X-ray properties of elliptical galaxies as determined by feedback from their central black holes

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OUTLINE:

1. Basic facts about central black holes (MBH) and the ISM of early-type galaxies

2. A recent model for the coevolution of the ISM and the MBH:

   hydrodynamical **simulations** of spherical accretion including
   radiative + mechanical feedback

   (Ciotti & Ostriker 2007; Ciotti , Ostriker & Proga in prep.)

3. Resulting properties for the ISM and the MBH: comparison with **observations**

   (Pellegrini et al., in prep.)

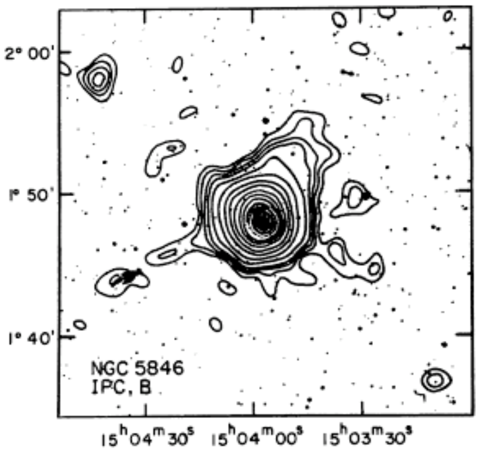
Basic facts

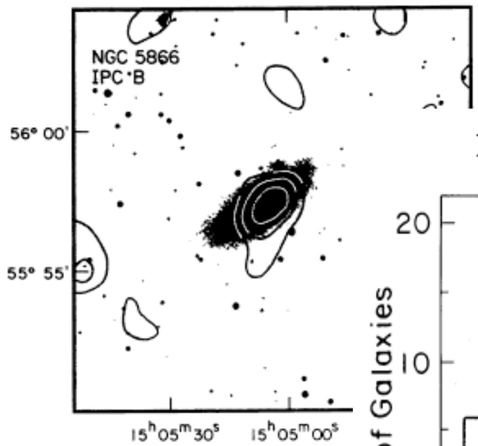
- **MBHs are present at the center of all spheroids** (e.g., Ferrarese & Ford 2005) with clear links with the host galaxies, as the M_{BH} - σ relation (e.g., Tremaine et al. 2002)

importance of coevolution

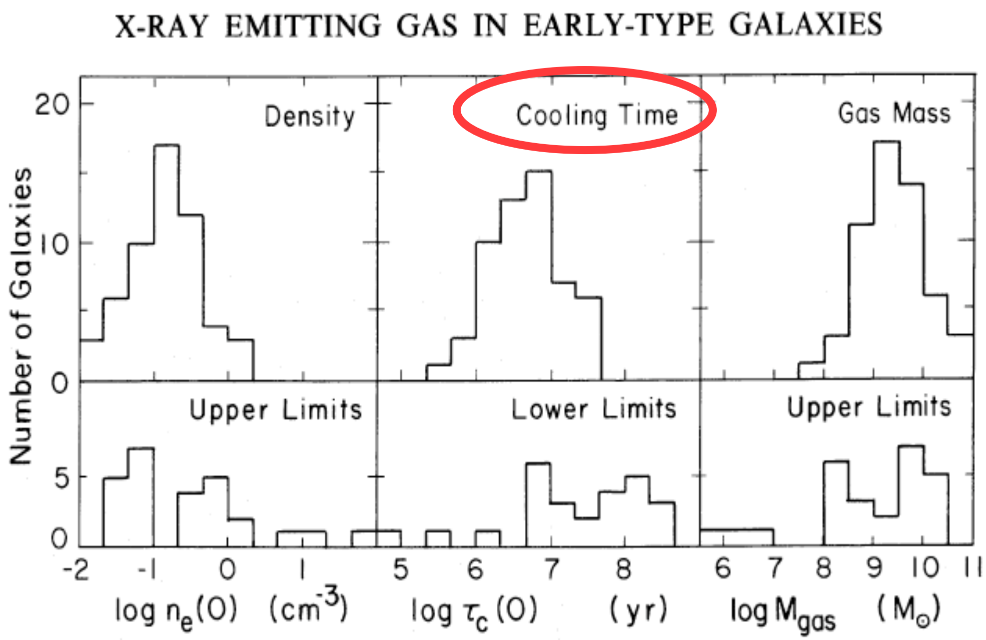
(e.g., Silk & Rees 1998, Sazonov et al. 2005, Murray et al. 05, Churazov et al. 05, Di Matteo et al. 07, Hopkins et al. 2006, Merloni et al.04, Omma et al. 2004, Croton et al. 2006, McNamara & Nulsen 2007, Rafferty et al. 2008, …)

- **A hot ISM is also present in early type galaxies** (kT~0.3-0.8 keV) **:**





Einstein's observations (Fabbiano et al. 1992, Canizares et al. 1987)



Origin of the ISM: evolving stars (Red Giants, PNe, SNe, …)

The **rate of mass loss** for a galaxy of mass M_* is :

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

for a passively evolving stellar population, of age ~0.5 to over 13 Gyrs.

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

Fate of the ISM:

$\dot{M}_*$ is heated by the thermalization of the kinetic energy of stellar motions + SNIa's ejecta

develops a **flow directed towards the galactic center** (e.g., Sarazin & White 1988, Ciotti et al. 1991, David et al. 1991, Pellegrini & Ciotti 1998).

The size of the inflowing region increases for deeper potential wells (on average, larger L_B)

central fuelling at a rate $\dot{M} \sim$ **0.01 - few $M_\odot$/yr**

can build up **$10^{10}\, M_\odot$** if undisturbed for many Gyrs…

Problems:

i) Ultimate fate of the cooling gas? Much debated, NOT OBSERVED.

MBHs of ~0.001 M_* at the center of Es (e.g., Magorrian et al. 1998) **:**

just ~ 1% of the available mass !

ii) Chandra & XMM-Newton showed **central mass cooling rates smaller** than above **(**Peterson et al. 2003, Peterson & Fabian 2006**)**

iii) Why QSOs are not seen in all Es, during their whole lifetime? (Fabian & Canizares 1988)

the answer could be →

Feedback modulated accretion

$L_{acc} \sim 10^{46}$ erg/s for accretion of $1\ M_{\odot}$ / yr

$L_{grav} \sim 10^{41}$ erg/s for extraction of $1\ M_{\odot}$ / yr from the galactic potential well

THE ISSUE: HOW and HOW MUCH **RADIATIVE** + **MECHANICAL** ENERGY

INTERACTS WITH the ISM

Can gas be **displaced** far from the galactic center
and even **removed** from the galaxy?

(Binney & Tabor 1994 … Omma et al. 2004; Ciotti & Ostriker 1997… 2008; Di Matteo et al. 2003,
Sijacki et al. 2007)

Ciotti, Ostriker & Proga (in prep.):

a high resolution hydrodynamical code, with a detailed treatment of
radiative + mechanical energy input & transfer to the ISM

- GALAXY STRUCTURE: **cuspy stellar** model (Jaffe) + **dark halo** (Keeton et al. 07)
  + internal dynamics from Jeans equations
- **stellar mass losses** from stellar evolution theory
- **SNIa rate** (Cappellaro et al. 1999) with temporal evolution of recent models (Greggio 05)
- **RADIATIVE** FEEDBACK:

  Gas heating & cooling for photoionized plasma in equilibrium with average quasar SED (Sazonov et al. 2005)

  Radiation pressure and absorption from radiative transport equation
- **MECHANICAL** FEEDBACK:

  Quasar outflows (observed: Chartas et al. 03,07; Crenshaw et al. 03, Pounds et al. 03, Blustin et al. 07;
  modelled numerically: Proga 03, McKinney 06)
- Star-formation via conventional formalism

CON: SPHERICAL SYMMETRY

PROs: **ACCRETION & FEEDBACK** EFFECTS **consistently determined**
and followed for the whole galactic evolution

Recipes. 1. **MBH accretion**

MASS:

inside the first grid point (2.5 pc) a disc is assumed : $\boxed{\dot{M}_{disc,gas} = \dot{M}_{in} - \dot{M}_{BH} - \dot{M}_{W} - \dot{M}_{SF}}$

$\dot{M}_{BH} = \dot{M}_{feed} / (1+ \eta_d)$, with $\left\{ \begin{array}{l} \dot{M}_{feed} = M_{disc,gas} / \tau , \\ \eta_d = \dot{M}_{feed} / 2\dot{M}_{Edd} \end{array} \right.$

$\tau = 2\pi/\alpha \sqrt{r_{disc}^3 / GM_{BH}}$, α =disc viscosity

r_{disc} = MBH sphere of influence

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

so that :

η_d **<<1:** gas accreted at $\dot{M}_{feed}$

η_d **>>1:** gas accreted at $2\dot{M}_{Edd}$

Outside the first grid point , accretion is self-consistently determined.

LUMINOSITY:

$L_{BH} = \varepsilon\, \dot{M}_{BH}\, c^2$ where $\boxed{\varepsilon = 0.1\, A\, \dot{m} / (1+ A\, \dot{m})}$ **ADAF-like** radiative efficiency (Narayan & Yi 94)

$\dot{m} = \dot{M}_{BH} / \dot{M}_{Edd}$

A=100

so that:

$\dot{m} > 10^{-2}$: $\varepsilon \sim 0.1$

$\dot{m} < 10^{-2}$: $\varepsilon \sim 0.1\, A\, \dot{m} < 0.1$

Recipes. 2. **Radiative heating & cooling rates**

From the Sazonov et al. 05 formulae for a plasma in photoionization equilibrium with the radiation field of an **average quasar SED**, with spectral temperature **T_X = 2 keV > T_{VIR}**.

Includes: **bremsstrahlung** losses (S_1), **Compton heating & cooling** (S_2), **photoionization heating** plus **line and recombination cooling** (S_3):

E=gas internal energy

$$\boxed{\dot{E} = n^2(S_1 + S_2 + S_3) \equiv H - C,}$$

where (all cgs):

$$S_1 = -3.8 \times 10^{-27}\sqrt{T},$$

$$S_2 = 4.1 \times 10^{-35}(T_X - T)\,\xi$$

$$S_3 = 10^{-23}\frac{a + b\,(\xi/\xi_0)^c}{1 + (\xi/\xi_0)^c}$$

T_x : AGN Compton temperature

ξ= ionization parameter
= L(r) / n(r) r^2

$$\xi_0 = \frac{1}{1.5/\sqrt{T} + 1.5 \times 10^{12}/\sqrt{T^5}} + \frac{4 \times 10^{10}}{T^2}\left[1 + \frac{80}{e^{(T-10^4)/1.5\,10^3}}\right]$$

$$a = -\frac{18}{e^{25(\log T - 4.35)^2}} - \frac{80}{e^{5.5(\log T - 5.2)^2}} - \frac{17}{e^{3.6(\log T - 6.5)^2}},$$

$$b = \frac{1.7 \times 10^4}{T^{0.7}},$$

$$c = 1.1 - \frac{1.1}{e^{T/1.8\,10^5}} + \frac{4 \times 10^{15}}{T^4},$$

Recipes. 3. **MECHANICAL FEEDBACK**

[1. Shock waves originated by purely radiative feedback]

2. AGN Winds

MASS: a fraction of disc mass $\mathbf{M_{disc,gas}}$ is lost in a wind: $\dot{\mathbf{M}}_\mathbf{W} = \eta_\mathbf{W}\,(\mathbf{l})\,\dot{\mathbf{M}}_\mathbf{BH}$

LUMINOSITY (from 2-D hydro for radiatively driven winds, Proga et al. 1998):

$$\mathbf{L_W = \varepsilon_W(l)\,\dot{M}_{BH}\,c^2} \qquad\qquad l = L_{BH} / L_{Edd}$$

ε_W^{max} ~ few 10^{-4} to few 10^{-3} is the maximum wind efficiency (for $l = 2$),

$v_W \sim 10^4$ km/s

The fraction of wind mass, momentum, energy **deposited in the ISM at each r** from a (phenomenological) differential equation dependent on $P_{ISM}(r) / P_{wind}(r)$. Typically released **within 100-300 pc**.

SUMMARIZING:

For $l \sim 1$ ➔ high $\varepsilon \sim 0.1$, high $\varepsilon_W \sim \varepsilon_W^{max}$ ("AGN mode")

For $l < 0.01$ ➔ low $\varepsilon < 0.1$, $\varepsilon_W \sim 0$

General evolution

Representative model: $M_* = 3\times10^{11}\ M_\odot$, $\mathbf{L_B=5\times10^{10}\ L_{B\odot}}$, central σ = 260 km/s
R_e=6.9 kpc (from fundamental plane)
$M_* = M_{dark}$ within R_e
$\mathbf{M_{BH,0} = 3\times10^8\ M_\odot}$ (close to Magorrian relation)

Initial conditions: low density gas at virial temperature, t_0 = 2 Gyr (for the stellar population)

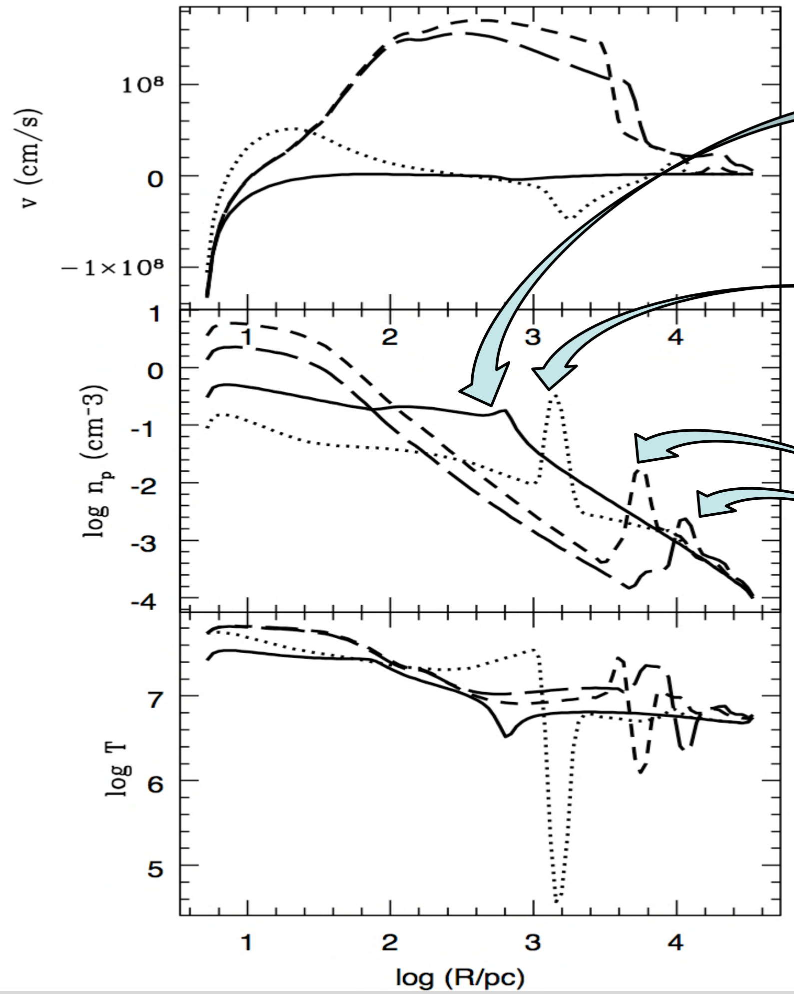
Typical cycle

cold collapsing shell ➔ accretion on MBH ➔ feedback

(shock waves + new cold shell + new collapse … central hot bubble, matter pushed out, huge degassing, accretion rate drops)

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

Hydro of an outburst (Δt ~ 0.2 Gyrs)



Δt=0.02 Gyrs :

t0 ————
t1 · · · · · ·
t2 — — — —
t3 —— —— ——

t0: low density hot accretion
a denser/colder **shell**
is forming (solid)

t1 : the shell has reached the center
a **radiative shock is moving outward**
it creates regions of hotter and colder gas,
and a new infalling shell

t2, t3: outward propagation of the second
larger outburst + hot/dense region at the
center

OBSERVATIONAL X-RAY PROPERTIES

ISM:

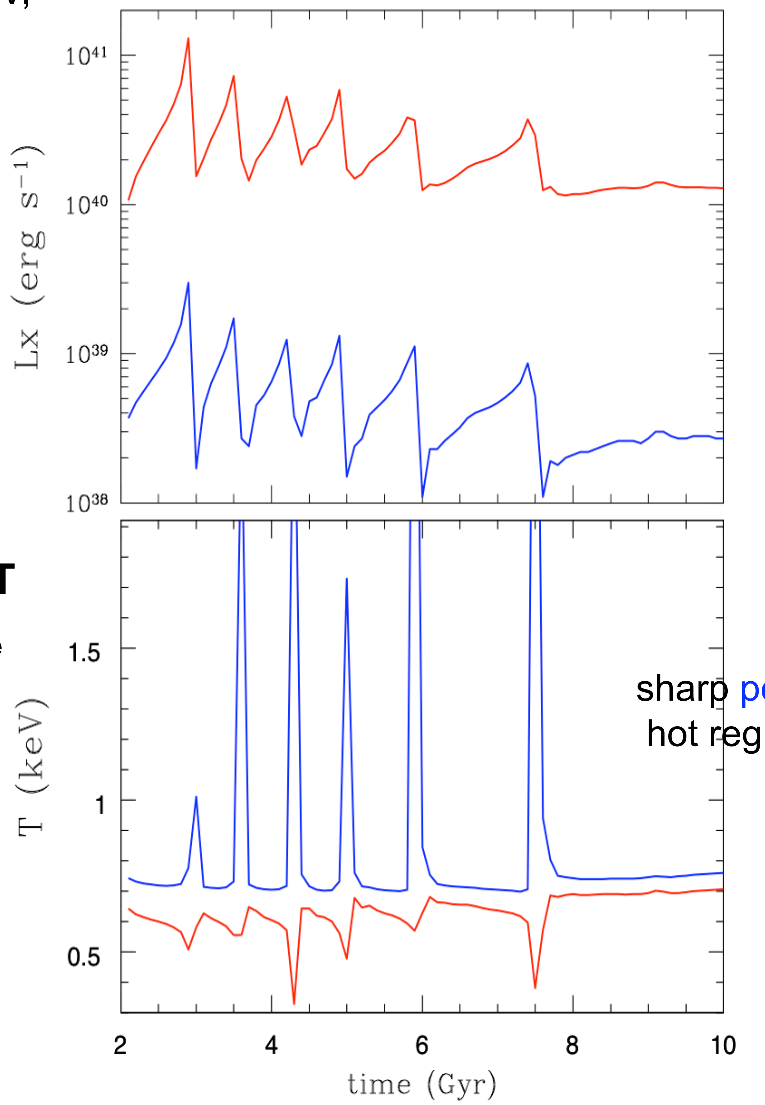
global T, L
brightness profiles

MBH:

nuclear L

Time evolution of gas emission and temperature

Gas emissivity $n_e(r)\, n_H(r)\, \Lambda(T,Z)$
with $\Lambda(T,Z)$ estimated over 0.3-8 keV,
for plasma with solar abundance
(Grevesse & Sauval 1998)
from APEC code within XSPEC



Red: 0.3-2 keV
Blue: 2-8 keV

emission weighted T within the optical R_e

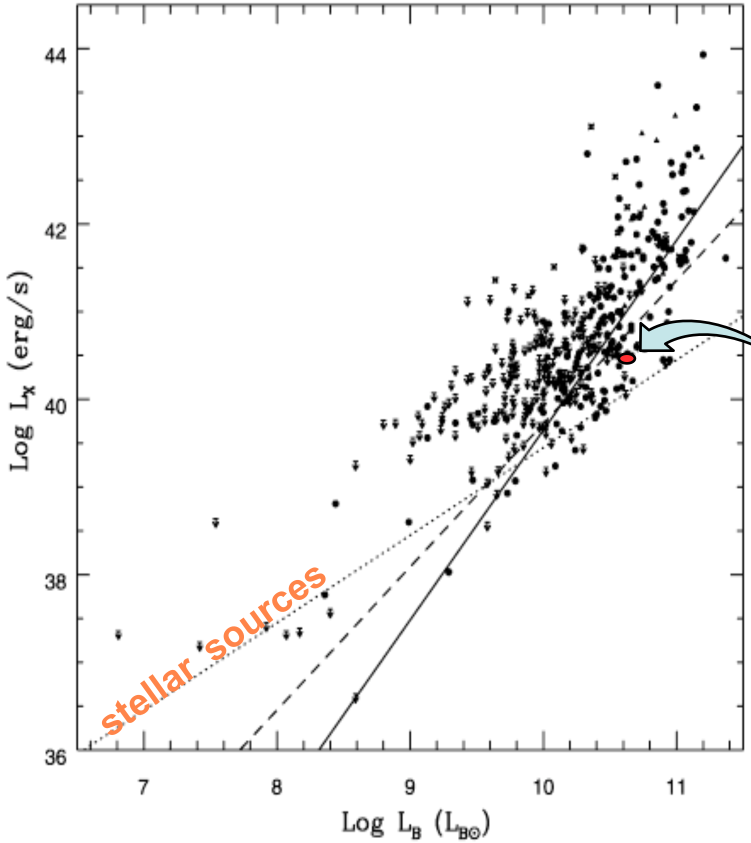
sharp peaks in **kT** :
hot regions during outbursts

decrements in **kT** :
cold shell and cold gas left by the passage of radiative shock waves

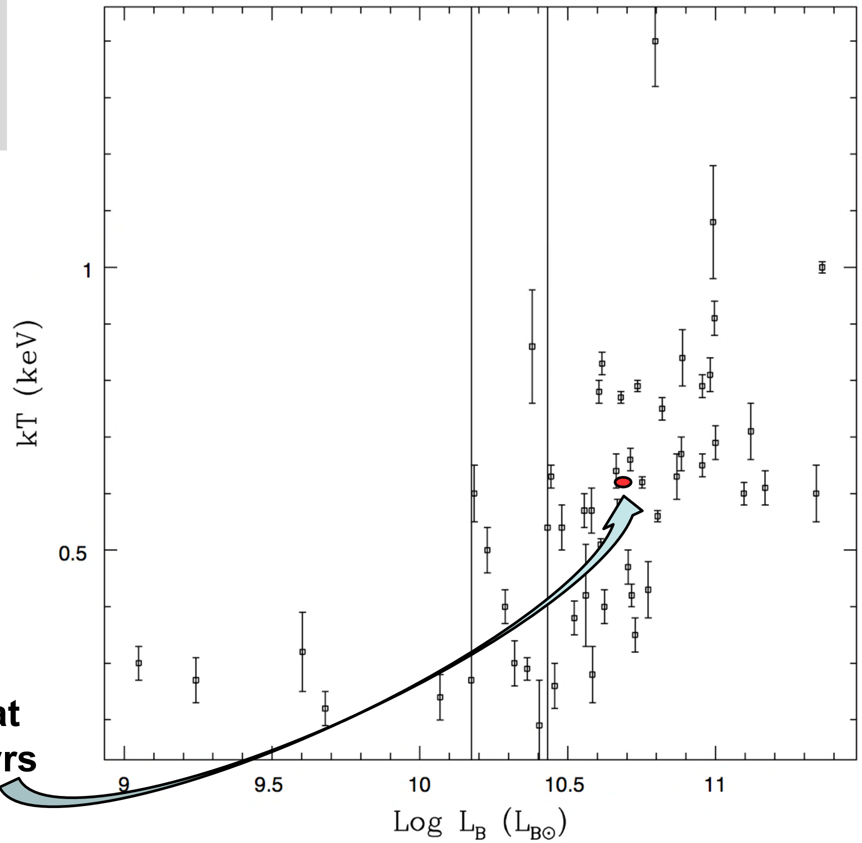
Lx and kT observed for the hot ISM (present time)

Observed 0.3-8 keV emission weighted T within Re (Athey 2007) :

Largest catalog of ISM X-ray emission (mostly ROSAT observations, O' Sullivan et al. 2001):

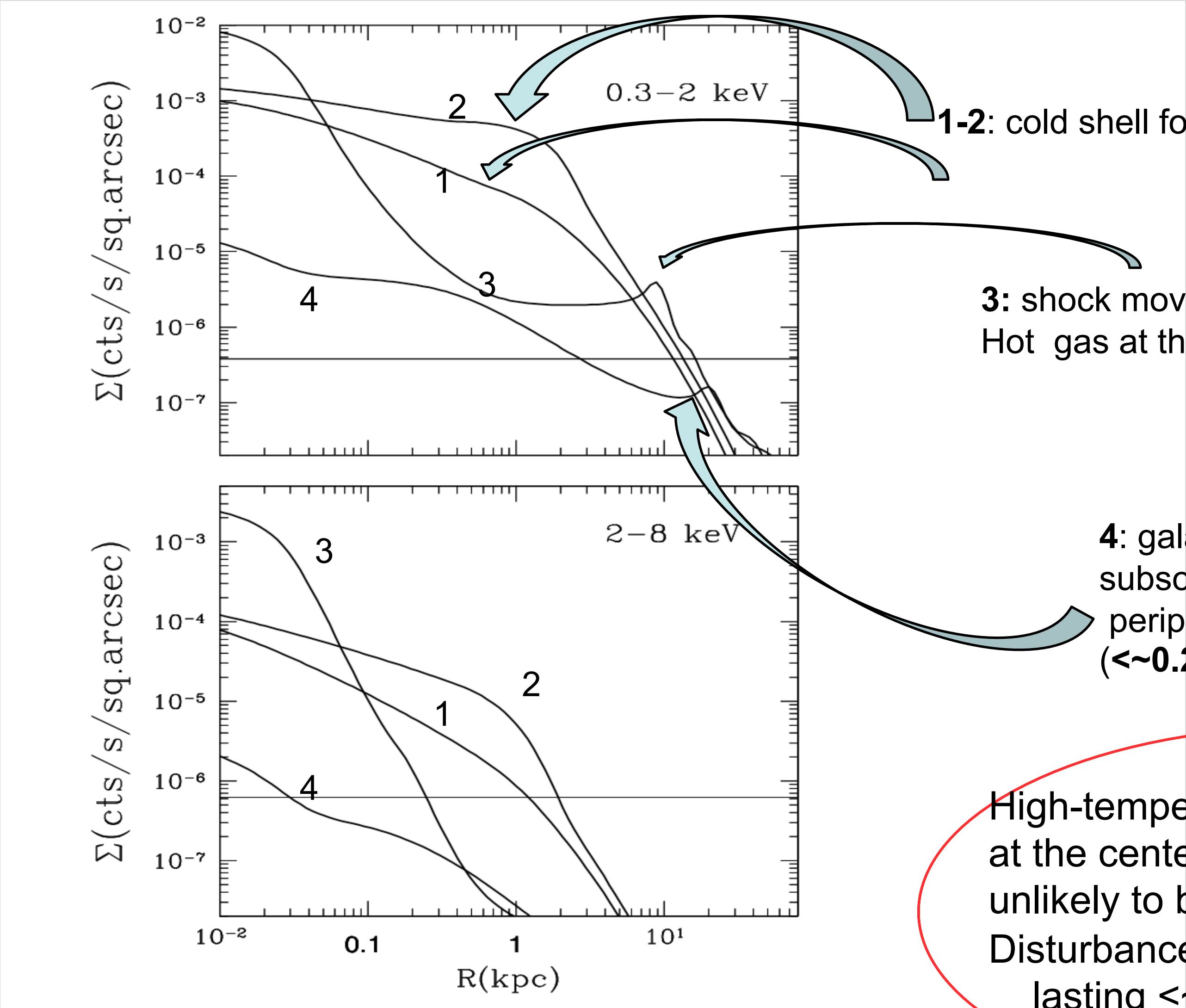


model at t~10 Gyrs



gure 2. Log L_X versus Log L_B for our full catalogue of 401 early-type galaxies. Triangles are cluster central galaxies; asterisks are AGNs; circles are all other tections; arrows are upper limits. The lines shown are: the best-fit line to the early-type galaxies excluding AGNs, BCGs and dwarfs (solid line); the best fit to e galaxies excluding all questionable objects (dashed line); and an estimate of the discrete-source contribution taken from Ciotti et al. (1991).

Brightness profiles pre-after burst



1-2: cold shell forming (**>~0.5 Gyr**)

3: shock moving outwards after a major burst
Hot gas at the center for **~ 2x10^7 yr**

4: galaxy has low density,
subsonic perturbations at the galaxy periphery
(**<~0.2 Gyr since outburst started**)

High-temperature, high-density phase at the center (**3**) very brief, unlikely to be observed.
Disturbances as shells, ripples lasting <~0.2 Gyrs more likely to be observed

Depending on SNIa's rate, central σ, dark matter,

bursts can take place even at **present epoch**

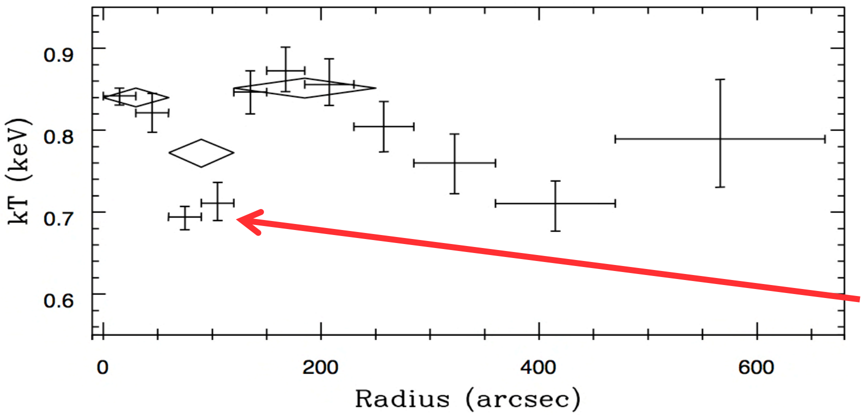
(though frequency difficult to estimate … duty cycle ~10^{-3} - 10^{-2} in the past few Gyrs)

Chandra revealed **widespread hot gas disturbances** in nearby early type galaxies
(e.g., "hot gas gallery" of 54 normal ellipticals, Diehl & Statler 2008)

a few have very weak nuclear sources
(at optical, radio, X)
& no evident jet activity

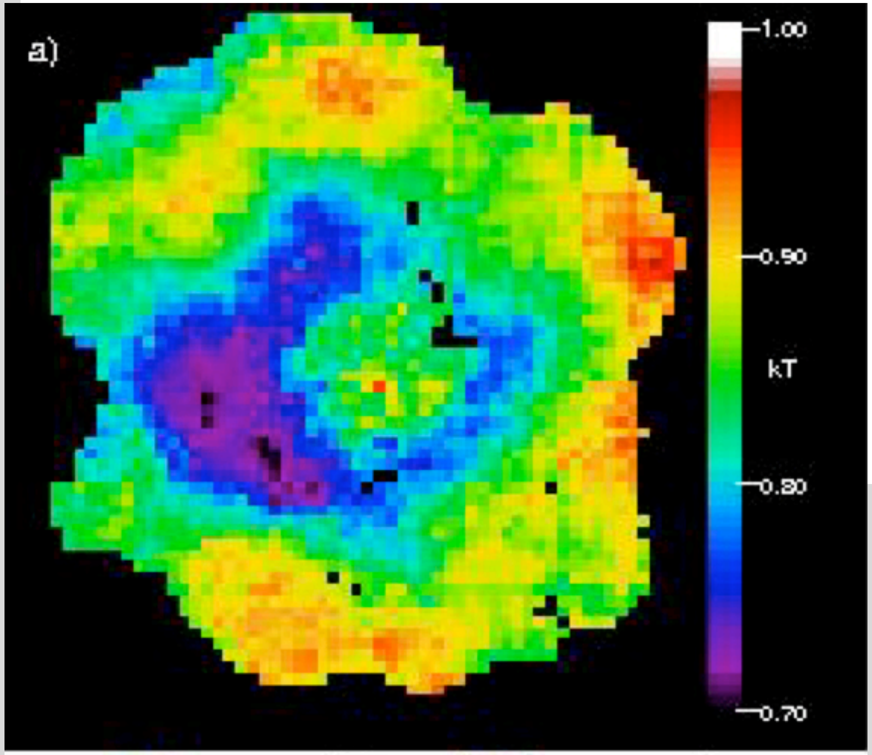
NGC3411 (O'Sullivan et al. 07)

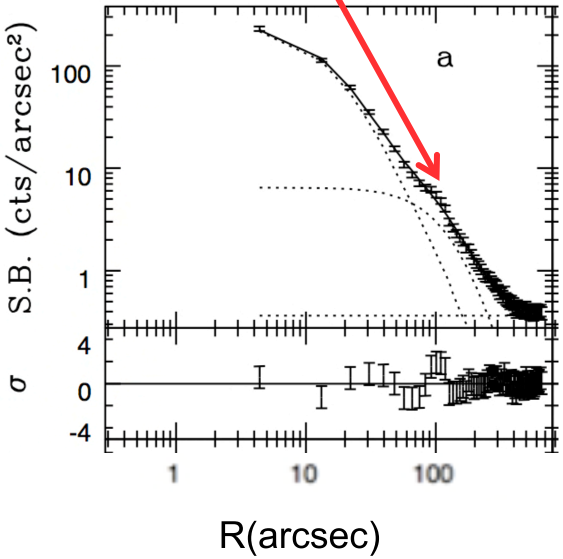
1'=19 kpc



cool shell

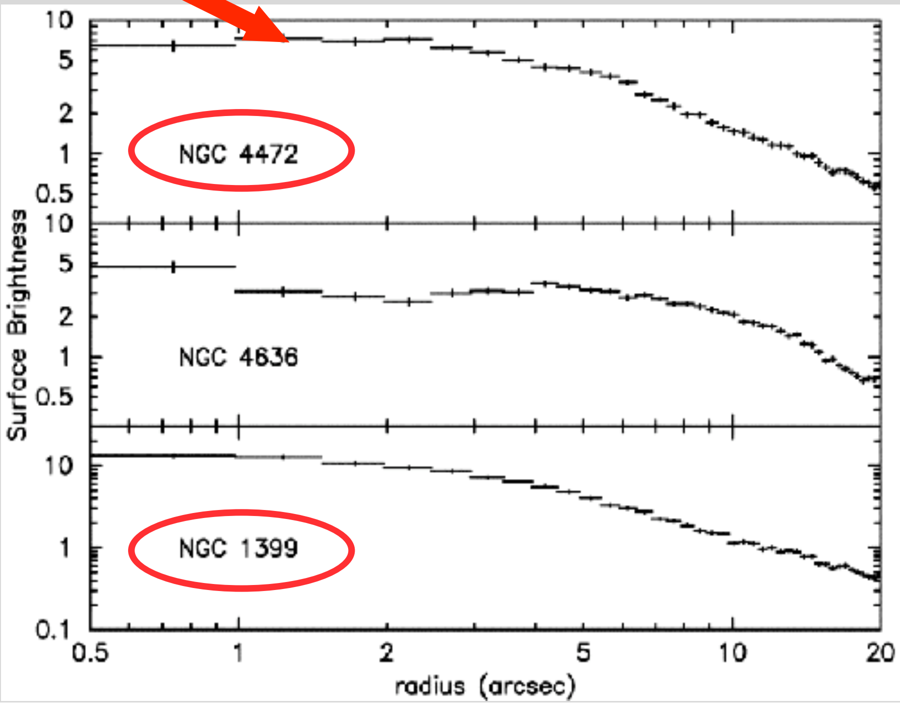
T-map (XMM)





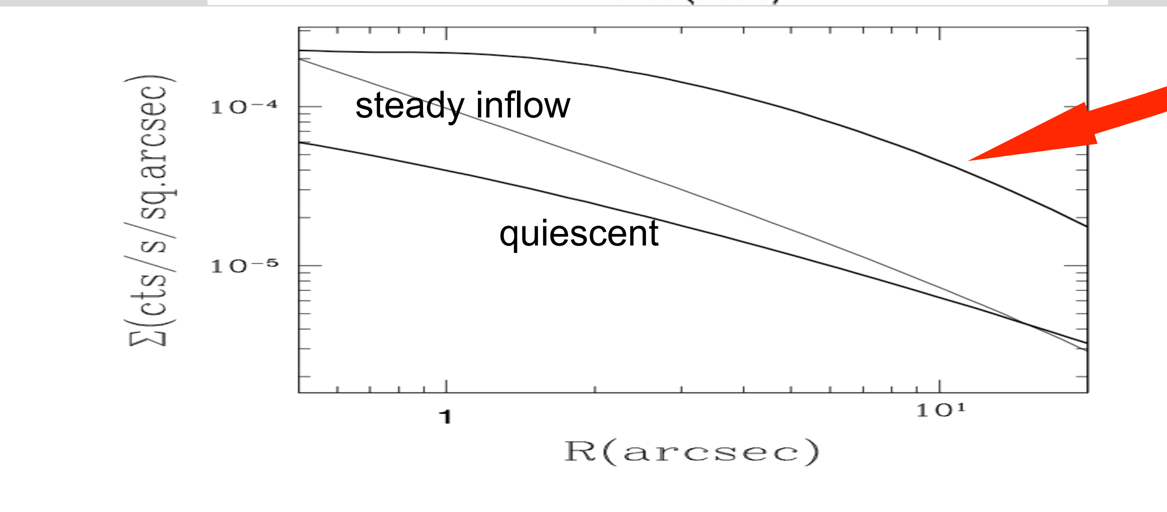
Chandra ACIS-S $\Sigma_x(R)$ of NGC1399, NGC4472 :

centrally ***"flat"*** **,** not as predicted for steady inflows



0.3-7 keV

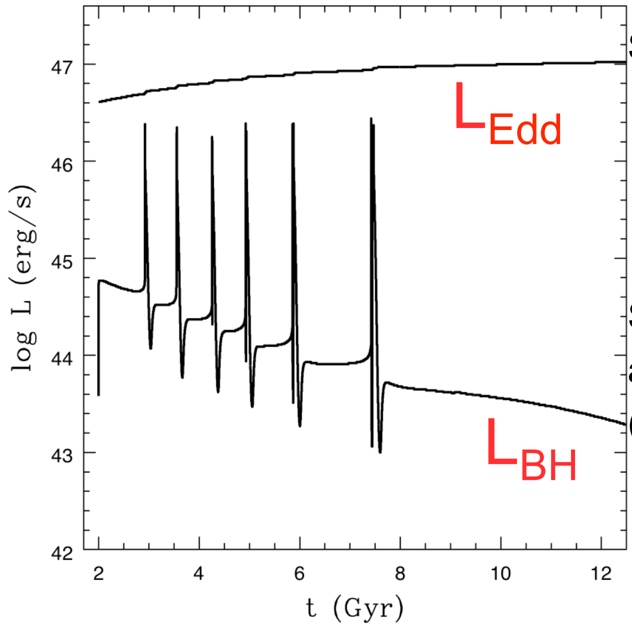
Loewenstein et al. (2001)



preburst phase
of models

(x-scale for the Virgo
distance)

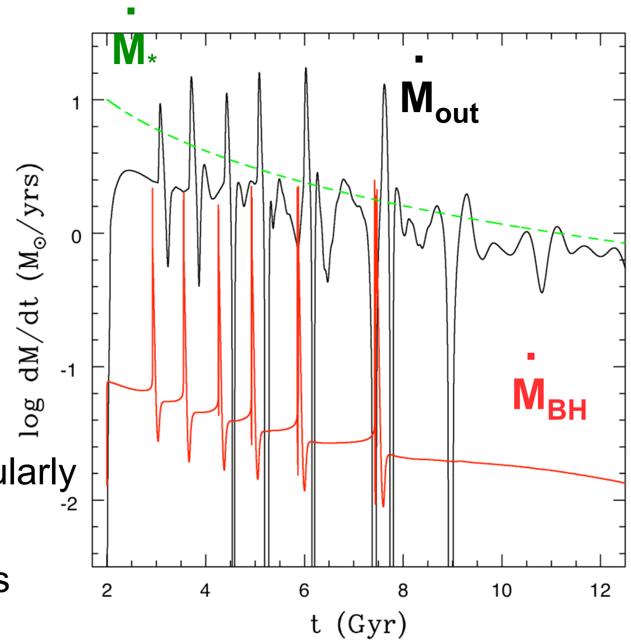
Nuclear luminosities



Strong intermittencies at early times, L_{BH} close to L_{Edd}

Smooth, very sub-Eddington accretion at low redshift (with rare outbursts)

Stellar mass loss rate secularly declines ➔ time lag between outbursts increases



- a negligible time in the (thin disk) phase of high luminosity
- most of the time in a "quiescent" phase ($l = L_{BH} / L_{Edd} < 10^{-2}$, $\dot{m} = \dot{M}_{BH}/\dot{M}_{Edd} < 10^{-2}$) (see also Hopkins et al. 06)

At the end, M_{BH}=8x10^8 $M_\odot$ (grown by 2.5x instead of 100x !)

Observed distribution of L_{BH}/L_{Edd}

- In the statistically complete **Palomar spectroscopic survey** (486 nearby galaxies with B_T<12.5mag of the northern emisphere ➔ contains **both active and inactive nuclei**,
  Ho et al. 97)

  ~50% of ellipticals has detectable emission line nuclei

  mostly of low level: $L_{H\alpha}<10^{40}$ erg/s

  87% of them are LINERs

  (Ho 2008, ARAA; Nagar et al. 05, Satyapal et al. 05, Flohic et al. 06: large fraction of LINERs are accretion powered)

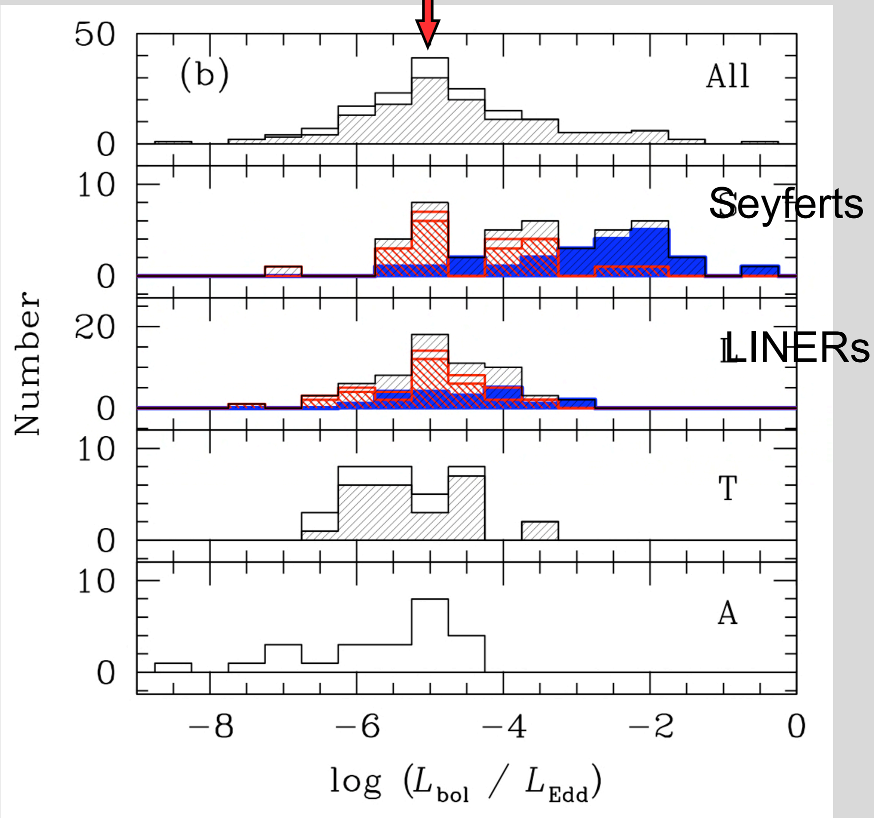
- In the sample of red sequence galaxies of the **SDSS** (r<17.77, median redshift z=0.1):

  ~52% have detectable line emission;

  >29% are LINERs, <17% are Seyferts (Yan et al. 2006)

From Palomar survey objects **with nuclear Lx measured:**

Average L_{bol}/L_{Edd} ~10^{-5}



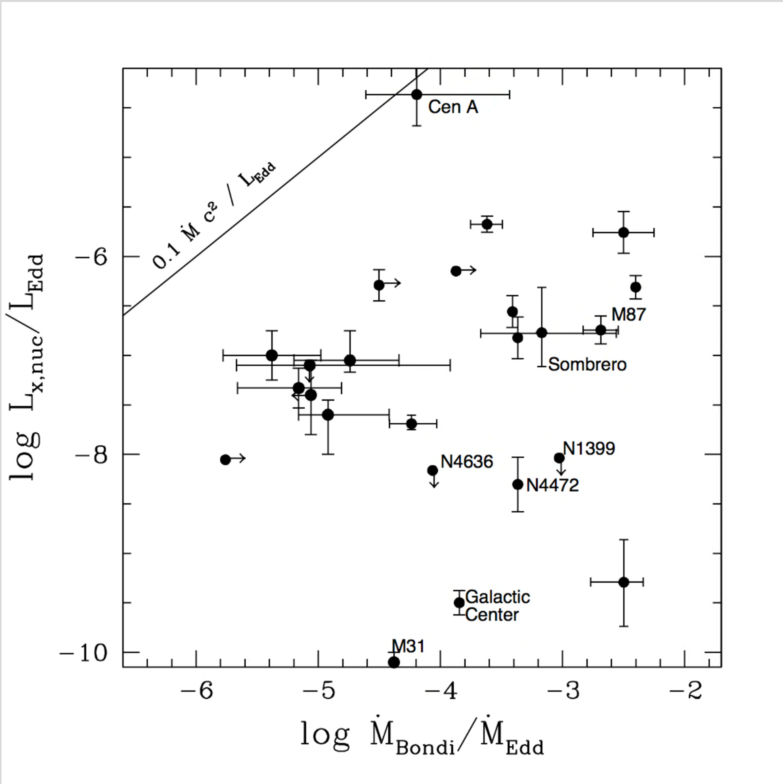
Ho (2008)

L_{bol} from L(2-10 keV)
(with L_{bol}/Lx=83, 28, 16 for QSO, Sey, LLAGN)

L_{Edd} from M_{BH}-σ

For many of the best studied nuclei L_{bol}/L_{Edd} is often much lower …

For a sample of “quiescent” nuclei of the local Universe :



(Pellegrini 2005, updated;
see also Gallo et al. 2008)

$L_{X,nuc}$ from Chandra observations

M_{BH} from specific (HST) measurements

$\dot{M}_{Bondi}$ from Chandra observations
(ISM ρ and T close to accretion radius)

l ~ 10^{-5} – 10^{-8} (<10^{-4} of models)

$\dot{M}_{BH}$ must be further reduced:

- central stellar profile **less cuspy** than Jaffe
- **angular momentum** at large radii (net flow reduced, e.g., Proga & Begelman 2003)
- convective motions or **coronal winds** transport energy and mass at large radii

  (Narayan & Yi 94, Stone et al. 99, Blandford & Begelman 1999, de Villiers et al. 2003, McKinney & Gammie 04)

  this has been found important for SgrA* (Quataert & Gruzinov 00, Yuan et al. 04)

Conclusions

Observational properties of a new class of models for joint MBH & ISM evolution:

feedback typical of high L/L_{Edd} phases (radiative & AGN wind) + SNIa's

effective in solving cooling flow problem AND maintaining "small" MBH masses
(gas lost in outflows or starbursts)

Conclusions

Hot ISM:

- **Global Lx, T** of the models at an age of ~10 Gyrs compare well with those of local galaxies.

  Large dispersion in observed Lx, T for a given L_B : different phases in the periodic activity ?

- **Disturbances** in the hot gas produced by an outburst (T-profile, brightness profile) are

  detectable with *Chandra*
  last for <~0.2 Gyrs.

Could match part of widespread disturbances observed in galaxies of the local Universe.

Conclusions

Nuclear luminosities:

- At an age of ~10 Gyrs the model MBHs are **very sub-Eddington** (L/L_{Edd} ~10^{-4}), close to peak L/L_{Edd} ~10^{-5} observed (for galaxies with measured $L_{X,nuc}$)

- **Many nuclei** (among the best observationally constrained) **have $L/L_{Edd} < 10^{-4}$** in the local Universe:

  additional reduction of the mass available for accretion ?

  is this reduction due to a **thermally driven wind** from an ADAF?

  is this wind producing **another form of feedback**, affecting the ISM evolution?