Mergers: two main types

Minor mergers

- large galaxy eats dwarf.
- May relate to
  - Growth of bulges (multiple nuclei in M31, metallicity range in MW bulge)
  - thick disks

Major mergers:

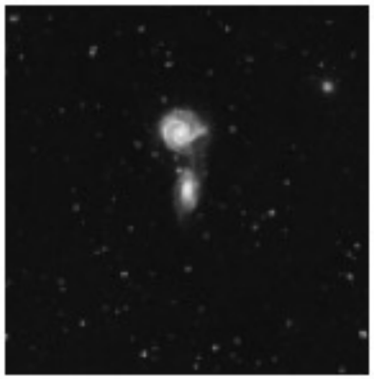
- two large galaxies
- Growth of cDs
- 2 spirals => E?

What fraction of E's formed this way?

The Toomre Merger Sequence

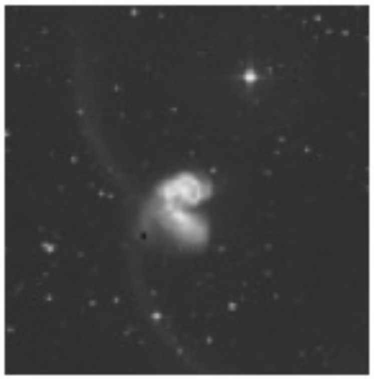
- For a major merger the mass ratio is 1/1 ~ 1/3.
- These types of merges will destroy the disks of both galaxies and eventually produce a spheroidal system (bulge like, elliptical galaxy).
- The transformation from a flattened disk system to a spheroidal occurs via *violent relaxation.*
  - Violent relaxation happens when force of gravity acting on the stars is large and changes quickly with time
  - Makes stars in two spirals forget their disk distribution and move in all directions, forming the spheroidal

The Toomre sequence (from simulations), below in images. A sequence of observed galaxies that are thought to be in different stages of major merger between two spirals.



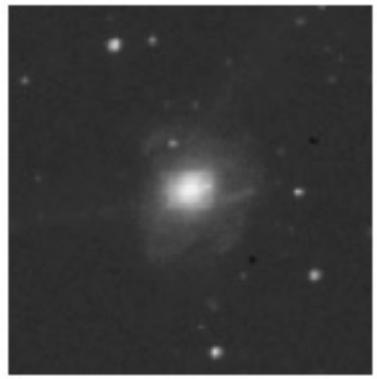
NGC5426/5427

Credit: DSS



NGC4038/4039

Credit: DSS



NGC7252

Credit: DSS

NGC3610

Credit: DSS

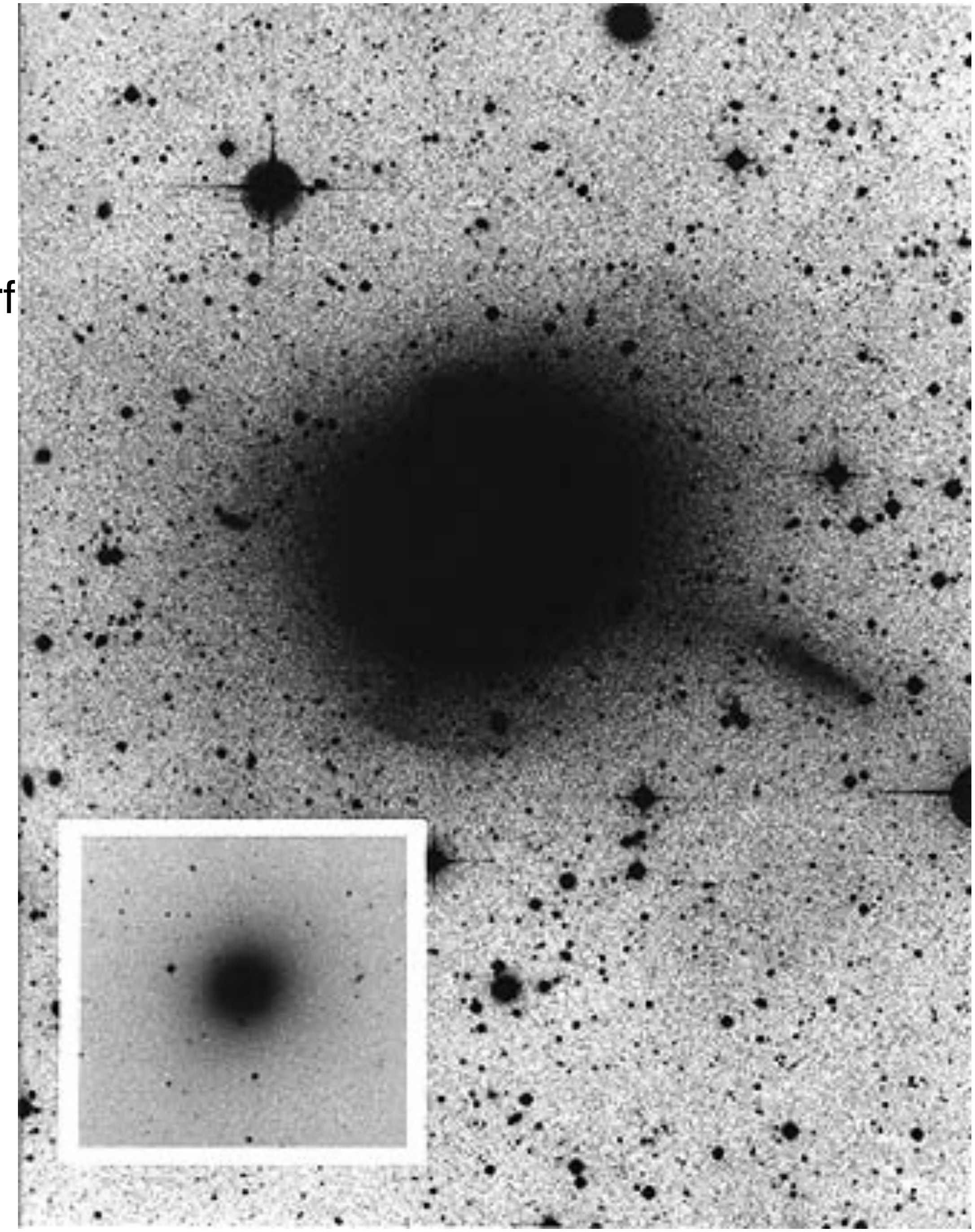
M89

Credit: DSS

A **Toomre Sequence** illustrating the merger process.

M89 deep image of the final merger product

Two shells and a disrupted dwarf galaxy tell the story of recent major merger.



1. Two spiral galaxies on a collision course …

2. Gravitational forces throw out stars and gas along two extended tails. The length of the two tails reflects the rotation of the two initial galaxies.

3. The stars in the tail fade away, but gas in the tails falls back into the galaxies to form stars.

4. The disks are destroyed via violent relaxation.

5. The end product is an elliptical galaxy.

Minor mergers

- Minor mergers have mass ratios < 1/4

- The disk of the larger galaxy will NOT be destroyed, but it will show distortions such as ripples, arcs and tails.

- The smaller galaxy may be tidally ripped apart by the interaction and its constituents (stars, gas, dust) scattered as debris within the larger galaxy, or as tails.

NGC1316

Elliptical galaxy which recently has cannibalized smaller spiral galaxies (1/10-1/100 of its mass). It has acquired lots of gas and dust.

Starbursts

- Interacting galaxies tend to be bluer, with high far-IR luminosities due to triggered star formation.
  - Both direct mergers and more indirect interactions can trigger star formation

- Caused by gas agglomerating, causing shocks triggering collapse
  - Starbursts often occur at galaxy center, due to gas cloud orbits being disrupted by encounter.
  - Example M82 a few $M_{\odot}$/yr in a nuclear area of 100 pc (similar to a large spiral!)

- May last 20Myrs

- We observe *ultra luminous infrared galaxies (ULIRGS)* which have very high star formation rates (100-1000 x MW value)

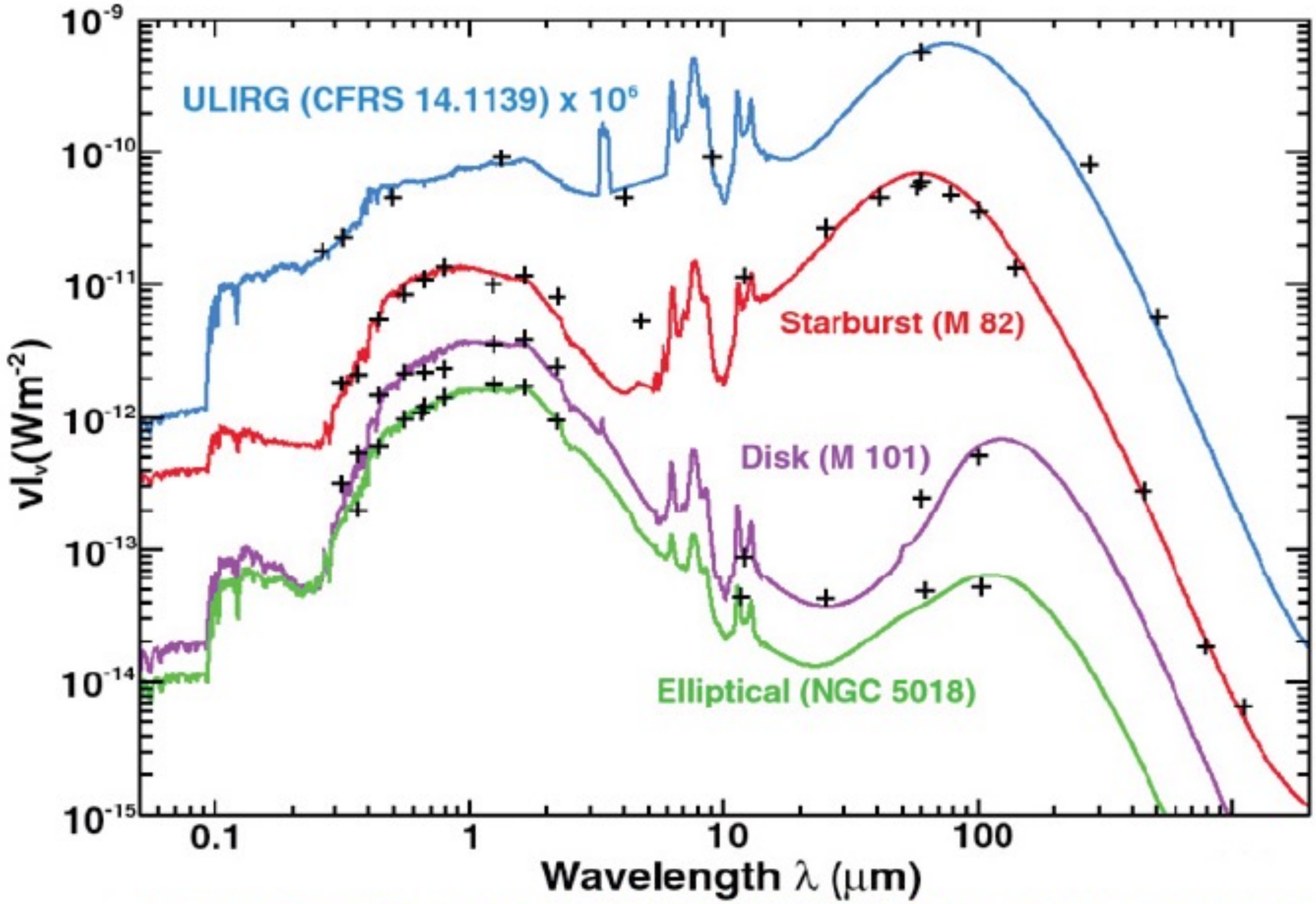


Fig 7.7 (P. Chanial, G. Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Other effects of interactions

- In a galaxy interaction, energy is drawn from the motions of the galaxies, via dynamical friction transferred to random motion of the stars.

- Before the interaction, a galaxy had a certain total energy E_0.

- The virial theorem says

$$2(K_0) + P_0 = 0 \quad \text{where } K = \text{Kinetic Energy, } P = \text{Potential Energy}$$

$$E_0 = K_0 + P_0 = -K_0$$

- Dynamical friction increases the kinetic energy in random stellar motions by ΔKE

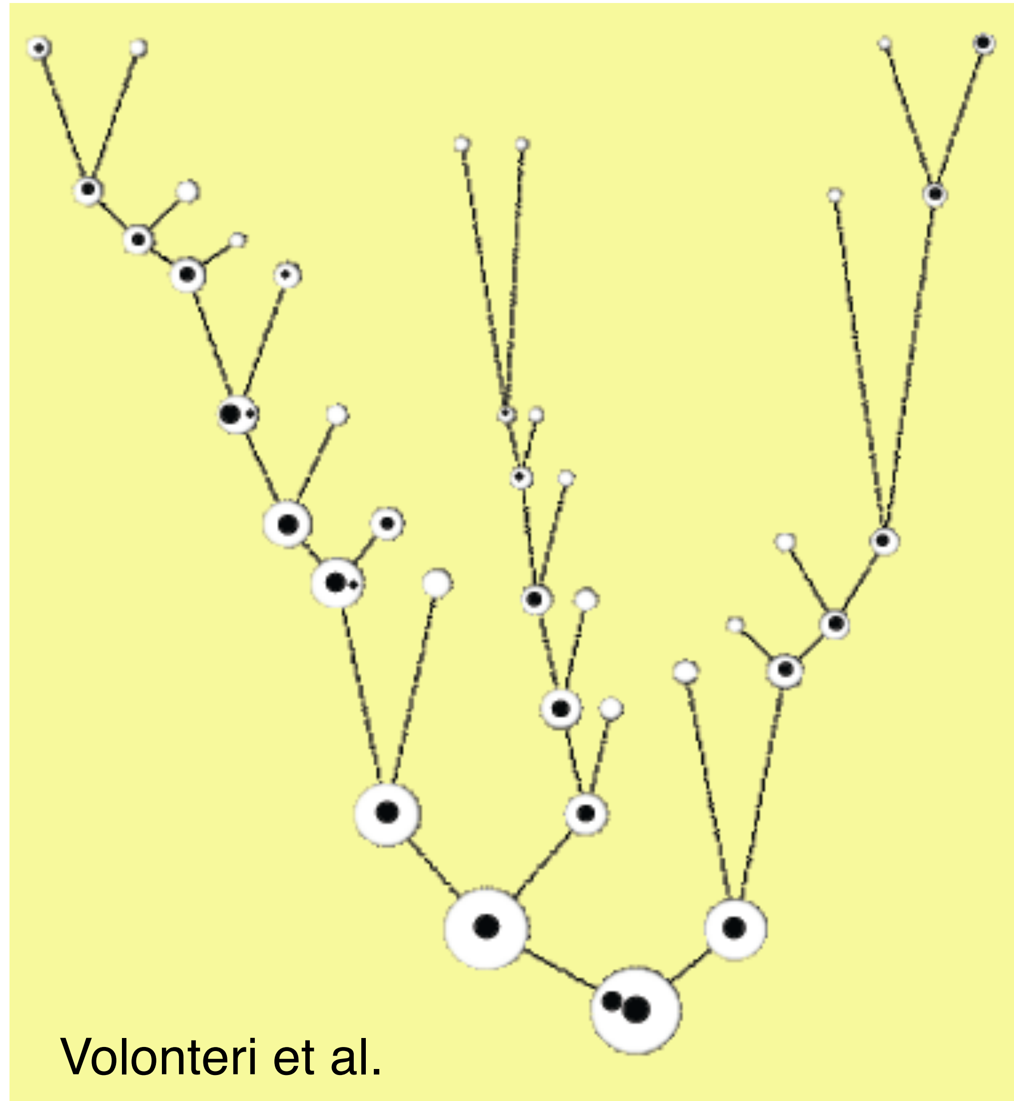
- Total energy must be conserved, so long after the encounter when the system is virialized again

$$K_1 = -E_1 = -(E_0+\Delta KE) = K_0 - \Delta KE$$

- Thus internal Kinetic Energy is decreased
  - This energy could go into increased PE (less negative): slight expansion of galaxy
  - Or, stars that acquire the most KE escape, the rest remain loosely bound, "puffing" up the disk.

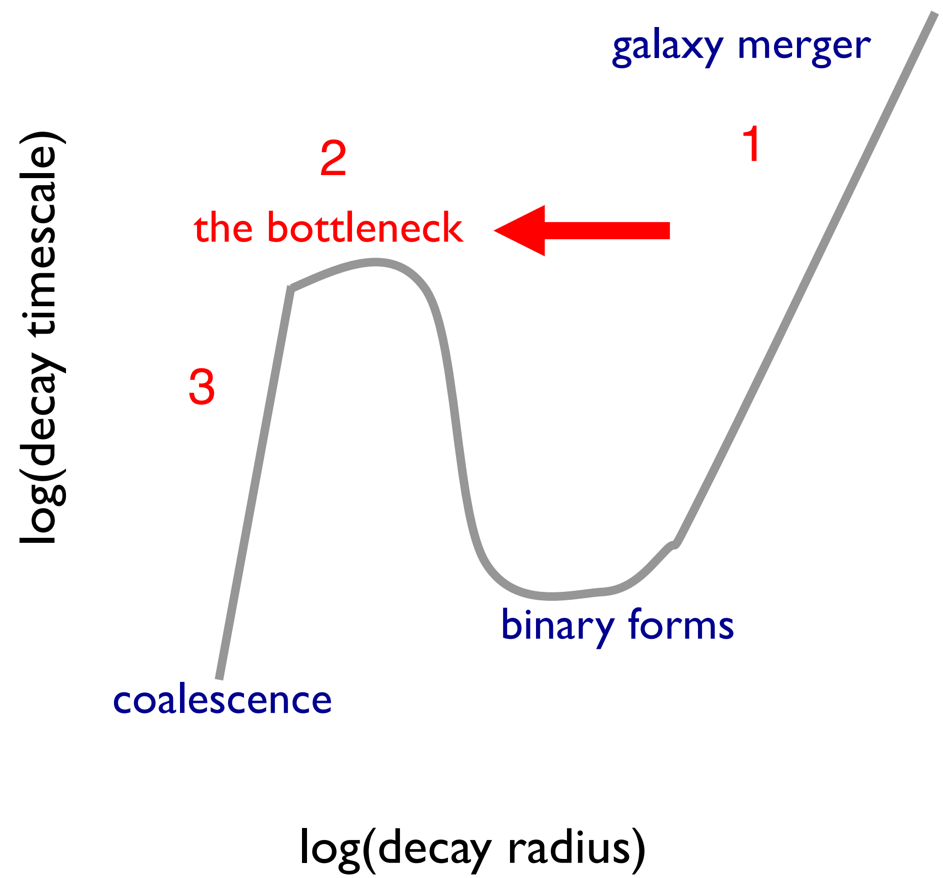
Black Hole Formation

- Assembly+accretion
- Gravitational Rocket problem (Fitchett 1983)
- Slingshot Problem (Volenteri 06)



The Three Stages of BH Merging

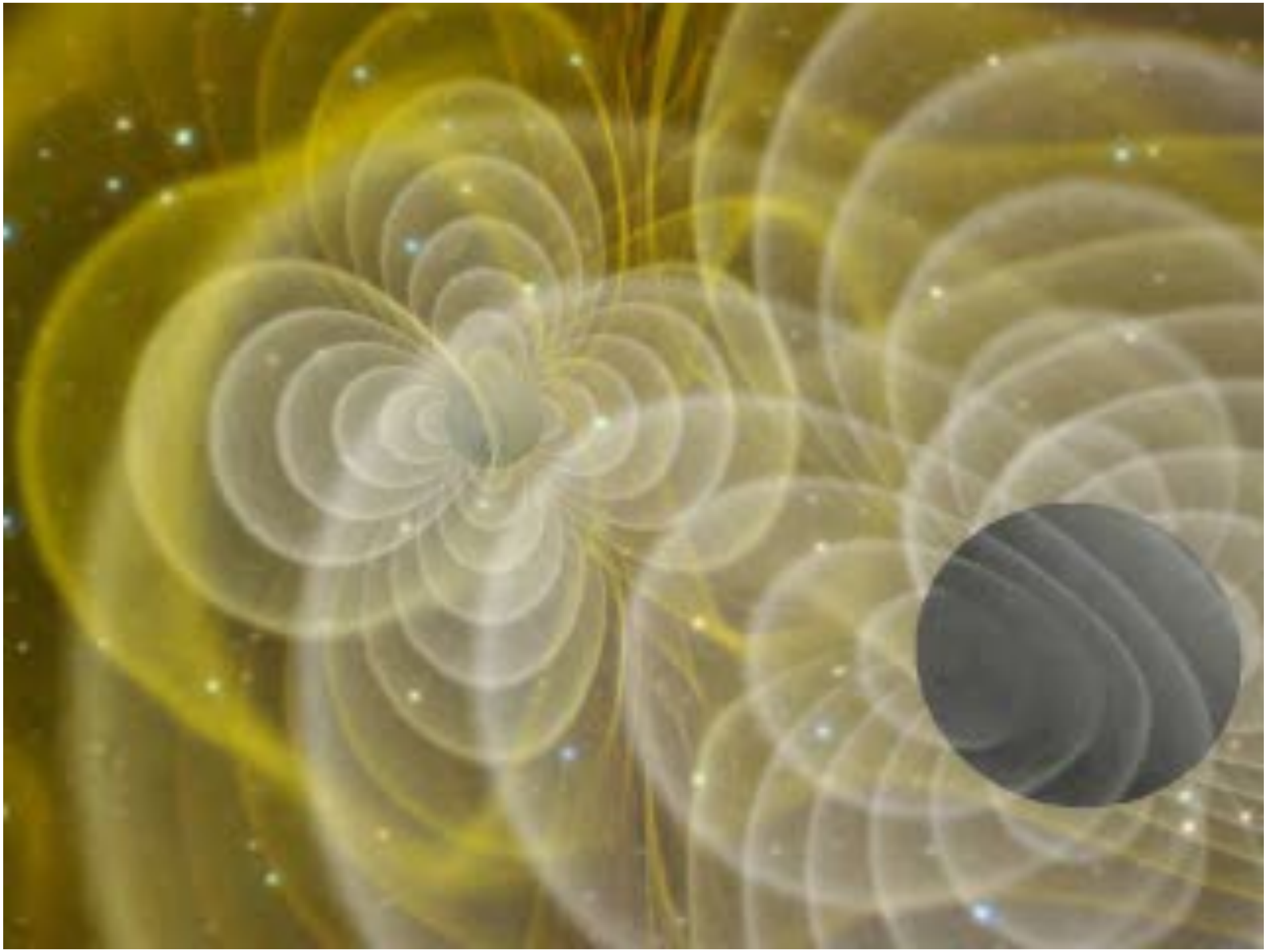
1. Dynamical Friction
2. Binary Hardening
3. Gravitational radiation



(Begelman, Blandford, Rees 1980)

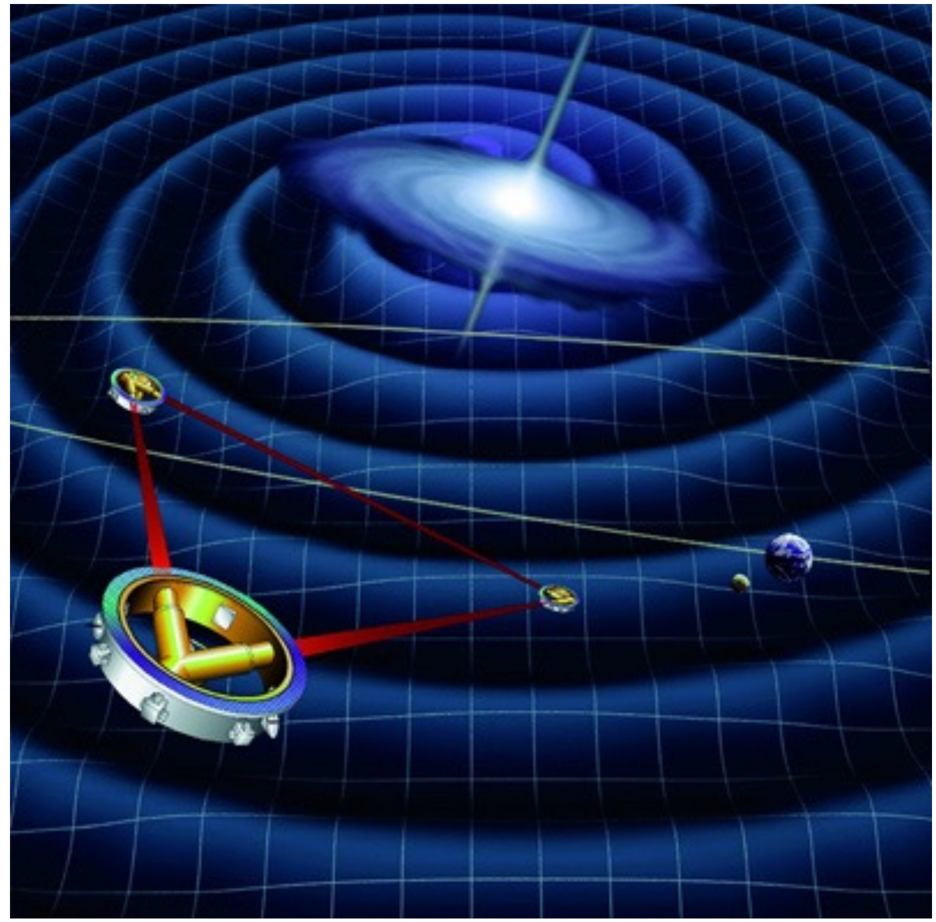
Merritt & Milosavljevic 2004

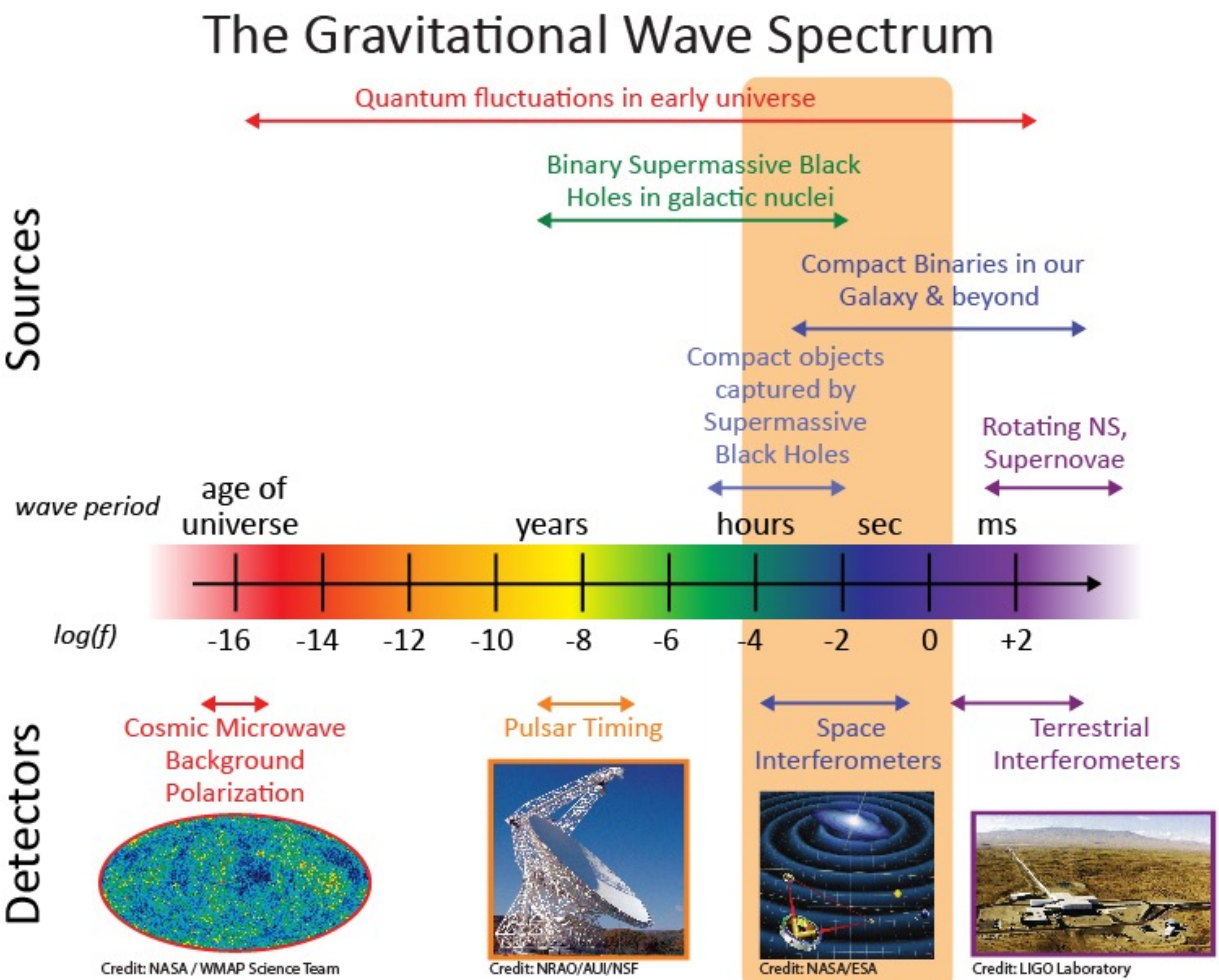
Simulations of Coalescence



Laser Interferometer Space Antenna (LISA)

- LISA hopes to detect gravitational waves from supermassive binary black holes (mass ~ 10^4 - 10^7)
- constraints on formation scenarios of high-z, low-mass galaxies (Menou 03)
- BH **mass** measurements (Hughes 02, Menou 03)
- **`standard candles´** (Hughes & Holz 03)
- Launch in 2037?

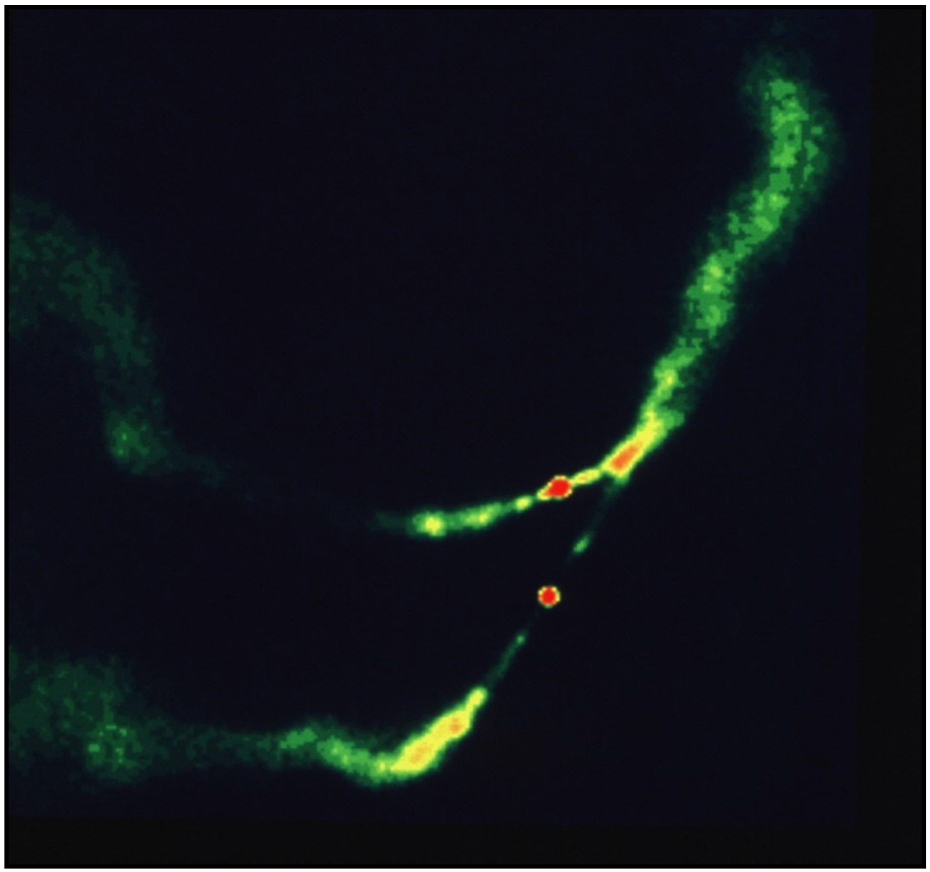



The Gravitational Wave Spectrum
Sources
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
wave period
age of universe
years
hours
sec
ms
log(f)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic Microwave Background Polarization
Pulsar Timing
Space Interferometers
Terrestrial Interferometers
Credit: NASA / WMAP Science Team
Credit: NRAO/AUI/NSF
Credit: NASA/ESA
Credit: LIGO Laboratory

Known Supermassive Binary Black Holes

3C 75

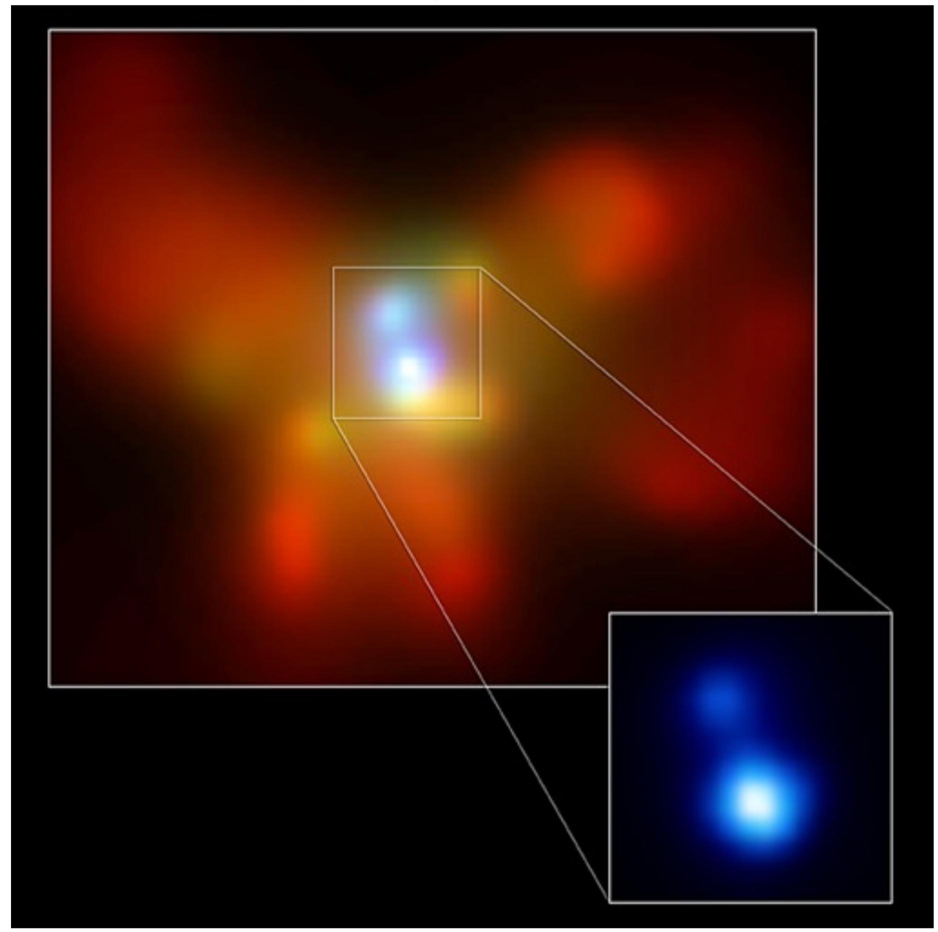
⇨ 7 kpc separation



VLA image of 3C 75 at 6 cm (Owen *et al.* 1985)

NGC 6240

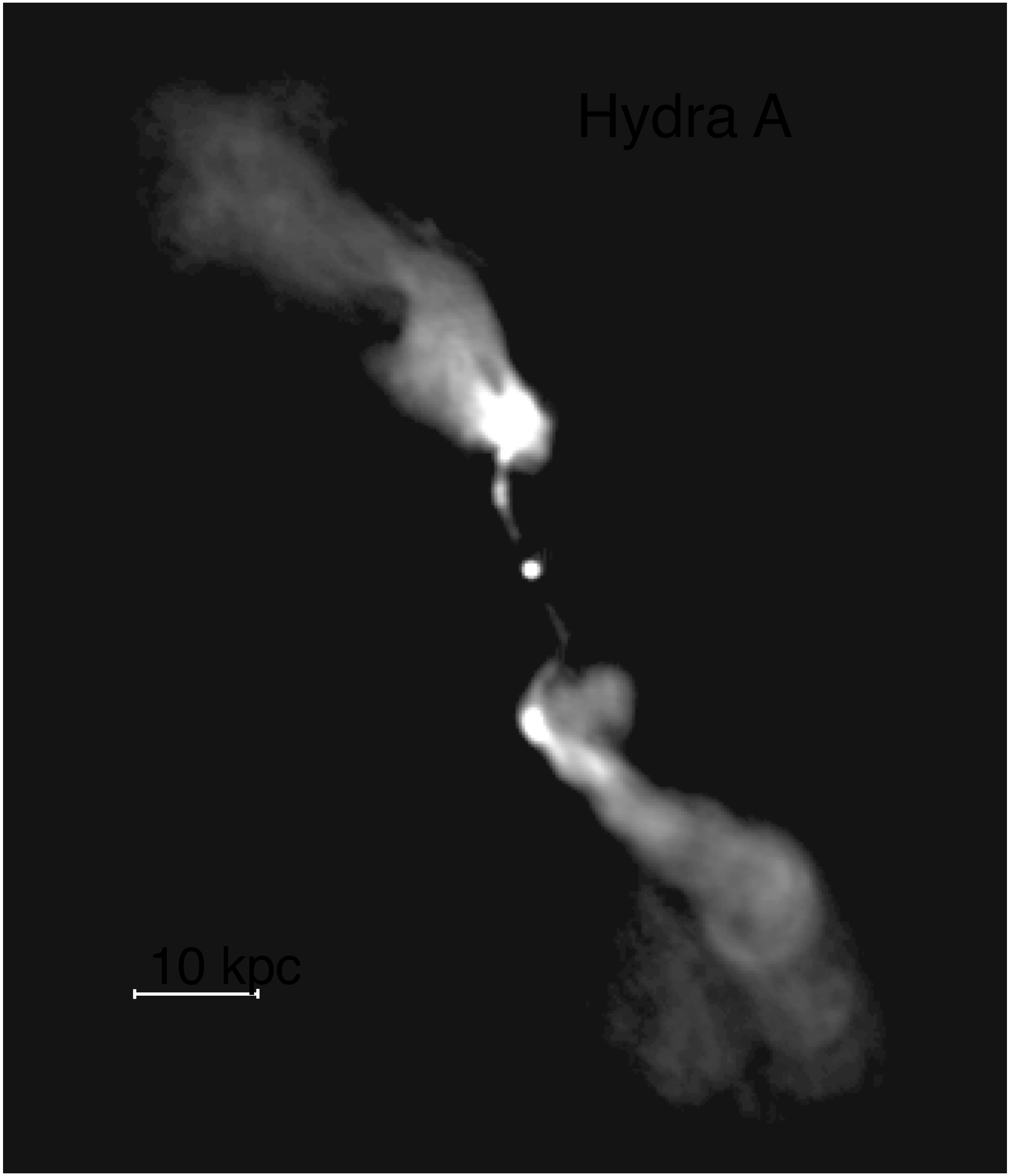
⇨ 1.4 kpc separation



Chandra image of NGC 6240 (Komossa *et al*. 2003)

Observing Compact SBBHs

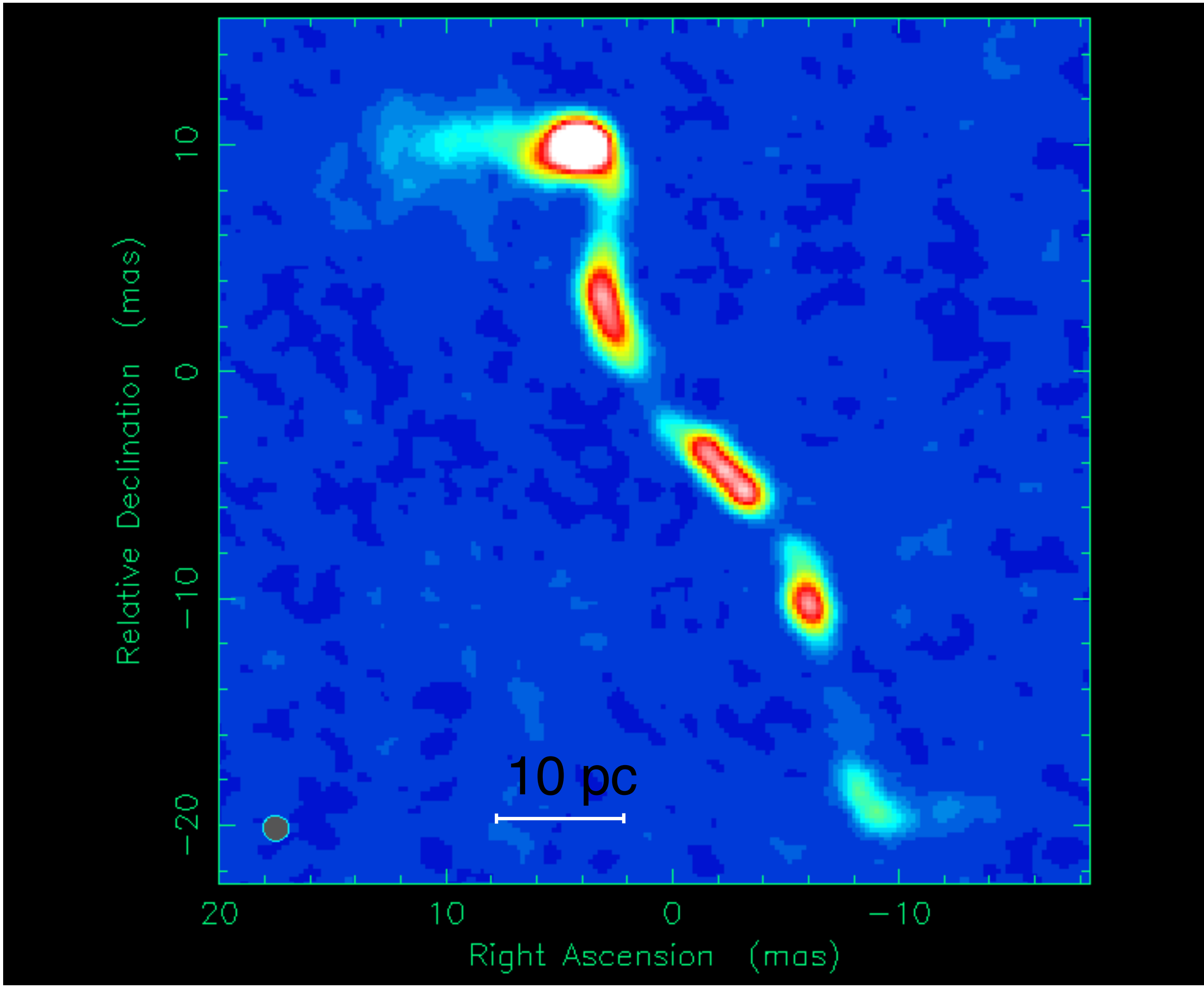
- Evidence for SBBHs
  - Indirect methods
    - Precession, periodic behaviors
    - Double optical lines
  - Direct Imaging with Very Long Baseline Interferometry
    - The radio galaxy 0402+379
- Searching for more SBBHs with the VLBA



P_precession ~ 300,000 y

Taylor et al. 1992

1946+708



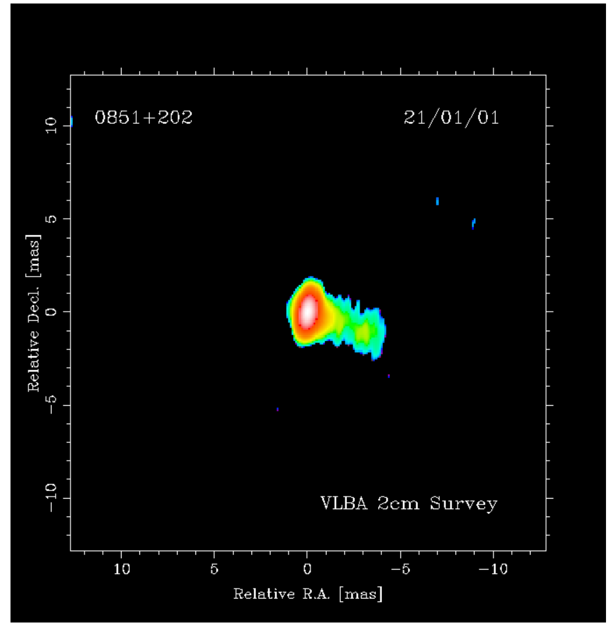
Precession
Period ~ 5700 y

Taylor & Vermeulen

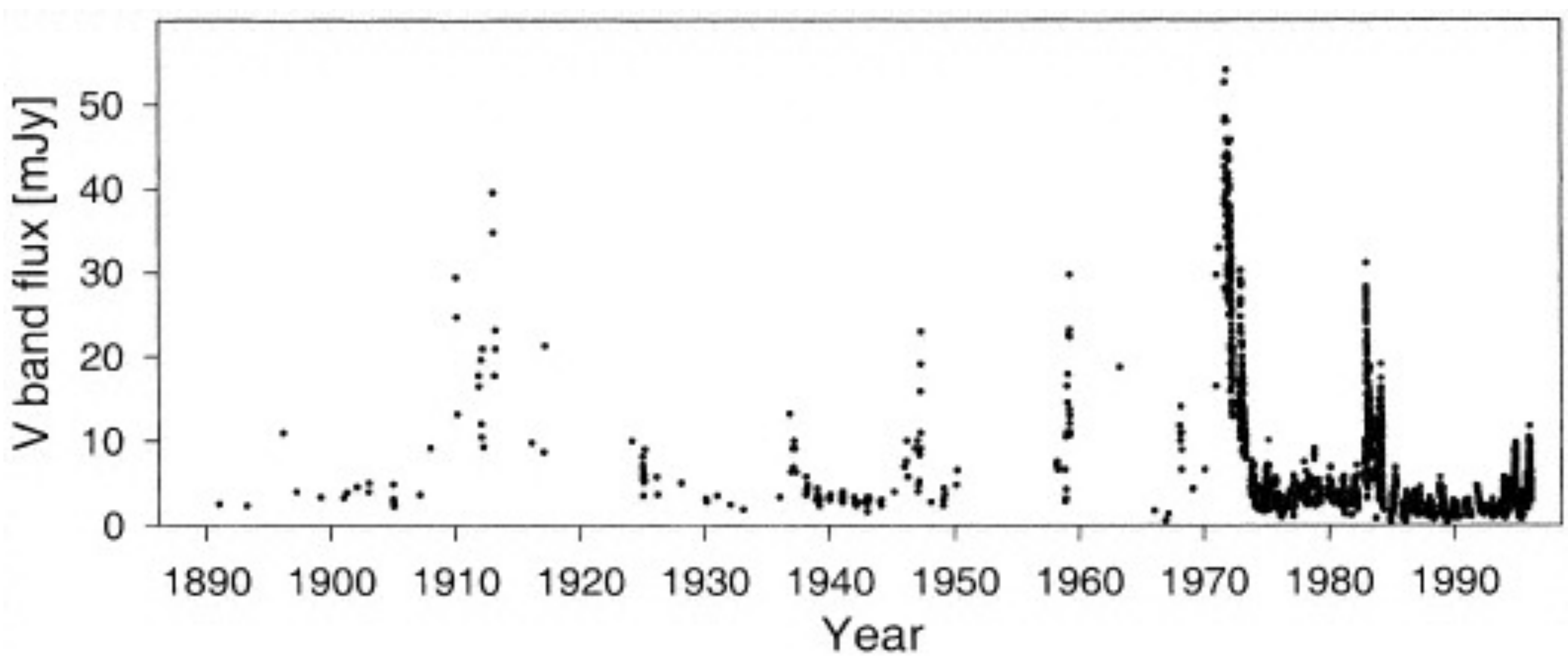
Quasi Periodic Behaviours

OJ287 Maxima every ~11.9 years

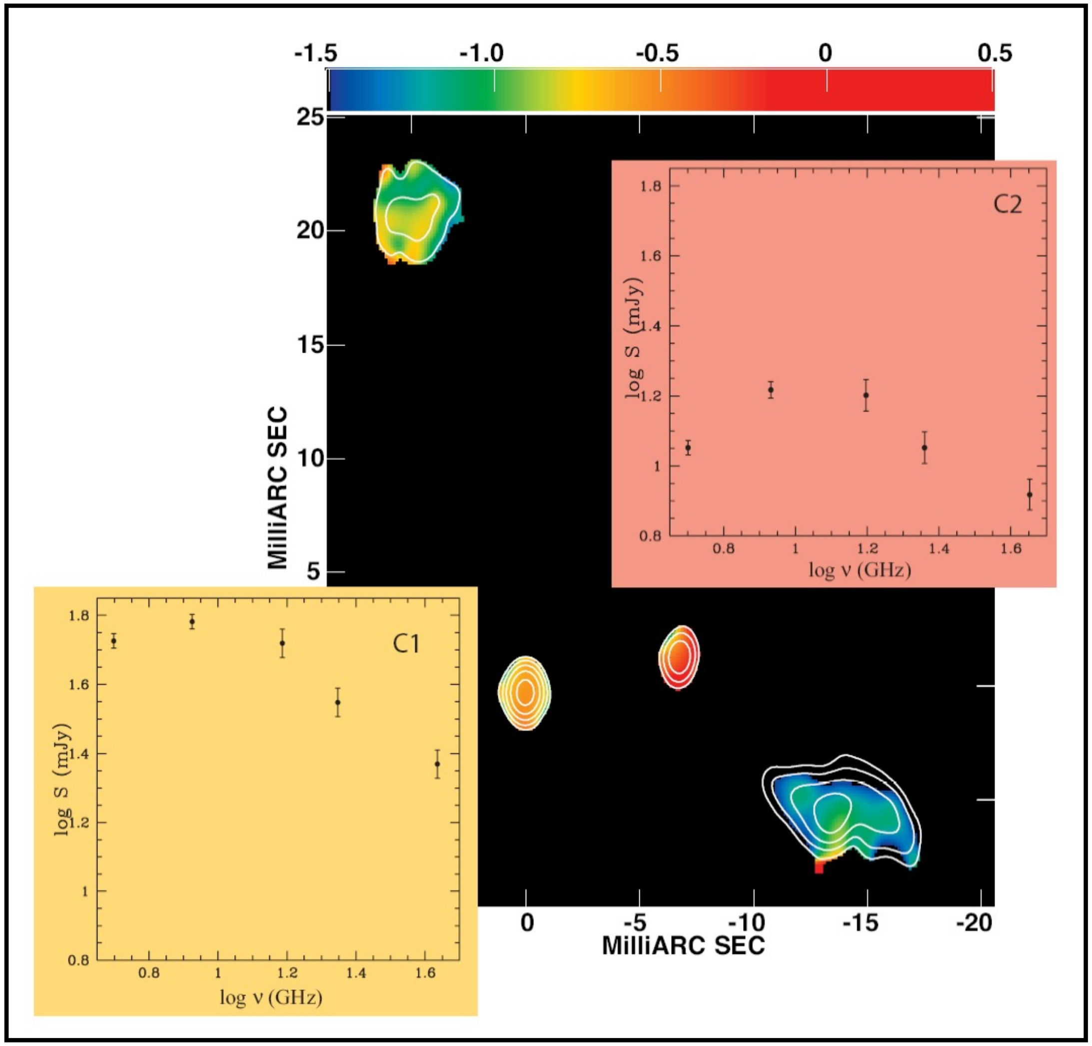
Similar behaviour seen sporadically in 3C273, 3C345, BL Lac, etc.



Valtaoja et al. 2000



Binary black hole in 0402+379 Radio Continuum Spectra



Spectral index distribution between 8 and 22 GHz from the 2005 VLBA observations.

In both hotspots of the source, N2 and S2, a steep spectrum was found.

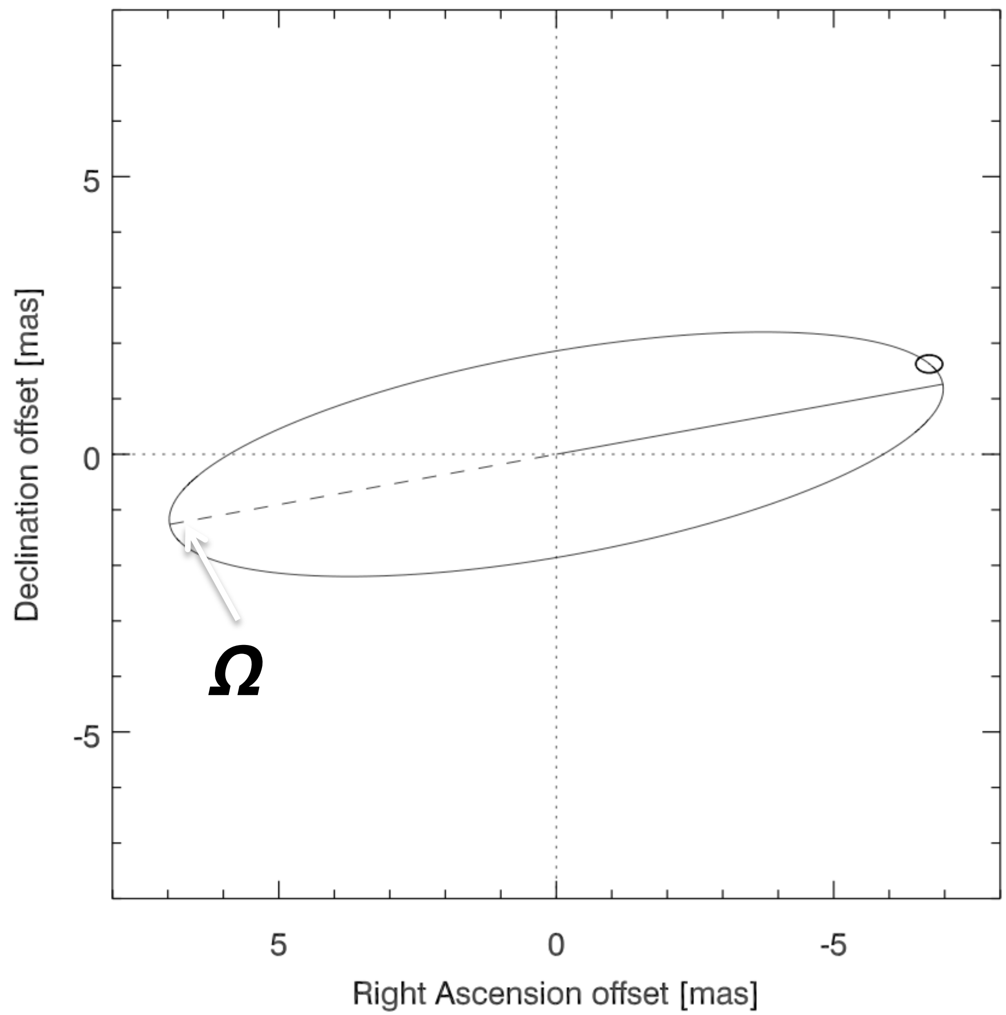
For both central components, C1 and C2, the spectrum peaks at ~10 GHz.

Circular orbit

- Small 7 pc separation and minimum energy leads to assumption of circular orbit
- Inclination *i* of 75° from HI absorption model
- Period *P* of 20,000 years from observed velocity of 0.007c.
- Initial guess of semi-major axis *a* = 6.9 mas from our astrometry, I guessed by eye the initial ascending node Ω and nodal passage epoch T_0.
- Perform fit for Ω and a T_0

Inclination = 75° circular orbit

a=7.08 ± 0.71 mas
e=0.0
i=75°
ω=0.0°
Ω=100.27° ± 2.71°
P=7,305,000 days
20,000 years
T_0 =2,194,481.1 (JD)
= 1296 AD Feb 29

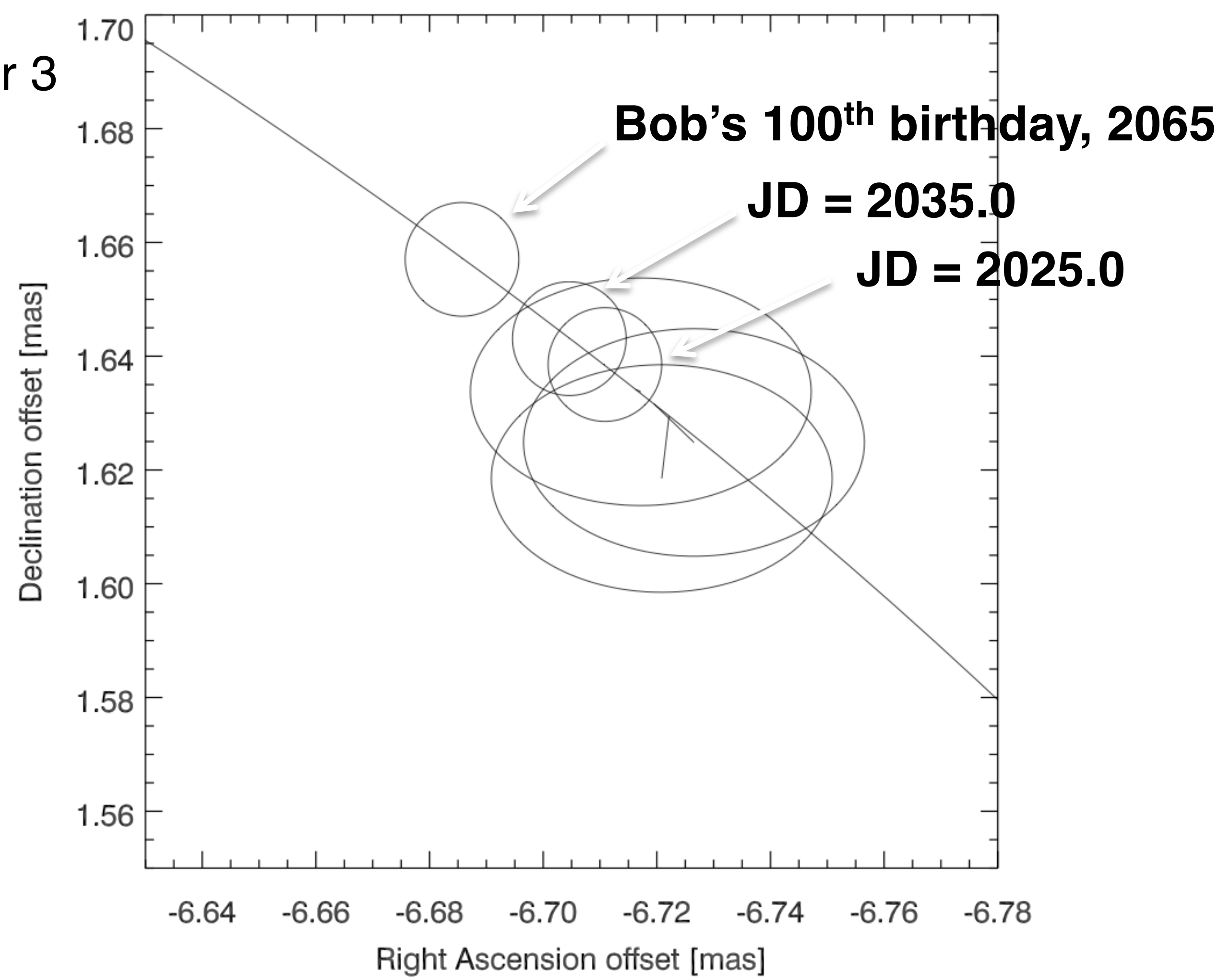


Our 3 observed points shown with 10x error ellipses for visibility

Close-up view, observed and predicted astrometry

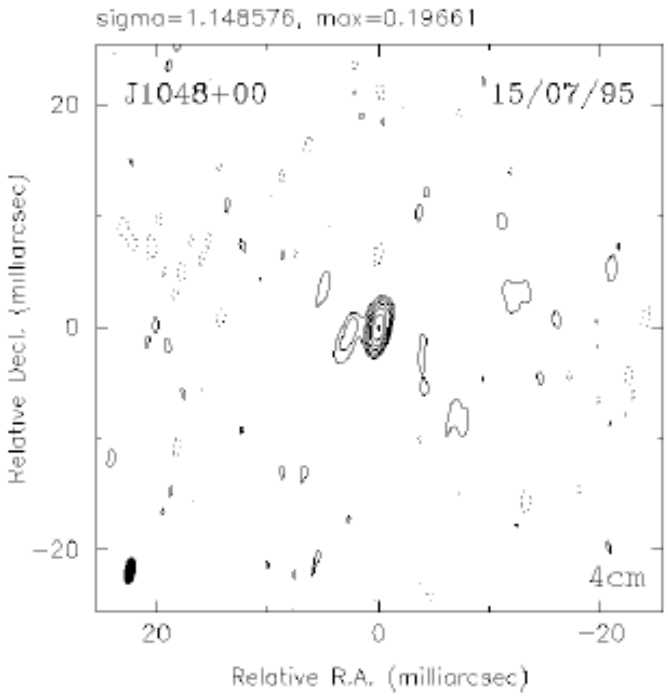
Large error ellipses are our 3 Observed 8 GHz points.

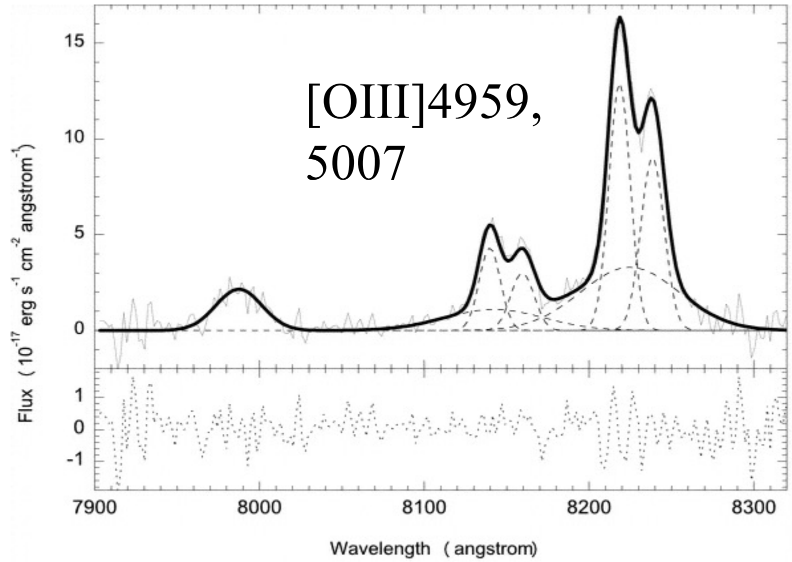
Small error circles are predicted future positions

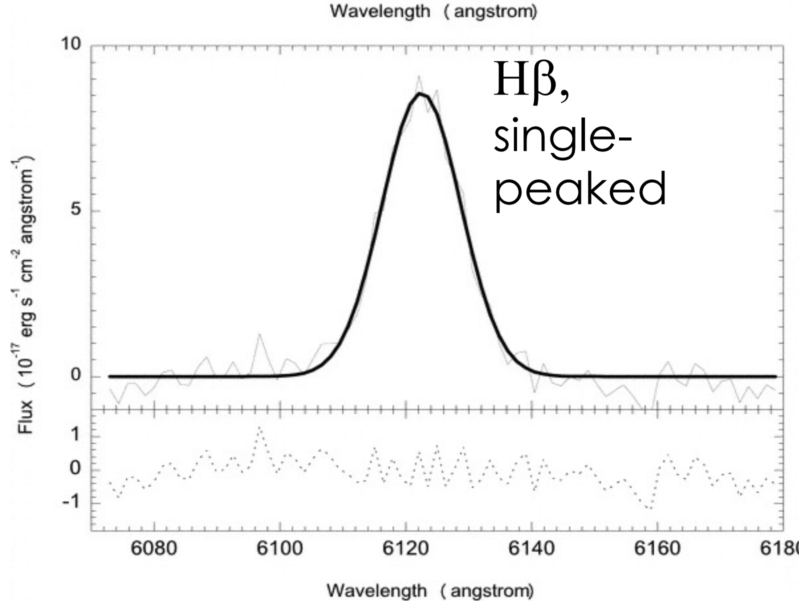


Double Peaked Narrow Lines

SDSSJ104807+005543







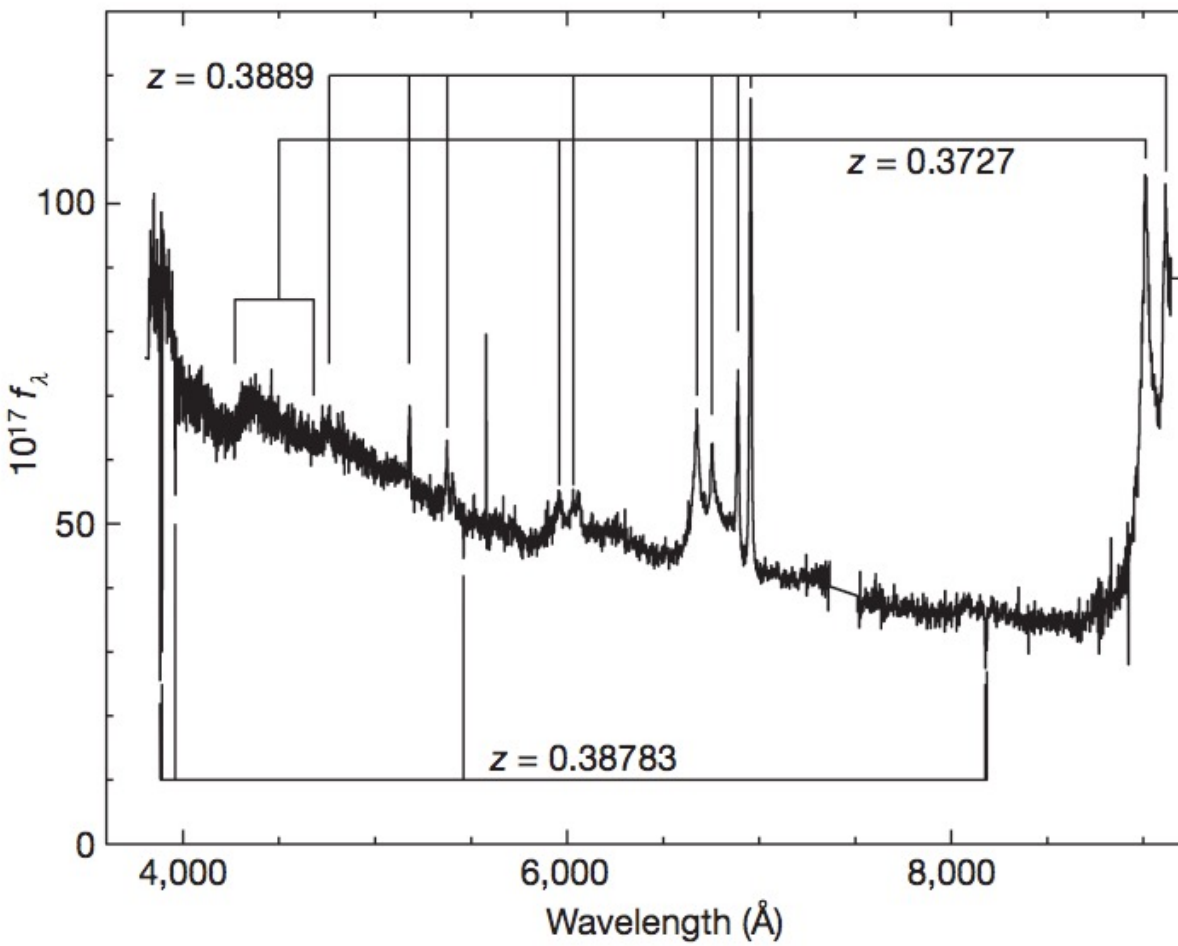
Alternatives: Disks, bipolar outflows

Zhou et al 2005

Double Peaked Broad Lines

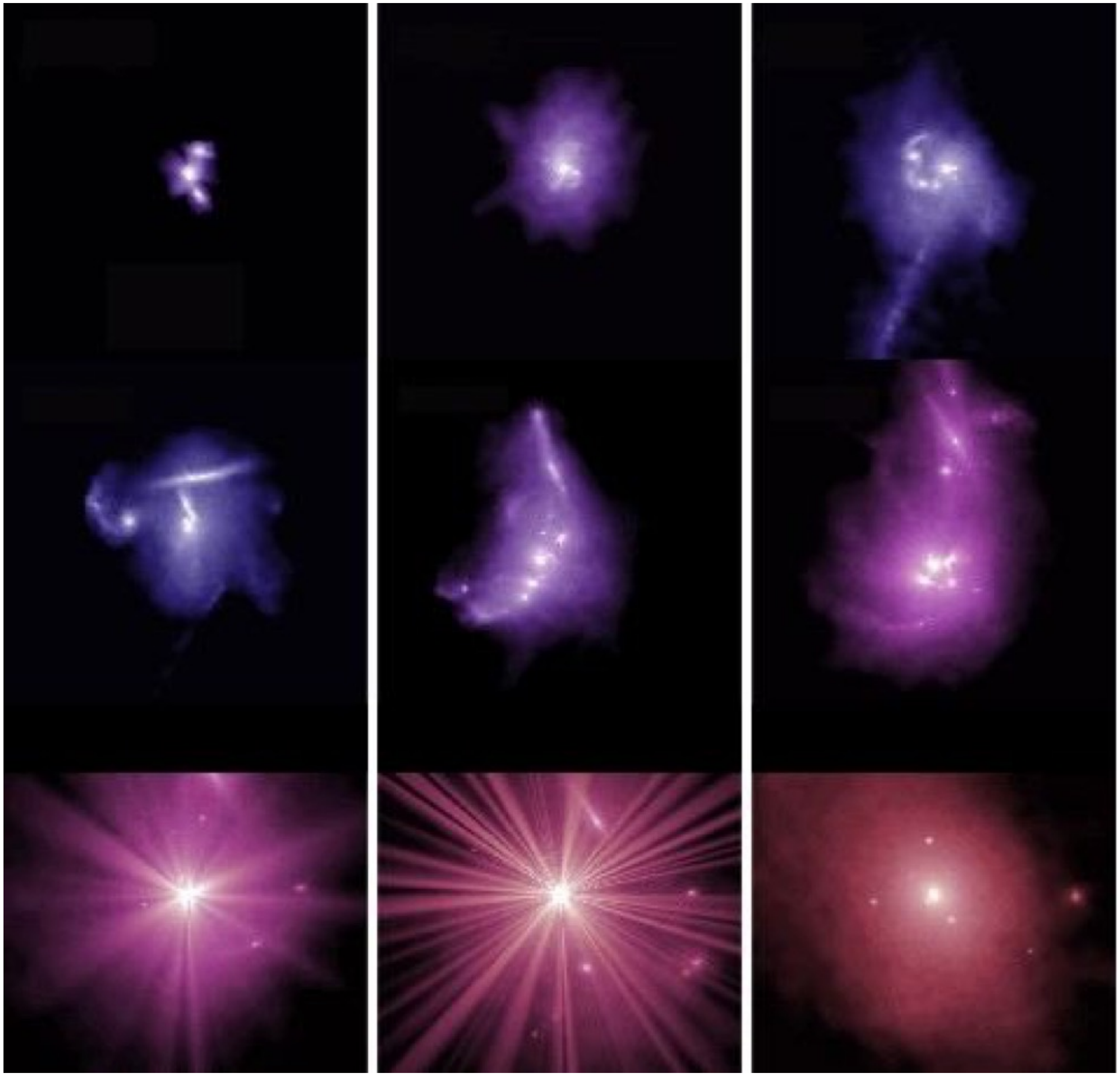
SDSSJ1536+0441

Boroson & Lauer 2009



Alternatives: Disks, bipolar outflows

Astronomy 537



Lecture 16: Galaxy Formation

Journal Class

- **Primordial rotating disk composed of at least 15 dense star-forming clumps at cosmic dawn**
- Fujimoto et al. 2025

Discussion leader: **Ella Hort**

Note: To encourage discussion everybody must pose at least one question during the group discussion

What about formation of ellipticals?

Old, single age stellar population, not rotationally supported.

- Complete star formation before disk could form?
  - does not agree so well with the hierarchical picture

- OR, only disk systems formed, E's made by mergers (recall Toomre sequence).
  - evidence for a small 'frosting' of younger stars
  - counter-rotating cores
  - Butcher-Oemler effect: more blue galaxies in high redshift clusters than in low redshift clusters
  - Morphology-density relation: more blue galaxies in the field, more red galaxies in cluster cores

Effects of the Environment on Galaxy Type

- Spirals are generally found in galaxy groups
- Ellipticals are more prevalent in rich clusters
- cD galaxies are only found at the center of rich clusters

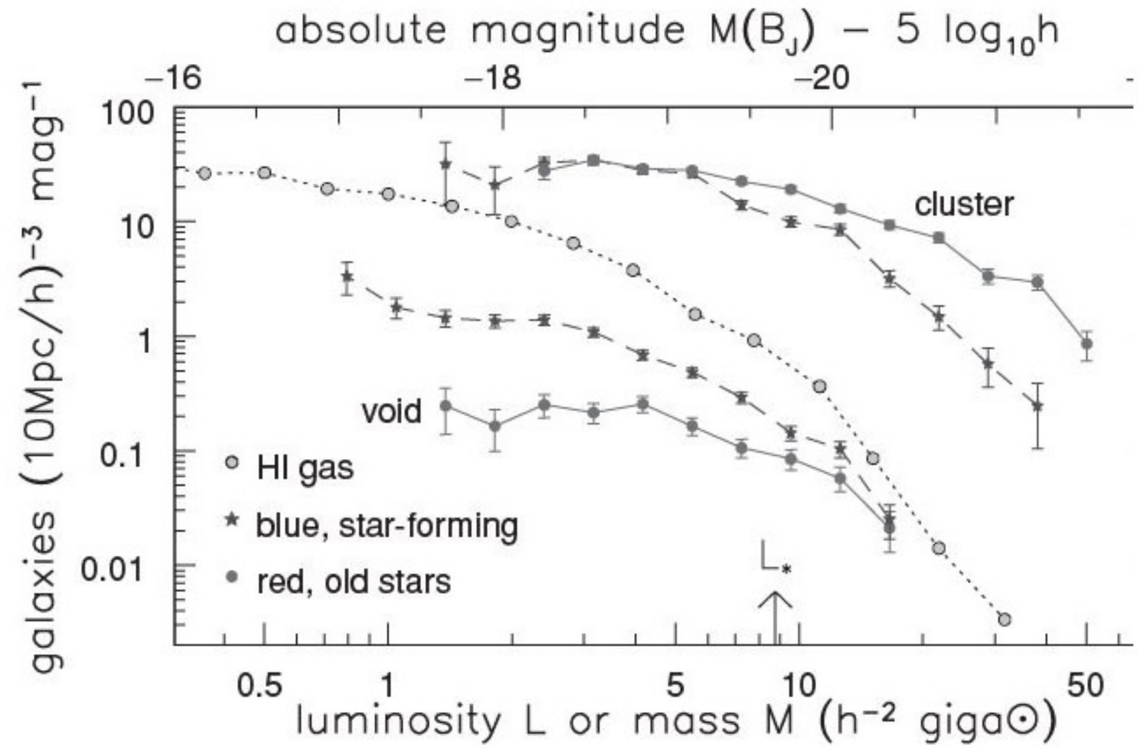
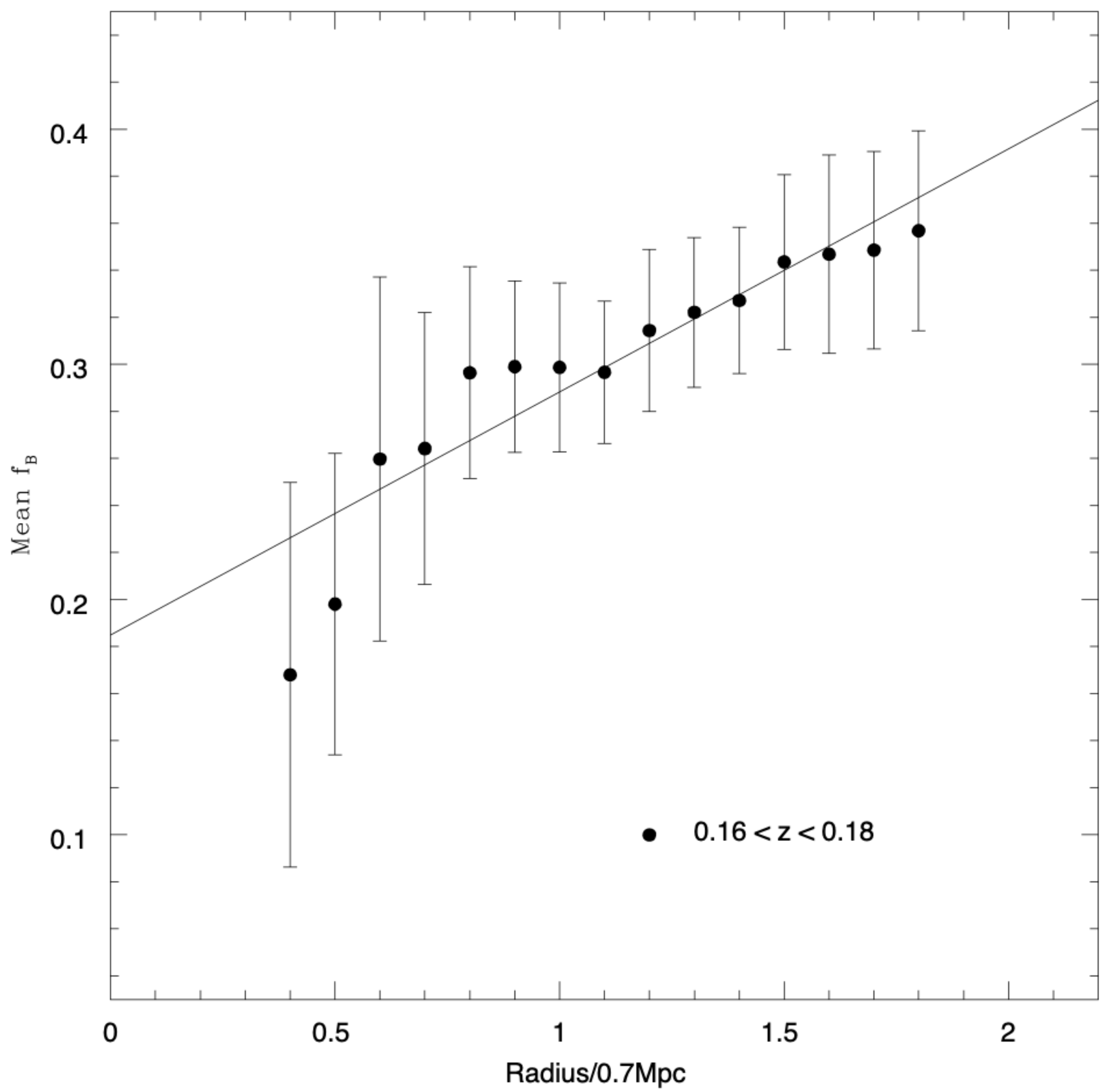


Fig. 7.11. Luminosity functions of blue star-forming galaxies (stars) and red galaxies (filled dots). Bright red galaxies predominate in clusters, but dim blue galaxies are more frequent in the low-density field or void regions. Clouds of neutral hydrogen, found in low-density regions, resemble blue galaxies in that small systems are far more common than big ones – D. Croton, 2dF survey; M. Zwaan, HIPASS.

Morphology – Density relation (Dressler 1980)

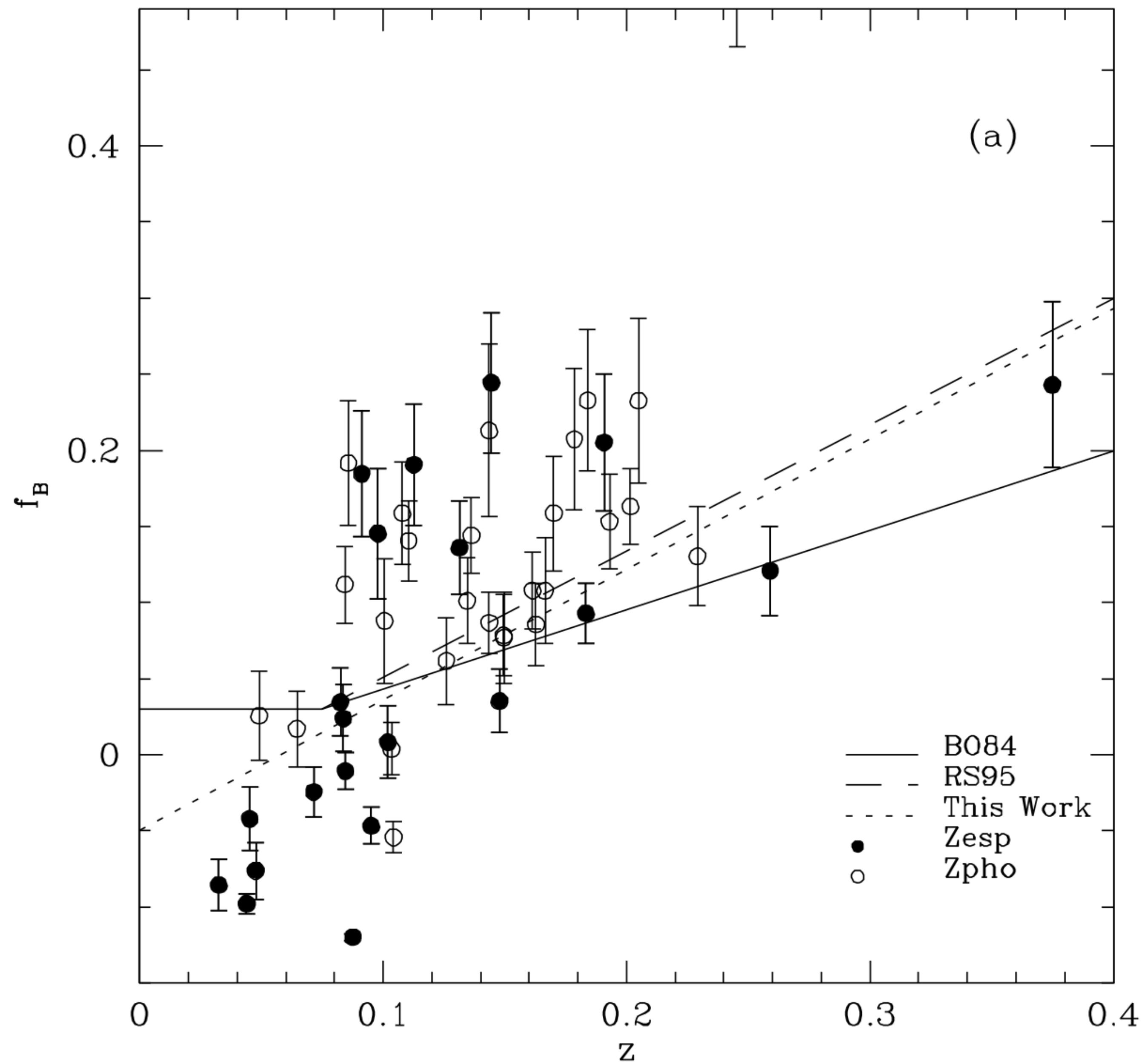


Margoniner & De Carvalho 2000

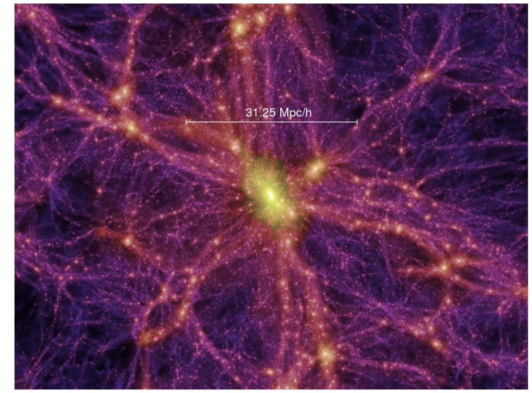
FIG. 5.—Dependence of the fraction of blue galaxies on the physical region of a cluster.

Butcher – Oemler effect

Blue fraction in central 0.7 Mpc of cluster



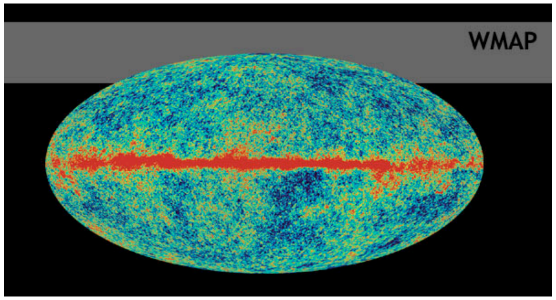
Margoniner & De Carvalho 2000



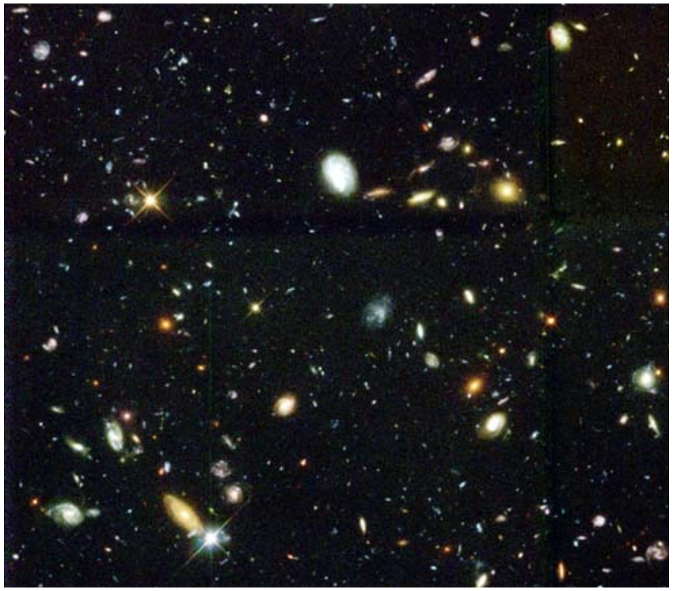
Progress in the last 10-20 years

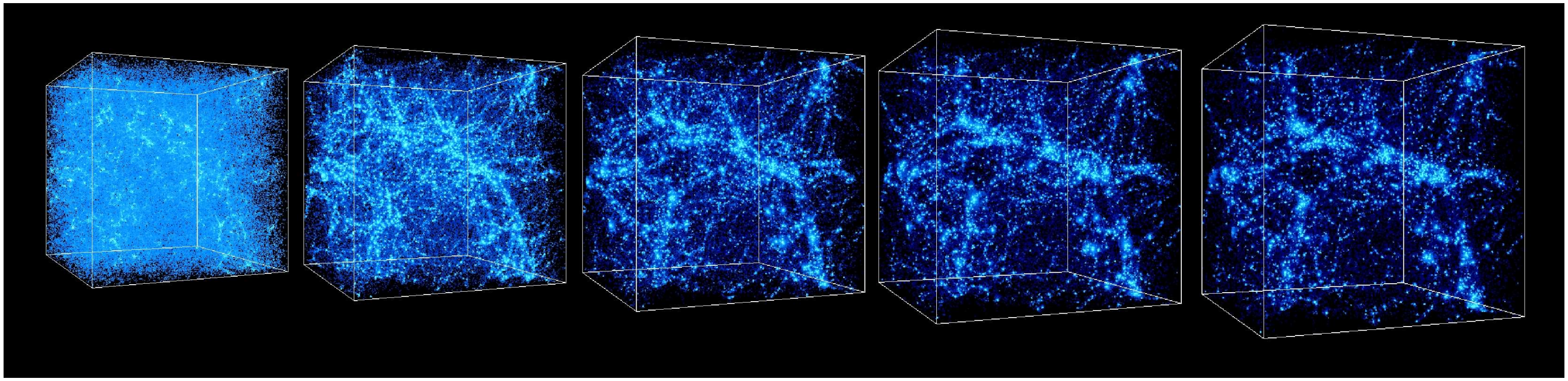
- ΛCDM paradigm shown to be consistent with broad range of observations (CMB, Ly-α forest, weak lensing, galaxy clustering, galaxy clusters)
- galaxy surveys:
  - large homogeneous samples at low z
  - huge progress in discovering & cataloging high-z galaxies
  - build-up of panchromatic view of the Universe
- development of detailed simulations of dark matter and (to some extent) gas processes
- developments of (not totally im-)plausible picture for galaxy formation within this framework

Putting it all together

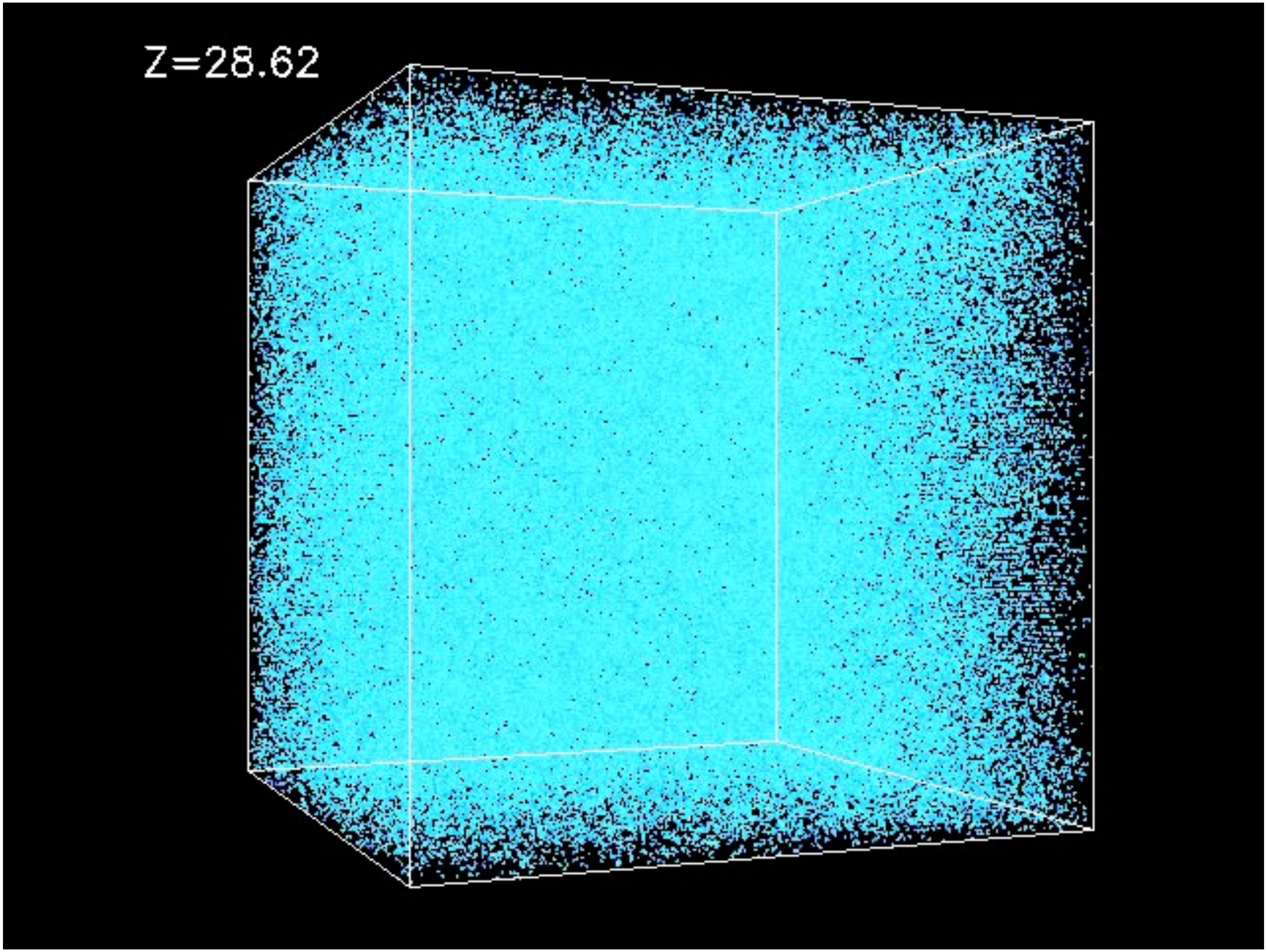


Numerical simulations are used to trace the gravitational collapse of matter (dark+luminous) across cosmic time

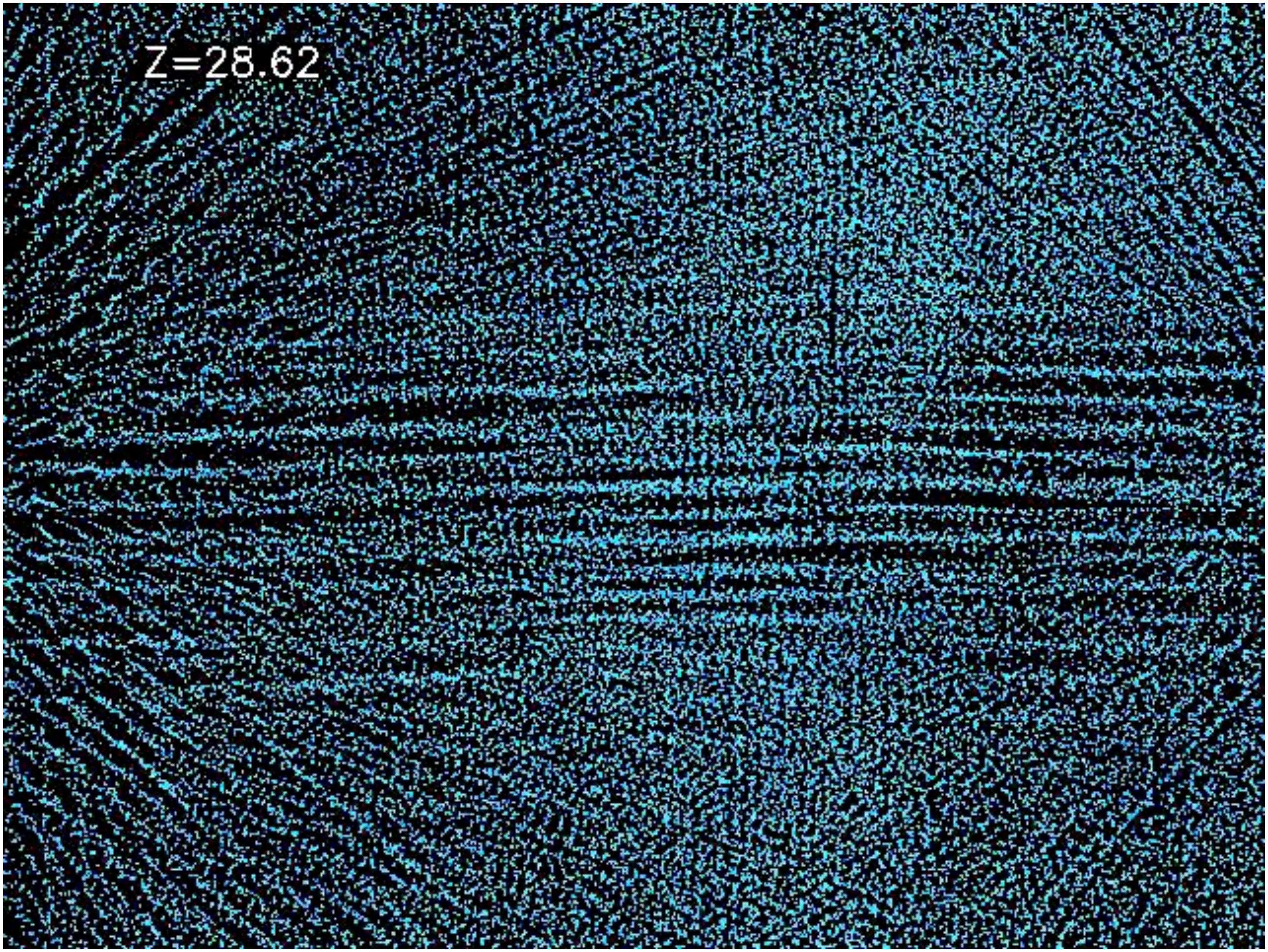




Simulating the Universe



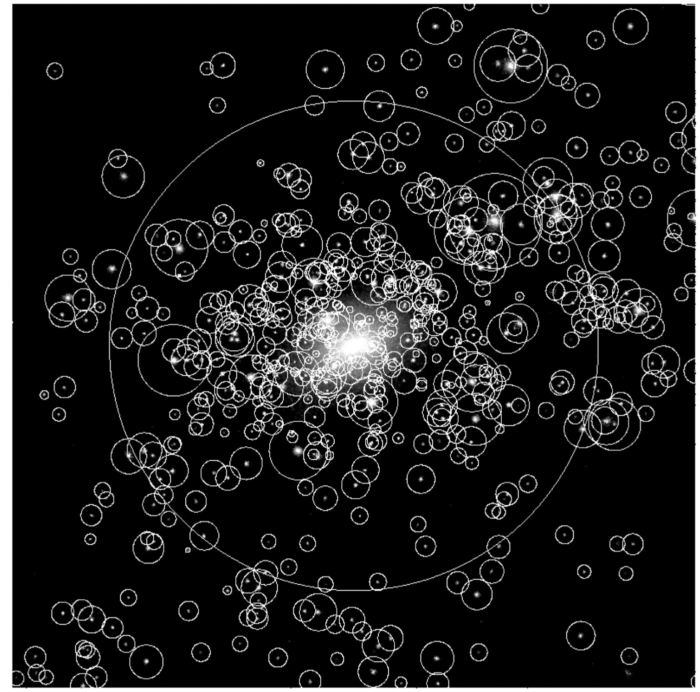
Growth of structure - The Cosmic Web



The "Missing Satellite Problem"

- Models/simulations predict large numbers of satellites => Logarithmic slope of the faint end of the CDM mass function ~ -1.8 (Press-Schechter value)
  - Kauffmann *et al.* (1993)
  - Klypin *et al.* (1999)

- But the current census does not count them (light not mass):
  - Faint end slope of the optical LF
  - Faint end slope of the HIMF



The HI Mass Function

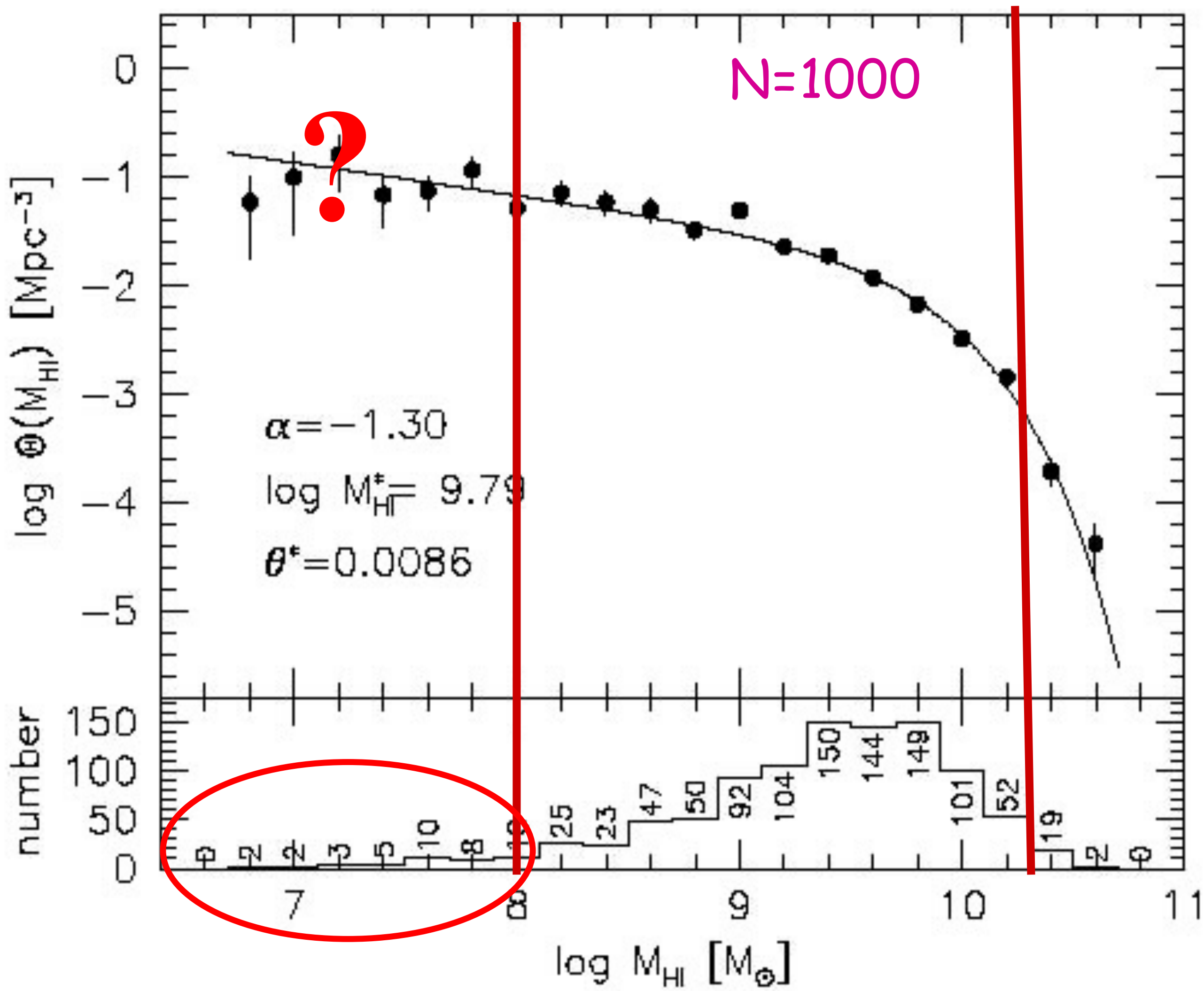
- Previous surveys have included few (if any) objects with HI masses less than 10^8 $M_\odot$.
- At lowest masses, differ by 10X:

Rosenberg & Schneider (2000)

versus

Zwaan et al. (1997)

- Statistics
- Systematics



Parkes HIPASS survey:
Zwaan et al. 2003

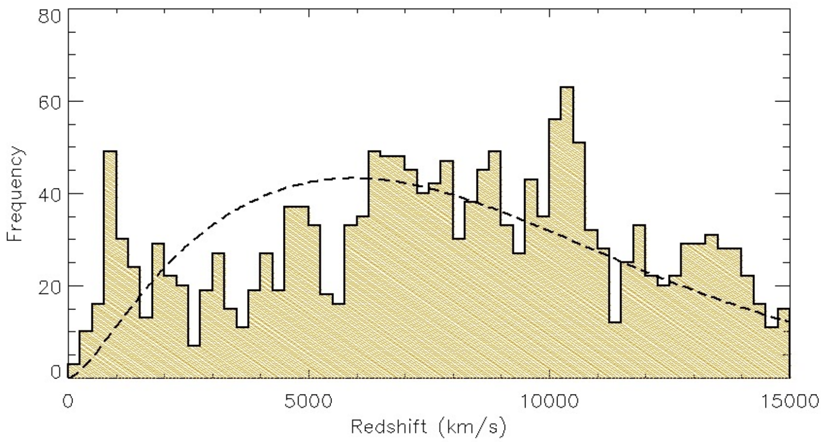
HIMF @ z=0 Challenges

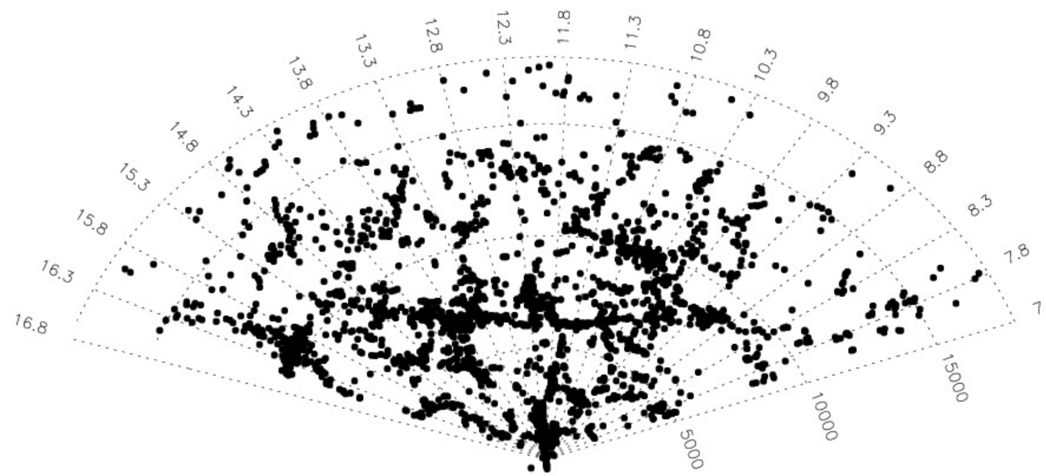
- Need better statistics: larger, more sensitive surveys
- At the faint end, all the galaxies are nearby
  - Redshift distances are highly unreliable
  - Large Scale Structure affects accuracy of flow models
    Masters, H & G 2004, ApJ 607 L115
- Need a "fair sample" to overcome (and allow study of) cosmic variance
  - $\Sigma(1/V_{max})$ corrections must account for Large Scale Structure
    - Not just that space density varies with distance
    - Fractional volume of space occupied by regions of a particular density do too

    Springob, H & G 2005, ApJ 621, 215

Cosmic variance

Must sample enough volume to acquire a "fair sample"





If we covered a similar slice in the opposite part of the sky (coming....) we would see a very DIFFERENT redshift distribution

At these distances, 540 square degrees is not enough.

Environment & the HIMF

Previous studies based only on Virgo have suggested that the HIMF in Virgo is flatter than in the field

- Only a single cluster
- Very small number statistics/systematics vs comparison
- Is this just HI deficiency?
- Watch out for morphological biases

Inconsistency: Symptom of inadequate volume?

Kovač, Oosterloo & van der Hulst (2005): CanVen

- Similar to Virgo (low mass slow flatter)

BUT........

Zwaan et al. (2005): HIPASS

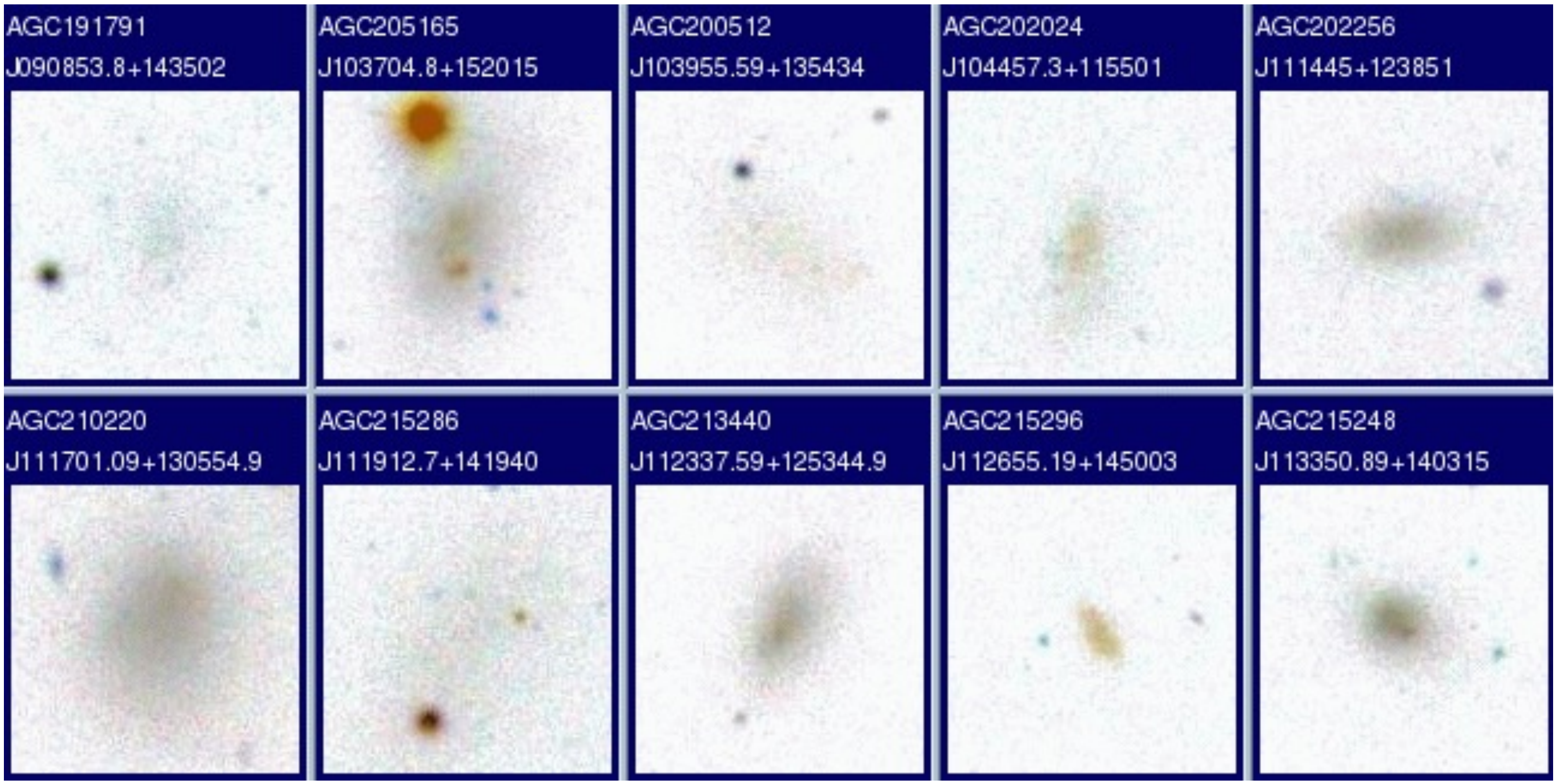
- Higher density regions => more low masses

HI and the "missing satellite" problem

- HIPASS result: no cosmologically significant population of HI-rich dark galaxies: ALFALFA agrees... but HIPASS $M_{HI} > 10^8\ M_{\odot}$
- Future studies will focus on extending
  Deeper in HI Mass than ALFALFA in Local Supercluster

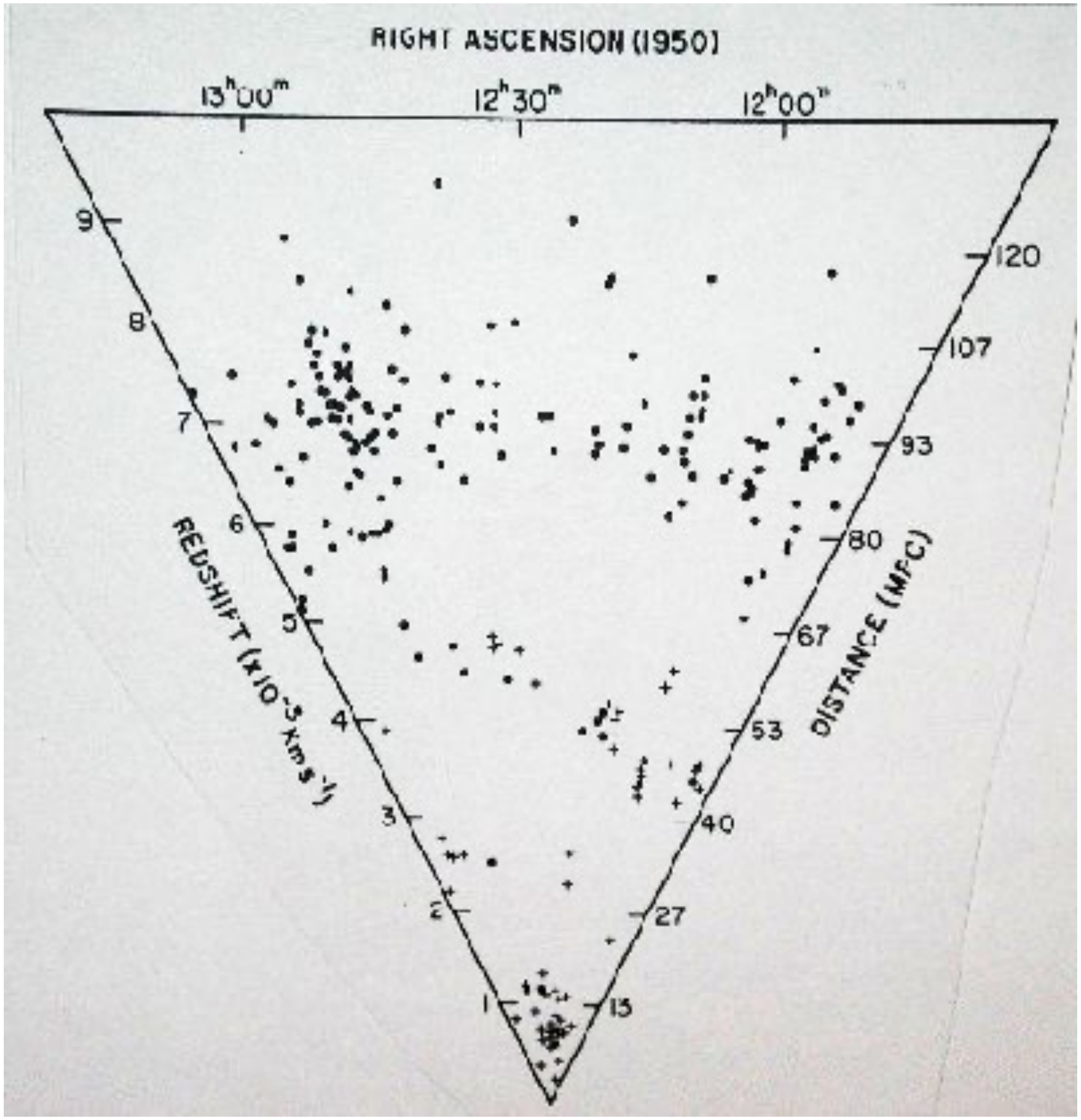
Lowest HI mass objects

log M_{HI} < 7.2



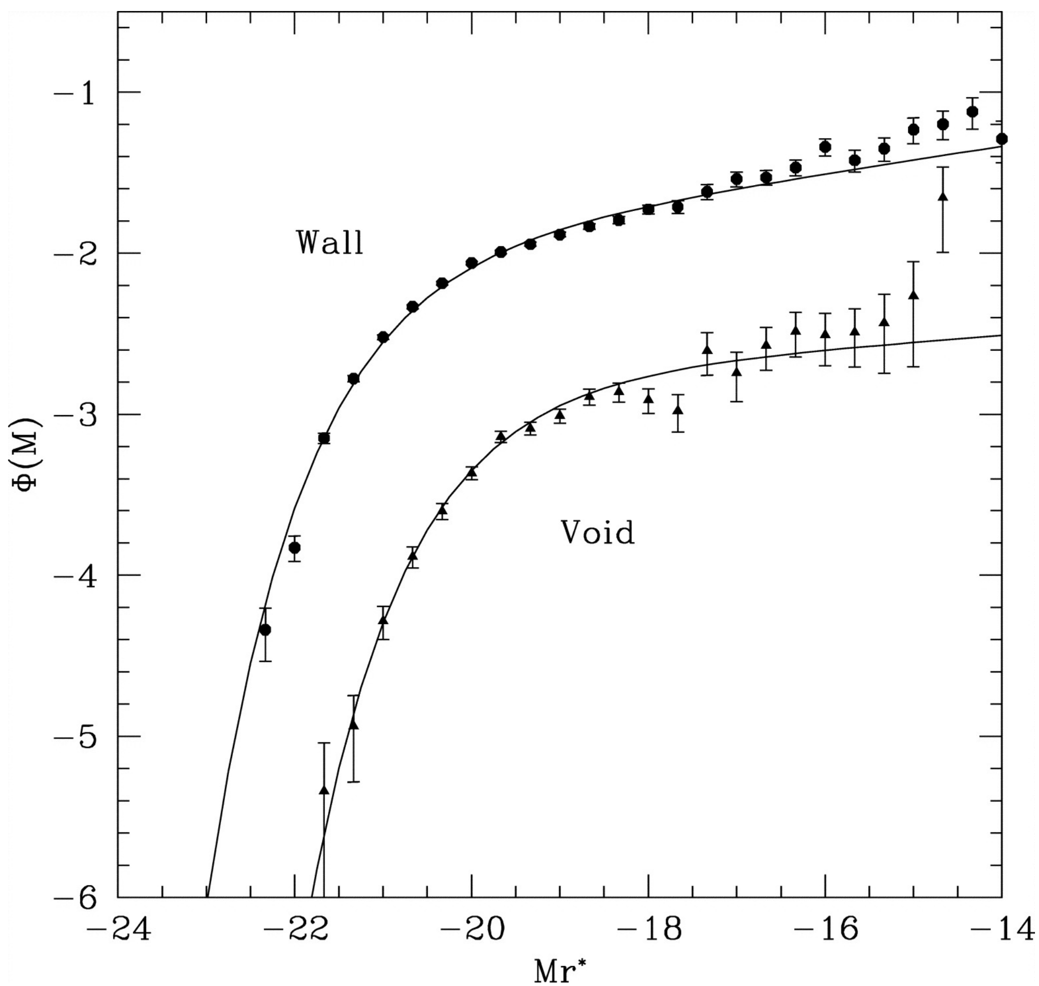
ALFALFA has already detected more objects with log M_{HI} < 7.5 than all other previous blind HI surveys combined

Voids and Superclusters



Gregory & Thompson (1978)

Luminosity function of void galaxies



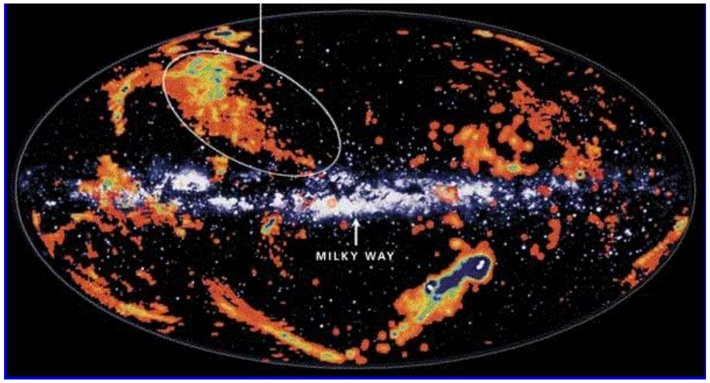
Void LF has a faint M* but a similar faint-end slope, compared to the overall LF

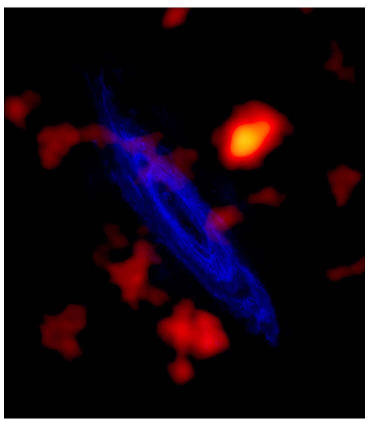
Void galaxies are blue, disk-like and have high Hα equivalent width => good HI targets

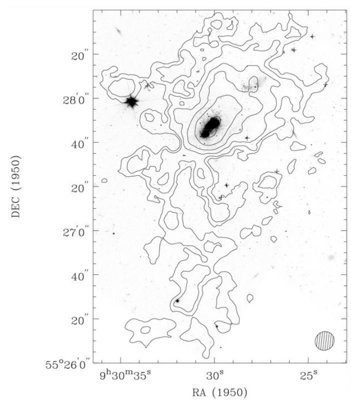
Void galaxies in the SDSS:
Hoyle et al (2005)

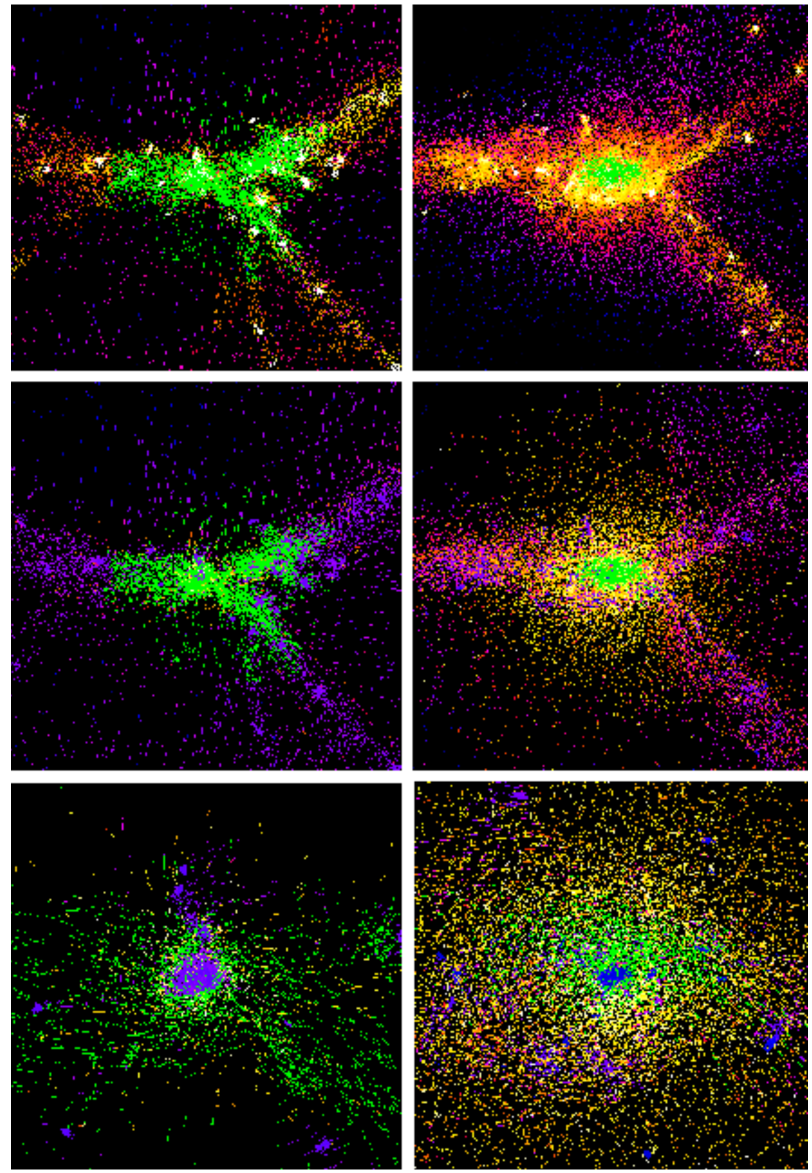
1000 galaxies in lowest density cells of total 155,000 galaxies (SDSS 2005)

How and when do galaxies acquire their gas?



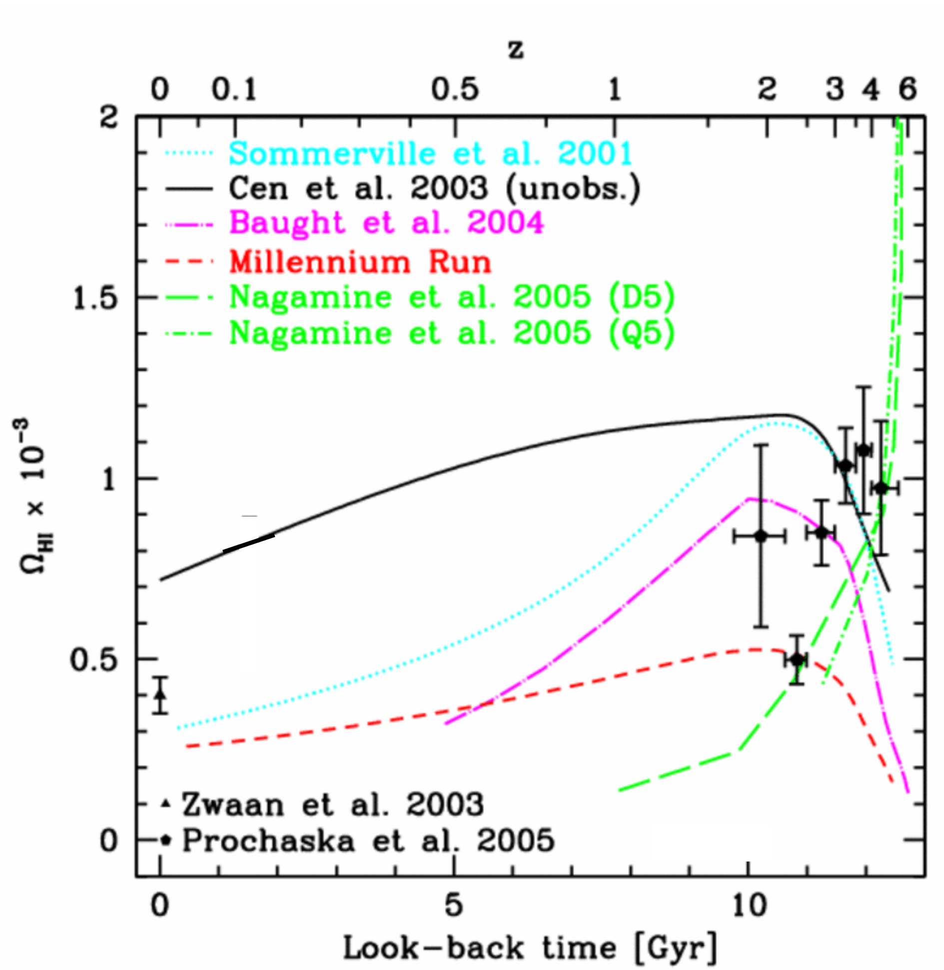


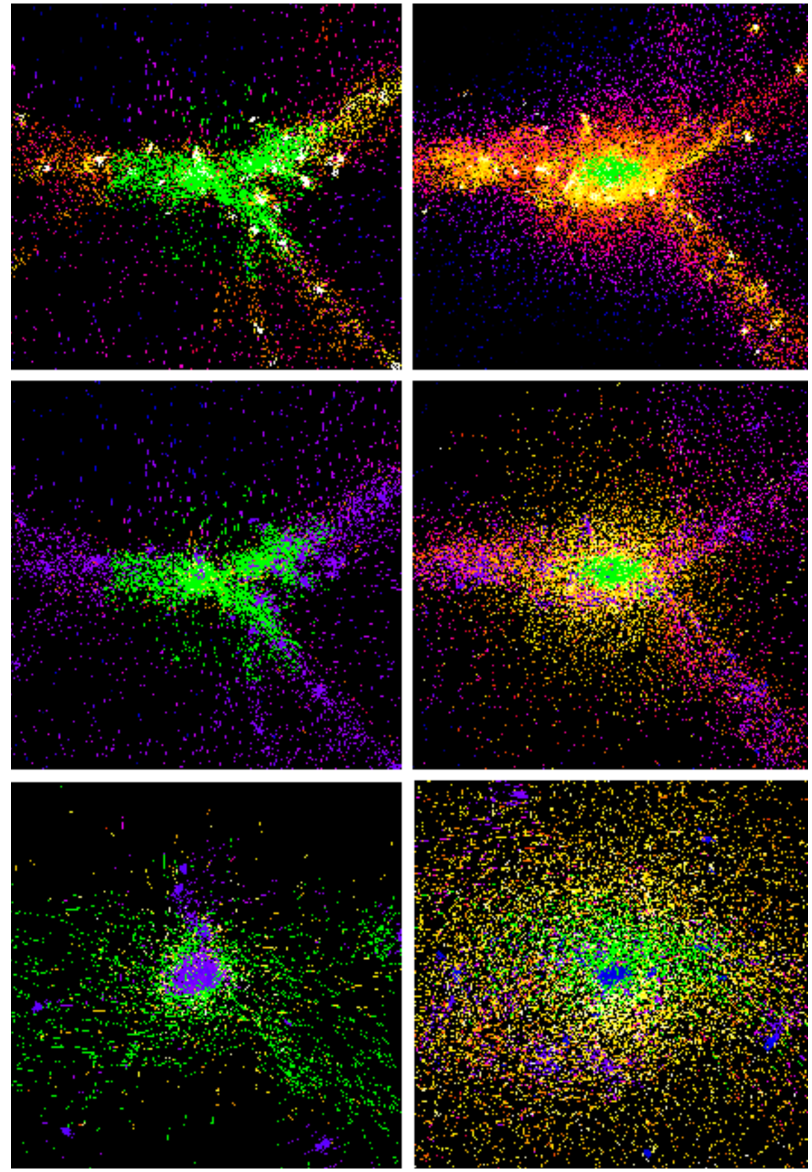




Kereš *et al.* (2005)

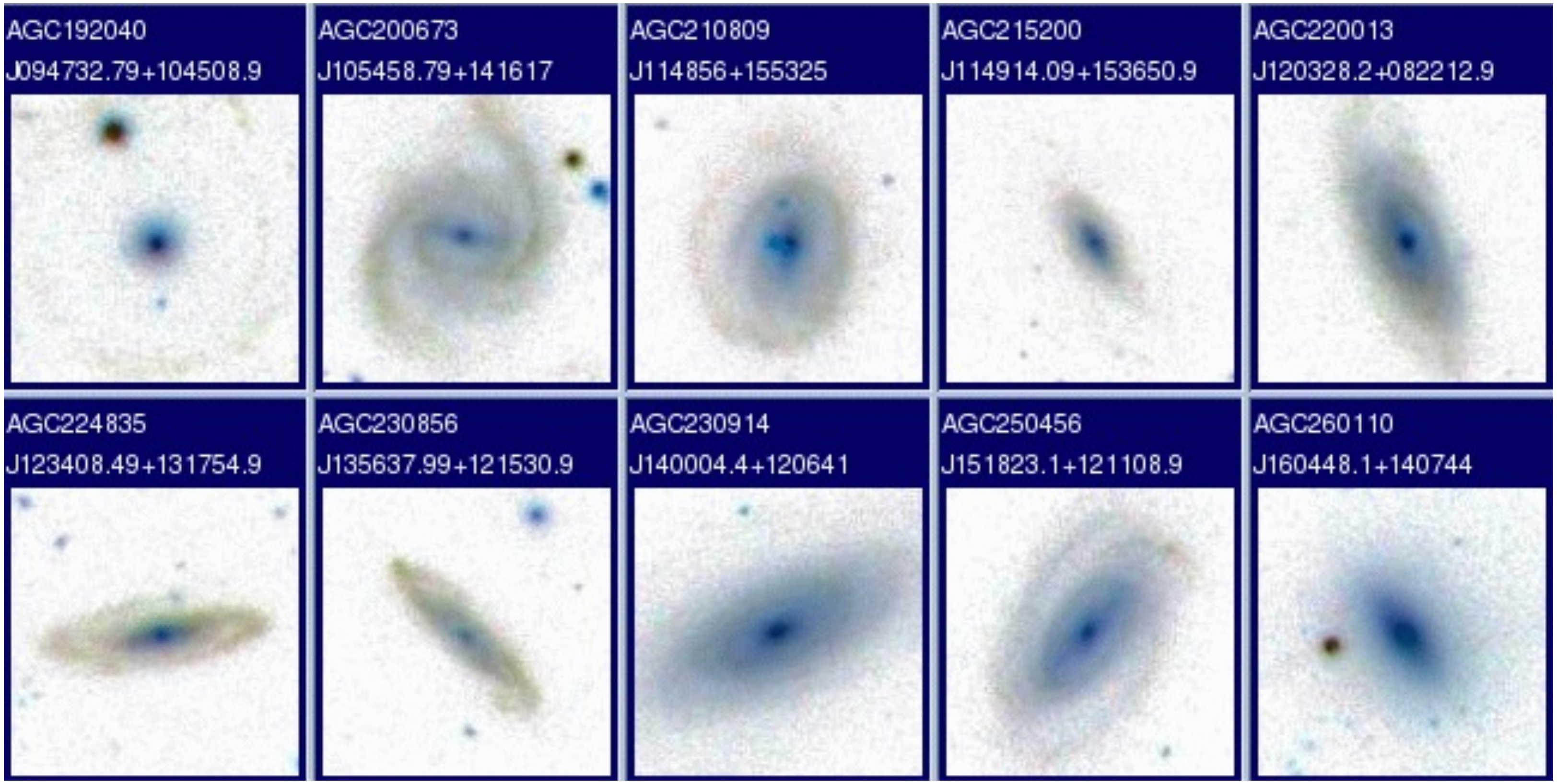
How and when do galaxies acquire their gas?





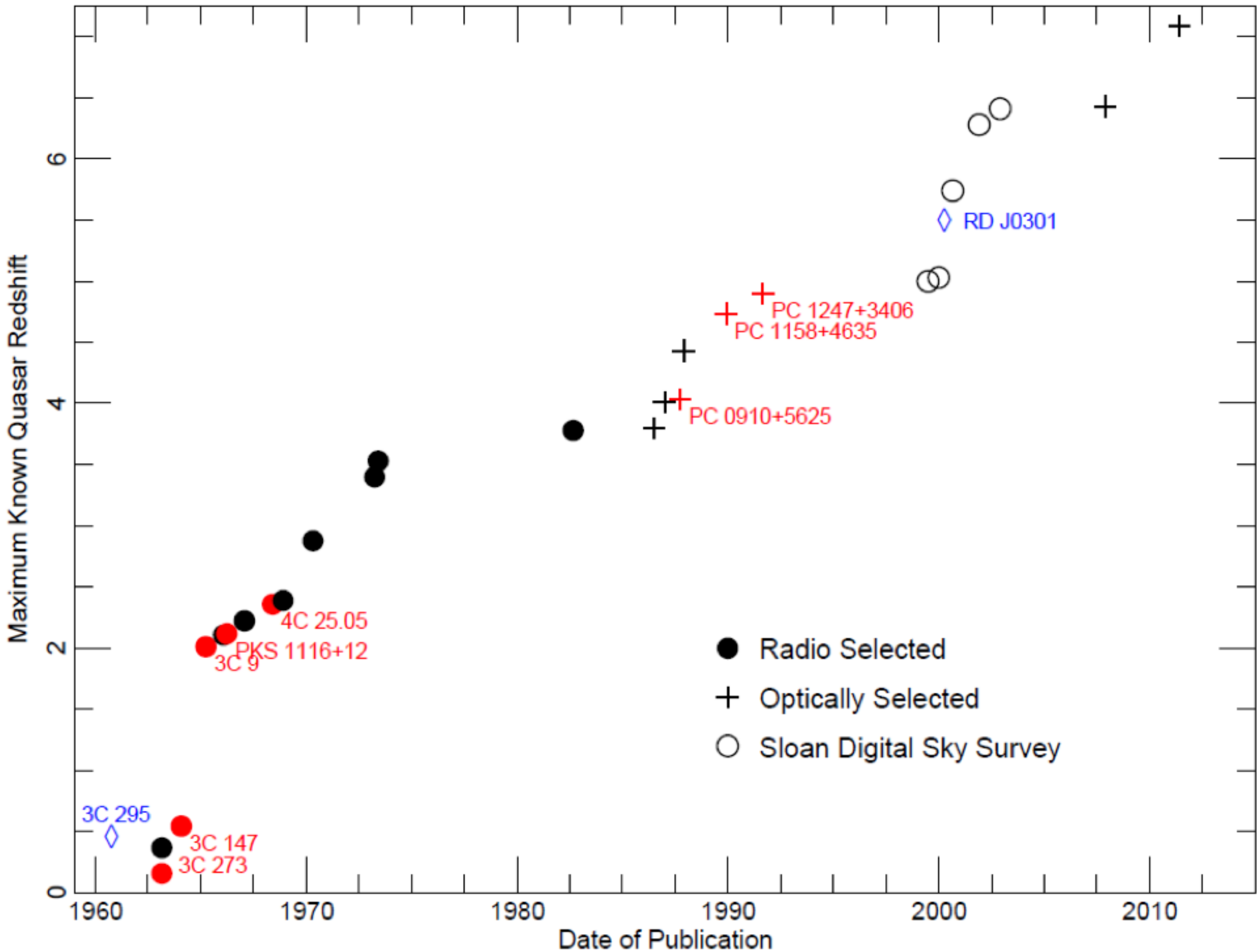
Kereš *et al.* (2005)

Highest mass objects: Challenge for SKA

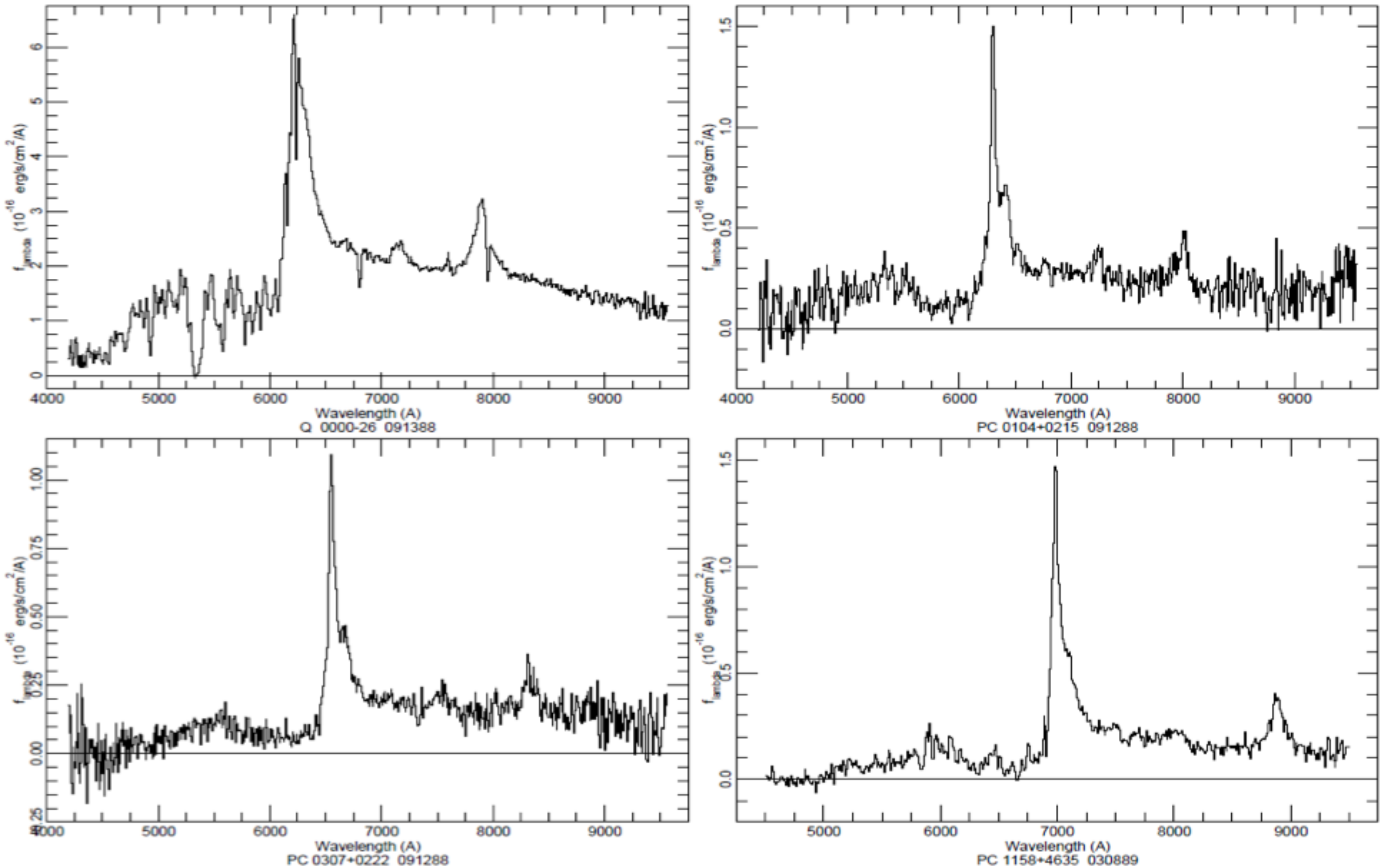


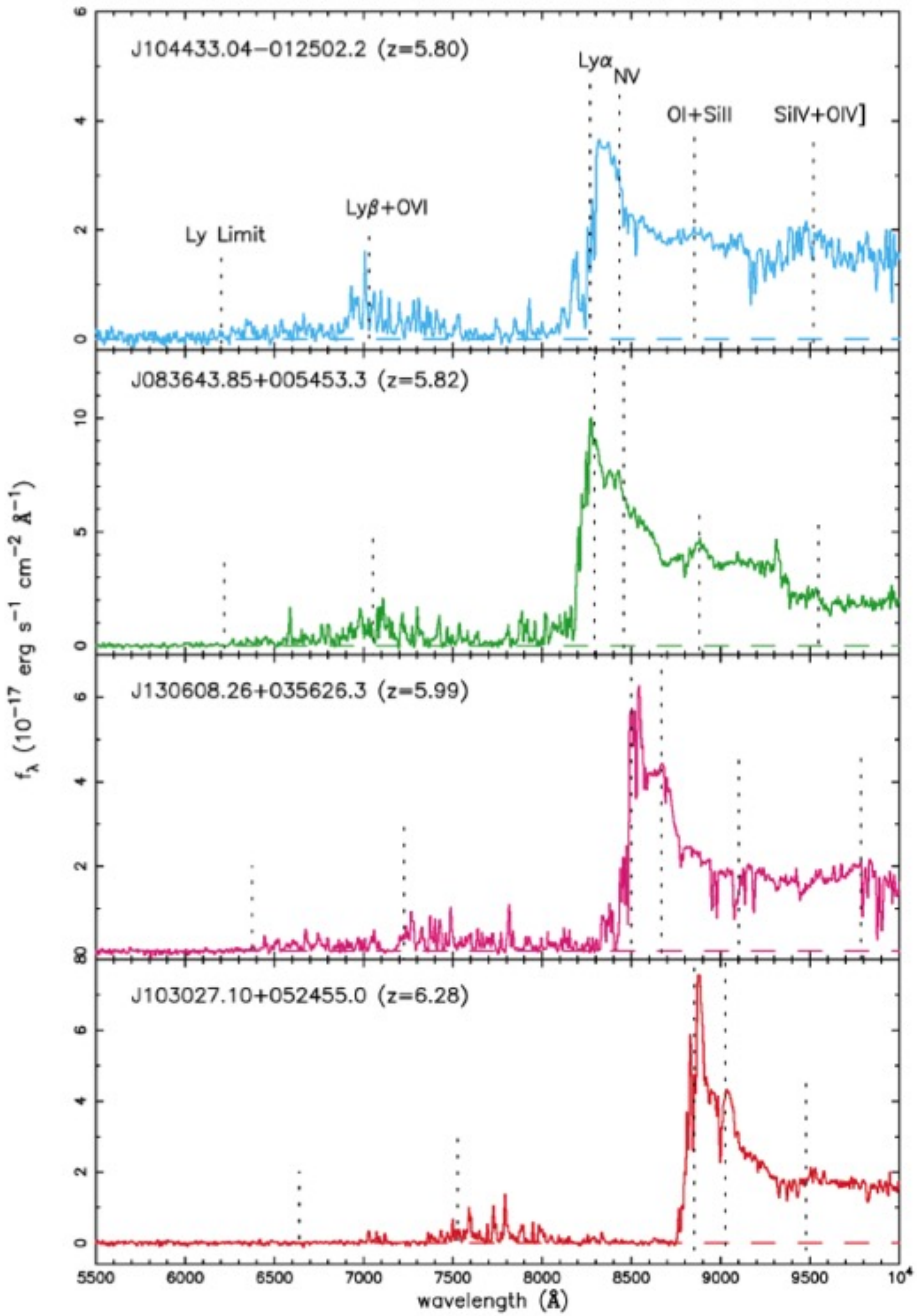
ALFALFA has already detected more than twice as many objects with log M_{HI} > 10.4 than all other previous blind HI surveys combined

High Redshift Quasars



Indications of rapid increase of H I Opacity at z ~ 4

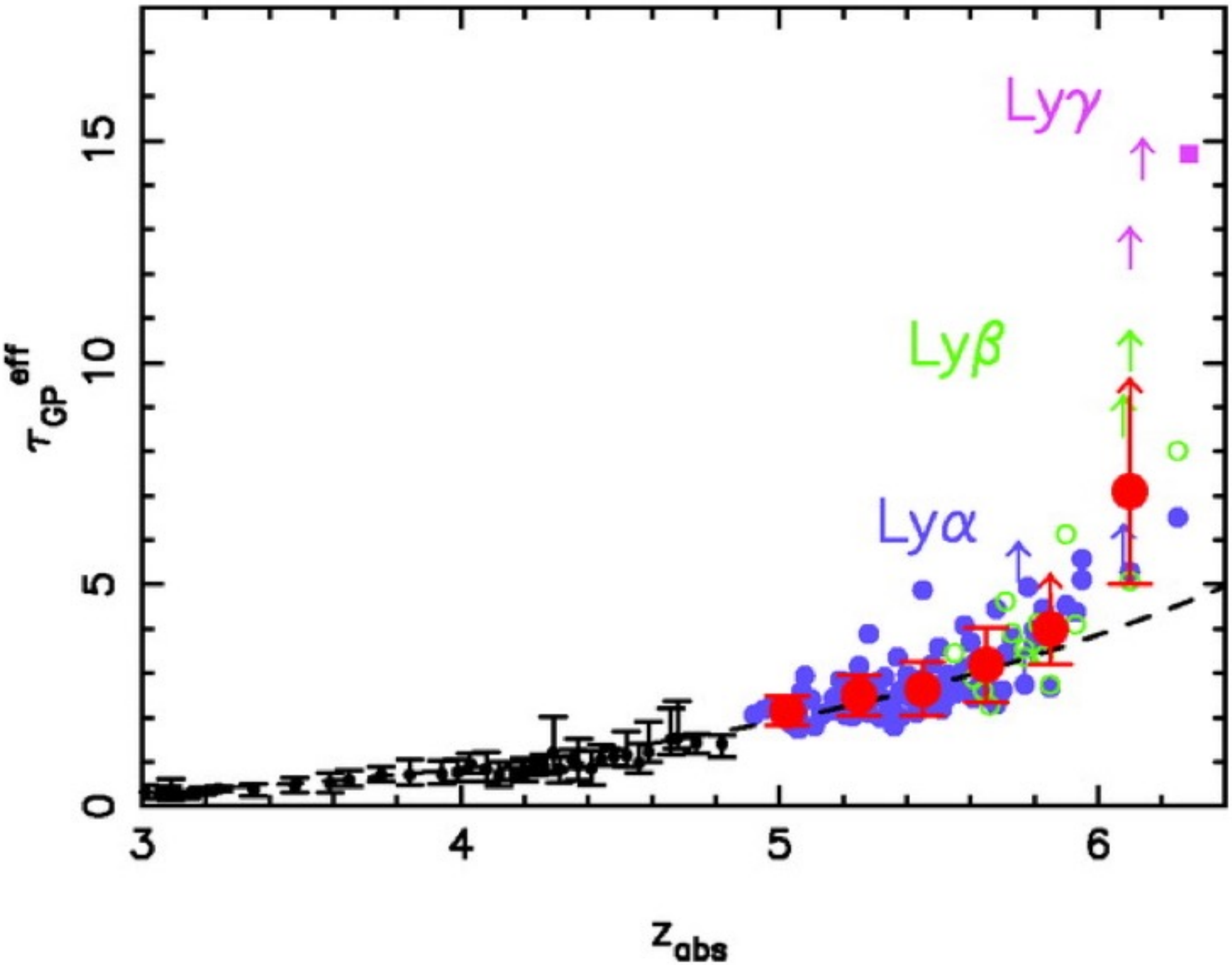




Detection of Gunn-Peterson Troughs in z ~ 6 Quasars in 2001

Becker et al (2001)

Rapid increase in H I Opacity at z ~ 6



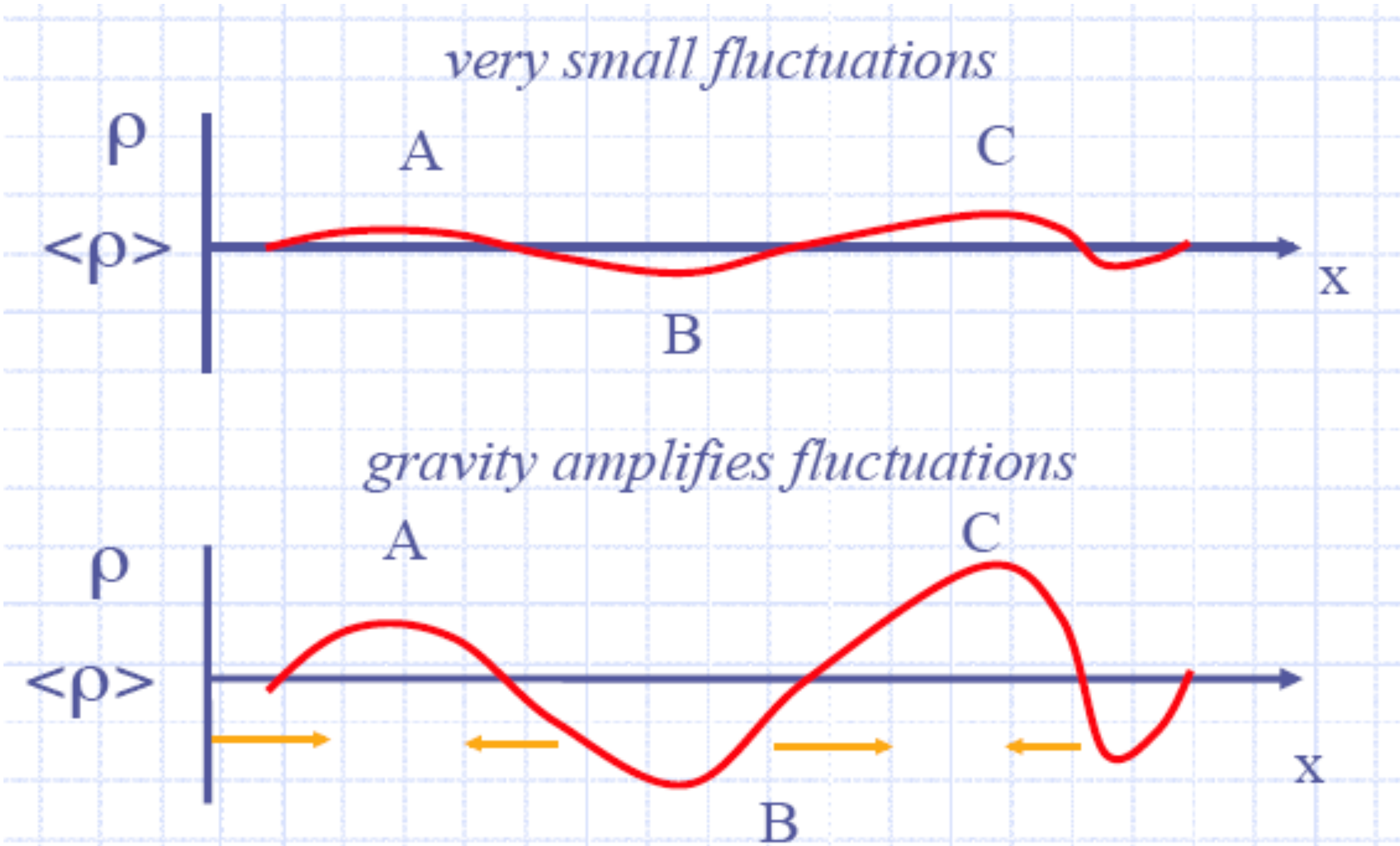
Fan et al (2006)

Structure formation - the big picture

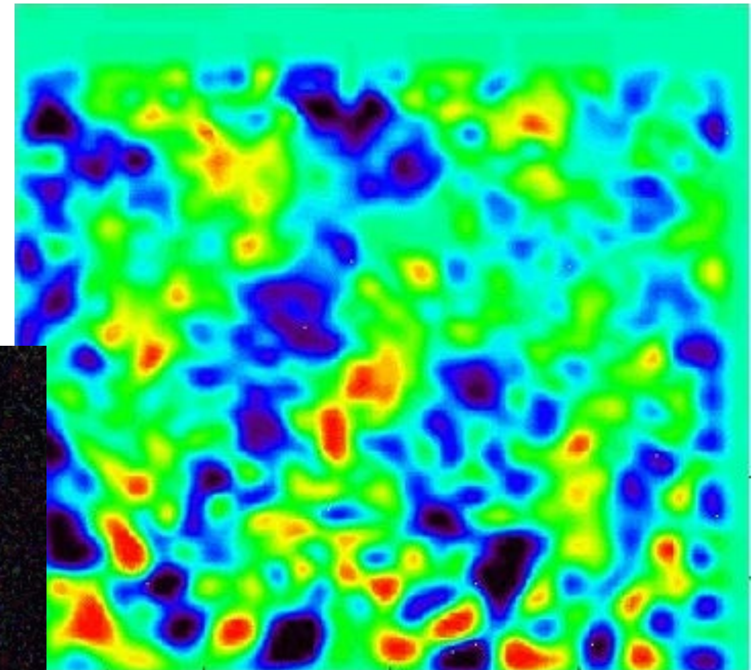
Structure formation is theory of transition from a very homogeneous state in the early universe, as reflected in the CMB, to the structure of galaxies and clusters we observe today.

- Quantum fluctuations from inflationary era were 'stretched' to cosmic scales
- Density fluctuations frozen in until matter-radiation equality
- Density fluctuations grow during matter-dominated era (>10,000 yr ABB) due to gravitational instability
- Astronomical structures form when fluctuation amplitude becomes large

Gravitational instability



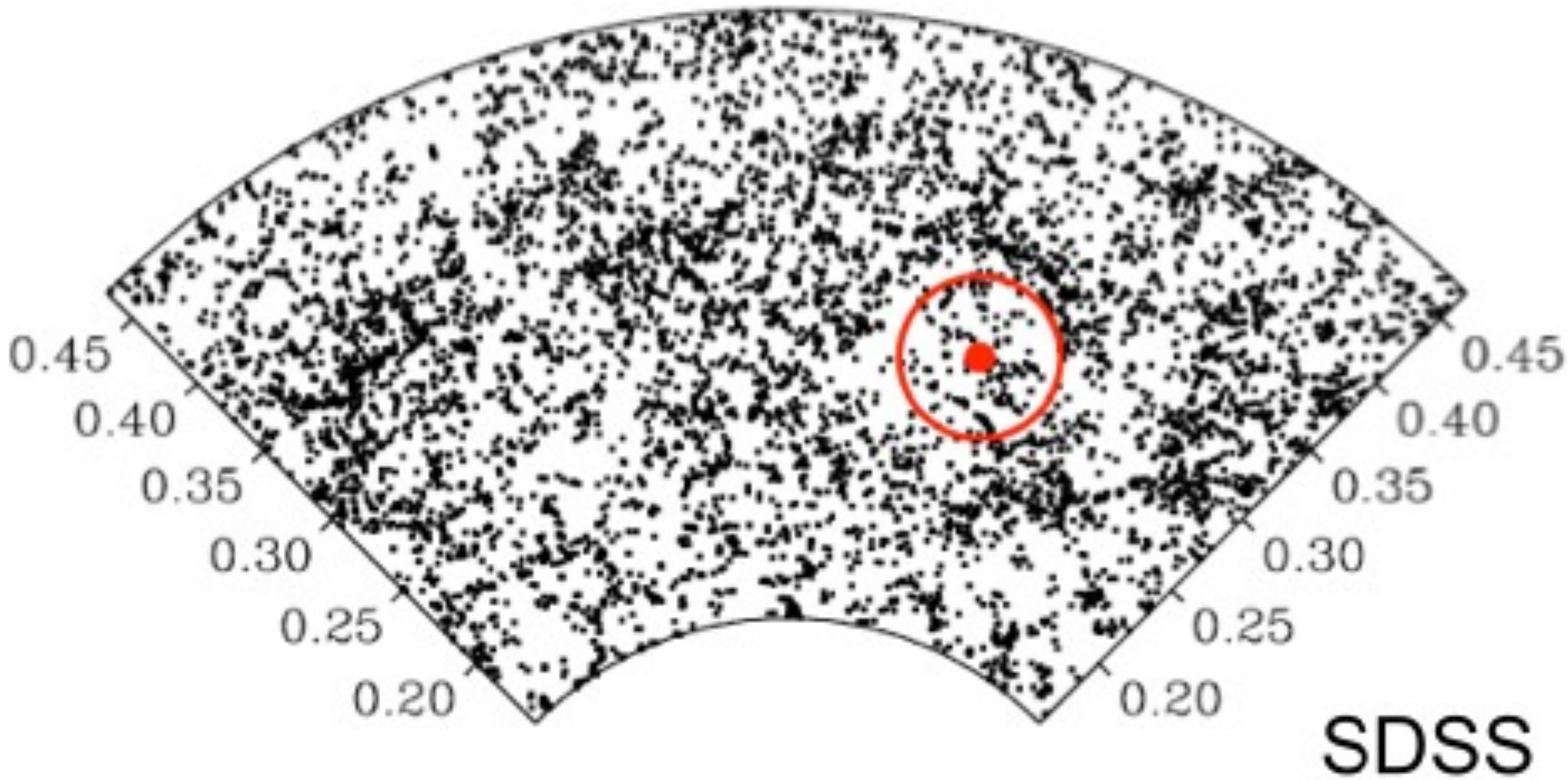
From CMB, we know that at the time of recombination perturbations were about 10^{-5} of the average density.



Now, it is about 10^{5} (in a galaxy).

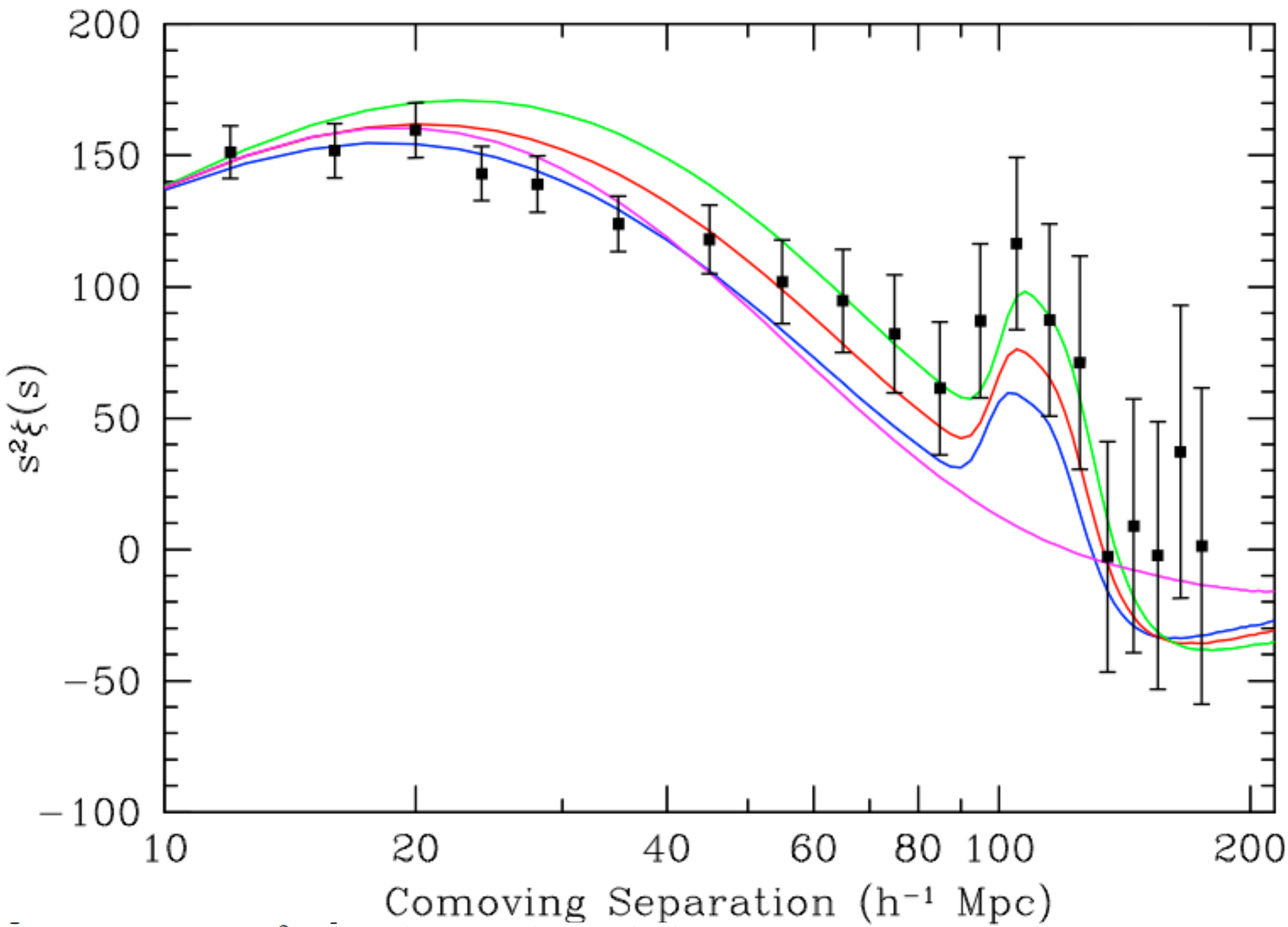
How do we get there?

Baryon Acoustic Oscillations



Eisenstein et al. 2004

Baryon Acoustic Oscillations



axis. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. It is interesting to note that although the data ap-

Eisenstein et al. 2004

- **Worksheet:** Problem: Tracking the Acoustic Sound Horizon. Starting from the physical sound horizon, estimate the Baryon Acoustic Oscillation (BAO) scale for the distribution of galaxies. Hint: the speed of sound during the radiation dominated era is about c/sqrt(3).