EVOLUTION OF A GAS CLOUD EXPOSED TO AGN RADIATION

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INTRODUCTION

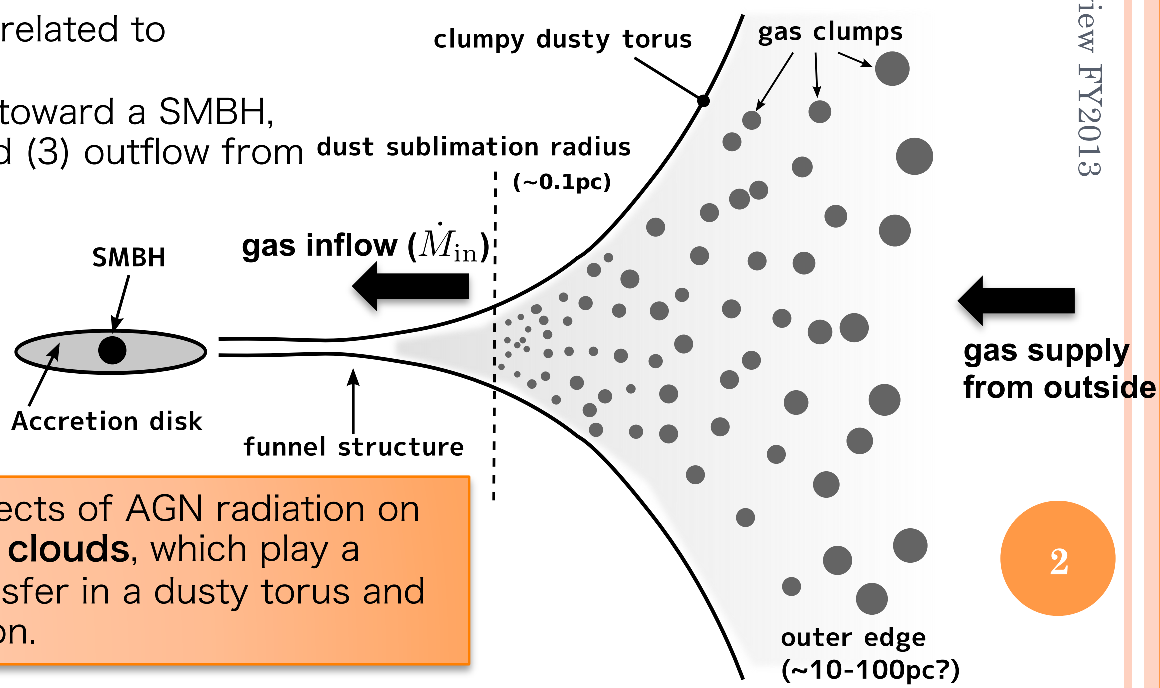
- AGN is one of the most luminous object in the Universe.
  - $L_{bol} \approx 10^{42}$-10^{46}[erg/s], the majority of energy is emitted in the optical/UV & X-ray bands.
  - AGNs feedbacks (by radiation and jets) are thought to play important roles in formation and evolution of galaxies (e.g., Benson 2003; Di Matteo et al. 2005)

- In order to understand the effects of AGNs on evolution of galaxies, we need to know

1) when and how AGN phenomenon is triggered,
2) what determines type(QSO/radio) and strength of AGN-activity,
3) how long its activity continues,

- Recent studies indicate a clumpy dusty torus associates with an luminous AGN.

- Mass of the torus, M_{torus}, must be related to duration of AGN phenomenon.
- M_{torus} decreases by (1) gas inflow toward a SMBH, (2) star formation in the torus, and (3) outflow from the torus.
- Clumpiness ⇒ gas inflow rate.



It is important to understand the effects of AGN radiation on the evolution of **optically-thick gas clouds**, which play a main role in angular momentum transfer in a dusty torus and which are main sites of star formation.

Previous Works

- Stability of static BLR clouds has been studied by photo-ionization calculations [Williams (1972), Weymann (1976), McKee & Tarter (1975), Krolik (1981)].

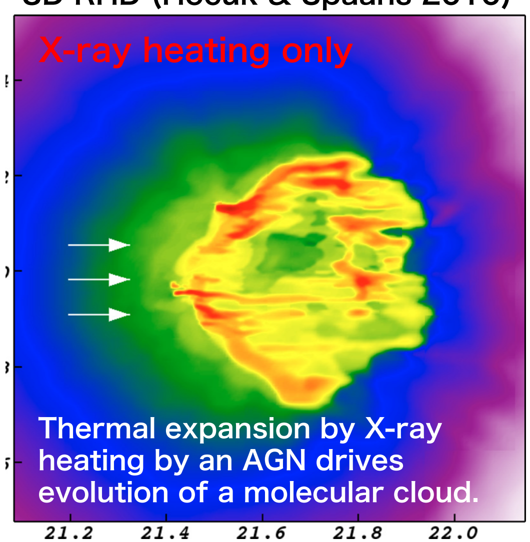
- Pier & Voit (1995) investigated mass loss process from a dusty gas cloud in an AGN torus by solving a spherically-symmetric steady-state wind equation, and showed that
  (1) Radiation pressure can reduce/suppress photo-evaporation flow,
  (2) Because evaporation timescale is longer than orbital period, a dusty gas cloud can penetrate inside the inner torus edge.

- Recent radiation hydrodynamic simulations [Schartmann et al. 2011; Hocuk & Spaans 2010,2011].

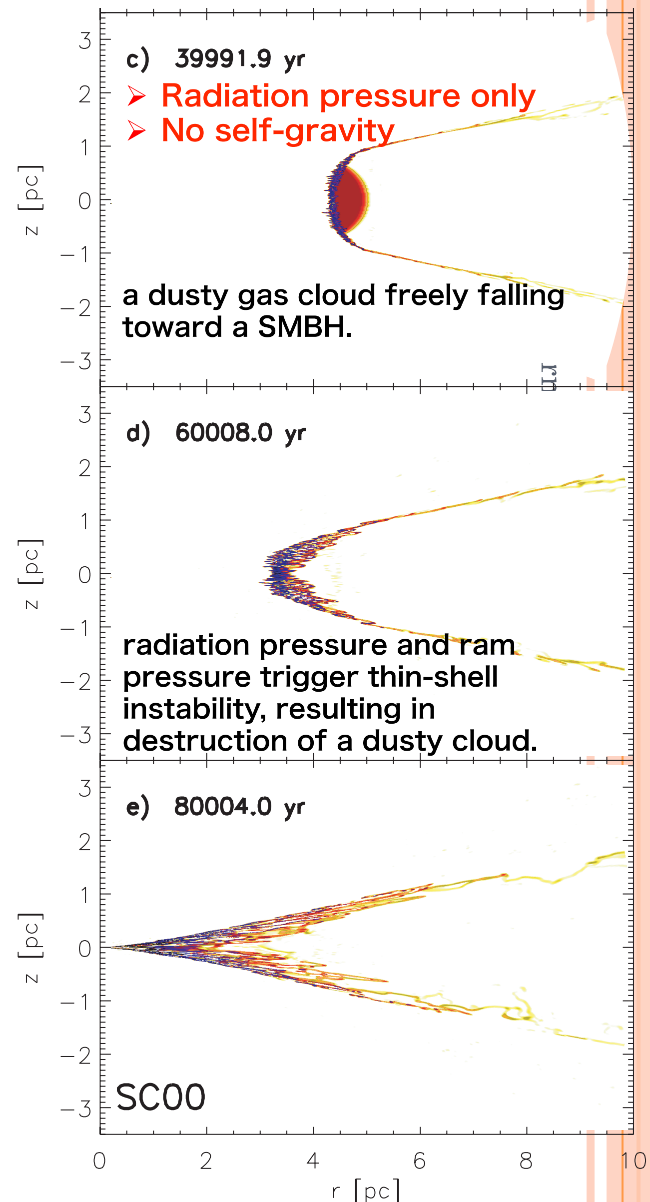
In a gas cloud that is directly irradiated by an AGN, **both** radiation pressure and photo-evaporation must be important to determine its evolution.

This is our motivation.

3D RHD (Hocuk & Spaans 2010)



2D RHD (Schartmann 11')



Purpose and Model

Purposes

Using 3D RHD simulations, we investigate evolution of a dusty gas cloud that is directly irradiated by an AGN. Especially, we focus on

① how radiation pressure and photo-evaporation control the evolution of a cloud if they act simultaneously,

② how cloud destruction timescale depends on the strength of incident radiation fields and the optically thickness of a cloud.

Model and model parameters

- Fundamental parameters are (r、r_{cl}、L_{bol}、n_H).
- Because it is not practical to explore this 4-dimensional parameter space, we examine the dependencies on the following two parameters:

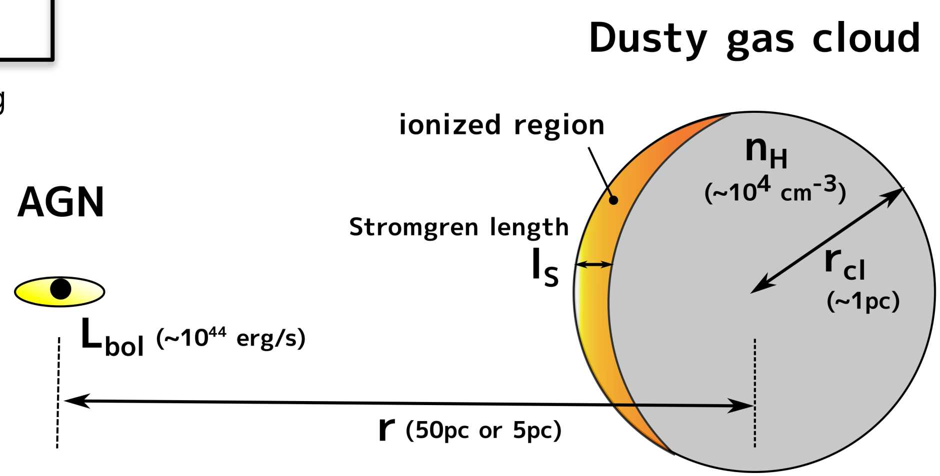
$\mathcal{U} = \frac{F_{\rm ion}}{c n_{\rm H}}$	Ionization parameter
$\mathcal{N}_S = \frac{2 r_{\rm cl}}{l_S}$	Strömgren number

where F_{ion} is the number flux of ionizing photons and l_S is the Strömgren length defined as

$$l_S = \frac{F_{\rm ion}}{\alpha_{\rm B} n_{\rm H}^2}$$

(α_B: case B recombination rate coef.)

$\mathcal{U}\approx 0.01$(Low-$\mathcal{U}$ models), 0.05(High-$\mathcal{U}$ models)
Choice of $\mathcal{U}$ is explained later.
For each $\mathcal{U}$, $\mathcal{N}_S \approx 5$, 10, 20 are examined.



NUMERICAL METHOD

Numerical Method

- Hydrodynamics: Density-Independent type SPH method (Hopkins 2013).
- Radiative Transfer: Tree-accelerated LONG method.
- Self-gravity: Tree method accelerated by the Phantom-GRAPE library.
- Chemistry: (e,p,HI,H_2,dust).
  - Photo-ionization of HI.
  - Photo-heating of HI and dust (to capture **photo-evaporation**).
  - **Radiation pressure** on HI and dust.

ISM model

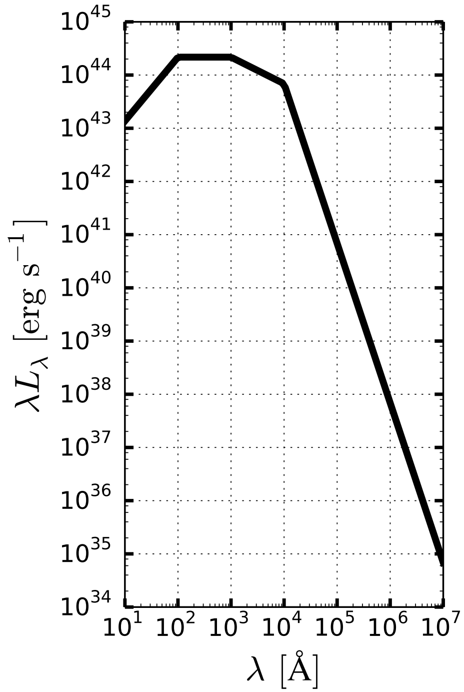
A reduced chemical network:

(1) $HI + e^- \rightarrow p + 2e^-$
(2) $p + e^- \rightarrow HI + \gamma$
(3) $H_2 + e^- \rightarrow 2HI + e^-$
(4) $HI + \gamma \rightarrow p + e^-$
(5) $H_2 + \gamma \rightarrow 2HI + e^-$
(6) $H_2 + HI \rightarrow 3HI$
(7) $H_2 + H_2 \rightarrow H_2 + HI$
(8) $2HI + dust \rightarrow H_2 + dust$
(9) $3HI \rightarrow H_2 + HI$
(10) $2HI + H_2 \rightarrow 2H_2$

Radiative processes:
- case B recombination cooling
- Bremsstrahlung cooling
- CI/CE cooling of HI and H_2
- Latent heat of H_2
- Heat exchange between gas and dust

AGN's SED

A SED peaking at UV is used.



ORDER ESTIMATION

In order to estimate the value of U at which radiation pressure becomes important, we perform order estimation of the ratio of radiative acceleration to pressure-gradient acceleration at the irradiated face of a cloud. The pressure-gradient acceleration is estimated as

$$|\boldsymbol{a}_{\mathrm{P}}| = \frac{\nabla p}{\rho} \sim \frac{p}{\rho l_S} \approx \frac{2 n_{\mathrm{H}} k_{\mathrm{B}} T_{\mathrm{gas}}}{m_{\mathrm{H}} n_{\mathrm{H}} l_S}$$

On the other hand, the order of the radiative acceleration averaged over a Strömgren length is

$$|\boldsymbol{a}_{\mathrm{rad}}| \sim \frac{L_{\mathrm{bol}}}{4\pi r^2 c} \frac{1}{m_{\mathrm{H}} n_{\mathrm{H}} l_S}$$

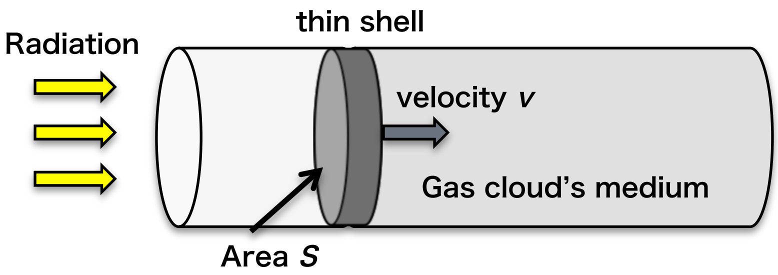
Then, the ratio becomes

$$\frac{|\boldsymbol{a}_{\mathrm{rad}}|}{|\boldsymbol{a}_{\mathrm{p}}|} = \boxed{\frac{L_{\mathrm{bol}}}{4\pi r^2 c n_{\mathrm{H}}}} \frac{1}{2 k_{\mathrm{B}} T_{\mathrm{gas}}}, \approx \frac{1\ \mathrm{eV}}{2 k_{\mathrm{B}} T_{\mathrm{gas}}} \left(\frac{\mathcal{U}}{1.5 \times 10^{-2}} \right) \left(\frac{h\nu_{\mathrm{ion}}}{44\ \mathrm{eV}} \right) \left(\frac{\mathrm{BC}_{\mathrm{ion}}}{1.5} \right)$$

The gas temperature at an ionized region is always (1-3) × 10^4[K] and can be regarded as a constant. Therefore, we expect radiation pressure becomes important in High-$\mathcal{U}$ models ($\mathcal{U}$≈0.05).

VELOCITY OF A RADIATION-PRESSURE DRIVEN SHOCK

Assuming all the photons are absorbed in a very thin gaseous shell at the irradiated face of a cloud, equation of motion of the shell is written as



$$\frac{d}{dt}\left[m_{\rm H} n_H S R v\right] = p_r S$$

where $M_{\rm shell}(R) = m_{\rm H} n_{\rm H} S R$

We can rewrite this equation using v=dR/dt:

$$\frac{d}{dt}(R\dot{R}) = \frac{p_r}{m_{\rm H} n_H} \Rightarrow \frac{1}{2}\frac{d^2}{dt^2}(R^2) = \frac{p_r}{m_{\rm H} n_H}$$

Therefore, the solution is

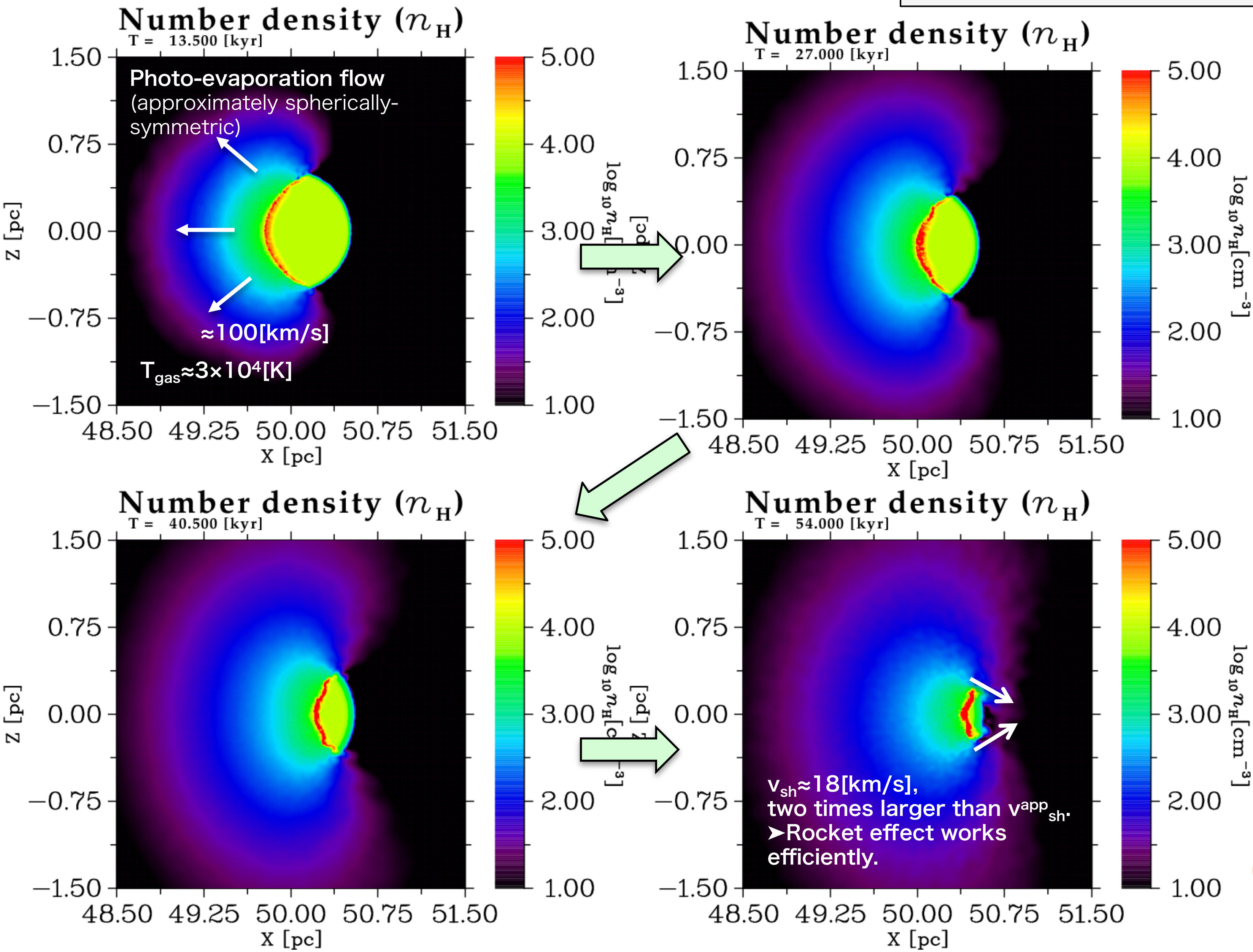
$$R(t) = \sqrt{\frac{p_r}{m_{\rm H} n_{\rm H}}}\,t \qquad v_{\rm sh}^{\rm app} = \frac{dR(t)}{dt} = {\rm const.} = \sqrt{\frac{p_r}{m_{\rm H} n_{\rm H}}} \propto \sqrt{\mathcal{U}}$$

In a radiation pressure-dominant regime, cloud destruction timescale can be estimated as :

$$t_{\rm sweep} = \frac{2 r_{\rm cl}}{v_{\rm sh}}$$

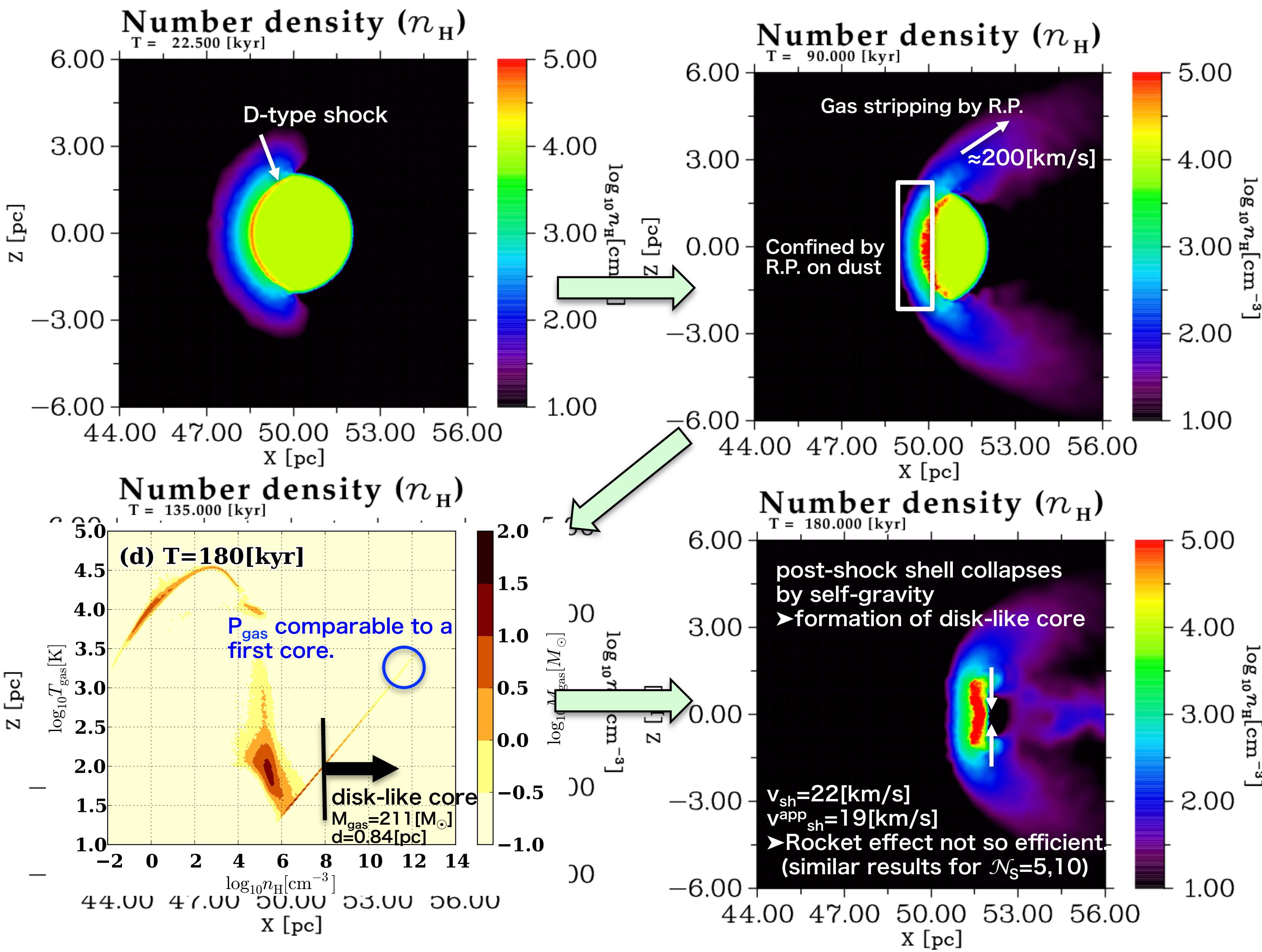
Density Evolution of L20 (Low-$\mathcal{U}$; $\mathcal{U}$≈0.01, $\mathcal{N}_S$=20)

r=50[pc]、$L_{bol}=1.25\times10^{44}$[erg/s]
r_{cl}=0.5[pc]、$n_H=10^4$[cm^{-3}]



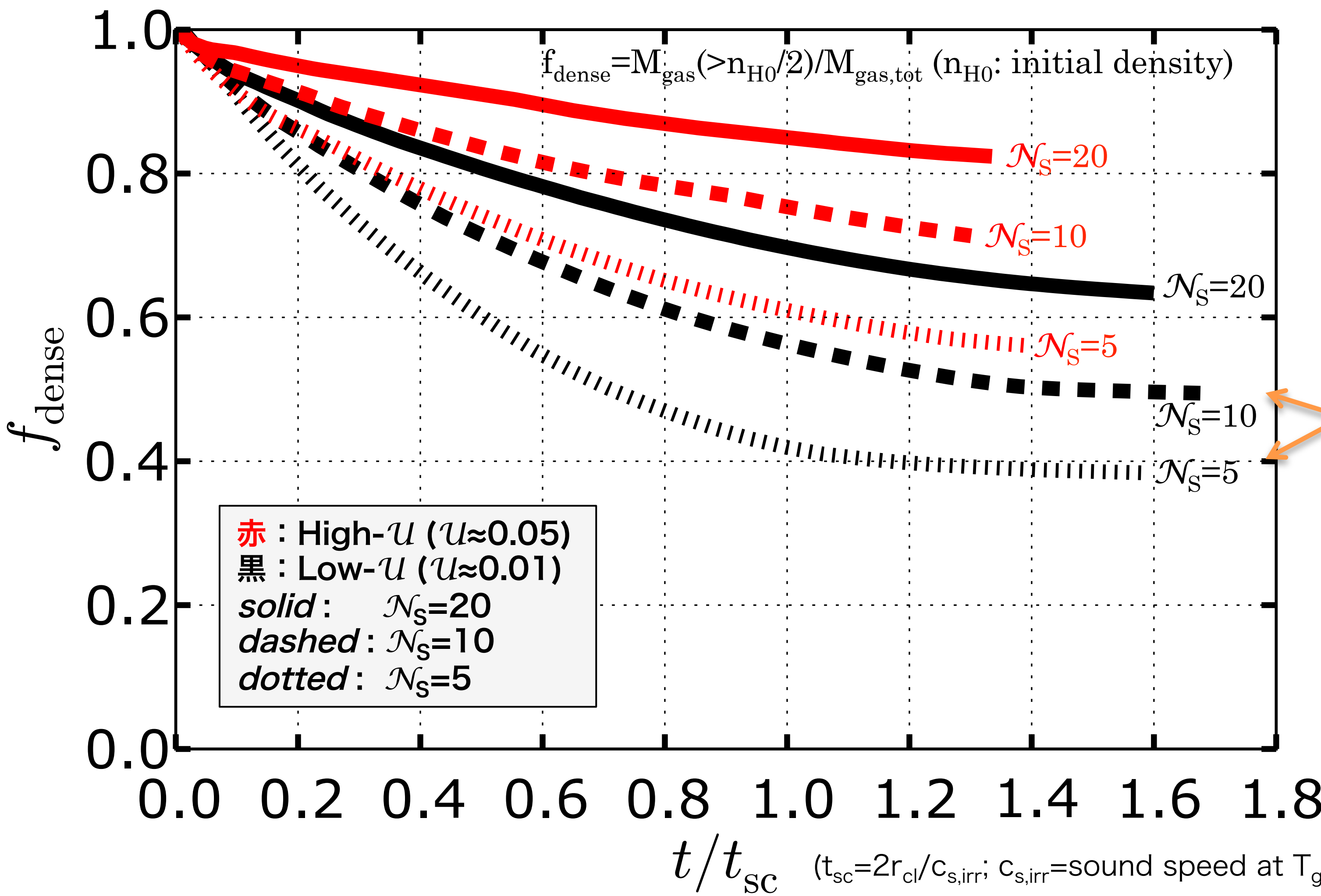
Density Evolution of H20 (High-$\mathcal{U}$; $\mathcal{U}\approx0.05$, $\mathcal{N}_S=20$)

$r=50$[pc]、$L_{bol}=5\times10^{44}$[erg/s]
$r_{cl}=2$[pc]、$n_H=10^4$[cm^{-3}]



Time evolution of dense gas fraction and cloud destruction timescales

- Mass loss is larger in Low-$\mathcal{U}$ models than High-$\mathcal{U}$ models, since radiation pressure reduces mass loss in High-$\mathcal{U}$ models.
- The reason why f_{dense} saturates in Low-$\mathcal{U}$ models is that geometric surface area of the irradiated face of the cloud becomes small with time.
- For all the models, $\mathbf{t_{dest} \approx (1\text{-}2) t_{sc}}$. Especially, $\mathbf{t_{dest} \approx t_{sweep}}$ for High-$\mathcal{U}$ models.



($t_{sc}=2r_{cl}/c_{s,irr}$; $c_{s,irr}$=sound speed at $T_{gas}=3\times10^4$[K])

Discussion:
Gas clumps in AGN torus

Physical properties of gas clumps in AGN torus
(Kawaguchi & Mori 2011+ α)

We estimate physical properties of gas clumps in AGN tori assuming that a gas clump is stable for tidal shearing and its self-gravity:

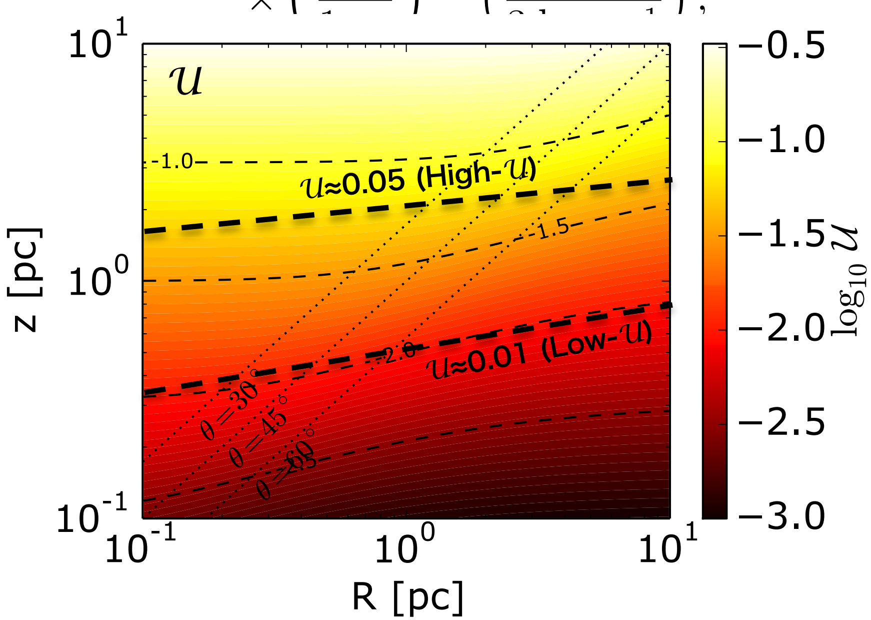
$$n_{\rm H,cl} = 2.12 \times 10^{8}\ {\rm cm}^{-3} \left(\frac{M_{\rm BH}}{10^7\ {\rm M}_\odot}\right)\left(\frac{r}{1\ {\rm pc}}\right)^{-3}$$

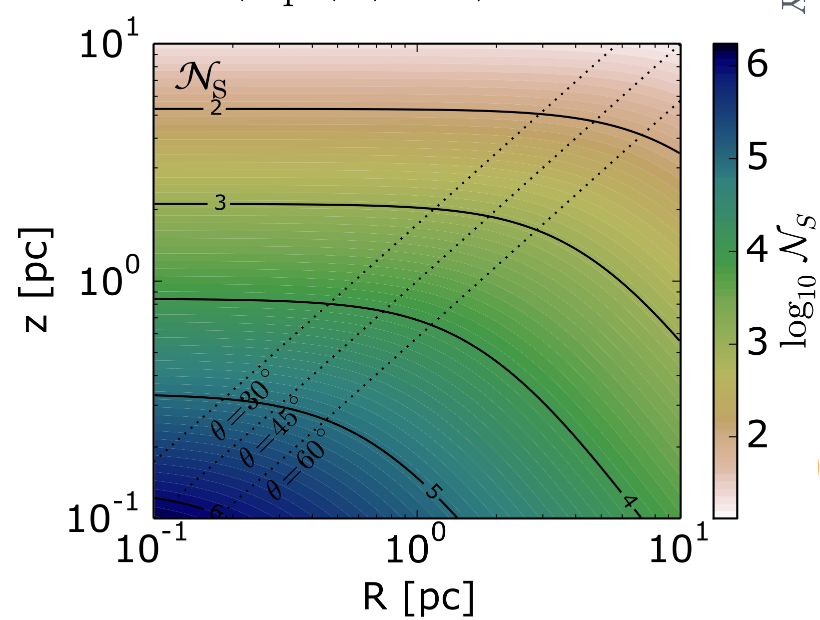
$$r_{\rm cl} = 0.0182\ {\rm pc} \left(\frac{M_{\rm BH}}{10^7\ {\rm M}_\odot}\right)^{-0.5}$$

$$\times \left(\frac{r}{\ldots}\right)^{1.5}\left(\frac{c_s}{\ldots}\right),$$

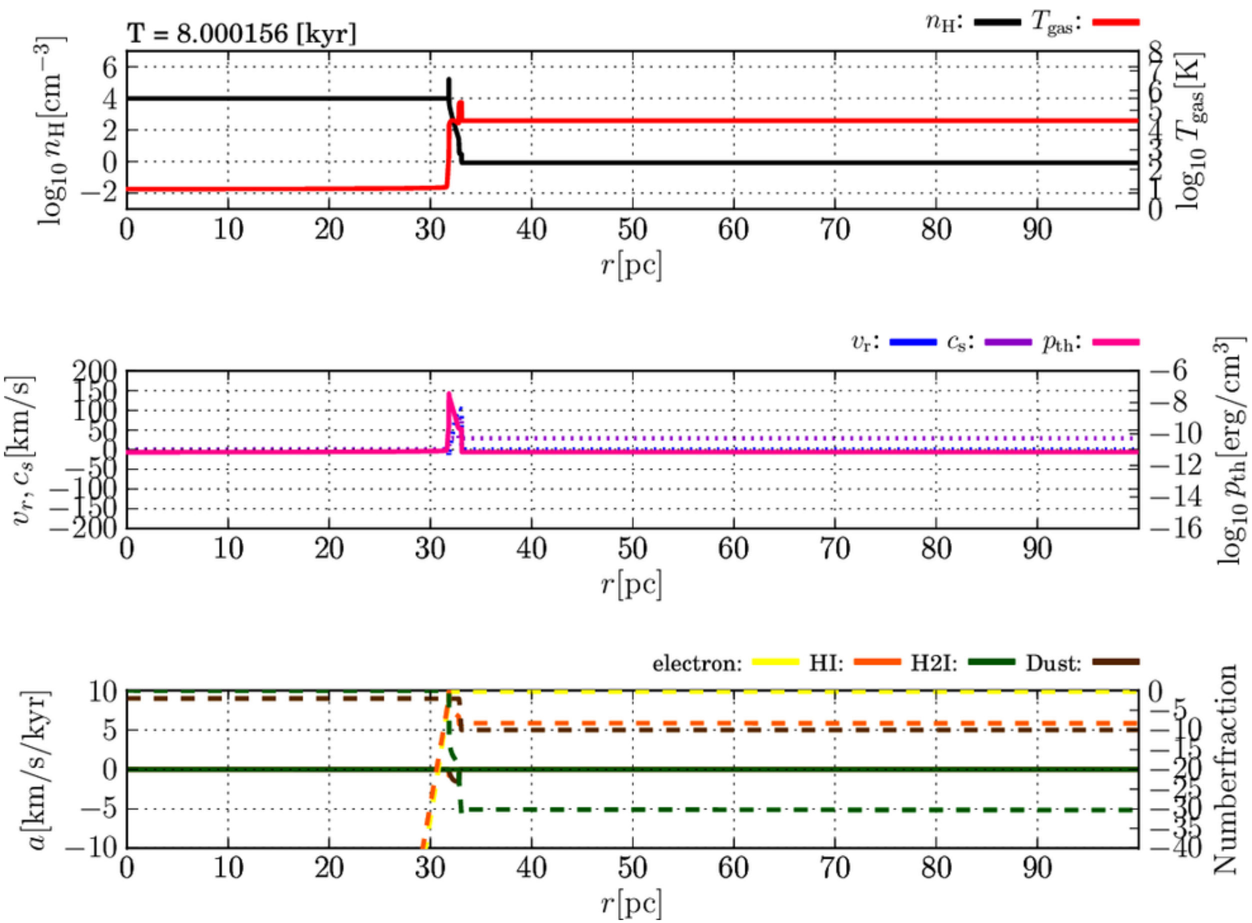
Assuming a SED adopted in this study and AGN radiation is isotropic, ($\mathcal{U}$,$\mathcal{N}_{\rm S}$) is obtained as follows:

$$\mathcal{U} = 1.3 \times 10^{-2} \left(\frac{L_{\rm bol}}{10^{45}\ {\rm erg\ s^{-1}}}\right) \times \left(\frac{M_{\rm BH}}{10^7\ {\rm M}_\odot}\right)^{-1}\left(\frac{r}{1\ {\rm pc}}\right) \approx 1.3 \times 10^{-2}\left(\frac{r}{1\ {\rm pc}}\right)\left(\frac{\lambda_{\rm Edd}}{1}\right)$$





1D Spherically-symmetric RHD simulations



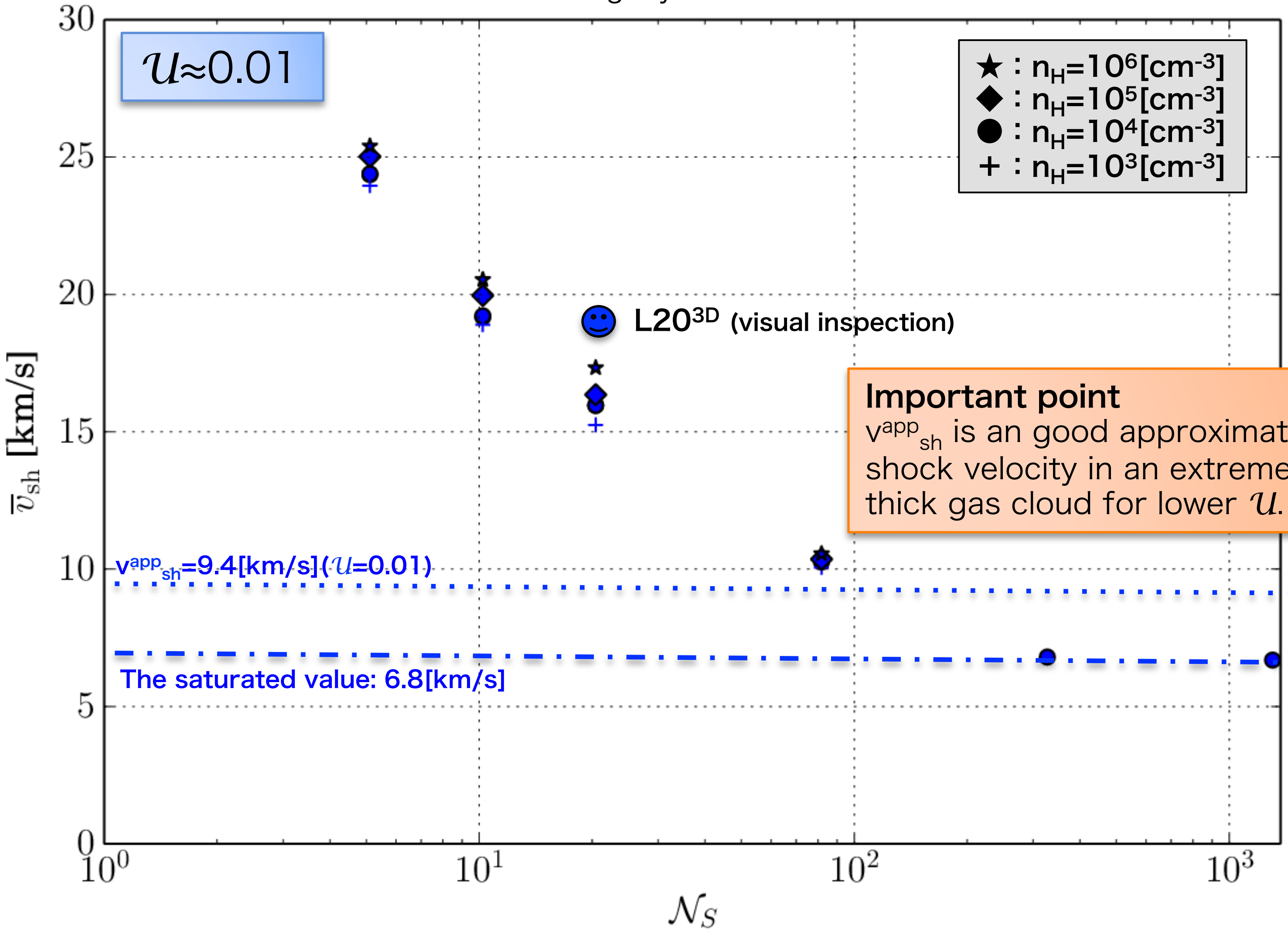
$\mathcal{U}$≈0.01, $\mathcal{N}_S$=1280

- HLL scheme with 2nd order MUSCL interp.
- TVDRK2.
- CMA method.
- A hybrid grid (uniform +logarithmic)
- The same chemical network as that in SPH code.

Radiation pressure confines a photo-evaporation flow in an early phase of the evolution even for small $\mathcal{U}$. This result indicates that for a given $\mathcal{U}$ there is a value of $\mathcal{N}_S$, above which a photo-evaporation flow is confined before the shock reaches the center or the opposite side of the cloud. In this case, evolution becomes radiation pressure-driven.

Time-averaged shock velocity and its dependencies on $\mathcal{N}_S$ and n_H

- Time-averaged shock velocity, v_{sh}, is almost independent of n_H.
- v_{sh} becomes small with $\mathcal{N}_S$ and saturates at large $\mathcal{N}_S$. The saturated value is close to v^{app}_{sh}. The difference between v_{sh} and v^{app}_{sh} may be attributed to that all the photons are not absorbed by the post-shock layer.
- The difference between 1D and 3D calc. can be attributed to (1) that an ionized gas can escape from the system in 3D (more effective rocket-effect), and (2) that our 3D RHD code tends to overestimate radiative acceleration slightly.



Important point
v^{app}_{sh} is an good approximation for shock velocity in an extremely optically-thick gas cloud for lower $\mathcal{U}$.

Lifetime of gas clumps in AGN tori

If v^{app}_{sh} is a good approximation for shock velocity for a extremely optically-thick gas cloud, we can estimate destruction times of gas clumps:

$$v_{\rm sh}^{\rm app} = 9.04\ {\rm km\,s^{-1}} \left(\frac{L_{\rm bol}}{10^{45}\ {\rm erg\ s^{-1}}}\right)^{0.5} \times \left(\frac{M_{\rm BH}}{10^7\ {\rm M_\odot}}\right)^{-0.5} \left(\frac{r}{1\ {\rm pc}}\right)^{0.5},$$

$$t_{\rm sweep} = 4016\ {\rm yr} \left(\frac{L_{\rm bol}}{10^{45}\ {\rm erg\ s^{-1}}}\right)^{-0.5} \times \left(\frac{r}{1\ {\rm pc}}\right) \left(\frac{c_s}{3\ {\rm km\,s^{-1}}}\right),$$

t_{sweep} is much shorter than the orbital period:

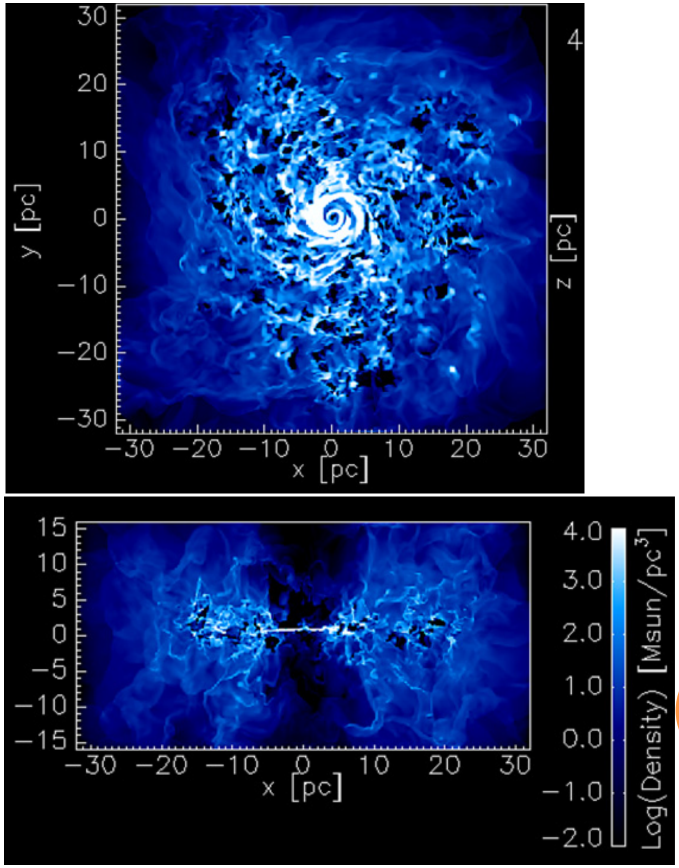
$$t_{\rm orb} = 2.98 \times 10^4\ {\rm yr} \left(\frac{M_{\rm BH}}{10^7\ {\rm M_\odot}}\right)^{-0.5} \left(\frac{r}{1\ {\rm pc}}\right)^{1.5},$$

It seems that gas clouds that are located near the surface of a AGN torus are rapidly destroyed. If the clumpy structure is maintained for long periods, we can think of two possibilities:

First possibility
gas clumps are intrinsically transient and some mechanism continues to create gas clumps to offset destruction of them. A possible mechanism may be turbulence driven by stellar feedbacks (e.g., Wada & Norman 2002; Wada et al. 2009)

Wada et al. (2009)

3D HD simulation of a starburst circumnuclear disk. A clumpy structure is maintained by SNe.



Second possibility

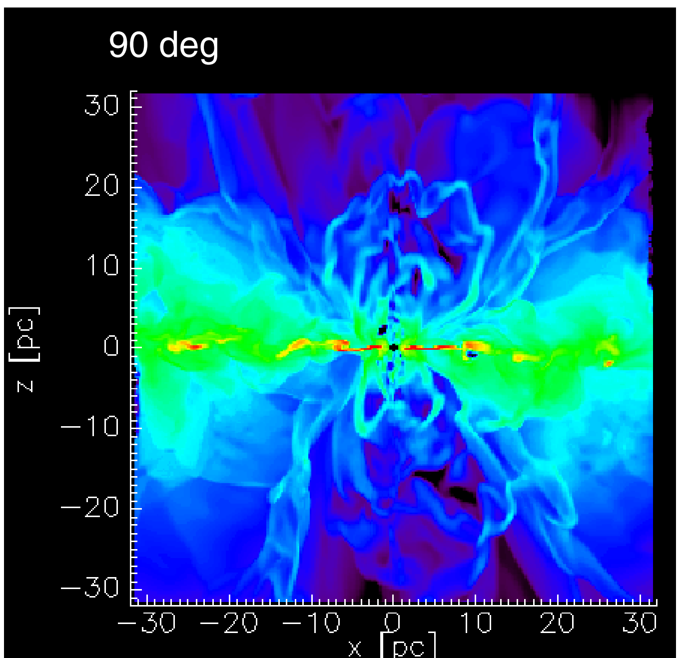
The most of gas clumps are exposed to sufficiently weak radiation fields and therefore a shock does not form. The causes to reduce $\mathcal{U}$ include

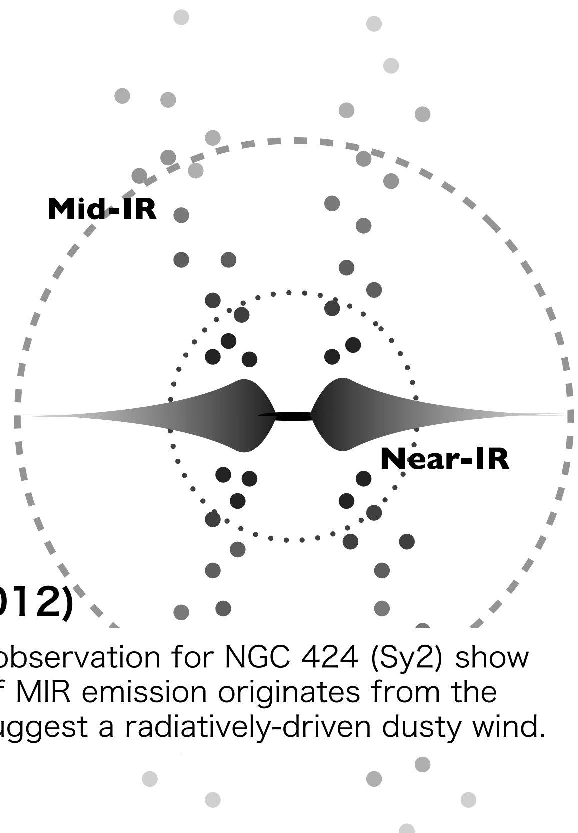
(1) average density of gas clumps is higher than critical density w.r.t. tidal shearing,
(2) anisotropic AGN radiation,
(3) extinction by inter-clump medium.

Another interesting mechanism is that a dusty wind that is launched from the inner edge of the torus shields the main body of the torus. This seems to compatible to recent numerical study (Wada 2012) and observational studies (Czerny & Hryniewicz 2011; Tristram et al. 2012; Hönig et al. 2012, 2013).

Wada (2012)

A 3D RHD global simulation of a circumnuclear gas disk in a AGN-hosting galaxy.





Hönig et al. (2012)

IR interferometric observation for NGC 424 (Sy2) show that the majority of MIR emission originates from the polar region and suggest a radiatively-driven dusty wind.

SUMMARY

- In order to investigate the evolution of a gas cloud exposed to AGN radiation and its destruction timescale, we perform 3D/1D RHD simulations of an AGN-irradiated gas cloud.

- Based on the 1D simulations, for a given $\mathcal{U}$, there is a critical value of $\mathcal{N}_{\mathrm{S}}$, above which a photo-evaporation flow is confined by radiation pressure before a shock reaches the center of a cloud. Evolution of a cloud can be classified as follows:
  1. **photo-evaporation driven**: $\mathcal{N}_{\mathrm{S}} \ll \mathcal{N}_{\mathrm{S}}^{\mathrm{crit}}(\mathcal{U})$.
  2. **radiation pressure driven**: $\mathcal{N}_{\mathrm{S}} \gg \mathcal{N}_{\mathrm{S}}^{\mathrm{crit}}(\mathcal{U})$.

- For an extremely optically thick cloud, cloud destruction timescale is well approximated by t_{sweep} for any $\mathcal{U}$.

- A simple estimate suggests that gas clumps in an AGN torus is rapidly destroyed if volume filling factor is very small. For the clumpy structure to be stable for long periods, (1) some creation mechanism(s) of gas clumps, or (2) some mechanism(s) that weaken radiation fields incident on gas clumps are needed.

Thank you !