Radio continuum diagnostics of Virgo spiral galaxies

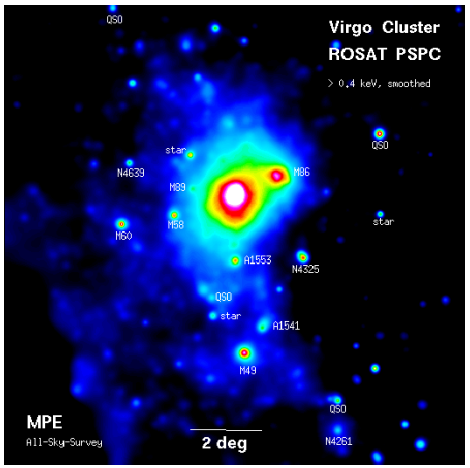
Bernd Vollmer

CDS, Observatoire de Strasbourg

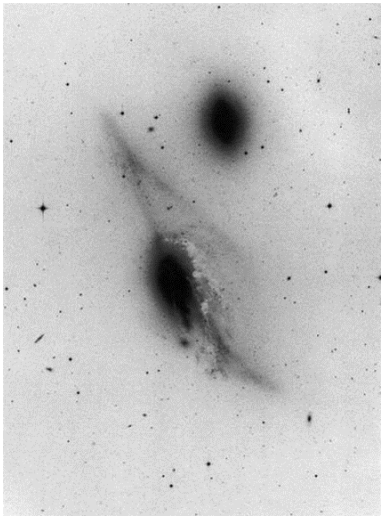
(VIVA: J. Kenney, J. van Gorkom, A. Chung, H. Crowl,
R. Beck, M. Soida, J. Braine)

Interaction of a spiral galaxy with its environment

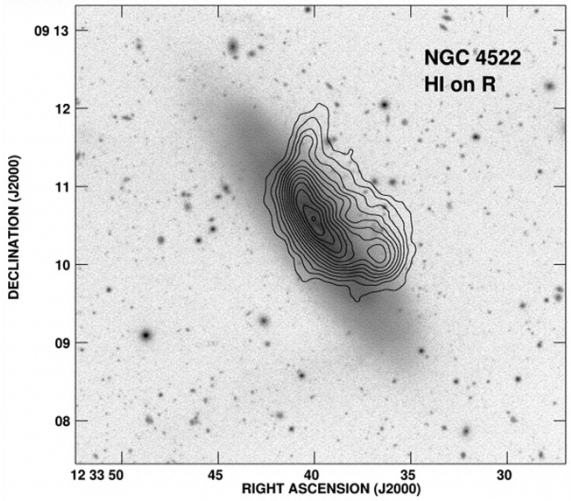
- Gravitational interaction galaxy - cluster
- Gravitational interaction galaxy - galaxy
- Ram pressure galaxy ISM – intracluster medium (ICM)



(Böhringer et al. 1994)



(Kenney et al. 1995)

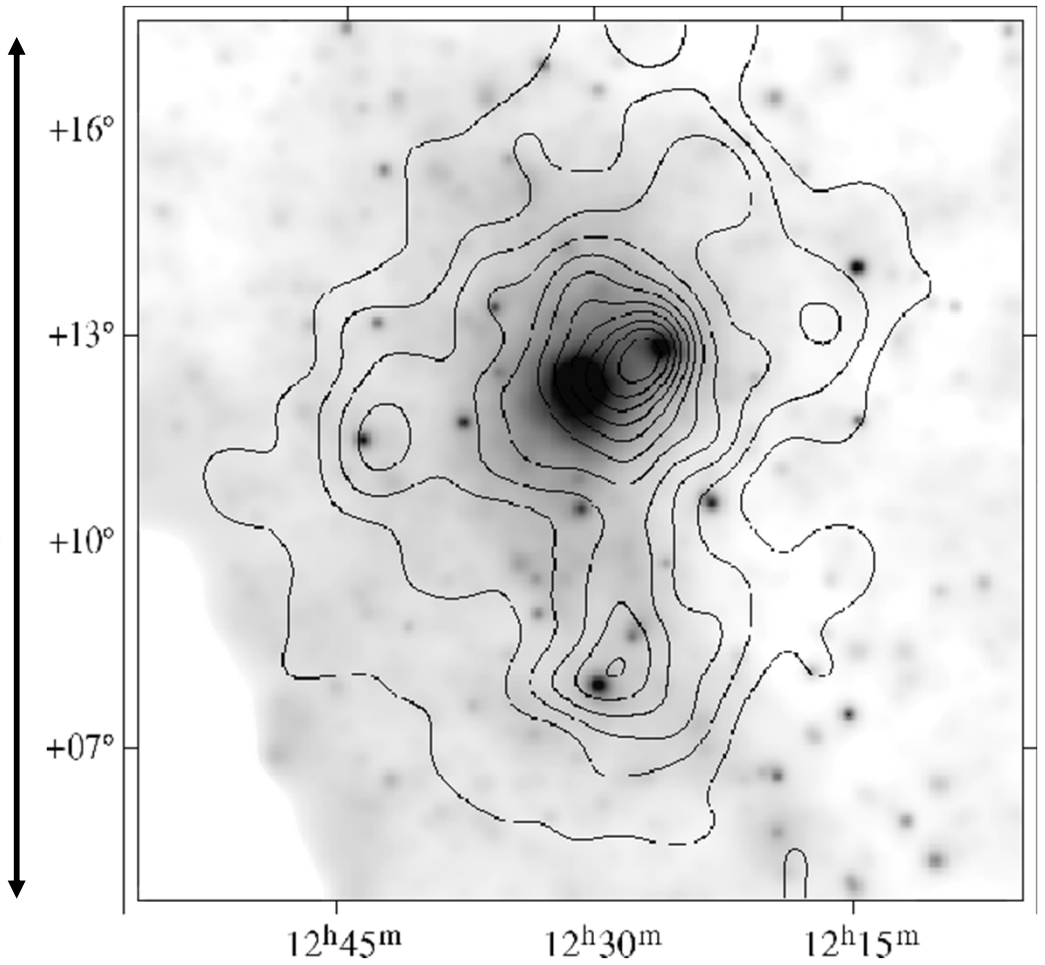


(Kenney et al. 2004)

The Virgo Cluster

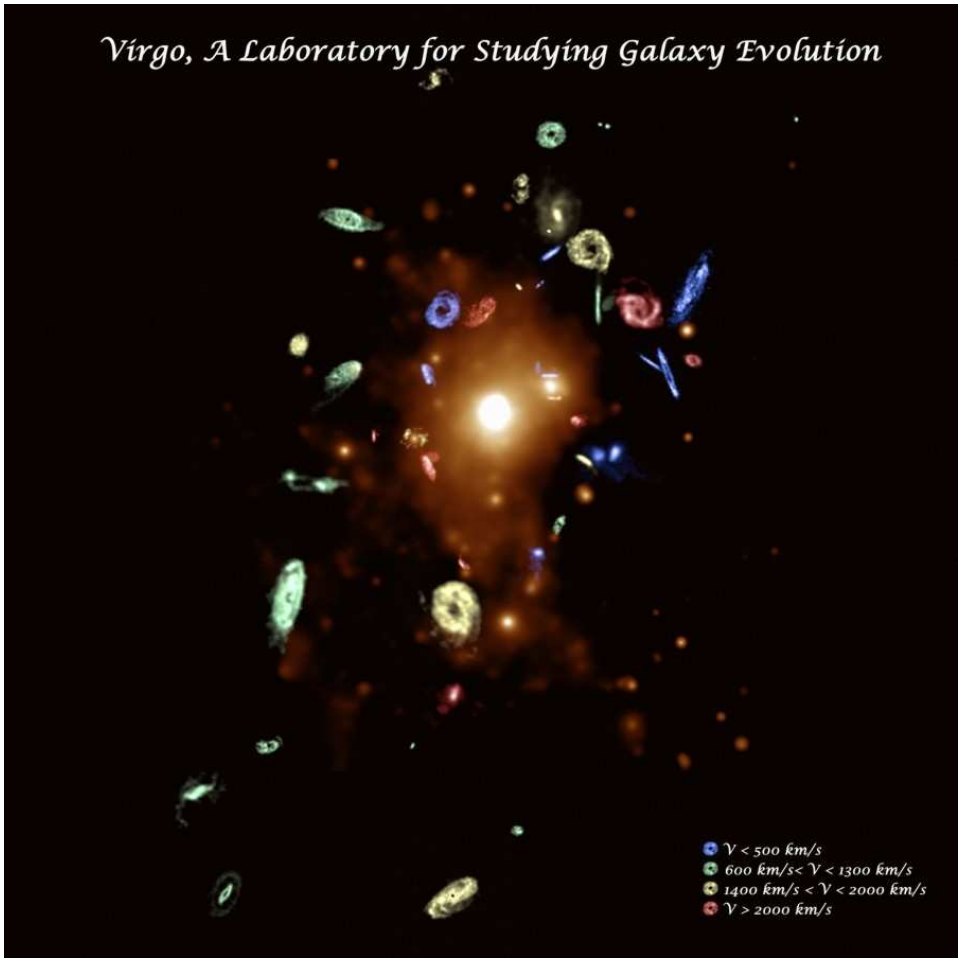
- Distance: ~17 Mpc
- 1’ = 5 kpc
- Velocity dispersion: ~700 km/s
- Dynamically young cluster
- Mass: ~10^{14} M_{solar} at R=1 Mpc
- M_{gas}/M_{tot} ~ 14%
- M_{gal}/M_{tot} ~ 4%
- M/L ~ 500

Greyscale: X-ray Contour: galaxy density



(Schindler et al. 1999)

Atomic gas: the HI view



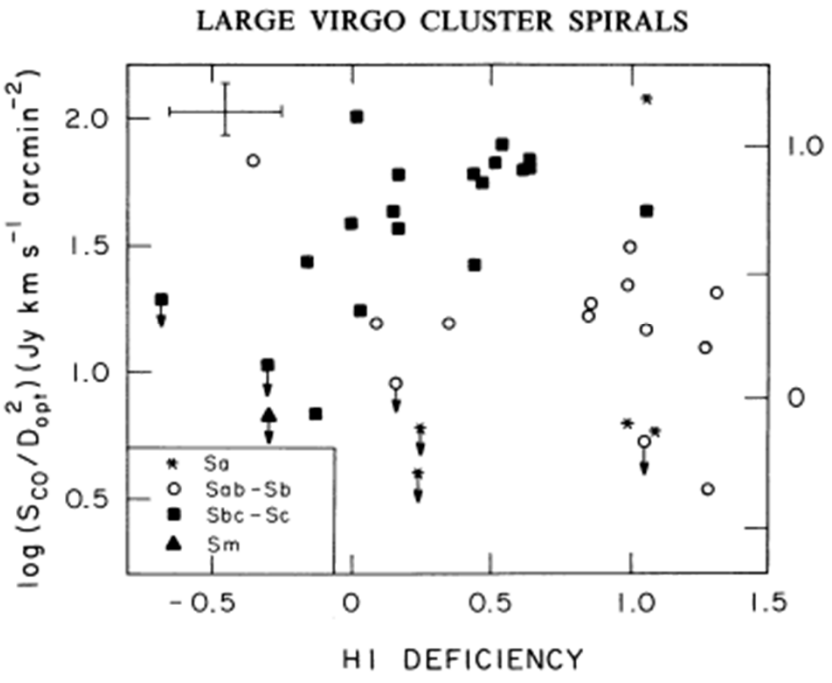
(Chung et al. 20009)

HI deficiency = log((expected HI mass)/(observed HI mass))

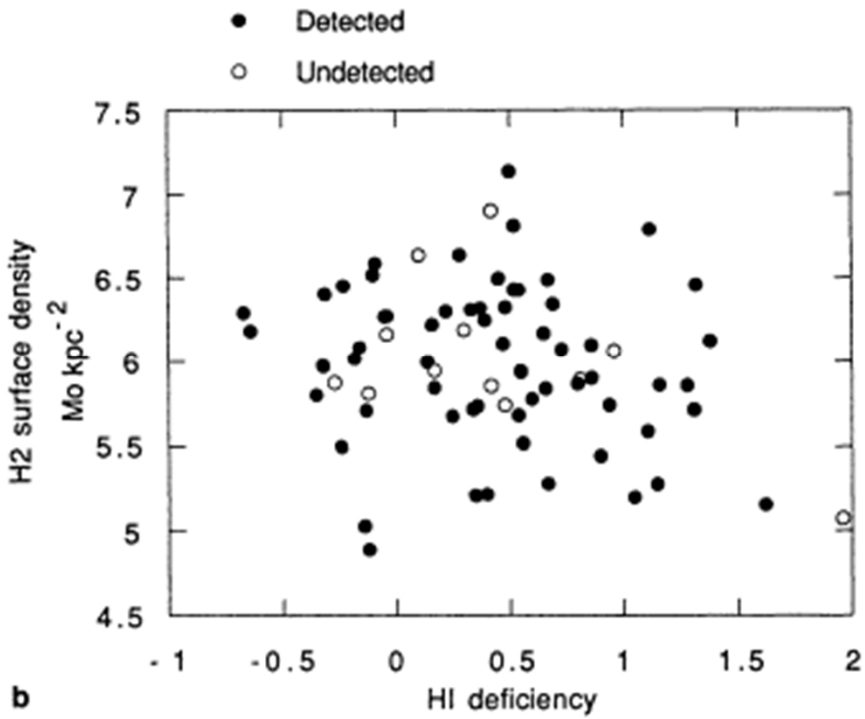
Cluster spirals are HI deficient and show truncated gas disks

Molecular gas: the CO view

(Kenney & Young 1989)



(Boselli et al. 1994)



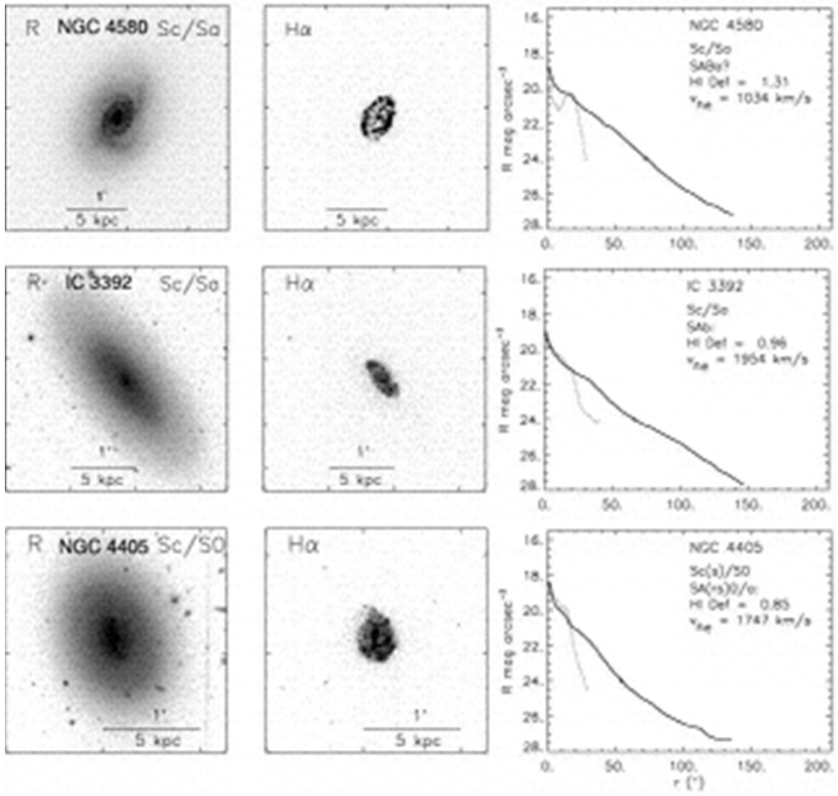
Cluster spirals are **NOT** CO deficient

Even the CO detection rate of Virgo early type galaxies is **NOT** different from that of the field (Atlas^{3D}; Young et al. 2011)

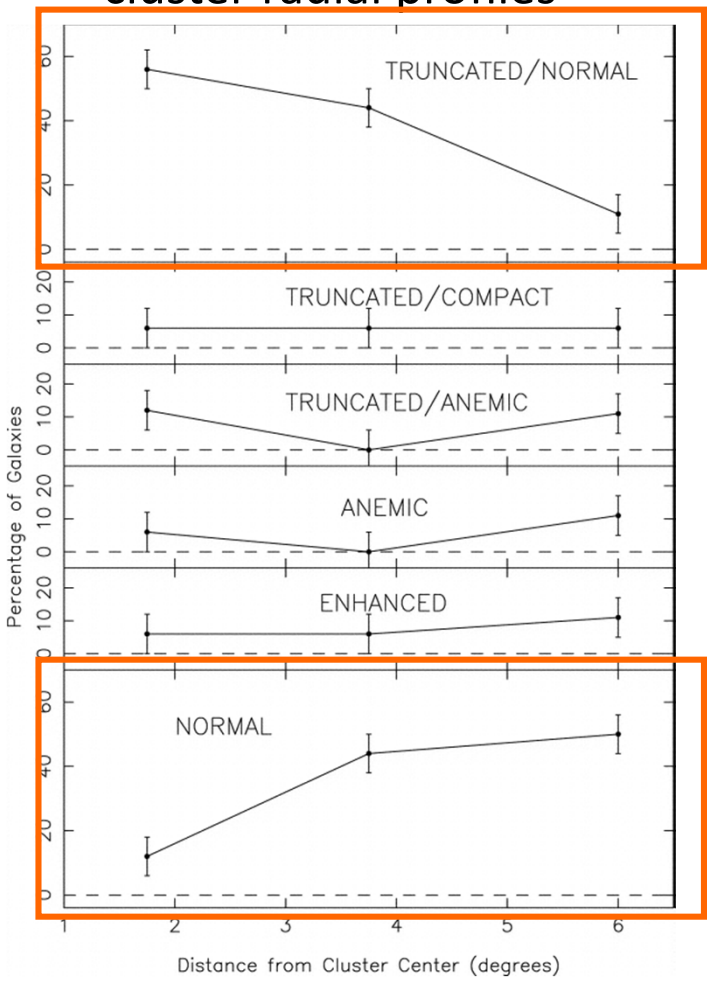
Star formation: the Hα view

(Koopmann & Kenney 2001, 2004)

truncated Hα disks

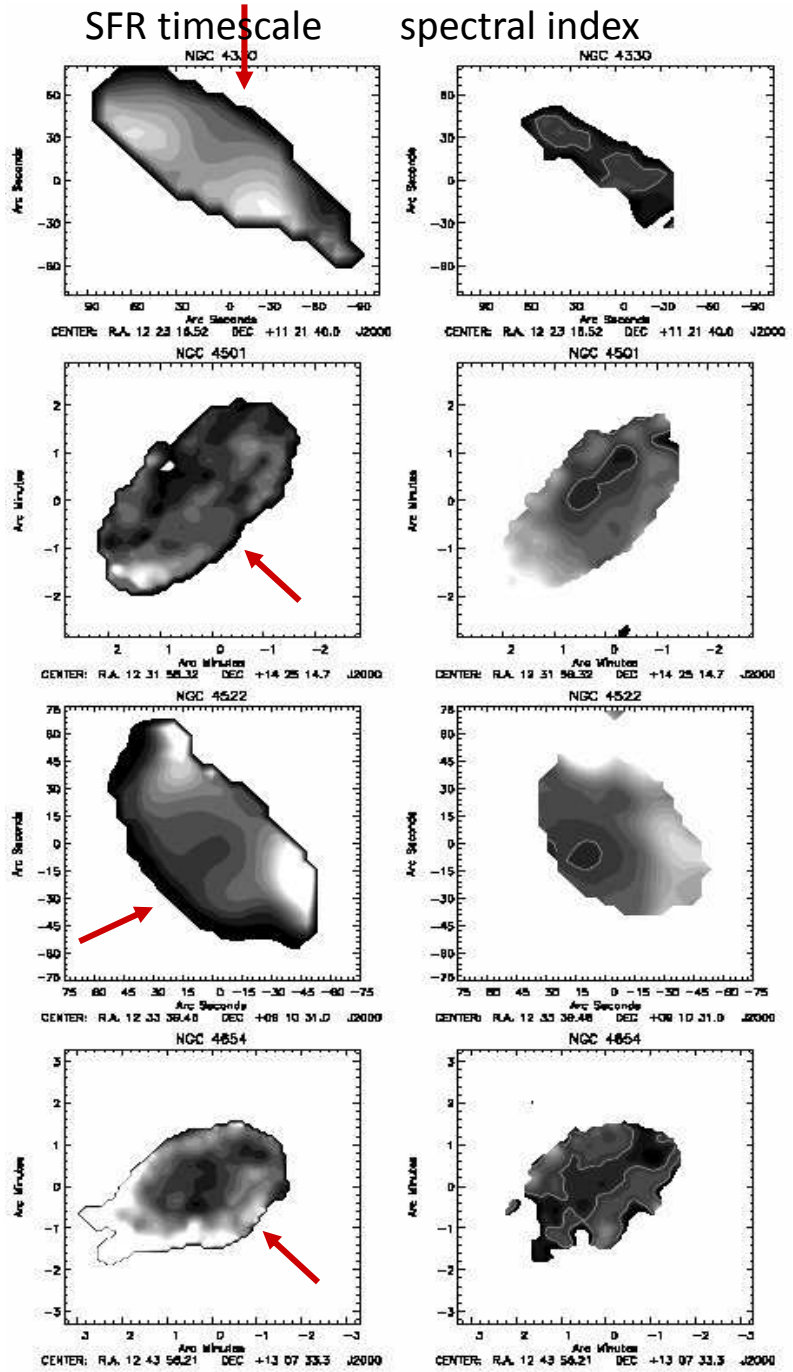


cluster radial profiles



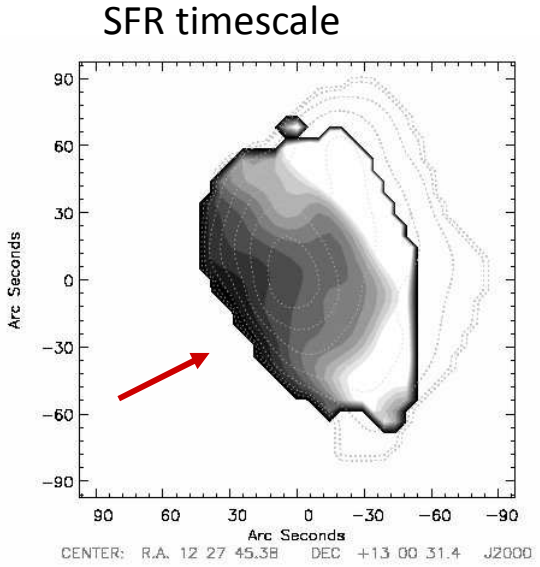
52 Virgo galaxies: 37% normal, 6% anemic, 6% enhanced, 52% truncated

Gas and star formation



- **Except for N4438, the cluster environment does not significantly change $SFR_{mol}=SFR/M_{mol}$**
- **continuous regions of low molecular star formation efficiencies in the compressed parts of NGC 4501**
- **NGC4330, NGC4438, N4522 show a depressed SFE_{tot} in the extraplanar regions**

NGC4438



Vollmer et al. (2012), Nehlig et al. (2016)

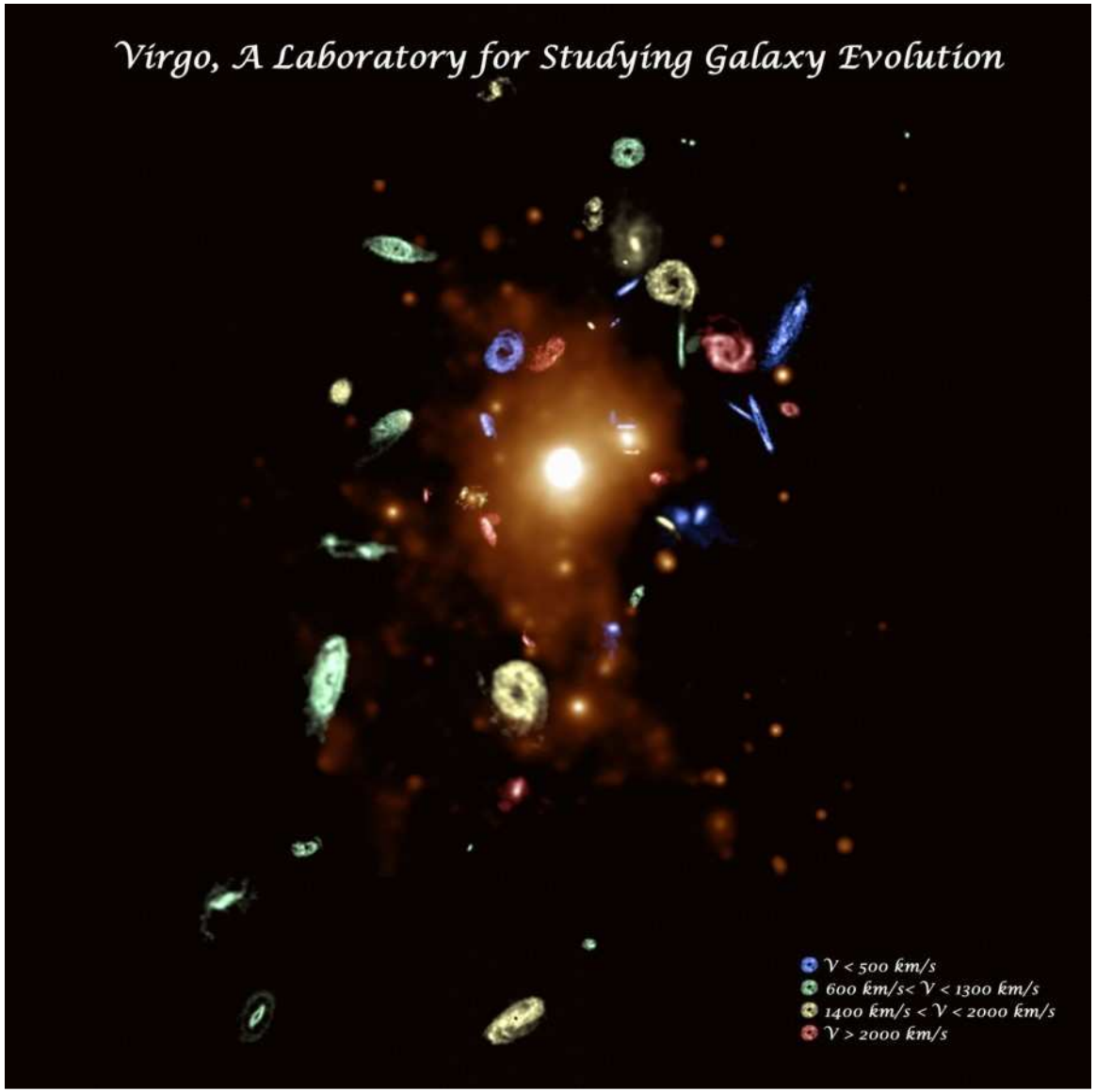
Interaction diagnostics

- Which interaction is responsible for the observed distorsions/perturbations?
- Determination of the interaction parameters
- Means: HI/CO maps and velocity fields, dynamical simulations, ***polarized radio continuum emission***,

  photometry+ spectroscopy + stellar population synthesis

VIVA = VLA Imaging of Virgo in Atomic Gas

(A. Chung, J. van Gorkom, J. Kenney, H. Crowl, B. Vollmer)

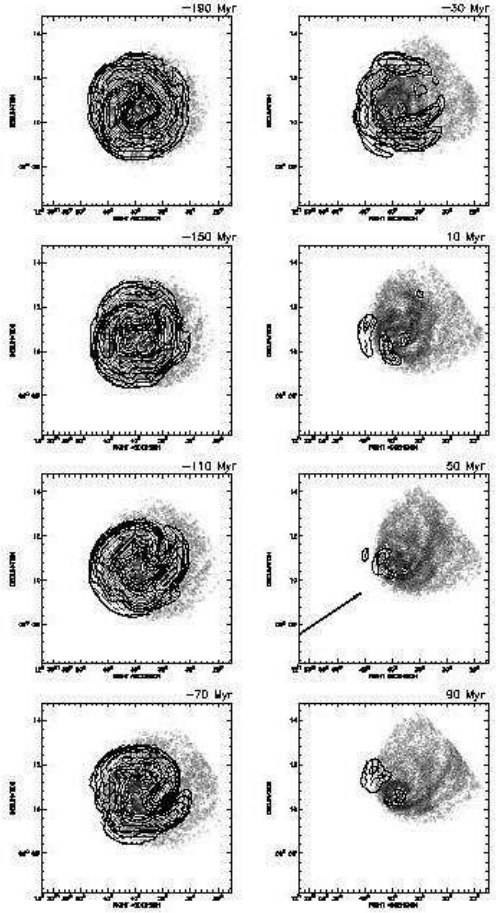


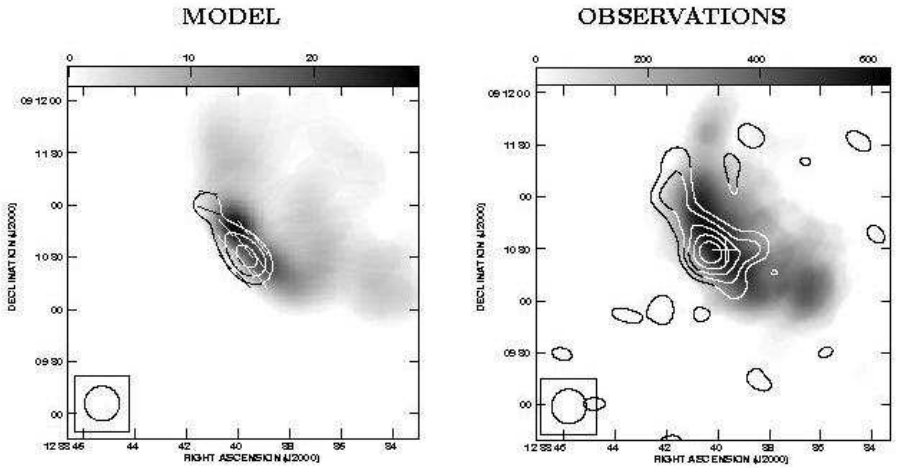
MHD simulations

(M. Soida, Krakov)

- Solve the induction equation on the velocity fields of the sticky particle simulations

  evolution of the large scale regular magnetic field
- Assume relativistic electron distribution evolution of the polarized radio continuum emission





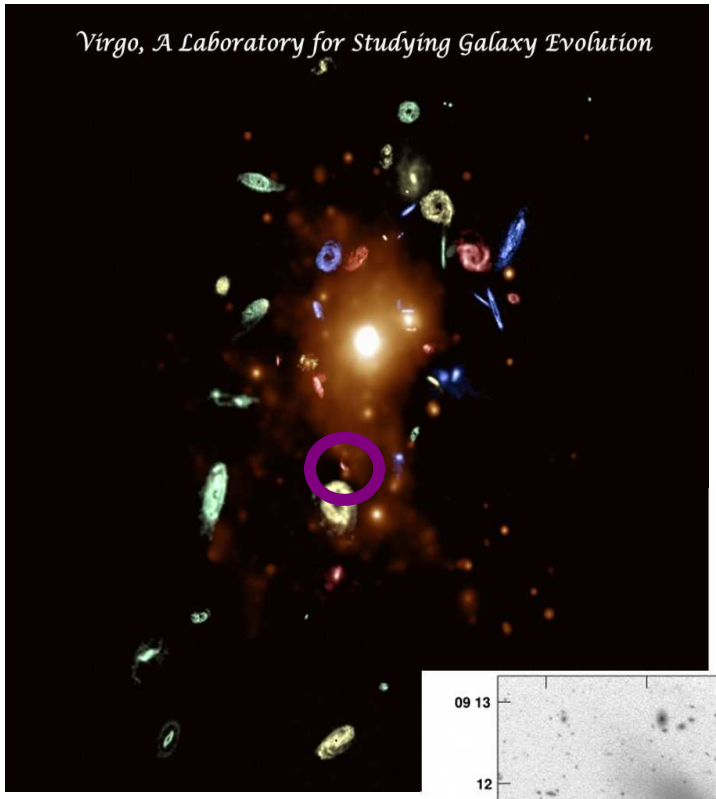
grey: HI, contours: PI
(Vollmer et al. 2006)

Comparison between the models and the observations

- *Known*: systemic velocity, distance from cluster center, i, PA, gas distribution **and** velocity field
- *Unknown*: maximum ram pressure, time to maximum, angle between galactic disk and ram pressure wind

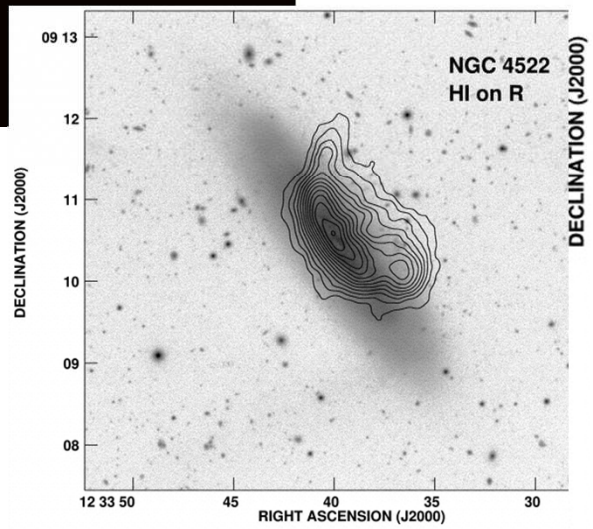
Ram pressure stripping criterion:
Gunn & Gott (1972): $\Sigma_{gas}\, v_{rot}^2/R = \rho_{ICM}\, v_{gal}^2$

A case study: NGC 4522

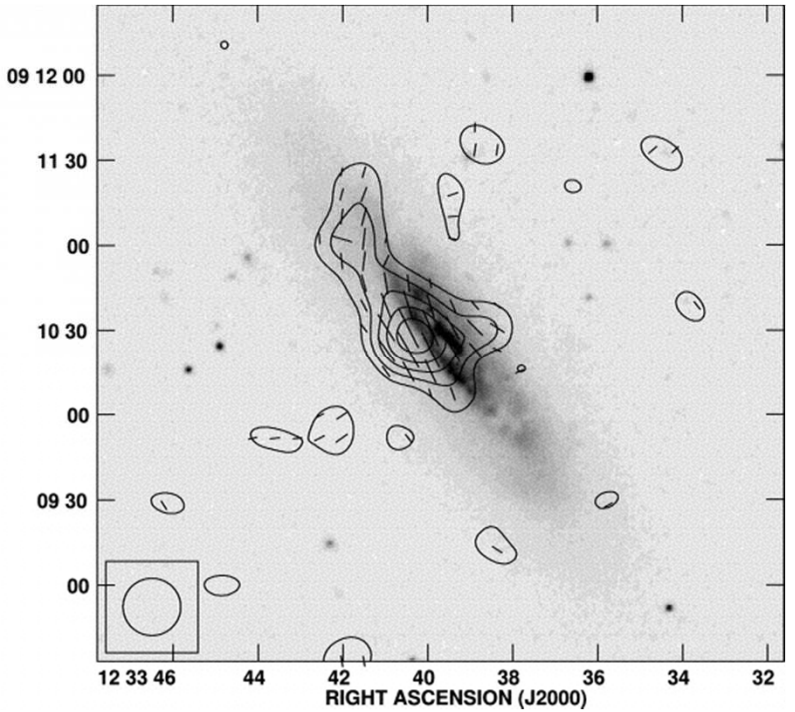


- Distance from M87:

  3.3° ~ 1 Mpc
- Radial velocity: +1000km/s w.r.t. M87
- View: edge-on

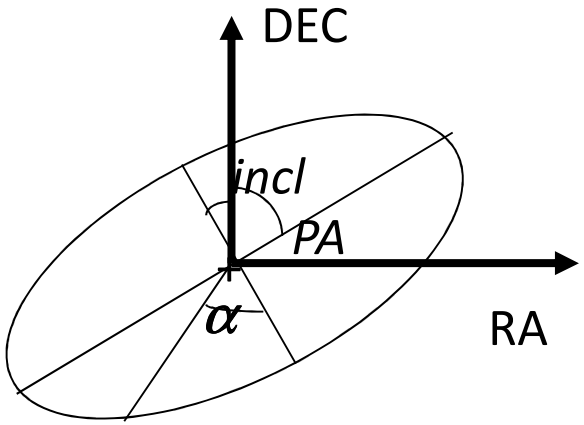


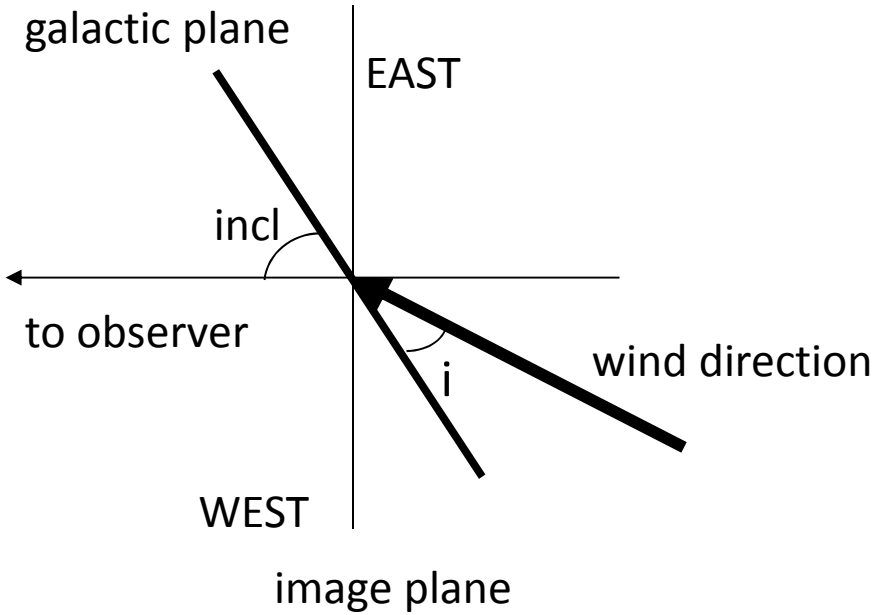
(Kenney et al. 2004)

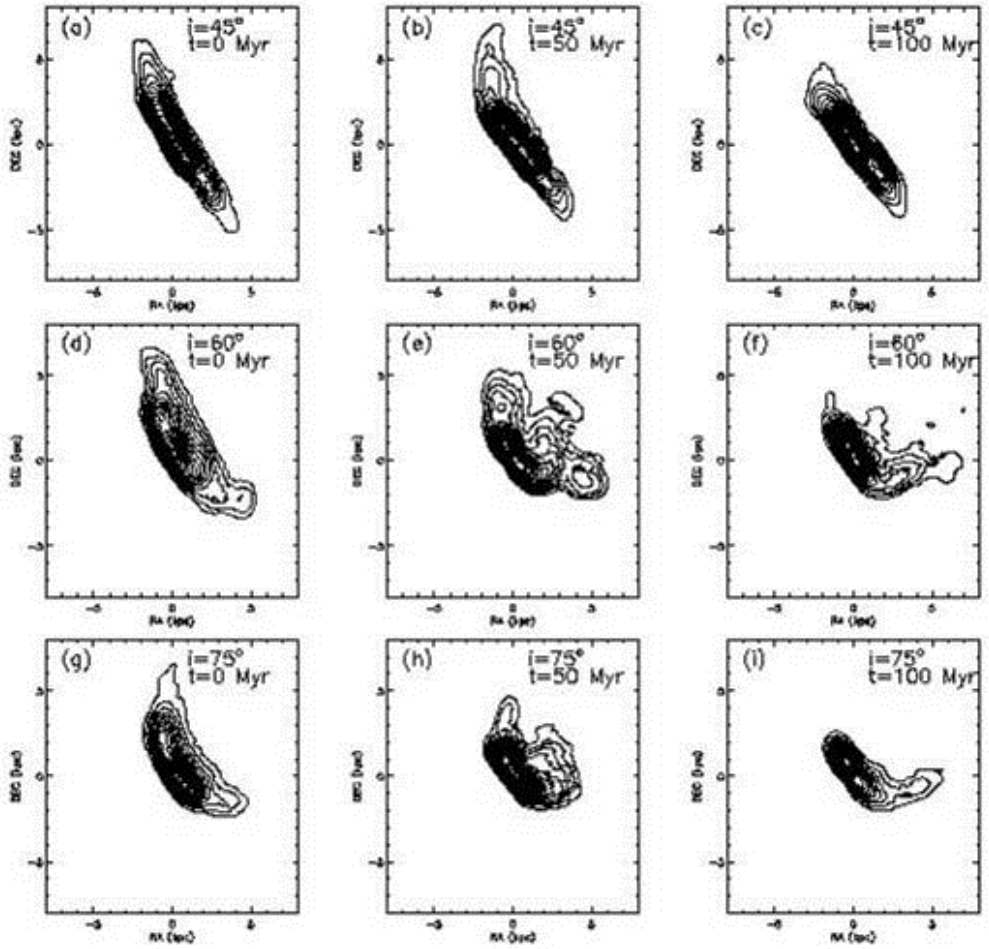


(Vollmer et al. 2004)

NGC 4522: the « best fit » model

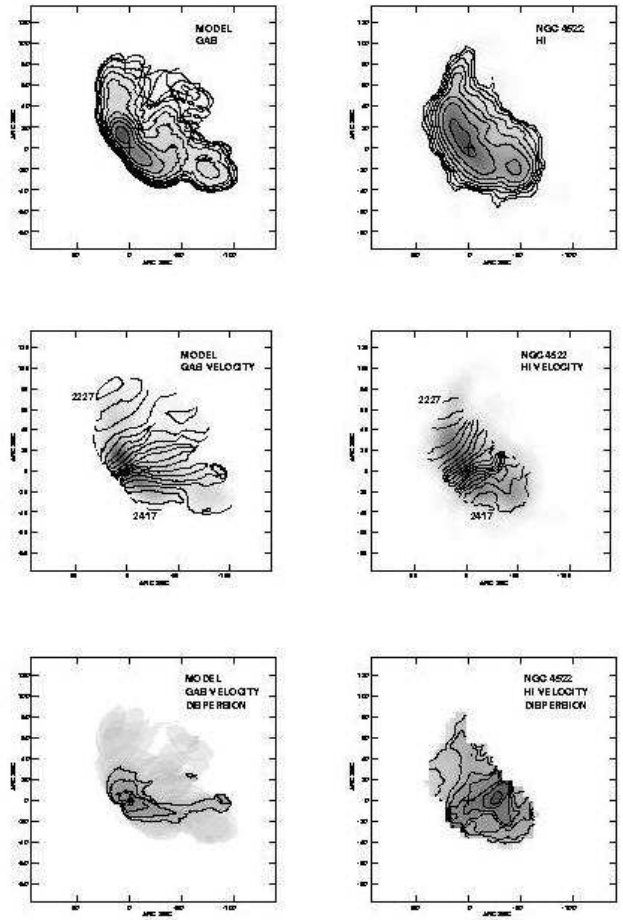


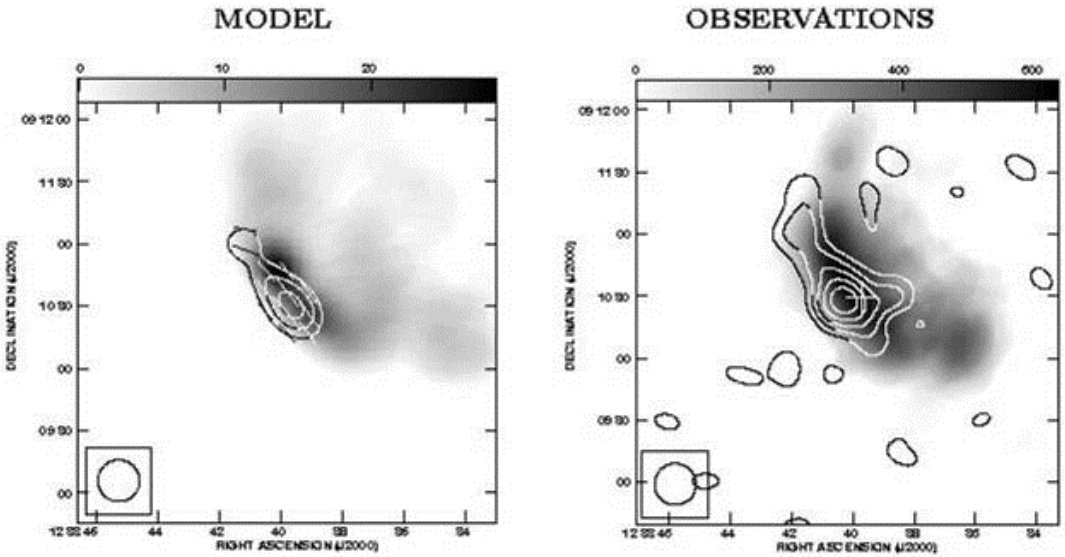




NGC 4522: final result

model HI





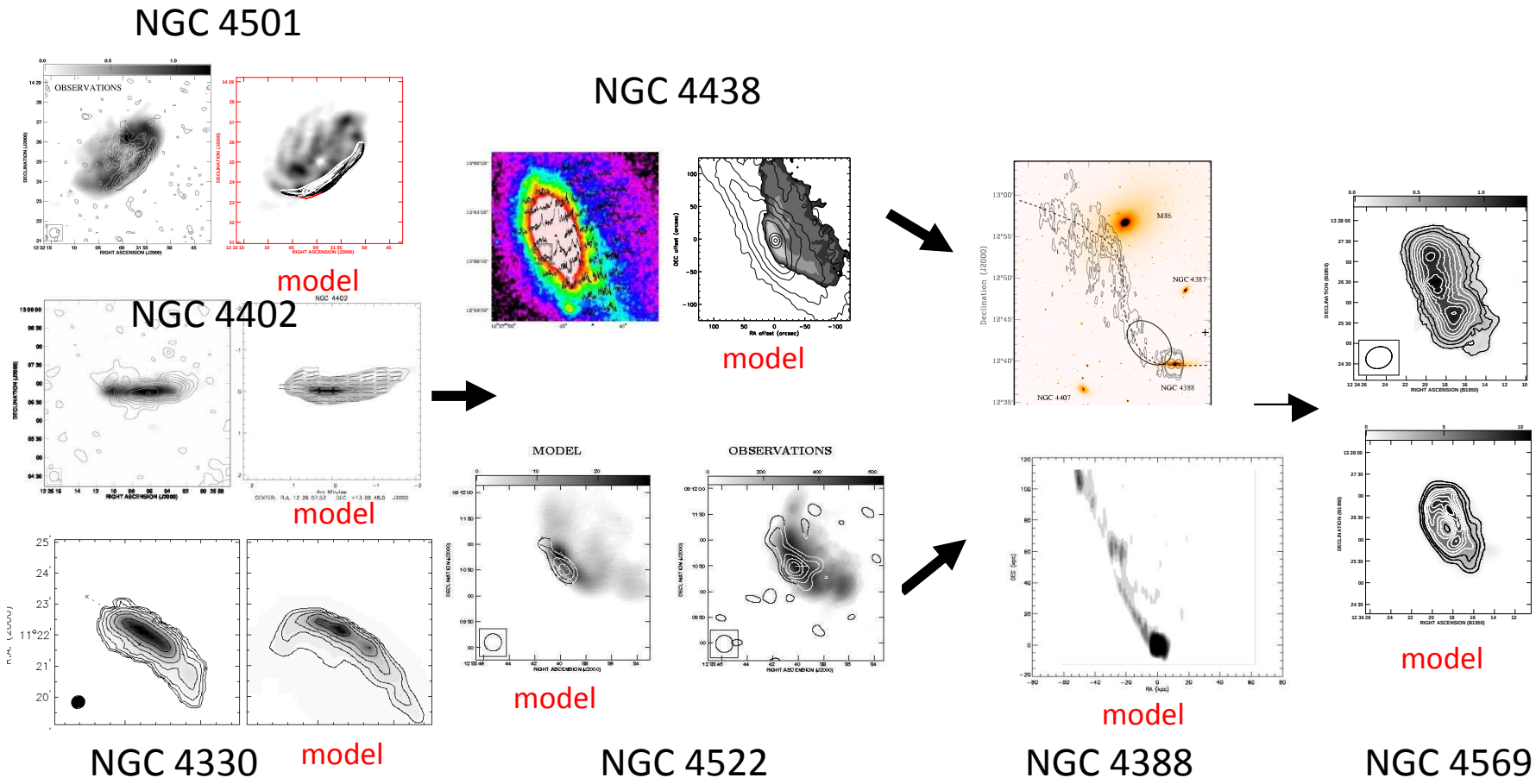
Greyscale: gas;
Contours: polarized radio continuum emission

(Vollmer et al. 2007)

→ **near peak ram pressure stripping**

Ram pressure stripping time sequence

Vollmer (2009) - **update**

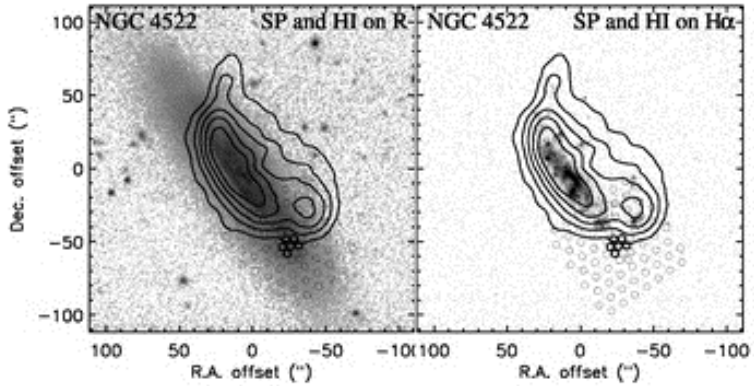


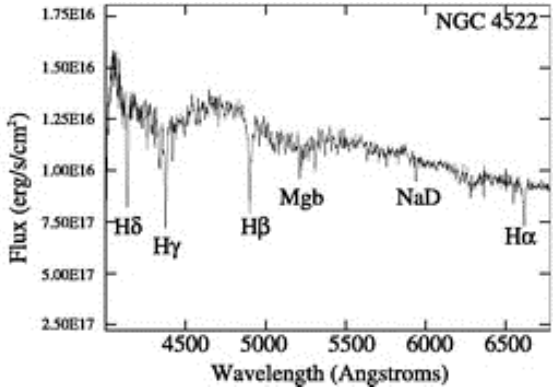
pre-peak near peak ~200Myr after peak ~300Myr after peak

Independent confirmation of stripping ages

- NGC 4522 (Crowl & Kenney 2007, 2008)

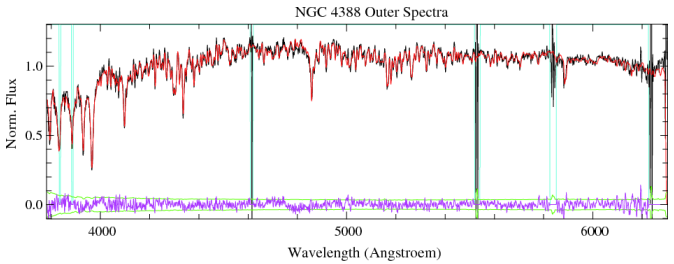
WIYN SparsePack
& GALEX UV

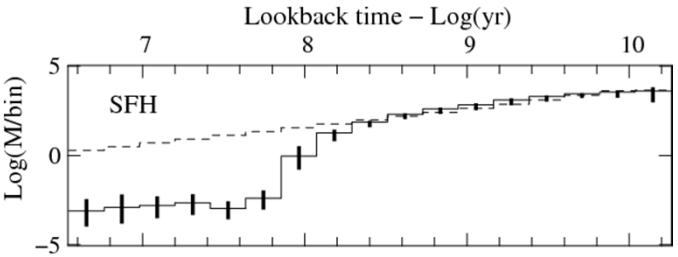




- NGC4388 (Pappalardo et al. 2010)

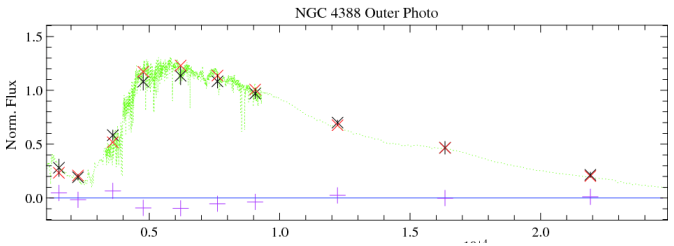
VLT FORS spectrum





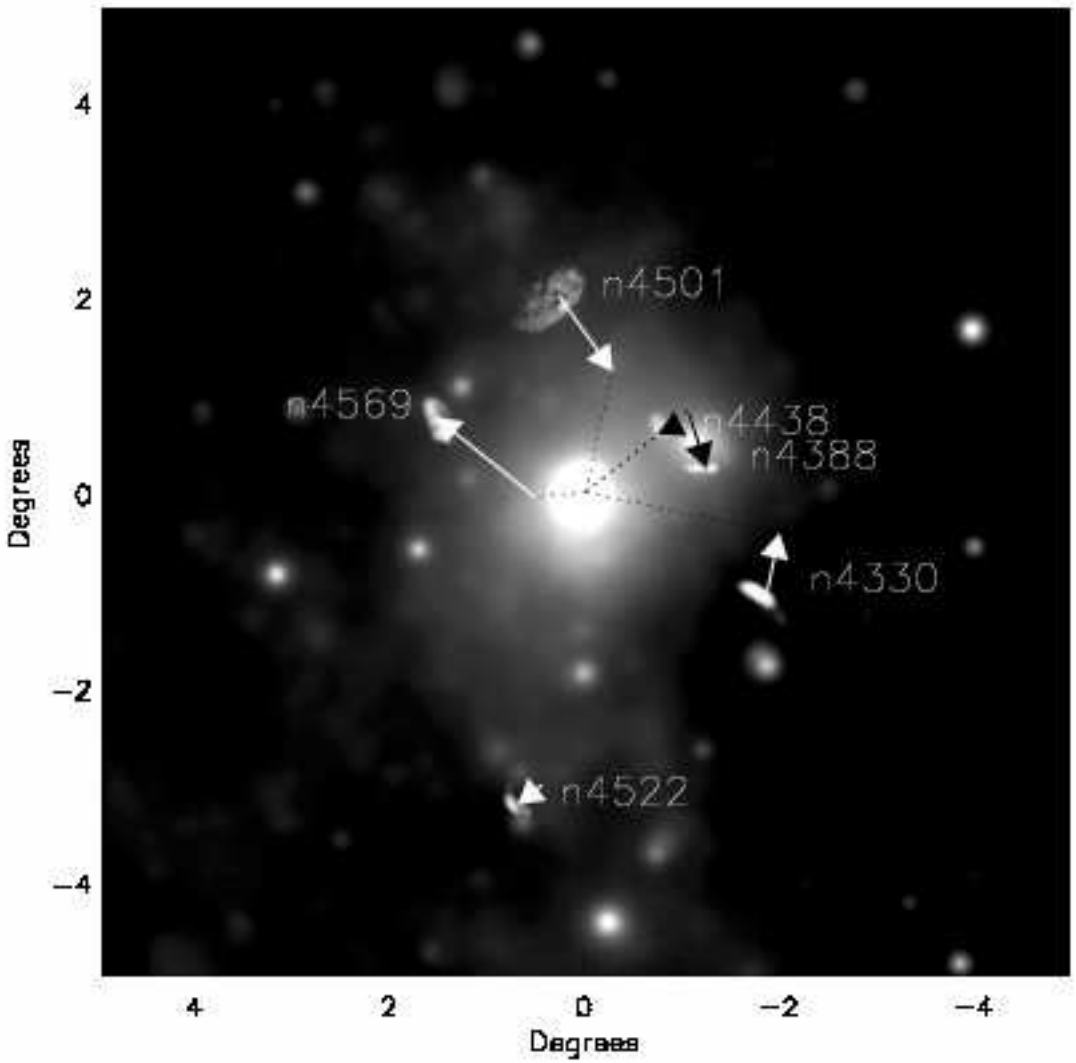
star formation history

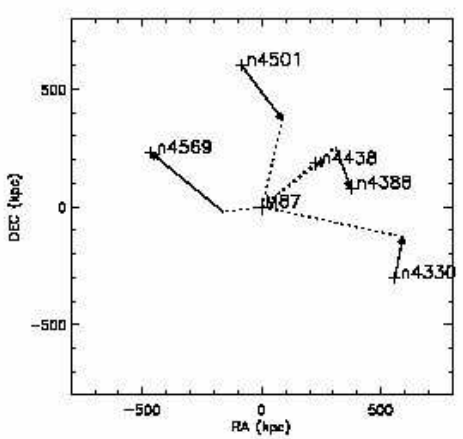
VLT FORS spectrum +
multi-λ photometry

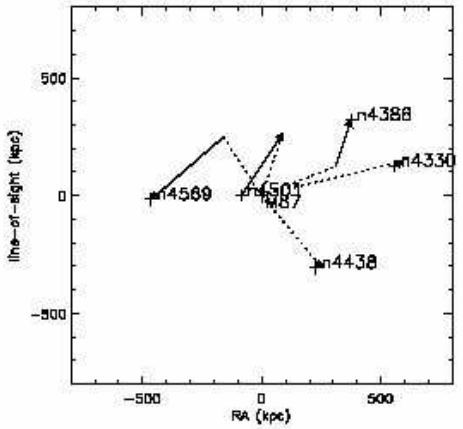


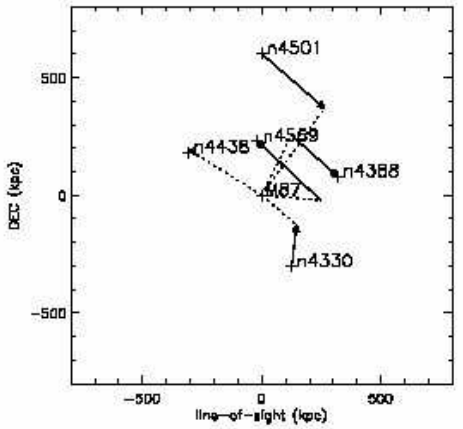
The 3D view

Vollmer (2009)



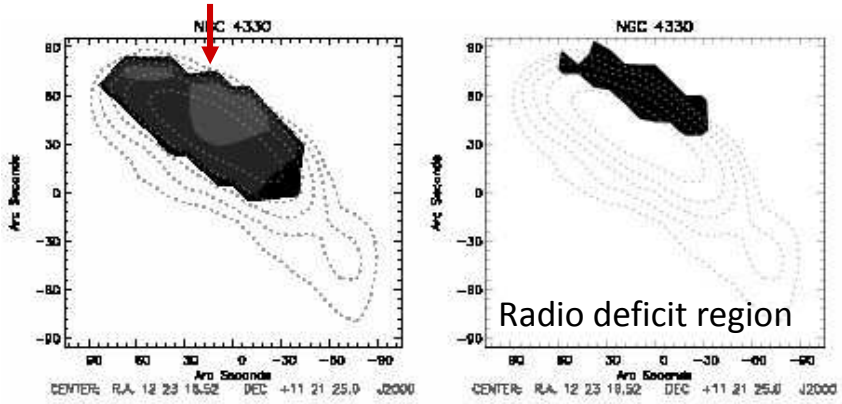


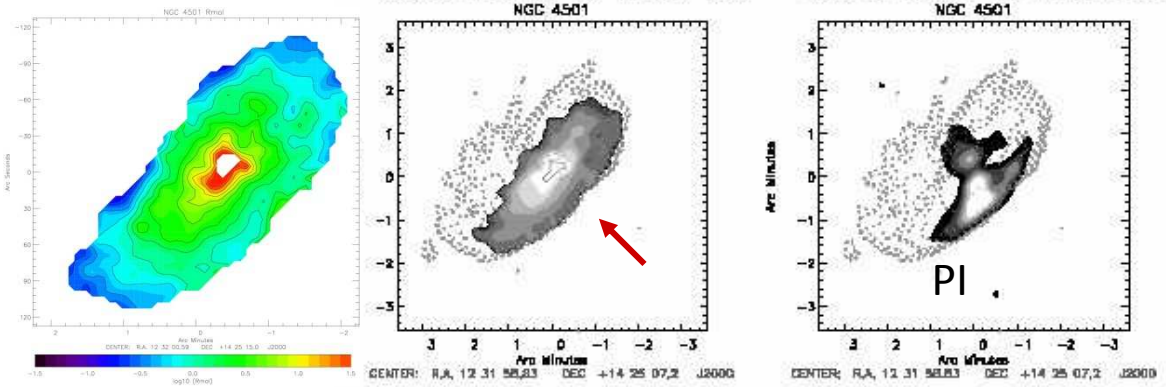


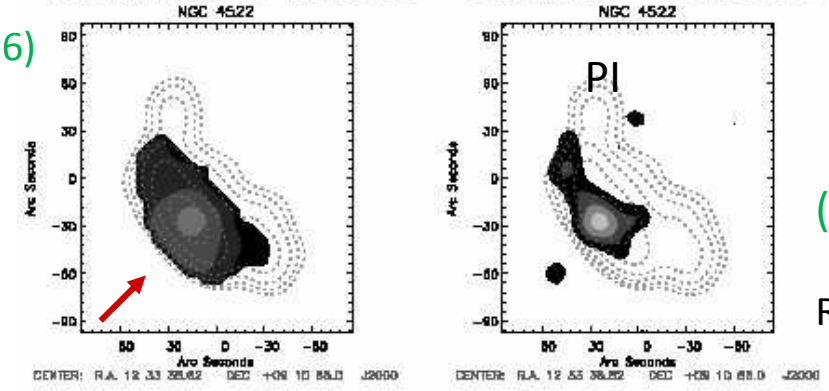


Ram pressure and the multiphase ISM

Molecular gas fraction







- **Inside the truncation radius, gas disks are normal**
- **Enhanced molecular fraction in**

  3 galaxies (NGC4330, NGC4501, NGC4522)

Nehlig et al. (2016)

(Vollmer et al. 2012)

Radio deficit: Murphy et al. (2009)

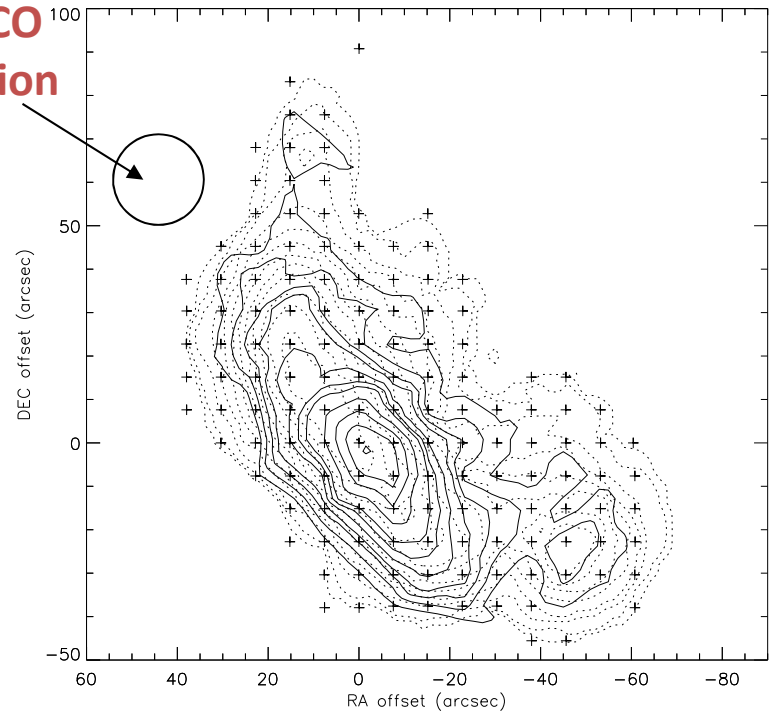
Ram pressure stripping of the multiphase ISM

Vollmer et al. (2008)

- IRAM 30m HERA CO(2-1) observations

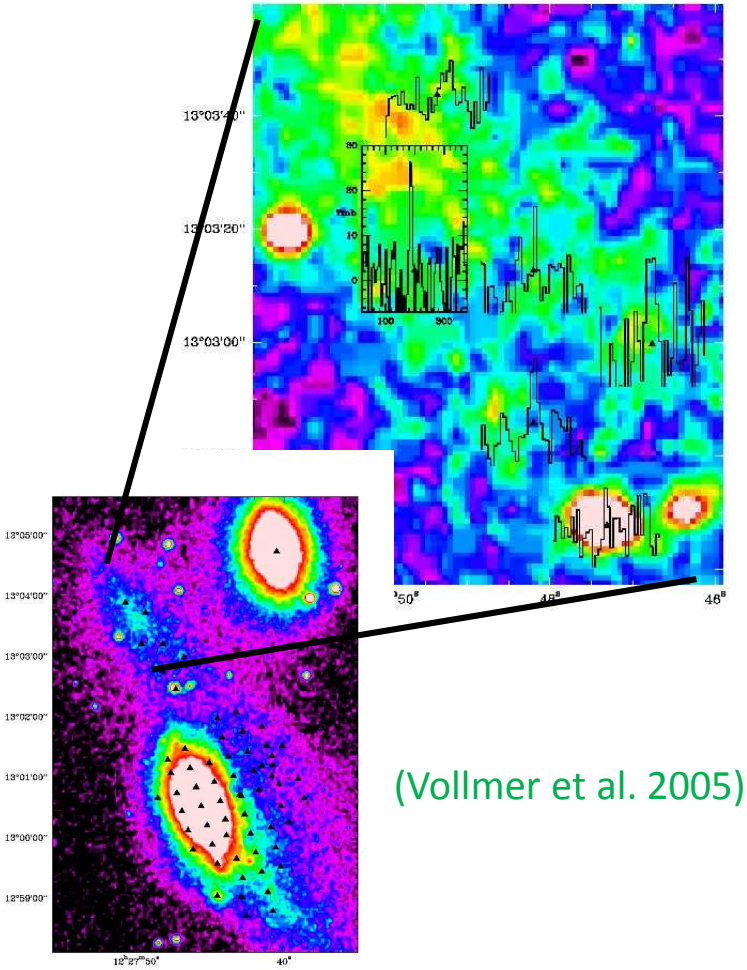
NGC 4522: decoupled moecular clouds

faint CO emission



Dashed: HI (Kenney et al. 2004)
Solid: CO(2-1)

NGC 4438: decoupeled molecular clouds

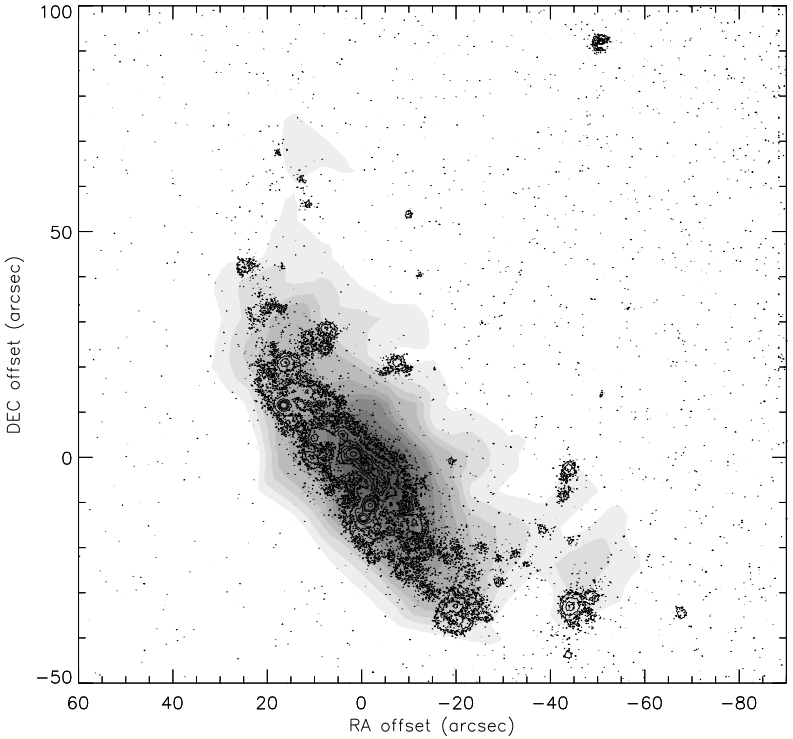


(Vollmer et al. 2005)

Star formation in the stripped gas

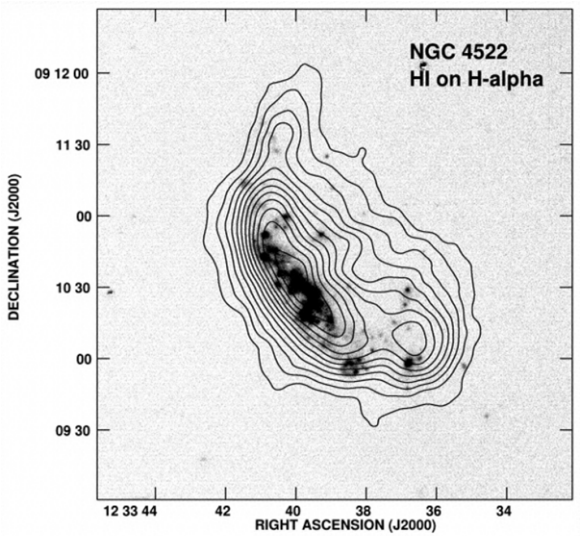
(important for radio continuum emission)

Vollmer et al. (2008)



Greyscale: CO(2-1)

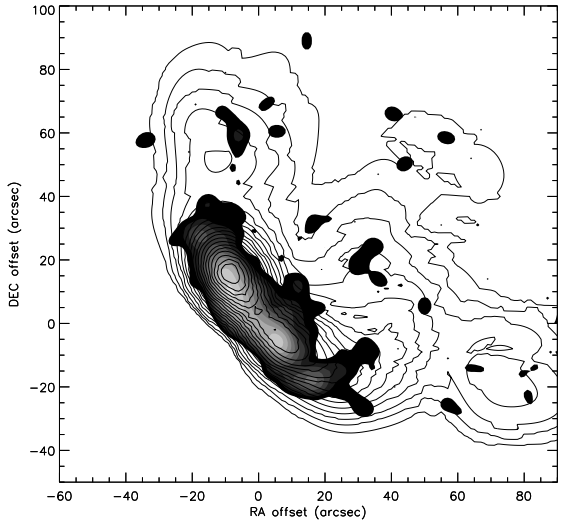
Contours: Hα (Kenney et al. 2004)



Greyscale: Hα

Contours: HI

from Kenney et al. (2004)



model

Greyscale: Hα

Contours: HI

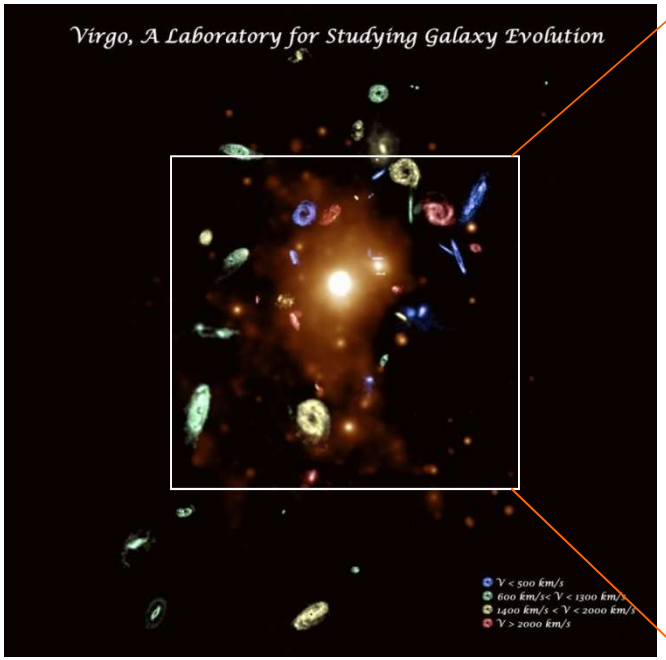
VLA large proposal: survey of 19 Virgo cluster spiral galaxies in polarized radio continuum emission

B. Vollmer, M. Soida, R. Beck, C. Chyzy, K. Otmianowska-Mazur,
M. Urbanik, M. Wezgowiec, J. van Gorkom, J. Kenney

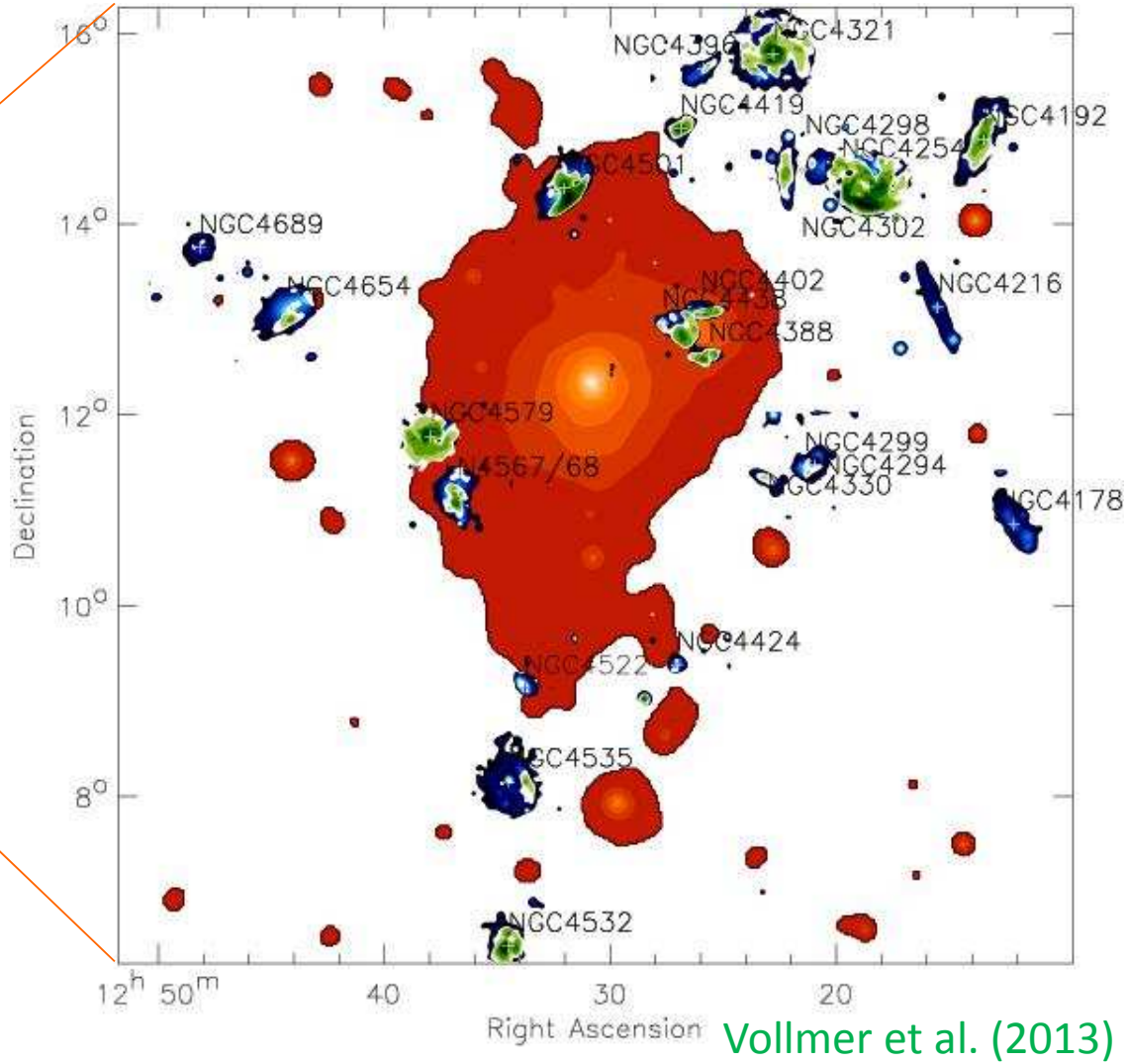
- 19 Virgo spiral galaxies
- ~200h of VLA observations
- 20cm C array; 6cm D array
- Resolution: ~20’’
- Sensitivity: 10μJy/beam at 6cm

Radio continuum observations of Virgo cluster galaxies

red: ICM; blue: TP; green: PI



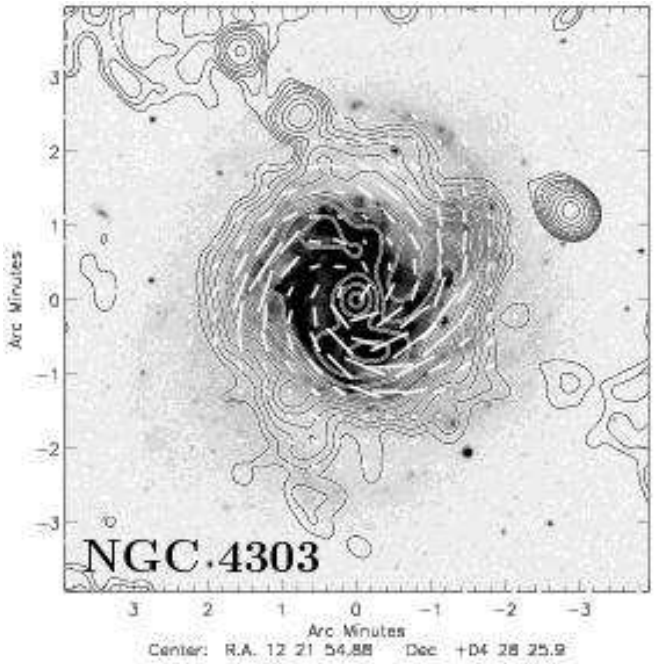
VIVA Chung et al. (2009)

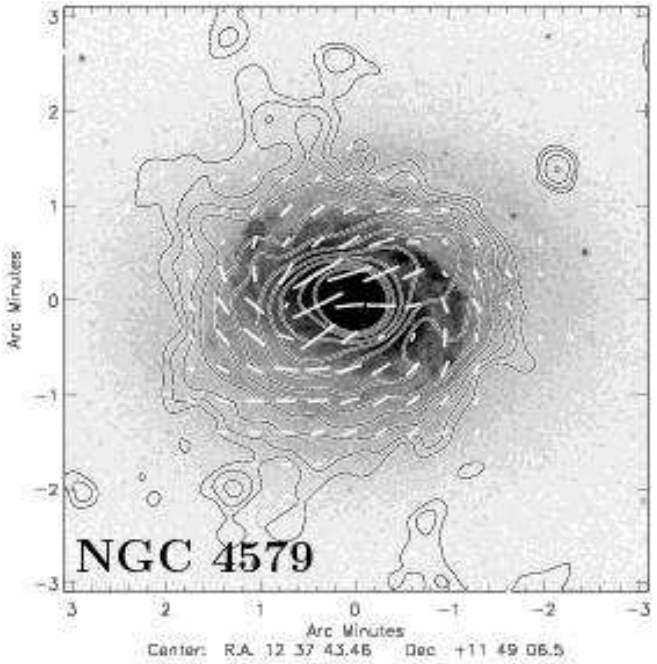


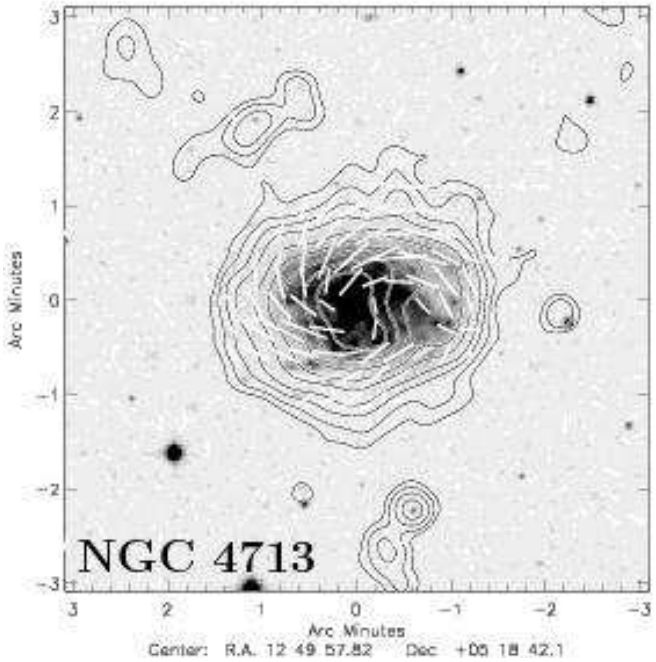
Vollmer et al. (2013)

Radio continuum basics

- Radio continuum emission α $n_{CR}B^2$
- Total power -> total magnetic field (large- and small-scale)
- Diffusion of CR electron
- Polarized emission -> large-scale B (resolution)
- Polarized emission sensitive to compression and shear motions







Symmetric spirals

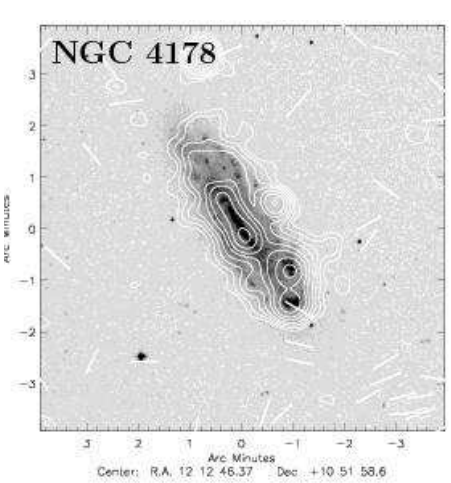
Magnetic spiral arms

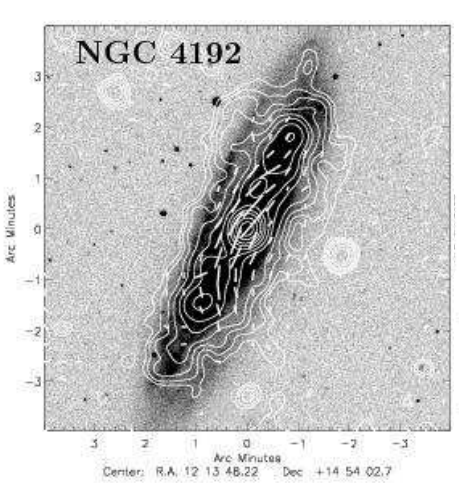
Radio halos

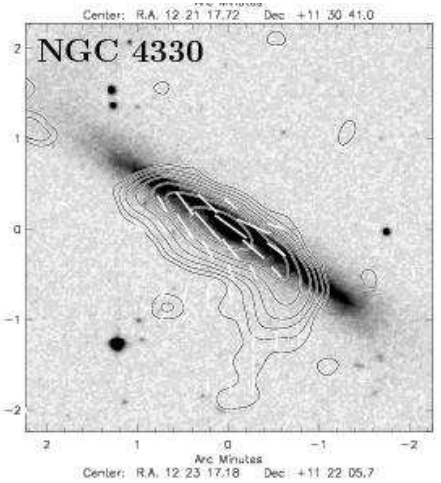
CR electron diffusion/streaming/transport

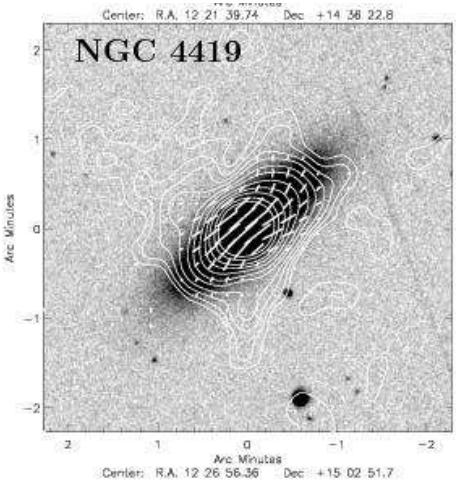
ram pressure

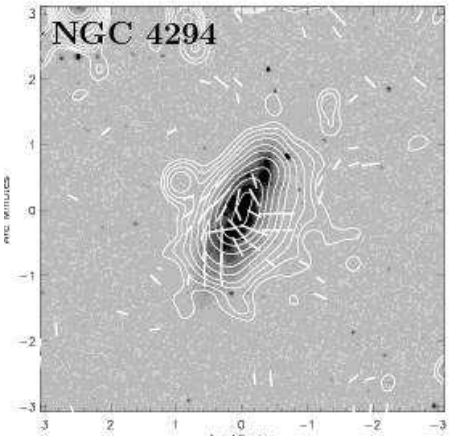
truncated gas disk

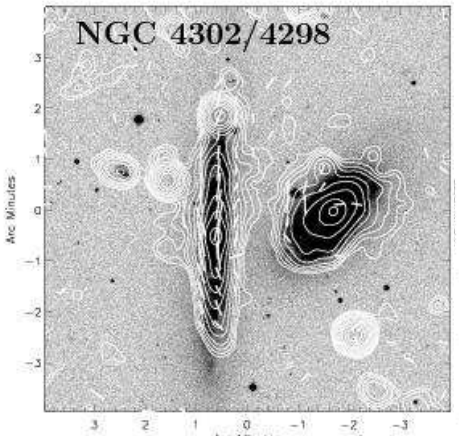


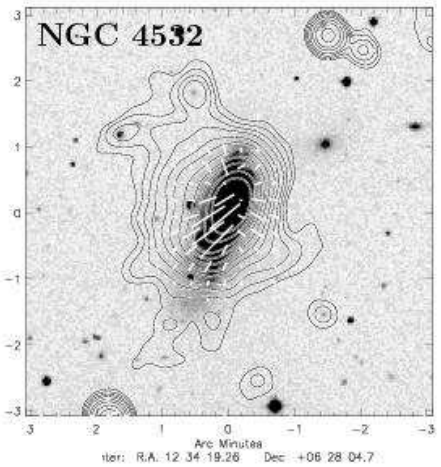


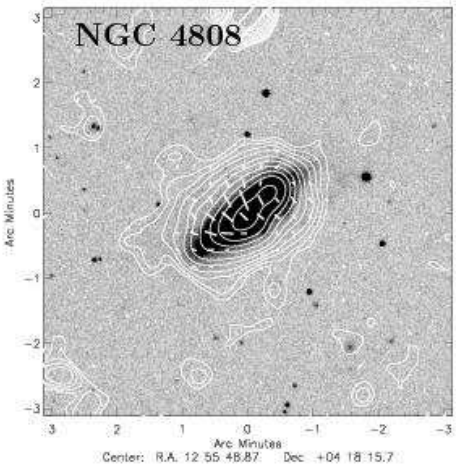












companion

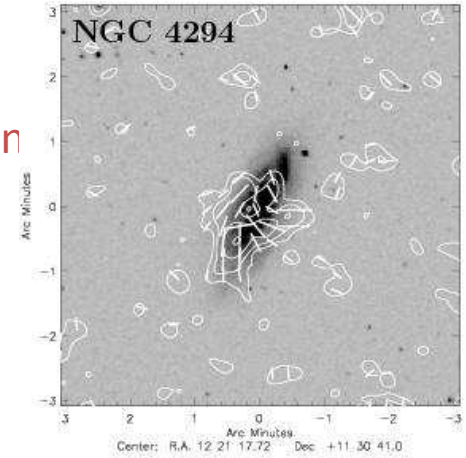
interacting

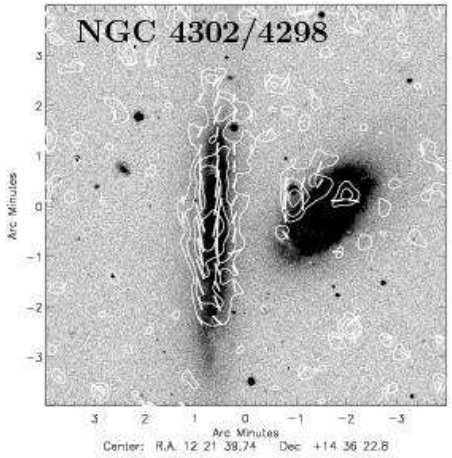
HI envelope

HI envelope

Asymmetric distributions of polarized radio continuum emission

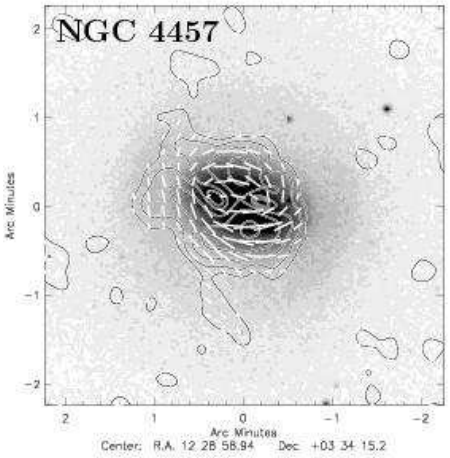
companion

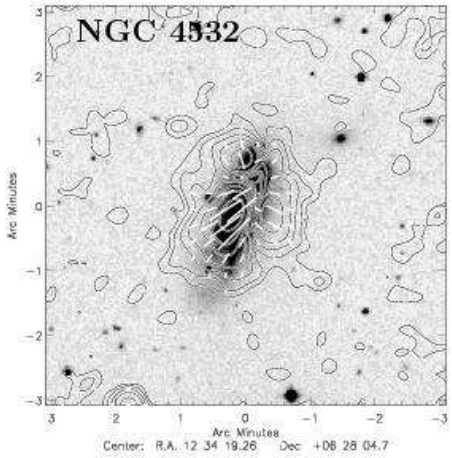




interacting

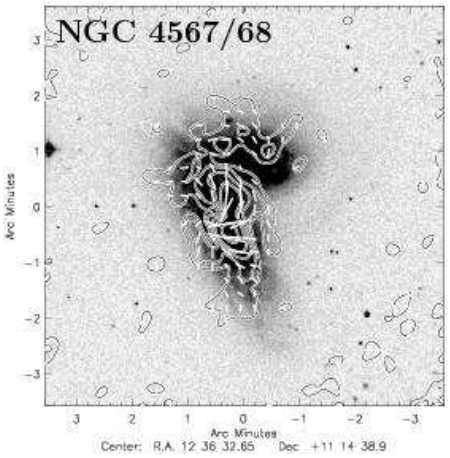
minor merger?

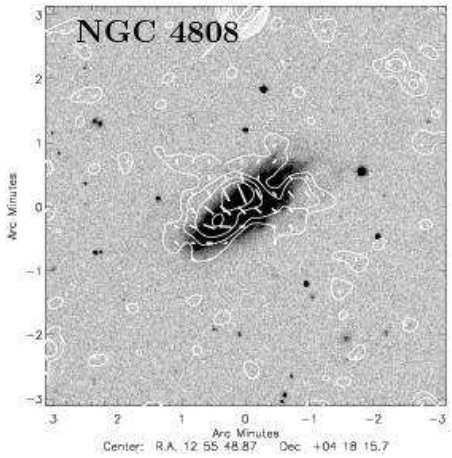




HI Envelope

interacting

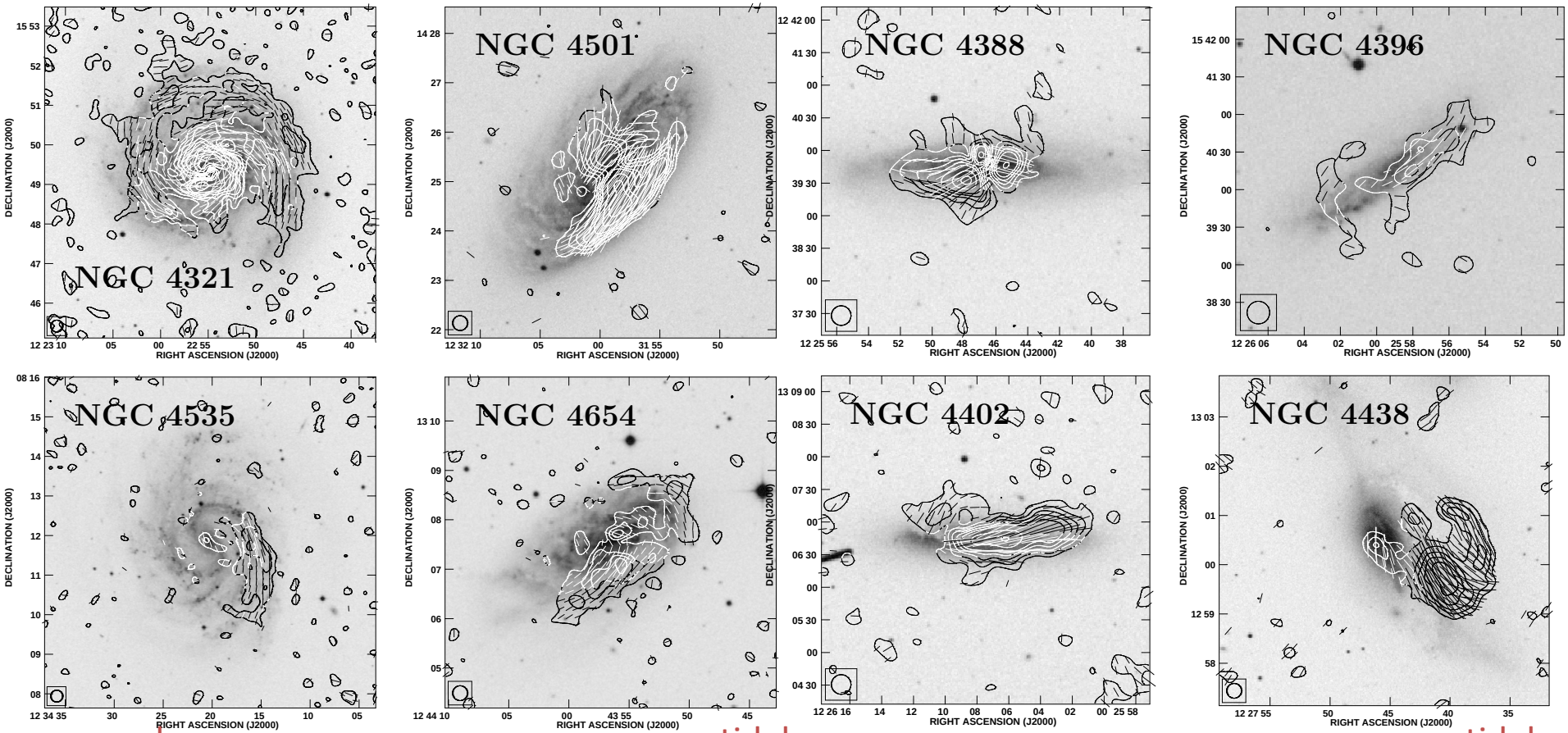




HI envelope

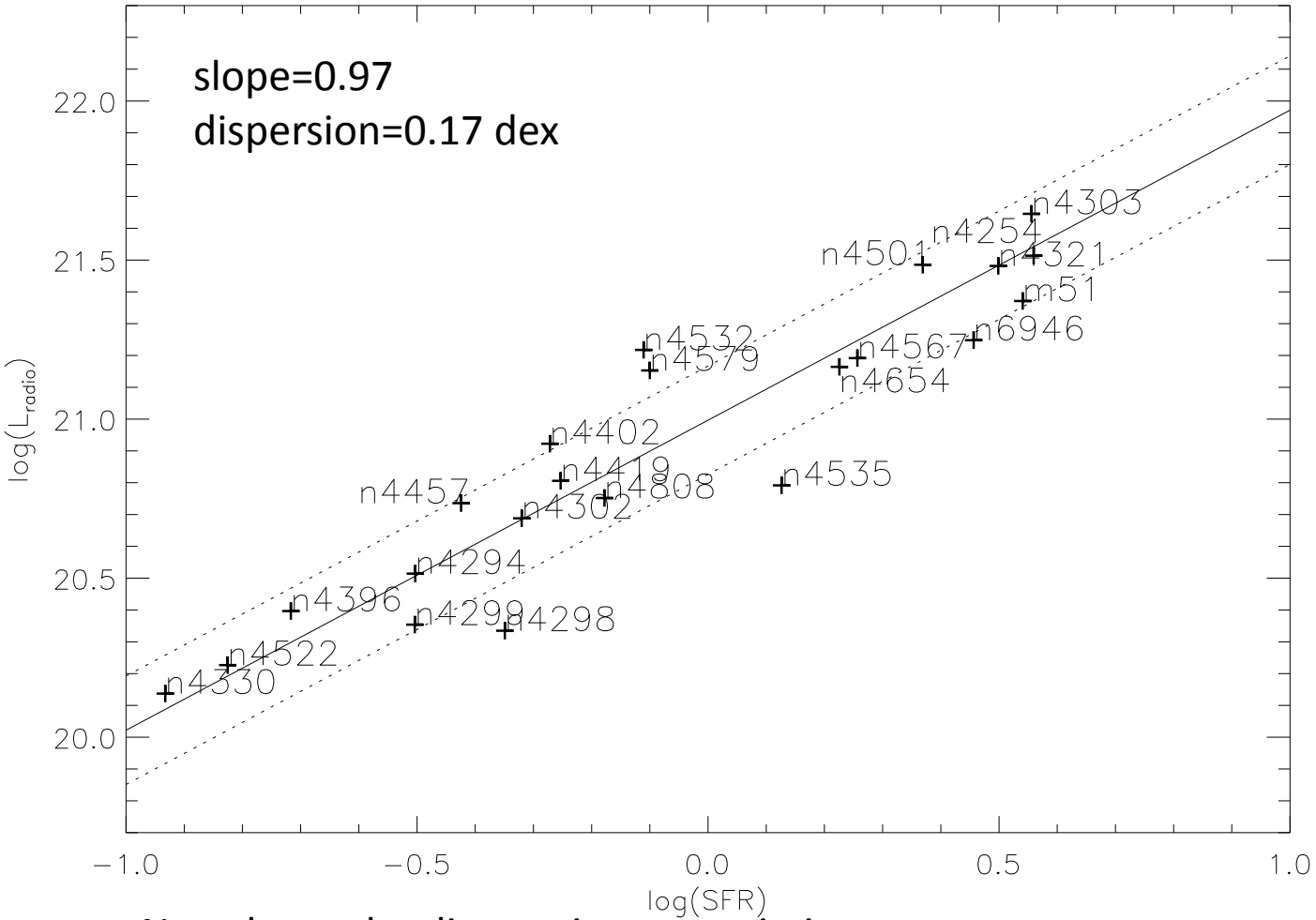
Asymmetric ridges of polarized radio continuum emission

Greyscale: optical B band; contour: 4.85GHz polarized radio continuum emission



Vollmer et al. (2007)

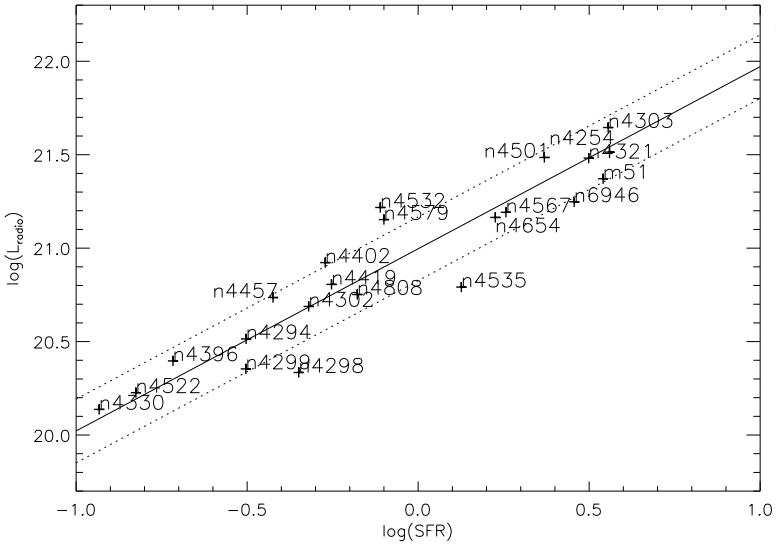
Integrated radio continuum – SFR correlation

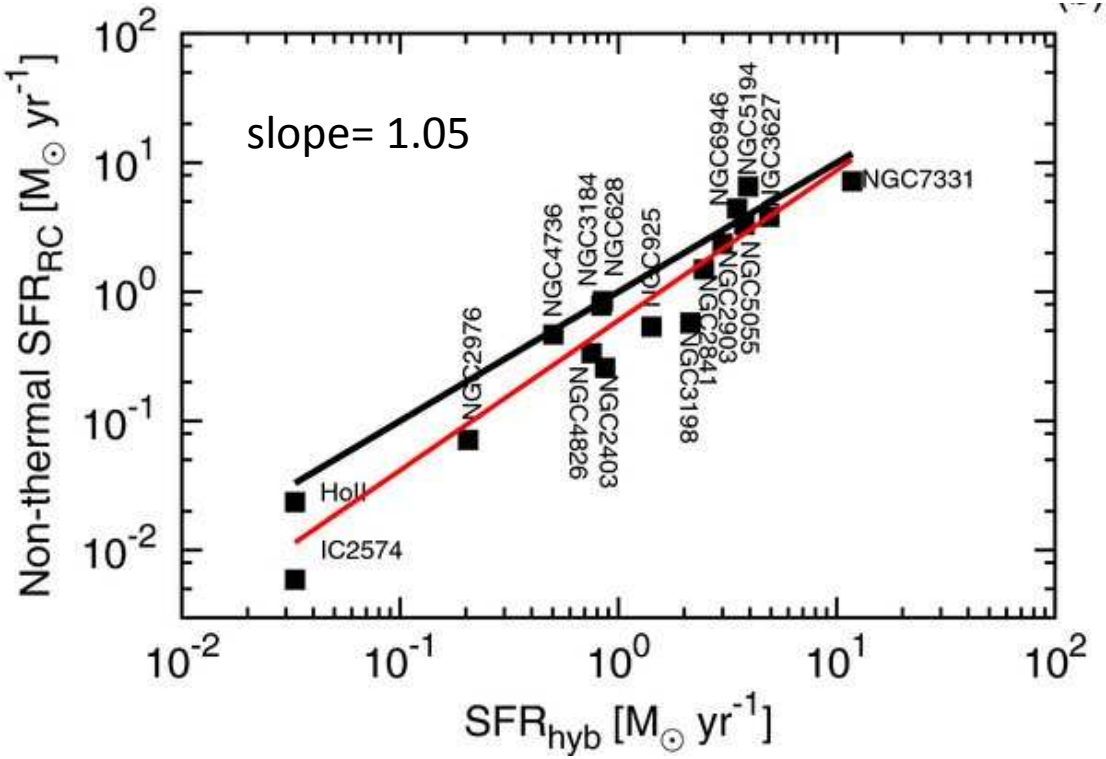


Non-thermal radio continuum emission

Recipe for thermal emission from Murphy et al. (2006) based on 24 μm

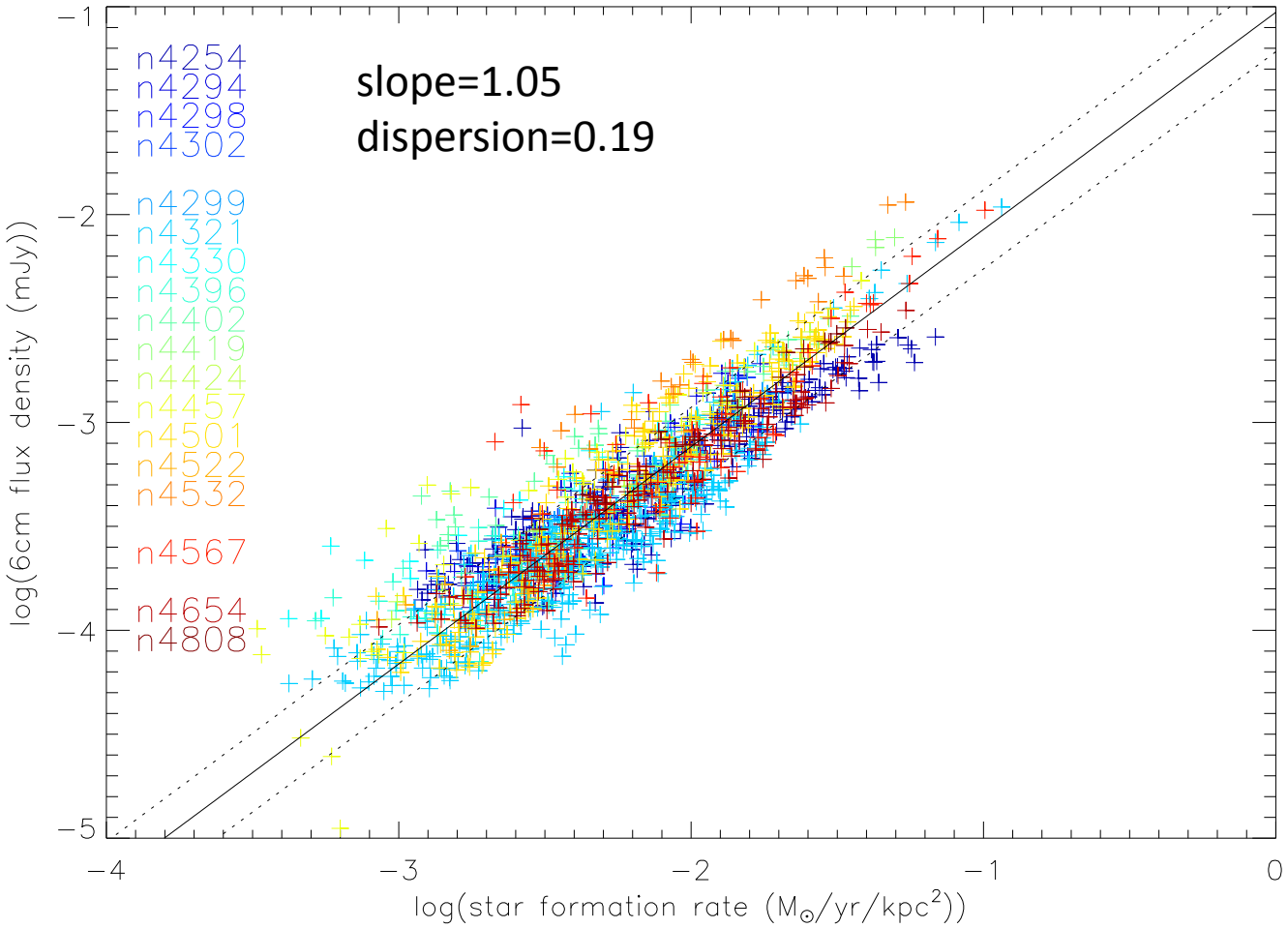
Integrated radio continuum – SFR correlation





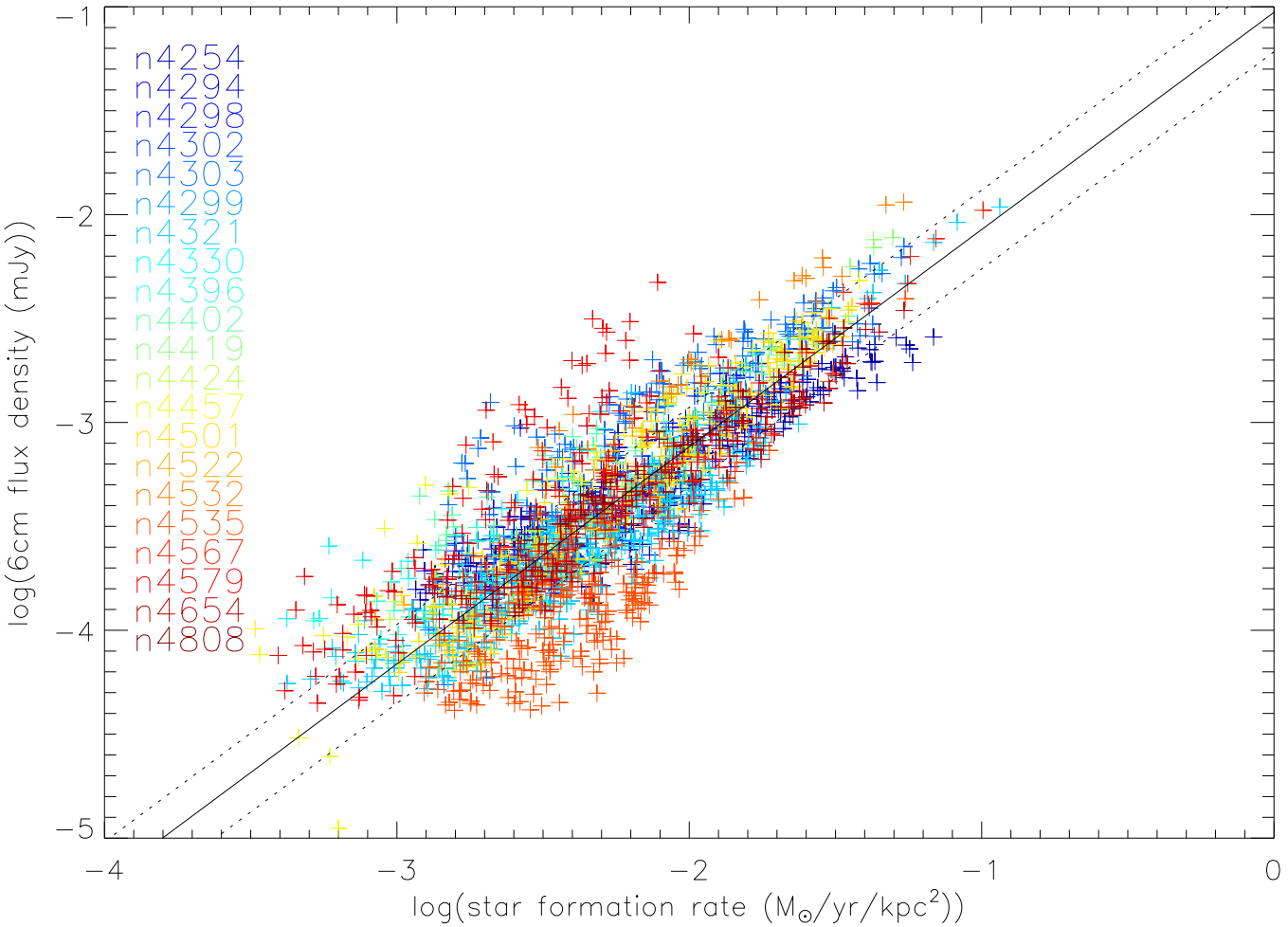
Heesen et al. (2014)

Radio continuum –SFR correlation



SFR = GALEX FUV + Spitzer 24 μm (+ Spitzer 70 μm or Herschel 100 μm)

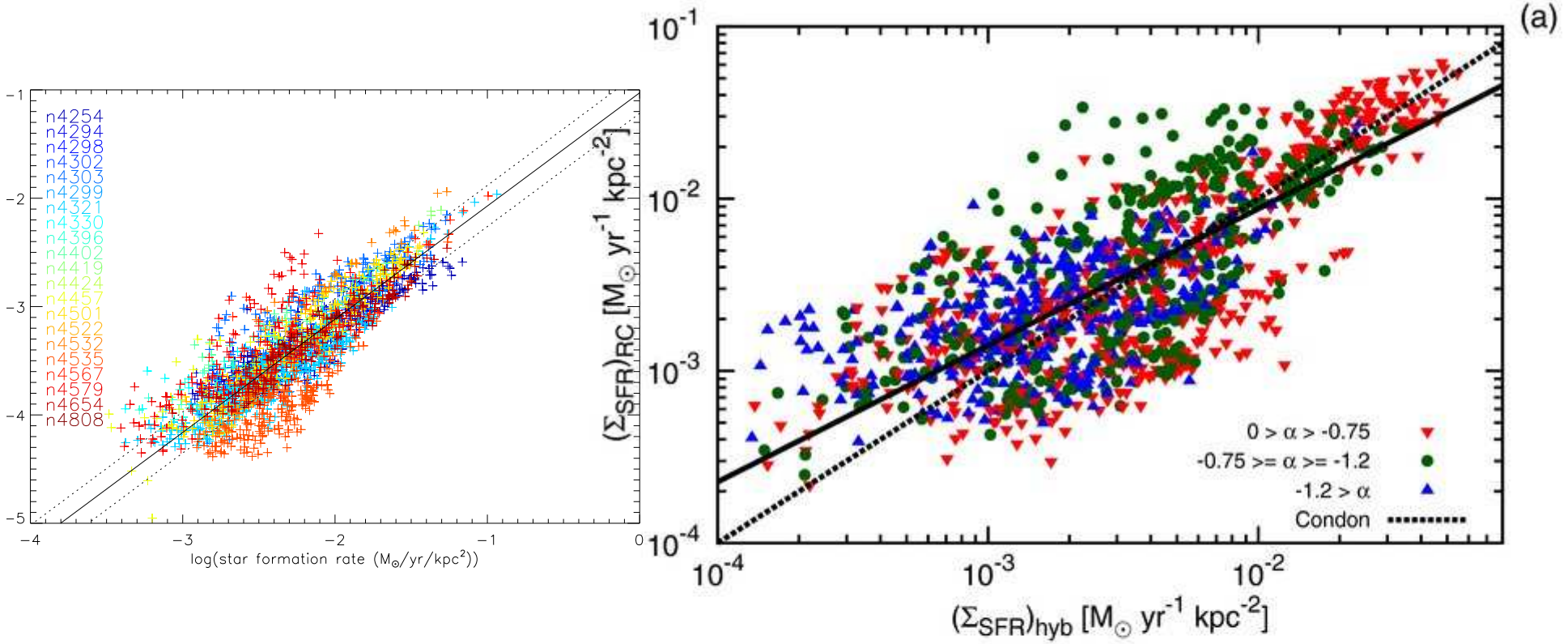
Radio continuum –SFR correlation



SFR = GALEX FUV + Spitzer 24 μm (+ Spitzer 70 μm or Herschel 100 μm)

Radio continuum –SFR correlation

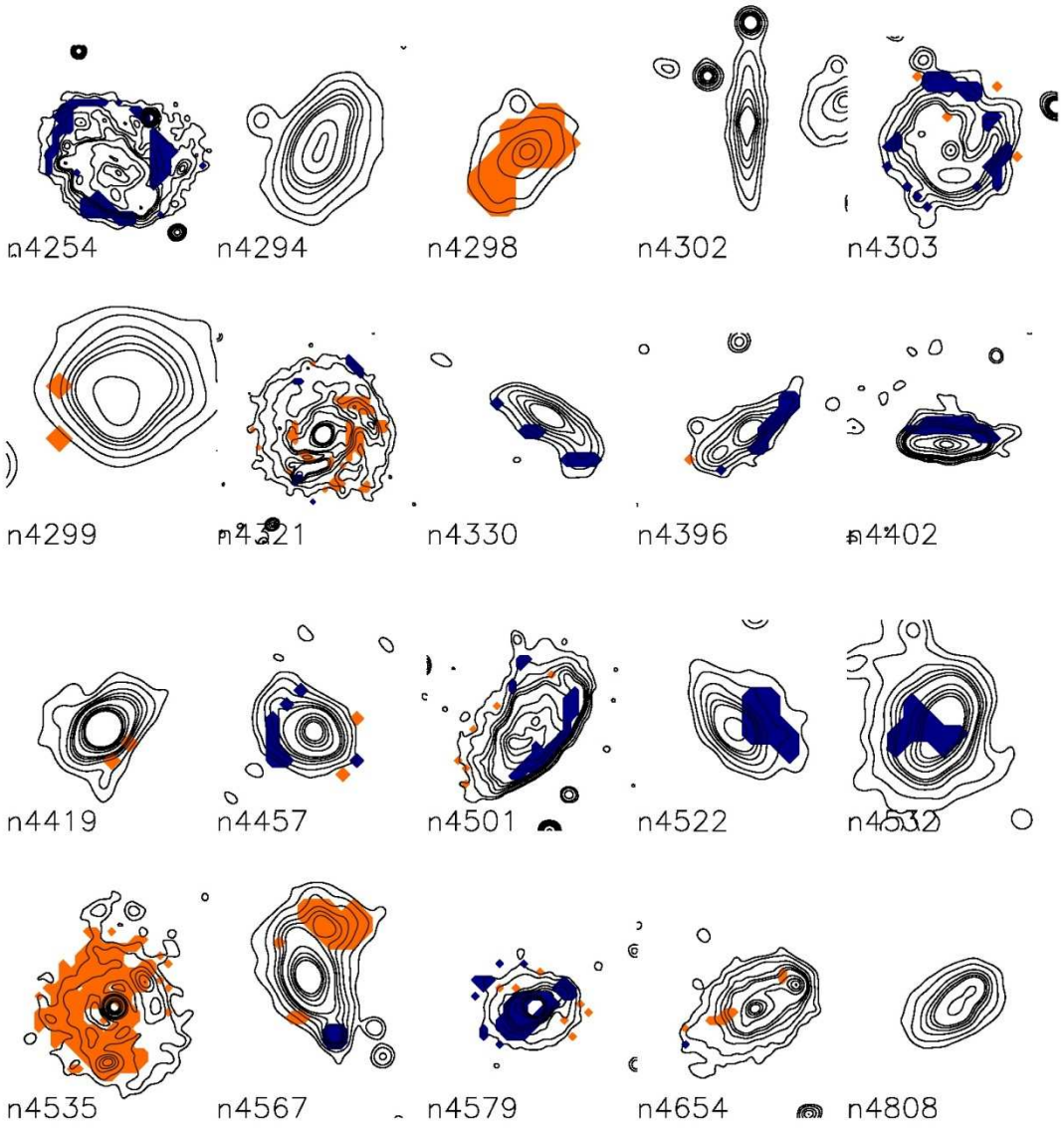
Heesen et al. (2014)



Radio bright or radio dim regions

blue:
radio bright

red:
radio dim



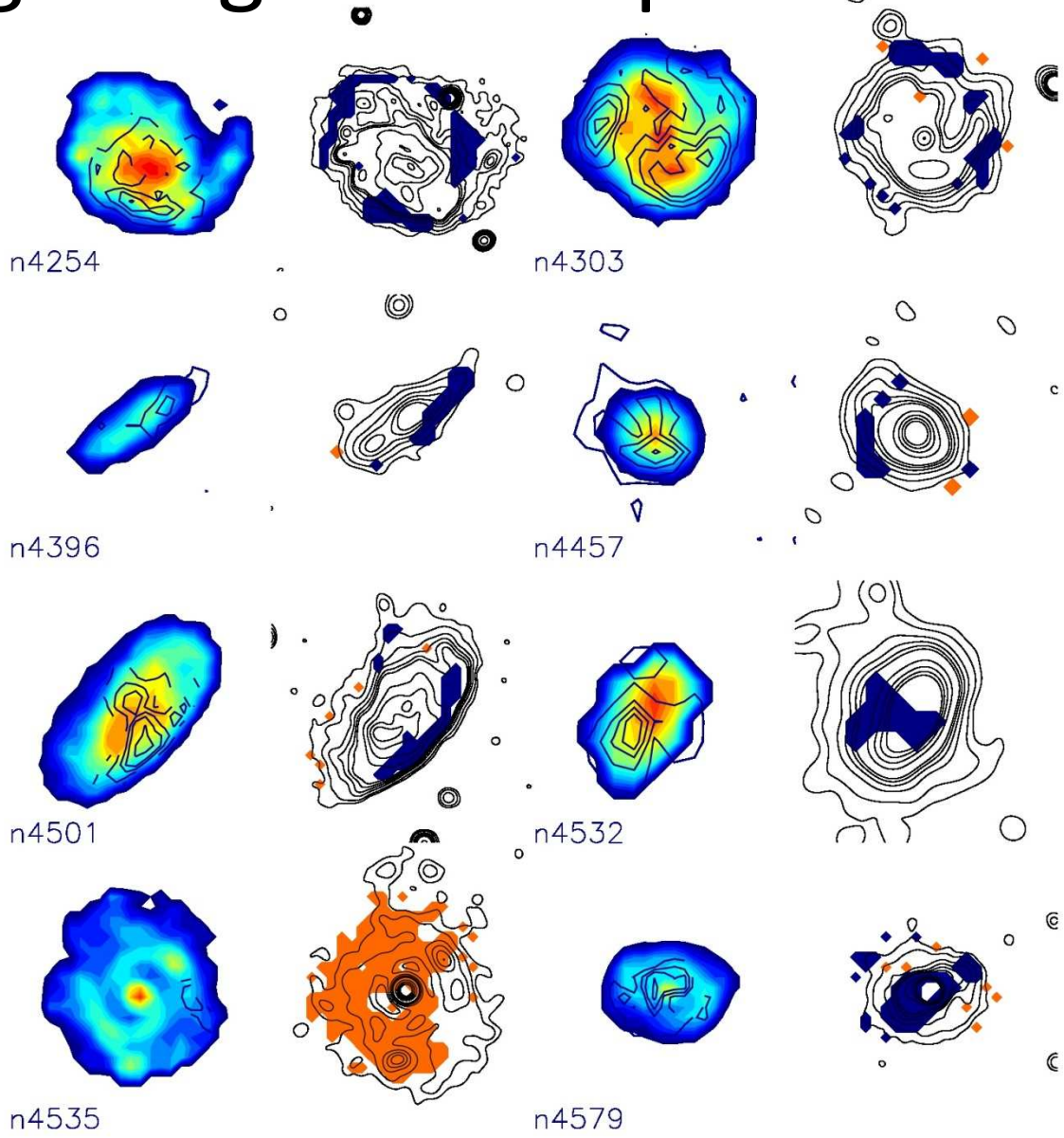
Radio deficient regions in Virgo spiral galaxies

Murphy et al. (2009)

Radio bright regions and polarization

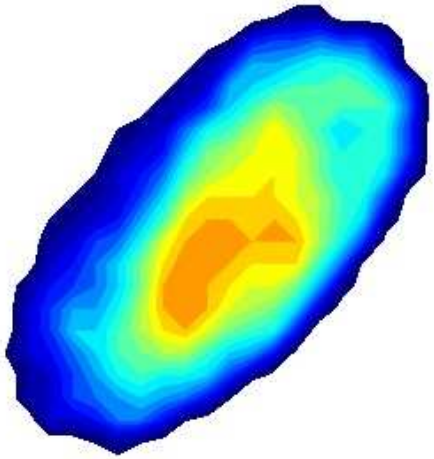
color: SFR
contour on color:
polarized radio contiuum

blue: radio bright
red: radio dim

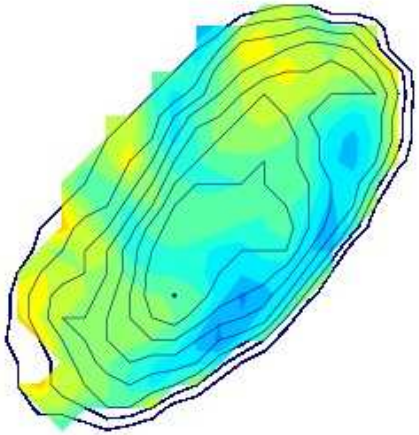


NGC 4501 (pre-peak)

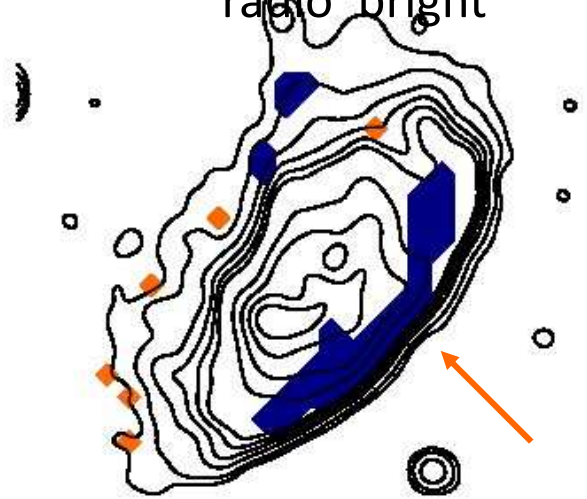
SFR

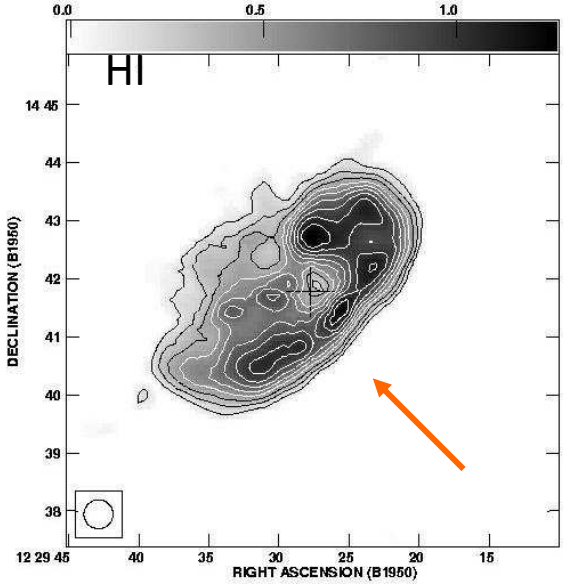


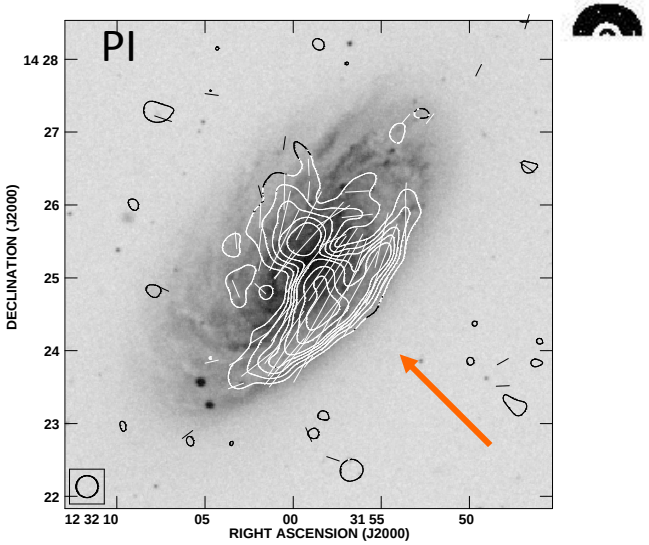
radio/SFR



radio bright



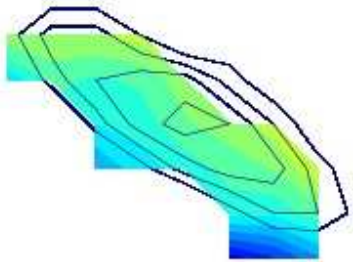




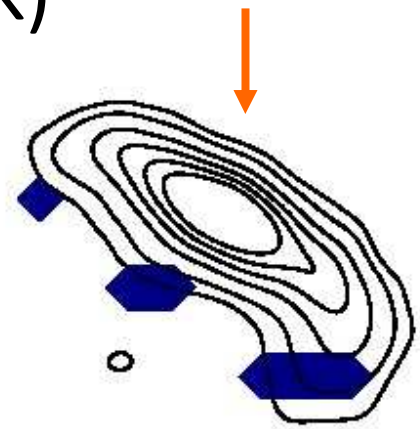
Vollmer et al. (2008)

NGC 4330 (pre-peak)

SFR

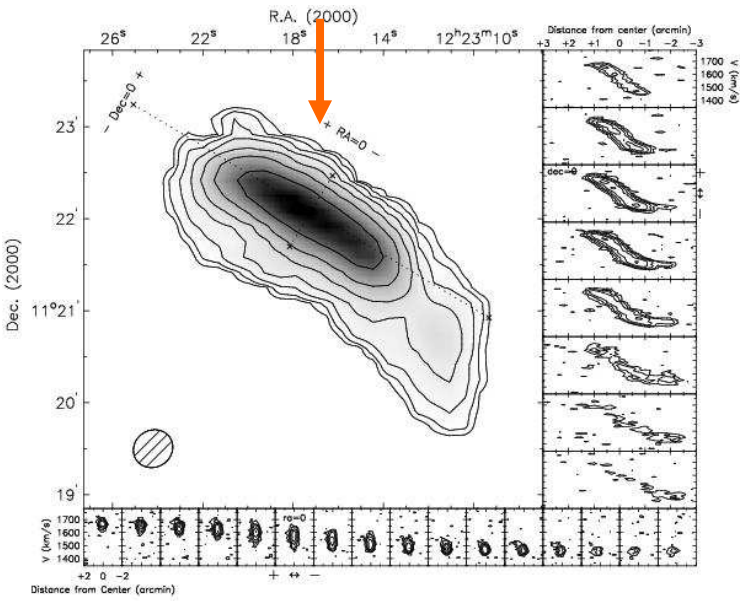


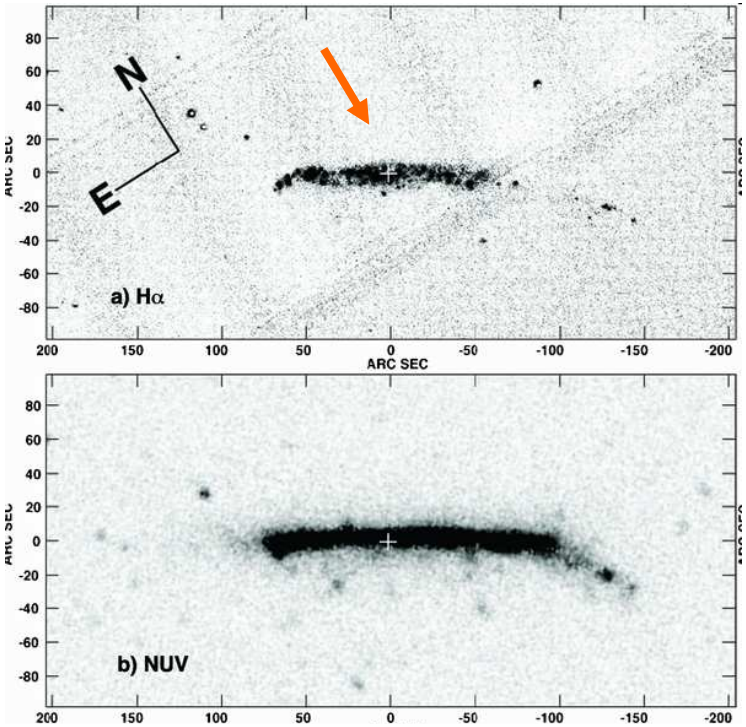
radio/SFR



radio bright

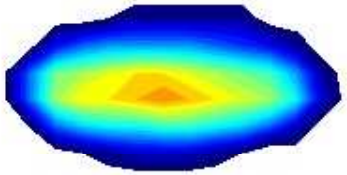
Abramson et al. (2011)



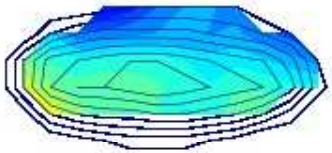


NGC 4402 (pre-peak)

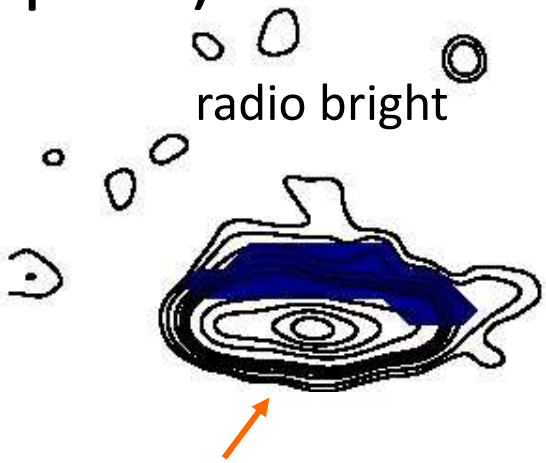
SFR

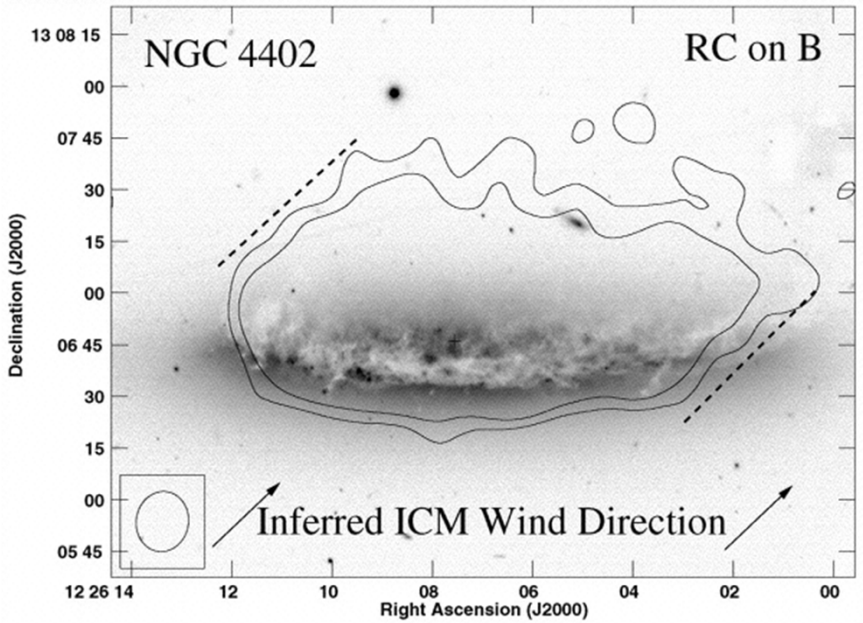


radio/SFR



radio bright

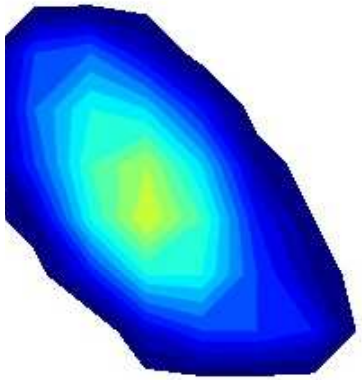




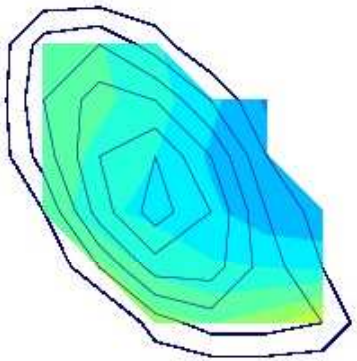
Crowl et al. (2005)

NGC 4522 (close to peak)

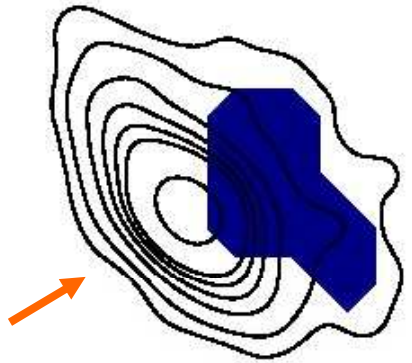
SFR

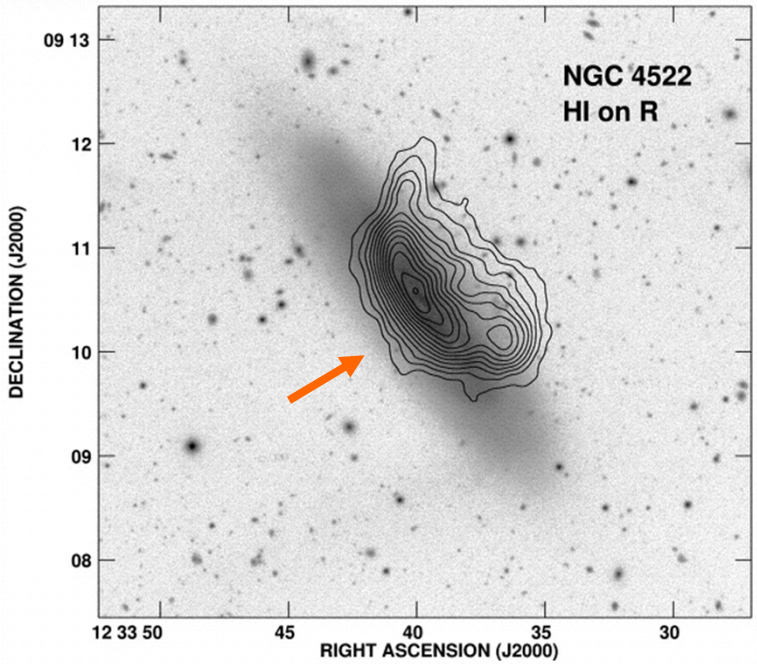


radio/SFR

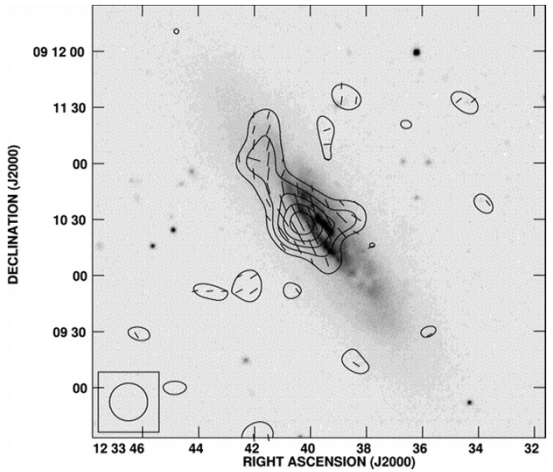


radio bright





(Kenney et al. 2004)



(Vollmer et al. 2004)

Conclusions I

- Polarized radio continuum emission is a useful tool for interaction diagnostics
- Efficiency of ram pressure stripping is ~1 (Gunn & Gott works) – overall the neutral ISM is stripped as an entity
- Temporal ram pressure sequence in the Virgo cluster
- Stellar population synthesis models confirm model stripping ages
- Neutral gas is stripped as an entity
- Indication of different stripping efficiencies of diffuse ionized ISM under certain circumstances
- Ram pressure quenches star formation

Conclusions II

- Radio –FIR / radio – SFR correlations show a slope of ~1
- 3 outliers out of 22 galaxies
- Radio strong/weak regions based on radio – SFR correlation
- Most peculiar regions in Virgo spiral galaxies are radio bright
- Positive correlation between PI and radio/SFR in 7 perturbed galaxies (compression/shear)
- Modelling of the radio emission is under way