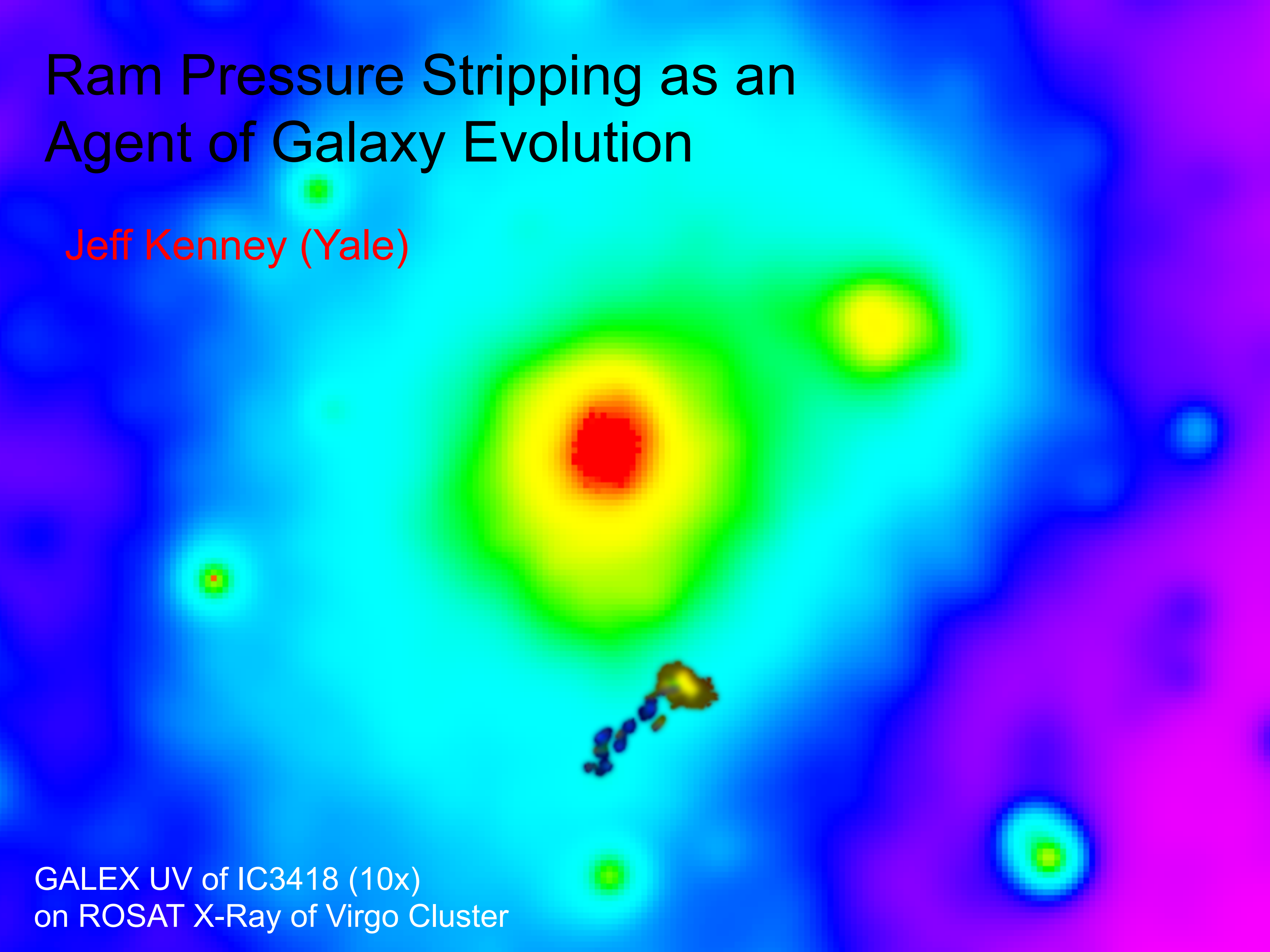
Ram Pressure Stripping as an Agent of Galaxy Evolution

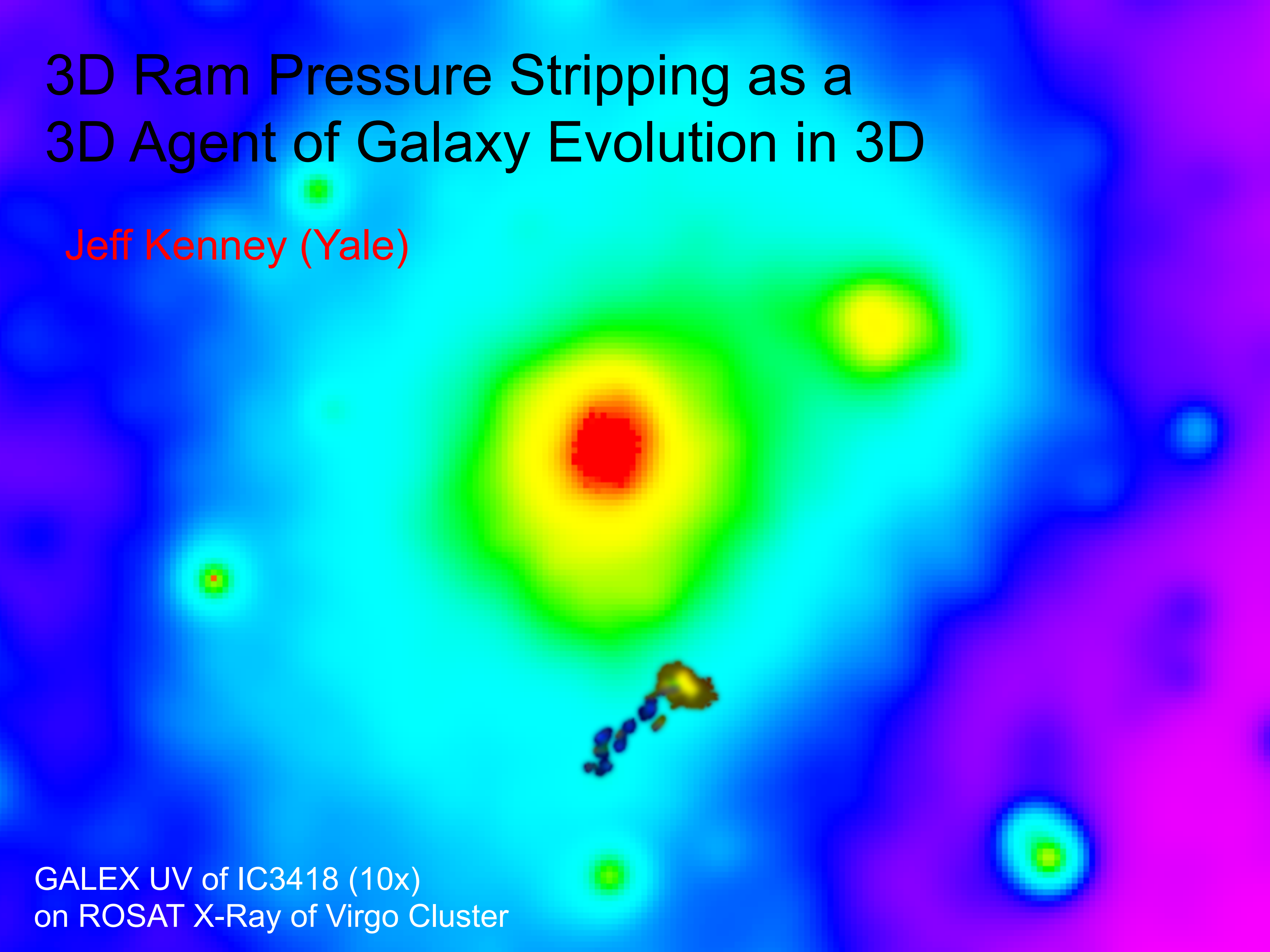
Jeff Kenney (Yale)



GALEX UV of IC3418 (10x)
on ROSAT X-Ray of Virgo Cluster

3D Ram Pressure Stripping as a 3D Agent of Galaxy Evolution in 3D

Jeff Kenney (Yale)



GALEX UV of IC3418 (10x)
on ROSAT X-Ray of Virgo Cluster

Summary: Ram Pressure Stripping does these things:

~completely strips dwarf galaxies in Virgo-like clusters

partially strips large spirals in Virgo-like ($M \sim 10^{14}\ M_{sun}$) clusters

~completely strips massive galaxies during first infall Into Coma-like ($M \sim 10^{15}\ M_{sun}$) clusters

~completely strips (small) dwarf satellite galaxies close enough to their (large) host galaxy

must be ***important starvation mechanism*** in high and medium density environments-- gas removed from outer galaxy or halo by r.p. will not settle to inner disk & form stars

RPS Hα tails in Coma galaxies

Hα on optical Subaru

Yagi+10

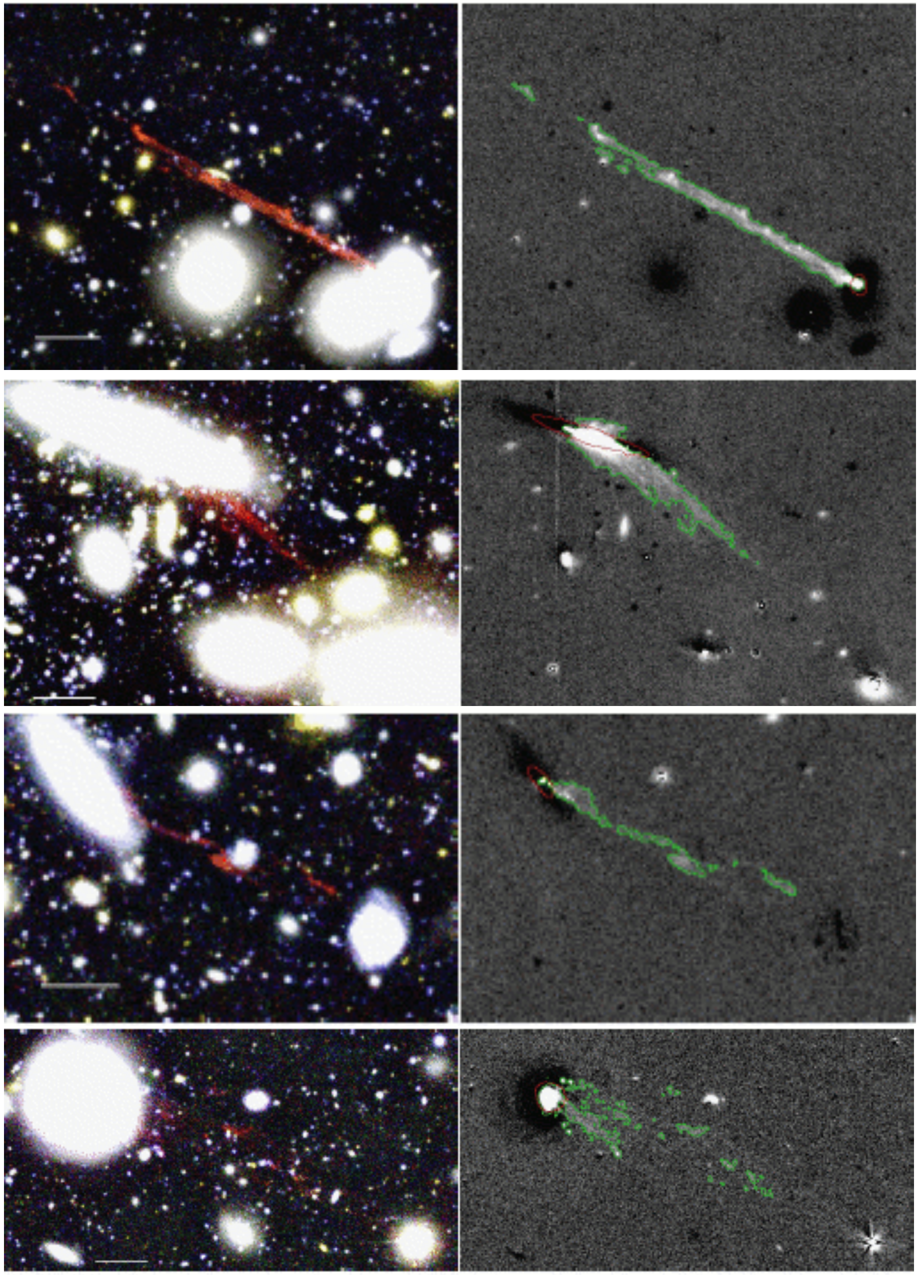
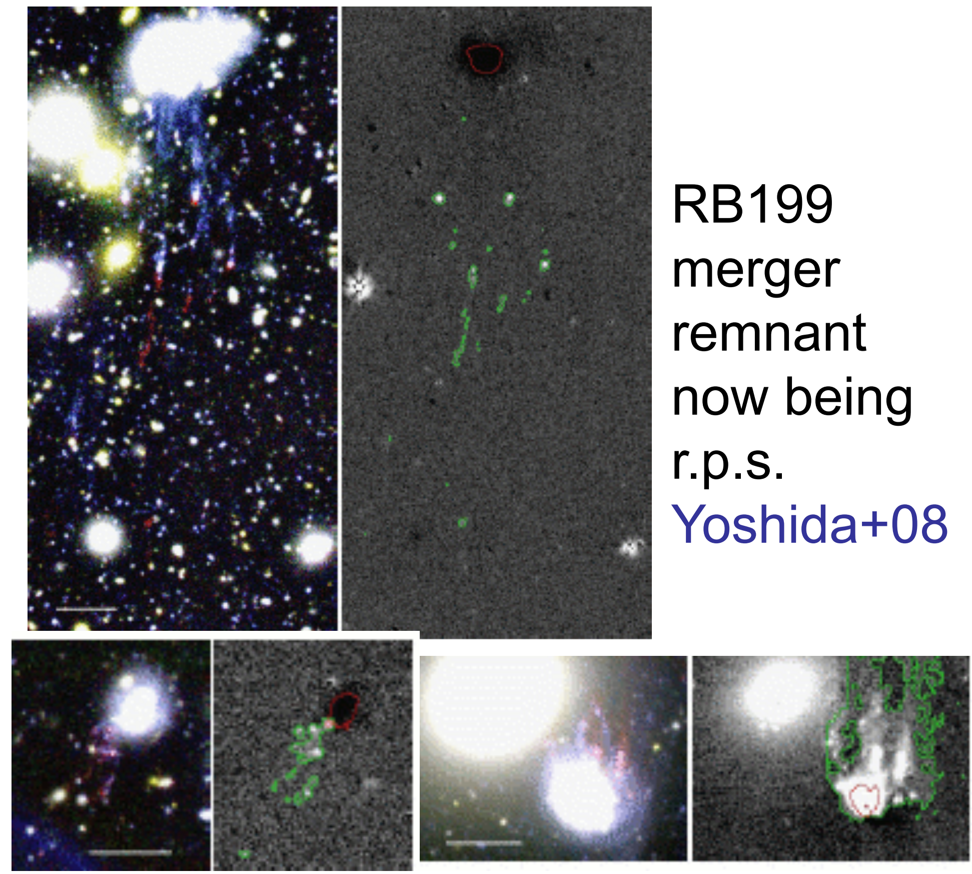


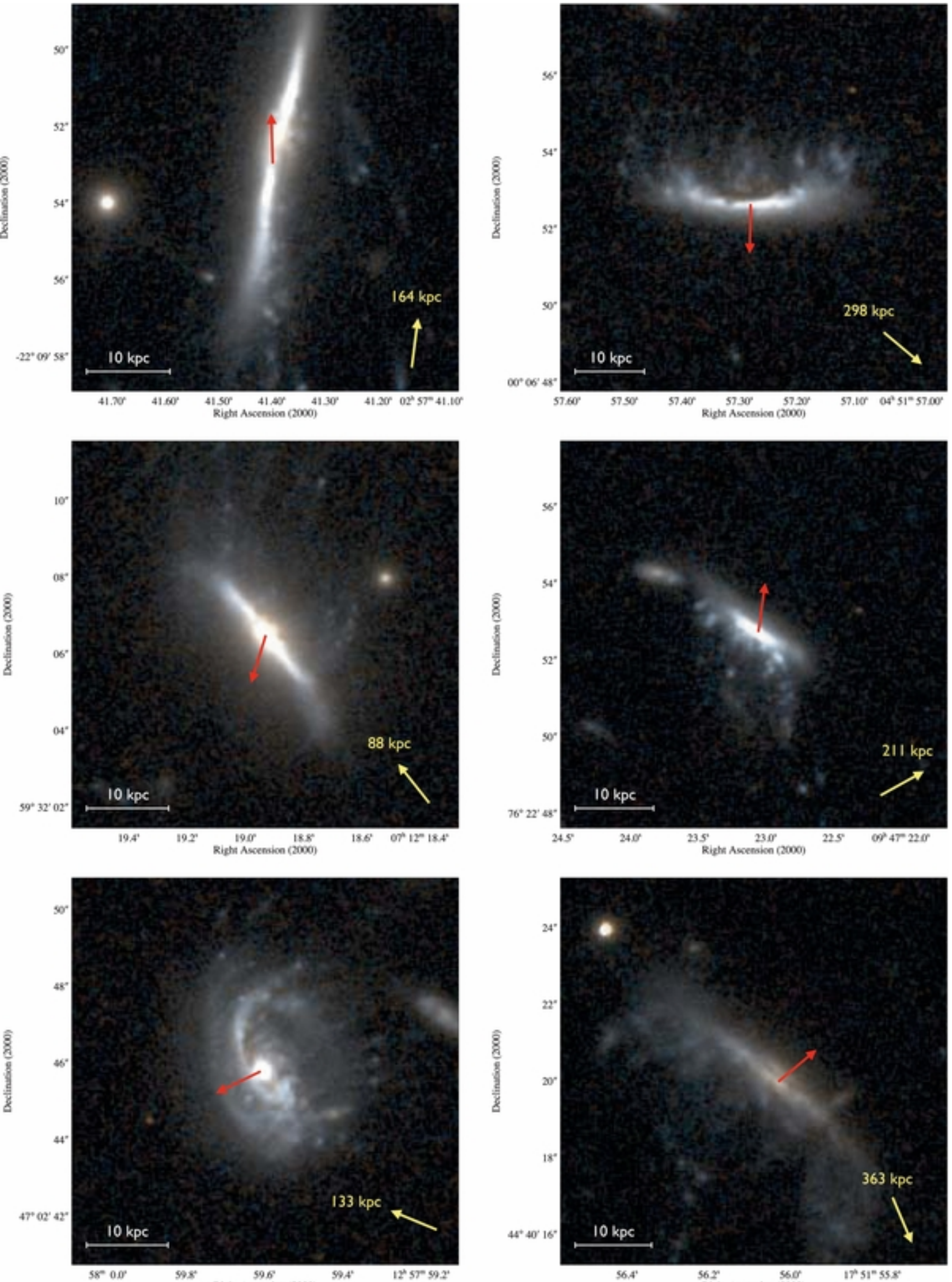
FIG. 4H— Same as Figure 4A, but of GMP3779.

peak ram pressure ~100x stronger than Virgo



RB199 merger remnant now being r.p.s.

Yoshida+08



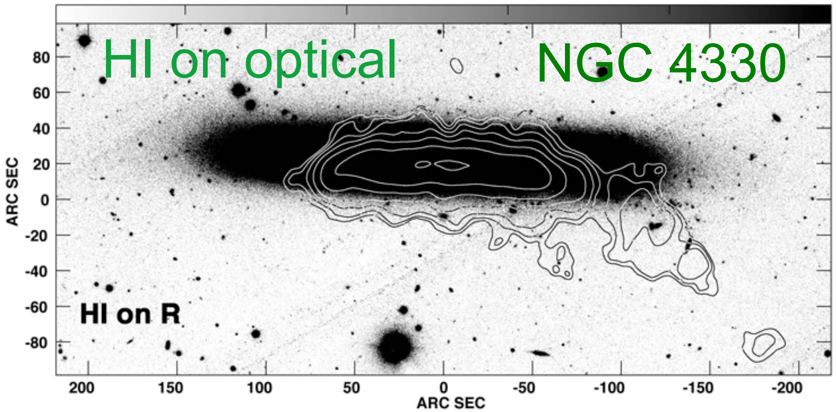
RPS of massive spirals in massive clusters at z=0.3-0.4

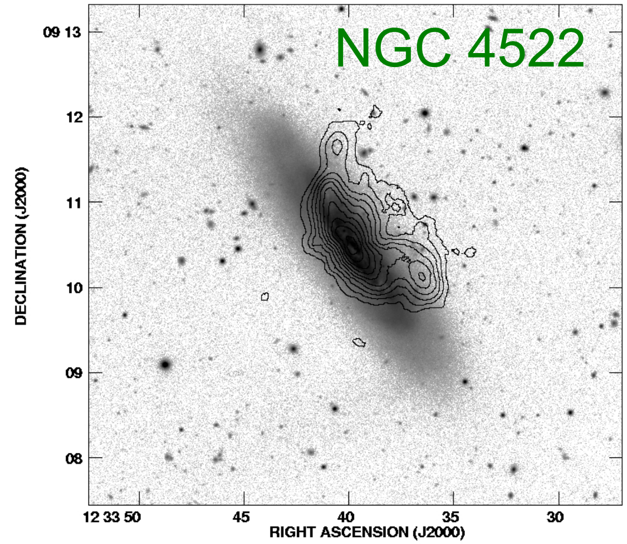
HST
F606+F814

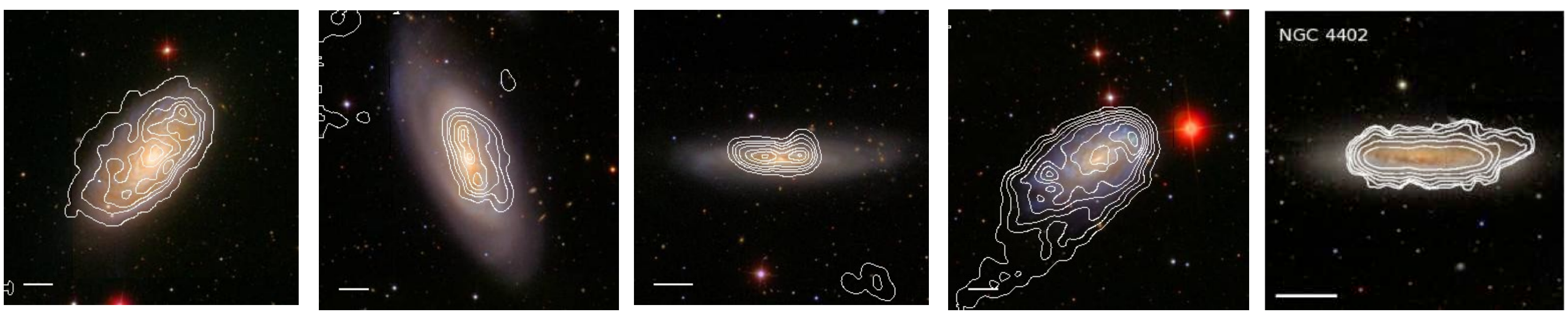
Ebeling+2014

Diagnostic of active ram pressure stripping: Gas vs. Stars

Virgo Cluster
VIVA survey
~50 spirals







Truncated gas disks with normal stellar disks & one-sided extraplanar gas features; outside-in gas removal

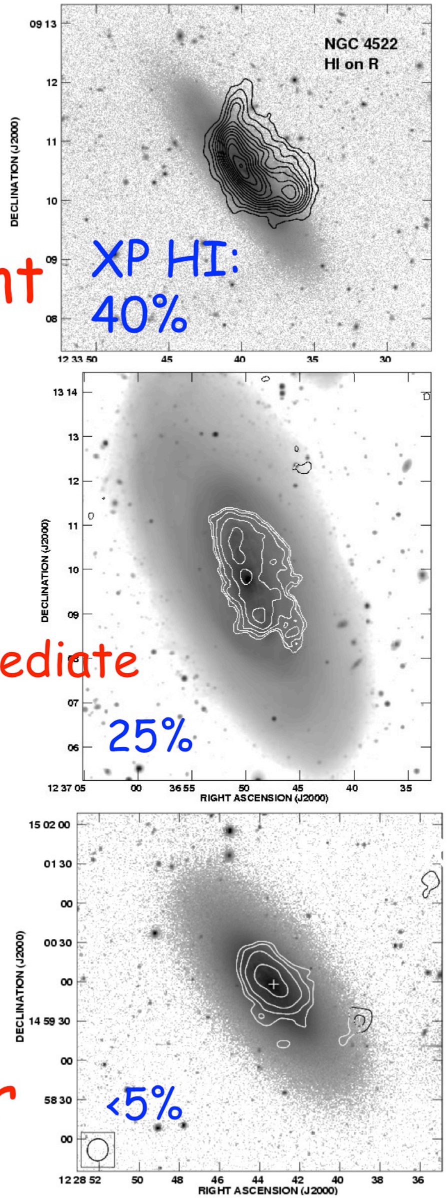
Abramson+11
Kenney+04
Chung+09

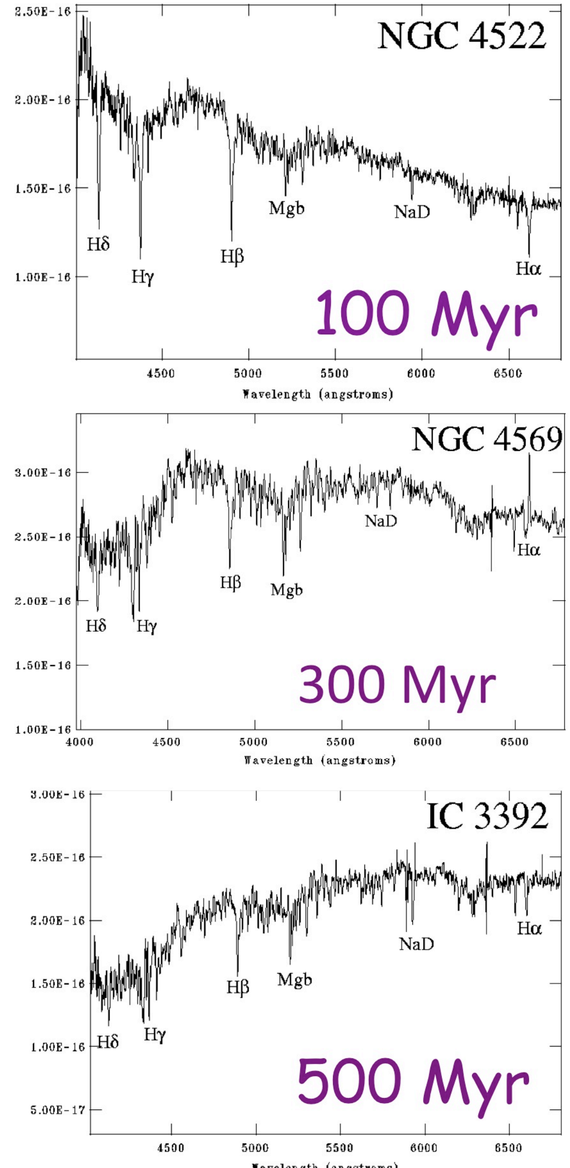
Time Sequence of Stripping

recent

intermediate

older





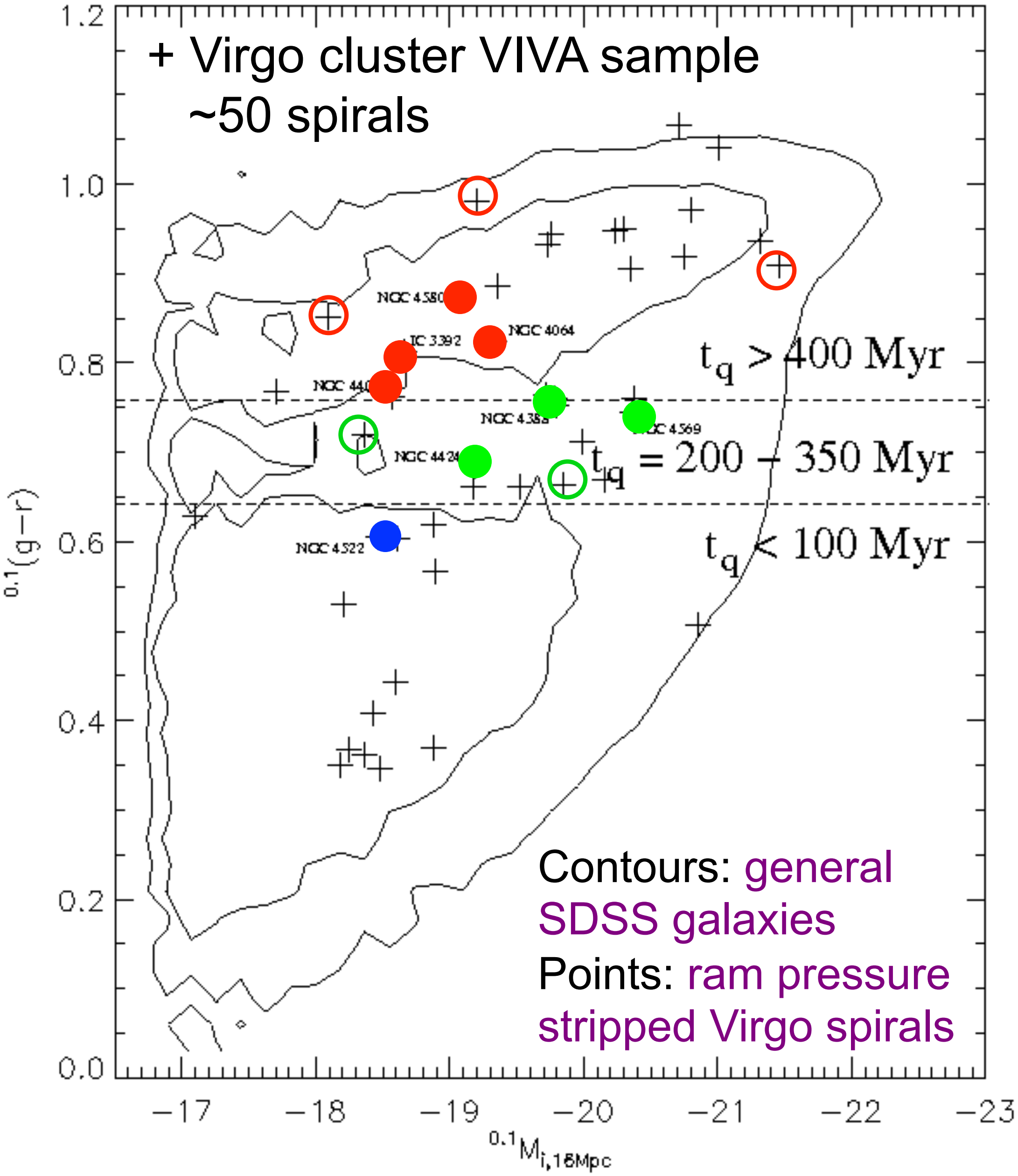
outer disk

HI on R

WIYN Optical spectra

SDSS Optical image

Ram pressure stripping & color evolution



Galaxies with good evidence for RPS:

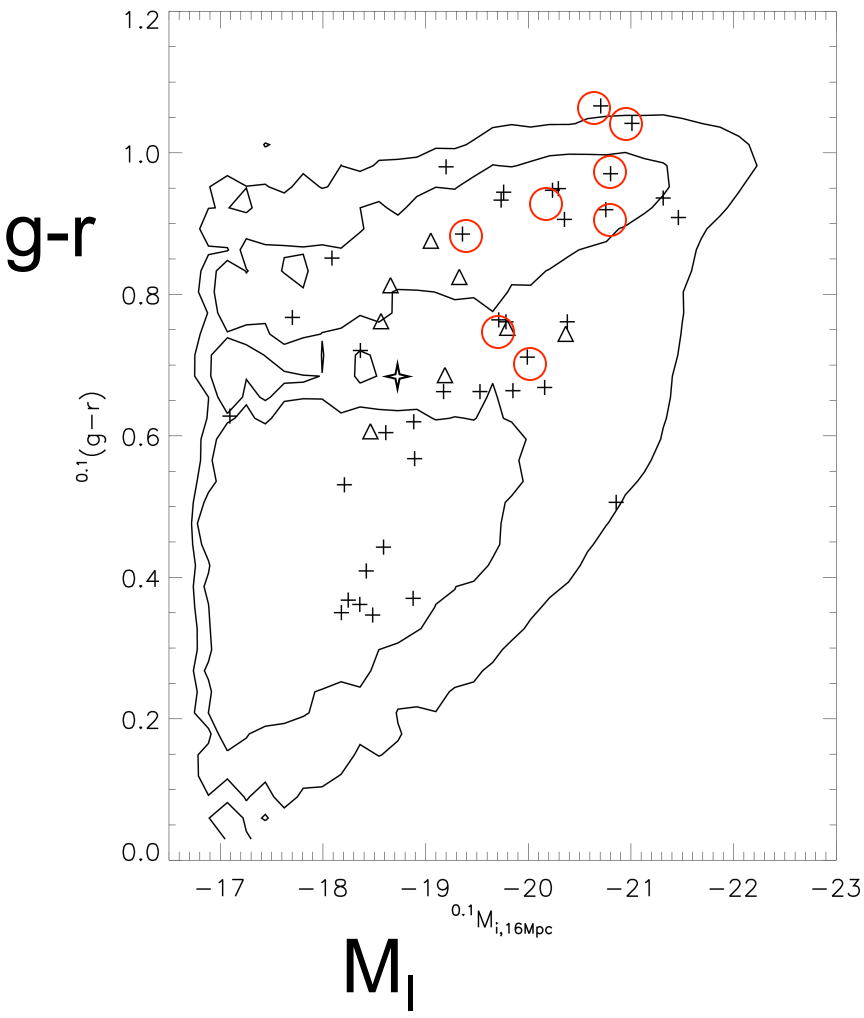
Quenching times from spectra

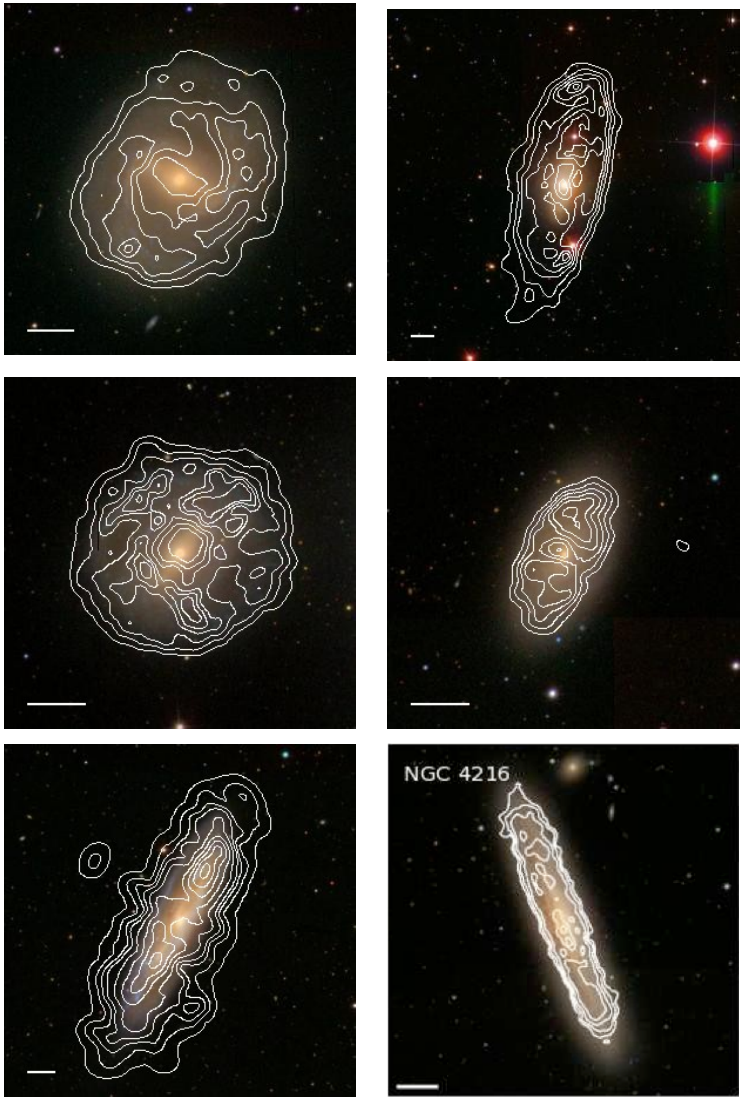
No spectra

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

Anemic galaxies: gas lost thru "starvation"?

Gas accretion to inner disk cut off by tidal forces or gas stripping





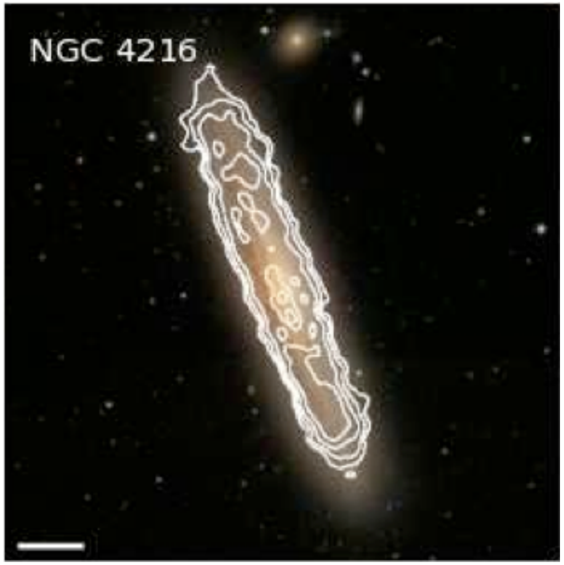
Starvation

removal of gas from outer galaxy disk or halo
so that it can't accrete to inner galaxy
can be caused by either tidal or rp stripping

starvation naturally accompanies incomplete rps

rps removes gas directly from outer galaxy, causing:

- immediate outer galaxy quenching
- gradual inner galaxy quenching by starvation



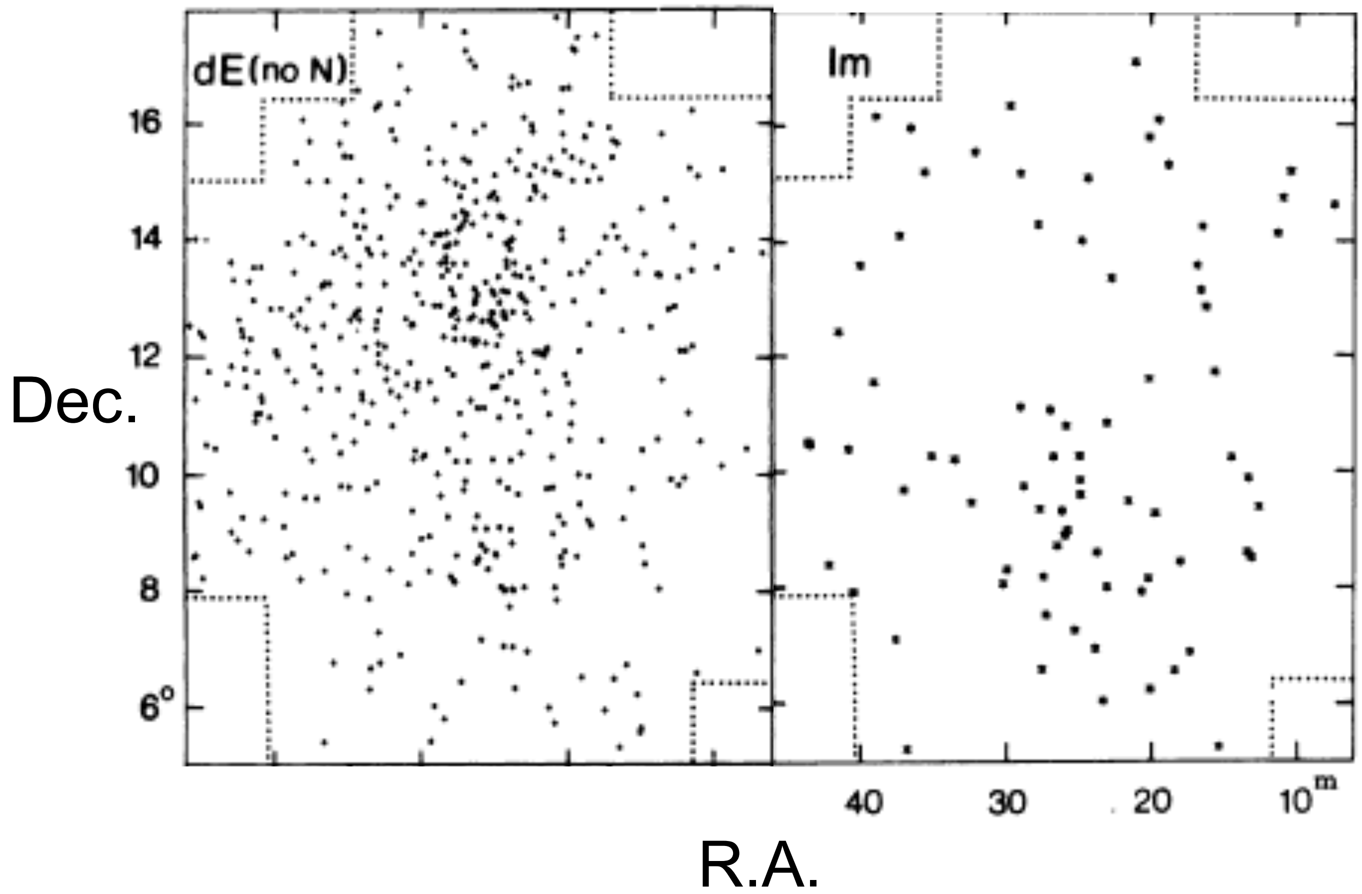
Virgo spiral NGC 4216
Weak star formation throughout disk (anemic)
On red sequence
No HI beyond optical diameter
Inner disk probably starved by past rps of outer galaxy

How does the universe turn dwarf irregular galaxies into dwarf elliptical galaxies?

I Zwicky 18: a dwarf irregular with lots of gas and star formation

NGC 185, a dwarf elliptical with no gas or star formation

Virgo Cluster Dwarfs

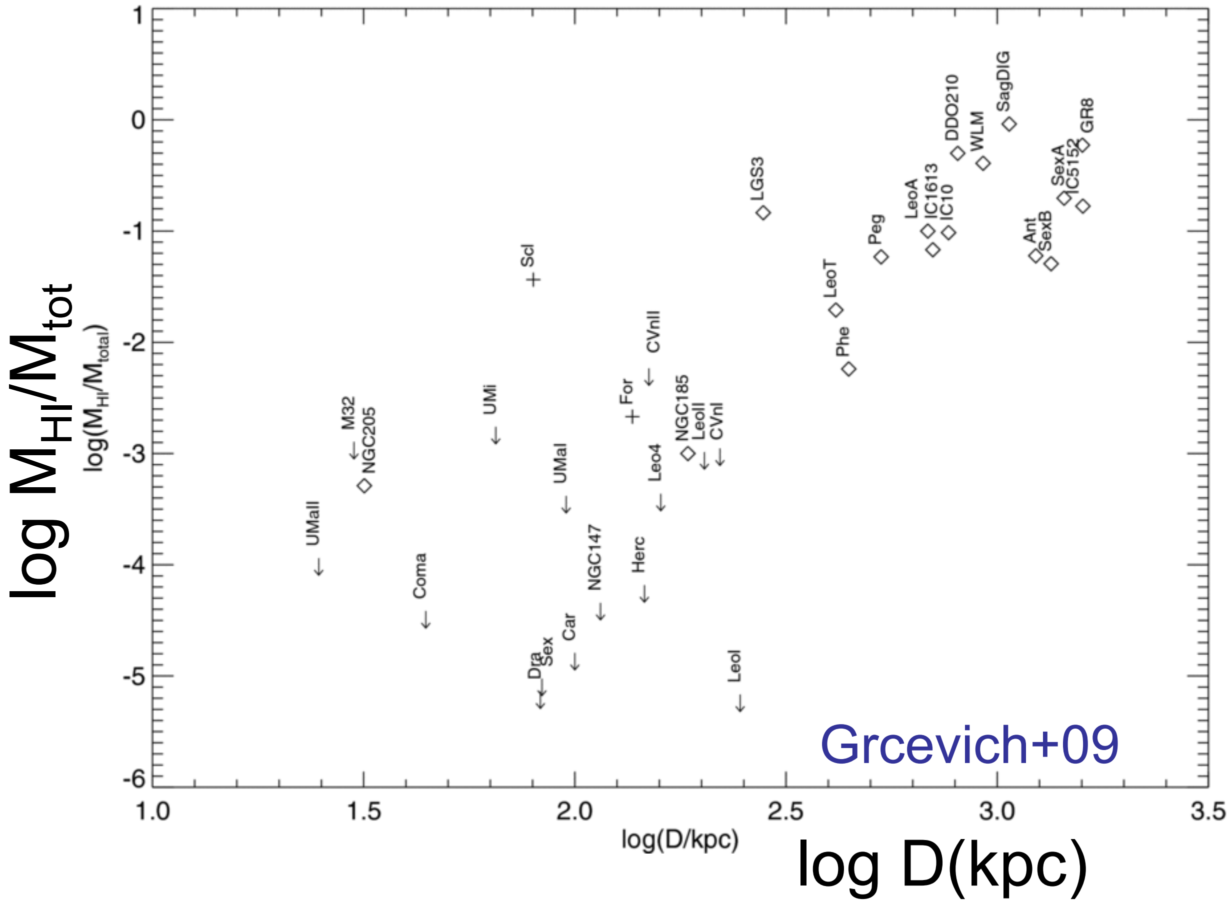


Binggeli Sandage & Tammann 1987

dI's least concentrated
dE's most concentrated

→ *Something transforms dwarfs from dI->dE in the cluster center*

Local Group Dwarfs: HI content vs. distance from MW or M31

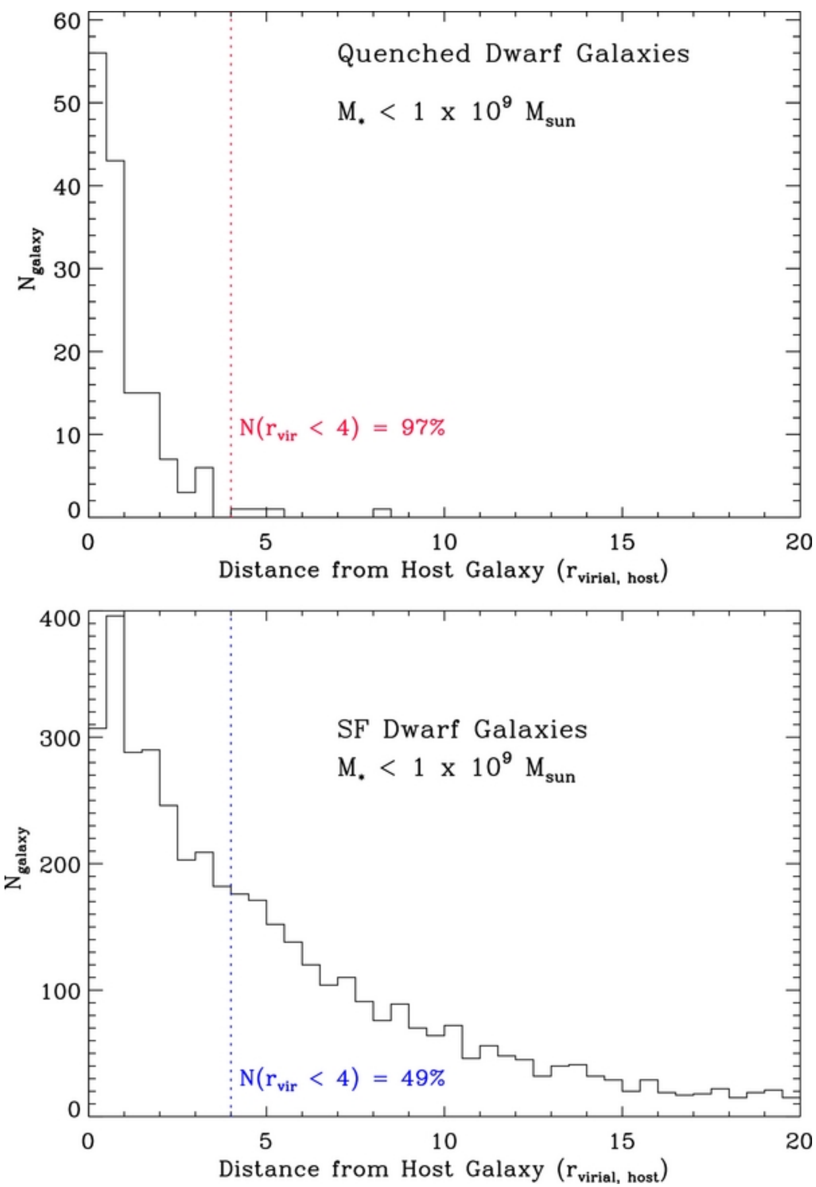


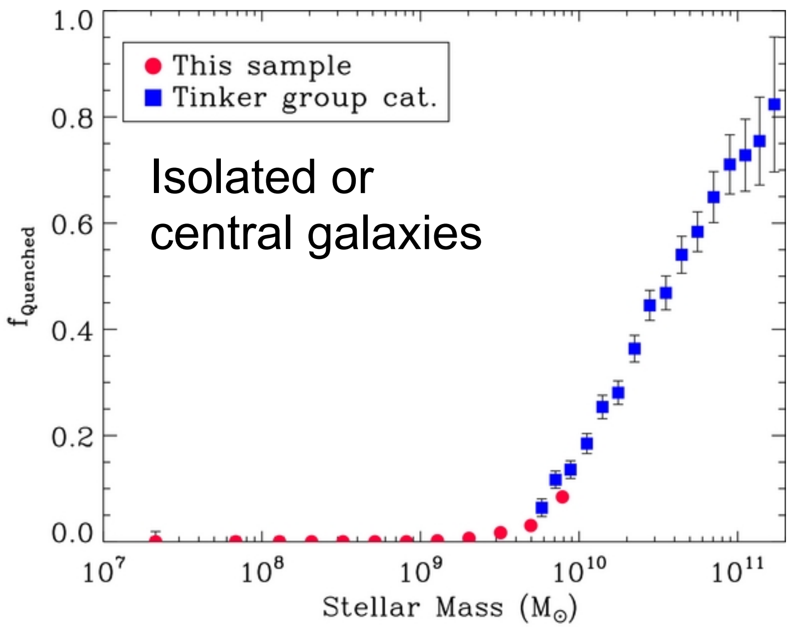
~All dwarfs D>300 kpc are gas-rich

~All dwarfs D<300 kpc are gas-poor

Dwarfs (spirals) get their gas r.p.stripped by the gaseous halo of their host galaxy (cluster) – just as spirals get their gas r.p.stripped by the gaseous halo of their host cluster

No isolated quenched dwarfs





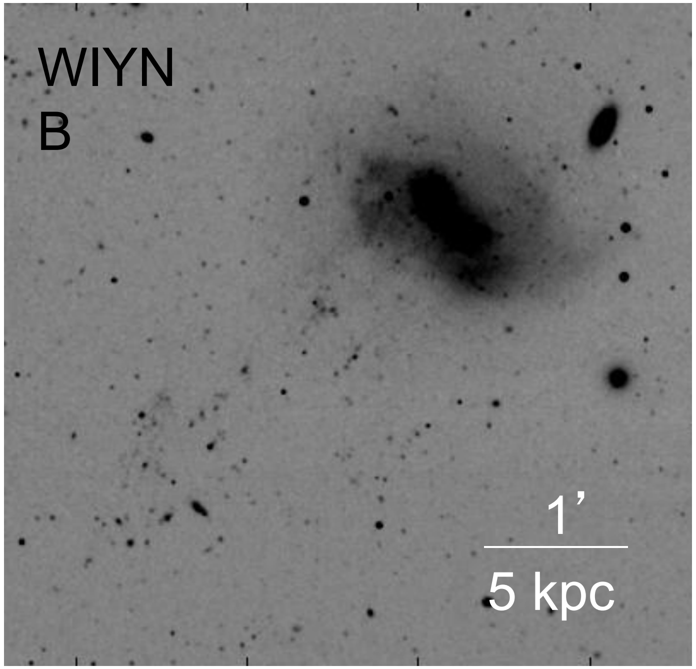
SDSS galaxies

Geha+12

There are no isolated quenched dwarf galaxies in mass range $10^7\ M_{sun} < M_{star} < 10^9\ M_{sun}$

Quenching mechanism works only near a massive central galaxy

Virgo dwarf IC3418: 1-sided tail of young stellar associations & linear streams



Chung+09; Hester+10; Fumagalli+11; Kenney+14

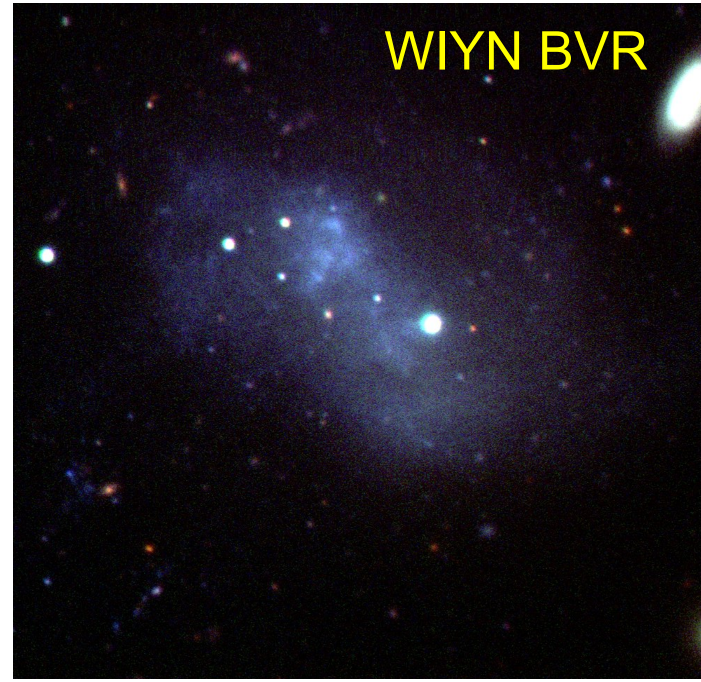
We are probably witnessing the transformation of a dwarf irregular galaxy into a dwarf elliptical galaxy by complete ram pressure stripping

Main body of IC3418

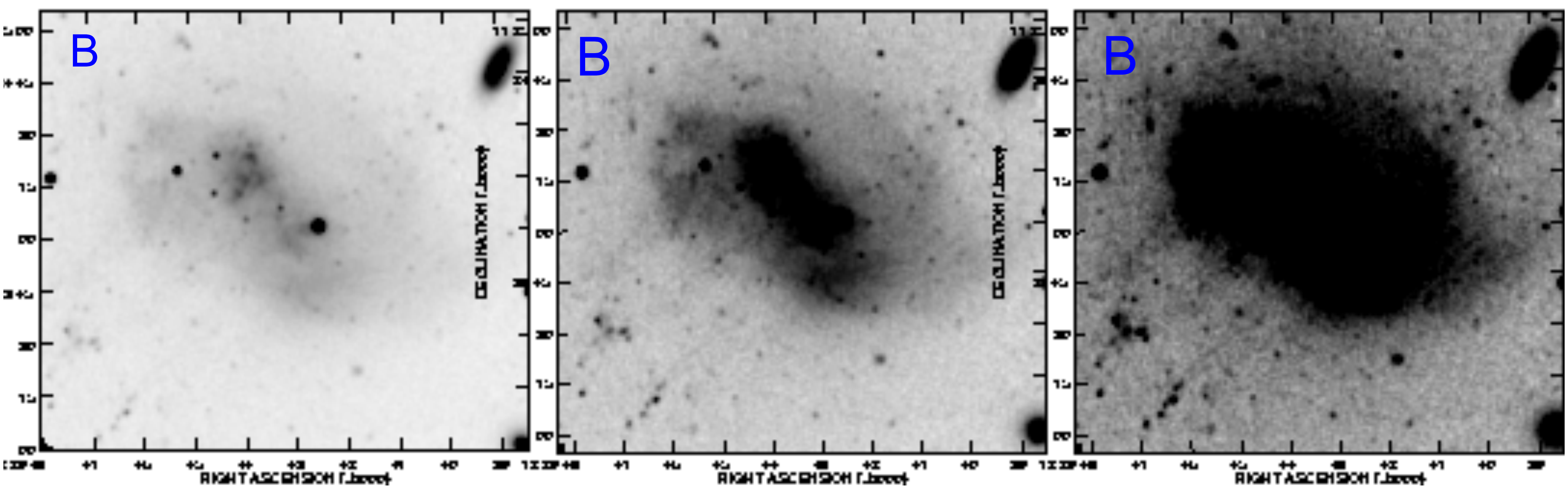
inner R<30" = 2 kpc
Morphology: substructure
=> recent star formation

outer R=30"-1' = 2-4 kpc
Morphology: spiral structure,
"Plume" of extra blue light on tail side

Radial light profile: exponential, just like nearly all other dIs and dEs



Kenney+2014



Smoothed "Deep" R-band image

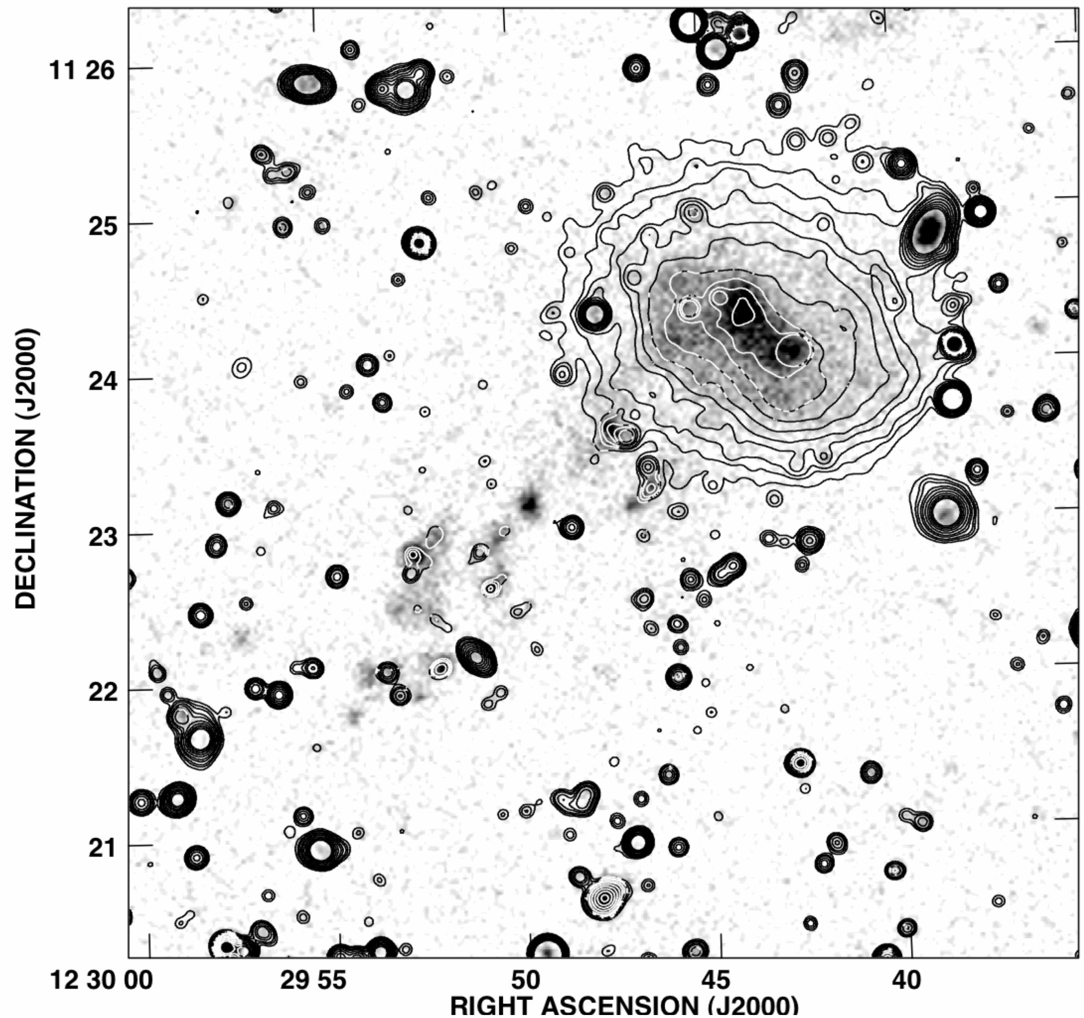
- Outer isophotes fairly regular => not (strongly) tidally disturbed
- Tail has no old smooth stellar component

(to μ_R = 26.5 mag arcsec^{-2})

only gas & young stars!

IC3418

WIYN Smoothed R on NUV

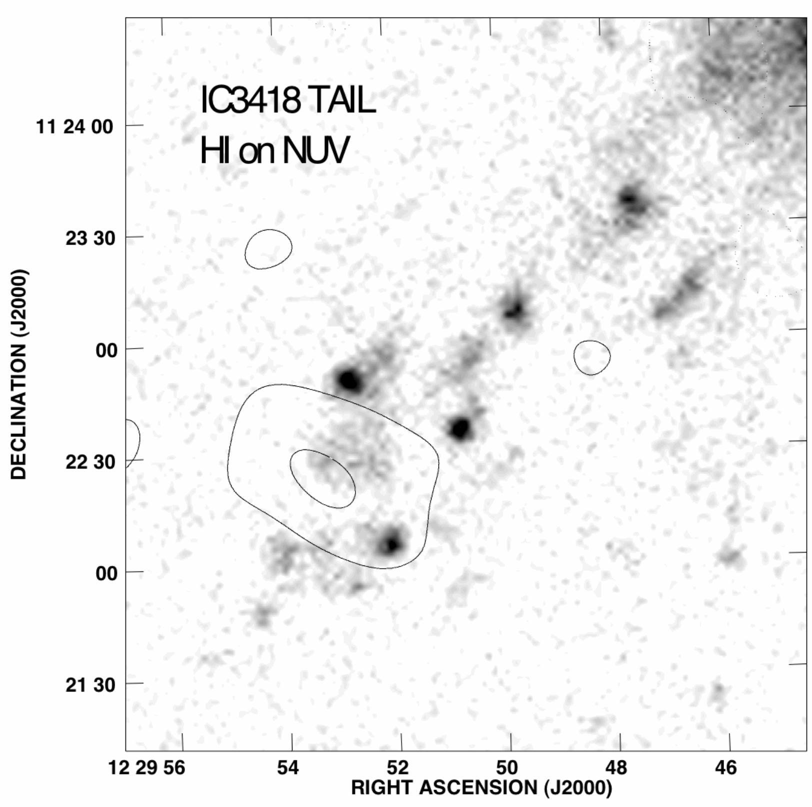


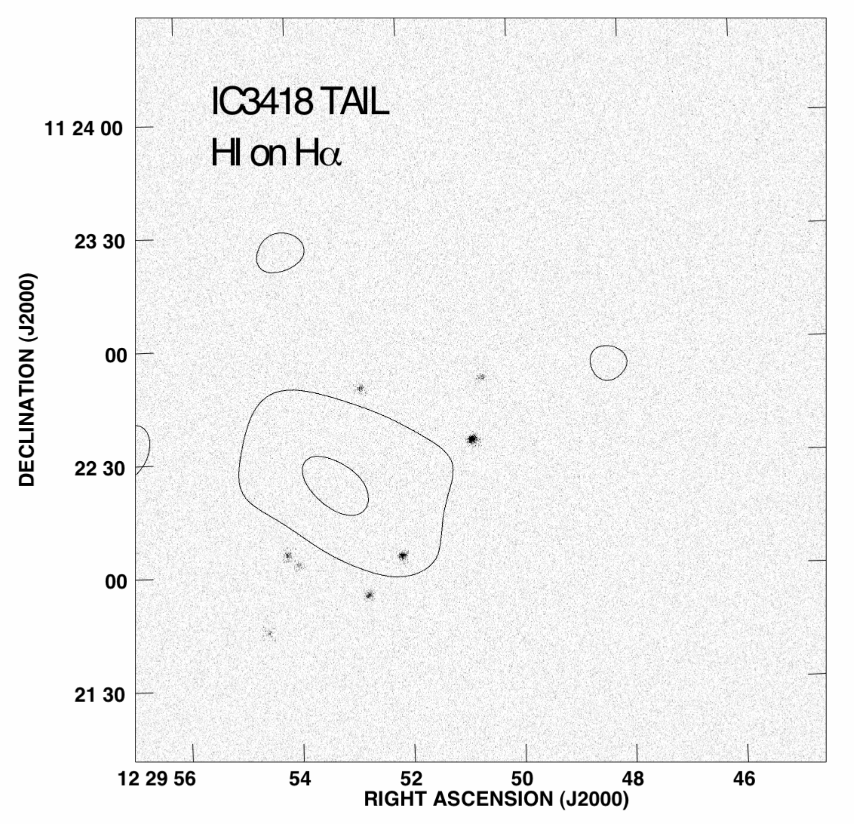
Kenney+2014

How we know tail is formed by ram pressure and not tidal interaction or starburst outflow

- Stellar body of galaxy appears undisturbed
- Tail is straight, one-sided, centered on galaxy center, composed of gas & young stars but not old stars
- “Fireball” phenomenon requires ram pressure

HI and Hα: none in body, a little in outer tail



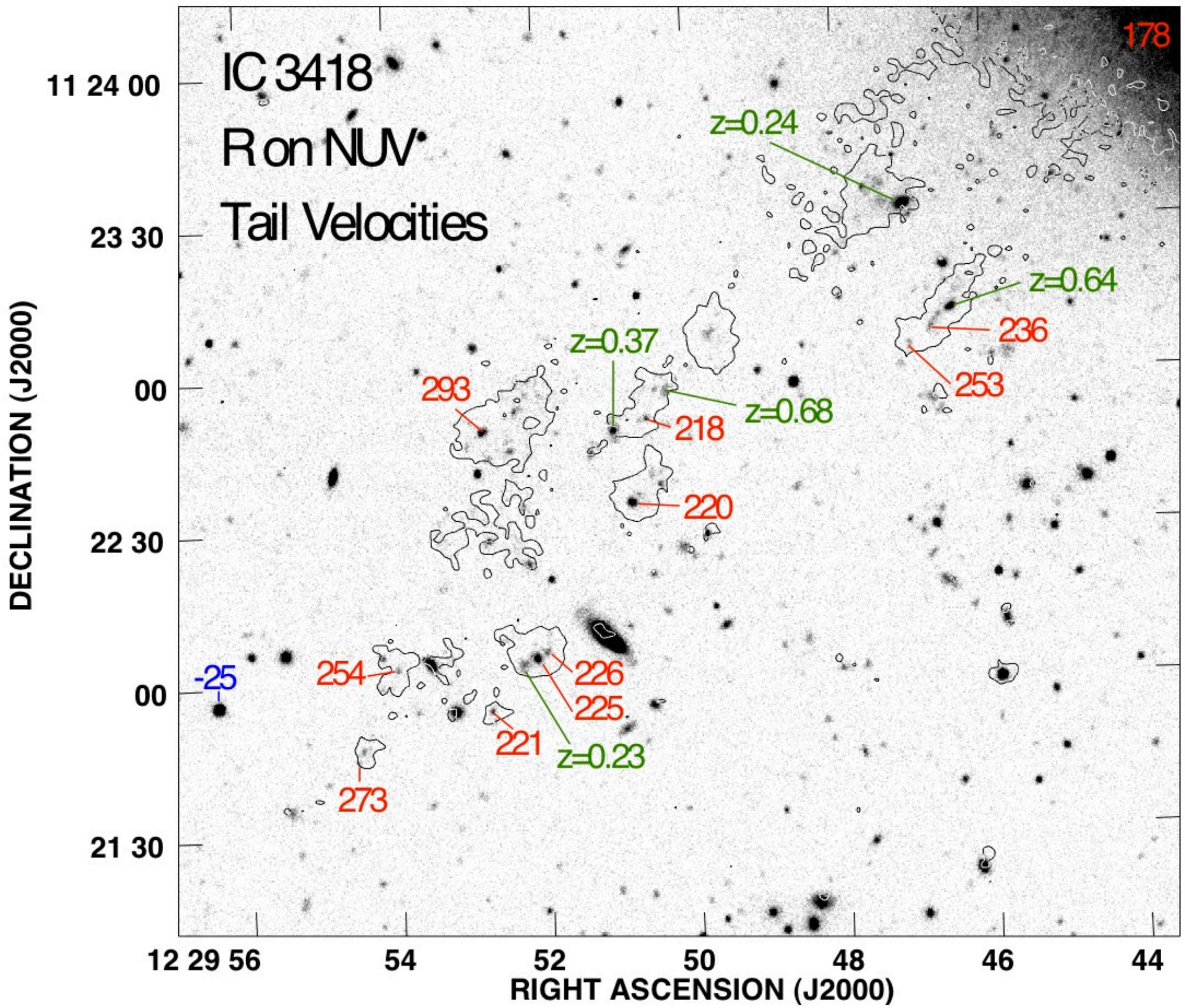


VLA VIVA survey data
HI detected (5σ) in only
one 10 km/s channel
Peak $\Sigma_{HI} = 3 \times 10^{19}$ cm^{-2}
$M_{HI} = 4 \times 10^{7}\ M_{sun}$

WIYN Hα image
8 HII regions in outer half of tail
$L_{H\alpha} = 2 \times 10^{38}$ erg/s
SFR ~ 0.002 M_{sun}/yr

Kenney+2014

Velocities of HII regions in tail from Keck DEIMOS spectroscopy



Tail HII regions V=+40-115 km/s wrt galaxy

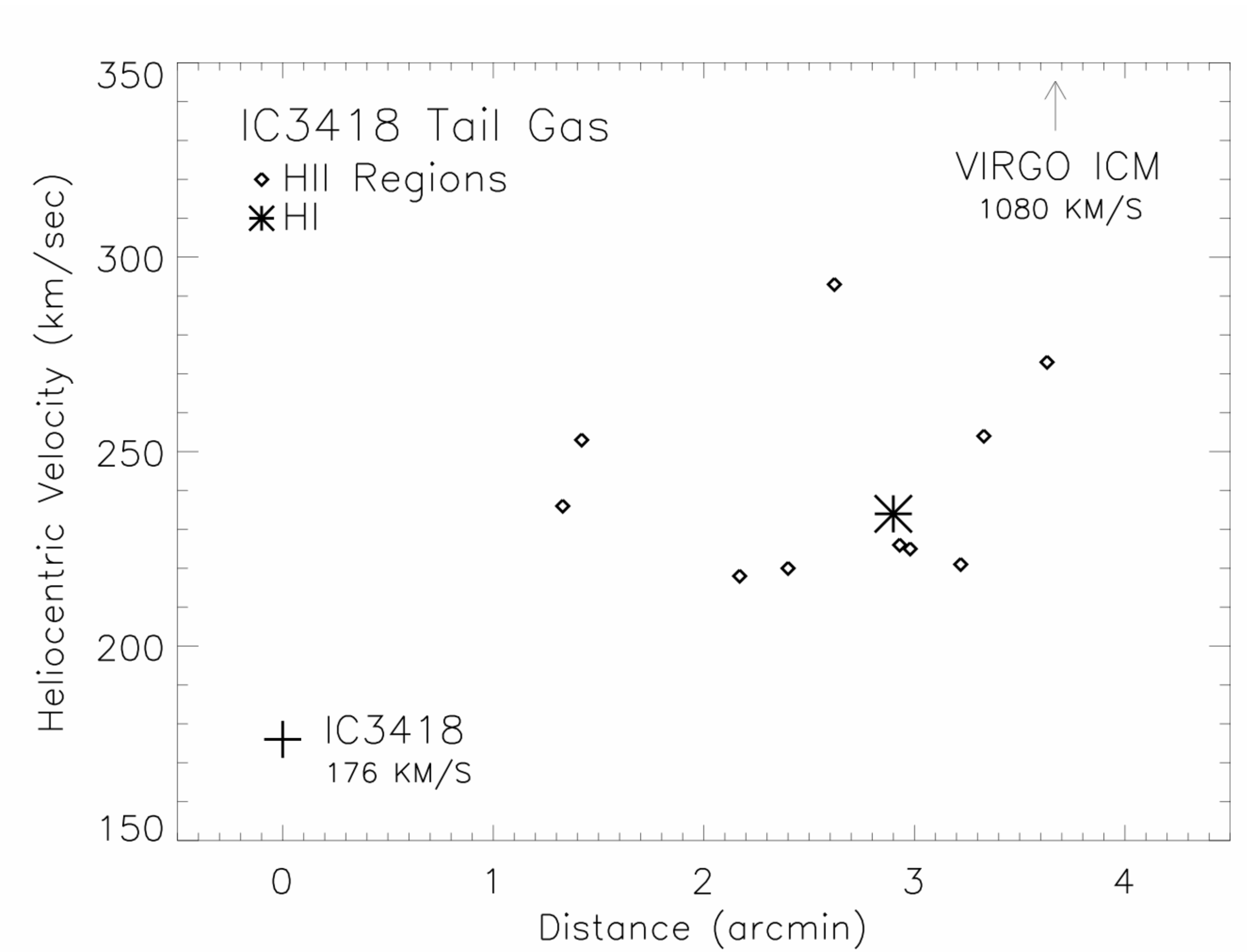
Redshifted, toward ICM velocity, as expected for ram pressure

Tail HII regions close to galaxy velocity of 170 km/s, *do not extend to cluster velocity of 1070 km/s*

In simulations tail extends to ICM velocity – tail in IC3418 may be much longer but only inner part has star formation

Kenney+2014

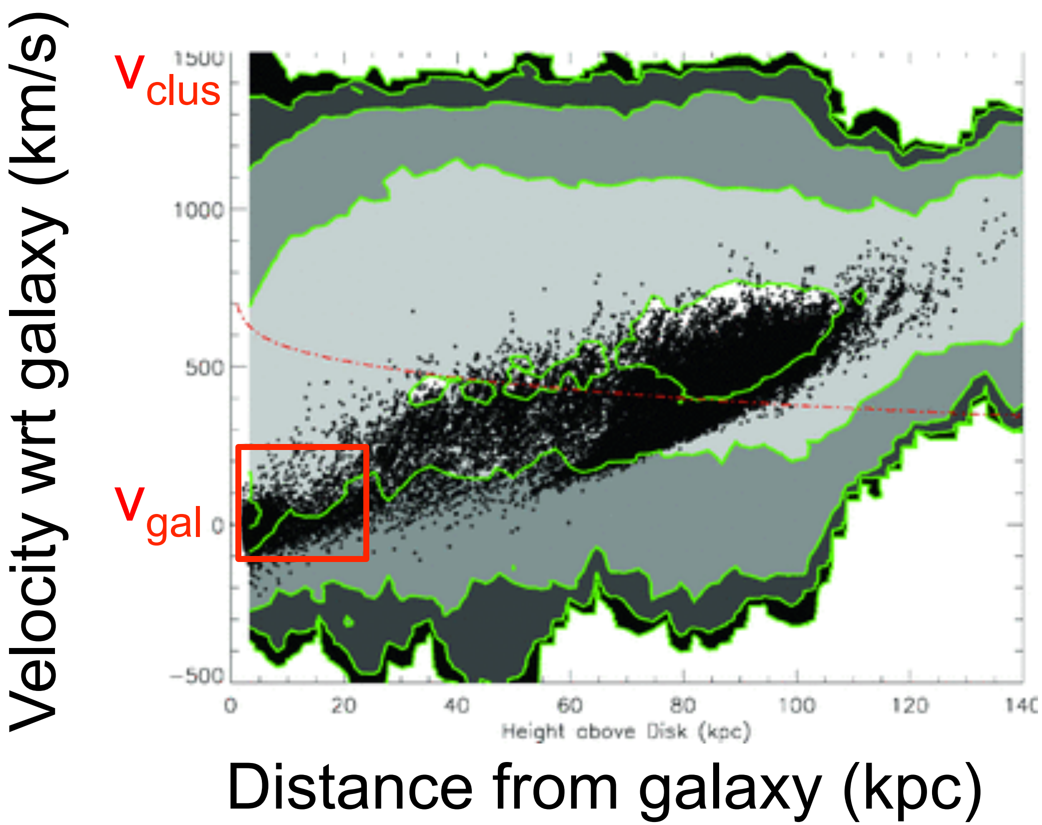
Gas kinematics in the tail



Velocities modestly (by 40-115 km/s) offset toward cluster velocity
Modest velocity gradient with significant scatter

Kenney+2014

Kinematics of gas in simulated tail



Gas density & velocity vs. distance from galaxy

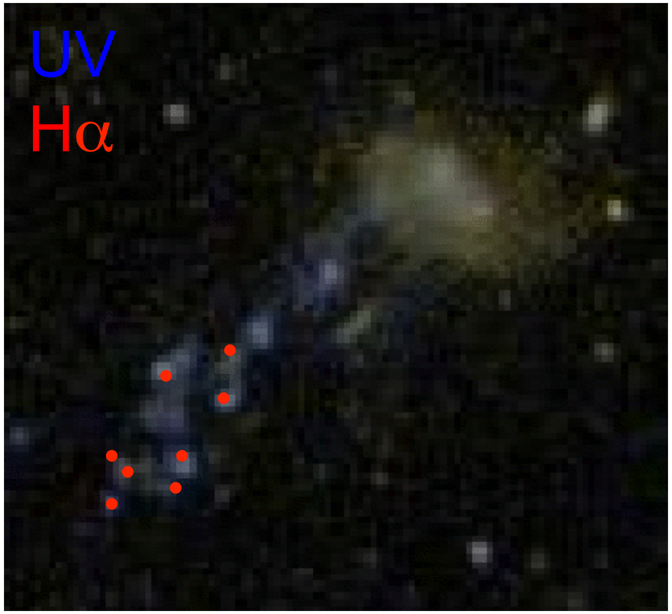
Contours: gas density
Points: stars

250 Myr after ICM wind hits disk (constant ram pressure)

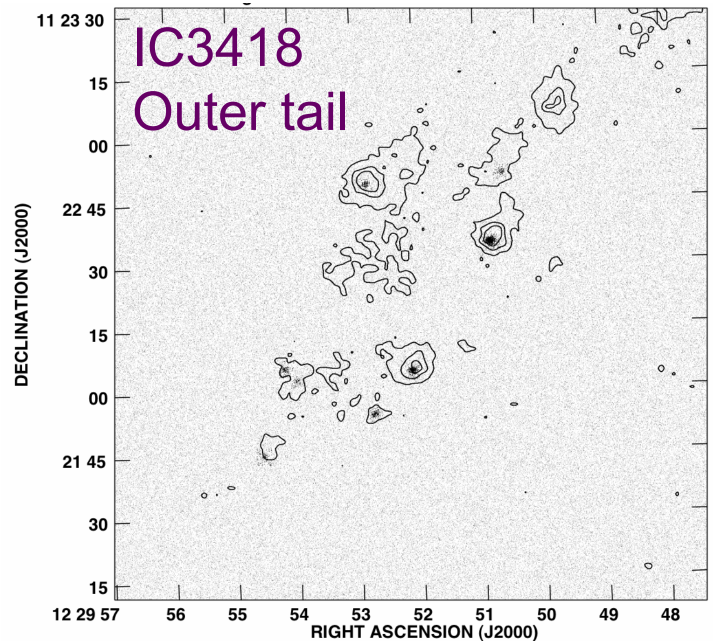
Tonnesen & Bryan 2012

Velocity gradient & scatter similar in IC3418 & simulations
But detected tail much shorter in IC3418 → *True tail probably much longer but conditions unsuitable for star formation*

“Fireballs” in Tail of IC3418

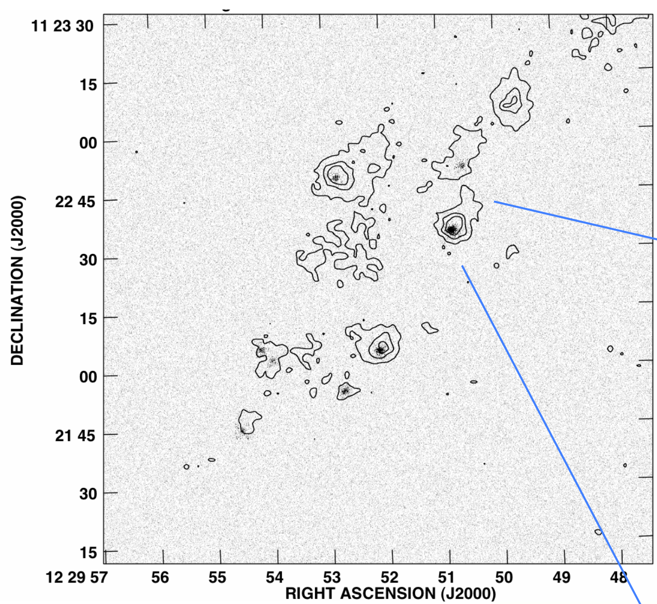


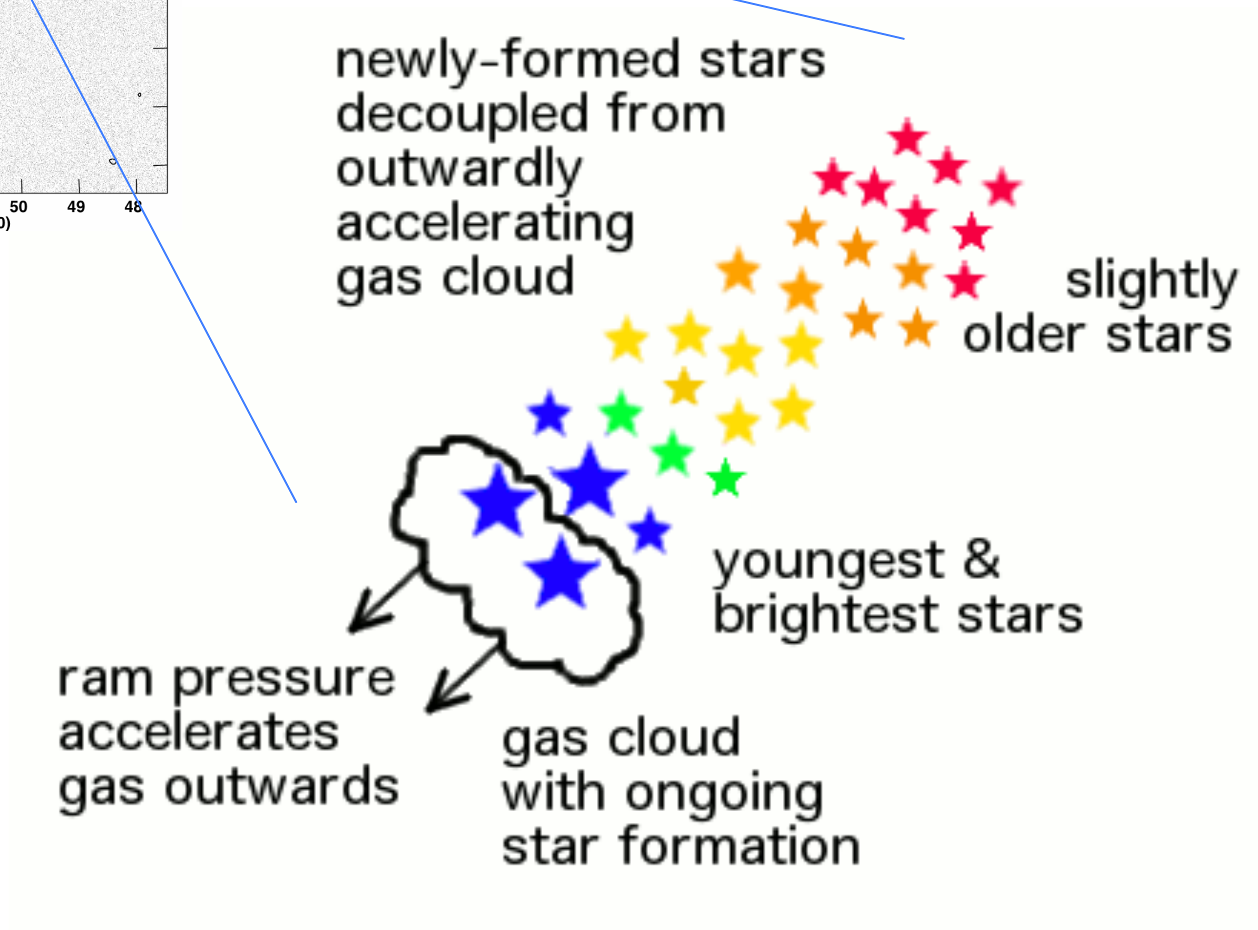
Hα on NUV



- 3 brightest outer tail UV sources have head-tail morphology with HII region at head (“fireballs”)
- Gas and newly-formed stars (HII regions) at outermost head of linear stellar streams
- Ha peaks offset outwards from UV peaks by 1-2” = 75-150pc
- Ram pressure continues to accelerate gas outwards, leaving behind trails of newly formed stars which decouple from the gas since they don’t feel ram pressure

Fireball model





“Fireballs” in Coma cluster galaxy RB199

(massive merger remnant)

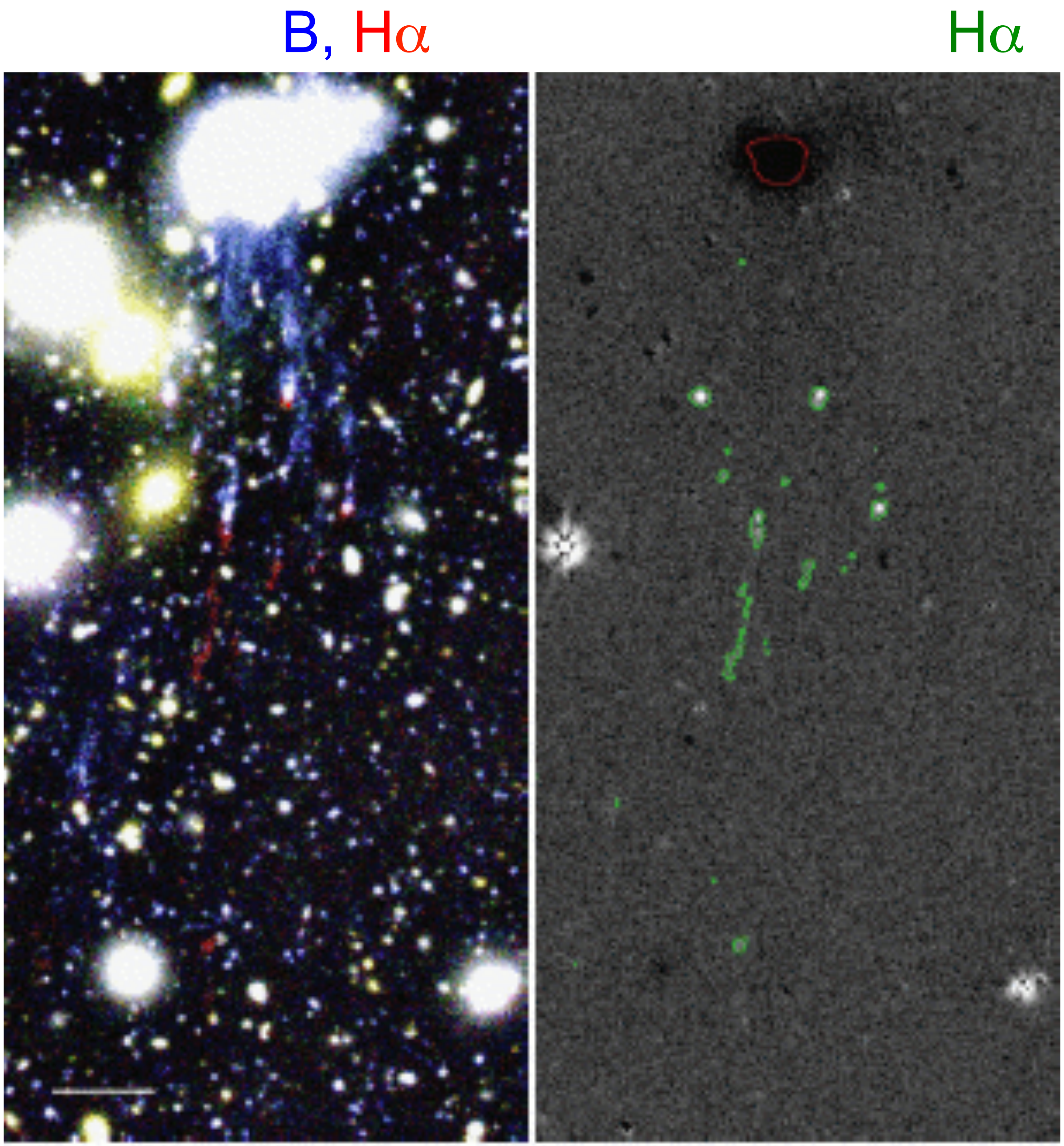


FIG. 4L.— Same as Figure 4A, but of GMP4060.

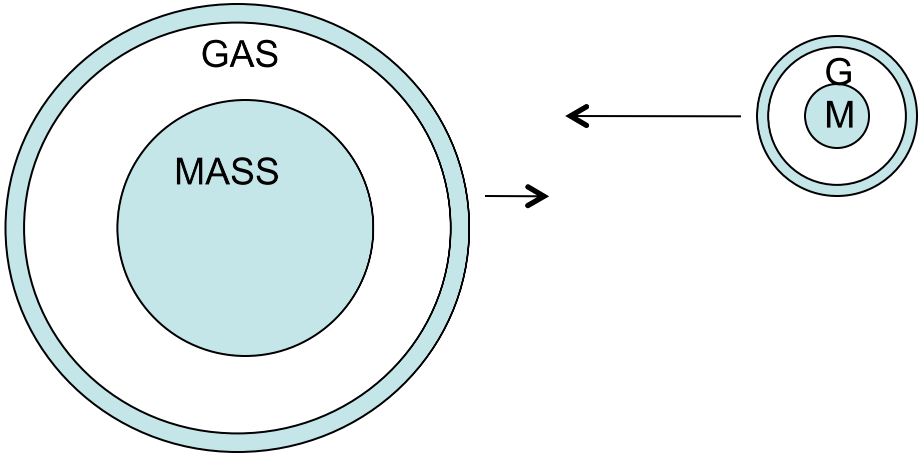
Yoshida+08 ; Yagi+10

Inner tail: B only

Outer tail: B+Hα

Gas closer to galaxy has been stripped downstream

When smaller things fall into bigger things….



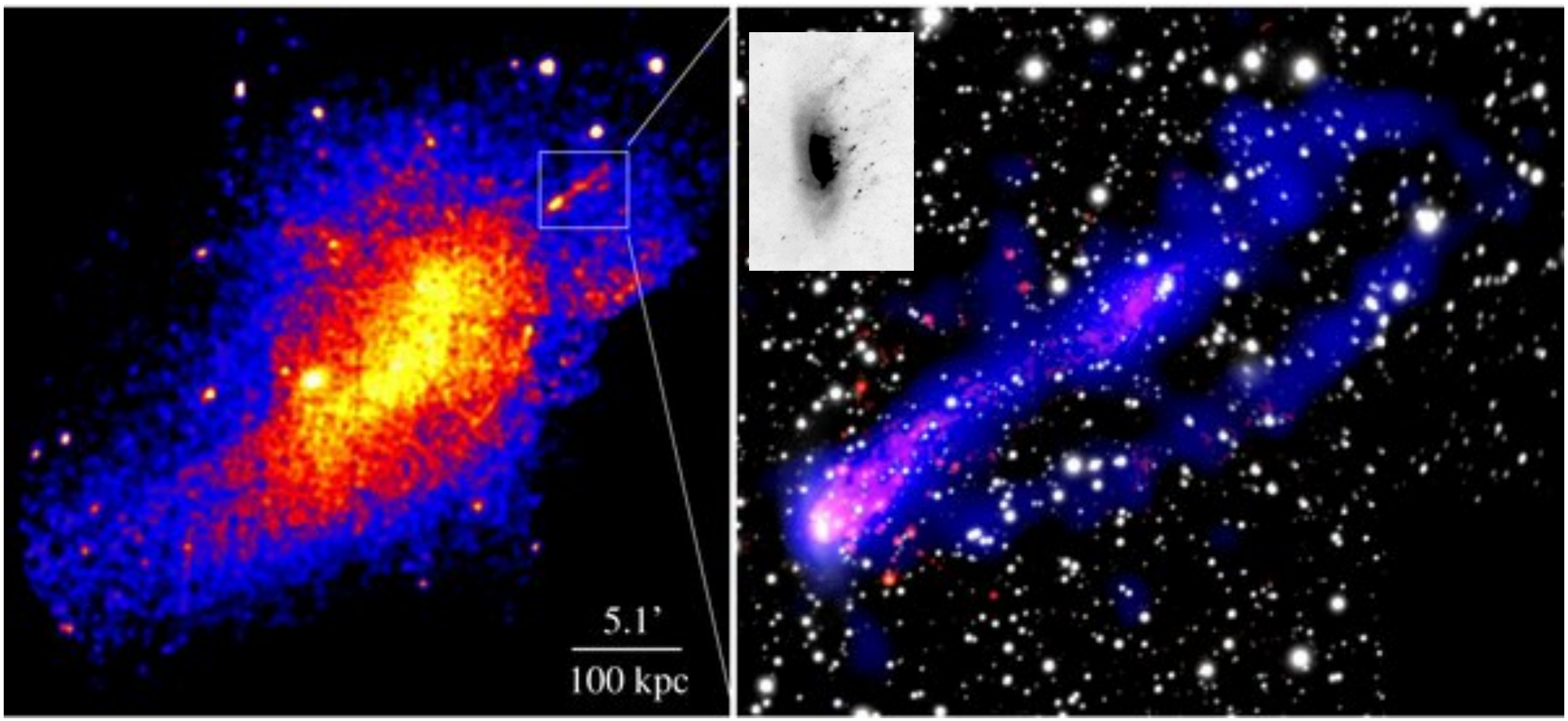
…expect BOTH a mass-mass (i.e. tidal) AND a gas-gas (e.g. r.p.s.) interaction

…small thing loses its gas to big thing by r.p.s.

…small thing loses outermost stars and gets remaining stars dynamically heated by tidal interaction

BOTH MUST happen to some degree, but relative strength of 2 effects varies, and timing of 2 effects generally very different

Spectacular ram-pressure stripped 70–kpc X-Ray tail in ESO137-001 (Norma cluster $M \sim 10^{15}\ M_{sun}$)



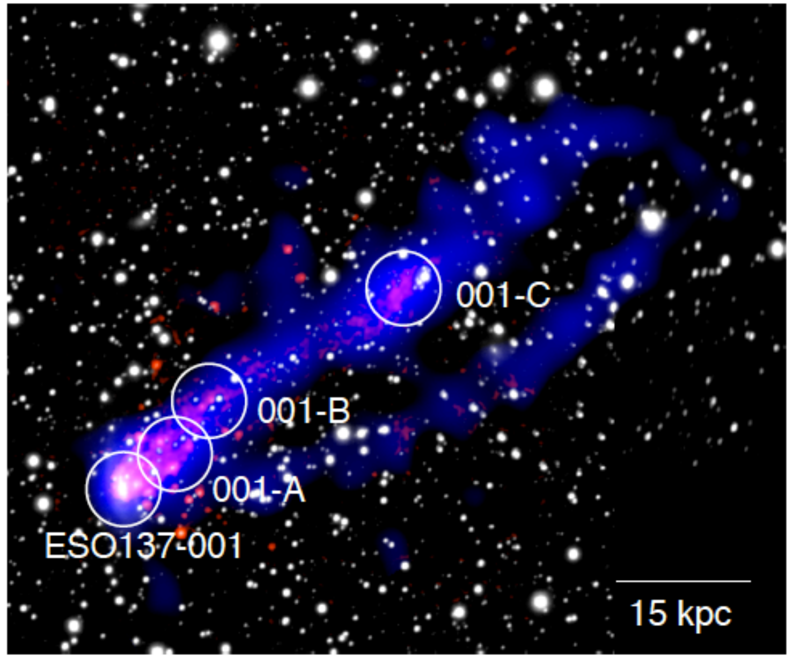
Blue: Chandra X-Ray 0.6-2 keV
Red: SOAR Hα (Sun+10)
Inset: Optical (Woudt+08)

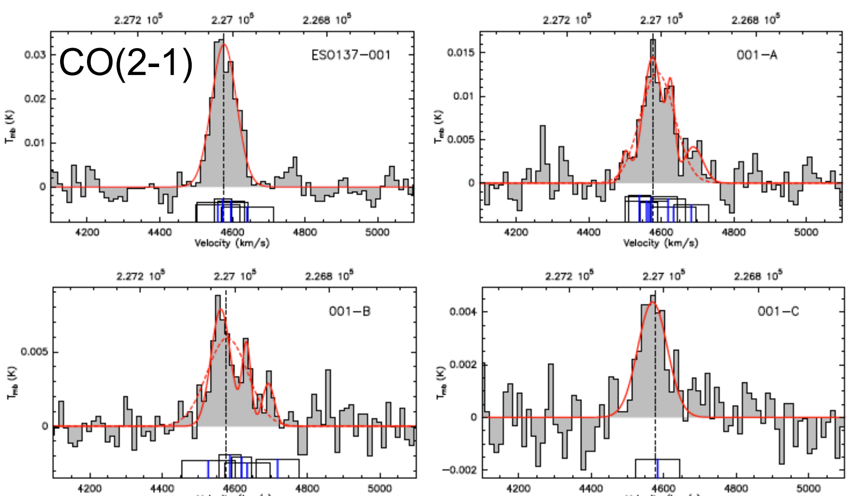
CO in Stripped Gas Tail of ESO137-001

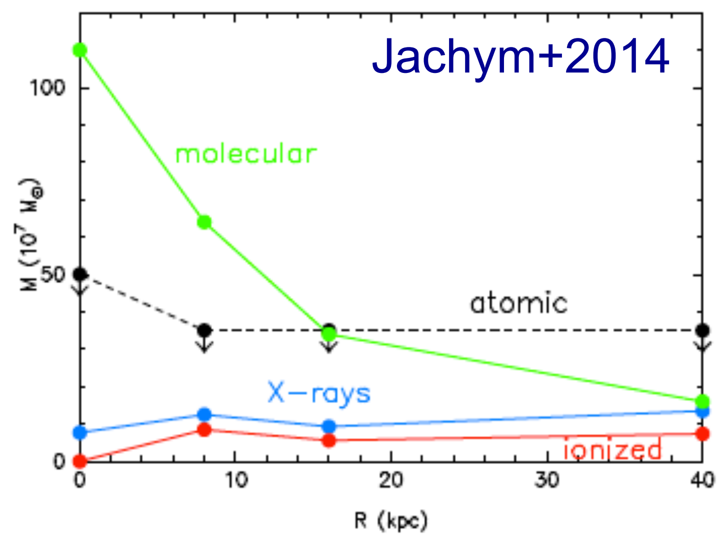
Blue: Chandra X-Ray
Red: SOAR Hα
(Sun+10)

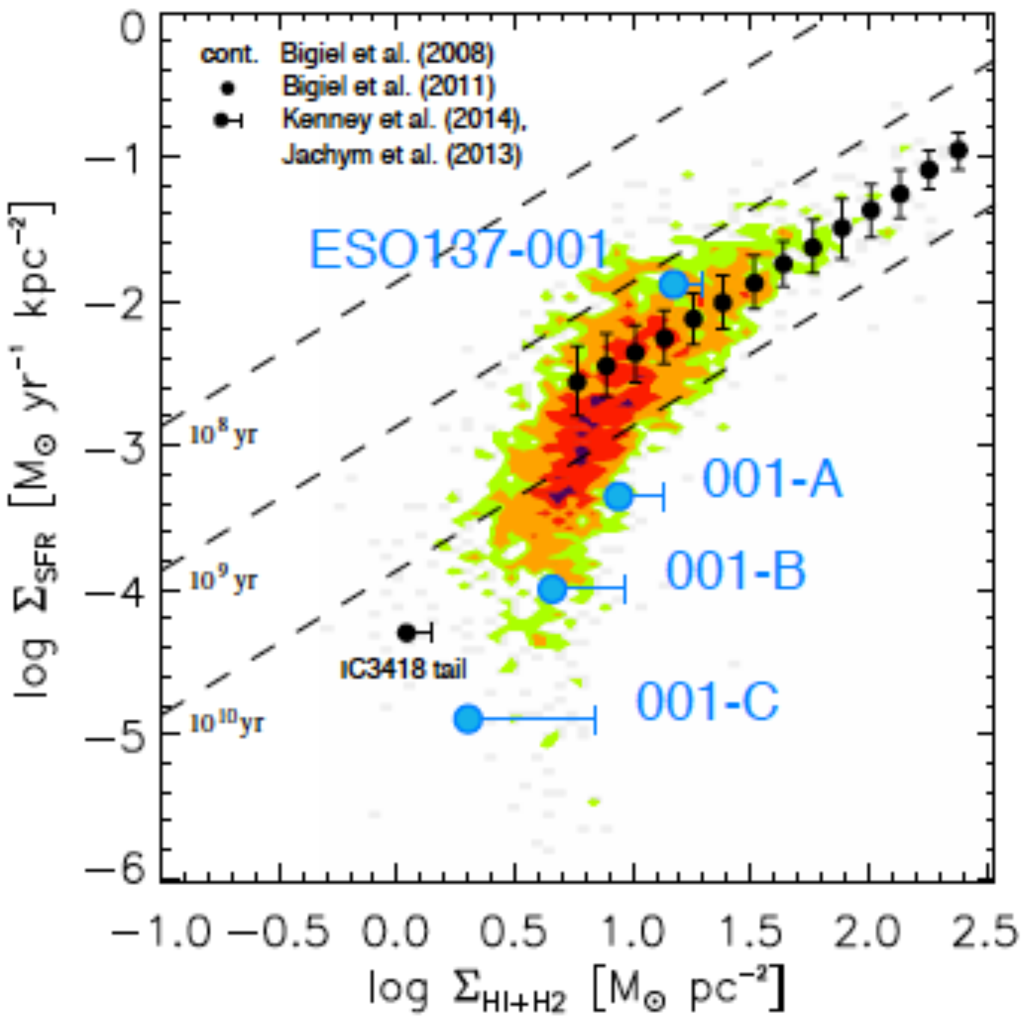
Circles: APEX CO(2-1)
(Jachym+14)

Tail has:
~10^9 M_{sun} hot gas (X-Ray)
~10^9 M_{sun} cold gas (CO)





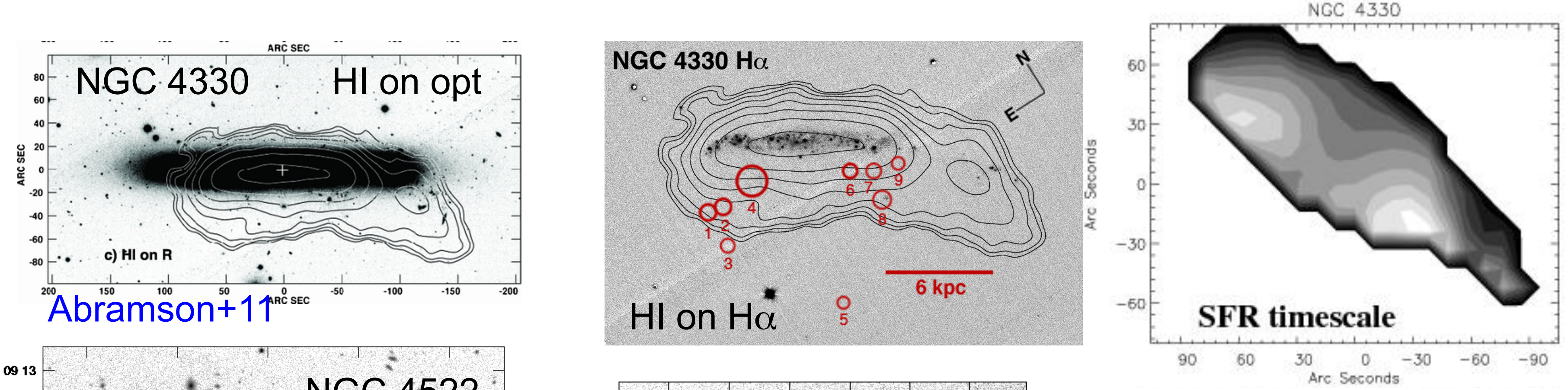


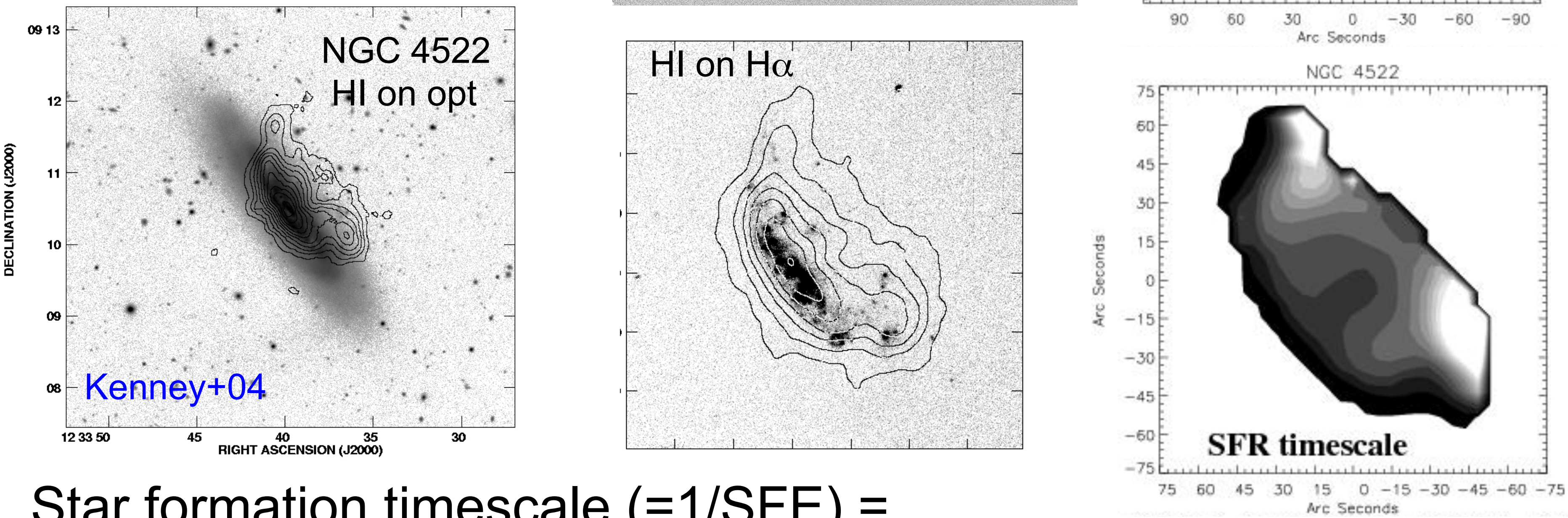


Jachym+2014
similar results Vollmer+2012

Star formation timescale (=1/SFE) $=T_{gas} = M(HI+H_2)/SFR$
is 2-50x longer in stripped extraplanar gas than in disks
→ Most stripped gas doesn't form stars but joins the ICM

Inefficient star formation in stripped gas





Vollmer+12

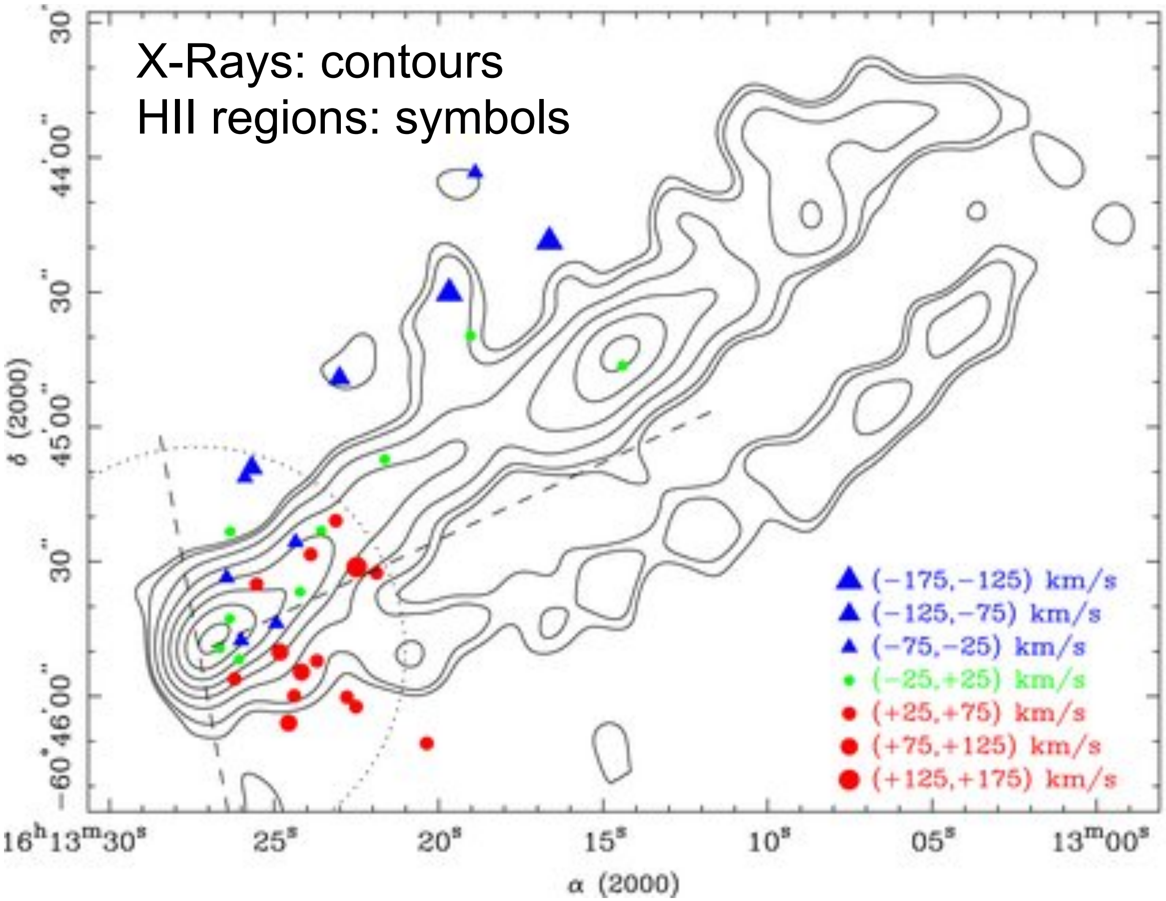
Star formation timescale (=1/SFE) =

T_{gas} = M(HI+H_2)/SFR(UV+FIR)

is 2-5x longer in stripped extraplanar gas than in disks

→ Most stripped gas doesn't form stars but joins the ICM

Complexity of ESO137-001 tail



Double tail in x-rays
Due to magnetic fields?
Ruszkowski+2014 simulations

Sun+2010

Broad tail of "orphan HII regions"
from earlier stage of stripping the outer disk?
dense star-forming clouds decouple from lower density gas which gets accelerated downstream

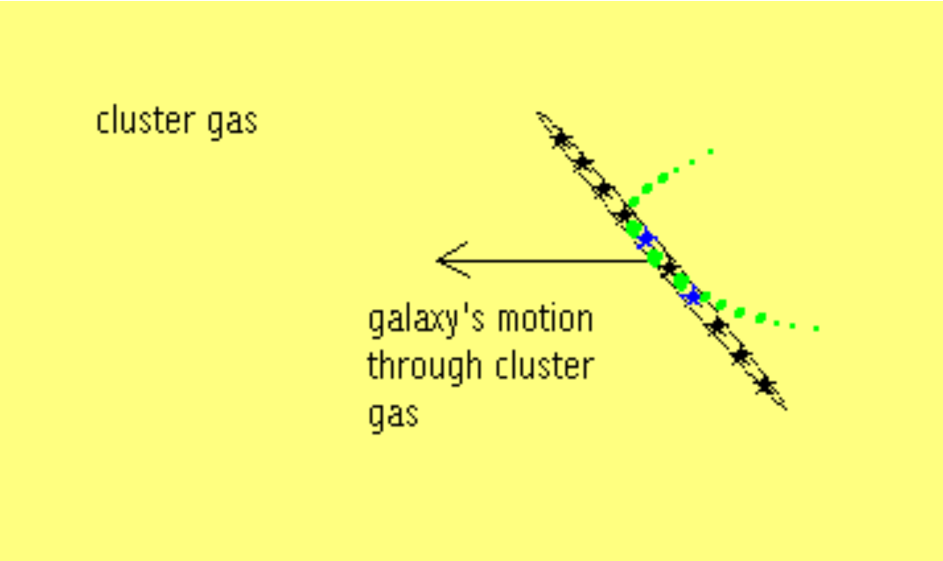
Gunn & Gott (1972) criterion for rps

Galaxies moving through gas (from ICM/IGM/ISM) will experience a ram pressure which will push the ISM gas if:

$$\rho_{ICM} v^2 > \Sigma_{ISM}\, d\Phi/dz$$

Ram pressure

Gravitational Restoring force (per area)



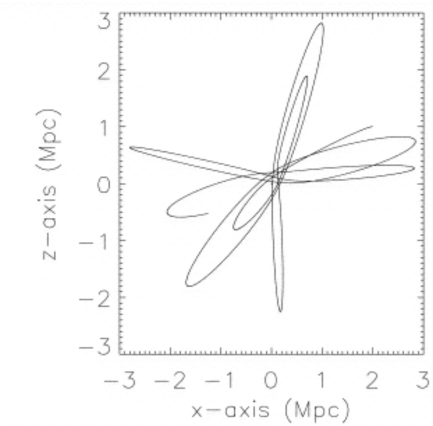
This is criterion for ***accelerating*** gas not ***removing*** it!

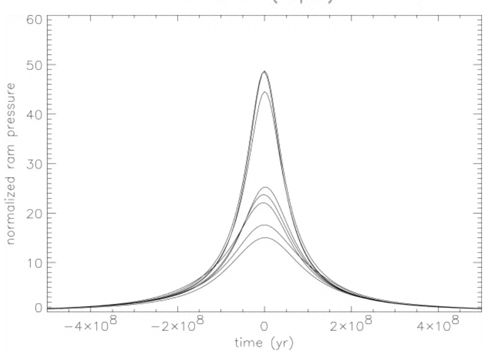
Efficiency of rps relative to GG72 depends on

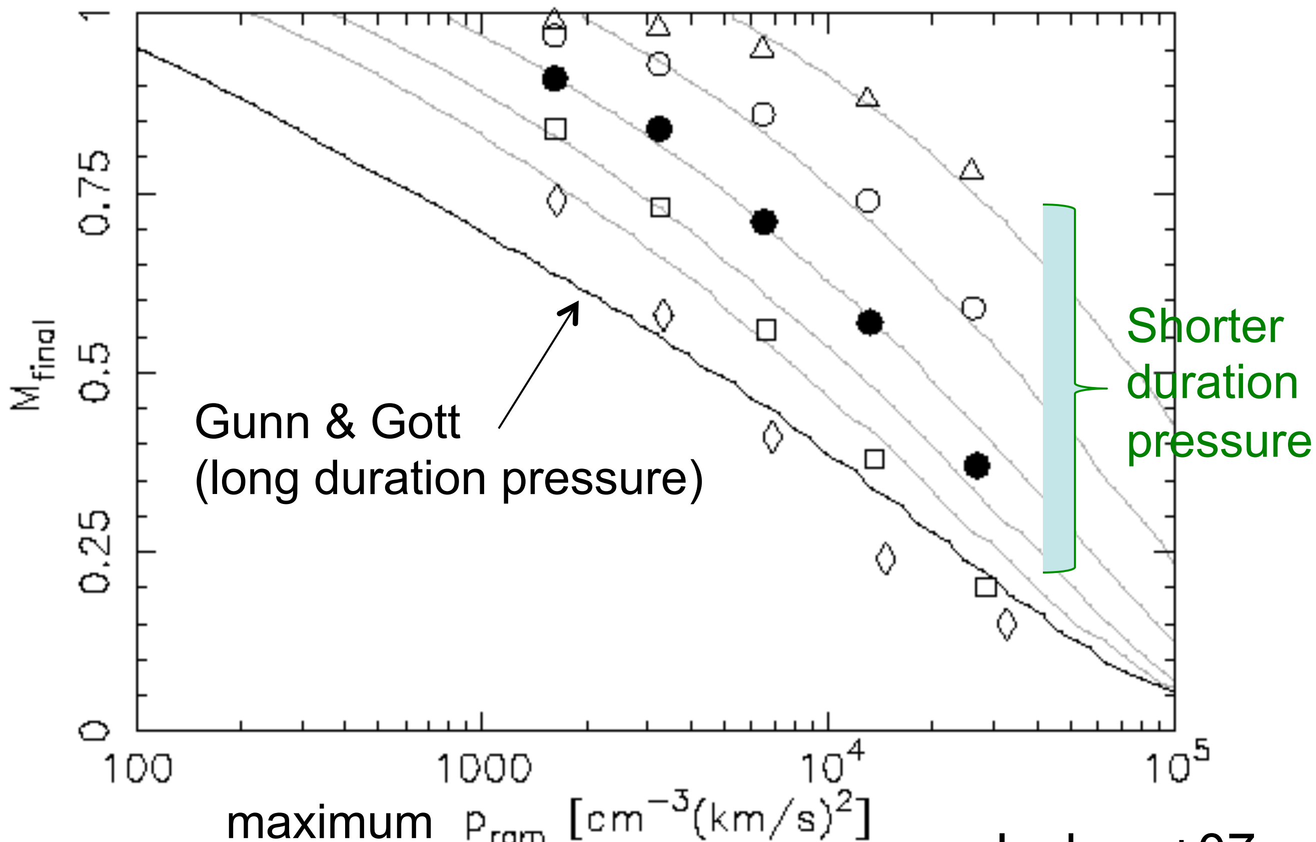
- Duration of ram pressure
- Disk-wind angle
- Galaxy rotation
- ISM substructure
- Magnetic fields

Stripping efficiency duration effect

~Radial orbits
in cluster



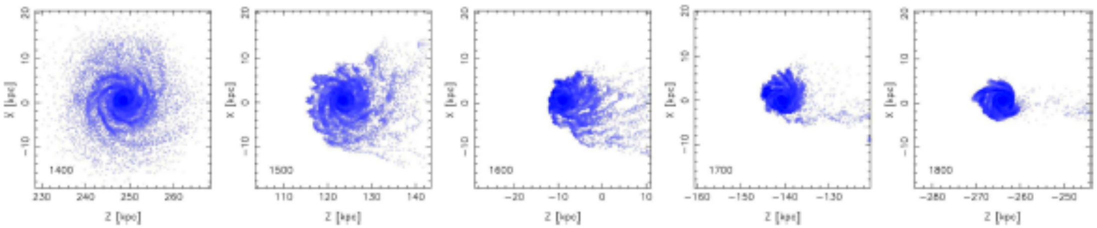




Jachym+07

Ram pressure vs. time over 1 orbit

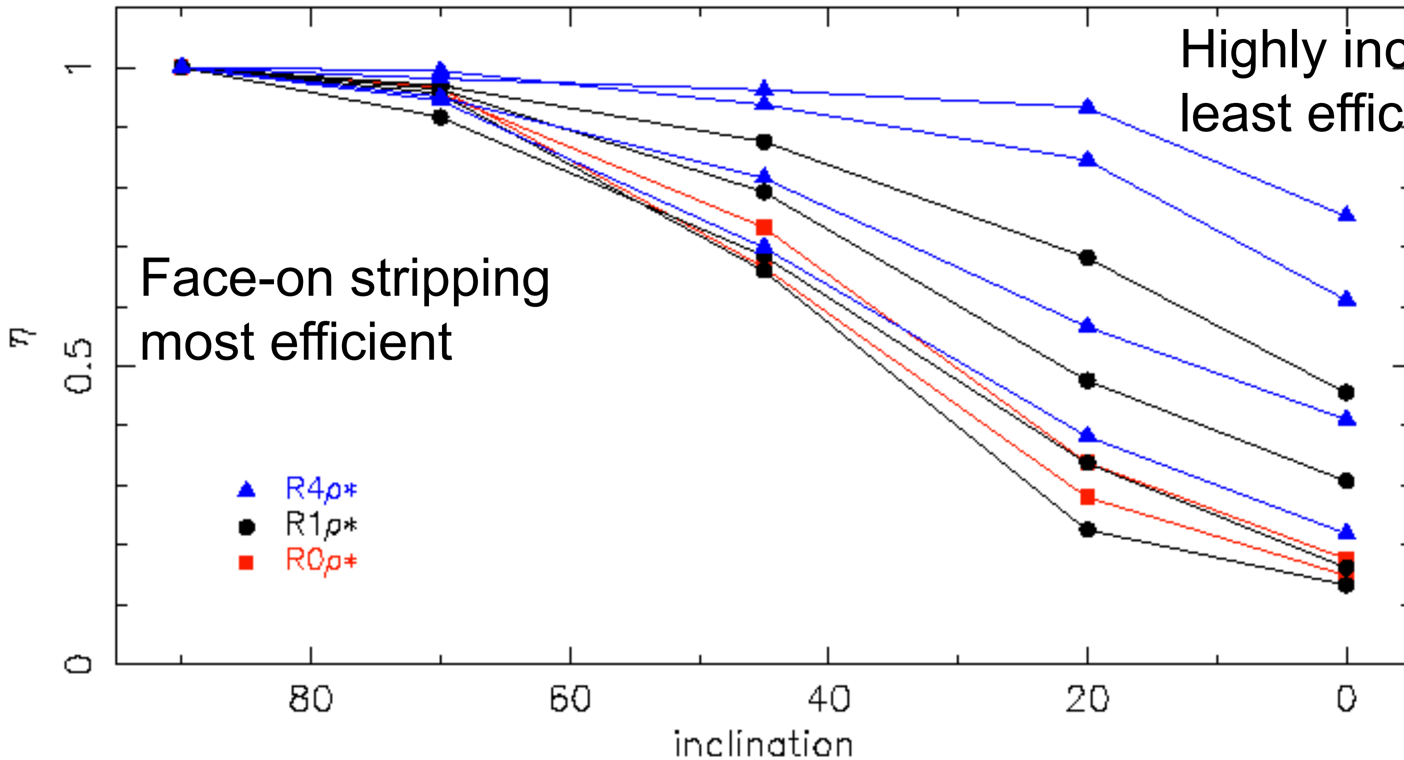
Stripping efficiency inclination effect



Jachym+09 simulations galaxies falling on radial orbits thru simple cluster

Highly inclined stripping least efficient

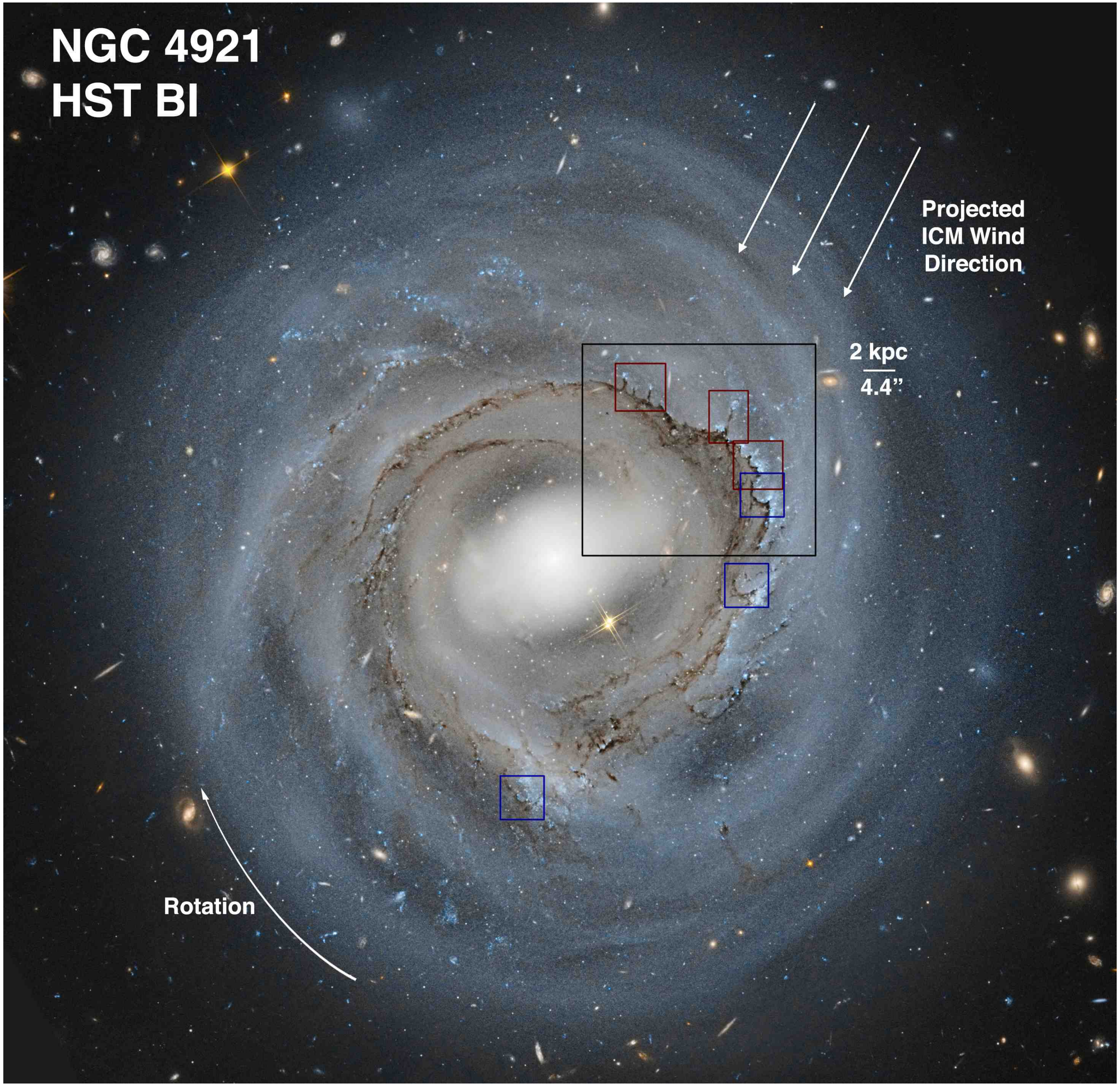
Face-on stripping most efficient



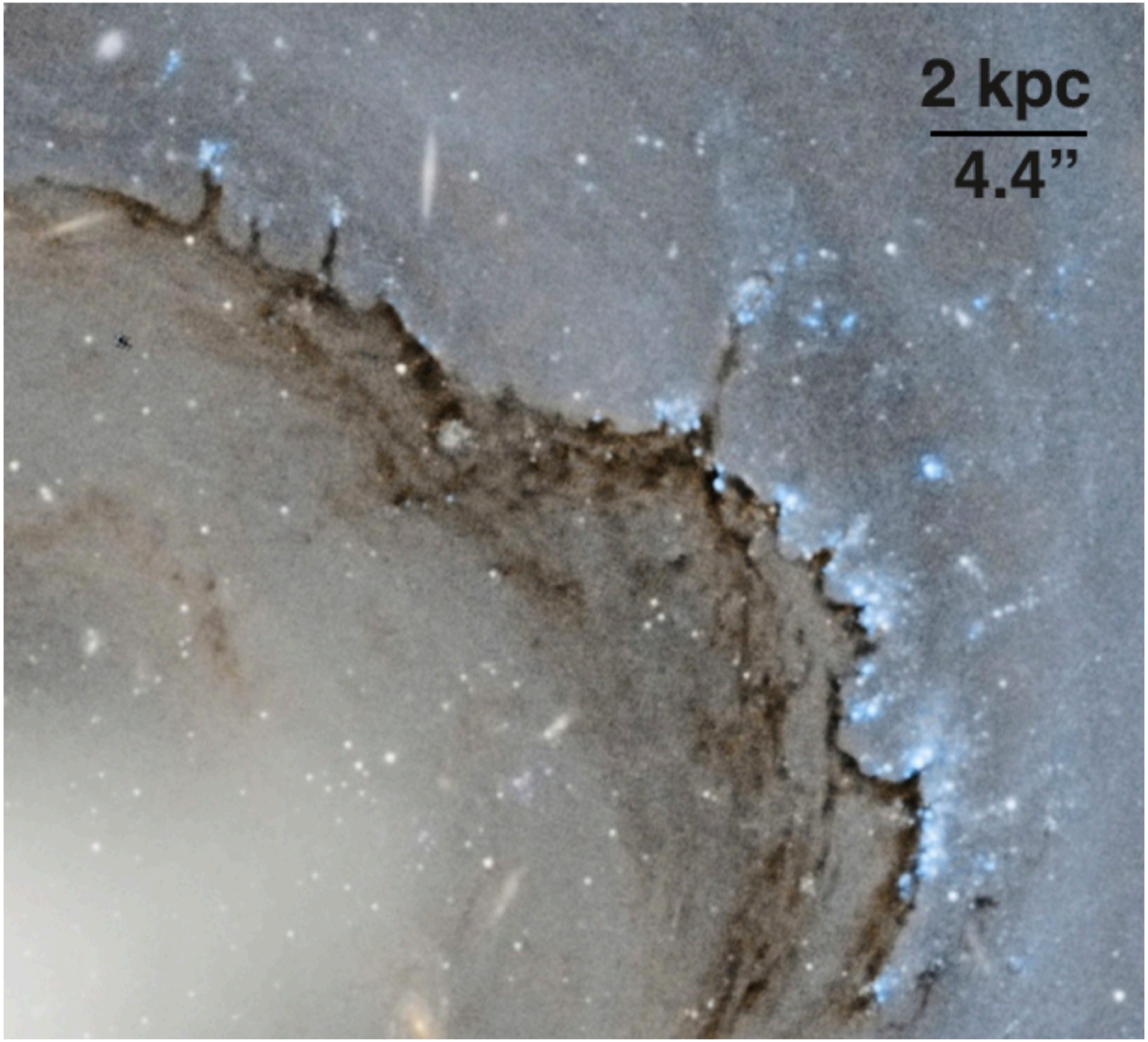
Jachym+09

Bigger inclination effect for weaker peak ram pressure and shorter duration ram pressure

Stripping the most massive Coma spiral



HST data obtained by K. Cook for Cepheid program

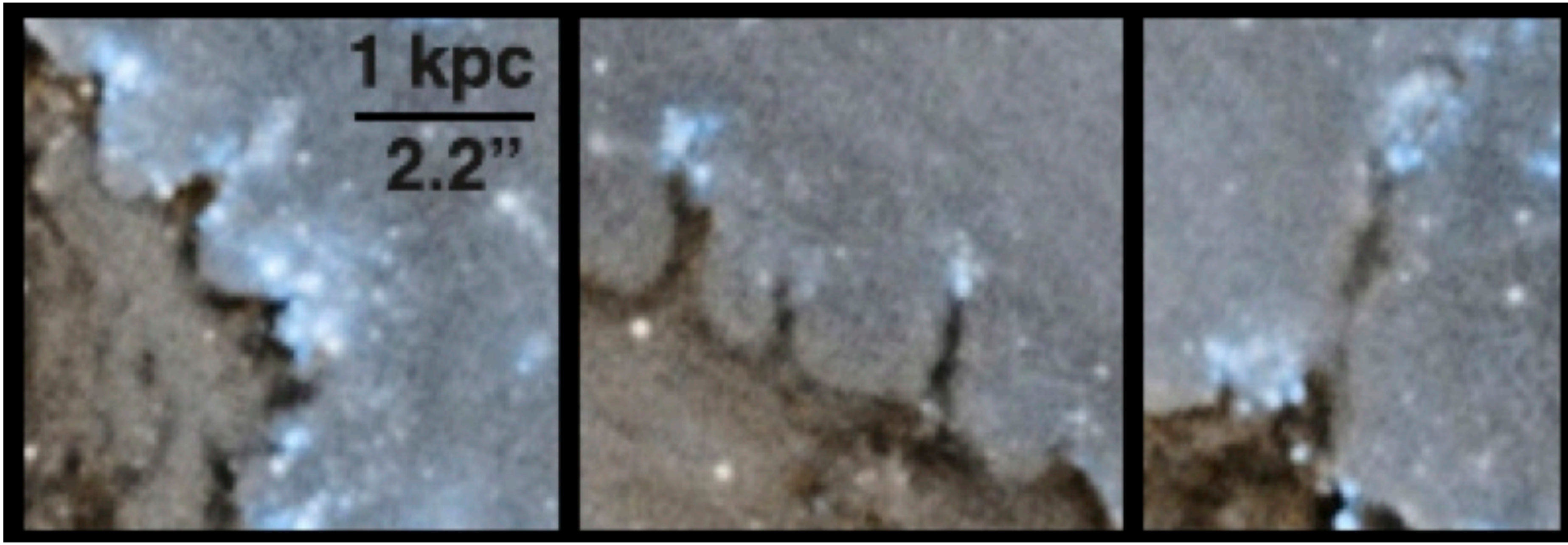


Coma spiral
NGC 4921

Kenney & Abramson 2014

“Dust front”
Swept-up ISM along leading edge of ICM-ISM interaction

Linear & V-shaped head-tail filaments protruding from dust front

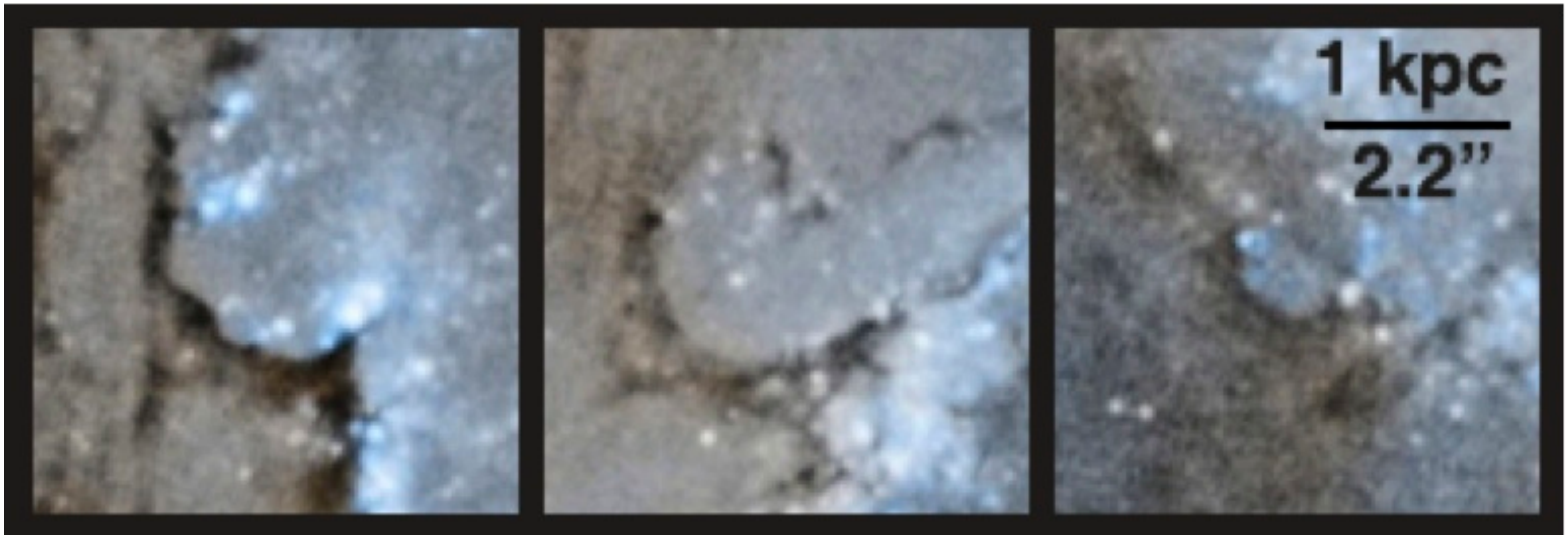


young star complexes at heads

Dense gas clouds too dense to strip are decoupling from lower density gas which is accelerated downstream by rp

BUT decoupling inhibited by magnetic(?) binding

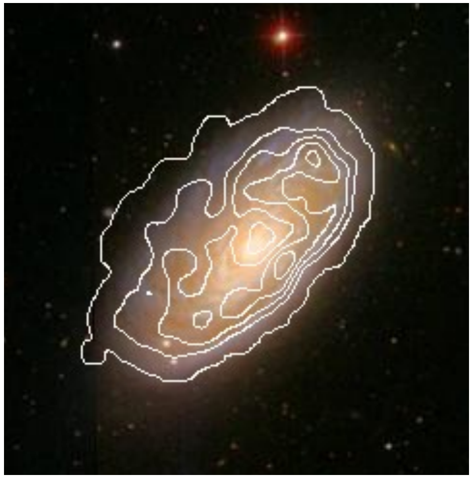
C-shaped filaments along dust front

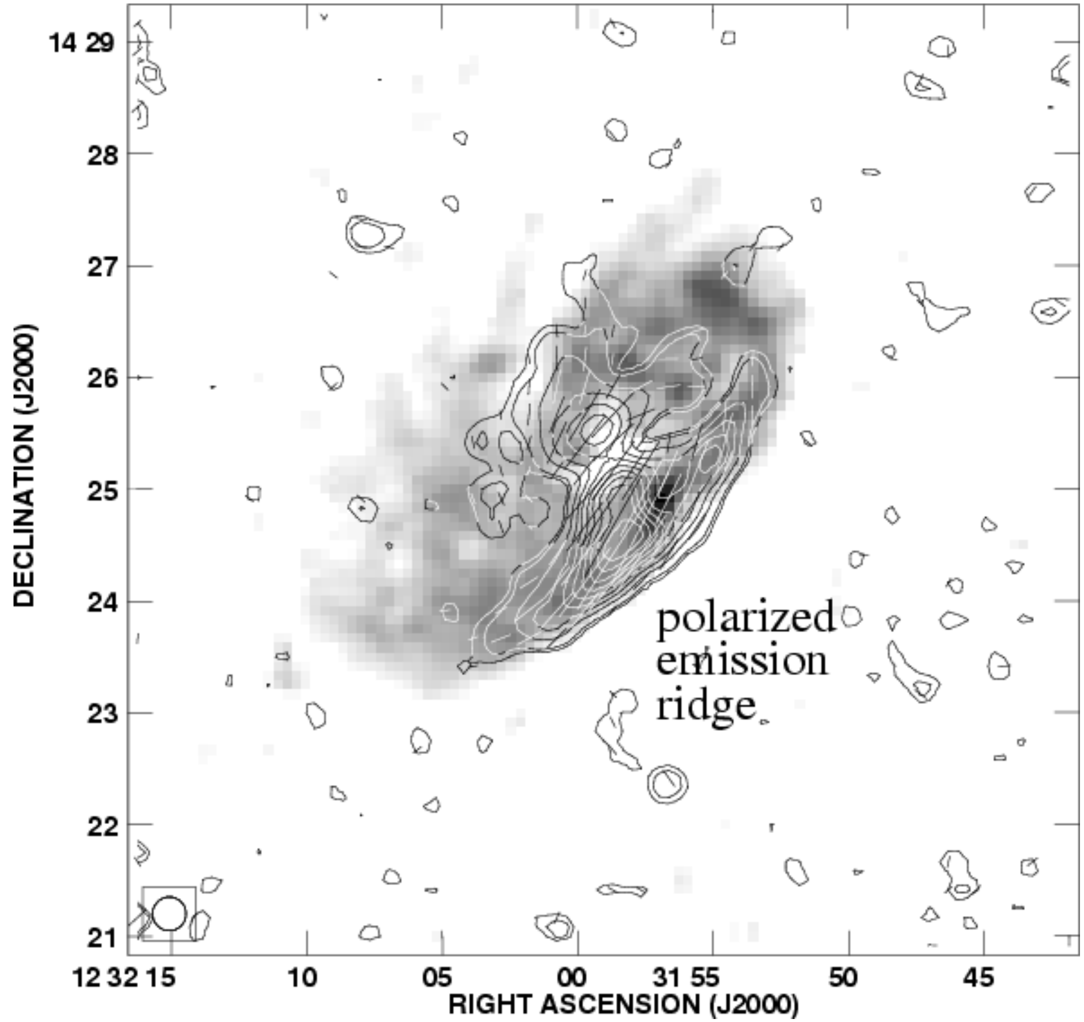


Kenney & Abramson 2014

Lower density gas pushed by ram pressure remains connected by magnetic fields to decoupling higher density gas clouds

Virgo spiral NGC 4501





Vollmer+2009

Ridge of strong radio polarization at leading edge
magnetic fields aligned with edge
r.p. compresses gas & magnetic fields

Decoupling dense clouds during rps

Head-tail dust filaments:

Length ~ 1000 pc

Width ~ 100 pc

$M_{gas} \sim 10^7 M_{sun}$

Abramson & Kenney 2014

Filament morphology not consistent with ablation or shadowing but is consistent with magnetic binding

Summary: Ram Pressure Stripping does these things:

~completely strips dwarf galaxies in Virgo-like clusters

partially strips large spirals in Virgo-like ($M \sim 10^{14}\ M_{sun}$) clusters

~completely strips massive galaxies during first infall Into Coma-like ($M \sim 10^{15}\ M_{sun}$) clusters

~completely strips (small) dwarf satellite galaxies close enough to their (large) host galaxy

must be ***important starvation mechanism*** in high and medium density environments-- gas removed from outer galaxy or halo by r.p. will not settle to inner disk & form stars