

# HI Distributions of Virgo Cluster Galaxies: Ram Pressure Stripping and Galaxy Evolution

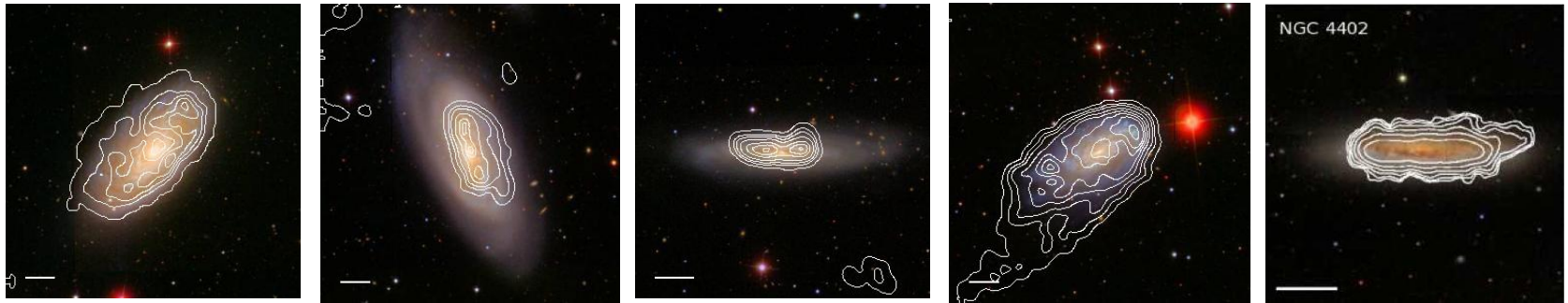
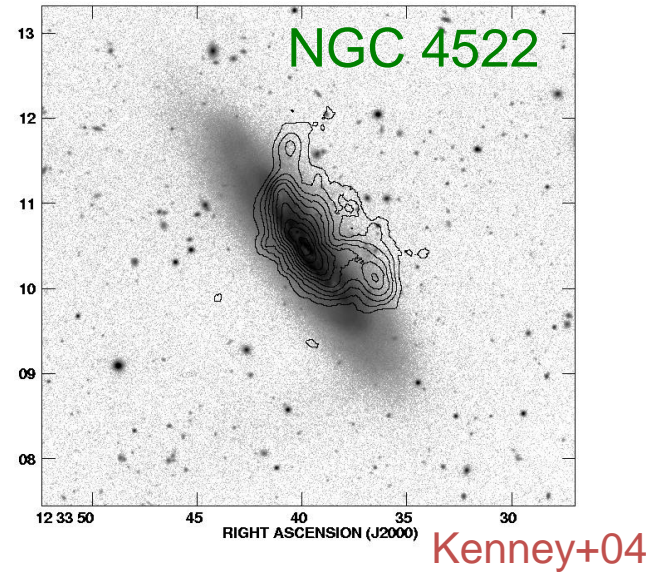
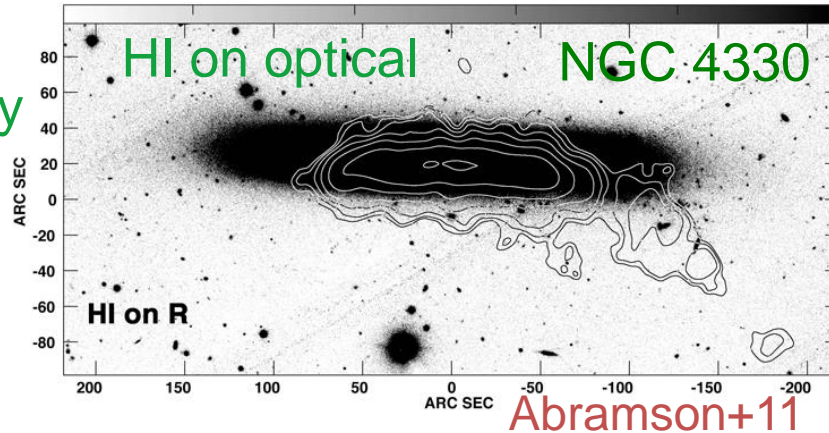
Jeff Kenney (Yale U.)

Ringberg December 2017

# Diagnostics of **active** ram pressure stripping:

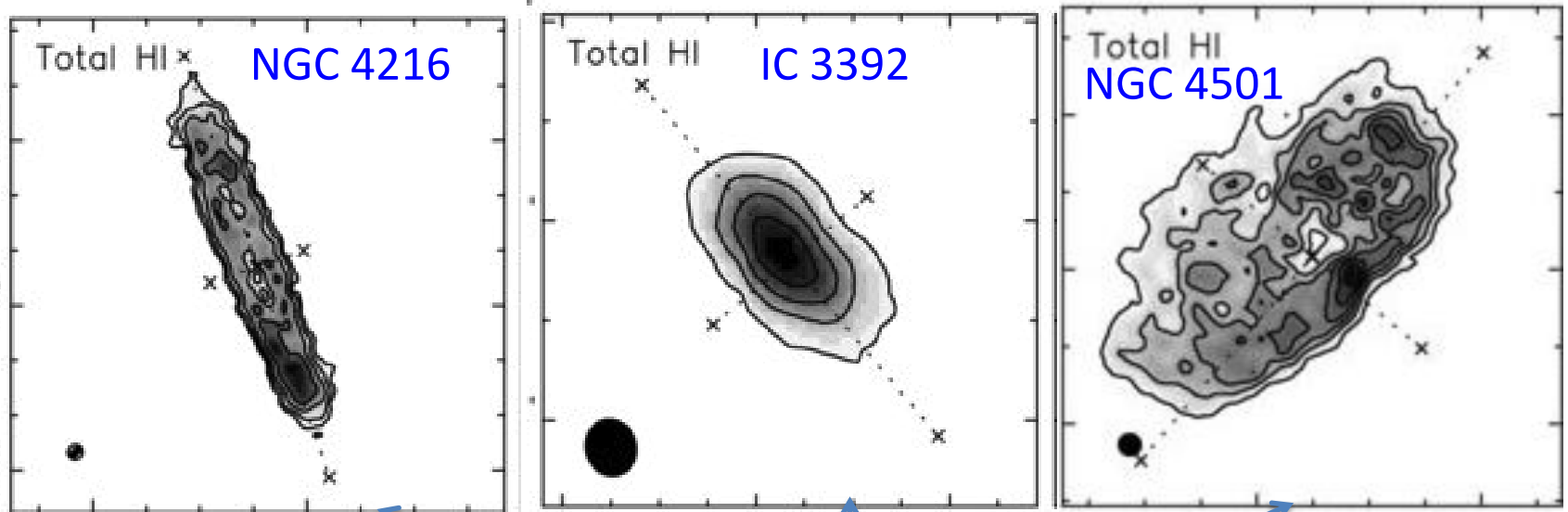
*Gas not Stars, outside-in, one direction*

Virgo Cluster  
VIVA HI survey  
~50 spirals



Large fraction of Virgo spirals have truncated gas disks with normal stellar disks & one-sided extraplanar gas features

standard way to measure asymmetries:  
compare flux in two halves of galaxy



global head-tail ratio: 0.78 0.70 0.79 (1.00 is symmetric)

*NGC 4501 has a clear head-tail morphology but its global head-tail ratio is the same as galaxies with no head-tail morphology !?!?*

standard asymmetry measures don't work to identify rps galaxies

but! .... we haven't had ***objective quantifiable measures of gas distribution*** to indicate ***active ram pressure stripping*** ... until now

... new analysis of VIVA HI data

Kenney + in prep

collaborators:

**Elijah Mas**

**Michael Warrener**

Aeree Chung

Jacqueline van Gorkom

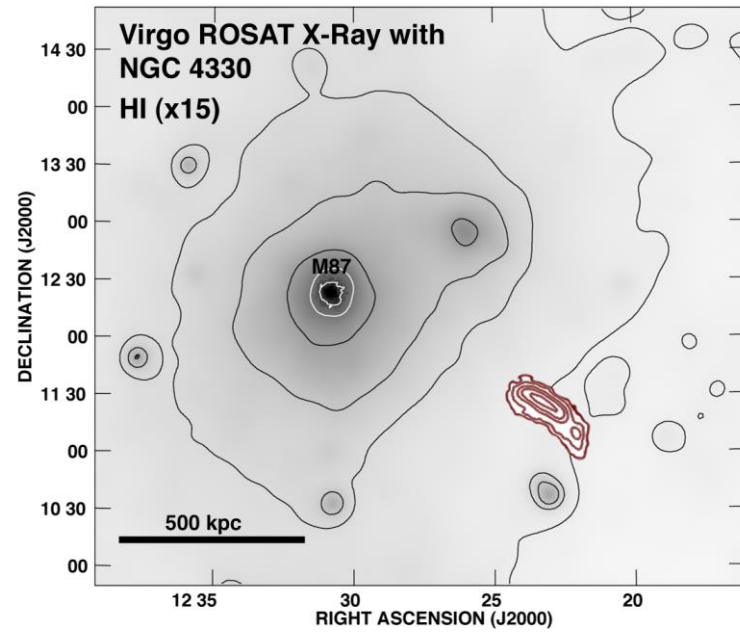
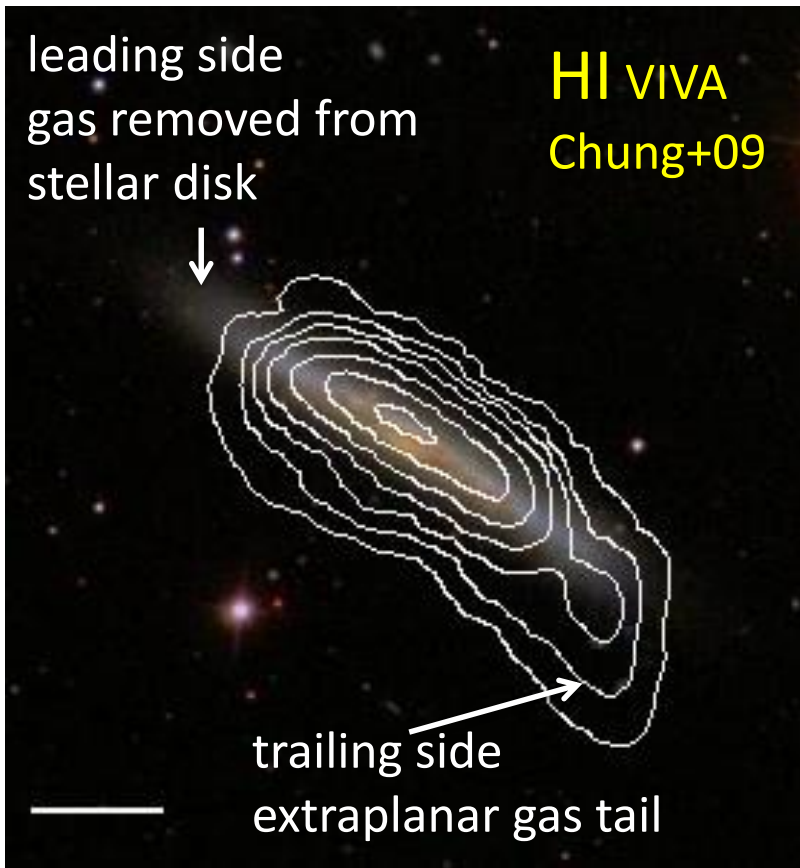
Hugh Crowl

Bernd Vollmer

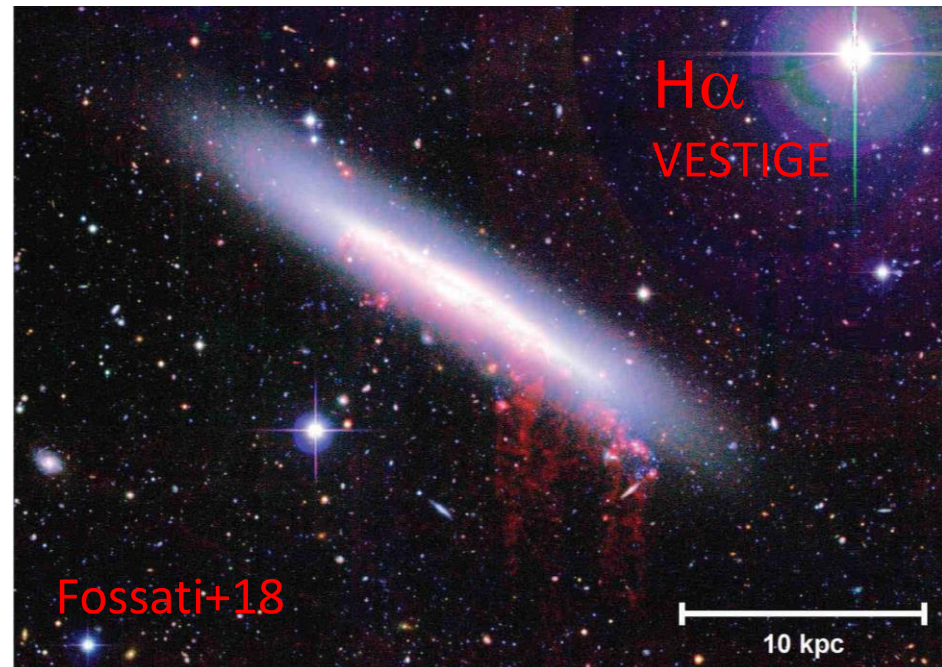
identify cases of weaker rps, different evolutionary stages of rps

# NGC 4330

clear case of active stripping

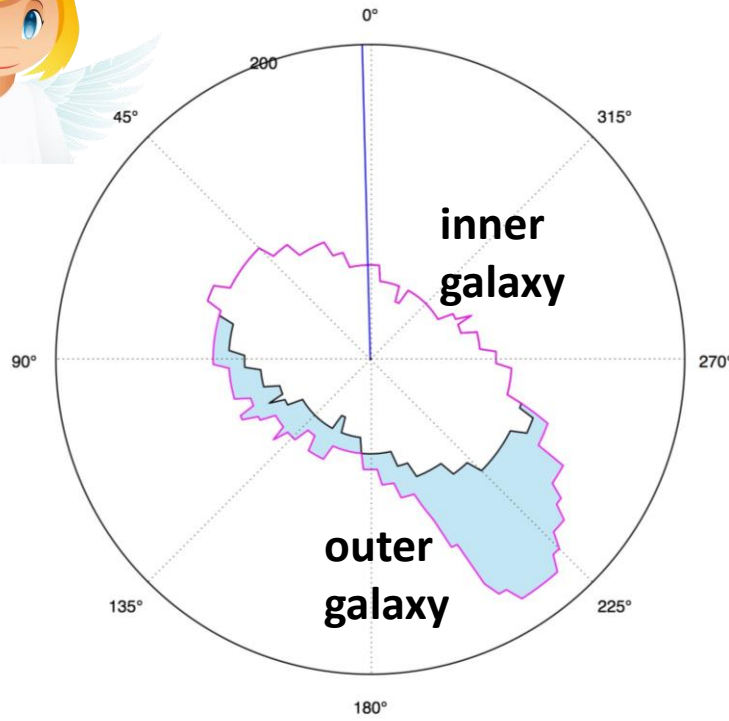


Abramson+11

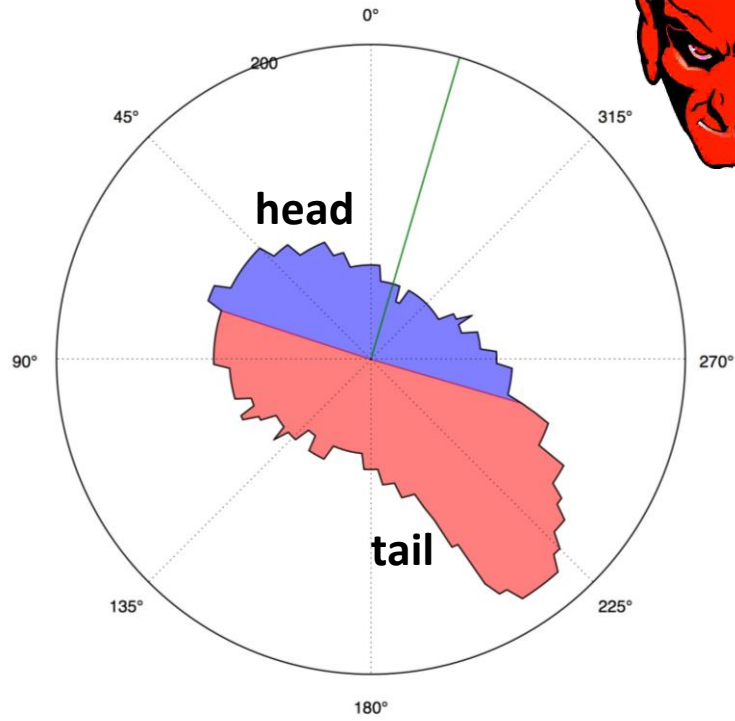




**YES!**

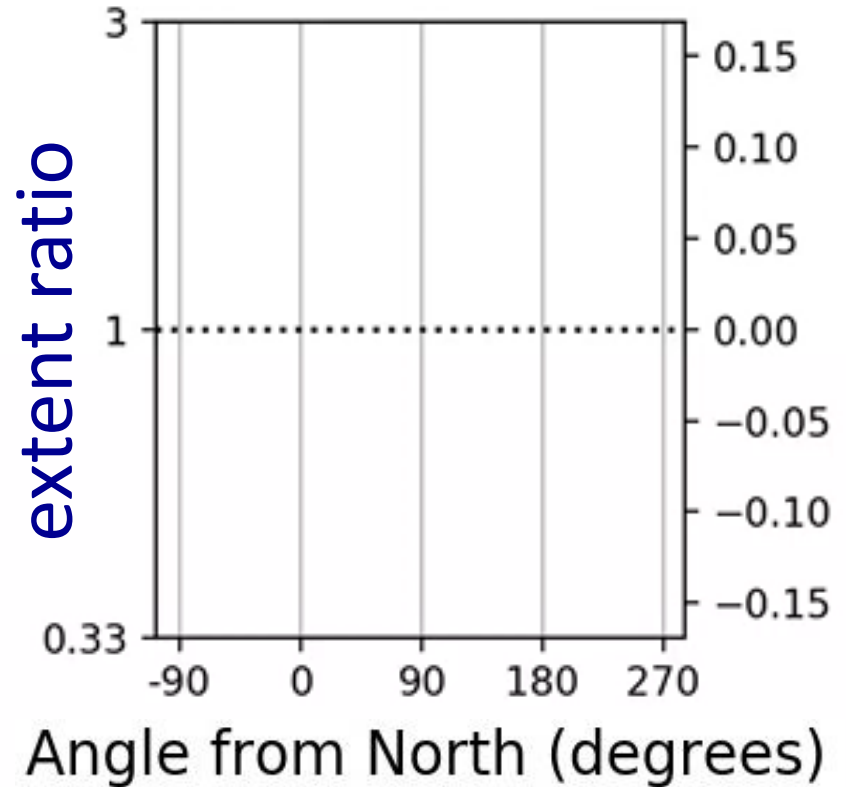
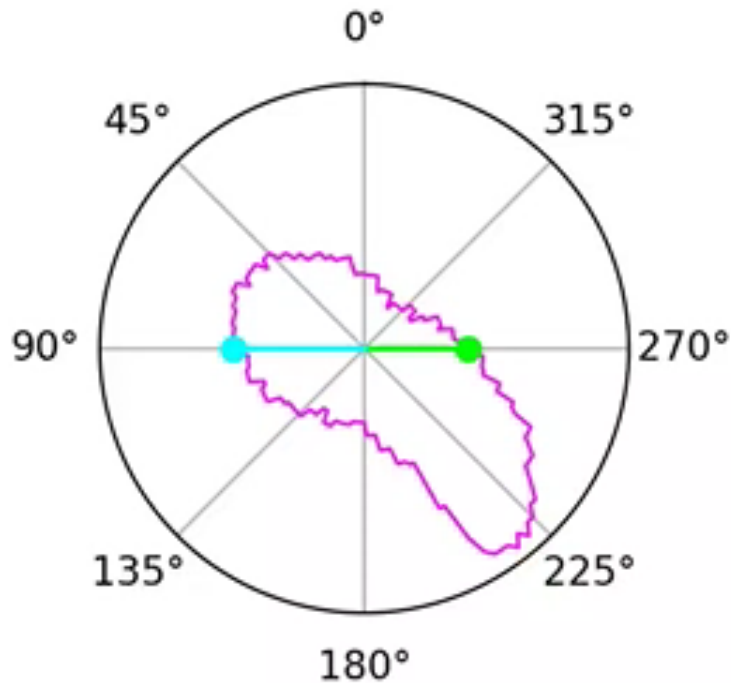


**NO!**



- want to measure something from HI map that traces active rps
- global head-tail asymmetry (of all the gas) **doesn't work well**
- head-tail asymmetry of *outer* gas **works well**

# extent ratio & defining the inner galaxy



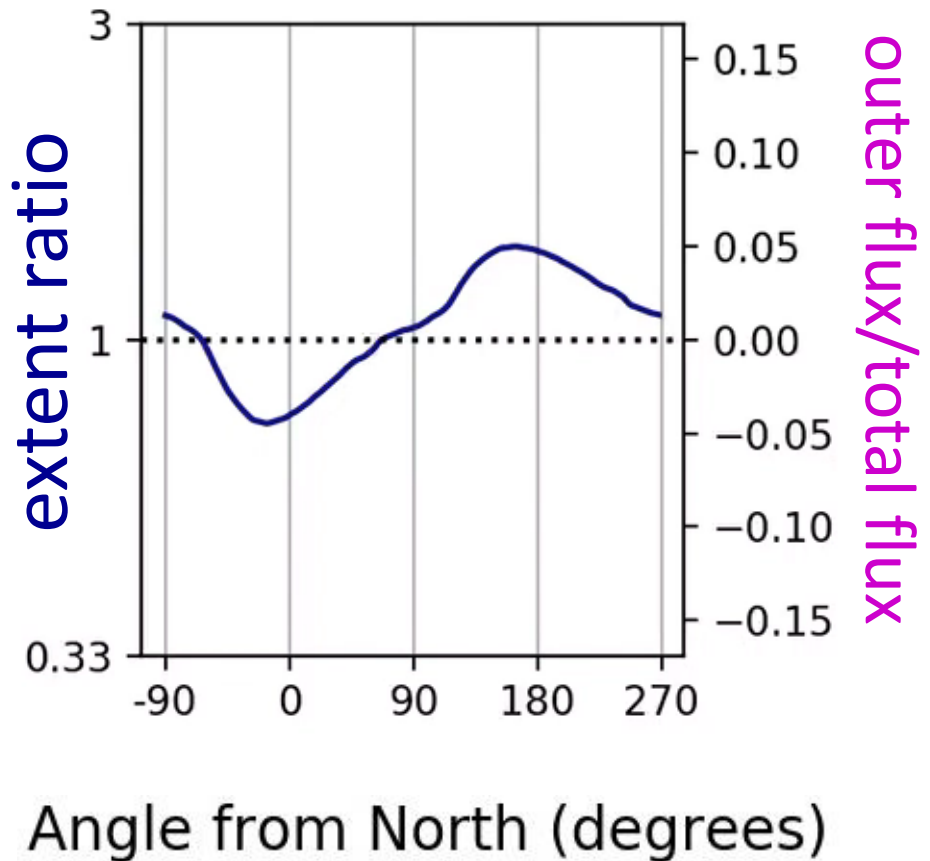
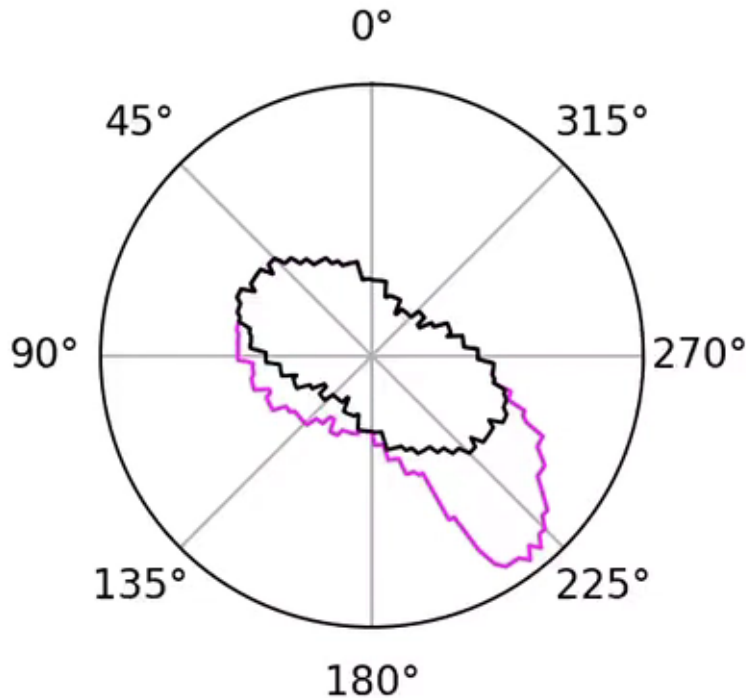
extent ratio: ratio of radial extents of contour at points 180 deg apart

first version: unsmoothed

second version: smoothed over 180 deg

(to indicate outer head-tail asymmetry)

# outer tail-to-total flux ratio

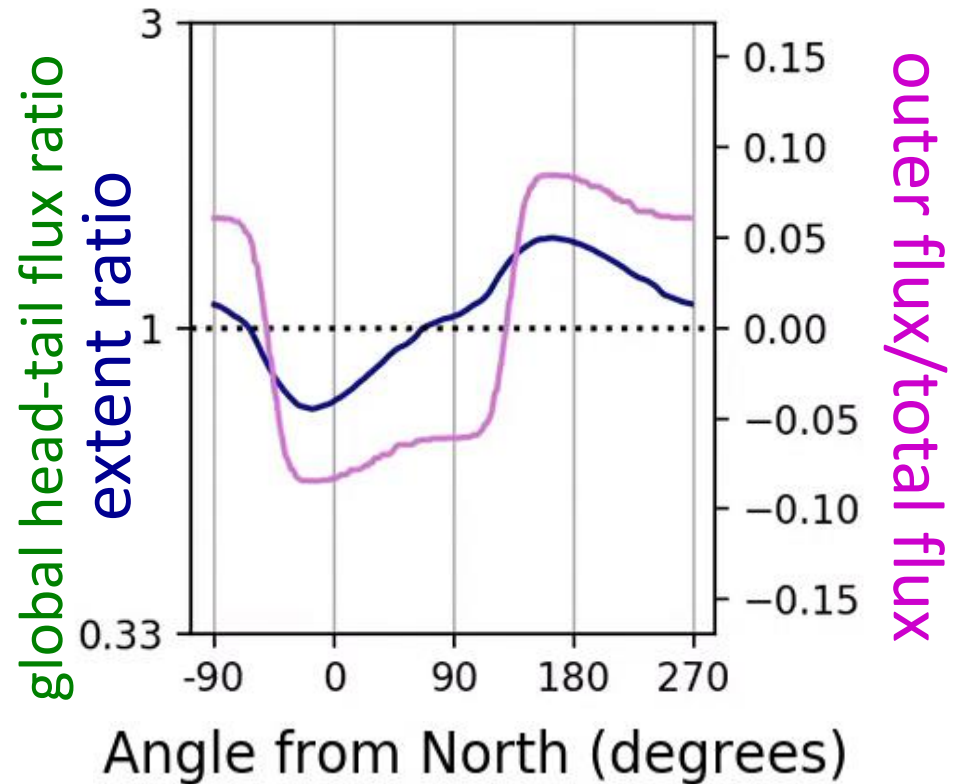
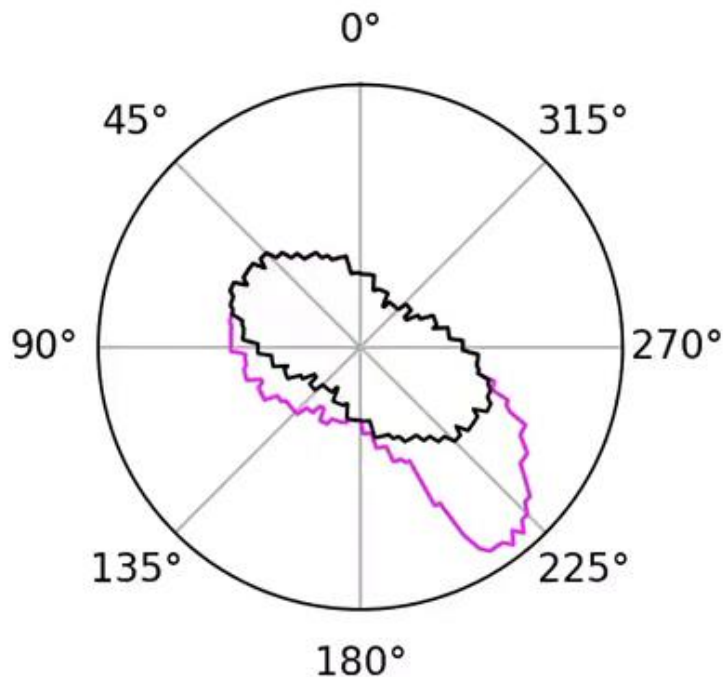


outer tail to total flux ratio:

flux in *outer galaxy over 180 deg* / total flux



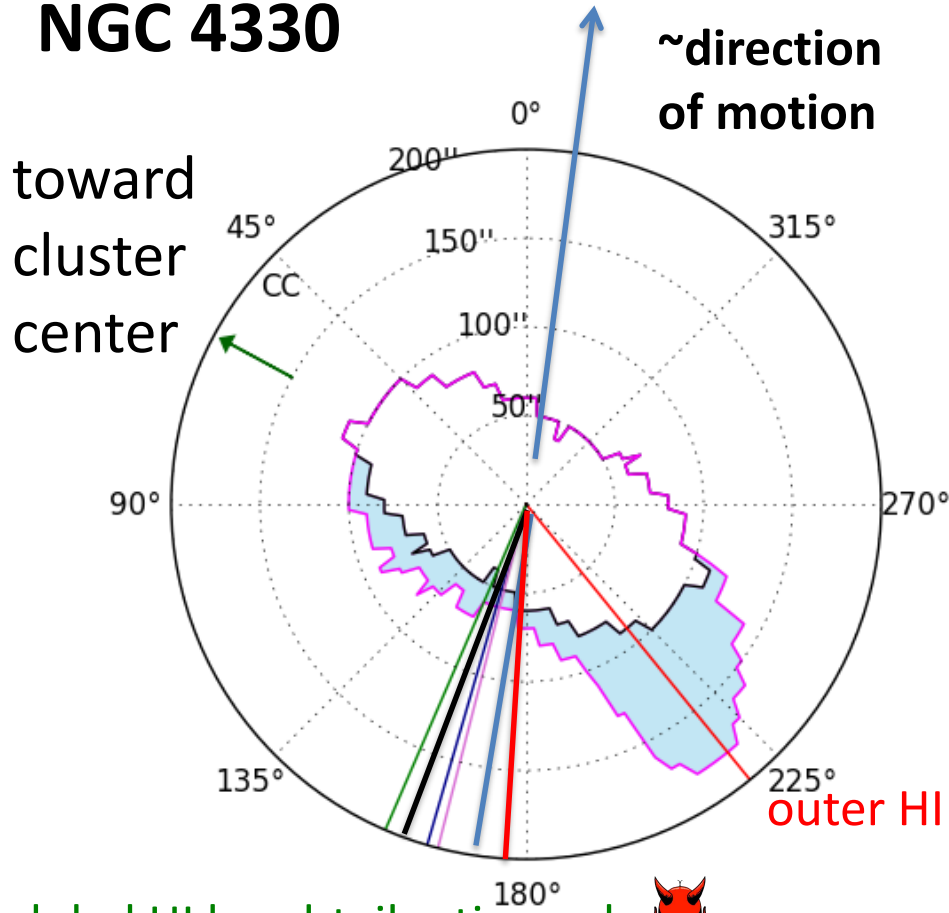
# global head-tail flux ratio



global head-tail flux ratio:

flux over 180 deg / flux over opposite 180 deg

# NGC 4330



extent ratio and outer flux ratio give good appx measures of **projected wind direction**, since they do good job identifying compressed & extended sides

global HI head-tail ratio angle 🐉

simulation angle (Vollmer+12)

HI extent ratio angle 🧚

HI outer flux ratio angle 🧚

radio deficit angle

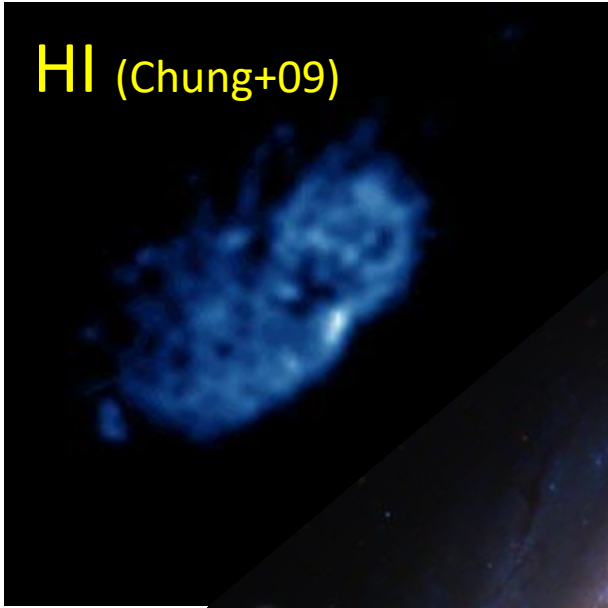
H $\alpha$  filament angle

outer HI angle 🐉

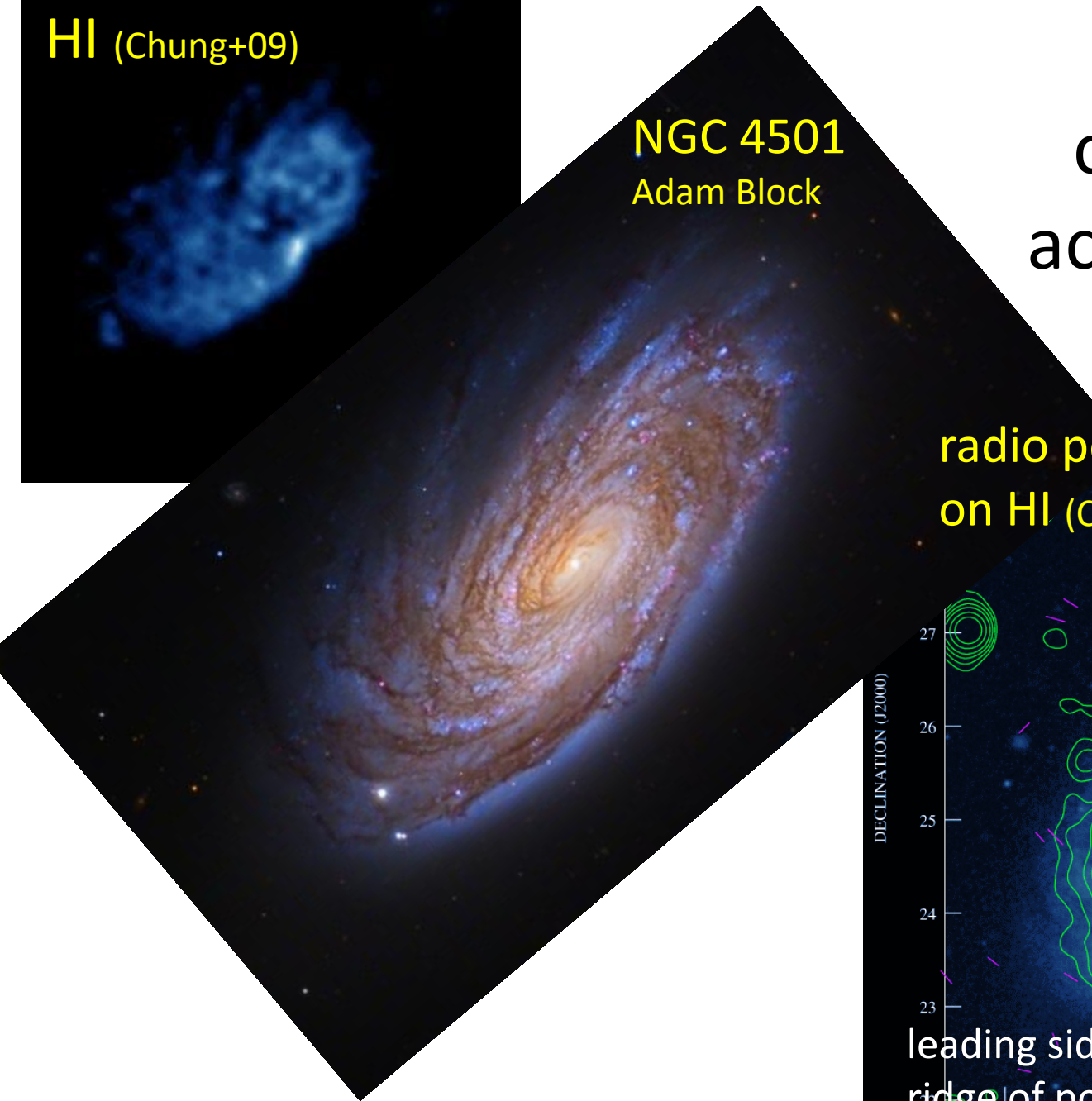


radio deficit region on radio map (Murphy+09)

HI (Chung+09)

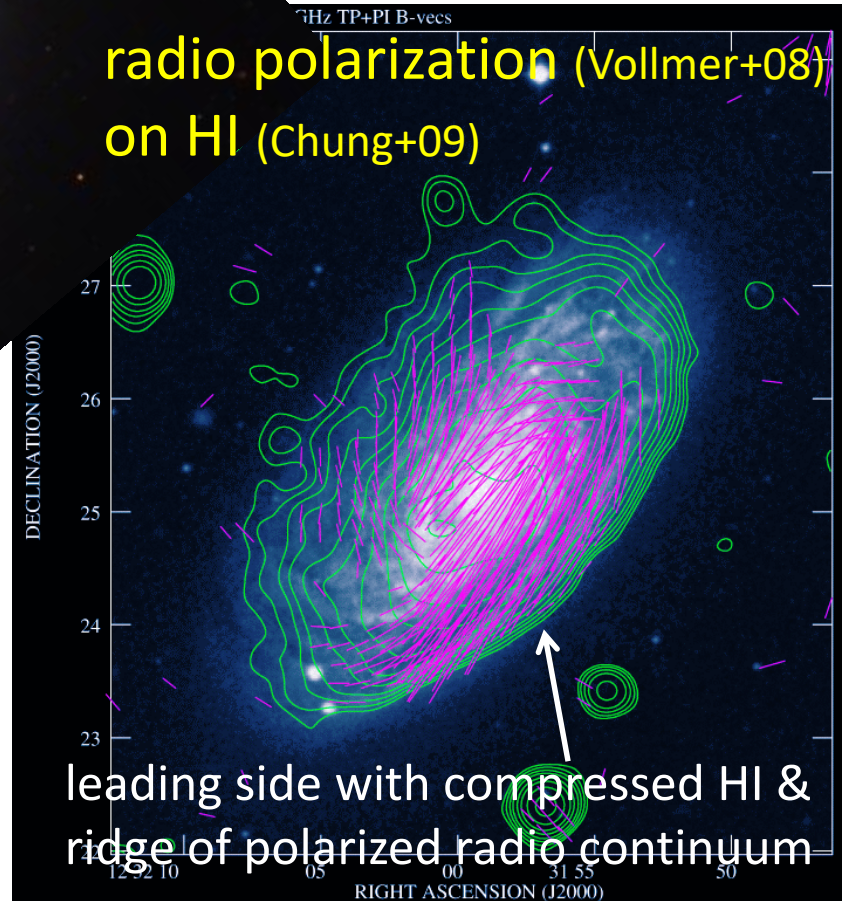


NGC 4501  
Adam Block

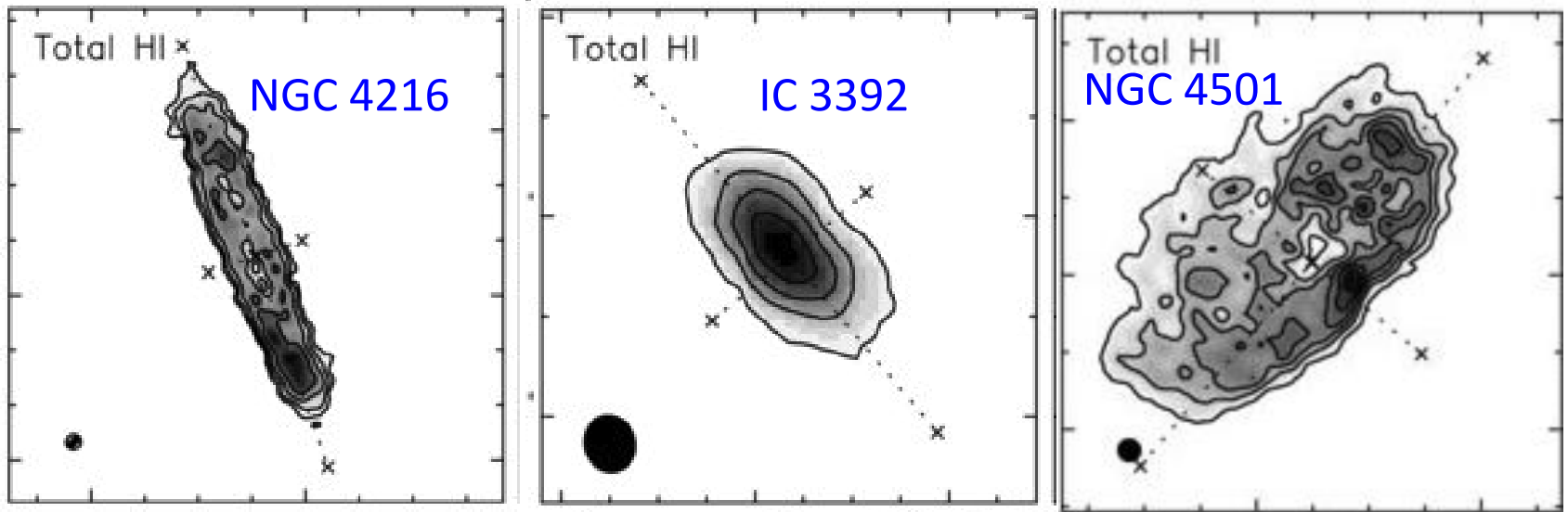


NGC 4501  
clear case of  
active stripping

radio polarization (Vollmer+08)  
on HI (Chung+09)



leading side with compressed HI &  
ridge of polarized radio continuum

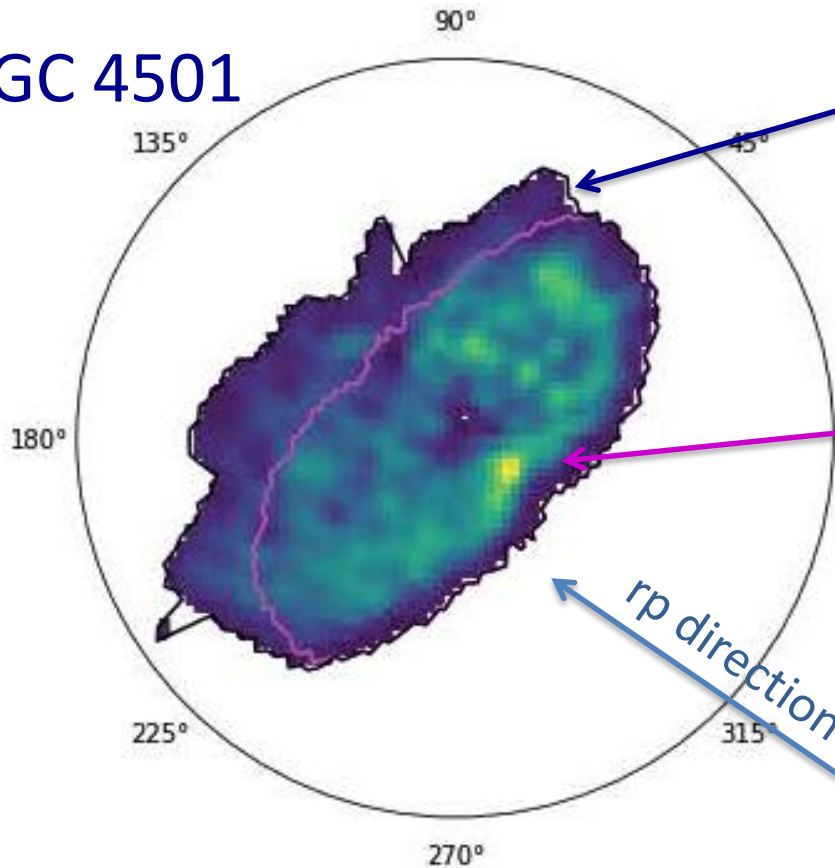


global head-tail ratio: 0.78 0.70 0.79 (1.00 is symmetric)

*NGC 4501 has a clear head-tail morphology but its global head-tail ratio is the same as galaxies with no head-tail morphology ?!?!?*

# inner galaxy flux dominates that from outer galaxy

NGC 4501  
HI



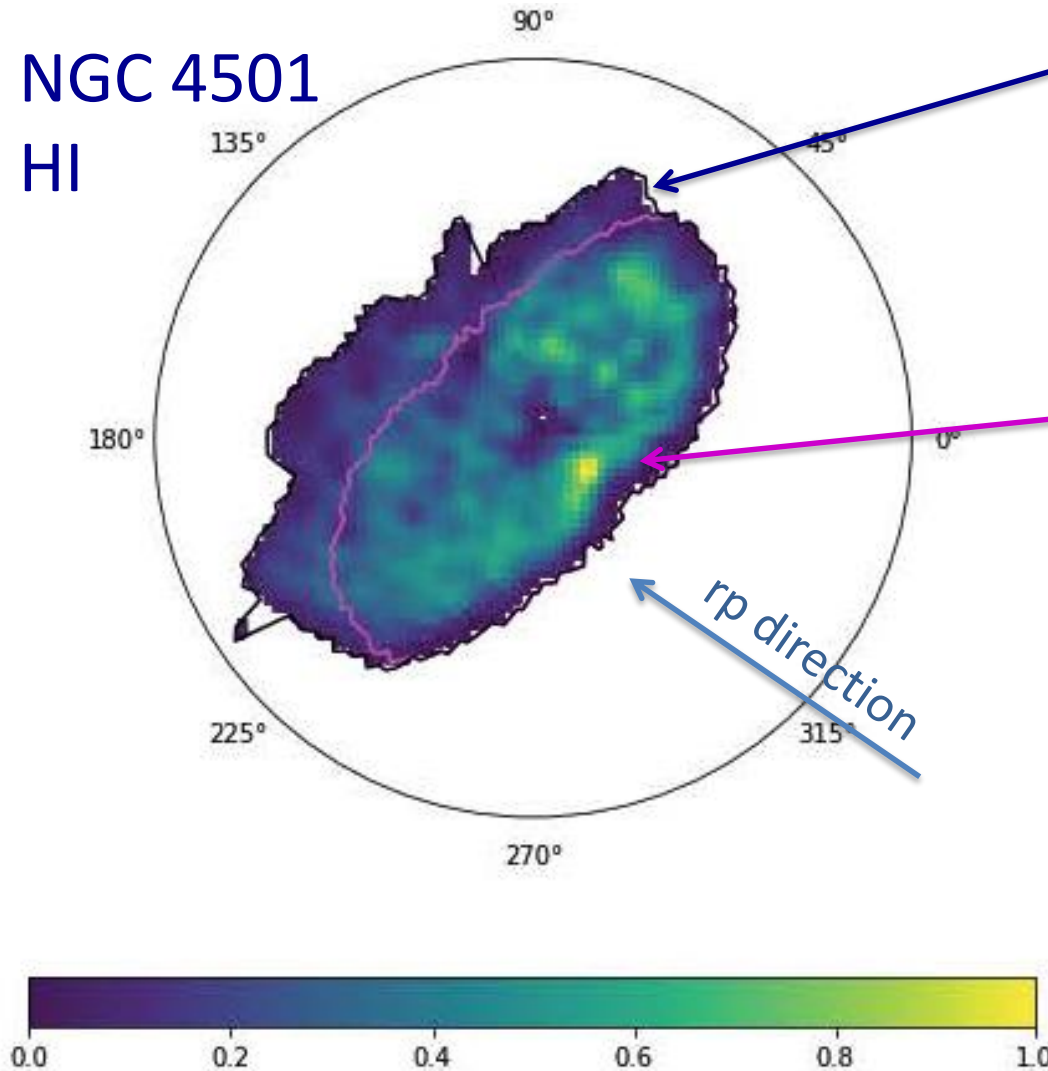
outer galaxy = "tail",  
where there is gas only  
over 180 degrees

inner galaxy: where  
there is gas at every  
angle



# asymmetries of inner & outer galaxy are typically opposite or unrelated

NGC 4501  
HI



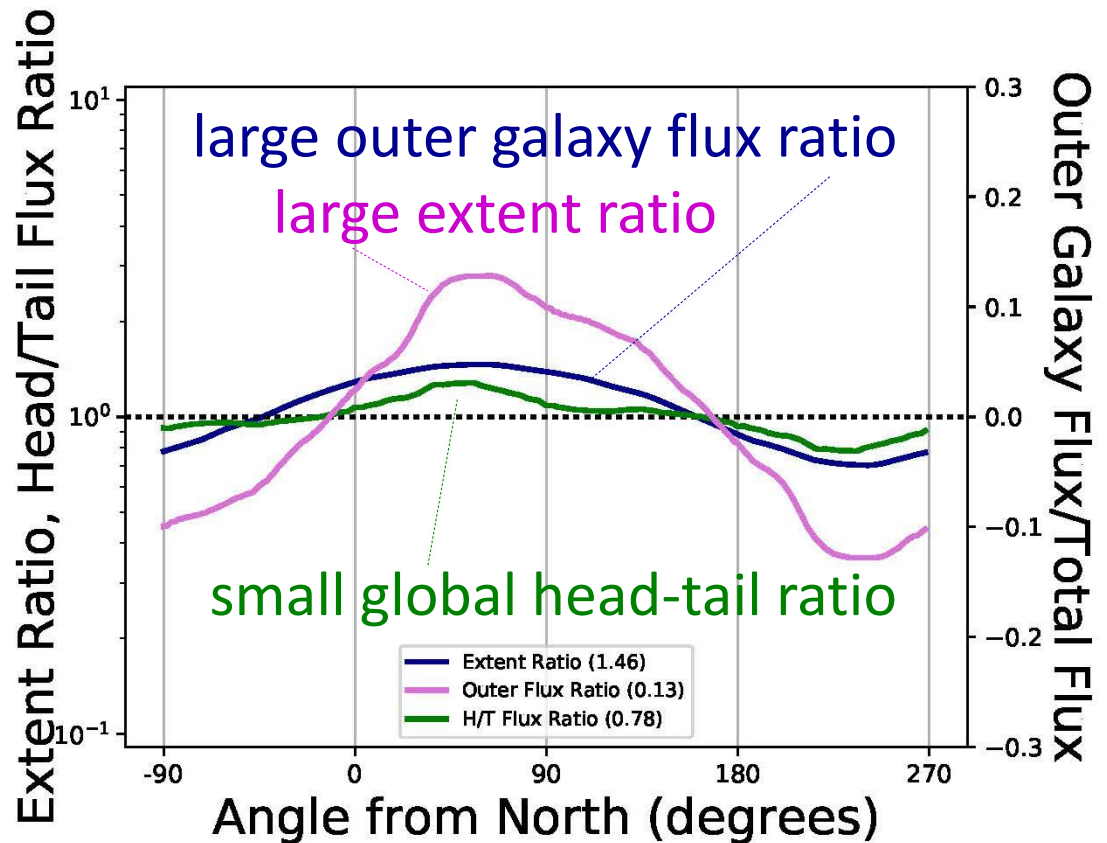
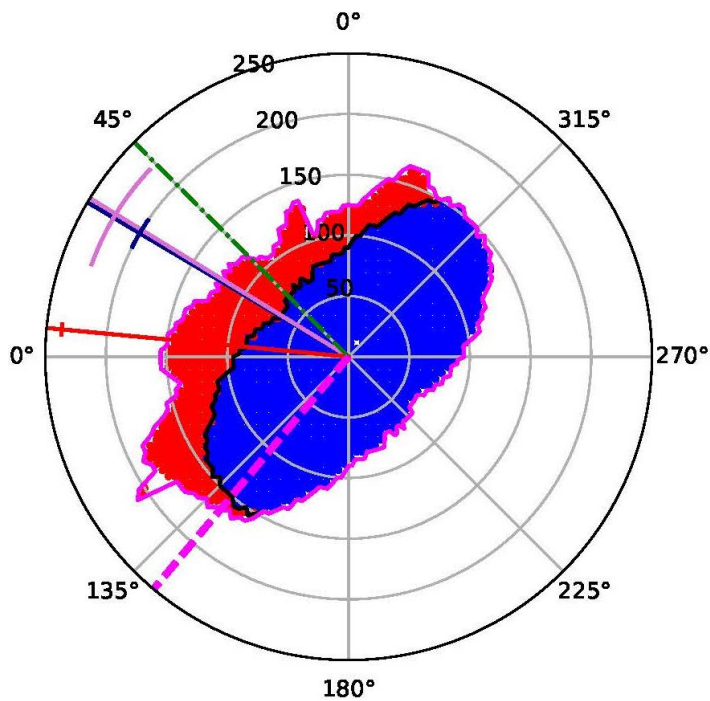
outer galaxy has more HI flux on trailing side (tail) due to r.p.

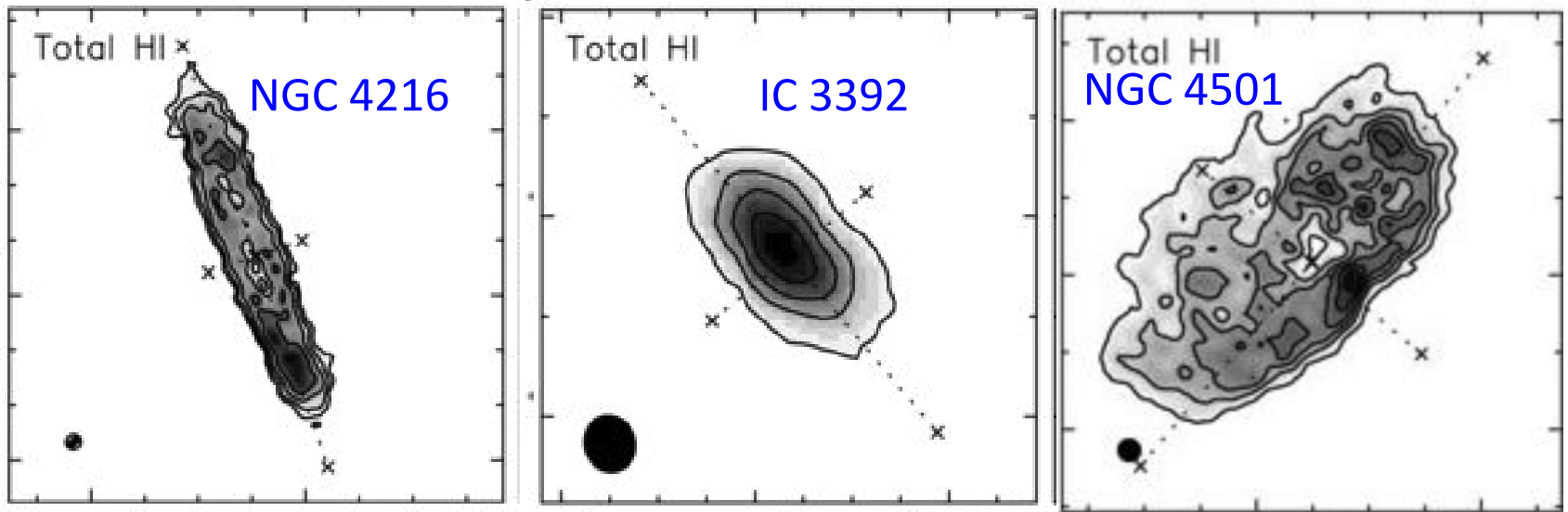
*inner galaxy has more HI flux on leading side (head) due to r.p. compression*

2 effects tend to cancel each other out so total head-tail flux ratio is poor indicator of the asymmetry

# NGC 4501

global head-tail ratio is small because inner and outer HI asymmetries are opposite





global head/tail ratio:	0.78	0.70	0.79 (1.00 is symmetric)
outer tail/total flux ratio:	0.01	0.01	<b>0.13</b> (0.00 is symmetric)
head-tail extent ratio:	1.04	1.05	<b>1.46</b> (1.00 is symmetric)

*the extent ratio and outer tail-to-total flux ratio are much higher in NGC 4501*

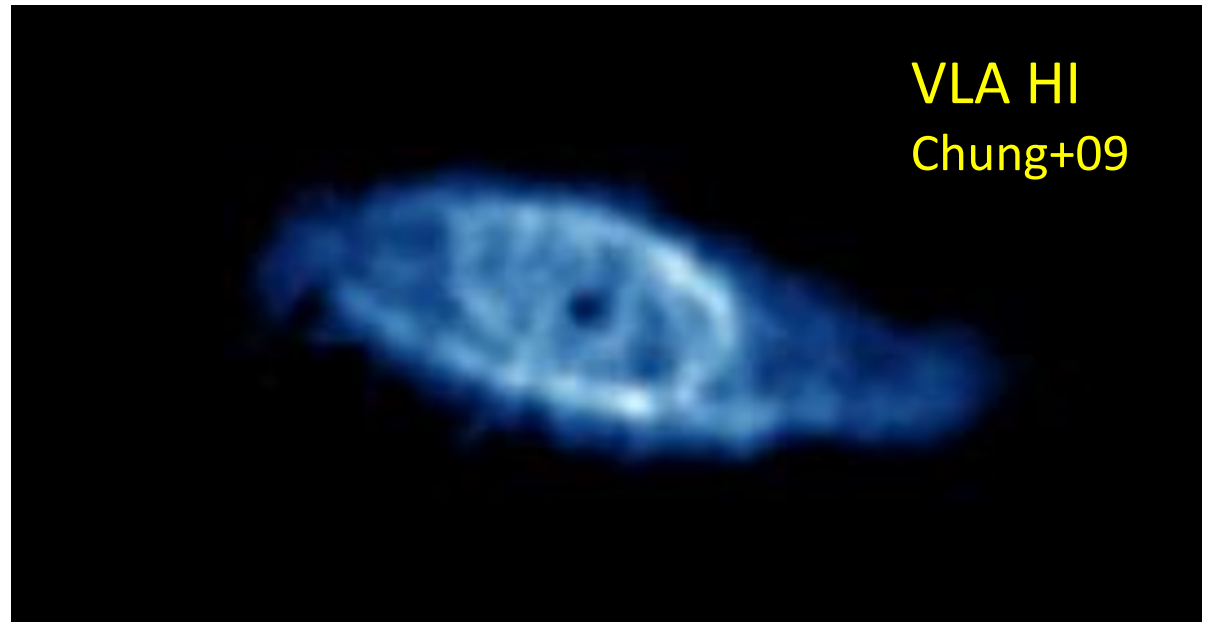


NGC 4651

“Umbrella  
Galaxy”

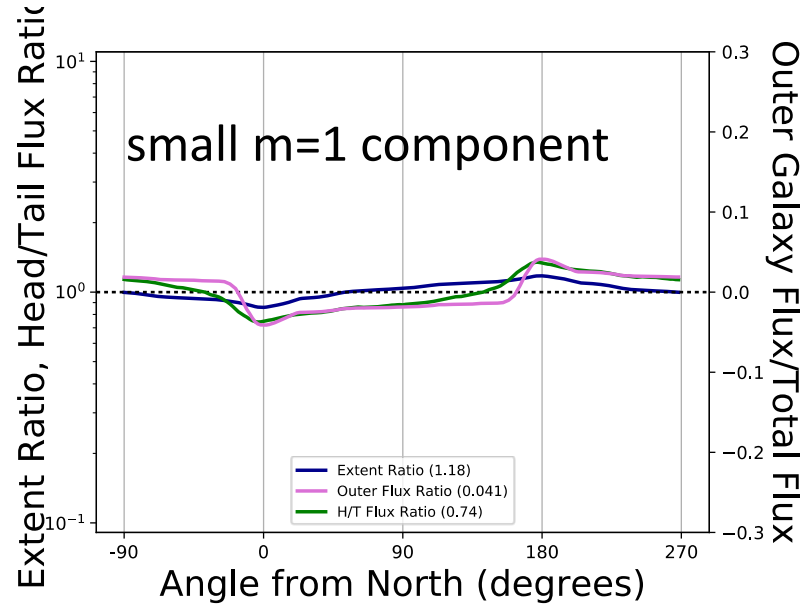
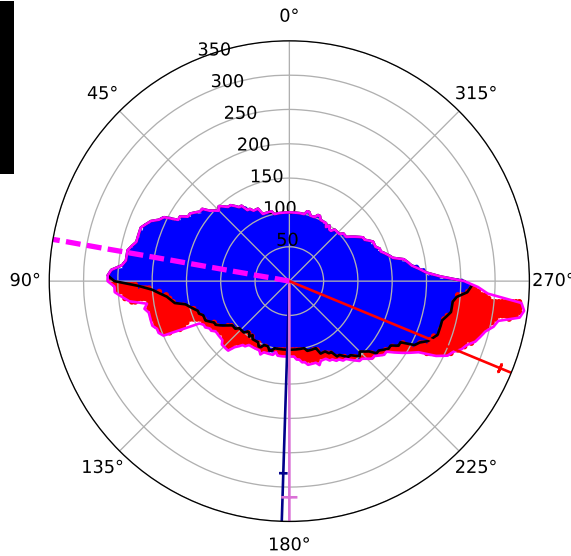
outer Virgo cluster

outer galaxy has  
stellar shells &  
linear plume due  
to minor merger

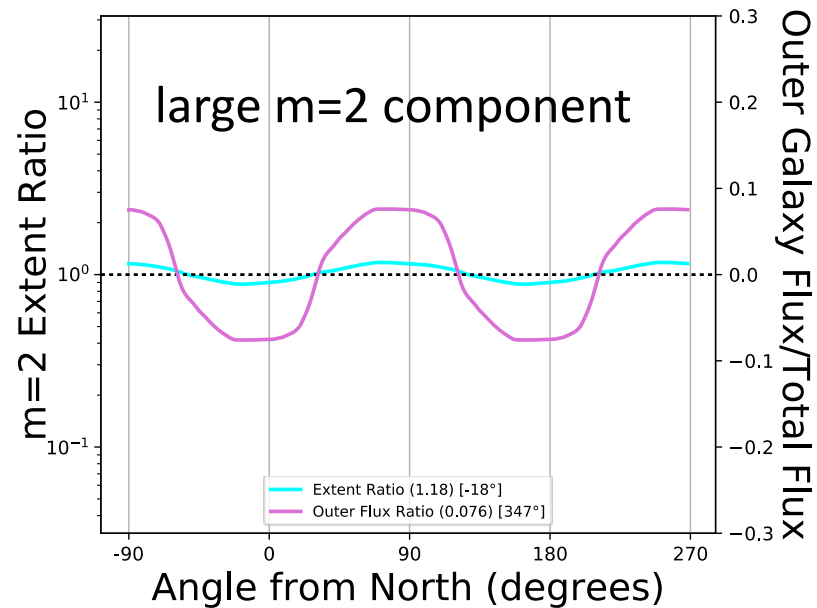
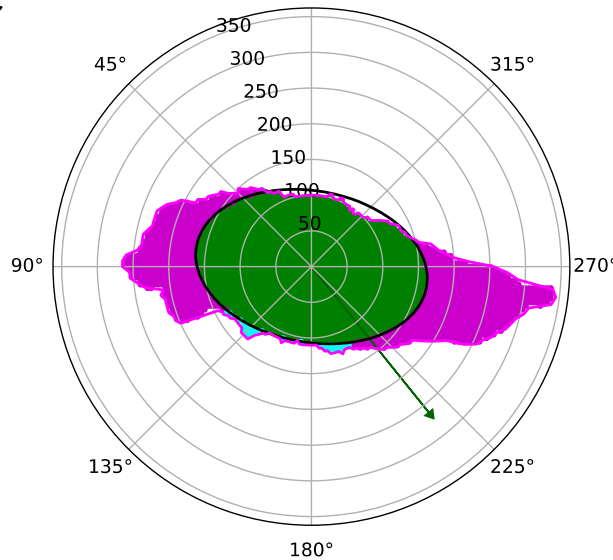


# NGC 4651

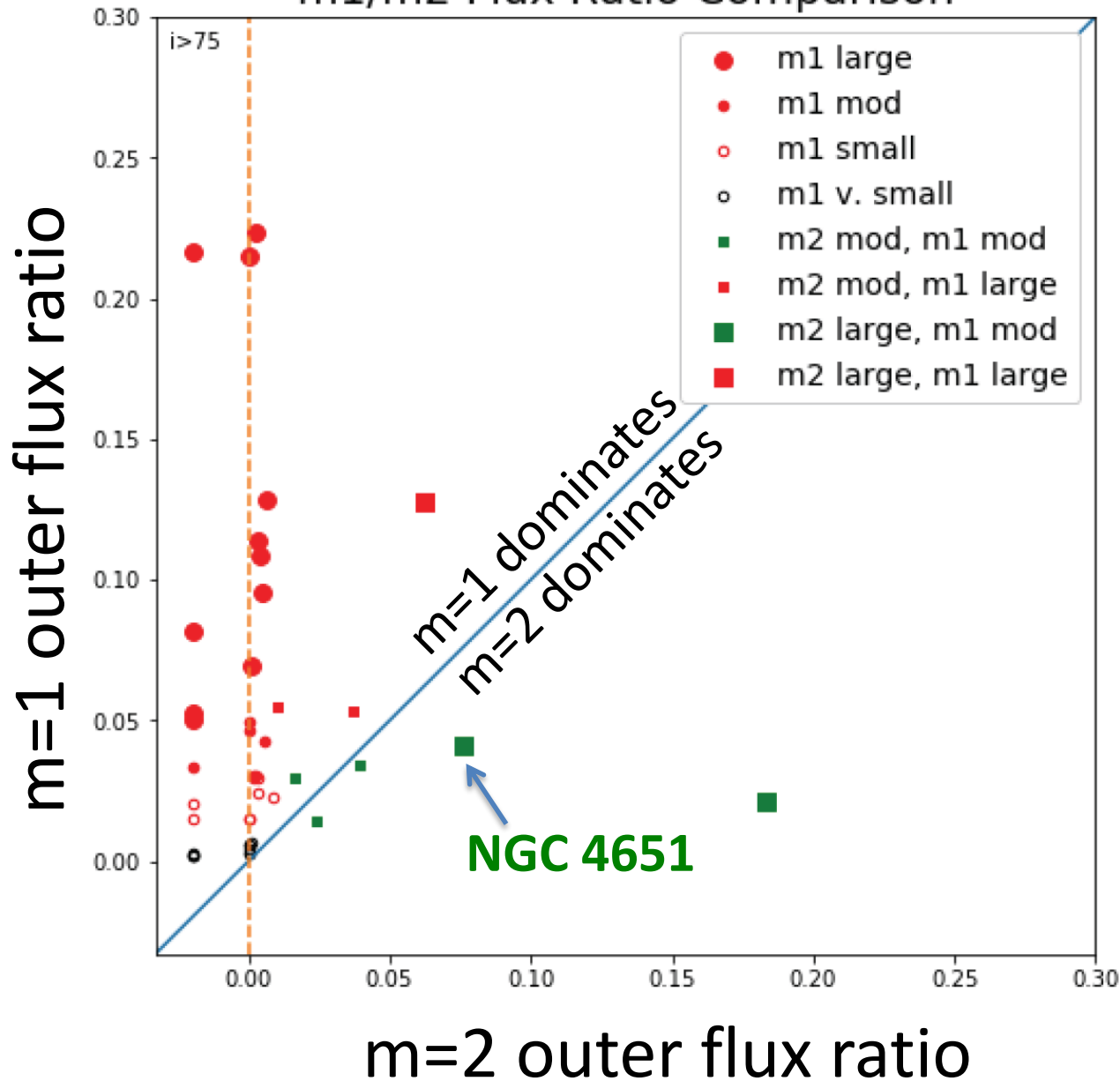
large  $m=2$  component due to minor merger  
small  $m=1$  component – irregularity in accreted thing?



*need to check for  $m=2$  as well as  $m=1$  components to be sure about rps*



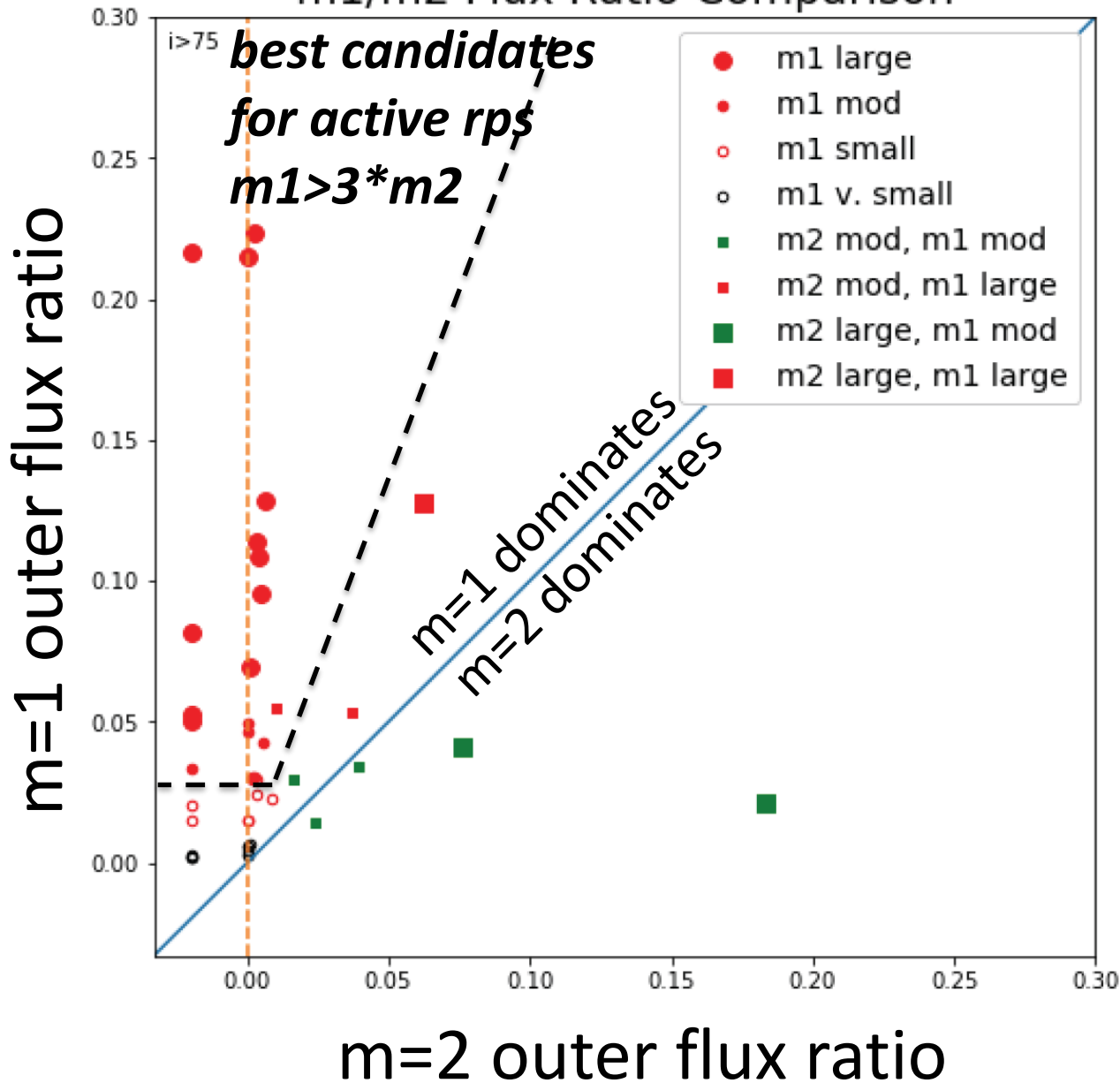
m1/m2 Flux Ratio Comparison



head-tail (m=1) vs  
m=2 components  
of outer HI gas  
distributions

**m=1 dominates in  
most Virgo spirals**

m1/m2 Flux Ratio Comparison

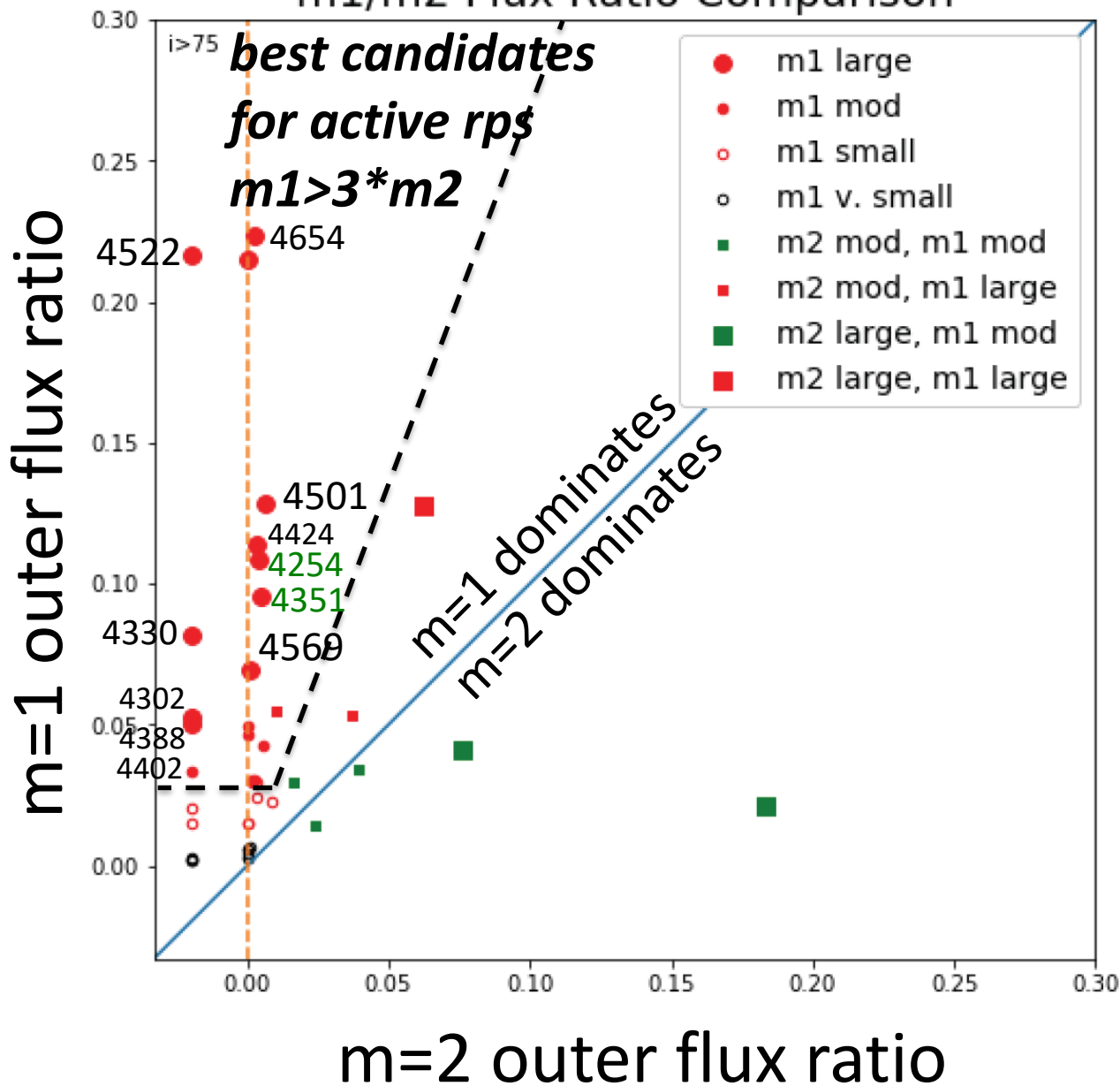


head-tail ( $m=1$ ) vs  $m=2$  components of outer HI gas distributions

$m=1$  dominates in most Virgo spirals

**>18/50 Virgo galaxies show evidence for ongoing rps**

m1/m2 Flux Ratio Comparison

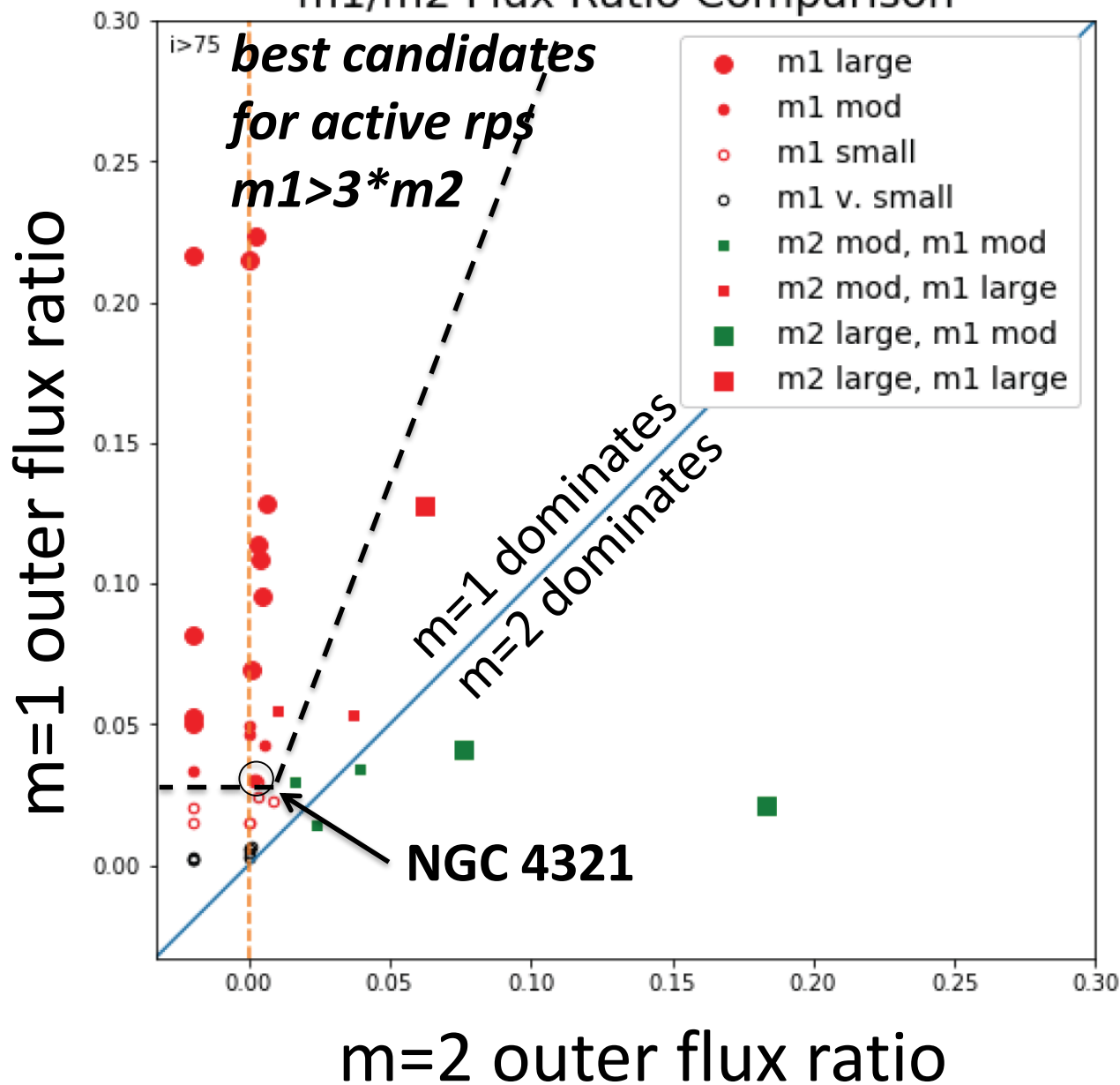


head-tail (m=1) vs  
 m=2 components  
 of outer HI gas  
 distributions

m=1 dominates in  
 most Virgo spirals

*all galaxies with  
 independent  
 evidence for active  
 rps are in expected  
 part of diagram*

## m1/m2 Flux Ratio Comparison



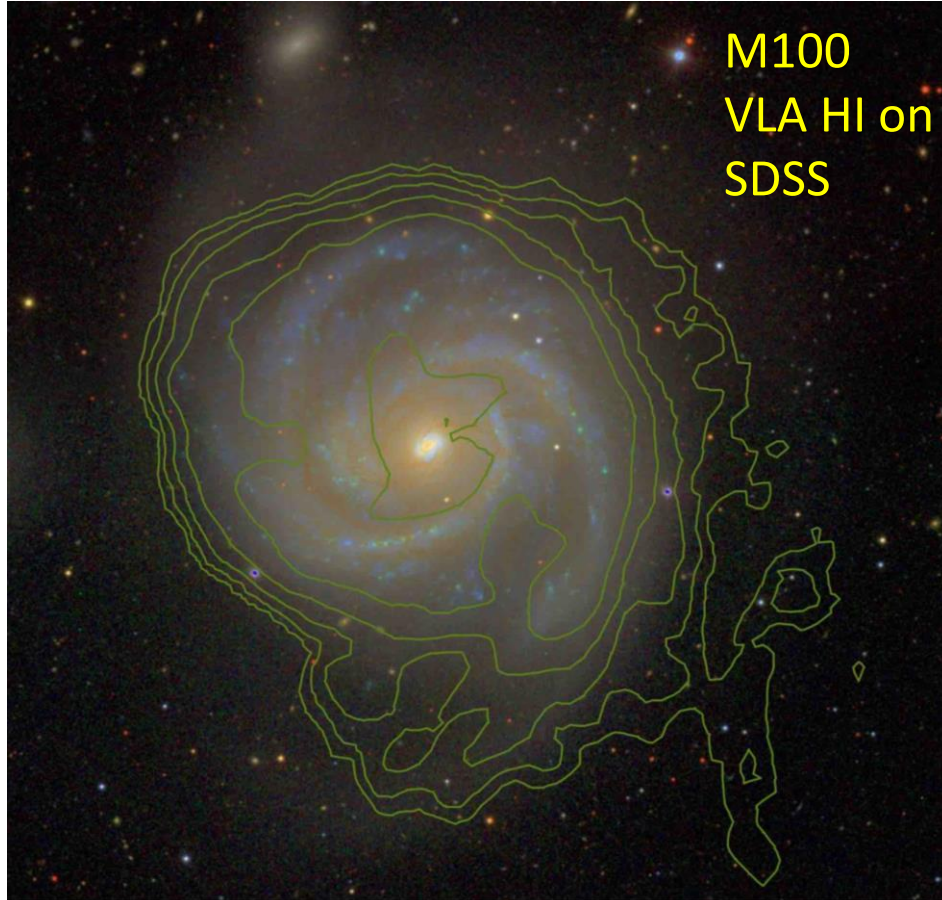
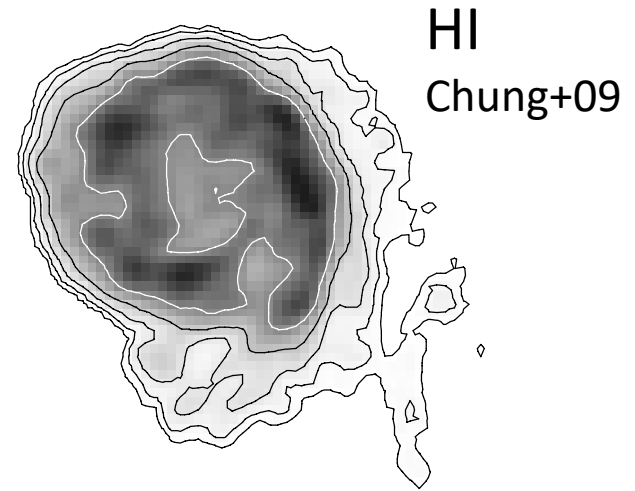
head-tail (m=1) vs  
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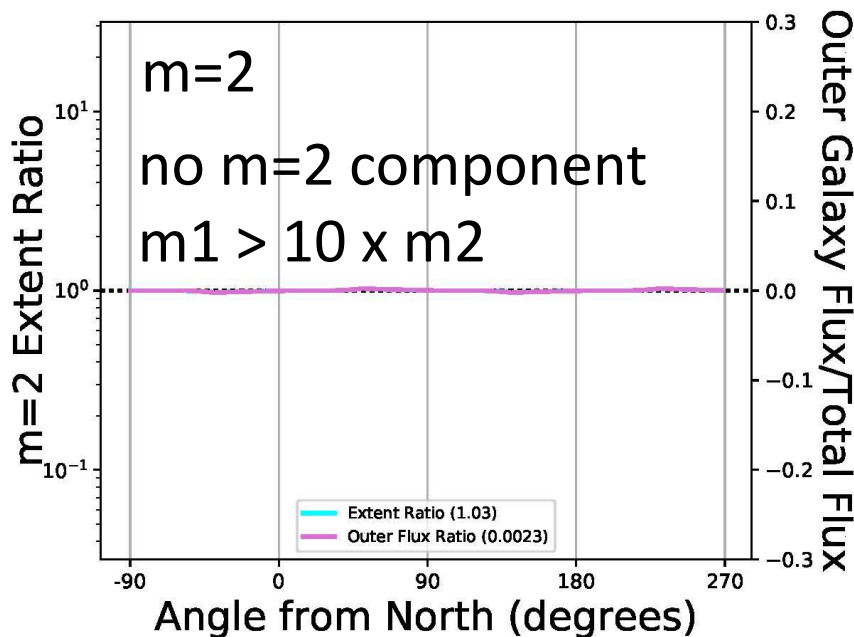
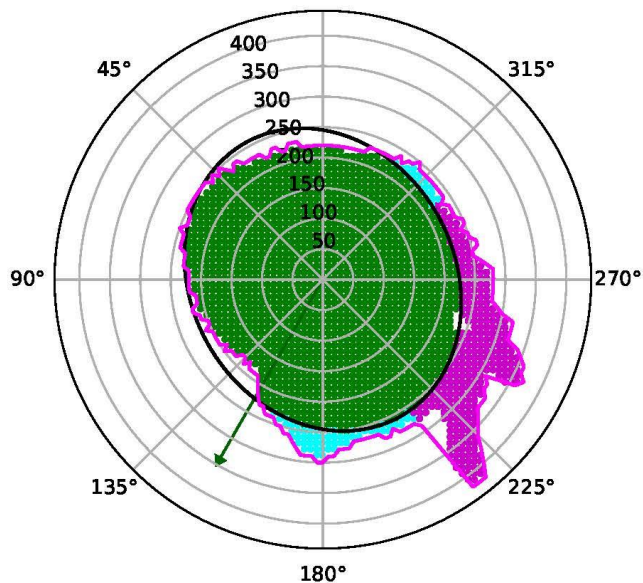
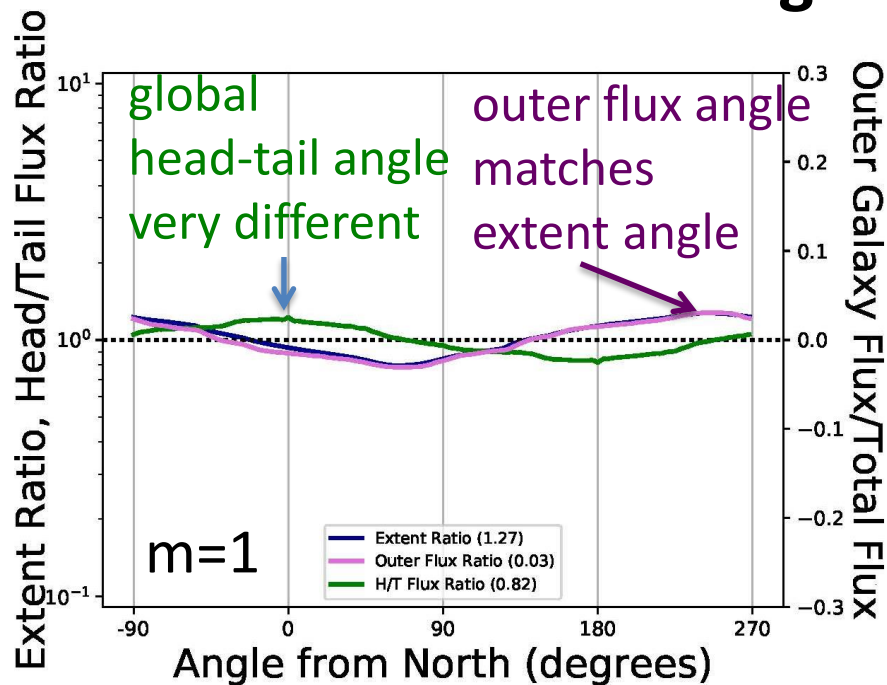
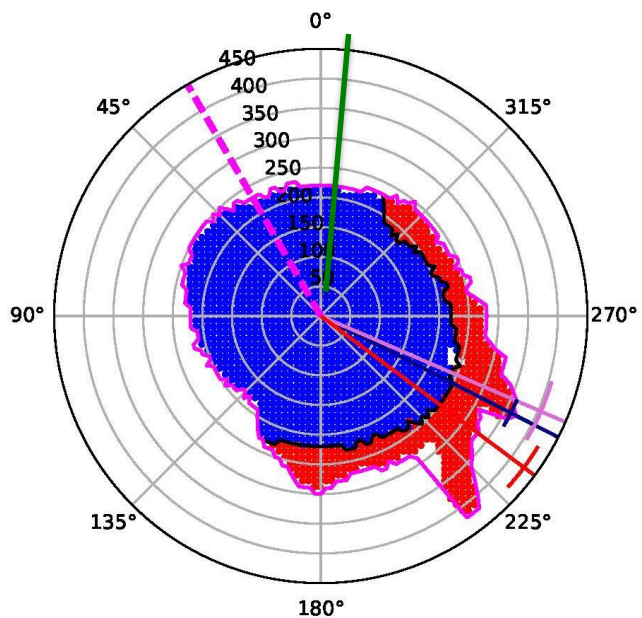
# M100 = NGC 4321

clear head-tail gas morphology &  
stellar arm without dust or young stars  
extends beyond gas truncation radius in NE



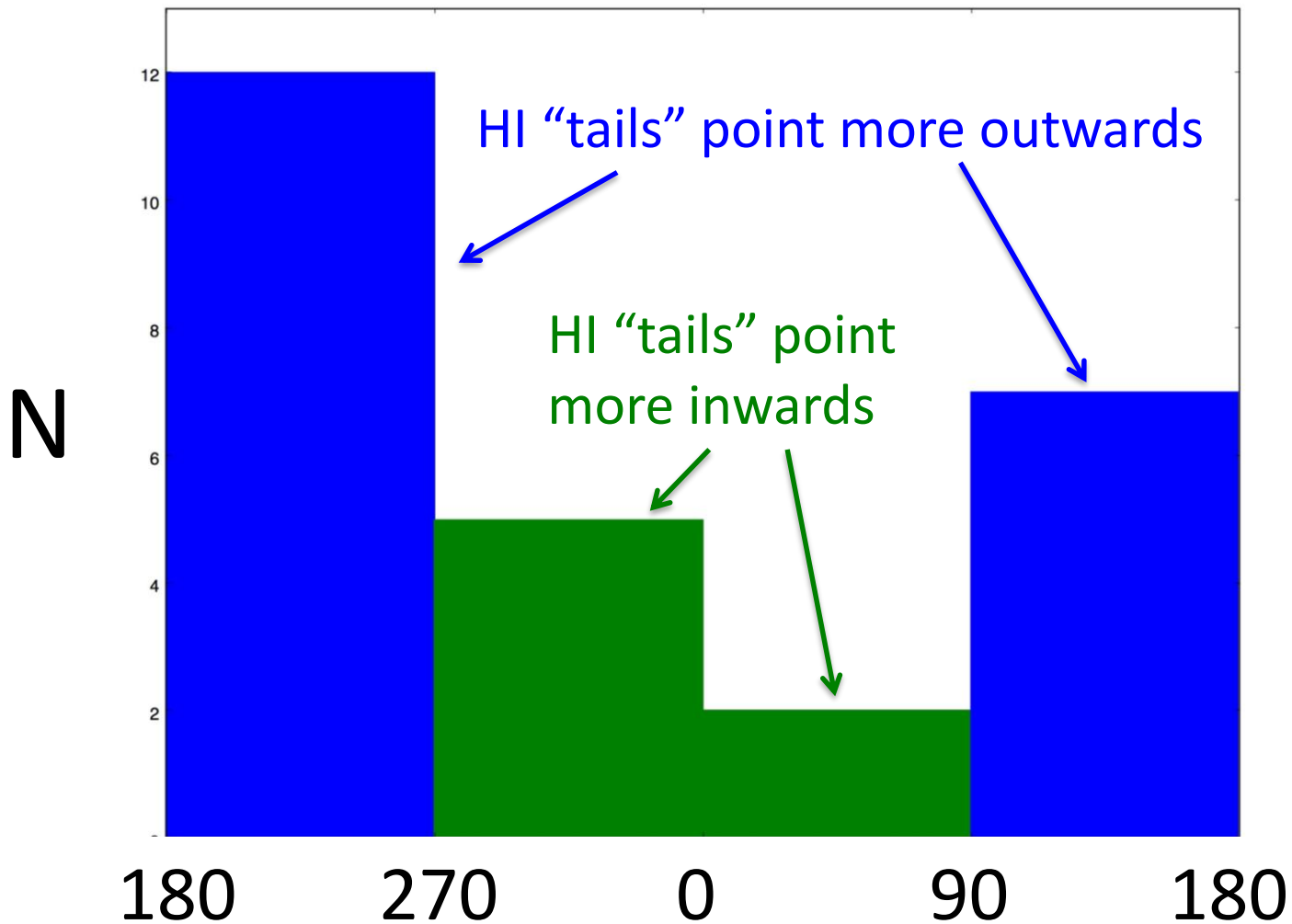
gas disk truncated in NE at  $r = 1.0 R_{25}$   
*far out so not previously recognized as clear case of rps*

# M100: only 3% of HI flux in tail but HI extent 20% greater





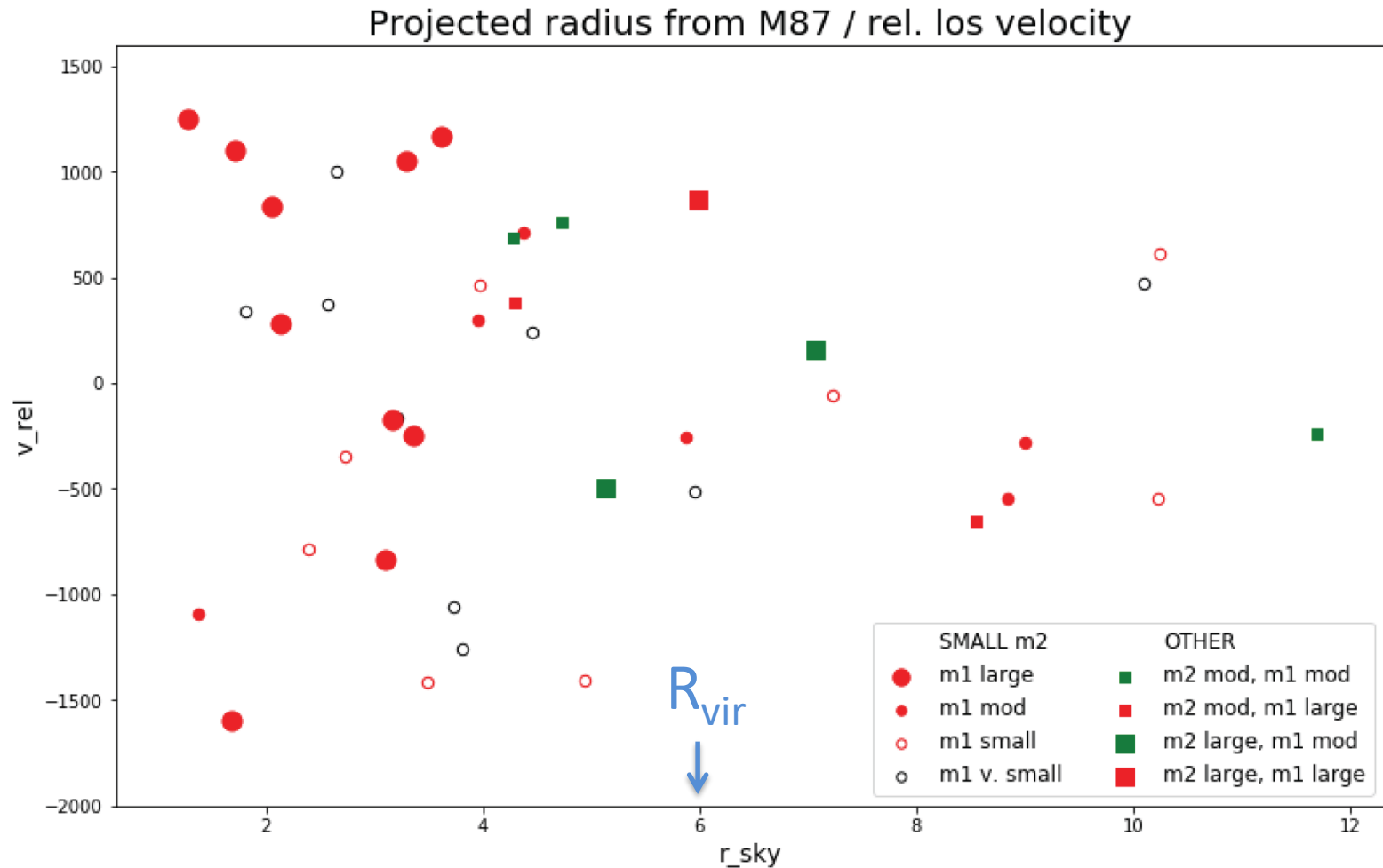
# tail angles relative to Virgo cluster center



~3x more HI tail angles point outwards

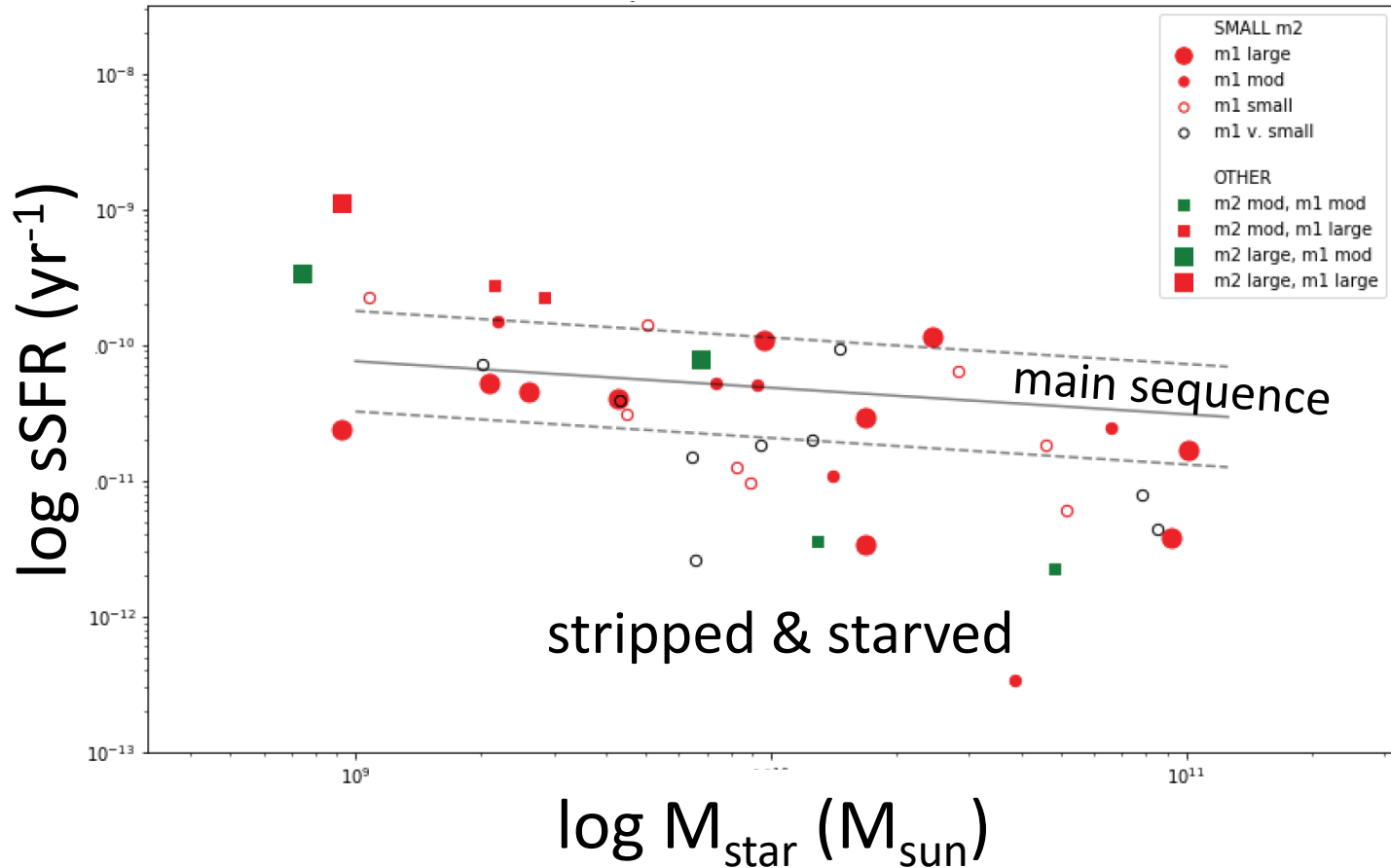
HI asymmetries more common on inward parts of orbit

# HI asymmetries in Virgo phase space diagram



all galaxies with large outer head-tail asymmetries at  $r < 0.6 R_{vir}$   
& many of these at highest velocities in ps distribution (recent infallers)  
some galaxies with moderate outer head-tail asymmetries to  $r = 1.5 R_{vir}$

# stripping & evolution of SFR



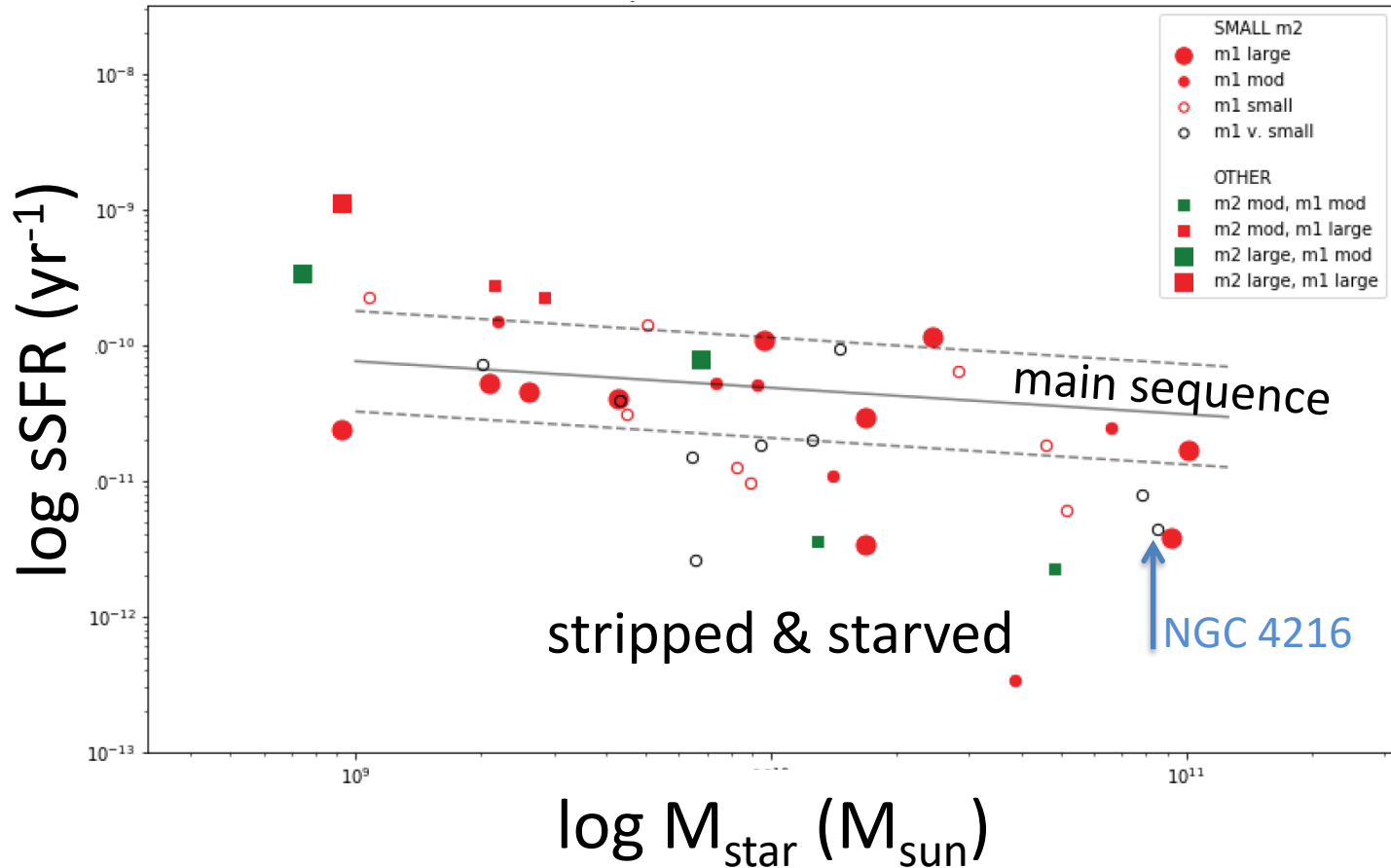
high HI asymmetry galaxies with high stripping rates:

*mostly near SF main sequence*

most quenched spiral galaxies are HI deficient with low  $\Sigma_{\text{HI}}$  and small

HI asymmetries: *post-stripped galaxies that are starved by rps*

# stripping & evolution of SFR



high HI asymmetry galaxies with high stripping rates:

*mostly near SF main sequence*

most quenched spiral galaxies are HI deficient with low  $\Sigma_{\text{HI}}$  and small

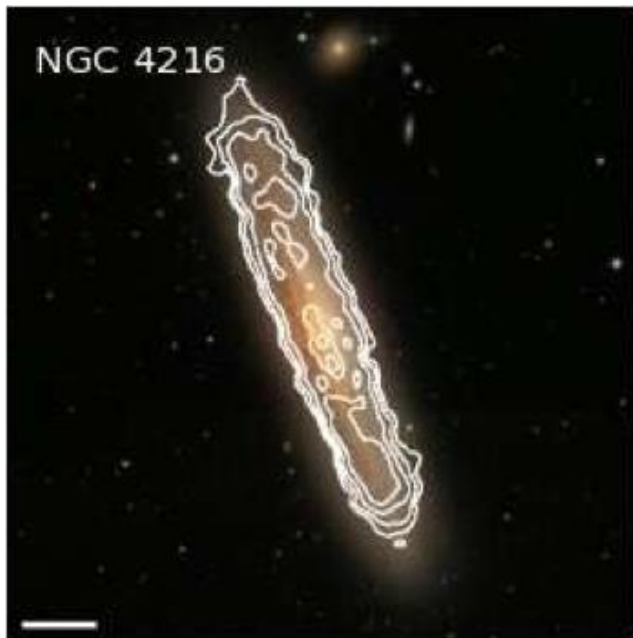
HI asymmetries: *post-stripped galaxies that are starved by rps*

# Starvation by rps

*starvation necessarily 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

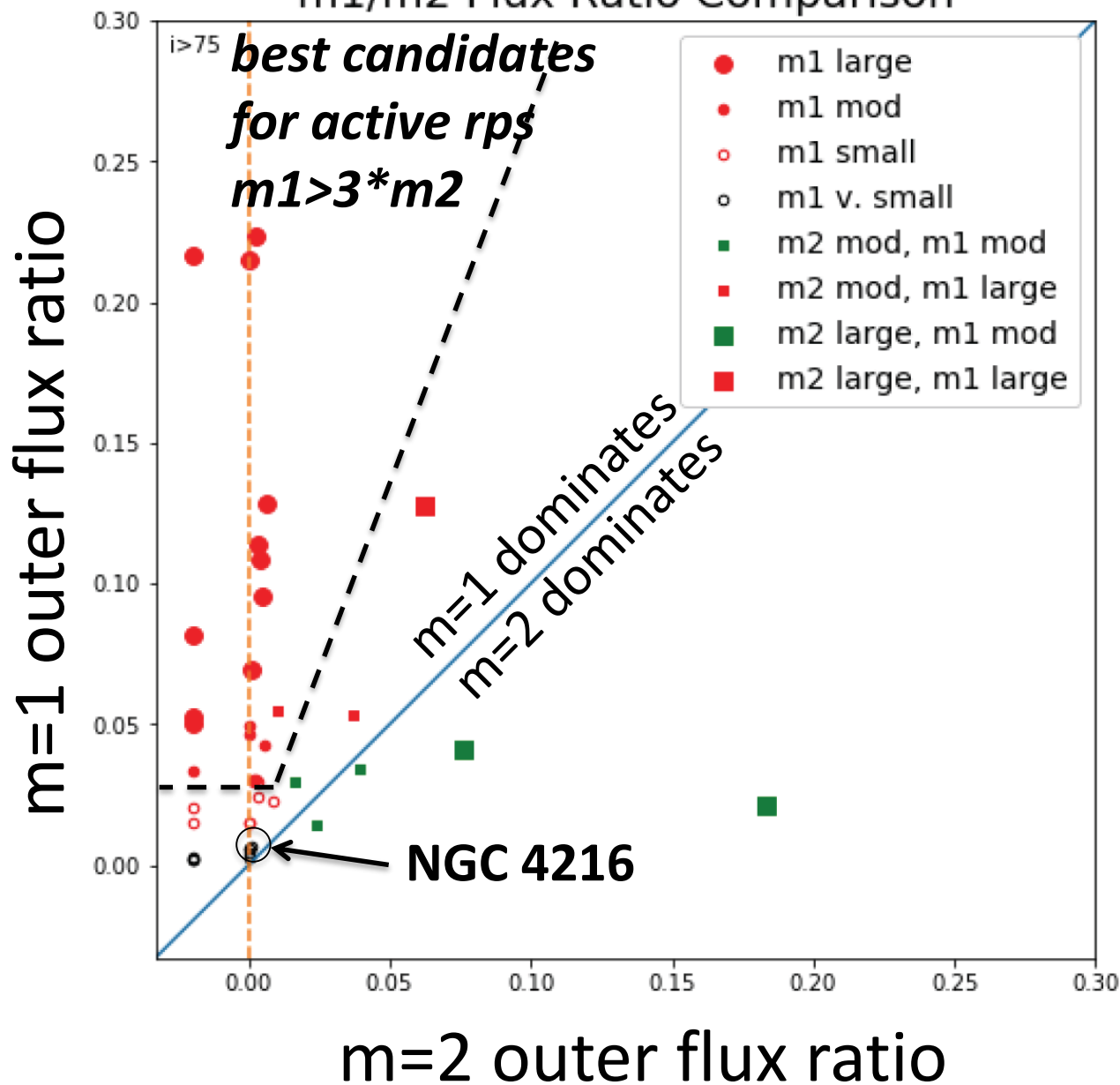
No HI beyond optical diameter

Very symmetric outer HI disk

Inner disk probably starved by past rps of outer galaxy

**Clearest example of starved galaxies?  
Spirals whose disks were partially rps a while ago**

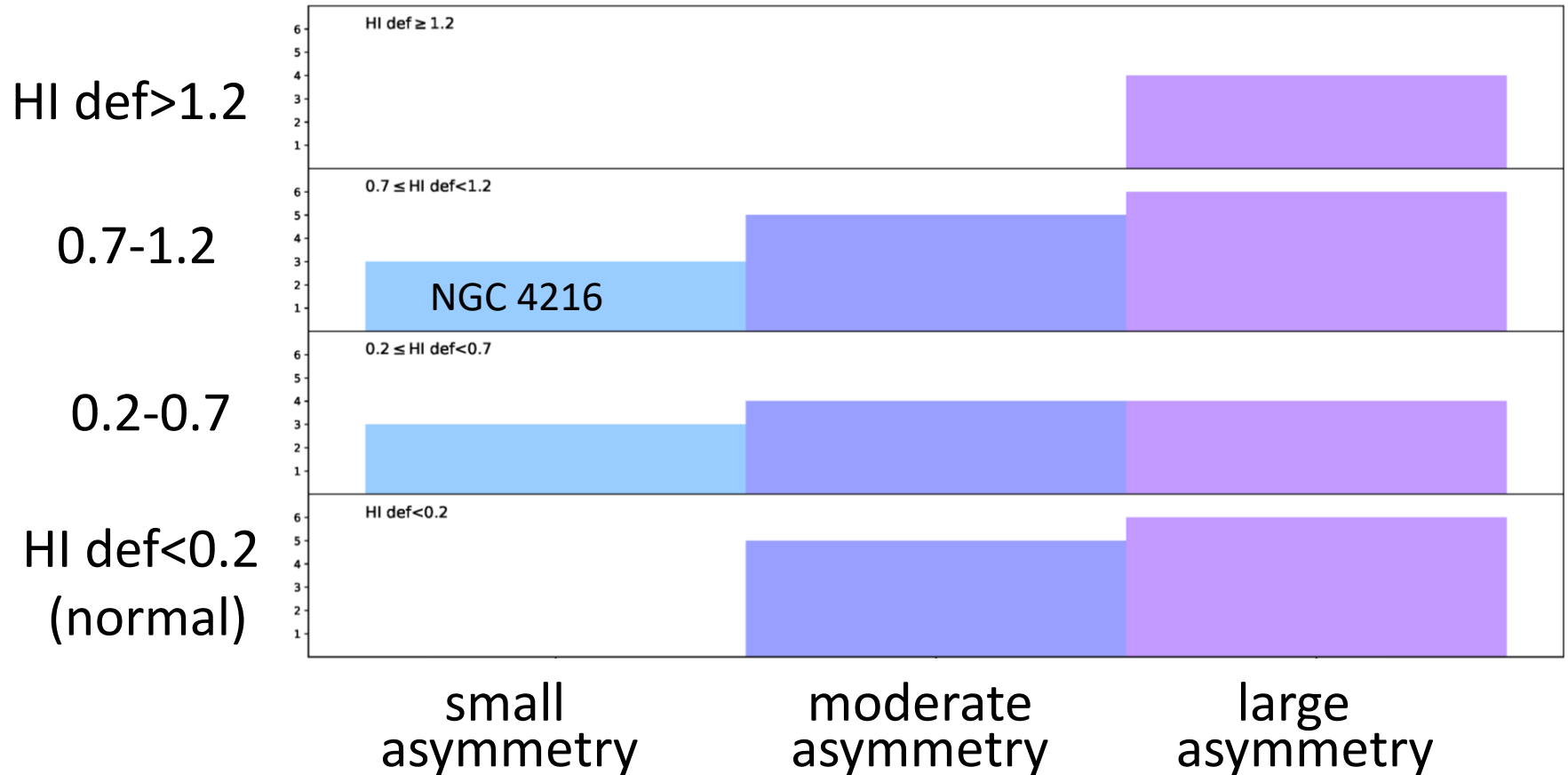
## m1/m2 Flux Ratio Comparison



head-tail ( $m=1$ ) vs  $m=2$  components of outer HI gas distributions

*some galaxies have very small outer gas asymmetries – only HI-deficient, HI-truncated galaxies*

# outer HT flux asymmetry vs HI deficiency



no HI normal galaxies with small asymmetries

all galaxies with small asymmetries are HI deficient & probably stripped

rps can symmetrize outer gas disk (weak rp acting over long time)



Herzog Luitpold  
in Bayern

# summary



Friedrich  
Attenhuber

- ***outer*** gas head-tail asymmetry is good indicator of active rps, much better than total head-tail flux ratio
- outer gas head-tail HI asymmetry *traces recent (last ~200 Myr?) stripping rate*
- most galaxies with highest asymmetries/stripping rates are still close to SF main sequence
- most galaxies below SF main sequence are HI deficient with truncated HI disks, low outer HI asymmetries and low inner HI surface densities, are **likely post-stripped galaxies that have been starved by rps of halo gas**