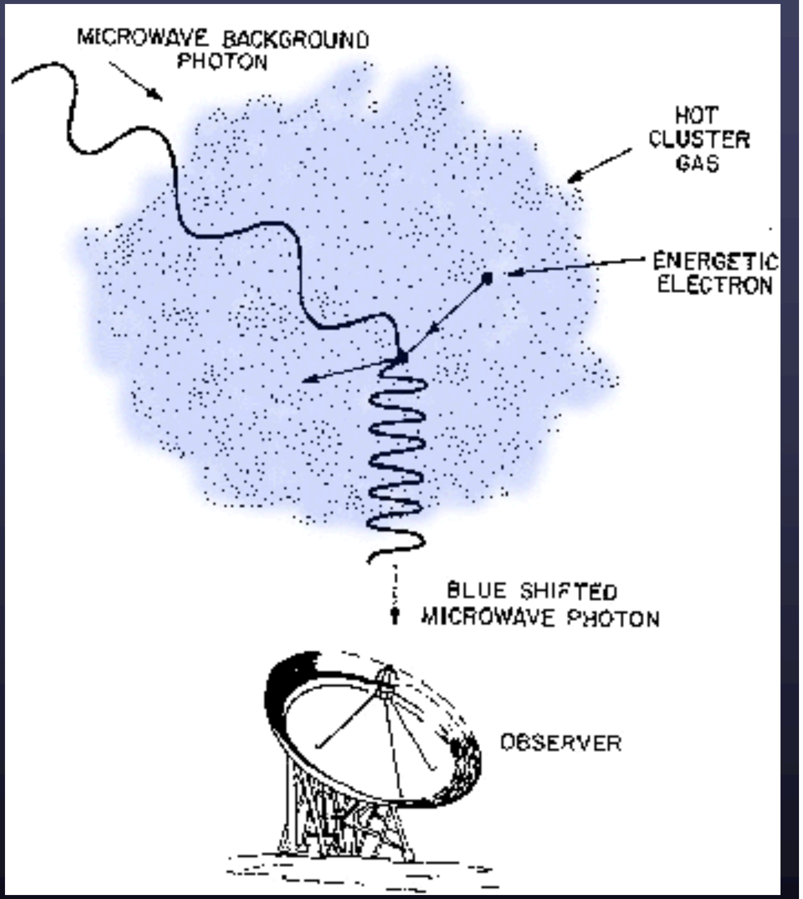
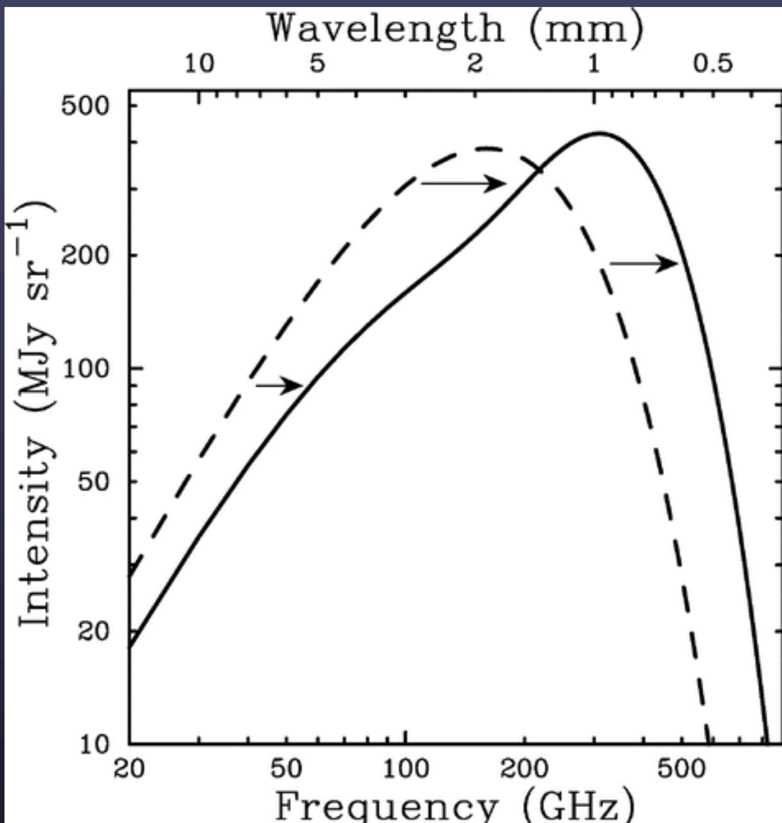
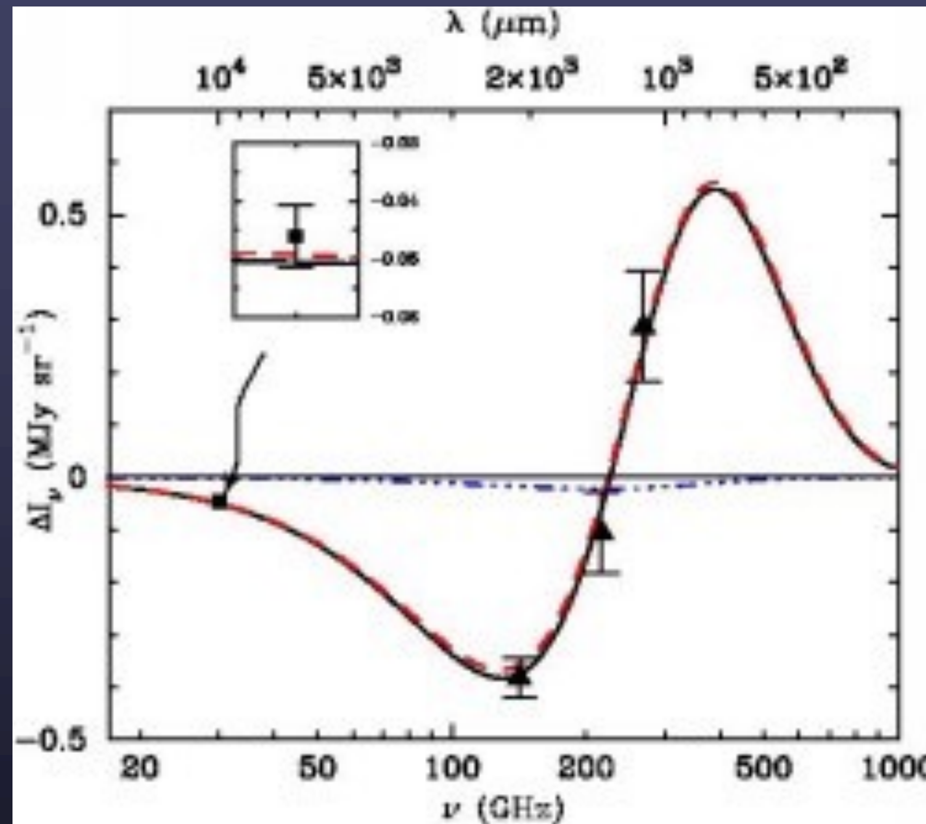
Sunyaev-Zeldovich effect

- The Sunyaev-Zeldovich effect
  - Photons of the CMB are scattered to higher frequencies by hot electrons in galaxy clusters, causing a negative brightness **decrement** below the peak frequency.
  - Decrement is proportional to integral of electron pressure through the cluster, or electron density if cluster is isothermal.
  - Electron density and temperature can be estimated from X-ray observations, so the linear scale of the cluster is determined.
  - This can be used to measure the cluster distance and combined with z to get H_0.



Sunyaev-Zeldovich effect





SZ images

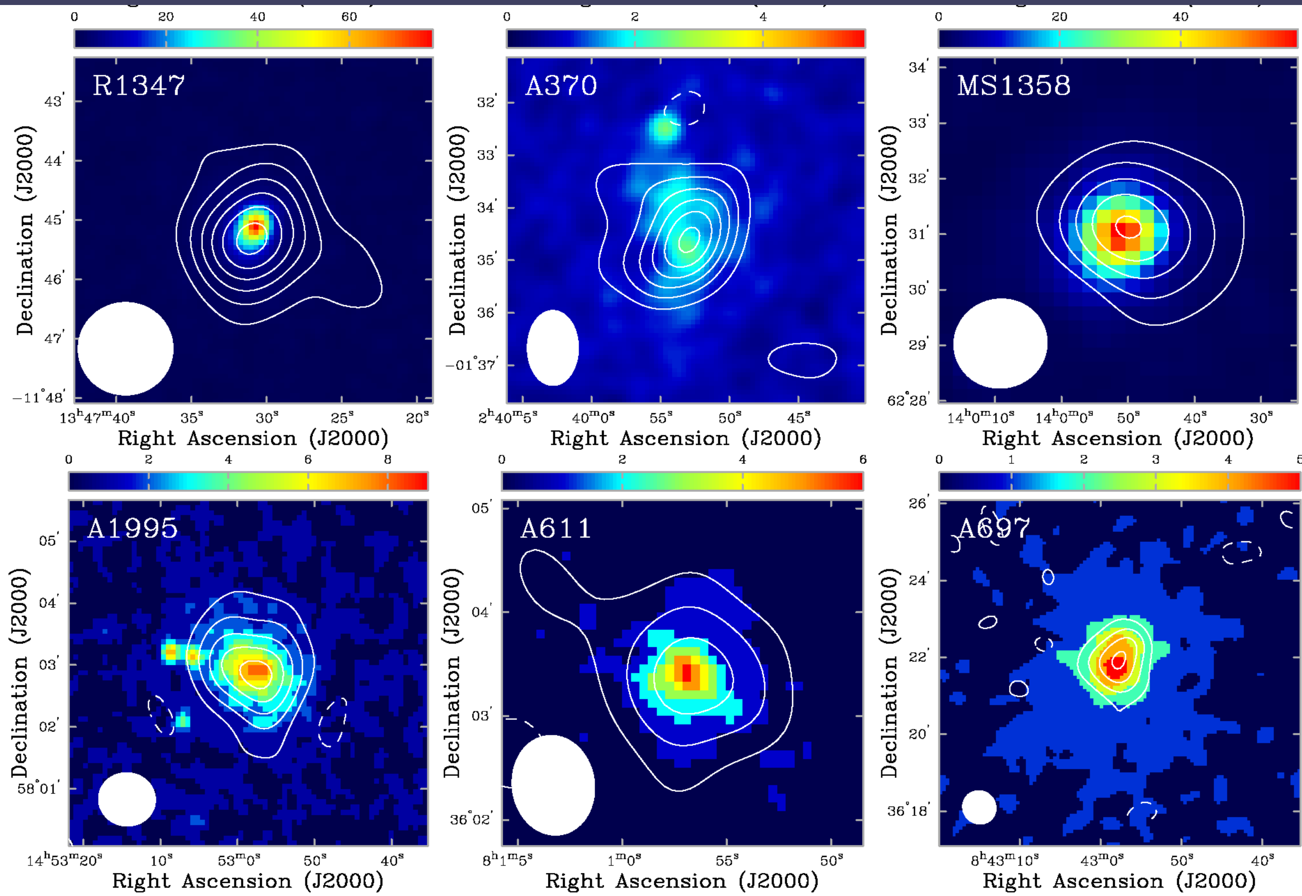


FIG. 2.—SZE (contours) and X-ray (color scale) images of each cluster in our sample. Negative contours are shown as solid lines. The contours are multiples of 2 σ and the FWHM of the synthesized beams are shown in the bottom left corner. The X-ray color scale images are raw counts images smoothed with Gaussians with $\sigma = 15''$ for PSPC data and $\sigma = 5''$ for HRI data. There is a color scale mapping for the counts above each image. The 30 GHz image statistics are summarized in Table 4.

Reese et al. astro-ph/0205350

Thermal SZ effect

THE ASTROPHYSICAL JOURNAL, 647:25–54, 2006 August 10

DETERMINATION OF THE COSMIC DISTANCE SCALE FROM SUNYAEV-ZEL'DOVICH EFFECT AND *CHANDRA* X-RAY MEASUREMENTS OF HIGH-REDSHIFT GALAXY CLUSTERS

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Received 2005 December 8; accepted 2006 April 5

ABSTRACT

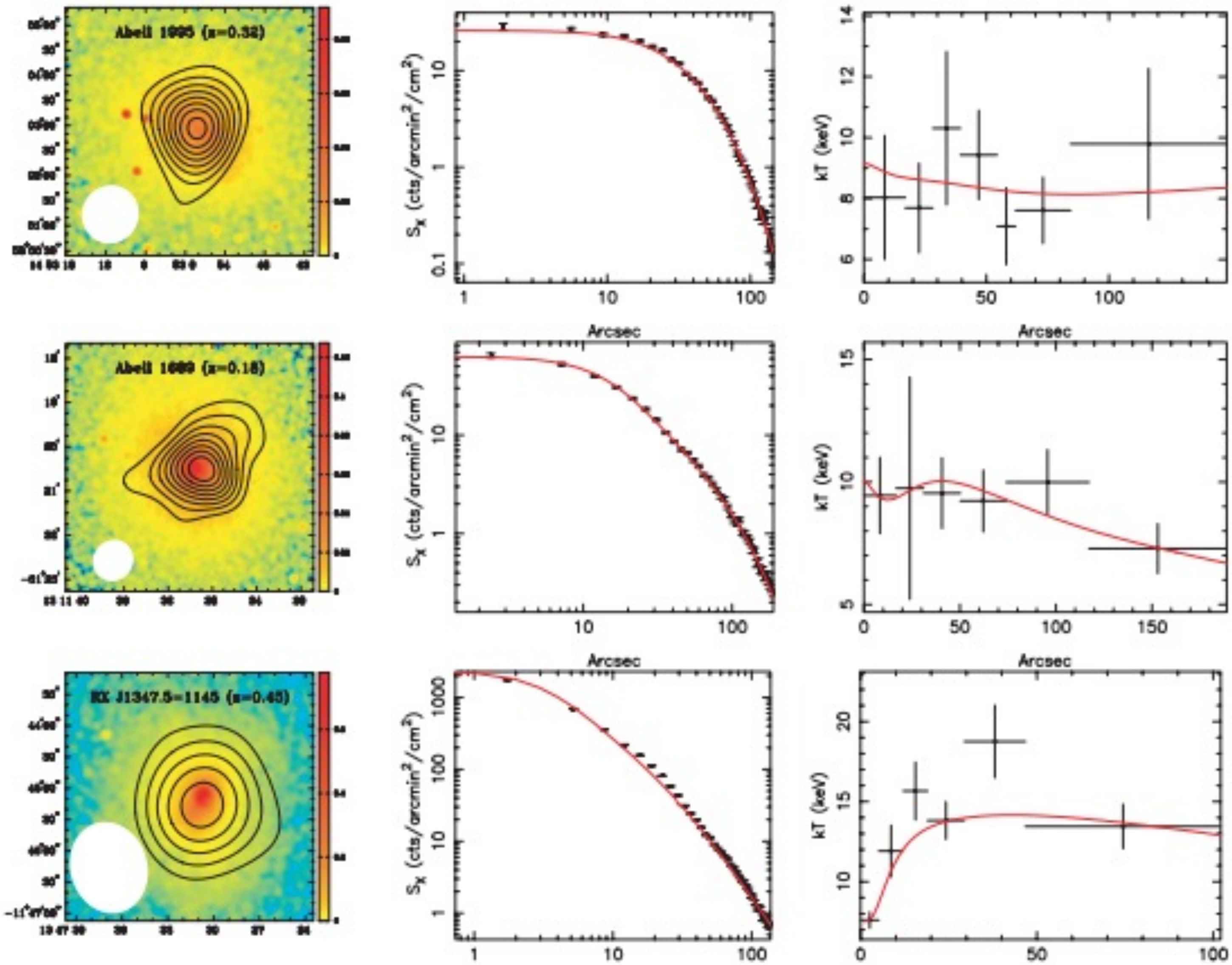
We determine the distance to 38 clusters of galaxies in the redshift range $0.14 \le z \le 0.89$ using X-ray data from *Chandra* and Sunyaev-Zeldovich effect (SZE) data from the Owens Valley Radio Observatory and the Berkeley-Illinois-Maryland Association interferometric arrays. The cluster plasma and dark matter distributions are analyzed using a hydrostatic equilibrium model that accounts for radial variations in density, temperature, and abundance, and the statistical and systematic errors of this method are quantified. The analysis is performed via a Markov chain Monte Carlo technique that provides simultaneous estimation of all model parameters. We measure a Hubble constant of $H_0 = 76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0}$ km s^{-1} Mpc^{-1} (statistical followed by systematic uncertainty at 68% confidence) for an $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology. We also analyze the data using an isothermal β-model that does not invoke the hydrostatic equilibrium assumption and find $H_0 = 73.7^{+4.6}_{-3.8}{}^{+9.5}_{-7.6}$ km s^{-1} Mpc^{-1}; to avoid effects from cool cores in clusters, we repeated this analysis excluding the central 100 kpc from the X-ray data and find $H_0 = 77.6^{+4.8}_{-4.3}{}^{+10.1}_{-8.2}$ km s^{-1} Mpc^{-1} (statistical followed by systematic uncertainty at 68% confidence). The consistency between the models illustrates the relative insensitivity of SZE/X-ray determinations of H_0 to the details of the cluster model. Our determination of the Hubble parameter in the distant universe agrees with the recent measurement from the *Hubble Space Telescope* Key Project that probes the nearby universe.

Subject headings: cosmic microwave background — distance scale — X-rays: galaxies: clusters

Online material: color figures, machine-readable table

$$H_0 = 76.9^{+3.9}_{-3.4}{}^{+10.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

SZ profiles



Abell 1995 (z=0.32)
Abell 1689 (z=0.18)
RX J1347.5-1145 (z=0.45)
S_X (cts/arcmin^2/cm^2)
kT (keV)
Arcsec

SZ Results

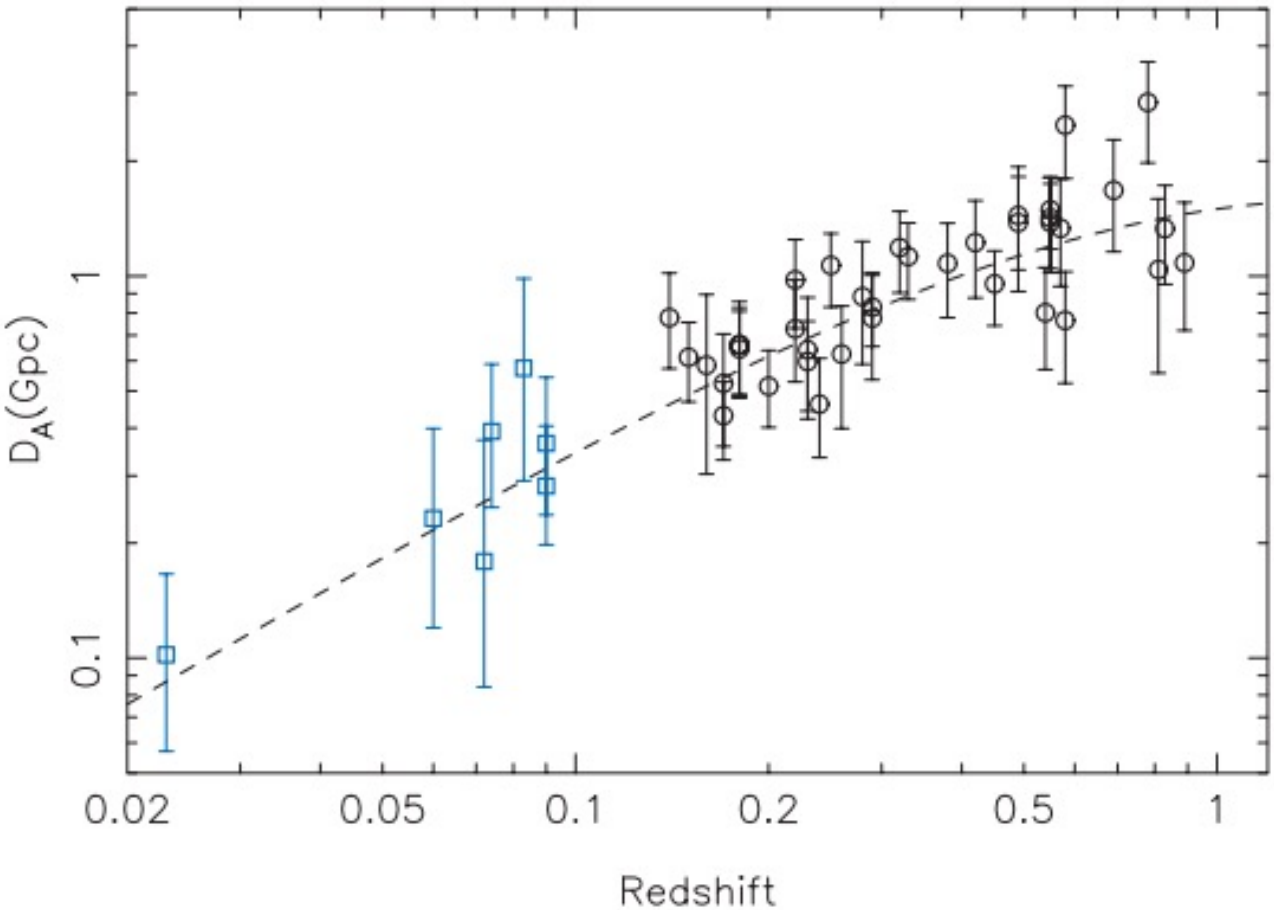


FIG. 3.—Angular diameter distances of the 38 clusters (*circles*). The error bars are the total statistical uncertainties, obtained by combining the X-ray and SZE data modeling uncertainties (Table 2) and the additional sources of random error described in § 3.3 and Table 3. The systematic errors of Table 3 are not shown. The dashed line is the angular diameter curve using the best-fit Hubble constant $H_0 = 76.9$ km s^{-1} Mpc^{-1} and $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. The squares are from the low-redshift sample of Mason et al. (2001), and they are not included in the fit.

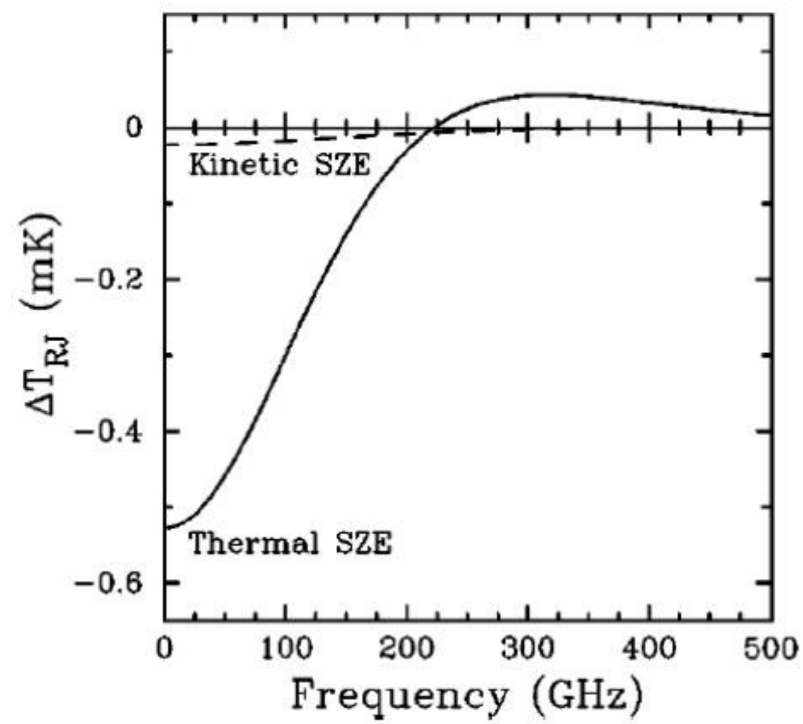
The University of New Mexico

kSZ Effect

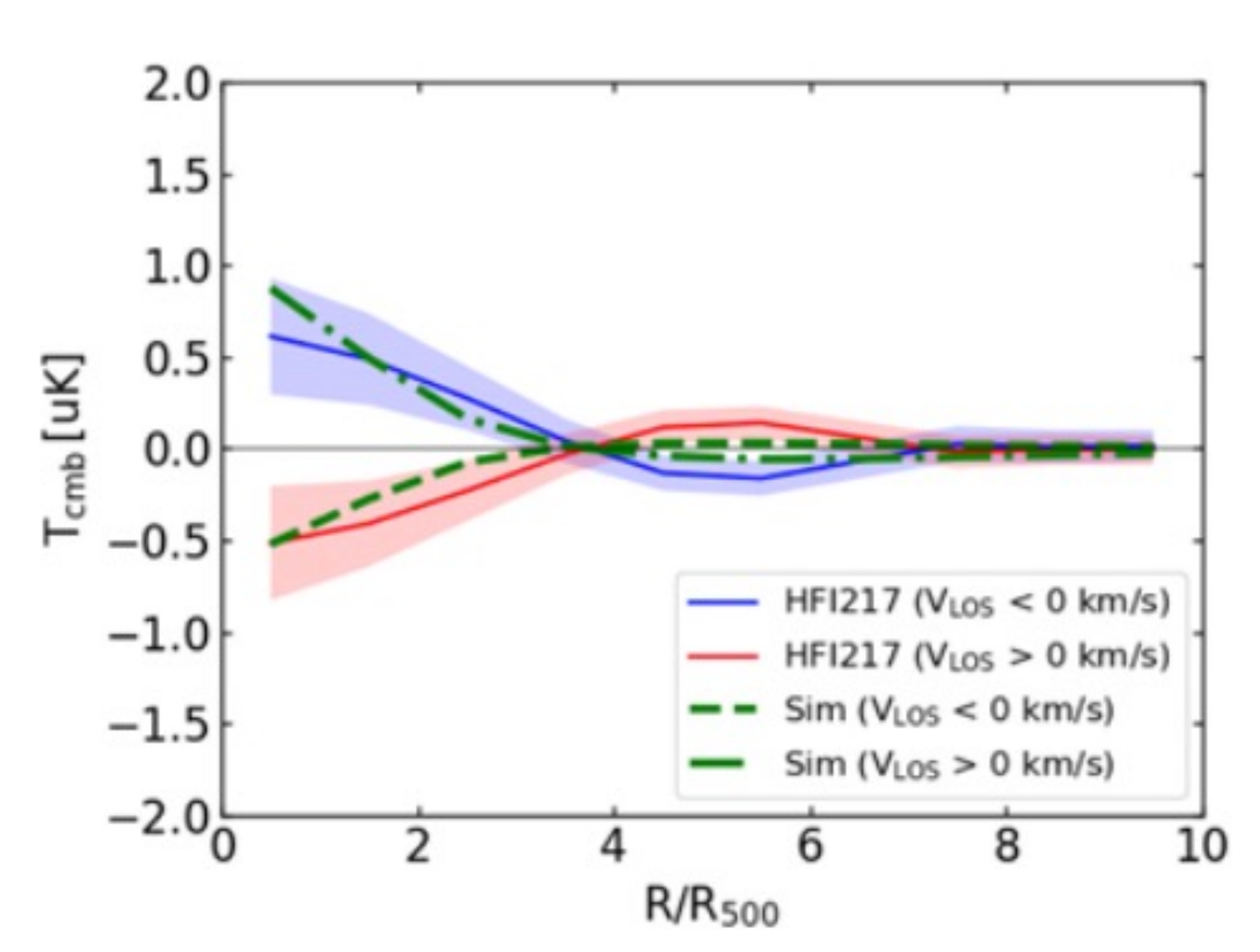
The Doppler effect of line of sight cluster velocity -> observed shift of the CMB spectrum.

In the nonrelativistic limit, the spectral signature of the kinetic SZE is a pure thermal distortion of magnitude of the CMB signal:

$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right)$$



Kinetic SZ Results



Tanimura et al. 2021

Hot Gas in Clusters

- There is lots of gas, in the richest clusters up to 10 times more than in stars

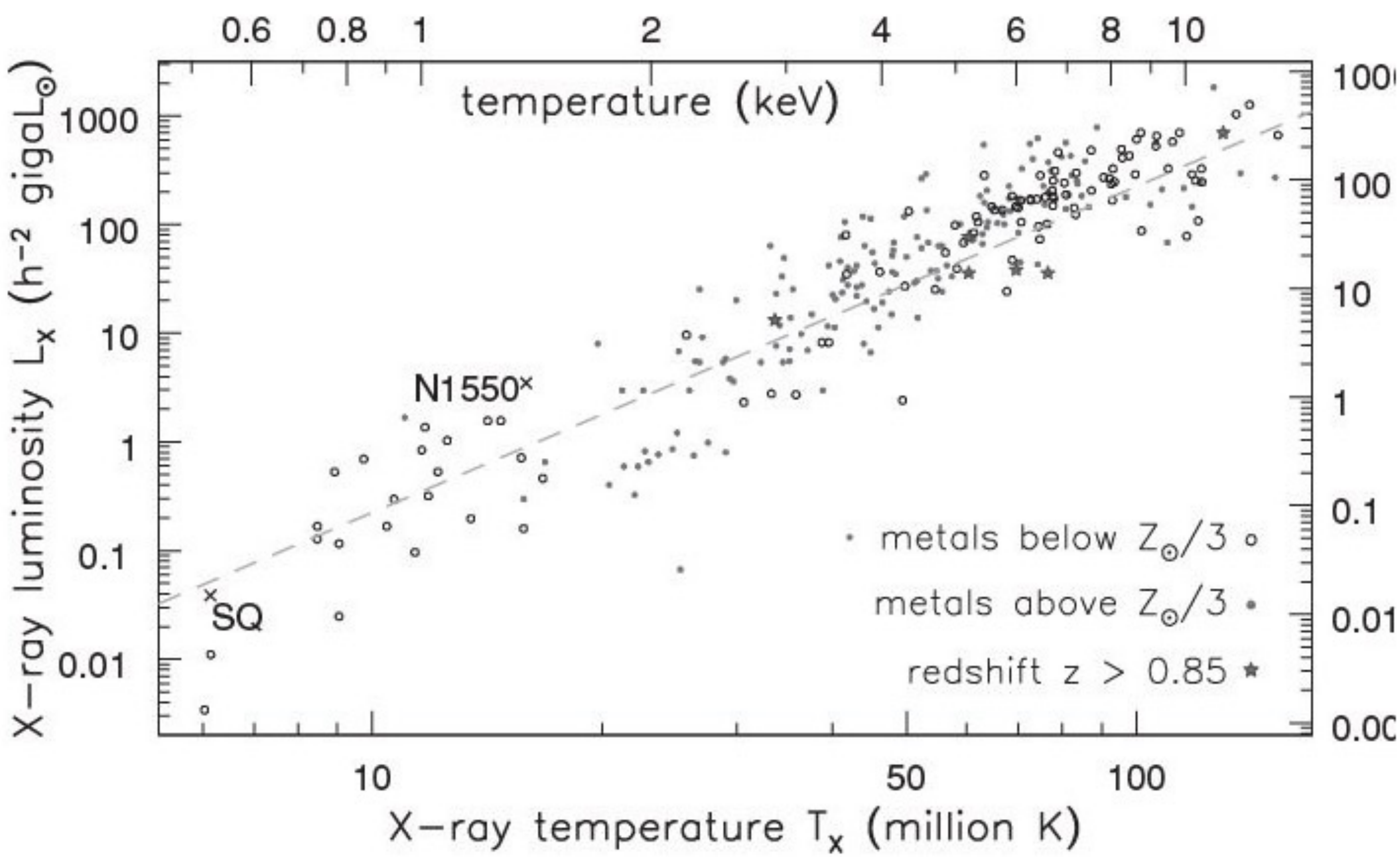


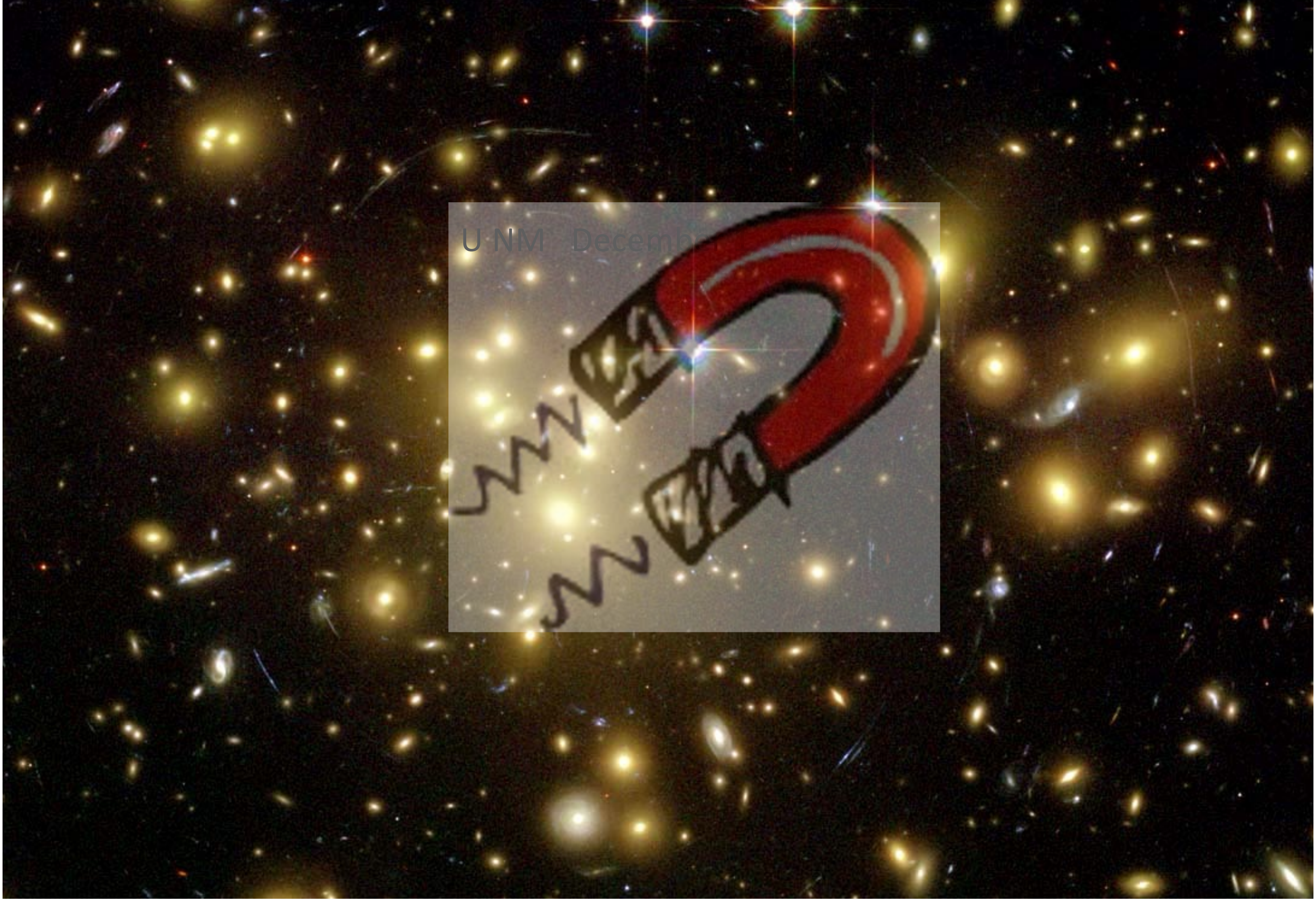
Fig. 7.12. The X-ray luminosity L_X of a galaxy cluster or group, in units of the Sun's bolometric luminosity, increases with the gas temperature T_X: the dashed line shows $L_X \propto T_X^3$. Stephan's Quintet and the NGC 1550 group follow the same trend. This relation has changed little since redshift $z \approx 1$. In most clusters with $T_X > 3 \times 10^7$ K, the gas has roughly one-third of the solar content of iron – D. Horner.

Hot Gas in Clusters

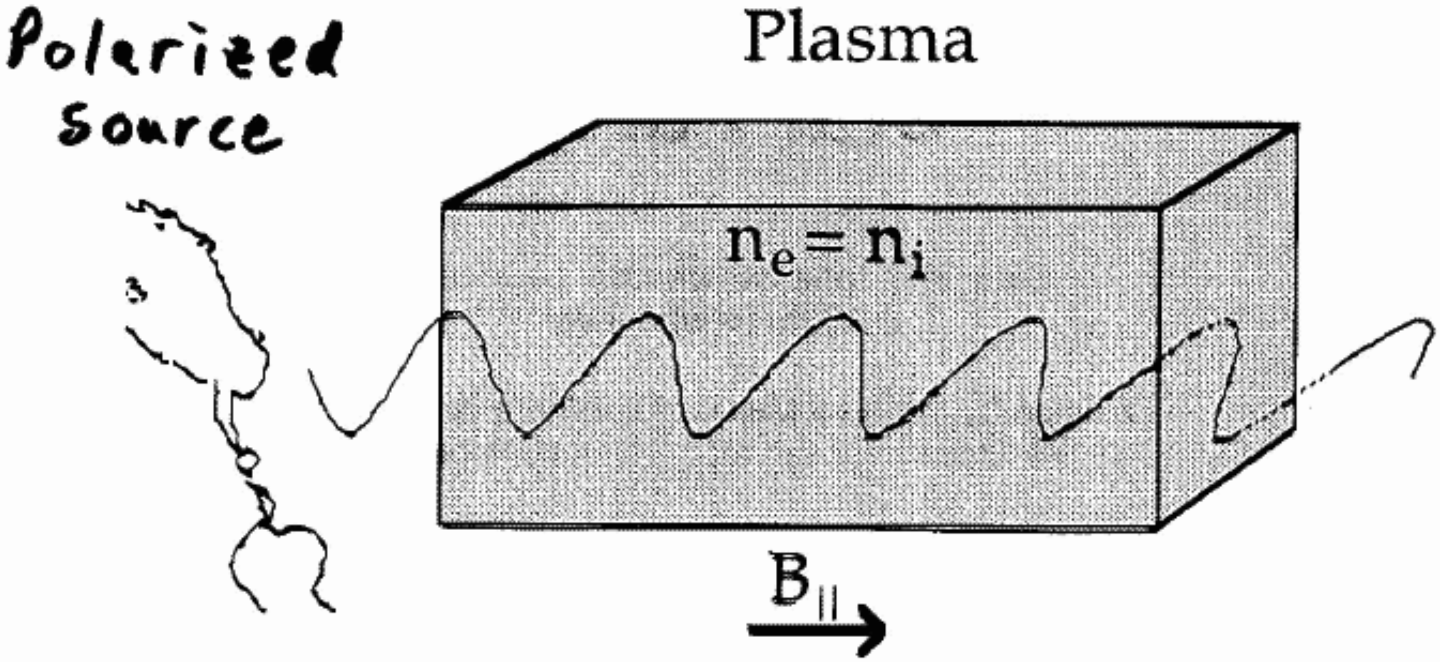
- The gas is densest near the center of the cluster, and drops off
With radius as you might expect
Since X-ray emission goes as n^2 the gas at the center should cool,
Generate optical line emission, and form molecular gas and stars
There is some evidence for cooler gas, but not enough

$$t_{\rm cool} = \frac{3nk_{\rm B}T}{3\times 10^{-27}n^2\sqrt{T}}\ {\rm s} \approx 14\left(\frac{10^{-3}\ {\rm cm}^{-3}}{n}\right)\left(\frac{10^7\ {\rm K}}{T}\right)^{1/2}\ {\rm Gyr}.$$

Clusters are Very Large Magnets



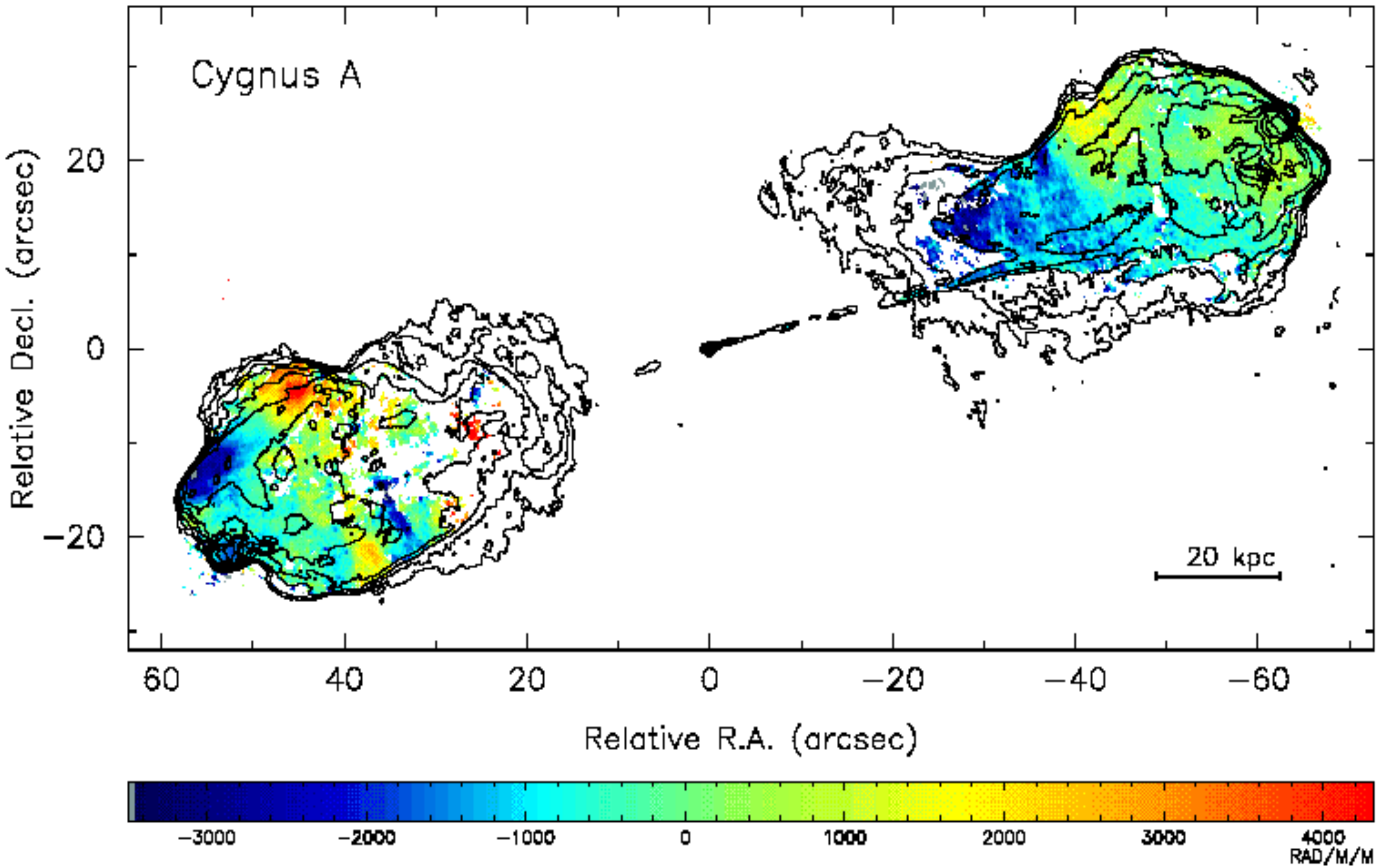
Faraday Rotation



$$\Psi = \Psi_o + RM\,\lambda^2$$

kpc (L), μGauss ($B_{||}$), cm⁻³ (n_e)

$$RM = 812 \int_0^L n_e B_{||}\, dl \text{ radians/m}^2$$

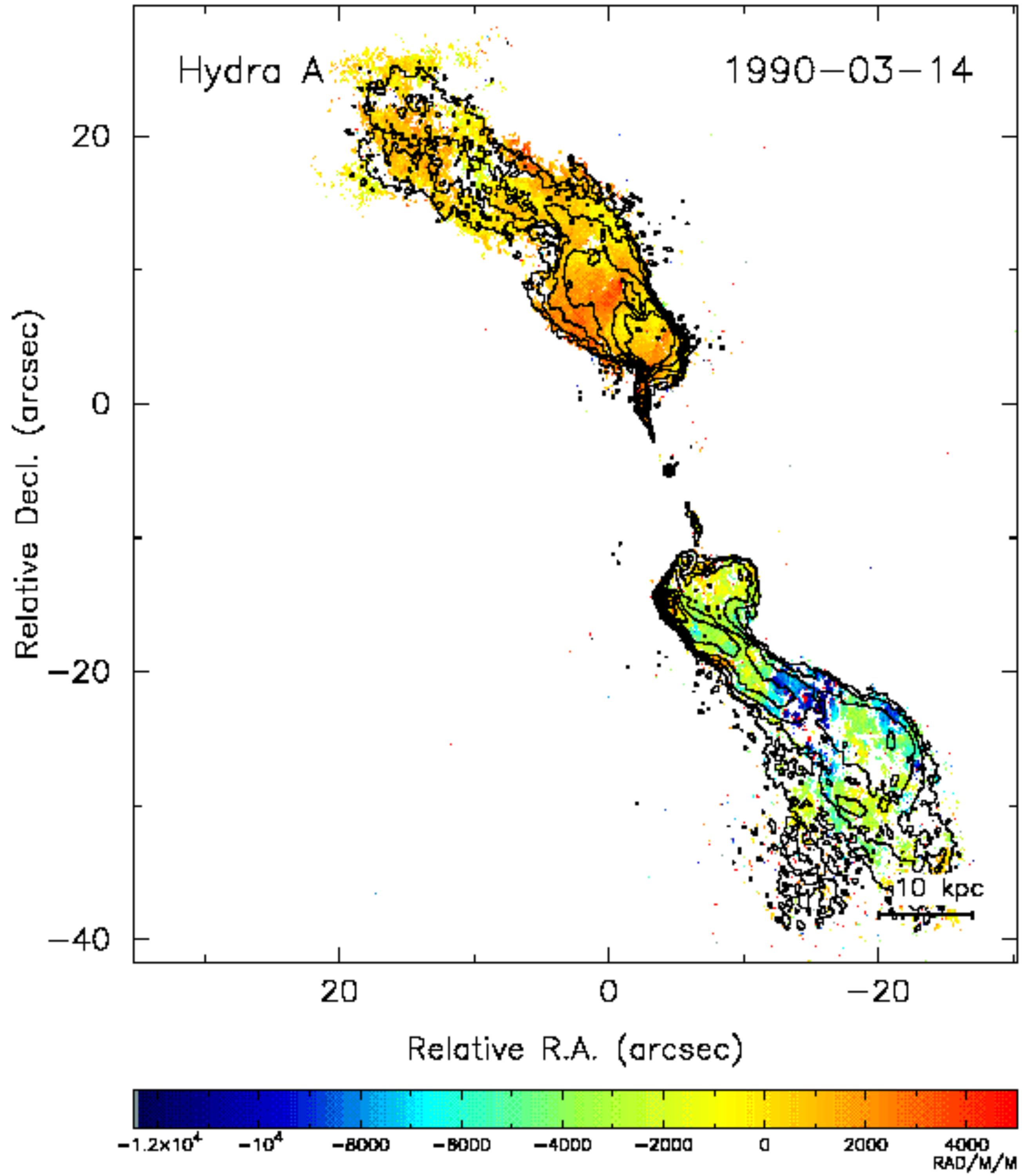


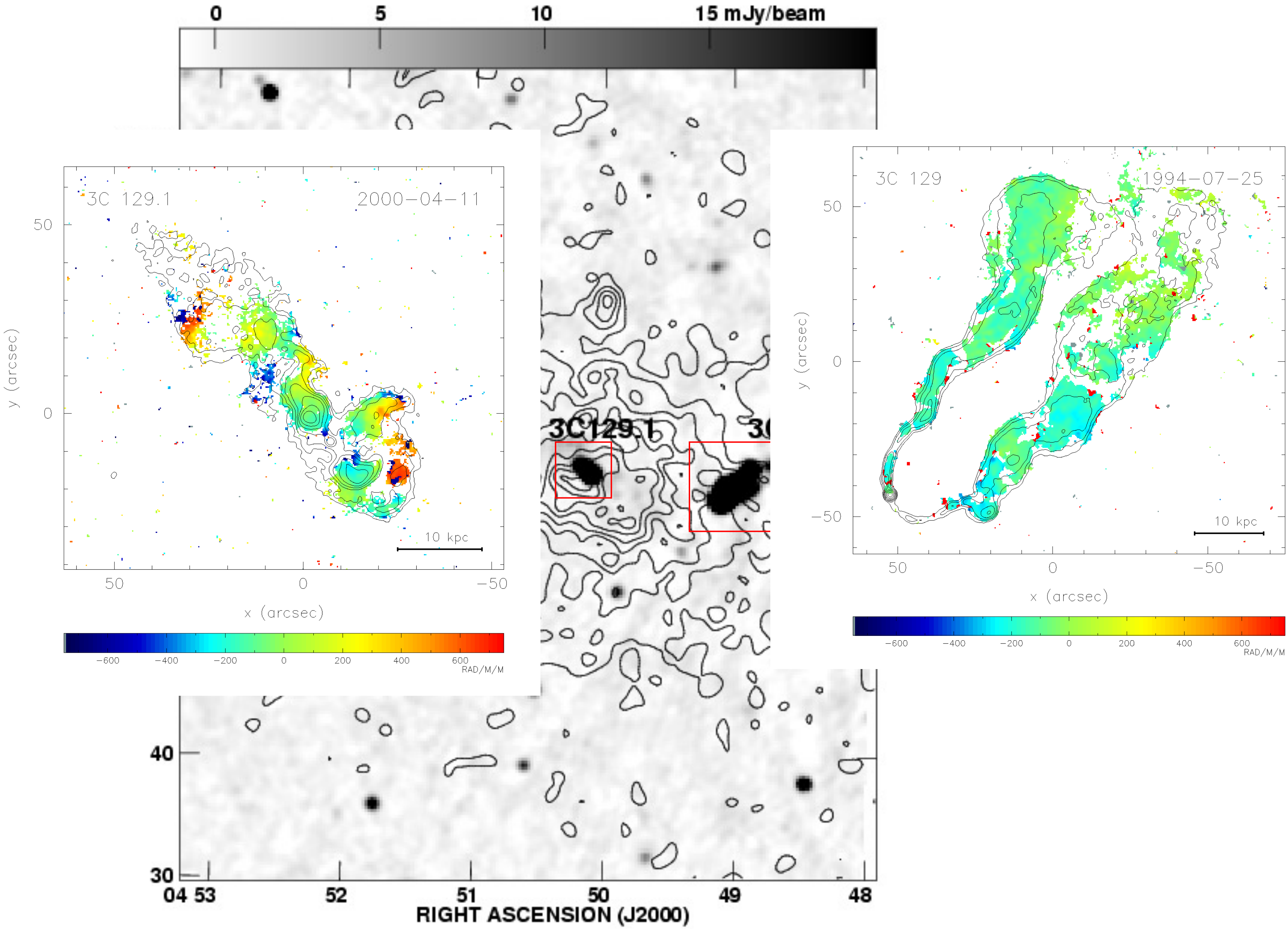
Carilli & Taylor 2002 (ARA&A)

Hydra A

Faraday Rotation Measures

B ~ 30 μG

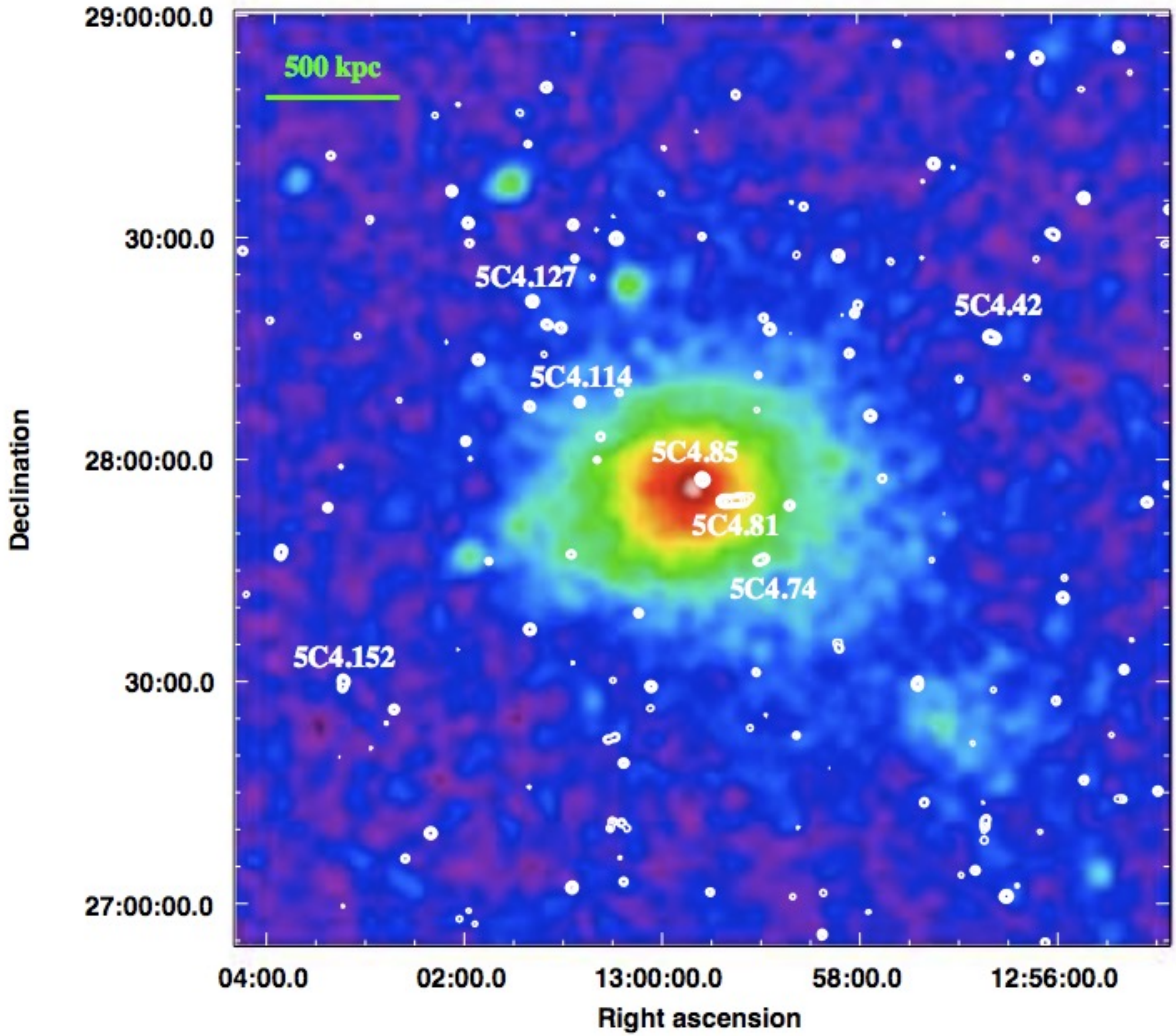




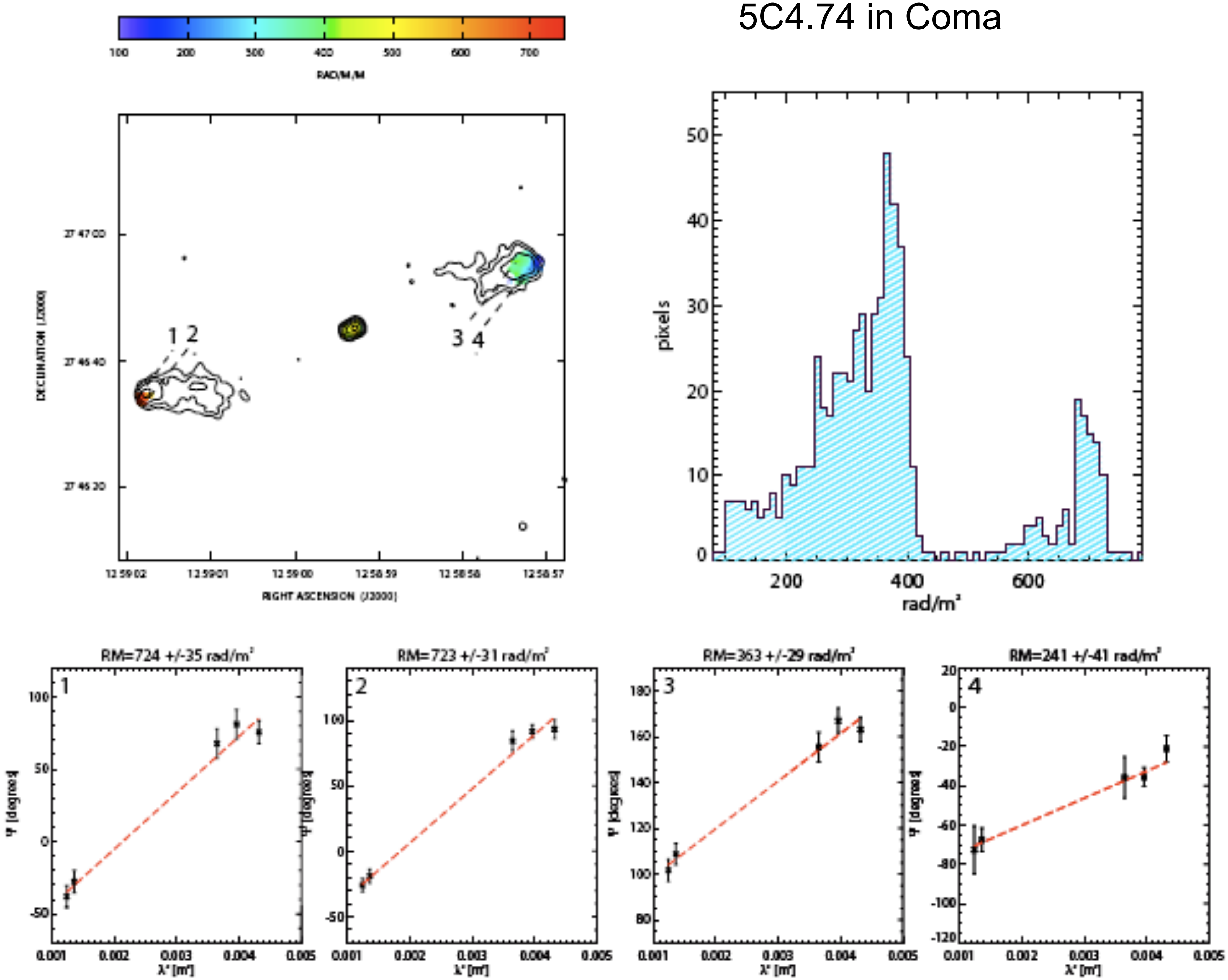
0
5
10
15 mJy/beam
3C129.1
3C 129.1
2000-04-11
y (arcsec)
x (arcsec)
10 kpc
RAD/M/M
3C 129
1994-07-25
40
30
04 53
52
51
50
49
48
RIGHT ASCENSION (J2000)

Coma

X-ray
+
radio



5C4.74 in Coma

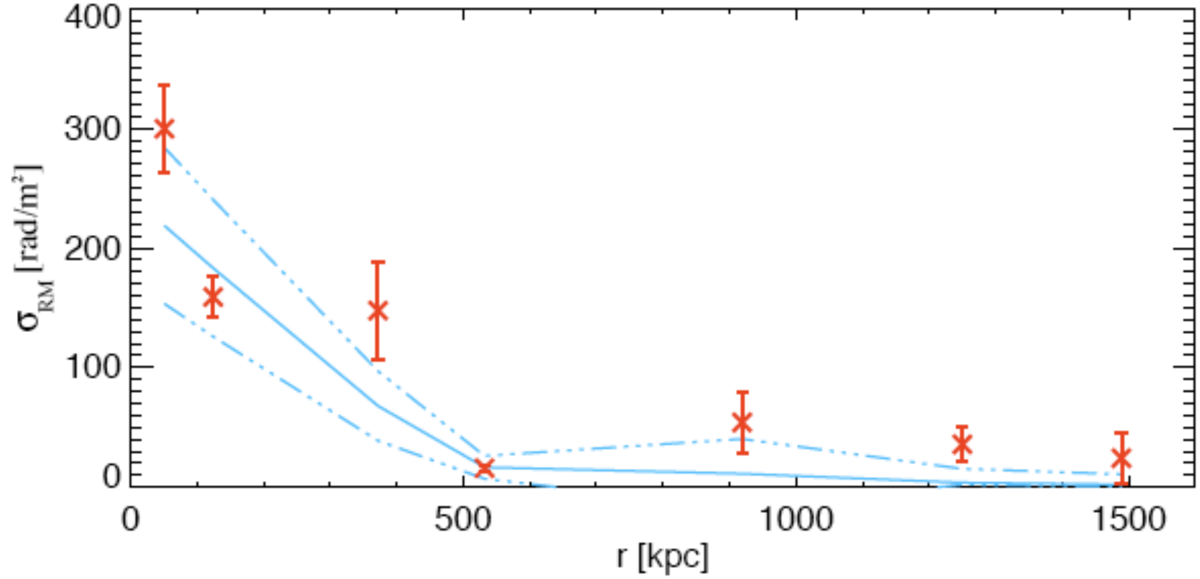


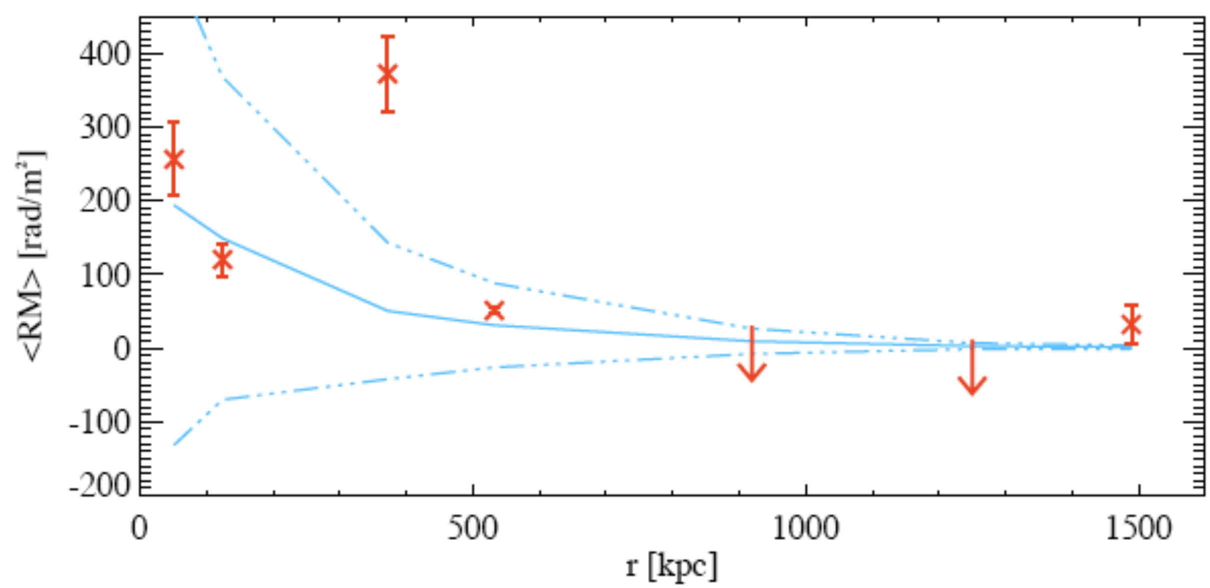
Results

B_0 = 4.6 +/- 0.7 μG

scale lengths between 2 and 30 kpc

average B ~ 2 μG





Bonafede et al. 2009

Astronomy 422

Lecture 15: Galaxy Mergers

Key concepts:

Tidal stripping

Dynamical friction

Supermassive Binary Black Holes

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

Galaxy interactions

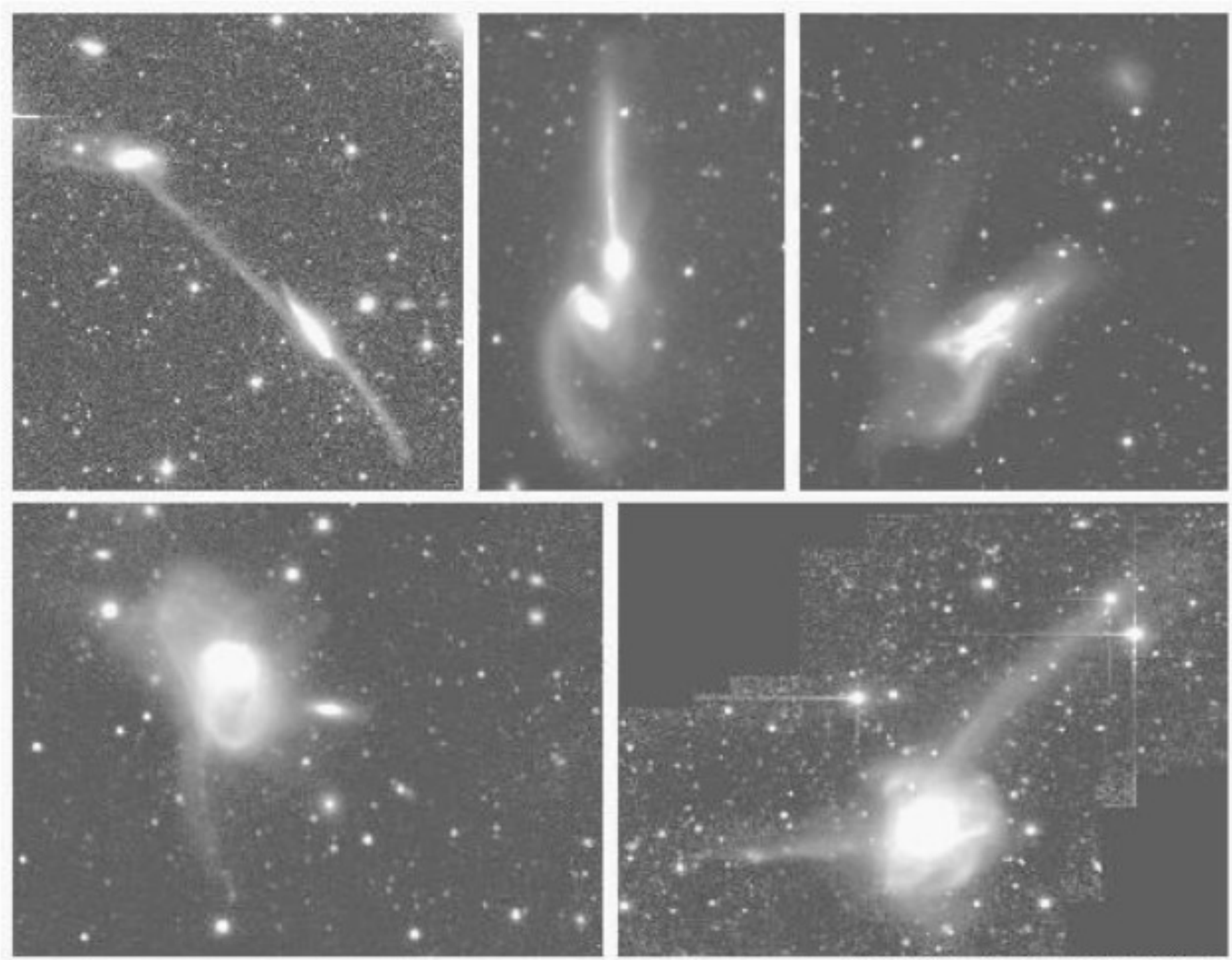
Not all galaxies fall on the Hubble sequence, many are *peculiar.*

Arp made an Atlas of Peculiar Galaxies in 1966 (based on the Palomar Sky Survey), later extended to the Southern hemisphere (1982).

Arp found

- Very distorted morphologies
- Tidal tails
- Polar rings around ellipticals
- Ring shaped galaxies
- Rings of dust and gas
- Warps in spiral disks
- Shells and ripples around ellipticals
- Accretion of dwarf galaxies

Hibbard & van Gorkom 1996



Galaxy interactions

The typical spacing between galaxies is relatively small compared to the spacing between stars.

spacing ~ 100 x galaxy diameter

Compare to stars:

Take spacing ~ 1pc = 3×10^{16} m

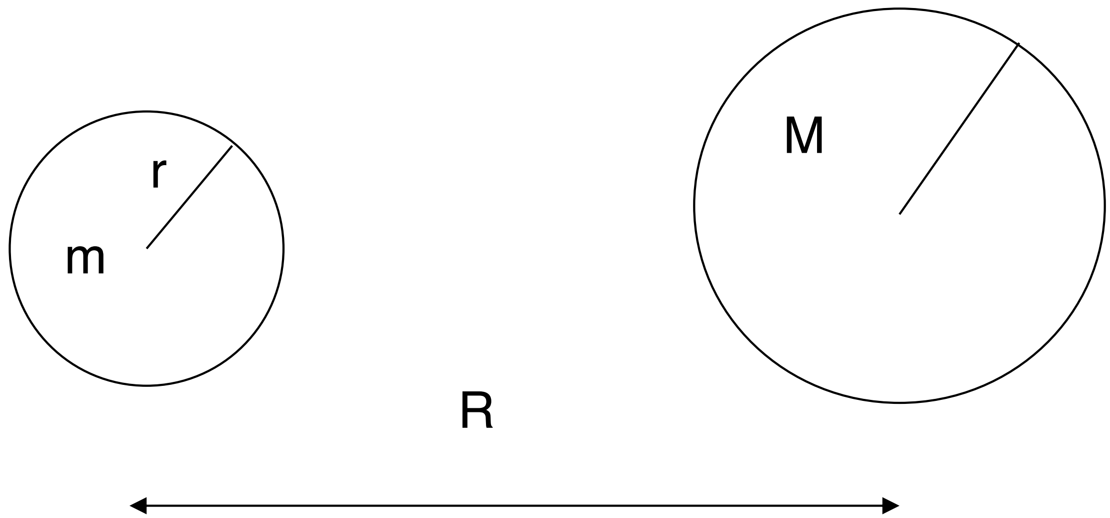
radius ~ 7×10^{8} m = $R_{\odot}$

spacing of stars ~ 10^{7} x stellar diameter

Thus, galaxies are much more likely to interact!

Tidal stripping

Consider two galaxies:



Galaxy m, radius r is self-gravitating as is galaxy M.

The gravitational acceleration at center of m due to M is:

$$a_{cent} = \frac{GM}{R^2}$$

But at near and far edges:

$$a_{near} = \frac{GM}{(R-r)^2} \qquad a_{far} = \frac{GM}{(R+r)^2}$$

So difference between center and edge:

$$\Delta a = \frac{GM}{R^2} - \frac{GM}{(R+r)^2} \simeq \frac{GM}{R^2} - \frac{GM}{R^2}\left(1 - \frac{2r}{R}\right) \quad \mathrm{if\, r \ll R}$$

$$\Delta a = \frac{2GMr}{R^3}$$

Stars at edge of m feel gravitational acceleration to m of

$$a_m = \frac{Gm}{r^2}$$

That means that stars will be *stripped* off m if :

$$\frac{2GMr}{R^3} > \frac{Gm}{r^2}$$

$$\text{or} \;\; R < \left(\frac{2M}{m}\right)^{1/3} r$$

Roche limit

Worksheet: Roche limit a) Express the Roche limit in terms of density of the smaller galaxy m. b) Now given a large spiral with M = 500 m and a dwarf galaxy of mass m, calculate the Roche limit in terms of the radius of the dwarf galaxy, r.

Roche limit in terms of density

$$\rho_m = \frac{3m}{4\pi r^3}$$ average density of m

stripping when $$R < \left(\frac{3M}{2\pi\rho_m}\right)^{1/3}$$

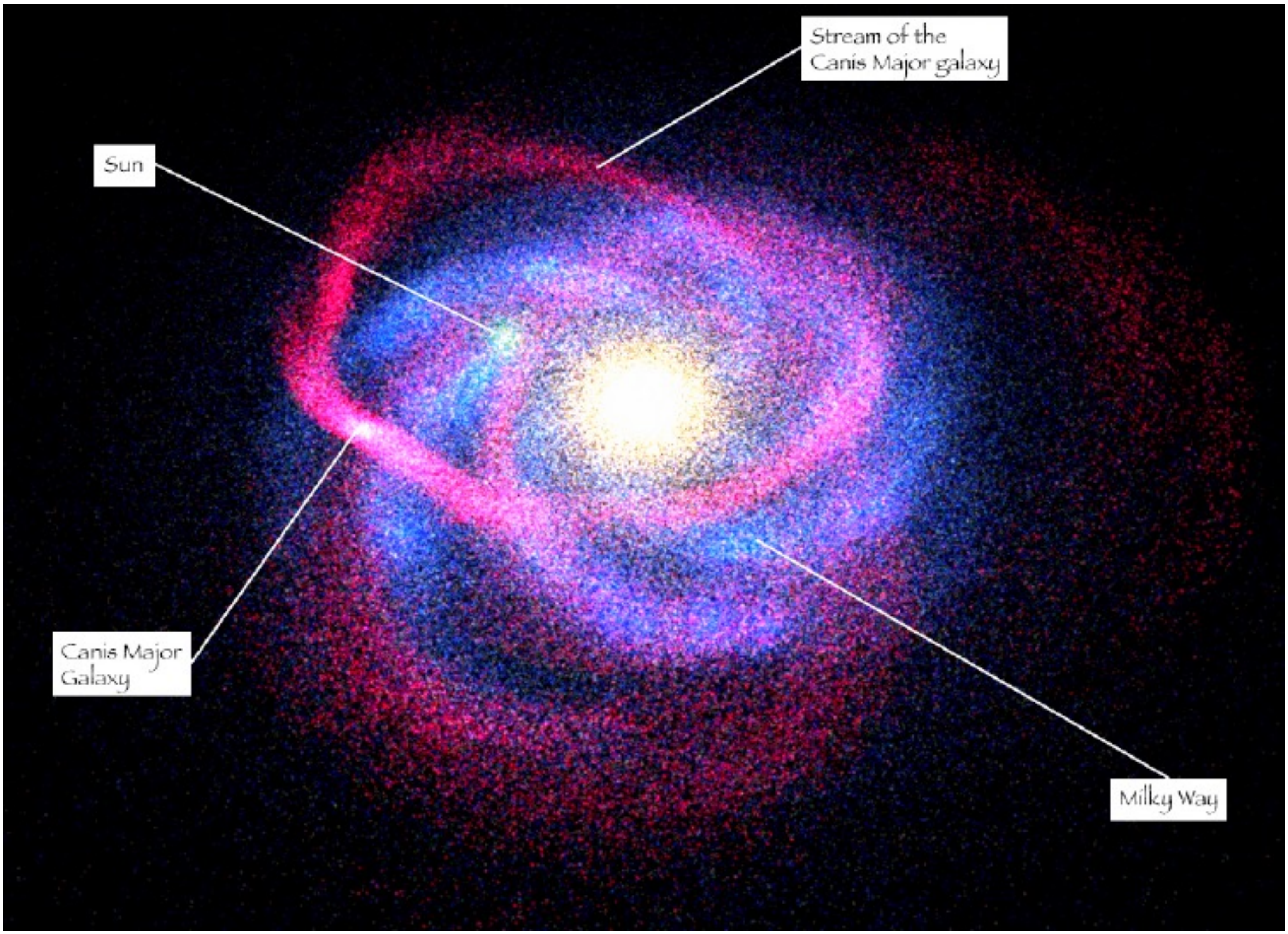
But galaxies aren't uniform density:

=> low density outer parts stripped away at larger *R*

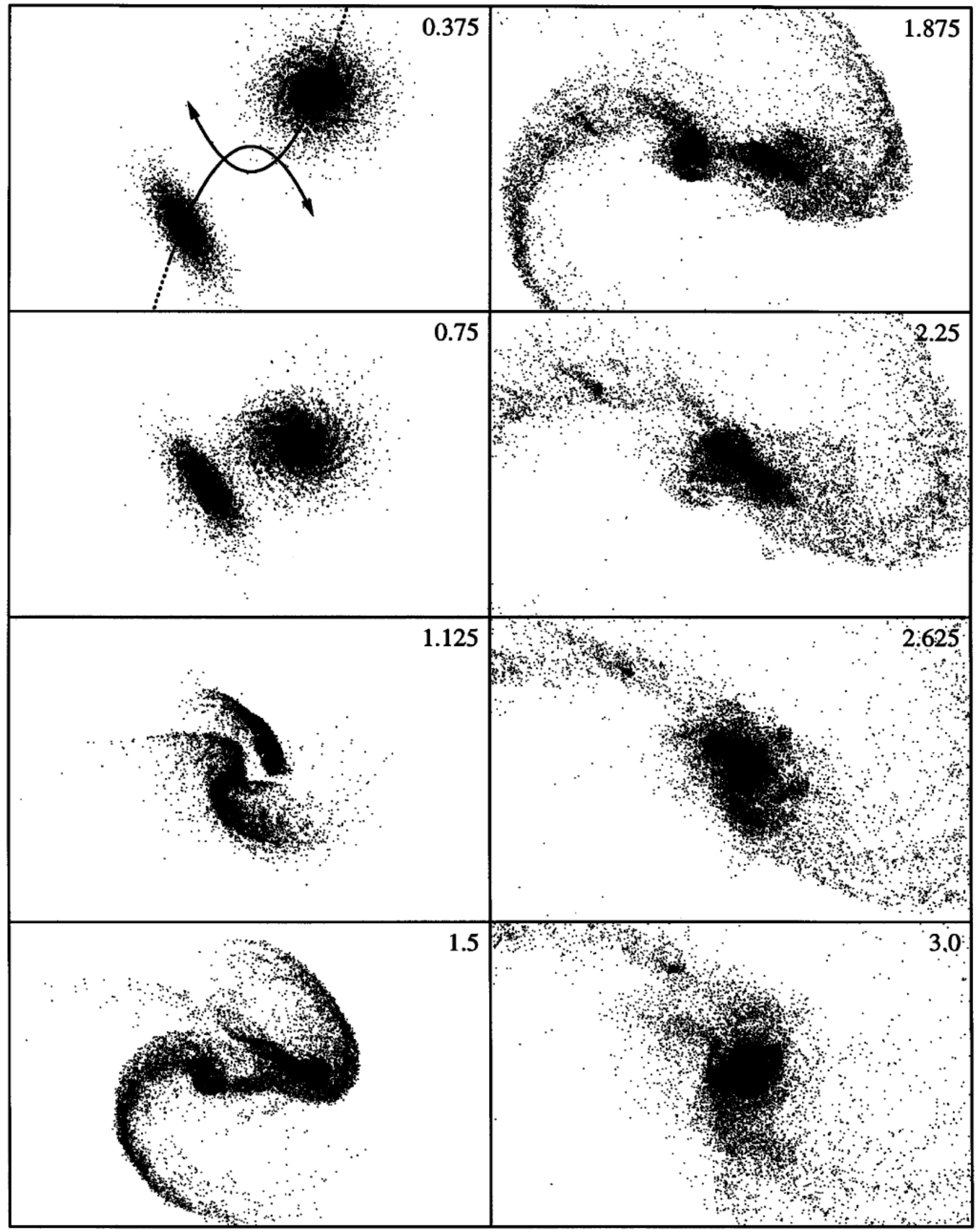
=> high density cores may survive, *merge* with M before disruption

Tidal morphologies are complex.

Ibata et al. 2003: Canis Major galaxy.



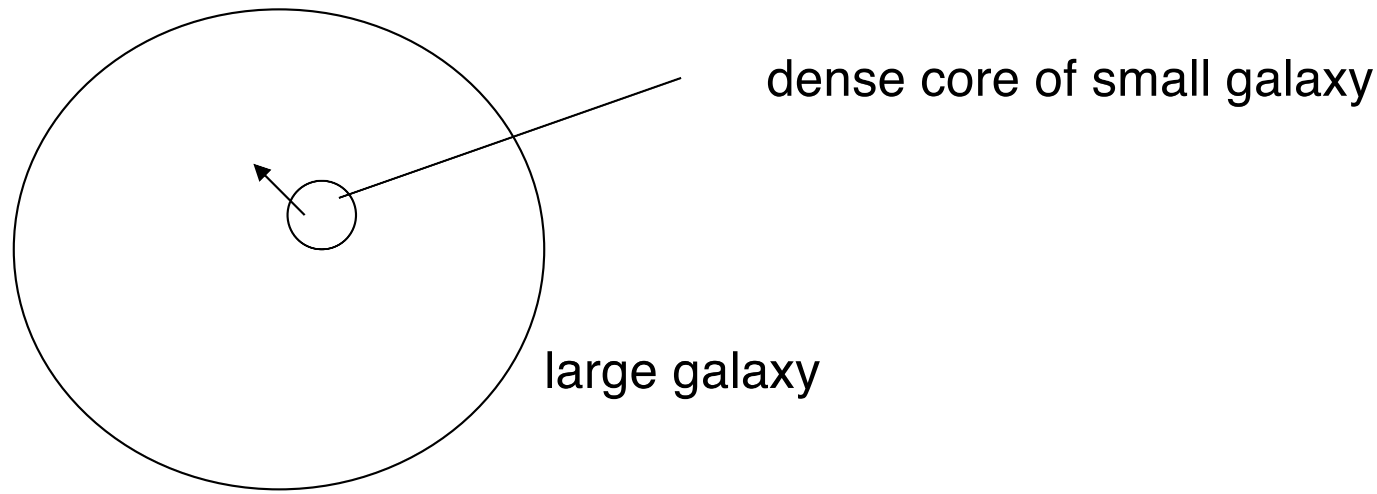
Barnes & Hernquist 1996



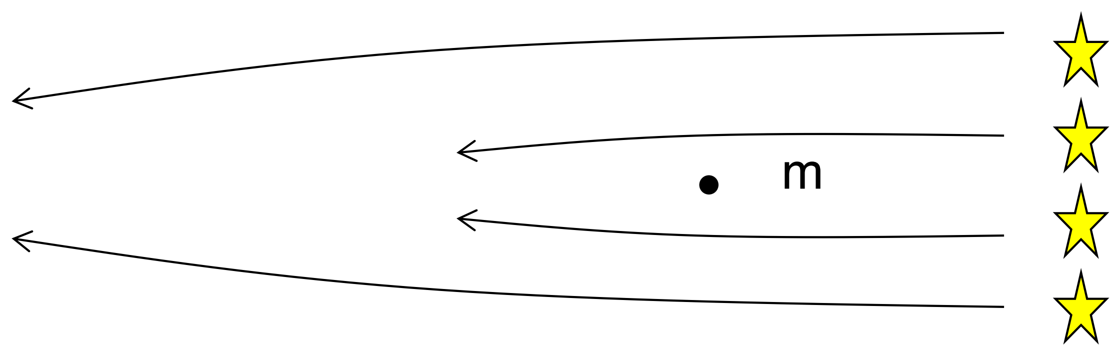
'IG. 4.—Evolution of the stellar distribution in encounter A, projected onto the orbital plane. The scale is the same as in Fig. 3.

Dynamical friction

How large galaxies eat dense cores of victims!



Represent core as point mass m. In its frame, stars are streaming by:



How it works:

- As a massive galaxy moves through a sea of stars, gas, (and the dark halo), it causes a wake behind, increasing the mass density in this region
- This increase in density causes the galaxy to slow down and lose kinetic energy
- The galaxy will eventually fall in and merge with the companion

Force of dynamical friction, *drag force,* should depend on M, V_m and surrounding stellar density ρ.

This force is expressed as: $f_d \simeq \frac{CG^2 M^2 \rho}{V_m^2}$

Reality check:

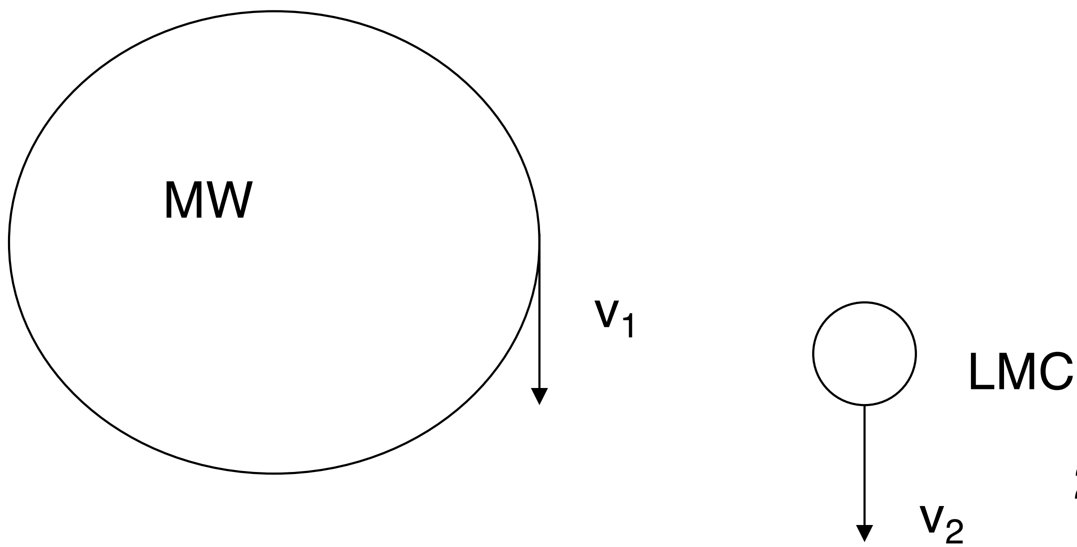
1) $f_d \propto \rho$ Why? Doubling density doubles number of objects.

2) $f_d \propto M^2$ One M from effectiveness of creating overdensity.
Another from gravitational force due to overdensity.

3) $f_d \propto V_m^{-2}$ Slower encounters more effective.

Example

Time for MW to swallow LMC



265 +/- 65 km/s
Kroupa & Bastian 2005

Assume v_1=v_2=v. MW flat rotation curve implies

$$\rho(r) = \frac{v^2}{4\pi G r^2}$$

Then

$$f_d = \frac{CGM^2}{4\pi r^2}$$

Assume orbit of LMC is circular with radius r. Angular momentum is

$$L = Mrv$$

Dynamical friction causes torque

$$\tau = r f_d = \frac{dL}{dt}$$

$$L = \frac{dL}{dt} = Mv\frac{dr}{dt} = -\frac{CGM^2}{4\pi r^2} \quad r$$

Integrating

$$\int_{r_i}^{0} r dr = -\frac{CGM}{4\pi v} \int_0^t dt$$

$$\Rightarrow \quad t = \frac{2\pi v r_i^2}{CGM}$$

$$v = 220\,\mathrm{km\,s^{-1}} \qquad r_i = 50\,\mathrm{kpc} \ \ (\mathrm{current\,r})$$

$$M = 2 \times 10^{10}\,\mathrm{M_\odot} \qquad c = 23$$

$$t = 1.7 \times 10^9 y$$

Actually if we assume an elongated orbit is a much longer merging time, ~5 Gyr.

We can't watch mergers happen, so how do we study them instead?

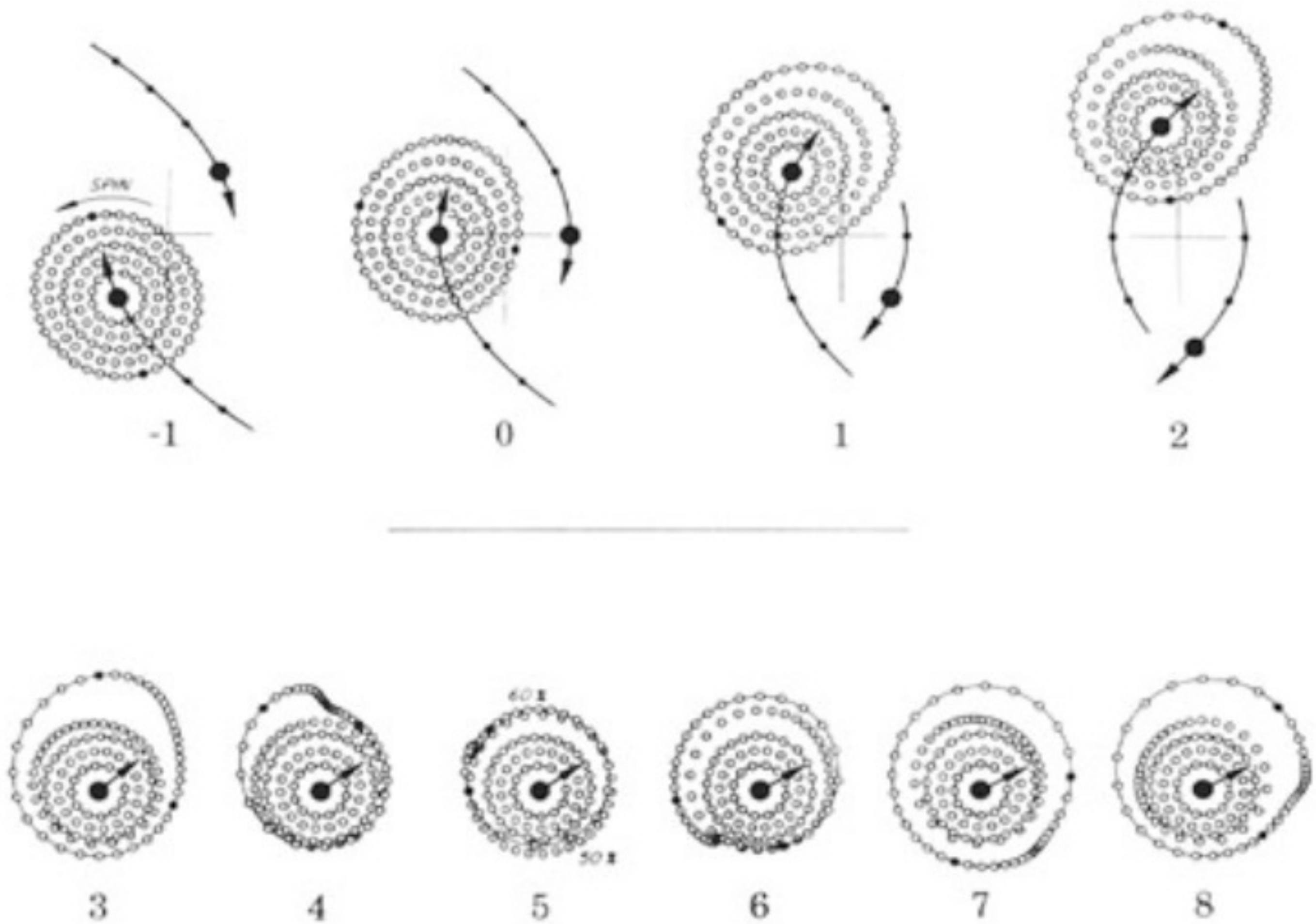
Galaxy Interactions

- Interactions studied via N-body simulations, attempting to include effects of gas, star formation and dark halo mass.

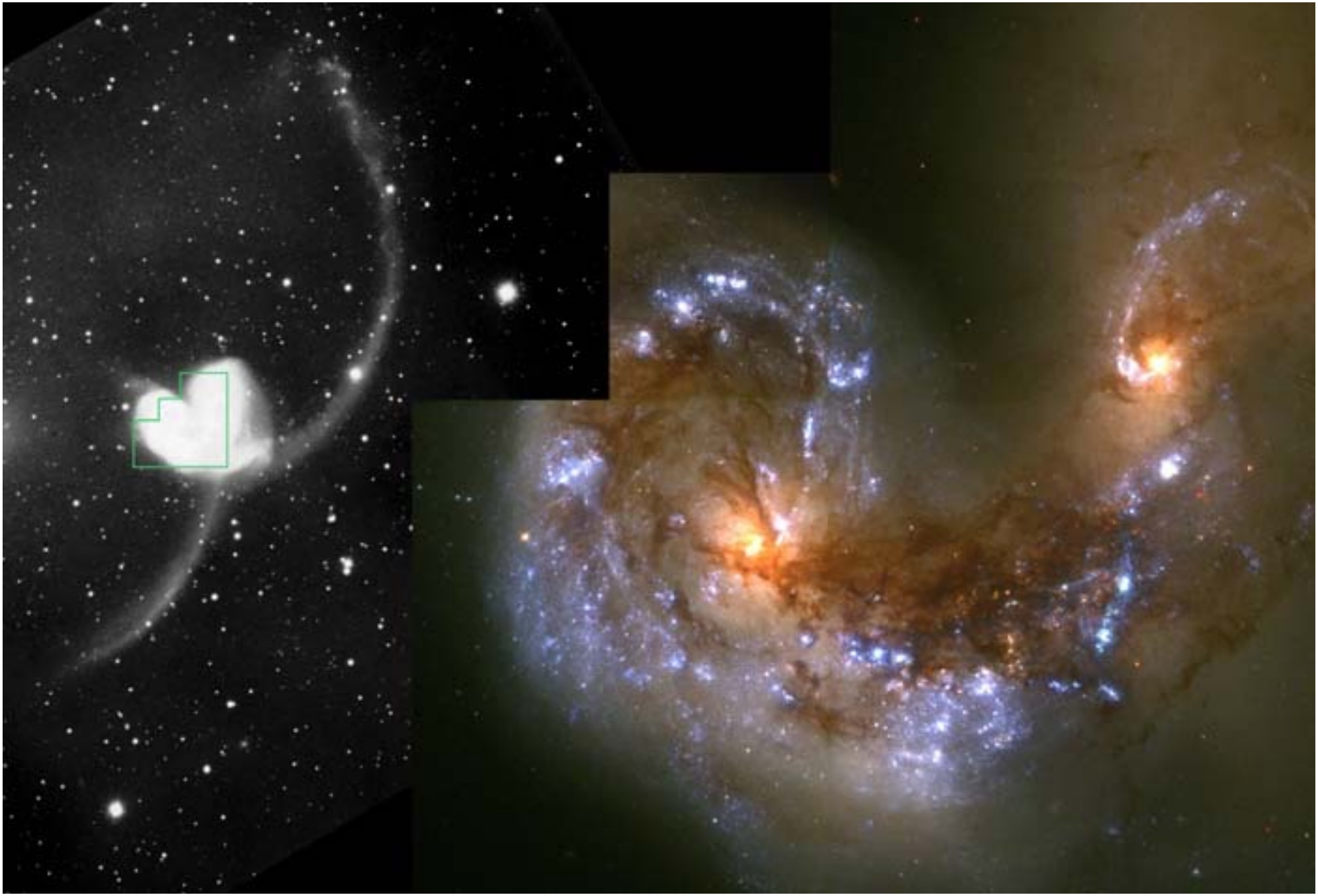
- The field started by Toomre and Toomre work in 1972
  - They could reproduce many observed features with relatively simple simulations (~100 particles, no gas, no dark matter)

- Terminology:
  - Retrograde: galaxy is rotating in opposite direction as velocity of intruder
  - Direct: galaxy is rotating in same direction as velocity of intruder
  - Impact radius: distance between center of galaxies
  - Inclination angle between galaxy and intruder
  - Viewing angle: our l.o.s. to the merger

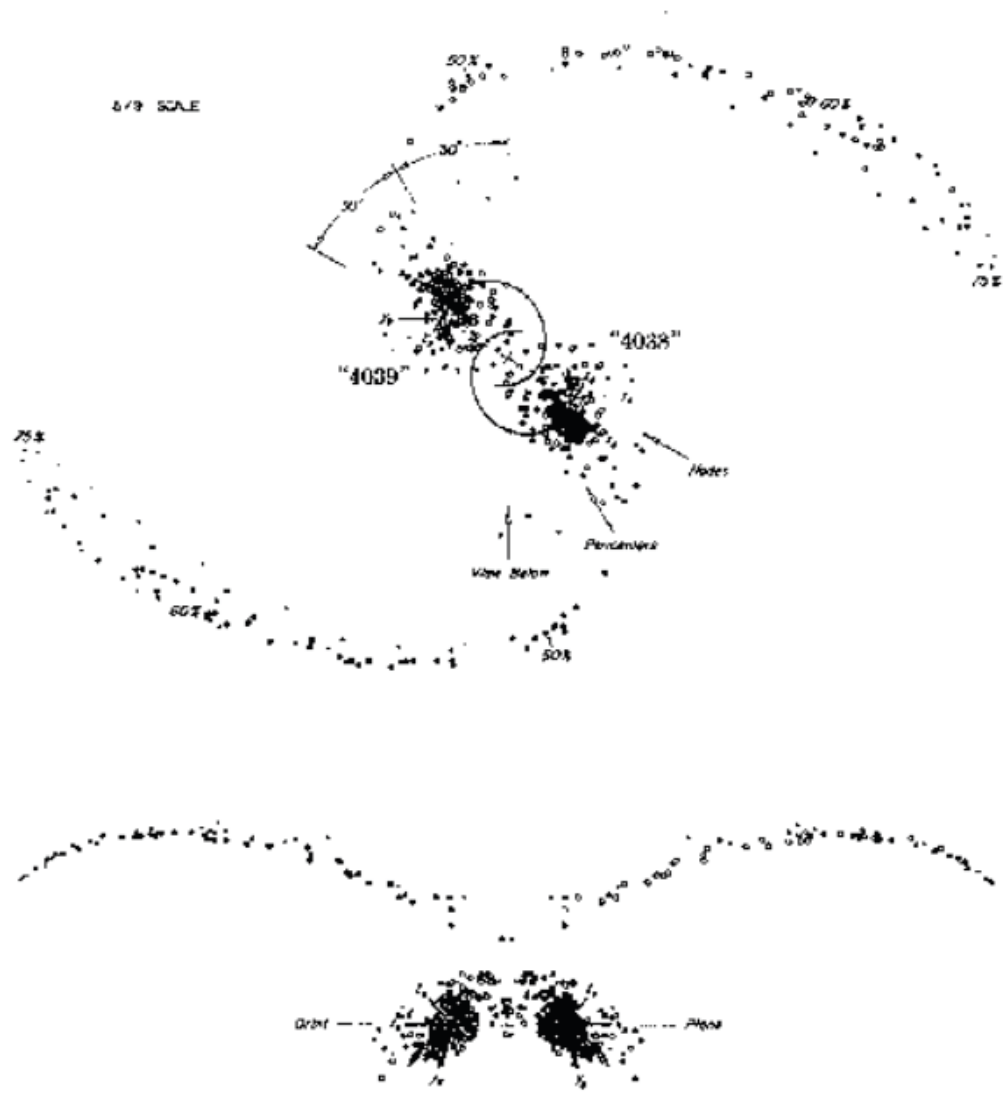
Retrograde encounter (Toomre & Toomre 1972)



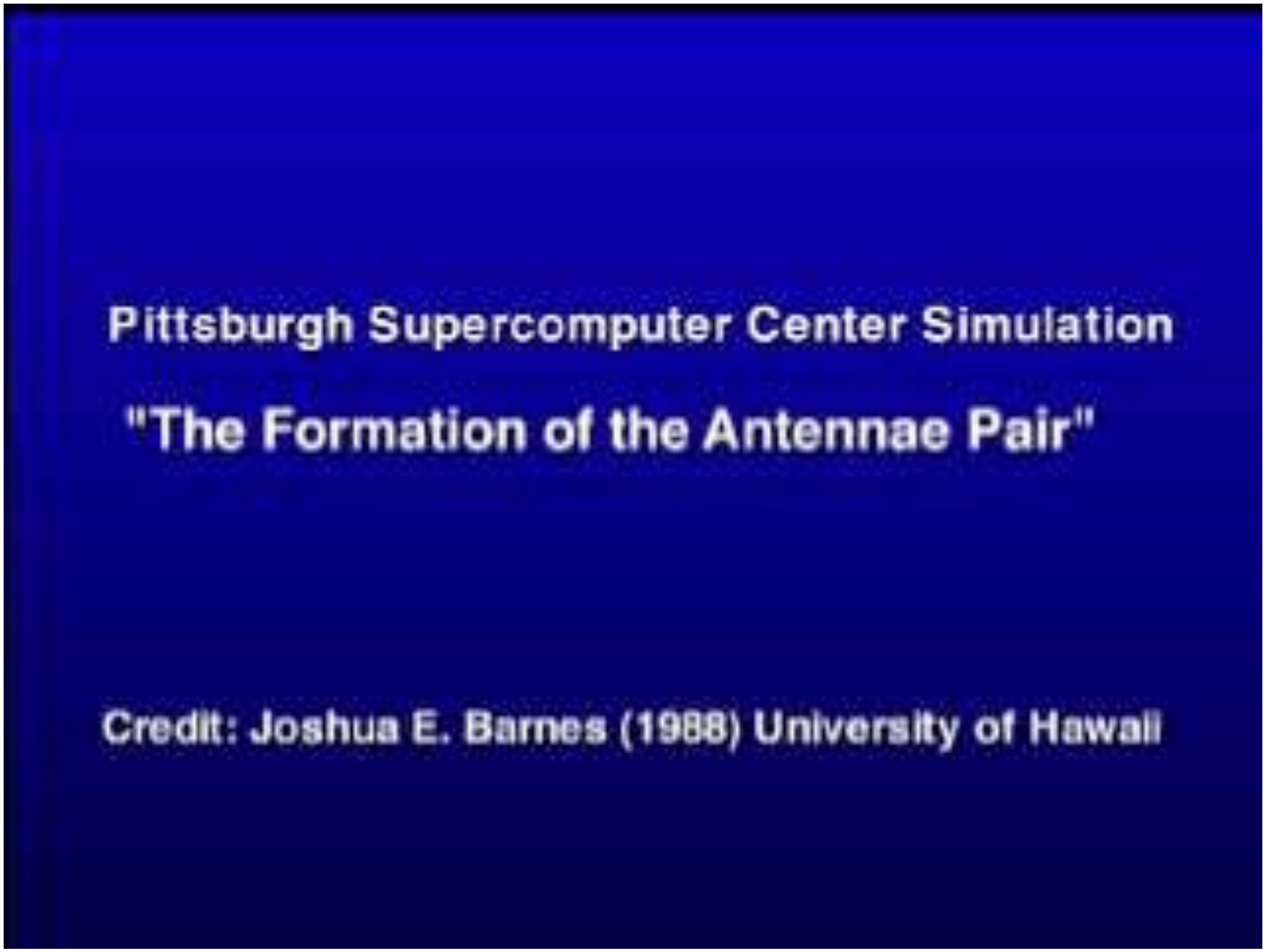
Direct encounter (Toomre & Toomre 1972)

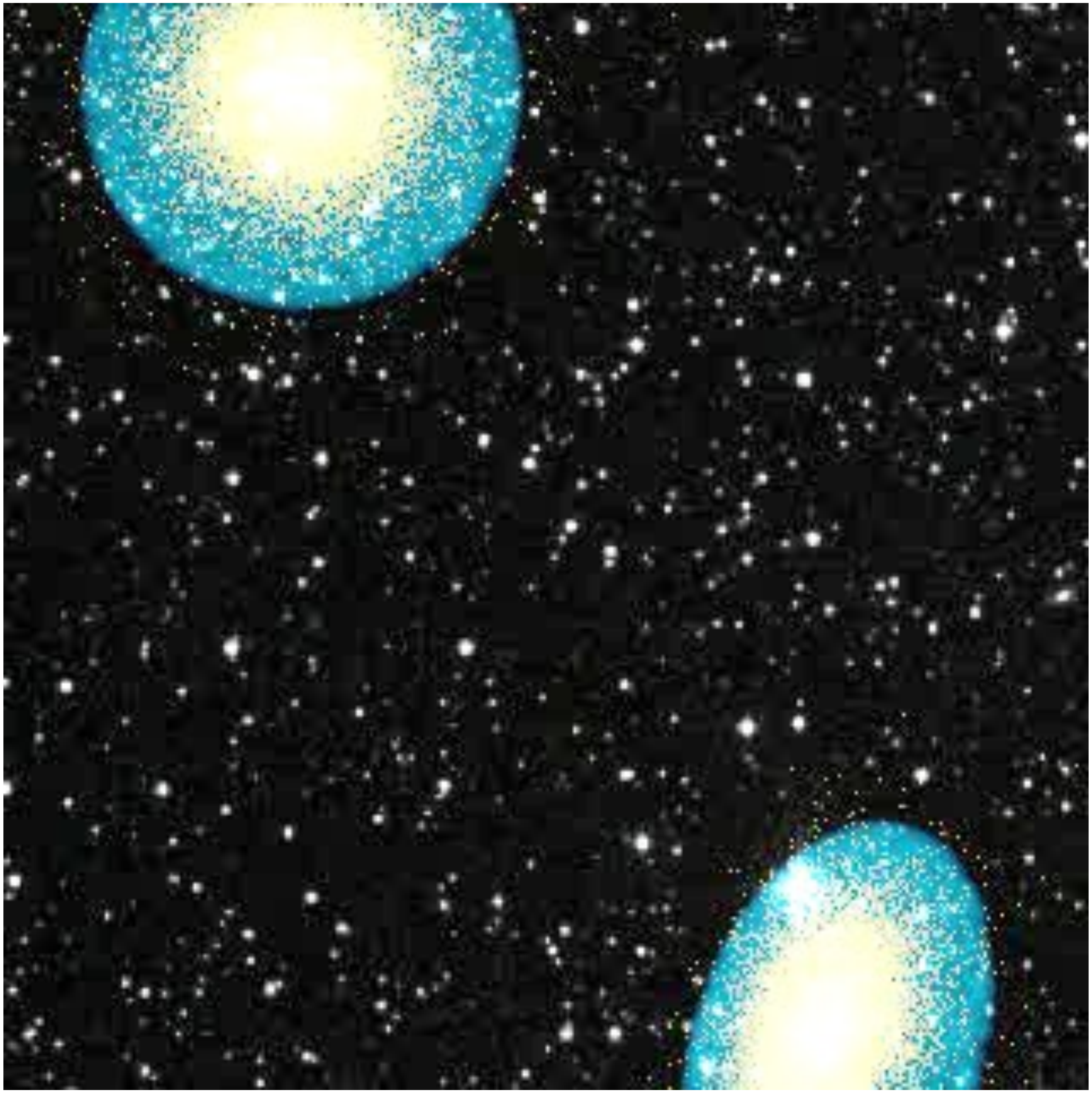


Toomre & Toomre 1972 reproducing the Antennae



Simulations of the Antenna, Barnes 2000





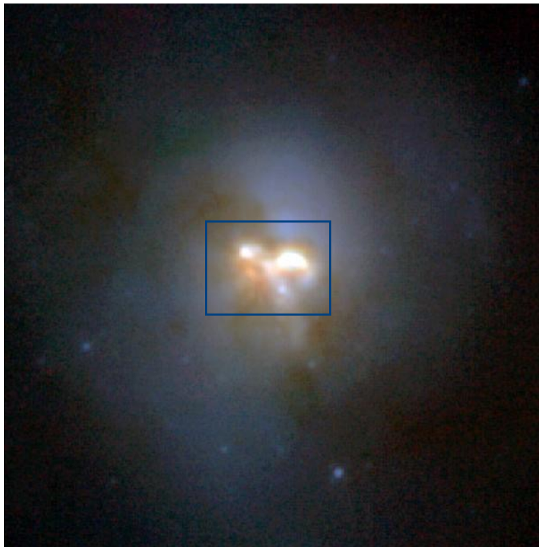
Yellow = stars
Blue = gas

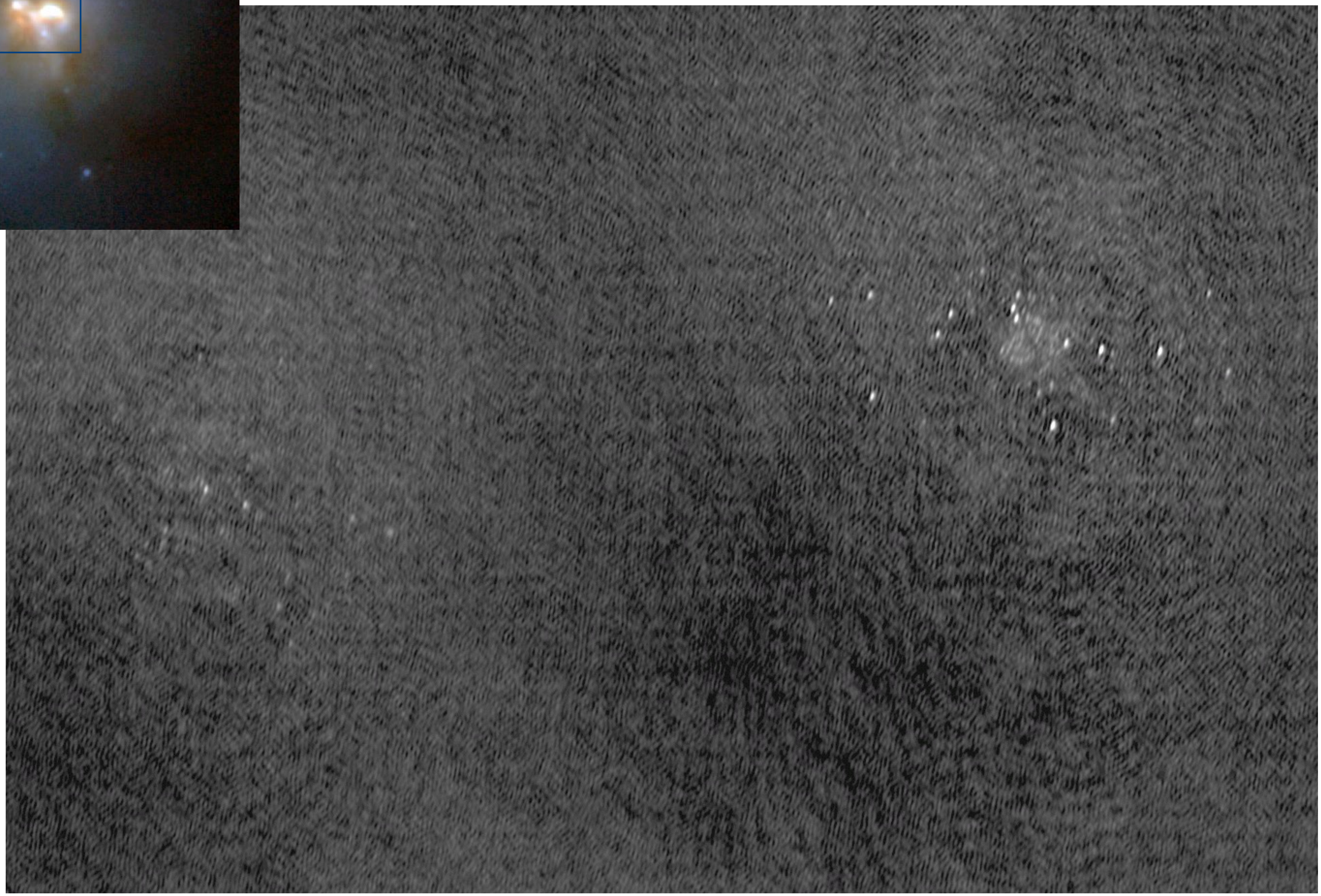
Mihos et al.

Interactions and mergers also lead to "starbursts": unusually high rates of star formation. Cause is the disruption of orbits of star forming clouds in the galaxies. They often sink to the center of each galaxy or the merged pair.   Resulting high density of clouds => squeezed together, many start to collapse and form stars.

M82

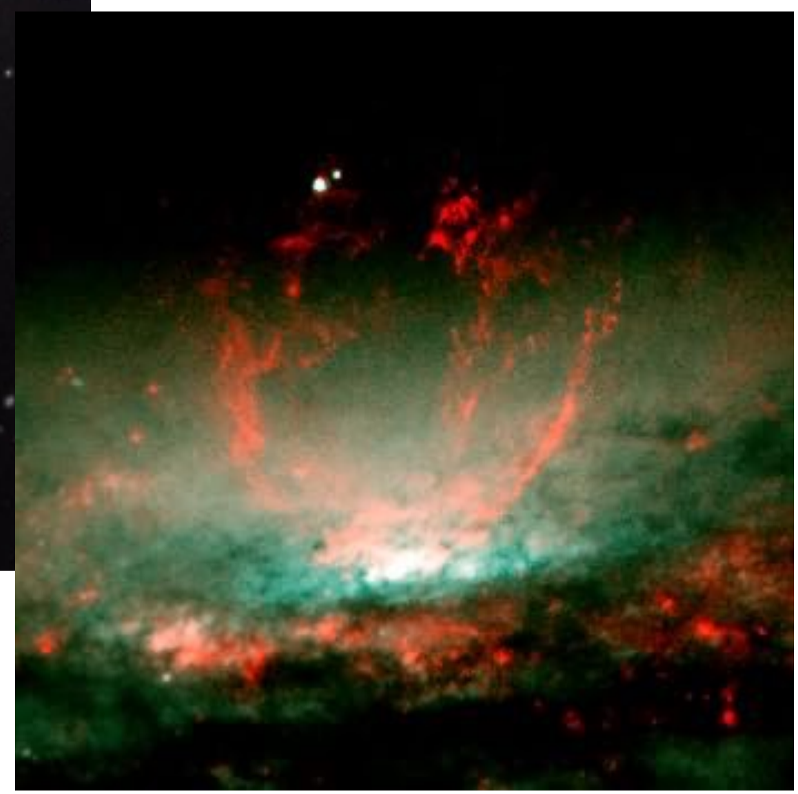
Arp 220 - A starburst Galaxy





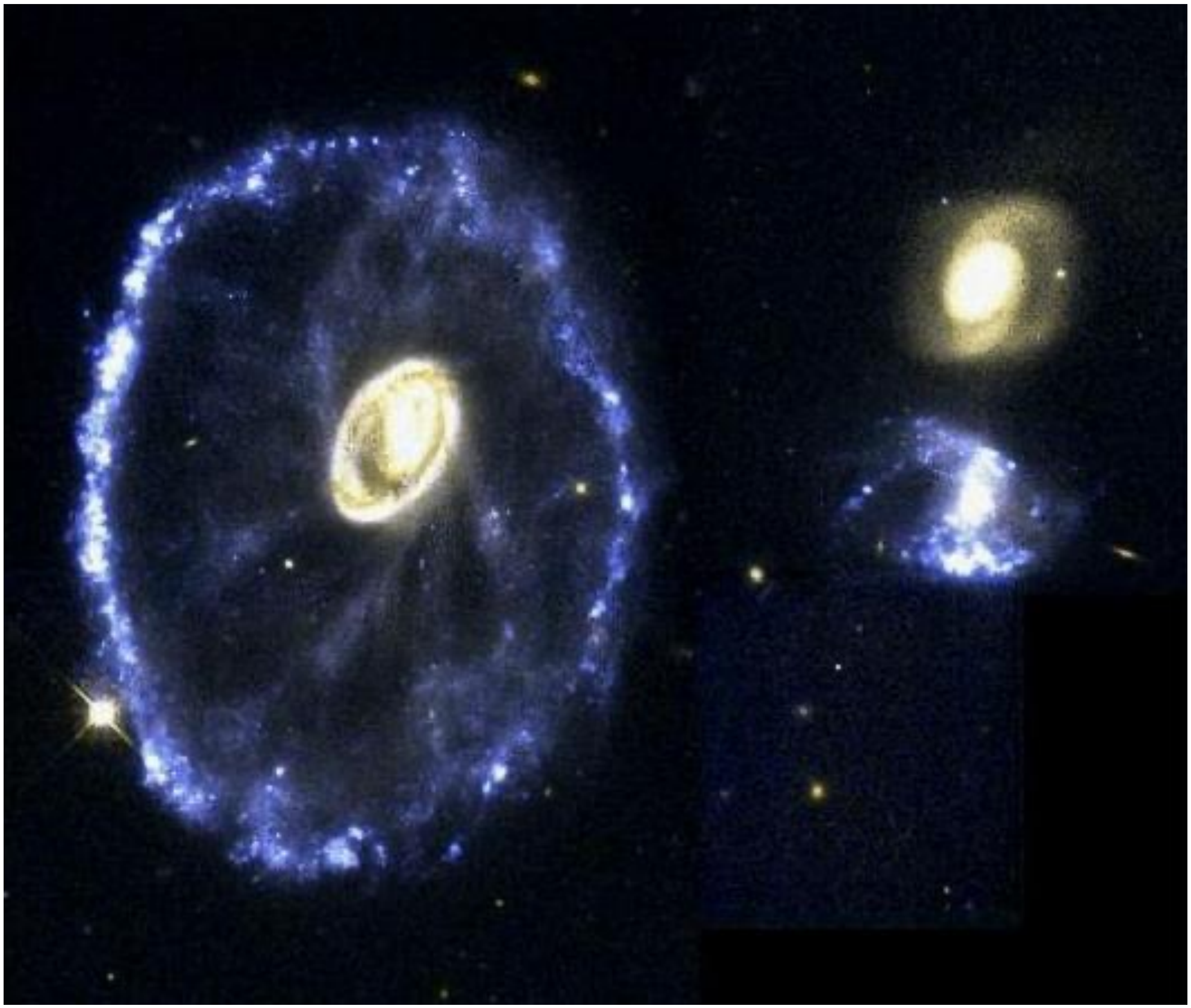
VLBA Image of the core of Arp 220 at 1.4 GHz - Lonsdale et al. in prep

In some starbursts, supernova rate so high that the exploded gas combines to form outflow from disk.

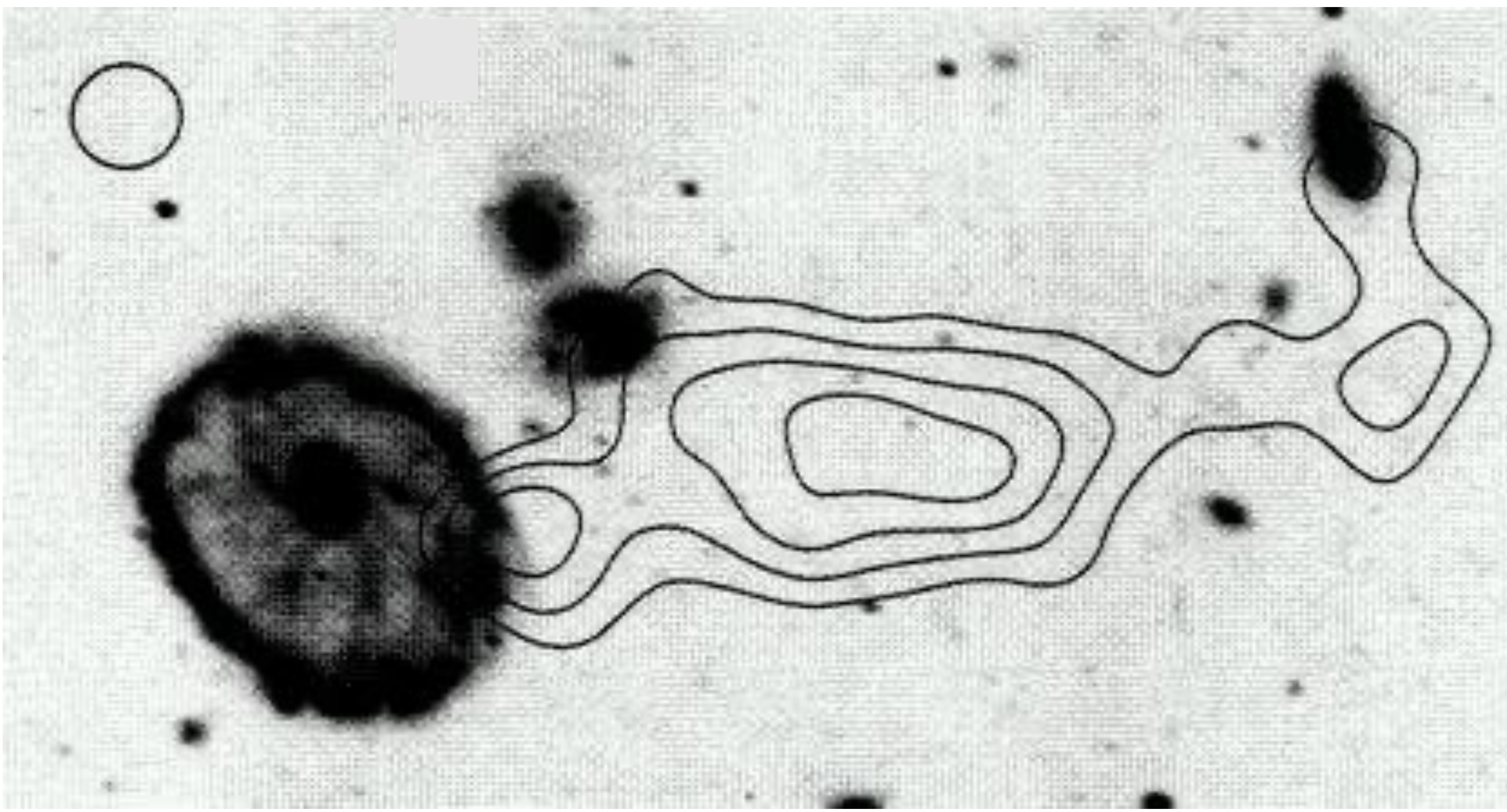


Sometimes a galaxy may pass right through another one, creating a ring galaxy.

Hubble image of The “Cartwheel” galaxy



VLA observations show a bridge of atomic gas connecting Cartwheel and a more distant galaxy.



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:

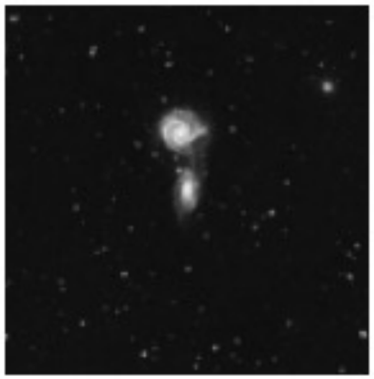
- two large galaxies
- Growth of cDs
- 2 spirals => E?

What fraction of E's formed this way?

The Toomre Merger Sequence

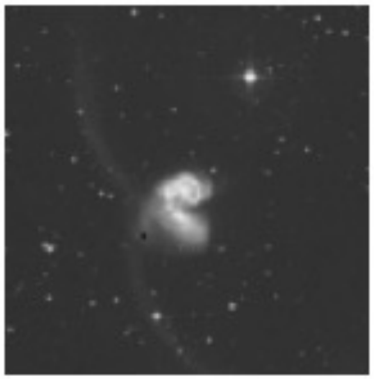
- For a major merger the mass ratio is 1/1 ~ 1/3.
- These types of merges will destroy the disks of both galaxies and eventually produce a spheroidal system (bulge like, elliptical galaxy).
- The transformation from a flattened disk system to a spheroidal occurs via *violent relaxation.*
  - Violent 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.



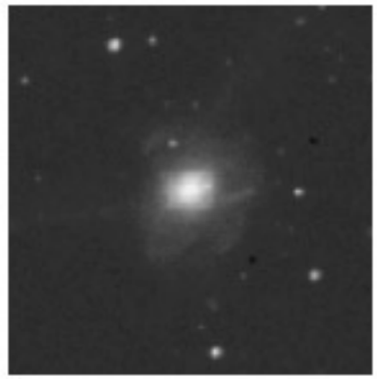
NGC5426/5427

Credit: DSS



NGC4038/4039

Credit: DSS



NGC7252

Credit: DSS

NGC3610

Credit: DSS

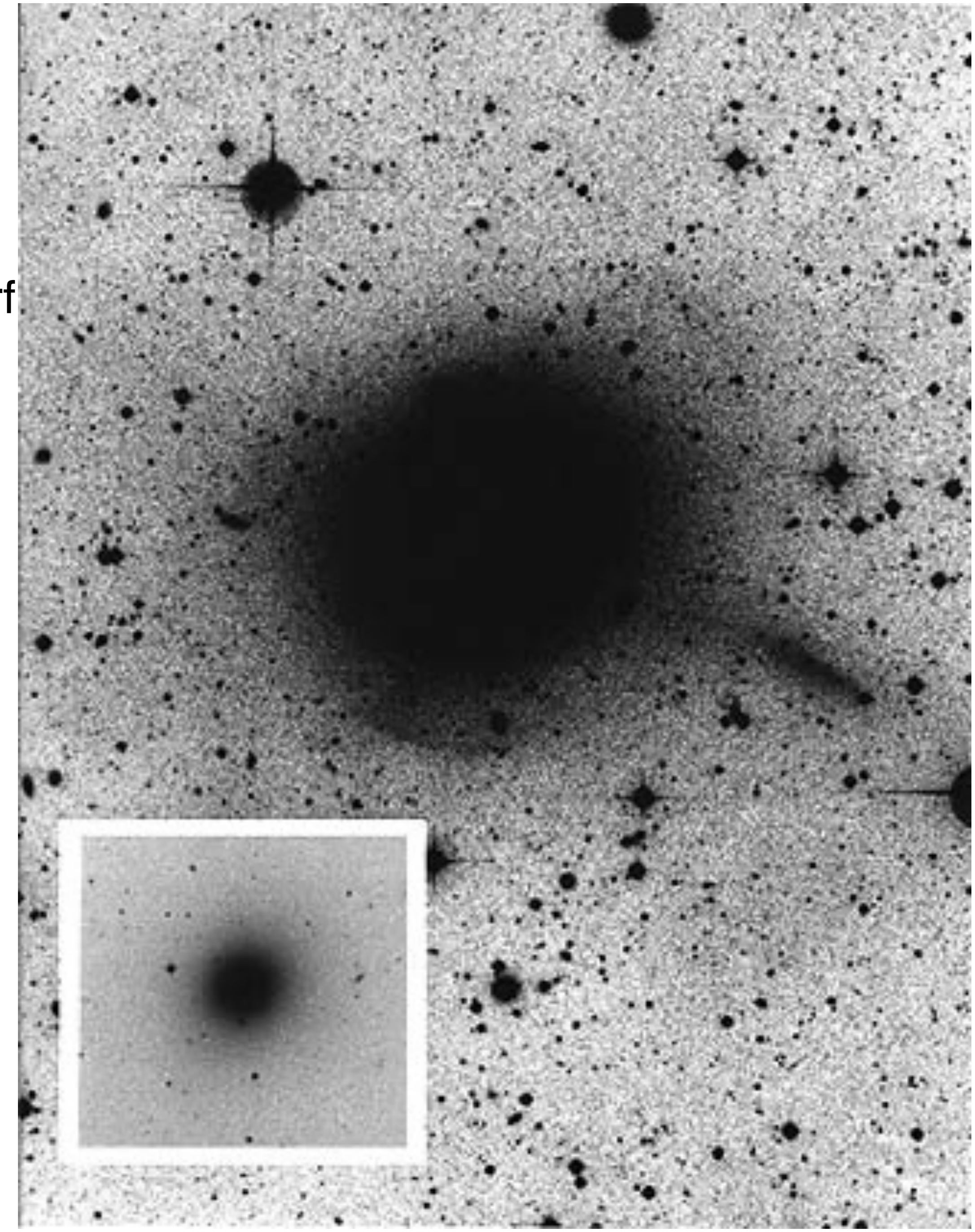
M89

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 (theoretically 10^8-10^9 yrs). Why so short?

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

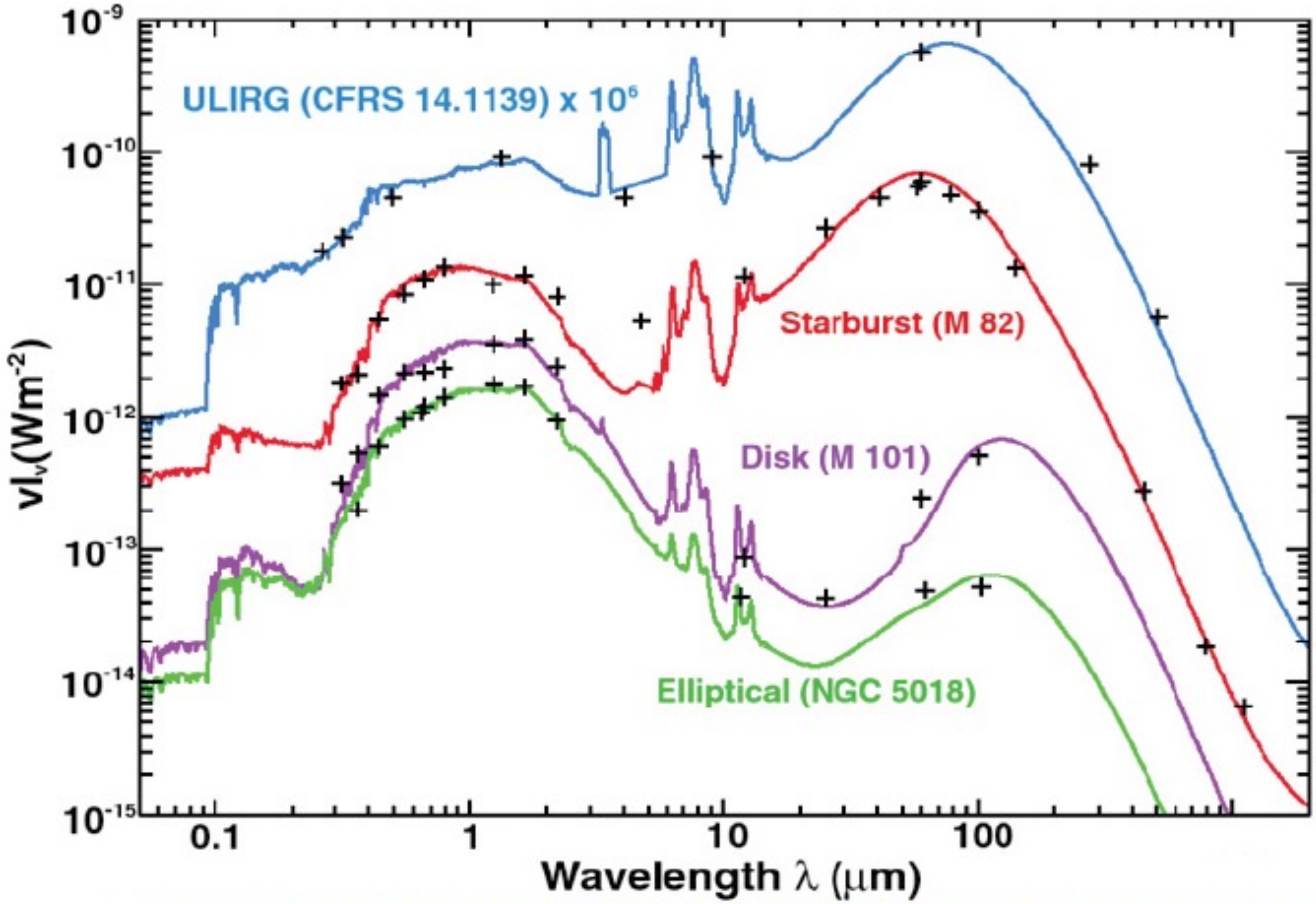


Fig 7.7 (P. Chanial, G. Lagache) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

$2(K_0) + P_0 = 0$ where K = Kinetic Energy, P = Potential Energy

$E_0 = K_0 + P_0 = -K_0$

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

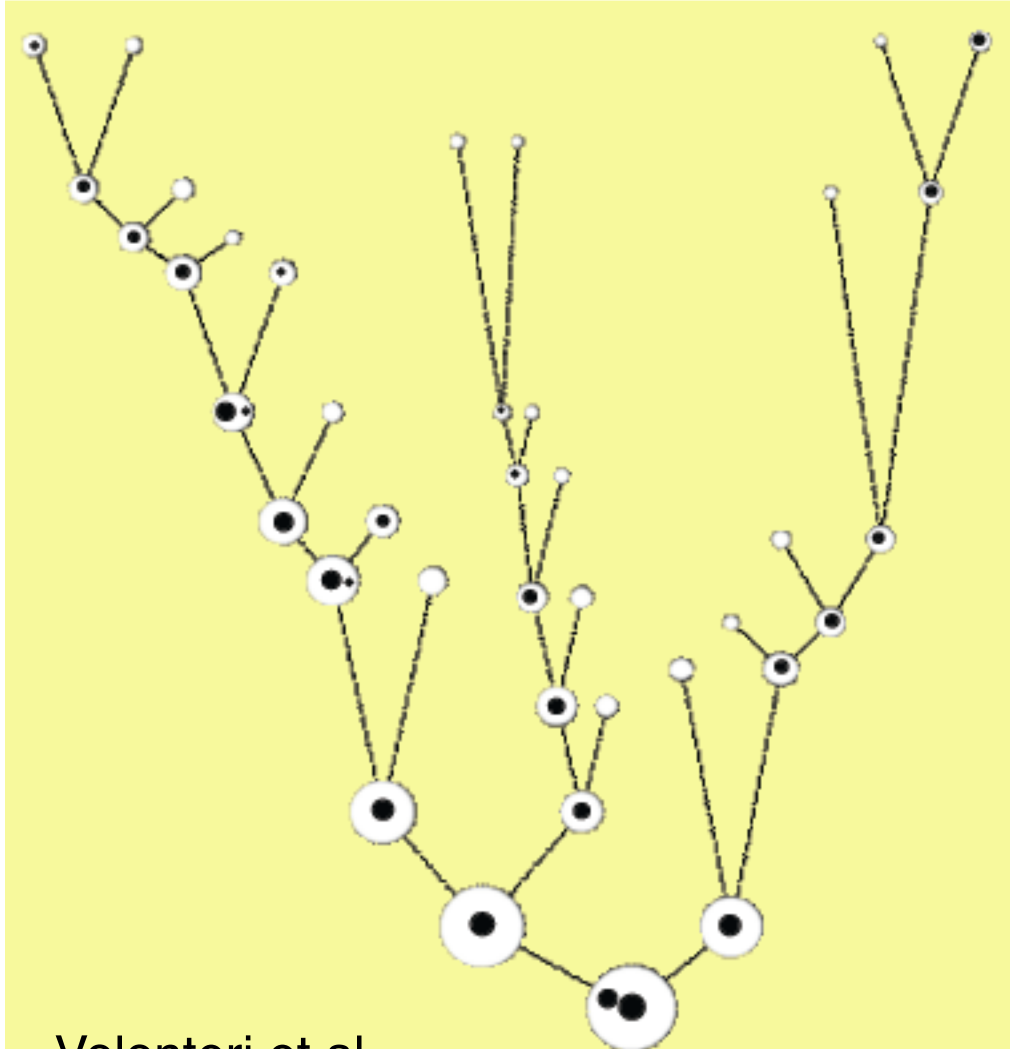
- Total energy must be conserved, so long after the encounter when the system is virialized again

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

- 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

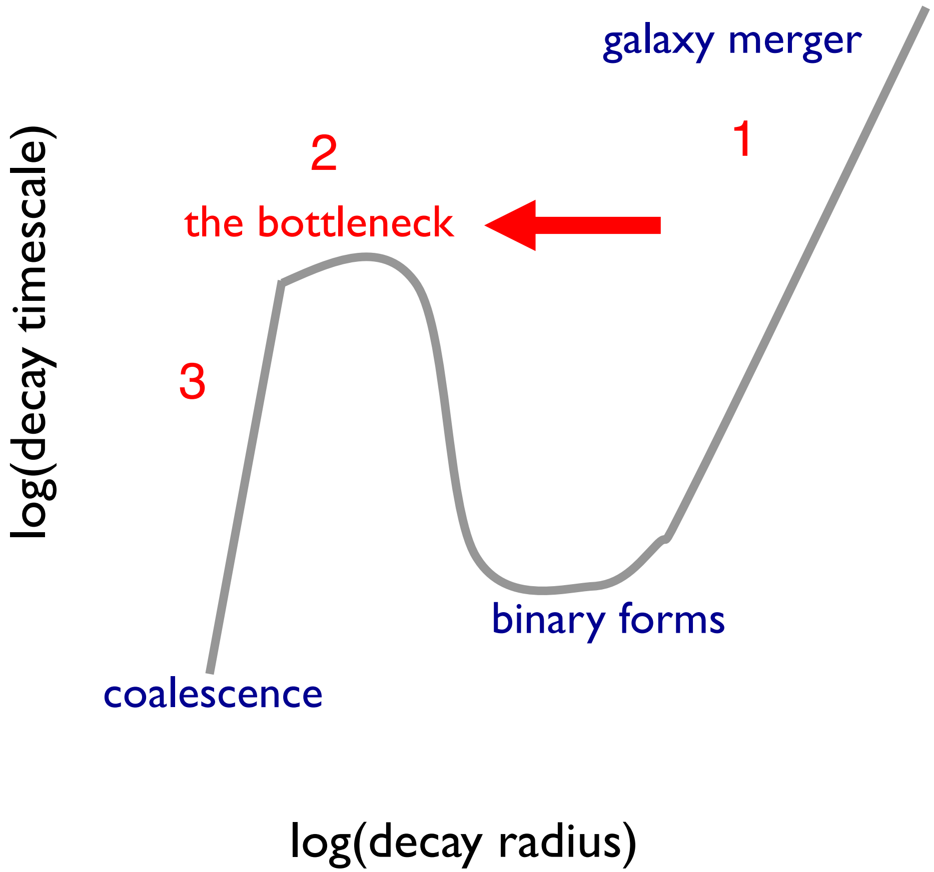
- Assembly+accretion
- Gravitational Rocket problem (Fitchett 1983)
- Slingshot Problem (Volenteri 06)



Volonteri et al.

The Three Stages of BH Merging

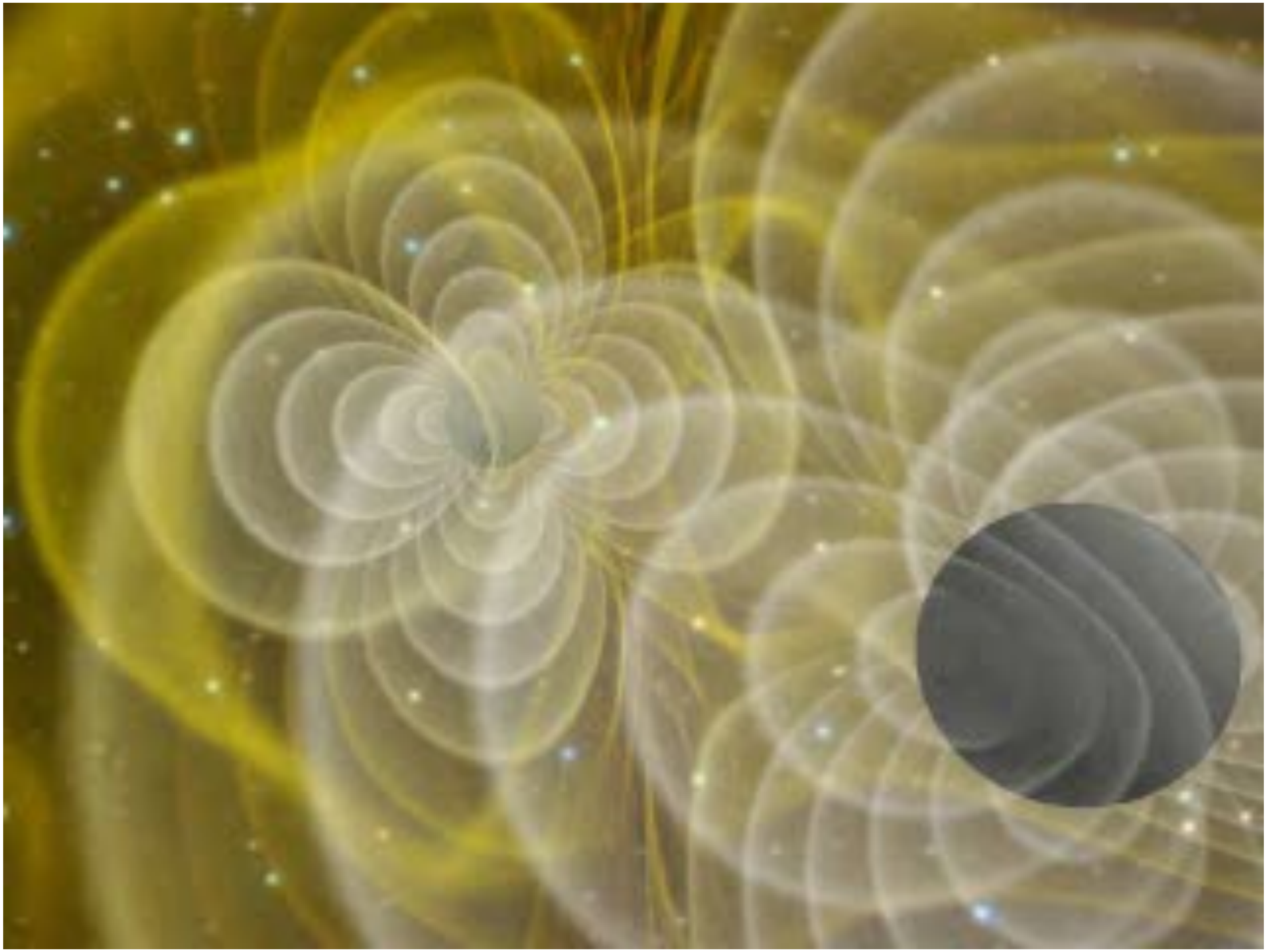
1. Dynamical Friction
2. Binary Hardening
3. Gravitational radiation



(Begelman, Blandford, Rees 1980)

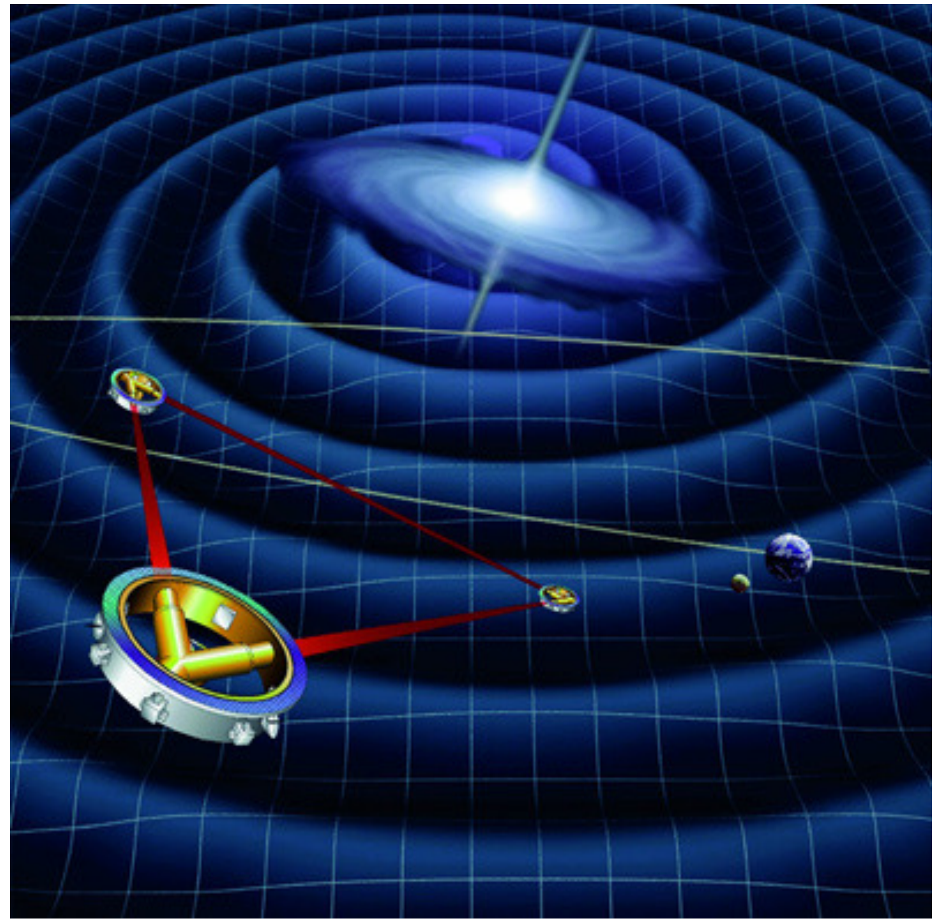
Merritt & Milosavljevic 2004

Simulations of Coalescence

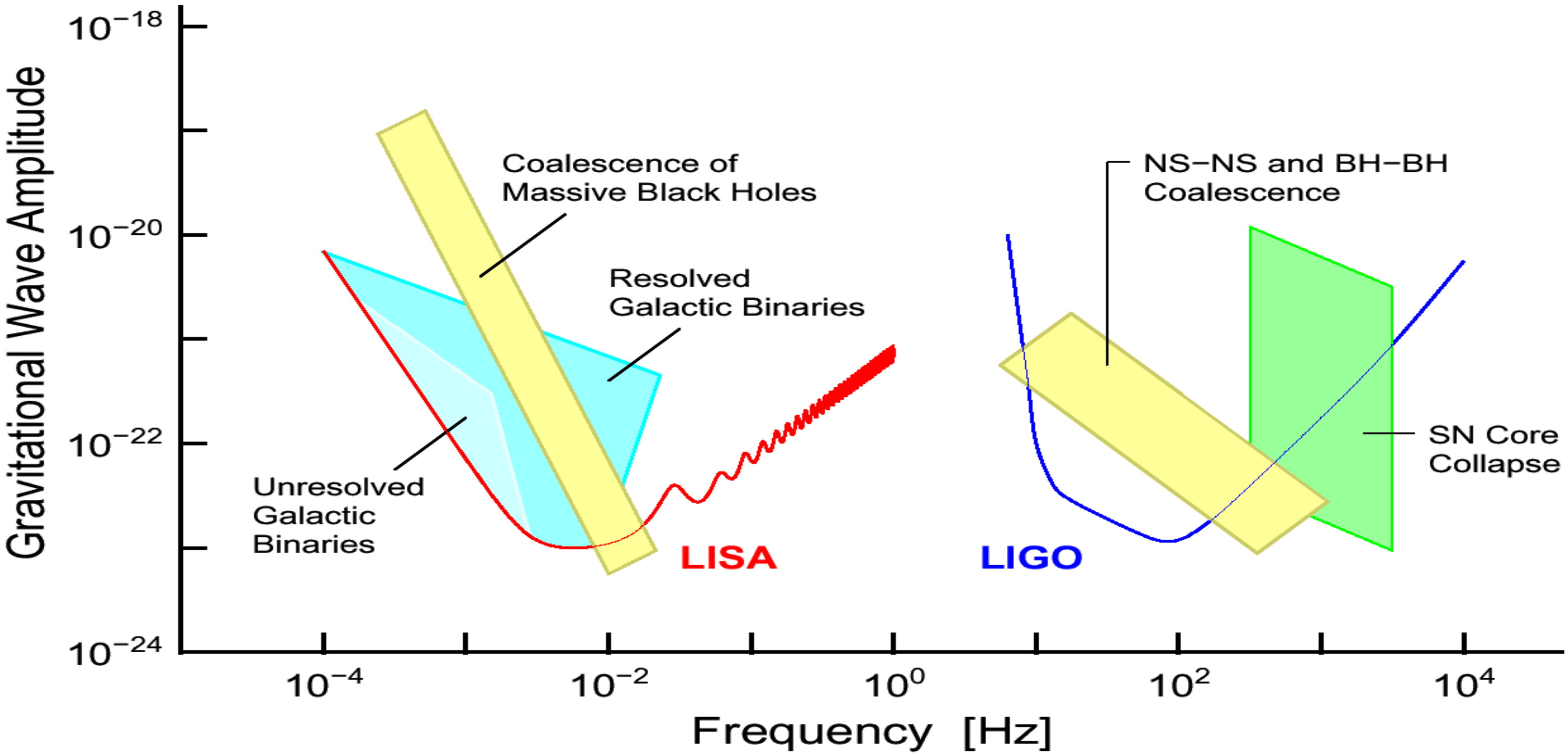


Laser Interferometer Space Antenna (LISA)

- 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)



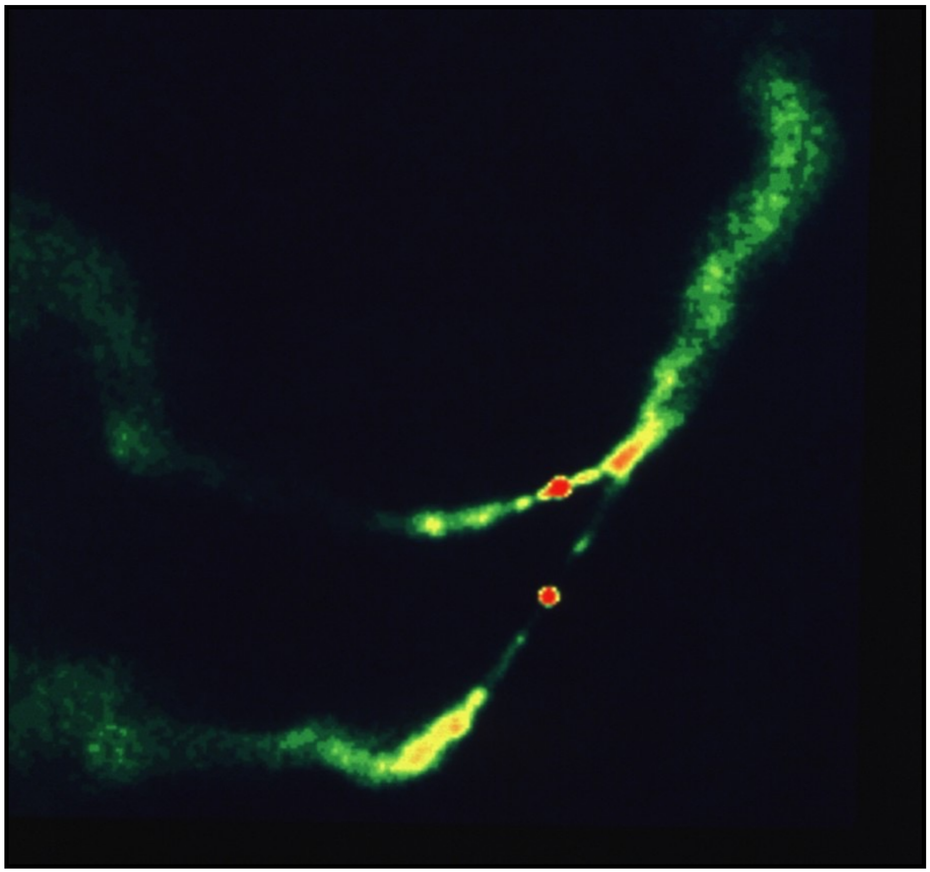
Gravitational Wave Spectrum…



Known Supermassive Binary Black Holes

3C 75

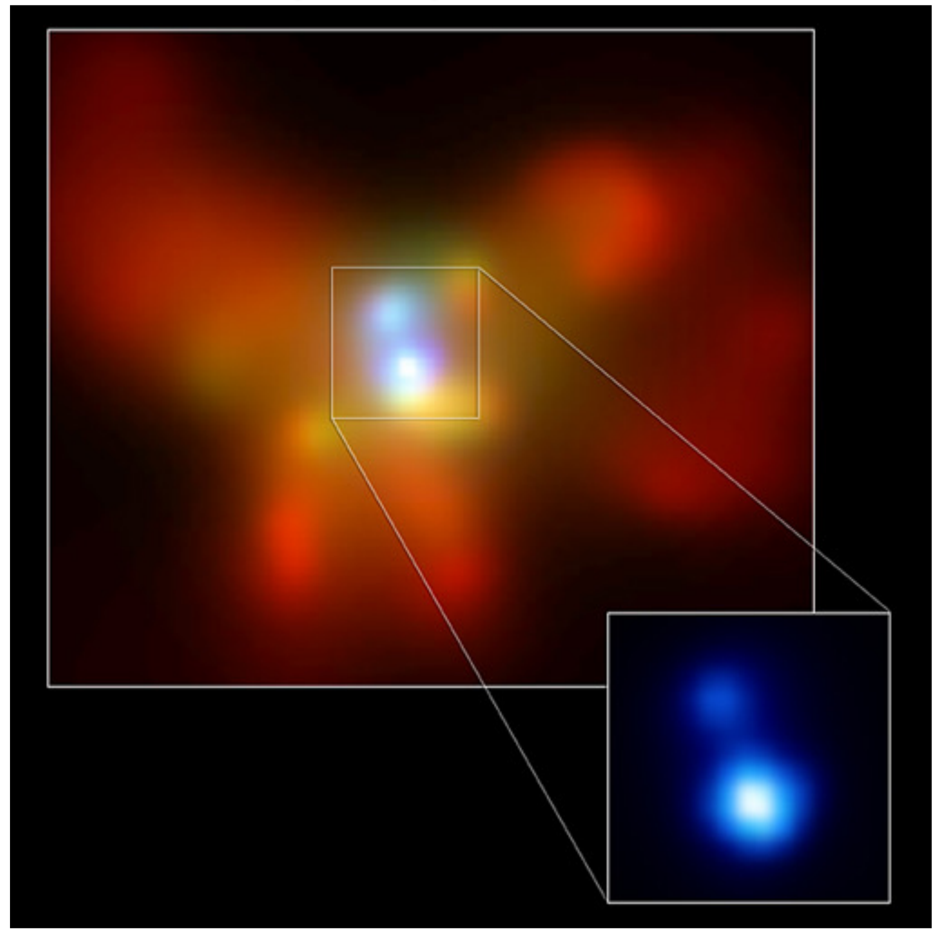
⇨ 7 kpc separation



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

NGC 6240

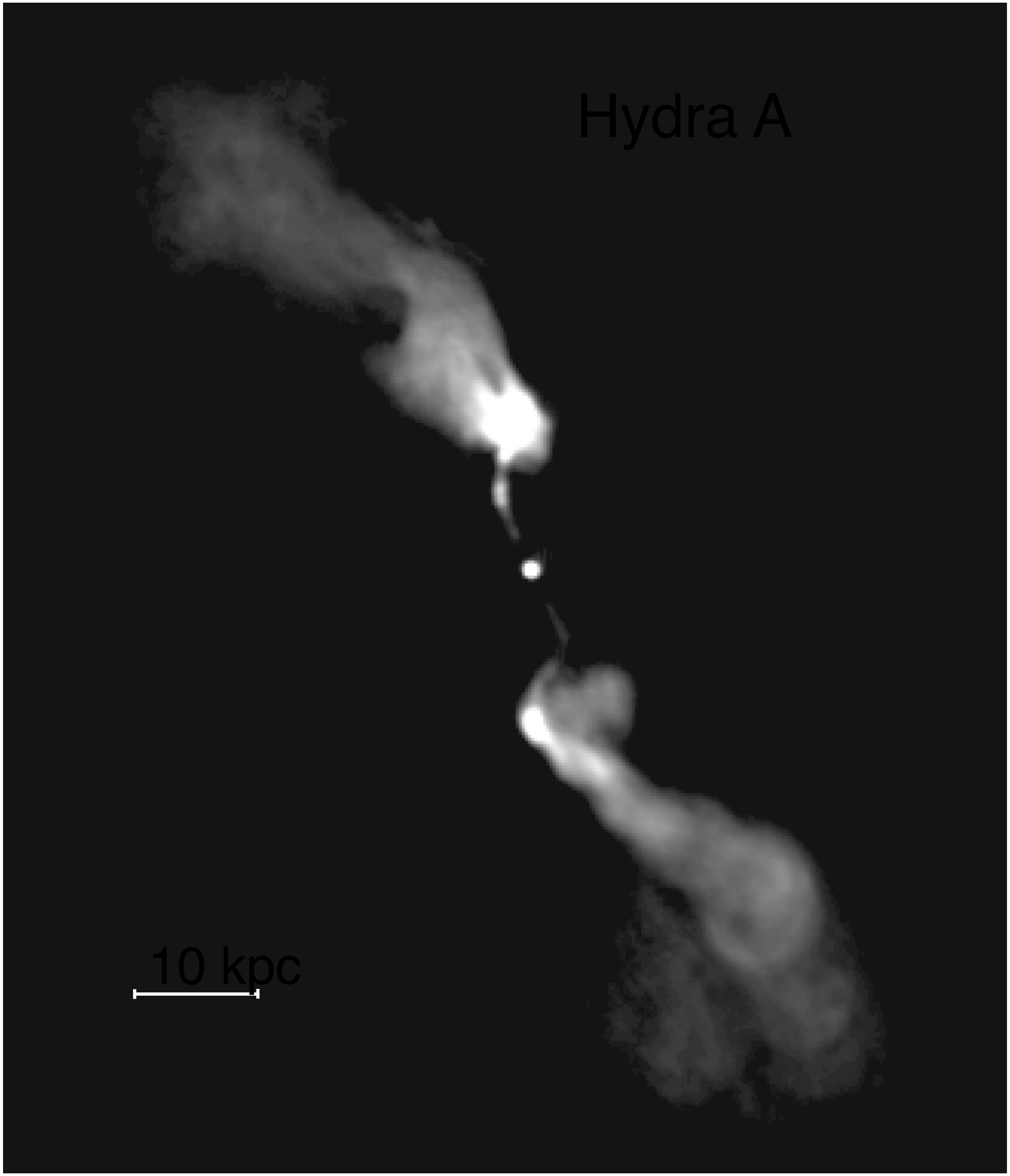
⇨ 1.4 kpc separation



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

Observing Compact SBBHs

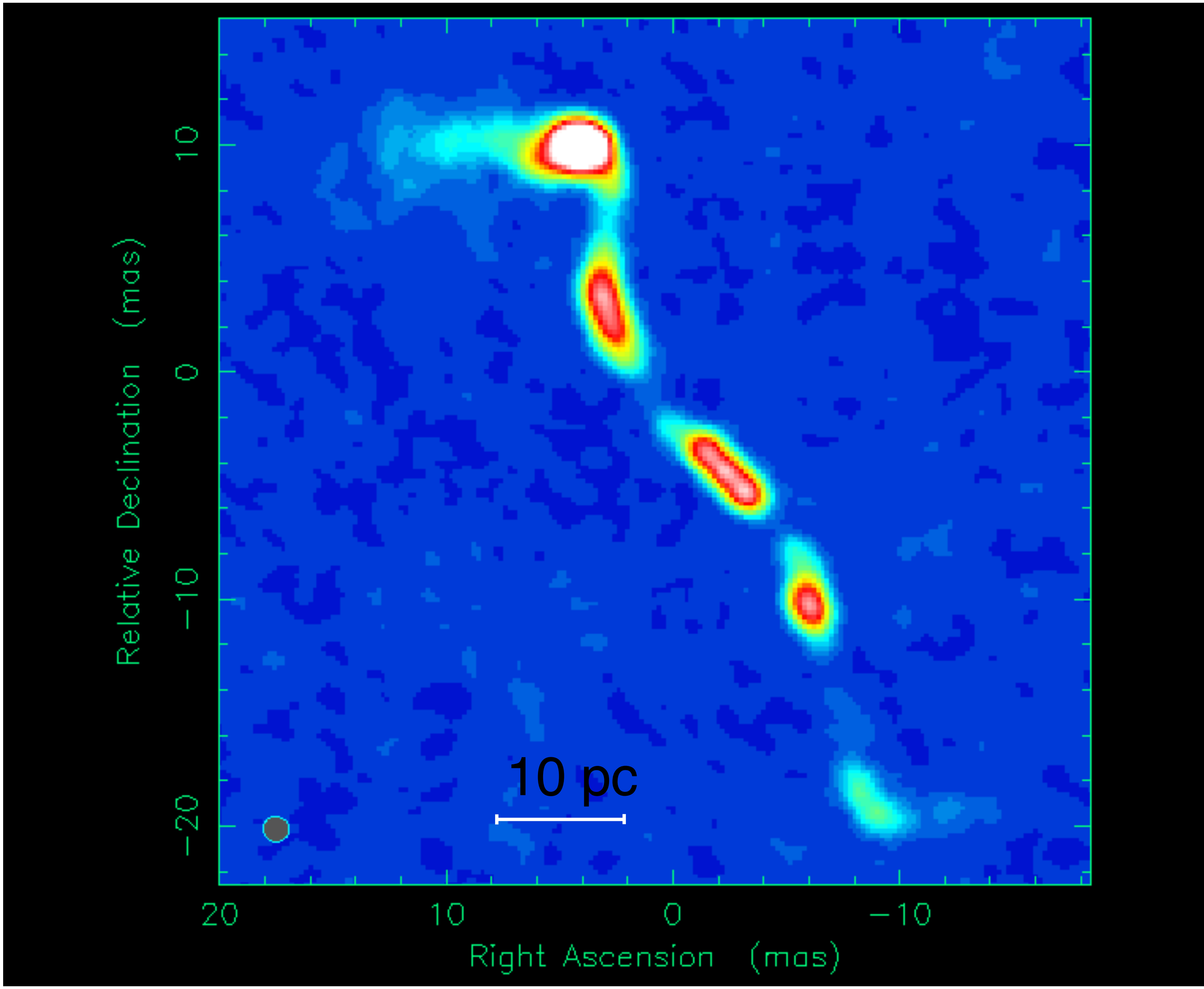
- Evidence for SBBHs
  - Indirect methods
    - Precession, periodic behaviors
    - Double optical lines
  - Direct Imaging with Very Long Baseline Interferometry
    - The radio galaxy 0402+379
- Searching for more SBBHs with the VLBA



P_precession ~ 300,000 y
P_orbital ~ 17 y

Taylor et al. 1992

1946+708



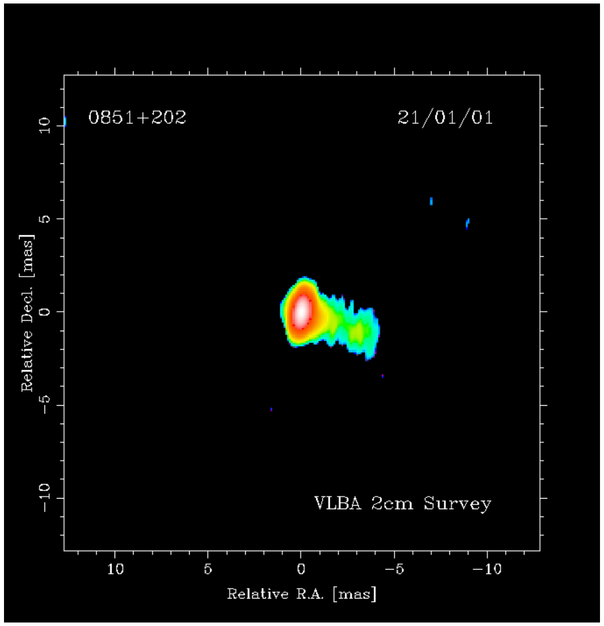
Precession
Period ~ 5700 y

Taylor & Vermeulen

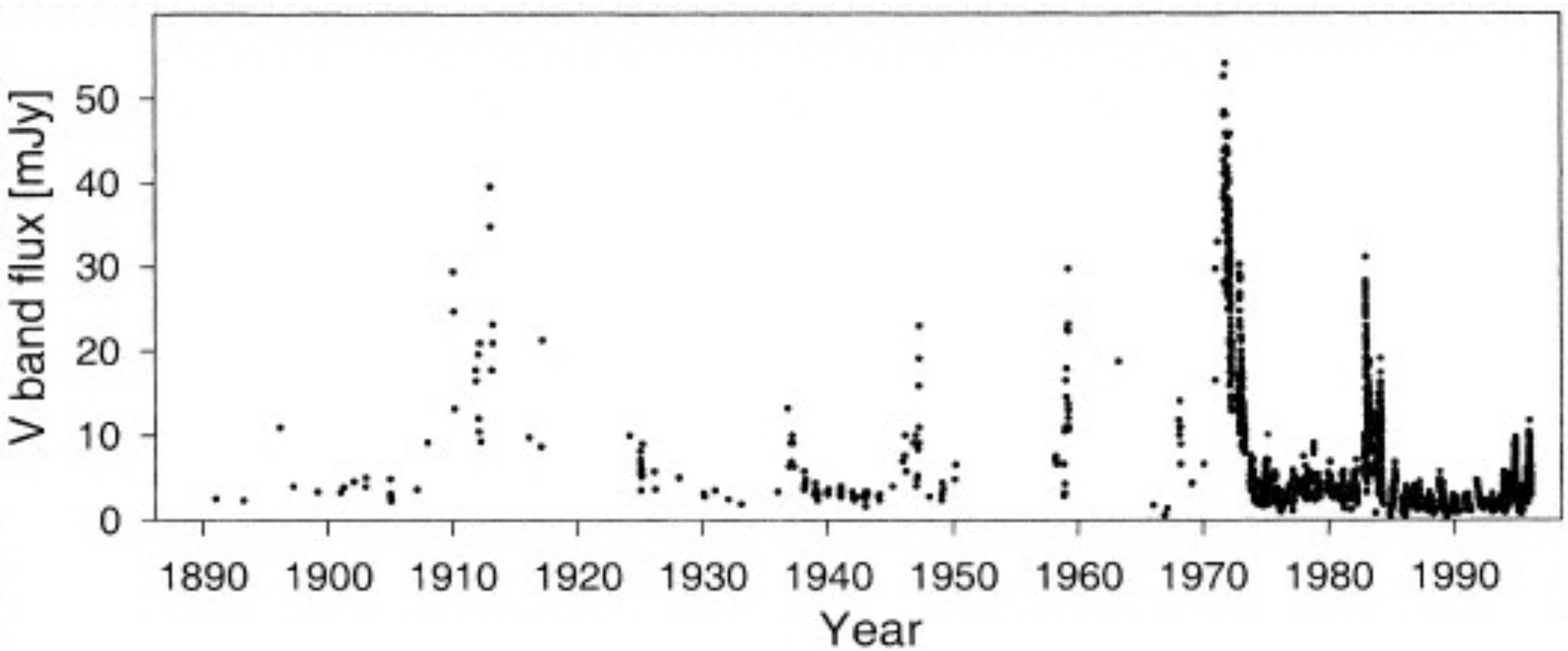
Quasi Periodic Behaviours

OJ287 Maxima every ~11.9 years

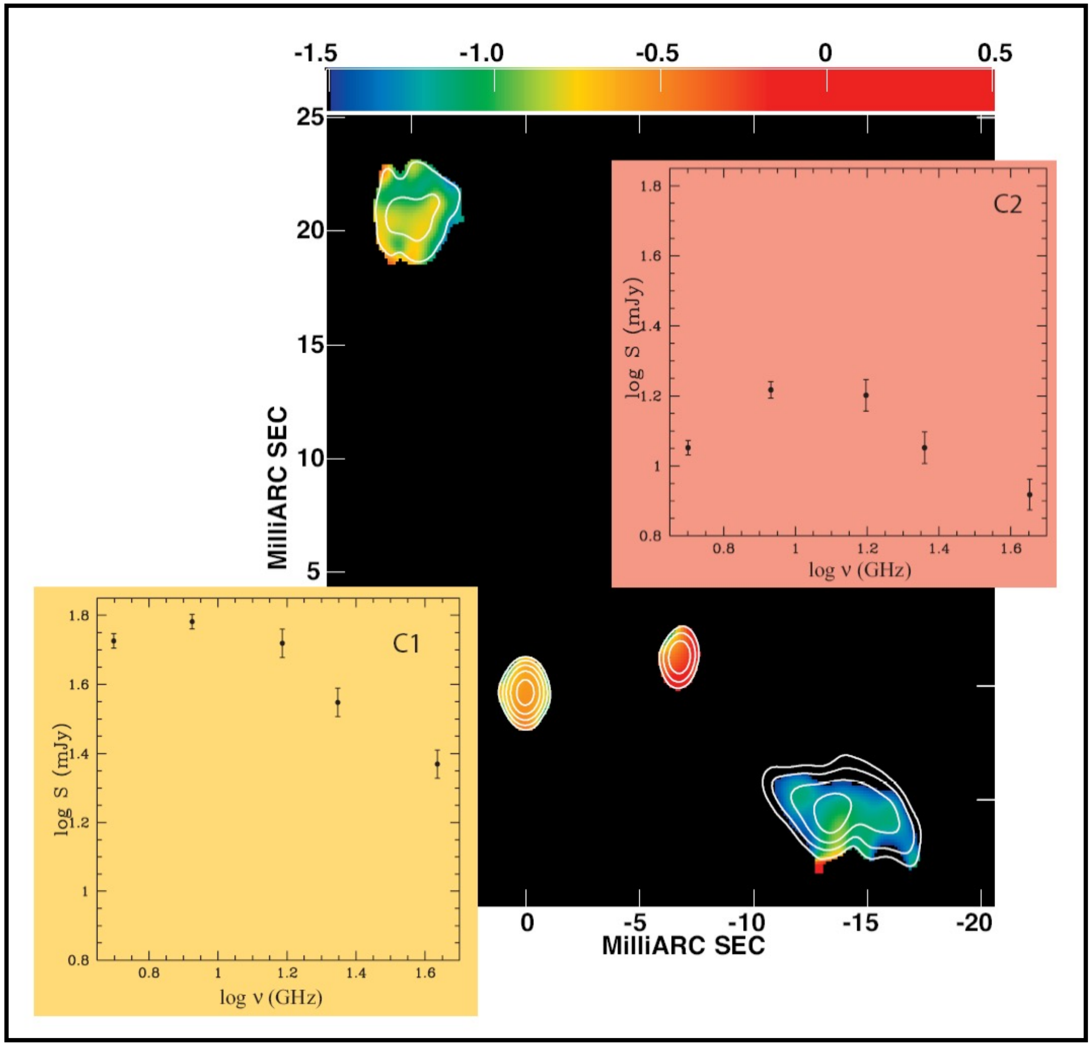
Similar behaviour seen sporadically in 3C273, 3C345, BL Lac, etc.



Valtaoja et al. 2000



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.

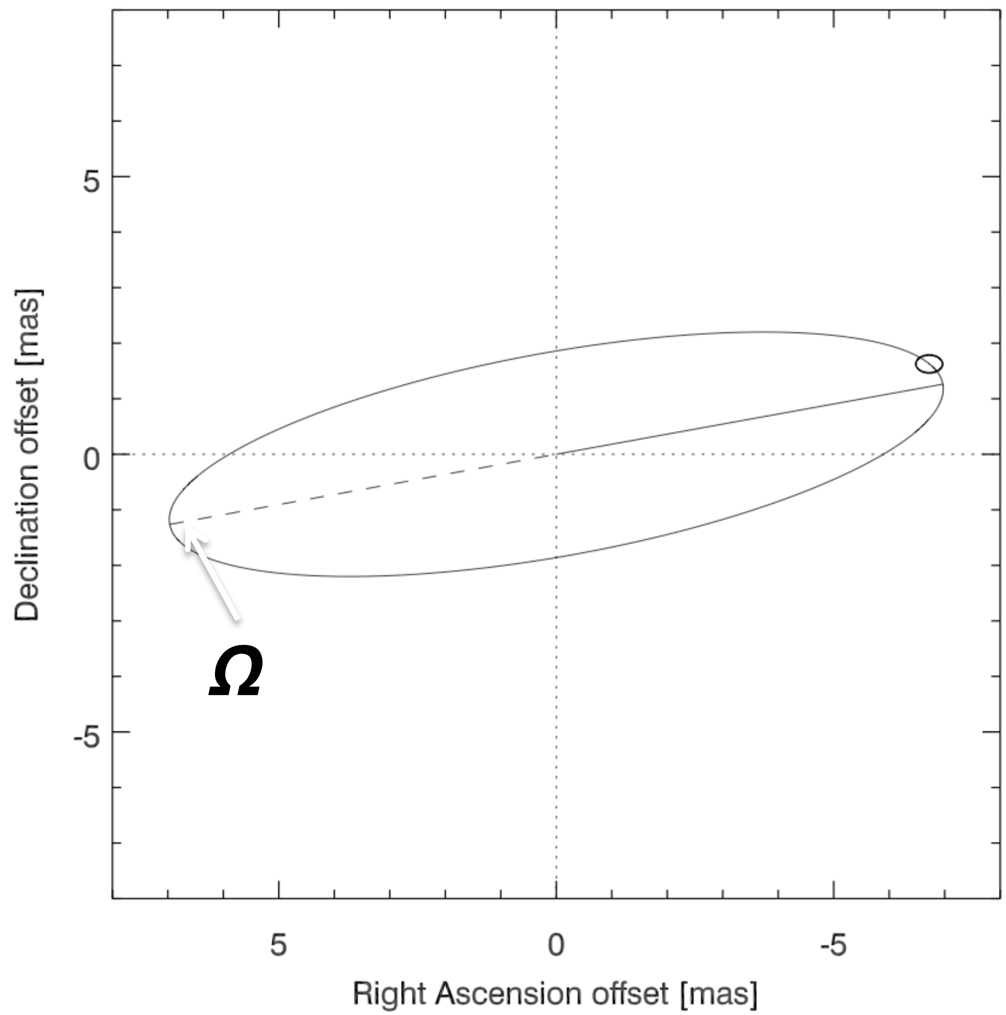
Circular orbit

- 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
T_0 =2,194,481.1 (JD)
= 1296 AD Feb 29

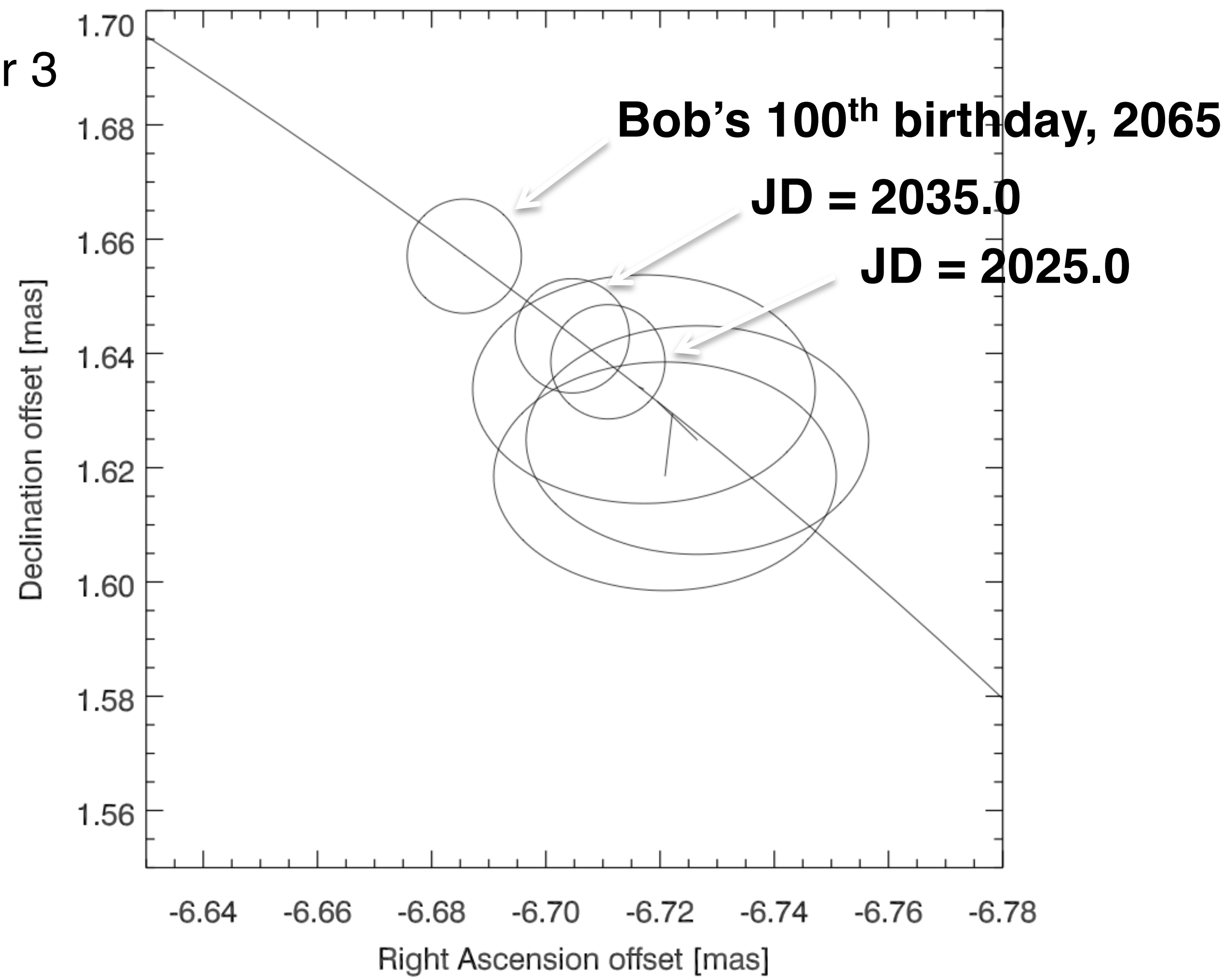
Our 3 observed points shown with 10x error ellipses for visibility



Close-up view, observed and predicted astrometry

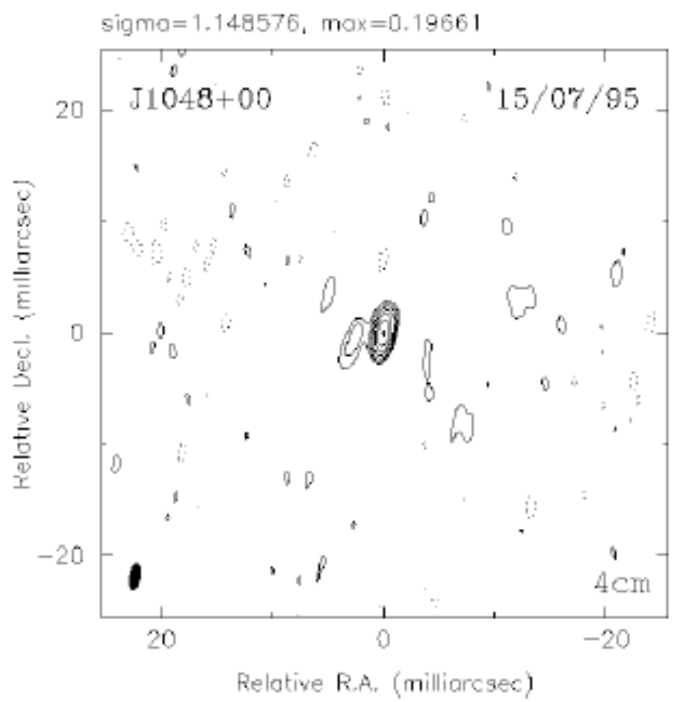
Large error ellipses are our 3 Observed 8 GHz points.

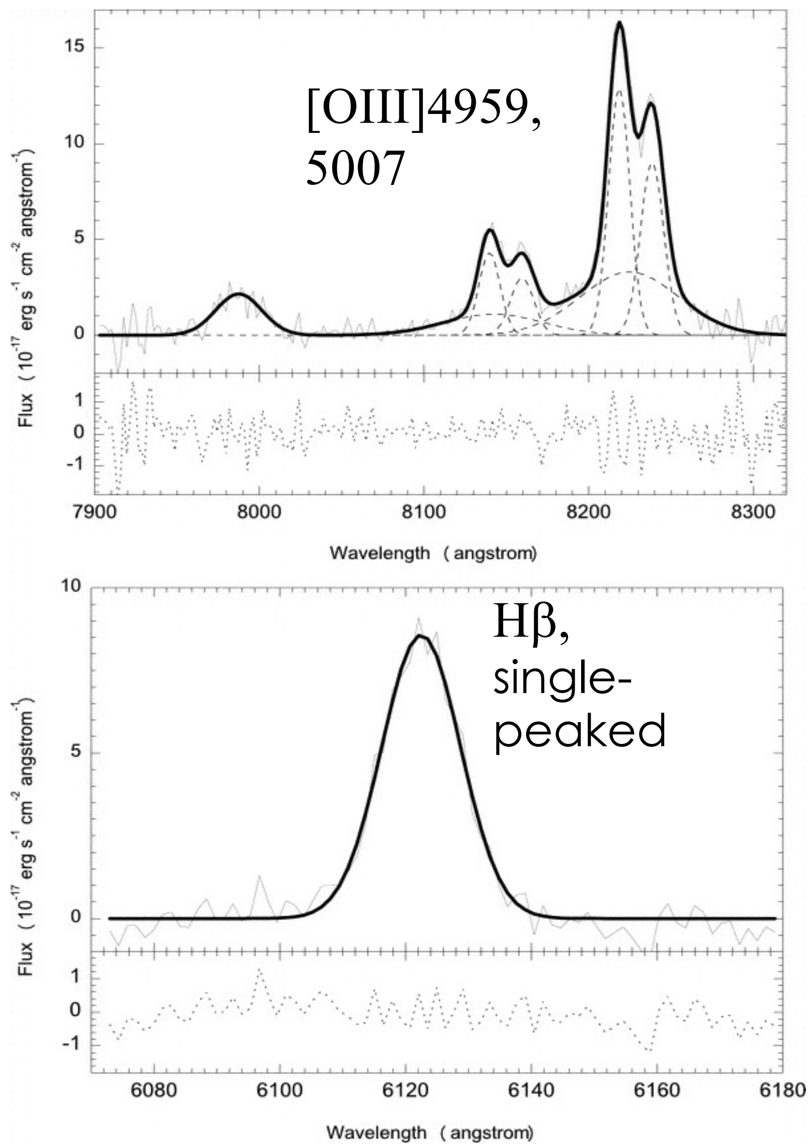
Small error circles are predicted future positions



Double Peaked Narrow Lines

SDSSJ104807+005543





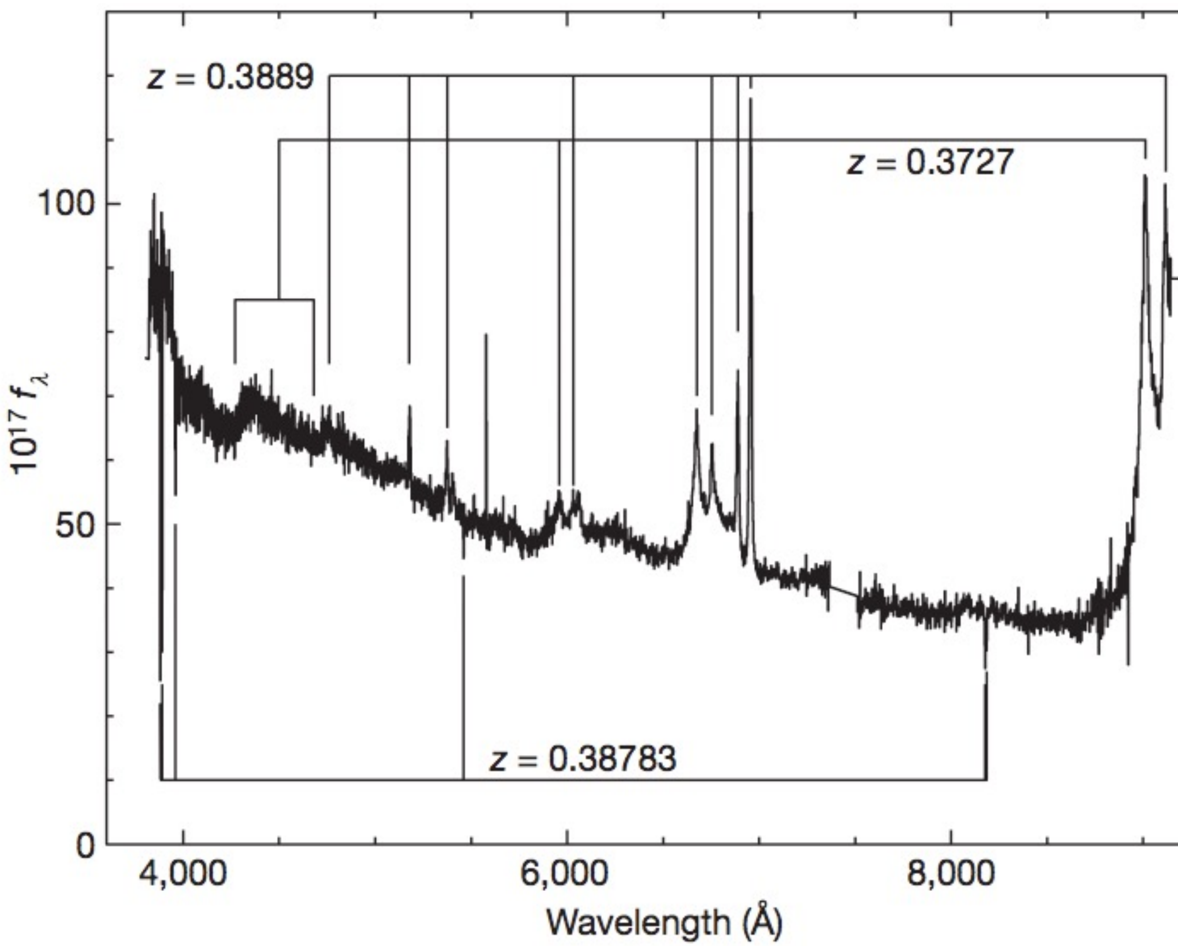
Alternatives: Disks, bipolar outflows

Zhou et al 2005

Double Peaked Broad Lines

SDSSJ1536+0441

Boroson & Lauer 2009



Alternatives: Disks, bipolar outflows