Galaxy-IGM workshops 2018

Transonic analysis of galactic outflows in star-forming galaxies

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Star-forming galaxies with galactic outflows

high SFR comparing to normal spirals

→ injecting energy into ISM

→ ejecting ISM with galactic outflows

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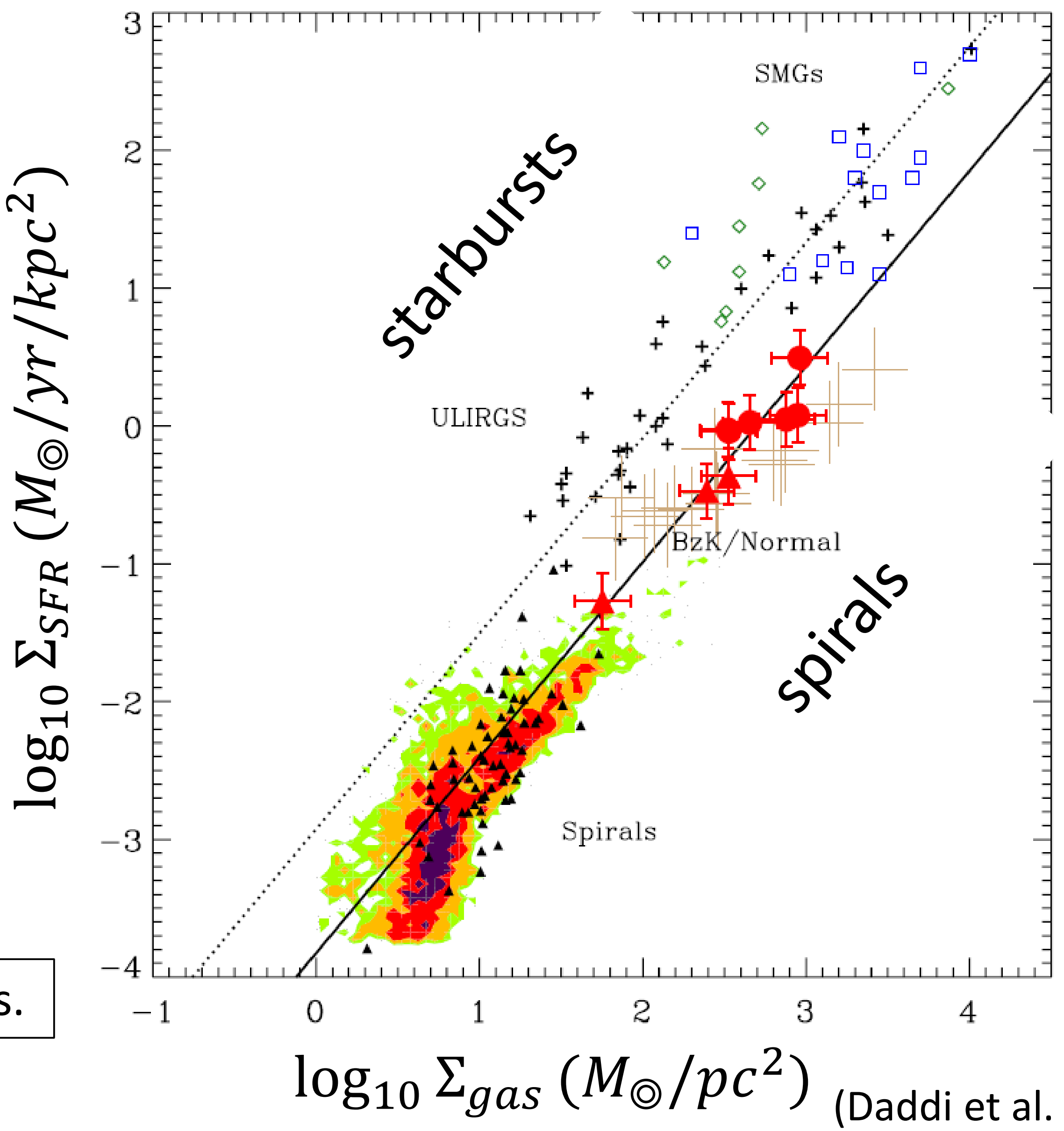
1. suppressing star formation
2. metal enrichment in IGM

These effects depend on mass flux of galactic outflows.

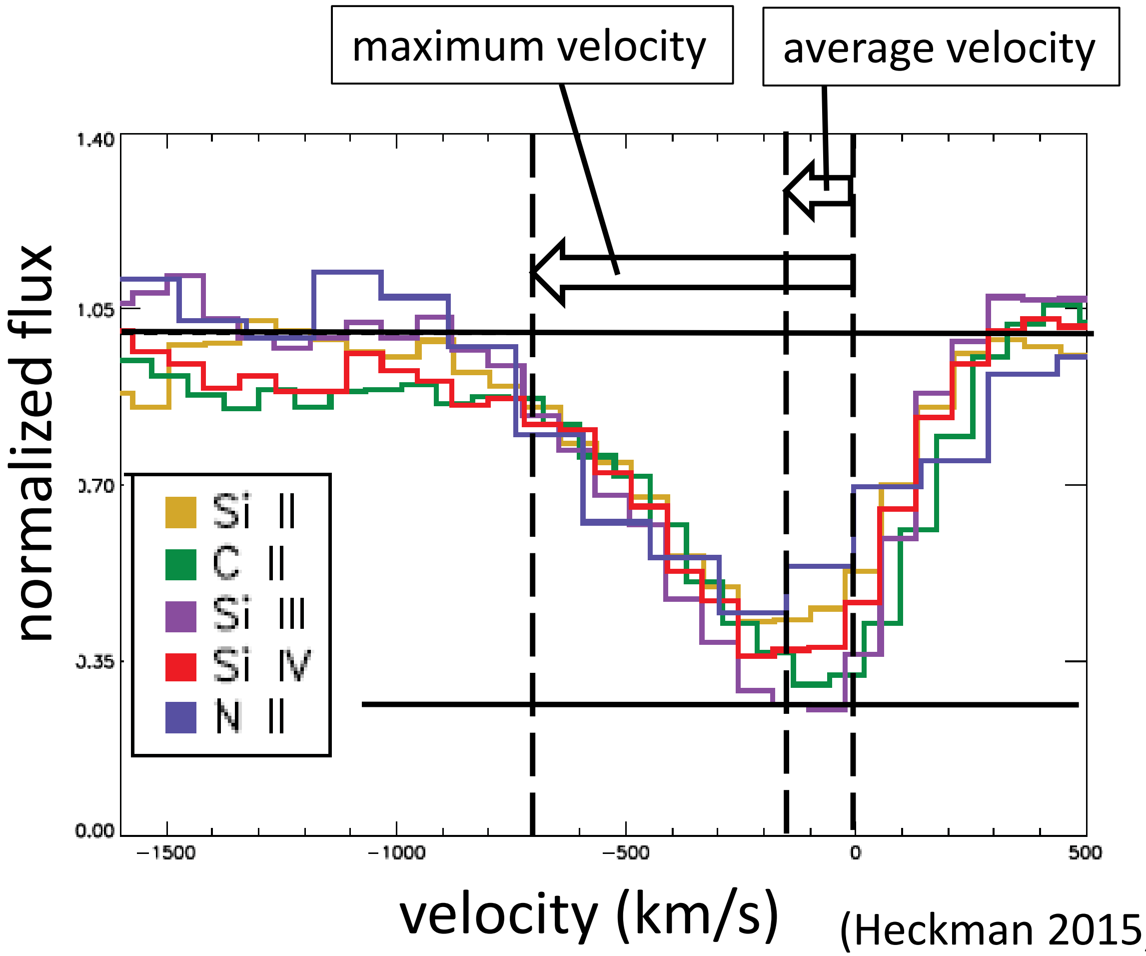
Kennicutt-Schmidt law for spirals and starbursts



(Daddi et al. 2010)

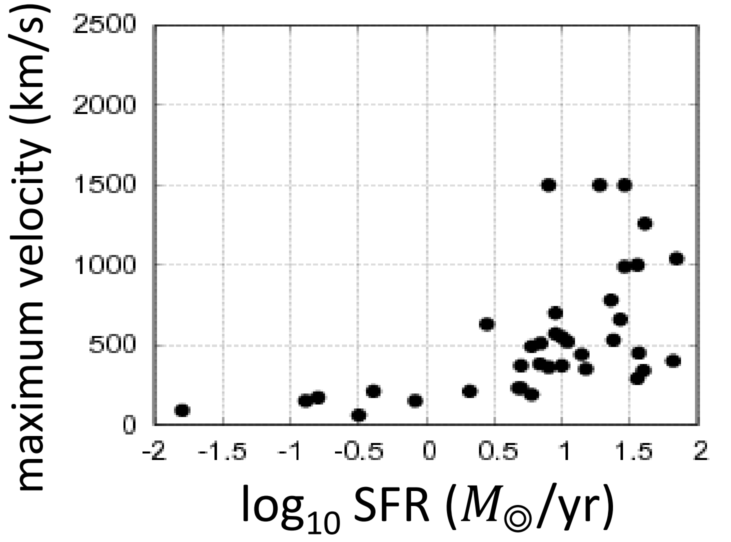
Galactic outflows

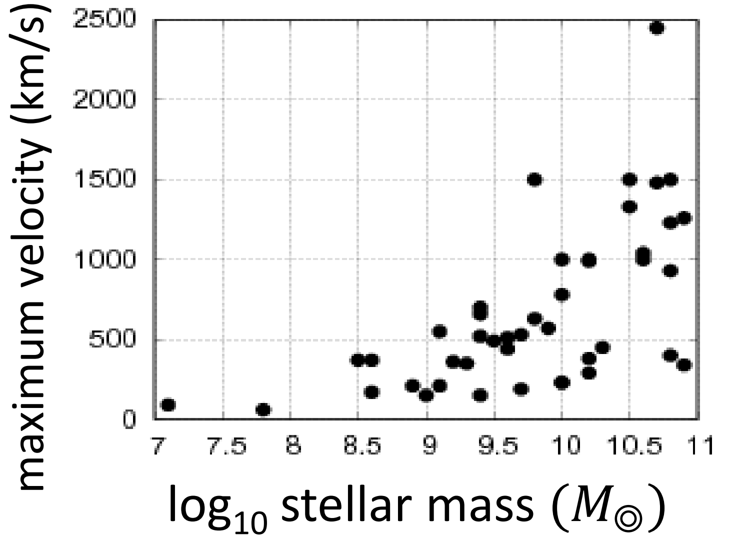
metal absorption lines indicating outflow velocities



(Heckman 2015, 2016)

correlations between velocity, SFR and stellar mass

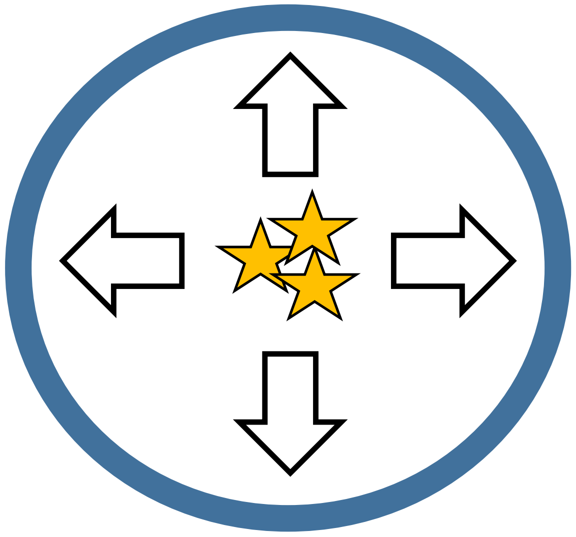




We can estimate mass flux from these relations !

Shell outflow model

mass loading factor = mass flux / SFR



$\dot{\mathrm{m}}$: mass flux

N_H: hydrogen column density

$\langle m \rangle$: mean mass per particle

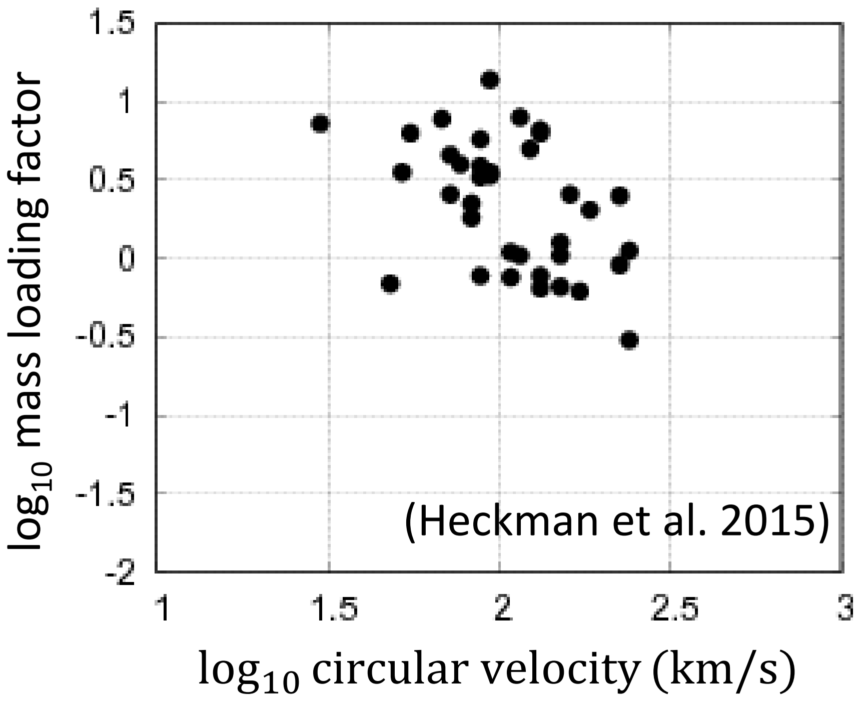
v_{out}: average velocity

r_{out}: sonic radius

$$\dot{m} \sim 4\pi\, N_H\, \langle m \rangle\, v_{out}\, r_{out}$$

N_H can be predicted by ionic column density.

$\mathrm{r_{out}}$ is assumed to be $\sim 2 \times$ effective radius (UV)



Mass loading factors represent the efficiency of carrying ISM to intergalactic space.

The dependence on halo gravity is not clear.

There is variability in N_H and r_{out}.
Additionally, there is the other possibility of wind process.

Transonic analysis

We focus on the transonic acceleration process.

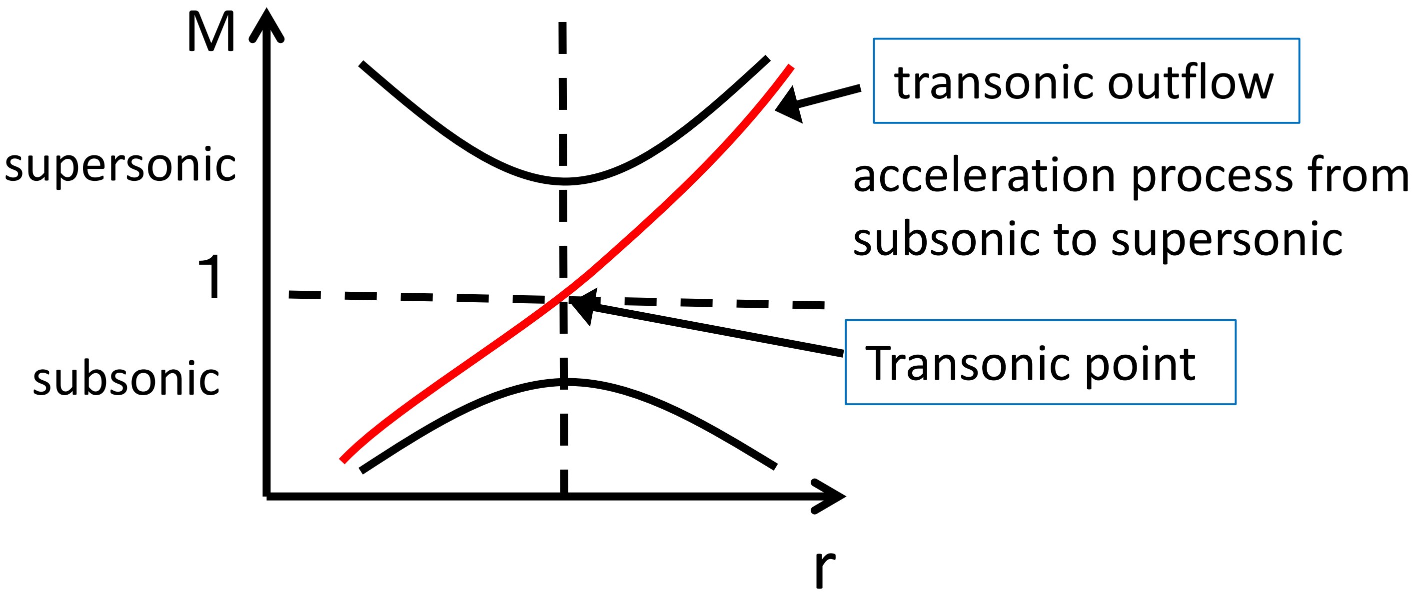
example: solar wind model (Parker 1958)

1.equation of continuity $4\pi\rho v r^2 = const.$

2.equation of motion $v\frac{dv}{dr} = -\frac{c_s^2}{\rho}\frac{d\rho}{dr} - \frac{d\Phi}{dr}$

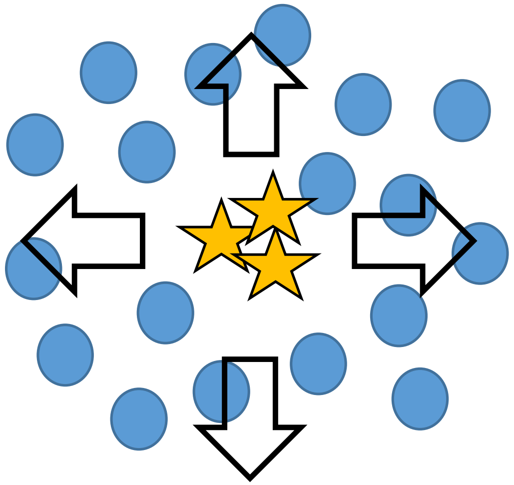
$$\frac{M^2-1}{M^2}\frac{dM^2}{dr} = \frac{4}{r} - \frac{2}{c_s^2}\frac{d\Phi}{dr} \quad \left(\Phi(\mathrm{x}) \propto -\frac{1}{r}\right)$$

M: Mach number (= velocity / sound speed)



Transonic flow is entropy-maximum solution.
Therefore, we consider galactic outflows to be transonic.

Transonic outflow model



adiabatic spherically-symmetric steady model

1.equation of continuity $\frac{1}{r^2}\frac{d}{dr}(\rho v r^2) = \dot{\rho_m}$

2.equation of motion $\rho v \frac{dv}{dr} = -\frac{dP}{dr} + \rho g - \dot{\rho_m} v$

3.energy equation $\frac{1}{r^2}\frac{d}{dr}\left\{ v r^2 \left(\frac{1}{2}\rho v^2 + \frac{\Gamma}{\Gamma - 1} P \right) \right\} = \rho v g + \dot{q}$

$\dot{\rho}_m$: mass injection

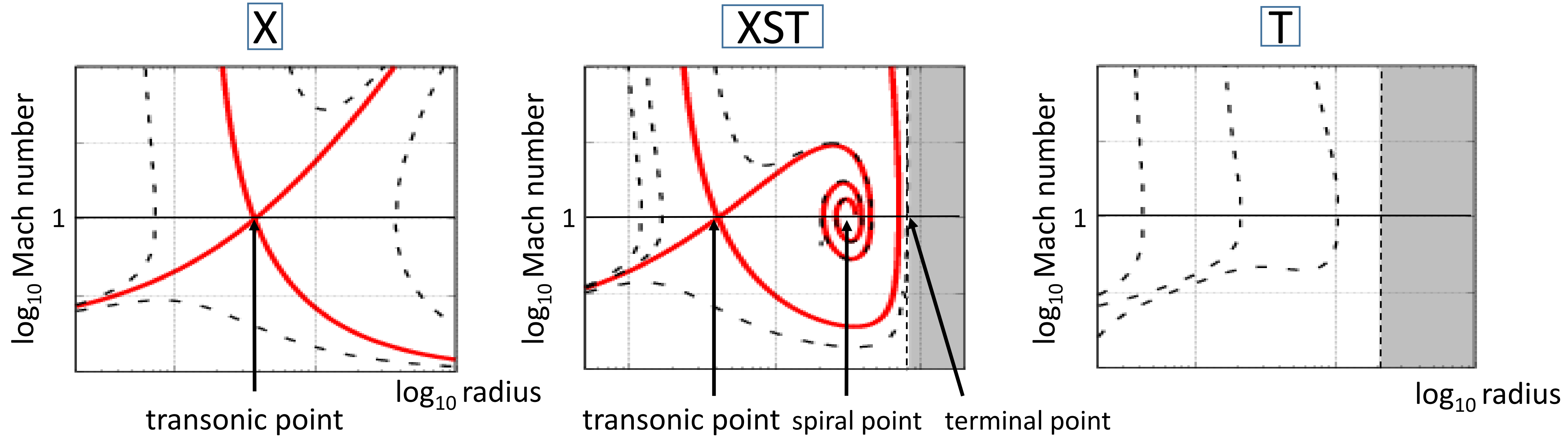
$\dot{q}$: energy injection

$$\Rightarrow \frac{M^2 - 1}{M^2\{(\Gamma - 1)M^2 + 2\}} \frac{dM^2}{dr} = \frac{2}{r} - \frac{\Gamma + 1}{2(\Gamma - 1)} \frac{\dot{m}}{\dot{e} - \dot{m}\Phi} \frac{d\Phi}{dr} - \frac{\Gamma M^2 + 1}{2} \frac{\dot{e} - 2\dot{m}\Phi}{\dot{e} - \dot{m}\Phi} \frac{1}{\dot{m}} \frac{d\dot{m}}{dr}$$

assuming mass and energy injected by SNeII

assuming the gravity of dark matter (DM) halo and stellar mass

Transitions of transonic outflows



Transonic outflow expands to infinity.

Transonic outflow expands.

no transonic solution

gravity ($\propto$ DM halo mass) →

← energy injection ($\propto$ SFR)

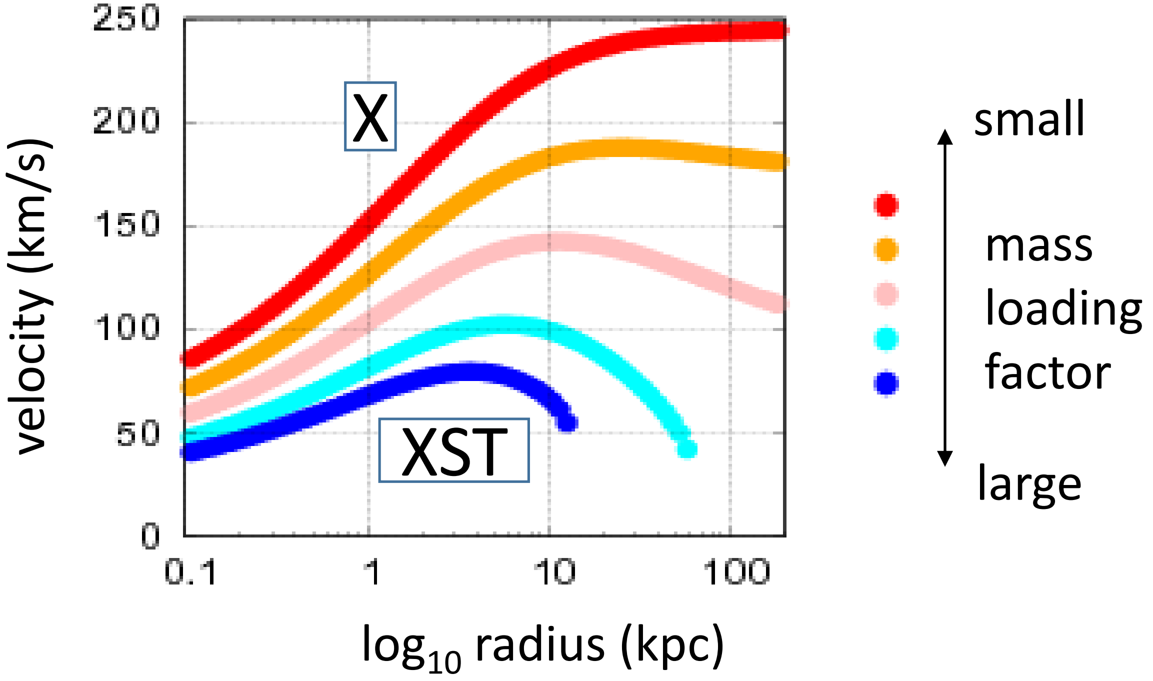
mass injection ($\propto$ mass loading factor $\equiv$ mass flux / SFR) →

Velocity distribution and mass loading factor

DM halo mass distribution is predicted from redshift stellar mass using theoretical model (Behroozi et al. 2010, 2013; Bullock et al. 2001; Munoz-Cuartas et al. 2011).

Stellar scale radius is predicted by redshift and stellar mass using empirical relation (Shibuya et al. 2015).

example: stellar mass = $10^{8.6}\ M_\odot$
DM halo mass = $10^{10.96}\ M_\odot$
SFR = 10 $M_\odot$/yr



Maximum velocity depends on mass loading factor.

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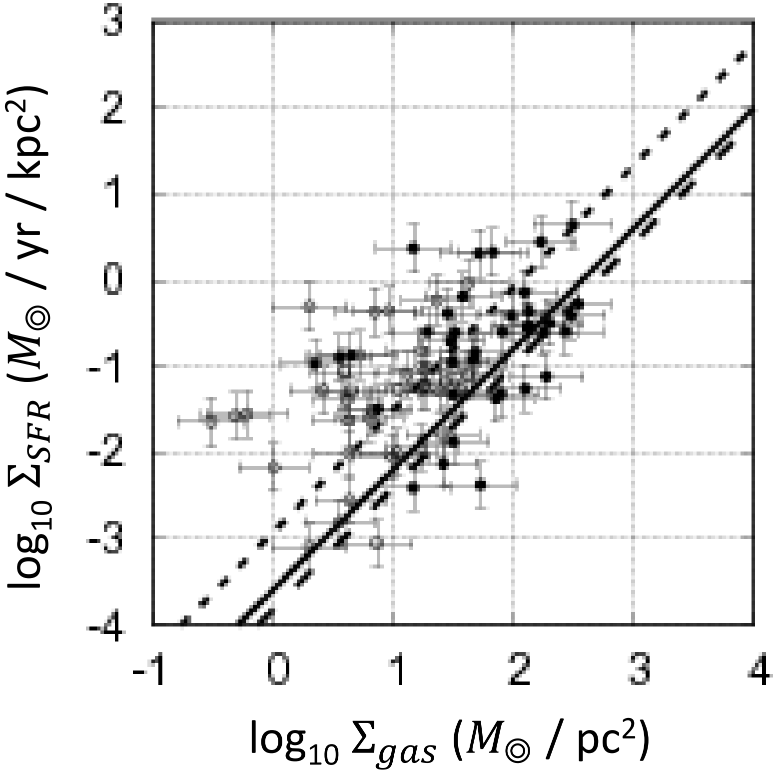
Mass loading factor can be predicted by observed maximum velocity.

This model can predict mass flux consistently.

Result: column density

We compare results and observed Kennicutt-Schmidt law.

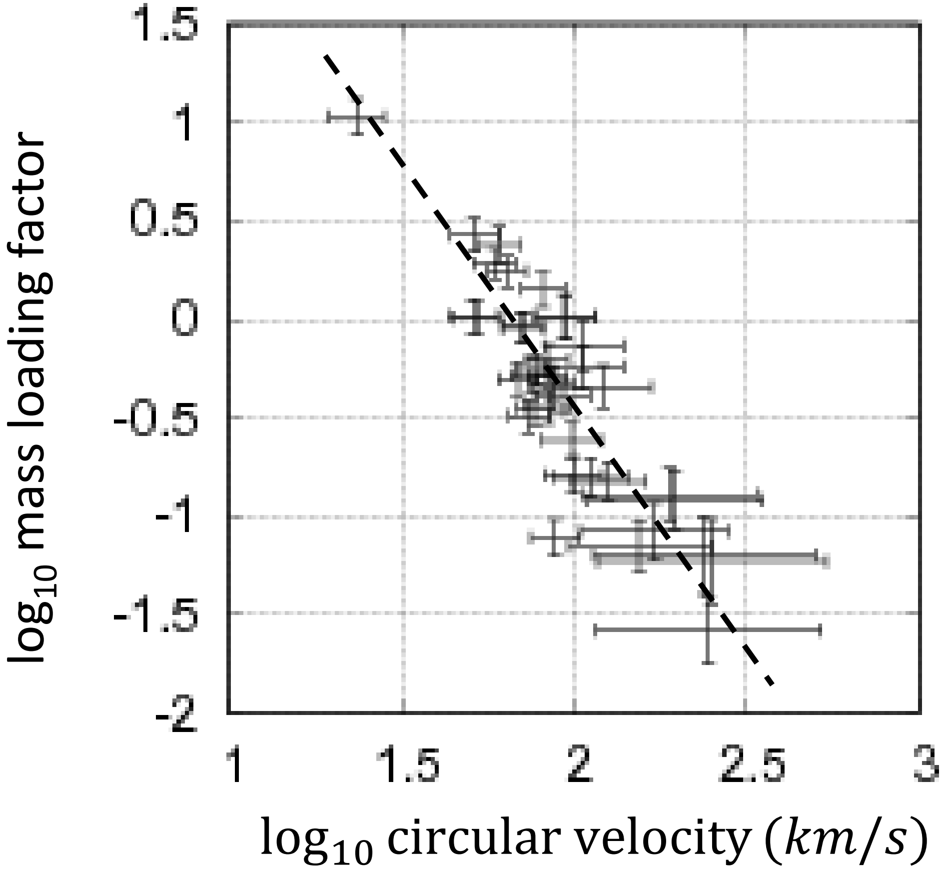


The estimated column densities are roughly consistent with observational relations.

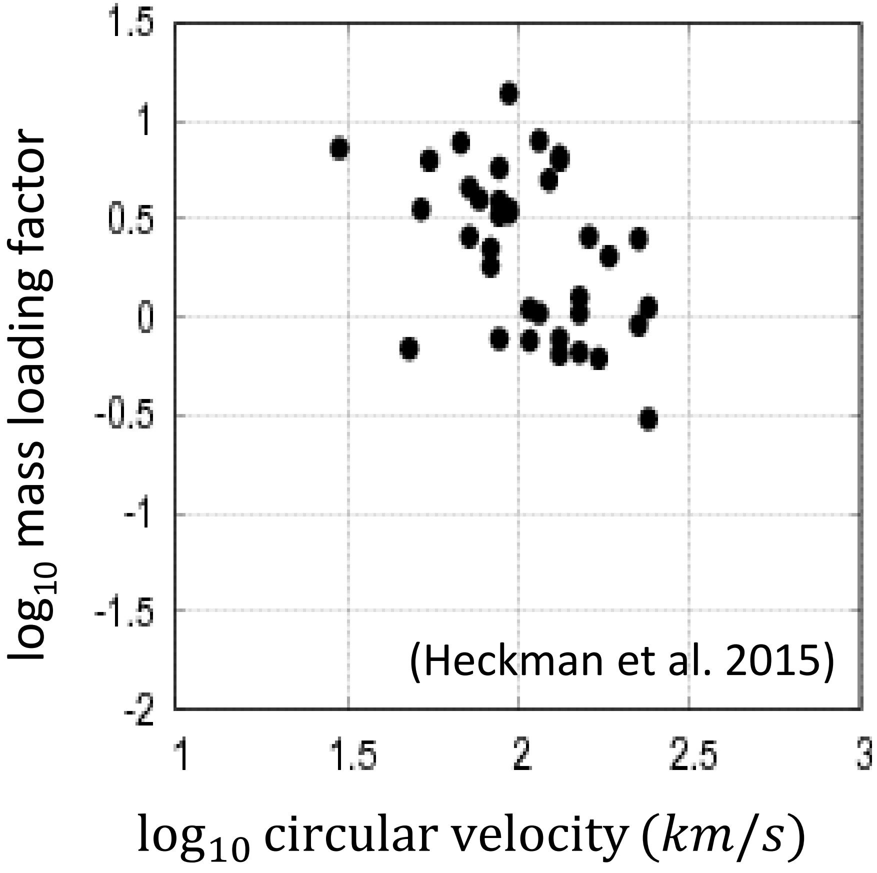
Result: dependence on dark matter halo

We estimate mass loading factors from observed maximum velocity.
Mass loading factors (= mass flux /SFR) strongly depend on gravity of DM halo.

Transonic outflow model



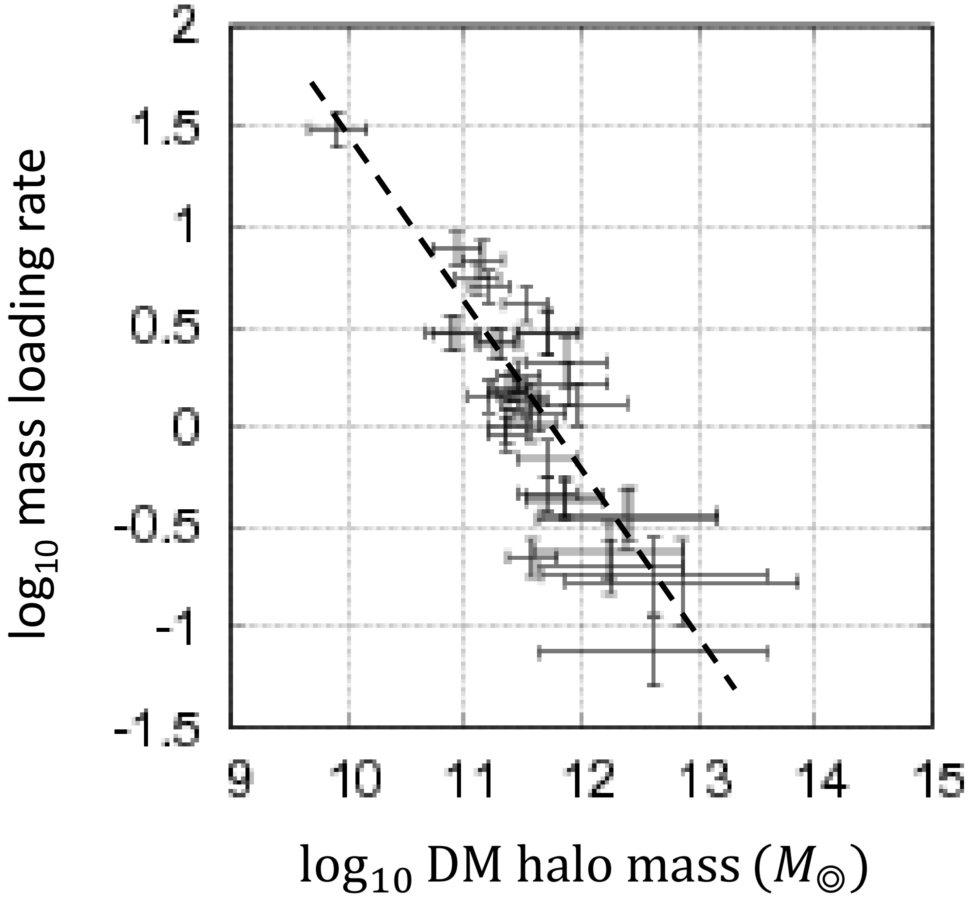
Shell outflow model



Result: dependence on dark matter halo

mass loading rate ≡ mass flux / ejected mass from SNeII

(ejected mass from SNeII = 0.35 x SFR)



$M_{DMH} \ll 10^{11.5} M_{\odot}$: mass loading rate $\gg 1$

efficient gas loss in small galaxies
(suppressing star formation)

$M_{DMH} \sim 10^{11.5} M_{\odot}$: mass loading rate ~ 1

gas loss comparable to ejected mass from SNeII

($M_{DMH} \gg 10^{11.5} M_{\odot}$: mass loading rate $\ll 1$)

(inefficient gas loss)

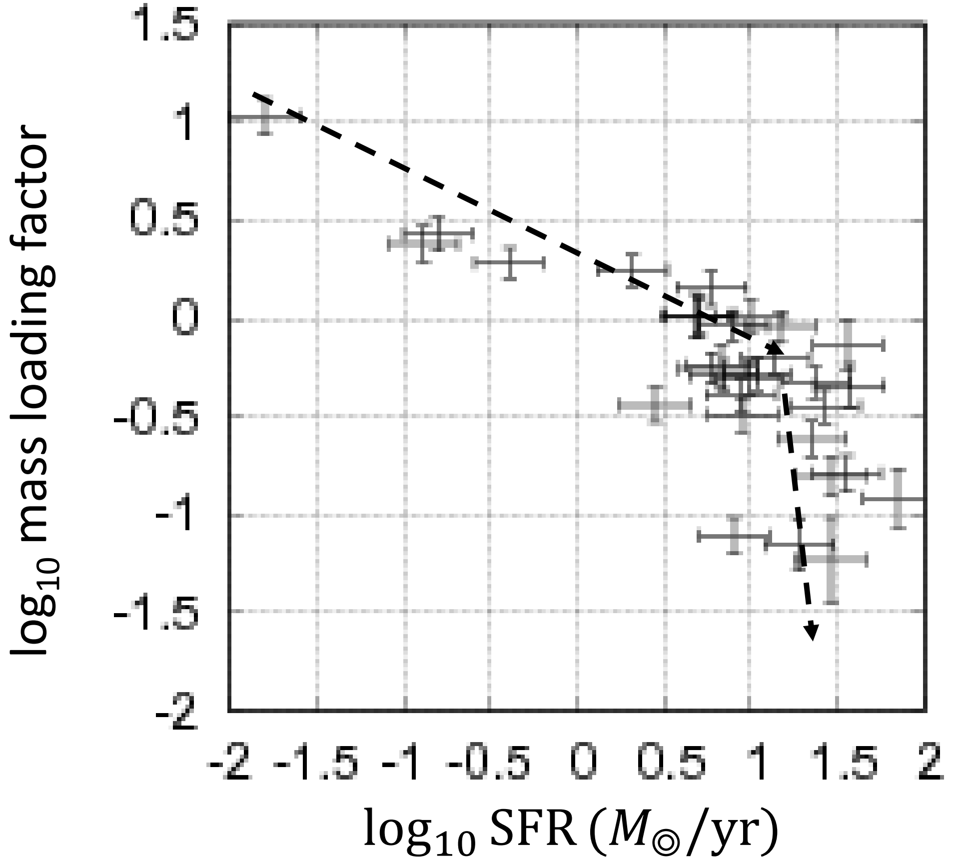
Conclusion

- With transonic outflow model, the estimated mass loading factor strongly depends on dark matter halo mass. Large mass loading factor in small-mass galaxies indicates the high efficiency of gas loss.

Future work

- We apply to high-z galaxies and clarify the dependence on redshifts.

discussion



1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
$\log_{10}$ mass loading factor
$\log_{10}$ SFR ($M_{\odot}$/yr)

Transonic outflow model

r: radius
v: velocity
ρ: density
c_s: sound speed
P: pressure

g: graviry
M: Mach number
Γ:specific heat ratio
$\dot{\rho}_m$: mass injection
$\dot{q}$: energy injection

adiabatic spherically-symmetric steady model

1.equation of continuity $\frac{1}{r^2}\frac{d}{dr}(\rho v r^2) = \dot{\rho_m}$

2.equation of motion $\rho v \frac{dv}{dr} = -\frac{dP}{dr} + \rho g - \dot{\rho_m} v$

3.energy equation $\frac{1}{r^2}\frac{d}{dr}\left\{ v r^2 \left(\frac{1}{2}\rho v^2 + \frac{\Gamma}{\Gamma - 1} P \right) \right\} = \rho v g + \dot{q}$

mass flux $\dot{m} \equiv 4\pi\rho v r^2$

energy flux

$$\dot{e} \equiv \left\{ \frac{1}{2} v^2 + \frac{1}{\Gamma - 1} c_s^2 + \Phi \right\} \dot{m}$$

$$\Rightarrow \quad \frac{M^2 - 1}{M^2\{(\Gamma - 1)M^2 + 2\}} \frac{dM^2}{dr} = \frac{2}{r} - \frac{\Gamma + 1}{2(\Gamma - 1)} \frac{\dot{m}}{\dot{e} - \dot{m}\Phi} \frac{d\Phi}{dr} - \frac{\Gamma M^2 + 1}{2} \frac{\dot{e} - 2\dot{m}\Phi}{\dot{e} - \dot{m}\Phi} \frac{1}{\dot{m}} \frac{d\dot{m}}{dr}$$

assuming mass and energy injected by SNeII

mass and energy injections

$\dot{\rho}_m = \lambda_{MLF}(SFR/M_{st})\rho_{st}$
$\dot{q} = e_{SN}(SFR/M_{st})\rho_{st}$

e_{SN}: injected energy per stellar mass
(= 0.1 x 1.86 x 10^{-2} x 10^{51} erg)

λ_{MLF}: mass loading factor (=massflux/SFR)

stellar mass distribution (Hernquist 1990)

$$\rho_{st}(r) = \frac{M_{st}}{2\pi} \frac{r_H}{r} \frac{1}{(r + r_H)^3} \quad \left(r_H = \frac{r_{1/2}}{1 + \sqrt{2}} \right)$$

M_{st}: total stellar mass
r_{H}: scale radius
$r_{1/2}$: half light radius

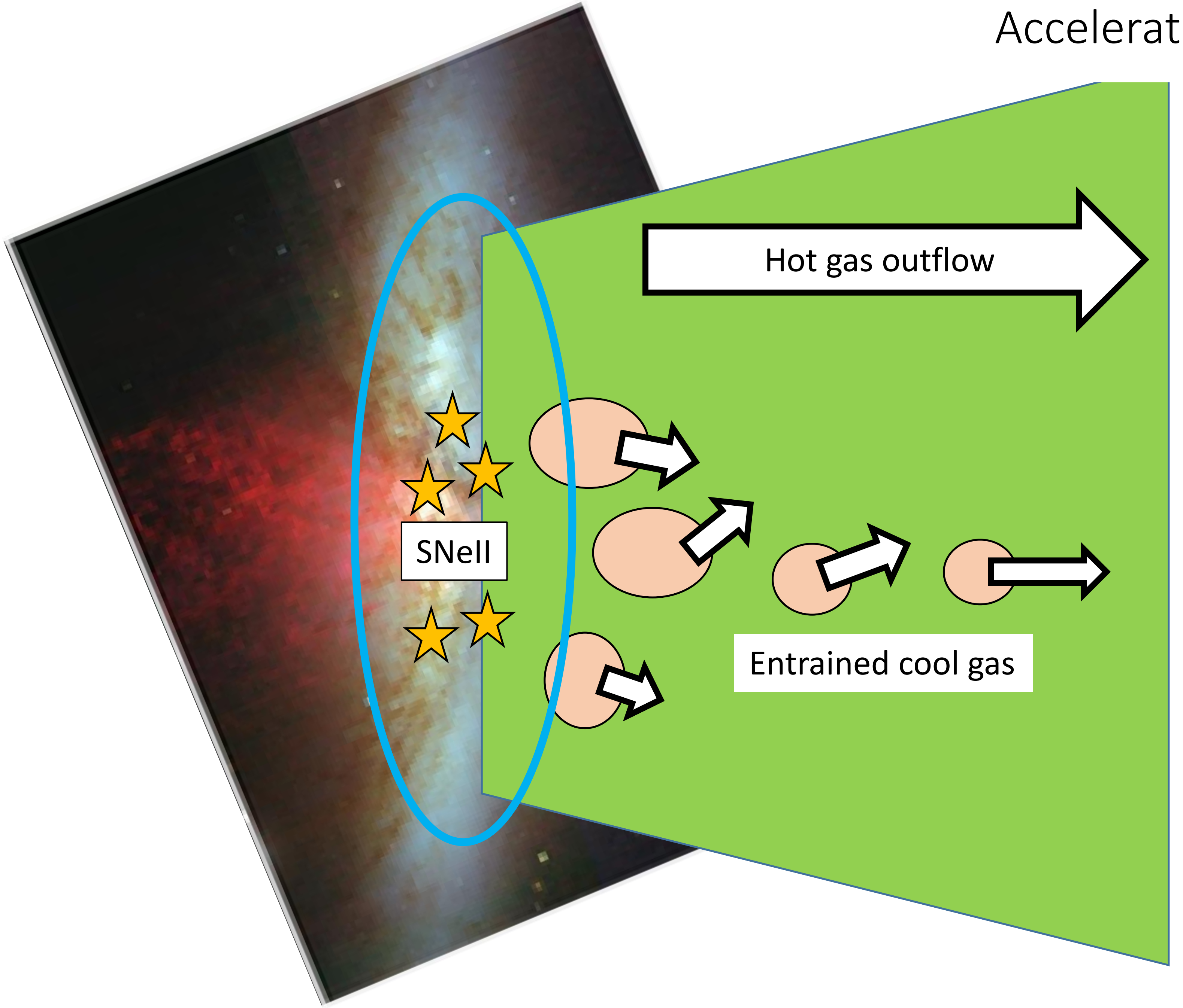
assuming the gravity of dark matter (DM) halo and stellar mass

DM halo mass distribution indicted by CDM scenario (Navarro et al. 1996)

$$\rho_{DMH}(r) = \frac{\rho_{dmh} r_{dmh}^3}{r(r + r_{dmh})^2}$$

r_{dmh}: DM halo scale radius
ρ_{dmh}: DM halo scale density

Acceleration process of galactic outflows



star formation in central region

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SNeII

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acceleration process

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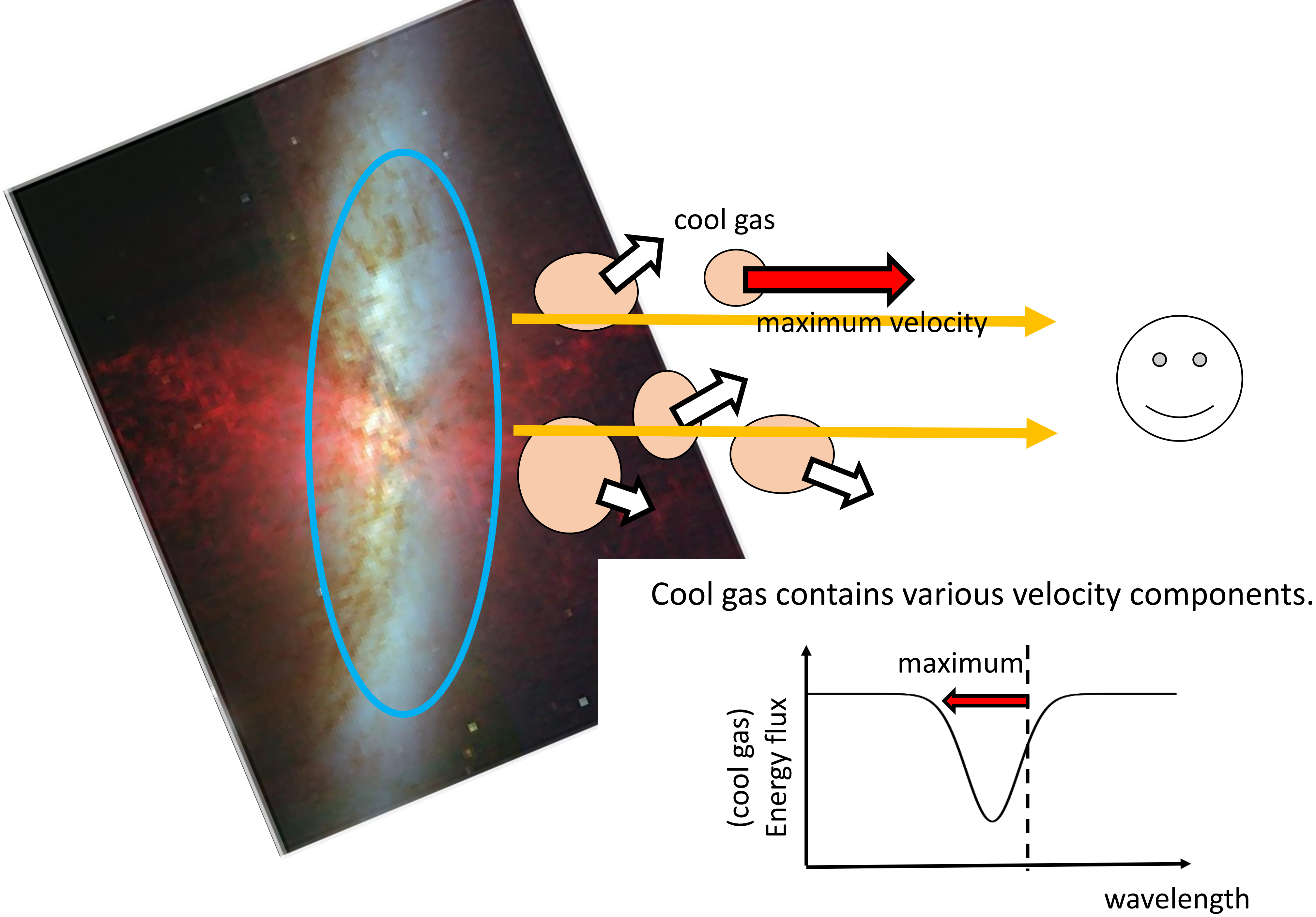
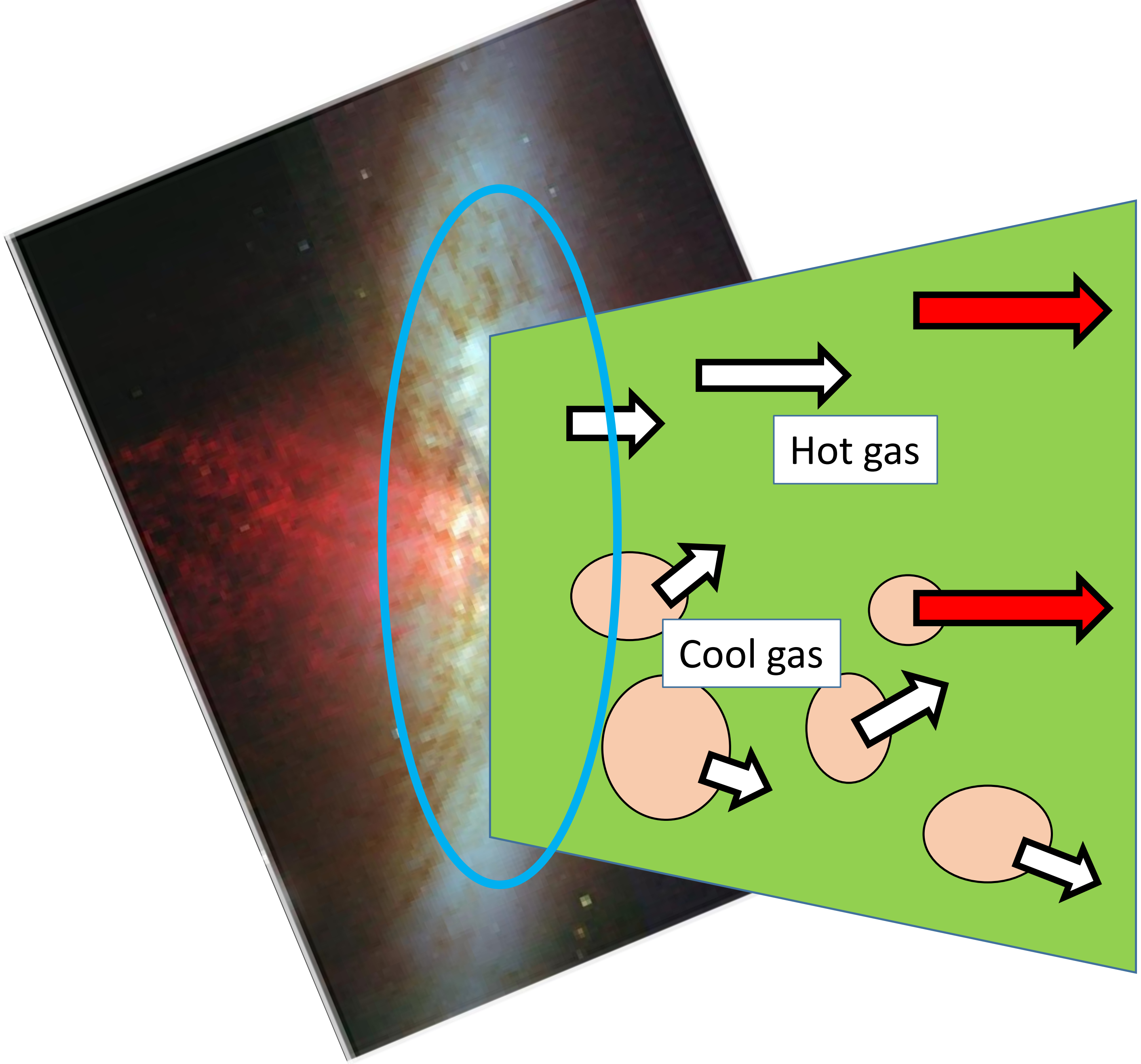
Hot gas outflow
(entraining cool gas)


cool gas
maximum velocity
Cool gas contains various velocity components.
maximum
(cool gas)
Energy flux
wavelength



Cool gas accelerating
with hot gas flow

maximum velocity of cool gas

≀

maximum velocity of hot gas
(lower limit)

Classification of transonic solutions

6 parameters : $(\lambda, SFR, M_{DMH}, M_{st}, r_H, r_d)$

$\dot{m}_{inj}(\lambda, SFR) \equiv \lambda R_f SFR$: total mass flux (M_o/yr)

$\dot{e}_{inj}(SFR) \equiv \eta \in_{SN} SFR$: total injected energy (erg/yr)

$\dot{e}_{\Phi,dmh}(\lambda, SFR, M_{DMH}, r_d) \equiv \dot{m}_{inj}\, G\left(\frac{4}{3}\pi\rho_d r_d^3\right) r_d^{-1} \sim \dot{m}_{inj}\frac{GM_{DMH}}{r_d}$: work of DM halo (erg/yr)

$\dot{e}_{\Phi,H}(\lambda, SFR, M_{st}, r_d) \equiv \dot{m}_{inj}\frac{GM_{st}}{r_d}$

3 non-dimensional parameters: $\left(\frac{r_H}{r_d}, \frac{\dot{e}_{\Phi,dmh}}{\dot{e}_{inj}}, \frac{\dot{e}_{\Phi,H}}{\dot{e}_{inj}}\right)$

$$\frac{M^2-1}{M^2\{(\Gamma-1)M^2+2\}}\frac{dM^2}{dx} = \frac{2}{x} - \frac{\Gamma+1}{2(\Gamma-1)}\frac{\dot{m}_n}{\dot{e}_n - \dot{m}_n\Phi_n}\frac{d\Phi_n}{dx}$$

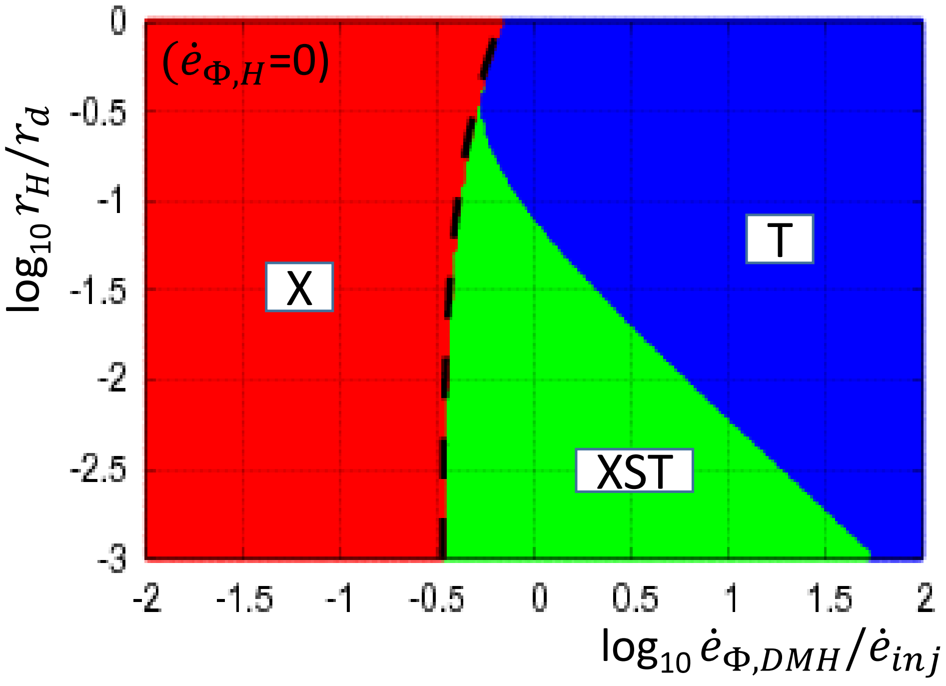
$$-\frac{\Gamma M^2+1}{2}\frac{\dot{e}_n - 2\dot{m}_n\Phi_n}{\dot{e}_n - \dot{m}_n\Phi_n}\frac{1}{\dot{m}_n}\frac{d\dot{m}_n}{dx} - \frac{\Gamma M^2+1}{2}\frac{1}{\dot{e}_n - \dot{m}_n\Phi_n}\frac{d\dot{e}_n}{dx}$$

$$\Phi_n \equiv \frac{\Phi}{\dot{e}_{inj}/\dot{m}_{inj}} \qquad \dot{m}_n \equiv \frac{\dot{m}}{\dot{m}_{inj}} \qquad \dot{e}_n \equiv \frac{\dot{e}}{\dot{e}_{inj}}$$

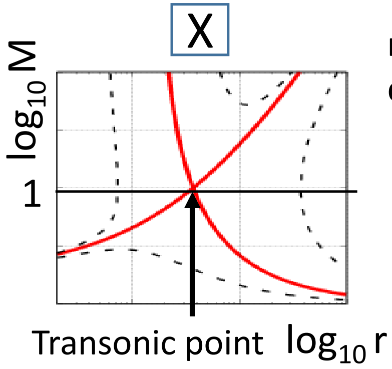
Classification of transonic solutions

$$\frac{r_H}{r_d} = \frac{\text{Stellar scale length}}{\text{DM halo scale length}} \qquad \frac{\dot{e}_{\Phi,dmh}}{\dot{e}_{inj}} \sim \frac{\text{Work of DM hlao gravity}}{\text{Injected energy}}$$

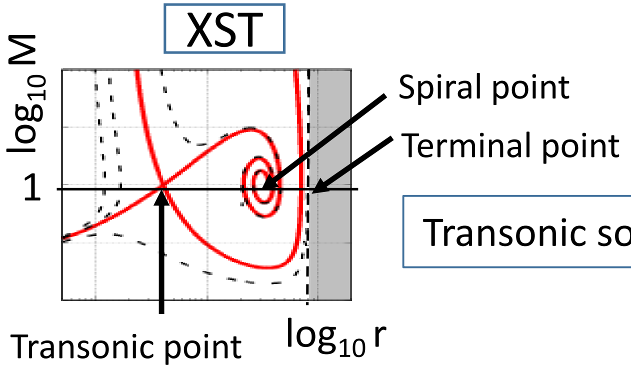
There are 3 patterns of transonic solutions.



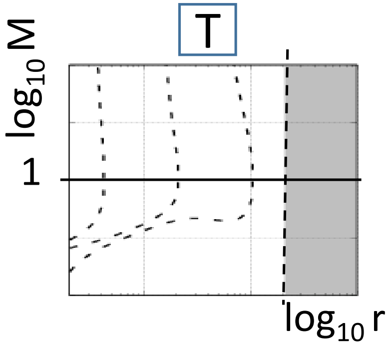
red : transonic solution
dashed : other solution



Transonic solution expands to infinity.



Transonic solution stops.

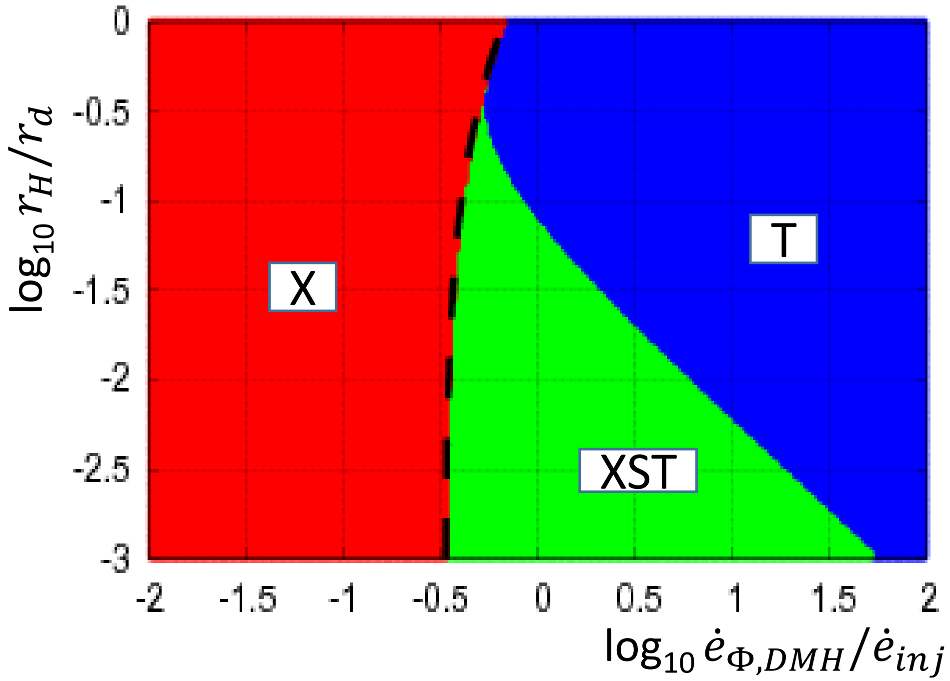


No transonic solution

Classification of transonic solutions

$$\frac{r_H}{r_d} = \frac{\text{Stellar scale length}}{\text{DM halo scale length}} \qquad \frac{\dot{e}_{\Phi,dmh}}{\dot{e}_{inj}} \sim \frac{\text{Work of DM hlao gravity}}{\text{Injected energy}}$$

$(\dot{e}_{\Phi,H}$=0)



Dashed line shows the case that the total energy becomes 0 in $x \to \infty$,

$$\dot{e} - \dot{m}\Phi = 0$$

$$\frac{\dot{e}_{\Phi,dmh}}{\dot{e}_{inj}} = \frac{(1 - r_H/r_{dmh})^2}{3r_H/r_{dmh}} \times \left(\log(r_H/r_{dmh}) + \frac{1 - r_H/r_{dmh}}{r_H/r_{dmh}}\right)^{-1}.$$

Classification of transonic solutions

$$\frac{r_H}{r_d} = \frac{\text{Stellar scale length}}{\text{DM halo scale length}} \quad \frac{\dot{e}_{\Phi,dmh}}{\dot{e}_{inj}} \sim \frac{\text{Work of DM hlao gravity}}{\text{Injected energy}}$$