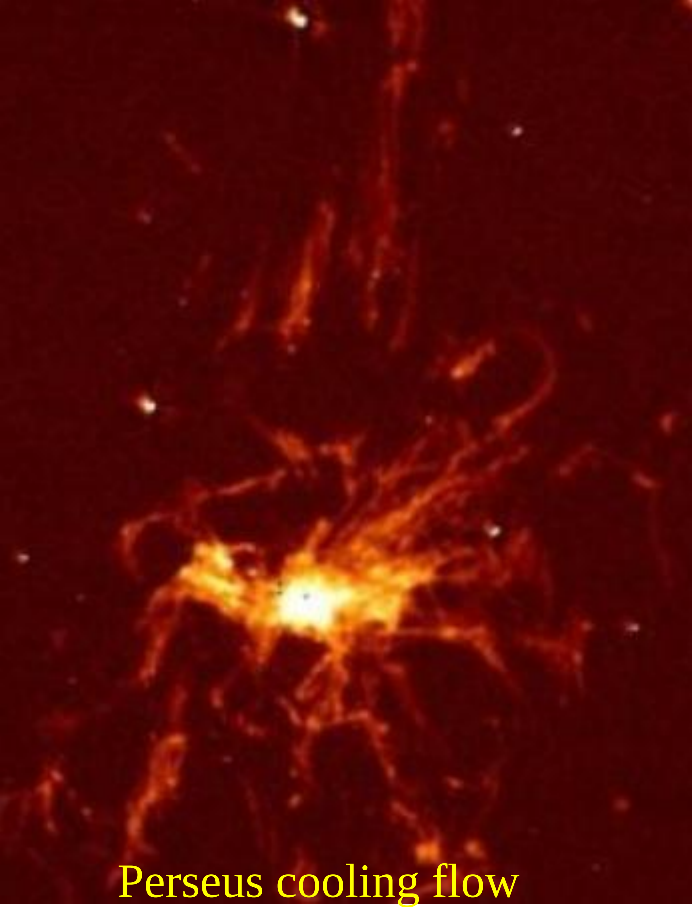
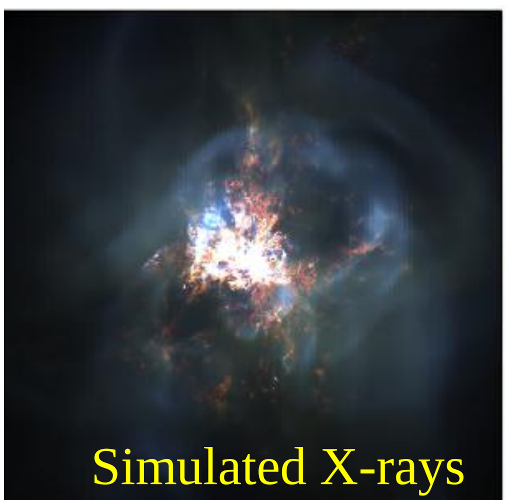
Françoise Combes
July 9, 2014

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

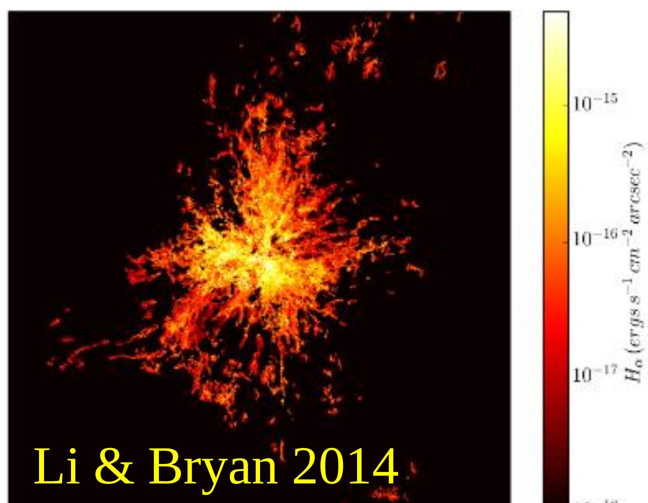
Models of AGN Feedback



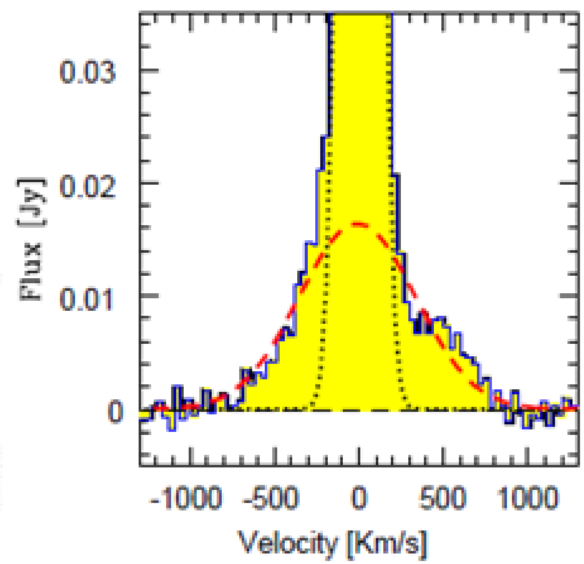
Perseus cooling flow



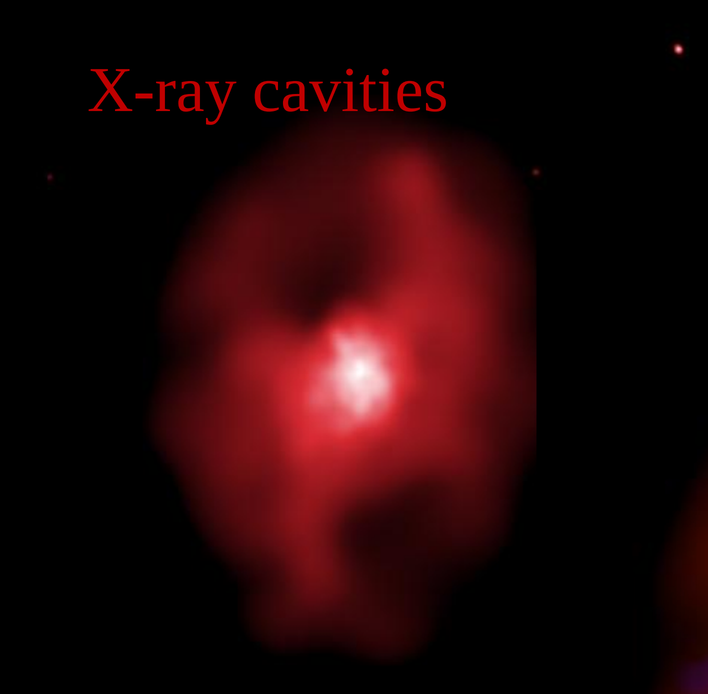
Simulated X-rays



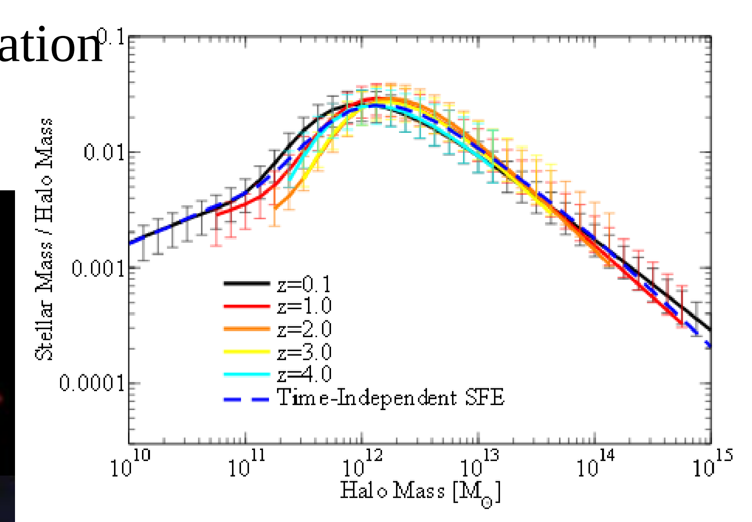
Li & Bryan 2014

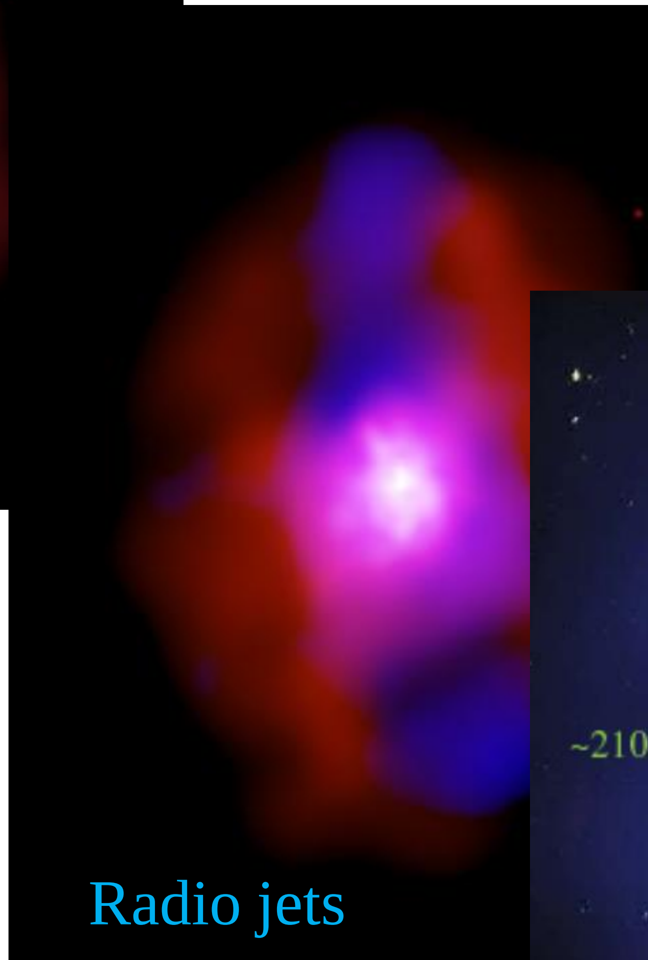


Mrk 231



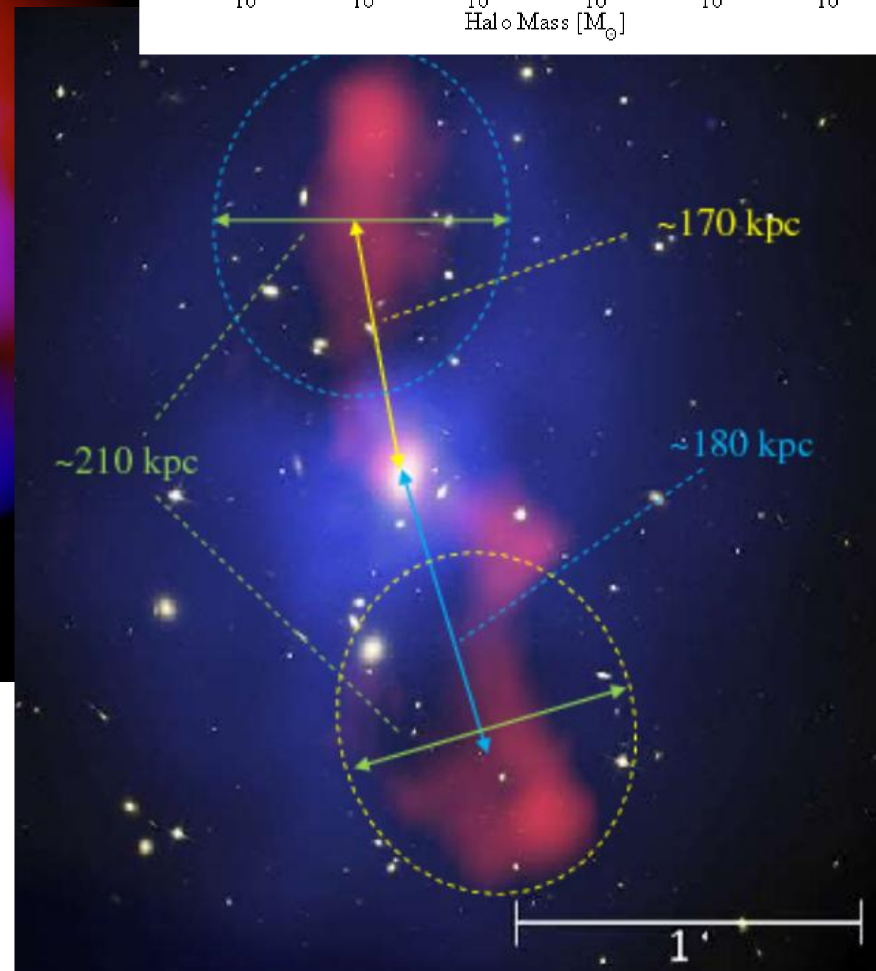
Inefficient star formation
Behroozi et al 2013



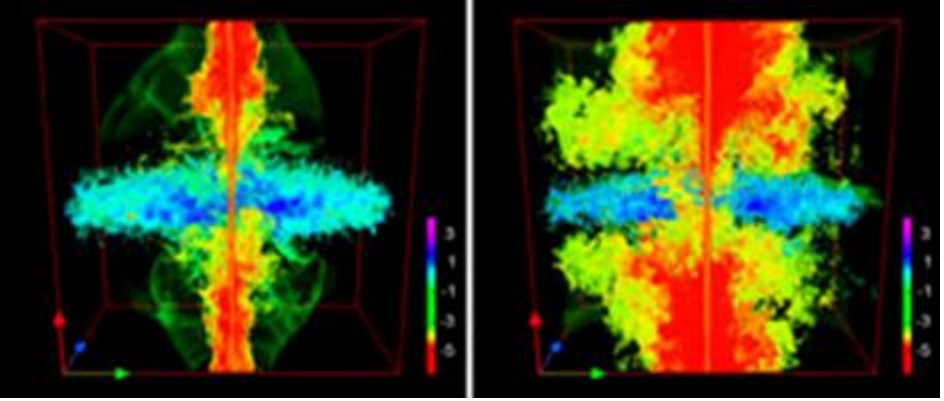


Cool-cores in
70-90% clusters
(Edge et al 1992)

The others are mergers, un-relaxed



MS0735.6+7421 cluster
(McNamara et al. 2009)



Gaibler et al 2012

Outline

M_{BH}=1-2 10^{-3} M_{gal} $E_{gal} \sim M_{gal}\,\sigma^2$

$E_{BH} \sim 0.1 M_{BH} c^2$ ➔ $E_{BH}/E_{gal} > 80$

1- AGN feedback moderating cooling flows

2- SN+AGN inflow/outflow in galaxies

3- Mechanisms -- Energetics

4- Modes of quenching

Two main modes for AGN feedback

Quasar mode: radiative or winds

When luminosity close to Eddington, young QSO, high z

$L_{Edd} = 4\pi G M_{BH} m_p c/\sigma_T$ ➔ $M_{BH} \sim f\, \sigma^4$, f gas fraction

Same consideration with radiation pressure on dust, with σ_d

$\sigma_d / \sigma_T \sim 1000$, limitation of Mbulge to 1000 M_{BH} ?

Radio mode, or kinetic mode, jets

When $L < 0.01\, L_{edd}$, low z, Massive galaxies, Radio E-gal

Not destructive: keeps a balance cooling-heating

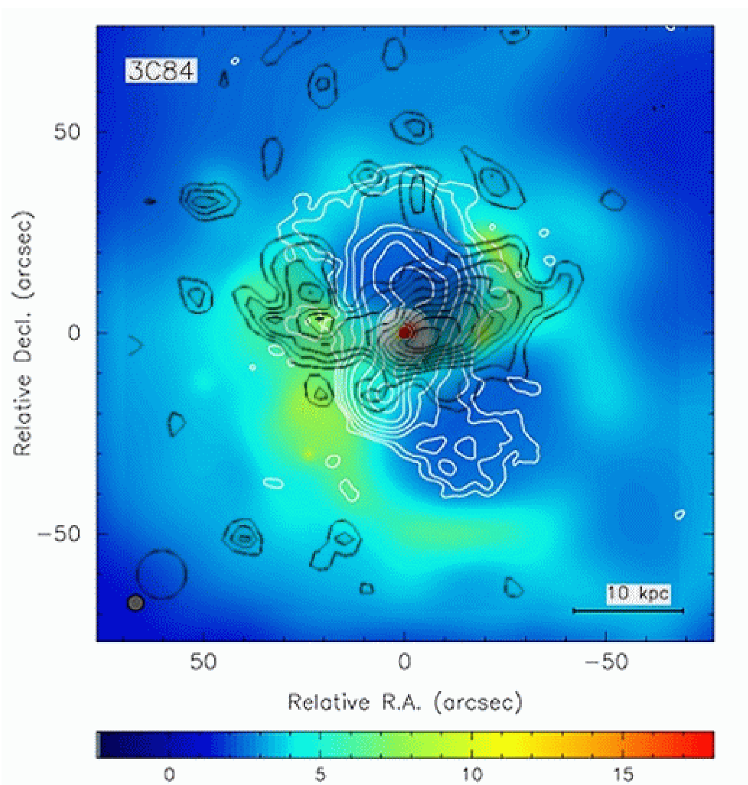
Radiatively inefficient flow ADAF

High frequency of cooling flows in clusters,

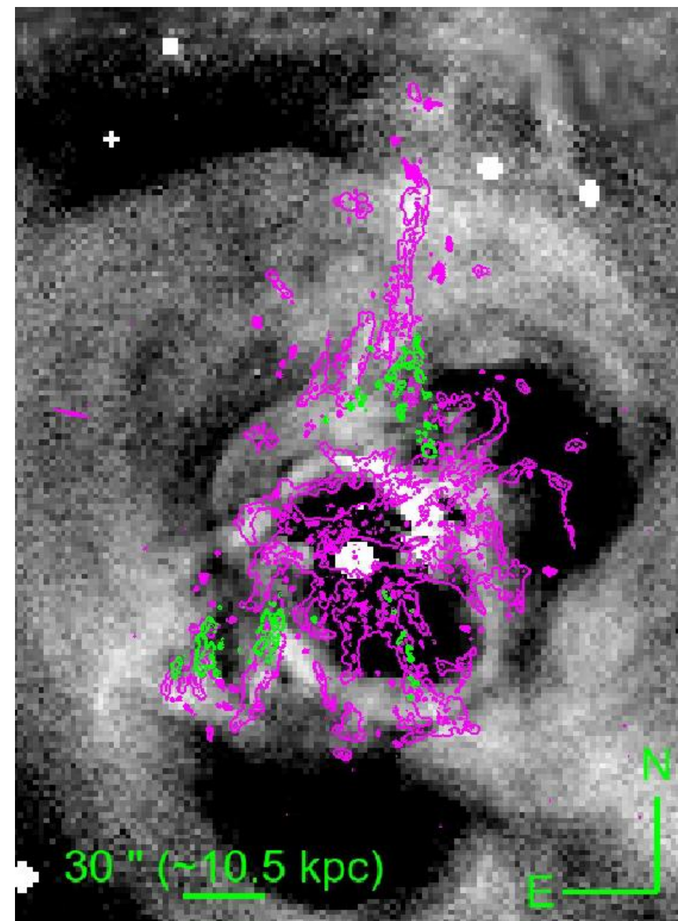
Low-luminosity AGN Seyferts..

1- Gas flow in cool core clusters

Star formation (green)
Canning et al 2014



Molecular Gas Salomé et al 2006



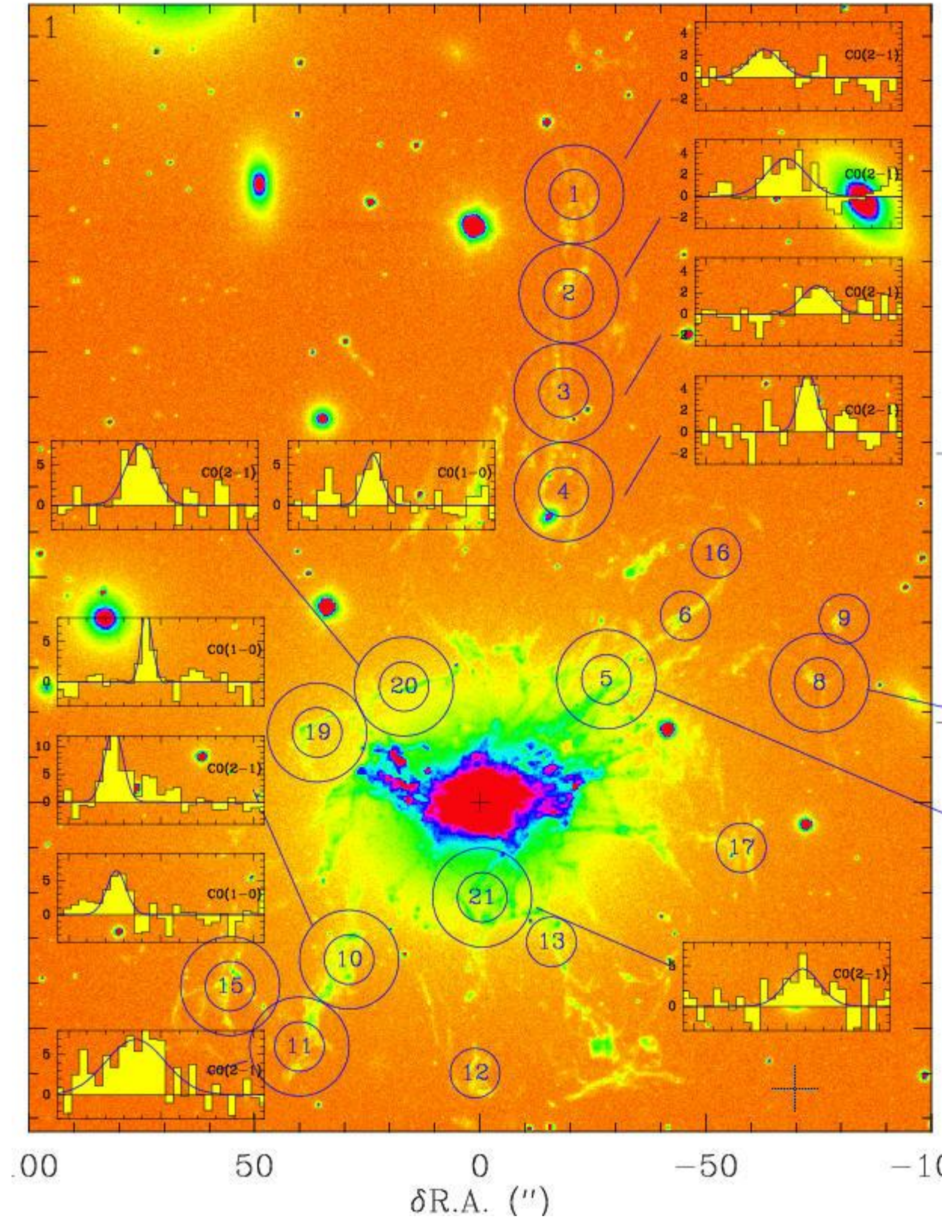
Cold gas in filaments

Inflow and outflow coexist

The molecular gas coming from previous cooling is dragged out by the AGN feedback

The bubbles create inhomogeneities and further cooling

The cooled gas fuels the AGN

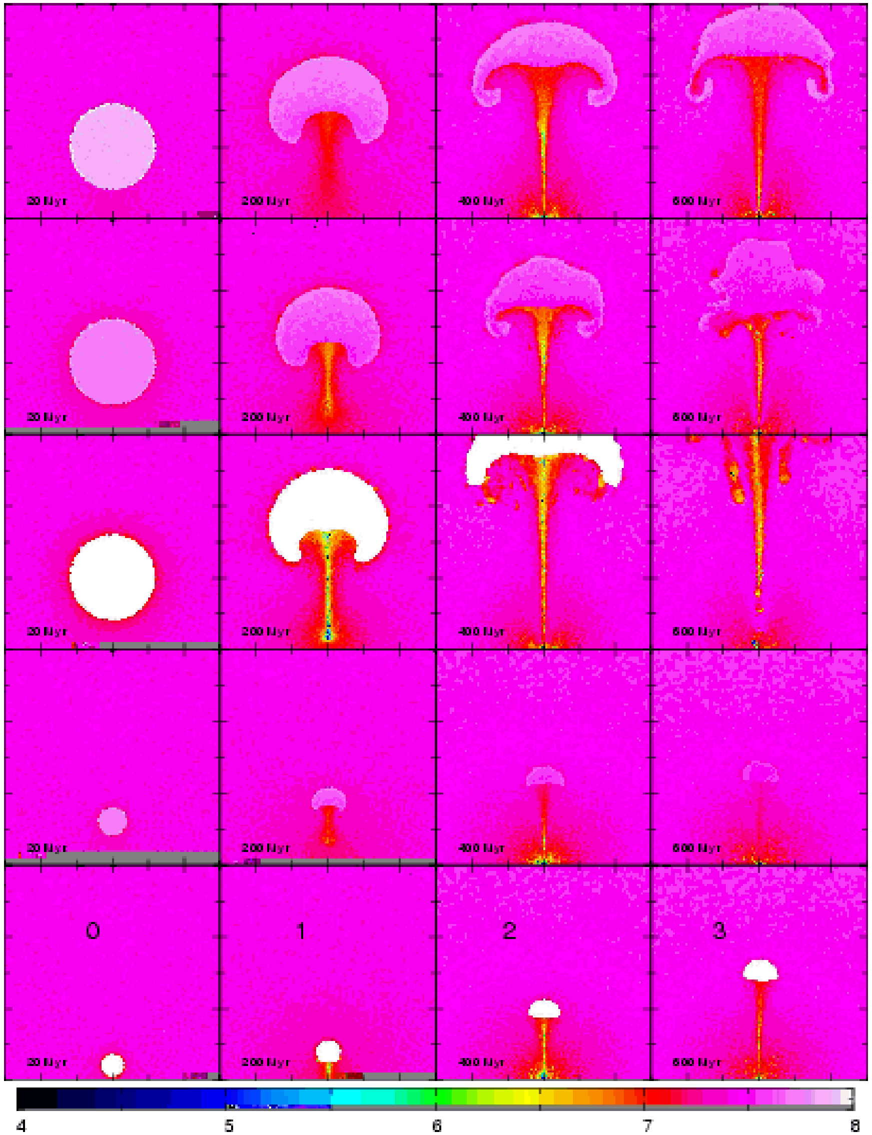


Velocity much lower than free-fall

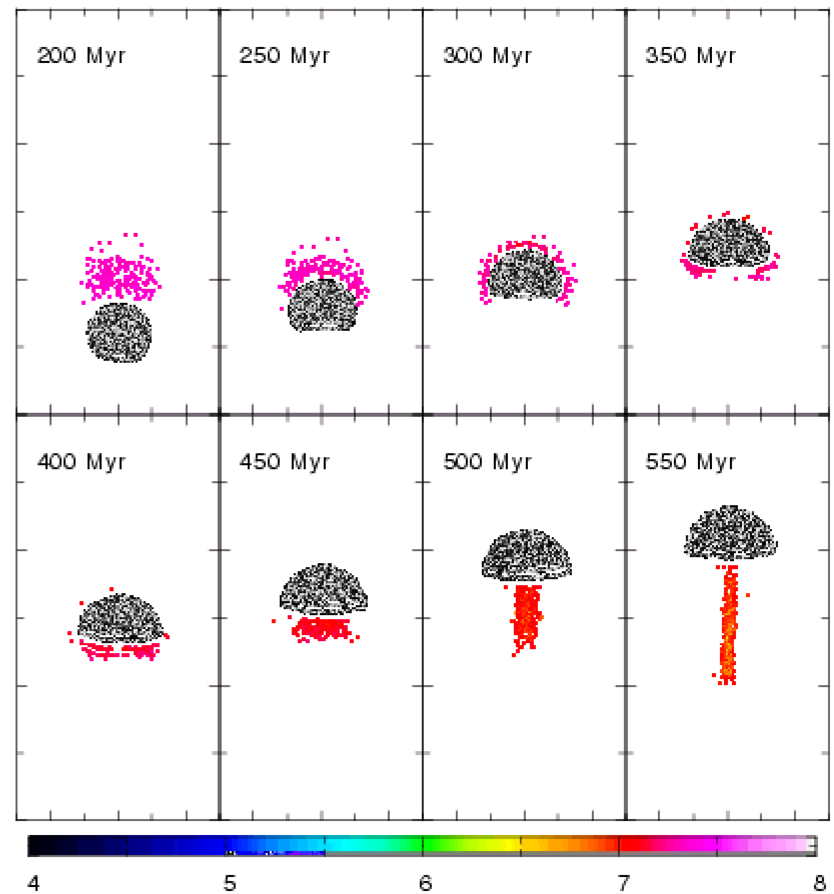
Salome et al 2008

Numerical simulations (Revaz, Combes, Salome 2007)

Buoyant bubbles, compression and cooling at the surfaces
+Cold gas dragged upwards



Log Temperature (150kpc)



Log density (25x50kpc)

Large variety of simulations

Brueggen et al 2007, Cattaneo & Teyssier 2007, Dubois et al 2010, Gaspari et al 2011, 2012 for clusters, or massive elliptical galaxies

Cooling rate ~ boosted Bondi rate, **but Cold gas accretion better**

Radiation pressure insufficient

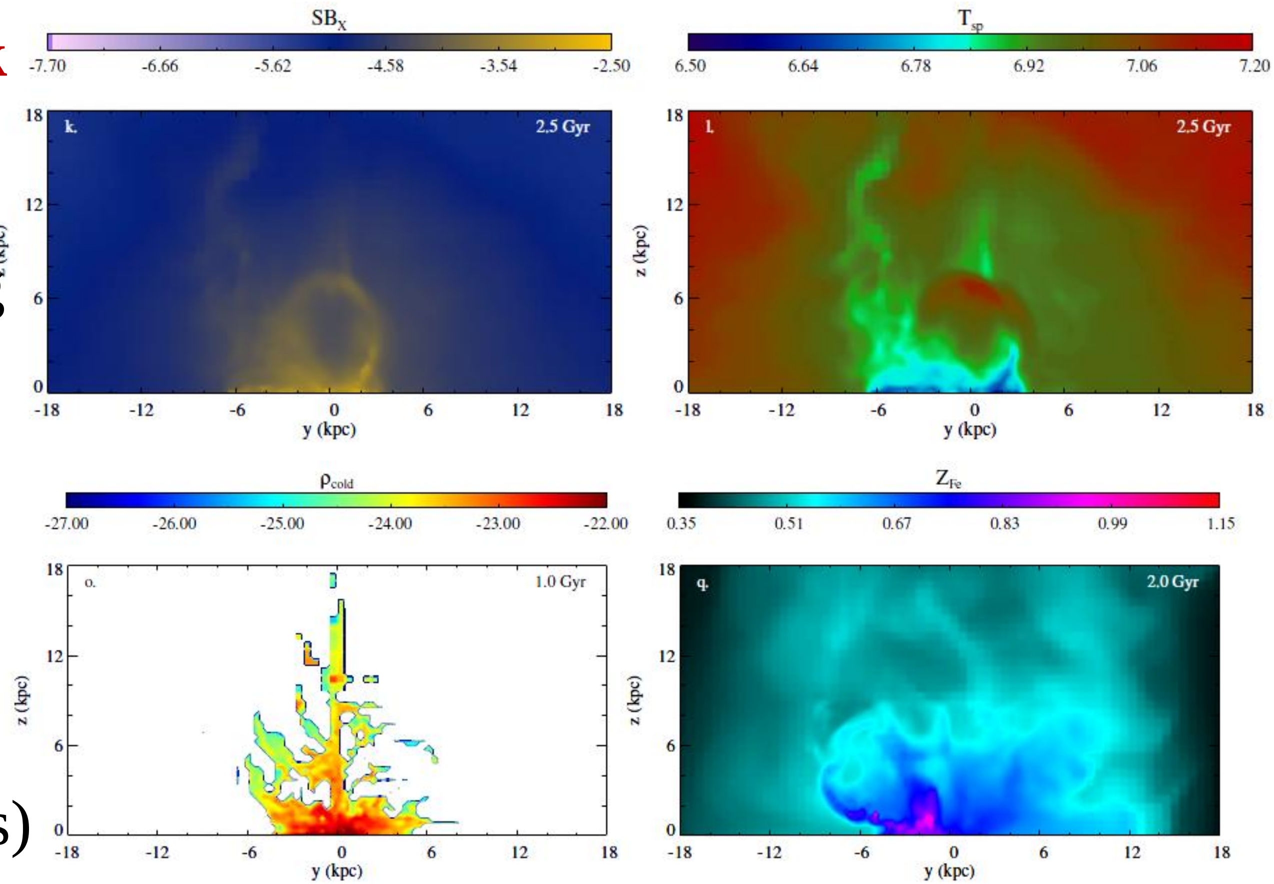
Mechanical feedback with jets or winds

Success in moderating the cooling, keeping the CC structure

Efficiency scaled to the structure scale

Gaspari et al 2012

3e-4 (E-gal) 5e-3 (clus)

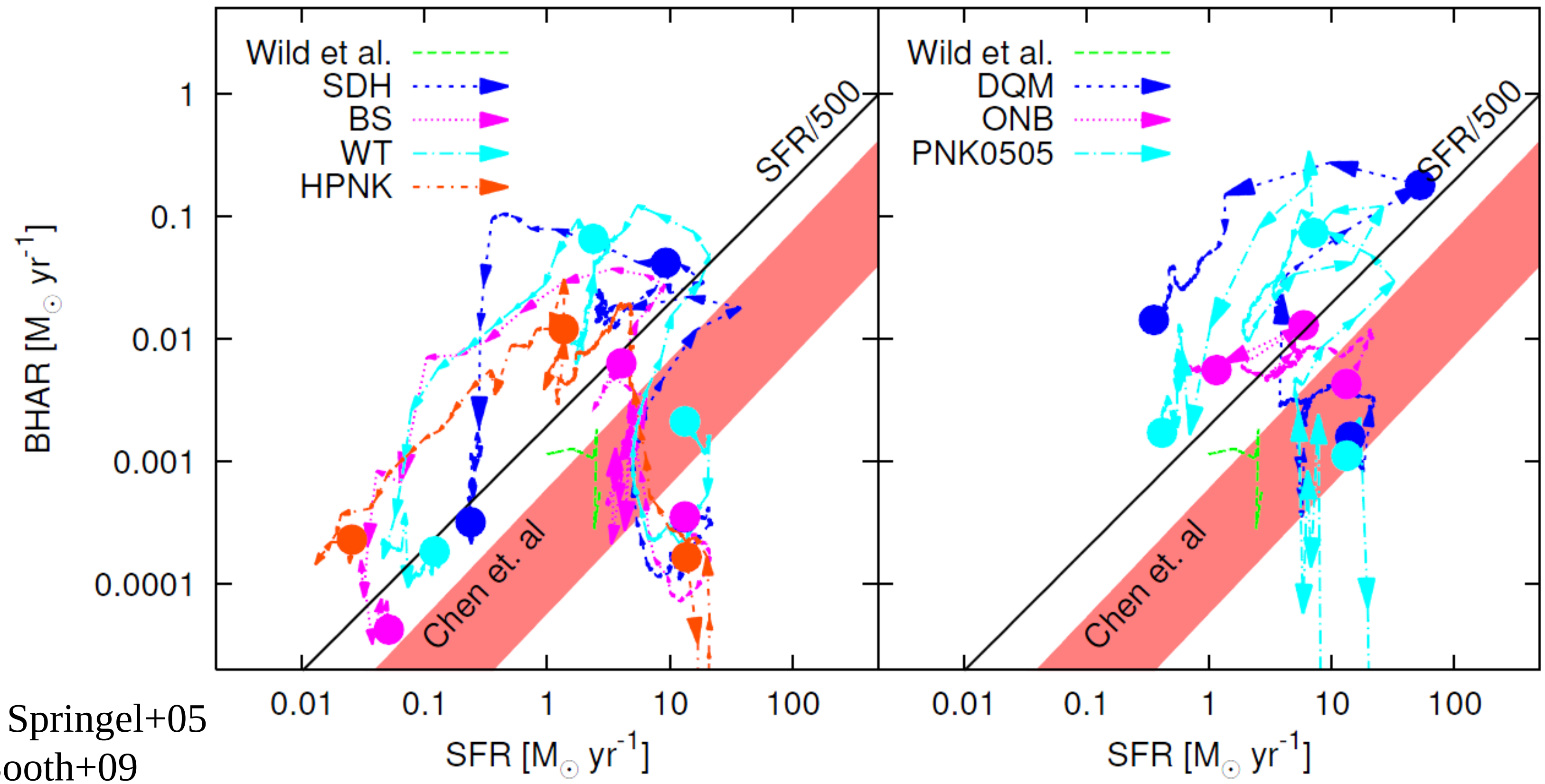


Comparison between models

During a merger, accreted gas fuels SFR and BHAR

BHAR delay, since SN-feedback too strong at the beginning (Wild et al 2010)

Bondi accretion | Other accretion models

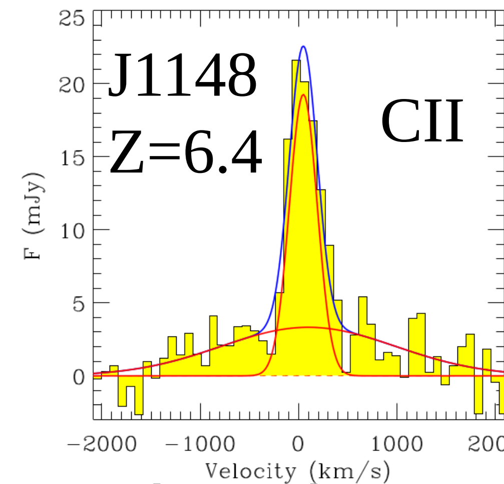


SDH Springel+05
BS Booth+09
WT Wurster+13
HPMK Hobbs+12

Thacker et al 2014

DQM Debuhr +11
ONB Okamoto+08
PNK Power+1

2- Molecular outflows



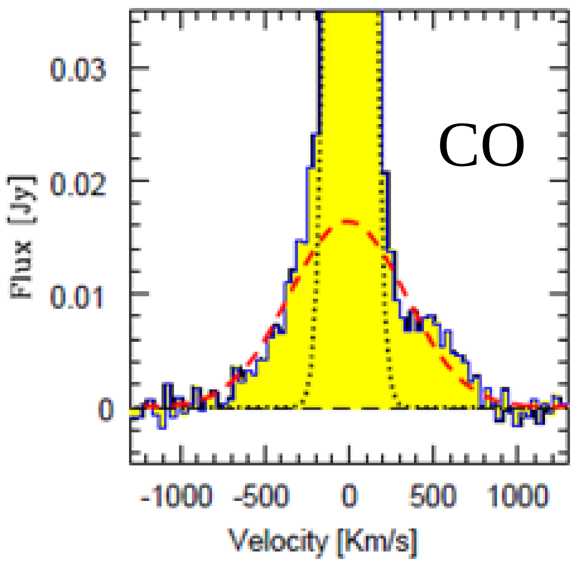
Maiolino et al 2012

Mrk 231

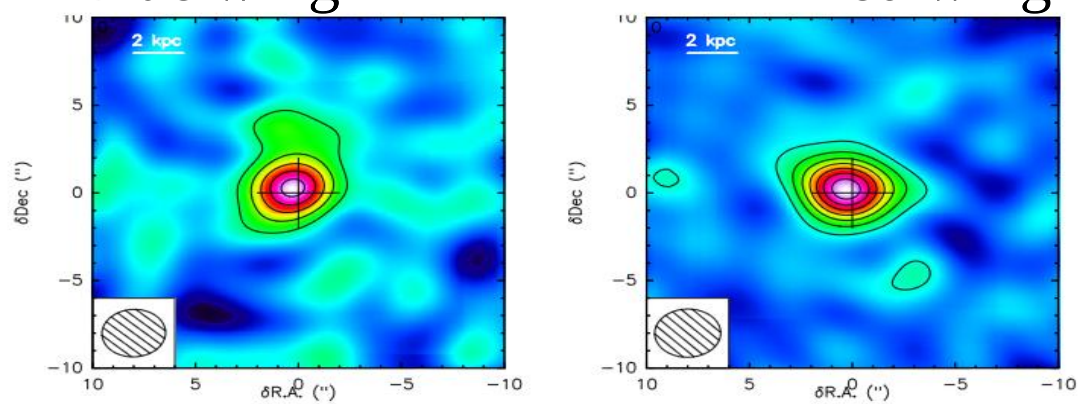
AGN and also nuclear
Starburst, 10^7-10^8Mo
Outflow 700Mo/yr

On kpc scales, ➔
affects the galaxy, quenches SF

IRAM *Ferruglio et al 2010*



Blue wing Red wing

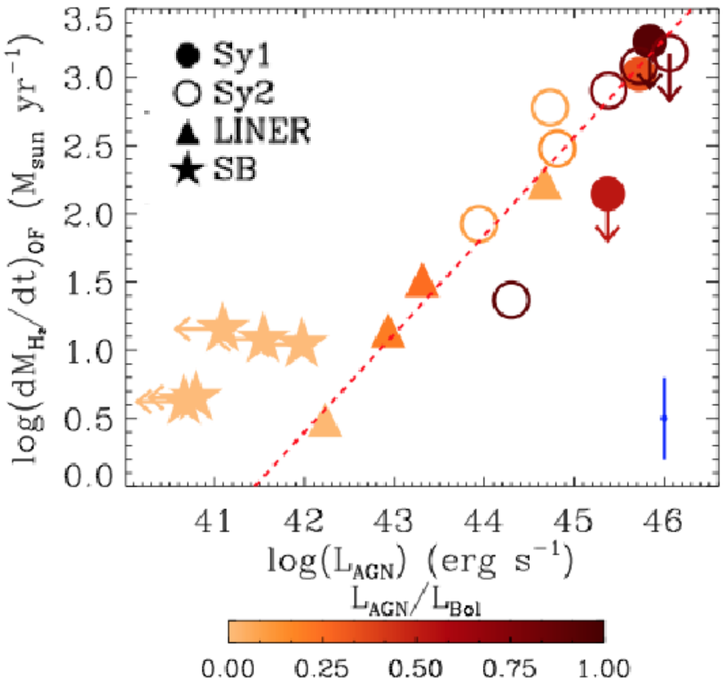


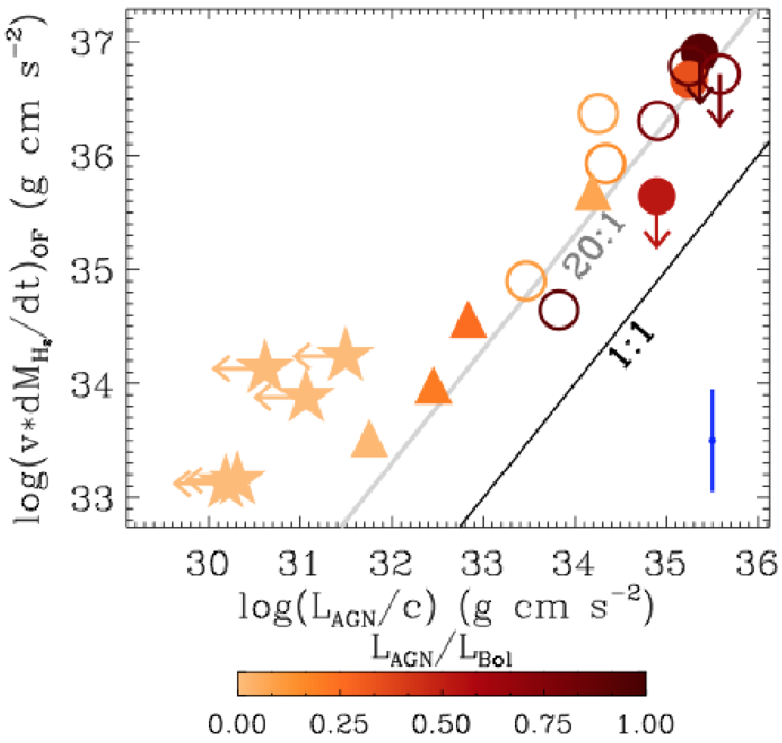
Cicone et al 2012

dM/dt = 3v M_{OF}/R_{OF} ~1000 Mo/yr, (5xSFR)
Kinetic power ~2 10^{44} erg/s ➔ AGN

High density, HCN, HCO+, *Aalto et al 2012*

Relations outflows with AGN





For AGN-hosts, the outflow rate Correlates with the AGN power

Cicone et al 2014

$dM/dt\ v \sim 20\ L_{AGN}/c$

Can be explained by **energy-driven outflows** (Zubovas & King 2012)

3-Why molecular outflows?

Outflowing gas is accelerated by a shock, and heated to 10^6-10^7K

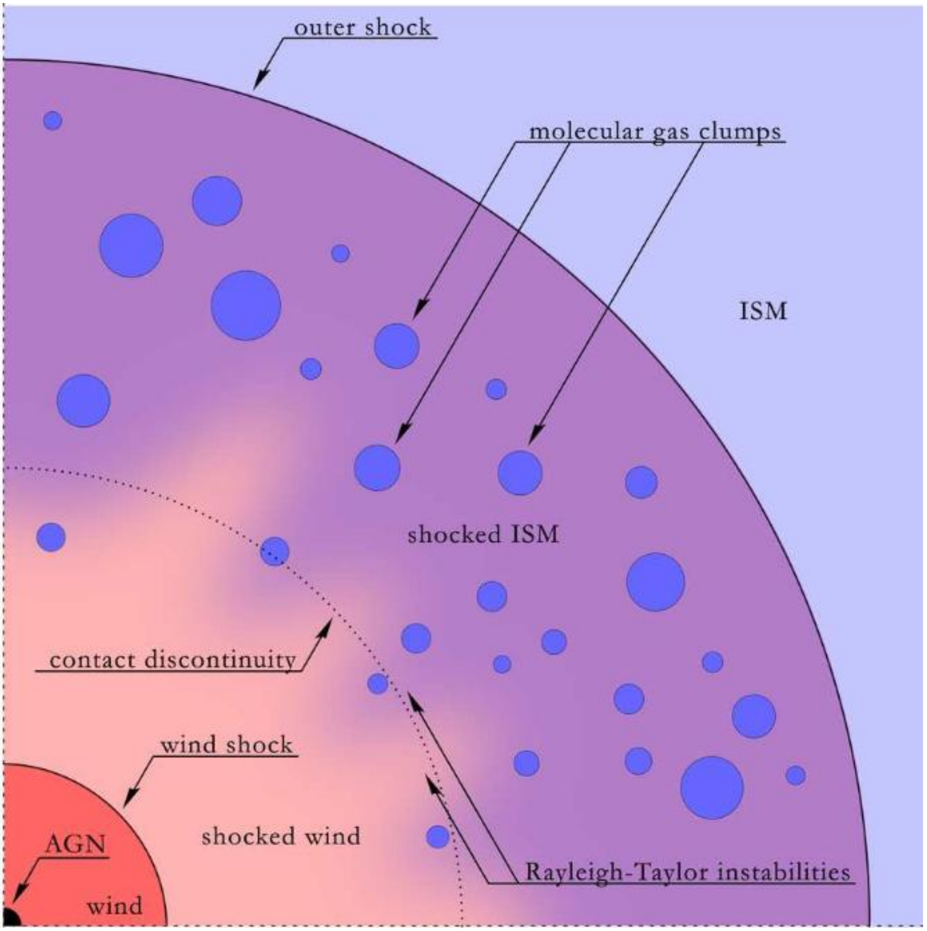
Molecules should be dissociated at such temperatures
Even if cold clumps are carried out in the flow➔ shock signature?

Radiative cooling is quick enough to reform molecules in a large fraction of the outflowing material (Zubovas & King 2014)

With V~1000km/s, and dM/dt ~1000 Mo/yr, efficient cooling produces multi-phase media, with triggered star formation

AGN winds more than SF outflows?

Zubovas & King 2014



Cooling efficient (free-free, metals)
Flow unstable, if R=Prad/Pgas<0.5 (Krolik 1981), and
$R \sim 0.07\ M_{BH}/M_{crit}\ f_{EDD} \sim 0.07$
➔Multiphase, with RT instabilities

Time-scale for cooling << 1Myr
At kpc scales, ➔SF induced

The SF results in a Luminosity
Comparable to L_{AGN} 100Mo/yr!

This means that SB or AGN outflows are difficult to disentangle
All could be due to AGN

Energy-conserving outflows?

If the cooling is very efficient, ➔ momentum-conserving outflow

But for very fast winds > 10 000km/s, radiative losses are slow
➔energy-conserving flow (Faucher-Giguère & Quataert 2012)

In some cases, even slow winds v_{in} ~1000km/s driven by radiation pressure on dust, could be energy-conserving
Push by the hot post-shock gas, boost the momentum
Vs of the swept-up material

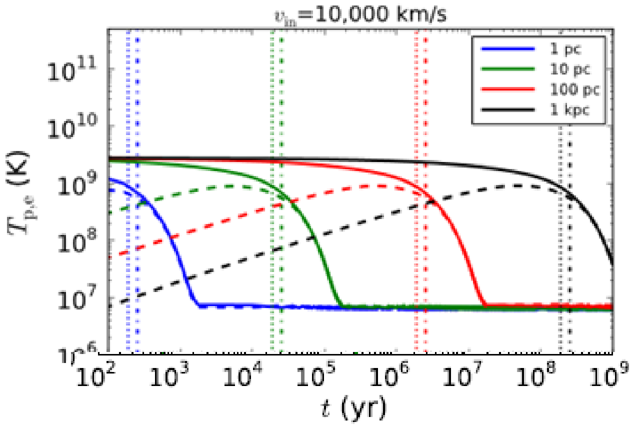
Boost of v_{in} /2 Vs ~50! Explains why momentum flux >> L_{AGN}/c

// Adiabatic phase, or Sedov-Taylor phase in SN remnant

Slow cooling --High momentum fluxes

T behind R_{SW}

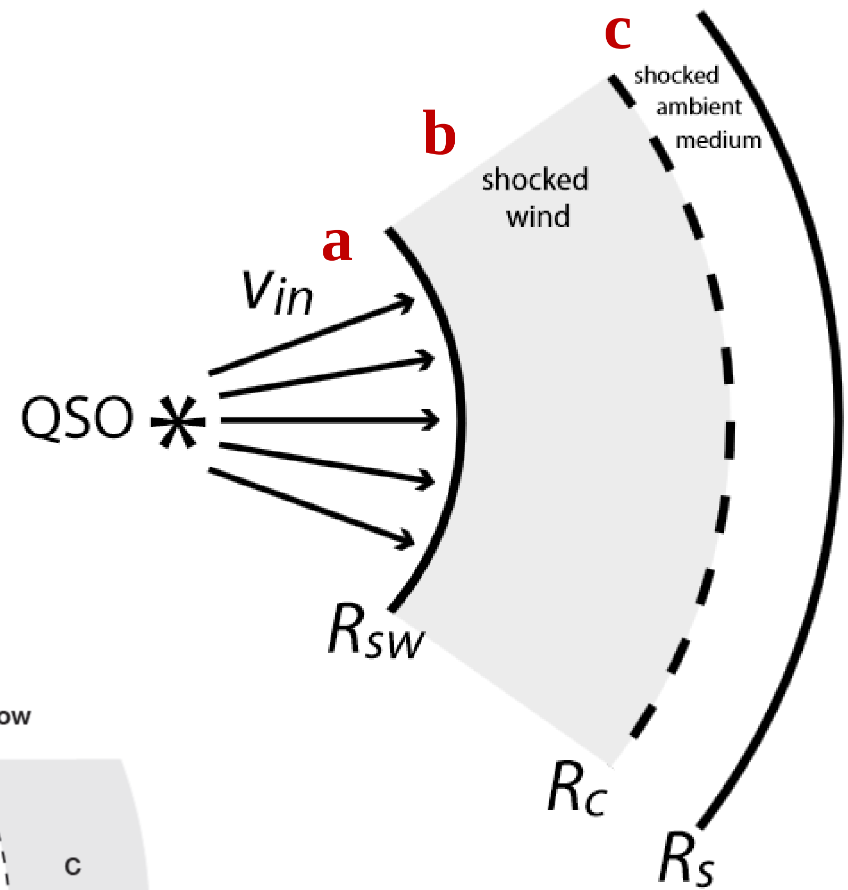
Faucher-Giguère & Quataert 2012



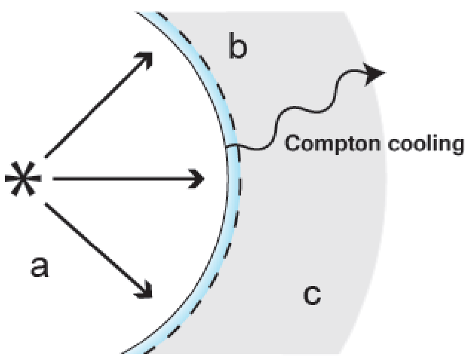
Full: protons

Dash: electrons

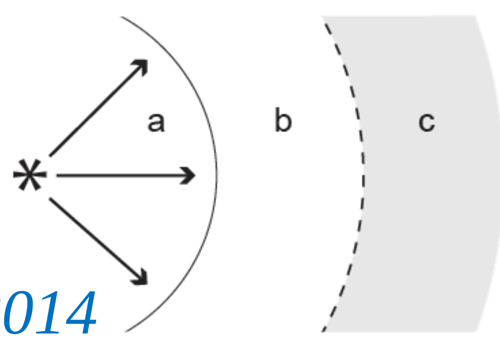
T_{Comp}= 2 10^7K



Momentum-driven outflow

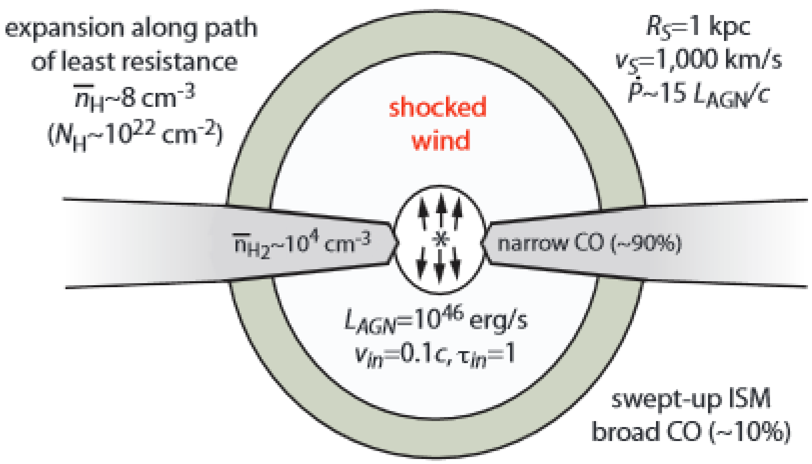


Energy-driven outflow



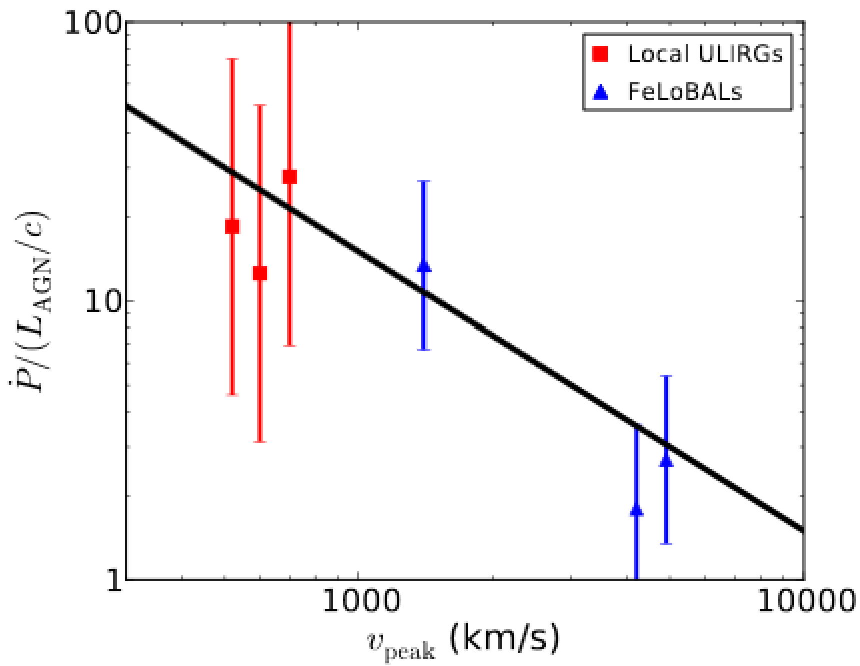
Costa, Sijacki, Haehnelt, 2014

Outflow solutions



Momentum boost

$$\dot{M}_{\rm s} v_{\rm s}^2 \approx \frac{1}{2} \dot{M}_{\rm in} v_{\rm in}^2,$$

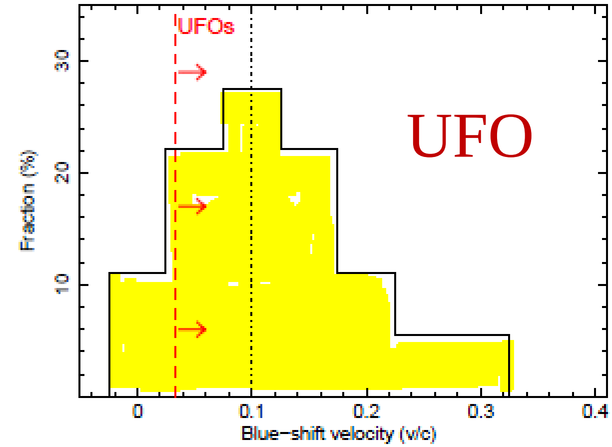


Represent the typical case of Mrk231, face-on, R~3kpc V~1000km/s

Momentum flux =15 L_{AGN}/c

Faucher-Giguère & Quataert 2012

Winds launch

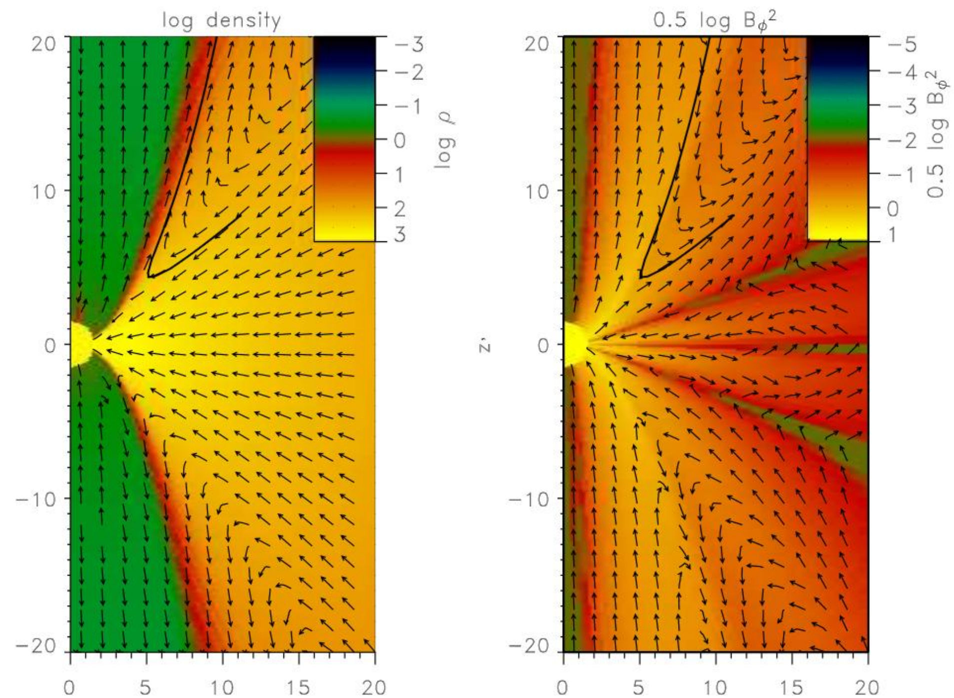


From accretion disks, as seen in UV abs lines
BAL quasars, or from X-rays coronae
Thermal heating (Compton) makes the gas reach Vesc
Radiation on electrons (> Eddington)

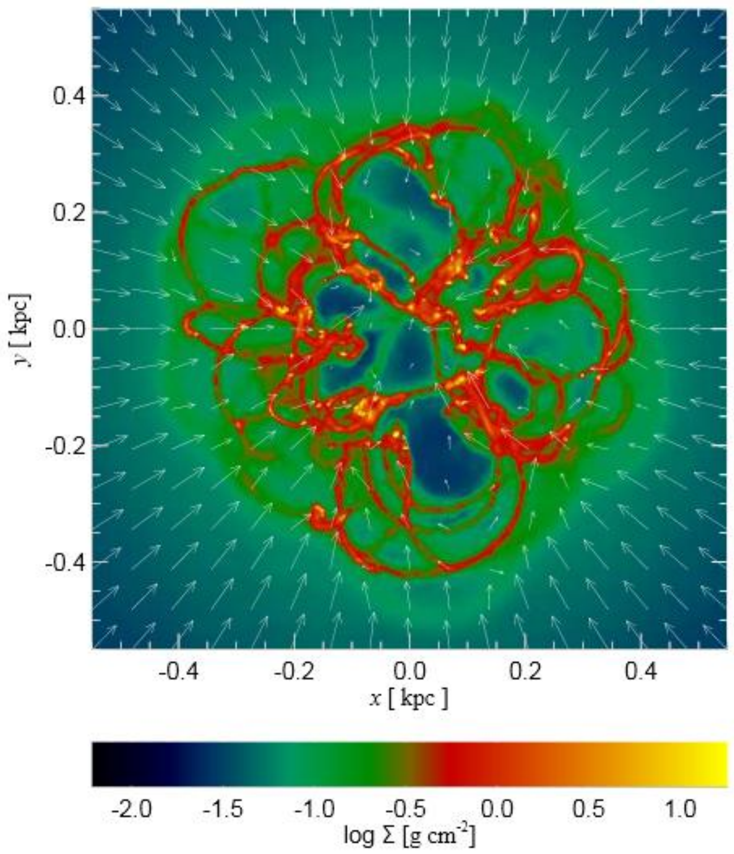
Tombesi 10, 14

Or even radiation pressure on dust

Or magnetic driving
(Proga 2003, 2005)
More realistically,
all driving mechanisms together!



Quasar mode:Two-phase simulations

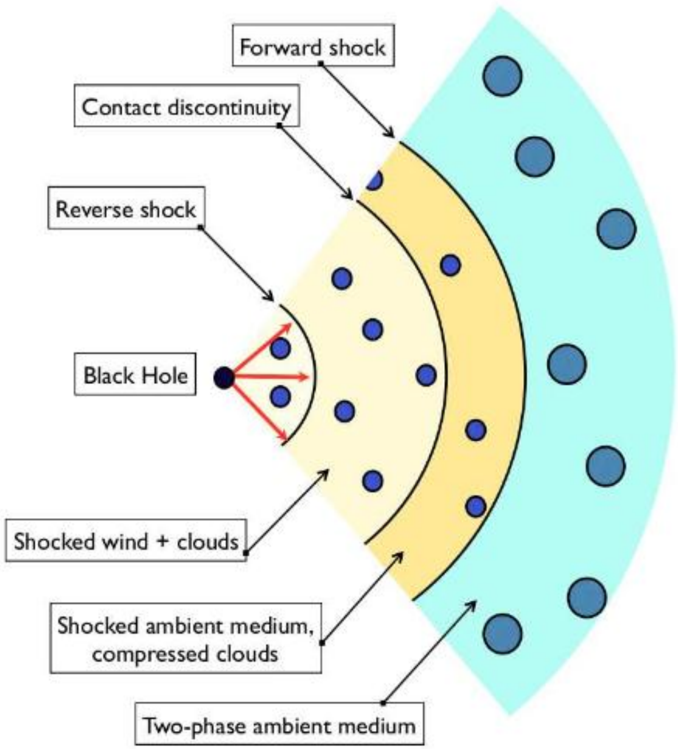


Most of the outflow kinetic energy escapes through the voids

Positive and negative feedback

Cold gas is pushed by ram-pressure

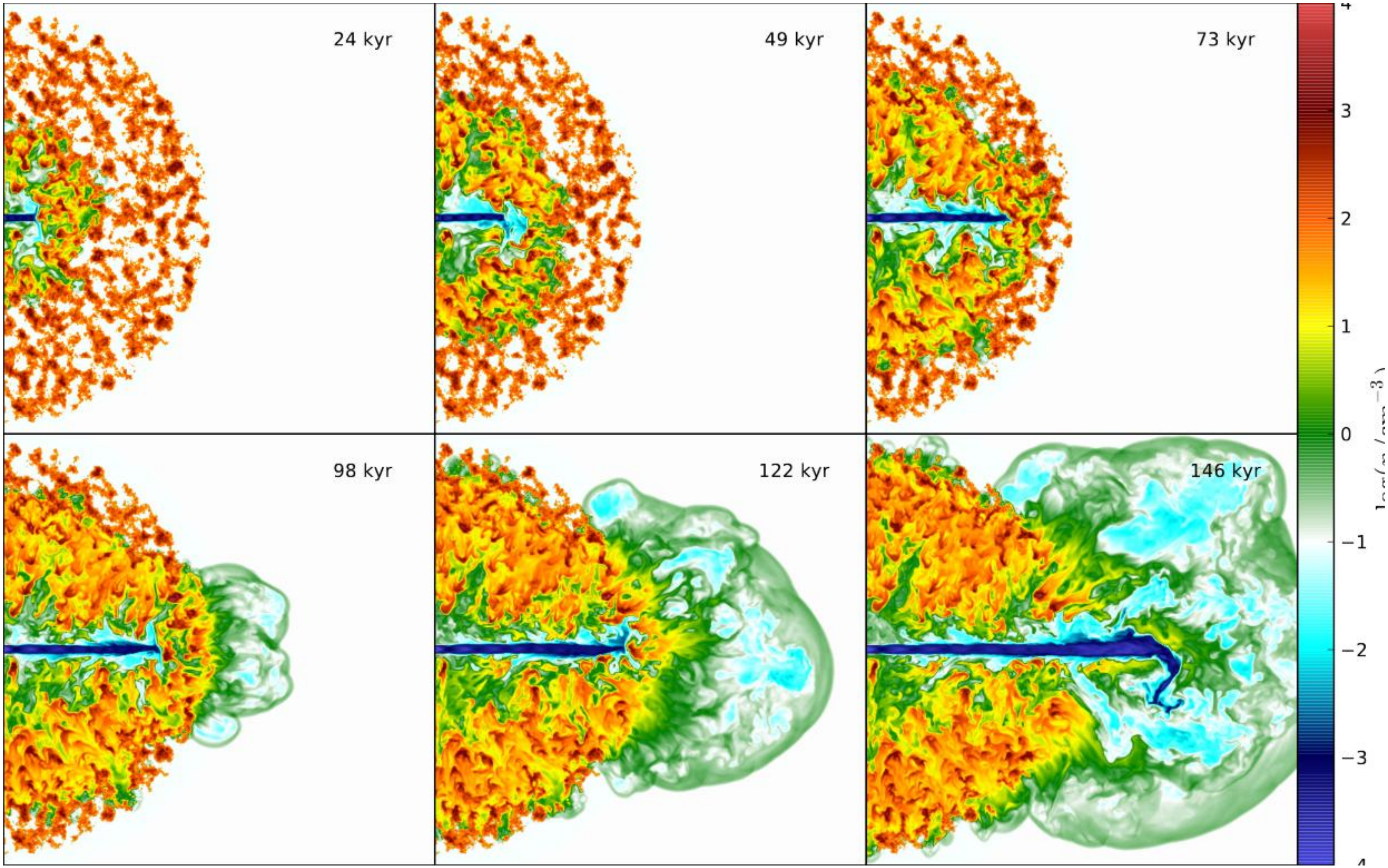
More feedback on low-density gas



Could lead to M-σ relation

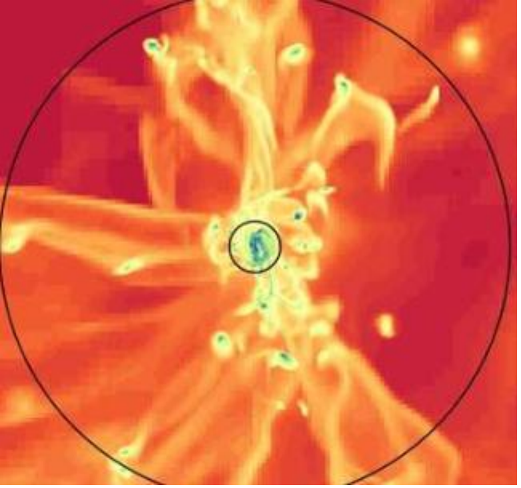
Nayakshin 2014

Radio mode: Fractal structure 2pc-1kpc



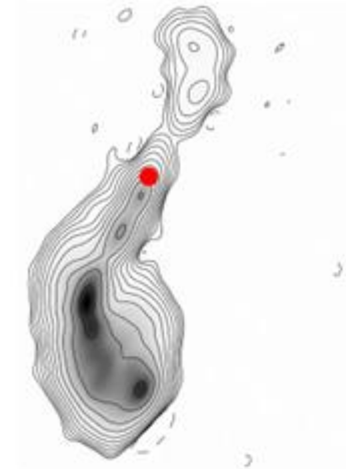
Efficient relativistic jets; Influence of the porosity

Wagner & Bicknell 2011

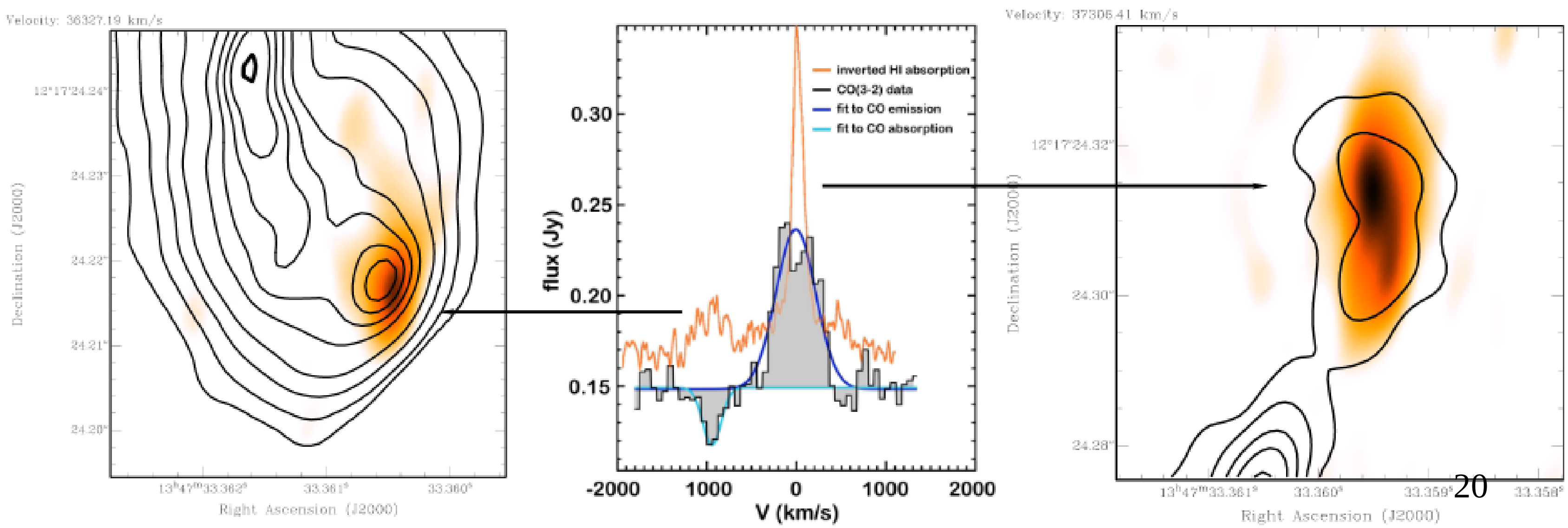


Positive AGN feedback
Radio jets triggered SF

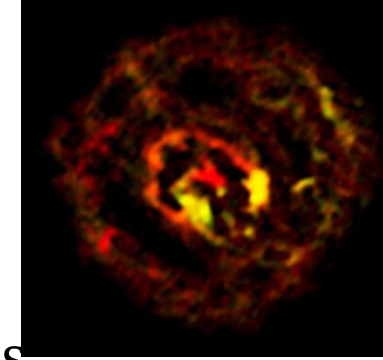
Silk 2005, Dubois et al 2013



Young, restarted radio loud AGN 4C12.50
The outflow is located 100 pc from the nucleus
where the radio jet interacts with the ISM
Morganti et al 2013, Dasyra & Combes 2012



Feedback in low-luminosity AGN



NGC 1433: barred spiral, **CO(3-2) with ALMA**
Molecular gas fueling the AGN, + outflow // the minor axis

M_{H2}= 5.2 10^7 M_o in FOV=18"

100km/s flow
7% of the mass= 3.6 10^6 Mo
Smallest flow detected

➔ L_{kin}=0.5 dM/dt v^2 ~2.3 10^{40} erg/s
L_{bol} (AGN)= 1.3 10^{43} erg/s
Flow momentum > 10 L_{AGN}/c

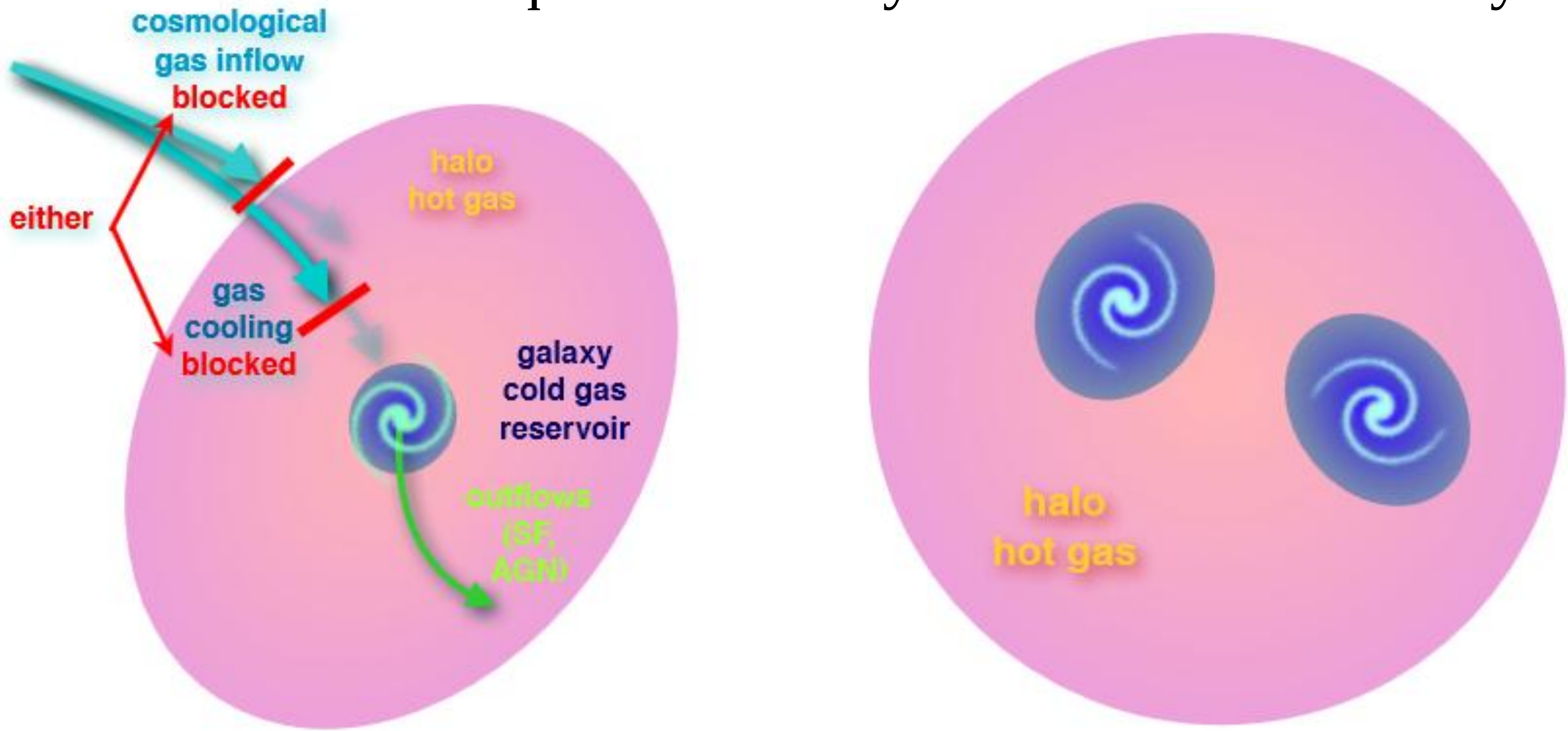
Combes et al 2013

4- Modes of Quenching

➔ **Rapid:** Feedback from SF, from AGN
➔ **Slow:** Morphological quenching, after bulge formation

T-quench ~2-4 Gyr

100 Myr



LTG

ETG

Schawinski 2013

Feedback loop?

Torque limited growth

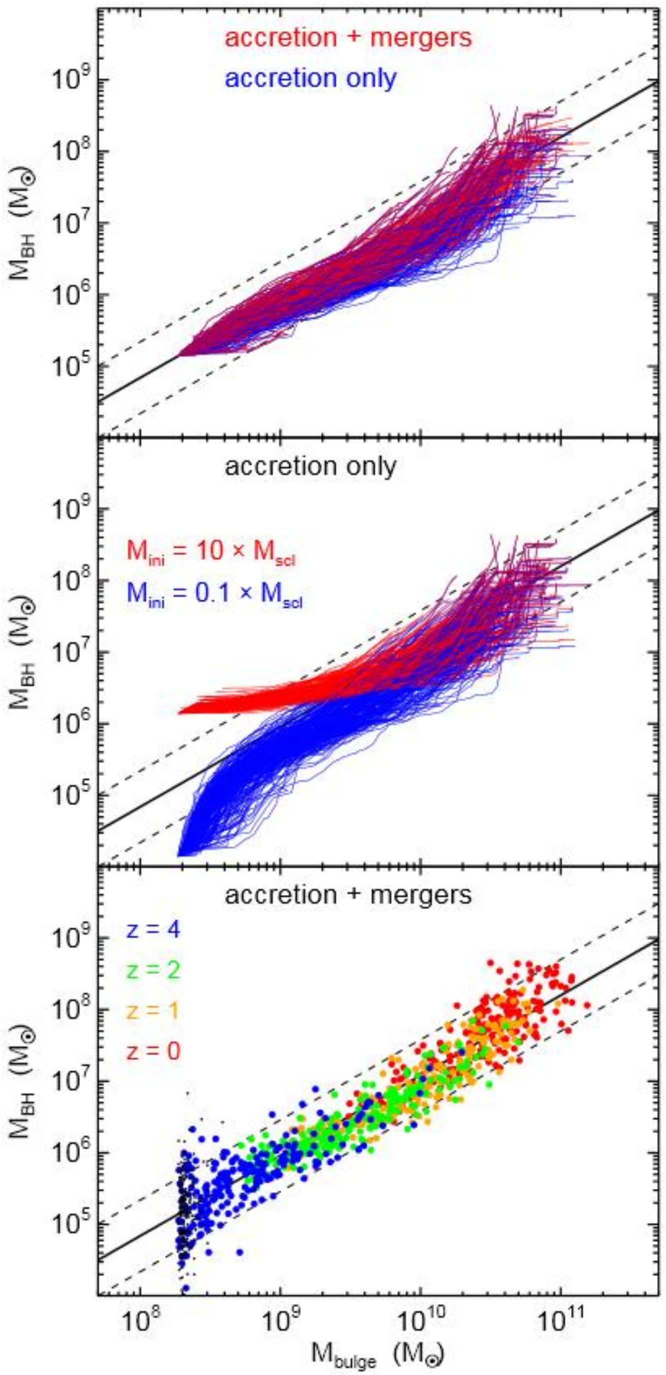
Mostly gas accretion, sometimes
Mergers (but not essential)

Numerical evolution
M-σ relations for seeds

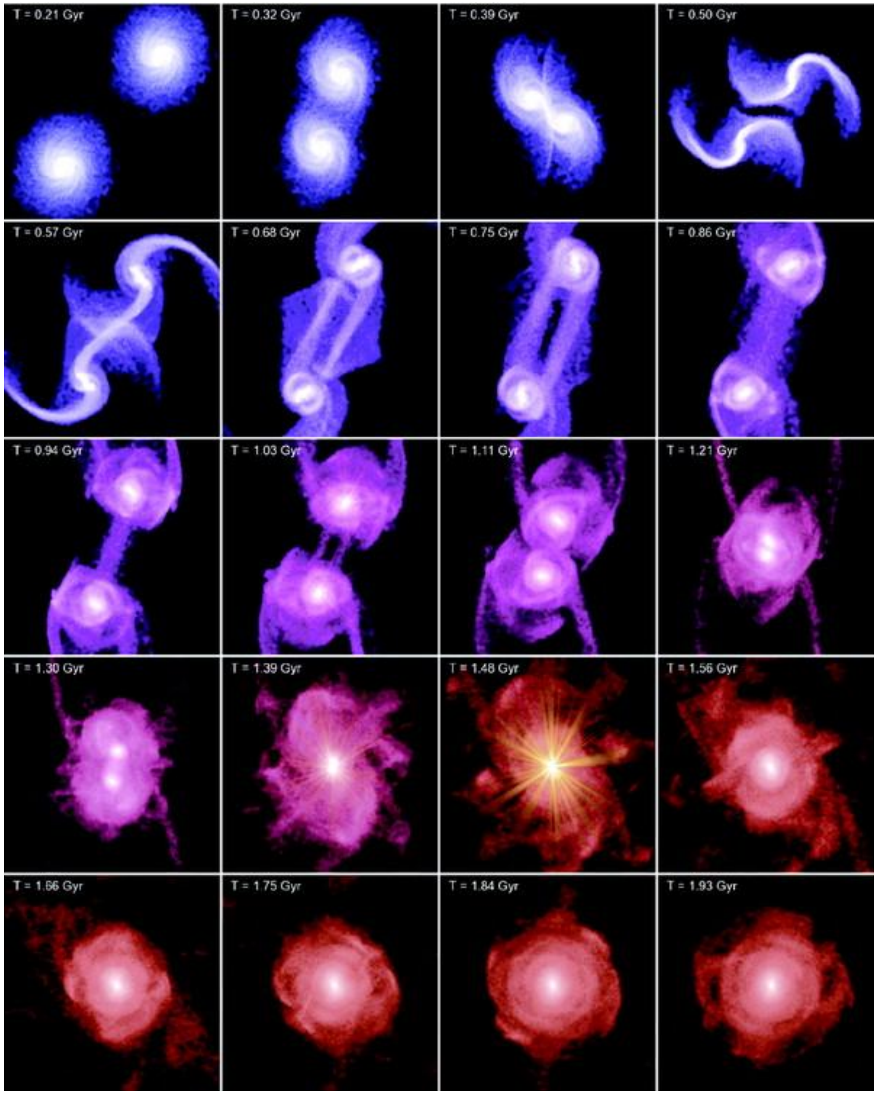
Effects of initial conditions are
Quickly erased

dM_{BH}/dt ~SFR with scatter
No feedback loop required

Angles-Alcazar et al 2013

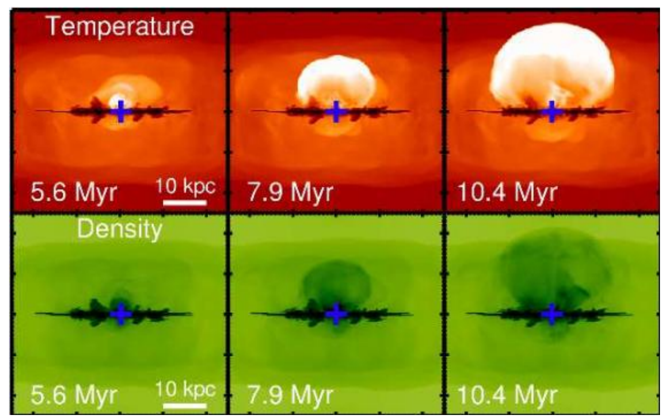


AGN feedback in mergers



SFR $\sim\rho^n$ with n=1, 1.5, 2
SN feedback+
BH growth and associated feedback

Sub-grid physics
How much feedback?



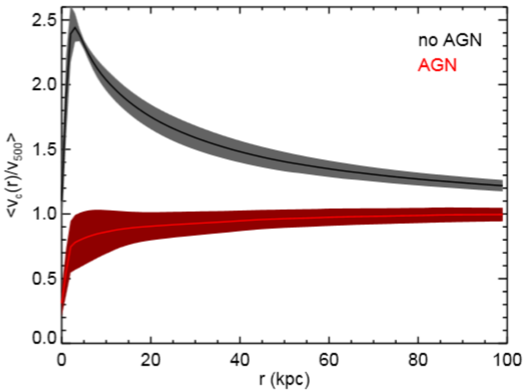
thermal model

Springel et al. (2003-2005), Hopkins et al. 2006

Gabor & Bournaud 2014:
No quenching effect

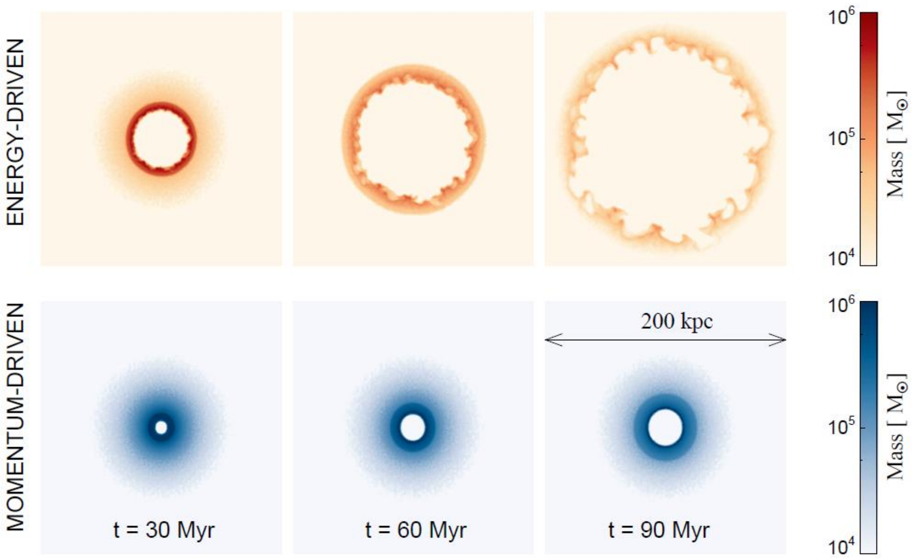
Several modes simulated

Quasar mode, when $dM_{BH}/dt > 0.01$ Edd – Energy released spherically
Radio-jets otherwise: $V = 10^4$km/s, in a cylinder perp. to the disk



Efficiency to form stars reduced by a factor 7
Decrease the baryon concentration
Dubois et al 2012, 2013

Costa et al 2014



Energy-driven, much more efficient
then momentum-driven
AGN outflows with > 10 Ledd/c

Entrained cold gas > 10^9 Mo
If after-shock cooling with metals

SUMMARY: AGN feedback

➔ AGN feedback is very efficient in **Cool Core clusters** to moderate the cooling: mechanical with radio jets, cold gas accretion

➔ Molecular outflows are now observed frequently, around AGN, v=200-1200km/s 10^7-10^9 Mo, load factors >3

➔ Mechanisms: Quasar modes (winds), Radio modes (jets), for more massive galaxies with lower Edd ratios (and lower z)
Either mass accretion or mergers

➔ Energy-conserving flow: Momentum boost 20 L_{AGN}/c