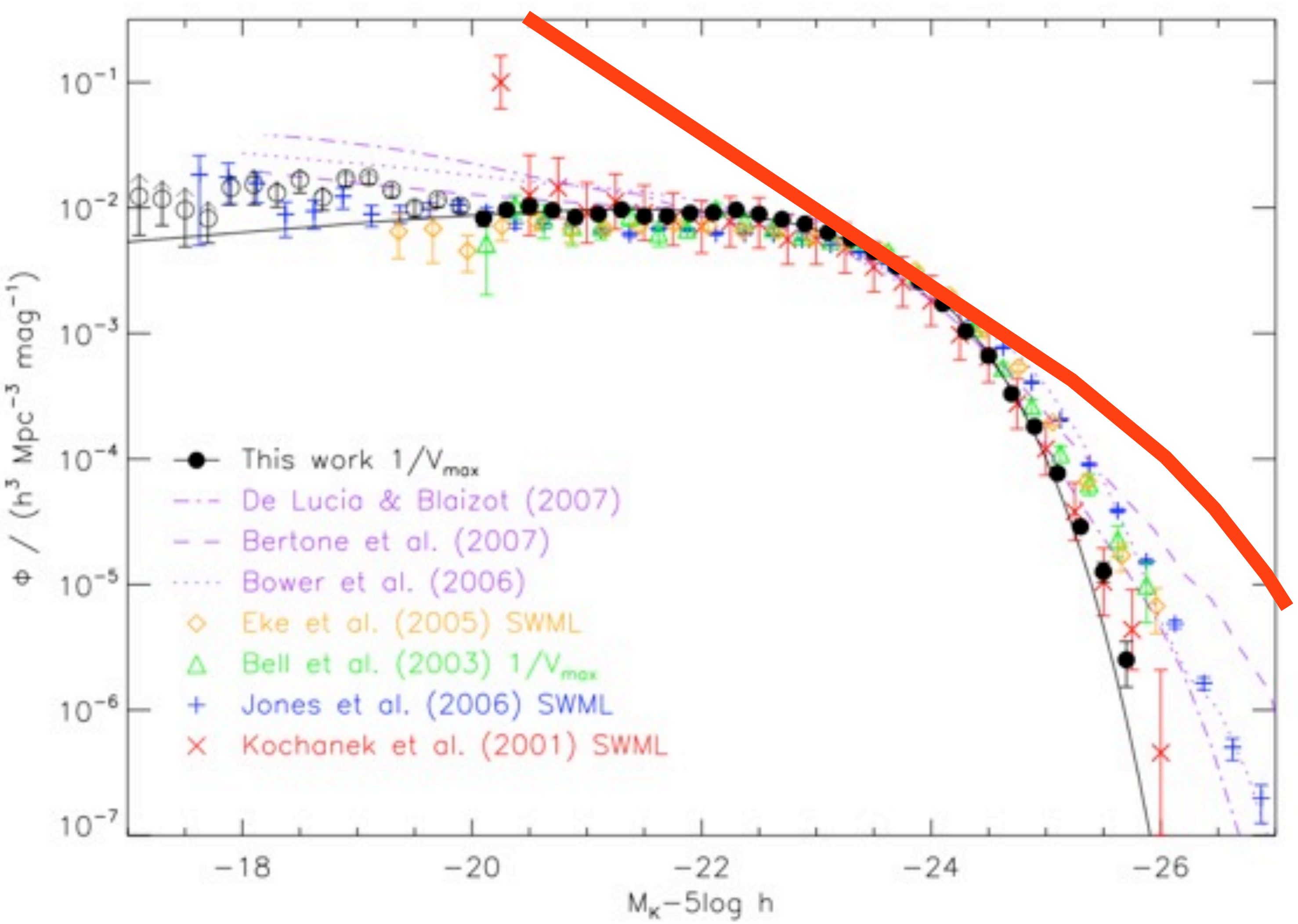
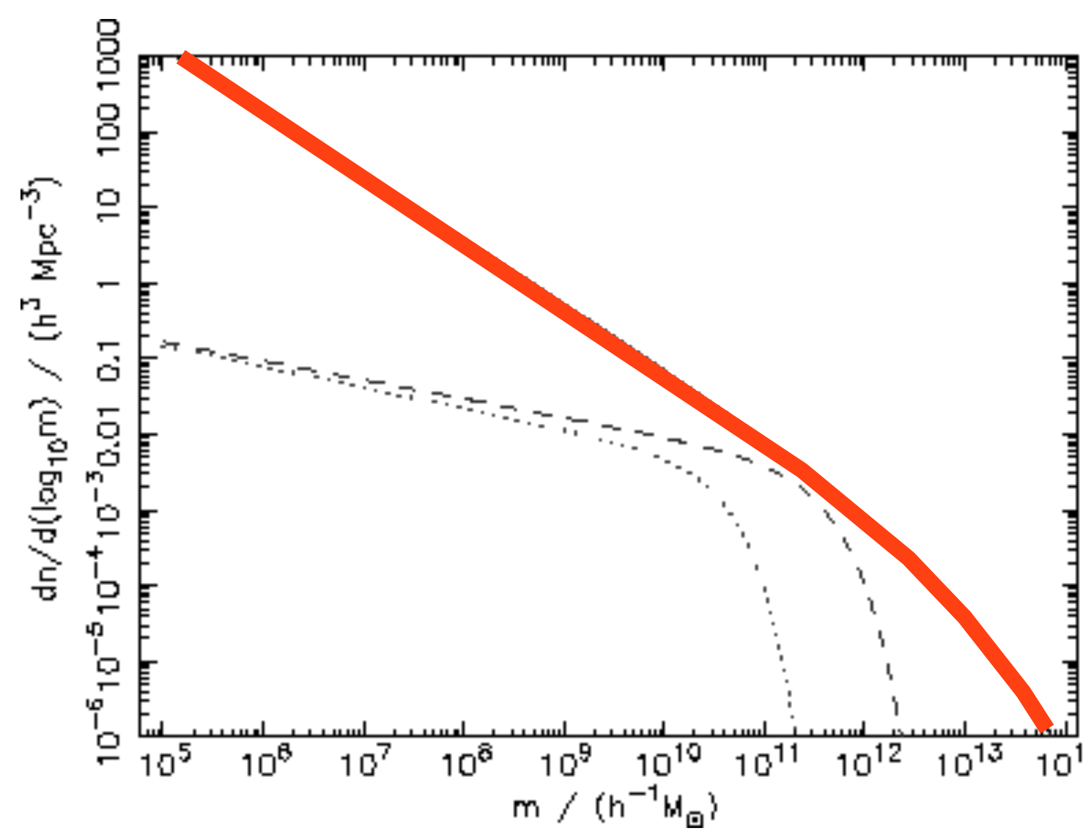
Physics of Galaxy Evolution: What drives SF?

Observations vs. Theory



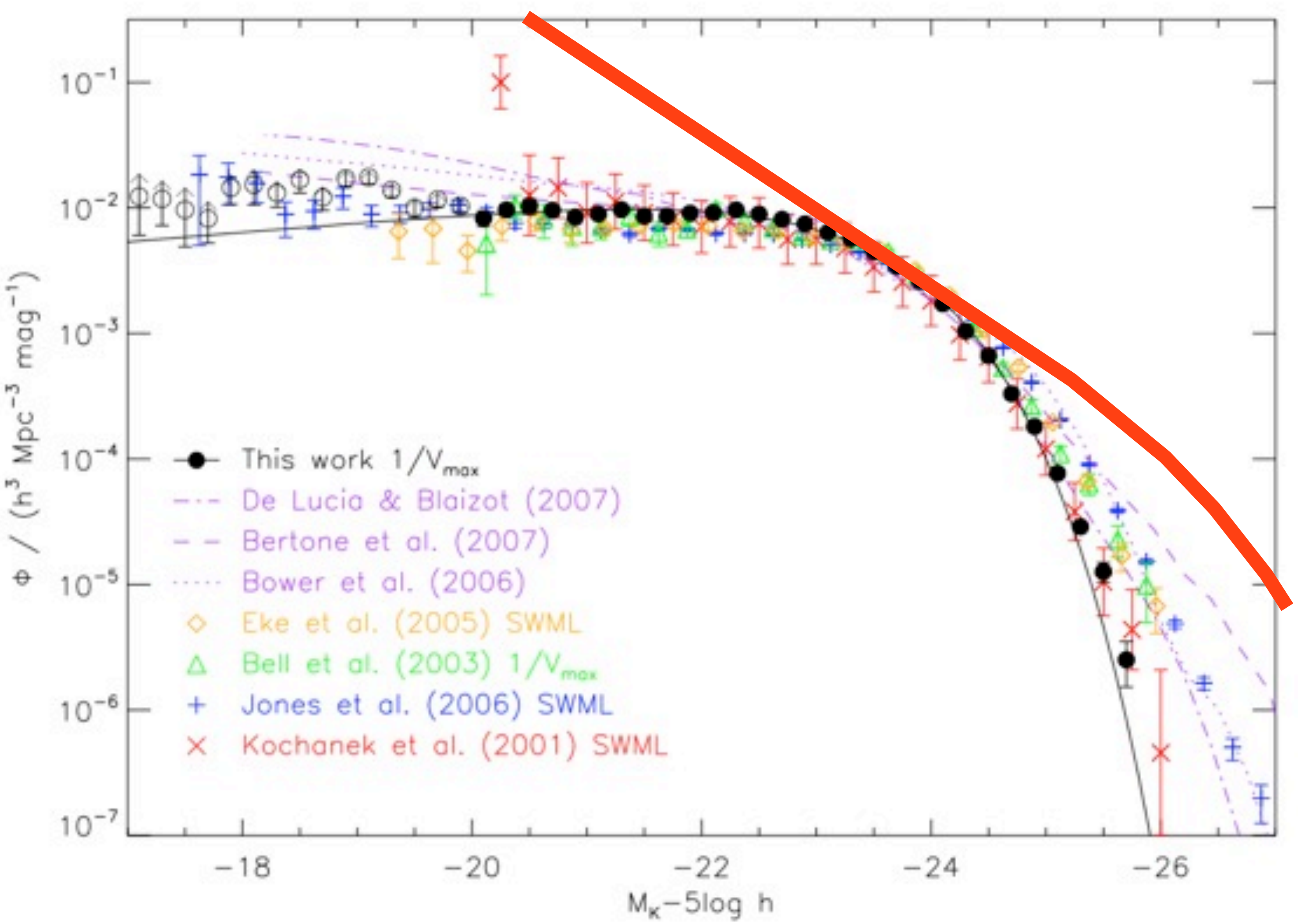
observed galaxy luminosity function...

...is in major disagreement w/ CDM simulations



Somerville et al. 2008, Springel et al. 2005

Observations vs. Theory

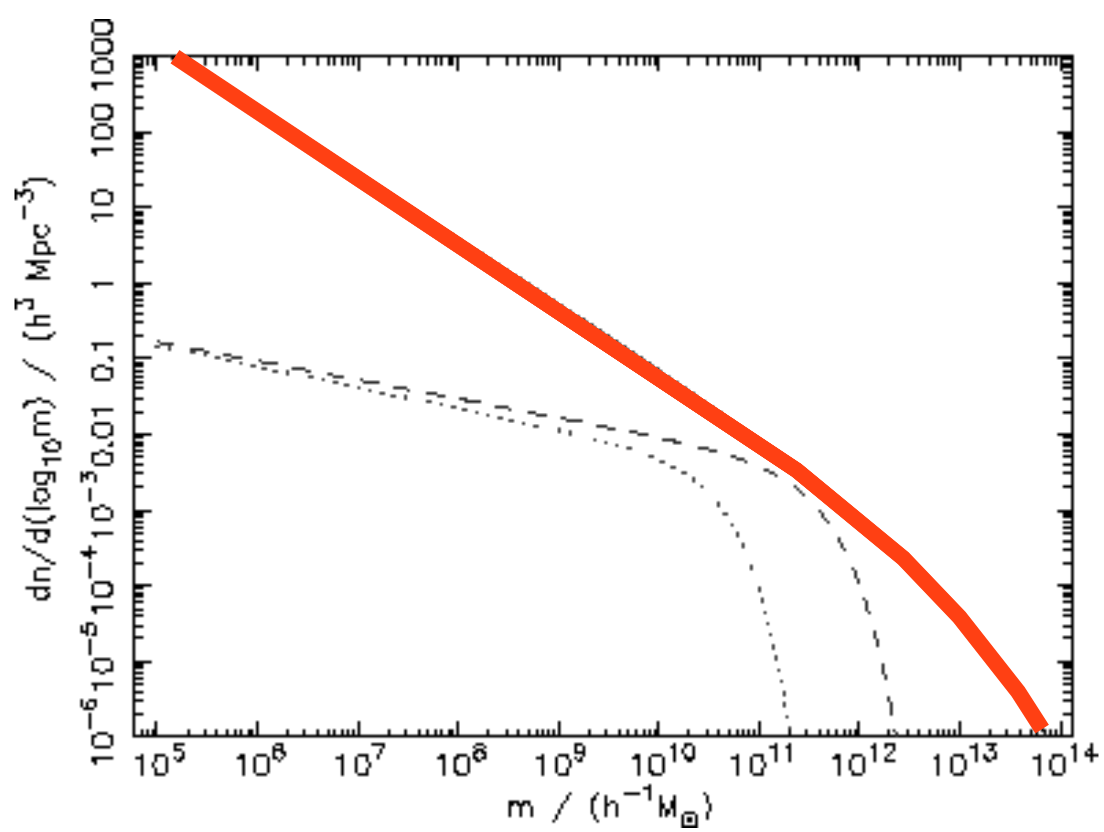


observed galaxy luminosity function...

...is in major disagreement w/ CDM simulations

under the assumption that dark matter halos host gas: need to find mechanisms why conversion to stars is less efficient in low and high mass systems

either gas can never cool or gas gets reheated/removed



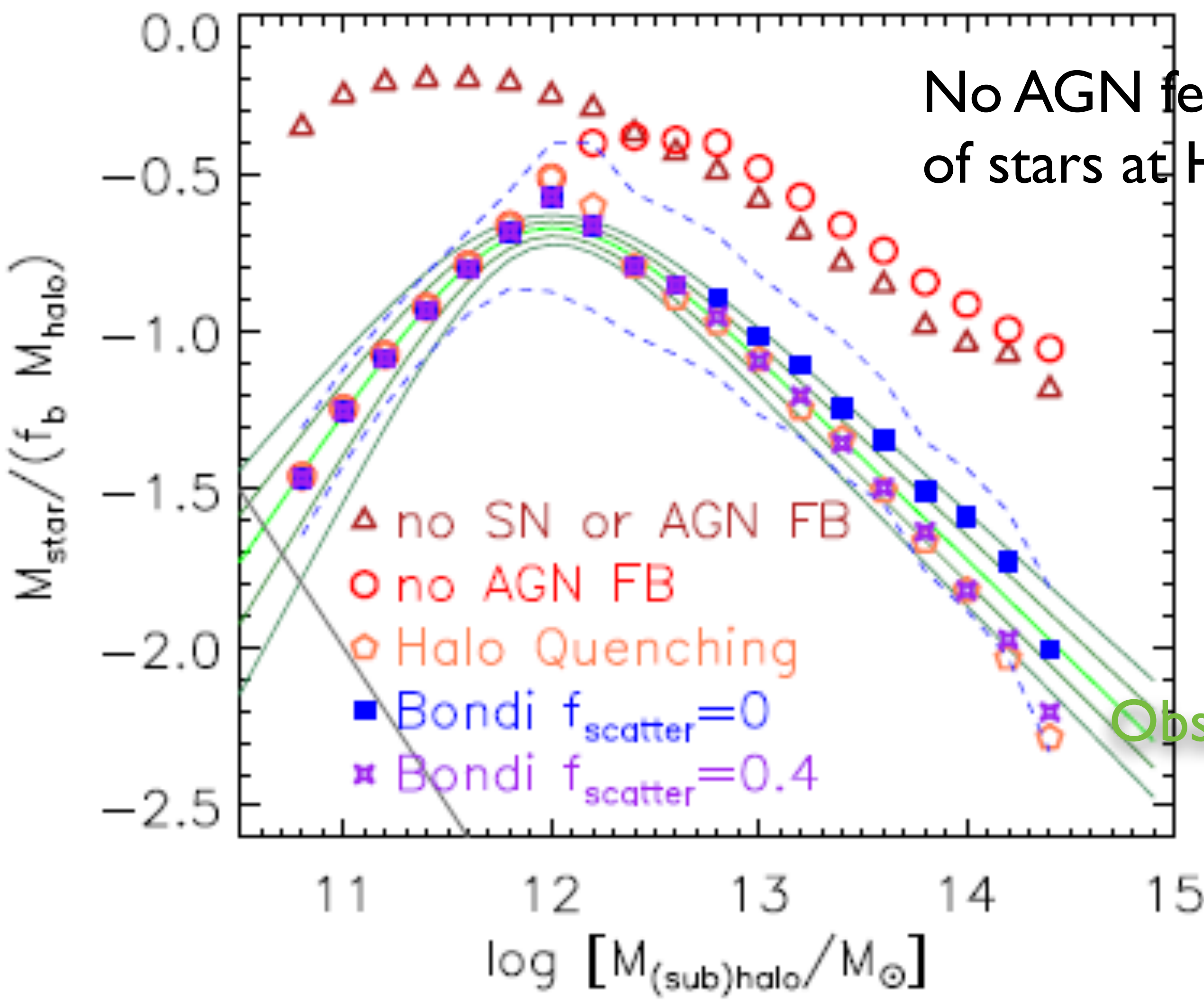
Somerville et al. 2008, Springel et al. 2005

Comparison: Data vs. Model

No feed-back: vast overprediction
of stars at all halo masses

No AGN feed-back overprediction
of stars at HIGH halo masses

Log(fraction) of baryons that have ended up (at z~0)
as stars in halos of mass M_{halo}



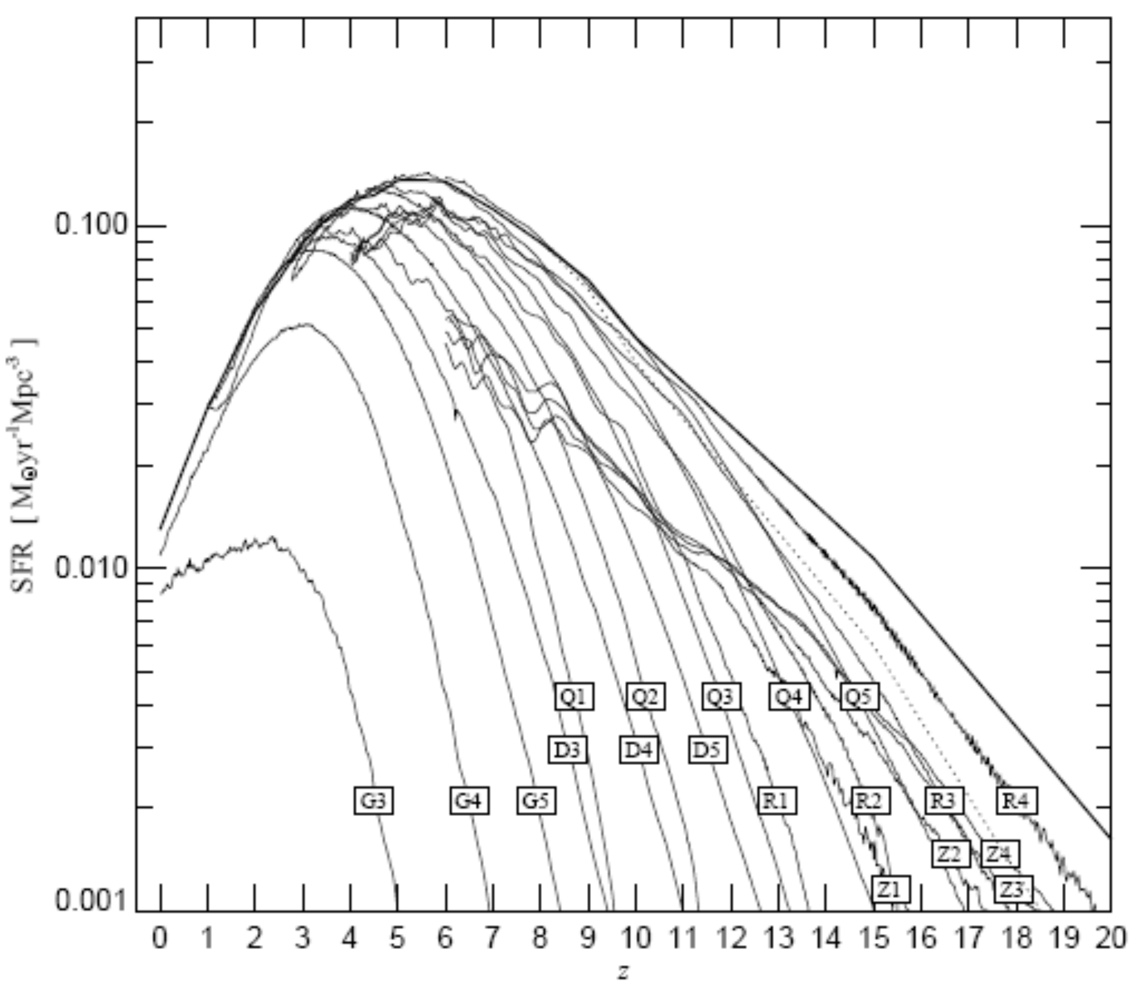
Observational constraints

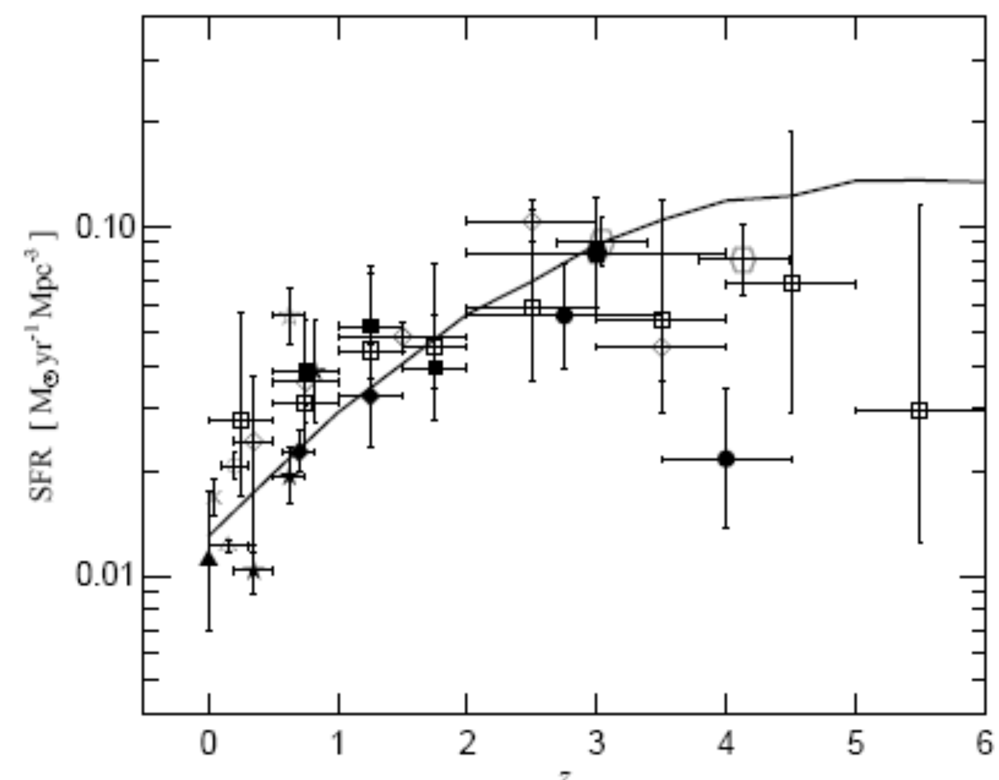
Somerville et al. 2009

Different assumptions on feedback: different <SFR>(z)

No feed-back: stars form too early (and too many of them)

The history of star formation in a Λ-CDM universe

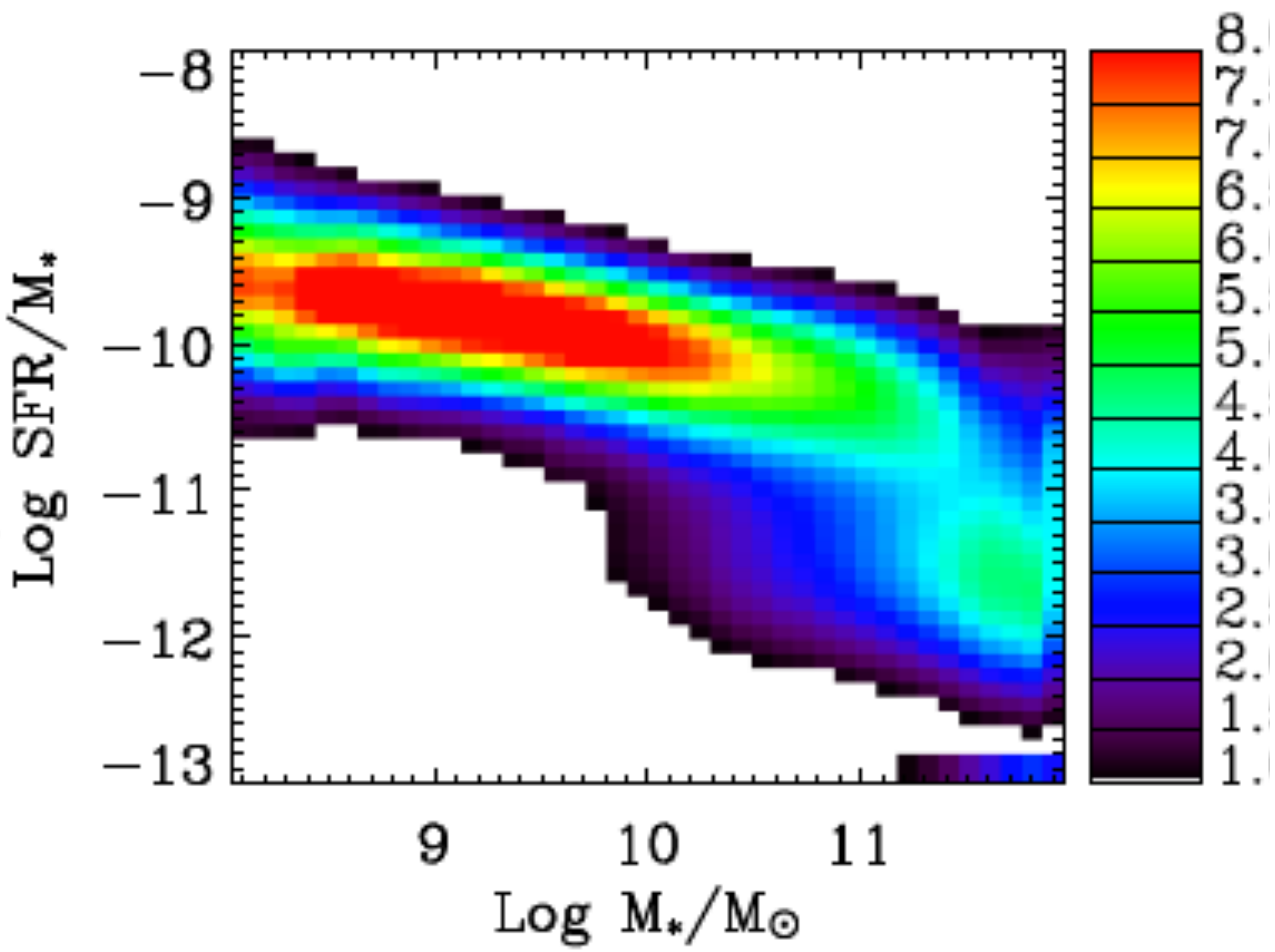




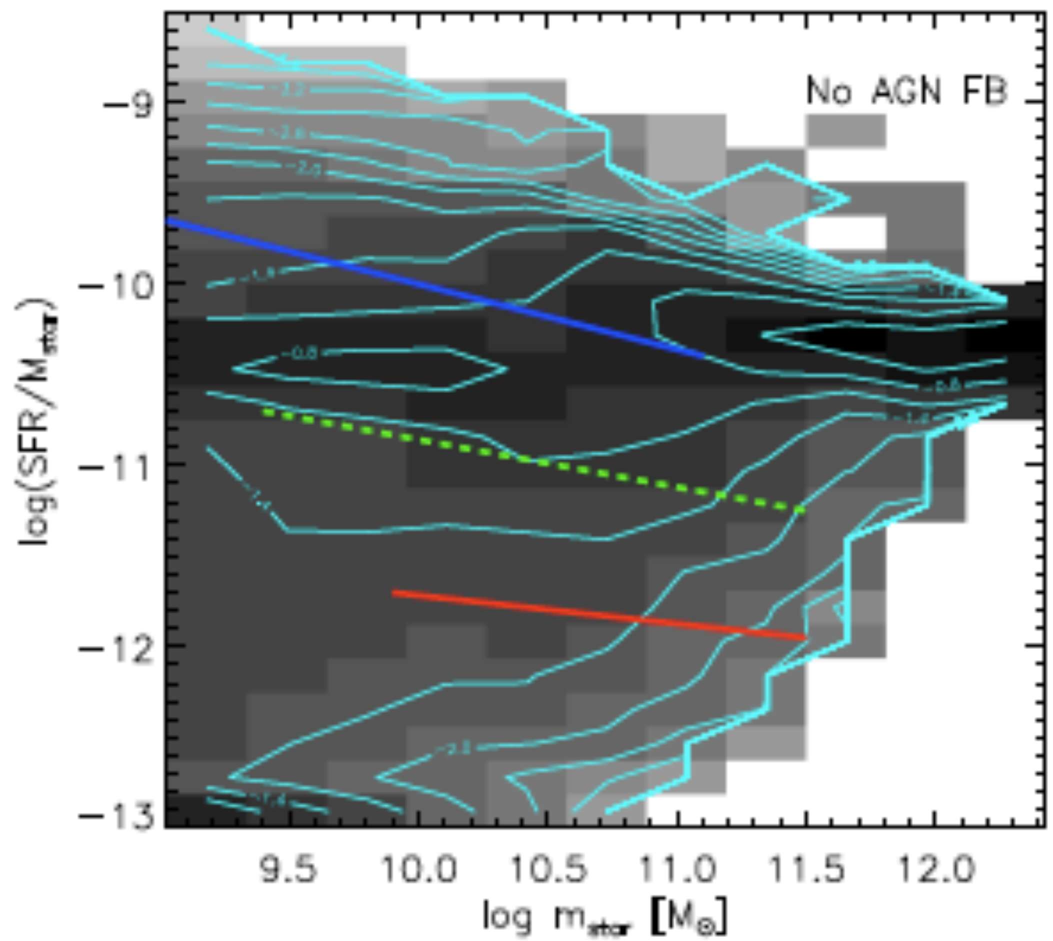
There are plausible (not unique) approaches to SF and feed-back descriptions that match <SFR>(z)

Rate of feedback will also affect specific star formation rate

observed:



w/ no AGN feedback:



Low-mass end: Galactic winds

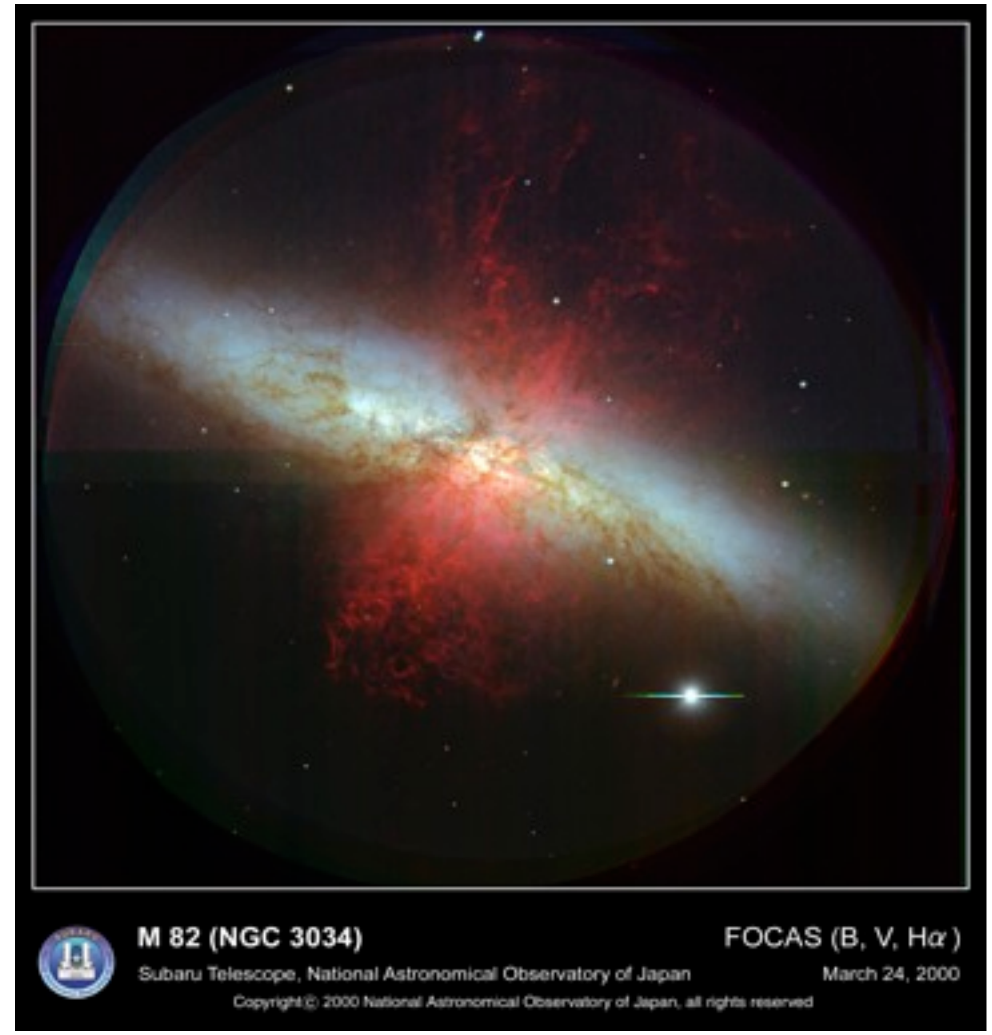
winds can play an important role in the evolution of galaxies (particular low-mass) by removing gas from central parts

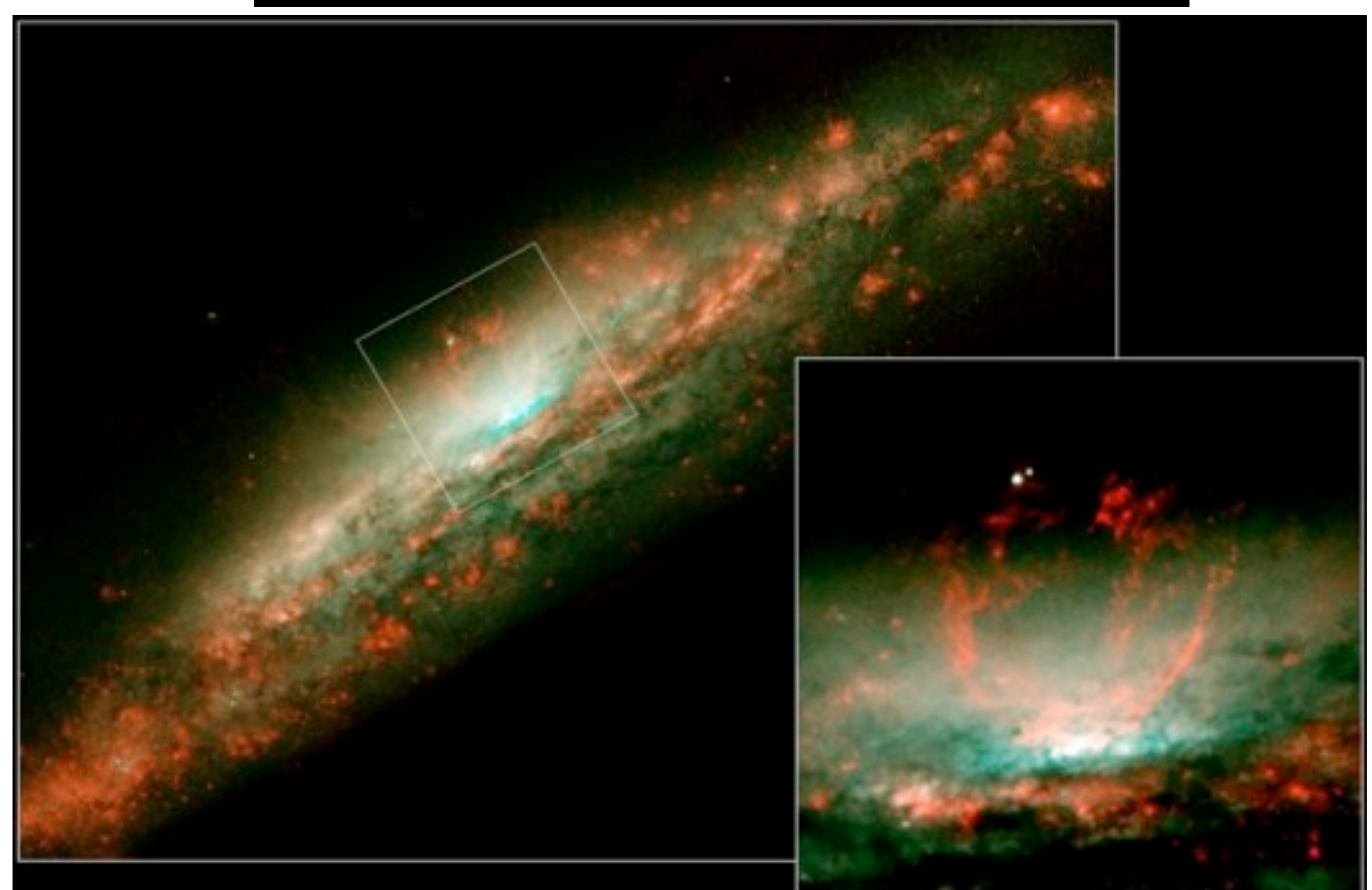
may explain:

- shape of luminosity function at low mass end

- metal deficiency of dwarf galaxies

- (part of) enrichment of IGM





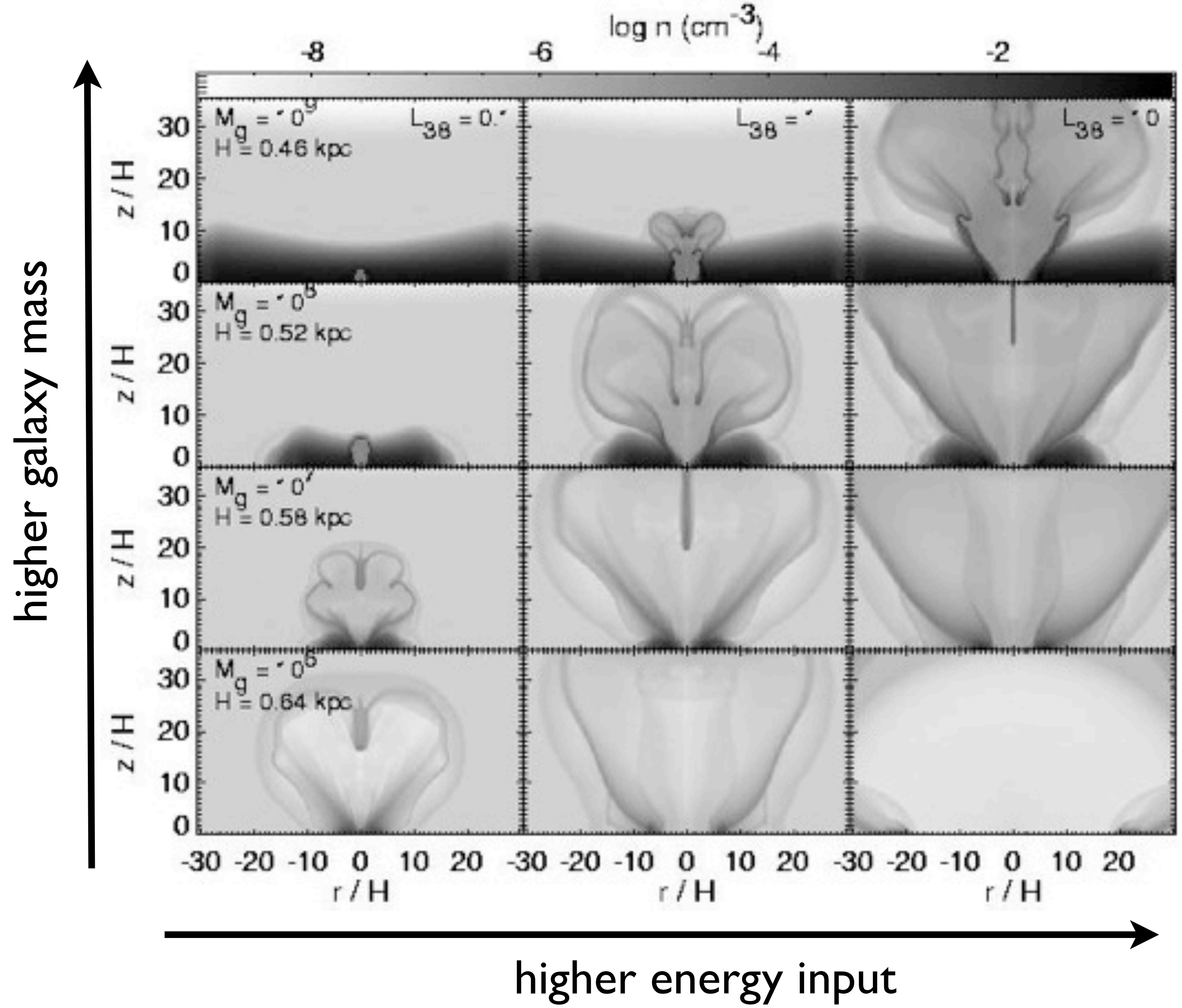
Wind models for (dwarf) galaxies

- dwarfs with masses $10^6\ M_{sun} \leq M \leq 10^9\ M_{sun}$,
  - mechanical luminosities $L \sim 10^{37} \cdots 10^{39}$ erg s^{-1} (over 50 Myr)
  - significant ejection of ISM only for galaxies with $M \leq 10^6\ M_{sun}$
  - efficient metal depletion for galaxies with $M \leq 10^9\ M_{sun}$

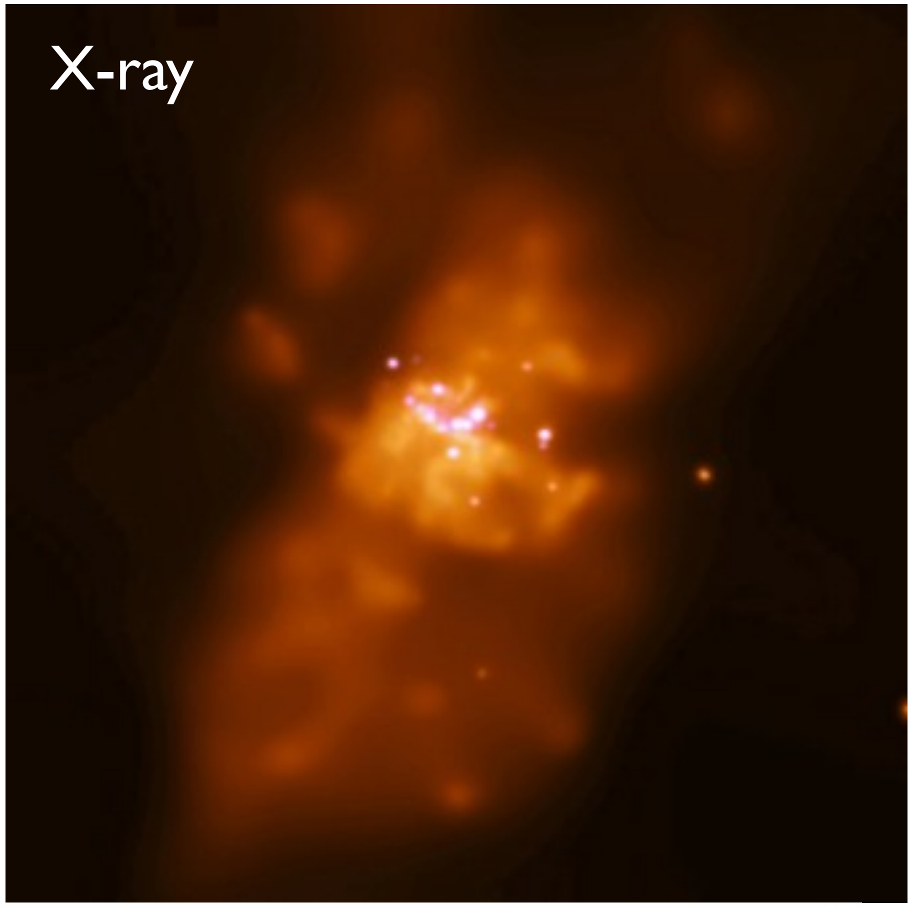
Mc Low & Ferrara (1999)

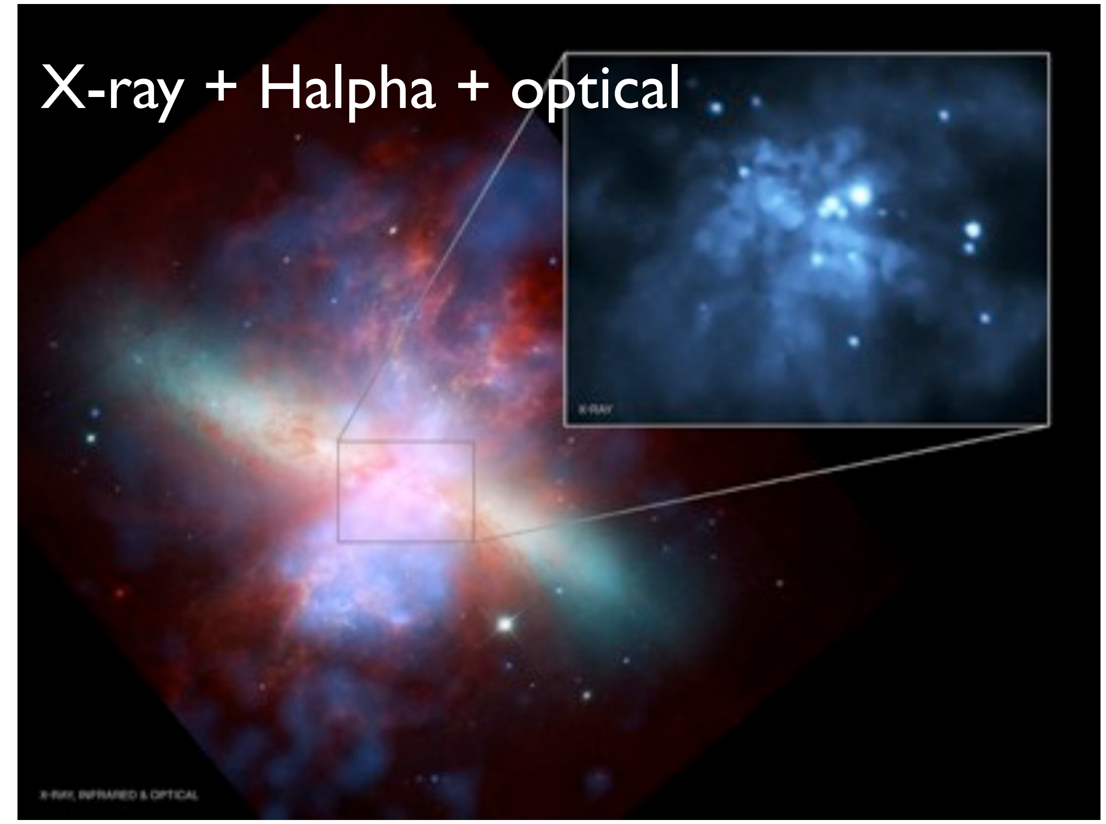
numerical simulations:
for mechanical luminosity $L = 10^{38}$ erg s^{-1}
blow-out occurs in $10^9\ M_{sun}$ galaxy

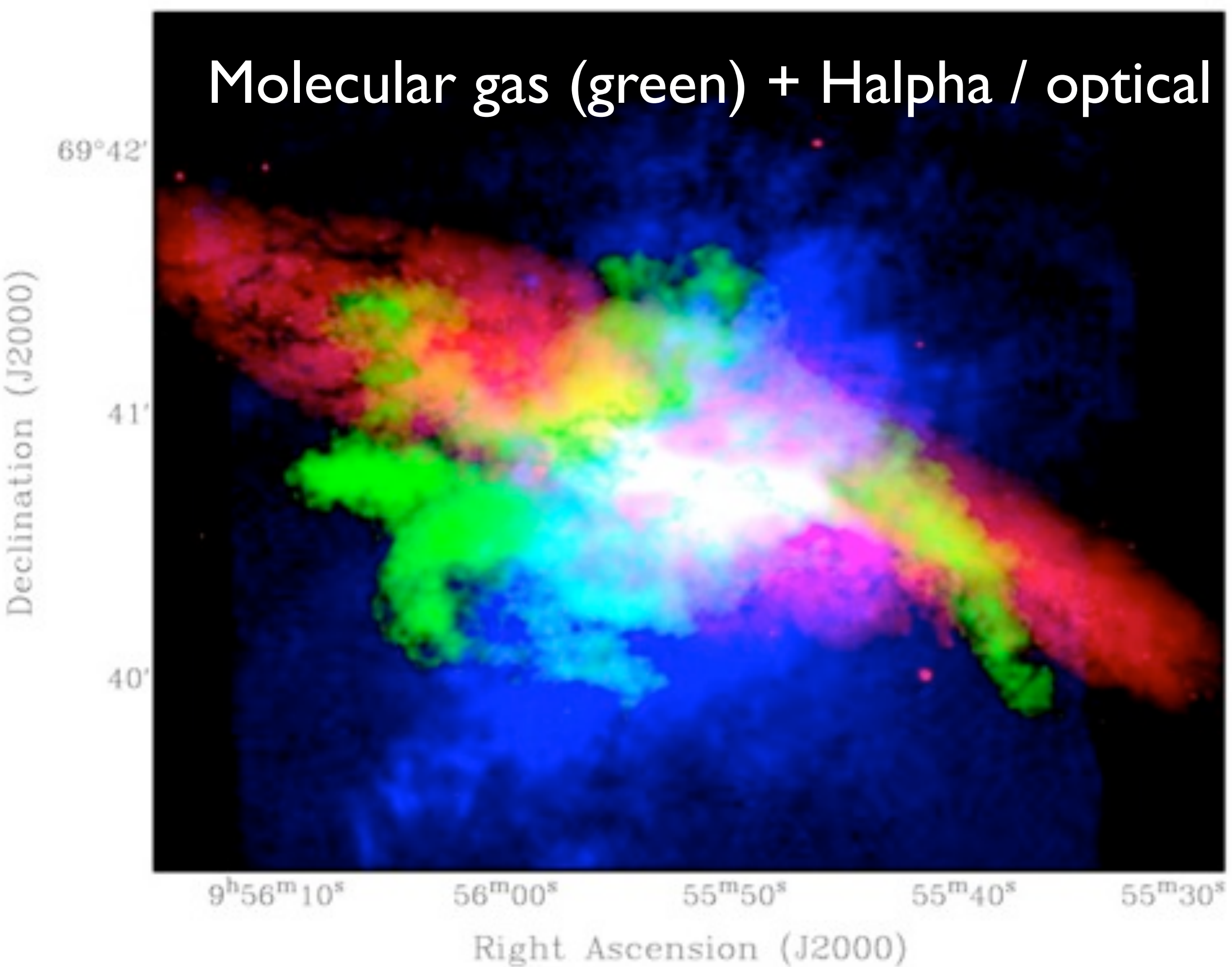
→ only ~30% metals retained

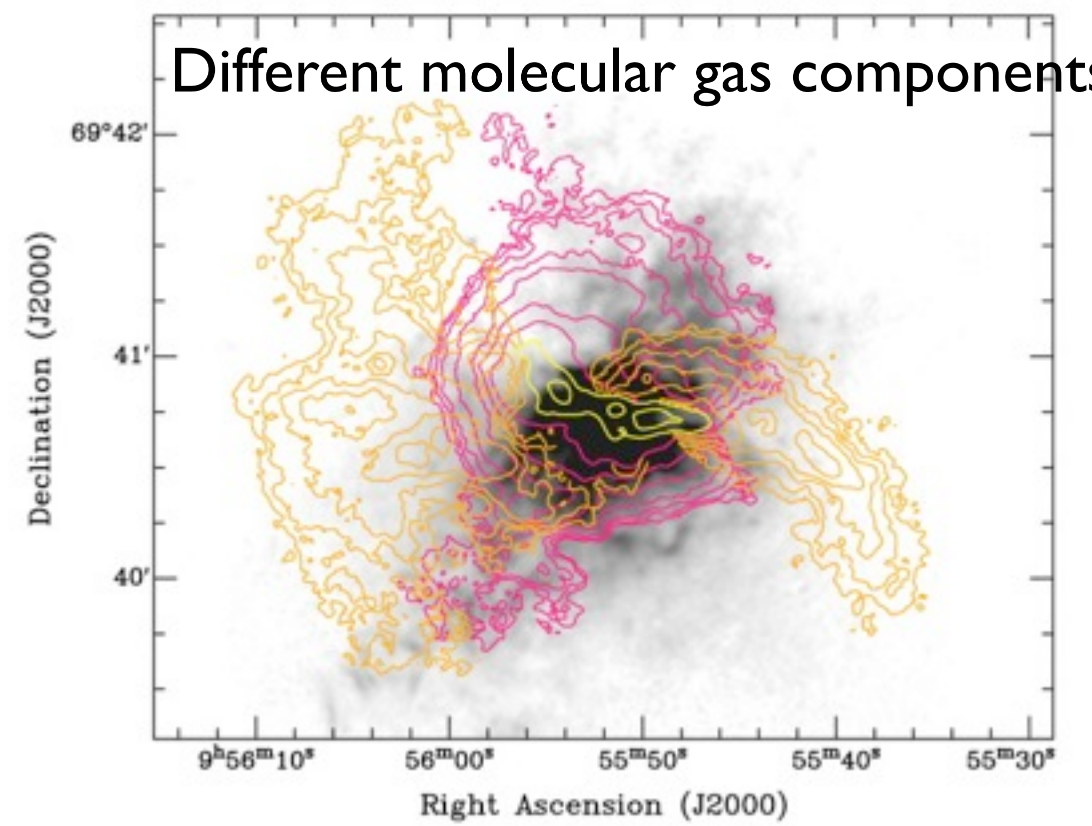


Perhaps most famous example: M82

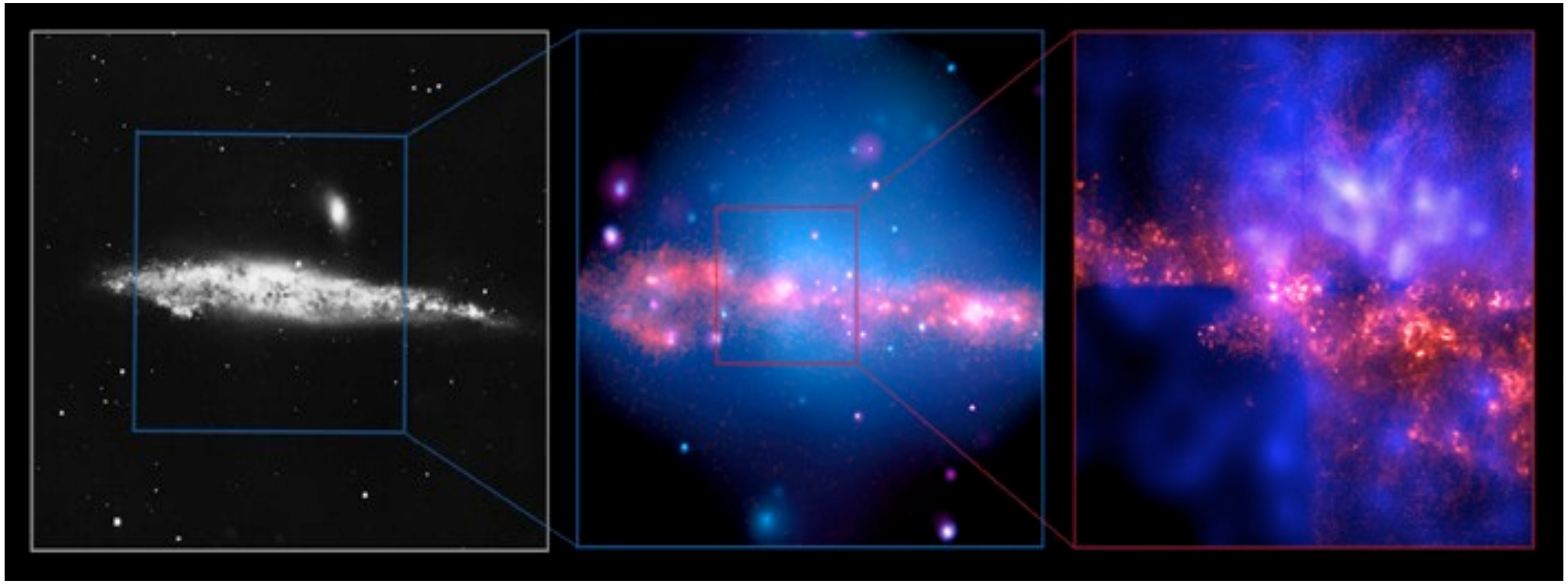




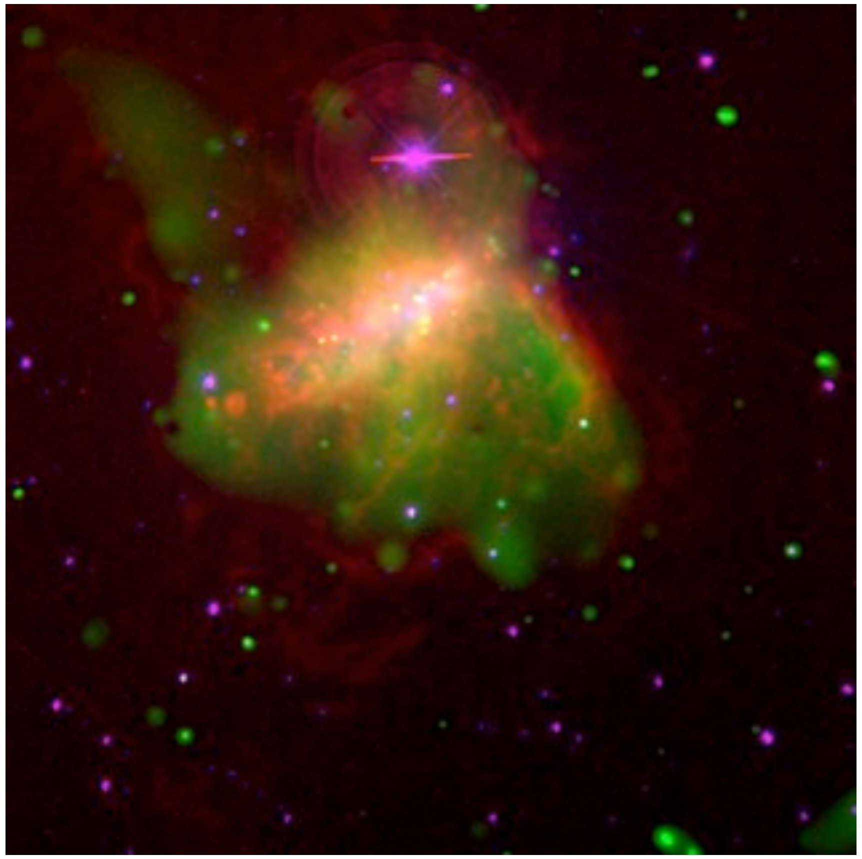




Other examples:



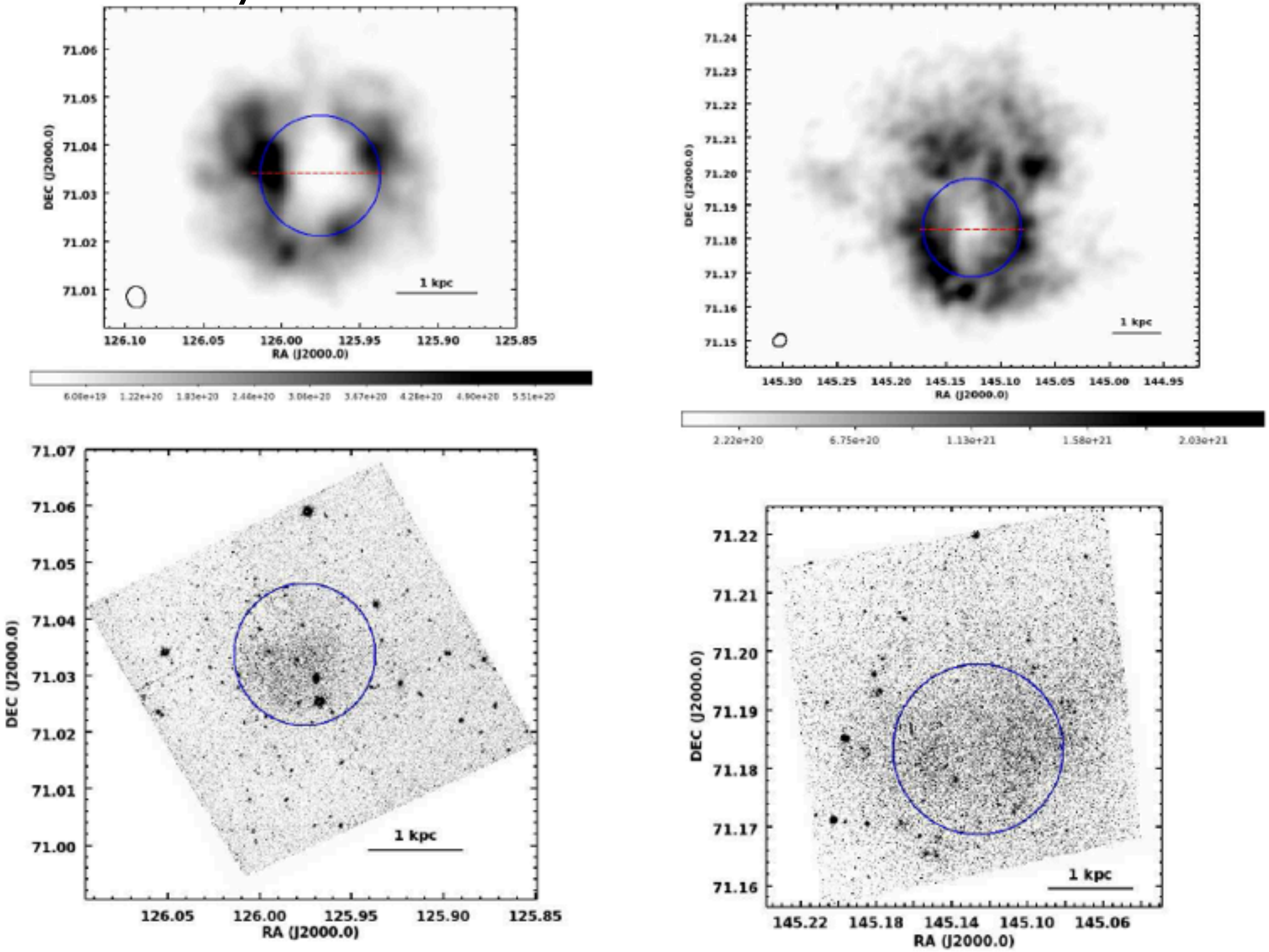
NGC4631



NGC 1569

At the lowest masses: possible blow-away?

Some of the lowest mass dwarf galaxies ($<10^9$ M_{sun}) show evidence for 'blow-away'



VLA HI imaging

optical (HST) imaging

At the highest masses:

Evidence for AGN feedback...

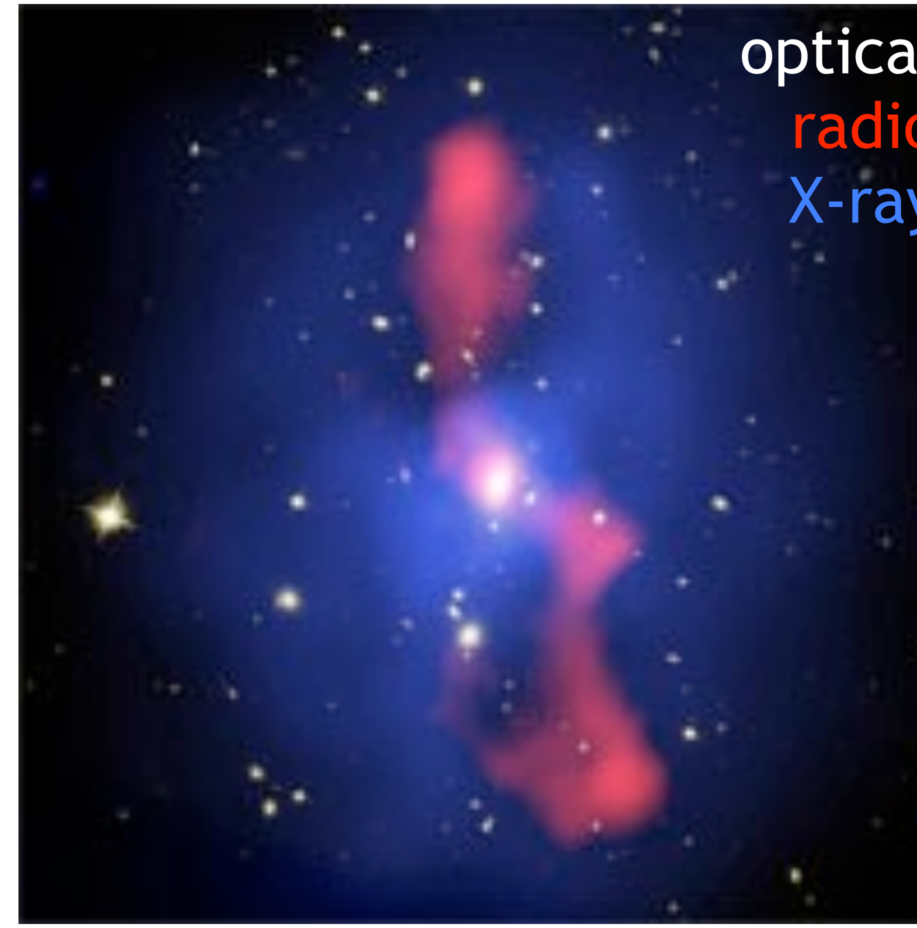
seen in simulations, but also observations?

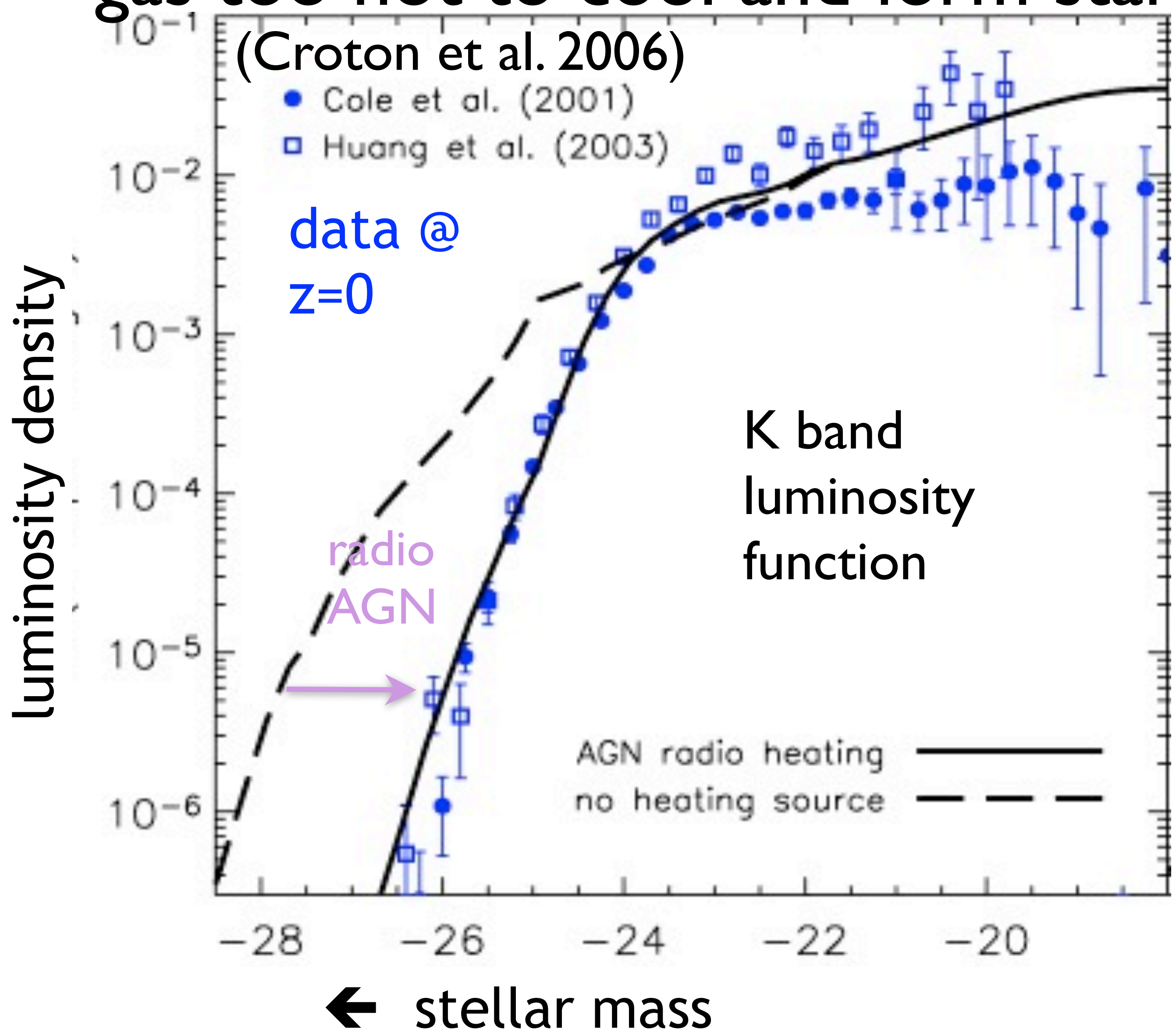
di Matteo, Spingel, Hernquist

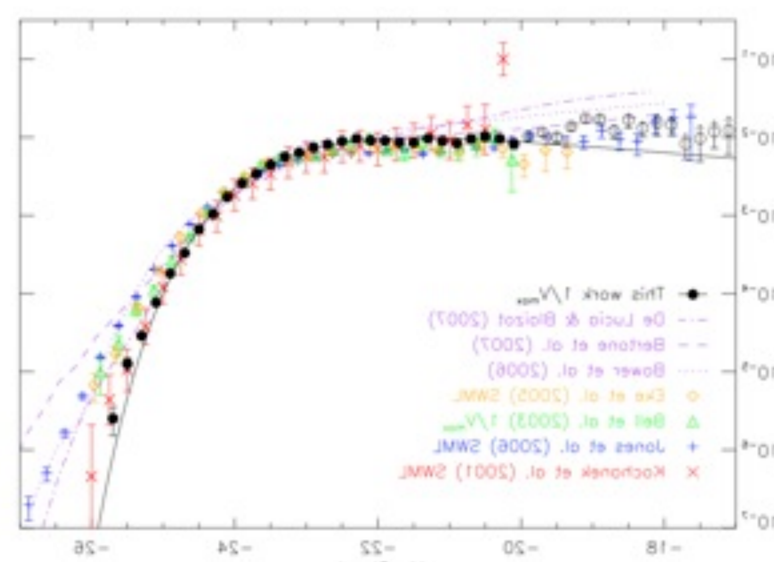
AGN Feedback – radio (low accretion/X-ray faint) mode

Wanted: Process to prevent star formation that is only effective in massive galaxies

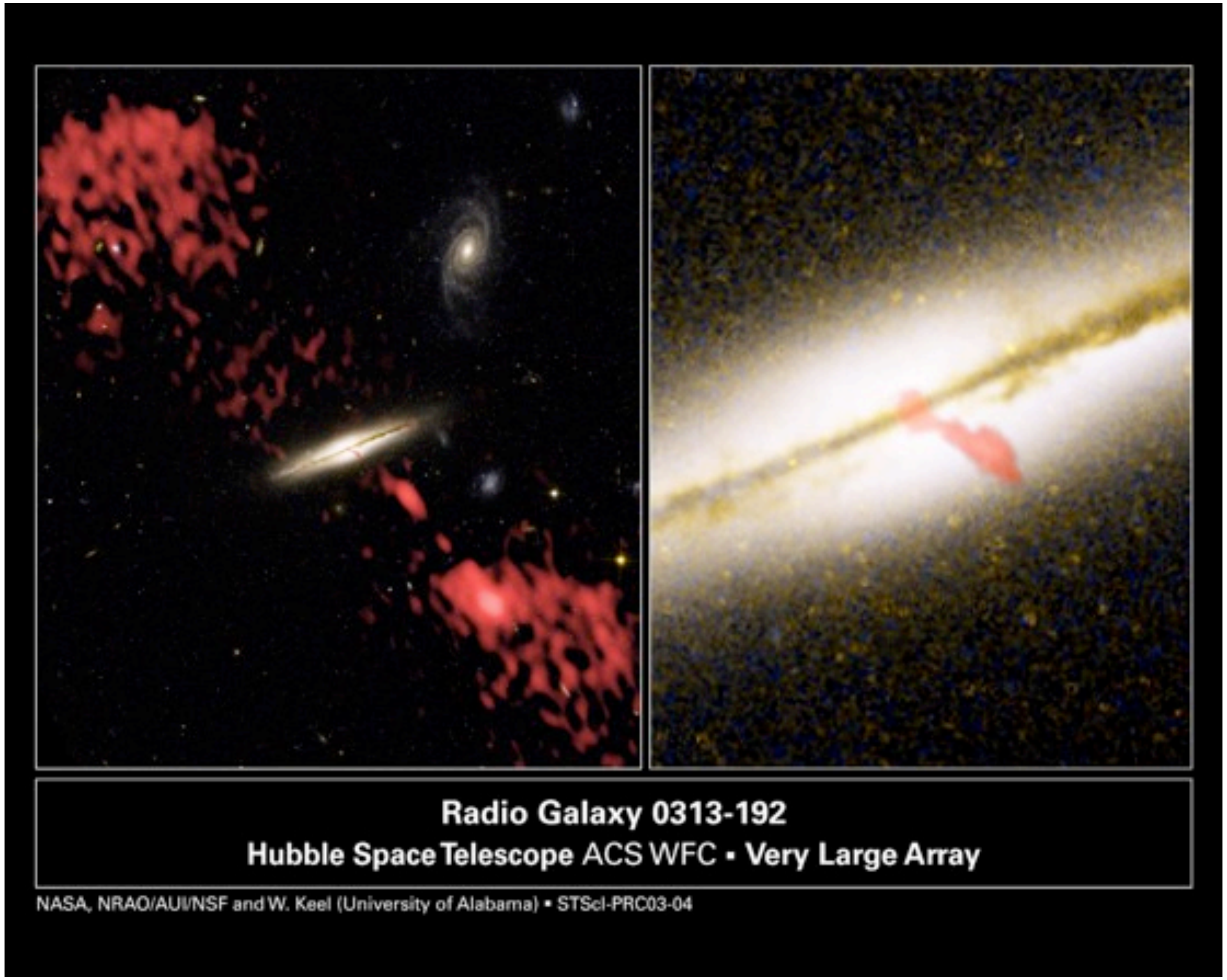
Idea: radio jets heat intracluster medium --gas too hot to cool and form stars



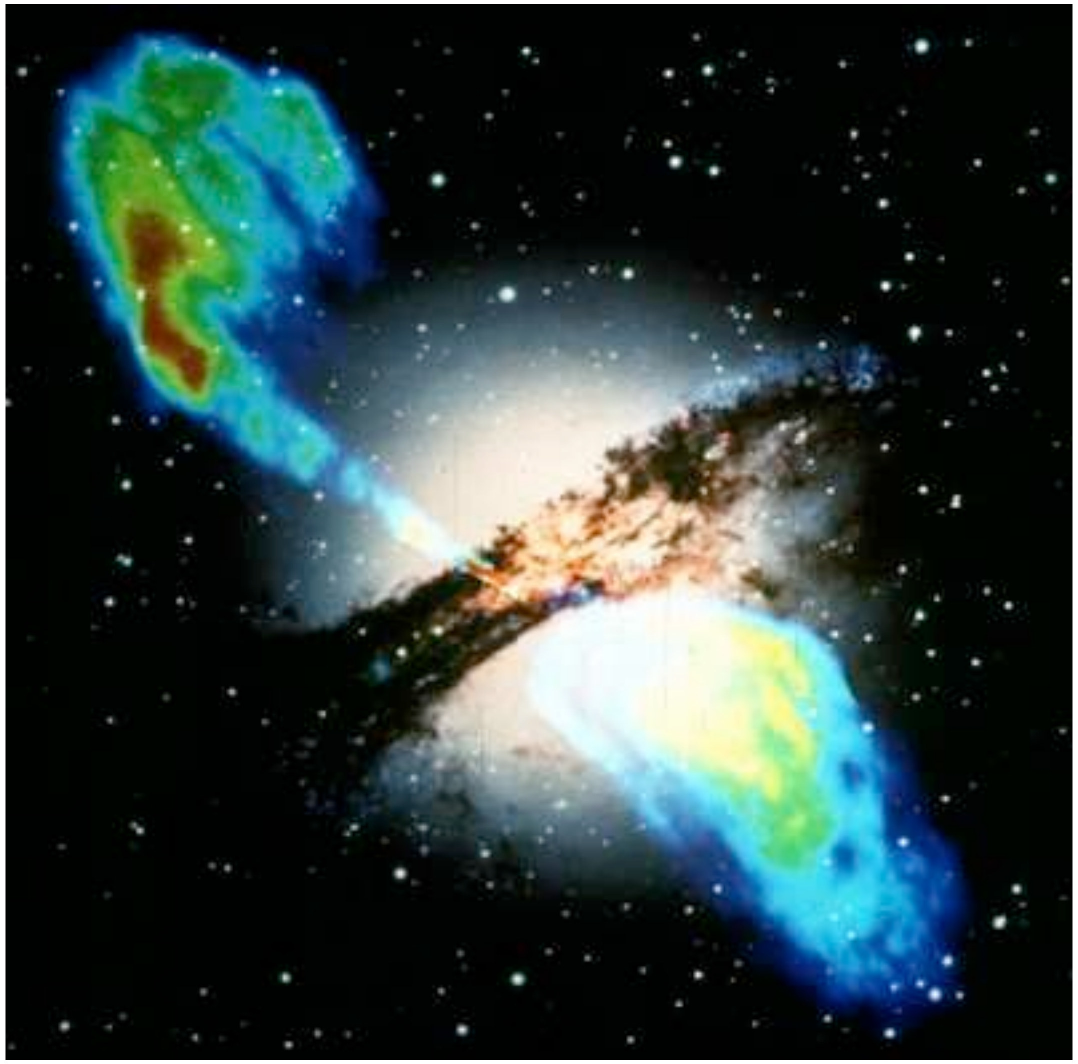




Impact of (current) radio jets



the first spiral galaxy known to be producing a giant radio-emitting jet

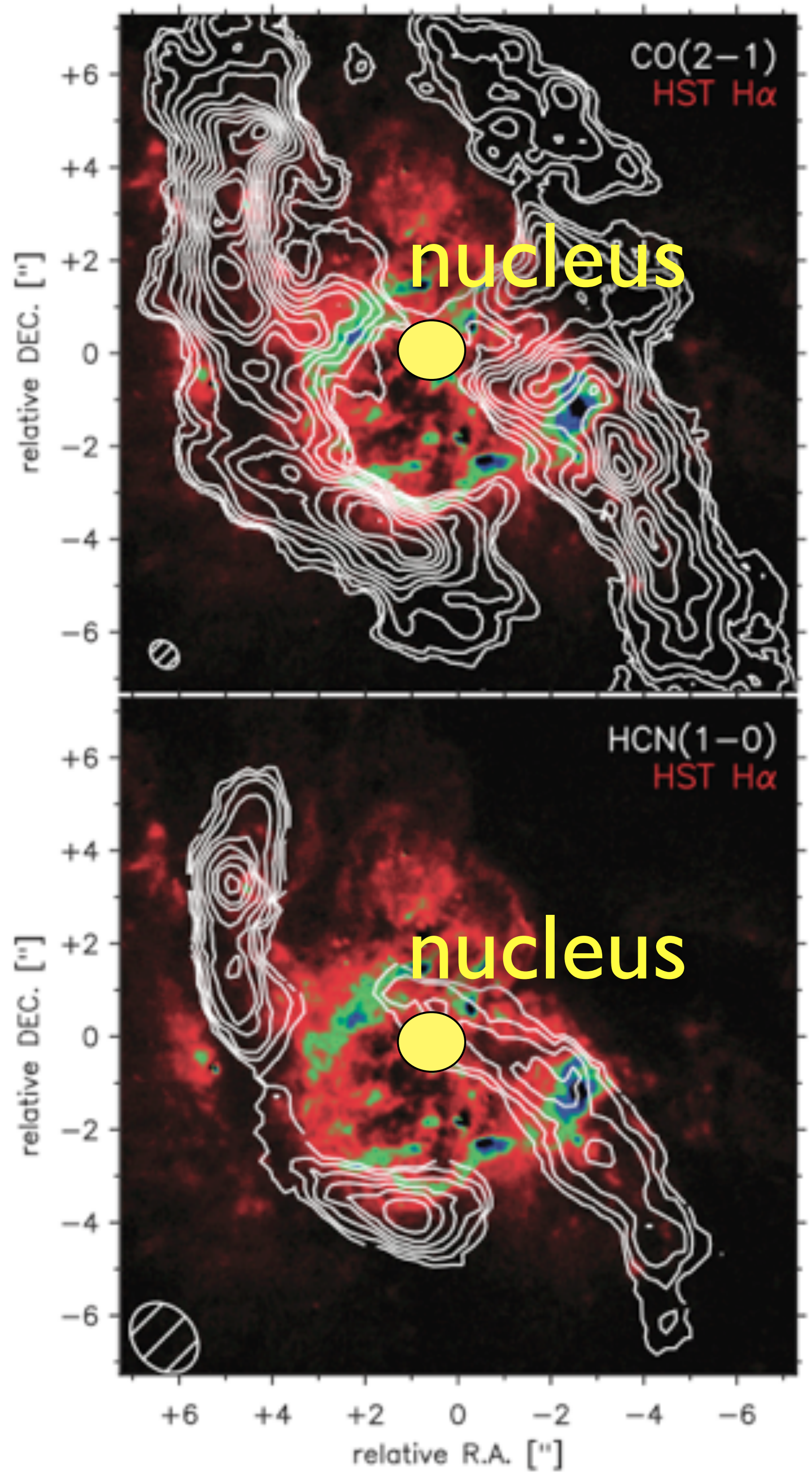


Centaurus A

current AGN activity **do not appear** to have a major impact on the host galaxy (see also AGN lecture)

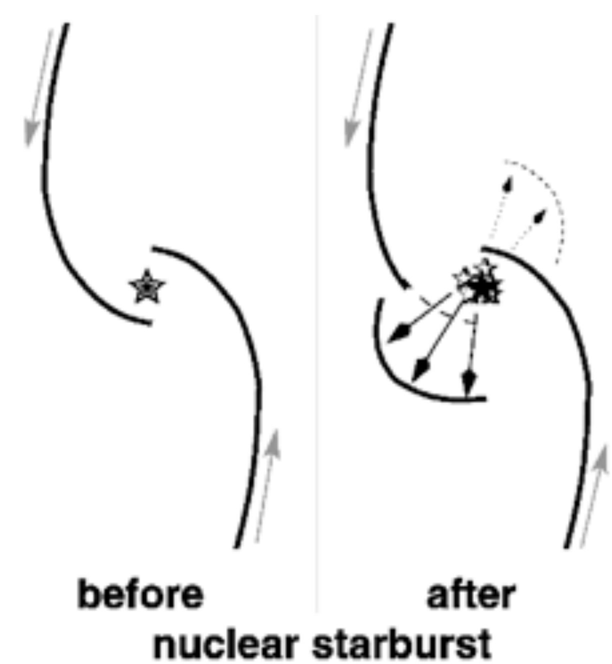
Small Scale: AGN Feedback can 'starve' central AGN

Impact of nuclear activity on small scales, e.g., IC 342



Schinnerer et al. 2008

cartoon:

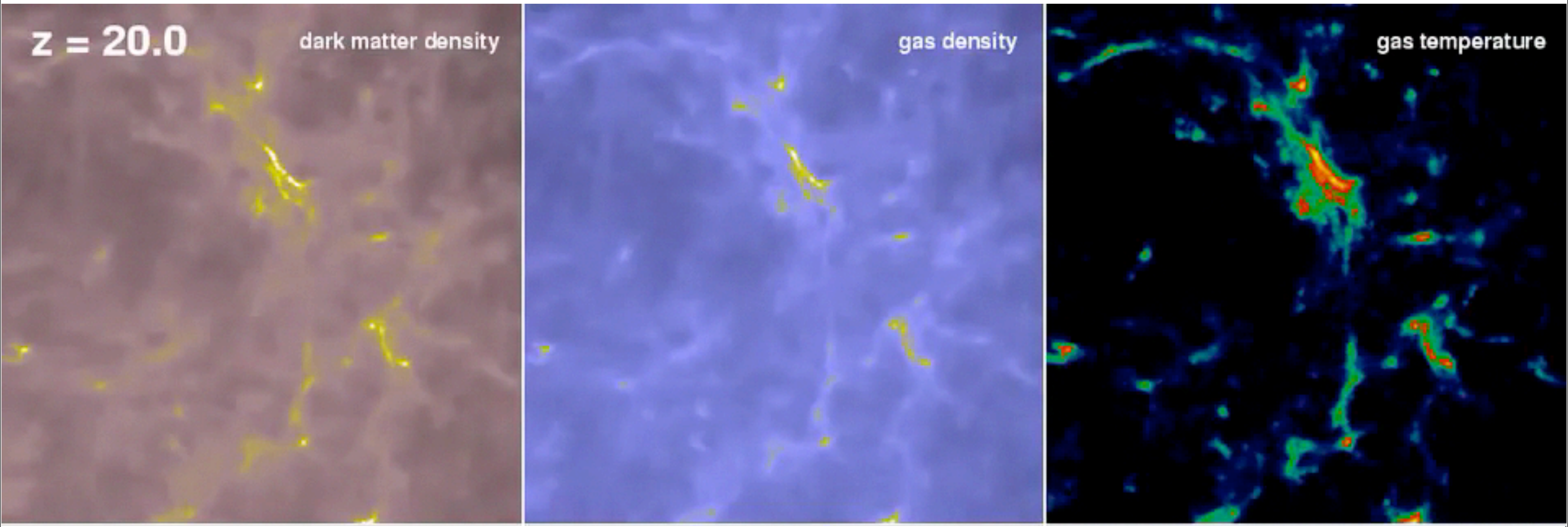


Feedback exists -- but efficiency unclear.

Detailed SF process

how do galaxies get their gas? and how does the gas form stars?

a key ingredient to galaxy simulations and vital for our understanding of star formation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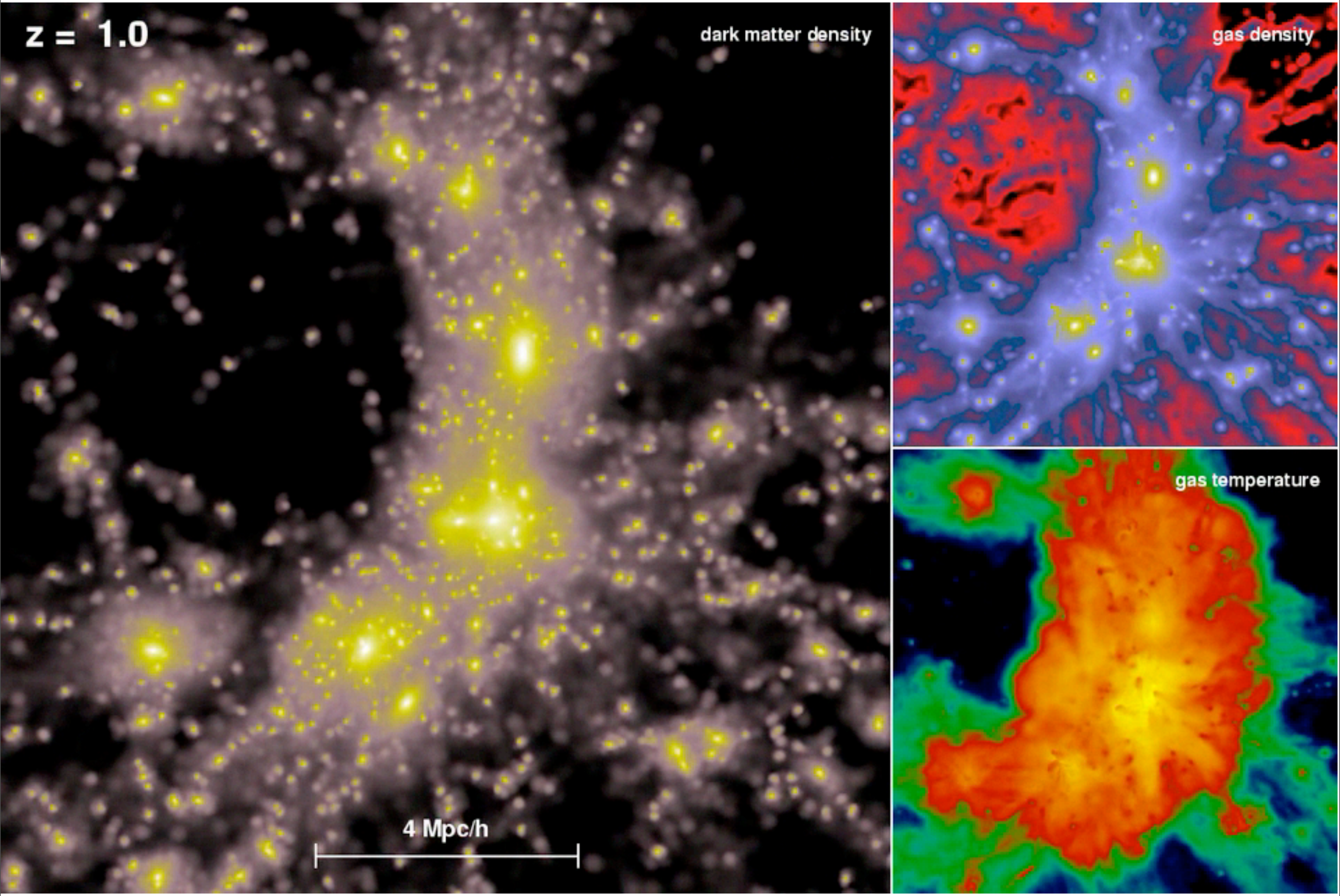
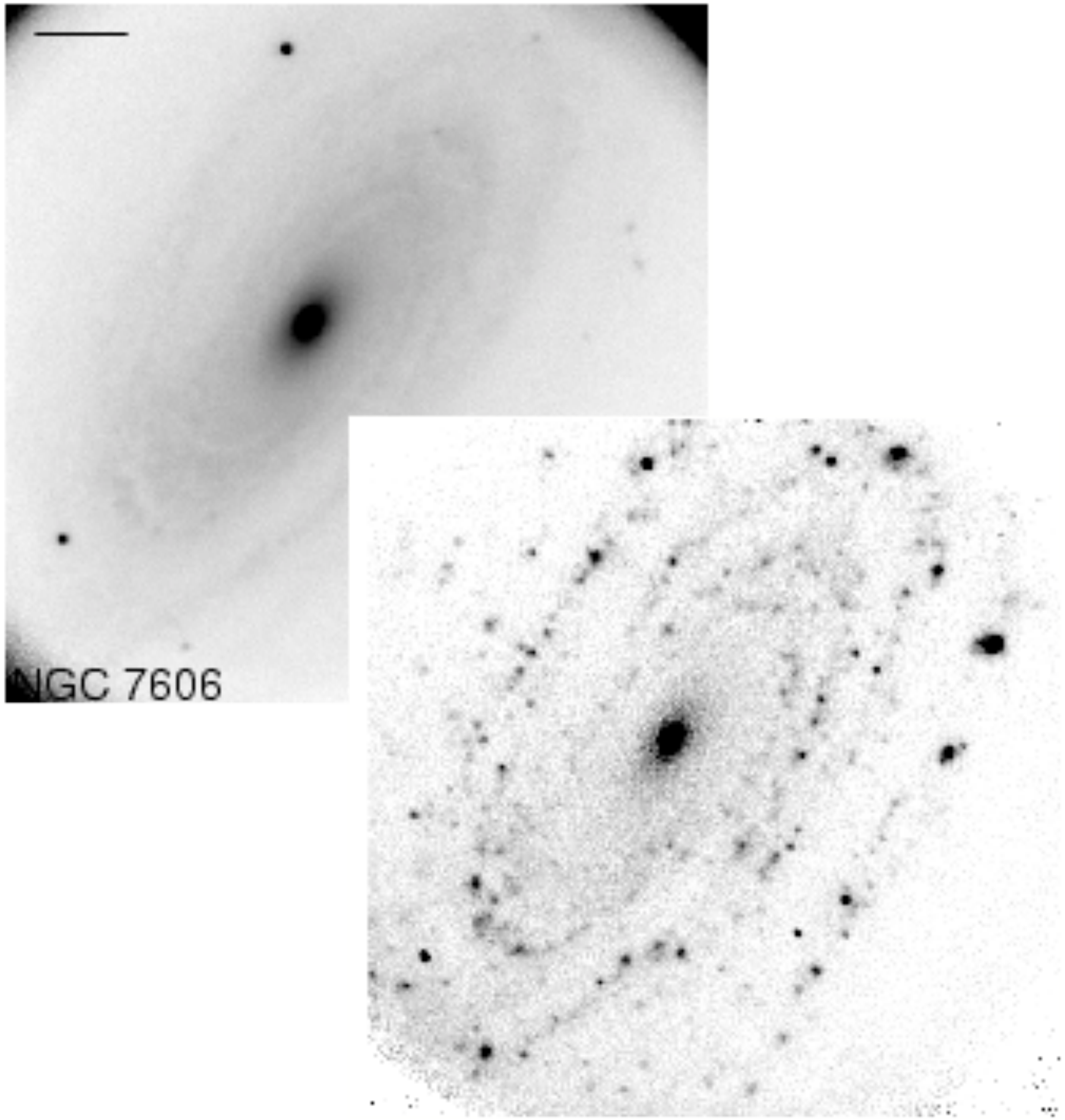
dark matter density
gas density
gas temperature

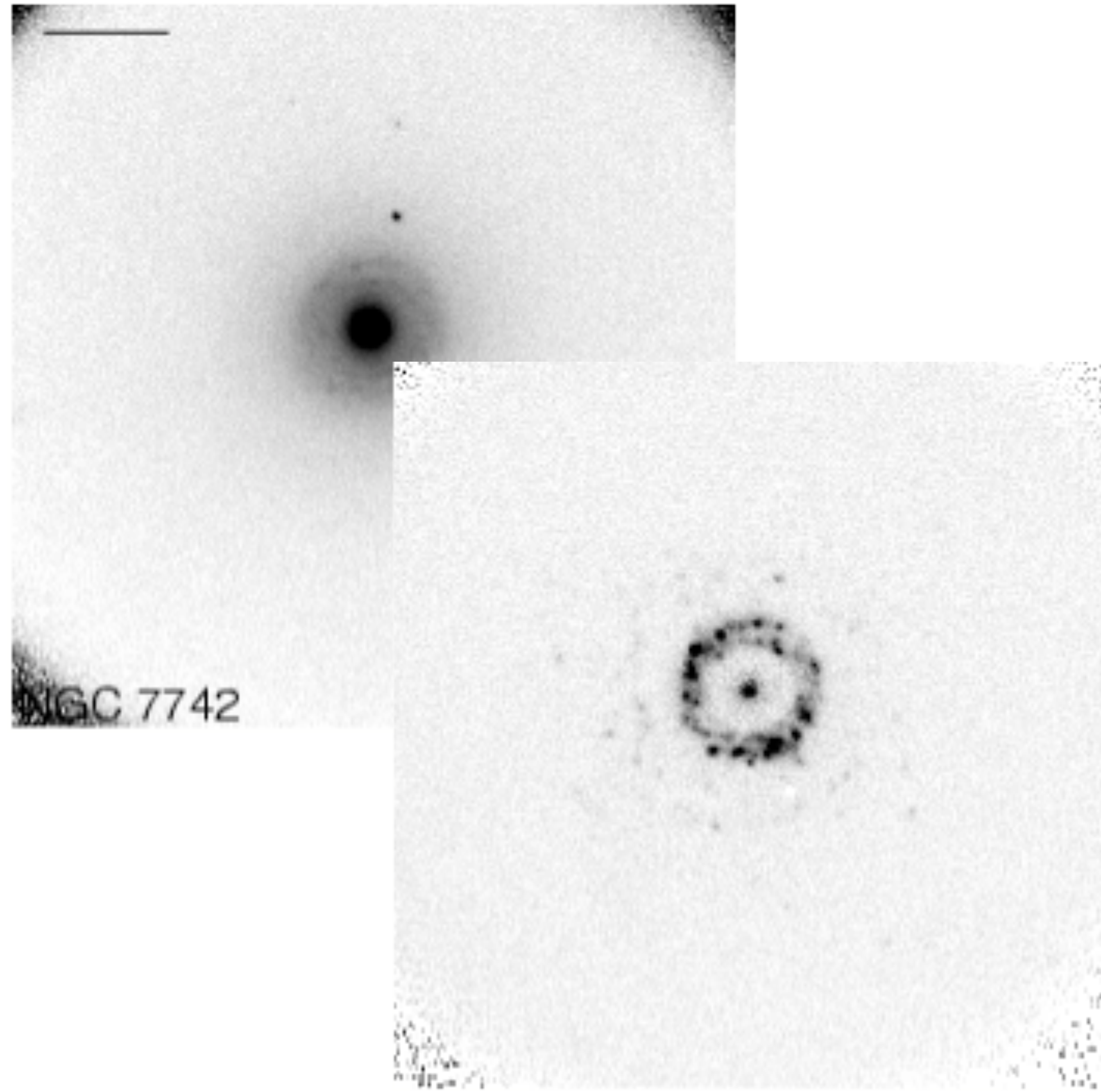

z = 1.0
dark matter density
4 Mpc/h
gas density
gas temperature

SF -- Where - Global

Galactic Disks



(Circum)nuclear

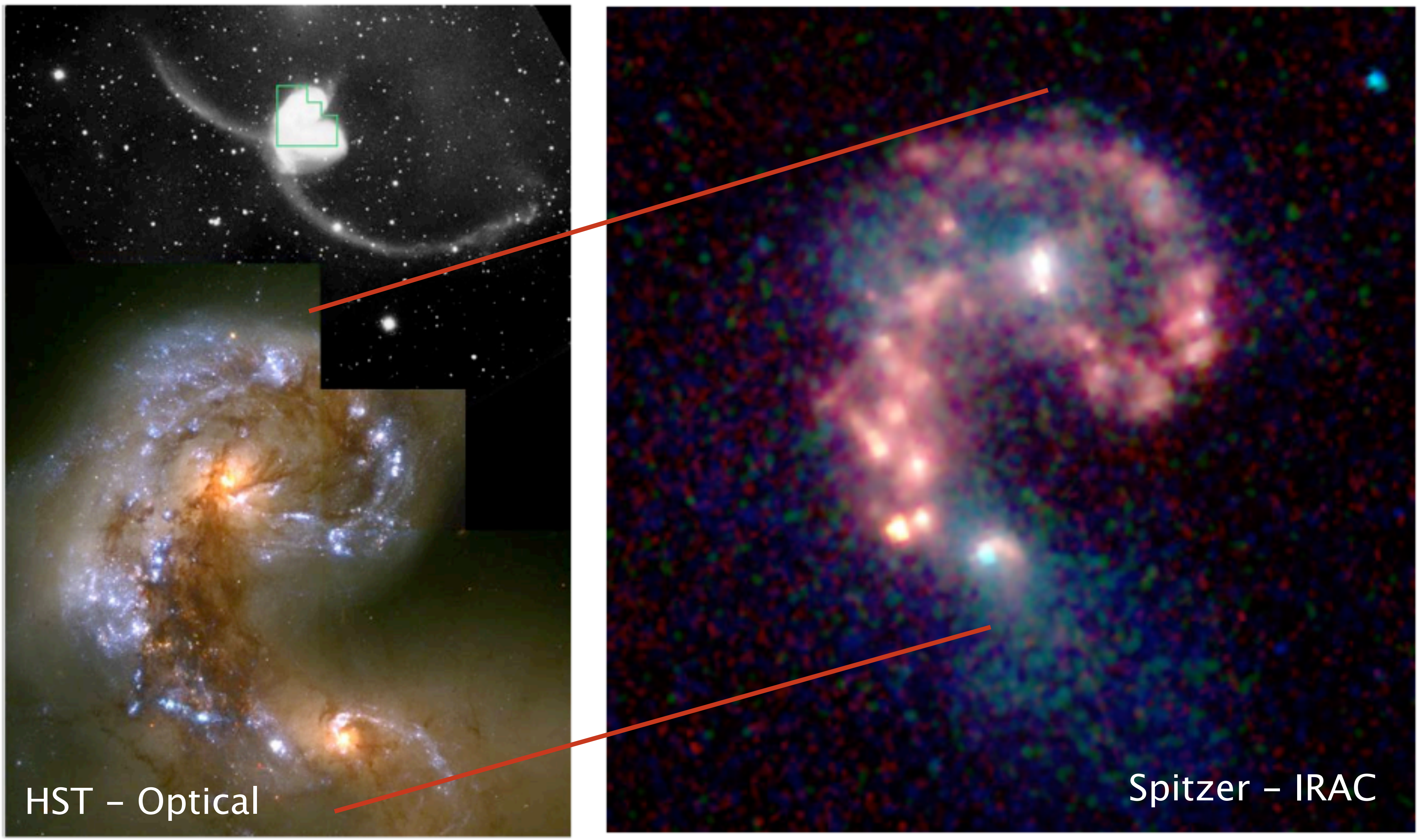


SF needs dense molecular gas
what creates these high density regions?
global dynamics vs. self-gravity vs. stochasticity?

Where - Special Cases

ULI[R]G - Merger - Dust heated by SF and/or AGN

e.g. Antennae (NGC 4038/9)



SF Triggering Mechanisms

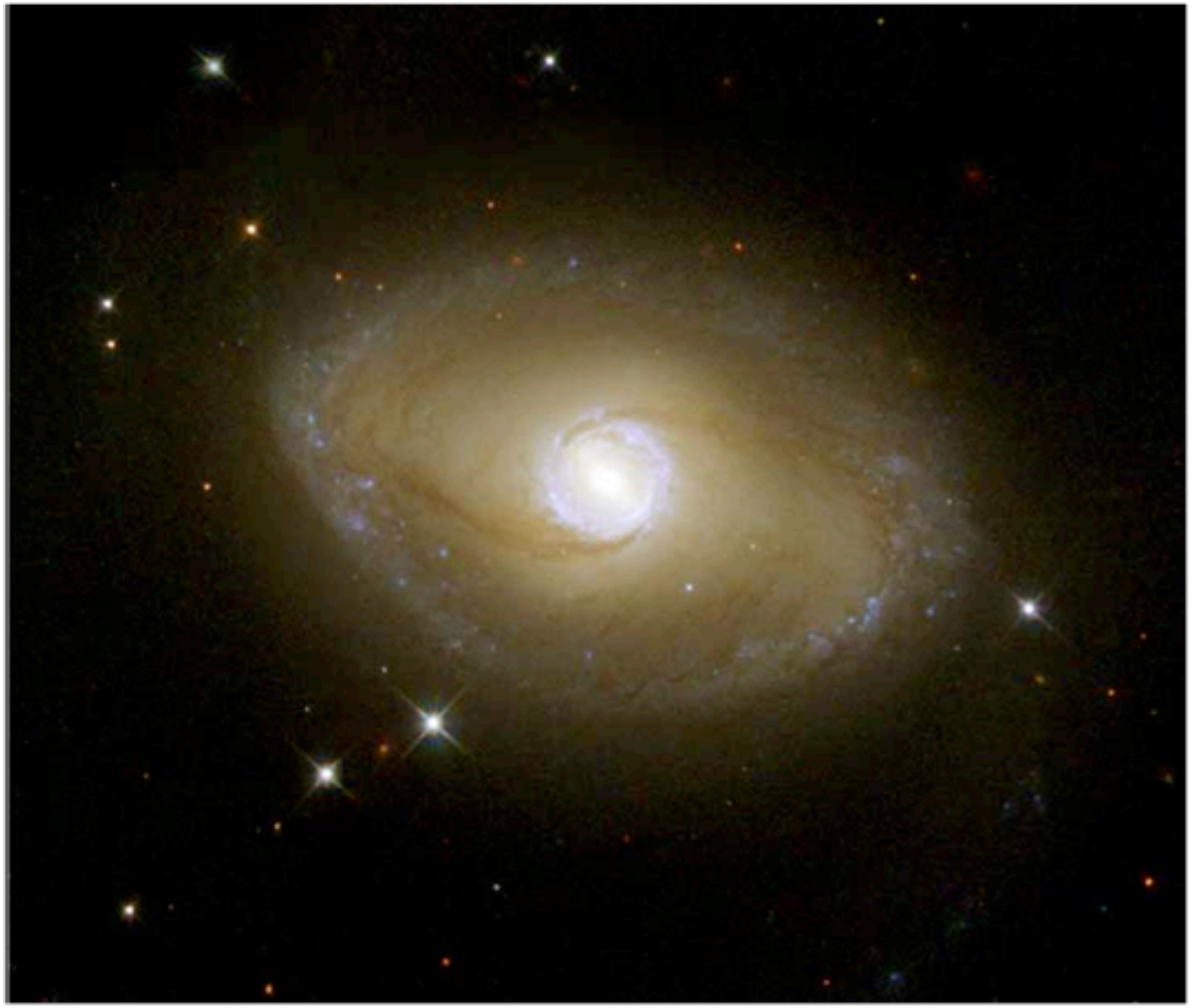
Galactic Scale :

- Density Waves (Spiral Arms, Bars)
- Disk Instabilities
- Tidal Interaction --> Mergers
- Ram Pressure Stripping

+ Local Triggers: Turbulent compression (?)
Expanding Shell Collapse (?)

Bars as SF triggers

- Drive Gas to Central Kiloparsec(s)
- Cause Star Forming Rings



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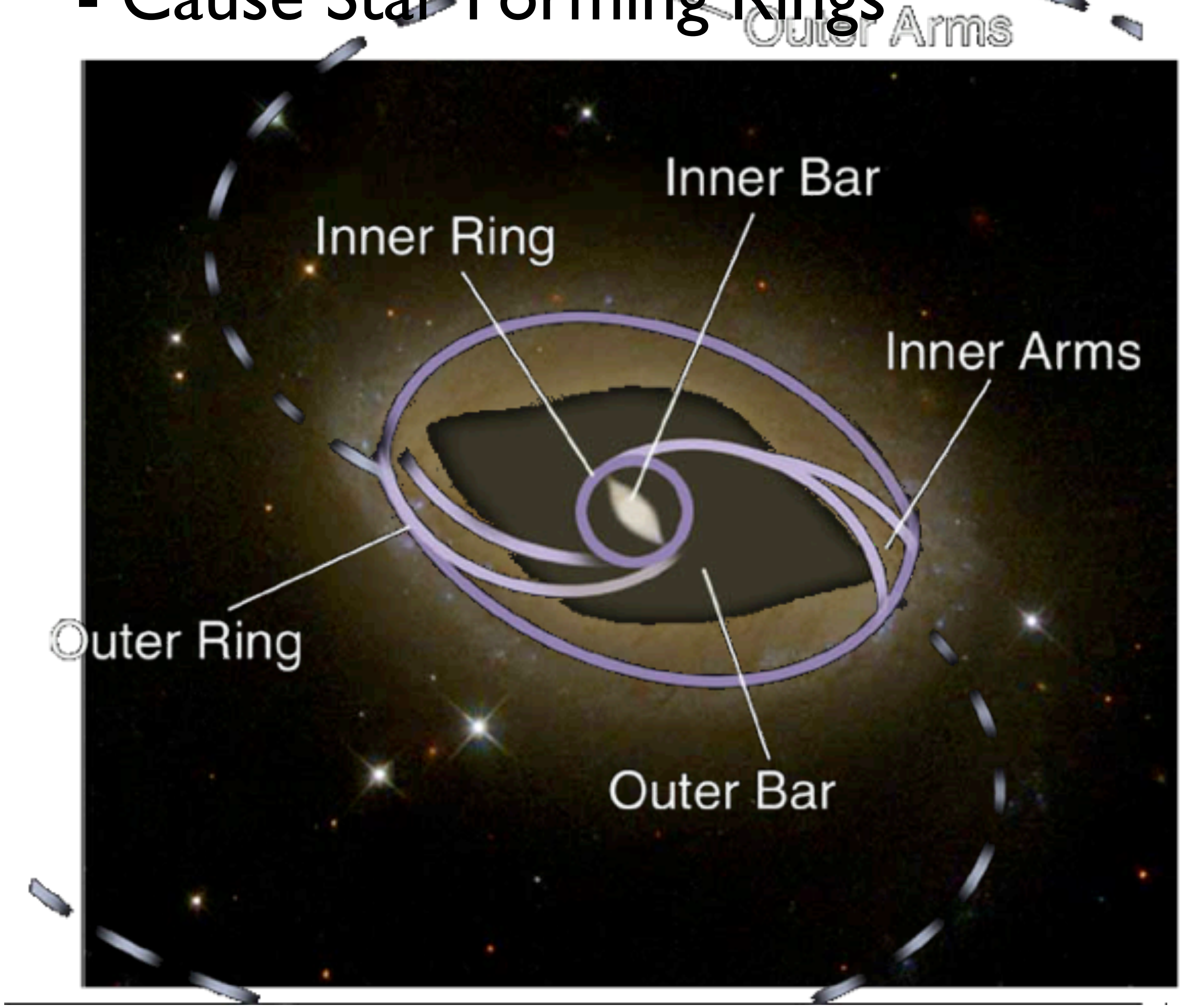
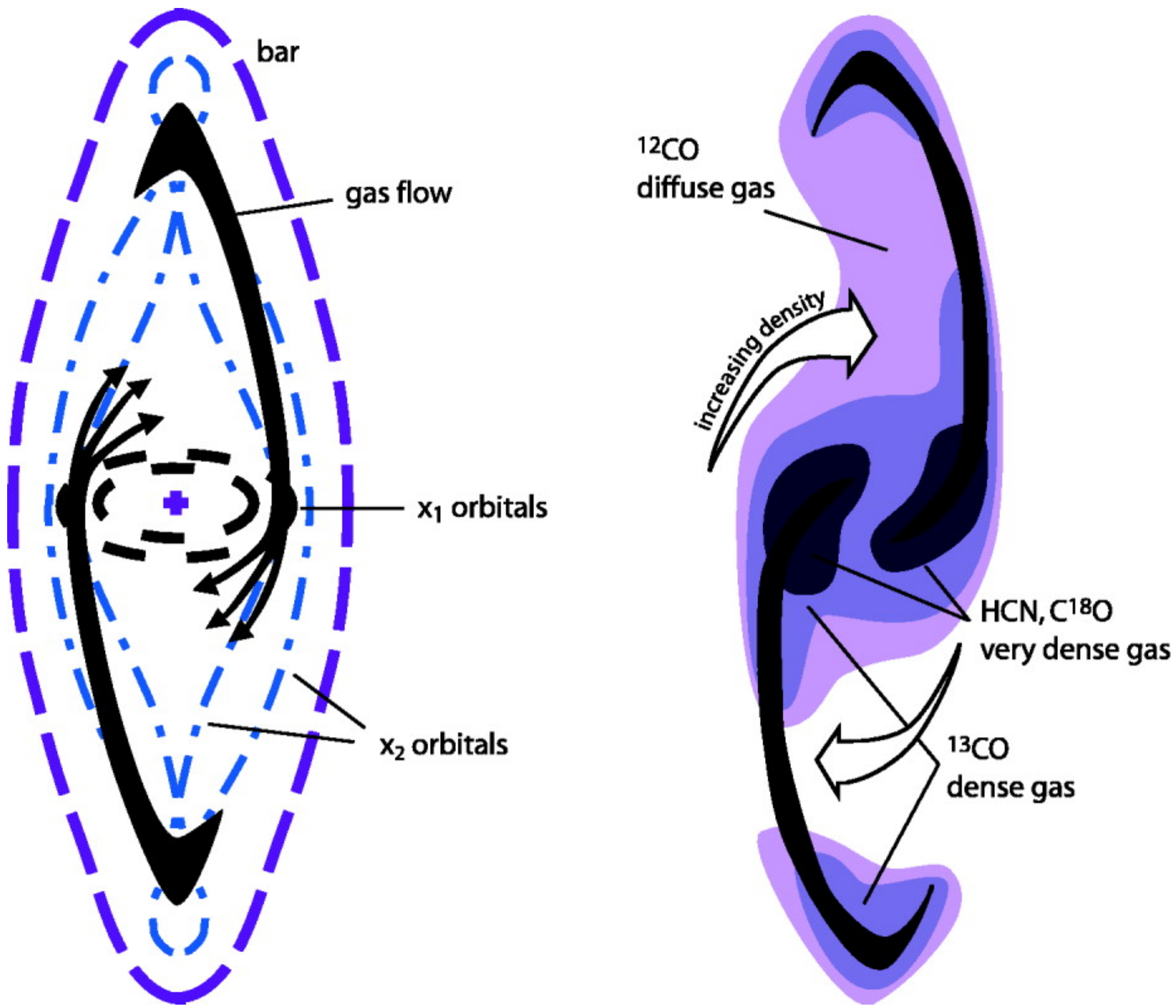
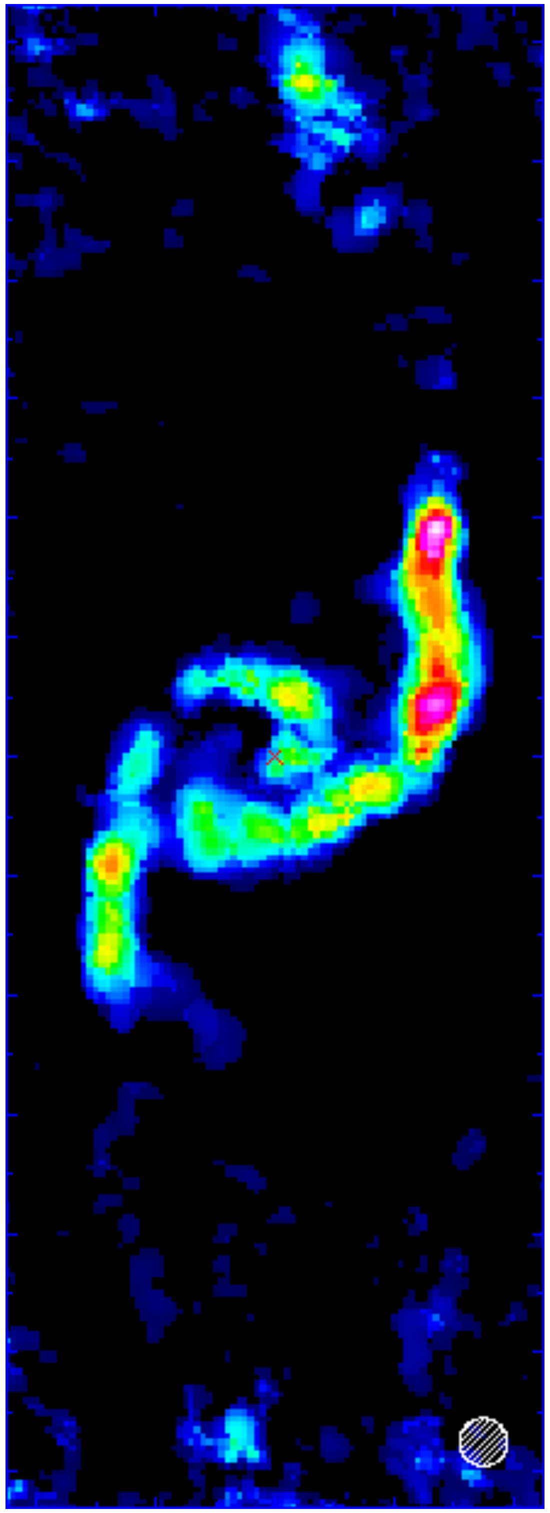


Bars as SF triggers



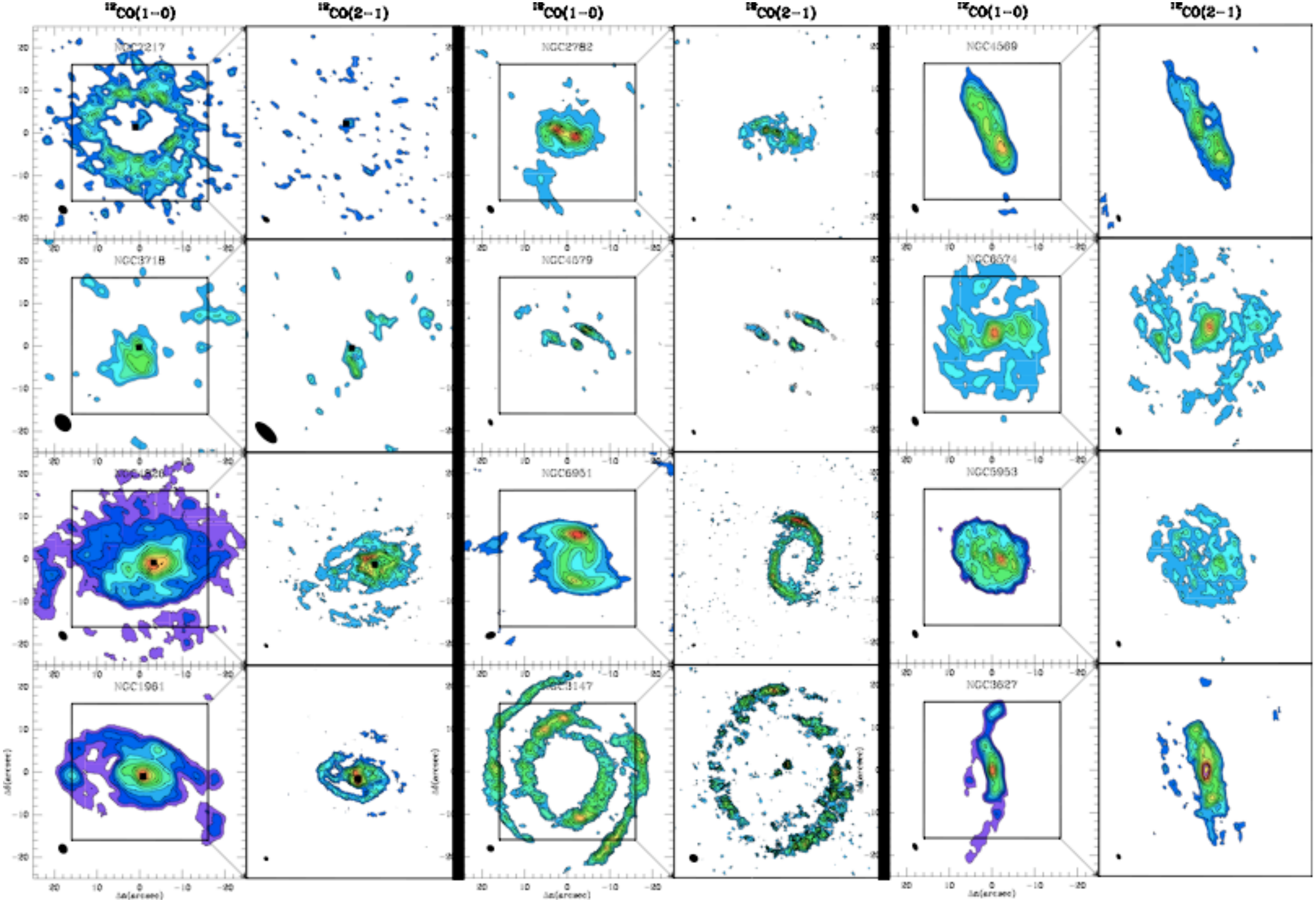
Meier & Turner 2004

Observations:
CO(1-0) in NGC 4303

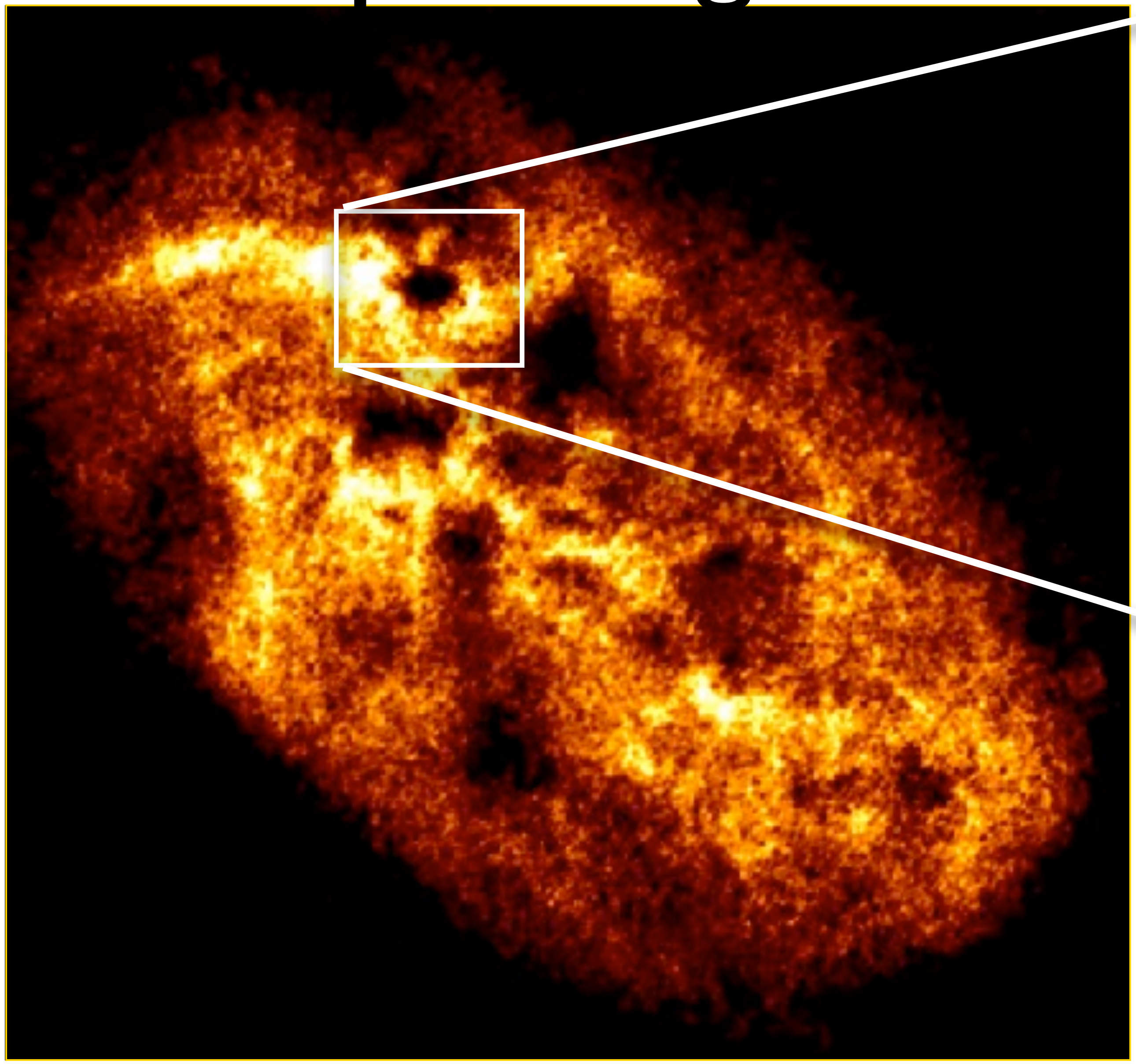


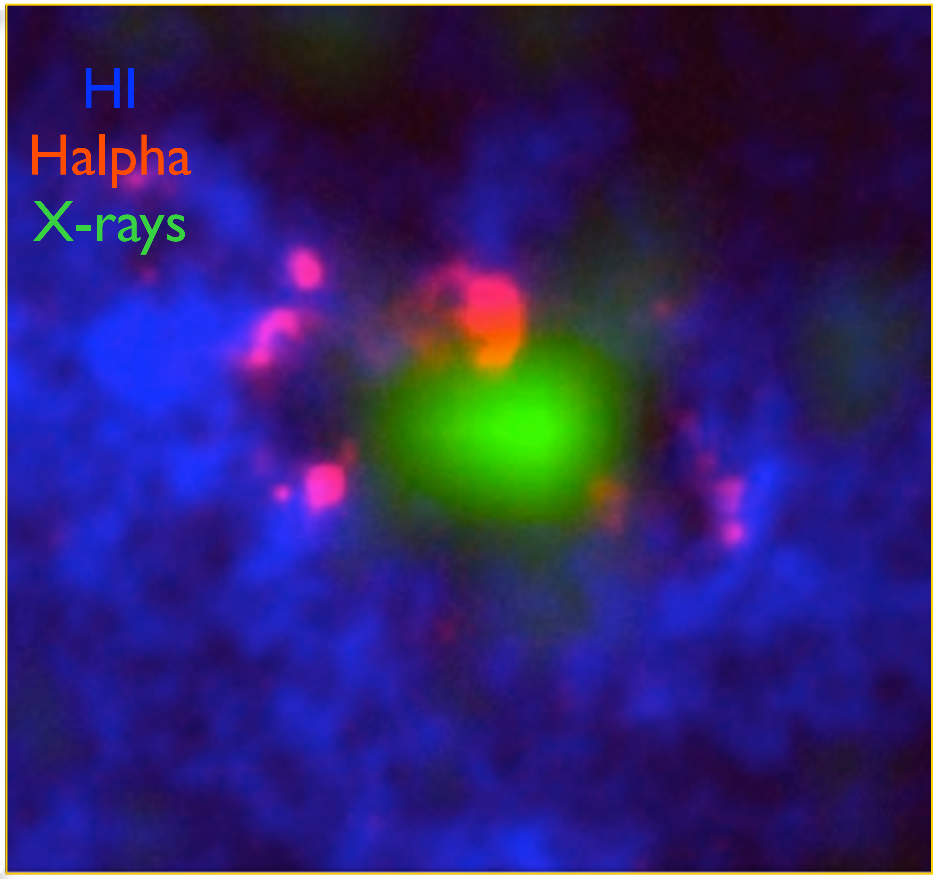
Schinnerer et al. 2002

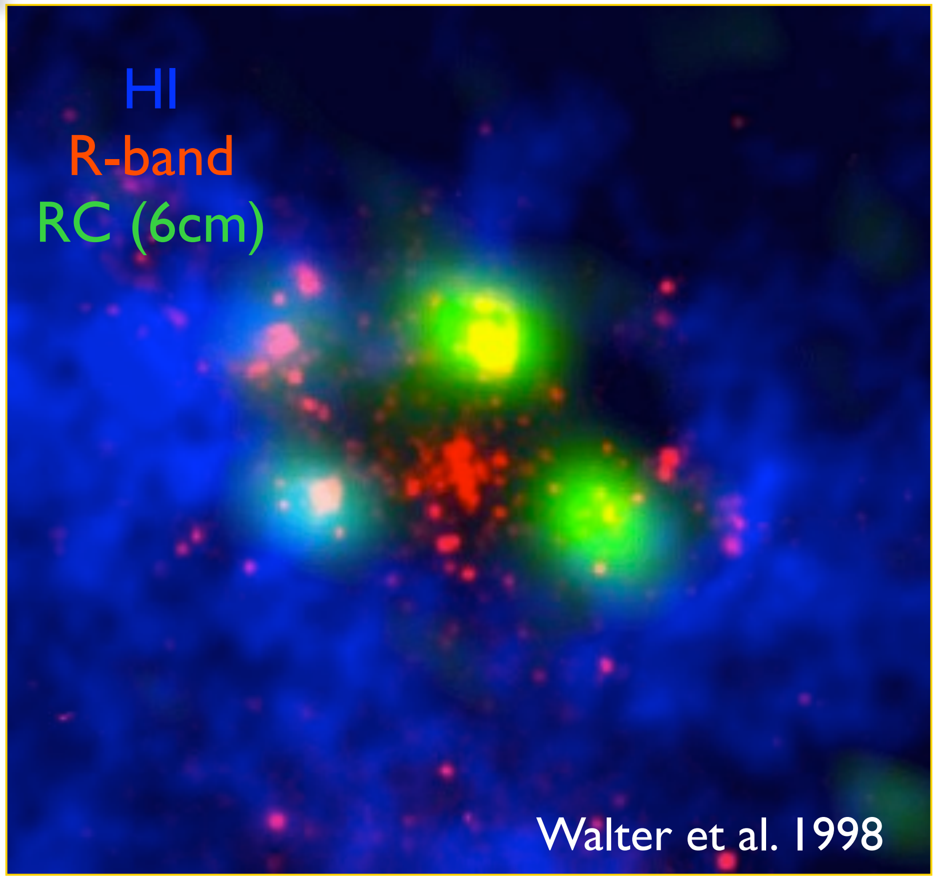
Only a fraction of active galaxies have central bar



Small Scale: SF Triggered by Expanding SN Shell



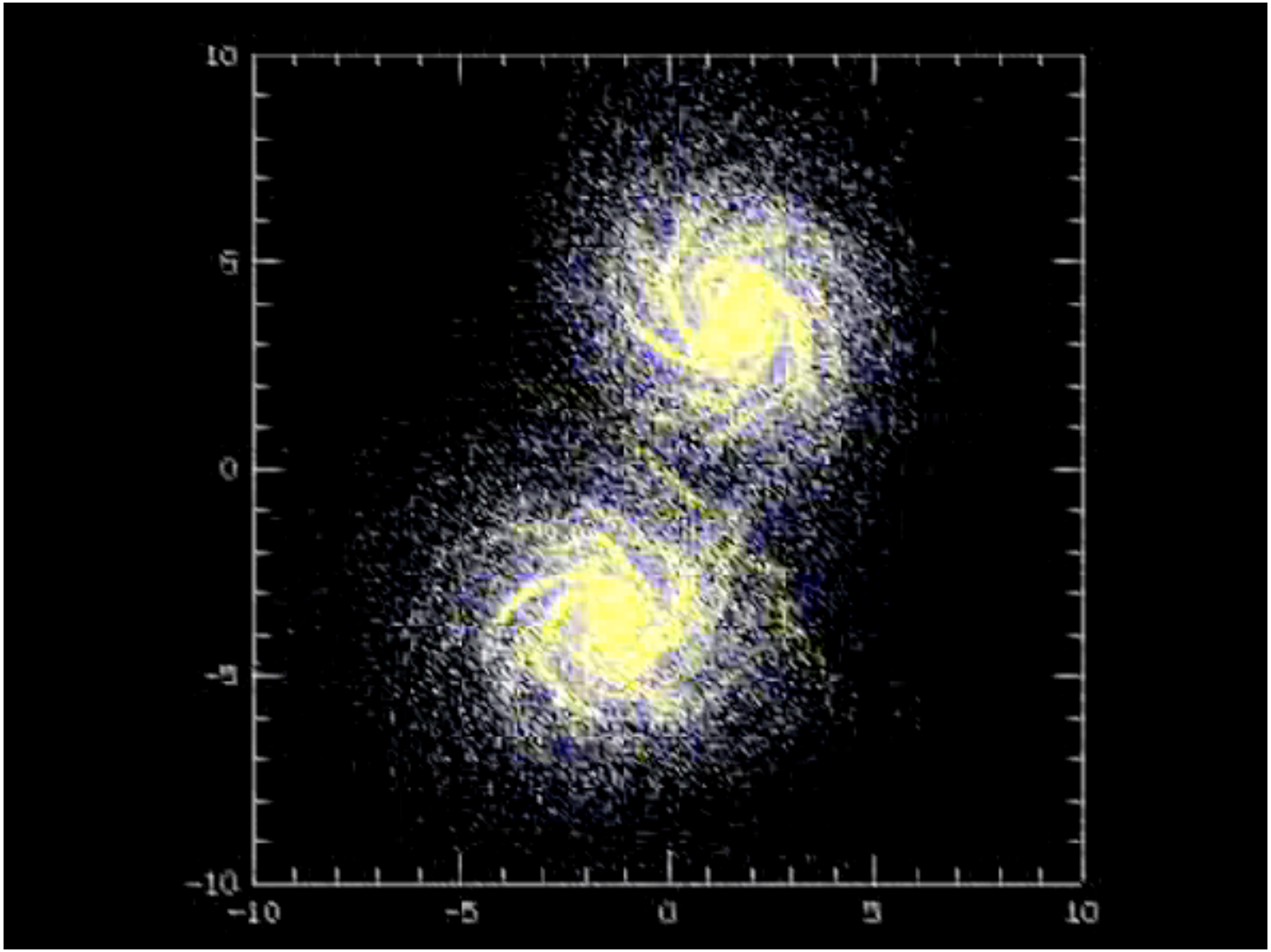




Example: IC 2574 (VLA HI)

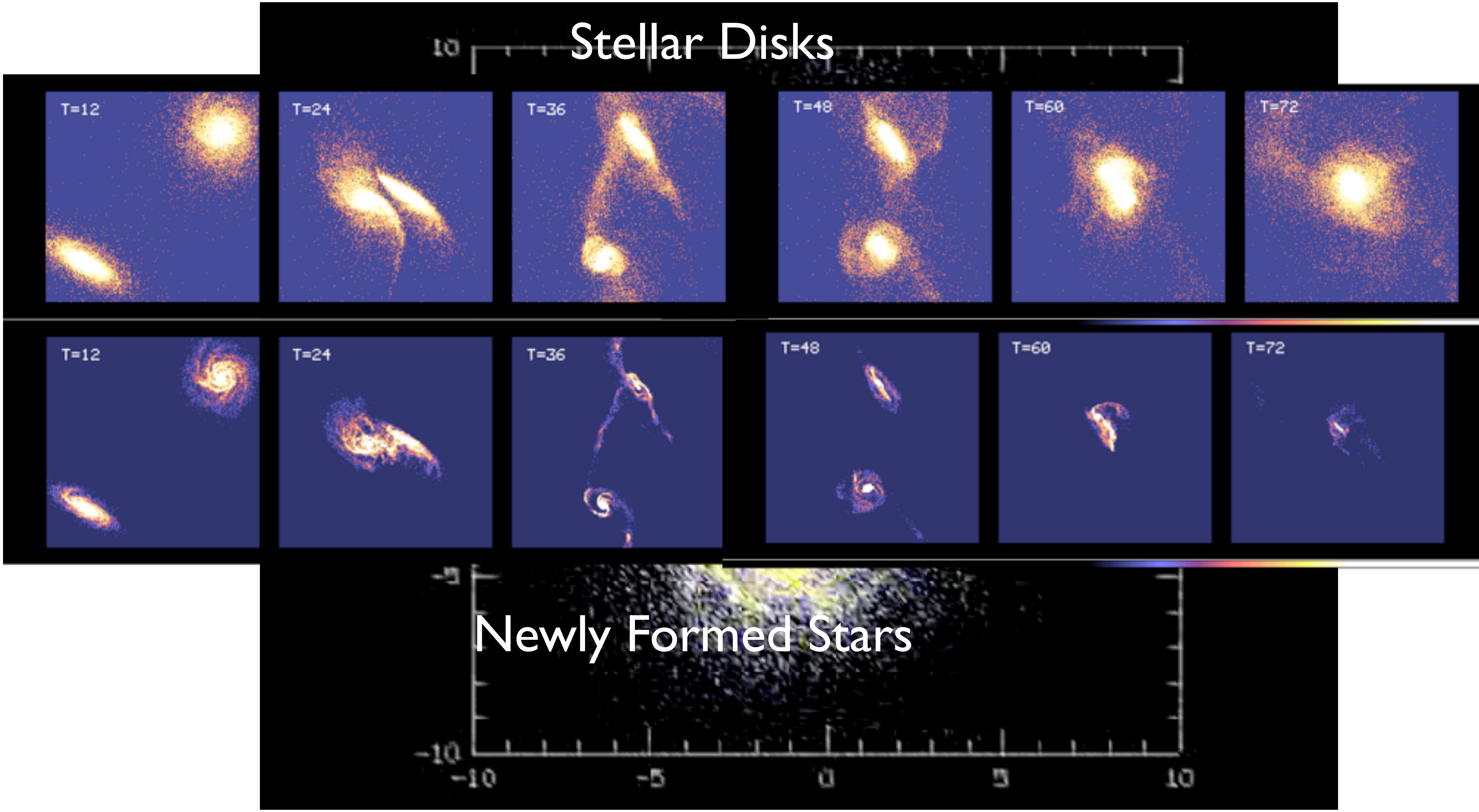
Large-Scale: SF Triggered by Mergers

Stars
Gas



Simulations by C. Mihos

Large-Scale: SF Triggered by Mergers



Simulations by C. Mihos

The Star Formation ‘Law’

connecting star formation to gas surface densities

this is a key ingredient to galaxy simulations

The ‘Star Formation Law’

$$\Sigma_{SFR} = A\ \Sigma_{gas}^{N}$$

(going back to Schmidt 1959)

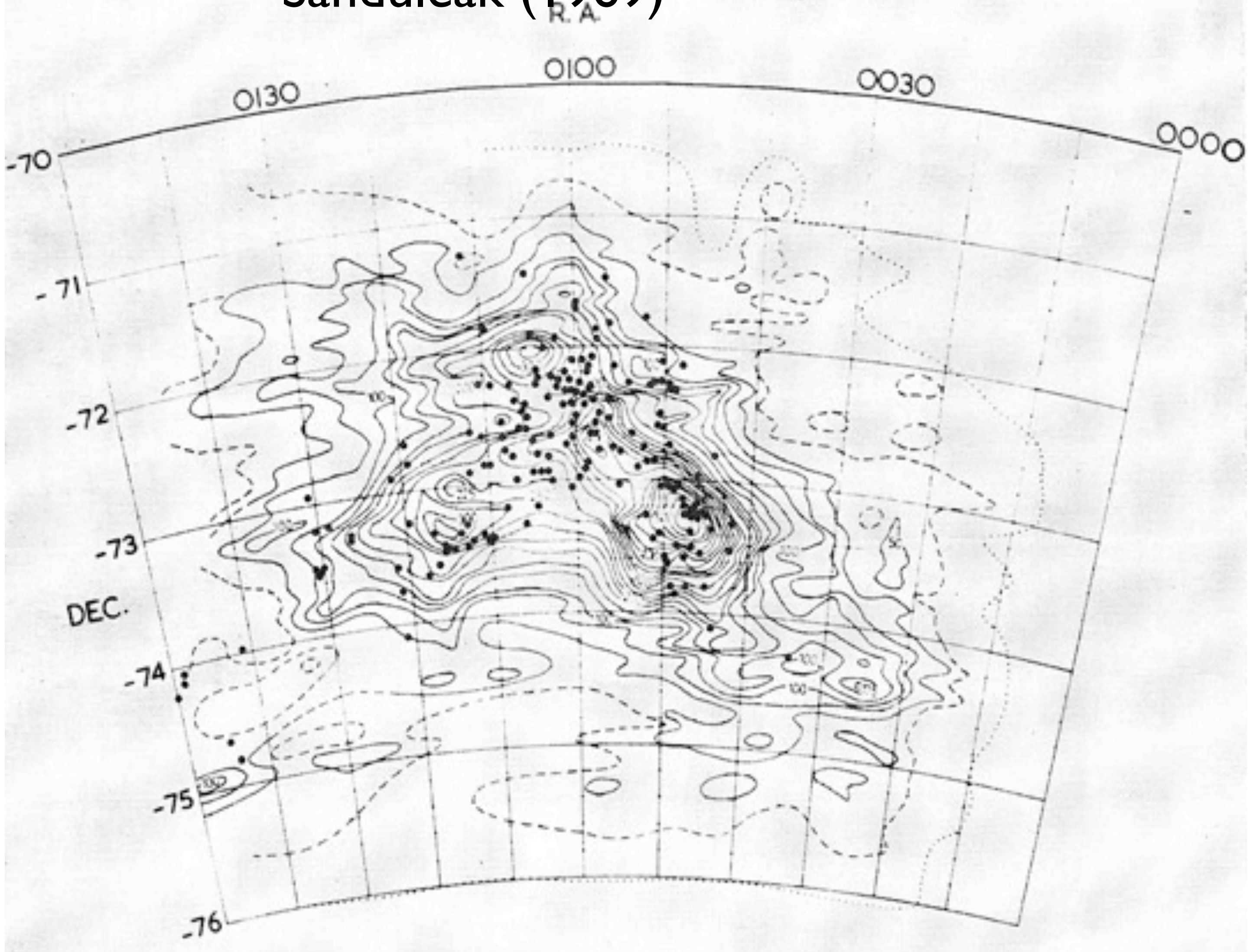
- physical insight into what drives SF
- SPH modeling of galaxy formation
- Predictive power: measure Σ_{gas} : estimate Σ_{SFR}

Historical Note:

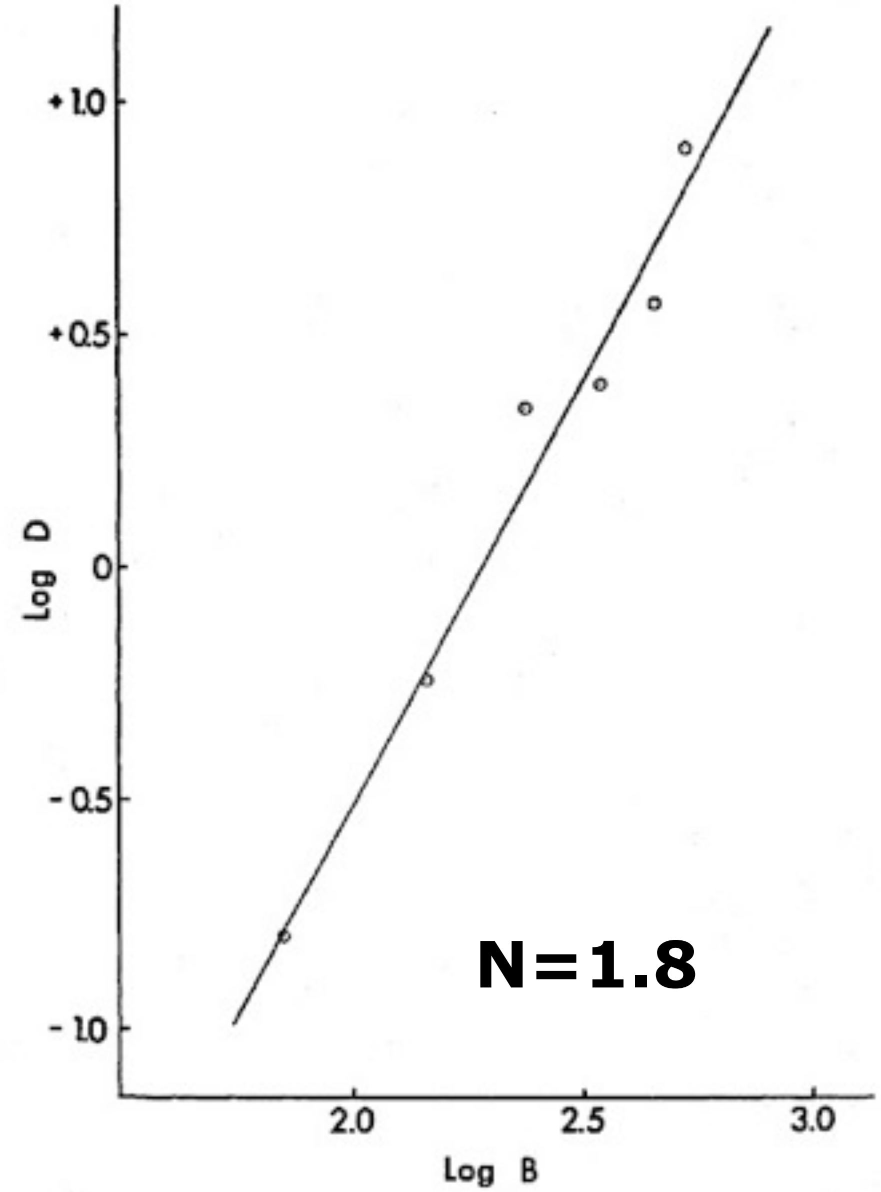
SMC: Neutral Hydrogen and

Individually Resolved OB Stars

Sanduleak (1969)



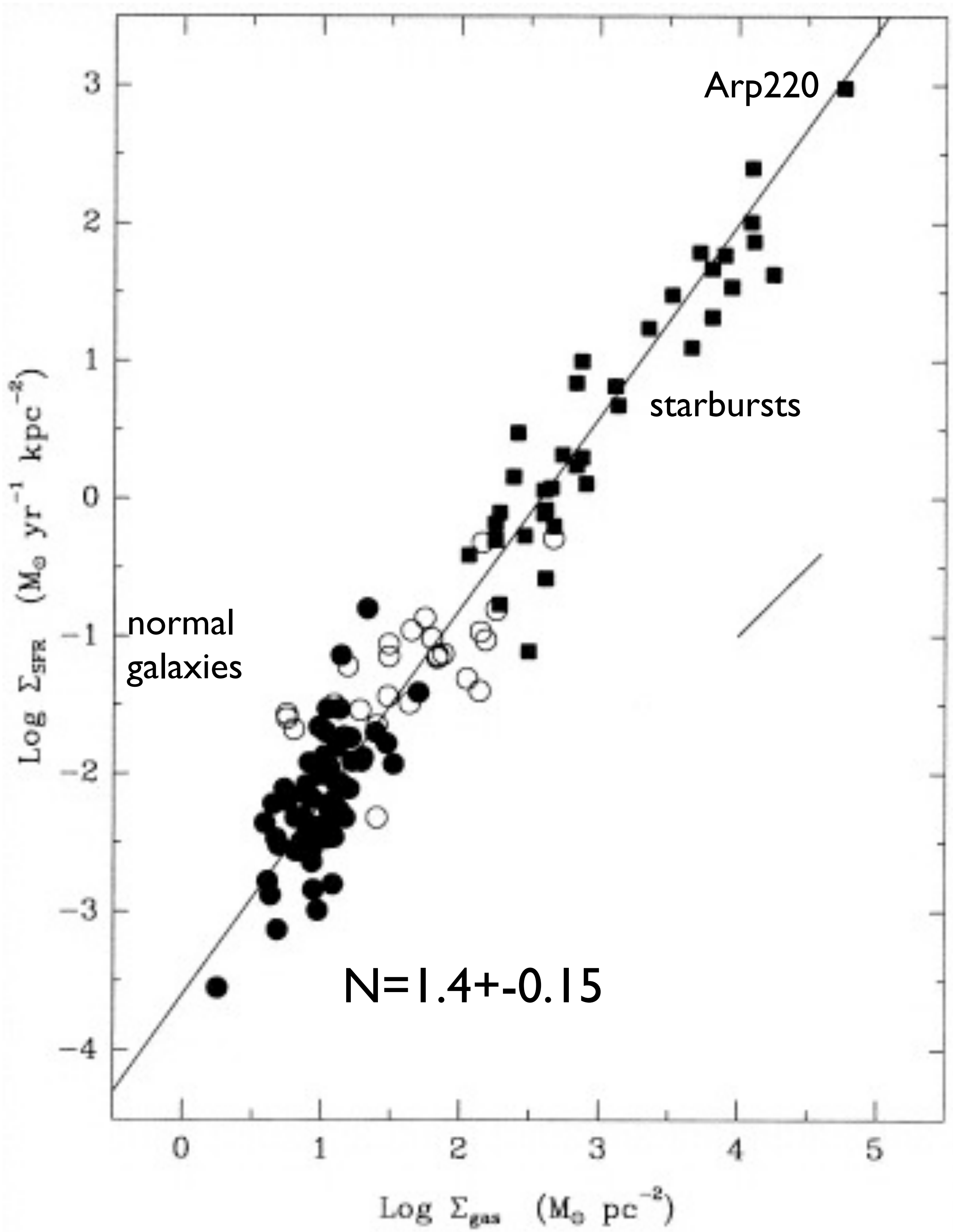
stellar surface density



N=1.8

HI brightness

The 'Star Formation Law'



star formation surface density

gas surface density

...also called 'Schmidt Law', 'Schmidt-Kennicutt Law'

Y-axis:
Hα + 1.1 mag ext.corr

X-axis:
CO:FCRAO (const. X_{CO})
+HI from literature

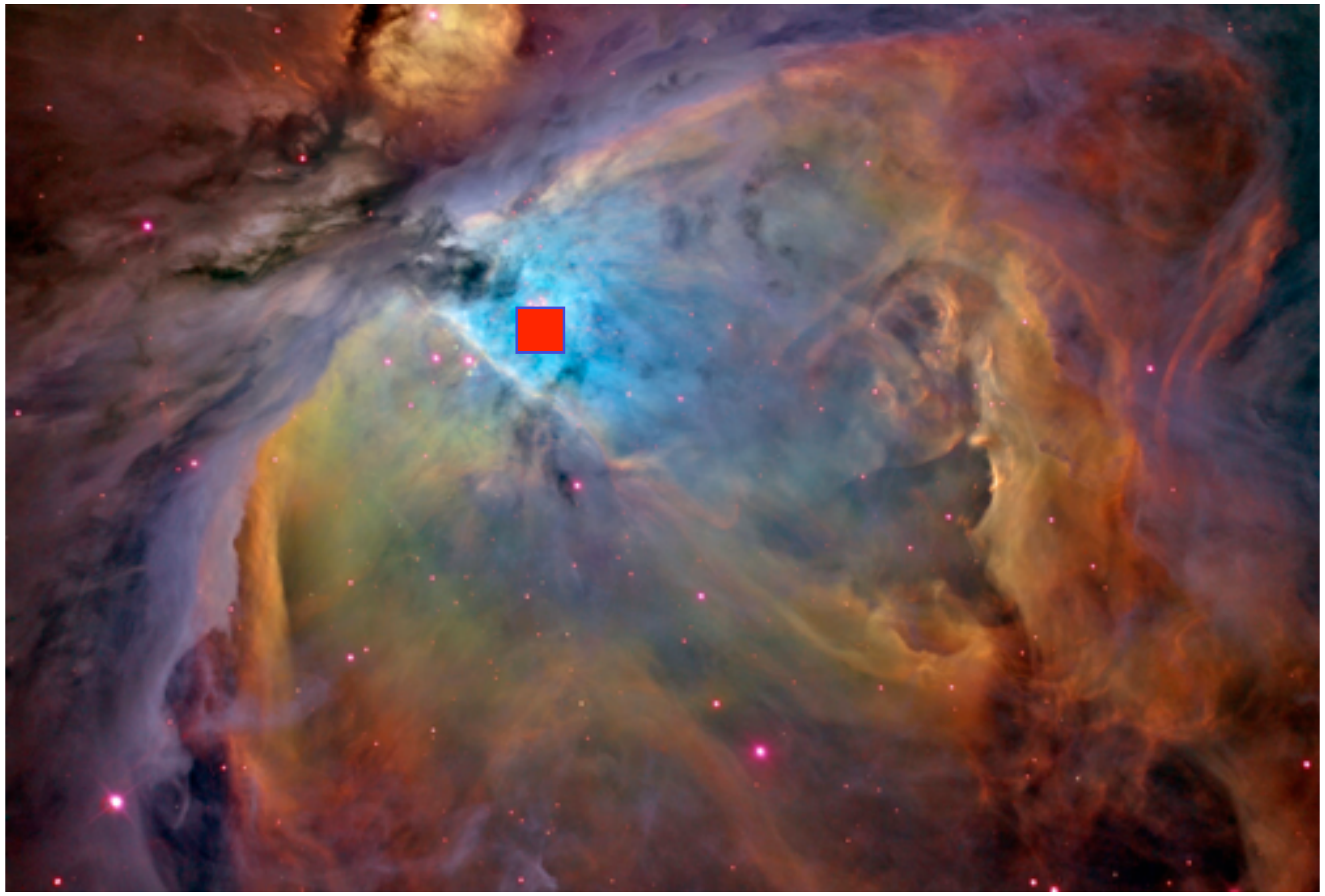
both: divided by RC2 area

i.e., galactic average

Kennicutt (1998)

quick poll!

$SFRSD=1000\ M_{sun}\ yr^{-1}\ kpc^{-2}$!!??



Comparison to star formation rate surface density in Orion?!

$SFRSD_{Arp220}=1000\ M_{sun}\ yr^{-1}\ kpc^{-2}$

A) $SFRSD_{Orion} = 10^{-6} \times SFRSD_{Arp220}$
B) $= 10^{-3} \times SFRSD_{Arp220}$
C) $= 1 \times SFRSD_{Arp220}$

quick poll!

SFRSD=1000 M_{sun} yr^{-1} kpc^{-2} !!??

Comparison to star formation rate surface density in Orion??

$SFRSD_{Arp220}=1000\ M_{sun}\ yr^{-1}\ kpc^{-2}$

- ✖ A) $SFRSD_{Orion} = 10^{-6} \times SFRSD_{Arp220}$
- ✖ B) $= 10^{-3} \times SFRSD_{Arp220}$
- ✔ C) $= 1 \times SFRSD_{Arp220}$

quick poll!

SFRSD=1000 M_{sun} yr^{-1} kpc^{-2} !!??

Comparison to star formation rate surface density in Orion??

$SFRSD_{Arp220}$=1000 M_{sun} yr^{-1} kpc^{-2}

- ✖ A) $SFRSD_{Orion}$ = 10^{-6} x $SFRSD_{Arp220}$
- ✖ B) = 10^{-3} x $SFRSD_{Arp220}$
- ✔ C) = 1 x $SFRSD_{Arp220}$

The Astrophysical Journal, 630:167–185, 2005 September 1

RADIATION PRESSURE–SUPPORTED STARBURST DISKS AND ACTIVE GALACTIC NUCLEUS FUELING

Todd A. Thompson,[1,2] Eliot Quataert,[2] and Norman Murray[3,4,5]
Received 2005 March 1; accepted 2005 May 14

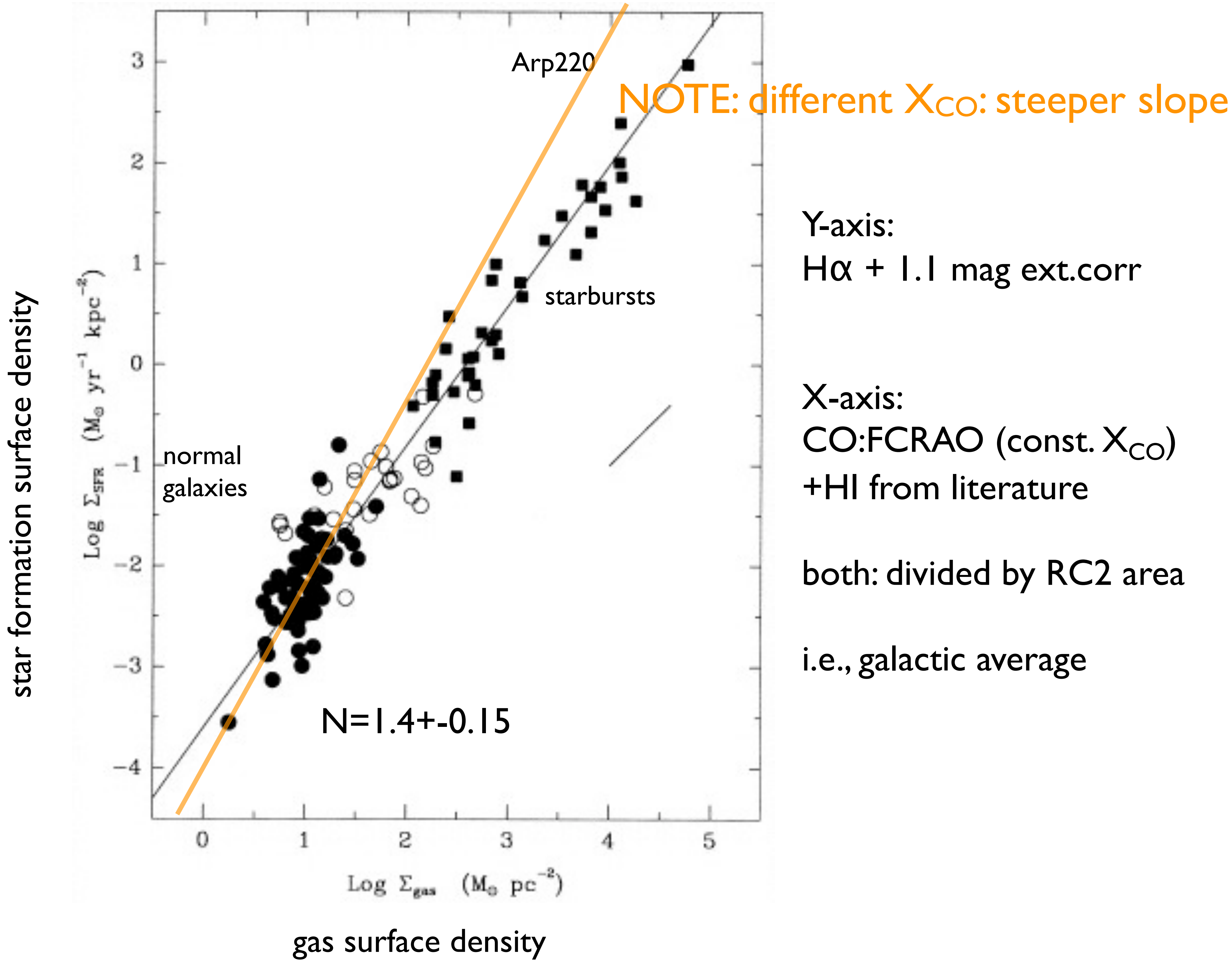
ABSTRACT

We consider the structure of marginally Toomre-stable starburst disks under the assumption that radiation pressure on dust grains provides the dominant vertical support against gravity. This assumption is particularly appropriate when the disk is optically thick to its own infrared radiation, as in the central regions of ULIRGs. We argue that because the disk radiates at its Eddington limit (for dust), the "Schmidt law" for star formation changes in the optically thick limit, with the star formation rate per unit area scaling as $\dot{\Sigma}_\star \propto \Sigma_g/\kappa$, where Σ_g is the gas surface density and κ is the mean opacity of the disk. Our calculations further show that optically thick starburst disks have a characteristic flux, star formation rate per unit area, and dust effective temperature of $F \sim 10^{13}\ L_\odot\ kpc^{-2}$, $\dot{\Sigma}_\star \sim 10^3\ M_\odot\ yr^{-1}\ kpc^{-2}$, and $T_{eff} \sim 90$ K, respectively. We compare our model predictions with observations of ULIRGs and find good agreement. We extend our model of starburst disks from many hundred parsec scales to subparsec

density and κ is the mean opacity of the disk. Our calculations further show that optically thick starburst disks have a characteristic flux, star formation rate per unit area, and dust effective temperature of $F \sim 10^{13}\ L_\odot\ kpc^{-2}$, $\dot{\Sigma}_\star \sim 10^3\ M_\odot\ yr^{-1}\ kpc^{-2}$, and $T_{eff} \sim 90$ K, respectively. We compare our model predictions with observations of ULIRGs

the starburst disk on parsec scales can approach ..., perhaps accounting for the nuclear obscuration in some type 2 AGNs. We also argue that the disk of young stars in the Galactic center may be the remnant of such a compact nuclear starburst.

The ‘Star Formation Law’



Y-axis:
Hα + 1.1 mag ext.corr

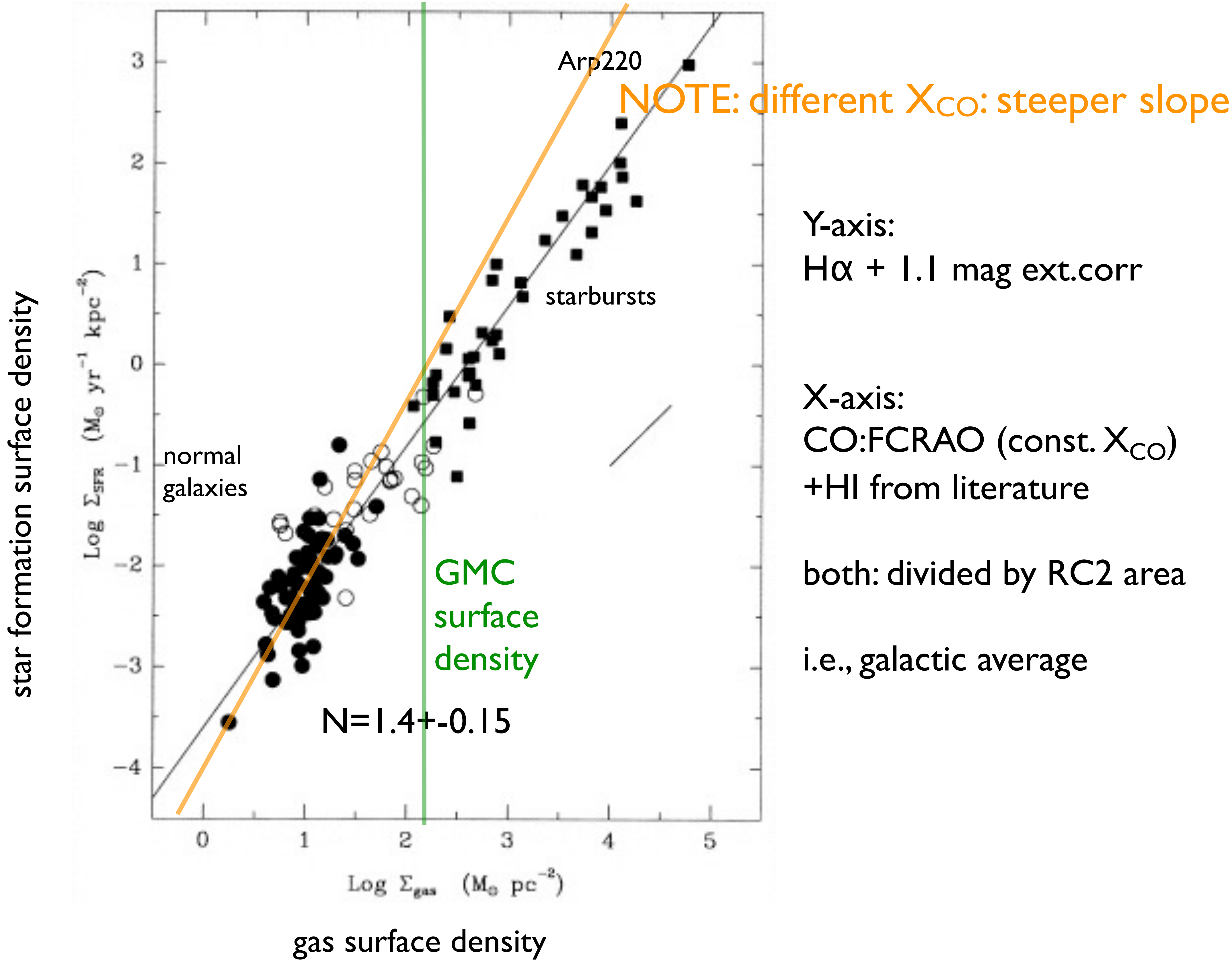
X-axis:
CO:FCRAO (const. X_{CO})
+HI from literature

both: divided by RC2 area

i.e., galactic average

Kennicutt (1998)

The ‘Star Formation Law’



Y-axis:
Hα + 1.1 mag ext.corr

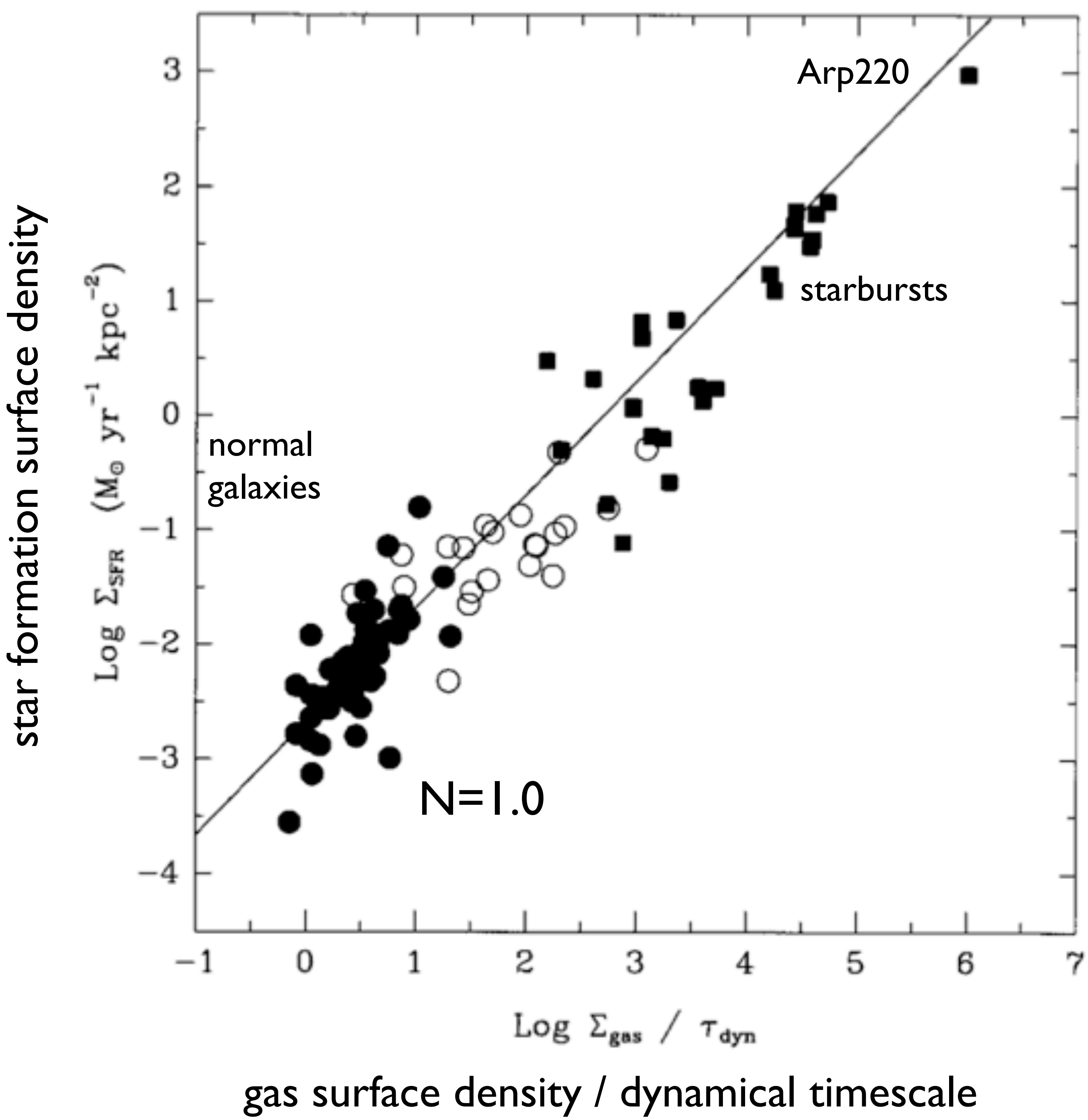
X-axis:
CO:FCRAO (const. X_{CO})
+HI from literature

both: divided by RC2 area

i.e., galactic average

Kennicutt (1998)

Dividing gas density by dynamical timescale



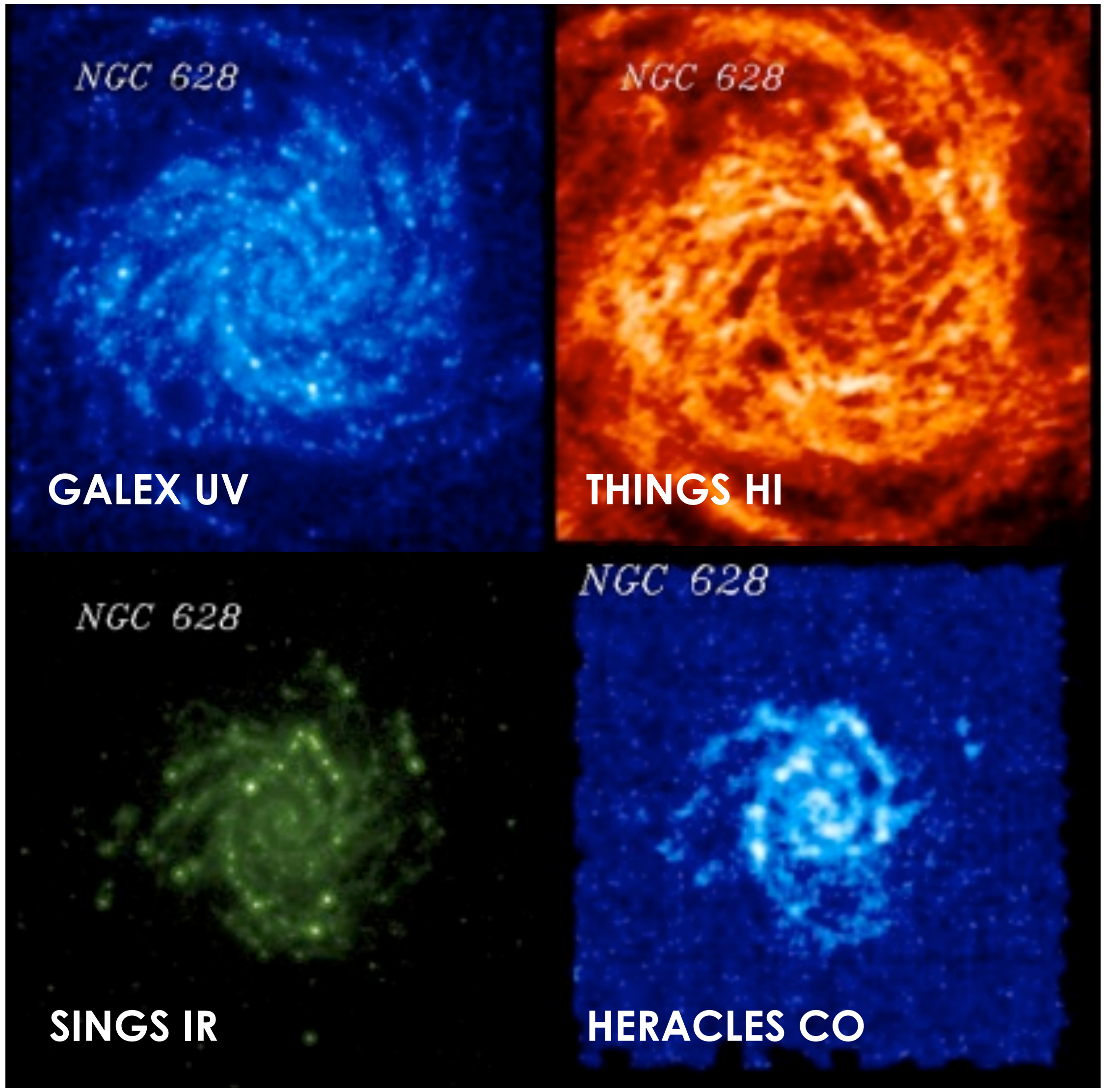
Y-axis:
same as before

X-axis:
same as before / orbital time

(e.g., SF triggered by
spiral arm/bar passage)

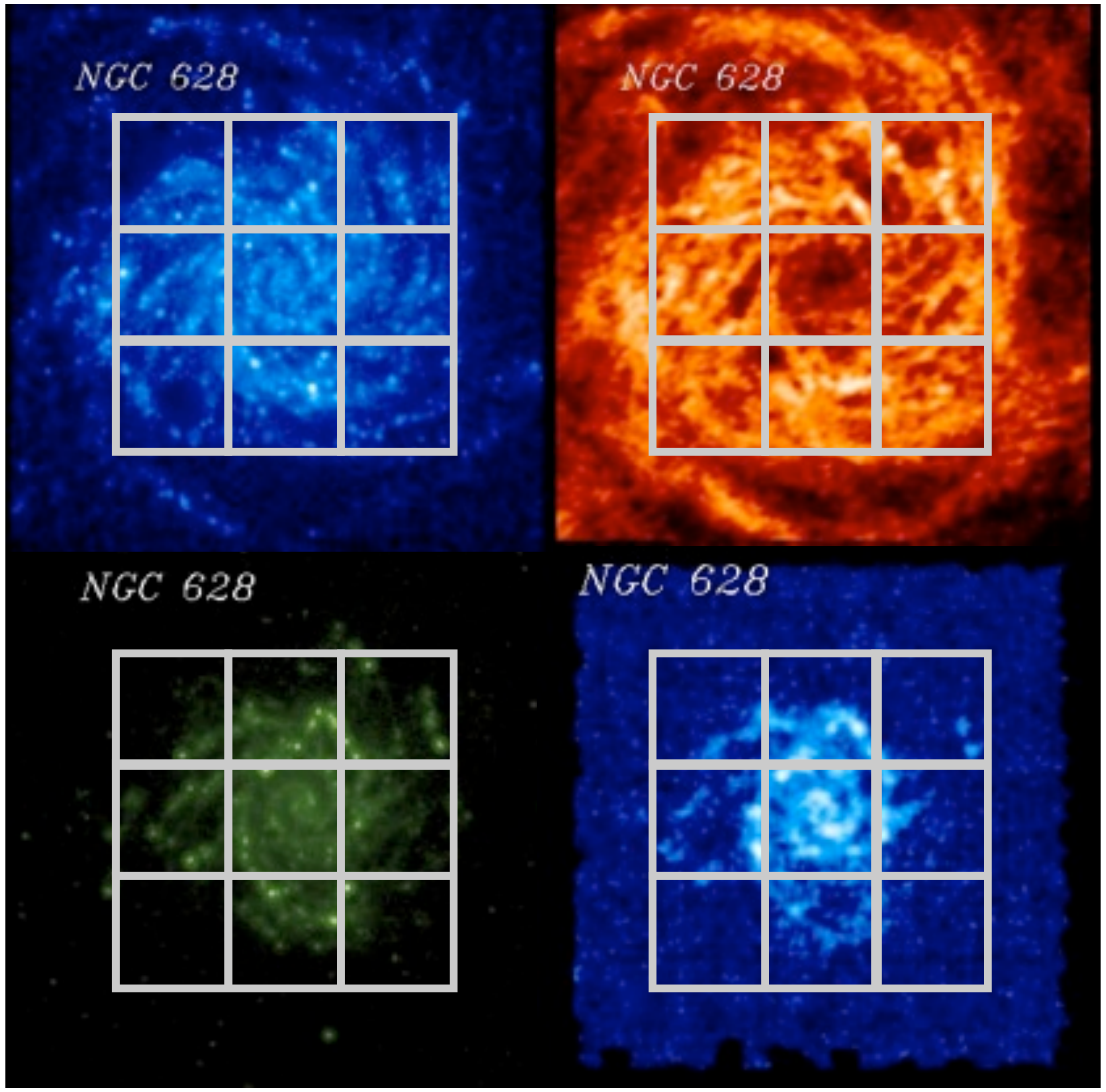
Kennicutt (1998)

So far: integrated SF / gas measurements



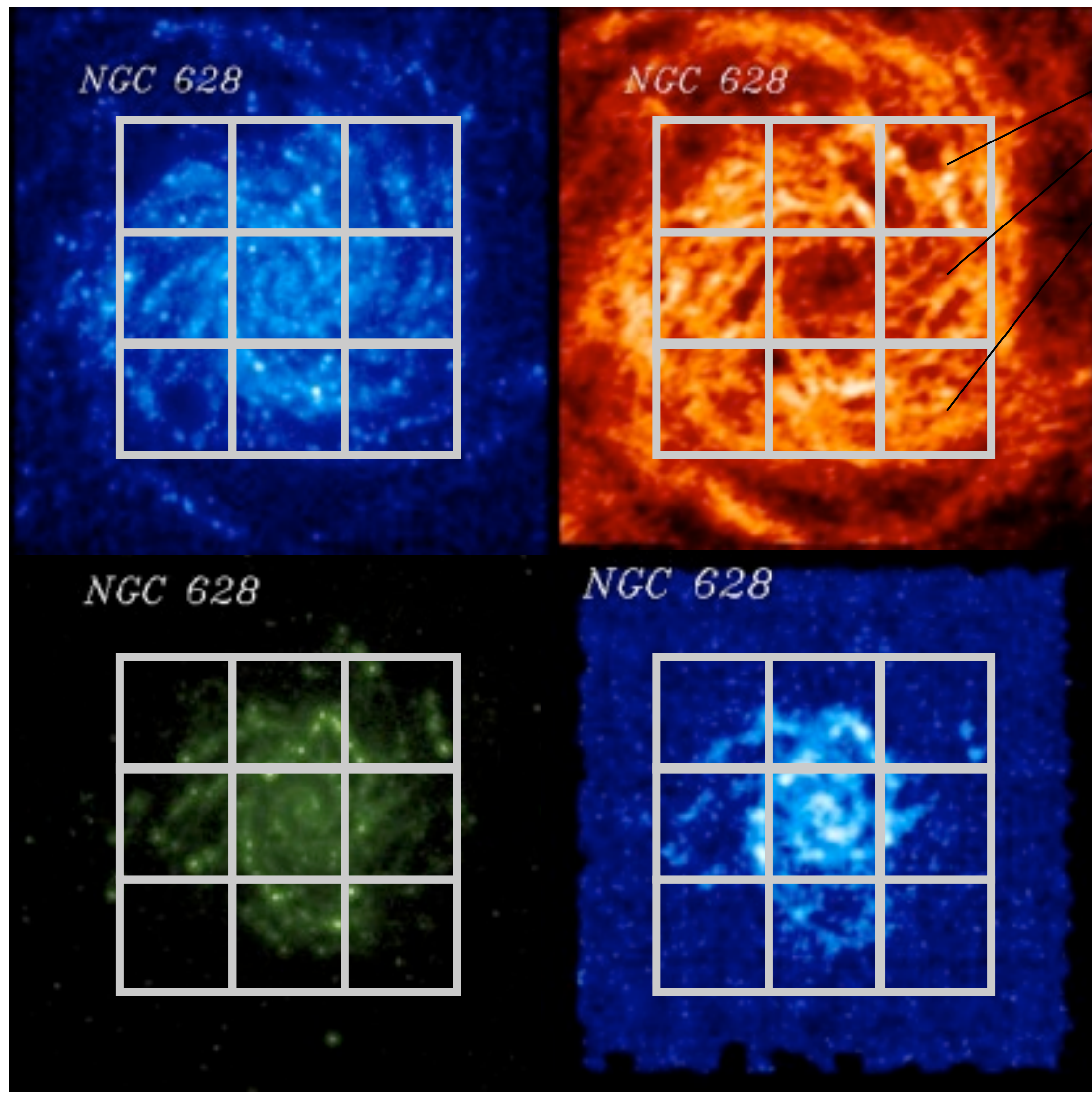
So far: integrated SF / gas measurements

With state-of-the-art data this can also be done pixel-by-pixel



So far: integrated SF / gas measurements

Extract physical information for each element…



Local…

HI Surface Density

H_2 Surface Density

Stellar Surface Density

Star Formation Rate

Rotation Velocity

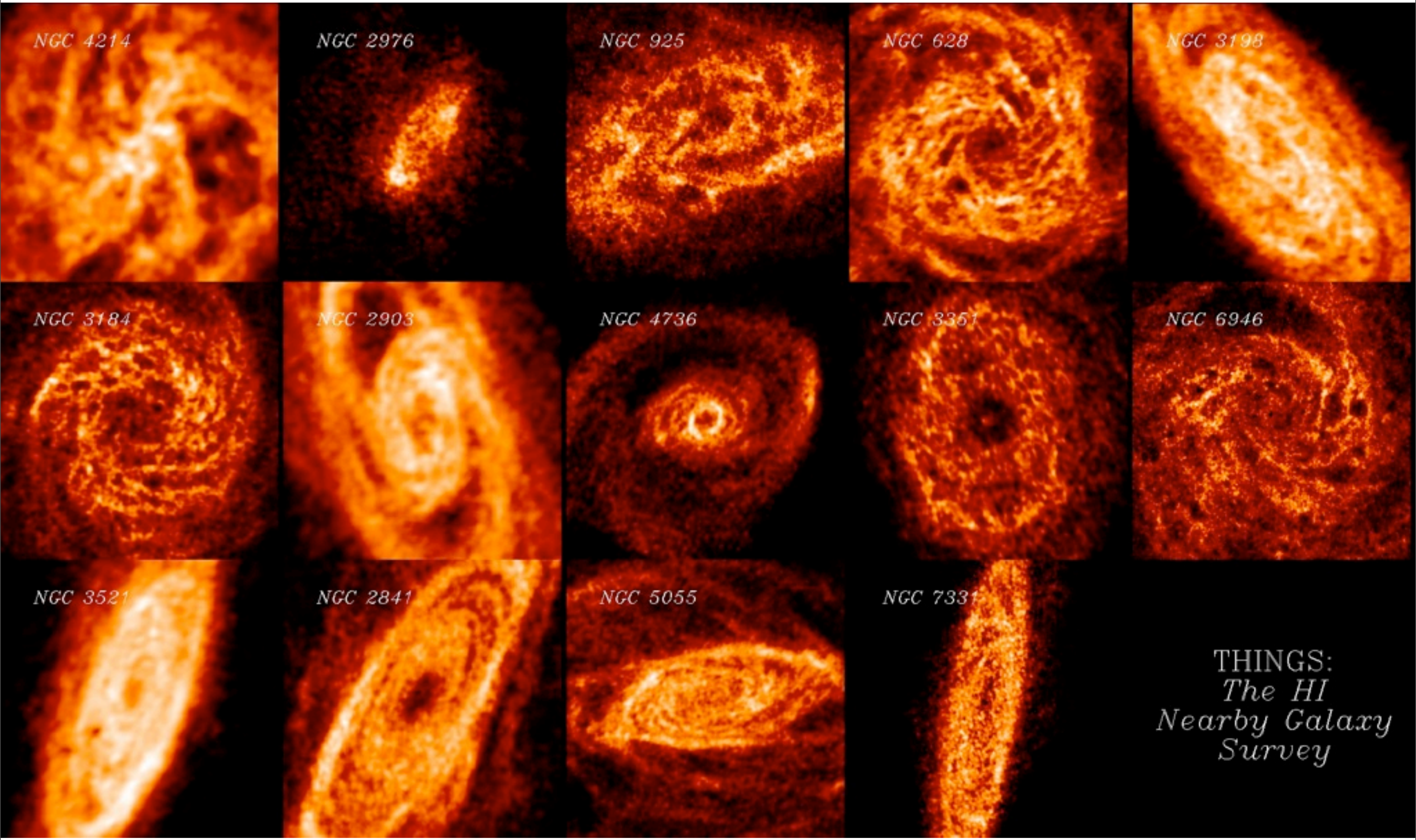
Gas Velocity Dispersion

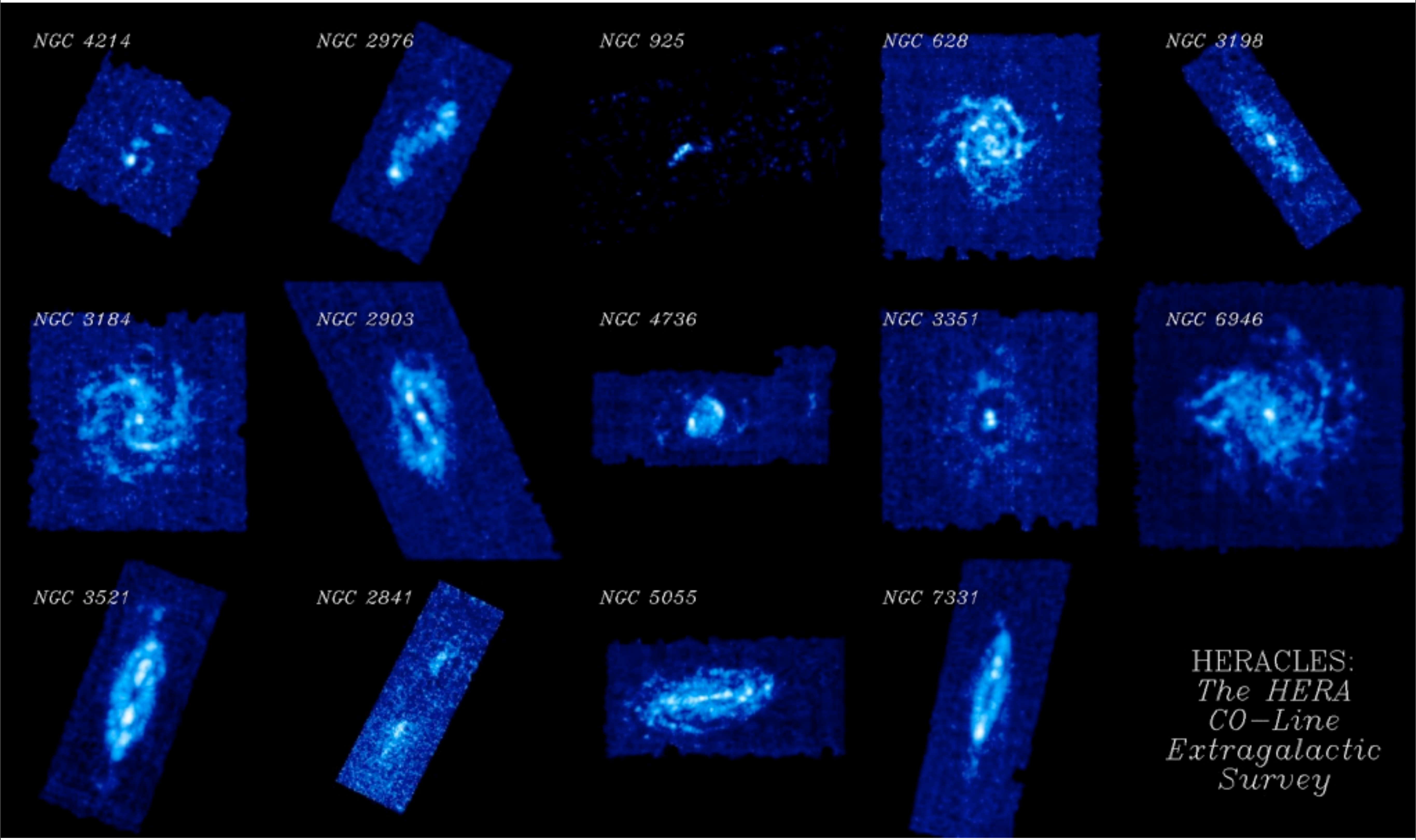
Stellar Velocity Dispersion

Dust-to-Gas Ratio

Radiation Field

Midplane Pressure


NGC 4214
NGC 2976
NGC 925
NGC 628
NGC 3198
NGC 3184
NGC 2903
NGC 4736
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
THINGS:
The HI
Nearby Galaxy
Survey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NGC 925
NGC 628
NGC 3198
NGC 3184
NGC 2903
NGC 4736
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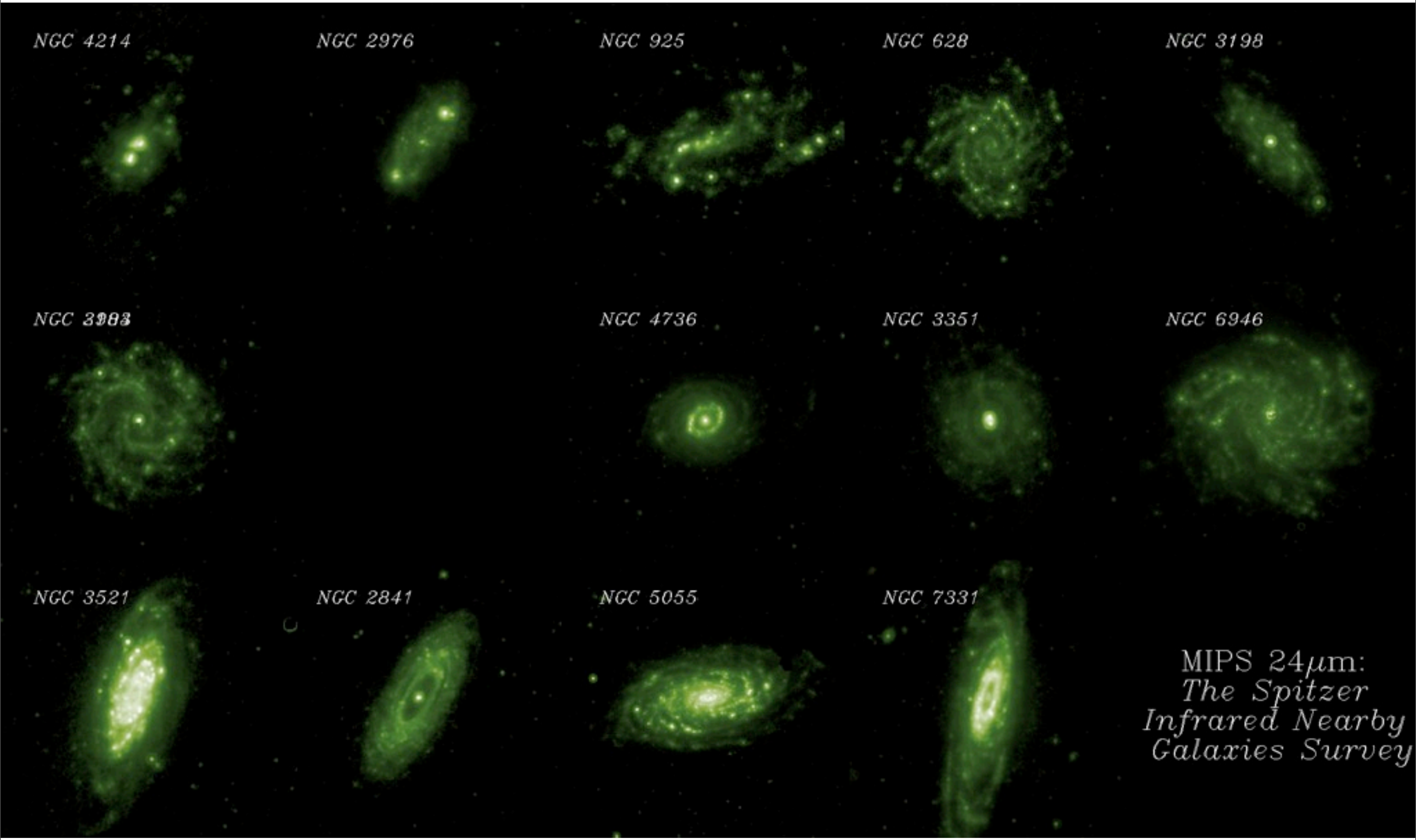
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
HERACLES:
The HERA
CO–Line
Extragalactic
Survey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NGC 2976
NGC 925
NGC 628
NGC 3198
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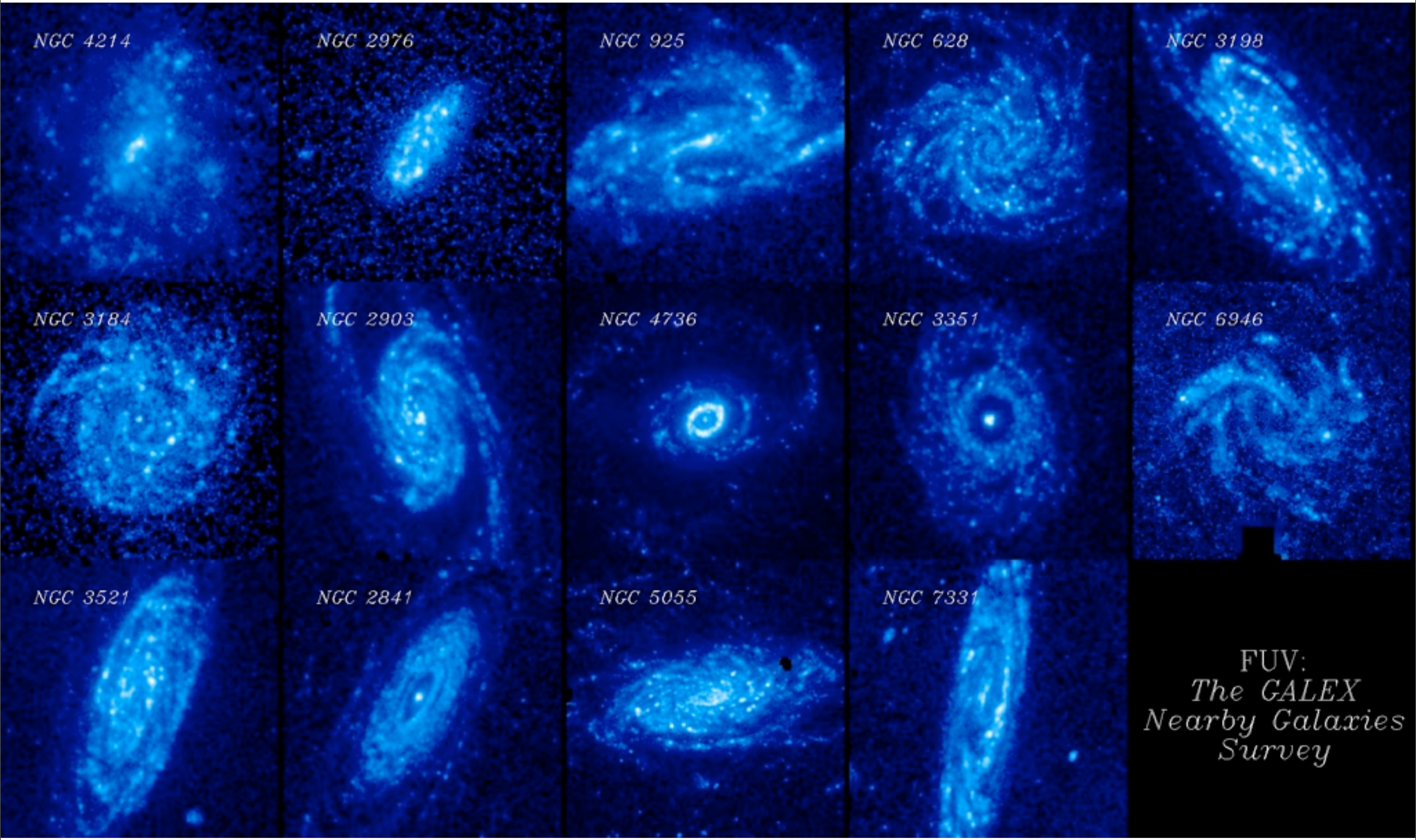
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
MIPS 24μm:
The Spitzer
Infrared Nearby
Galaxies Survey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NGC 925
NGC 628
NGC 3198
NGC 3184
NGC 2903
NGC 4736
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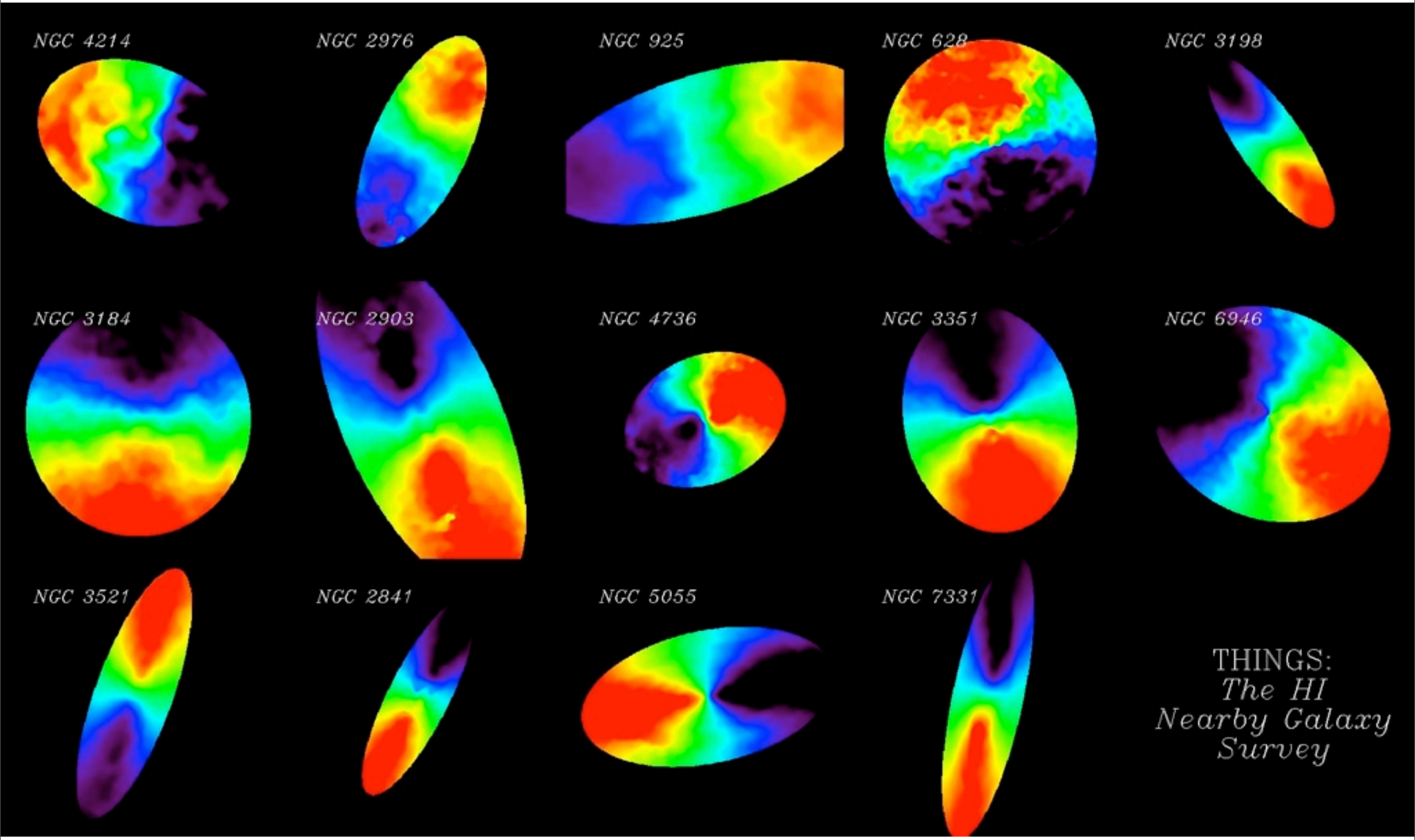
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
FUV:
The GALEX
Nearby Galaxies
Survey


NGC 4214
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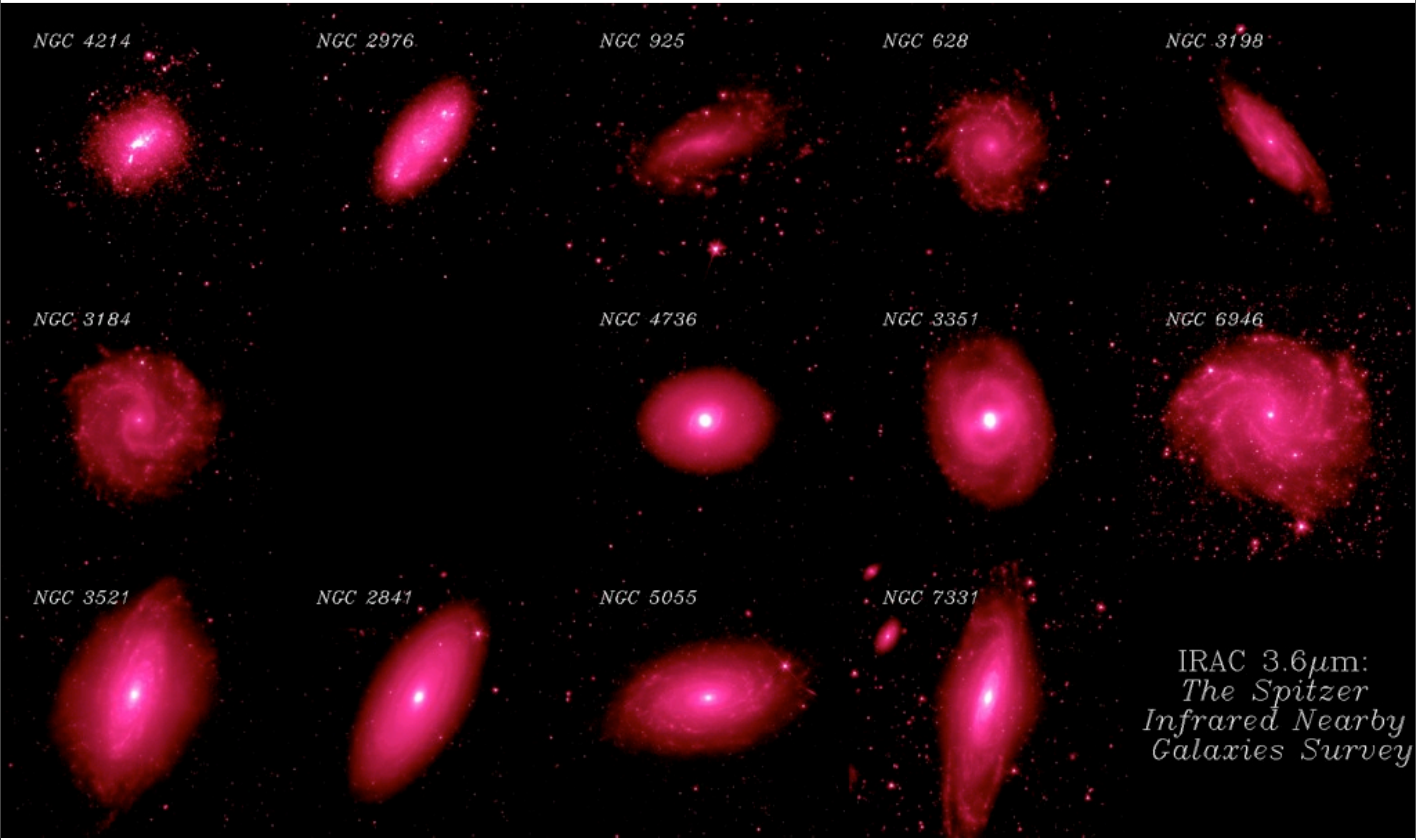
NGC 4736
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
THINGS:
The HI
Nearby Galaxy
Survey


NGC 4214
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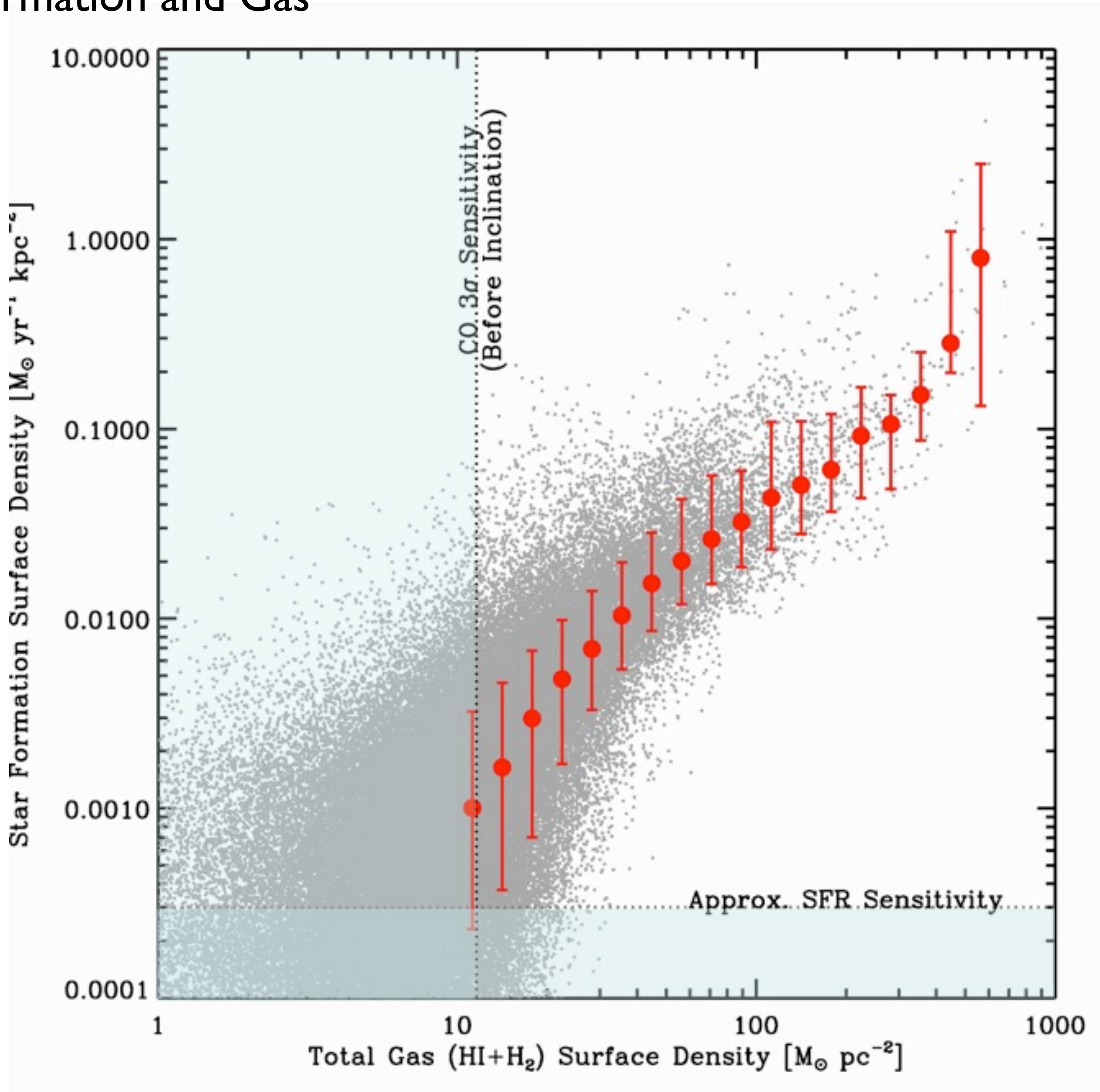
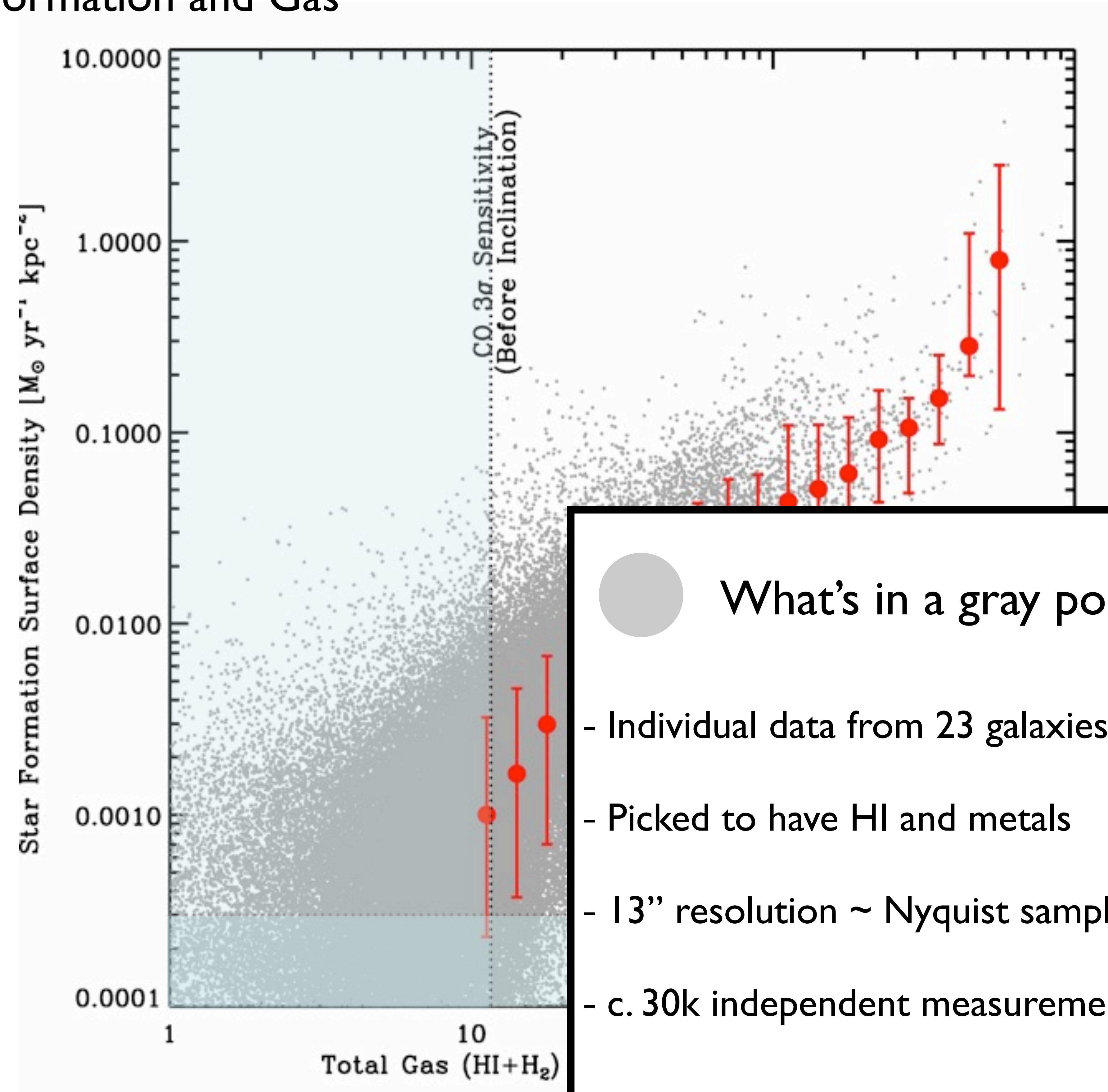
NGC 925
NGC 628
NGC 3198
NGC 3184
NGC 4736
NGC 3351
NGC 6946
NGC 3521
NGC 2841
NGC 5055
NGC 7331
IRAC 3.6μm:
The Spitzer
Infrared Nearby
Galaxies Survey

Star Formation and Gas



Bigiel et al. 2008/10, Leroy et al. 2008/11,

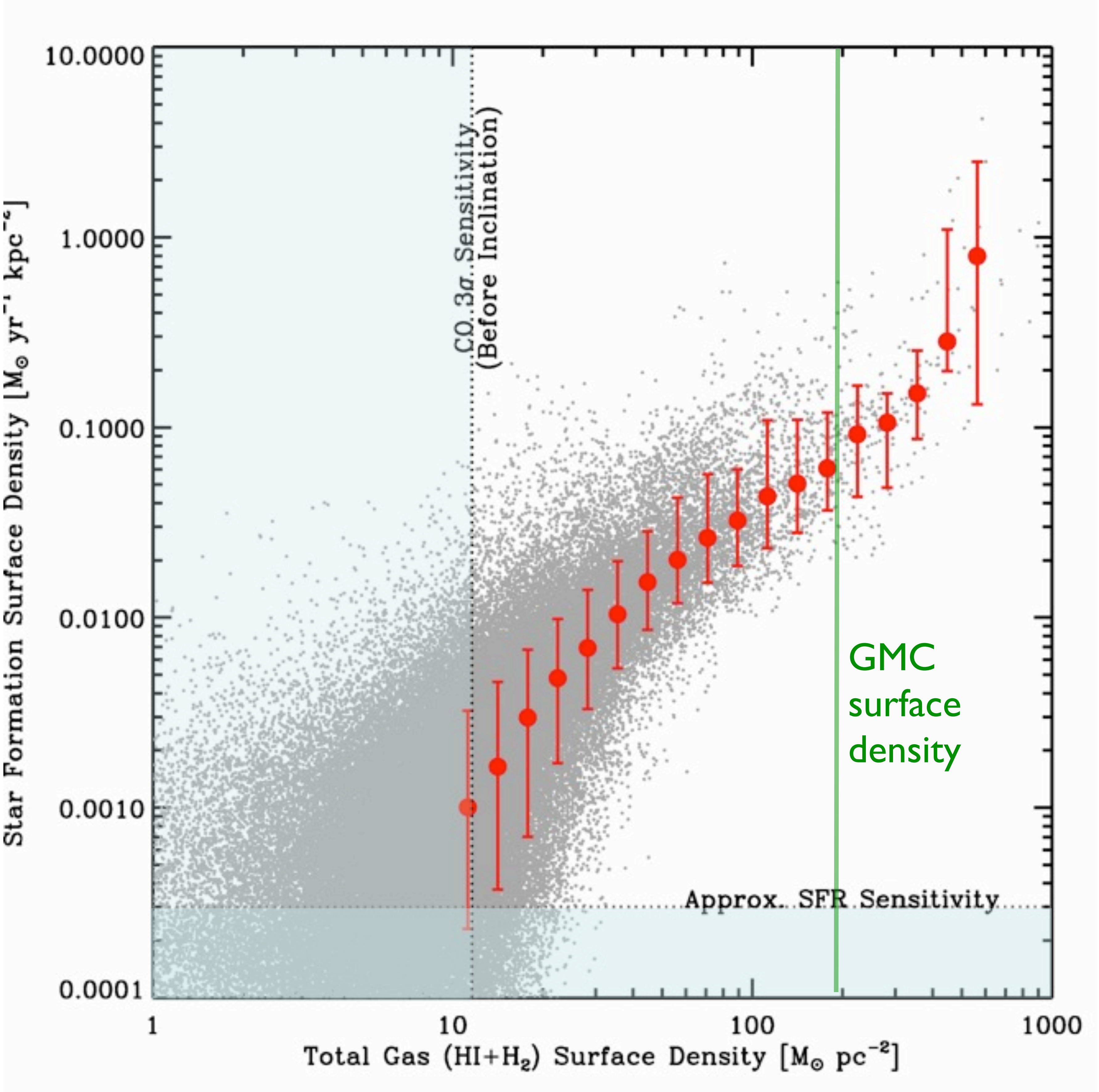
Star Formation and Gas



What's in a gray point?

- Individual data from 23 galaxies.
- Picked to have HI and metals
- 13" resolution ~ Nyquist sampled.
- c. 30k independent measurements.

Bigiel et al. 2008/10, Leroy et al. 2008/11,

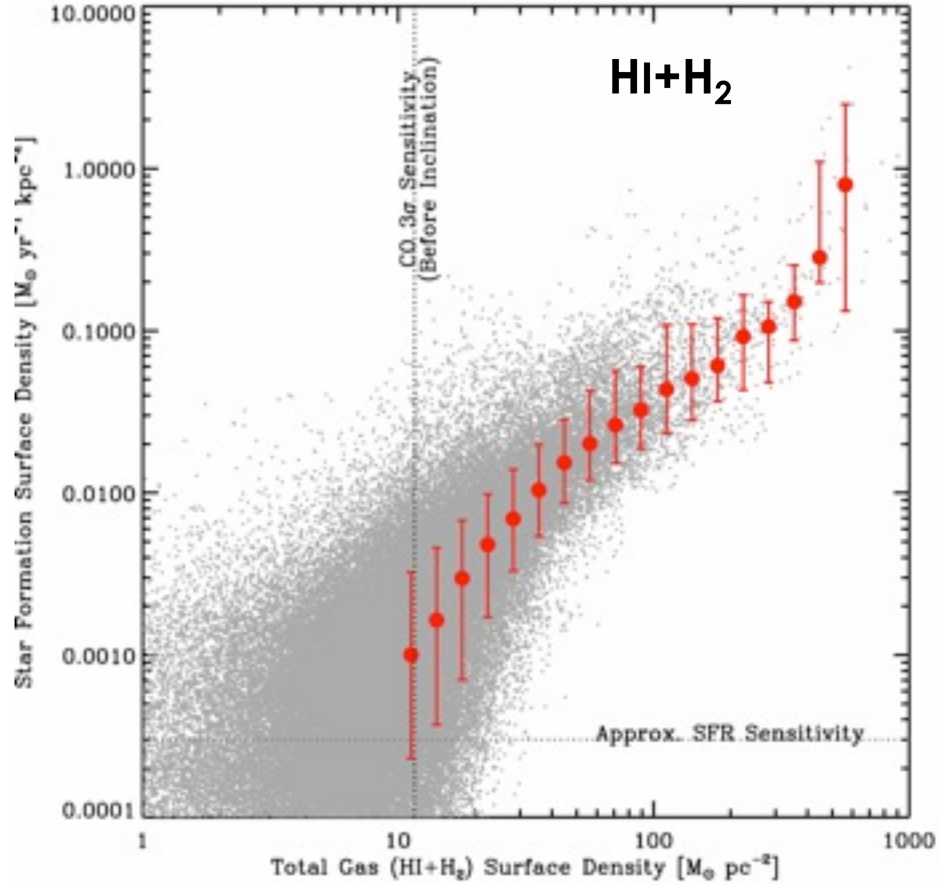


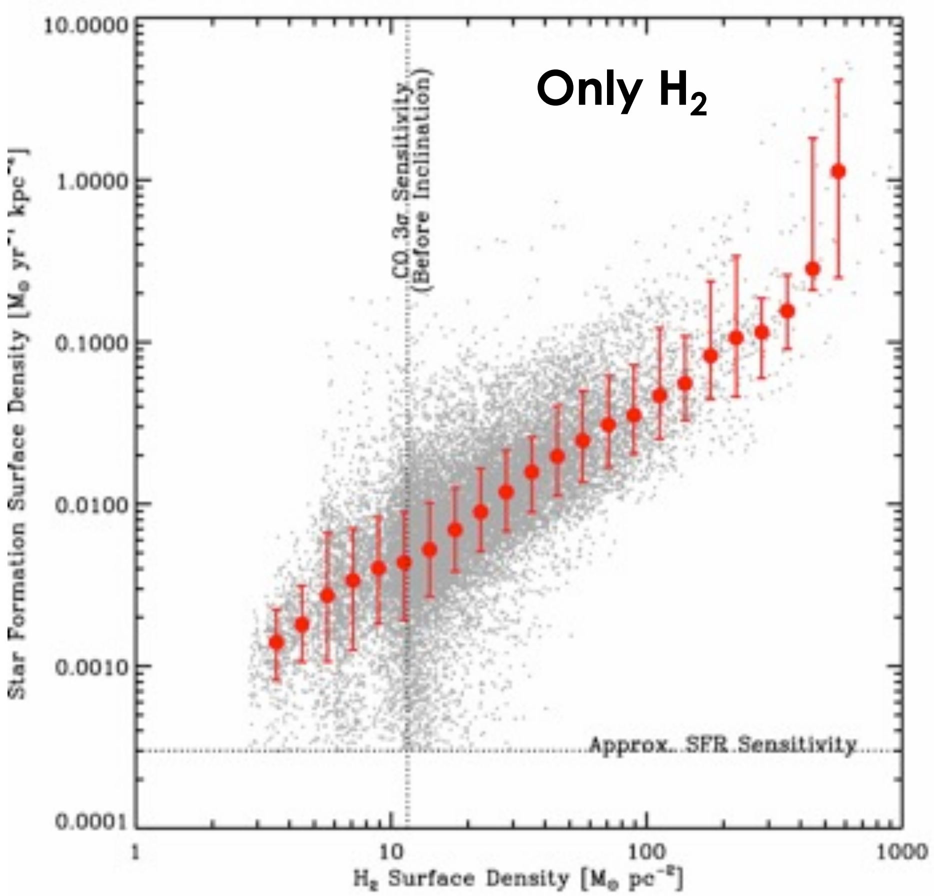
Bigiel et al. 2008/10, Leroy et al. 2008/11,

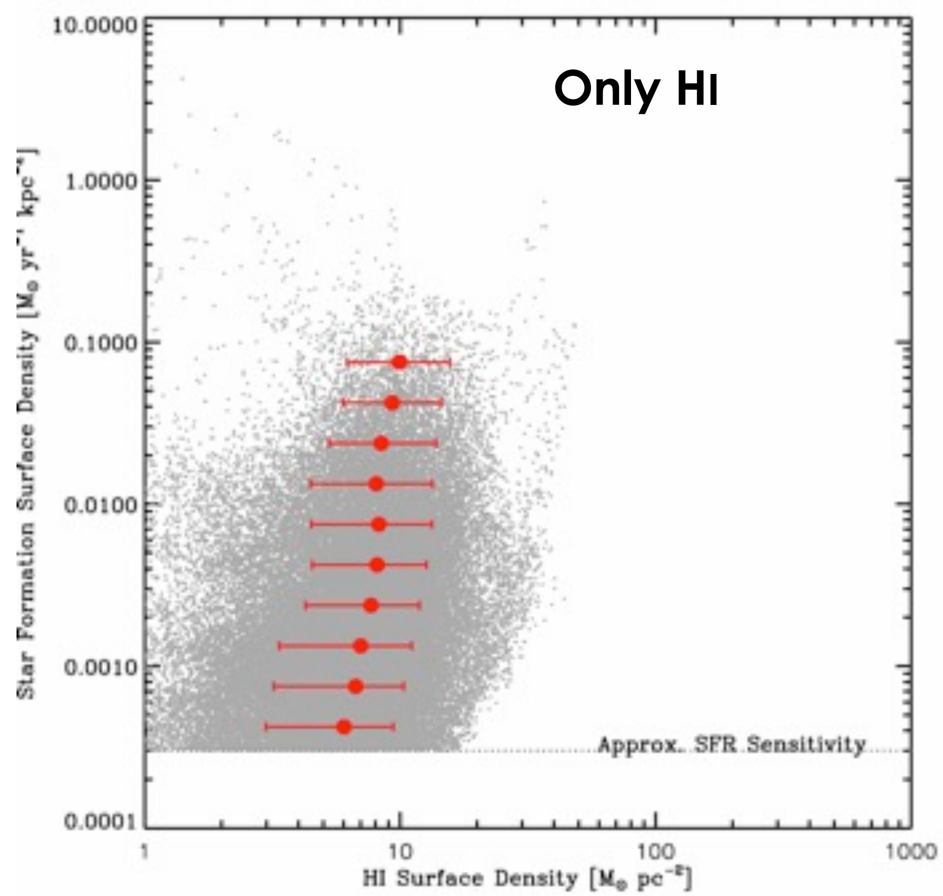
HI vs. H2

very significant difference

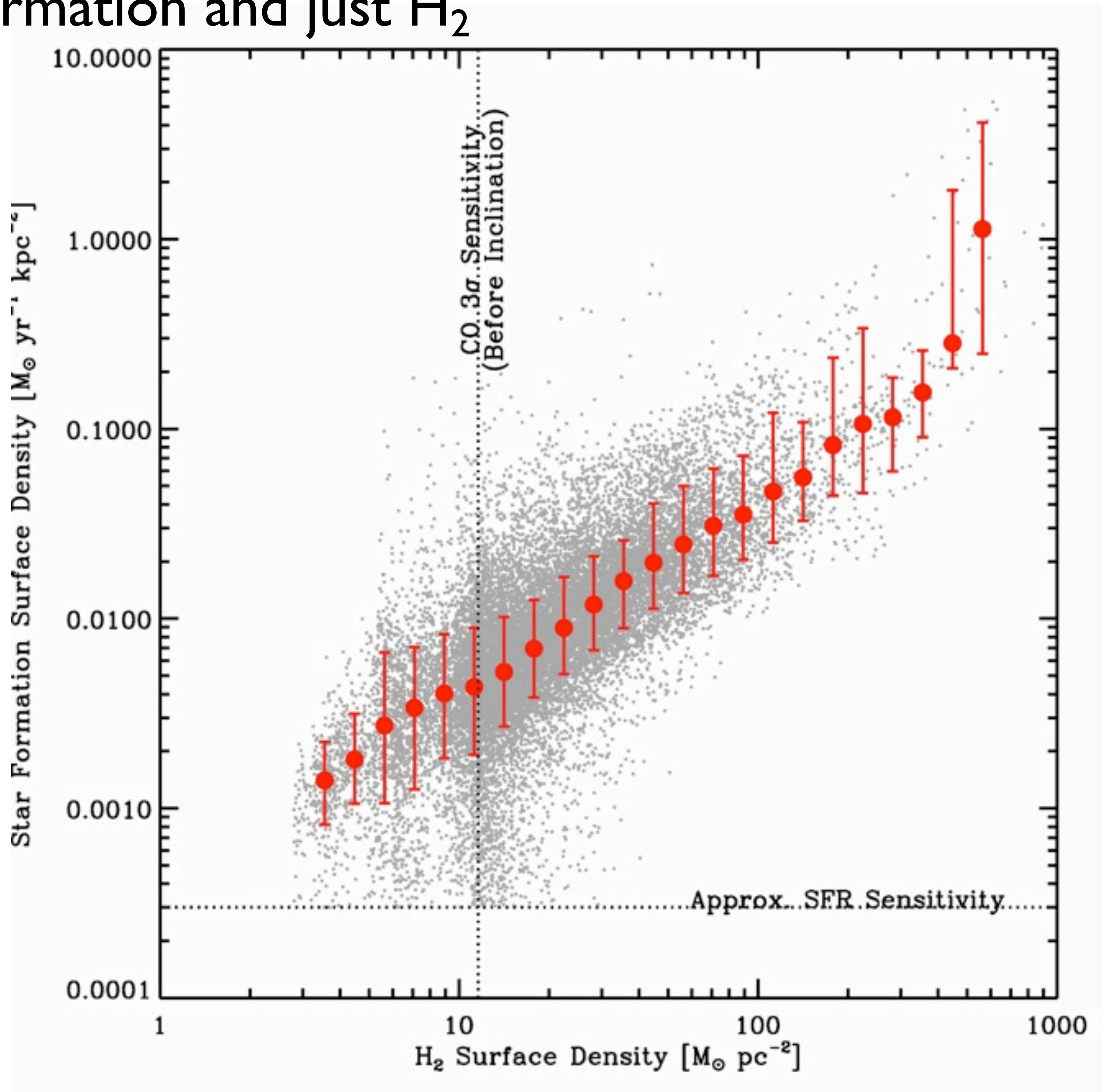
HI appears to be irrelevant for SF process







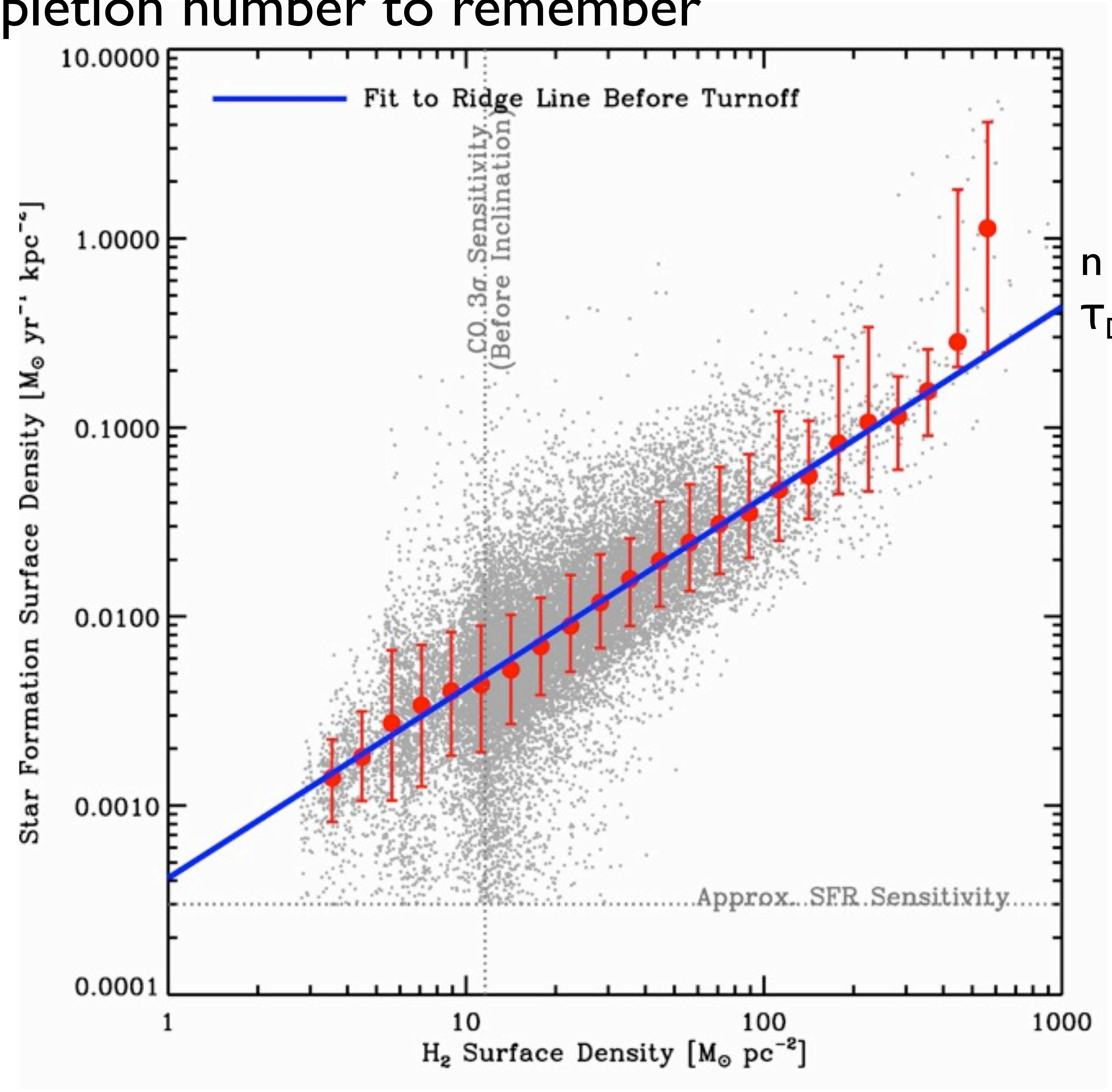
Star Formation and just H_2



Bigiel et al. 2008/10, Leroy et al. 2008/11,

Key depletion number to remember

Rownd & Young 99, Wong & Blitz '02, Murgia+ '02, Kennicutt+ '07, Bigiel+ '08



$n = 1.0$

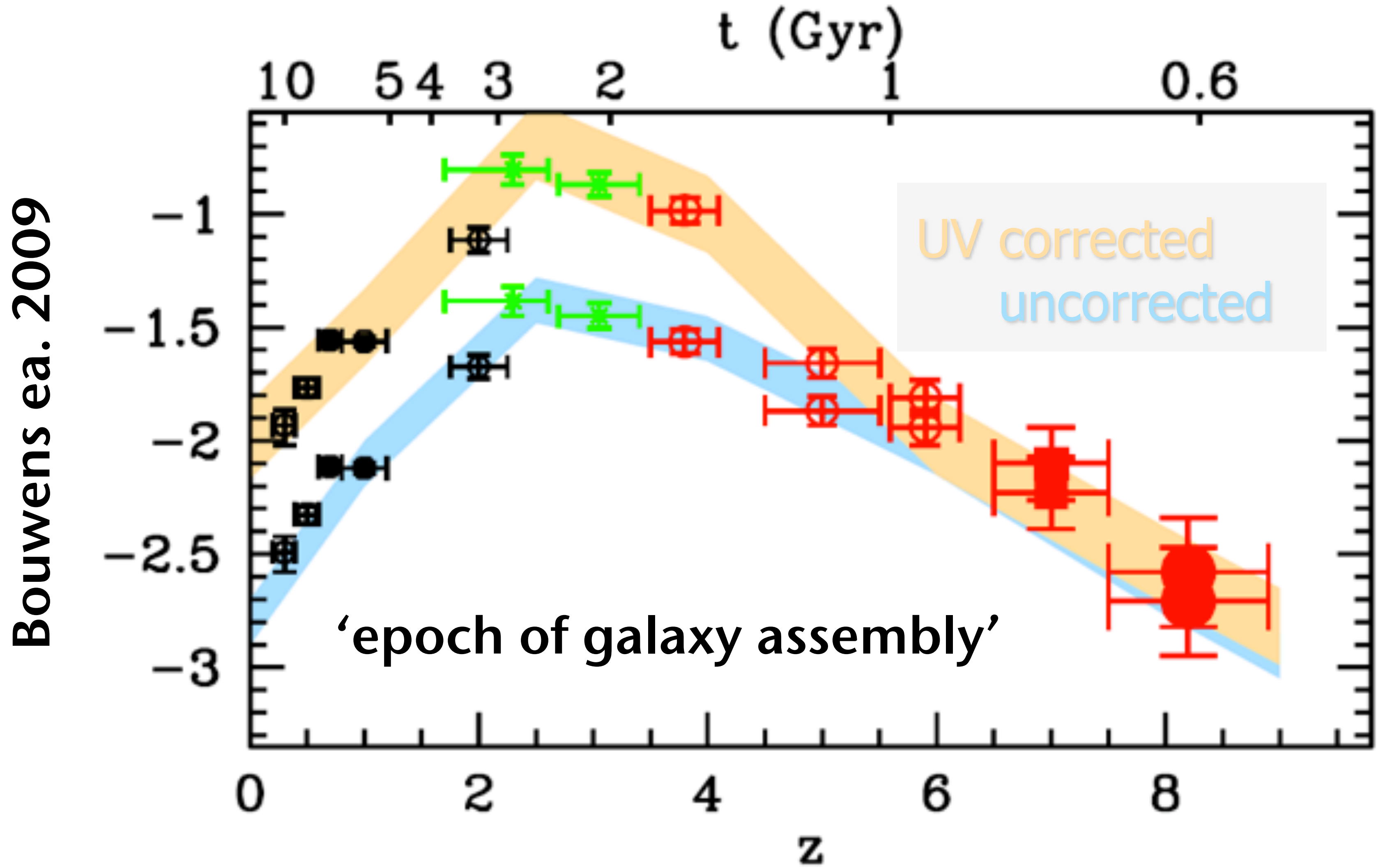
$\tau_{Dep} \sim 2.5$ Gyr

'SF law' breaks down on scales of 300pc (Schruba et al. 2010)

The Star Formation ‘Law’ at high redshift.

needed as recipe for star formation in galaxy evolution simulations

IF conversion gas-stars was known...

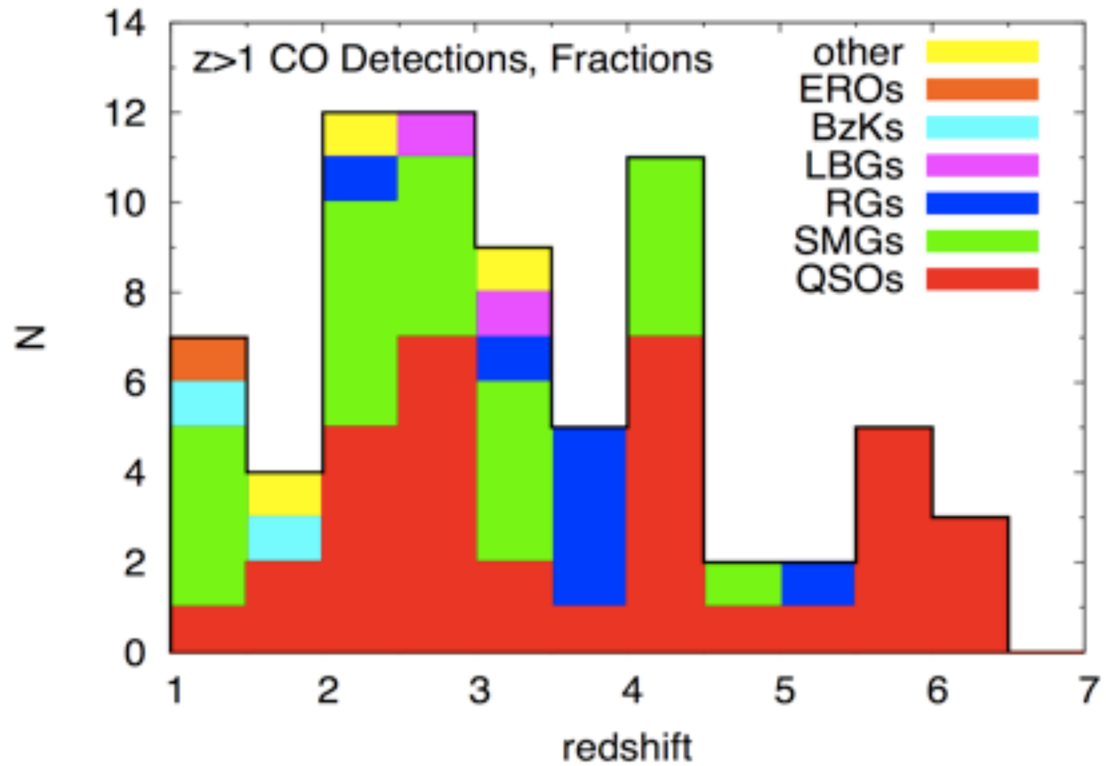


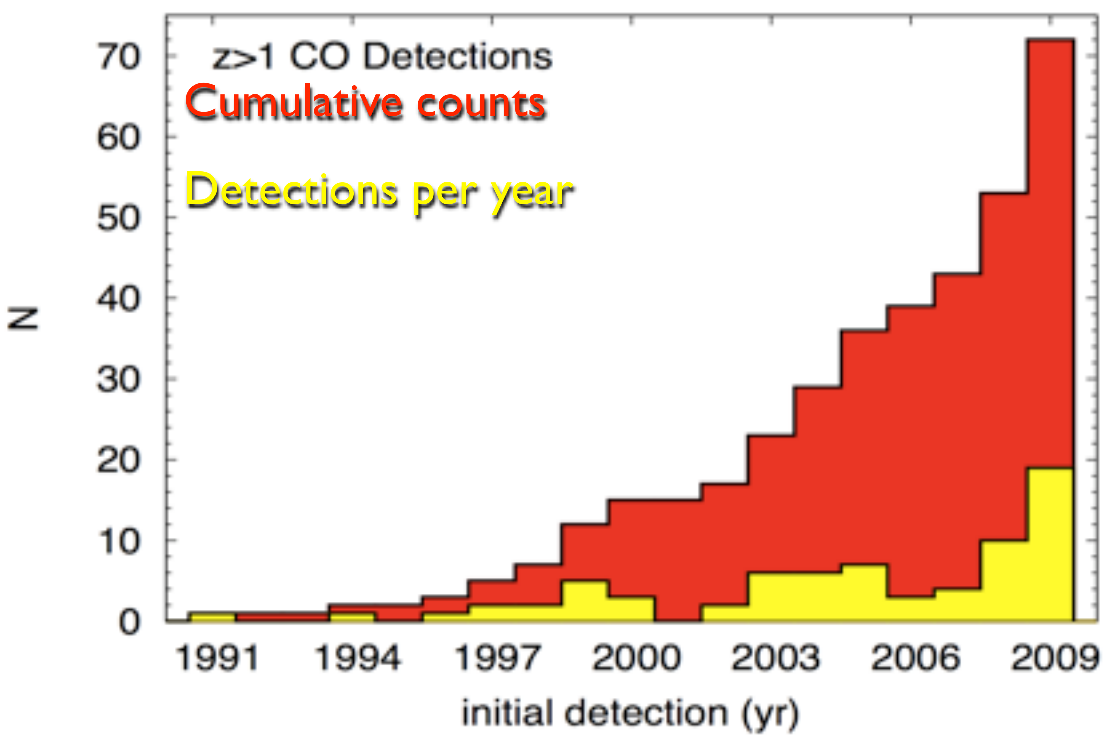
...Ω(H2) can be directly inferred from Ω(SFR)

i.e., no need to measure molecular gas content!

But one needs to check if this assumption is correct

Not too many high-z CO detections





- molecular gas observations at high-z help to constrain:

SFR	(cosmic SF history)
M_{gas}	(fuel for SF & evol. state)
M_{dyn}	(hierarchical models, M-σ)
n_{gas}, T_{kin}	(conditions for SF)

- evidence for mergers?

  (triggering of QSO activity & SF)

- cold accretion?

Note: molecular gas now routinely detected to z~6

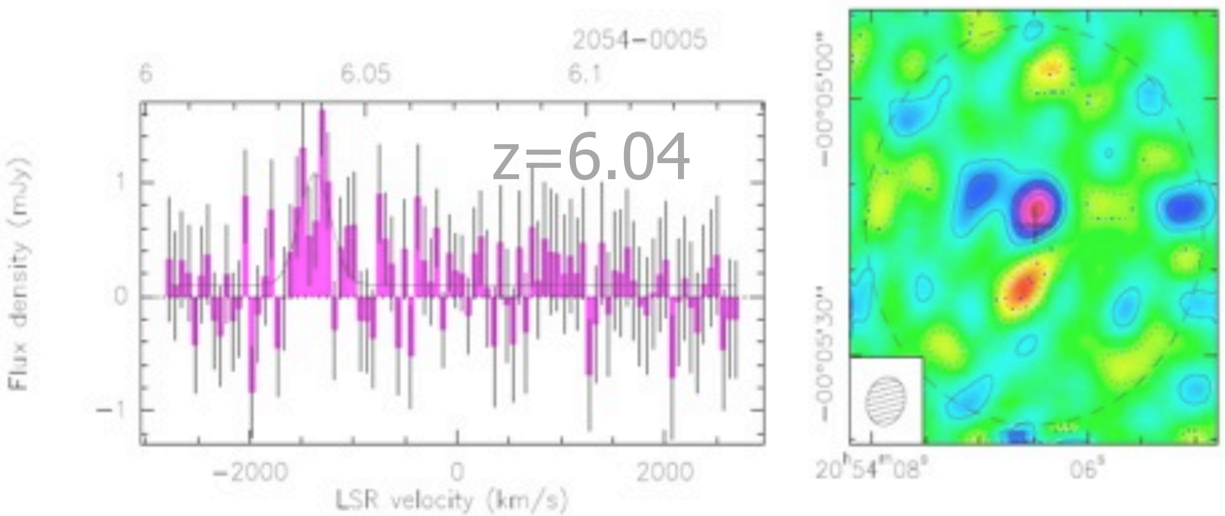


Figure 1: The spectrum and velocity-integrated image of J2054-0005.

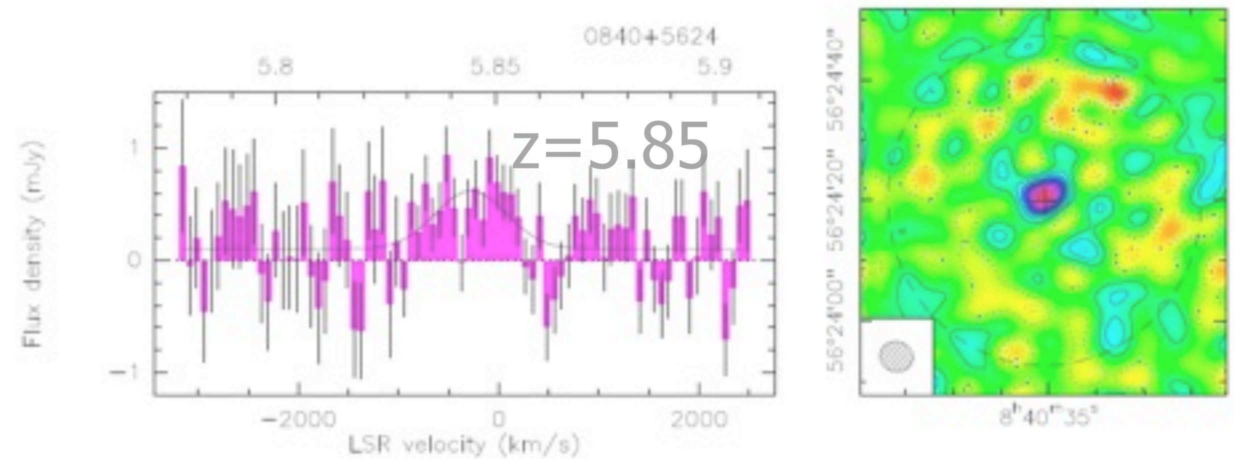


Figure 3: The spectrum and velocity-integrated image of J0840+5624.

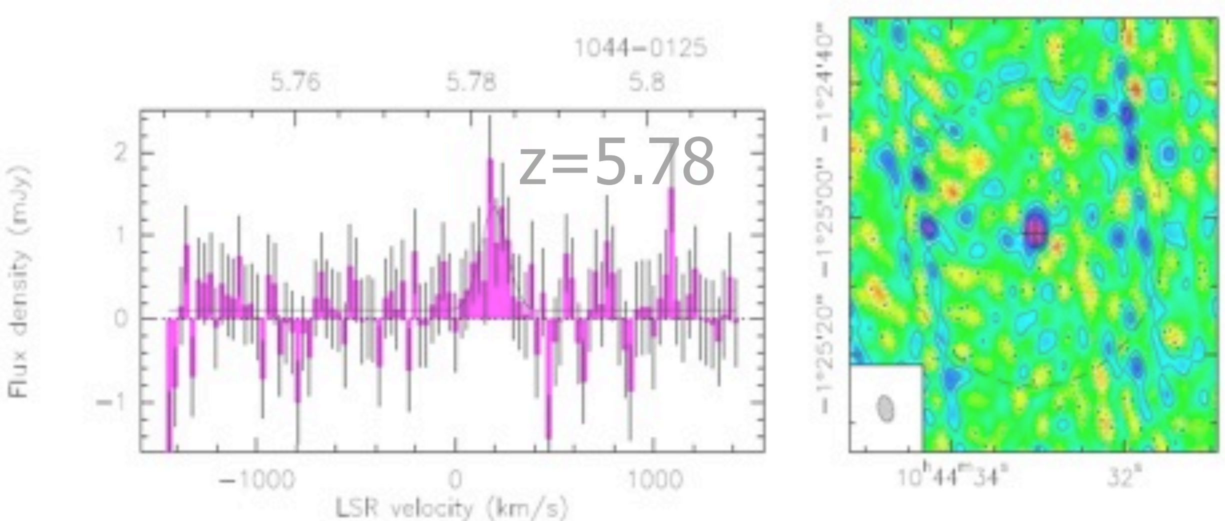


Figure 2: The spectrum and velocity-integrated image of J1044-0125.

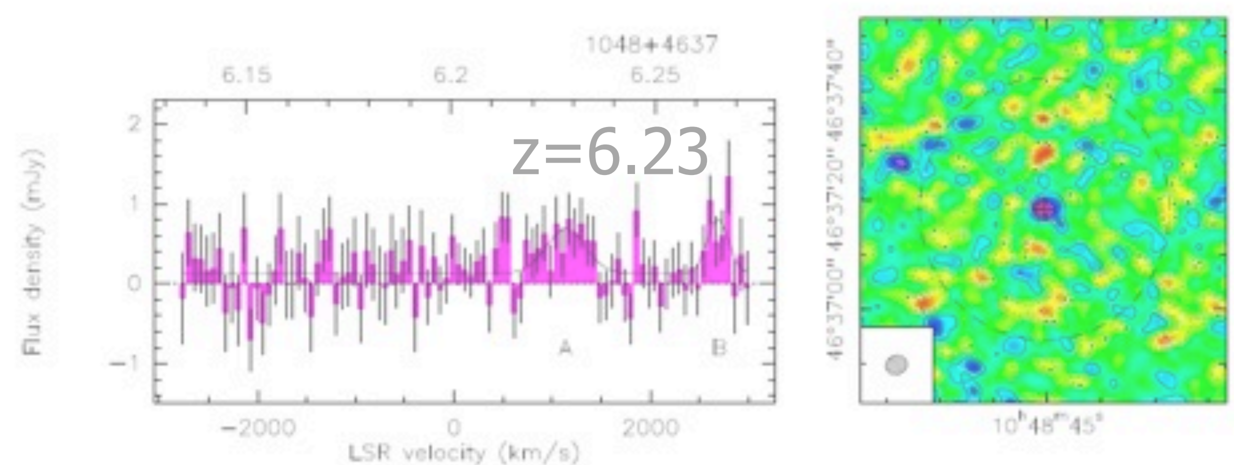


Figure 4: The spectrum and velocity-integrated image of J1048+4637.

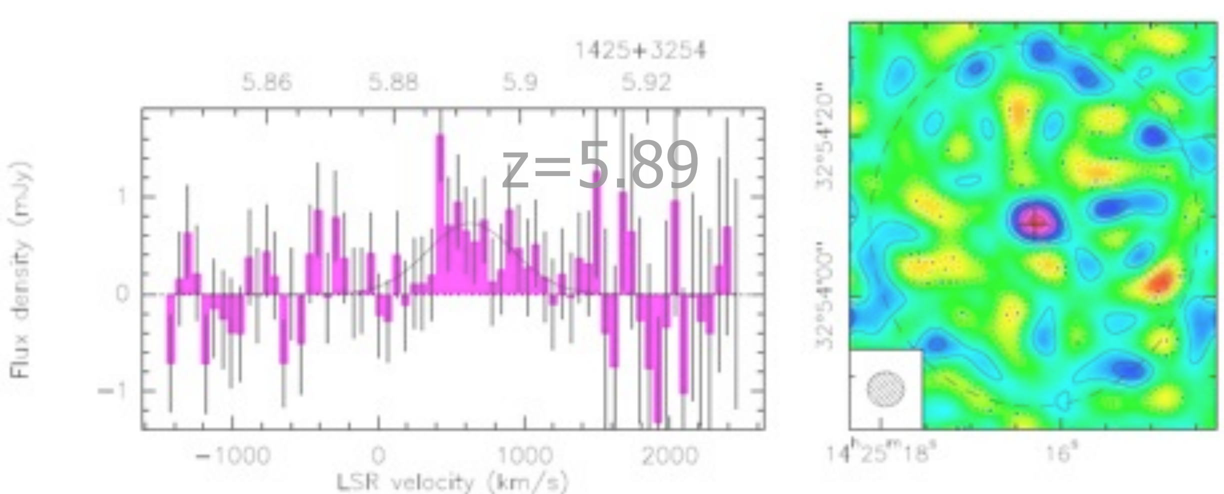


Figure 6: The spectrum and velocity-integrated image of J1425+3254.

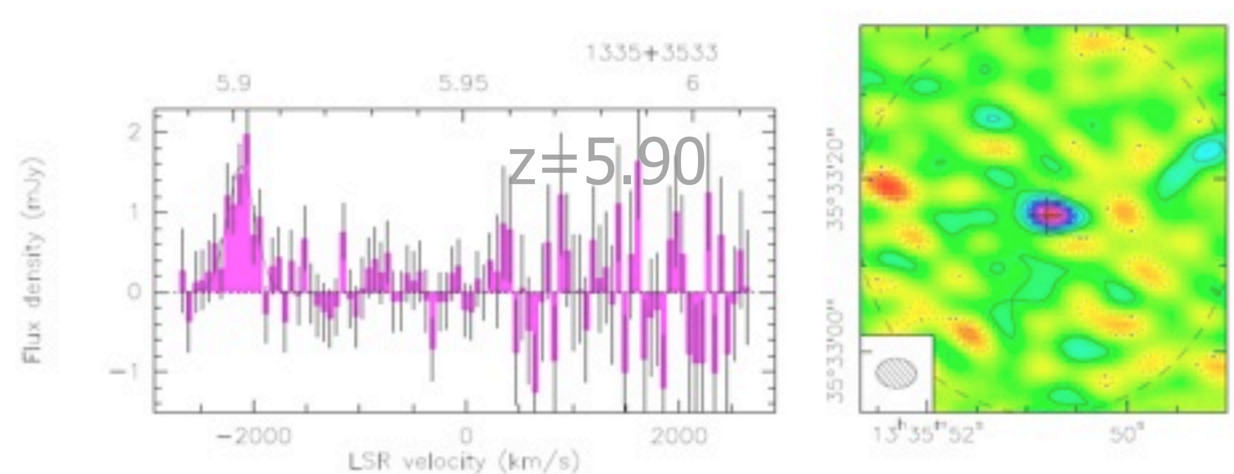


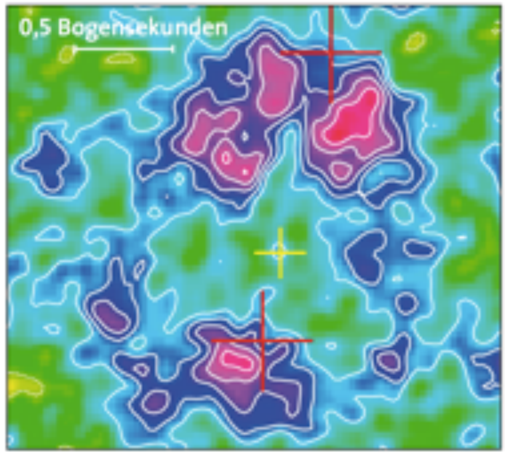
Figure 5: The spectrum and velocity-integrated image of J1335+3533.

Wang et al. 2009: CO(6-5) lines

☆ High-z quasars: now routinely detected in CO

(a few examples shown here)

at high z the CO lines are moved to ~1cm (VLA)

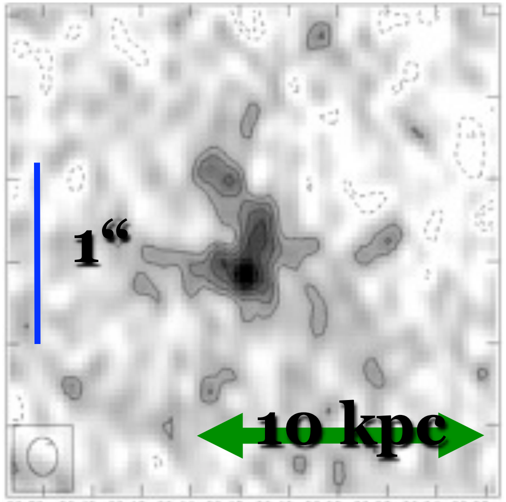


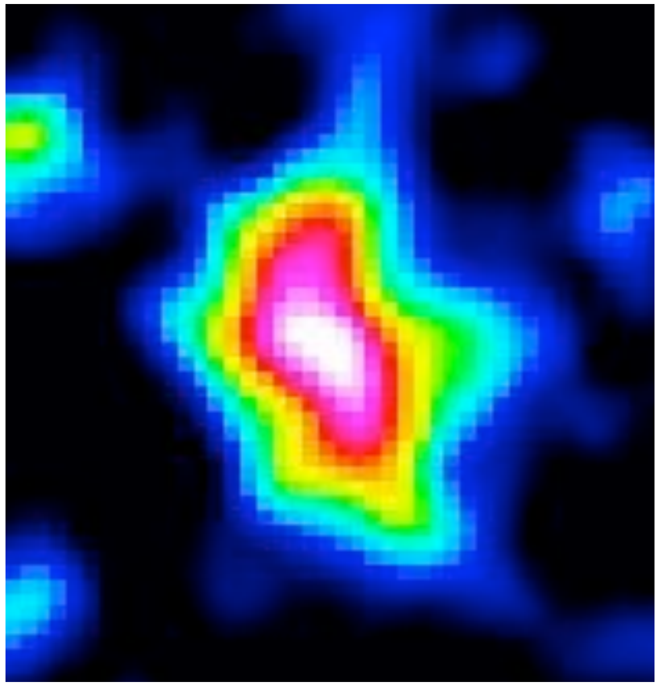
CO: 1-5 kpc size,

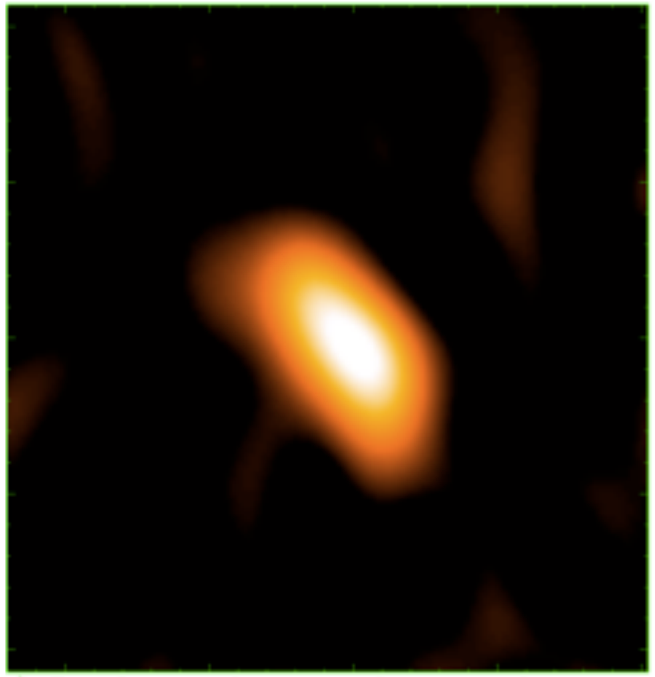
v_{CO}=300 -500 km s^{-1}

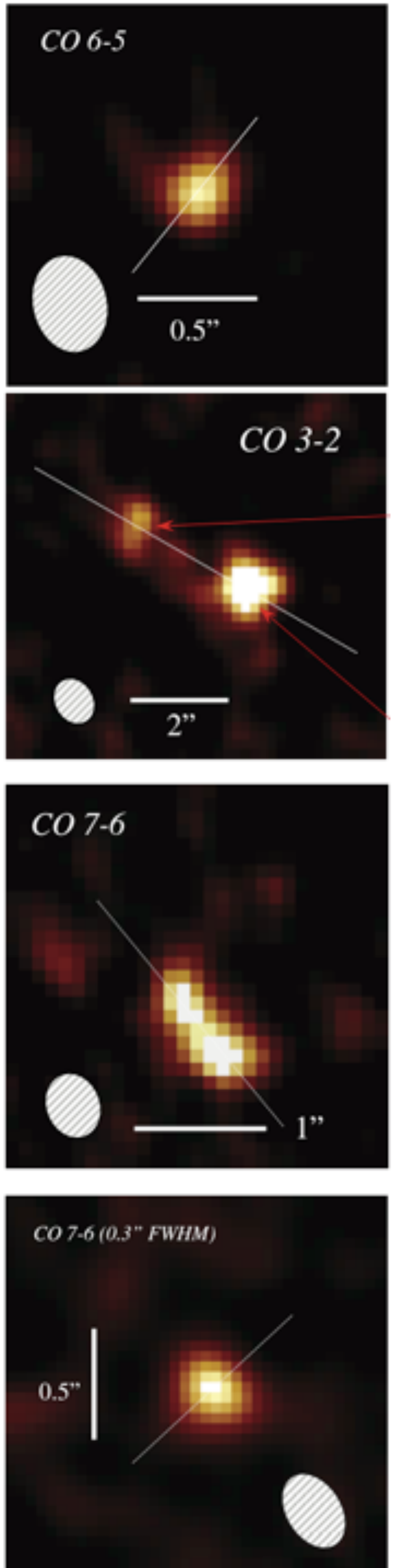
H_2 masses: few 10^{10} M_{sun}

-- using low X_{CO} (otherwise M_{gas}>M_{dyn})









SMGs vs. QSOs

SMGs

CO: 2-4 kpc size,

v_{co}=400 -800 km/s

- $M_{gas} = 4\text{-}7 \times 10^{10}\ M_\odot$
- $M_{dyn} = 9\text{-}35 \times 10^{10}\ M_\odot$
- $M_{BH} = 2\text{-}30 \times 10^{7}\ M_\odot$ (??)

$\Rightarrow f_{gas} \sim 0.4$

$\Rightarrow M_{dyn}/M_{BH} > 1000$

QSOs

CO: 1-5 kpc size,

v_{co}=300 -500 km/s

- $M_{gas} = 2\text{-}15 \times 10^{10}\ M_\odot$
- $M_{dyn} = 4\text{-}25 \times 10^{10}\ M_\odot$
- $M_{BH} = 1.5\text{-}20 \times 10^{9}\ M_\odot$

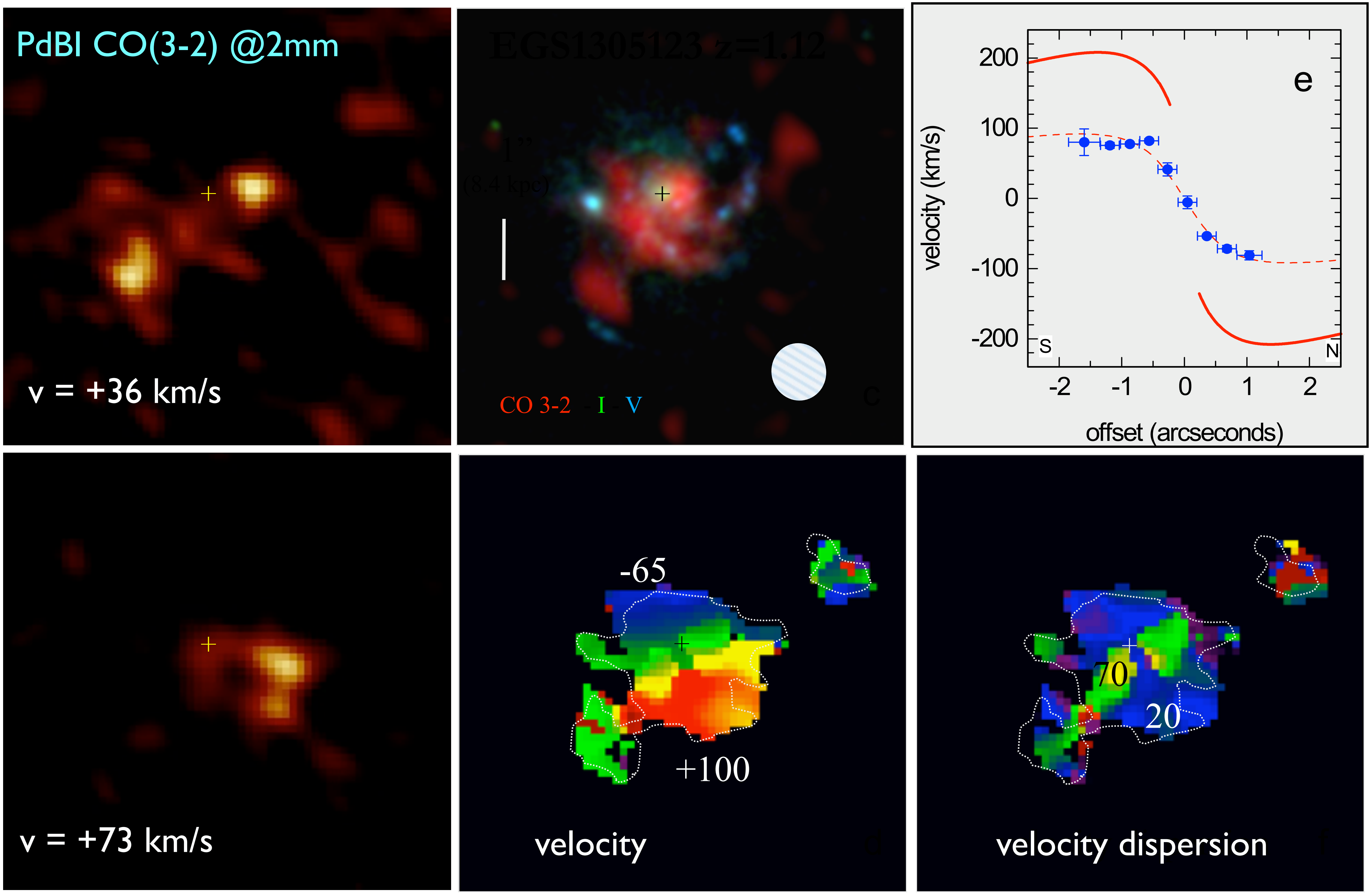
$\Rightarrow f_{gas}=0.4\text{-}0.9$

$\Rightarrow M_{dyn}/M_{BH}=20\text{-}30$

both SMGs and QSOs are gas rich and have high gas fractions.

there is significant overlap between both populations (historical definitions)

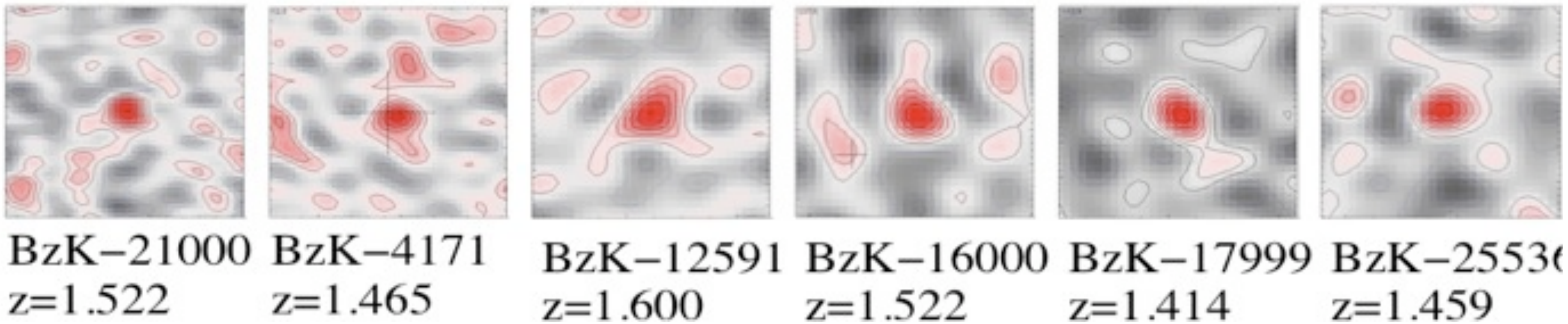
Example: Spatially Resolved CO in a z=1.12 Disk Galaxy



M_{gas}~7×10^{10} $M_{\odot}$; , M_*~ 2×10^{11} $M_{\odot}$, f_{gas} ~0.3, v_{rot}/σ = 8±2

Tacconi et al.2009

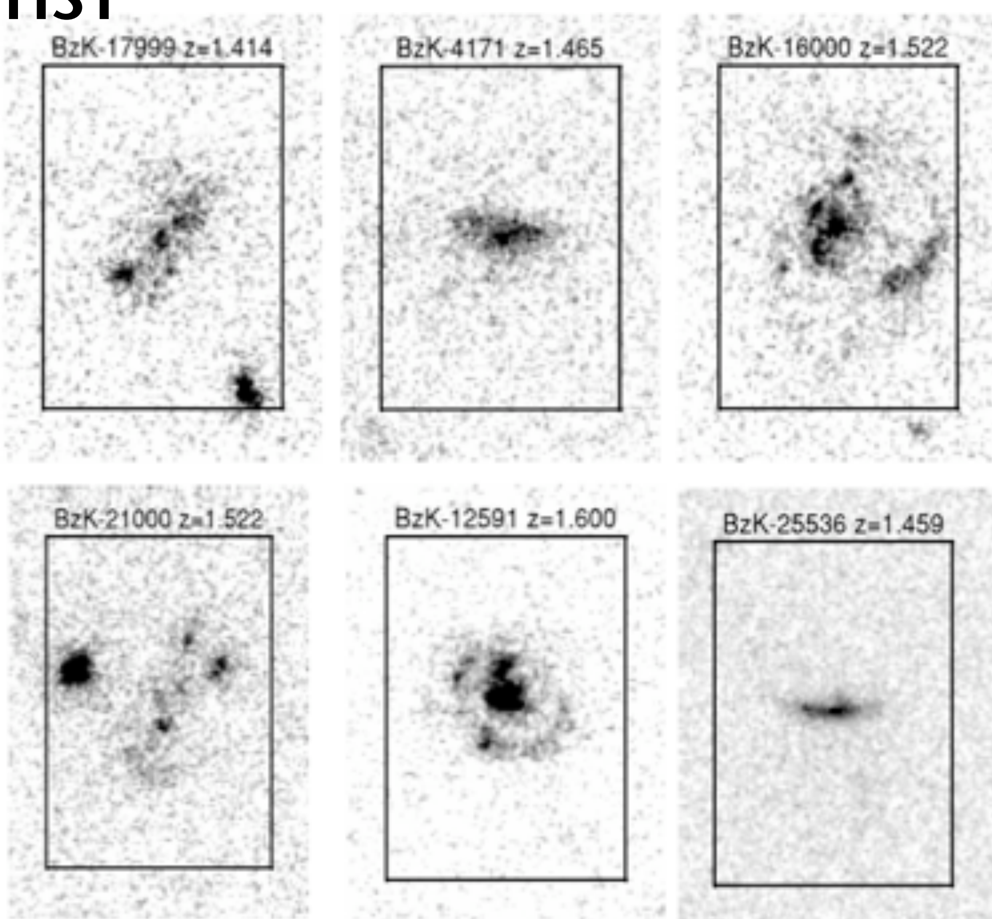
Example: CO detection in ‘normal’ star forming galaxies at z~1.5



PdBI

CO(2-1)

HST



- $M_{gas} > 10^{10}\ M_o$ ~ high-z HyLIRG (SMG, QSO host)

But:

- SFR < 10% HyLIRG
- 5 arcmin^{-2} (vs. 0.05 for SMGs)

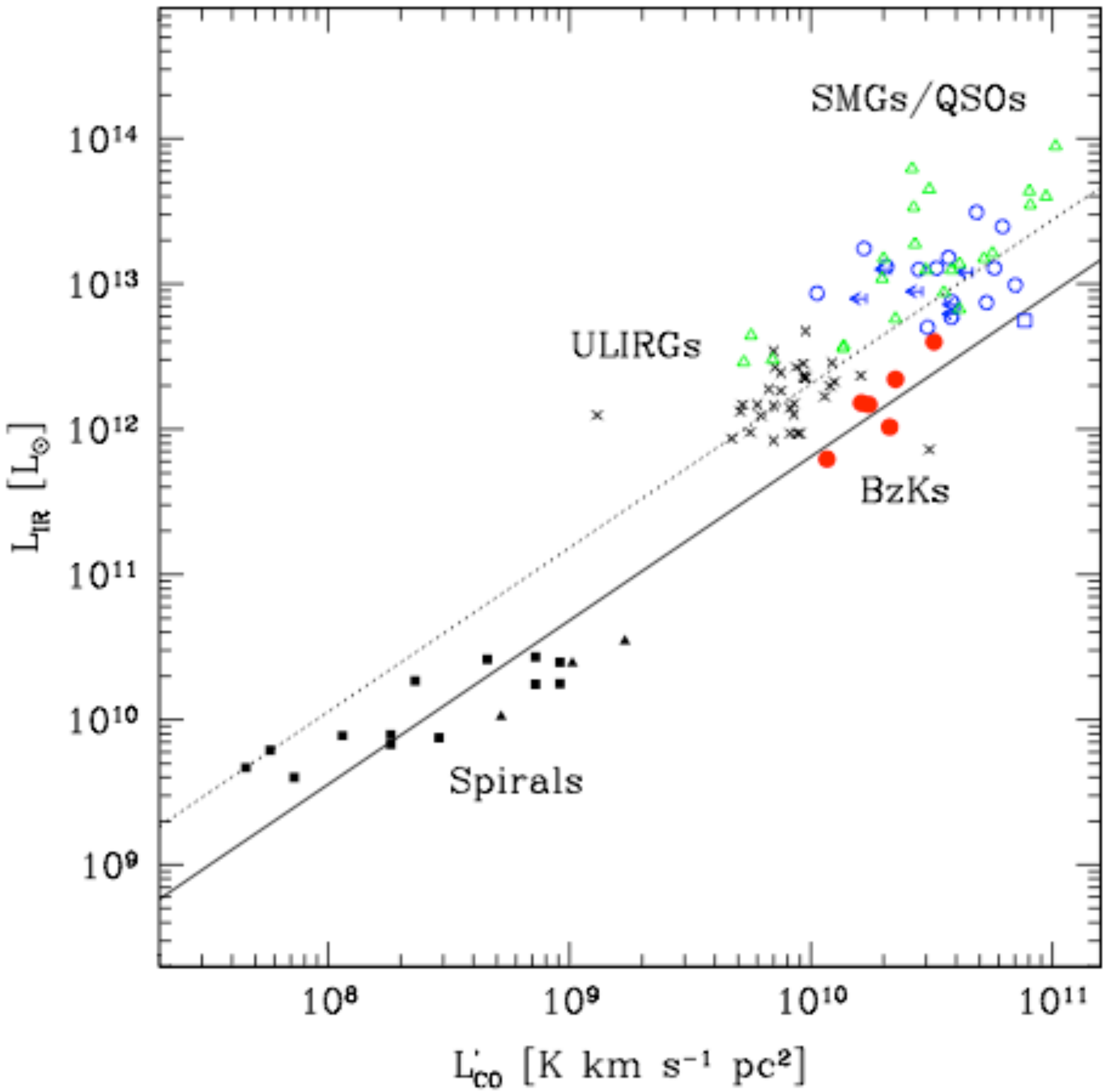
=> common, ‘normal’ high-z galaxies

Daddi ea. 2007, 2008, 2009

L_{IR} vs L_{CO}

in the current high-z sample

(observables only)

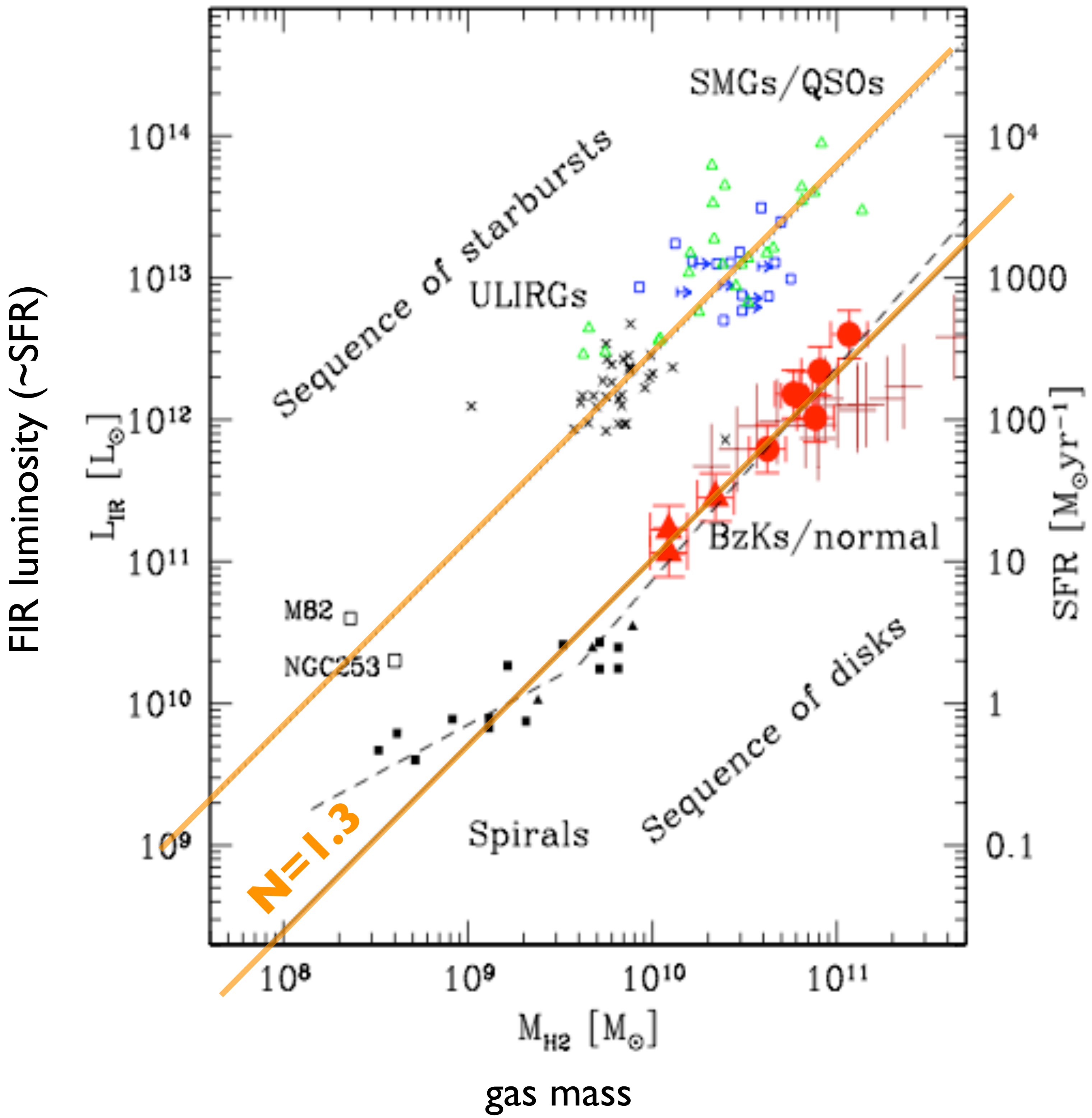


BzKs have significantly less L_{IR} for given L_{CO}

This plot is likely biased for high luminosities

Daddi et al. (2010)

The integrated high-z Star Formation Law.



studies have shown that the conversion factor for BzK's is much larger than for ULIRGs (Daddi et al. 2010).

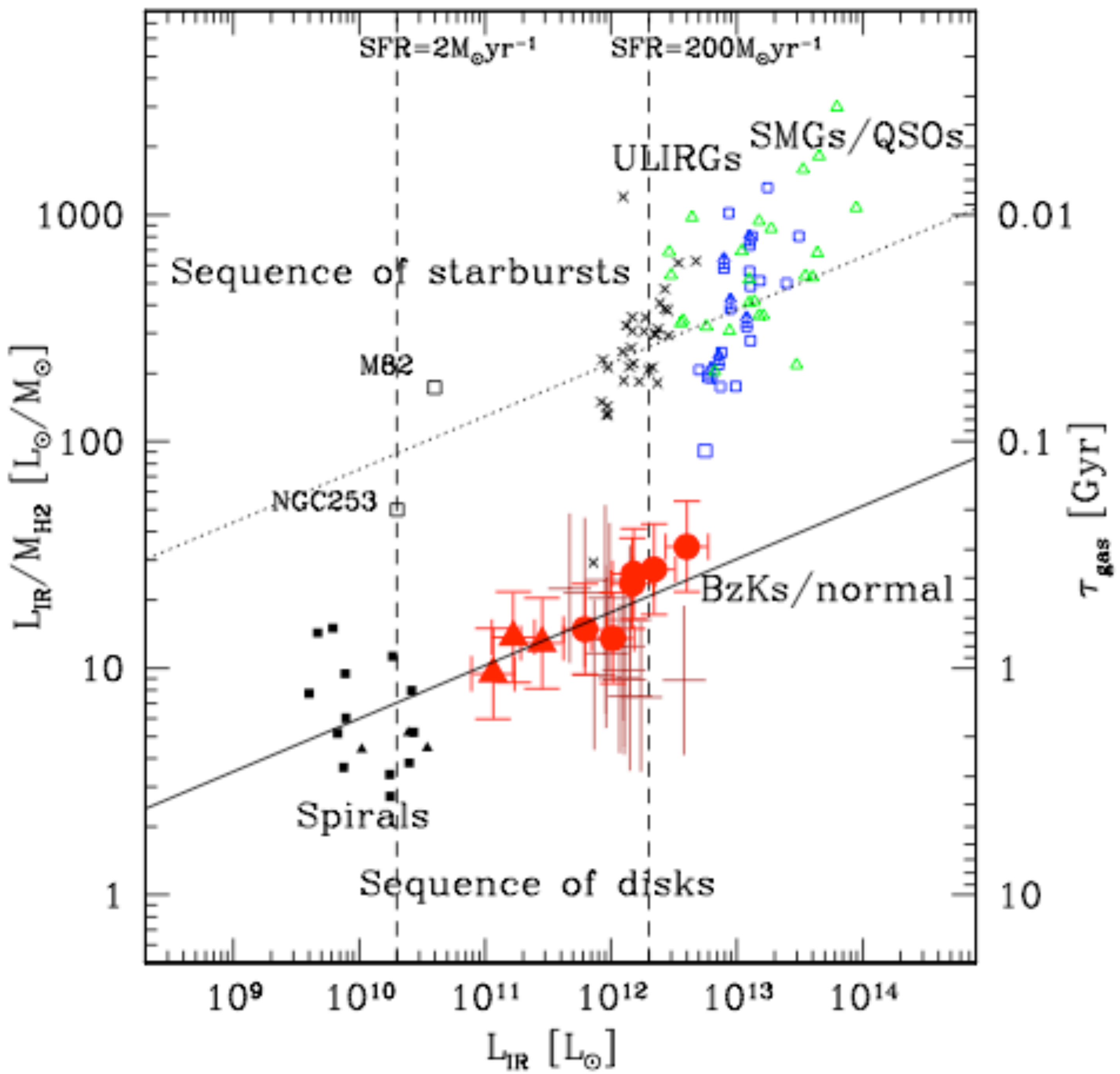
As a consequence the offset seen in the earlier diagram increases

i.e. **two** sequences:

disks & starbursts

Daddi, et al. (2010)

Resulting Star Formation Efficiencies and Depletion Times at high z



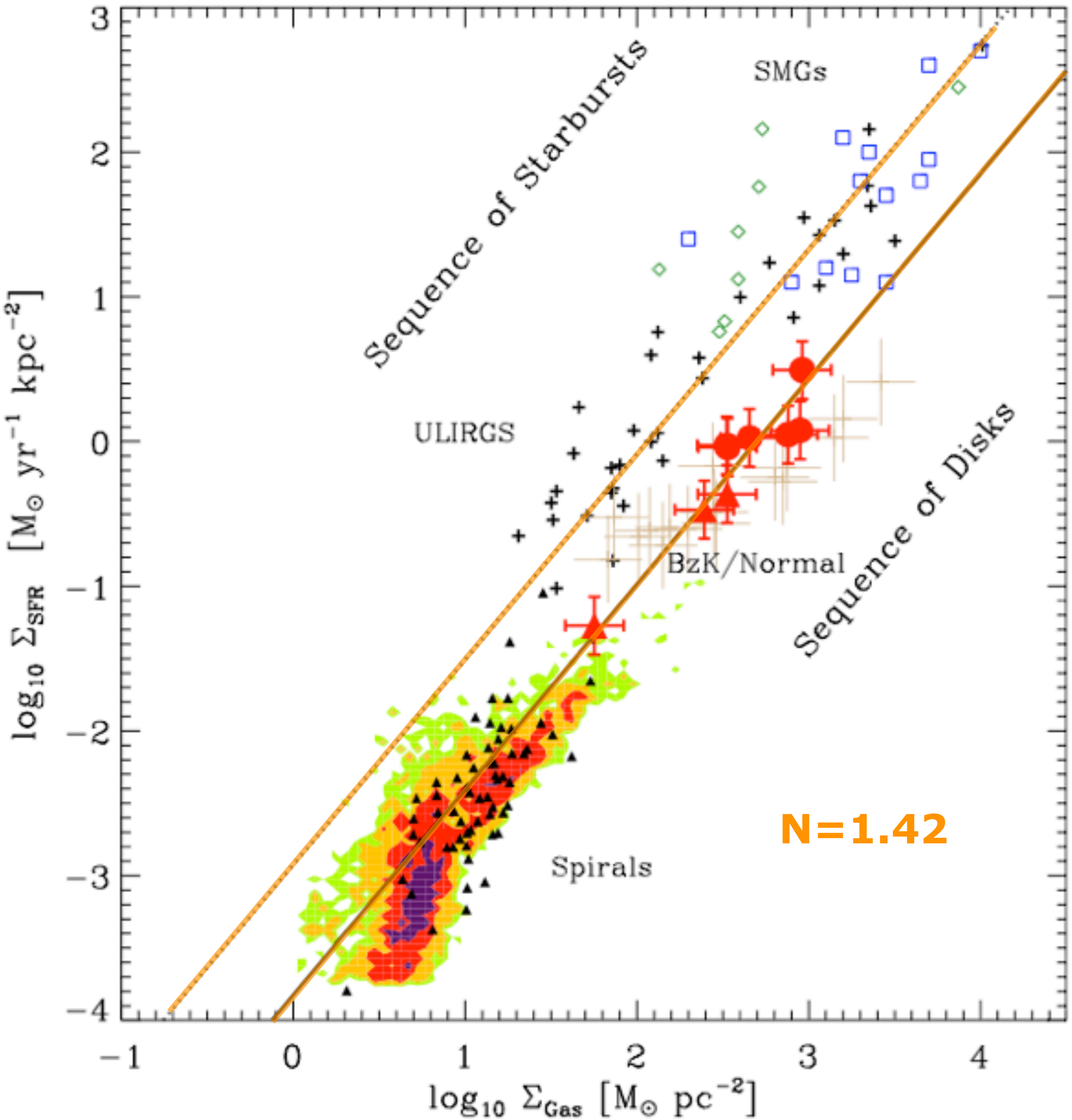
immediate implication:

gas depletion times LONG for BzKs (sim. to spirals)

SHORT for SMGs/ QSOs

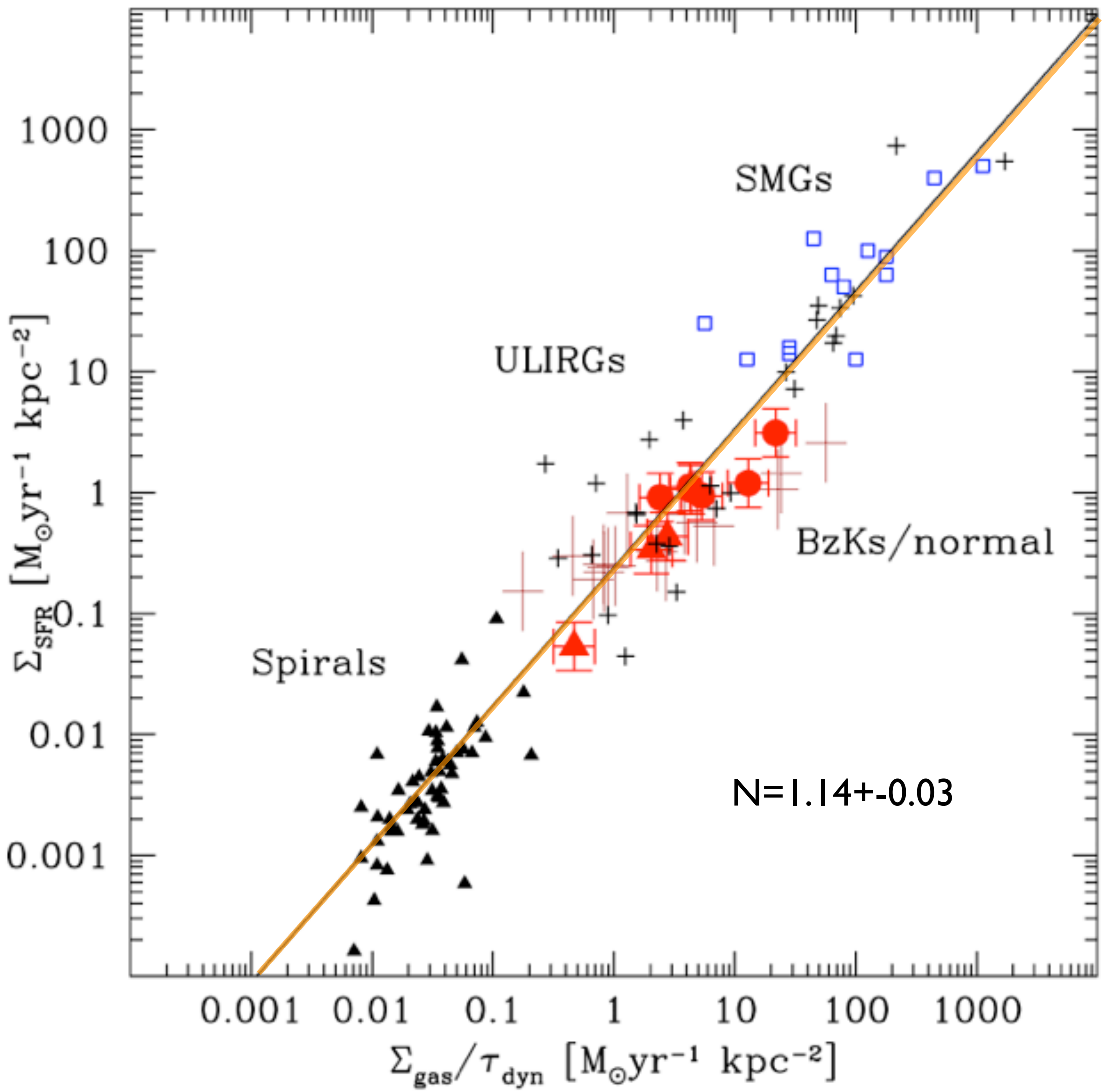
Daddi et al. (2010)

The high-z Star Formation Law.



Daddi, Elbaz, FW et al. (2010)

Dividing by the orbital time:



one slope (1.1) fits all!

Daddi et al. 2010, Genzel et al. 2010

Different processes lead to star formation (mergers, interactions, bar driving, spiral structure)

Need to invoke feedback both at the low and high mass end of galaxy mass function to bring observations in agreement with CDM simulations

Star formation ‘law’ is a molecular only law.

Depletion times at low z ~2E9 years

At high redshift ~E7 years (note: selection bias)

Need empirical description of SF process as input for numerical simulations.