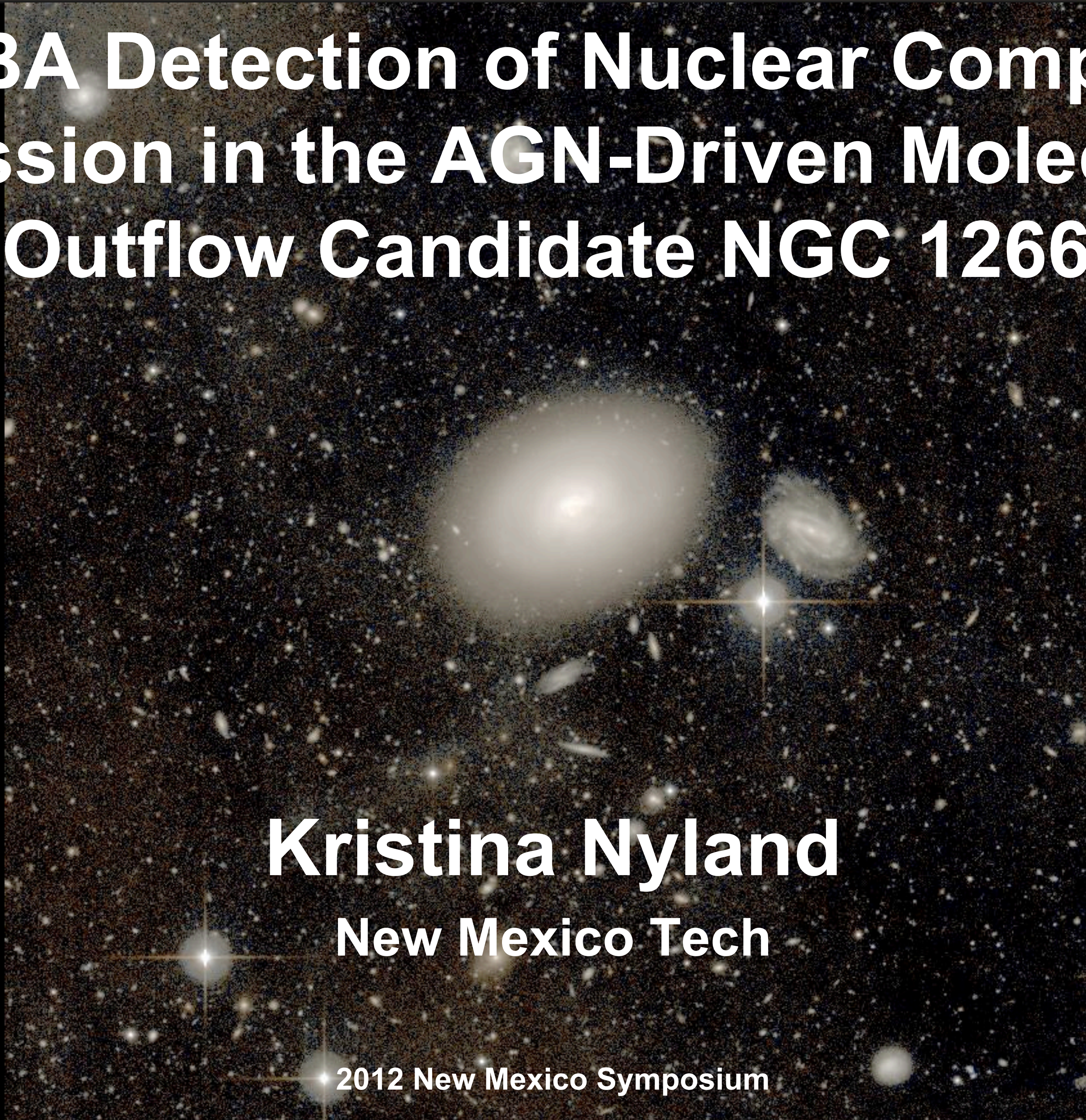
VLBA Detection of Nuclear Compact Emission in the AGN-Driven Molecular Outflow Candidate NGC 1266



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2012 New Mexico Symposium

Outflows in Galaxies

- Can help regulate star formation and SMBH growth
- May be responsible for various empirical scaling relations in galaxies (e.g., Faber-Jackson relation)
- Driving mechanisms:
  - Stellar feedback
    - Radiation pressure
    - Stellar winds (young O stars, AGB stars)
    - Supernovae
  - AGNs
    - Quasar mode (radiative)
    - Radio mode (mechanical/kinetic)

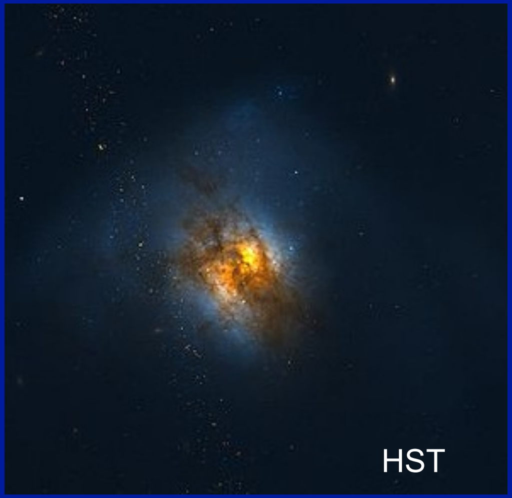
Starburst-Driven Molecular Outflows

M82 (Walter+02)

- Prototypical SB galaxy
- Interacting with M81
- Molecular gas entrained in starburst wind
- $M_{outflow} = 3 \times 10^8\ M_{sun}$
- $dM/dt = 30\ M_{sun}$/year
- $v_{outflow} = 100$ km/s

Arp 220 (Sakamoto+09)

- ULIRG
- merger remnant
- (But AGN may play a see role, Rangwala+11)
- $M_{outflow} = 5 \times 10^7\ M_{sun}$
- $dM/dt = 100\ M_{sun}$/year
- $v_{outflow} = 100$ km/s



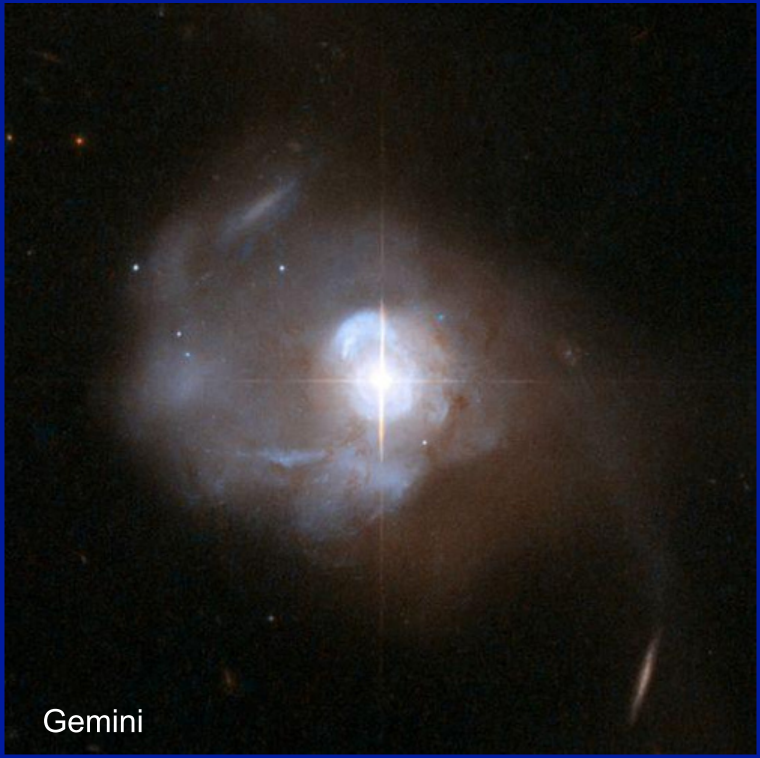
AGN-Driven Molecular Outflows

- Outflows of neutral/ionized gas relatively common in AGNs
- *Molecular outflows* potentially powered by AGNs are *rare*
- Much of the evidence is circumstantial
  - e.g., SDSS statistical analyses of timing of starbursts and AGN activity
- Many candidates for direct evidence are high-redshift quasars
  - local candidates needed!

AGN-Driven Molecular Outflows

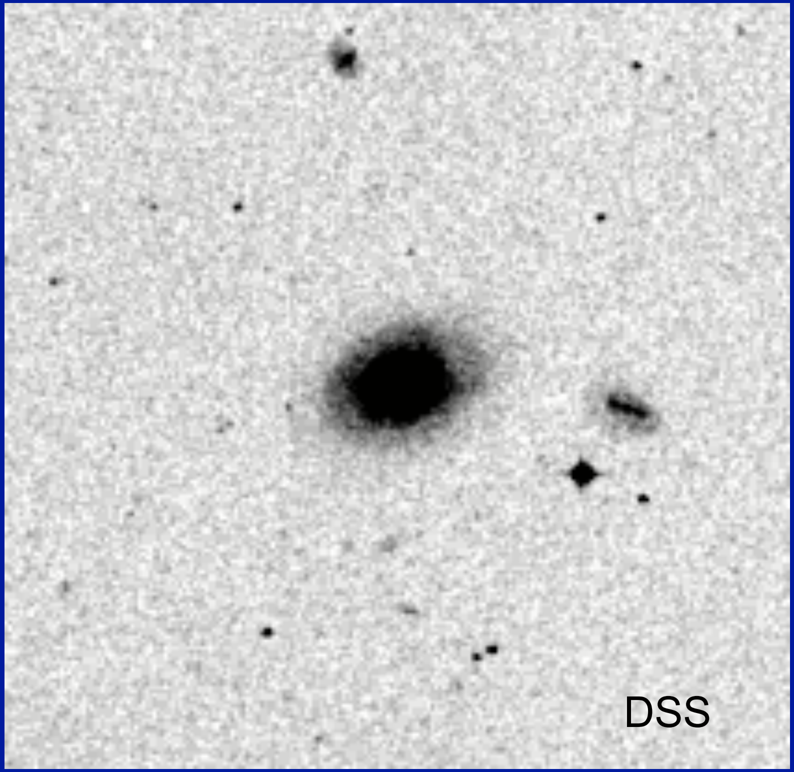
Mrk 231 (Feruglio+10)

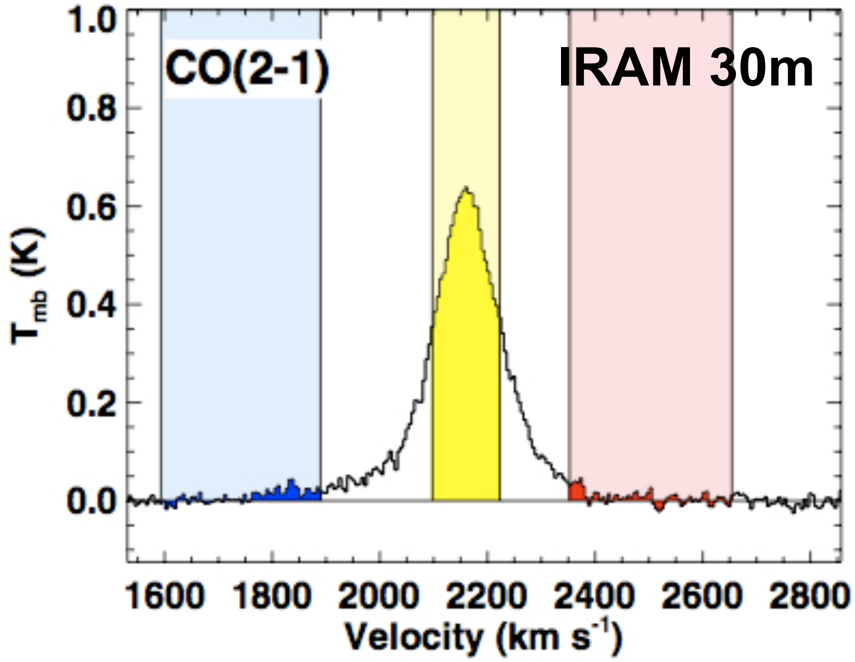
- Nearest quasar host
- Interacting system
- $M_{outflow} = 5.8 \times 10^8\ M_{sun}$
- $dM/dt = 100\text{-}700\ M_{sun}/yr$
- $v_{outflow} = 700$ km/s



NGC 1266: Local Candidate AGN-driven Molecular Outflow Host?

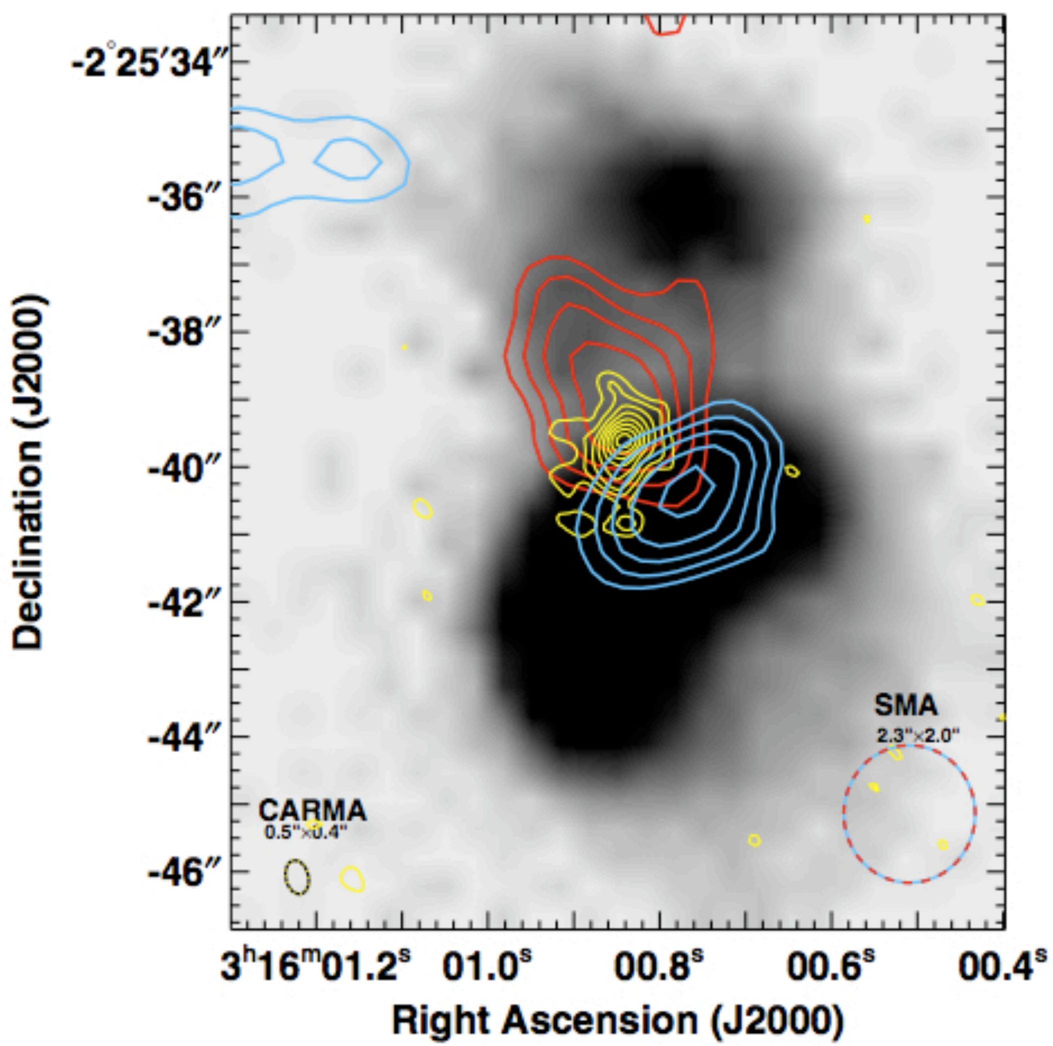
- Morphology: S0
- Environment: Field
  - *no evidence of recent major merger*
- Distance: 29.9 Mpc
- M_K = -22.93
- σ_* = 79 km/s
- M_{BH}: ~3.2×10^6 M_{sun}





CO Emission

Figures from Alatalo et al. 2011



Yellow: CARMA CO(1-0) integrated intensity

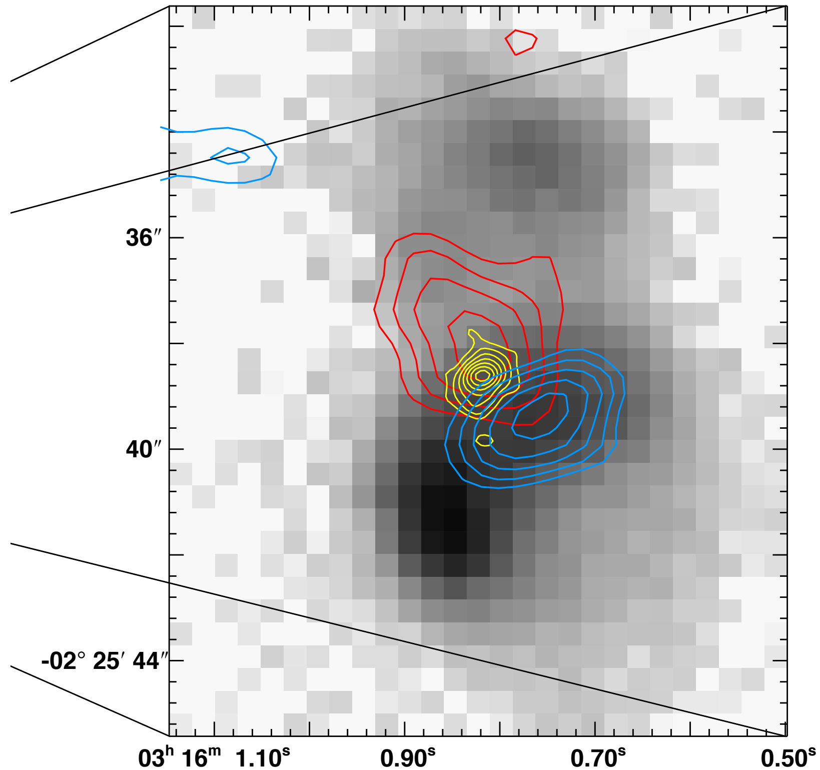
Red/Blue: SMA CO(2-1) redshifted/blueshifted wings

Greyscale: narrowband Hα (SINGS)

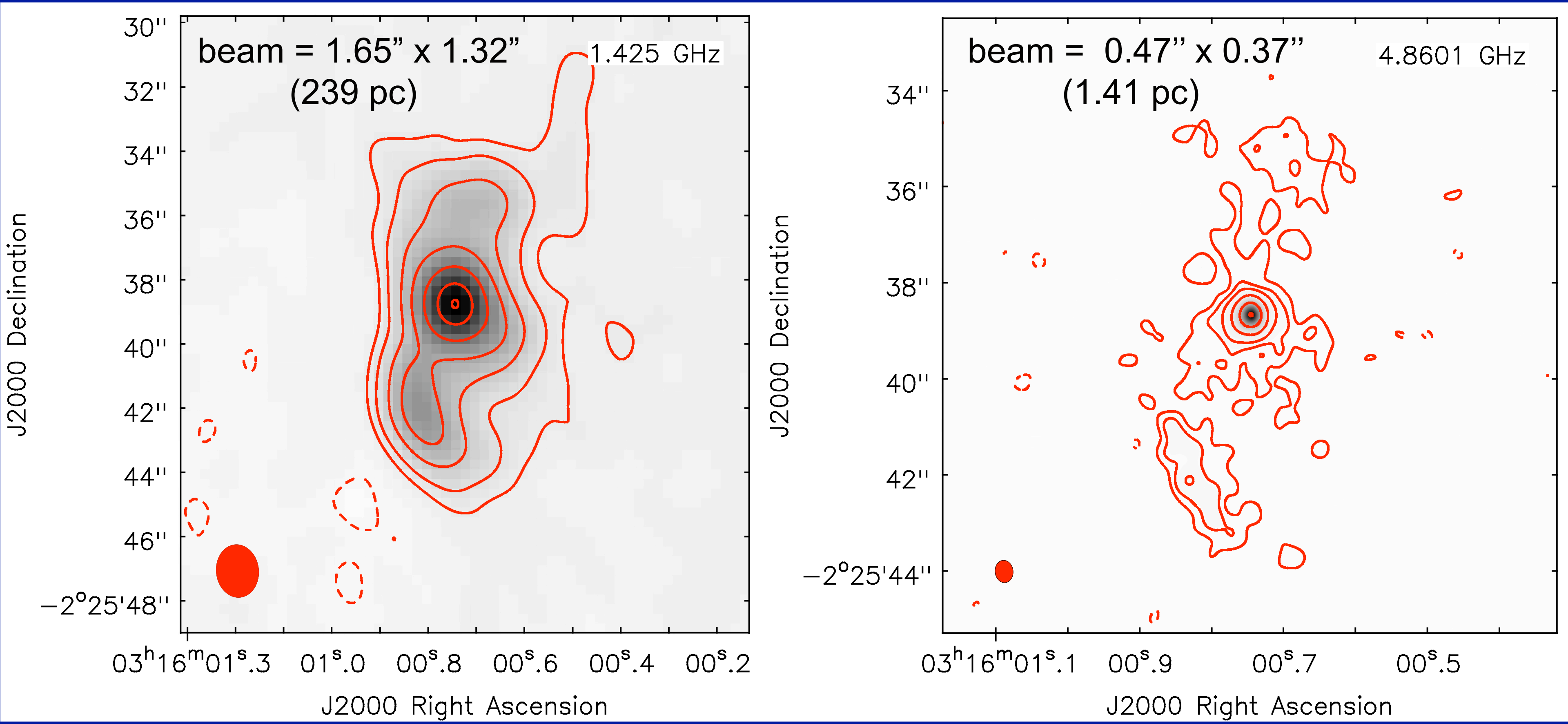
The Molecular Outflow in NGC 1266

NGC 1266 Characteristic Properties

Derived Property	Value
$M_{\rm nucleus}$	$4.1 \times 10^8\ M_\odot$
$R_{\rm nucleus}$	60 pc
$M_{\rm CVC}$	$1.1 \times 10^9\ M_\odot$
$\langle \Sigma(\rm H_2)_{\rm nucleus} \rangle$	$2.7 \times 10^4\ M_\odot\ \rm pc^{-2}$
$\langle N(\rm H_2)_{\rm nucleus} \rangle$	$1.7 \times 10^{24}\ \rm cm^{-2}$
$\langle n(\rm H_2)_{\rm nucleus} \rangle$	$6.9 \times 10^3\ \rm cm^{-3}$
$M_{\rm HI+H_2,outflow}$	$3.3 \times 10^7\ M_\odot$
$M_{\rm H_2,outflow}$	$2.4 \times 10^7\ M_\odot$
$R_{\rm outflow}$	450 pc
$v_{\rm outflow}$	$177\ \rm km\ s^{-1}$
$\tau_{\rm dyn}$	2.6 Myr
$\dot{M}$	$13\ M_\odot\ \rm yr^{-1}$
$\rm KE_{outflow}$	1.0×10^{55} erg
$L_{\rm outflow}$	$1.3 \times 10^{41}\ \rm erg\ s^{-1}$
$\tau_{\rm dep}$	85 Myr



Archival VLA Maps



- Relative contour levels = [-3, 3, 9, 25, 49, 100, 180, 240] x unit contour (0.15 mJy/beam).
- Core integrated flux density = 70.53 +/- 2.20 mJy (7.54e21 W/Hz)

- Relative contour levels = [-3, 3, 6, 12, 36, 81, 150, 196] x unit contour (0.07 mJy/beam).
- Core integrated flux density = 31.43 +/- 1.29 mJy (3.36e21 W/Hz)

What is Driving the Outflow?

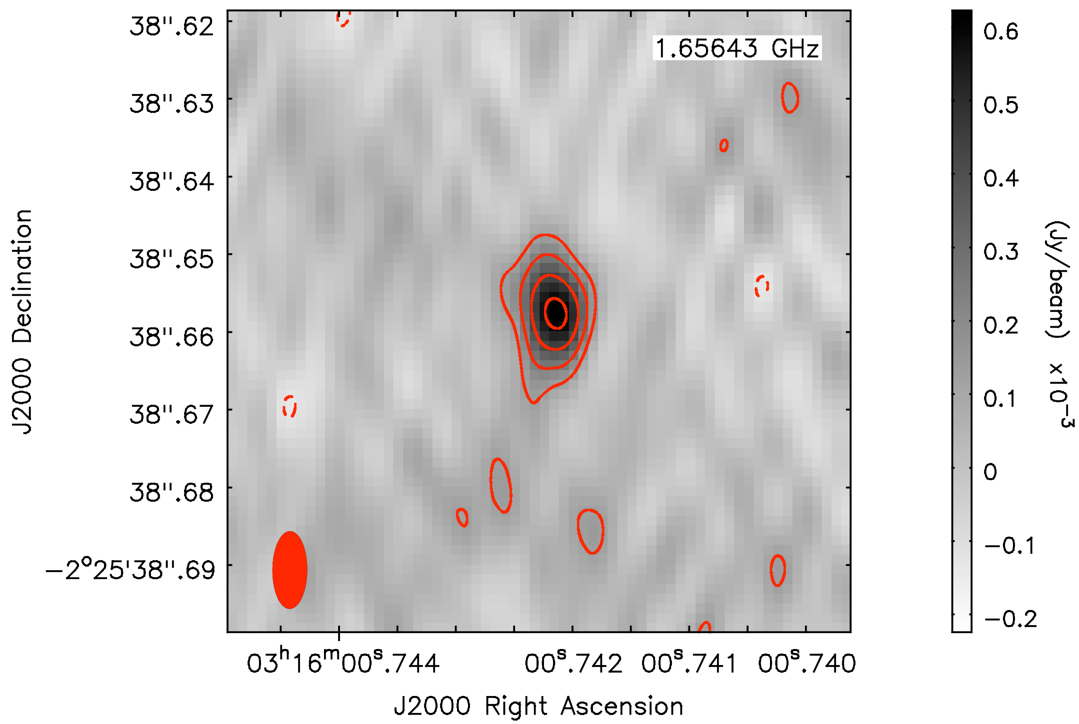
- Starburst?
  - Available molecular gas could potentially fuel a compact, obscured nuclear starburst
  - SFR estimates:
    - K-S law: 3.1 M_{sun}/yr
    - FUV: 0.003 M_{sun}/yr
    - 24 micron: 1.5 M_{sun}/yr
    - PAH (8 micron): 0.57 M_{sun}/yr
    - Total FIR: 2.2 M_{sun}/yr
    - Radio continuum: 1.1-7.1 M_{sun}/yr
  - ***All SFR estimates < the mass outflow rate***

What is Driving the Outflow?

- AGN?
  - Mass outflow rate is at least 13 M_{sun}/yr
    - Implies that SF alone cannot power the outflow
  - Presence of compact radio emission with an outflow-like, extended morphology in archival VLA data
- Caveats
  - Signature of an obscured AGN difficult to distinguish from shocks/nuclear star formation
  - Energetics of the AGN uncertain

VLBA Observations

- Observation Date: Oct 5, 2011
- Project: BA99
- Integration time: 8 hours total; 4 on-source
- Frequency: 1.65 GHz (18 cm)
- Bandwidth: 16 MHz



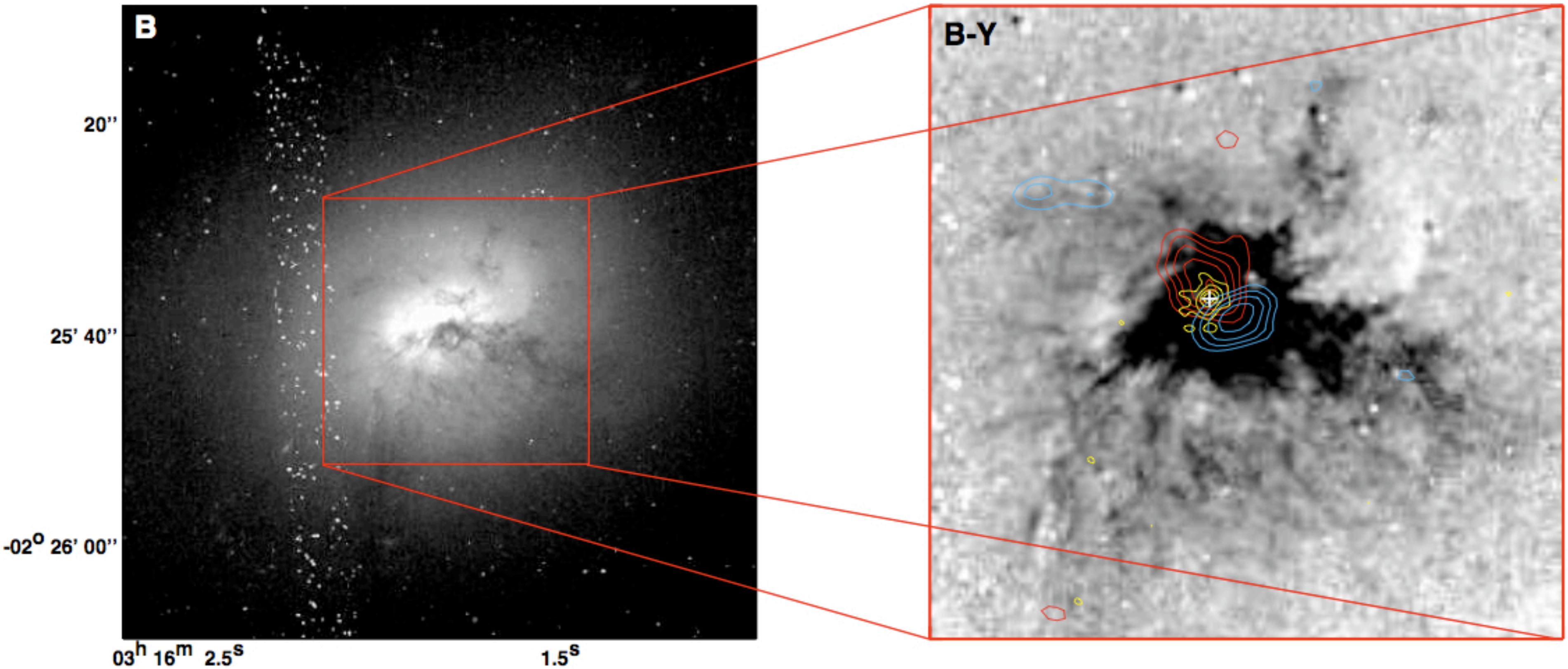
The VLBA Detection

Above: Uniformly-weighted clean image of NGC 1266. Unit contour is rms noise (42 μJy beam^{-1}). Relative contours are [-3, 3, 6, 10, 14]. Beam major axis = 1.14 pc.

VLBA observational parameters of NGC 1266

Frequency	(MHz)	1656[a]
rms noise	(μJy beam^{-1})	42[b]
Beam	**Parameters**	
$\theta_M \times \theta_m$	(mas)	9.75×4.31[c]
P.A.	(deg)	-0.39[d]
Source	**Parameters**	
$\theta_M \times \theta_m$	(mas)	$7.98 \pm 1.46 \times 6.19 \pm 0.96$[e]
P.A.	(deg)	10.39 ± 40.88[f]
$M \times m$	(pc)	$1.16 \pm 0.21 \times 0.89 \pm 0.14$[g]
S	(mJy)	1.38 ± 0.12[h]
$\log(P_{\rm rad})$	(W Hz^{-1})	20.17[i]
$T_{\rm b}$	(K)	1.5×10^7 [j]

The VLBA Detection



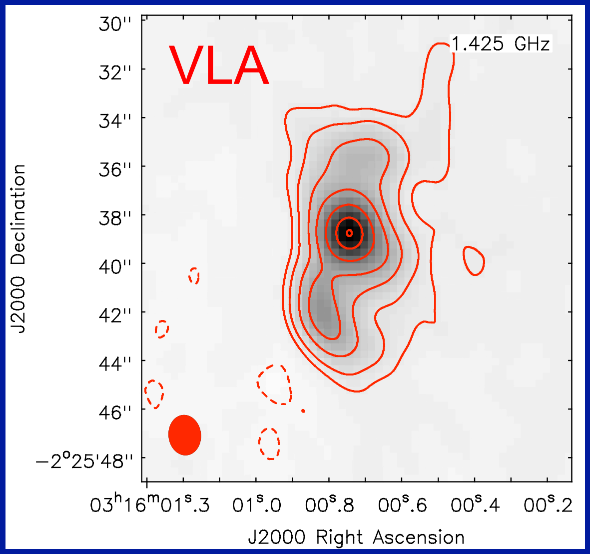
Left: HST B-band image showing the extent of the dust extinction in NGC 1266.

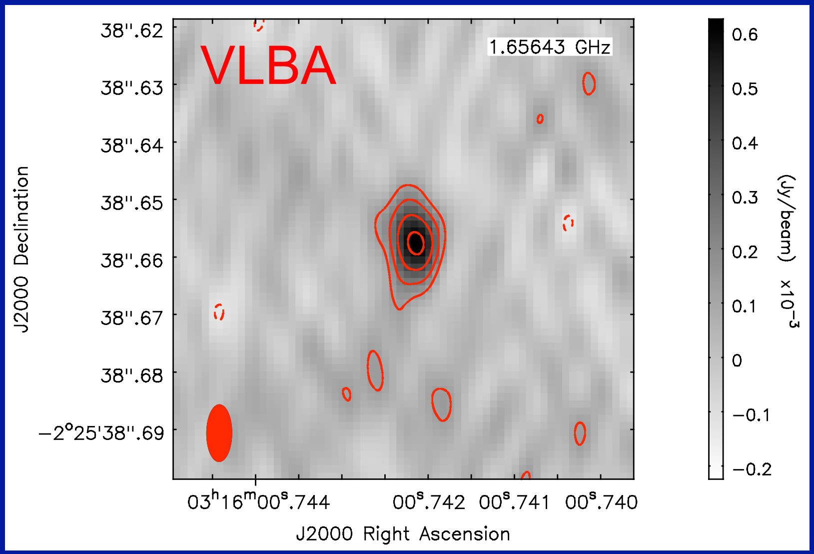
Right: HST B-Y image highlighting the central dust features overlaid with contours showing CARMA (yellow) and blue/redshifted SMA (blue/red) emission. The position of the VLBA emission is marked by a white cross.

Origin of the Compact Emission?

- Compact Starburst? – No
  - Compact nuclear starbursts limited to $T_b < 10^5$ K
  - For NGC 1266, $T_b > 1.5 \times 10^7$ K
- Young Supernova Remnant? – Probably not
  - SNR similar to Cas-A is too faint
  - Difficult to completely rule out a young ultraluminous SNR, but:
    - No evidence of super star clusters
    - No signs of recent supernovae in optical monitoring programs
- Accreting SMBH? – Most likely
  - Low-level AGNs commonplace in the centers of local galaxies
  - Radio power (1.48×10^{20} W/Hz) is consistent with other LLAGNs imaged with the VLBA
  - Lower-resolution radio images indicate radio outflow-like features

Missing VLA Flux Density?





S_{core} = 70.53 +/- 2.20 mJy

S_{total} = 1.38 +/- 0.12 mJy

- VLBA recovered only ~2% of the core VLA flux density
- Extended, resolved-out emission could be due to:
  – Widespread nuclear star formation
  – Radio outflow from the AGN
  – Extended shock region
- Future HSA observations needed!

Summary

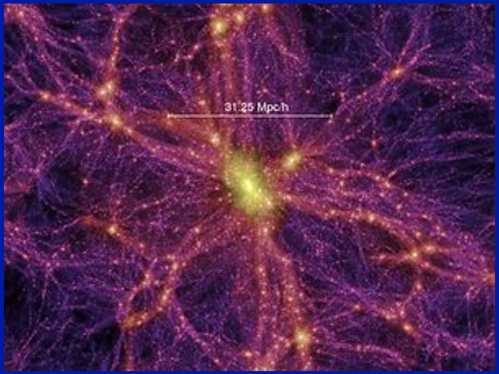
- NGC 1266 harbors a massive molecular outflow and is a rare, local candidate for AGN-driven SF quenching/suppression
- Recent VLBA observations revealed compact, high brightness temperature emission in the nucleus of NGC 1266 most consistent with originating from accretion onto the central SMBH
- Evidence directly implicating the AGN as the driver of the molecular outflow is still lacking, but may be revealed in future studies

Future Work

- HSA Observations capable of resolving some of the missing VLA flux density

- Improved X-ray imaging/ spectroscopy to determine AGN properties

- Dynamical modeling aimed at explaining how the gas in NGC 1266 lost its angular momentum



Questions?

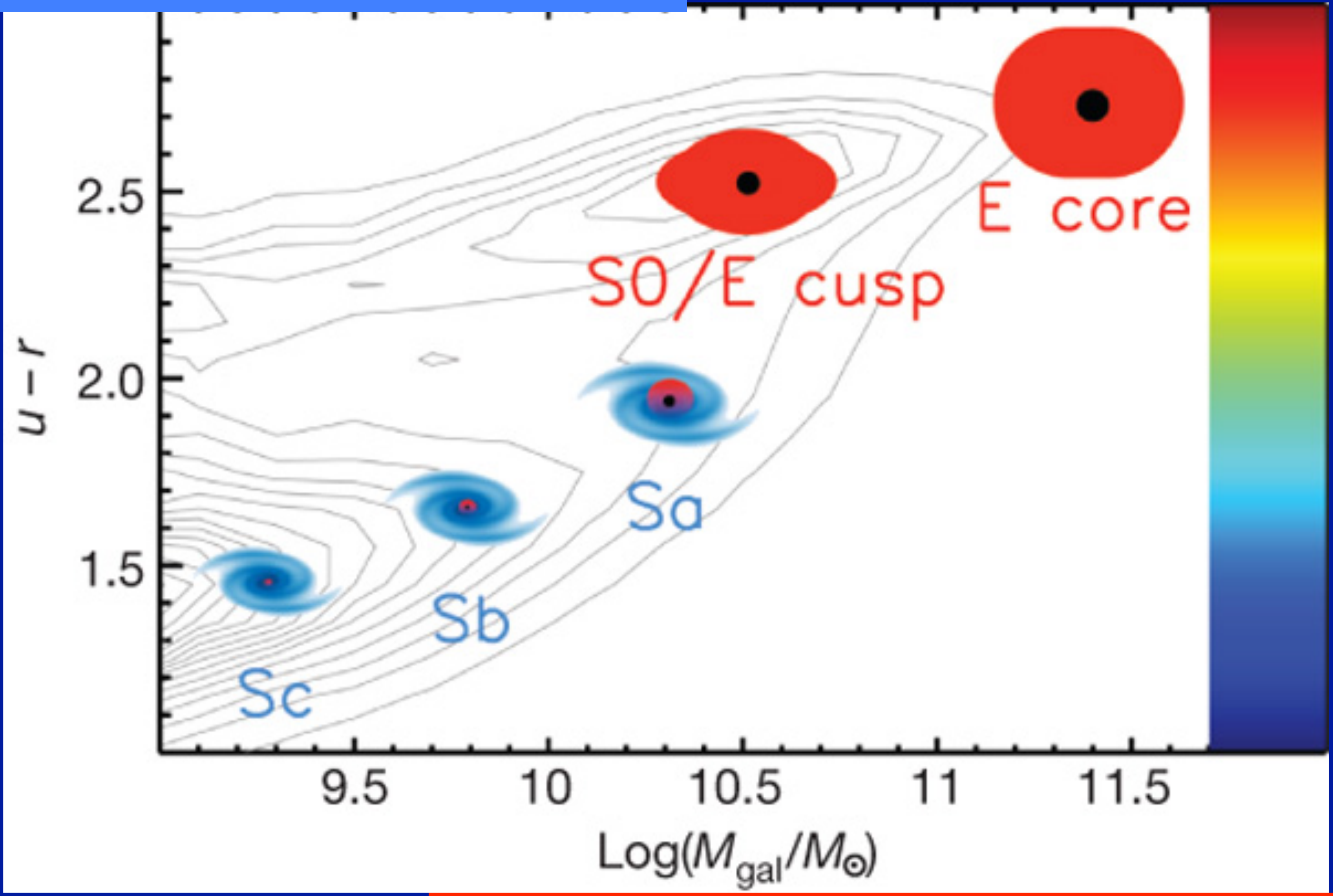
Questions?

Outflows: Impact on Galaxy Evolution

Key question: What drives the galaxy-color bimodality?

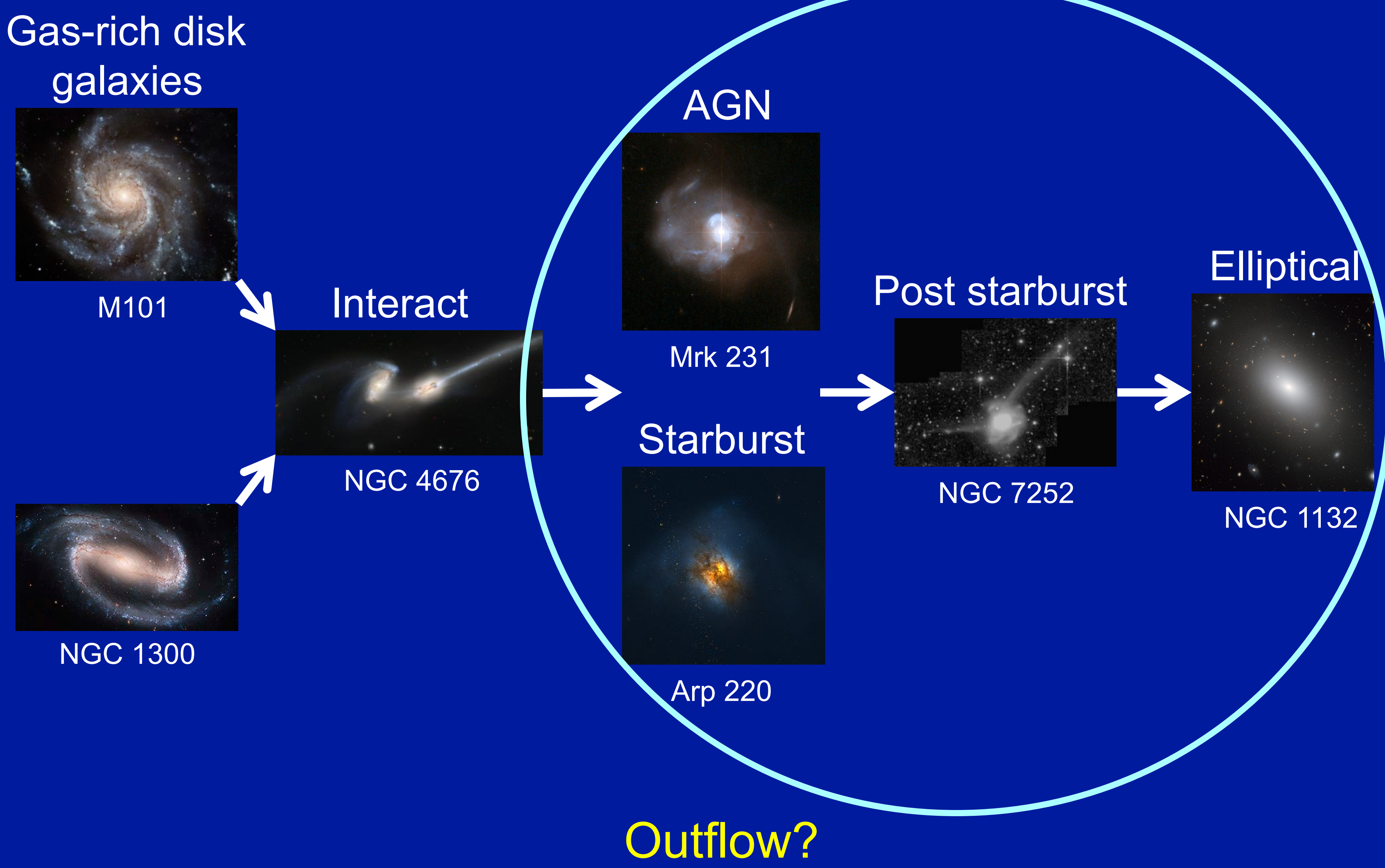
Blue Cloud: star-forming spirals

Cattaneo, et al. 2009 (Nature)

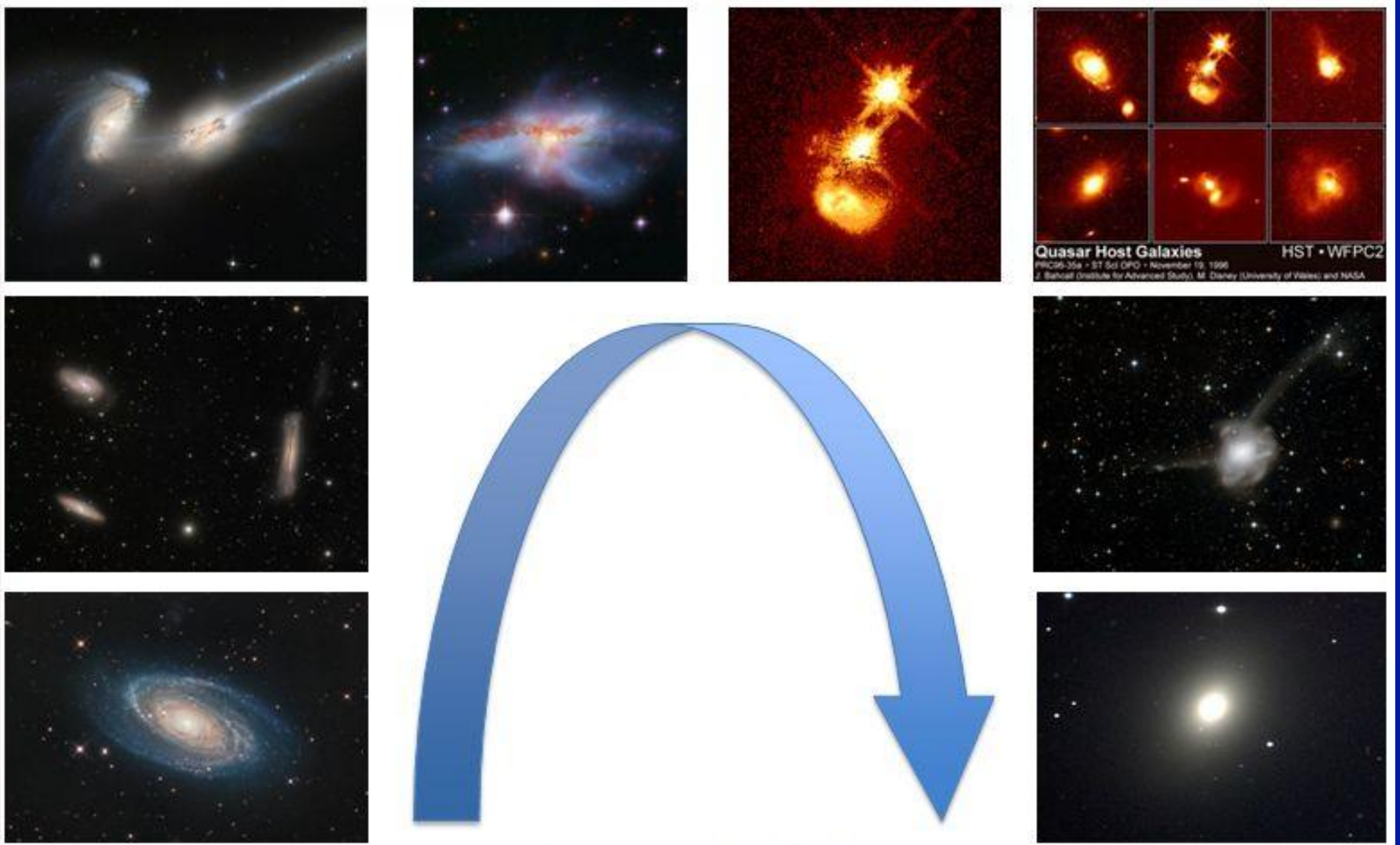


Red Sequence: non-star-forming ETGs

The Standard Paradigm



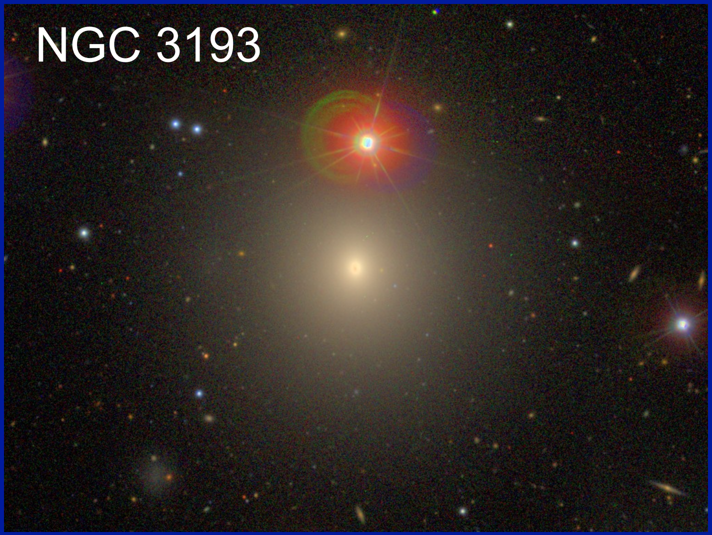
The Standard Paradigm



Hopkins, Philip, et al. 2008, ApJS, 359

The Red Sequence: Ellipticals

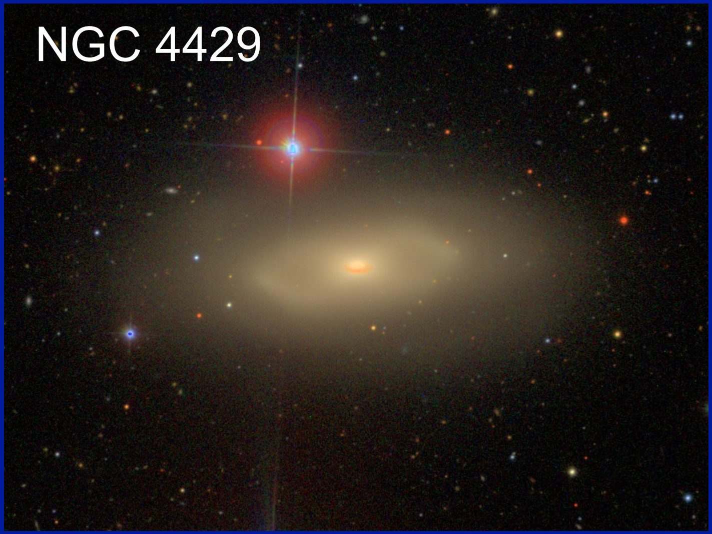
- No stellar disk
- Old stellar population
- Lack of cool ISM material
- More common in the local universe than at high-z
- Predominantly located in dense clusters
- Brighter, more massive E's are redder

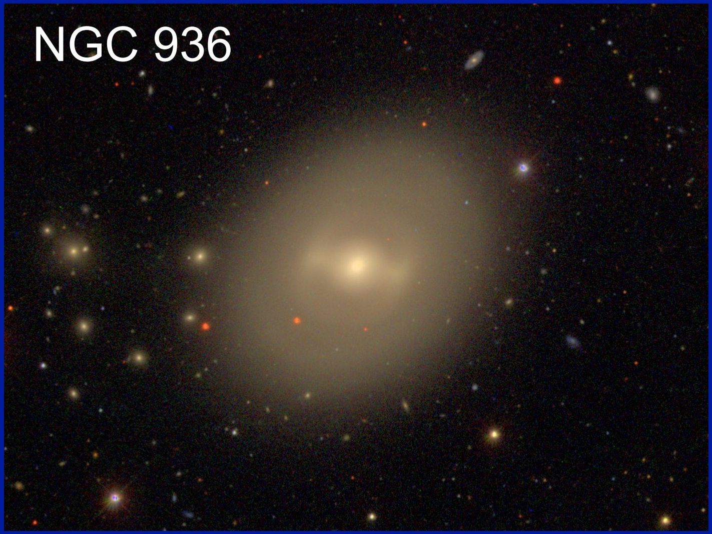


David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration

Red Sequence: Lenticulars (S0s)

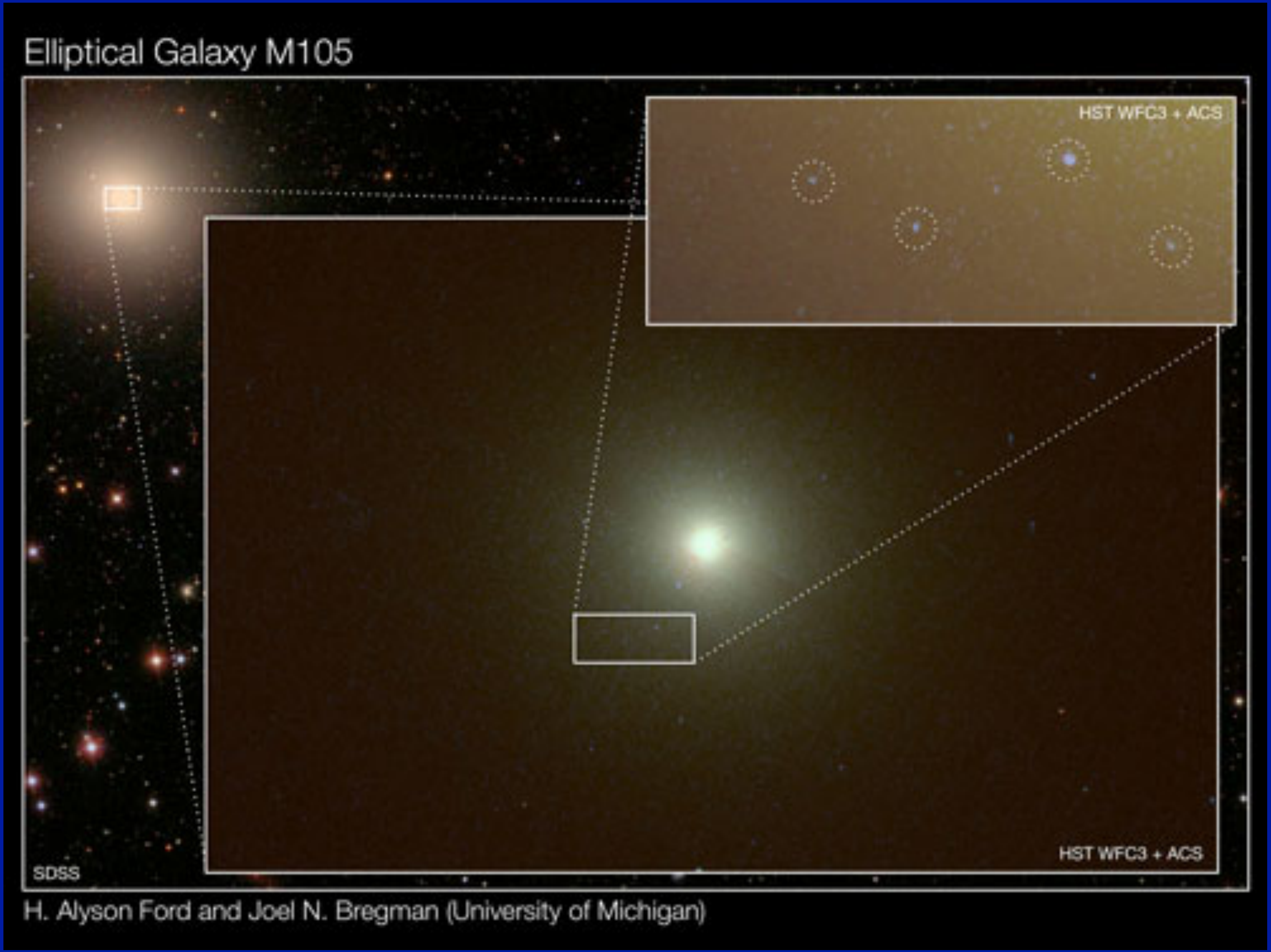
- Like spirals:
  - Bulge, sometimes a bar
  - Rapidly rotating disk
  - Similar surface brightness profile
- Like ellipticals:
  - Lack spiral arms
  - Little cool gas/recent SF
  - Common in clusters
- Remnants of gas-depleted spirals?





David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration

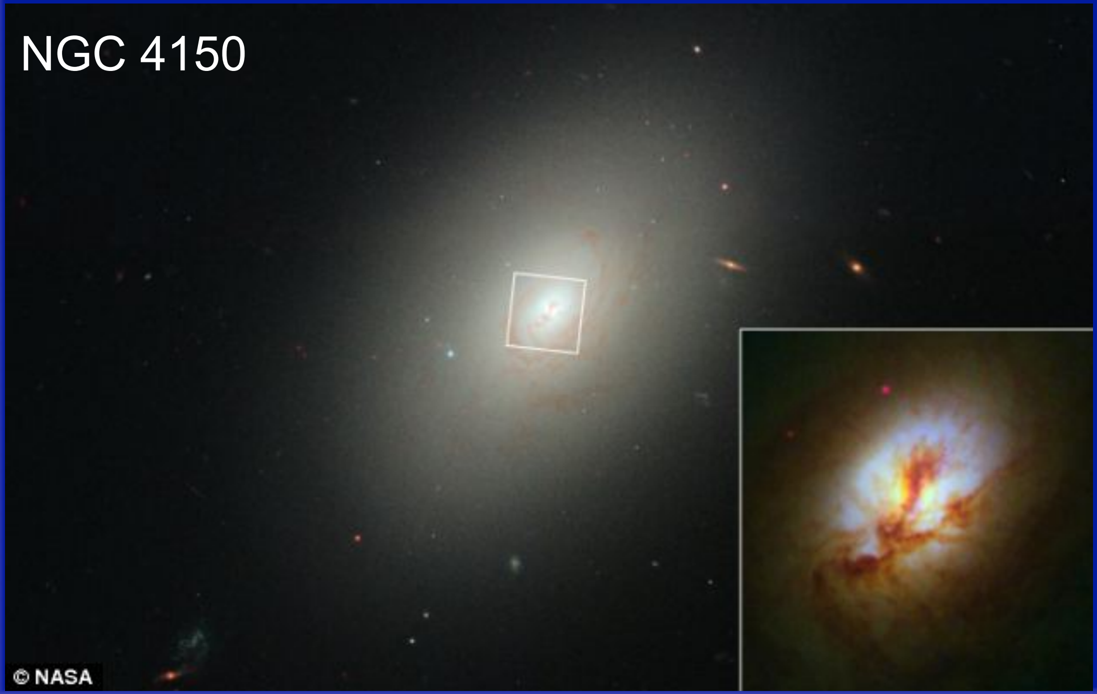
Old, Red and Dead?

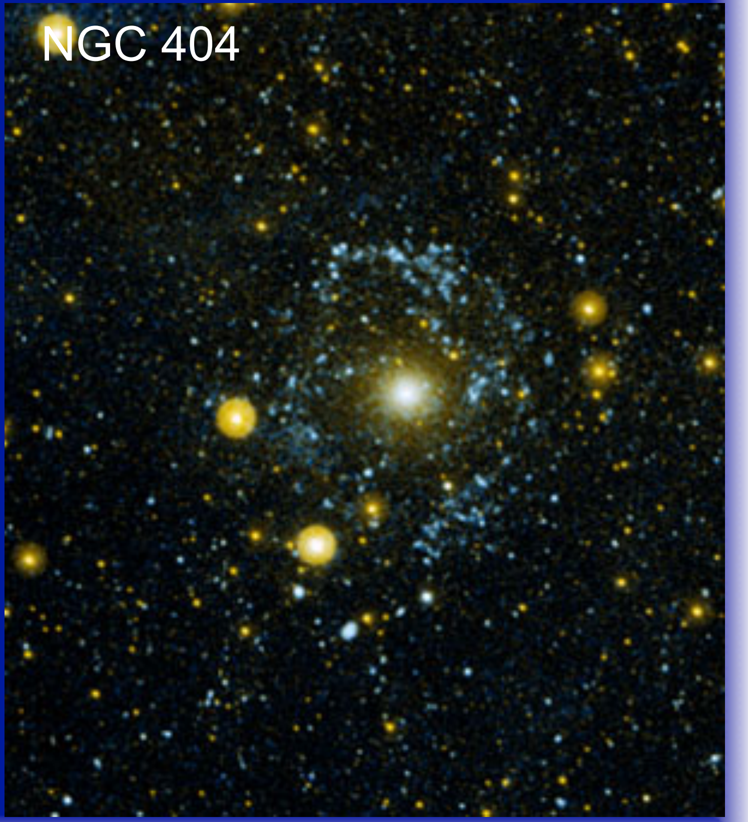


Star Formation in ETGs

- Still lack an understanding of the details!
  - Efficiency?
  - Dependence on gas surface density?
  - Feedback mechanisms?

Thilker, et al. 2010





Star Formation Quenching: The Role of AGNs

- SF and AGN activity may be evolutionarily linked
  - The most massive galaxies are quenched the fastest and also have the most massive SMBHs
  - Support from DSS statistical studies and simulations
- Direct observational evidence
  - Markarian 231
  - NGC 1266

Star Formation Quenching/ Suppression Mechanisms

1) Consumption of cold gas reservoir
2) Cold gas stripping
3) Gravitational heating of cold gas disks by clumpy mass in-fall
4) Virial shock heating of cold gas as it in-falls through a massive dark matter halo
5) Morphological quenching due to deep potential wells of spheroidal galaxies which leave cold gas intact but render it stable against collapse
6) AGN feedback

Star Formation Quenching: Which Mechanism?

Dominant quenching mechanism likely depends on:

- –merger history
- –halo size
- –environment

★ 260 Early-Type Galaxies

★ D < 42 Mpc

★ $M_K < -21.5$ mag

Goal: to reveal how SF and feedback processes affect the transformation of galaxies through the use of multiwavelength observations along with numerical simulations and semi-analytic models

Multiwavelength Observations

William Herschel Telescope

260

WSRT

170

IRAM 30m

259

Canada-France-Hawaii Telescope

70

SDSS

260

Isaac Newton Telescope

CARMA

32

Molecular Gas Observations

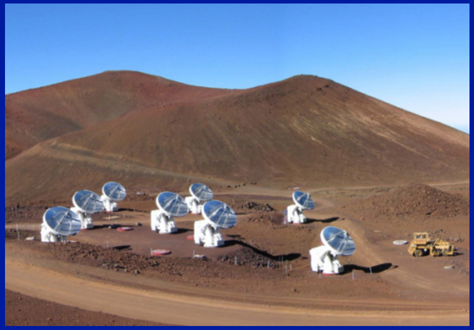
IRAM 30m

CO(1-0)

CO(2-1)

CARMA

CO(1-0)



SMA

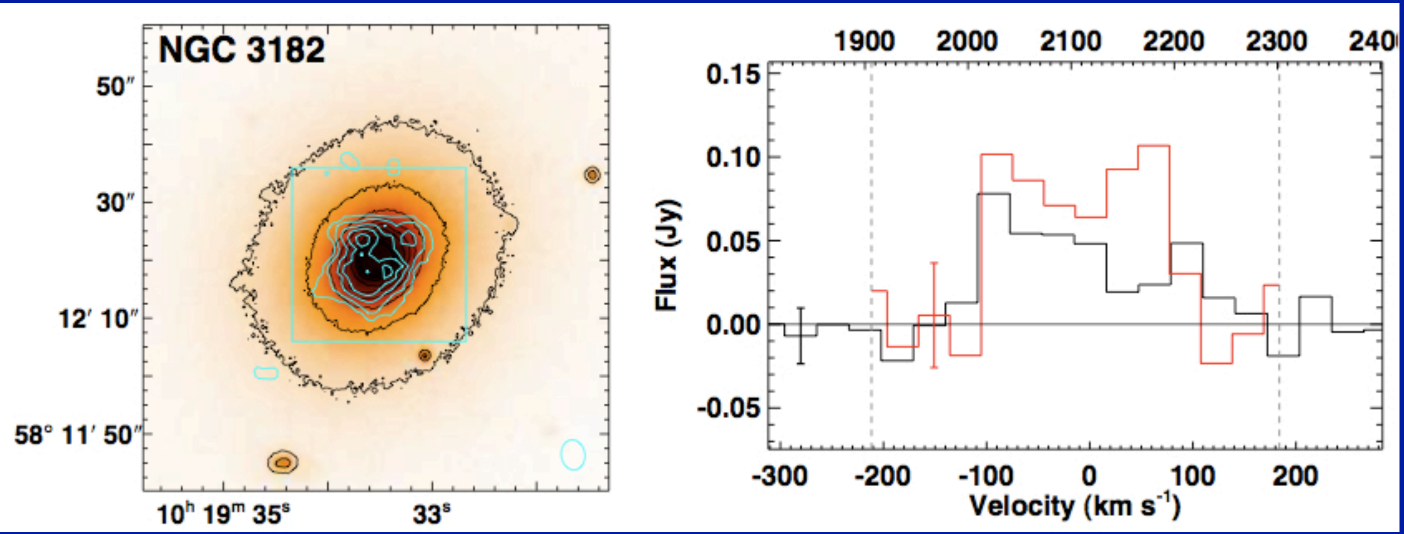
CO(2-1)

$^{13}CO(2-1)$

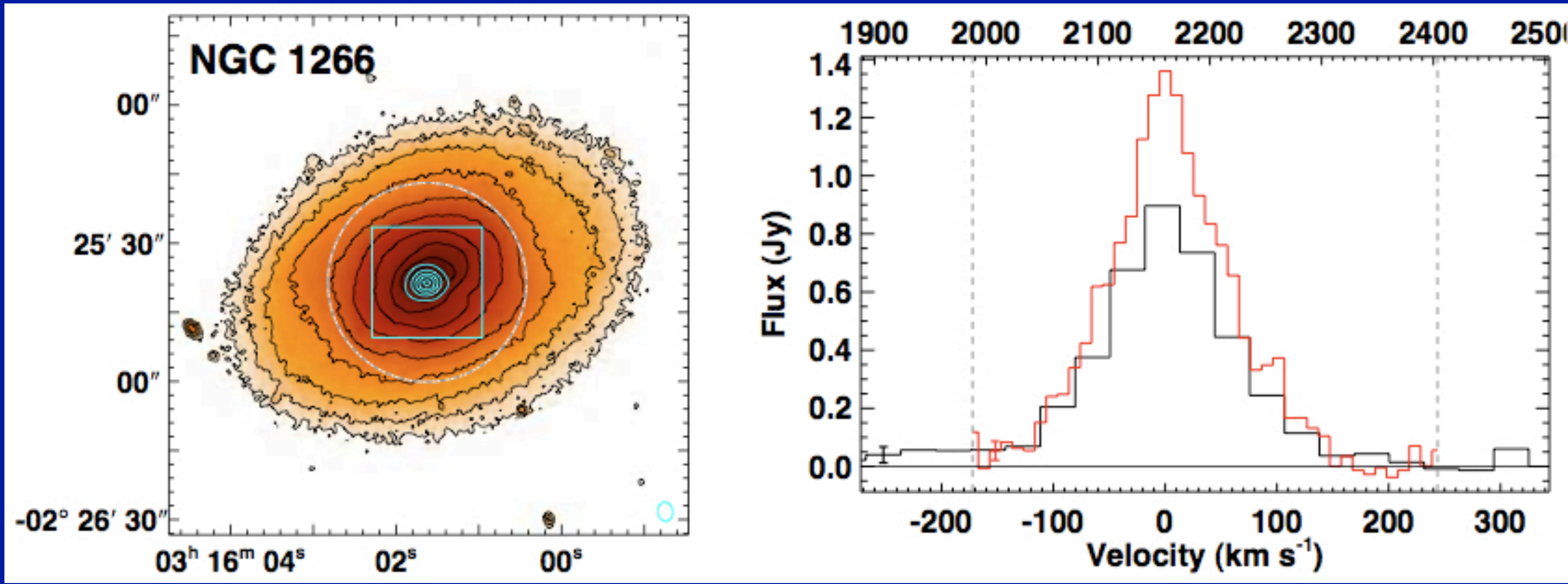
CO(3-2)

$HCO^{+}(4-3)$

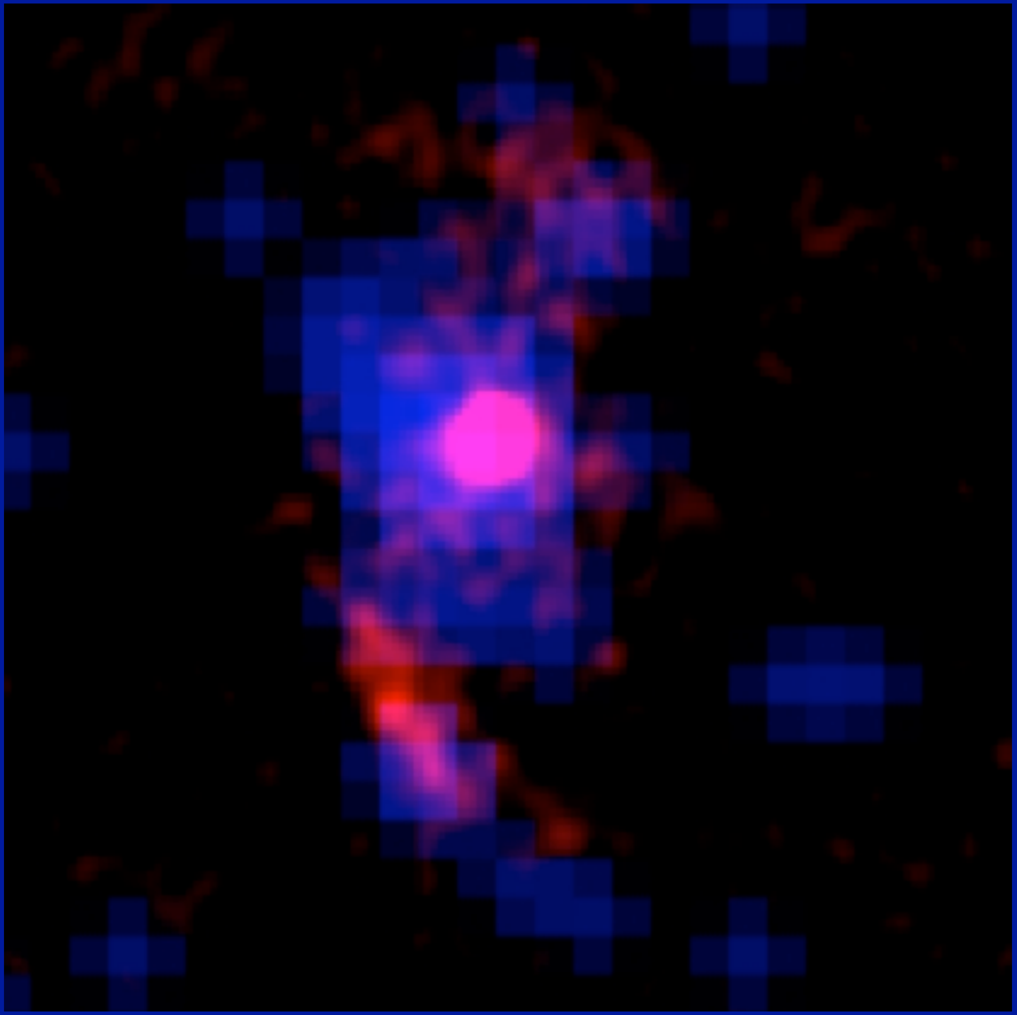
Spectral Profile



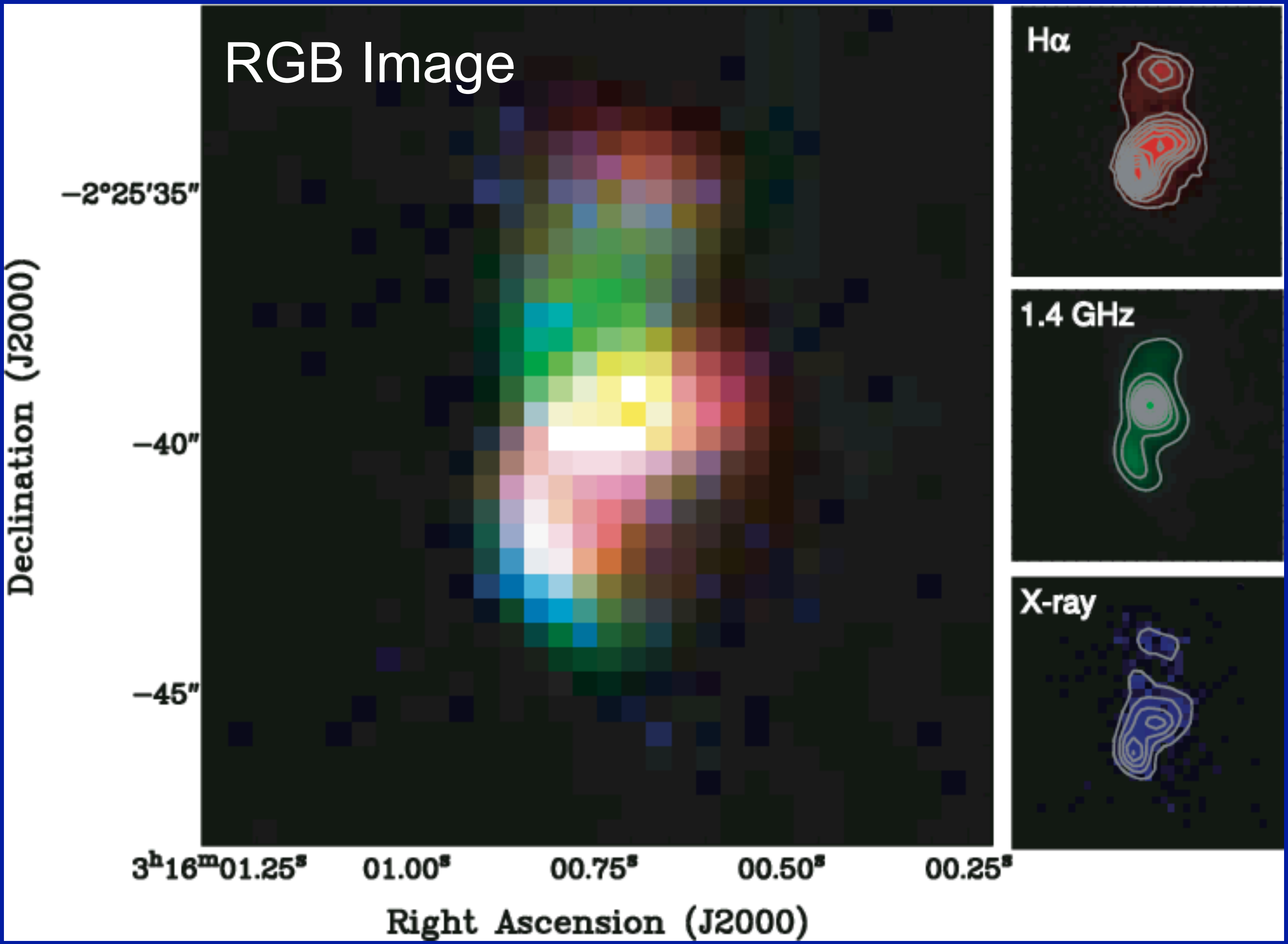
Black: IRAM 30m
Red: CARMA



Chandra X-ray Observations



Blue: smoothed hard (4-8 keV) X-rays (Chandra)
Red: archival VLA 5 GHz



Hα, 1.4 GHz & unsmoothed hard X-ray emission appear co-spatial, suggesting the outflow is truly multi-phase