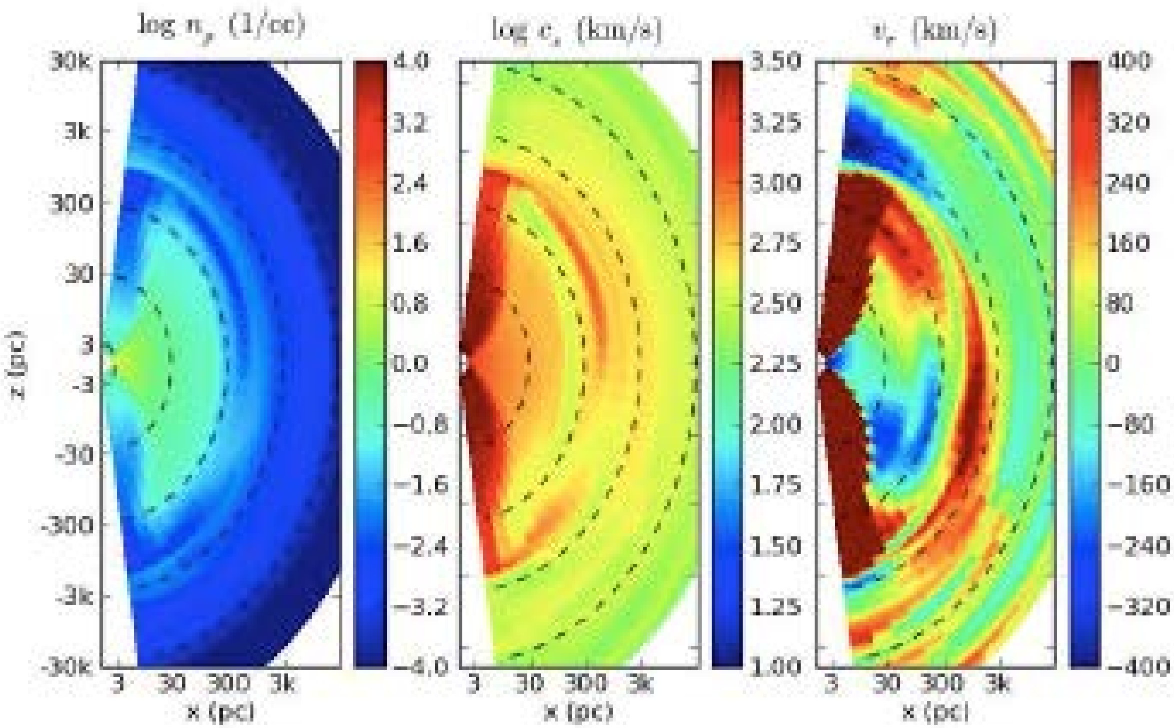
Riccardo Giacconi, The Chandra Telescope and X-Rays from Massive Galaxies



Co-conspirators*:

E. Choi

Z. Gan

L. Ciotti

T. Naab

D. Proga

S.Y.Sazonov

R.A.Sunyaev

Riccardo

- Uhuru (1970), Einstein (1978)
- Chandra (1999 -)
- With others established X-ray astronomy as co-equal with other branches of observing the universe.
- A gentleman and a scholar.
- A friend.
- +++++++++++++++++++++++++++++++++
- X-ray observations critical to understanding massive galaxies.

Massive Galaxies: Current Cosmo Simulation Problems

- Galaxies are too massive compared to parent halos by a factor 2-5.
- No good mechanism for BH/Gal mass ratio.
- Too small, especially at high redshift.
- Too much late star formation (too blue) compared to real ellipticals.
- ***Embedded in too much X-ray emitting gas.***
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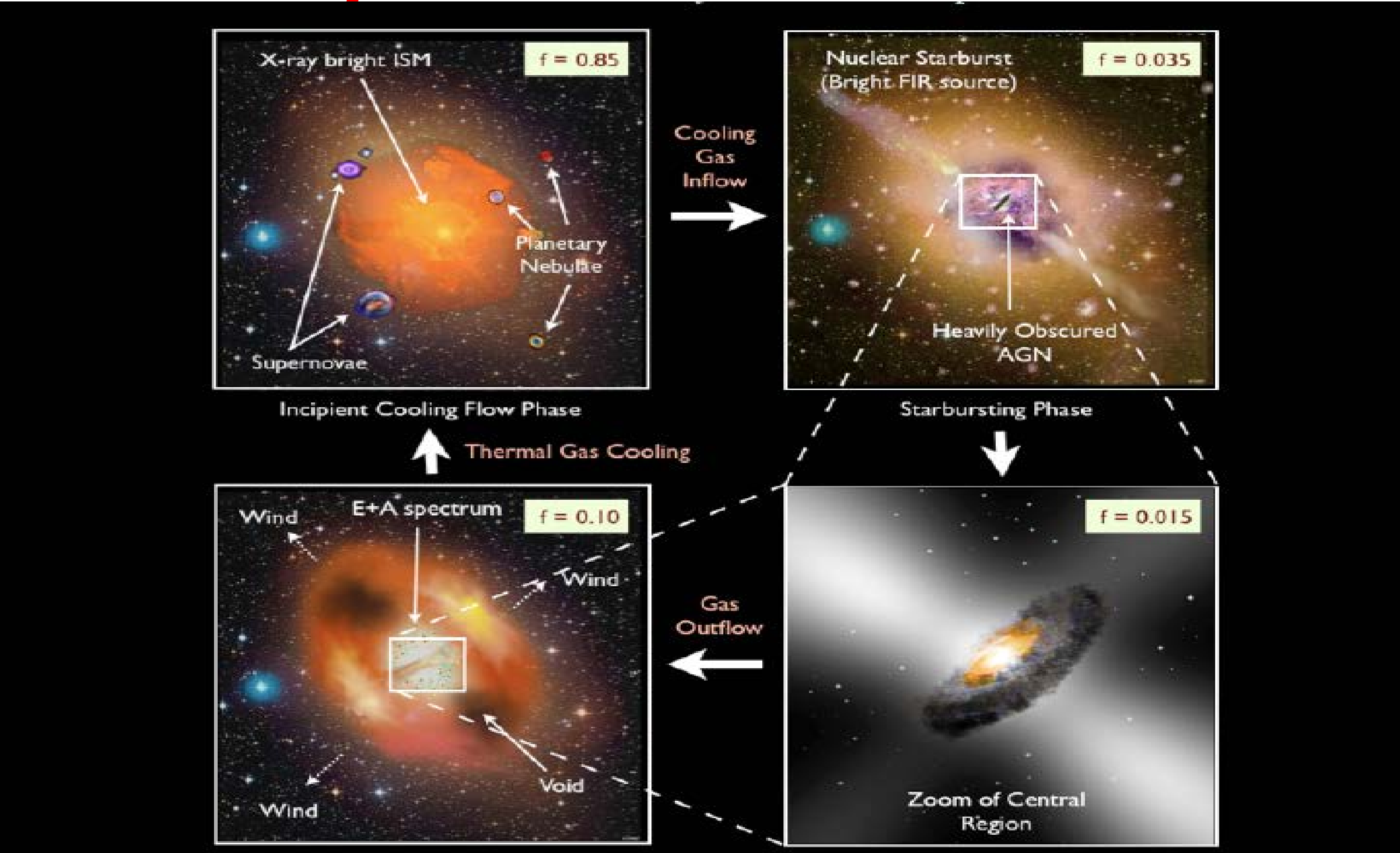
- *Widespread belief that AGN feedback from resident black holes can solve the problems.*

Cartoon of Co-Evolution of Elliptical and MBH/AGN



AGNs & Starbursts: physical processes consequent to normal galactic evolution

- Co-incident and co-terminous: gas added to the center of galaxies feeds central black hole *AND* also fuels starburst. Processes comparable in importance.
- Gas added via mergers probably not dominant.
- Gas source from recycled gas is ***25%*** of stellar mass; galactic merger induced gaseous in-fall may be comparable but less, especially at late times ($z < 1.5$).
- Energy and momentum input to galaxy due to
  - Radiative input: UV from stars, and UV-Xray from AGN
  - **Mechanical**: BAL winds & SN from stars
  - [Most sims ignore these observed feedbacks and use "thermal feedback" instead]

AGN ***observed*** output in units of stellar mass x c^2

- Multiply efficiency by $r_{BH} = M_{BH}/M^* = 0.0013$
  - $\varepsilon_{EM,AGN} = 0.12 \times 0.0013 = 1.6 \times 10^{-4}$
  - $\varepsilon_{X,AGN} = \varepsilon_{EM} \times 0.1 = 1.6 \times 10^{-5}$
  - $\varepsilon_{mech,AGN} = 0.005 \times 0.0013$ (BAL) $= 6.5 \times 10^{-6}$

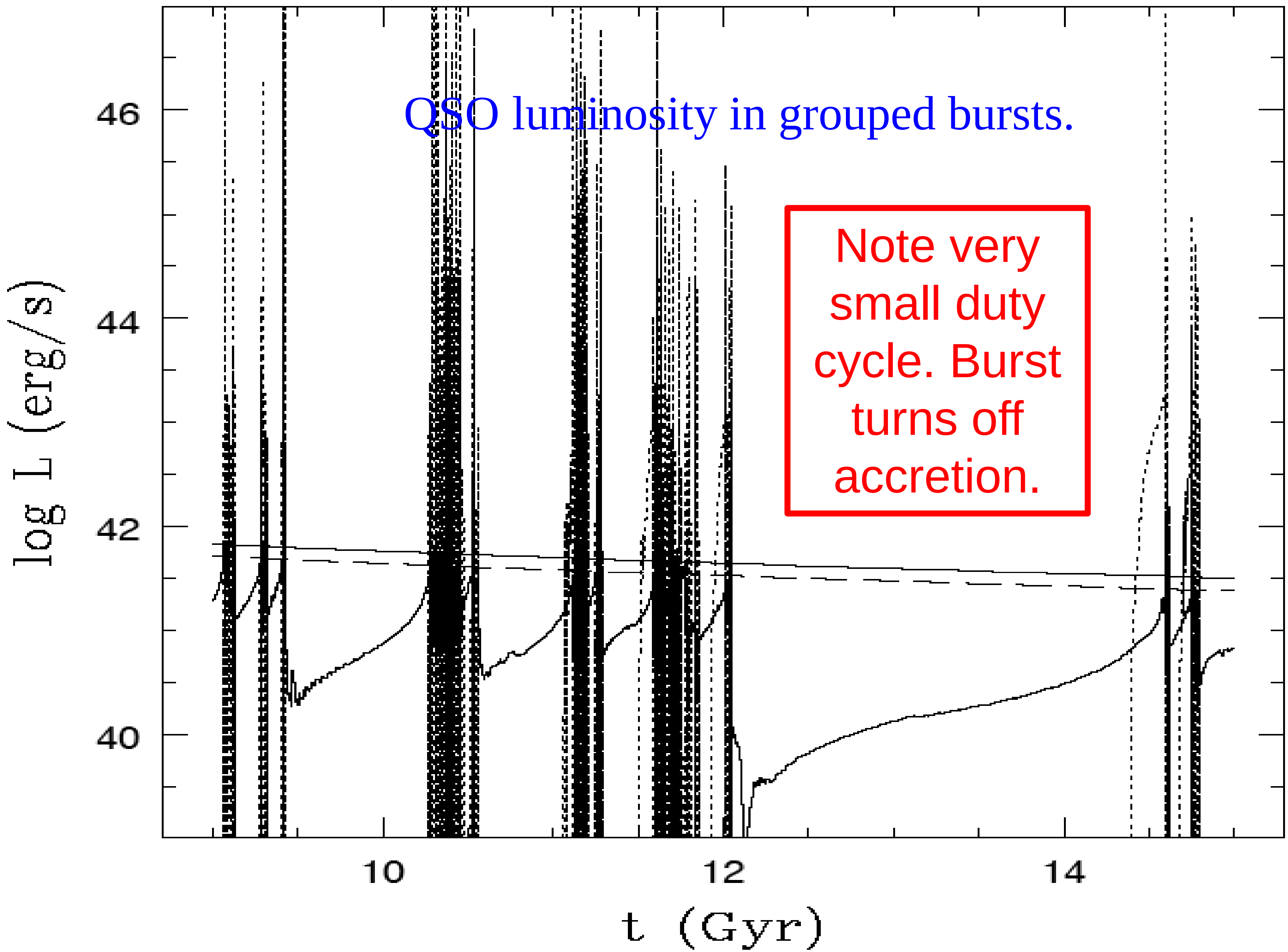
Winds dominate* because coupling is most efficient.

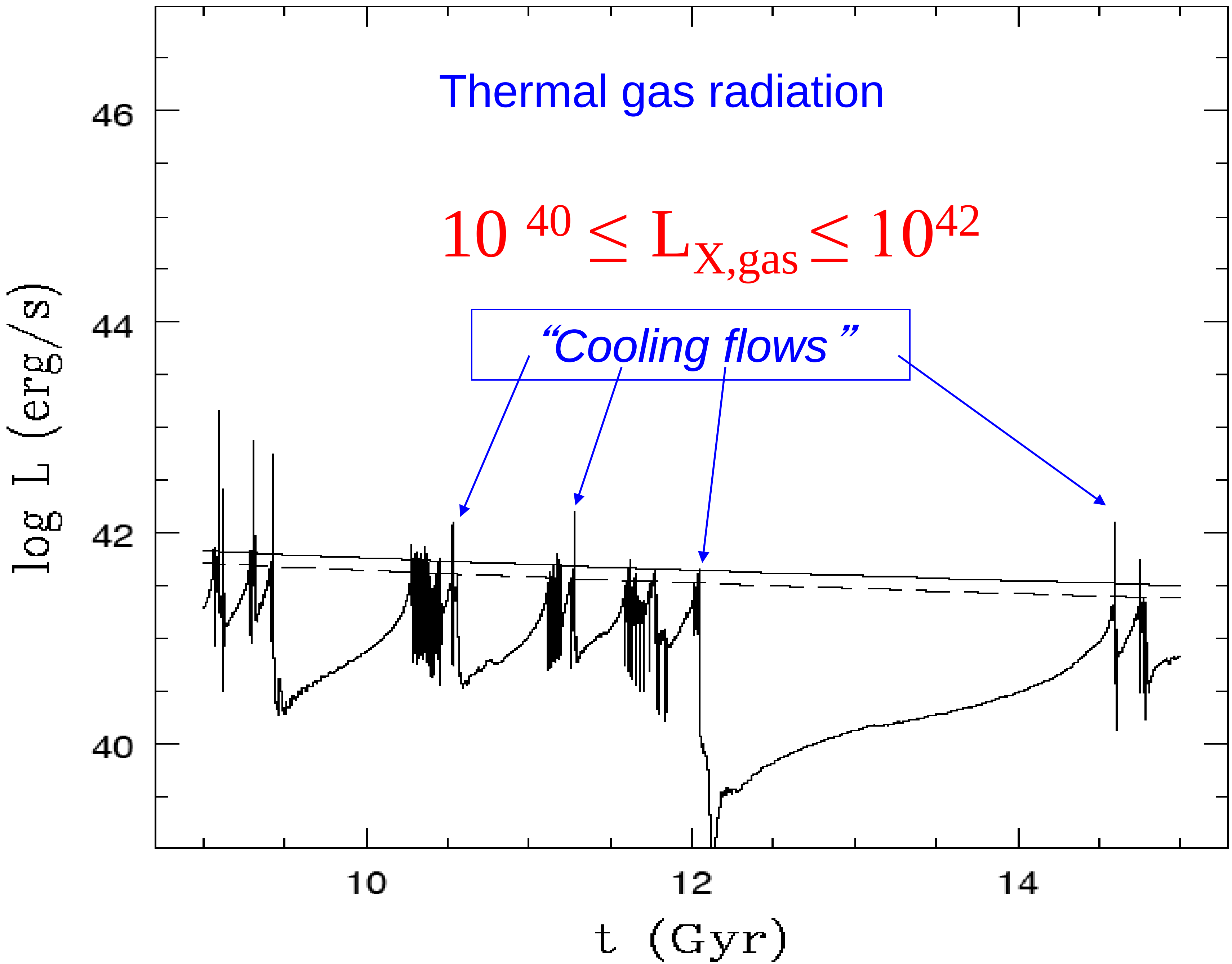
- Relativistic jets also have an ave efficiency of 10^{-6} but deposit energy into the IGM only.

→> *The "radio mode" is unimportant for the galaxy.*

Computation: 1D Accretion by MBH within an elliptical galaxy (w L. Ciotti)

- Detailed spherically, symmetric, time-dependent hydro of accreting MBH in E galaxy with
- Assumed accretion efficiency (0.001 -> 0.100).
- Assumed Spectrum with $T_{compt} = 10^{7.5}$->$10^{9.0}$.
- Mass supply from evolving stars.
- Star formation from dense cold gas.


QSO luminosity in grouped bursts.
Note very small duty cycle. Burst turns off accretion.
log L (erg/s)
t (Gyr)
40
42
44
46
10
12
14



Thermal gas radiation
$10^{40} \leq L_{X,gas} \leq 10^{42}$
"Cooling flows"
log L (erg/s)
46
44
42
40
10
12
14
t (Gyr)

Luminosity Distribution as Observed

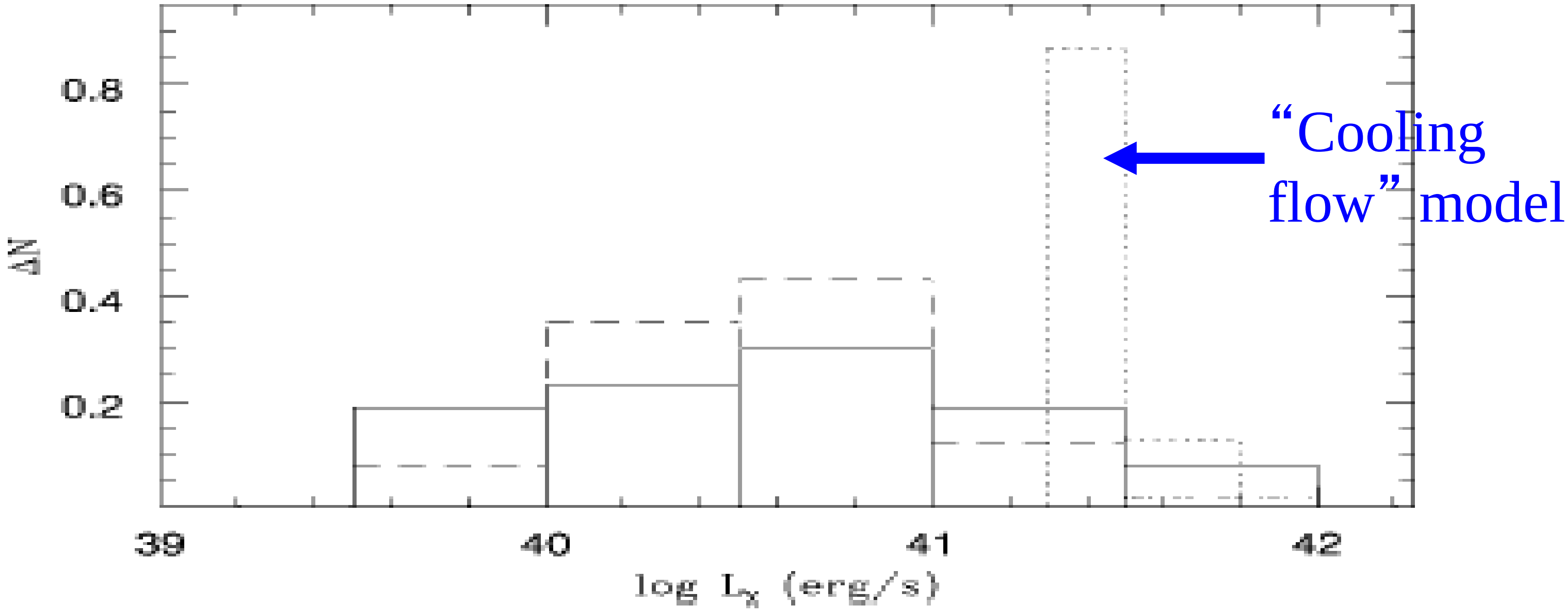
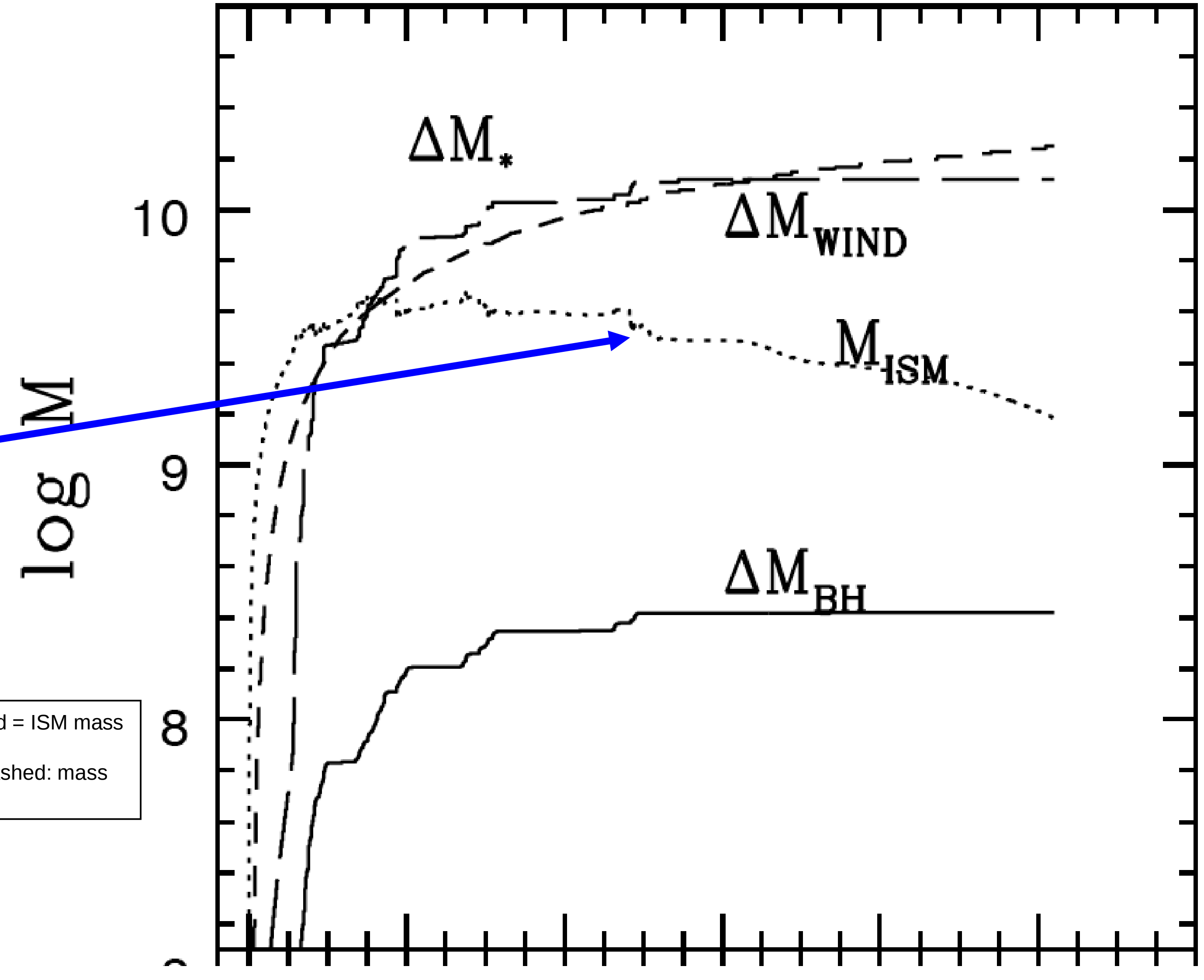


FIG. 3.—Statistical distribution of L_X for observed galaxies (*solid histogram*) in the range $10.4 < \log(L_B/L_\odot) < 10.8$ derived from Fig. 1 of CDPR. The dashed histogram represents the time distribution of L_X for the presented model from 9 to 15 Gyr, while the dotted histogram shows the cooling flow ($\epsilon = 0$) model; clearly the bursting model provides a better fit to the observed distribution of L_X.

Very low final gas fraction



At late times the gas mass in the galaxy is less than the ejected and consumed mass

TOP: solid = total BH accreted mass; dotted = ISM mass in the galaxy
BOTTOM: same as above, but for rates; dashed: mass loss rate from the galaxy as a wind

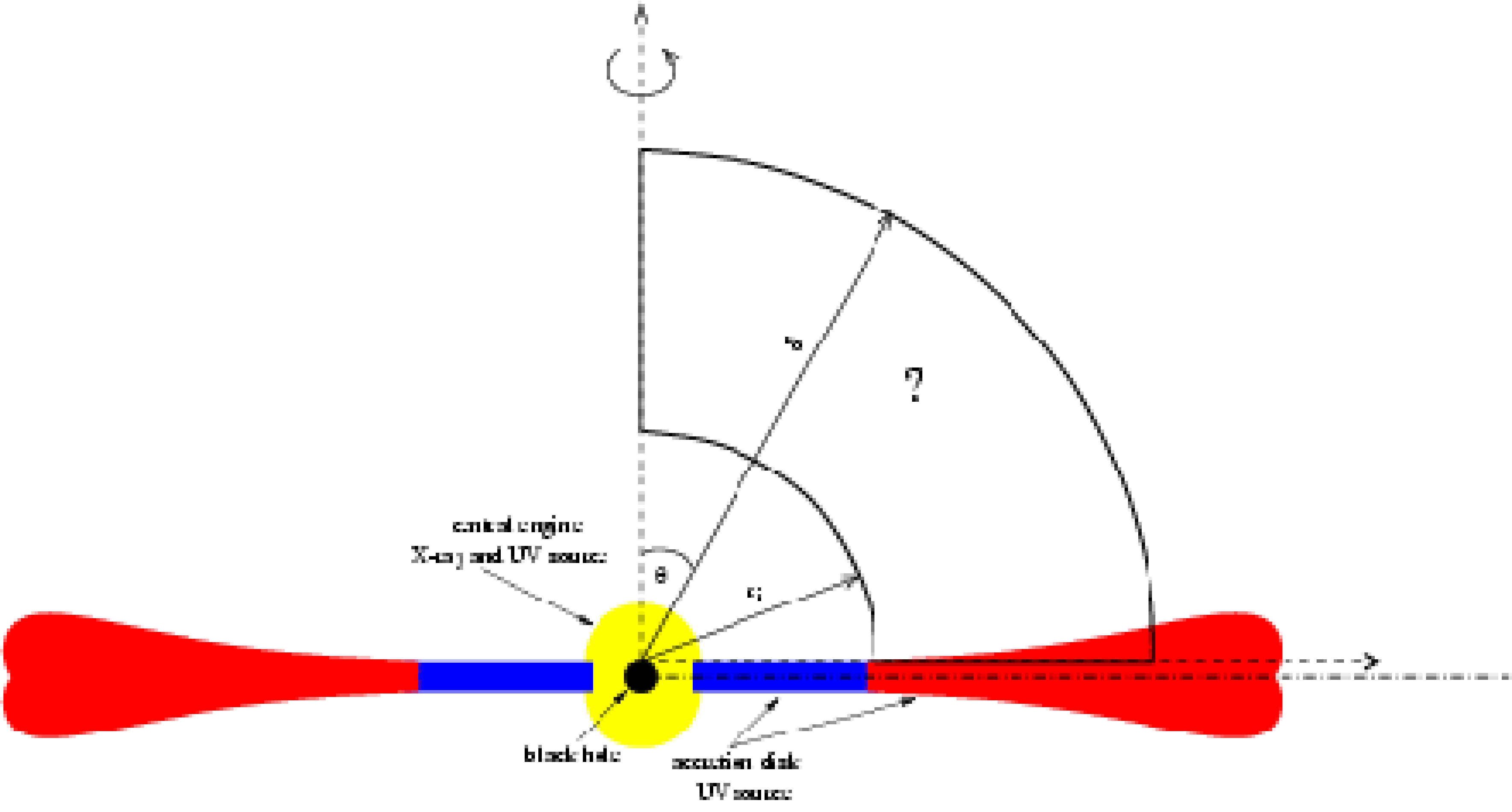
Overall Results

- Lx, gas in right range.
- M_{BH} appropriate (not too large).
- Modest mass outflow driven by momentum
  - BAL wind input
  - X-ray heating and momentum input
  - and radiation on dust the biggest drivers
- Duty cycle ~ 0.006.
- --
- Appears most times as a normal elliptical, some time as an incipient cooling flow and during very brief intervals as a quasar.

2-D Hi Resolution Solutions of Central Regions (Proga&O)

- Wind produced with $M_{dot,w}$ >~ $M_{dot,acc}$
- Small solid angle until Edd Luminosity approached.
- Energy efficiency ~ 1 x 10^{-4}
- Cold cloud ejection at high Eddington rates.

Computational domain bounded by inner and outer BC

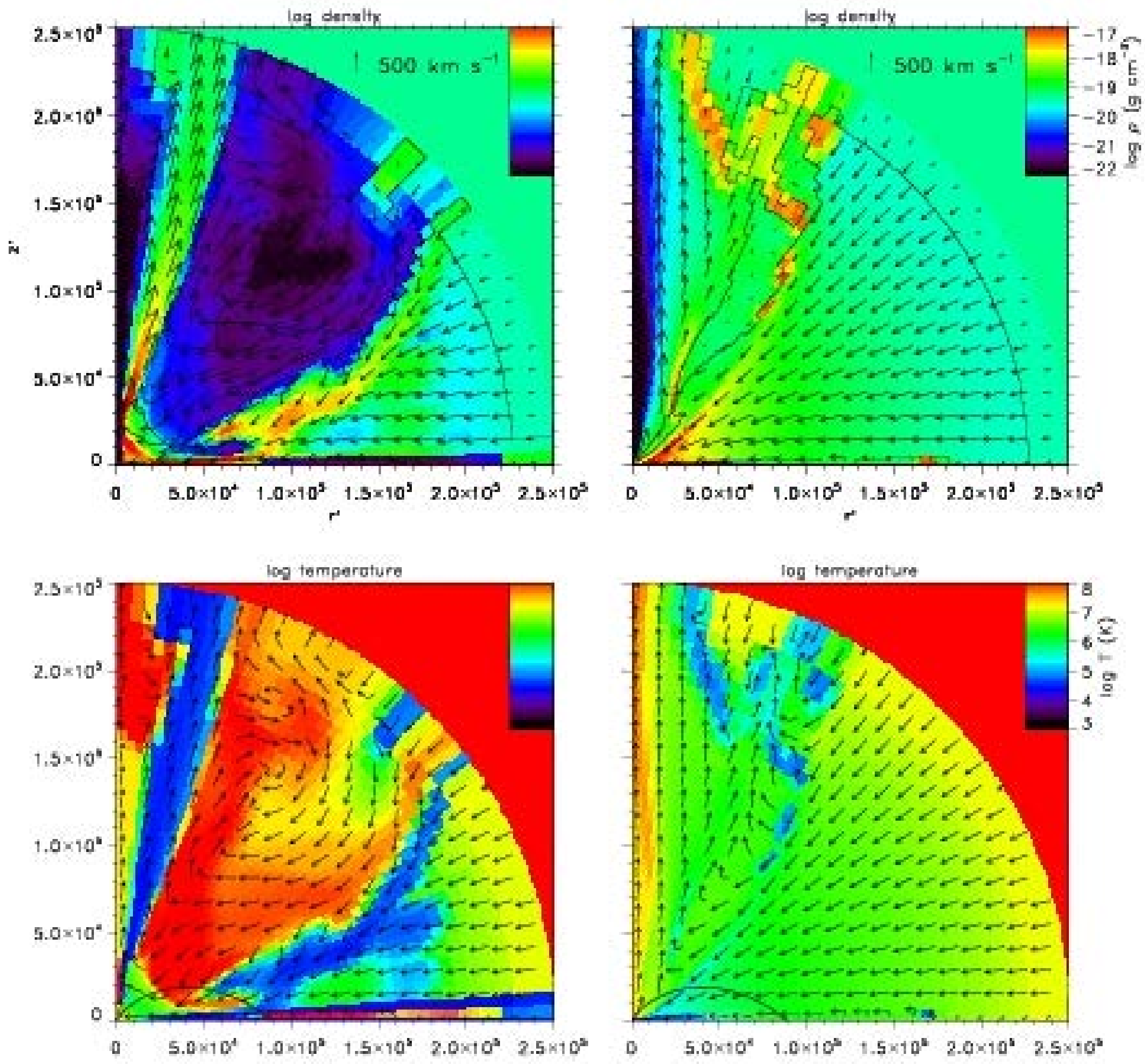


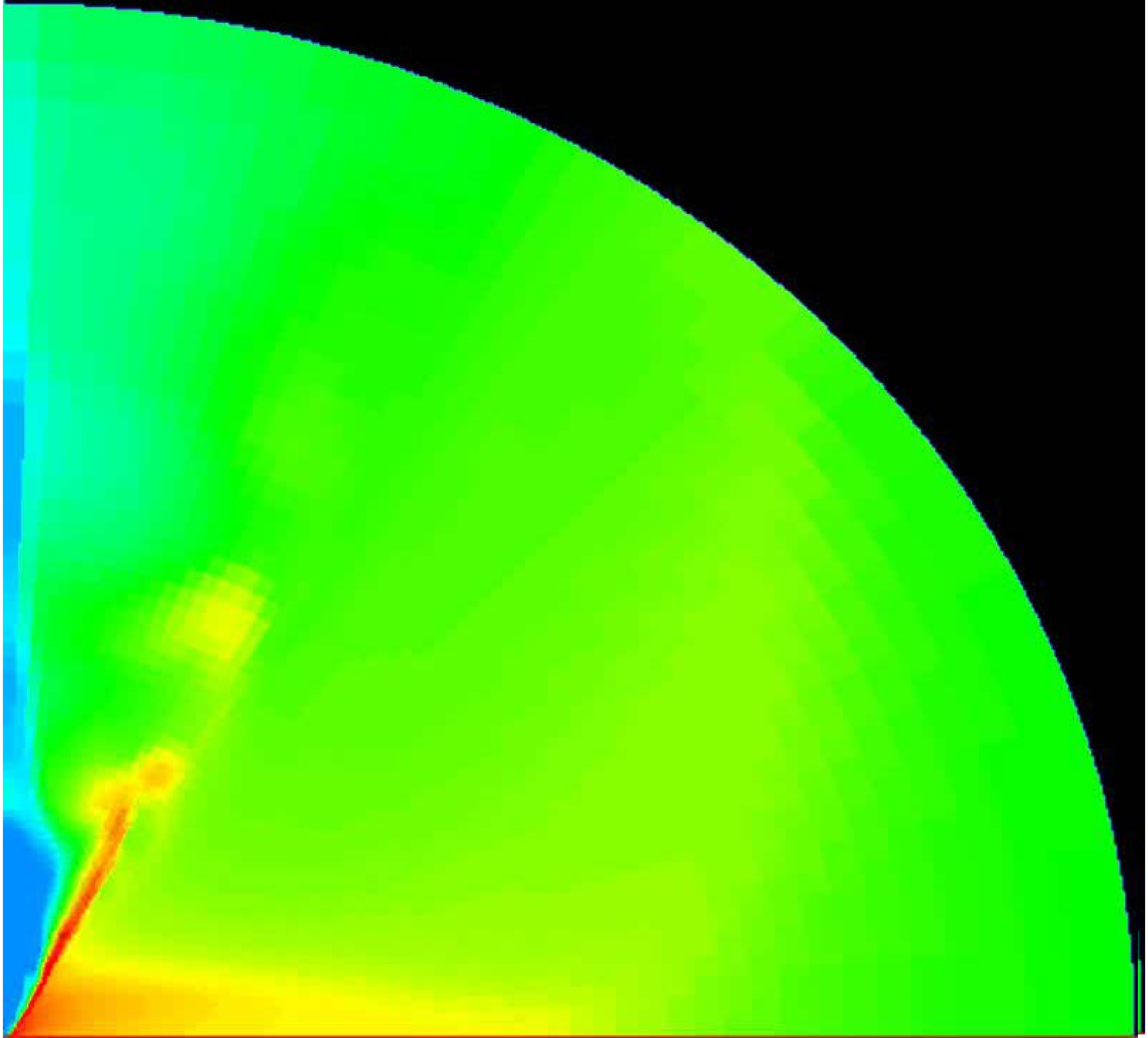
No X-ray Heating   X-ray Heating

Higher density at outer boundary (x 10)

And

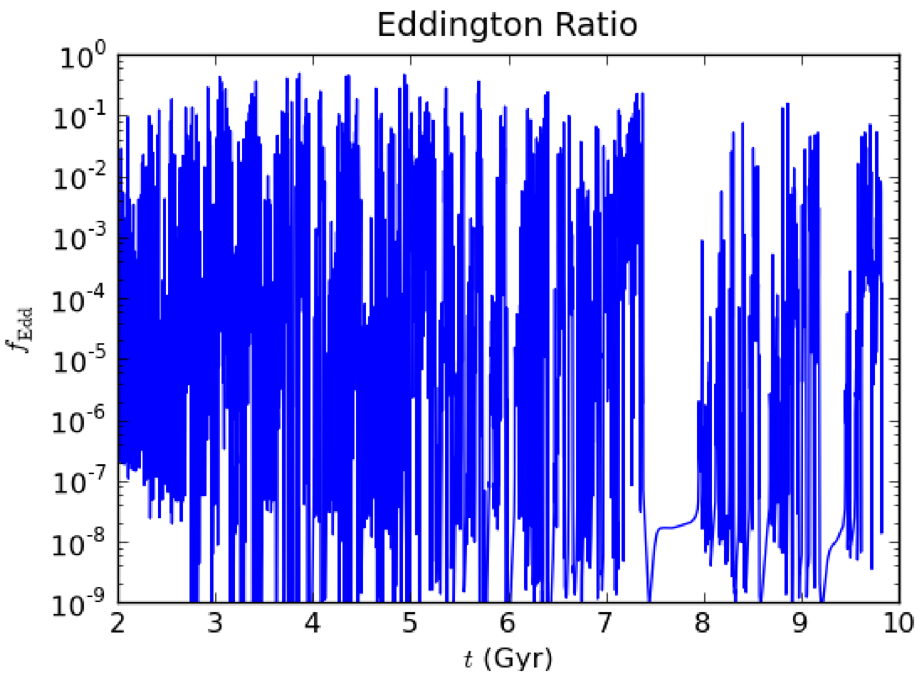
Possibility of background X-ray heating

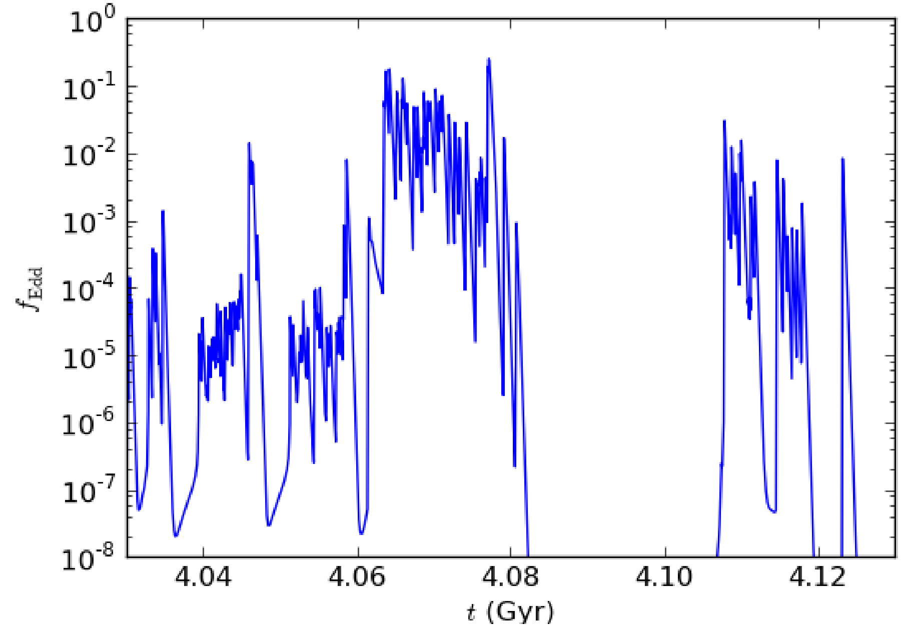


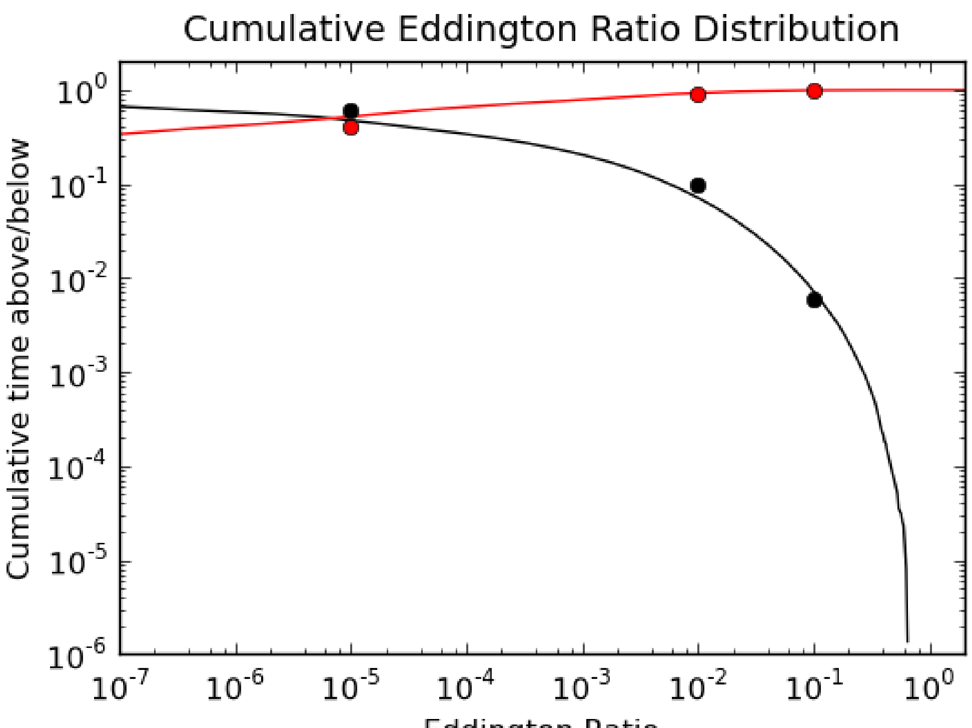


Details of Large-Scale 2-D Sims

- Done with Greg Novak (Princeton) using the ZEUS (J.Stone) code. Rotation added with Zaoming. Gan (2019).
- Logarithmic scale from 2.5 pc (inside R_{bondi}) to 250kpc in increments of dR/R of 10%.
- Gas added as per Choi cosmological sims.
- Accretion not "assumed at Bondi rate" or by any other formula but computed by standard hydrodynamical means with infall inner BC.
- ++++++++++++++++++++++++++++++++++++++
- Very dense (n > 10^5 /cc) cold disk forms.



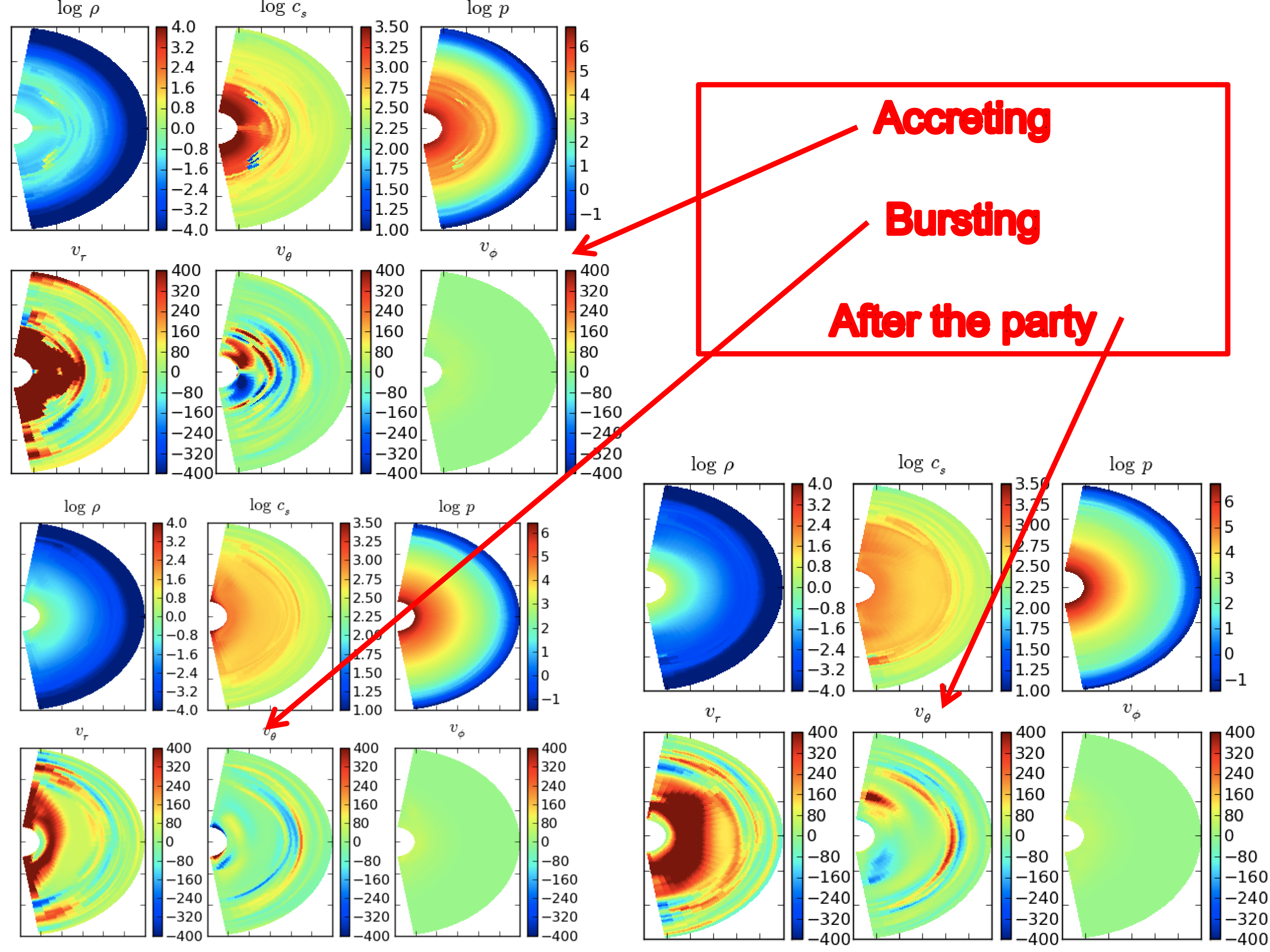




Bursting more irregular than in 1-D case, infalling shells fragment via R-T instability.

Data

Heckman et al, 613,109 (2004)
Greene & Ho, 637,131 (2007)
Ho, 699,626 (2009)

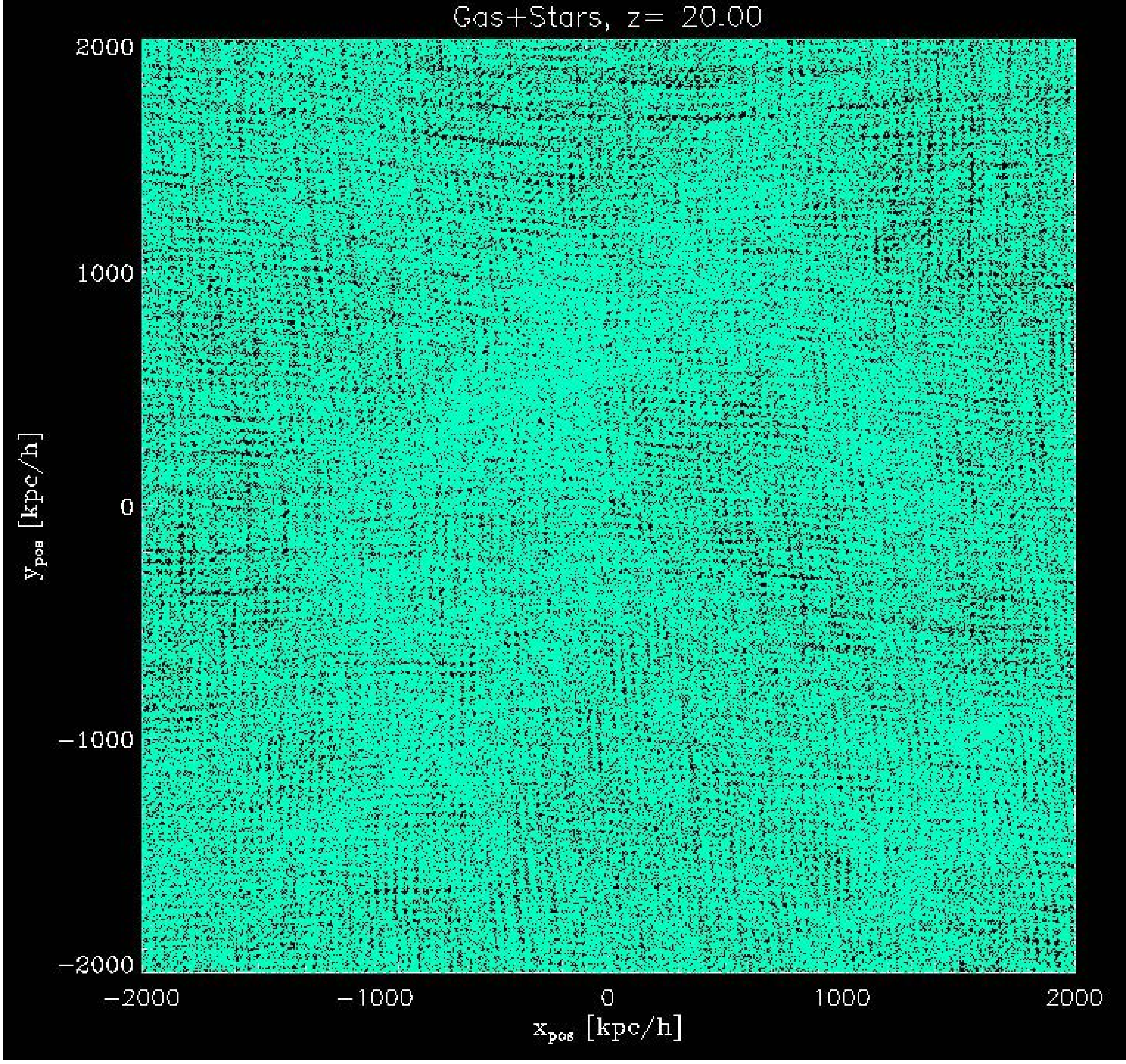


Accreting
Bursting
After the party
log ρ
log c_s
log p
v_r
v_θ
v_ϕ

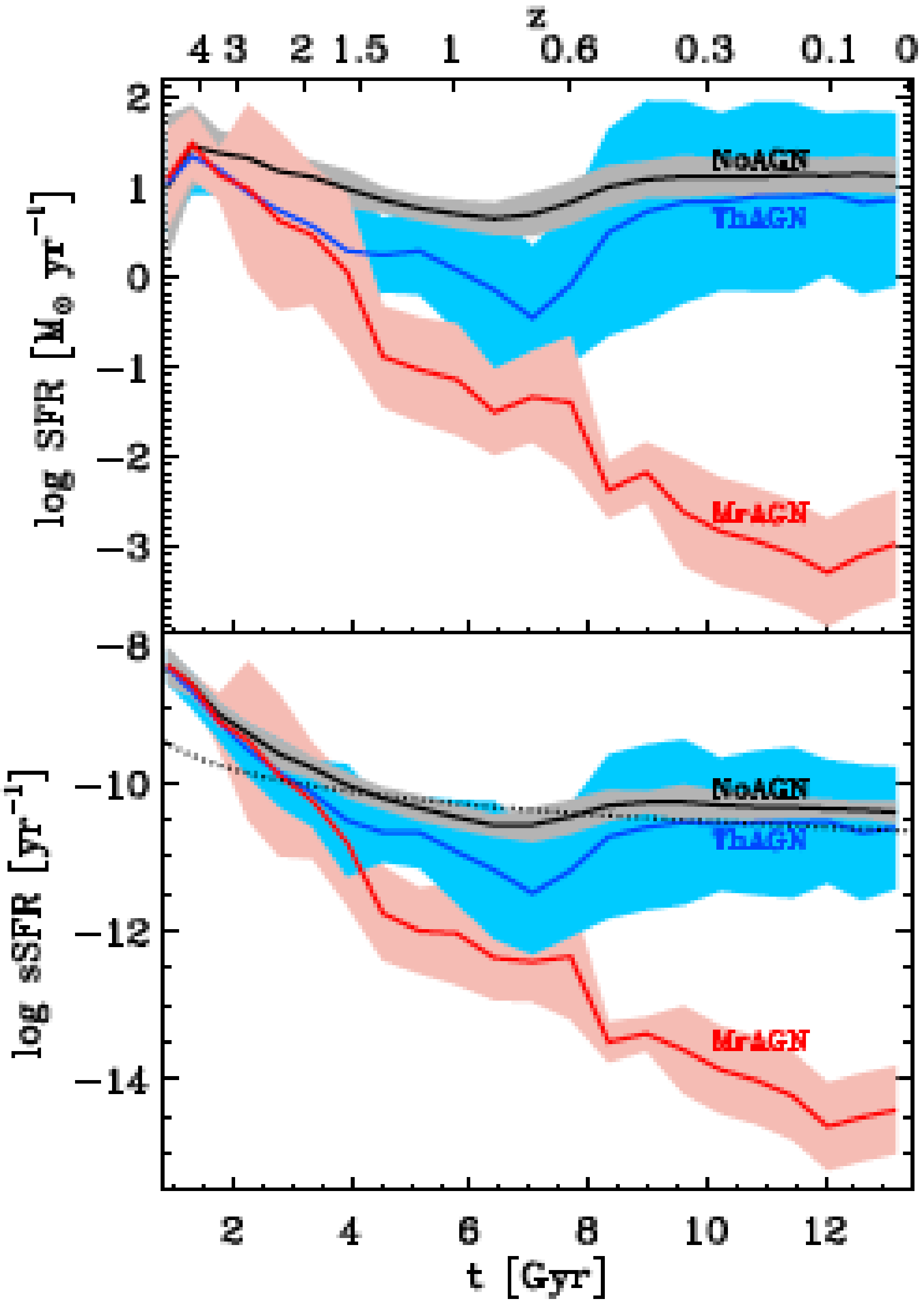
3 D work w E. Choi

- Accretion limited (statistically) in SPH calculation to particles bound to BH (Bondi).
- Eddington force and X-ray radiation effects (heating and momentum input) included.
- Winds – taken from Proga work and obs allowed for, with mass, momentum and energy input to the surrounding fluid.

Momentum and radiation driving



”Quenching” of star formation in massive galaxies is far more effective with momentum feedback from AGN than with thermal feedback.



How well does it work for X-rays: M_{BH} *vs* L_X ?

Good fit and standard thermal FB is too high.

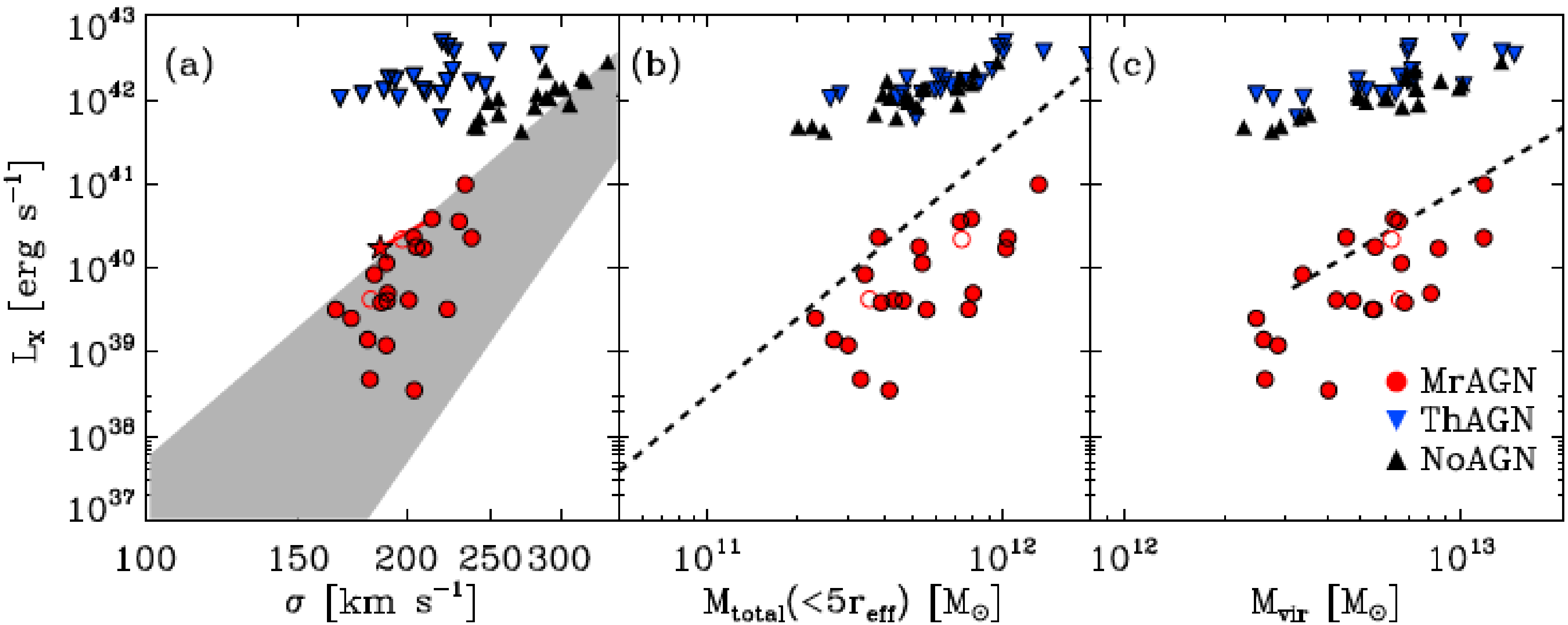
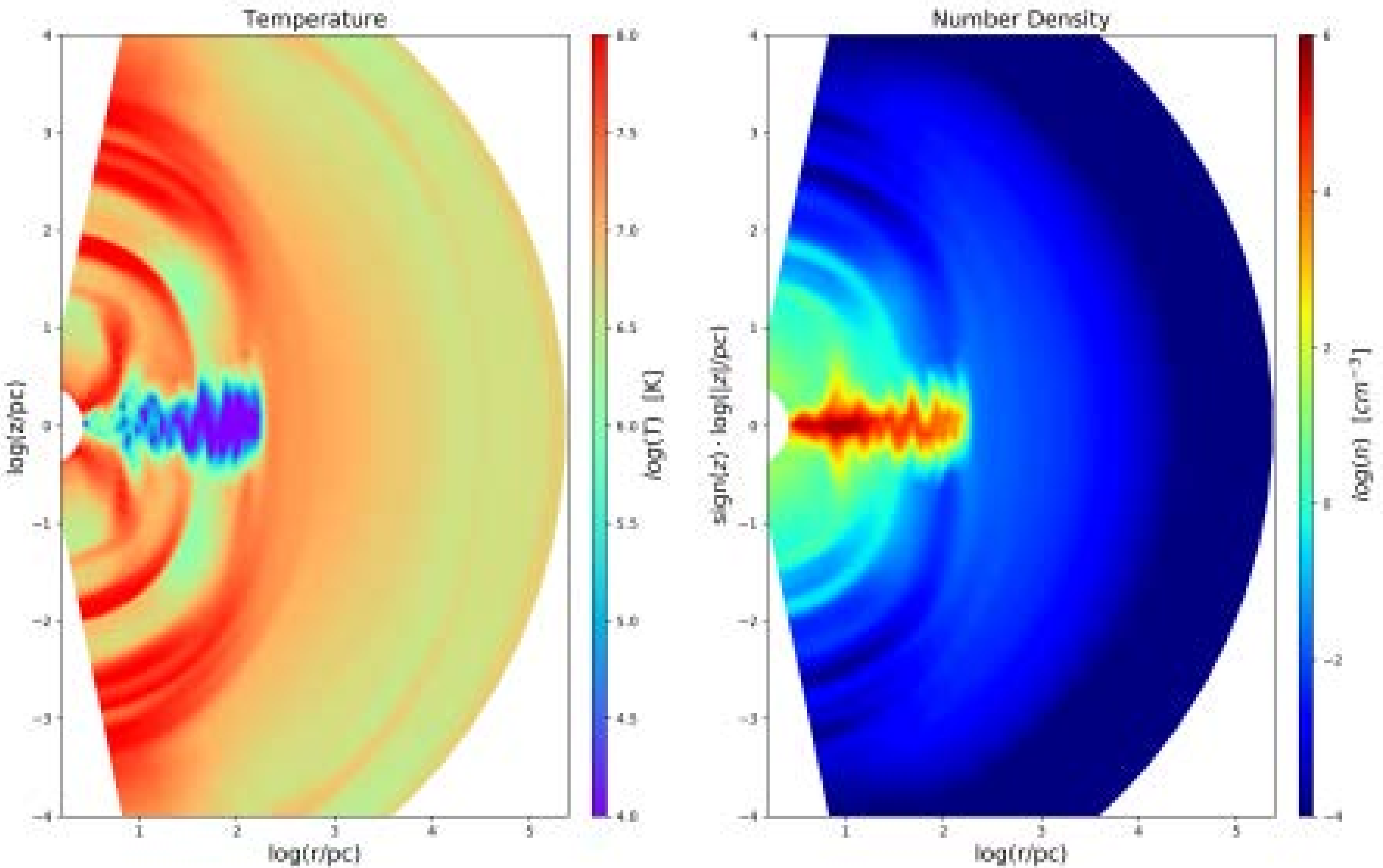


Figure 4. X-ray luminosity versus (a) stellar velocity σ, (b) total mass within $5r_{eff}$, and (c) virial mass M_{vir} of the simulated galaxies at $z = 0$ for the model without AGN feedback (NoAGN, black triangles), thermal feedback (ThAGN, blue upside down triangles), and

Summary of Physically Motivated AGN Feedback

- At same energy efficiency, wind driving is far more effective than thermal in driving outflow. And thermal X-rays have dramatically better fit to observations.
- X-ray heating from AGN a significant effect in regulating BH growth.
- Bursting phenomenon dominates. Small duty cycle produced.
- Galaxy properties remarkably like real ellipticals and quenching is effective.

Cold Gas Central Disk Forms



Star formation, AGN in Bursts

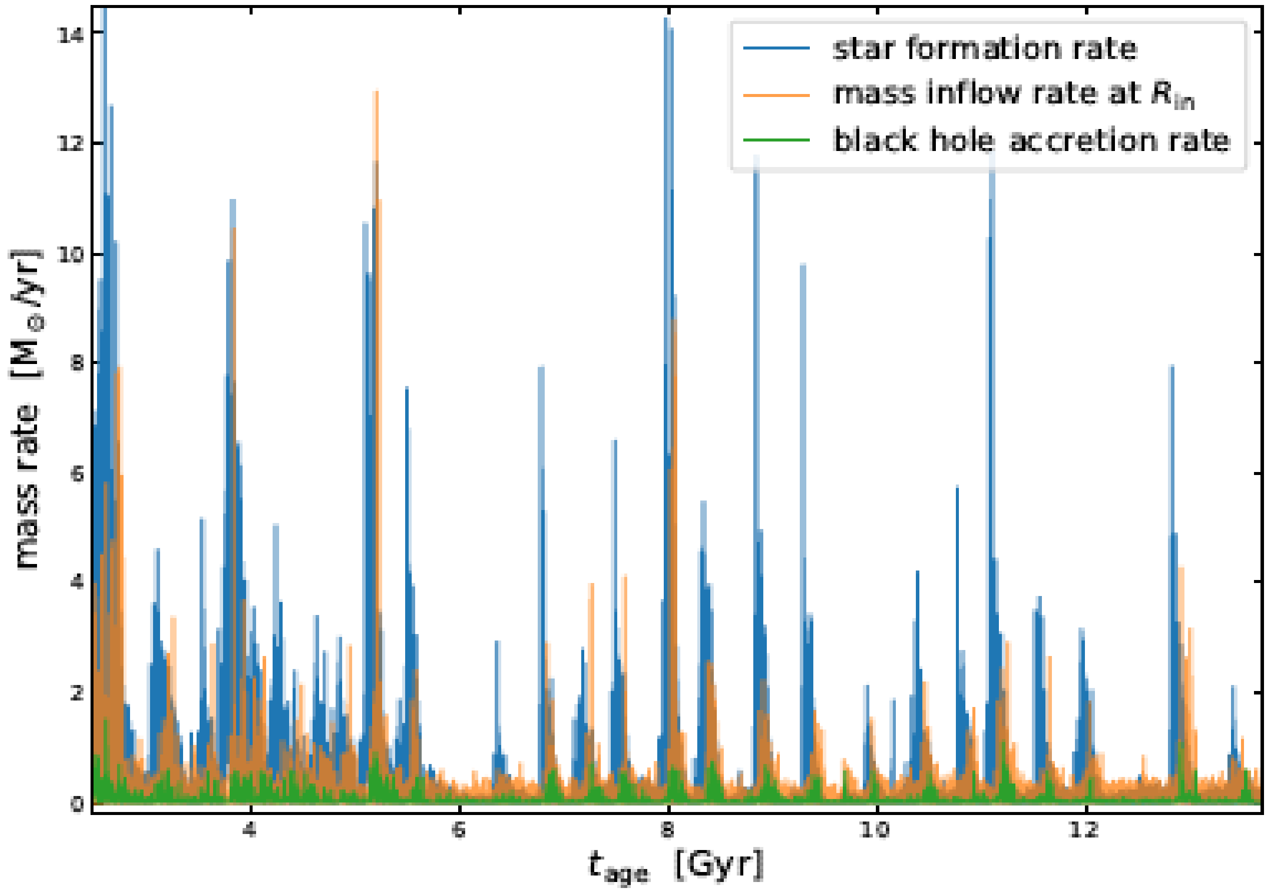


Figure 4. History of the star formation and AGN activities. The blue, green, and orange lines show the variations of the star formation rate, mass inflow rate onto the galaxy center through the inner boundary (R_{in}), and the black hole accretion rate, respectively. As shown in the figure, black hole accretion events usually associate with star formation.

Star formation in Disk

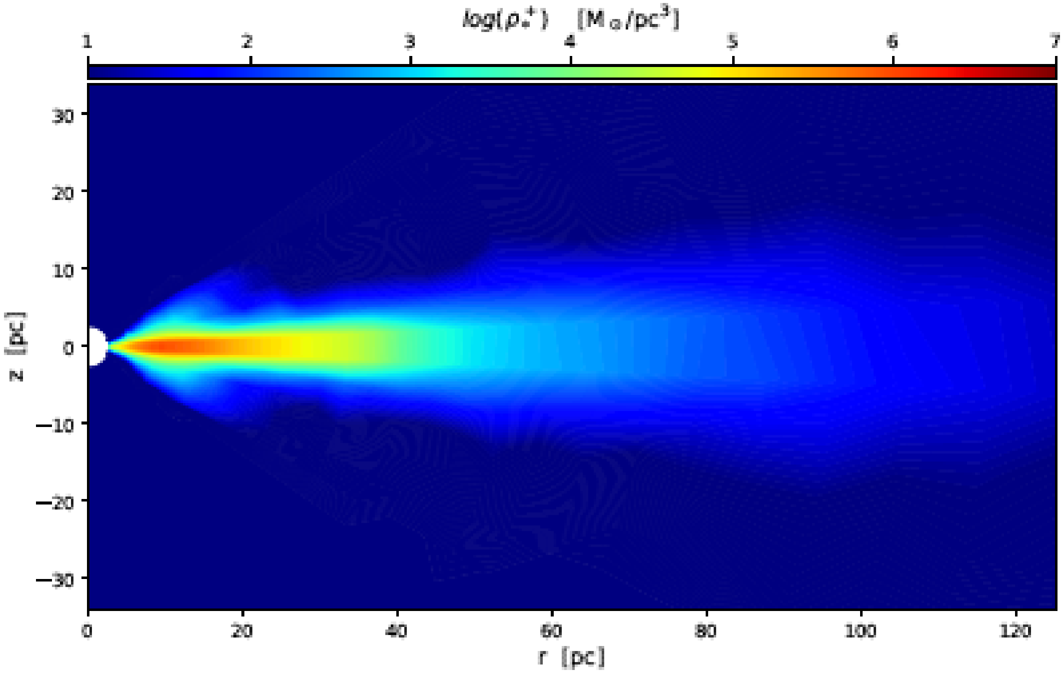
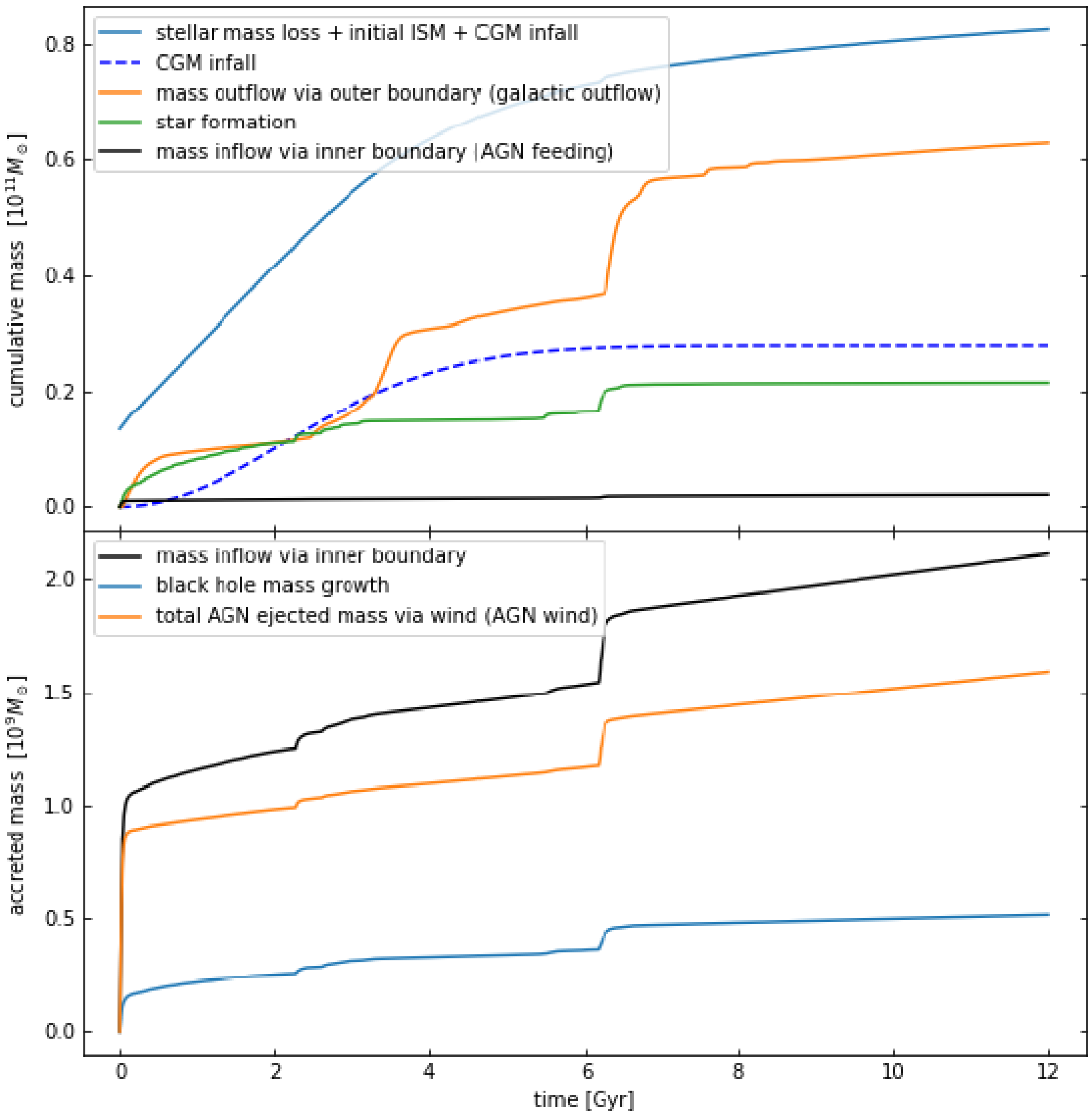


Figure 3. Cumulative star formation in the circumnuclear disk at $t_{\rm age}$ = 12.1 Gyr. The size of the stellar disk is < 150 parsec. The cumulative star formation in the disk is $\sim 6.5 \times 10^9 M_\odot$. The averaged age and metallicity of the new stellar population are 7.52 Gyr and $Z/Z_\odot = 5.82$, respectively.

Mass Budget



stellar mass loss + initial ISM + CGM infall
CGM infall
mass outflow via outer boundary (galactic outflow)
star formation
mass inflow via inner boundary (AGN feeding)
cumulative mass [$10^{11} M_\odot$]
0.8
0.6
0.4
0.2
0.0
mass inflow via inner boundary
black hole mass growth
total AGN ejected mass via wind (AGN wind)
accreted mass [$10^{9} M_\odot$]
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
time [Gyr]

Spectra

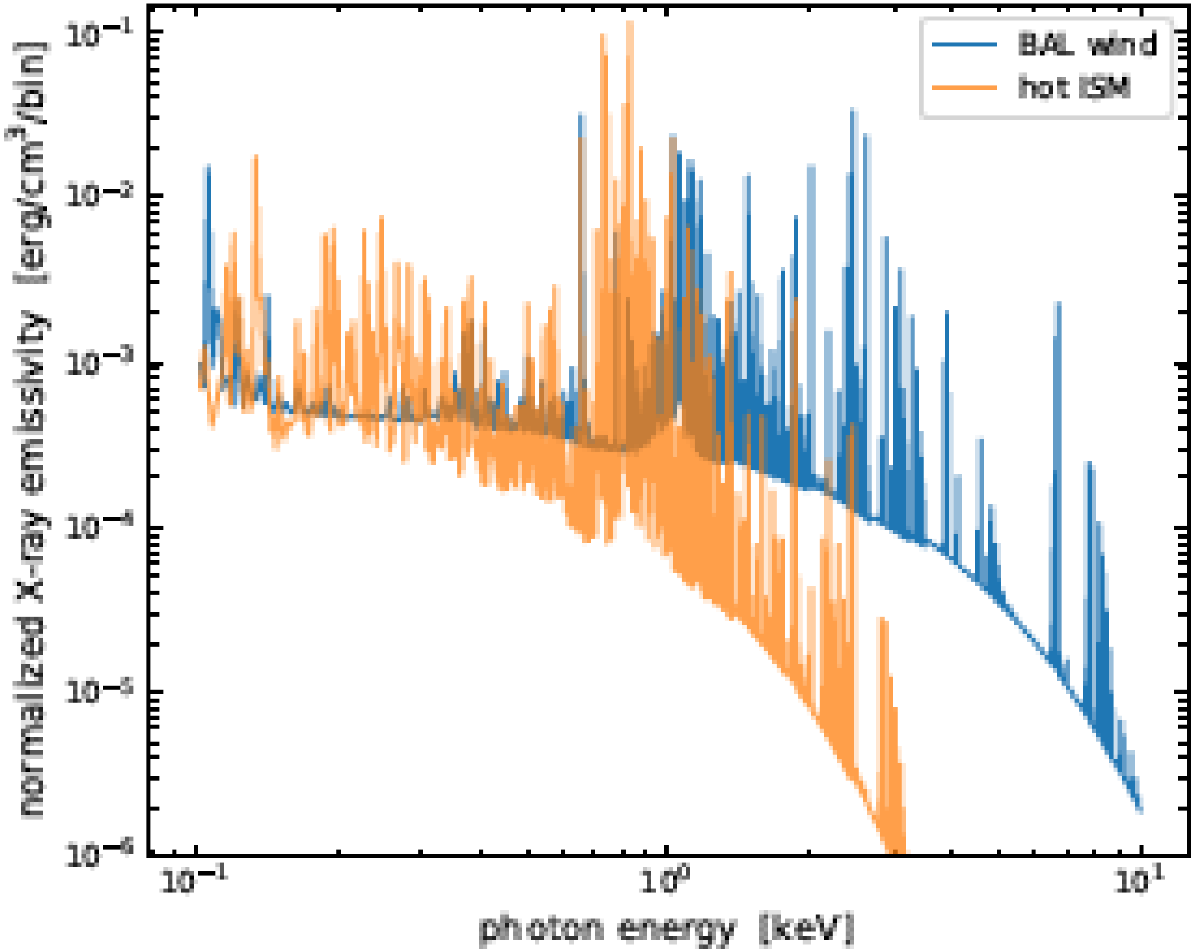


Figure 9. Metallicity-dependent X-ray emissivities with the sampled metal abundances in Table 2. The BAL sample is of a typical temperature $\sim 2 \times 10^7$ K, and that of the hot ISM is $\sim 5 \times 10^6$ K.

Summary of High Resolution AGN Driven Massive Galaxy

- At same energy efficiency, wind driving is far more effective than thermal in driving outflow. And thermal X-rays have dramatically better fit to observations.
- BH growth is well regulated.
- Central cold gas disk forms periodically.
- Bursting phenomenon dominates. Small duty cycle produced.
- Galaxy properties remarkably like real ellipticals and global quenching co-exists with central starbursts.