Credit: C. Hull

Molecular gas, AGN feedback, and the unusual case of NGC 1266

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ATLAS^{3D}

CO Effort

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ATLAS^{3D}

a <u>volume-limited</u> survey of nearby early-type galaxies

$D < 42$ Mpc

$M_K < -21.5$

$(M_{gal} > 6 \times 10^9\ M_\odot)$

$|\delta - 29°| < 35°$

$|b| > 15°$

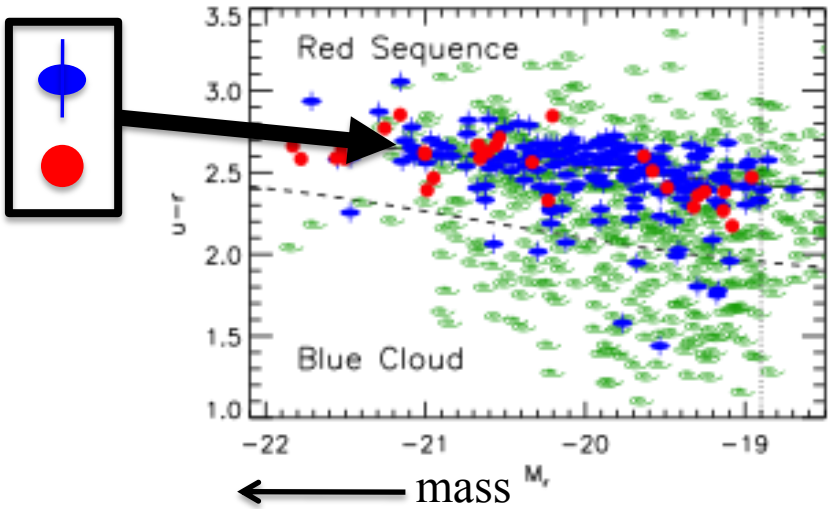
871 possible galaxies

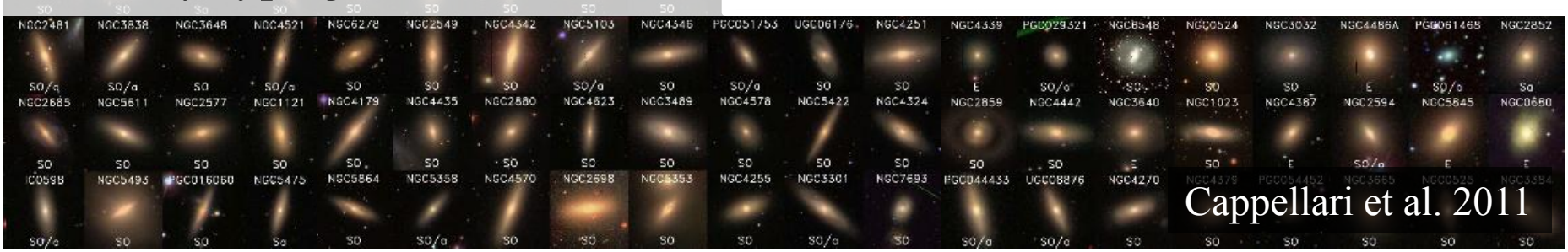
morphologically selected

(only elliptical, E or lenticular, S0)

261 early-type galaxies

ATLAS^{3D} ETGs





Cappellari et al. 2011

ATLAS^{3D} : CO Results

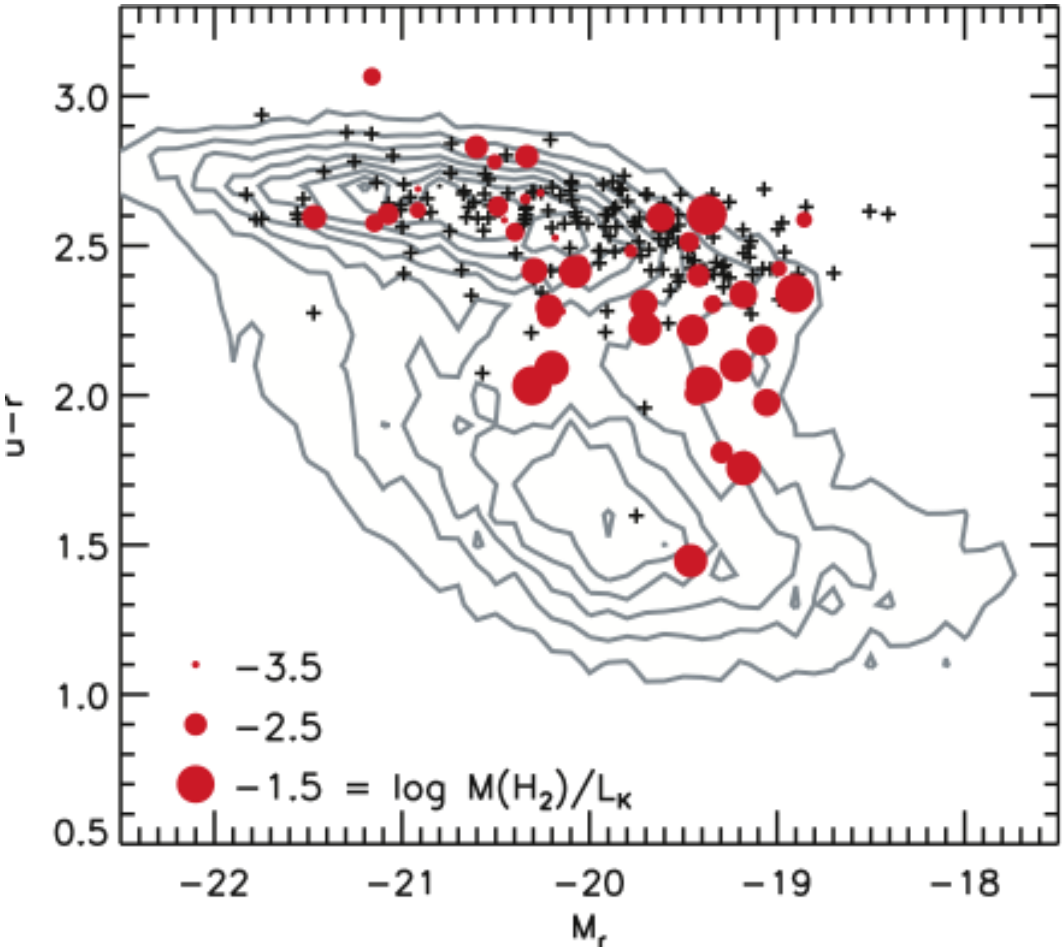
22% of ETGs contain molecular gas

- no mass or environment preference

-strong preference for rotation-dominated

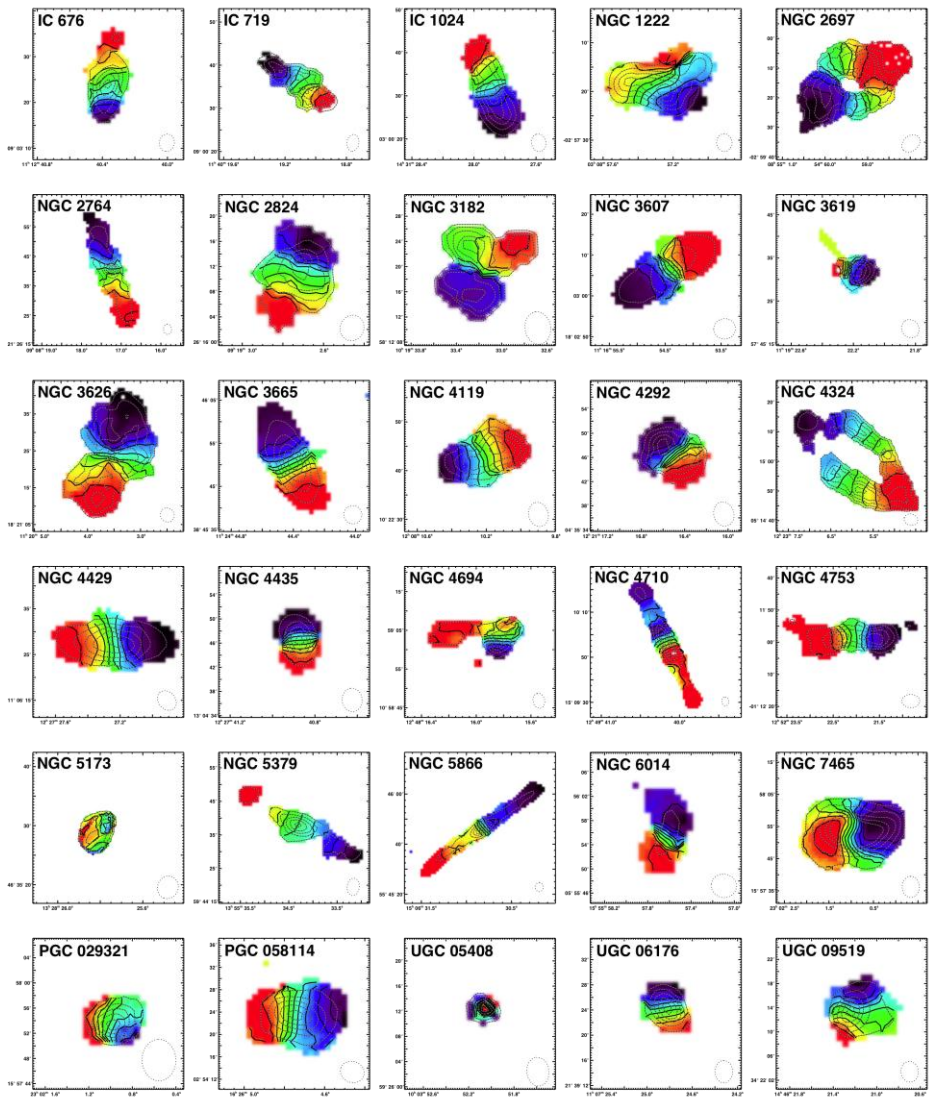
- "green valley" objects more likely to contain molecular gas

Young et al. 2011



L. Young, Private Communication

who said red and dead?



32 galaxies, 30 ATLAS^{3D} galaxies

Complete down to 18.5 Jy km/s
*(leaving **14** detected faintest galaxies un-imaged)*

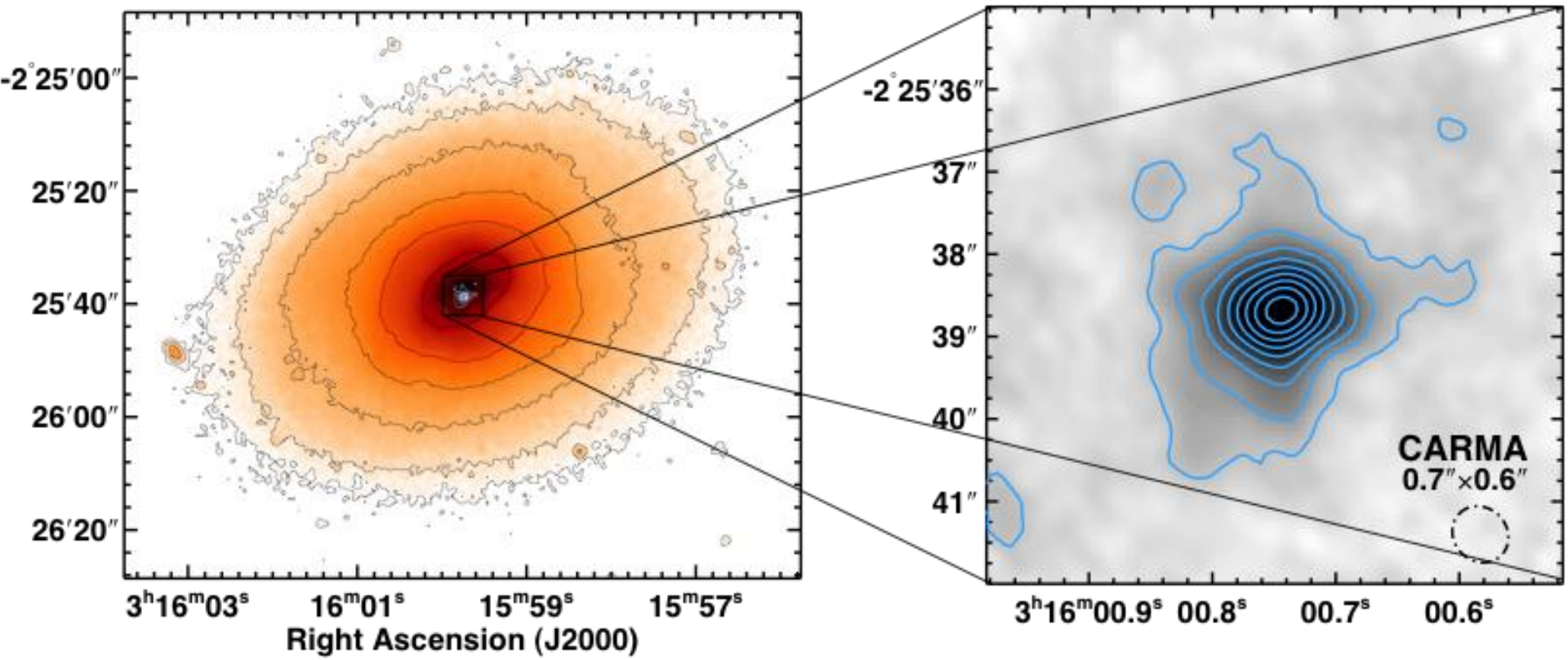
467 hours of CARMA time
5 semesters

Pre-ATLAS^{3D} CARMA
~20 CO-imaged ETGs
(work of Wrobel & Kenney, L. Young, F. Combes, A. Crocker and L. Wei)

Now:
~50 (> a factor of 2 increase)

3D data cubes (channel maps), integrated intensity (mom0) and integrated velocity (mom1) to be made available publically for all ATLAS^{3D} galaxies

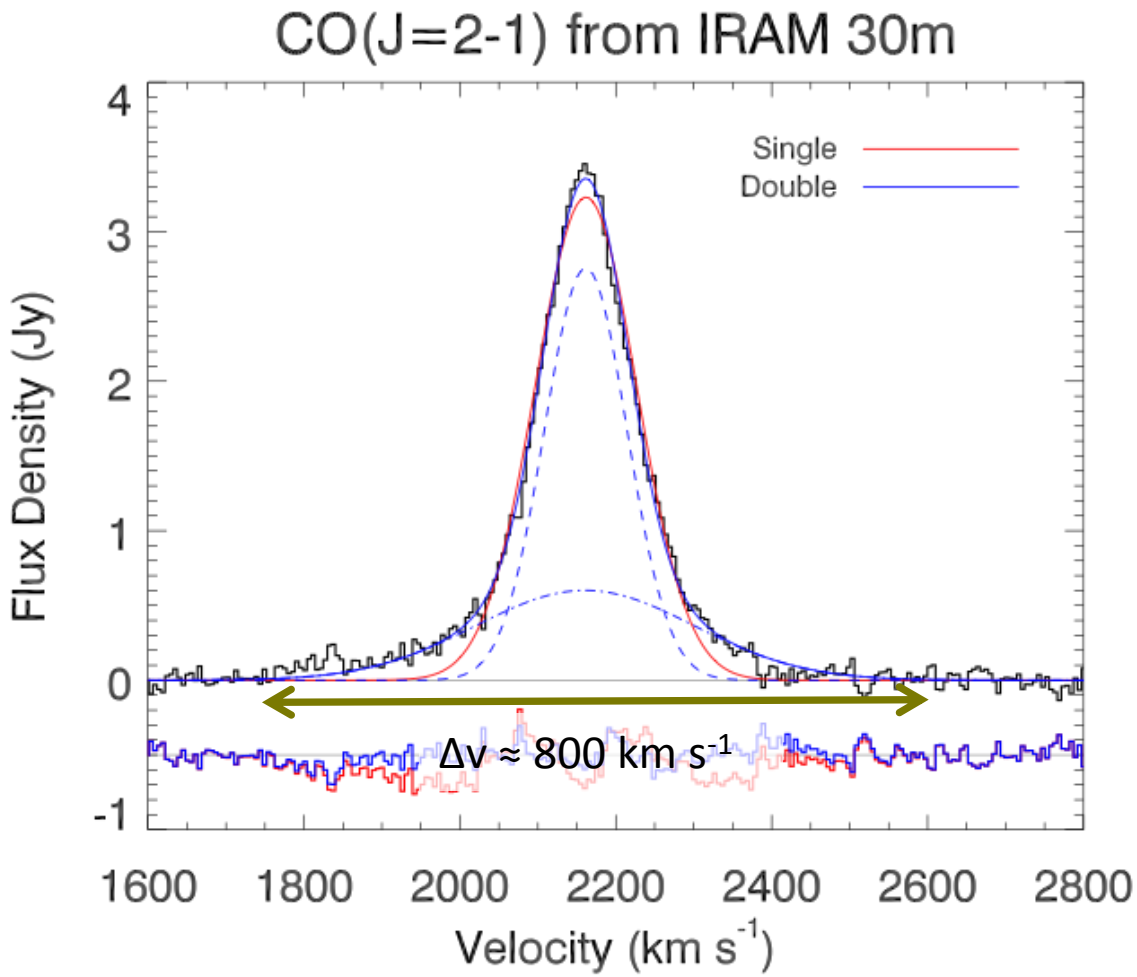
NGC 1266



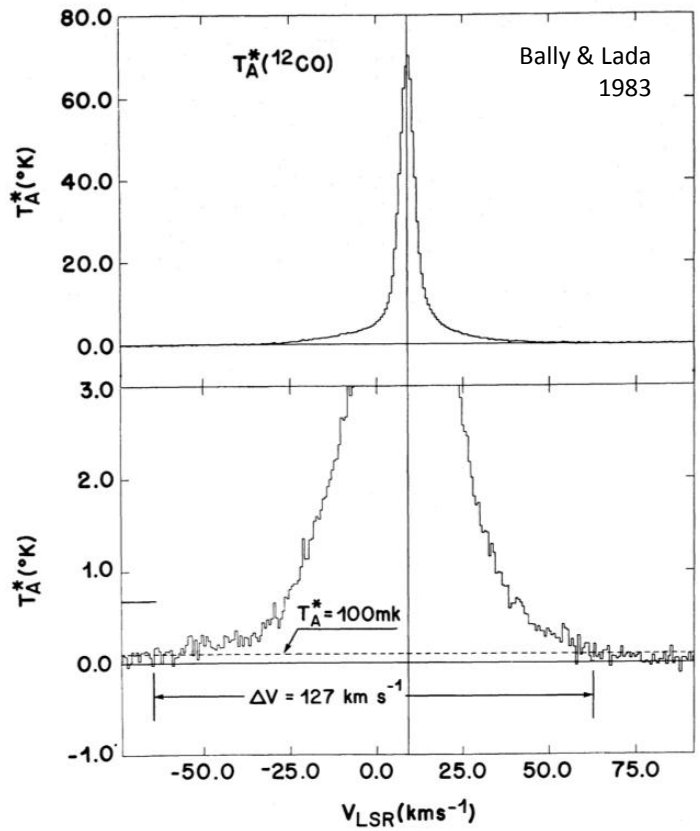
10^9 $M_\odot$ of gas in nuclear region
Hosts a massive molecular outflow
Local example of AGN feedback?
No signs of interaction

Alatalo et al. 2011

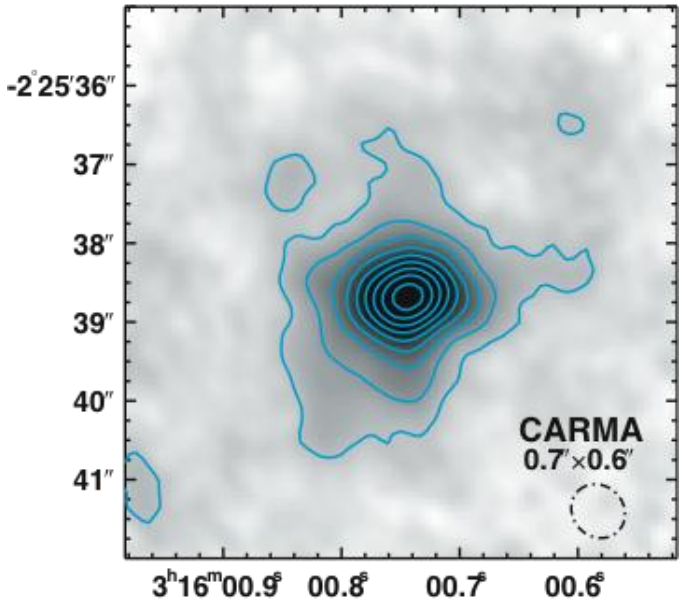
IRAM 30m CO spectrum



Orion outflow



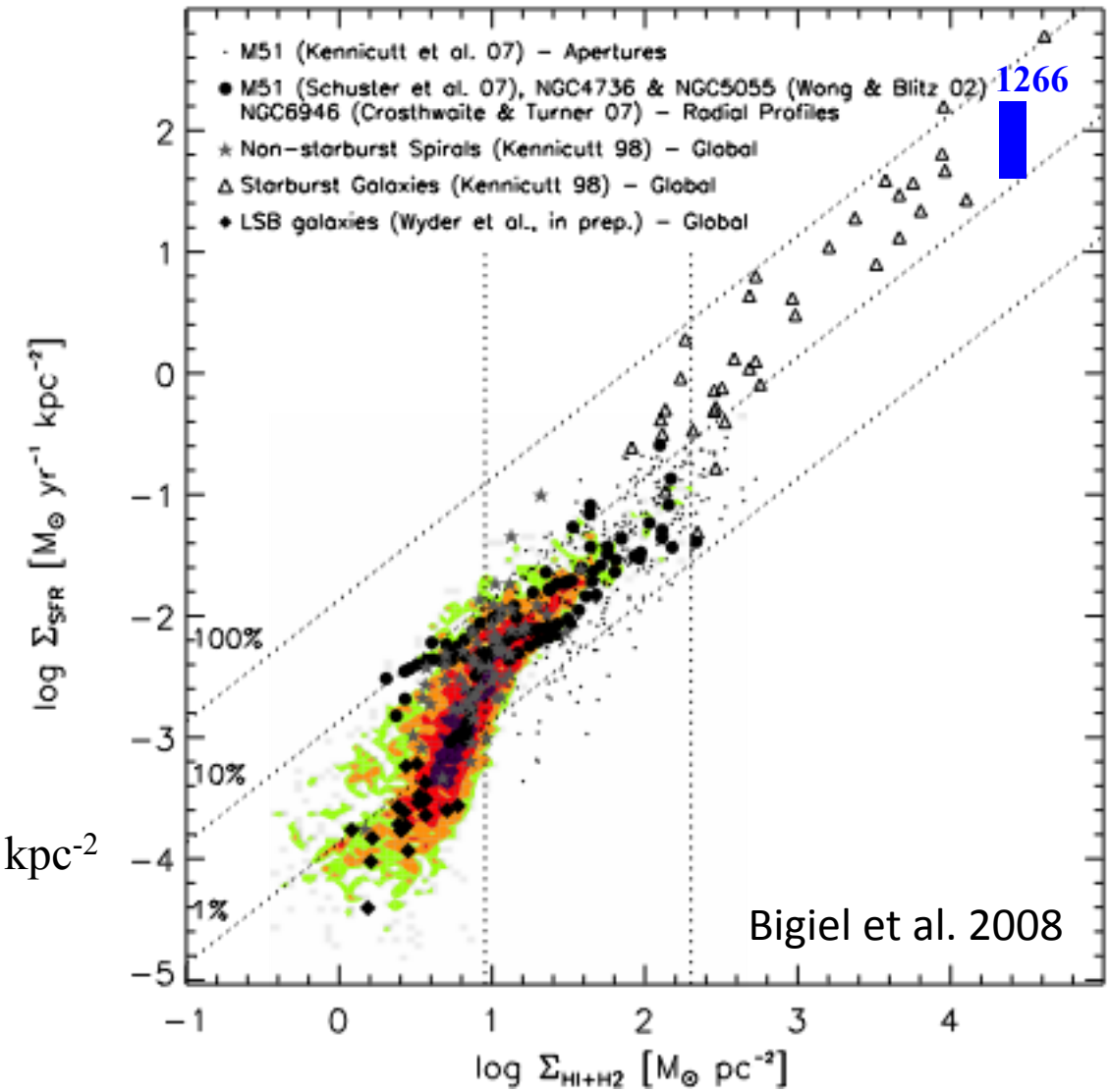
Nuclear Gas



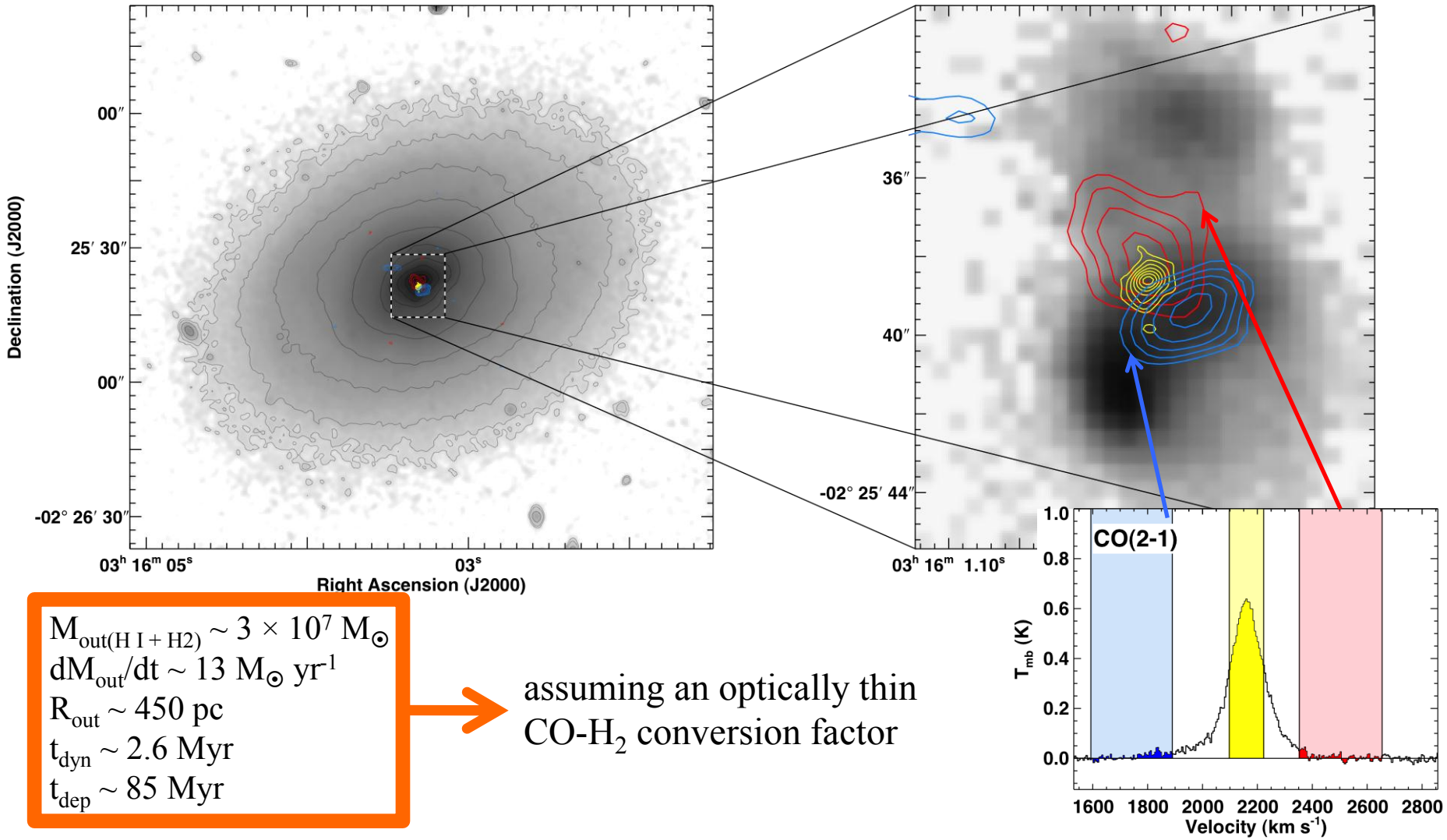
$4 \times 10^8\ M_\odot$ of gas (H_2 + He) is concentrated within central **100 pc**

$\Sigma_{gas} = 2.7\times10^4\ M_\odot\ pc^{-2}$

expected SFR from K-S: 285 $M_\odot\ yr^{-1}\ kpc^{-2}$
calculated SFR from L_{FIR} and L_{PAH}:
$\Sigma_{SFR}(FIR) = 195\ M_\odot\ yr^{-1}\ kpc^{-2}$
$\Sigma_{SFR}(PAH) = 53\ M_\odot\ yr^{-1}\ kpc^{-2}$



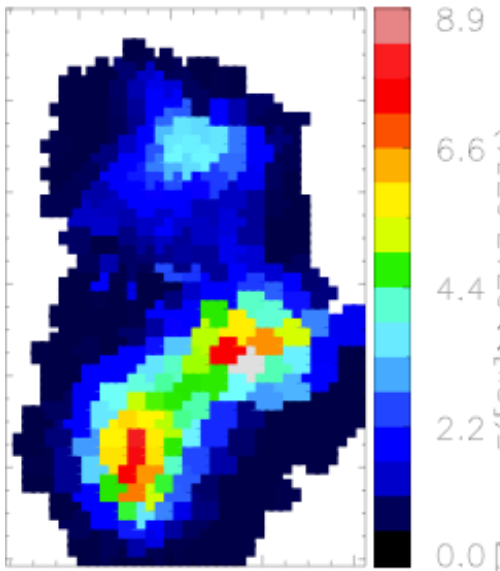
NGC 1266 hosts a massive molecular outflow



$M_{out(H\,I + H2)} \sim 3 \times 10^7\ M_\odot$
$dM_{out}/dt \sim 13\ M_\odot\ yr^{-1}$
$R_{out} \sim 450$ pc
$t_{dyn} \sim 2.6$ Myr
$t_{dep} \sim 85$ Myr

assuming an optically thin CO-H_2 conversion factor

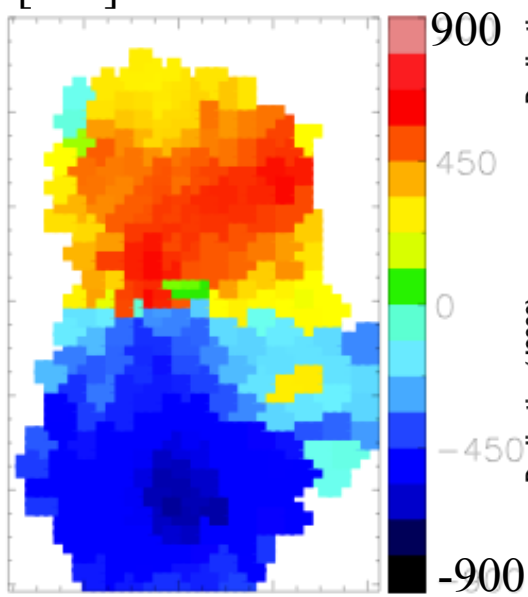
Outflow appears to be multi-phase

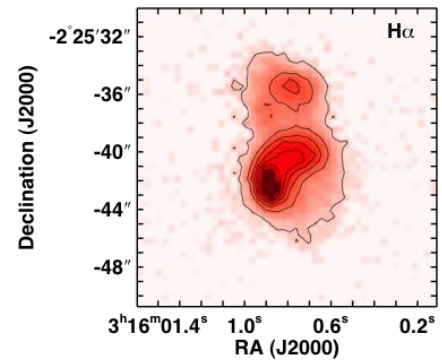


[S II] moment 0

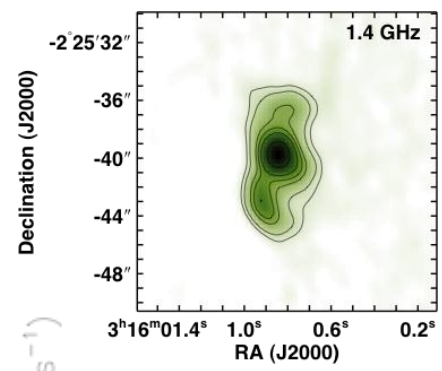
[S II] from Gemini GMOS, which includes the velocity information

[S II] moment 1

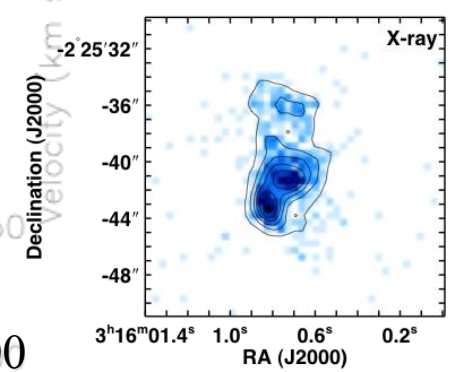




SINGS photometry of Hα show that most of the emission from shock



1.4 GHz continuum shows both unresolved peak in nucleus and shock "spurs"

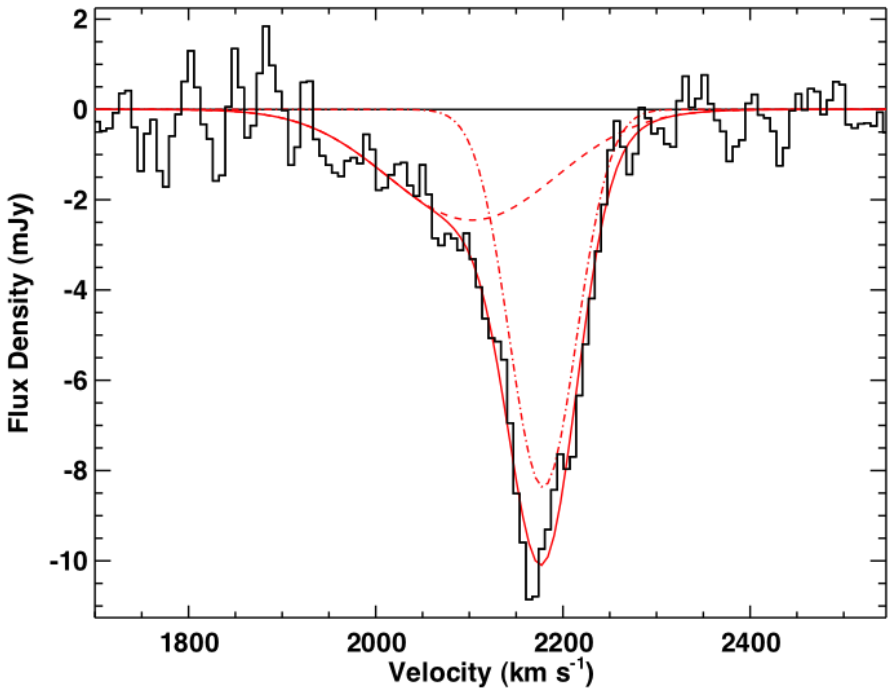


X-ray data shows bulk of emission is from shock with T ~ 0.5 keV

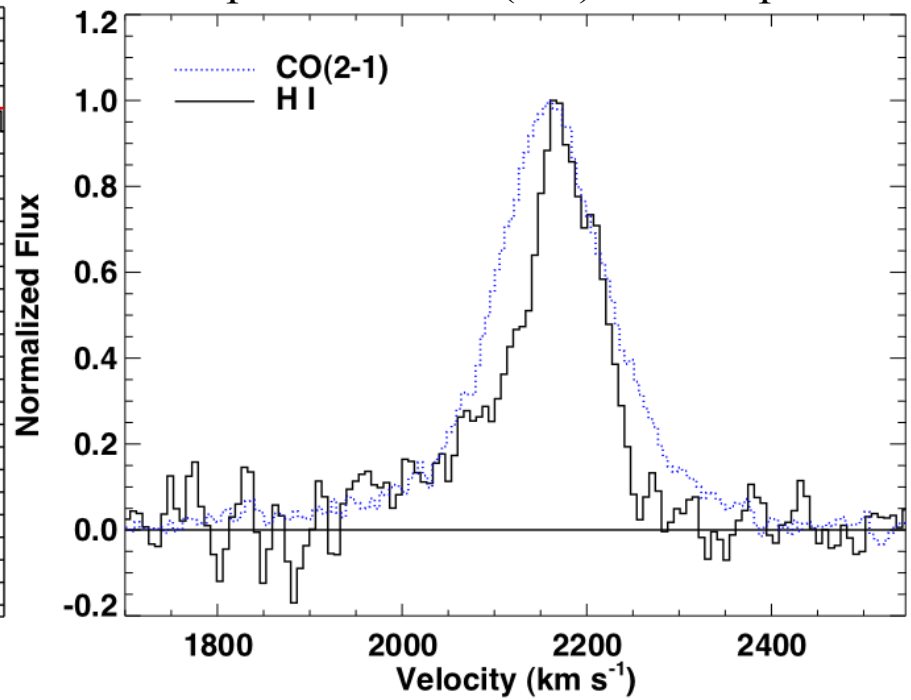
Davis. et al, in prep

H I absorption

Continuum-subtracted H I profile



Comparison of CO(2-1) and H I profiles



H I is only found in absorption in NGC 1266, but shares the blueshifted wing emission

$N(\text{H I})_{\text{outflow}} = 9 \times 10^{20}$ cm^{-2}

$M(\text{H I})_{\text{out}} \approx 2 \times 10^{6}\ M_{\odot}$

H I confirms outflow hypothesis (blueshifted material must be in front of continuum source)

Driving NGC 1266

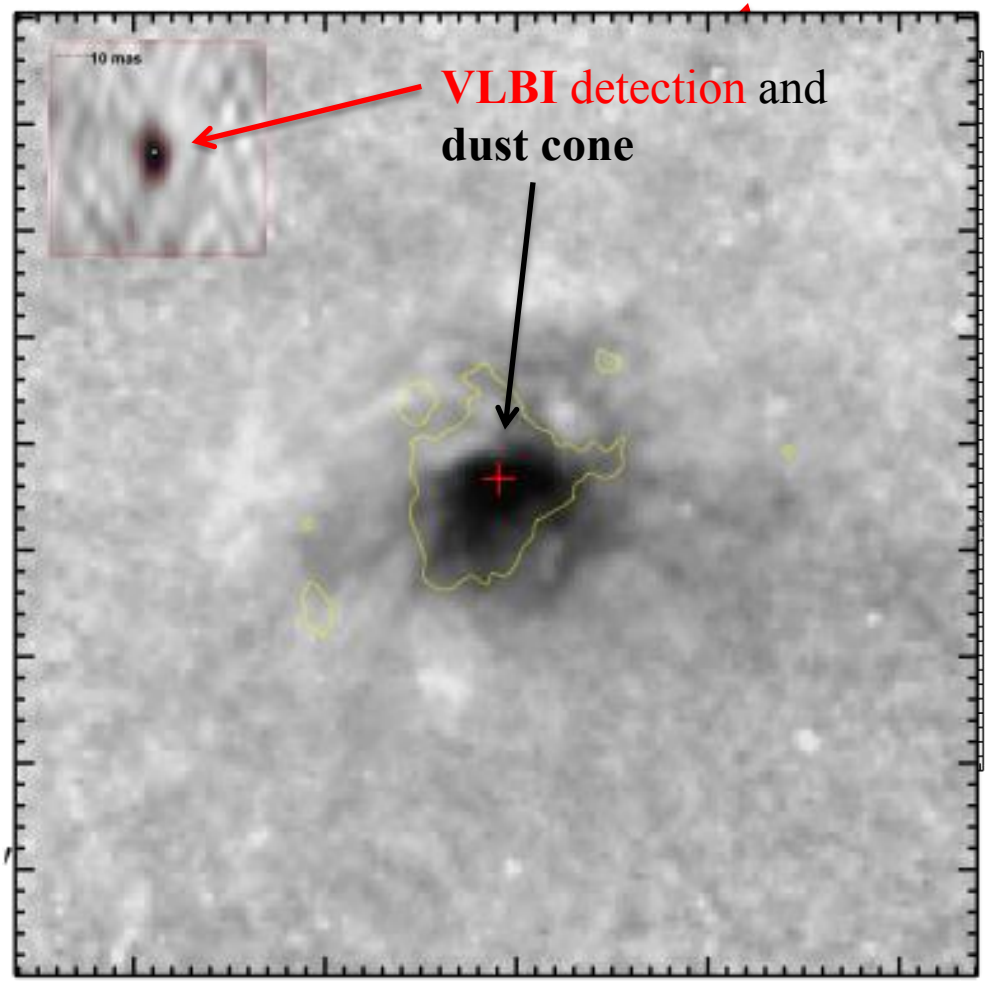
Hard X-rays and radio continuum confirm AGN in system

Molecular outflow of >13 $M_\odot$ yr^{-1}

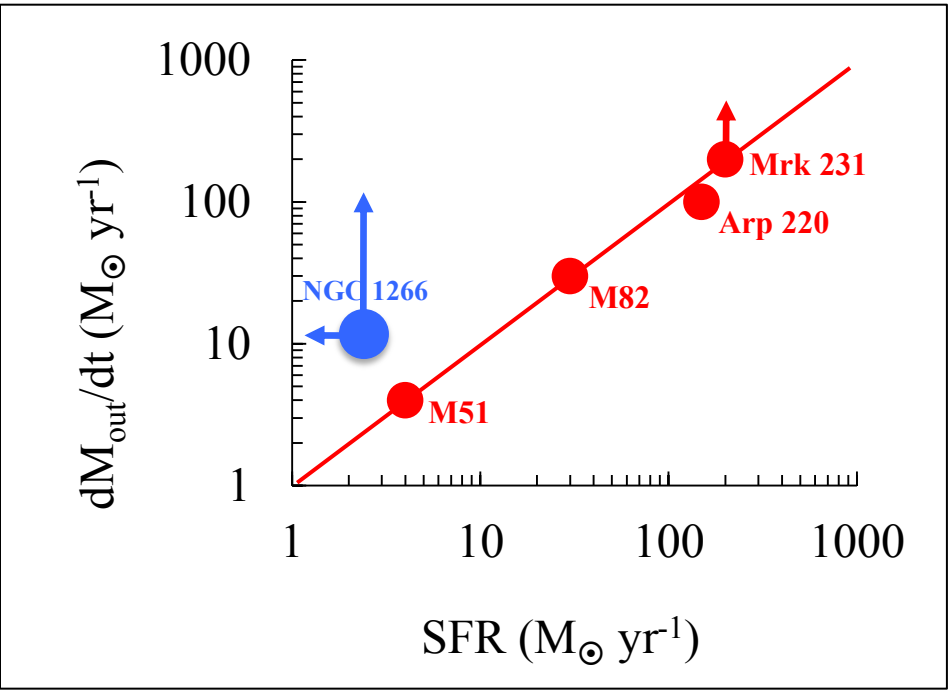
SFR of 2.2 $M_\odot$ yr^{-1} (from TIR) too low to sustain outflow (Murray et al. 2005)

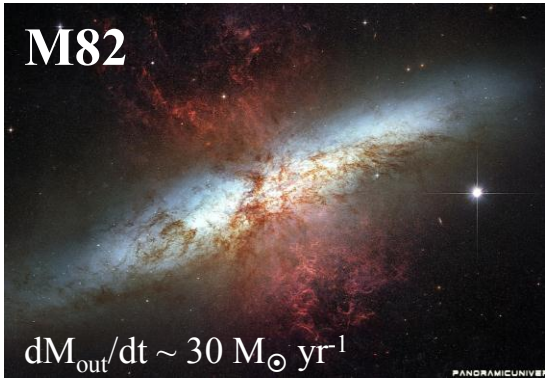
Using the $P_{1.4GHz} - P_{jet}$ relation from Bîrzan et al. (2008) radio jet contains sufficient mechanical energy (6×10^{42} ergs s^{-1}) to drive the molecular outflow (10^{41} ergs s^{-1}) and requires a **2%** coupling

Coincident 4-8 keV and 5 GHz continuum = AGN

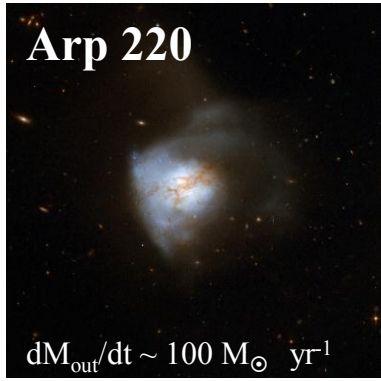


Other molecular outflows



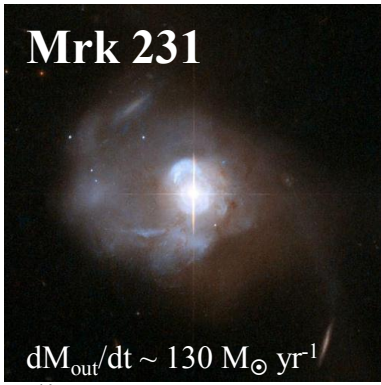


discovery:
Walter et al. 2002

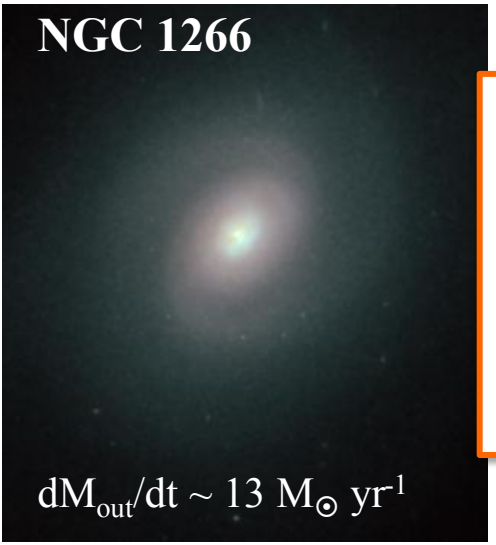


discovery:
Sakamoto et al. 2009

$dM_{out}/dt \sim 4\ M_\odot\ yr^{-1}$
discovery:
Matsushita et al. 2007



discovery:
Feruglio et al. 2010

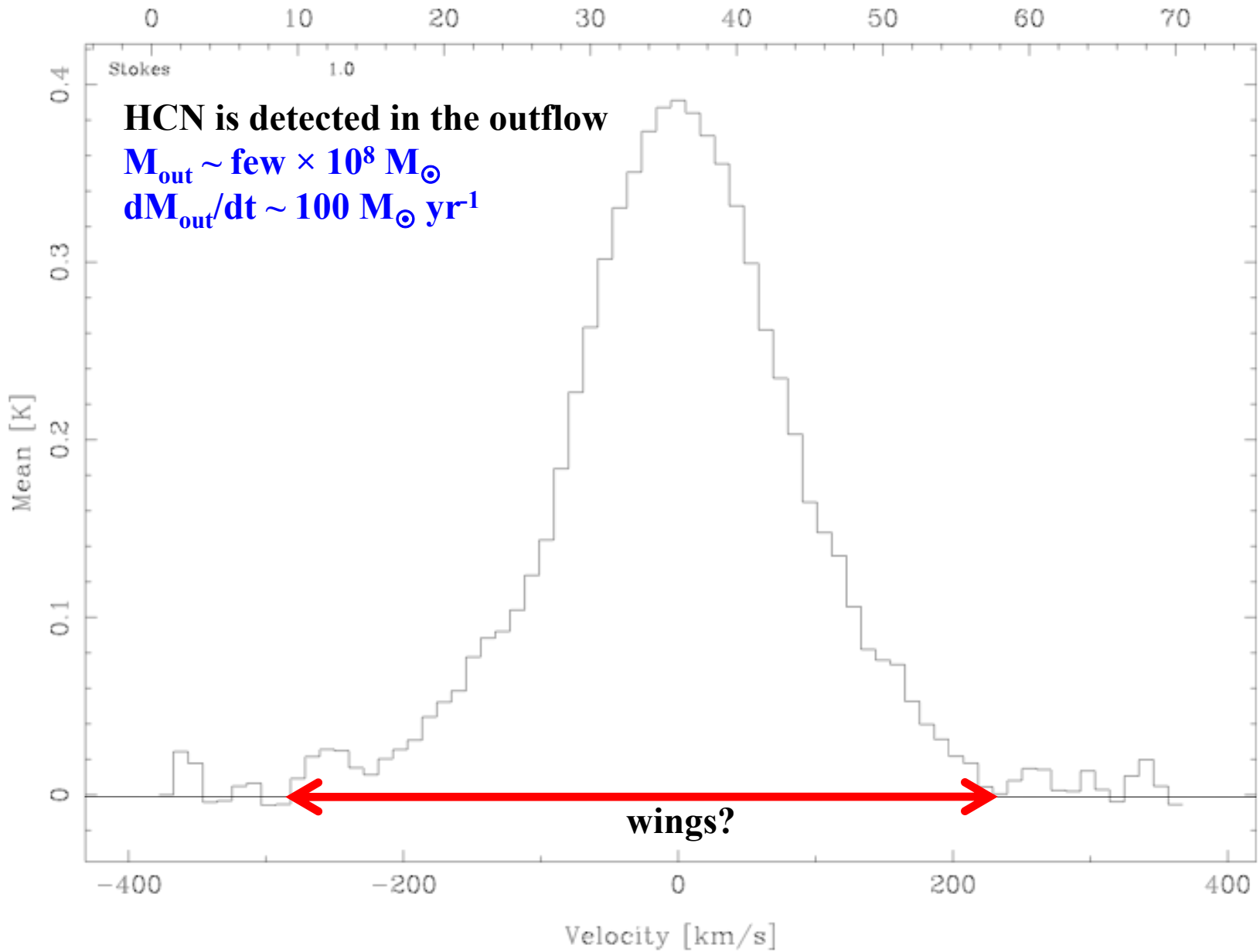


$M_{outflow} \sim$ few $\times\ 10^7\ M_\odot$

$dM_{out,min}/dt > 5x\ SFR_{max}$
cannot be driven by star formation (Murray et al. 2005)

no evidence that it has undergone an interaction

HCN : >>13 $M_\odot$ yr^{-1}



NGC 1266 molecular gas

HCN detection

Mass of the Core	$\approx 4 \times 10^8\ M_\odot$
Radius of the Core	≈ 60 pc
Core Surface Density	$\approx 2.7 \times 10^4\ M_\odot\ pc^{-2}$
	$\approx 100\times\ \Sigma_{MW}$
Outflow mass	**$\approx$ few $\times 10^8\ M_\odot$**
Outflow mass flux	**$\approx 100\ M_\odot\ yr^{-1}$**
Outflow energy	**$\approx 10^{56}$ ergs**
Outflow luminosity	**$\approx 10^{42}$ ergs s^{-1}**
Outflow velocity	≈ 400 km s^{-1}
	$> v_{esc}$
Outflow dynamical time	≈ 2.6 Mvr
Outflow duration	**< 10 Myr**

Highly concentrated gas in nucleus
Σ_{SFR} sits within the K-S scatter

Molecular outflow **100** M yr^{-1}
CO line wings exceed v_{esc}
Ionized gas exhibits wings ($\pm$700 km s^{-1})
Shocks in X-ray, radio continuum, H I
Blueshifted H I absorption

AGN has energy to drive outflow
SFR is unable to sustain outflow
X-ray and radio confirm presence of AGN
Jet power from radio requires **20%** coupling
coupling

Unanswered questions

Is the outflow in NGC1266 a one-time event?

- timescale (few Myr) sufficiently short to explain the discovery of only one event in ATLAS^{3D}

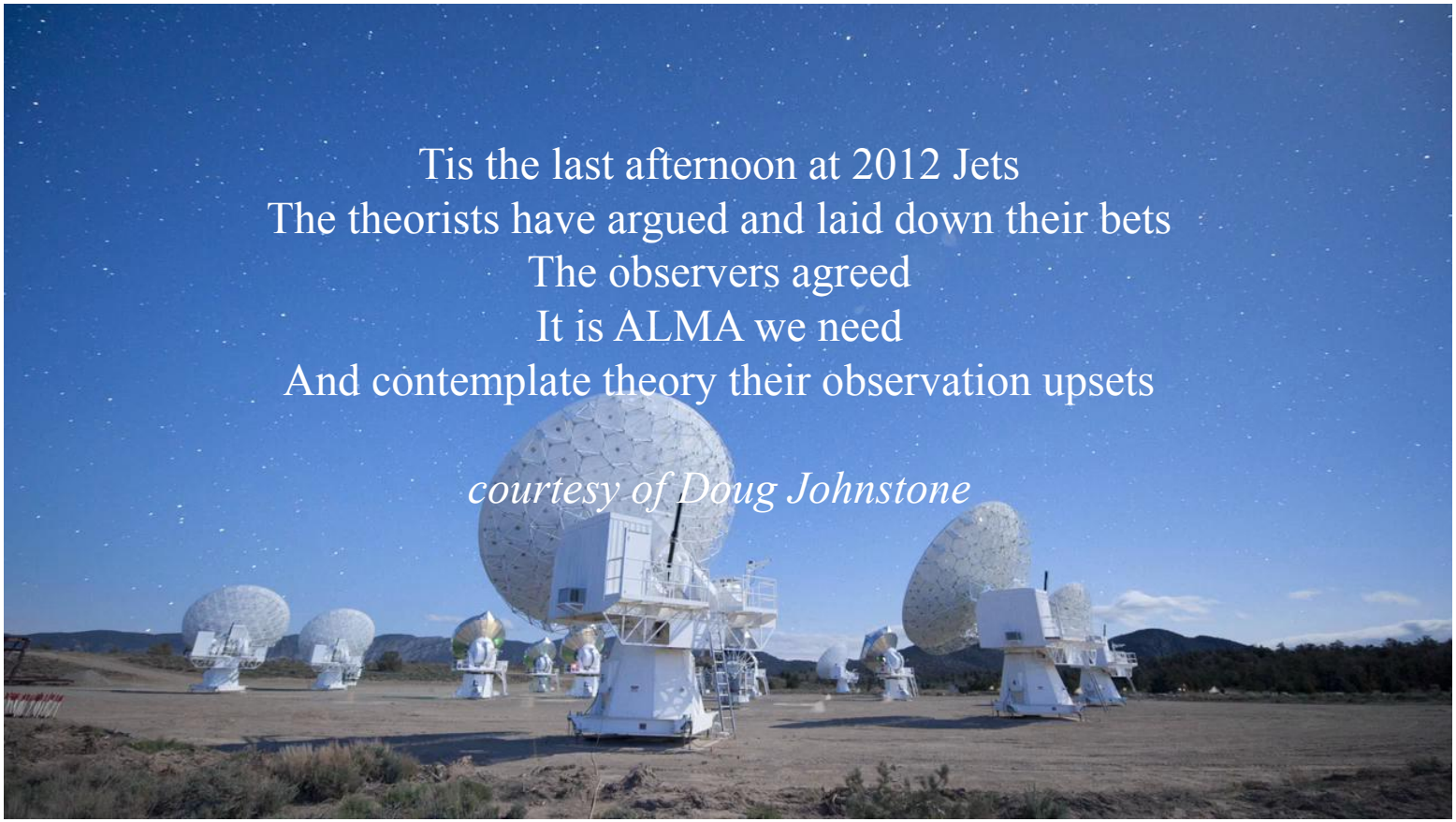
How did the gas get to the center of NGC1266?

- accretion event or outside-in?

How was the AGN able to accelerate the gas without dissociating it?

What are the implications for the high-*z* universe?

The End


Tis the last afternoon at 2012 Jets
The theorists have argued and laid down their bets
The observers agreed
It is ALMA we need
And contemplate theory their observation upsets
courtesy of Doug Johnstone

Star formation in the nucleus

$\Sigma_{gas} = 2.7\times10^4\ M_\odot\ pc^{-2}$

Σ_{SFR} predicted for H_2 using the Kennicutt-Schmidt (K-S) relation:

$\Sigma_{SFR} = 274\ M_\odot\ yr^{-1}\ kpc^{-2}$

SFR(TIR) = 2.2 $M_\odot\ yr^{-1}$

Σ_{SFR} from TIR (Kennicutt 1998):

$\Sigma_{SFR}(TIR) = 195\ M_\odot\ yr^{-1}\ kpc^{-2}$

(upper limit: unknown AGN contribution)

SFR(24μm) = 1.5 $M_\odot\ yr^{-1}$

Σ_{SFR} from 24μm (Calzetti et al. 2007):

$\Sigma_{SFR} = 133\ M_\odot\ yr^{-1}\ kpc^{-2}$

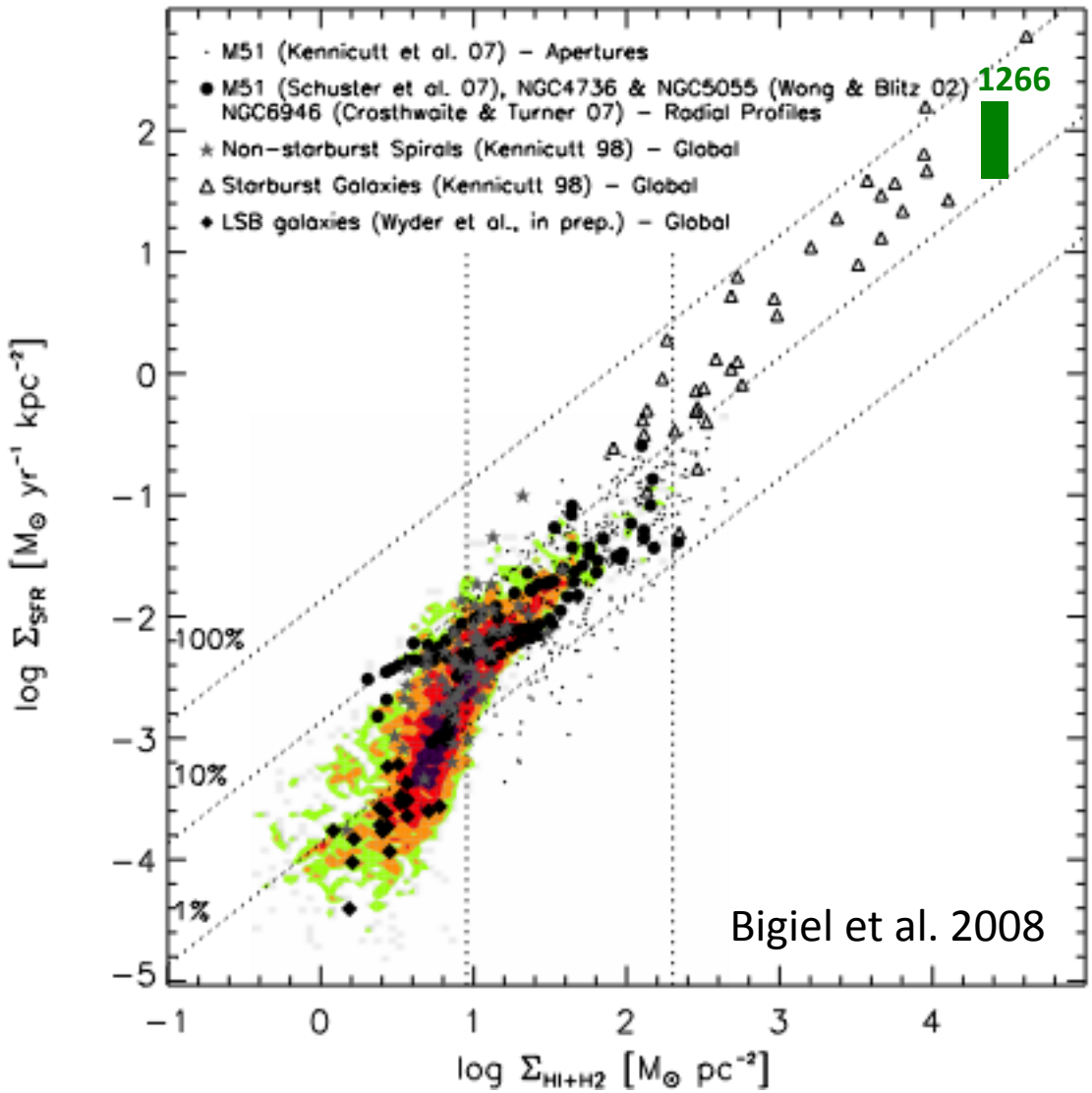
(unknown AGN contribution)

SFR(PAH) = 0.6 $M_\odot\ yr^{-1}$

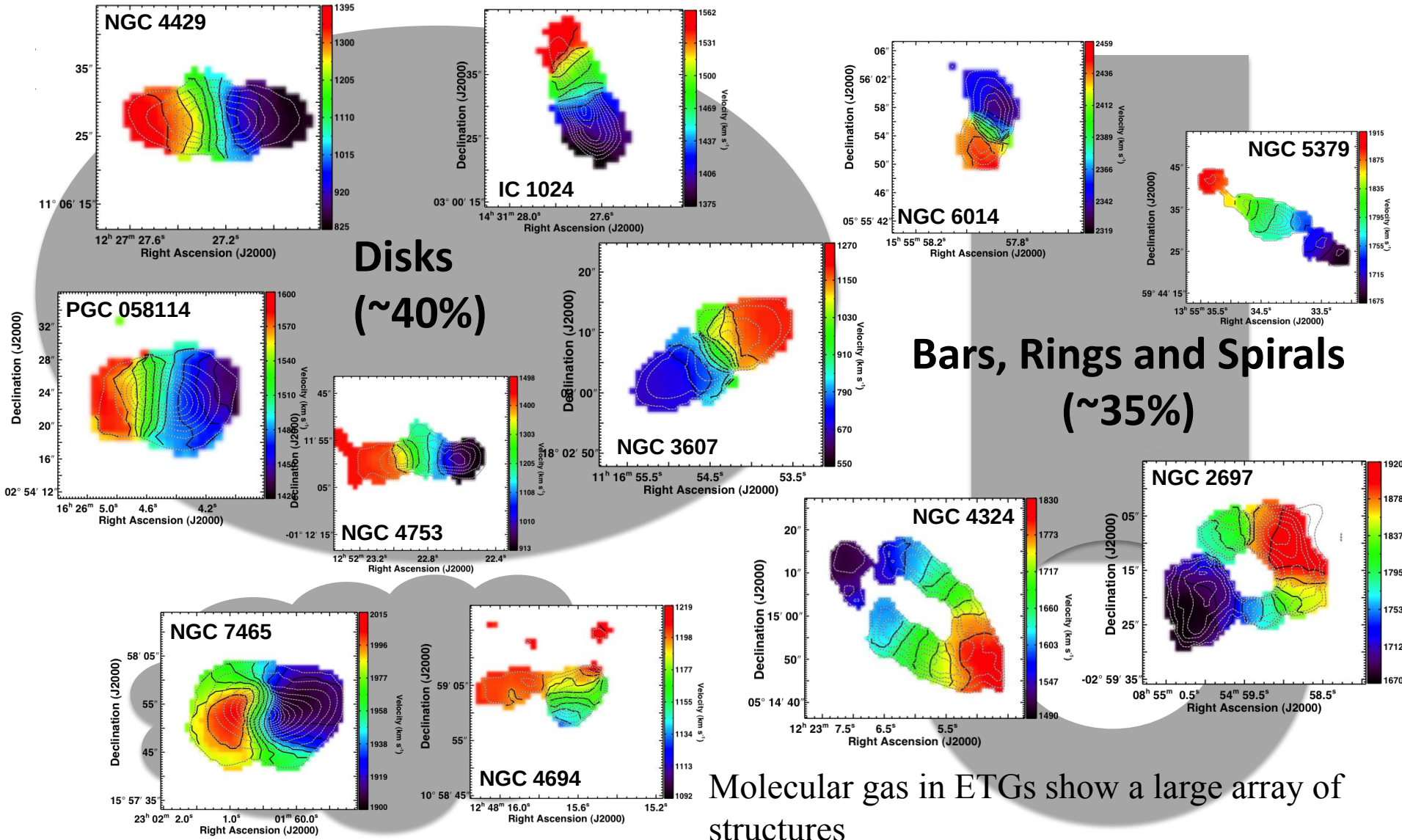
Σ_{SFR} from 8μm PAH emission (Falcón-Barroso et al, in prep):

$\Sigma_{SFR}(PAH) = 53\ M_\odot\ yr^{-1}\ kpc^{-2}$

(possible PAH destruction due to AGN)



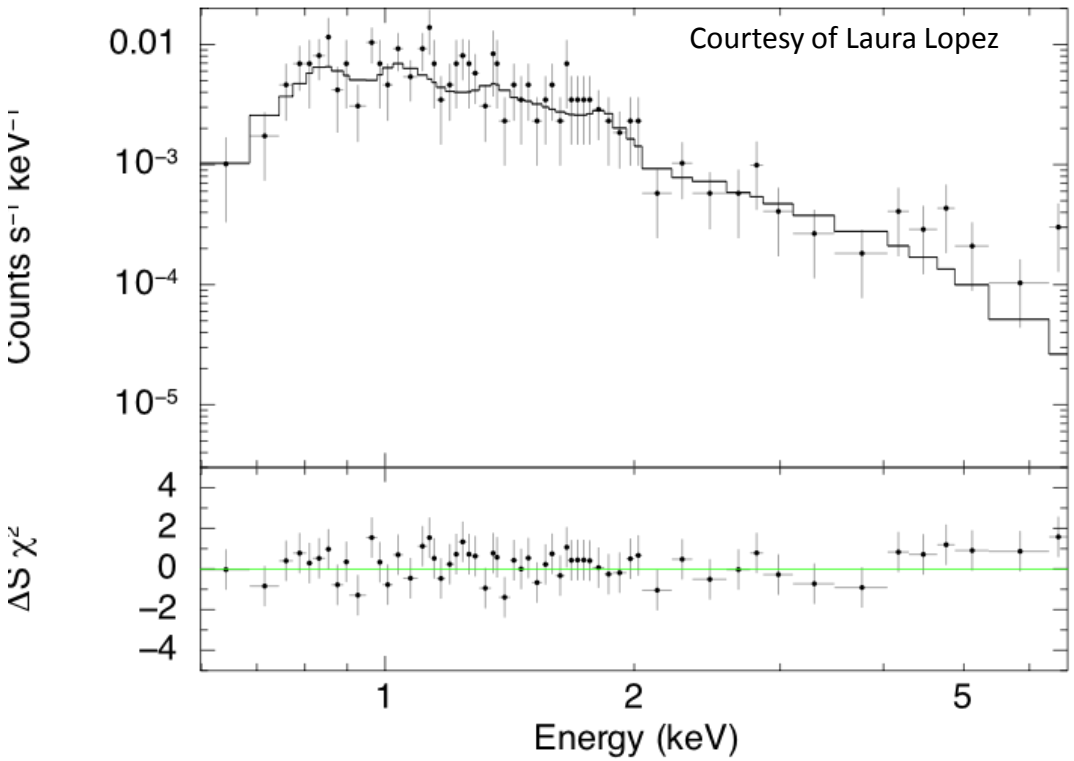
CO morphologies

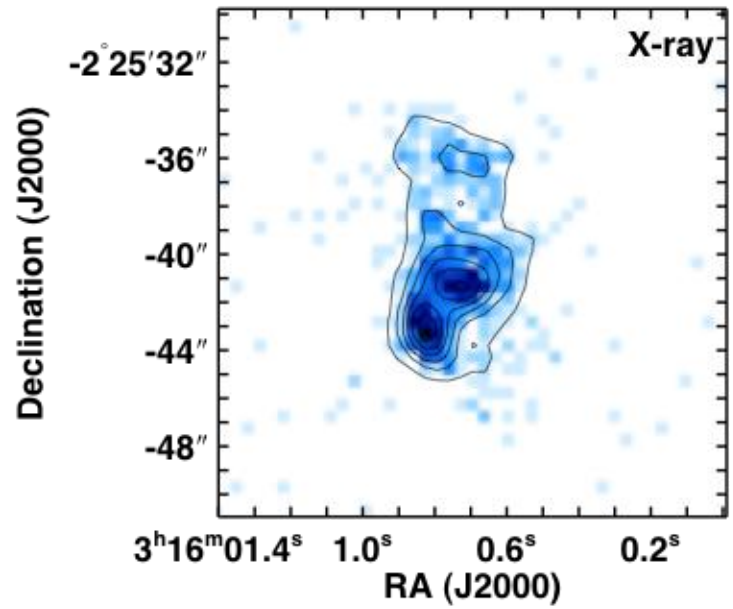


Molecular gas in ETGs show a large array of structures

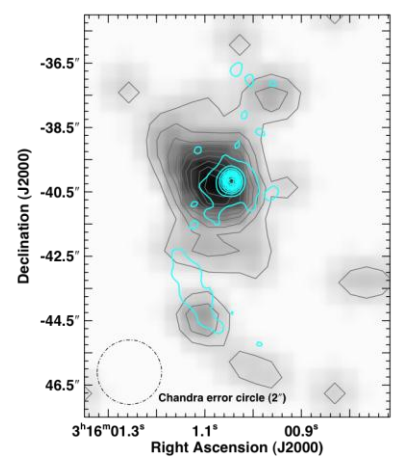
Davis et al., in prep; Alatalo et al., in prep

Chandra Observations





4-8 keV overlaid with 5 GHz

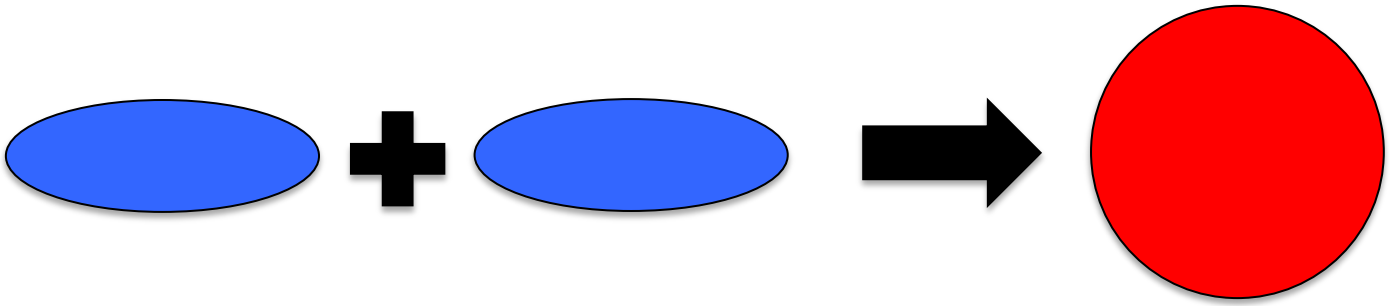


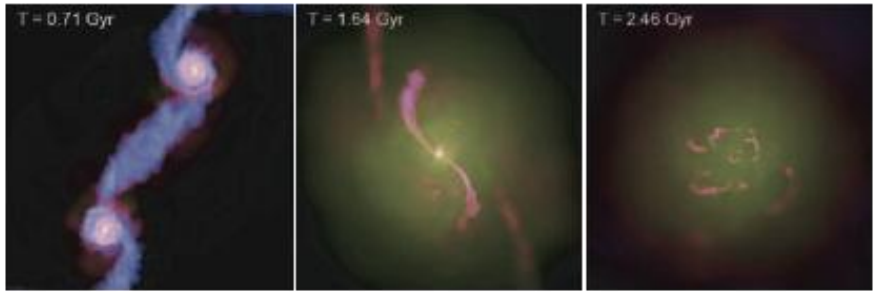
Spectrum fit most of the flux with thermal bremsstrahlung (T = 0.5 keV) and minor contribution from a power law component.

4-8 keV photons are cospatial with the 5 GHz peak : AGN

The Hubble sequence
a morphological classification

How to create a ETG : mergers





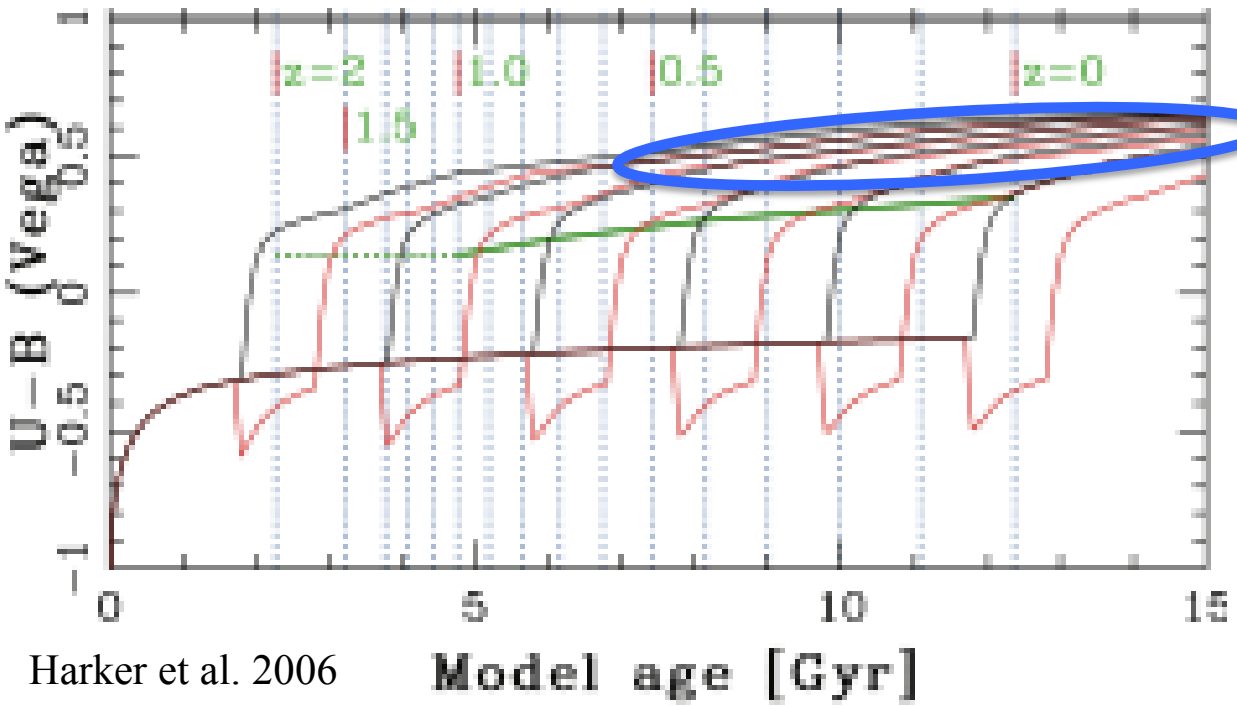
Toomre & Toomre 1972

Springel, di Matteo & Hernquist 2005

Elliptical

Galaxy color classification

How to create a RSG : quench star formation



Harker et al. 2006

conversion to red sequence takes ~1 Gyr after SF quenching, followed by minimal evolution

are red
alaxies

K. Schawinski

Color-Morphology Unification

RSGs :
galaxies sitting on the red sequence (quenched)

ETGs :
galaxies lacking spiral structure (merged)

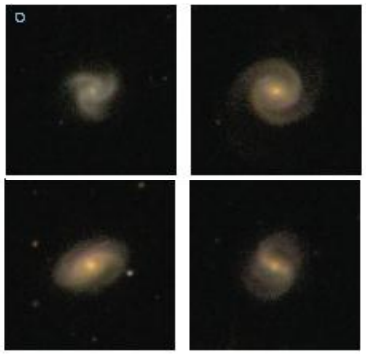
Quiescent "red and dead" ETGs

Outliers: Red Spirals

6% are dusty starbursts (Yan et al. 2006)

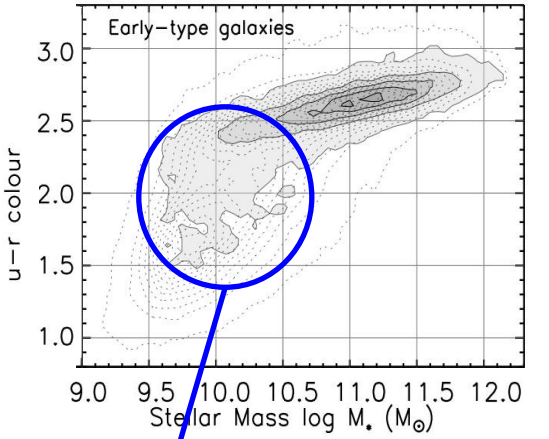
Passive disks

see: Masters et al. 2010, Bundy et al. 2010



Masters et al. 2010

Outliers: Blue ETGs



K. Schawinski

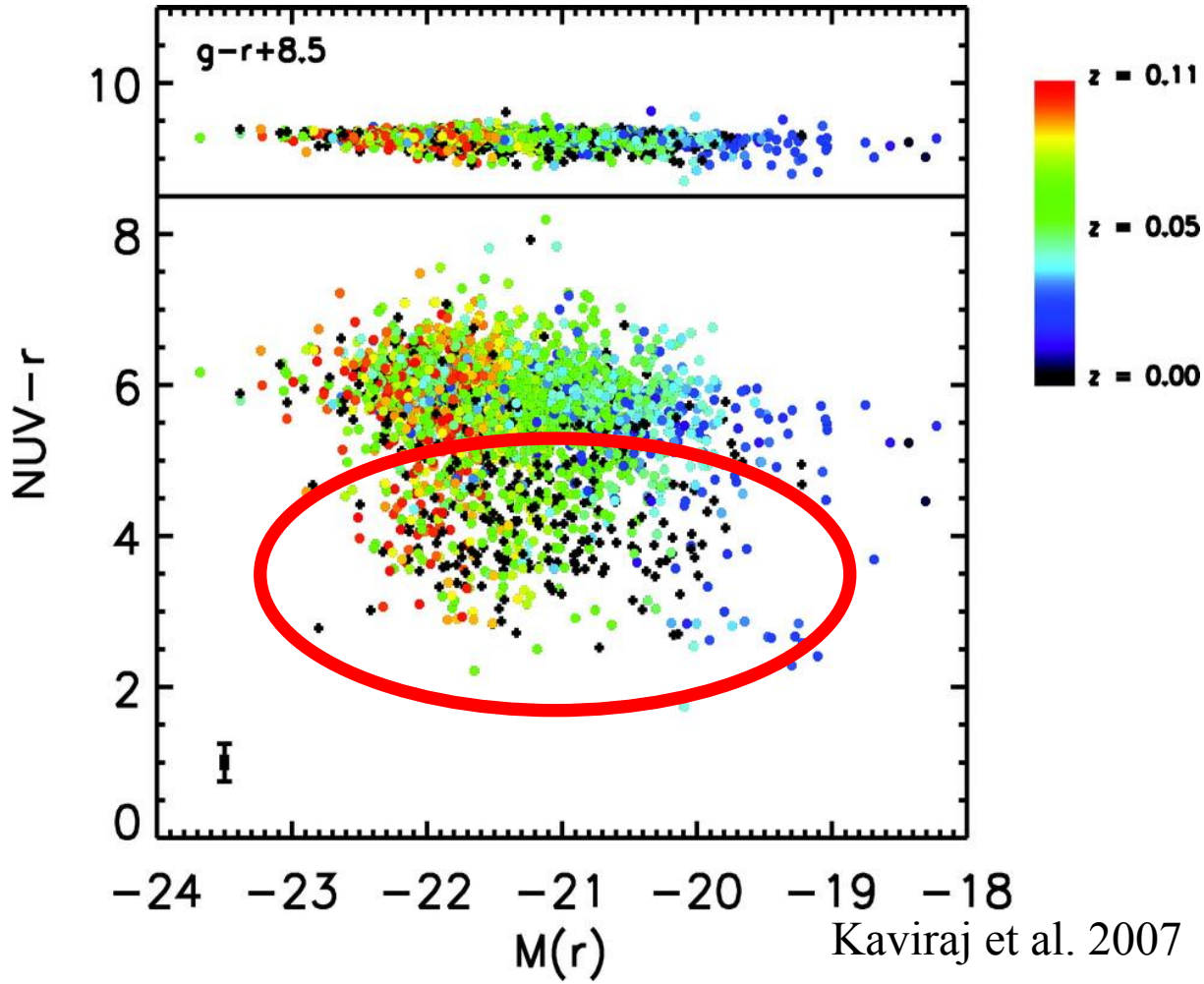
"blue" ETGs

Not completely "red and dead"

15% contain H I
(Knapp et al. 1985)

> 50% have detectable dust
(Knapp et al. 1989)

30% have signs of recent star formation in NUV
(Kaviraj et al. 2007)



Kaviraj et al. 2007

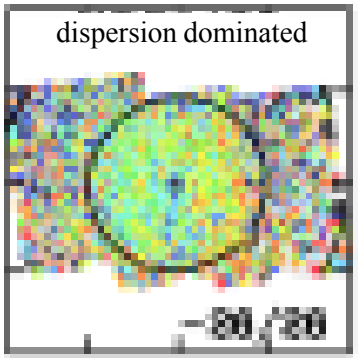
ATLAS^{3D} : Some Results

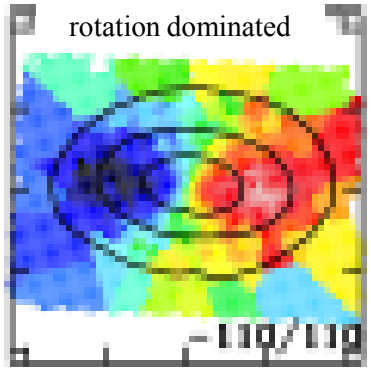
Of the 260 ATLAS^{3D} ETGs:

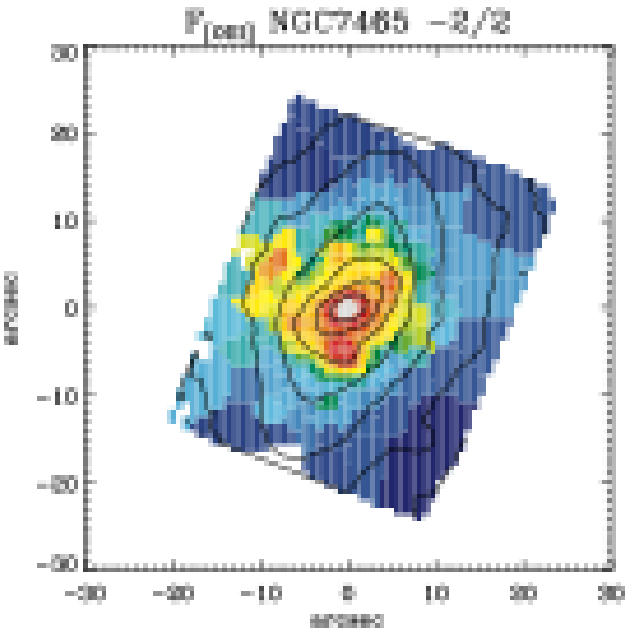
86% are rotation dominated
14% are dispersion dominated
Krajnović et al. 2011

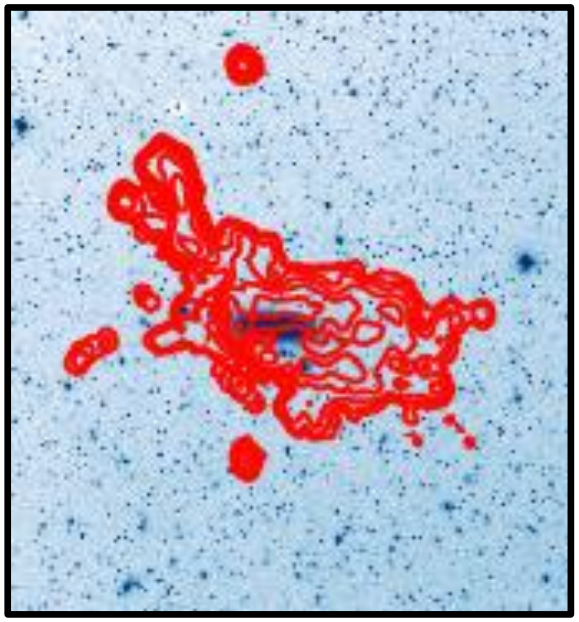
68% have ionized gas emission
Private Communication:
M. Sarzi

40%* contain H I
*(field galaxies, above δ=10°)
Serra et al. 2011

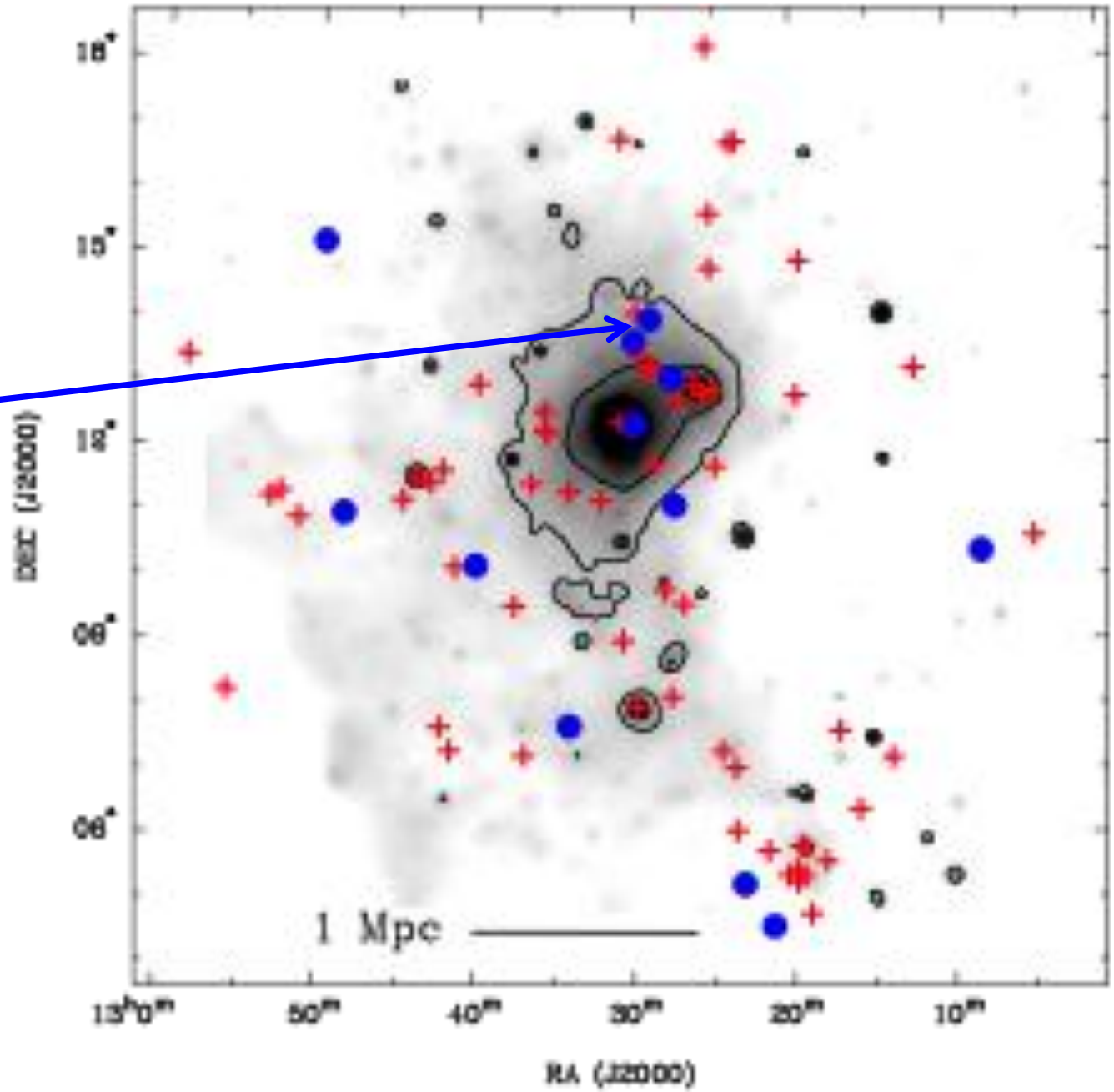








many CO detections fully virialized within Virgo



Young et al. 2011

Gray is ROSAT image of Bohringer et al (1994)

Molecular gas : the ultimate tracer

1.) Molecular gas = star formation

2.) CO/HCN lines… are unambiguously identifiable

3.) Interferometry provides a clear picture

- spatial extent to 0.1” resolution
- spatially significant kinematic information (can trace outflows of gas)

Sample selection and CARMA set-up

Survey galaxies selected to be the brightest **31** galaxies from the single-dish detections

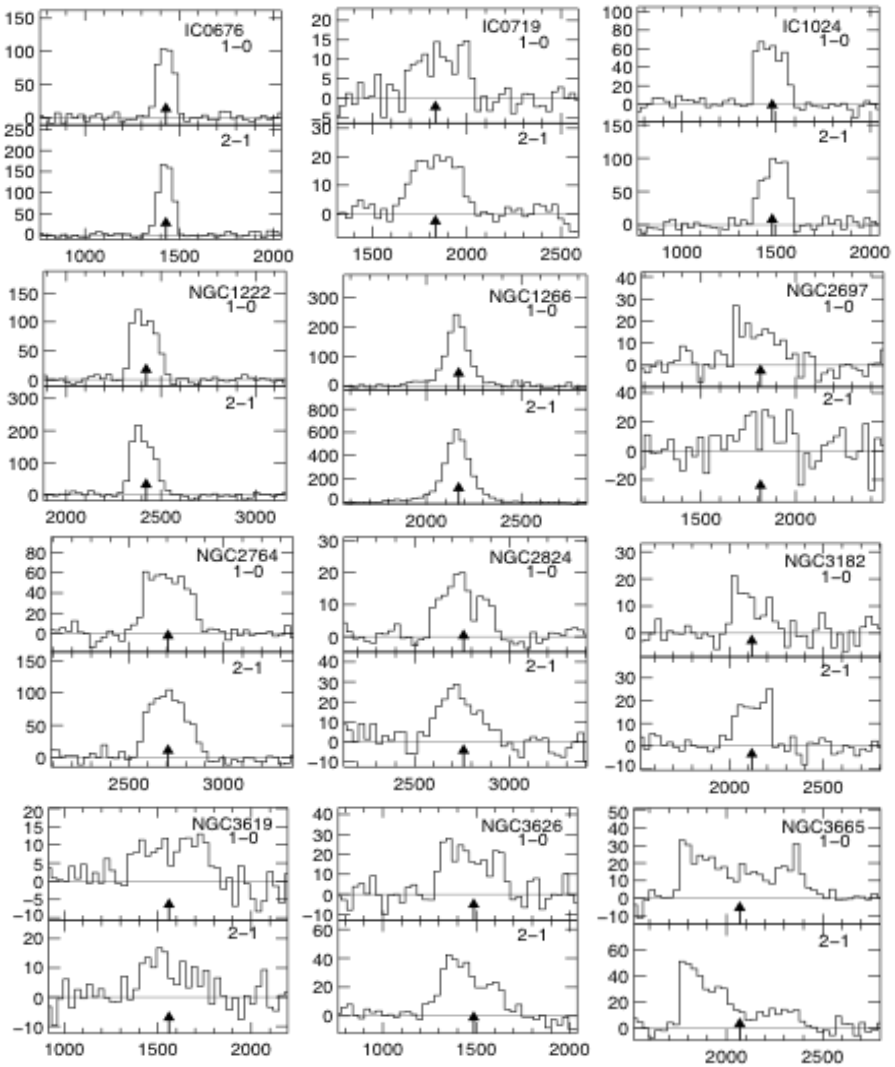
Observations carried out in CARMA D-array resolution range: 4 - 56”

Correlator configuration:
22 galaxies at 420 km s^{-1} bandwidth with 2.5 km s^{-1} channels
9 galaxies with 975 km s^{-1} bandwidth with 1 km s^{-1} channels (upgraded correlator)

All 31 with >3σ CO(1-0) detections

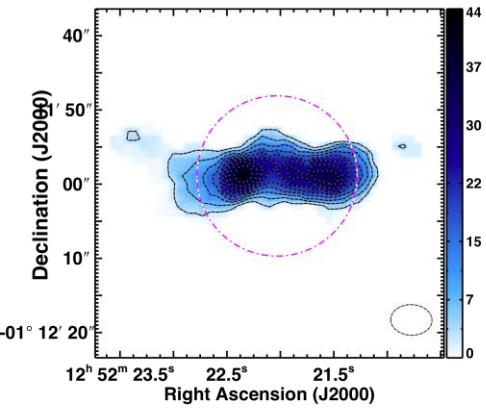
Concurrent ^{13}CO observations of 21 galaxies
8 detections

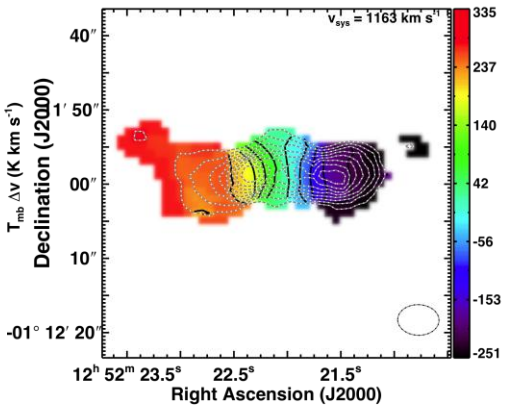
3mm continuum detected in 2 sources

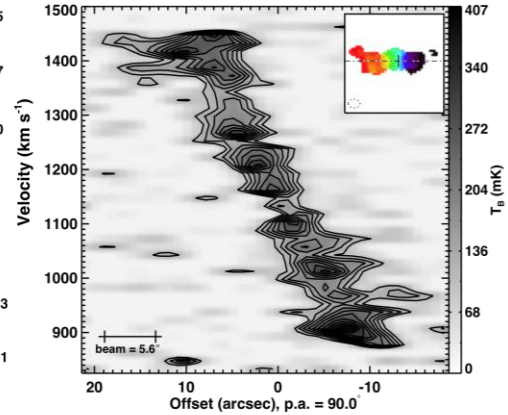


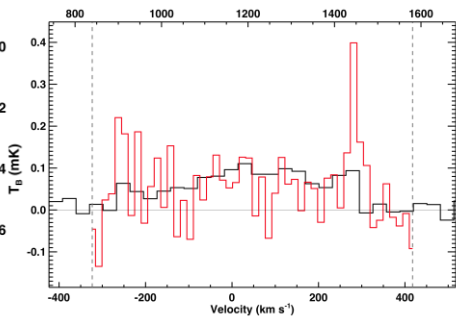
Young et al. 2011

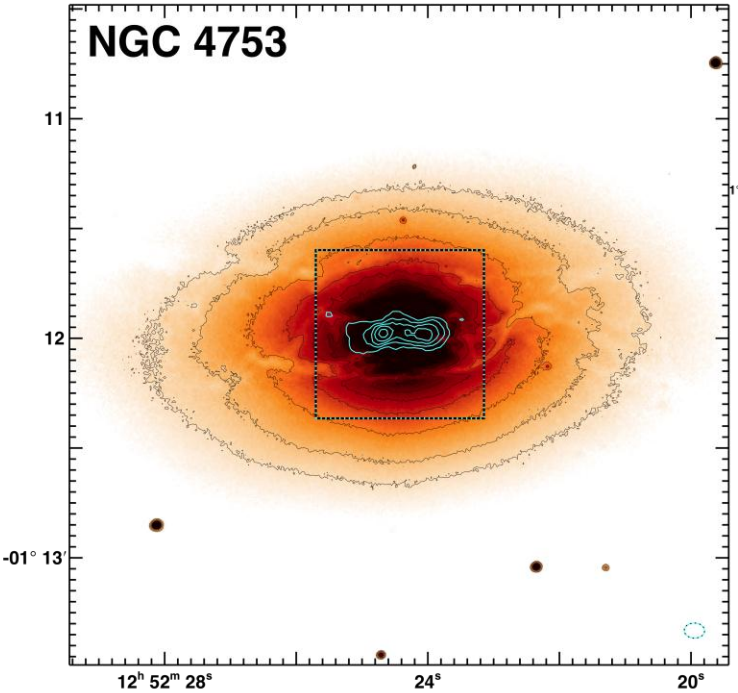
NGC 4753

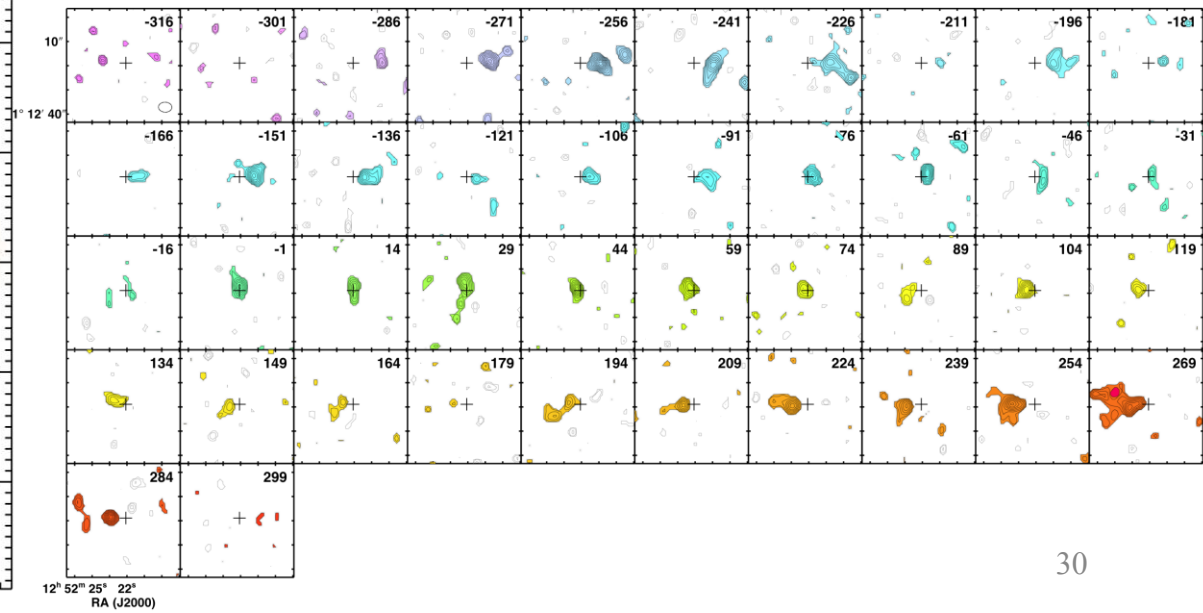

Declination (J2000)
Right Ascension (J2000)
$T_{mb}\,\Delta v$ (K km s^{-1})


v_{sys} = 1163 km s^{-1}
Declination (J2000)
Right Ascension (J2000)

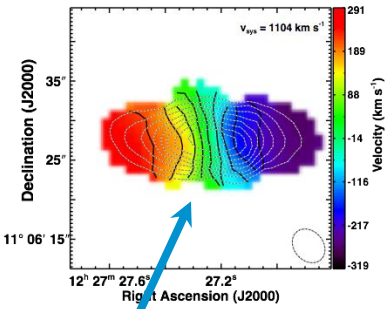

Velocity (km s^{-1})
Offset (arcsec), p.a. = 90.0°
beam = 5.6"


T_B (mK)
Velocity (km s^{-1})

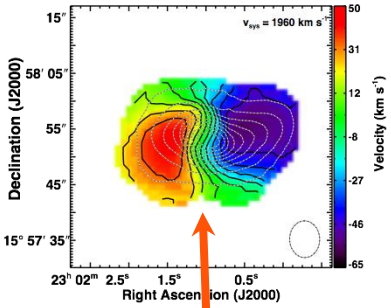

NGC 4753


RA (J2000)

Morphologies



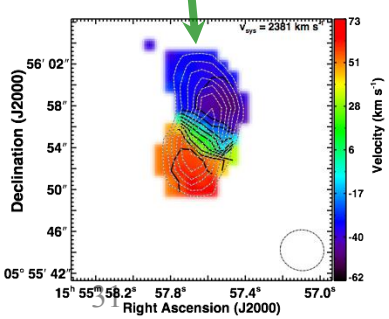
Morphological Configuration	Symbol	Number (out of 39)	Fraction (%)
Disk	D	19	49
Spiral	S	3	8
Ring	R	5	13
Bar+Ring	B+R	5	13
Weak disruption	M	4	10
Strong disruption	X	3	8

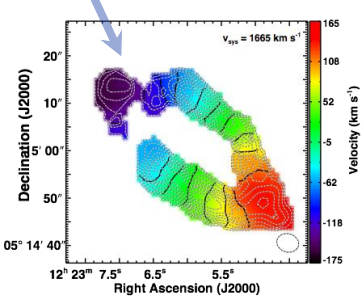


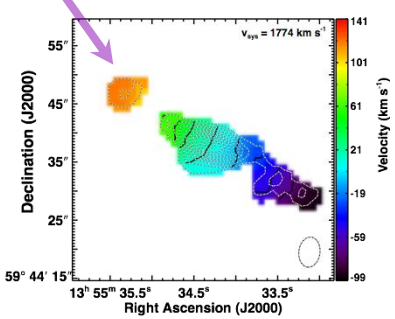
Disks (D) have regular kinematics and a disk shape. **Spirals (S)** have visible spiral arms. Some disks might in fact be unresolved spirals.

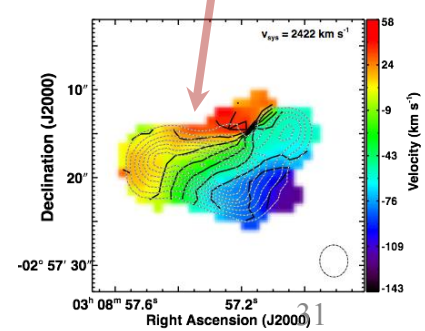
Rings (R) have holes in the PVDs and in well-resolved moment maps. **Bars + rings (B)** show X-shaped PVDs. Bars are not seen to be independent of rings in the sample, likely meaning that B systems evolve into R systems.

Weakly (M) and **Strongly (X)** disrupted objects exhibit unsettled kinematics. M objects tend to be associated with counterrotating H I (Serra et al. 2011)





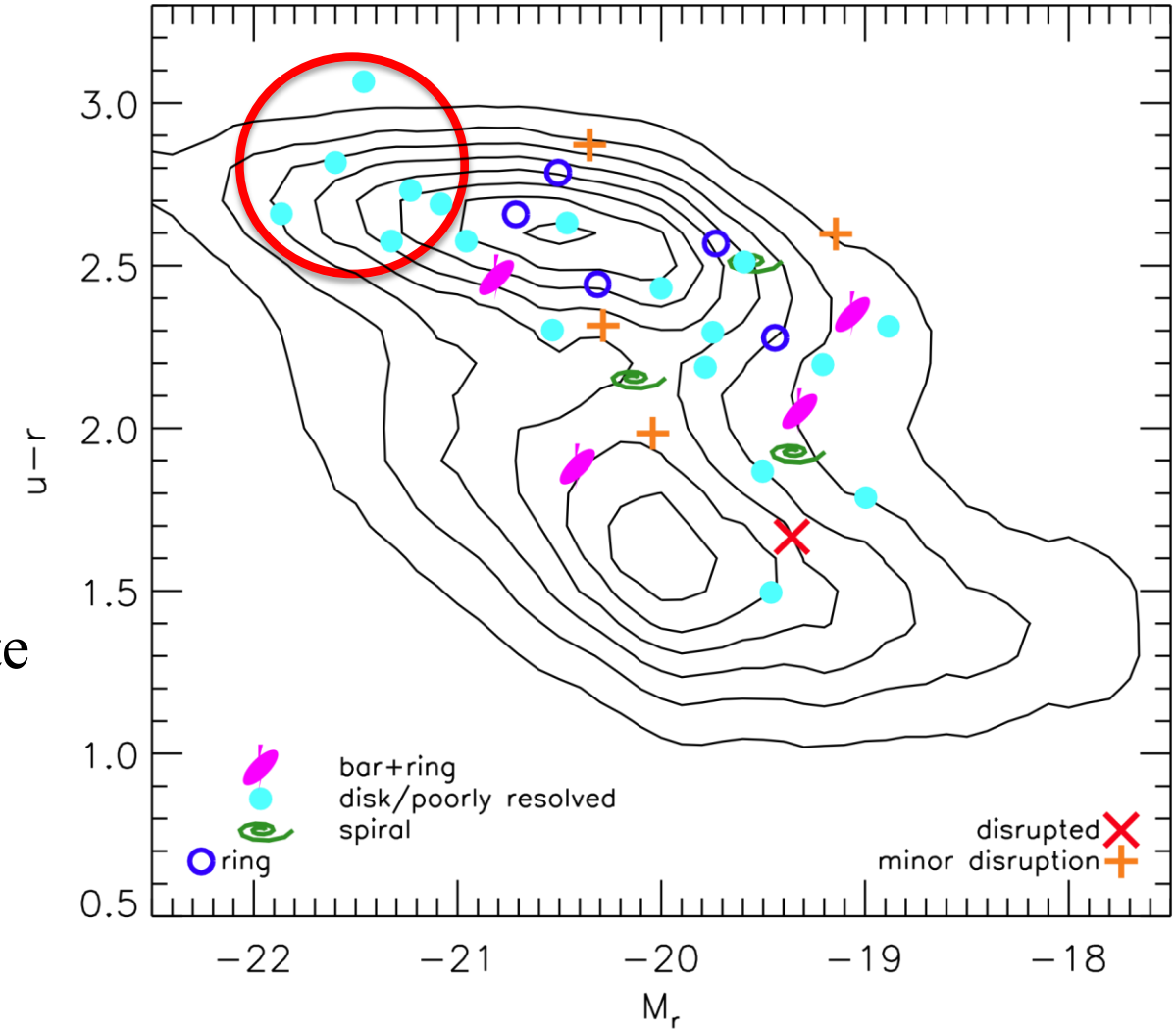




Morphologies and the CMD

Most morphologies show no correlation with color or mass (except)...

Disks tend to populate the highest mass objects



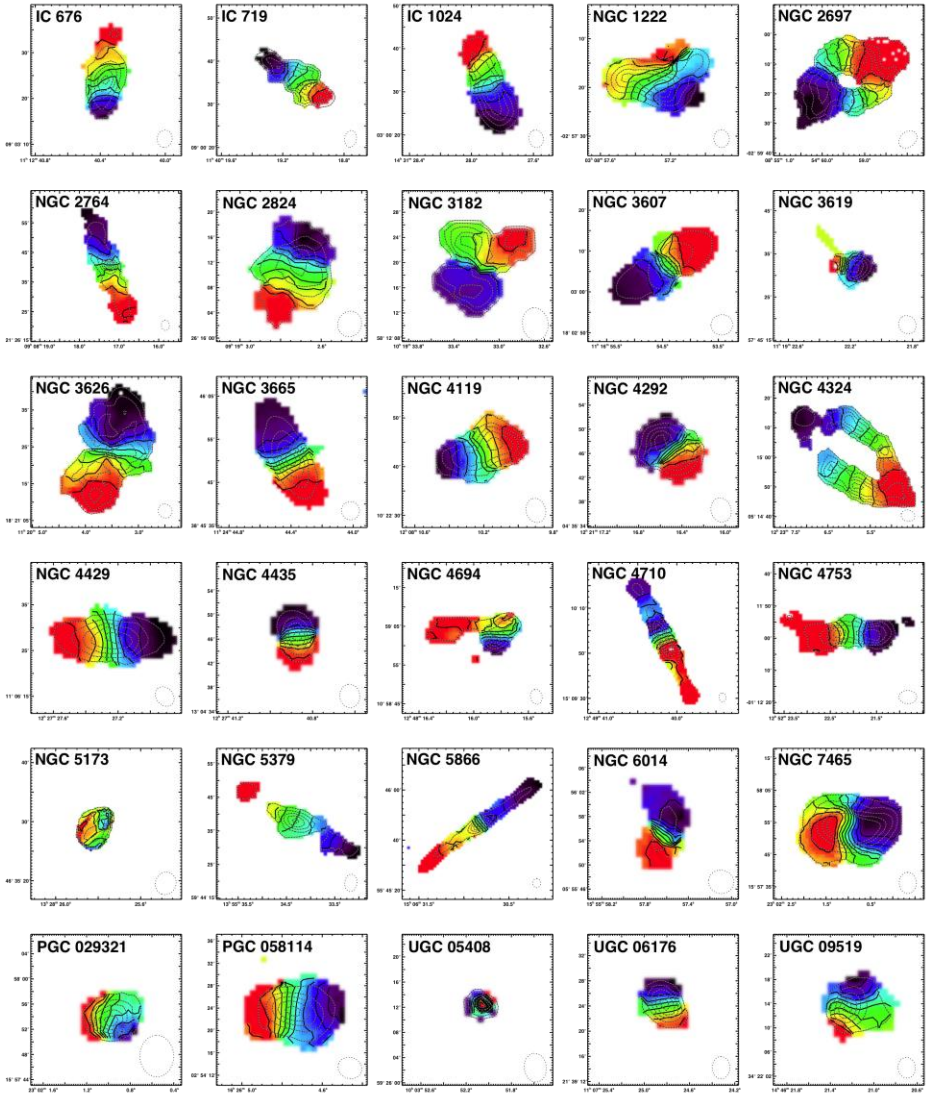
who said red and dead?

467 hours of CO data on 29 ATLAS^{3D} ETGs from CARMA

The ATLAS^{3D} CO survey more than doubles the total ETGs imaged in molecular gas

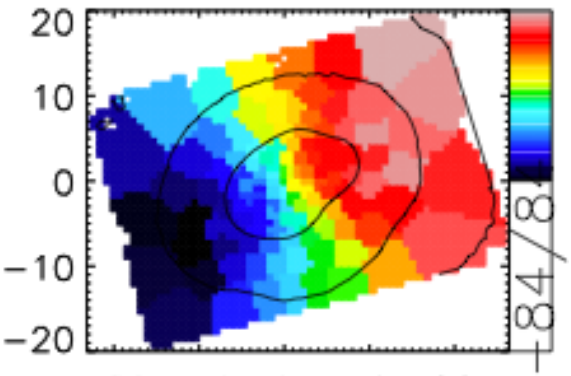
3D data cubes (channel maps), integrated intensity (mom0) and integrated velocity (mom1) to be made available publically for all ATLAS^{3D} galaxies

Molecular gas in galaxies show a variety of morphologies, with the most massive galaxies appearing to have a preference for disk configuration



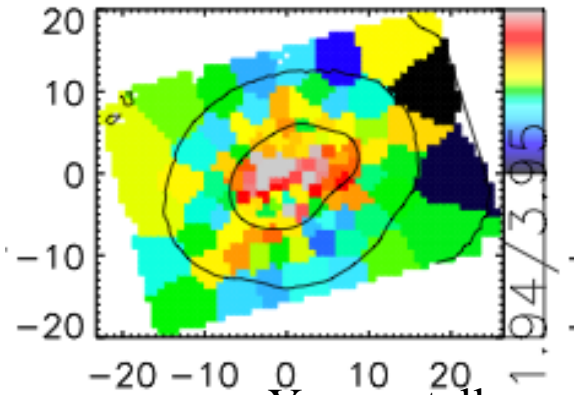
SAURON NGC 1266 Observations

Stellar Kinematics

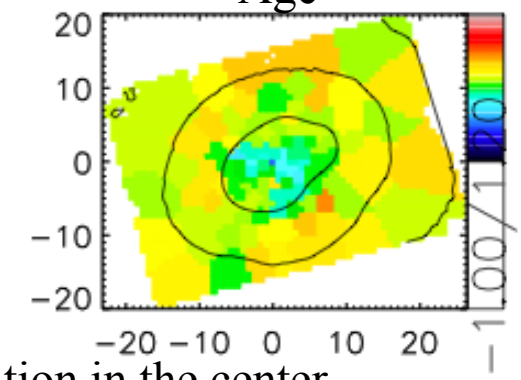


Unperturbed rotation

Hβ absorption

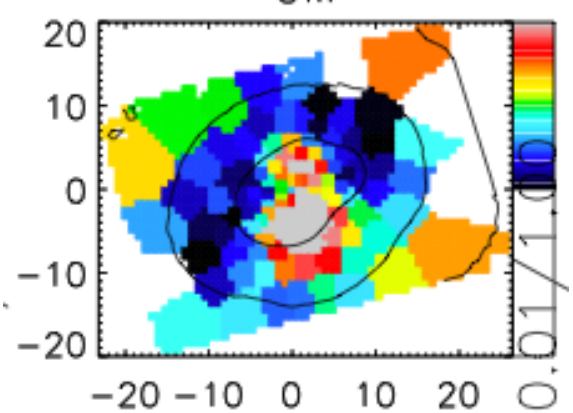


Age

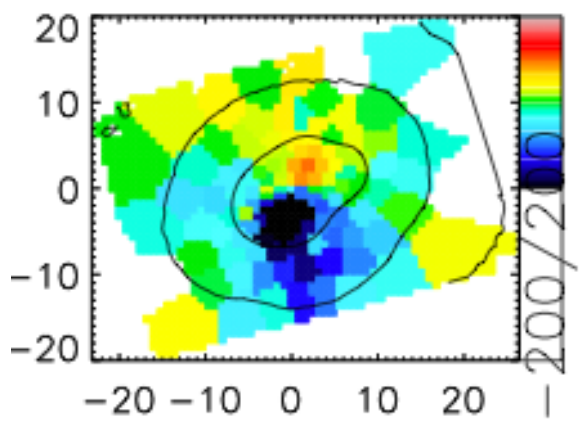


Young stellar population in the center

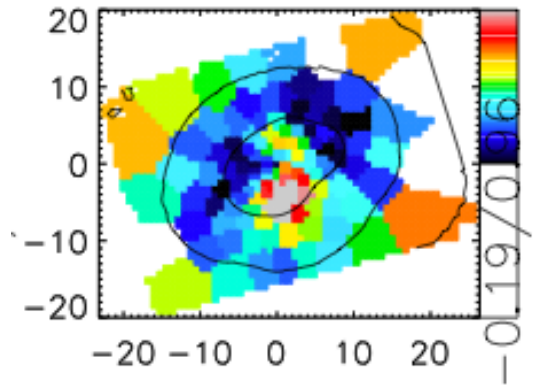
OIII



Gas V



HB Gas



Ionized gas emission consistent with emission from a centrally star-forming, rotating disk (or an outflow)

- Many ETGs host molecular reservoirs, with many differing morphologies
- NGC 1266, a non-interacting field SB0, hosts a compact nuclear disk and massive molecular outflow
  - $\Sigma_{gas} = 100\ \Sigma_{MW}$, $M_{out} \leq 2.5\times10^{7}\ M_{\odot}$
  - HCN detection points to higher masses and outflows
- Unlike most other examples of molecular outflows (M51, M82, Arp 220, Mrk 231), NGC 1266 most likely is driven by an AGN (rather than SF)