PROBING DISTANT CLUSTERS USING RADIO GALAXIES

George Miley, Leiden Observatory

- 1. INTRODUCTION - EXTRAGALACTIC RADIO SOURCES
- 2. HOSTS OF DISTANT POWERFUL RADIO SOURCES –> cD PROGENITORS
  - $z > 2$ Luminosity L (500MHz rest) > 10^{27} W/Hz
- 3. RADIO-SELECTED PROTOCLUSTERS TO z ~ 5
  - Kinematic and population studies
- 4. INNER CITIES OF PROTOCLUSTERS
  - Constituents of luminous distant radio galaxies/ cD progenitors
  - Studies of processes - ongoing merging, AGN feedback, downsizing
- 5. PROBING EARLIER WITH LOFAR
  - Next-generation radio telescope
- 6. FUTURE FUN

1. EXTRAGALACTIC RADIO SOURCES

PROBES OF EARLY UNIVERSE

EXTRAGALACTIC RADIO SOURCES

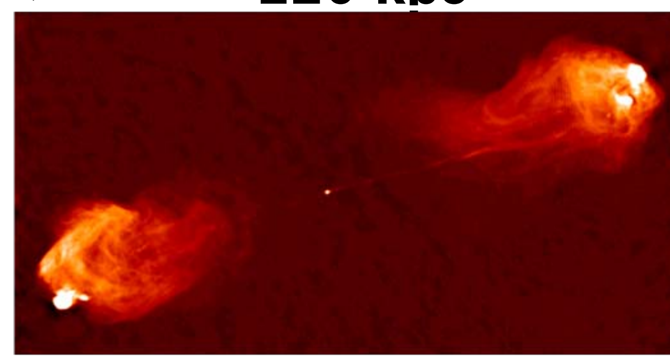
- Huge Radio Sizes: up to ~4 Mpc
  - >> sizes of optical galaxies
- Radiation Process
  - Synchrotron Emission
    - Spectral energy distributions, Polarization
- Powers
  - up to ~ 10^{28} W/Hz
    - 10^{46} ergs/s
- Radiative lifetimes
  - ~ $10^7 - 10^8$ y
    - $t_{Radio} << t_{Universe}$ ~ 13.7×10^9 y
      Short on cosmological scale
- Total Energies
  - up to 10^{61} erg
    - Huge

PROTOTYPE: CYGNUS A identified 1948

Radio: 2nd brightest in sky

Visible: faint galaxy, z=0.06

<----   ~ 120 kpc   ---

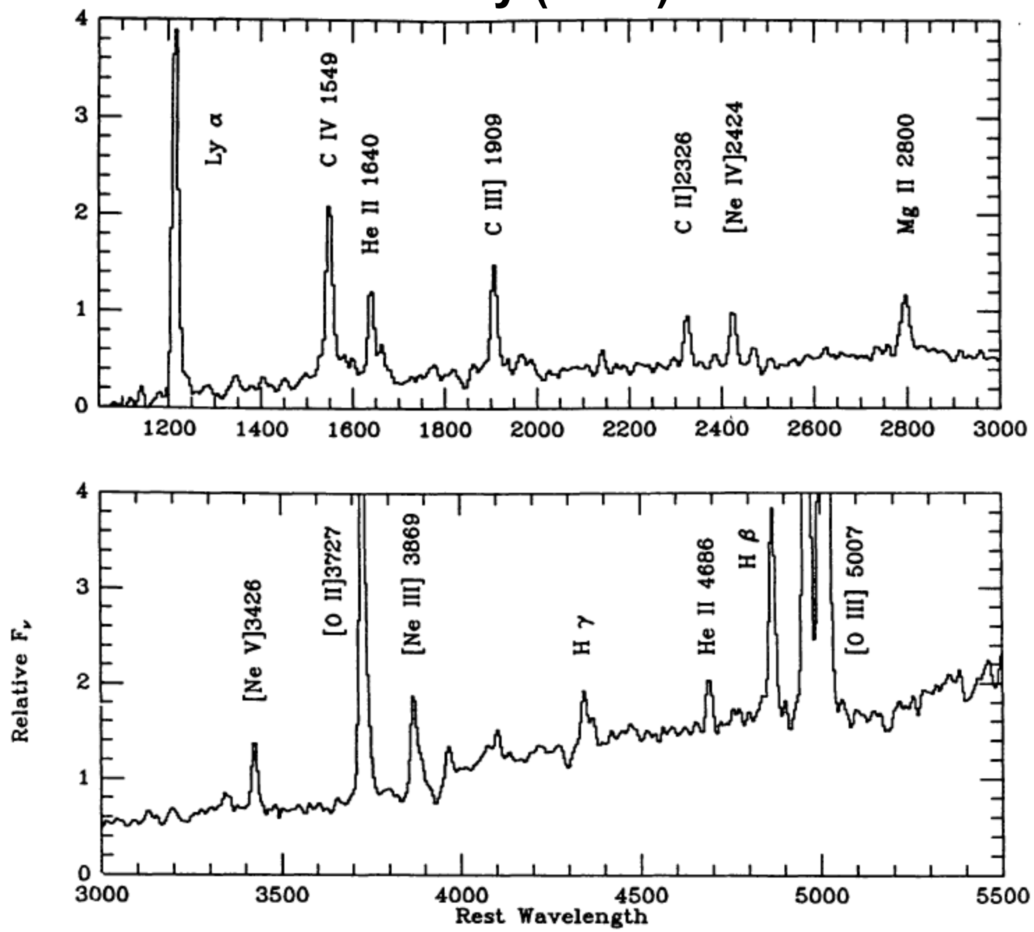


In principle observable to z > 10

RADIO GALAXIES AS OPTICAL BEACONS

Usually bright emission lines due to warm ~10^{4-5}K gas

Composite spectrum: Radio galaxies 0.1 < z < 3
McCarthy (1993)



Allow redshift to be measured easily to high z

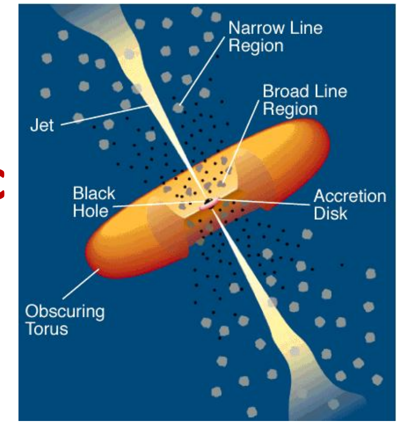
Important diagnostic of physical conditions

For z > 2, bright lines are:
Lyα 1216
CIV 1549
HeII 1640
CIII] 1909
[OII] 3727
[OIII] 5007

RADIO SOURCE POWERHOUSE

- SOURCE OF ENERGY
  - Radio core < 10^{17} cm
    - Enormous energy from tiny region
  - Alignment of core (pc) and extended Mpc
    - Can remember orientation for > 10^8y

$M_{SMB} \sim 10^9\ M_{Sun}$



- ROTATING MASSIVE BLACK HOLE
  - Accretes material from galaxy
  - Converts mass to kinetic energy powers radio sources
  - Spews out relativistic plasma

RADIO SOURCES PINPOINT
MOST MASSIVE BLACK HOLES IN THE EARLY UNIVERSE

2. HOSTS GALAXIES OF $z > 2$ POWERFUL RADIO SOURCES?

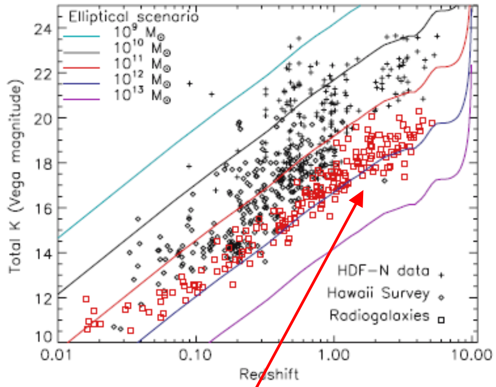
cD PROGENITORS

HOST GALAXIES OF DISTANT RADIO SOURCES

- CLUES TO THEIR NATURE
  - Brightest > Most Massive

Rocca-Volmerange et al. 2004

Log IR Flux

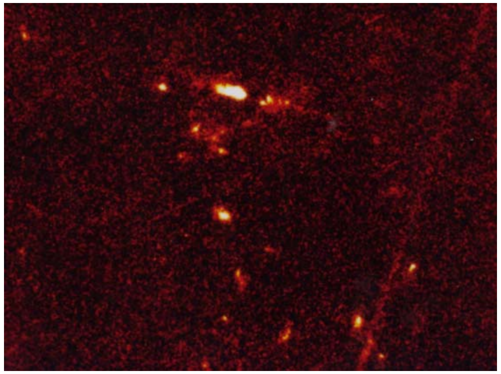


Redshift

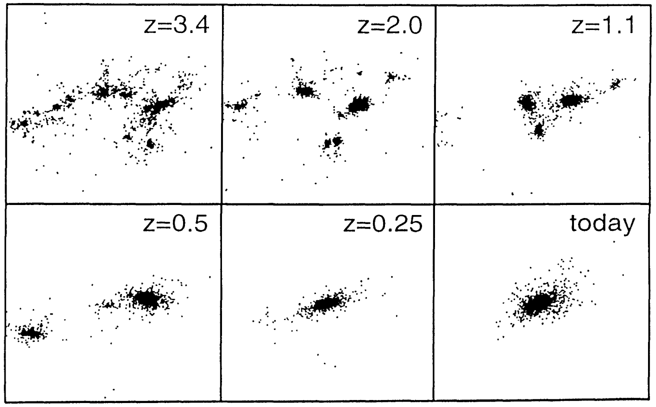
Radio Galaxies
form bright envelope

HOST GALAXIES OF DISTANT RADIO SOURCES

- CLUES TO THEIR NATURE
  - Brightest > Most massive
  - Clumpy > Structure assembling (hierachically)



HUBBLE: 4C41.17 z = 3.8

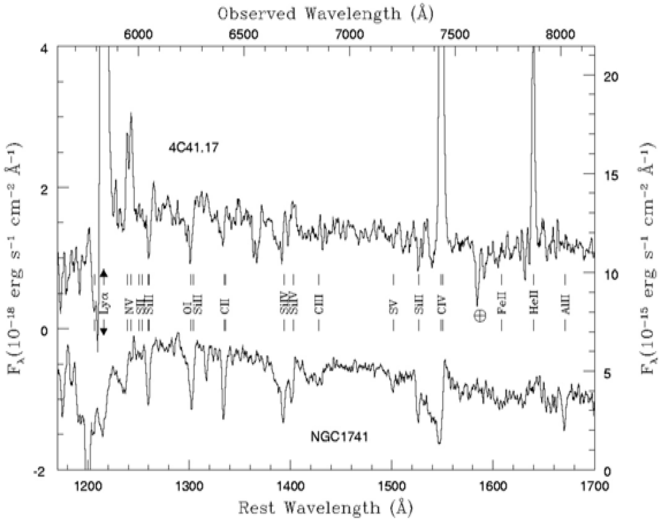


Simulations of forming massive galaxies

HOST GALAXIES OF DISTANT RADIO SOURCES

- CLUES TO THEIR NATURE
  - Brightest > Most Massive
  - Clumpy (HST) > Structure assembling
  - Spectroscopy > star-forming
    (few x 10^2 M_{Sun}/yr)

Spectrum resembles
starburst galaxy
Dey et al.



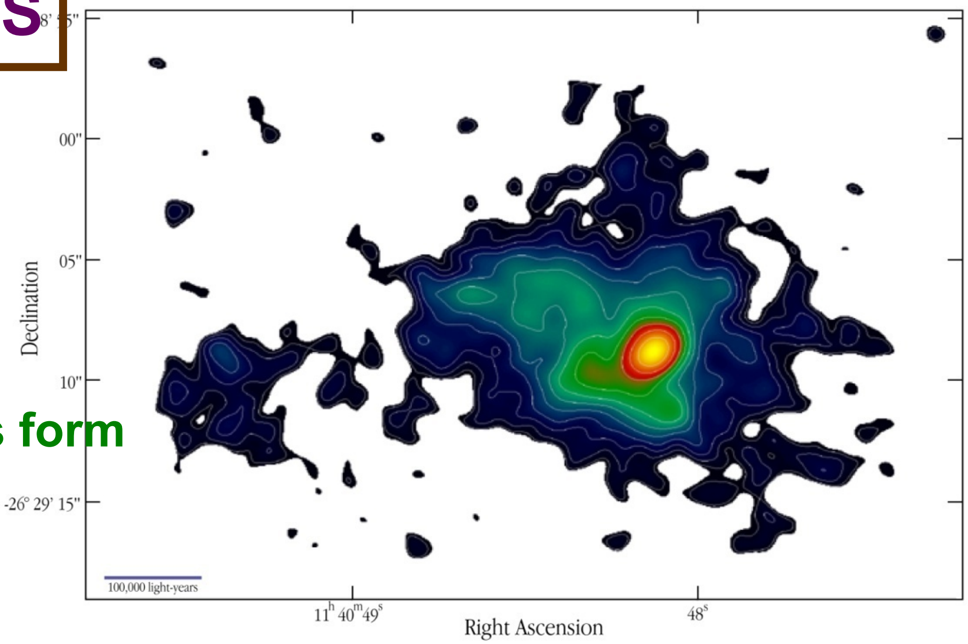
RADIO SOURCES PINPOINT
MOST MASSIVE FORMING GALAXIES
IN THE EARLY UNIVERSE

HOST GALAXIES OF DISTANT RADIO SOURCES

- **CLUES TO THEIR NATURE**
  - **Luminous in IR > Most Massive**
  - **Clumpy (HST) > Structure assembling**
  - **Spectroscopy > star-forming (few x 10^2 M_{Sun}/yr)**

FORMING MASSIVE GALAXIES

1138-26 at z =2.2, Kurk et al. 2003



- **Giant Ly α Halos**
  - **~100kpc, cD-sized**
- **CDM SIMULATIONS:**
  Largest Overdensities >
  - **Most massive galaxies form**

  AND
  - **Richest clusters form**

FORMING DOMINANT CLUSTER GALAXIES?

3. RADIO-SELECTED PROTOCLUSTERS

ENVIRONMENT OF POWERFUL z> 2 RADIO SOURCES

UNIQUE LABORATORIES OF CLUSTER FORMATION

TECHNIQUES FOR FINDING z > 2 PROTOCLUSTERS

- **Narrow-band imaging**
  - **Emission line excesses**
  - **Lyα , Hα , [OIII], [OII]**
    - **Ideally suited to HzRG environment**
      - Redshift known

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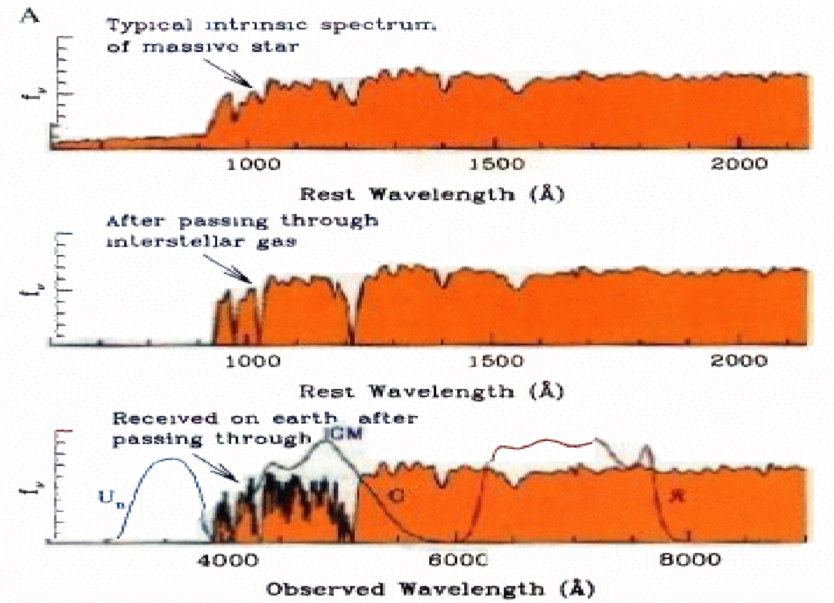
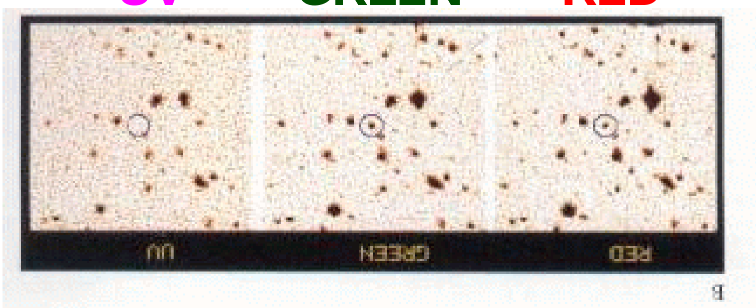


- Broad-band imaging (colours)
  - Features in continuum spectra
  - – Lyman break
  - – Balmer/4000A breaks

- Follow-up spectroscopy
  - – Usually MOS



Each technique selects specific galaxy population

ENVIRONMENT OF DISTANT RADIO SOURCES

- Lyα EXCESS TECHNIQUE – ESO LARGE PROJECT (Bram Venemans thesis)

- GALAXY OVERDENSITIES (3 – 15)
  - 6/8 of luminous radio sources (6/6 of the MOST luminous ones)

- MASSES ~ ANCESTOR OF RICH CLUSTERS
  - Size ~ 3 – 5 Mpc
  - $M_{overdensity} \sim \langle\rho\rangle V(1+\delta_M) \sim$ Few x 10^{14} - 10^{15} M_{Sun} ~ Coma Cluster

ALL INGREDIENTS OF PROTOCLUSTERS

- STATISTICS CONSISTENT WITH **ALL** LOCAL CLUSTERS HAVING PREVIOUSLY HOUSED A LUMINOUS RADIO SOURCE
  - HzRGs are rare ~ 1 per 100 Mpc^3
  - Lifetime of radio source few x 10^7 y
  - Age of Universe 13 x 10^9 y
    - >100 times more “dead” radio galaxies as active ones

RADIO SOURCES PINPOINT ANCESTORS OF RICH GALAXY CLUSTERS IN THE EARLY UNIVERSE

DIAGNOSTICS

HISTORY OF MASSIVE GALAXIES AND PROTOCLUSTERS

Interconnections

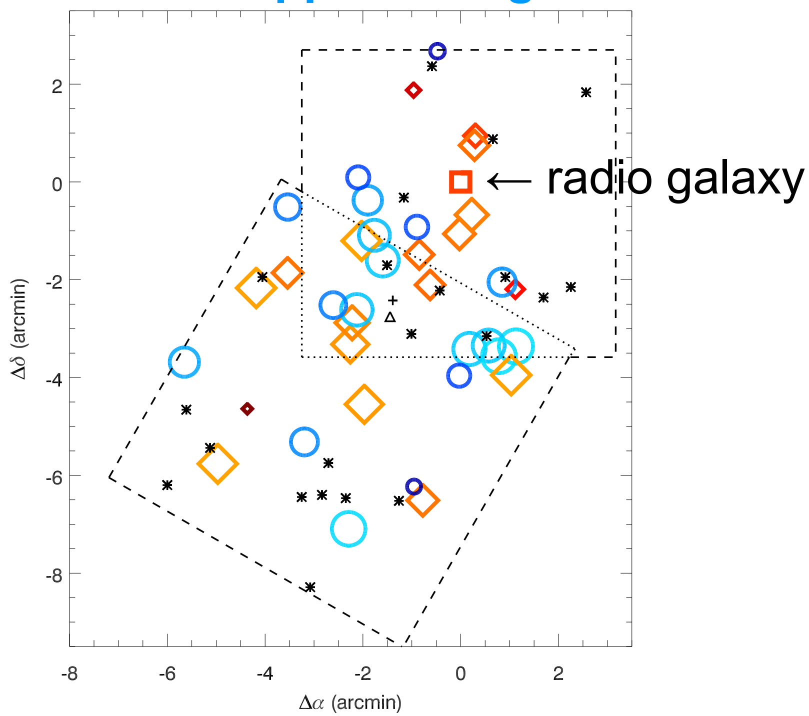
- SPECTRAL ENERGY DISTRIBUTIONS
  - Stars
    - When did star formation begin
    - How does it progress
- MORPHOLOGIES (HST) AND KINEMATICS (LYα)
  - Structure assembly
    - When did galaxy structures begin to form
    - How does the structure evolve?
- RADIO AND AGN PROPERTIES
  - AGN and MBH assembly and evolution

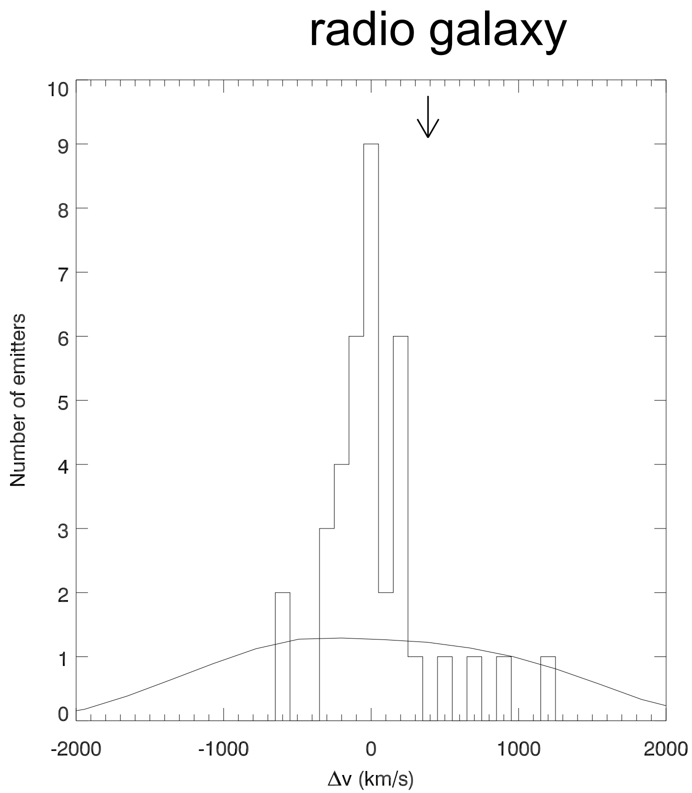
CAREFUL!: MANY ASSUMPTIONS

PROTOCLUSTER KINEMATICS FROM Lyα
1338-19 at z = 4.1

Venemans et al Astrophys. J. 569, L11
Miley et al. Nature 427, 47
Venemans et al. Astron & Astrophys. 461,823

7' x 7' VLT/FORS FIELD
Red: receding
Blue: approaching

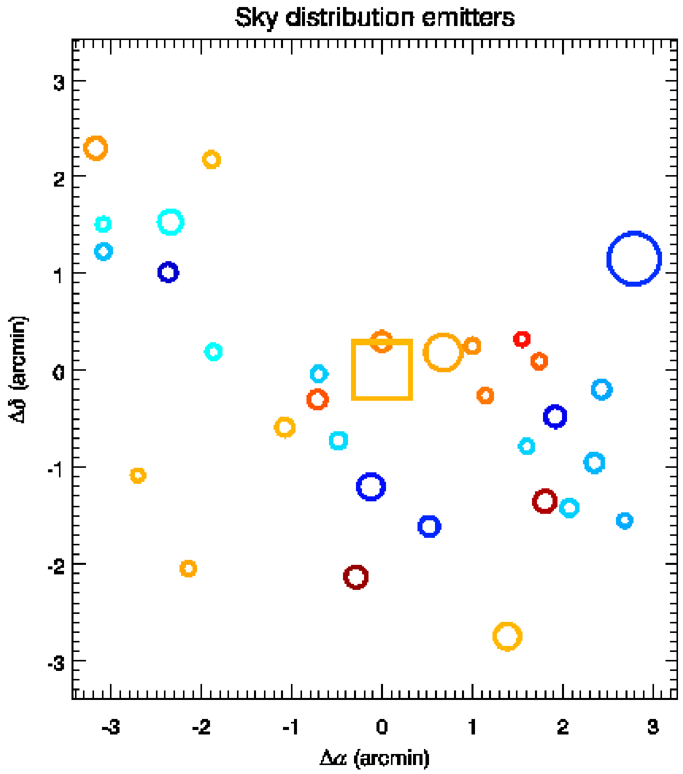


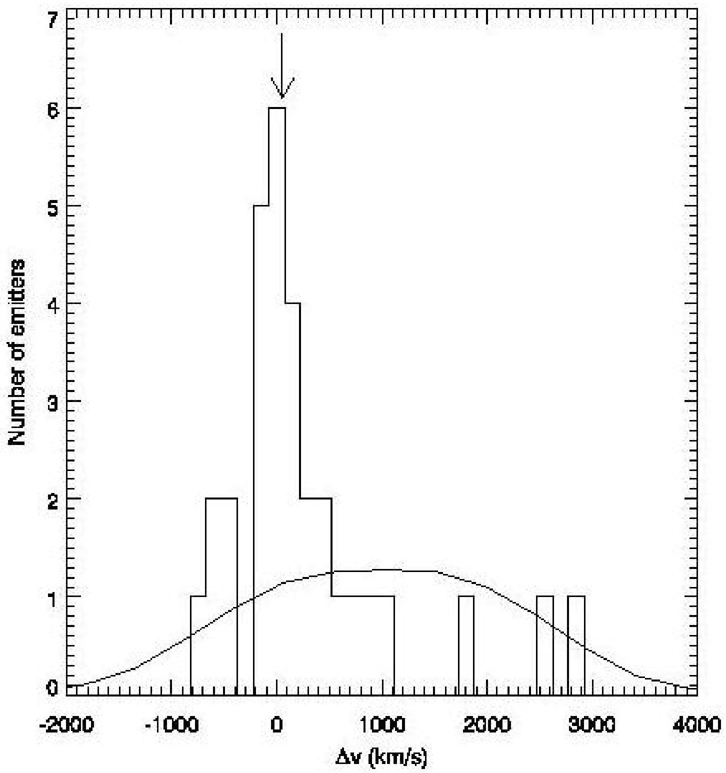


σv ~ 325 km/s

PROTOCLUSTER KINEMATICS FROM Lyα
0316-26 at z = 3.1

Venemans et al. 2004, Astron & Astrophys. 431,793

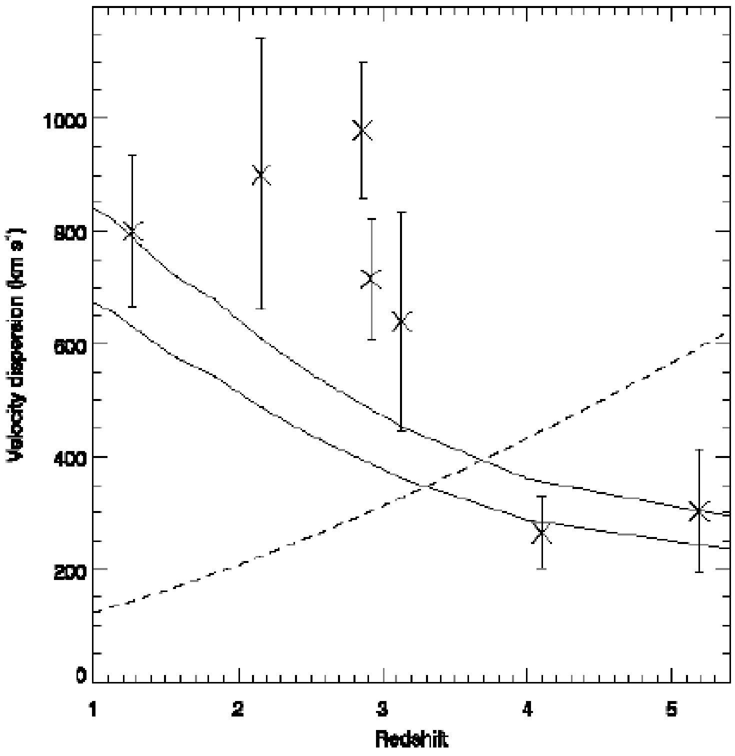




“EVOLUTION” IN Lyα VELOCITY DISPERSIONS

Venemans et al. 2007, Astron & Astrophys. 461,823

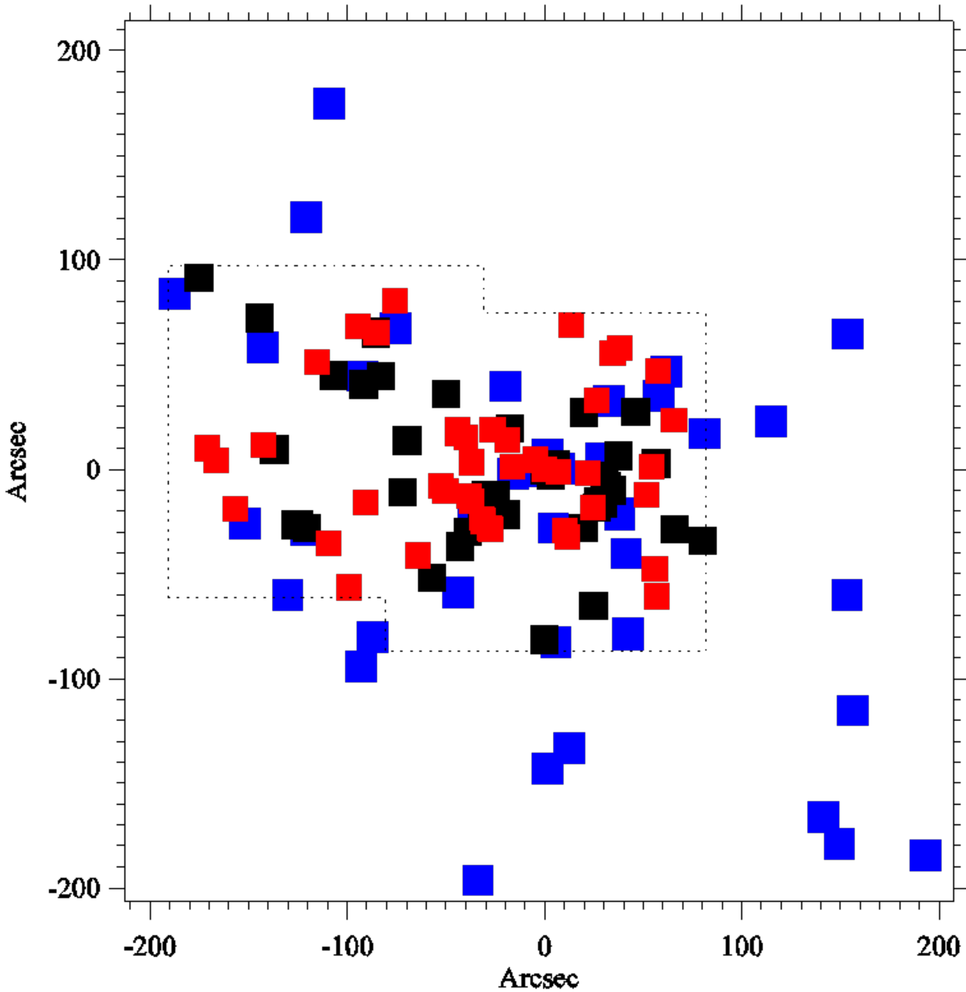
- Suggestion that velocity dispersion increases with
  - Consistent with simulations
    - e.g. Eke et al. 1998, Saro et al. 2009, Overzier et al 2009



- Larger sample needed
  - Grantecan (GTC) – UNIQUE
    - Sensitive camera with tunable filter
      - Arbitrary z
  - Allocated ESO large project - 19 additional protoclusters
    - Eventual detailed study of kinematics, subclustering and dynamic evolution

PROTOCLUSTER HISTORY: POPULATION SEGREGATION?

1138-26 z =2.2 (see Kurk et al A&A 428, 793)



BLUE SYMBOLS

Lya excess galaxies

– YOUNG POP?

RED AND BLACK SYMBOLS

Red and Ha excess galaxies

– OLD POP?

Red and black objects are more concentrated than Lya

Consistent with more massive and older

PROTOCLUSTER POPULATION STUDIES

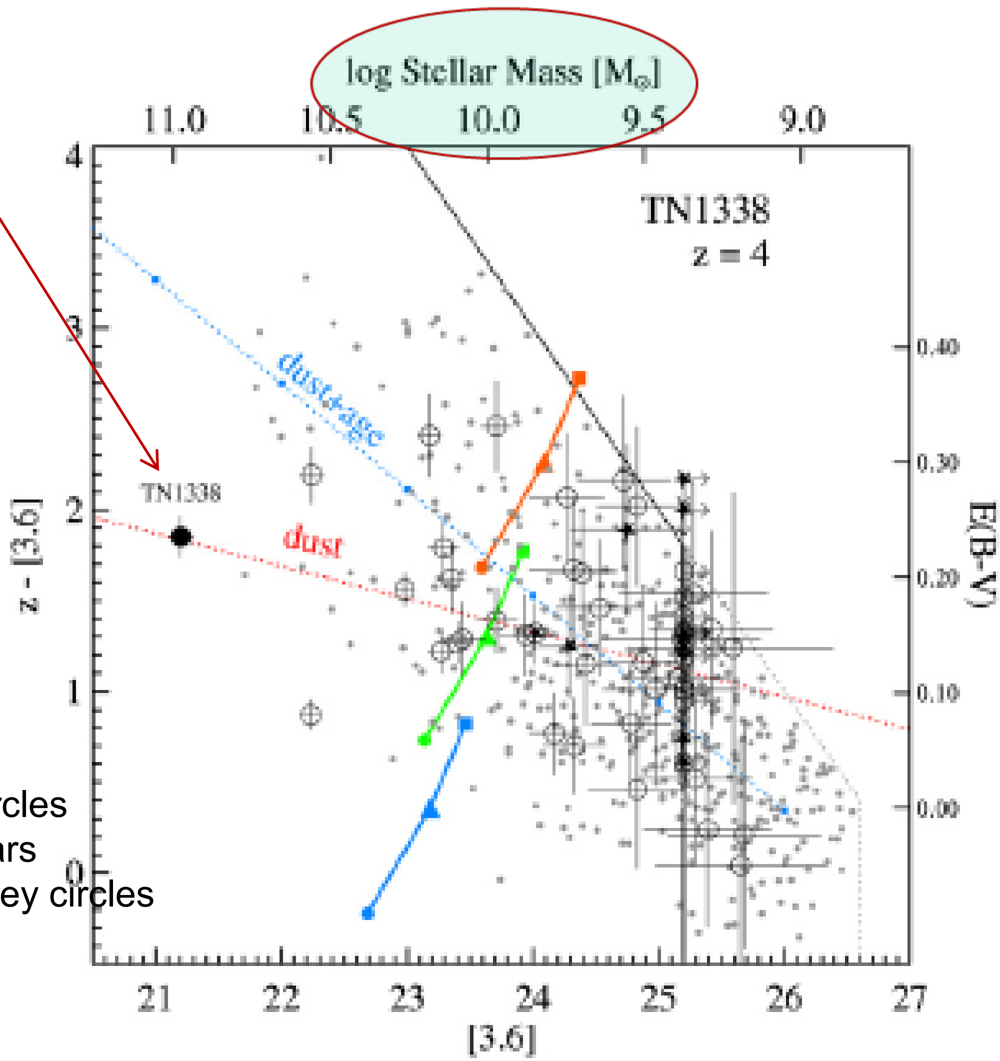
- e.g. Talks by
  - Nina Hatch
    - Population studies at z ~ 2.4 (VLT/HAWKI)
  - Audrey Galametz
    - Red sequence at z ~ 1.5
  - Ernst Kuiper
    - Population study in 0316-257 at z ~ 3.1
  - Taddy Kodama
    - 3 > z > 2 Red sequence emerging (SUBARU)
  - Andrew Zirm
    - Red sequence at z ~ 2.2 (HST/NICMOS)

- Evidence that between 3 > z > 1.5
  - Fraction of red and dead galaxies increase
  - Red sequence emerges
  - Star formation decreases

STELLAR MASSES OF z ~ 4 PROTOCLUSTER GALAXIES

Overzier et al ApJ 704, 548 (2009)

- **Radio galaxy is by far the most massive galaxy in the protocluster**
- **Comparison between protocluster and field galaxies**
  - **Mass distribution comparable**
  - **Density larger**



Protocluster LBGs	open circles
Protocluster LαEs	filled stars
GOODS LBG candidates	small grey circles

4. INNER CITIES OF PROTOCLUSTERS

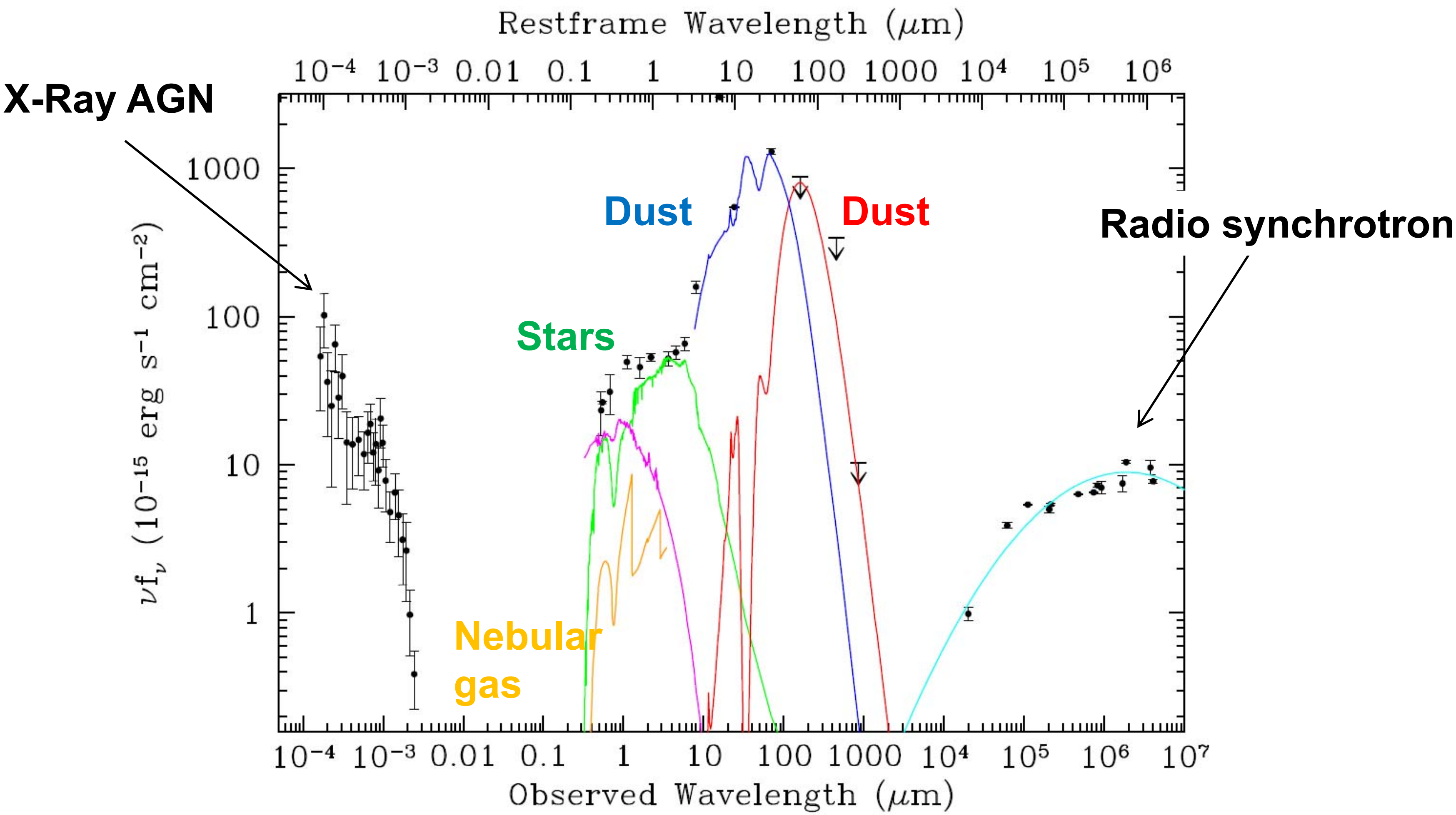
POWERFUL DISTANT RADIO GALAXIES
cD PROGENITORS

CONSTITUENTS
ONGOING PROCESSES

"EMPERORS" OF THE EARLY UNIVERSE

SPECTRAL ENERGY DISTRIBUTION

4C23.56 z = 2.5 (De Breuck et al 2008)



BUILDING BLOCKS OF (RADIO) cD PROGENITORS

CONSTITUENT	OBSERVABLE	TYPICAL DIAGNOSTICS	MASS ($M_\odot$)
Relativistic plasma	Radio continuum	Magnetic field, age, energetics, pressure, particle acceleration. Jet collimation and propagation	
	X-ray continuum	Magnetic field, equipartition, pressures	
Hot ionized gas $T_e \sim 10^7$-10^8K $n_e \sim 10^{-1.5}$cm^{-3}	Radio (de)polarisation	Density, magnetic field,	10^{11-12}
	X-rays	Temperature, density mass	
Warm ionized gas $T_e \sim 10^4$–10^5K $n_e \sim 10^{0.5-1.5}$cm^{-3}	UV-optical emission lines	Temperature, density, kinematics, mass, ionisation, metallicity, filling factor	10^{9-10}
	UV-optical nebular continuum	SED contamination	
Cold atomic gas $T_s \sim 10^3$K n(HI) $\sim 10^1$cm^{-3}	HI absorption	Kinematics, column densities, spin temperature, sizes, mass	10^{7-8}
	UV-optical absorption lines	Kinematics, mass, column densities, metallicity	
Molecular gas T $\sim 10^2$K n(H2) > 10^3 cm^{-3}	(Sub)millimeter - IR lines	Temperature, density, mass	10^{10-11}
Dust T ~ 50 - 500K	UV-optical polarisation	Scattering properties, mass, hidden quasar	10^{8-9}
	(Sub)millimeter continuum	Temperature, mass	
Old stars t > 1Gyr	Optical – IR continuum	Age, mass, formation epoch	10^{11-12}
Young stars t < 0.5Gyr	UV-optical continuum & Lyα	Star formation rates, ages, history	10^{9-10}
Quasar (hidden or dormant)	UV-optical polarisation	Luminosity	
Supermassive black hole(SMBH)	Radio structure, Optical Quasar	Formation, evolution	10^{9-10}

Relativistic Plasma →

Gas

Dust →

Stars

Active Nucleus

from Miley & De Breuck

Astronomy & Astrophysics Reviews 2008, Vol. 15, pp67-144

Mass ~ $10^{11} – 10^{12} M_{sun}$

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from
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Astronomy & Astrophysics Reviews
2008,
Vol. 15, pp67-144

Constituents interact

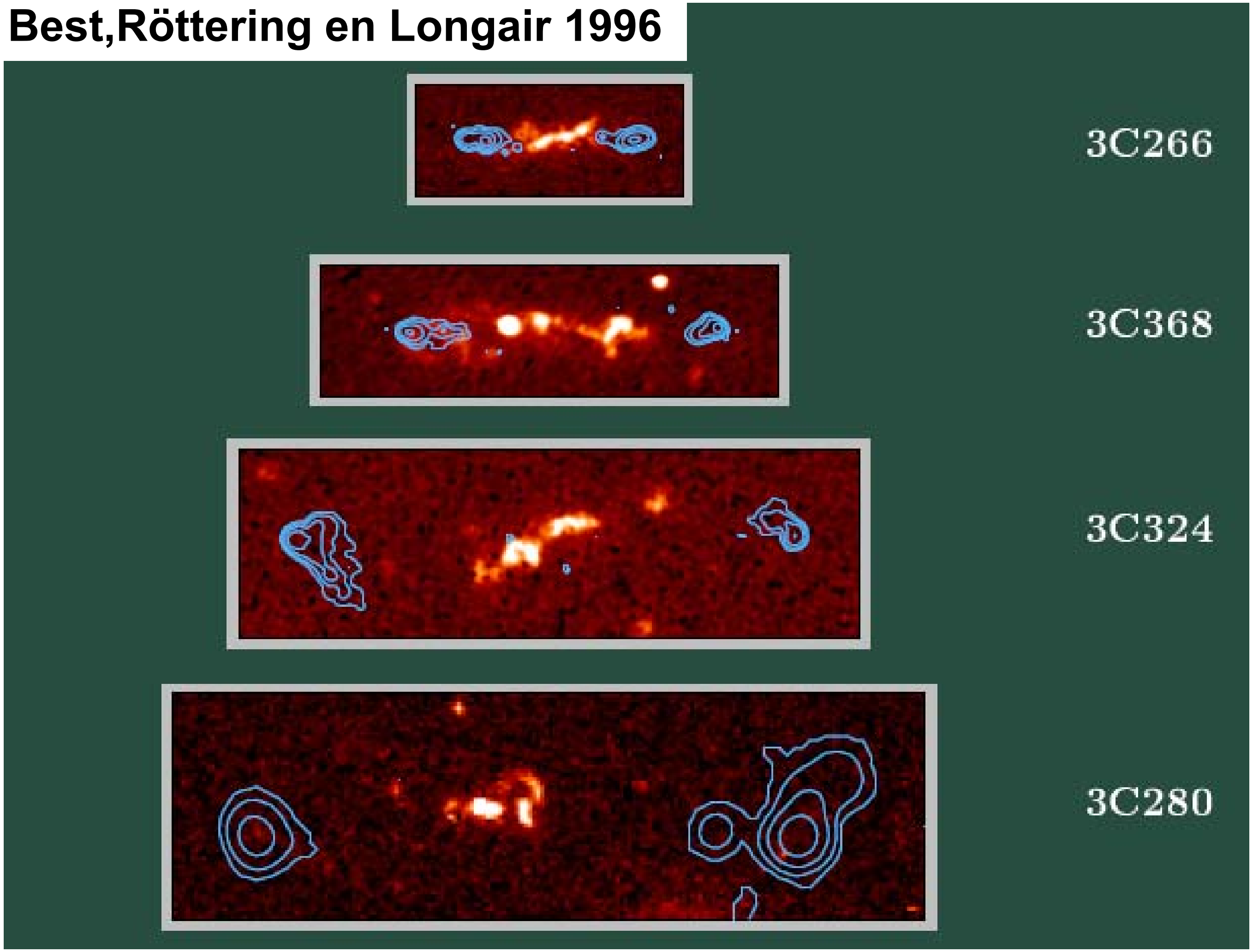
↓

Feedback

EXAMPLE OF INTERACTION
RADIO–OPTICAL CONTINUUM ALIGNMENT EFFECT

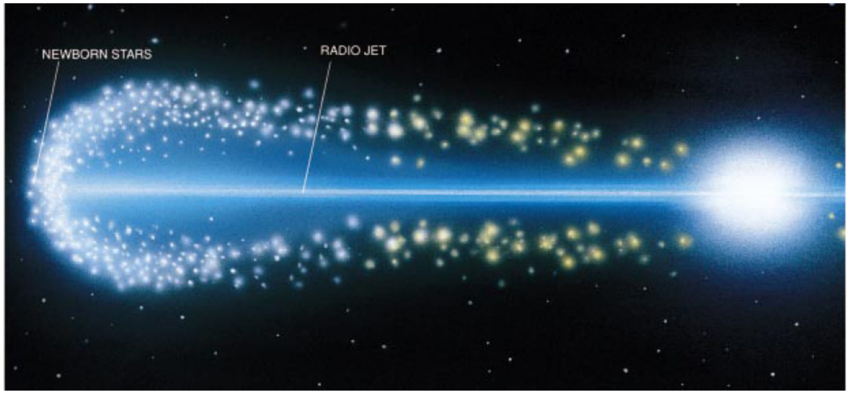
Chambers, Miley and van Breugel (1987, Nature 329,604), McCarthy et al. (1987, ApJ, 321, L29)

Best,Röttering en Longair 1996

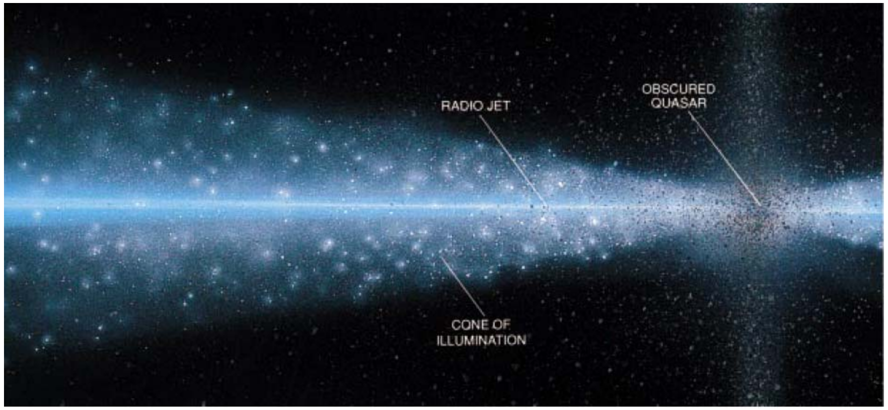


MAIN EXPLANATIONS FOR ALIGNMENT EFFECT

- Jet-induced star formation
  - (e.g. Rees 1988) Begelman & Cioffi, De Young,)
  - WYSIWYG
  - Few x $10^2 M_{Sun}$/yr



- Scattering of obscured quasar light
  - Dust
  - Electrons



OBSERVATIONS RULE OUT SINGLE EXPLANATION

PROPERTY	ANISOTROPIC SCATTERING			JET-INDUCED STARBURST
	Dust	Electrons $T\sim10^4K$	Electrons $T\sim10^8K$	
Blue-radio alignment	OK	OK	OK	OK
Red-radio alignment	x	OK	OK	OK
Similar small-scale wiggles	x	x	x	OK
Sometimes UV polarization	OK	OK	OK	x
SED	x	x	x	OK
Extended luminosities	x	x	x	OK
No extended broad lines	x	x	OK	OK

AGN FEEDBACK CAN
TRIGGER STAR FORMATION AS WELL AS QUENCH IT!

AN INNER CITY CASE STUDY

SPIDERS AND FLIES AT $z \sim 2.2$

MERGING, AGN FEEDBACK, DOWNSIZING

MASSIVE CD EVOLUTION - CASE STUDY

1138-262, z = 2.2

IR Luminosity ~ 10^{12} M_{Sun}: One of most massive galaxies in Universe

DEEP IMAGE WITH HST/ Advanced Camera

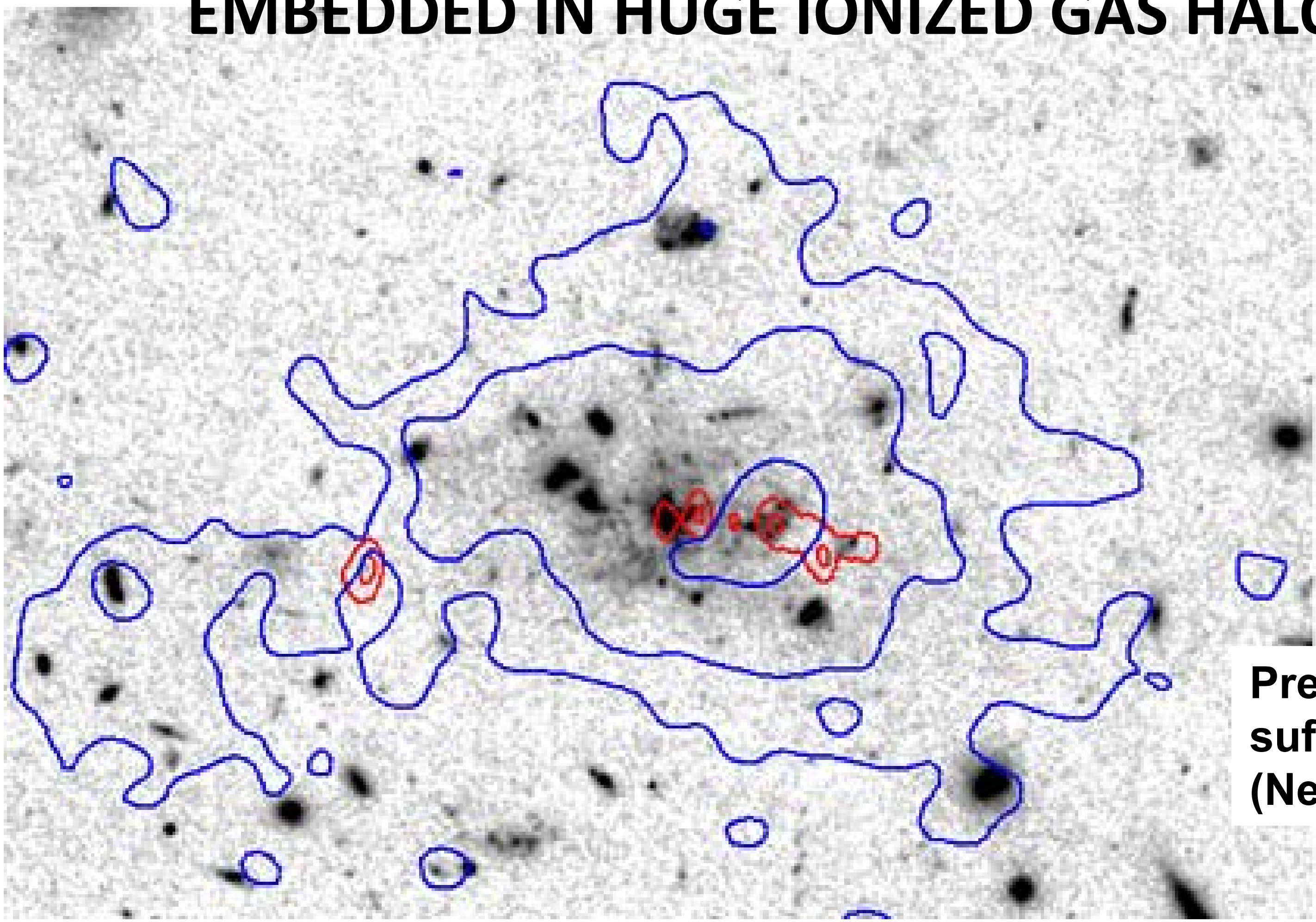
SPIDERWEB GALAXY

Miley et al. 2006, Astrophys. J. 650, 29L

- Laboratory for studying ongoing
  - Merging
  - AGN feedback
  - Downsizing
    - Most massive galaxies form earlier

Small satellite galaxies are "flies" in the "spiderweb"

SPIDERWEB GALAXY z = 2.2
EMBEDDED IN HUGE IONIZED GAS HALO



Lyα
Ionized gas
(Kurk et al)

Radio Synchrotron
Relativistic plasma
(Carilli et al)

Pressure of radio jet
sufficient to expel gas
(Nesvadba et al 2007)

~ 200 kpc
6×10^5 light yr

LABORATORY OF ON-GOING AGN FEEDBACK

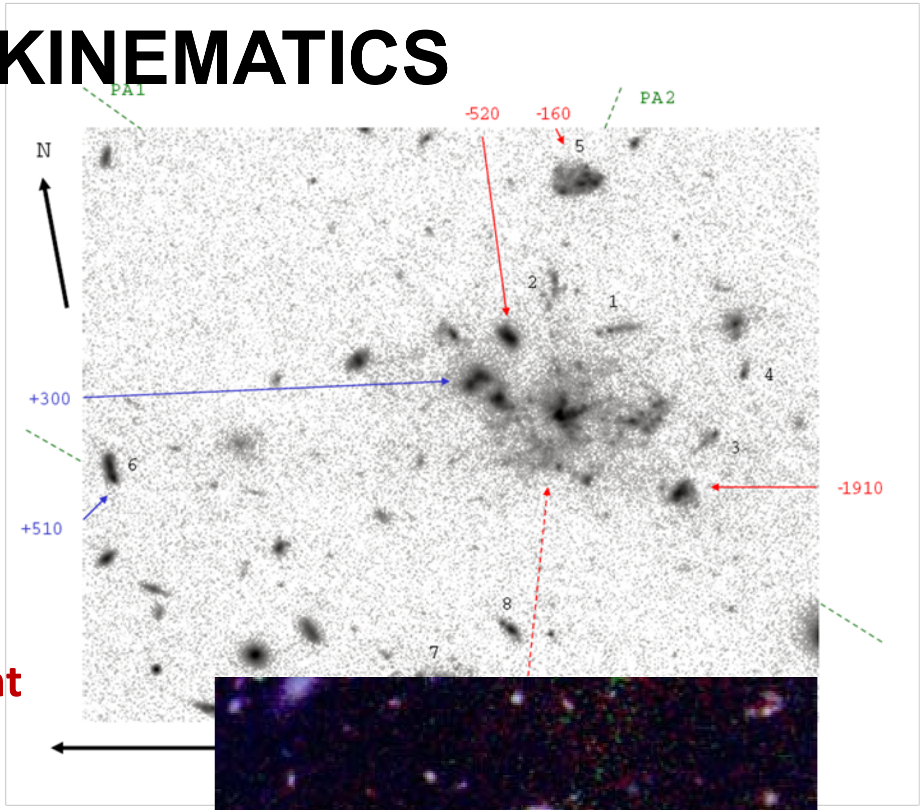
SPIDERWEB GALAXY z = 2.3
MAPPING THE KINEMATICS

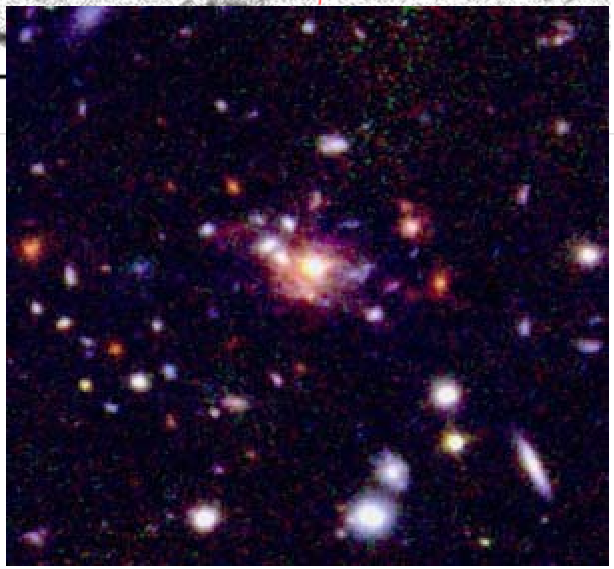
- Velocities of flies
  - few hundred km/s

- What will happen to Spiderweb?
  - Between z ~ 2.3 and z ~ 0

    (t ~10.6 x 10^9 yr)

    flies will traverse Spiderweb complex several times
  - Consistent with formation of smooth giant elliptical galaxy



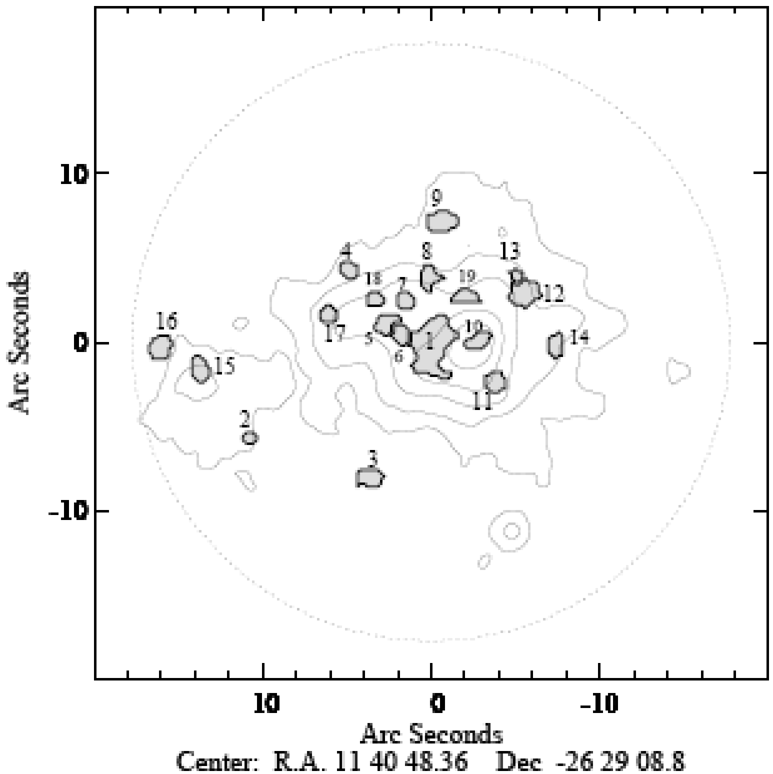


BEST EVIDENCE THAT GALAXY MERGERS ARE IMPORTANT IN BUILDING MOST MASSIVE GALAXIES

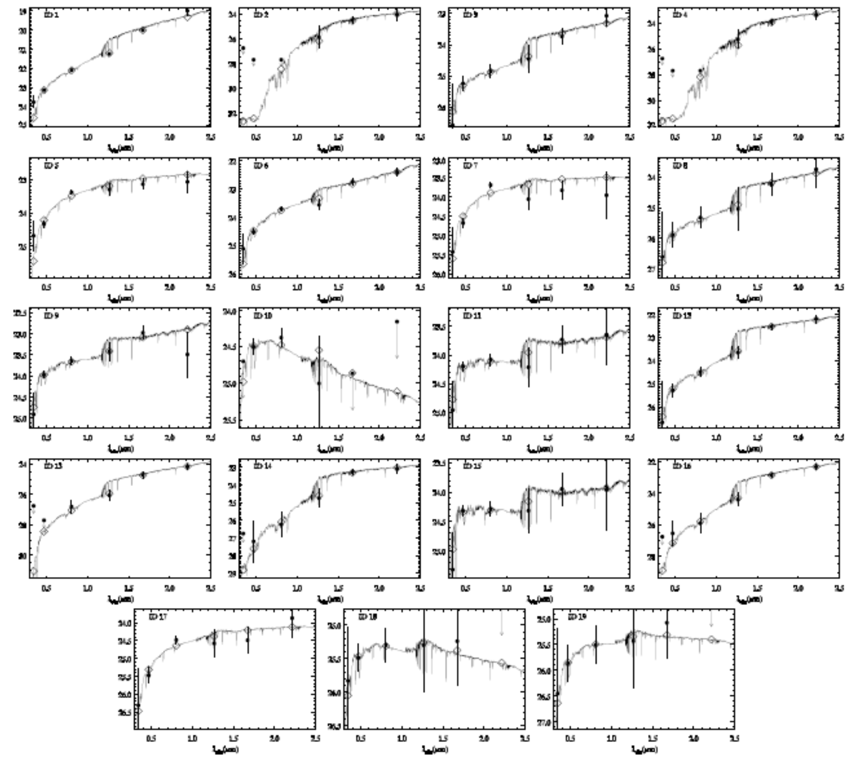
LABORATORY FOR STUDYING MERGING

SEDs OF CENTRAL GALAXY AND 18 SATELLITES

Hatch et al. MNRAS 395, 114 (2009)



radio gal 1

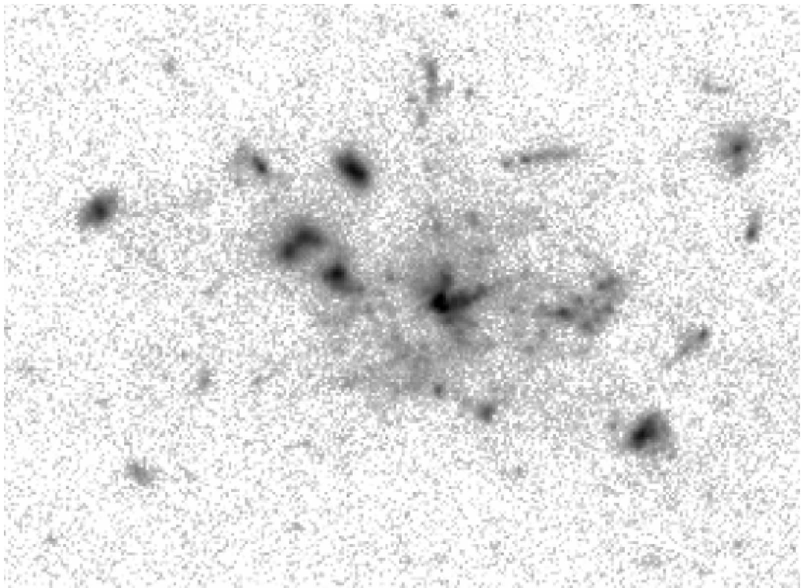


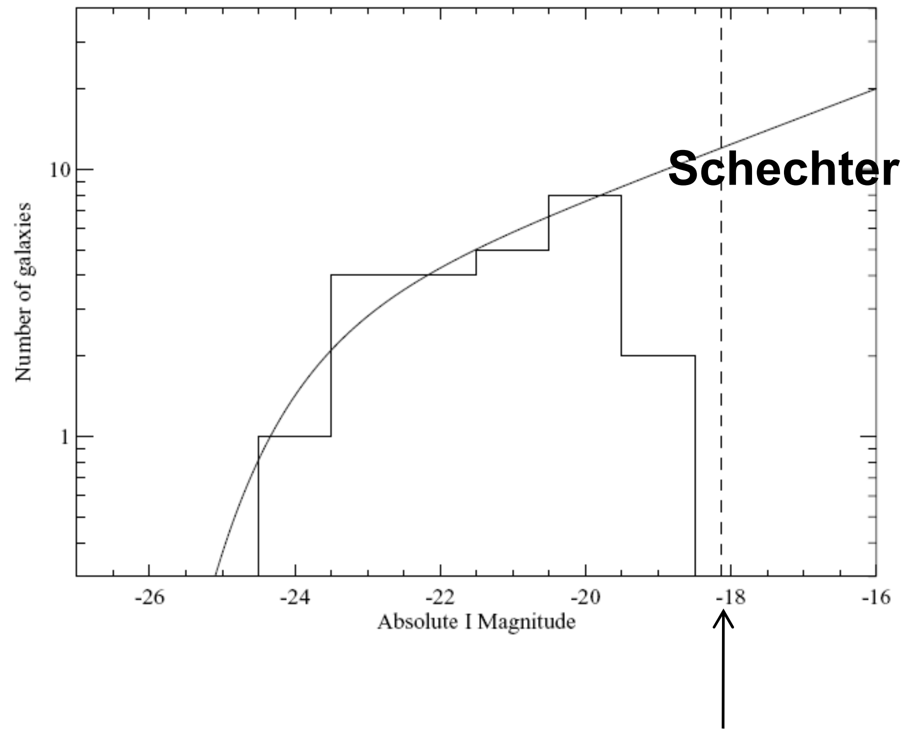
- Stellar mass Total ~ $10^{12}M_{Sun}$ ~ 70% in central blob
  - Satellites ~ $10^{8} – 10^{11}M_{Sun}$
- SFR Total 63 ± 8 M_{Sun}/yr ~ 75% in satellites
  - Satellites typically 1 – 3 M_{Sun}/yr

LABORATORY OF ON-GOING DOWNSIZING

EXTENDED STAR FORMATION BETWEEN "FLIES"

Hatch et al. MNRAS 383, 931 (2008)

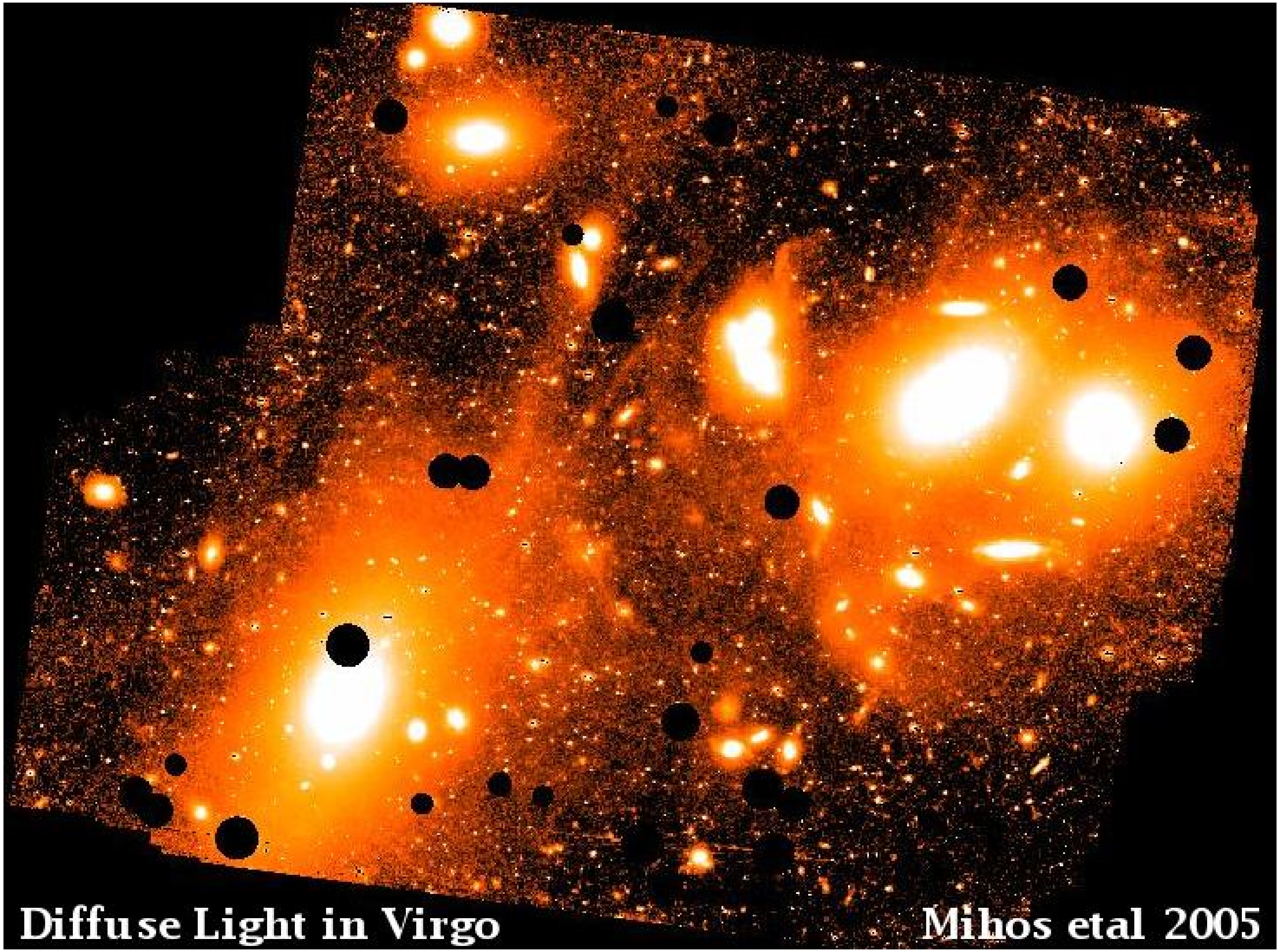




Extended component

- Diffuse emission – not a simple sum of faint galaxies
  - Discontinuity in galaxy luminosity function
- Probably star formation
  - Other mechanisms unlikely
    - 57 ± 8 M_{Sun}/yr 44% of SFR within central 70 kpc
- Seems to become bluer with distance from centre
  - SFR increases

DIFFUSE CLUSTER LIGHT AT LOW –z?

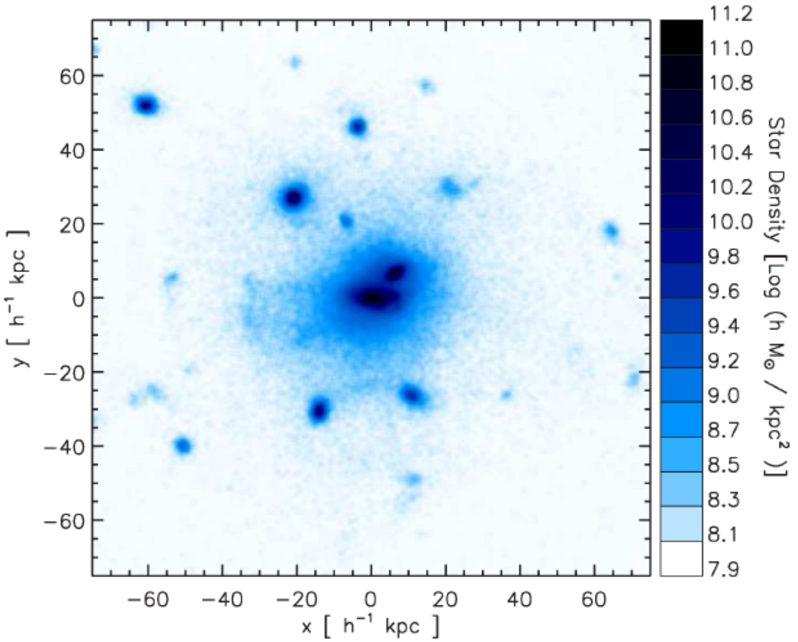


SPIDERWEB GALAXY AT z = 2.2
DETAILED STUDY UNDERWAY

- **Detailed properties of flies being measured**
  - **3D-Spectroscopy > kinematics etc**
    - **IR VLT SINFONI** (with Nicole Nesvadba)
    - **Optical GEMINI GMOS** (Nina Hatch)
      - Data being reduced (Ernst Kuiper)

- **Compare with simulations**
  - **e.g. Alex Saro, Stefano Borgani, Gabriella De Lucia, +++**
  - **Note the presence of linear flies**

- **Search for 3 additional Spiderweb galaxies**
  - **HST: 30 orbits allocated**



Saro et al. 2009, MNRAS, 392, 79

4. PROBING EVEN EARLIER WITH LOFAR

A NEXT-GENERATION RADIO TELESCOPE

www.lofar.nl

LOFAR

LOW FREQUENCY RADIO ARRAY

~ 15 MHz - ~ 230 MHz

New-tech. Radio Telescope
Phased arrays not dishes
Multidisciplinary sensor array
(e.g. Geophysics sensors)

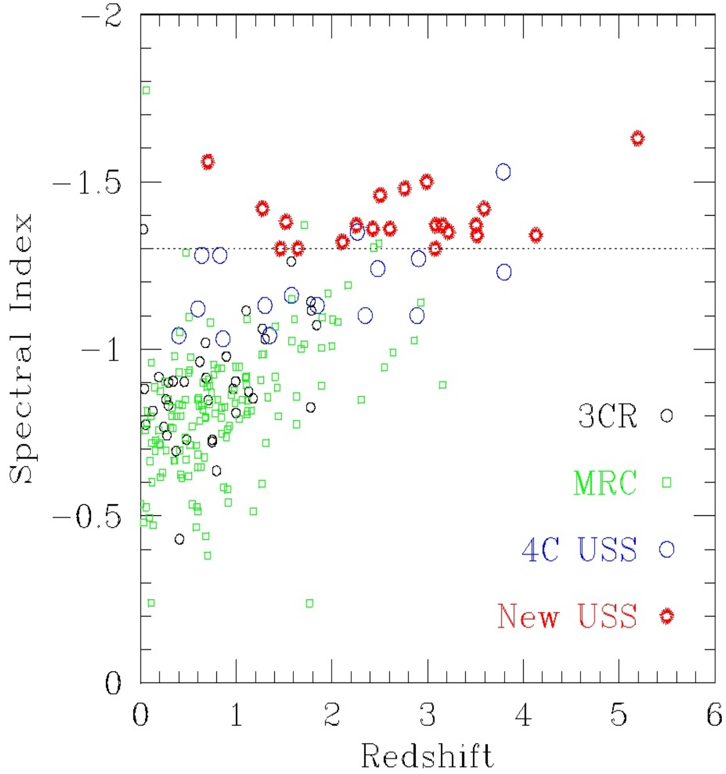
Full operation: 2010

Netherlands ~ 100 km:	36 NL stations
Europe ~ 700 km:	5 Germany, 1 UK, 1 France, 1 Sweden

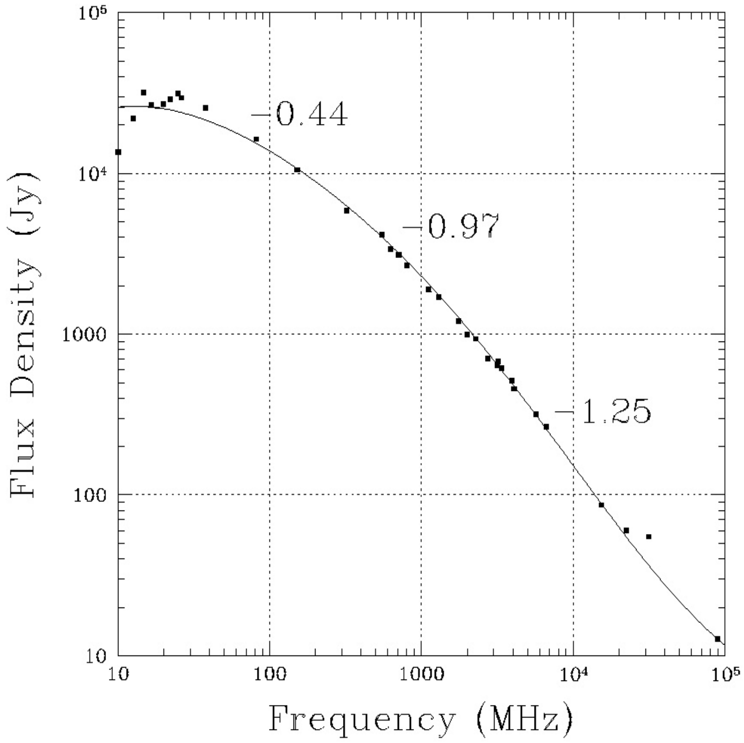
Additional?:

MOST DISTANT RADIO SOURCES HAVE STEEPER SPECTRA

e.g. Blumenthal & Miley 1988



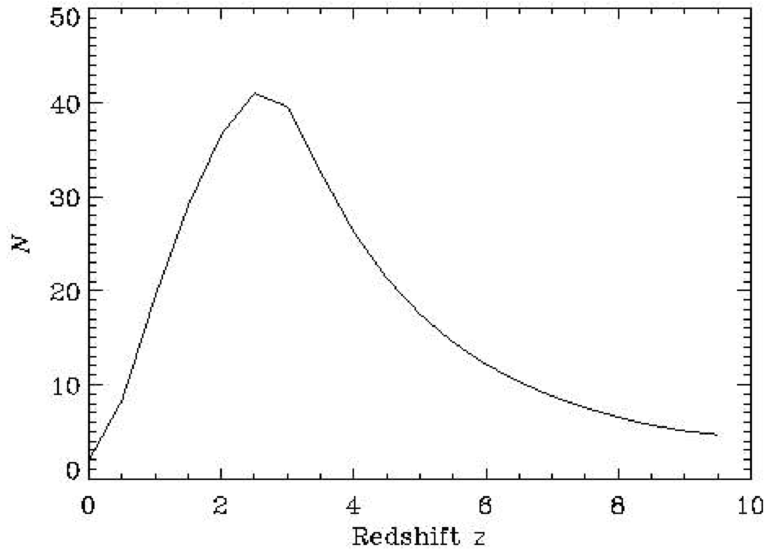
Radio spectrum
Cygnus A



Larger redshifts > higher frequencies > steeper spectra
LOFAR WILL DETECT STEEPEST SPECTRA
(MOST DISTANT SOURCES)

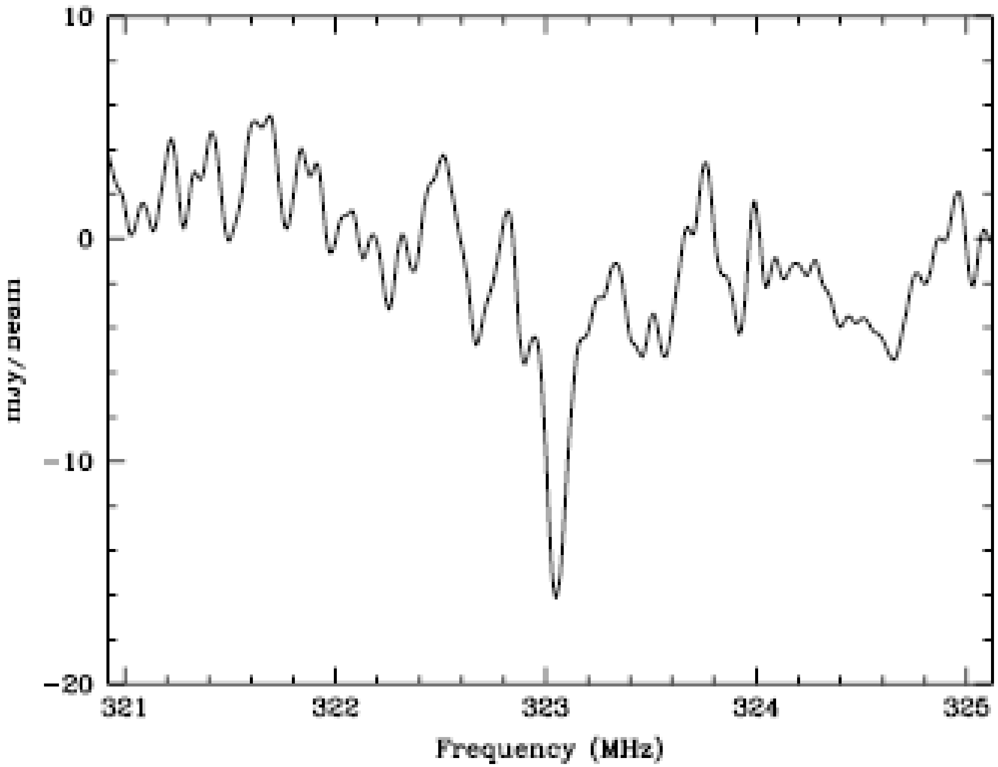
LOFAR WILL BE SENSITIVE TO SYNCHROTRON RADIO SOURCES TO z ~ 8

PREDICTED LOFAR REDSHIFT DISTRIBUTION FOR SOURCES HAVING ULTRA-STEEP SPECTRA ($\alpha < -1.3$)



LOFAR WILL LOCATE FORMING MASSIVE GALAXIES AND PROTOCLUSTERS TO z ~ 8 (IF THEY EXIST)

HI ABSORPTION
0902 +34 AT z = 3.4

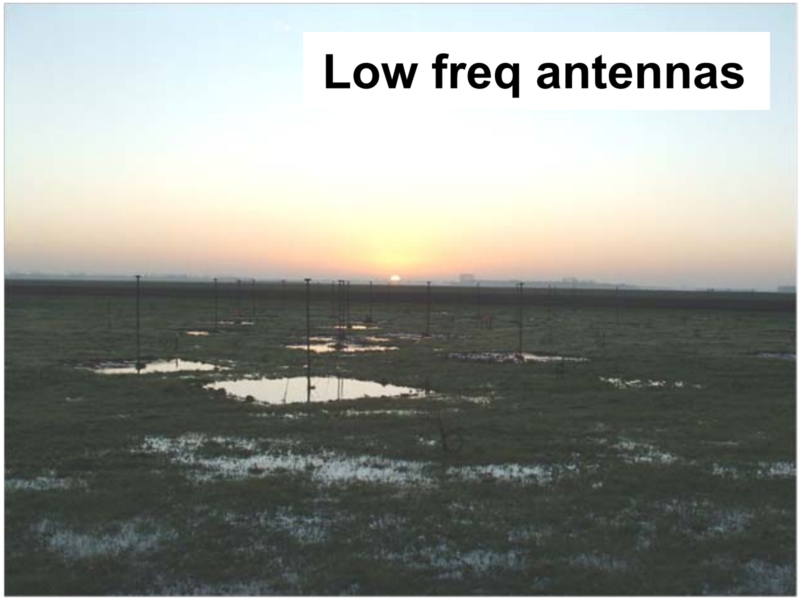


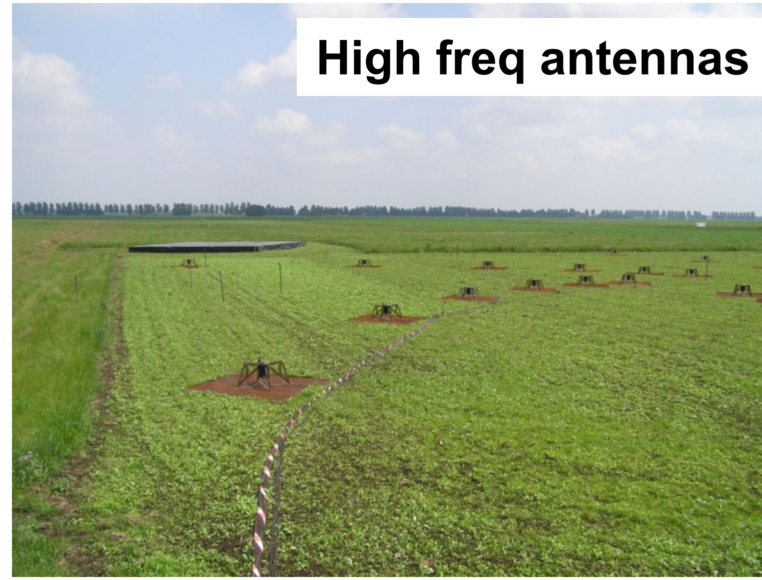
N(HI) ~ 3 x 10^{21} cm^{-2}
Ts ~ 1000K
M ~ 10^7 M_{Sun}

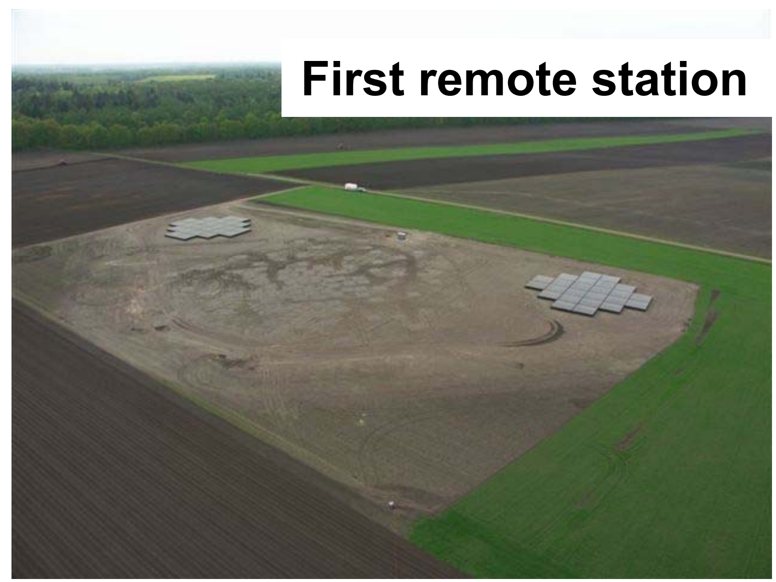
e.g. Cody & Braun, 2003

For radio galaxies with z > 6.5,
HI absorption probes
Epoch of Reionization

LOFAR BECOMES REAL

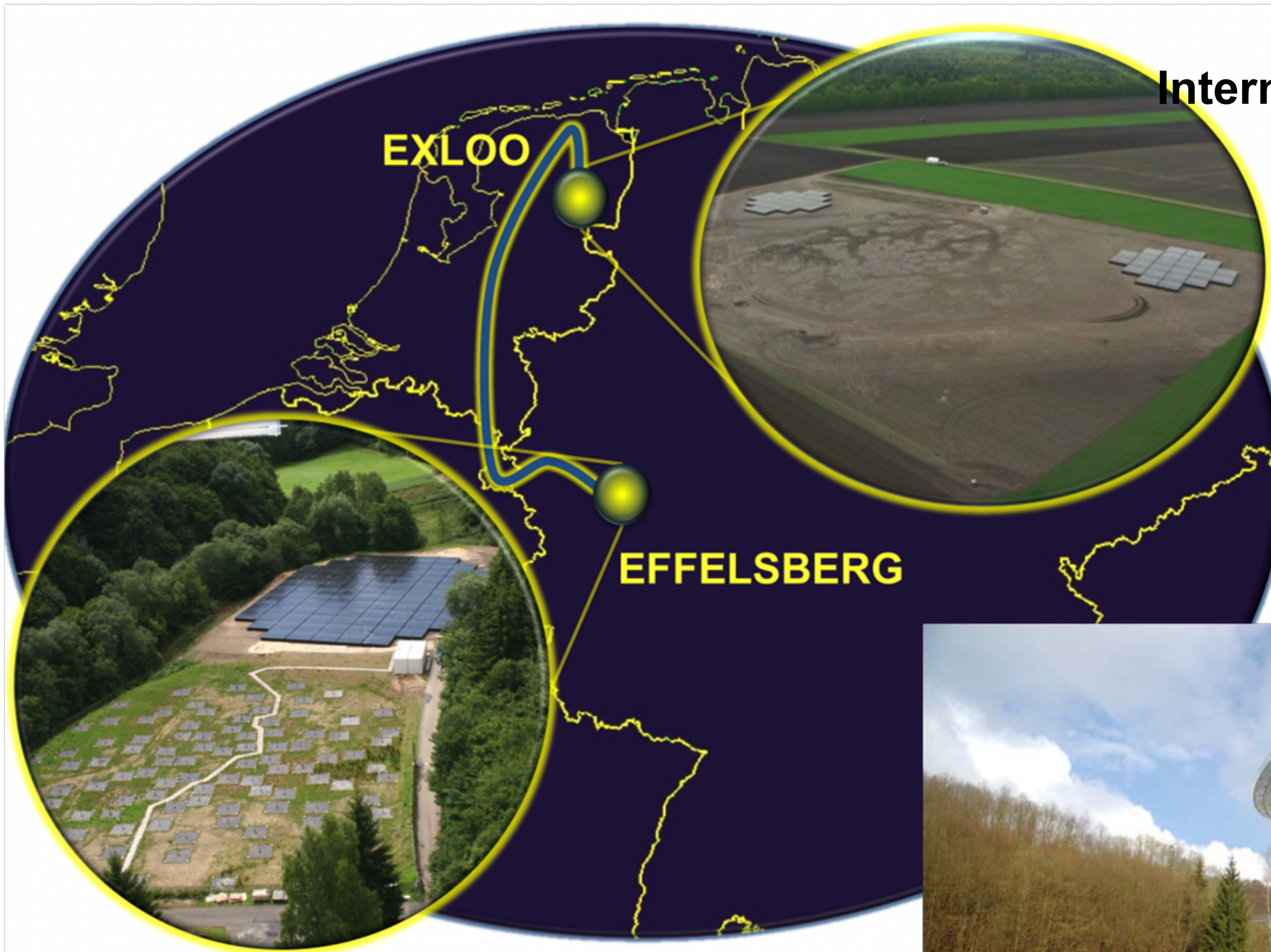






FIRST FRINGES WITH EFFELSBERG

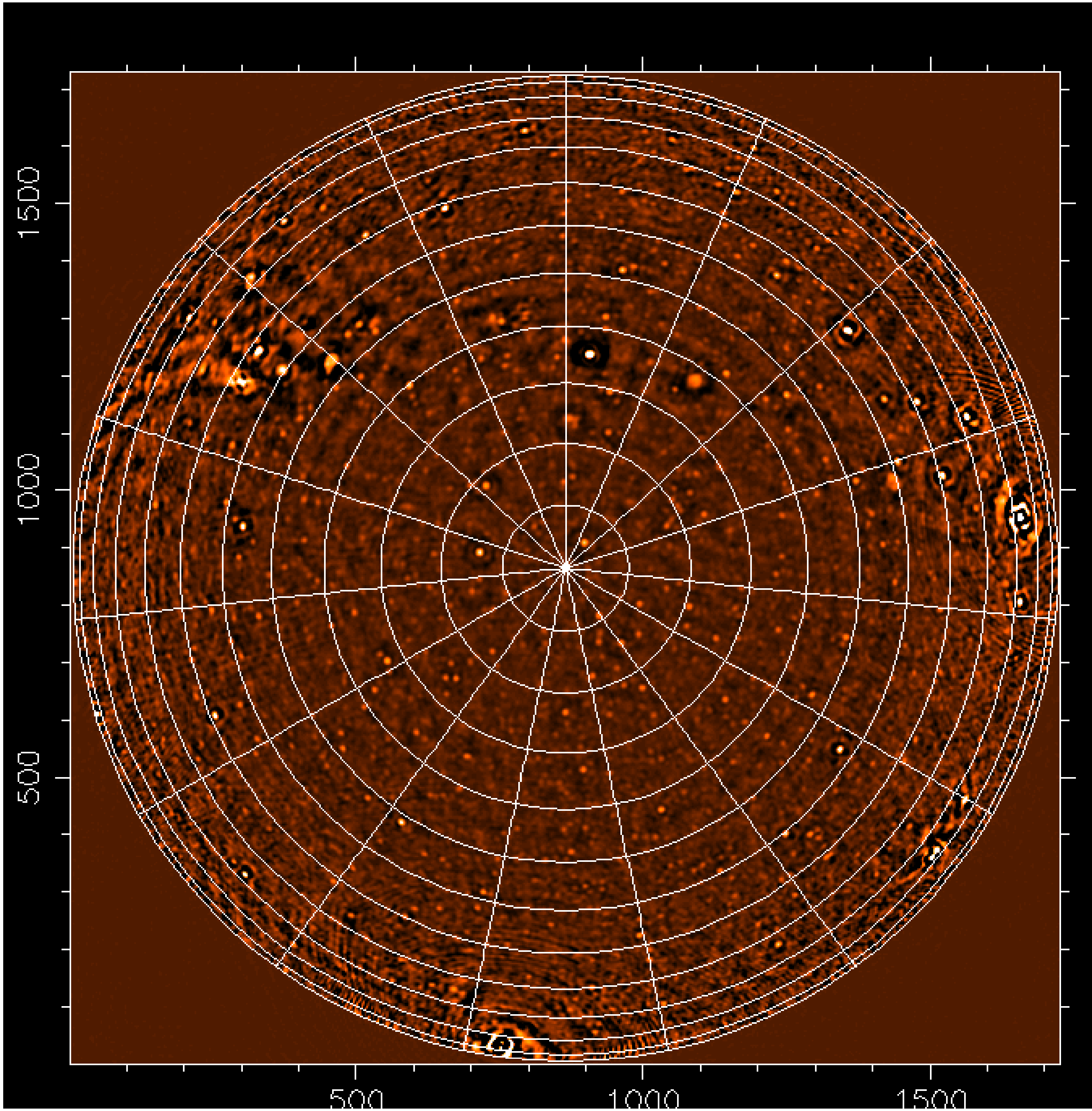
International Stations



LOFAR TEST SURVEY 60 MHz

1 OF 40 LOFAR STATIONS

1% OF FINAL SPATIAL RESOLUTION



SOME CONCLUSIONS

- DISTANT RADIO GALAXIES
  - Best signposts of distant protoclusters and their central massive galaxies
  - Unique laboratories for studying evolution during crucial epoch $5 > z > 1$
    - AGN Feedback, Downsizing
    - Essential to study physical processes to properly understand statistics
- HIERARCHICAL PROCESSES (MERGING) INVOLVED IN BOTH
  - Massive galaxies + rich galaxy clusters
    - Small units merge to create larger ones
    - Interaction between various components important: stars, gas, dust, active nucleus
    - Star formation decreases substantially from $3 > z > 2$.
- SEVERAL INTRIGUING UNANSWERED QUESTIONS, e.g.

  How does galaxy merging affect feeding SMBHs, AGN triggering and star formation?

  How does AGN affect detailed evolution of cluster galaxies?

  Why do $z > 2$ extended radio sources have much steeper spectra than $z < 1$ radio sources?

  Is jet-induced star formation important in the early Universe?

SOME FUN FOR THE NEAR FUTURE - 1

- LOFAR
  - Demographic evolution
    - Timeline of MBH and galaxy formation
      - Luminosity function at $z > 2$
  - Are there HzRGs (massive galaxies, protoclusters, SMBHs) at $z > 6$ in the EoR?
    - Possible probes of EoR
  - Nature of ultra-steep radio spectra and alpha-z correlation

- EVLA/ALMA
  - Molecular gas
    - CO ladder. CI and other lines
  - Radio emission from star formation
    - Flies and protocluster members

SOME FUN FOR THE NEAR FUTURE - 2

- GRANTECAN (GTC) WITH OSIRIS TUNABLE FILTER (UNIQUE)
  - Large samples of $z > 2$ protoclusters (redshifted Lyα)
    - Arbitrary z
    - Kinematics, subclustering
    - History of cluster assembly

- HST
  - Large sample of spiderweb galaxies
    - Merging, feedback and downsizing at protocluster centres

- JWST
  - Assembly history of distant LOFAR HzRGs
  - Role of jet-induced star formation in early Universe

MORE DISTANT FUN

- JWST/ELT
  - Assembly history of distant LOFAR HzRGs
  - Role of jet-induced star formation in early Universe
- CONSTELLATION X
  - Kinematics of hot depolarizing gas

THE ANTROPOLOGY OF CLUSTERS

HOMO SAPIENS & THE EARTH

- Cities of People
  - Why and how?
    - Find and study first towns and cities
      - Jericho 7000 BC: 9 kyr old
- Oldest Cities
  - Walls and temples are signposts
    - Indicators of social organization
- Towns and cities through the ages
  - Laboratories for studying human evolution
    - Comparison with non-city dwellers

GALAXIES & THE UNIVERSE

- Clusters of Galaxies
  - Why and how?
    - Find and study first protoclusters
      - 1338-19: 12 Gyr old
- Oldest "protoclusters"
  - Radio (massive) galaxies are signposts
    - Indicators of large gravitational potential
- Protoclusters and clusters through the ages
  - Laboratories for studying galaxy evolution
    - Comparison with "field" galaxies