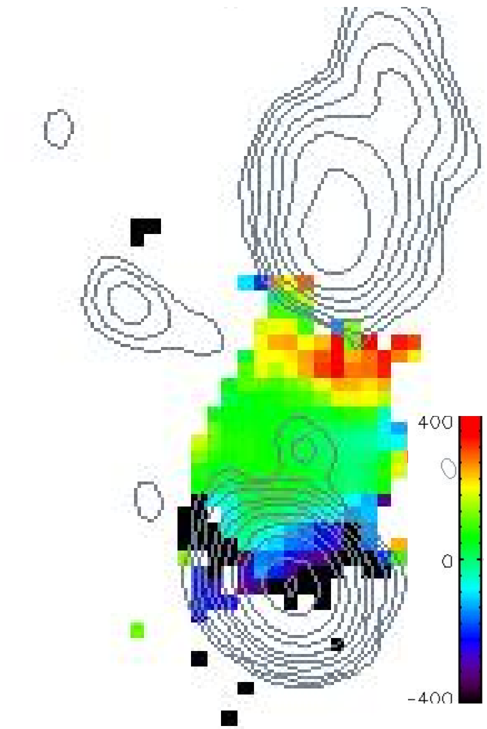


Radio galaxy at z=2.5
[OIII]5007 velocities, VLT/SINFONI

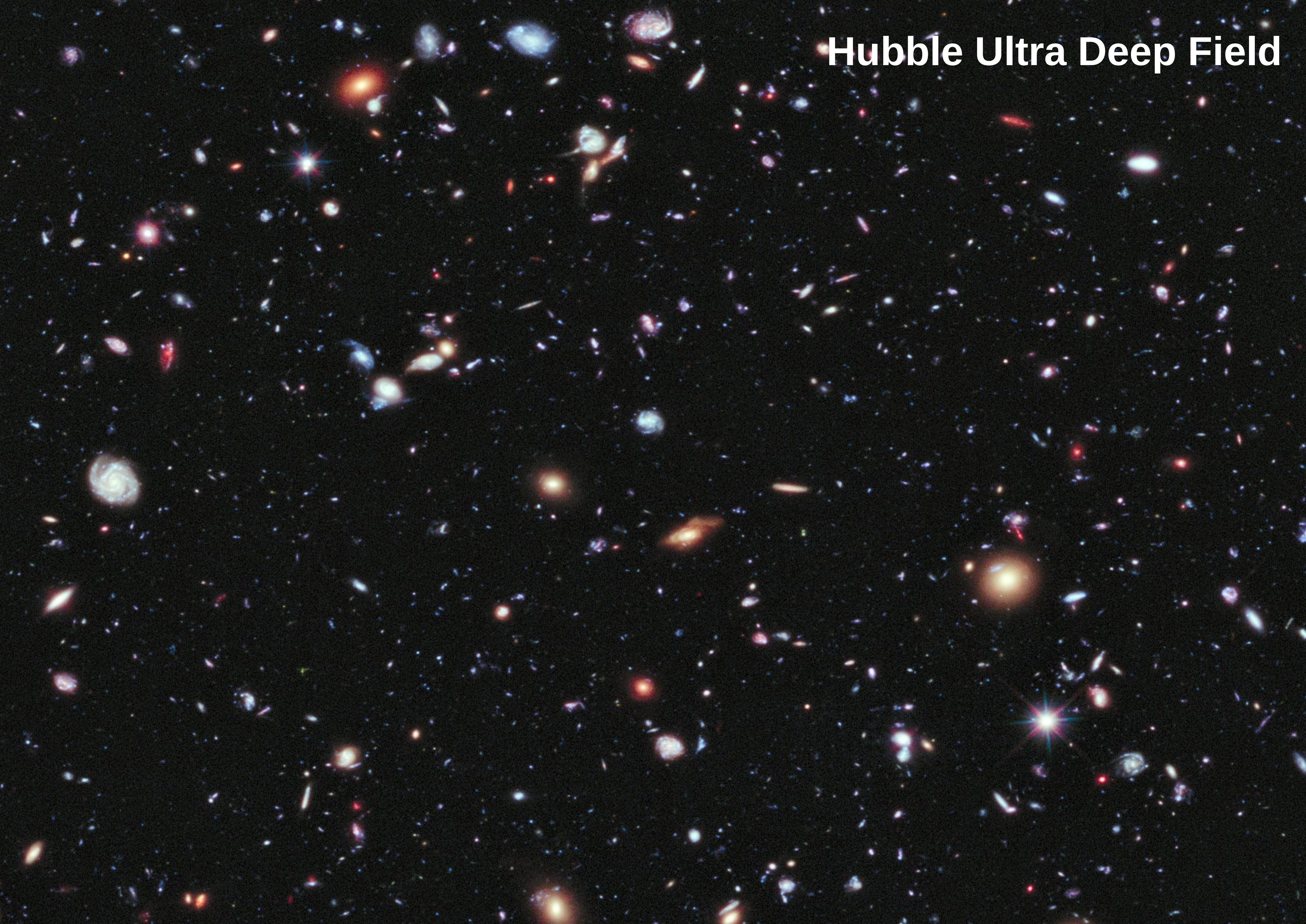
The power of the radio :
Witnessing AGN feedback and how it regulates galaxy growth through cosmic history

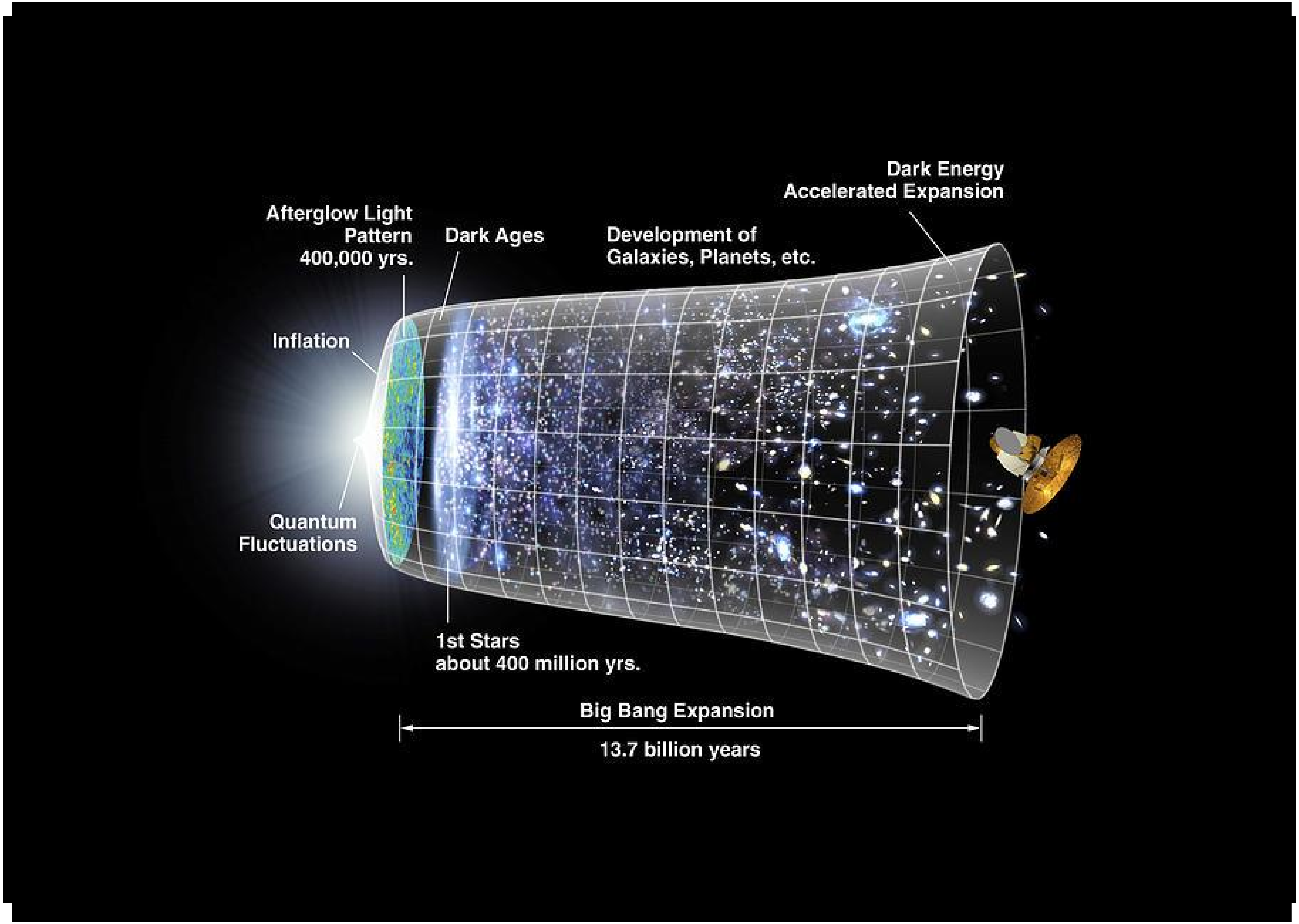
Nicole Nesvadba, Laboratoire Lagrange, OCA, UCA, CNRS

In collaboration with: **C. Collet, H. Zovaro, R. Canameras**, P. Best, G. Bicknell, F. Boulanger, C. De Breuck, **D. Dicken**, G. Drouart, P. Guillard, **R. Janssen**, M. Lehnert, D. Mukherjee, H. Rottgering, D. Rupke, C. Tasse, S. Veilleux, A. Wagner, D. Wylezalek, N. Zakamska, and others.

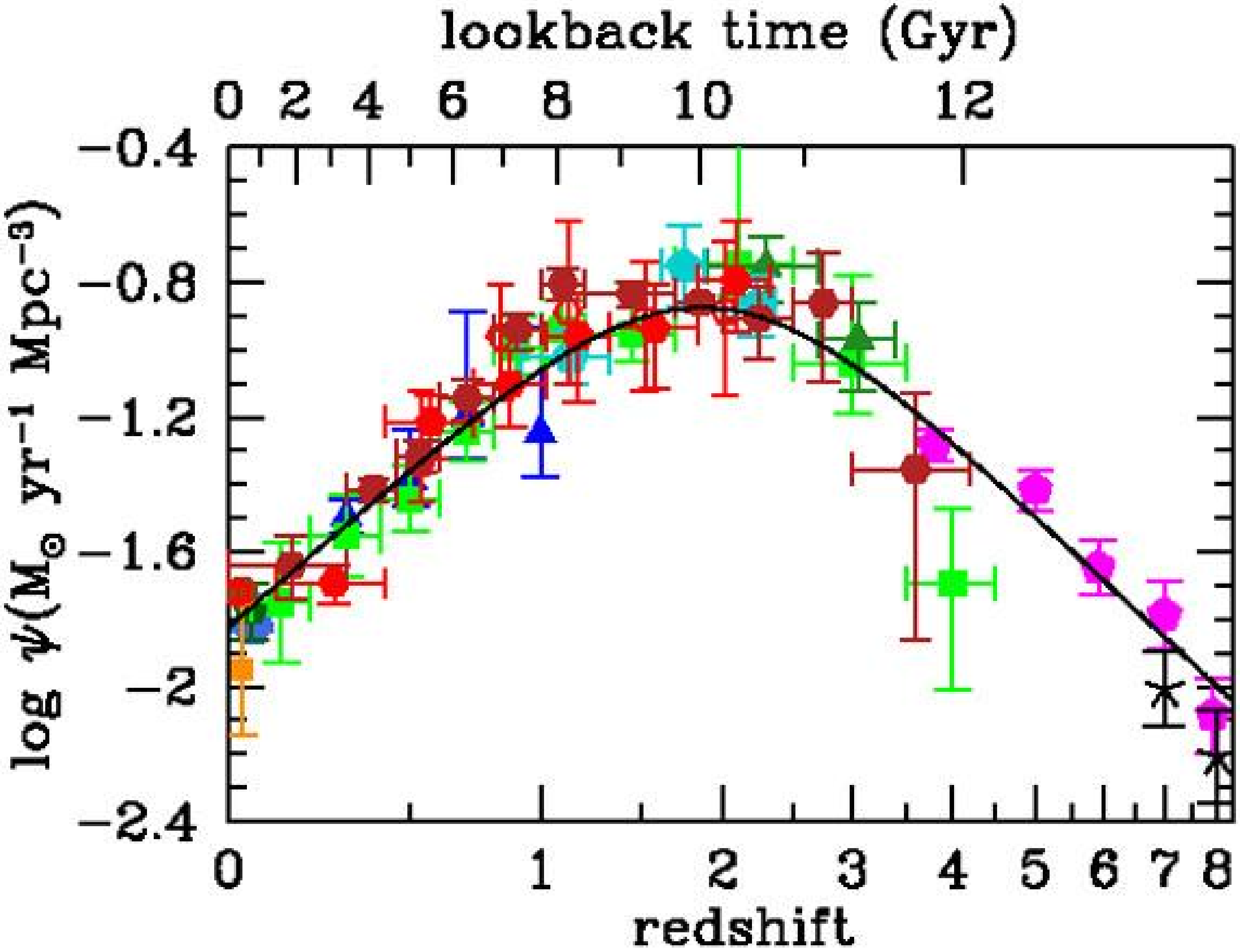
LAGRANGE

cnrs dépasser les frontières


Hubble Ultra Deep Field


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic star formation history



Madau & Dickinson (2014)

& roughly parallel evolution for the growth rate of supermassive black holes in the centers of galaxies.

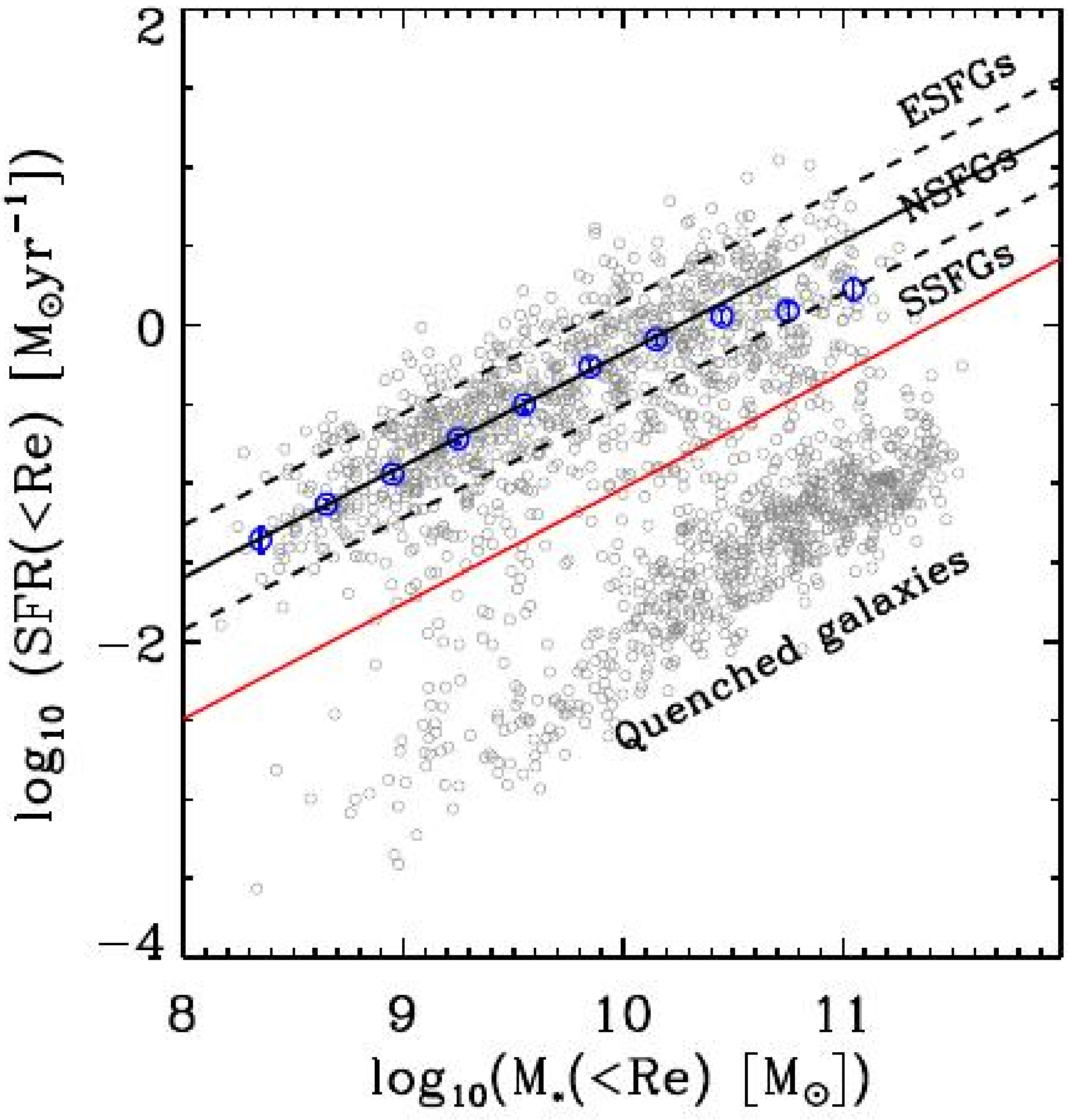
Main sequence of star-forming galaxies

Rate of star formation in galaxies depends on galaxy mass.

Balance between gas infall and star formation.

Origin unclear.

A subset (another sequence?) at lower star-formation rates : « Quenching »



Wang et al. (2019), Belfiore et al. (2018)

Star-formation efficiency and gas supply

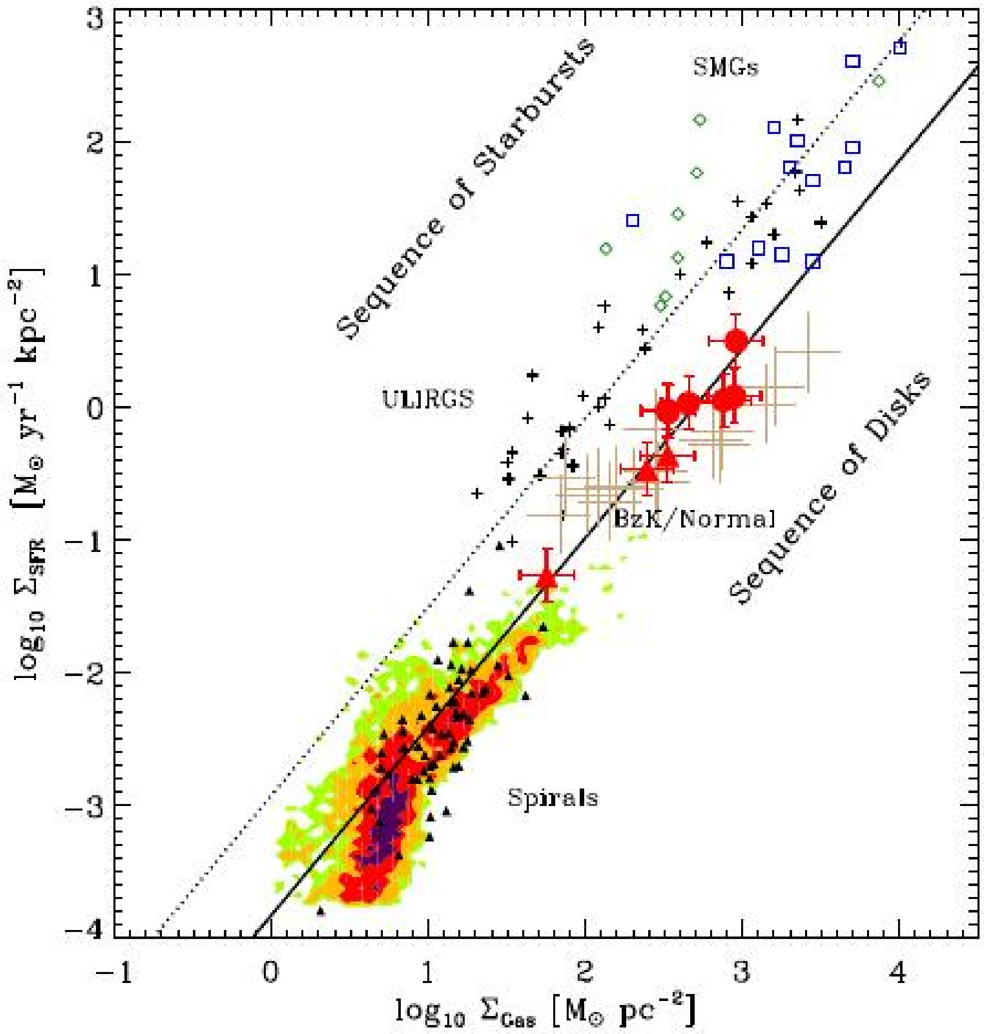
Schmidt-Kennicutt law of star formation
(Schmidt 1959, Kennicutt et al. 1989, 1998)

Correlation between star-formation rate surface density and gas mass surface density

Local star-formation rate depends on local gas mass surface density

Star-formation efficiency ?

Physical drivers of star formation in galaxies ?



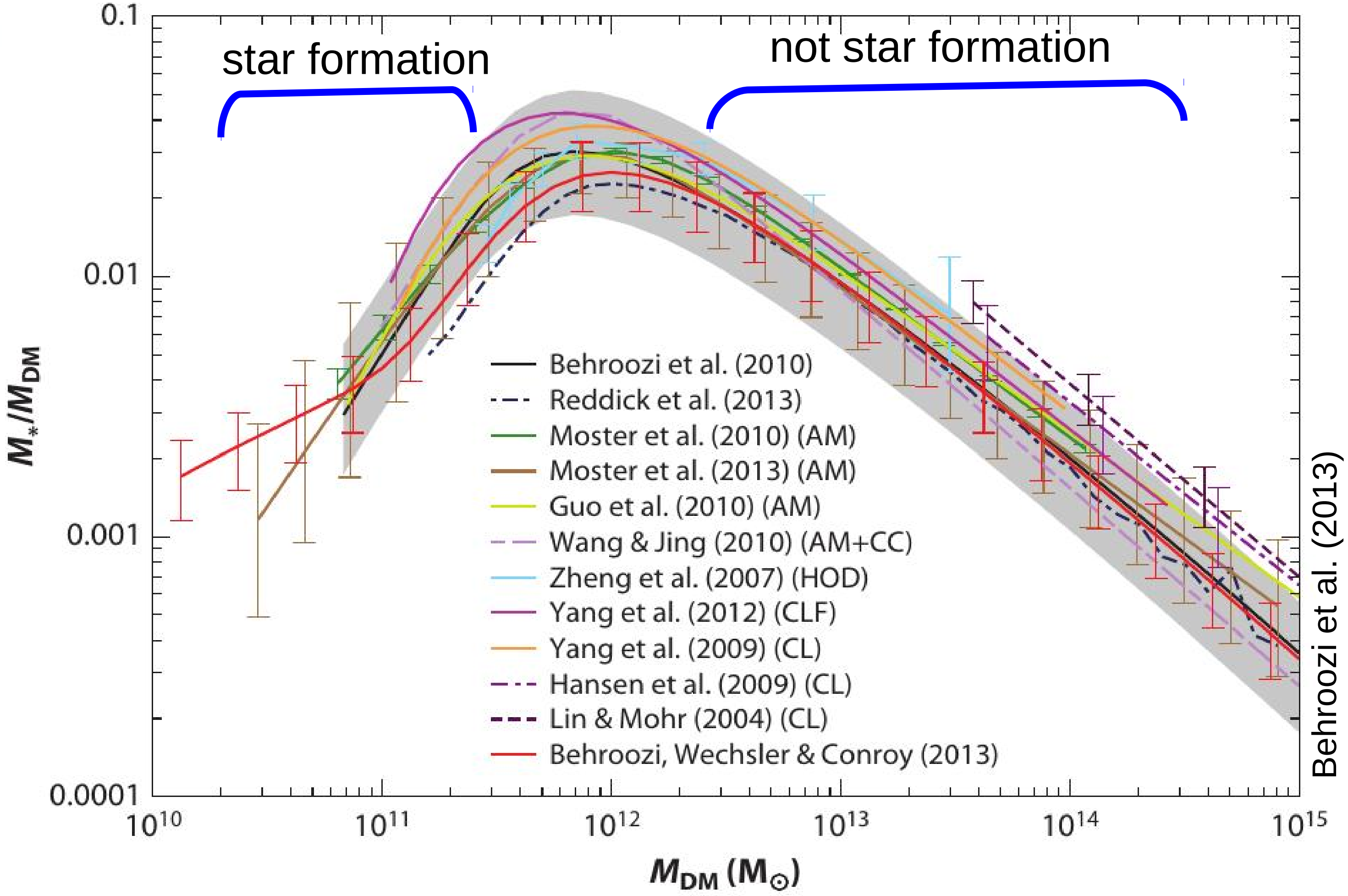
Bigiel et al. (2008),, Daddi et al. (2010)

MS & SK : Is star formation in galaxies set locally or globally ?

Why is baryon cooling in galaxies inefficient ?

Cosmic baryon cooling onto galaxies is ***highly inefficient***

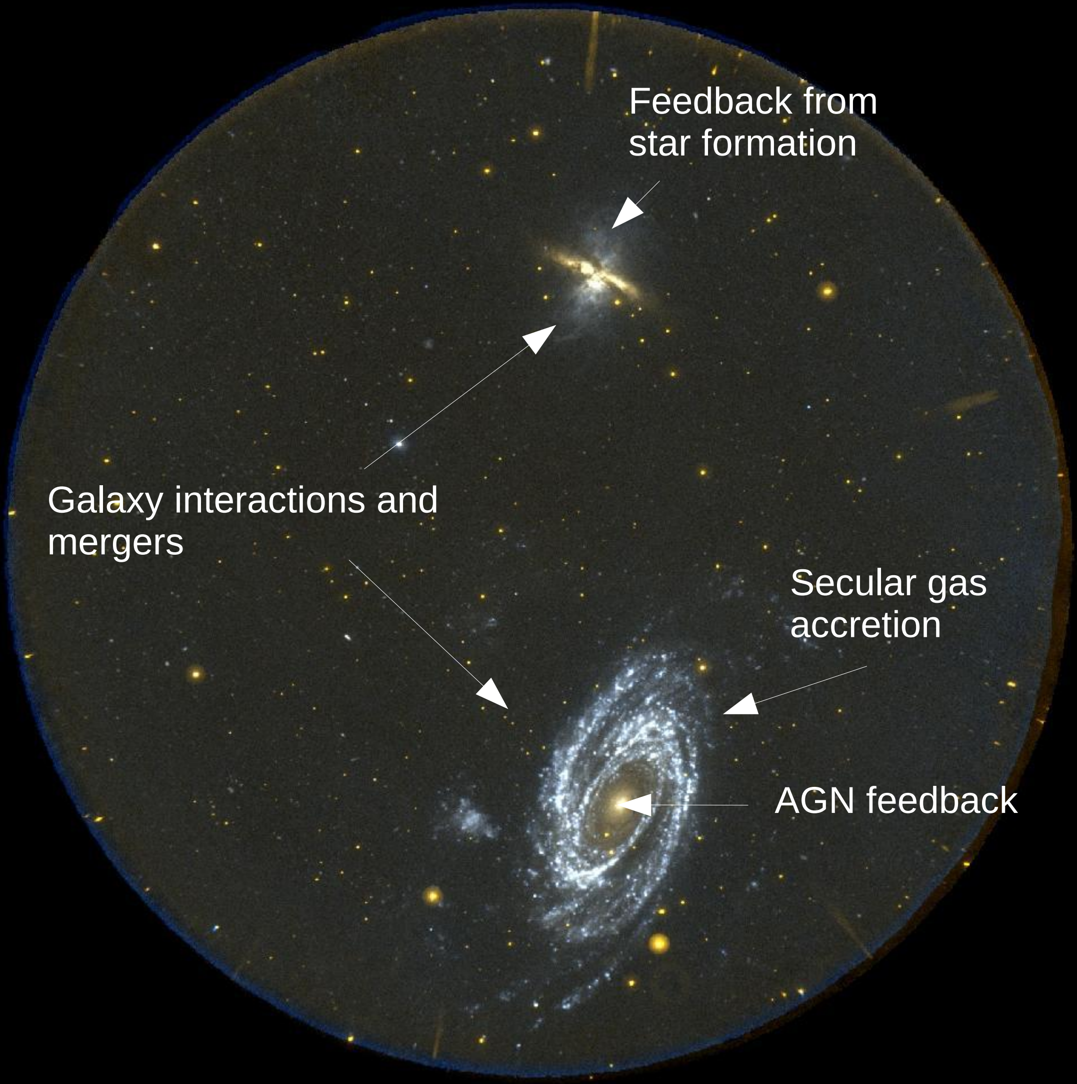
- ~20% of average cosmic baryon fraction in 10^{12} $M_{\odot}$ halos
- less in higher and lower mass halos



…WHY?

- Environmenal effects :
  - Interactions / stripping
- Stellar mass surface densities
- Shape of the gravitational potential
- Gas cooling / heating mechanisms ?
-
- ***A missing energy source ?***

Short, transformative stages



Injection of kinetic energy

↓

Dissipation of kin. Energy, gas relaxation

↓

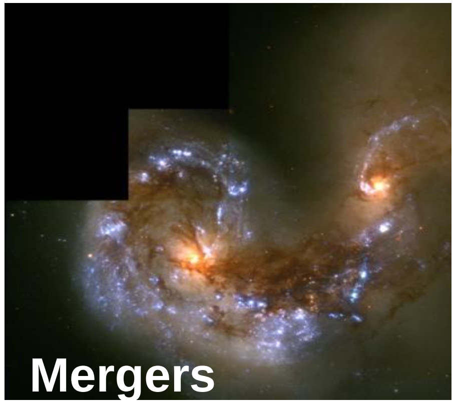
Regulation of star formation

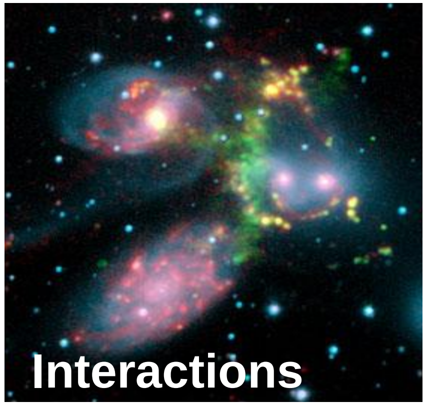
↓

Regulation of galaxy growth, and the internal structure of the galaxy and surrounding dark-matter halo

Short vigorous stages of transformation

Release of large quantities of kinetic energy, ~ E_{bind}
Not all energy is thermalized into the hot plasma.





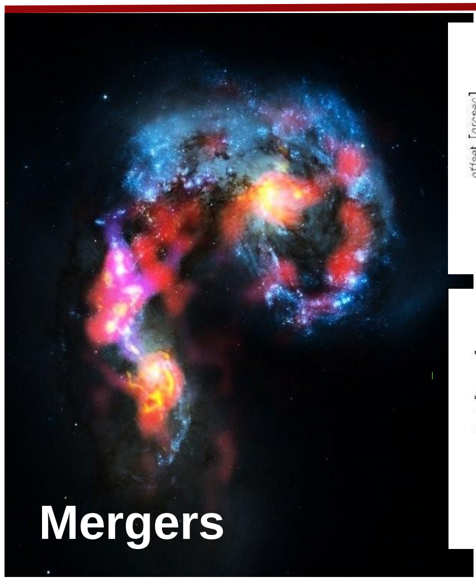
Feedback

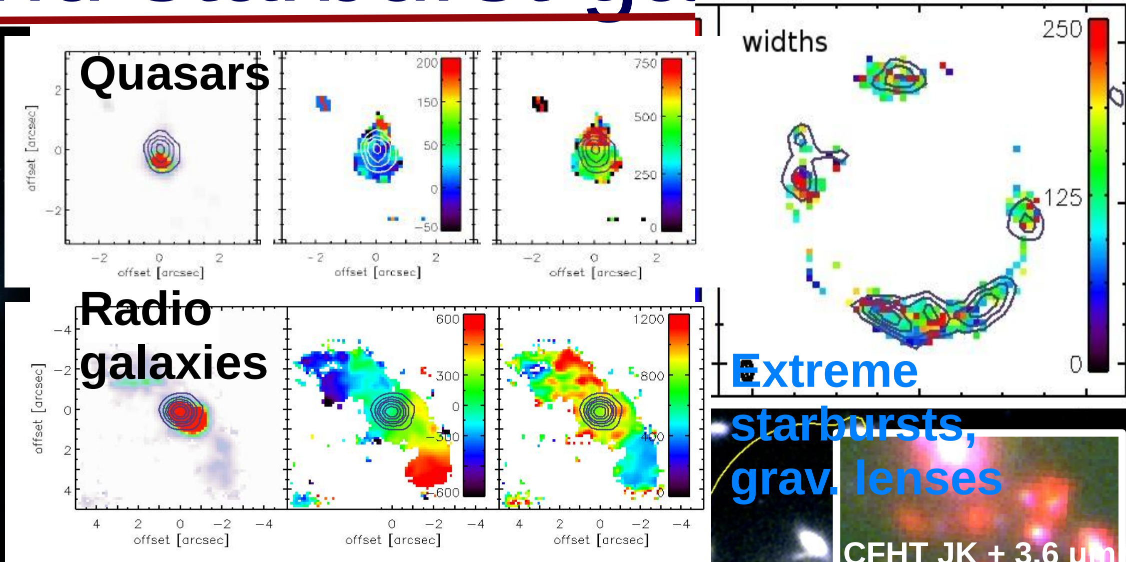
Time scales $10^{7\text{-}8}$ yrs → ~ 1 to few t_{dyn} → ~ 1 to few t_{diss}

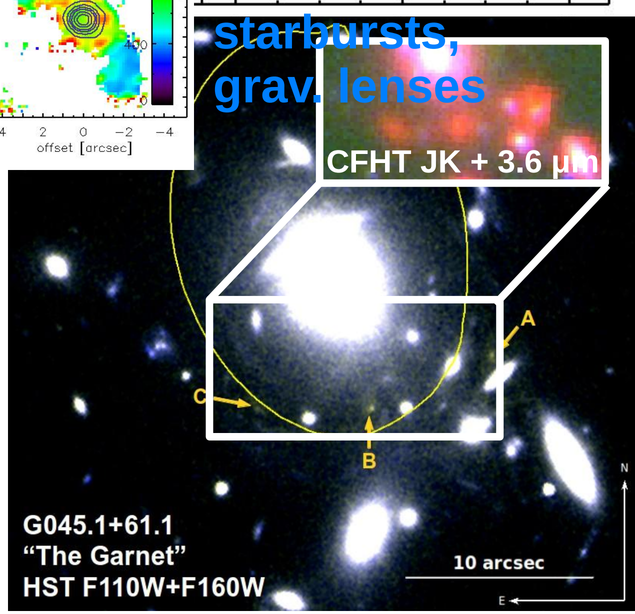
Where does the energy go?
multi-wavelength observations
& interpretation that borrows from galaxy evolution and star formation modeling.

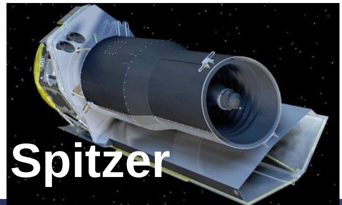
Impact on star formation?

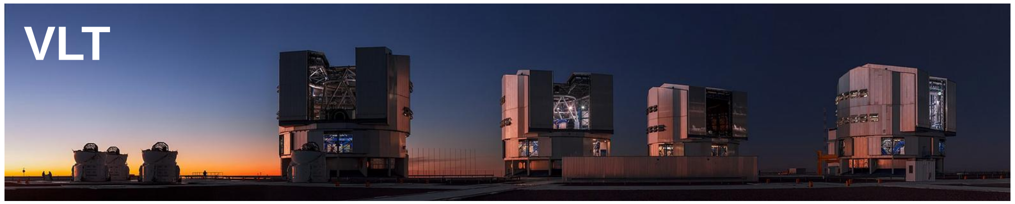
Regulation of star formation in AGN and starburst galaxies



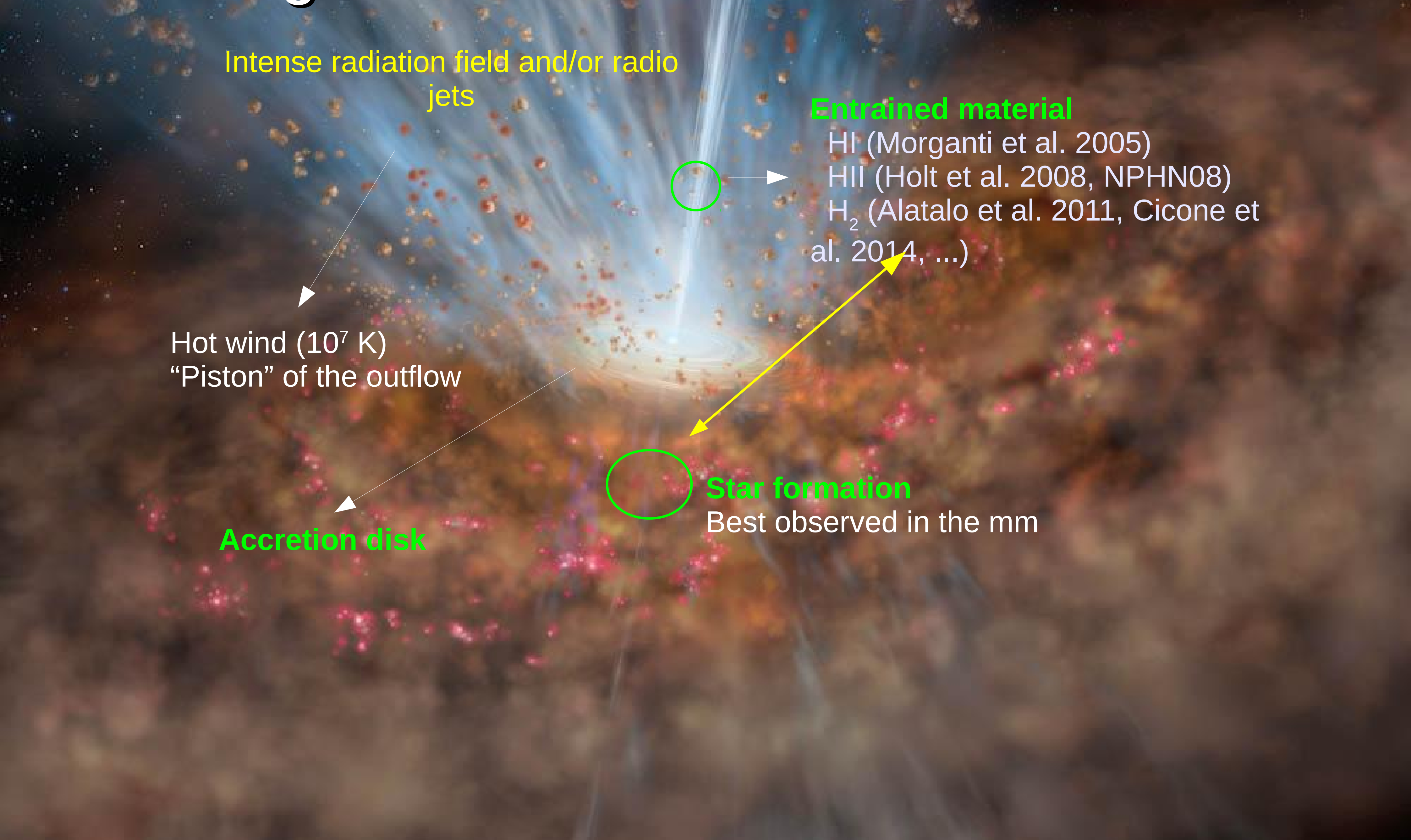








Active galactic nuclei



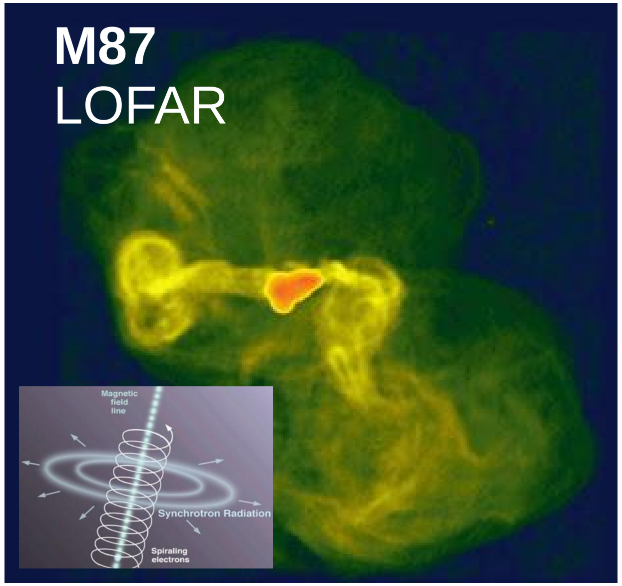
Bolometric vs. radio emission from AGN

Two forms of AGN energy output

→ Bolometric radiation
→ Relativistic particle beams (radio jets)

[**QSO zoology :** QSOs, Quasars, Seyferts, Radio galaxies FRI/FRII, BLERGS/LERGS, Blazars, BL Lacs, …]

How does each mechanism affect star formation in their host galaxy ?



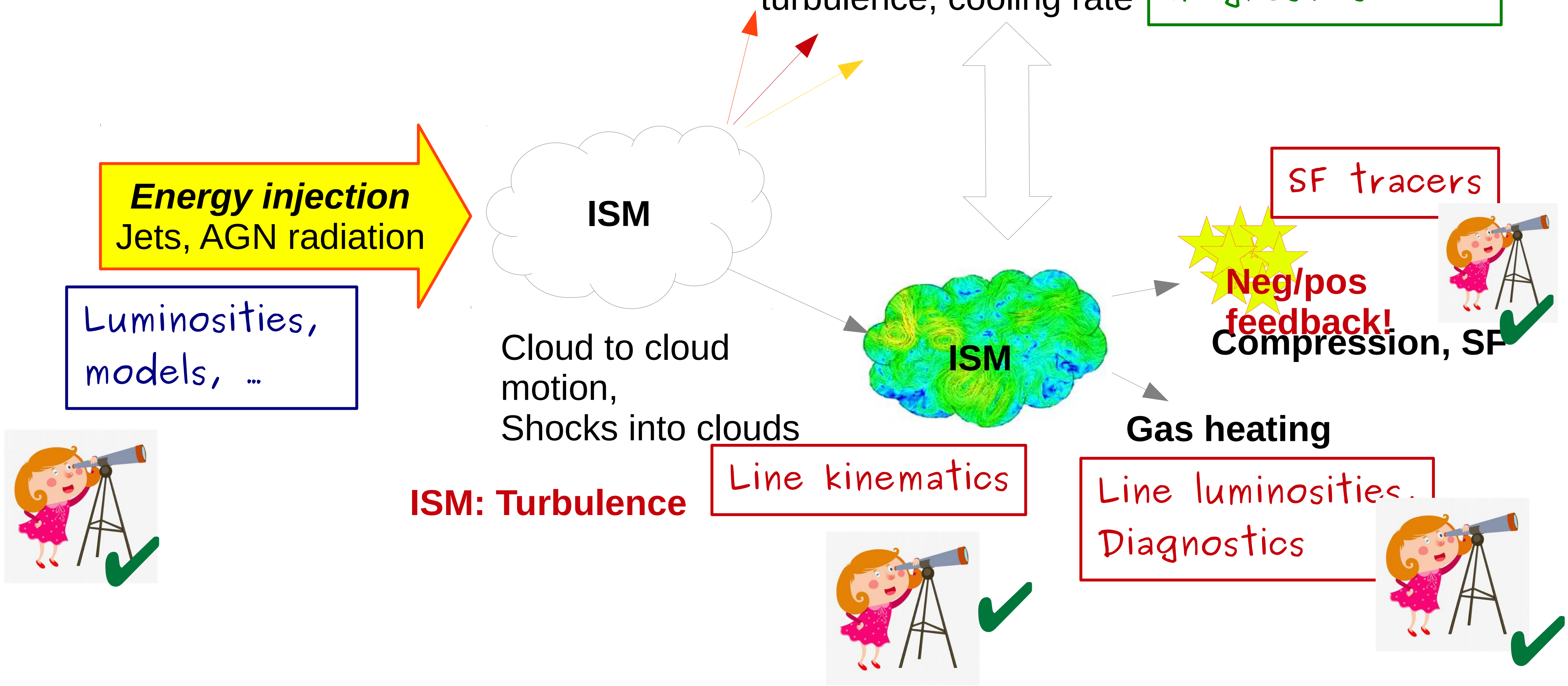
Bolometric radiation
(Often) in actively star-forming, low/intermediate mass galaxies, high black hole accretion rates

Radio sources
At low-z (often) in very massive, early-type galaxies with radio sources, low black-hole accretion rates.

→ **Impact on gas in the host galaxy ?**
→ **Impact on star formation ?**

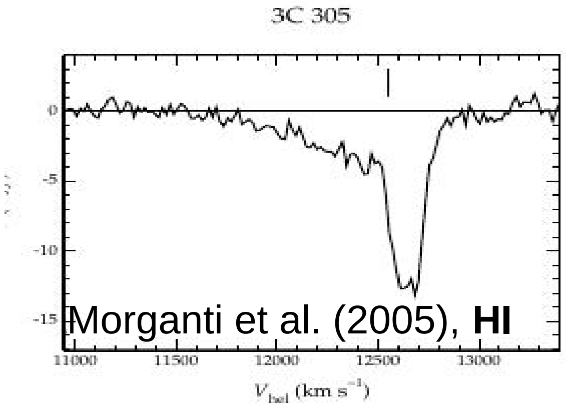
How do AGN regulate star formation in galaxies?

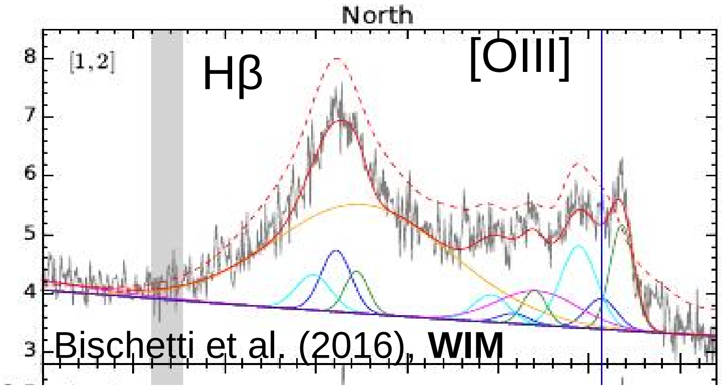
- *Where does the energy go?*
- *How efficiently is it deposited?*
- *What happens then ?*

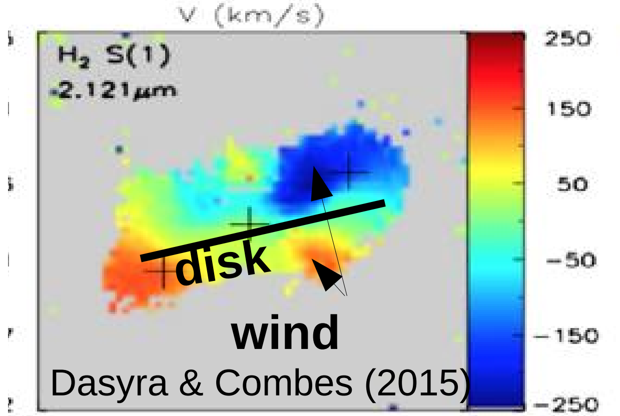


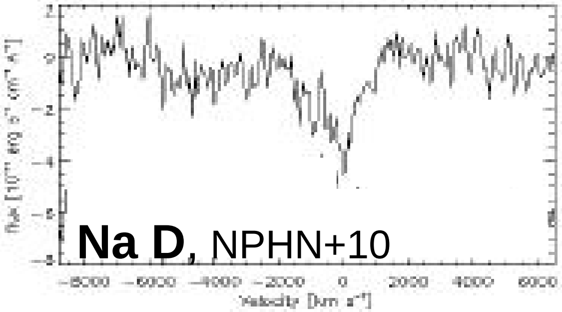
Winds as feedback mechanism

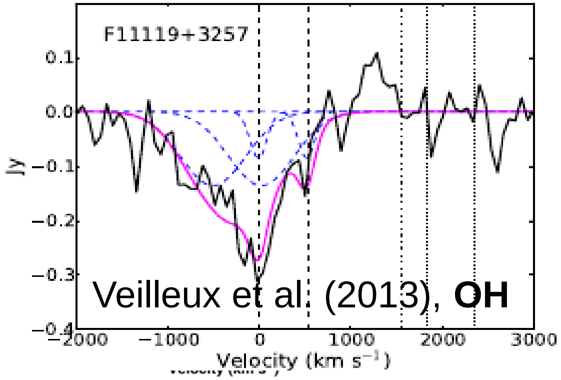
AGN-driven winds in galaxies are common !

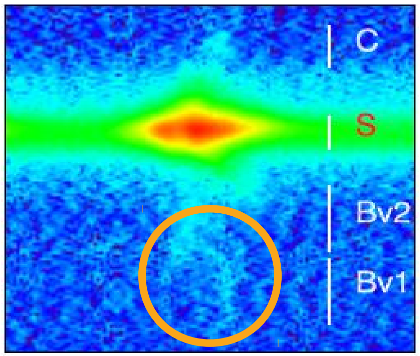




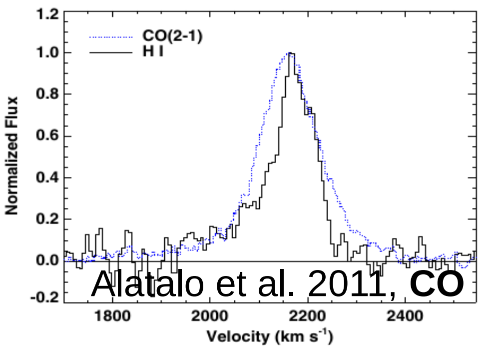


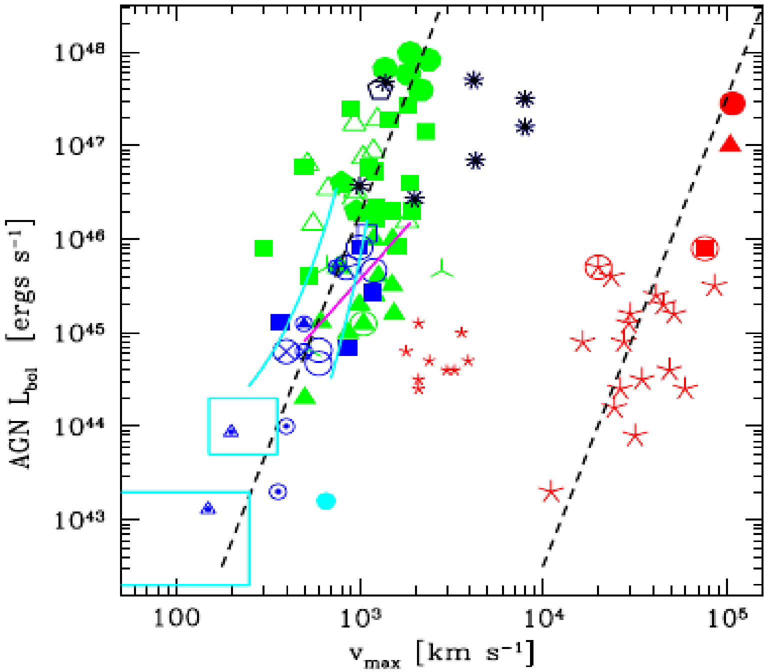






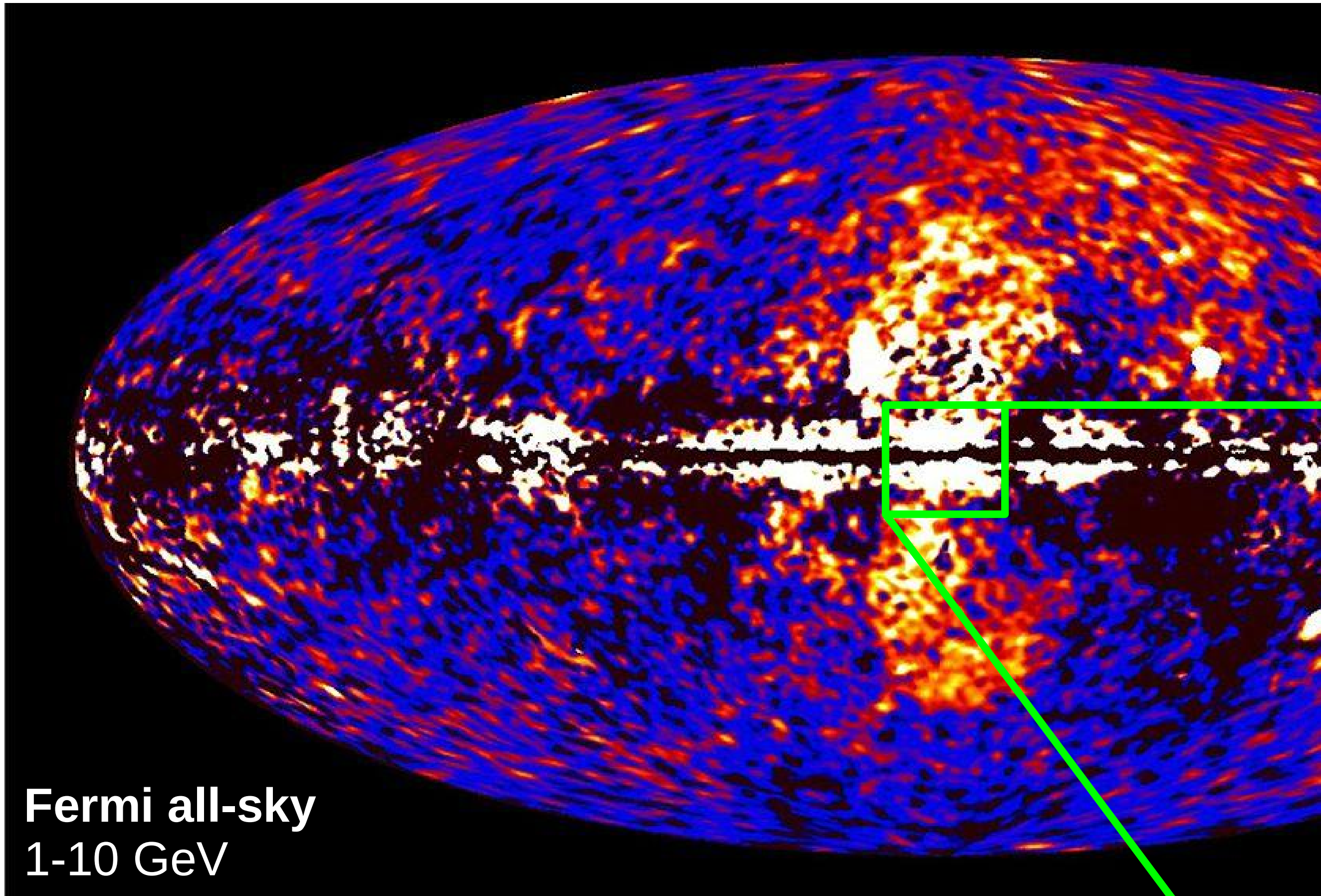
Greene & Zakamska (2012), **WIM**





Wind scaling relationships (Fiore et al. 2017)

Milky Way : Fermi bubbles



Finkbeiner et al. (2017)

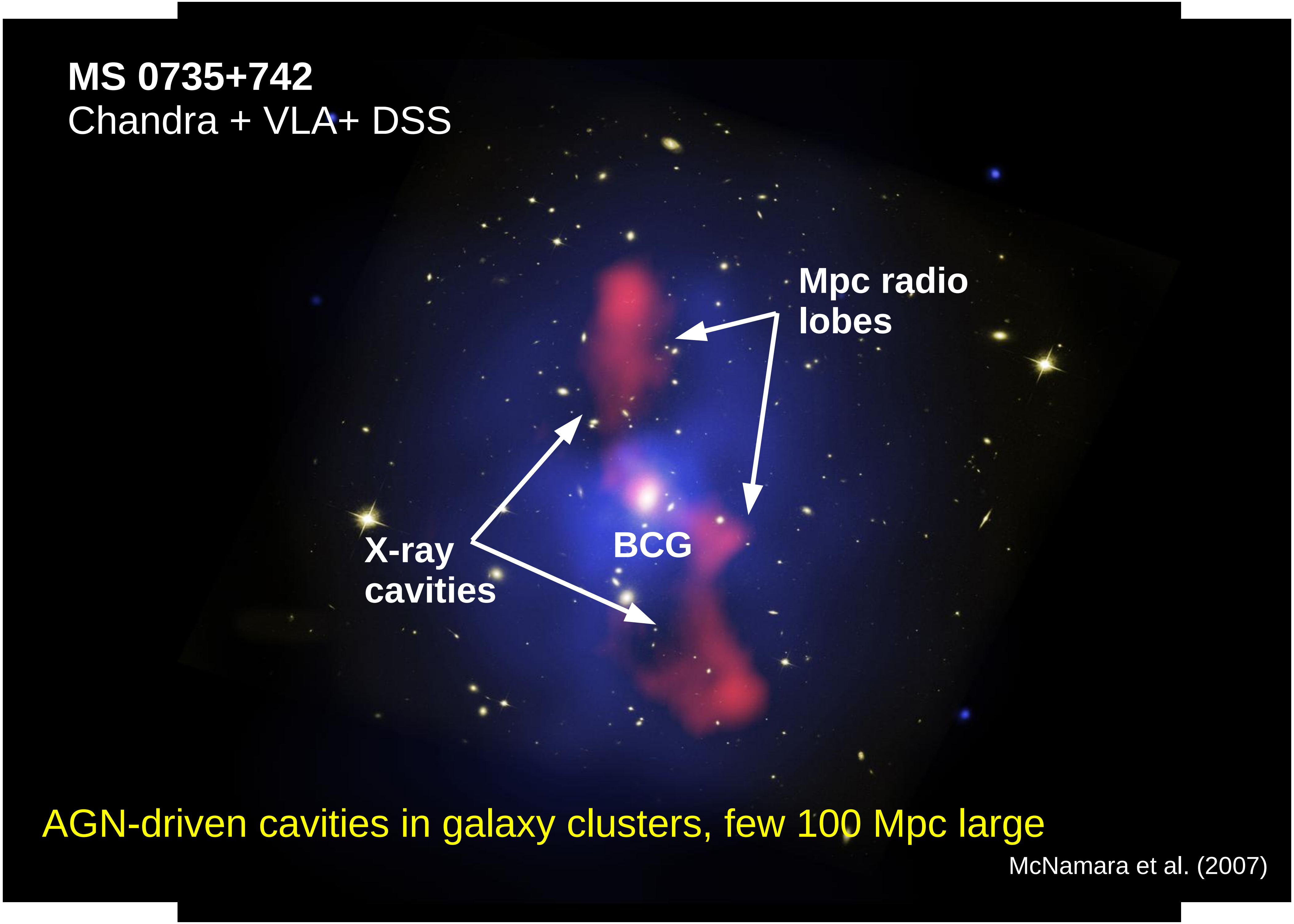
Haywood et al. (2019)

E_{kin} = 7x10^{52} erg,

driving mechanism unclear. Star formation? Sgr A* ?

MS 0735+742

Chandra + VLA+ DSS

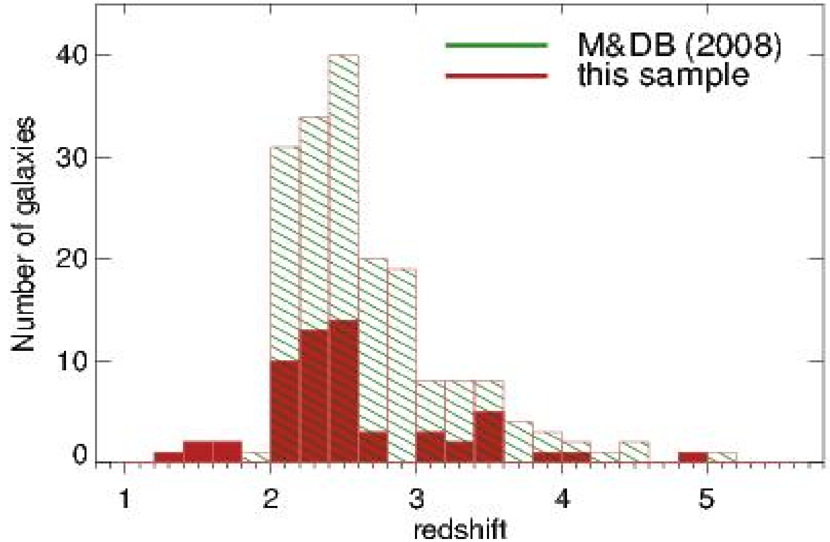


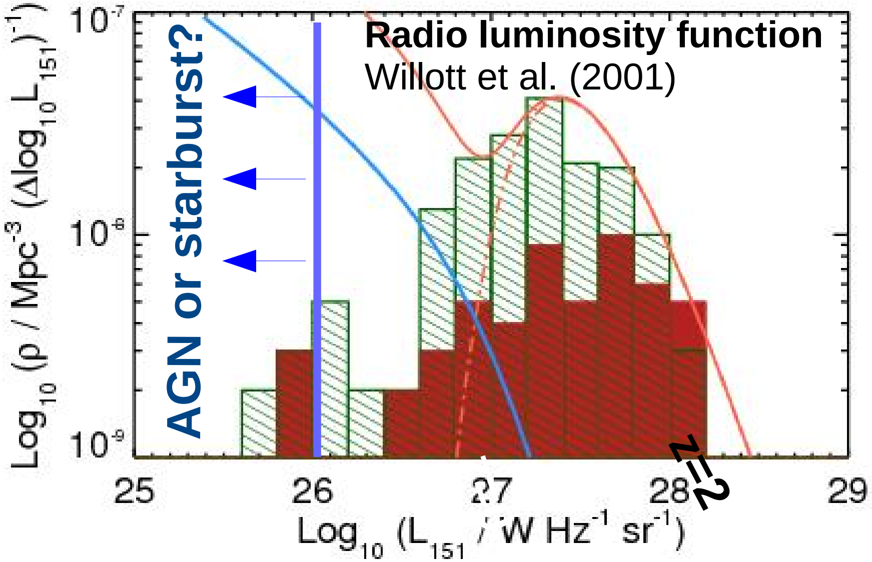
AGN-driven cavities in galaxy clusters, few 100 Mpc large

McNamara et al. (2007)

The SINFONI survey of powerful radio galaxies at z~2

Nesvadba et al (2017a, A&A 599,123)

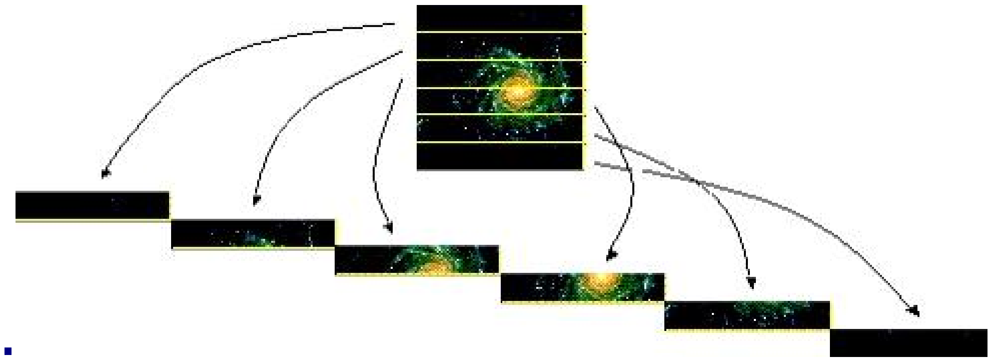




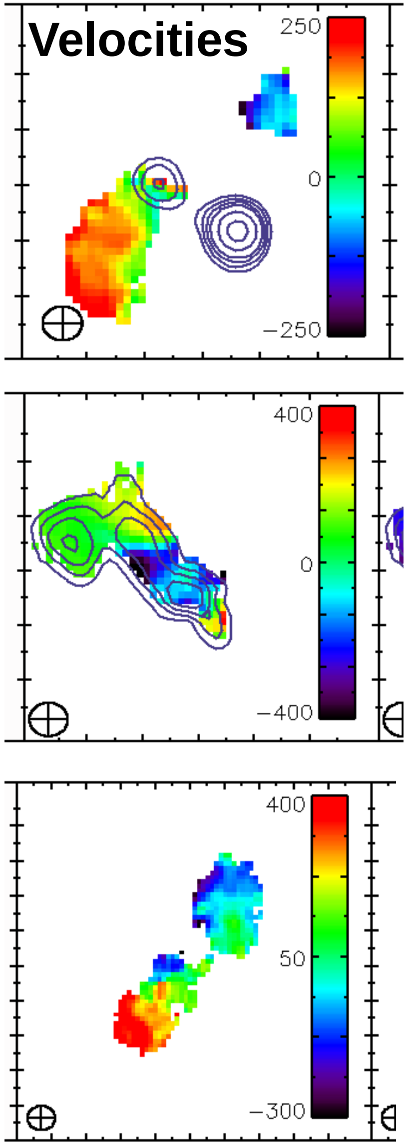
Small range in bolometric, large range in radio power

→ **systematic study of impact of radio source.**

NIR imaging spectroscopy : WIM kinematics and diagnostics of 49 powerful radio galaxies



Gas kinematics and kinetic energy



Velocities

Consistent w/ back-to-back outflows

Δv up to 1500 km s^{-1}

Kinetic energy

$E_{kin,mech} = ½\, \Sigma\, m_i\, v_i^2\, t_{dyn}$

$= \text{few } 10^{58}$ erg

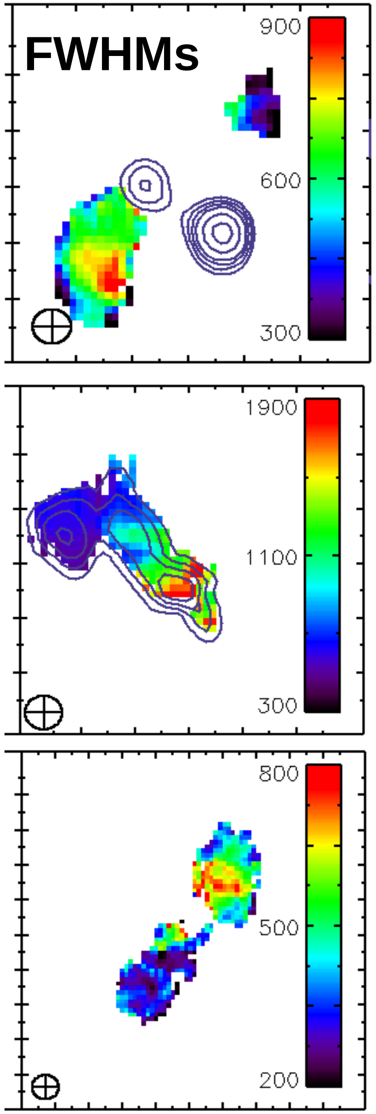
$E_{kin.blast} = 1.5x10^{46} r^2_{10},\ v^3_{1000}\, n_{0.5}\ t_{dyn}$ erg s^{-1}

$= \text{few } 10^{59}$ erg

Dynamical timescale

t_{dyn} = size / (½ Δv)

= few 10^7 yrs



FWHMs

Consistent w/ high turbulence

FWHM up to 1500 km s^{-1} (typically 500-1000 km s^{-1})

$E_{kin,turb} = 3/2\, \Sigma\, m_i\, \sigma_i^2$

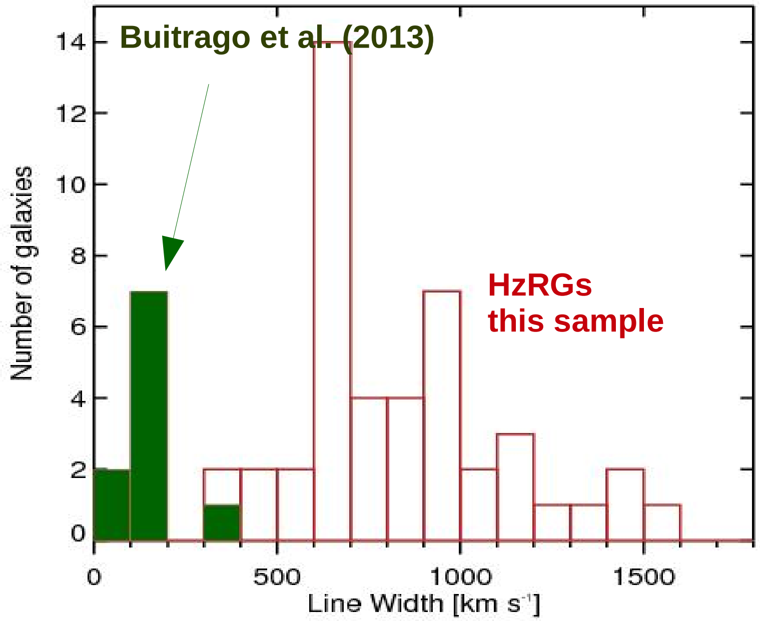
$= \text{few } 10^{58}$ erg

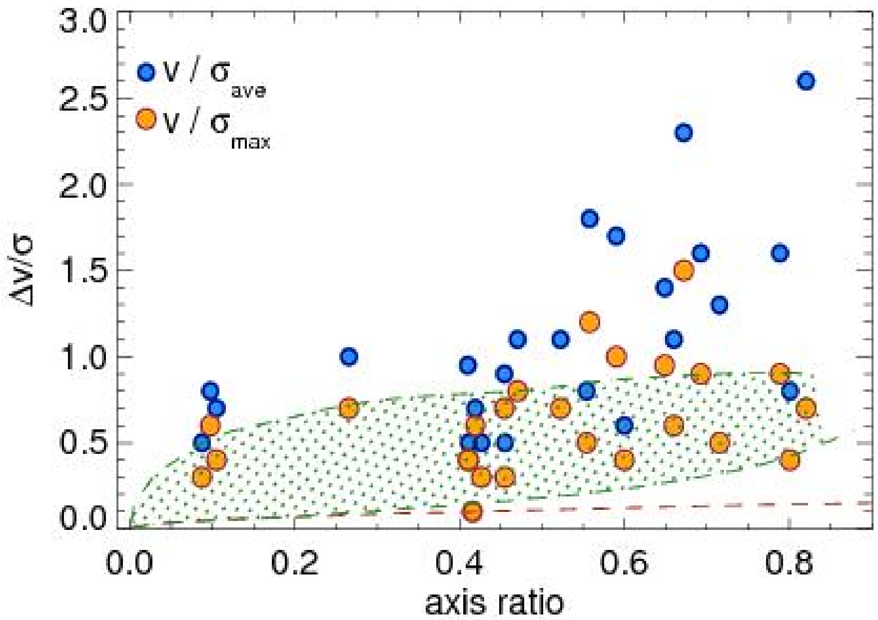
- **$\sigma / v \sim 1$**
- **$v > v_{escape}$ for P(500) ≥ 10^{28} W Hz^{-1}**
- **$E_{kin} \sim 10^{-2}\, M_{BH}$**

Expected signatures of AGN-driven winds

No signatures of gravitational motion

- line widths ≫ than in mass-selected samples of high-z galaxies with $M_{stellar}$ = few 10^{11} $M_\odot$
- no trends between kinematics and stellar mass estimates
- higher ratio of bulk / random motion than in pressure-supported (early-type) galaxies → **No evidence of rotationally dominated kinematics**





Nesvadba et al. (2017a,b)

Jet, QSO or star formation? Empirical arguments

Size of the gas ≤ jet size

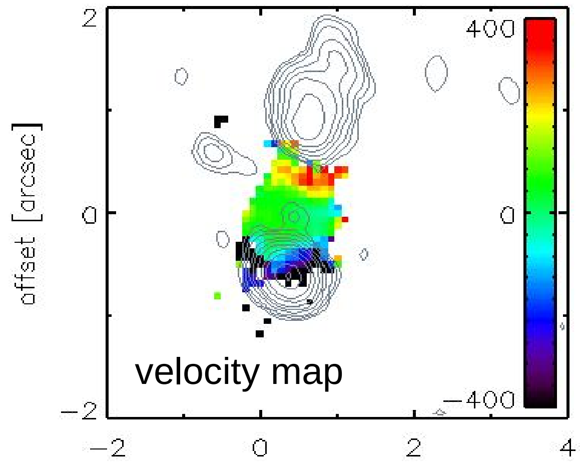
≠ diffuse Lyα halos (Villar-Martin et al. 2003)

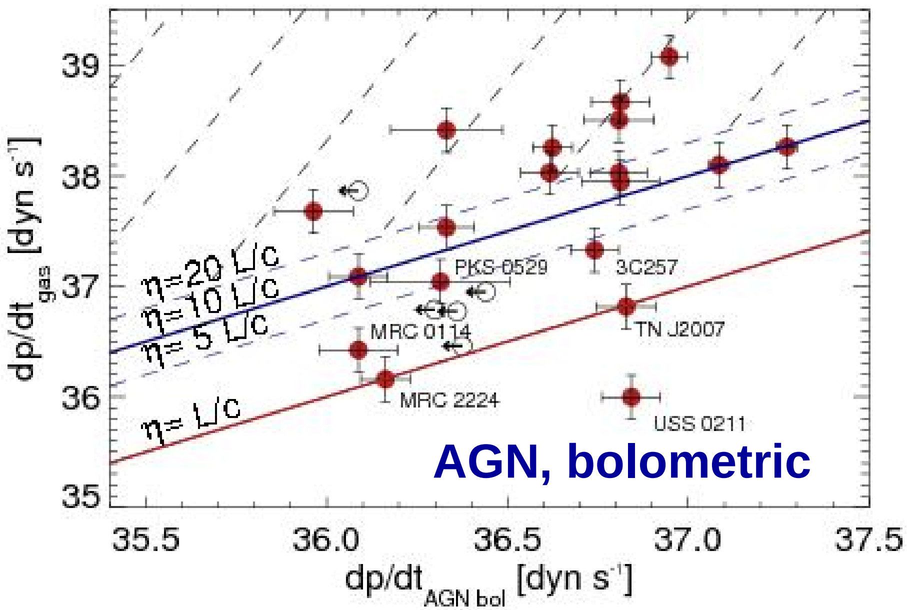
Good alignment of jet and gas

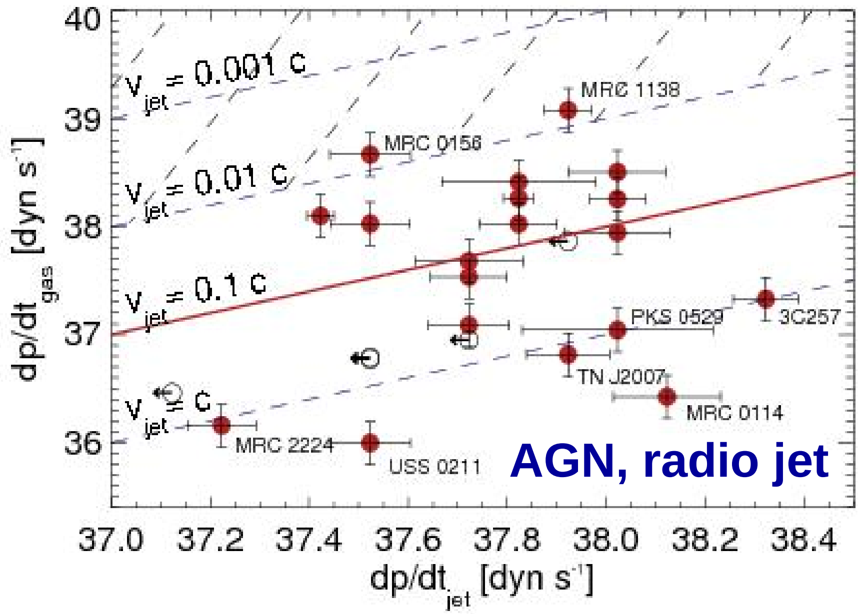
(“alignment effect”), e.g., Cimatti et al. (1997)

Energy constraints

Jet kinetic energy > gas kinetic energy







Dynamical times: $t_{dyn,\ gas}$ ~ 10^7 yrs ~ t_{jet}

Nesvadba et al. (2006, 08, 11, 17), Collet, NPHN et al. (2015, 16)

...are winds all there is to feedback?

probably not ...

Three main arguments

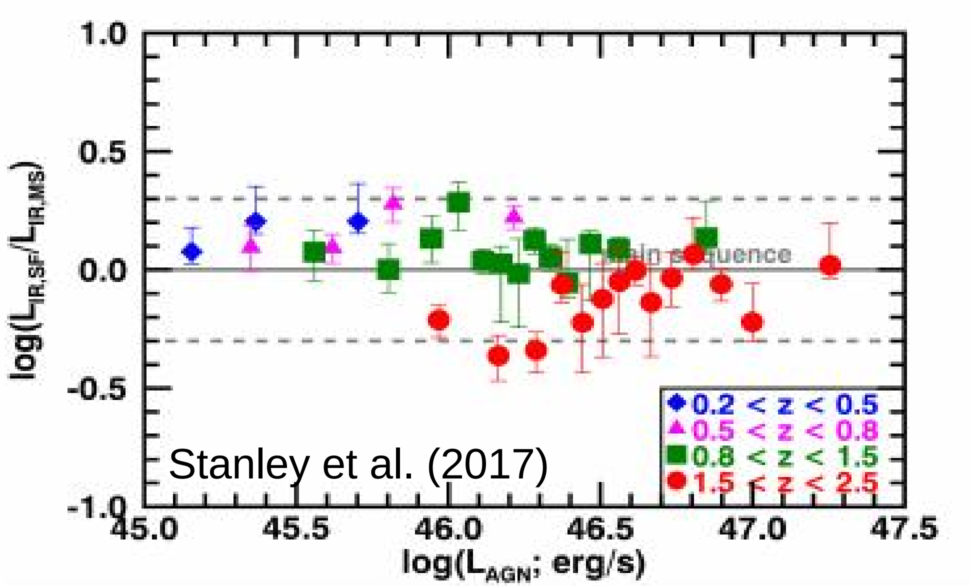
(I) The basic picture that galaxies w/o star formation are also poor in gas is oversimplified

(II) AGN activity is variable, but feedback is continuous.

(III) What is the impact on star formation ?

AGN feedback and star formation

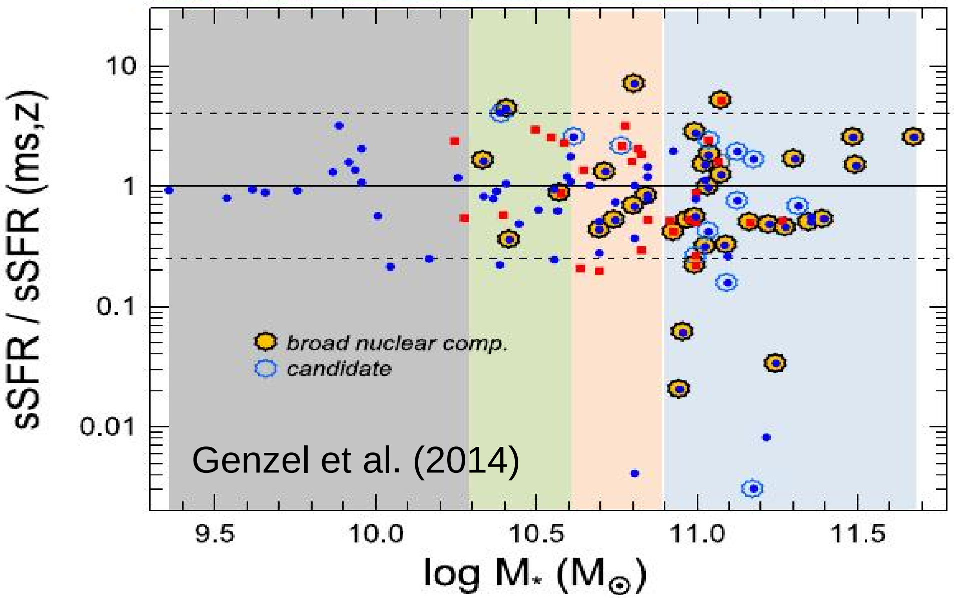
Bright optically selected quasars



FIR SED fitting, Herschel-Atlas

Quasars are near the main sequence, for optically, radio-loud/radio-quiet, and X-ray selected sources.

Star-forming AGN hosts

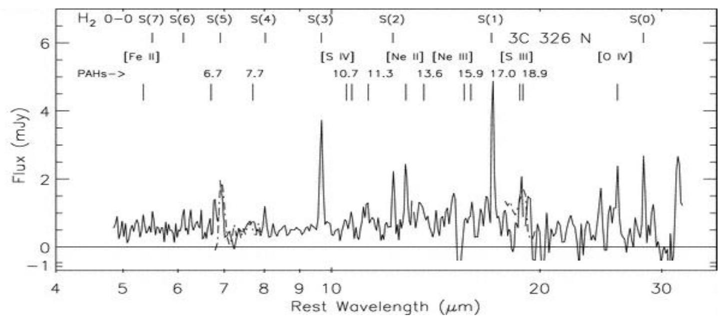


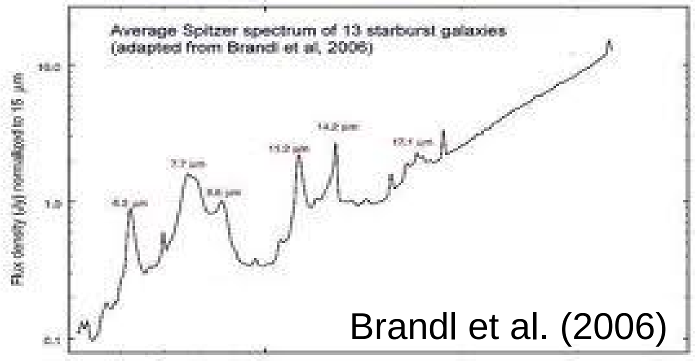
SINS and other IFU surveys of optically selected SFGs

AGN hosts do not show significant offsets from the main sequence.

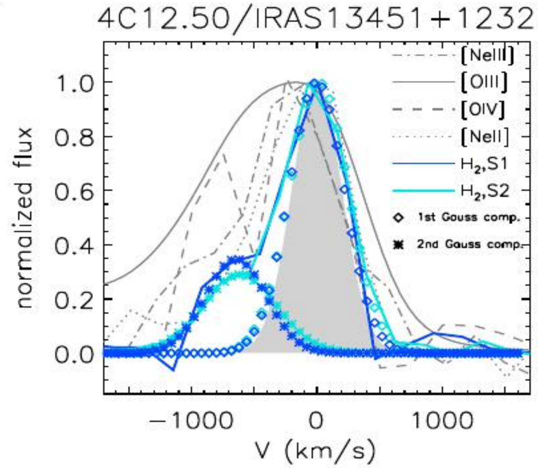
Warm H_2 in radio galaxies

Ogle et al. (2007)

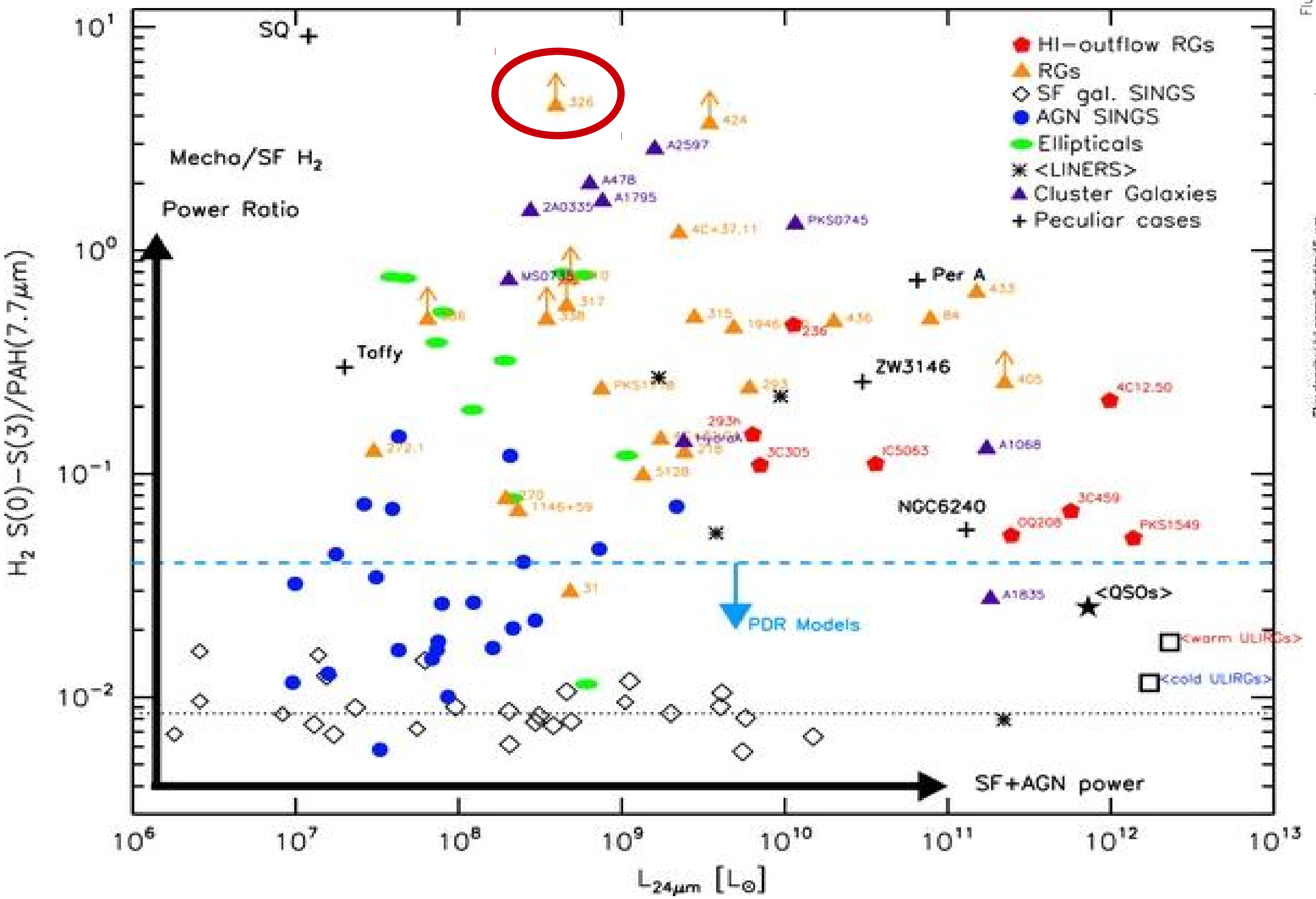




Brandl et al. (2006)



Dasyra et al. (2011)



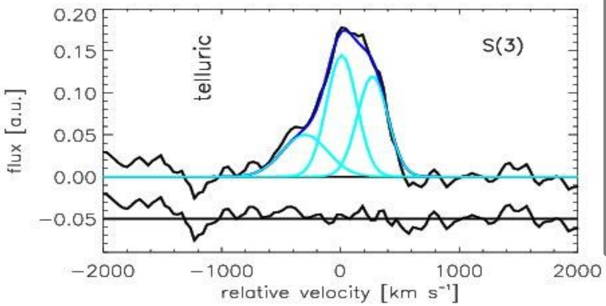
Guillard et al. (2012), Ogle et al. (2010)

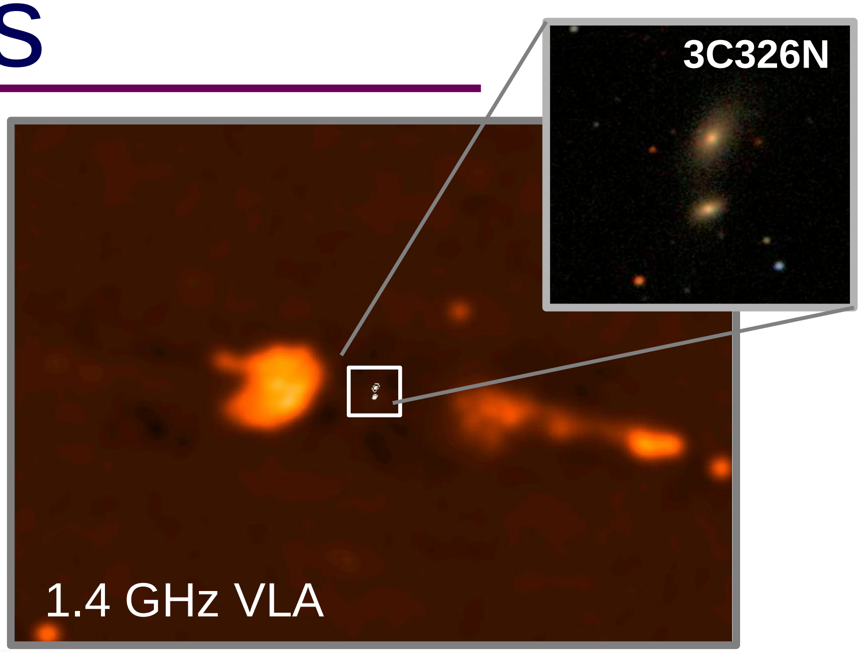
Gas-rich radio galaxies

a particularly clear example...

3C326 N – a textbook elliptical:
"old, red, and dead"

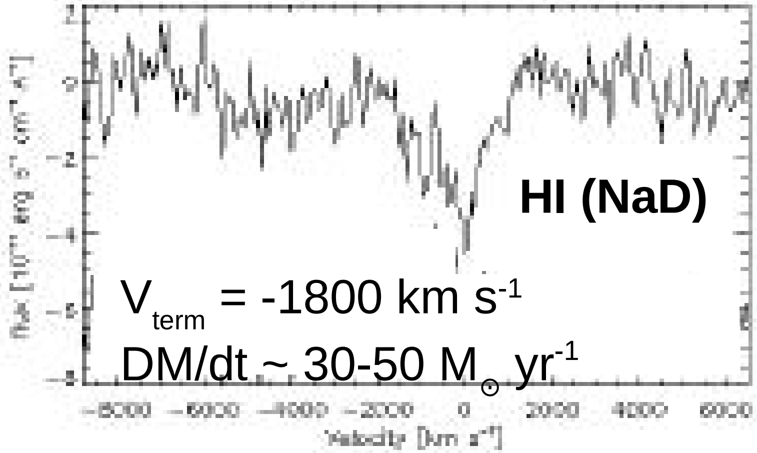
Distance	400 Mpc
Stellar mass	$3\times10^{11}\ M_\odot$
$Age_{stellar}$	$> 10^{10}$ yr
$M_{young\ stars}$	$< 10^{6}\ M_\odot$
Age_{jet}	2×10^{8} yrs
$P_{mech,jet}$	$\sim 10^{44\text{-}45}$ erg s^{-1}





NO SF $<0.07\ M_\odot\ yr^{-1}$
(upper limit Spitzer 70 μm, Ogle+07)

NPHN+10



"NO" AGN ($L_x \sim 10^{40.6}$ erg s^{-1})

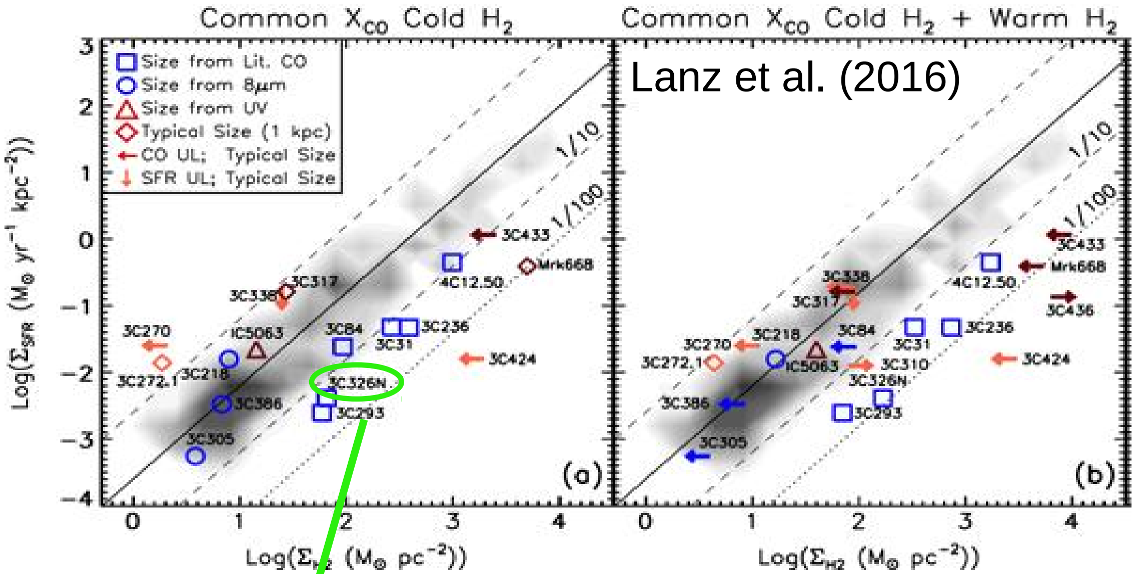
$\mathbf{M_{H2,\ warm} \sim M_{H2,\ cold} \sim 2\times10^{9}\ M_\odot}$ ~100x 'normal'

$\mathbf{L(H_2) = 10^{42}\ erg\ s^{-1}\ ;\ \sim100 \times L_x}$
(Ogle+07)

A wind w/o starburst or AGN radiation

Nesvadba et al. (2010, 2011)

Inefficient star formation in radio galaxies

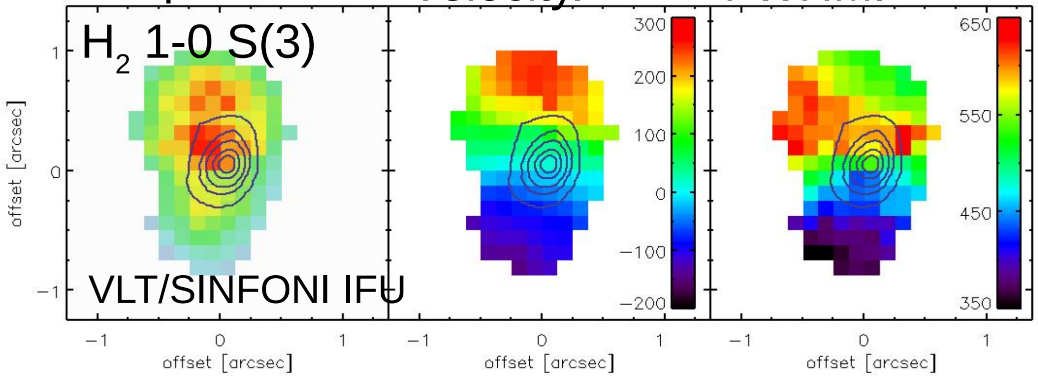


Significant offsets from Schmidt-Kennicutt relationship for low-z radio galaxies. → Signature of lower star-formation efficiency ?

ALSO : Large reservoirs of warm (shocked) molecular gas, few 10^9 $M_\odot$

See also: Nesvadba, Boulanger et al. (2010), Alatalo et al. (2011), Guillard et al. (2015), Nyland et al. (2016, 17)

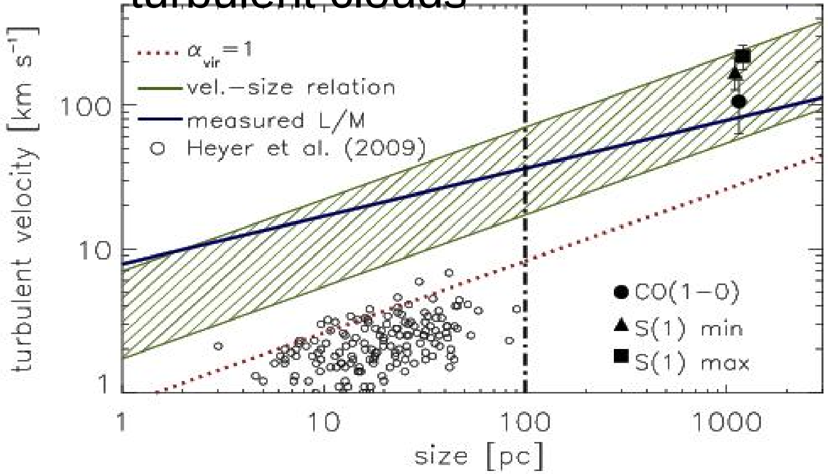
Morph. Velocity. FWHM.



Nesvadba et al. (2011)

3 kpc disk of warm dense H_2 in galaxy w/o star formation !

Larson (1981) relationships for turbulent clouds

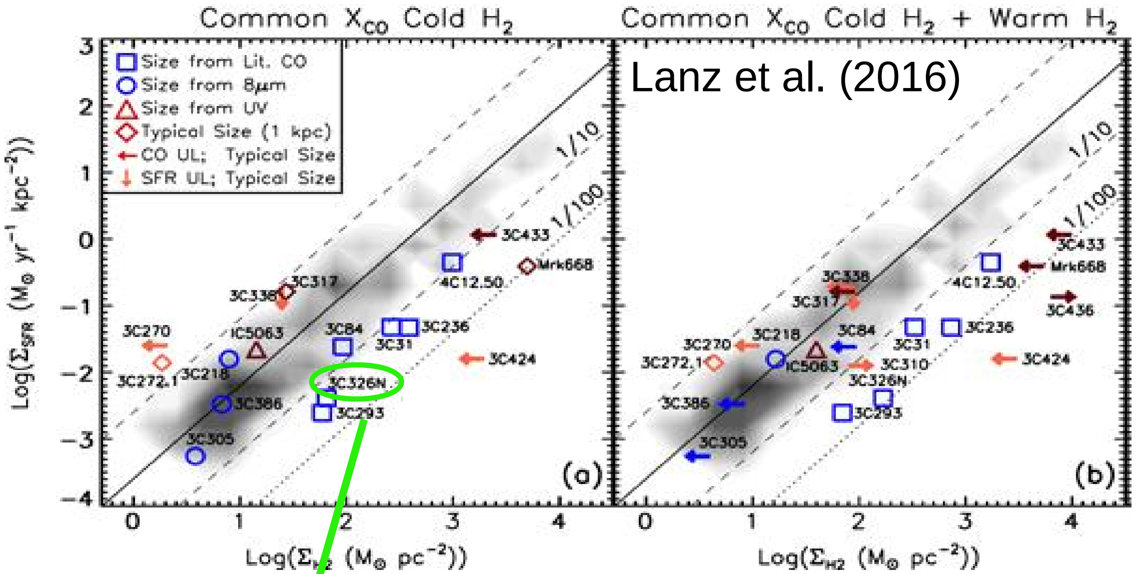


$$\alpha_{vir} = E_{turb}/E_{grav} = 5\sigma / \pi G R\Sigma_{gas}$$

$L/M = \sigma^3 \times f_c / R_{cl} = 0.06$

McKee & Ostriker (2007)

Inefficient star formation in radio galaxies **(???)**



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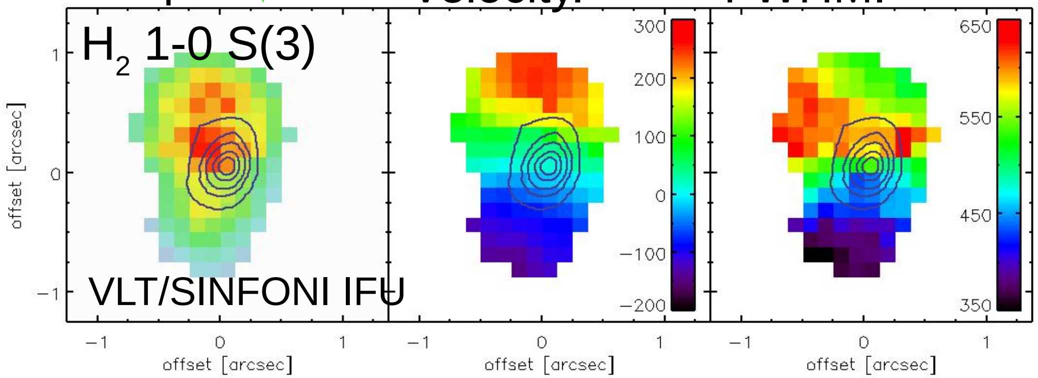
Morph. Velocity. FWHM.



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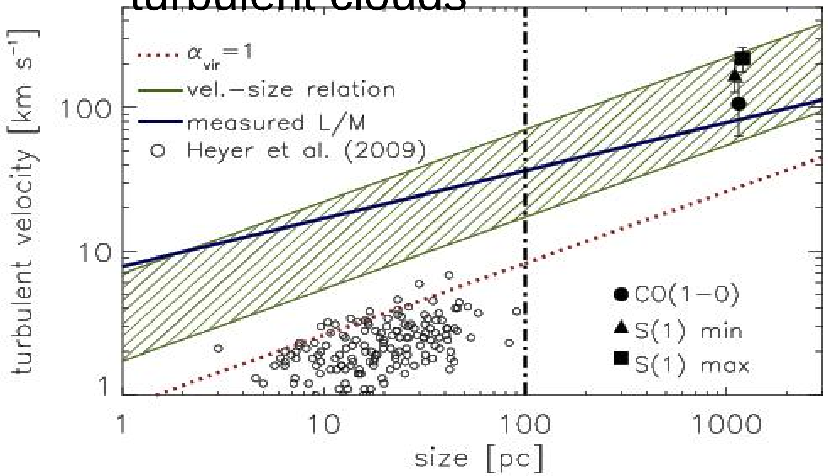
ALSO : Large reservoirs of warm (shocked) molecular gas, few $10^9\ M_\odot$

Larson (1981) relationships for turbulent clouds

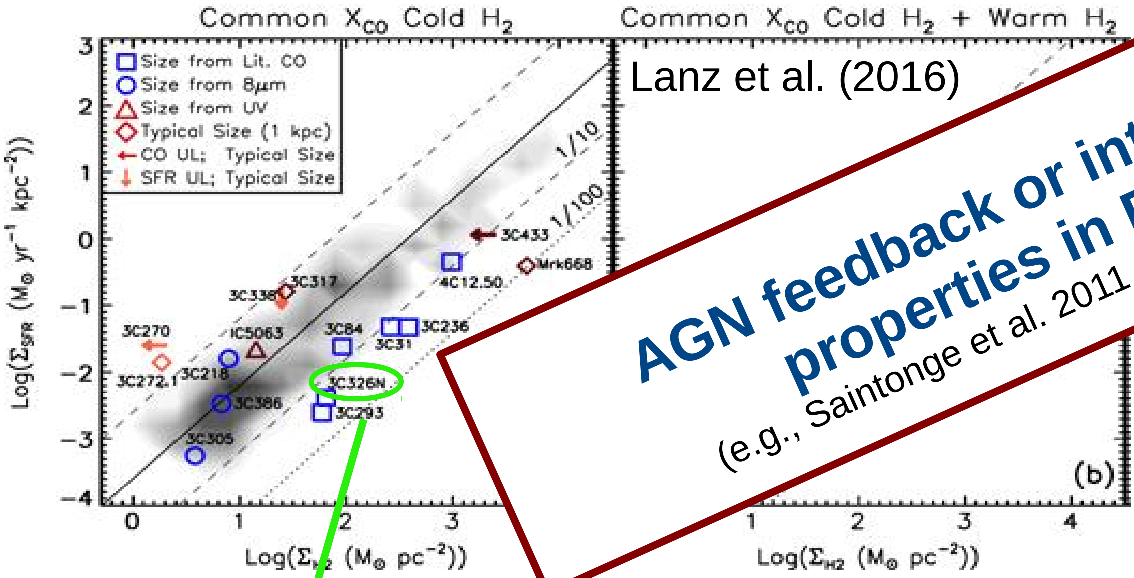


$$\alpha_{vir} = E_{turb}/E_{grav} = 5\sigma / \pi\ G\ R\Sigma_{gas}$$

$L/M = \sigma^3 \times f_c\ /\ R_{cl} = 0.06$

McKee & Ostriker (2007)

Inefficient star formation in radio galax... (???)



AGN feedback or intrinsic gas properties in ETGs ?
(e.g., Saintonge et al. 2011, Martig et al. 2009)

...n Schmidt-
...p for low-z radio
...gnature of lower star-
...n efficiency ?
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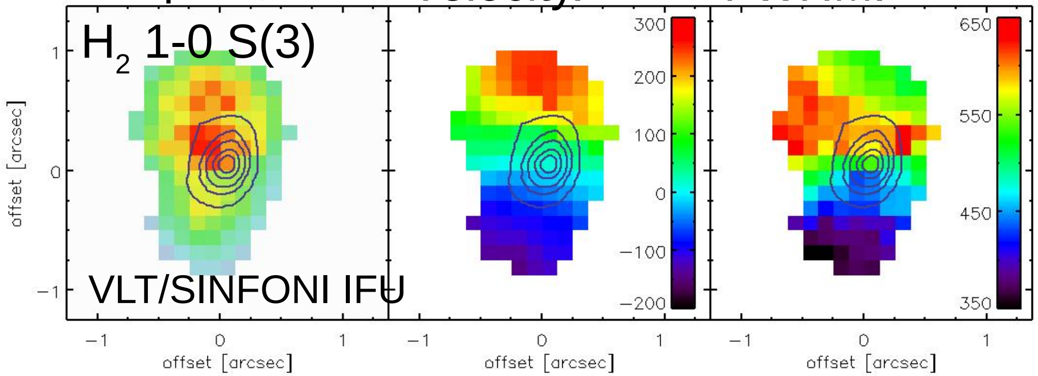
See also: Nesvadba, Boulanger et al. (2010), Alatalo et al. (2011), Guillard et al. (2015), Nyland et al. (2016, 17)



Nesvadba et al. (2011)

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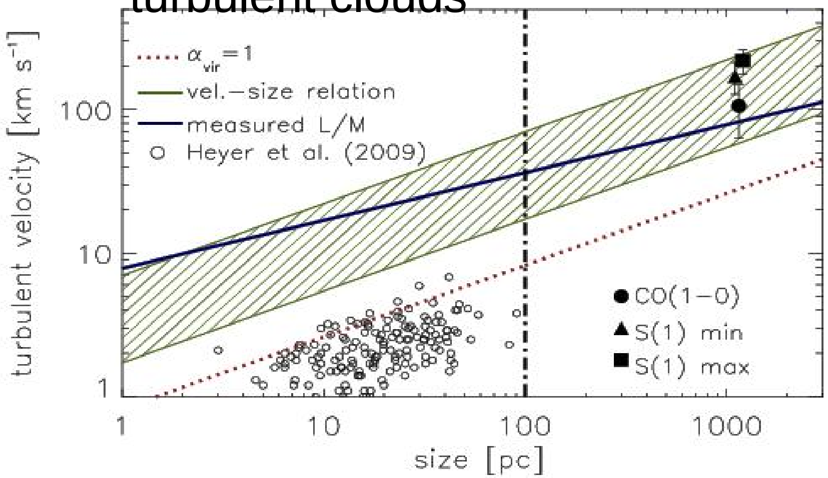

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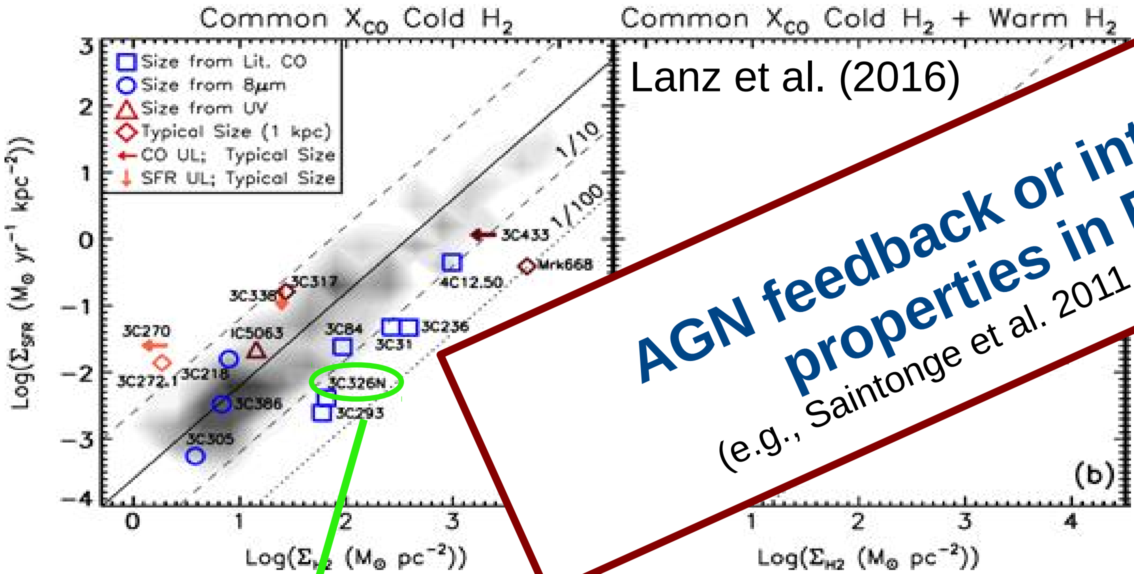

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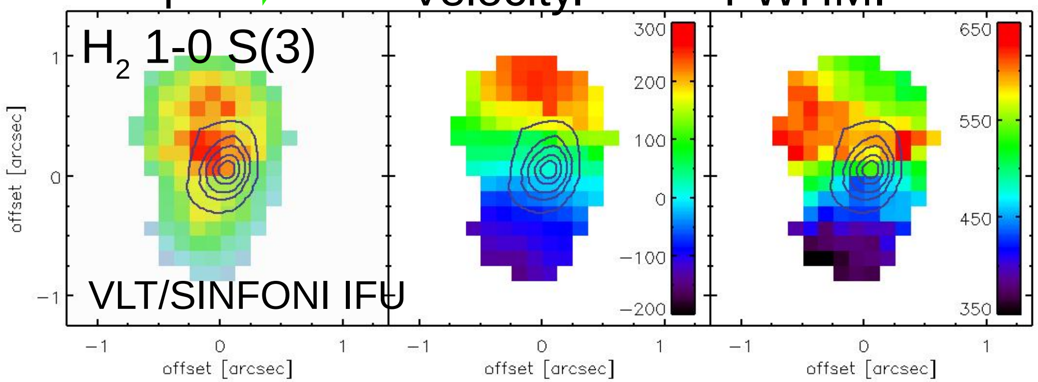
Morph. Velocity. FWHM.



Nesvadba et al. (2011)

3 kpc disk of warm dense H_2 in … galaxy w/o star formation !

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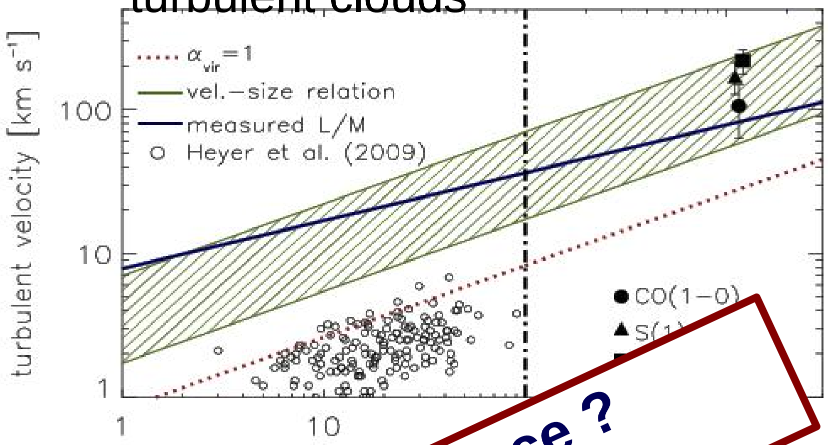


α_{vir} = … / π G RΣ_{gas}

Is it really turbulence ?

Needs to be shown !

… = σ^3 x f_c / R_{cl} = 0.06

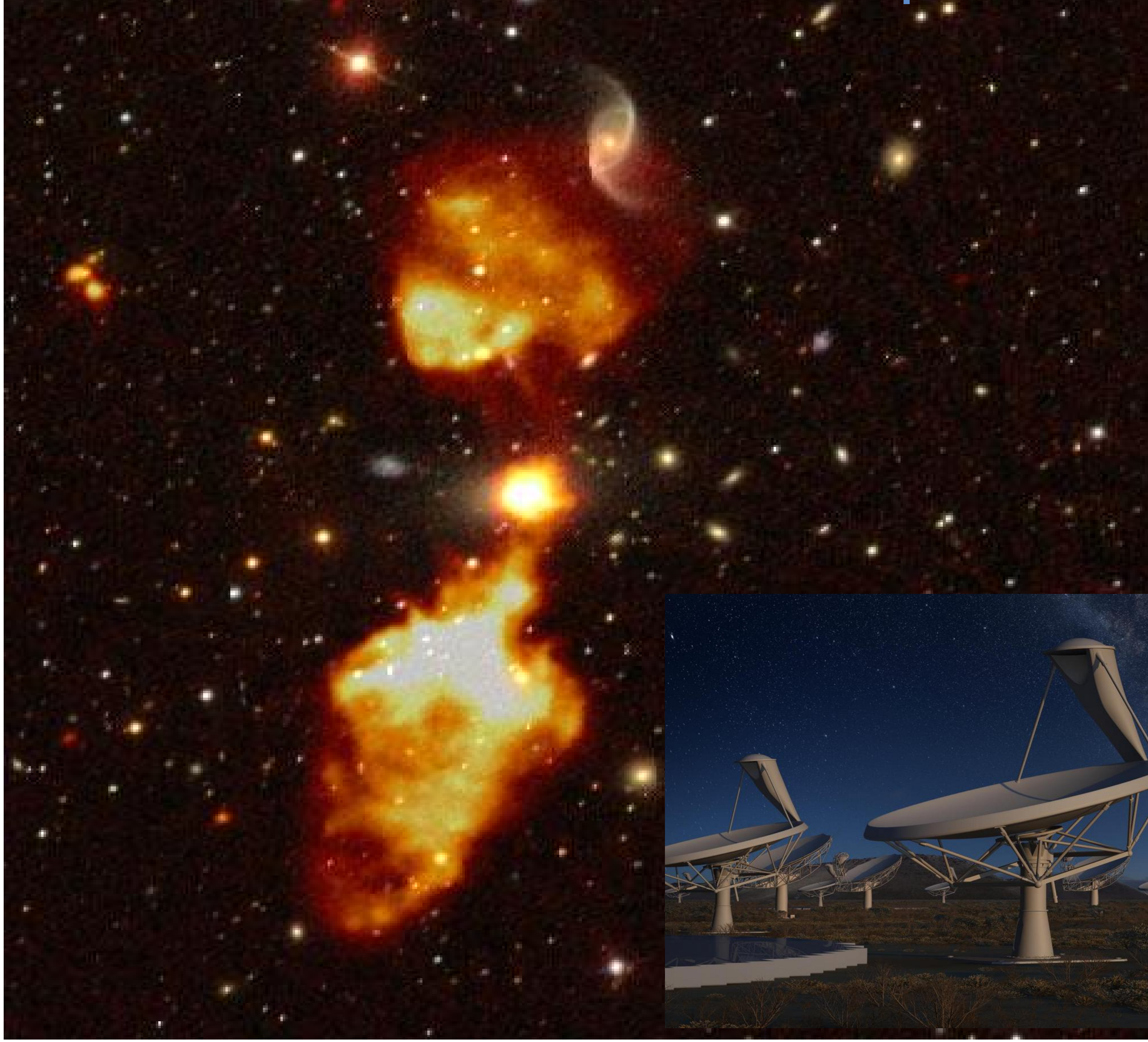
McKee & Ostriker (2007)

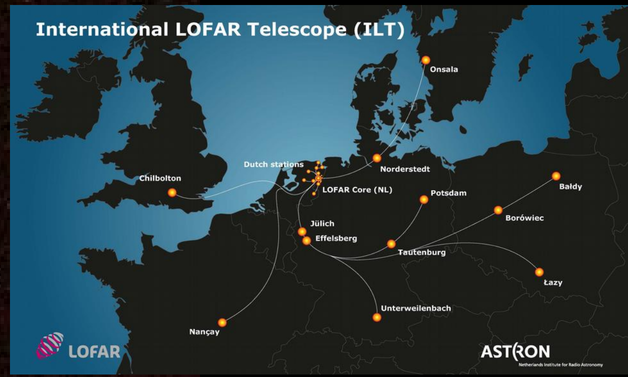
Feedback in galaxy evolution

- After 20 years of work: Winds are very frequent in many types of AGN hosts, but are not enough by themselves to explain why star formation is inefficient in massive galaxies.
- We need to identify in detail how it works: alternatives are not ruled out.
- Next step: Constrain well how, when, and where the energy is pumped into the gas. What effect does this have on the gas, and is this enough to limit star formation within the theoretical framework of turbulence-regulated star formation that we currently have ? → This is best done in the radio !
- Many new questions to be addressed, before answering the main one :

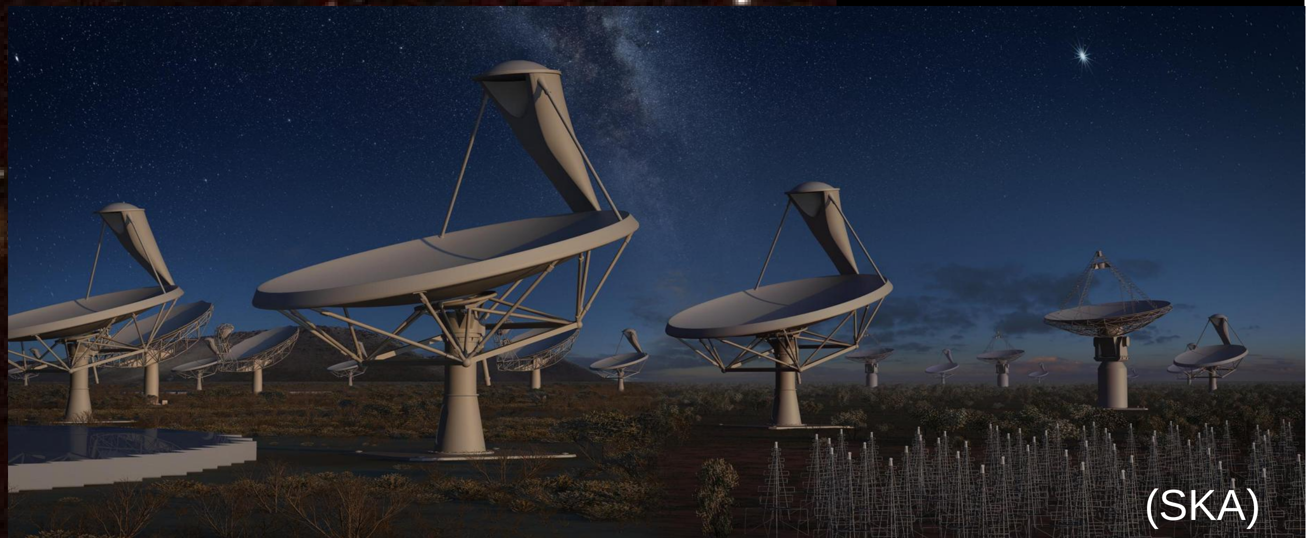
(How) Do AGN regulate galaxy growth ?

LOFAR, JVLA, SKA : New possibilities in the (c)m





LOFAR: 10-250 MHz, 100 km
LoTSS : 100 μJy all-sky, 5'' (25'')



Importance of low frequency, low surface brightness

Radio sizes :

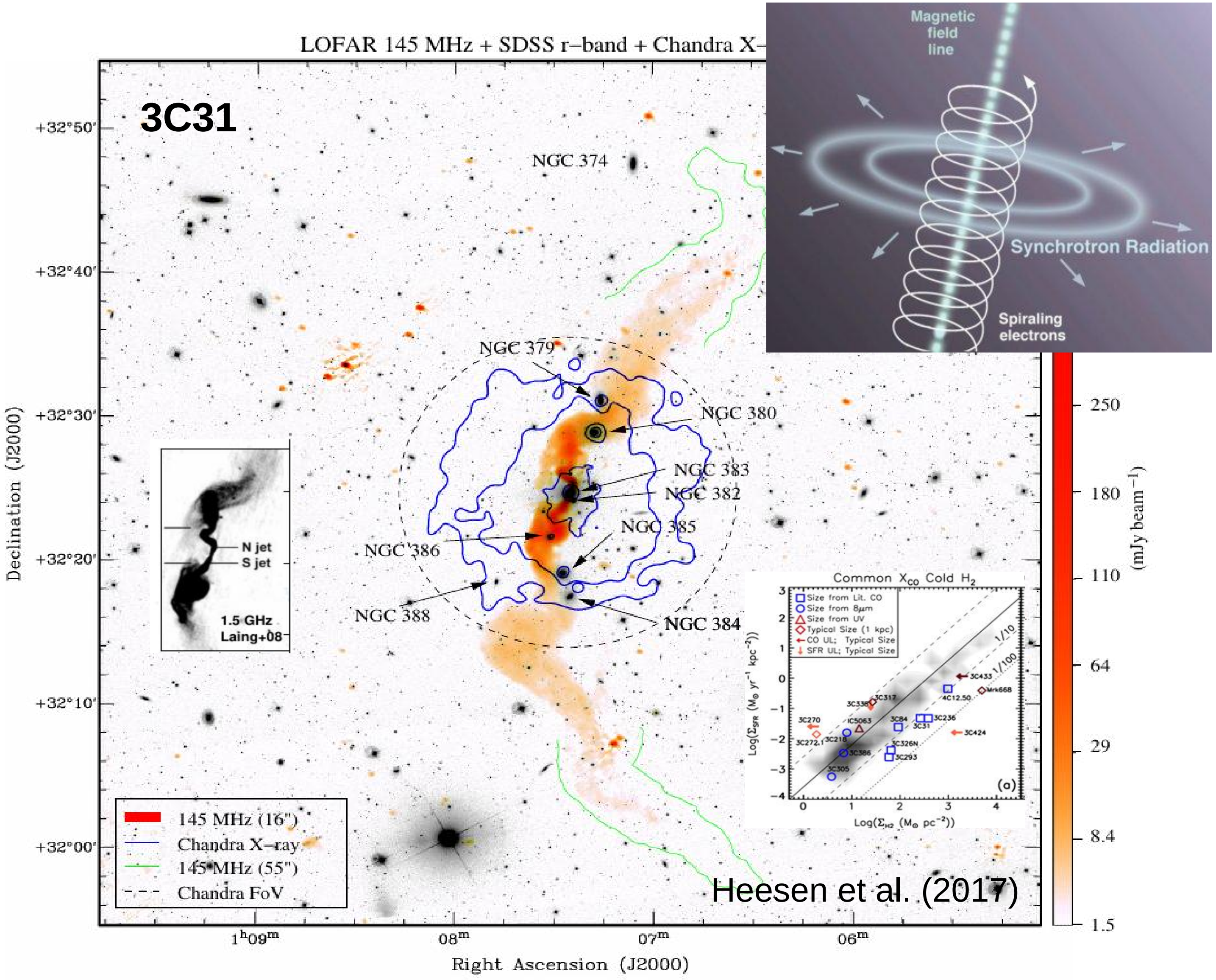
- Timescale of energy injection ?
- Total energy over activity period
- Jet advance speed
- Reacceleration processes ?
- Probe of environment
- Range of impact

Radio ages :

- Timescale of energy injection ?
- Duty cycle / global impact of feedback

Radio relics :

- Dissipation of kinetic energy in the ISM
- Long-term effect of turbulence

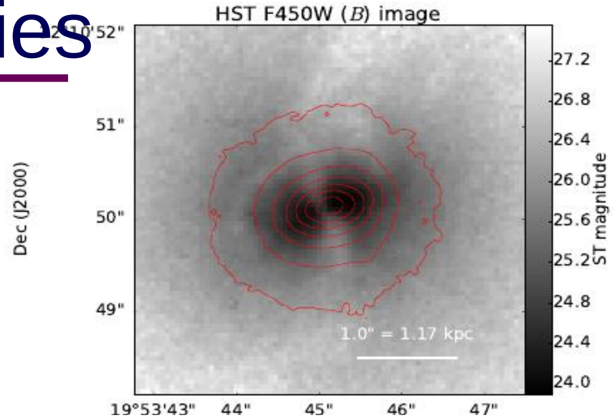


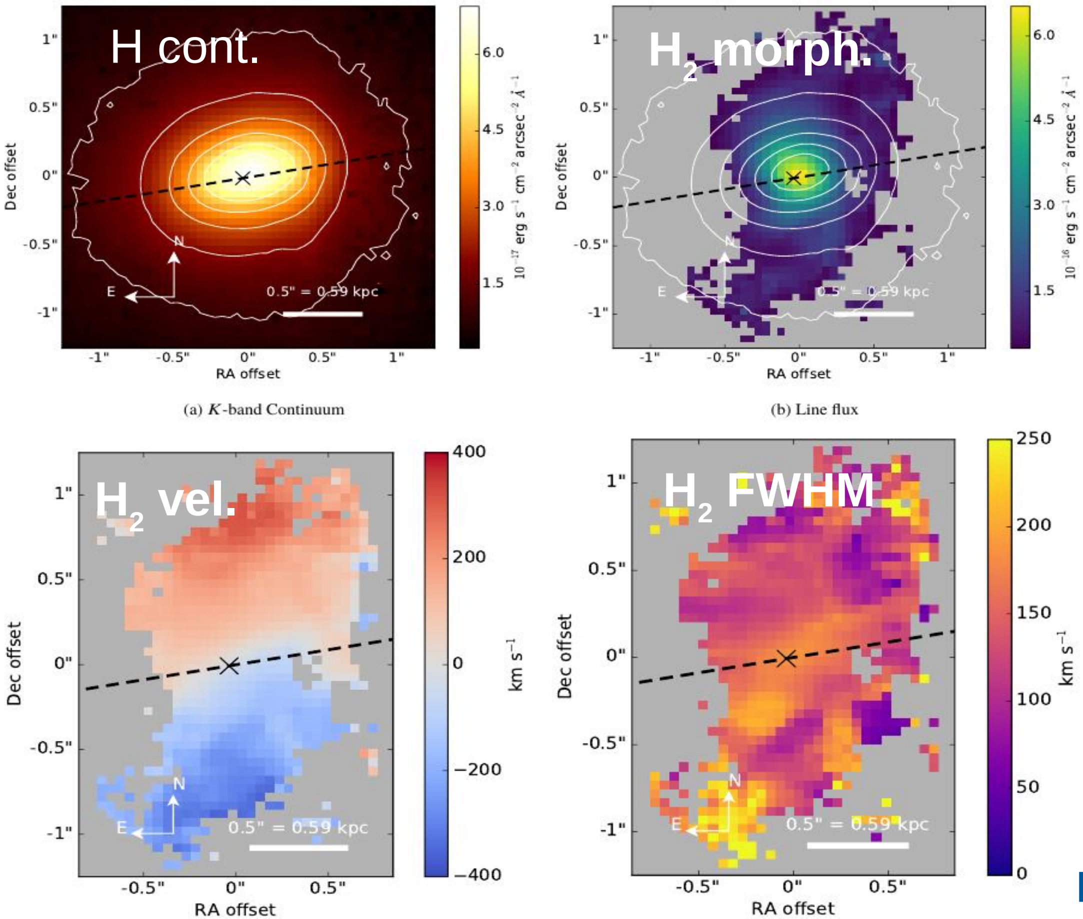
More energetic electrons ''age'' faster :
Kinetic jet power best measured at low frequencies !!! → AGN energy input

Extended gas disks in nearby radio galaxies

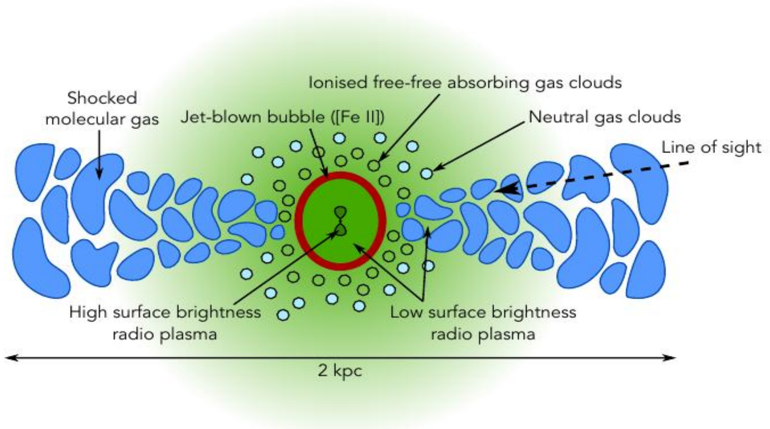
Zovaro et al. (2019a,b)

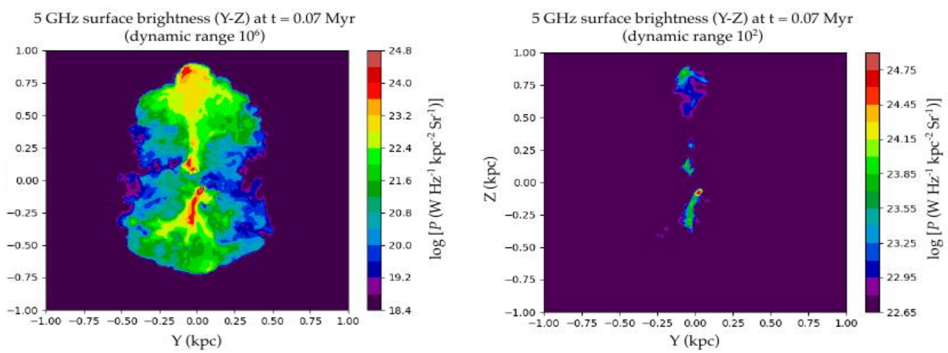
4C31.04, CSS, z=0.06,
GEMINI/NIFS LGSF





(a) K-band Continuum
(b) Line flux



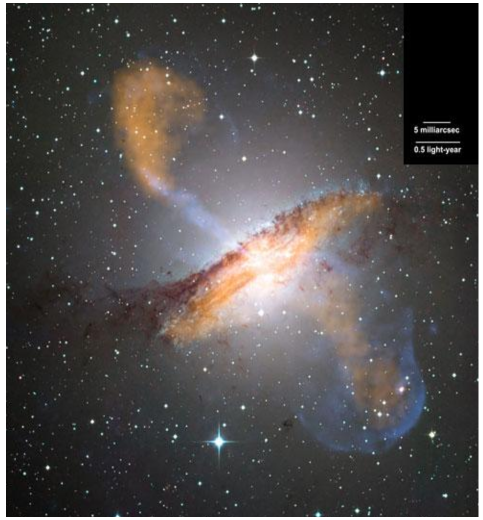


Mukherjee et al. (2016) jet models

Low-surface brightness radio emission would not be seen w/ observations.

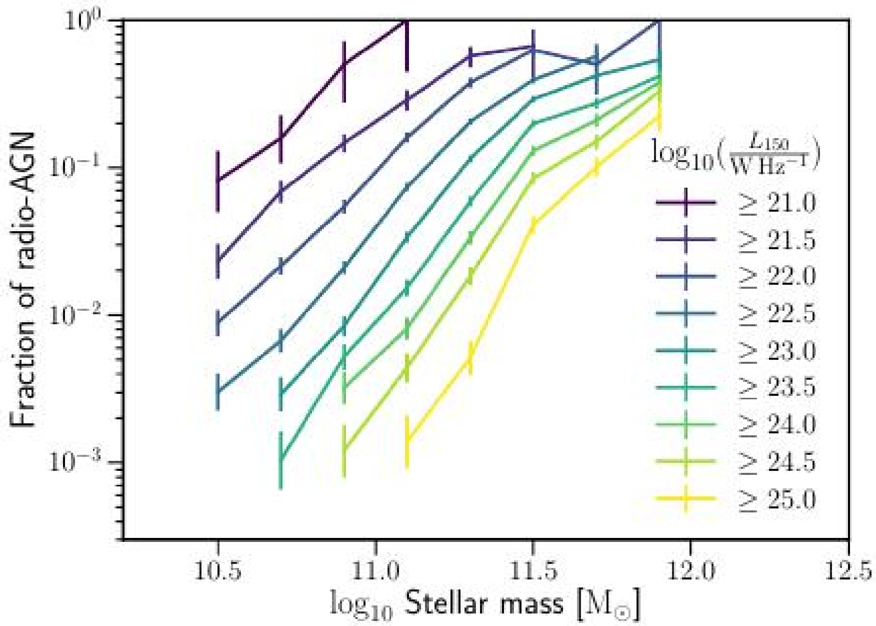
Radio AGN are frequent !

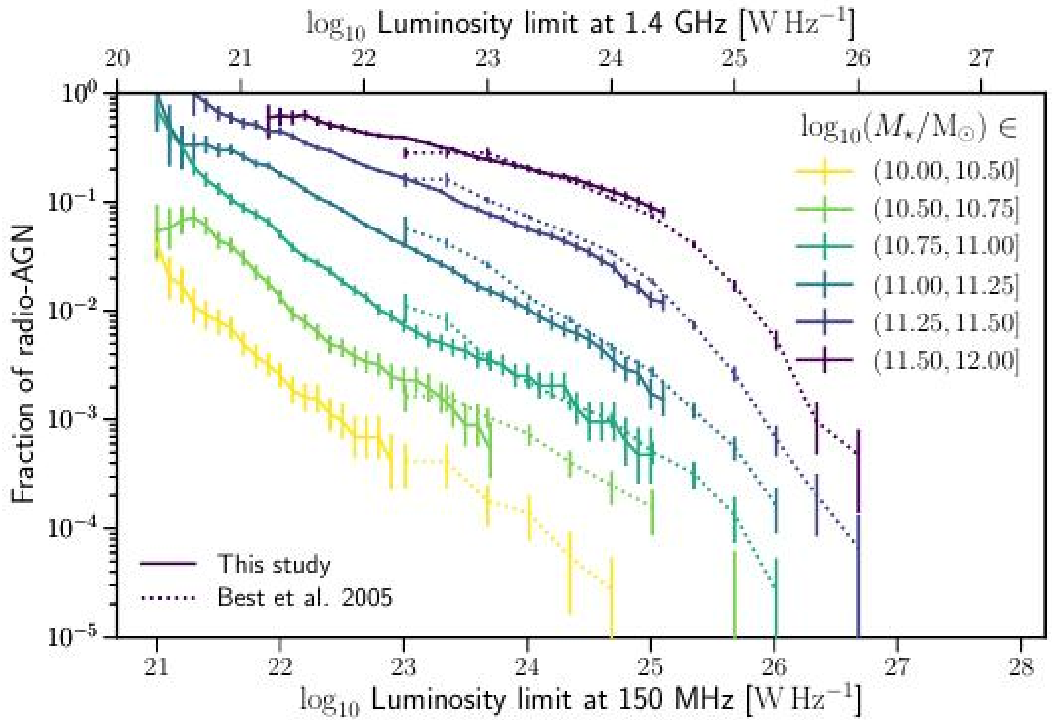
Sabater et al. (2018), LoTSS :



All massive galaxies w/ $M_{stellar}$ > 10^{11} $M_\odot$ have nuclear radio source w/ > 10^{21} W Hz^{-1} !

However, more powerful sources are very rare …
What does that imply for feedback ?? Impact during galaxy formation at high redshift? Intermittency, duty cycle? Feedback mechanism? Efficiency of interaction?



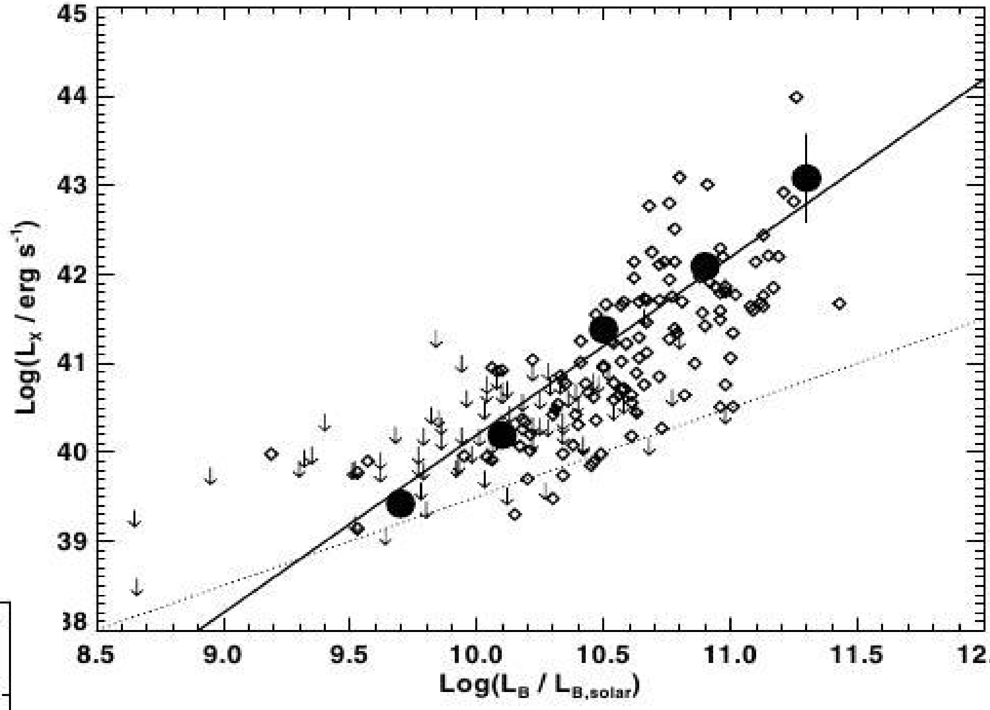


Sabater et al. (2018)

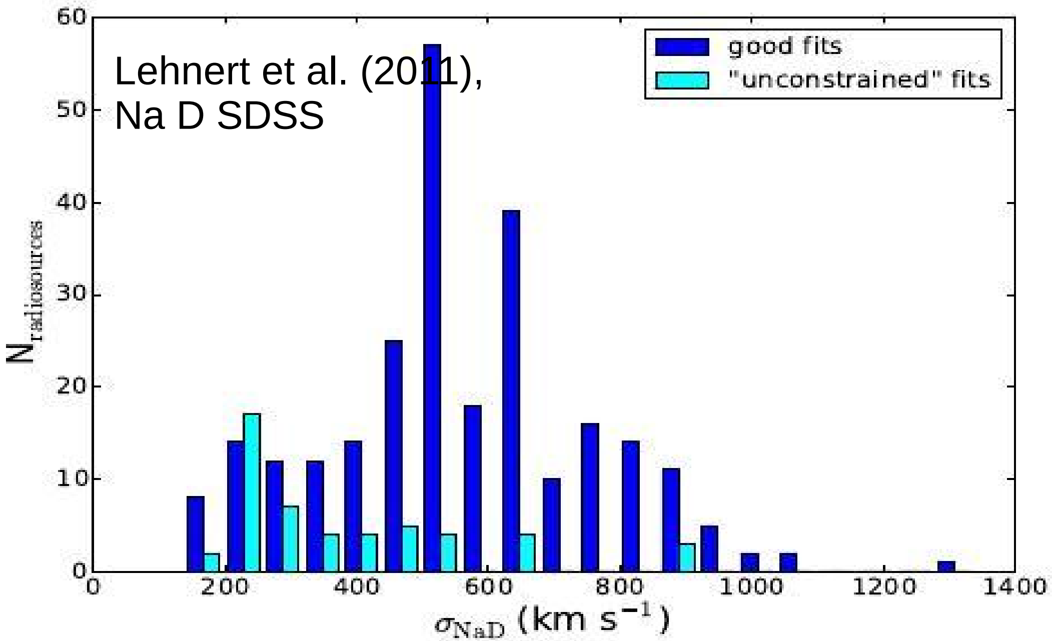
Population studies

- Low-power radio sources in up to 30% of early-type galaxies in the SDSS (Best et al. 2005)

→ $E_{mech,jet}$ balances L_X
(Best et al. 2006)



Best et al. (2006), SDSS



Lehnert et al. (2011), Na D SDSS

- 30% of radio galaxies in the SDSS have broad, slightly blueshifted interstellar NaD absorption.

→ $dM/dt \sim 10\ M_s\ yr^{-1}$
→ $dE/dt \sim 10^{42}$ erg s^{-1}, 1-10% E_{jet}

(Lehnert, Tasse, NPHN et al. 2011)

Mechanism of radio emission ?

Alternative mechanisms to relativistic jets

- Shocks from radiation-driven winds in radio-quiet quasars ? (Zakamska et al. 2014)

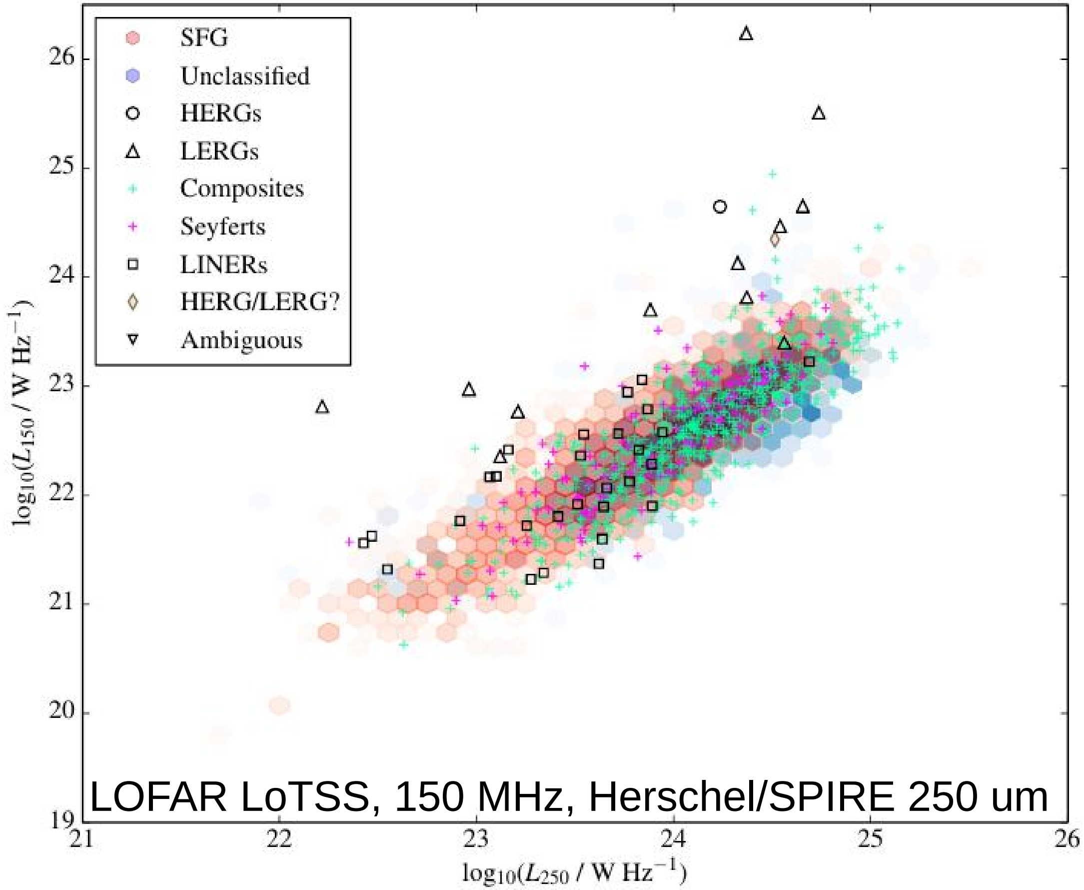
- Star formation?

Far-infrared radio correlation
- Supernova remnants
- Free-free emission in HII regions

Redshift surveys of star-forming galaxies with SKA-1.

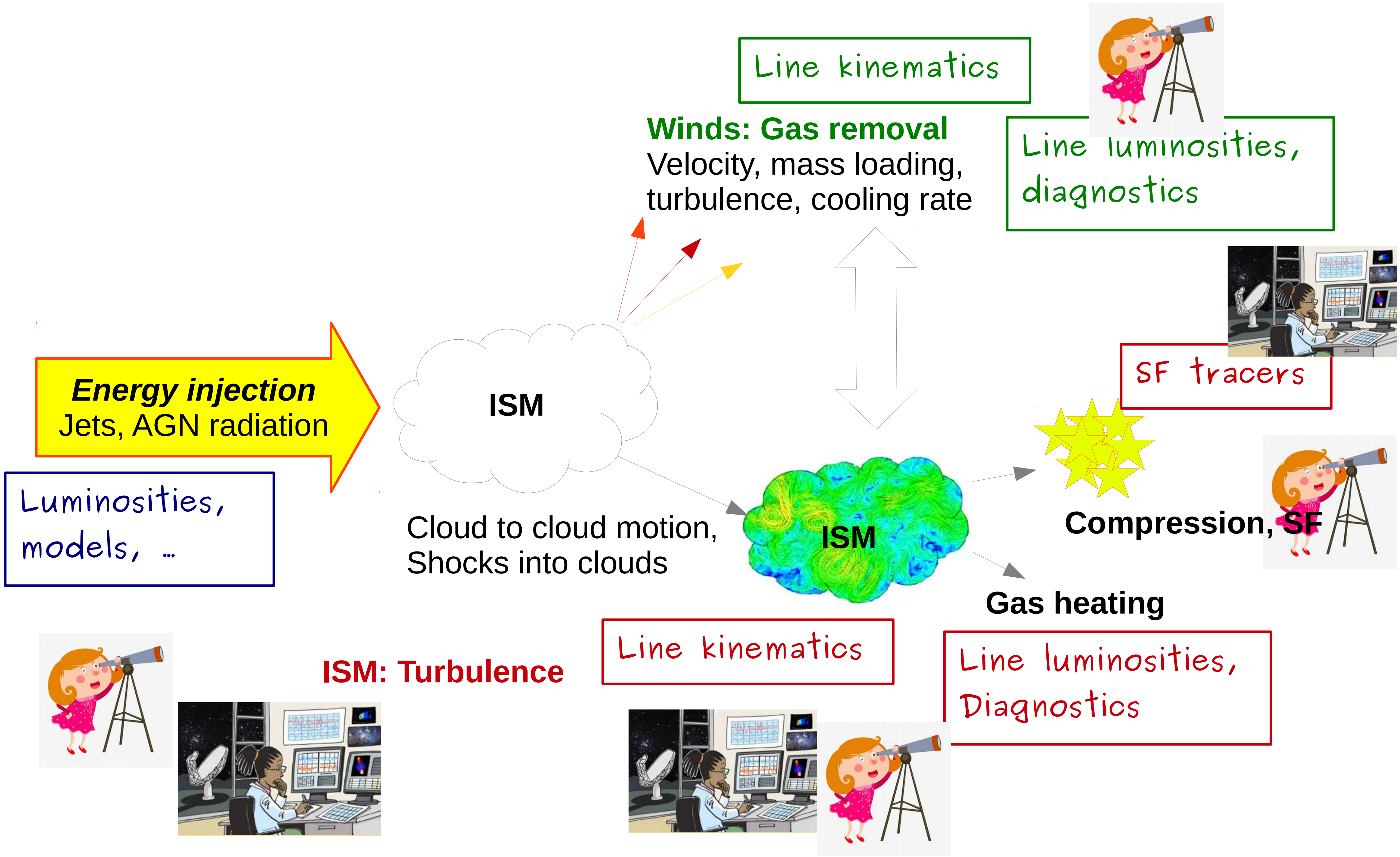
Distinguish different mechanisms producing radio emission !!

The far-infrared radio correlation



Guerkan et al. (2018)

Summary


Line kinematics
Winds: Gas removal
Velocity, mass loading, turbulence, cooling rate
Line luminosities, diagnostics
Energy injection
Jets, AGN radiation
ISM
Luminosities, models, ...
SF tracers
Compression, SF
Cloud to cloud motion, Shocks into clouds
ISM
Gas heating
ISM: Turbulence
Line kinematics
Line luminosities, Diagnostics