Galaxy evolution in the Virgo cluster

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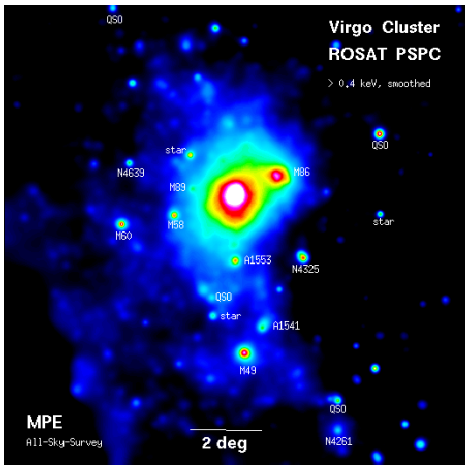
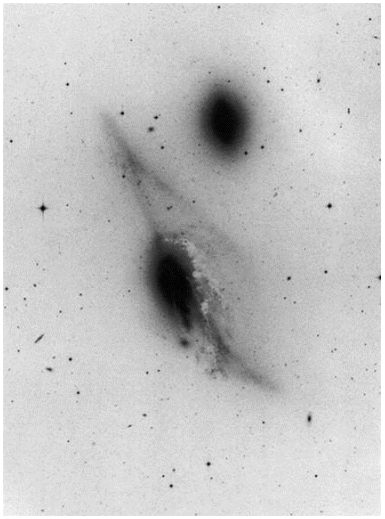
(VIVA: J. Kenney, J. van Gorkom, A. Chung, H. Crowl,
R. Beck, M. Soida, J. Braine)

Interaction of a spiral galaxy with its environment

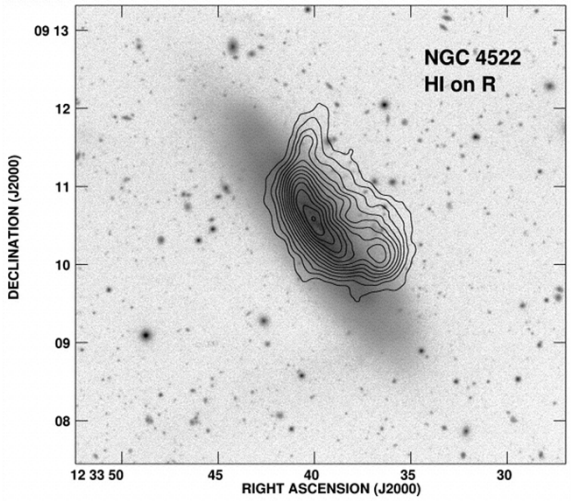
- Gravitational interaction galaxy - cluster
- Gravitational interaction galaxy - galaxy
- Ram pressure galaxy ISM – intracluster medium (ICM)



(Böhringer et al. 1994)

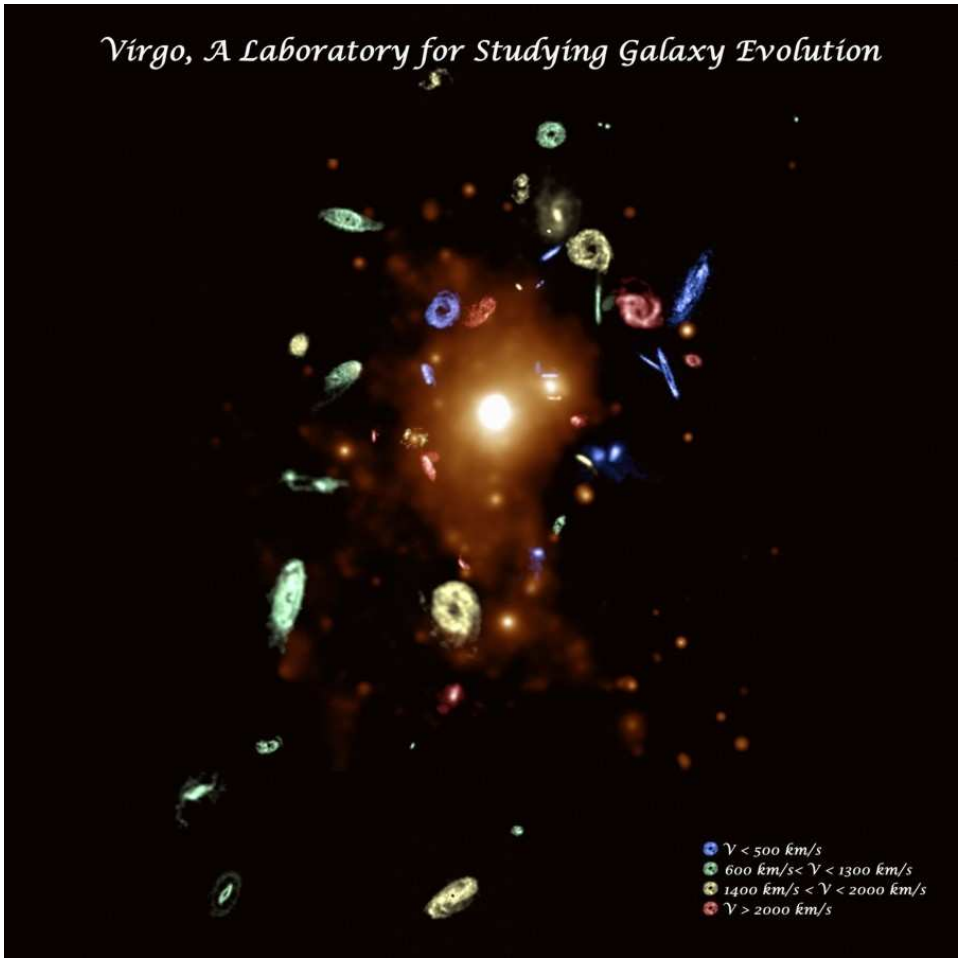


(Kenney et al. 1995)



(Kenney et al. 2004)

Atomic gas: the HI view

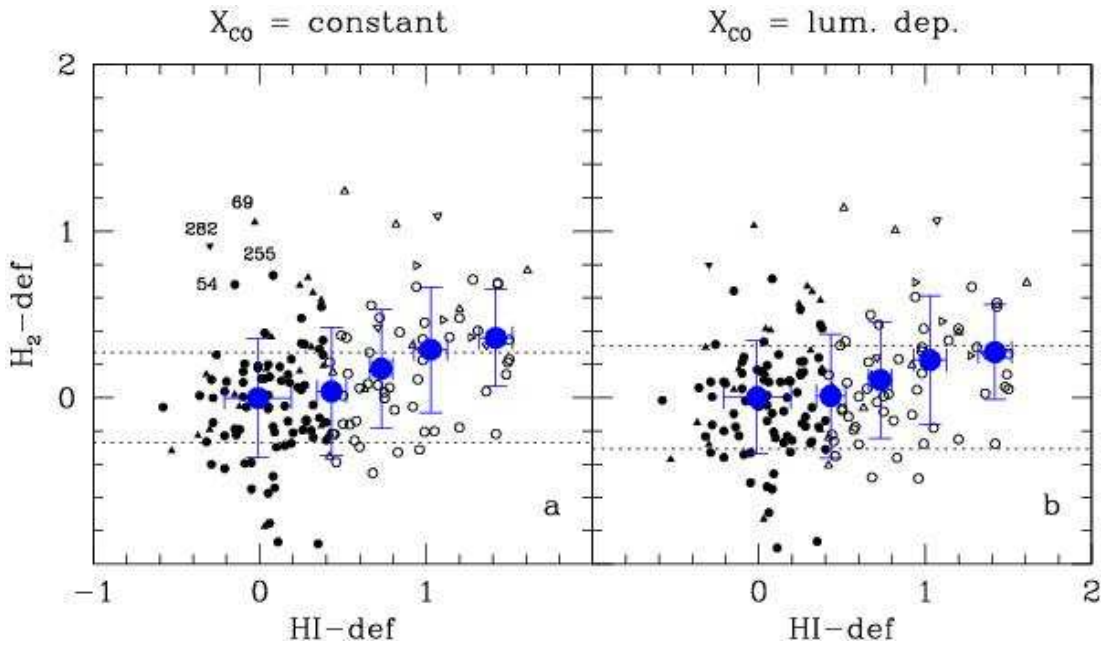


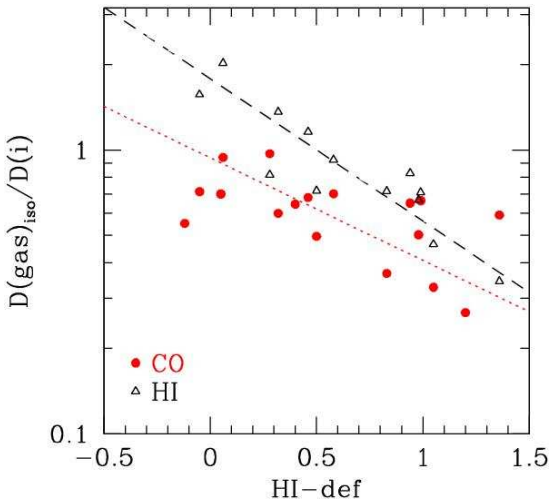
(Chung et al. 20009)

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

Cluster spirals are HI deficient and show truncated gas disks

Molecular gas in cluster galaxies





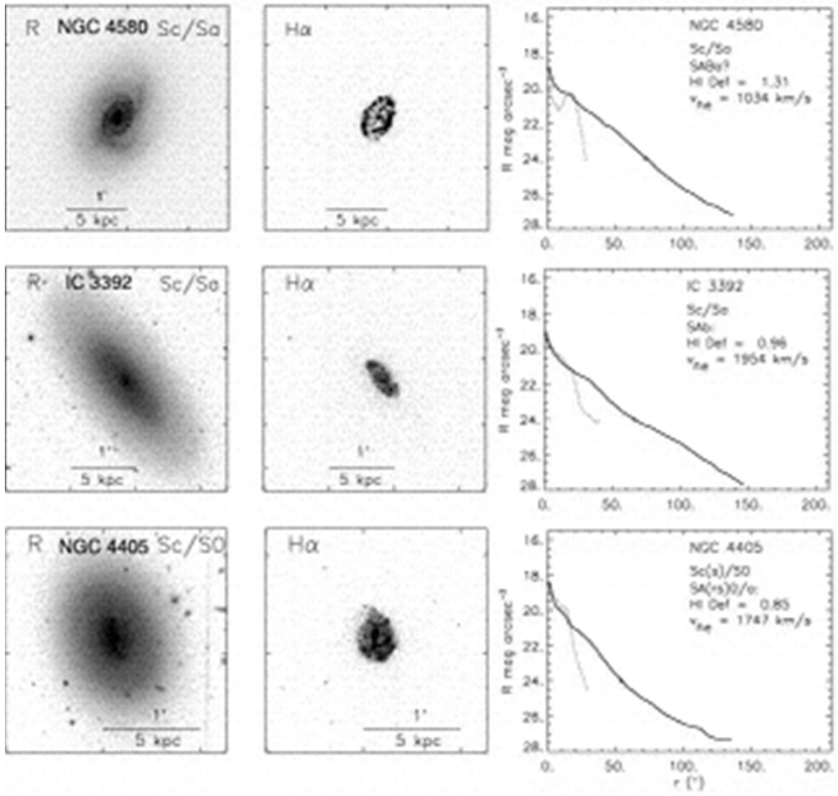
Boselli et al. (2014)

- only mildly molecular-gas deficient galaxies in the Virgo cluster
- HI-def galaxies have slightly smaller CO disks
- the CO detection rate of Virgo early type galaxies is **NOT** different from that of the field (Atlas^{3D}; Young et al. 2011)

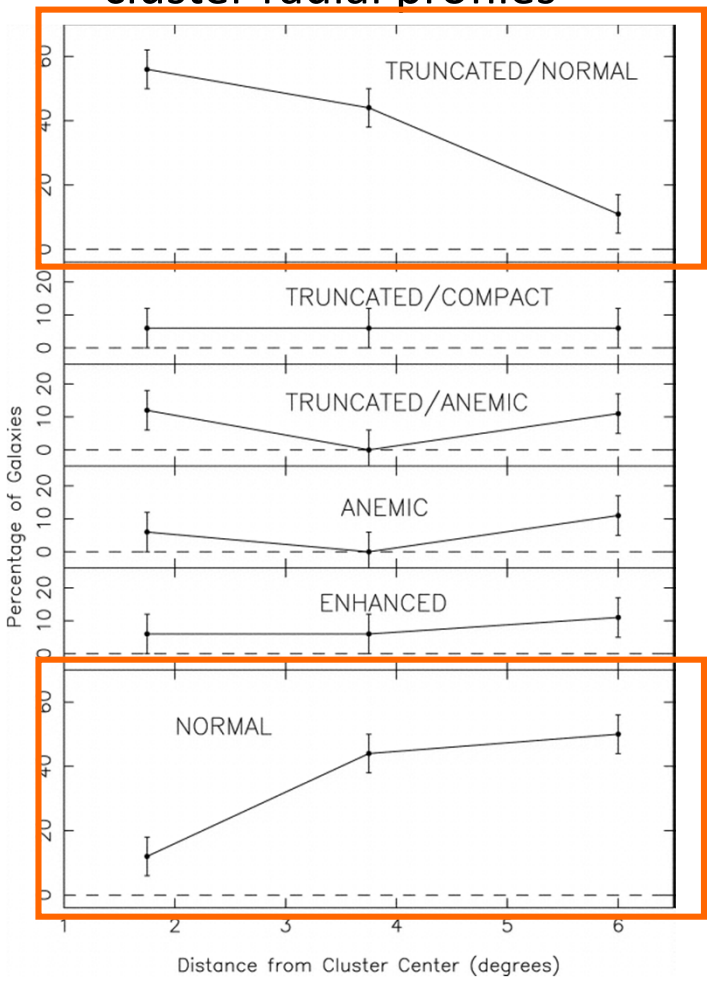
Star formation: the Hα view

(Koopmann & Kenney 2001, 2004)

truncated Hα disks

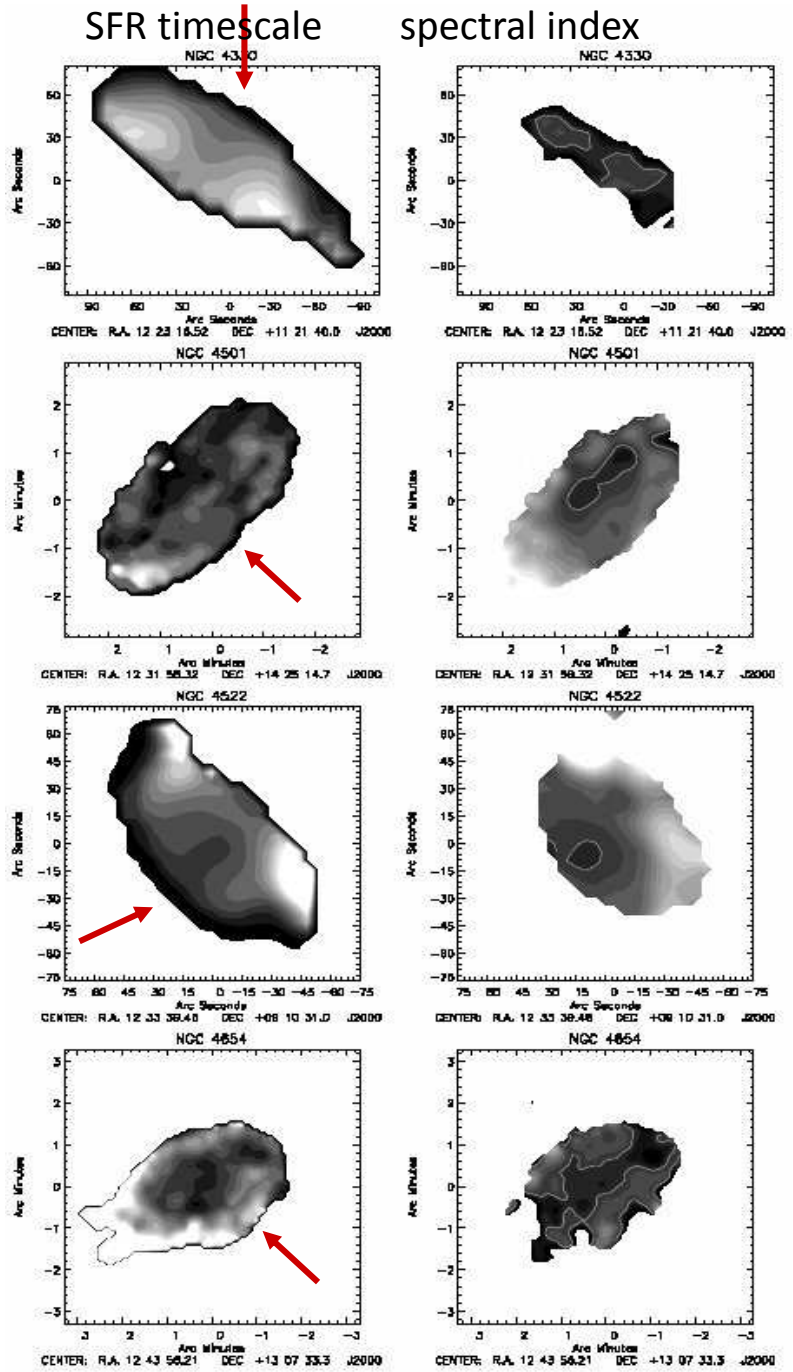


cluster radial profiles



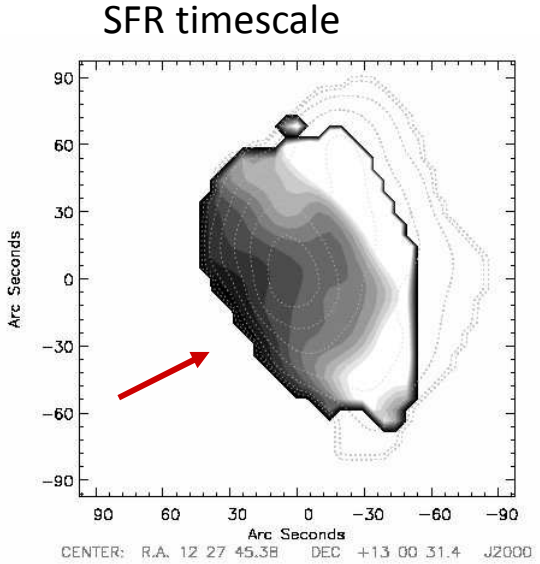
52 Virgo galaxies: 37% normal, 6% anemic, 6% enhanced, 52% truncated

Gas and star formation



- **Except for N4438, the cluster environment does not significantly change $SFR_{mol}=SFR/M_{mol}$ in the disks**
- **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)

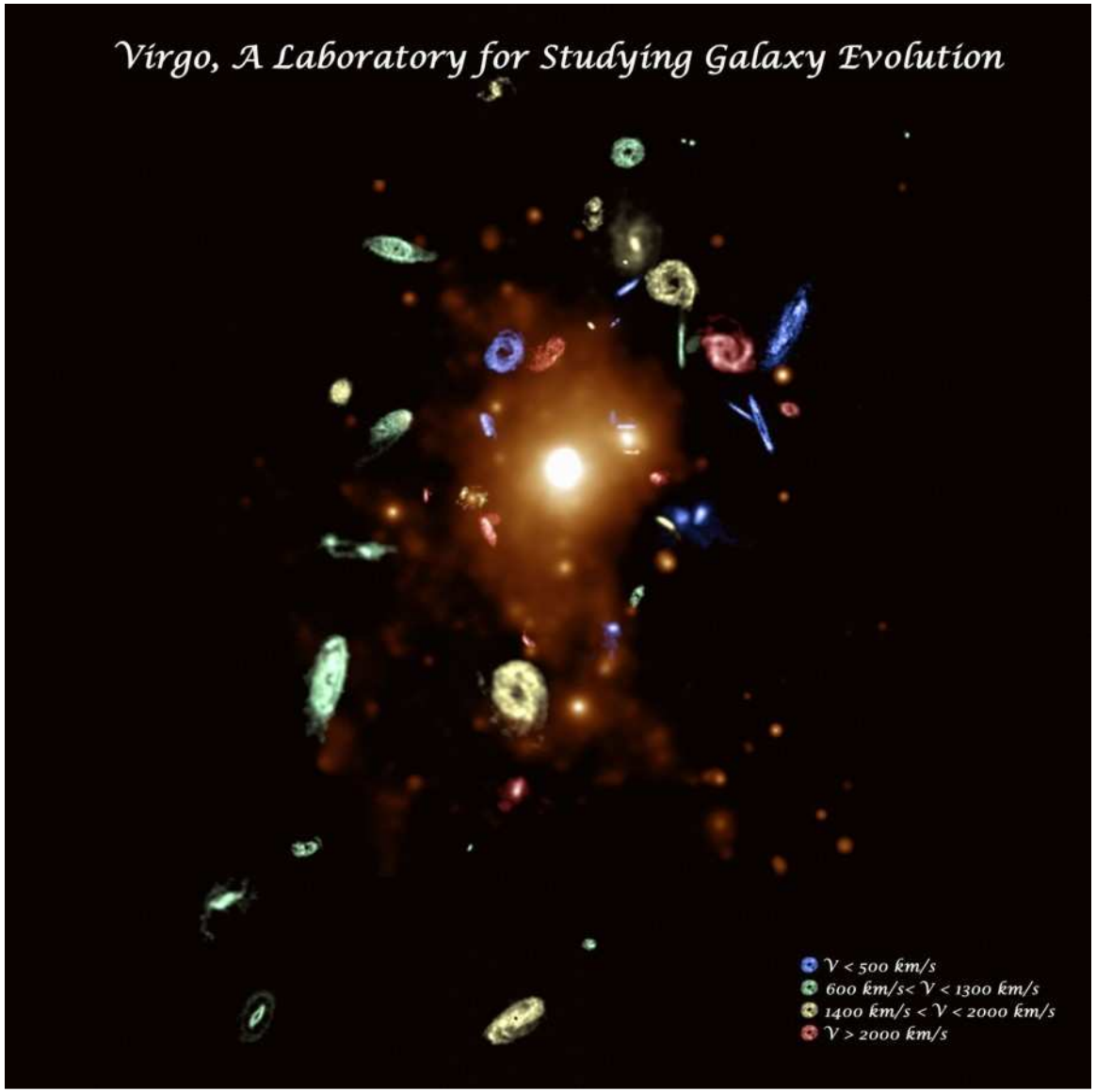
Interaction diagnostics

- 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)

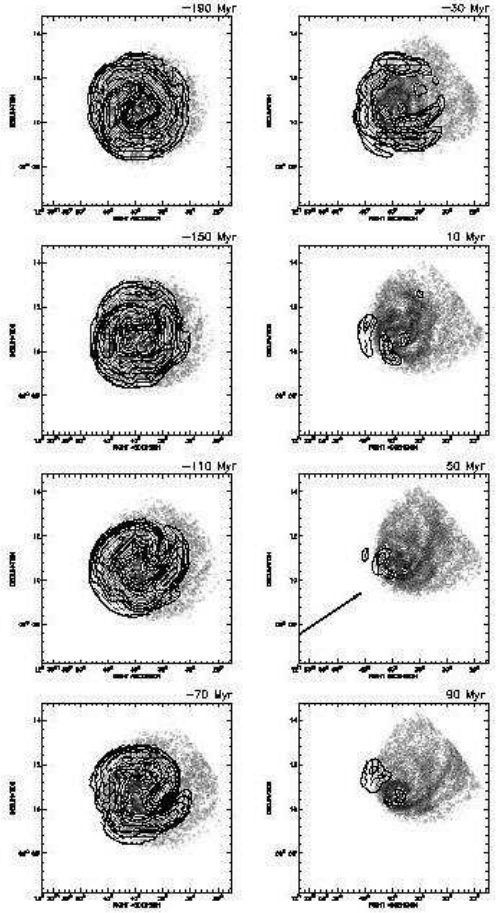


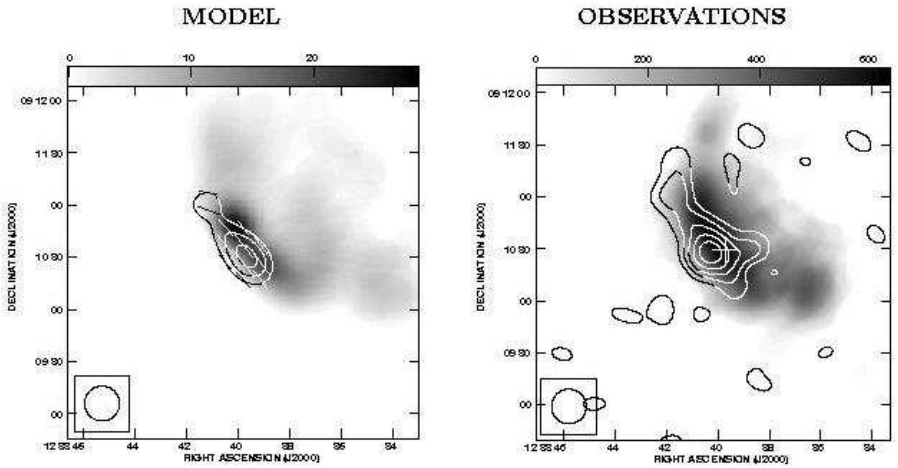
MHD simulations

(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





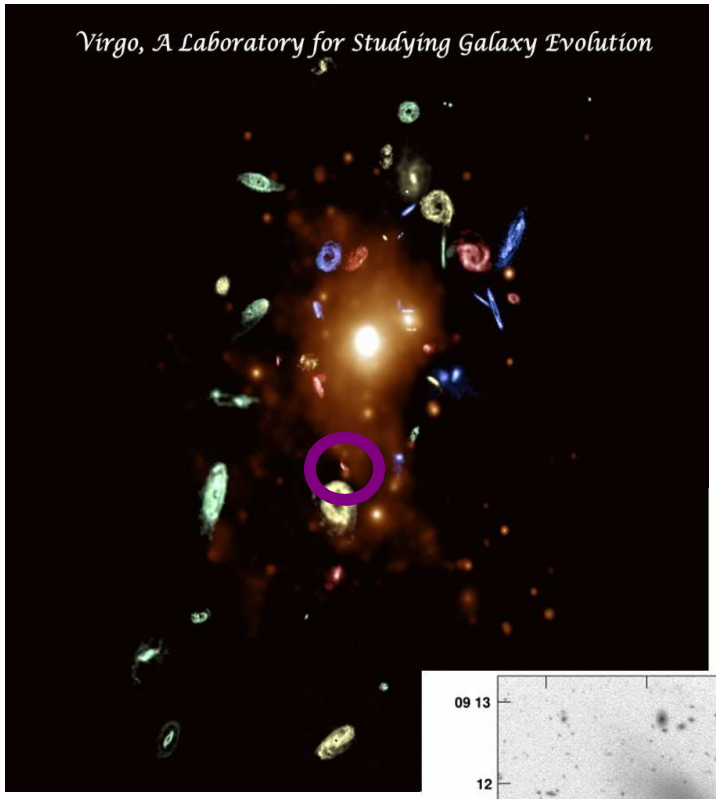
grey: HI, contours: PI
(Vollmer et al. 2006)

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

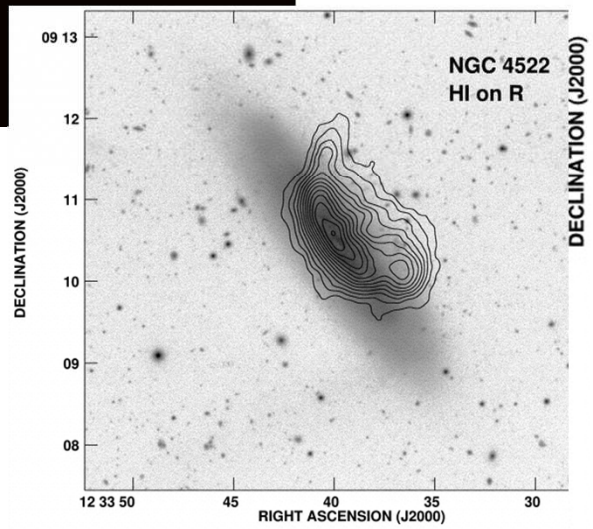
Ram pressure stripping criterion:
Gunn & Gott (1972): $\Sigma_{gas}\, v_{rot}^2/R = \rho_{ICM}\, v_{gal}^2$

A case study: NGC 4522

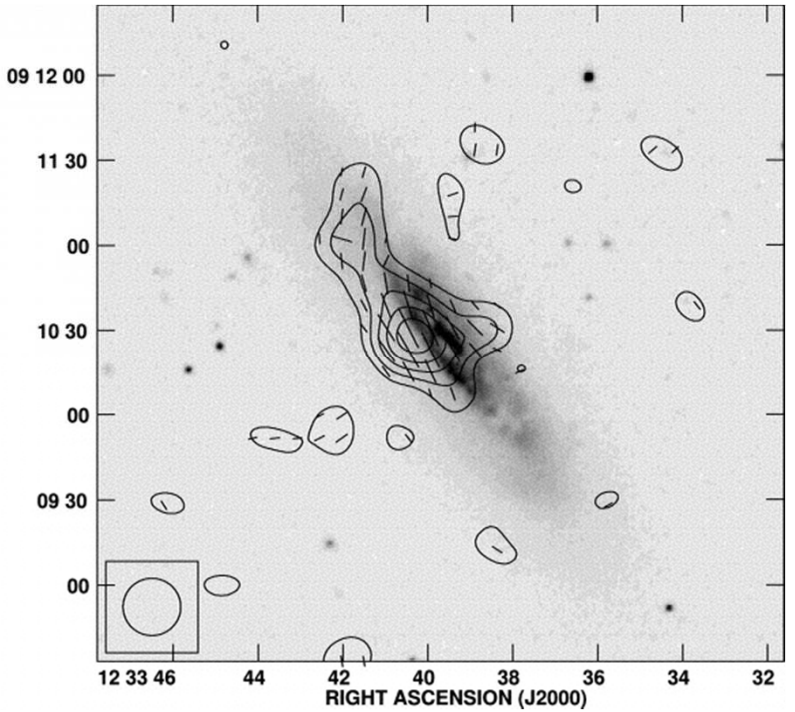


- Distance from M87:

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

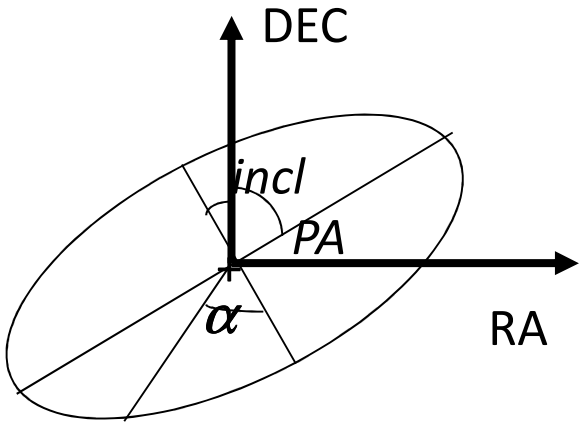


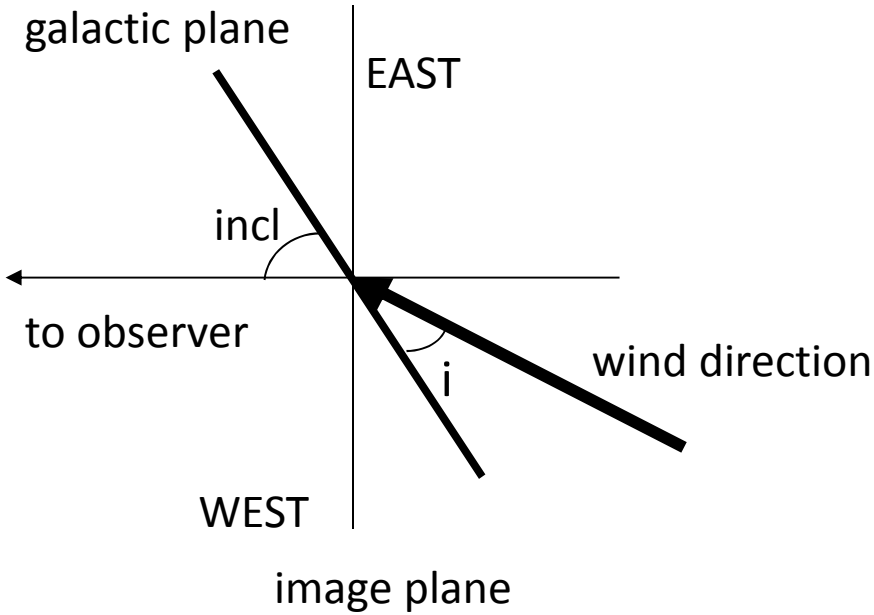
(Kenney et al. 2004)

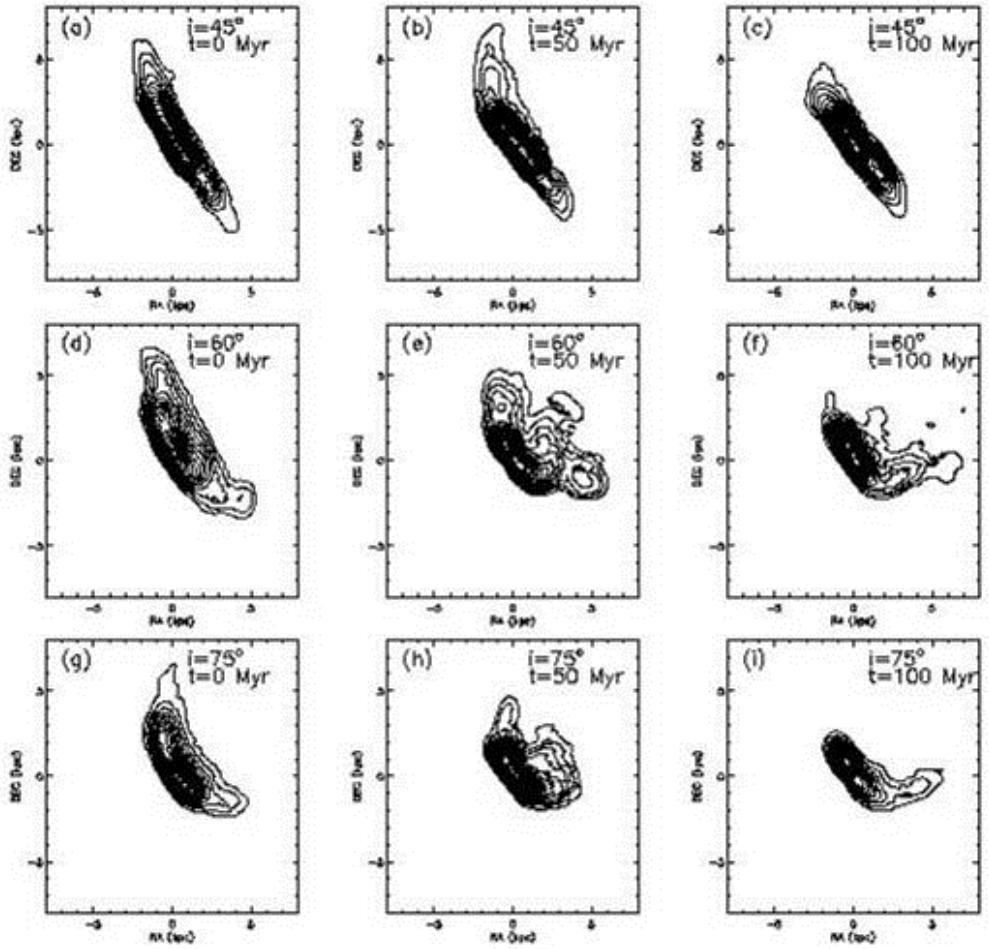


(Vollmer et al. 2004)

NGC 4522: the « best fit » model

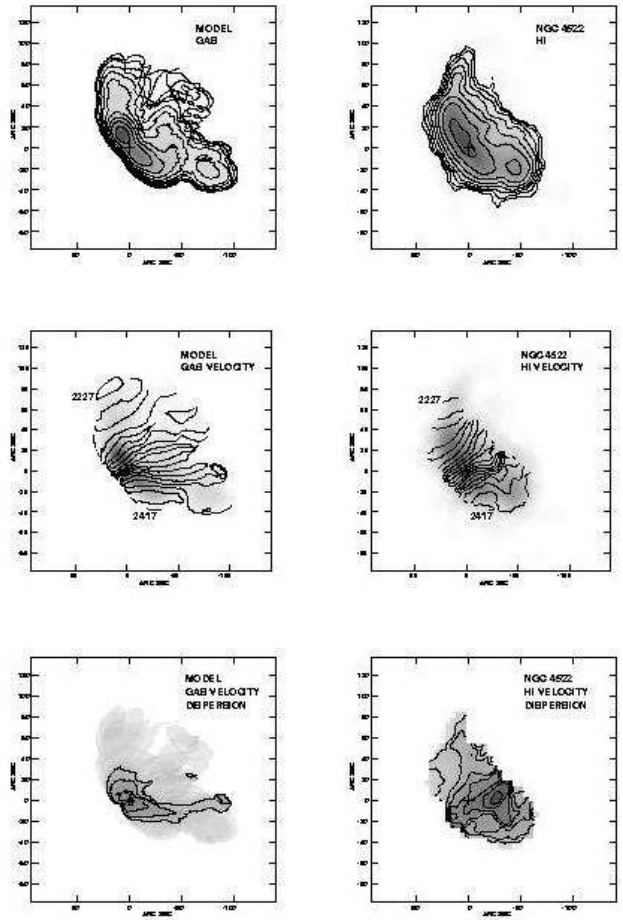


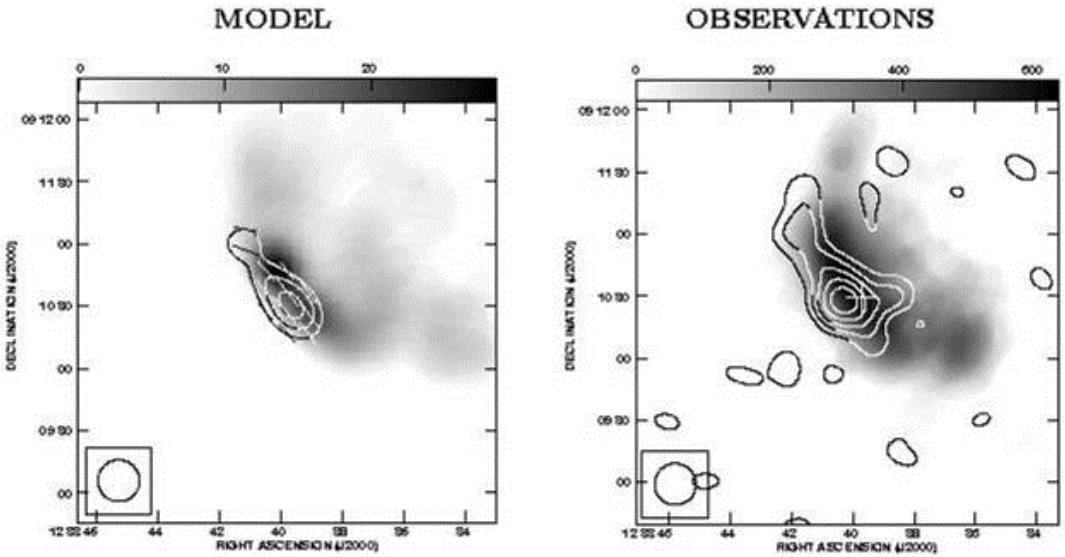




NGC 4522: final result

model HI





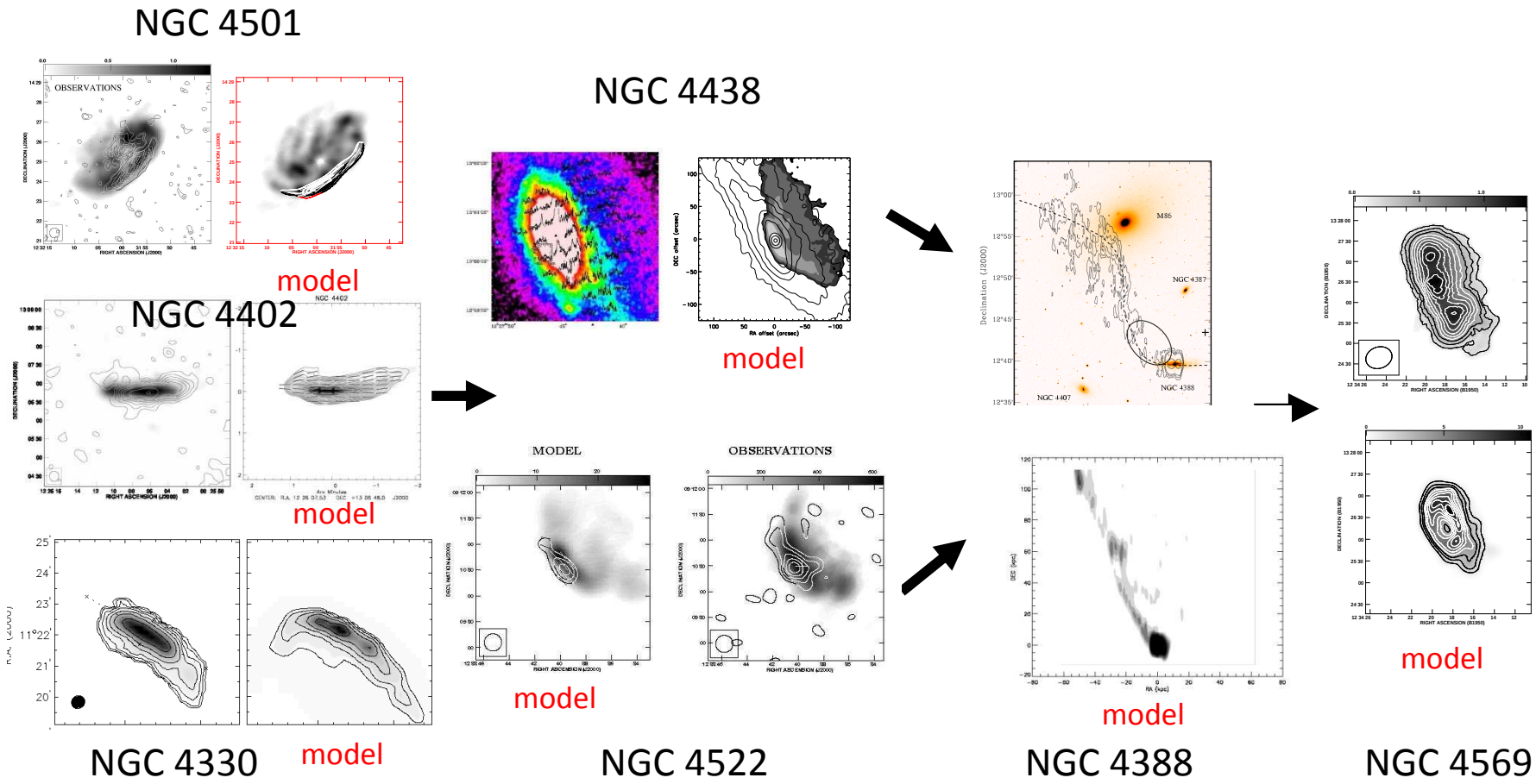
Greyscale: gas;
Contours: polarized radio continuum emission

(Vollmer et al. 2007)

→ **near peak ram pressure stripping**

Ram pressure stripping time sequence

Vollmer (2009) - **update**

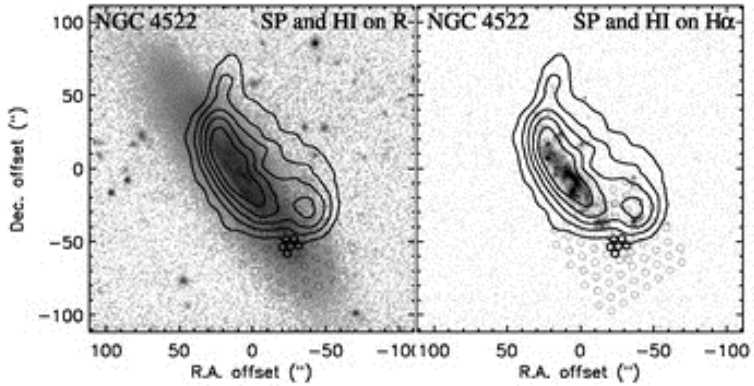


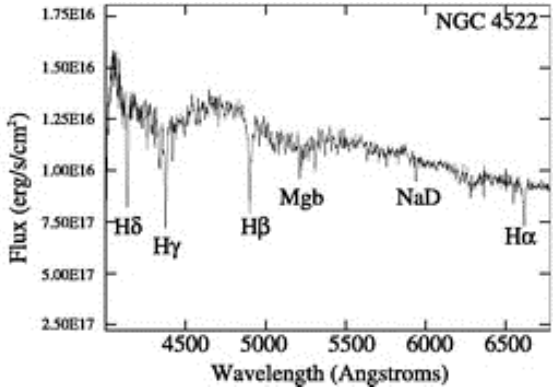
pre-peak near peak ~200Myr after peak ~300Myr after peak

Independent confirmation of stripping ages

- NGC 4522 (Crowl & Kenney 2007, 2008)

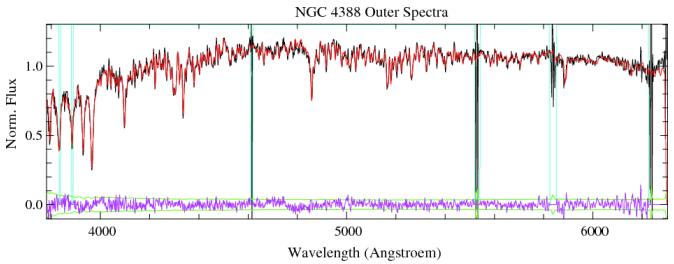
WIYN SparsePack
& GALEX UV

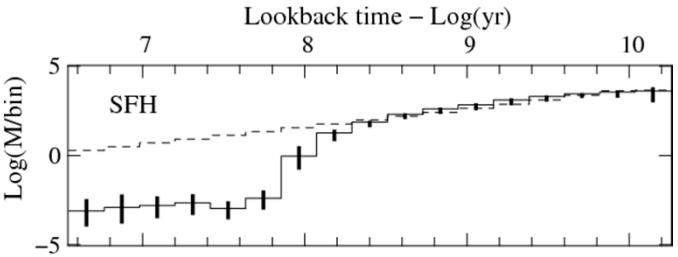




- NGC4388 (Pappalardo et al. 2010)

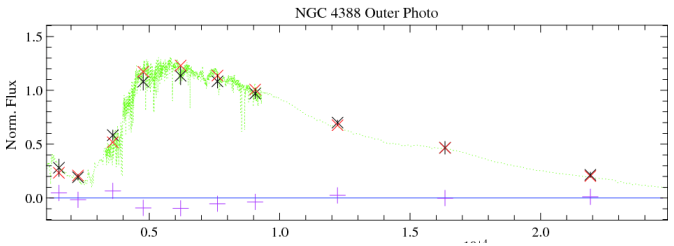
VLT FORS spectrum





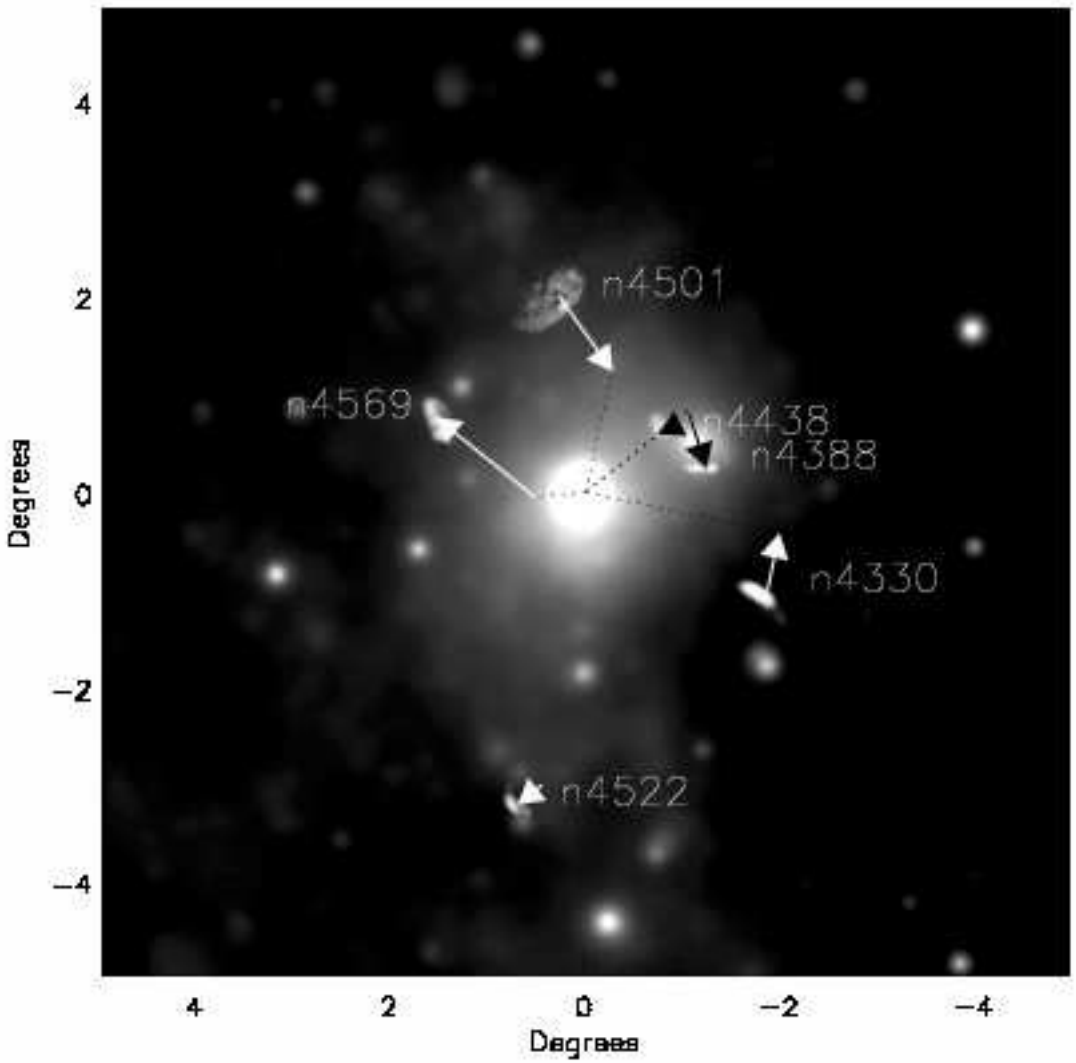
star formation history

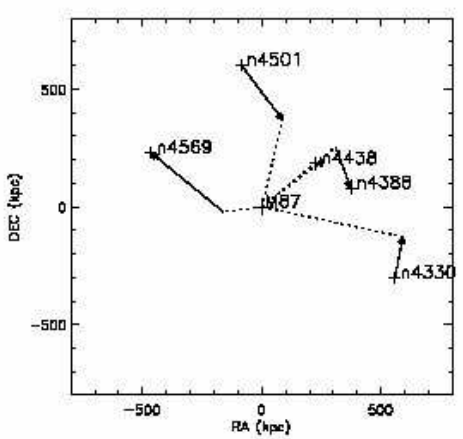
VLT FORS spectrum +
multi-λ photometry

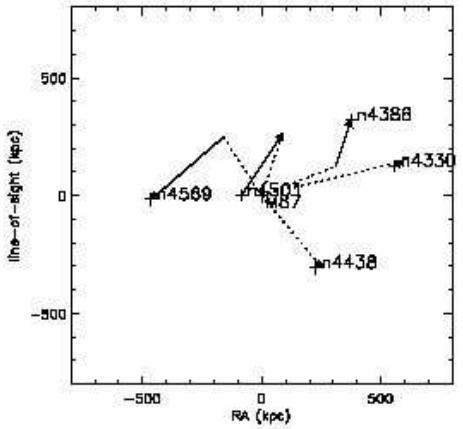


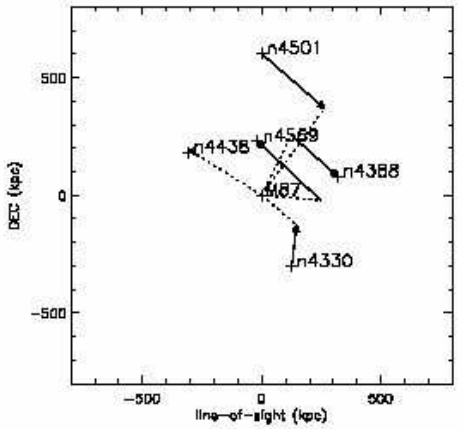
The 3D view

Vollmer (2009)



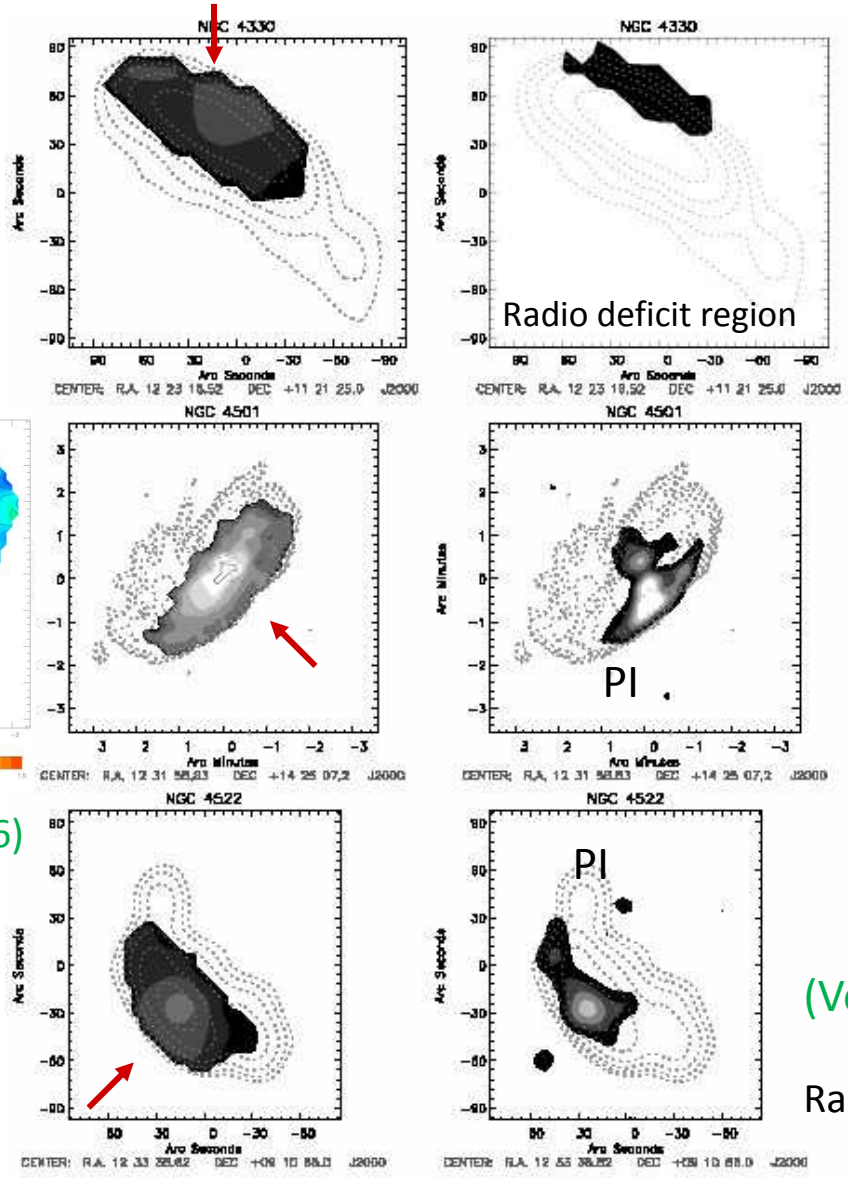






Ram pressure and the multiphase ISM

Molecular gas fraction



Nehlig et al. (2016)

- **Inside the truncation radius, gas disks are normal**
- **Enhanced molecular fraction in 3 galaxies (NGC4330, NGC4501, NGC4522)**

(Vollmer et al. 2012)

Radio deficit: Murphy et al. (2009)

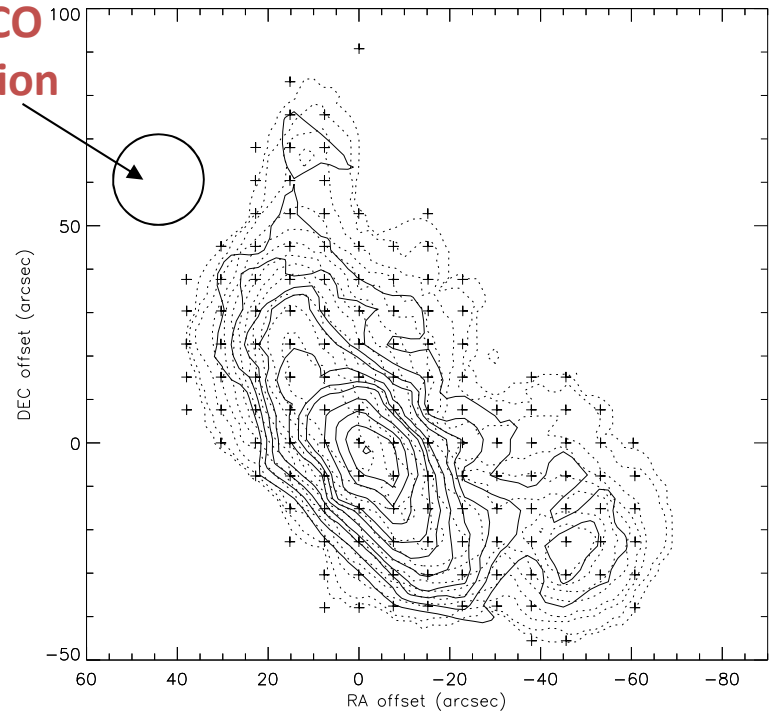
Ram pressure stripping of the multiphase ISM

Vollmer et al. (2008)

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

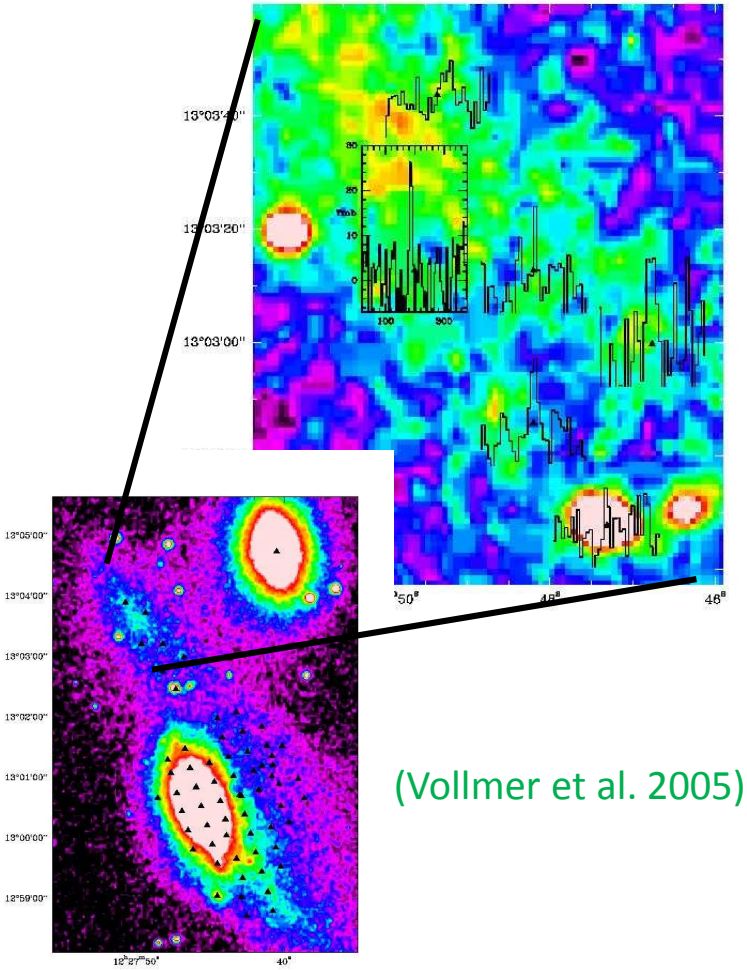
NGC 4522: decoupled moecular clouds

faint CO emission



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

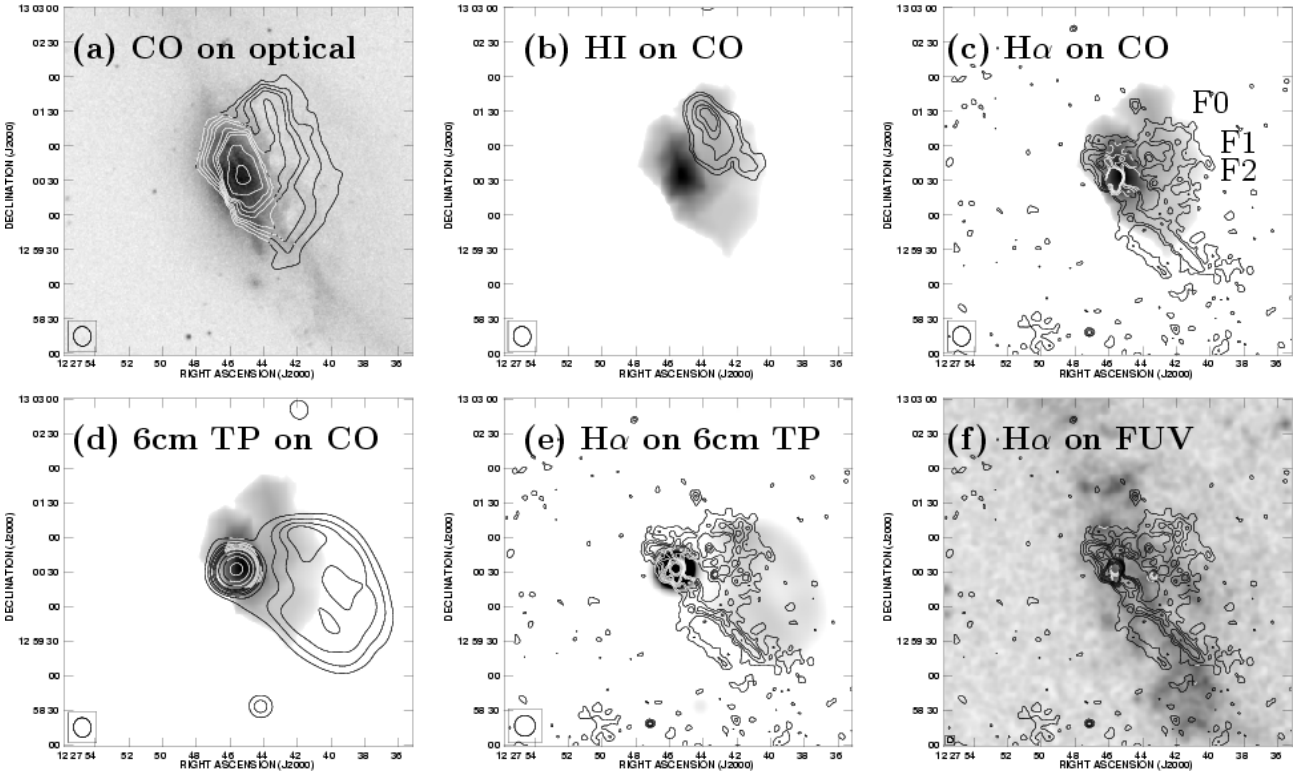
NGC 4438: decoupeled molecular clouds



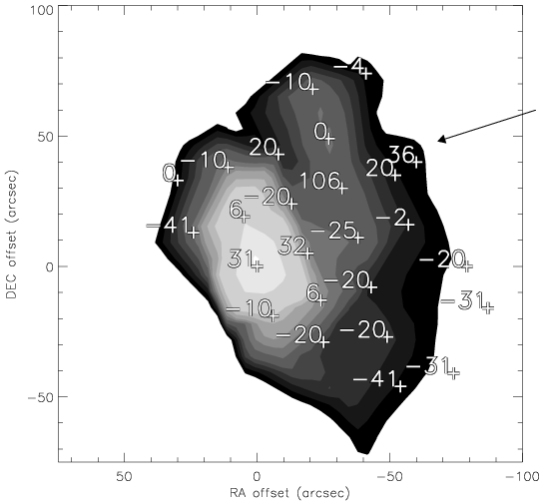
(Vollmer et al. 2005)

Ram pressure stripping of the multiphase ISM

NGC 4438 Vollmer et al. (2009)



velocity differences
CO - Hα

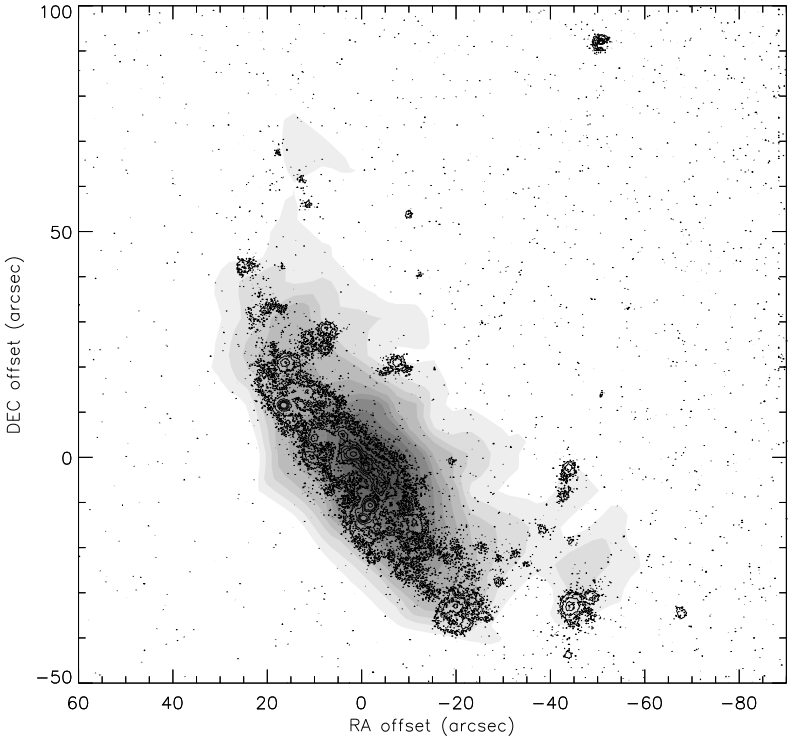


Diffuse ionized gas (Hα) is stripped more efficiently -> lower column density

Star formation in the stripped gas

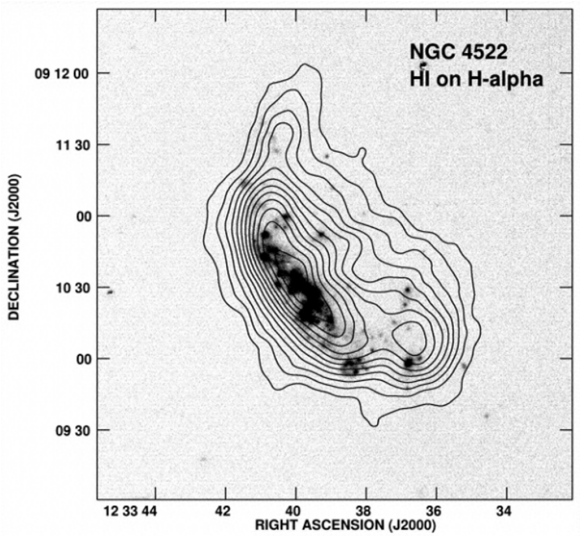
(important for radio continuum emission)

Vollmer et al. (2008)



Greyscale: CO(2-1)

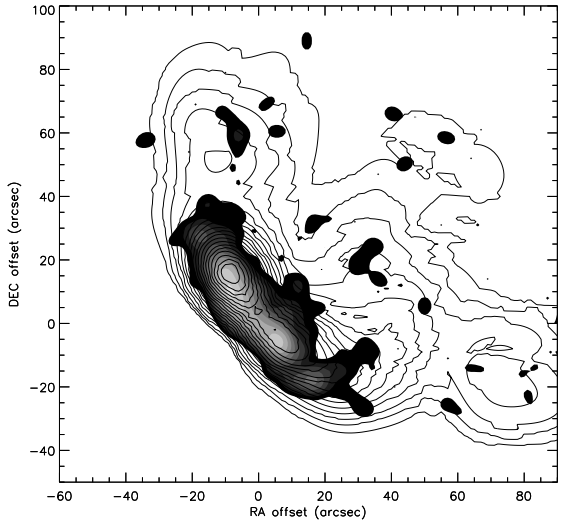
Contours: Hα (Kenney et al. 2004)



Greyscale: Hα

Contours: HI

from Kenney et al. (2004)



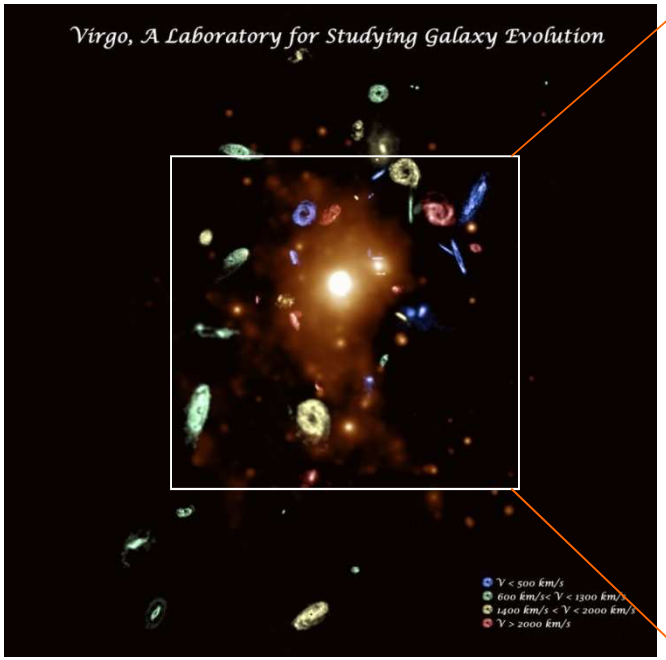
model

Greyscale: Hα

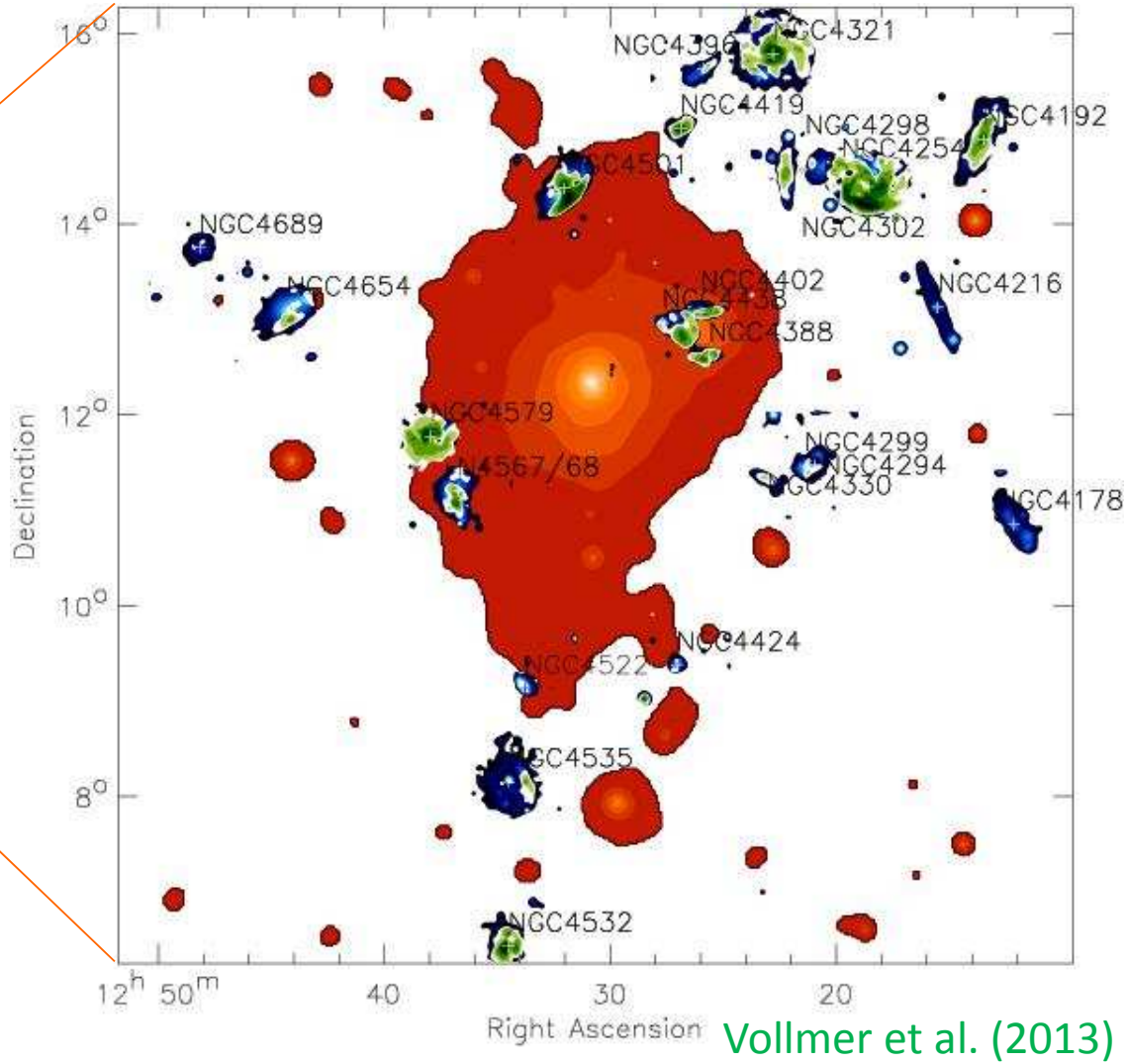
Contours: HI

Radio continuum observations of Virgo cluster galaxies

red: ICM; blue: TP; green: PI



VIVA Chung et al. (2009)

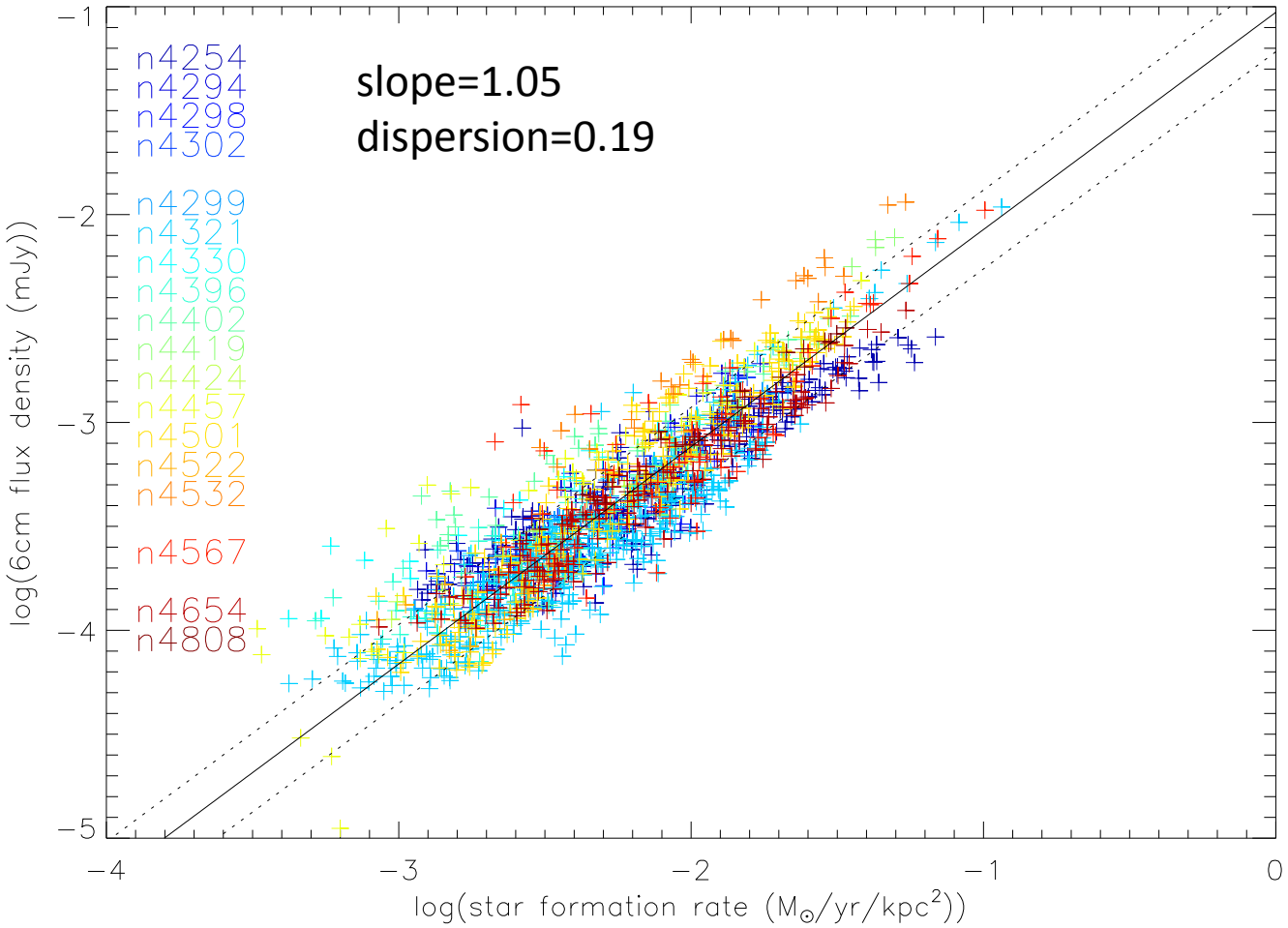


Vollmer et al. (2013)

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

Radio continuum –SFR correlation

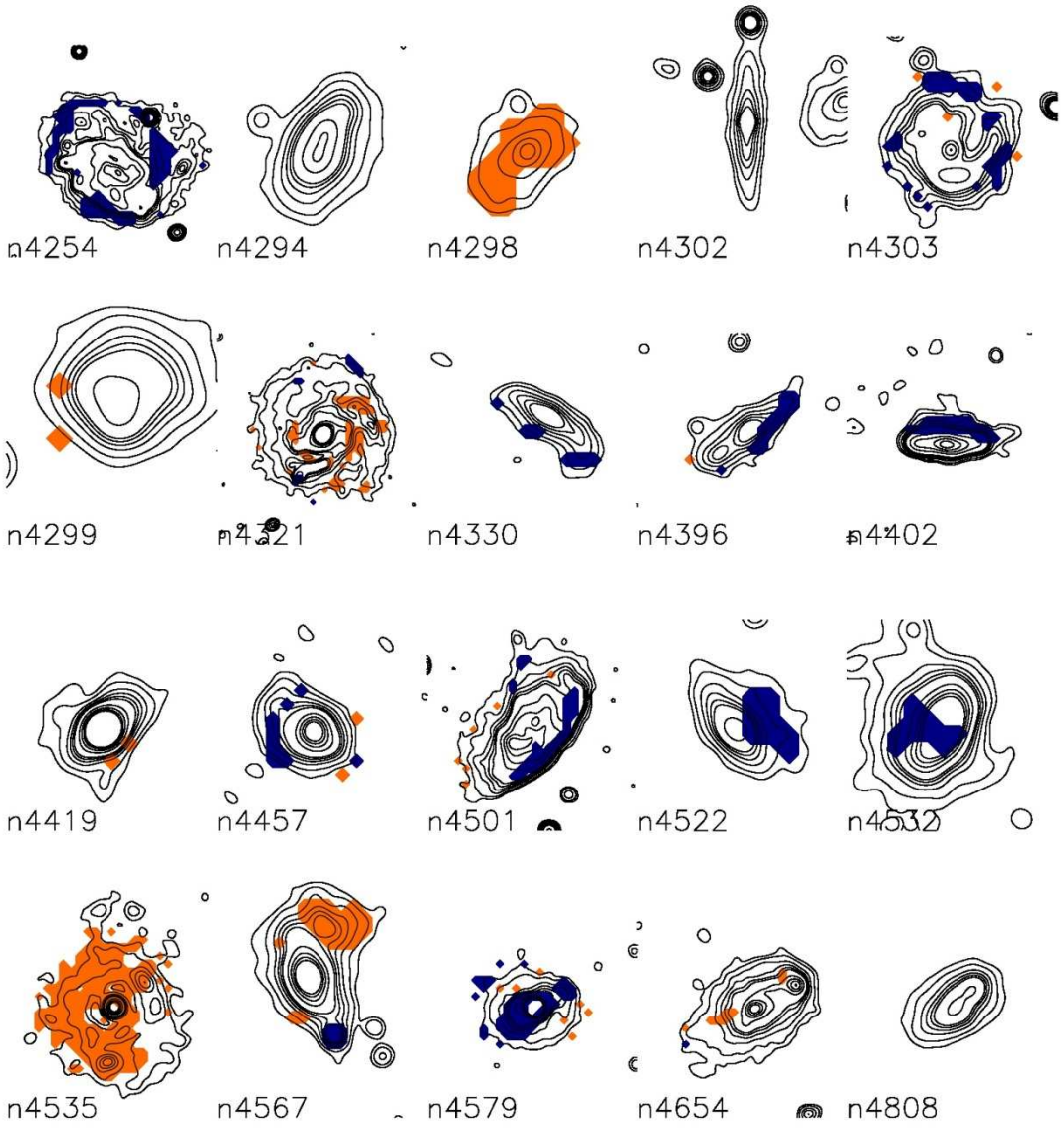


SFR = GALEX FUV + Spitzer 24 μm (+ Spitzer 70 μm or Herschel 100 μm)

Radio bright or radio dim regions

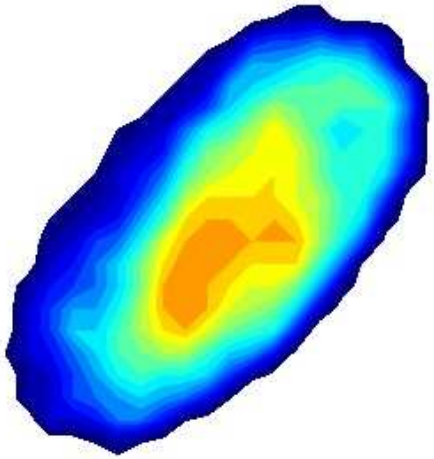
blue:
radio bright

red:
radio dim

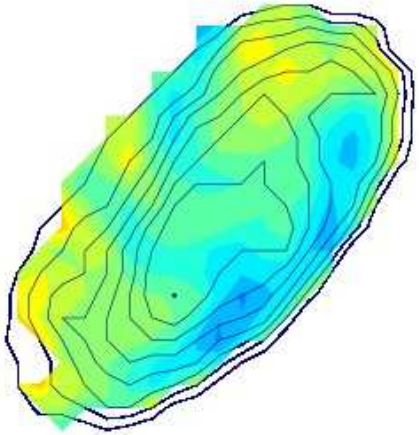


NGC 4501 (pre-peak)

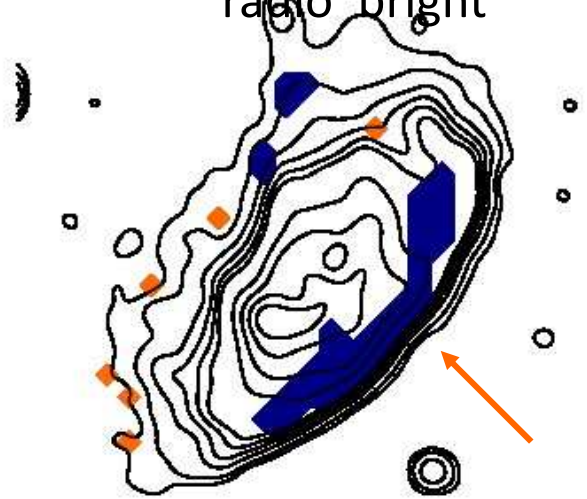
SFR

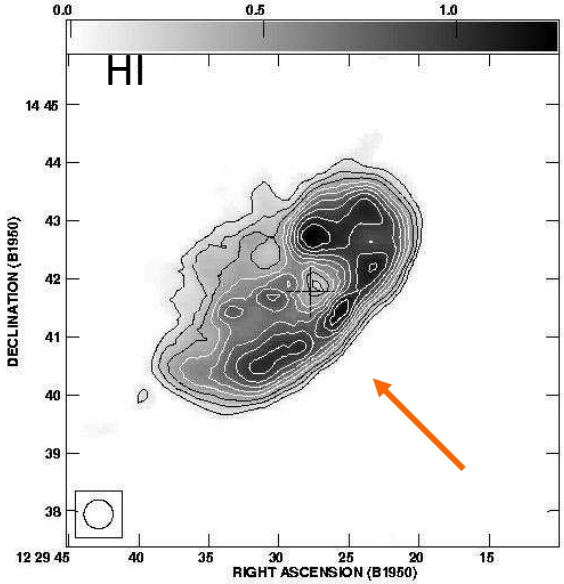


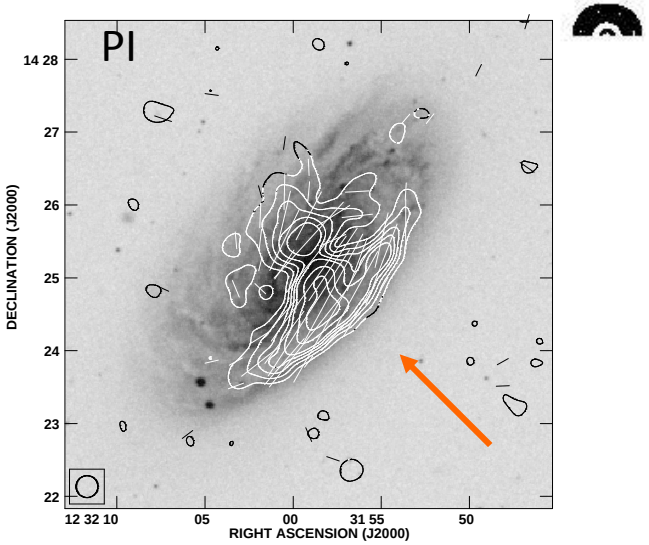
radio/SFR



radio bright



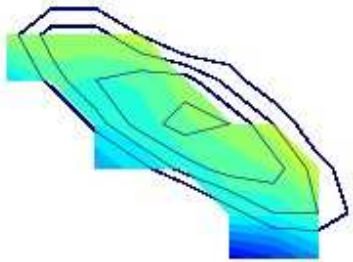




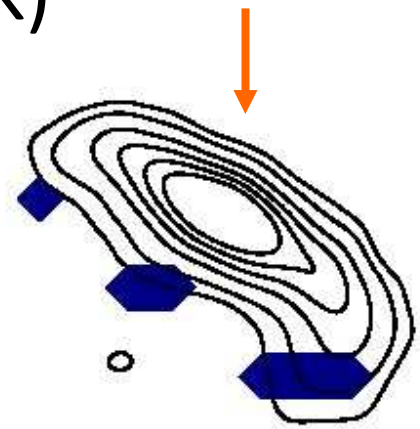
Vollmer et al. (2008)

NGC 4330 (pre-peak)

SFR

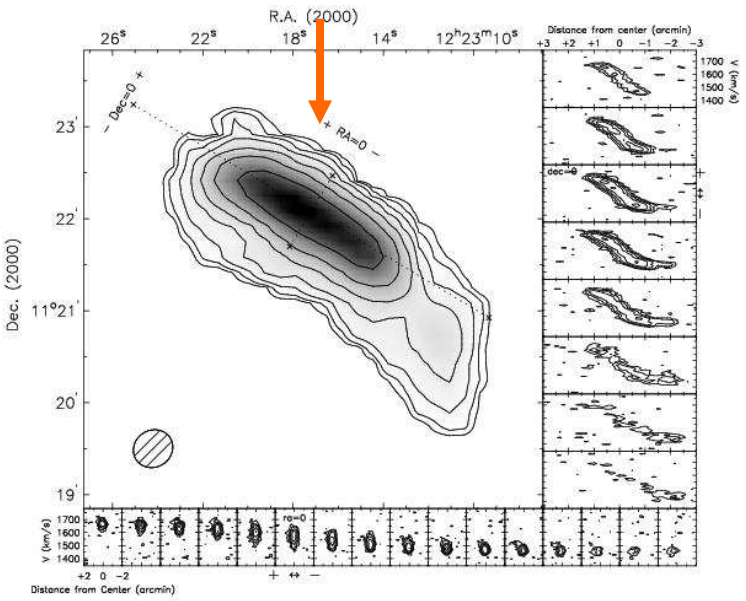


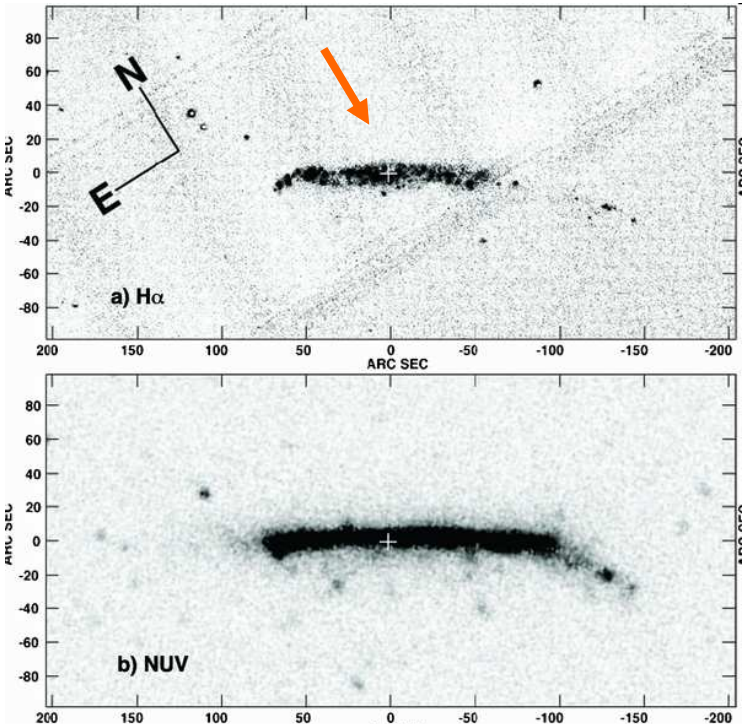
radio/SFR



radio bright

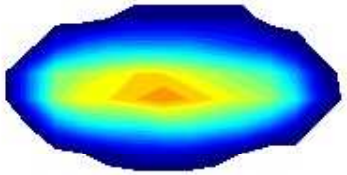
Abramson et al. (2011)



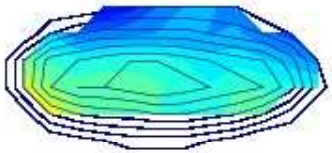


NGC 4402 (pre-peak)

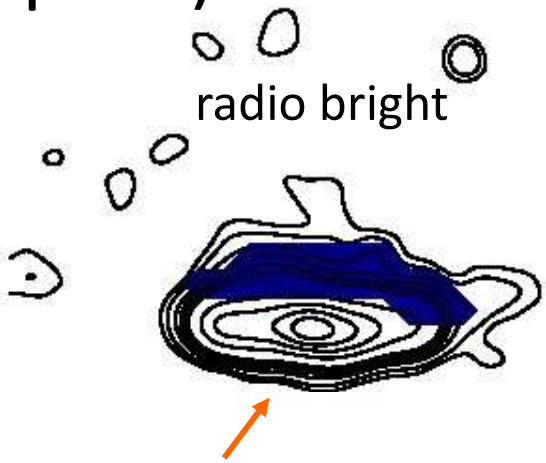
SFR

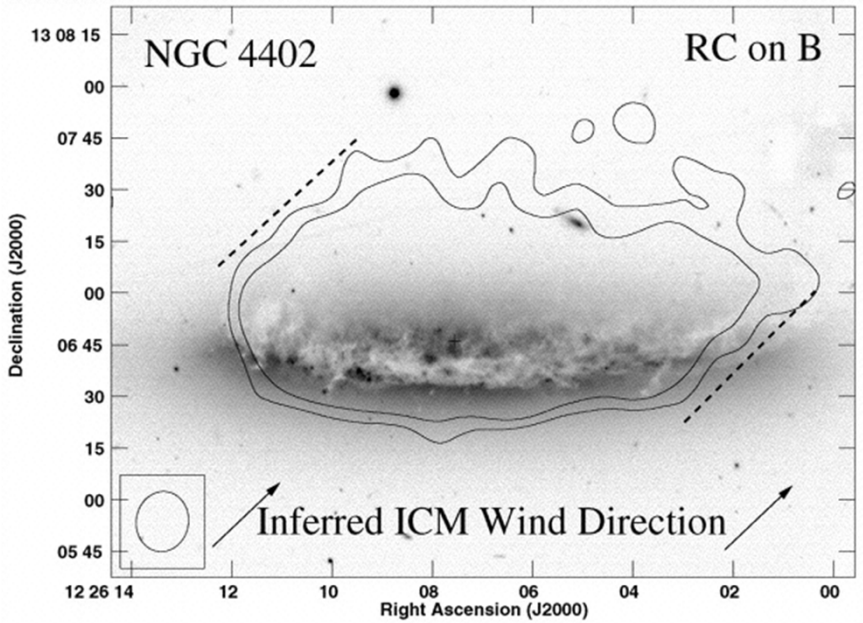


radio/SFR



radio bright

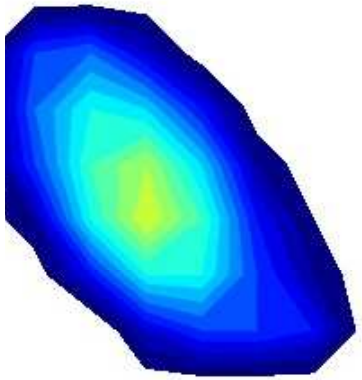




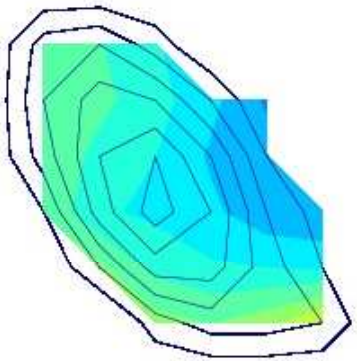
Crowl et al. (2005)

NGC 4522 (close to peak)

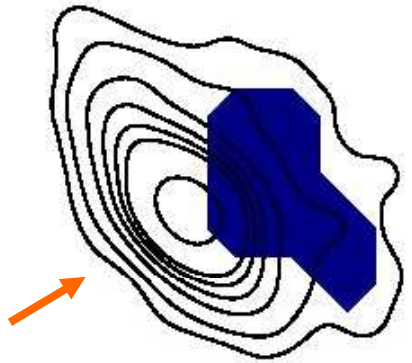
SFR

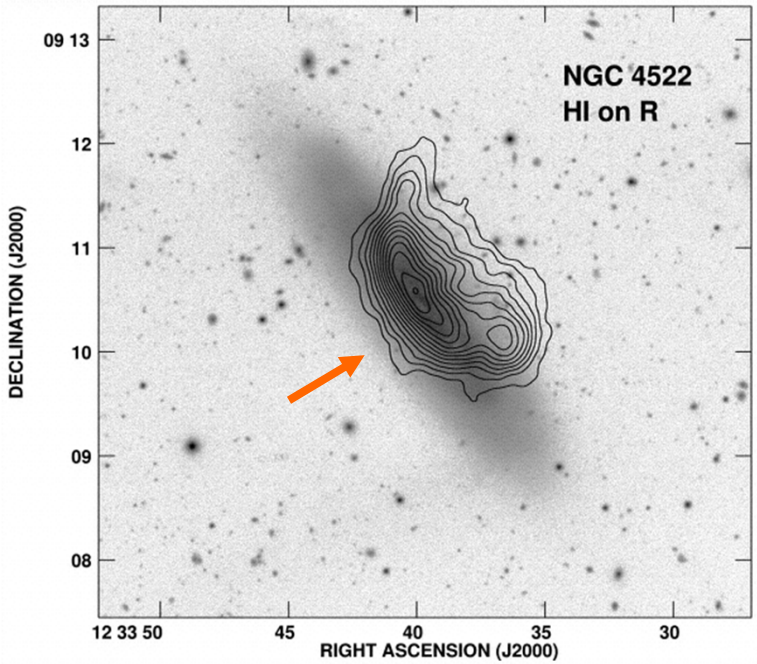


radio/SFR

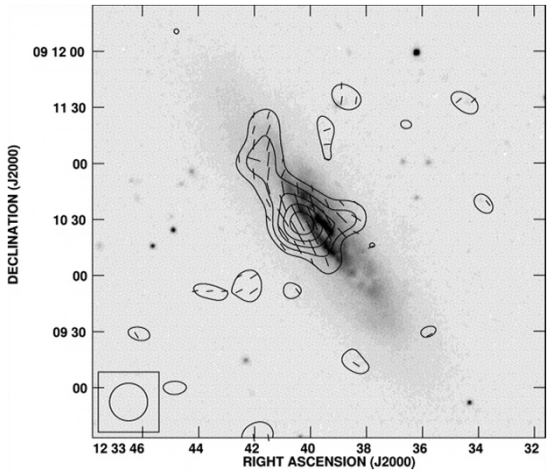


radio bright





(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 decreases star formation on small timescales

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 polarization and radio/SFR in 7 perturbed galaxies (compression/shear)
- Modelling of the radio emission is under way