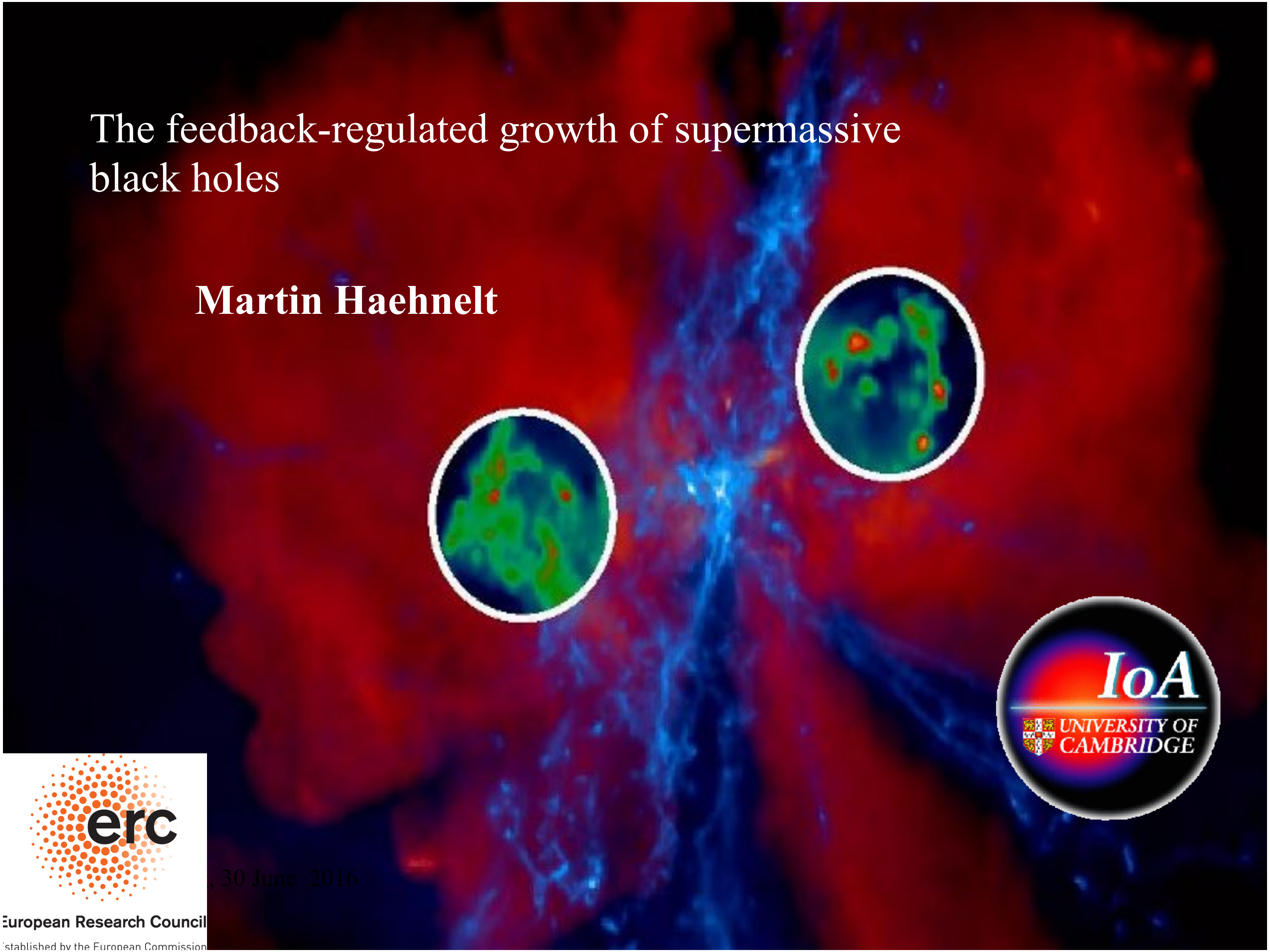

The feedback-regulated growth of supermassive black holes

Martin Haehnelt

, 30 June 2016

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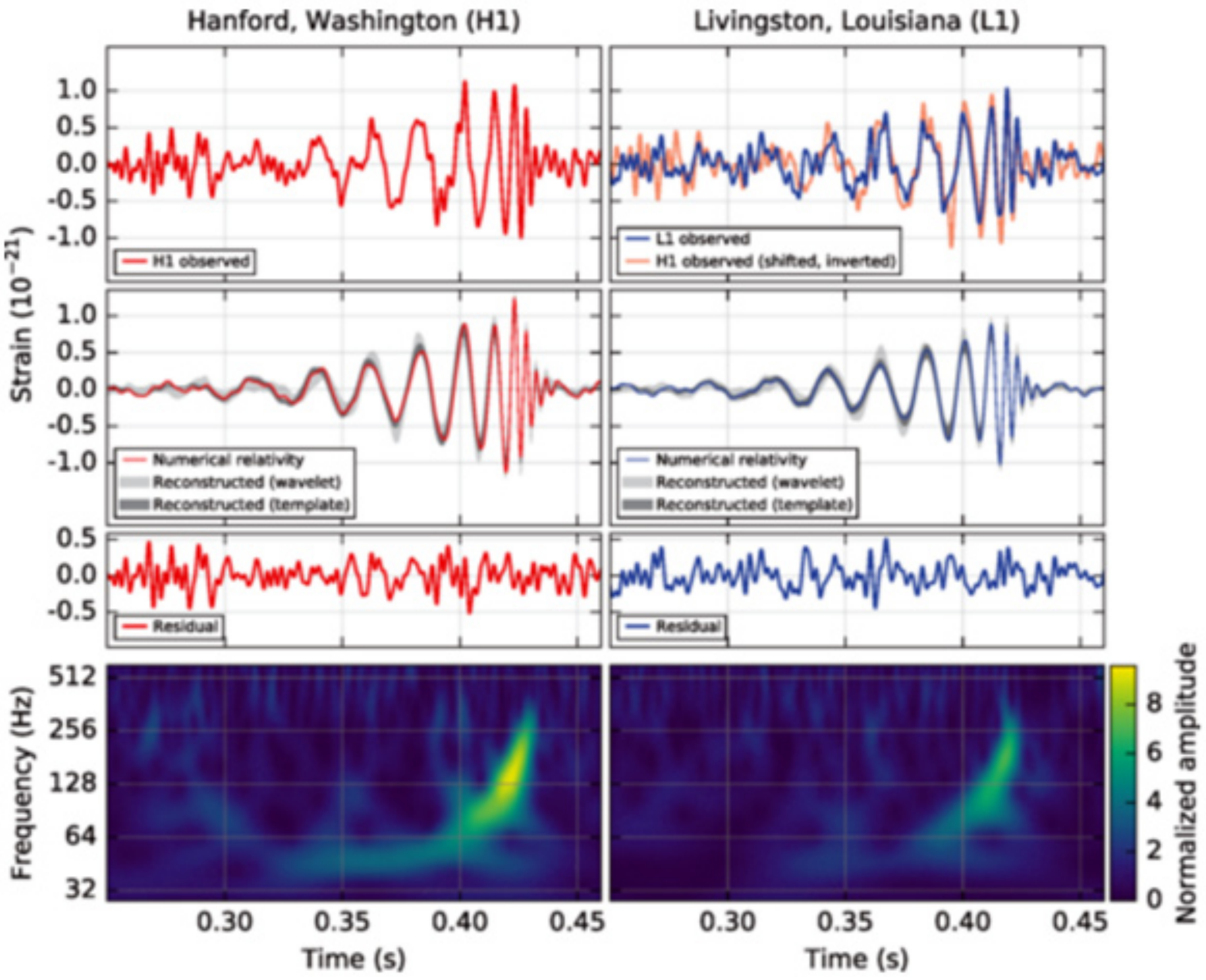

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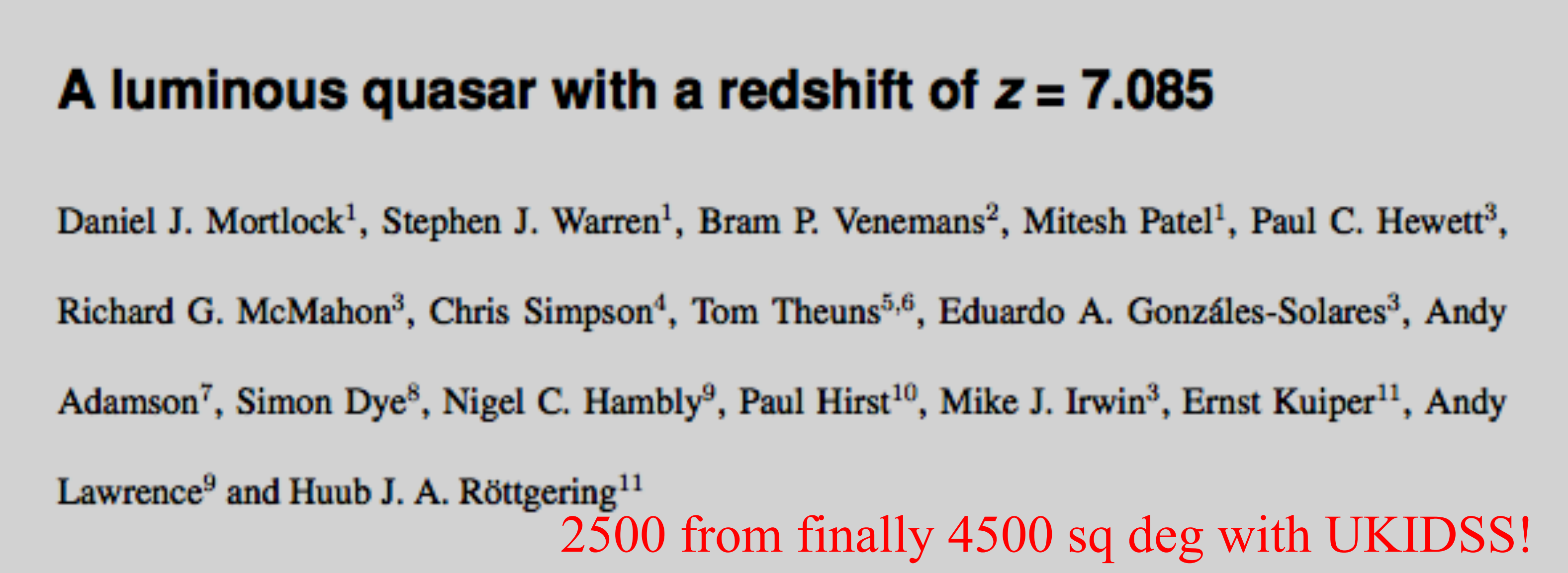
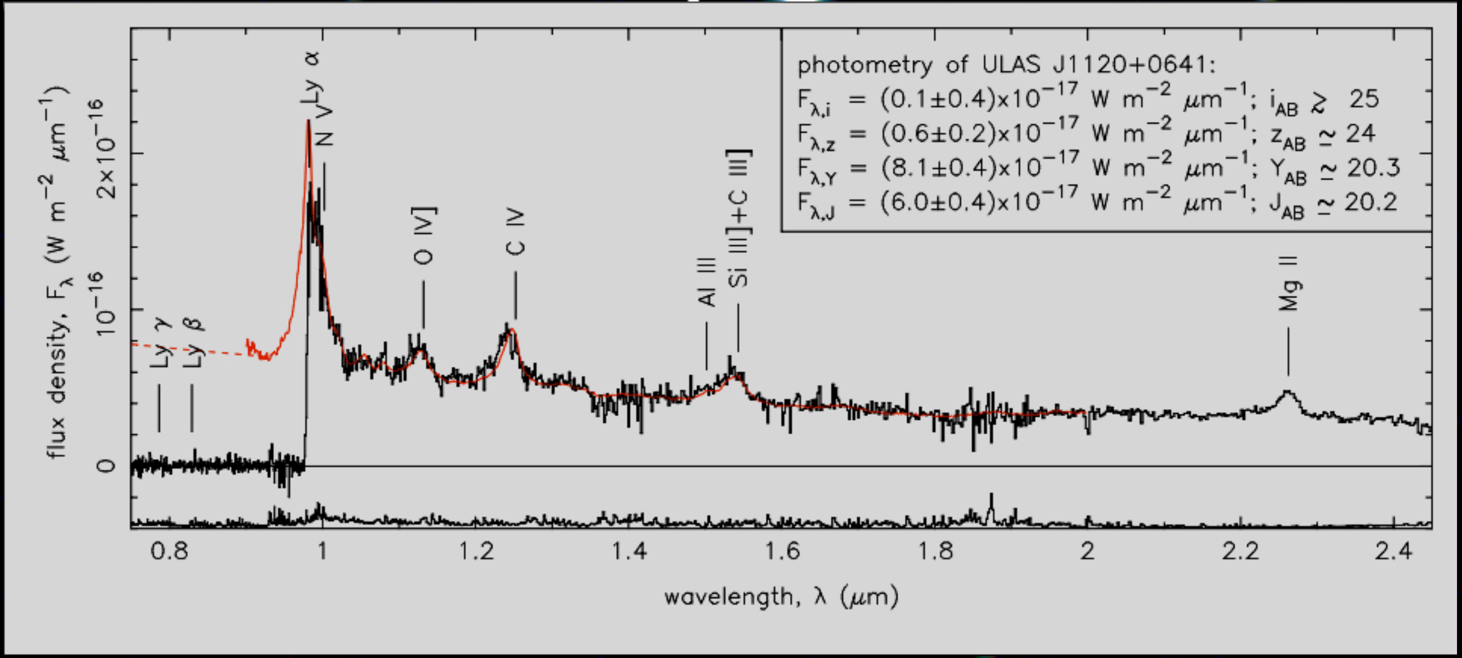


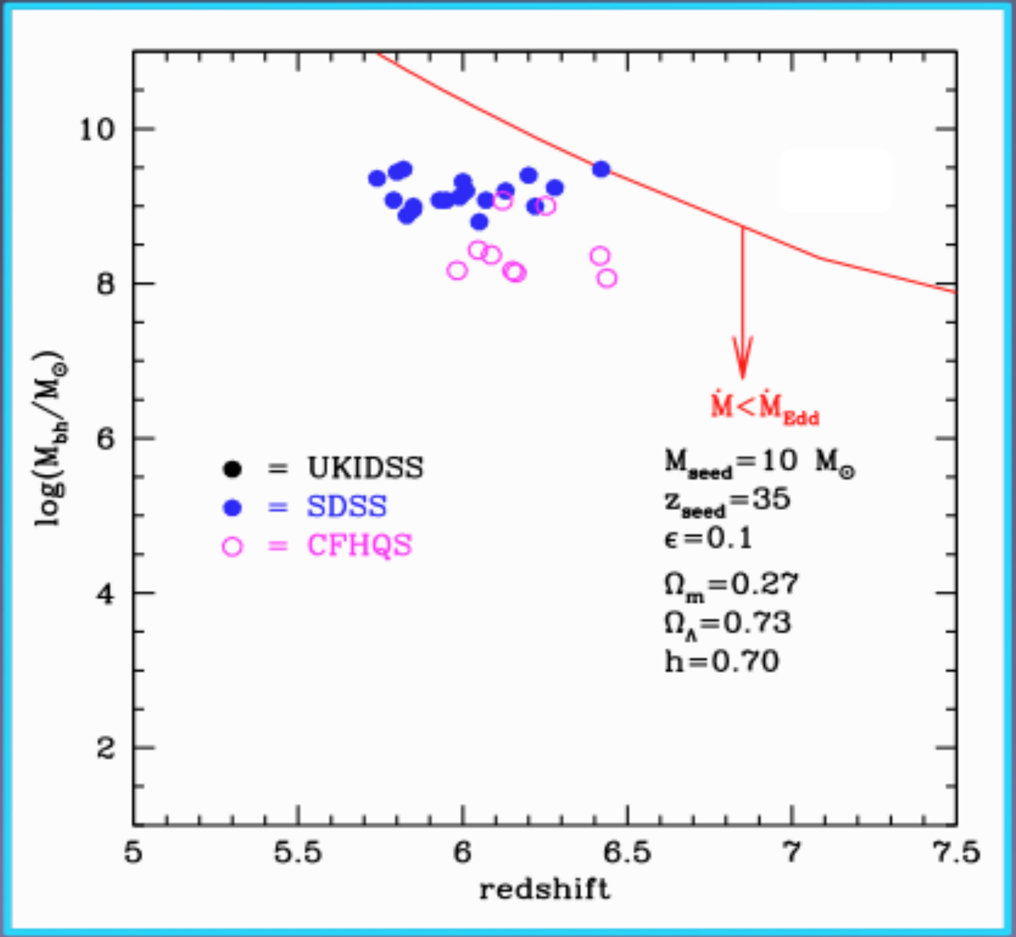
A luminous quasar with a redshift of $z = 7.085$

Daniel J. Mortlock[1], Stephen J. Warren[1], Bram P. Venemans[2], Mitesh Patel[1], Paul C. Hewett[3], Richard G. McMahon[3], Chris Simpson[4], Tom Theuns[5,6], Eduardo A. Gonzáles-Solares[3], Andy Adamson[7], Simon Dye[8], Nigel C. Hambly[9], Paul Hirst[10], Mike J. Irwin[3], Ernst Kuiper[11], Andy Lawrence[9] and Huub J. A. Röttgering[11]

2500 from finally 4500 sq deg with UKIDSS!



“Maximum” SMBH Masses



e-folding (Edd) time:
M/(dM/dt) = 4 (ε/0.1) 10^7yr

Age of universe (z=6-7)
(0.8 - 1) x 10^9 yr

Must start early!

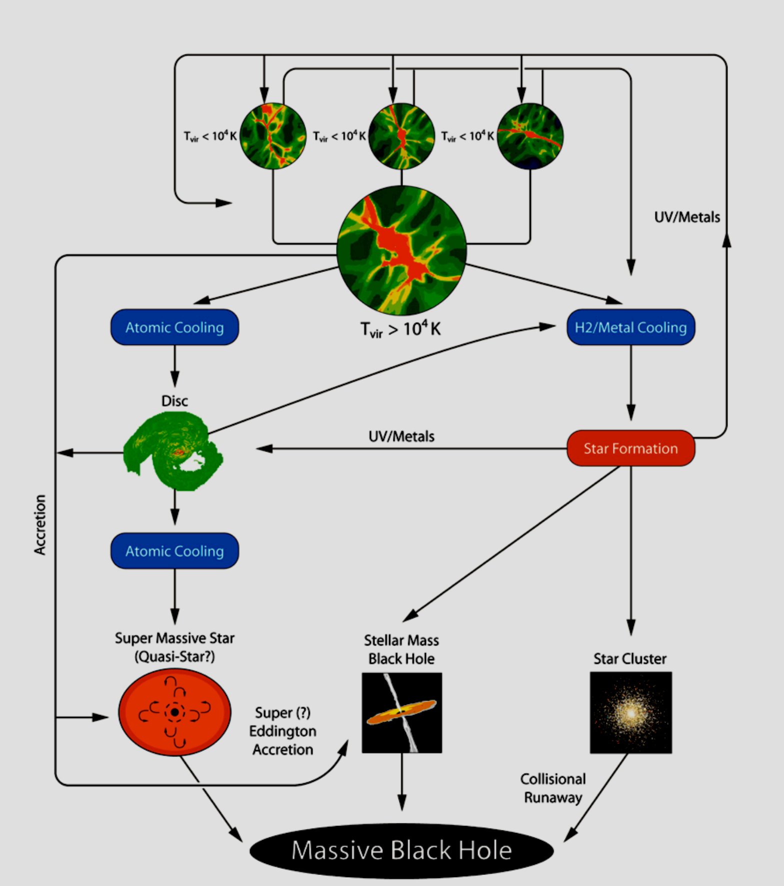
Accretion rate must keep up w/ Eddington at all times

Obvious alternatives:
(1) grow faster or
(2) merge many BHs

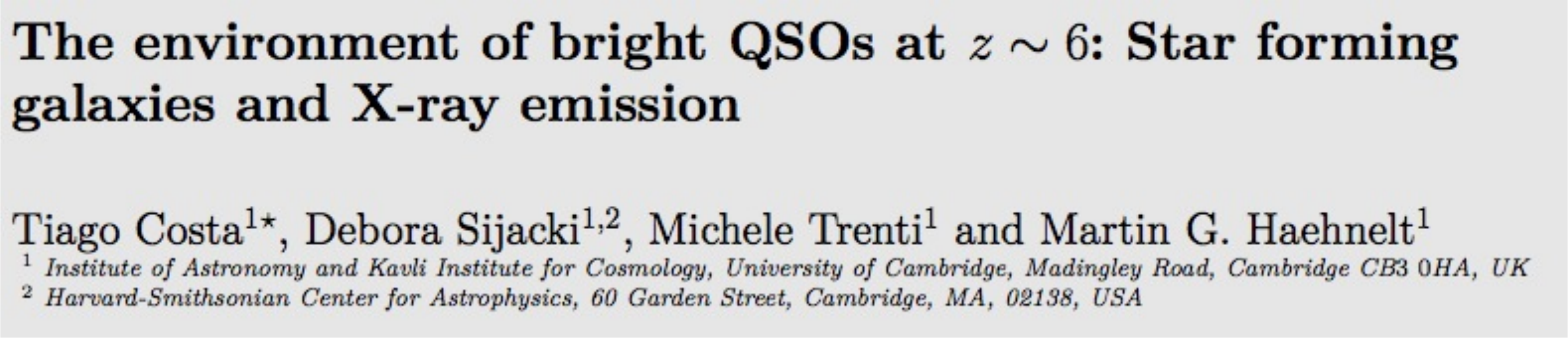
Masses estimated from: Fan et al. (2006); Willott et al. (2010); Mortlock et al. (2011)

slide from Zoltan Haiman

Massive seed black holes?

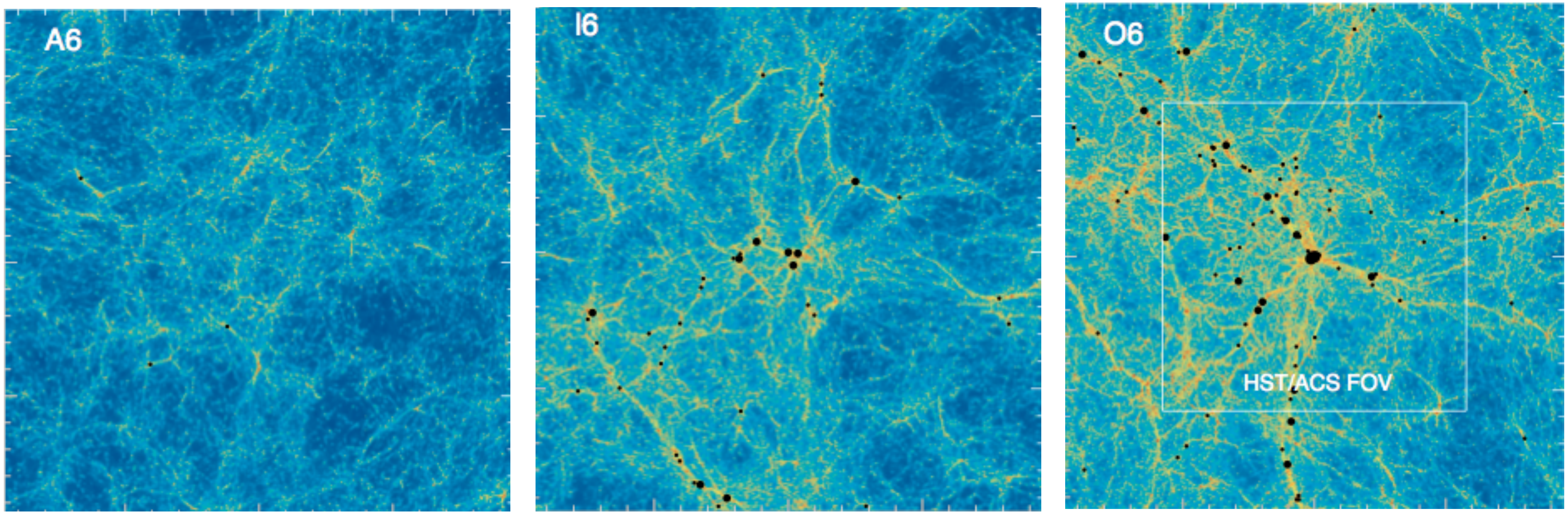


Regan & Haehnelt 2009



The environment of bright QSOs at $z \sim 6$: Star forming galaxies and X-ray emission

Tiago Costa[1]*, Debora Sijacki[1,2], Michele Trenti[1] and Martin G. Haehnelt[1]
[1] Institute of Astronomy and Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, 02138, USA



Average density

Intermediate overdensity

“Most massive” halo

Billion solar mass black holes only form in highly overdense regions.

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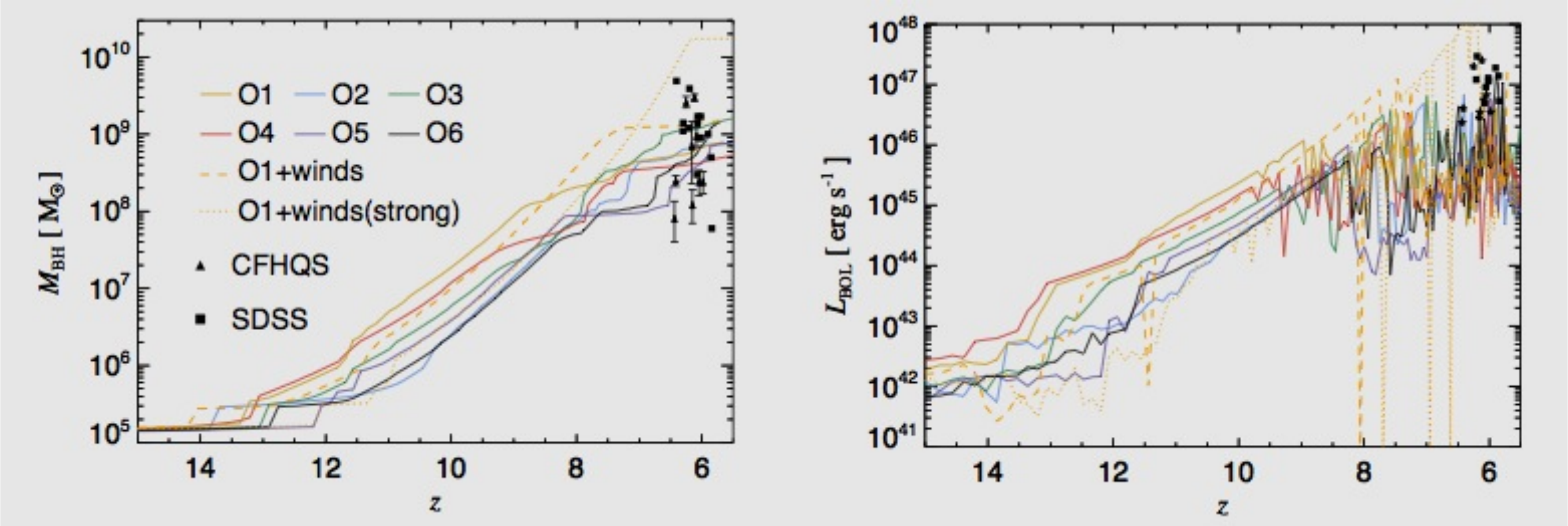
Early growth of the most massive black holes

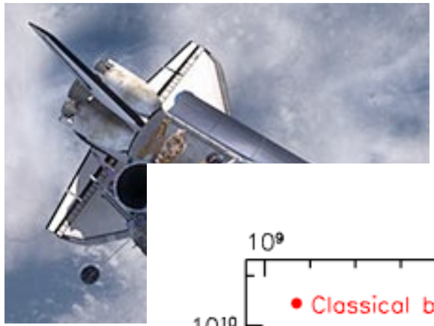


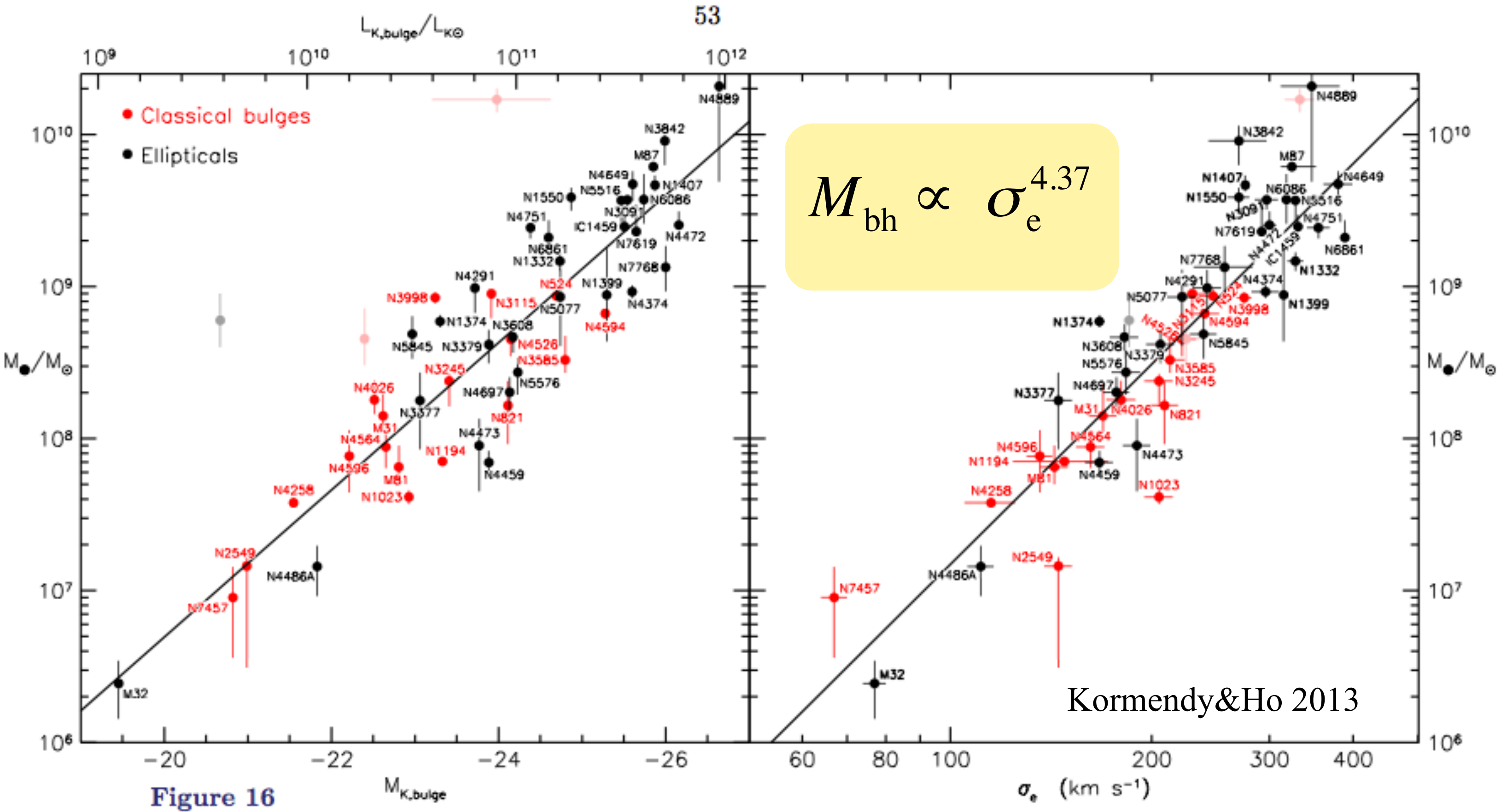
Two phases:

1. Eddington limited growth
2. Intermittent feedback limited growth

Costa et al. 2013
Sijacki et al. 2009

This assumes massive seed black holes!





$$M_{bh} \propto \sigma_e^{4.37}$$

Kormendy&Ho 2013

Figure 16

Correlation of dynamically measured BH mass $M_\bullet$ with (*left*) K-band absolute magnitude $M_{K,\mathrm{bulge}}$ and luminosity $L_{K,\mathrm{bulge}}$ and (*right*) velocity dispersion σ_e for (*red*) classical bulges and (*black*) elliptical galaxies. The lines are symmetric least-squares fits to all the points except the monsters (*points in light colors*), NGC 3842, and NGC 4889. **Figure 17** shows this fit with 1-σ error bars.

Self-regulation?
“Co-Evolution”

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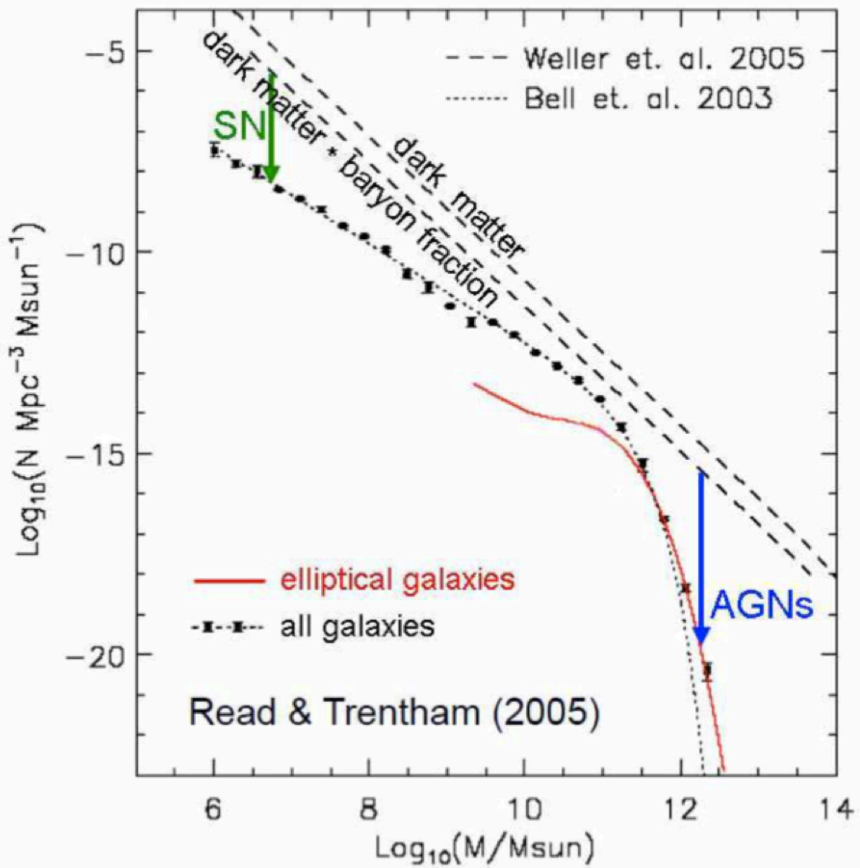
The need for (negative) feedback



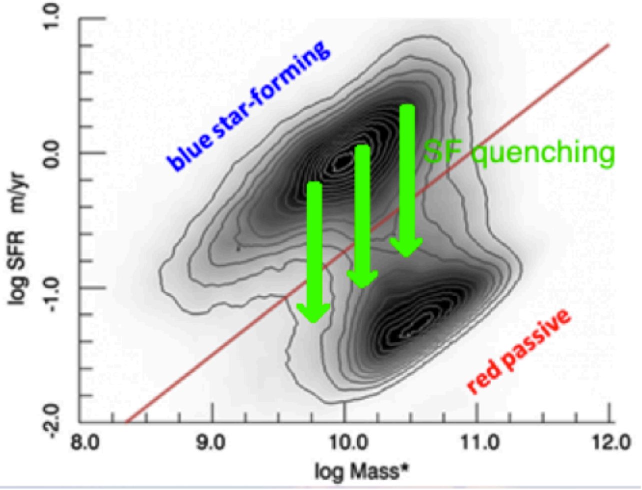
Theoretical expectations:

SNe feedback:

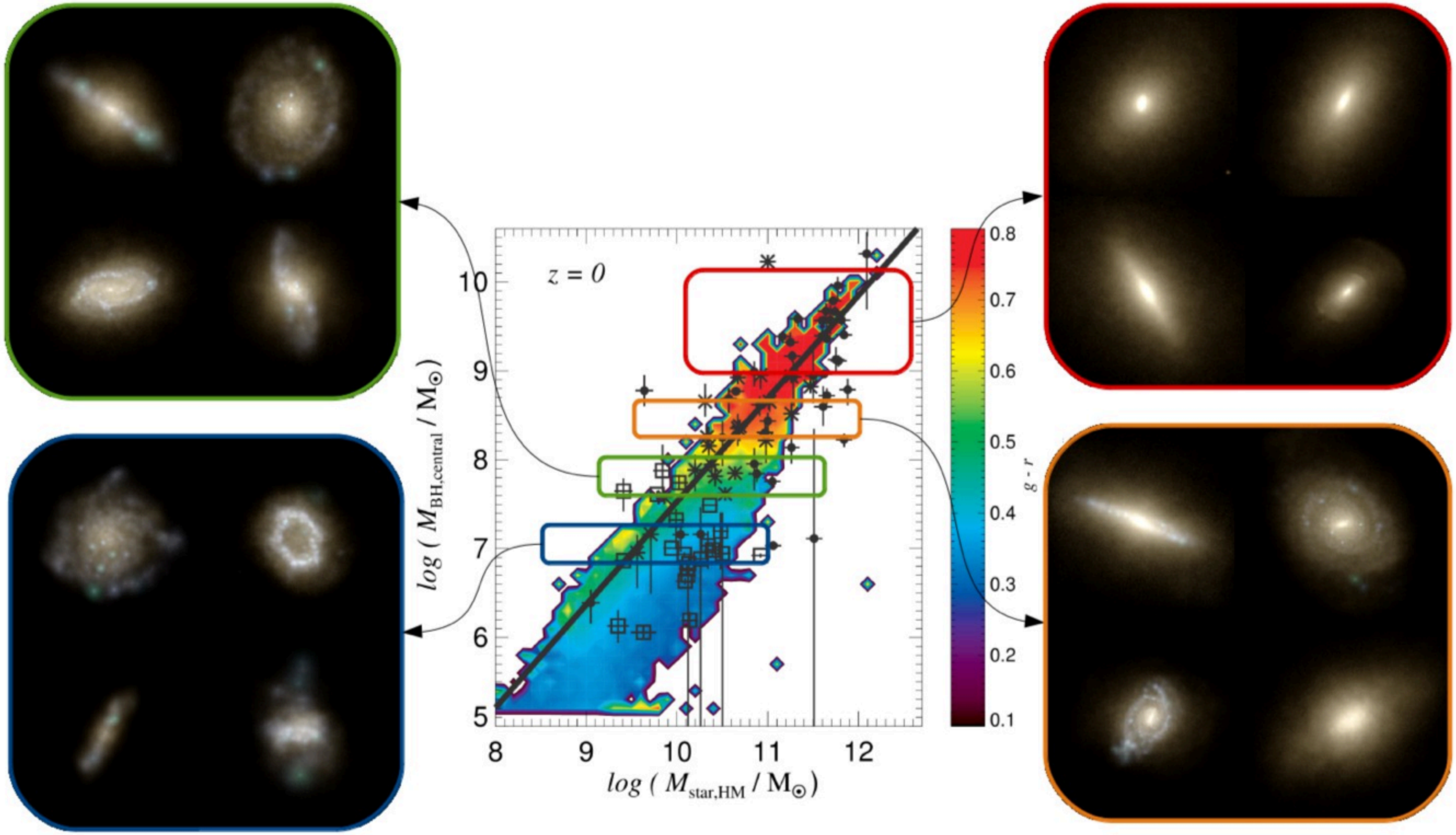
removes baryons from galaxies and reduce SF efficiency in low mass galaxies

AGN feedback:

- prevents overgrowth of massive galaxies
- invoked for the M_{BH}-M_{star} relation
- explains red-and-dead properties of local ellipticals

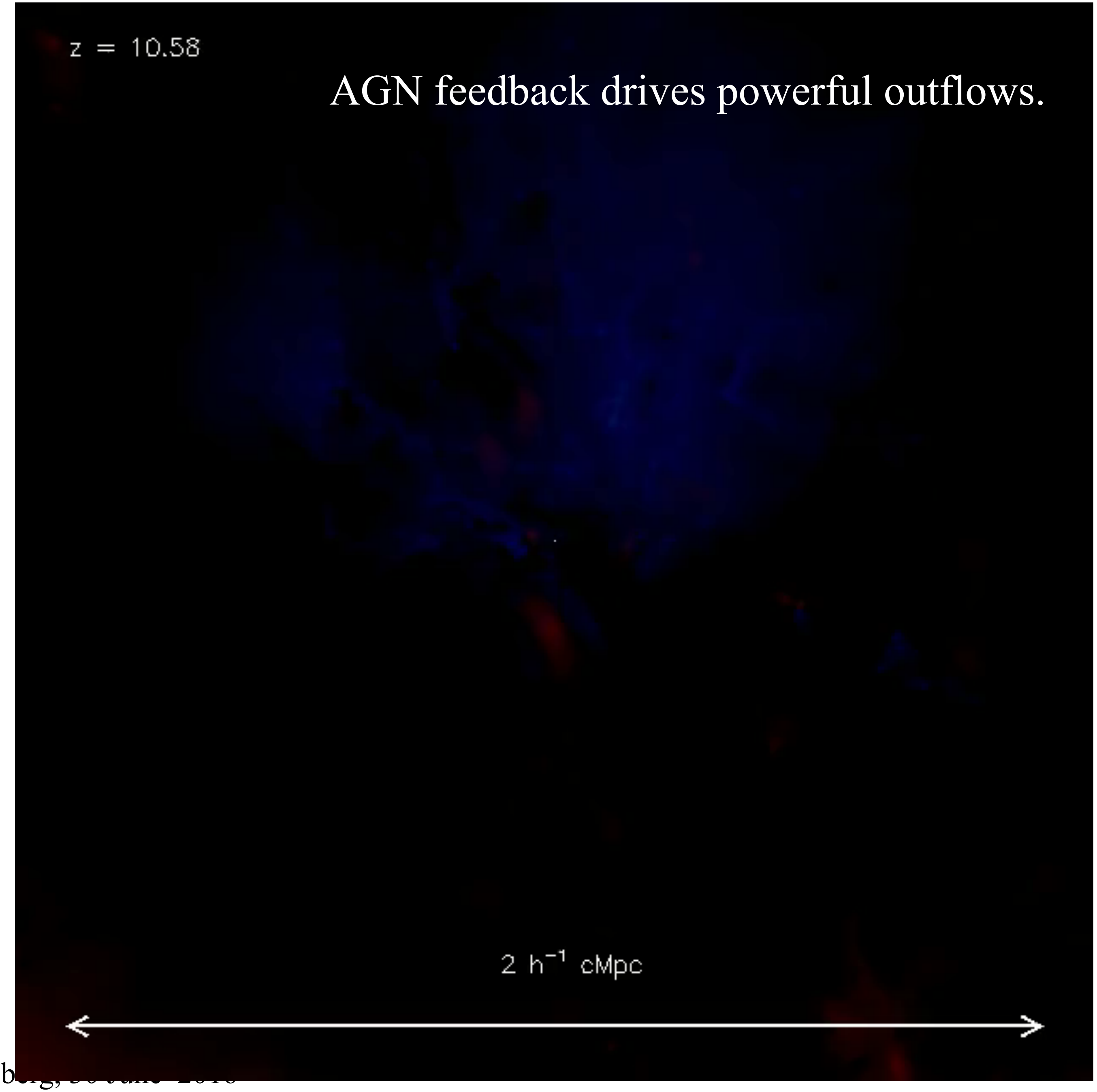


slide from Roberto Maiolino



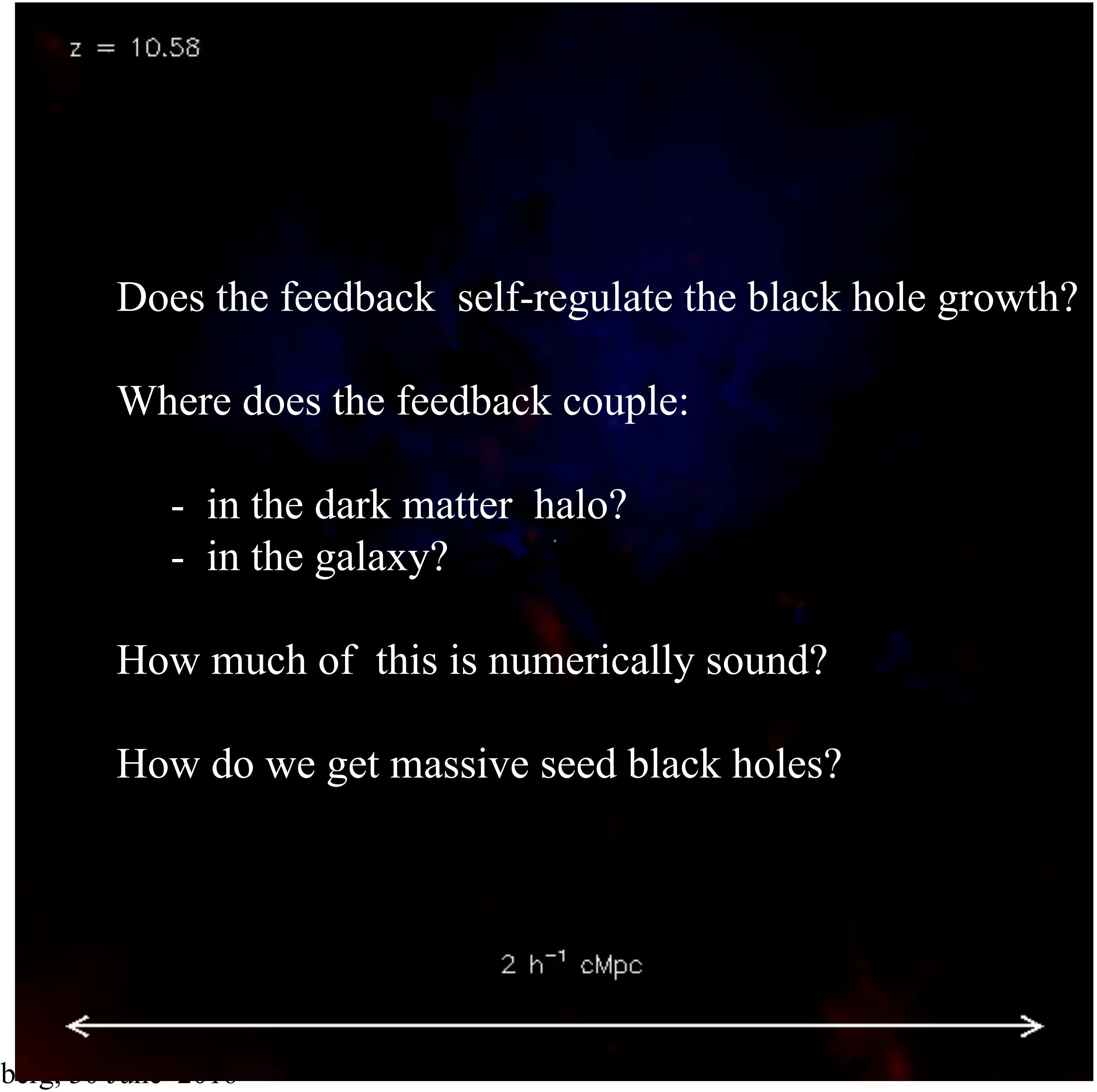
What is going on in the simulations?
Is it the correct physics?

Sijacki et al. 2015



AGN feedback drives powerful outflows.

simulation and movie by Tiago Costa



Does the feedback self-regulate the black hole growth?

Where does the feedback couple:

- in the dark matter halo?
- in the galaxy?

How much of this is numerically sound?

How do we get massive seed black holes?

simulation and movie by Tiago Costa

Feedback regulated growth
super-Eddington growth?
AGN-driven outflows

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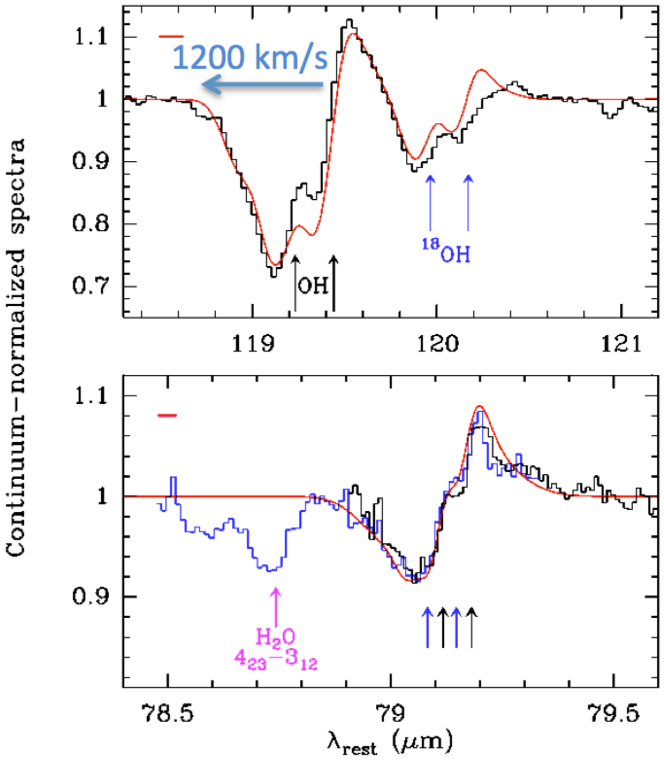
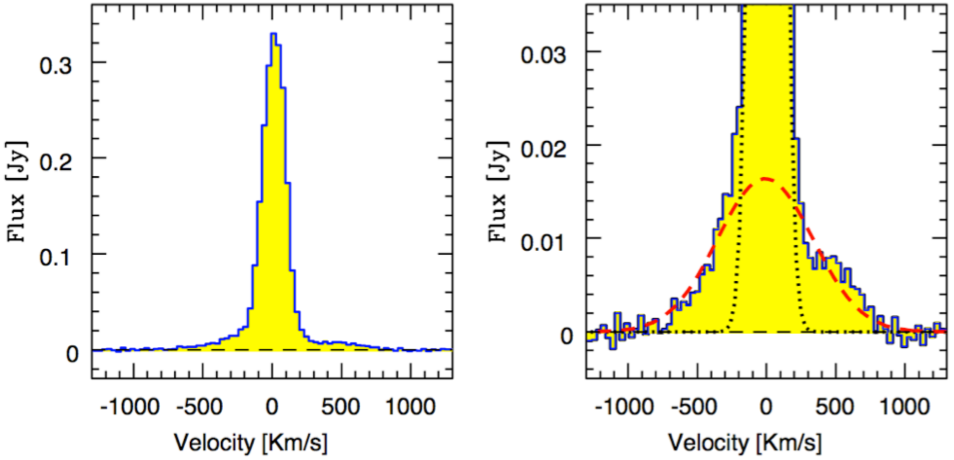
First evidence of quasar-mode feedback in local quasars achieved only recently

OH P-Cygni profiles

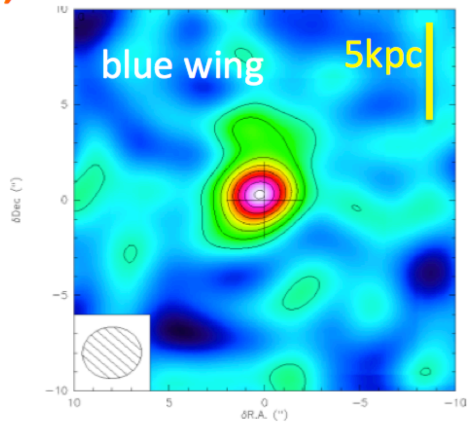


CO(1-0) high velocity wings



Fischer+10
Sturm+11

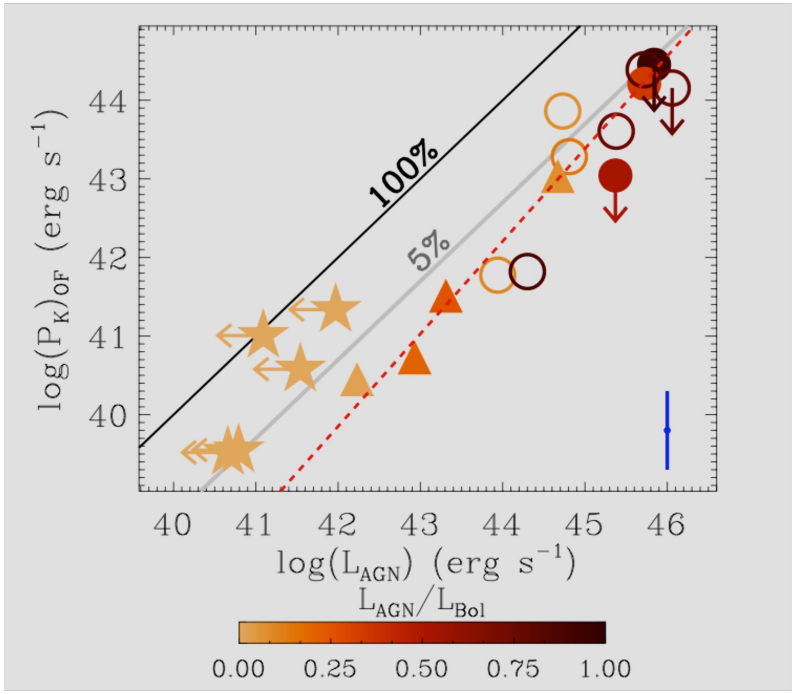
Feruglio+10,13

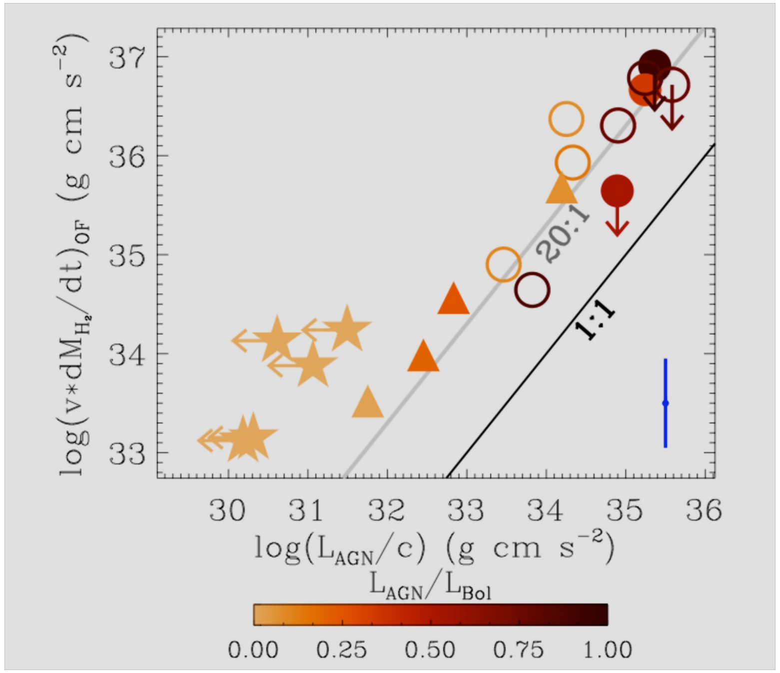


Massive molecular outflows (~1000 M$_\odot$/yr)
Extended on kpc scales

slide from Roberto Maiolino

AGN-driven molecular outflows in local ULIRGs





Cicone et al 2013

$L_{kin} \sim 0.05\ L_{AGN}$

$v_{outflow}\ (dM_{H2}/dt)_{outflow} \sim 20\ L_{AGN}/c$

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Feedback from Active Galactic Nuclei: Energy- versus momentum-driving

Tiago Costa*, Debora Sijacki and Martin G. Haehnelt
Institute of Astronomy and Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA

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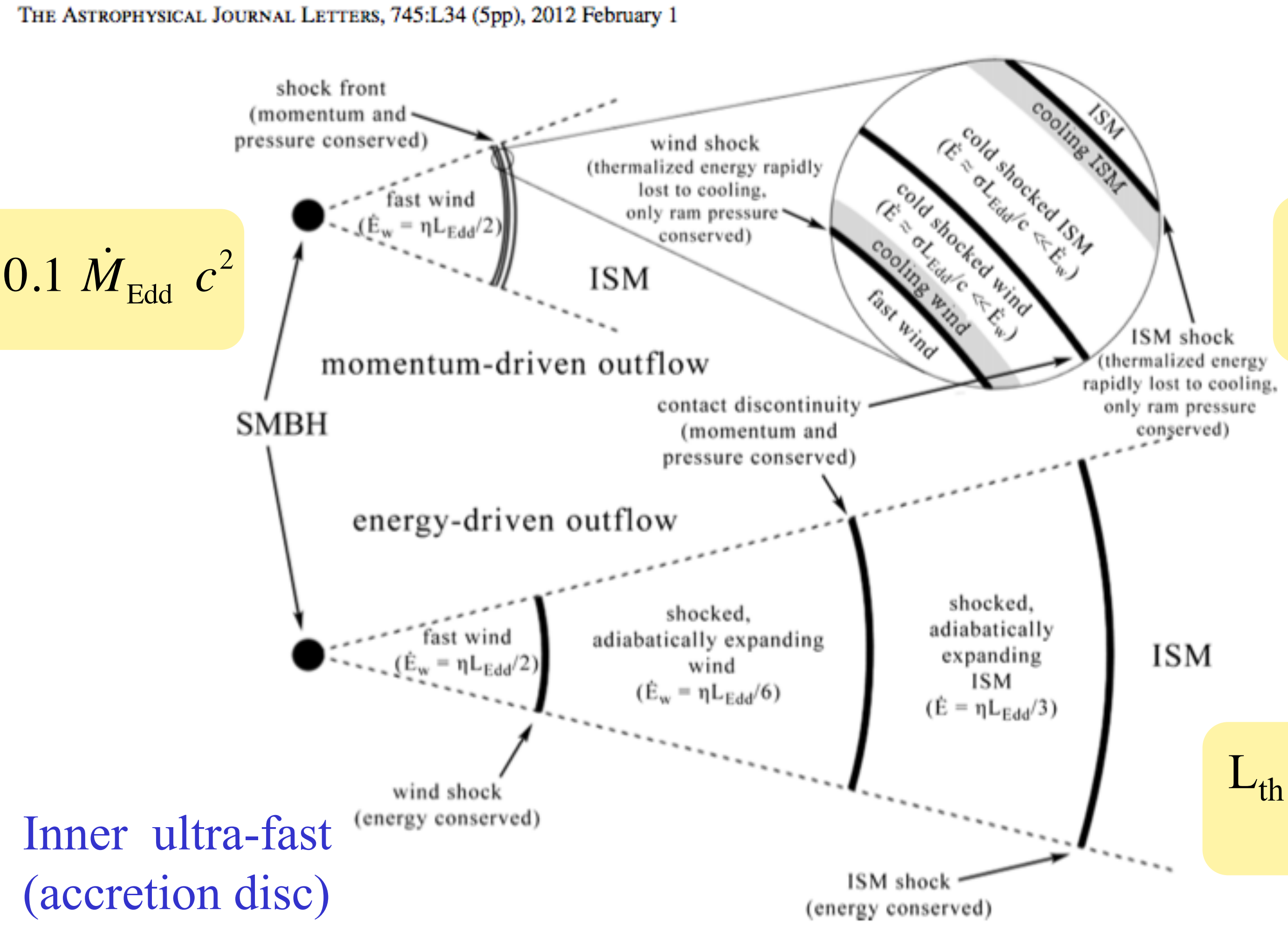
Momentum vs energy-driven outflows from AGN

$$L_{\mathrm{Edd}} = 0.1\ \dot{M}_{\mathrm{Edd}}\ c^2$$



The Astrophysical Journal Letters, 745:L34 (5pp), 2012 February 1 — Zubovas & King

$$\dot{P} = \frac{L_{\mathrm{edd}}}{c}$$

$$L_{\mathrm{th}} = \varepsilon_{\mathrm{th}}\ L_{\mathrm{edd}} = 0.05\ L_{\mathrm{edd}}$$

Inner ultra-fast
(accretion disc)
wind

Outer (galactic) wind

The $M_{bh} - \sigma$ relation in the initially momentum-driven King model

Equation of motion for shell:

$$\frac{d\left[M_{\rm shell}(R)\dot{R}\right]}{dt} = 4\pi R^2 \overset{\overset{\frac{L_{\rm edd}}{c}}{\|}}{P} - \frac{G M_{\rm shell}(R) M_{\rm tot}(<R)}{R^2}$$

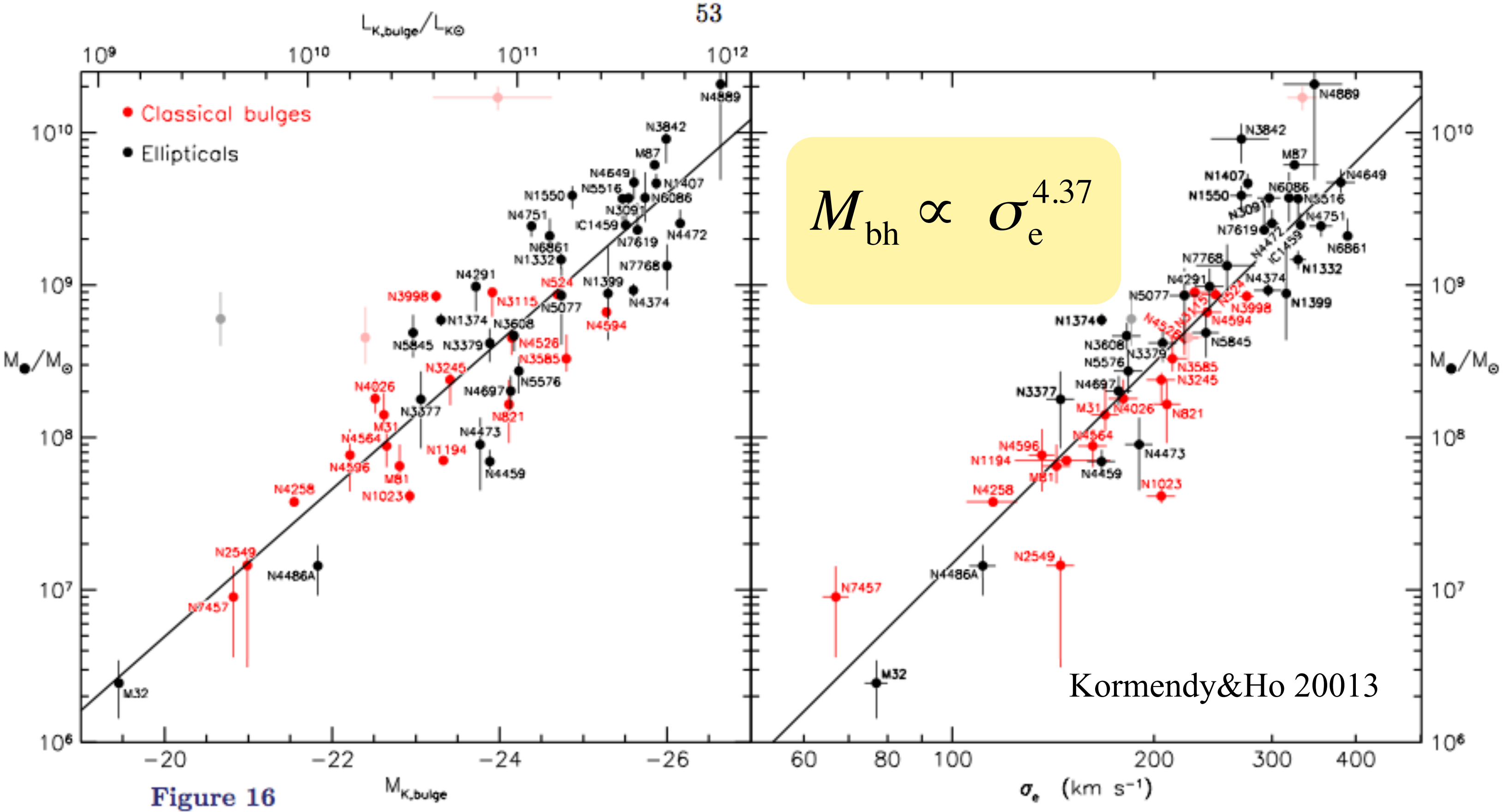
For isothermal halo with velocity dispersion σ:

$$\frac{d\left(R\dot{R}\right)}{dt} = -2\sigma^2\left(1 - \frac{M_{\rm BH}}{M_\sigma}\right) - \frac{G M_{\rm BH}}{R}$$

Gas is unbound for:

$$M_{\rm bh} \geq M_\sigma = \frac{f_{\rm gas}\kappa}{\pi G^2}\sigma^4 \quad \sim 3\,\mathrm{x}10^8\, M_\odot\, (\sigma/200\mathrm{kms}^{-1})^4$$

Gives the right slope <u>and</u> normalization!



$$M_{\mathrm{bh}} \propto \sigma_{\mathrm{e}}^{4.37}$$

Kormendy&Ho 20013

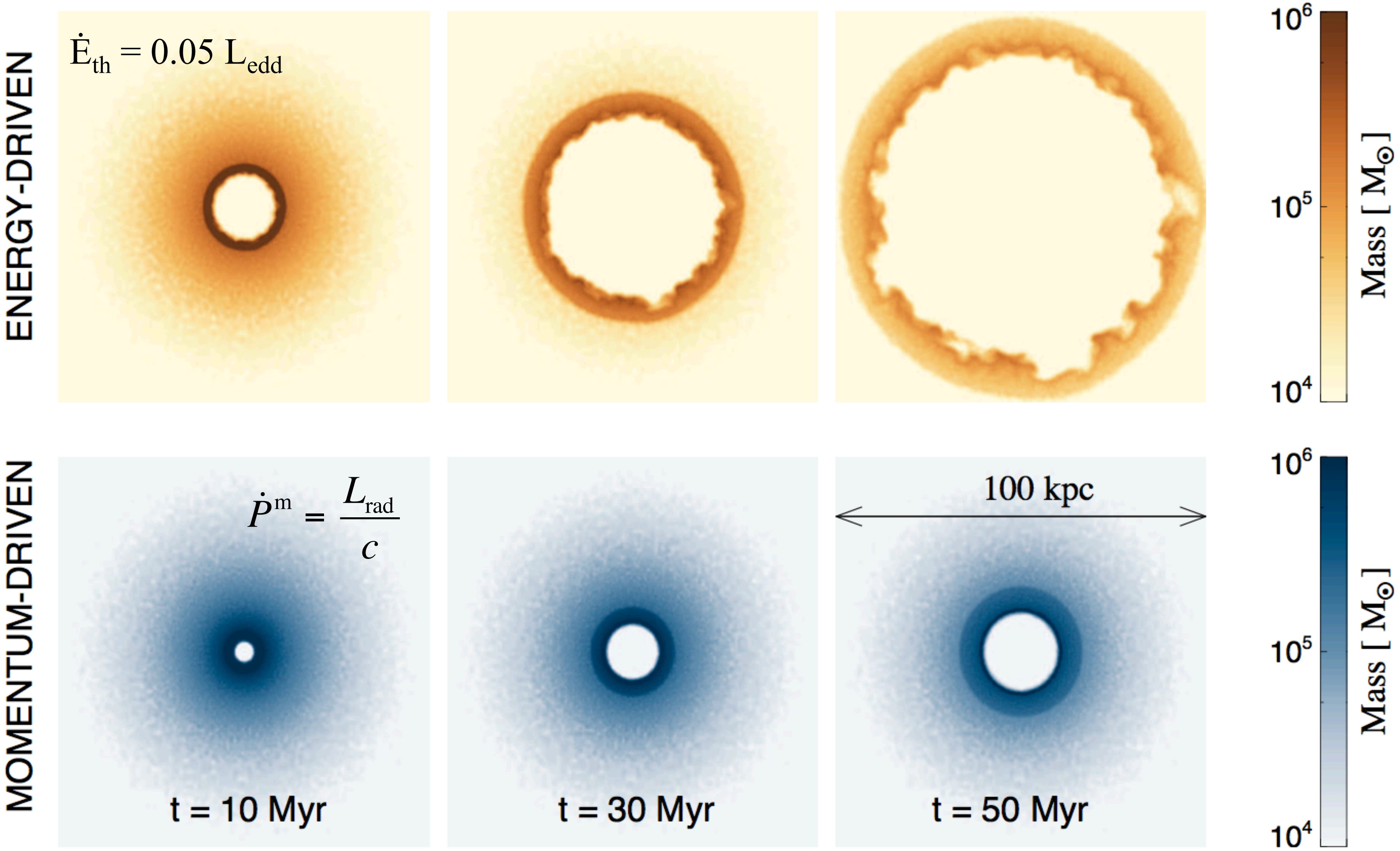
Figure 16

Correlation of dynamically measured BH mass $M_\bullet$ with (*left*) K-band absolute magnitude $M_{K,\mathrm{bulge}}$ and luminosity $L_{K,\mathrm{bulge}}$ and (*right*) velocity dispersion σ_e for (*red*) classical bulges and (*black*) elliptical galaxies. The lines are symmetric least-squares fits to all the points except the monsters (*points in light colors*), NGC 3842, and NGC 4889. **Figure 17** shows this fit with 1-σ error bars.

Self-regulation?

“Co-Evolution”

Spherical haloes filled with gas in hydrostatic equilibrium simulated with AREPO



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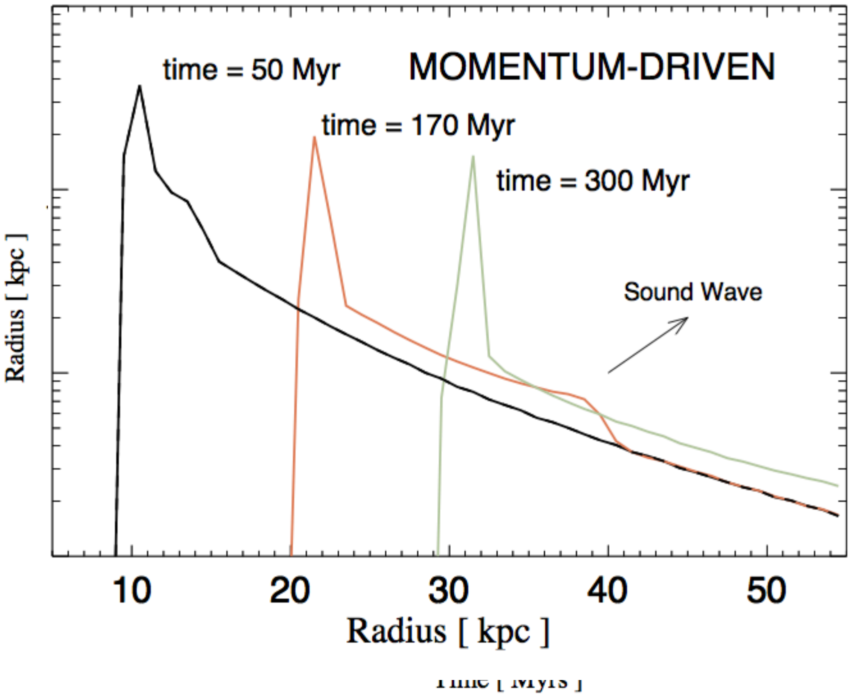
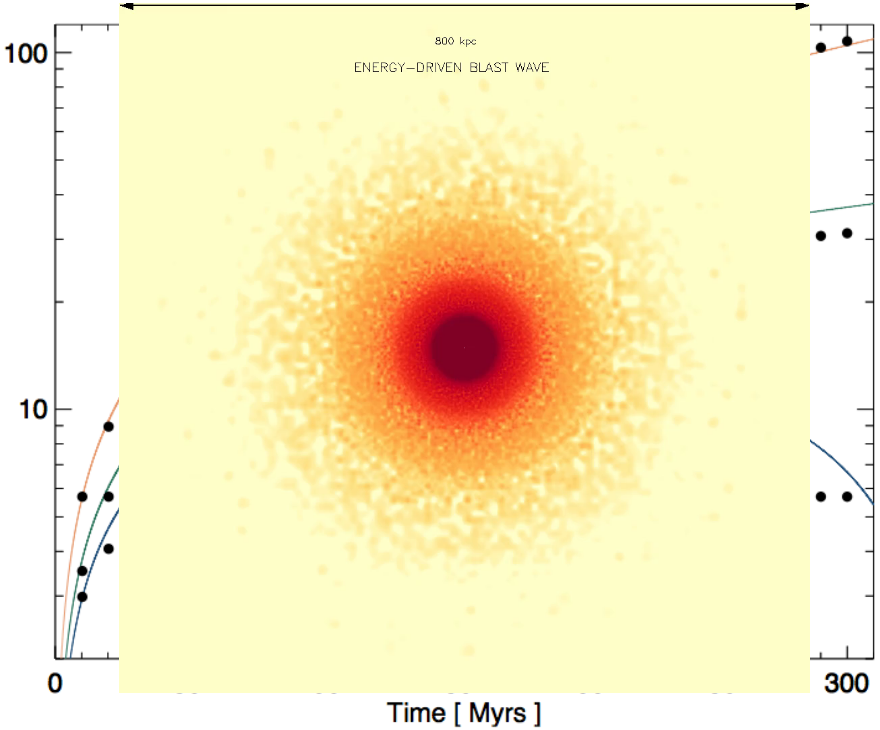
Costa, Sijacki & Haehnelt 2014

$$\frac{d\left[M_{\rm shell}(R)\dot{R}\right]}{dt} = 4\pi R^2 P - \frac{G M_{\rm shell}(R) M_{\rm tot}(< R)}{R^2}$$

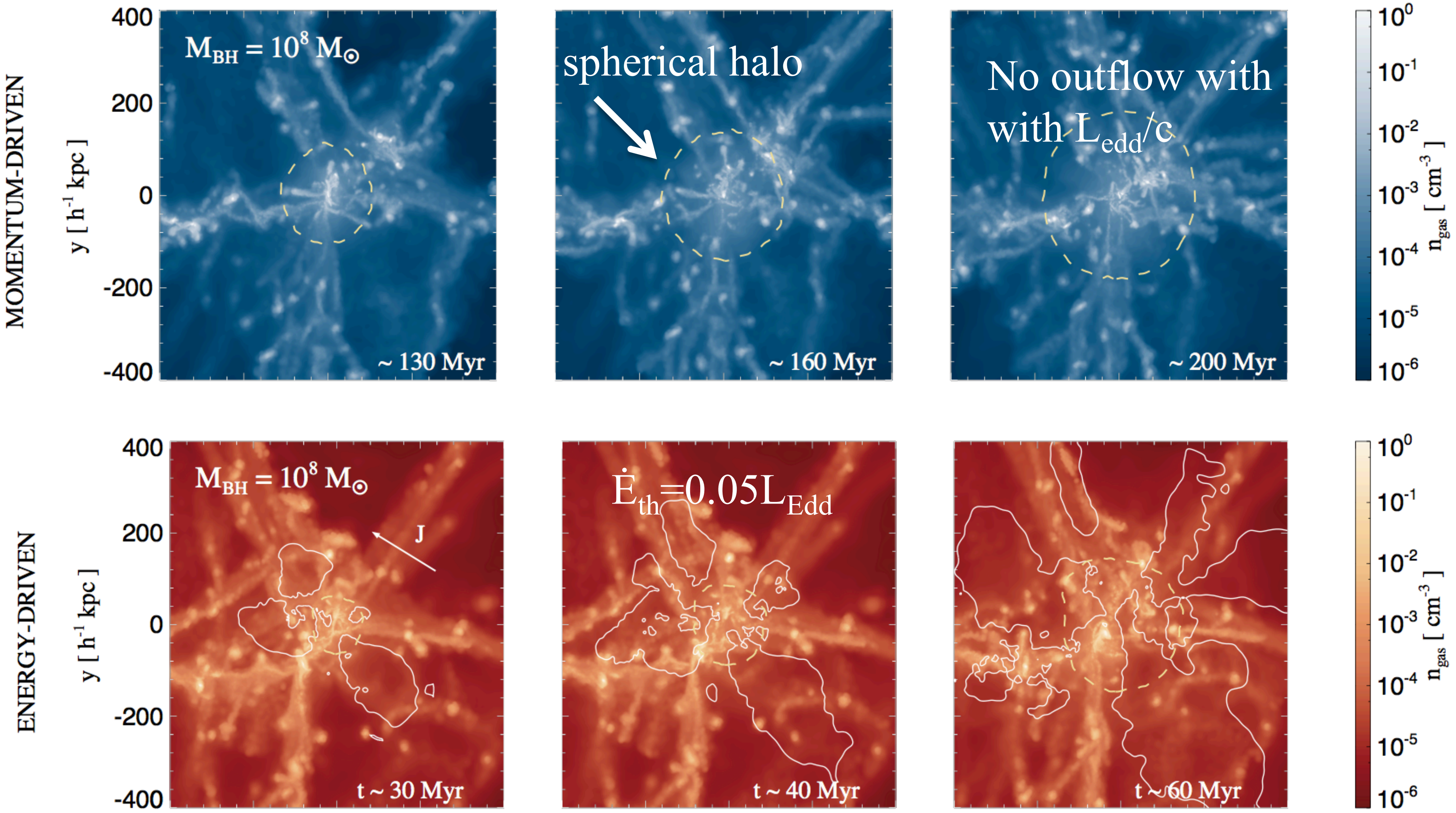




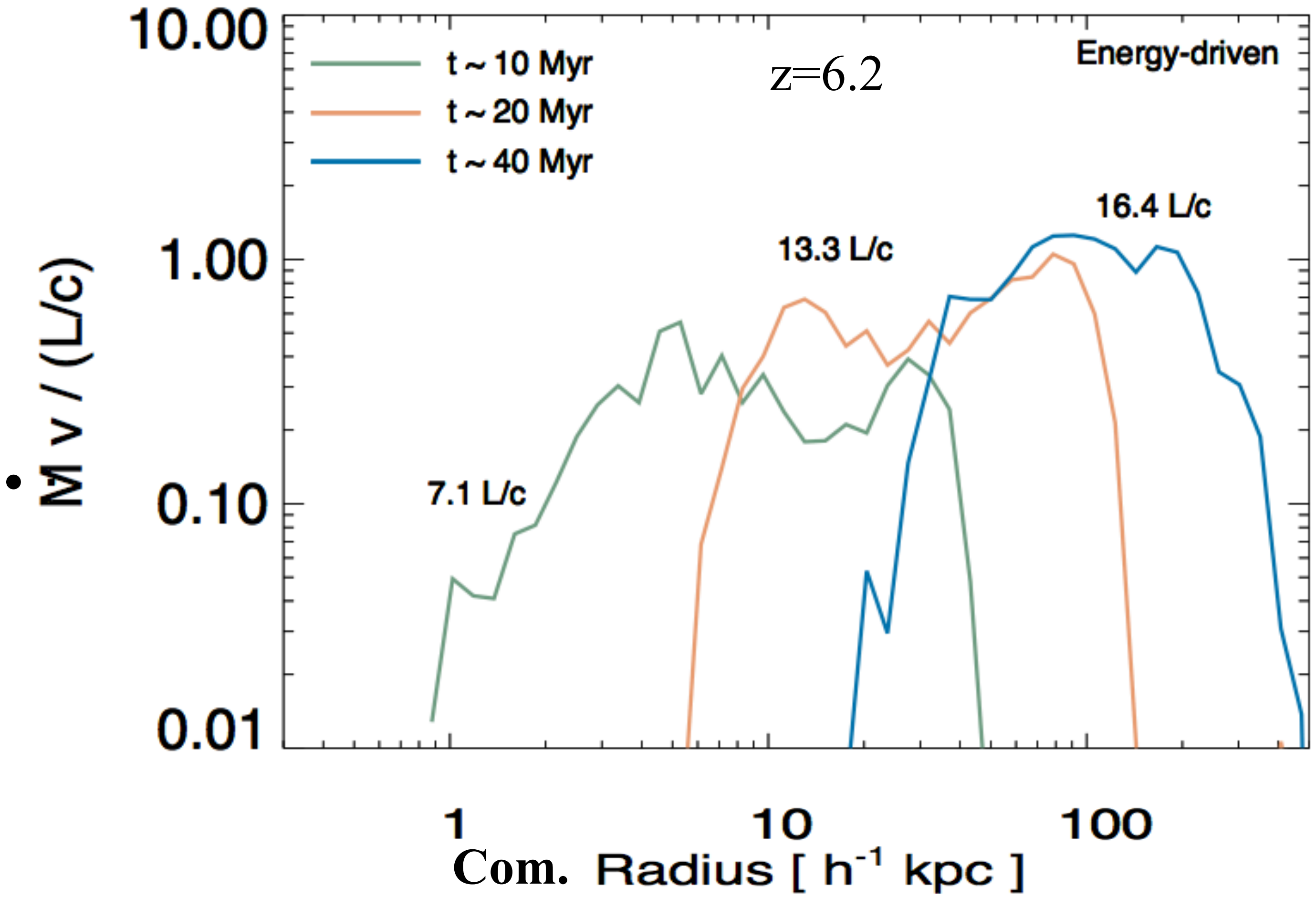
The hydrodynamical simulation reproduce the analytical solutions well

The differences are well understood and physical.

But this is a for a spherical halo with gas in hydrostatic equilibrium.

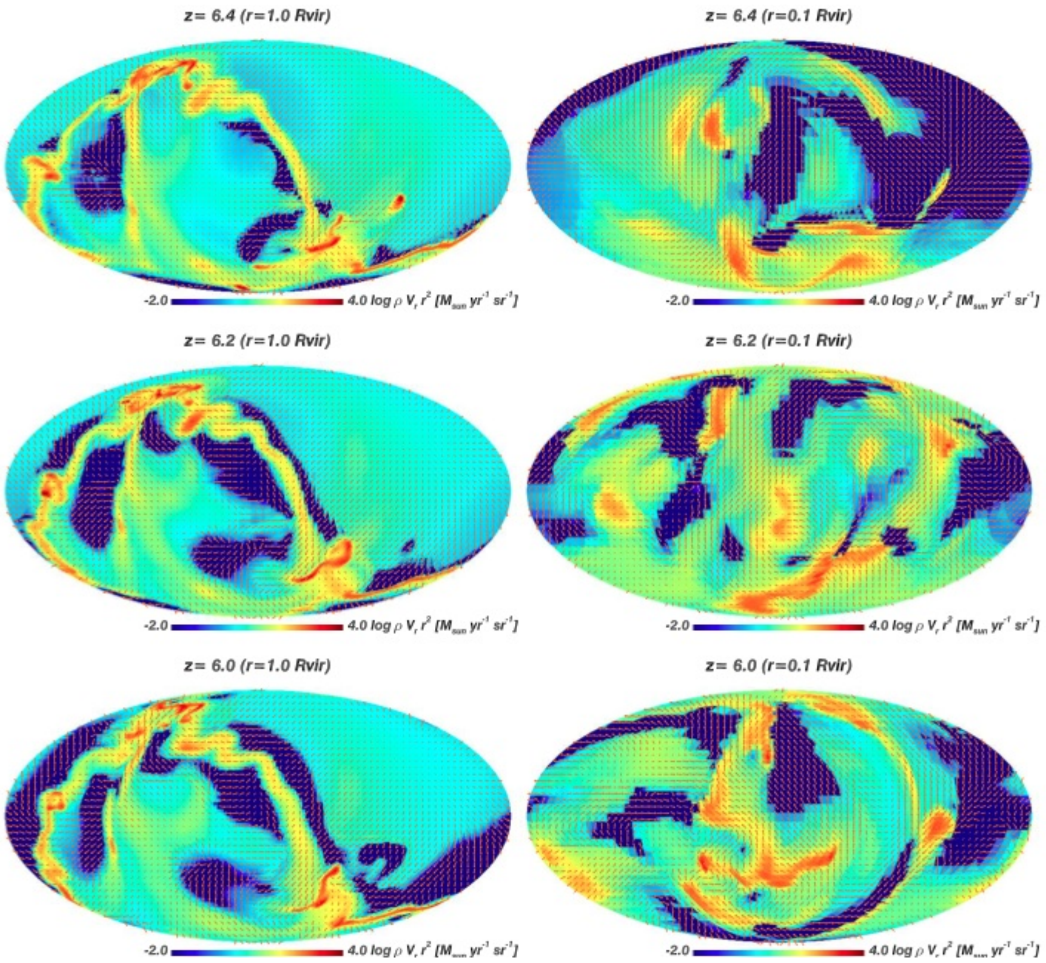


The infalling and cooling gas in cosmological simulation significantly reduces the effect of AGN feedback. The outflows become bipolar preferentially escaping into the voids and avoiding the filamentary inflows. A momentum flow of L_{edd}/c falls short by a factor ~10.



10-20L$_{Edd}$/c are required strongly favouring an energy-driven outflow on galactic scales. The amount of entrained cold gas is very sensitive to the cooling properties. In cosmological environment there are no thin shells.

at R_{vir} at $0.1R_{vir}$



angular distribution of mass inflow rates (in $M_\odot$ $yr^{-1}sr^{-1}$)

- The inflows cover a small solid angle. This makes AGN feedback inefficient.
- Thermal energy input of 5% L_{edd} does the job.
- The kinetic energy of the inner ultra-fast outflow has to be thermalized while the outflow velocity is still fast and the mass loading is still low.

Dubois et al 12

Can we observationally test this further?

Yes, with spatially resolved spectroscopy.

Massive quasar outflow detected at z=6.4

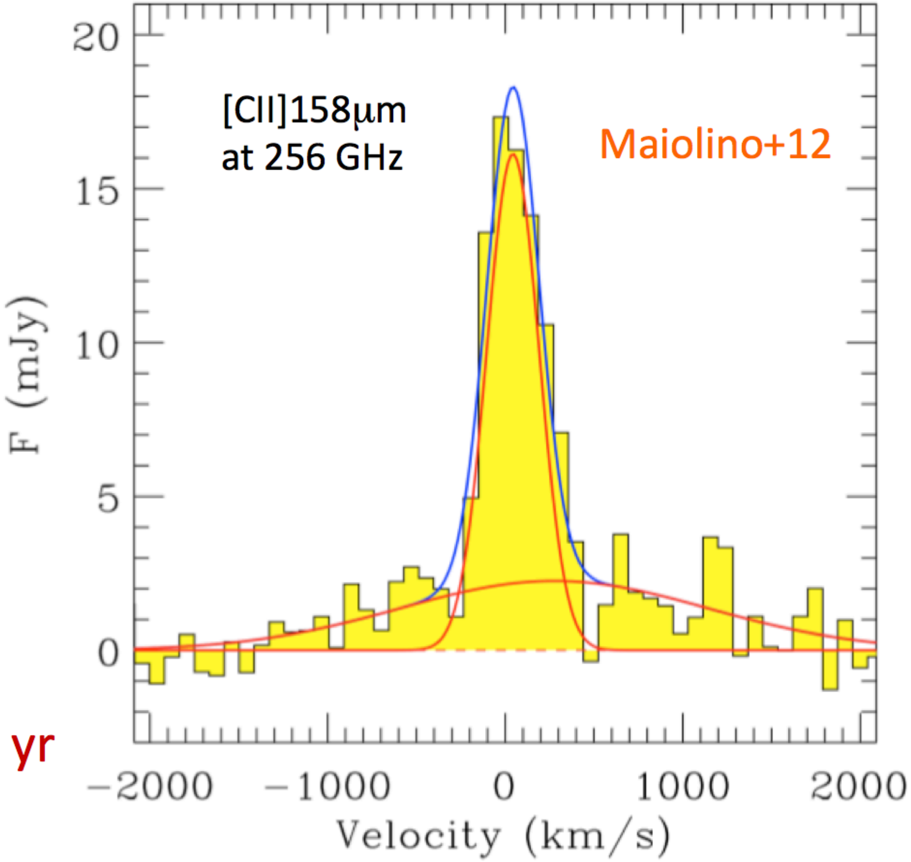
Broad wings
tracing outflow
with v~1300 km/s

Size: ~16 kpc !

$\dot{M}_{outflow} > 3500\ M_{\odot}/yr$

Depletion timescale < 10^7 yr

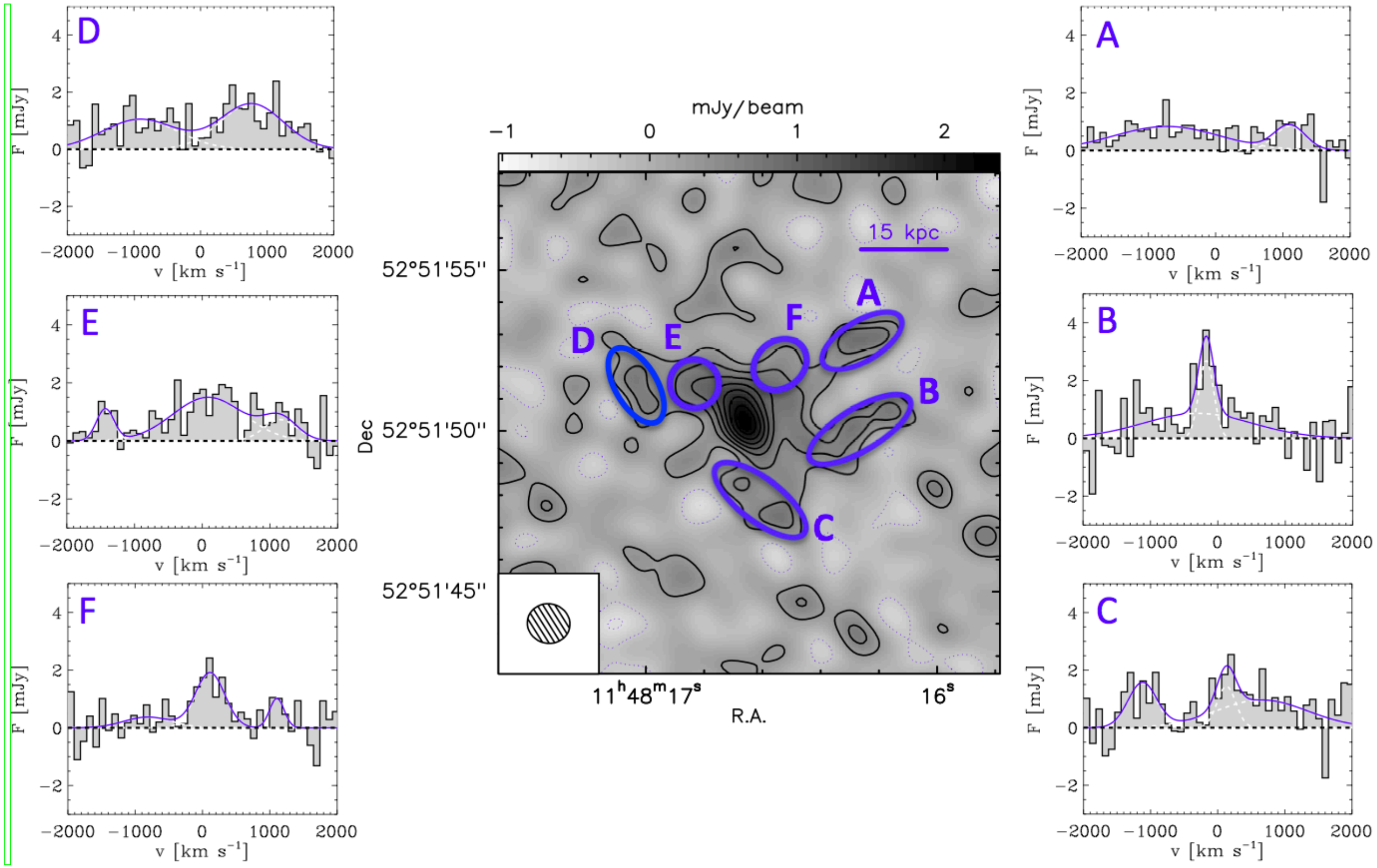
α-enhancement
in massive spheroids



**Efficient quenching of
star formation in the early Universe**

slide from Roberto Maiolino

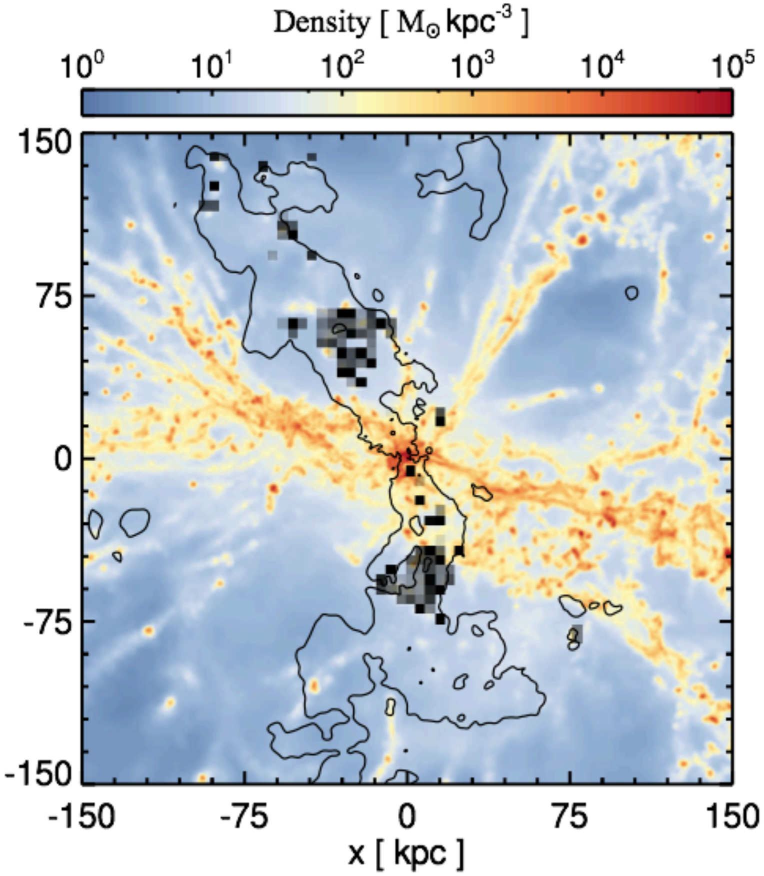
C. Cicone et al.: Very extended cold gas, star formation and outflows in the halo of a bright QSO at $z > 6$

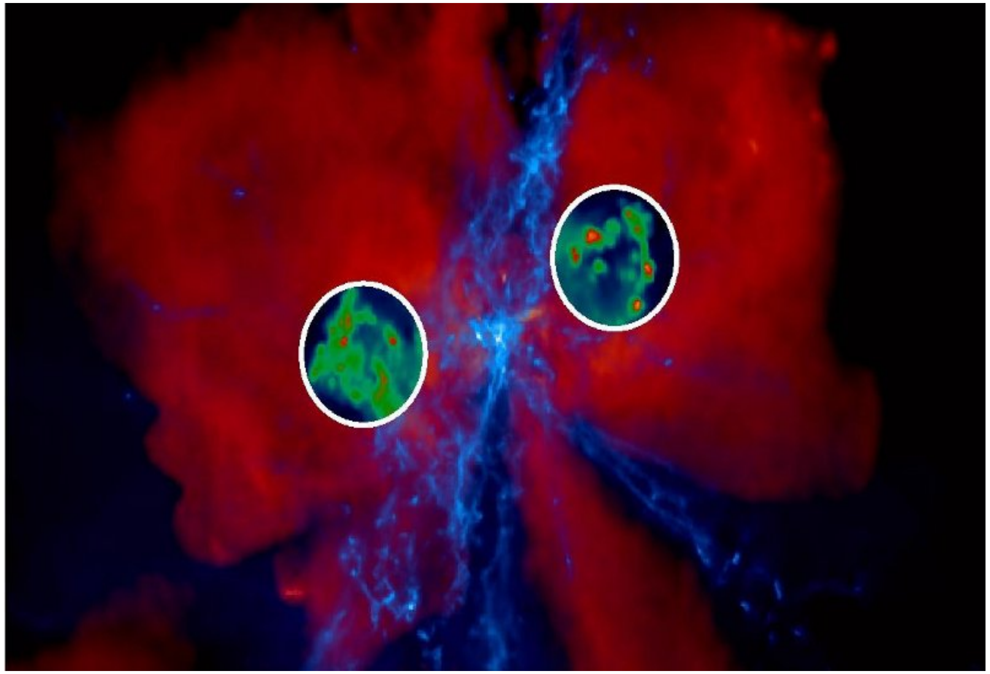


The fast cold outflow reaches a (projected) distance of 30kpc.

Fast cold gas in hot AGN outflows

Tiago Costa*, Debora Sijacki and Martin G. Haehnelt
Institute of Astronomy and Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK





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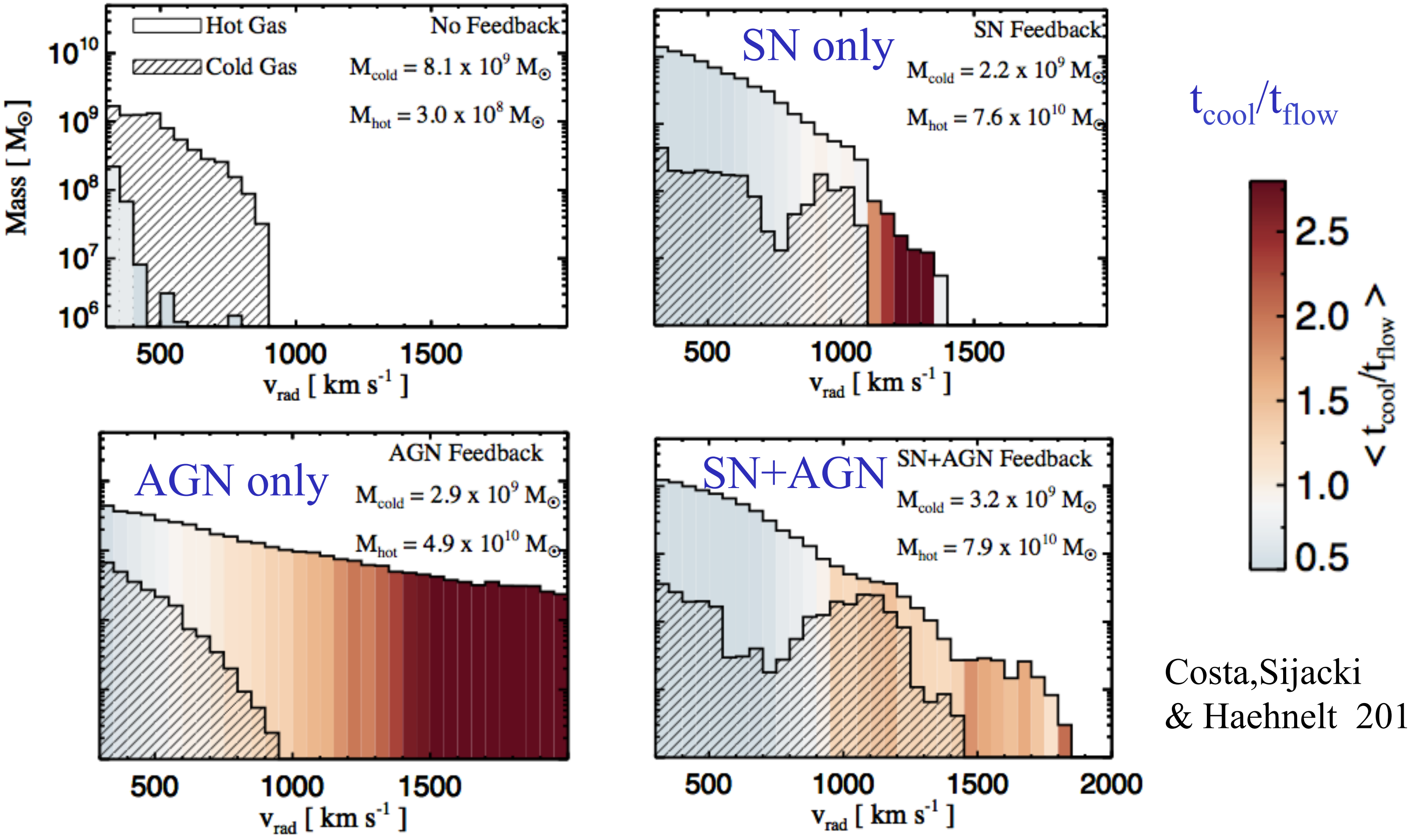
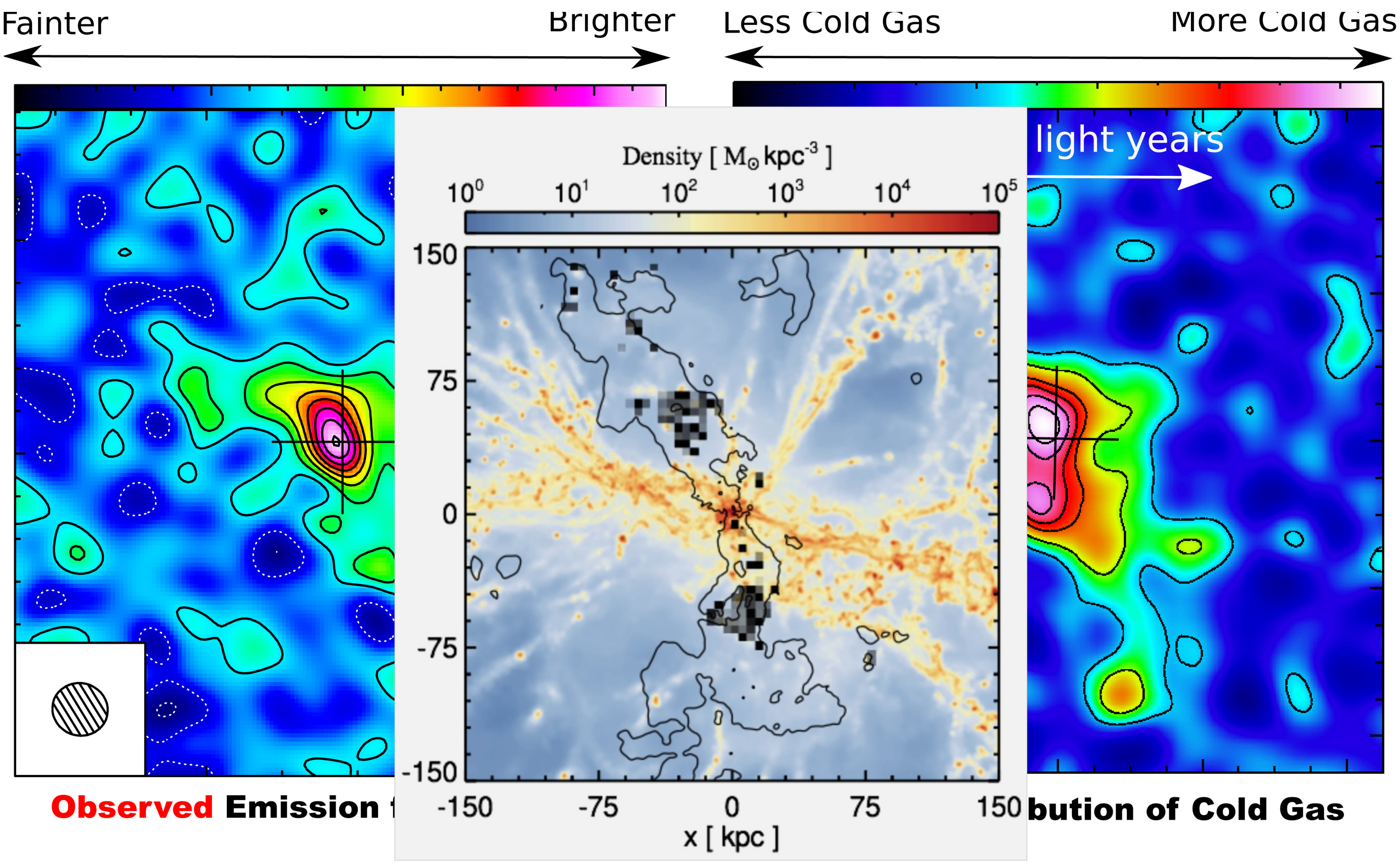
The role of SN vs AGN feedback



t_{cool}/t_{flow}

Costa,Sijacki
& Haehnelt 2014

Gas pre-enriched with metals by SN feedback is entrained in hot AGN outflow and cools to form cold outflow.

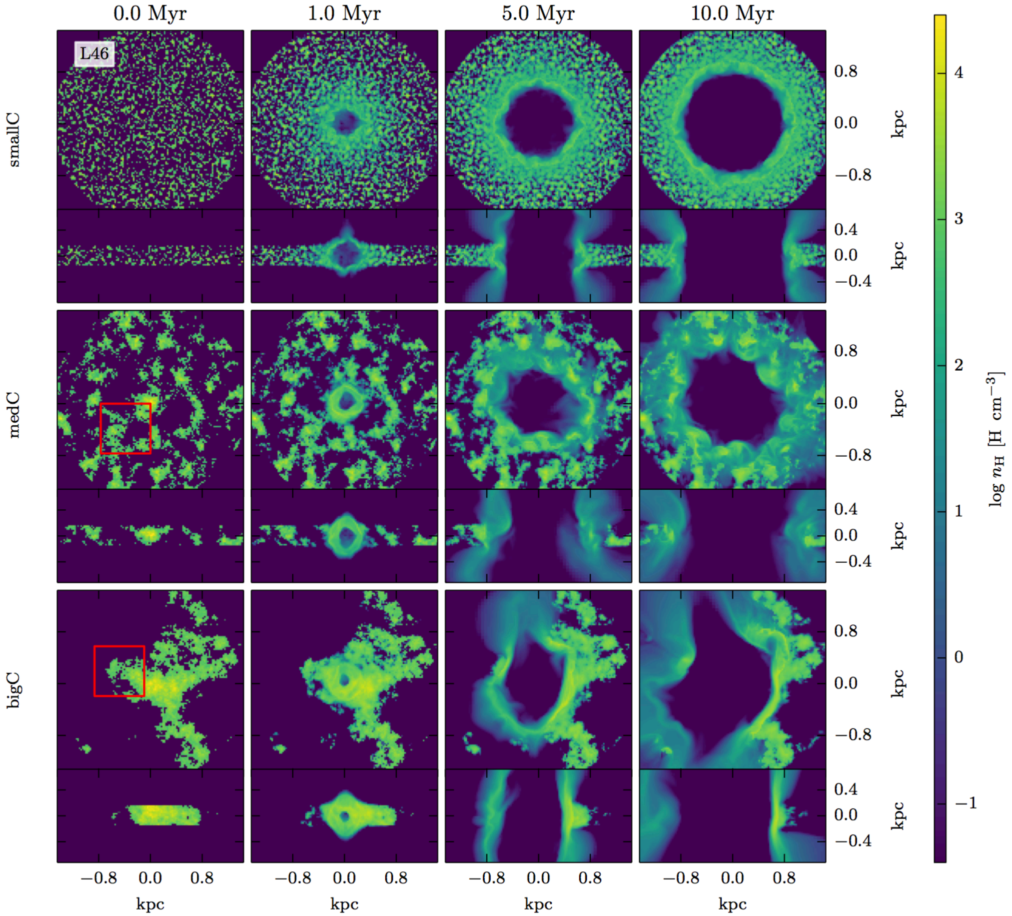


Cicone et al. 2015

Costa et al. 2015

Outflows Driven by Quasars in High-Redshift Galaxies with Radiation Hydrodynamics

Rebekka Bieri[1]∗, Yohan Dubois[1], Joakim Rosdahl[2], Alexander Wagner[3], Joseph Silk[1,4,5,6], and Gary A. Mamon[1]



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Summary

- feedback-regulated growth of supermassive black holes phenomonologically reasonably well understood
- ~10-20 L_{edd}/c required for efficient feedback
- AGN driven galactic winds appear to be energy driven hot winds with significant amounts of cooling out of entrained cold gas metal-enriched by SN feedback