Galaxy evolution in the Virgo Cluster

Bernd Vollmer

CDS, Observatoire de Strasbourg

Tout d’abord: un grand merci à

P. Amram, C. Balkowski, R. Beck, D. Bomans,
A. Boselli, J. Braine, V. Cayatte, F. Combes, A. Chung,
K. Chyzy, H. Crowl, W. Duschl, O. Garrido, W. Huchtmeier,
J. Kenney, M. Marcelin, K. Otmianowska-Mazur, W. Reich,
Y. Sofue, M. Soida, M. Urbanik, W. van Driel,
J. van Gorkom, R. Wielebinski

Galaxy evolution in the Virgo Cluster

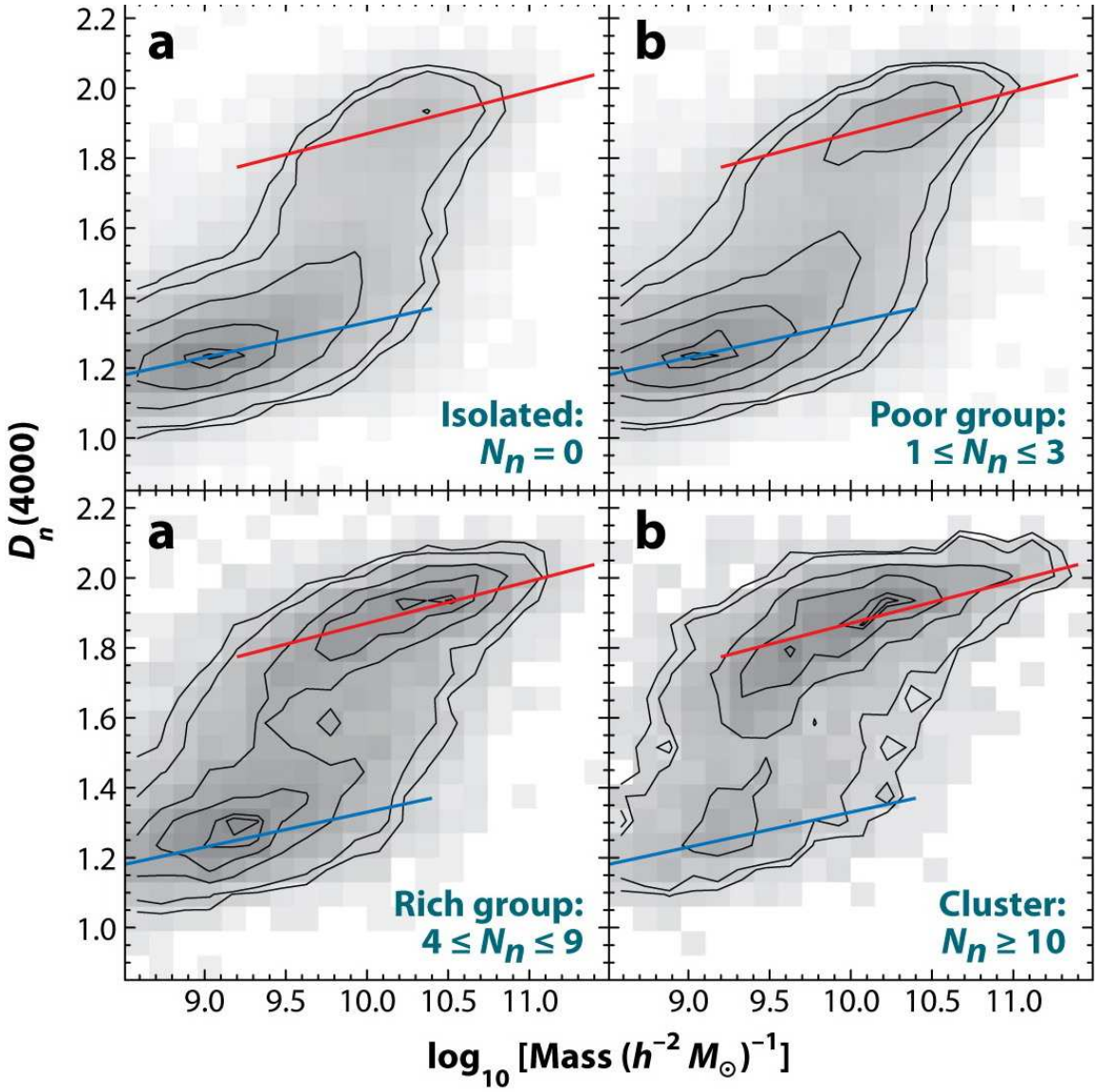
- Introduction
- Interactions of a cluster spiral with its environment
- The data
- The model
- NGC 4522 – a case study
- Ram pressure stripping time sequence
- Stripping of multiple gas phases
- Ram pressure stripping and star formation
- New VLA radio continuum observations

Galaxy evolution

old

young

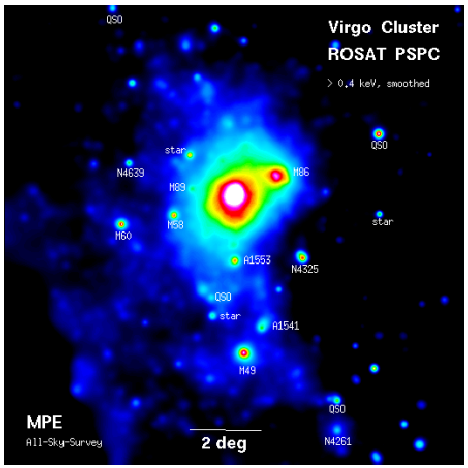
star formation history



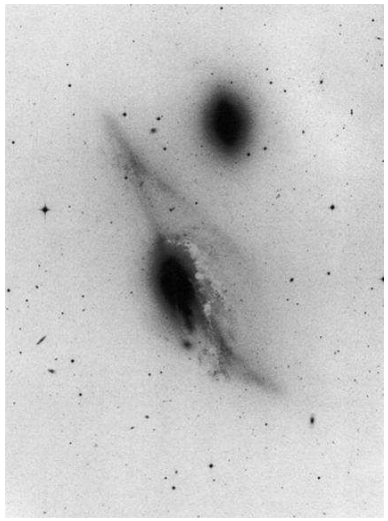
SDSS
Blanton & Moustakas (2009)

Interaction of a spiral galaxy with its environment

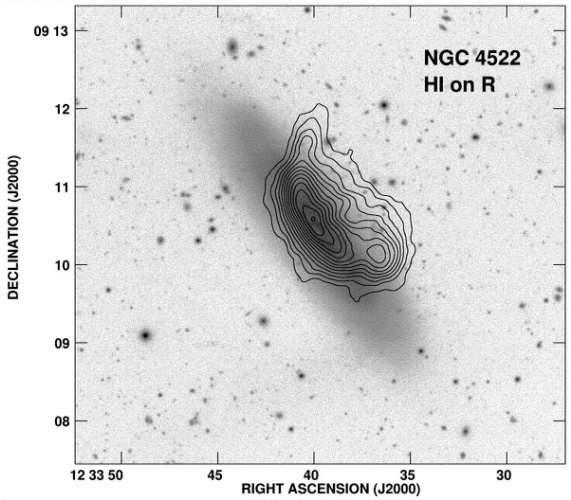
- Gravitational interaction galaxy - cluster
- Gravitational interaction galaxy - galaxy
- Ram pressure galaxy ISM – intracluster medium (ICM)



(Böhringer et al. 1994)

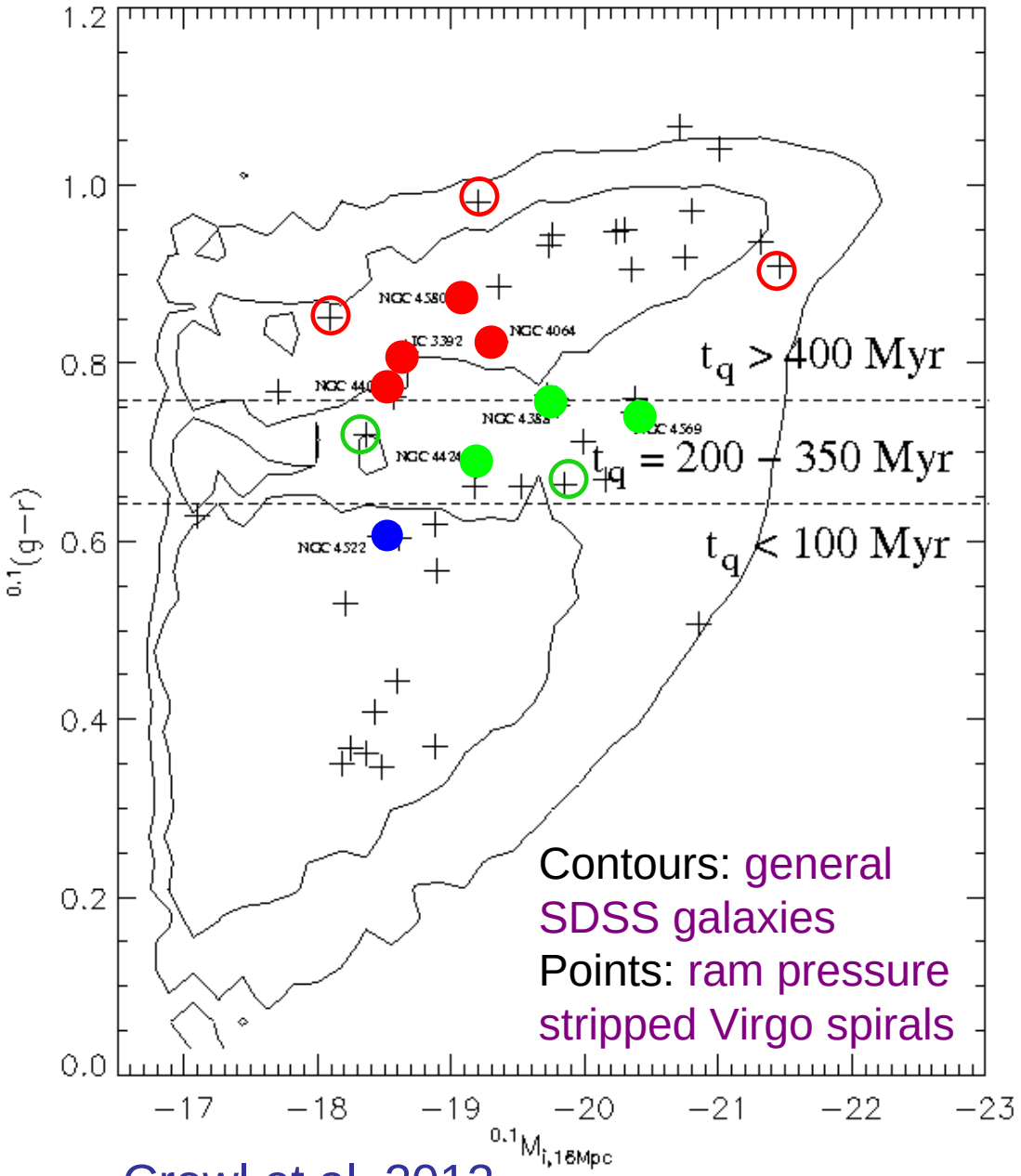


(Kenney et al. 1995)



(Kenney et al. 2004)

(slide from J. Kenney)



Crowl et al. 2012

Ram pressure stripping & color evolution

Galaxies with good evidence for RPS:

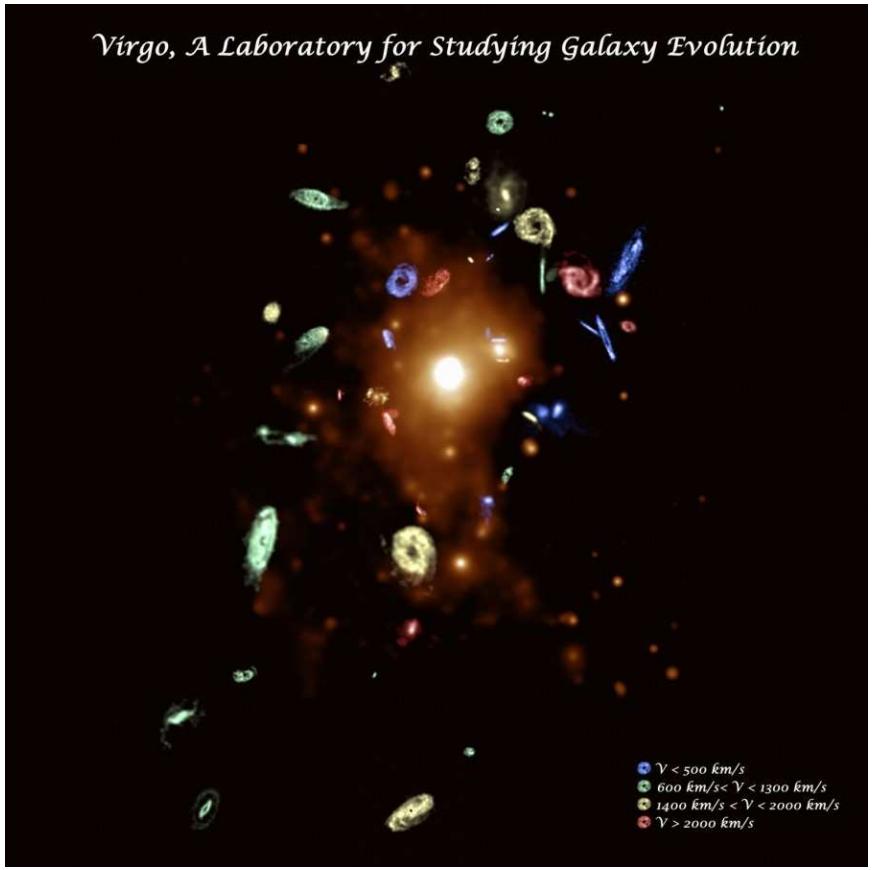
●●● Quenching times from spectra

○○○ No spectra

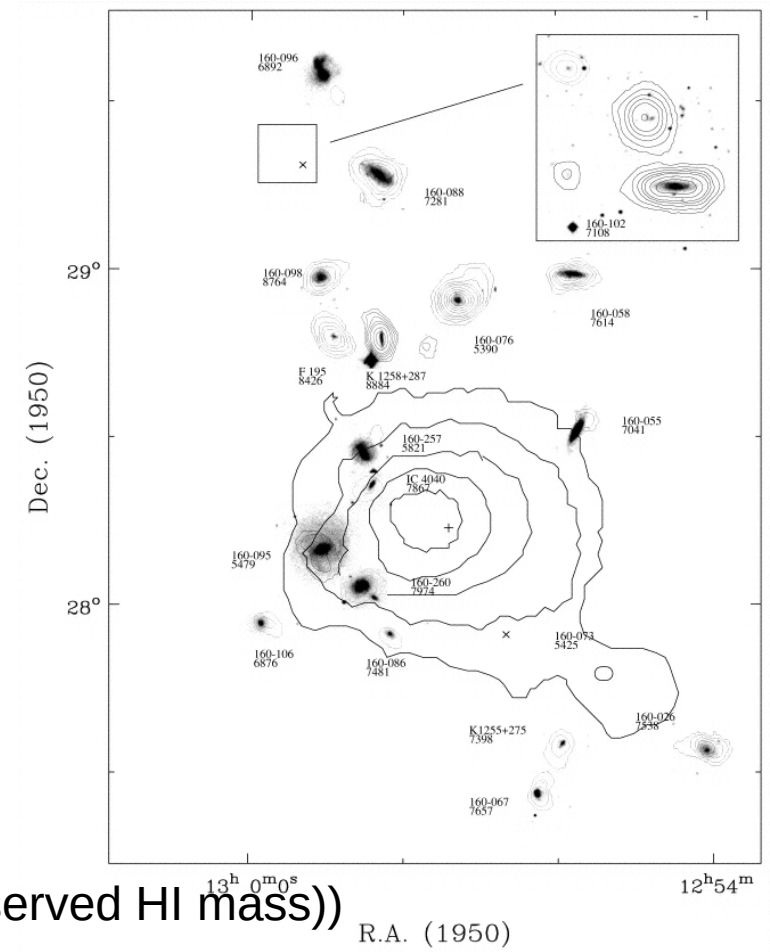
Ram pressure stripping partly responsible for cluster spirals in "green valley" & "red sequence"

Atomic gas: the HI view

(Chung et al. 2009)



(Bravo-Alfaro et al. 2000)

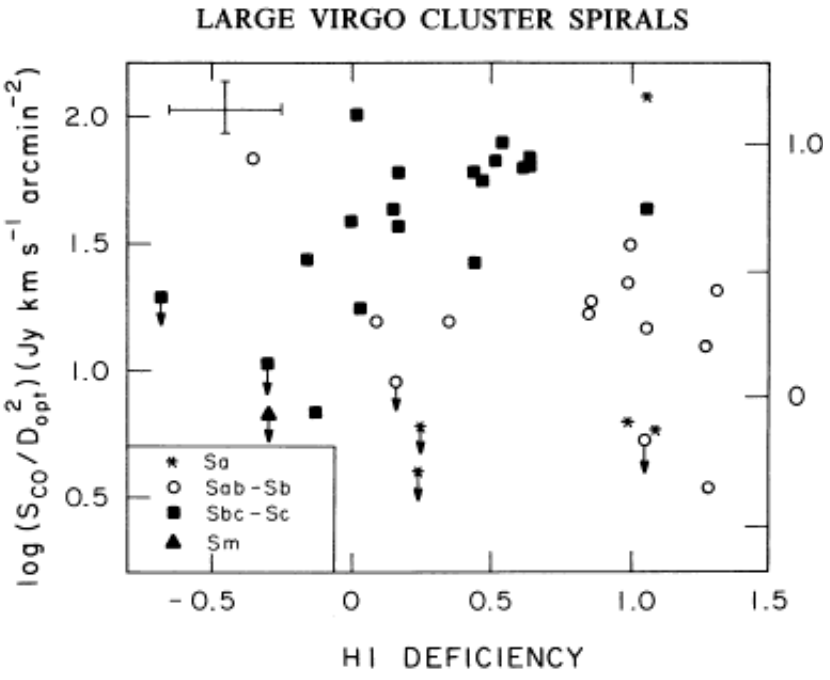


HI deficiency = log((expected HI mass)/(observed HI mass))

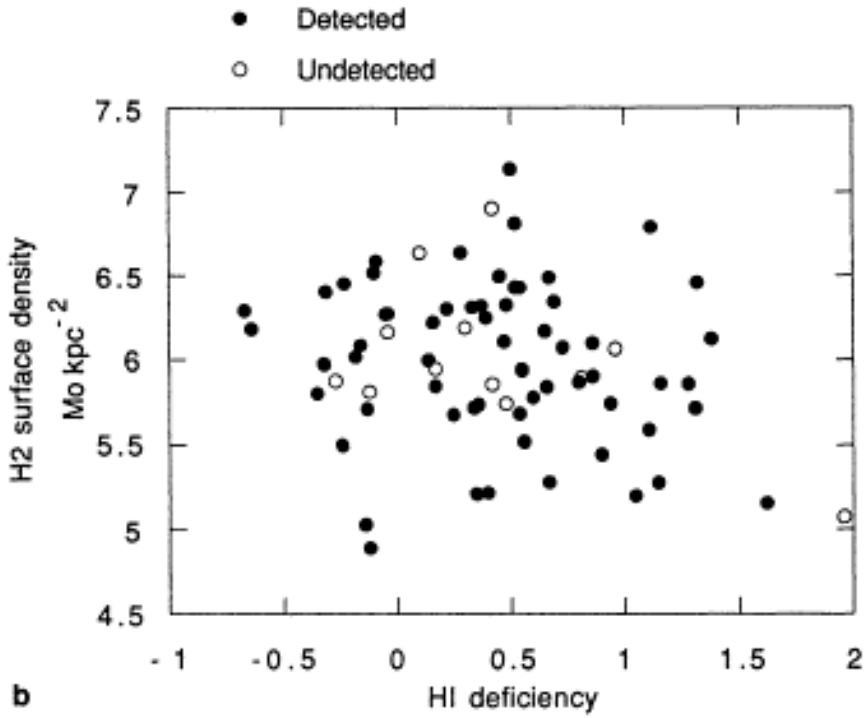
Cluster spirals are HI deficient and show truncated gas disks

Molecular gas: the CO view

(Kenney & Young 1989)



(Boselli et al. 1994)

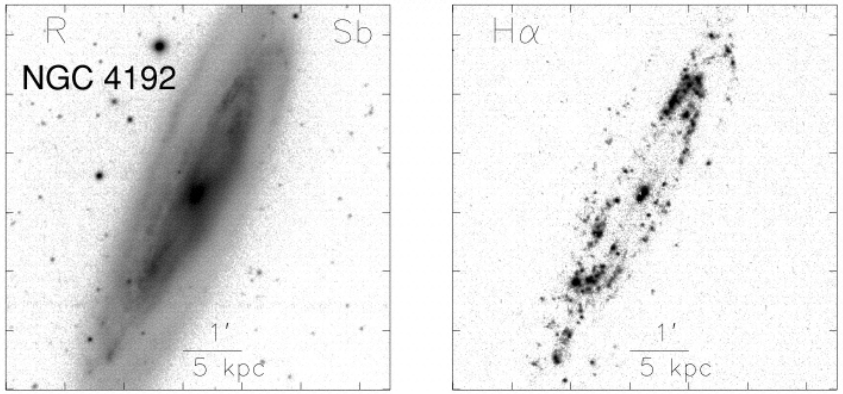


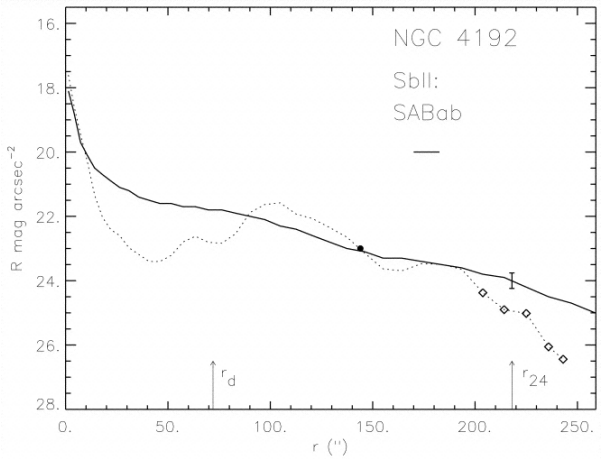
Cluster spirals are **NOT** CO deficient

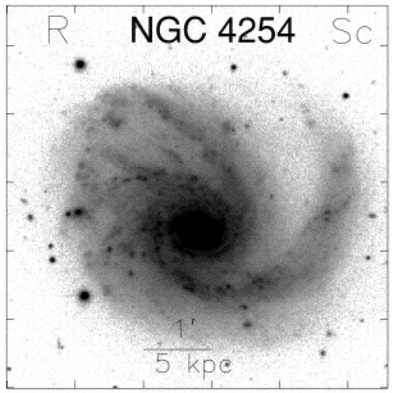
Even the CO detection rate of Virgo early type galaxies is **NOT** different from that of the field (Atlas^{3D}; Young et al. 2011)

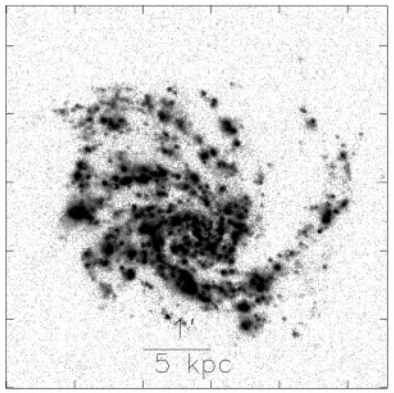
Star formation: the Hα view

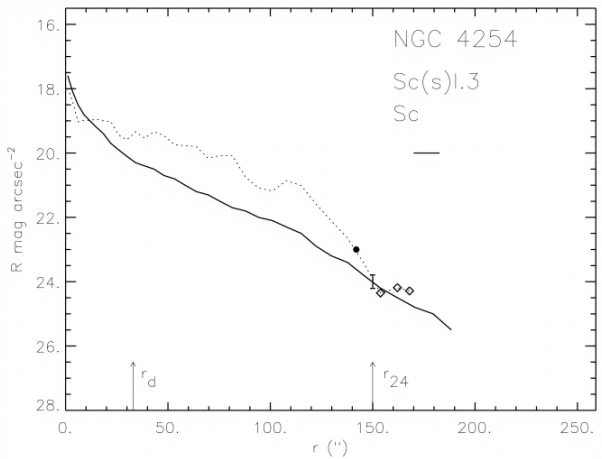
« normal » Hα disks (Koopmann & Kenney 2001,2004)









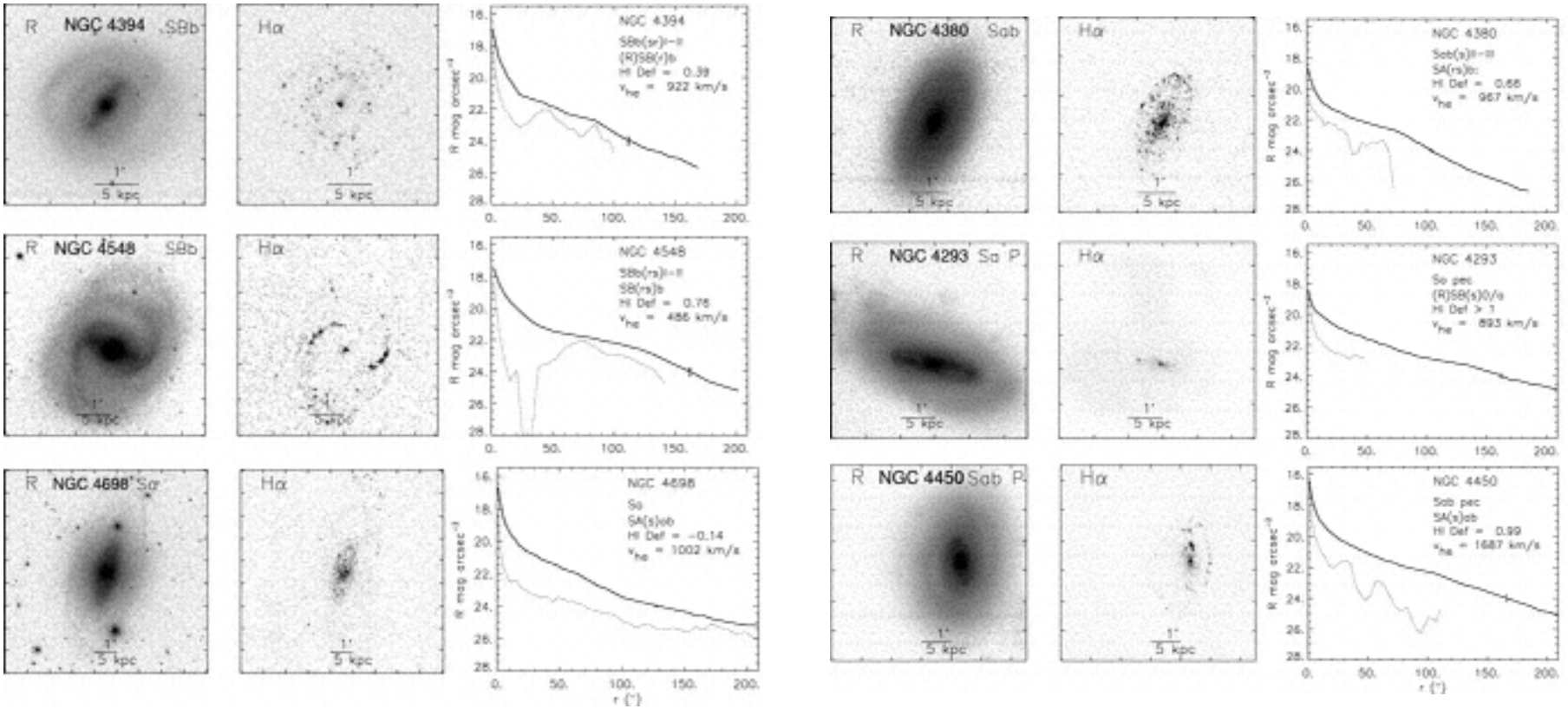


Star formation: the Hα view

(Koopmann & Kenney 2001, 2004)

anemic Hα disks

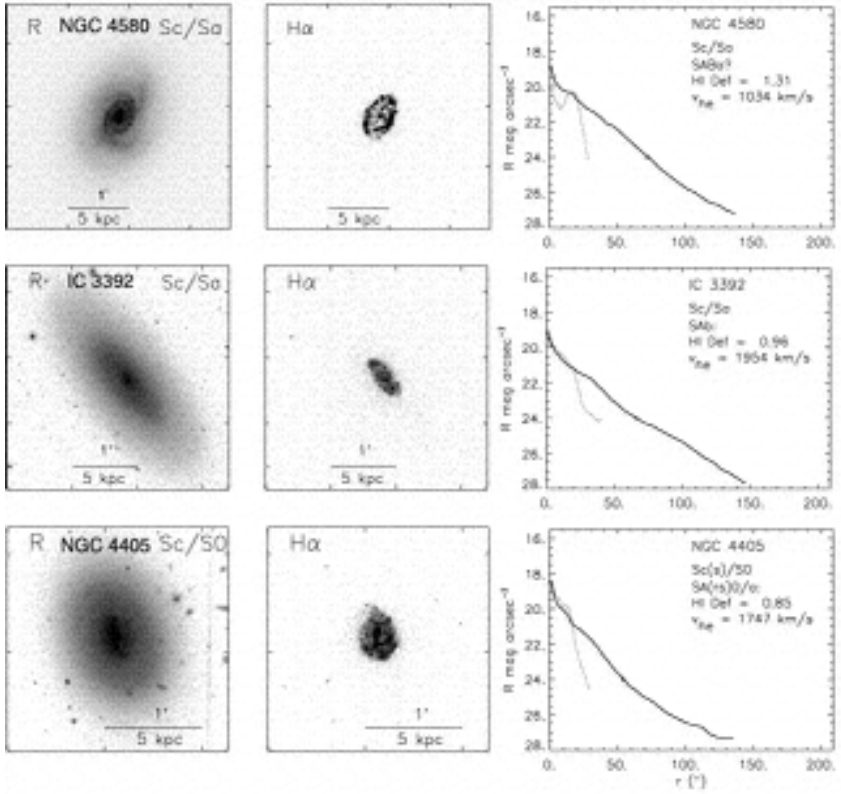
anemic truncated Hα disks



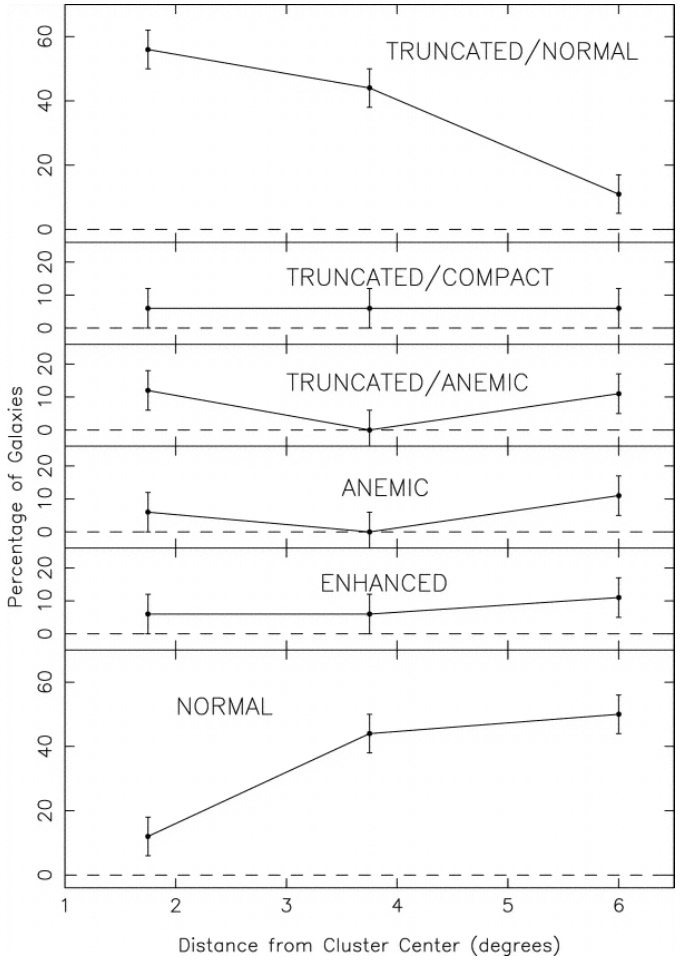
Star formation: the Hα view

(Koopmann & Kenney 2001, 2004)

truncated Hα disks



cluster radial profiles

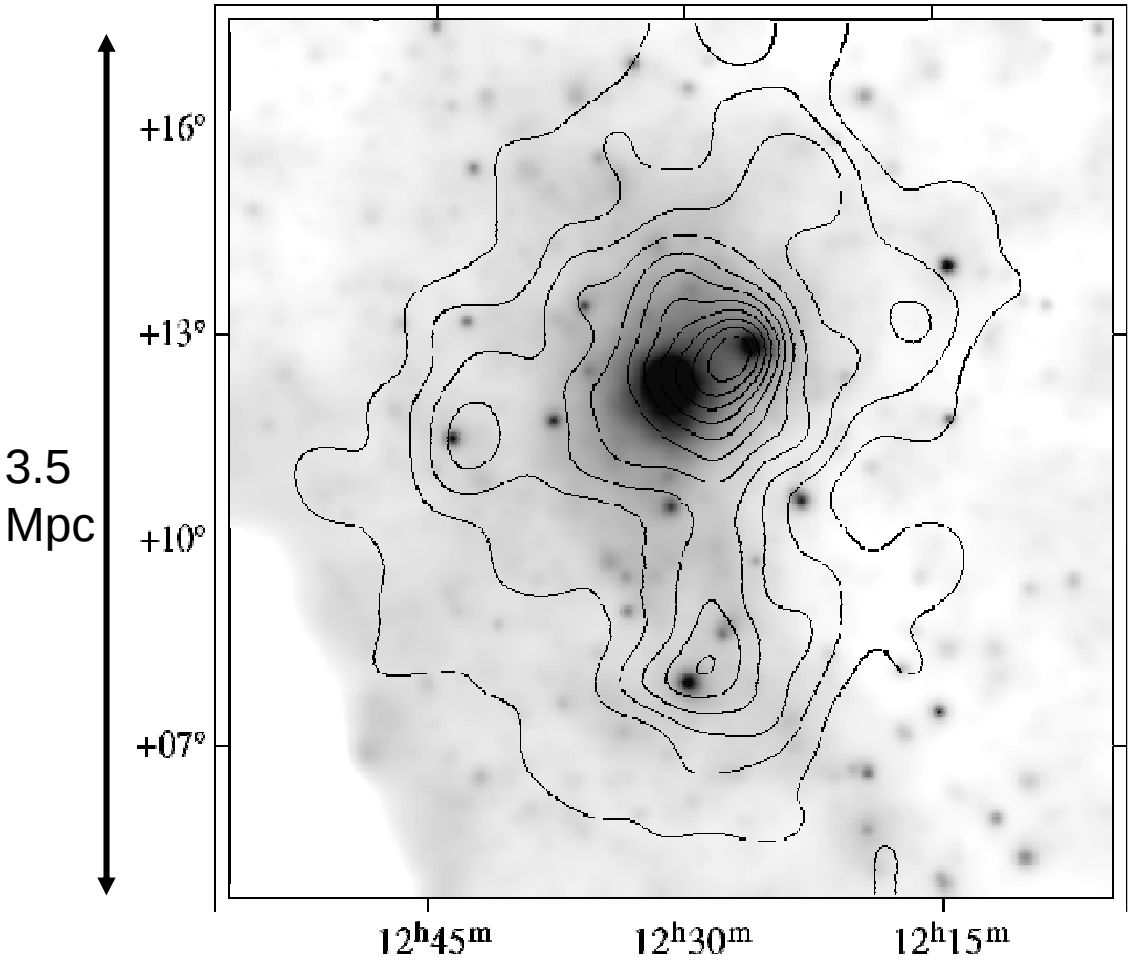


52 Virgo galaxies: 37% normal, 6% anemic, 6% enhanced, 52% truncated

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)

Virgo - Coma

- D=17 Mpc
- Mass: ~10^{14} M_{solar} at R=1 Mpc
- Velocity dispersion: ~700 km/s
- Large spiral fraction
- One central galaxy
- Asymmetric overall ICM distribution
- Dynamical young cluster

- D=100 Mpc
- Mass: ~5 10^{14} M_{solar} at R=1 Mpc
- Velocity dispersion: ~1200 km/s
- Small spiral fraction
- Two central galaxies
- Symmetric overall ICM distribution
- « relaxed » cluster

Interaction diagnostics

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

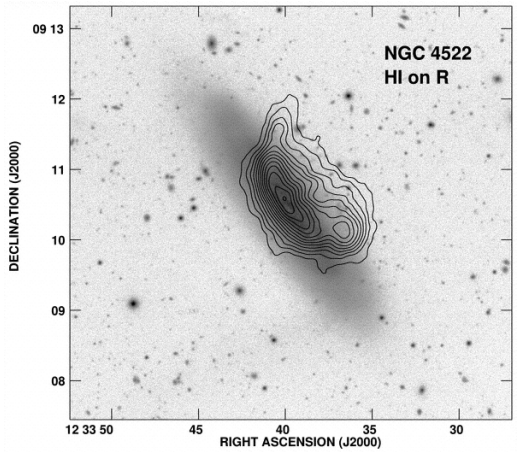
  photometry+ spectroscopy + stellar population synthesis

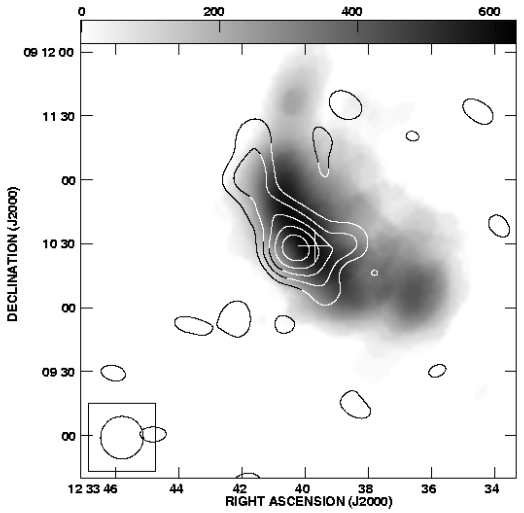
Polarized radio continuum emission – a new diagnostic tool for interactions

- Polarized radio continuum emission is proportional to the density of relativistic electrons and the strength of the large-scale regular magnetic field: $PI \propto n_e B^{2-4}$
- Polarized radio continuum emission is sensitive to shear and compression motions

NGC 4522
(Kenney et al. 2004)

Grey: optical
Contour: HI





(Vollmer et al. 2004)

Grey: HI
Contour: polarized radio continuum emission

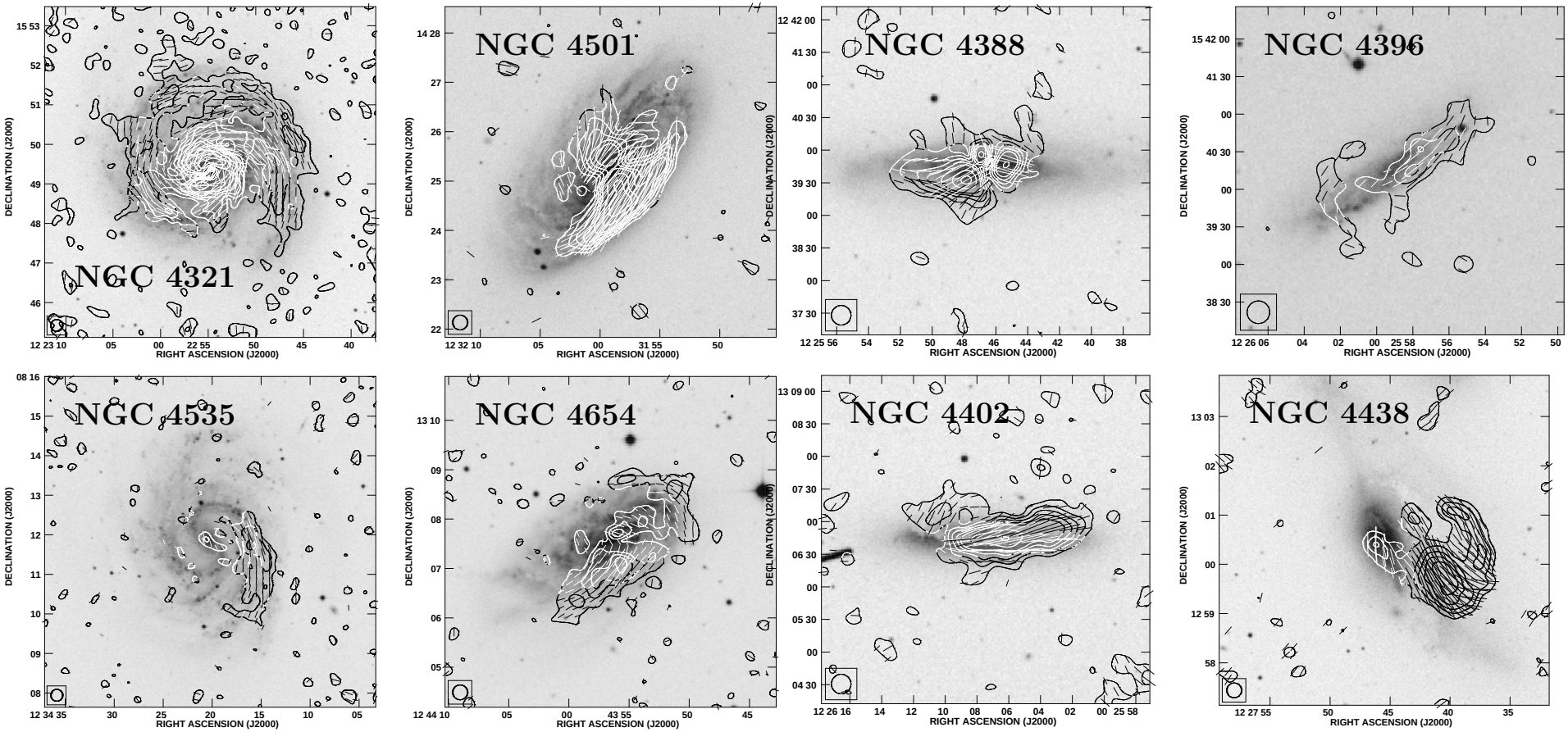
First survey of 8 Virgo cluster spiral galaxies in polarized radio continuum emission

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

- 8 bright Virgo spiral galaxies
- 90h of VLA observations
- 20cm C array; 6cm D array
- Resolution: ~20’’
- Sensitivity: 10μJy/beam at 6cm

VLA 6cm polarized radio continuum emission

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



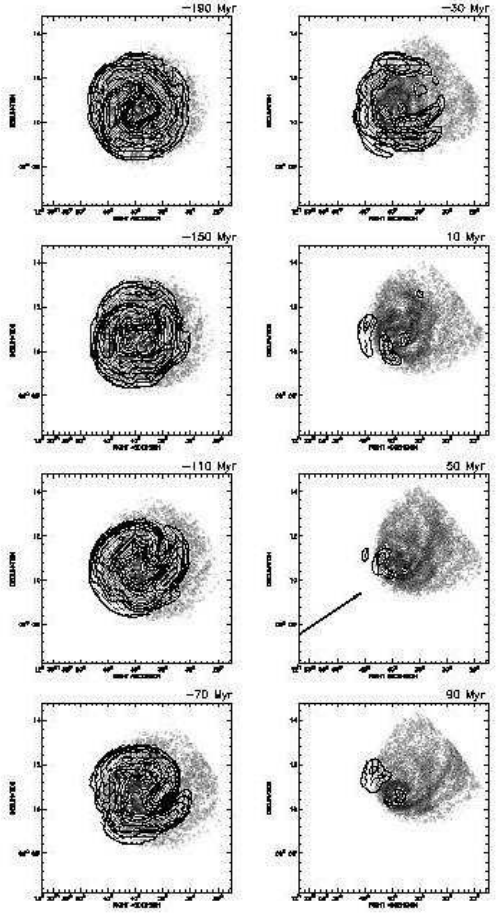
Vollmer et al. (2007)

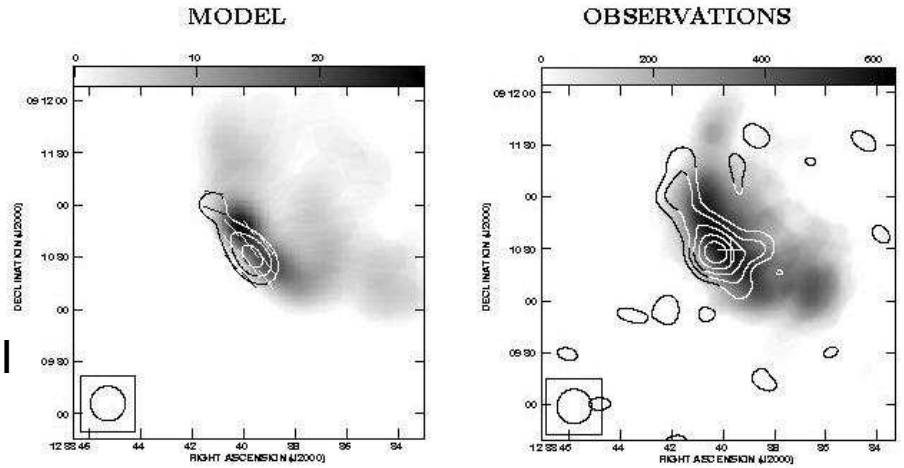
MHD simulations

(with M. Soida and K. Otmianowska-Mazur)

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

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

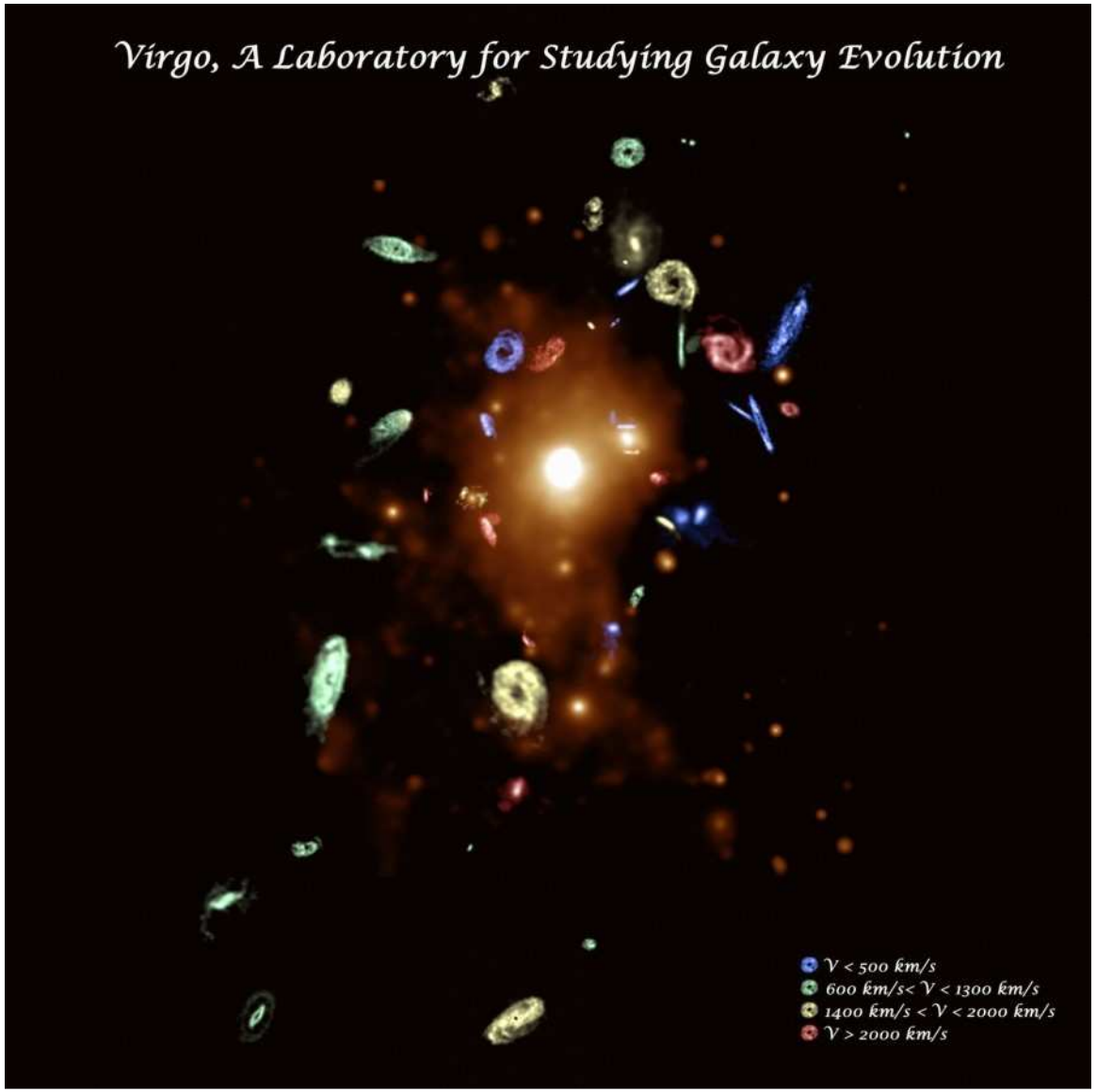




grey: HI, contours: PI
(Vollmer et al. 2006)

VIVA = VLA Imaging of Virgo in Atomic Gas

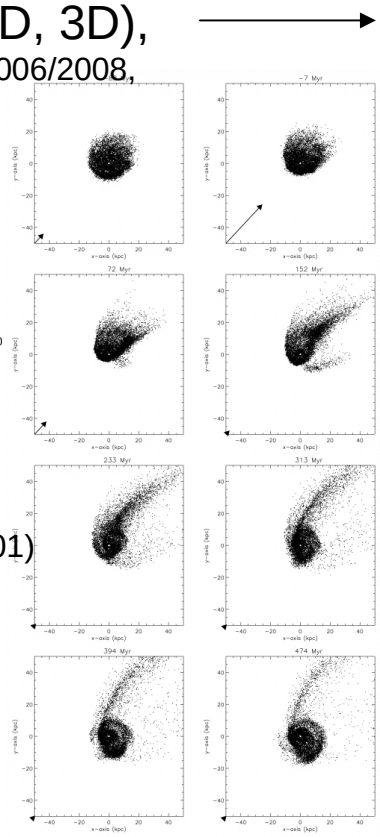
(A. Chung, J. van Gorkom, J. Kenney, H. Crowl, B. Vollmer)

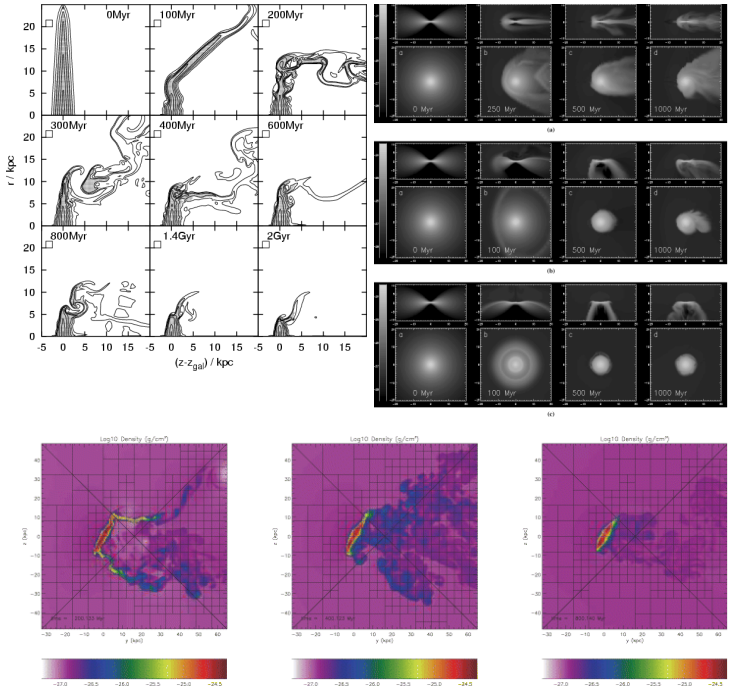


Numerical simulations

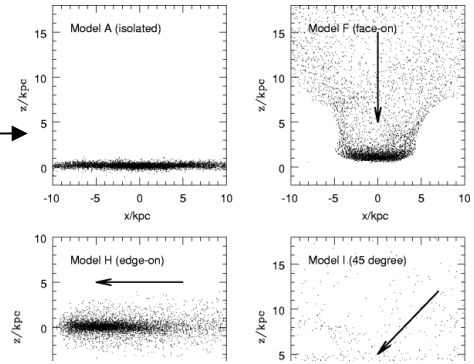
- ISM-ICM interaction + gravitational interaction
- turbulent/viscous stripping (Nulsen 1982; timescale ~1Gyr) ⟷
  ram pressure stripping (momentum transfer; timescale ~10Myr)
- constant ⟷ time dependent ram pressure
- Models: (i) Eulerian hydro (2D, 3D), →

(Roediger & Hensler 2005, Roediger & Brueggen 2006/2008,
Marcolini et al. 2003)





(ii) SPH, →



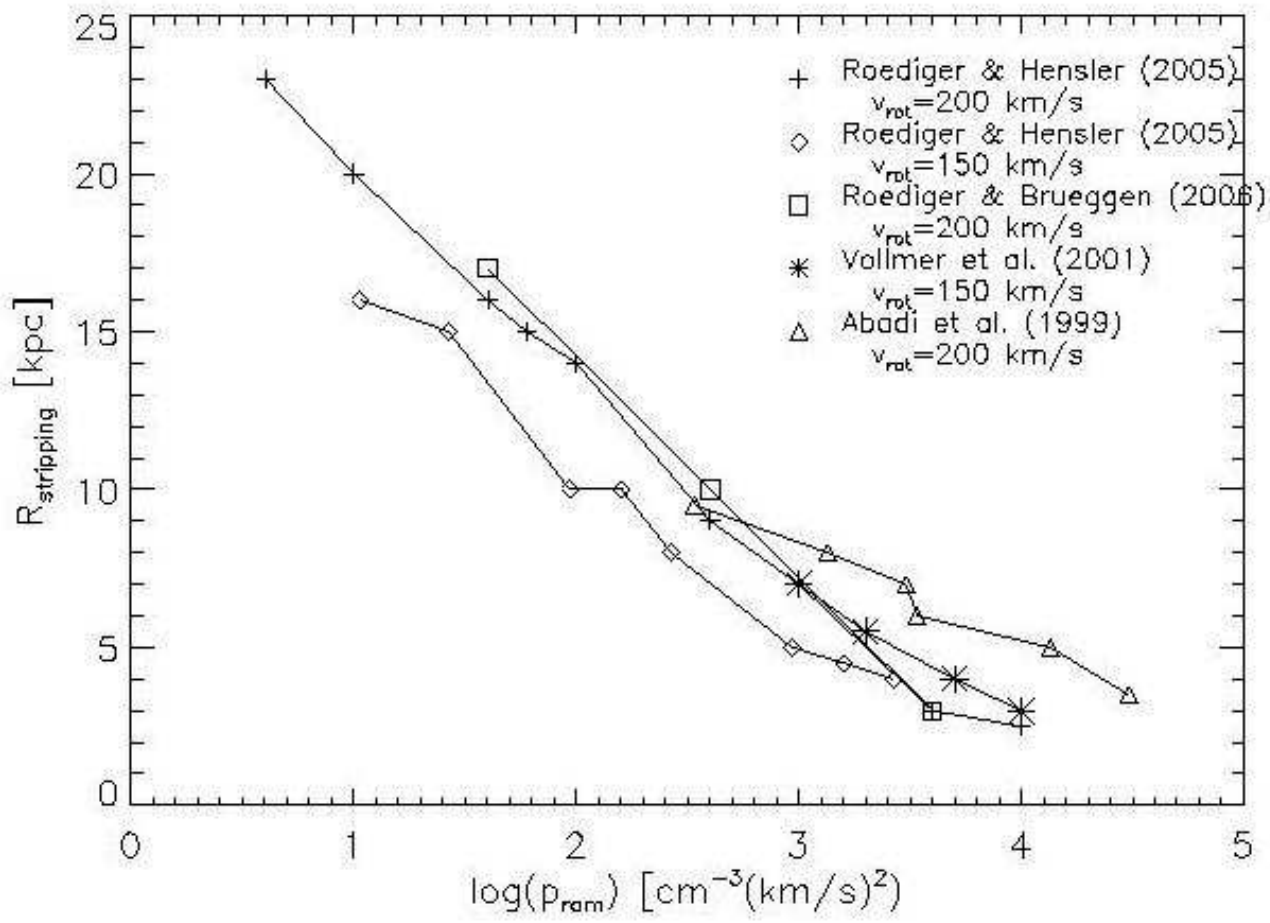
(Abadi et al. 1999, Schulz & Struck 2001)

(iii) sticky particles →

(Vollmer et al. 2001)

Comparison between the different codes

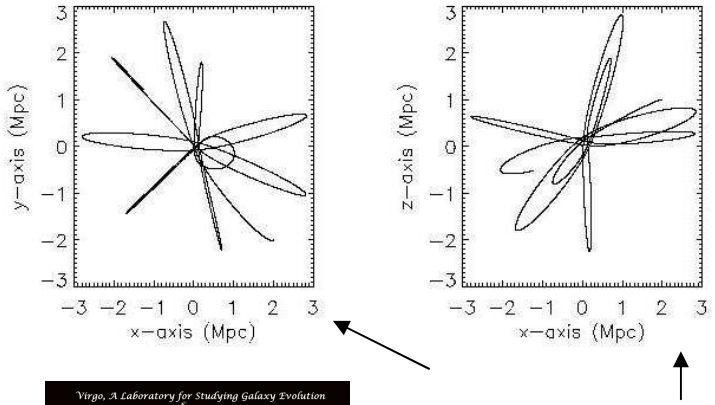
face-on stripping

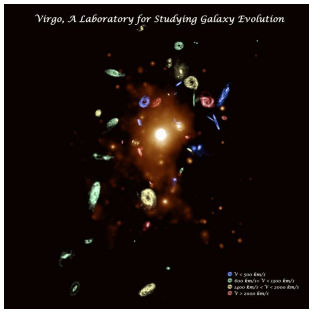


Conclusion: models are consistent within a factor 2: **Gunn & Gott works**

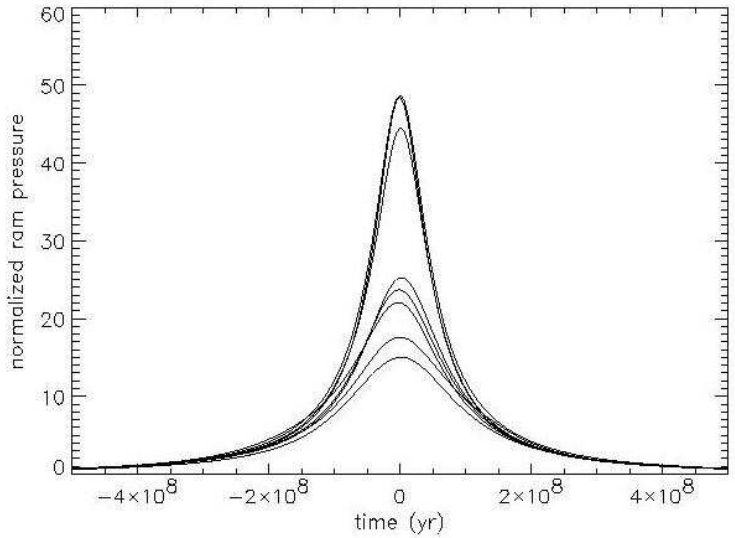
Simulations with time dependent ram pressure

- depends on galaxy orbits within the cluster
- simulations of galaxy orbits in the Virgo cluster and determination of temporal ram pressure profiles





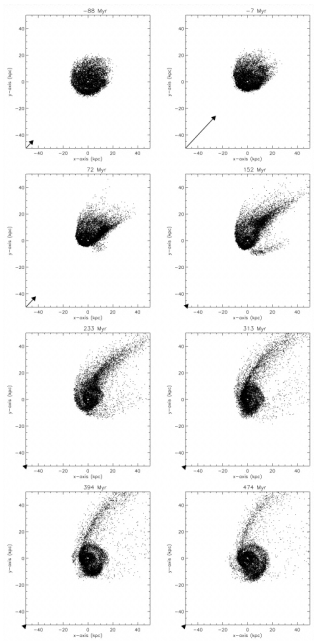
galaxy orbits

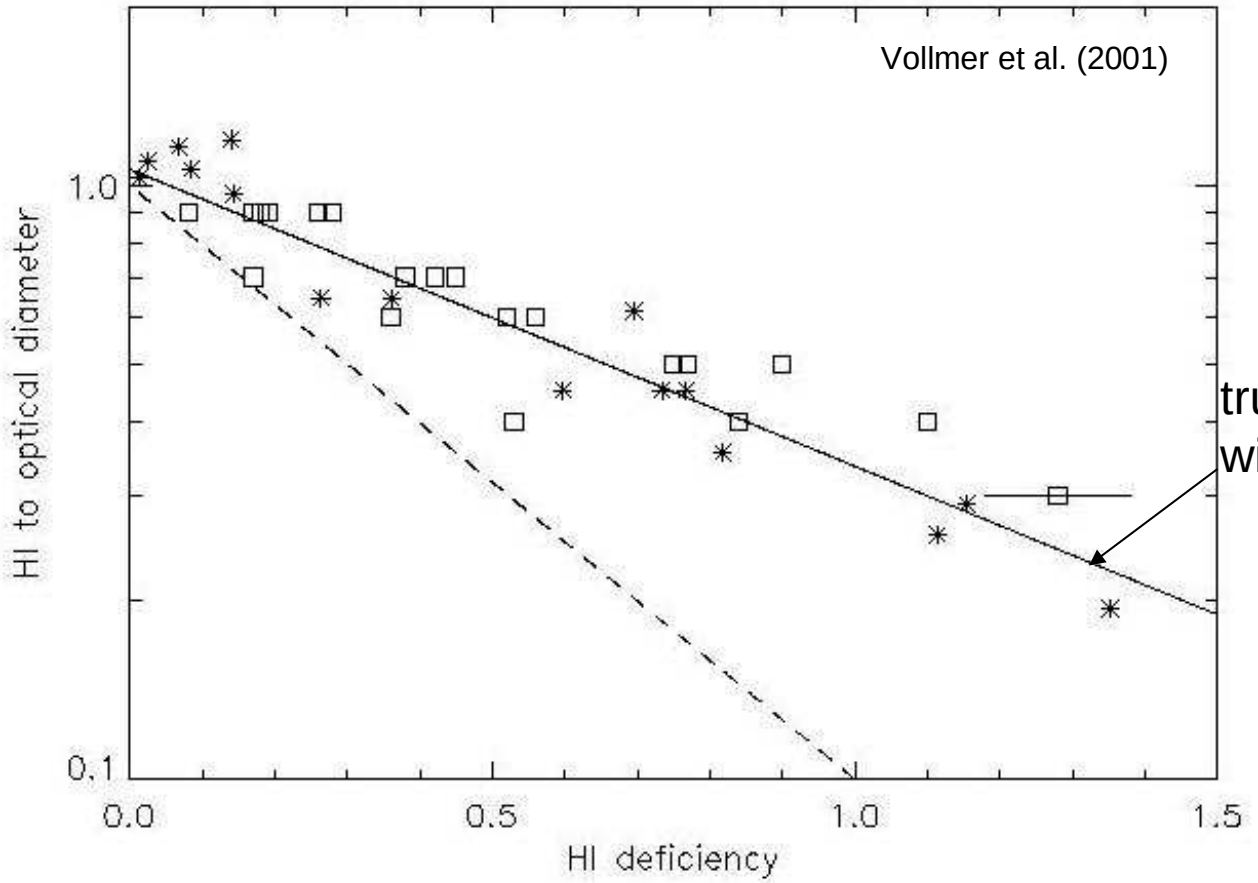


temporal ram pressure profile (ρv^2)

Normalization of the code

boxes: Cayatte et al. (1994); stars: simulations





truncated disk
with a 1/R profile

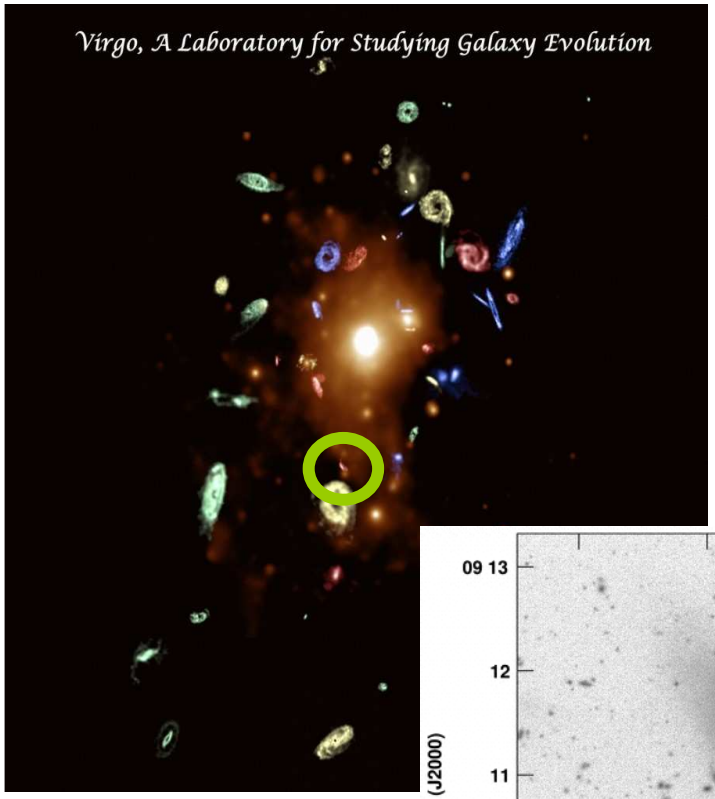
Conclusion: whatever you do with the disk, you will end up with a truncated gas disk

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

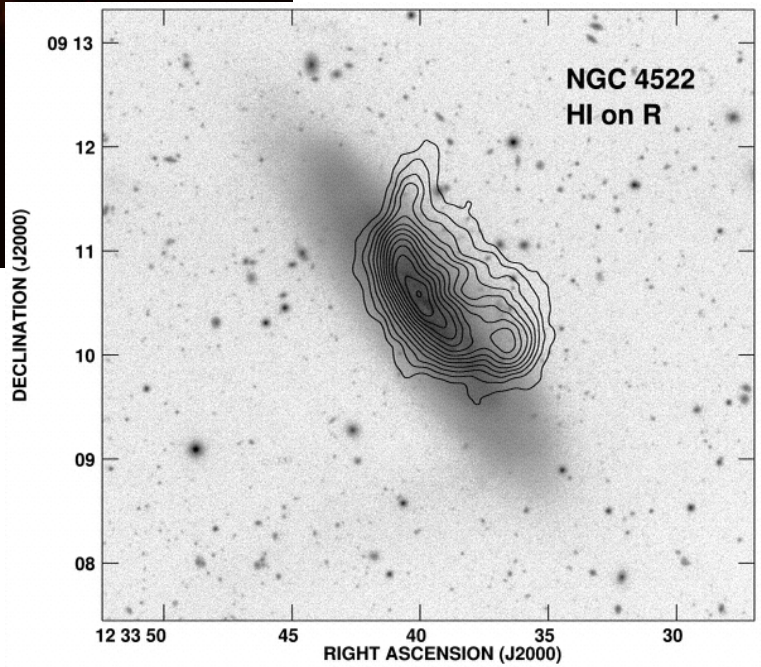
Ram pressure stripping criterion:
Gunn & Gott (1972): $\Sigma_{gas}\, v_{rot}^2/R = \rho_{ICM}\, v_{gal}^2$

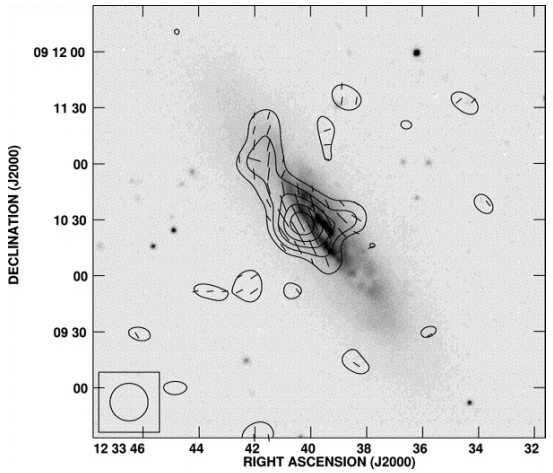
A case study: NGC 4522



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

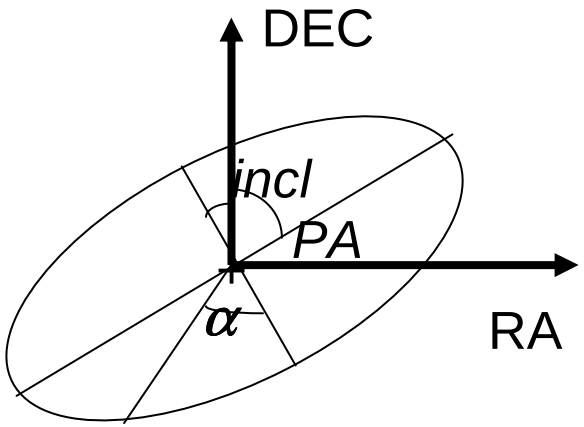
(Kenney et al. 2004)

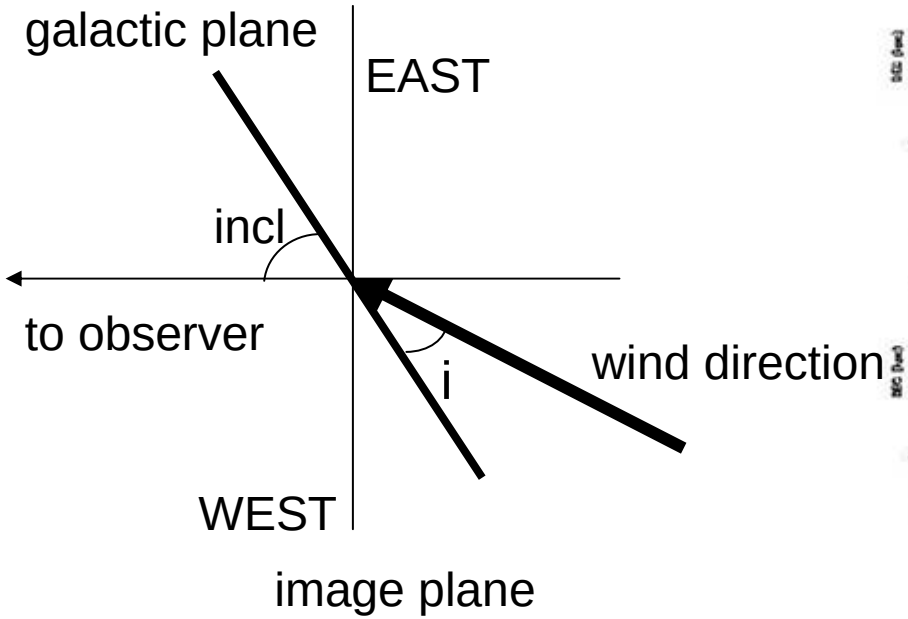


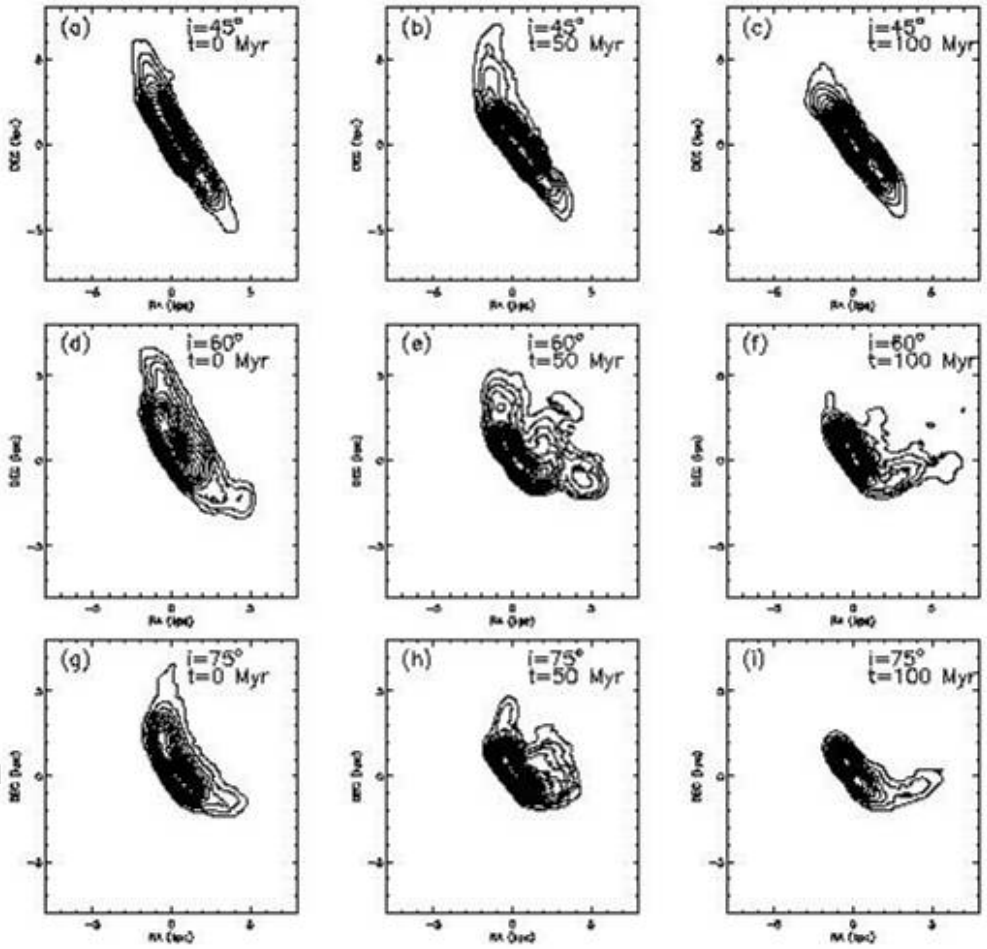


(Vollmer et al. 2004)

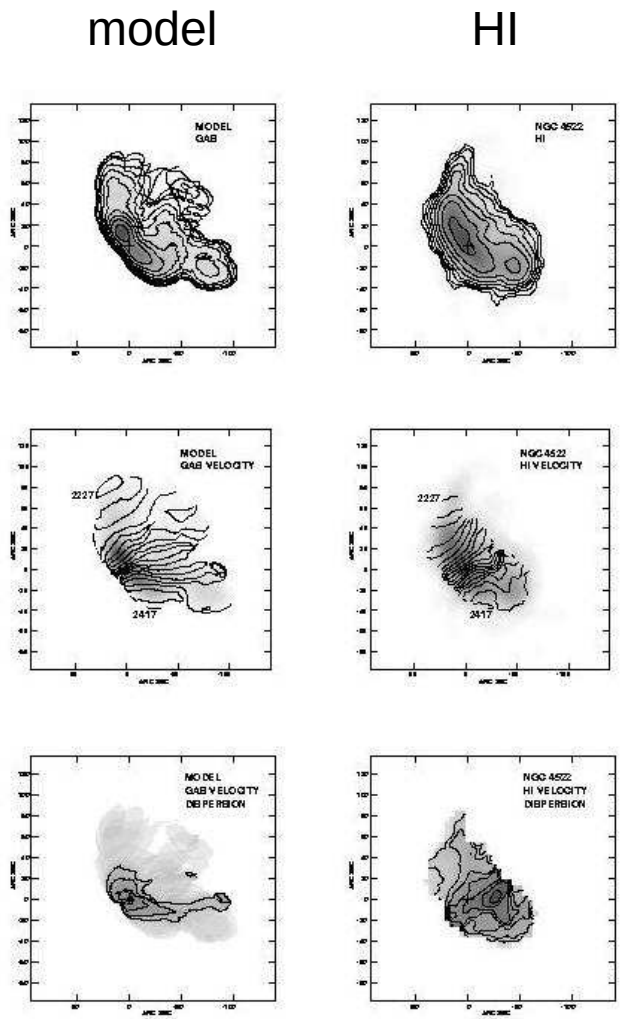
NGC 4522: the « best fit » model

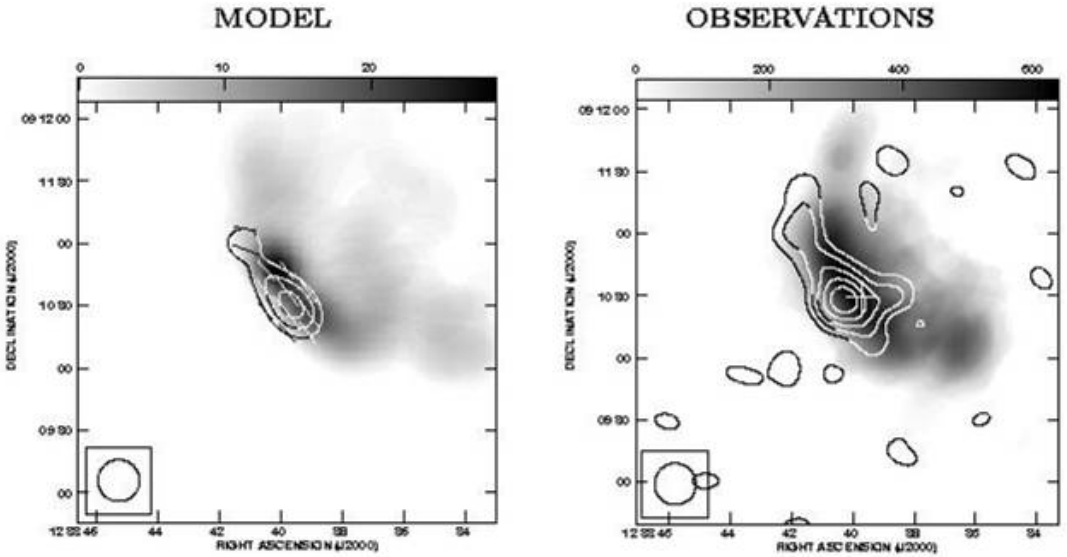






NGC 4522: final result





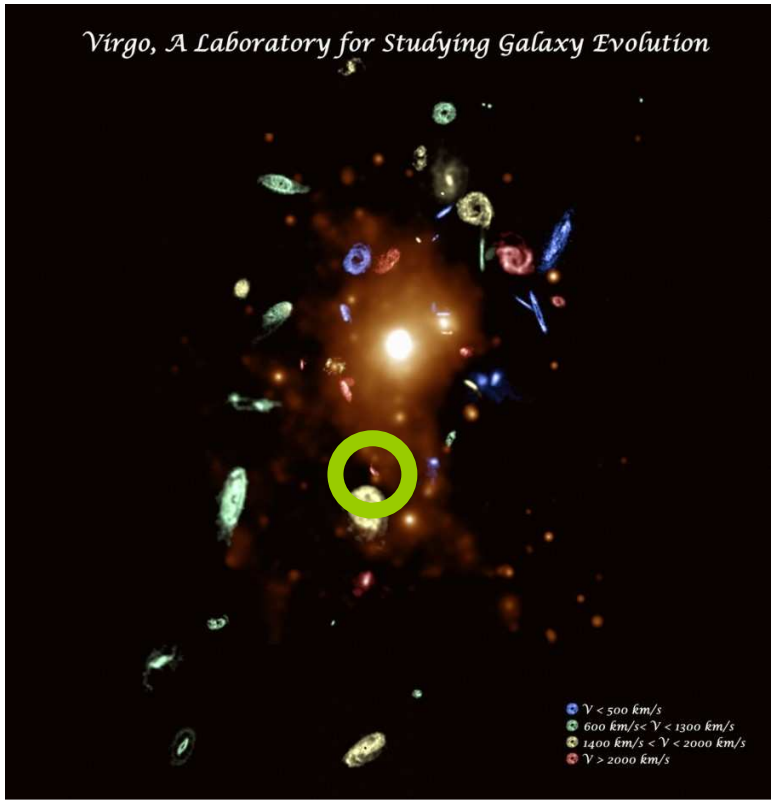
Greyscale: gas;
Contours: polarized radio continuum emission

(Vollmer et al. 2007)

→ **near peak ram pressure stripping**

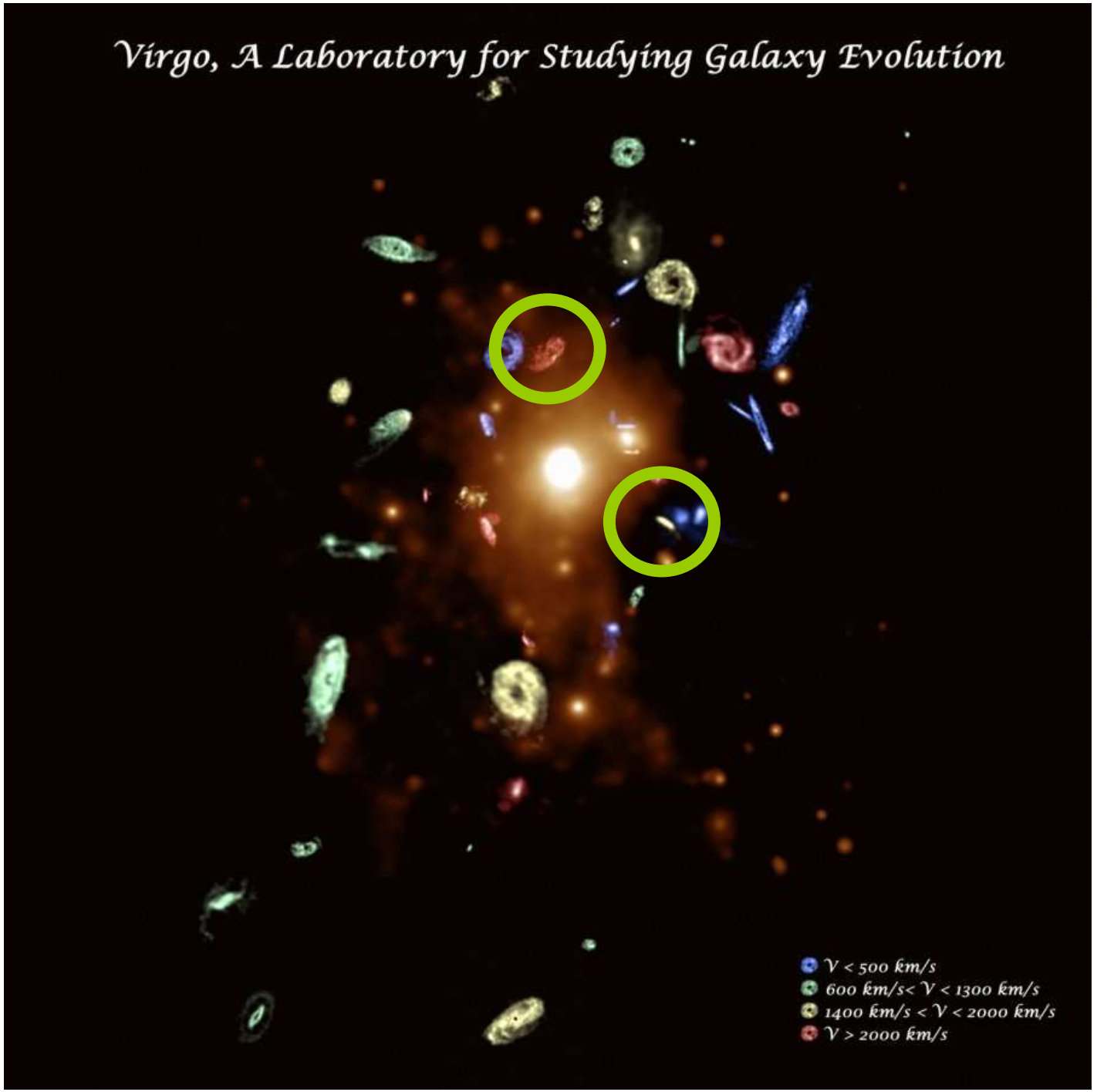
NGC 4522: peak ram pressure stripping +
projected distance of ~1 Mpc

moving intracluster medium due to infall of the M49 group of galaxies



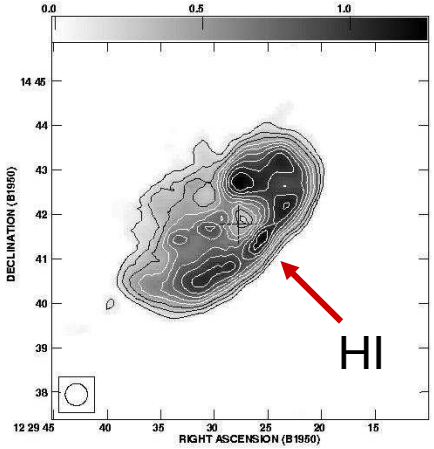
Observational gas characteristics

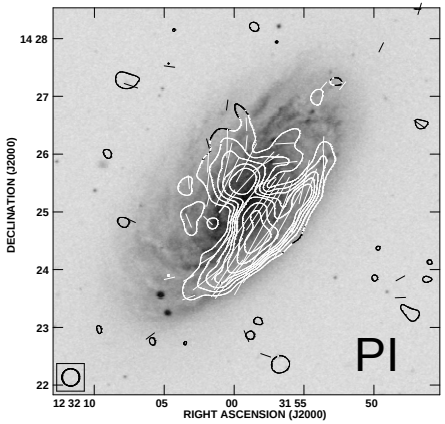
- Asymmetric ridge of polarized radio continuum emission at the outer disk (all)
- Gas disk truncated near the optical radius, asymmetric outer disk with tail structure (NGC 4501, NGC 4330)
- Truncated gas disk + extraplanar, high surface brightness gas (NGC 4522, NGC 4438)
- Truncated gas disk + extraplanar, very low surface brightness gas (NGC 4388)
- Truncated gas disk + perturbed, low surface brightness arms (NGC 4569)


Virgo, A Laboratory for Studying Galaxy Evolution
V < 500 km/s
600 km/s< V < 1300 km/s
1400 km/s < V < 2000 km/s
V > 2000 km/s

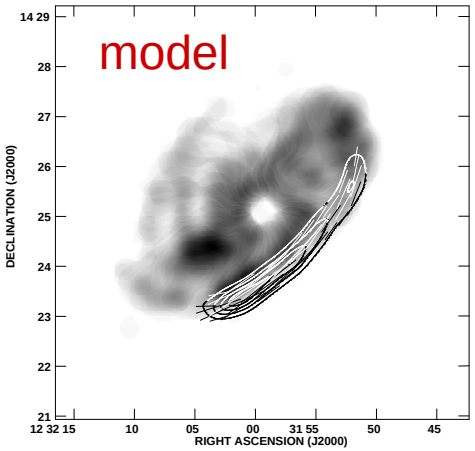
Gas disk truncated near the optical radius,
asymmetric outer disk with tail structure → **pre-peak stripping**

NGC 4501
observations



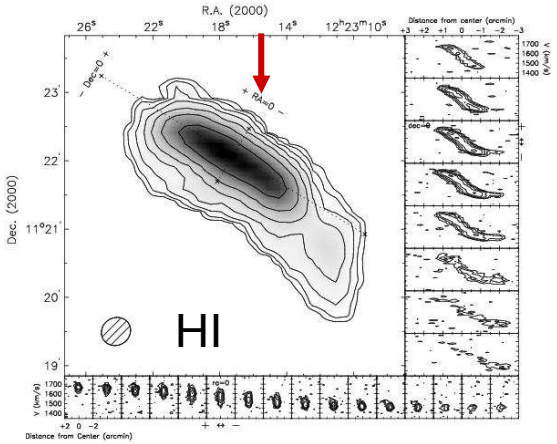


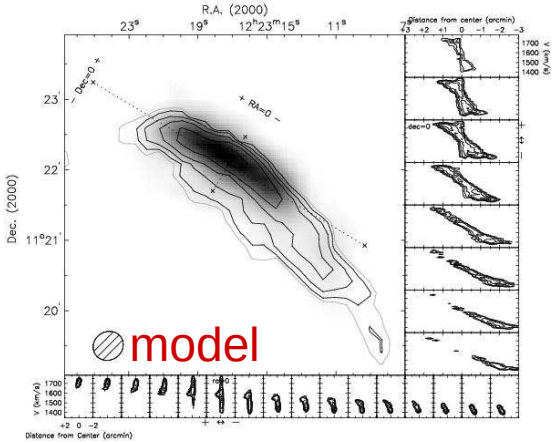
grey: HI, contours: PI



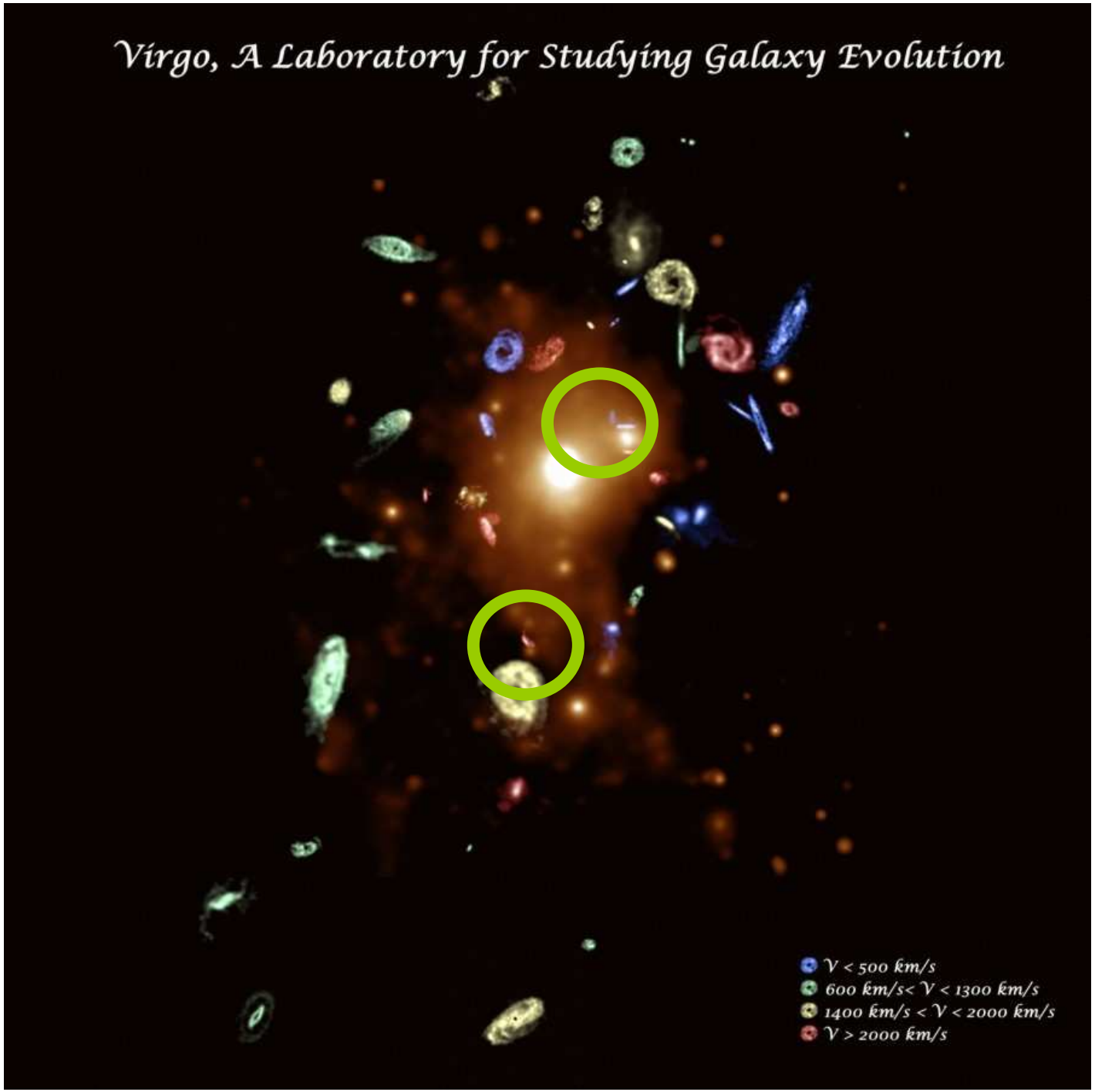
Vollmer et al. (2008)

NGC 4330
observations





Vollmer et al. (2012)

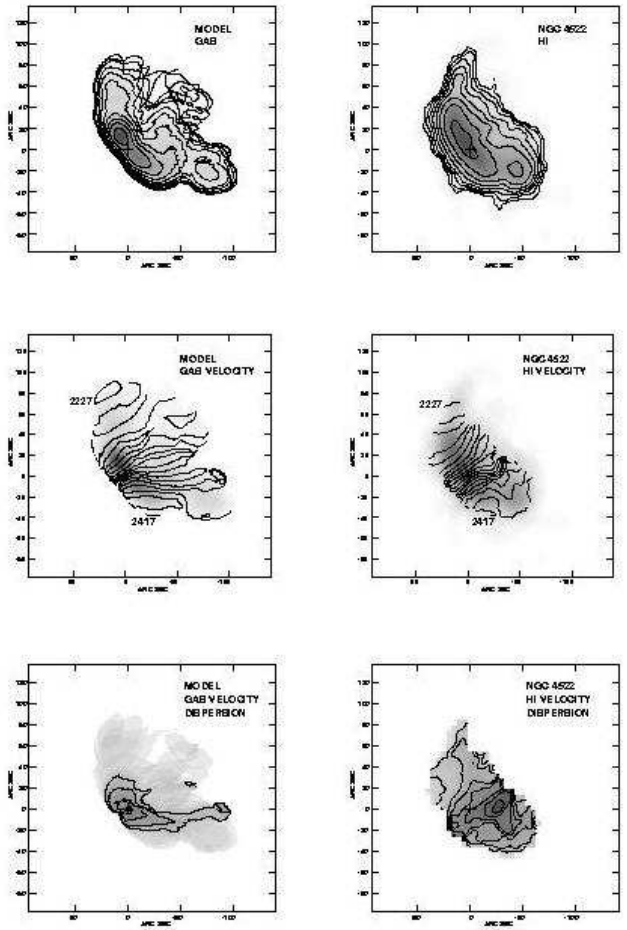

Virgo, A Laboratory for Studying Galaxy Evolution
V < 500 km/s
600 km/s< V < 1300 km/s
1400 km/s < V < 2000 km/s
V > 2000 km/s

Strongly truncated gas disk + extraplanar, high surface brightness gas

→ **near peak stripping**

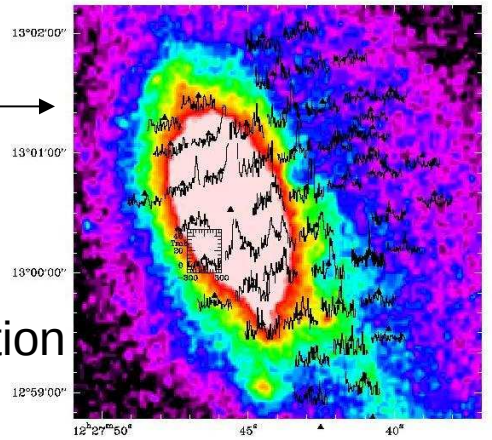
NGC 4522 (Vollmer et al. 2006)

model observations

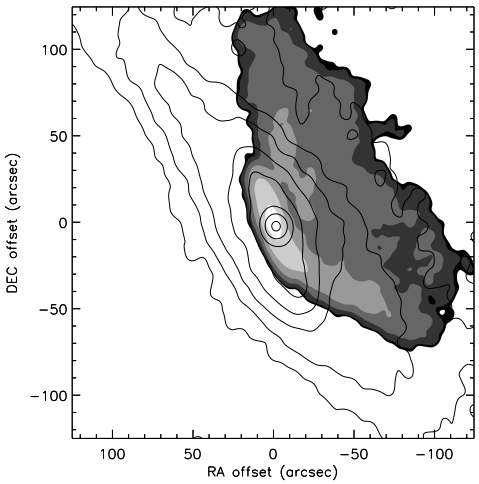


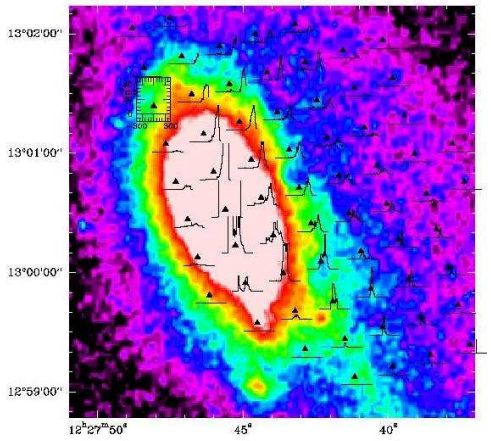
NGC 4438 (Vollmer et al. 2005)

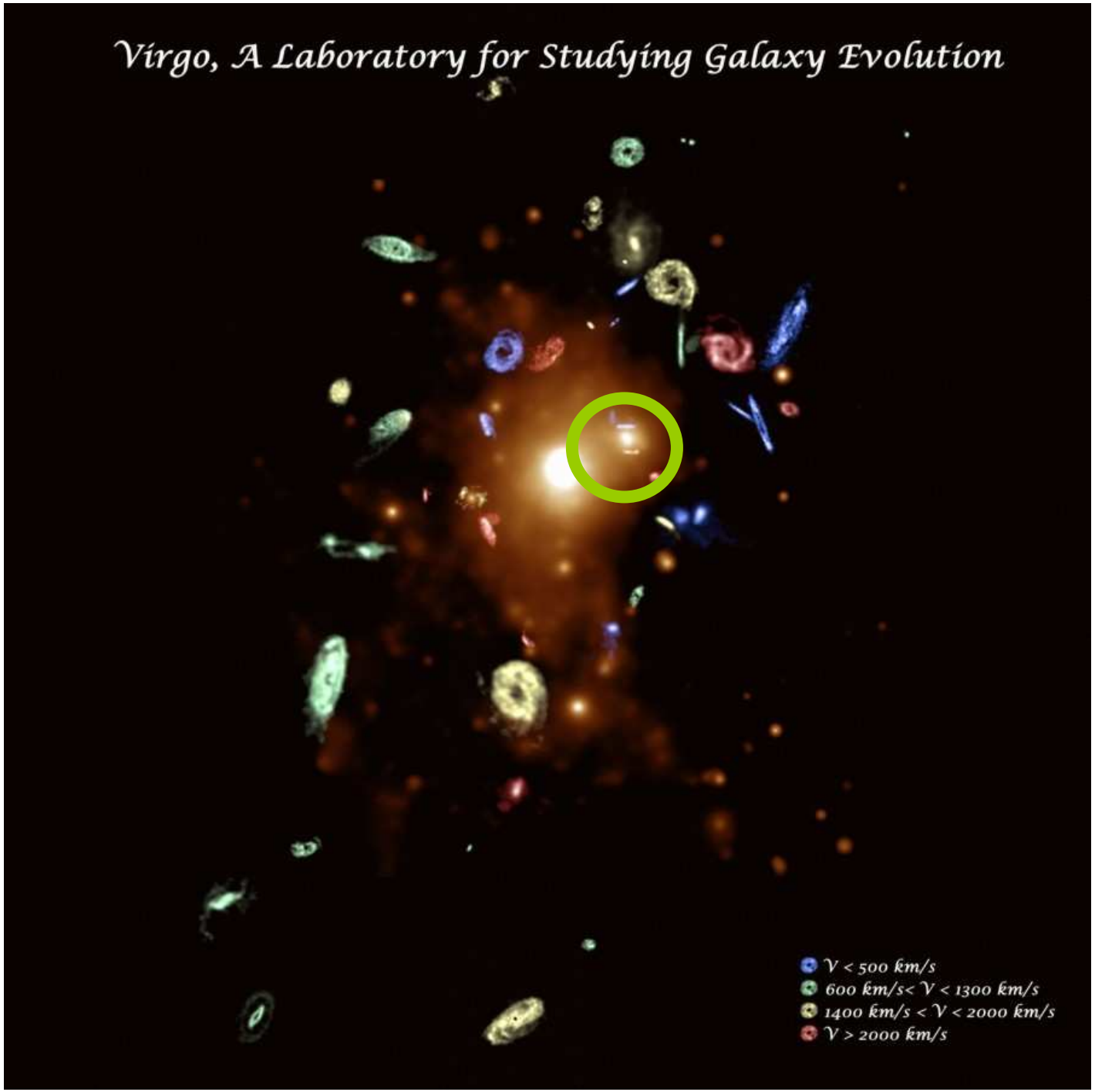
CO(1-0) IRAM30m →



model:
Gravitational interaction
+ ram pressure

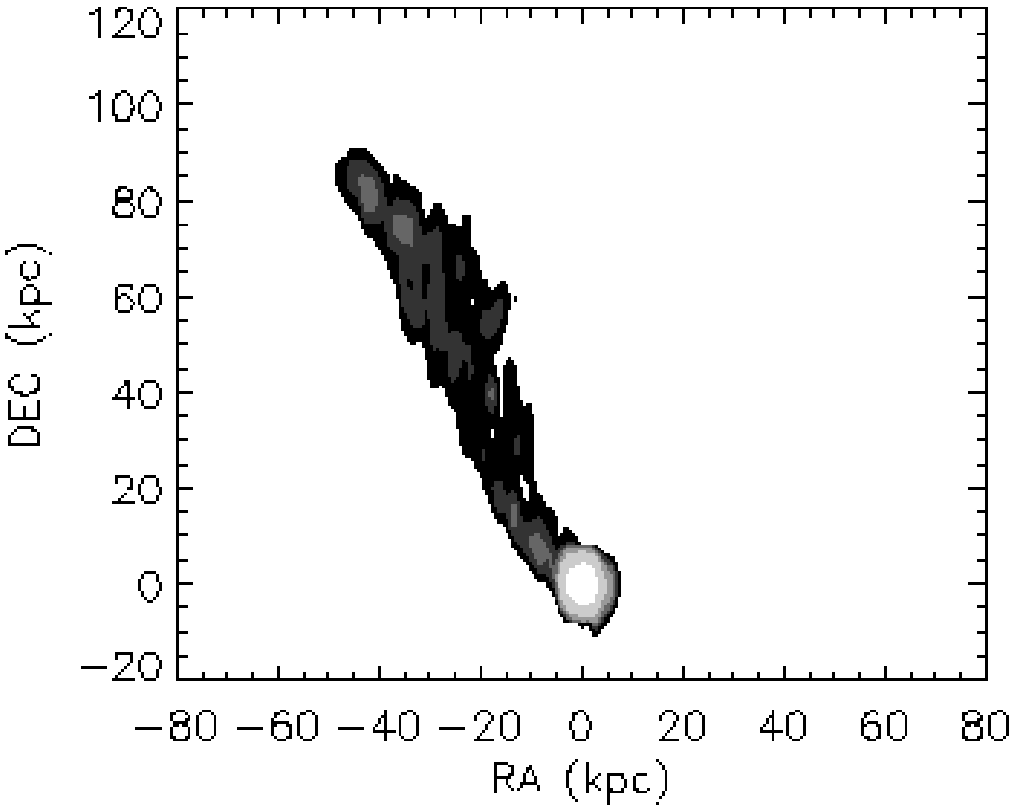


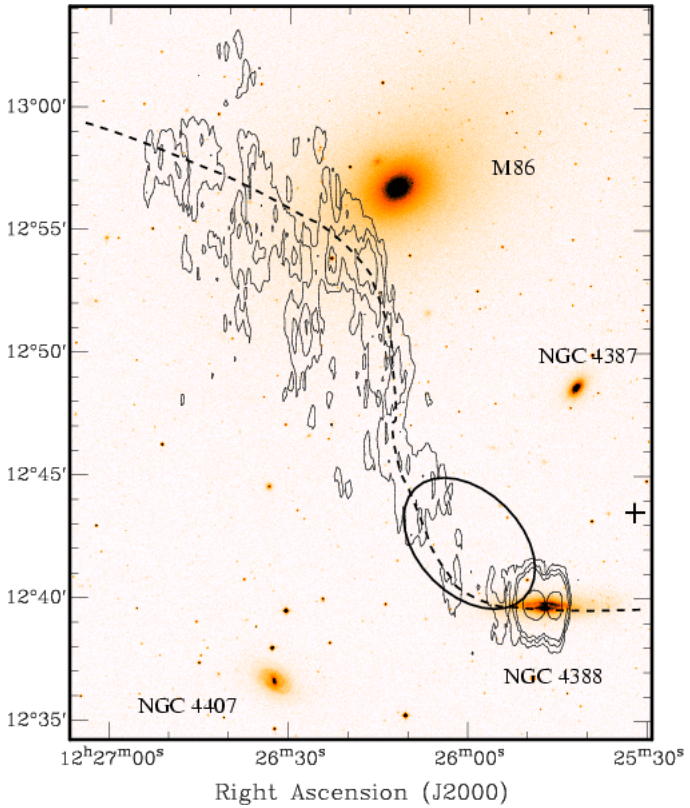



Virgo, A Laboratory for Studying Galaxy Evolution
V < 500 km/s
600 km/s< V < 1300 km/s
1400 km/s < V < 2000 km/s
V > 2000 km/s

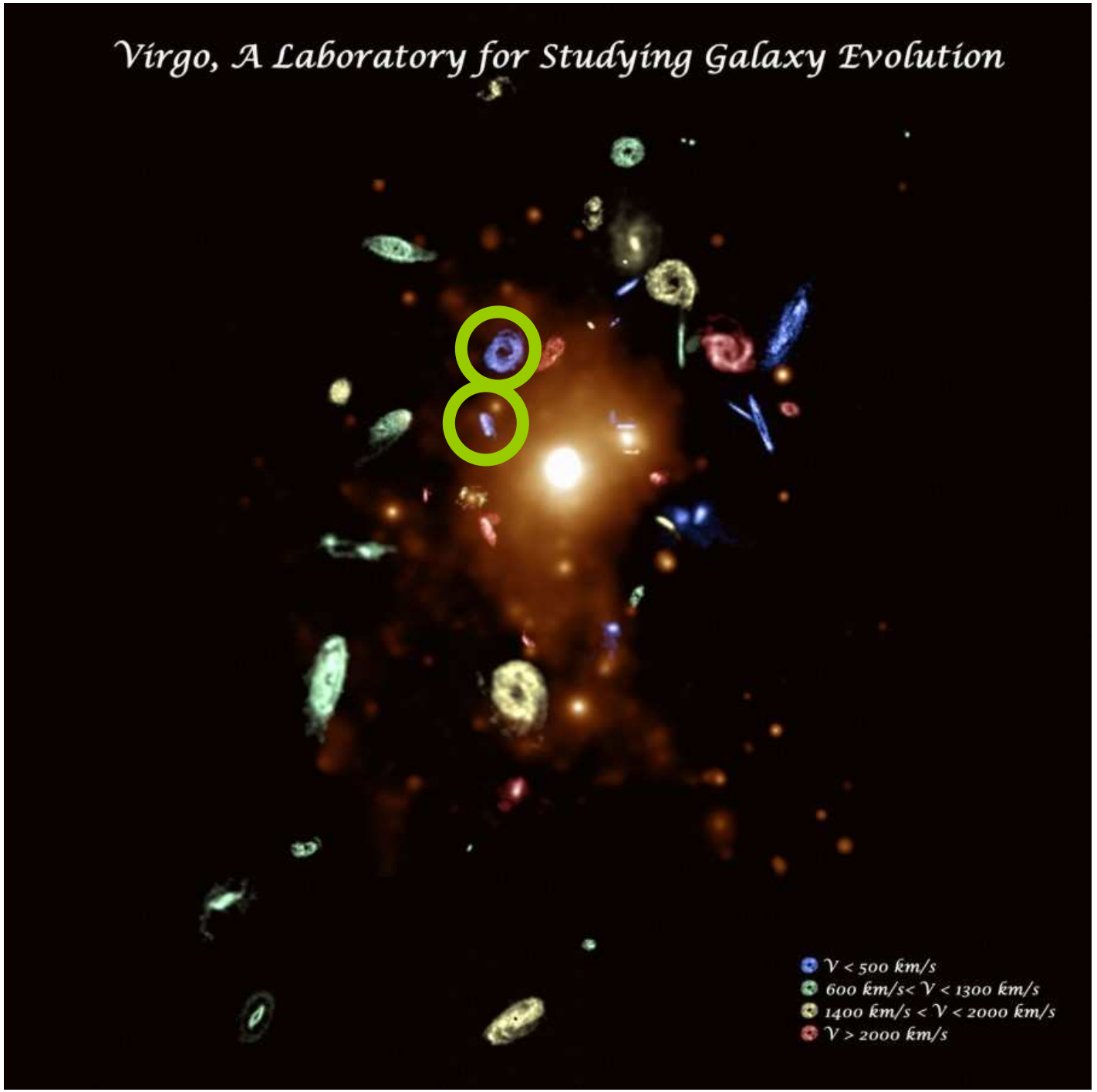
Truncated gas disk + extraplanar, very low surface brightness gas

⟶ **~100Myr after ram pressure peak**





(Oosterloo & van Gorkom 2005)


Virgo, A Laboratory for Studying Galaxy Evolution
V < 500 km/s
600 km/s< V < 1300 km/s
1400 km/s < V < 2000 km/s
V > 2000 km/s

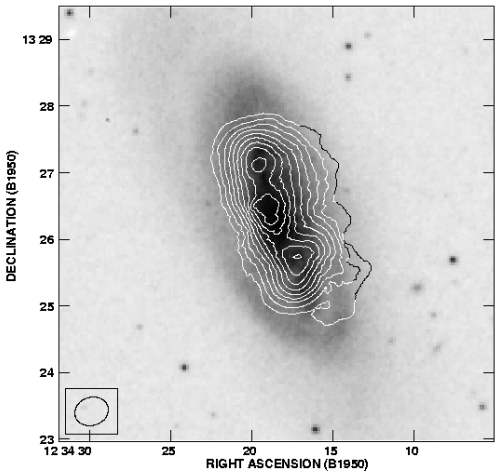
Truncated gas disk + perturbed, low surface brightness arms

⟶ **~300Myr after ram pressure peak**

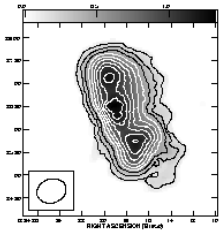
NGC 4569

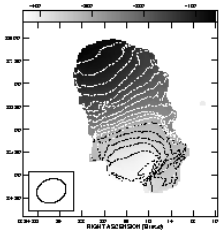
(Vollmer et al. 2004)

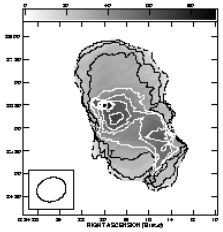
Contours: HI VLA C+D
Greyscale: B band



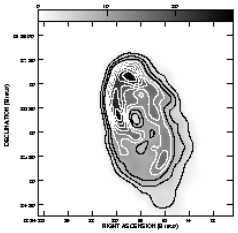
HI observations

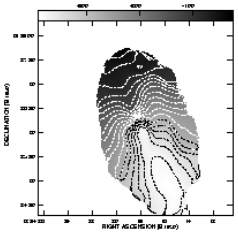


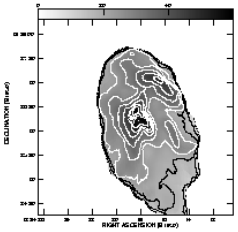




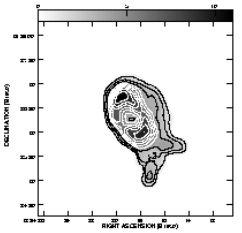
active stripping model

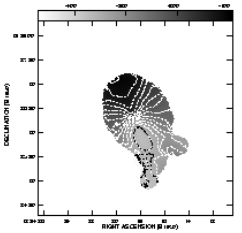


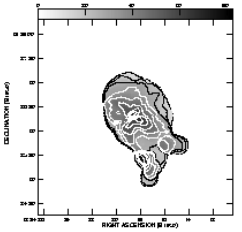




past stripping model



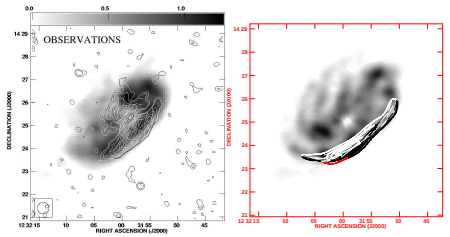




Ram pressure stripping time sequence

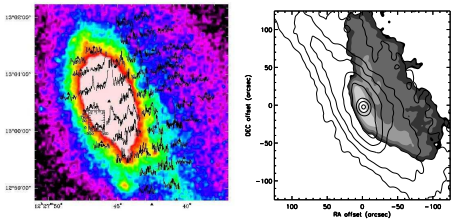
Vollmer (2009)

NGC 4501

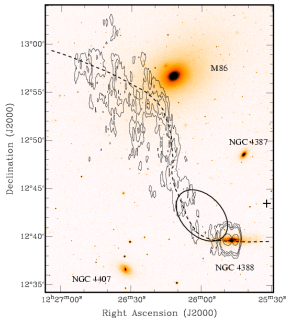


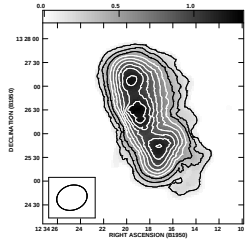
model

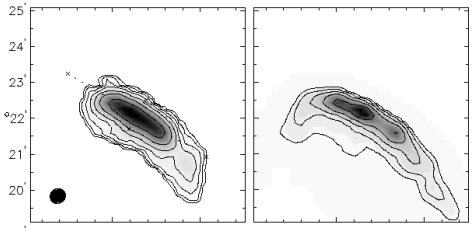
NGC 4438



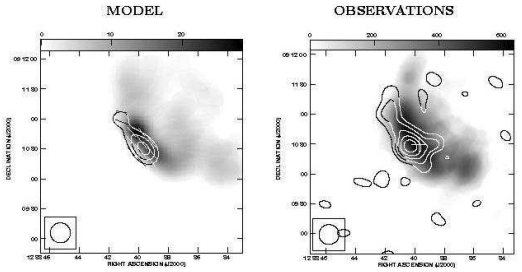
model



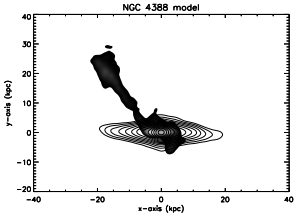




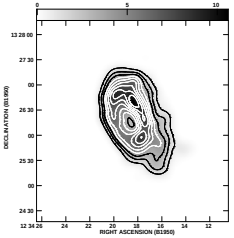
model



model



model



model

NGC 4330

NGC 4522

NGC 4388

NGC 4569

pre-peak

near peak

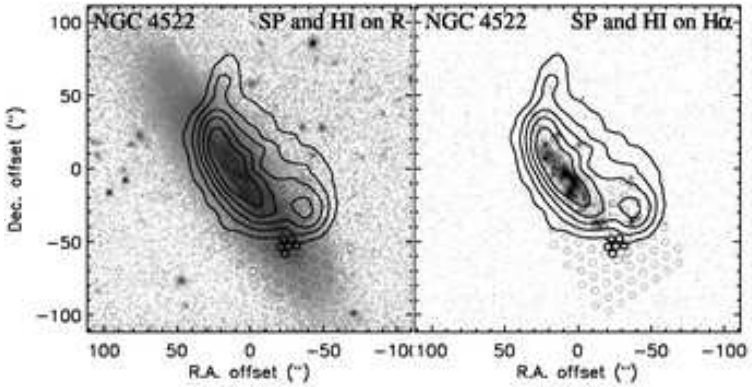
~150Myr after peak

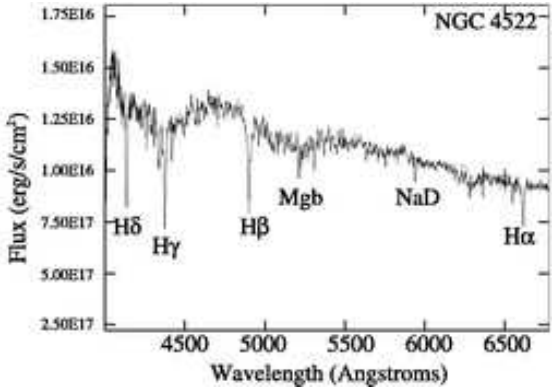
~300Myr after peak

Independent confirmation of stripping ages

- NGC 4522 (Crowl & Kenney 2007, 2008)

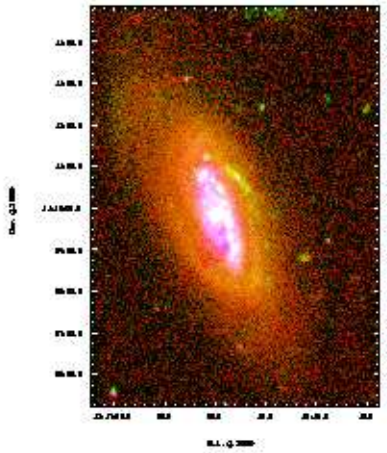
WIYN SparsePack & GALEX UV

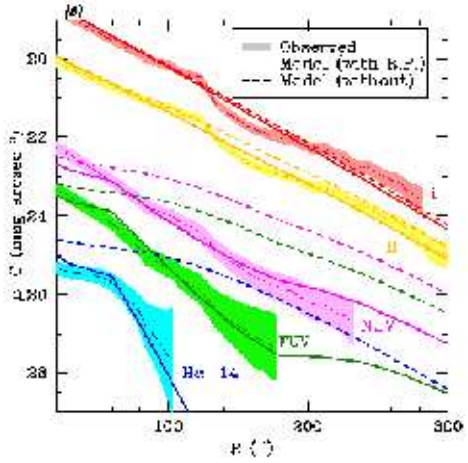


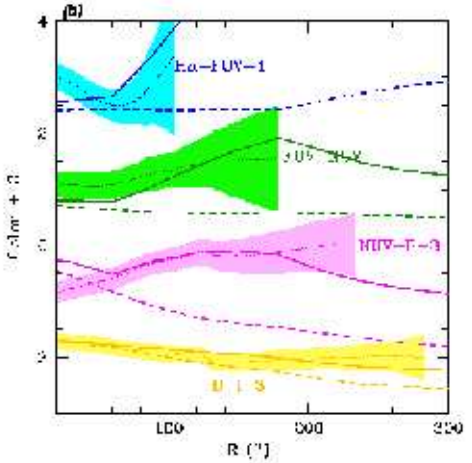


- NGC4569 (Boselli et al. 2007)

GALEX UV

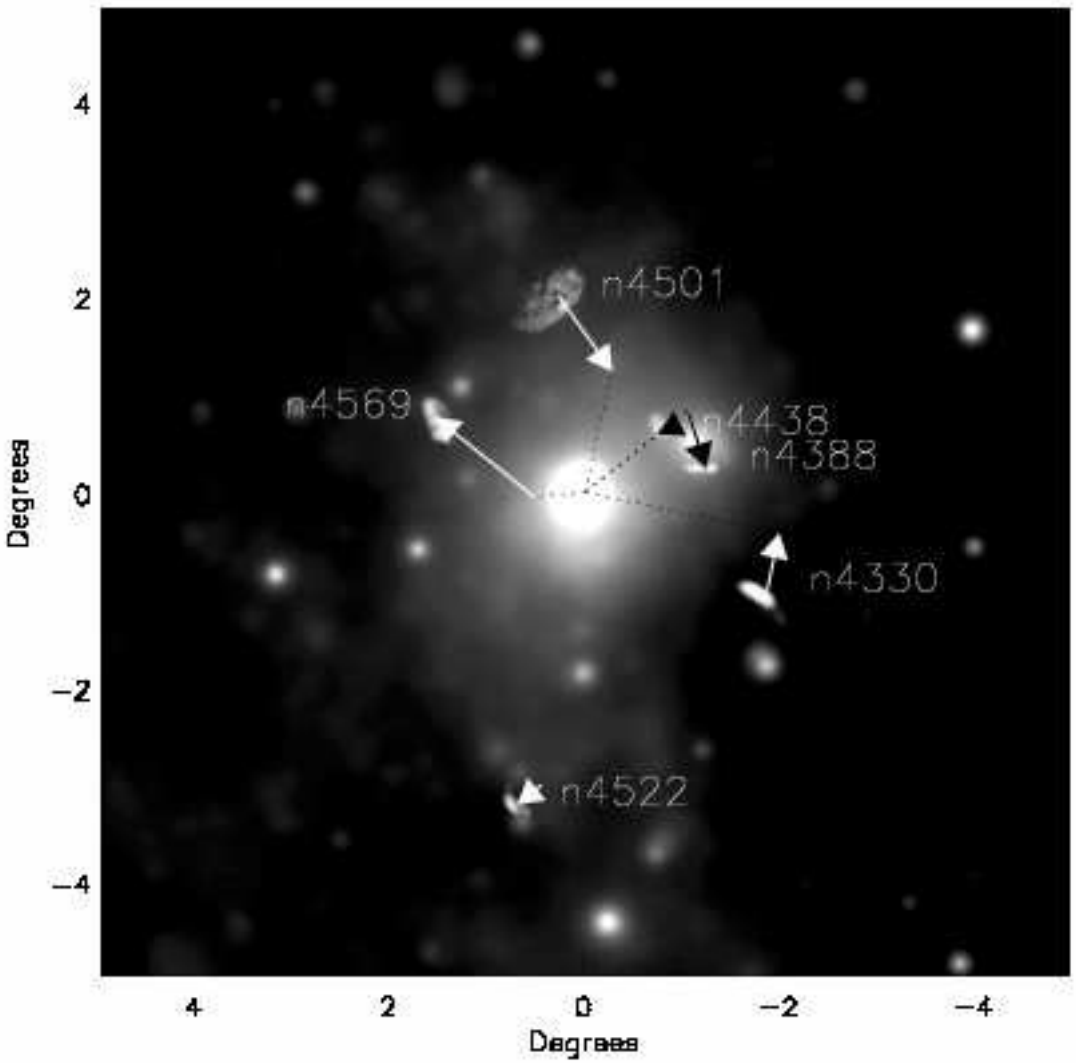


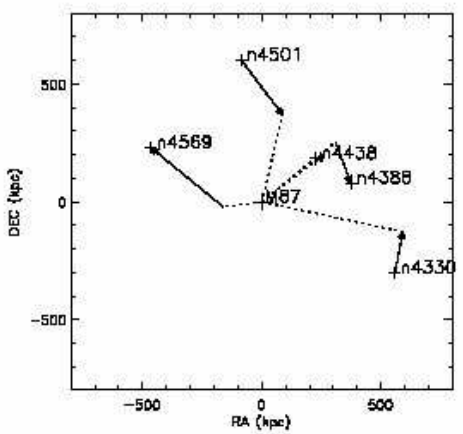


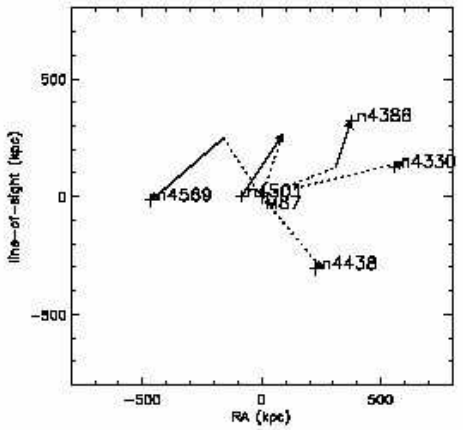


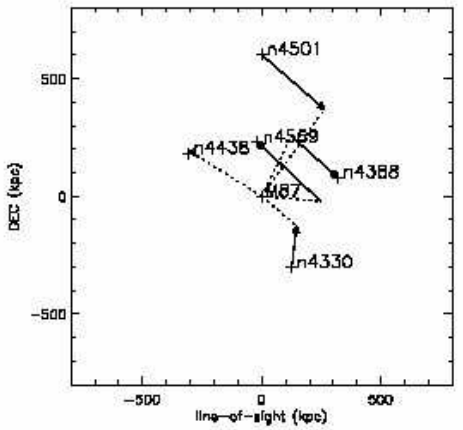
The 3D view

Vollmer (2009)

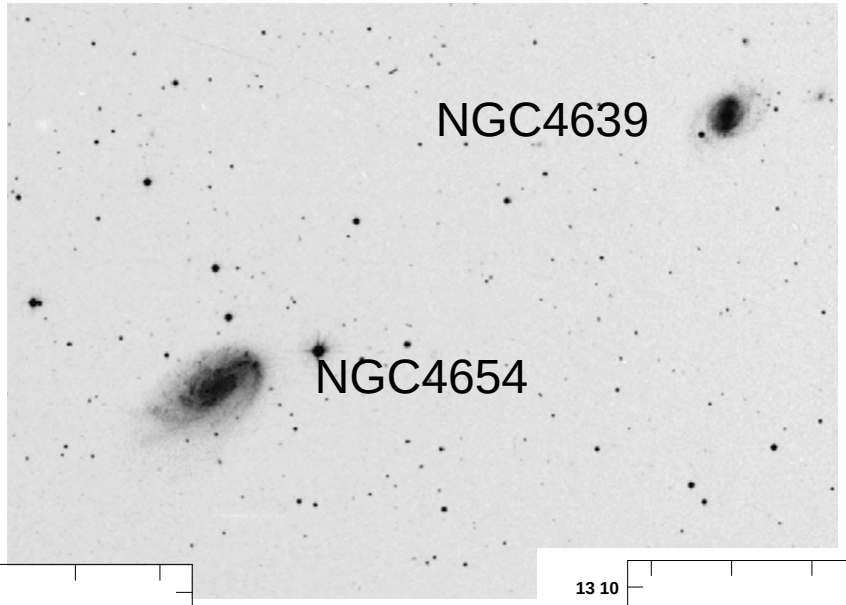




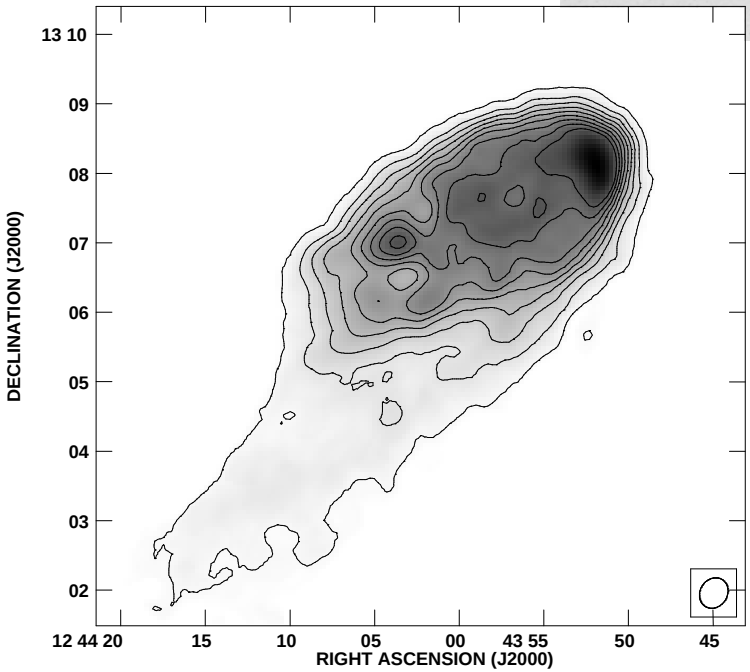




Tidally enhanced ram pressure stripping

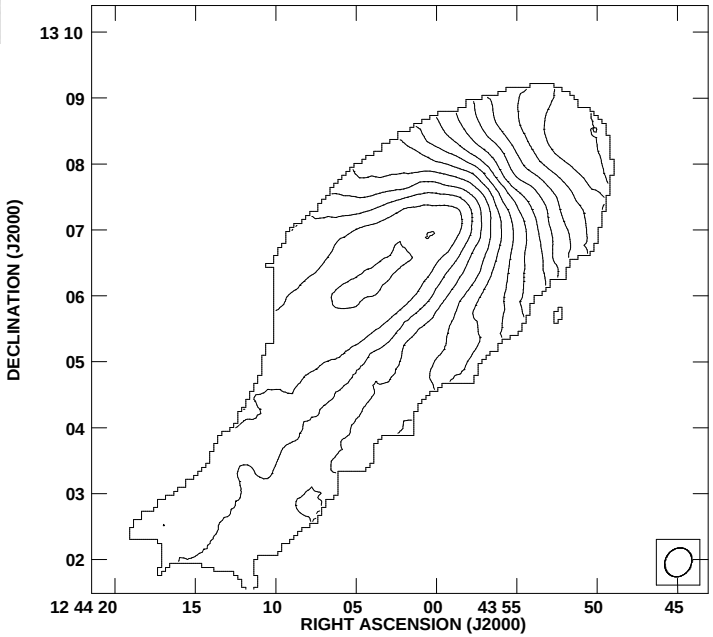


HI gas distribution



(Phookun & Mundy 1995)

HI velocity field



NGC 4654

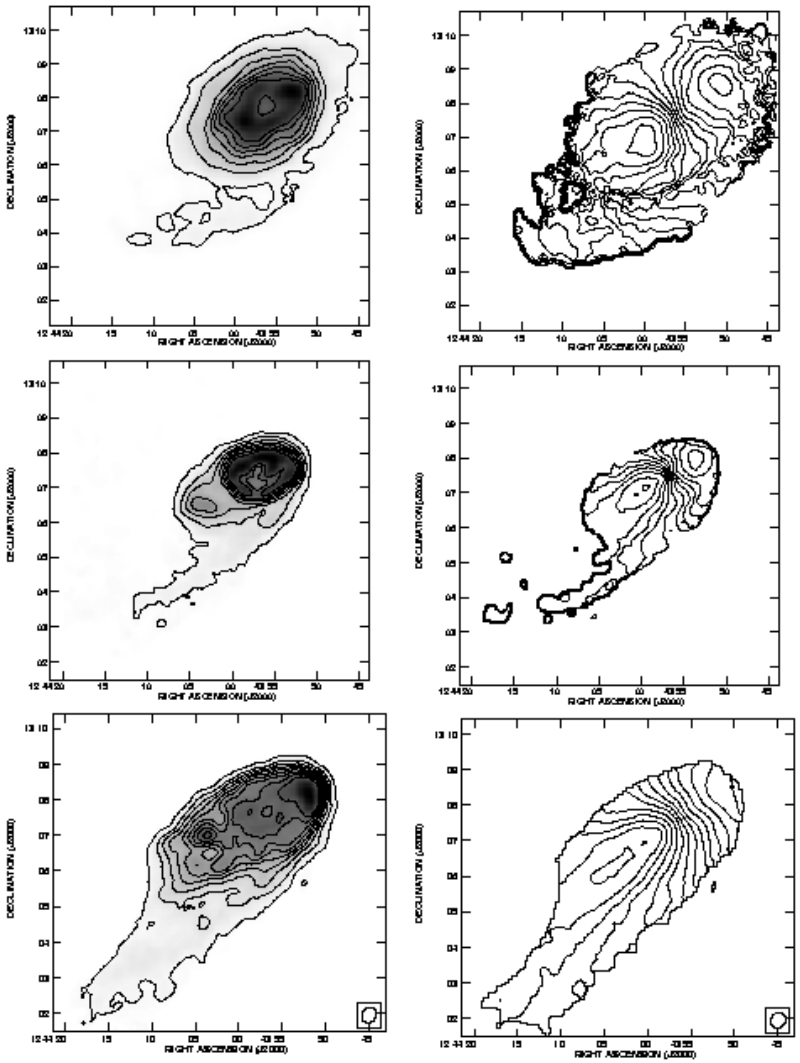
(Vollmer 2003)

model I:
ram pressure

model II:
ram pressure +
tidal interaction

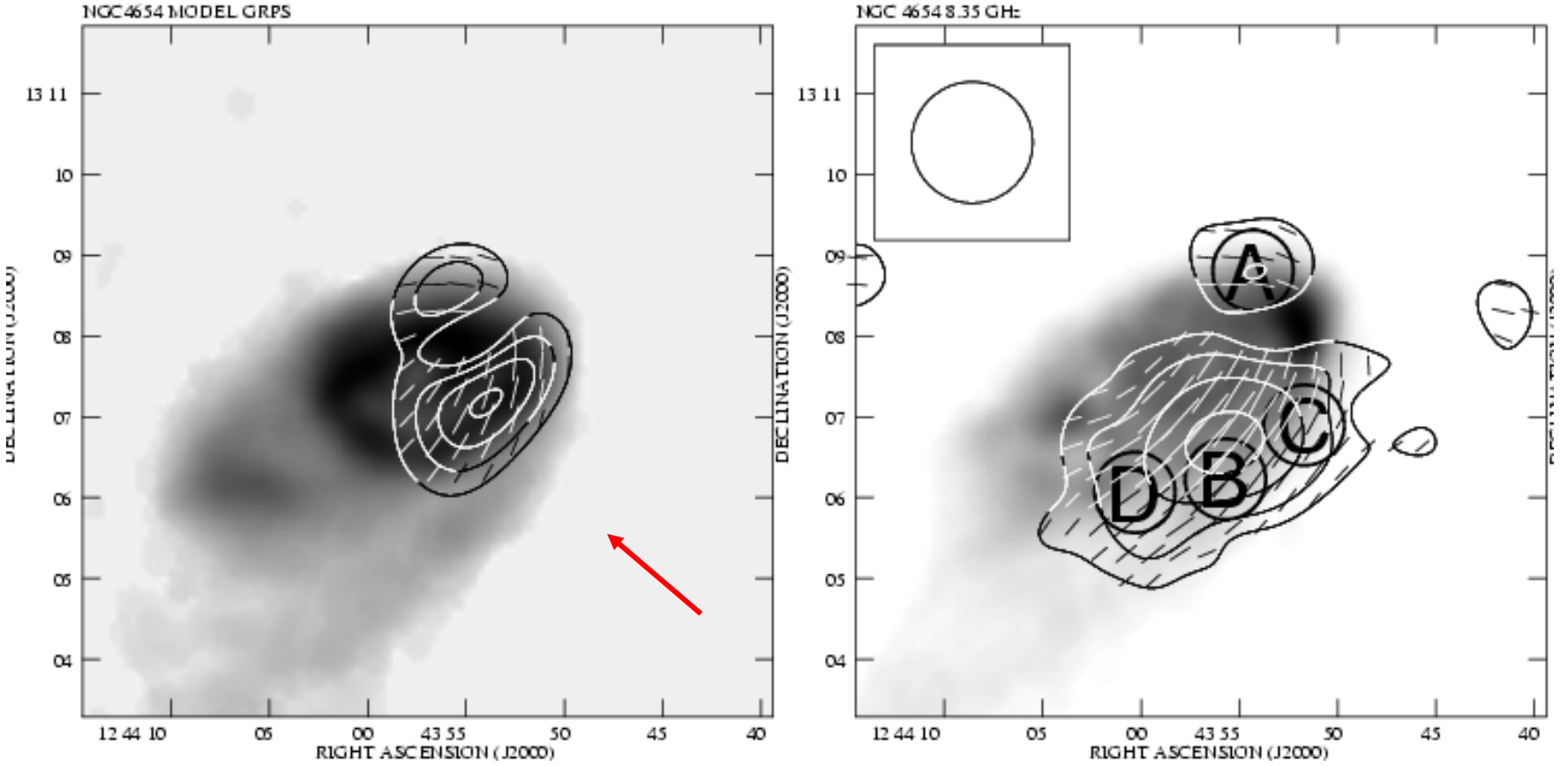
HI observations
(Phookun & Mundy 1995)

gas distribution velocity field



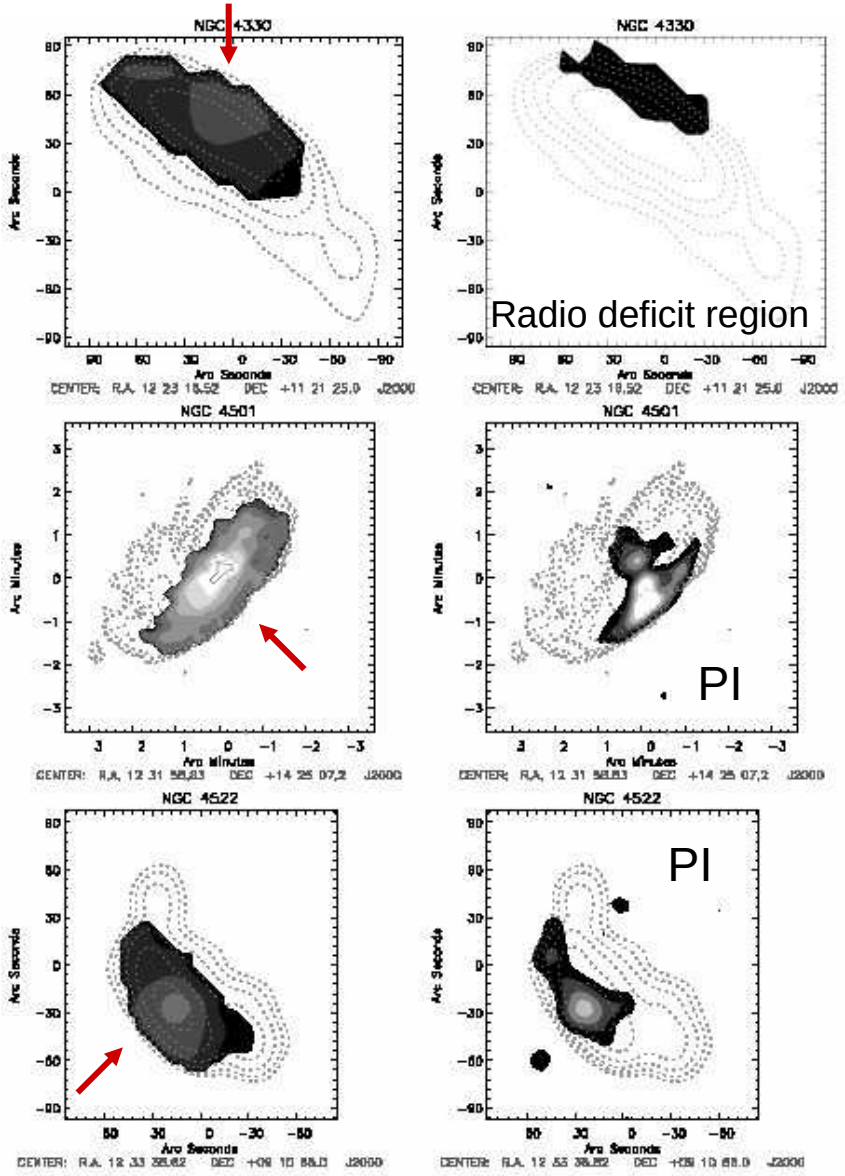
NGC 4654 – PI model

tidal interaction + ram pressure stripping
(Vollmer 2003 & Soida et al. 2006)



Ram pressure and the multiphase ISM

Molecular gas fraction



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

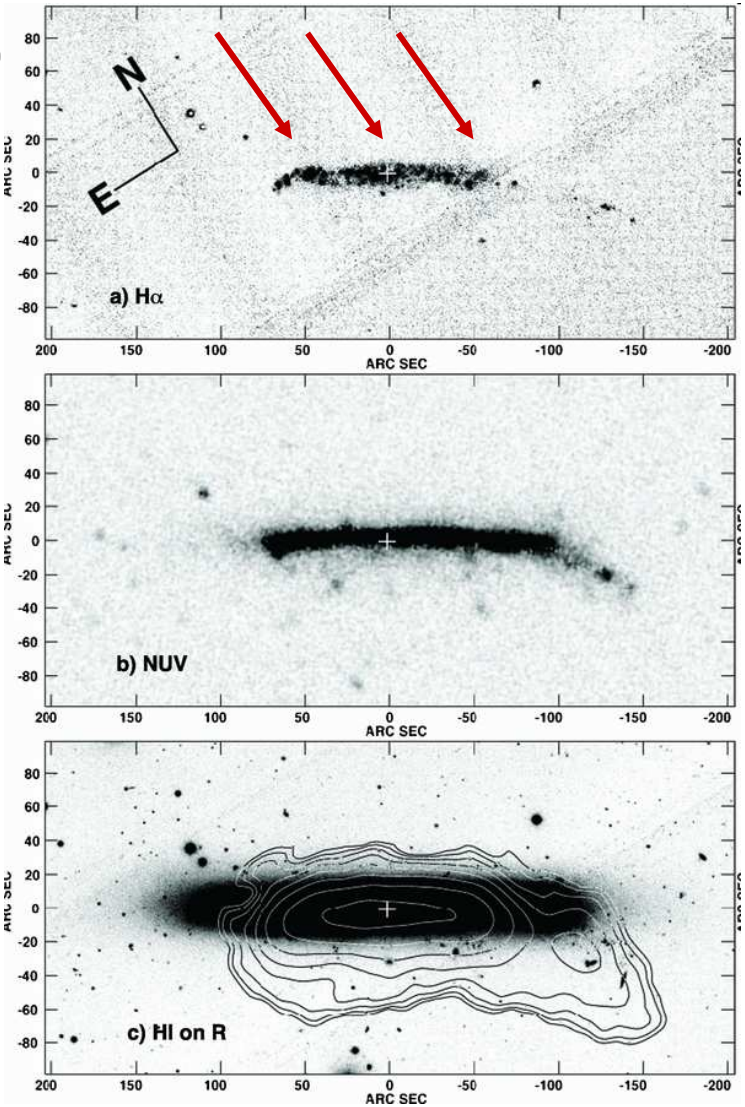
(Vollmer et al. 2012)

Radio deficit: Murphy et al. (2009)

Ram pressure and the multiphase ISM

NGC4330

Amramson et al. (2011)

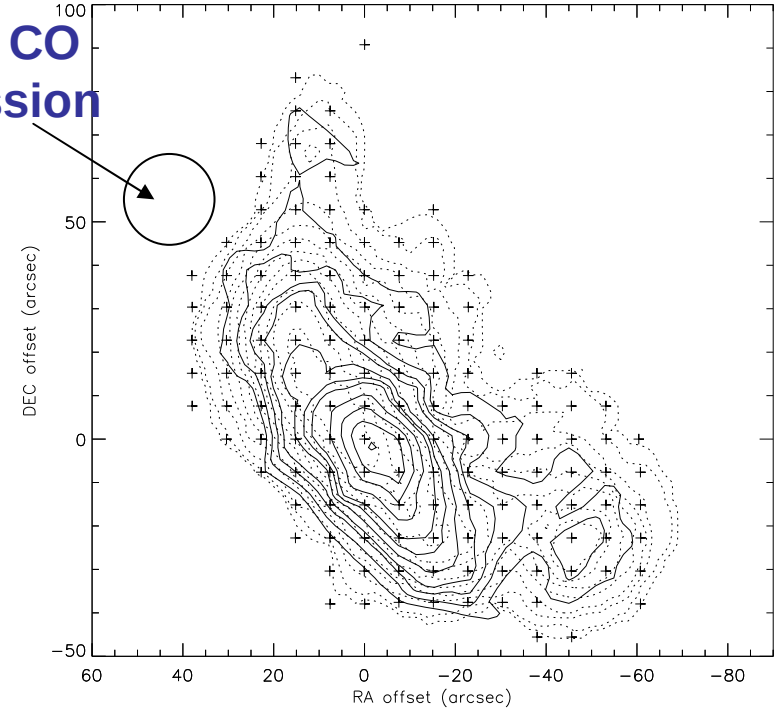


- The ISM is moved as an entity
- GMC lifetime < ram pressure dynamical time-scale

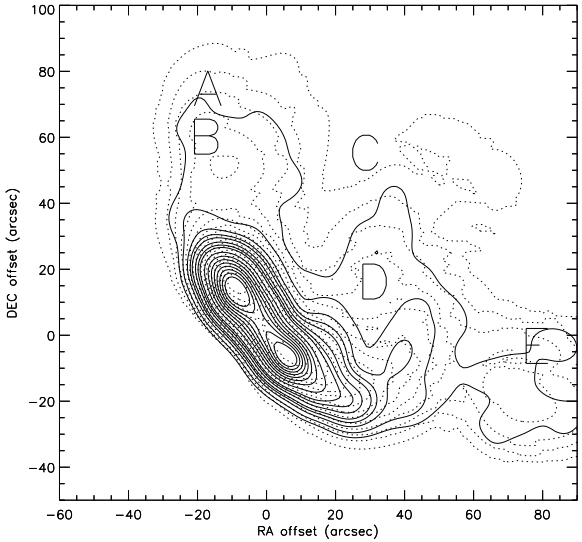
Ram pressure stripping of the multiphase ISM

Vollmer et al. (2008)

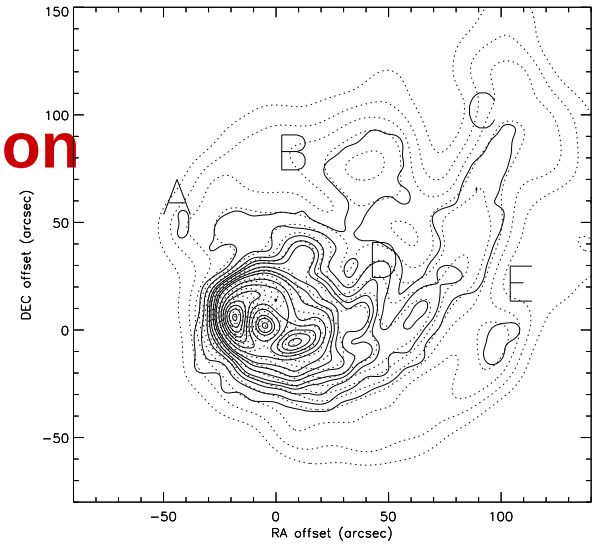
- IRAM 30m HERA CO(2-1) observations



model



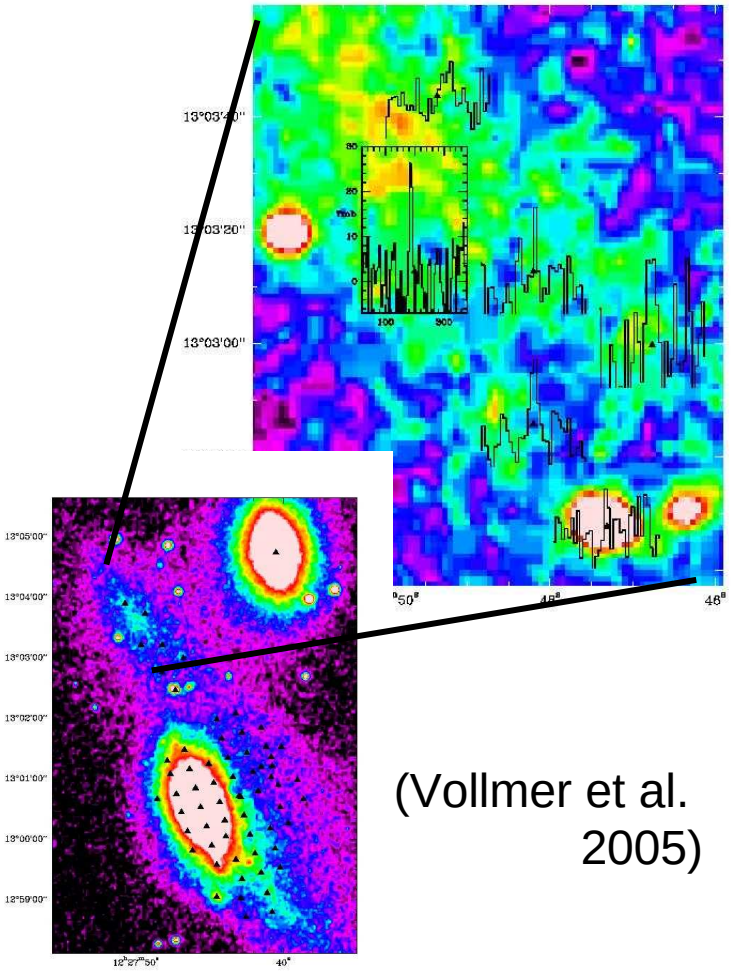
model deprojection



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

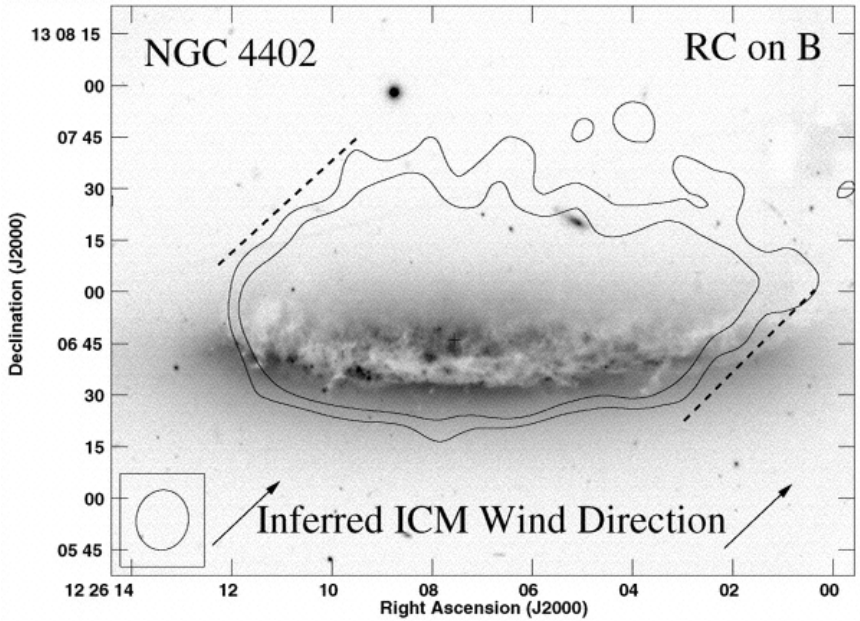
Ram pressure stripping of the multiphase ISM

- NGC 4438: decoupeled molecular clouds



(Vollmer et al. 2005)

- NGC 4402 (Crowl et al. 2005)

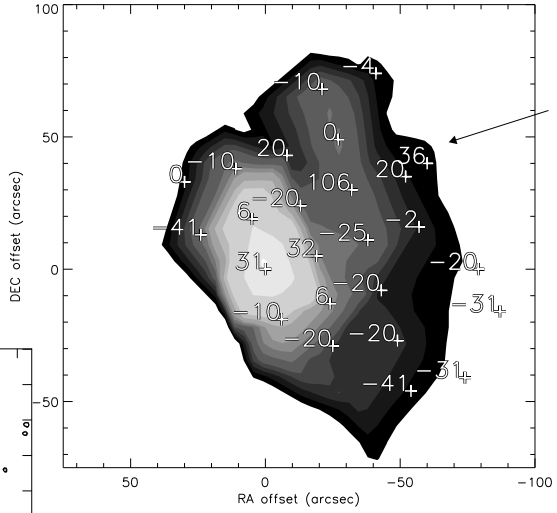


Contour: 20cm radio continuum emission;
Greyscale: B band

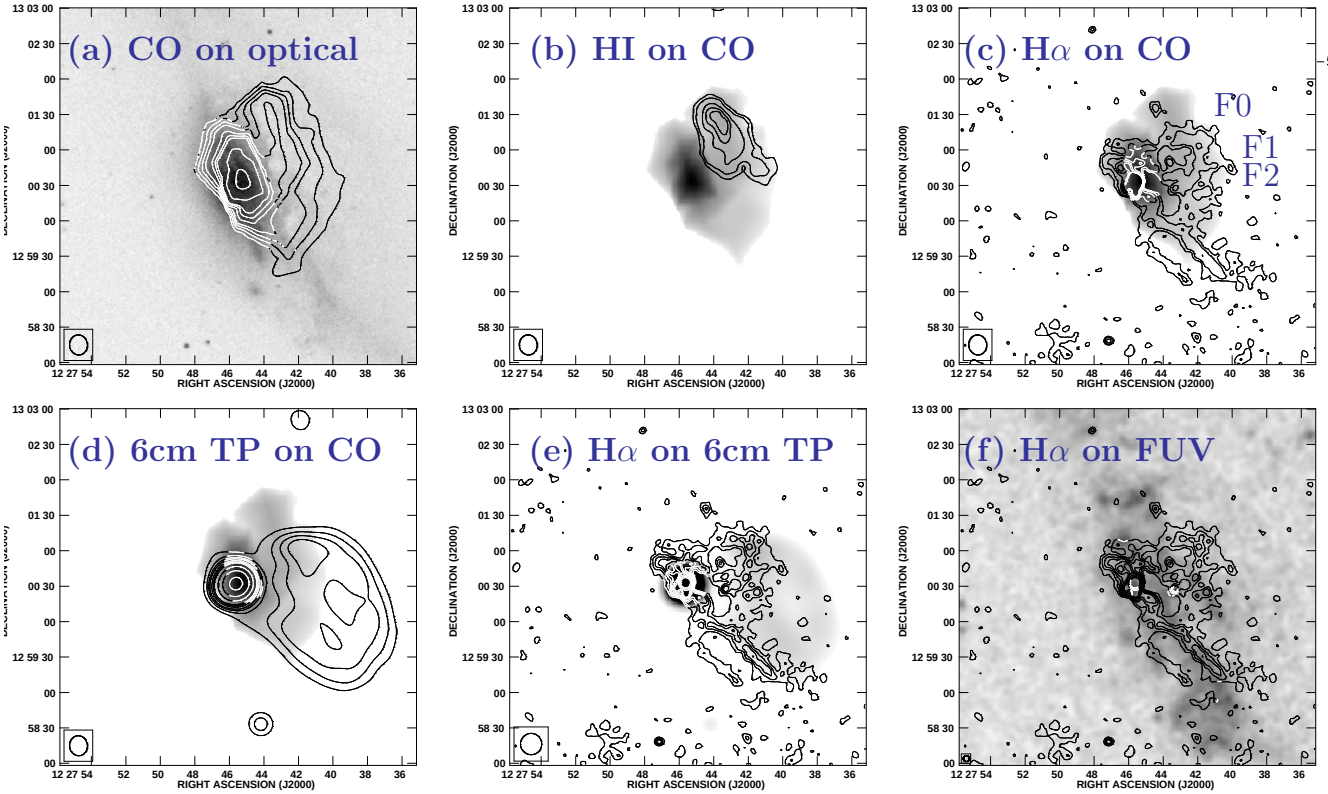
Ram pressure stripping of the multiphase ISM

Vollmer et al. (2009)

- **NGC 4438: diffuse ionized gas stripped more efficiently than neutral gas**
- **Role of gravitational interaction?**



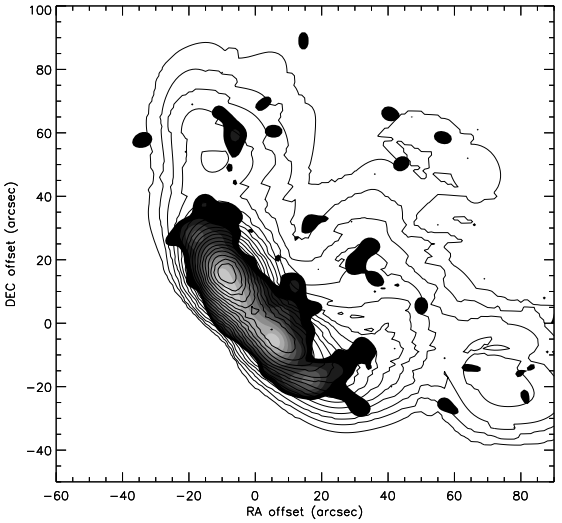
Velocity difference
Hα - CO



Vollmer et al. (2008)

Greyscale: Hα
Contours: HI
from Kenney
et al. (2004)

Greyscale: CO(2-1)
Contours: Hα (Kenney et al. 2004)



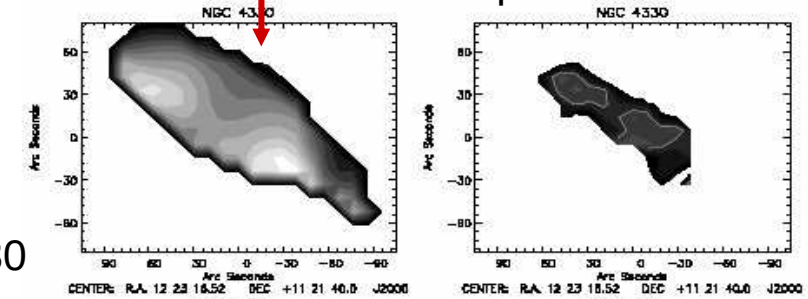
model
Greyscale: Hα
Contours: HI

Star formation in the stripped gas

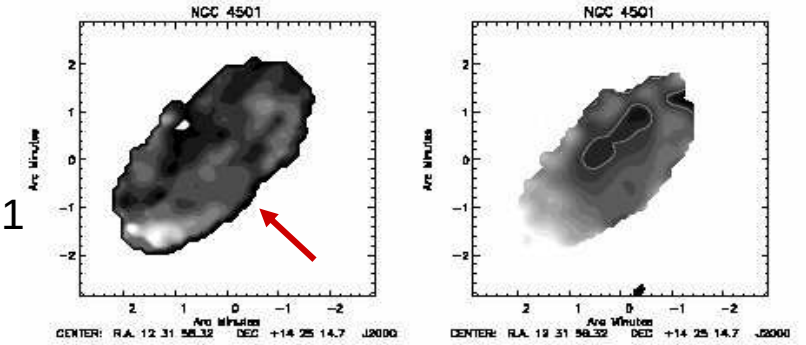
SFR timescale

spectral index

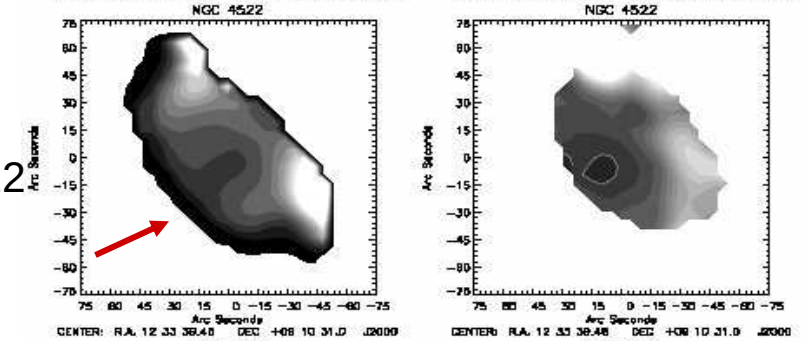
NGC4330



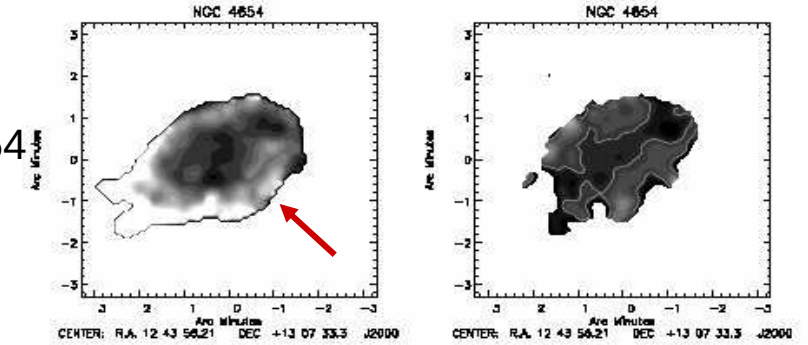
NGC4501



NGC4522



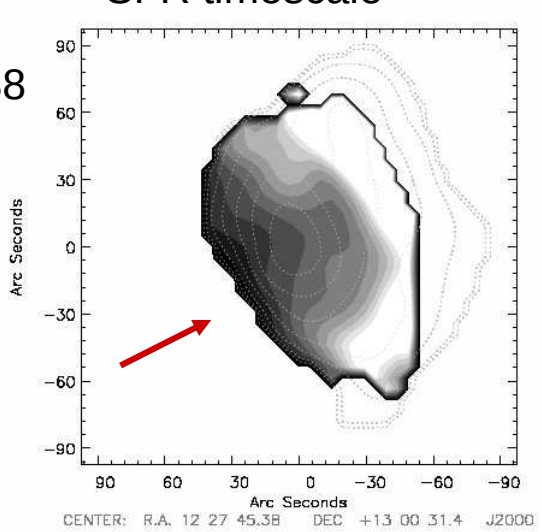
NGC4654



- **Except for N4438, cluster environment does not change $SFR_{mol}=SFR/M_{mol}$**
- **NGC4330, NGC4438, N4522 show a depressed SFE_{tot} in the extraplanar regions**
- **NGC4501, NGC4654 show regions of low SFE_{tot} within the disk with steep spectral index**

SFR timescale

NGC4438

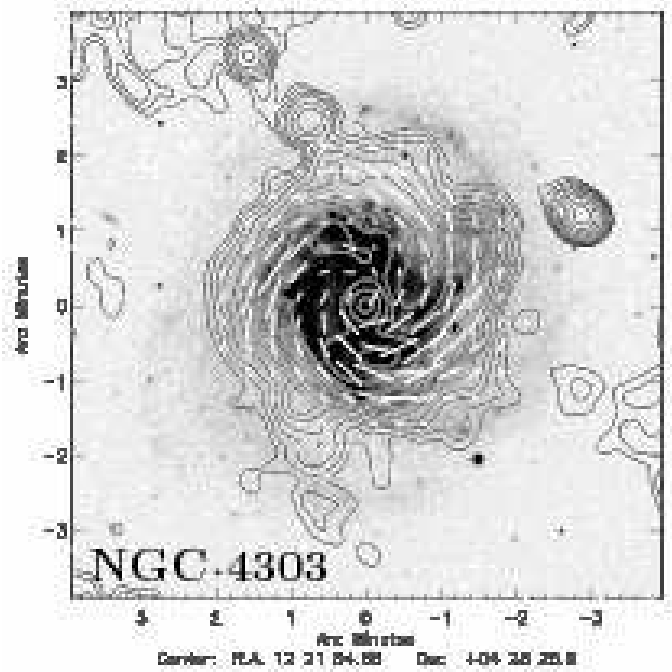


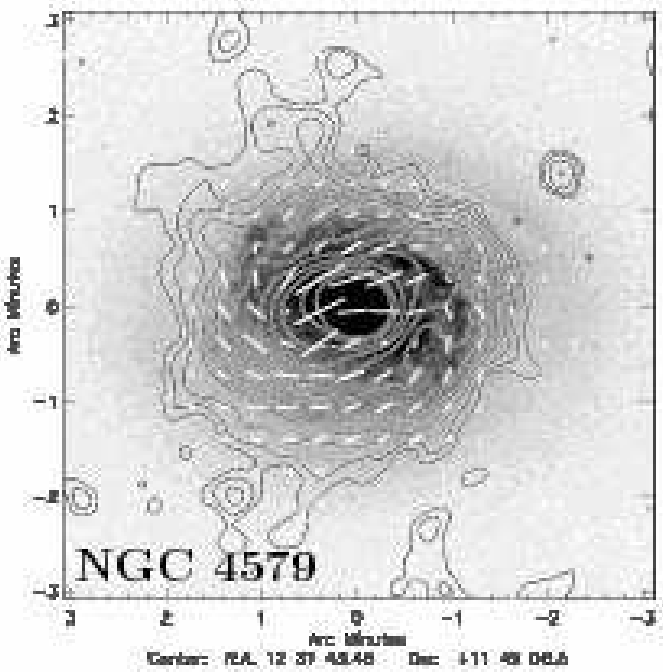
Vollmer et al. (2012)

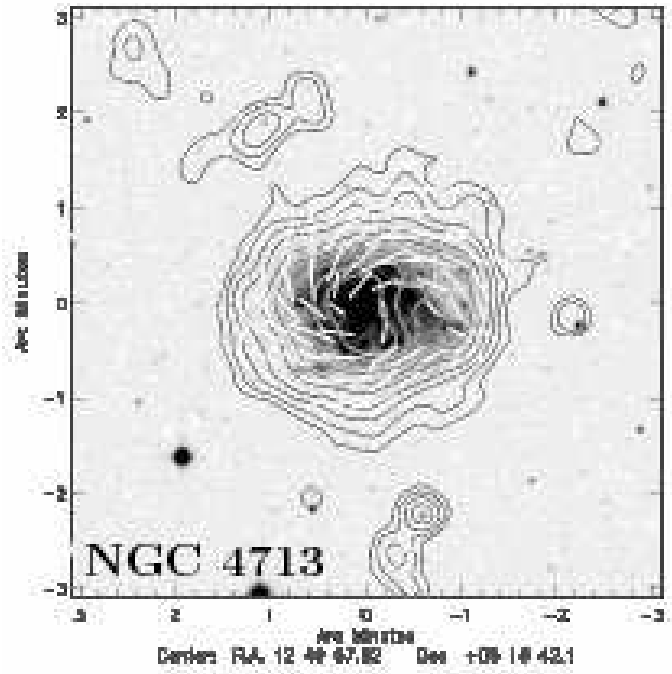
VLA large proposal: survey of 19 Virgo cluster spiral galaxies in polarized radio continuum emission

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

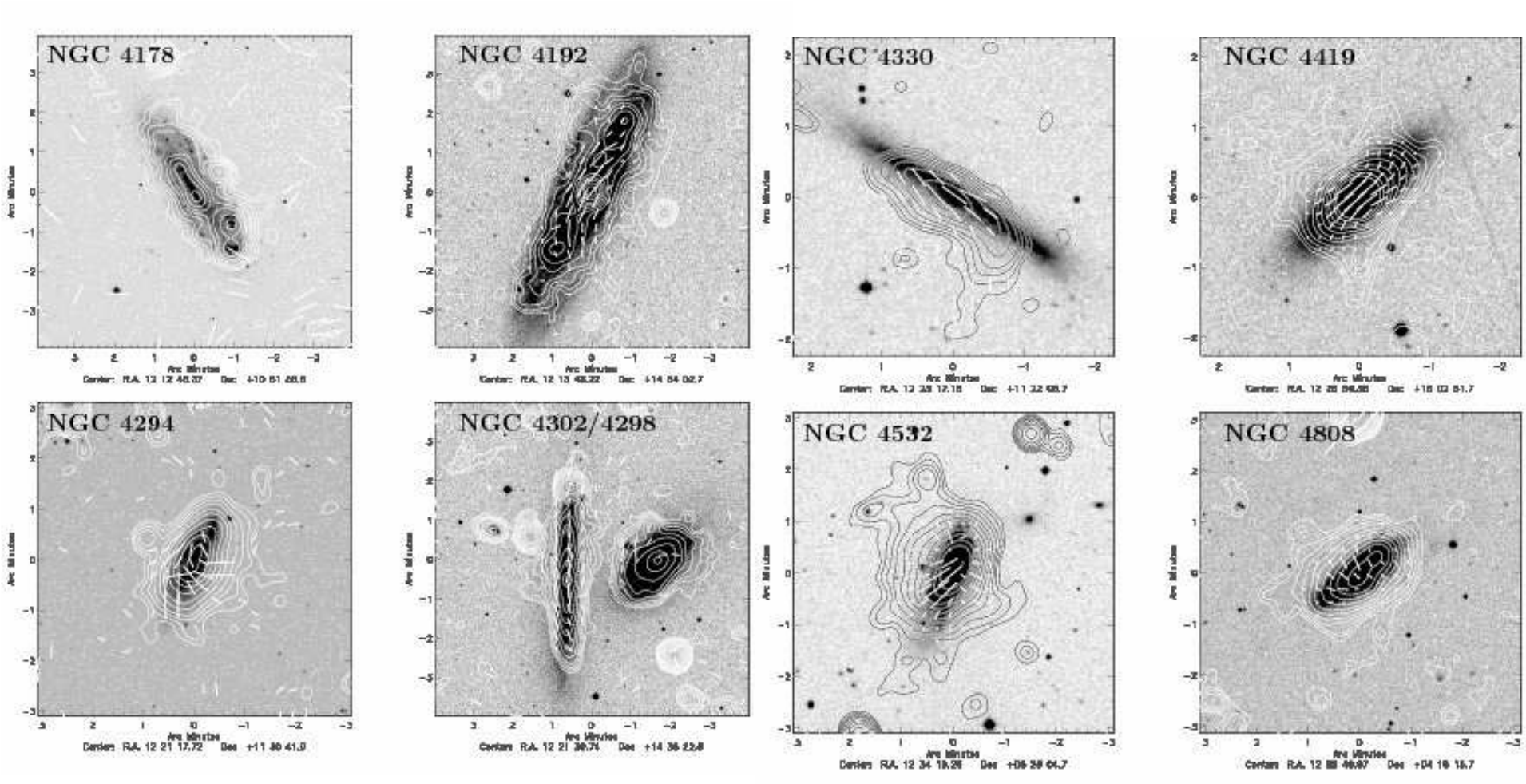




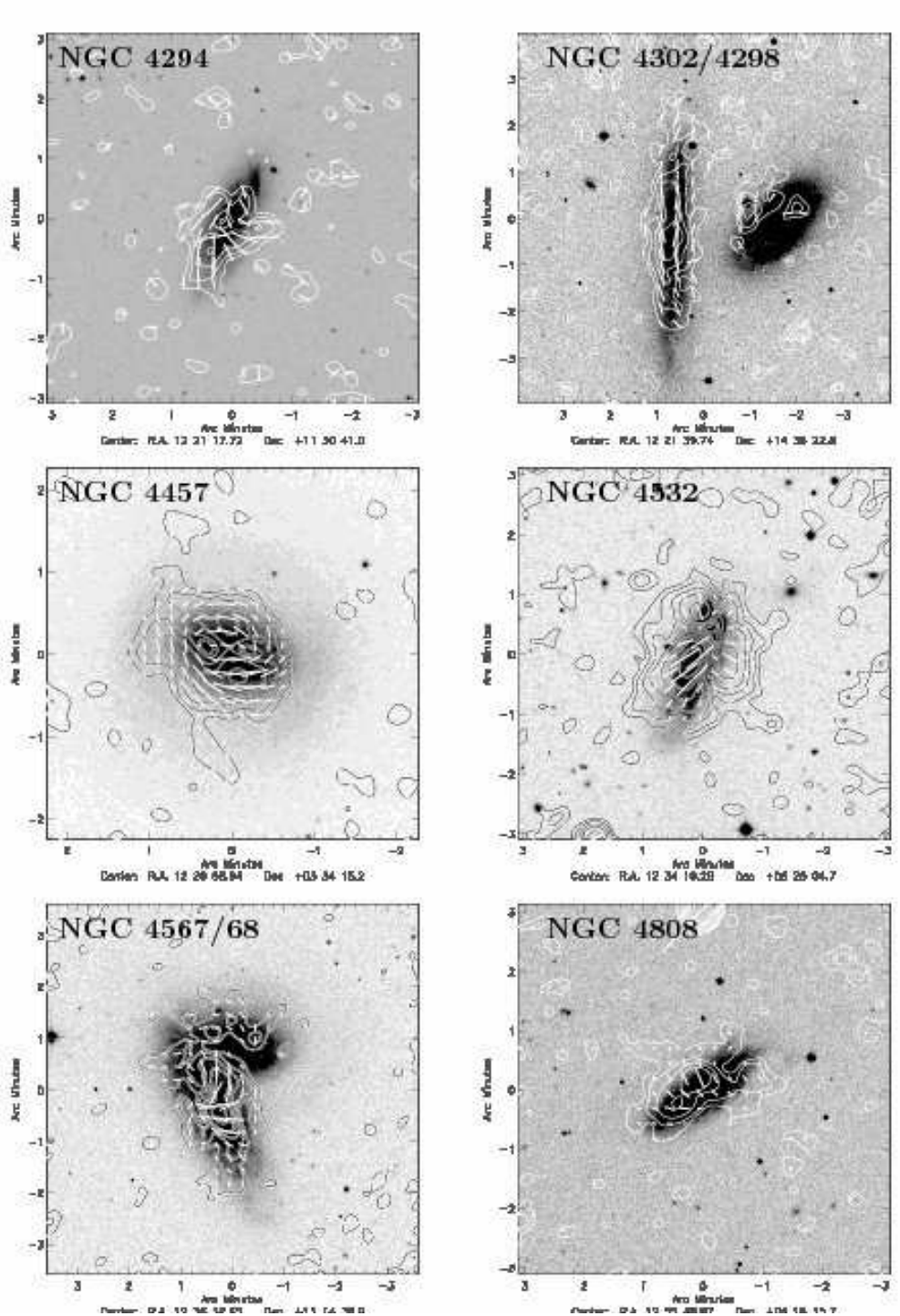


Symmetric spirals

Radio halos


NGC 4178
NGC 4192
NGC 4330
NGC 4419
NGC 4294
NGC 4302/4298
NGC 4532
NGC 4808

Asymmetric distributions of polarized radio continuum emission



Conclusions

- Polarized radio continuum emission is a useful tool for interaction diagnostics
- Efficiency of ram pressure stripping is ~1 (Gunn & Gott works) – overall the ISM is stripped as an entity
- For NGC 4522 a moving ICM is needed
- Temporal ram pressure sequence in the Virgo cluster
- Stellar population synthesis models confirm model stripping ages (NGC 4388, NGC 4569, NGC 4522; *PhD thesis of H. Crowl, Yale*)
- Indication of different stripping efficiencies of diffuse ionized ISM under certain circumstances
- Ram pressure quenches star formation
- Ram pressure stripping plays an important role in the evolution of Virgo cluster spirals