be used to study a wide range of problems.
It acts like a telescope and focuses light so we can study more distant objections magnified by the lens.
We can also study the lens itself which tells us about the amount and distribution of mass in the lens.
Lensing is often used to construct maps of the amount of dark matter in clusters for example.

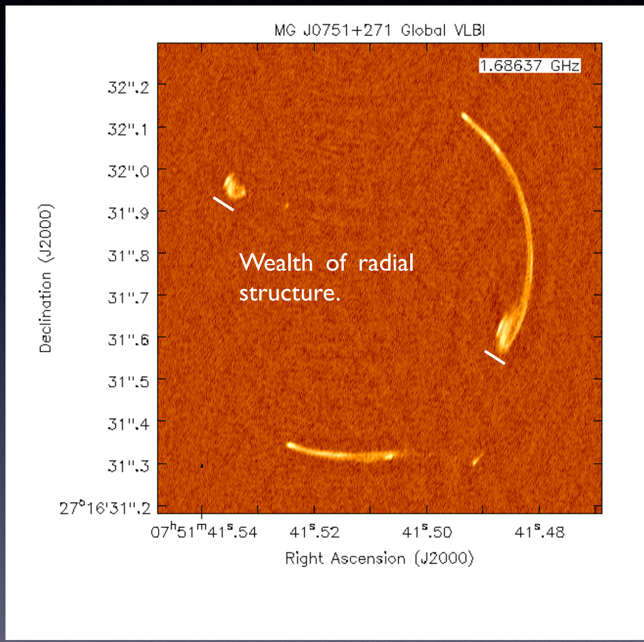
Mass Structure of Galaxies



The geometry of the lensing system can be complicated. Have to model the mass distribution in both the background source and the lens. Makes for a complicated fitting problem.
Data with high angular resolution places tighter constraints on the fitting process.
Tighter fit constraints translate into better models for the mass distributions.
Radio data with high angular resolution can provide these constraints.

Extended Arcs

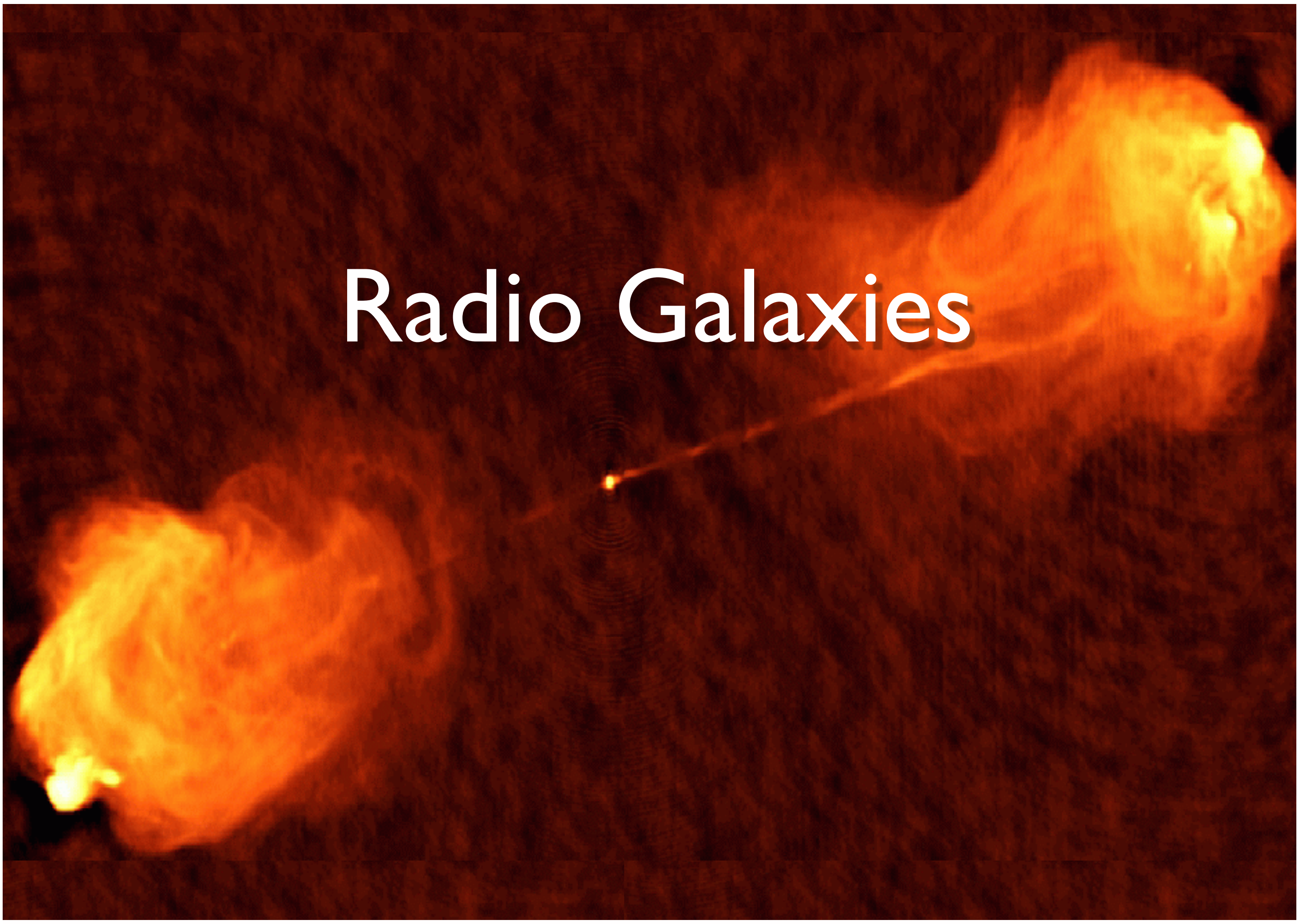




New datasets using the upgraded global VLBI array (23 telescopes spread across the world) detect gravitational arcs extended over 0.8 arcsec with an angular resolution of just ~4 mas.

An example of some recent high resolution, radio lensing studies.
Those observed long, thin arcs give very strong constraints on the clumsiness of the underlying mass.

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)

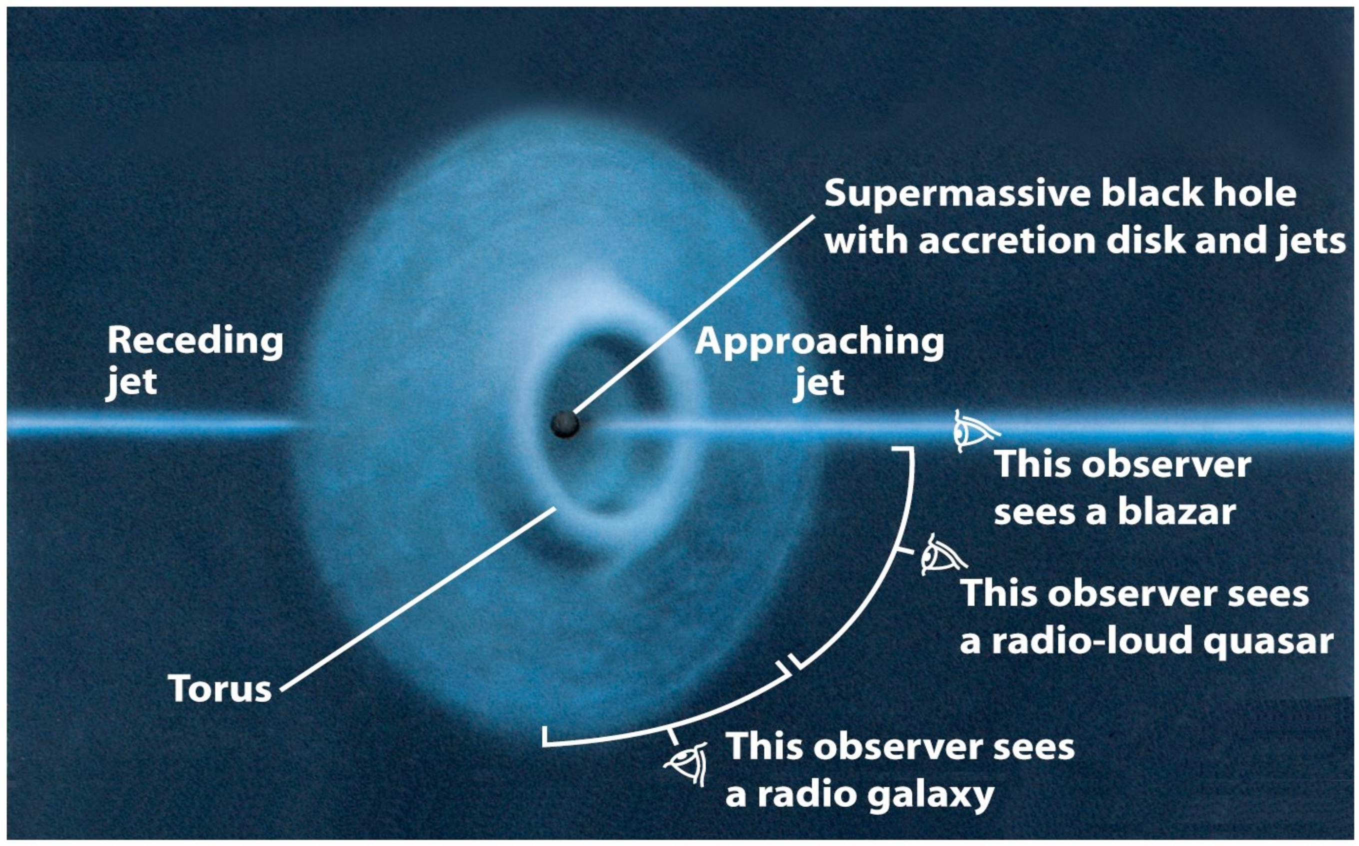
There are many different terms for the variety of AGN and radio galaxies.
Underlying picture is always the same, a supermassive black hole accreting matter and feedback energy and material into the surrounding medium.

The Radio Galaxy Zoo

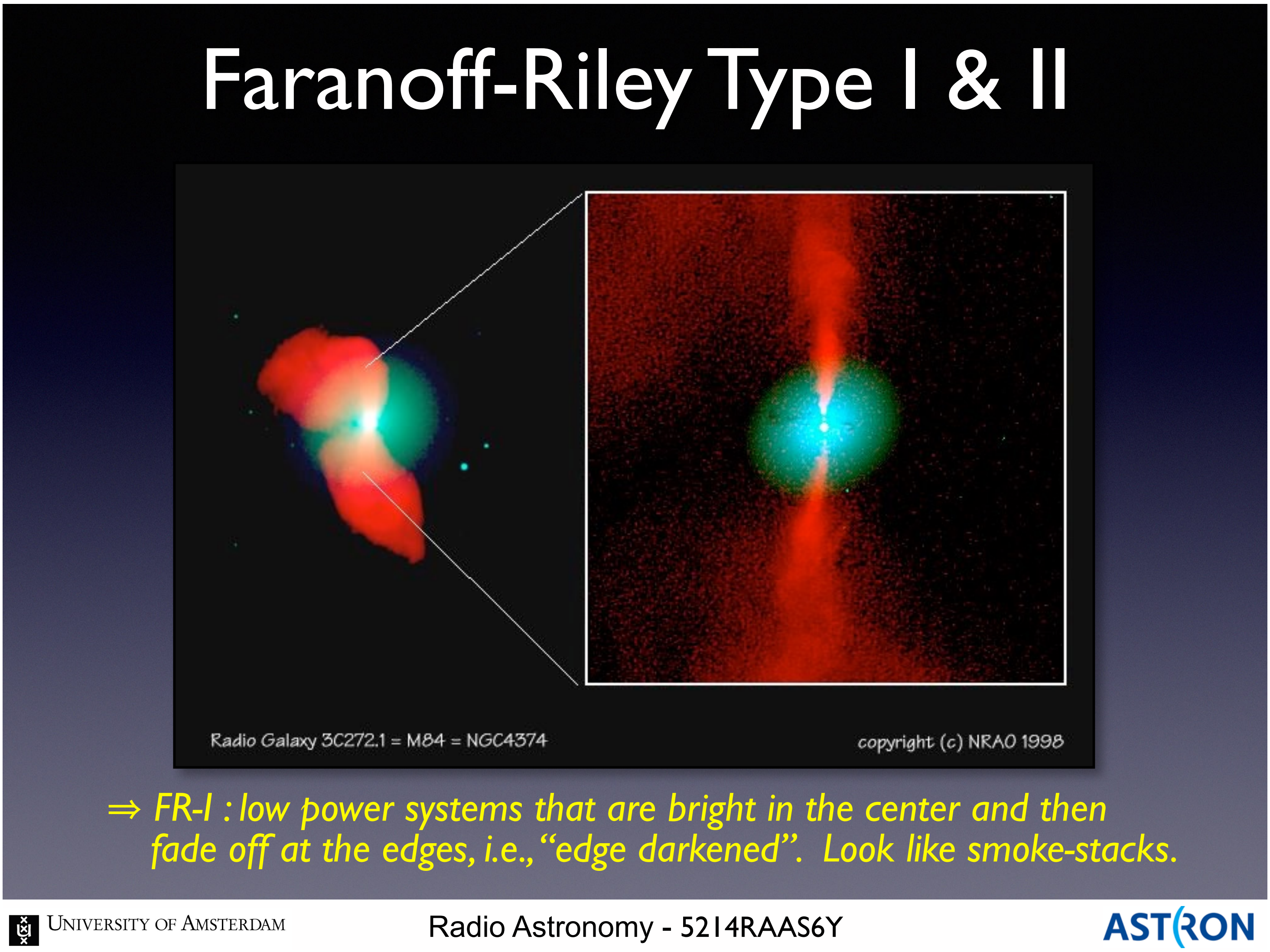
- **Radio Galaxies**
  - **Strong extended radio emission but rather weak nucleus. Can display either narrow optical emission lines (NLRG) or broad optical emission lines (BLRG)**
- **Radio Loud Quasars**
  - **Strong extended radio emission *and* a strong/variable nucleus showing broad optical emission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

Most varieties of AGN are based on the presence (or absence) or various observational signatures.

AGN Unification Schemes

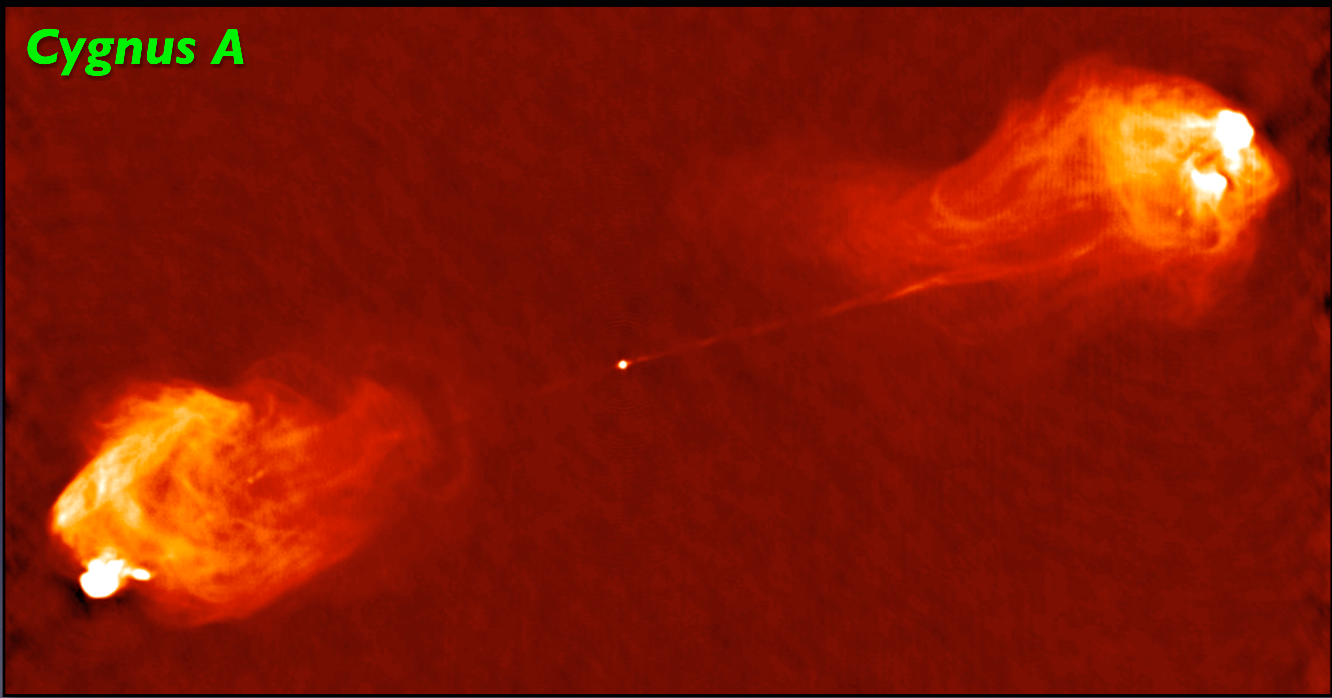


Many of the observed differences in AGN can be explained by assuming we seeing essentially the same general source structure from different angles.



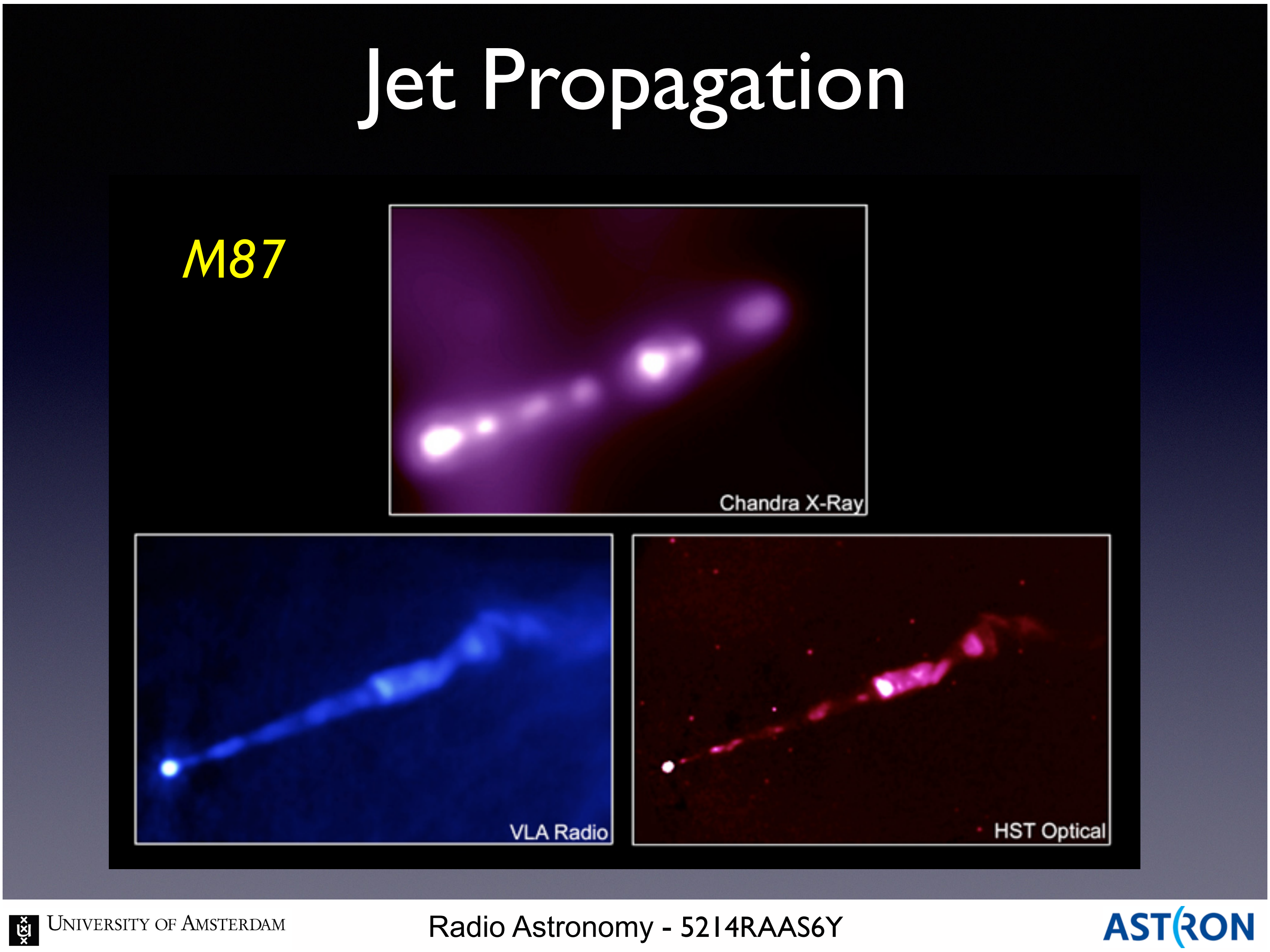
Historically, radio galaxies have been divided into two classes: FRI's and FRII's.
The classification is defined based on radio power. FRI's are lower power, and FRII's are high power.
The two types also have distinct morphological differences.
The question is what fundamental physical differences in the sources drive these observed differences.

Faranoff-Riley Type I & II



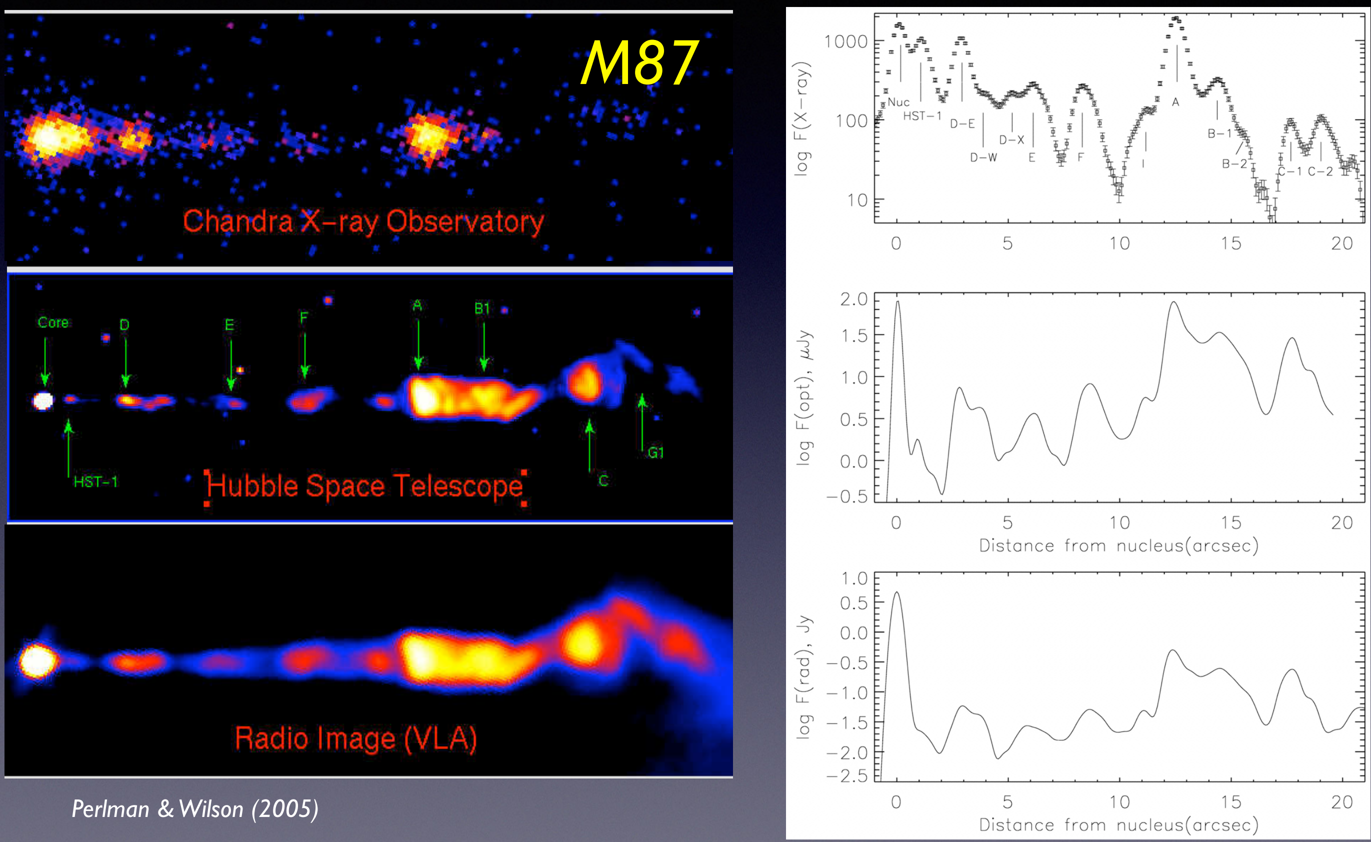
⇒ *FR-II : high power systems that brighten at the edges (edge-brightened). Often look like directed "explosions".*

Could be due to differences in the black hole itself, the amount of fuel available, density and makeup of the surrounding medium, or the history of the larger environment (i.e. cluster mergers).
Lots of radio astronomers busily at work trying to answer these questions. Me included.



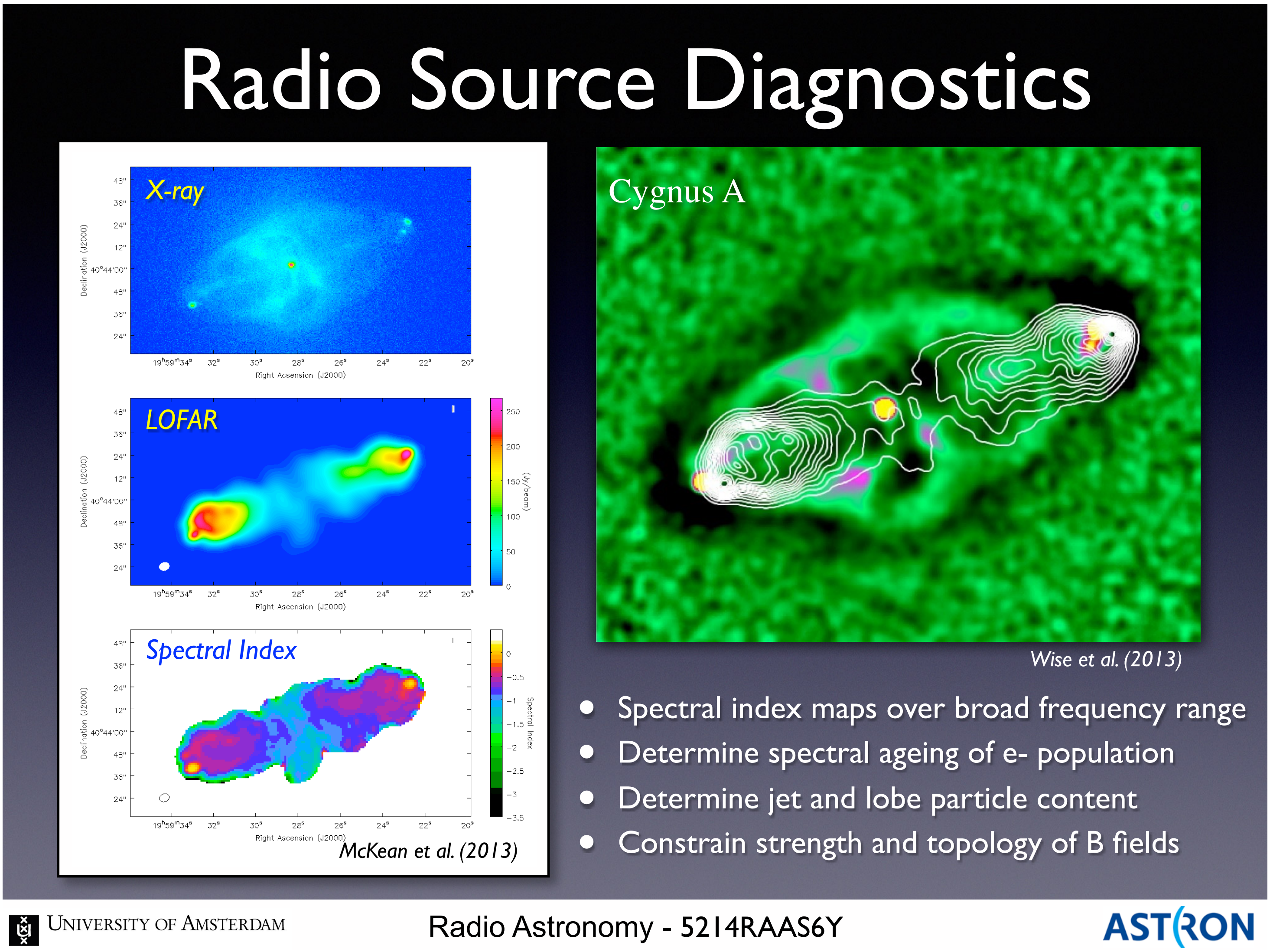
Jets are a very common observational signature of accretion onto BHs.
Jets are seen in many radio galaxies (and even on smaller scales).
Jets are seen at all wavelengths (though not in all objects).
Jets are one of the primary conduits for carrying energy liberated by accretion away from the immediate vicinity of the black hole.

Jet Propagation

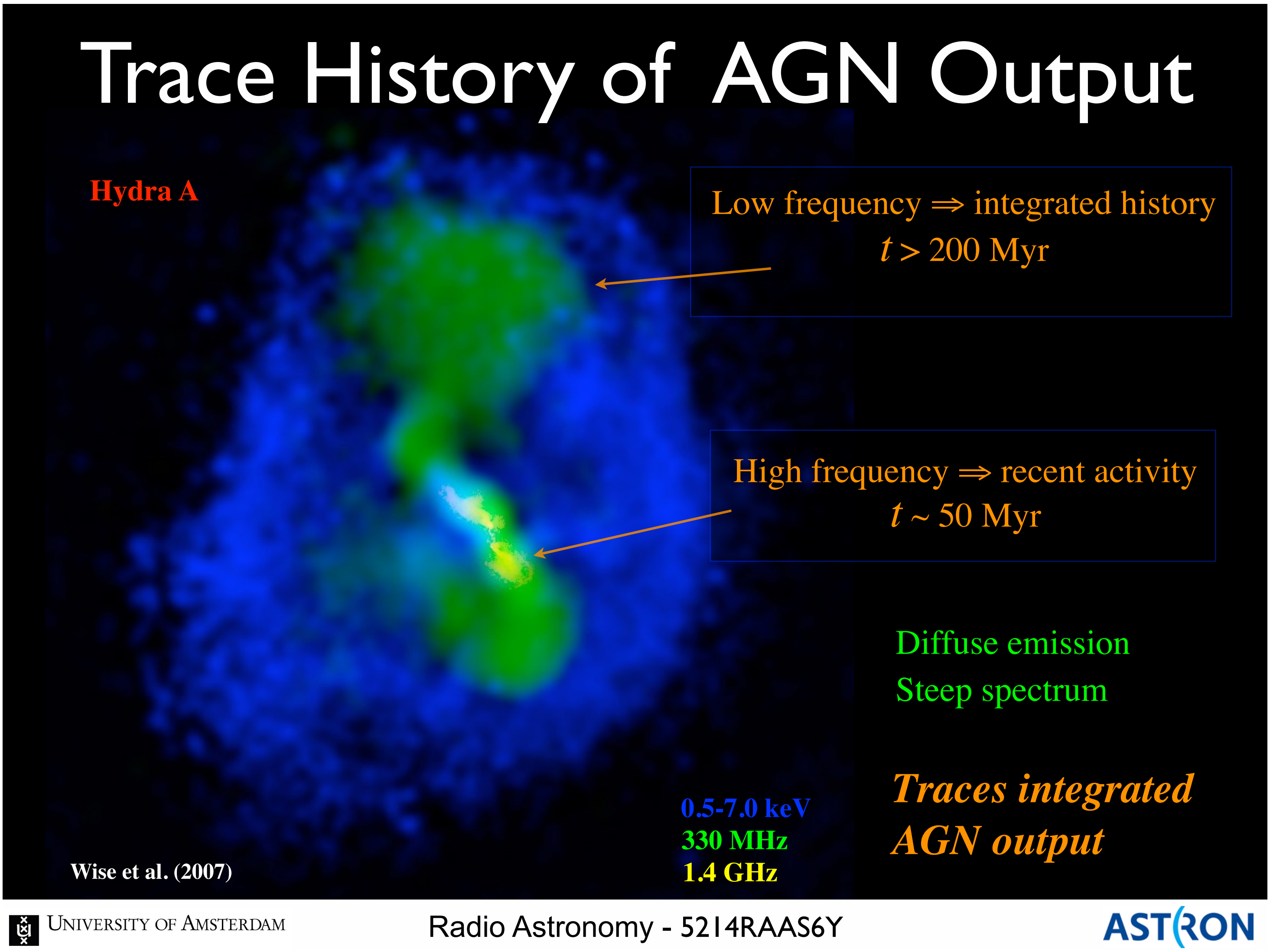


Perlman & Wilson (2005)

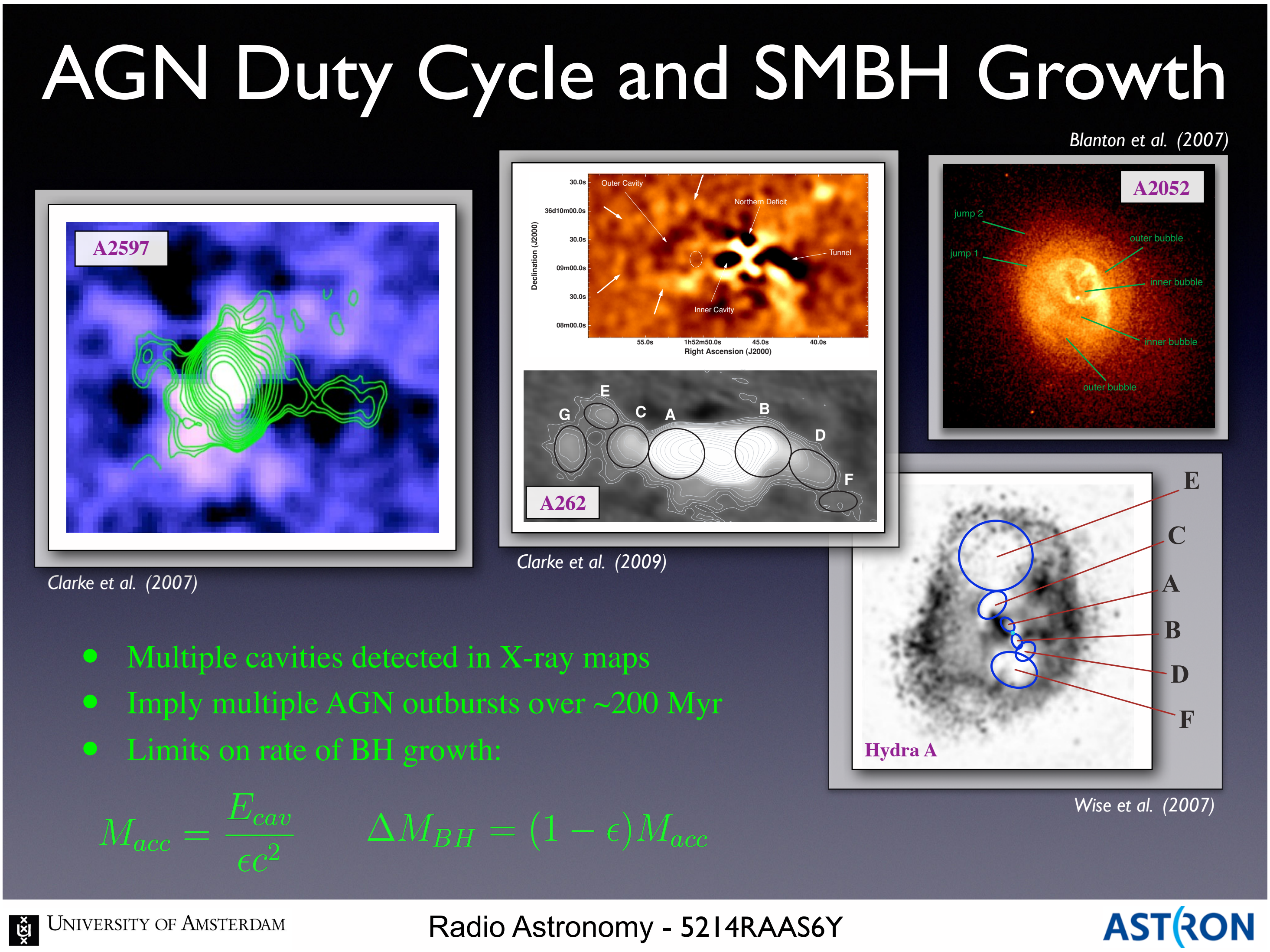
By combining observations of jets at many wavelengths, we can follow the flow of that accretion energy out into the surrounding medium.
Long baseline radio observations let us see trace that flow closer into the black hole than in any other wavelength.



Radio observations provide uniques diagnostics about radio galaxies.
For example, using spectral information in the radio, we can derive the age of the emitting material.
Must assume something about the underlying initial spectrum.
This technique can give us an estimate for how the output of the AGN varies over time.

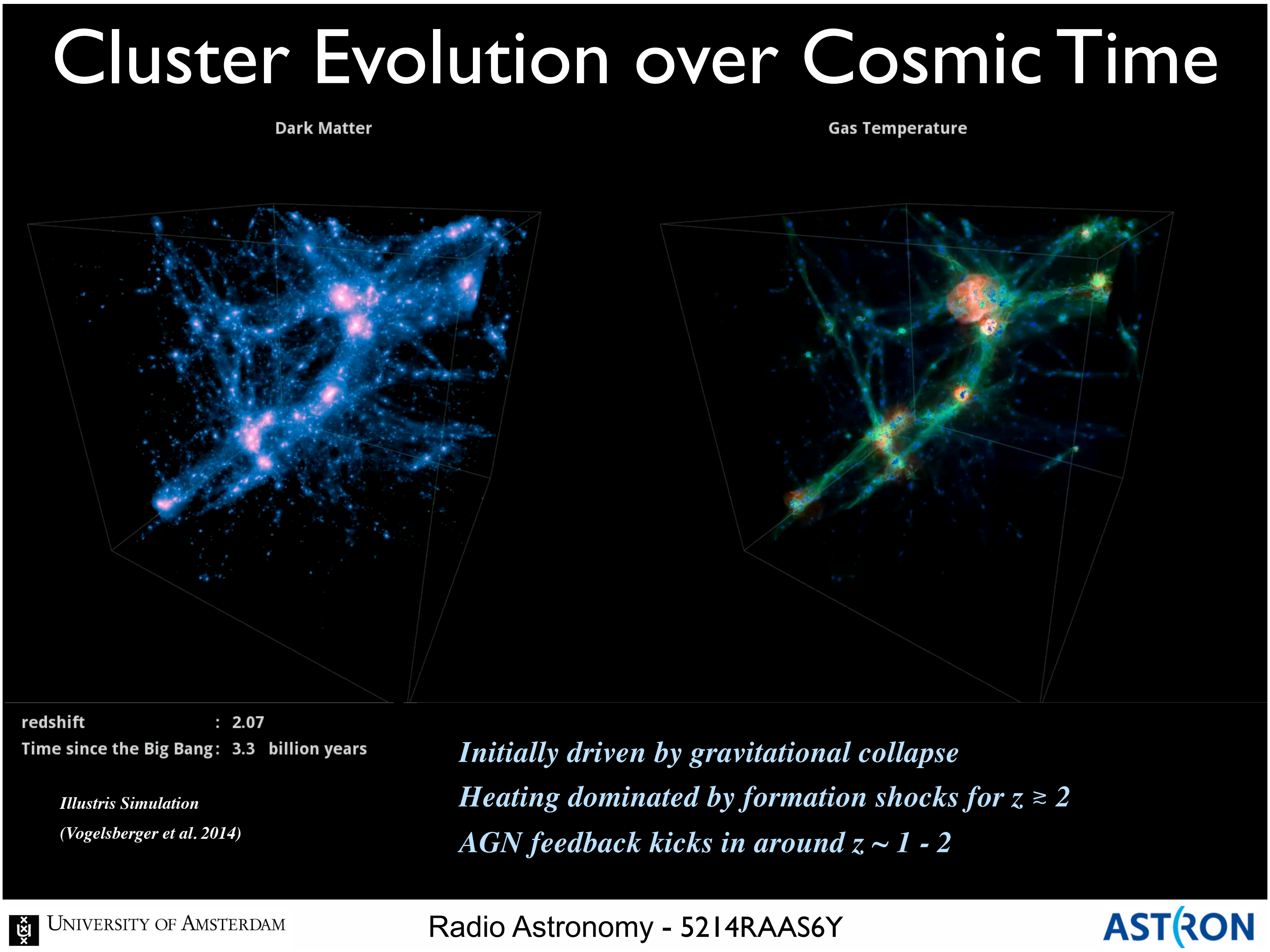


We see evidence for the long-term evolution of AGN output in both the radio and X-ray.
Observations at low and high frequency radio give us data points for the AGN output spread over 100’s of millions of years.

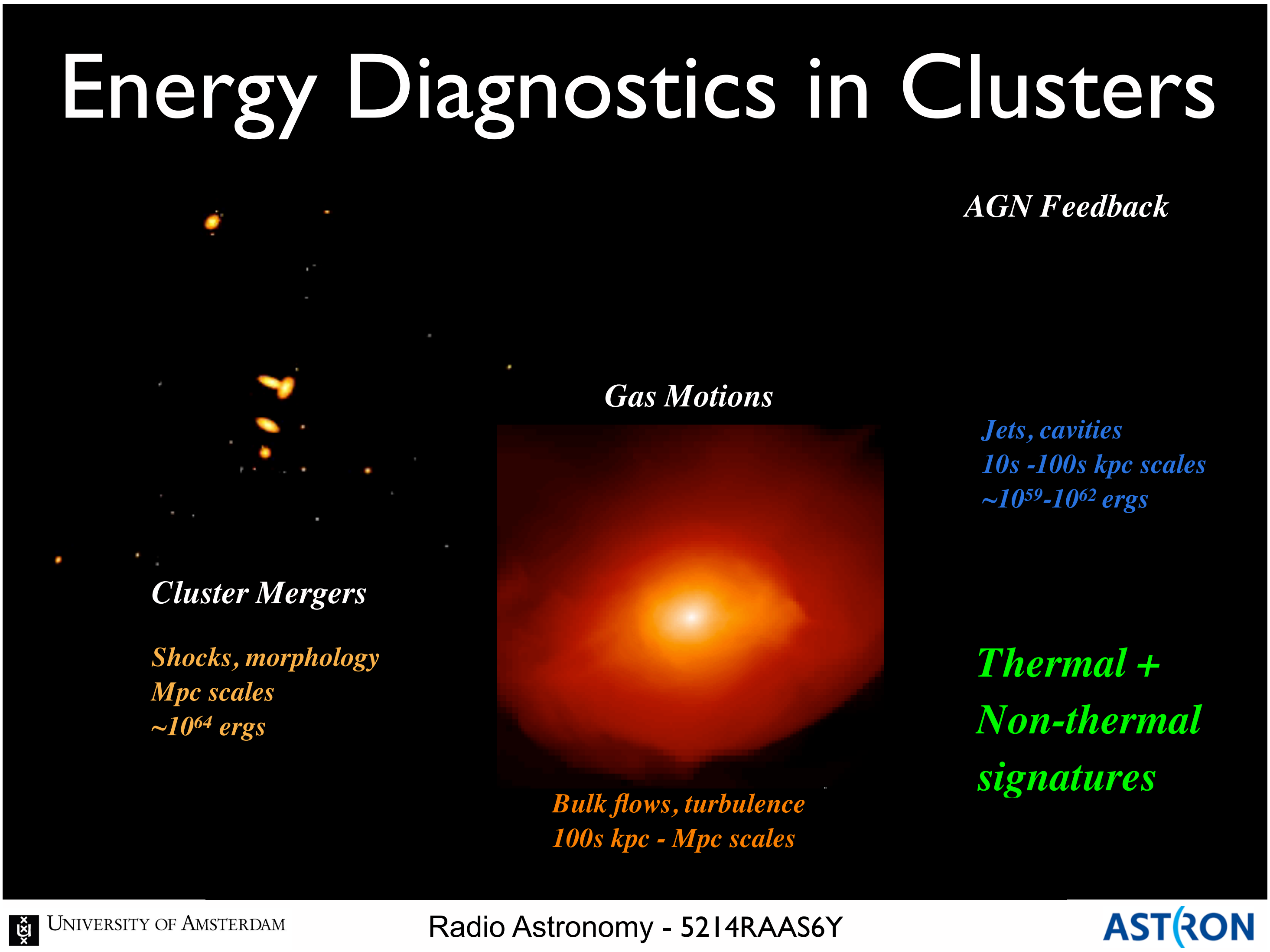


We can turn these observations around and say something about how black holes grow.
If the energy we see in the radio (and X-ray) was released by matter accreting onto the black, then each outburst gives us an estimate for the increase in the mass of the black hole over time.

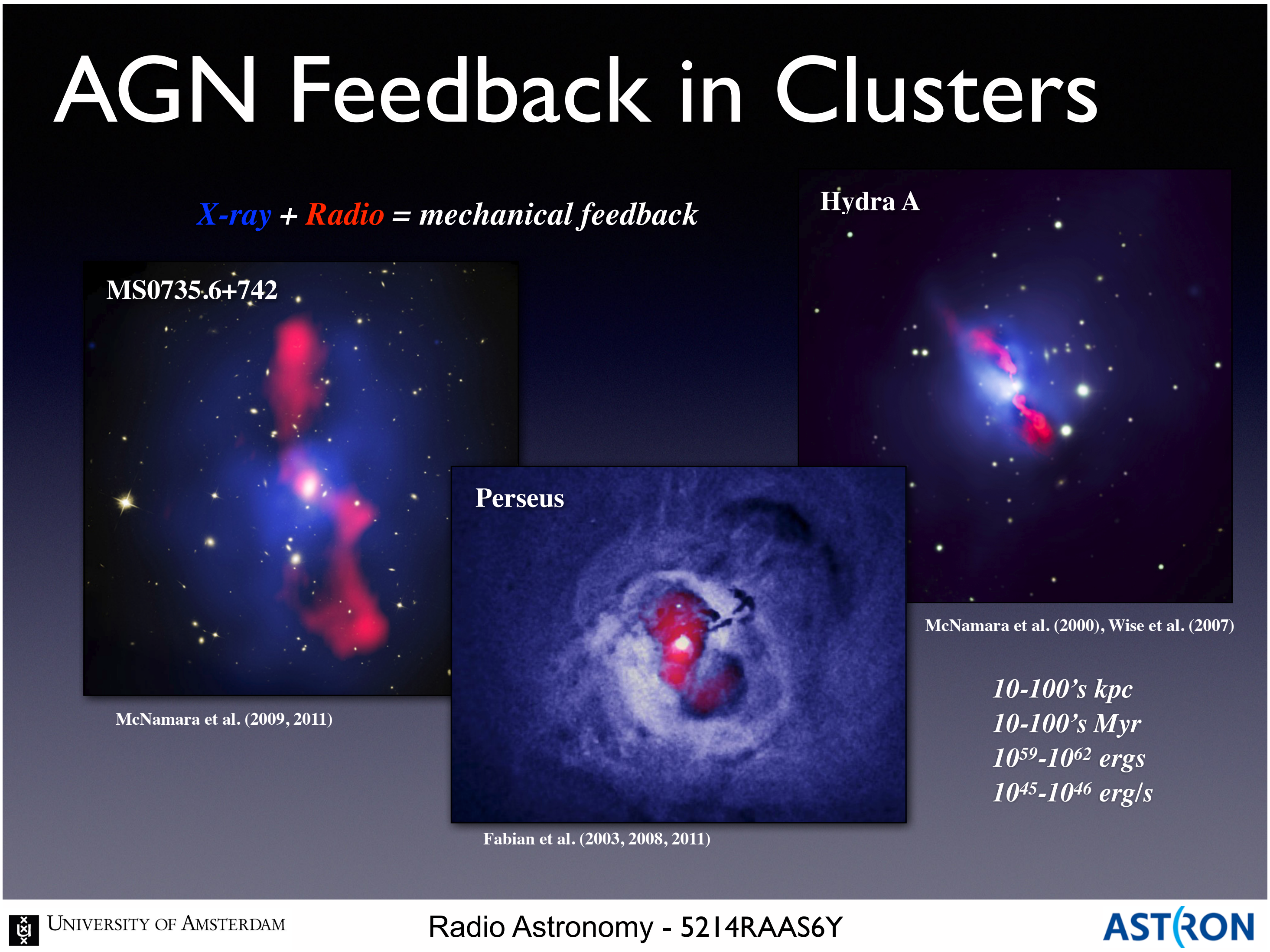

Clusters of Galaxies
& AGN Feedback



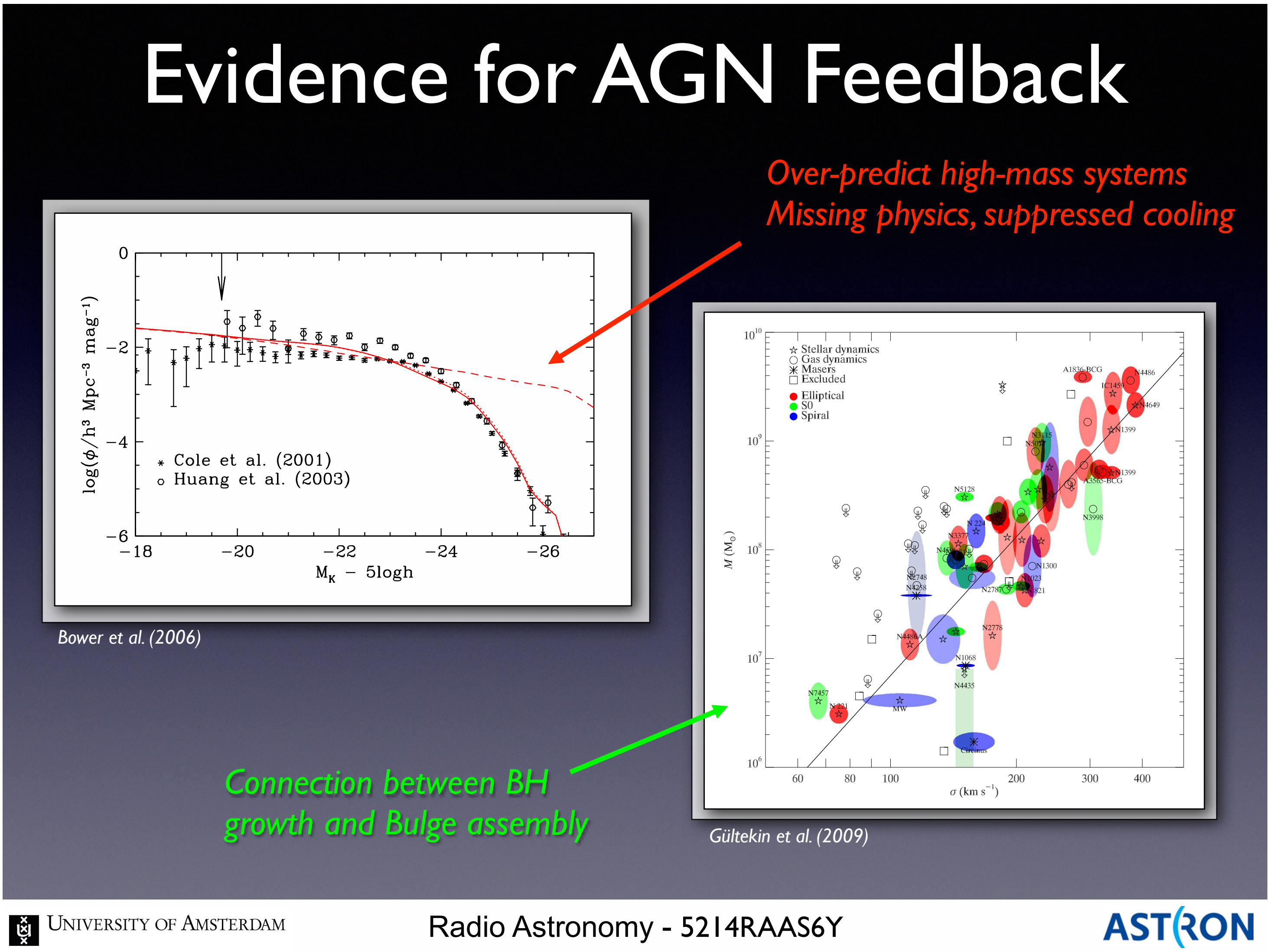
Simulation showing the growth of large-scale structure in the universe.
Gravity dominates the early growth, but from z ~2 till today AGN feedback plays a major role energetically. The explosions seen on the right are AGN outbursts dumping energy into the cluster environment.



The energy budget in cluster evolution is driven by several physical processes.
All of these physical processes have thermal and non-thermal signatures.
With X-rays we can generally study the thermal processes.
All of these processes produce non-thermal emission that we can observe in the radio.
You really need both to get the full picture.



We see feedback almost everywhere we look. A truly ubiquitous phenomena.
Occurs over a large range of physical scales and over a wide range in energy.
Cavities in the surrounding gas carved out by the effects of the AGN were first clearly identified in the X-ray.
Radio observations provided the crucial evidence that the central AGN was causing these cavities.



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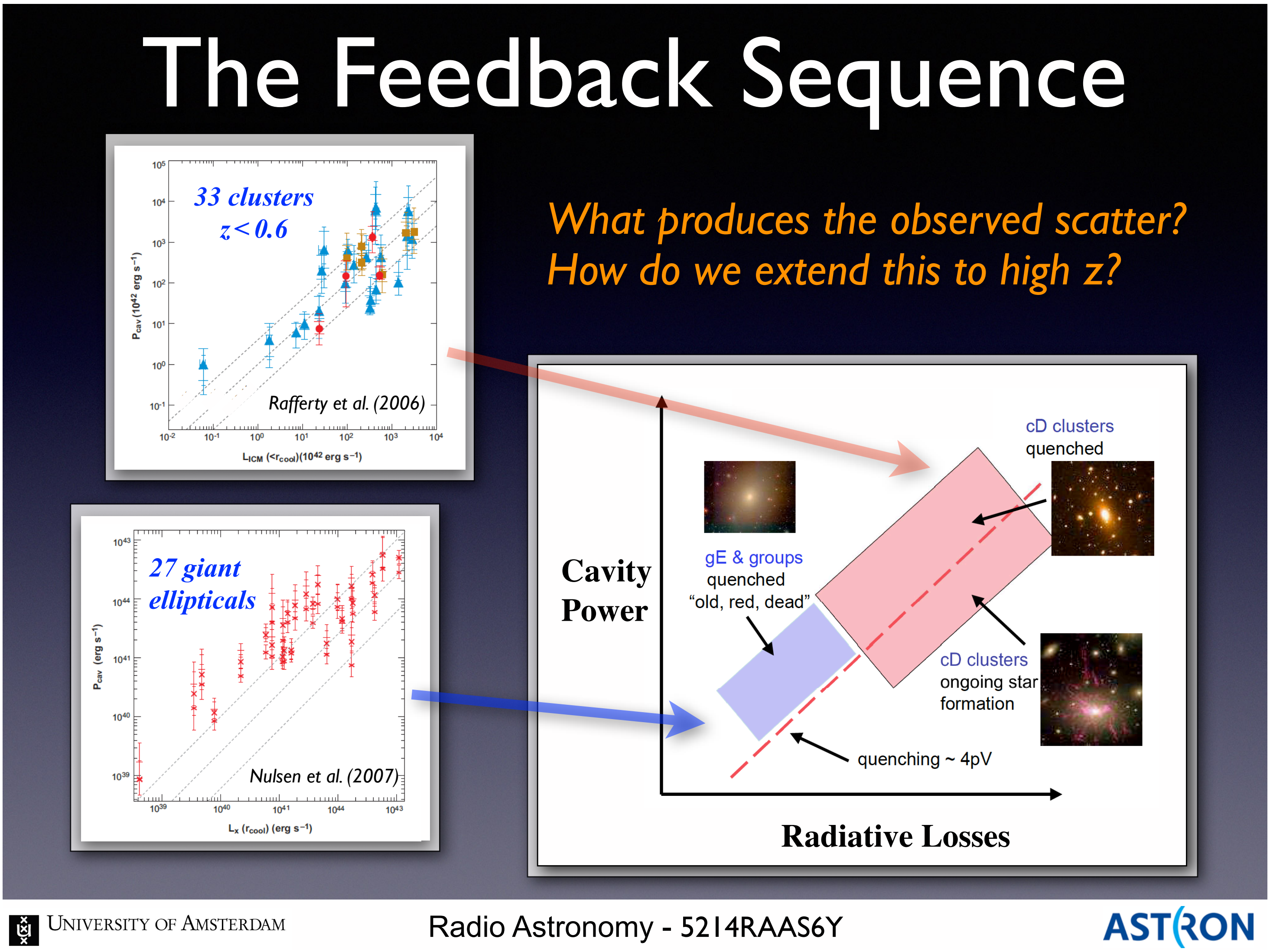
We had already had clues that AGN were affecting the growth of galaxies.
Simulations without AGN feedback produce too many very big galaxies.
Simulations with AGN feedback produce the right number —> Feedback regulates the growth of galaxies.
There is a correlation between the mass of the galaxy and the mass of the central black hole.
So whatever physics drives the growth of the BH also controls the growth of the surrounding galaxy.



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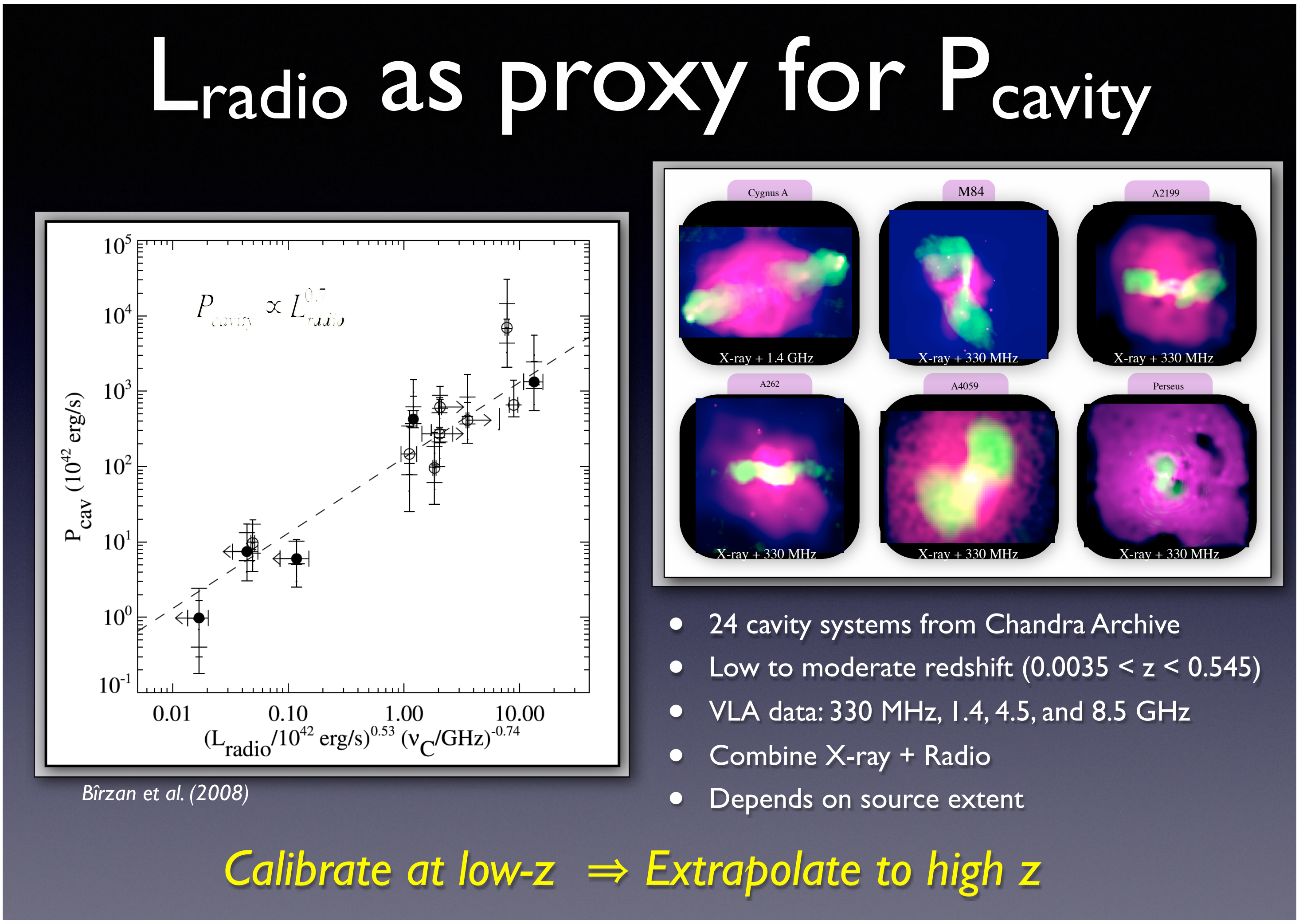
We can calculate the amount of energy required to create the cavities seen in the X-ray.
The amount of energy required is enough to balance the cooling of the gas.
This equivalence has been shown to hold at low redshift. We don't know if it holds at higher redshift.
We can't do this analysis at high redshift in the X-rays because the sources are too faint, so we need a different tracer. Guess what...that's right radio data.

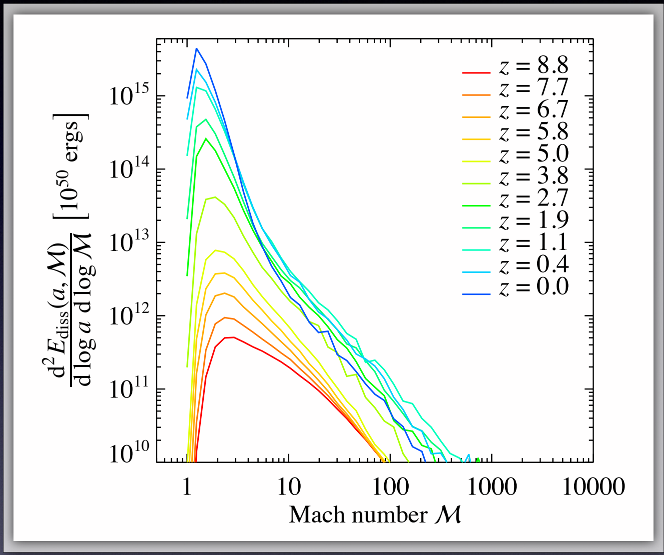


Like with the star formation, we can show that the radio emission correlates well with the energy required to create the X-ray cavities. This relationship holds because ultimately both the X-ray cavities and the radio emission are being driven by the same basic physics, i.e. accretion onto a massive black hole.
We can't observe the X-rays out to high z, but we can do it in the radio.

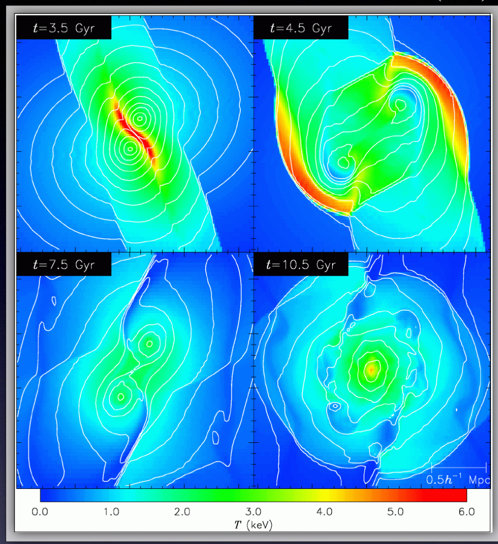
Blue is inferred dark matter halo from lensing data, Red is thermal gas from X-ray data.
Cluster mergers are another main source of energy input into the cluster atmosphere.
Cluster form by a serious of mergers, small and large.
We see radio signatures of both kinds of mergers.

Merger Shocks

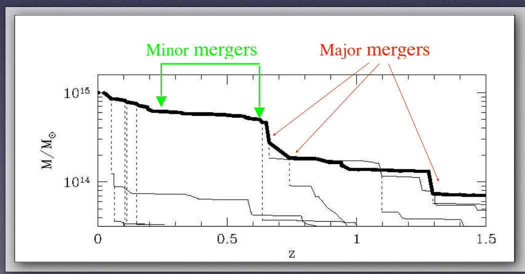
Pfrommer et al. (2007)



Ricker & Sarazin (2001)

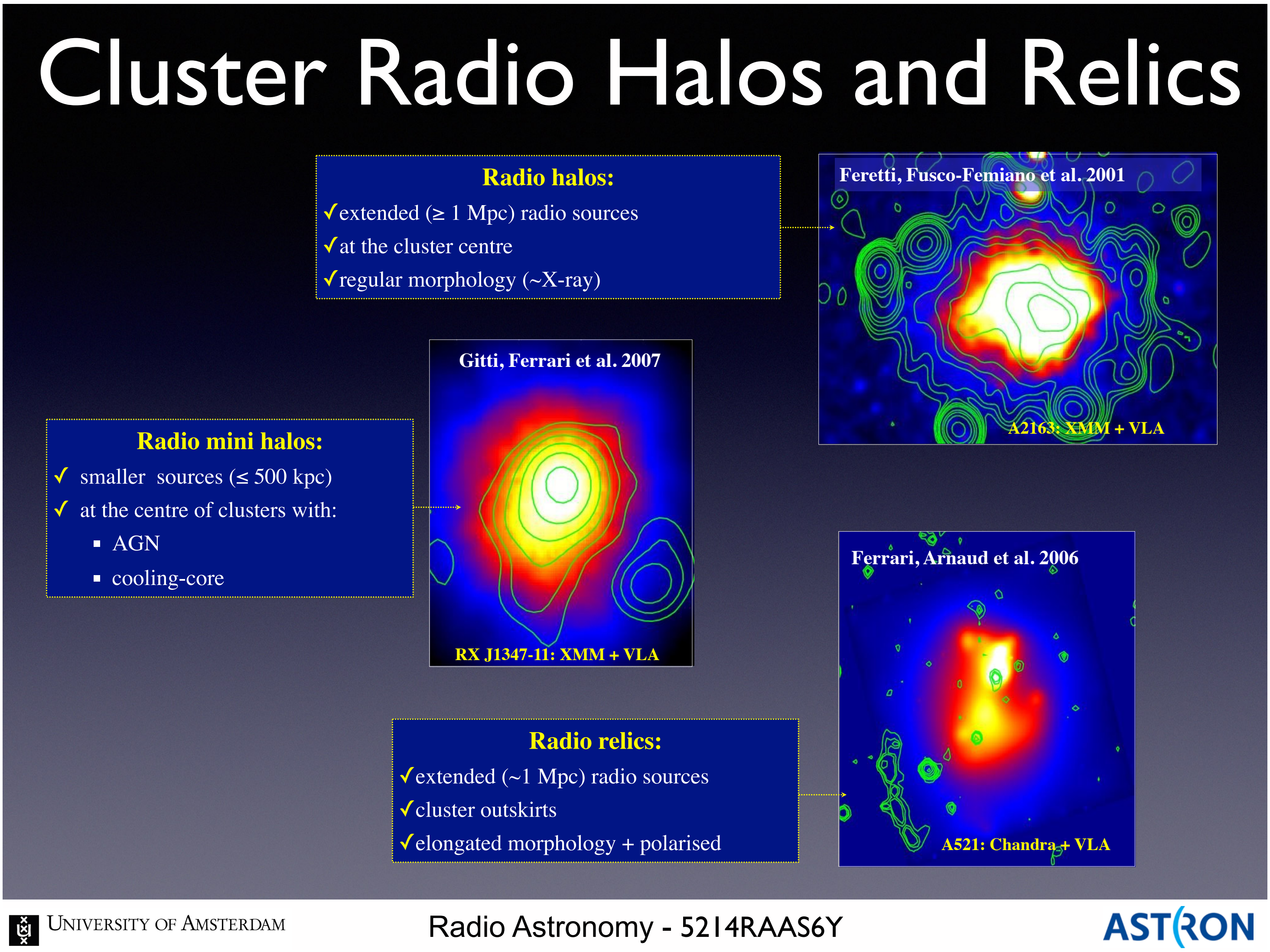


- Main heating mechanism of intracluster gas
- More energy is dissipated at later times
- Mean Mach number decreases with time

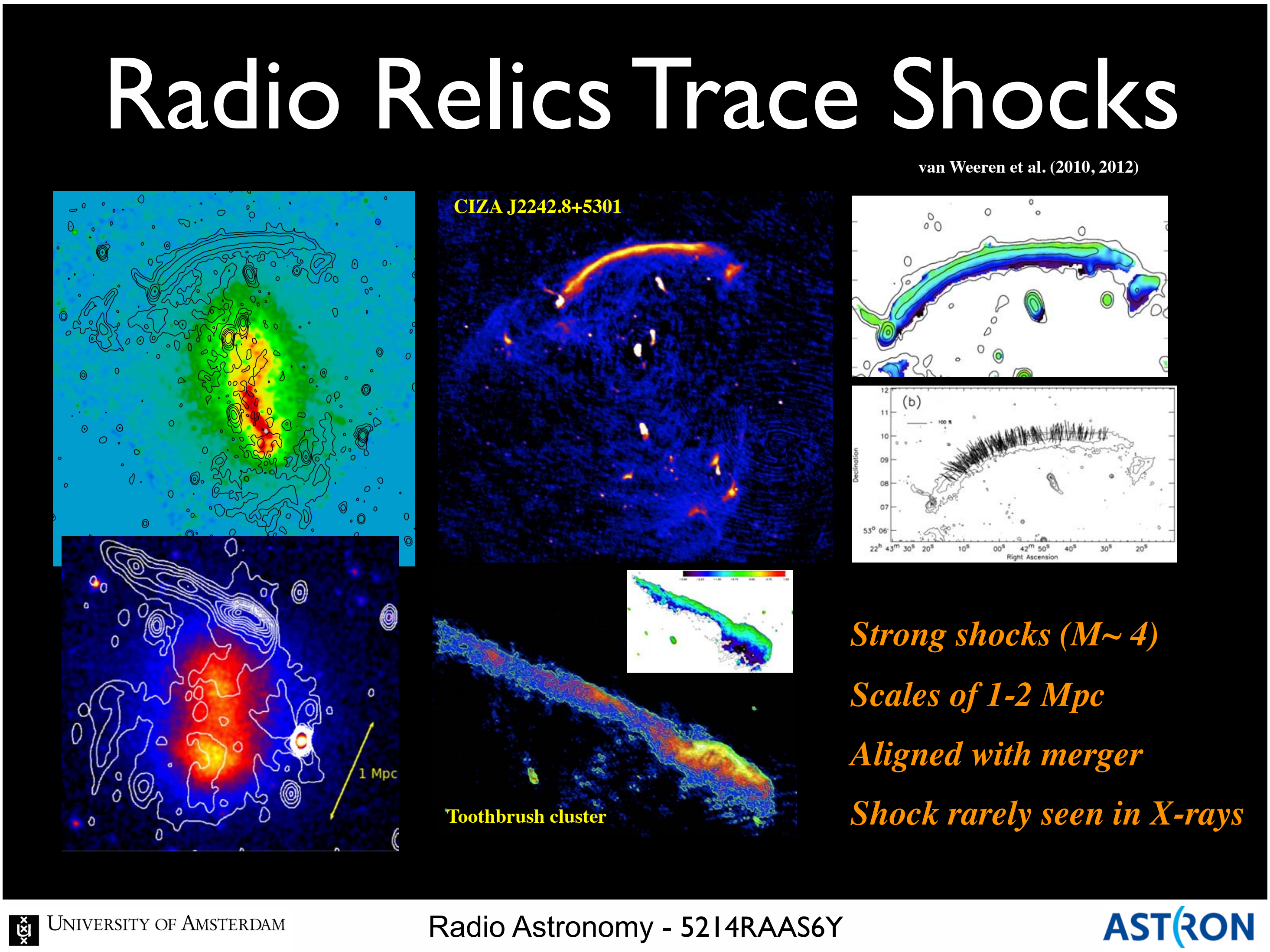


Cavaliere et al. (2002)

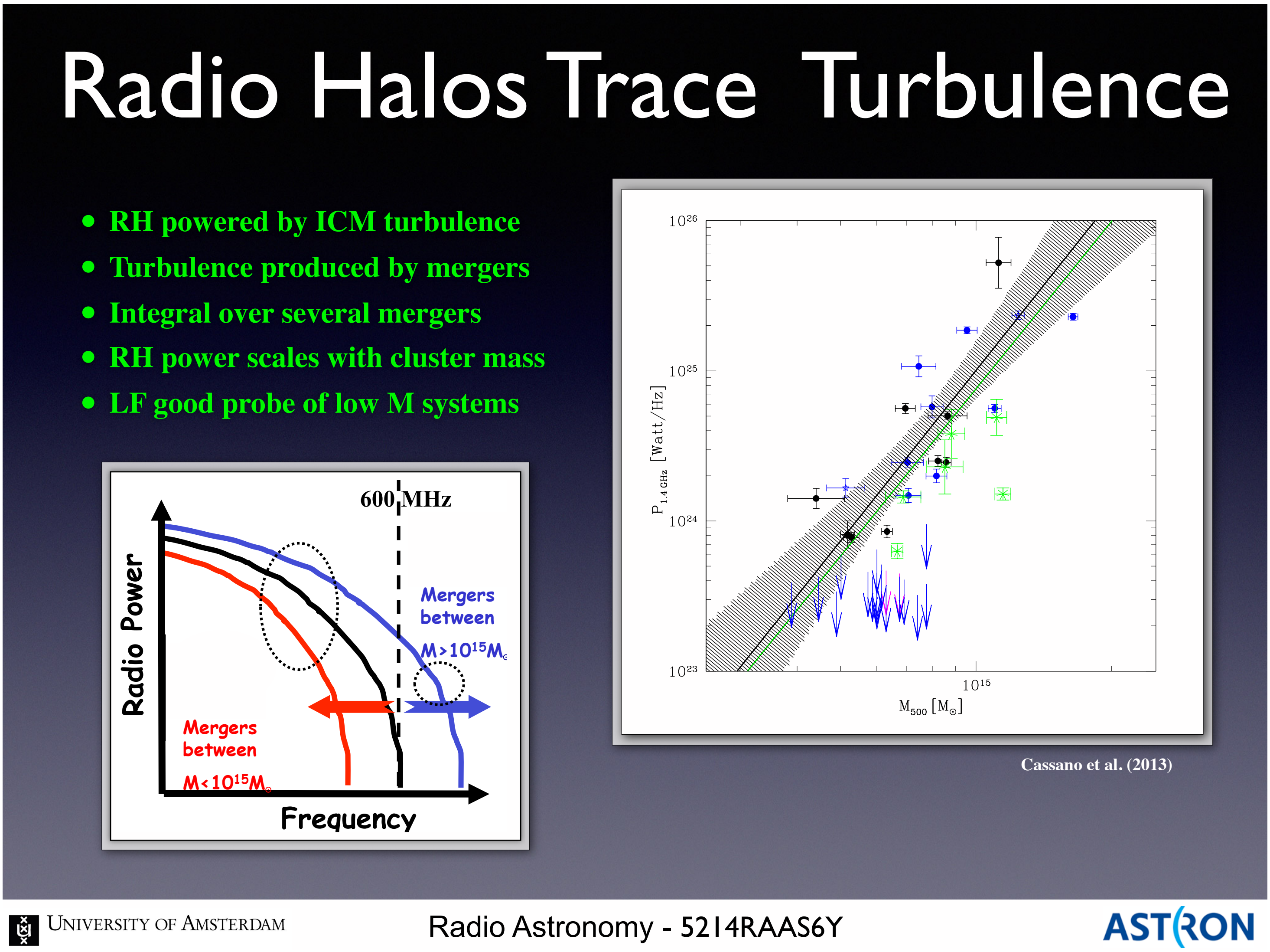
The formation history of given cluster is primarily dominated by a few major mergers (mostly at high redshift).
At low redshift, the cluster sees many more smaller mergers.
Major versus minor is defined as the ratio of the masses of the two sub-clusters that are merging. Major merger means a ratio close to ~1.
The energy dumped into the environment by a merger depends on the mass of the merging sub-clusters and their relative speed.



We see a variety of diffuse radio emission associated with mergers in clusters.
Relics are associated with single, major mergers and relatively easy to turn into energy dumped in the cluster.
Halos (mini and regular) are *probably* the accumulated turbulence caused by the integrated effects of several smaller mergers stirring up the gas.

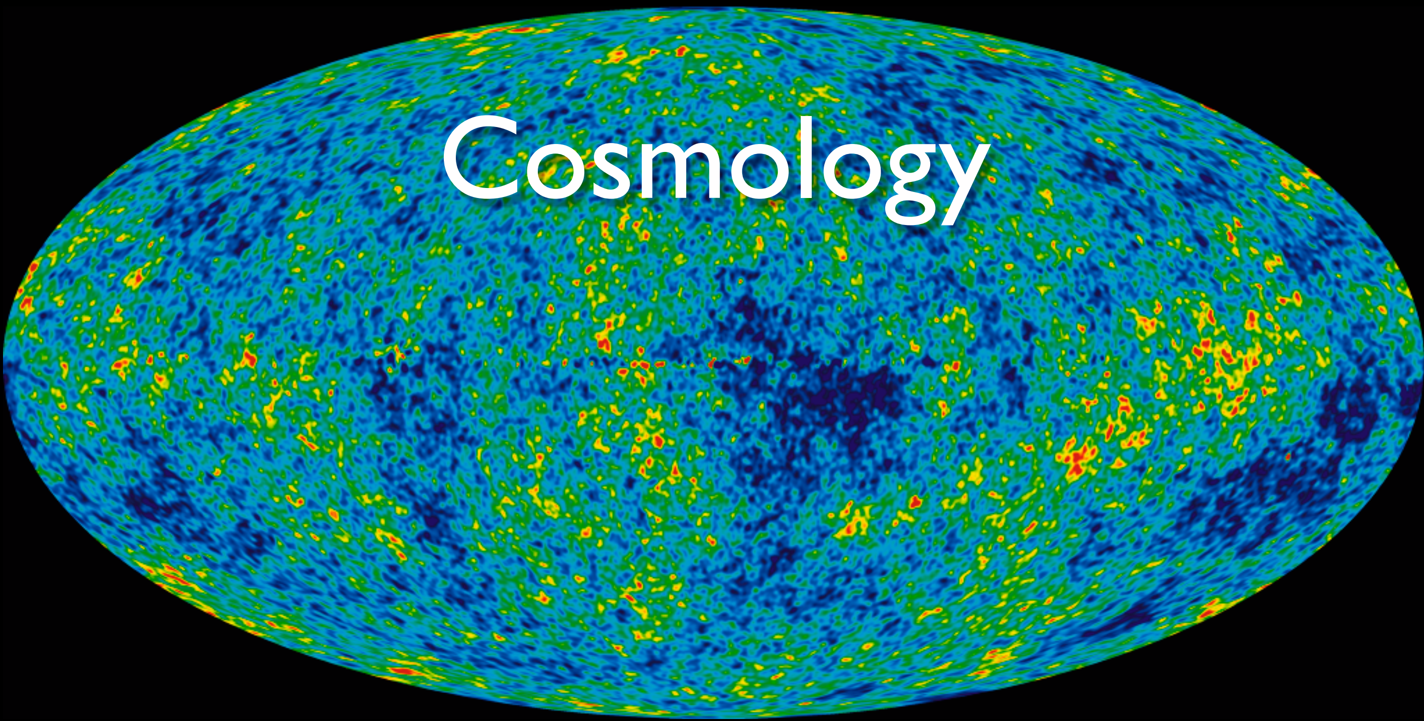


Examples of combined X-ray and radio observations of radio relics in clusters.
These relics are associated with the shock front caused by the major merger traveling through the medium.
The radio emission is caused by the shock compressing an older remnant population of electrons and effectively powering them back up.
Much easier to calculate the energy injected into the cluster by a single shock.



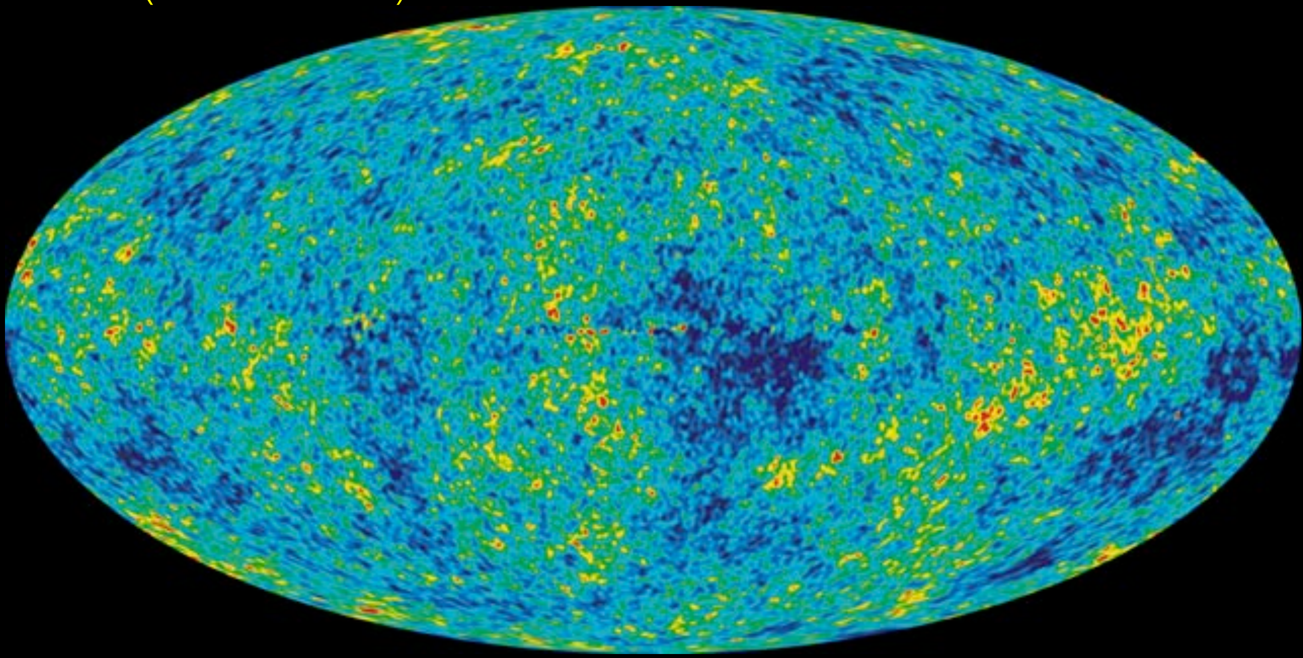
The current theory for radio halos is that they are caused by many smaller shocks stirring up turbulence in the gas.
The energy is therefore an integral quantity so we lose information about the evolution with time.
To get the time information back, we have to look at a sample of both small and large halos.
This way we can see halos "grow". The mass scale therefore becomes a proxy for time.
To get the lowest masses (and "youngest" halos) we need low frequency radio —> LOFAR!

Cosmology



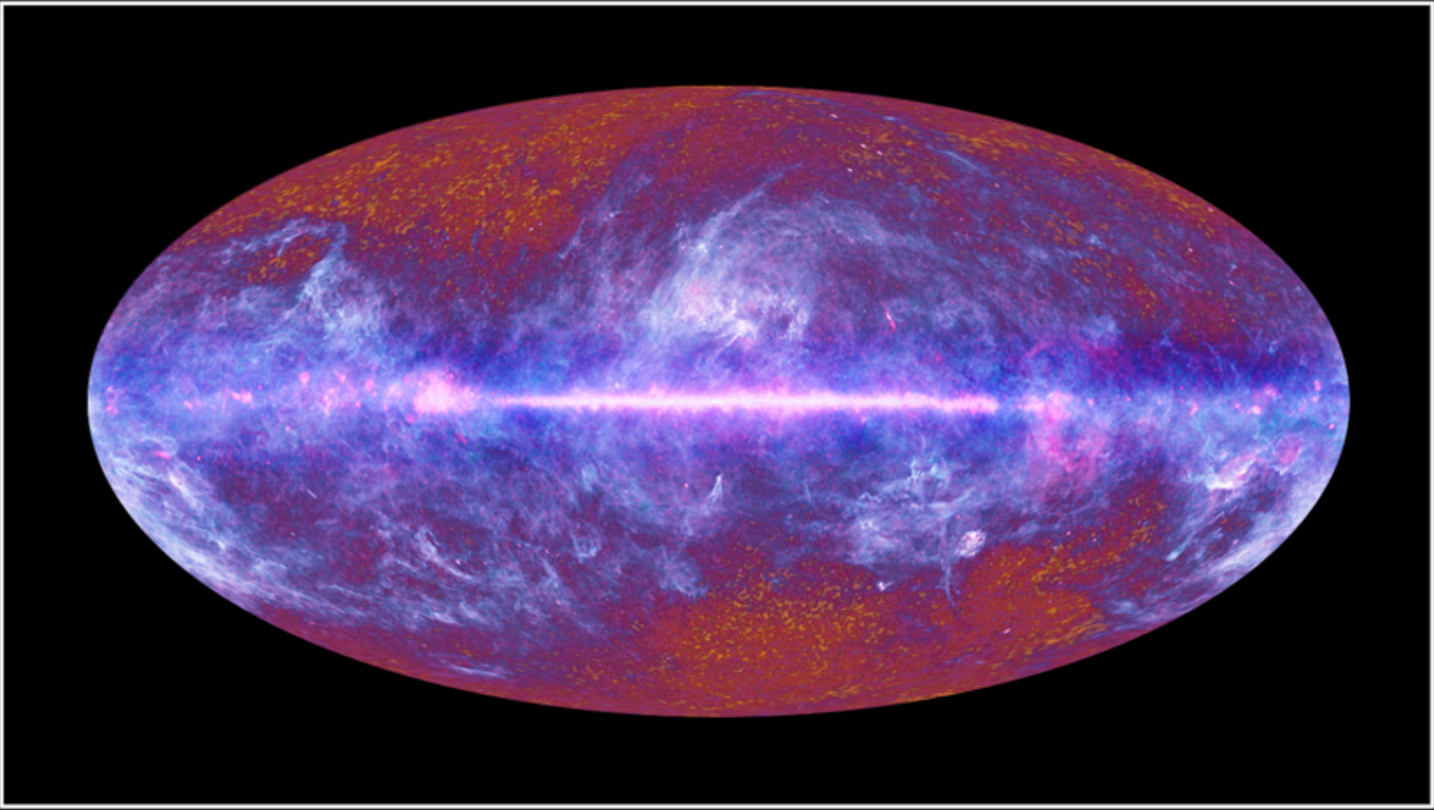
Cosmic Microwave Background

WMAP (20 - 100 GHz)



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

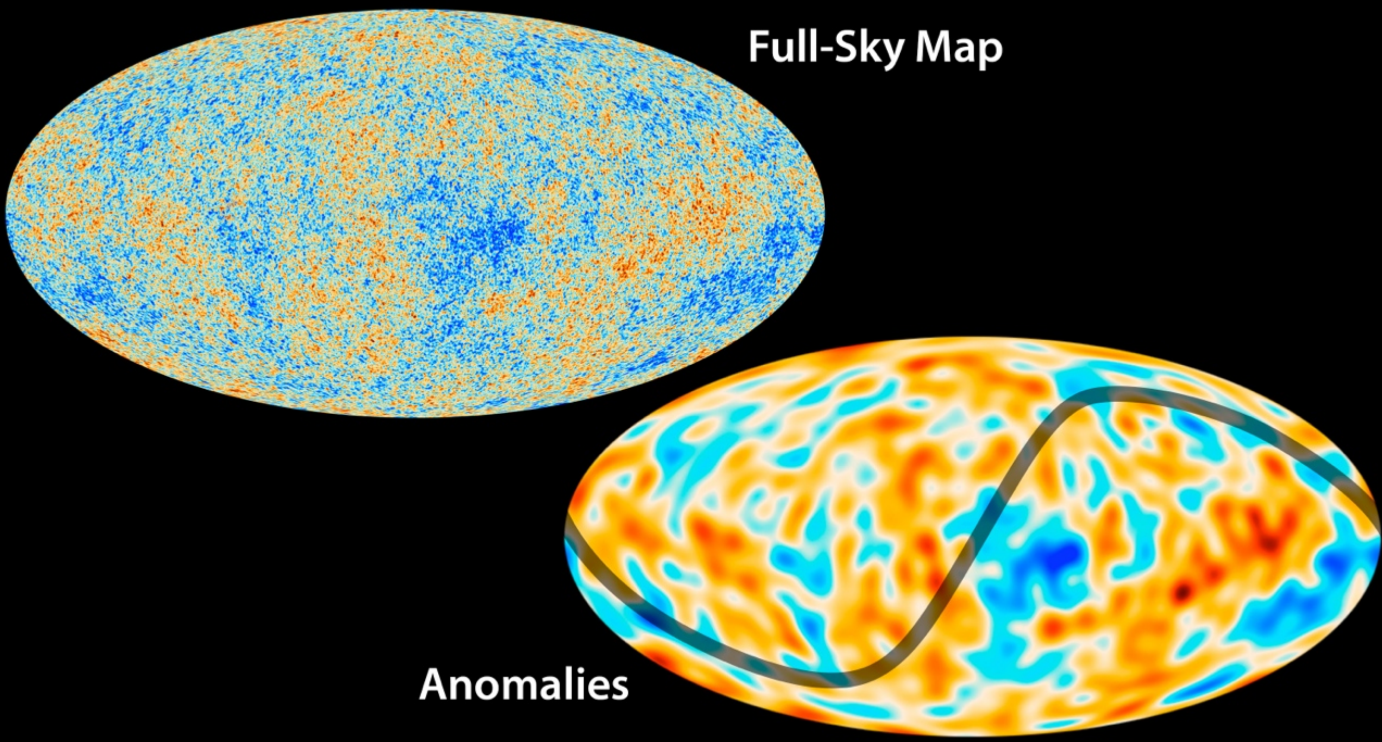
Planck Mission



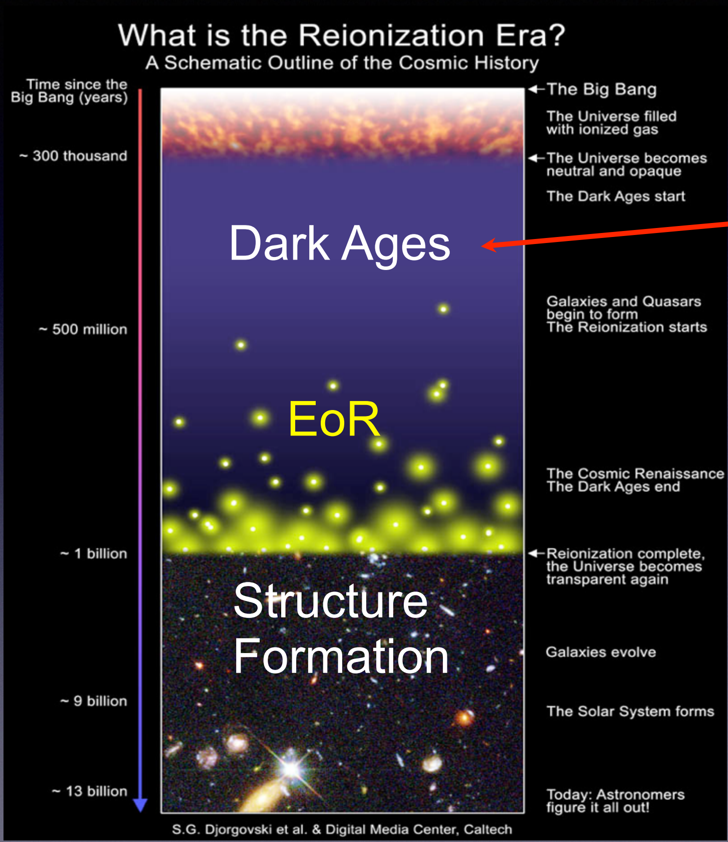
(30 - 857 GHz)

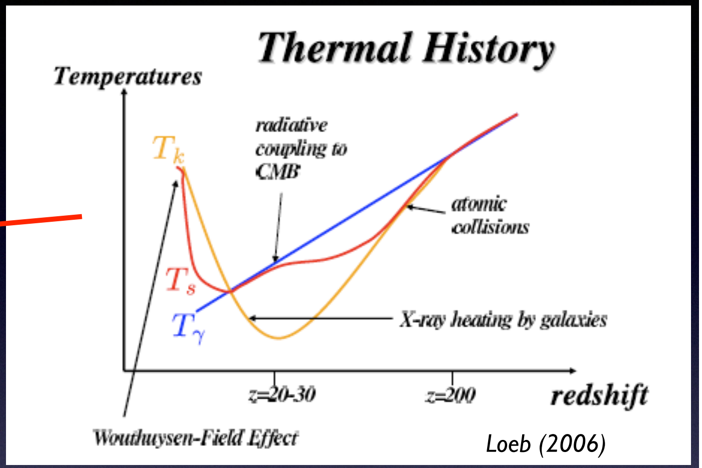
Resolution ~ x5 better

Planck Mission



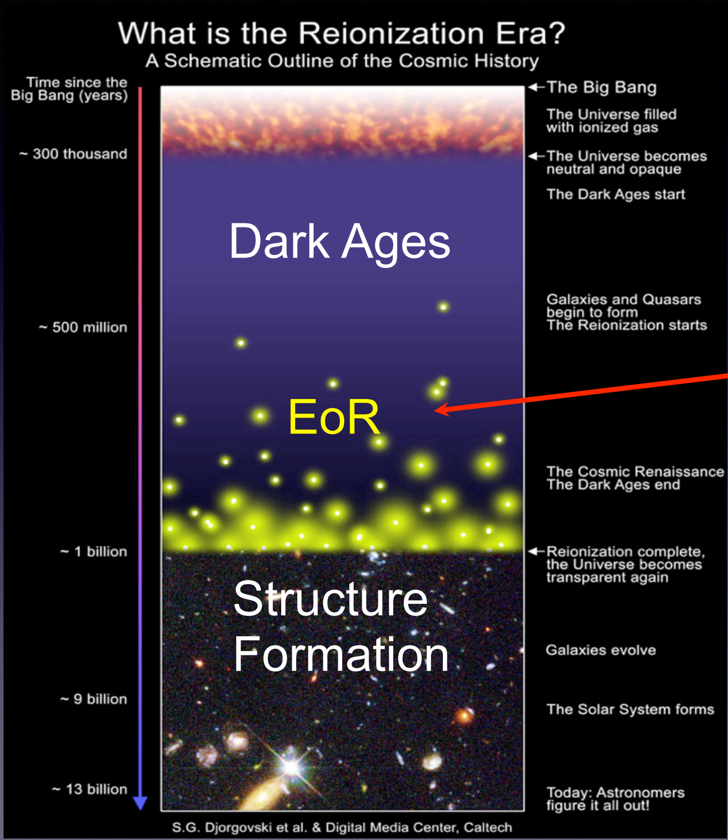
Dark Ages

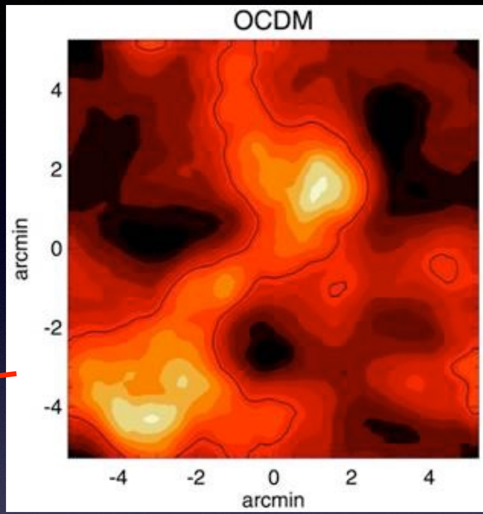




- Spin temperature decouples from CMB at z~200 (ν =7 MHz) and remains below until z~30 (ν =45 MHz)
- Neutral hydrogen absorbs CMB and imprints inhomogeneities

Epoch of Reionization



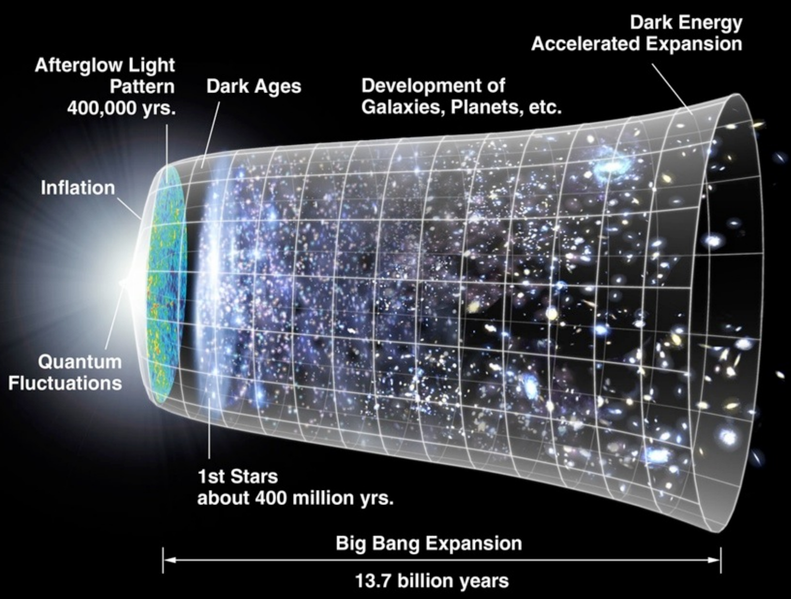


Tozzi et al. (2000)

- 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

LOFAR EoR Experiment



- When was the Universe reionized ?
- How (fast) did reionization proceed ?
- Which objects were responsible ?
  stars/galaxies , QSOs, or …

Redshifted HI to frequency mapping

z =6.7 ⇒ 185 MHz

z = 8.5 ⇒ 150 MHz

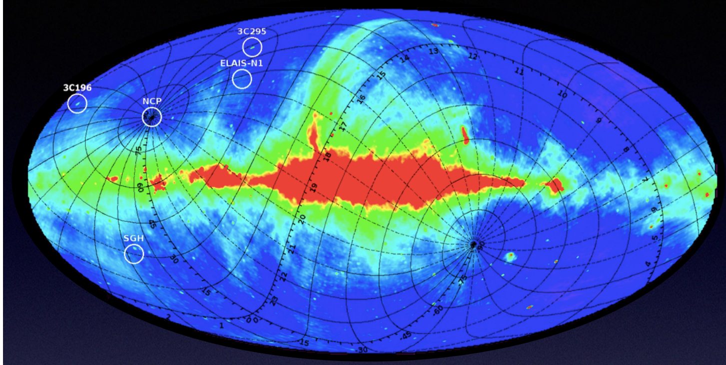
z = 11.4 ⇒ 115 MHz

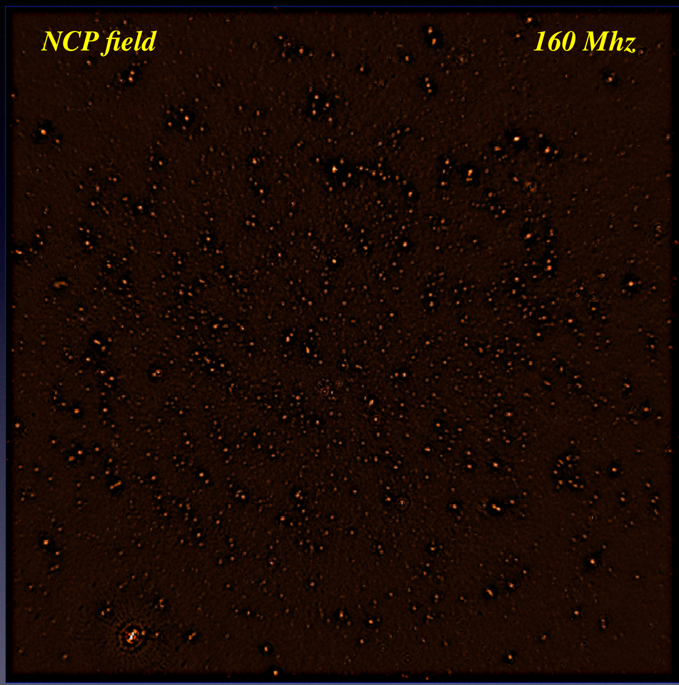
$\delta T_b \approx 28mK$

Goal: Detect cosmological 21cm signal (*z*~6-10) from the Epoch of Reionization

⇒ 1.5 Pbytes and 10^{21}-10^{22} FLOP to extract signal!

LOFAR EoR Experiment





(courtesy S. Yatawatta and the EoR KSP Team)

- Total 17 observations, 170 hours
- Concentrating on 3 distinct fields
- Custom processing on EoR cluster

$\sigma \sim 30\ \mu Jy \qquad \theta \sim 6''$

70 hrs, 96 MHz bandwidth
8º x 8º, 15000x15000 pixels, 2" pixels

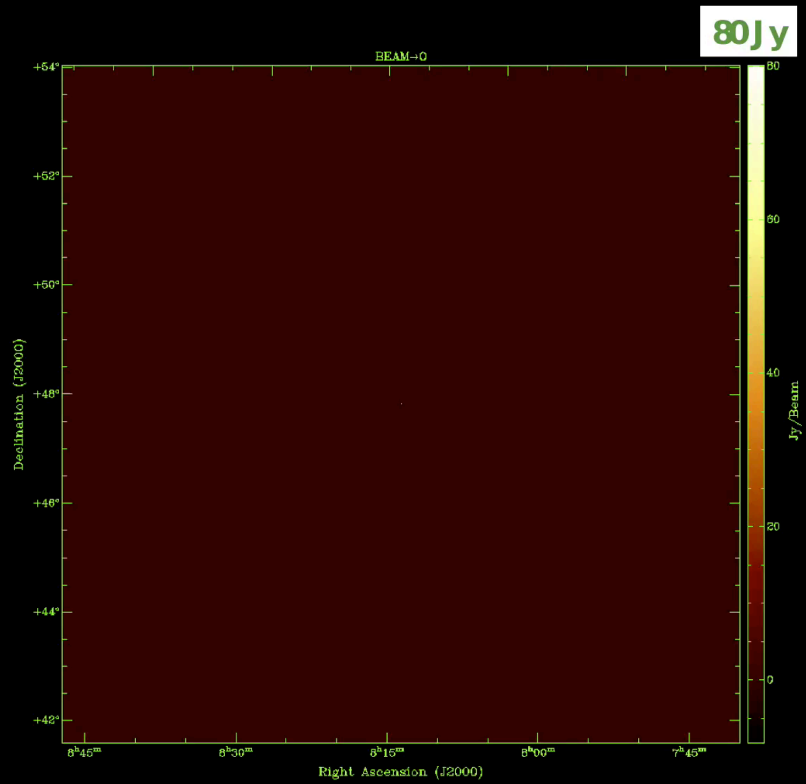
LOFAR EoR Experiment

Requires high

3C196 field

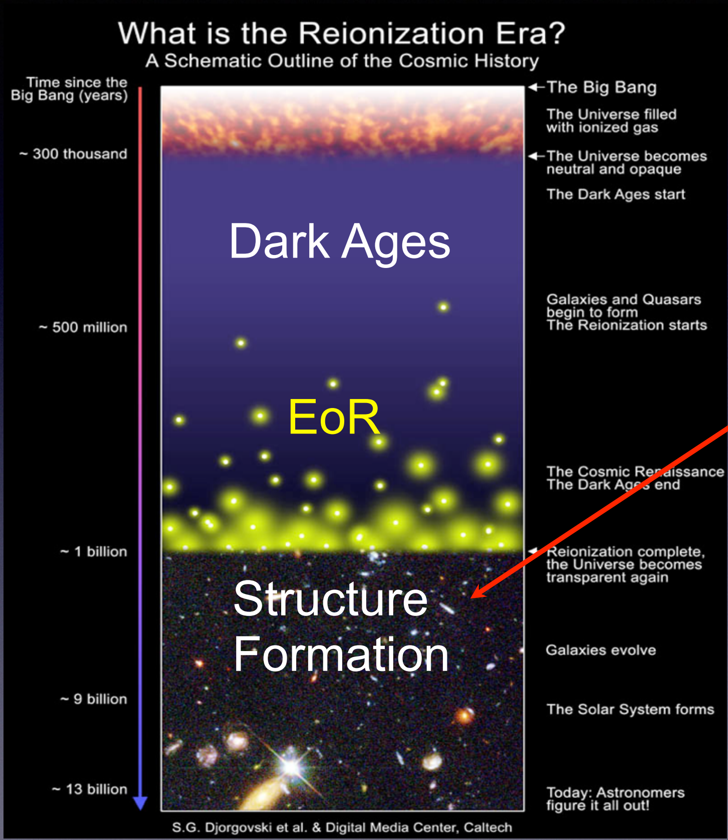
160 MHz, 32 hrs, 96 MHz bandwidth

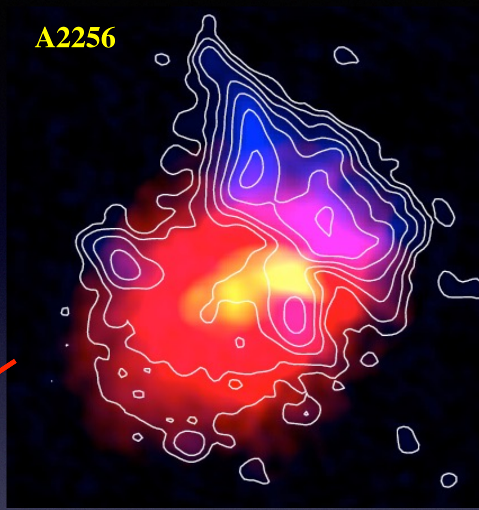
DR ~ 1,000,000:1!



(images courtesy V. Pandey)

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?