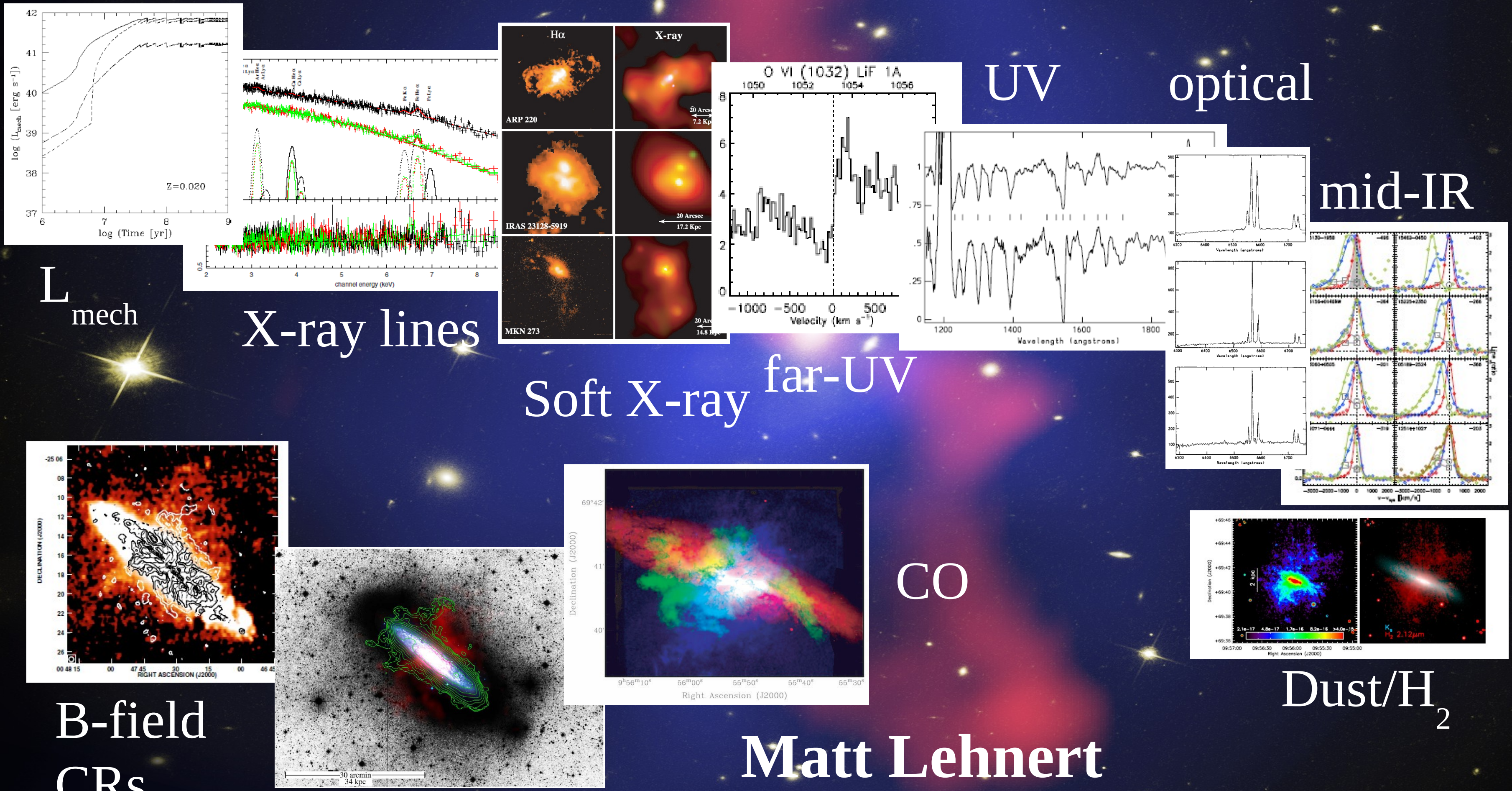
Energetic Processes and the Drivers of Galaxy Evolution



L_{mech}

X-ray lines

Soft X-ray

far-UV

UV

optical

mid-IR

B-field
CRs

HI

CO

Dust/H_2

Matt Lehnert
GEPI, Observatoire de Paris

What are Starbursts?

Two definitions of star-bursts:

1) $t_{\text{gas-consumption}} < 2\text{-}10 t_{\text{dyn}} \ll t_{\text{Hubble}}$

2) $\Sigma_{\text{star-formation}} \gg \langle \Sigma_{\text{star-formation}} \rangle \; M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$

Both definitions are essentially equivalent but ... at high redshift … do these make sense … what about causality … or self-regulation?

$$\dot{M}_{SFR,max} \approx M_{tot} f_{gas} t_{cross}^{-1}$$

$$P_{\text{midplane}} \approx P_{\text{wind}}$$

Which Galaxies Drive Winds?

Comprehensive statistical study of infrared selected starburst galaxies:

- **large IR luminosities ($L_{IR} > 10^{44}$ ergs s^{-1})**
- **large IR excesses ($L_{IR}/ L_B > 2$)**
- **warm IR colors ($S_{60\mu m}/ S_{100\mu m} > 0.5$)**

Show strong evidence for driving winds. Equivalent criteria for UV-selected

These criteria imply that only star-formation surface densities, $\Sigma_{SFR} > 0.05\ M_\odot\ yr^{-1}\ kpc^{-2}$ drive substantial winds.

Superwinds are ubiquitous!

Lehnert & Heckman (1996)

Lessons from Superwinds for high-z/AGN

Star-formation is self-regulating

“Feedback” is be a multi-wavelength phenomenon

Must understand both heating and cooling – when, where and how

Simultaneous AGN activity can make life difficult

There are no golden observations!

Physics of Winds

Superwinds – the outflow driven by the collective thermalization of stellar winds and supernova

Thermalization of SNe:

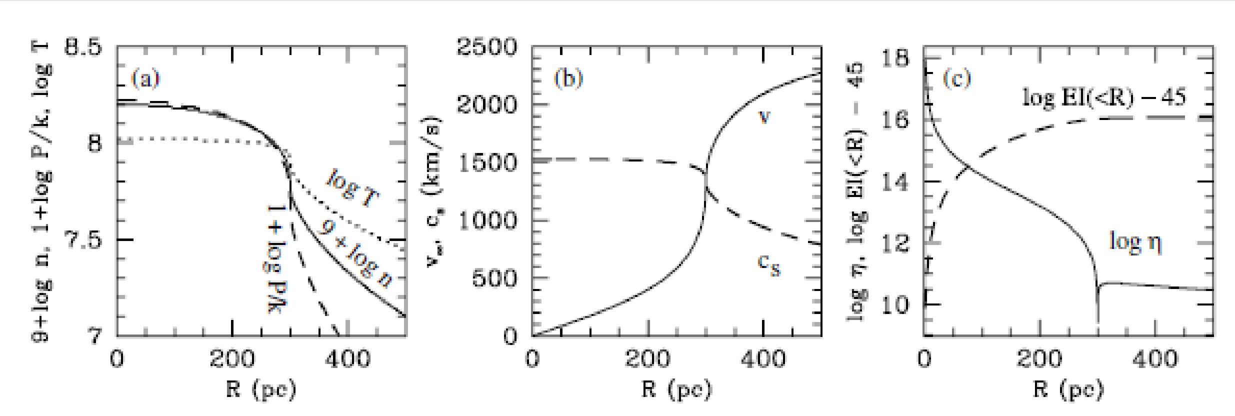
$$T_{postshock} = \frac{3}{16} v_{ejecta}^2 m_H / k = 9.1\, x\, 10^7 v_{ejecta,2000}^2 K$$

Injection region:

$$T_c = 0.4\, \mu\, m_H \dot{E}_{total} / k \dot{M}_{total}$$

$$\rho_c = 0.3\, \dot{M}_{total}^{3/2} \dot{E}_{total}^{-1/2} R_{SB}^{-2}$$

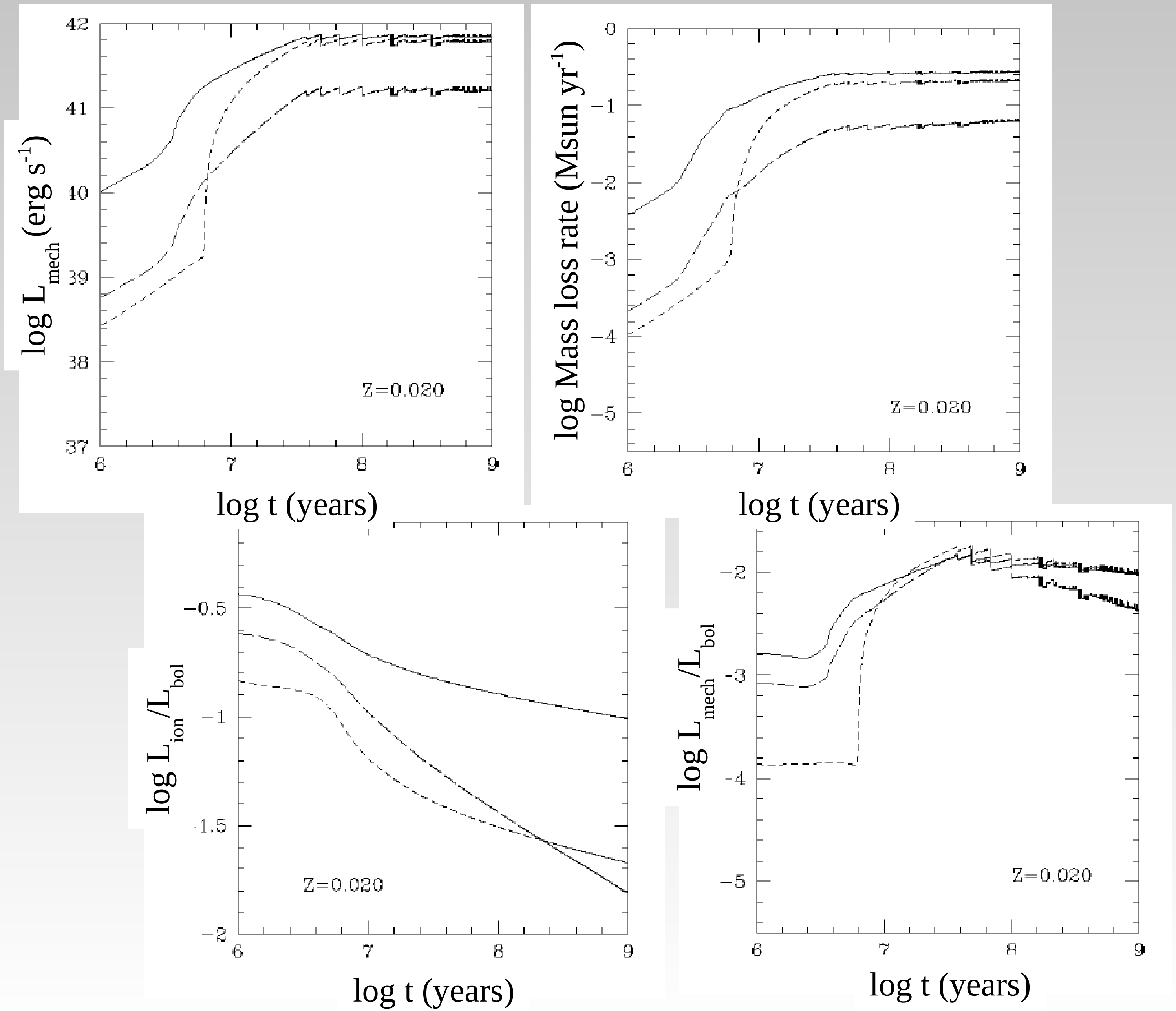
$$v_\infty = \sqrt{2}\, \dot{E}_{total}^{1/2} \dot{M}_{total}^{-1/2}$$



But what about the ISM, turbulence, radiation, etc

Chevalier & Clegg (1985), Strickland & Heckman (2009)

Energetics of Star-formation

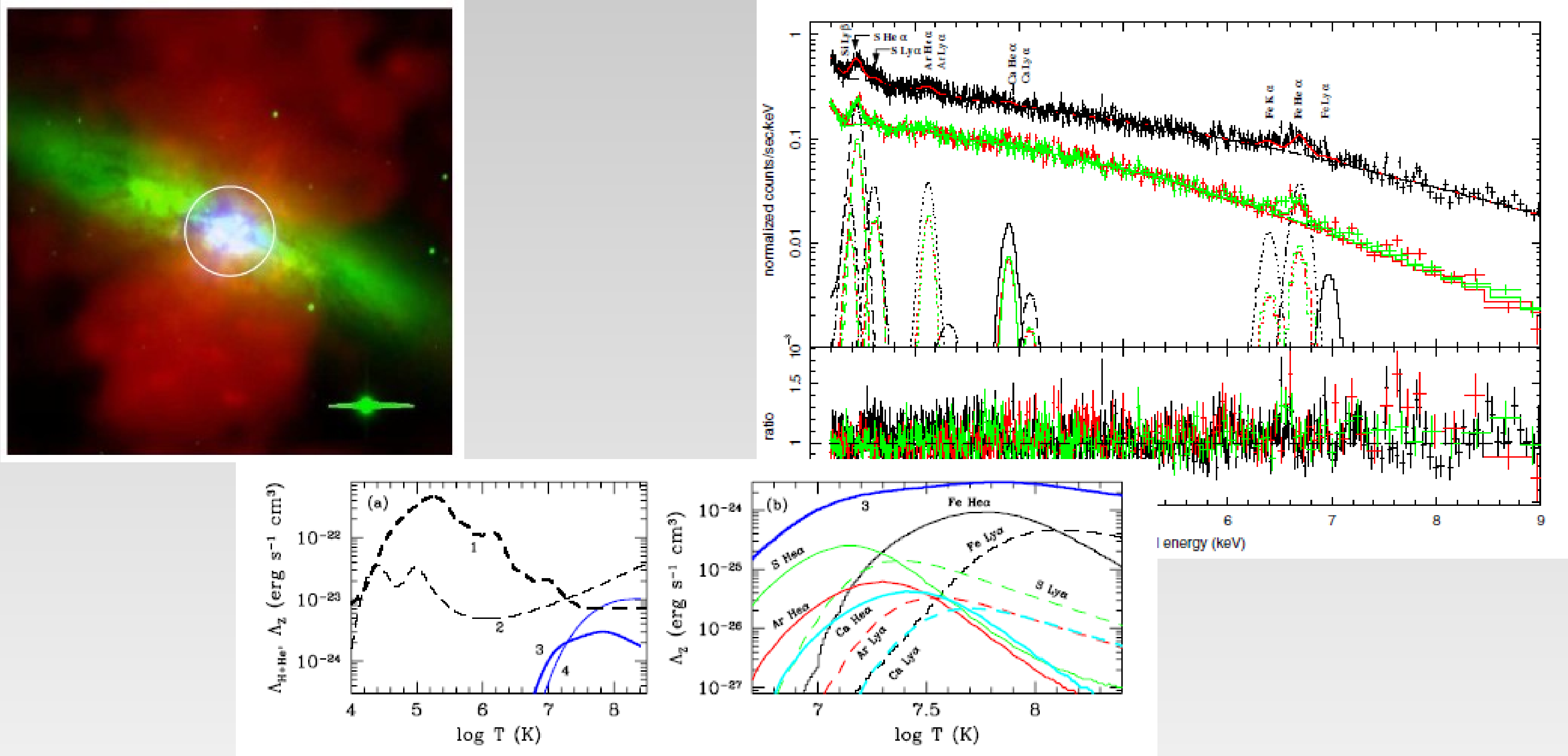


Leitherer et al. (1999)

Constituent	Observable	Diagnostic
Relativistic Plasma	Radio continuum X-ray continuum	Magnetic field, aging of electrons, relativistic or thermal pressure, jet collimation star-formation rate, number of X-ray binaries
Hot ionized gas $T \sim 10^7$ to 10^8 K log $n_e \sim -3$ to -1 cm^{-3}	X-ray continuum, emission and absorption lines Radio depolarization	Thermal pressures, metal abundances, density, mass, cooling rate, viscosity, turbulence, outflow rate
Warm ionized gas $T \sim 10^4$ to 10^6 K log $n_e \sim -1$ to 3 cm^{-3}	UV absorption lines Optical emission lines Radio recombination lines Far-IR emission lines	Temperature, shock heating or photoionization rate, density, mass, turbulence, dynamics, metallicity, filling factor, pressure, outflow rate, cooling rate
Warm neutral gas $T \sim 4\text{-}8 \times 10^3$ K log $n_e \sim 0$ to 2 cm^{-3}	Optical em/abs lines HI emission and absorption Mid-IR H-H lines Far-IR lines of neutral species	Filling factor, temperature, column densities, cooling rate, pressures,masses, etc.
Cold neutral gas $T \sim 10^2$ K log $n_e \sim -1$ to 0 cm^{-3}	HI emission and absorption	Filling factor, temperatures, column densities, cooling rate, pressure, masses, etc.
Warm molecular gas $T \sim 0.5\text{-}2 \times 10^3$ K log $n_e \sim 1$ to 4 cm^{-3}	Mid-IR H-H lines High order molecular lines of neutral and ionized species	Filling factor, temperatures, column densities, cooling rate, pressure, masses, etc.
Cold molecular gas/dust $T < 10^2$ K log $n_e > 4$ cm^{-3}	Molecular lines Infrared dust continuum Mid-infrared features	Heating and cooling rates, dynamics, turbulence, masses, densities, temperature, pressure, cosmic ray heating rate, interstellar chemistry, etc
Stars	UV/optical/near-infrared continuum	Mass, dynamics, star-formation history, metallicity, energy injection rate, mass return rate, etc.

Hot X-ray Plasma

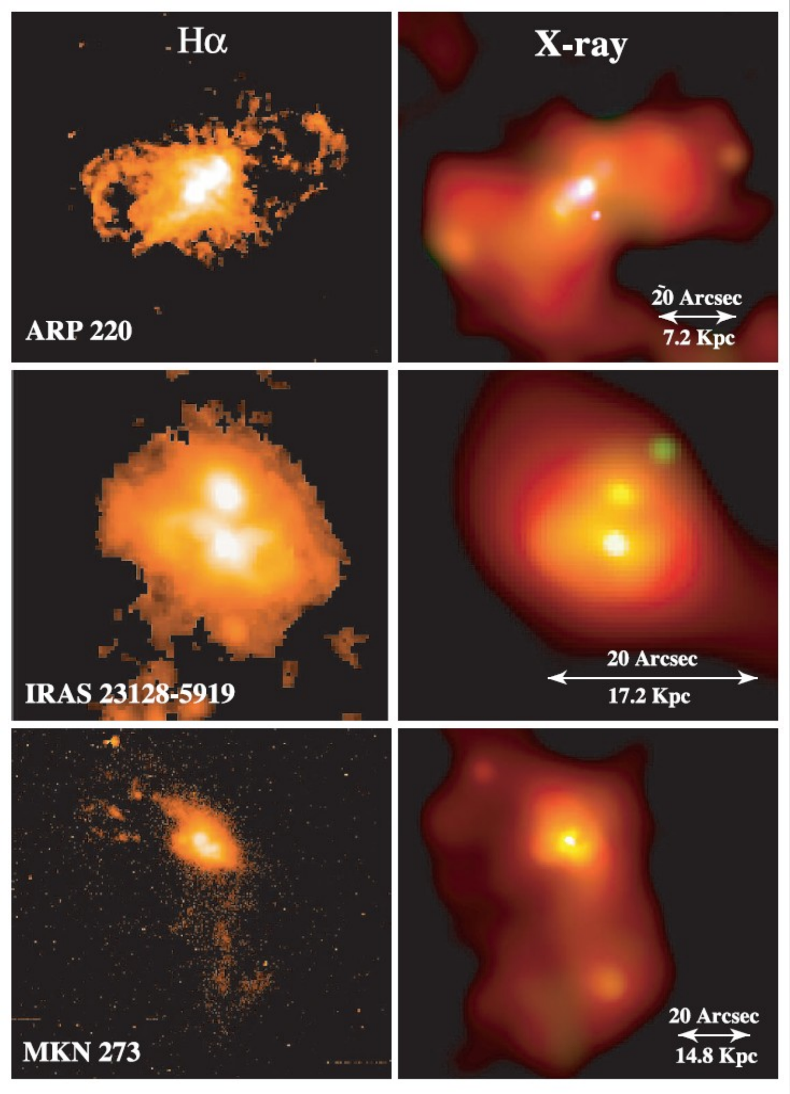
Constraining the piston … hot plasma emissivity too low …
line cooling the best diagnostic available ...

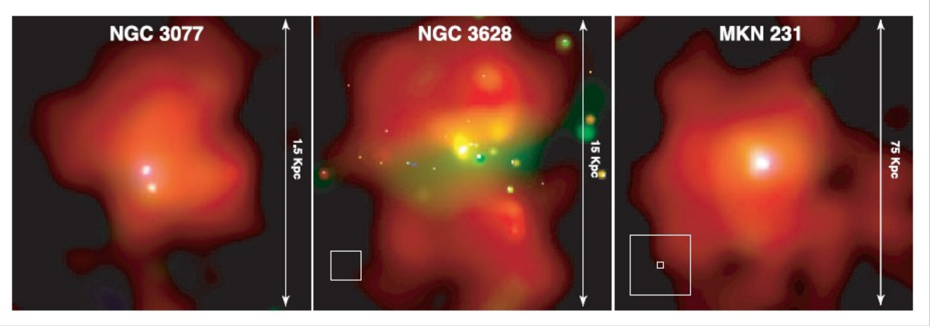


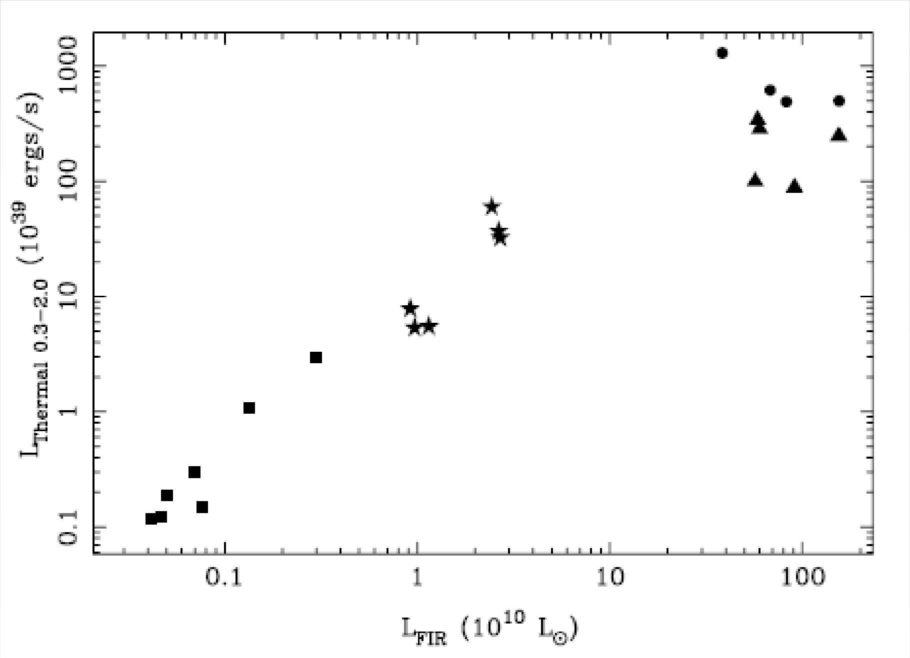
In the inner 500 pc of M82:
- temperature 30-80 million K
- thermalization efficiency 0.3 to 1
- mass loading 1 to 3

Strickland & Heckman (2009)

Thermal X-rays





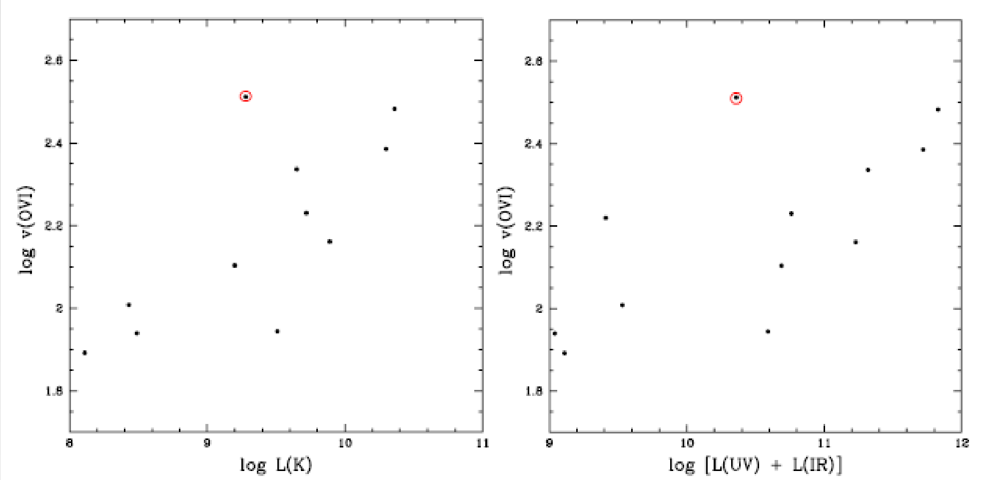


$$\dot{M}_{outflows} \approx \dot{M}_{star-formation}$$ Mass-loaded (~x10)

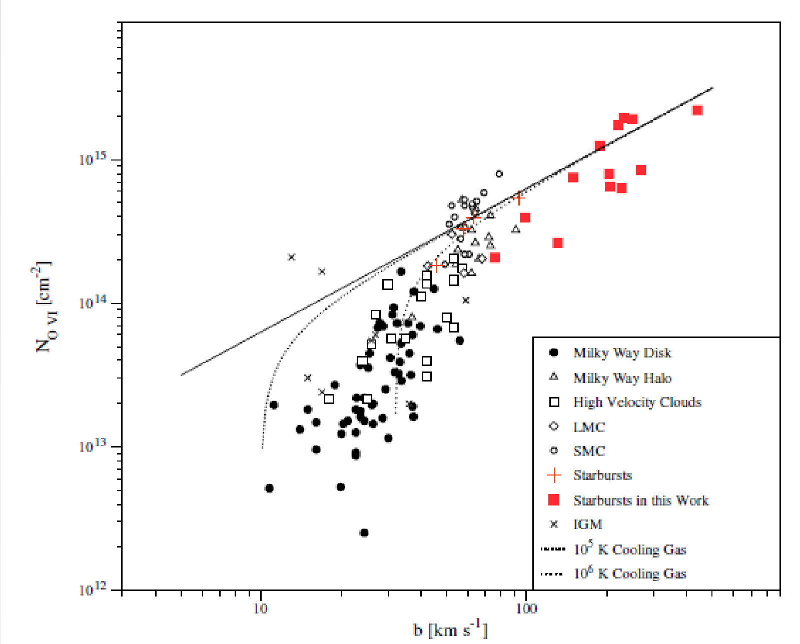
Grimes et al. (2005)
Moran, Lehnert, & Helfand (1999)

Far-UV coronal lines

Far UV observations – OVI cooling?



N – b implies collisionally ionized gas



OVI λ1032 samples T~$10^{5.5}$ K

-no emission seen – no strong cooling

-absorption always present

-velocity offset relative to systemic

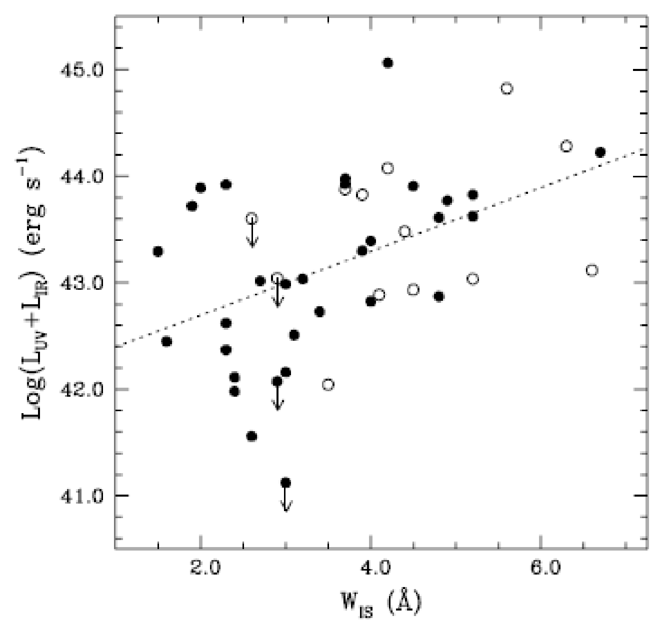
-magnitude of offset related to power and SSFR

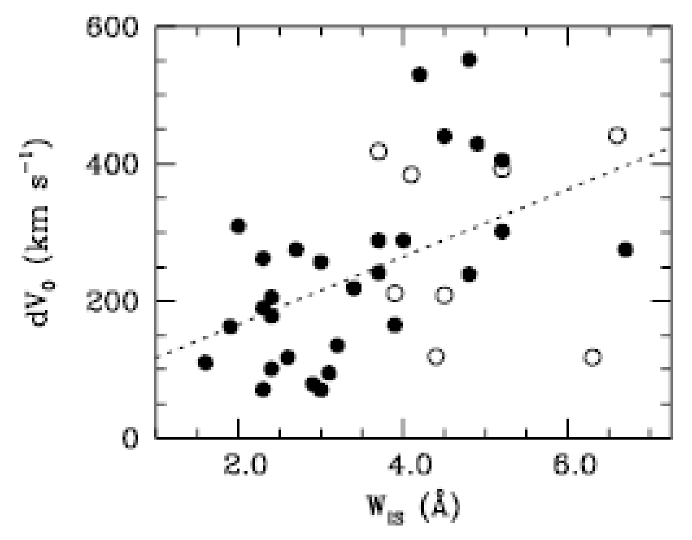
-likely mixing interfaces between cool entrained gas and outflow

Beware: these are dwarf UV bright galaxies

Grimes et al. (2009)

Near UV lines





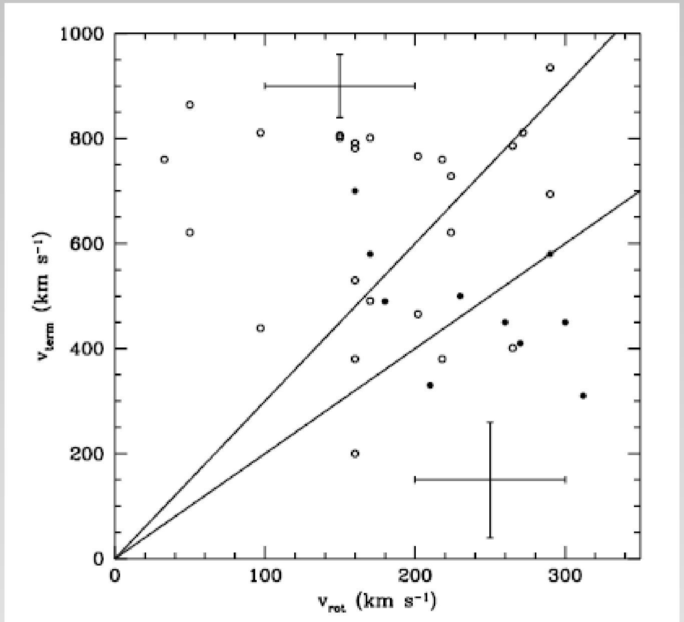
From the interstellar absorption lines – all saturated – EQWs proportional to σ_{3D} and C_f:

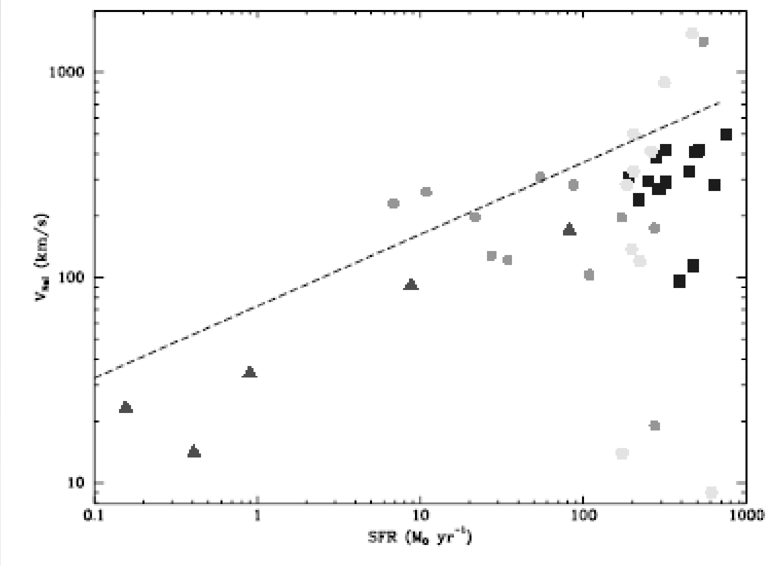
-large dispersions (300-500 C_f km s^{-1})

-more powerful galaxies have higher masses and broader lines – interstellar + wind components

Heckman et al. (1998)

Optical Absorption Line Gas





Na D/KI absorption reveals:

-gas is dusty (5.1 eV ionization potential)

-terminal velocities high and similar to X-ray estimates

-consistent w/ high C_f of outflowing gas

-dusty neutral gas likely escape the smallest halos

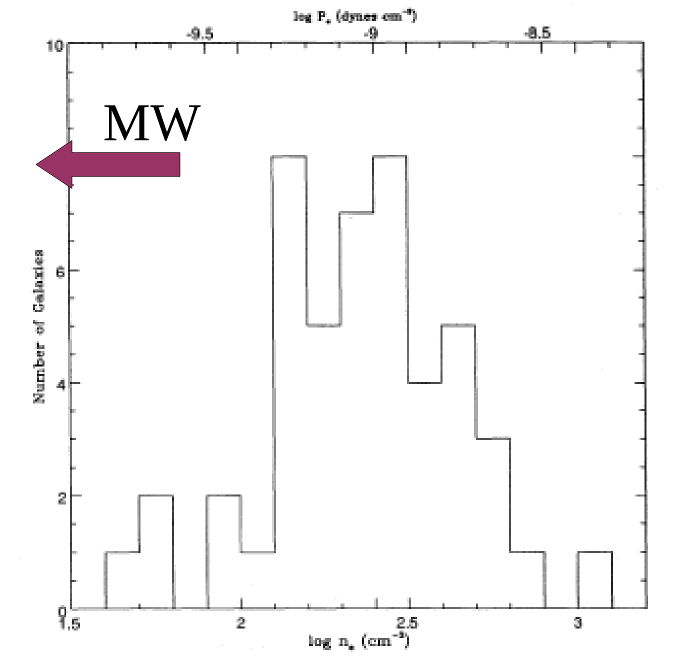
-evidence for momentum driven clouds?

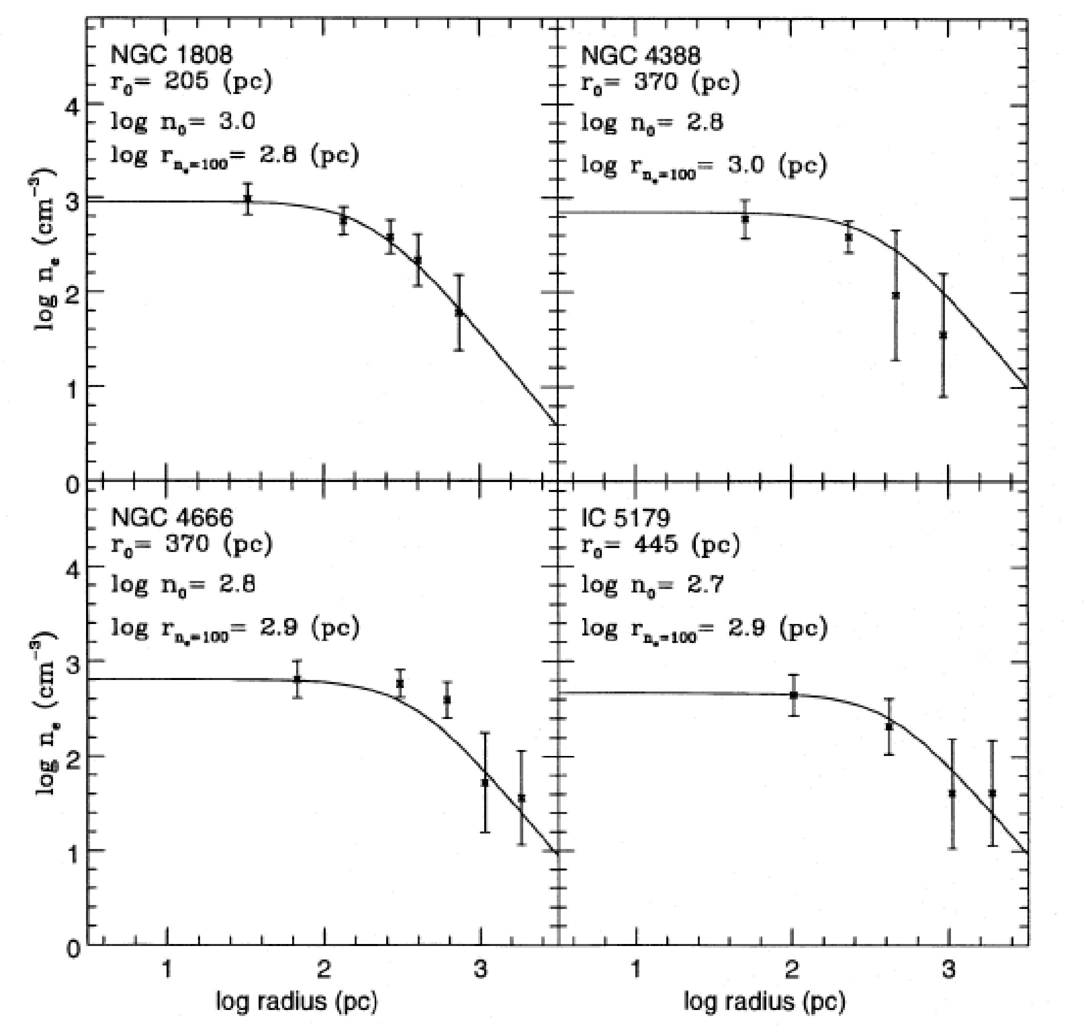
$$\dot{M}_{outflows} \approx \dot{M}_{star-formation}$$

-Winds are heavily mass loaded

Heckman et al. (2000), Martin (2005), Rupke et al. (2008)

Optical Emission Lines – High Over Pressures





Orders of magnitude higher than ambient solar neighborhood.

Pressure profiles consistent with outflow models, const + r^{-2}

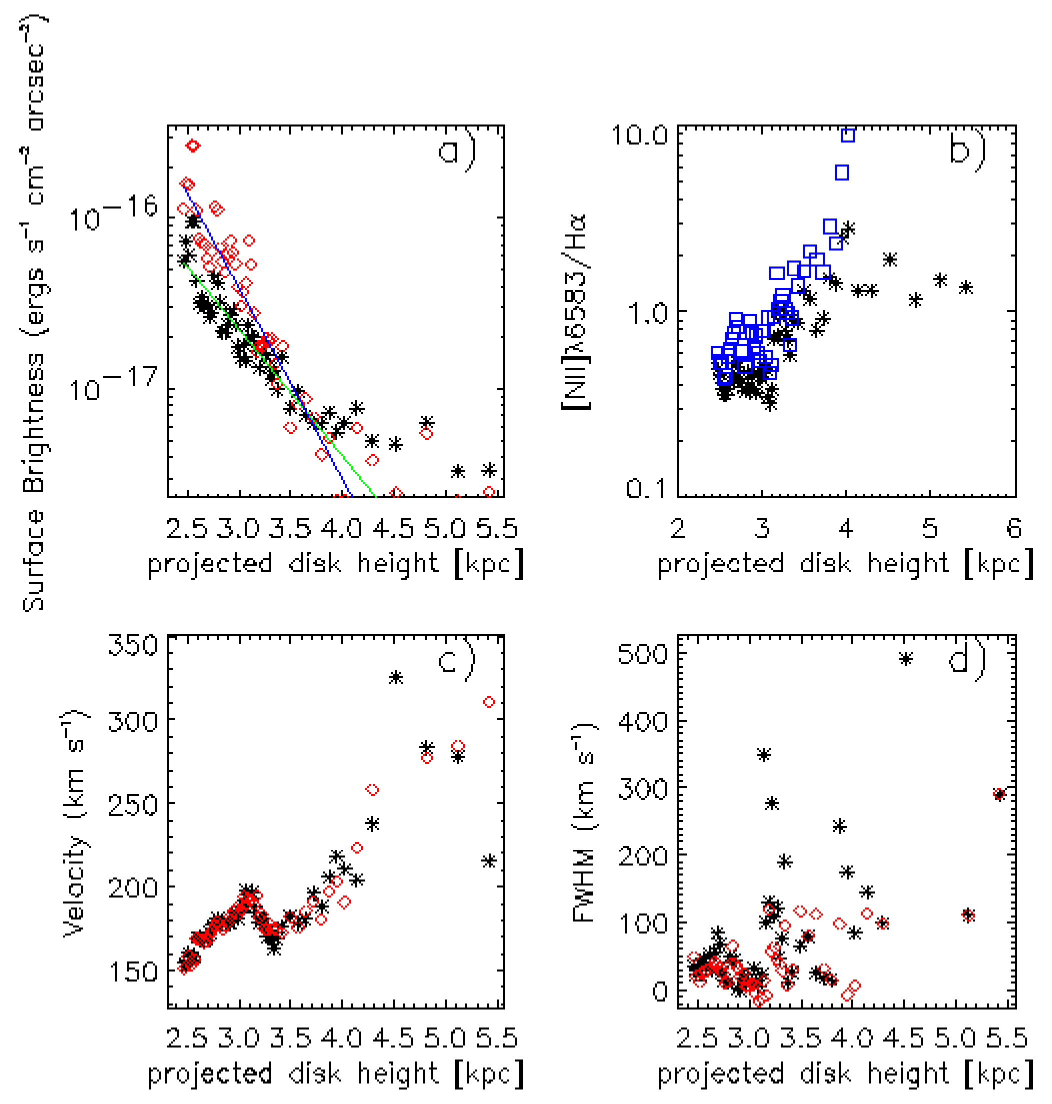
Heckman et al. (1990), Lehnert et al. (1996)

Optical emission line gas

Low ionization line ratios increase w/ increasing distance.

Lines appear to be accelerating.

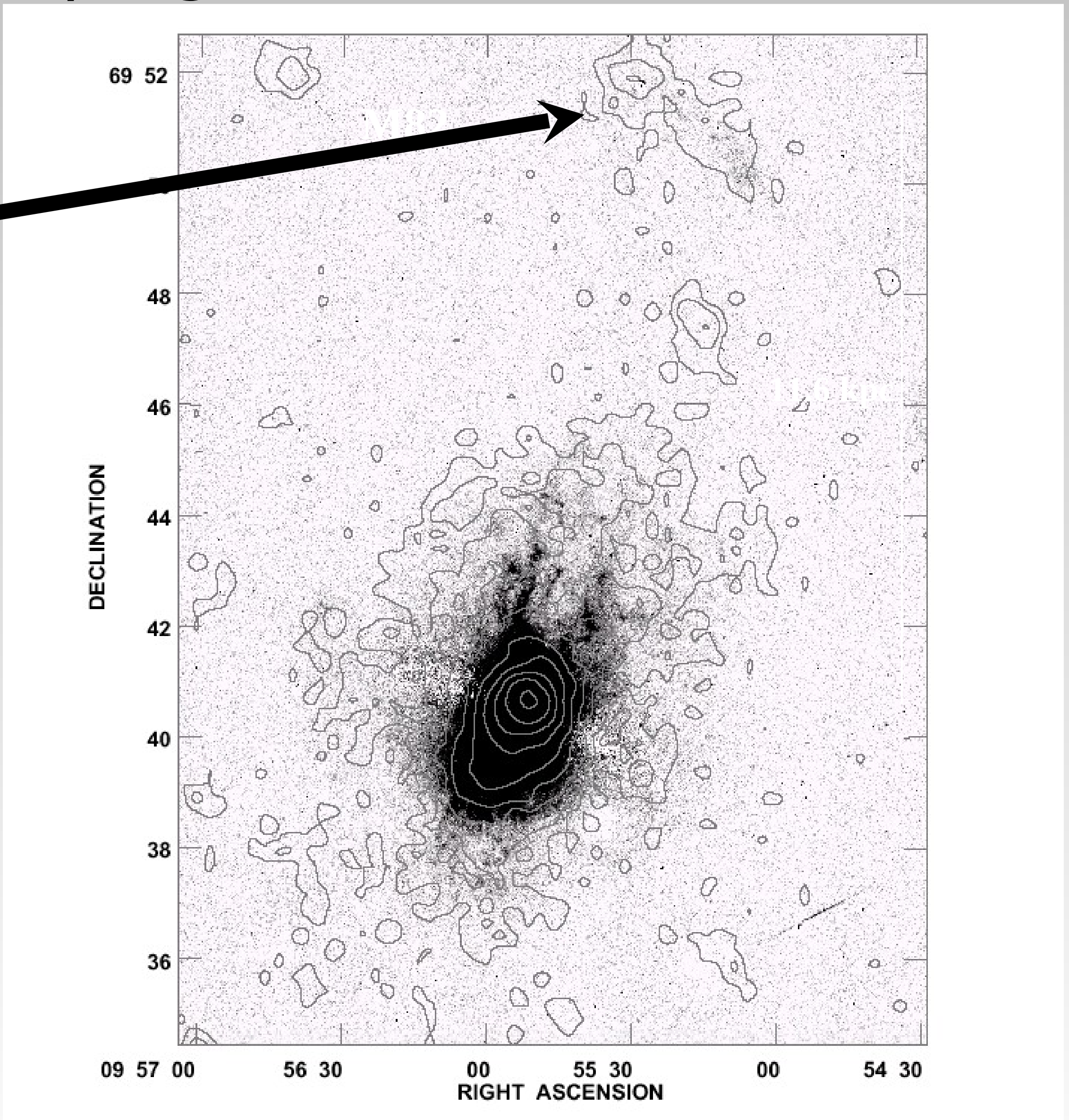
“Sudden” velocity decreases correspond to broad lines down stream. Interactions with halo clouds may be important.



Lehnert et al. in prep

Escaping Wind in M82

Region of spatially coincident X-ray and H-alpha emission



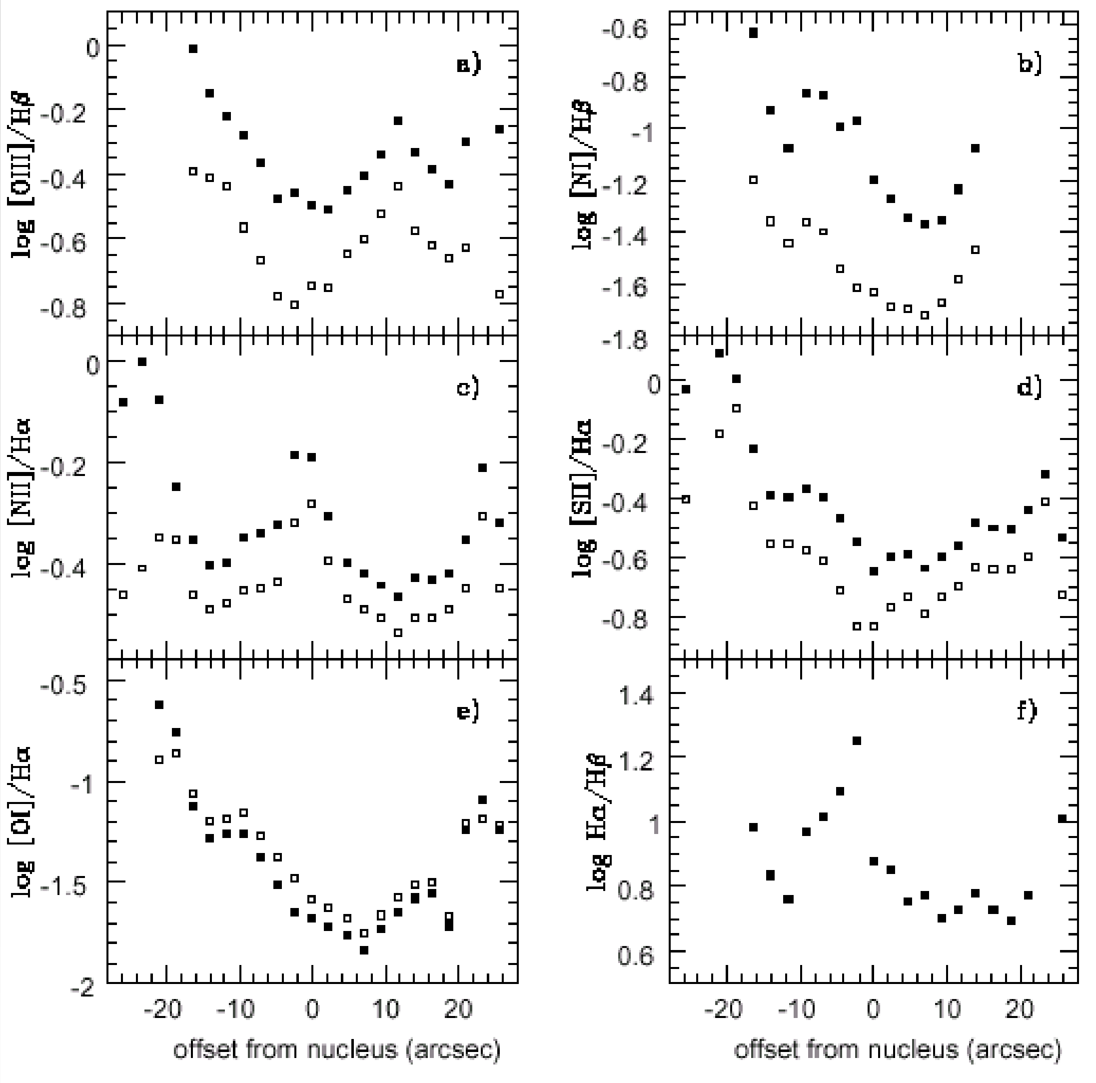
Characteristics suggest fast shock of 800 km s^{-1} being driven in an ambient halo cloud. $V_{shock} > V_{escape}$

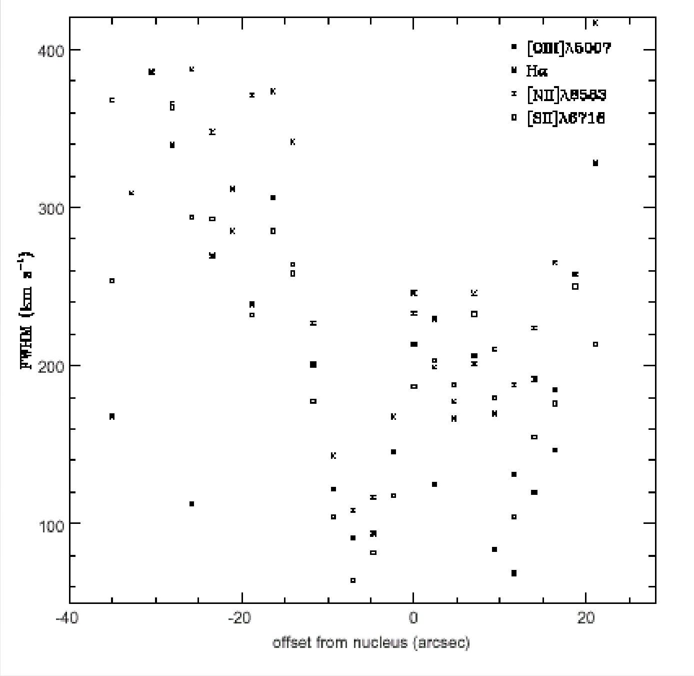
Escaping

Lehnert, Heckman, & Weaver (1999), reconsider this in Boulanger et al. in prep

Optical emission line gas

Line ratios become “shock-like”, not photoionized by massive stars … and broader



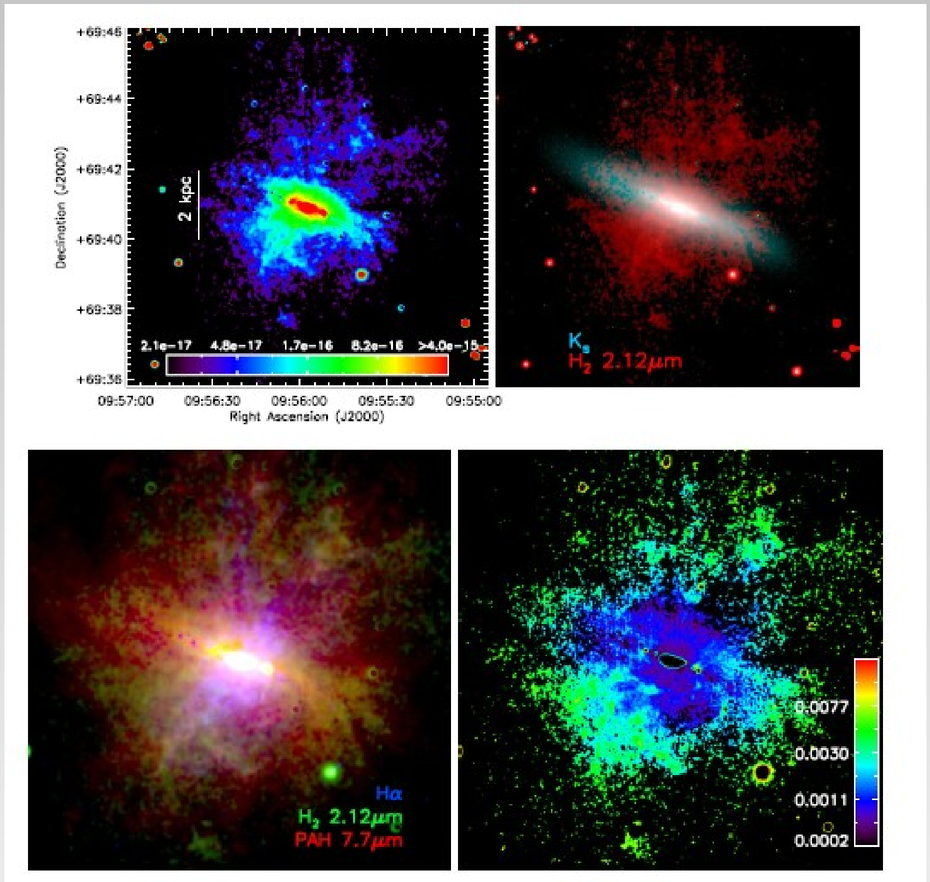


■= no correction

□= correction for extinction
and underlying absorption

Moran, Lehnert, and Helfand (1999)

Near-IR and Mid-IR Molecular emission



H_2-PAH ratio

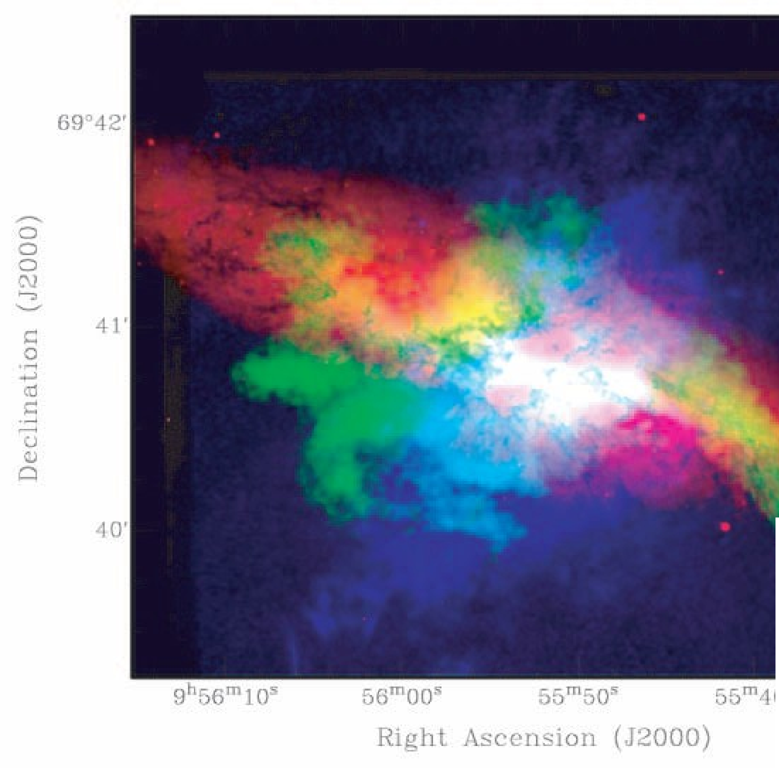
Warm H_2, PAHs, and H-alpha trace the same gas

-extends about 3 kpc above the plane
-likely to be shock heated – similar to the optical emission line gas
-authors favor entrainment and not significant energetically- it could be infall along the bridges to M81-NGC 3077

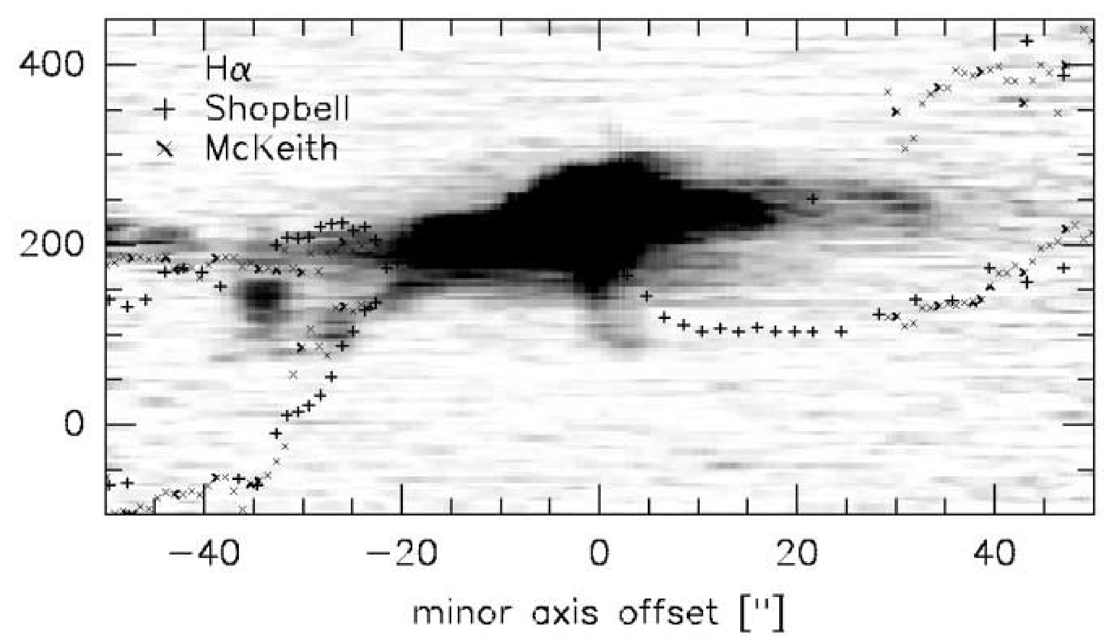
Veilleux et al. (2009)

Cold molecular emission

More evidence for entrainment?
CO and H_2 morphologies similar?



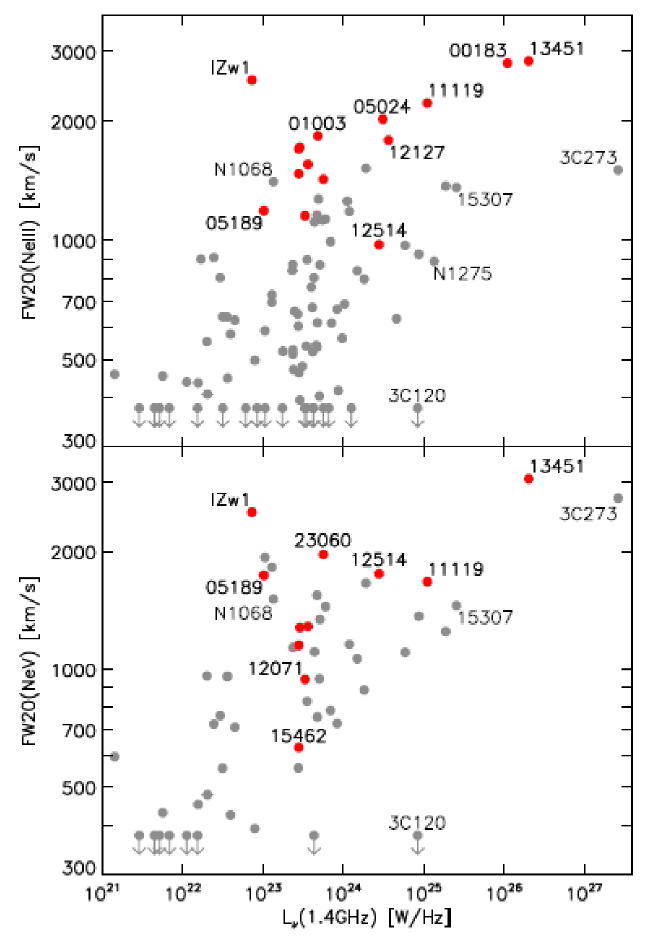
green CO emission
blue H-alpha emission

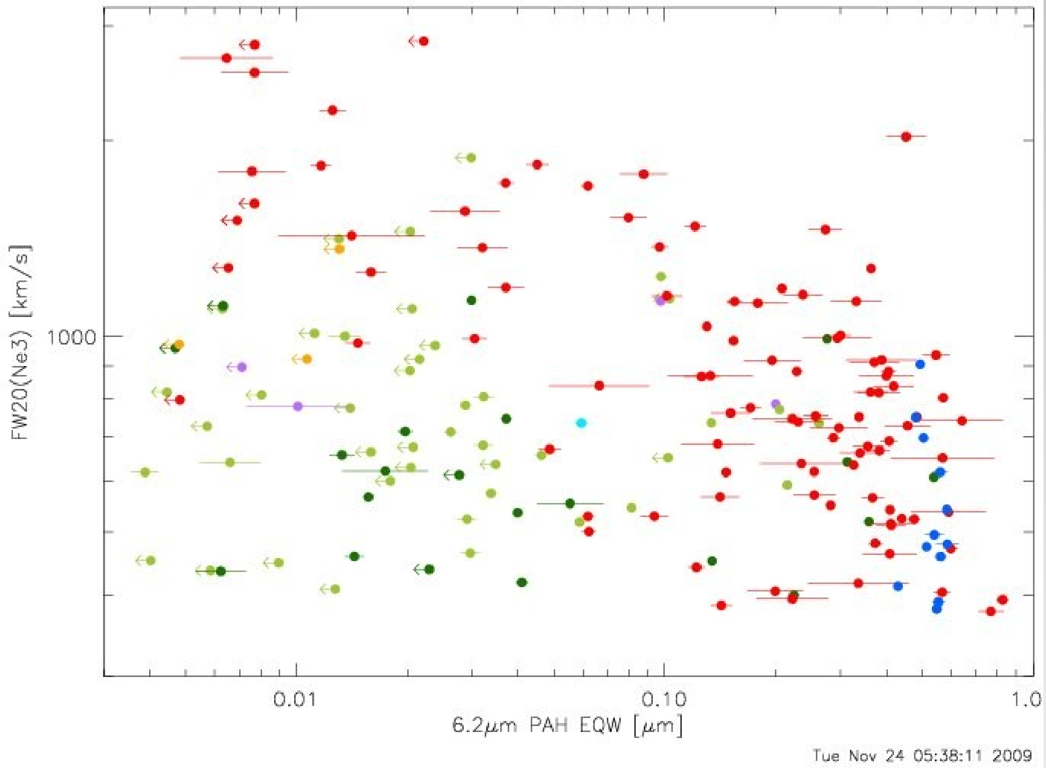


CO emission traces inner H-alpha kinematics

Walter et al. (2002)

Mid-infrared diagnostics





[NeIII]λ15.6µm and [NeV]λ14.3µm gas is turbulent and can have high offsets

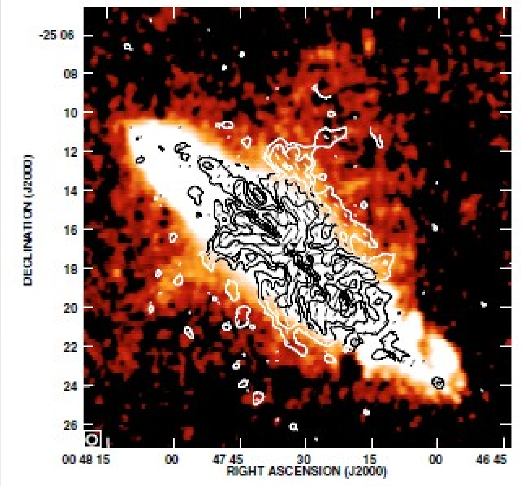
Radio sources are more extreme than star-bursts

Relationship between offset and width – mixing at interfaces

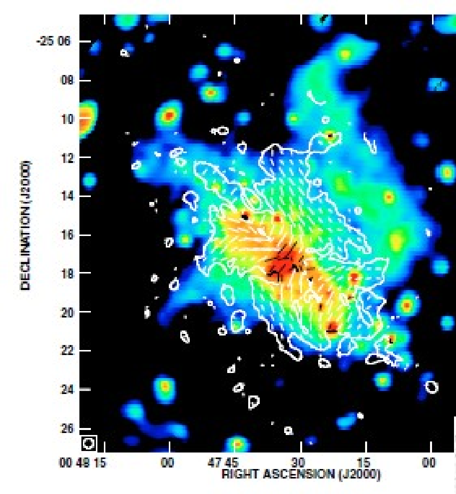
Not simply photoionized by AGN

Spoon & Holt (2009)
Spoon et al. priv comm.

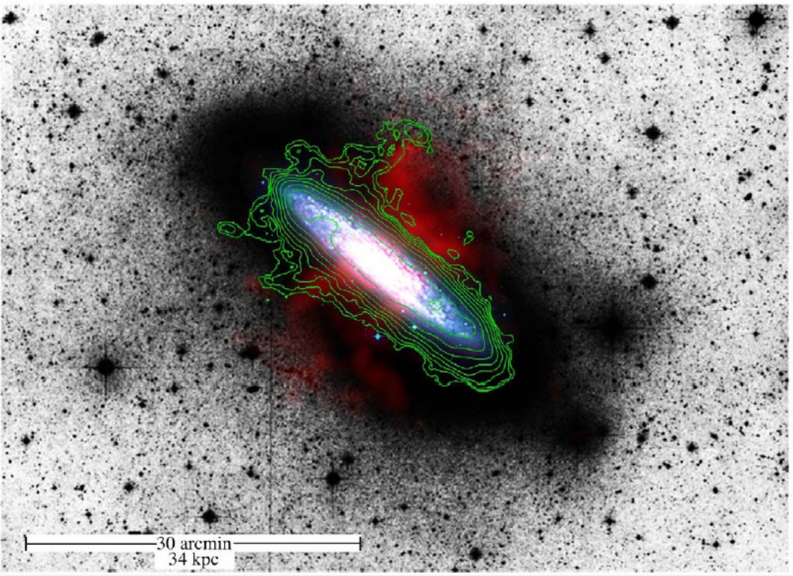
Relativistic Plasma and B-fields



B-field and H-alpha



B-field and X-ray



HI – green contours

High B-fields - 10-50 μG
Tied to disk but not in nucleus
CR convection speed about 300 km s^{-1}
External gas may contribute to B-field compression

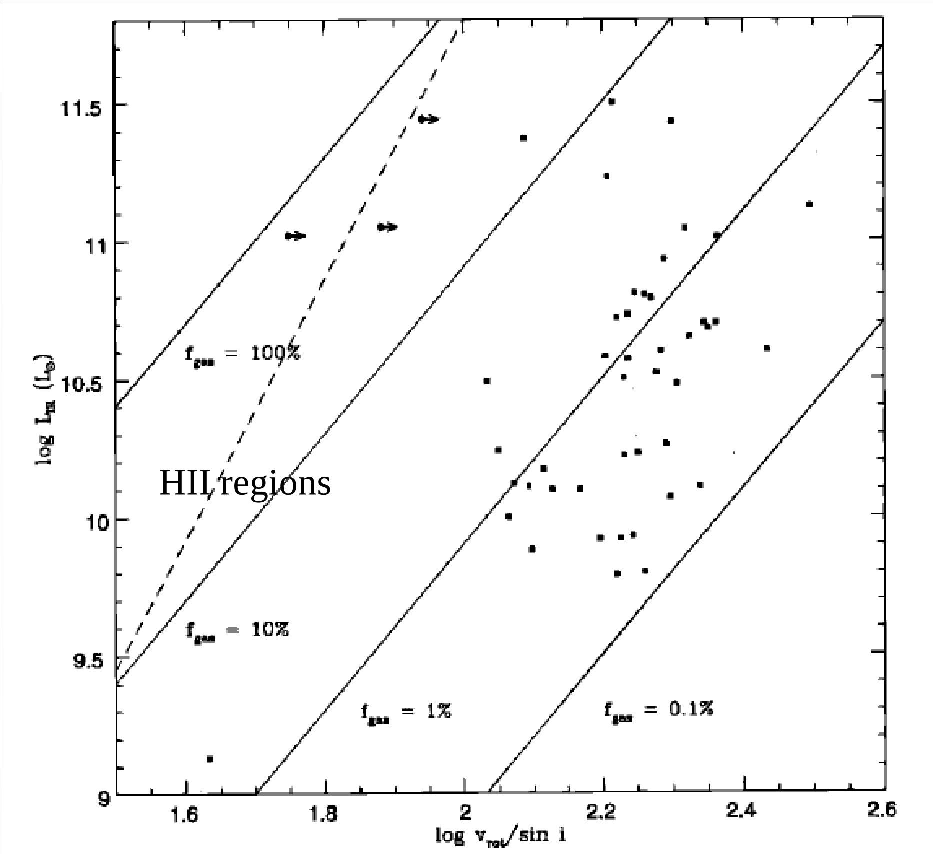
Heesen et al. (2009)
Boomsma et al. (2005)

But what limits the star-formation?

Is it the high mechanical energy?

Something else?

Causality Arguments



Limits to the availability of gas?

More powerful sources also follow this limit, but dynamics are more uncertain in mergers but consistent … no magic allowed

$$\dot{M}_{SFR,max} \approx M_{tot} f_{gas} t_{cross}^{-1} = 120\, v_{c,100}^{3} f_{gas} M_{sun}\, yr^{-1}$$

Lehnert & Heckman (1996)

Feedback and Self-Regulation

Could this be evidence for self-regulation?

Hydrostatic equilibrium implies,

$$P_{\mathrm{midplane}} = \tfrac{1}{2}\pi G \sigma_{\mathrm{tot}}\,\sigma_{\mathrm{gas}}$$

$$= 3 \times 10^{-10}\,(\sigma_{\mathrm{tot}}\,/10^{9}\,\mathrm{M}_{\odot}\,\mathrm{kpc}^{-2})\,(\sigma_{\mathrm{gas}}\,/10^{8}\,\mathrm{M}_{\odot}\,\mathrm{kpc}^{-2})\ \mathrm{dyn\ cm}^{-2}$$

Local starbursts have,

$$dp/dt_{\mathrm{winds}} \approx 3 \times 10^{34} L_{\mathrm{IR,11}}\ \mathrm{dyn}$$

Heckman et al. (1990), Lehnert & Heckman (1996)

$L_{\mathrm{IR}} \approx 4.6\times10^{12}\ L_{\odot}$ for SMM14011+0252

Tecza et al. (2004)

"self-regulation"

$$P_{\mathrm{midplane}} \approx P_{\mathrm{wind}}$$

Lehnert & Heckman (1996); Nesvadba et al. (2007)

Summary of Nearby Starbursts

Self-regulation of star-formation and galaxy growth:

Must understand the multi-phase ISM

Energy injection and dissipation/advection rates.

SF limited by gas supply or too much energy injection?

Dissipation depends on the physical characteristics of the “piston”

Energy is dissipated one wide range of scales as the wind density is very low...

$$v_{shock} \approx v_{wind} \left(\frac{\rho_{wind}}{\rho_{cloud}}\right)^{1/2}$$

Both causality and pressure/energy arguments are useful for understanding limits to star-formation intensities.

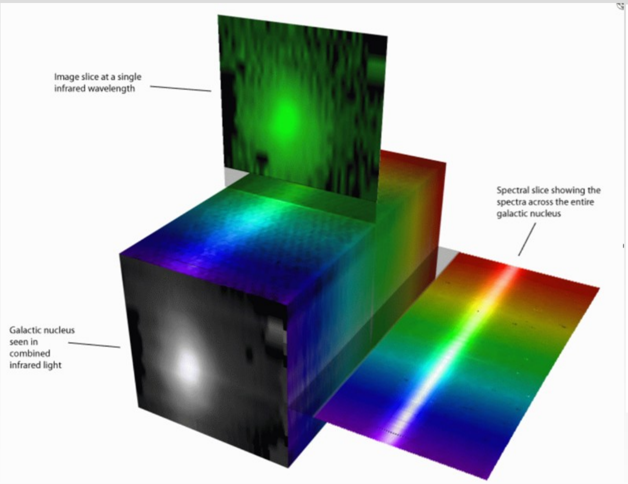
What about at high redshift?

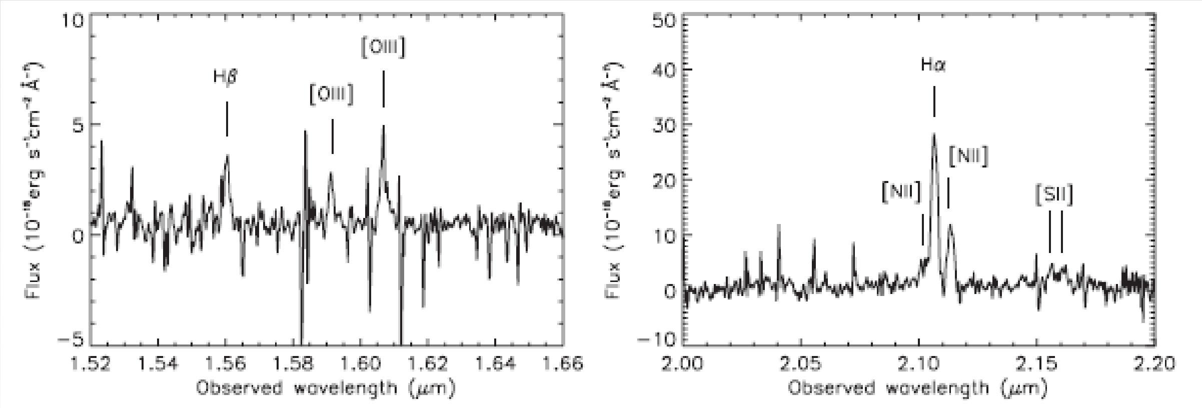
Can we apply these lessons to high redshift?

A large sample of star-forming galaxies observed with SINFONI (z=1-3)

Typically have rest-frame optical lines, Hα, [NII]λλ6548,6583, [SII]λλ6716,6731, sometimes [OI]λ6300, and a few spectra in the blue optical with [OIII]λλ4959, 5007 and Hβ.

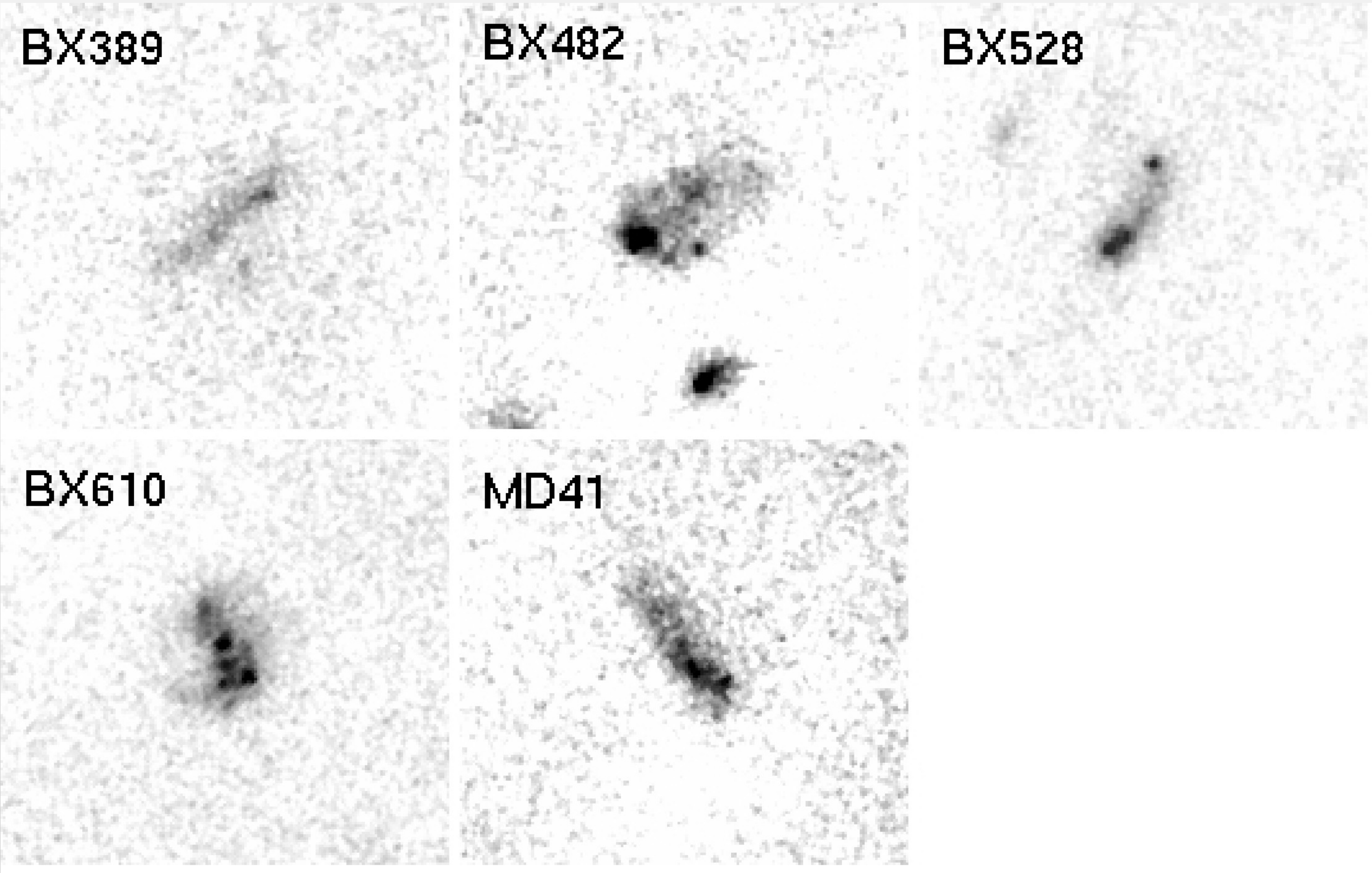
Much of this is/will be in the thesis of Loic Le Tiran – will discuss some “sub-samples”





Studies at high-z

This is what the mass distribution looks like in some of them ...

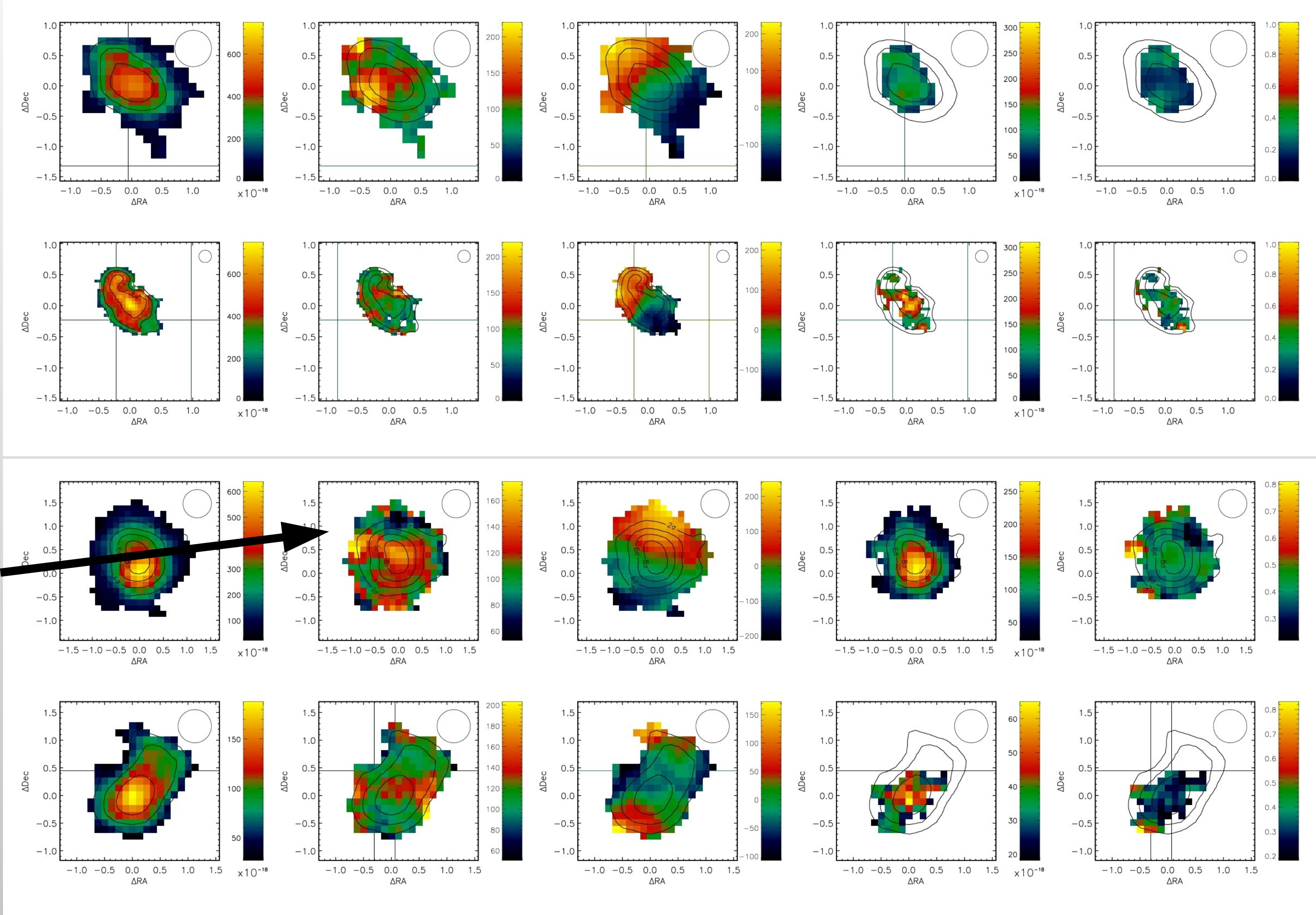


Deep H-band NICMOS images of 5 of them.

Lehnert et al. (2009)

SINFONI Data

Hα flux σ v-field [NII] flux [NII]/Hα

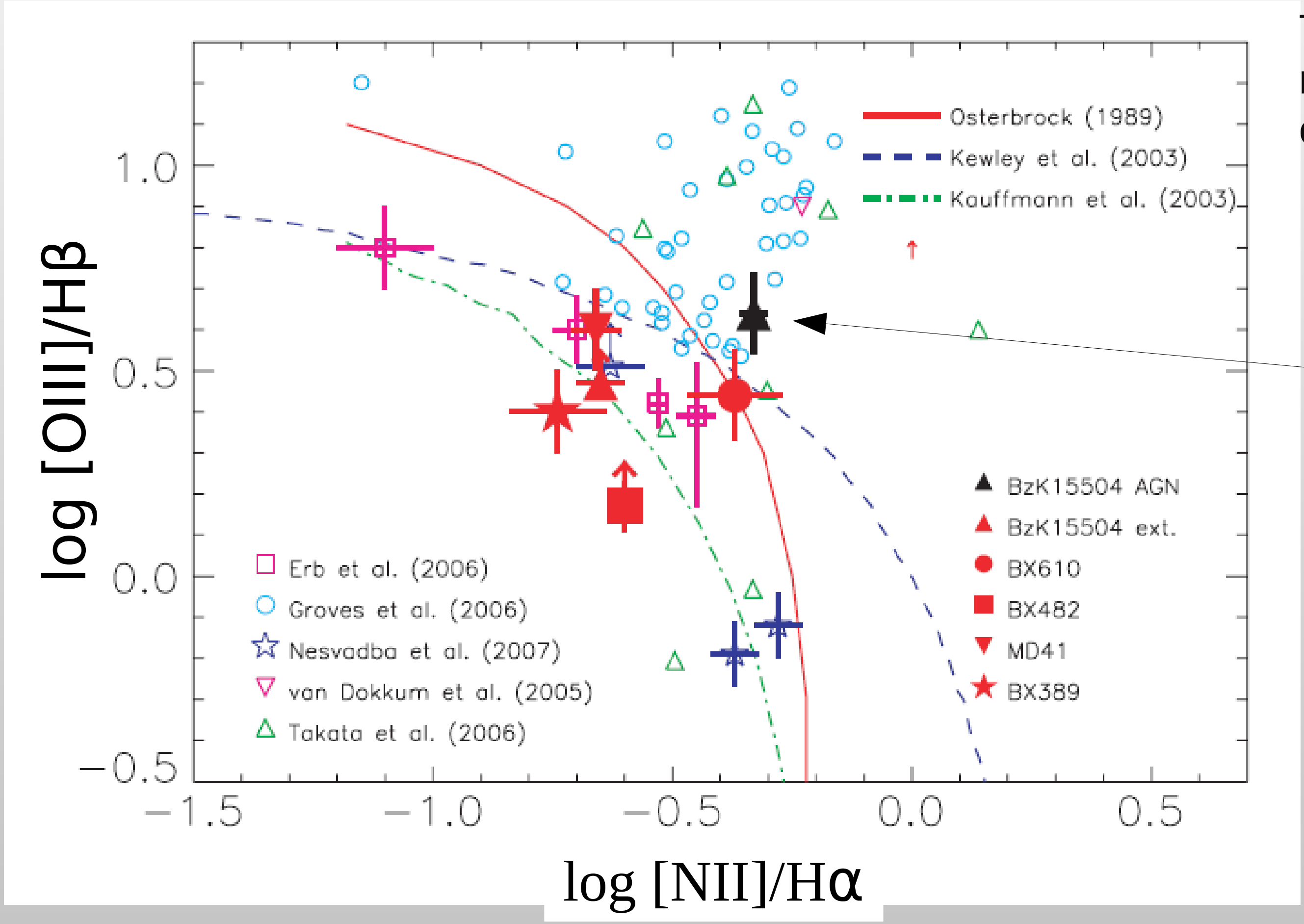


wind?

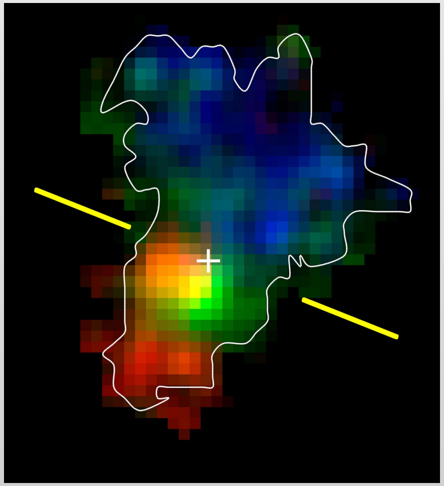
Lehnert et al. (2009)

Emission line ratios

High densities and moderate ionization parameters ...



This is the archetypal rotating disk … with an off-center powerful AGN!

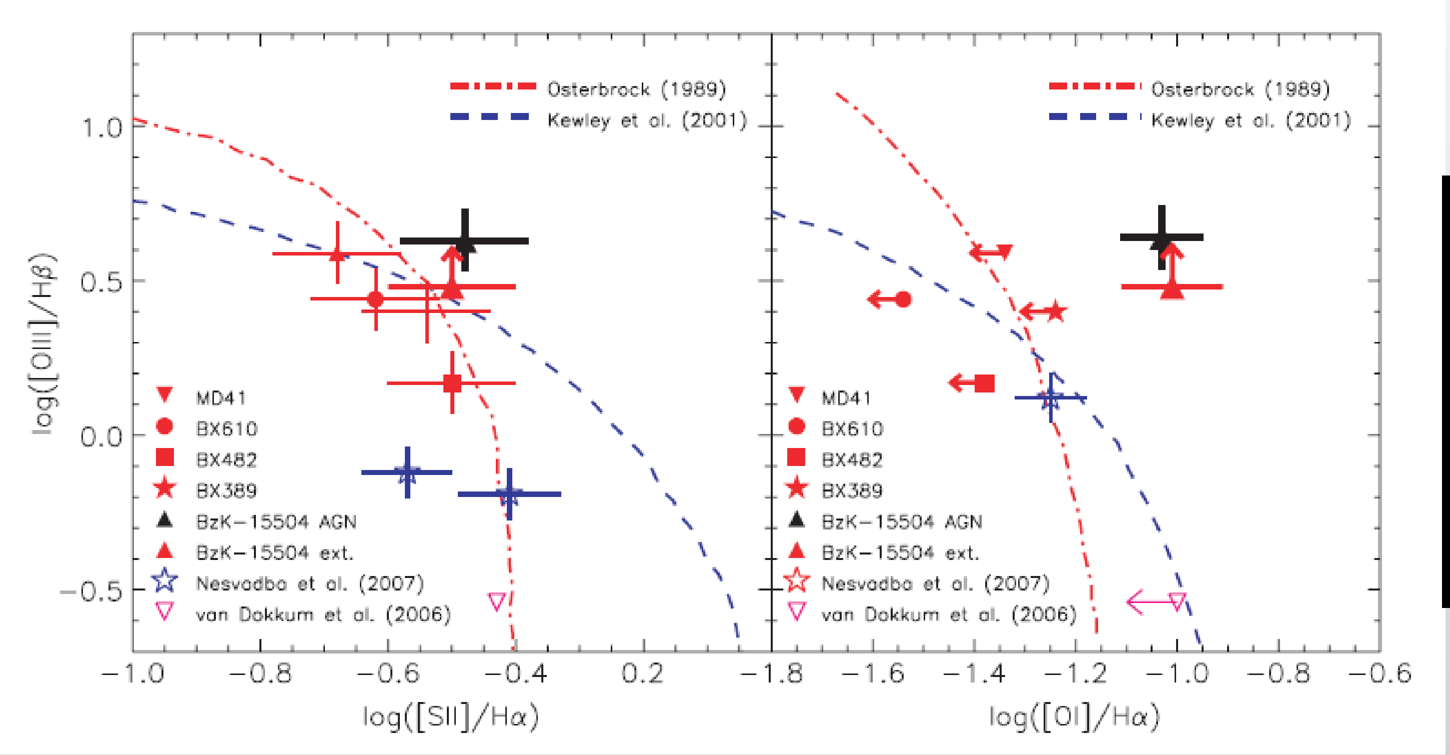


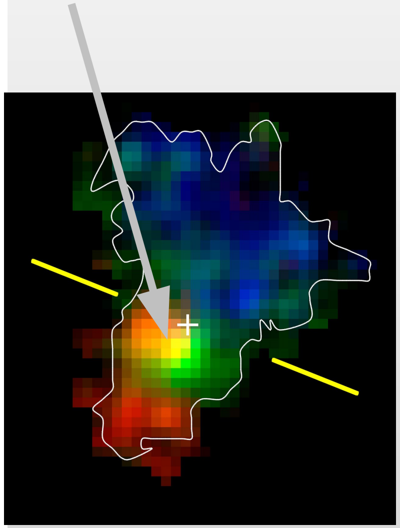
Genzel et al. (2006)

Lehnert et al. (2009)

Emission line ratios

Even weak lines are detected ...





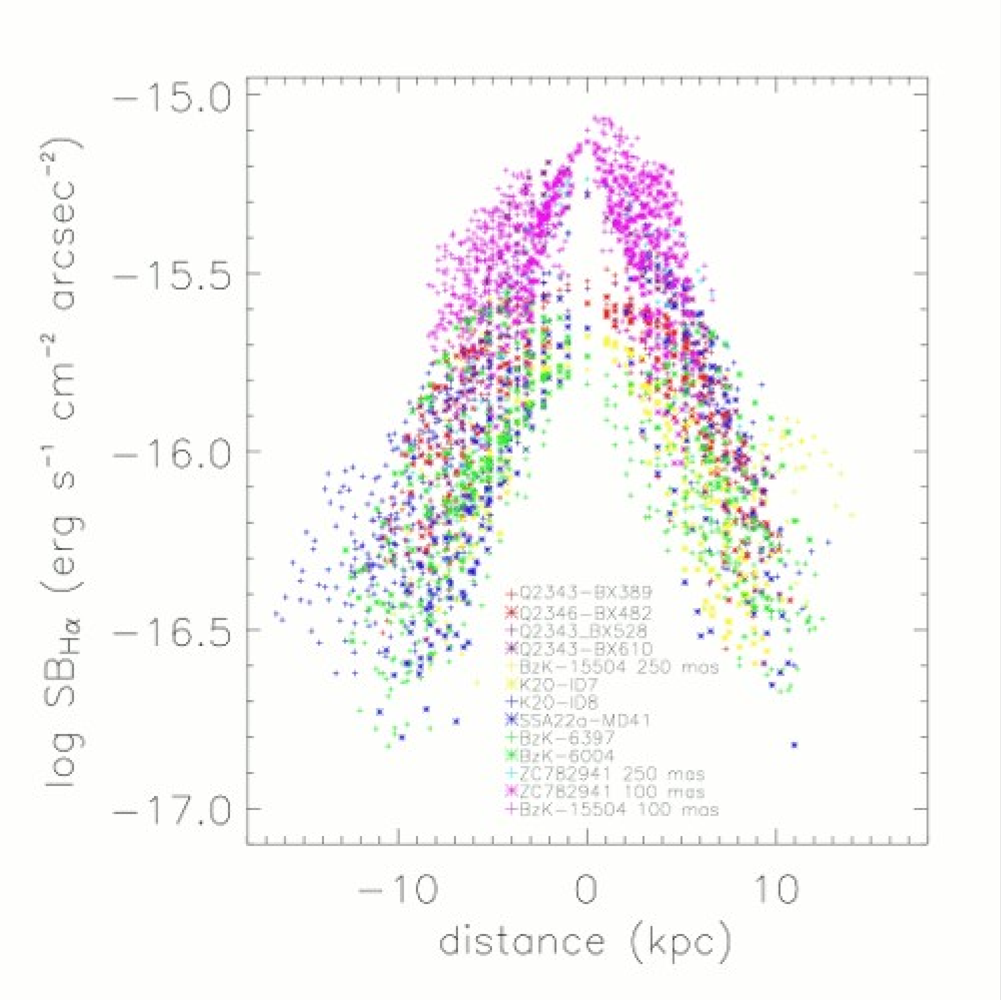
nucleus here

Mostly look like star-forming galaxies … except for BzK-15504, which is a giant QSO narrow line region like NGC 1068 (Veilleux et al. 2003) ...

Lehnert et al. (2009)

High Surface Brightnesses

All have very high surface brightnesses ...

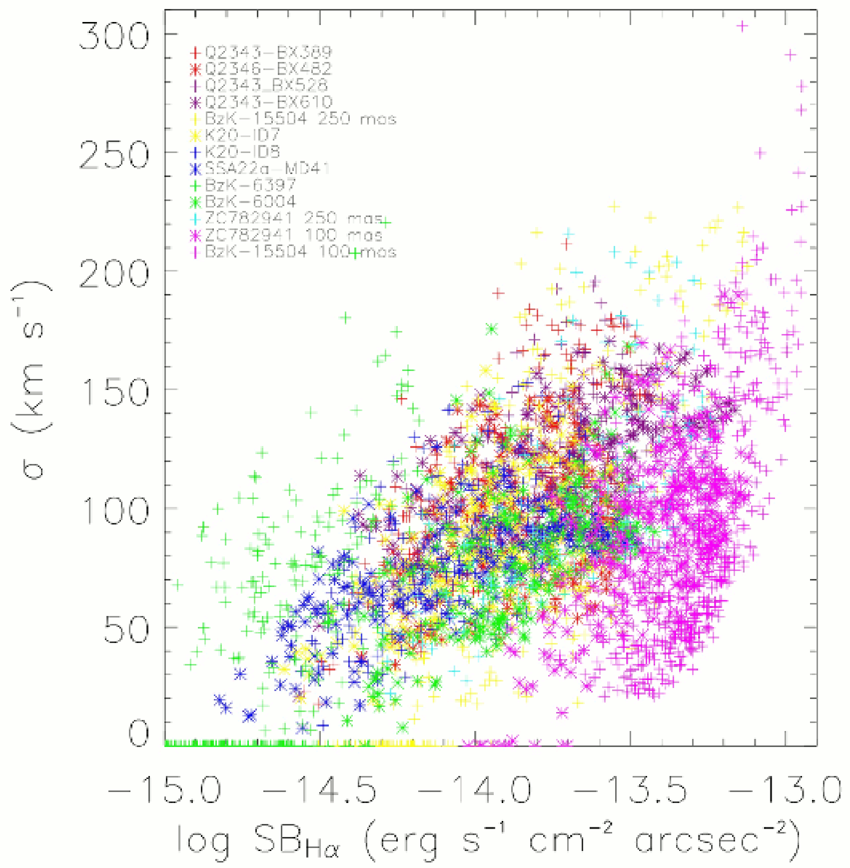


The only galaxies in the local Universe that come close are galaxies like M82 and some ULIRGs … but only on scales of a few kpc of less … not 20 kpc! These are monsters and star-formation must be really important.

Lehnert et al. (2009)

High Surface Brightnesses

Surface brightnesses are related to line widths ...

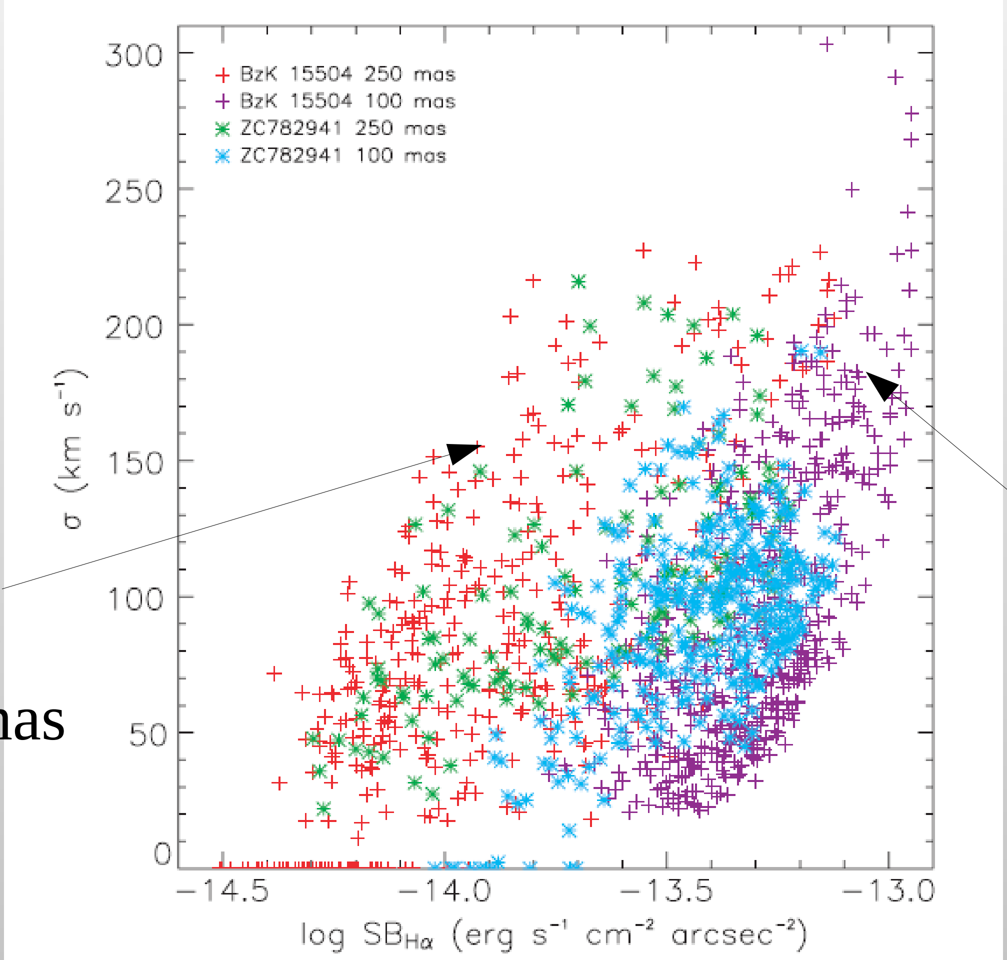


For our sample of 11 galaxies ...

Lehnert et al. (2009)

High Surface Brightnesses

Not due entirely to resolution ...



Appears to be a relationship between surface brightness and velocity dispersion …

Resolution … no … AO and non-AO show the same

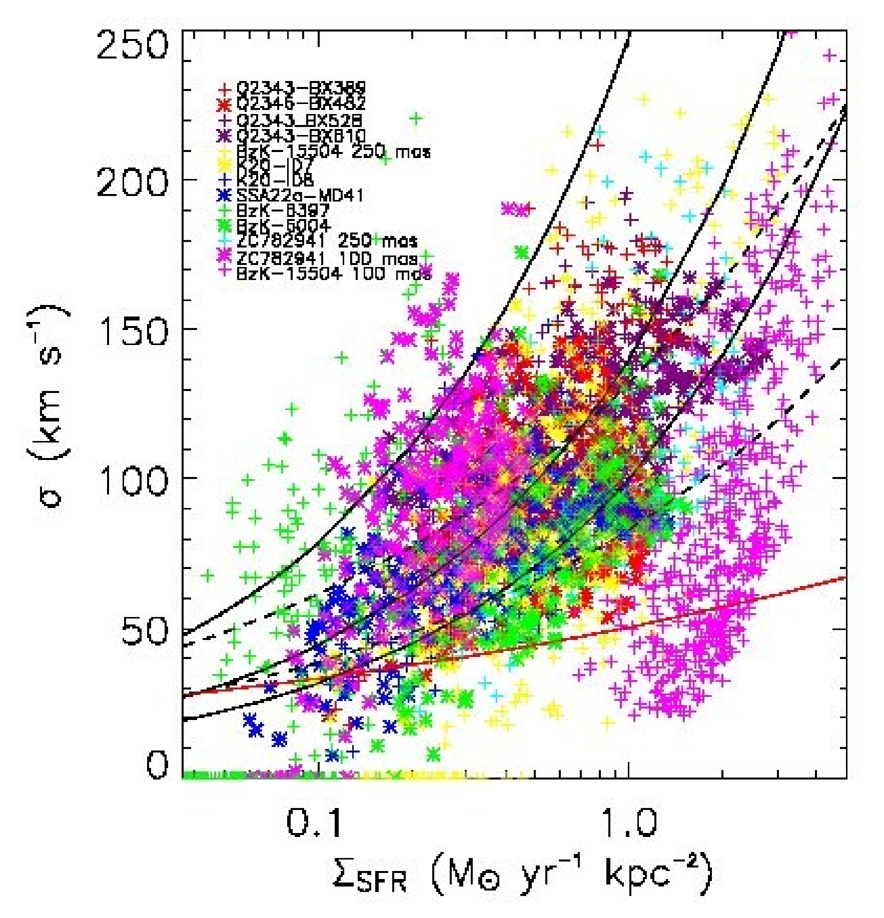
No AO
~500 mas

AO ~100 mas

Lehnert et al. (2009)

High Surface Brightnesses

To star-formation intensity ...

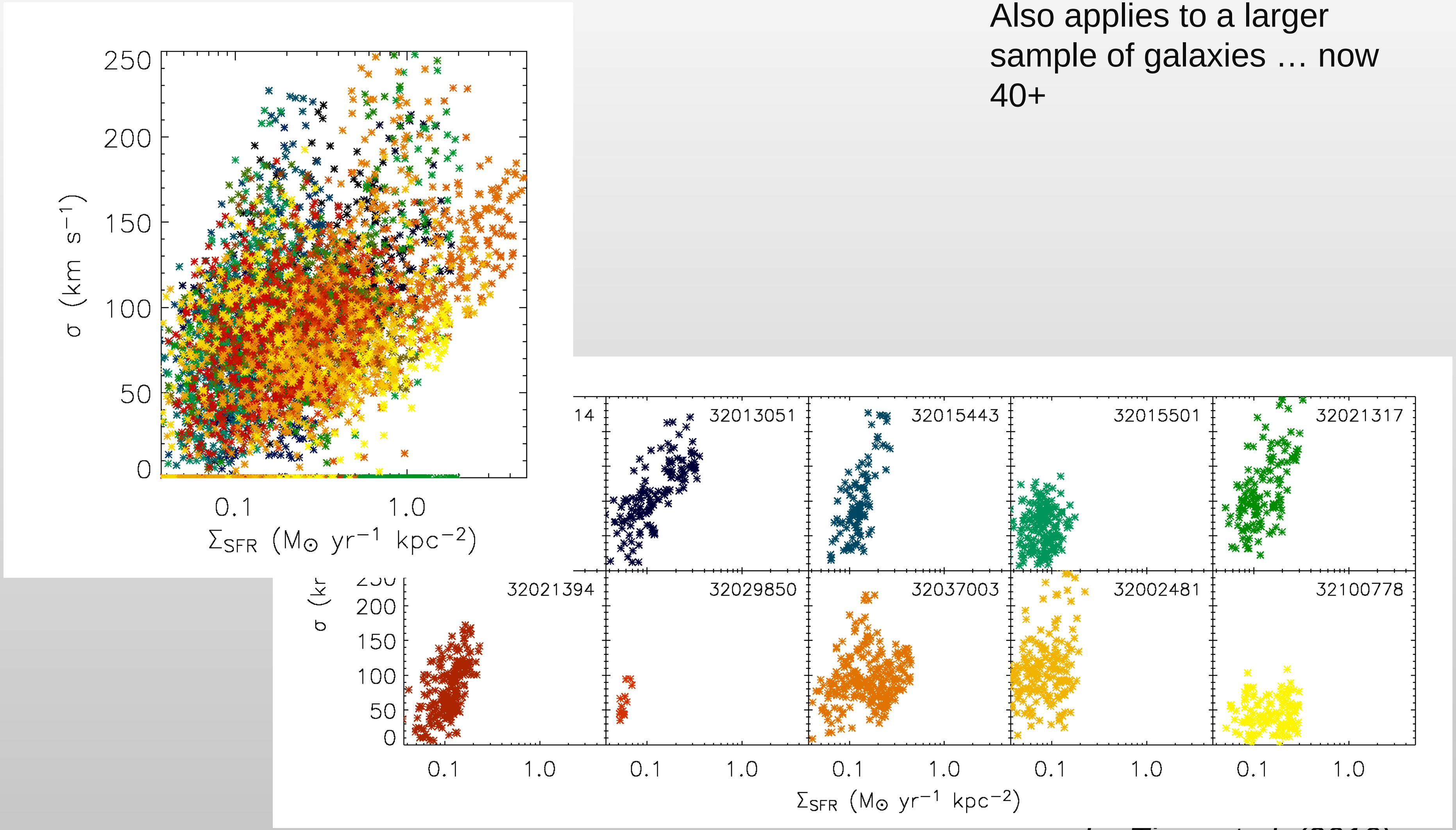


Lehnert et al. (2009)

High Surface Brightnesses

Surface brightnesses are related to line widths ...

Also applies to a larger sample of galaxies … now 40+



Le Tiran et al. (2010)

Is this due to Cosmological gas accretion?

Heating rate due to accretion is:

$$\dot{\mathrm{E}}_{heating} = \mid \Delta\phi \mid \dot{M}_{\rm gas} = 4.8 \dot{M}_{\rm gas} V_c^2 \\ = 10^{43.1} \dot{M}_{\rm gas,100} V_{c,200}^2 \ \mathrm{erg\ s^{-1}}$$

Dekel & Birnboim (2008)

Dissipation due to turbulence:

$$\dot{\mathrm{E}}_{\rm kin} \simeq -n_\nu m \tilde{k} v_{\rm rms}^3$$

MacLow (1999)

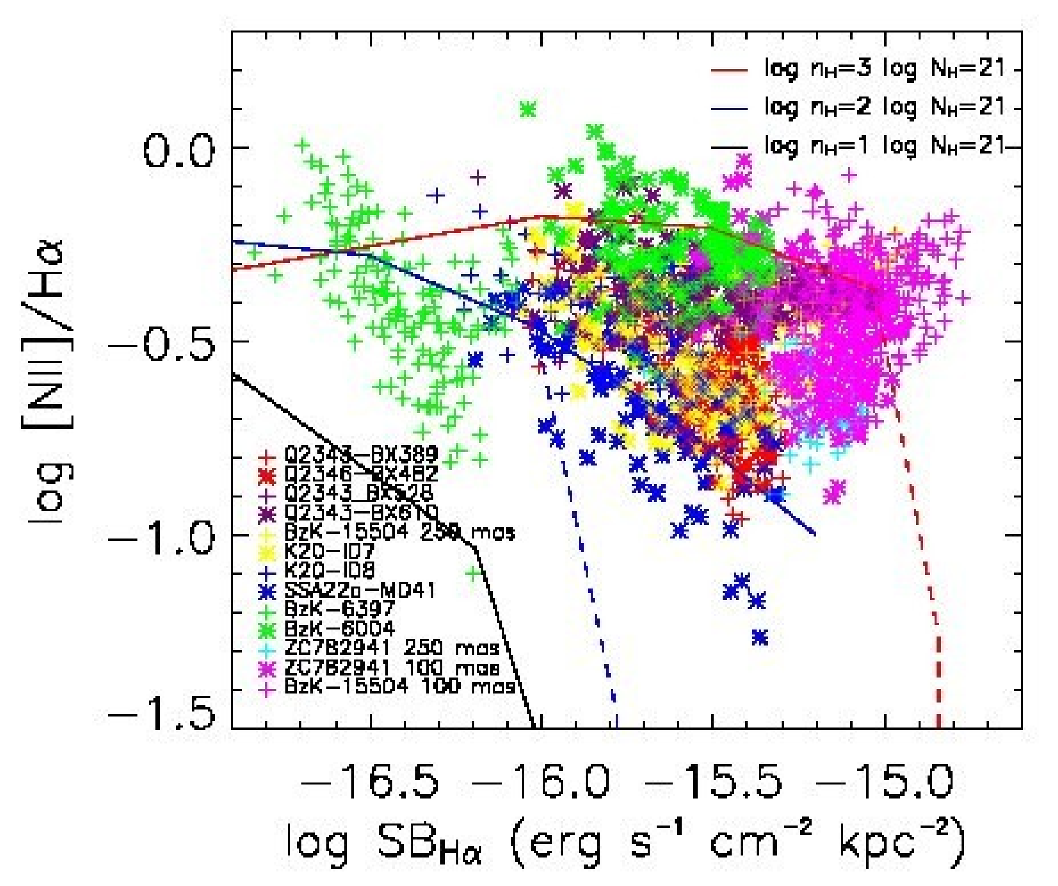
v_{rms}	rms velocity
$\tilde{k}$	driving wavenumber
n_ν	proportionality constant

If gas accretion is dissipated as super-sonic turbulence (2% in Hα), then it under-predicts, the Hα flux by about two orders of magnitude, even w/ >100 $M_\odot$ yr^{-1}. The total energy dissipated is about $10^{44.3}$ erg/s. This emission is not driven by accretion flows.

Le Tiran et al. (2010)

ISM reaches high densities

High densities and moderate ionization parameters ...



Photoionization of clouds of high column densities …

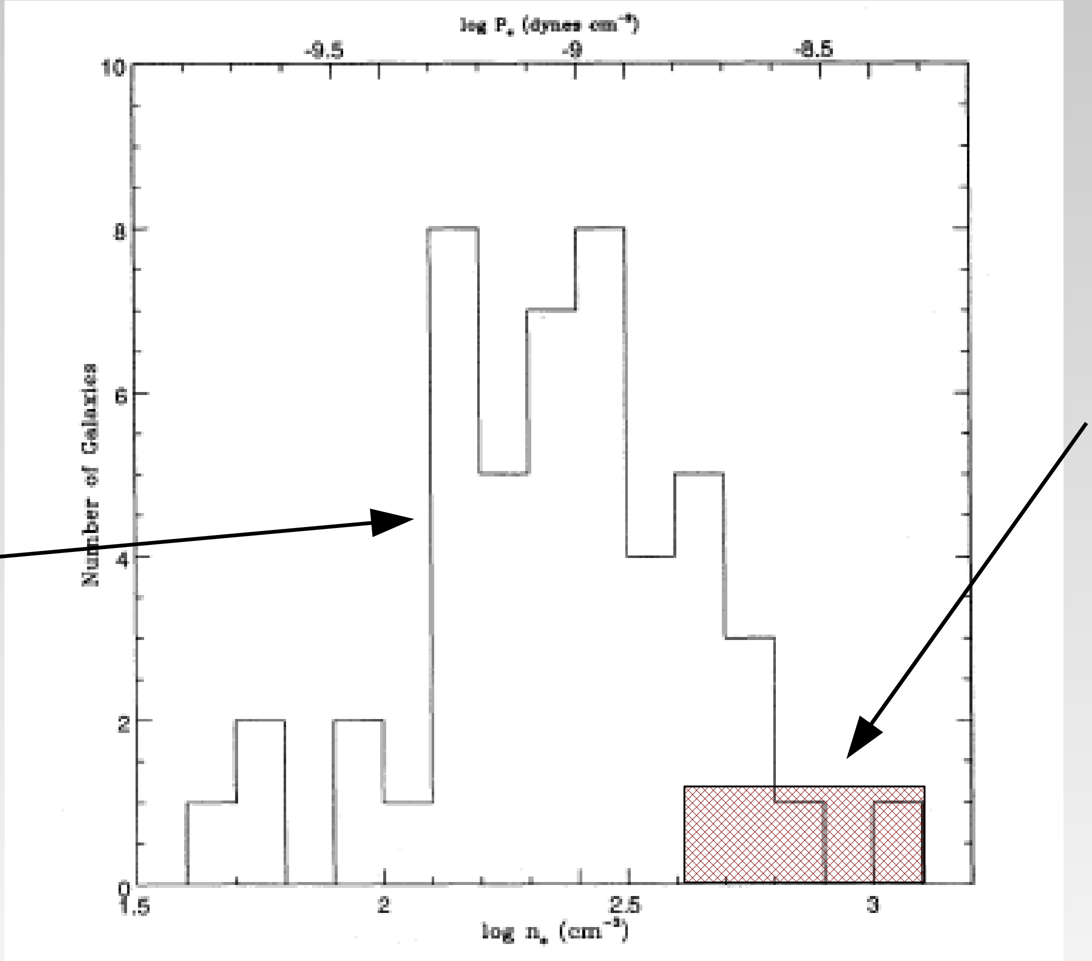
Implies that clouds have high thermal pressures … much higher than in the MW and more like M82 …

[SII]λ6716/[SII]λ6731 suggests $P/k=10^{6-7}$ K

Explains why galaxies high extremely high surface brightnesses necessary for good IFU observations

Lehnert et al. (2009)

Optical Emission Lines – High Pressures



4 z~2 galaxies w/
[SII]λλ6716,6731

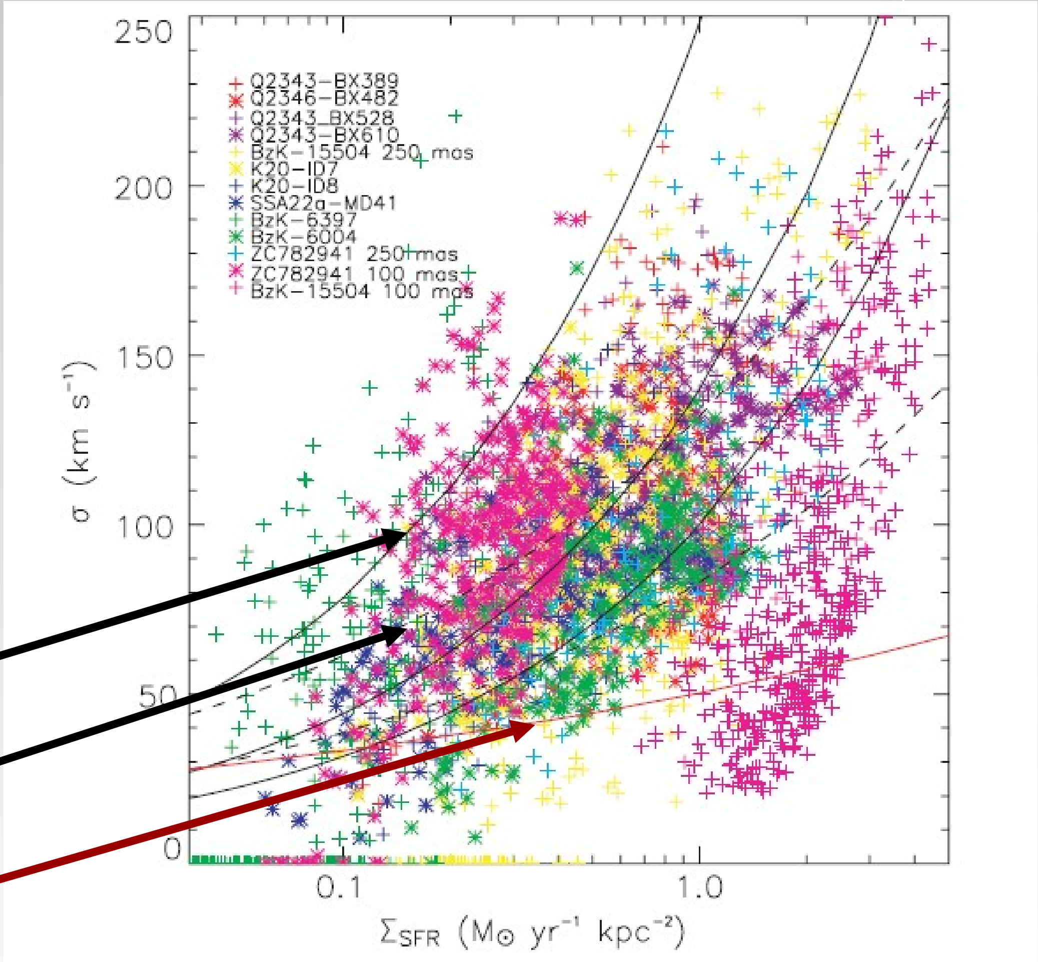
50 IR warm local
galaxies

More to come ...

Lehnert et al. (1996), Lehnert et al. (2009)

Star-formation regulates the ISM

Many distant galaxies have H-alpha surface brightness well above nearby galaxies. M82-like over 10-20 kpc



Self regulation:

- shocks
- cloud-cloud collisions
- pressure and turbulence regulated ISM

Likely not completely explained by gravitational instabilities

$\Sigma_{SFR} \approx 5\times10^{-2}\ M_\odot\ yr^{-1}\ kpc^{-2}$ drive outflows; Lehnert & Heckman (1996), Heckman (2001)

$$\sigma = (\epsilon \Sigma_{SFR})^{1/2}$$

$$\sigma = (\epsilon \Sigma_{SFR})^{1/3}$$

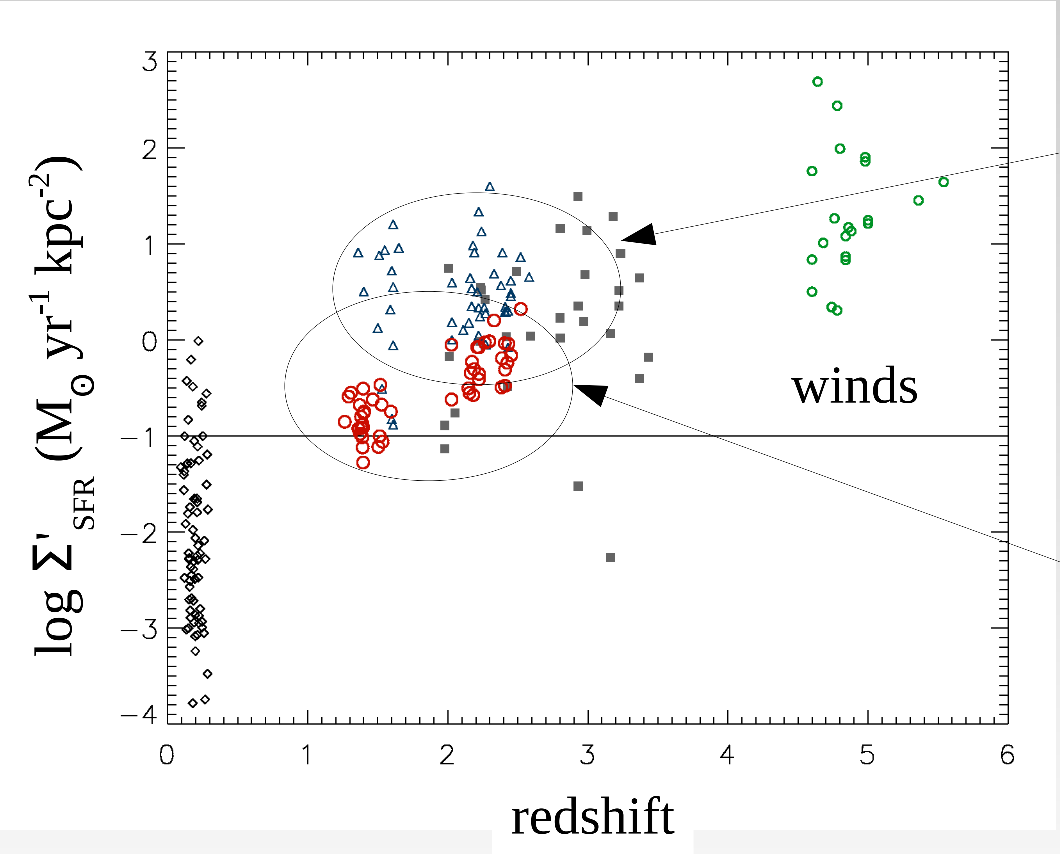
Jeans Instability for $10^9\ M_\odot$ clump

$$\sigma_{gas} \sim M_J^{1/4} G^{1/2} \Sigma_{gas}^{1/4} = 54 M_{J,9}^{1/4} \Sigma_{SFR}^{0.18}\ \mathrm{km\ s^{-1}}$$

Lehnert et al. (2009)

Star-formation Intensities

SF Intensity of UV starbursts over a range of epochs ... not surprisingly, they likely drive winds ...



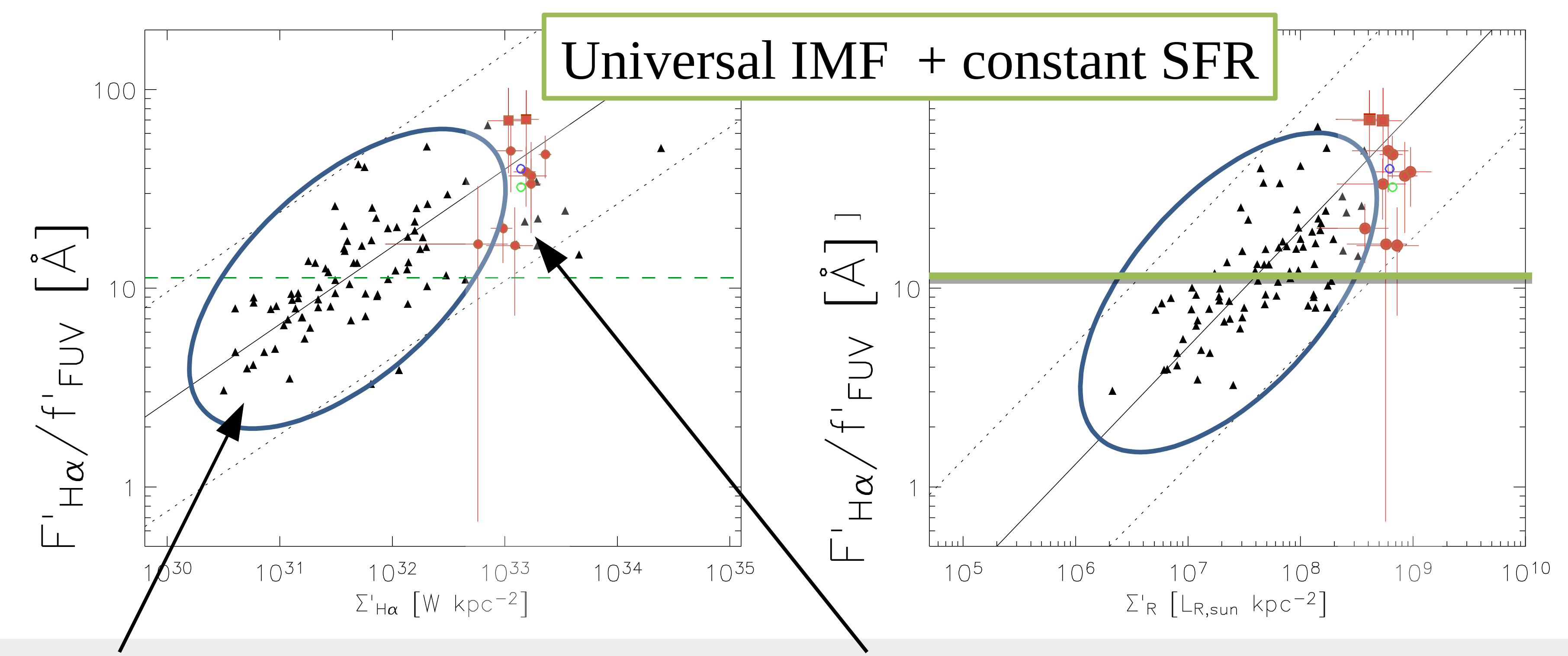
SINS sample, Forster-Schreiber et al.

40+ galaxies discussed here

Le Tiran et al. (2010), Lehnert et al. (2007), Verma et al. (2007), Papovich et al. (2004), Heckman et al. (2000)

Bursty Star-formation or IMF

Fundamental relation between Hα and far-UV … IMF … different SF histories



Universal IMF + constant SFR

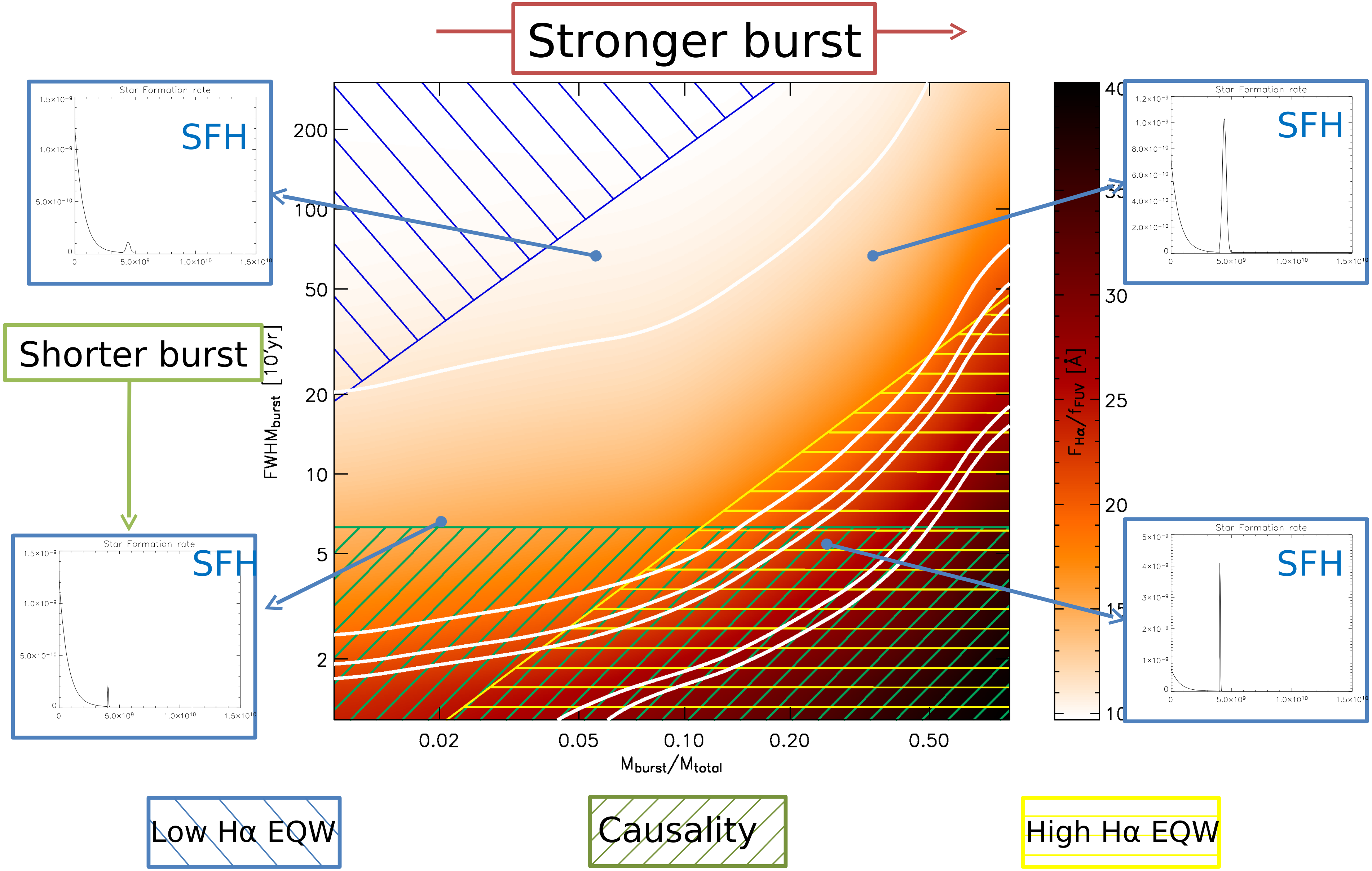
local HI selected galaxies

Massive star-forming galaxies at z~1.4

Single parameter family that distant galaxies follow ...

Meurer et al. (2009); Le Tiran et al. (2010)

Burst of Star Formation?



Stronger burst

Shorter burst

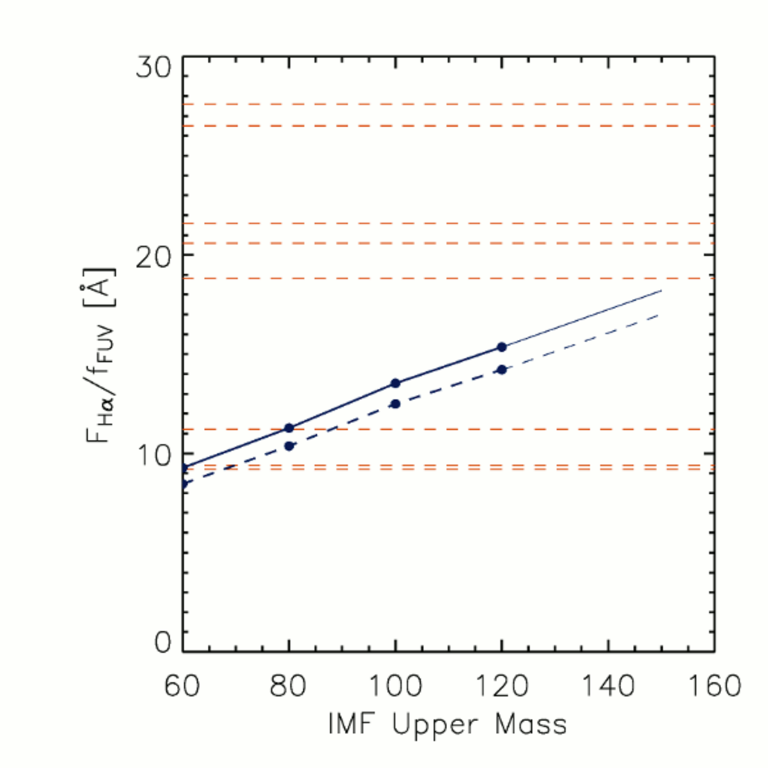
Low Hα EQW

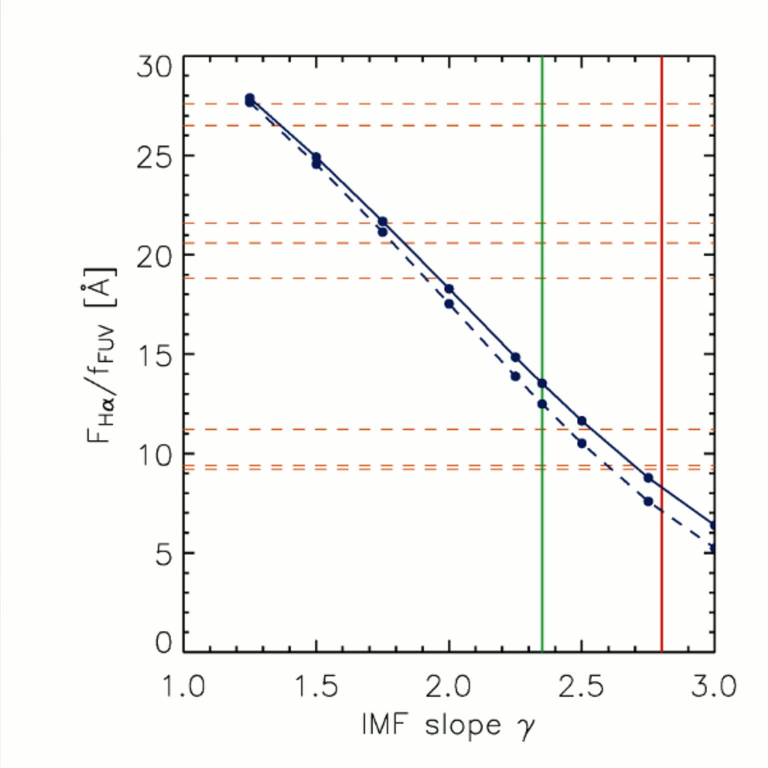
Causality

High Hα EQW

IMF appears plausible

Modelling with B&C and SB99 suggest that an IMF variation is OK, but slope is more effective ...





Helps to explain the high surface brightnesses … so would higher star-formation efficiency ...

Le Tiran et al. (2010)

Conclusions … sort of …

Superwinds are manifestations of starbursts – ubiquitous – and we can learn a lot from them to interpret galaxies in the high-z universe

Winds/self-regulation are manifestation of the collective thermalization of St. winds and SNe

“Piston” has yet to be observed in detail – emissivity very low – but winds are mass loaded

Radiative cooling is not important … neither is gravity … can some gas escape even in massive halos?

Complex interaction between phases: mixing layers, cloud entrainment and disruption, convection of cosmic rays, enhancement of B-field and advection, conduction (?), interaction halo gas (additional cooling), range of velocities and hence escape … can only determine where the energy goes by considering a range of phases.

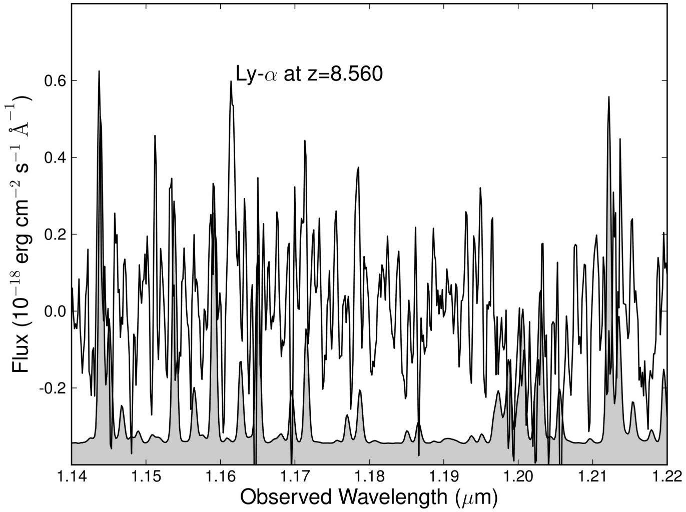
Causality and self-regulation are likely to be both important

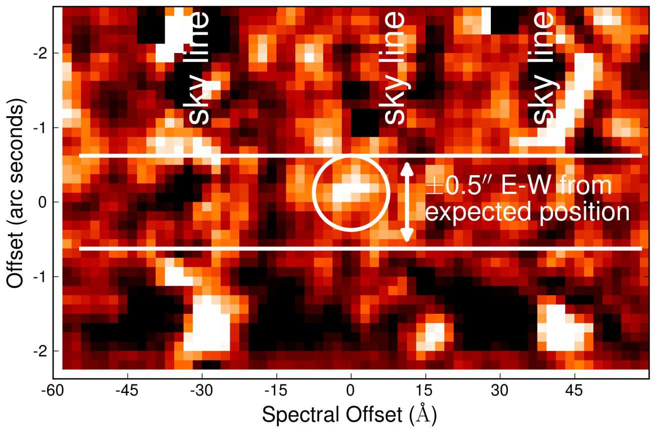
Starbursts in the distant universe exhibit some of the same phenomenology but overall heating/cooling rates may be larger – the high SB is a selection effect.

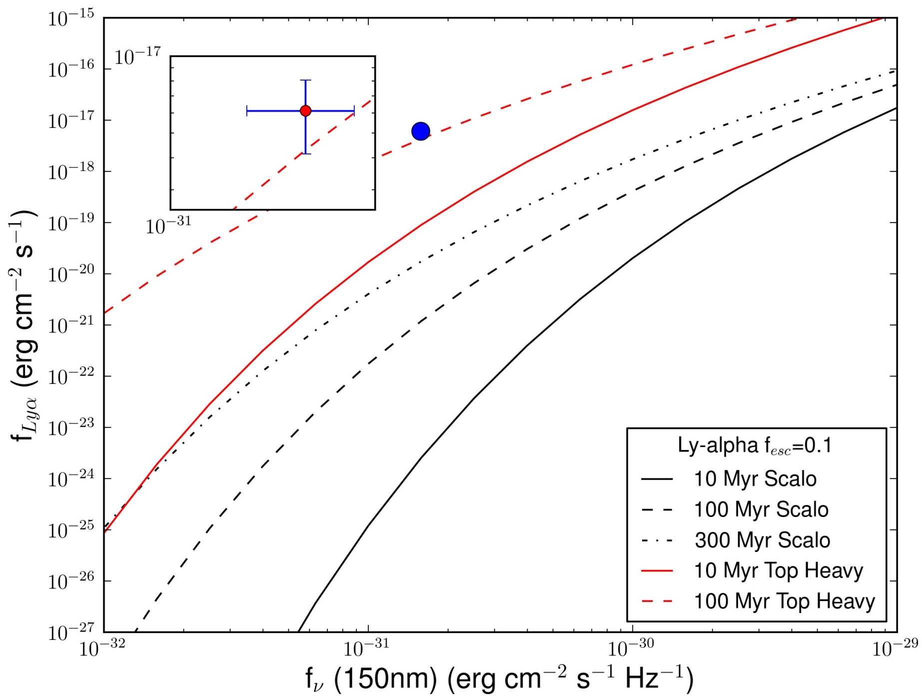
The high turbulence of the ISM – it is turbulence moderated – may influence the IMF and “star-formation efficiency” (10-30%) – the higher pressures may skew this – either could help to explain high SBs – gas accretion not powering the line emission.

Arguments in Lehnert et al. (2009) are naïve … I have lots to learn!

The most distant galaxy?







Lehnert et al. (2010) to appear in Nature Oct 21