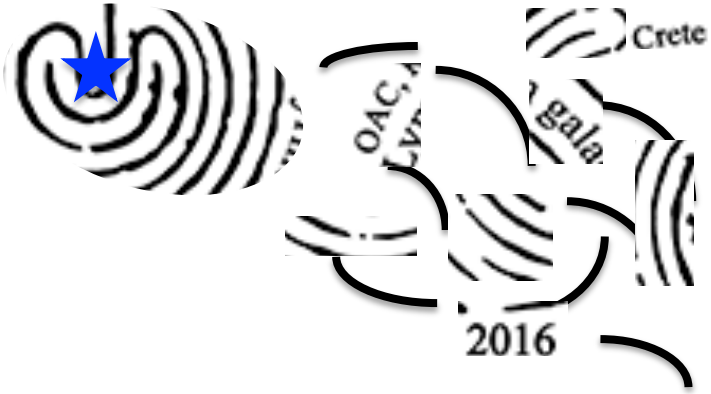
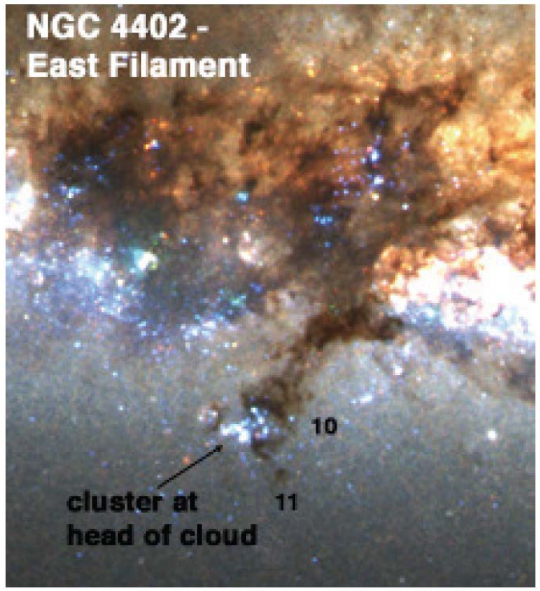
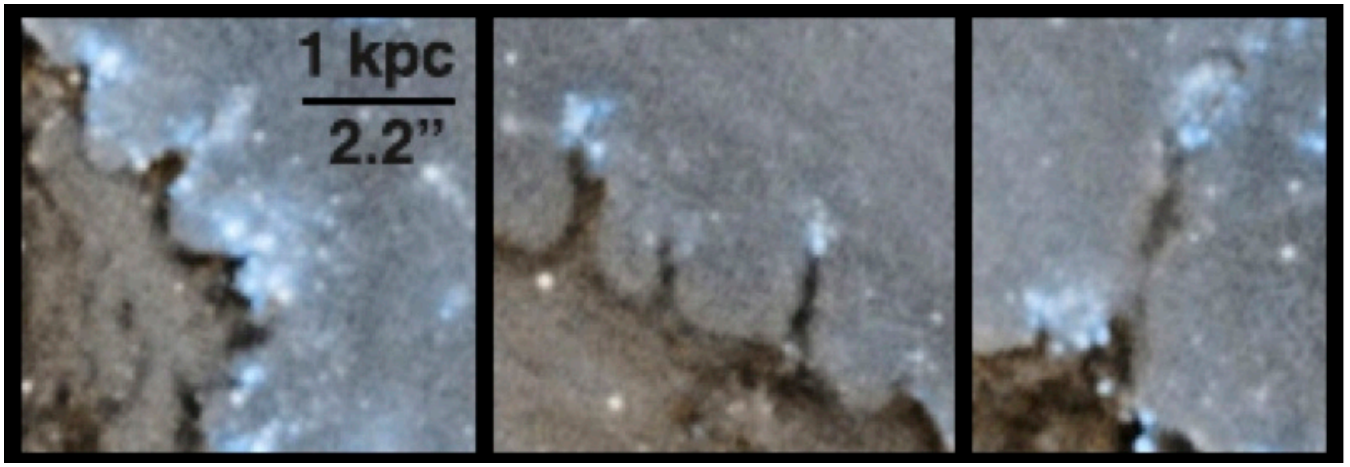
# Ram Pressure Stripping of HII Regions in Cluster Galaxies Promoting the Escape of Lyman Continuum Photons

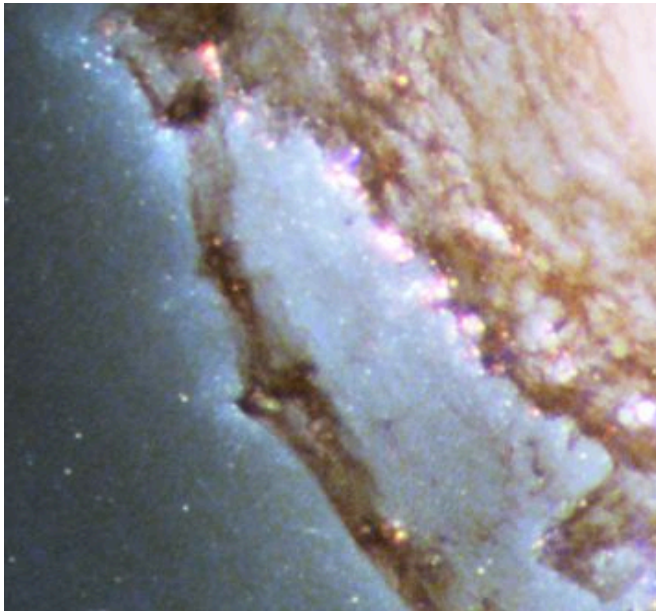
Jeff Kenney
Yale University

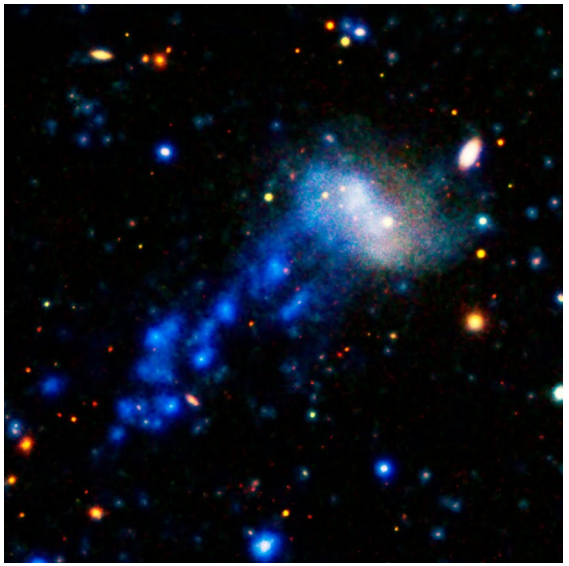
# Ram Pressure Stripping of HII Regions in Cluster Galaxies Promoting the Escape of Lyman Continuum Photons

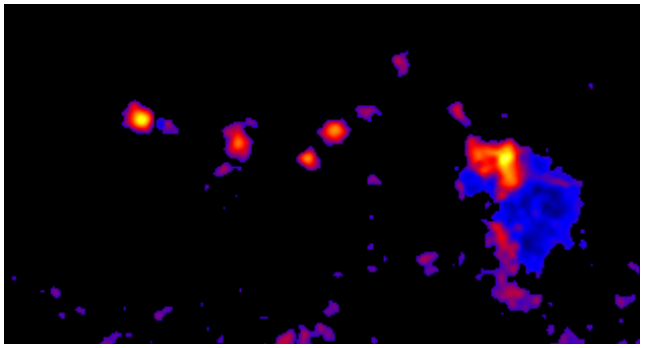


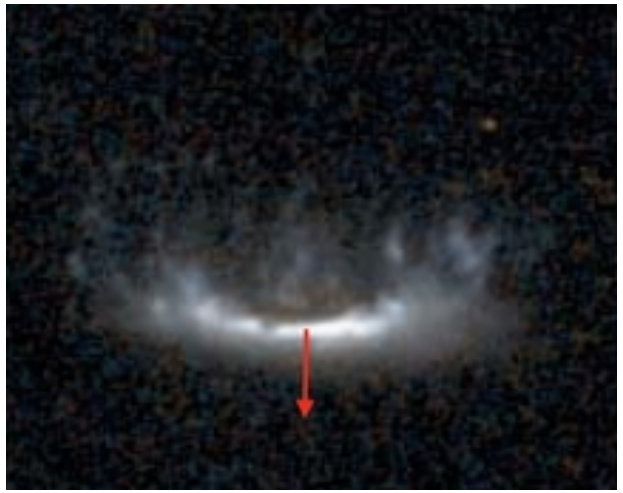






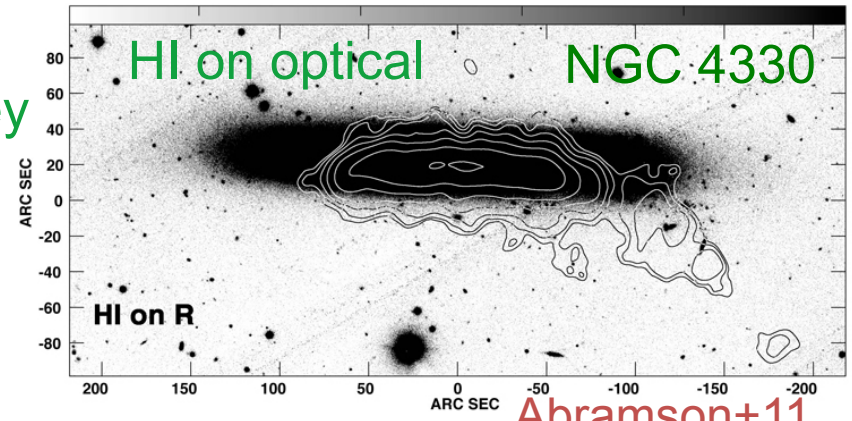


impacts of ram pressure on star forming regions

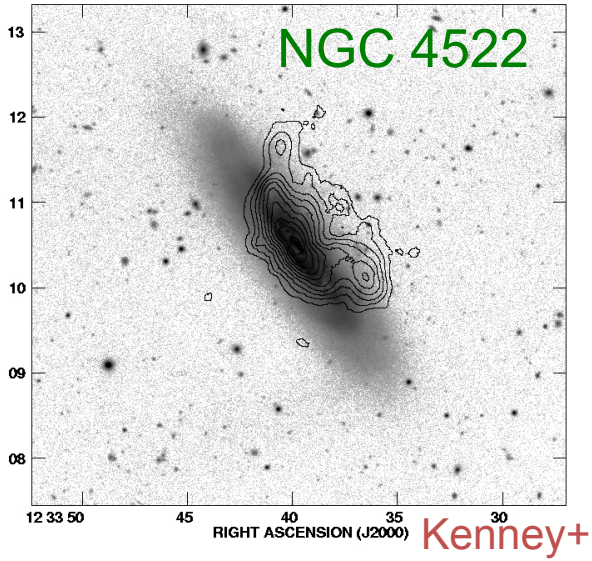
# Diagnostics of active ram pressure stripping:

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

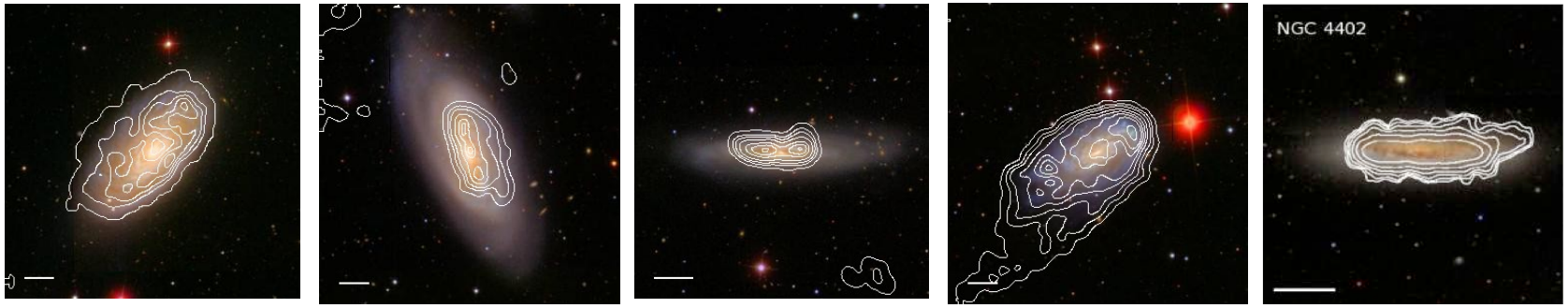
Virgo Cluster
VIVA HI survey
~50 spirals




Abramson+11




Kenney+04



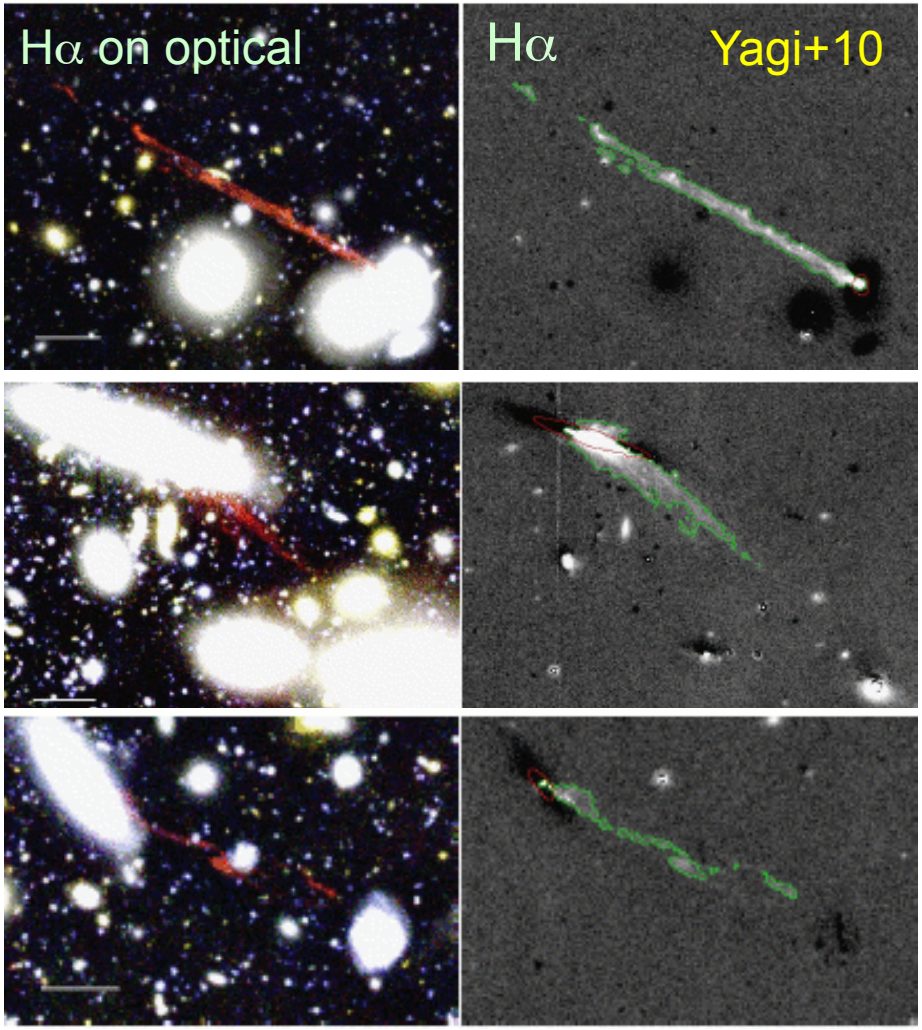

Large fraction of Virgo spirals have truncated gas disks with normal stellar disks & one-sided extraplanar gas features

Chung+09

# Peak ram pressure ~100x stronger in Coma than Virgo

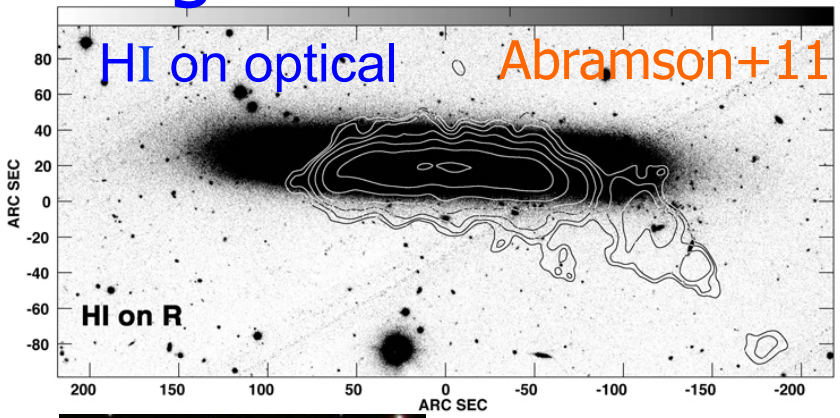
## Coma

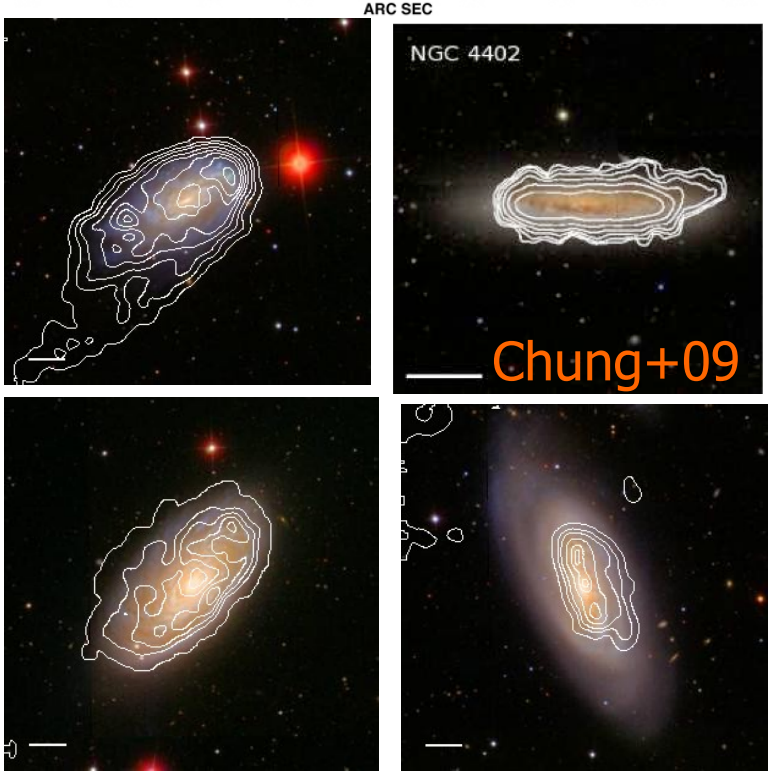
$M \sim 3 \times 10^{15} M_{sun}$
~complete stripping of spirals




## Virgo

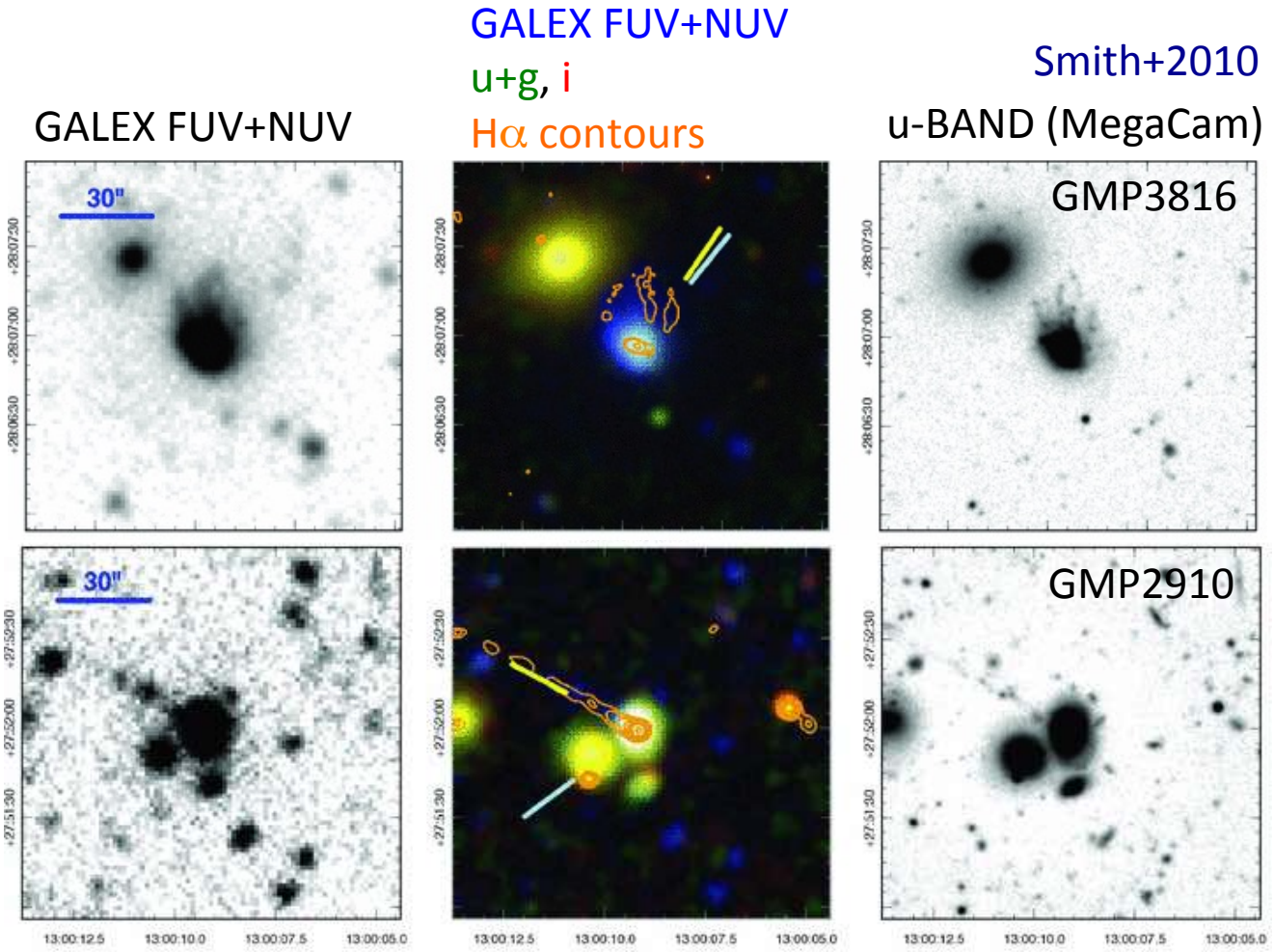
$M \sim 3 \times 10^{14} M_{sun}$
partial stripping of spirals



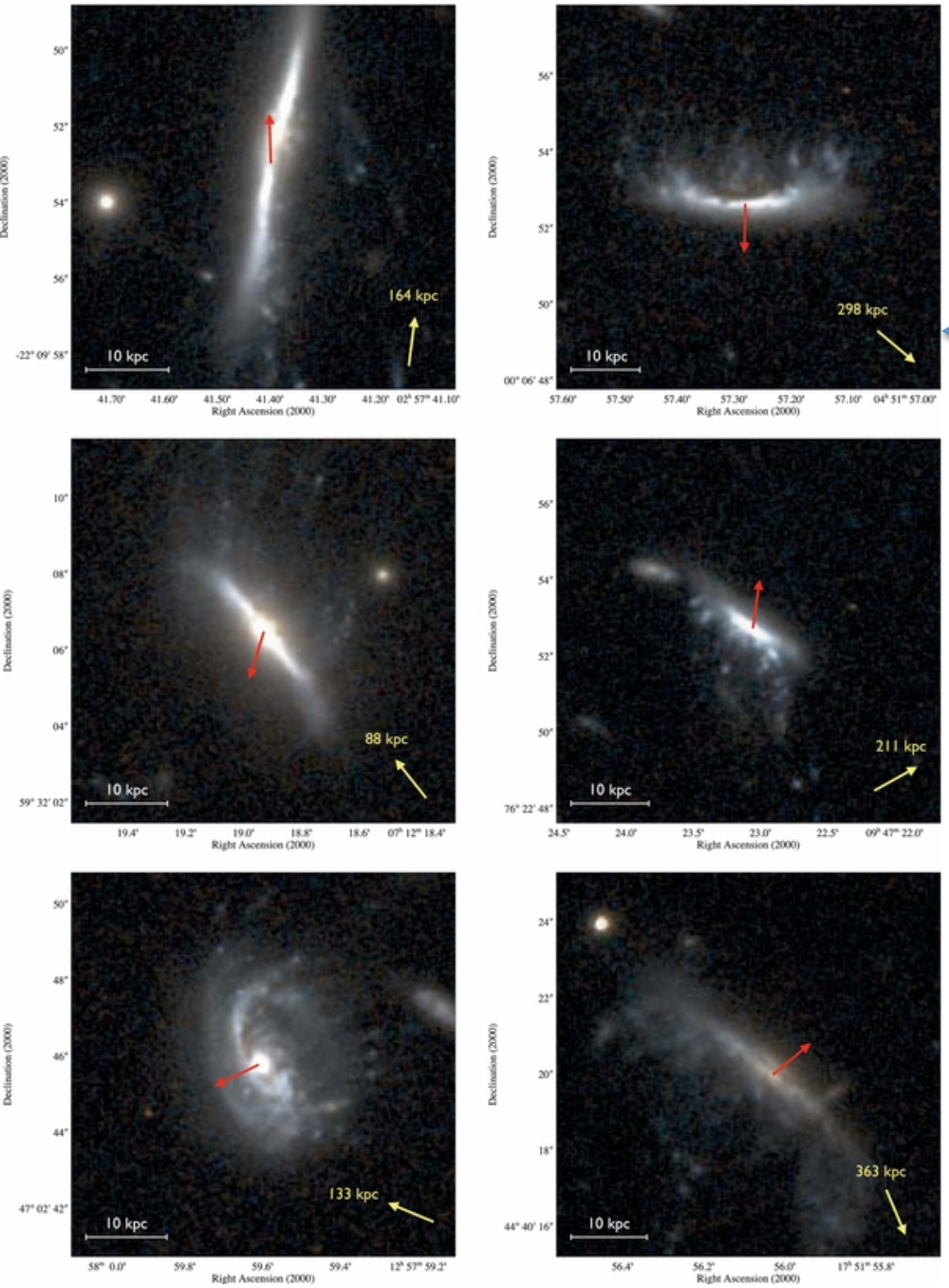




Truncated gas disks & normal stellar disks
& one-sided extraplanar gas features

# UV-bright tails of young stars in Coma galaxies undergoing rps



# “Jellyfish Galaxies”




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

HST F606+F814

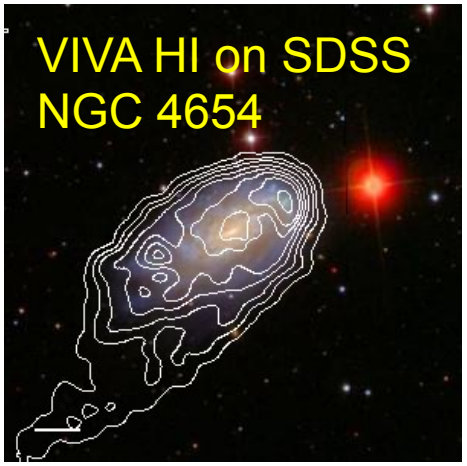
Ebeling+2014

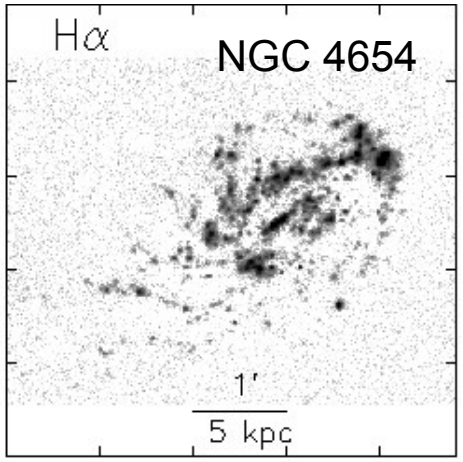

Abramson & Kenney 2014; Abramson+2016

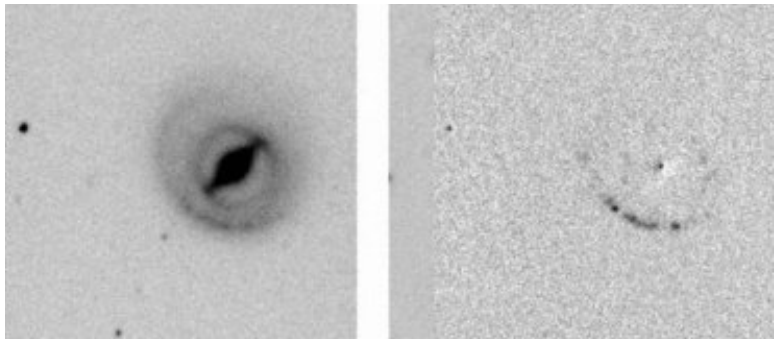
*2 places in ram pressure stripped galaxies where Lyman continuum photons from HII regions should have easier escape*

1. extraplanar tails
2. leading edge of disk

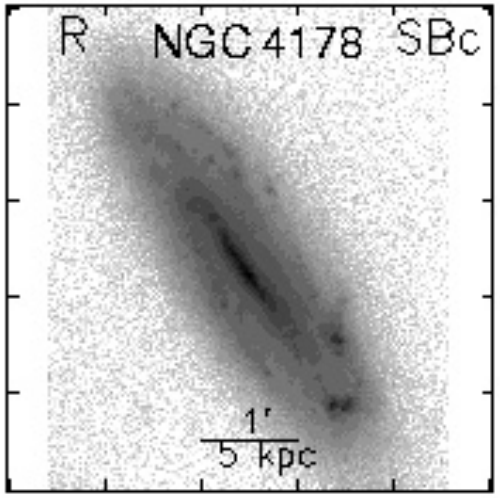
# Enhanced star formation at leading edges of galaxies undergoing ICM-ISM interactions

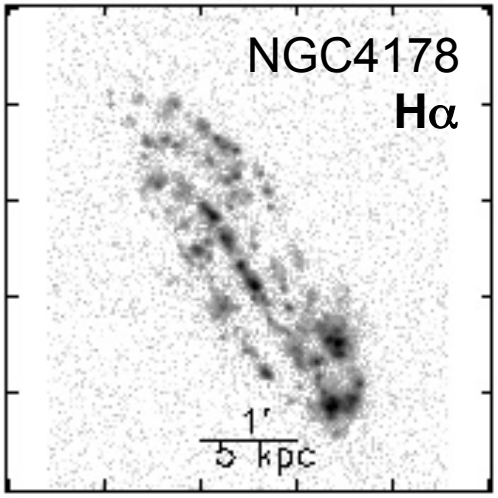


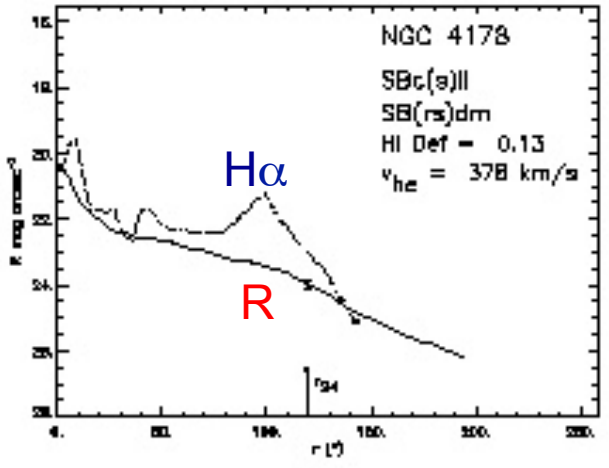



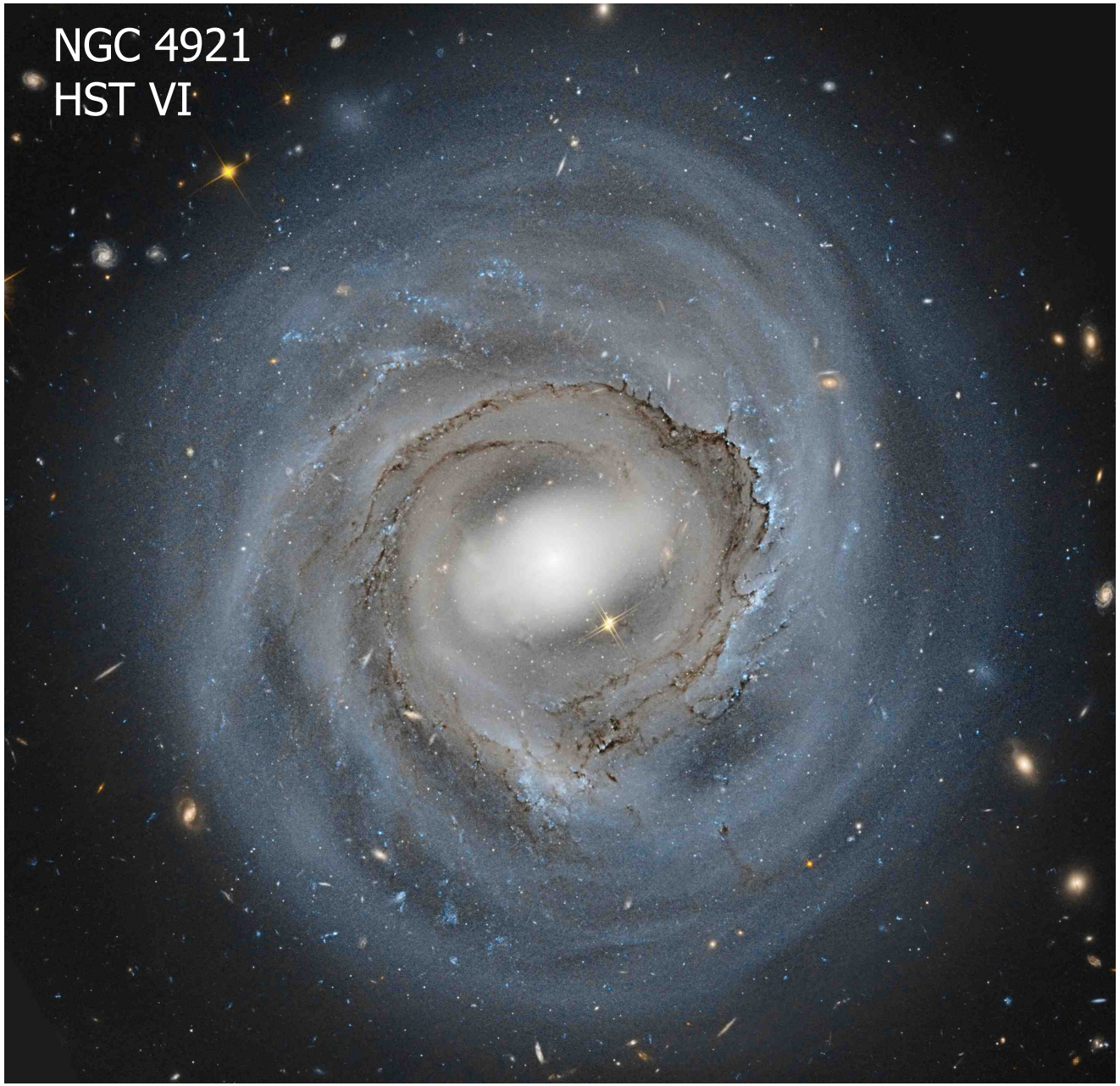
CGCG 059–019 in Pegasus I (Rose+2010)




NGC 4654, NGC 4178 in Virgo (Koopmann & Kenney 2004; Chung+2009)



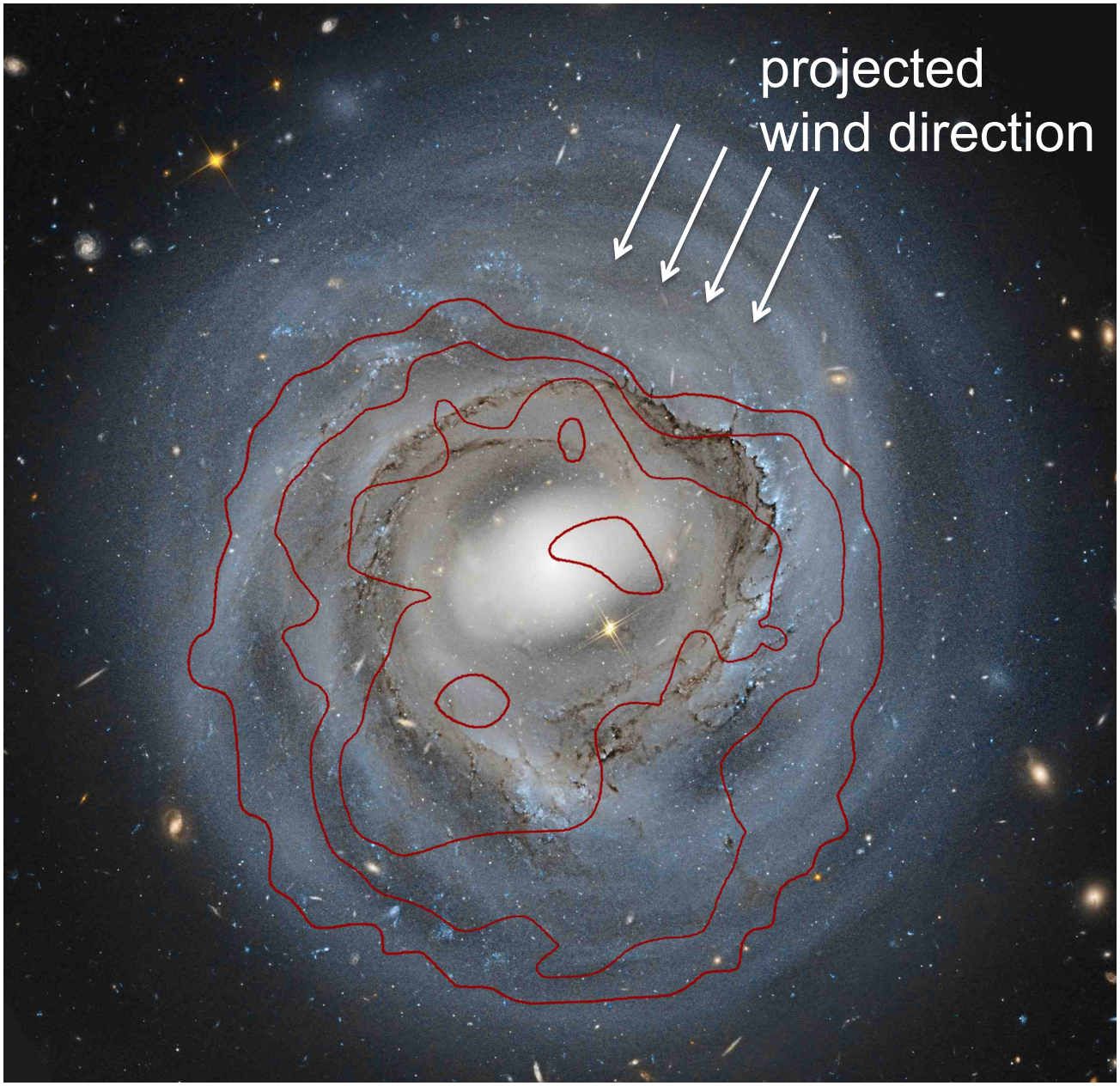

# Stripping the most massive Coma spiral

Clearest view of effects of strong ram pressure on dense ISM in spiral disk

HST resolution
0.05” = 30 pc at
Coma (D=100 Mpc)

Deep image (17 hrs)
V (F606W) 62 ksec
I (F814W) 37 ksec

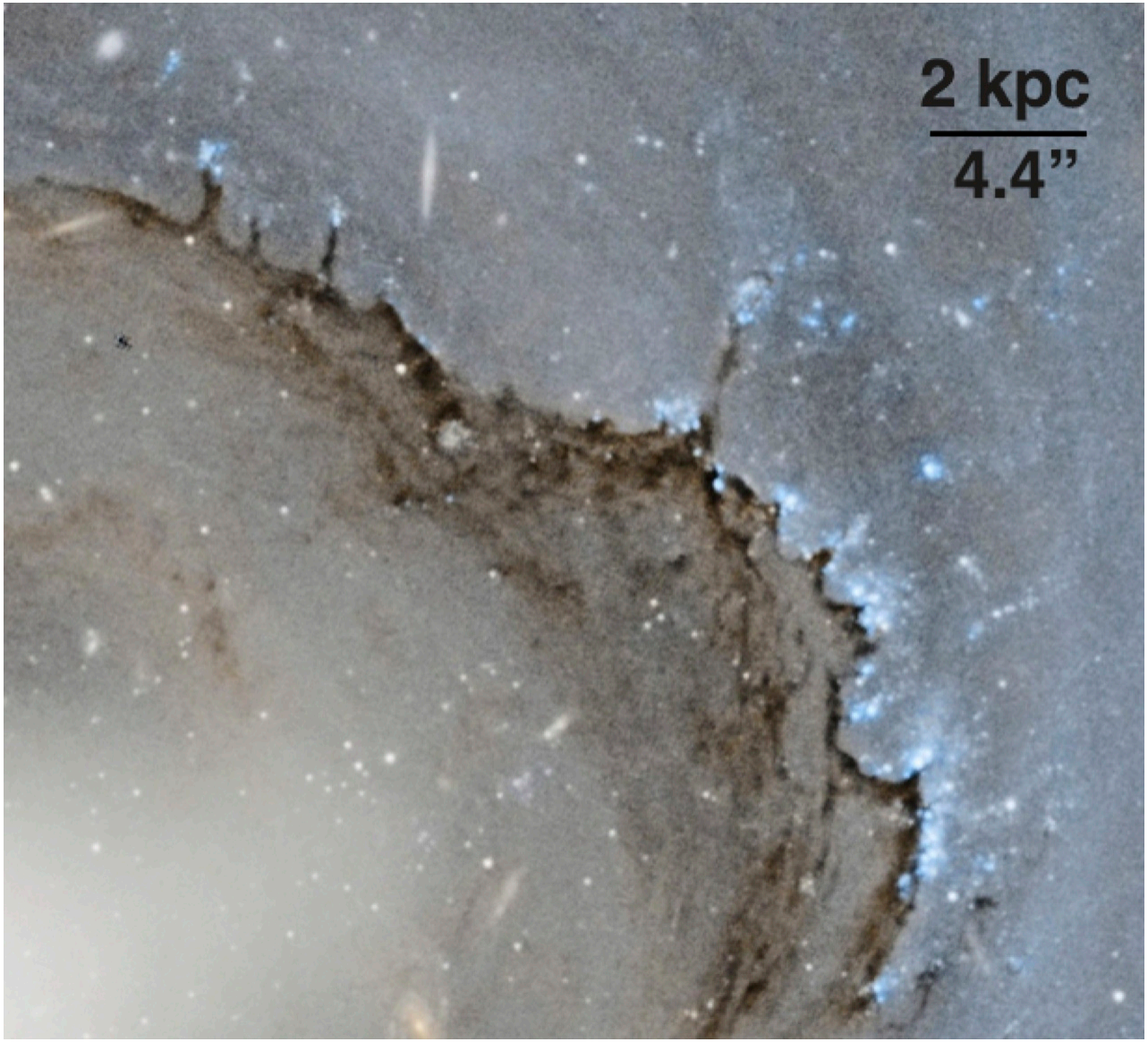
HST data obtained by K. Cook for Cepheid program Image by Roberto Colombari




# HI (VLA) on HST image of NGC 4921

Kenney, Abramson
& Bravo-Alfaro 2015

HI disk is truncated & asymmetric; compressed in NW, extended in SE



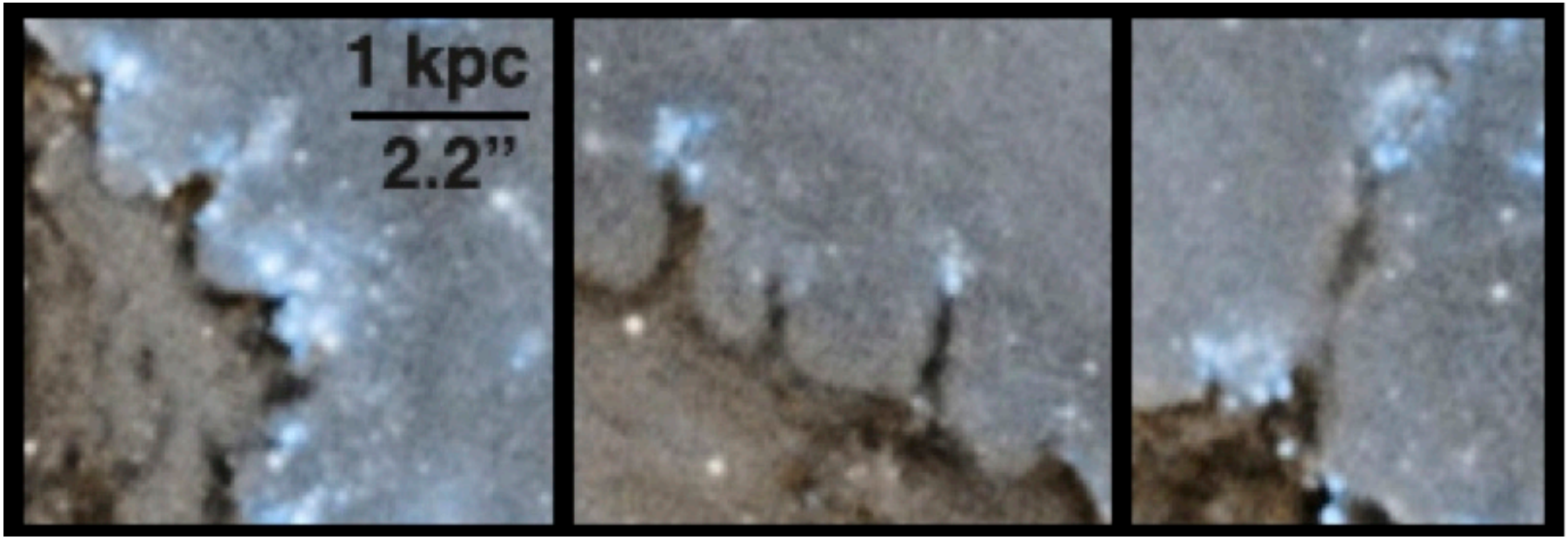

“Dust front” in Coma spiral NGC 4921

Extends
90 deg = 20 kpc

Kenney+2015

“Dust front” = Swept-up gas and dust along leading edge of ram pressure interaction

# V-shaped & ~Linear head-tail dust filaments with young star complexes at heads protruding from dust front

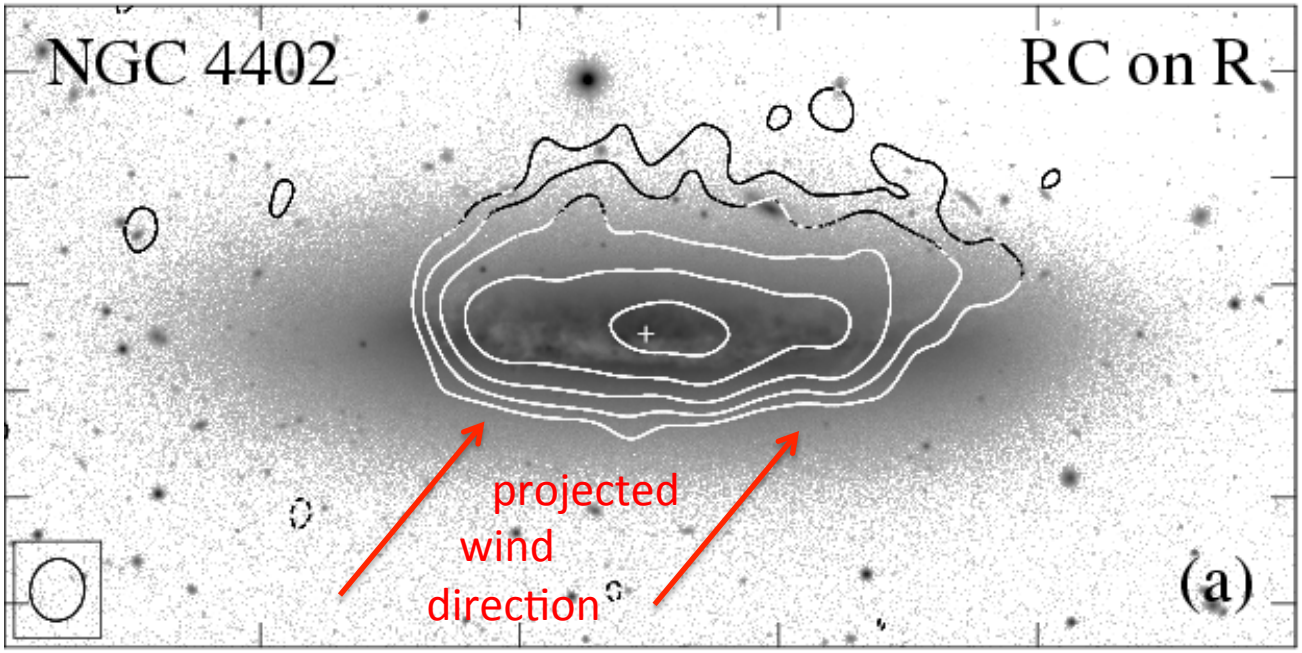



Proposed evolutionary sequence of dense cloud decoupling

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***

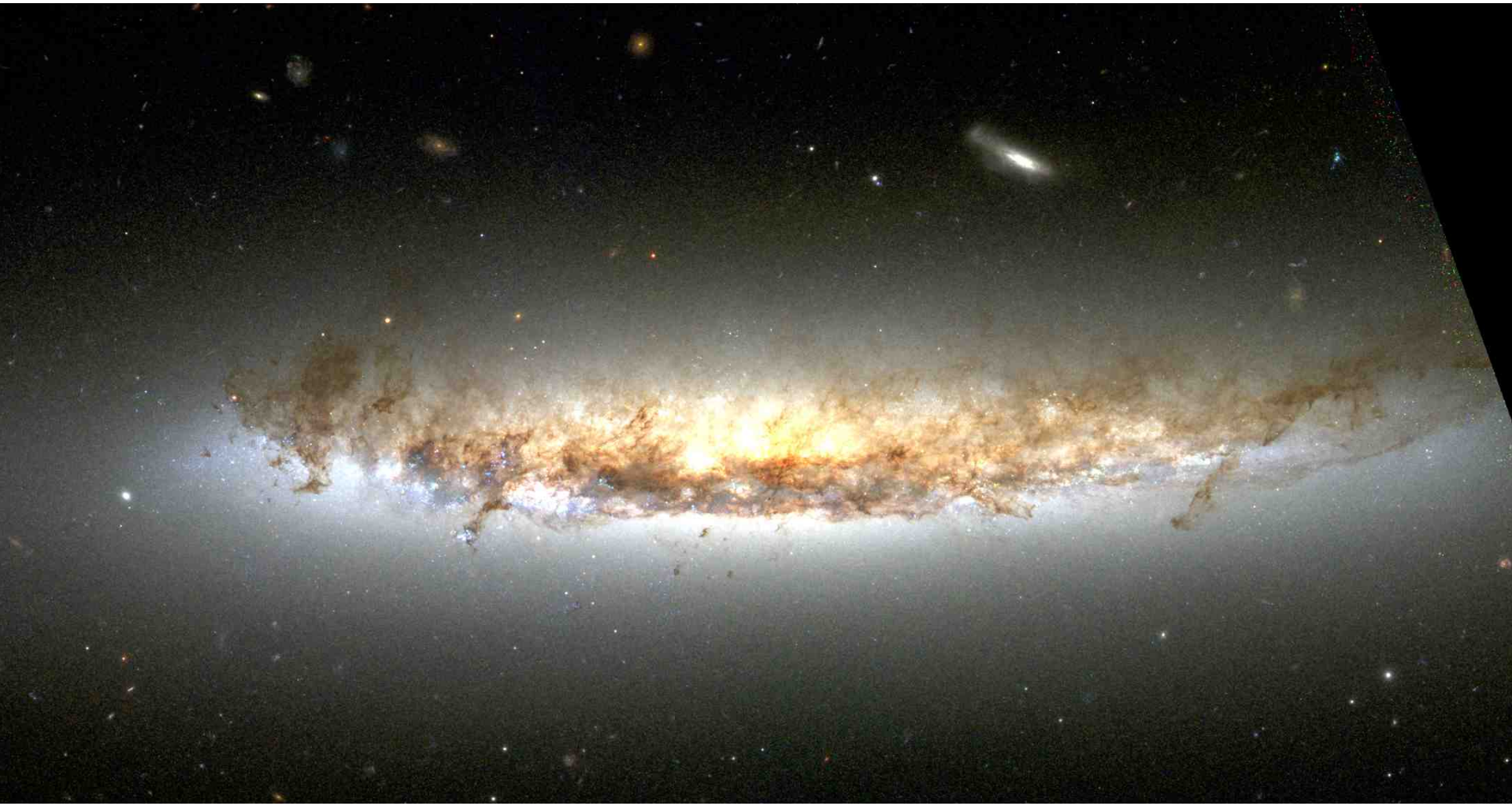
***much of surrounding dust (& gas?) blown away by ram pressure, making it easier for Lyman continuum photons to escape***

# stripped Virgo spiral NGC 4402

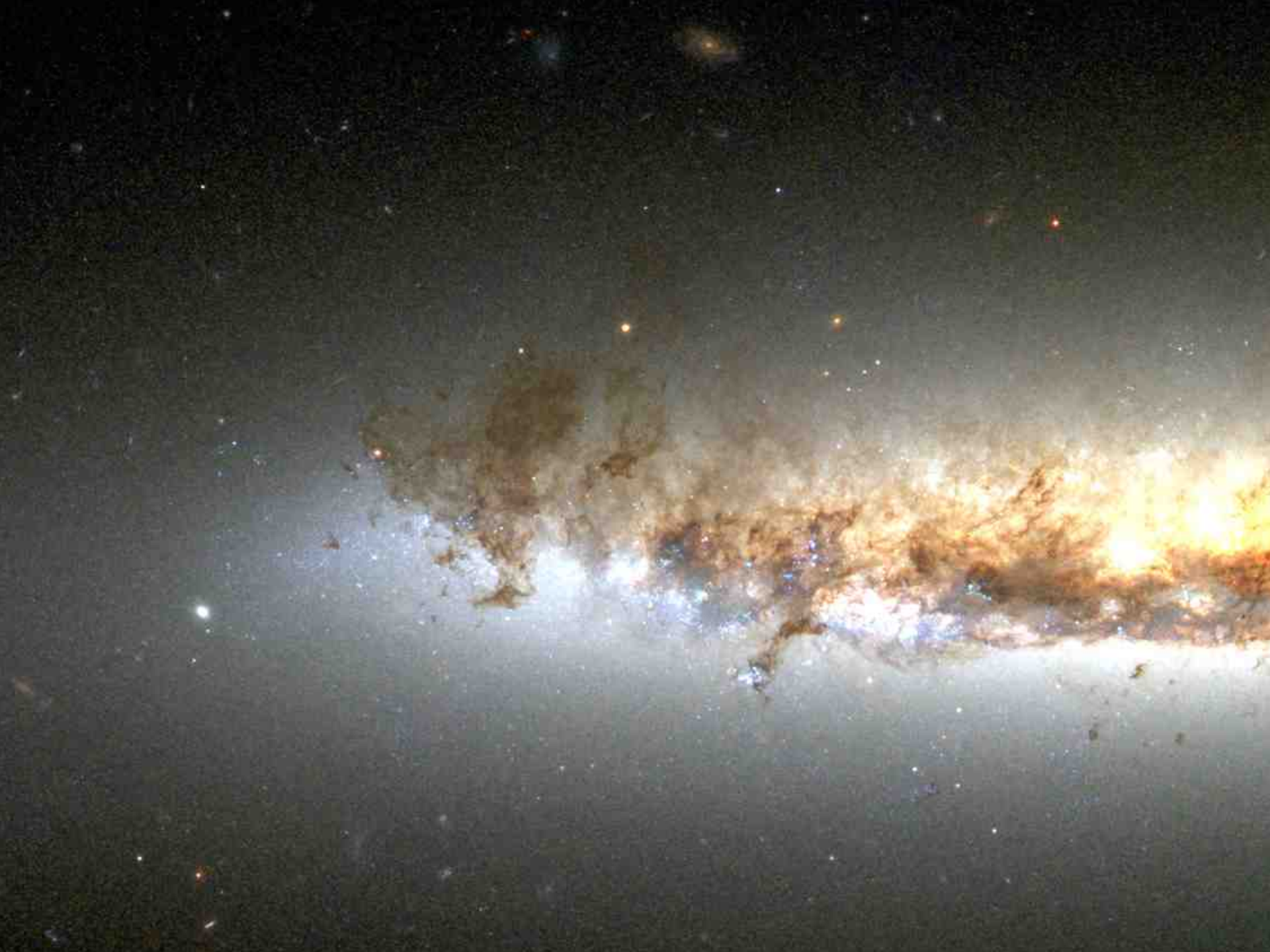


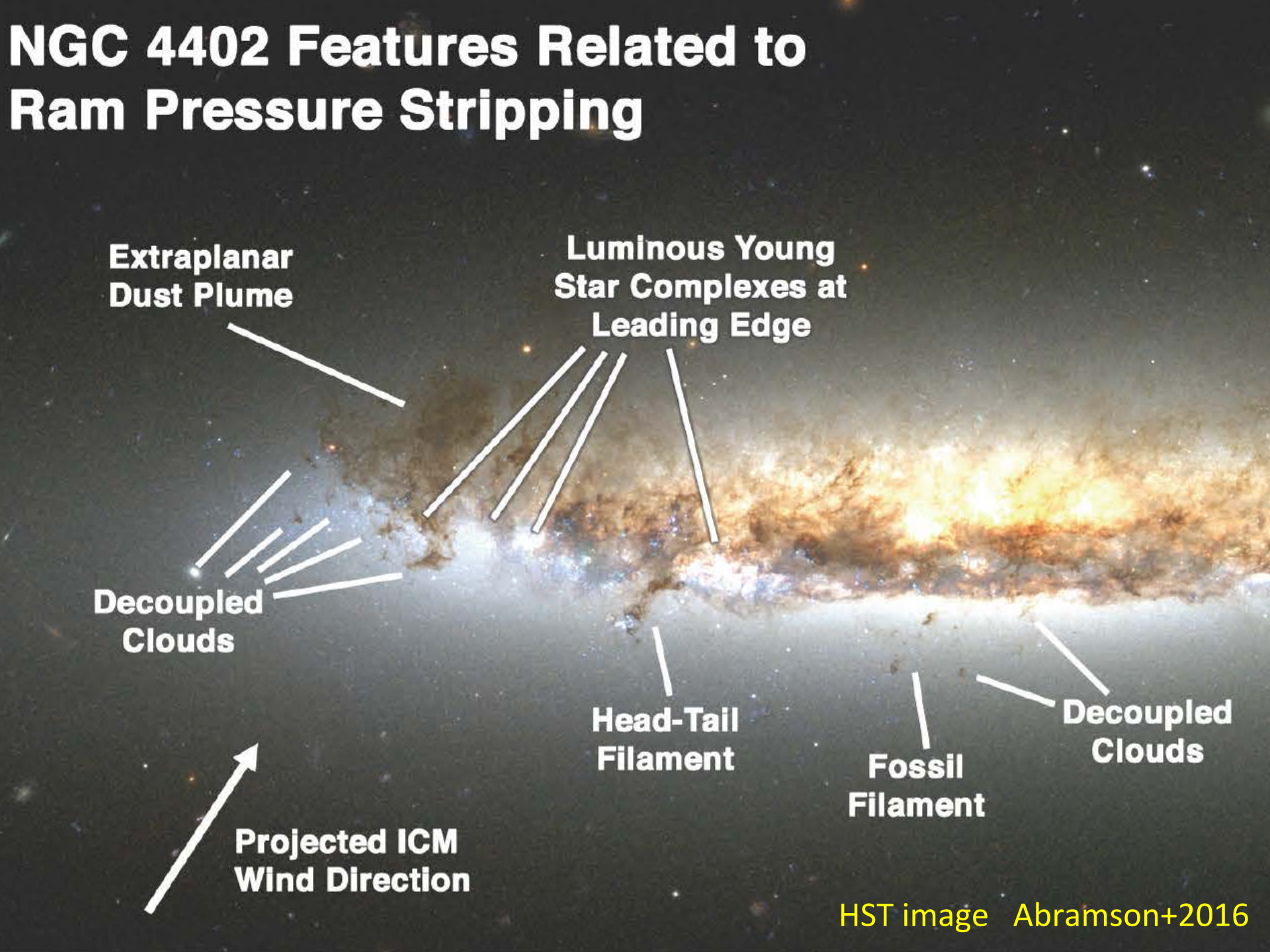

Crowl+2005

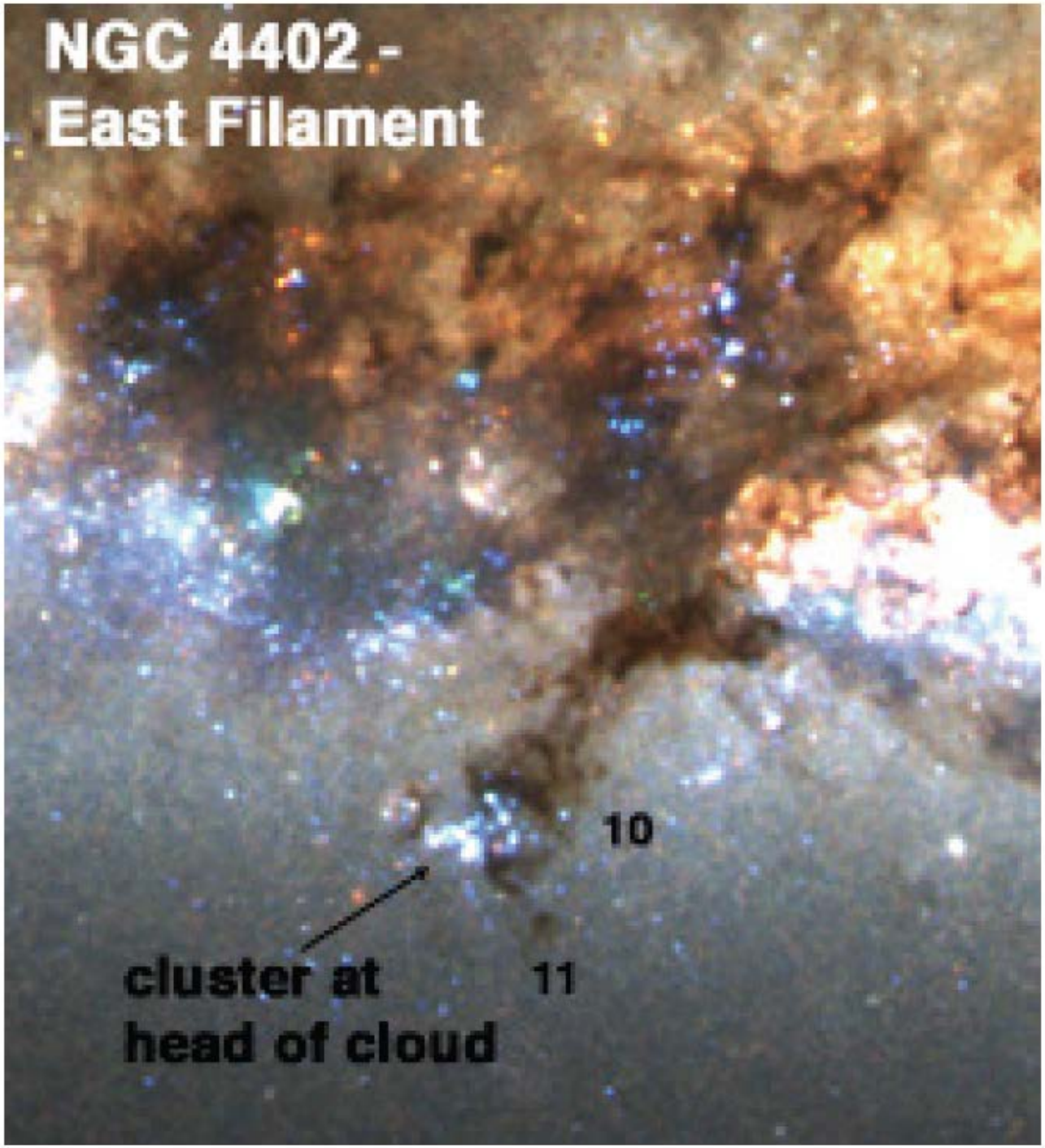

bright UV from young star complexes at leading edge of stripped gas disk

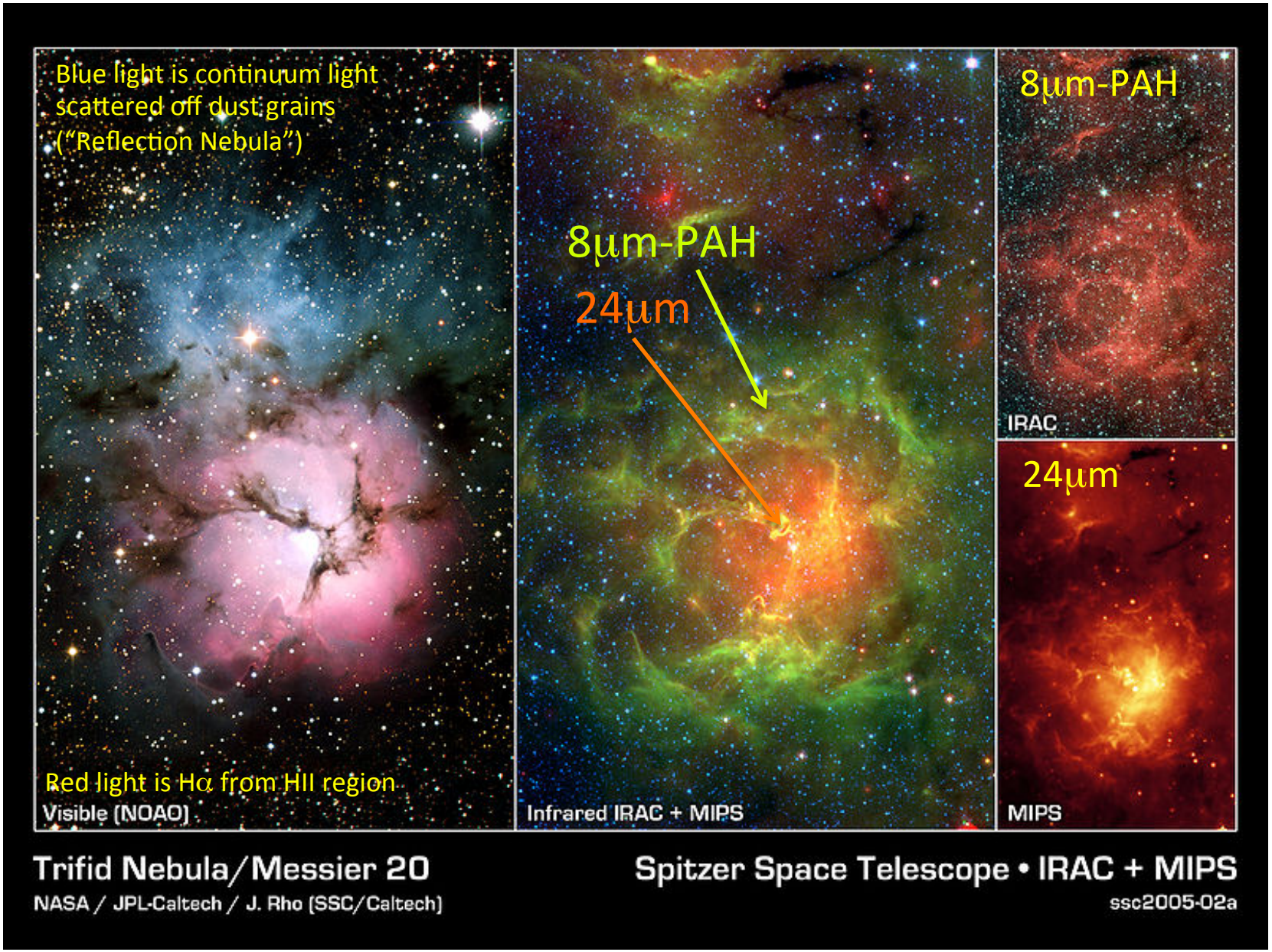


NGC 4402 Virgo Cluster
HST image Abramson+2016




NGC 4402 Features Related to Ram Pressure Stripping
Extraplanar Dust Plume
Luminous Young Star Complexes at Leading Edge
Decoupled Clouds
Head-Tail Filament
Fossil Filament
Decoupled Clouds
Projected ICM Wind Direction
HST image Abramson+2016


NGC 4402 -
East Filament
10
cluster at
head of cloud
11



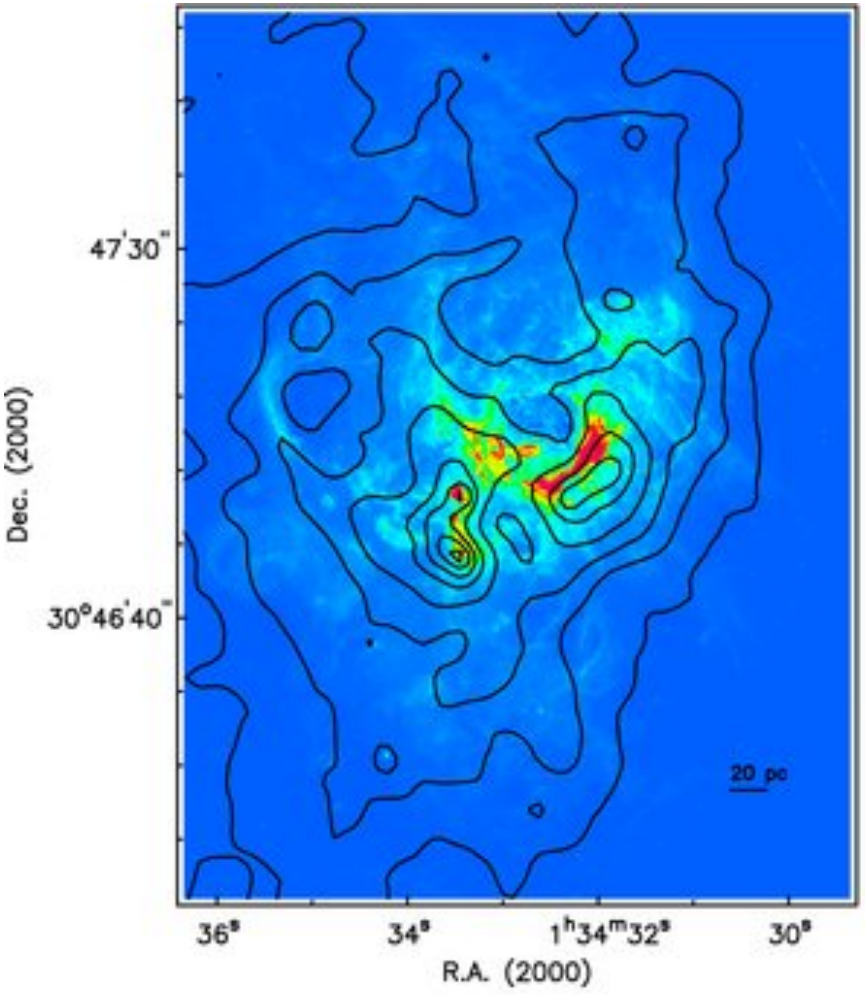

24μm peaks on HII region

**8μm-PAH peaks at periphery of HII region & extends far beyond it**

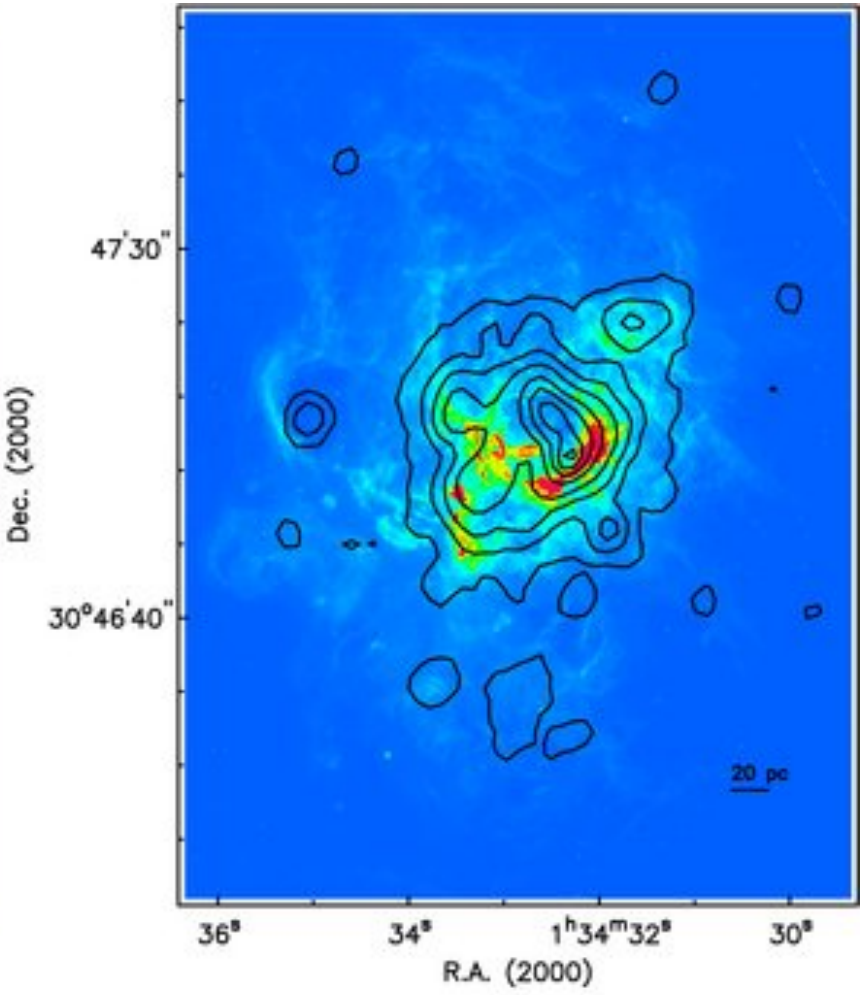
# Giant HII region NGC 604 in M33

Relano & Kennicutt 2009

8μm contours on Hα

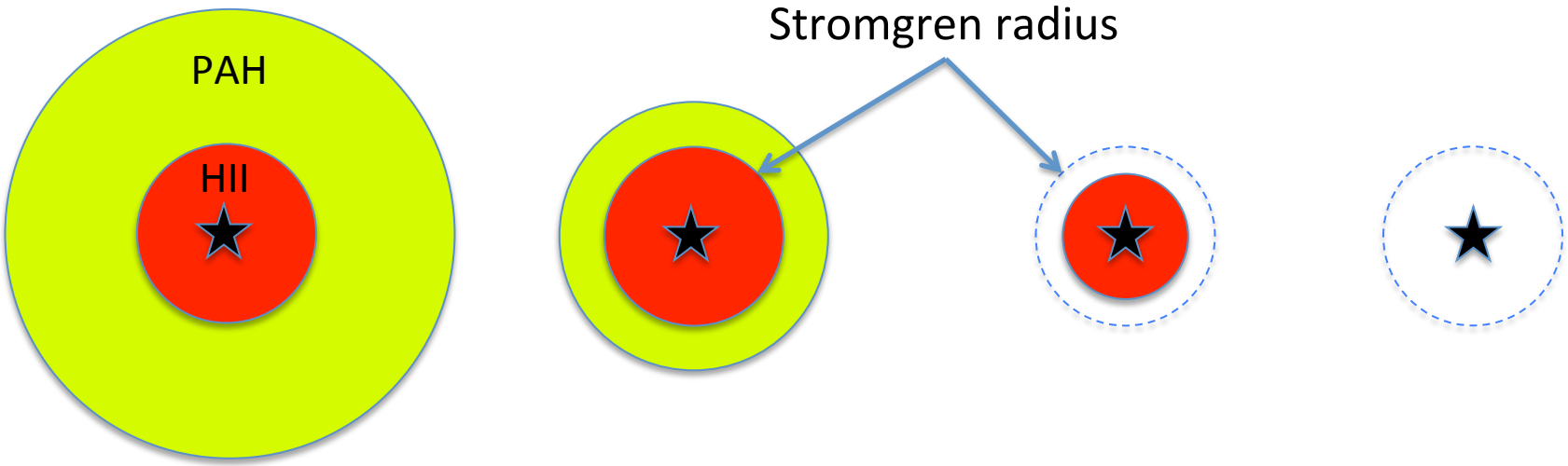



UV contours on Hα




**8μm-PAH peaks at periphery of HII region & extends far beyond it**

# different stages of decoupling of HII region from surrounding ISM



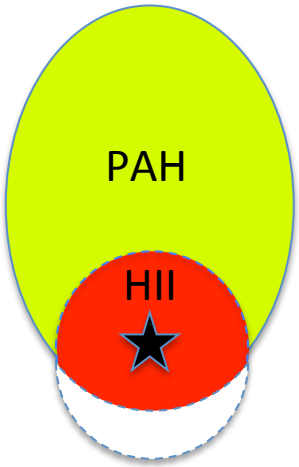

normal
ionization-bounded

PAH envelope stripped
ionization-bounded

PAH envelope stripped
HII region gas partly stripped
**density-bounded**
**LyC escape**

naked O star
**density-bounded**
**LyC escape**

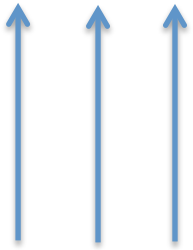
# different stages of decoupling of HII region from surrounding ISM

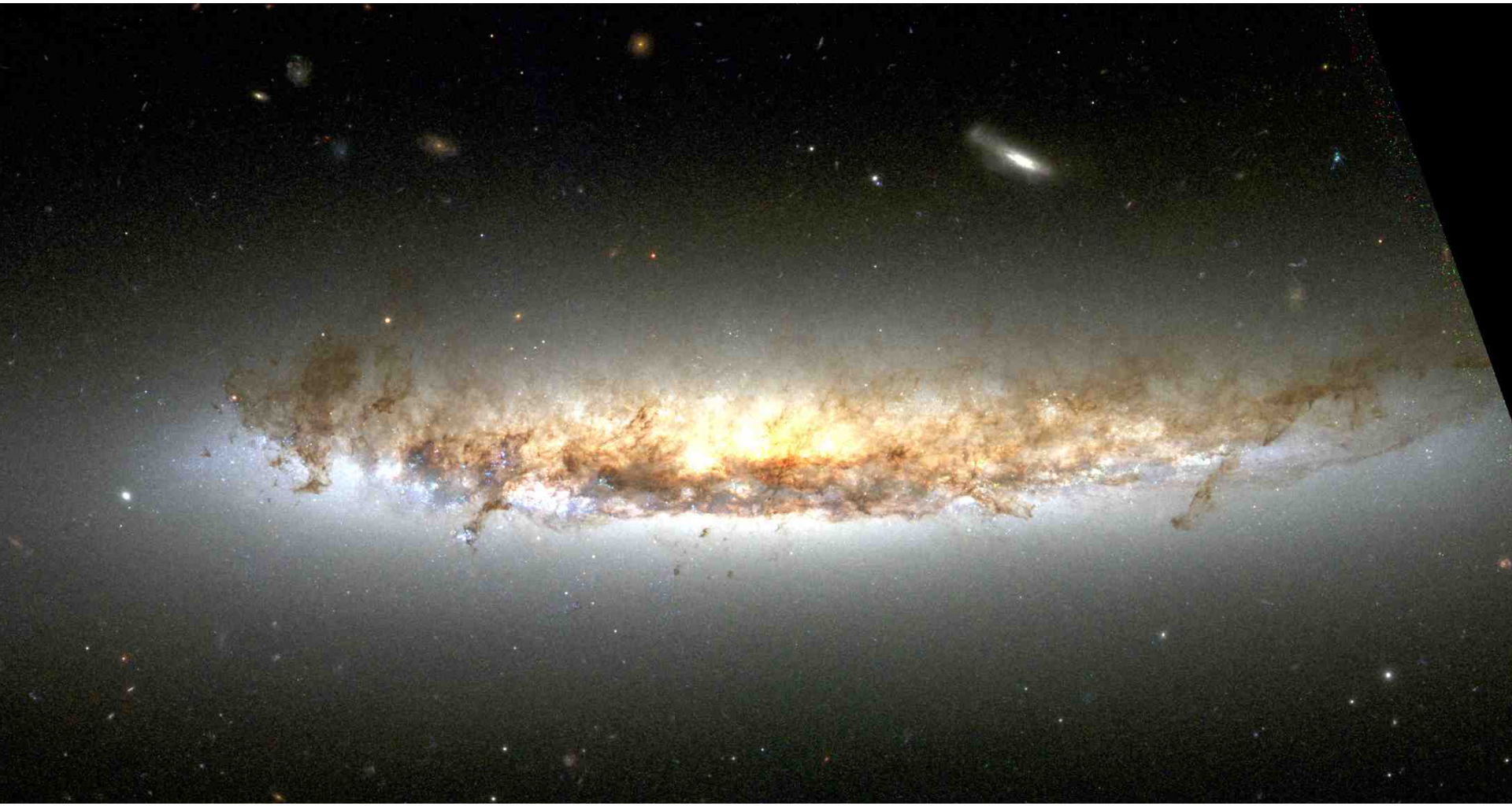



trailing side
ionization-bounded
no LyC escape

leading side
**density-bounded**
**LyC escape**

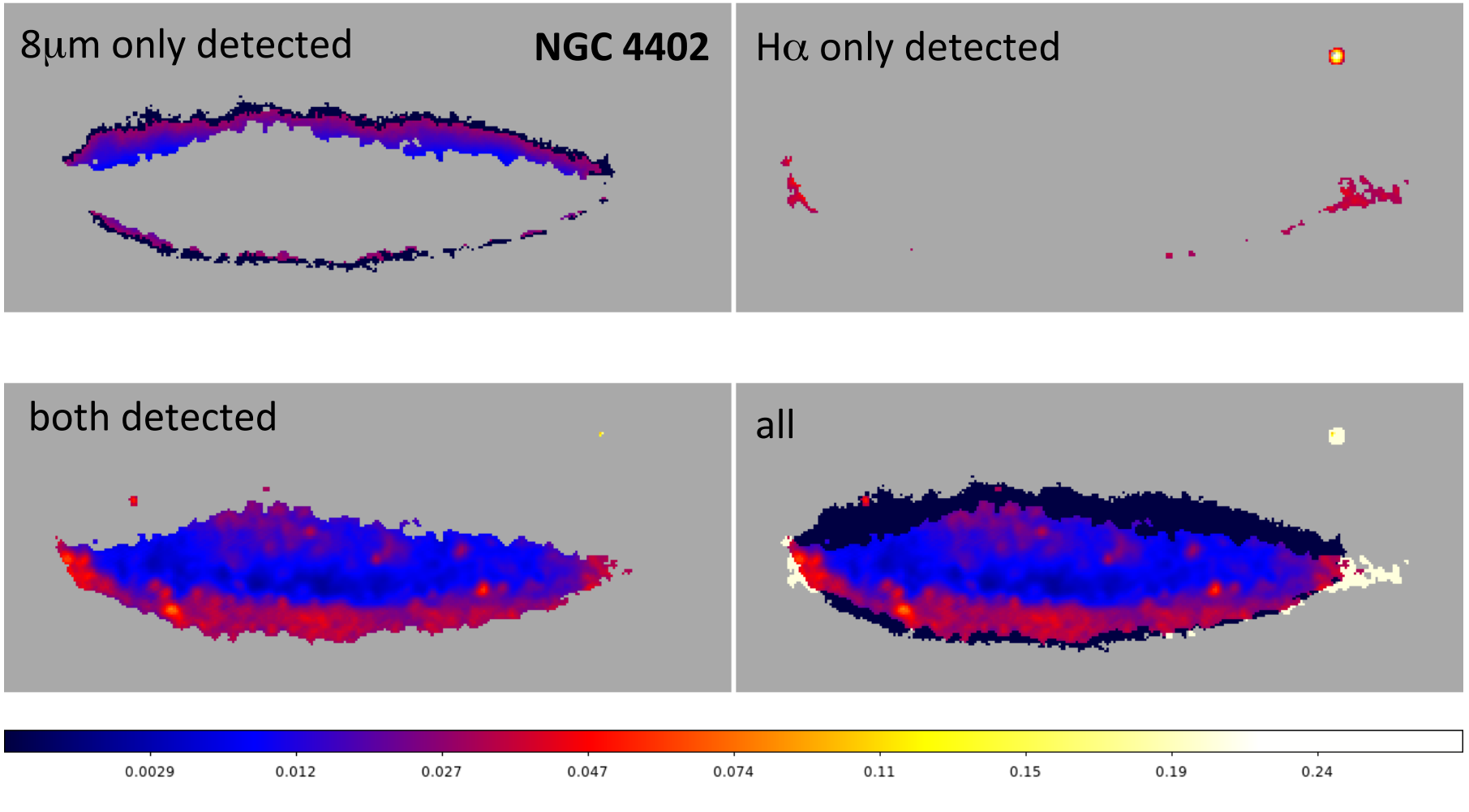
ram pressure
wind



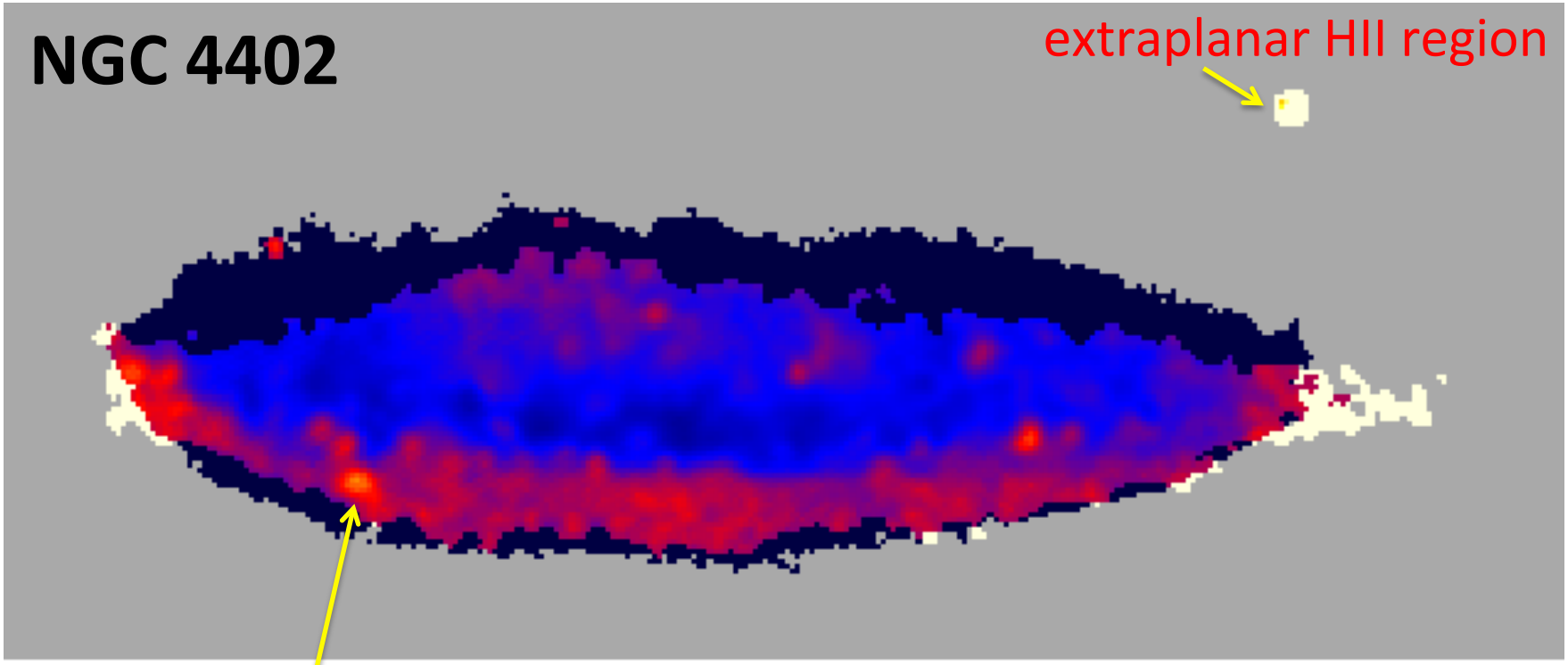


NGC 4402 Virgo Cluster
HST image Abramson+2016

# high Hα/8μm-PAH ratios as tracers of decoupled HII regions

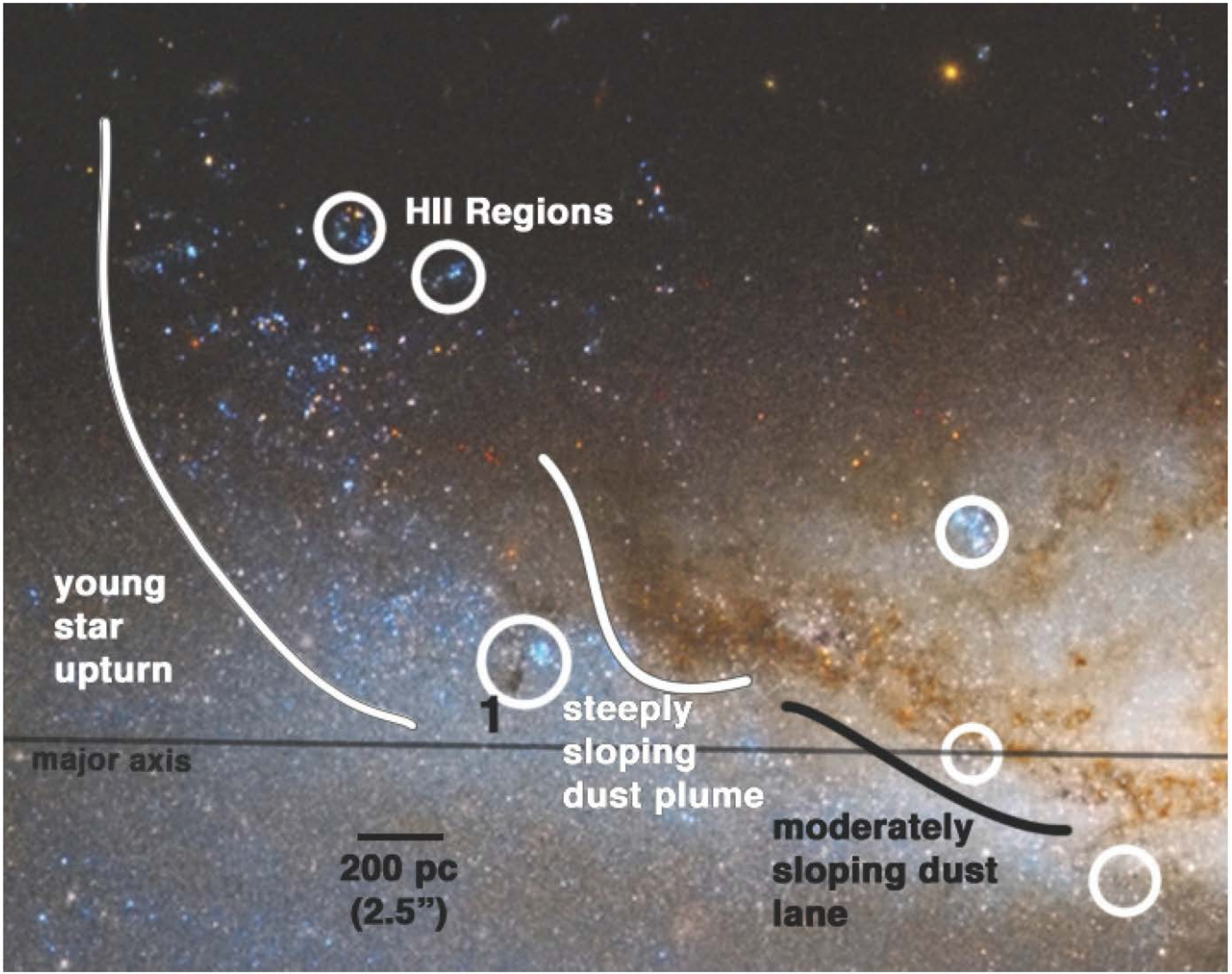


# high Hα/8μm-PAH ratios as tracers of decoupled HII regions

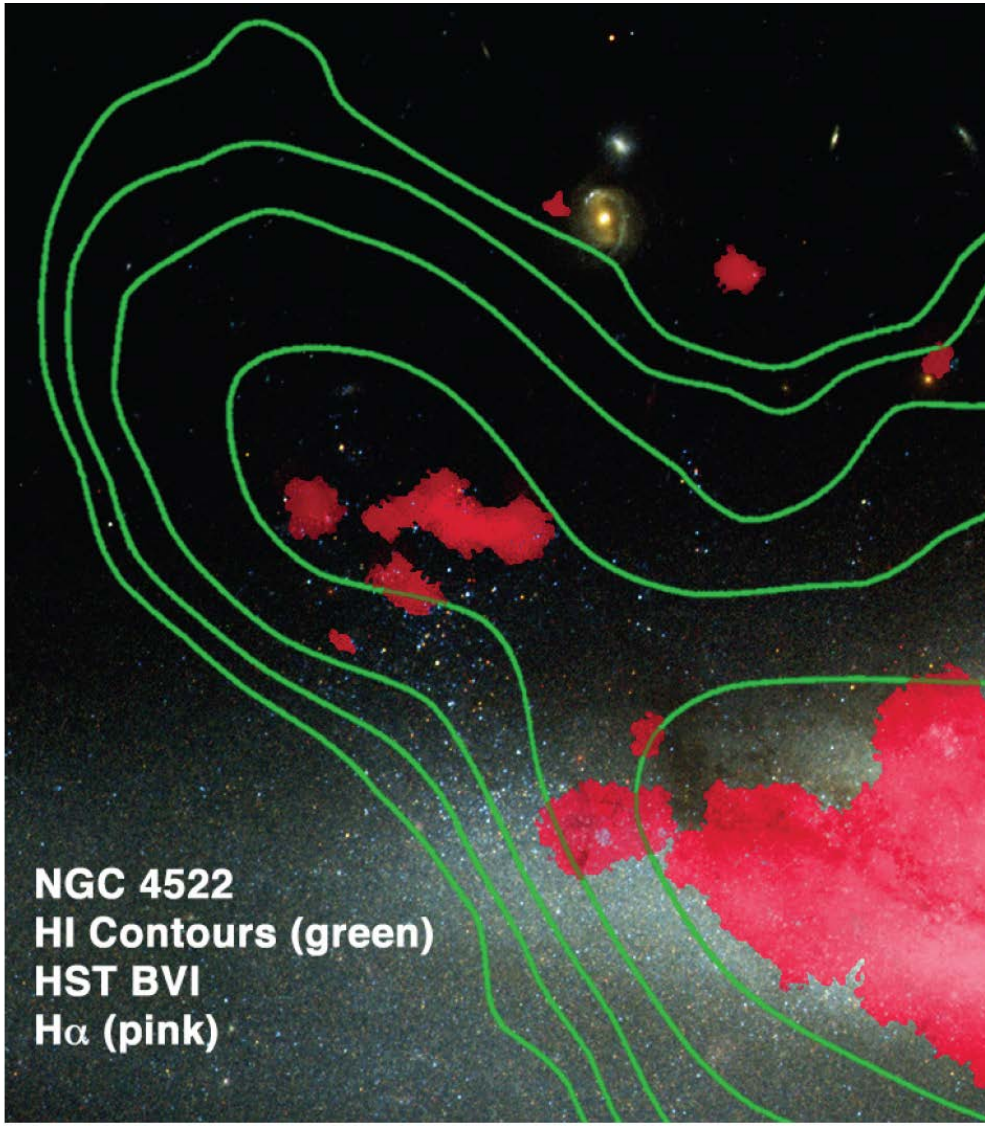


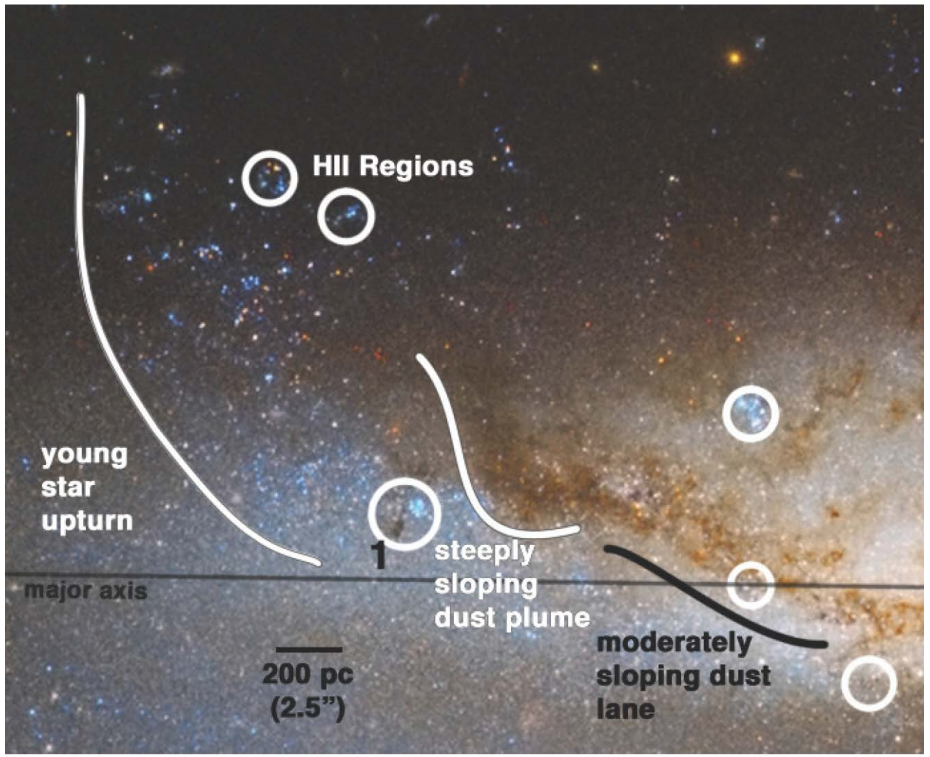

Kenney+ in prep


NGC 4522 Virgo Cluster
HST image Abramson+2016


HII Regions
young
star
upturn
1
steeply
sloping
dust plume
major axis
200 pc
(2.5")
moderately
sloping dust
lane

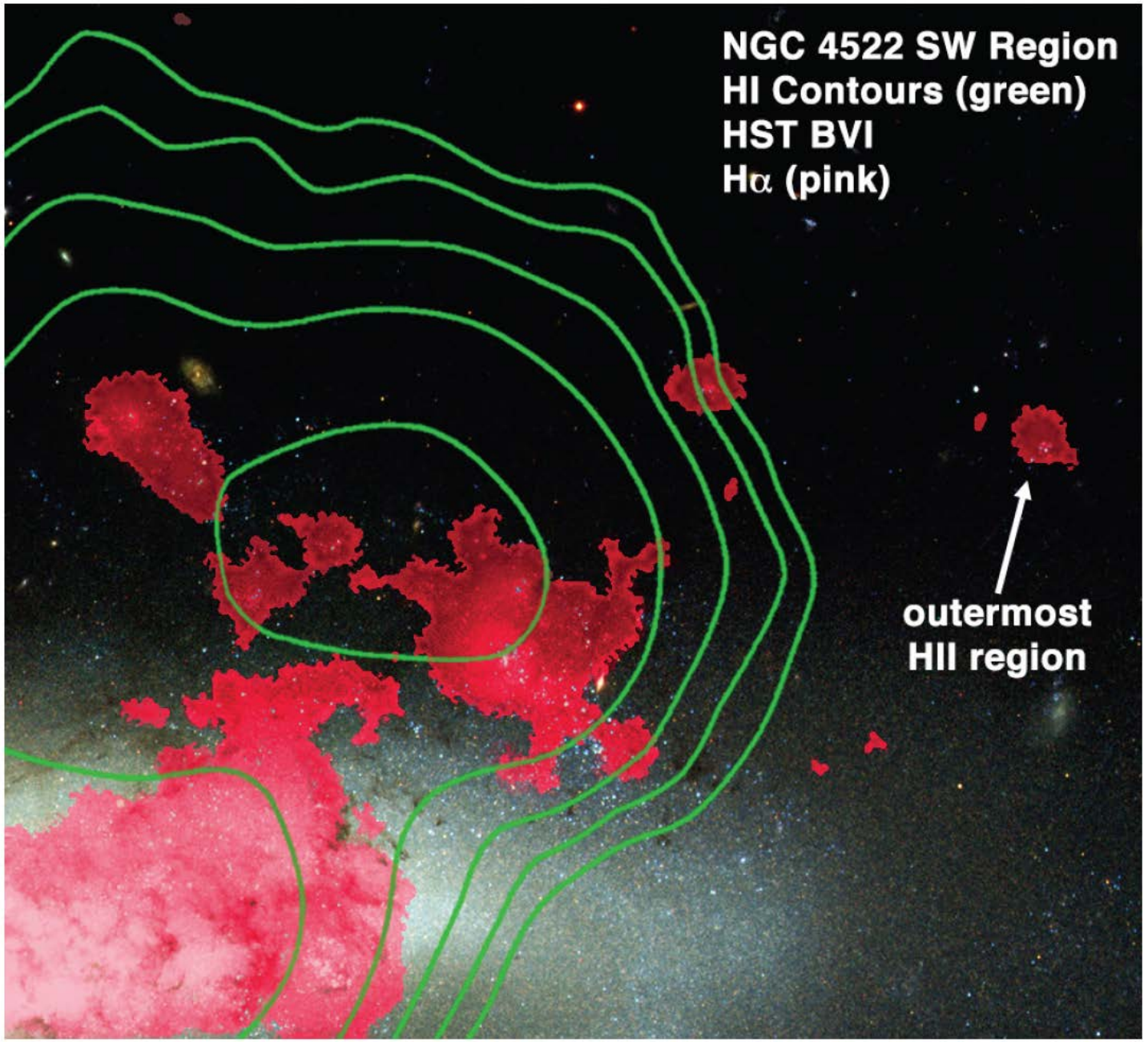
# NGC 4522 upturn region



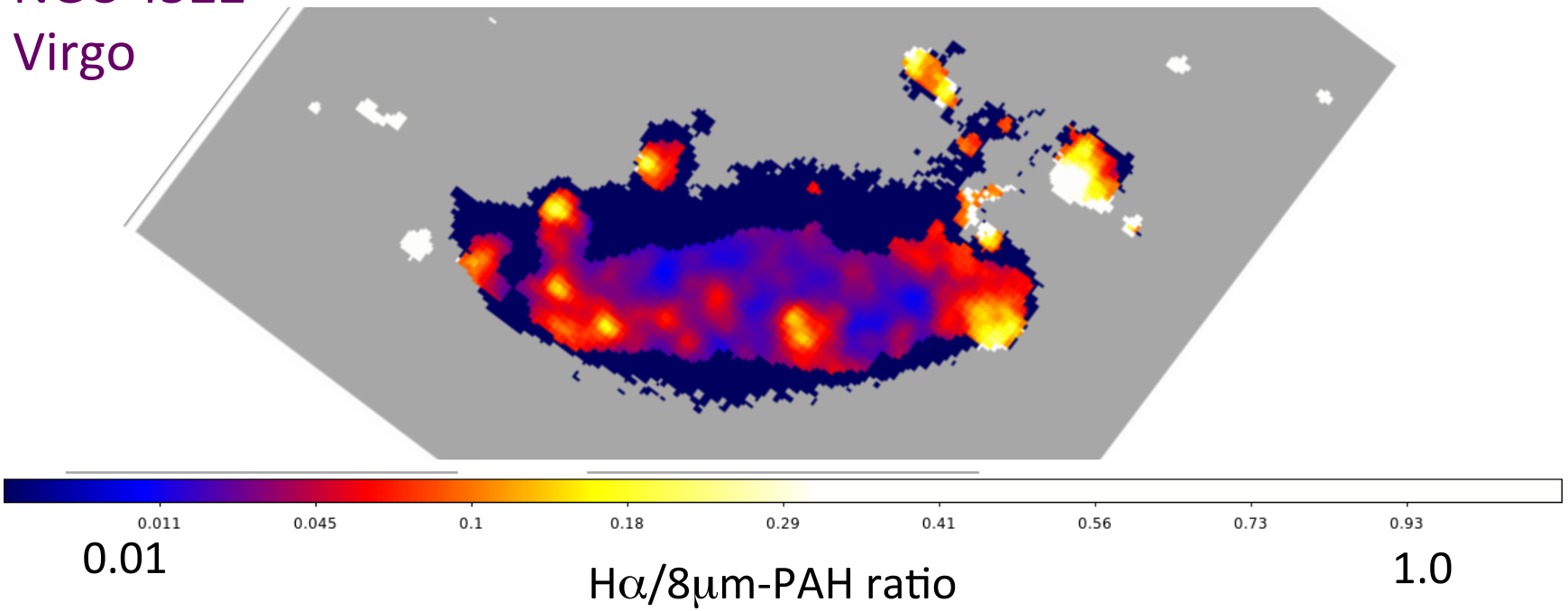

Abramson+2016

extraplanar stream of young stars without dust or gas(?)
except for HII regions at the top
-> gas has been pushed downstream

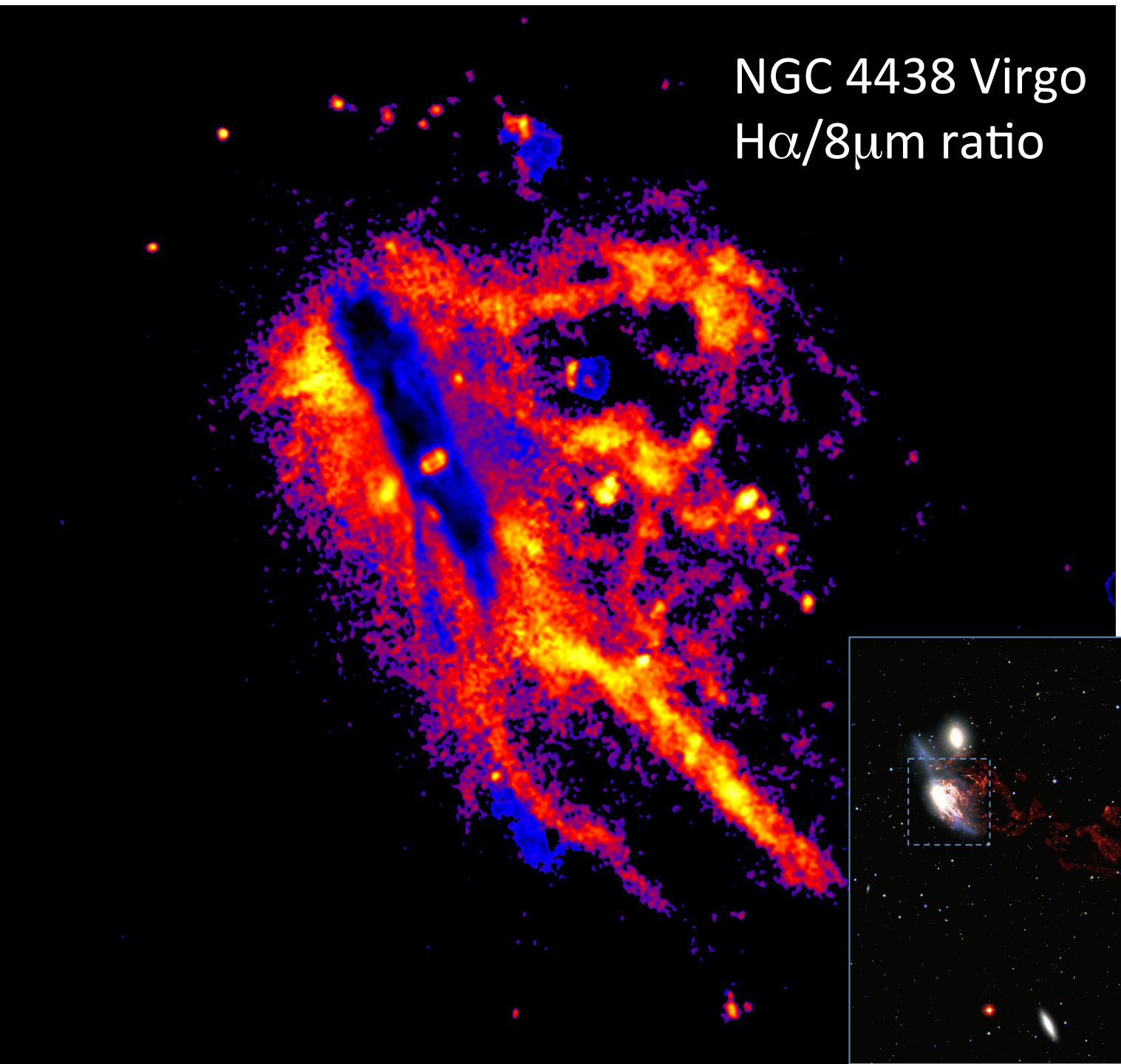

NGC 4522 SW Region
HI Contours (green)
HST BVI
Hα (pink)
outermost
HII region

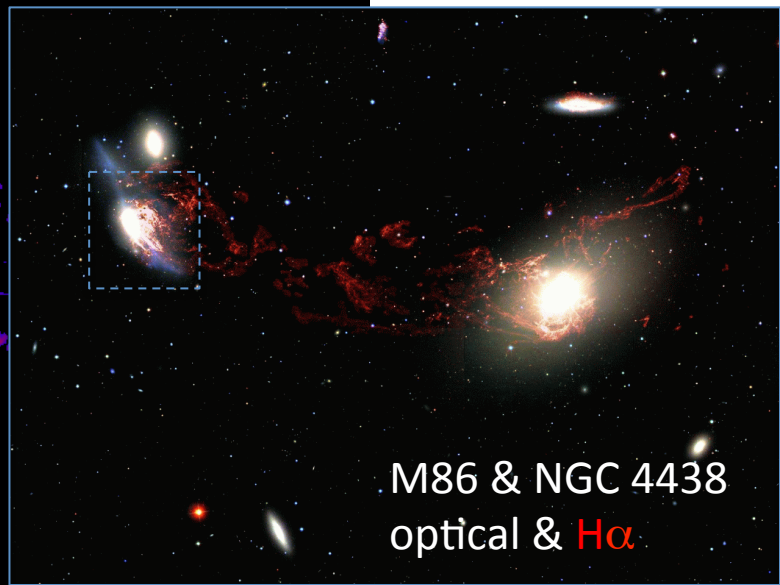
# high Hα/8μm-PAH ratios as tracers of decoupled HII regions

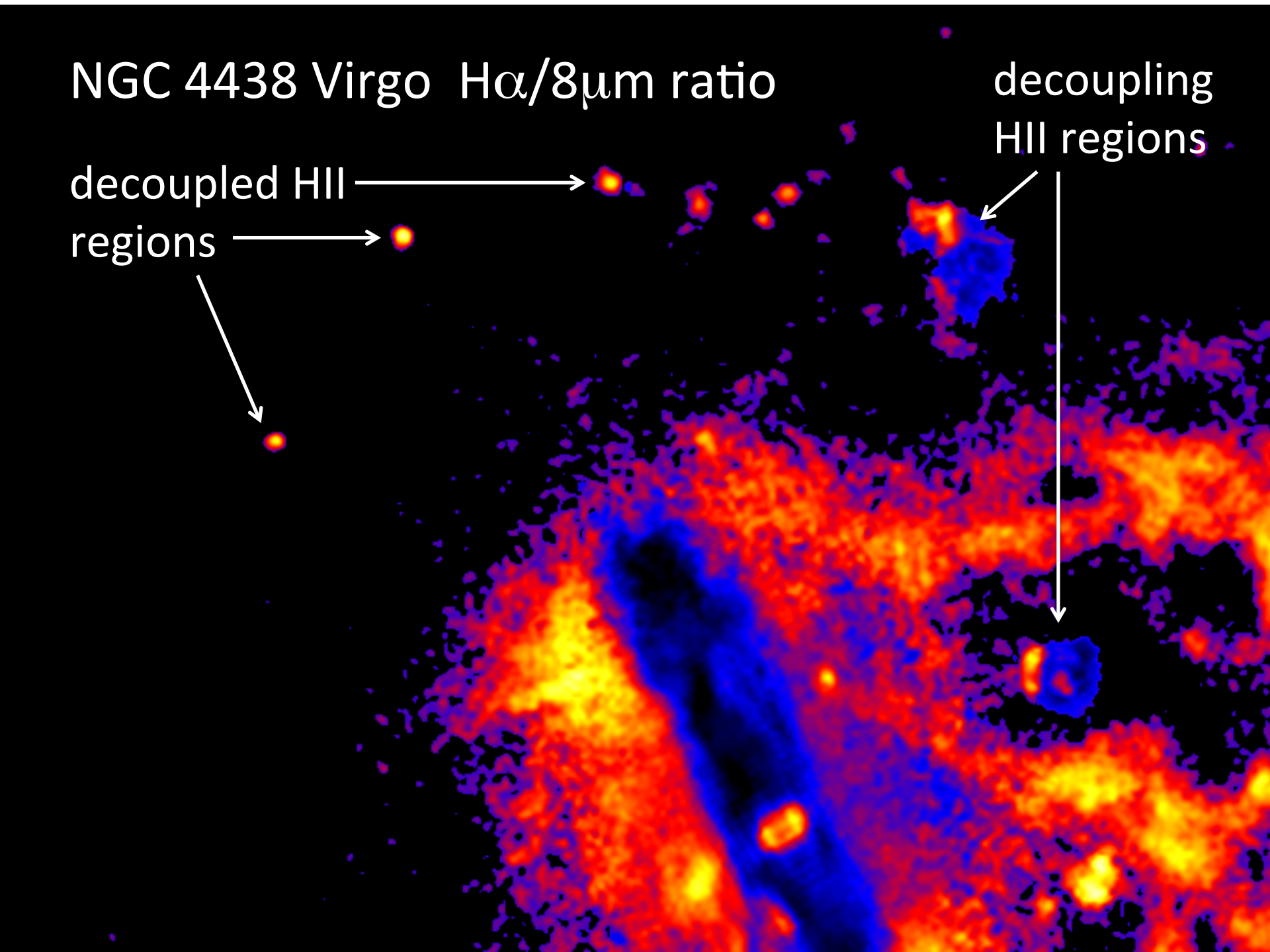
NGC 4522
Virgo




10% of Hα is from extraplanar HII regions
which have Hα/8μm ratios 10-100x higher than galaxy average
so might easily be the dominant source of escaping LyC photons

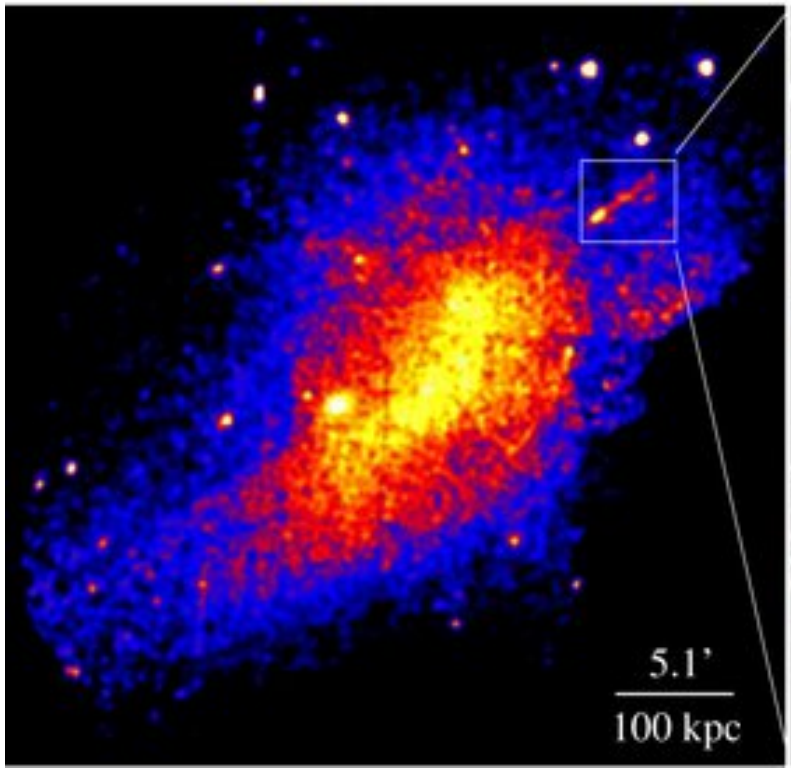

NGC 4438 Virgo
Hα/8μm ratio


M86 & NGC 4438
optical & Hα

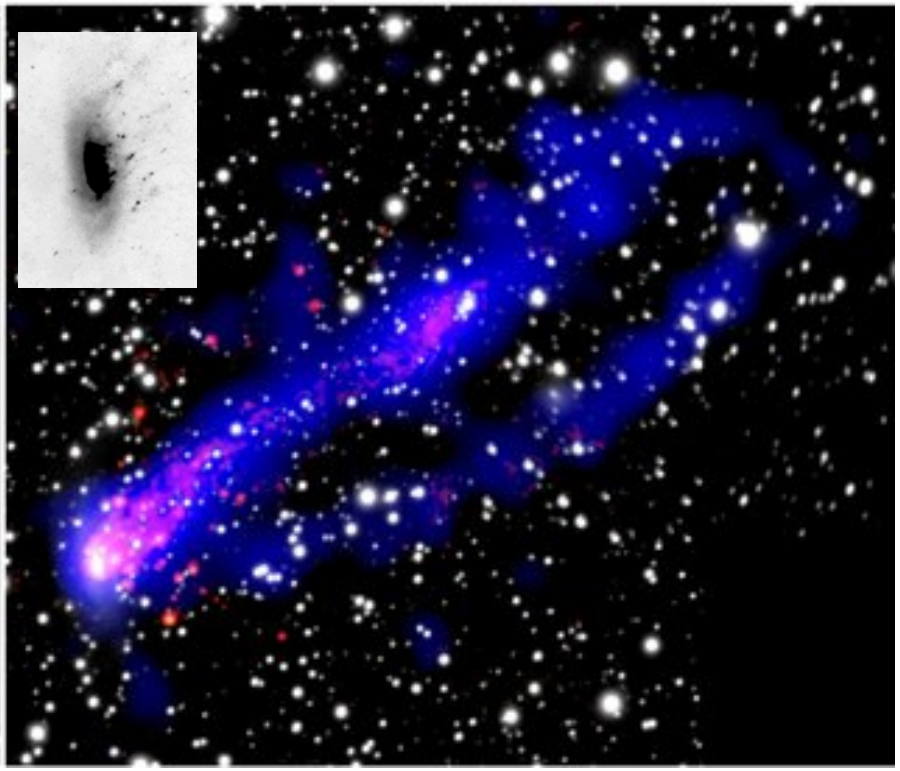

NGC 4438 Virgo Hα/8μm ratio
decoupled HII regions
decoupling HII regions

# Spectacular ram-pressure stripped 70–kpc X-Ray tail in ESO137-001

(Norma cluster M~$10^{15}$ $M_{sun}$)



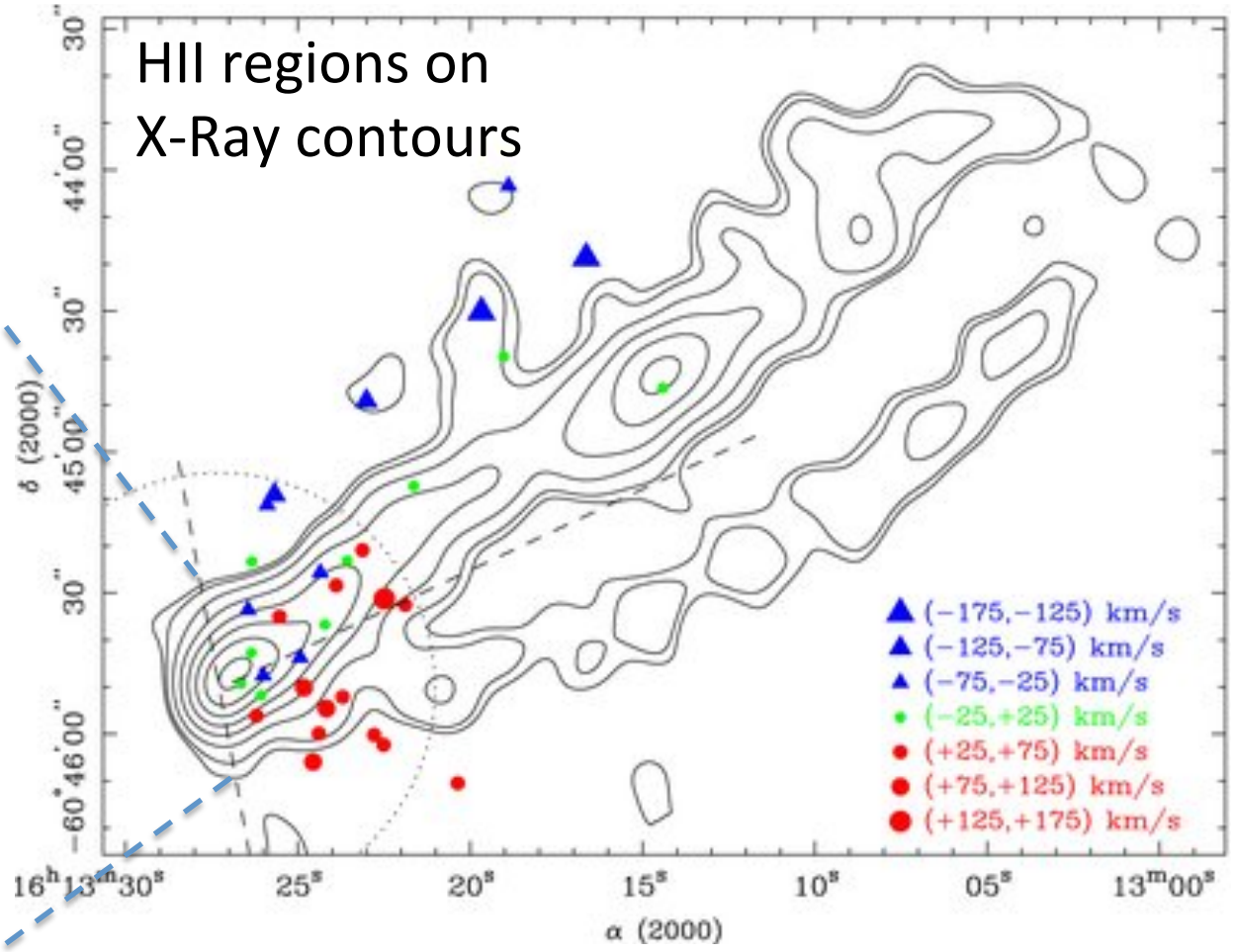

Chandra X-Ray 0.6-2 keV



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

# HII regions in rps tail of ESO137-001

HST

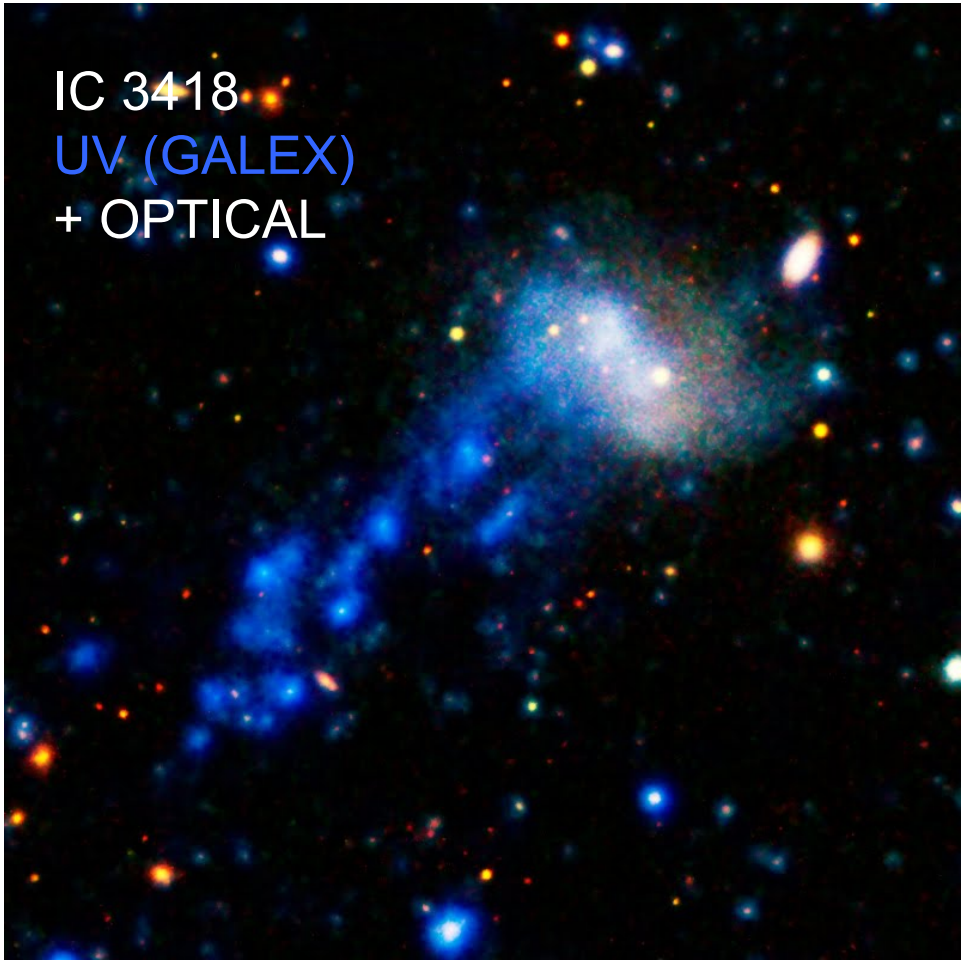

Sun+2010

**orphan HII regions outside main gas (x-ray) tail**
from earlier stage of stripping outer disk
***these are most decoupled HII regions!***

# RPS completely strips dwarf galaxies in Virgo

Virgo Dwarf IC3418: “Smoking Gun” example of
dI -> dE Transformation by Ram Pressure Stripping

Kenney+14

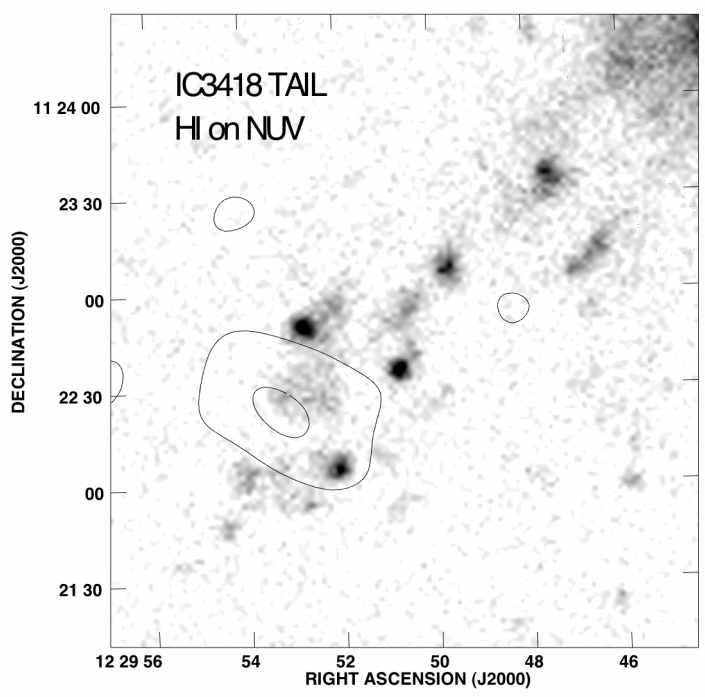


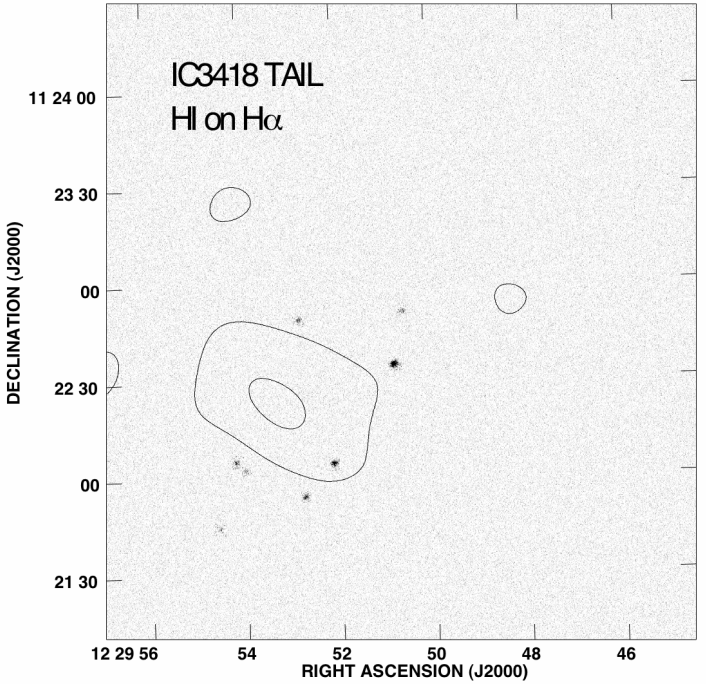

No gas or star formation
in main body:
SF quenched 300 Myr ago

1-sided tail of
gas (HI, Hα) & young stars
with “fireball”
morphology

see also Chung+09; Hester+10; Fumagalli+11

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



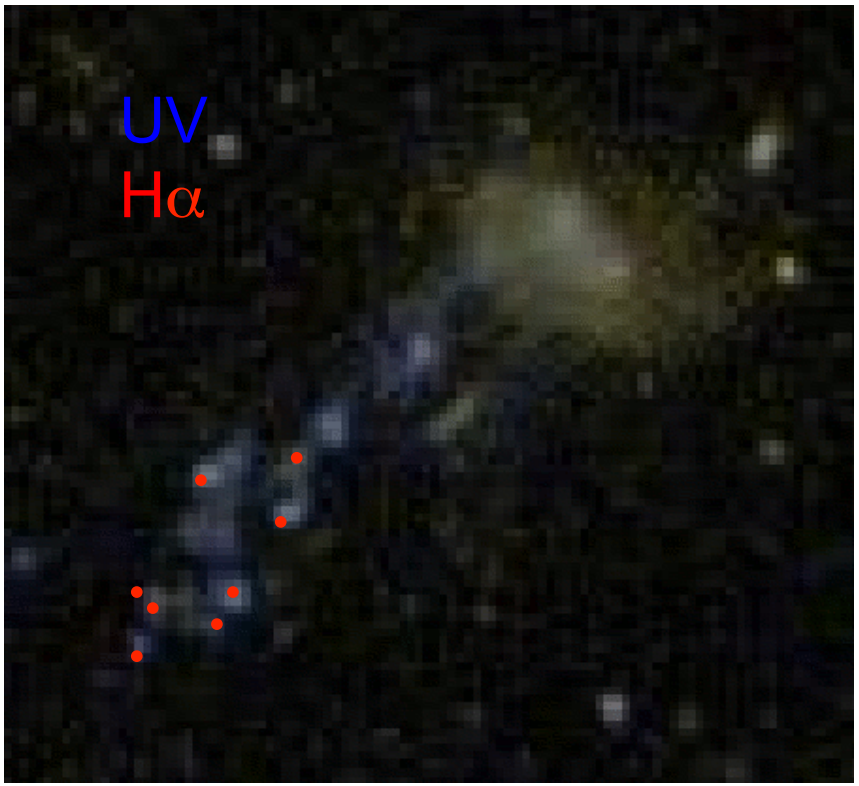

Kenney+2014

VLA VIVA survey data
HI detected (5σ) in only
one 10 km/s channel
$M_{HI}$ = 4 x $10^7$ $M_{sun}$

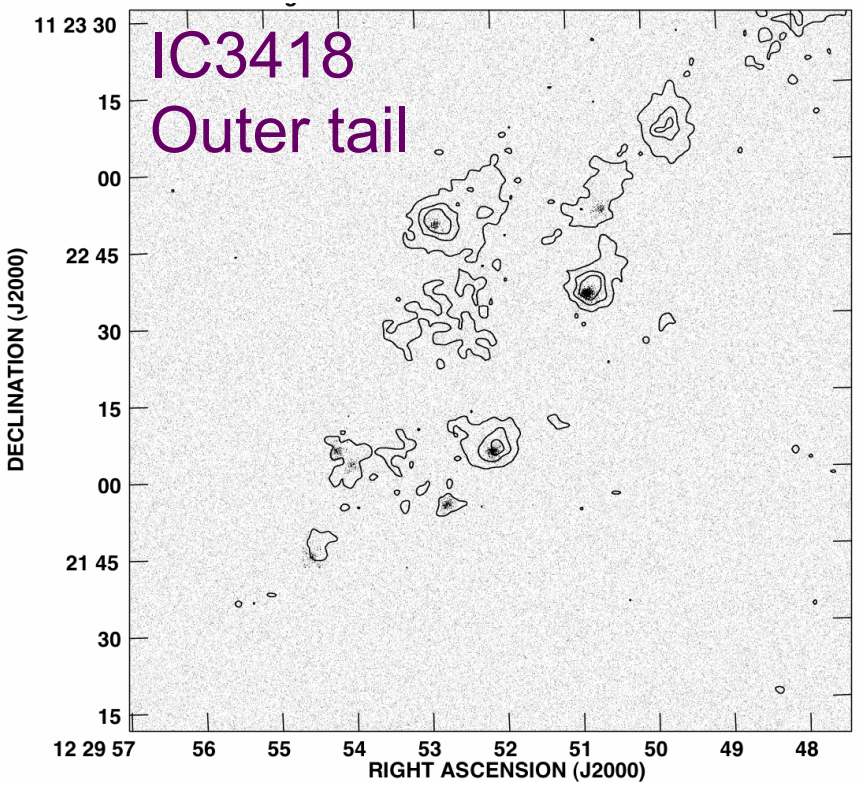
WIYN Hα image
8 HII regions in outer half of tail
$L_{H\alpha}$ = 2x$10^{38}$ erg/s
SFR ~ 0.002 $M_{sun}$/yr

**No CO, X-Ray, FIR – most of gas is "missing"**
**Where is the gas?** Mostly $10^4$-$10^6$ K?
Mostly further downstream and low surface density?

# “Fireballs” in Tail of IC3418




Hα on NUV

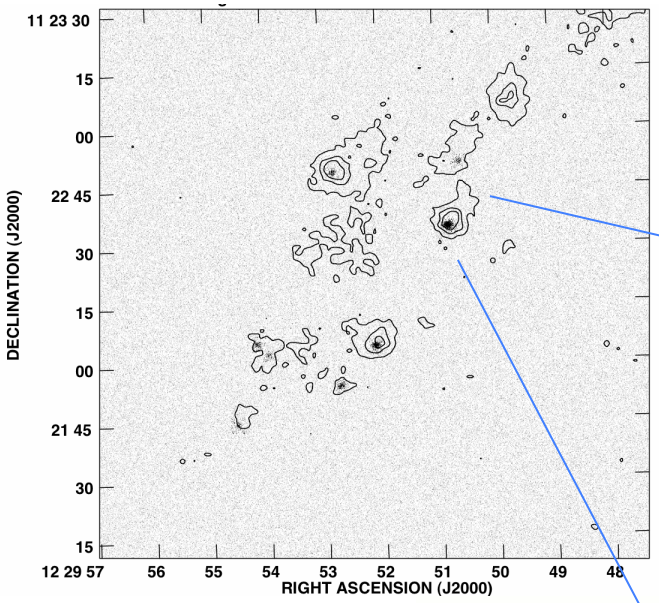



Gas and newly-formed stars (HII regions) at outermost head of linear stellar streams (“fireballs”)

Hα 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 cartoon




newly-formed stars decoupled from outwardly accelerating gas cloud

slightly older stars

youngest & brightest stars

ram pressure accelerates gas outwards

gas cloud with ongoing star formation

young stars without surrounding gas – potential sites for naked O stars…

# summary

galaxies in clusters experiencing ram pressure have 2 places where Lyman continuum photons from HII regions should have easier escape:  the leading edges of disks and extraplanar tails

high H$\alpha$/8$\mu$m-PAH ratios indicate HII regions which have decoupled from the surrounding ISM, and may be leaking Lyman continuum photons