AGN feedback and the origin and fate of the hot gas in early-type galaxies

S. Pellegrini

Dept. of Physics and Astronomy, University of Bologna, Italy

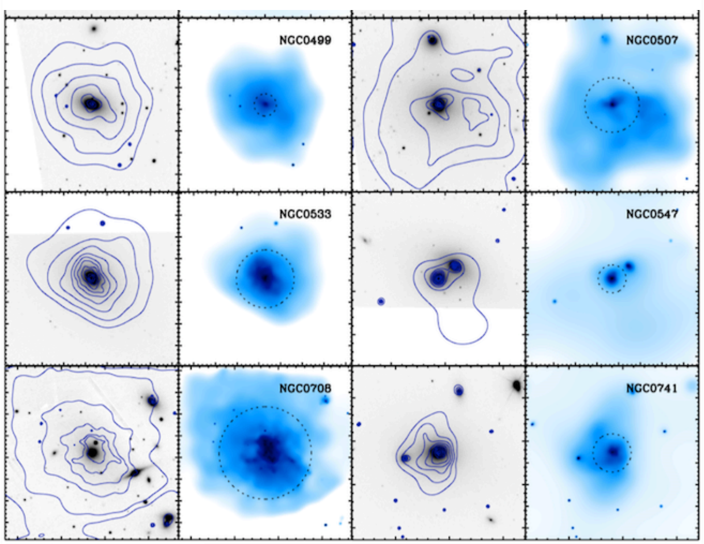
collaboration with **L. Ciotti** (Univ. of Bologna),

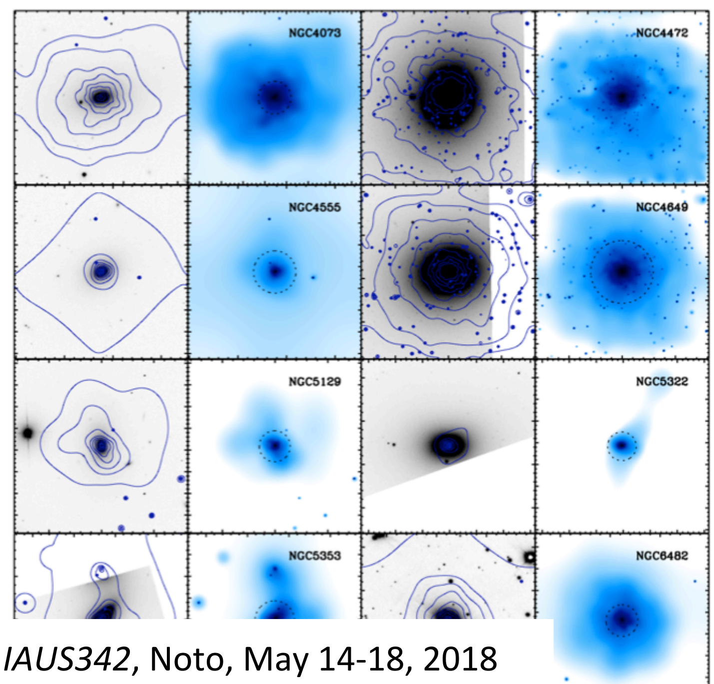
A. Negri (Instituto de Astrofísica de Canarias, Spain),

J.P. Ostriker (Columbia Univ., NY)

Optical and *Chandra* ACIS images, 4x4 arcmin cutouts

Goulding et al. 2016





Left: optical
with logarithmic X-ray contours overlaid (solid blue).

Right: adaptively smoothed X-ray images; dashed circles have $R=R_e$

OUTLINE

1. **Basic facts** about central black holes (MBH), the ISM, and the stellar population of early-type galaxies (ETGs)

2. **Modeling** the coevolution of the ISM and the MBH, in ETGs:

   2D hydrodynamical **simulations** including AGN **radiative + mechanical feedback**

3. (some) **Results** and comparison with **observations**

References:

- <u>physical modeling of AGN feedback and early results</u>:

  Ciotti & Ostriker 2007 (ApJ) … 2012 (chapter in "Hot Interstellar Matter in Elliptical Galaxies", ASSL vol. 378, eds. D.-W. Kim & S. Pellegrini, Springer, p. 83)

- <u>recent 2D hydrodynamical simulations</u>:

  Ciotti L., Pellegrini S., Negri A., Ostriker J.P. 2017 (ApJ) "The Effect of the AGN Feedback on the ISM of ETGs: 2D Hydrodynamical Simulations of the Low-Rotation Case" **(C17)**

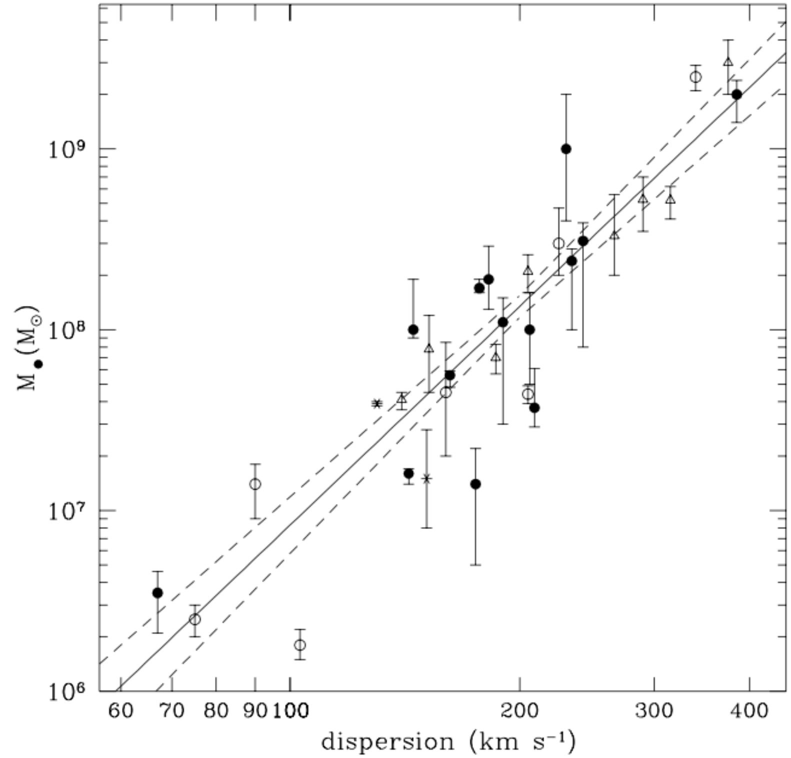
- <u>comparison with observational scalings</u>:

  C17
  Pellegrini S., Ciotti L., Negri A., Ostriker J.P. 2018 (ApJ) "AGN Feedback and the Origin and Fate of the Hot Gas in ETGs" **(P18)**

1. Basic facts

1) **ETGs host central MBHs**, following the M_{BH}–σ relation

➔ estimate of the local MBH mass density, consistent with the density of quasar remnants
(Soltan 1982; Fabian & Iwasawa 1999; Yu & Tremaine 2002)



Tremaine et al. 2002

high-mass MBHs (M_{BH}≥$10^8 M_\odot$) mostly built by accretion during bright QSO phases

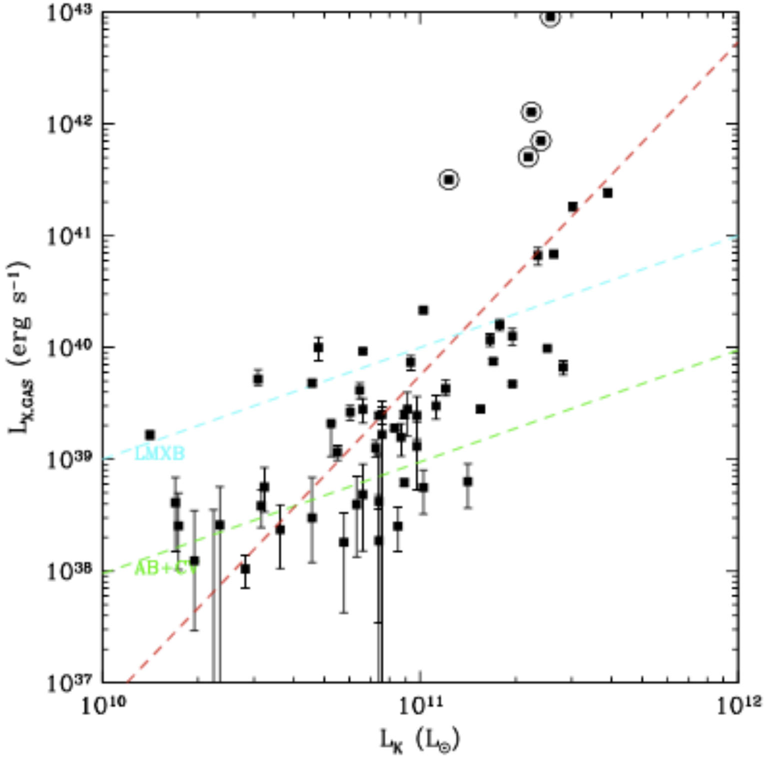
2) In ETGs:

- star formation stopped at early times (Silk & Rees 1998; Di Matteo et al. 2008; Debuhr et al. 2012; Vogelsberger et al. 2013; Barai et al. 2017 ...)

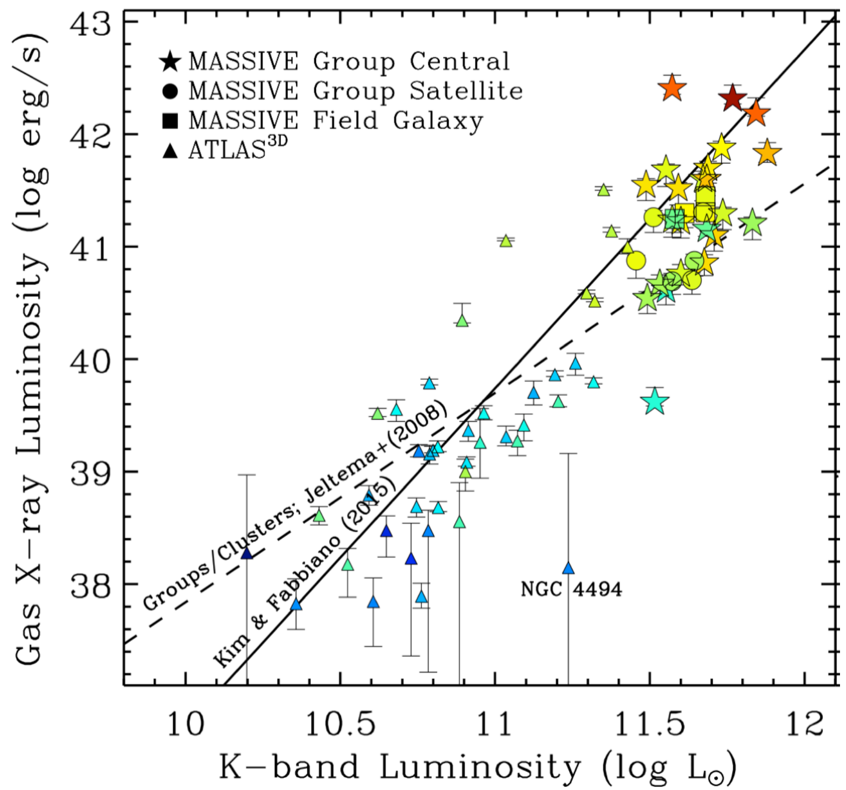
- local ETGs show **very low levels of SF** (Yi et al. 2005, Ford & Bregman 2013); Young et al. 2011; Sarzi et al. 2013; Davis et al. 2014, Pandya et al. 2017)

and **little (if any) young** stellar population (Kuntschner et al. 2010)

3) ETGs contain a **hot ISM**; the diffuse X-ray luminosity L_X scales with their L_K :



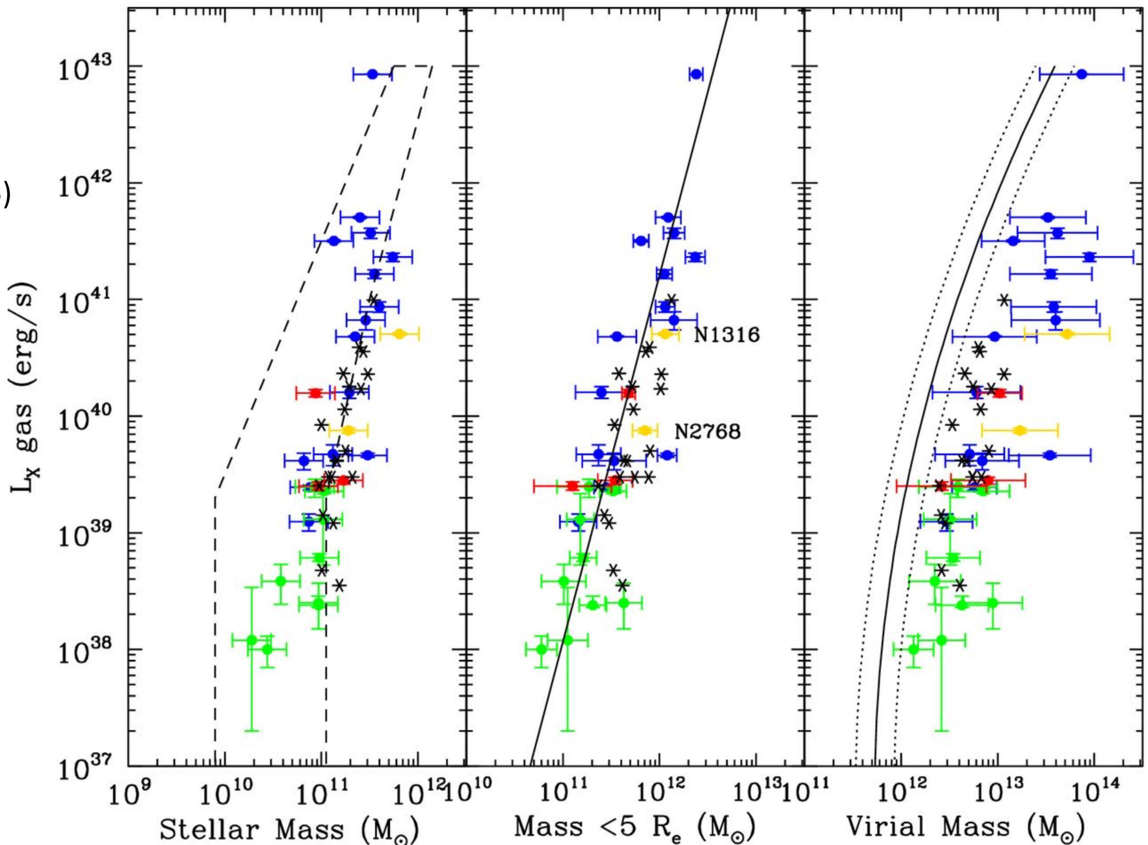
61 ATLAS^{3D} ETGs observed with *Chandra*
Kim & Fabbiano 2015



…combined with 33 ETGs with logL_K ($L_\odot$)>11.4 within 108 Mpc, from the MASSIVE survey
Goulding et al. 2016

… and L_X scales with the mass of ETGs:

L_X (0.3–8 keV) from *Chandra* data (Kim & Fabbiano 2015)



from *K*-band luminosity

dynamical mass within $5R_e$ from GC kinematics

extrapolated

colour-coded by central optical light profile (blue = core, gold = intermediate, green = cusp, red = unknown).

Forbes et al. 2017

4) The ISM is **continuously replenished** by the collective mass input provided by the stellar population (Red Giants, AGB, PNe, …) during its normal ageing

This **source of mass** has a rate of:

$$\dot{M}_* (t) \sim \mathbf{10^{-11}\, L_B}(L_{B\odot})\, \mathbf{t}(12\ \mathrm{Gyrs})^{\mathbf{-1.3}} \quad M_\odot/yr$$

for a passively evolving stellar population, of age >1 Gyr (~insensitive to the slope of the IMF).

Present rate ~ 0.1 – 1 $M_\odot$/yr

The stellar mass **lost during the galaxy's lifetime is >~10%** of its initial value !

$\dot{M}_*$ is **heated** by thermalization of the kinetic energy

- ✓ of the stellar motions
- ✓ of the SNIa's ejecta (rate $R_{SN} \propto t^{-1.1}$; e.g., Maoz et al. 2012)

the collective mass input develops a **flow**, (in part) **directed towards the galactic center**

(e.g., Sarazin & White 1987, 1988, Ciotti et al. 1991, David et al. 1991, …)

central fuelling ➔ AGN feedback

Questions

- ✓ can the MBH accretion energy prevent MBH masses from growing too much (w.r.t. those at the end of the quasar phase) ?

- ✓ how does the accretion energy interact with the galactic ISM?

  absorbed? effects on the hot ISM? gas **displaced** from the galactic center/**removed** from the galaxy?

  consequence for L_X and scaling laws?

- ✓ does SF remain low?

2. Modeling of MBH – galaxy coevolution

high resolution 2D hydrodynamical simulations (**grid-type**: ZEUS-MP)
➔ evolution of the ISM with stellar and AGN feedback

from an age of ~2 Gyr (after the main formation phase) for ~10 Gyr
in isolated ETGs

- ✓ secularly evolving **stellar mass losses** $\dot{M}(t)$, as prescribed by stellar evolution theory
- ✓ secularly evolving SNIa's $\mathbf{R_{SNIa}(t)}$ at observed rate
- ✓ **star formation** (with SNII)

- ✓ **ACCRETION** on the MBH & **FEEDBACK**

detailed and self-consistent implementation
of **radiative + mechanical (AGN wind) energy and momentum input**
& its absorption and transmission by the ISM

- ✓ *parsec-scale central resolution* (Bondi radius resolved)

- ✓ a large set of realistic galaxy models (various galactic masses $M_\star$;
shapes E0, E4, E7;
rotational support v/σ)

Galaxy models

components: **MBH** + **stars** (de Vaucouleurs) + NFW **DM halo** (with low DM fraction within R_e)

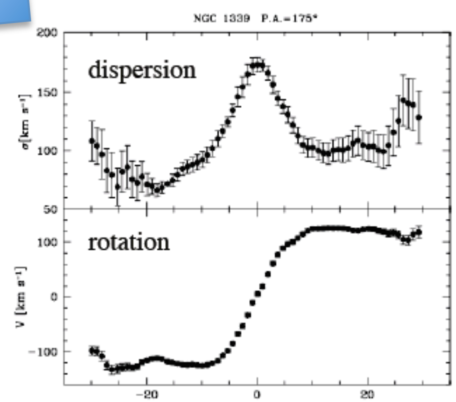
Cappellari+ 07; Gavazzi+ 07, Barnabe'+ 09

(L_B, R_e, σ_e) lie on the **Faber-Jackson** and **size–luminosity** relations for observed ETGs

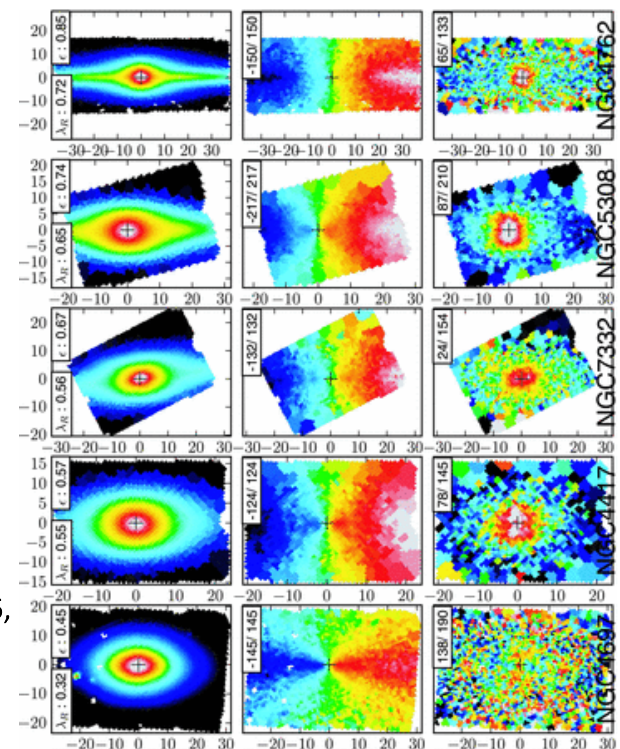
a **large set** of axisymmetric galaxy models, with varying:

- ✓ stellar mass ($M_\star$)
- ✓ intrinsic flattening (ε)
- ✓ internal kinematics (**ordered rotation vs. anisotropy**)

internal dynamics from Jeans equations



kinematics along major axis



ATLAS^{3D} (Cappellari et al. 2006, 2015)

The hydrodynamical equations

with sources of mass, energy, momentum

mass input from SNII

from **star formation**

from **AGN** wind

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = \dot{\rho}_{\mathrm{Ia}} + \dot{\rho}_{\star} + \dot{\rho}_{\mathrm{II}} - \dot{\rho}_{\mathrm{SF}} + \dot{\rho}_{\mathrm{w}},$$

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = - \nabla p - \rho \nabla \Phi_{\mathrm{tot}} - \nabla p_{\mathrm{rad}} + (\dot{\rho}_{\mathrm{Ia}} + \dot{\rho}_{\star} + \dot{\rho}_{\mathrm{II}}) \times (\boldsymbol{v}_{\star} - \boldsymbol{u}) + \dot{\rho}_{\mathrm{w}} (\boldsymbol{v}_{\mathrm{w}} - \boldsymbol{u}),$$

C17

momentum source due to AGN wind

heating&cooling (includes radiative feedback)

$$\frac{\partial E}{\partial t} + \nabla \cdot (E \boldsymbol{u}) = -p \nabla \cdot \boldsymbol{u} + \overbrace{H - C} + \dot{E} - \dot{E}_{\mathrm{SF}} + \frac{\dot{\rho}_{\mathrm{w}}}{2} \|\boldsymbol{v}_{\mathrm{w}} - \boldsymbol{u}\|^2$$

$$\dot{E} = \dot{E}_{\mathrm{Ia}} + \dot{E}_{\mathrm{II}} + \frac{\dot{\rho}_{\mathrm{Ia}} + \dot{\rho}_{\star} + \dot{\rho}_{\mathrm{II}}}{2} [\, \|\boldsymbol{v}_{\star} - \boldsymbol{u}\|^2 + \mathrm{Tr}(\boldsymbol{\sigma}^2)]$$

energy injection rate from the thermalization of the kinetic energy of SNIa and SNII, and of the relative motions between stars and the ISM

Star formation

- cold gas produces SF that removes mass, momentum, and energy from the grid;
- simple scheme based on physical arguments, reproduces well the **Kennicutt-Schmidt relation** (Negri et al. 2015)
- the newly born stellar population includes type II supernovae, injecting new mass and energy

$$\dot{\rho}_{\rm SF} = \frac{\eta_{\rm SF}\rho}{\tau_{\rm SF}} \qquad \tau_{\rm SF} = \max(\tau_{\rm cool},\, \tau_{\rm dyn})$$

$\eta_{\rm SF}$ =0.1

$$\tau_{\rm cool} = \frac{E}{C}, \qquad \tau_{\rm dyn} = \min(\tau_{\rm jeans},\, \tau_{\rm rot})$$

$$\tau_{\rm jeans} = \sqrt{\frac{3\pi}{32G\rho}}, \qquad \tau_{\rm rot} = \frac{2\pi r}{v_c(r)}$$

estimate of radial period

C17

circular velocity
in equatorial plane

energy and momentum sinks associated with SF:

$$\dot{E}_{\rm SF} = \frac{\eta_{\rm SF}E}{\tau_{\rm SF}}, \qquad \dot{\boldsymbol{m}}_{\rm SF} = \frac{\eta_{\rm SF}\boldsymbol{m}}{\tau_{\rm SF}} = \dot{\rho}_{\rm SF}\boldsymbol{u}.$$

Radiative heating and cooling

plasma in photoionization equilibrium with the radiation field of an average quasar SED with a spectral temperature of T_c=2 keV (Sazonov et al. 2005, 2008)

Includes: **bremsstrahlung** losses (S_1), **Compton heating & cooling** (S_2),

photoionization heating plus **line and recombination cooling** (S_3)

heating (H) − cooling (C) rate =
=net heating/cooling rate per unit volume: $$H - C \equiv n^2(S_1 + S_2 + S_3),$$

Mechanical feedback from AGN winds

Outside of the first grid point (r_{in}=2.5 pc), the mass accretion rate is determined by the hydrodynamical evolution.

Gas that flows within r_{in} ($\dot{M}_{in}$) either accretes onto the MBH ($\dot{M}_{BH}$) or flows back into the grid as a bi-conical wind ($\dot{M}_{out}$):

$$\dot{M}_{in}=\dot{M}_{BH}+\dot{M}_{out}$$

$\dot{M}_{in}$= mass inflow rate at **r_{in} ≤Bondi accretion radius**

Mass accretion rate on the MBH $$\dot{M}_{BH} = \frac{\dot{M}_{in}}{1+\eta},$$

Mass outflow rate in the wind $$\dot{M}_{out} = \eta \dot{M}_{BH},$$

Mechanical feedback from AGN winds

Mass accretion rate on the MBH $\dot{M}_{\rm BH} = \dfrac{\dot{M}_{\rm in}}{1+\eta},$

Mass outflow rate in the wind $\dot{M}_{\rm out} = \eta \dot{M}_{\rm BH},$

$$\eta \equiv 2\epsilon_{\rm w} c^2 / v_{\rm w}^2$$

$$L_{\rm w} = \epsilon_{\rm w} \dot{M}_{\rm BH} c^2$$

ε_W = efficiency of generating mechanical energy with an AGN wind

$$\dot{p}_{\rm w} = \dot{M}_{\rm out} v_{\rm w},$$

v_w = modulus of the AGN wind velocity

these expressions guarantee the **conservation** of mass, energy, and momentum carried by the wind (Ostriker et al. 2010)

ε_W and v_w **scale with the mass accretion rate**, and saturate to ε_{W0} and v_{w0}:

$$\epsilon_{\rm w} = \frac{\epsilon_{\rm w0} A_{\rm w} \dot{m}}{1 + A_{\rm w} \dot{m}}, \qquad v_{\rm w} = \frac{v_{\rm w0} A_{\rm w} \dot{m}}{1 + A_{\rm w} \dot{m}}$$

$A_{\rm w} = 1000$
$\varepsilon_{W0} = 10^{-4}$
$v_{w0} = 10^4$ km/s

$$\dot{m} \equiv \frac{\dot{M}_{\rm BH}}{\dot{M}_{\rm Edd}} = \frac{\epsilon_0 \dot{M}_{\rm BH} c^2}{L_{\rm Edd}}$$

ε_0=0.125

ε_W not known very well, from observations and simulations $10^{-4} \le \varepsilon_W \le 10^{-3}$ (Proga & Kallman 2004; Krongold et al. 2007; Yuan et al. 2012, 2015; Bu & Mosallanezhad 2018)

v_{w0} : the wind velocity in the quasar mode (relatively well constrained by observations) ≈10^4 km/s

[see, e.g. the outflow velocity in UV absorption lines of BAL AGNs; Murray et al. 1995; Crenshaw et al. 03, Chartas et al. 07, Moe et al. 2009, Liu et al. 2013; Tombesi et al. 2015; Zakamska et al. 2016; Xu et al. 2018]

The wind injects mass, momentum, and energy within *two symmetric cones* above and below the equatorial plane.

half-opening angle of each of the two cones is 40°

This aperture encloses half of the mass, momentum, and energy injected in each of the two half-spaces.

Radiative feedback

$$L_{\rm BH} = \epsilon_{\rm EM} \dot{M}_{\rm BH} c^2$$ (central boundary condition)

$$\epsilon_{\rm EM} = \frac{\epsilon_0 A_{\rm EM} \dot{m}}{1 + A_{\rm EM} \dot{m}}$$

ADAF-like
(Yuan & Narayan 2014)

reaches
ε_0=0.125

$A_{\rm EM} = 100$, so that:
$\dot{m} \gg 10^{-2}$: $\varepsilon_{\rm EM} \sim \varepsilon_0$
$\dot{m} \ll 10^{-2}$: $\varepsilon_{\rm EM} \sim \varepsilon_0 A_{\rm EM} \dot{m} \ll 0.1$

Force per unit mass due to photoionization + Compton opacity :

$$(\nabla p_{\rm rad})_{\rm photo} = -\frac{\rho \kappa_{\rm photo}}{c} \frac{L^{\rm eff}_{\rm BH,photo}(r)}{4\pi r^2} \boldsymbol{e}_r$$

$L^{\rm eff}_{\rm BH,photo}(r)$ =**effective accretion luminosity L_{BH} at radius r** calculated *along each radius*, for the ISM density and temperature given by the hydrodynamics at each time step (heating and cooling are **not** spherically symmetric)

due to electron scattering :

$$(\nabla p_{\rm rad})_{\rm es} = -\frac{\rho \kappa_{\rm es}}{c} \frac{L_{\rm BH}}{4\pi r^2} \boldsymbol{e}_r$$

$$\kappa_{\rm es} = 0.35 \ {\rm cm^2 \ g^{-1}}$$

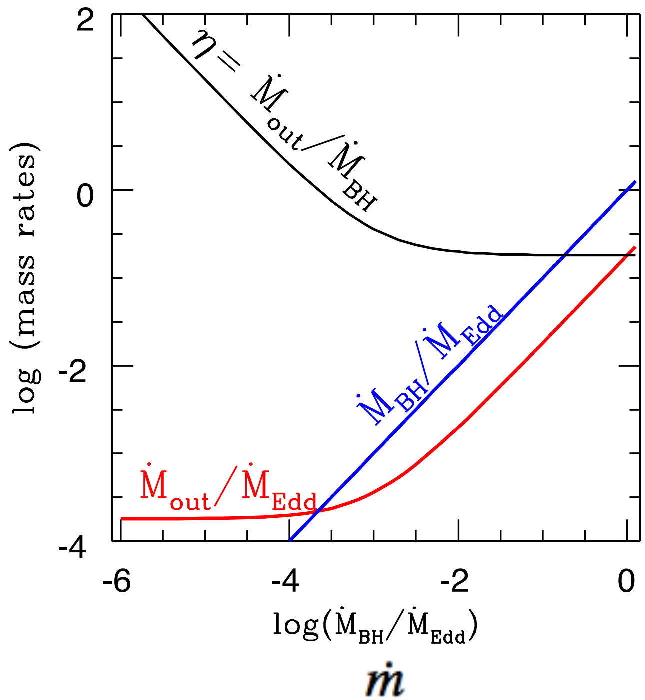
$$\kappa_{\rm photo} = \frac{4\pi r^2 H(r)}{\rho(r) L^{\rm eff}_{\rm BH,photo}(r)}$$

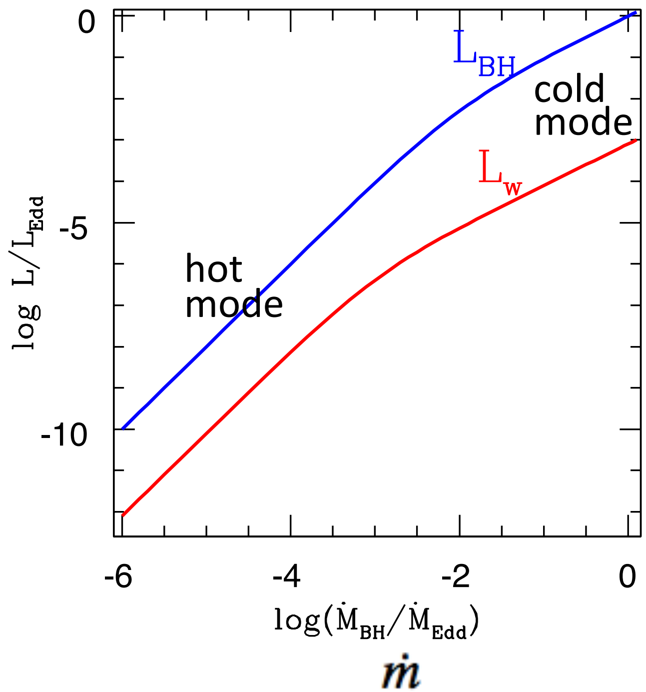
(No effect of radiation pressure on the dust)

SUMMARIZING:

For $\dot{m}$ >0.01 ➔ high $\varepsilon_{EM} \sim \varepsilon_0$, high $\varepsilon_W \sim \varepsilon_{W0}$ ("cold mode")

For $\dot{m}$ < 0.01 ➔ low ε_{EM}, ε_W ("hot mode")





(see also Yuan et al. 2018)

3. Results

hydro 2D code ZEUS-MP 2 in spherical coordinates

radially logarithmic grid (r, θ) of 128 × 32 meshpoints

first grid point : 2.5 pc, last grid point: 250 kpc (the whole extent of the galaxy is well resolved)

Large set of simulations: for each galaxy (with chosen $M_\star$, shape, ...) the models have

no feedback from the MBH (NOF models),

only mechanical feedback (**MF** models),

radiative+mechanical feedback (**FF** models)

(rotating galaxies are only of NOF type)

Many outputs of the simulations:

gas: hydro-maps, L_X, T_X, surface brightness maps + their evolution
stars: SFR maps + age,mass, distribution of stars formed
MBH: mass growth, nuclear luminosity, duty cycle

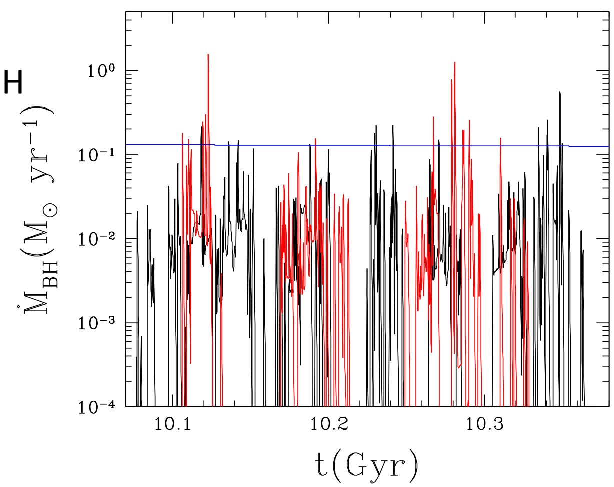
General evolution

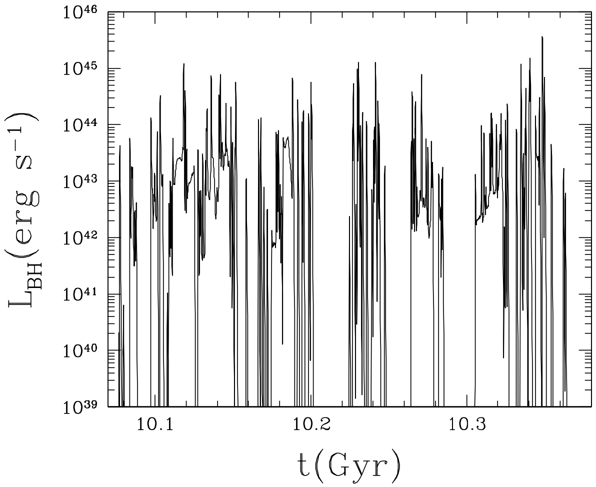
major accretion episode ➔ feedback ➔ gas heated and pushed out, accretion rate drops

the central region cools, the galaxy starts replenishing again ➔ a new major infall

mass accretion rate on the MBH

NOF
MF
FF

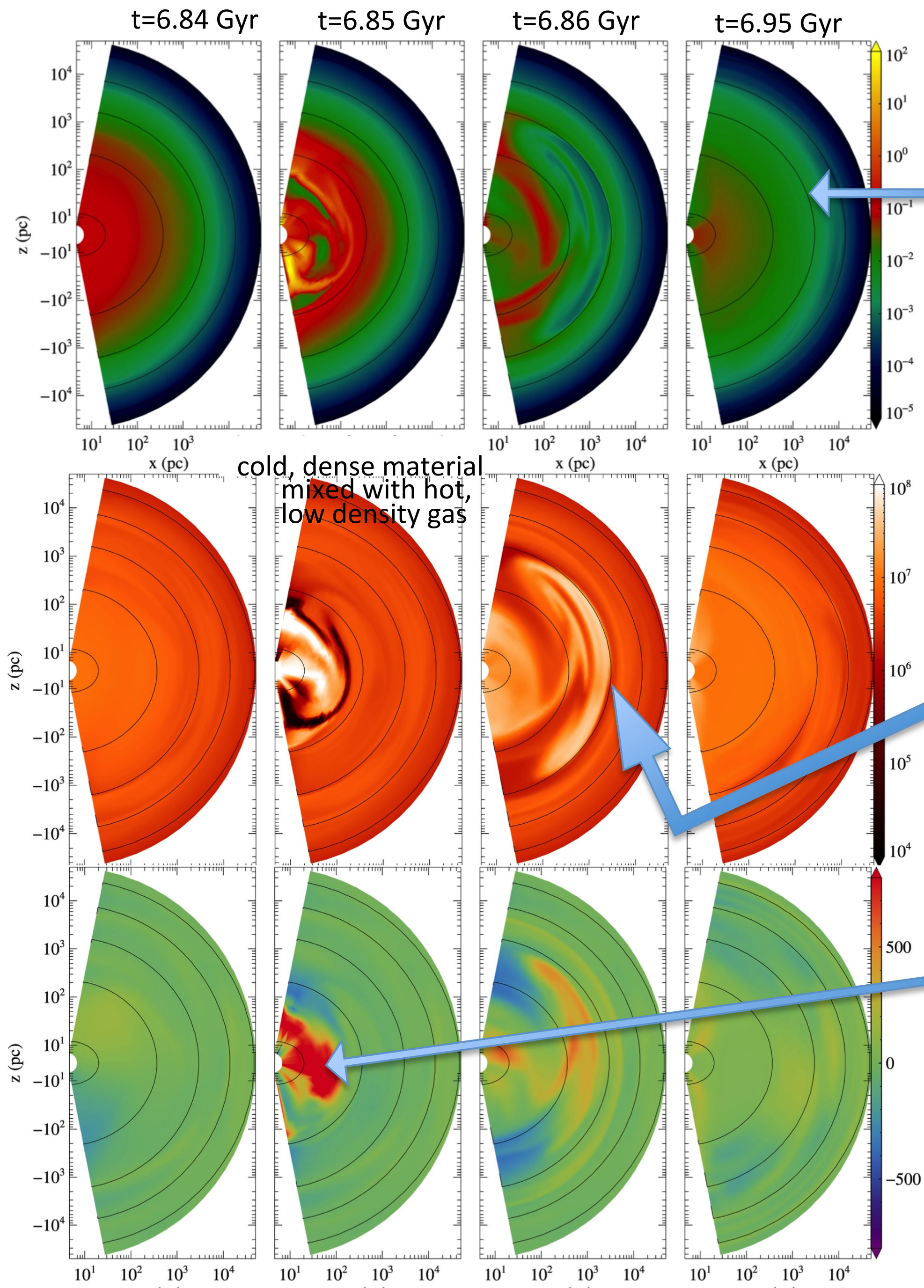




Nuclear luminosity

Typical outburst:

effects on the gas



density

main outburst effects vanished, galaxy left with less dense gas than before the outburst, within central few kpc

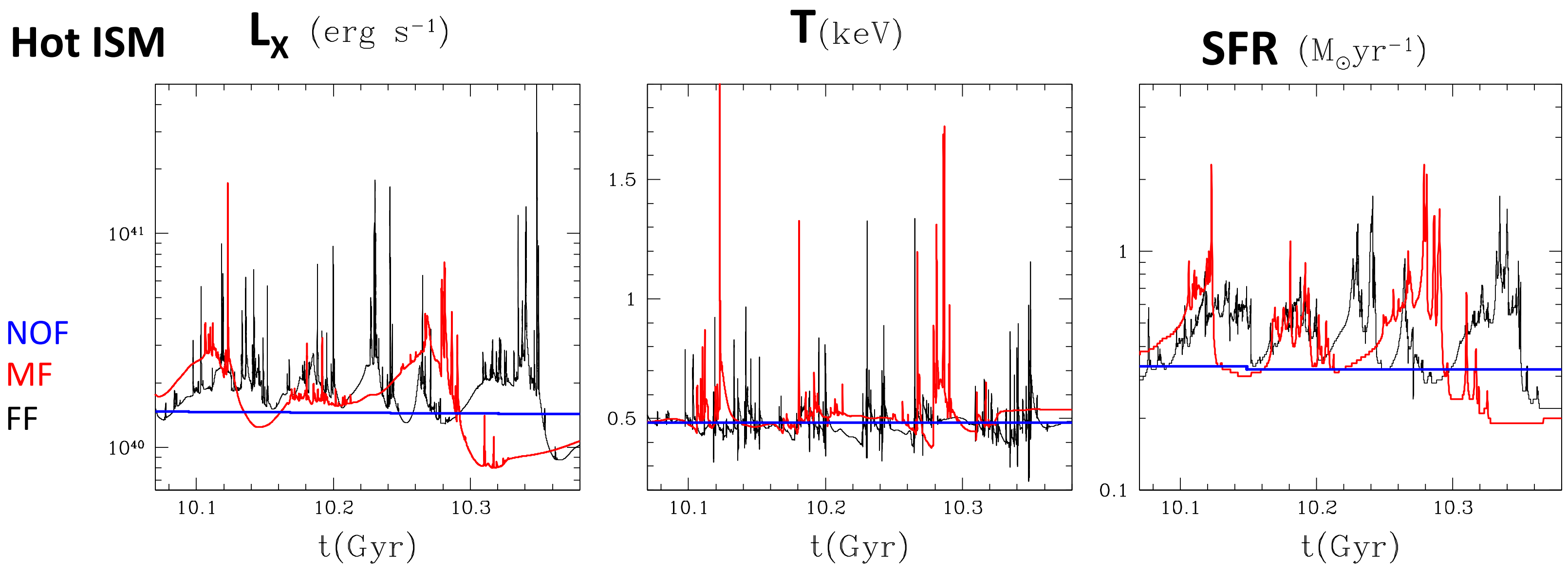
temperature

still some hot outflowing material at a r~1 kpc

instabilities disrupt cold material created by shock waves; cold gas can accrete, while hot gas escapes from the center (e.g., Novak et al. 2012; Barai et al. 2012; Nayakshin & Zubovas 2012; Gaspari et al. 2013)

radial component of **velocity**

outflow (hot; red) and inflow (cold; blue) regions coexist around the galactic center



after each outburst, L_X of FF, MF models, *within (1–2)R_e*,
drops down to ~1/10 the L_X of the corresponding NOF models

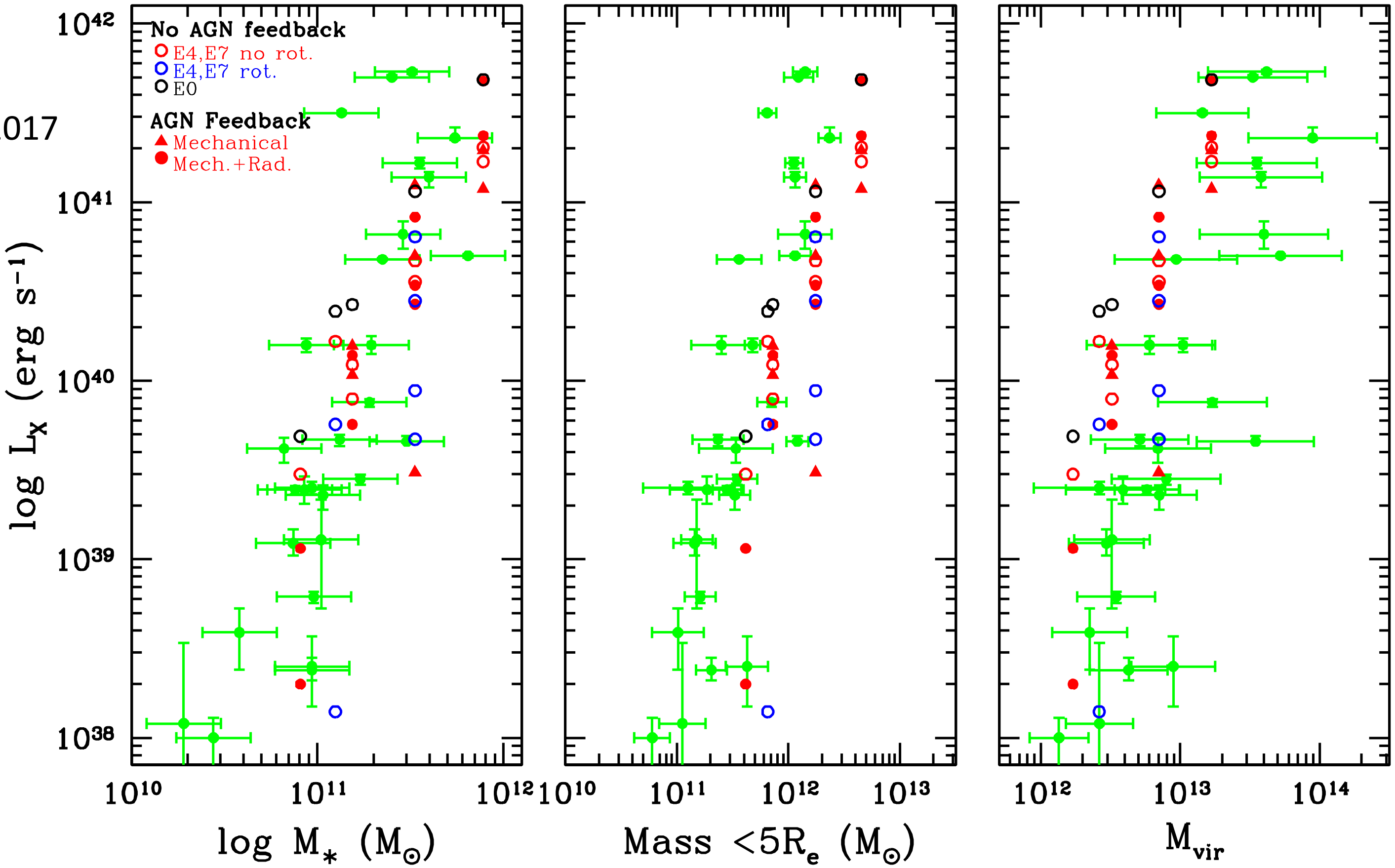
recurrent AGN feedback *temporarily displaces* the gas from the central regions (out to r<~10 kpc),
thus L_X is temporarily reduced (even considerably);
but AGN feedback does not clear the whole galaxy from the gas

What is the overall effect of AGN feedback on the hot gas content, *originated in the stellar population***?**

compare L_X for the whole set of models, at the present epoch, with the set of local ETGs of Forbes et al. 2017…

observed ETGs
from Forbes et al. 2017

Lowest Lx :
large outflowing regions due mostly to SNIa's:
no global degassing due to AGN only

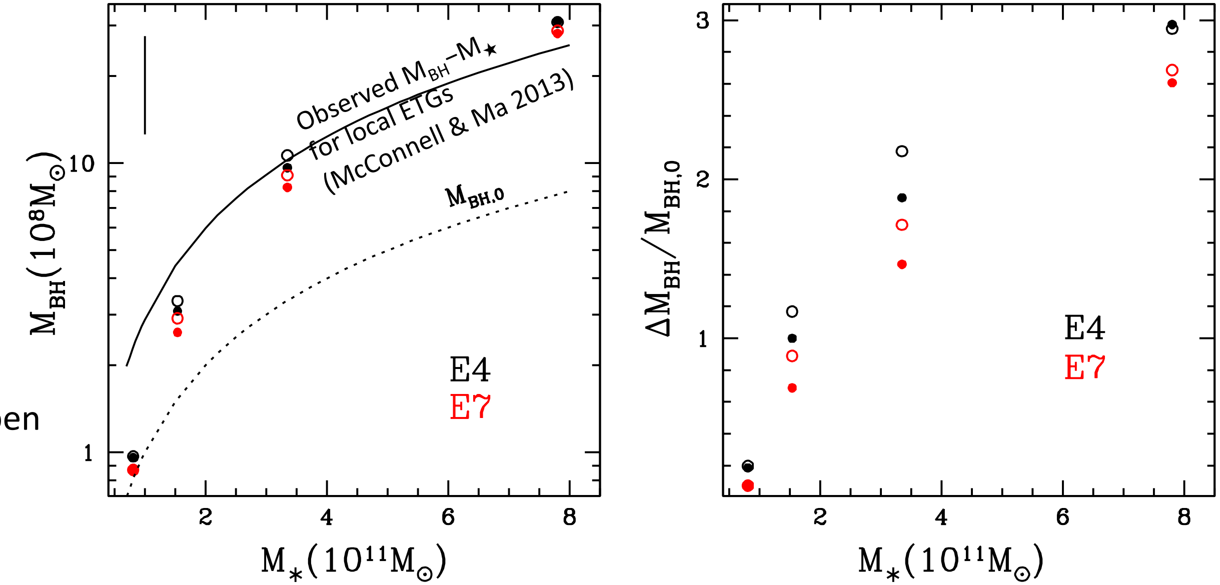


P18

1) agreement between L_X of models and that observed ➔ the *mass input from the stellar population can account* for a major part of the observed L_X

2) NOF, MF, and FF models occupy similar regions ➔ total L_X not significantly affected by AGN fdbk ➔ *present-day L_X is not a diagnostic of the impact of* past *AGN activity*

Final M_{BH} mass



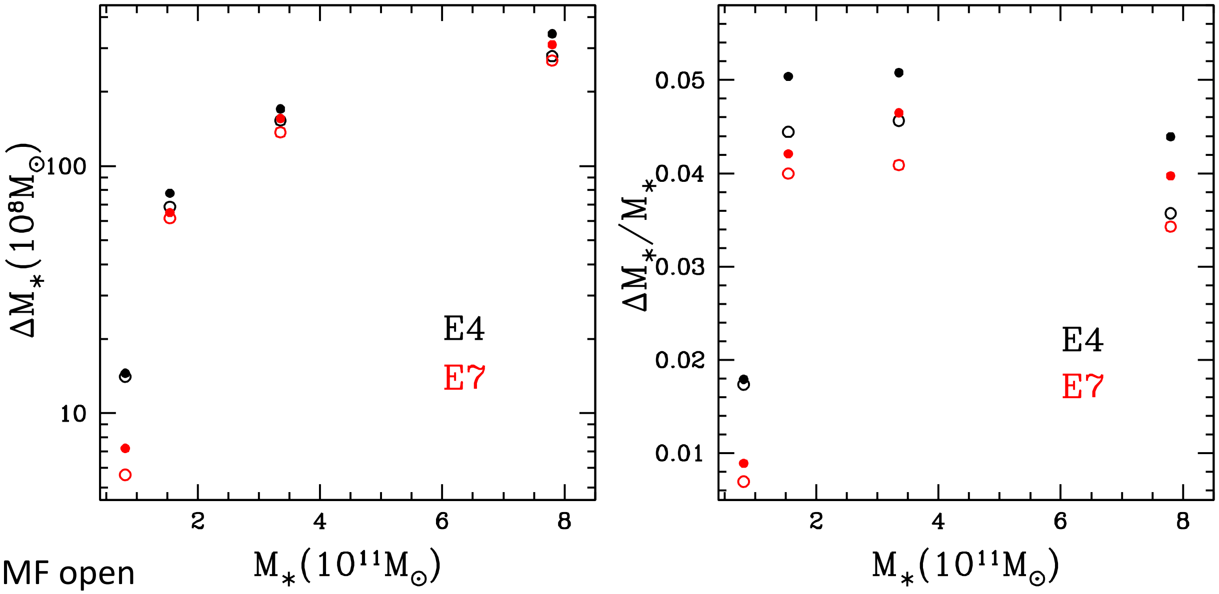
MF open
FF full

At the end, M_{BH} has grown by 2–3x instead of 100x

At fixed $M_\star$ and galaxy shape, ΔM_{BH} **decreases** from NOF to MF to FF models

C17

Final mass in newly born stars $\Delta M_\star$



MF open
FF full

New stars are a few % of original $M_\star$

At fixed $M_\star$ and galaxy shape, $\Delta M_\star$ **increases** from NOF (not shown) to MF to FF models ➔ ***positive* feedback action on SF**

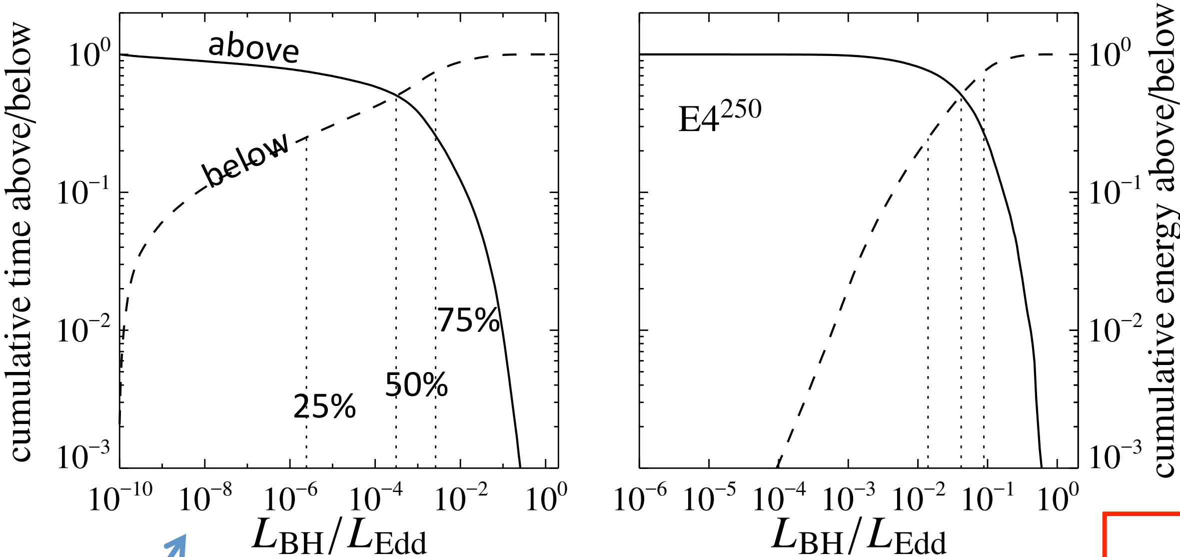
lowest $M_\star$ models end with low $\Delta M_\star$
gas keeps mostly outflowing
(little accretion and little possibility of SF)

present-epoch SFR: typically <0.5 $M_\odot$/yr,
current rates observed for local
ATLAS^{3D} ETGs: median of 0.15 $M_\odot$/yr
(Davis et al. 2014)

Distribution of radiative energy injection with $\mathbf{l} = L_{BH}/L_{Edd}$ and duty cycle

Fraction of total **time** (11 Gyr) spent above (solid) and below (dashed) the $\mathbf{l}$ on the x-axis

Fraction of total **energy** emitted above (solid) and below (dashed) the $\mathbf{l}$ on the x-axis



- negligible time in the (cold mode) phase of high $\mathbf{l}$
- most of the time in a "quiescent", low nuclear luminosity phase ($\mathbf{l} < 10^{-2}$)

Vertical lines: Eddington ratios below which the model spends 25%, 50%, and 75% of the total time (left), emits 25%, 50%, and 75% of the total energy (right)

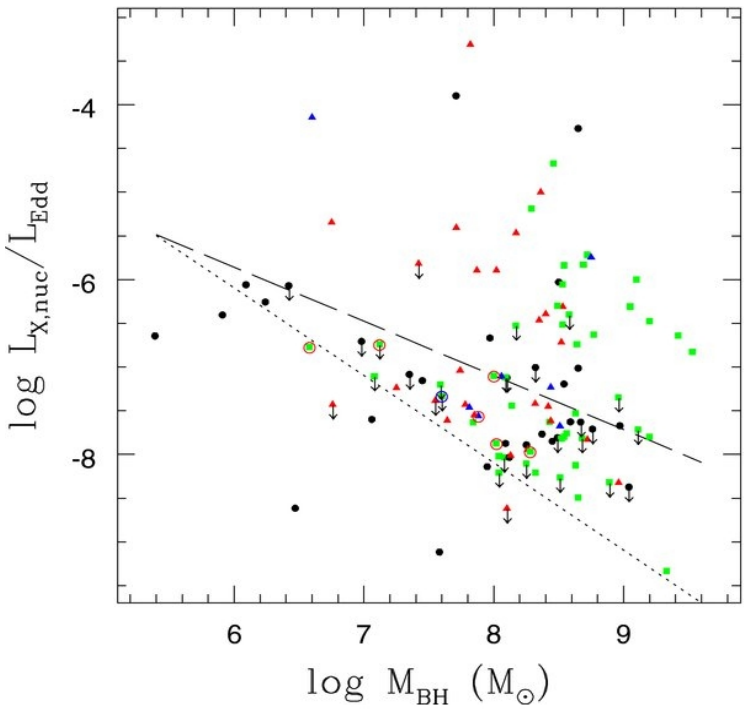
- the energy is emitted at high $\mathbf{l}$:

25% of the total energy emitted at $\mathbf{l} > 0.1$

only 20% below $\mathbf{l} = 0.01$

- the duty- cycles of AGN activity (=fraction of time spent above $L_{Edd}/30$) range from 3 to 5%.

From *Chandra* nuclear L(2–10 keV) of 112 ETGs within 70 Mpc



Pellegrini (2010)

Eddington-scaled 2–10 keV nuclear luminosity vs. the M_{BH} mass (from direct estimates or the M_{BH}–σ relation)

$L_{X,nuc}$ ranges from 10^{38} to 10^{42} erg s^{-1}

Summary & Conclusions

2D hydro-sim.'s with detailed and self-consistent implementation of AGN feedback:

- **high resolution** (Bondi accretion radius resolved), whole extent of the galaxy considered
- **self-consistent** treatment of the mass, energy and momentum balance of the **inflowing and outflowing** material
- **radiative** and **mechanical efficiencies**, including their variation with the mass accretion rate, in agreement with current observational and theoretical findings

the heating of the ISM resulting from the accretion process is self-determined
➔ the "strength" of AGN feedback not "adjusted"

1) AGN feedback successful to maintain massive ETGs in a *time-averaged* quasi-steady state;
star formation at the low observed levels, black hole masses on the $M_{BH}-\sigma$ relation

2) $\Delta M_\star/M_\star$ is of the order of 0.04–0.05, $\Delta M_{BH}/M_{BH}$ a factor of few (<3).
AGN feedback tends to have a *positive* effect on SF.

3) *most of the time* is spent at very *low nuclear* luminosities, *most of the energy* is emitted at *high Eddington ratios* >0.01;
duty-cycles of nuclear activity are 3−5%.

4) the mass input from the stellar population is able to account for a *major part of the observed* L_X.
AGN feedback produces *an increase* in the ejected mass from the galaxy,
it does not produce a global/major outflow, after z~2