20250919 EANAM10
Jeju Island, South Korea

Dust-free and dusty outflows in sub-parsec region of AGN

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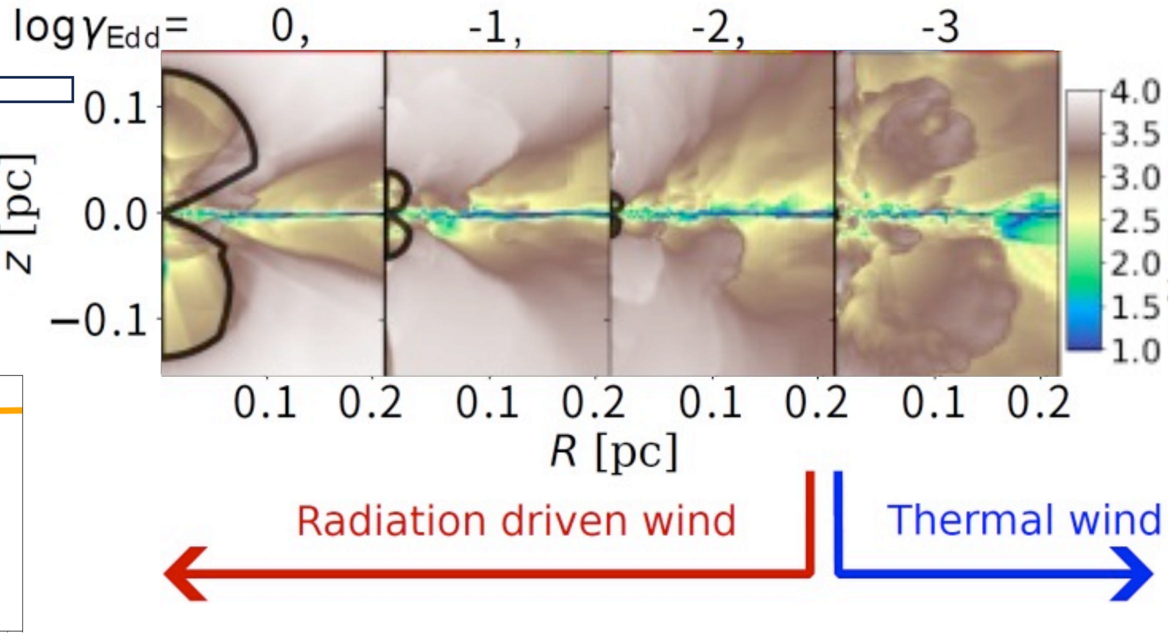
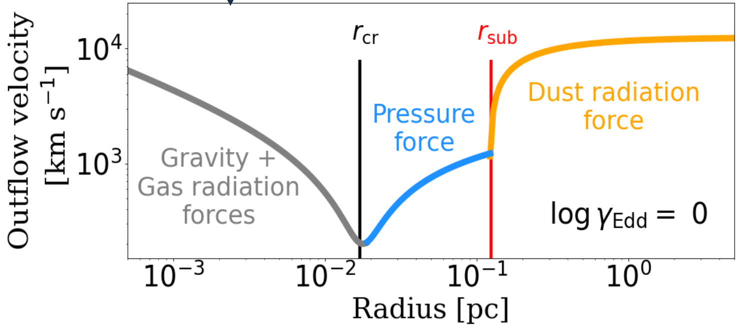


Time-averaged
Radial profile

Analytic solution

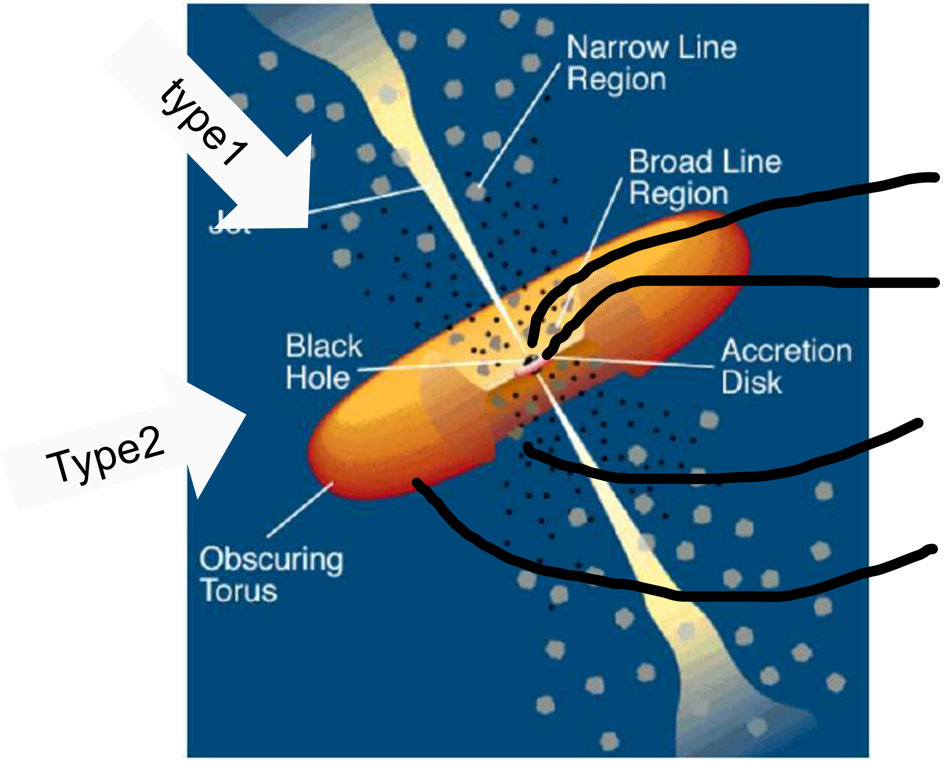


AGN unified model : Gas structure

Antonucci 1993, Urry & Padvani 1998

The unified model of AGNs is composed of the structures:
SMBH, accretion disk, broad-line region (BLR), and dusty torus.
This model explains observations such as:

- Broad emission lines, visible (Type 1) or invisible (Type 2),
- Continuum from IR to X-rays.



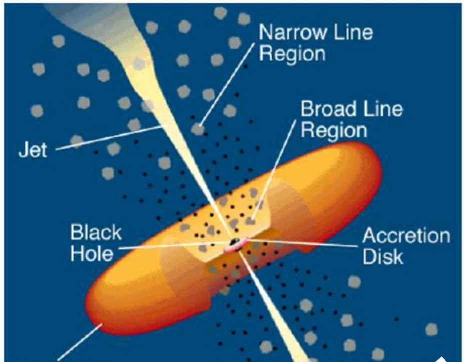
Spatial scale @ 10^7 $M_\odot$

SMBH
$\sim$1 Rg $\sim10^{-6}$ pc
Accretion disk
$\sim$100 Rs $\sim$ 10^{-4} pc
BLR
$\sim$ 10^3 Rs $\sim10^{-3}$ pc
Torus
$\sim$ 10^6 Rs $\sim$ 1 pc

Ionized (multiphase) dusty outflow

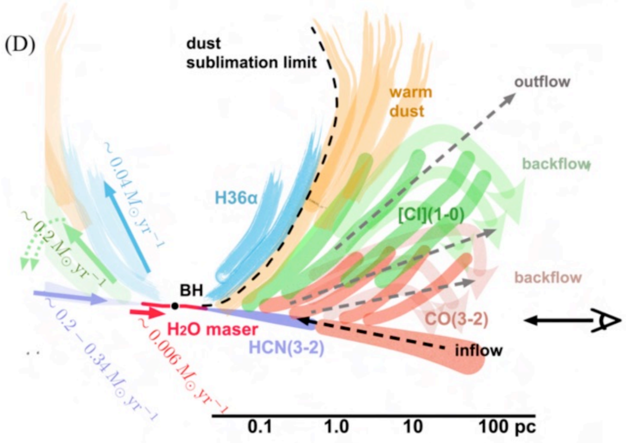
AGN gas unification

Antonucci 1993
Urry & Padvani 1998



Multiphase outflow

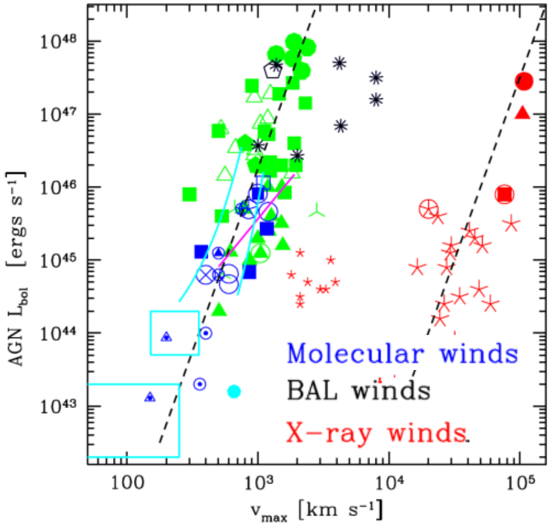
Circinus galaxy
Izumi et al. 2023

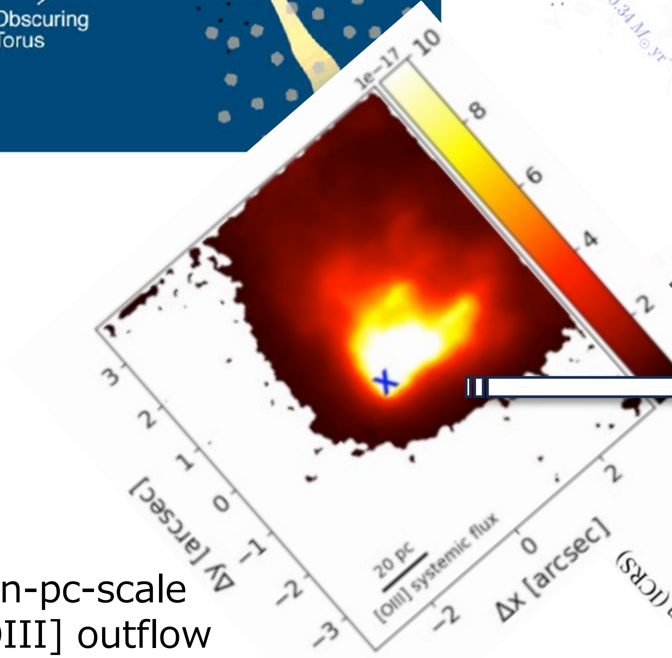


Correlation: v_{out} & L_{bol}

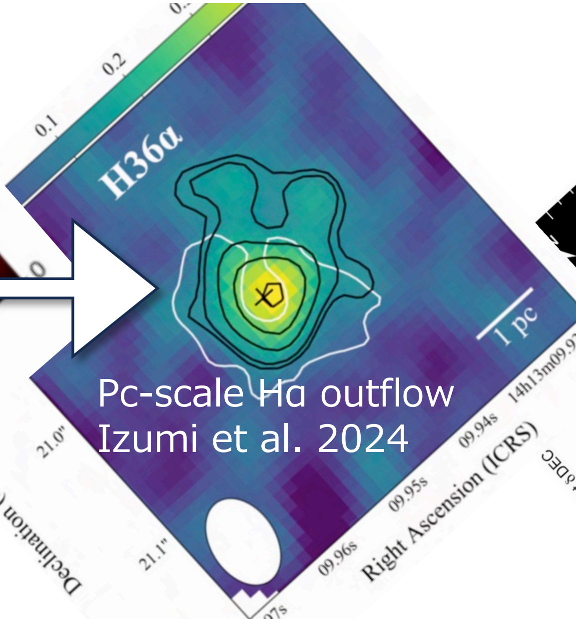
Fiore et al. 2016

$10^2 - 10^5$ km s^{-1}

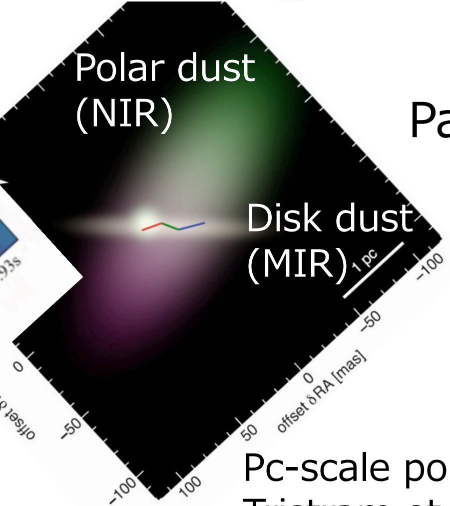




Ten-pc-scale
[OIII] outflow
Kakkad et al. 2023



Pc-scale Hα outflow
Izumi et al. 2024



Polar dust
(NIR)

Disk dust
(MIR)

Pc-scale polar Dust
Tristram et al. 2014

How does gas move near the dust sublimation radius?

- Dust temperature $\mathbf{T_{dust}}$ can be estimated from local thermal equilibrium (LTE) with the AGN irradiation and re-emission.
- If $\mathbf{T_{dust} > T_{sub} \approx 1500\ K}$, dust is destroyed.
- The size of the dust-destroyed region is the **sublimation radius $\mathbf{r_{sub}}$**.
- r_{sub} is given by

$$r_{sub} \approx 0.05 \left(\frac{L_{AGN}}{10^{44}\ \mathrm{erg/s}}\right)^{1/2} \left(\frac{T_{sub}}{1500\ \mathrm{K}}\right)^{-2}\ \mathrm{pc}$$

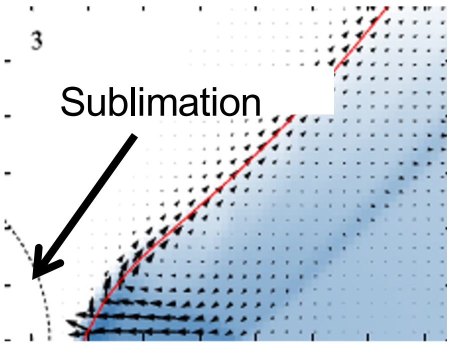
→ sub-parsec scale.

However, previous studies mainly simulated the region outside r_{sub}.

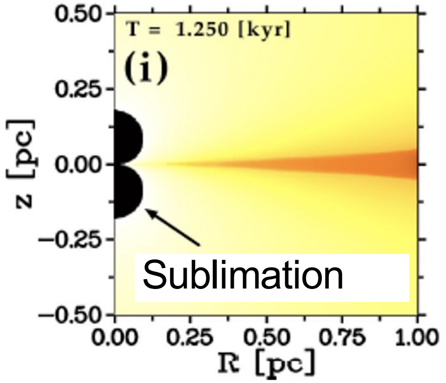
Aim:

- Perform simulations resolving both dust-surviving and dust-destroyed regions.
- Investigate dynamical structure of AGN outflows.

Chen & Krolik. 2016



Namekata et al. 2016



Simulation model

Physics (Kudoh et al. 2023)

- Dust-radiation-hydrodynamic equation
- SMBH gravity
- Dust

$M_{BH}=10^7$ $M_\odot$

  Dust-gas mass ratio = 0.01
  Radiation force modeled by opacity
  Dust destruction :
    sublimation, thermal sputtering
- Gas
  - Radiation force for Thomson opacity
  - Radiative cooling and heating
  - α-viscosity : α=0.1

Computational setup

- CANS+ (Matsumoto et al. 2019)
- Axisymmetric Cylindrical 2D(R, z)

10^{-4} pc (10^2 Rs) <R< 2 pc, |z|< 2 pc

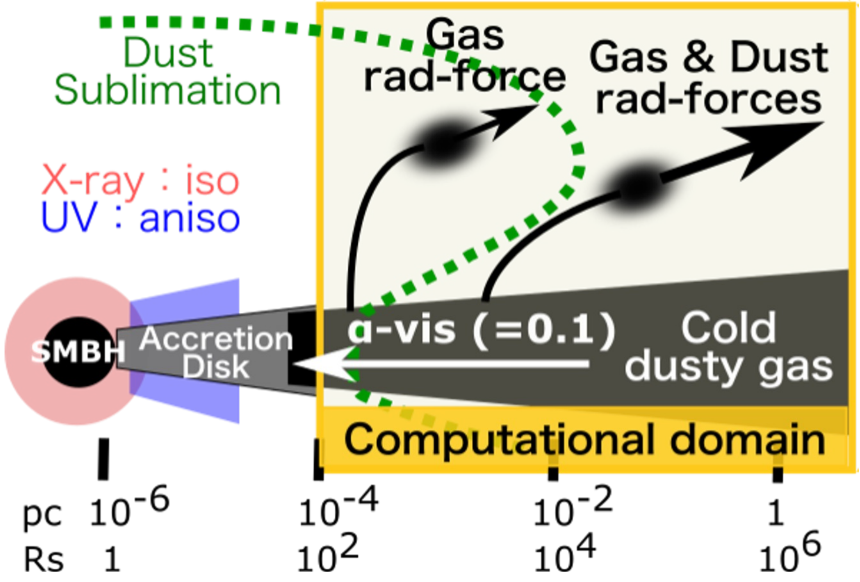
$\Delta R=\Delta z= 5\times10^{-5}$ pc = 50 Rs

- Initial Dusty disk
  with Keplerian rotation,
  and geometrically-thin cold gas

Spatially resolved
dust sublimation radius (r_{sub}).

$r<r_{sub}$: dust-free gas

$r>r_{sub}$: dusty gas



AGN steady radiation sources

$\gamma_{Edd} \propto L_{bol} / M_{BH}$

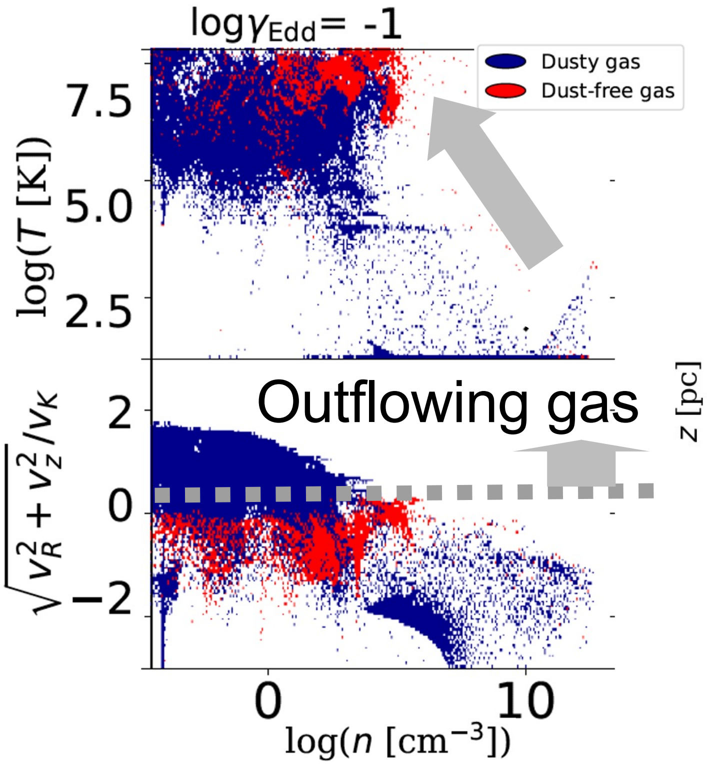
$\gamma_{Edd} = 1, 10^{-1}, 10^{-2}, 10^{-3}$

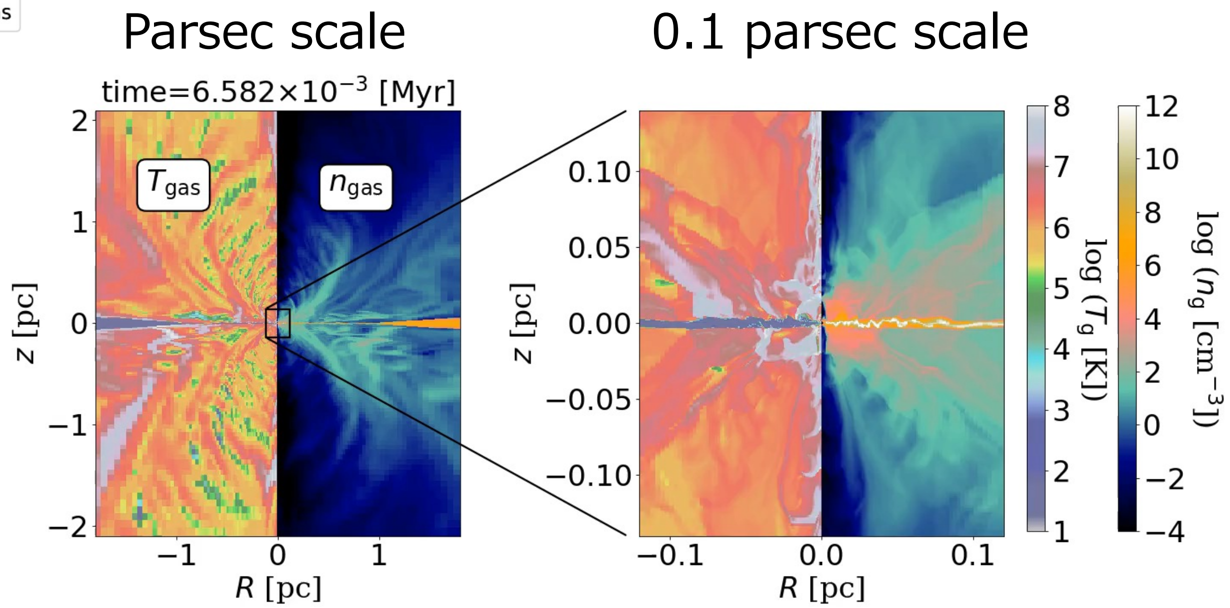
Multi-phase & multi-scale outflow

Case of γEdd=0.1 (Kudoh et al. 2023)

- Propagating shells accumulate →Torus (Wada 2012,2015)
- Radiation-driven outflow appear the shocked shells with variability.
- Inflow-induced outflow:

  disk (low T & high ρ) → outflow (high T & low ρ)
- Dusty gas can escape from the system, dust-free gas is bound

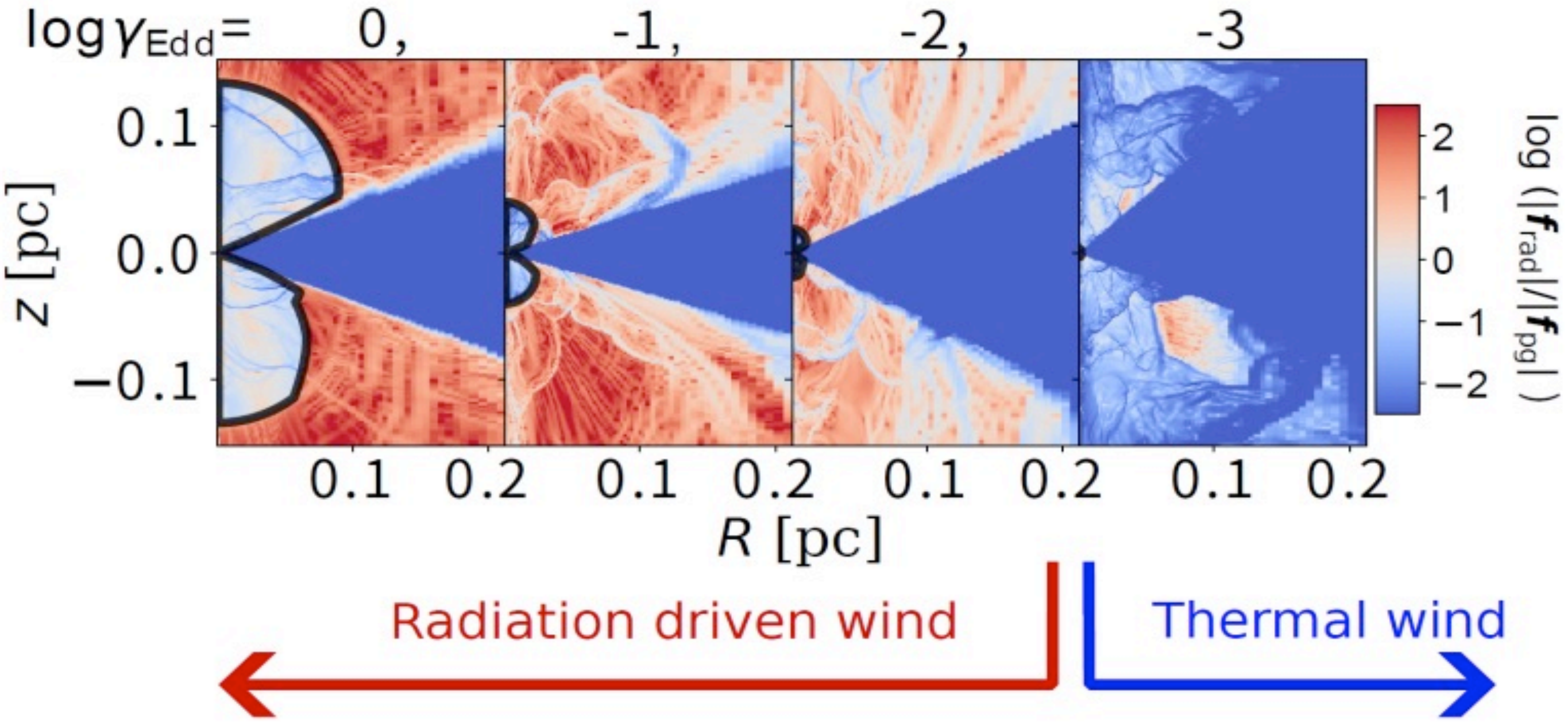




Which is the driving mechanism: Radiation or Gas pressure?

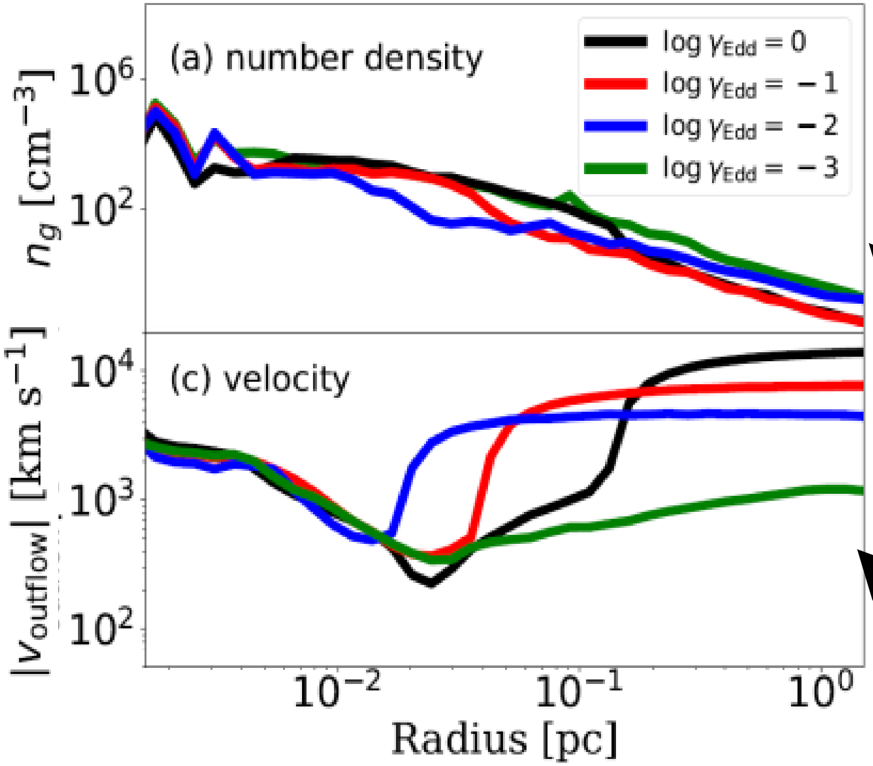
Dependence on the Eddington ratio $\gamma_{\mathrm{Edd}} \propto L_{\mathrm{bol}} / M_{\mathrm{BH}}$

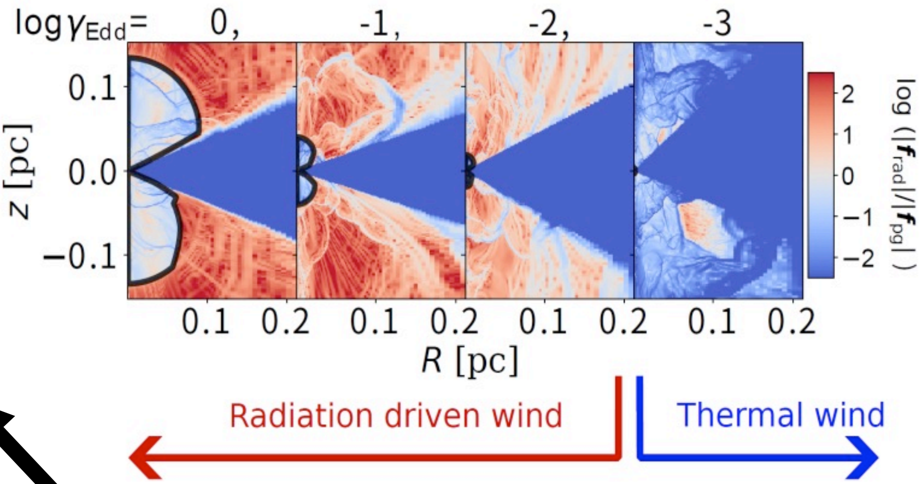
Strong radiation **Weak radiation**

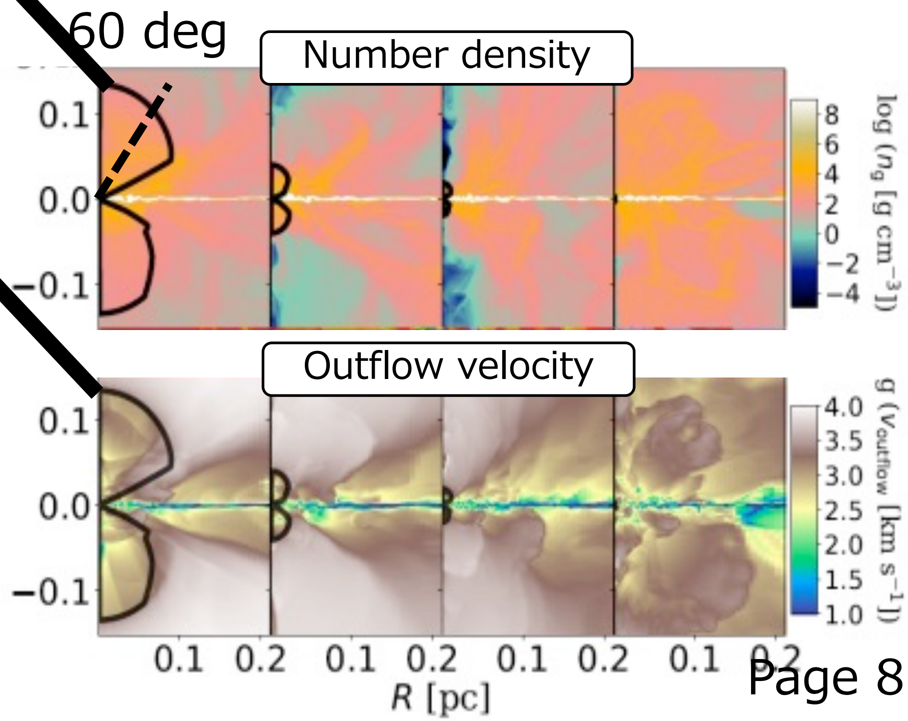


Dynamical structure: n, v_{outflow}

Time-averaged
Radial profile at 60 degree

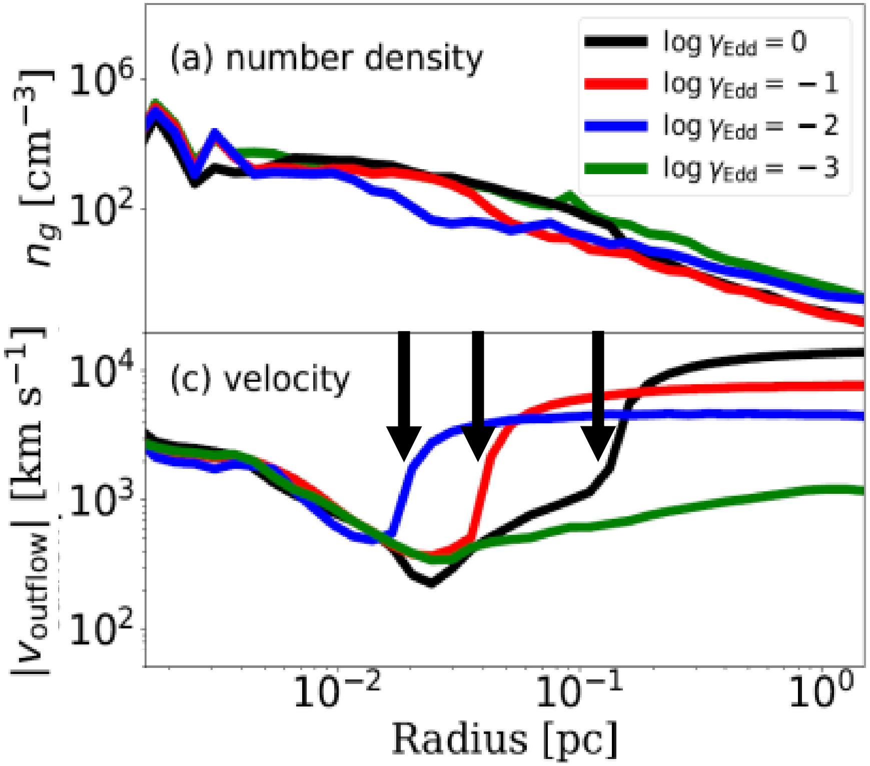




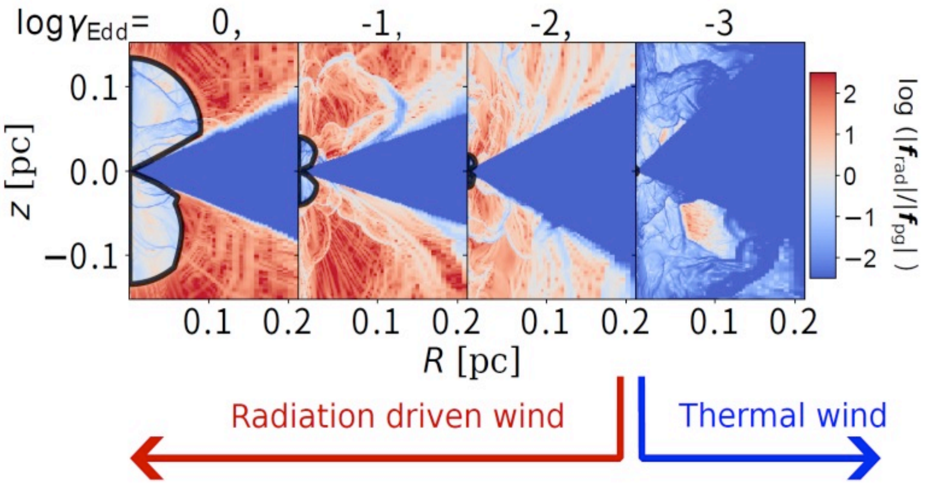


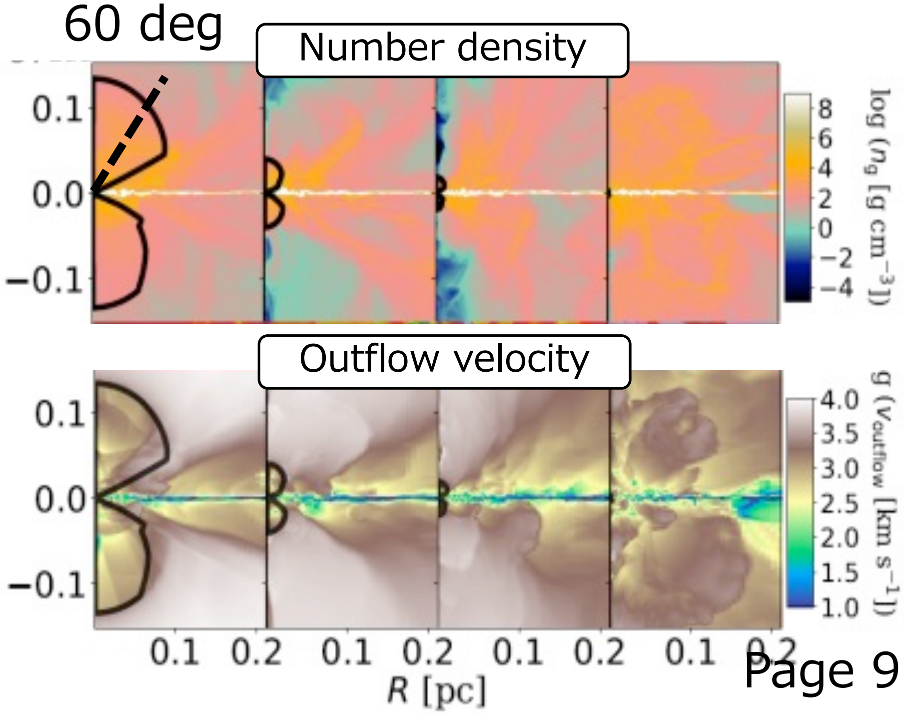
Dynamical structure: n, v_{outflow}

Time-averaged
Radial profile at 60 degree



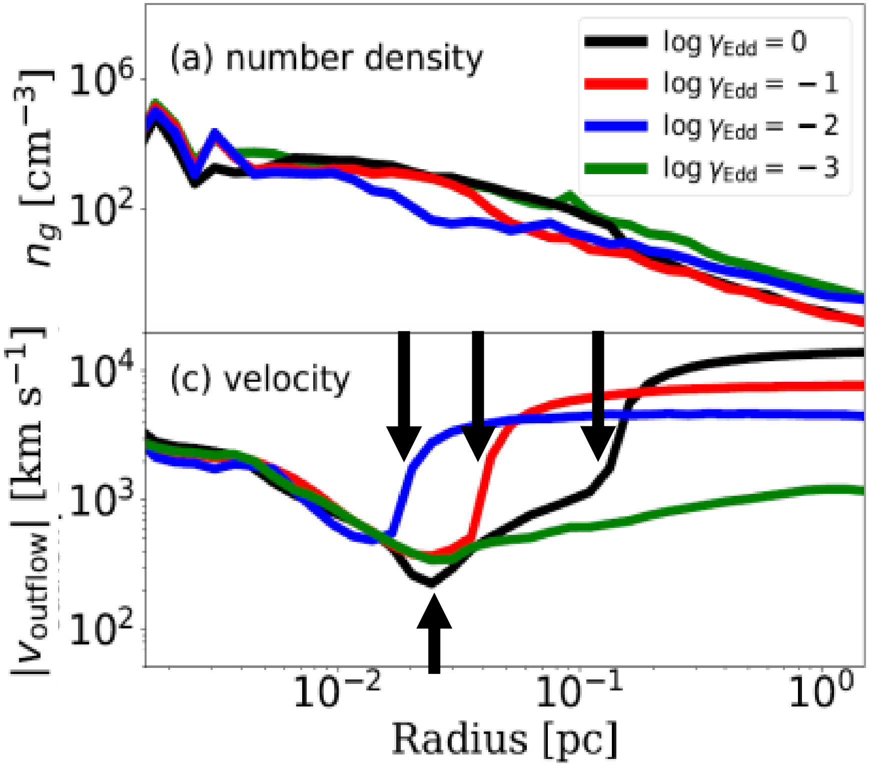
(1) Acceleration point





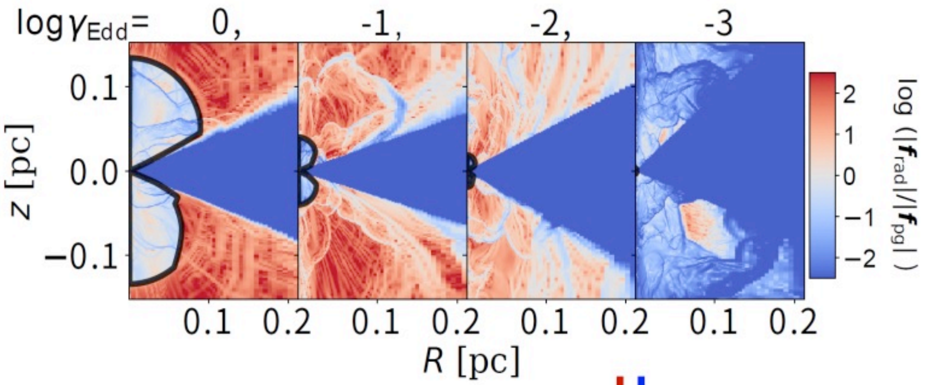
Dynamical structure: n, $v_{outflow}$

Time-averaged
Radial profile at 60 degree



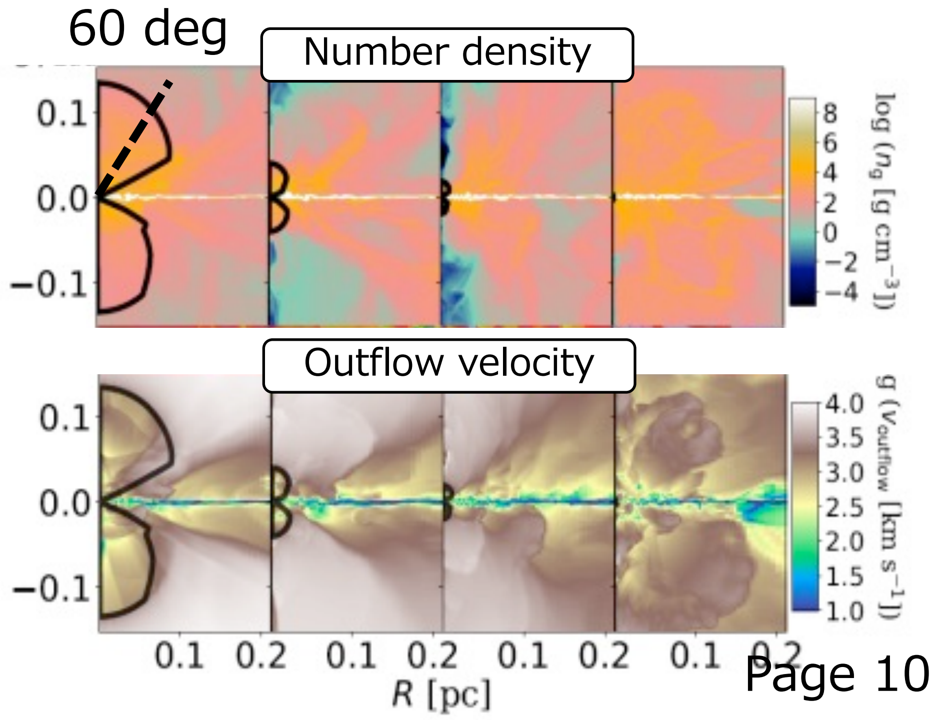
(1) Acceleration point

(2) Velocity Minimum



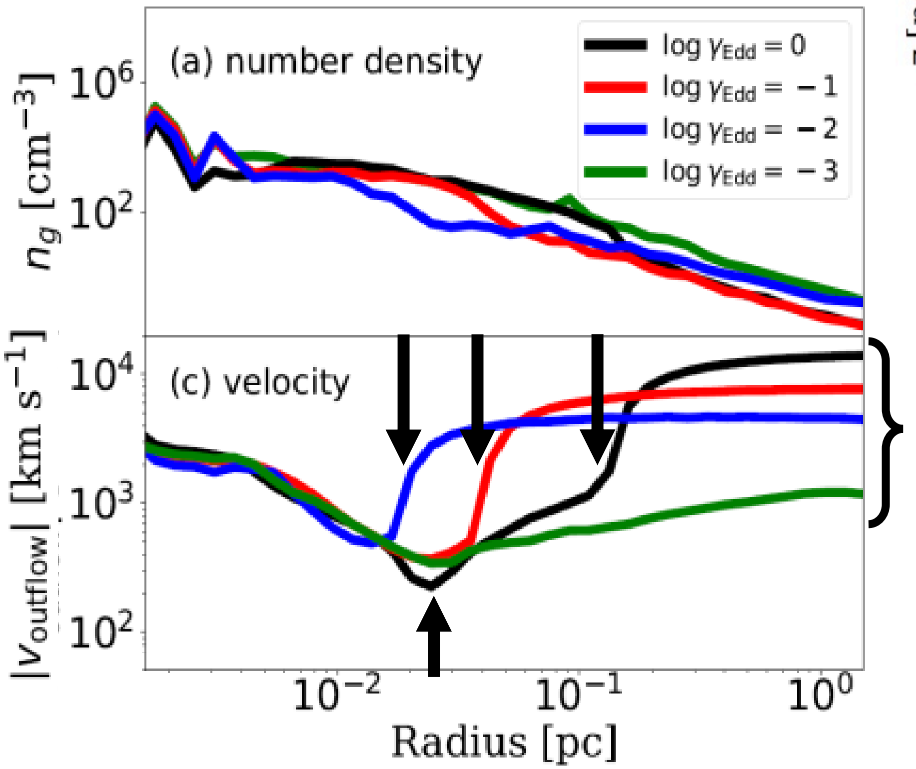
Radiation driven wind

Thermal wind

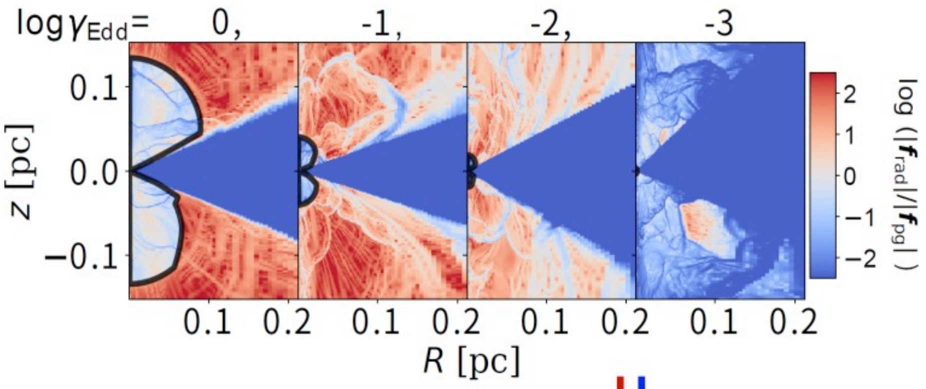


Dynamical structure: n, $v_{outflow}$

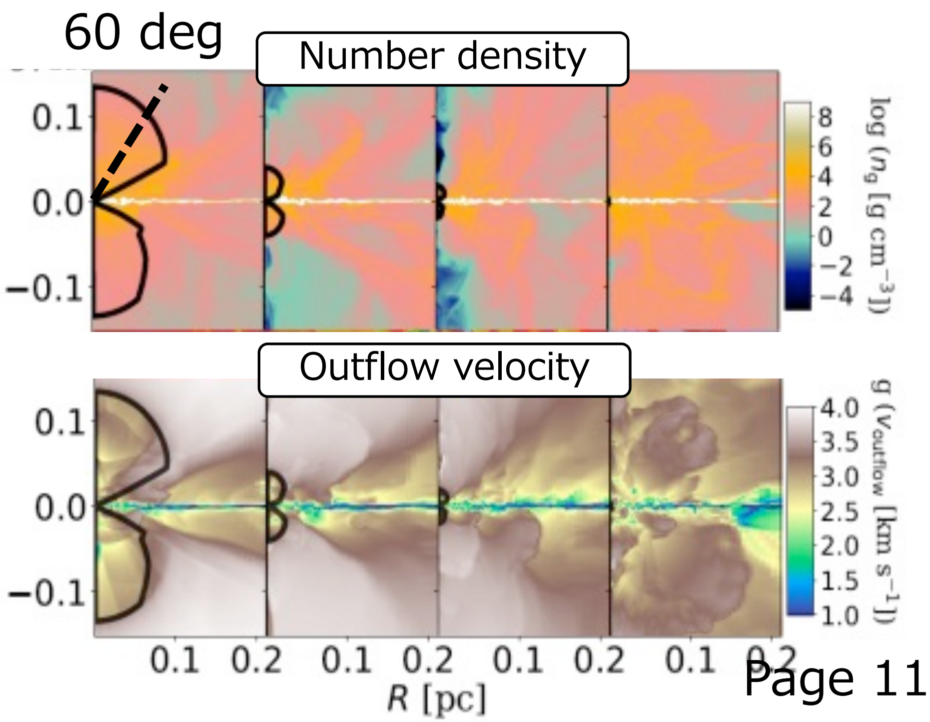
Time-averaged
Radial profile at 60 degree



- (1) Acceleration point
- (2) Velocity Minimum
- (3) Terminal velocity



Radiation driven wind ← | → Thermal wind



Analytical model of outflowing shells

Equation of motion radiation + gravity + gas pressure (isothermal)

$$\frac{dv(r)}{dt} = \left(\underline{\frac{\kappa}{c}\frac{L}{4\pi}} - \underline{GM_{\rm SMBH}}\right)\frac{1}{r^2} + \underline{\frac{c_s^2}{\gamma p}\frac{dp}{dr}} \qquad d/dr \sim r^{-1}$$

$$\frac{dv(r)}{dt} \sim (\underline{\Gamma_{\rm Edd}} - \underline{1})\frac{r_{\rm g}}{r}\frac{c^2}{2r} + \underline{\frac{c_s^2}{\gamma r}}$$

Solutions for outflow velocity

$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\underline{\Gamma_{\rm Edd}} - 1)\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right] + \frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)$$

Force ratio of radiation to gravity

Dusty gas $\Gamma_{\rm Edd,d} = \frac{\kappa}{\kappa_{\rm T}}\delta_L\gamma_{\rm Edd}$

Dust-free gas $\Gamma_{\rm Edd,g} = \delta_L\gamma_{\rm Edd}$

$\gamma_{\rm Edd} \propto L_{\rm bol} / M_{\rm BH}$

$r_{\rm g} = 2GM_{\rm SMBH}/c^2 \sim 10^{-6}\ {\rm pc}\ \left(M_{\rm SMBH}/10^7 M_\odot\right)$

Dynamical structure (log $\gamma_{\rm Edd} = 0$)

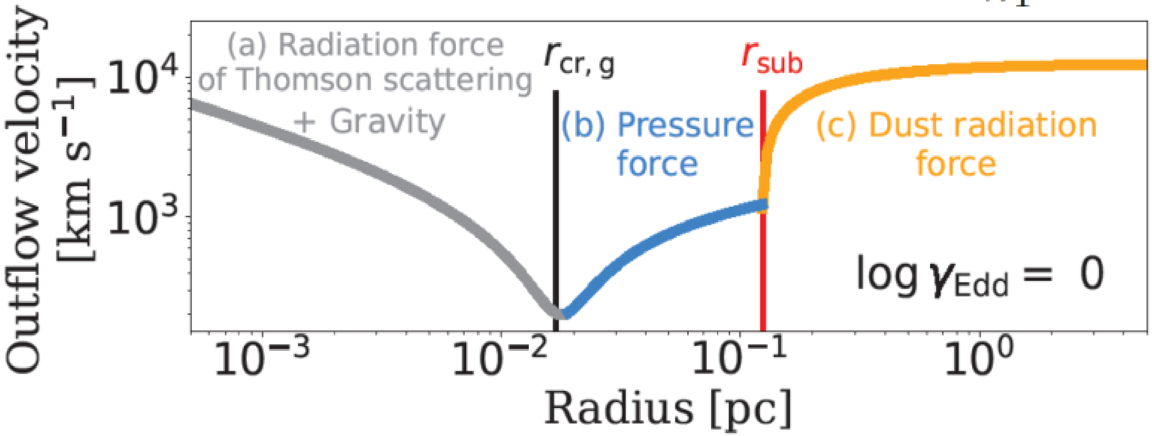
Analytic solution

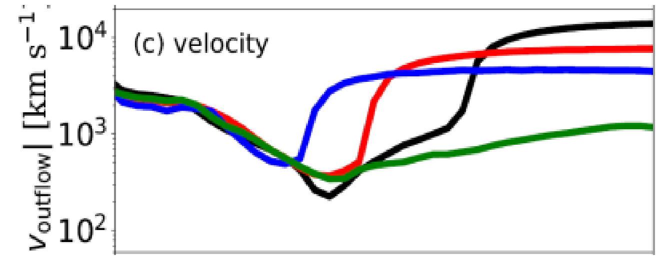
radiation gravity gas pressure

$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\underline{\Gamma_{\rm Edd}} \underline{- 1)}\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1-\left(\frac{r}{r_0}\right)^{-1}\right] + \underline{\frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)}$$

Dust-free gas **Dusty gas**

$$\Gamma_{\rm Edd,g} = \delta_L \gamma_{\rm Edd} \quad \Gamma_{\rm Edd,d} = \frac{\kappa}{\kappa_{\rm T}}\delta_L \gamma_{\rm Edd}$$





(1) Acceleration point

(2) Velocity Minimum

(3) Terminal velocity

Critical point (dv/dt =0)

$$r_{\rm cr} = (1-\Gamma_{\rm Edd})\,\frac{\gamma}{2}\left(\frac{c}{c_s}\right)^2 r_{\rm g}$$
$$= 0.017\ {\rm pc}\ \ (1-\Gamma_{{\rm Edd},i})\left(\frac{c/c_s}{200}\right)^2\left(\frac{M_{\rm SMBH}}{10^7 M_\odot}\right)$$

Dust sublimation radius

$$r_{\rm sub} = \sqrt{\frac{\delta_L L_{\rm bol}}{4\pi\sigma_{\rm SB}T_d^4}}$$
$$= 0.176\ {\rm pc}\ \left(\frac{M_{\rm SMBH}}{10^7 M_\odot}\right)^{\frac{1}{2}}\left(\frac{\delta_L}{0.5}\right)^{\frac{1}{2}}\left(\frac{\gamma_{\rm Edd}}{1}\right)^{\frac{1}{2}}\left(\frac{T_{\rm d}}{1500\ {\rm K}}\right)^{-2}$$

Dynamical structure

Domain (a) gravity
(b) gas pressure
(c) dust radiation force

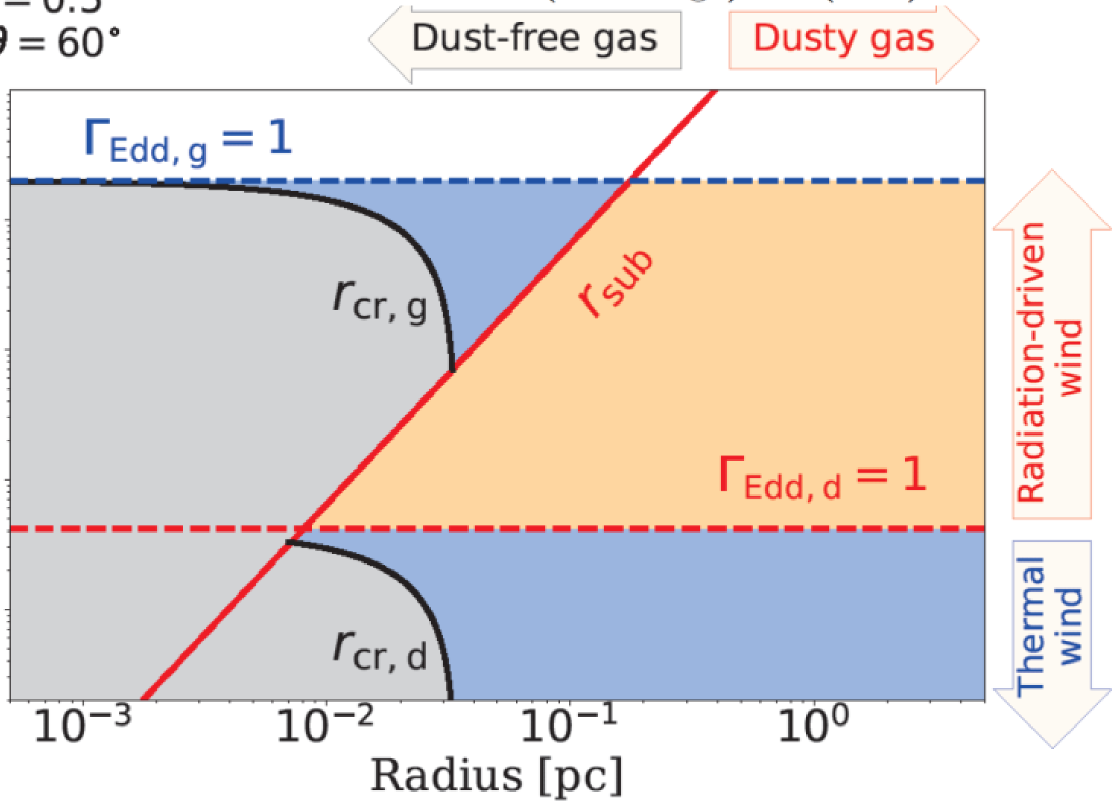
(a), (b) → Solar wind solution (Parker 1960)

(c) → Dusty stellar wind solution with terminal velocity (Lamers & Cassinelli 1999)

$$r_{\rm sub} = 0.176\ {\rm pc}\ \left(\frac{M_{\rm SMBH}}{10^7 M_\odot}\right)^{\frac{1}{2}} \left(\frac{\delta_L}{0.5}\right)^{\frac{1}{2}} \left(\frac{\gamma_{\rm Edd}}{1}\right)^{\frac{1}{2}}$$

$\gamma_{\rm Edd} \propto L_{\rm bol} / M_{\rm BH}$

$\delta_L = 0.5$
at $\theta = 60^\circ$

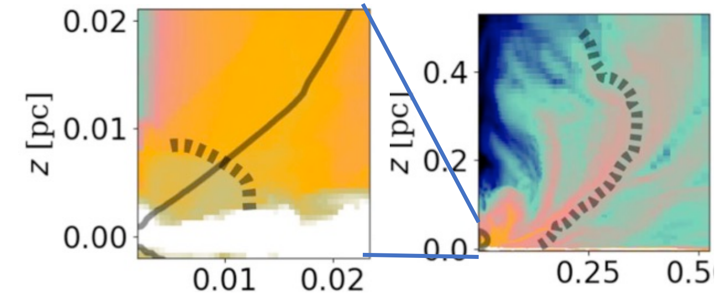


$$\Gamma_{\rm Edd,g} = 0.5 \left(\frac{\delta_L}{0.5}\right) \left(\frac{\gamma_{\rm Edd}}{1}\right)$$

$$\Gamma_{\rm Edd,d} = 240 \left(\frac{\kappa/\kappa_{\rm T}}{480}\right) \left(\frac{\delta_L}{0.5}\right) \left(\frac{\gamma_{\rm Edd}}{1}\right)$$

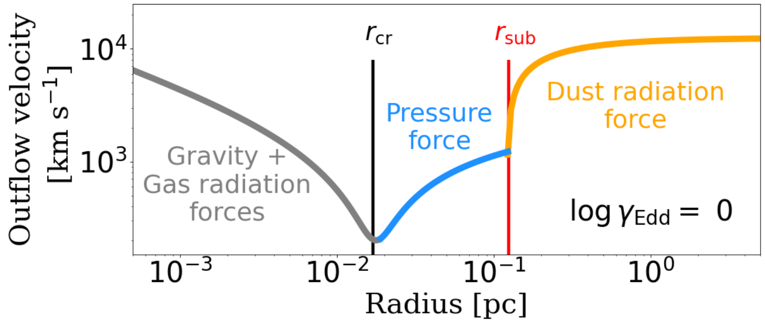
Summary

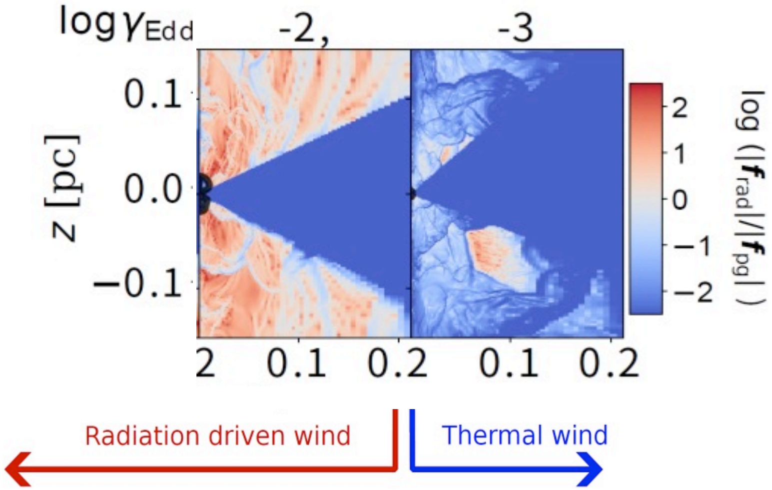
- We investigated the dependence of the Eddington ratio on sub-pc-scale outflows using axisymmetric 2D simulations.
- **Outflowing shells with variability** are described as the **analytic solutions of steady**.
- Dusty wind activated on when Eddington ratio > -3.
-Important parameters are $r > r_{\mathrm{sub}}$ and $\Gamma_{\mathrm{Edd,d}} > 1$.

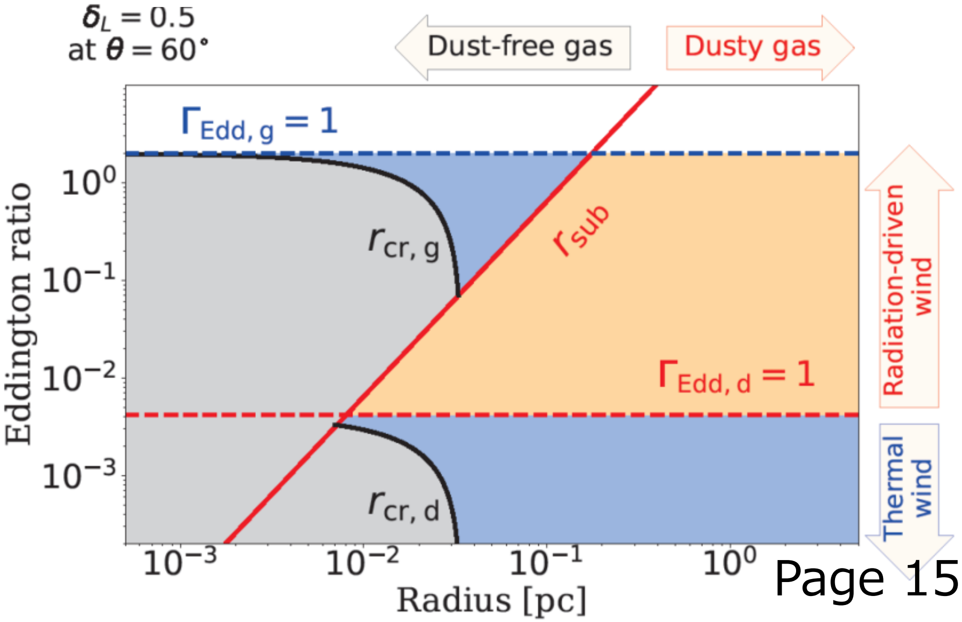


Shocked shells (Variability)

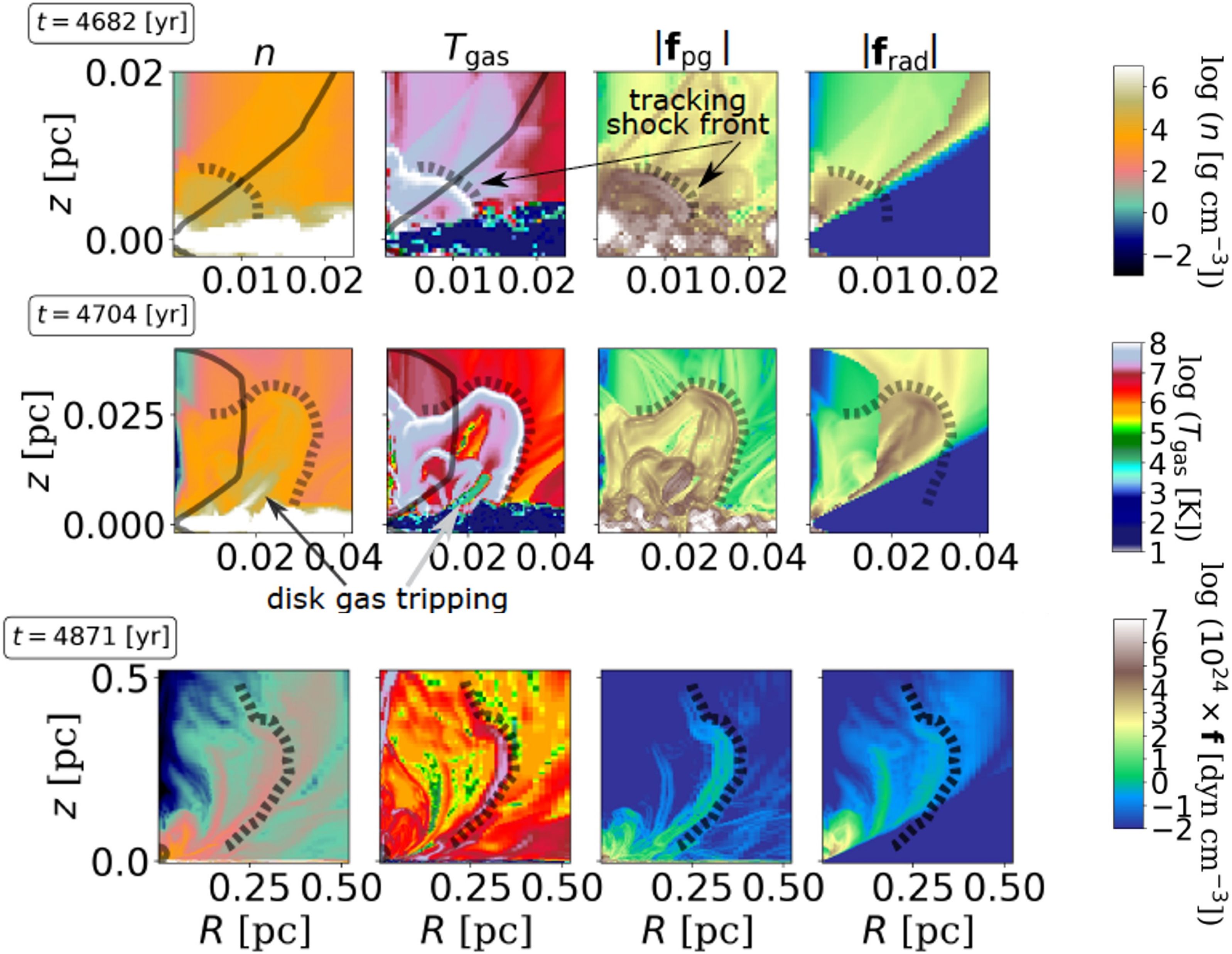
Wind solution (Time-averaged)







Shell propagation with shock



Gas-dust radiation hydrodynamic equations

- Mass conservation (dust & gas)

dust-to-gas mass ratio

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot [\rho \boldsymbol{v}] = 0 \qquad \rho = \rho_{\rm gas} + \rho_{\rm dust} \sim \rho_{\rm gas} \qquad \frac{\rho_{\rm dust}}{\rho_{\rm gas}} = \text{const.}$$

Sublimation : $T_{\rm dust}$ > 1500 K, $r_{\rm sub}$~ 0.01pc @ a=0.01 μm)
Sputtering : $t_{\rm spu} < \Delta t_{\rm hydro}$ @ a=0.01 μm)

- Momentum conservation O(v/c)

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \boldsymbol{\nabla} \cdot [\rho \mathbf{vv} + P_{\rm g}\mathbf{I}] = \boxed{\boldsymbol{f}_{\rm rad}} + \boldsymbol{f}_{\rm grav} + \boldsymbol{f}_{\rm vis} \qquad \boldsymbol{f}_{\rm rad} = \int_{10^{10}\,\rm Hz}^{10^{20}\,\rm Hz} \frac{(\rho_{\rm d}\kappa_{{\rm d},\nu} + \rho_{\rm g}\kappa_{\rm T})}{c} F_\nu \boldsymbol{e}_r \, d\nu$$

Radiation force

- Energy conservation

$$\frac{\partial e}{\partial t} + \boldsymbol{\nabla} \cdot [(e + P_{\rm g})\boldsymbol{v}] = \boxed{-\rho\mathcal{L} + \boldsymbol{v} \cdot \boldsymbol{f}_{\rm rad}} + \boldsymbol{v} \cdot \boldsymbol{f}_{\rm grav} + W_{\rm vis}$$

Cooling/Heating Work for rad-force

Gas fluid
Dust fluid
Rad eq.

➡

gas-dust centroid
gas-dust relative
Rad eq.

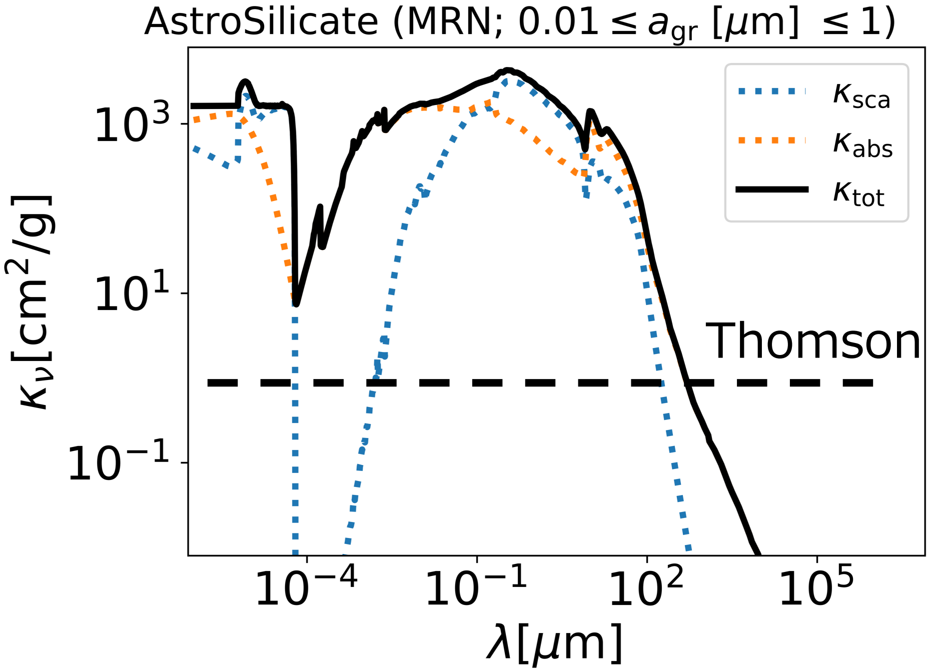
➡

Assume steady state
- gas-dust mass ratio relative velocity
- radiation field

We solve the gas-dust centroid system.

Dust model

Dust opacity (astroSilicate; Draine 2003)



Dust radiation force

$$f_{\mathrm{rad}} = \int_{10^{10}\mathrm{Hz}}^{10^{20}\mathrm{Hz}} \frac{(\rho_{\mathrm{d}}\kappa_{\mathrm{d},\nu} + \rho_{\mathrm{g}}\kappa_{\mathrm{T}})}{c} F_\nu e_r d\nu$$

Opacity

Radiation flux

Size distribution: MRN model
0.01<a<1 μm
(Mathis et al. 1977, Drain & Lee 1984)

$$n(a)da = A n_H a^{-\beta} da \quad \beta = -3.5$$

Dust destruction

- Sublimation

(Namekata et al. 2016
Chan and Krolic 2017)

$$\int \frac{L_\nu e^{-\tau_\nu}}{4\pi r^2}\kappa_{\mathrm{d},\nu}(a)\frac{4\pi}{3}a^3\rho_{\mathrm{grain}}n(a)d\nu da - \int 4\pi B_\nu(T_{\mathrm{d}})\kappa_{\mathrm{d},\nu}(a)\frac{4\pi}{3}a^3\rho_{\mathrm{grain}}n(a)d\nu da = 0,$$

T_{dust} > 1500 K, t_{spu} < $\Delta t_{\mathrm{hydro}}$

- Sputtering

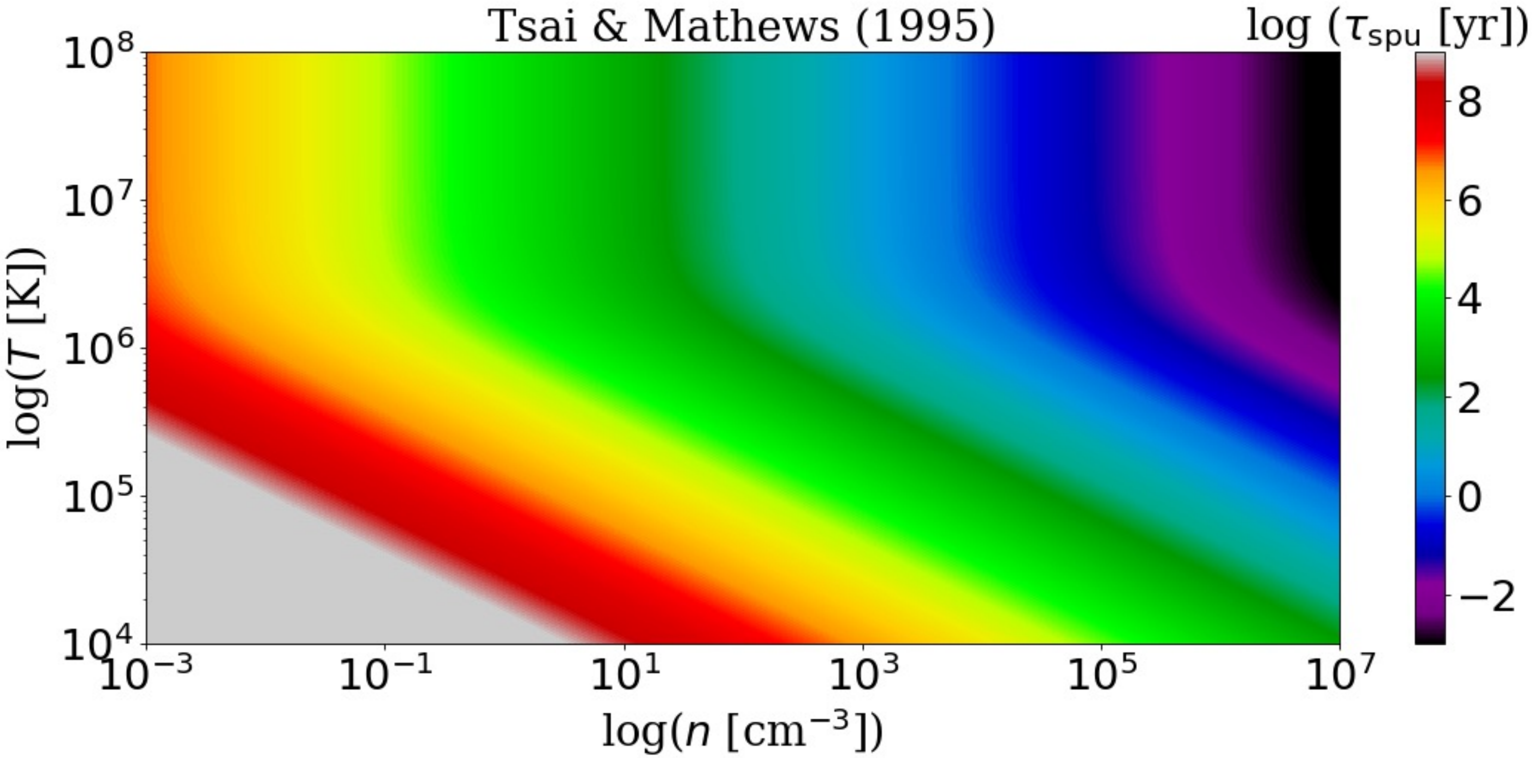
(Tasai and Mathews 1995)

$$\tau_{\mathrm{sp}} = 5.5\times 10^3\ \mathrm{yr}\ \left(\frac{n}{1\ \mathrm{cm}^{-3}}\right)^{-1}\left(\frac{a}{0.01\ \mu\mathrm{m}}\right)\left[\left(\frac{2\times 10^6}{T}\right)^{2.5}+1\right]$$

Dust destruction processes

Dust sputtering (collisional)

$$\tau_{\rm sp} = 5.5 \times 10^3 \text{ yr } \left(\frac{n}{1 \text{ cm}^{-3}}\right)^{-1} \left(\frac{a}{0.01 \ \mu\text{m}}\right) \left[\left(\frac{2 \times 10^6}{T}\right)^{2.5} + 1\right]$$



Simulation setup

Dusty outflow in Eddington ratio 0.1

Physics (Wada 2012, 2015)

- Dust-radiation-hydrodynamic equation
- SMBH gravity
- Dust

$M_{BH}=10^7\ M_\odot$

AGN steady radiation field

- Eddington ratio γEdd = 0.1

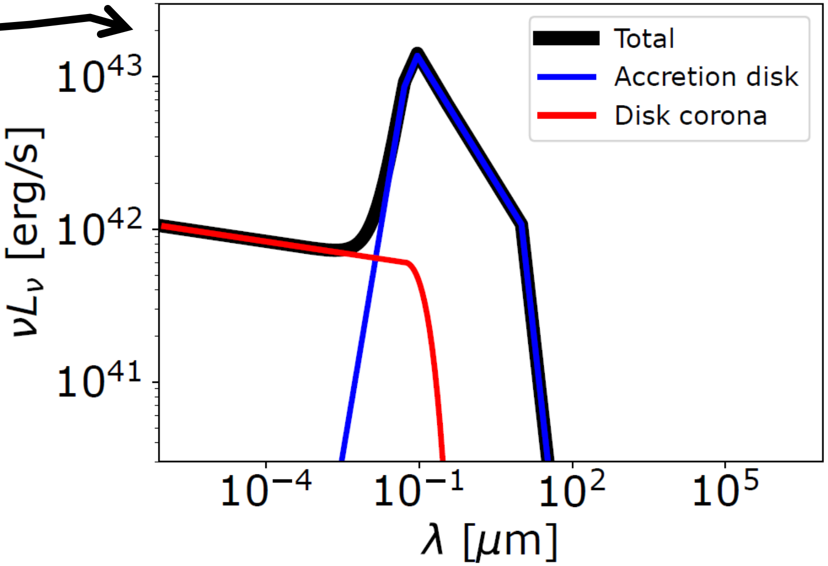
Eddington luminosity (Given)

$$L_{\rm Edd} = 1.41 \times 10^{45} \left(\frac{M_{\rm BH}}{10^7 M_\odot} \right) \ {\rm erg/s}$$

Eddington ratio γEdd $\equiv \dfrac{L_{\rm bol}}{L_{\rm Edd}}$ =0.1

(Given)

Generate AGN SED



Simulation model

Physics (Kudoh et al. 2023)

- Dust-radiation-hydrodynamic equation
- SMBH gravity

$M_{BH}=10^7$ M⊙

- Dust
  - Dust-gas mass ratio = 0.01
  - Radiation force for dust opacity
  - Dust destruction : sublimation, sputtering
- Gas
  - ・Radiation force for Thomson opacity
  - ・Radiative cooling and heating
  - ・α-viscosity : α=0.1

Computational setup

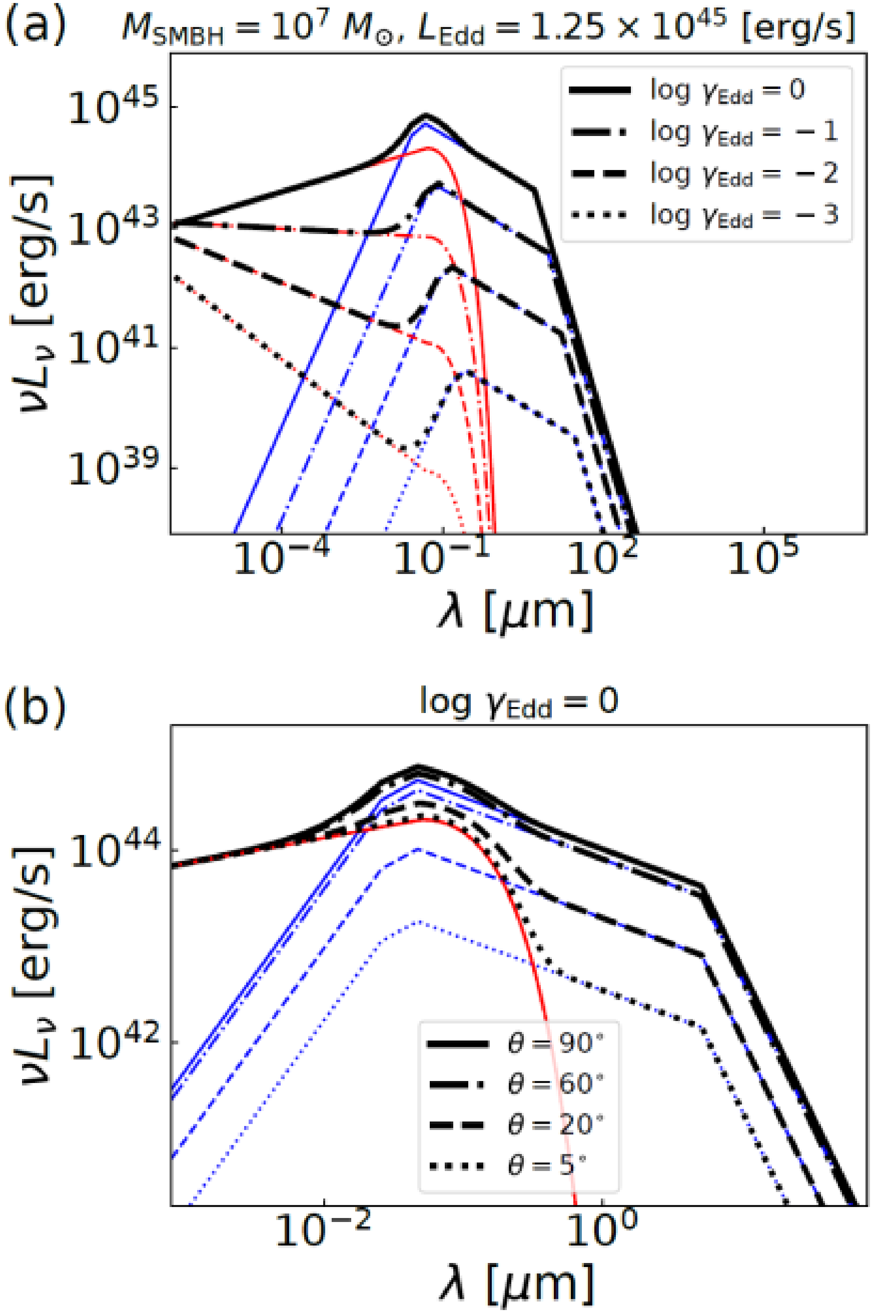
・CANS+ (Matsumoto et al. 2019)

・Axisymmetric Cylindrical 2D(R, z)

10^{-4} pc (10^2 Rs) <R< 2 pc, |z|< 2 pc

ΔR=Δz= 5×10^{-5} pc = 50 Rs

・Initial Dusty disk
with Keplerian rotation,
and geometrically-thin cold gas

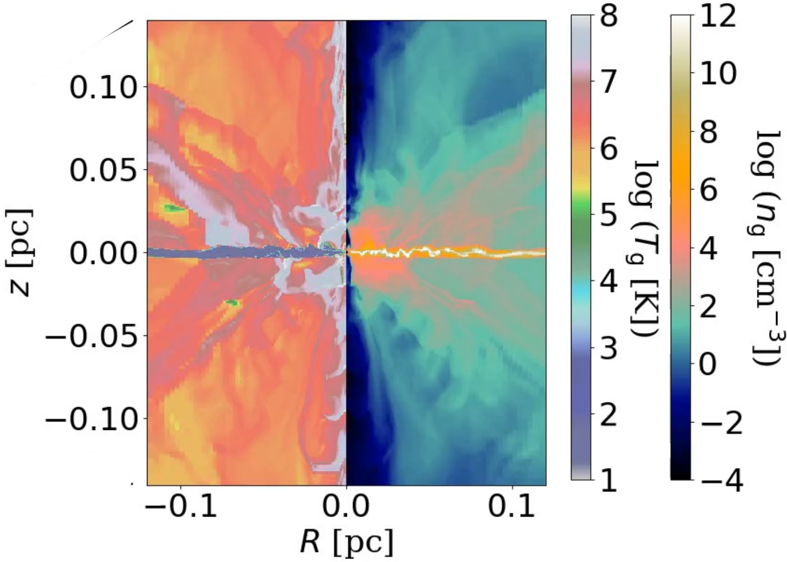


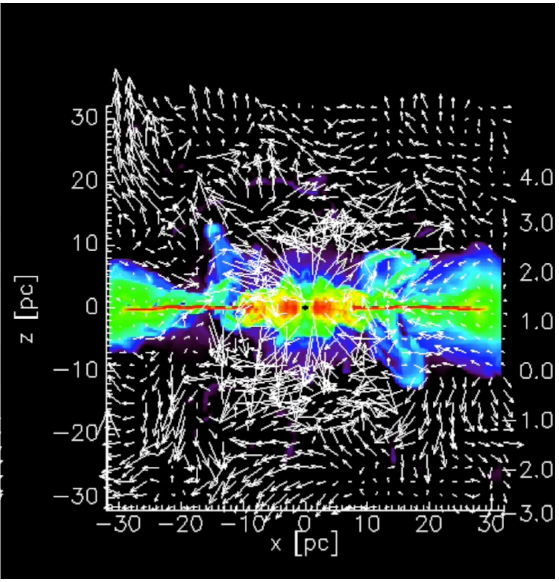
Ionized Dusty Outflow: Simulation

The torus is an accumulation of dusty outflow.

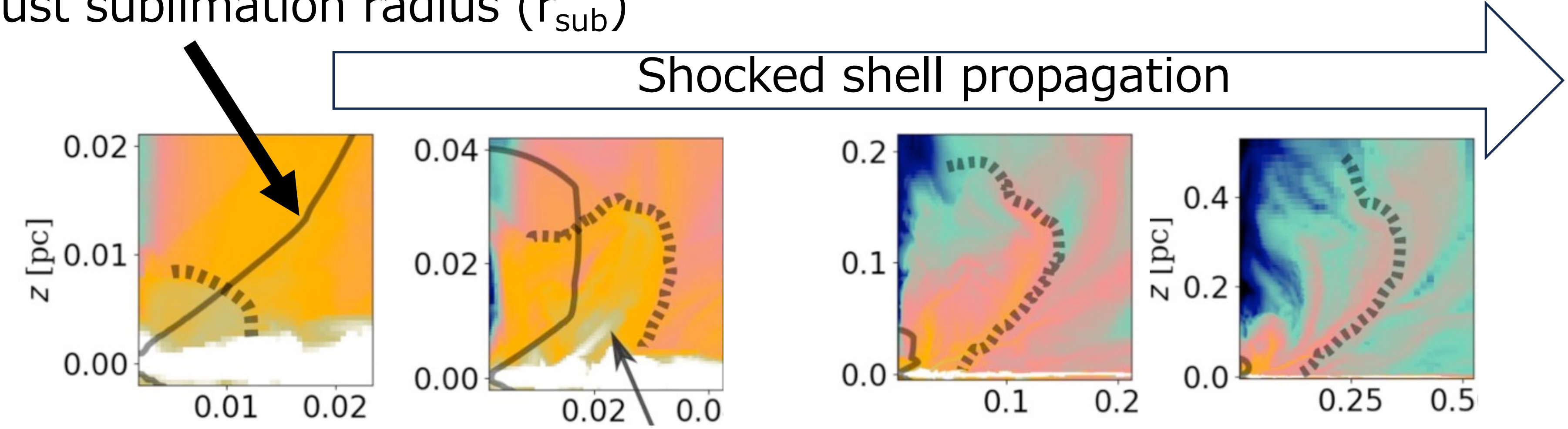
Sub-pc-scale: Kudoh et al. 2023

Ten-pc-scale: Wada 2015





Dust sublimation radius (r_{sub})

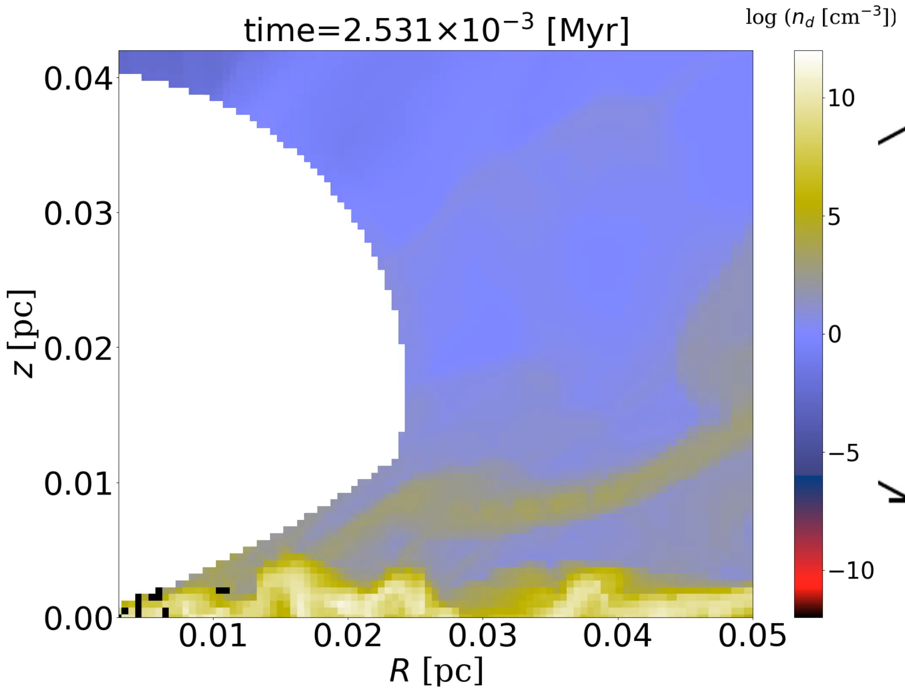

Shocked shell propagation

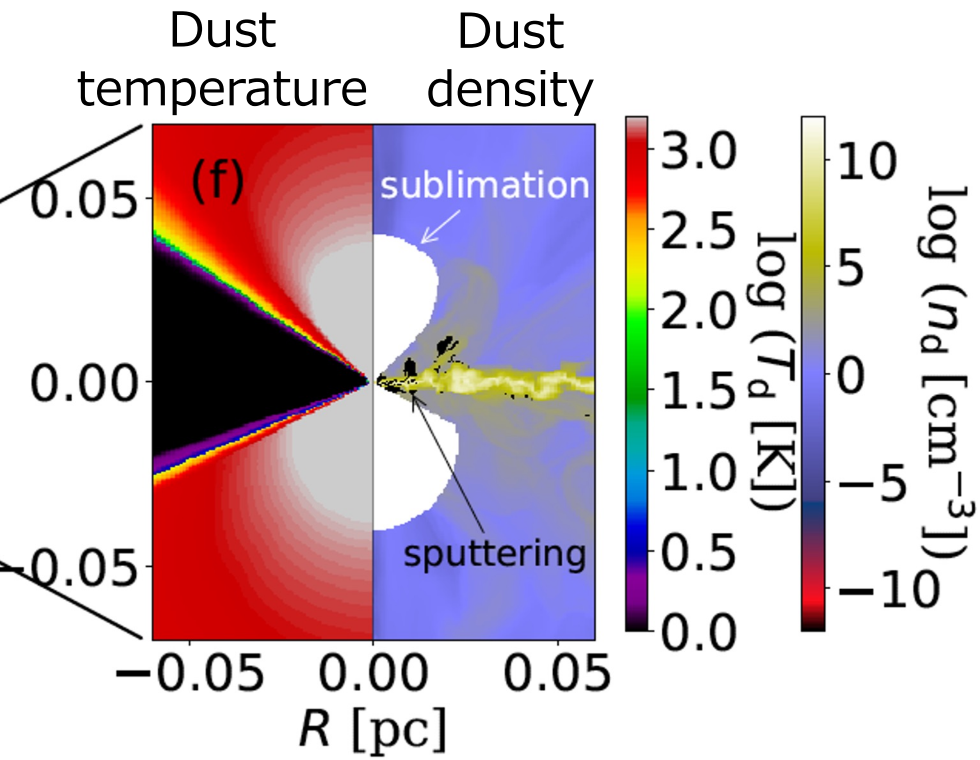
Dust distribution

- Dust density: Shape of dust sublimation region has time-variability.
- Dust temperature:

Around mid-plane, cold dust appear due to attenuation by outflow.

Dust density distribution
White: dust sublimation region,
Black : dust sputtering region.





Velocity field & Force ratio
Where outflow are accelerated?

Inside the dust sublimation region,
gas is gravitationally bound and gas pressure are dominated.

A part of gas lifted by the gas pressure
is accelerated by dust radiation force.

- Velocity arrows

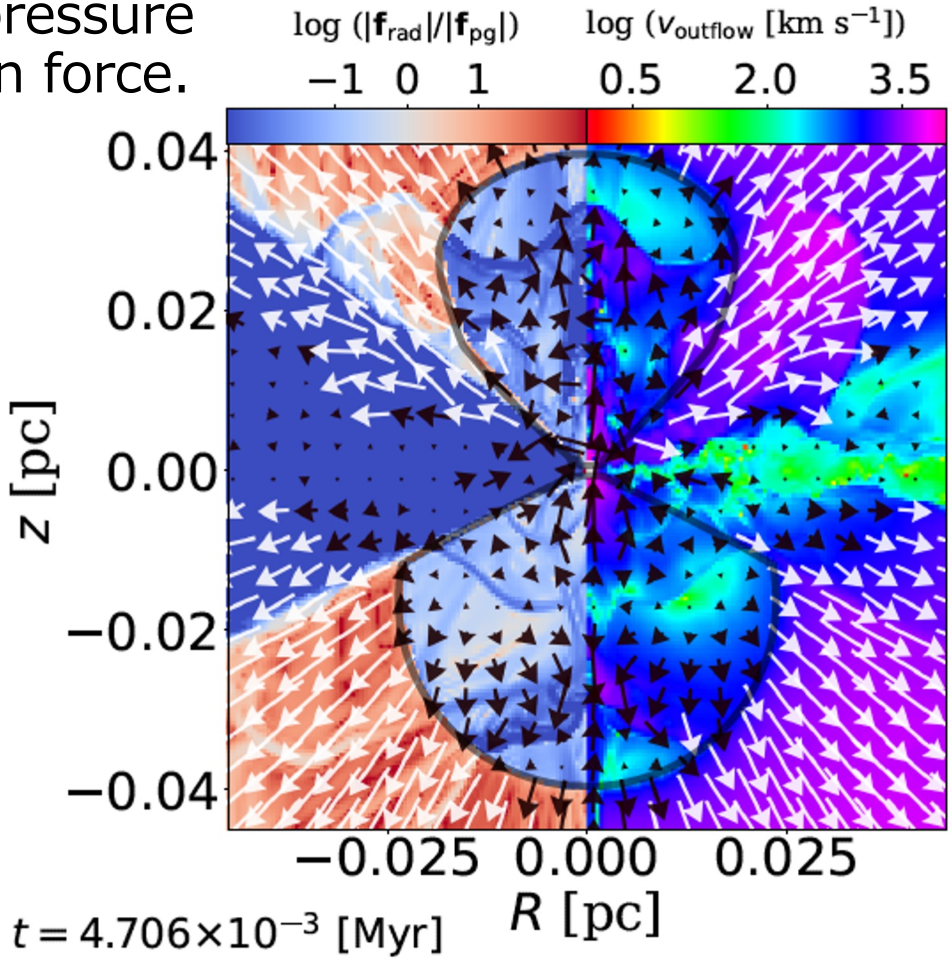
While: gas escapable
Black: gravitationally bound

- Left hand side

Red : Radiation force
Blue : Gas pressure force

- Right hand side

Magnitude of poloidal velocity



Dynamical structure ($\log \gamma_{\rm Edd} = 0$)

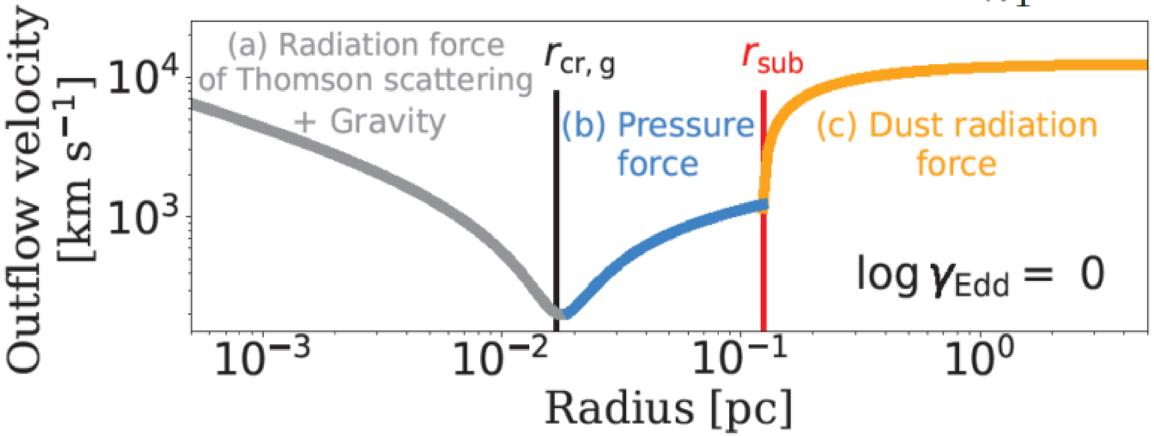
Analytic solution

radiation gravity gas pressure

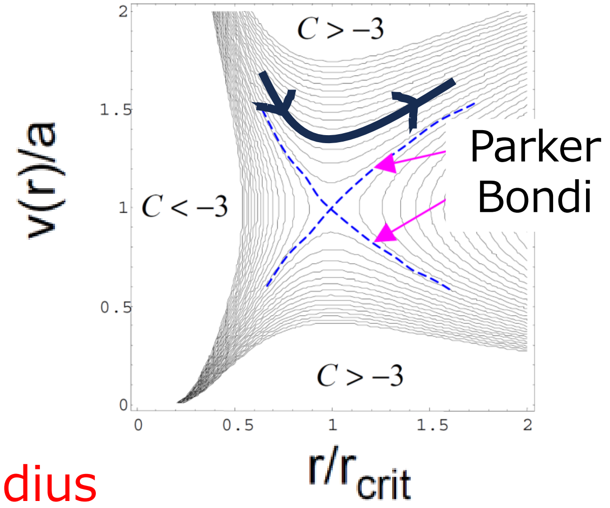
$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\underline{\Gamma_{\rm Edd}}\ \underline{-\ 1})\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1-\left(\frac{r}{r_0}\right)^{-1}\right] + \underline{\frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)}$$

Dust-free gas **Dusty gas**

$$\Gamma_{\rm Edd,g} = \delta_L \gamma_{\rm Edd} \qquad \downarrow \qquad \Gamma_{\rm Edd,d} = \frac{\kappa}{\kappa_{\rm T}}\delta_L \gamma_{\rm Edd}$$



Steady stellar/solar wind



Critical point (dv/dt =0)

$$r_{\rm cr} = (1-\Gamma_{\rm Edd})\,\frac{\gamma}{2}\left(\frac{c}{c_s}\right)^2 r_{\rm g}$$

$$= 0.017\ {\rm pc}\ (1-\Gamma_{{\rm Edd},i})\left(\frac{c/c_s}{200}\right)^2\left(\frac{M_{\rm SMBH}}{10^7 M_\odot}\right)$$

Dust sublimation radius

$$r_{\rm sub} = \sqrt{\frac{\delta_L L_{\rm bol}}{4\pi\sigma_{\rm SB}T_d^4}}$$

$$= 0.176\ {\rm pc}\ \left(\frac{M_{\rm SMBH}}{10^7 M_\odot}\right)^{\frac{1}{2}}\left(\frac{\delta_L}{0.5}\right)^{\frac{1}{2}}\left(\frac{\gamma_{\rm Edd}}{1}\right)^{\frac{1}{2}}\left(\frac{T_{\rm d}}{1500\ {\rm K}}\right)^{-2}$$

Dynamical structure (log $\gamma_{\rm Edd}$ = 0)

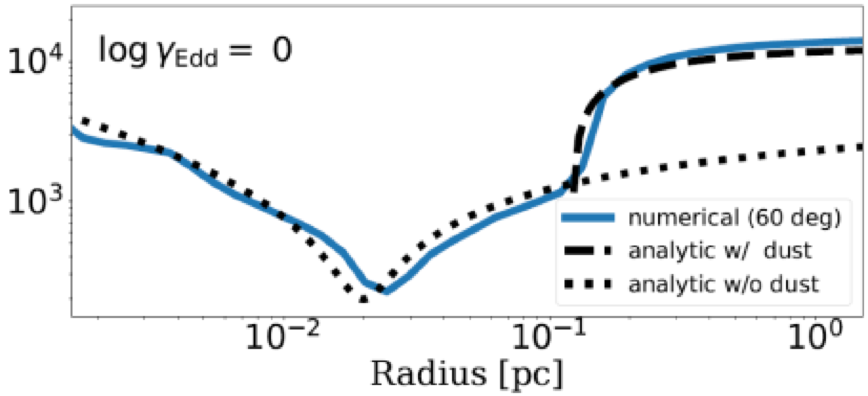
Analytic solution

$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\overset{\text{radiation}}{\underline{\Gamma_{\rm Edd}}} - \overset{\text{gravity}}{\underline{1}})\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right] + \overset{\text{gas pressure}}{\underline{\frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)}}$$

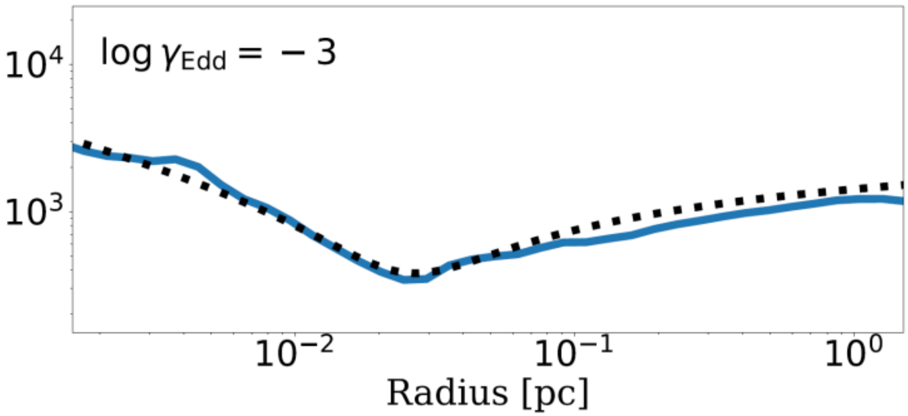
Numerical solutions vs Analytic solutions

Dotted lines : Dust-free gas
Dashed line : Dusty gas

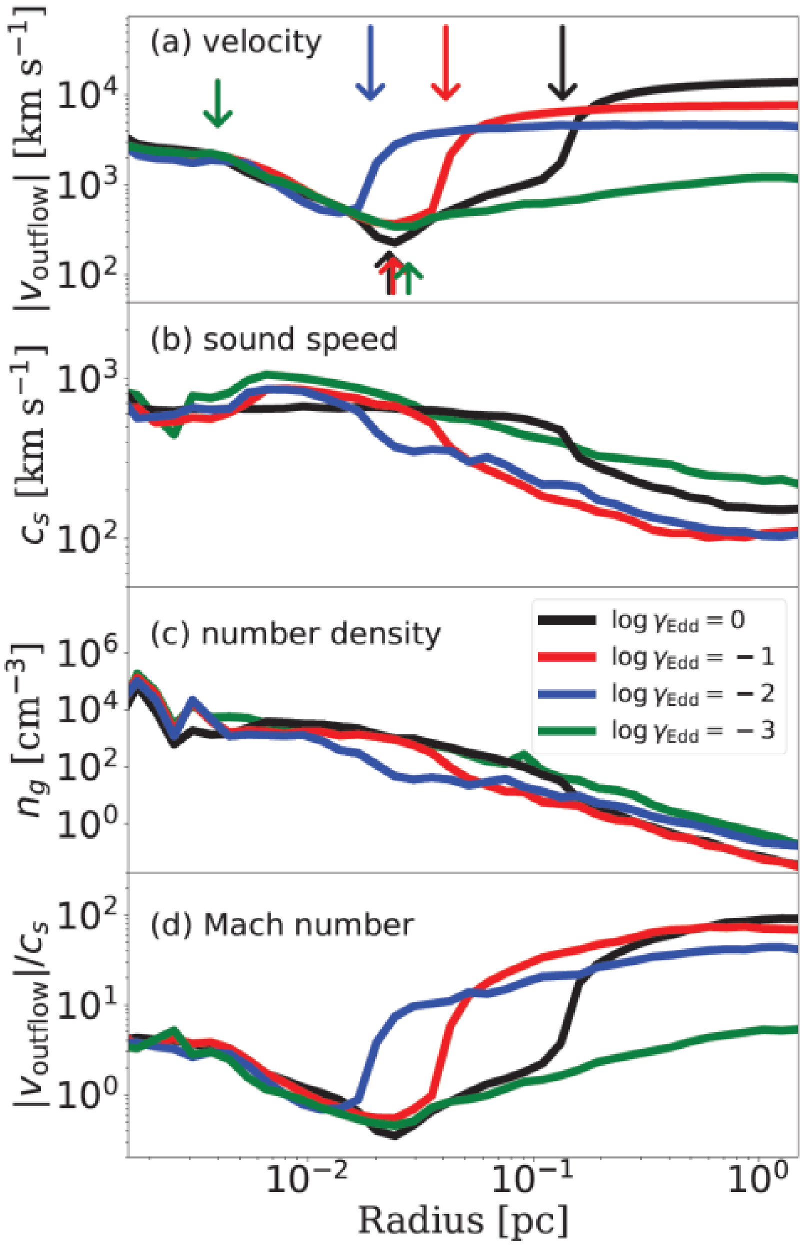
Radiation driven wind



Thermal wind



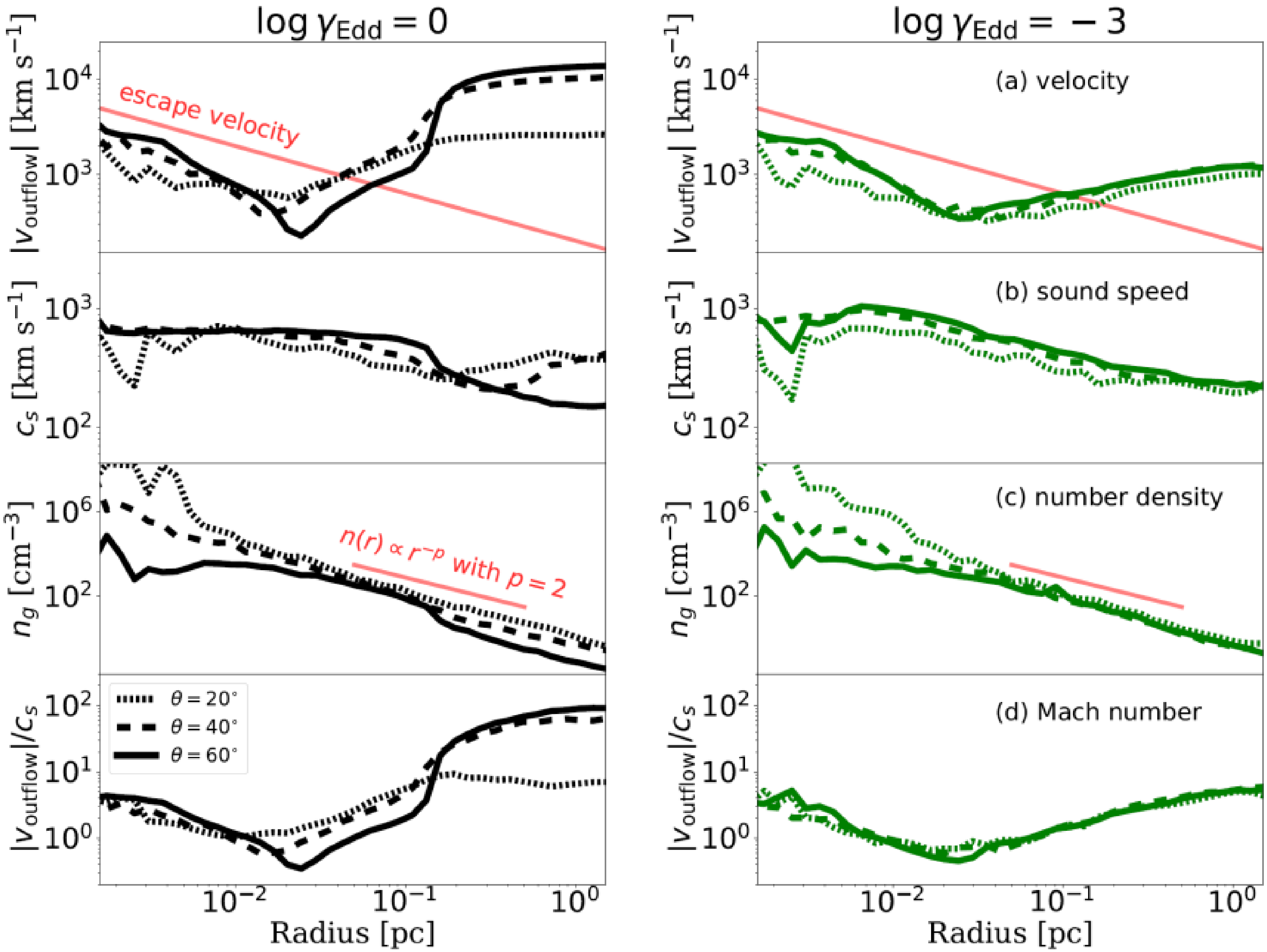
Eddington ratio dependence



Inclination angle dependence

Radiation driven wind

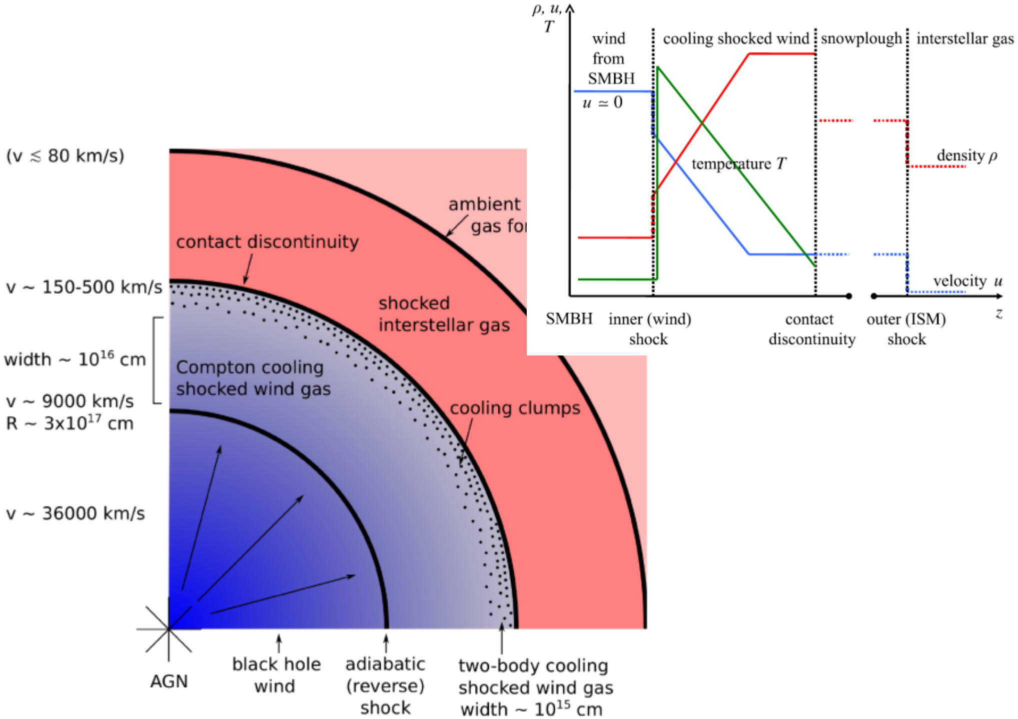
Thermal wind



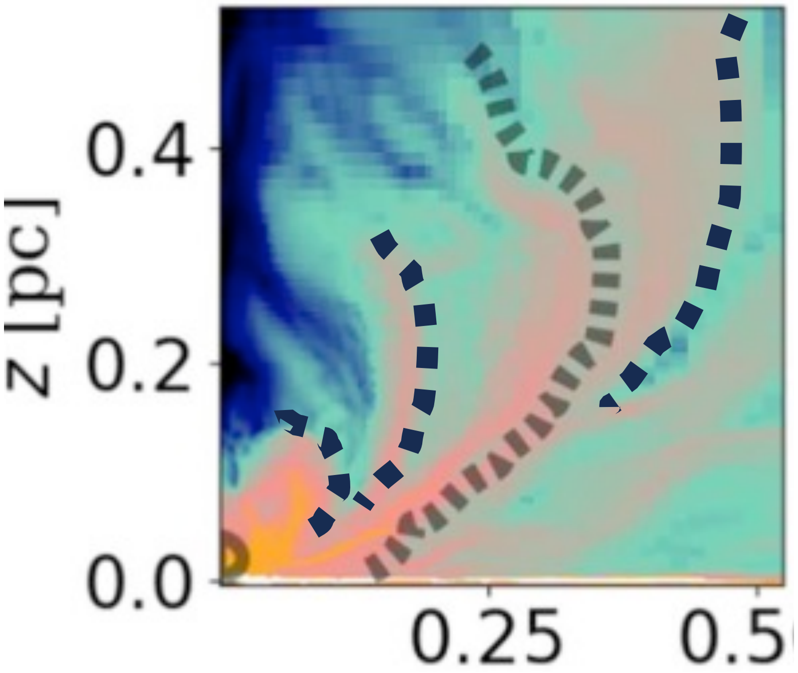
Dynamic structure of ionized dusty outflow

We clarify an analytical model of ionized dusty outflow characterized by repetitive shell formation.

Shock propagation model
King 2014, 2015



Ionized dusty outflow
Kudoh et al. 2023



What is happening around sub-pc (dust sublimation) scale?

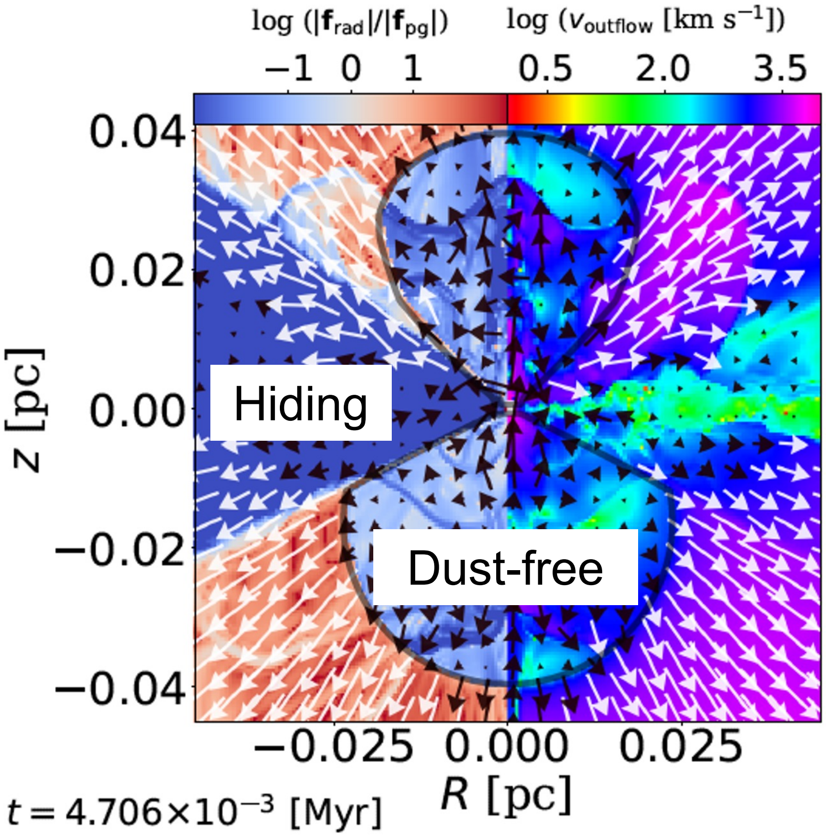
Exceeding escape velocity due to dust radiation force

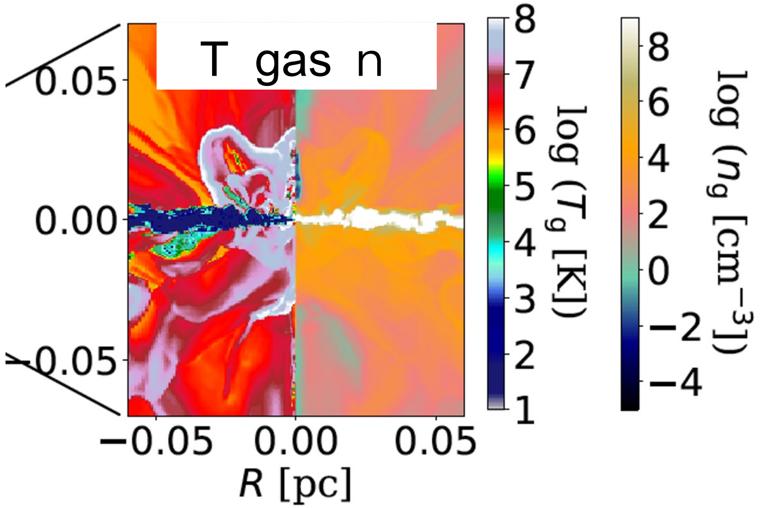
Red : Radiation force

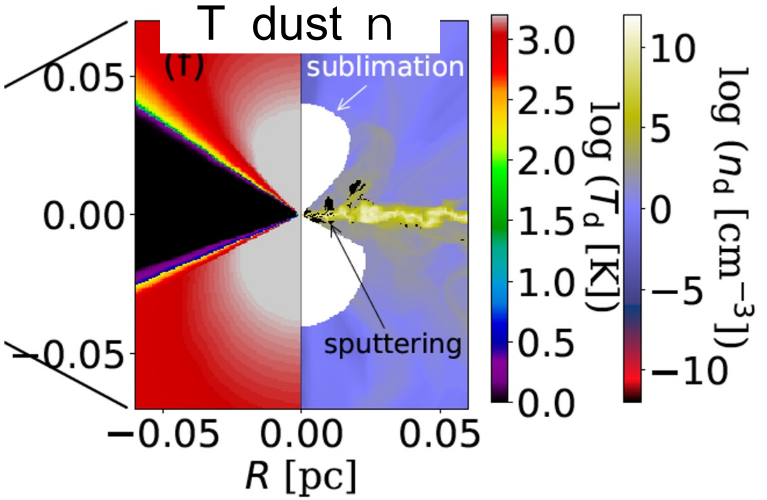
Blue : Gas pressure force

Magnitude of

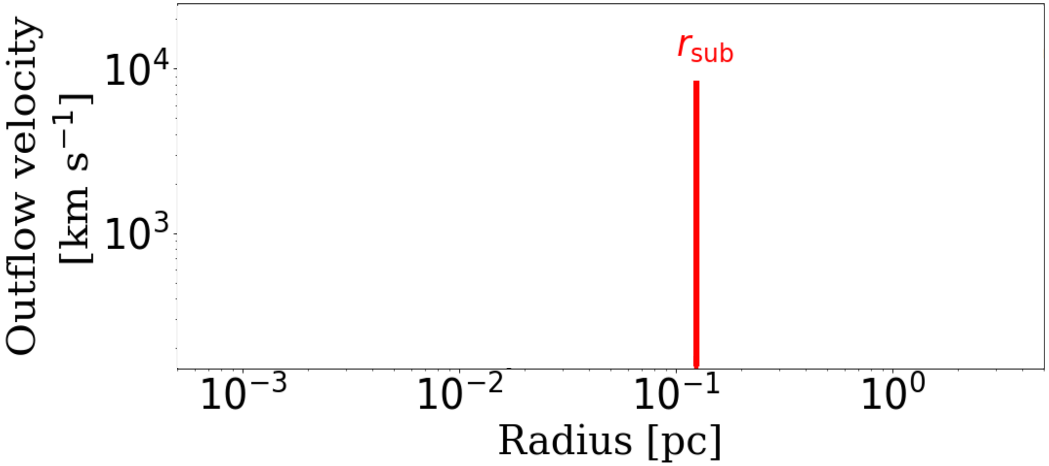
Poloidal velocity







Procedure



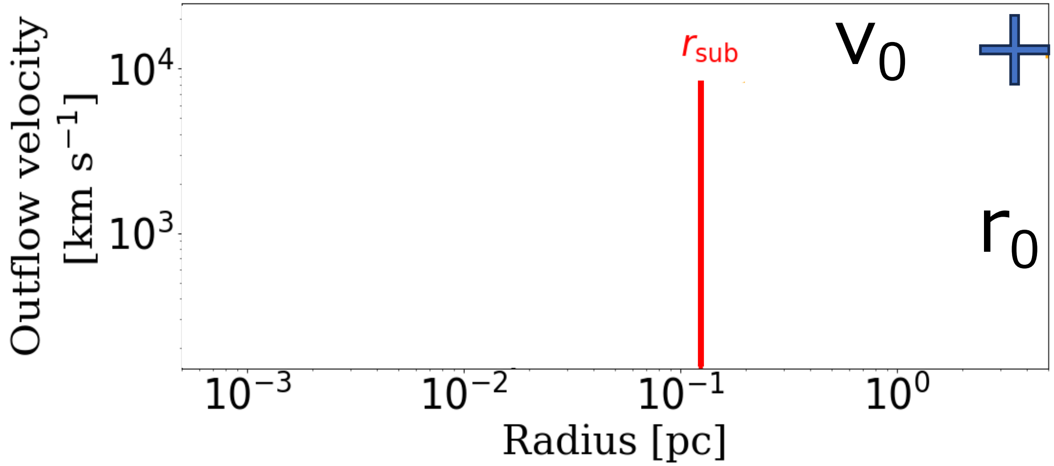
AGNs with known

- $\gamma_{\rm Edd}$: Eddington ratio
- $M_{\rm SMBH}$: BH masses

0. Estimate the dust sublimation radius.

$$r_{\rm sub} = \sqrt{\frac{\delta_L L_{\rm bol}}{4\pi \sigma_{\rm SB} T_d^4}} \sim 0.176\ {\rm pc} \left(\frac{\delta_L \gamma_{\rm Edd}}{0.5}\right)^{1/2} \left(\frac{M_{\rm SMBH}}{10^7 M_\odot}\right)^{1/2} \left(\frac{T_{\rm d}}{1500\ {\rm K}}\right)^{-2}$$

Procedure



AGNs with known

- γ_{Edd}: Eddington ratio
- M_{SMBH}: BH masses

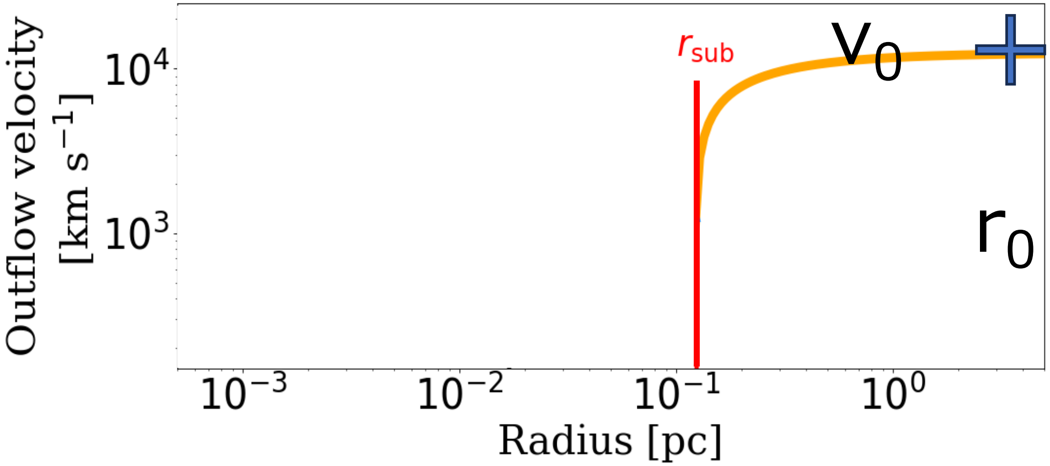
0. Estimate the dust sublimation radius.

1. The observed velocity is considered the terminal velocity, v_0. (Temperature information is also desirable.)

→ Given r_0 and v_0.

$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\Gamma_{\text{Edd}} - 1)\left(\frac{r_{\text{g}}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right] + \frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)$$

Procedure



AGNs with known

- $\gamma_{\rm Edd}$: Eddington ratio
- $M_{\rm SMBH}$: BH masses

0. Estimate the dust sublimation radius.

1. The observed velocity is considered the terminal velocity. (Temperature information is also desirable.)

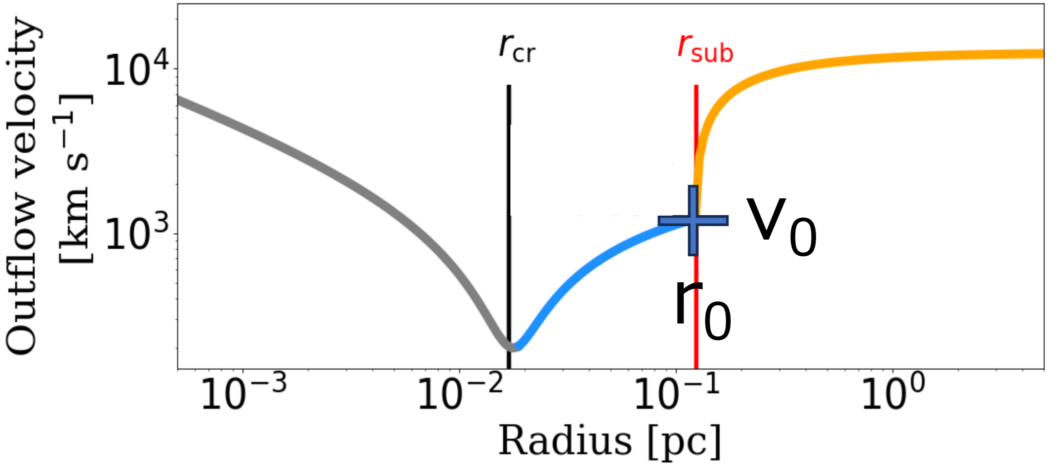
$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\Gamma_{\rm Edd} - 1)\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right] + \frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)$$

2. For r>rsub, apply the Dusty wind solution.

$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + \Gamma_{\rm Edd,d}\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right]$$

$$\Gamma_{\rm Edd,d} = \frac{\kappa}{\kappa_{\rm T}}\delta_L \gamma_{\rm Edd} = \frac{\text{Dust radiation force}}{\text{Gravity force}}$$

Procedure



AGNs with known

- $\gamma_{\rm Edd}$: Eddington ratio
- $M_{\rm SMBH}$: BH masses

0. Estimate the dust sublimation radius.

1. The observed velocity is considered the terminal velocity. (Temperature information is also desirable.)

$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\Gamma_{\rm Edd} - 1)\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right] + \frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)$$

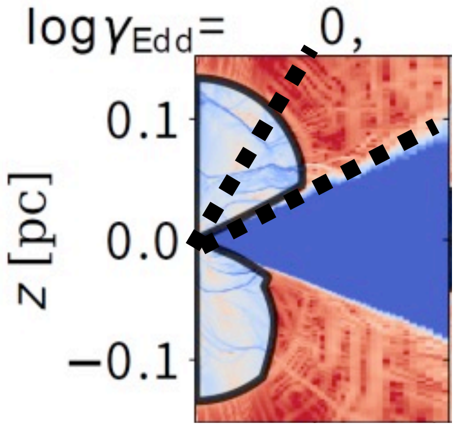
2. For r>rsub, apply the Dusty wind solution.

3. For r<rsub, apply the Stellar wind solution.

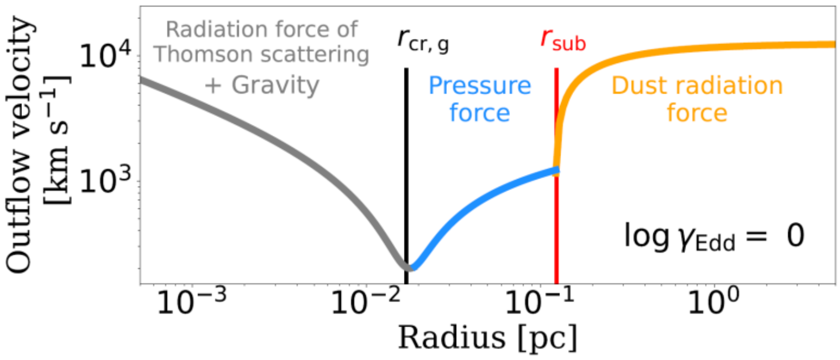
→ Given v_0 and r_0 at the dust sublimation radius

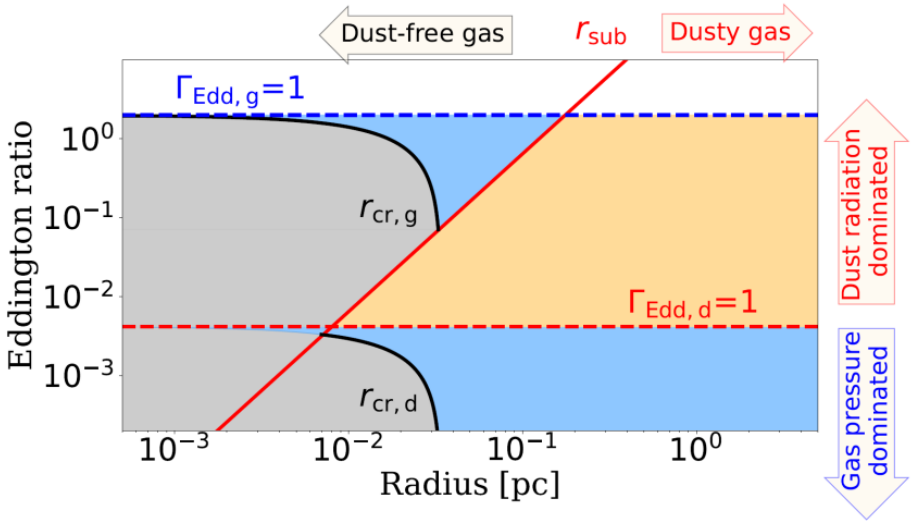
$$\left[\frac{v(r)}{v_0}\right]^2 = 1 + (\Gamma_{\rm Edd,g} - 1)\left(\frac{r_{\rm g}}{r_0}\right)\left(\frac{c}{v_0}\right)^2\left[1 - \left(\frac{r}{r_0}\right)^{-1}\right] + \frac{1}{\gamma}\left(\frac{c_s}{v_0}\right)^2 \ln\left(\frac{r}{r_0}\right)$$

Analytic solution

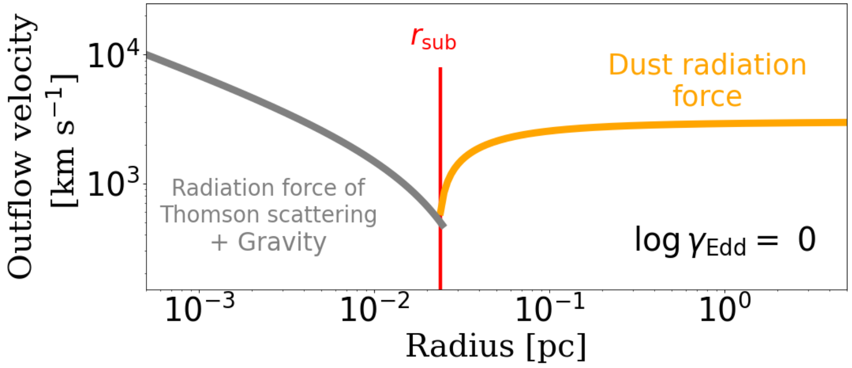


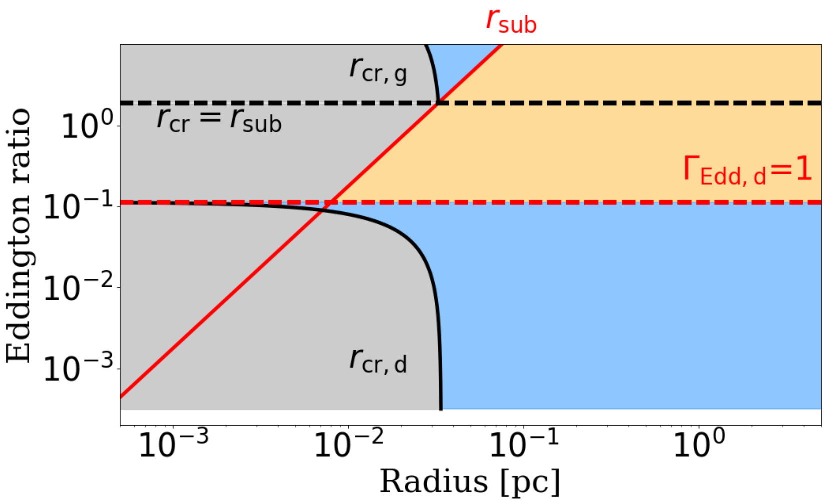
60 degree



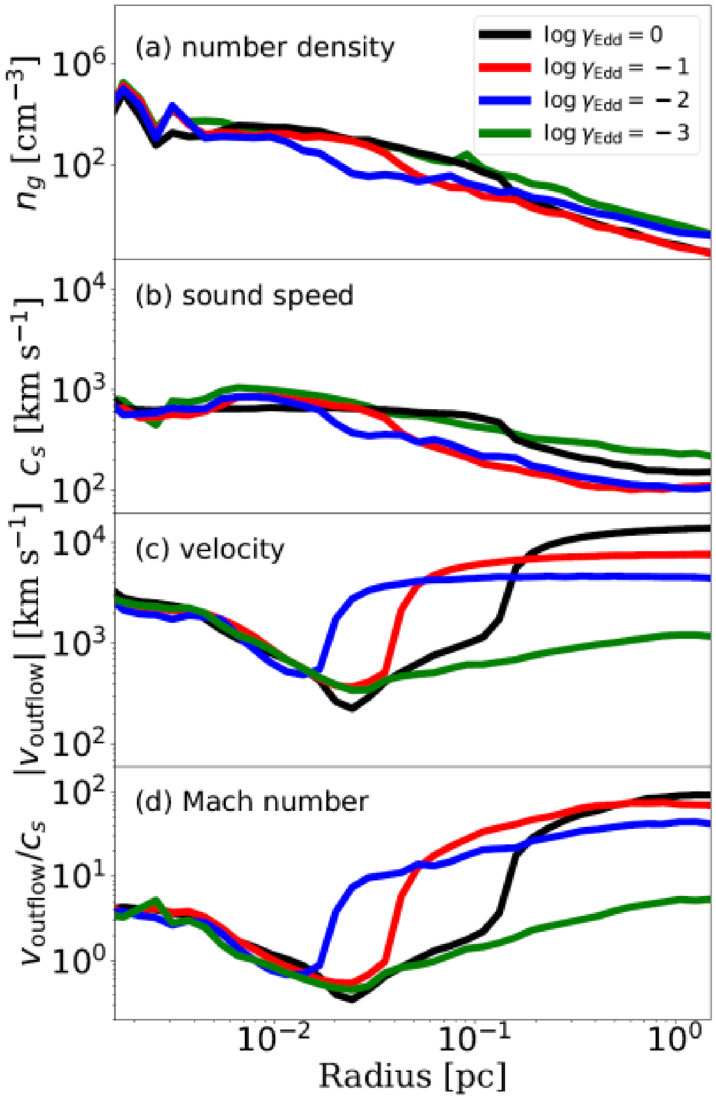


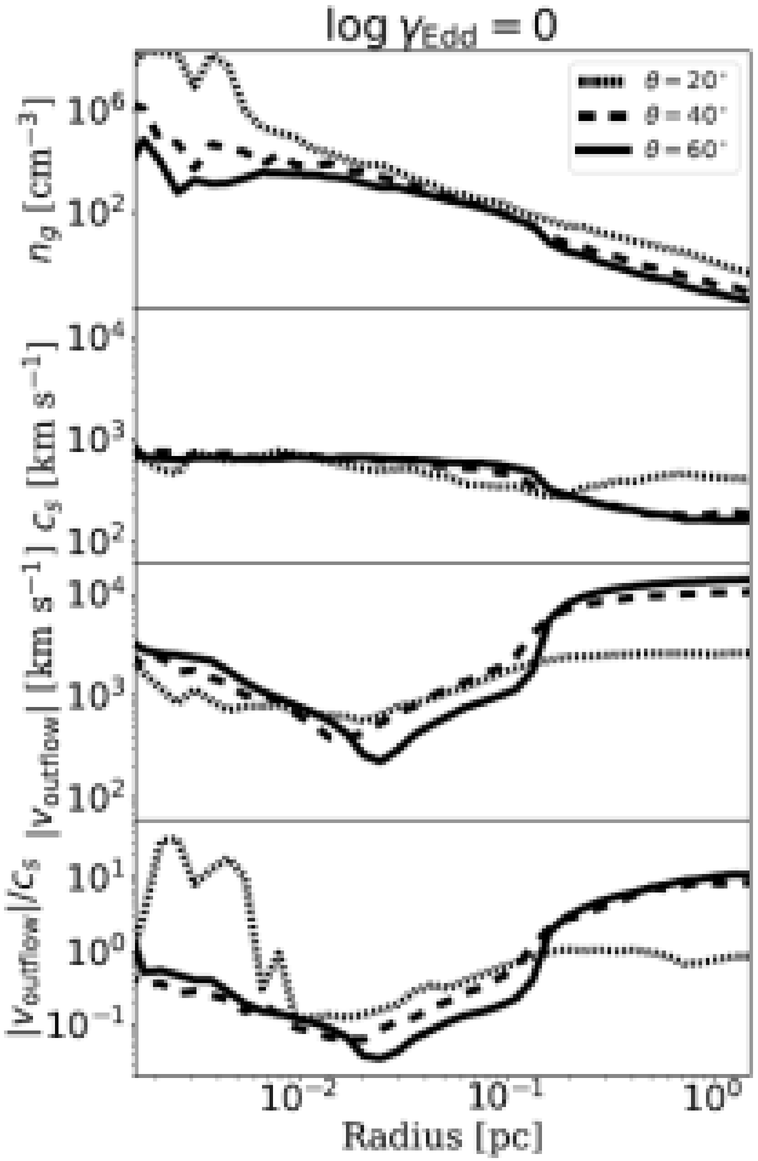
30 degree





Inclination angle

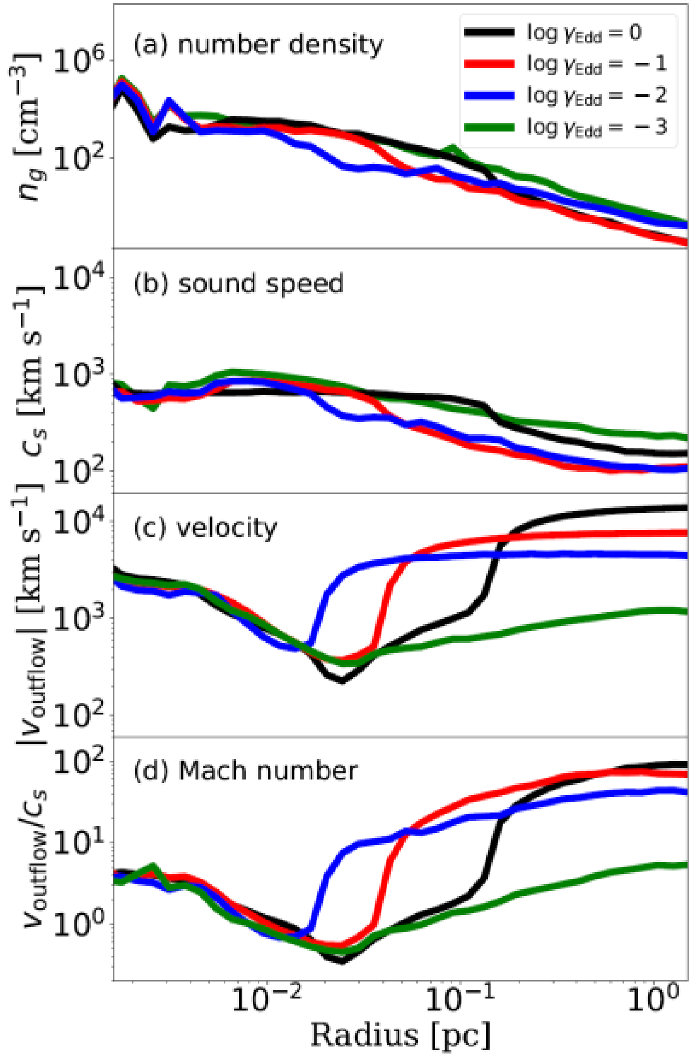


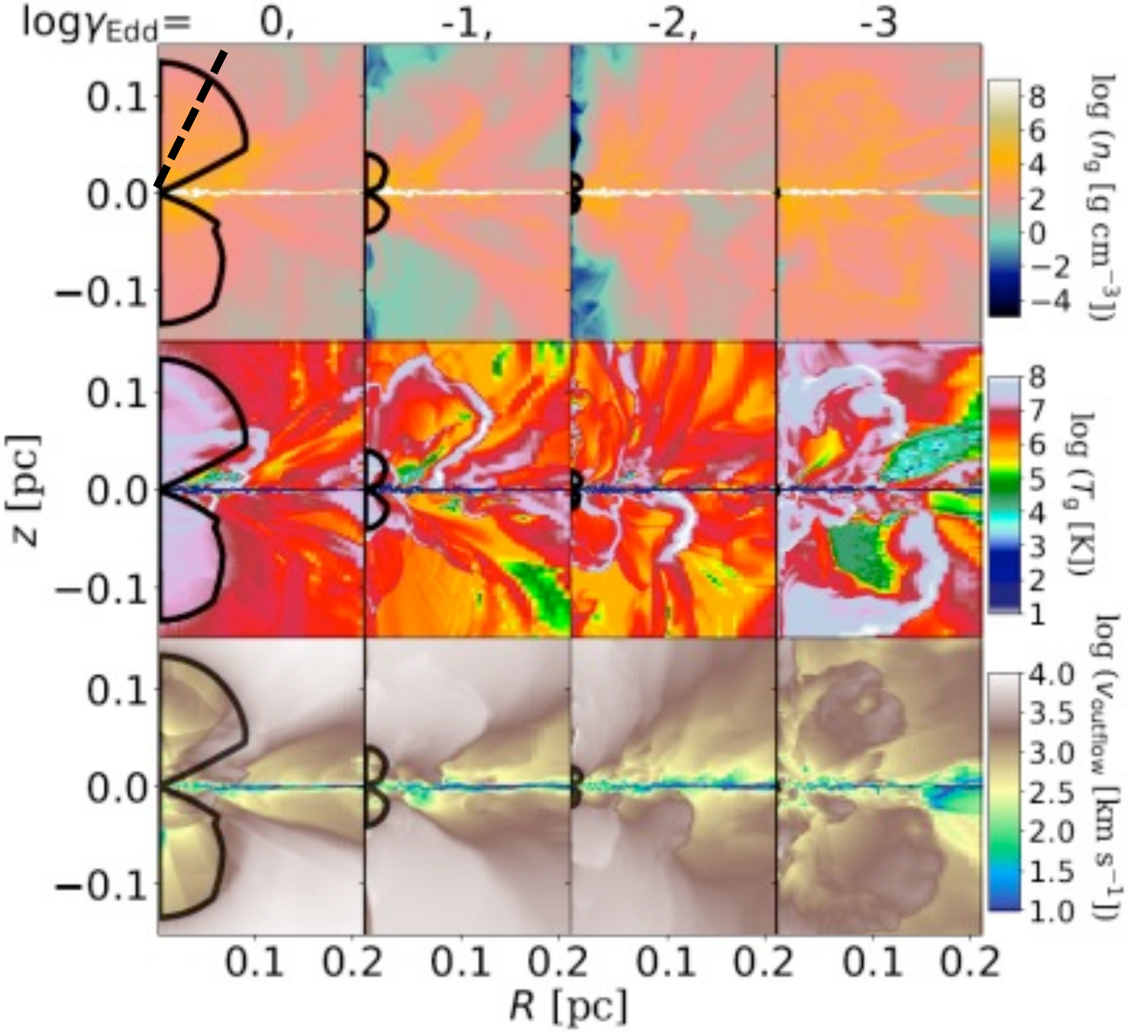


Time averaged outflows are similar

Snapshots in R-z plane

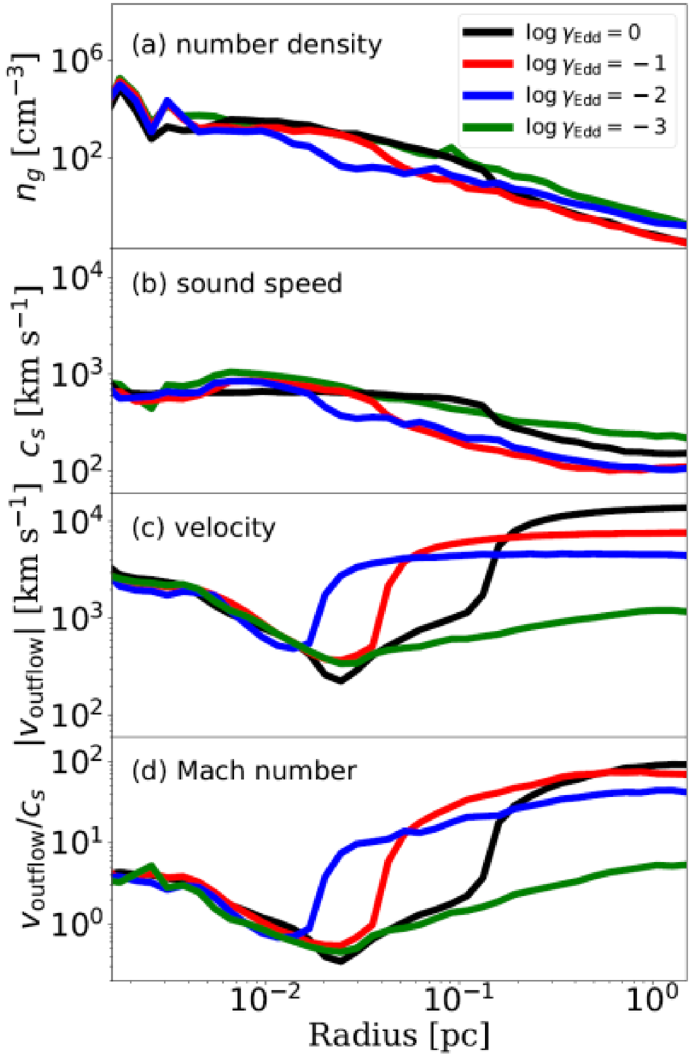
Time-averaged
Radial profile at 60 deg

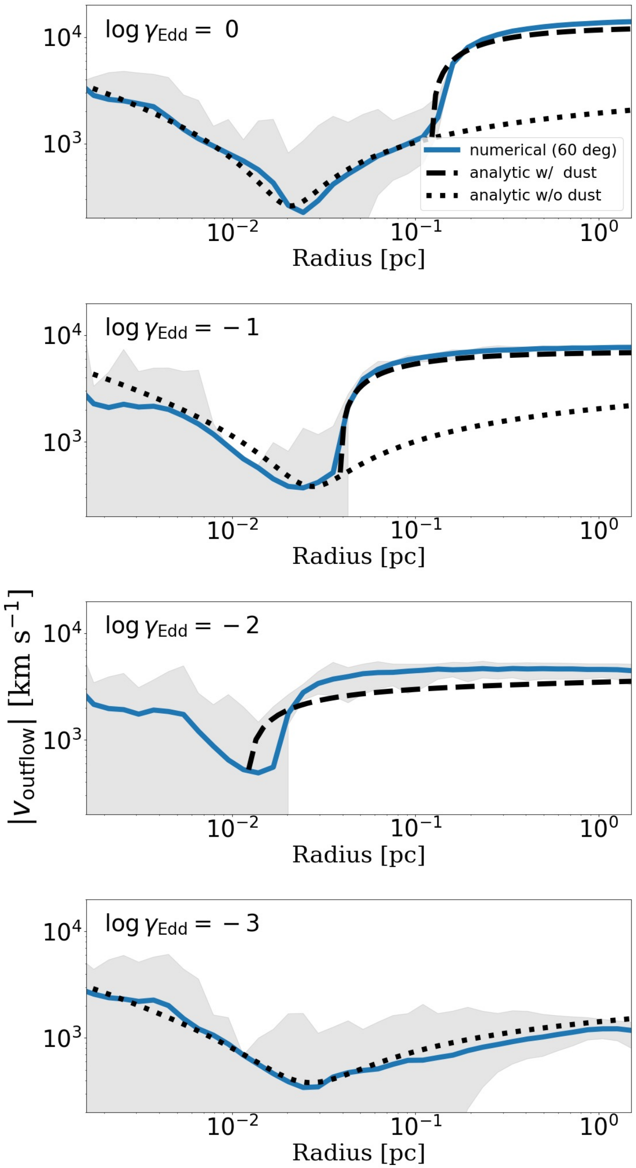




Analytic solution vs Numerical soliution

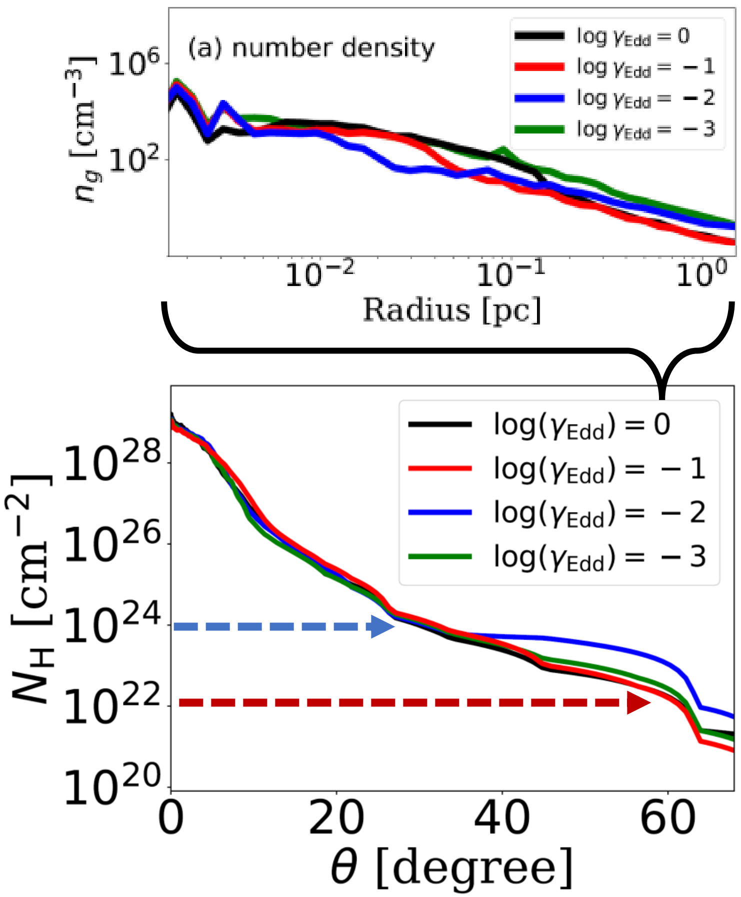
Time-averaged
Radial profile at 60 deg



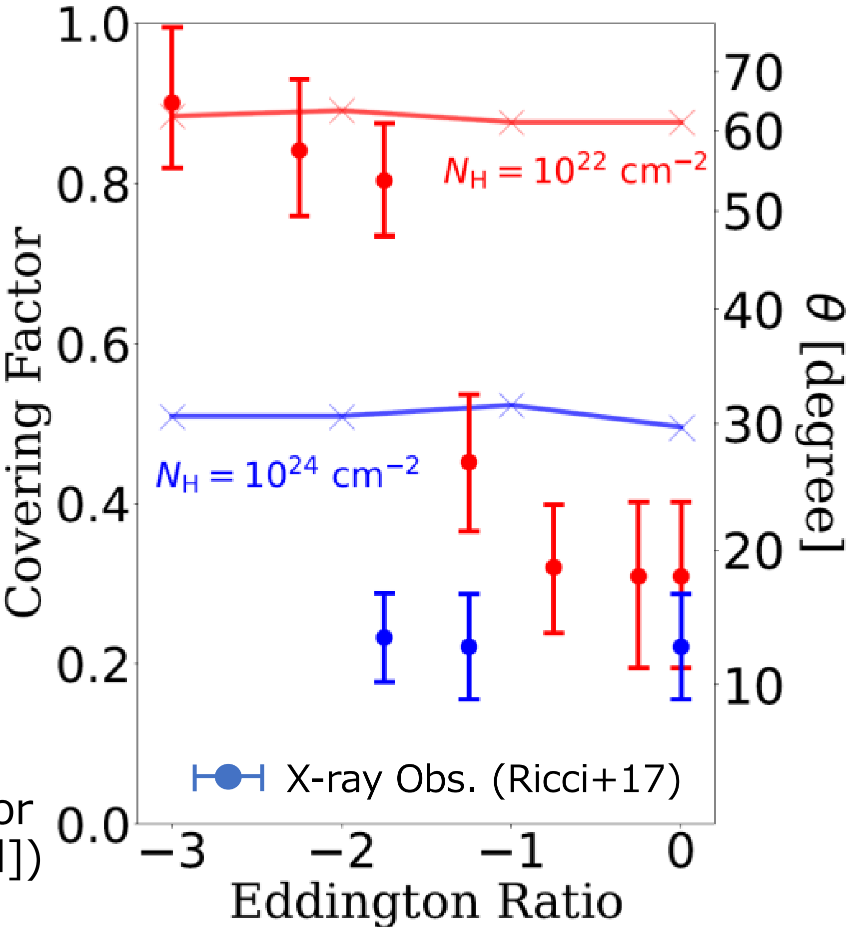


Covering factor
Column density: simulation vs observation

- Column density is determined by the sub-pc scale.
- The same r-profile ↔ θ-profile independent of the Eddington ratio.
- Large covering factor can be explained by our model.

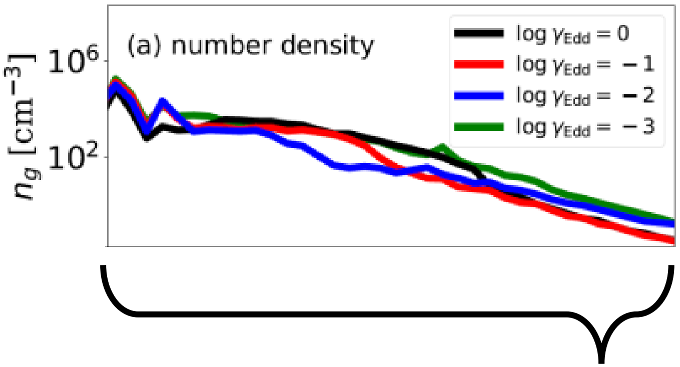


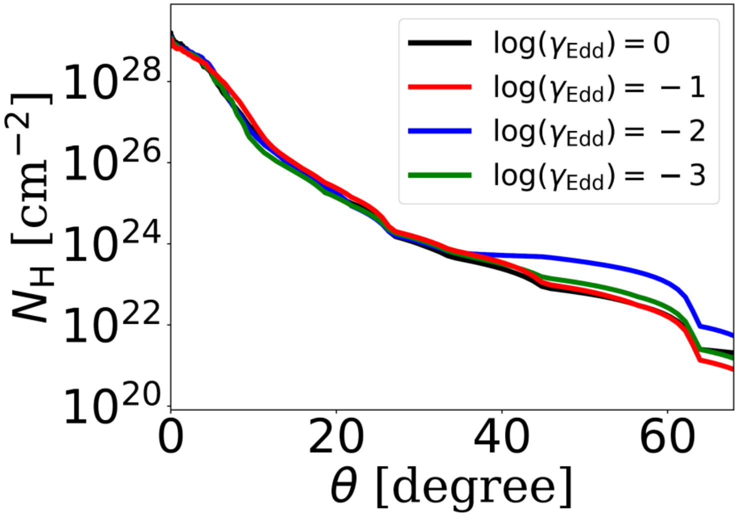
Covering factor $\propto$ sin (θ [rad])



Covering factor
Column density: simulation vs observation

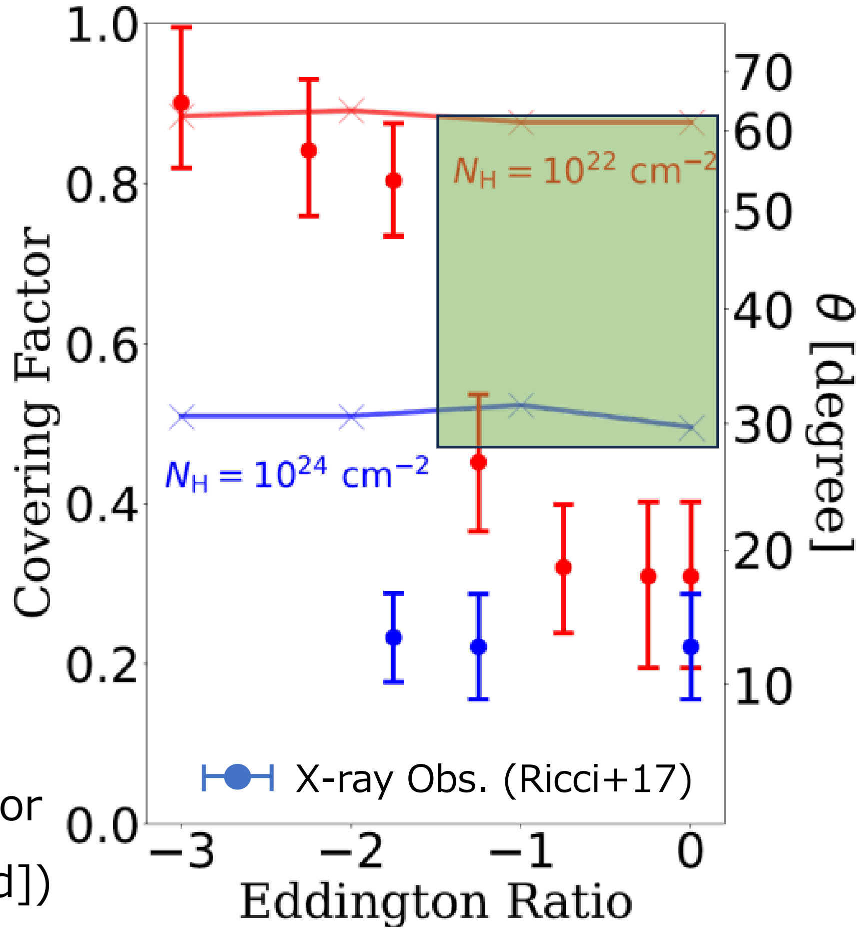
- Why is large Eddington ratio small CF?
  →Outflow from smaller than sub-pc scale.
  Line-driven outflow (e.g. Nomura+20) is would blow out sub-pc-scale gas.



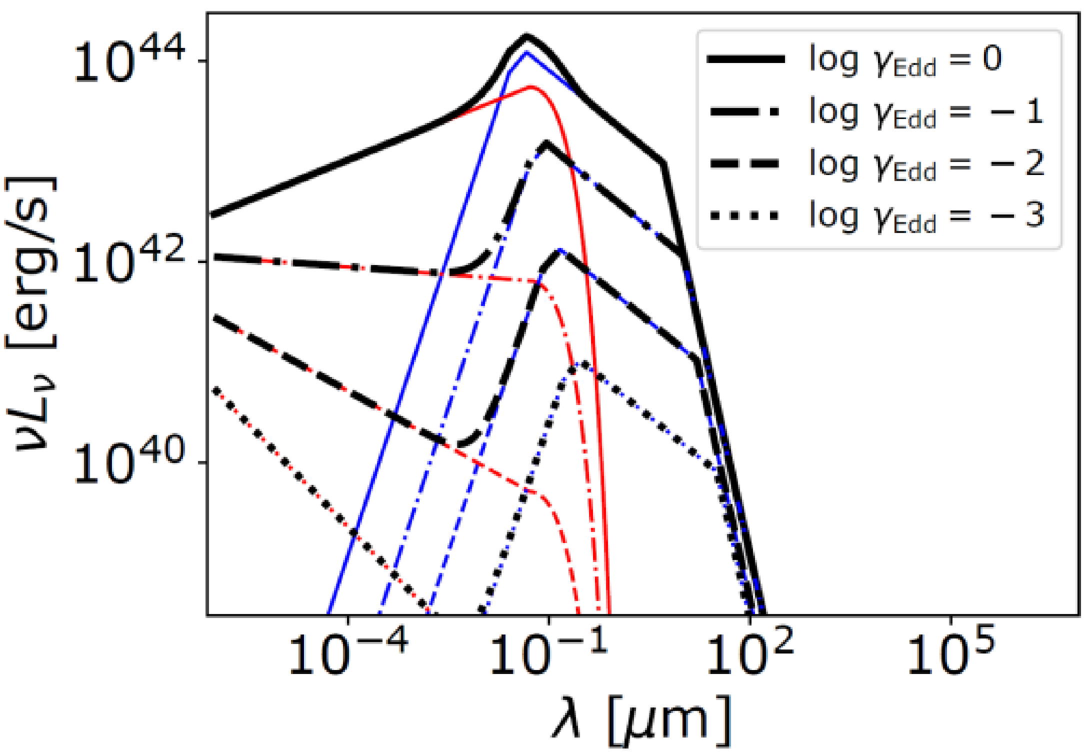


Covering factor

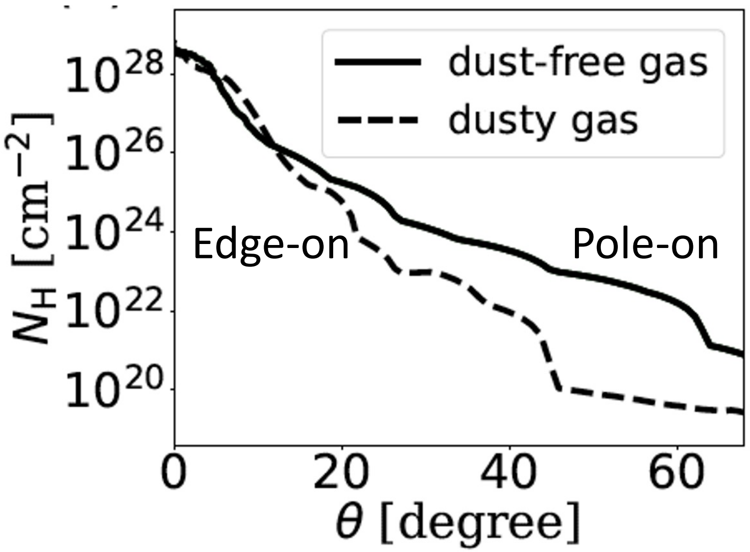
$\propto$ sin (θ [rad])

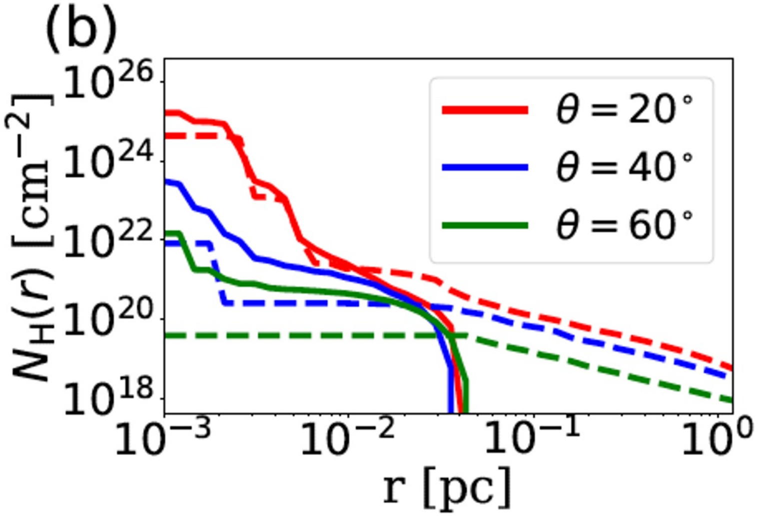


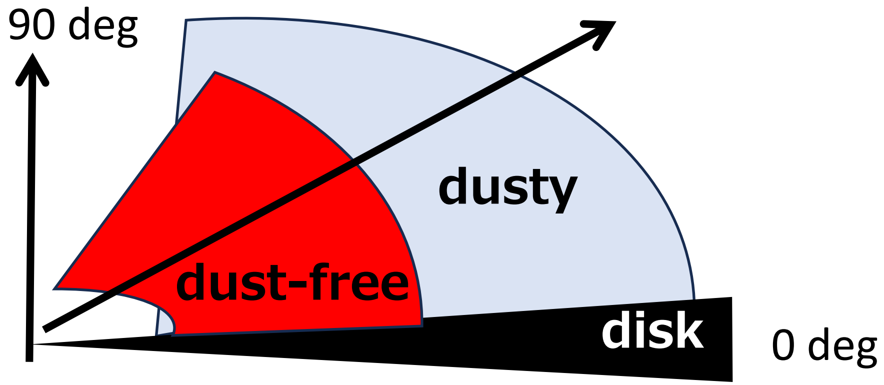
Radiation field



Column density ($L_{bol}/L_{Edd} = 10^{-1}$) for dust-free/dusty gases







- **Column density is determined by dust-free gas** inside the dust sublimation radius.

$$N_H(r) = \int_{2\mathrm{pc}}^{r} n(l)dl$$

X線観測では dust-free gas をみてるだろう
IRでは昇華半径外縁部の dusty outflow

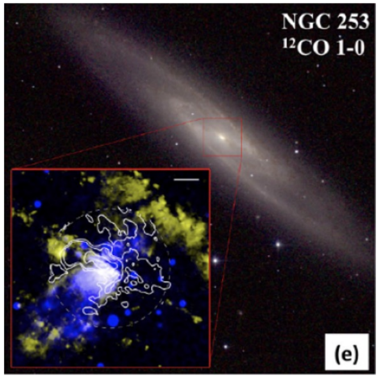
AGN outflows
not pictured in AGN unified model

Sub-mm - IR　　Opt – UV　　X-ray

- ･Atomic/Molecular gas

Molecular outflow (10-100 km/s)

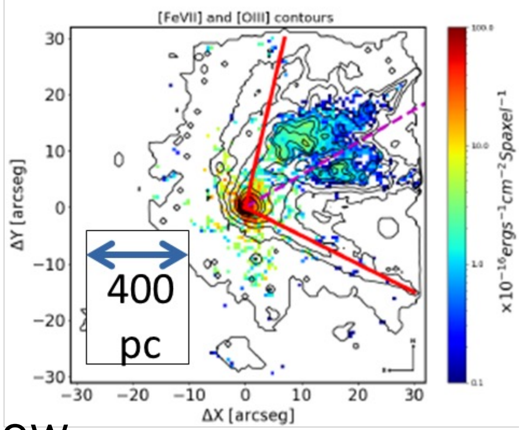
Bolatto+ 2013a, Veilleux+ 2020



- ･Ionized gas

(100-1000 km/s)

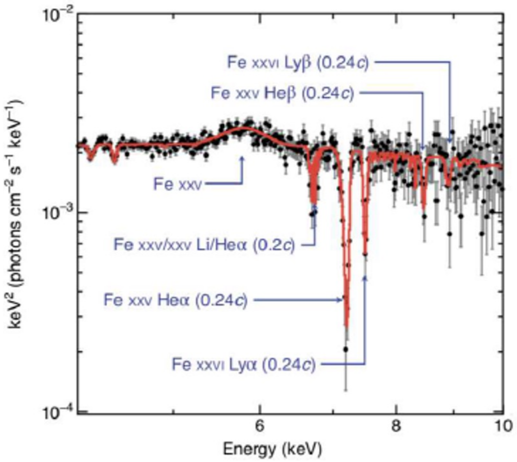
Rodriguez-Ardila+ 2022



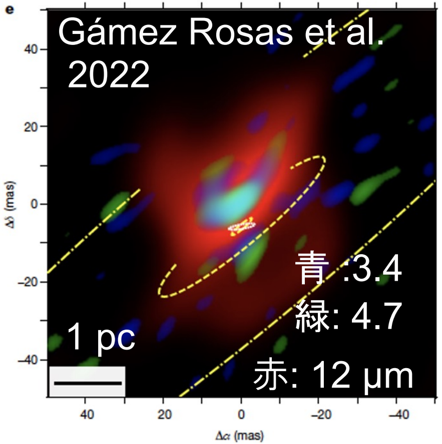
- ･High ionized metal

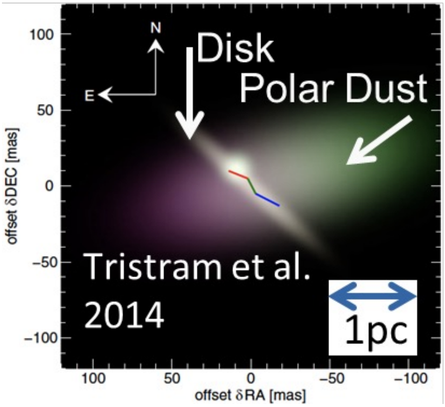
Ultra fast outflow (0.1c)

Laha et al. 2020



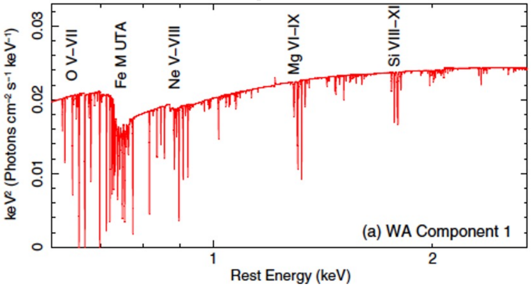
- ・Dusy outflow





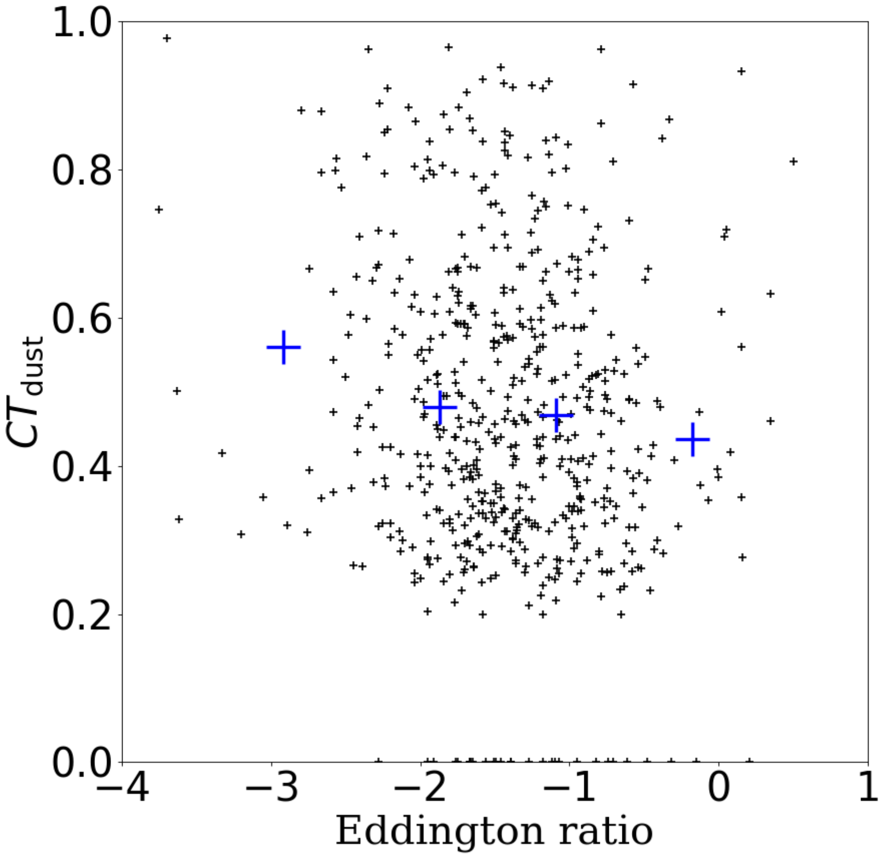
- ・Low ionized metal

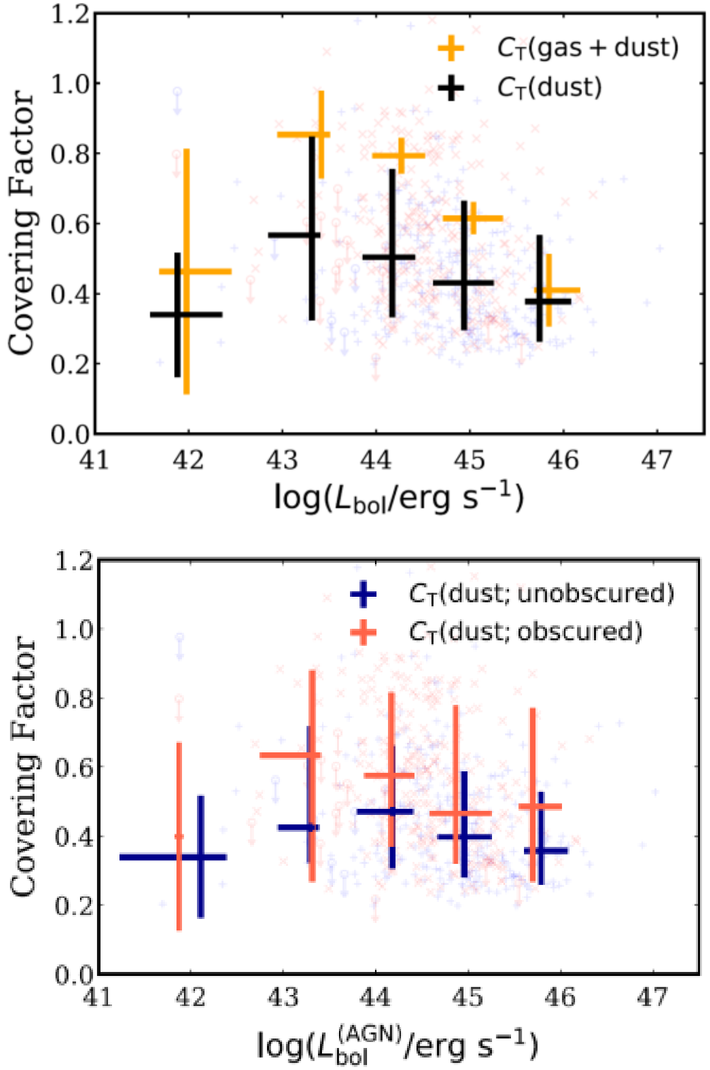
Warm absorber (100-1000 km/s)



CF の Eddington ratio 依存性

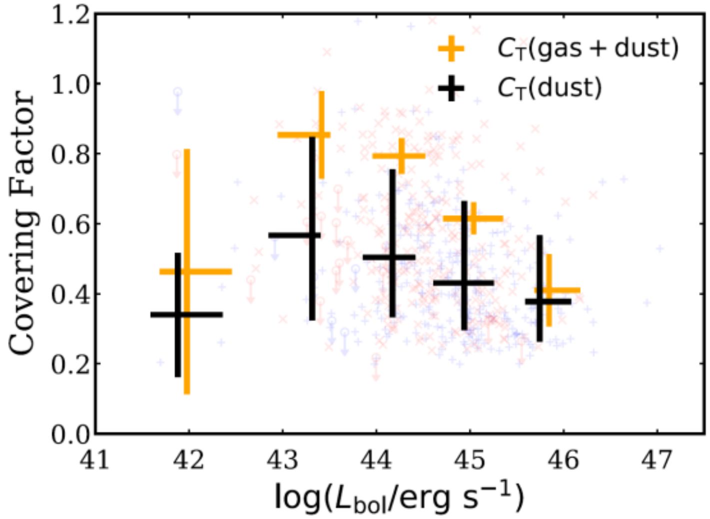
Ichikawa+19 の ダストCF
Koss+22 の Eddington ratio　　を組み合わせてみた　（天体の選択はIchikawa+19）

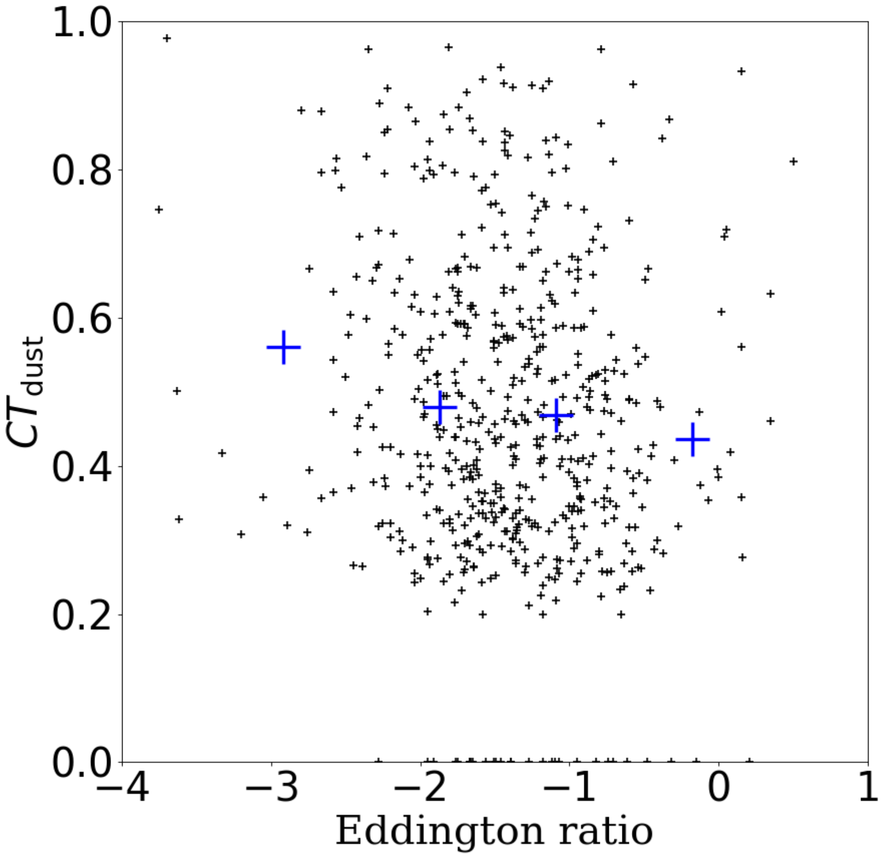


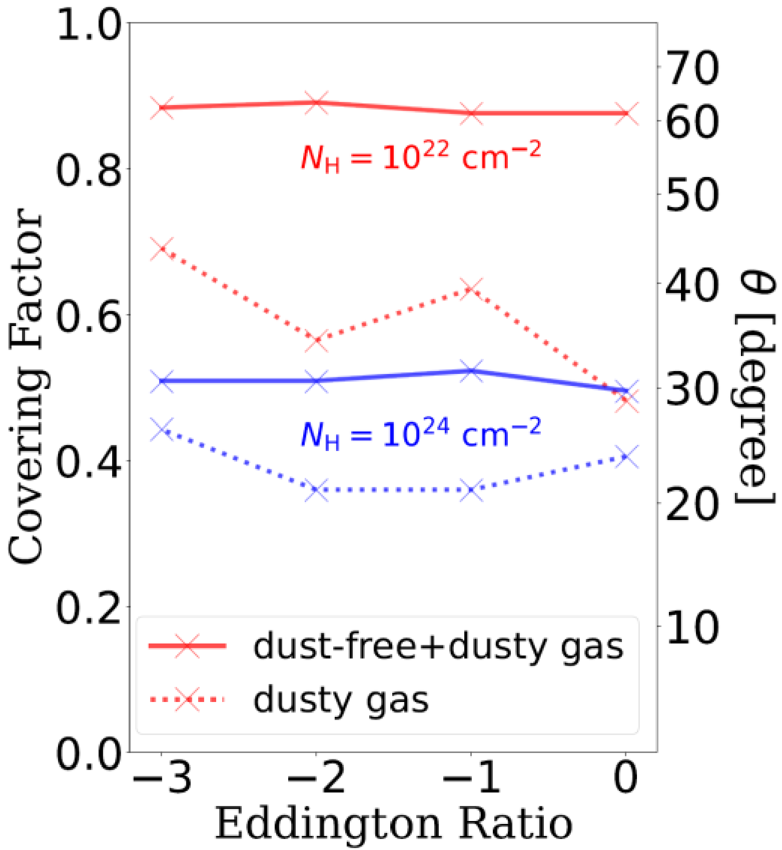


CF の Eddington ratio 依存

Ichikawa+19 の ダストCF
Koss+22 の Eddington ratio を組み合わせて

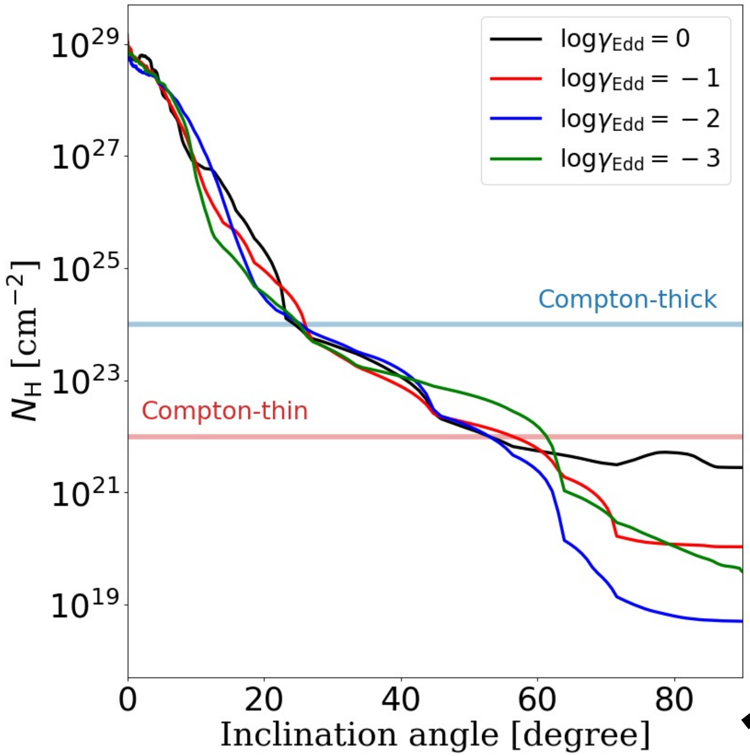




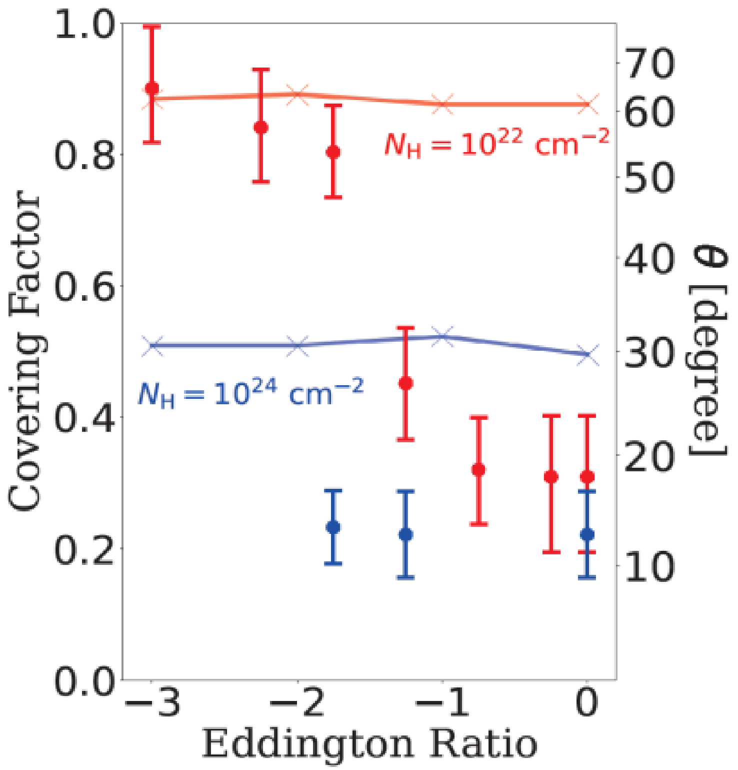


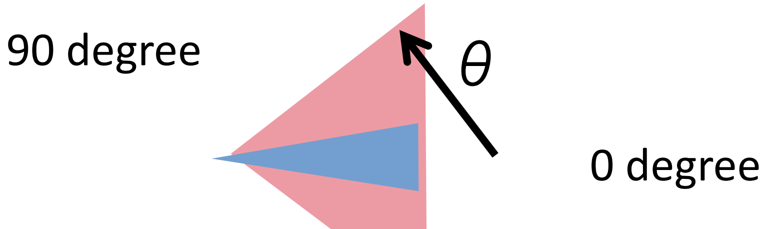
Column density v.s. inclination angle

Column density NH(θ) as a function of angle θ is independent of Eddington ratio.



Convert to
Covering factor
CF = sin θ





Column density v.s. inclination angle

- X-ray observed CF is determined by dust-free gas.
- CF estimated by IR and X-ray would be different.

Decompose into dust-free gas (solid) and dusty gas (dotted)