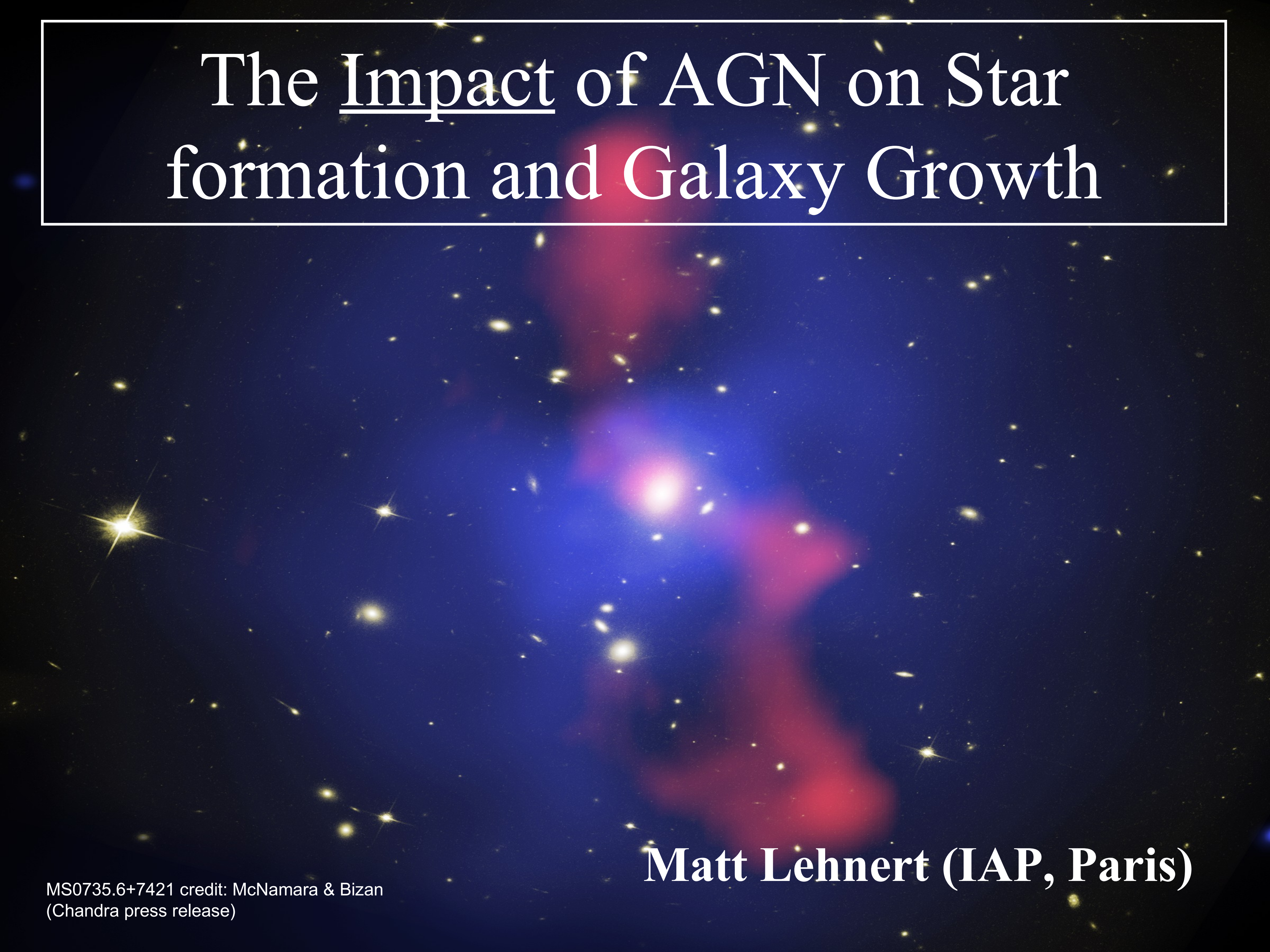
The Impact of AGN on Star formation and Galaxy Growth



Matt Lehnert (IAP, Paris)

MS0735.6+7421 credit: McNamara & Bizan
(Chandra press release)

Cosmological Perspective

Since the late 1960s, we have made substantial progress in physics.

We now have:

A standard model for particle physics

A standard model for cosmology with tightly constrained parameters

A solid frame work for understanding the growth of structure – ΛCDM

We are here to understand the non-linear growth of structure and how the baryons follow this growth.

Why is this perspective relevant?

This non-linear growth is simply driven by gravity

Further growth can be understood as other processes trying to regulate the collapse of structures through gravity:

- cold accretion/cooling of halo gas (instabilities important)
- disk instabilities and clumps
- star formation
- generation of radiative and mechanical energy from AGN ….

Via the virial theorem, about half of this gravitational energy is feeding a turbulent cascade …

My Summary of Galaxy evolution (ala Hopkins)

$$P_{final}(k) = \Pi P_i(k)$$

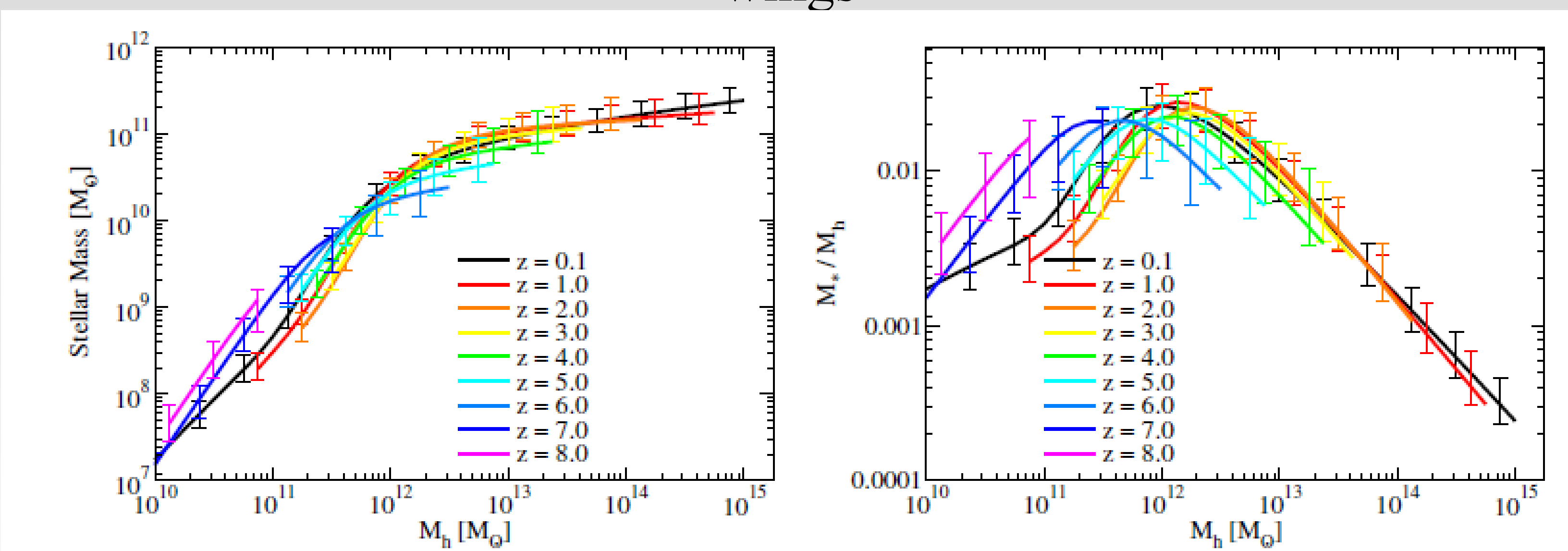
$$P_{final}(k) = \Sigma P_i(k)$$

Central limit theorem → log-normal + wings

AGN + SF + accretion:

Turbulent pressure, cosmic ray pressure, B-field pressure, radiation pressure, ionization, shocks, gravitational instabilities ….

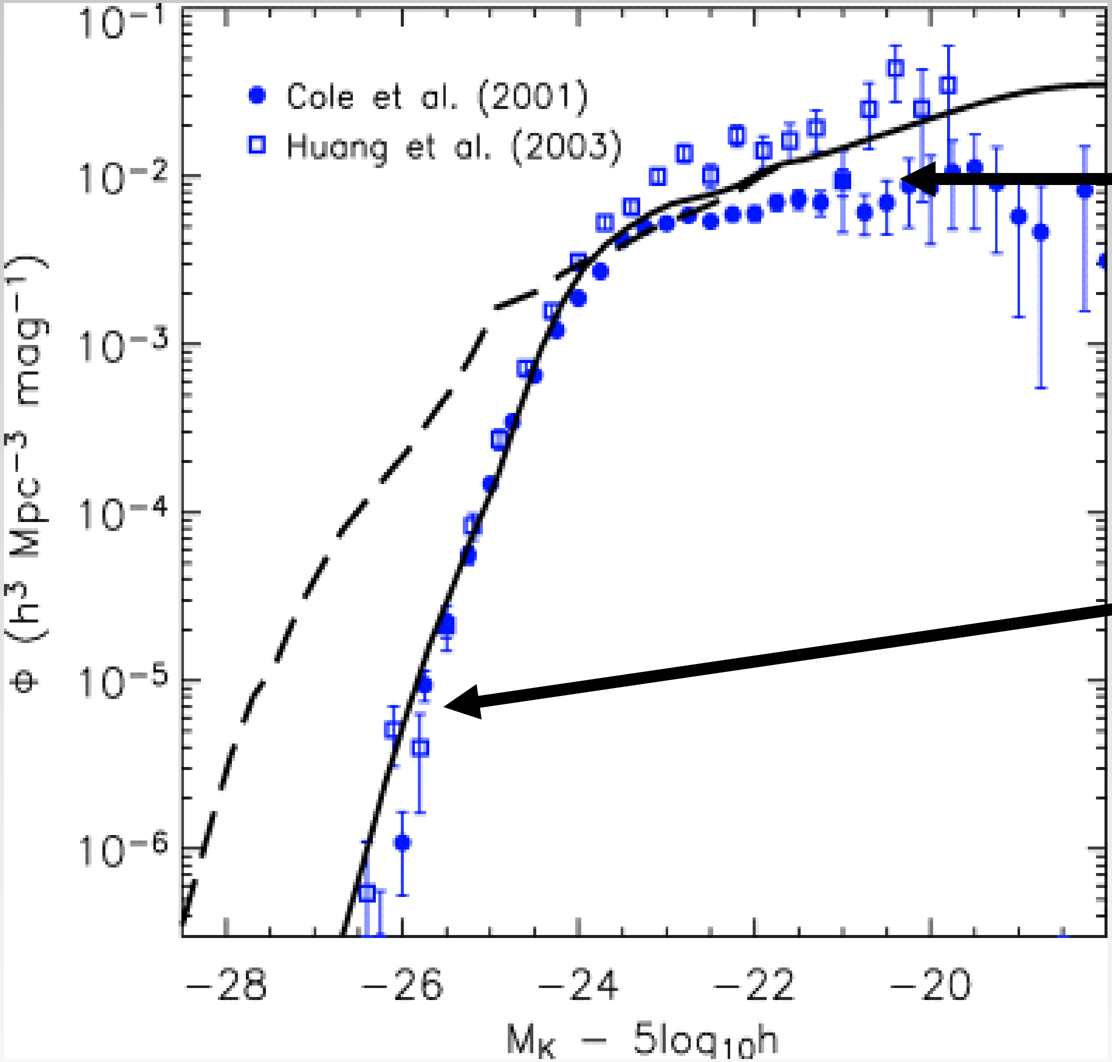
Like what one sees in Eddington ratios in Kaufmann & Heckman?



Galaxy formation is inefficient … most baryons not in galaxy proper ...

Behroozi et al. (2012)

Need for (Self-)regulation



Flatness of mass function
Wide range of ages
Wide range of stellar densities
Φ(gal) < Φ(halo) at low mass

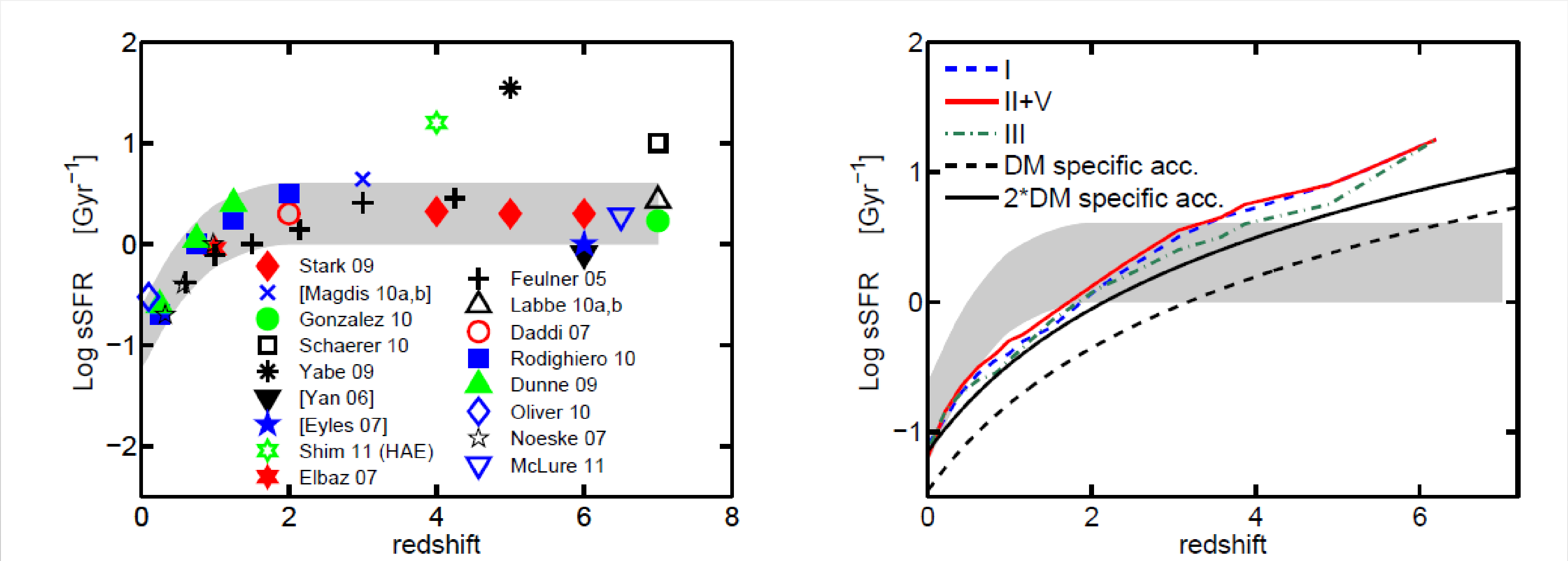
Steepness of mass function
Old, red, & dead
Φ(gal) < Φ(halo) at high mass
M_{BH} M_{Sph} relation

Hypothesize:
1) quenching (high-z)
2) maintenance (low-z)

Nonetheless, need some self-regulation of BHs for exponential cut-off

Benson et al. (2003)

What drives the time evolution of the mass growth?



Weinmann et al. (2011)

Why doesn't the specific growth rate follow the specific accretion rate of the gas? Too simple as growth rates are mass dependent.

Outflows and feedback?

Angular momentum?

Accretion rate over-estimated (over-cooling)?

Weinmann et al. (2011)

My talk title is:

“What is the impact of AGN on star formation?”

This is a fool errand … we don't understand how stars form!

So we are stuck with: “positive”, “negative”, or none and have to compare active, not active, and impact on “star formation laws”.

Star formation: some "laws"

Provide insights into how AGN might influence star formation ...

General law:

$$\dot{\Sigma}_* = f_{H_2} \epsilon_{ff} \frac{\Sigma}{t_{ff}}.$$

locally

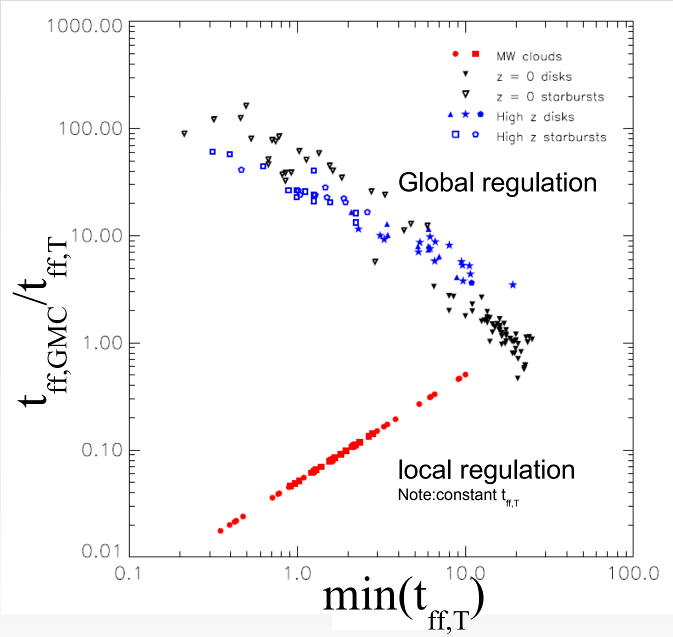
$$t_{ff,GMC} = \frac{\pi^{1/4}}{\sqrt{8}} \frac{\sigma}{G(\Sigma_{GMC}^3 \Sigma_{gal})^{1/4}}.$$

Toomre:

$$Q = \frac{\sqrt{2(\beta+1)}\sigma\Omega}{\pi G \Sigma},$$

globally

$$t_{ff,T} = \sqrt{\frac{3\pi^2 Q^2}{32(\beta+1)\phi_P}} \frac{1}{\Omega}.$$

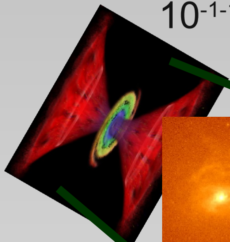


Efficiency of molecular formation (pressure):

$$\dot{\Sigma}_* = \epsilon_{SF} \Sigma_{gas} \omega$$

Krumholz et al. (2005)

Influence of AGN

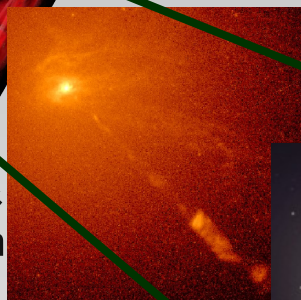


$10^{-1\text{-}1}$ pc

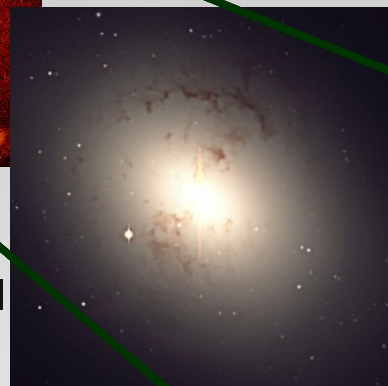
$10^{1\text{-}3}$ pc

$10^{3\text{-}4}$ pc

[M/H] and $\vec{B}$

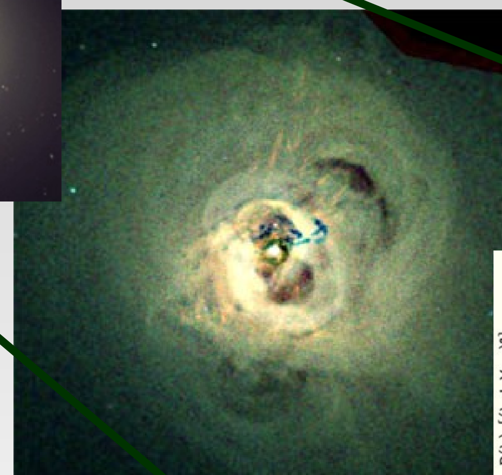


Self-reg & Eddington limiting



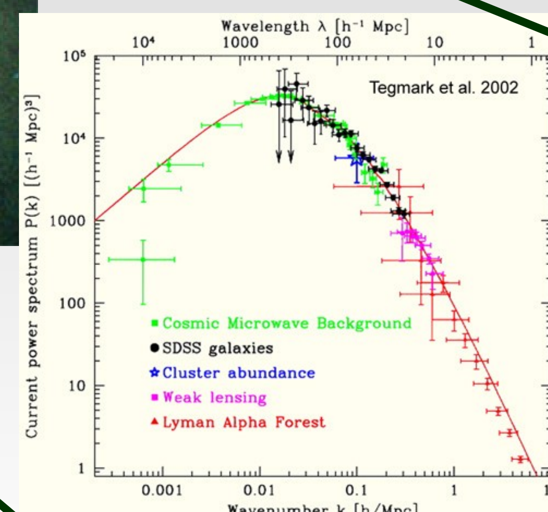
M_{BH}-σ & mass disposal

$10^{4\text{-}6}$ pc



$10^{6\text{-}8}$ pc

Regulate ISM Galaxy formation

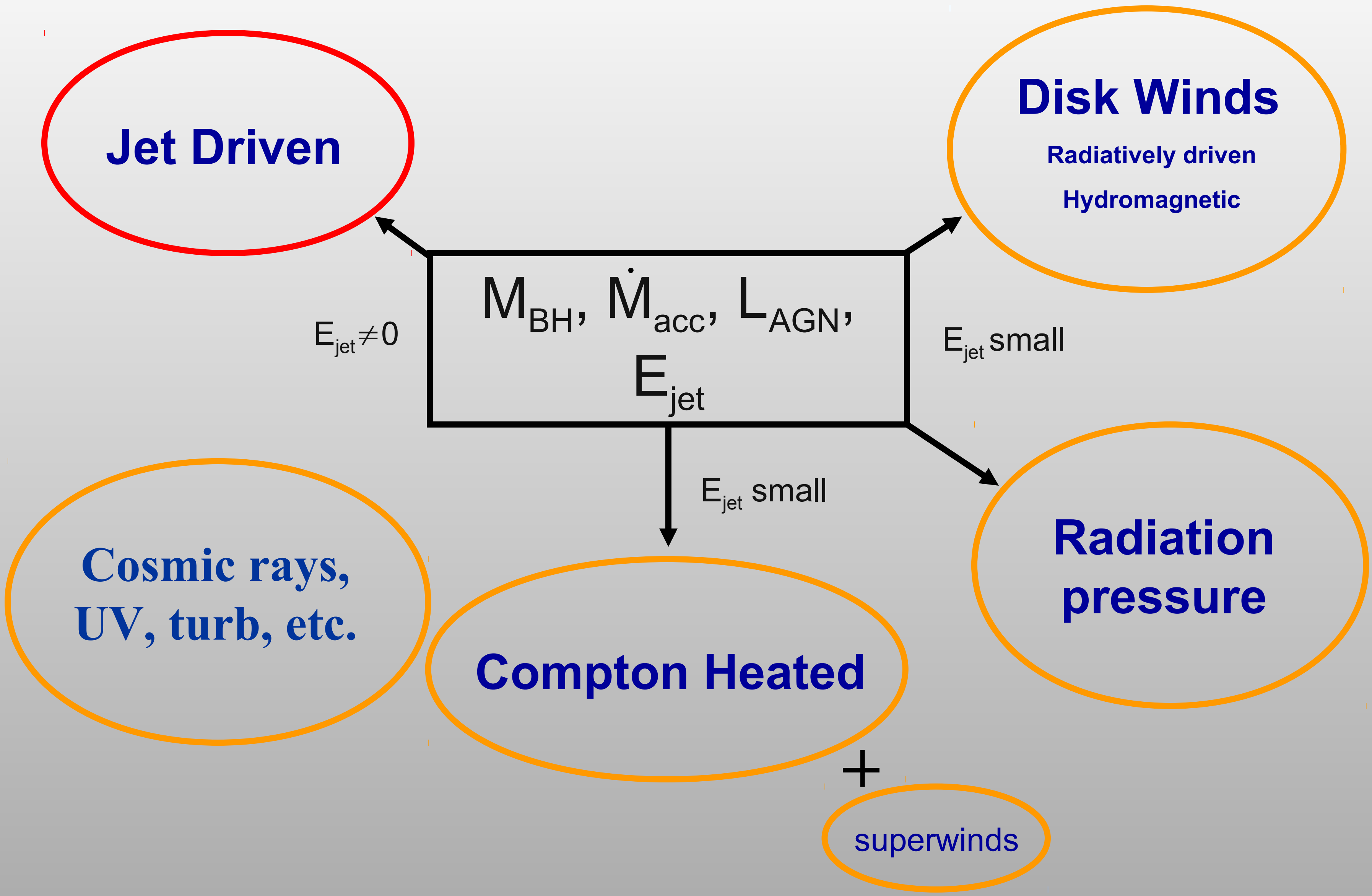


Dynamical evolution of galaxy centers & star-clusters

Heat halo & cluster gas

LSS

Underlying Mechanisms for AGN Feedback



Ideas for limiting star formation

Prevention: Prevent gas from cooling or accreting onto the galaxy proper … no gas, no star formation

Problems: Mass return alone is significant and in disk galaxies and lenticulars, the velocity dispersions are low … short cooling time, << t_{H0}

Removal: Outflows appear ubiquitous.

Problems: Do they remove all the gas? What is their long term evolution? Coordination problem? Turn on when needed and shut down quickly?

Inhibition: Radiative and pressure effects (UV, cosmic rays, magnetic fields), generate and maintain strong turbulence, prevent the transition from WNM to CMM.

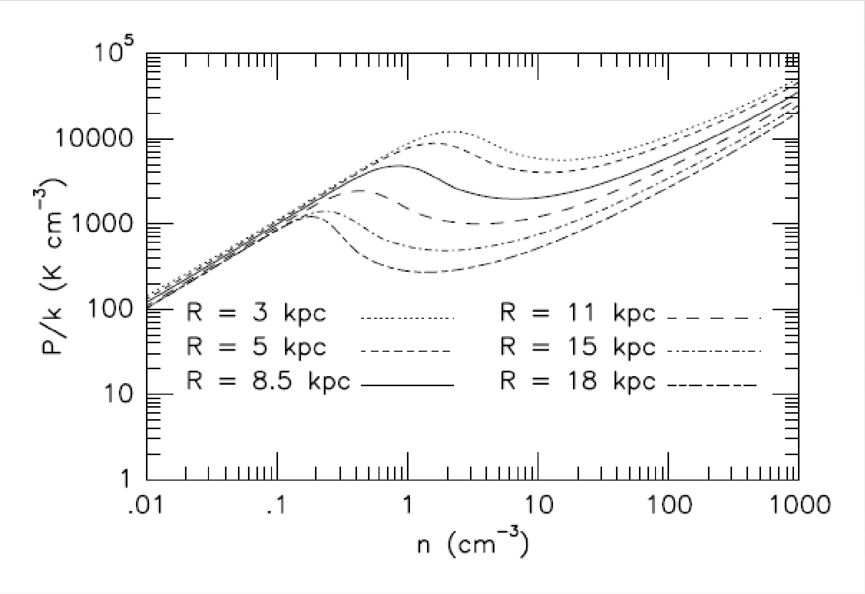
Problems: Little evidence! Also, complicated and difficult to pin down.

Ideas for enhancing star formation

Compression: Compress critically stable clouds

Enhancements: Shorten the formation of molecular gas through increased turbulence or pressure

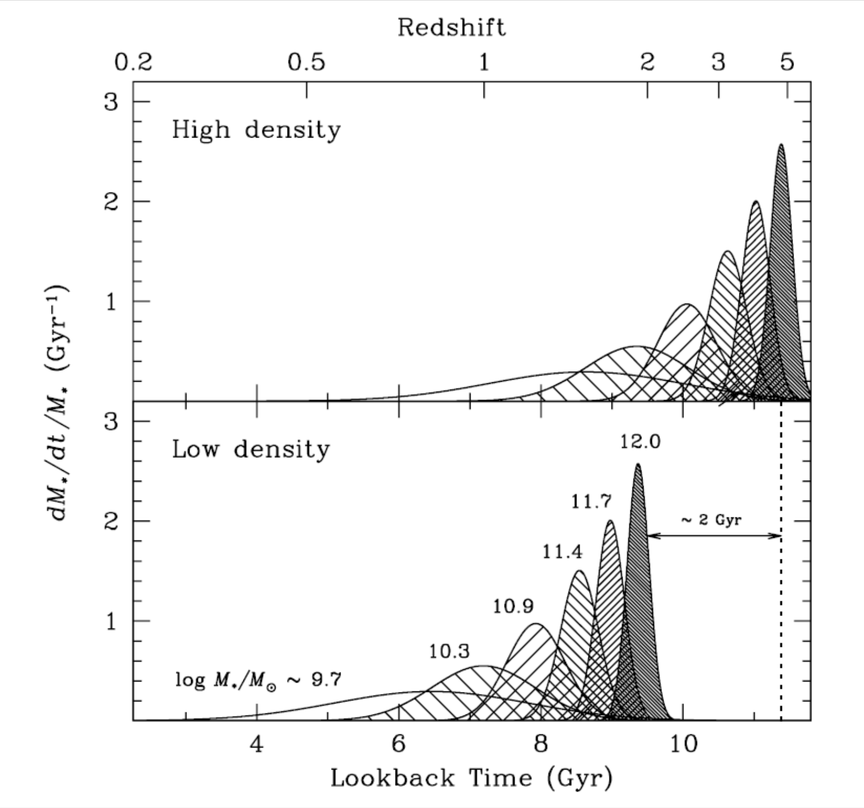
Ionization: Deeply penetrating cosmic rays or X-rays/UV may increase the ionization state and allow for the formation of H_2 likely important for low metallicity gas

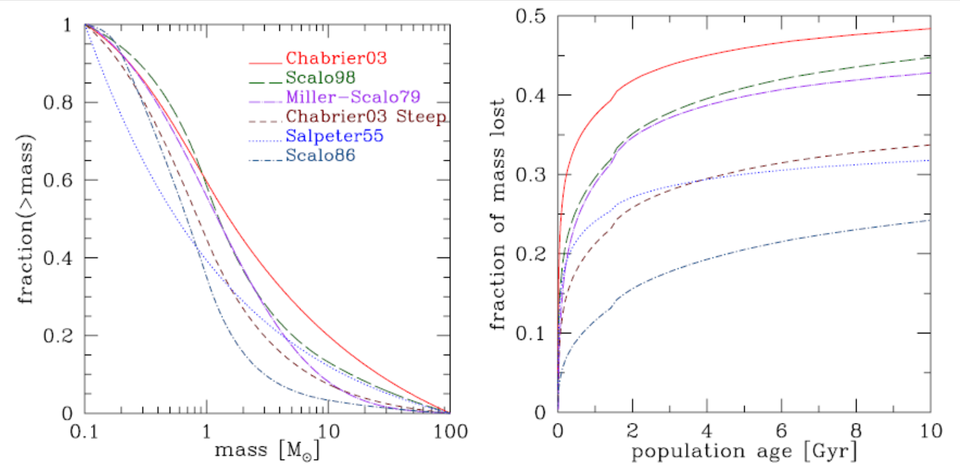


Wolfire et al. (2003)

Mass dependent

We have discussed the efficiency of outflows, but the need for a catastrophic phase of outflow or inhibition depends of mass.





But mass return is ~20-40% for old populations … and cooling time is $<t_{H0}$ ….

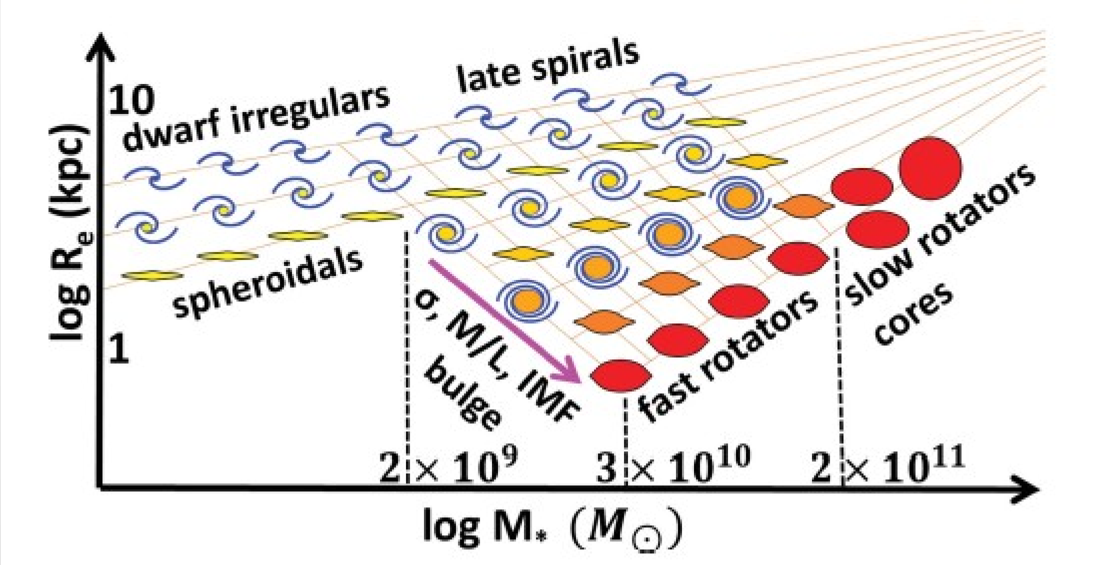
internal velocity dispersions are not extreme … 10s km s^{-1}

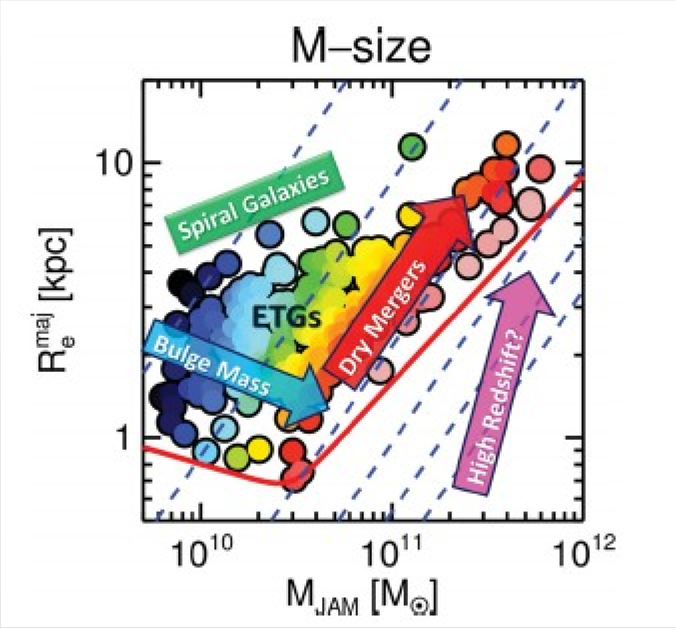
Thomas et al. (2005); Leitner & Kravtsov (2011)

ETGs

<u>Slow rotators</u>
Weakly triaxial
No disk
Elliptical isophotes

<u>fast rotators</u>
disks
axisymmetric
disk E to S0 to
almost bulgeless S0

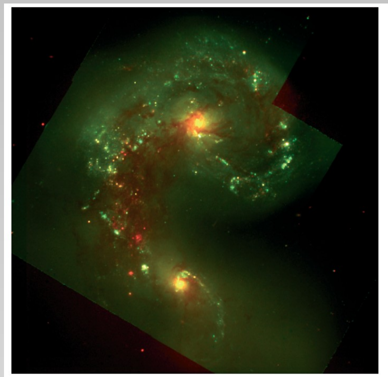




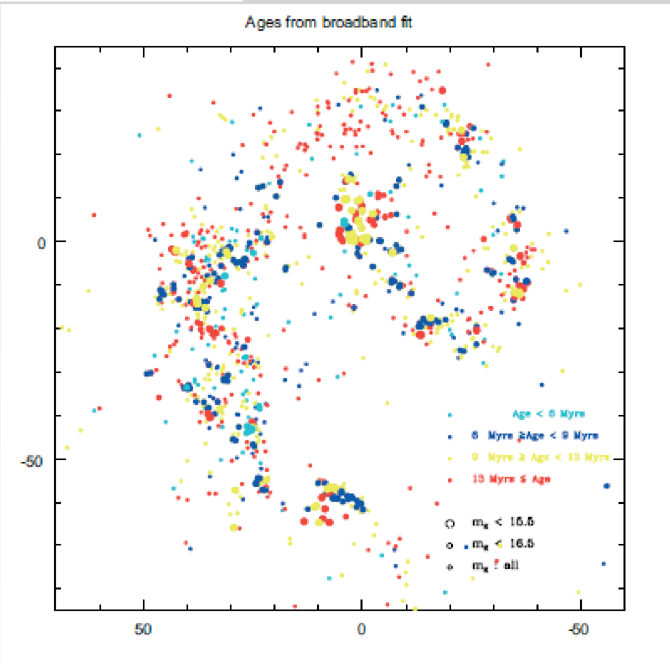
Does the IMF really vary systematically in ETGs?

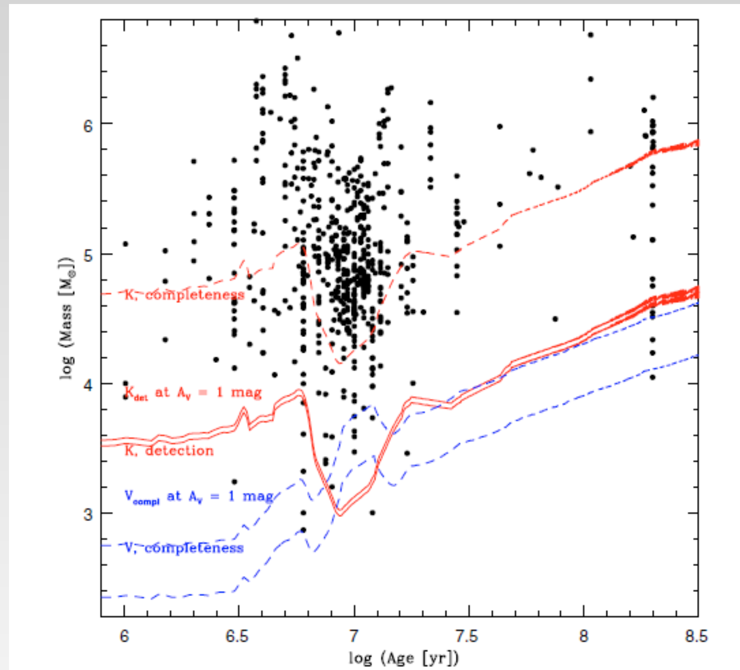
Atlas[3D] collaboration; Cappellari et al. (2013)

The ISM they are living in



In mergers, the star formation is coordinated, the ISM has been shaped by the merger and is critically unstable.





AGN evolve globally in a “frozen ISM” … t_{dyn}~10^8 vs. t_{AGN}~10^7 yrs, this depends on scale, circumnuclear scales important for impact.

Mengel et al. (2005)

Physics of Winds

Outflows driven by the collective thermalization of stellar winds and supernova

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

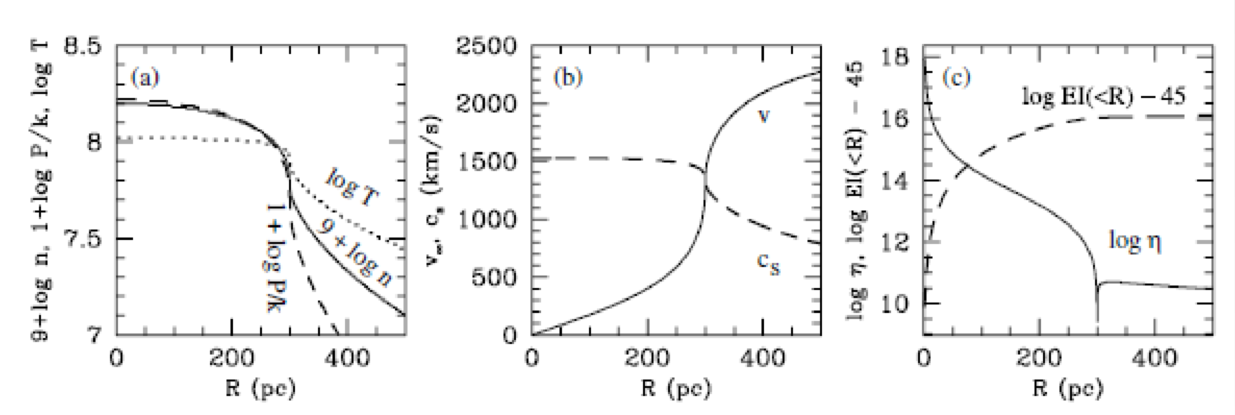
Injection region: $T_c = 0.4 \mu m_H \dot{E}_{total} / k \dot{M}_{total}$

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

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

$$\frac{\dot{M}_{wind}}{SFR} \neq \eta$$

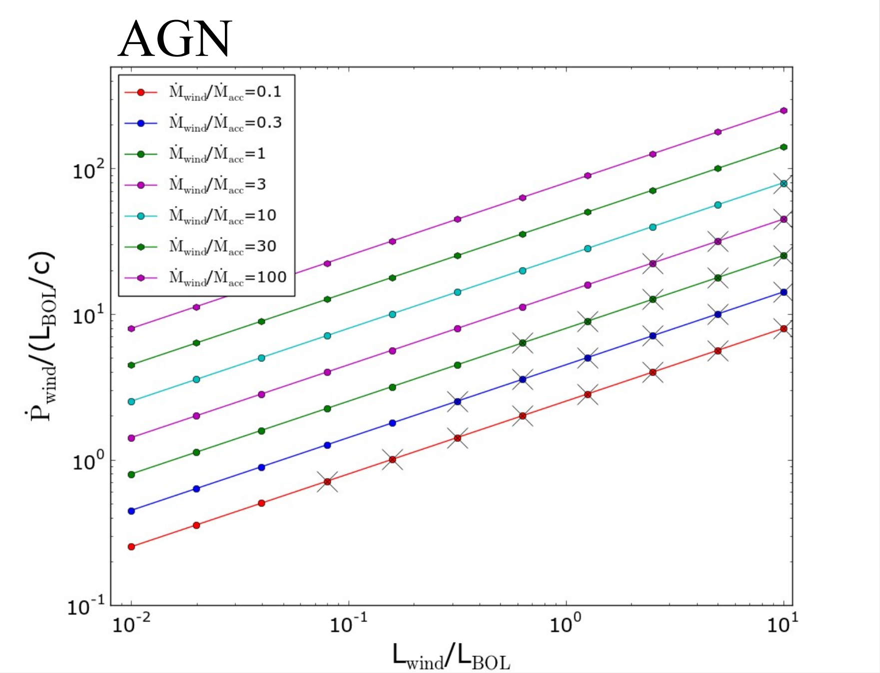
SNe/SW are efficiently thermalized

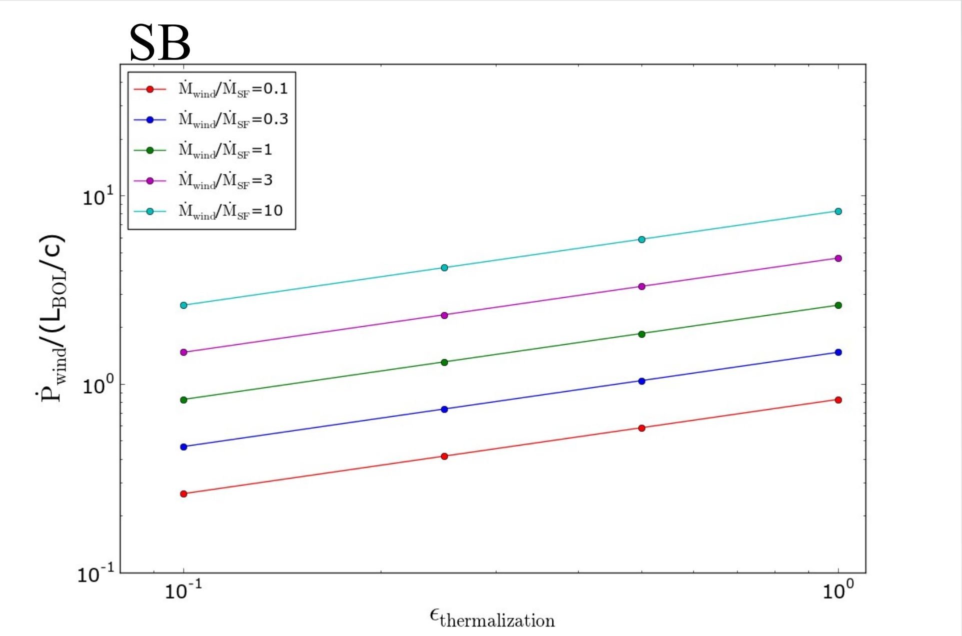


Chevalier & Clegg (1985), Strickland & Heckman (2009)

Momentum flux

Momentum flux depends on the terminal velocities of the most mass components and the AGN is like a “disk wind”/radio jet.





An intralude

Starburst driven winds tell us that the distribution of the phases is the only way of determining the heating, cooling, and dissipation ...

In analogy with stellar systems, heat capacity of gas can be positive or negative … fate of energy depends on the ISM/ICM/IGM in which it flows...

Intense star formation is self regulating ...

What we think may drive the turbulence, bulk motions, and phase distribution of ISM depends on the dissipation timescales in the various phases ...

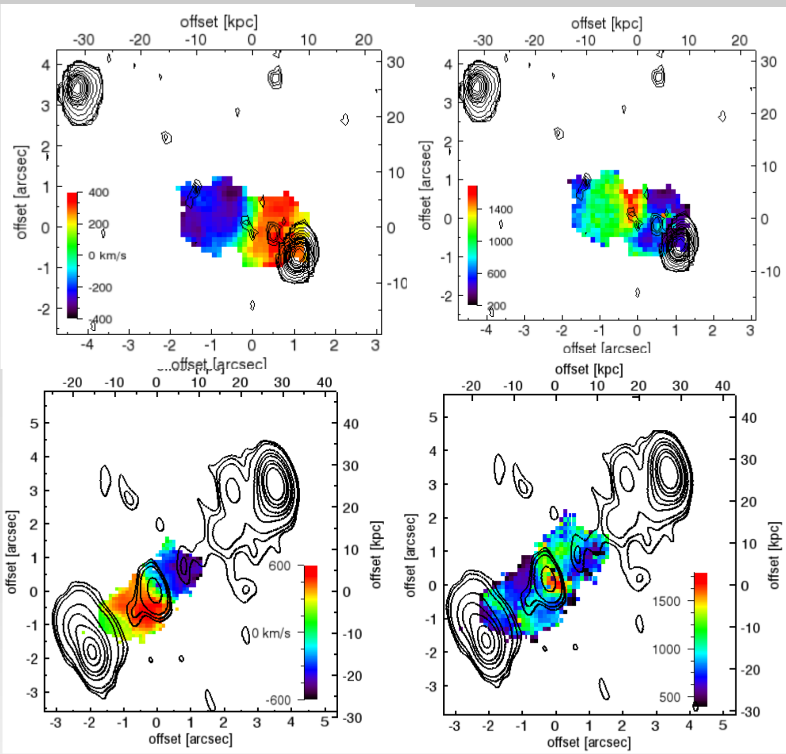
Outflows are unlikely to be as efficient as we need to remove the gas or suppress star formation completely … and there is always mass return ...

How might the “quenching” work or not?

Some illustrations

Quenching at high redshift

Powerful radio galaxies at high-z are driving incredible outflows …



$10^{60\text{-}61}$ ergs of bulk kinetic energy

Outflow rates of 100-1000 $M_\odot$ yr^{-1}

L_{mech}~L_{bol} and about 10% coupling

$E_{outflow}$ ~ $0.002E_{rest\text{-}mass}$ of blackhole

$M_{molecular}/M_{warm\text{-}ionized}$ ~ 1 (in SB it's 10^3)

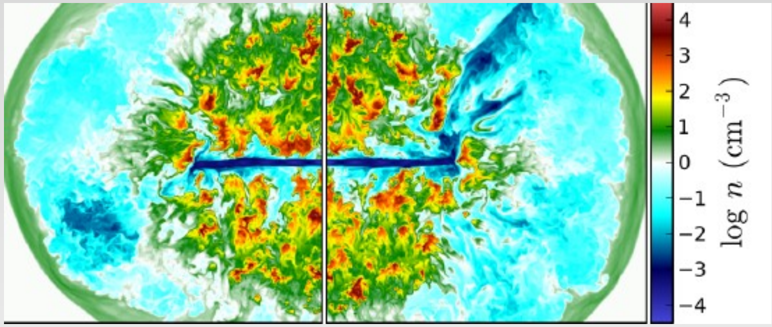
Unbind large masses of gas

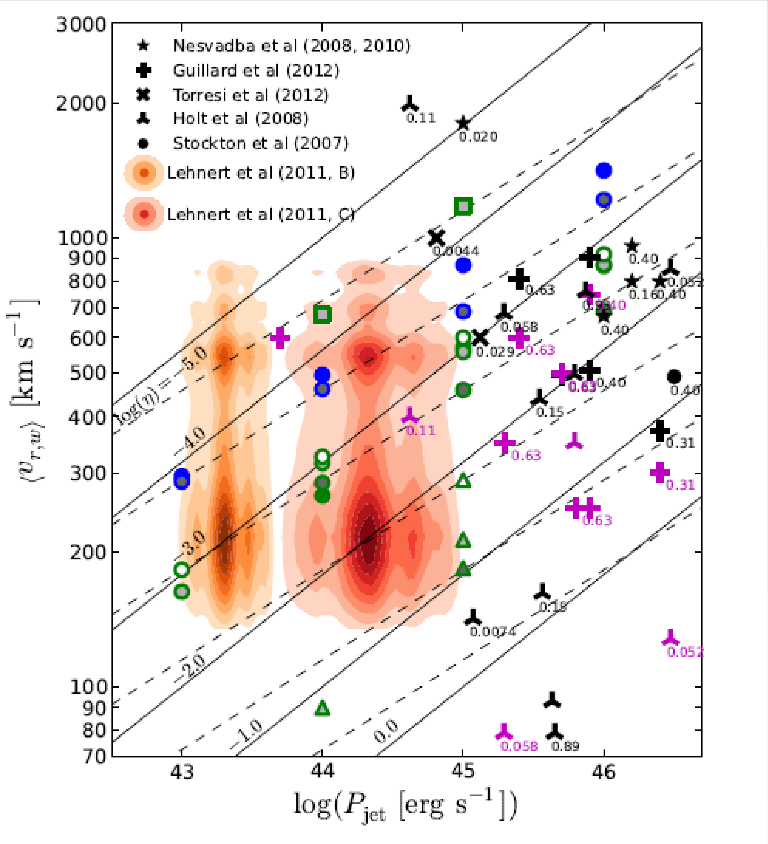
Illustrative: ~50 galaxies at high redshift have been analyzed … many of these show strong on-going star formation (e.g. Drouart et al. 2014) … positive feedback (e.g. Silk 2013)?

Nesvadba et al. 2006

Jet Simulations

Outflows are only one part of the equation for maintenance …

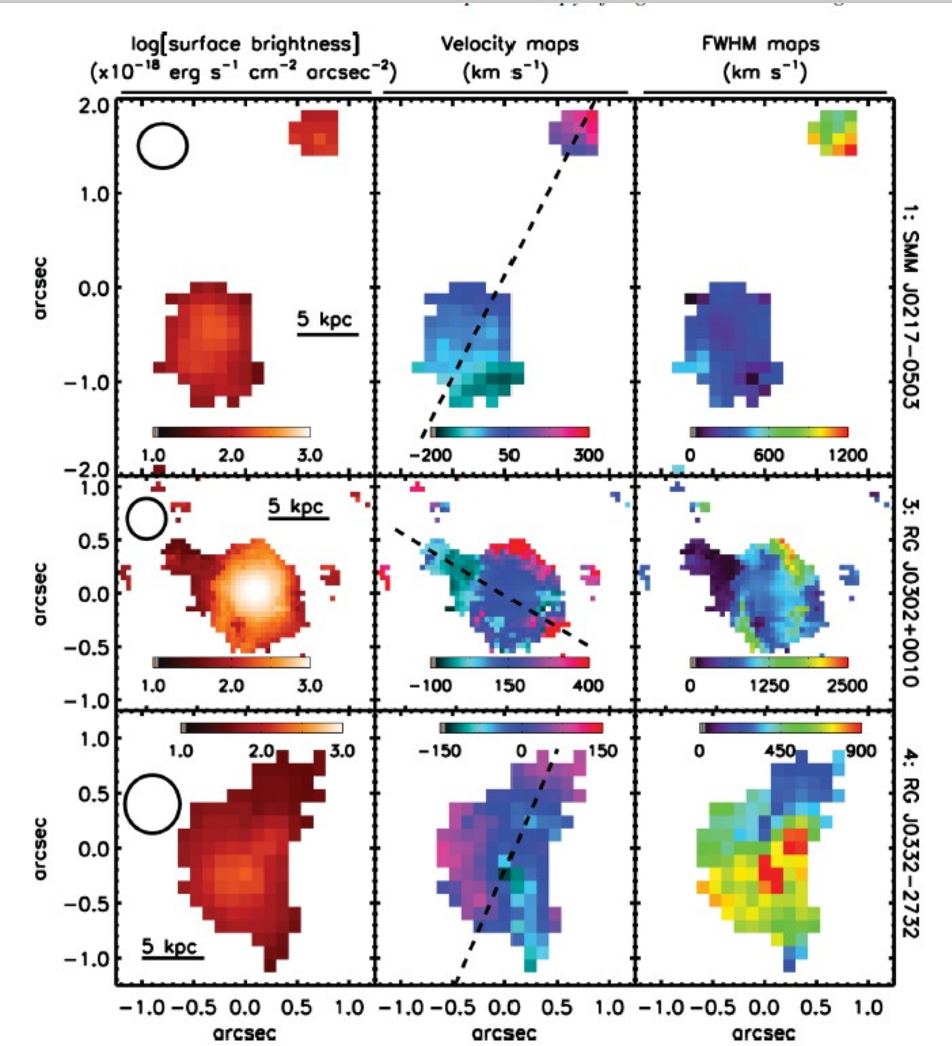


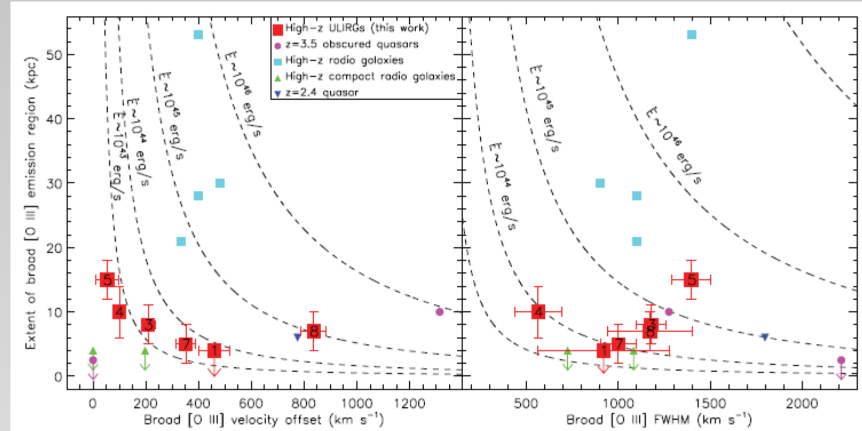


Scaled jet power by galaxy dispersion, log η > -3.5 to -4 affect evolution through cloud dispersal and gas removal…

Wagner et al. (2012)

Radio Quiet QSOs



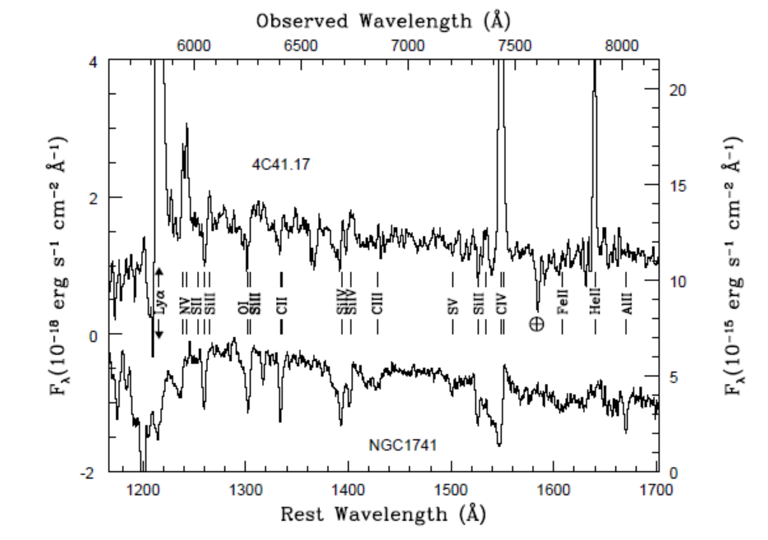


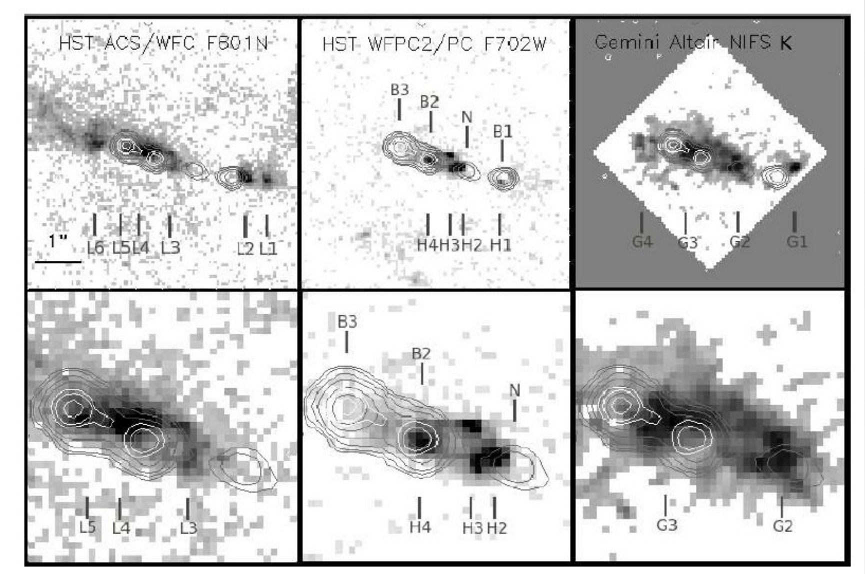
Overall, similar to RGs, but more dispersion dominated and less extended

Harrison et al. (2012); see also Harrison et al. (2014), Lui et al. (2013) for low z

Positive feedback

Radio jets associated with young stars … other evidence





Dey et al. (1997); Steinbring (2014)

How might the “maintenance mode” work?

Given the differences in RG and QSO populations, jets perhaps play a key role for ETGs

A sketch of a naïve cycle

Large Scale Feedback Cycle

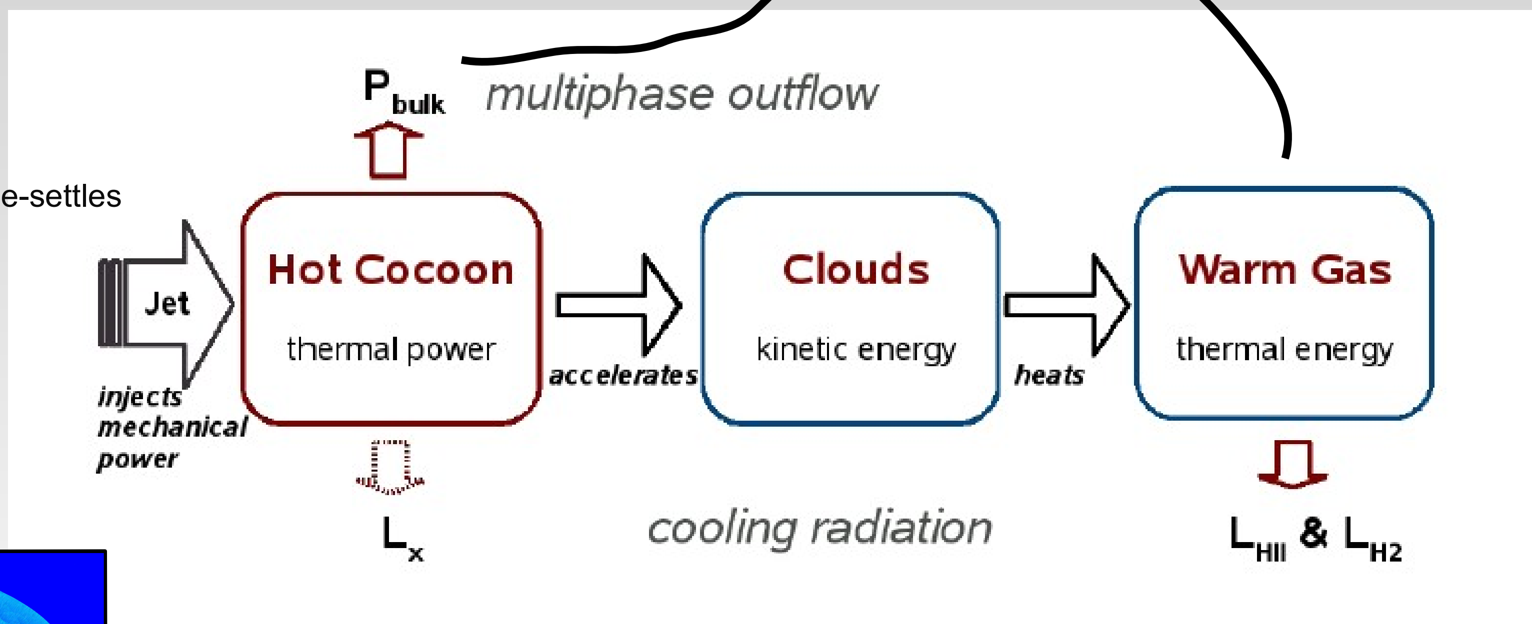
The game is to find out were the energy goes … dissipation vs advection

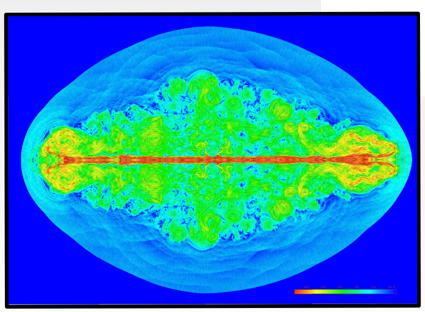
Ejected from halo

Cools and rains back down

Bulk flow of hot and warm ionized gas,
warm neutral gas, and warm molecular gas

Long dissipation time-settles
down and fuels BH





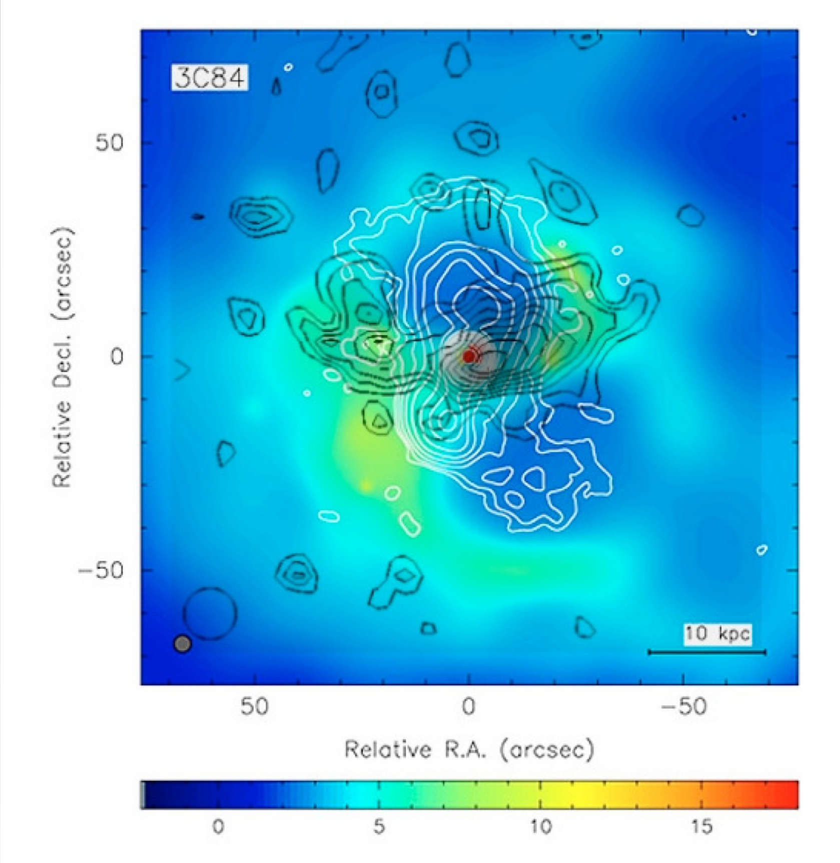
thermal Bremsstrahlung &
line cooling

Dissipation of mechanical
and thermal energy as
turbulent cascade down
to small scales and dense material

Cools through optical-IR atomic
recombination and molecular lines

Large scale molecular gas

mm and strong optical line emission …



M_{H_2}~2-5 x 10^{10} $M_{\odot}$

Nice correlation between line emission and molecular mass.

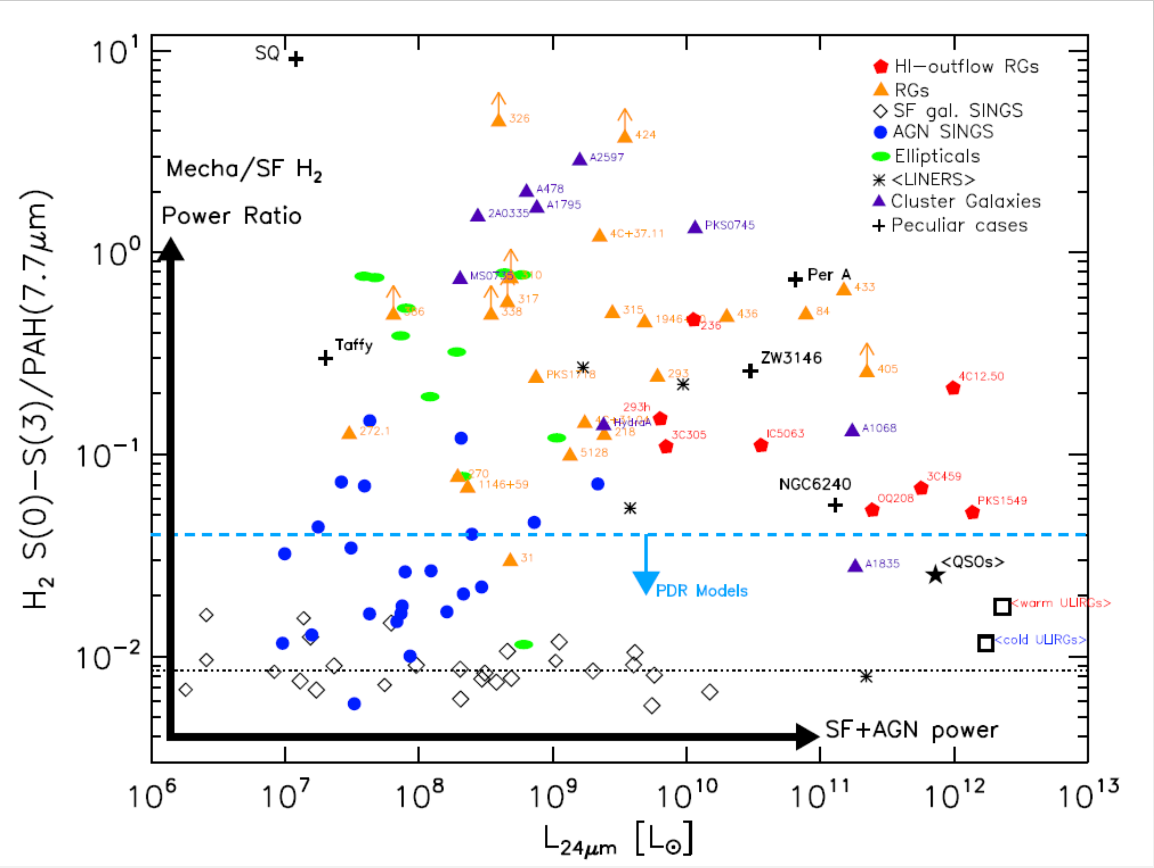
Perseus core; Salomé et al. (2006)

Energy injection can lead to the formation of cold gas …

H_2 Luminous Galaxies

H_2 luminous galaxies show the importance of global shock heating ...

Mechanical heating/star-formation



Bolometric power – Star-formation + AGN

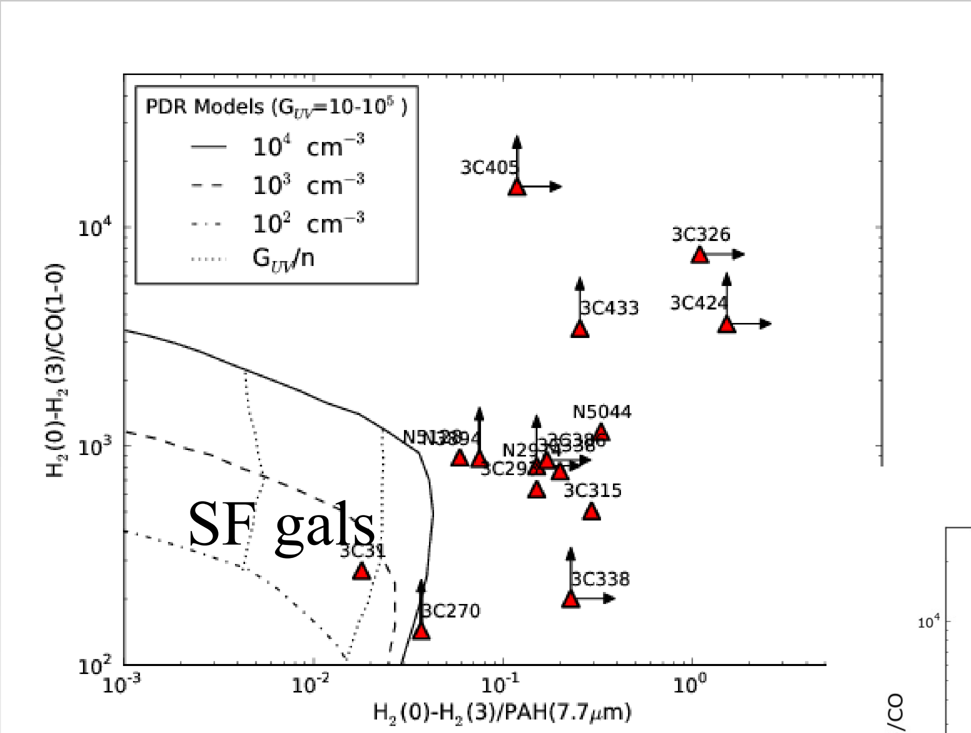
Normal star-forming galaxies have H_2/PAH~0.01

many AGN and mergers have elevated ratios – importance of shock heating

Ogle et al. (2010); Guillard et al. (2012)

H_2 Luminous Galaxies

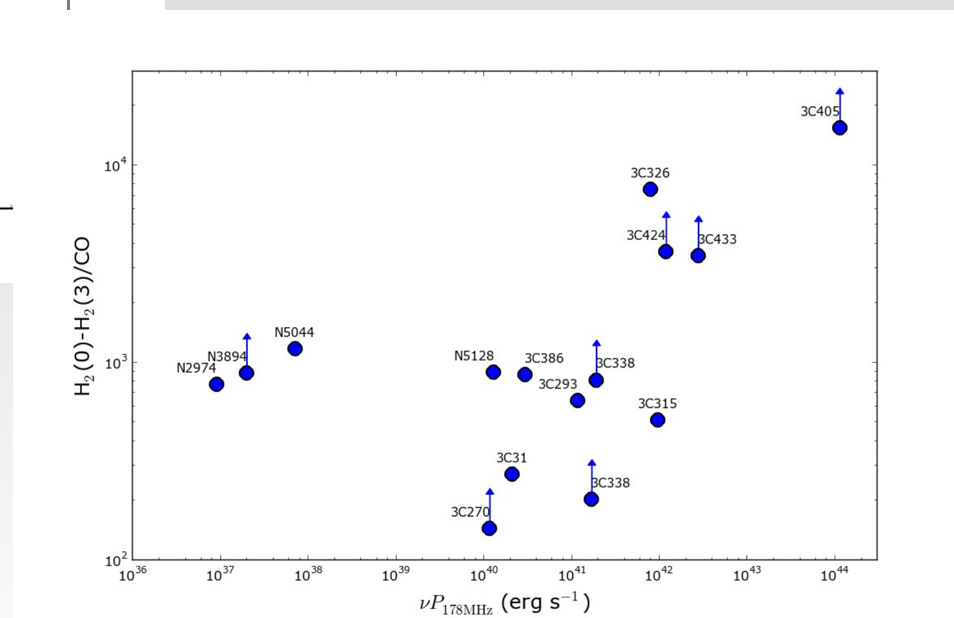
Despite being rich in cold molecular gas … little star-formation ...



These radio galaxies can have large H2 masses as derived from CO:

log M_{H2} = <7.3 to 10.3 $M_\odot$

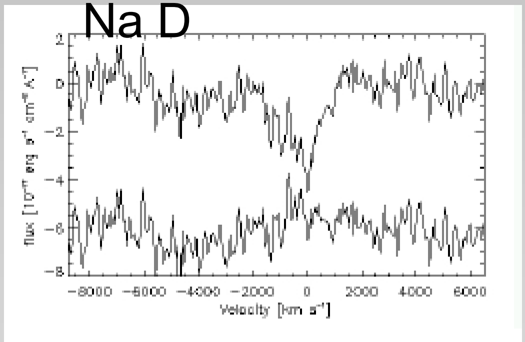
CO lines are often very broad 300-600 km/s



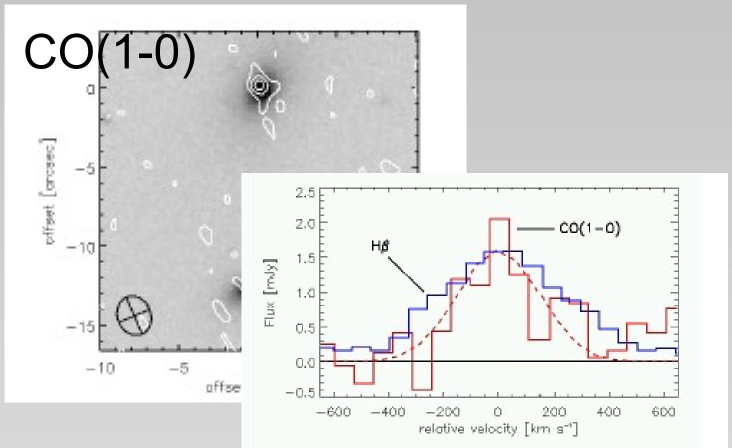
Fraction of warm to cold molecular gas depends on radio power but not for low power sources … other processes … molecular gas diffuse? Gas accretion?

Nesvadba et al. (2010); Lehnert et al. (2014)

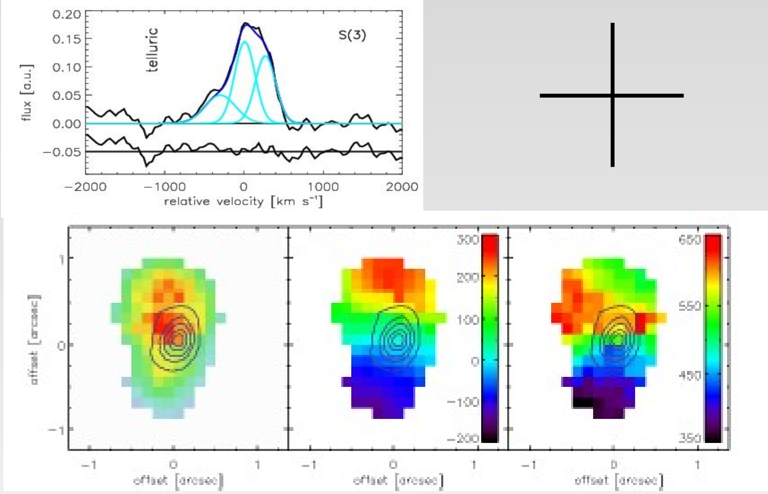
The case of 3C326 N



dM/dt = 30-40 M_s yr^{-1}
dE/dt = 10^{42} erg s^{-1}



n-IR H2 lines



$M_{H2,\ warm}$ ~ $M_{H2,\ cold}$ ~ $2x10^9$ M_s & W_{CO}~350 km/s
Normal galaxies: $M_{H2,\ warm}$ ~ 0.01-0.1 $M_{H2,\ cold}$
WIM and CNM have similar kinematics (K.E. flow)

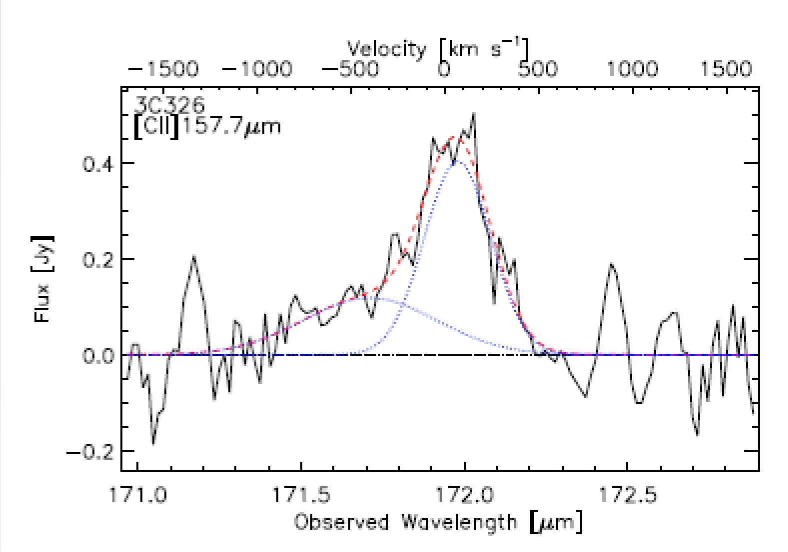
$t_{blowaway}$~$5x10^7$ yrs
t_{diss}~$1.5x10^7$ yrs
t_{rot}~$3x10^7$ yrs

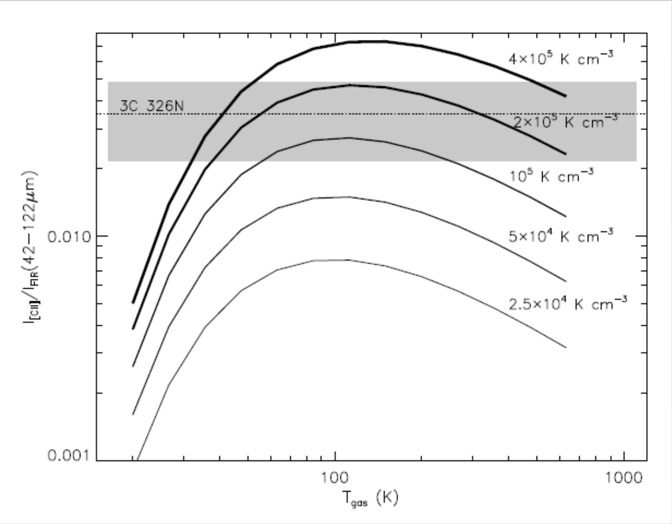
Rotating disk with broad lines 350-600 km/s and is shocked heated

t_{AGN}~6-20 x 10^7 yrs > other time scale, replenishment and high pressures favor molecular gas over HI/WNM ...

3C326N

However, observations of the [CII] line suggest a more subtle picture ...





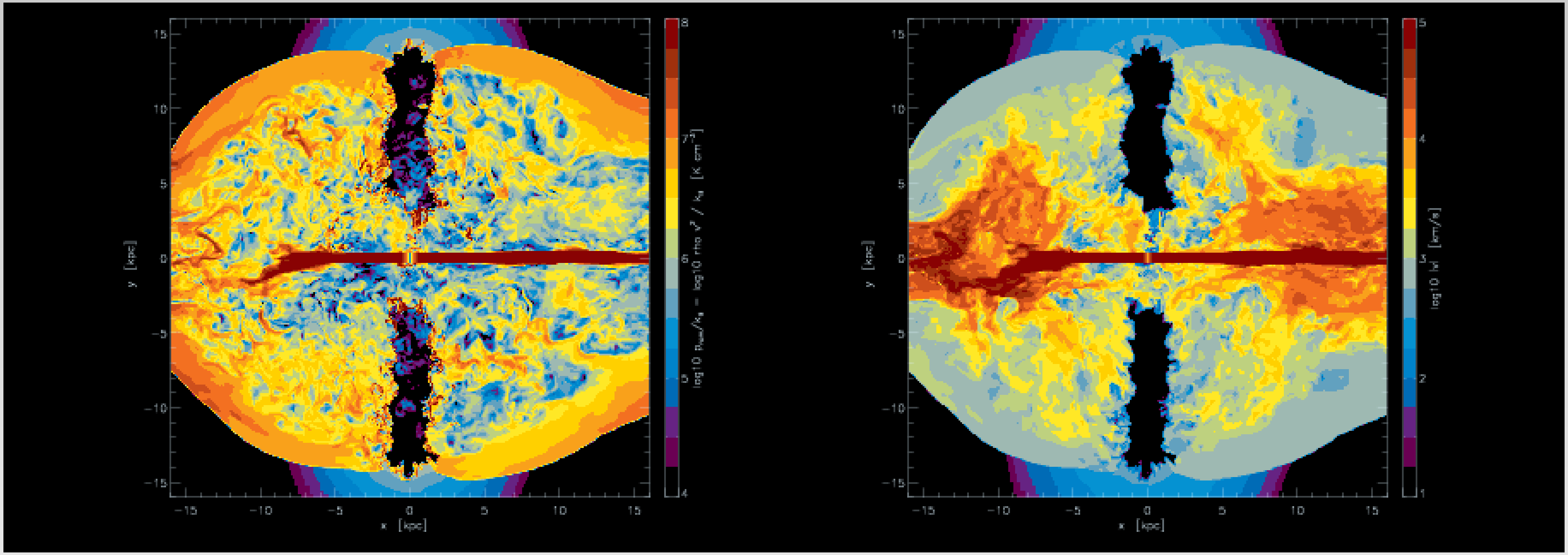
Luminous [CII] emission suggest disk is forming WMM very rapidly (ala Wolfire et al. and its large width suggests the gas is extremely turbulent with some bulk motions … combined with its mass surface density and that of the ETG, the disk is not self-gravitating on any scale (key point)

… is this why feedback is positive and negative ….

Guillard et al. (2014)

3C326N

The backflow of the radio jet is likely ...



- Transfering energy into the disk through its ram pressure;
- Helping to shape and actually confine the disk;
- Speculative: the moderate pressures are responsible for creating the molecular disk in the first place … positive feedback and negative feedback

Gaibler et al. (2010)

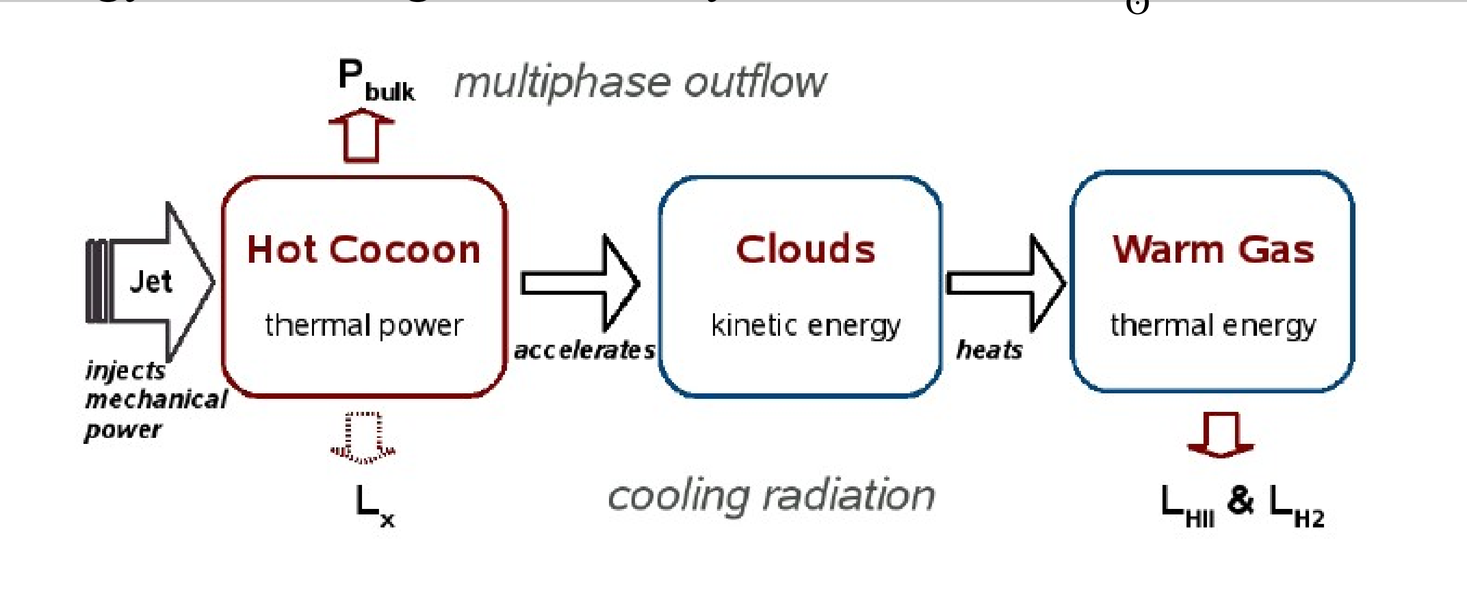
A Case Study: 3C326 a local radio galaxy

Distribution of energy … tracking down the cycle … ~$2 \times 10^9\ M_\odot$ warm cold H_2

Energy injection rate

L_{radio}~10^{42} erg s^{-1}

L_{mech}~10^{44-45} erg s^{-1}



thermal Bremsstrahlung & line cooling

???
Missing the piston

Kinematics of emission and abs NaD line gas

$E_{kinetic} = \Sigma_{phases} M\sigma^2$

$E_{kinetic}$~10^{42-43} erg s^{-1}

Line Cooling from IRS and optical spectroscopy

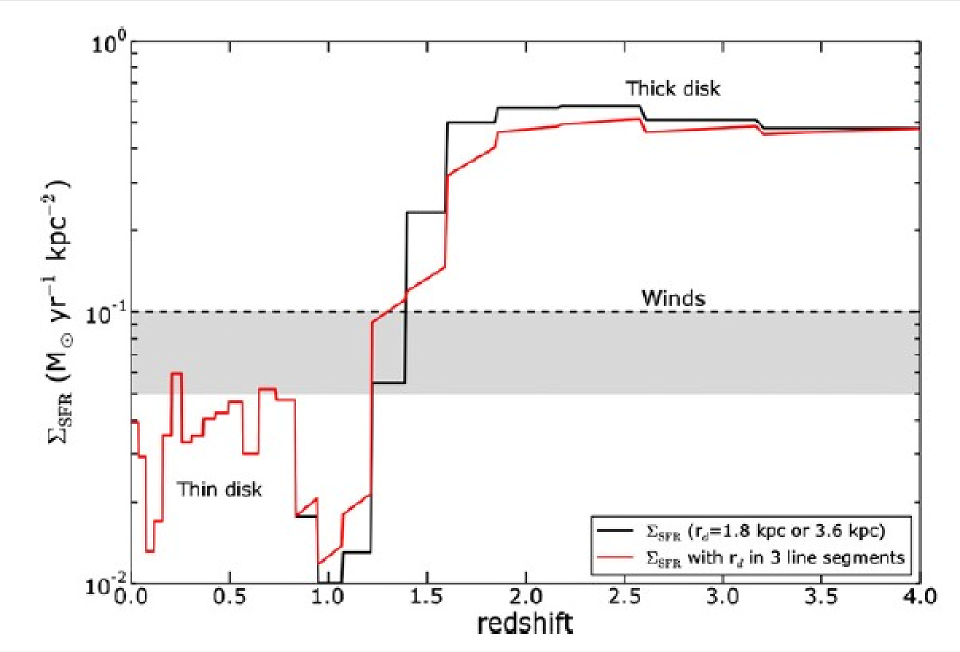
L_{lines}~10^{42} erg s^{-1}

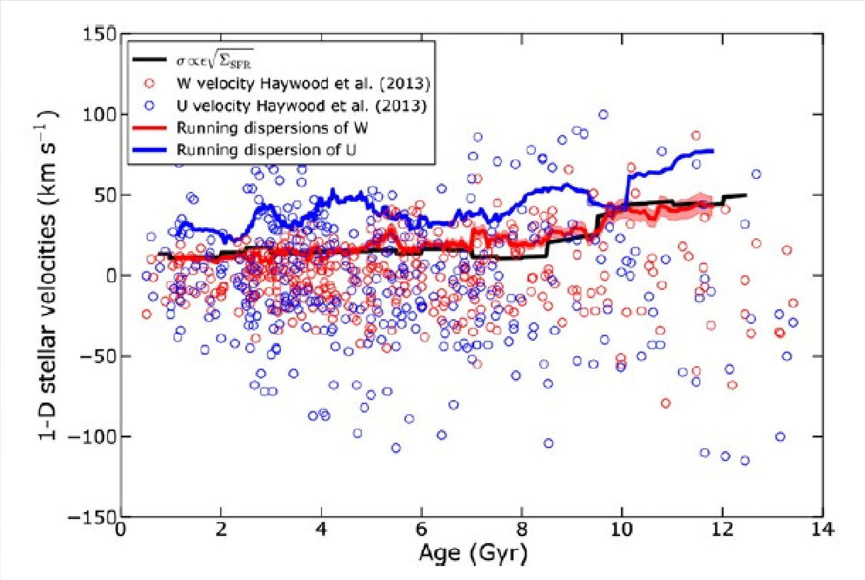
$M_{outflow}$~30-40 $M_\odot$ yr^{-1}, $\tau_{dissipation}$~few x 10^7 yrs < t_{AGN} ~$t_{duty\text{-}cycle}$

E_{cycle}~1-10% of L_{mech} where there is a ~50-50 split outflow and dissipation

Energy important for maintaining disk … SFR low ... gas-rich but lies off of the S-K relation

MW as a distant galaxy





Lehnert et al. (2014)

Some final thoughts

The questions we are asking are often not well formulated. What is it exactly what we want AGN to do?

Outflows are only one part of the equation … important yes, but cannot be the whole story … feedback is a cycle … what does feedback regulate?

Angular momentum of the gas is likely to be very important … much of the stellar mass is in rotating disks/pseudo-bulges … secular effects important too. Self-gravity is important in the relation between SF and AGN implying stellar mass surface density is important ...

To test the impact, global relations are not enough, need to find the mechanisms … if any … say, efficiency of molecular gas formation/efficiency of star formation ...

The environment in which the AGN evolve is strongly redshift dependent … the effects may be the same, but phenomenology will be different … disks are thick at high z …

Outflows are a mass and energy flow … mass and energy moves between and changes phases ...