Transonic solutions of isothermal galactic outflows in gravitational potential of a dark matter halo and a super massive black hole

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We present fundamental properties of transonic galactic outflows in gravitational potential of a dark matter halo and a super-massive black hole assuming isothermal, steady and spherically symmetric state (Igarashi et al. 2014, arXiv:1405.3432). Transonic solutions of galactic outflows are classified according to the perspective of their topological features. We found that there are mainly two types of transonic solutions characterized by different locus of the transonic point; one transonic point is formed at a central region (<0.01kpc), and another is at a very distant region (>100kpc). Because these two transonic solutions have substantially different mass fluxes and starting points, these solutions may have different influences on the evolution of galaxies and the release of metals into intergalactic space.

We have applied our model to the Sombrero galaxy and obtained a new type of the galactic outflow: a slowly accelerated transonic outflow through the transonic point at very distant region (126kpc). In this galaxy, previous works reported that although the trace of the galactic outflow is observed by X-ray, the gas density distribution is consistent with the hydrostatic state. We have clarified that the slowly accelerating outflow has a gas density profile quite similar to that of the hydrostatic solution in the widely spread subsonic region. Thus, it is difficult to distinguish the wide subsonic region from hydrostatic state. Such galactic outflows in quiescent galaxies with inactive star formation are different from the conventional supersonic outflows observed in star-forming galaxies.

Subject :	:	oral
Topics	:	Astrophysics

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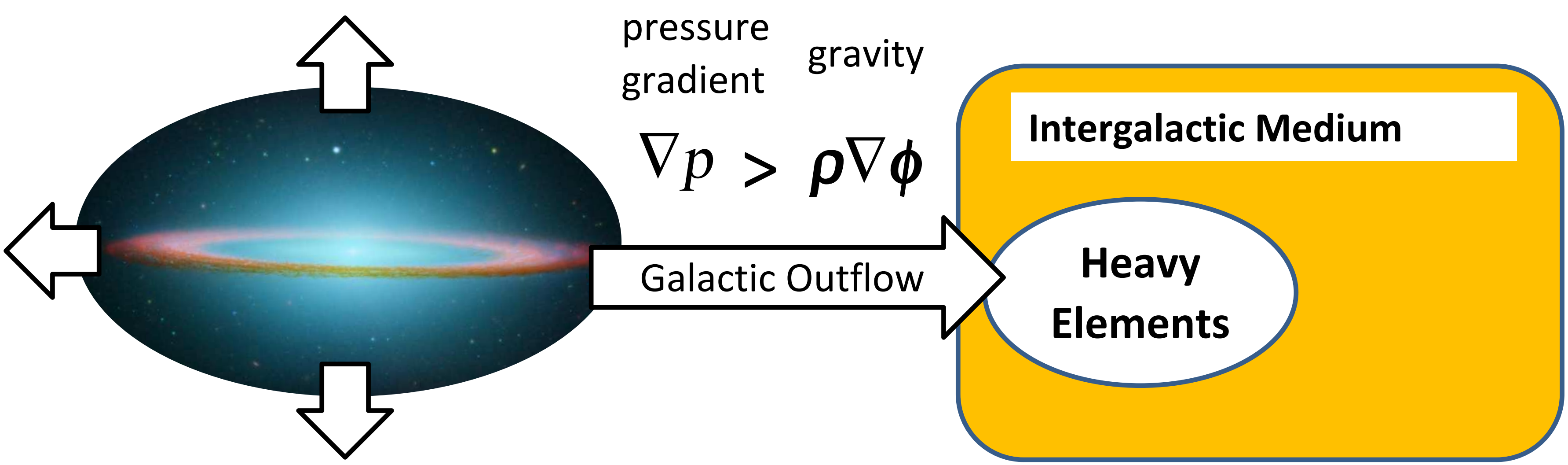
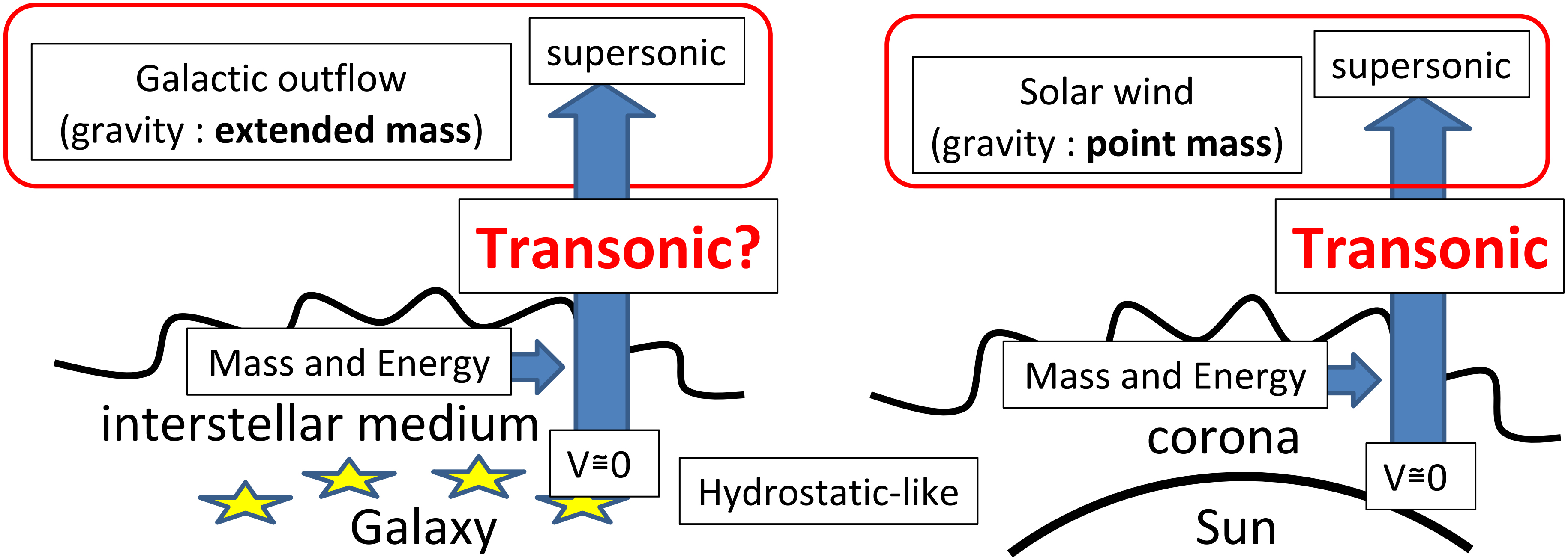
Galactic Outflows

- consist of interstellar medium (hot gas) from galaxies.
- are ubiquitous at high-redshift galaxies (Weiner et al. 2009).
- influence to evolution of galaxies.
- carry heavy elements to intergalactic space.

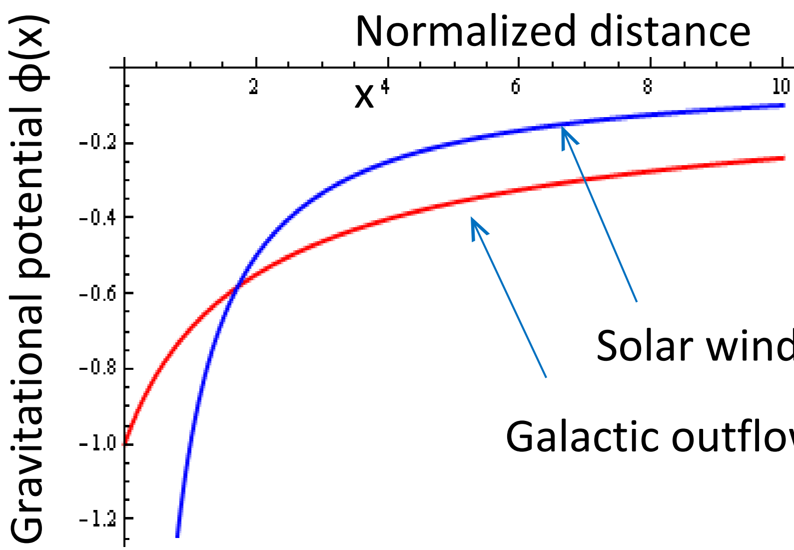


Galactic outflows strongly depend on the mass distribution.

Picture of Our Model



thermal equilibrium with hot interstellar medium at virial temperature



Source of gravity

Solar wind : sun

Galactic outflow : cold dark matter halo

Mass distribution plays an essential role to form transonic solution.

Transonic Outflow with Point Mass

(Parker 1958)

- isothermal, steady and spherically symmetric model

Mass conservation $4\pi \rho v r^2 = const.$

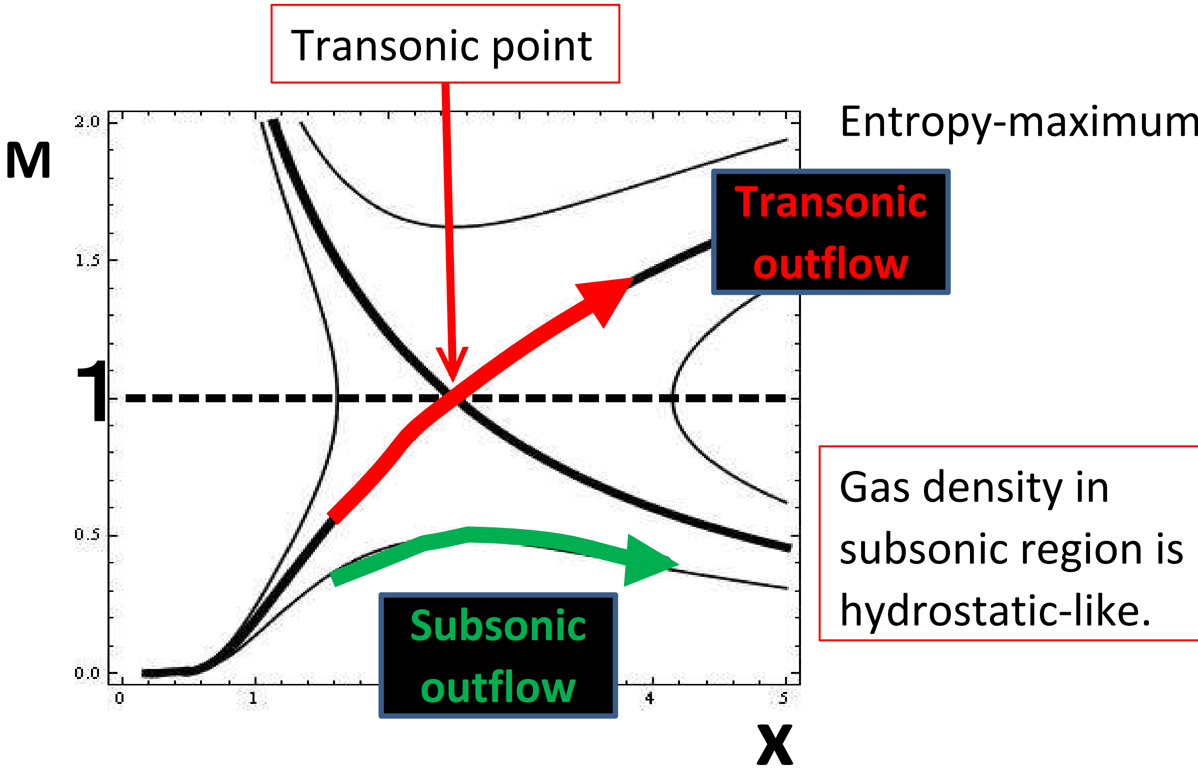
Momentum conservation $v\frac{dv}{dr} = -\frac{c_s^2}{\rho}\frac{d\rho}{dr} - \frac{d\Phi(r)}{dr}$

V : velocity
Cs : sound speed
ρ : density
ϕ : potential

$$\frac{dM^2}{dx} = \frac{\frac{4}{x} - \frac{2}{c_s^2}\frac{d\Phi}{dx}}{1 - \frac{1}{M^2}}$$

$$\Phi(x) \propto -\frac{1}{x}$$

X : normalized distance
M : Mach number



Gas density in subsonic region is hydrostatic-like.

Transonic Outflow with Dark Matter Halo

(Tsuchiya et al. 2013)

Basic equations

$$4\pi \rho v r^2 = const.$$

$$v\frac{dv}{dr} = -\frac{c_s^2}{\rho}\frac{d\rho}{dr} - \frac{d\Phi(r)}{dr}$$

Dark matter halo mass distribution

$$\rho_{DMH} = \frac{\rho_d r_d^3}{r(r+r_d)^2}$$

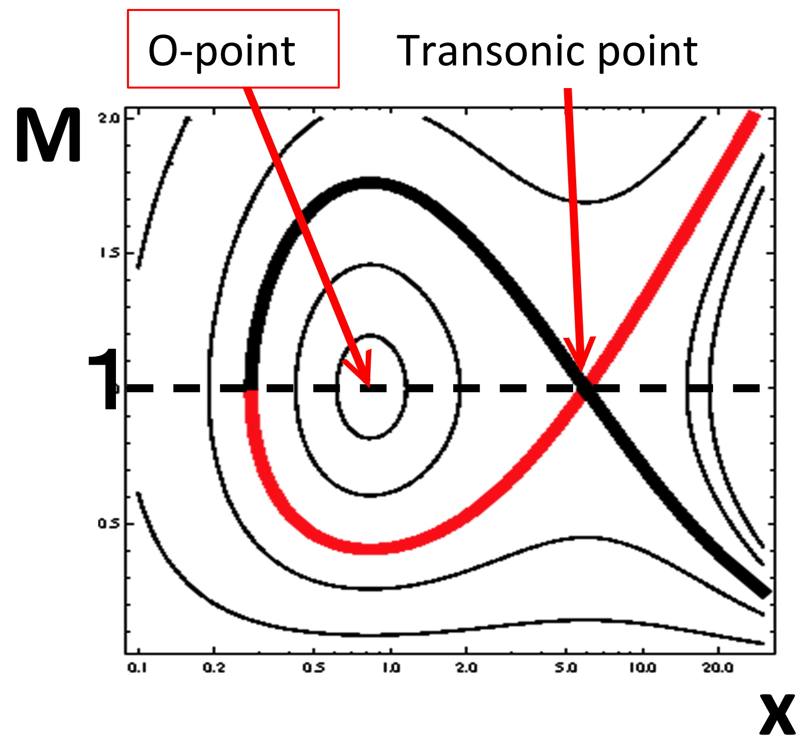
predicted by cosmological N-body simulations (NFW model [Navarro et al. 1997])

$$\frac{dM^2}{dx} = \frac{\frac{4}{x} - \frac{2}{c_s^2}\frac{d\Phi}{dx}}{1 - \frac{1}{M^2}}$$

$$\Phi(x) \propto -\frac{\log(x+1)}{x}$$

X : normalized distance

M : Mach number



Transonic Outflow with Dark Matter Halo and Super-Massive Black Hole (Igarashi et al. 2014)

Basic equations

$$4\pi \rho \, v r^2 = const.$$

$$v\frac{dv}{dr} = -\frac{c_s^2}{\rho}\frac{d\rho}{dr} - \frac{d\Phi(r)}{dr}$$

Dark matter halo mass distribution

$$\rho_{DMH} = \frac{\rho_d r_d^3}{r(r+r_d)^2}$$

Super-massive black hole mass

$$+ \; M_{BH}$$

$$\frac{dM^2}{dx} = \frac{\frac{4}{x} - \frac{2}{c_s^2}\frac{d\Phi}{dx}}{1 - \frac{1}{M^2}}$$

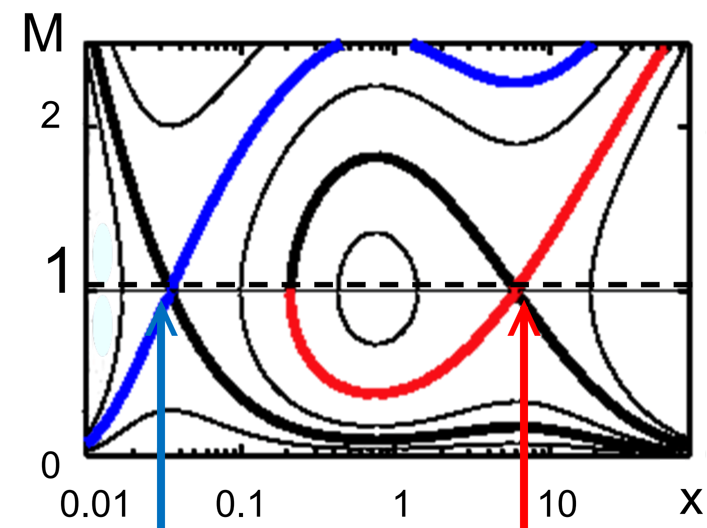
Dark Matter Halo

Super-Massive Black Hole

$$\frac{1}{2c_s^2}\Phi(x) = -K_{DMH}\frac{\log(x+1)}{x} - K_{BH}\frac{1}{x}$$

$$K_{DMH} = \frac{2\pi G \rho_d r_d^2}{c_s^2} \approx \frac{DMH \; gravitational \; energy}{thermal \; enrgy}$$

$$K_{BH} = \frac{GM_{BH}}{2r_d c_s^2} \approx \frac{SMBH \; gravitational \; energy}{thermal \; energy}$$

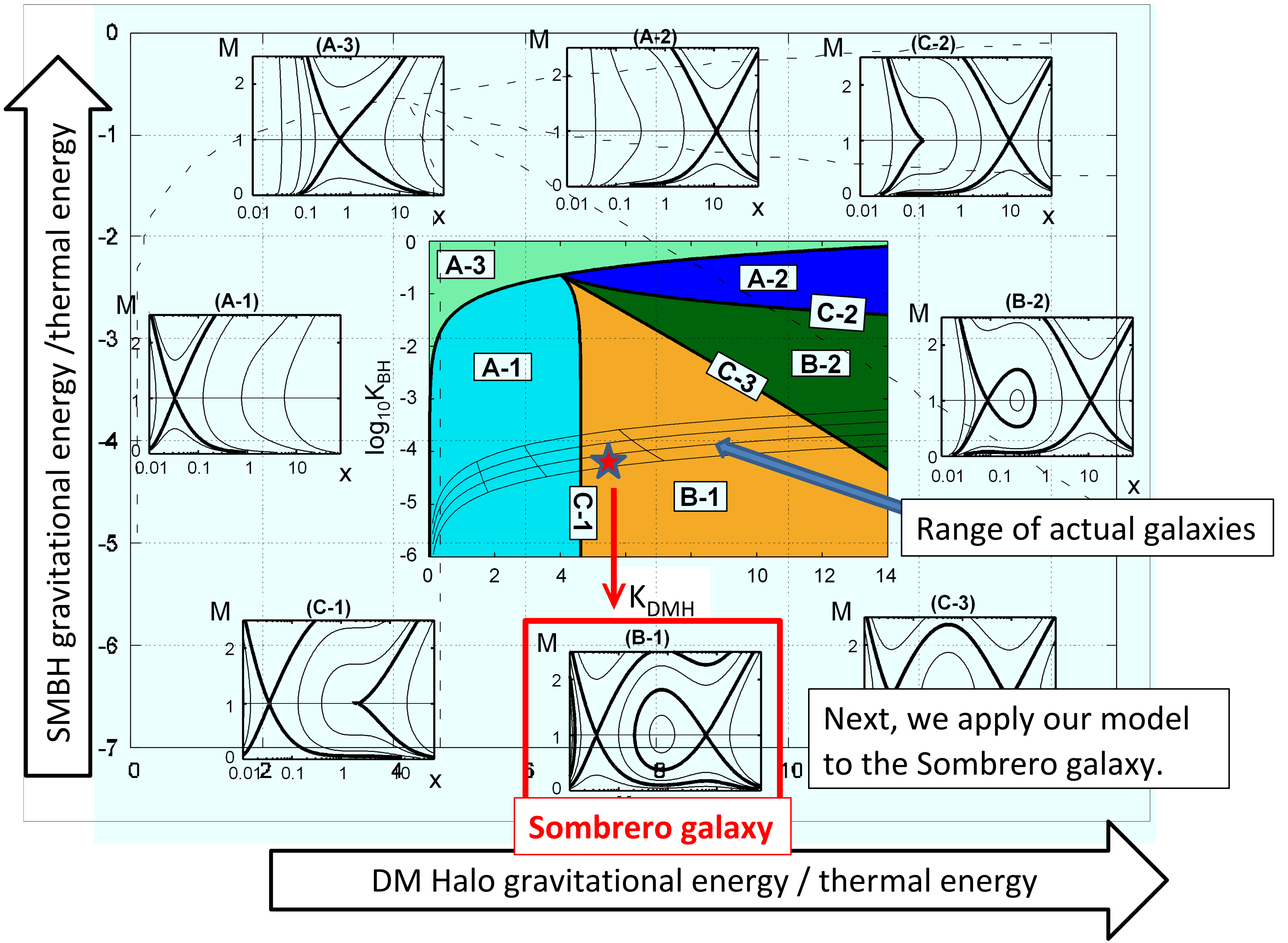


inner transonic solution

outer transonic solution

Two transonic solutions!

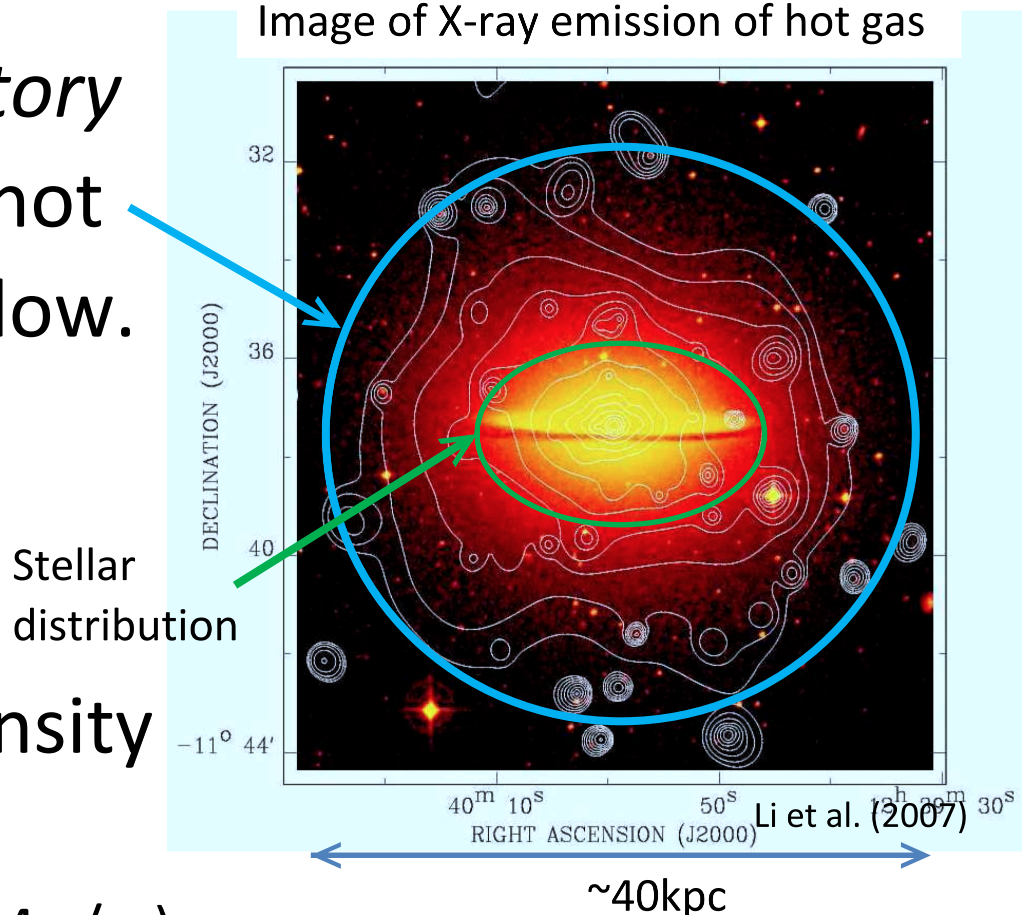
Variety of Solutions for Isothermal model



Paradox in the Sombrero galaxy

Chandra X-ray observatory observed wide-spread hot gas as the trace of outflow.
(Li et al. 2011)

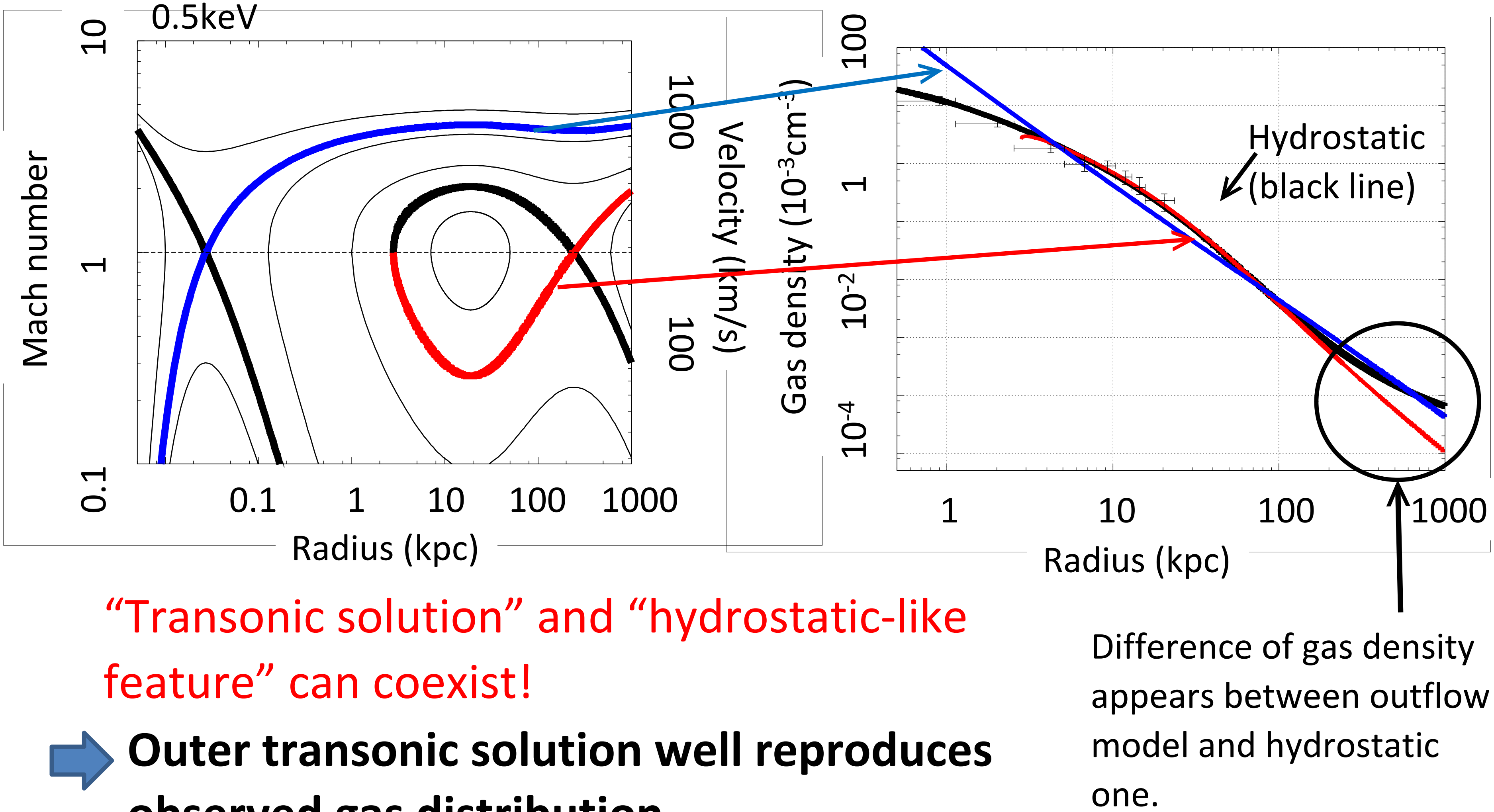
Hydrostatic-like gas density distribution
inactive star-formation (~0.06M$_{\odot}$/yr)
(Li et al. 2007, Kennicutt 1998)



Galactic outflow : to be or not to be ? That is the question!

Application to the Sombrero galaxy

- We fitted transonic solutions to gas density data (<25kpc), using observed temperature and mass distribution. (Li et al. 2011, Bridges et al. 2007, Kormendy et al. 1996).



“Transonic solution” and “hydrostatic-like feature” can coexist!

➡ **Outer transonic solution well reproduces observed gas distribution.**

Discussion : Polytropic Model

polytropic, steady and spherically symmetric model

Basic equations

Mass conservation $4\pi \rho \, v r^2 = const.$

Momentum conservation $v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{d\Phi(r)}{dr}$

Energy conservation $\frac{v^2}{2} + \frac{c_s^2}{\gamma - 1} + \Phi(r) = E$

Polytropic relation $P \propto \rho^{\gamma}$

r : radius
ρ : density
v : velocity
c_s : sound speed
M : Mach number
P : pressure
γ : polytropic index
Φ : potential
E : total energy

$\gamma = 1$: isothermal

Dark matter halo mass distribution

$$\rho_{DMH} = \frac{\rho_d r_d^3}{r(r + r_d)^2}$$

\+ Super-massive black hole mass

$$M_{BH}$$

$$\frac{M^2 - 1}{M^2\{(\gamma-1)M^2 + 2\}}\frac{dM^2}{dr} = \frac{2}{r} - \frac{\gamma+1}{2(\gamma-1)}\frac{1}{E-\Phi}\frac{d\Phi}{dr}$$

Dark Matter Halo

Super-Massive Black Hole

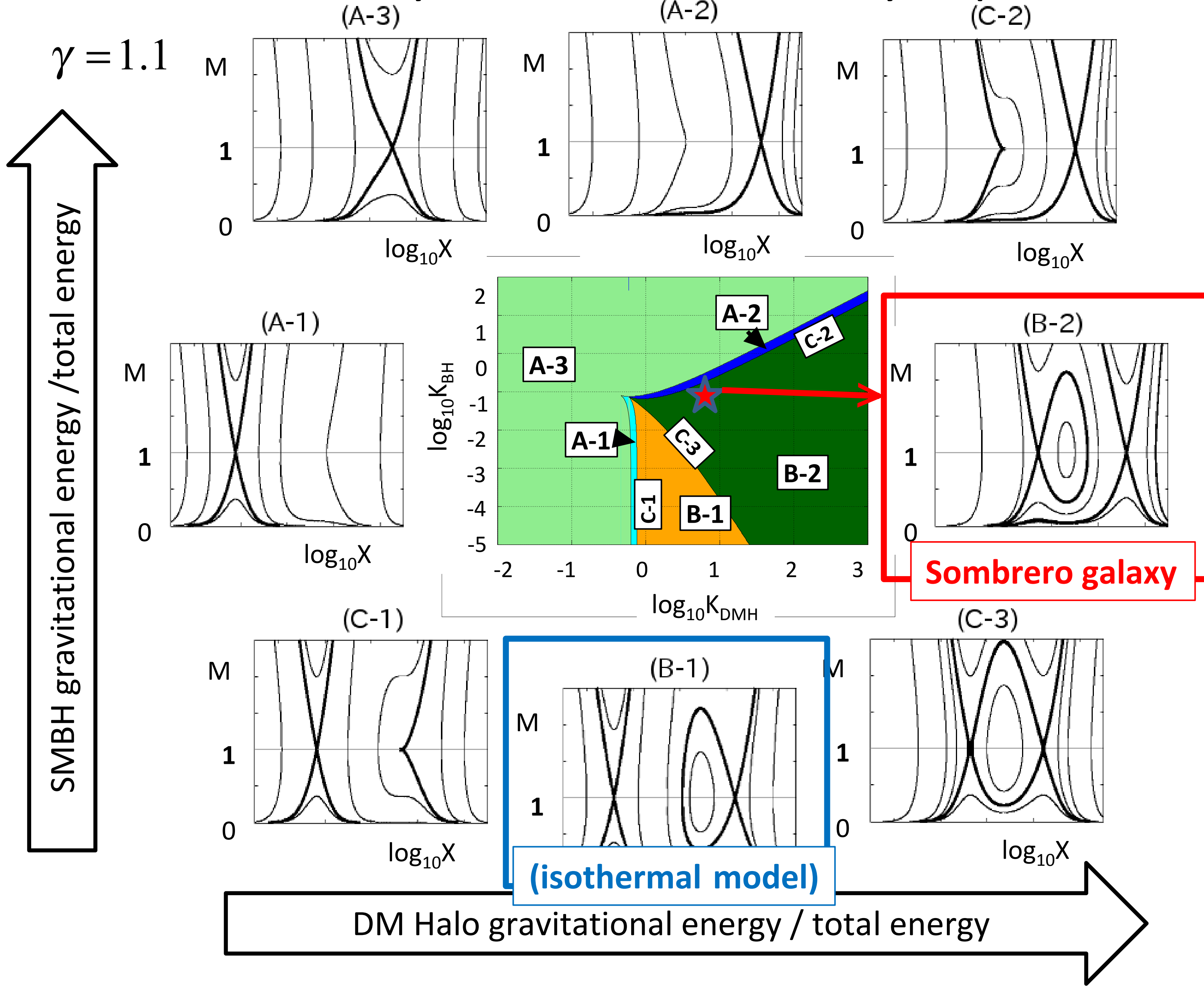
$$\frac{1}{2E}\Phi(x) = -\boxed{K_{DMH}\frac{\log(x+1)}{x}} - \boxed{K_{BH}\frac{1}{x}}$$

$$K_{DMH} = \frac{2\pi G \rho_d r_d^2}{E} \approx \frac{DMH \ gravitational \ energy}{total \ enrgy}$$

$$K_{BH} = \frac{G M_{BH}}{2 r_d E} \approx \frac{SMBH \ gravitational \ energy}{total \ energy}$$

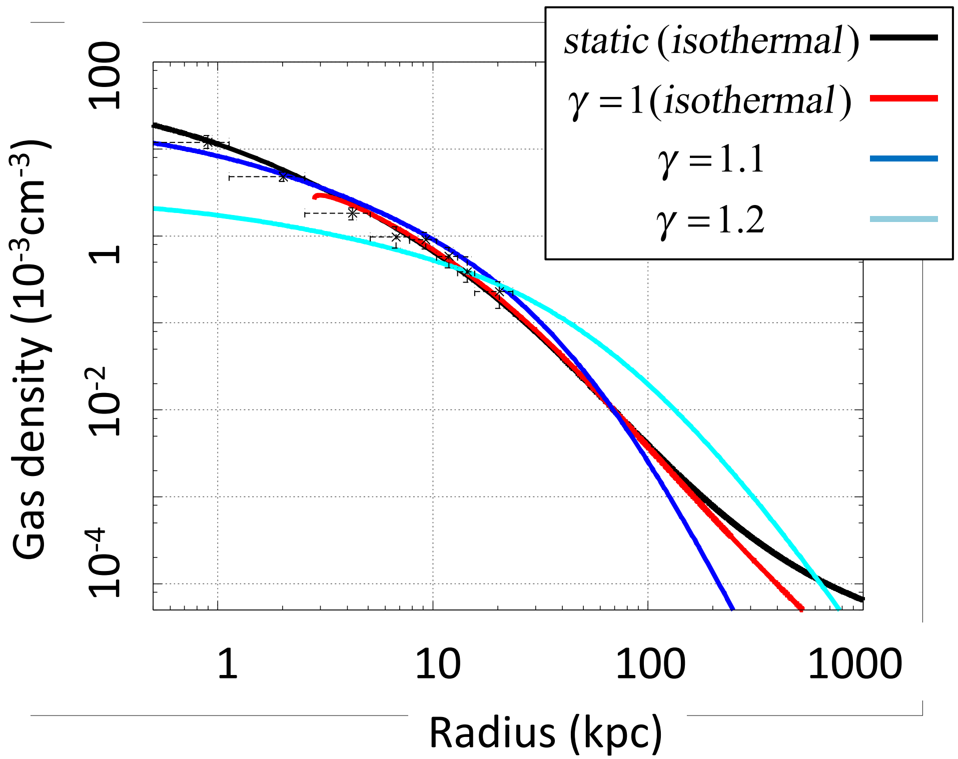
Transonic galactic outflow can exist also in **polytropic** model ?

Discussion : Variety of Solutions for Polytropic Model



Discussion : Transonic Outflow in Sombrero galaxy

We fitted polytropic transonic solutions to gas density data (<25kpc), using observed mass distribution.



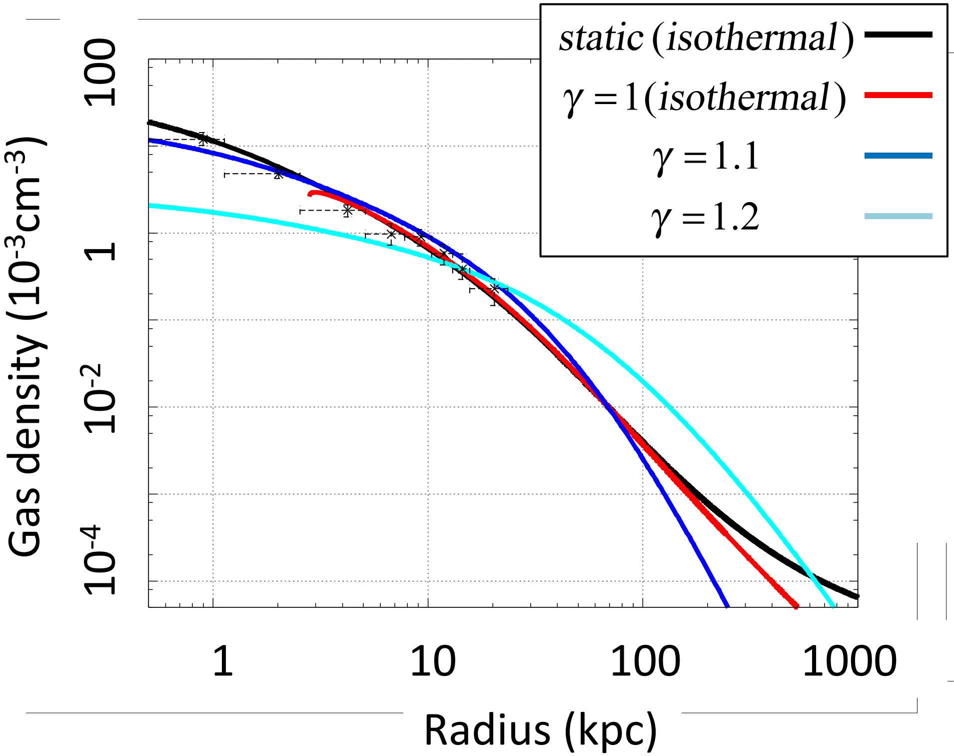
Outer transonic solution well reproduces observed gas distribution.

Polytropic model (approximating cooling/heating process) improves density profile.

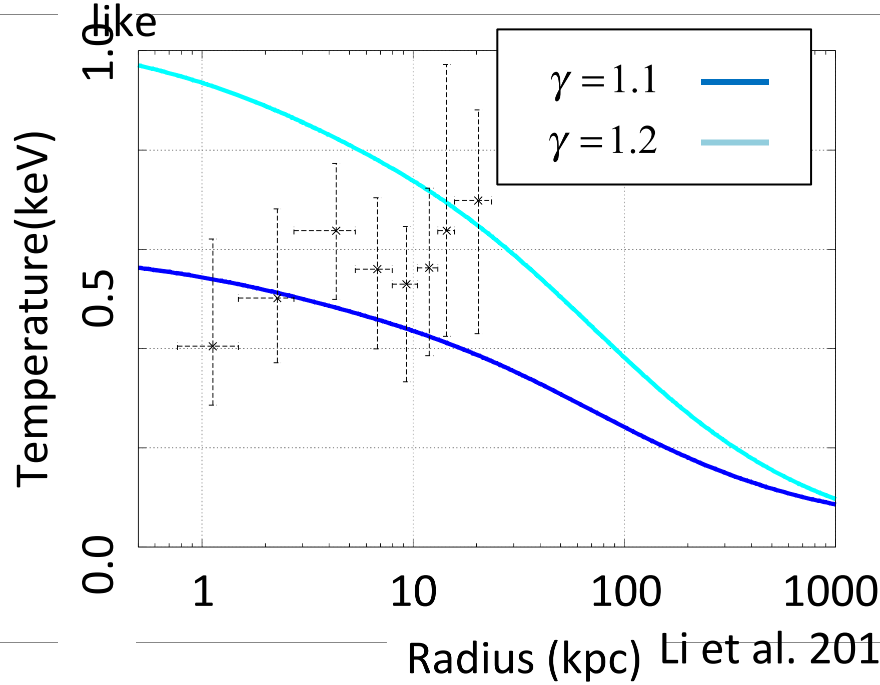
Summary and Discussion

- We investigated the galactic outflows in a cold dark matter halo with a super-massive black hole.
- We topologically categorized the variety of transonic solutions. There are 2-types of transonic solutions passing inner transonic point or outer one.
- In the Sombrero galaxy, our model successfully reproduced observed hydrostatic –like gas density profile by the outer transonic solution. Even for the quiescent galaxies (inactive star-forming galaxies), the transonic outflows can exist.
- Polytropic model can improve density profile.

Temperature Distribution in Sombrero galaxy



Observed temperature : isothermal-like

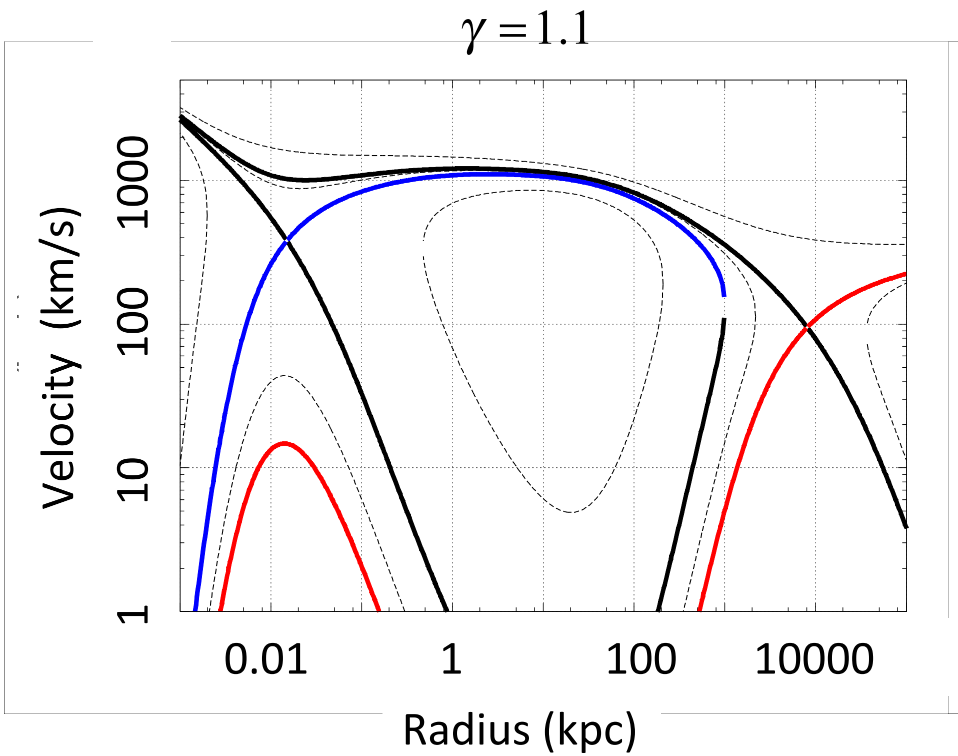


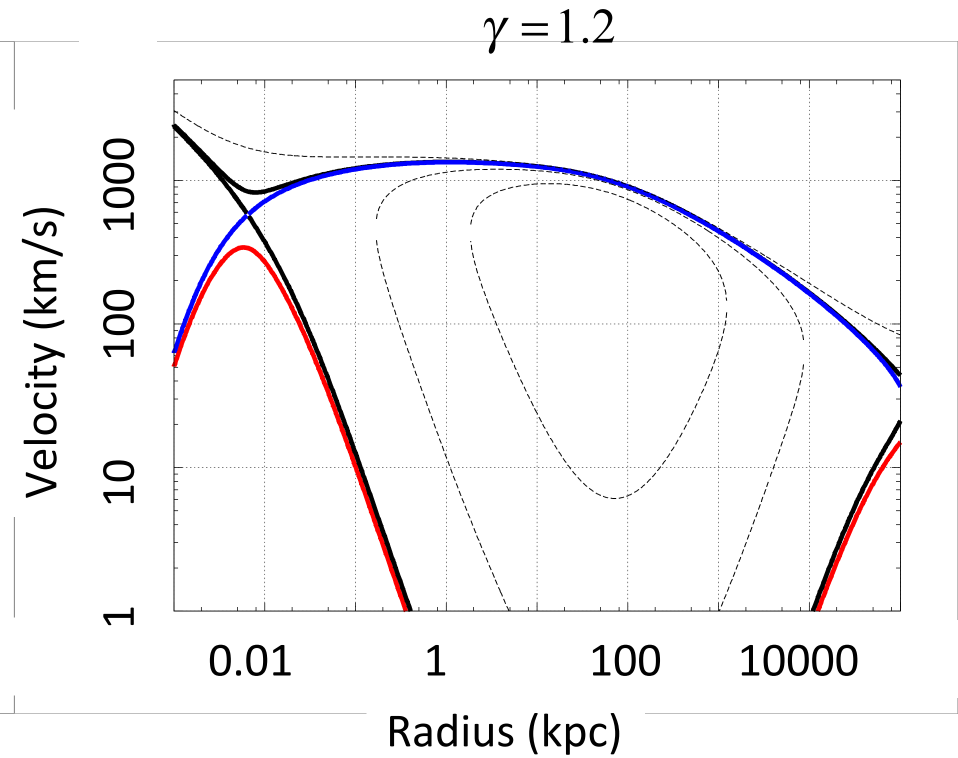
Li et al. 2011

Outer transonic solution well reproduces observed gas distribution with small polytrpic index γ.

Additional cooling (and heating) is required !

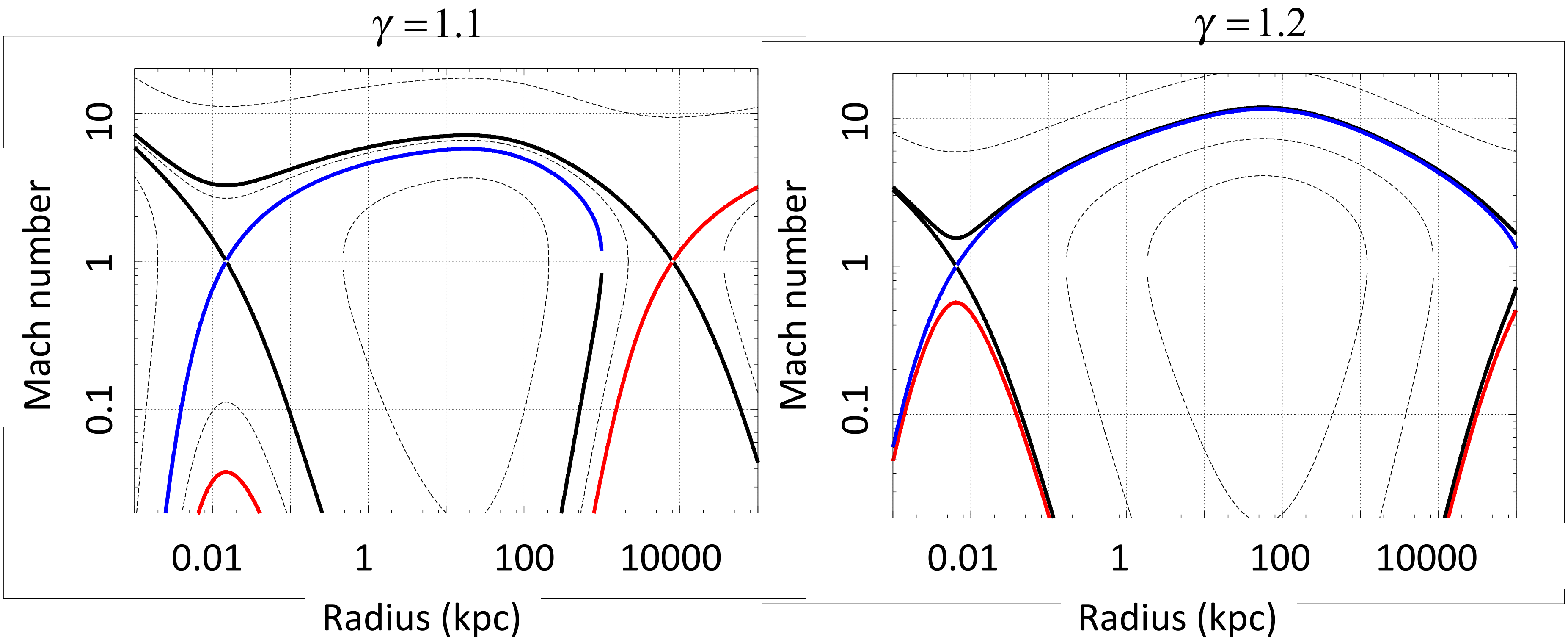
Velocity Distribution





Polytropic model indicates low velocity in wide region.

Mach-Number Distribution



Polytropic model indicates low Mach number.

Variation of Mass Flux

Isothermal model (0.5keV)

$$\dot{M} = 1.84 M_{solar} / yr$$

Polytropic model

$$\gamma = 1.1 : \dot{M} = 1.41 M_{solar} / yr, \sqrt{E} = 270 km/s$$

$$\gamma = 1.2 : \dot{M} = 0.15 M_{solar} / yr, \sqrt{E} = 43.7 km/s$$

Mass supply by Sne II and stellar winds

(Bajaja et al. 1984,1991;Athey et al. 2002;Knapp et al. 1992;Mannucci et al. 2005;Cappellaro et al. 1999)

$$\dot{M} = 0.3 - 0.5 M_{solar} / yr$$

If steady outflow, massflux indicated by polytropic model is close to observerd mass supply.

Entropy-Maximum Solution

Polytropic model

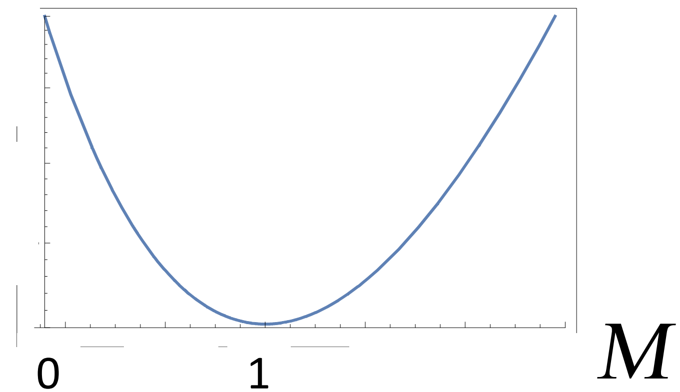
$$M^{-1}\left\{\frac{(\gamma-1)M^2+2}{2(\gamma-1)}\right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$

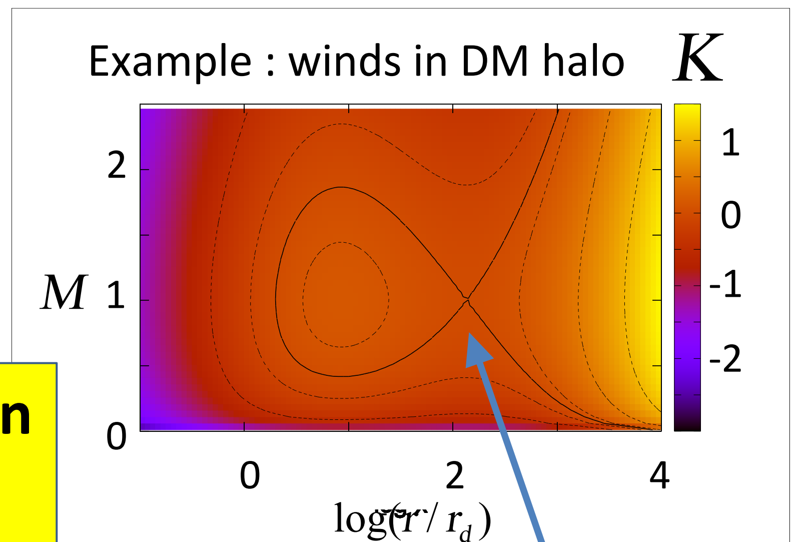
$$=(\gamma K)^{-\frac{1}{\gamma-1}}\dot{M}^{-1}r^2(E-\Phi)^{\frac{\gamma+1}{2(\gamma-1)}}\quad(\gamma>1)$$

$K: magnitude\ of\ entropy$

$\dot{M},\ E=const.$

$$M^{-1}\left\{\frac{(\gamma-1)M^2+2}{2(\gamma-1)}\right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$

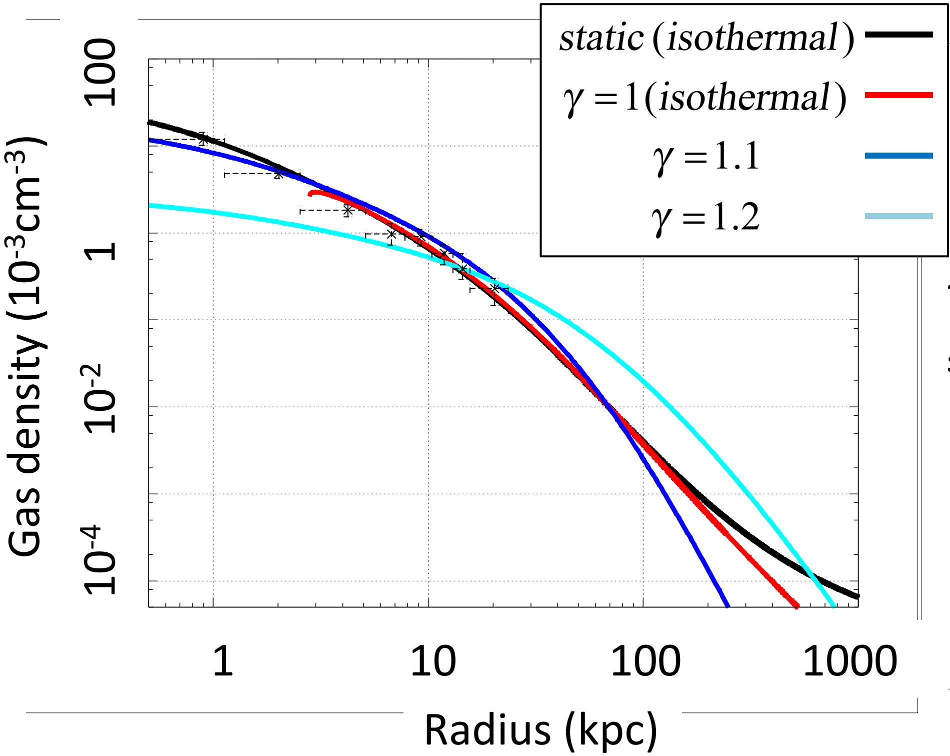


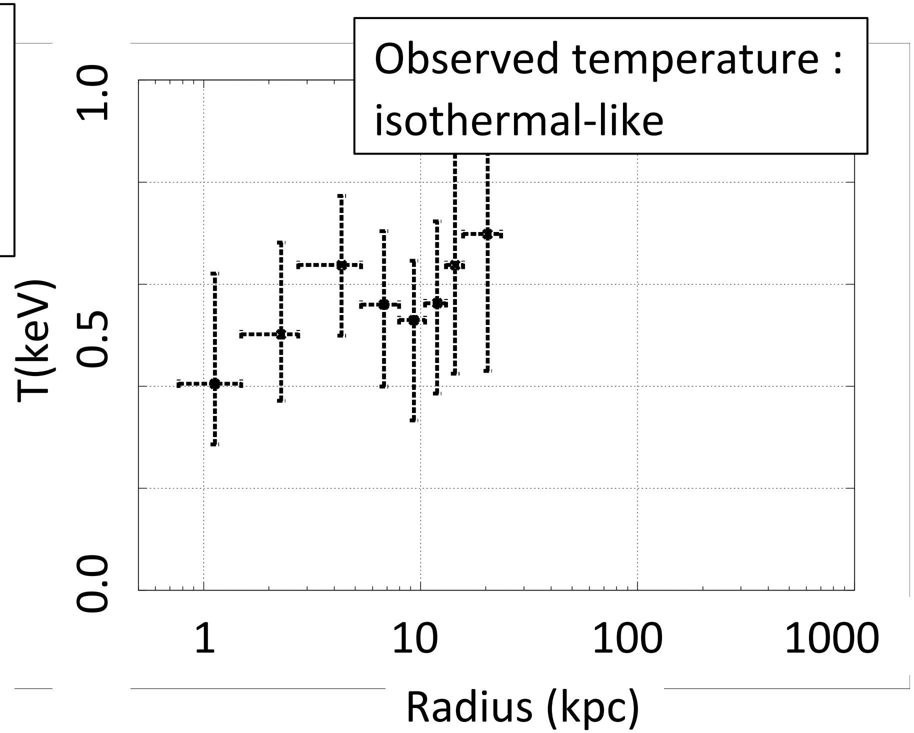


Entropy-Maximum ⇨ Transonic solution
This property is independent on the form of gravitational potential.

Entropy is maximum at transonic point.

Polytropic transonic outfow in the Sombrero





Outer transonic solution well reproduces observed gas distribution with small polytrpic index γ.

Cooling (and heat transfer) changes gas state to isothermal-like in gas-rich region?

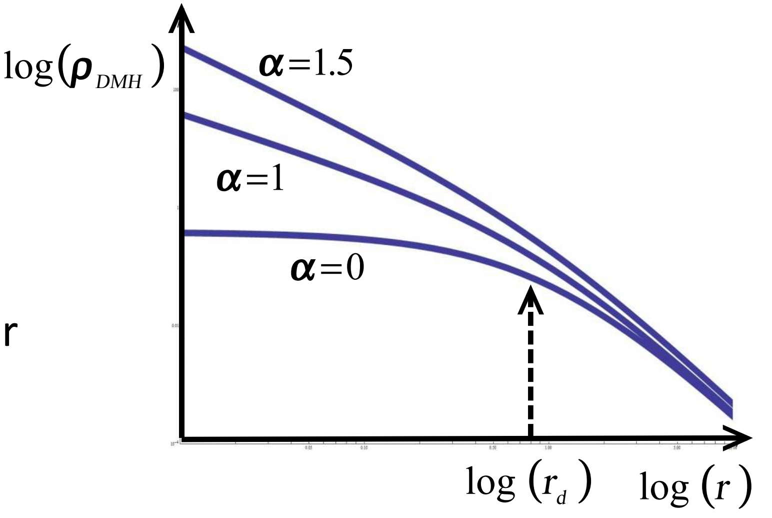
Dark Matter Density Distribution

Cosmological N-body simulations drives double power-law mass distribution.

DM Halo profile

$$\rho \propto \frac{1}{r^{\alpha}(r+r_d)^{3-\alpha}}$$

α : concentration parameter

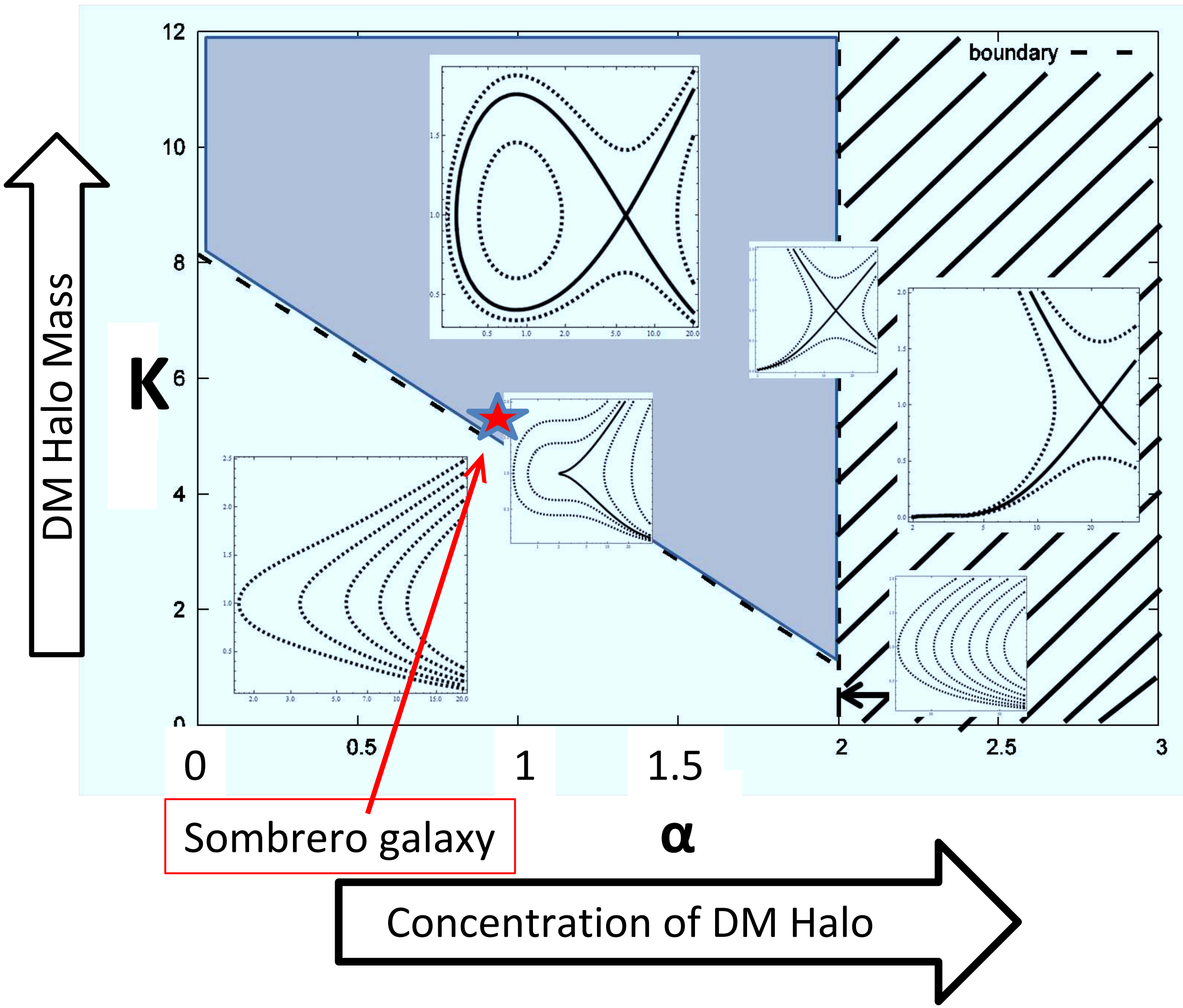


α=0.0 : **weak concentration**
observed in globular clusters (Burkert 1995)

α=1.0 : **moderate concentration**
driven by cosmological N-body simulation (Navarro et al. 1997)

α=1.5 : **strong concentration** like point mass gravity
driven by cosmological N-body simulation (Moore et al. 1999)

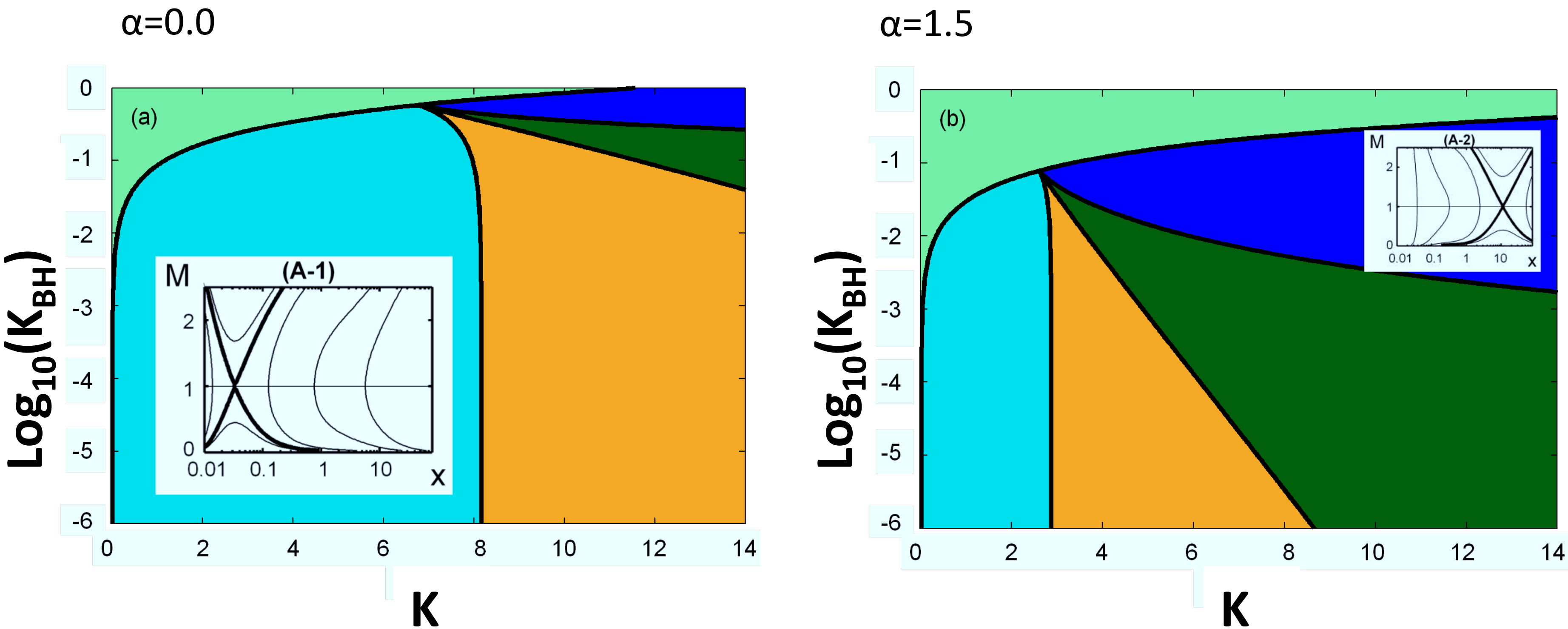
Transonic Solutions with DM Halo (Tsuchiya et al. 2013)



$$K_{DMH} = \frac{2\pi G \rho_d r_d^2}{c_s^2}$$

Large α represents point-mass-like gravity.

Dependence of α with the Super-Massive Black Hole



Large α conducts the large concentration of dark matter halo mass.

➔ strengthen gravity of dark matter halo

K_{DMH} and K_{BH} in Actual Galaxies

- Assuming virial temperature

$$c_s^2 \approx \eta \frac{GM_{DMH}}{r_{vir}}$$

η : factor of correction

$\Rightarrow$

$$K_{DMH} = \frac{2\pi G \rho_d r_d^2}{c_s^2} = \frac{c}{2\eta}\left[\int_0^c x^{2-\alpha}(x+1)^{\alpha-3}\,dx\right]^{-1}$$

$$K_{BH} = \frac{GM_{BH}}{2 r_d c_s^2} = \frac{c}{2\eta}\frac{M_{BH}}{M_{DMH}}$$

- We used some relations between c, M_{DMH} and M_{BH}

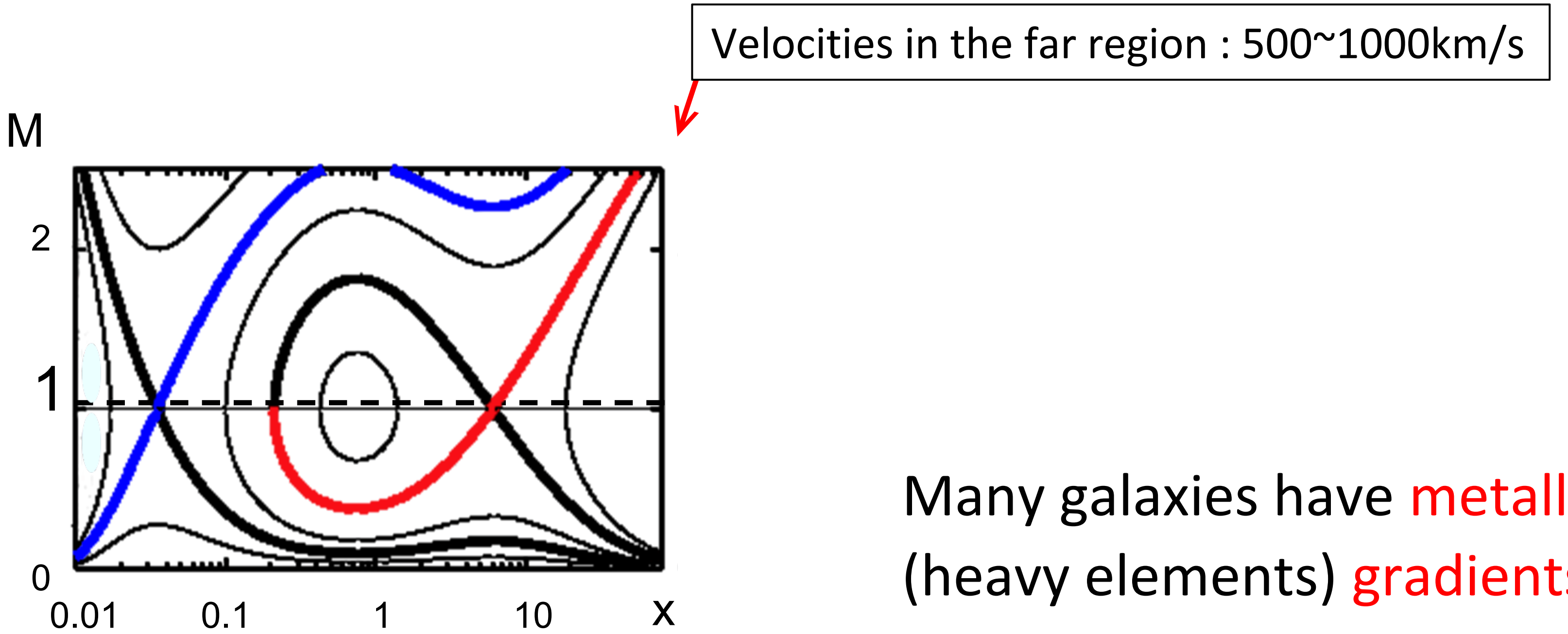
$$c = \frac{r_{vir}}{r_d} = a \times \left(\frac{M_{DMH}}{10^{12} M_\odot}\right)^b$$

a=12.8, b=-0.13 (Bullock et al. 2001)
a=9.35, b=-0.094 (Maccio et al. 2008)
a=9.7, b=-0.074 (Prada et al. 2012)

$$\frac{M_{BH}}{10^8 M_\odot} = \mu \times \left(\frac{M_{DMH}}{10^{12} M_\odot}\right)^\nu$$

μ=0.10, ν=1.65 (Baes et al. 2003)
μ=0.11, ν=1.27 (Ferrarese 2002)

Differences of Transonic Solutions

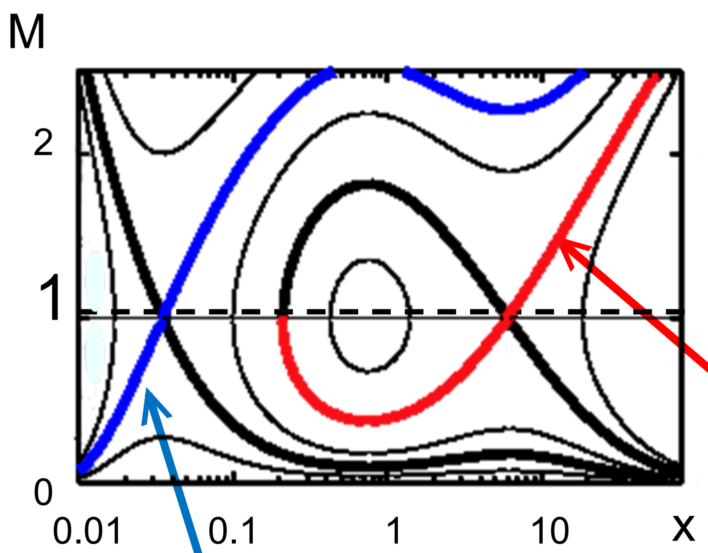


Many galaxies have metallicity (heavy elements) gradients.

Two transonic solutions have different starting points and mass fluxes.

➡ different effects to the amount of gas and the release of heavy elements from galaxies

Deduction of mass distribution from galactic outflow velocity



The outer transonic solution represents mass distribution of dark matter halo.

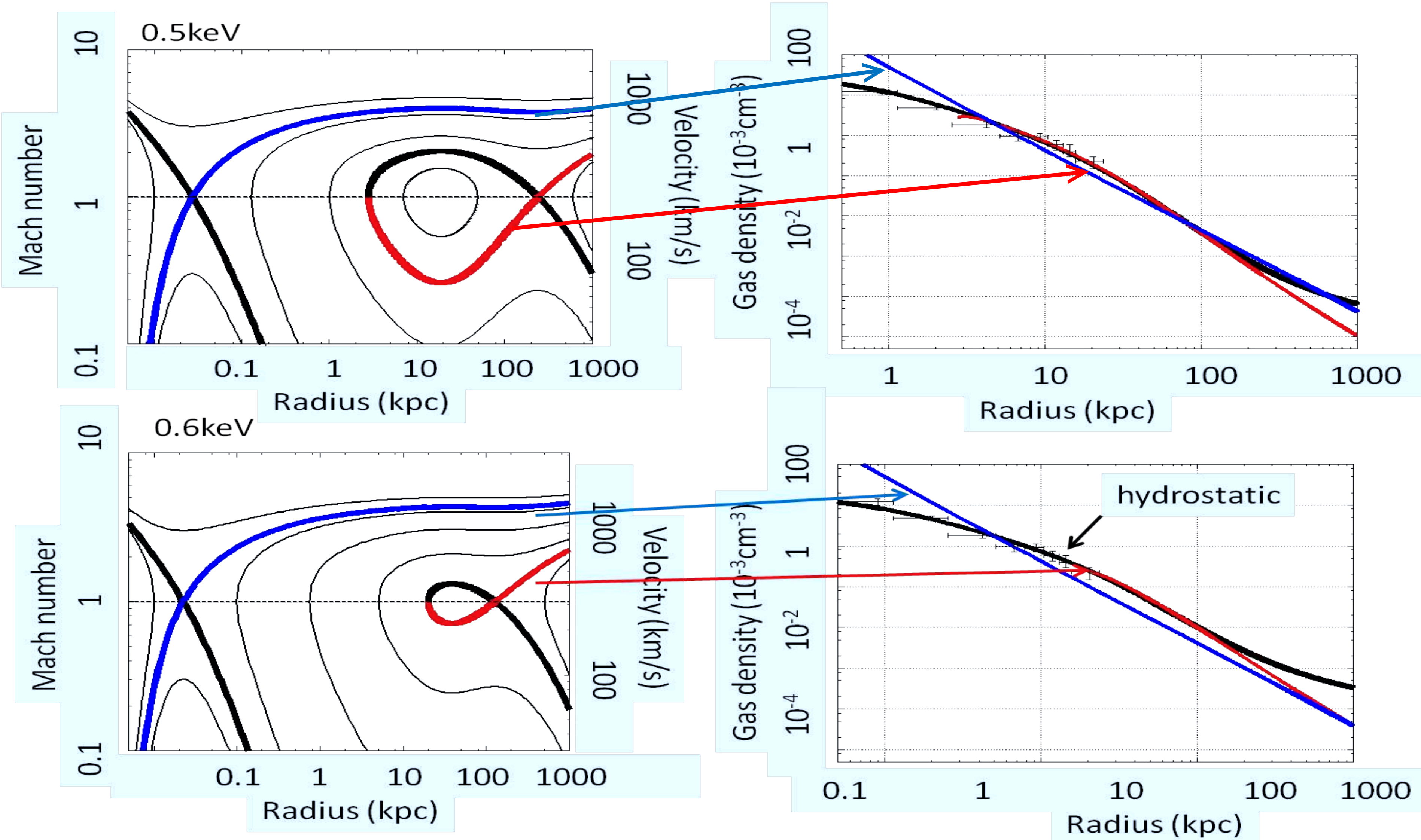
The inner transonic solution represents mass of super-massive black hole.

Future mission (e.g. Astro-H) may reveal outflow velocity structure.

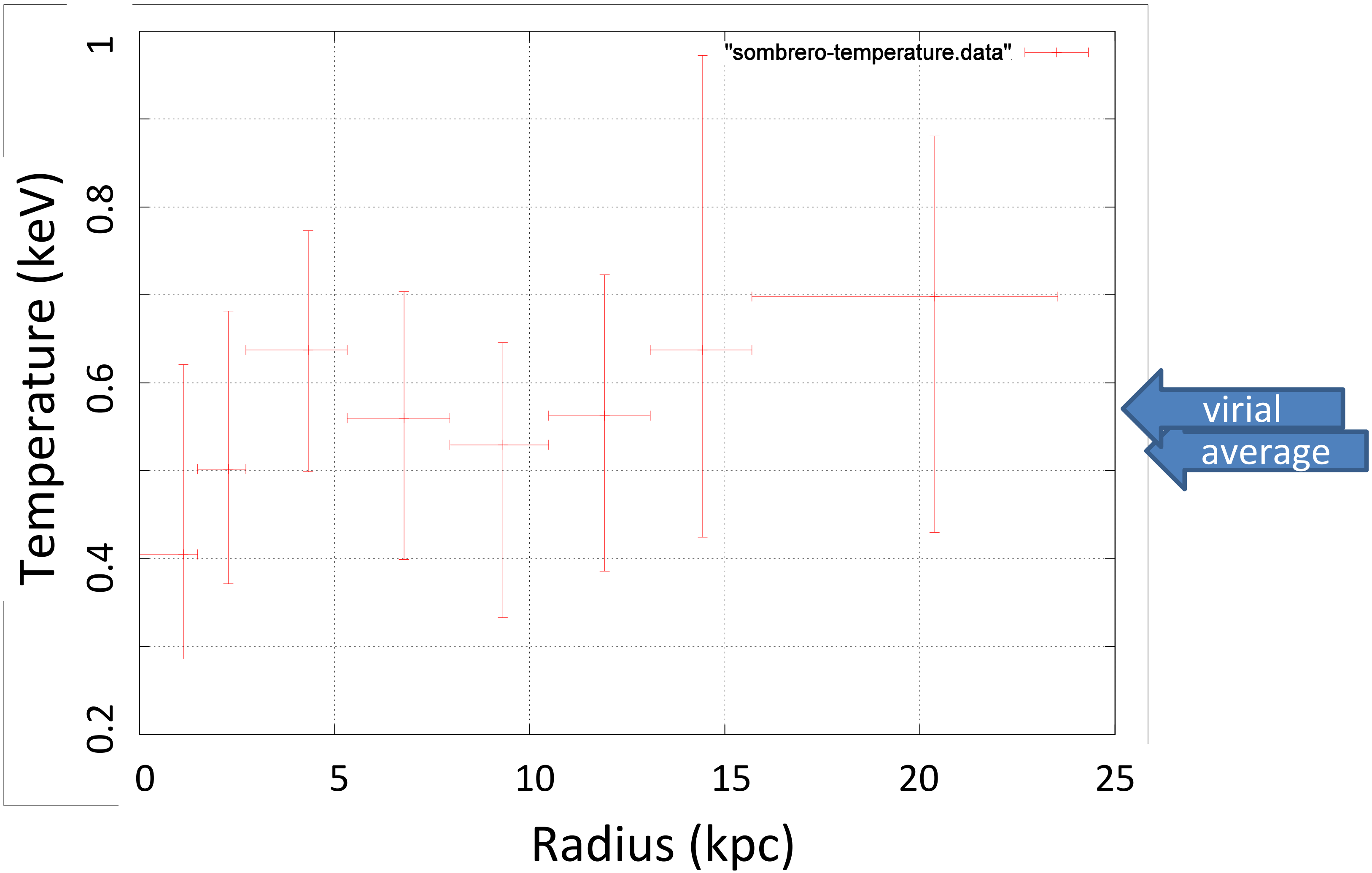
⇨ Our model deduces mass distribution in an galaxy.

Temperature Dependence of Transonic Solutions

Gas density profile in subsonic region is hydrostatic-like in observed range of temperature (0.6±0.3keV).



Temperature of the Sombrero galaxy



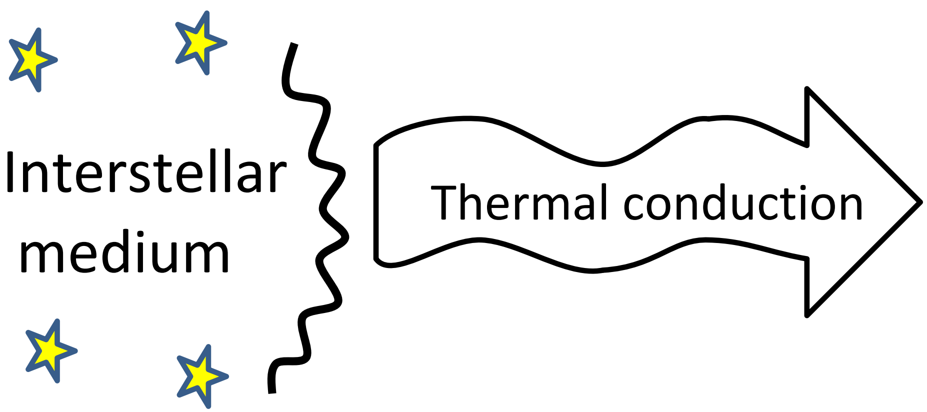
Assumptions

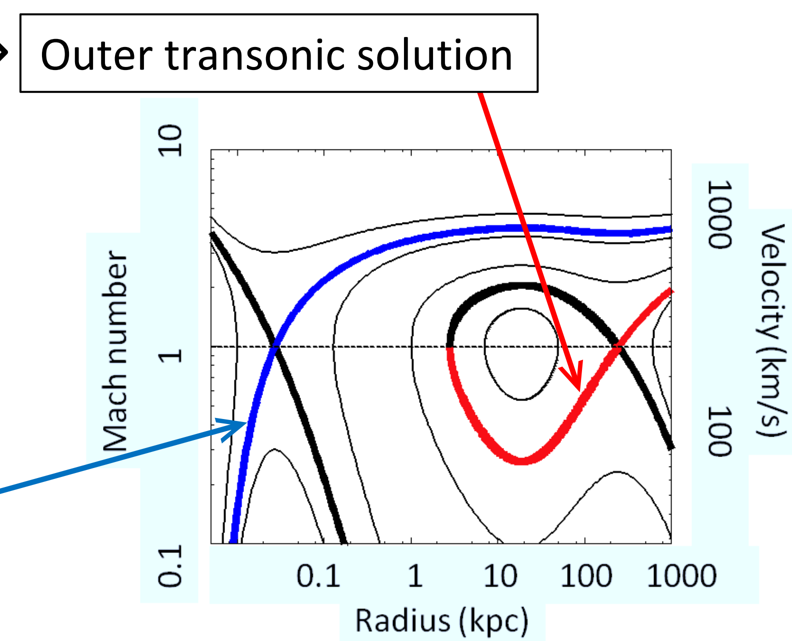
- isothermal assumption

Source of Energy

previous studies : supernovae by young and massive stars

Our model : hot interstellar medium at virial temperature



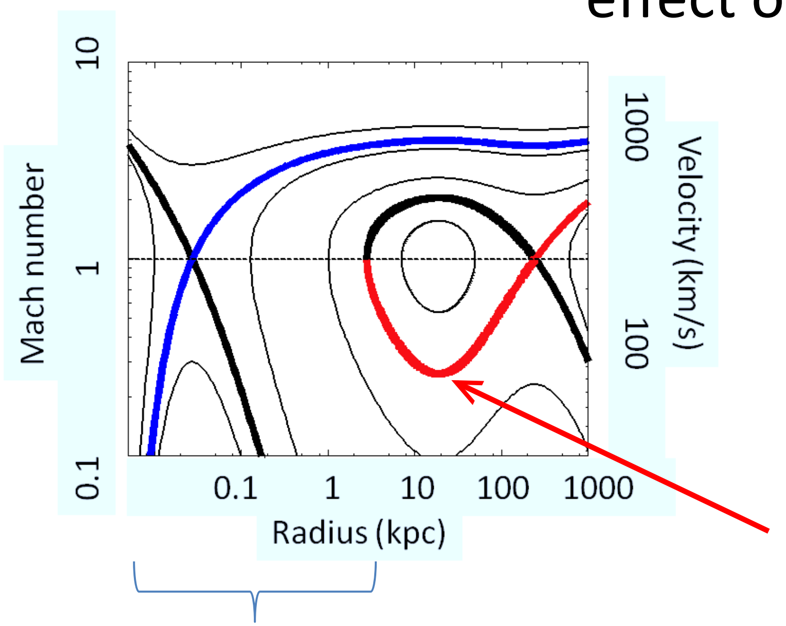


The inner transonic solution is accelerated by pressure gradient made from super-massive black hole.

Assumptions

- without mass injection

Mass injection : mass supply to galactic outflow
effect of momentum reduction



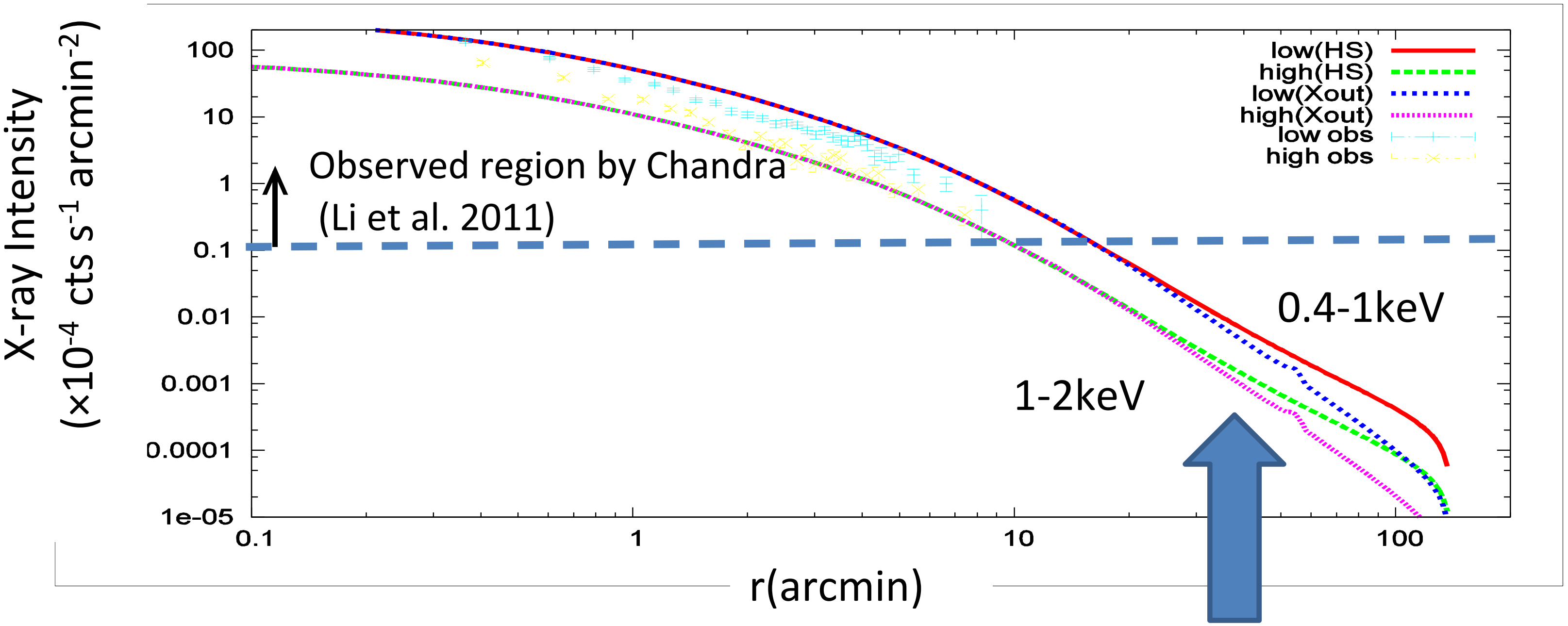
Stellar distribution (mass injection area)

Because outer transonic solution starts in far distance, it does not be affected by mass injection.

We study the influence of mass injection in future work.

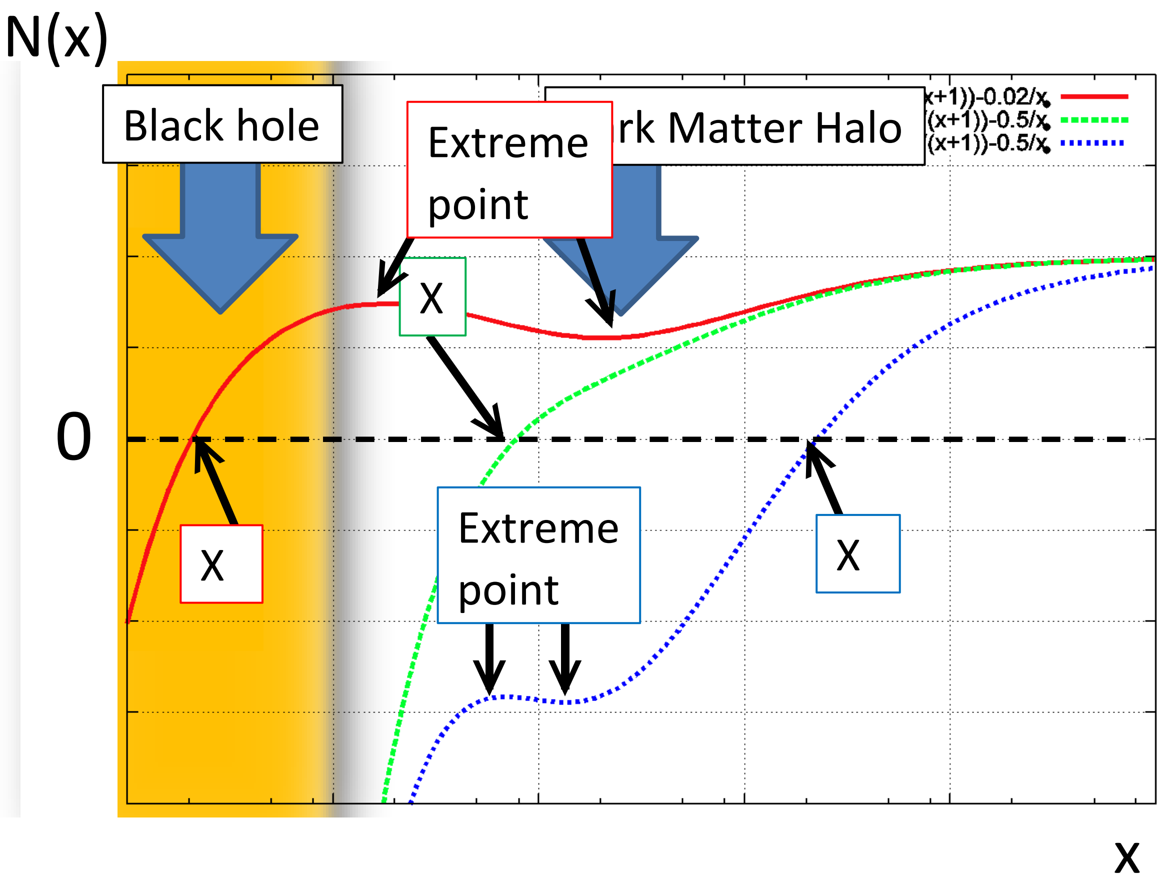
X-ray intensity in the Sombrero galaxy

Assming only Bremshralung for X-ray intensity



the diffenrence between
“outflow” and “hydrostatic”

Pattern A solutions



red :X-point by Black hole gravity
blue :X-point by dark matter halo gravity
緑 :X-point by both gravity

$$\frac{dM^2}{dx} = \frac{\frac{4}{x} N(x;\boldsymbol{\alpha}, K, K_{BH})}{1 - \frac{1}{M^2}}$$

$$N(x;\alpha,K) = 0 \quad \begin{cases} \frac{dN}{dx} > 0 : X - point \\ \frac{dN}{dx} < 0 : O - point \end{cases}$$

$$N(x;\boldsymbol{\alpha}, K, K_{BH}) = 1 - Kx^{2-\boldsymbol{\alpha}} \frac{{}_2F_1[3-\boldsymbol{\alpha}, 3-\boldsymbol{\alpha}, 4-\boldsymbol{\alpha}; x]}{3-\boldsymbol{\alpha}} - \frac{K_{BH}}{x}$$

$\alpha = 1 : NFW$ model