Hot ISM in early-type galaxies with stellar and AGN feedback: X-ray diagnostics of the origin and evolution of the hot gas

S. Pellegrini

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

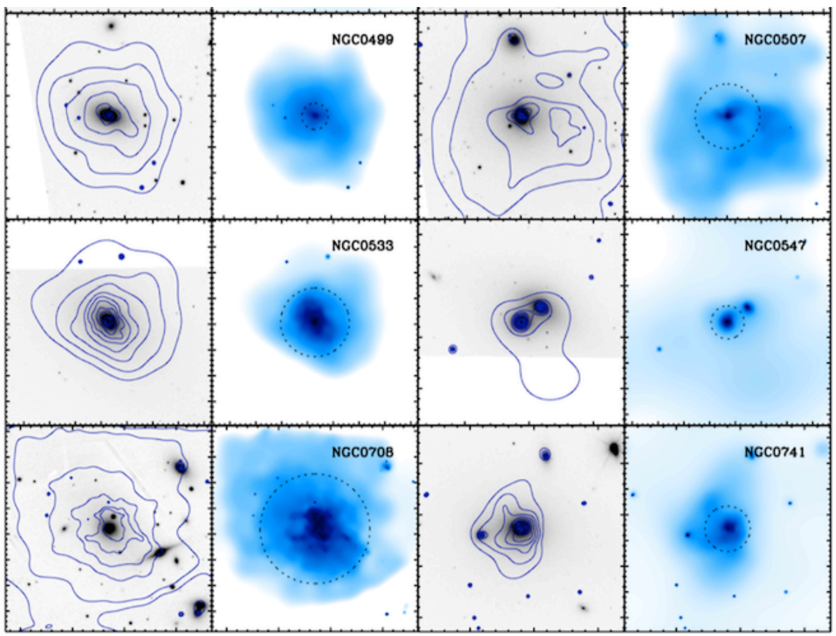
with:

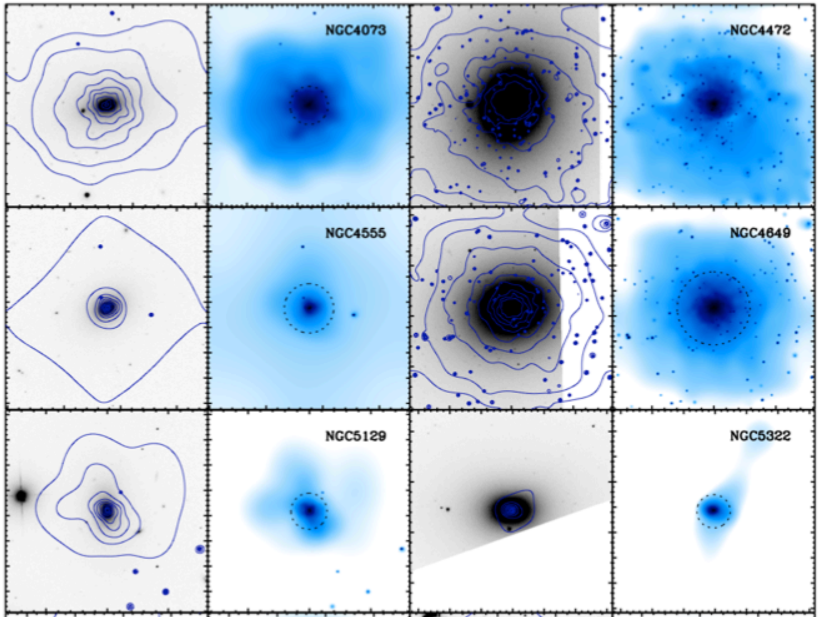
L. Ciotti (*Univ. of Bologna*),

Z. Gan, **J.P. Ostriker** (*Columbia Univ., NY*)

A. Negri (*Inst. de Astrofisica de Canarias, Spain*)

Optical and *Chandra* ACIS images, 4x4 arcmin





Goulding et al. 2016

SEE ALSO: Kim, D.-W. et al. 2019, *Chandra galaxy Atlas*

What observations provide (ETGs of local universe)

- Global L_x, T_x, Z
- Surface brightness profiles Σ_X (R)
- Temperature profiles T(R)
- Abundance profiles Z(R)

also: Fe(R)

what CAN these observations tell us about the origin an evolution of the (hot) ISM in ETGs ?

XMM-Newton and Chandra observations accumulated a detailed view of many of these properties

for a *large sample*

What observations provide
(ETGs of local universe)

- Global L_X, T_X, Z
- Surface brightness profiles Σ_X (R)
- Temperature profiles T(R)
- Abundance profiles Z(R)

also: Fe(R)

XMM-Newton and Chandra observations accumulated a detailed view of many of these properties

for a *large sample*

What modeling should include

- Realistic galaxy models
(mass distribution and stellar kinematics)
- Accurate sources of mass & metals
- Gas heating & cooling (AGN + SNe)
- Star formation
- Environment

simulations with *high* spatial *resolution*

follow a *significant part* of the galaxy *lifetime*

for *many* representative galaxies

($M_\star$, shape, v/σ, environment, ...)

Hydrodynamical modeling of the ISM evolution in ETGs

- 2D, grid-type, **high-resolution** (parsec-scale at the center) simulations
- ISM evolution followed for **Δt ~10 Gyr**

  [from age ~ 2 Gyr, after the main galaxy formation phase]

Modeling includes

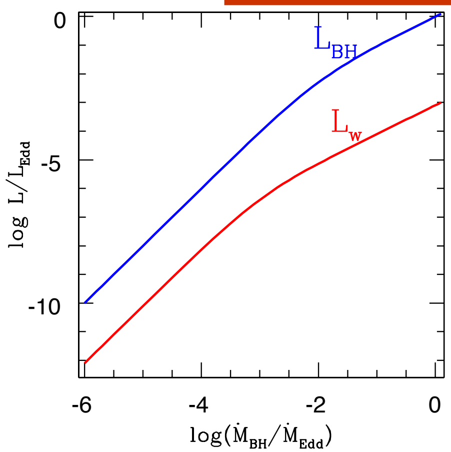
gas mass sources:

the **old**, ageing stellar population
new star formation
circumgalactic infall

heating sources:

SNIa, SNII

mechanical (from AGN winds)
and **radiative** AGN feedback



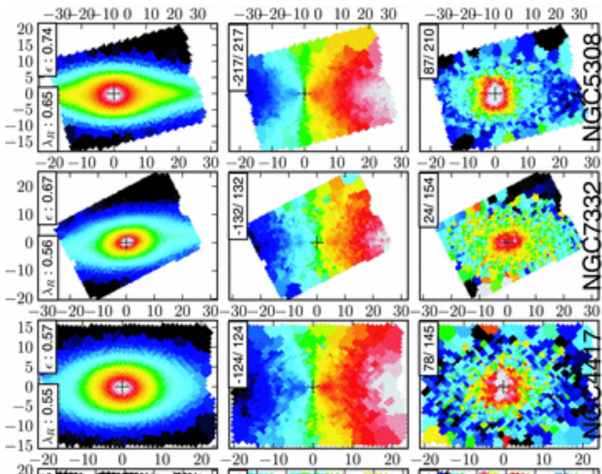
heating from accretion is self-determined
➔ the “strength” of AGN feedback is not “adjusted”

realistic ETGs models

3 components: **MBH** + **stars** (ellipsoidal Jaffe law) + **DM halo**

(L, R_e, σ_e) lie on the scaling laws observed for ETGs

stellar kinematics from Jeans equations
(random motions + streaming)

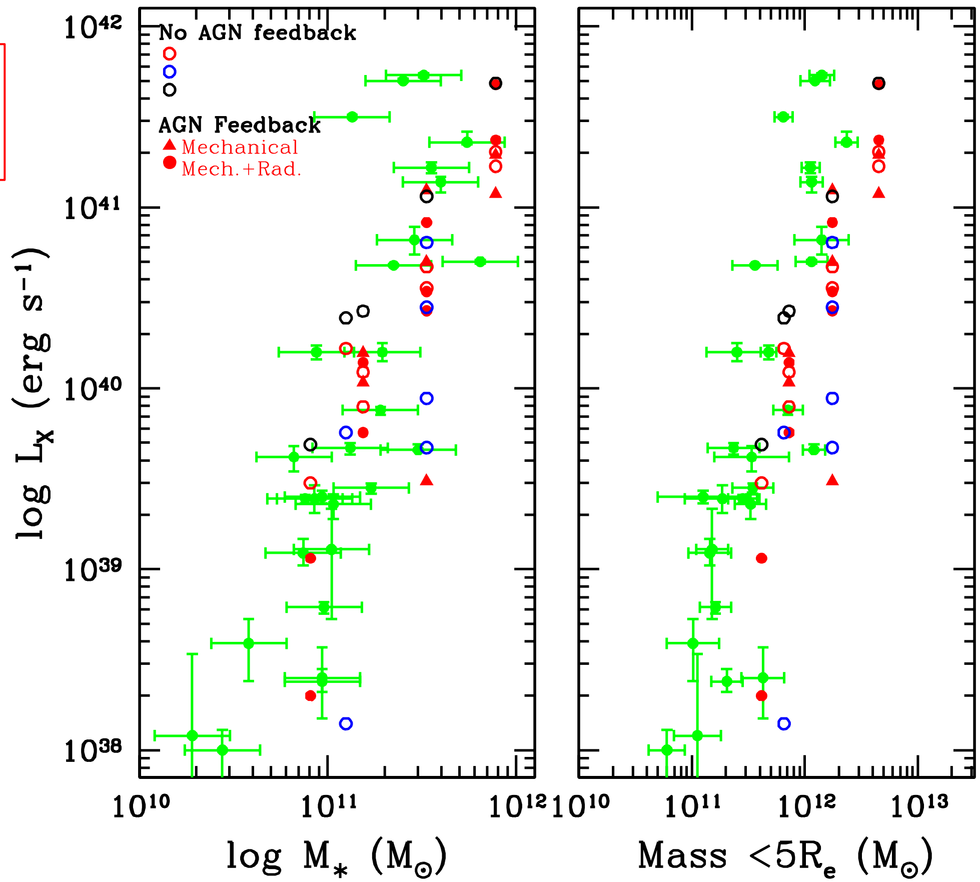


diagnostics considered:

- total L_x , average T_x
- T(R)
- abundance Z and Z(R)

AGN feedback and total L_X
[mass sources from stars only]

green points:
local ETGs
Forbes et al. 2017



isolated galaxy models

all at same epoch (t=12 Gyr)

Pellegrini et al. 2018

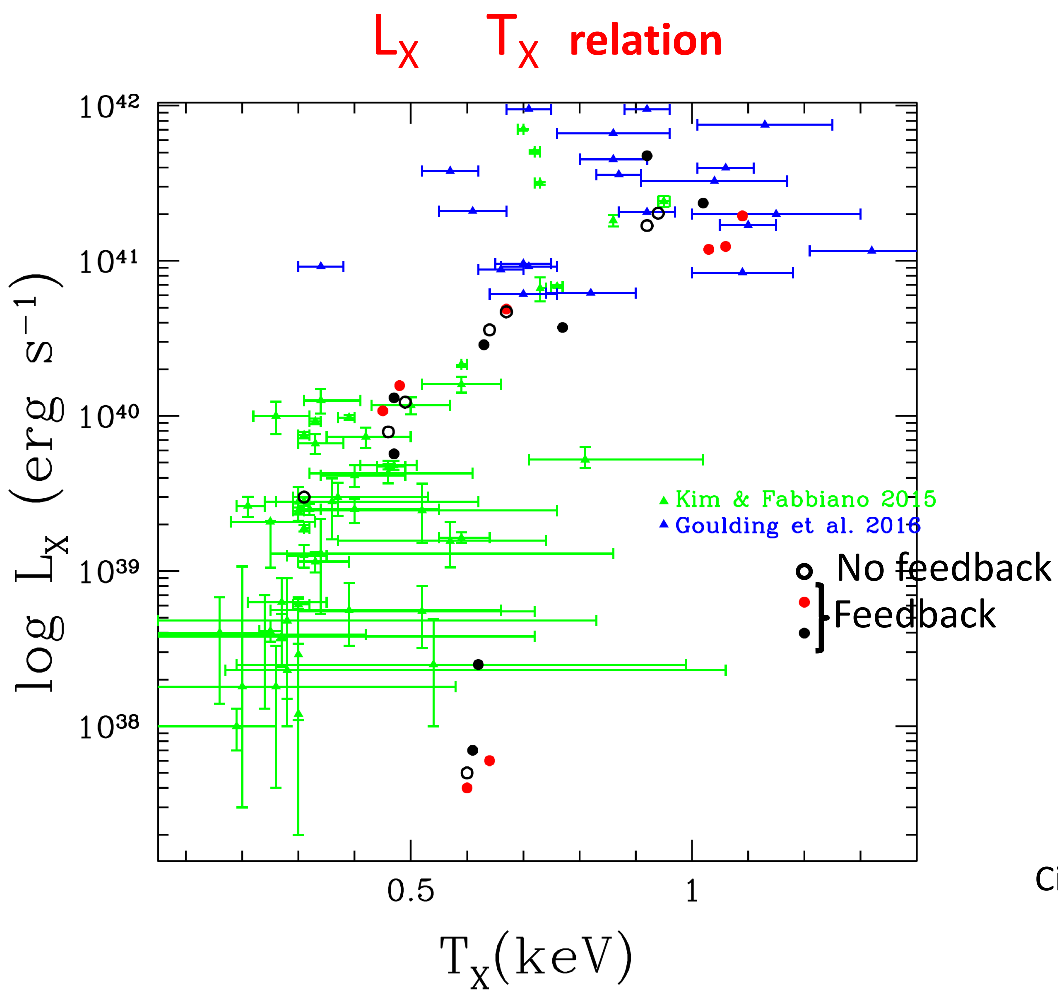
1) **total** L_X not significantly affected by AGN feedback

AGN feedback causes *an increase* in the ejected mass from the galaxy, not major outflows, after *z*~2

➔ *present-day* L_X *is not a diagnostic of the impact of* past *AGN activity*

2) the *mass input from the stellar population can account* for a major part of the observed L_X
(for ETGs that are NOT central in groups or clusters)

AGN feedback and average T_X [mass sources from stars only]



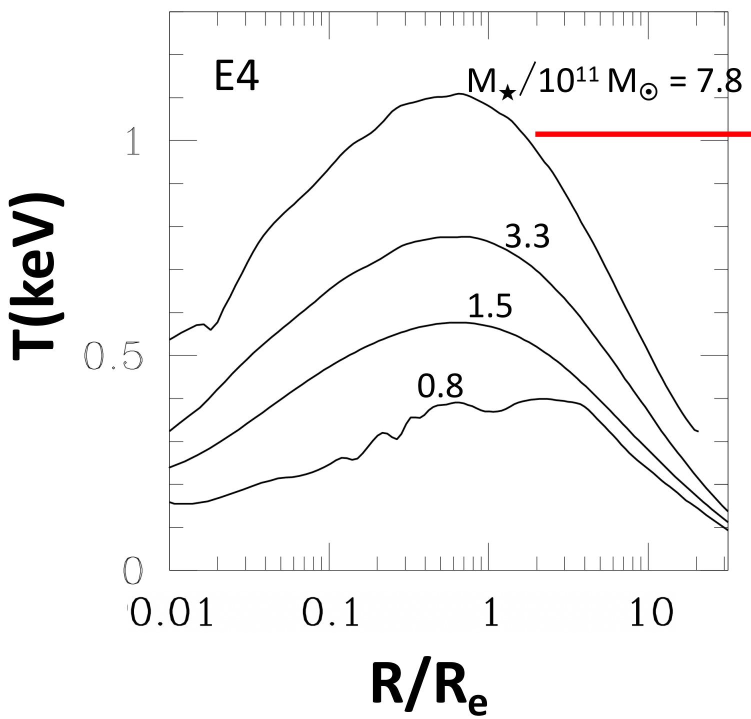
Ciotti et al. 2017

Feedback and NO Feedback models occupy similar regions ➔ **average T_X** not significantly affected

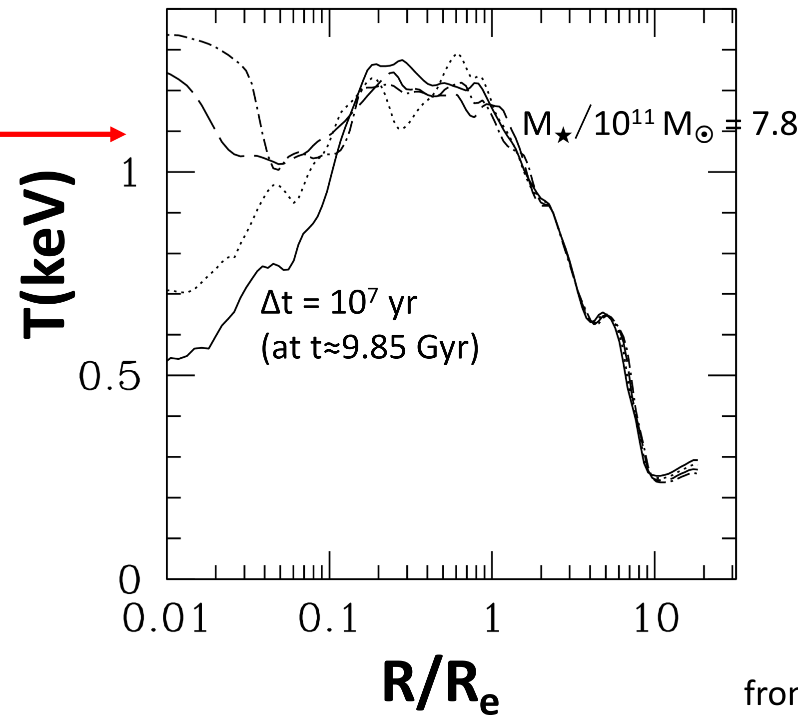
AGN feedback and temperature profiles

X-ray emission-weighted, projected and circularized **T(R)**

NO AGN feedback



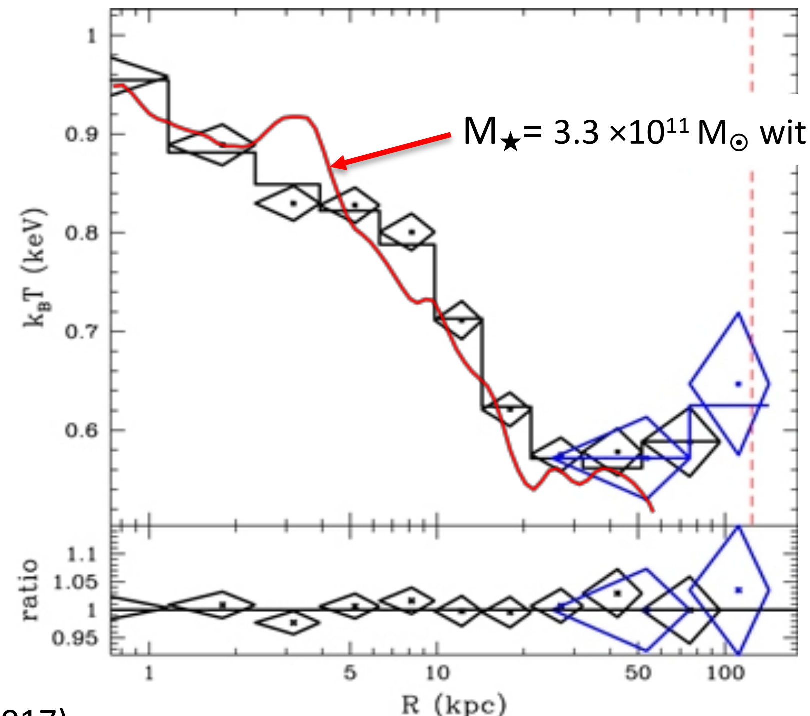
with AGN feedback



from isolated,
NON-ROTATING
galaxy models
in Ciotti et al. 2017

An example of a massive, isolated ETG: NGC6482

L_K=3.3 10^{11} $L_{K\odot}$



$M_\star$= 3.3 ×10^{11} $M_\odot$ with AGN feedback, t=12 Gyr

Buote (2017)
Chandra observation

But:
how common are T(R) like this?

large set of T(R) profiles in

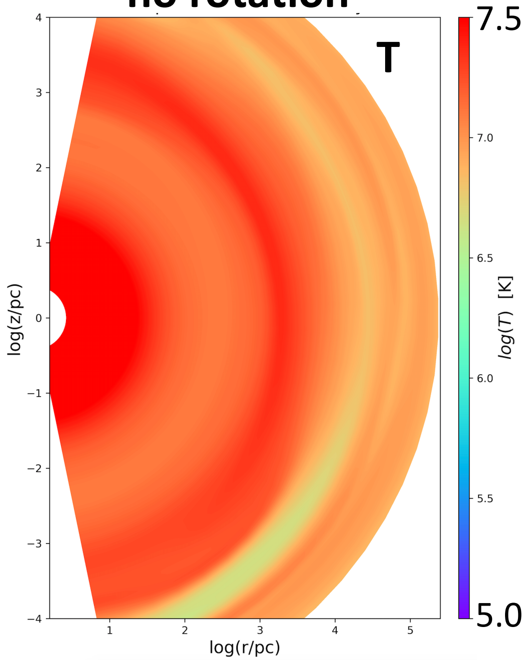
Lakhchaura et al. 2018
Chandra Galaxy Atlas (talk by D.-W. Kim)

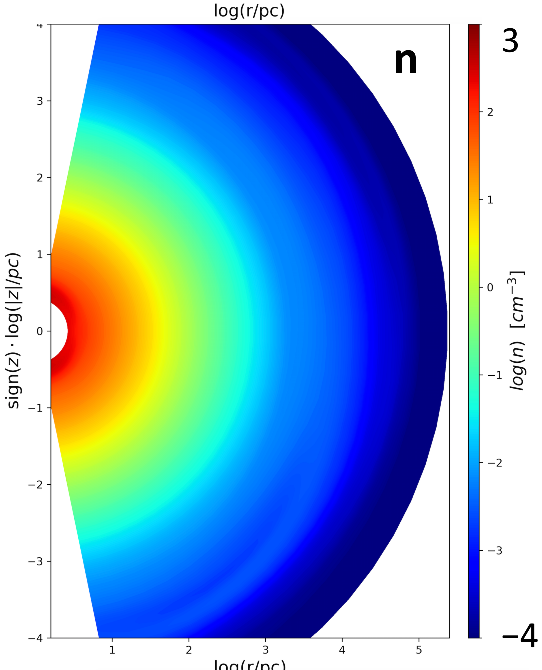
T(R) promising, powerful diagnostic:

how frequently the AGN is on?
how efficiently does it heat the central few kpc?

Galactic rotation

no rotation





stellar streaming

↓

formation of a gas disk

↓

Toomre Instability

↙ ↘

star formation ➔ SNII's

mass inflow from the disk

↓

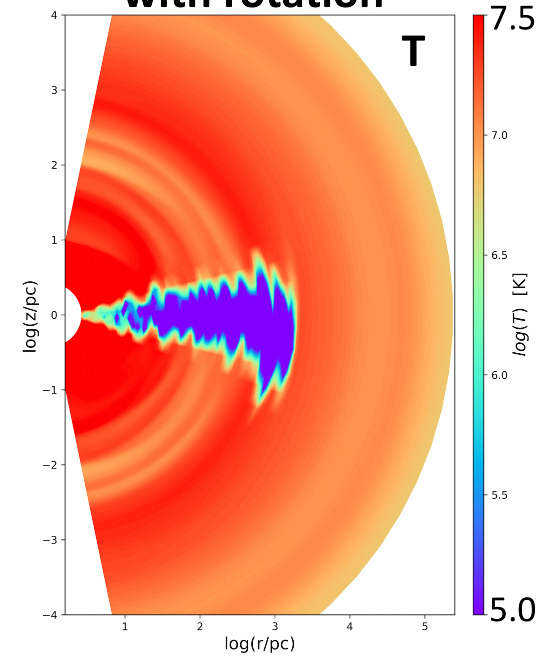
(delayed) MBH accretion

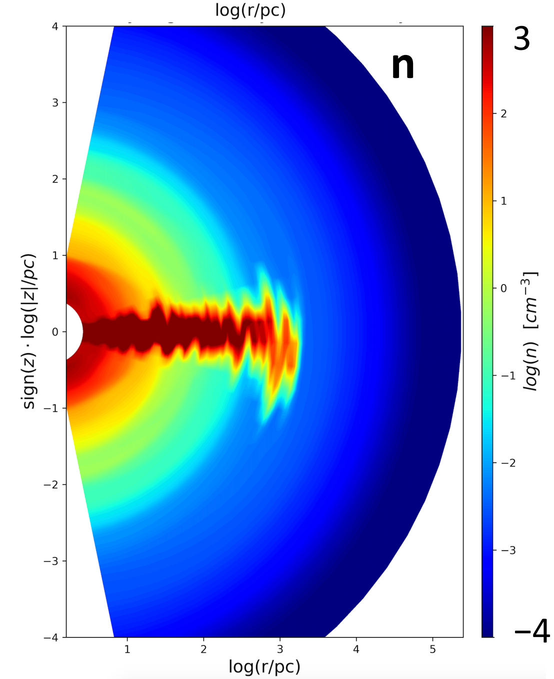
↓

AGN winds (*with the metal abundance of the disk*) cause metal transportation

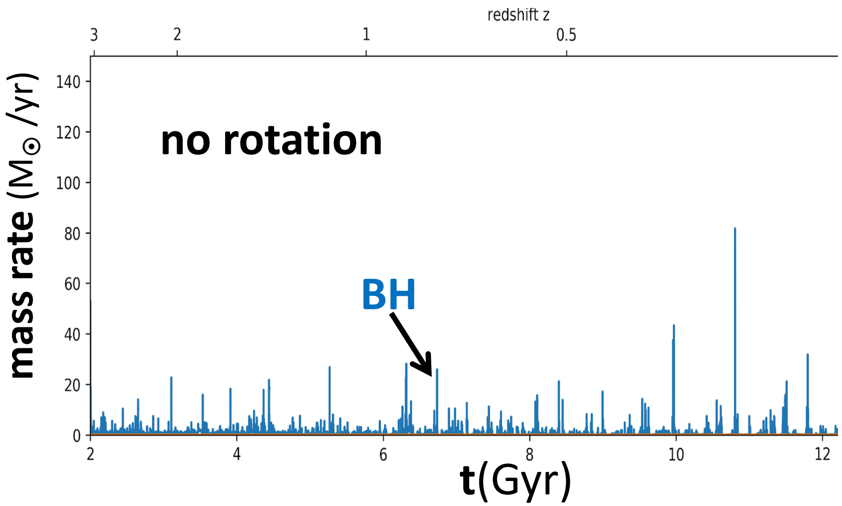
from simulations by Z. Gan

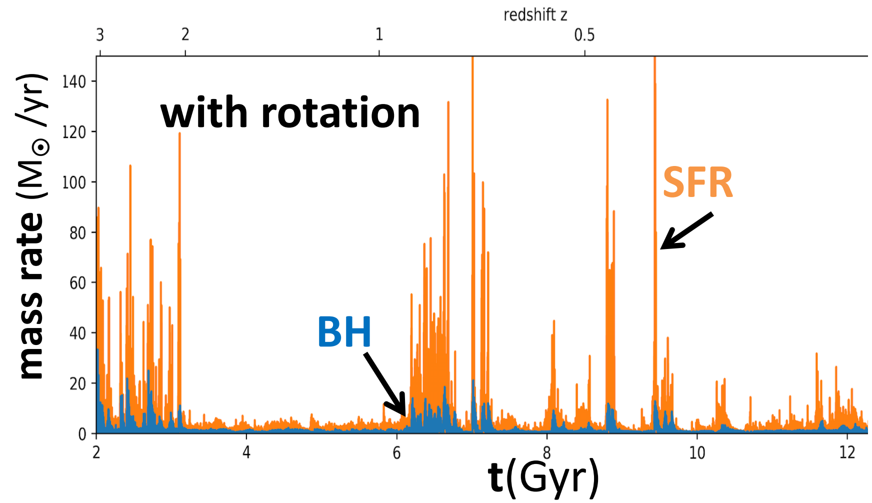
with rotation



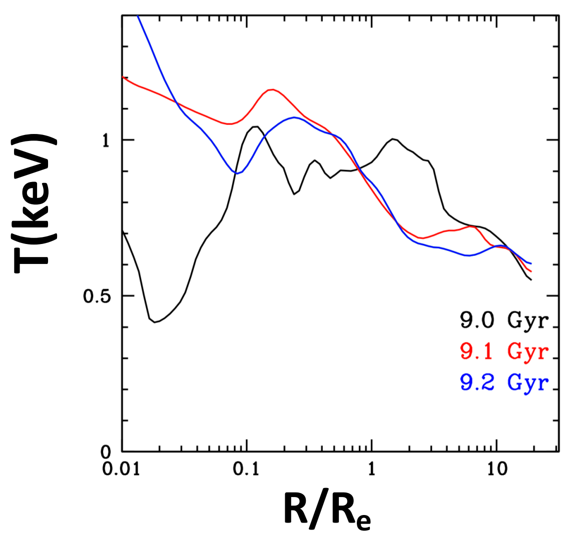


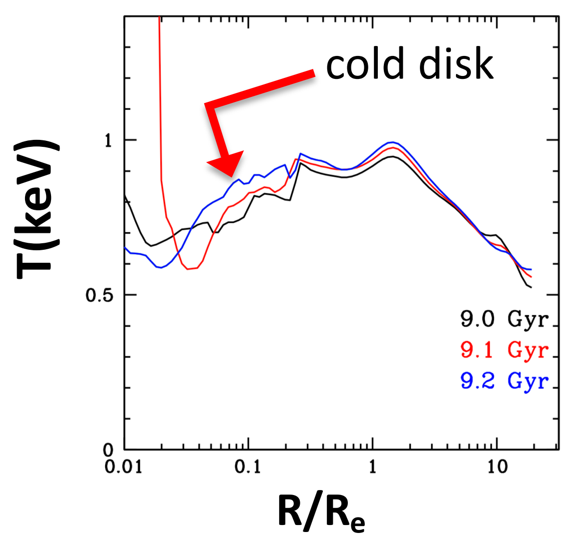
Evolution





AGN outbursts closely follow star formation





from simulations by Z. Gan

Tracking metals

evolution is tracked for 12 metal tracers X_i (i = 1, 2, … 12; mass of element *i* per unit volume) :

H, He, C, N, O, Ne, Mg, Si, S, Ca, Fe, Ni

additional continuity equations of the tracers (metals comove once injected into the ISM):

transport and mixing of the *i*-th species

$$\frac{\partial X_{\rm i}}{\partial t} + \nabla \cdot (X_{\rm i} \boldsymbol{v}) + \nabla \cdot \dot{\boldsymbol{m}}_{\rm Q,i} = \dot{X}_{\star,\rm i} + \dot{X}_{\rm I,i} + \dot{X}_{\rm II,i} - \dot{X}^{+}_{\star,\rm i}$$

old stars SNIa's SNII's

sources of metal enrichment

$$\dot{\boldsymbol{m}}_{\rm Q,i} = (X_{\rm i}/\rho) \cdot \dot{\boldsymbol{m}}_{\rm Q}$$

$$\dot{X}^{+}_{\star,\rm i} = (X_{\rm i}/\rho) \cdot \dot{\rho}^{+}_{\star}$$ = sink of local metals due to SF

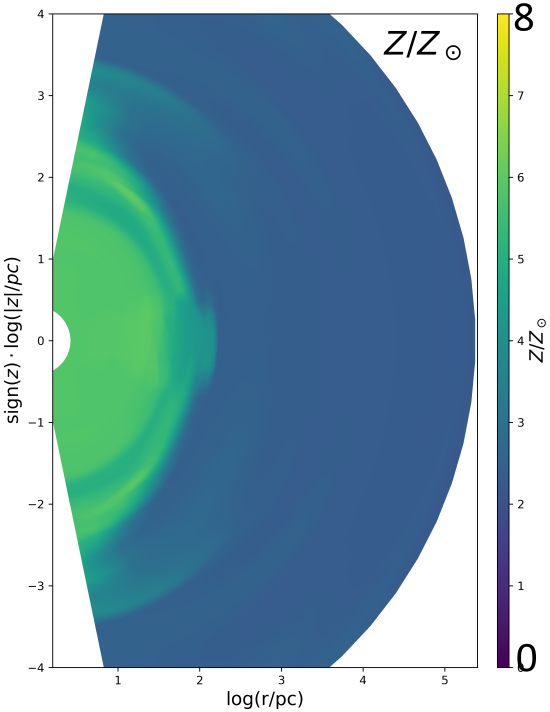
Gan et al. 2019

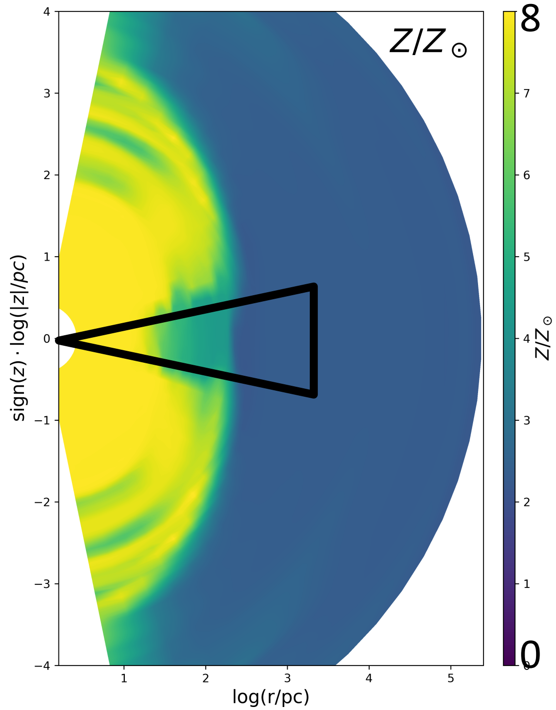
AGN winds inject back to the galaxy material with the instantaneous metal abundance of the disk

Z after an outburst

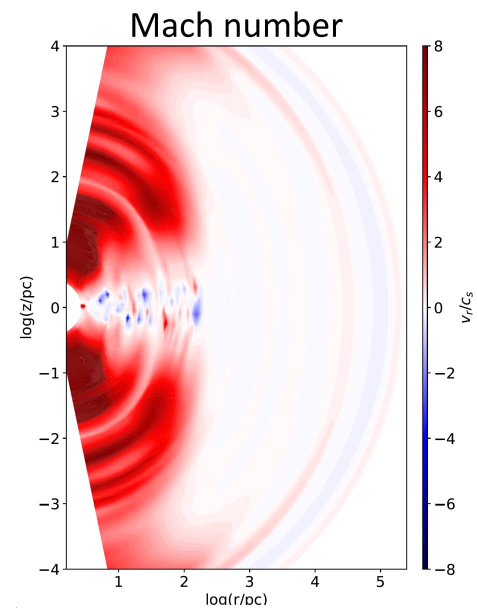
metals (SNII products, produced in the disk) transported outwards in a biconical wind

10^8 yr before





in the outflowing regions,
driven by the BAL wind
($v_r > 10^3$ km/s)
the mass-weighted
average $Z \simeq 4\ Z_\odot$



AGREEMENT with observations

Z of quasar BLR in massive galaxies is 0.3 to 1.0 dex larger
than Z of the host galaxies + does not evolve with cosmic time
➔ metal enrichment due to recent star formation

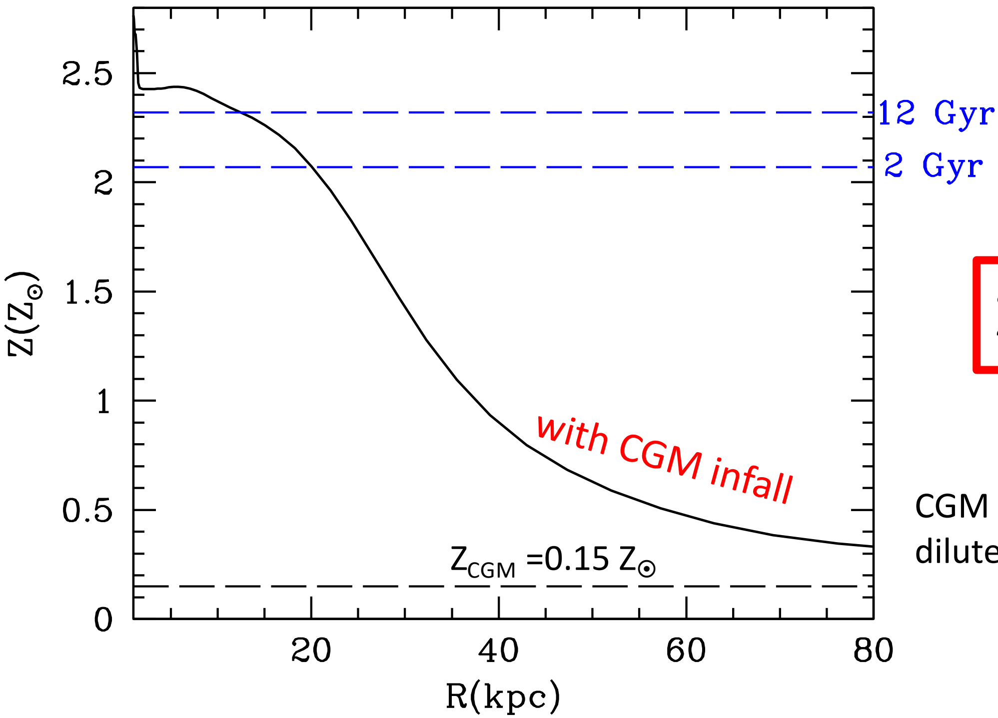
(Nagao et al. 2006; Xu et al. 2018)

Gan et al. 2019

Also:
for high Z the gas surrounding the MBH is more likely multiphase, and BLR clouds can exist (Chakravorty et al. 2009)

Average Z, and Z(R)

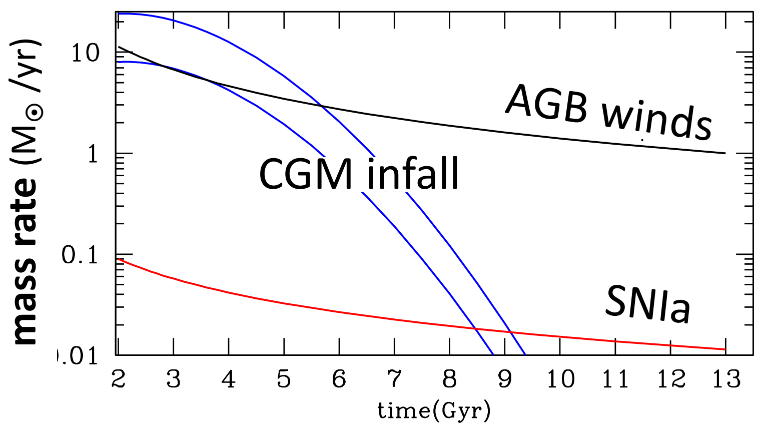
emission-weighted, projected and circularized Z(R);
rotating model when SSP age =12 Gyr



Z of mass ejected by AGB winds+SNIa's ($Z_\star$ = 1.5$Z_\odot$ for the SSP)

average Z on the whole galaxy: ~ 1.5 $Z_\odot$

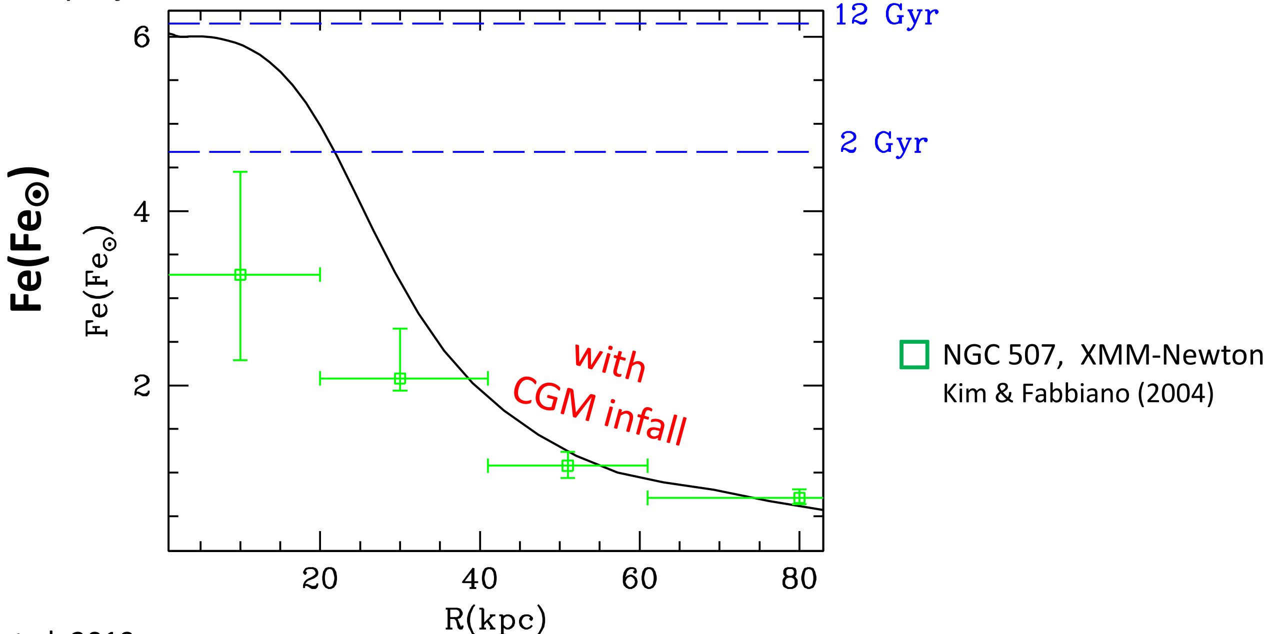
CGM infall through the galaxy outskirts: dilutes the ISM metals



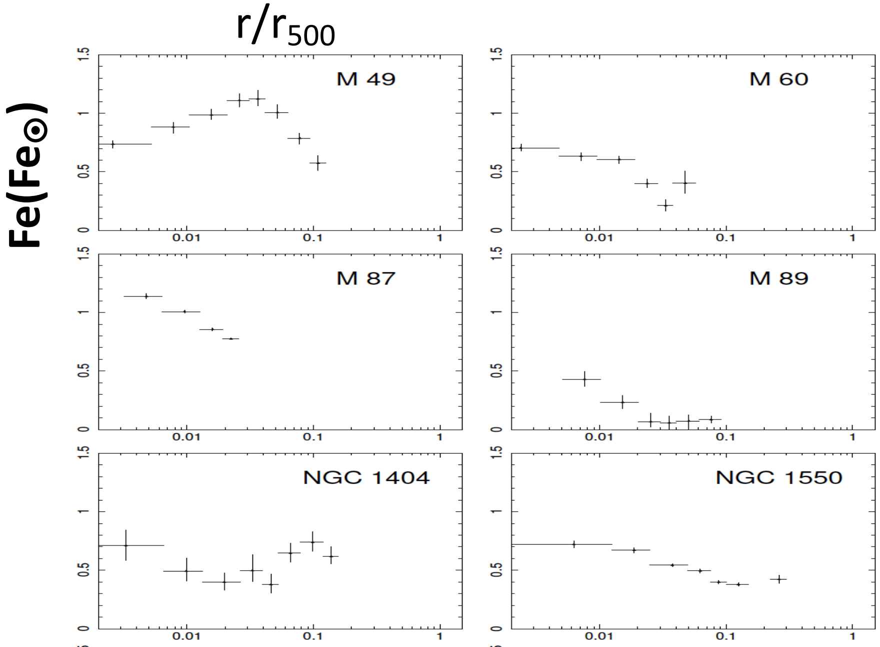
cosmological zoom-in simulations
→ accretion rate of 30 ellipticals with mean $M_\star$ =2 ×10^{11} $M_\odot$ (Brennan et al. 2018, Gan et al. 2019)

Fe(R)

emission-weighted, projected
and circularized



from models in Gan et al. 2019



deep XMM-Newton/EPIC
observations

Mernier et al. 2017
(also: Humphrey & Buote 2006,
Loewenstein & Davis 2010)

observed metal abundances lower than expected:
old problem

uncertainties in derived abundances? (Kim 2012, de Plaa et al. 2017)

dust depletion of metals? (Panagoulia et al. 2013, Lakhchaura et al. 2019)

incomplete mixing of SNIa's ejecta? (Matsushita et al. 2000, Tang & Wang 2010)

changes in CGM infall?

mixing and stirring of metals between inner and outer regions, for
larger mechanical feedback efficiency, and/or infall of satellites

Conclusions

✓ the mass input from the stellar population accounts for a *major part of the observed* L_X of ETGs that are NOT central dominant in groups and clusters
AGN feedback does not cause major outflows, after z~2

✓ temperature profiles (central regions) are a promising diagnostic for AGN feedback

✓ galactic rotation is accompanied by star formation $\longrightarrow$ metal injection + transportation:
outflowing regions, driven by the BAL wind, can reach $Z \simeq 4\, Z_\odot$, as observed

✓ *average* hot ISM abundance $\mathbf{Z} \simeq 2.3\, Z_\odot$, down to $\simeq 1.5\, Z_\odot$ for CGM infall rates predicted by cosmol. sim.'s

observed Z(R) and **Fe**(R) **within 10-20 kpc** *are lower* than predicted