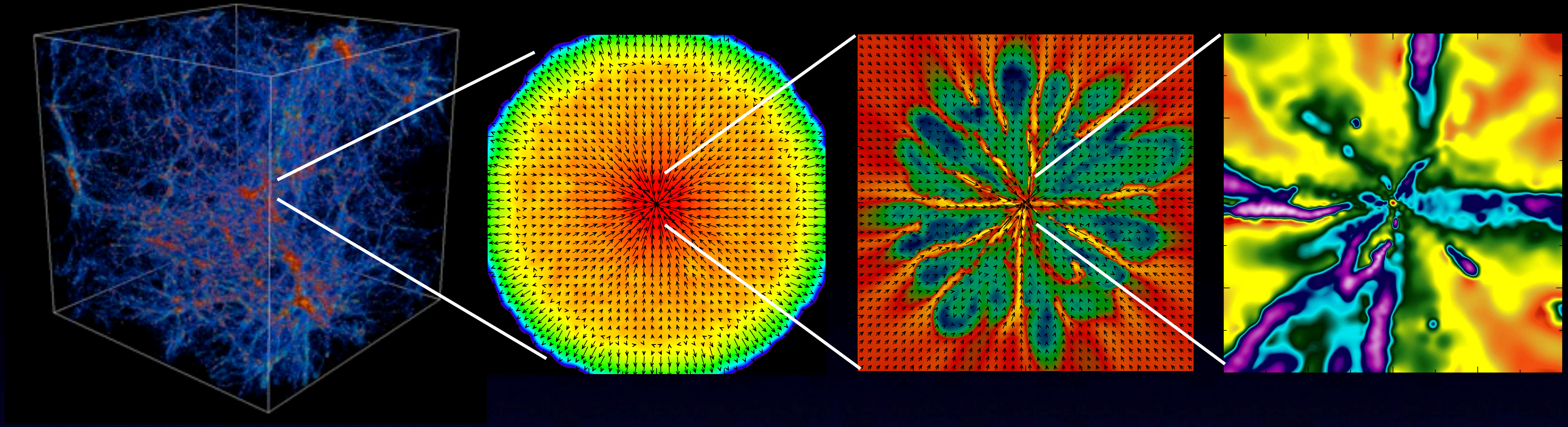


BH Accretion, FB Efficiencies & Thermal Instability:

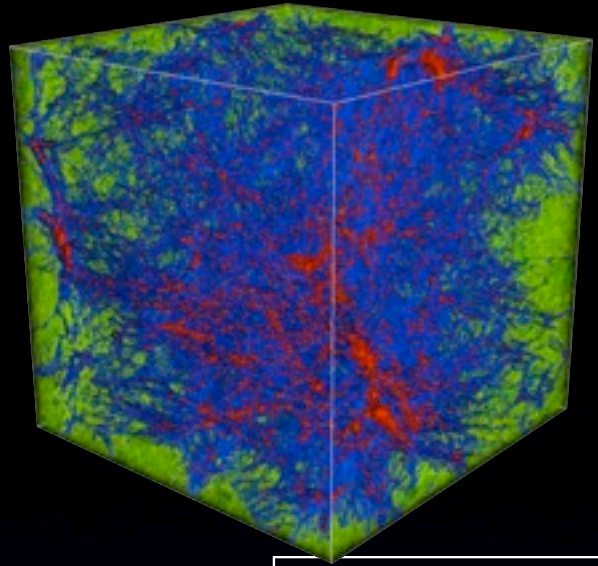
a step to modeling AGN feedback (FB)

Ken Nagamine (UNLV / Osaka)

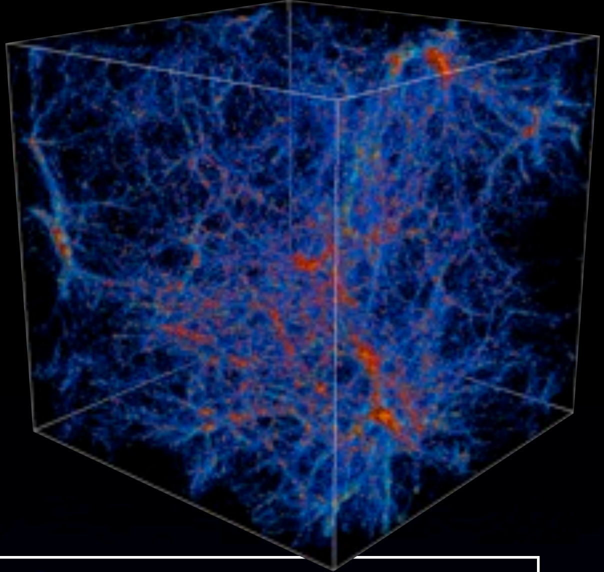
Daniel Proga (UNLV)
Paramita Barai (Trieste / UNLV)
Amit Kashi (UNLV)

Relevant papers:

Kurosawa, Proga, KN, 2009, ApJ, 707, 823
Barai, Proga, KN, 2011, MNRAS, 418, 591 (Paper I)
Barai, Proga, KN, 2012, MNRAS, 424, 728 (Paper II)
Moscibrodzka & Proga, 2013, ApJ, 767, 156
Kashi, Proga, KN, Barth, Greene 2013, arXiv:1306.1090



Outline



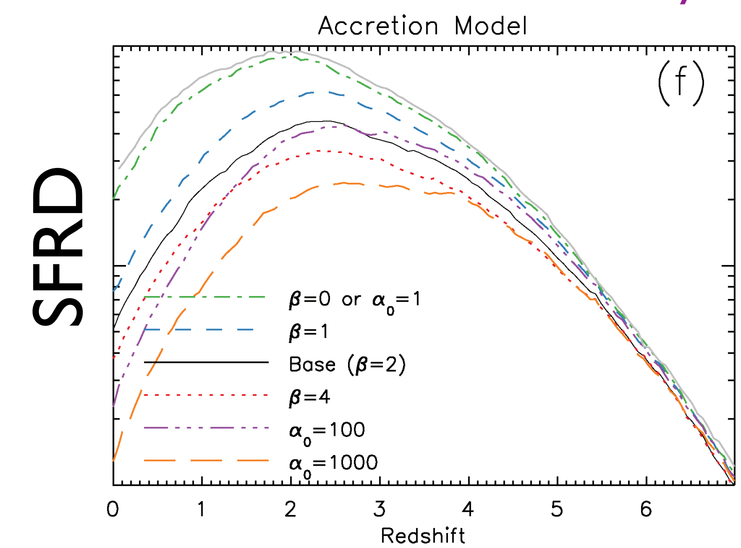
- Motivation: understand AGN feedback on small-scales and link to large-scales
- AGN feedback (FB) efficiencies
- Simulations: Bondi accretion (both SPH & Grid)
- Understanding Thermal Instability
- Implications for AGN feedback

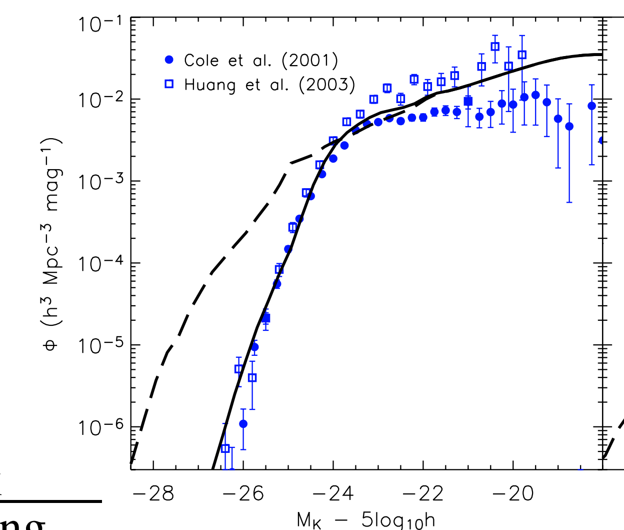
Kurosawa, Proga, KN, 2009, ApJ, 707, 823
Barai, Proga, KN, 2011, MNRAS, 418, 591 (Paper I)
Barai, Proga, KN, 2012, MNRAS, 424, 728 (Paper II)
Moscibrodzka & Proga, 2013, ApJ, 767, 156
Kashi, Proga, KN, Barth, Greene 2013, arXiv:1306.1090

Many Signs of AGN Feedback (FB) in Galaxy Formation

- AGN FB is considered to regulate star formation (quenching) in massive galaxies, causing the decline of cosmic SFRD at z≲1.
- Maybe it suppresses the massive-end of galaxy stellar mass func.
- Galaxy clusters show signs of central heating.

Booth & Schaye '09





Croton+ '06

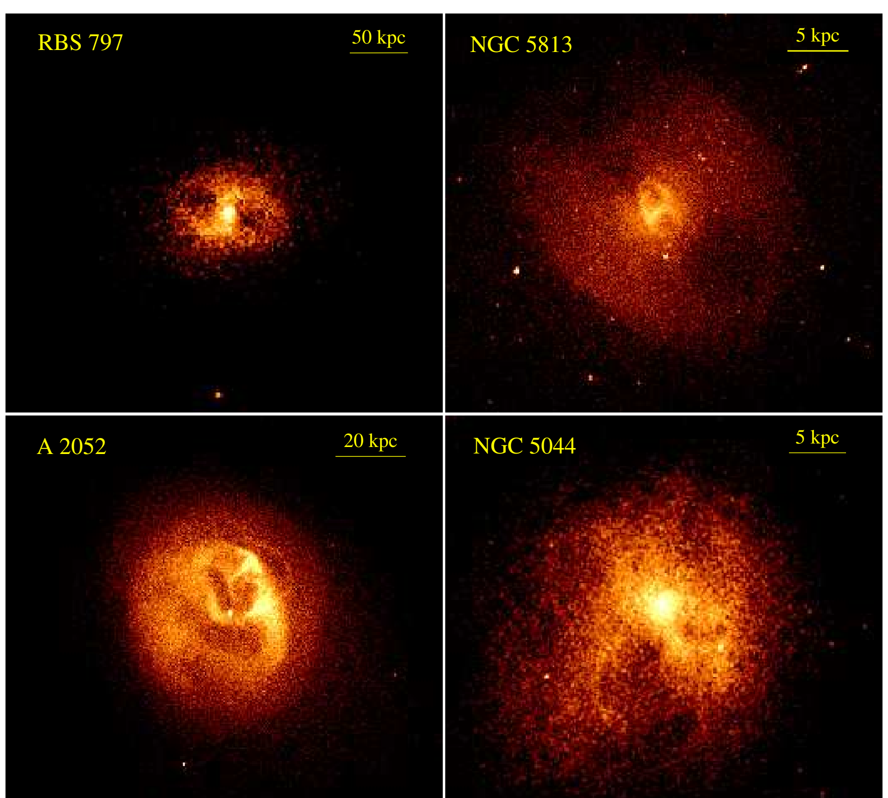


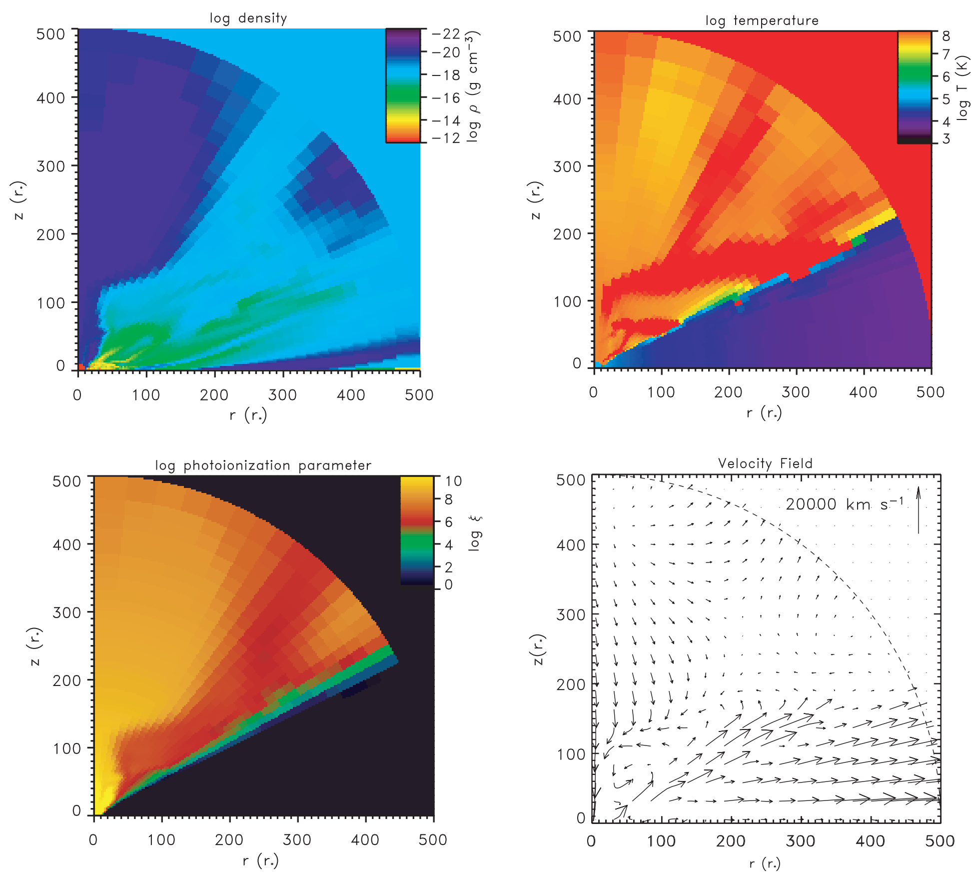
Table 1: Observational Evidence for AGN Feedback

High velocity broad absorption lines in quasars	strong
Strong winds in AGN	strong
1000 km/s galactic outflows	strong
Bubbles and ripples in BCGs	strong
Giant radio galaxies	strong
Lack of high SFR in cool cluster cores	indirect
$M-\sigma$ relation	indirect
Red and dead galaxies	indirect
Lack of high lambda, moderate N_H, quasars	indirect
Steep $L-T$ relation in low T clusters and groups	indirect

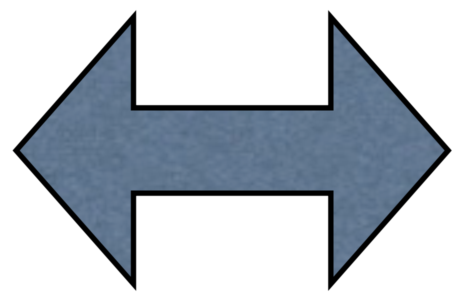
Fabian+ '12

Bridging the Gap btw Large & Small Scale

Small-scale sims
(≲ pc)

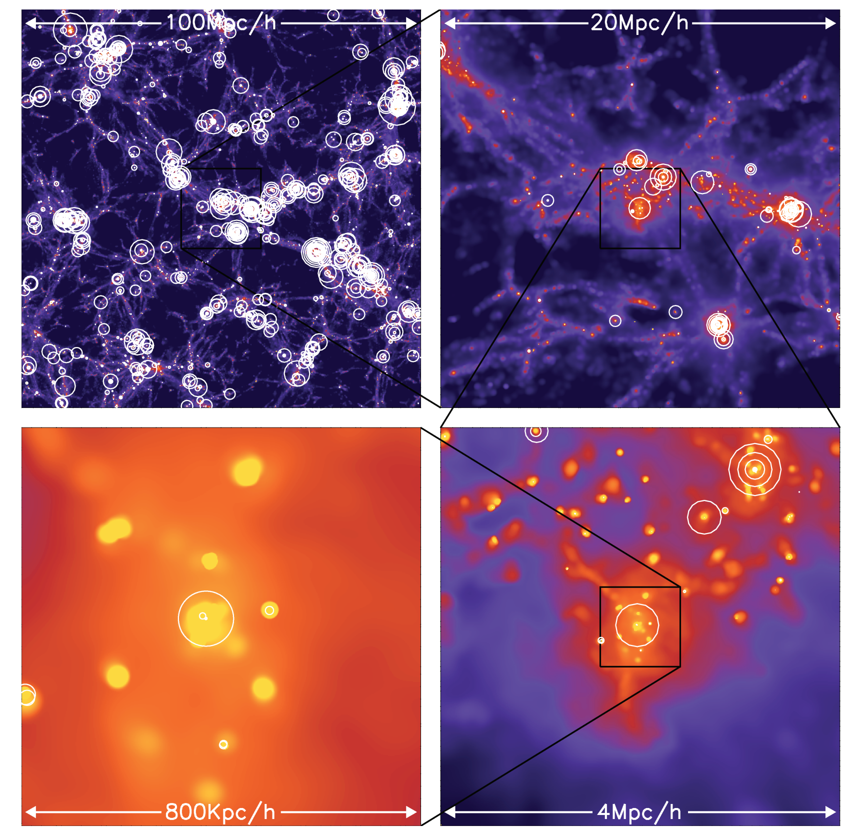


(Proga, Stone, Ciotti, Novak, Ohsuga, Park & Ricotti, ...)



Gap

Cosmological sims
(~kpc - 100 Mpc)



(Di Matteo, Booth & Schaye, Bellovary, Dubois, …)

- Still a large gap btw small-scale sims & cosmological sims.
- Cosmo. sims use ad-hoc BH accretion models as “sub-grid” physics.

Assumptions in Cosmo. Sims.

Bondi-Hoyle-Lyttleton mass accretion rate

$$\dot{m}_a = \alpha \frac{4\pi G M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \quad \& \quad \alpha \sim 100$$

(cf. Angles-Alcazar's talk yesterday for an alternative)

Radiative output from accretion

$$L_{\rm a} = \epsilon_{\rm r} c^2 \dot{M}_{\rm a},$$

radiative efficiency $\epsilon_{\rm r}$ (rest-mass energy conversion)

$$\epsilon_r \approx 10^{-1}$$

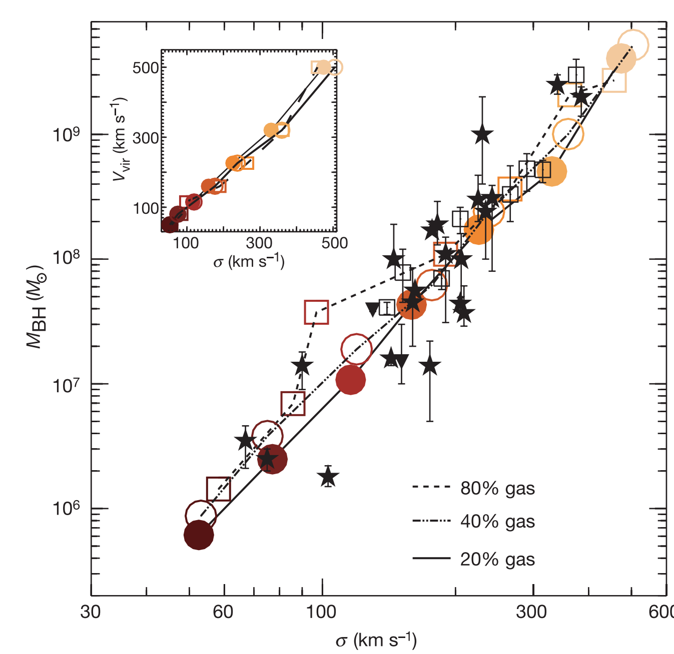
Shakura & Sunyaev '73

Feedback efficiency $\epsilon_{\rm f}$

$$\dot{E}_{\rm f} = \epsilon_{\rm f} L_a = \epsilon_{\rm f} \epsilon_{\rm r} \dot{M}_a c^2$$

Requirement from M_{BH}-σ rel.

$\epsilon_{\rm f} = 0.05$	Springel, Di Matteo, Hernquist '05
$\epsilon_{\rm f} = 0.15$	Booth & Schaye '09; Dubois+ '12
$\epsilon_{\rm f} \sim 10^{-3}$	Bellovary+ '10



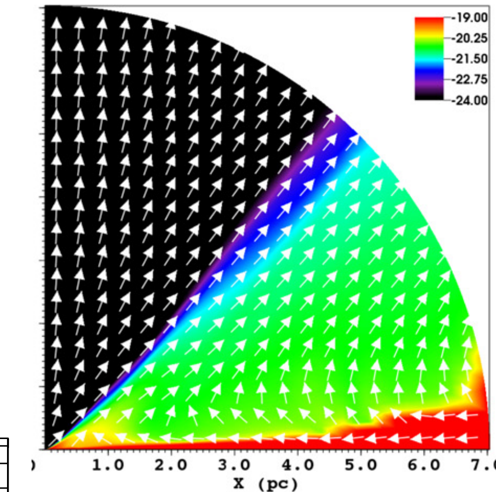
Di Matteo+ '05

FB Efficiency in small scale sim

THE ASTROPHYSICAL JOURNAL, 707:823–832, 2009 December 10

ON THE FEEDBACK EFFICIENCY OF ACTIVE GALACTIC NUCLEI

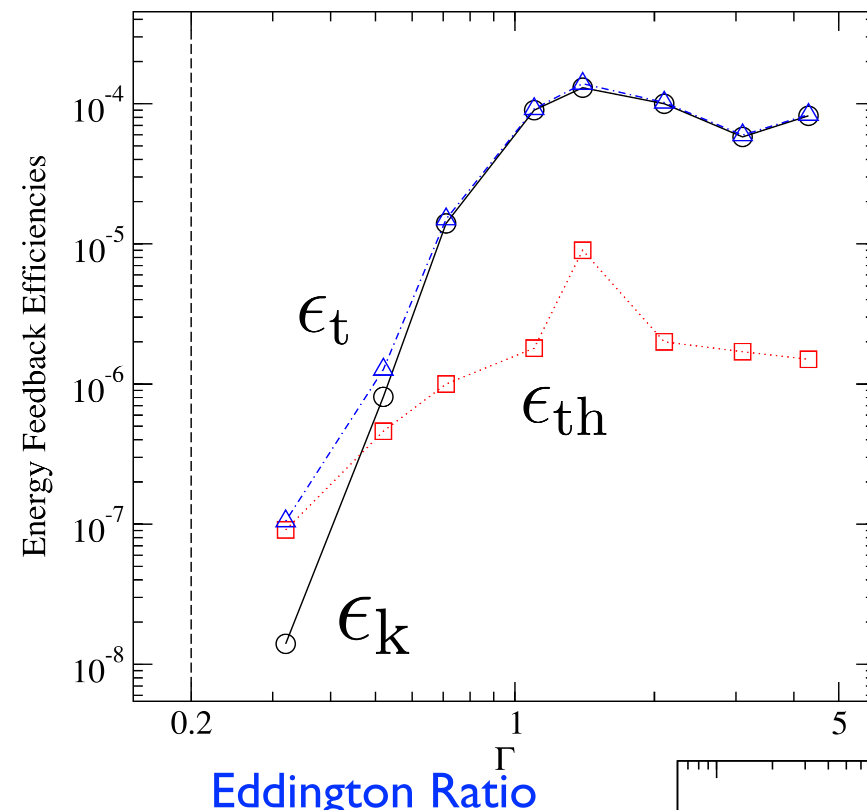
RYUICHI KUROSAWA[1], DANIEL PROGA, AND KENTARO NAGAMINE
Department of Physics and Astronomy, University of Nevada, Las Vegas, Box 454002, 4505 Maryland Pkwy, Las Vegas, NV 891541-4002, USA;
rk@physics.unlv.edu, dproga@physics.unlv.edu, kn@physics.unlv.edu
Received 2009 June 19; accepted 2009 October 27; published 2009 November 25



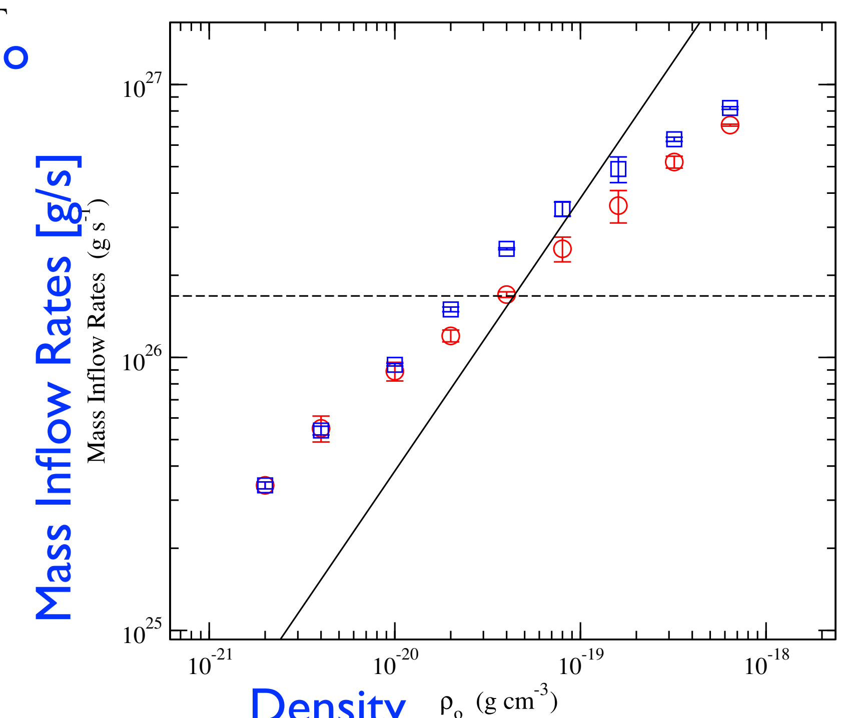
Using grid-based ZEUS code:

Total energy FB efficiency:

$$\epsilon_t = (P_k + P_{th})/L_a$$



kinetic energy FB efficiency	$\epsilon_k = P_k/L_a$
thermal energy FB efficiency	$\epsilon_{th} = P_{th}/L_a$
momentum FB efficiency	$\epsilon_p = p_w/(L_a/c)$
mass FB efficiency	$\epsilon_m = \dot{M}_{out}/\dot{M}_{in}$



Taking Simple Steps

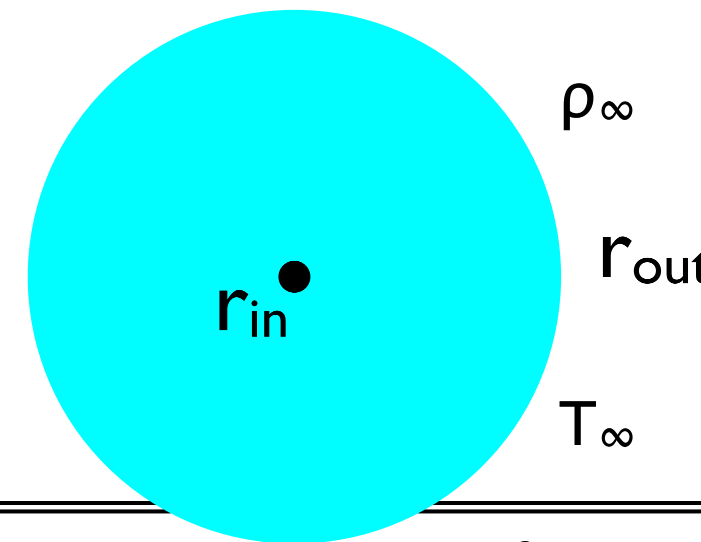
- First, check the code (Gadget SPH): the simplest case -- spherical Bondi accretion
- Include radiative cooling / heating -- only thermal feedback by X-rays
- Emergence of non-spherical accretion inflow/outflow, fragmentation due to thermal instability

Our goal is to test the simplest possible setup and see how the accretion flow reacts.

Barai, Proga, KN 2011, 2012

Simplest Case: Spherical Bondi Accretion Flow onto a SMBH

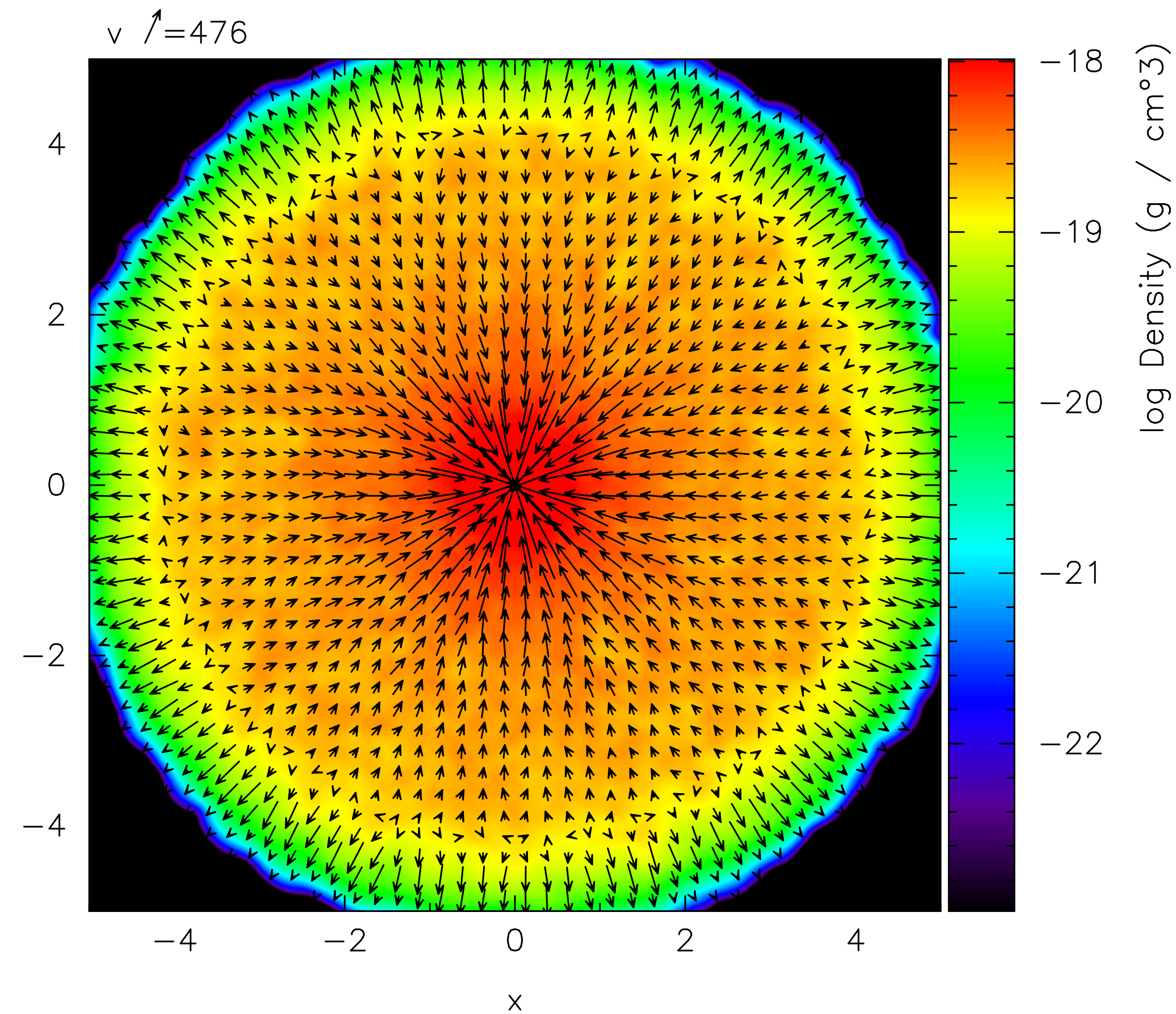
- GADGET-3 SPH (Springel '05)
- Central SMBH 10^8 $M_\odot$ represented by a pseudo-Newtonian Paczynsky & Wiita '80 potential
- r_{out}=5-20 pc, $N_{ptcl}=64^3-128^3$
- IC: uniform/spherical Bondi flow w/ γ=1.01, $\rho_\infty=10^{-19}$ g/cm^3, $T_\infty=10^7$K, $T_{init}=T_\infty$
- R_B=3pc, R_{sonic}=1.5pc, t_B=7.9e3yr
- All runs: **r_{in}=0.1pc**, γ=1.01
- DM halo potential is minimal



Run No.	r_{out} [pc]	N [b]	IC	$M_{tot,IC}$ [c] $[M_\odot]$	M_{part} [d] $[M_\odot]$	t_{end} [e] $[10^4$ yr$]$
1	5	64^3	Uniform [i]	3.96×10^5	1.51	3
2	10	64^3	Uniform	6.19×10^6	23.61	7.2
3	50	128^3	Uniform	7.73×10^8	368.60	20
4	5	64^3	Bondi [j]	1.81×10^6	6.89	2
5	10	64^3	Bondi	9.76×10^6	37.23	8
6	10	128^3	Bondi	9.76×10^6	4.65	8
7	20	128^3	Bondi	6.24×10^7	29.75	8
7a [k]	20	128^3	Bondi	6.24×10^7	29.75	80
7b [l]	20	128^3	Bondi	6.24×10^7	29.75	100
8	50	128^3	Bondi	8.48×10^8	404.35	16
9	20	128^3	$\rho_B, v_{init} = 0$	6.24×10^7	29.75	8
10	20	128^3	Uniform	4.95×10^7	23.60	8
11	20	128^3	Hernquist [m]	6.24×10^7	29.75	7.2
12 [n]	20	128^3	Bondi	6.24×10^7	29.75	8

Spherical Bondi Accretion Flow

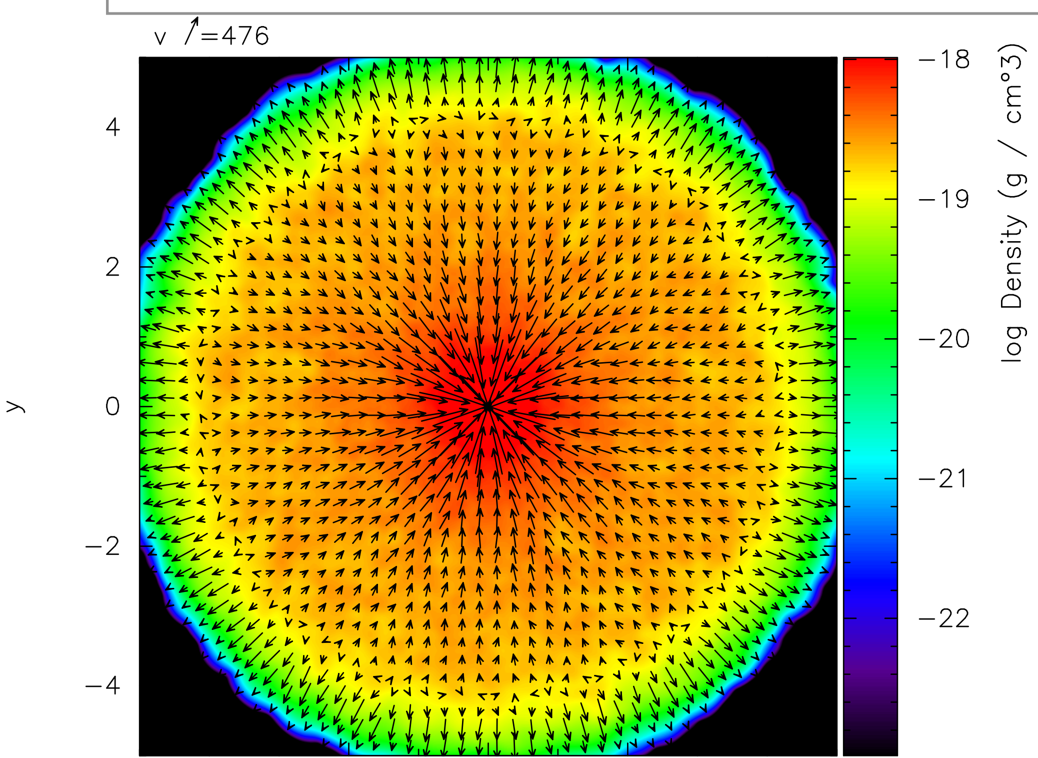
- Cross section, showing ρ_{gas}
- Run #4: r_{out}=5 pc, $N_{ptcl}=64^3$
- At t= 0.25t_B = 2e3 yr
- Smooth, spherical Bondi accretion flow is reproduced.
- Artificial outflow near the outer boundary due to vacuum outer B.C.
- Greater sim. volume reduces this effect on mass inflow.

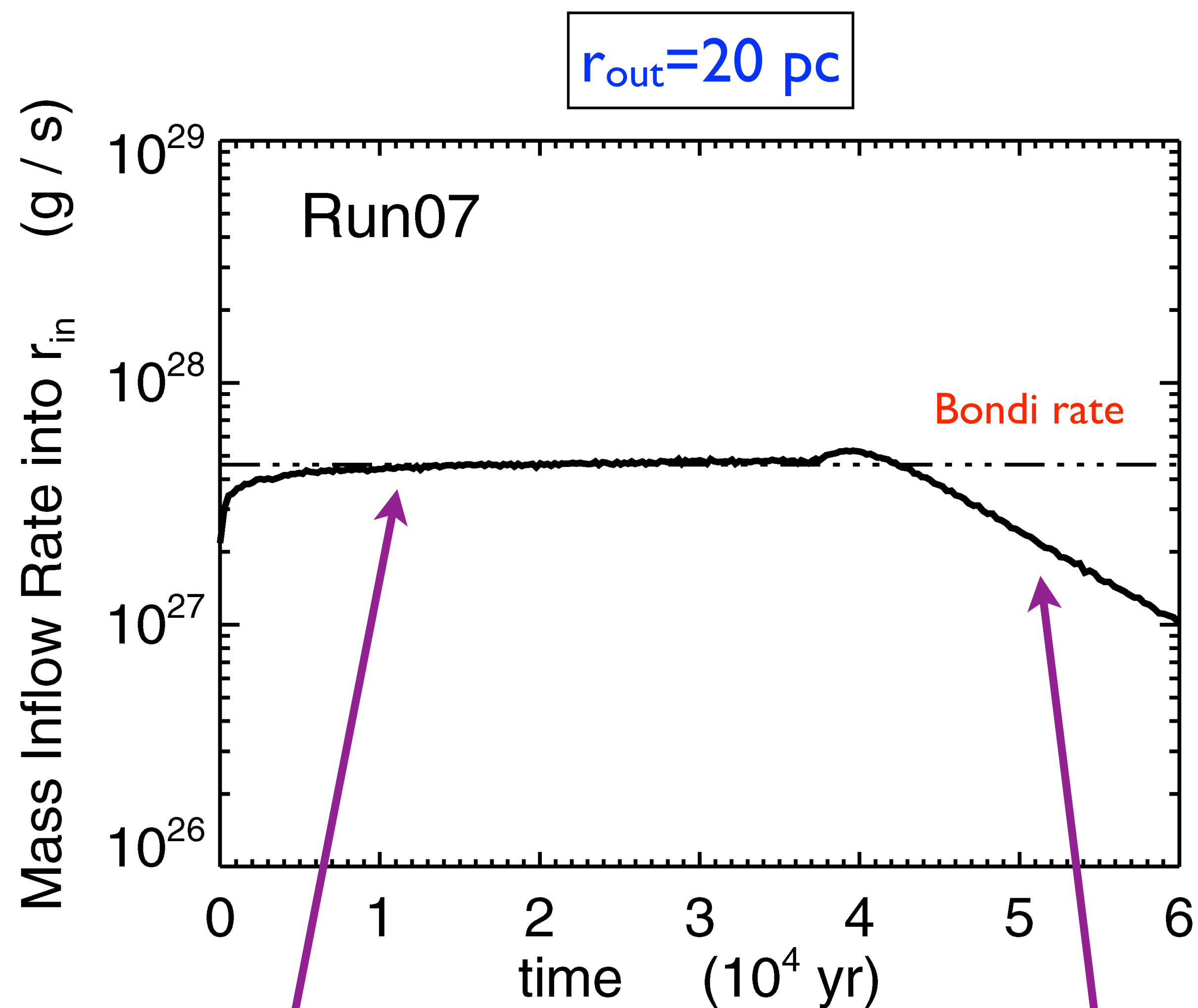


Barai, Proga, KN '11

Mass Inflow Rates at r_{in}

- the larger r_{out}, the longer duration of Bondi inflow rate
- If started from a Bondi flow, Bondi rate is achieved quickly.
- After a while, the inflow rate decreases due to the artificial outflow at the outer boundary.
- Greater sim. volume reduces this effect on mass inflow.





reproducing Bondi rate well.

due to outflow problem at outer BC

Barai, Proga, KN '11

Radiative Heating & Cooling

- Xray emitting corona irradiates the accretion flow

$$L_X = f_X L_{\rm Edd}, \qquad L_{\rm Edd} = \frac{4\pi c G m_p M_{BH}}{\sigma_e}, \qquad \textbf{Flux:} \quad F_X = \frac{L_X}{4\pi r^2}.$$

(f_X=0.05 in KP09)

- Approx. analytic heating/cooling rates from Blondin '94; opt-thin gas illuminated by a 10 keV bremsstrahlung.

net rate:

$$\rho\mathcal{L} = n^2 \left(G_{\rm Compton} + G_X - L_{b,l}\right) \quad [{\rm erg\ cm^{-3}\ s^{-1}}],$$

Compton h/c rate:

$$G_{\rm Compton} = 8.9 \times 10^{-36} \xi \left(T_X - 4T\right) \quad [{\rm erg\, cm^3\, s^{-1}}].$$

Net Xray photoioniz. heating and recomb. cooling rate:

$$G_X = 1.5 \times 10^{-21} \xi^{1/4} T^{-1/2} \left(1 - \frac{T}{T_X}\right) \quad [{\rm erg\ cm^3\ s^{-1}}].$$

Brems. and line cooling rate:

(Opt-thin: δ=1)

$$L_{b,l} = 3.3 \times 10^{-27} T^{1/2} + \left[1.7 \times 10^{-18} \exp\left(-1.3 \times 10^5/T\right) \xi^{-1} T^{-1/2} + 10^{-24}\right] \delta \quad [{\rm erg\ cm^3\ s^{-1}}].$$

$T_X = 1.16\times10^8$ K (=10keV, Blondin '94)

Runs with radiative cooling/heating

Run No.	r_{out} [pc]	N	$M_{tot,IC}$ [$M_\odot$]	M_{part} [$M_\odot$]	γ_{init}	T_∞ [K]	R_B [pc]	ρ_∞ [g/cm^3]	T_{init}	L_X [L_{Edd}]	t_{end} [10^5 yr]
13	20	128^3	5.81×10^5	0.277	1.4	10^7	2.19	10^{-21}	T_∞	0.5	1.0
14	50	128^3	8.23×10^6	3.92	1.4	10^7	2.19	10^{-21}	T_∞	0.5	2.9
15	20	128^3	5.81×10^{-1}	2.77×10^{-7}	1.4	10^7	2.19	10^{-27}	T_∞	0.5	1.0
16	20	256^3	5.81×10^{-1}	3.46×10^{-8}	1.4	10^7	2.19	10^{-27}	T_∞	5×10^{-4}	1.9
17	20	128^3	5.81×10^5	0.277	1.4	10^7	2.19	10^{-21}	T_{rad} [b]	5×10^{-4}	2.9
18	20	128^3	5.65×10^5	0.269	5/3	10^7	1.84	10^{-21}	T_{rad}	5×10^{-4}	3.0
19	20	128^3	1.47×10^7	7.0	5/3	10^5	183.9	10^{-21}	T_{rad}	5×10^{-4}	1.5
20	200	256^3	1.33×10^9	79.09	5/3	10^5	183.9	10^{-21}	T_{rad}	5×10^{-4}	6.5
21	200	256^3	4.95×10^8	29.50	5/3	10^7	1.84	10^{-21}	T_{rad}	5×10^{-4}	8.7
22	200	128^3	1.33×10^7	6.33	5/3	10^5	183.9	10^{-23}	T_{rad}	5×10^{-4}	70
23	200	256^3	1.33×10^7	0.791	5/3	10^5	183.9	10^{-23}	T_{rad}	5×10^{-4}	20
24 [c]	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	T_{Run23}	5×10^{-5}	19
25	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	T_{Run23}	5×10^{-3}	21
26	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	T_{Run23}	1×10^{-2}	22
27	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	T_{Run23}	2×10^{-2}	25
28	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	T_{Run23}	5×10^{-2}	50

Non-spherical outflow:

due to rad. feedback

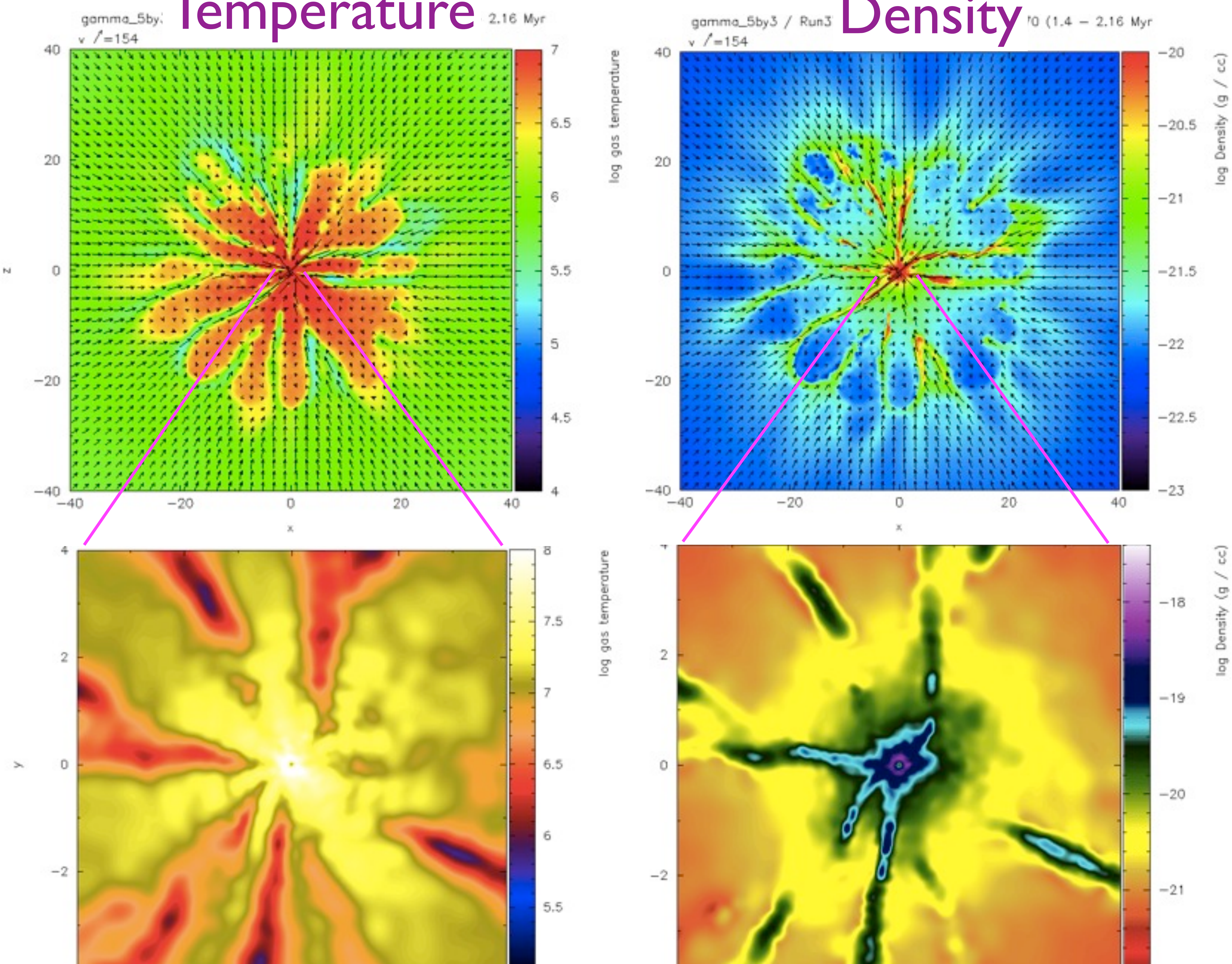
Run 26: r_{out}=200pc, Lx/L_{Edd}=0.01

Temperature

Density

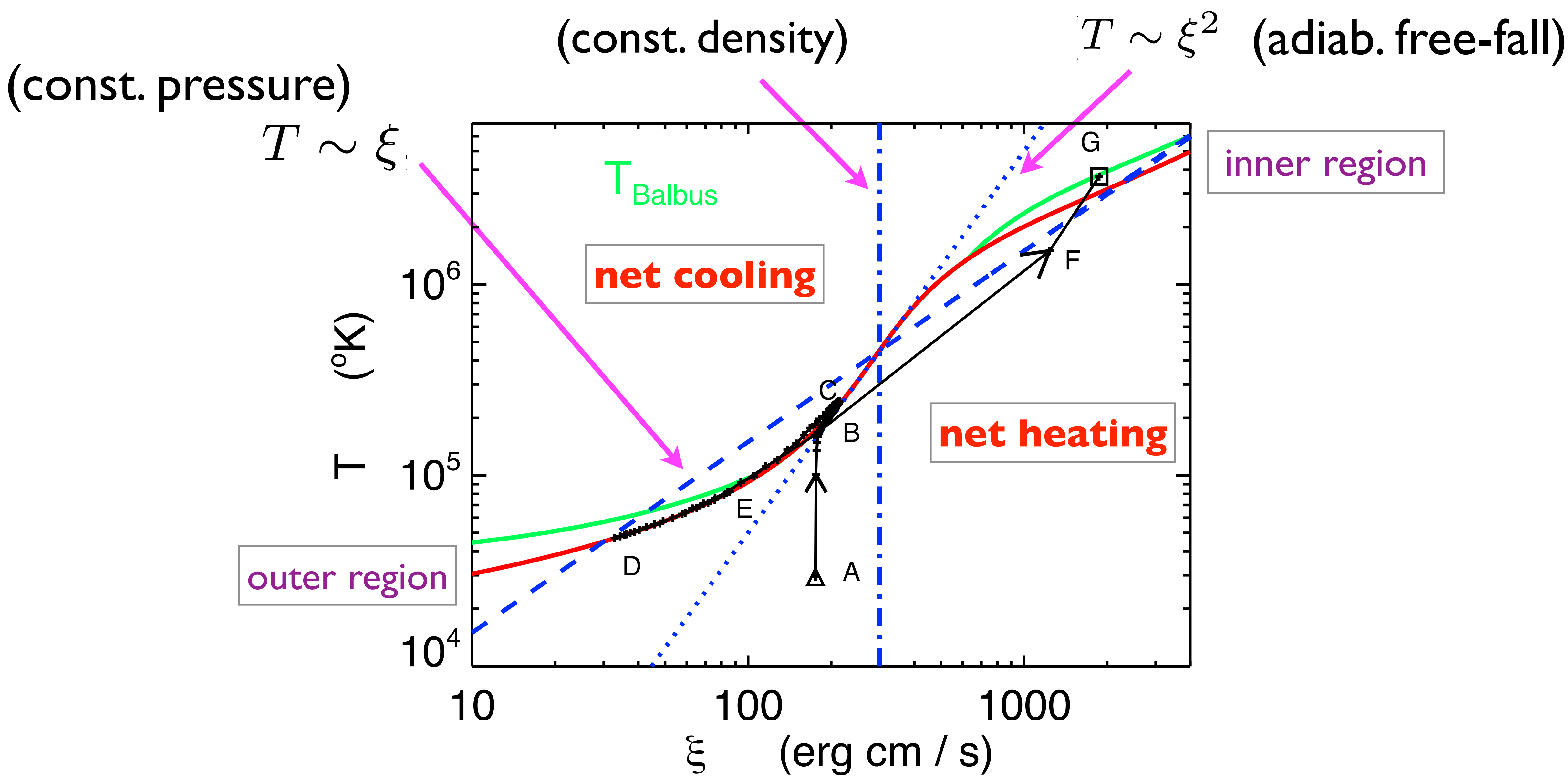
inner ±40pc

inner ±4pc



Indication of Thermal Instability

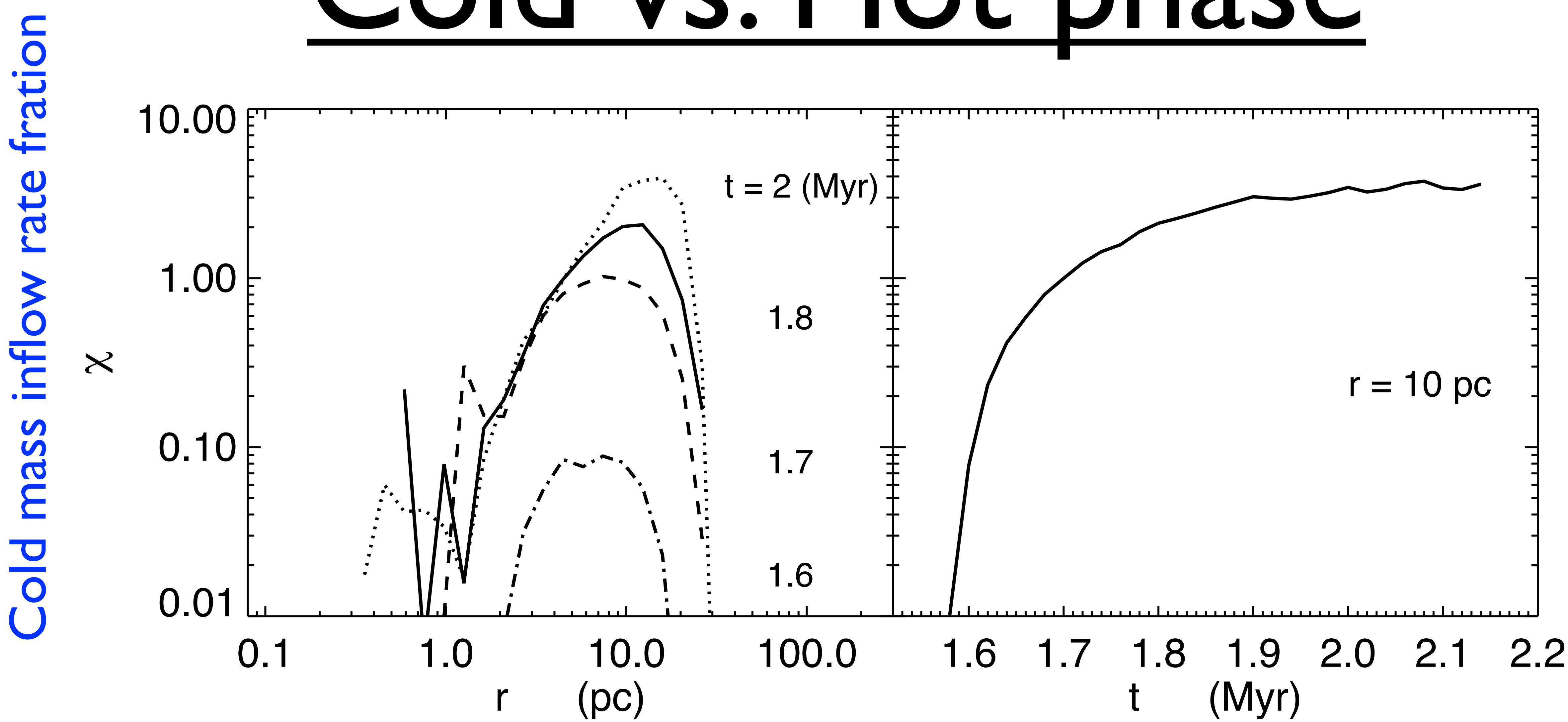
Run 26: r_{out}=200pc, Lx/L_{Edd}=0.01, t=2.0 Myr



Photoionization parameter:

$$\xi \equiv \frac{4\pi F_X}{n} = \frac{L_X}{r^2 n},$$

Cold vs. Hot phase



$$\chi = \dot{M}_{\rm in,cold}/\dot{M}_{\rm in,hot}.$$

cold: $T<10^5$ K hot: $T>10^5$ K

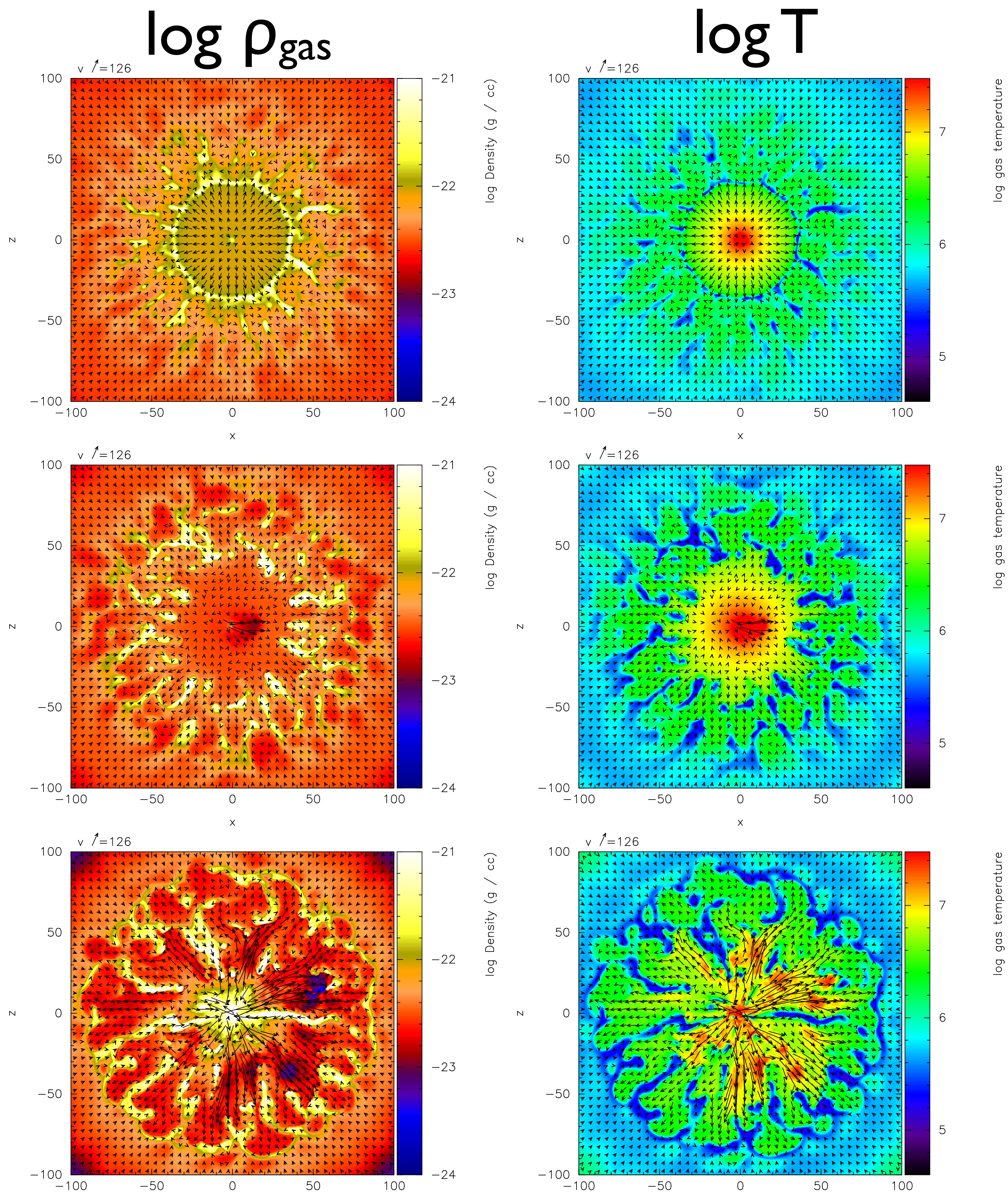
(Similar to the α-param used in cosmo sim.)

We find enhancements of only factor 3-4, not 100

Not const. in time & space. & We can measure it!

Run 27

r_{out}=200pc,
Lx/L_{Edd}=0.02



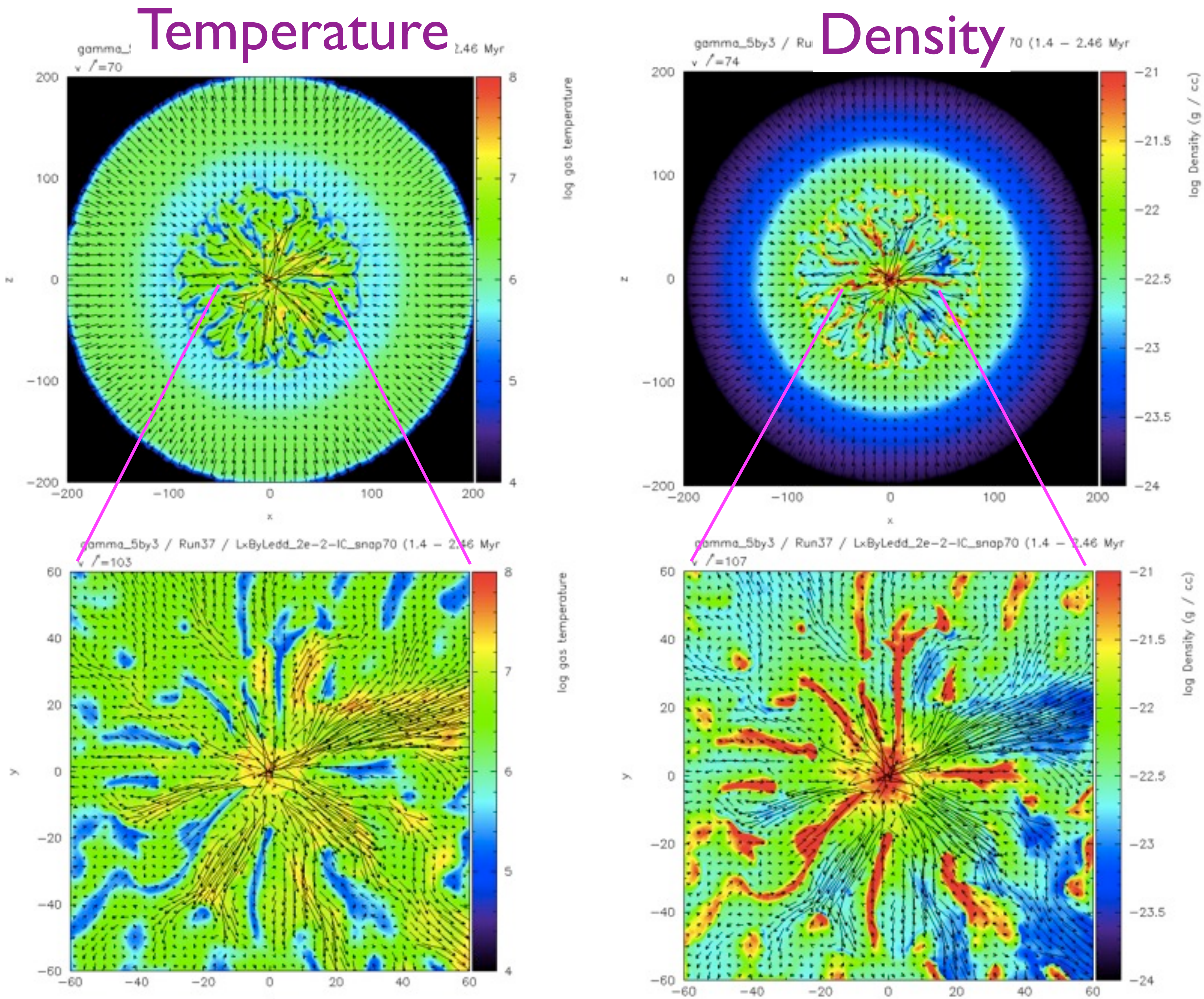
Non-spherical outflow:

due to rad. feedback

Run 27: r_{out}=200pc, Lx/L_{Edd}=0.02

± 200pc

inner ±60pc



Independent check of thermal instability with grid-based ZEUS code in 1,2,3-dimension

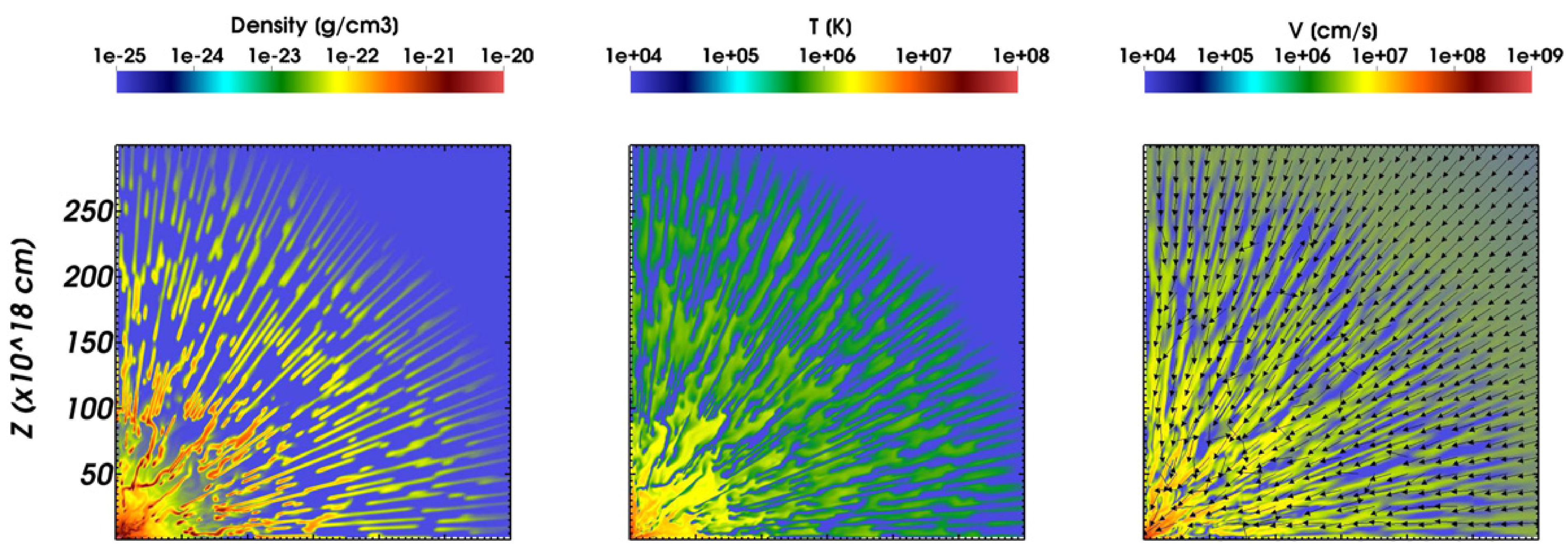
THE ASTROPHYSICAL JOURNAL, 767:156 (15pp), 2013 April 20

THERMAL AND DYNAMICAL PROPERTIES OF GAS ACCRETING ONTO A SUPERMASSIVE BLACK HOLE IN AN ACTIVE GALACTIC NUCLEUS

M. MOŚCIBRODZKA[1] AND D. PROGA
Department of Physics and Astronomy, University of Nevada, 4505 South Maryland Parkway, Las Vegas, NV 89154, USA
Received 2012 November 15; accepted 2013 March 2; published 2013 April 8

$M_{BH} = 10^8 M_\odot$ $L_X = 0.015\, L_{\rm Edd}$ -- right inbtw 1% and 2% $L_{\rm Edd}$.

Basically confirmed the results of Barai+ '11, '12 about fragmentation due to thermal instability

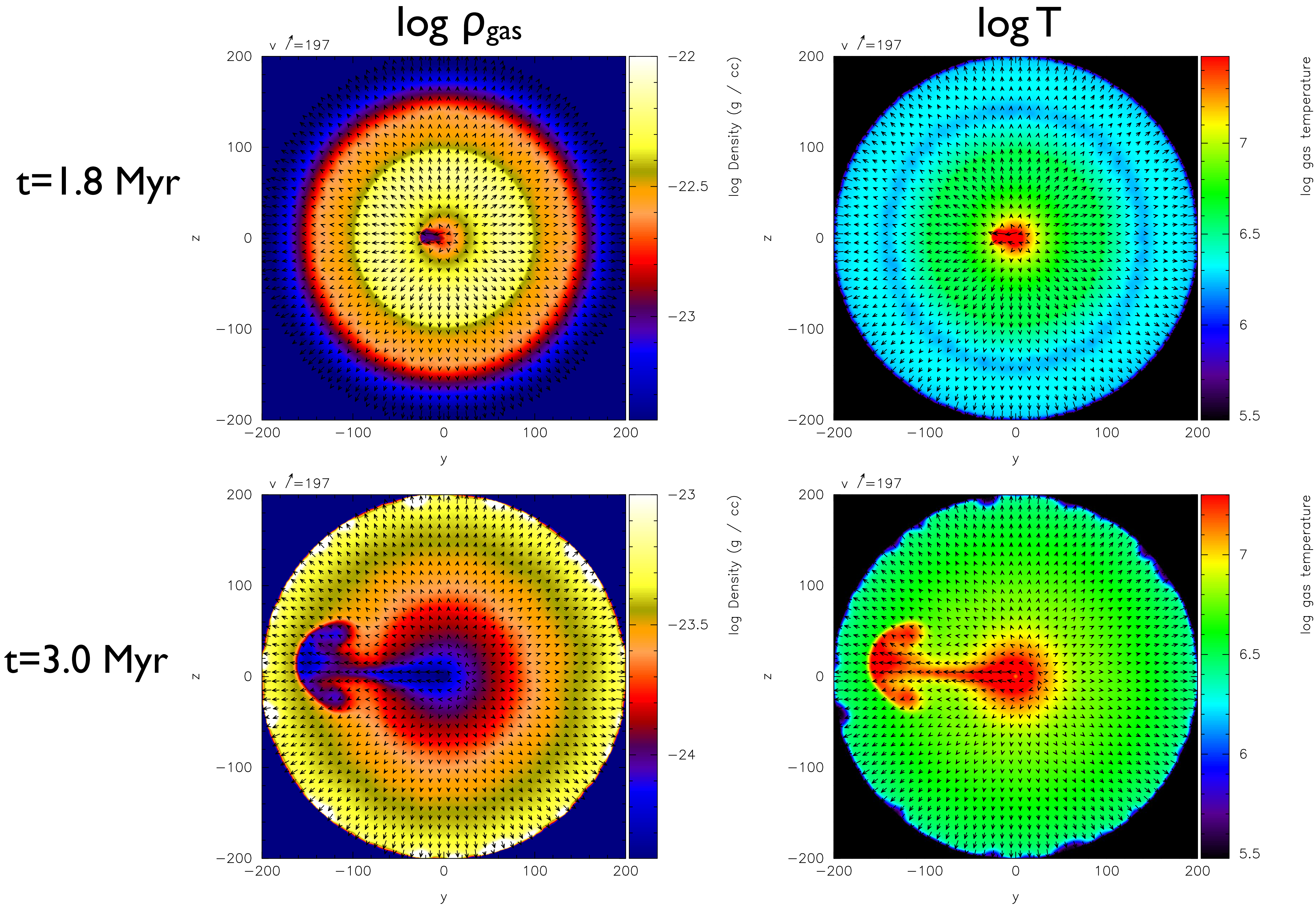


100 pc

ZEUS does not suffer from artificial outflow problem at the outer boundary, and we can run it longer. Proga will show long-term evolution of the flow.

Run 28

r_{out}=200pc, L_x/L_{Edd}=0.05



Conclusions & Future Work

- GADGET SPH code *can* reproduce the *spherical Bondi accretion* properly w. some limitations. (repeat w. new SPH)
- *Non-spherical inflow & outflow* develops due to rad. feedback via thermal instability, even in the simplest case that we studied --- connection with NLR
- AGN FB efficiencies measured in our sims are LOW ($\lesssim 10^{-4}$): cosmological implications? -- Is AGN FB really important for galaxy formation? (cf. Priya's talk, Ostriker+10)
- **Future:** include other physics; how do we apply these results to cosmo. sims? Maybe we should stop using Bondi formula in cosmo sims.