Winds and feedback at high-z: Lessons learned and open questions

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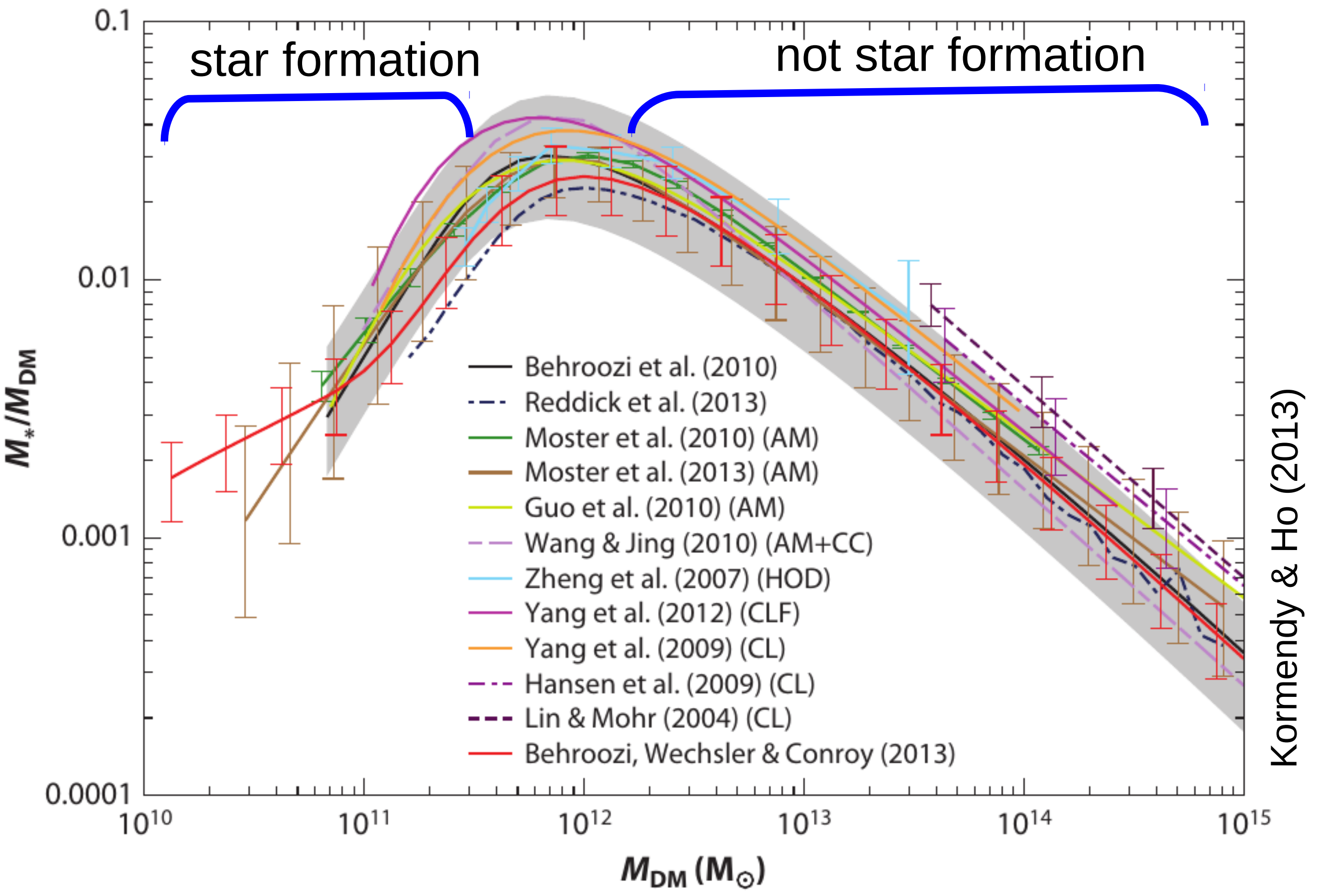
AGN feedback – motivation



Cosmic baryon cooling onto galaxies is ***highly inefficient***: ~20% of cosmic baryon fraction at best (at 10^{12} M_{DM} halo mass), even less in higher and lower mass halos

(see also Fuyan's talk this morning)

… why???

Two possible solutions

(1) Missing energy source?

Soltan (1982), Yu & Tremaine (2002):

SMBHs are nearly ubiquitous in galaxies

Silk & Rees (1998)

AGN lifetime (10^{7-8} yrs)

$E_{out}=10^{46}$ erg s^{-1}x10^{15} s = 10^{61} erg

~ E_{bind}, few 10^{11} M_s

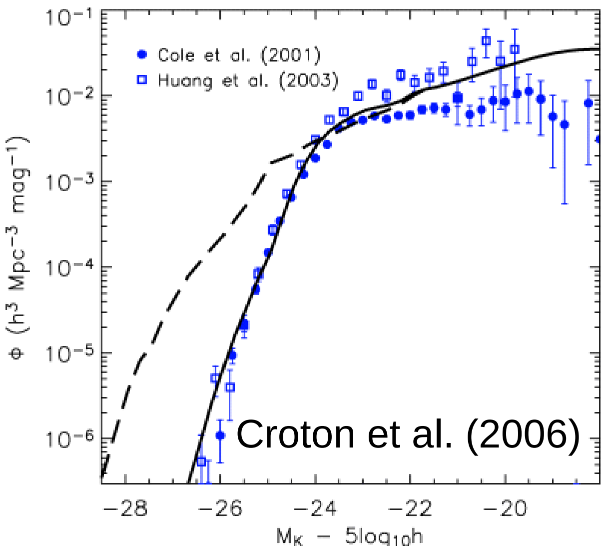
AGN energy enough to unbind the host galaxy

(2) A problem with gas cooling?

- **Heating through cosmological accretion**
  Birnboim & Dekel (2006),
  Keres et al. (2005)
- **Morphological quenching**
  Martig et al. (2009)
- **High stellar mass surface densities**
  Compaction
  e.g., Dekel & Burkart (2014)
- **Satellite quenching**
- **Energy dissipation within galaxies**
  e.g., Nesvadba et al. (2010)

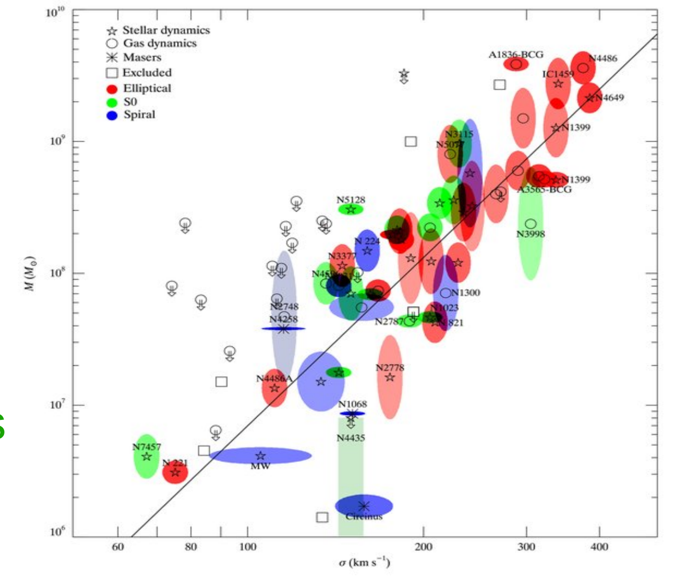
Do we really understand the physics of star-formation in galaxies well enough?

AGN feedback works!



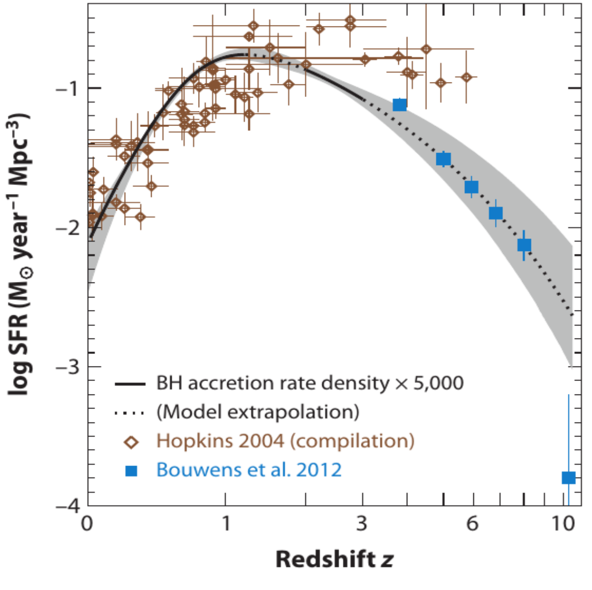
Croton et al. (2006)

… because their energy injection is high enough to explain the galaxy mass function



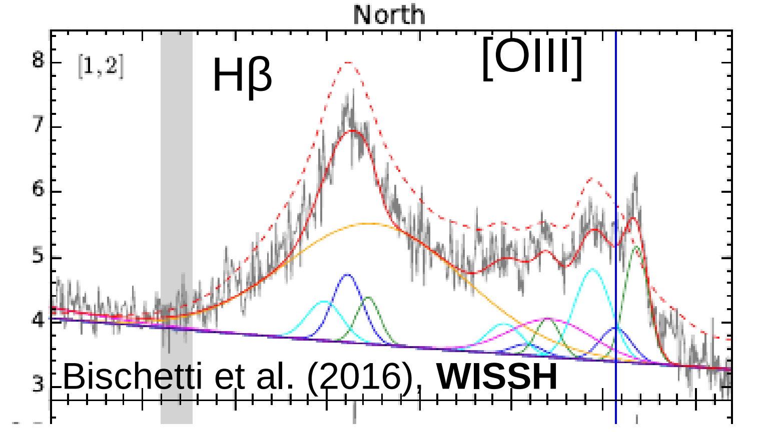
Gueltekin et al. (2009)

… because their rest-mass energy equivalent can be matched to the black-hole-bulge scaling relationships



… because they have the right timing matched to the cosmic star-formation history

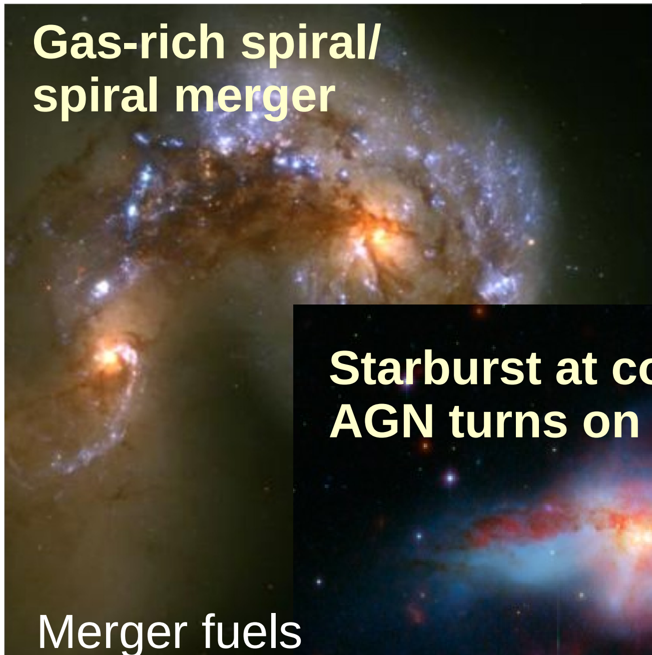
… and because we see signatures of a possible mechanism of how they work (winds)

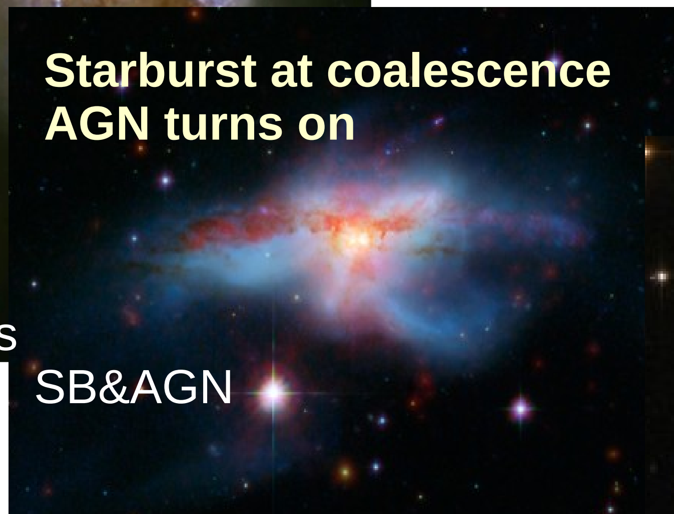


Bischetti et al. (2016), **WISSH**

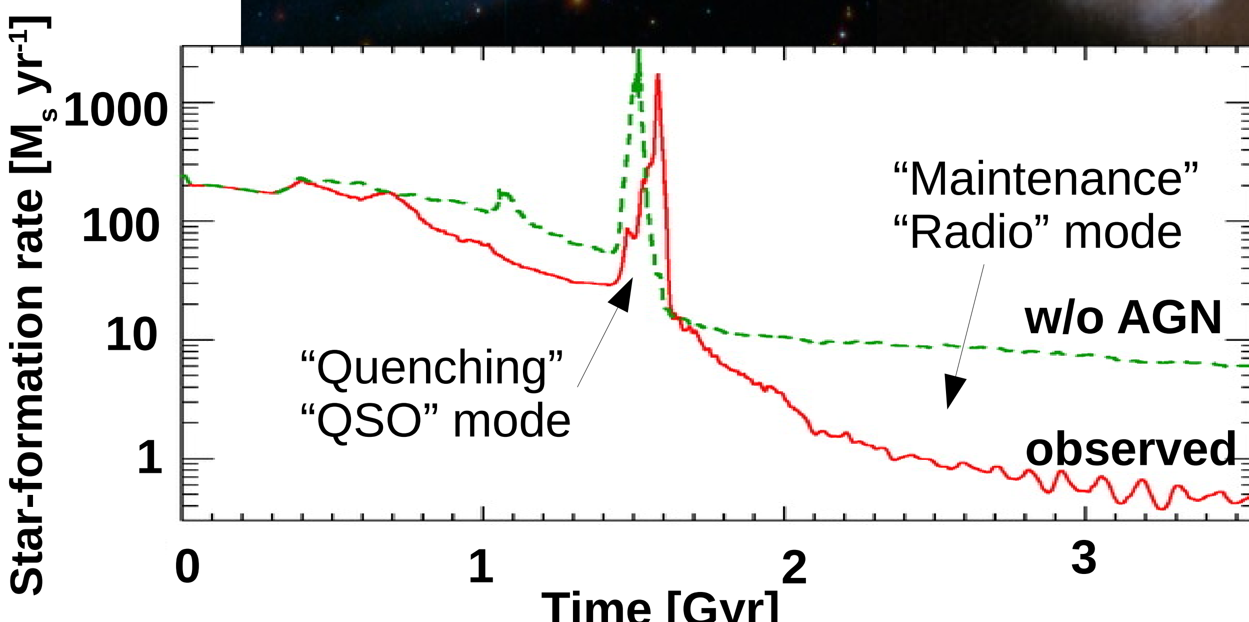
AGN feedback in a nutshell

Sanders 1988, Hopkins 2006, Tadhunter 2005, Granato 2006, Croton 2006, Scannapieco 2004, Schawinski 2007, ...



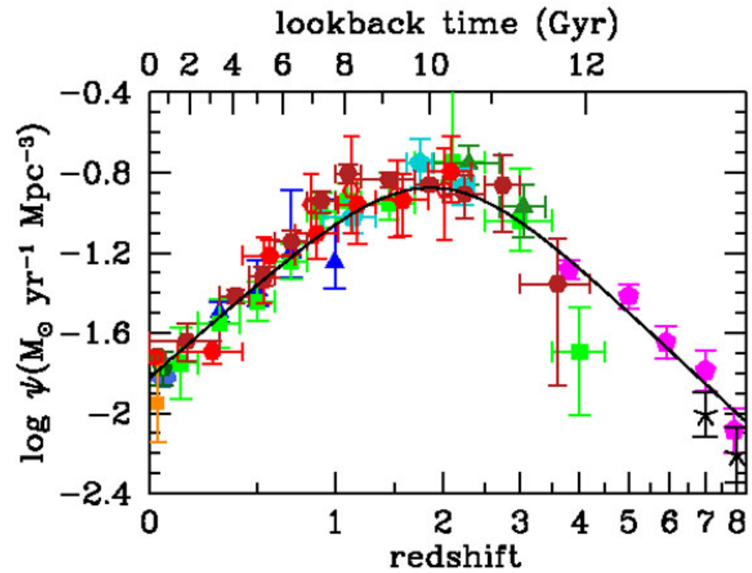


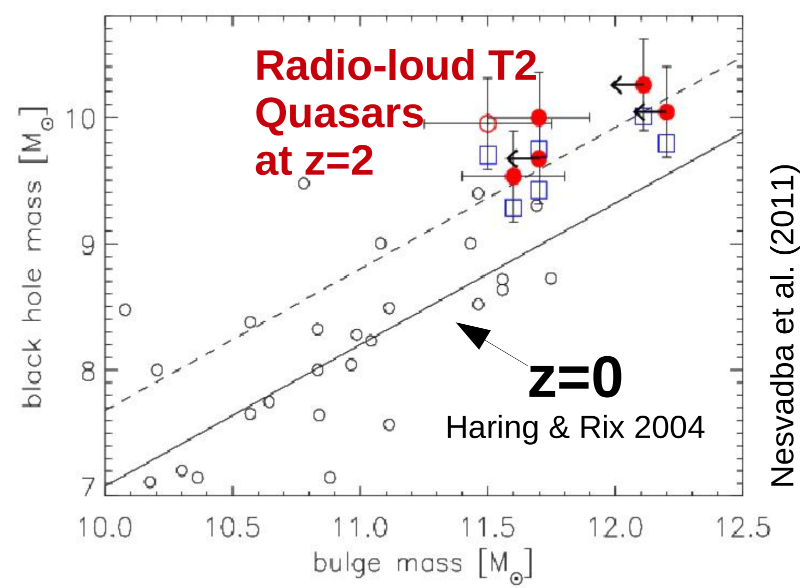
AGN winds
remove gas



High-z is important!

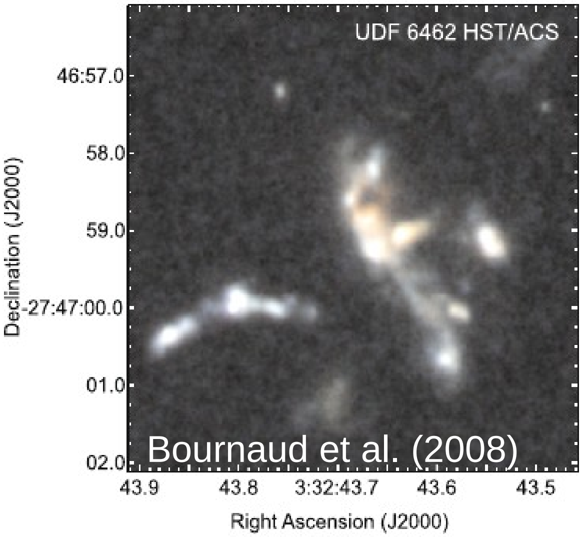
- Major growth phase of massive galaxies
- Main cosmic star-formation epoch
- Peak of unobscured cosmic QSO activity
- Epoch of most luminous radio AGN
- Properties of massive galaxies were put into place





→ SMBHs in most massive high-z galaxies already near the low-z black-hole bulge relationships

... and high-z is also different



Hopkins-Sanders sequence deeply rooted in | classical hierarchical galaxy assembly scenario:

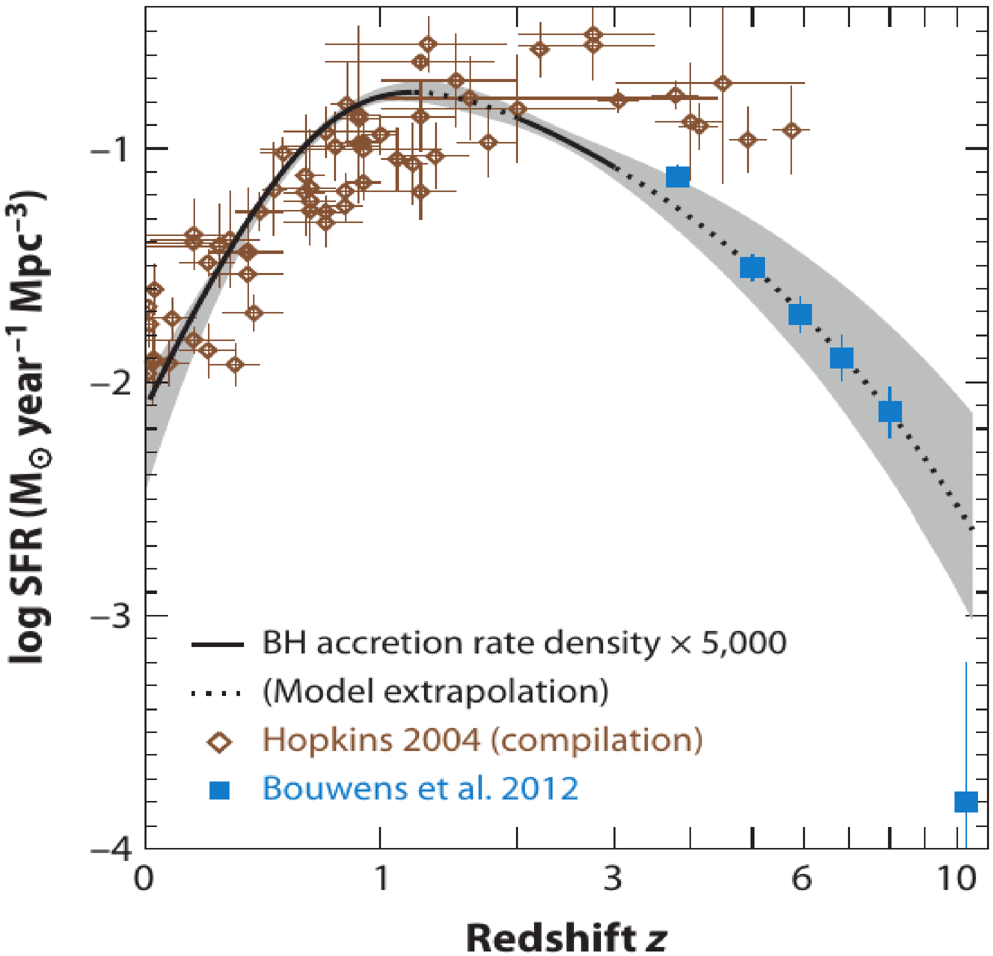
- role of mergers vs. clumpy disks in AGN fueling and feedback? (e.g., DeGraf et al. 2017)
- cosmic evolution of galaxy (major) merger rates?
- role of cosmic accretion,
- role of gradual galaxy assembly? E.g., cosmological zoom-in simulations: Powerful AGN feedback reduces infall along filament by 10% …. << 100% !! (e.g., Parai et al. 2017)

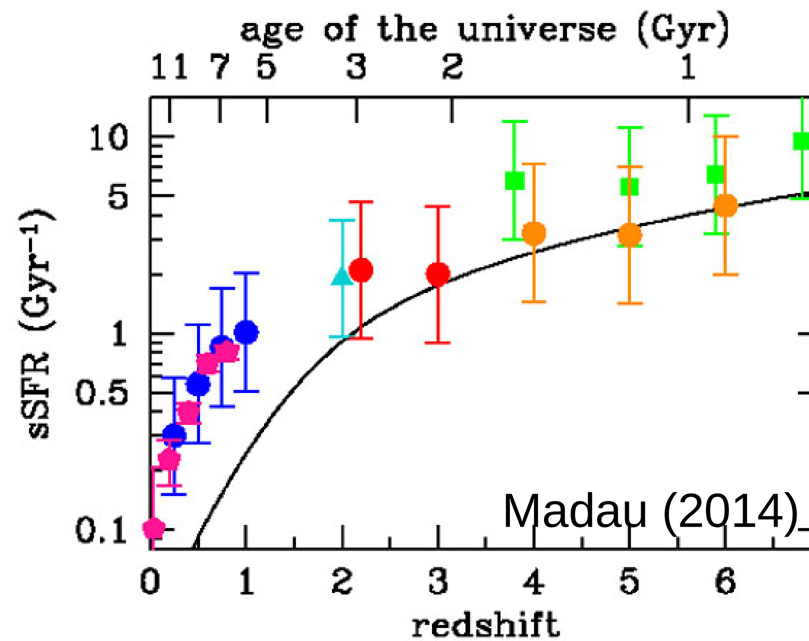
Questions raised:

- Do we understand star formation at high-z?
  (If not, then what can we know about the 'need' of AGN feedback?)

- How do intrinsic properties of high-z galaxies affect feedback efficiency?
  → Suppress or enhance (positive feedback, e.g., Silk 2013)?
  → Mechanisms of angular momentum loss and AGN fueling? (e.g.,
  → Global AGN duty cycles, number densities, AGN / SF coordination?

Cosmic co-evolution of AGN & hosts





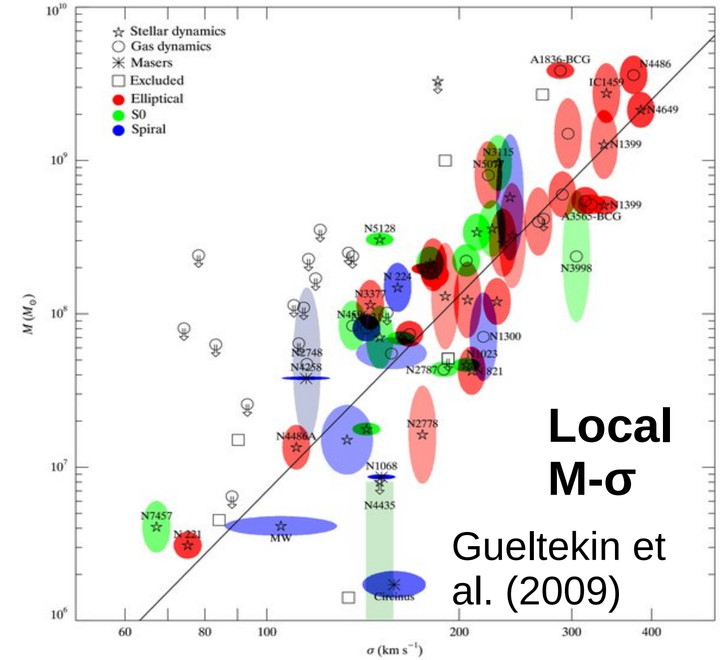
- A correlation driven by fueling rather than feedback? Need only a few 10 M_{sun} yr^{-1} to feed a quasar (e.g., Trakhtenbrot et al. 2014, Weigel et al. 2017)

- sSFRs increase with redshift by an order of magnitude, … *and feedback?*

Harrison et al. (2016): *“If AGN feedback is equally efficient at all redshifts, then how can it work at high-z with the higher sSFRs and gas mass surface densities?”*

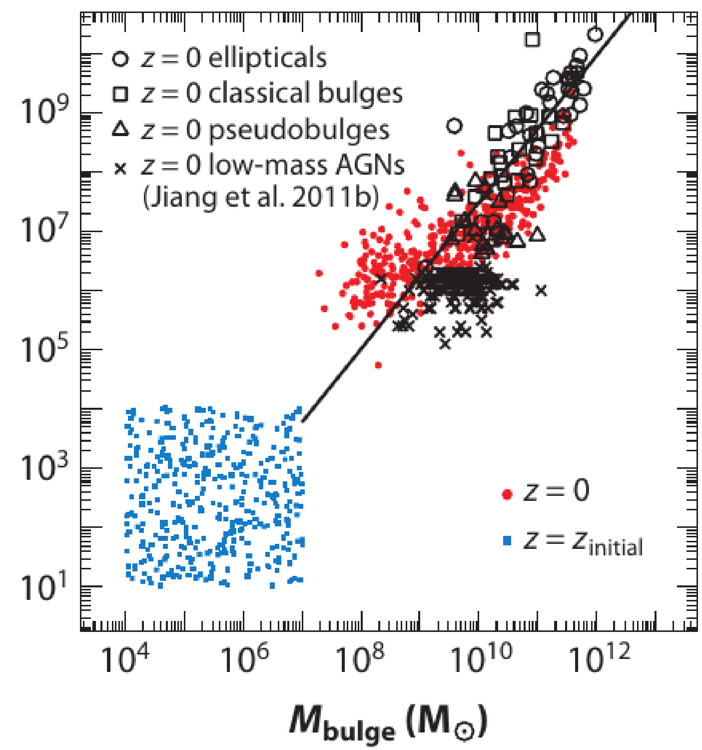
What does the M-σ relation really tell us?

Kormendy & Ho (2013), ARA&A

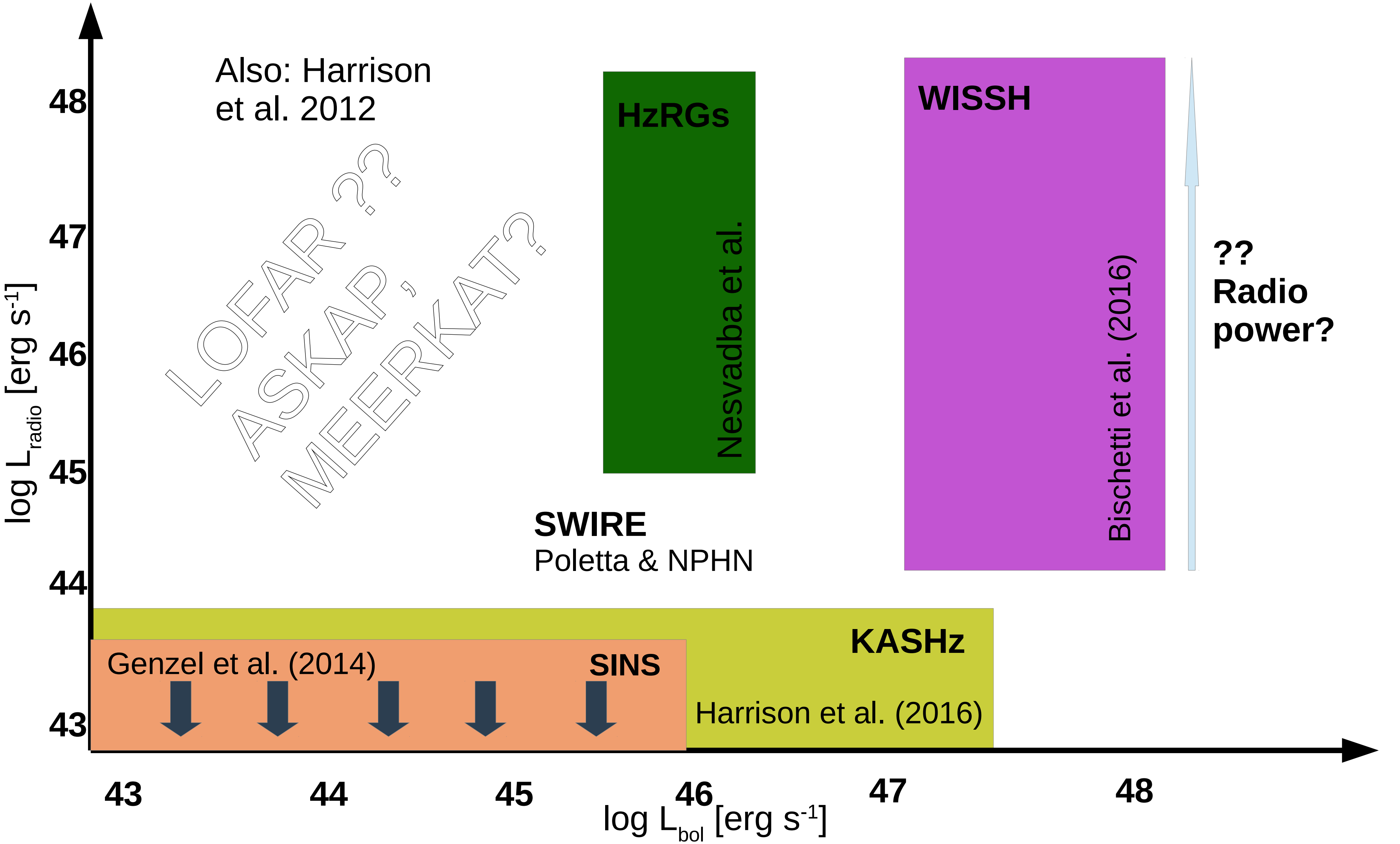


Central limit theorem instead of fueling and feedback processes?
→ can explain structural parameters of ETGs
→ tightening at high mass because of global uniformity of merger trees.

If associated with fueling / feedback, then put into place at high-z
→ but classical Hopkins-Sanders-sequence like AGN play a minor role for galaxy growth.
→ tightening at high mass because of global uniformity of merger trees.



Systematizing AGN feedback studies

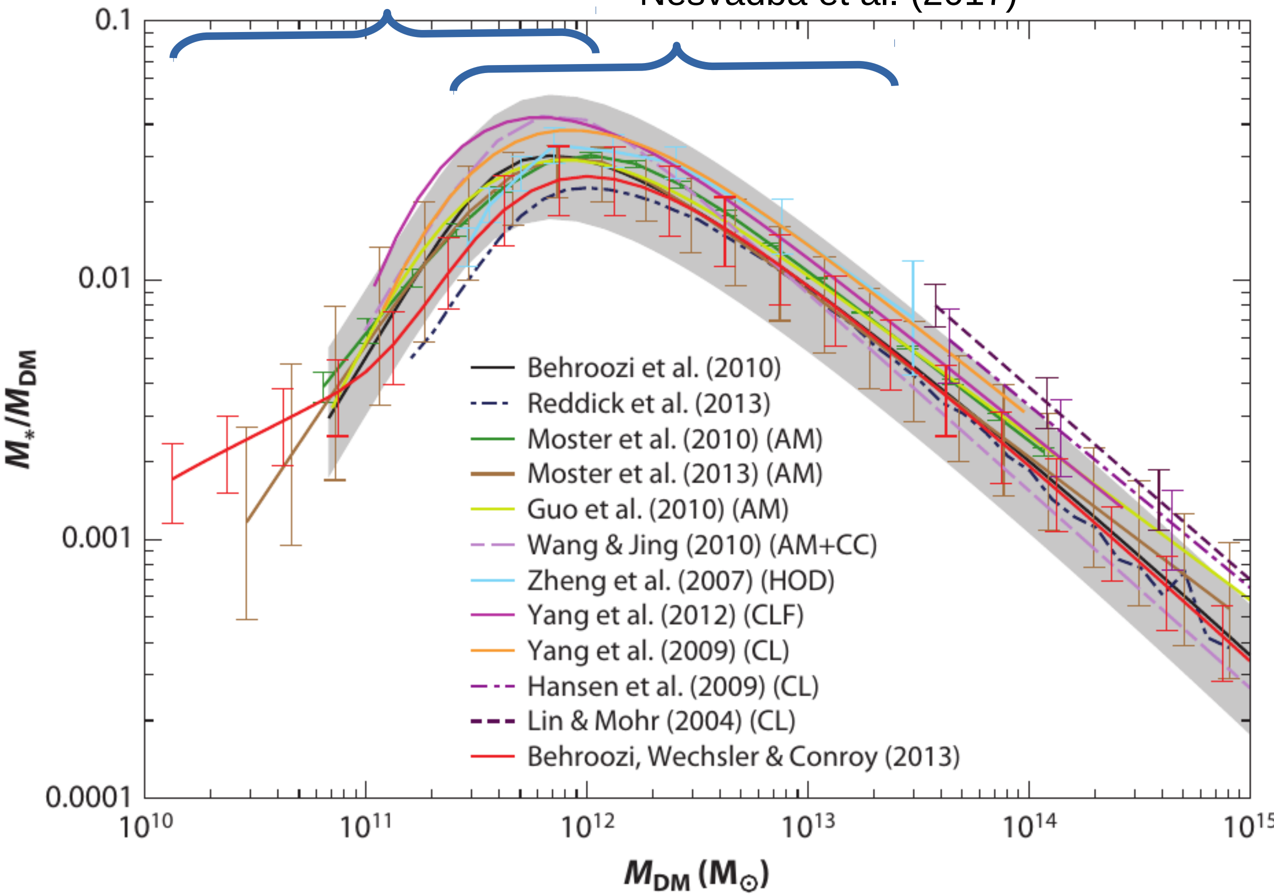


Systematic studies and DM halo mass

Harrison et al. (2012),
Harrison et al. (2016 ??)

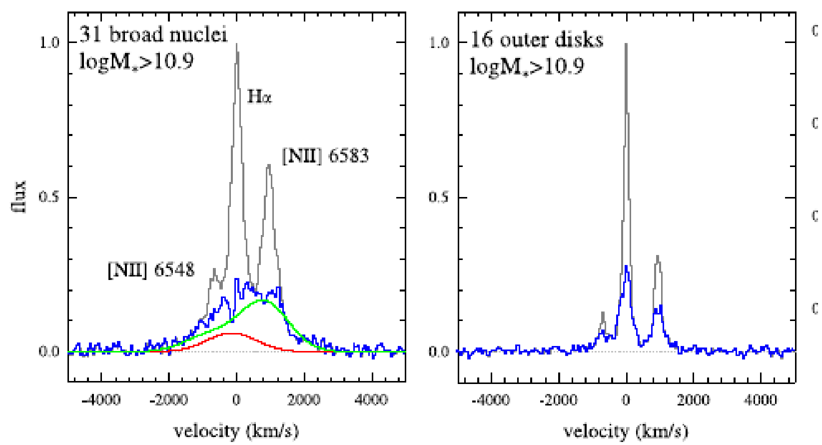
Genzel et al. (2014), Forster Schreiber et al. (2014)

Nesvadba et al. (2017)



Kormendy & Ho (2013)

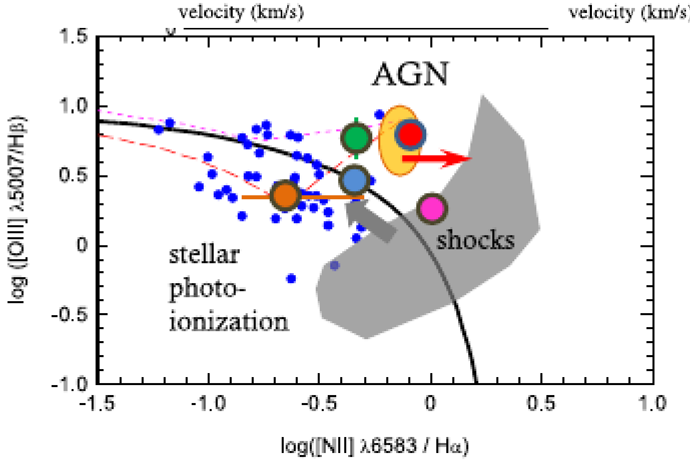
Systematic studies: Mass selected SFGs



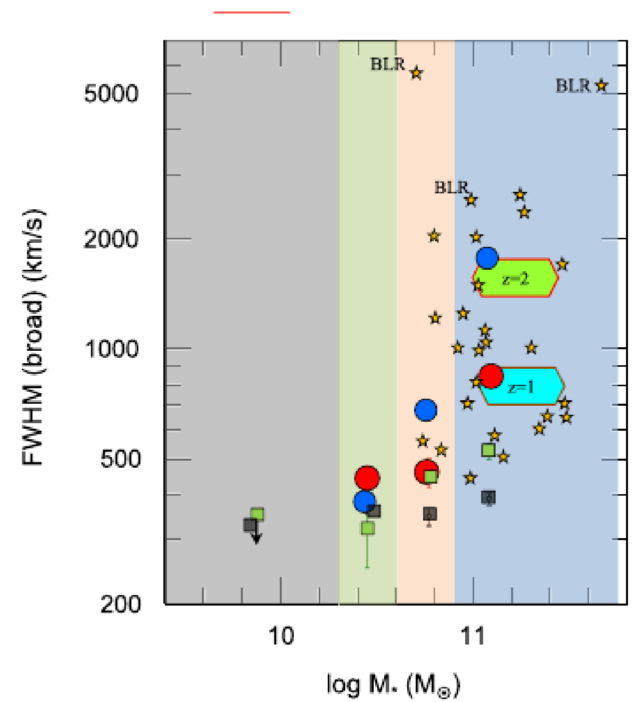
110 SINS, LUCI, GNIRS, KMOS^{3D} at z=2-3

Genzel et al. (2014), Forster-Schreiber et al. (2014)

- ~50% have MIR or X-ray or radio signatures of AGN,
  - few % at log M < 10-10.5
  - 15-30% at log $M_{stellar}$ > 11



- at log $M_{stellar} \gtrsim 10.9$, 2/3 broad nucl. components
  - FWHM~450-5300 km s^{-1} around nucleus
  - systemic line: FWHM=150-320 km s^{-1}.
  - mass loading ~ SFR
  - P = 5-10 x L_{SFR} / c



- Why are these signatures of AGN?
  - broad lines 2-3x more frequent in AGN hosts (down to X-ray / radio survey limits)
  - No Hα excess near nucleus → no circumnuclear starburst
  - Line ratios consistent with high-z AGN

Systematic studies: X-ray selected AGN

KASHz, Harrison et al. (2015),
89 targets incl. 40 w/ [OIII] detected at z=1.1-1.7

KMOS IFU, analysis of integrated spectra

$L_x = 10^{42-45}$ erg $s^{-1} \rightarrow L_{bol} \sim 10^{43-46}$ erg s^{-1}

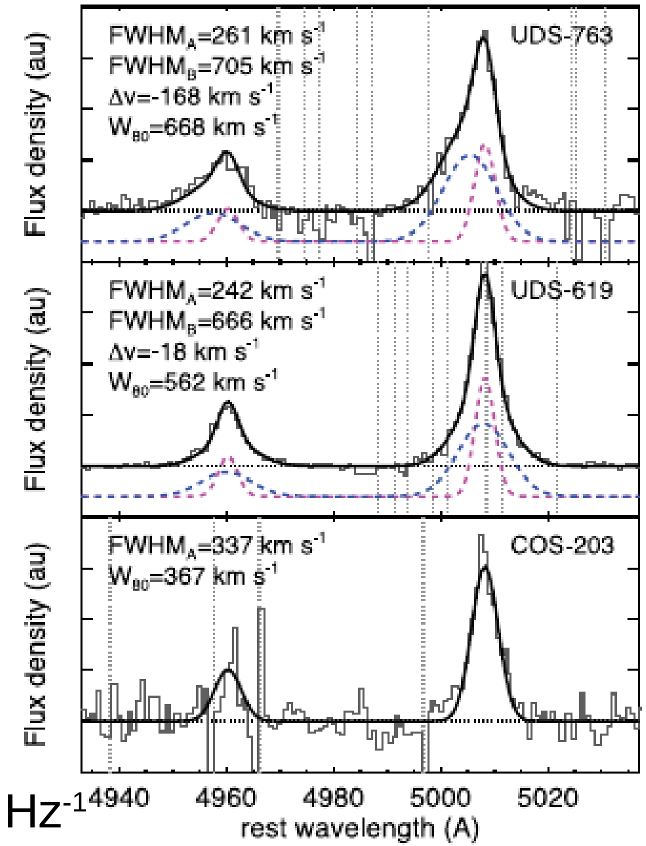
Δv (wing, syst.) = -500 km s^{-1}
FWHM = 400-1400 km s^{-1}

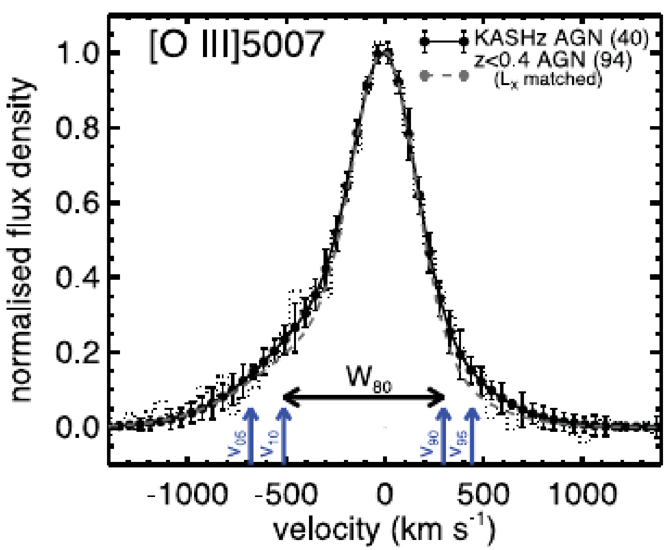
~50% have outflow signatures, W_{80} > 600 km s^{-1}

Winds are 2x more common at $L_x > 6 \times 10^{43}$ erg s^{-1}, and $L_R > 10^{23}$ W Hz^{-1}

Independent of X-ray obscuring columns

What is driving the outflows? Energy analysis does not show clear results

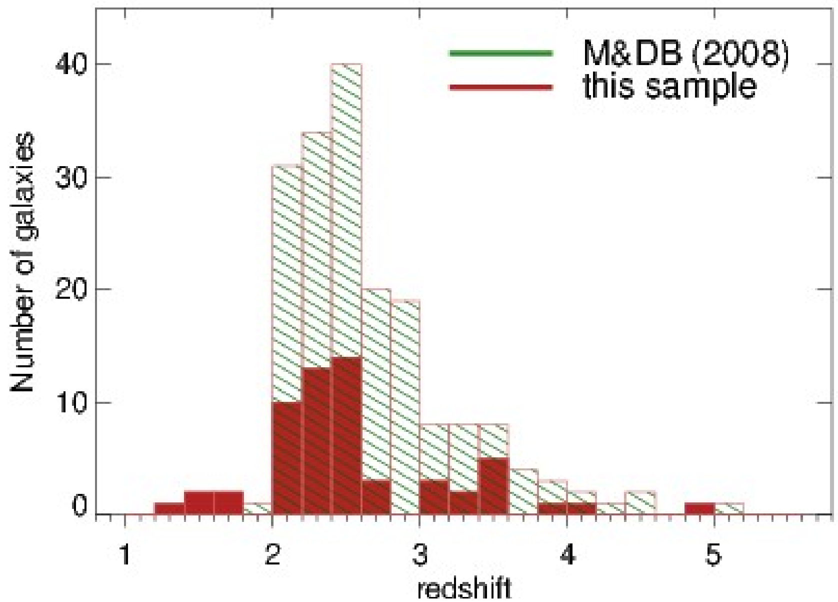


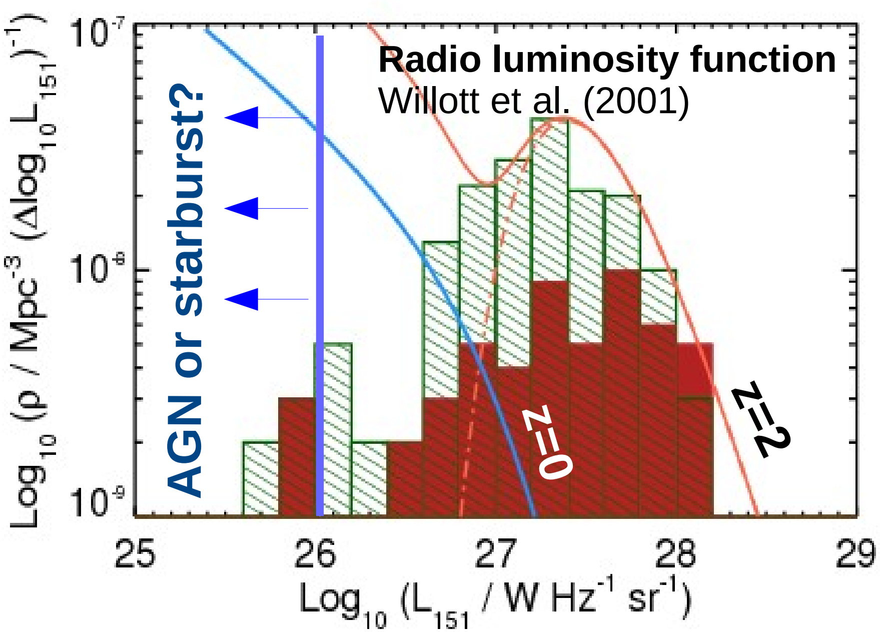


Stacked spectrum of z~1.5 AGN
… and of a luminosity-matched sample of
z=0.4 AGN → **very similar line profiles.**

Efficiency of high-z AGN for gas blow-out?

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





The SINFONI survey of powerful radio galaxies during the “Quasar Era”

- 49 HzRGs w/ [OIII] & Hβ, [OII] or [OIII], Hα, Hβ, [NII], [SII]
- about 200 sources known at z≥2 (Miley & De Breuck 2008)
- covering the bright end of the high-z radio luminosity function
- unique distinction jet / starburst

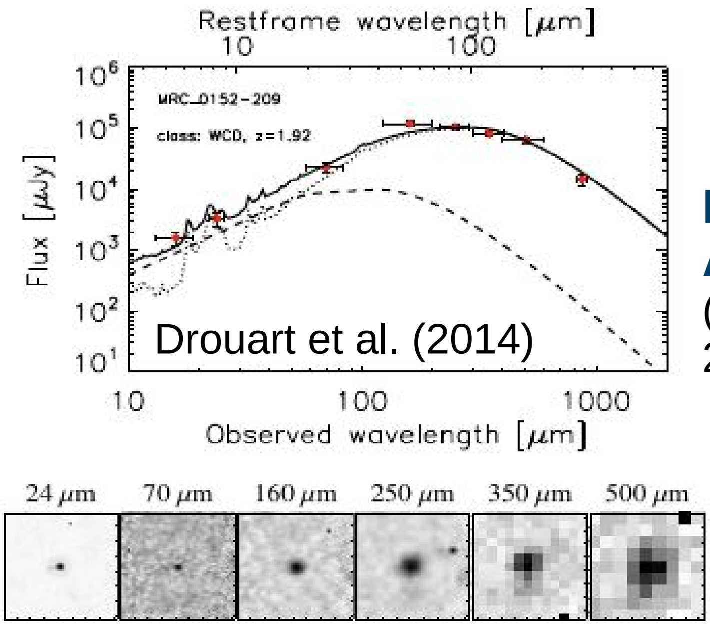
Spitzer/Herschel photometry for 24

Jet, QSO or starburst? Energy & Momentum

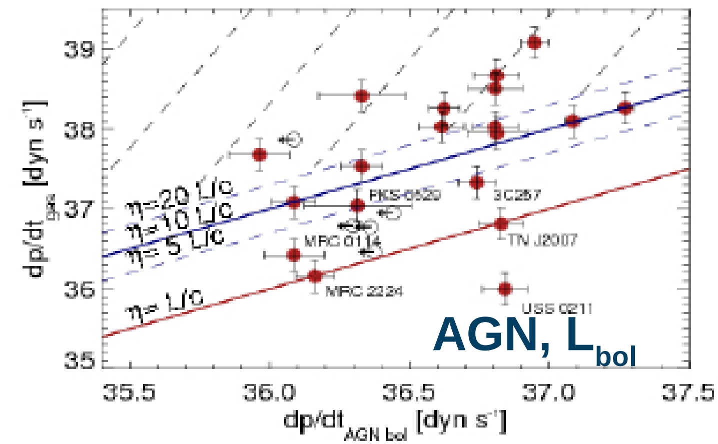
24 galaxies with SINFONI & mid to FIR SEDs

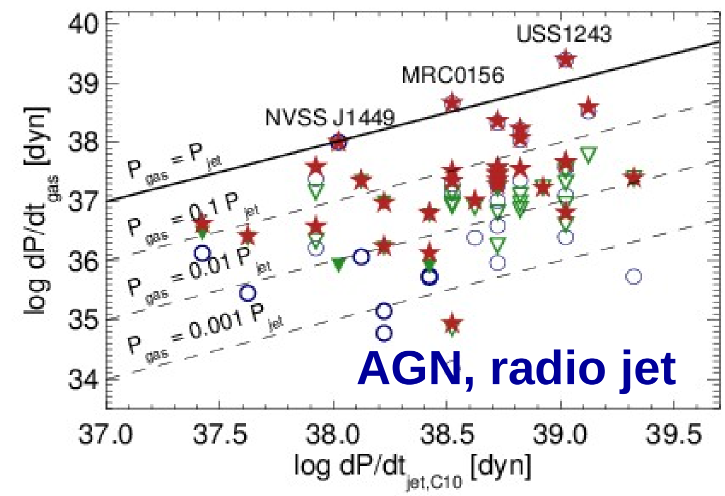
Nesvadba, Drouart, De Breuck et al. (2017), A&A 600,121

Compare kinetic energy, momentum in gas w/ input from star formation, AGN and radio source

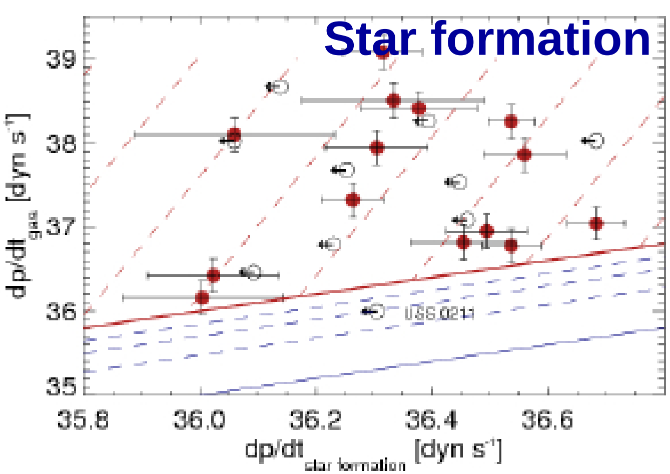


Decompose FIR from AGN and star formation (DecompIR, Mullaney et al. 2011)





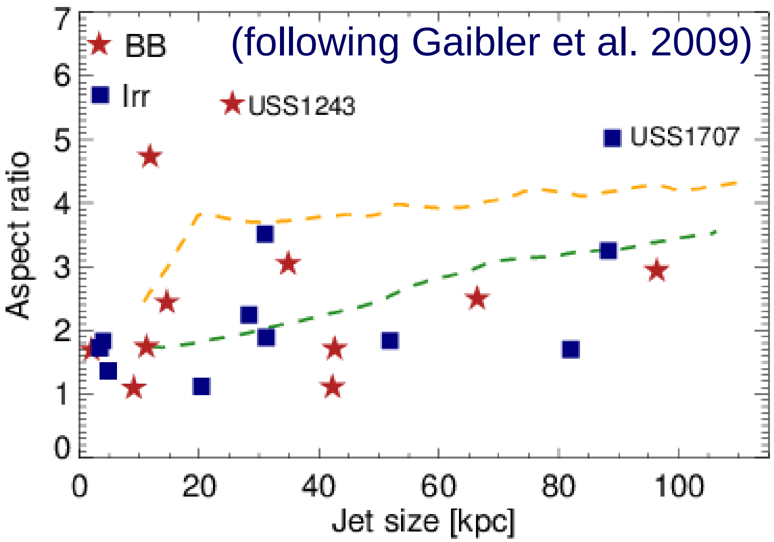
Similar distributions exist for kinetic energy (see paper)

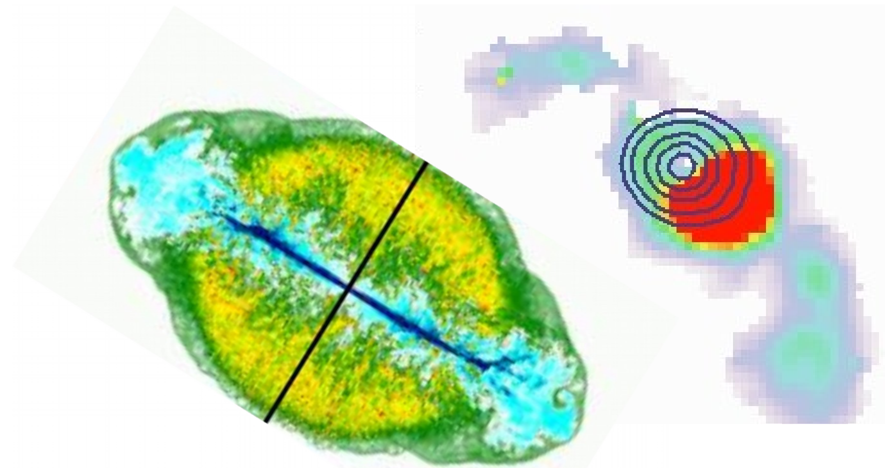


→ Only radio jets inject enough energy & momentum to power gas kinematics

Winds and feedback at high-z

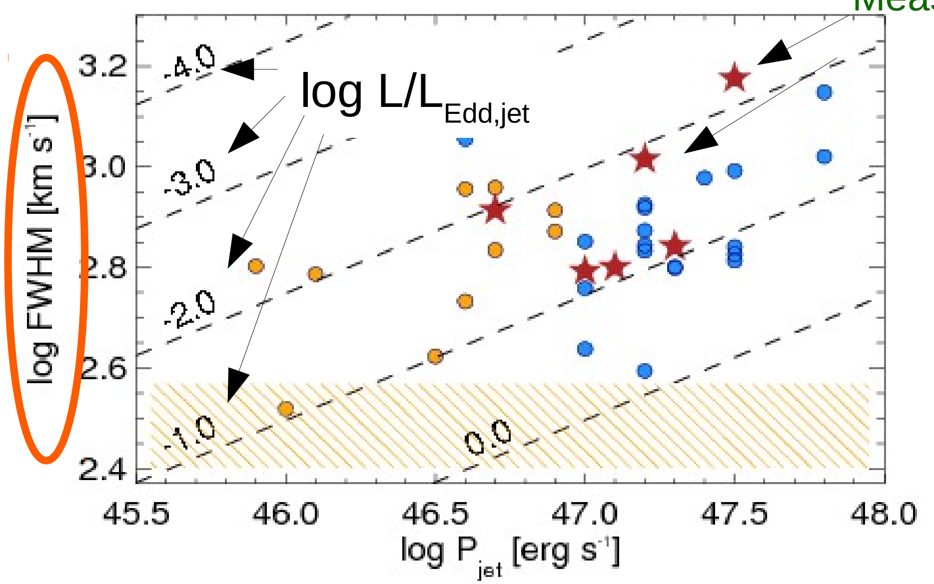
Tests of hydrodynamic models

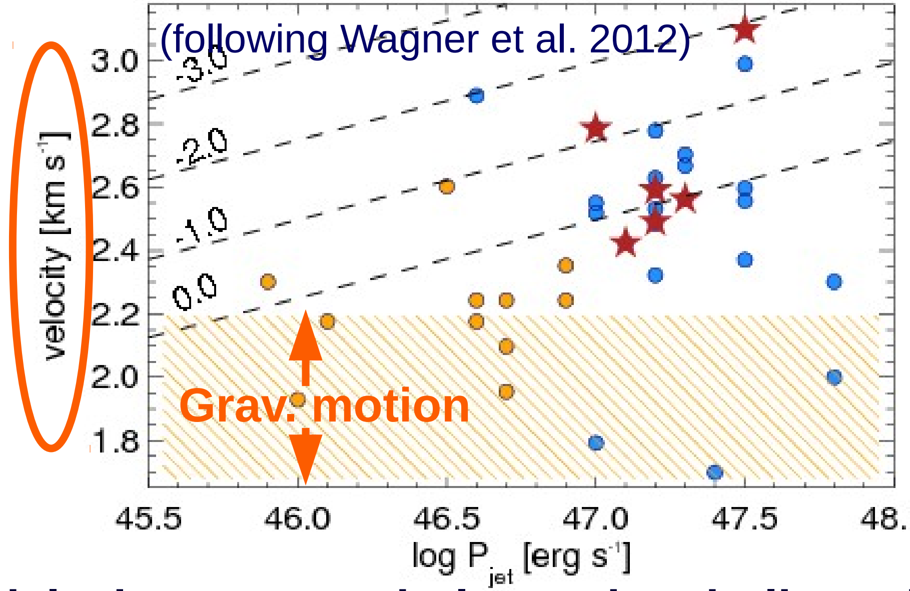




Predicted WIM density
(Wagner et al., 2012)

Measured accretion rates



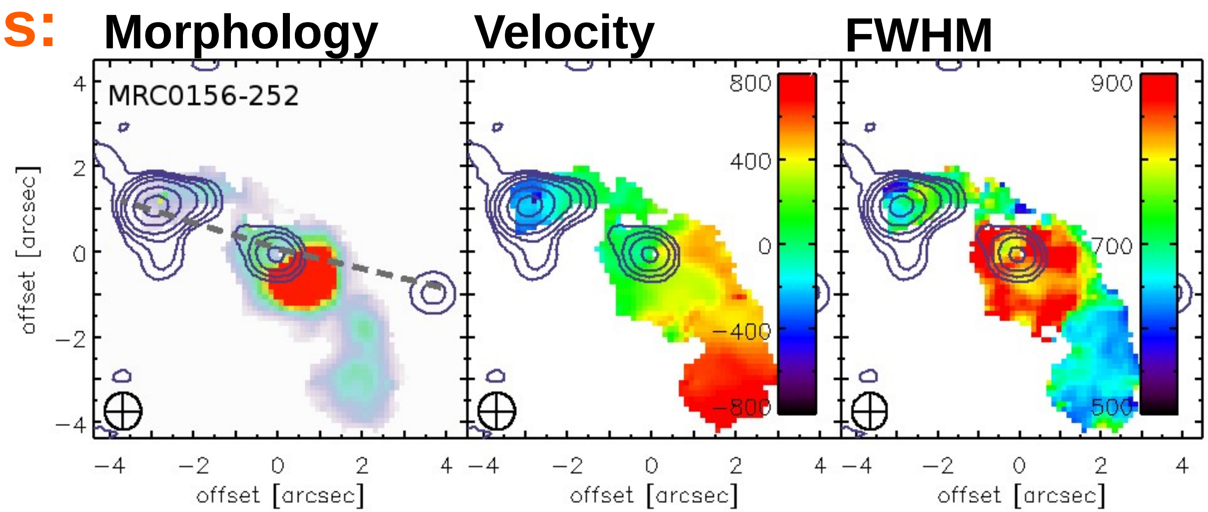


Broad agreement with models, but more turbulence than bulk motion!

High and low-power radio galaxies

I. High-power radio sources:

$P_{500} \gtrsim 10^{28}$ W Hz^{-1}:

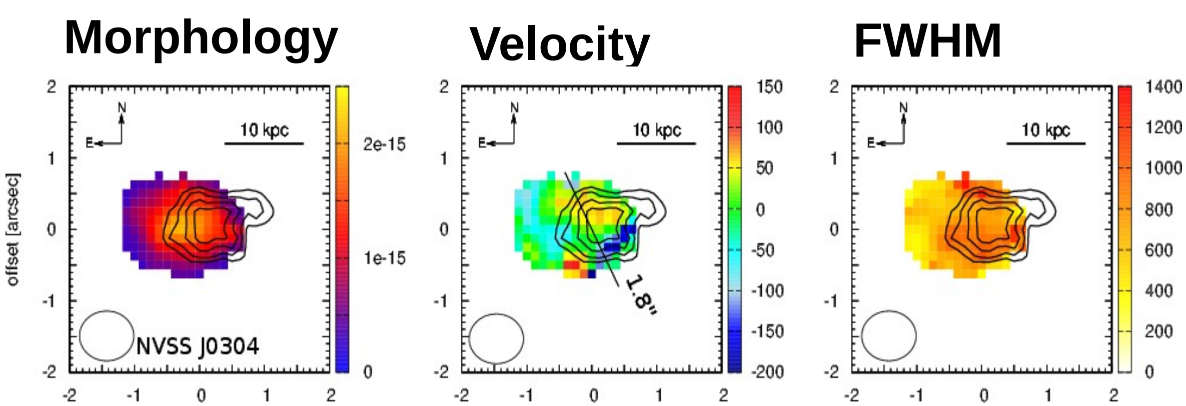


Clear outflow signatures:

- Δv up to 1500 km s^{-1}, $\gtrsim v_{esc}$
- $E_{kin,mech}$ few 10^{58} erg
- FWHM=800-1500 km s^{-1}
- $E_{kin} \sim 10^{-2}\ M^{BH}$

II. Low-power radio sources:

$P_{500} \sim 10^{26\text{-}27}$ W Hz^{-1}:



Smaller velocity gradients

$\Delta v \sim$ 200-300 km s^{-1}

→ $M_{dyn} \sim 10^{11} M_s$ → disks?

But: well aligned with jet axis

- often irregular velocity fields/FWHM
- large line widths: **800 km s^{-1}**

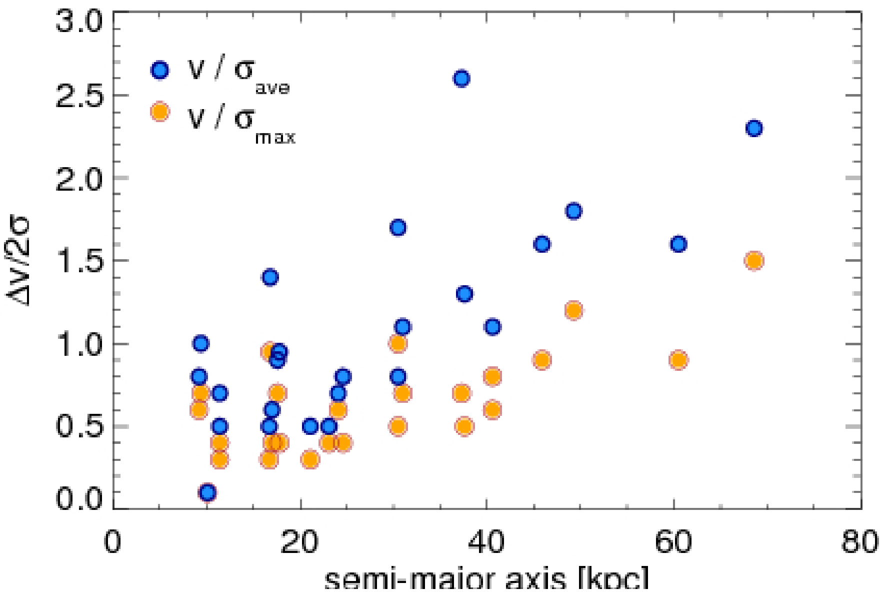
Localized outflows? High turbulence?

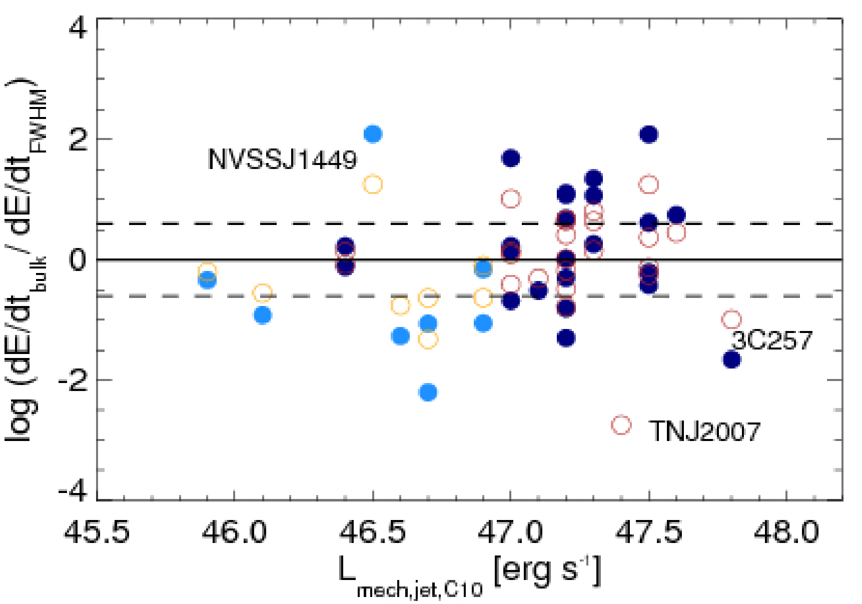
→ Bulk of the gas unlikely to escape

Disks, winds, or both?

Winds vs. turbulence in HzRGs

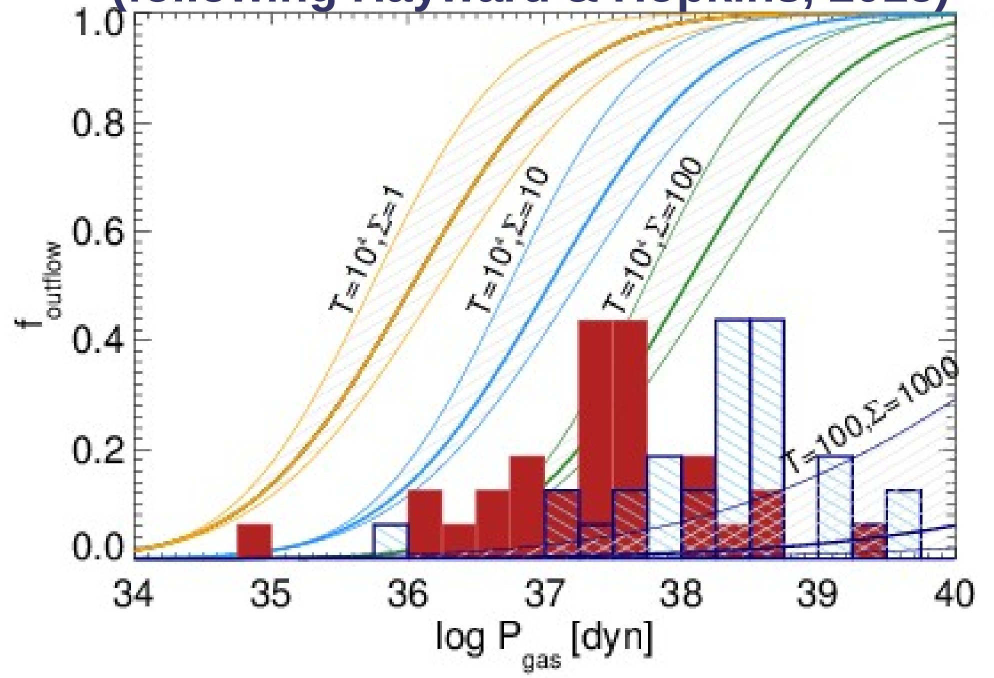
Nesvadba et al. (2017, A&A 599, 123)

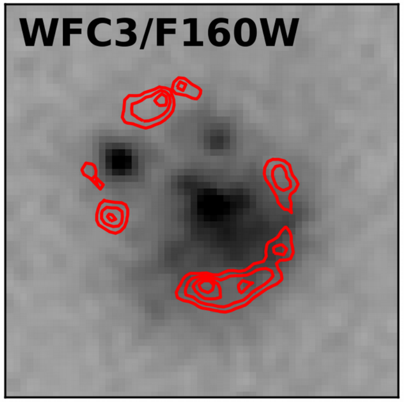




- Bulk motion becomes relatively more important for more extended gas and for more powerful radio sources.
- 'Disk bursting' when energy injection overcomes energy loss through, e.g., dissipation?
- Close analogy with recent analytic models

(following Hayward & Hopkins, 2015)



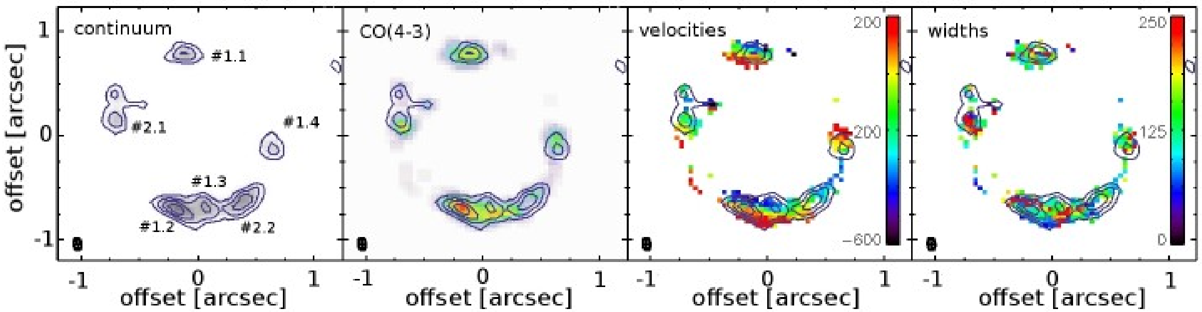


Birth environment of high-z AGN?

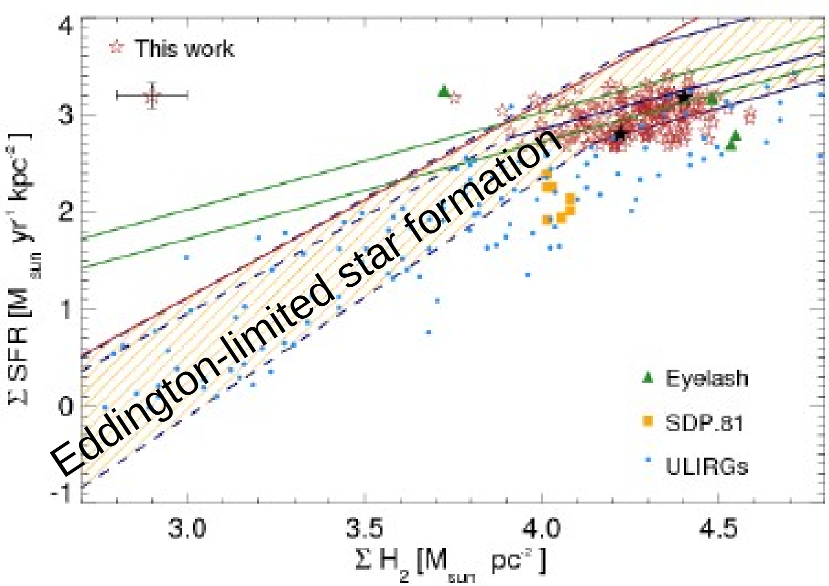
Canameras, NPHN et al. (2017a,b), A&A 600, L3 & A&A acc, astro-ph/1704.05853

"Ruby", z=3.0, L^{FIR} 2.6x10^{14} L_{sun} , **NO** bright AGN

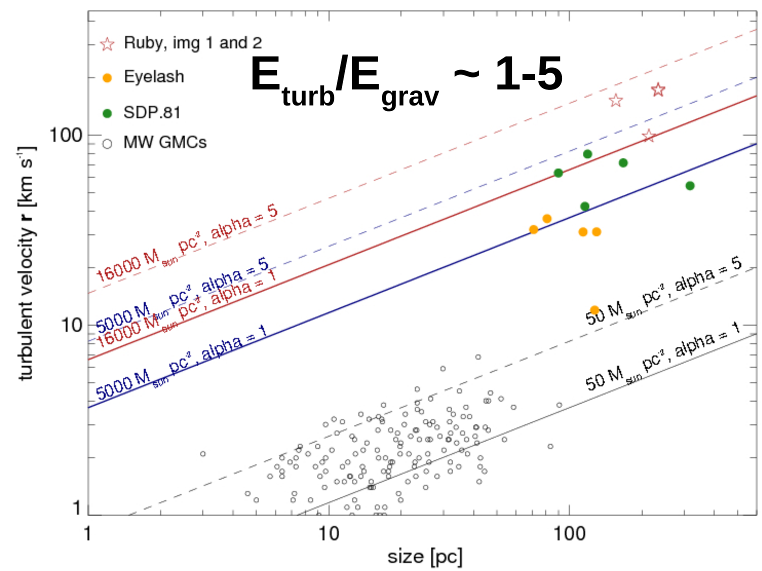
SF intensity ~2000 M_{sun} yr^{-1} kpc^{-2} μ ~ 10 – 40, beam < 100 pc source-plane



Star-formation is self-limited by mechanical energy from star-formation



Spatially-resolved star-formation law



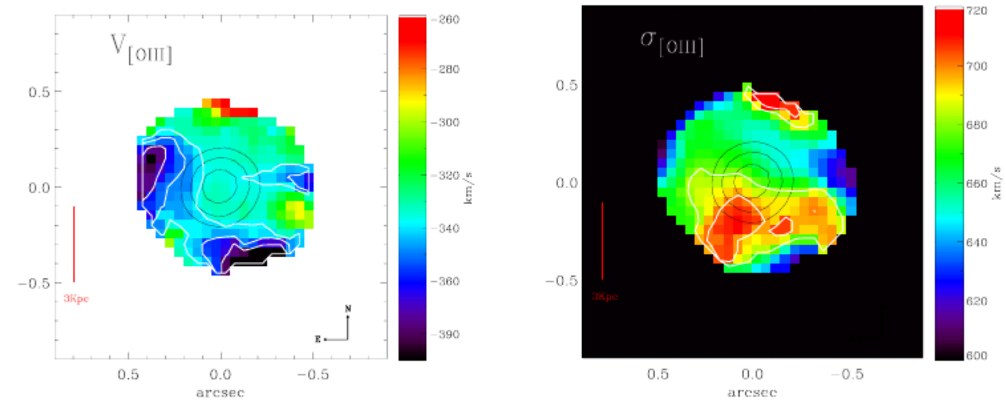
Gas is marginally bound, similar to MW

Evidence of suppression of SF in QSO

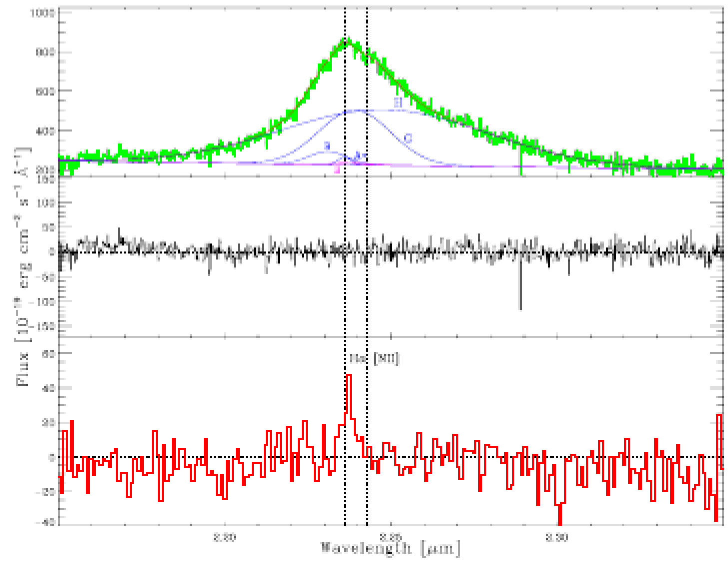
Cano-Diaz et al. (2012)

2QZ J002830-4281706, z=2.4

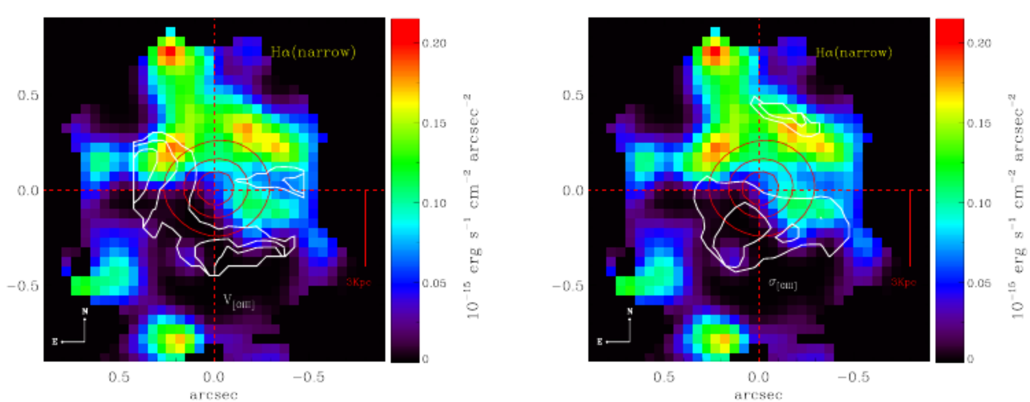
X-ray selected
L_{bol} = 4x10^{46} erg s^{-1}
$M_{WIM,[OIII]}$ = 10^{8} M_{sun}
V_{max} = 2000 km s^{-1}



[OIII]5007 velocities & line widths



Residual Hα in off-nuclear spectra, no [NII] seen



Hα morphology, avoids [OIII]
Contours [OIII] velocity (left) & dispersion (right)

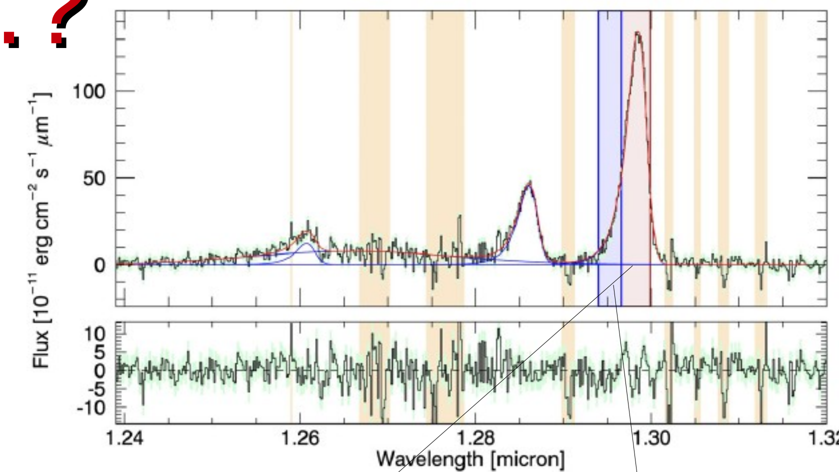
Cavity inflated by AGN wind?
Leads to absence of star formation?

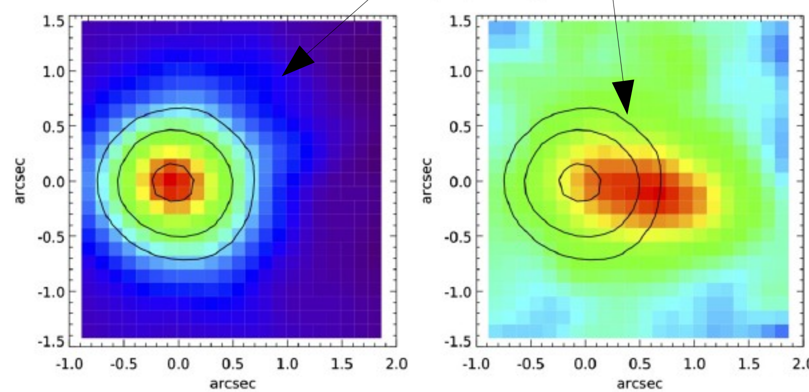
Evidence of bosted SF …?

Cresci et al. (2014)

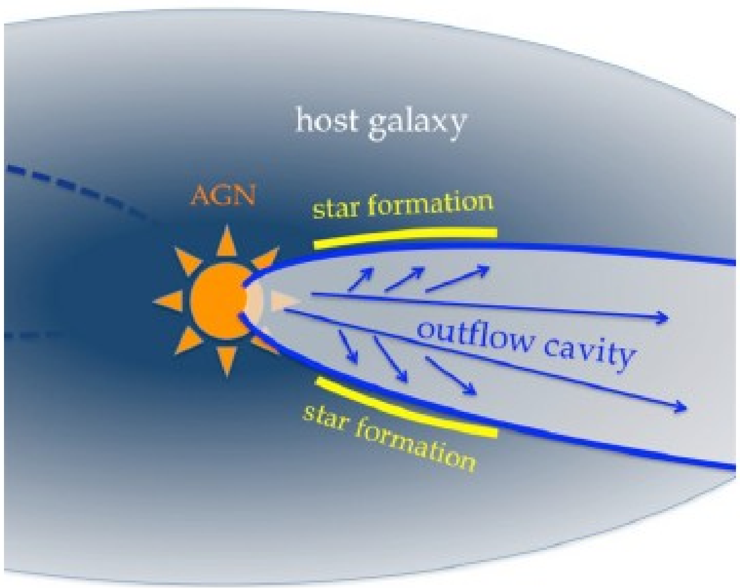
QSO @ z=1.6, XID 2028, Cosmos/XMM +
high MIR flux → high accretion rate

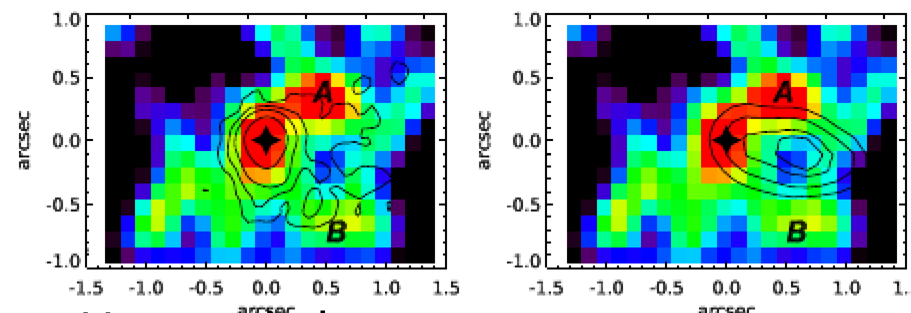
L_{bol} = 2x10^{46} erg s^{-1}, SFR = 275 M_{sun} yr^{-1} (PACS)
$L_{1.4}$=10^{24} W Hz^{-1}
M = few 10^{8} M_{sun}





[OIII] morphology: peak & wing

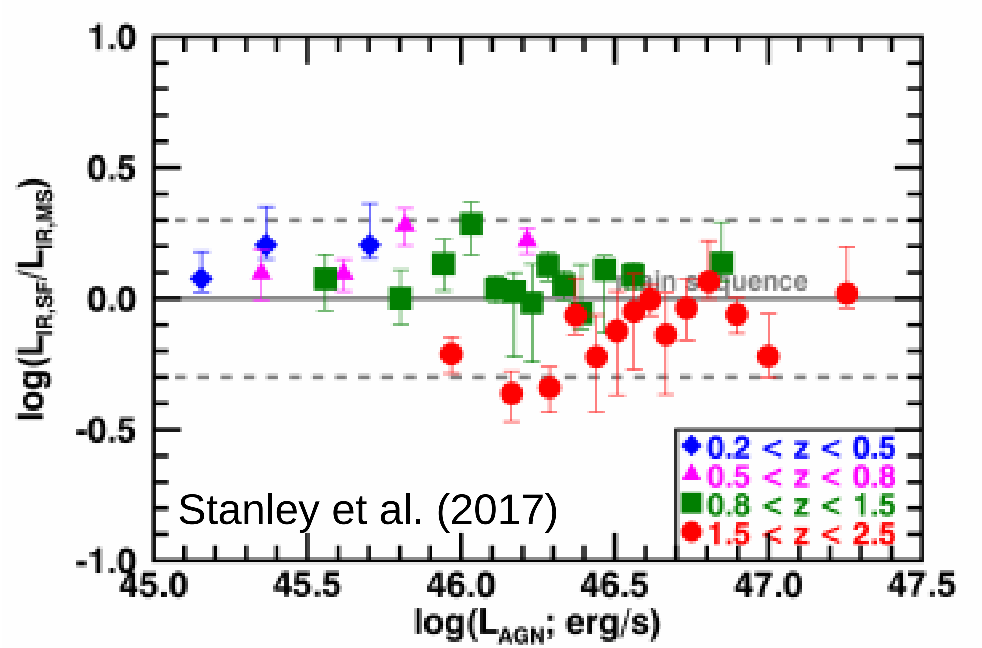




Hα morphology
Contours: ACS rest-UV & [OIII]

Ensemble studies

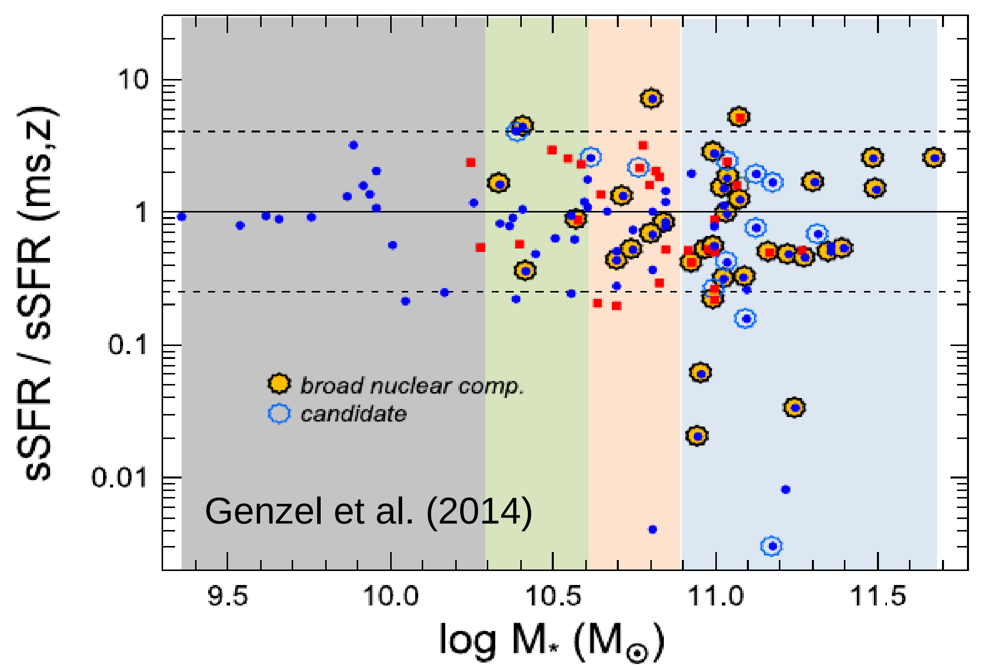
Bright optically selected quasars



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.

[Teresa's talk this morning: HzRGs on/below MS]

Winds are everywhere ...

Genzel et al. (2014), SINS **UV/optical selected SF** galaxies at **z~2** w/ SINFONI IFU data:
"The incidence of the most massive galaxies with broad nuclear components is at least as large as that of AGN identified by X-ray, optical, IR, or radio indicators."

Harrison et al. (2015), KMOS survey at **z=0.4 & z~1.5** of **40 X-ray selected AGN**:
"50% of the targets have ionized gas velocities indicative of gas that is dominated by outflows and/or highly turbulent material (i.e. overall line widths >~ 600 km s^{-1}). The most luminous half, L_x> 6x10^{43} erg s^{-1}, have a >~2x higher incidence of such velocities."

Harrison et al. (2012), NIFS/SINFONI data of **8 ULIRGs** w/ AGN at **z=1.4-3.4:**
"We find evidence in the 4 most luminous systems ($L_{[OIII]}$ > 10^{43} erg s^{-1}) for the signatures of large-scale energetic outflows. The four less luminous systems have lower quality data displaying weaker evidence for spatially extended outflows."

Nesvadba et al. (2017), SINFONI survey of **49 powerful radio-loud type II quasars at z~2-4.5**
"All sources have complex gas kinematics with brad line widths up to 1300 km s^{-1}. About half have bipolar velocity fields with offsets of up to 1500 km s^{-1}."

+ **individual targets,** e.g., Cano-Diaz et al. (2012), Cresci et al. (2015), …

De Graf et al. (2017): AMR (Ramses) simulations:
"We find this clumpy accretion to more efficiently fuel high-redshift black-hole growth […] which allows the black hole to efficiently evacuate gas from the central region of the galaxy, and suppressing star formation by as much as a factor 2."

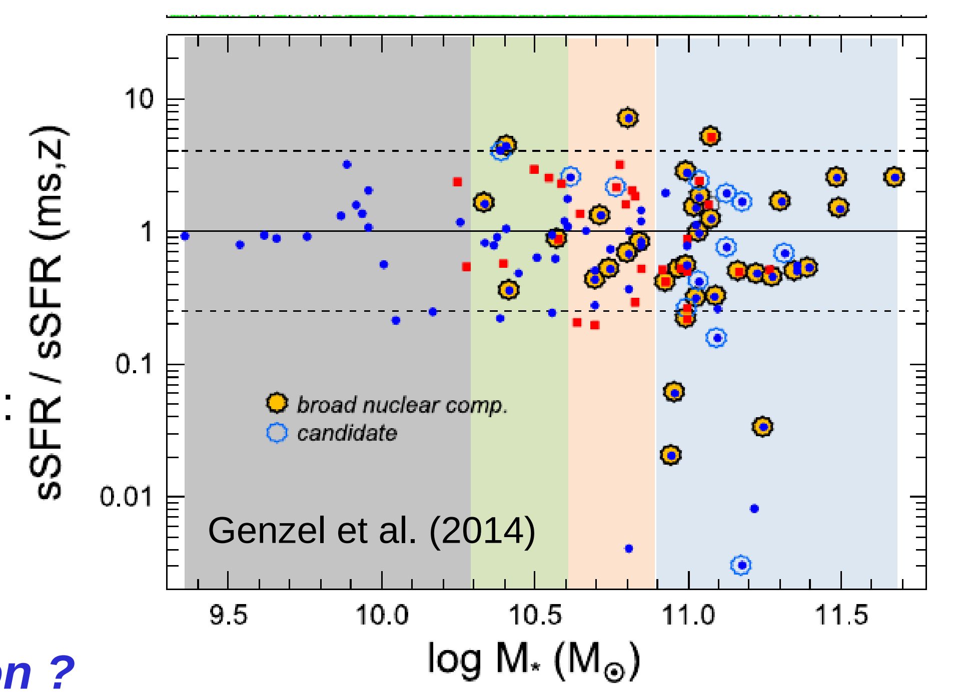
... but what are they really good for?

Harrison et al. (2016), ALMA 850 imaging of **5 X-ray AGN at z=1.4-4.5**, $L_x > 10^{42}$ erg s^{-1}:
"Our study suggests that the kpc-scale spatial distribution and surface density of star formation in high-redshift star-forming galaxies is the same irrespective of the presence of X-ray detected AGN."

Stanley et al. (2017): **3000 optically selected QSOs w/ Herschel/ATLAS photometry + WISE**, z=0.2-2.5: *"We find that the mean SFRs of our QSO (and radio-loud AGN) samples are consistent with galaxies on the main sequence."*

Drouart et al. (2014) **70 HzRGs w/ Spitzer & Herschel photometry**: *"The mean sSFRs of radio galaxies at z>2.5 are higher than those of main-sequence galaxies, but are similar or perhaps lower than them at z<2.5."*
But: Only 30% have detected SB components (~ z=0, Tadhunter et al. 2013)

Genzel et al. (2014): UV/optically selected galaxies: *"Our galaxies lie on the main sequence of star-forming galaxies at their redshift."*



The 'hard problem of AGN feedback' – how do you establish the link with star formation ?