




Radio Astronomy

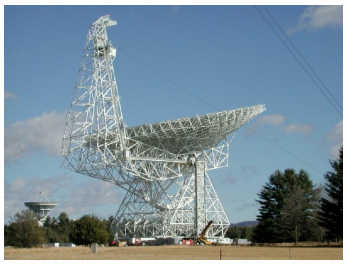
Lecture 2

The Science of Radio Astronomy: Extragalactic

Lecturer: Michael Wise (wise@astron.nl)

April 7th, 2017



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, FRBs, EHT
- Mass and ISM in Galaxies, Mapping HI, Dynamics, Star Formation, FIR-Radio Correlation, 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
- Cosmology, Cosmic Microwave Background, S-Z Effect, Dark Ages, EoR, and growth of 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)

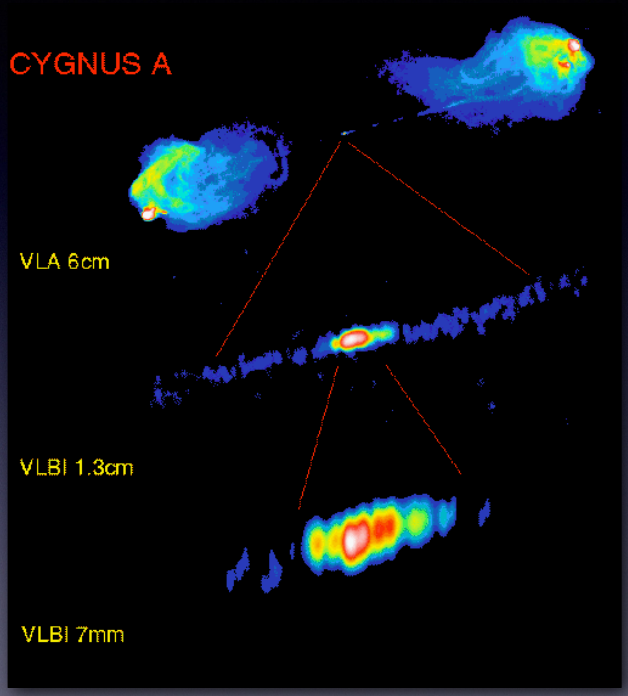
When we observe in different parts of the EM spectrum, we see different physics at work. Radio observations probe a wide range of physics. A wide range of physics translates into the ability to answer a wider range of scientific questions.

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^{-6} arcsec)



Carilli & Harris (1996)

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

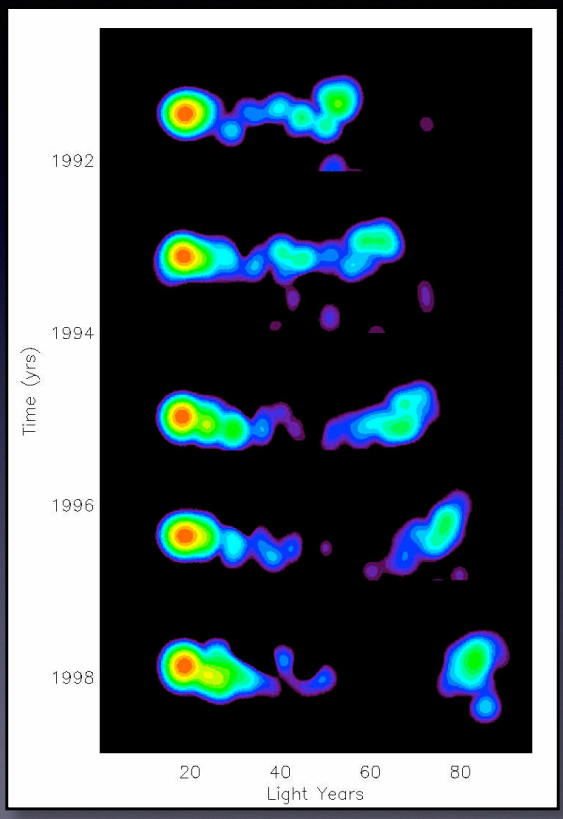
The highest angular resolution images currently possible are radio observations (down to micro-arcseconds).
Extragalactic sources by definition are very far away and very faint.
Studying their structure invariably requires high angular resolution and sensitivity to faint sources.
Radio observations are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

Why Radio Observations?

Why Synthesis Imaging?
⇒ 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)



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?

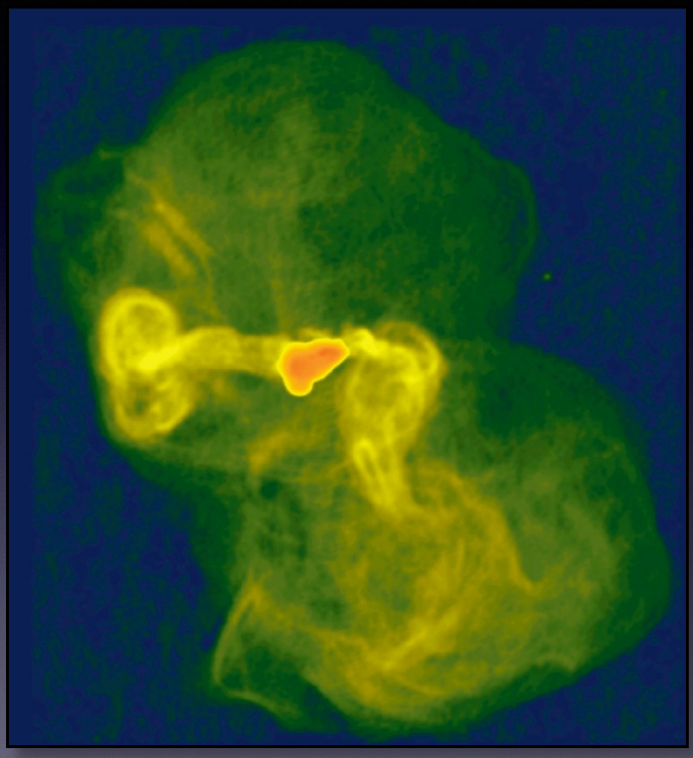
Why Synthesis Imaging?
⇒ Dynamic Range

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



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

Owen, Eilek, & Kassim (1999)

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?

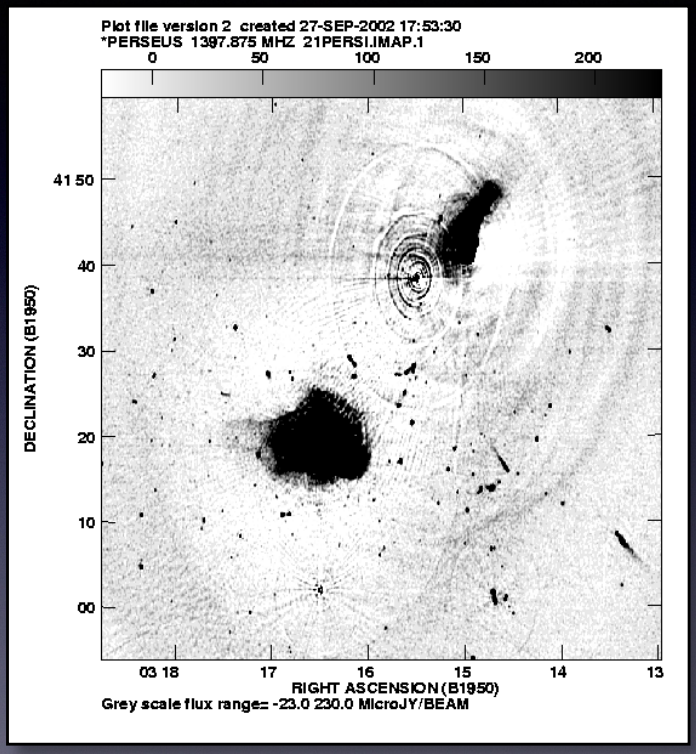
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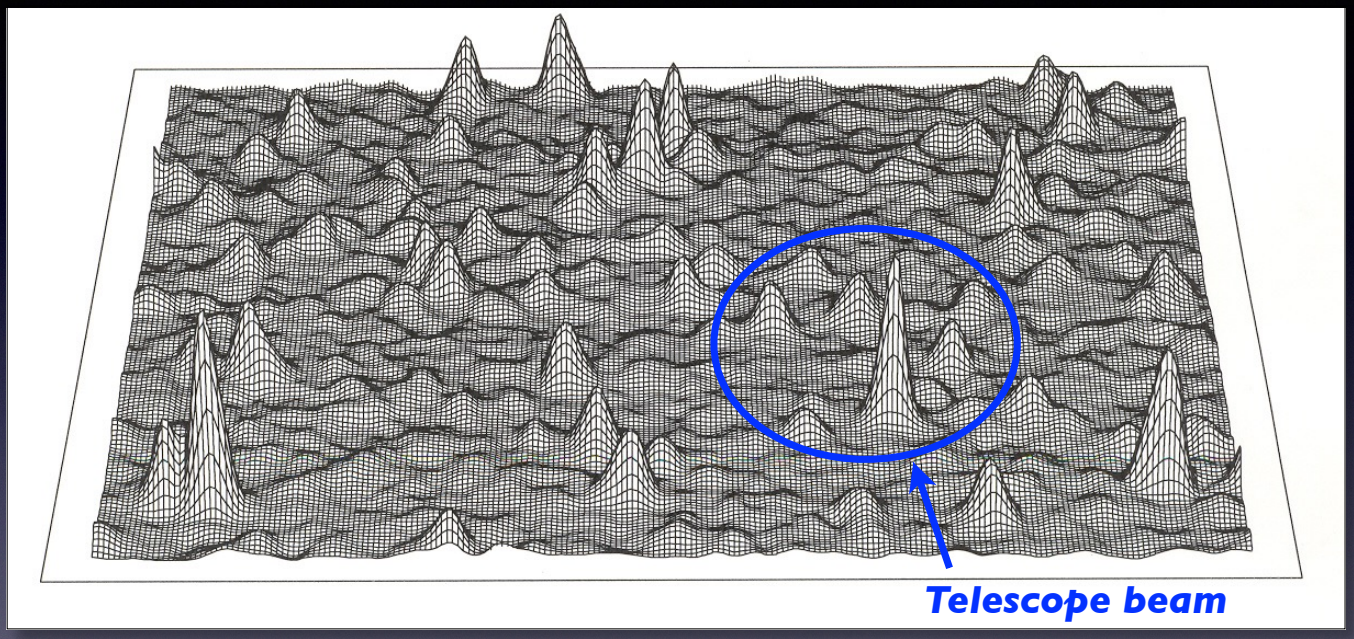
Detect faint sources and resolve "confusion" limitations



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.

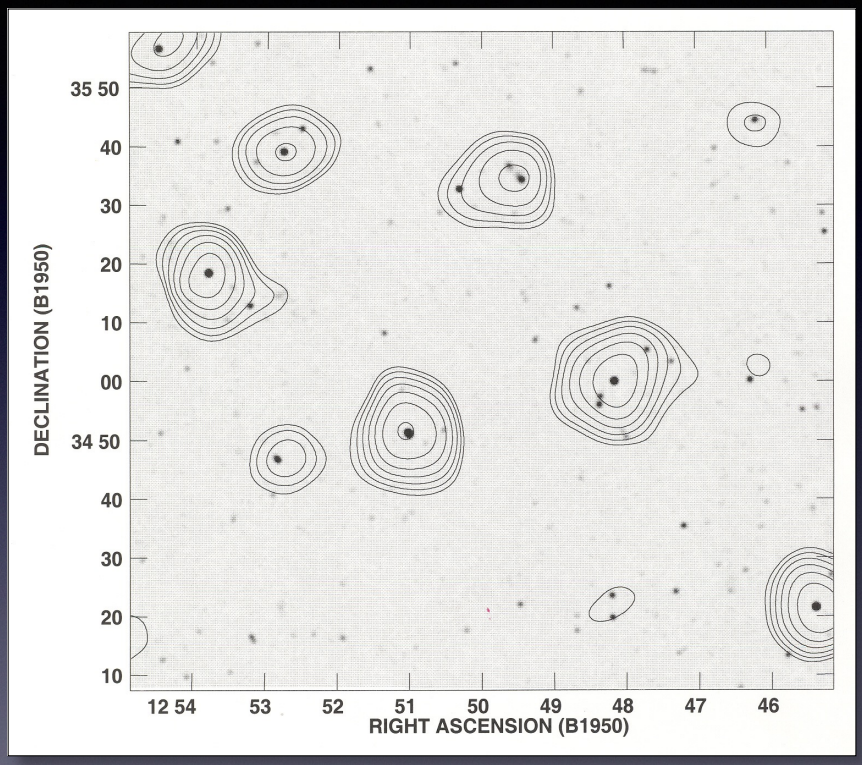
Beating Confusion

"RMS" confusion:

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

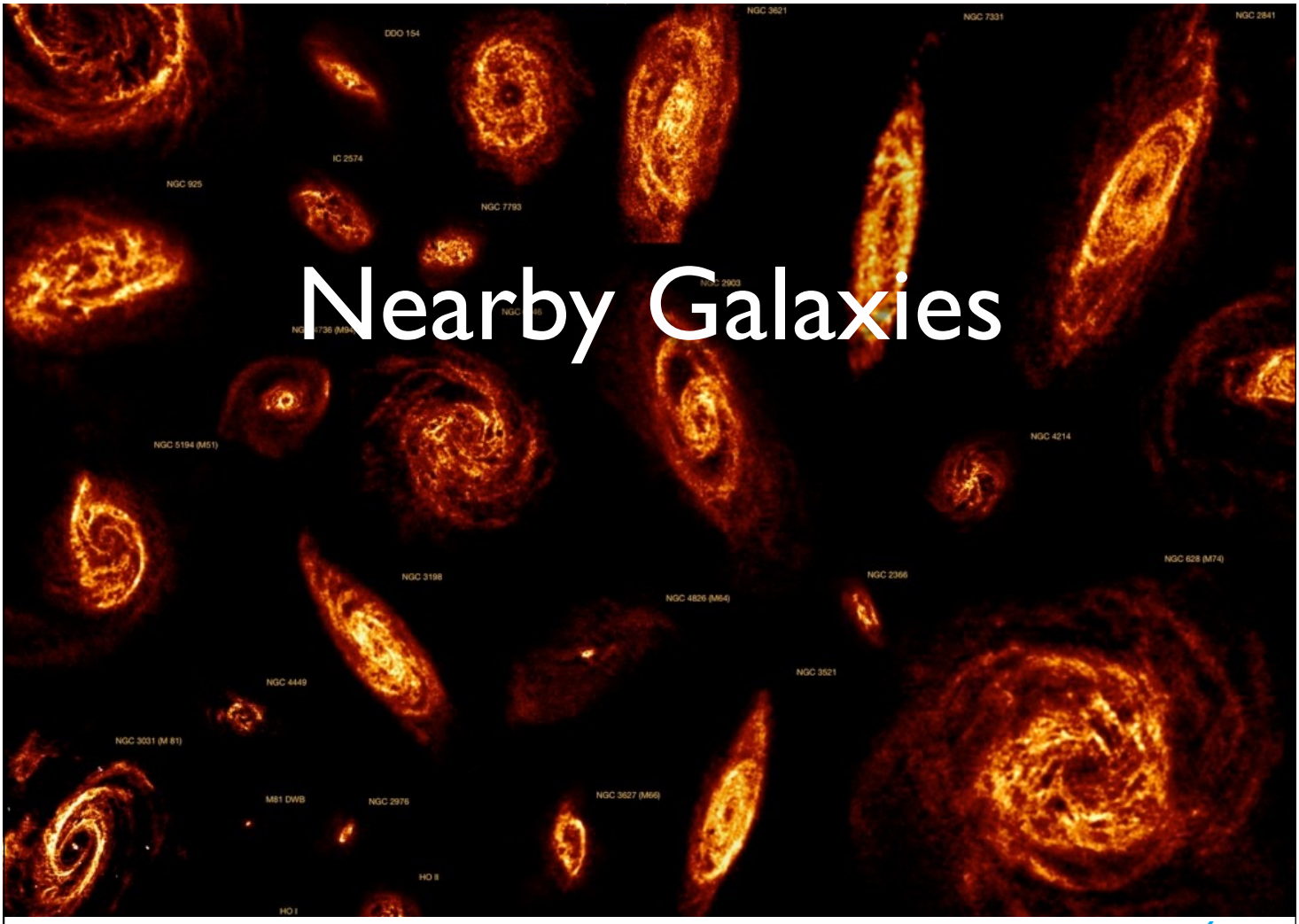
where

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



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

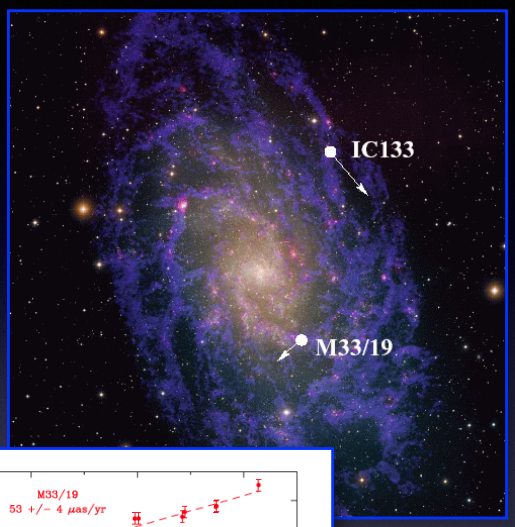
The best way to beat confusion and achieve greater sensitivity is to increase the resolution.
High angular resolution means we can separate all those fainter sources and get closer to the "true" noise.
Radio telescopes are great for high angular resolution.
We can increase the resolution *and* the sensitivity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

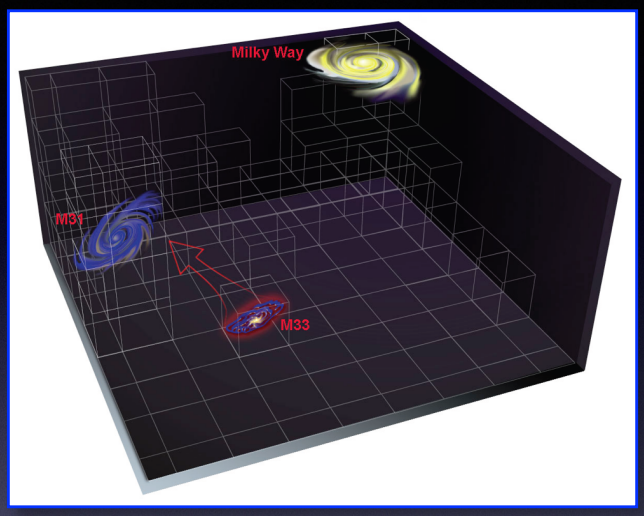


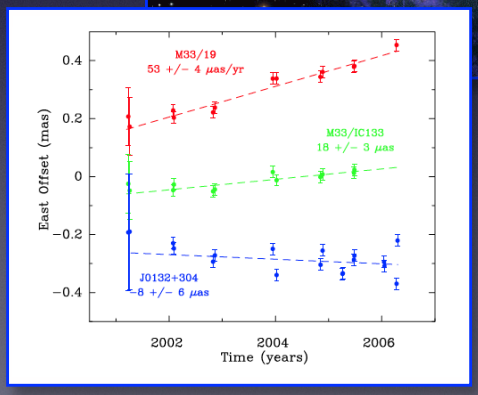
An atlas of HI maps for a sample of nearby galaxies created with the WRST.

“Nearby” is another poorly defined term, but basically we mean galaxies that are close enough to resolve their internal structures and the interesting objects within them.

Radio Astrometry





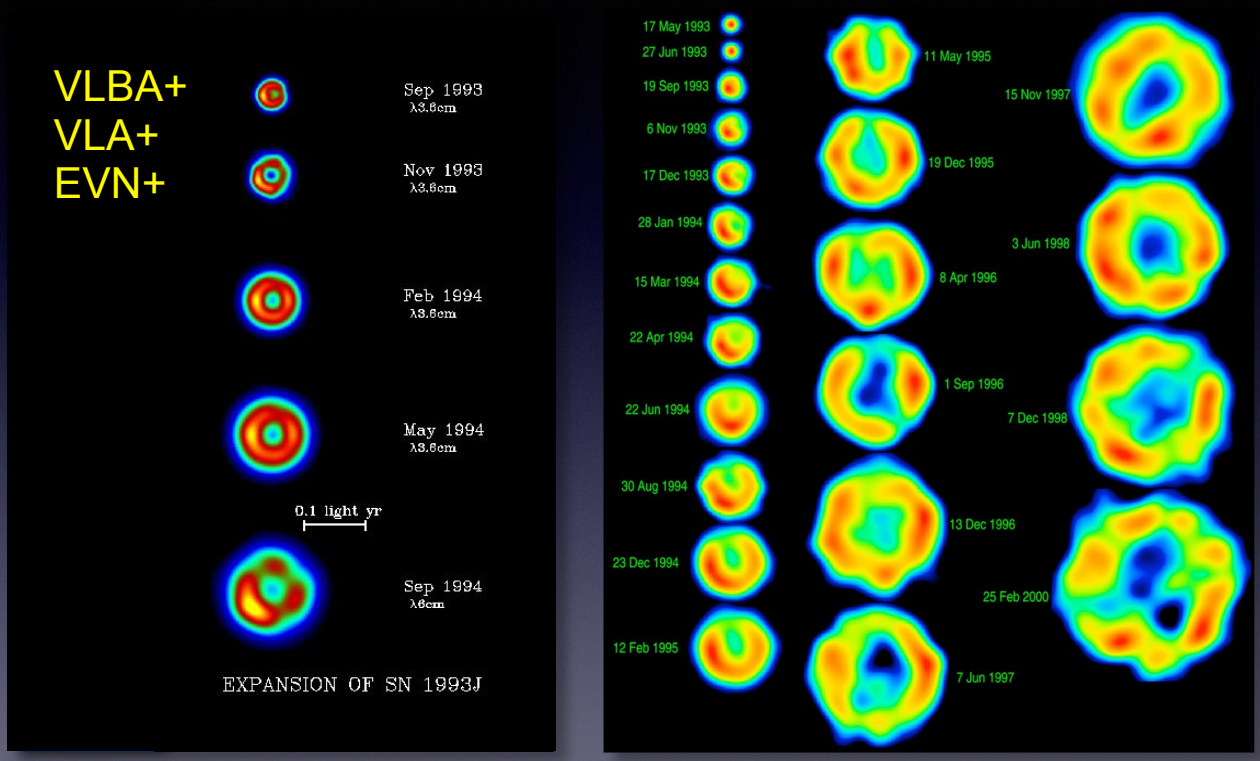


Brunthaler et al. (2000)

- 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

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.

Supernova Remnants

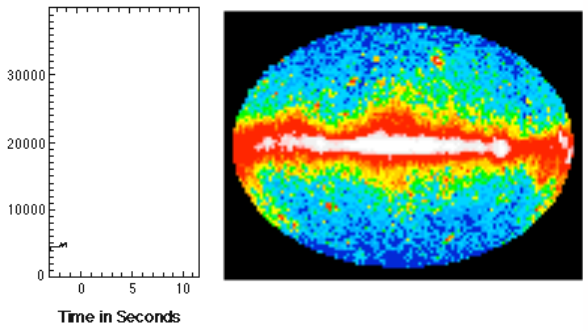


Radio monitoring of the supernova remnant from SN 1993J located in M81, a spiral galaxy in the constellation Ursa Major, from May 1993 to Feb 2000.

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.

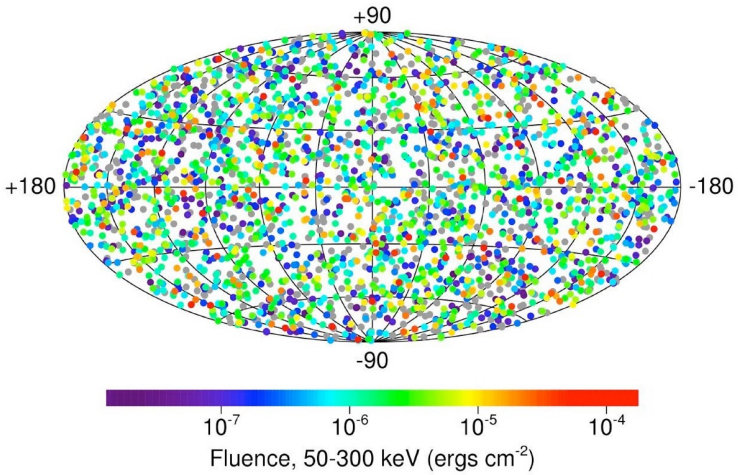
Gamma-ray bursts

⇒ *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.

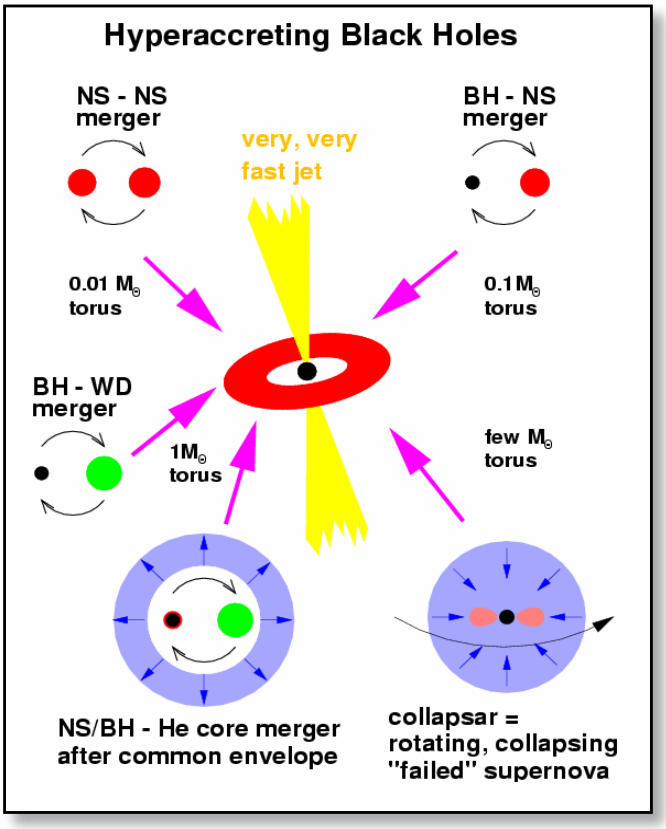
Gamma-ray bursts

Principal GRB Models

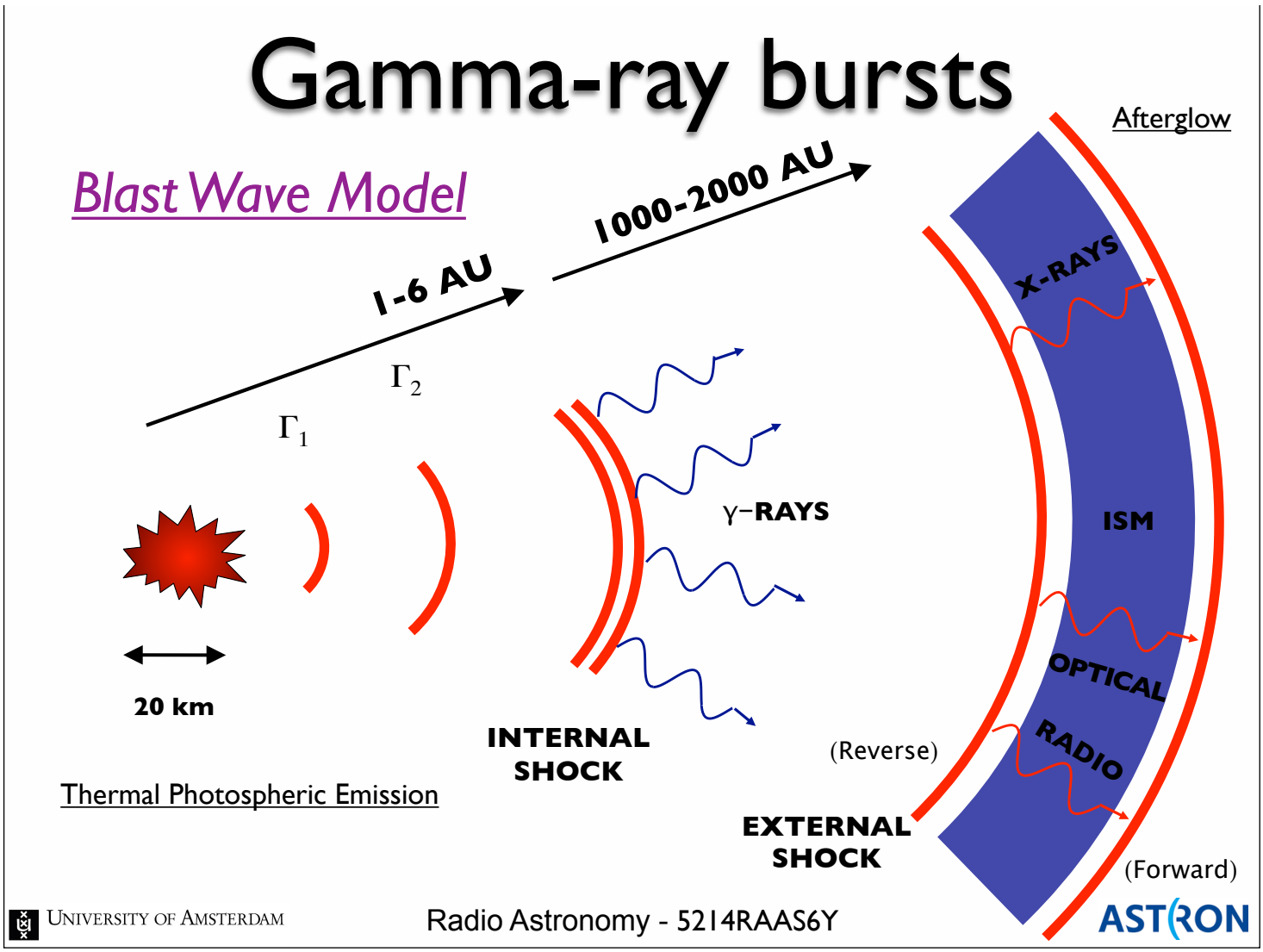
- Collapse of a rotating massive star
- Neutron Star – Neutron Star Mergers
- Black Hole – Neutron Star (He star) Mergers
- Black Hole – Neutron Star Mergers
- Black Hole – White Dwarf Mergers

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?

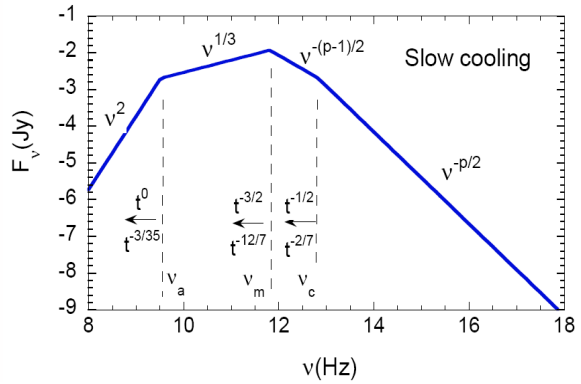


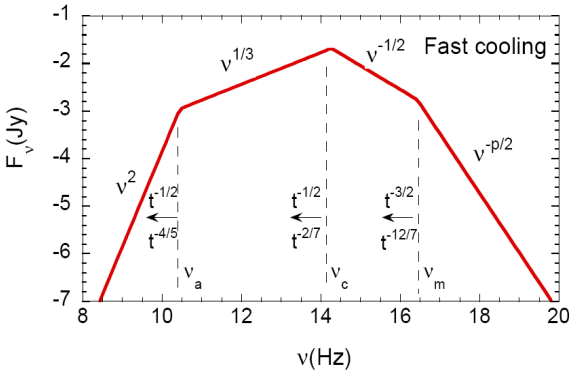
The emission from a gamma ray burst is believed to originate from a blast wave propagating outward. Emission at different wavelengths can occur at much later times than the immediate gamma ray burst itself.

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

Gamma-ray bursts

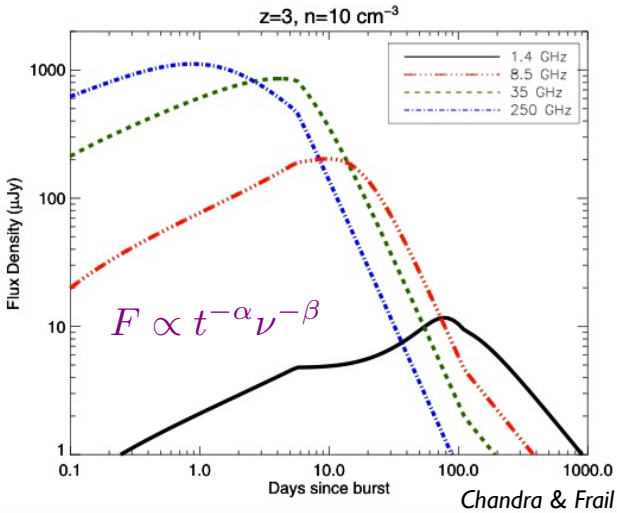
Synchrotron Afterglow Spectrum





Sari, Piran, and Narayan (1998)

Radio Emission from Forward Shock

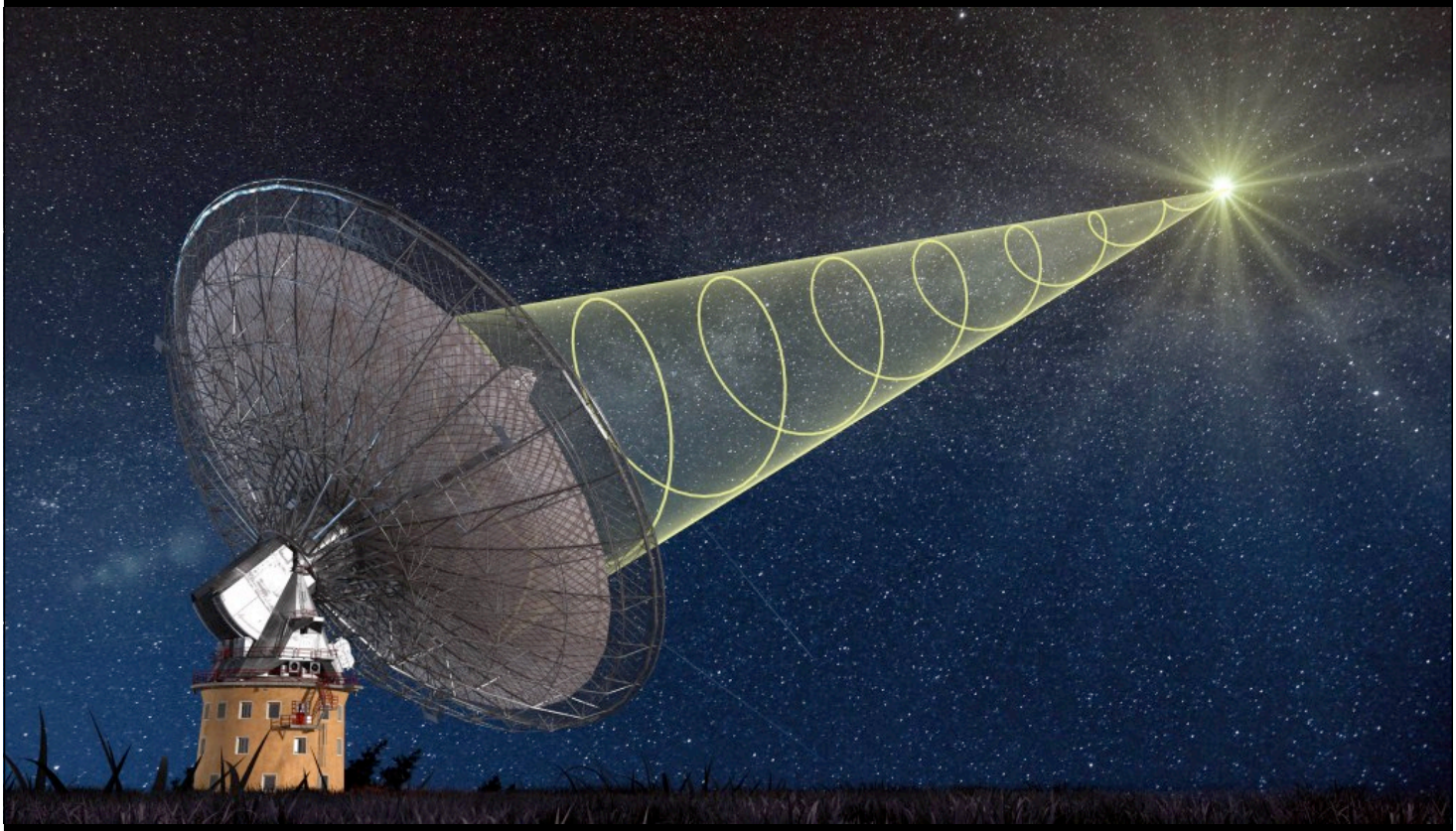


Chandra & Frail (2012)

- 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.

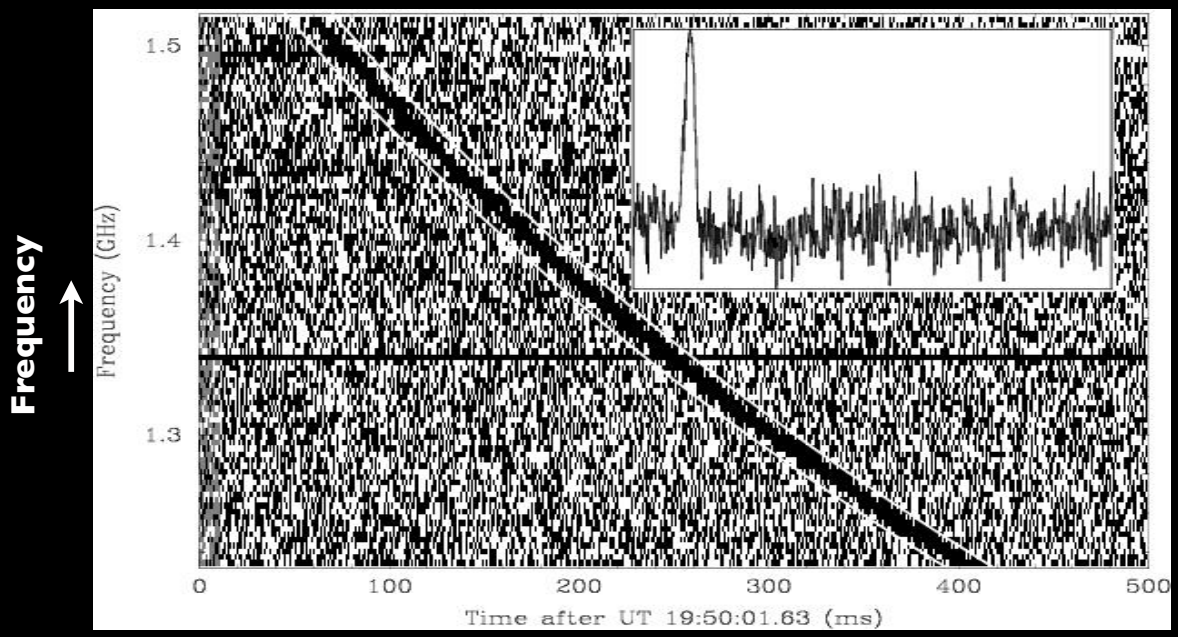
Fast Radio Bursts



Lorimer et al. 2007
Thornton et al. 2013

- Fast radio bursts (FRBs) are millisecond-duration radio flashes apparently originating at extragalactic distances.
- The physical origin of the FRBs is currently unknown.

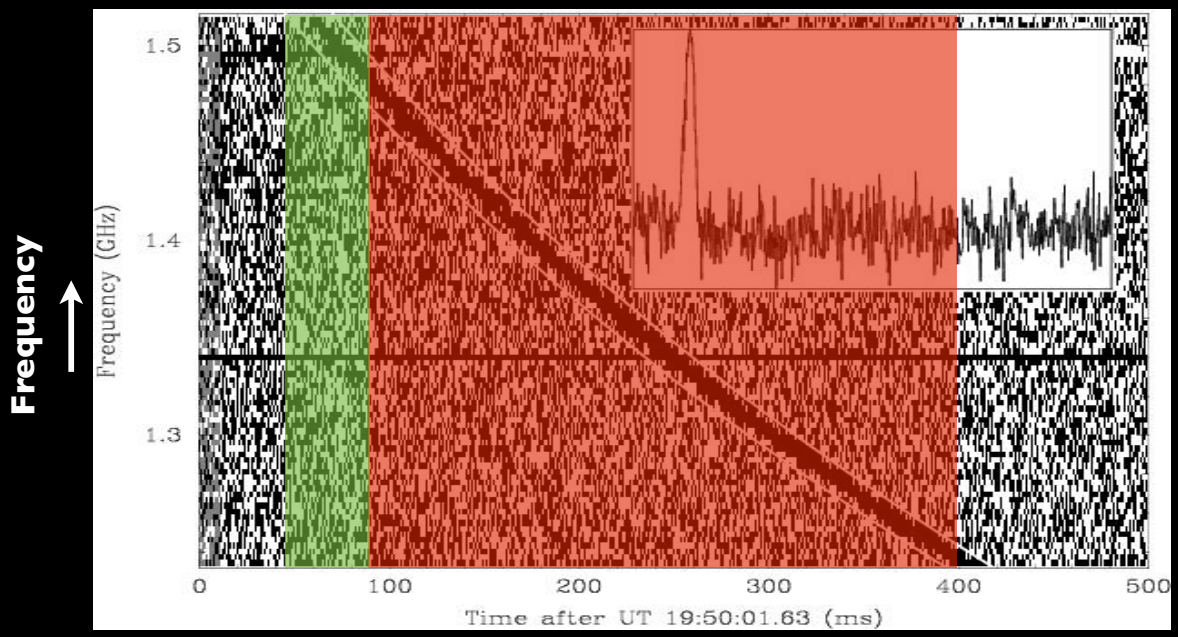
2007: The Lorimer Burst



Lorimer et al. 2007

- The first detected FRB, a.k.a. the "Lorimer Burst" was found in 2007 with the Parkes radio telescope (using archival data from 2001).
- The signal arrives progressively later towards lower radio frequencies because of dispersion in the ionized interstellar medium.

2007: The Lorimer Burst

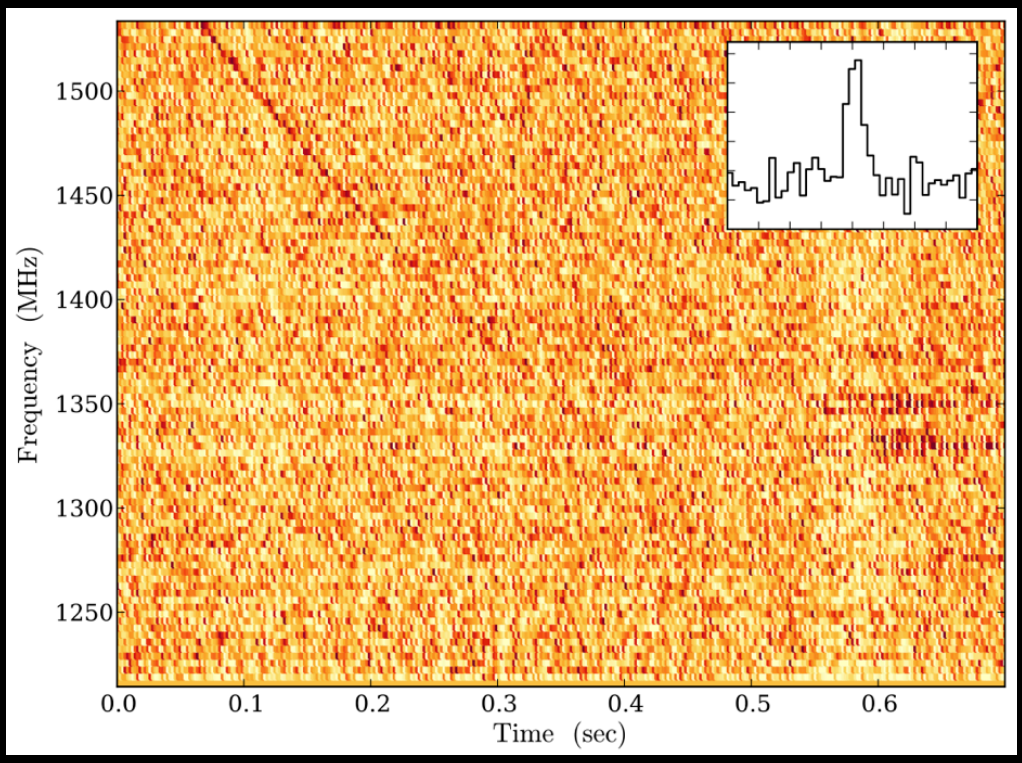


Delay too large to come from just the galaxy

Lorimer et al. 2007

- In the case of the Lorimer Burst, the dispersive sweep of the signal is much too large to be explained by dispersion from the Galactic free electron column density.
- Lorimer et al. thus concluded that the Lorimer Burst must originate in extragalactic space and that the dispersive sweep also has contributions from free electrons in the intergalactic medium and the host galaxy of the source.

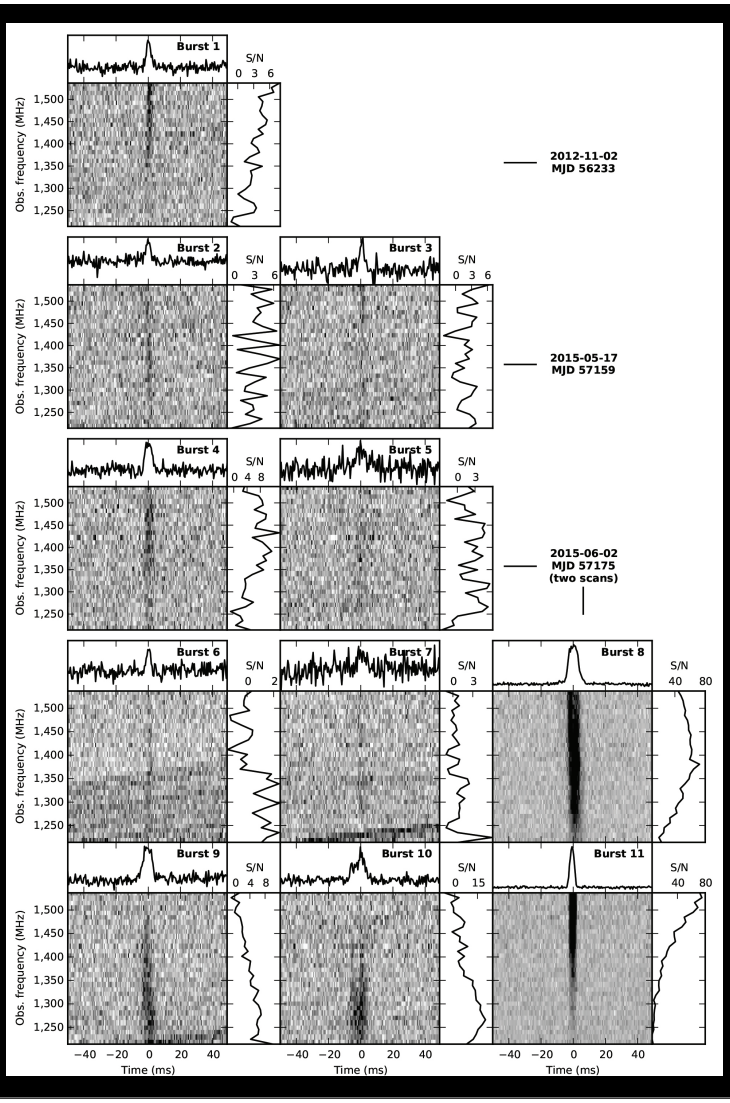
The Arecibo Burst



First non-Parkes FRB

Spitler, Cordes, Hessels et al. 2014

• Until recently, all FRBs had been discovered using the Parkes radio telescope. Arecibo was the first telescope besides Parkes to discover an FRB.



10 New AO Bursts!

First repeating Fast Radio Burst!

Scholz

Spitler, Scholz, Hessels et al. 2016

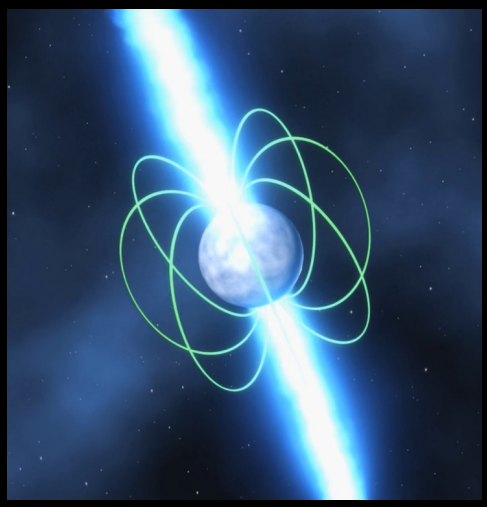
- The Arecibo FRB has turned out to be a very interesting source because follow-up observations have shown that it produces repeated radio flashes - unlike the other known FRBs, which have (so far) not shown repeat bursts.

Why important?

Rules out a cataclysmic source (at least for this FRB)



vs.

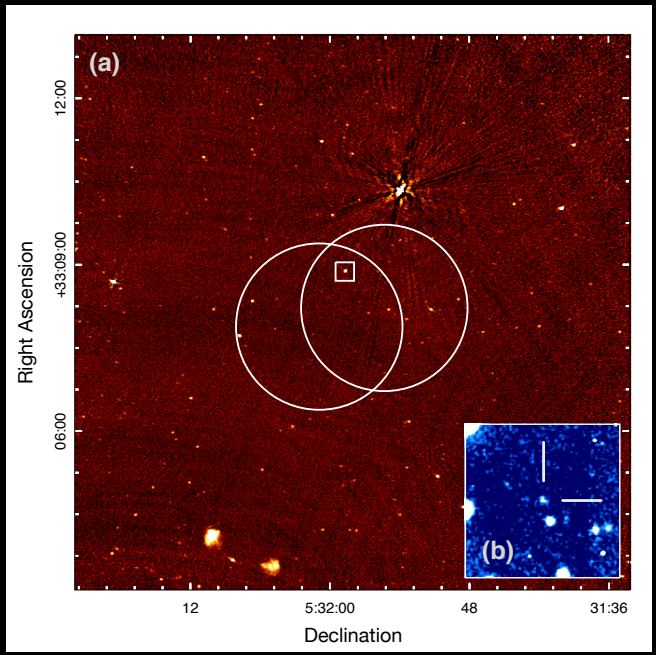


One-time-only explosion

Pulsar on steroids

- This leads to the immediate conclusion that the Arecibo FRB cannot originate in a cataclysmic explosion. Whatever is producing these bursts must survive and continue to be active.

VLA Localization

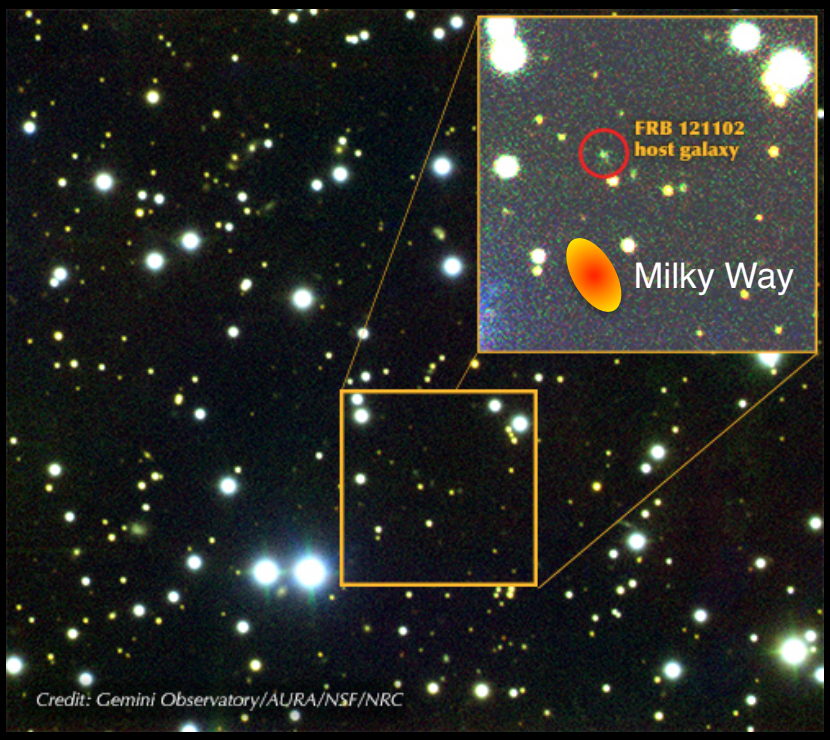


Association with persistent radio and optical sources

Chatterjee et al. 2017

- Because the Arecibo FRB repeats, it has been possible to wait for it to emit a pulse and to detect it with radio interferometers that can localize the source position to a fraction of an arcsecond.
- Precise localization of the Arecibo FRB has allowed scientists to associate the position of the bursts with both persistent radio and optical sources.

The Host Galaxy



- 25th mag., roughly 100 million times fainter than the naked eye limit.
- Each burst (briefly) outshines all other stars in the galaxy!!
- 1000x less massive than the Milky Way.
- 10x smaller.
- The SMC at 1Gpc.

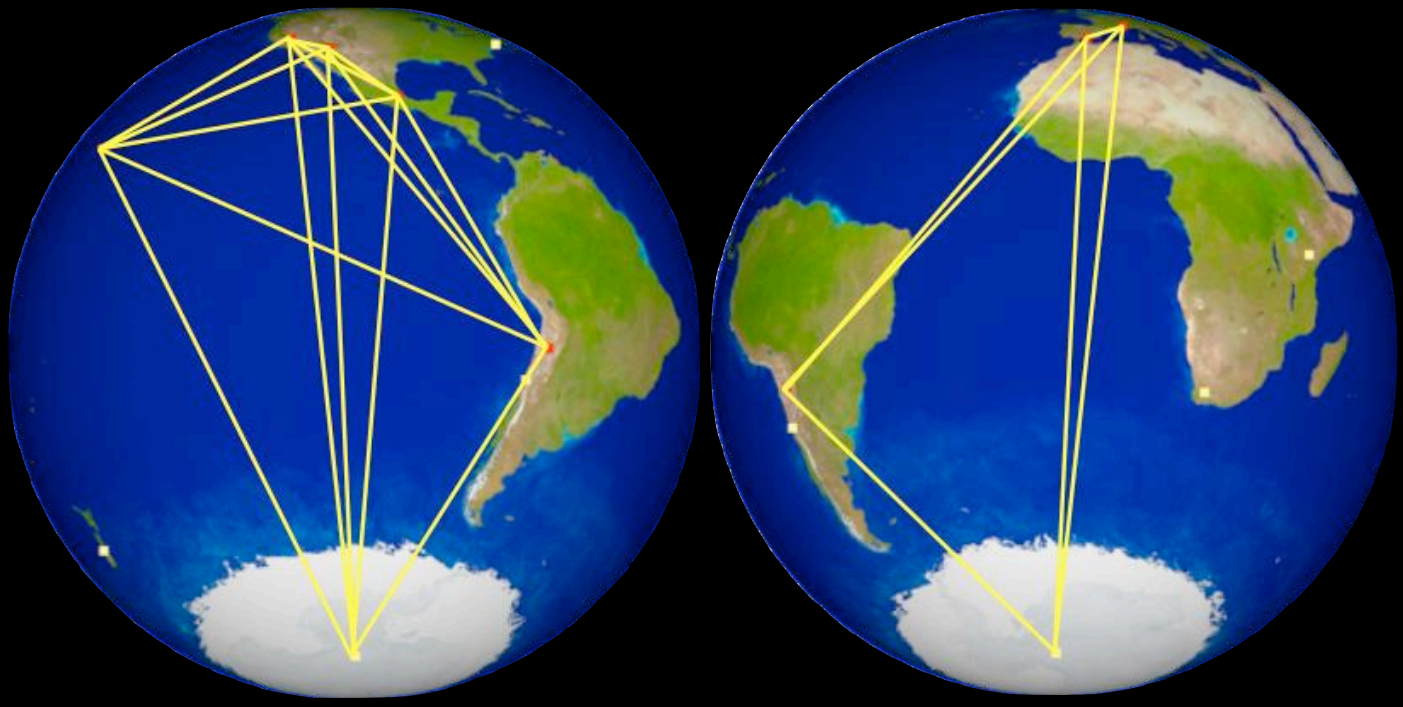
Relation to long GRBs and superluminous SNe?

- This has led to the unambiguous association of the Arecibo FRB with a host galaxy.
- The host turns out to be a puny dwarf galaxy at a distance of ~1 Gpc (redshift 0.193).
- Such galaxies are also known to preferentially host long gamma-ray bursts and super-luminous SNe, suggesting a possible evolutionary link between these types of explosions and the sources that create FRBs.

Event Horizon Telescope



Event Horizon Telescope

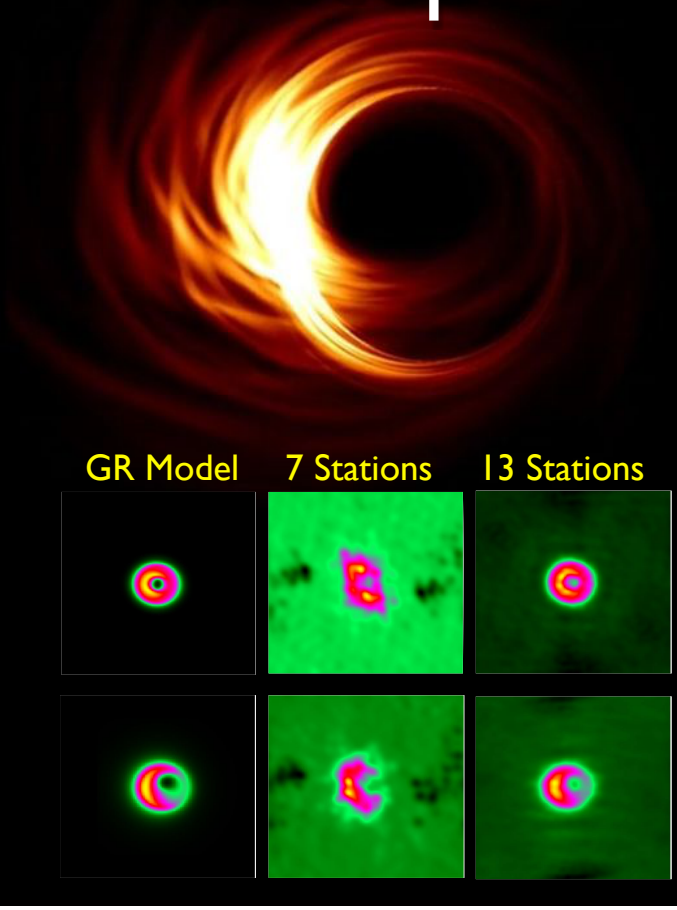


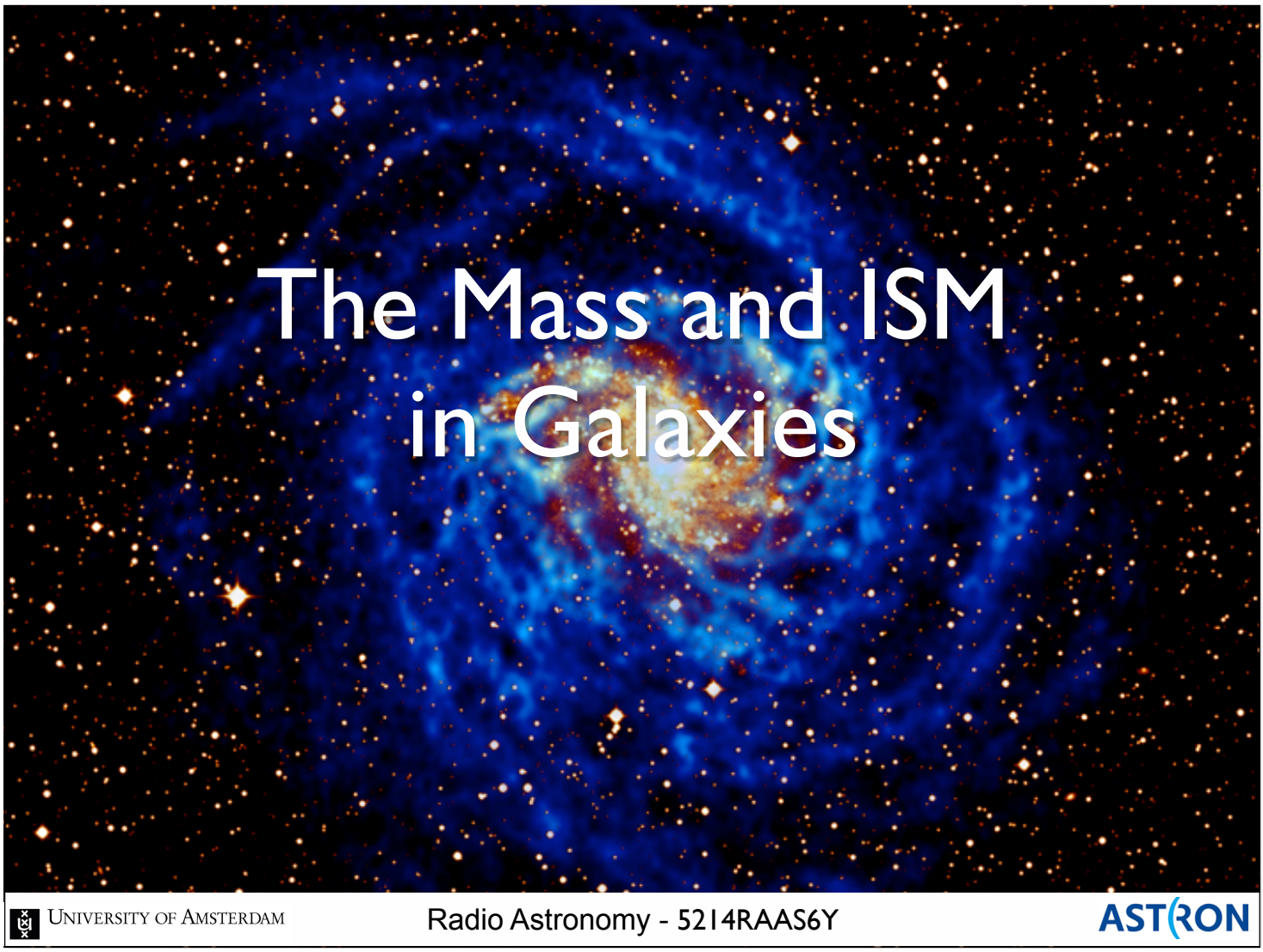
Global VLBI imaging of the SgrA black hole in the center of our galaxy!*

0.8-1.3 mm VLBI □ ~ 30 □° ≥● £ ~ R_{sch}

Event Horizon Telescope







A combined images showing the optical and radio maps for the nearby spiral galaxy NGC6496. The radio emission is much more extended than the optical light.

Radio data provide invaluable insights into the different components of the ISM in galaxies and how it is created and evolves over time.

We can also study the total mass content (visible + dark) of galaxies.

Starburst Galaxies

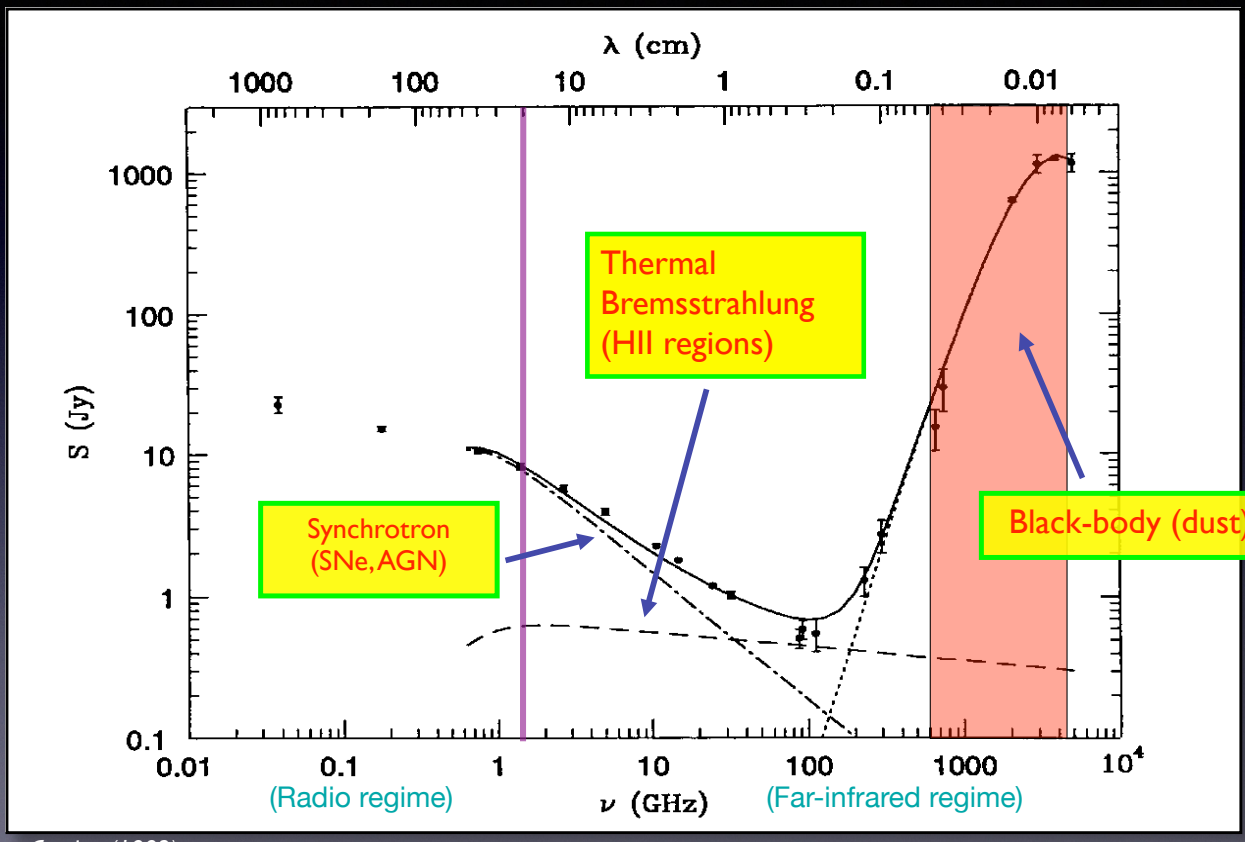
- Starburst galaxies have star-formation intensities of 1-100 $M_\odot$ yr^{-1} kpc^{-2} ($x10^3$ Milky Way)
- Starbursts often are stimulated by galaxy mergers or close passages
- Radio emission is thermal emission from HII regions ("super star clusters") or nonthermal emission from supernova remnants
- 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 Spectrum (M82)

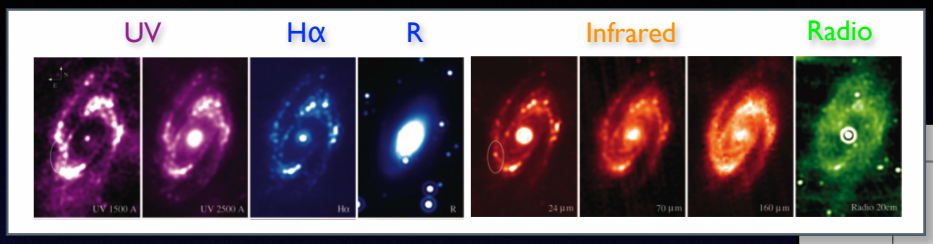


Condon (1992)

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

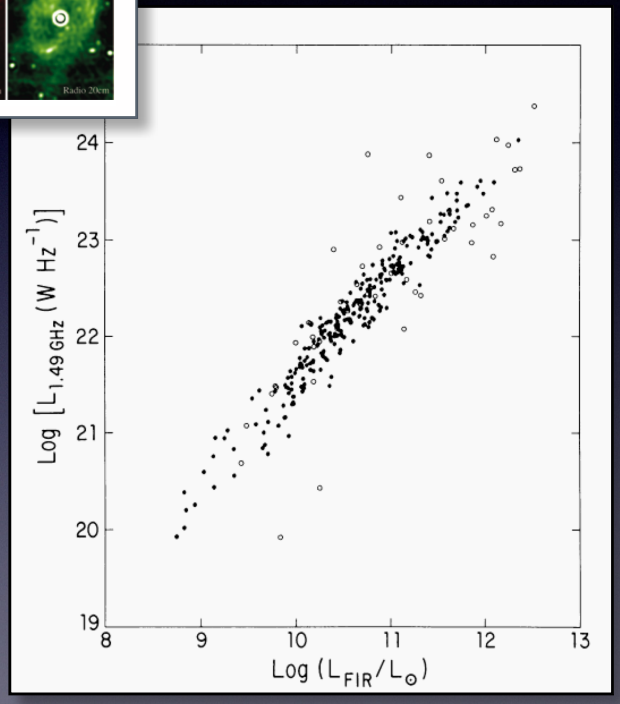


Gordon et al. (2004)

- 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!



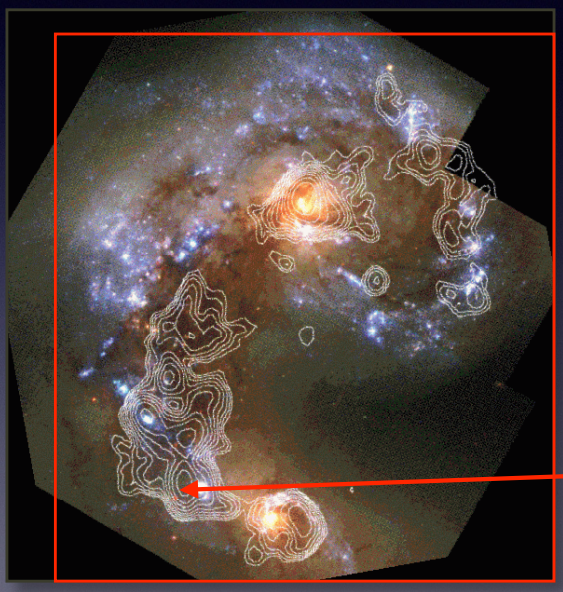
Kennicutt (1998)

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.

Merger Induced Starbursts

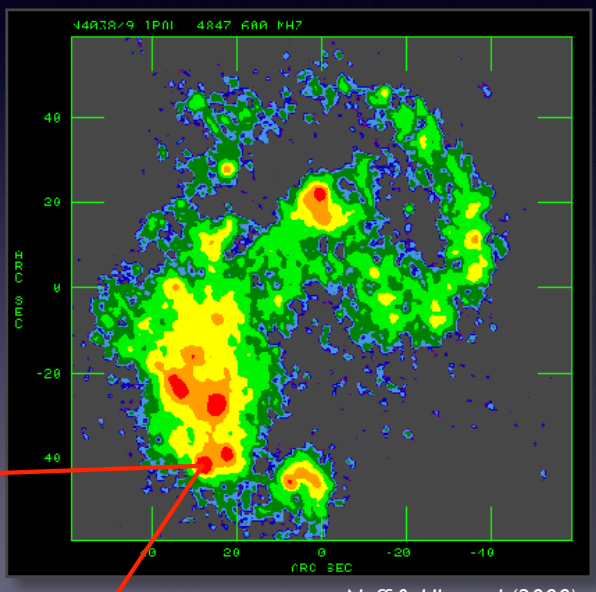
⇒ *Nearest Merger - The "Antennae"*

WFPC2 with CO overlay



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

VLA 5 GHz image



Neff & Ulvestad (2000)

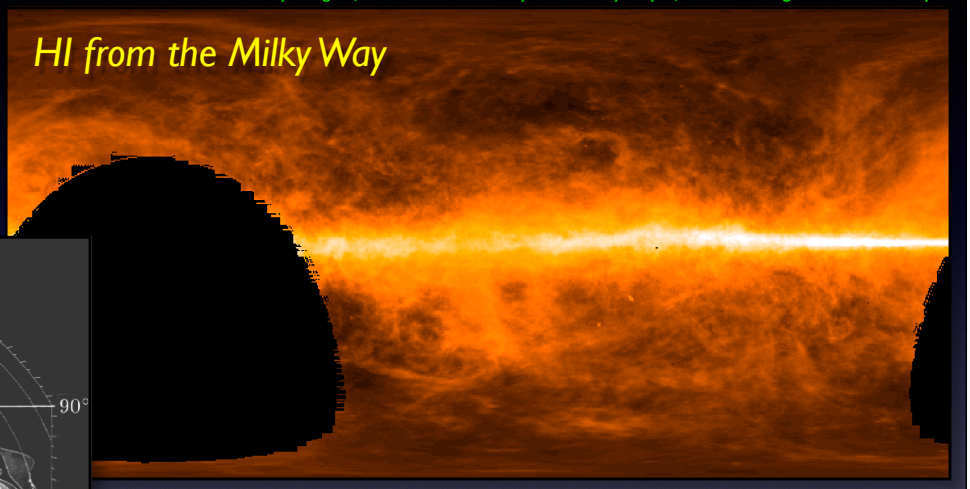
5 mJy ~ 30,000 O7-equivalent stars

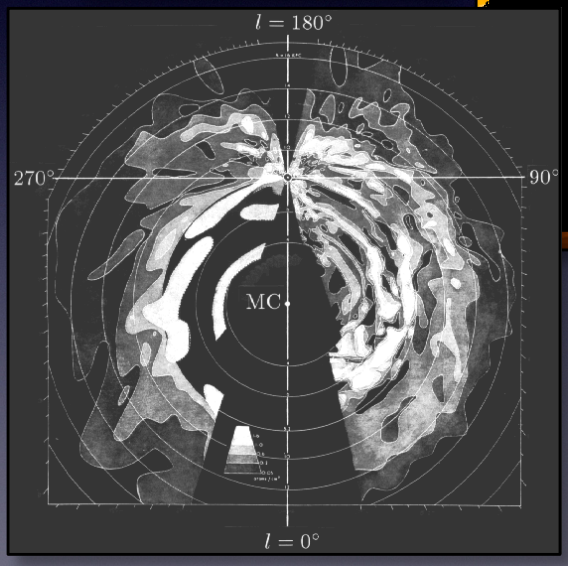
Comparison between optical+CO maps and radio image for a nearby merging galaxy.
Optical shows current distribution of stars, while CO shows cold material out of which the stars formed.
Images show how well radio emission traces the cold, star forming material.
Mergers are believed to be an important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





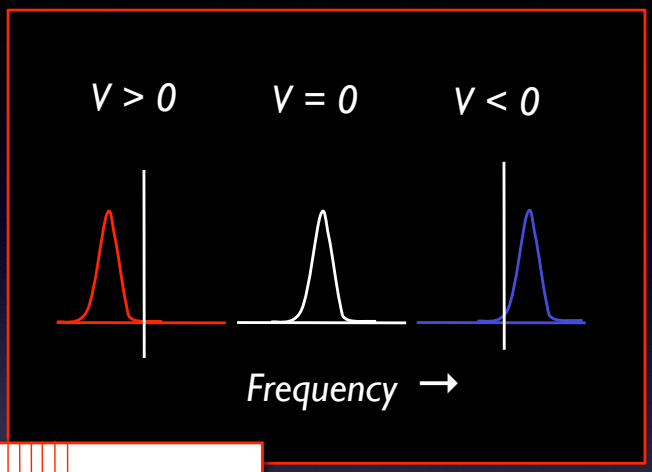
Oort, Kerr & Westerhout (1958)

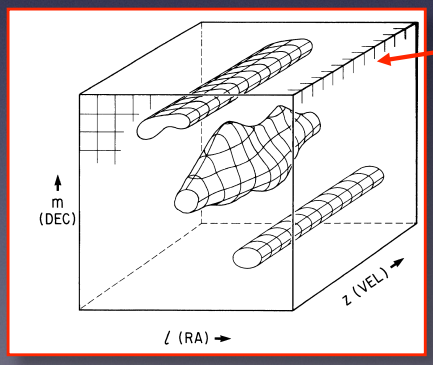
- HI comprises 5-10% mass in the Milky Way
- HI traces the "warm" interstellar medium
- Organized into diffuse clouds of gas and dust
- Traces structure and kinematics
- Traces streams and high velocity clouds
- Traces accretion and mergers
- Probe of dark matter
- Evolution of gas content with redshift

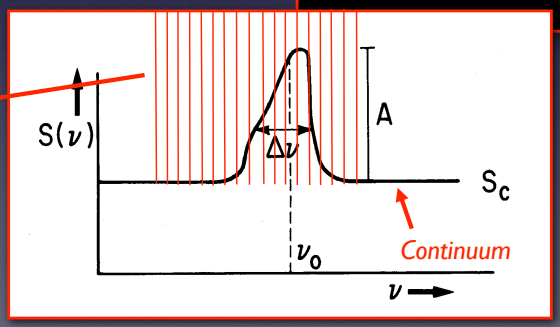
Radio emission from neutral hydrogen, HI (pronounced "H-1"), is one of the primary ways to study the evolution of mass in the universe.
Can use it to study mass distribution in our own galaxy and in others.

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





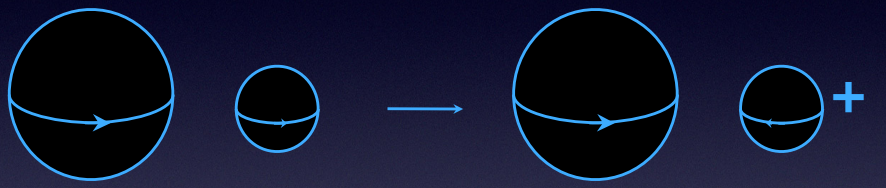


Every channel is one plane of the cube

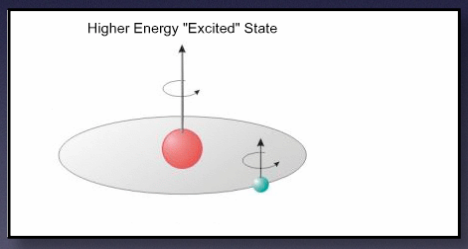
Radio observations of HI are based on detected an emission line from hydrogen.
HI line emission has a narrow intrinsic width which means we can more easily detect shifts due to gas motions.
Red and blue doppler shifts in the observed line translate into velocity motion away and towards us.
HI line emission 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 x 10^{-6} eV)



proton electron proton electron

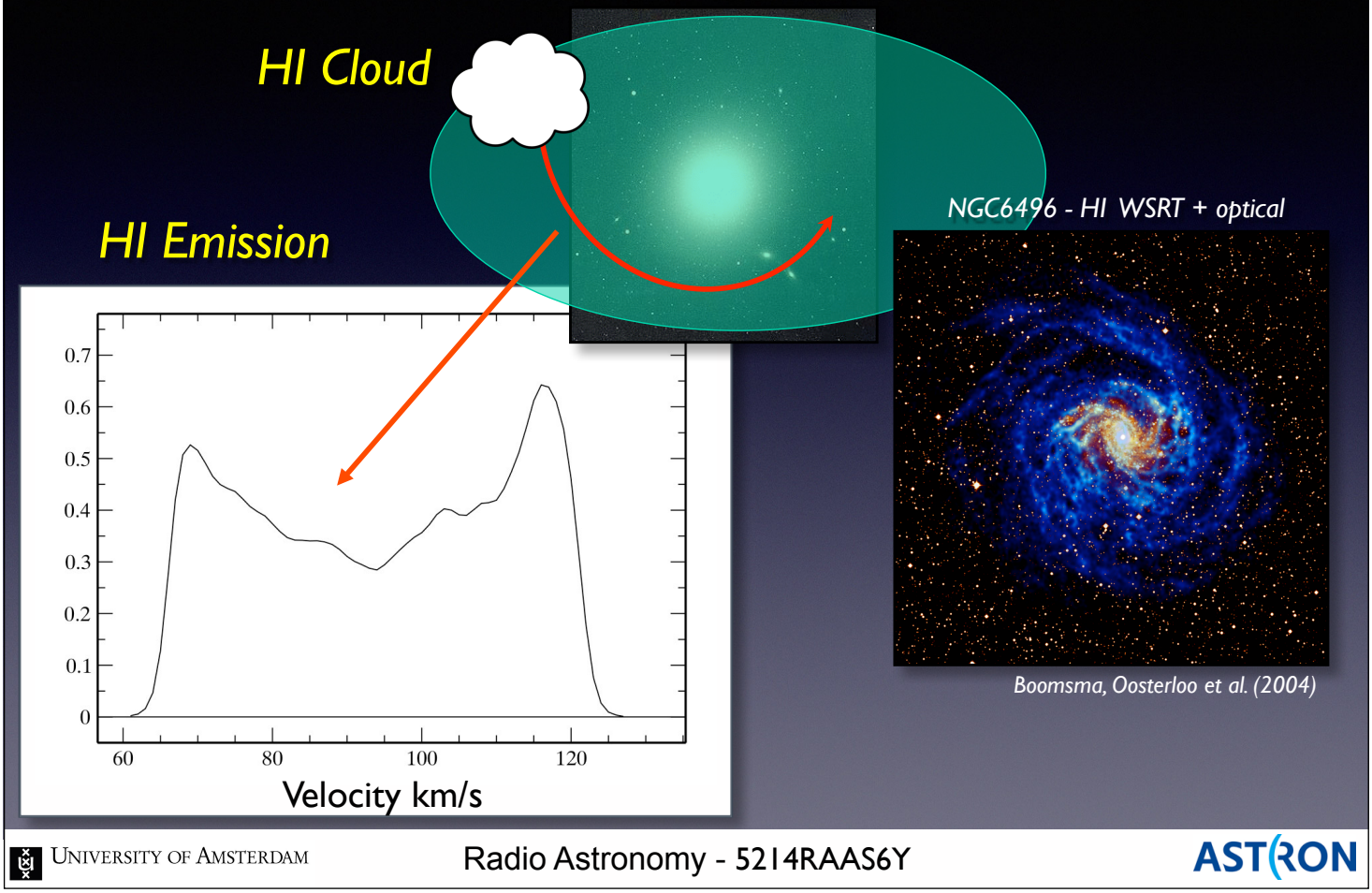


Frequency of the transition:
1420.405752 MHz (21.105 cm)
(Hendrik van de Hulst, 1944)

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

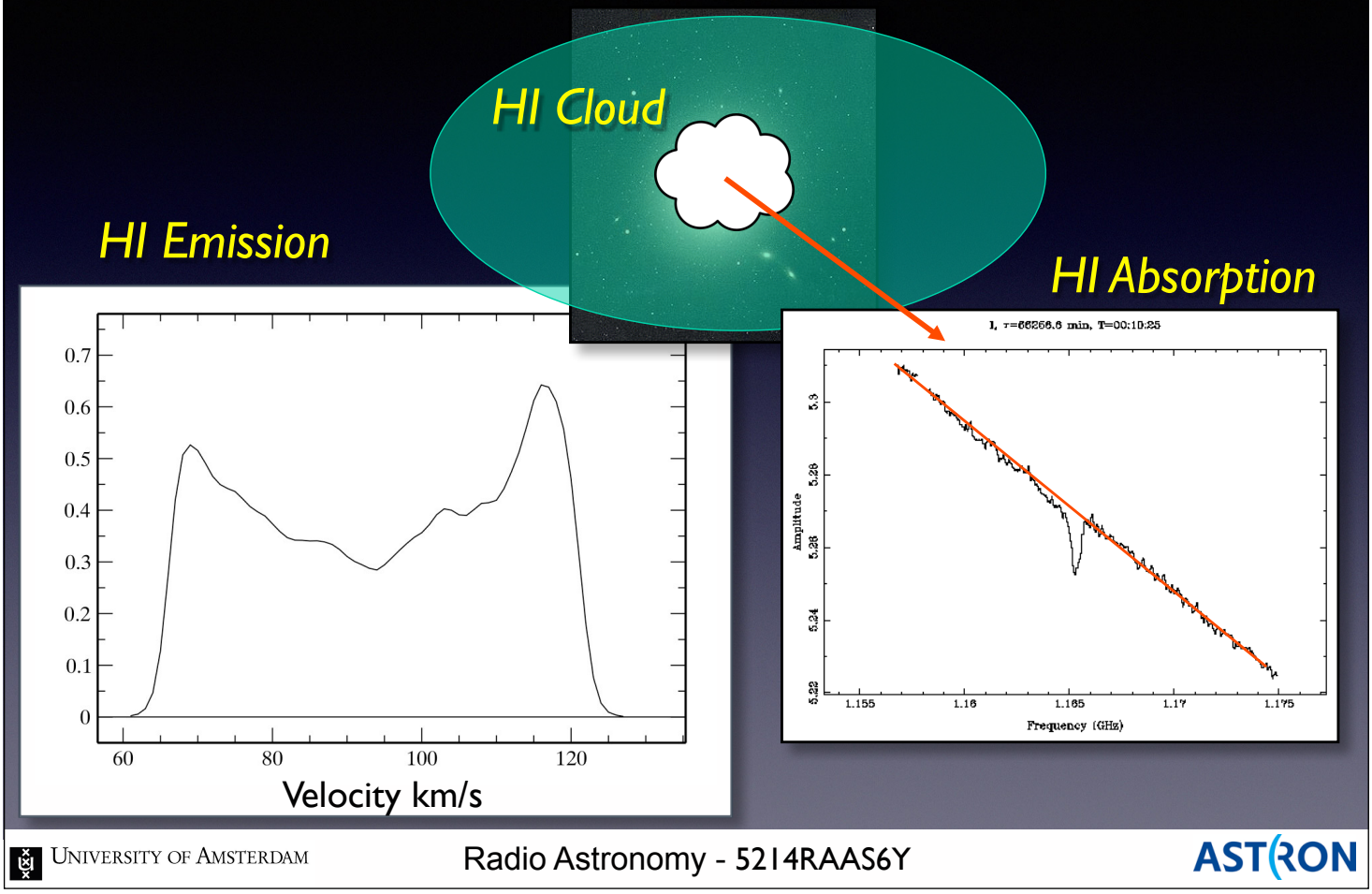
21 cm line emission from HI first predicted by a Dutchman in 1944. Hup Holland hup!

HI Detected in Emission



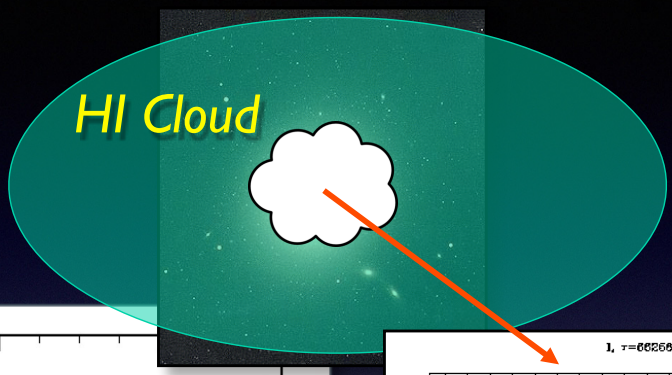
We can detect HI lines in both emission and absorption.
In emission, the shape of the line profile contains velocity information about the orbit of the HI cloud that emitted it.
The orbital velocity also contains information about the mass of the galaxy the HI cloud is orbiting.

HI Detected in Absorption

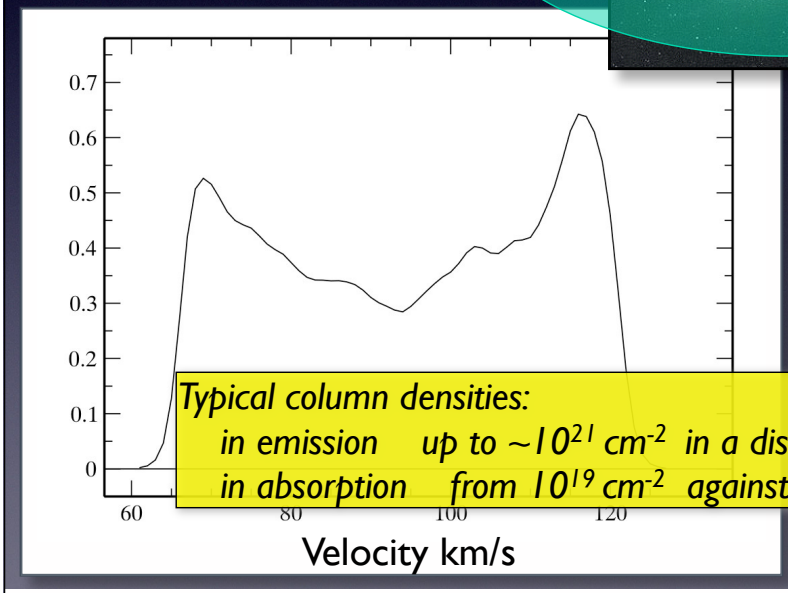


In absorption, the HI cloud blocks photons from a source behind the cloud.
The decrement in the observed spectrum is basically related to the amount of HI in the cloud.
Requires a bright background source.

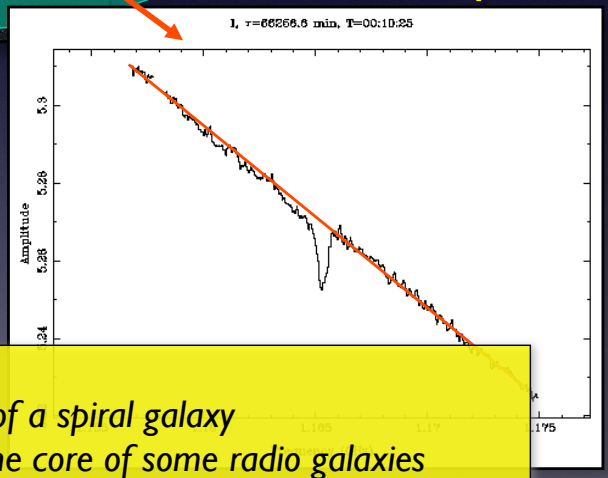
HI Detected in Absorption



HI Emission

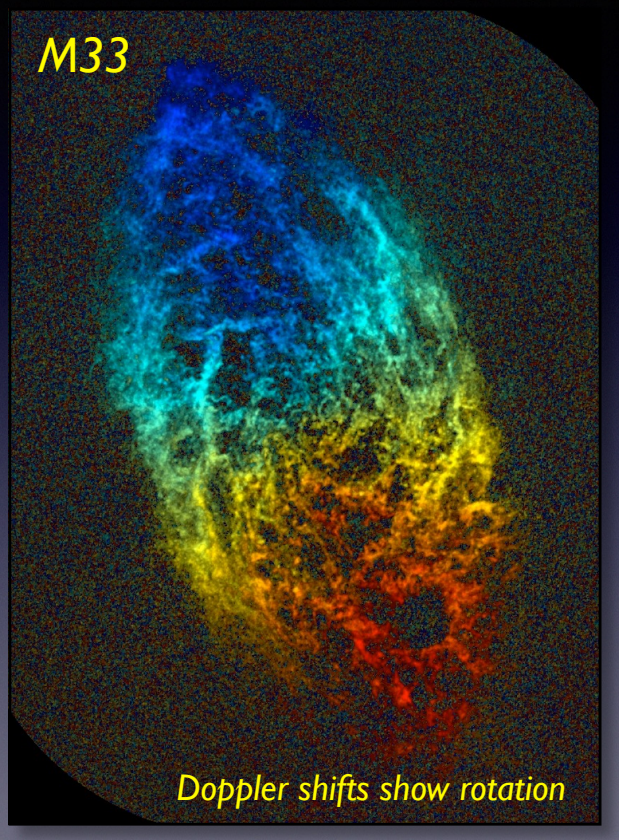


HI Absorption



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

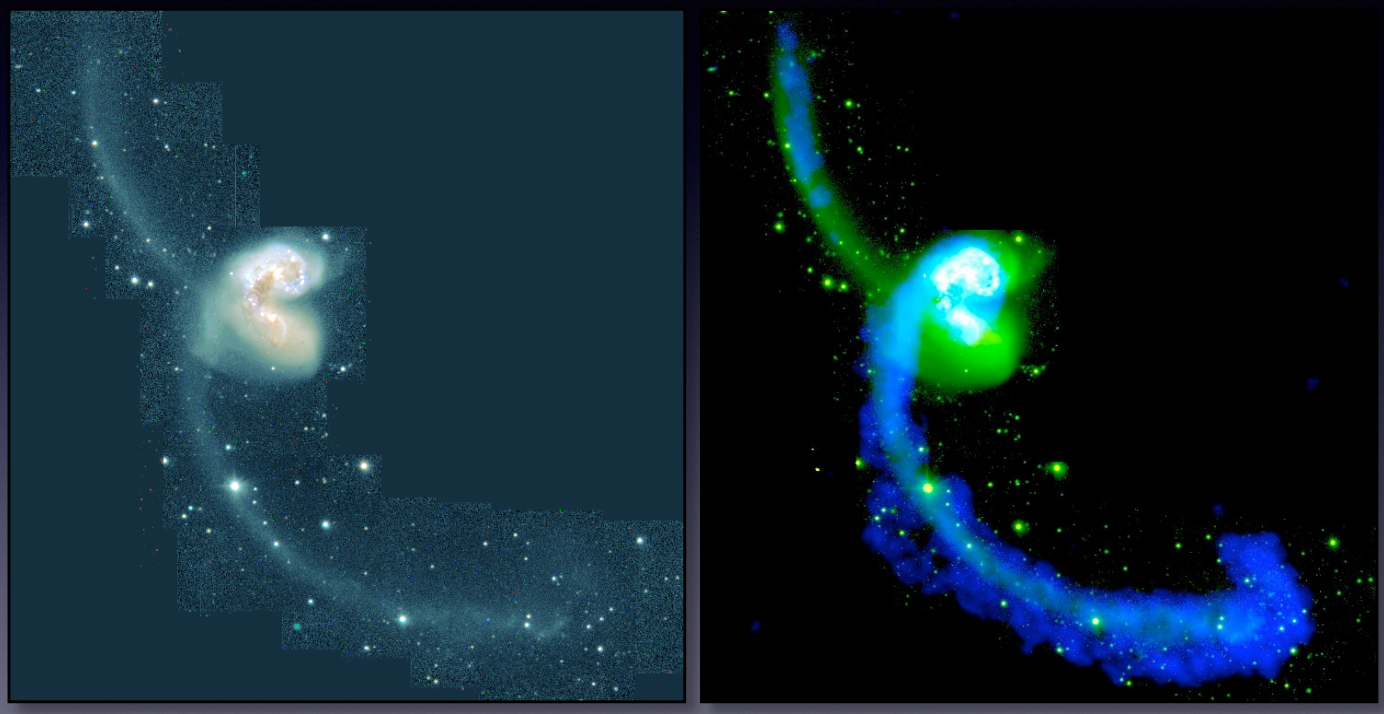


- Galactic studies , high velocity clouds, satellites of the Milky Way.....
- Nearby galaxies and gas accretion
- Dark matter studies
- Interacting systems (including the stream in our own Galaxy)
- Effects of dense cluster IGM on cluster member galaxies (e.g. stripping etc.)
- Gas and Active Galactic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

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

Interacting systems

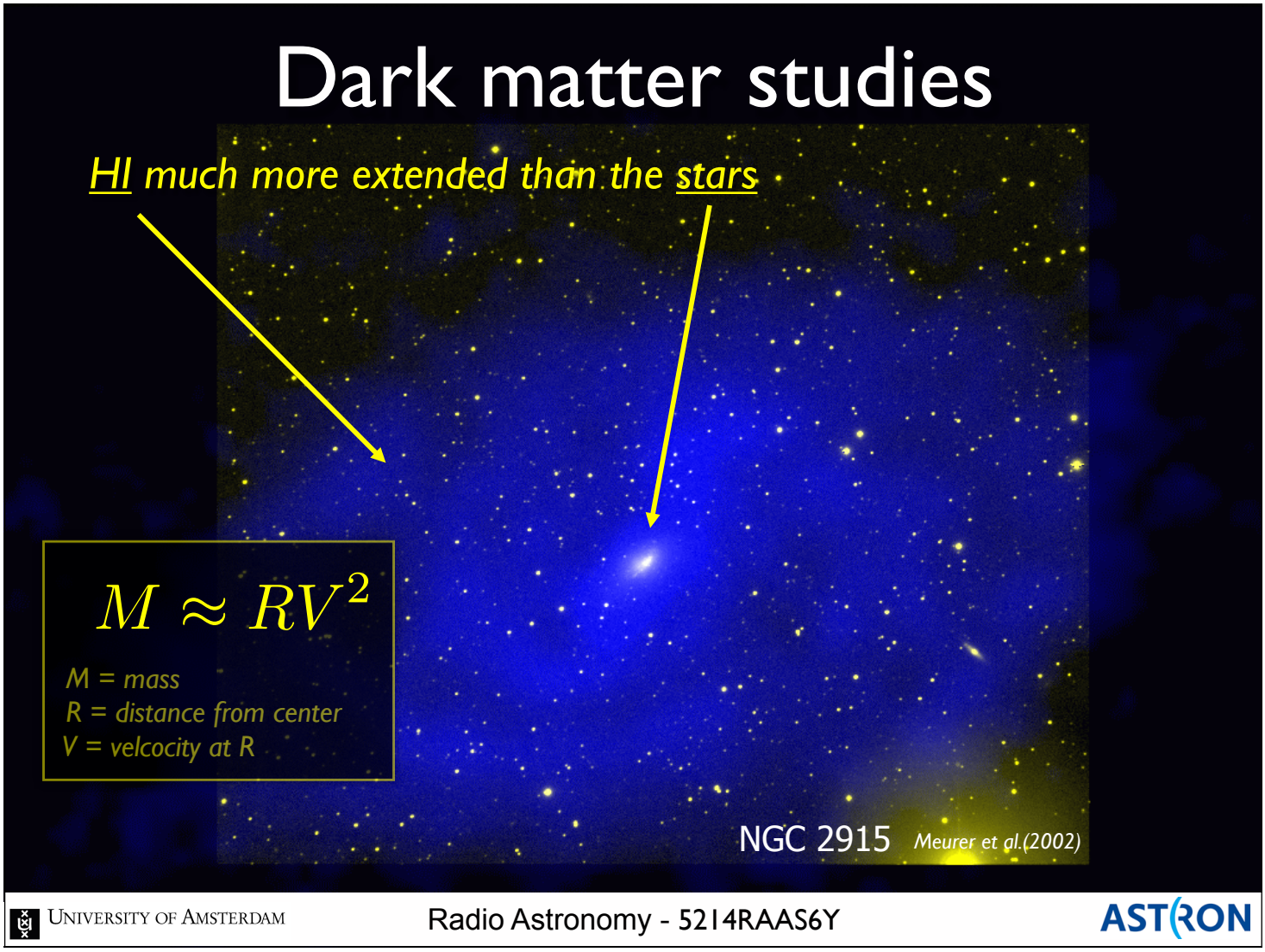
VLA C+D-array observations of NGC 4038/9 - "The Antennae"



Hibbard et al. (2001)

An example of using HI maps to trace the gas stripped out of two interacting galaxies. Green is optical and blue is HI.

Dark matter studies

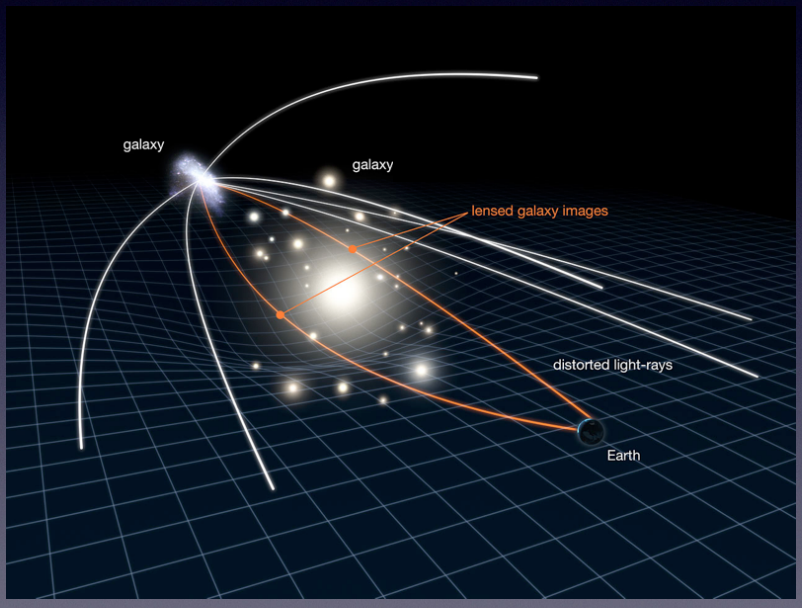


HI studies can allow us to study the rotation curves for gas in galaxies out to much larger radii.
The rotation velocity as a function of radius is related to the total mass inside that radius.
Total mass includes matter we see and also dark matter.
Measuring the HI velocity curve allows us to constrain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

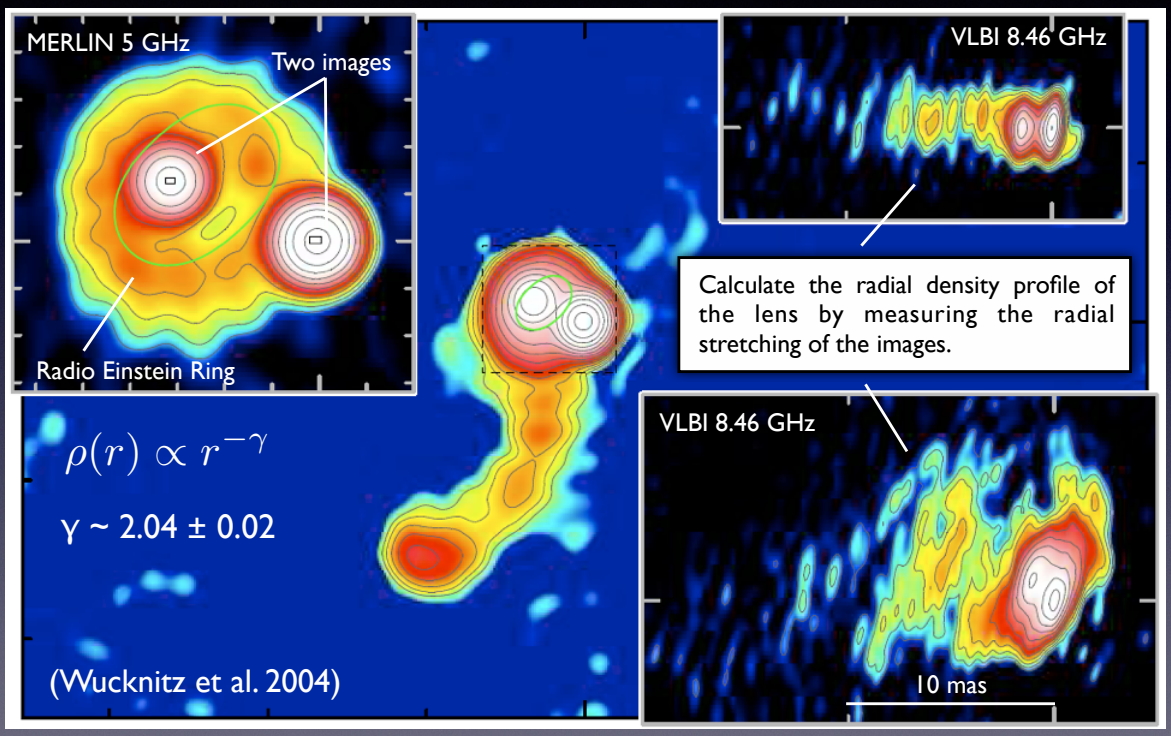
i) Study the mass distribution of the lens -- test galaxy formation and models for dark matter.

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

iii) Measure the cosmological parameters through the lensing statistics.

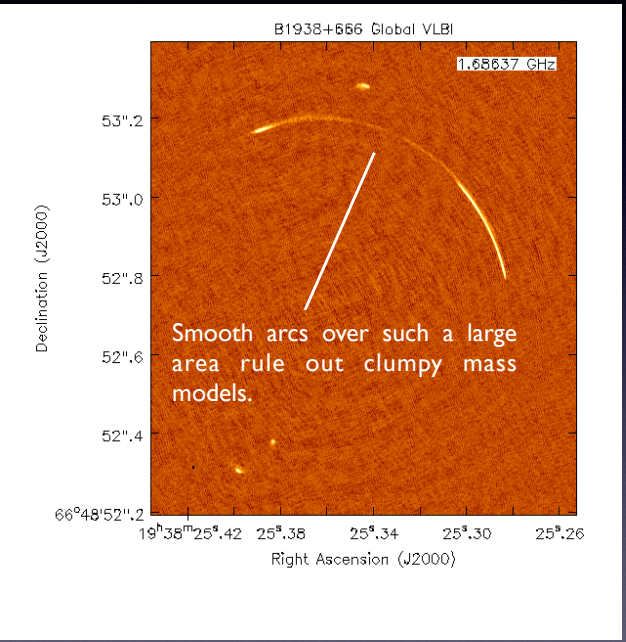
Gravitational lensing is a technique that can be used to study a wide range of problems.
It acts like a telescope and focuses light so we can study more distant objections magnified by the lens.
We can also study the lens itself which tells us about the amount and distribution of mass in the lens.
Lensing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

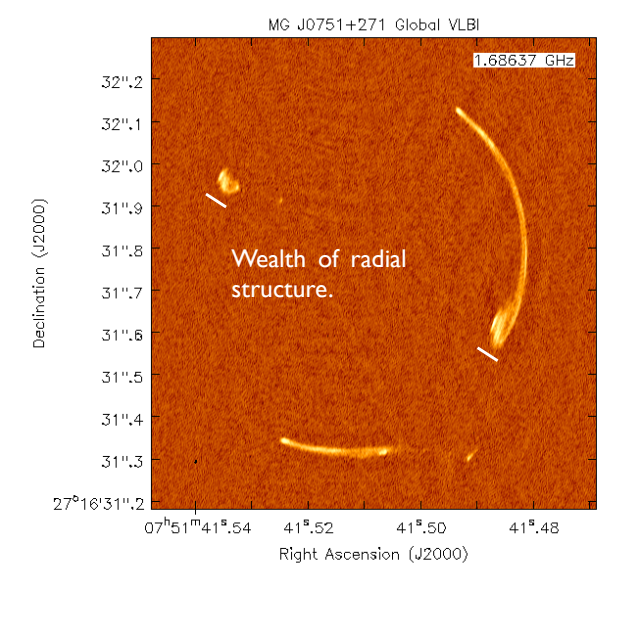
Mass Structure of Galaxies



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

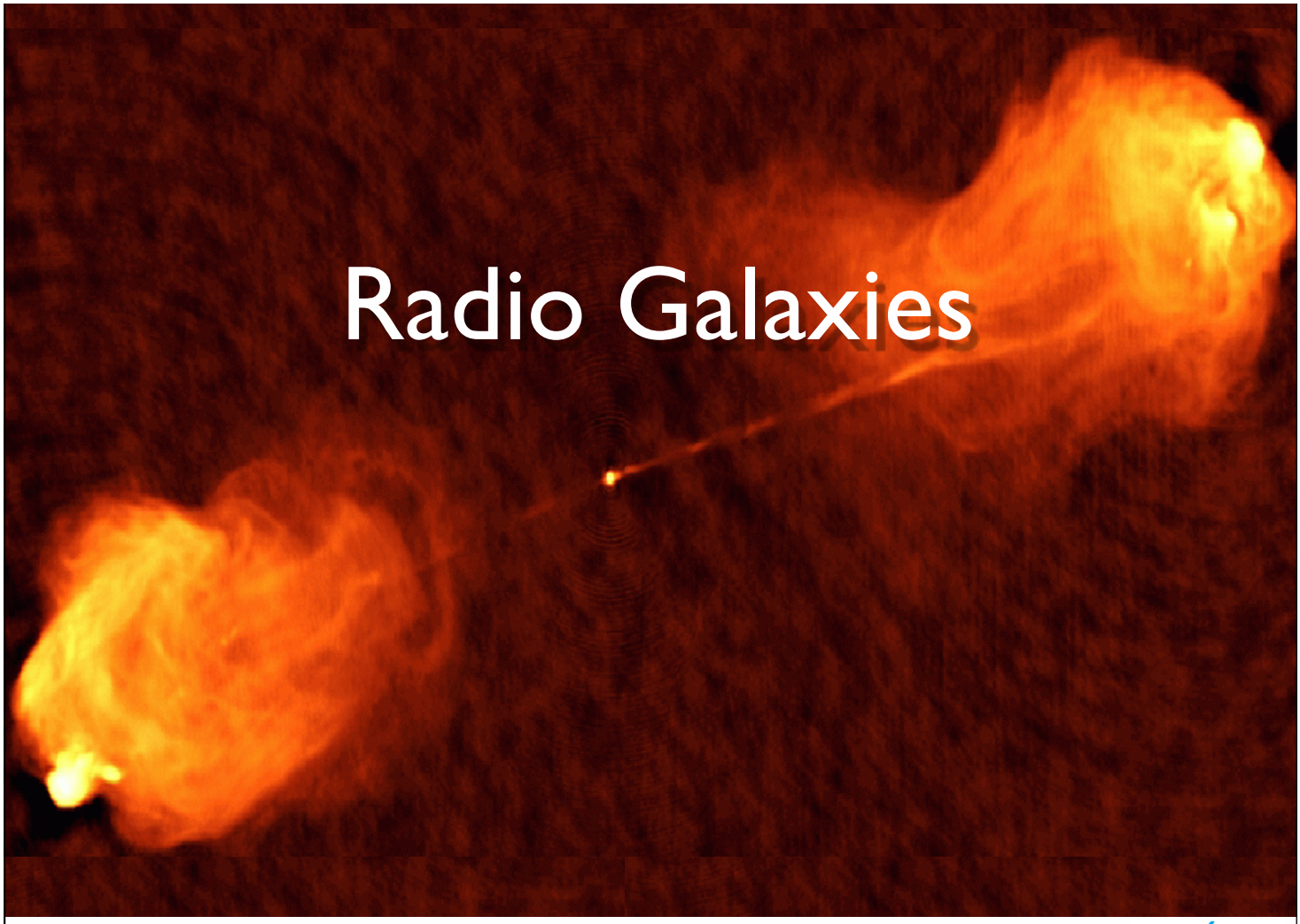




New datasets using the upgraded global VLBI array (23 telescopes spread across the world) detect gravitational arcs extended over 0.8 arcsec with an angular resolution of just ~4 mas.

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)

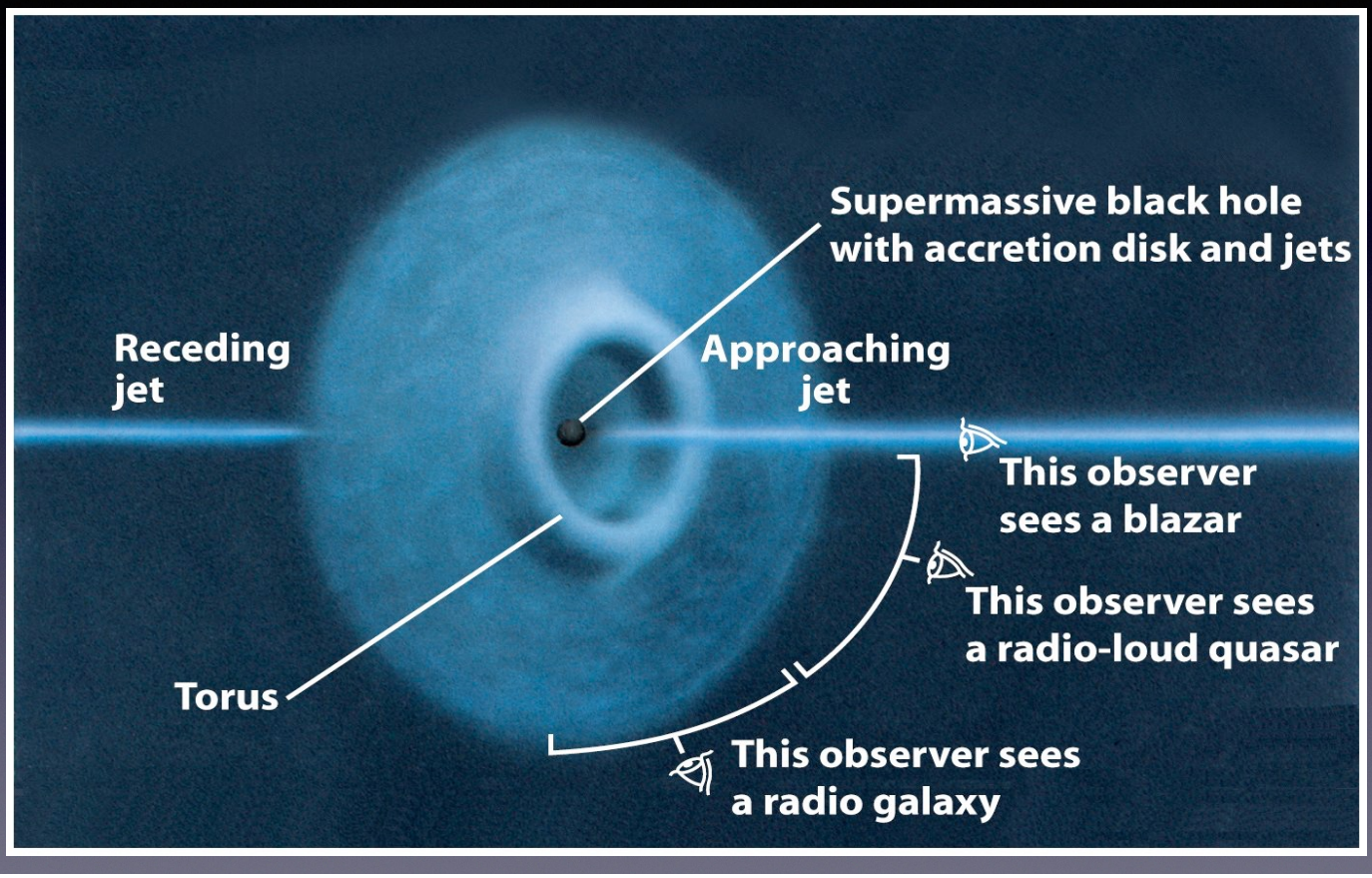
There are many different terms for the variety of AGN and radio galaxies.
Underlying picture is always the same, a supermassive black hole accreting matter and feedback energy and material into the surrounding medium.

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**

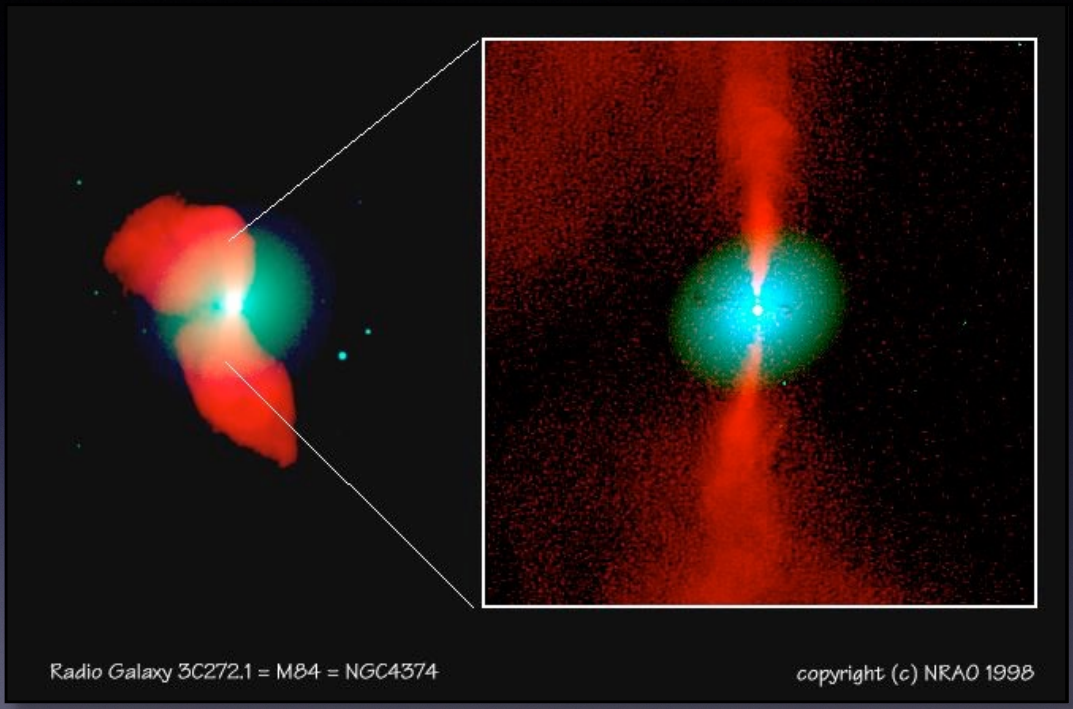
Most varieties of AGN are based on the presence (or absence) or various observational signatures.

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.

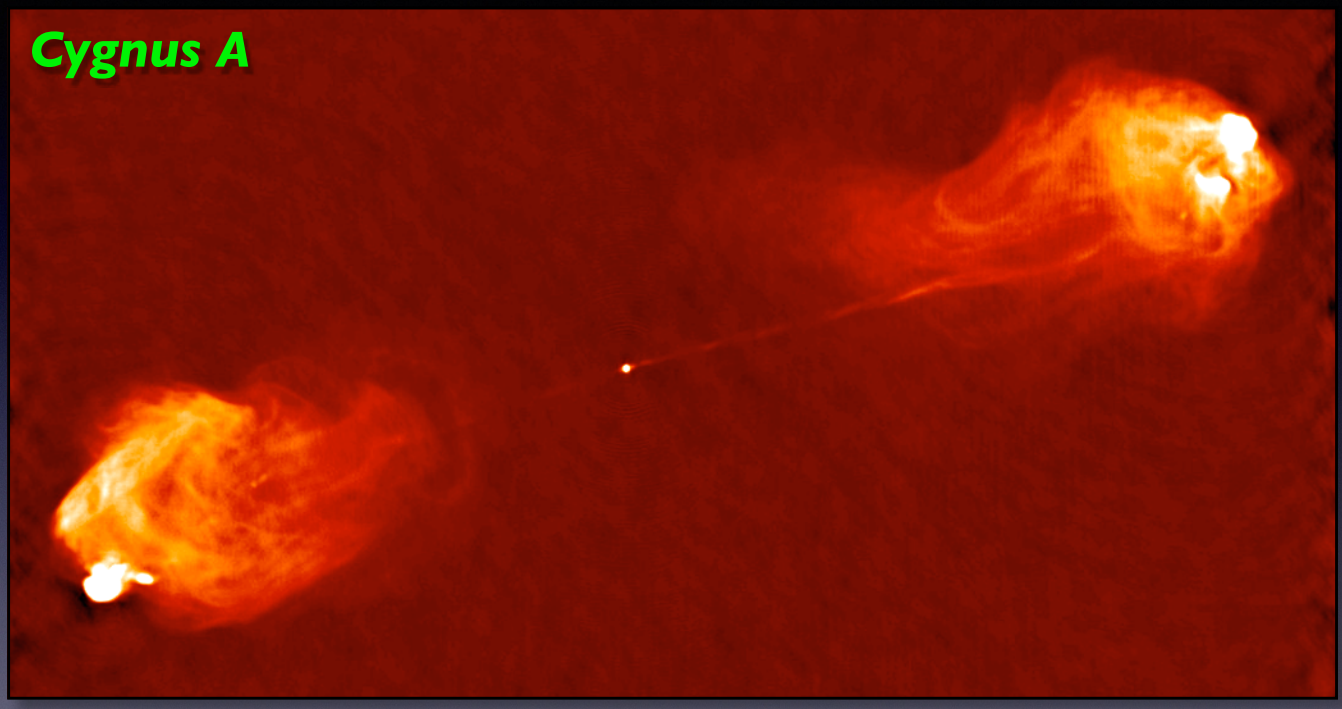
Faranoff-Riley Type I & II



⇒ *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.*

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.

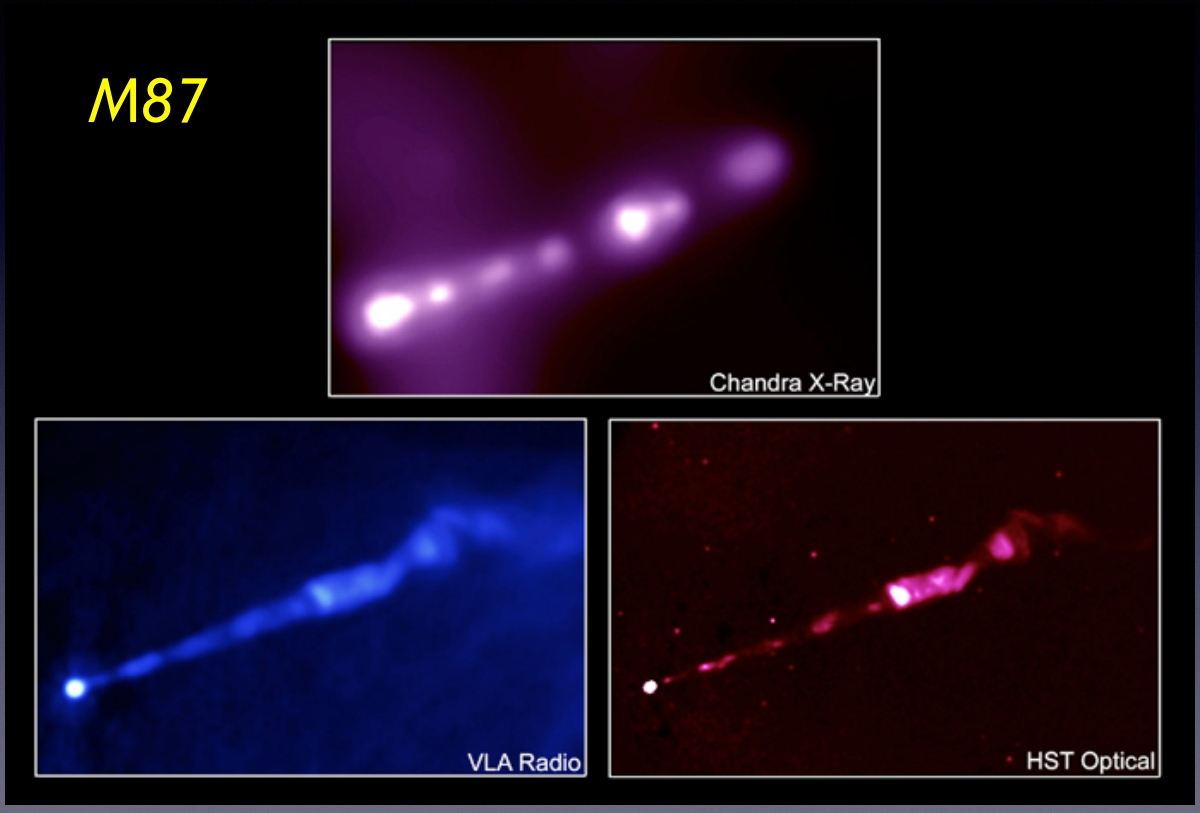
Faranoff-Riley Type I & II



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

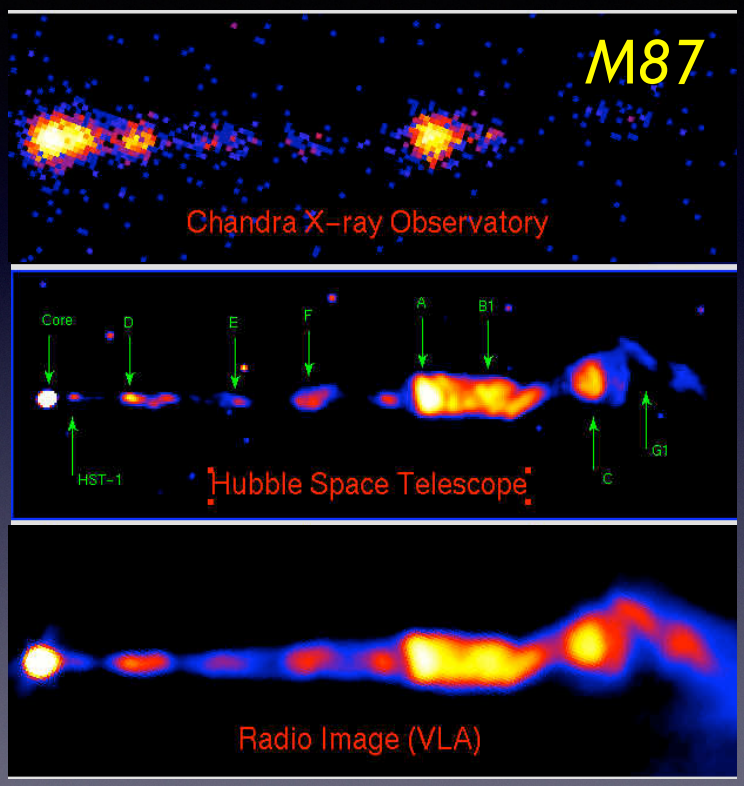
Could be due to differences in the black hole itself, the amount of fuel available, density and makeup of the surrounding medium, or the history of the larger environment (i.e. cluster mergers).
Lots of radio astronomers busily at work trying to answer these questions. Me included.

Jet Propagation

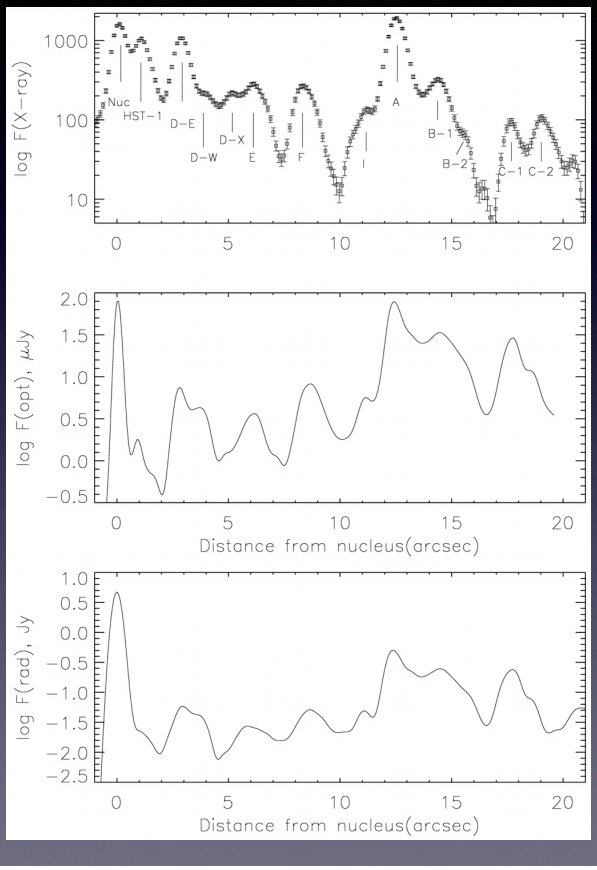


Jets are a very common observational signature of accretion onto BHs.
Jets are seen in many radio galaxies (and even on smaller scales).
Jets are seen at all wavelengths (though not in all objects).
Jets are one of the primary conduits for carrying energy liberated by accretion away from the immediate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

Jet Propagation

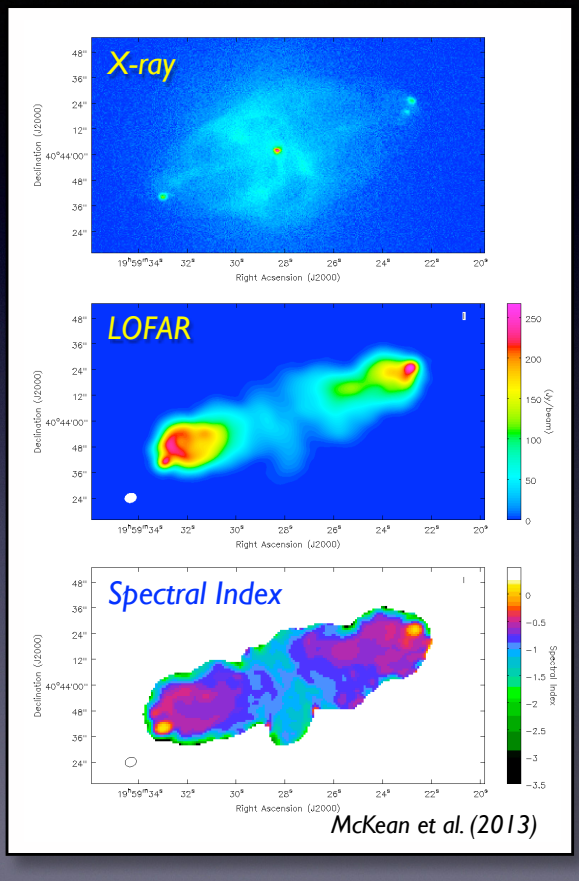


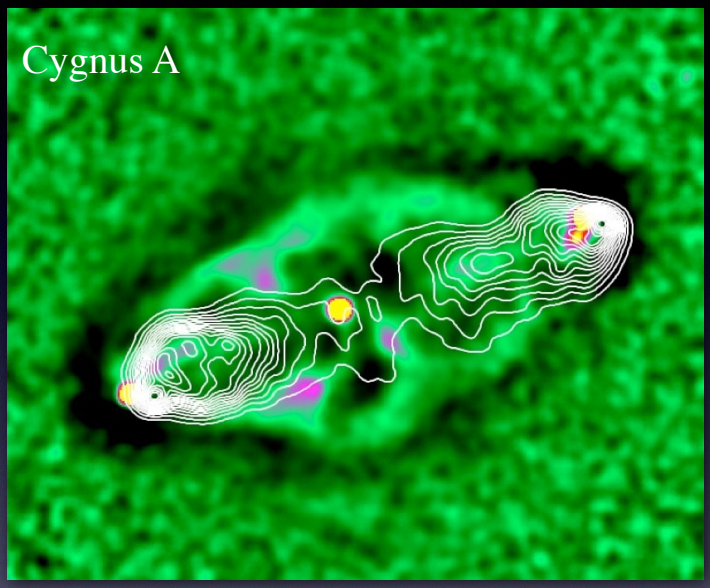
Perlman & Wilson (2005)



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 Source Diagnostics





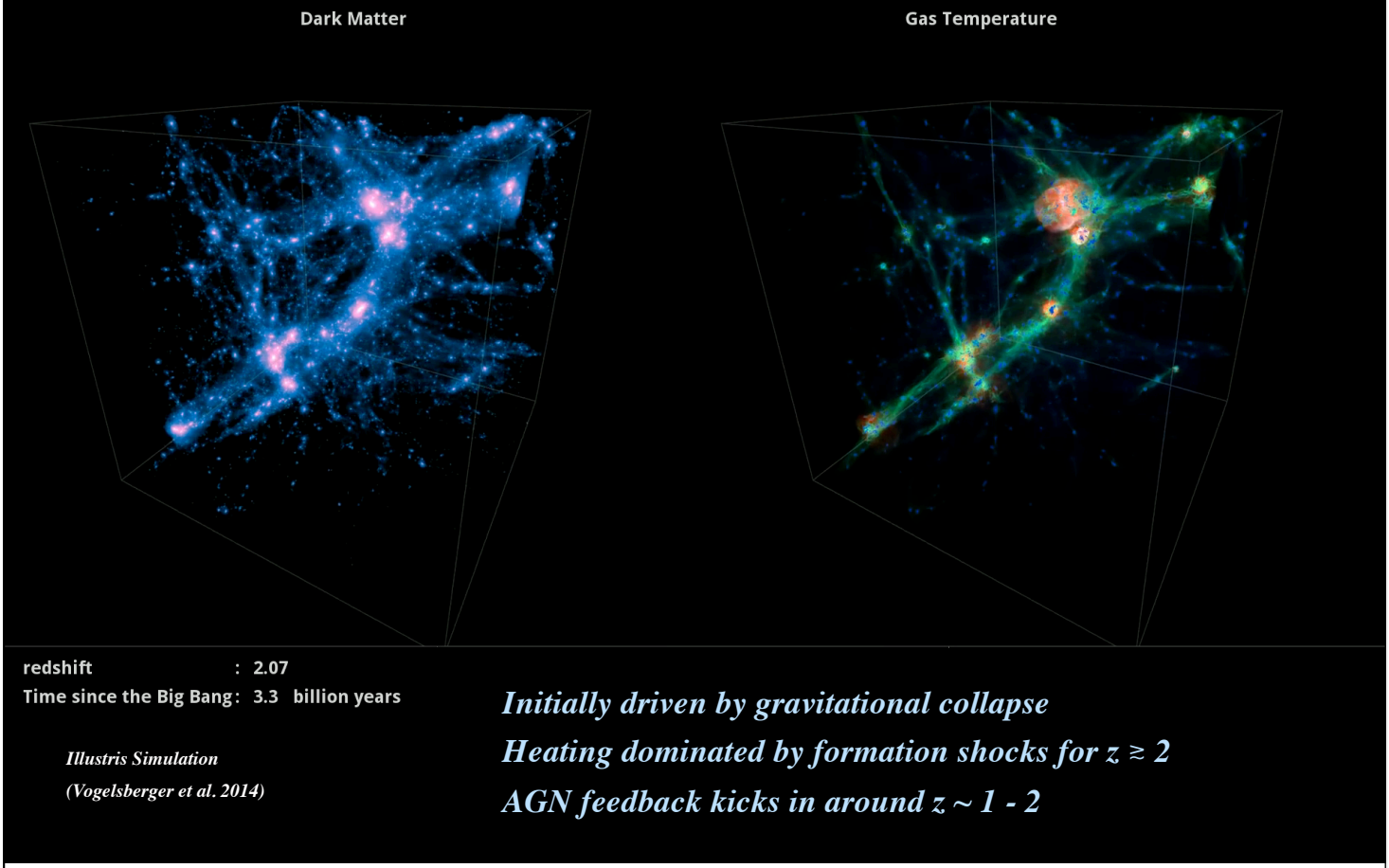
Wise et al. (2013)

- 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 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.


Clusters of Galaxies
& AGN Feedback

Cluster Evolution over Cosmic Time



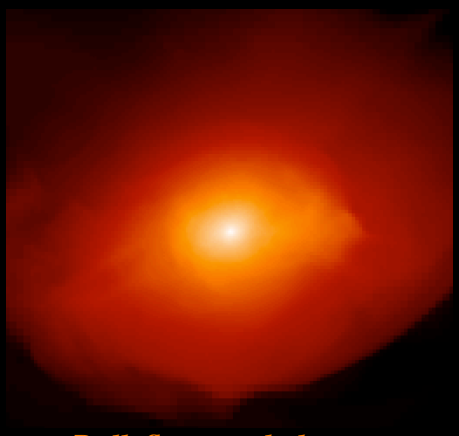
Simulation showing the growth of large-scale structure in the universe.
Gravity dominates the early growth, but from z ~2 till today AGN feedback plays a major role energetically.
The explosions seen on the right are AGN outbursts dumping energy into the cluster environment.

Energy Diagnostics in Clusters

AGN Feedback

Jets, cavities
10s -100s kpc scales
~10^{59}-10^{62} ergs

Gas Motions



Bulk flows, turbulence
100s kpc - Mpc scales



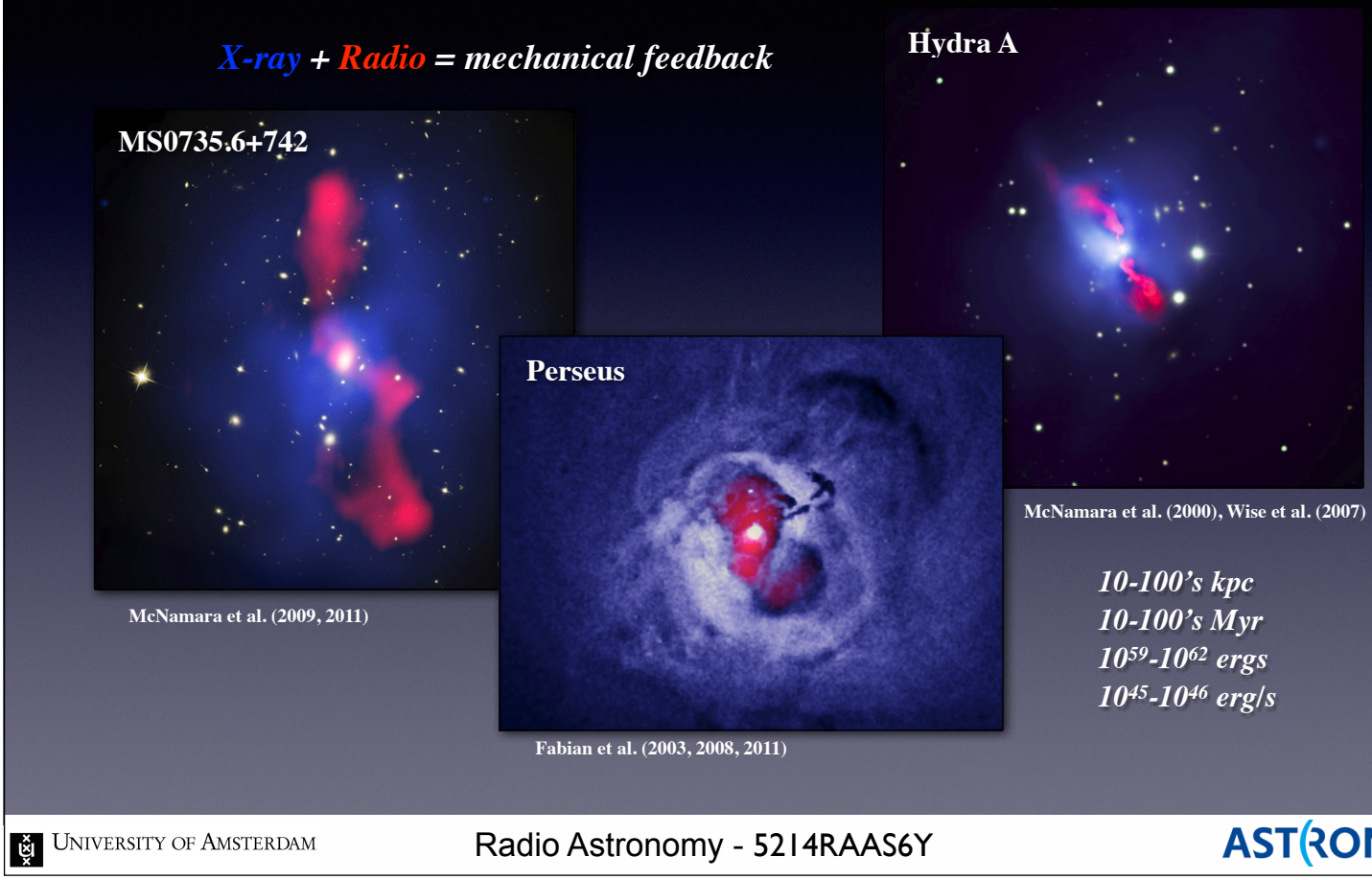
Cluster Mergers

Shocks, morphology
Mpc scales
~10^{64} ergs

Thermal + Non-thermal signatures

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.

AGN Feedback in Clusters



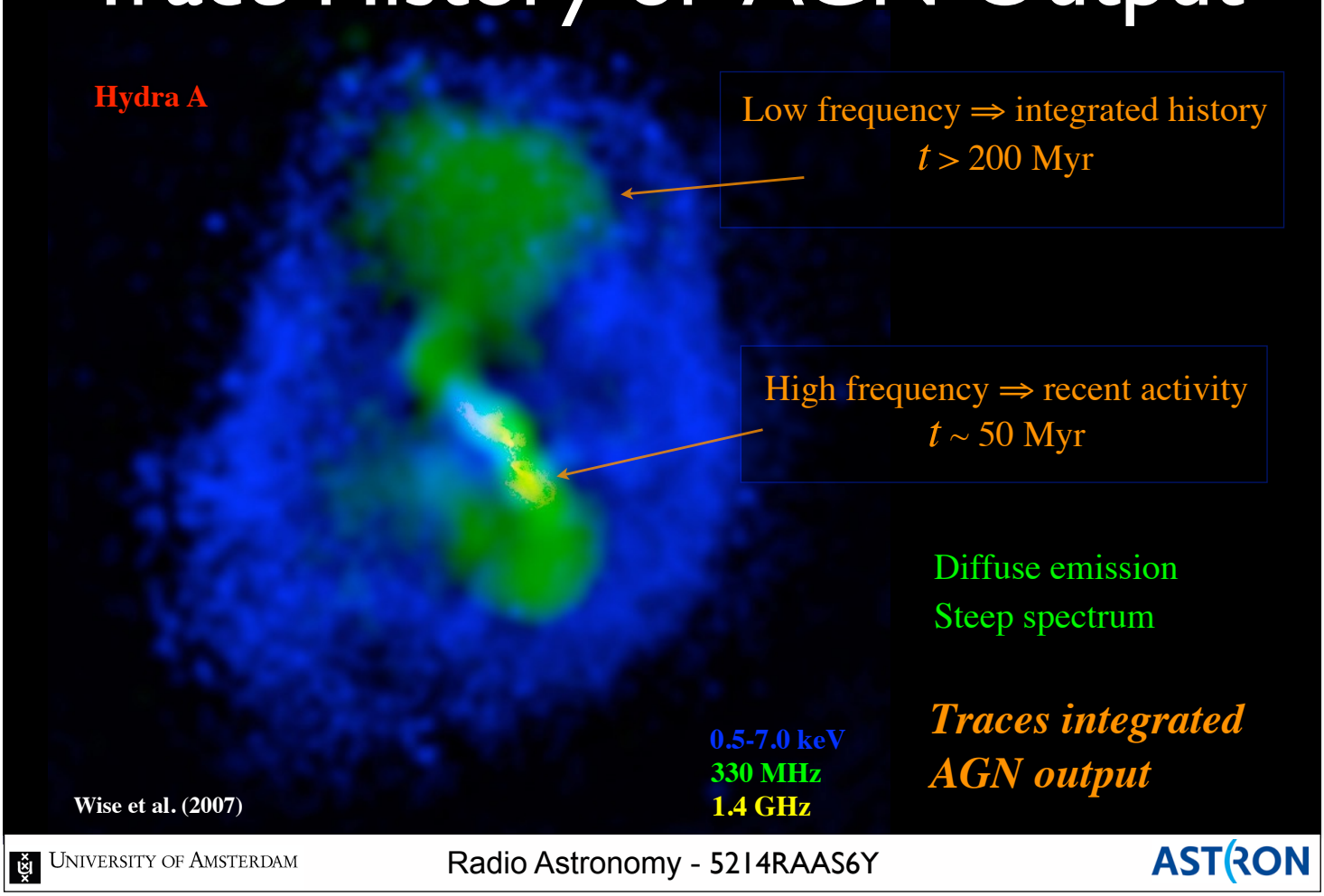
We see feedback almost everywhere we look. A truly ubiquitous phenomena.

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.

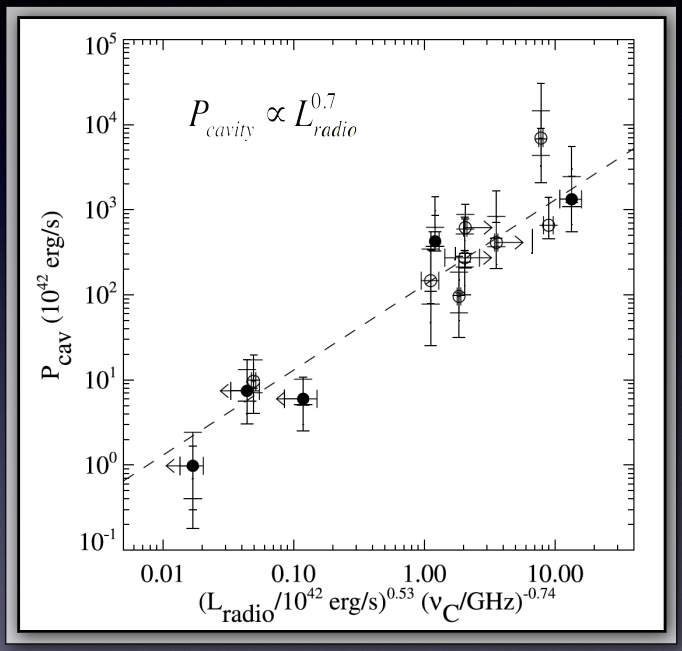
Radio observations provided the crucial evidence that the central AGN was causing these cavities.

Trace History of AGN Output

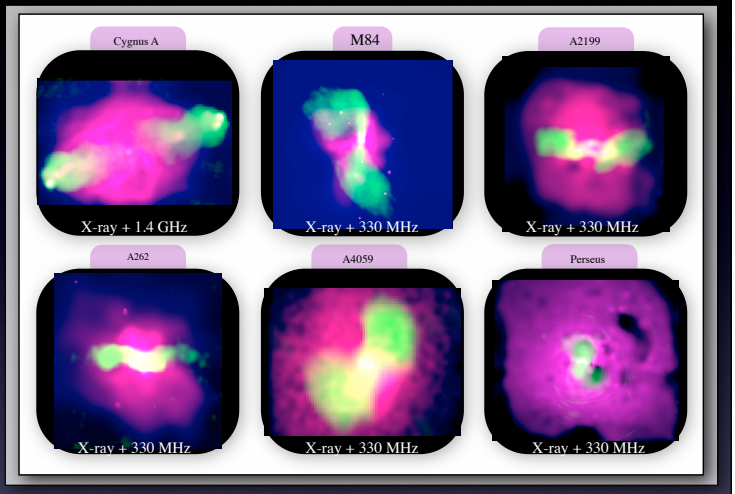


We see evidence for the long-term evolution of AGN output in both the radio and X-ray.
Observations at low and high frequency radio give us data points for the AGN output spread over 100's of millions of years.

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

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.

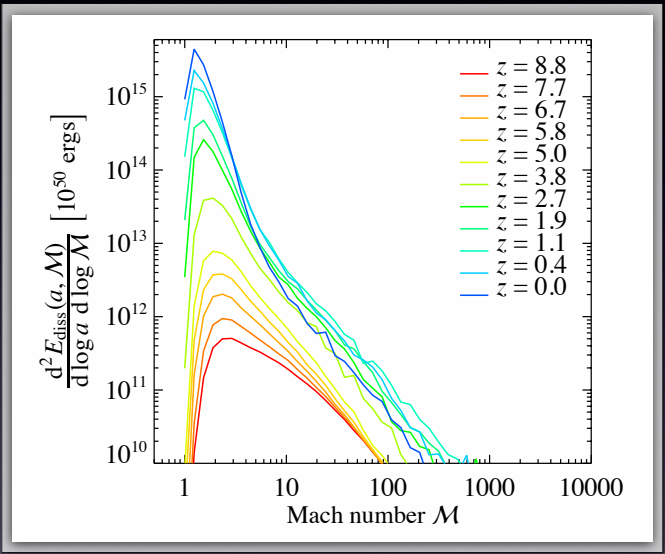
We can't observe the X-rays out to high z, but we can do it in the radio.



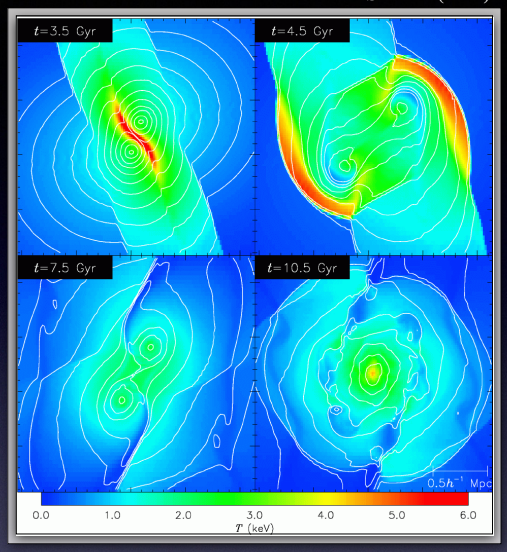
Blue is inferred dark matter halo from lensing data,
Red is thermal gas from X-ray data.
Cluster mergers are another main source of energy input into the cluster atmosphere.
Cluster form by a serious of mergers, small and large.
We see radio signatures of both kinds of mergers.

Merger Shocks

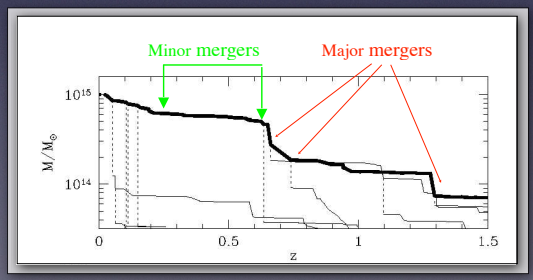
Pfrommer et al. (2007)



Ricker & Sarazin (2001)



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

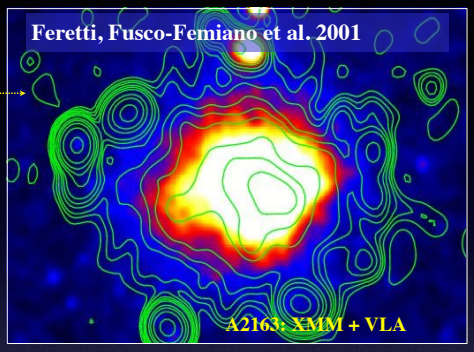


Cavaliere et al. (2002)

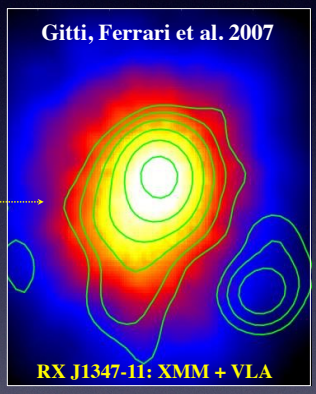
The formation history of given cluster is primarily dominated by a few major mergers (mostly at high redshift).
At low redshift, the cluster sees many more smaller mergers.
Major versus minor is defined as the ratio of the masses of the two sub-clusters that are merging.
Major merger means a ratio close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

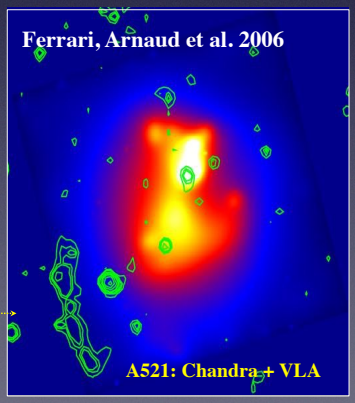
Cluster Radio Halos and Relics

Radio halos:
- ✓extended (≥ 1 Mpc) radio sources
- ✓at the cluster centre
- ✓regular morphology (~X-ray)



Radio mini halos:
- ✓ smaller sources (≤ 500 kpc)
- ✓ at the centre of clusters with:
  - AGN
  - cooling-core



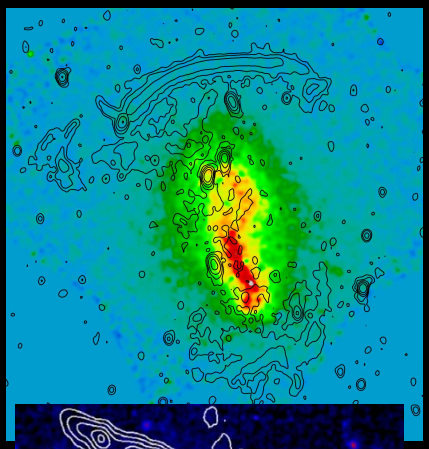


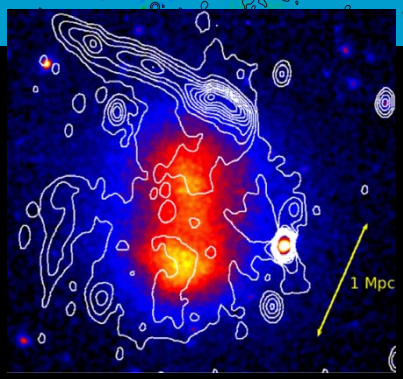
Radio relics:
- ✓extended (~1 Mpc) radio sources
- ✓cluster outskirts
- ✓elongated morphology + polarised

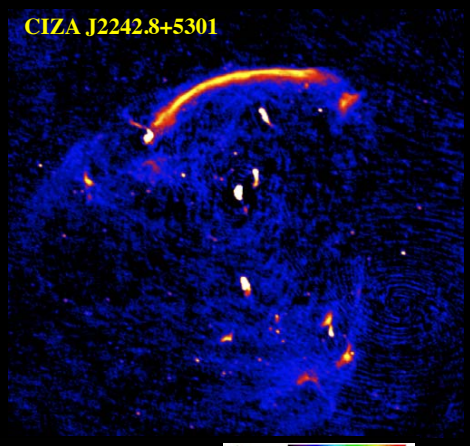
We see a variety of diffuse radio emission associated with mergers in clusters.
Relics are associated with single, major mergers and relatively easy to turn into energy dumped in the cluster.
Halos (mini and regular) are *probably* the accumulated turbulence caused by the integrated effects of several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

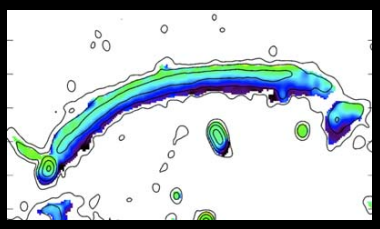
Radio Relics Trace Shocks

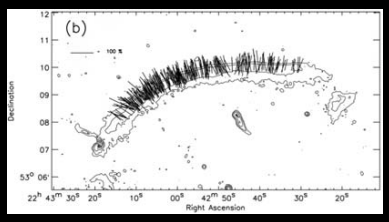
van Weeren et al. (2010, 2012)

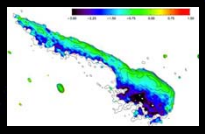


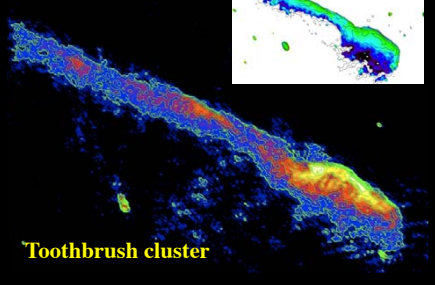












Strong shocks (M~ 4)

Scales of 1-2 Mpc

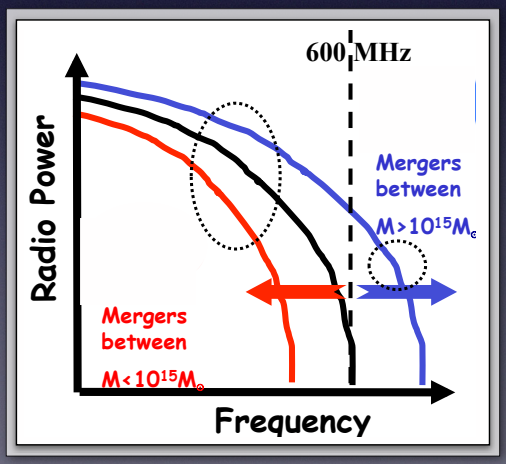
Aligned with merger

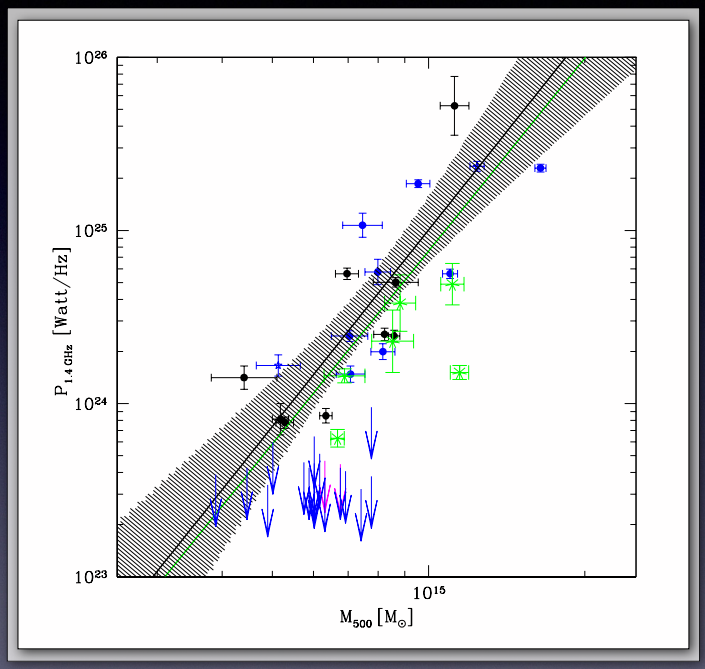
Shock rarely seen in X-rays

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.

Radio Halos Trace Turbulence

- RH powered by ICM turbulence
- Turbulence produced by mergers
- Integral over several mergers
- RH power scales with cluster mass
- LF good probe of low M systems

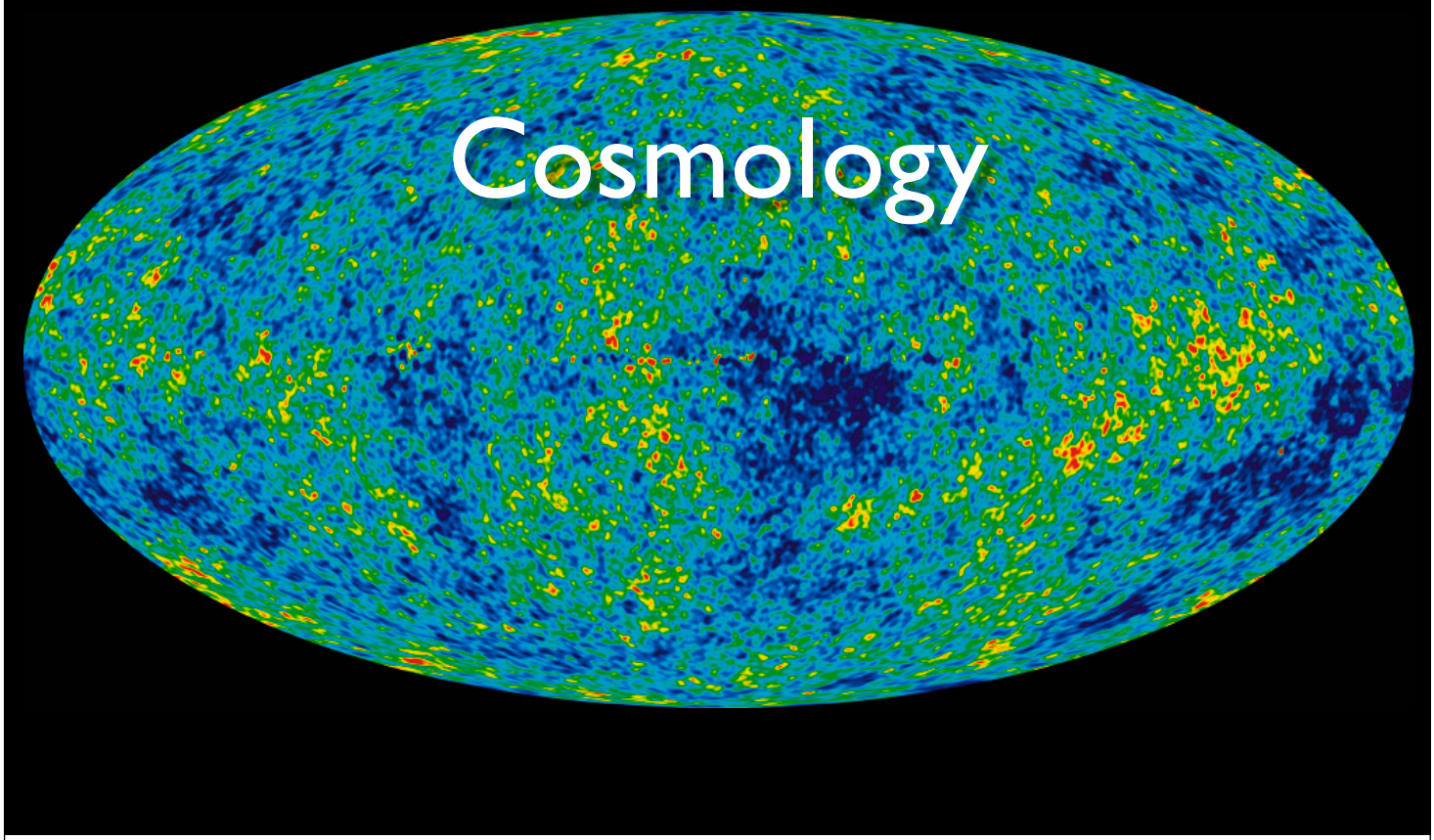




Cassano et al. (2013)

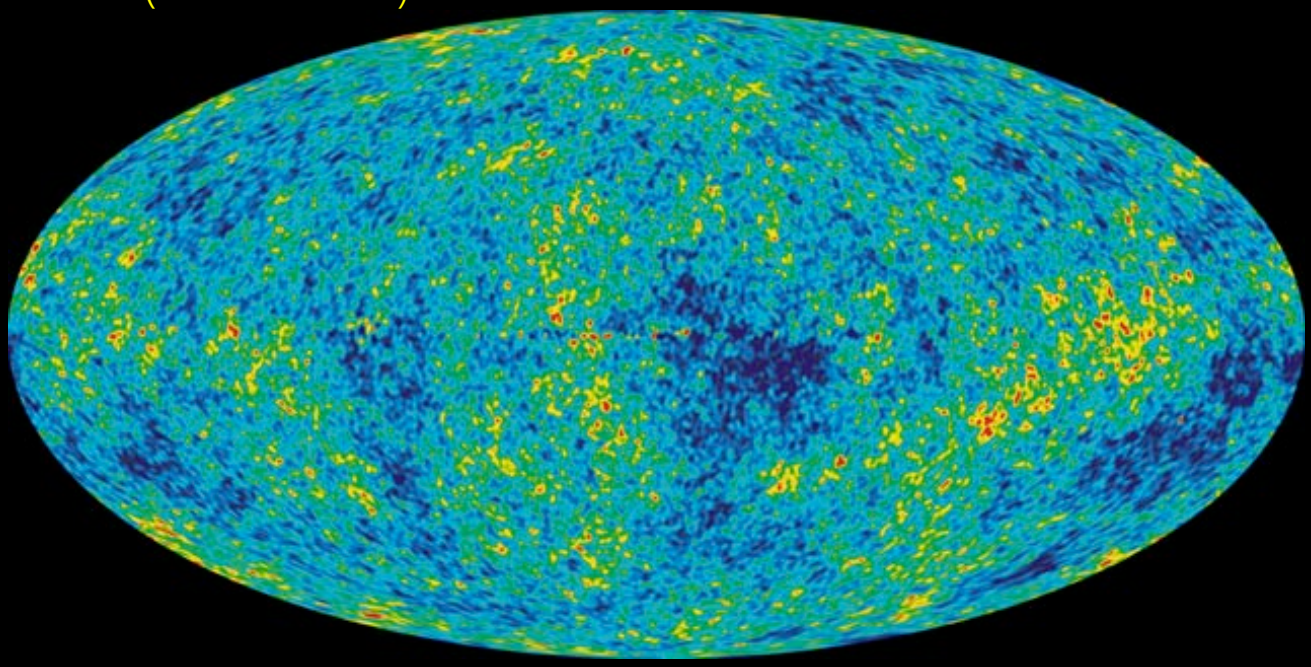
The current theory for radio halos is that they are caused by many smaller shocks stirring up turbulence in the gas.
The energy is therefore an integral quantity so we lose information about the evolution with time.
To get the time information back, we have to look at a sample of both small and large 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



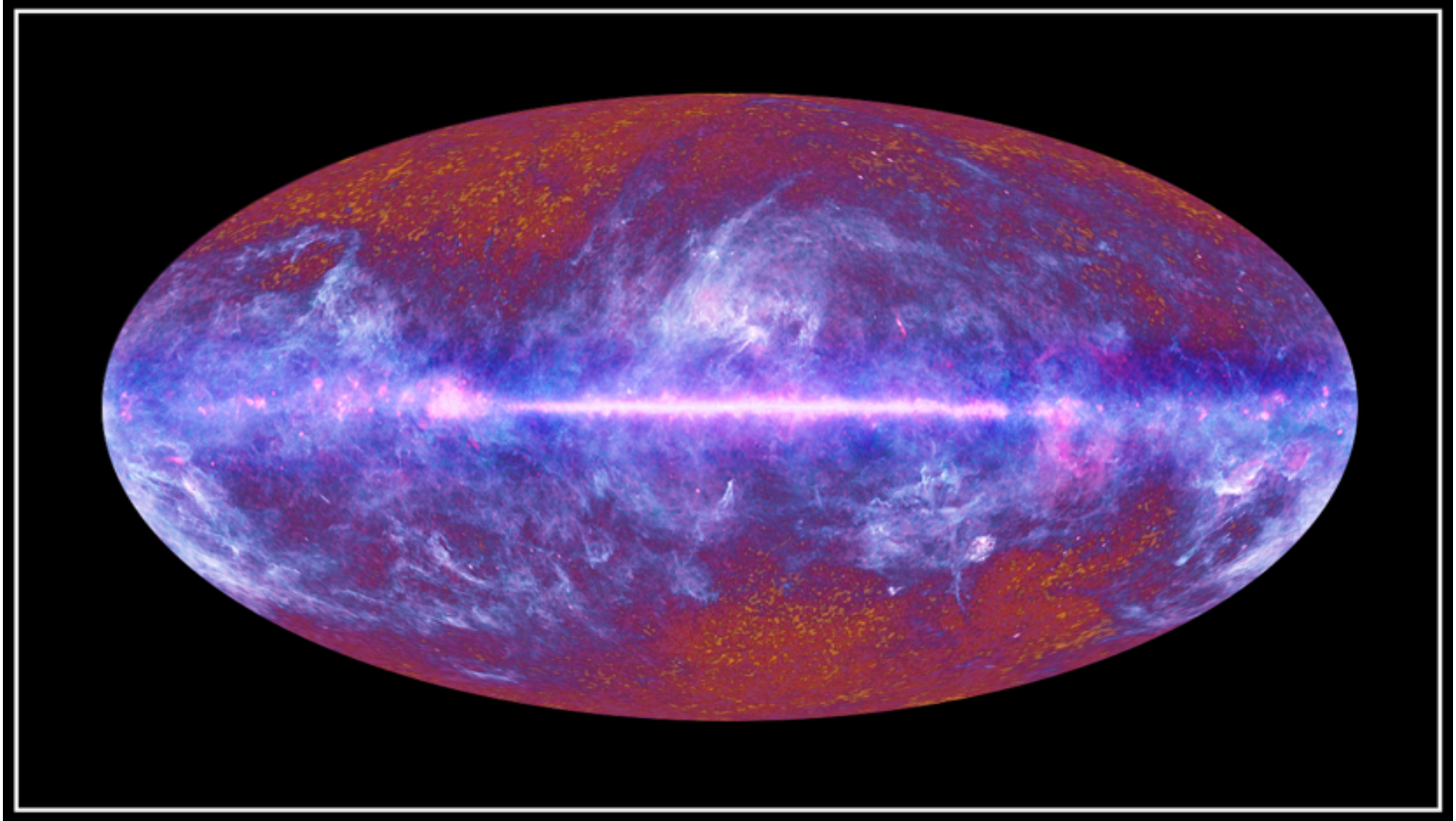
Cosmic Microwave Background

WMAP (20 - 100 GHz)



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

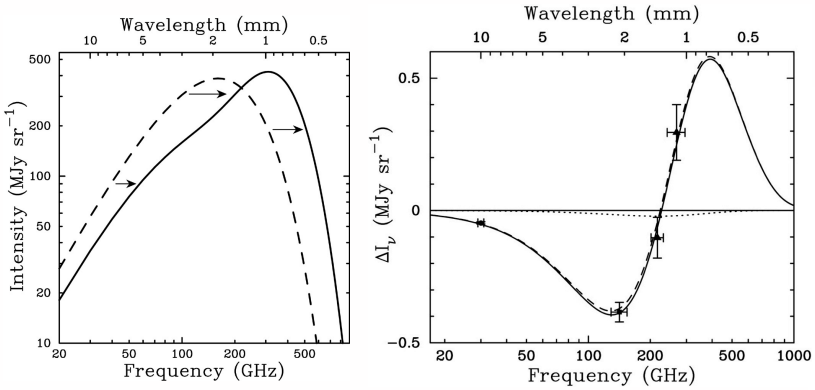
Planck Mission



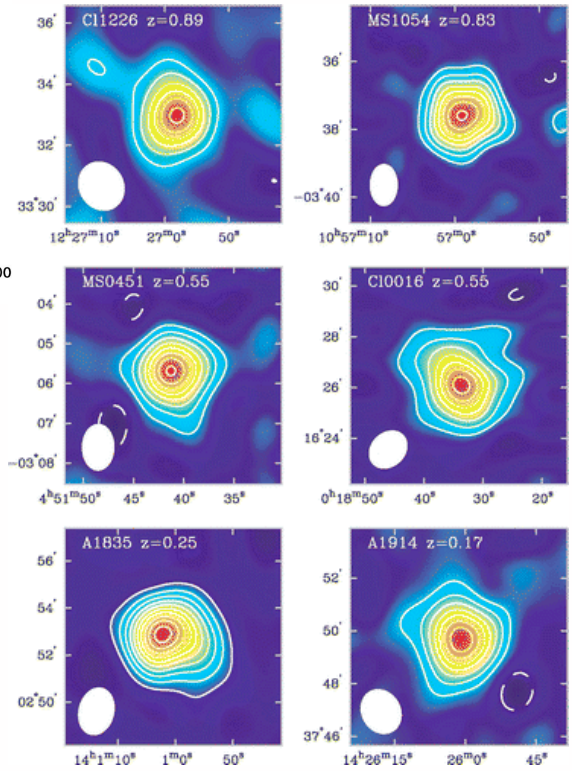
(30 - 857 GHz)

Resolution ~ x5 better

Sunyaev-Zel'dovitch Effect



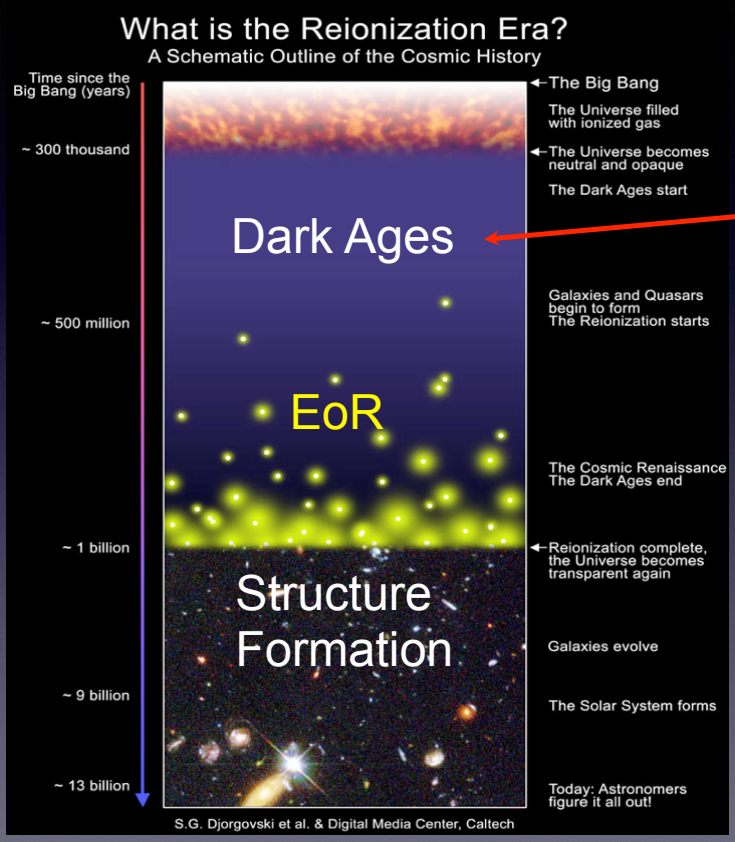
OVRO 30 GHz

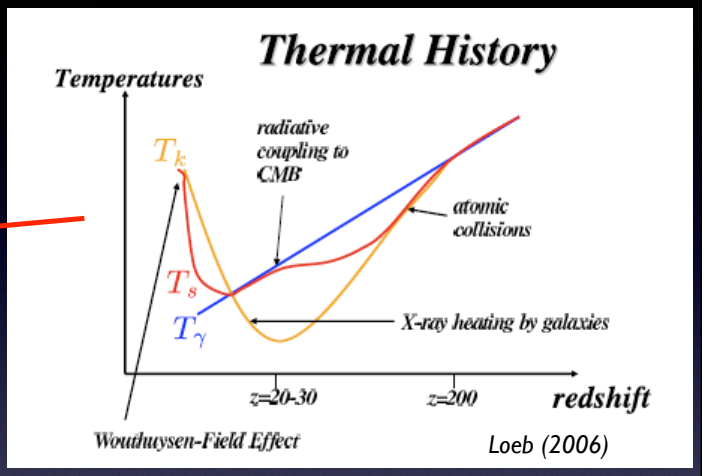


- Temperature shift proportional to gas pressure,
- CMB photon energies boosted by ~$kT_e/(m_ec^2)$
- kTe ~ 10 keV, Te ~ 108 K relativistic
- x = h/(kT_e)
- f(x) is the spectral dependence
- Notice that the T shift is redshift independent
- Unbiased surveys for clusters

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

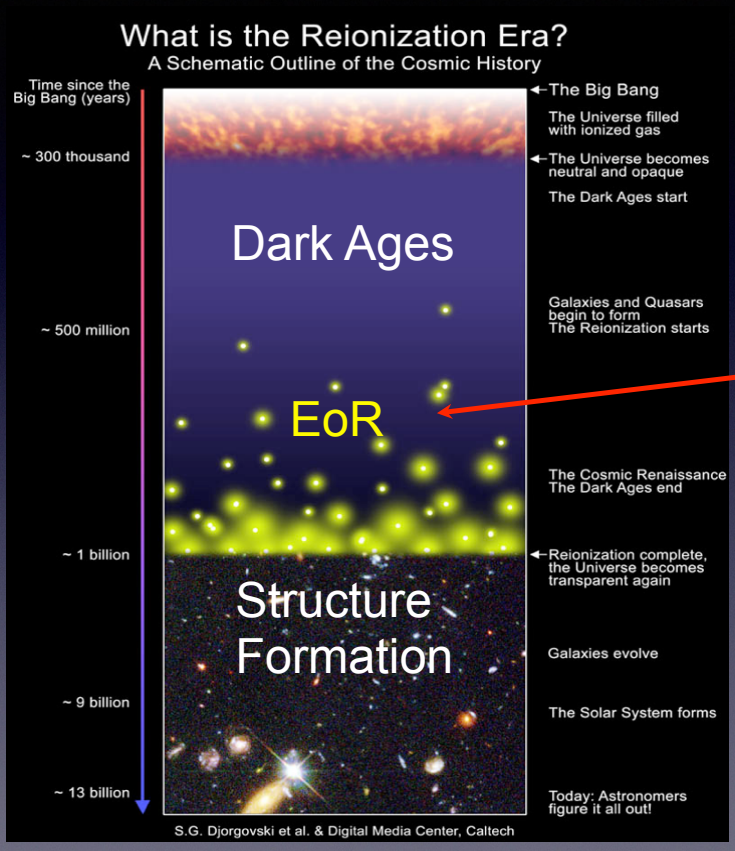
Dark Ages

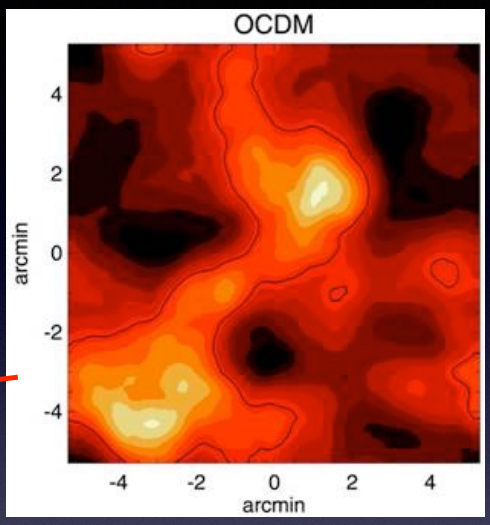




- Spin temperature decouples from CMB at z~200 (ν =7 MHz) and remains below until z~30 (ν =45 MHz)
- Neutral hydrogen absorbs CMB and imprints of the inhomogeneities

Epoch of Reionization



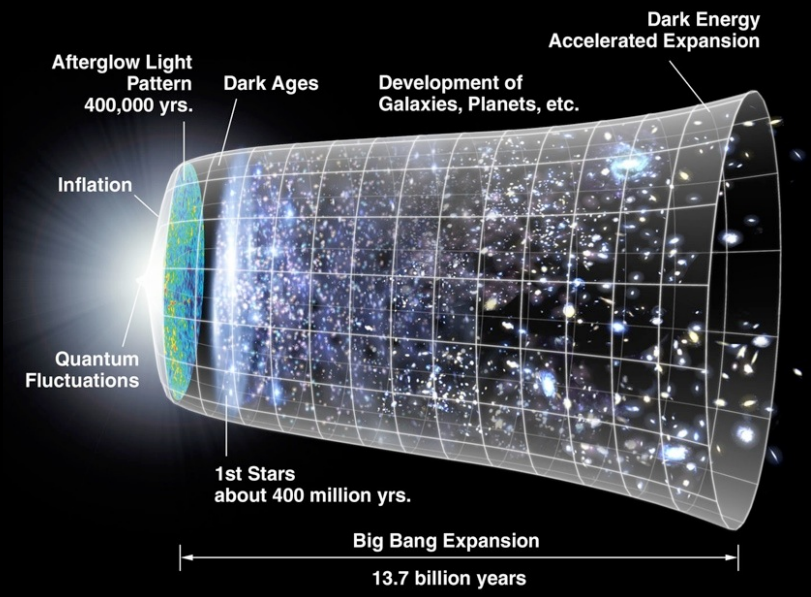


Tozzi et al. (2000)

- 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

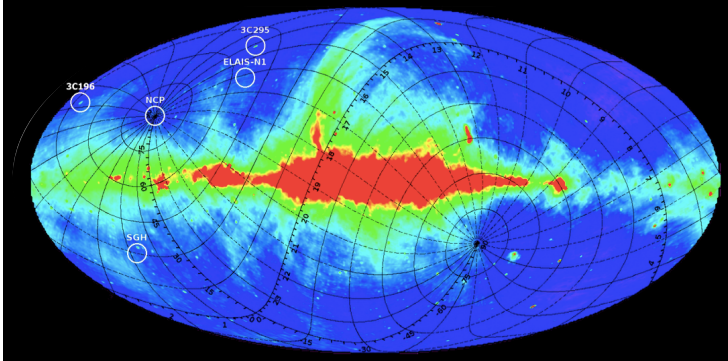
z = 11.4 ⇒ 115 MHz

$$\delta T_b \approx 28mK$$

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



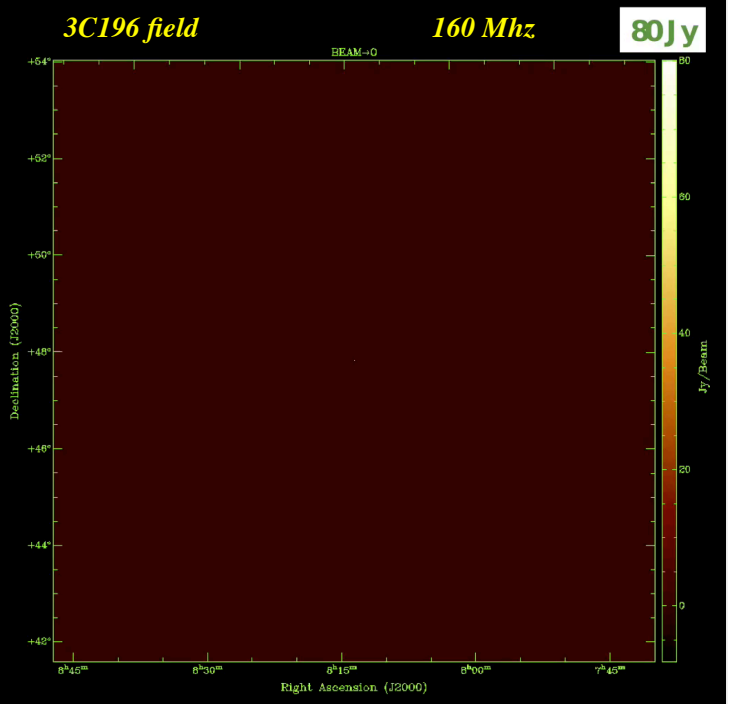
- Requires high dynamic range imaging
- Concentrating on 3 distinct fields
- Current exposure is approaching 500 hrs

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

DR ~ 1,000,000:1!

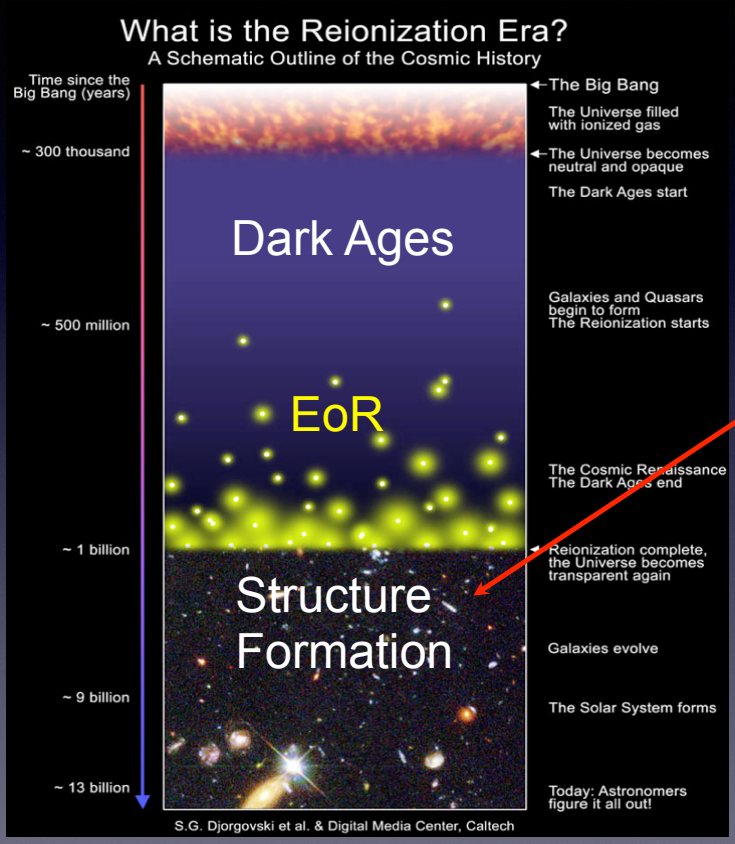
100 hrs, 96 MHz bandwidth
8° x 8°, 15000x15000 pixels, 2" pixels

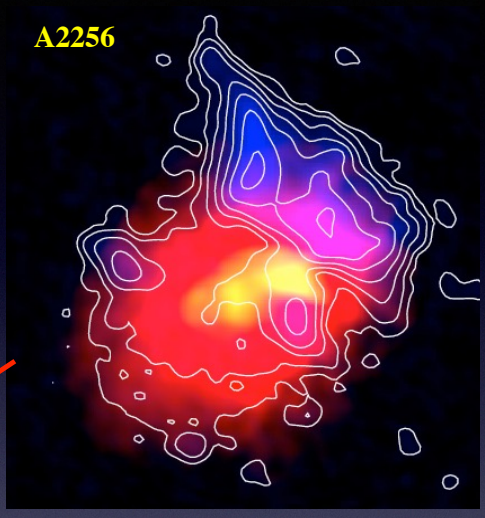
3C196 field ***160 Mhz***



(courtesy S. Yatawatta and the EoR KSP Team)

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?