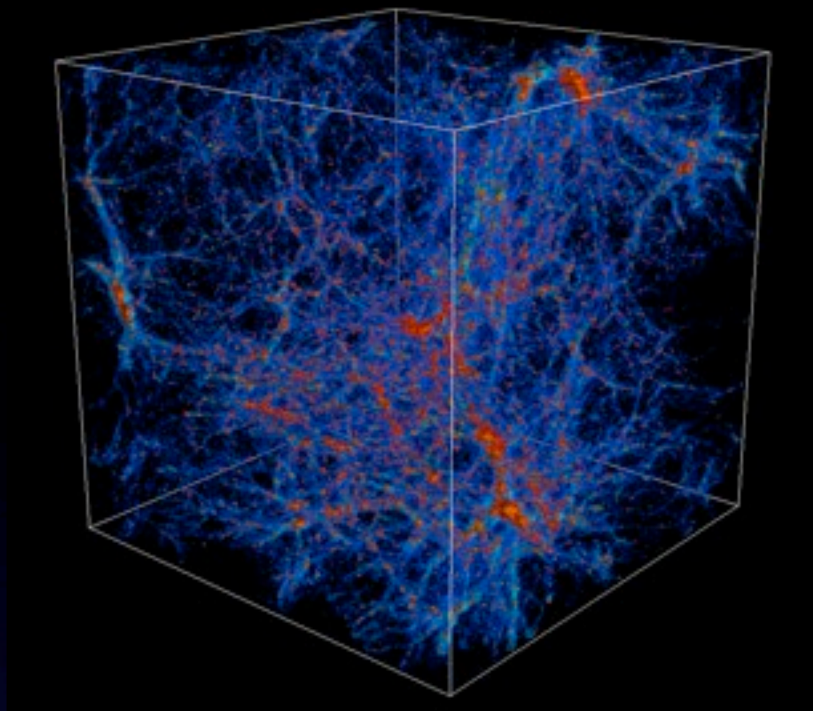
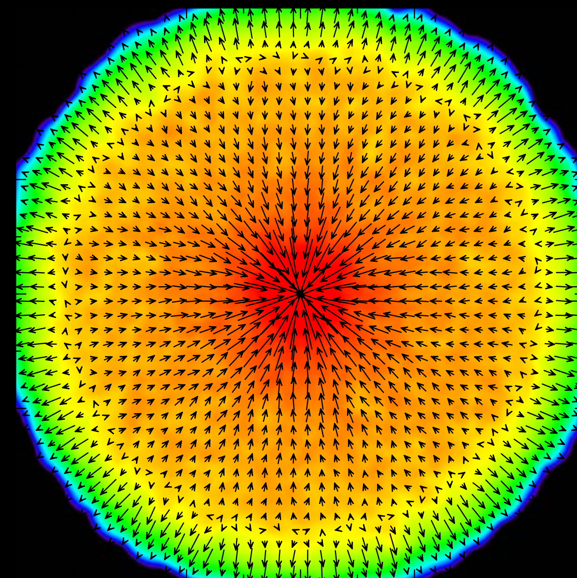
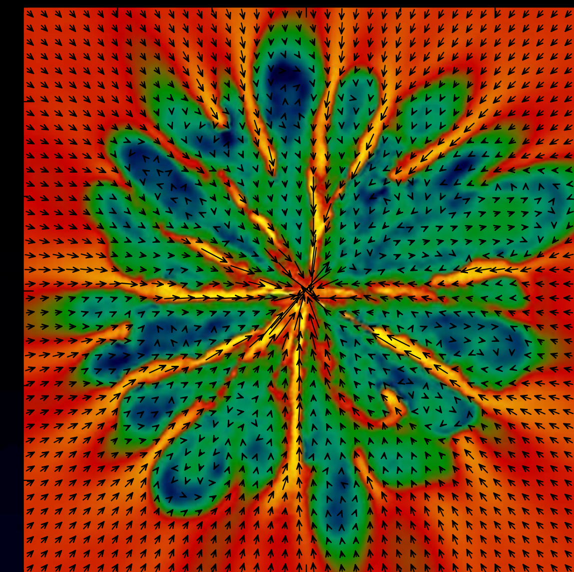
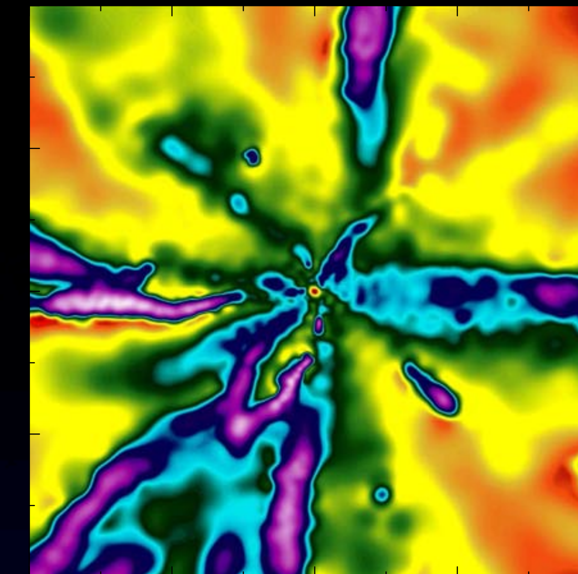








Gas Accretion onto a Supermassive Black Hole:

a step to modeling AGN feedback in cosmological simulations

Ken Nagamine

Univ. of Nevada, Las Vegas (UNLV)

Collaborators: Paramita Barai (UNLV / INAF Trieste)

Daniel Proga (UNLV)

Outline

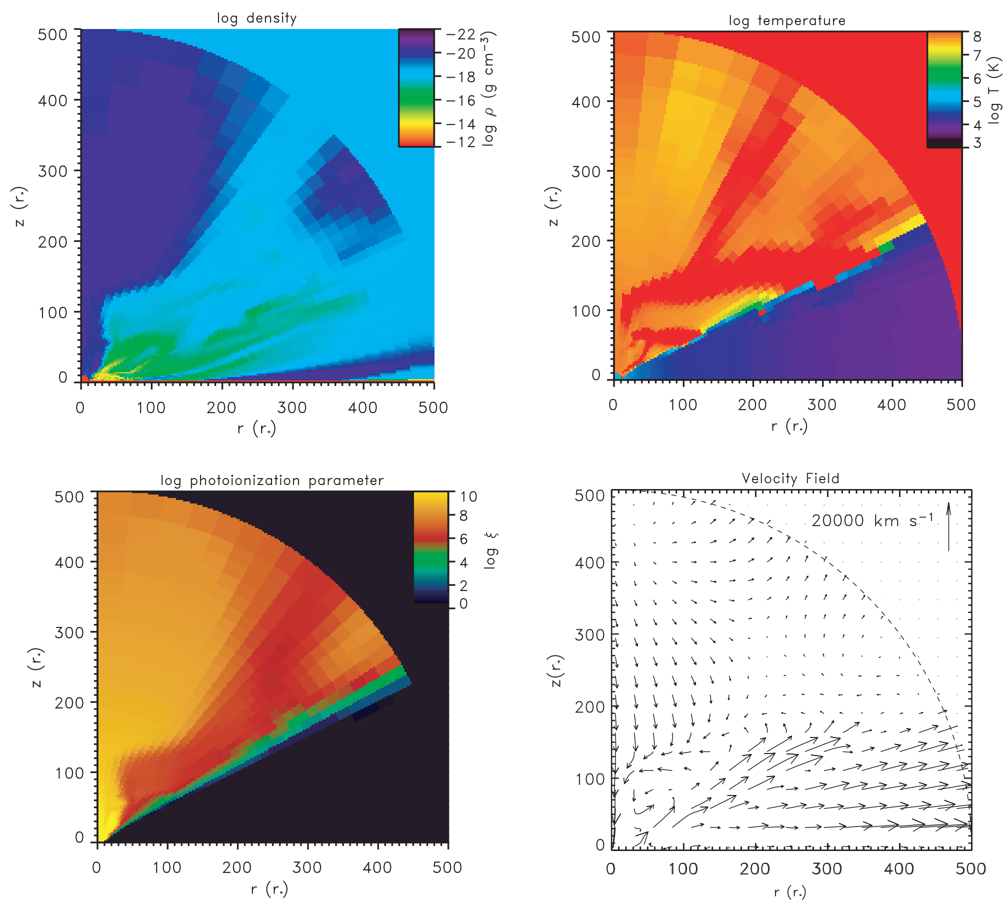
- Intro / Motivation
- The simplest case: spherical Bondi accretion
- Include radiative cooling / heating -- radiative feedback by X-rays

  Barai, Proga, KN, 2011, MNRAS, in press (arXiv:1102.3925)
- Non-spherical accretion flow, fragmentation due to thermal instability

  Barai, Proga, KN, 2011, in prep. (Paper II)
- Conclusions

Motivation

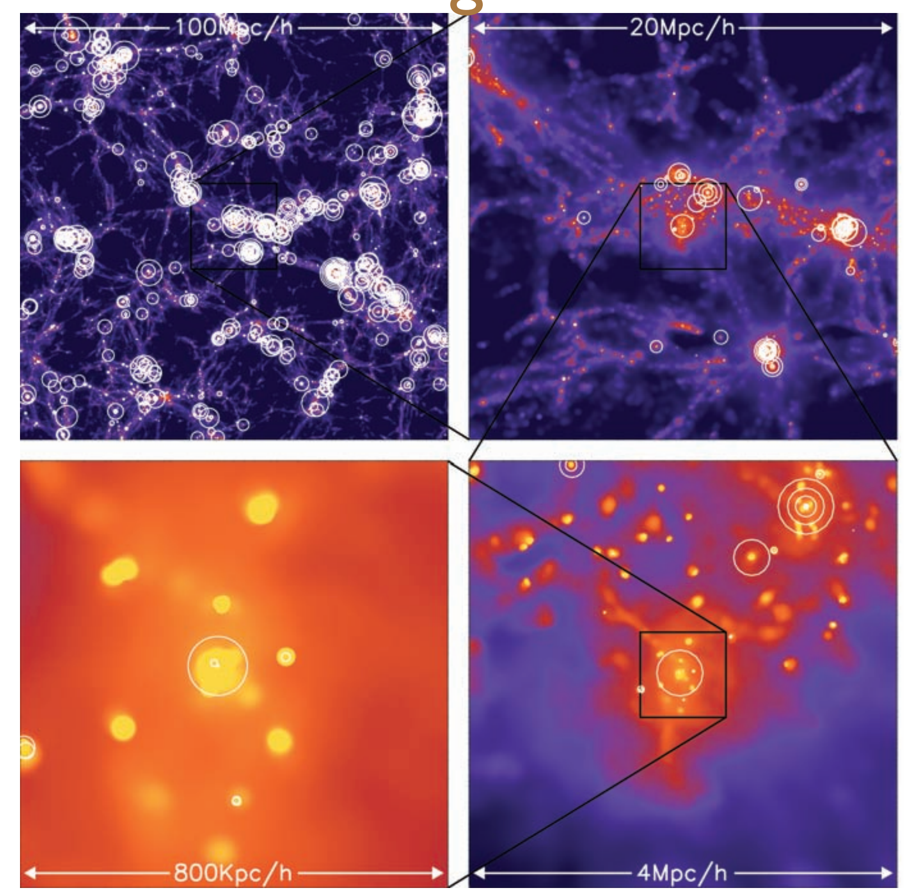
Small-scale sims



(e.g. Ohsuga, Proga, …)

Gap

Cosmological sims



(e.g. Di Matteo+, Booth & Schaye, …)

- Still a large gap btw small-scale sims & cosmological sims.
  (≲ pc) (~kpc - 10 Mpc)
- Cosmo sims uses ad-hoc AGN accretion models as "sub-grid" physics.
- How well can a cosmological SPH code (e.g. GADGET) handle accretion onto a SMBH?

The Bondi Accretion Problem

- Spherically symmetric accretion onto a central mass (Bondi 1952)
- Gas is at rest at infinity, with ρ_∞ & p_∞. Increase in the central mass is ignored.
- Two equations are solved:

$$\dot{M} = -4\pi r^2 \rho v = \text{constant.}$$ (Continuity Eq.)

$$\frac{v^2}{2} + \left(\frac{\gamma}{\gamma - 1}\right) \frac{p_\infty}{\rho_\infty} \left[\left(\frac{\rho}{\rho_\infty}\right)^{\gamma-1} - 1\right] = \frac{GM_{BH}}{r},$$ (Bernoulli's Eq.)

- One of the solutions:

$$\dot{M}_B = 4\pi\lambda_c \frac{(GM_{BH})^2}{c_{s,\infty}^3} \rho_\infty, \qquad \lambda_c = \left(\frac{1}{2}\right)^{\frac{(\gamma+1)}{2(\gamma-1)}} \left(\frac{5-3\gamma}{4}\right)^{\frac{(3\gamma-5)}{2(\gamma-1)}}.$$

- Characteristic scales:

Bondi radius: $R_B = \frac{GM_{BH}}{c_{s,\infty}^2}.$ Sonic radius: $R_s = \left(\frac{5-3\gamma}{4}\right) R_B.$

Bondi time: $t_B = \frac{R_B}{c_s} = \frac{GM_{BH}}{c_{s,\infty}^3}.$

Simplest Case: Spherical Bondi Accretion Flow onto a SMBH

- GADGET-3: 3-d cosmological SPH/ N-body code (Springel '05)
- Central SMBH 10^8 $M_\odot$ represented by a pseudo-Newtonian Paczynsky & Wiita (1980) potential
- r_{out}=5-20 pc, $N_{ptcl}=64^3-128^3$
- Set IC to uniform/spherical Bondi flow w/ γ=1.01, $\rho_\infty=10^{-19}$ g/cm^3, $T_\infty=10^7$K, $T_{init}=T_\infty$
- Corresponding Bondi solution: R_B=3pc, R_{sonic}=1.5pc, t_B=7.9e3yr
- All runs: **r_{in}=0.1pc**, γ=1.01

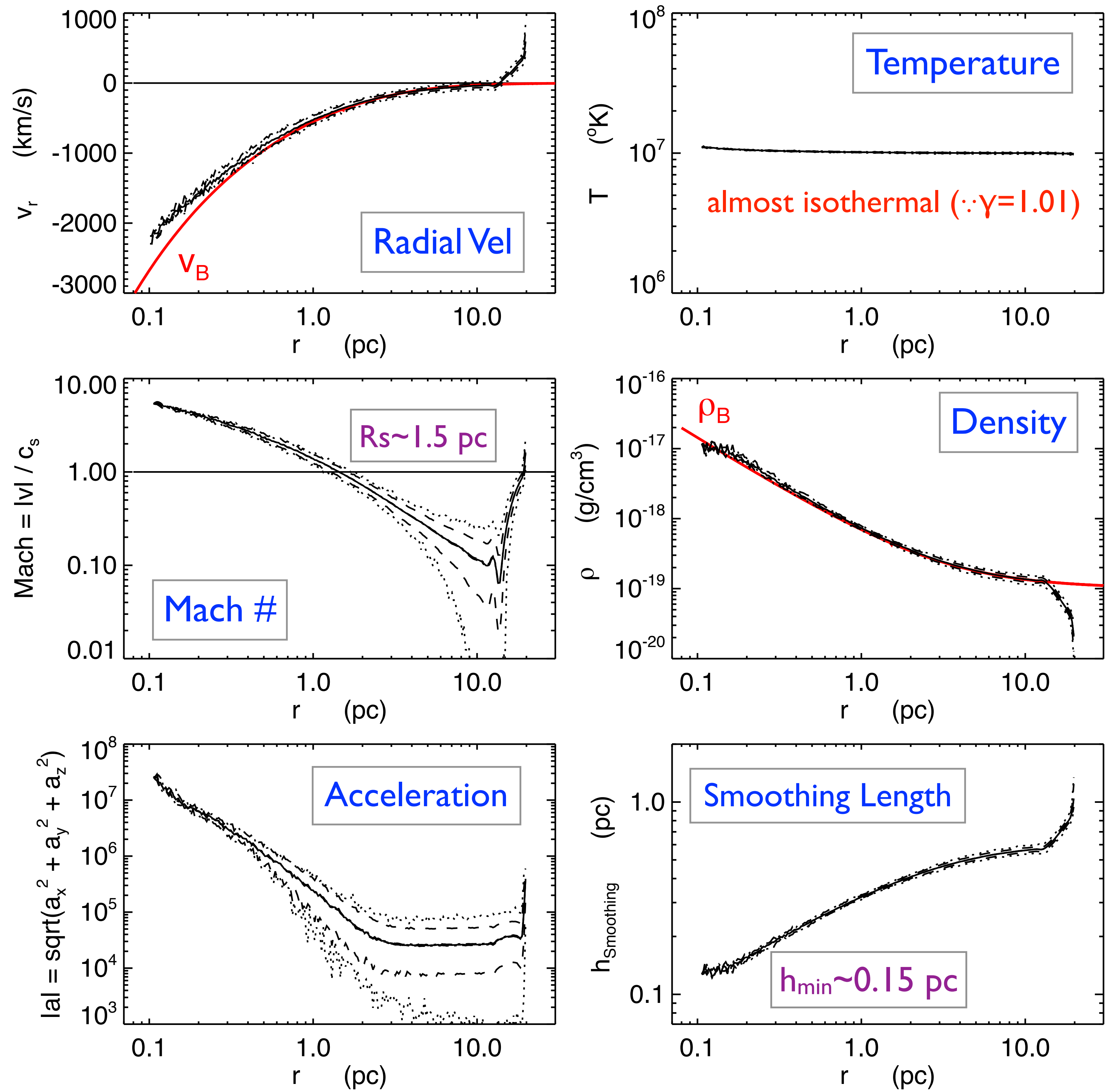
3-d spherical volume, vacuum boundary condition

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

Example: Properties of Particles

Run 7:

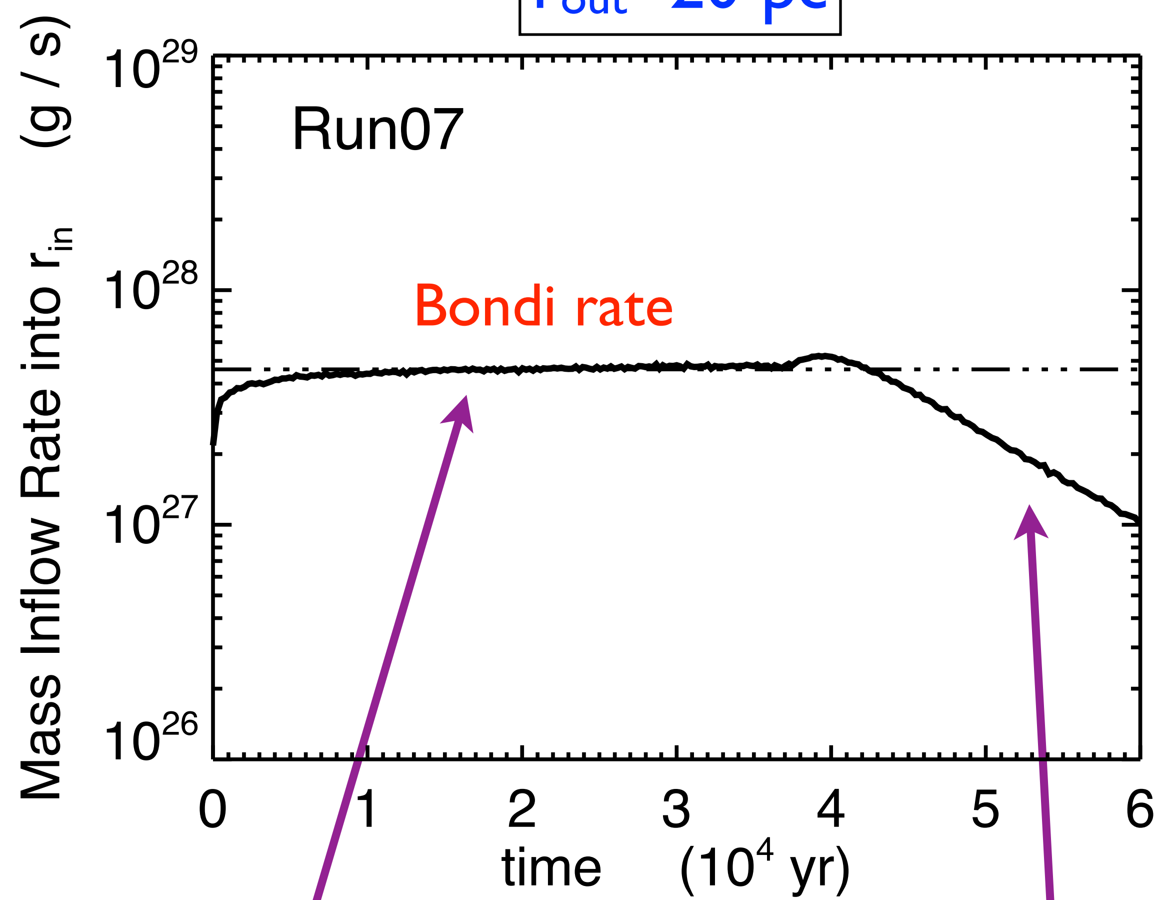
- r_{out}=20 pc, $N_{ptcl}=128^3$
- Snap at $t=2t_B$=1.6e4 yr
- Follows the Bondi solution (red curve) well except the very inner part
- Inner part: supersonic (M~6), outerpart: subsonic



Mass Inflow Rates at r_{in}

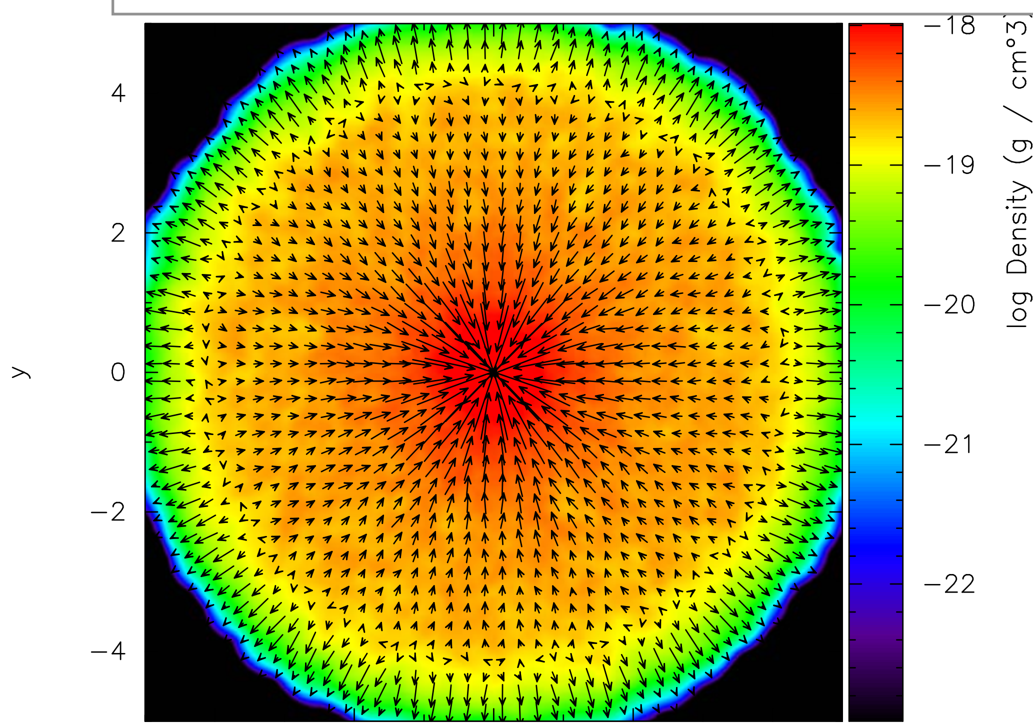
- the larger r_{out}, the longer duration of Bondi inflow rate
- If started from a Bondi flow, Bondi rate is achieved quickly.
- After a while, the inflow rate decreases due to the artificial outflow at the outer boundary.
- Greater sim. volume reduces this effect on mass inflow.

r_{out}=20 pc



reproducing Bondi rate well.

due to outflow problem at outer BC



Radiative Heating & Cooling

- Xray emitting corona irradiates the accretion flow

$$L_X = f_X L_{\rm Edd}, \qquad L_{\rm Edd} = \frac{4\pi c G m_p M_{BH}}{\sigma_e},$$

Flux: $$F_X = \frac{L_X}{4\pi r^2}.$$

- 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: $$G_{\rm Compton} = 8.9\times10^{-36}\xi\,(T_X - 4T) \quad [{\rm erg\,cm^3\,s^{-1}}].$$

Net Xray photoioniz. heating and recomb. cooling rate: $$G_X = 1.5\times10^{-21}\xi^{1/4}T^{-1/2}\left(1-\frac{T}{T_X}\right) \quad [{\rm erg\ cm^3\ s^{-1}}].$$

Brems. and line cooling rate:

(Opt-thin: δ=1)

$$\begin{aligned} L_{b,l} &= 3.3\times10^{-27}T^{1/2} \\ &\quad + \left[1.7\times10^{-18}\exp\left(-1.3\times10^5/T\right)\xi^{-1}T^{-1/2} \right. \\ &\quad \left. + 10^{-24}\right]\delta \qquad [{\rm erg\ cm^3\ s^{-1}}]. \end{aligned}$$

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

Runs with radiative cooling/heating

Run No.	$r_{\rm out}$ [pc]	N	$M_{\rm tot,IC}$ $[M_\odot]$	$M_{\rm part}$ $[M_\odot]$	$\gamma_{\rm init}$	T_∞ [K]	R_B [pc]	ρ_∞ [g/cm^3]	$T_{\rm init}$	L_X $[L_{\rm Edd}]$	$t_{\rm end}$ [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}	$T_{\rm rad}$ [b]	5×10^{-4}	2.9
18	20	128^3	5.65×10^5	0.269	5/3	10^7	1.84	10^{-21}	$T_{\rm rad}$	5×10^{-4}	3.0
19	20	128^3	1.47×10^7	7.0	5/3	10^5	183.9	10^{-21}	$T_{\rm rad}$	5×10^{-4}	1.5
20	200	256^3	1.33×10^9	79.09	5/3	10^5	183.9	10^{-21}	$T_{\rm rad}$	5×10^{-4}	6.5
21	200	256^3	4.95×10^8	29.50	5/3	10^7	1.84	10^{-21}	$T_{\rm rad}$	5×10^{-4}	8.7
22	200	128^3	1.33×10^7	6.33	5/3	10^5	183.9	10^{-23}	$T_{\rm rad}$	5×10^{-4}	70
23	200	256^3	1.33×10^7	0.791	5/3	10^5	183.9	10^{-23}	$T_{\rm rad}$	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}	$T_{\rm Run23}$	5×10^{-5}	19
25	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	$T_{\rm Run23}$	5×10^{-3}	21
26	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	$T_{\rm Run23}$	1×10^{-2}	22
27	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	$T_{\rm Run23}$	2×10^{-2}	25
28	200	1.24×10^7	9.77×10^6	0.791	5/3	10^5	183.9	10^{-23}	$T_{\rm Run23}$	5×10^{-2}	50

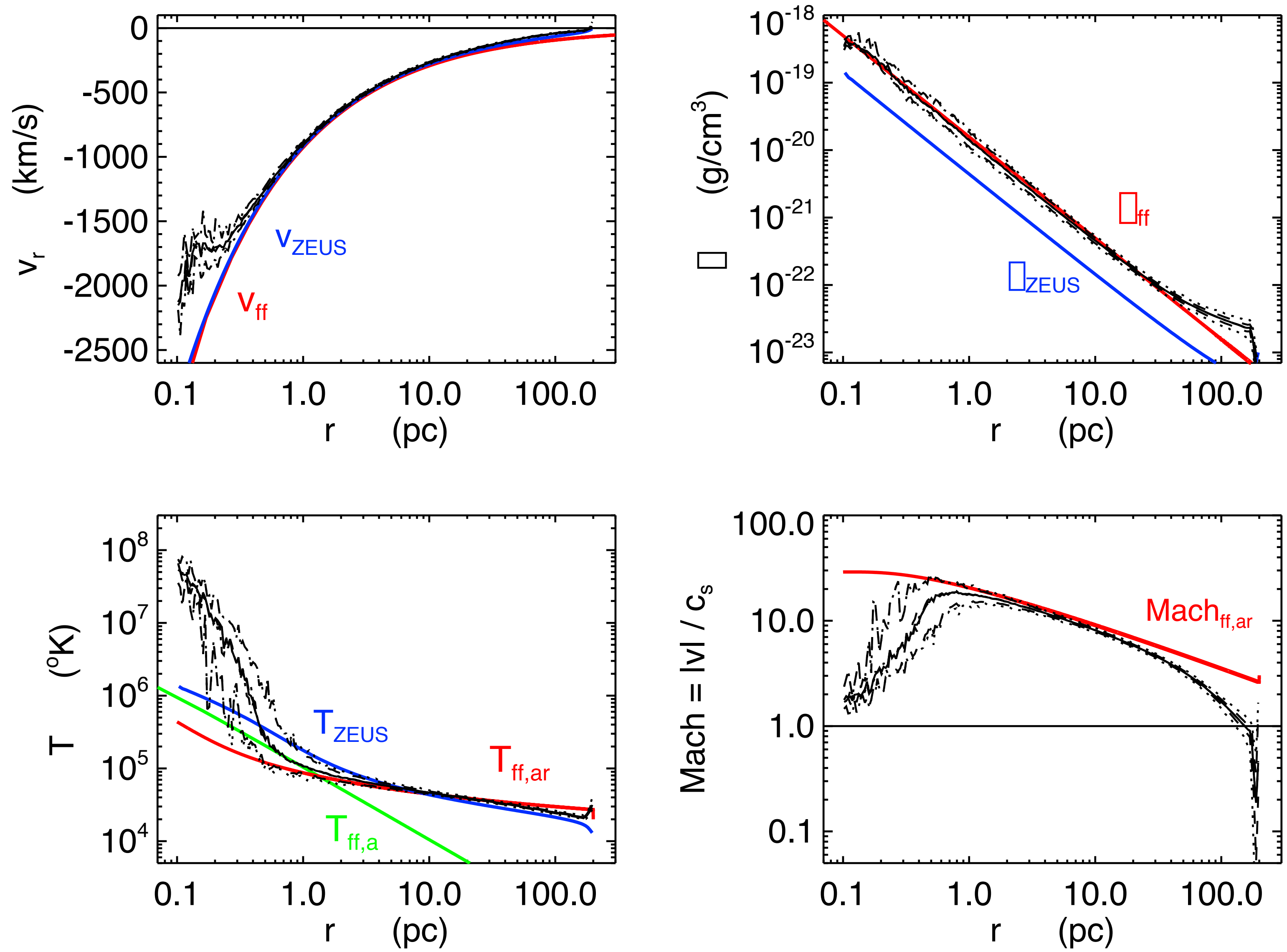
Ptcl properties w/ radiative heating & cooling

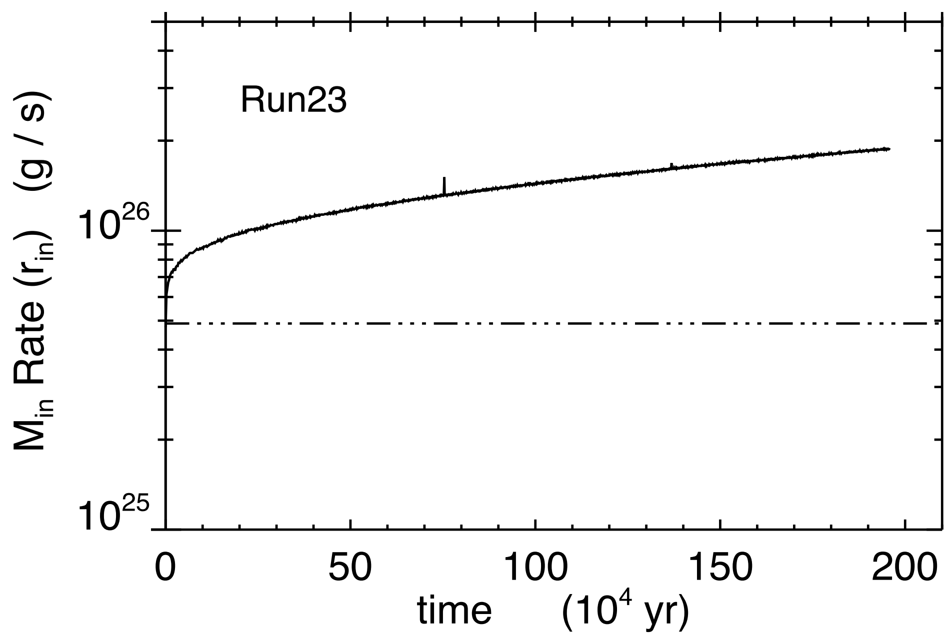
Representative run:

- red: free-fall scaling
- blue: ZEUS-2d result
- Near the inner radius, excess heating by artificial viscosity is seen.
- Inflow rate is enhanced above Bondi rate, due to lower gas temp: $T(r_{out}) < 10^5$ K, $T_\infty = 10^5$ K

Run #23: t=1Myr, L_X=5e-4L_{Edd}, γ=5/3

r_{out}=200pc, 256^3 ptcls



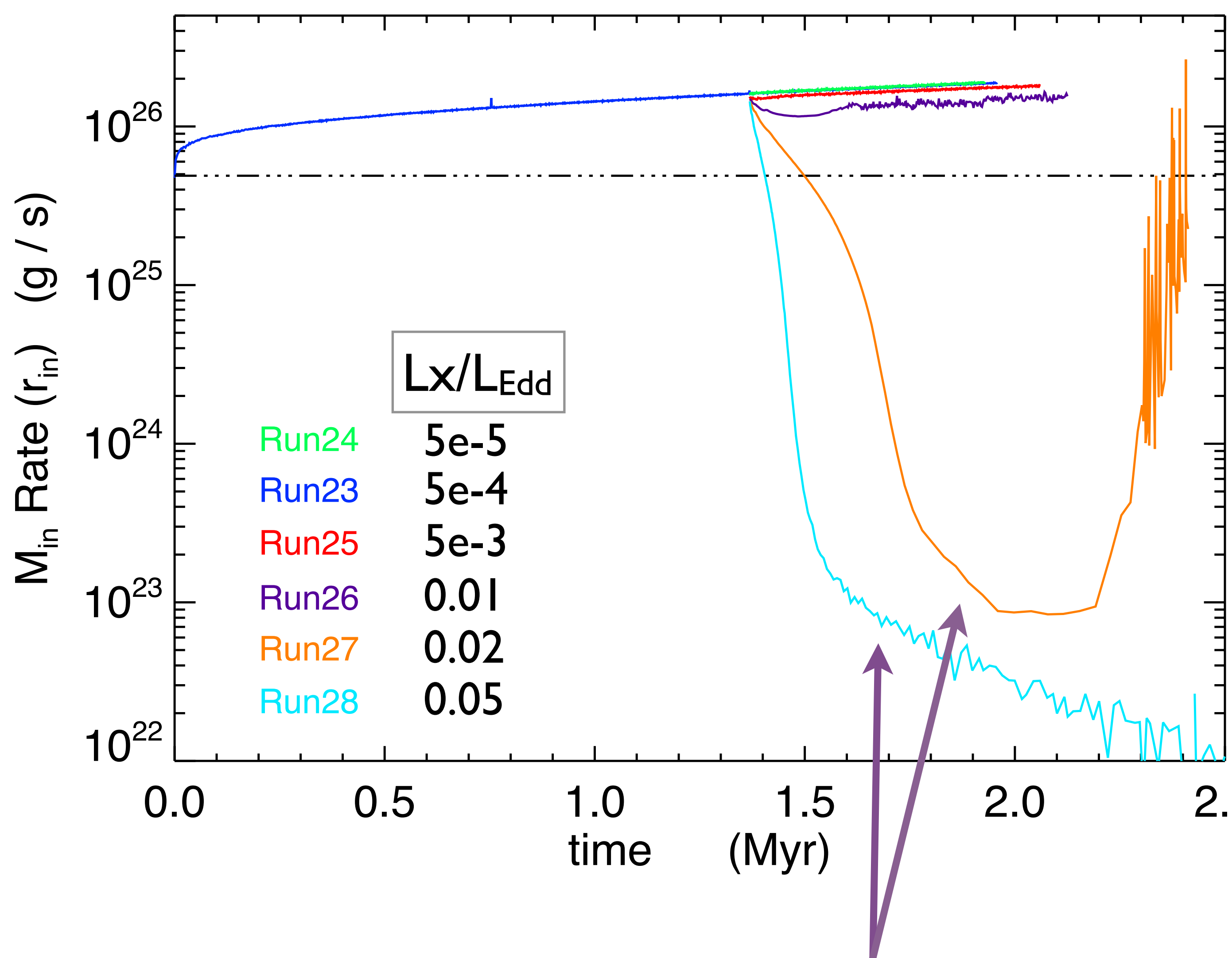


green: free-fall scaling w/ only adiabatic term

$T_{ff,ar}$: solving internal energy eq. w/ both radiative & adiabatic term

Impact of varying Lx on inflow rates

- Restart Run #23 at t=1.4 Myr, Lx/L_{Edd}=5e-4 orig.
- Runs 24-28: increase Lx
- Dramatic decrease in $\dot{M}_{in}$ at Lx/L_{Edd}>0.01 --- transition from net inflow to net outflow



net outflow; non-spherical fragmentation observed.

Thermal instability due to rad. feedback

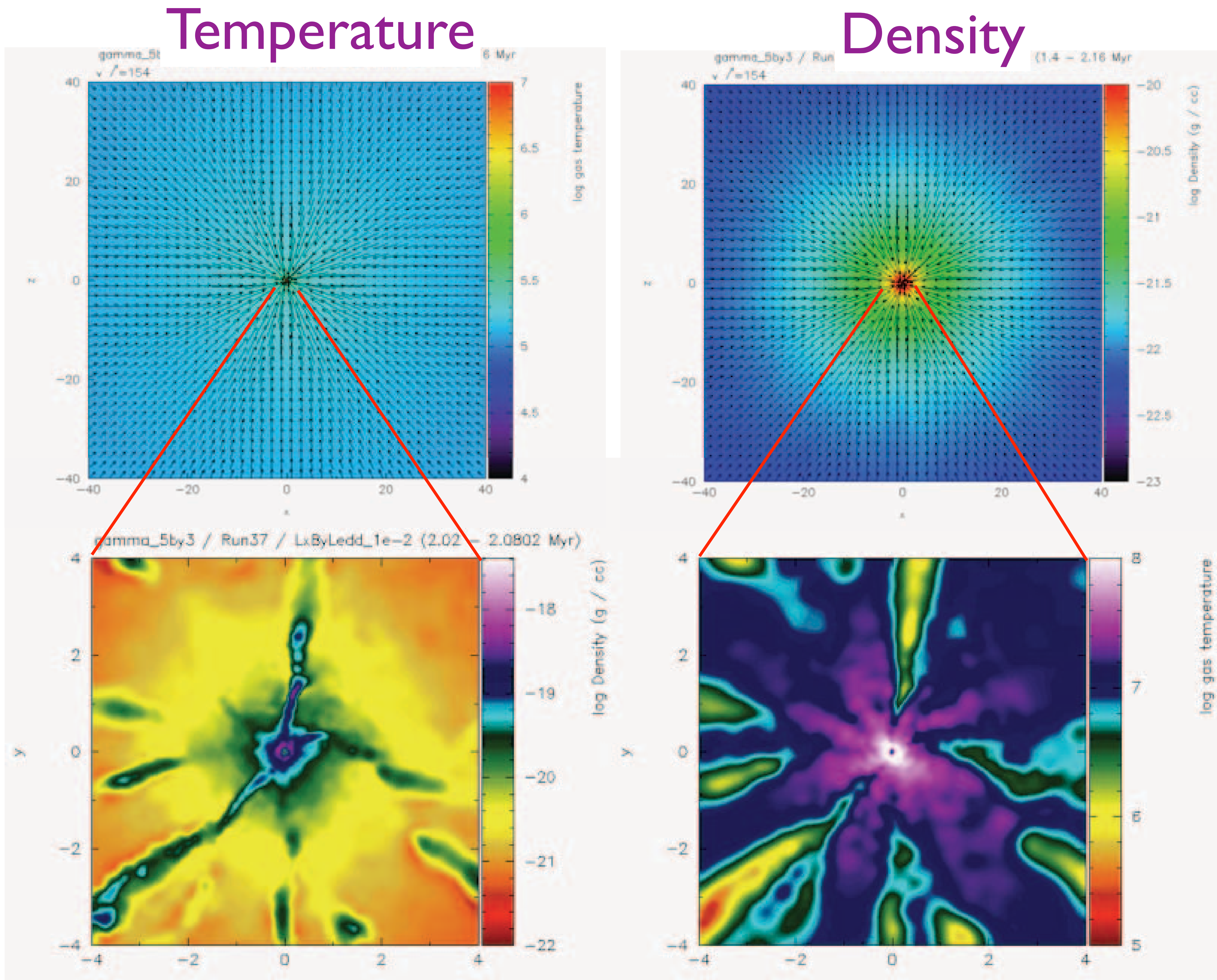
Non-spherical outflow:

due to rad. feedback

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

inner ±40pc

inner ±4pc



Ptcl Properties: impact of rad feedback

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

Large scatter due to thermal instability --- cold inflow and hot outflow

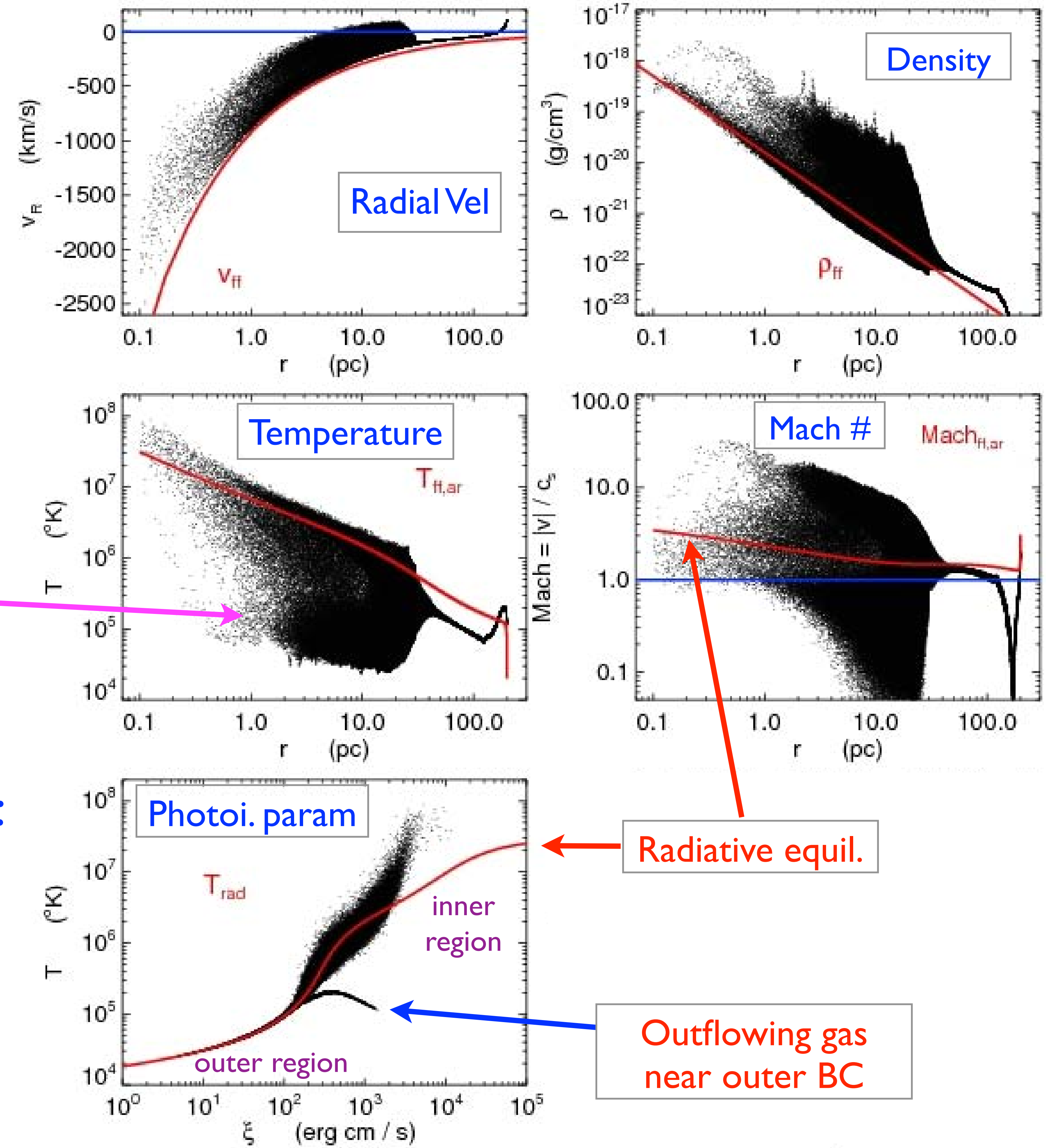
Cold component

Photoionization parameter:

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

Radiative equil.

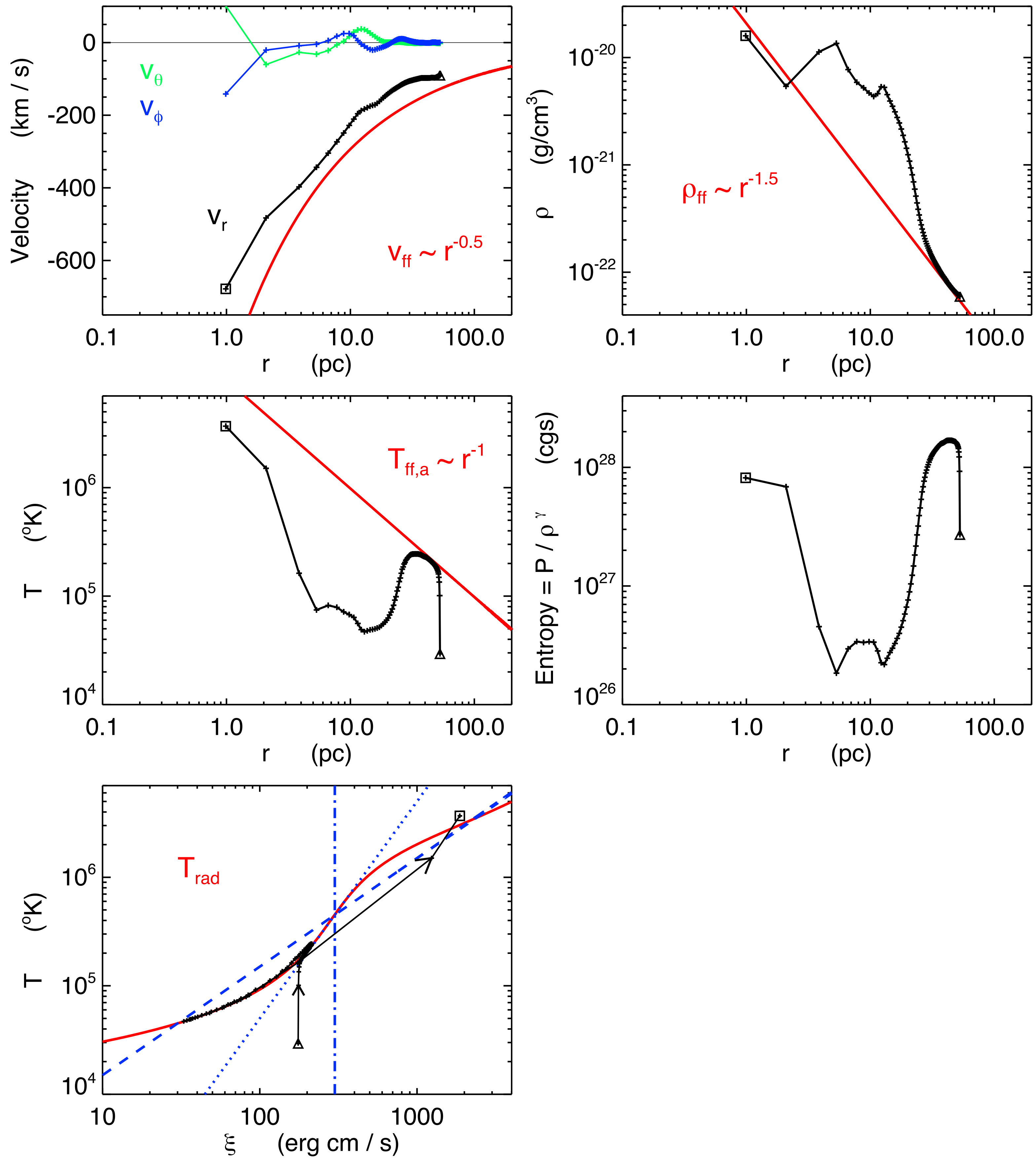
Outflowing gas near outer BC



Time Evolution of a Single Ptcl

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

- Start (triangle): r=53 pc, t=1.4 Myr
- End (square): r=1pc, t=1.8 Myr
- + symbol: dt=0.004 Myr



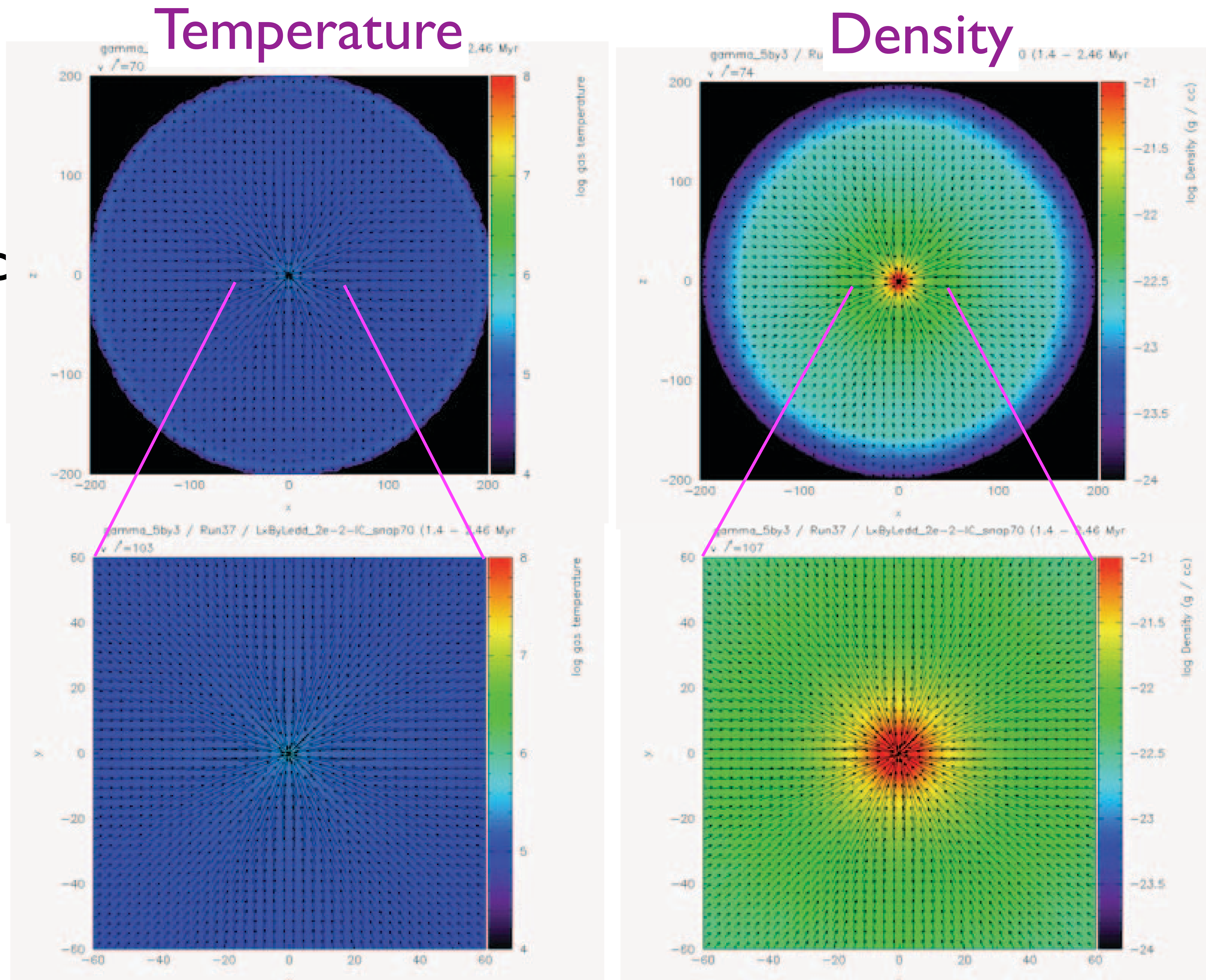
Non-spherical outflow:

due to rad. feedback

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

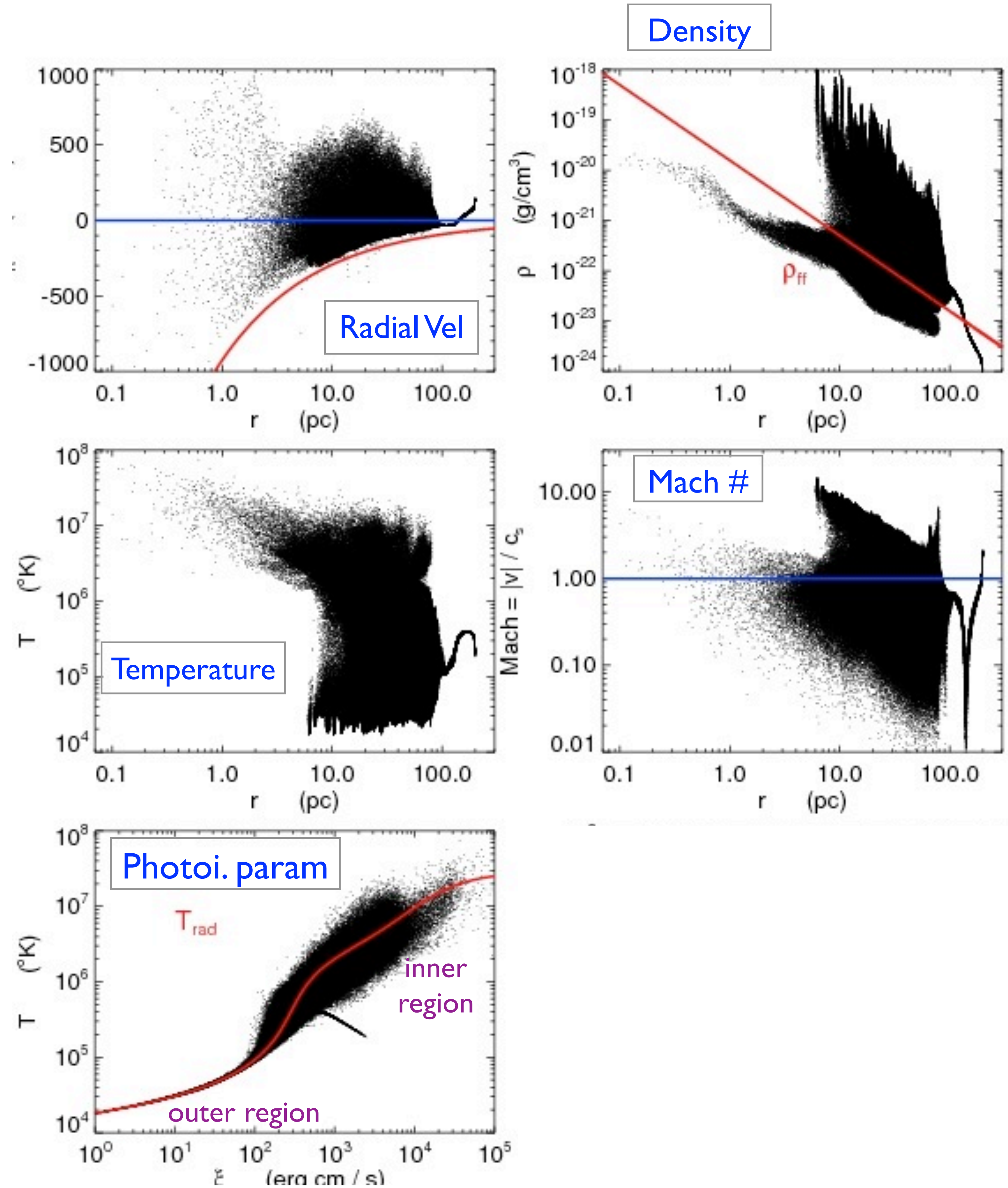
± 200pc

inner
±60pc



Ptcl Properties: impact of rad feedback

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



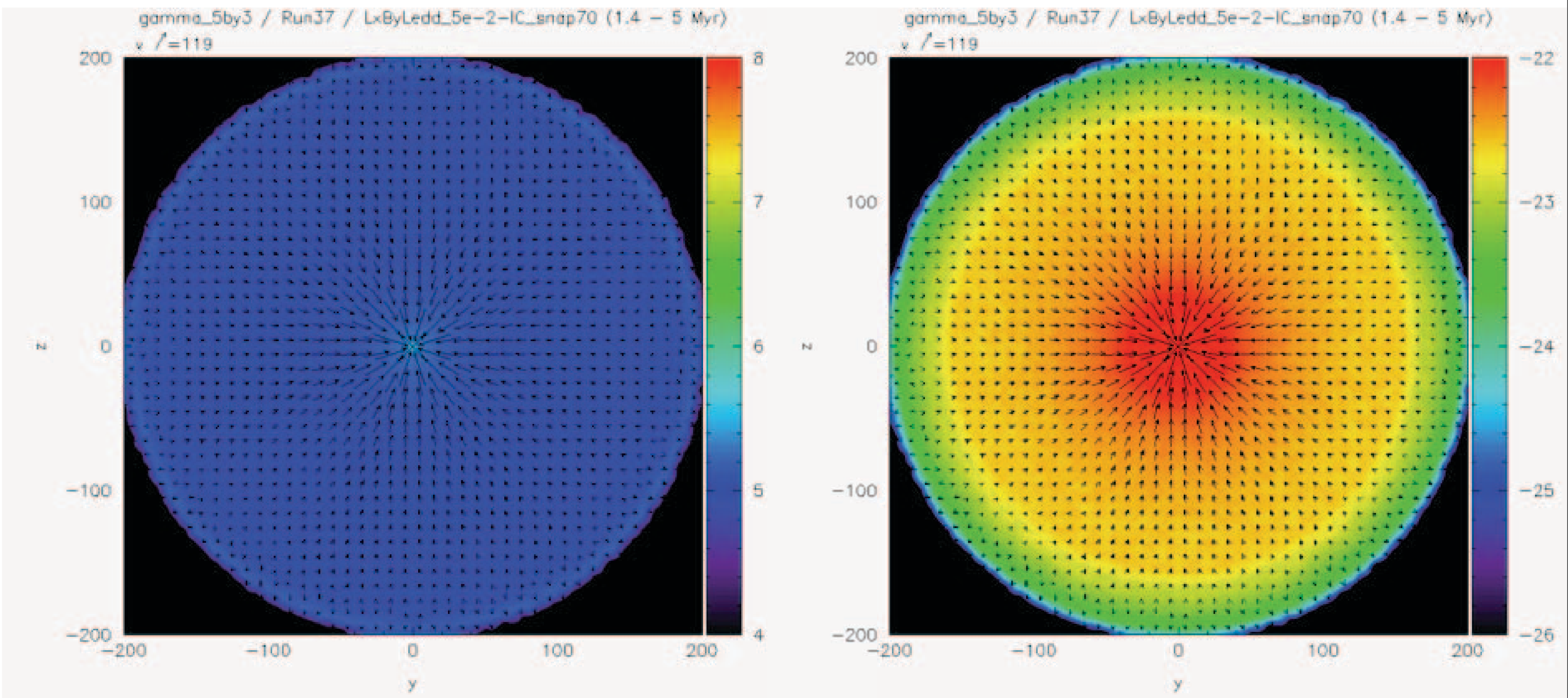
Non-spherical outflow:

due to rad. feedback

Run 28: r_{out}=200pc, Lx/L_{Edd}=0.05

Temperature

Density



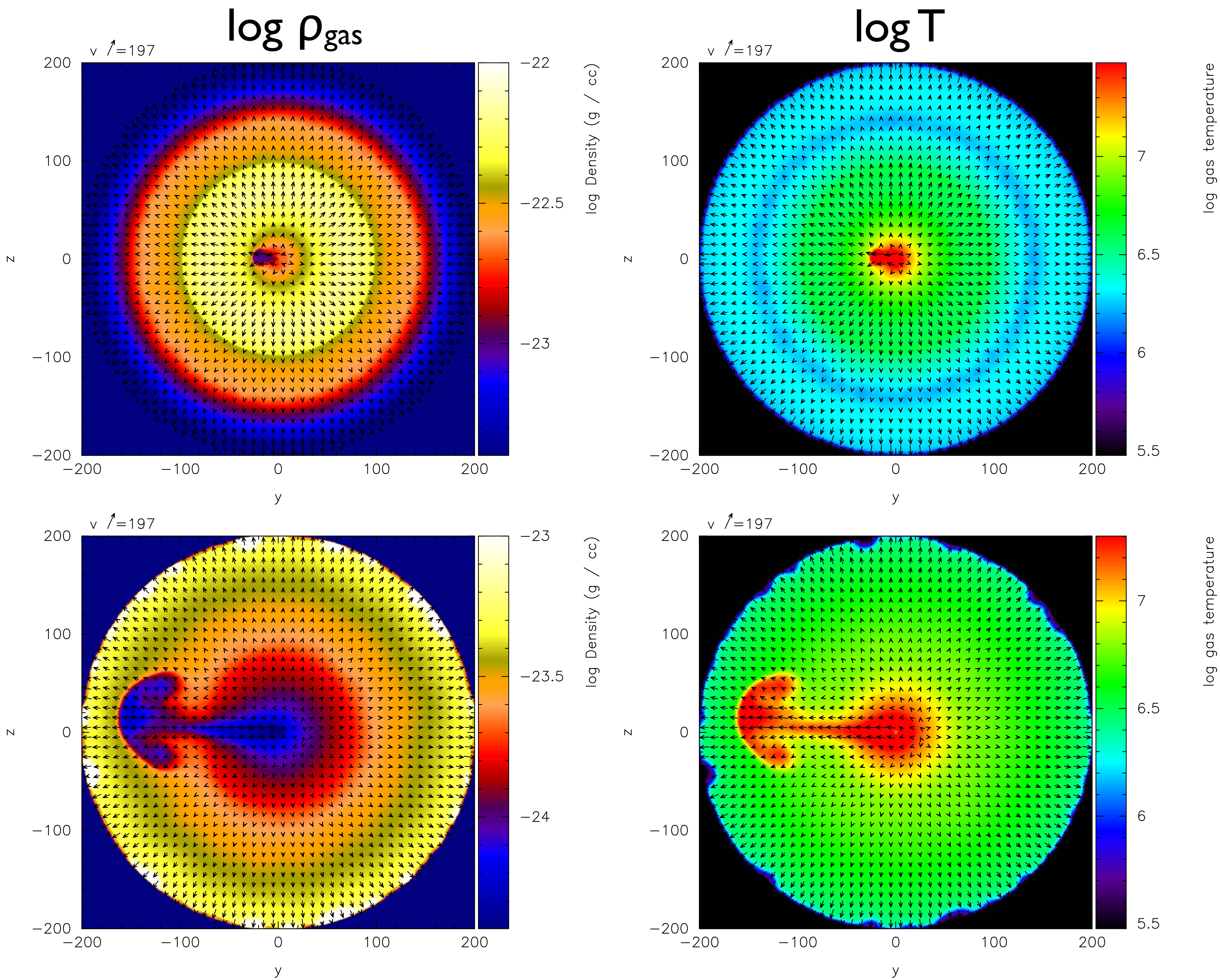
± 200pc

Run 28

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

t=1.8 Myr

t=3.0 Myr

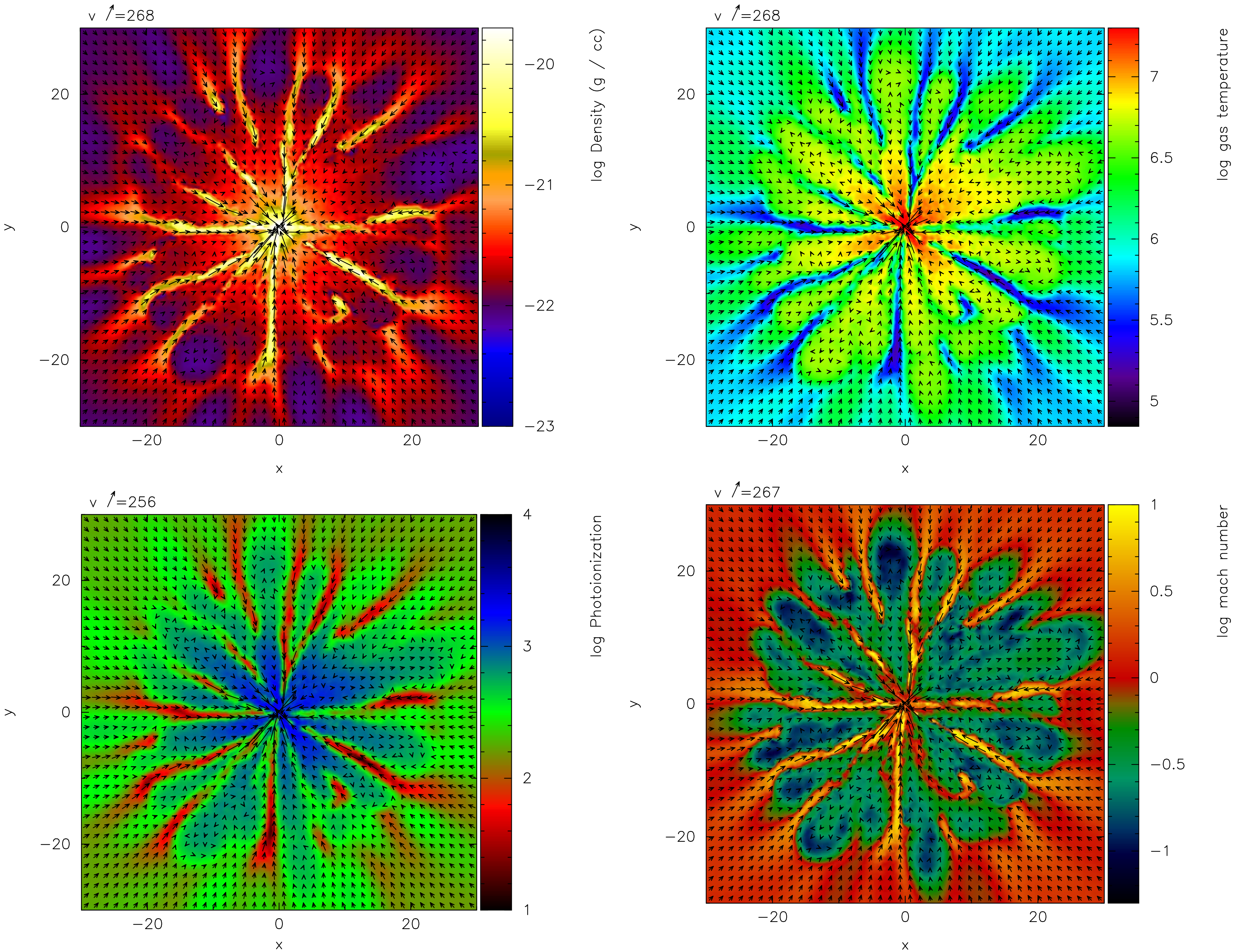


Conclusions

- GADGET-3 SPH code can reproduce the spherical Bondi accretion rate properly, but with some limitations.
- spurious heating by Artificial Viscosity near r_{in} & artificial outflow at r_{out} due to outer BC are problems for SPH.
- non-spherical in/outflow develops due to rad. feedback via thermal instability, even in the simplest situation that we studied --- connection with NLR? (Paper II)
- Future work: include rad. pressure, rotation, diff geometry, comparison w/ NLR obs, connect with cosmological sim

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

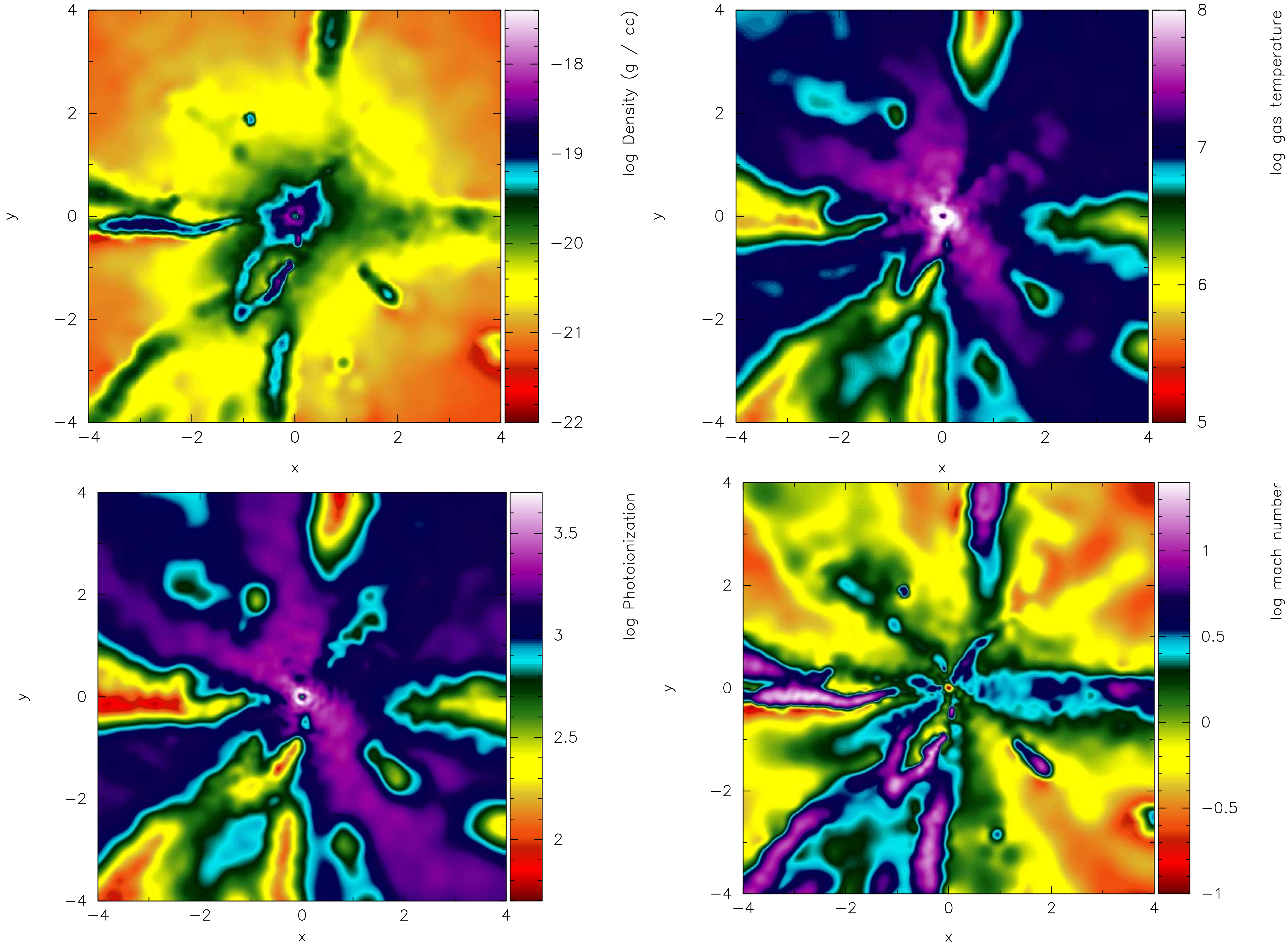
± 30 pc range (t = 2.047 Myr)



colder, denser filament-like structures due to non-spherical fragmentation

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

Zoom-in: inner 4 pc



Run 27

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

log ρ_{gas} log T

t=1.86 Myr

t=2.12 Myr

t=2.46 Myr