Galaxy-IGM workshop 2020

16：10-16:30 0804

遷音速アウトフローモデルによる高赤方偏移星形成銀河の mass loading factorの推定
(mass loading factor of high-z star-forming galaxies with transonic outflow model)

五十嵐朱夏、森正夫（筑波大）、新田伸也（筑波技大）

(Igarashi, A., Mori, M. & Nitta, S.)

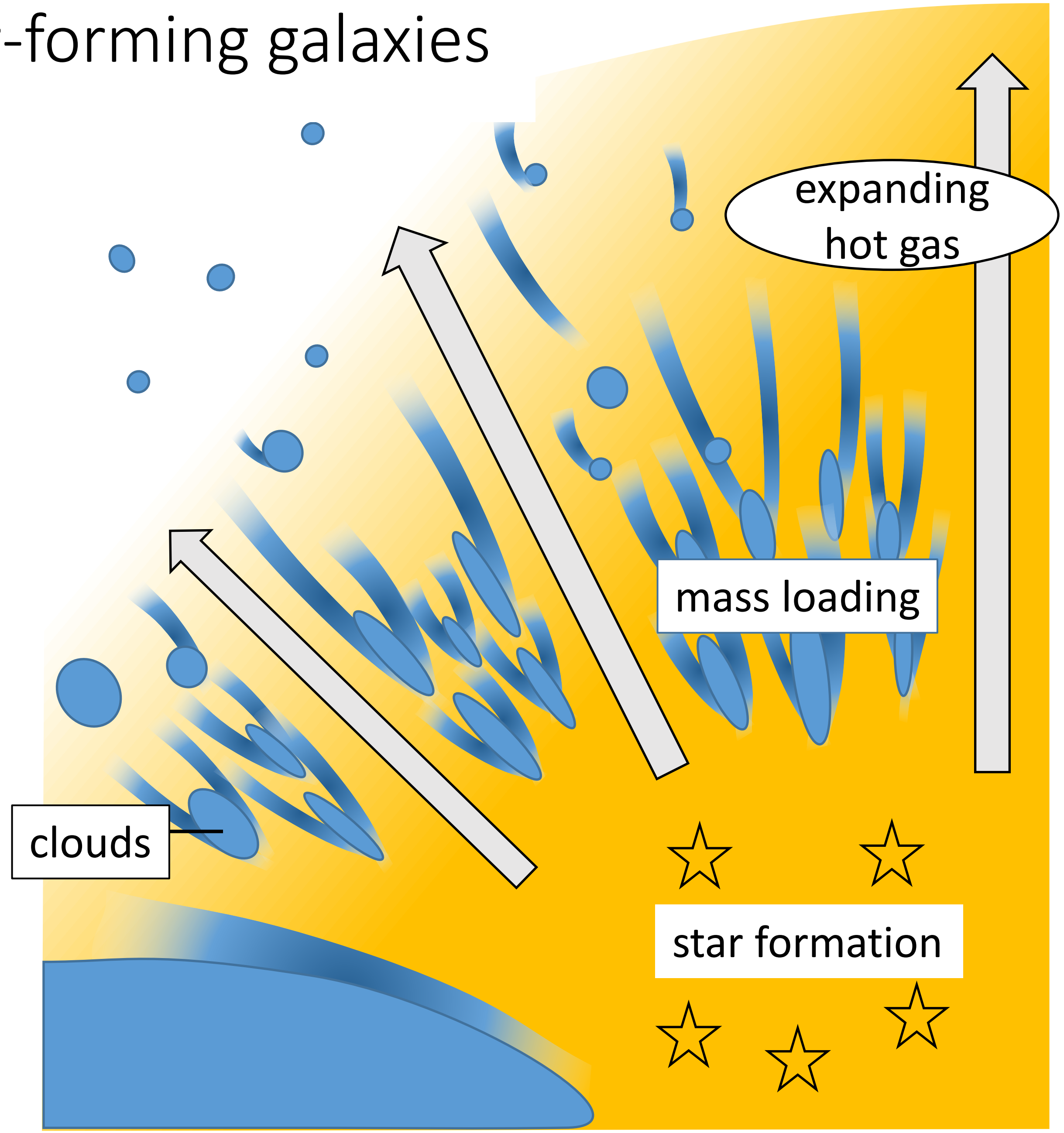
Introduction: Galactic winds in star-forming galaxies

High SFR

→ inject energy to ISM

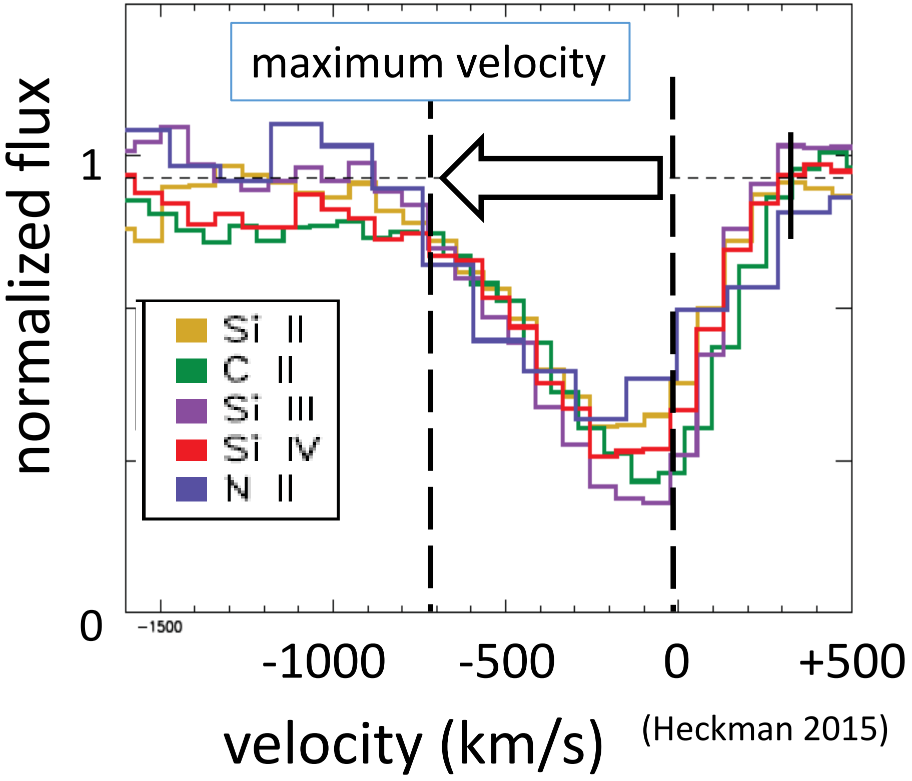
→ galactic winds

1. suppress star formation
2. metal enrichment in intergalactic space



Introduction: outflow velocity

shifted absorption lines
→ outflow velocity

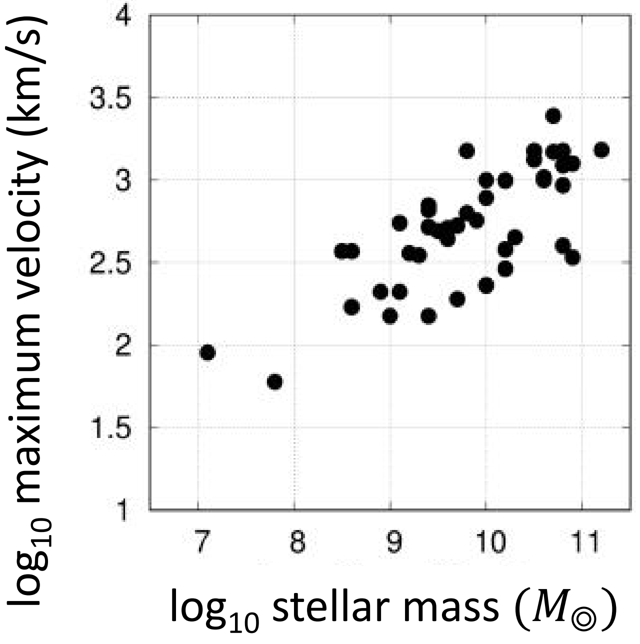


(Heckman 2015)

observed maximum velocity
≀
maximum velocity of hot gas (lower limit)

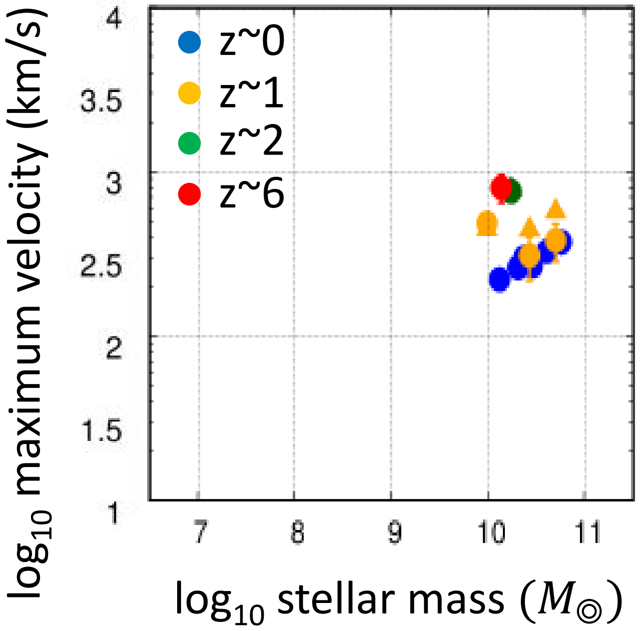
local star-forming galaxies

(Heckman 2015, 2016)



high-z star-forming galaxies

(Sugahara et al. 2017, 2019)



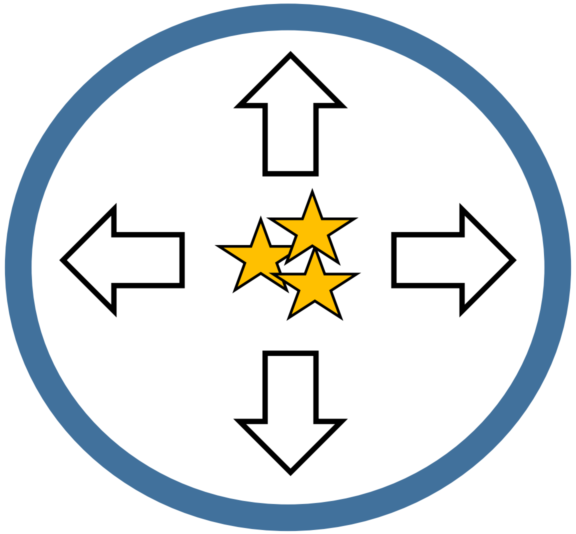
positive correlation to stellar mass (and SFR)

The influence of galactic winds depends on { velocity / massflux }

outflow model to estimate massflux

shell model vs **transonic outflow model**

Introduction: shell outflow model



$\dot{M}$: massflux
N_H: column density
$\langle m \rangle$:average mass
v_{out}: average velocity
r_{out}: shell radius

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

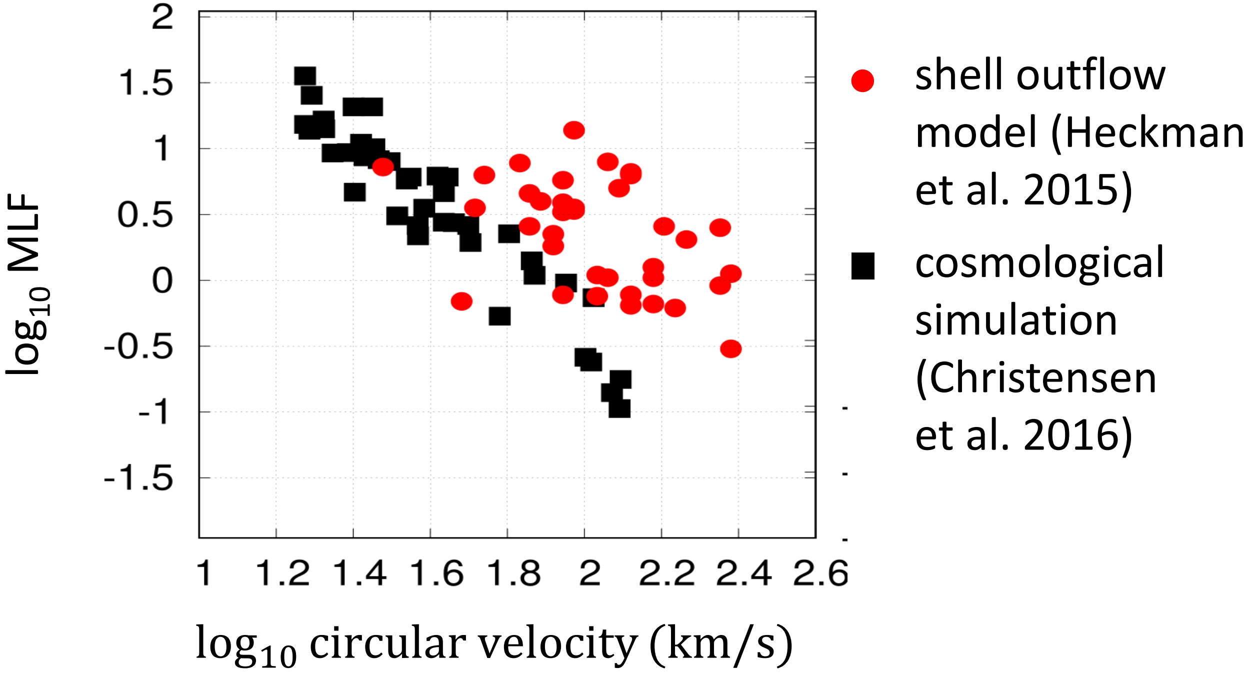
N_H estimated from metal column density

r_{out} assumed to be 2 x effective radius (UV)

N_H and r_{out} have uncertainty

mass loading factor (MLF) = $\dot{M}$ / SFR

MLF → efficiency of mass loading

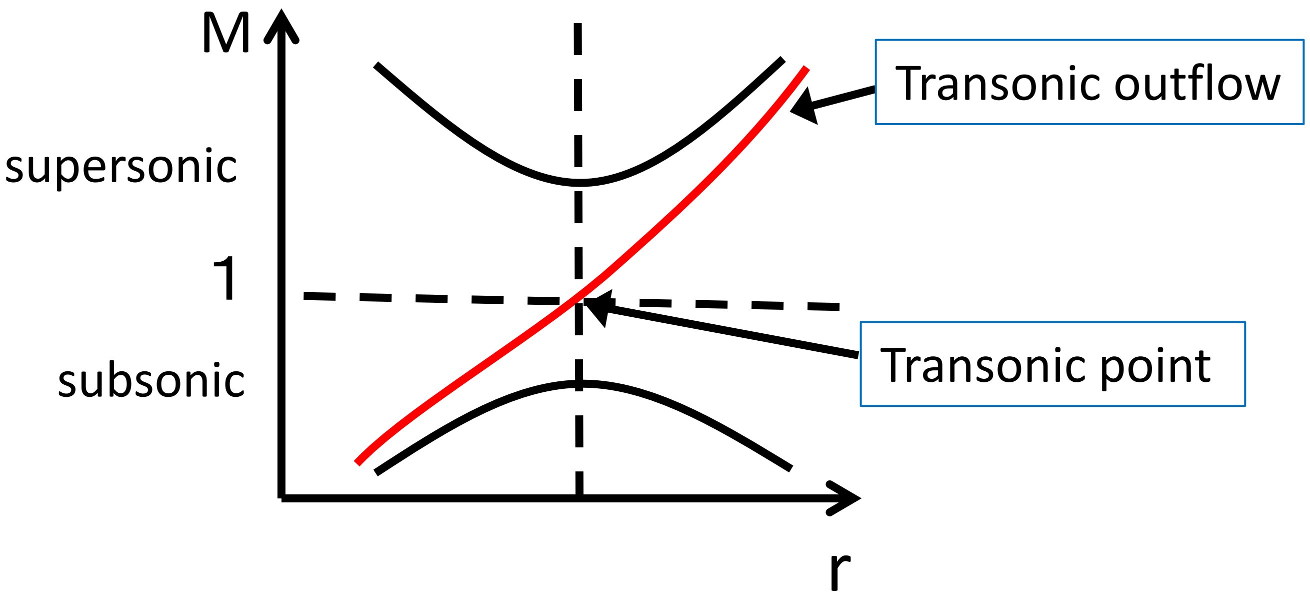


- slightly depends on halo mass
- not agree with theoretical prediction

⇨ **re-analyse observed velocity with new outflow model**

Introduction: transonic outflow model

example: solar model (Parker 1958)



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

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

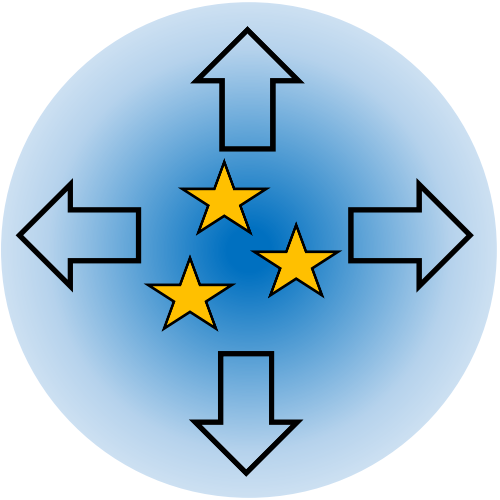
⇩

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

M: Mach number (= velocity / sound speed)

Transonic process has maximum entropy
→ assume transonic outflow of hot gas

Model: transonic outflow model

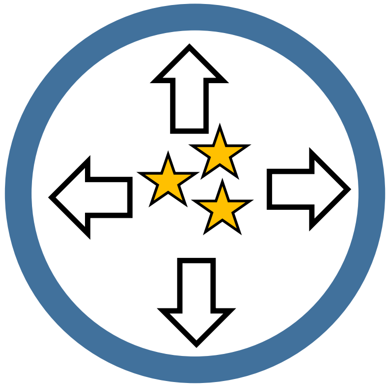


spherically symmetric steady model

$\dot{\rho}_m$: mass injeciton
(with mass loading)

$\dot{q}$: energy injeciton

Shell outflow model



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

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

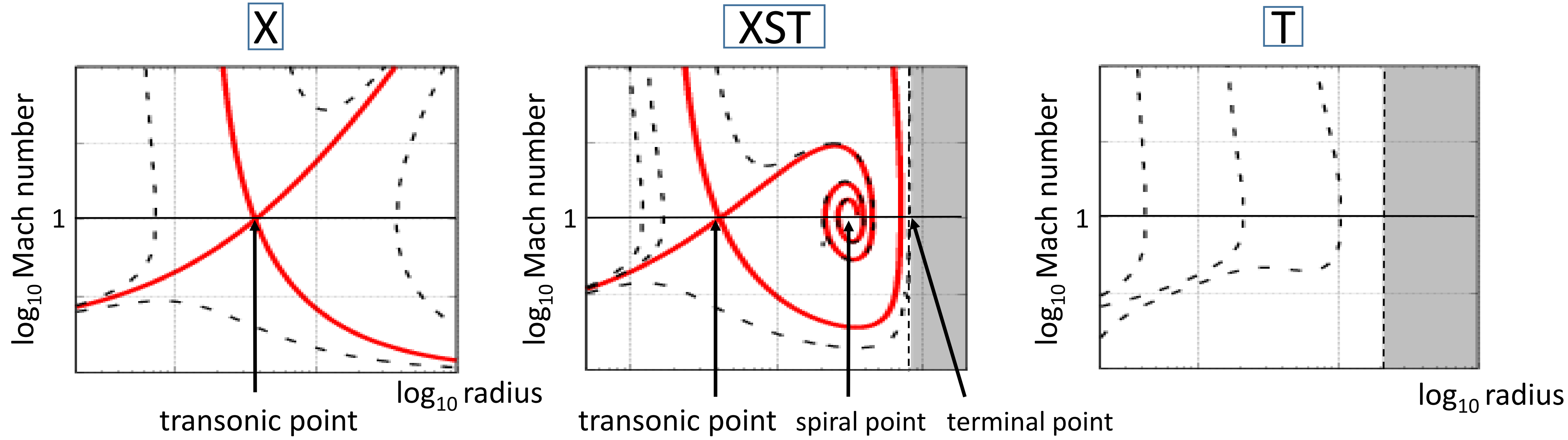
3. energy equation
$$\frac{1}{r^2}\frac{d}{dr}\left\{ v r^2 \left(\frac{1}{2}\rho v^2 + \frac{\Gamma}{\Gamma - 1} P \right) \right\} = \rho v g + \dot{q}$$

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

assume energy injection from SNeII

assume dark halo and stellar mass to the gravitational potential

Model: relation of solution type and massflux



Outflows can escape from galaxies

Outflows stop in dark halo

No transonic solution

low

gravity ($\propto$ dark halo mass)

high

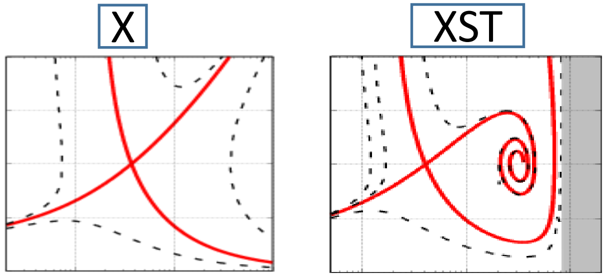
injected energy ($\propto$ SFR)

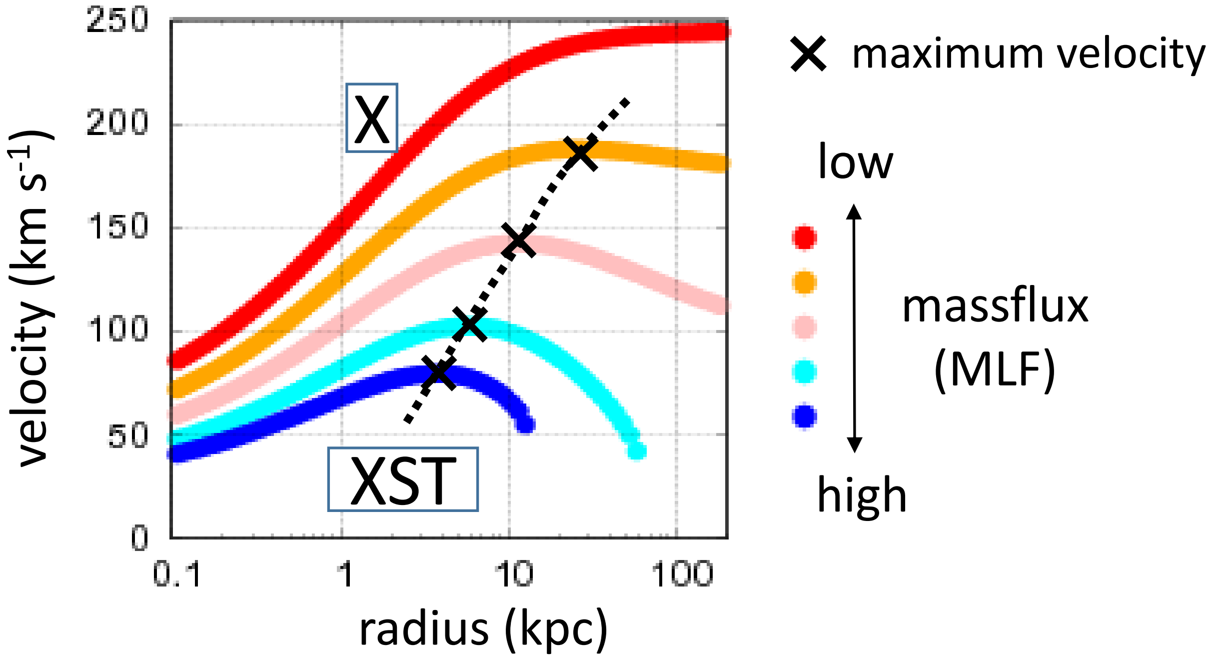
massflux

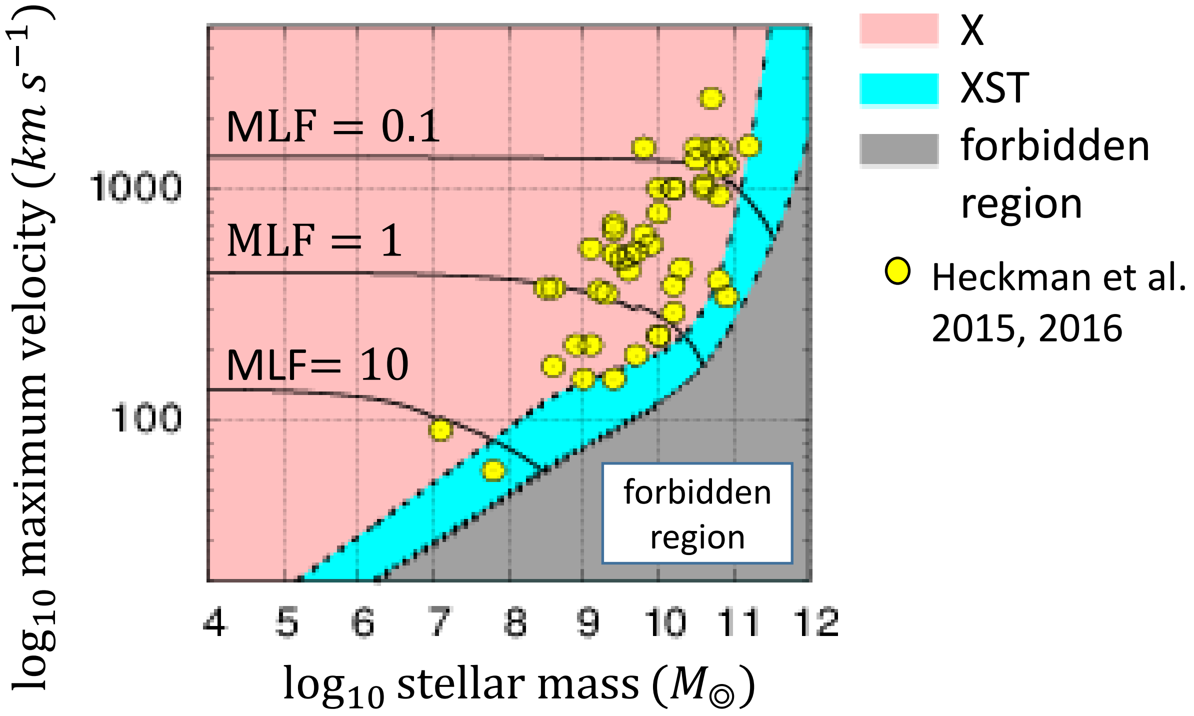
Result: velocity profile to mass loading factor (MLF)

$$\mathrm{MLF} = \dot{M} \,/\, \mathrm{SFR}$$

example: stellar mass = $10^{8.6}\,M_{\odot}$
(dark halo mass = $10^{10.96}\,M_{\odot}$)





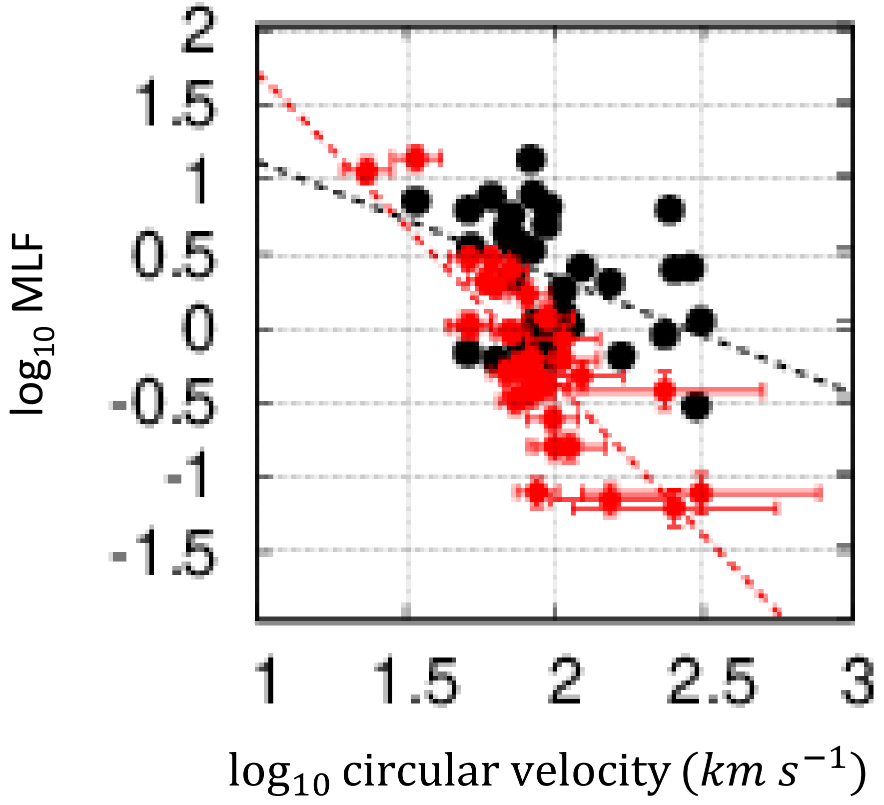


maximum velocity ⟺ massflux (MLF)

estimate MLF with transonic outflow model from observed maximum velocity

Result: in low-z star-forming galaxies

$\text{MLF} = \dot{M}\ /\ \text{SFR}$



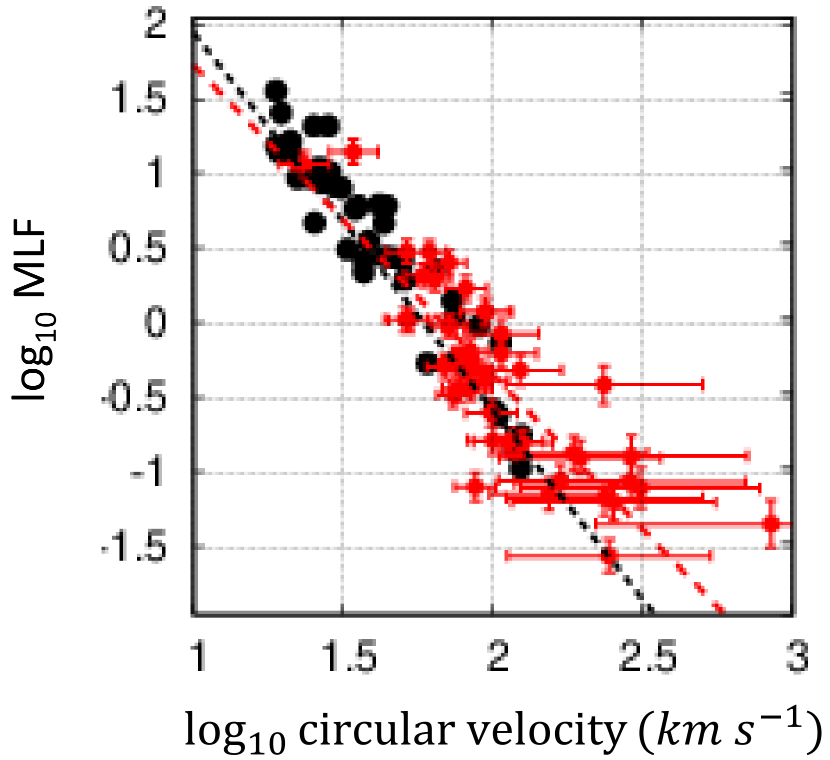
transonic outflow model

shell model (Heckman et al. 2015)

MLF depends on halo mass (MLF $\propto V_{\rm circ}^{-2.5}$)
→ ISM can effectively escape from small galaxies.

transonic outflow model

cosmological simulation (Christensen et al. 2016)
(reproduce stellar-halo mass relation、Tully-Fisher relation、mass-metallicity relation)

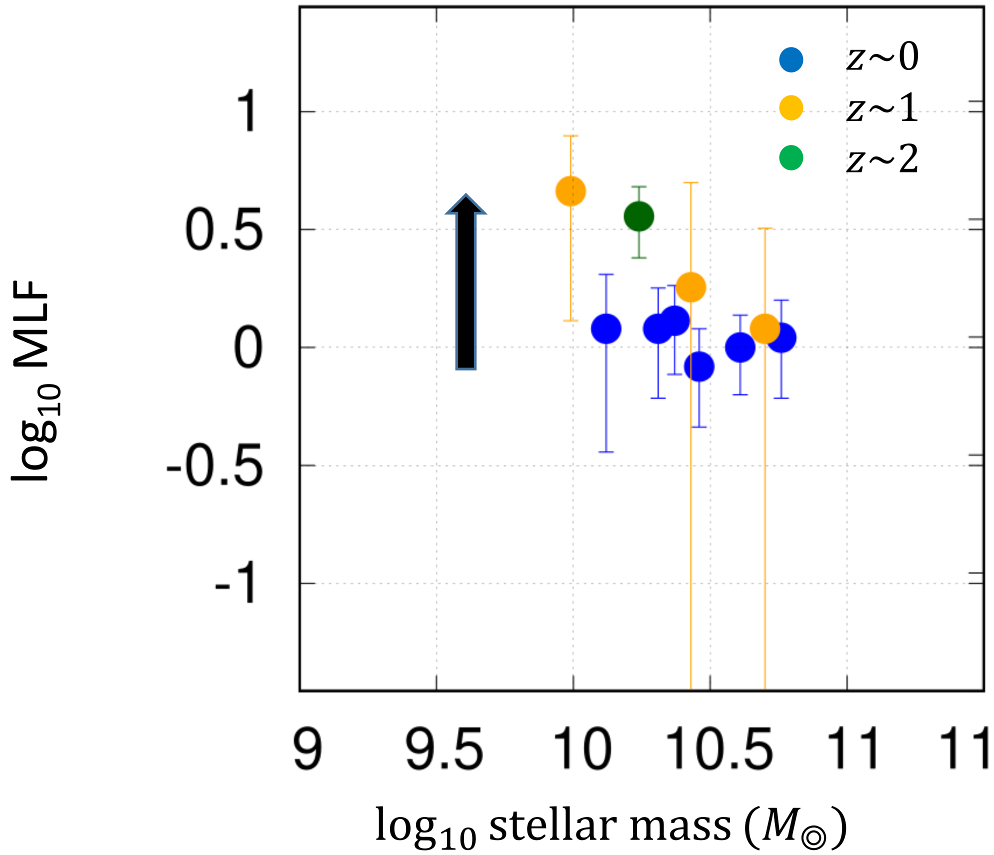


MLF becomes smaller than shell model.
MLF is comparable to theoretical prediction.
→ theoretical studies can reproduce velocity observation.

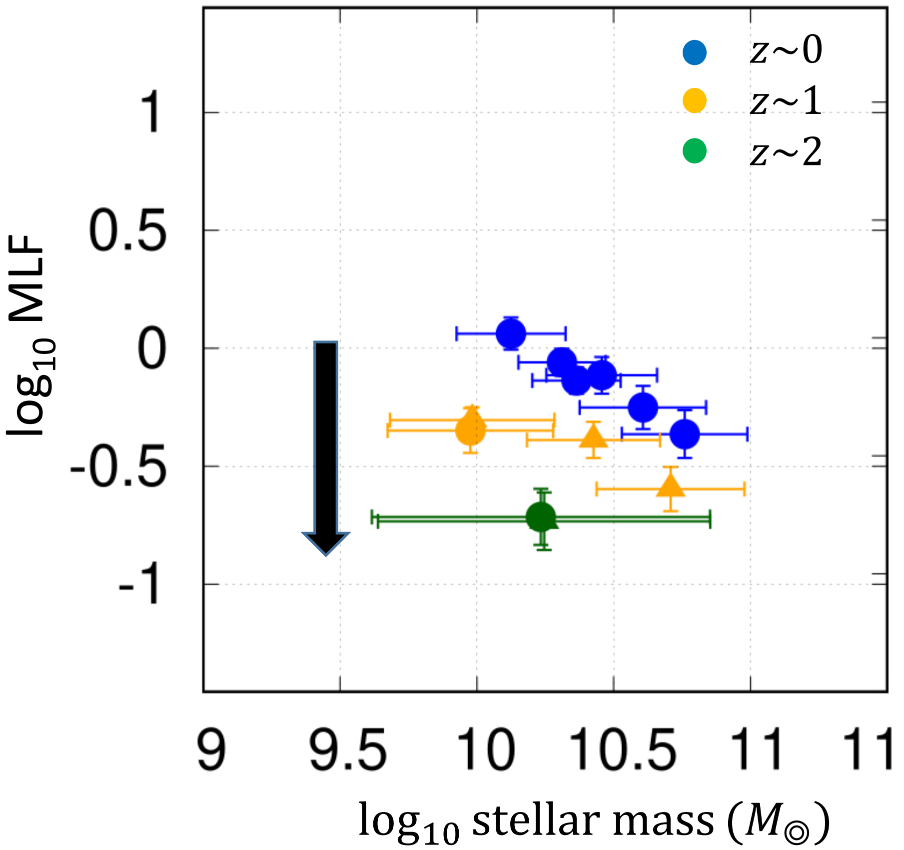
Result: in high-z star-forming galaxies

$\text{MLF} = \dot{M} / \text{SFR}$

shell model (Sugahara et al. 2017)



transonic outflow model



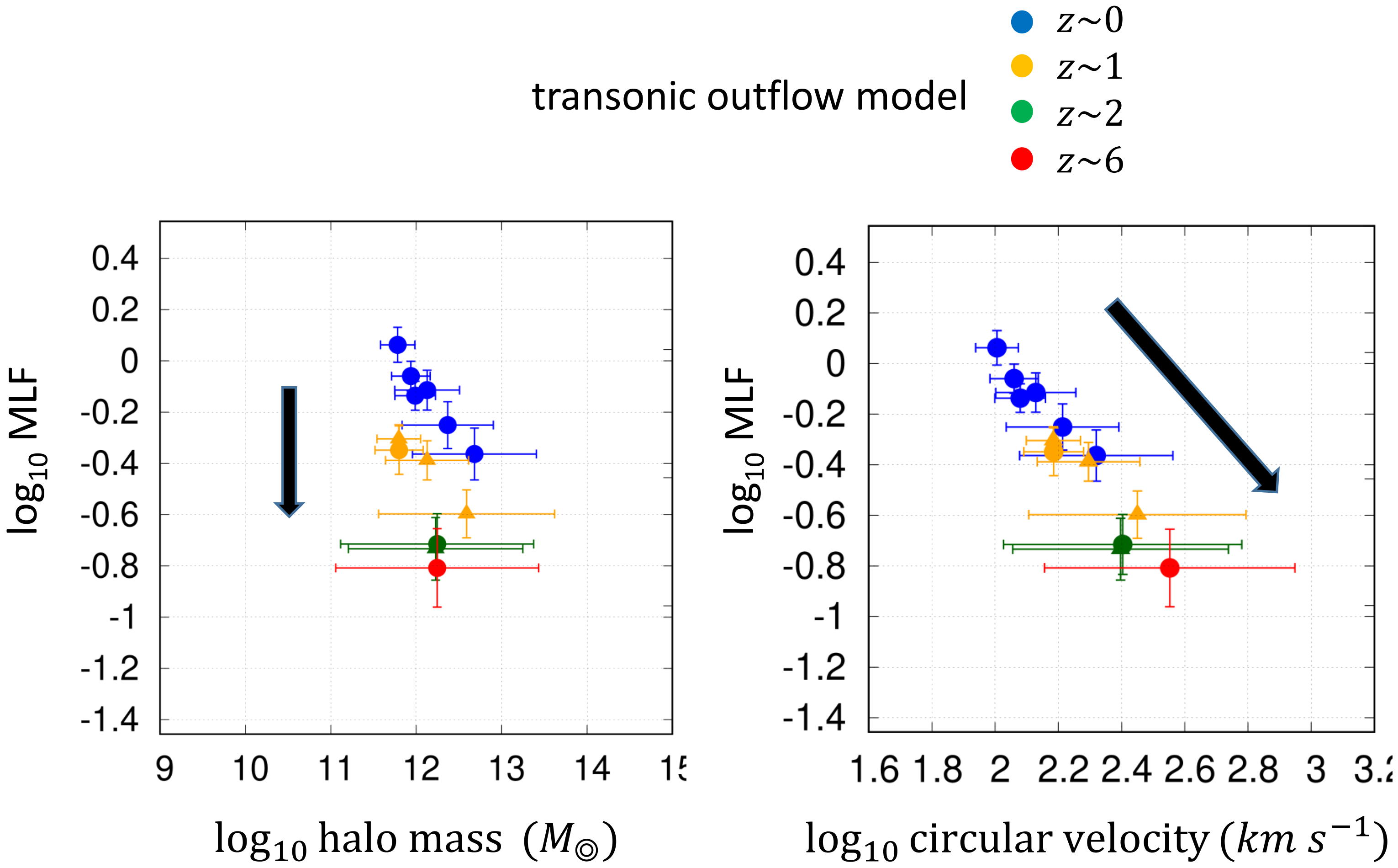
MLF decreases in high-z galaxies

→ opposite trend from shell model

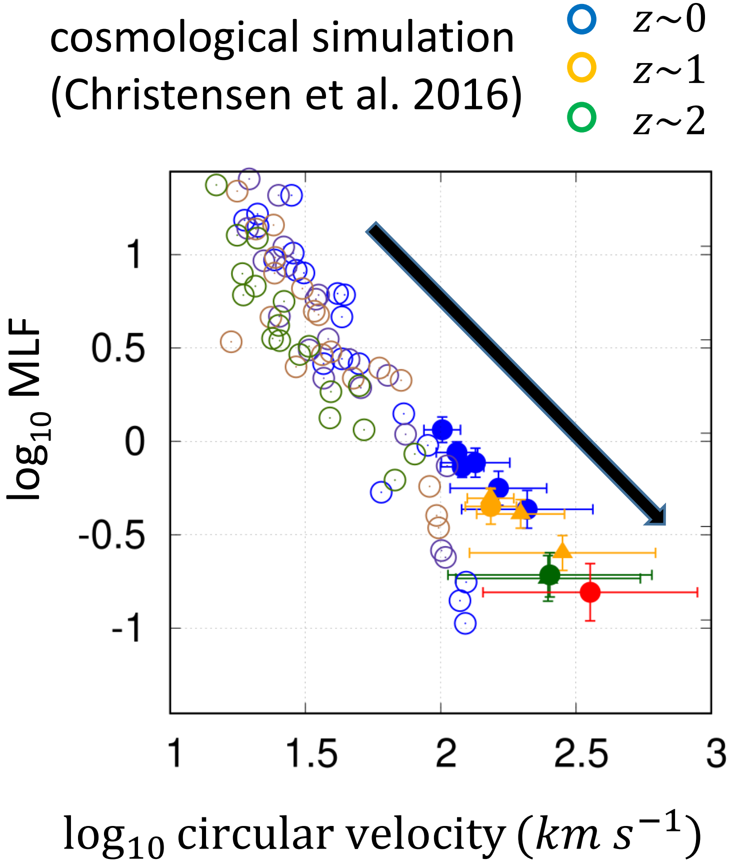
Result: in high-z star-forming galaxies

$$\mathrm{MLF} = \dot{M} \,/\, \mathrm{SFR}$$

transonic outflow model



cosmological simulation (Christensen et al. 2016)



MLFs depend on circular velocities.
→ structure of gravitational potential determines outflow acceleration

similar trend to cosmological simulation

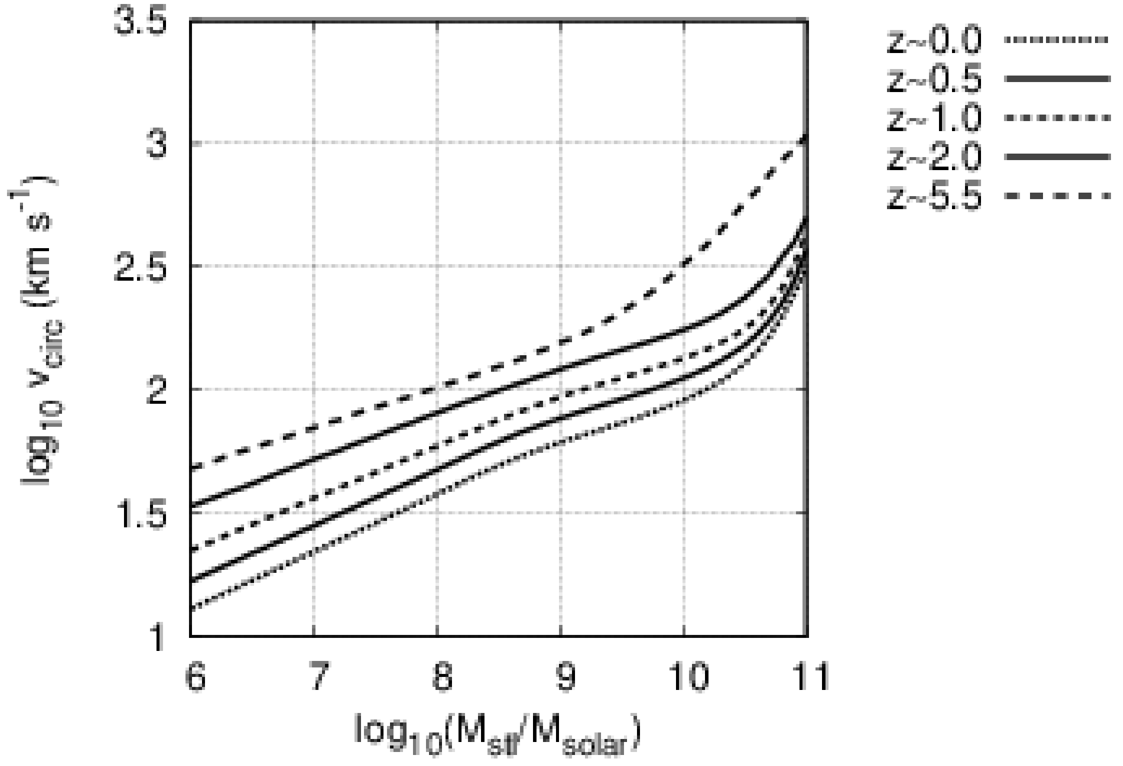
Conclusion

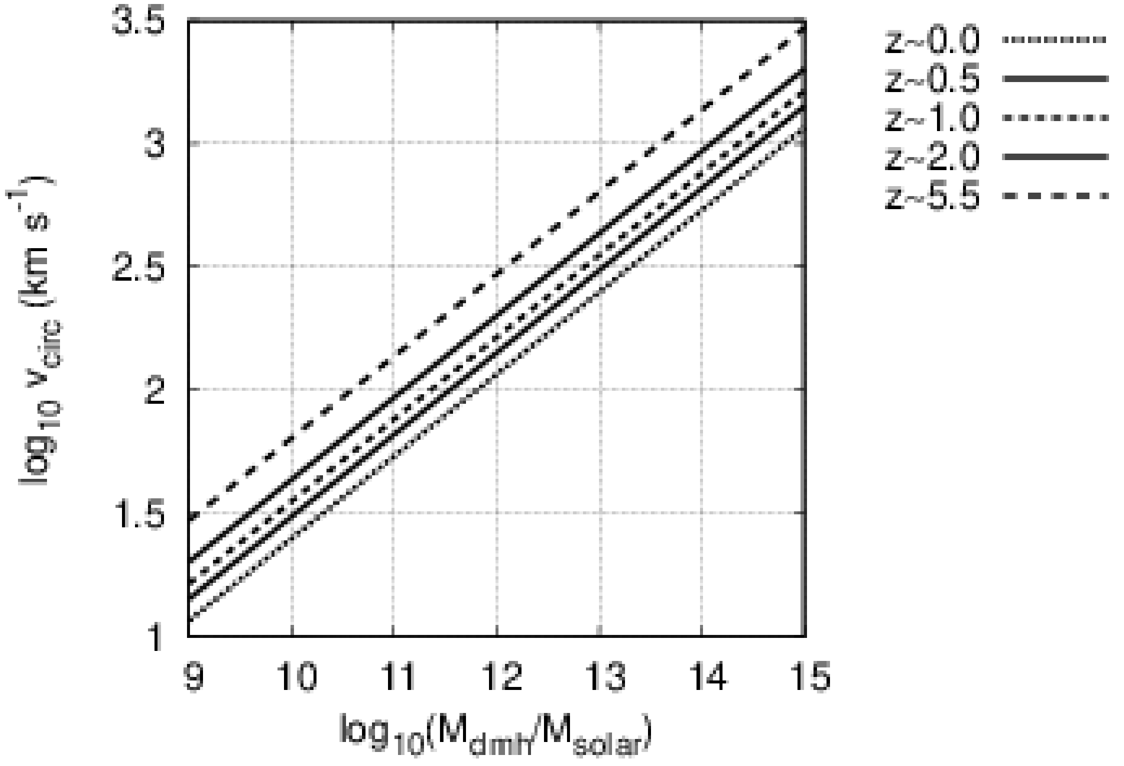
- In transonic outflow model, mass loading factor (MLF) depends strongly on gravitational potential of star-forming galaxies.
- We estimate MLF from observed velocities with transonic outflow model.

- The estimated MLFs become smaller than that of shell outflow model.
- Small galaxies can effectively eject interstellar gas with large MLFs.
- The theoretical predictions can reproduce velocity observations.

- In contrast to shell model, the estimated MLFs decrease in high-z star-forming galaxies .
- The MLFs depend on the structure of gravitational potential and change with circular velocities of star-forming galaxies.

Galaxy mass vs circular velocity





Transonic outflow model

adiabatic spherically-symmetric steady 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

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

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

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

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)

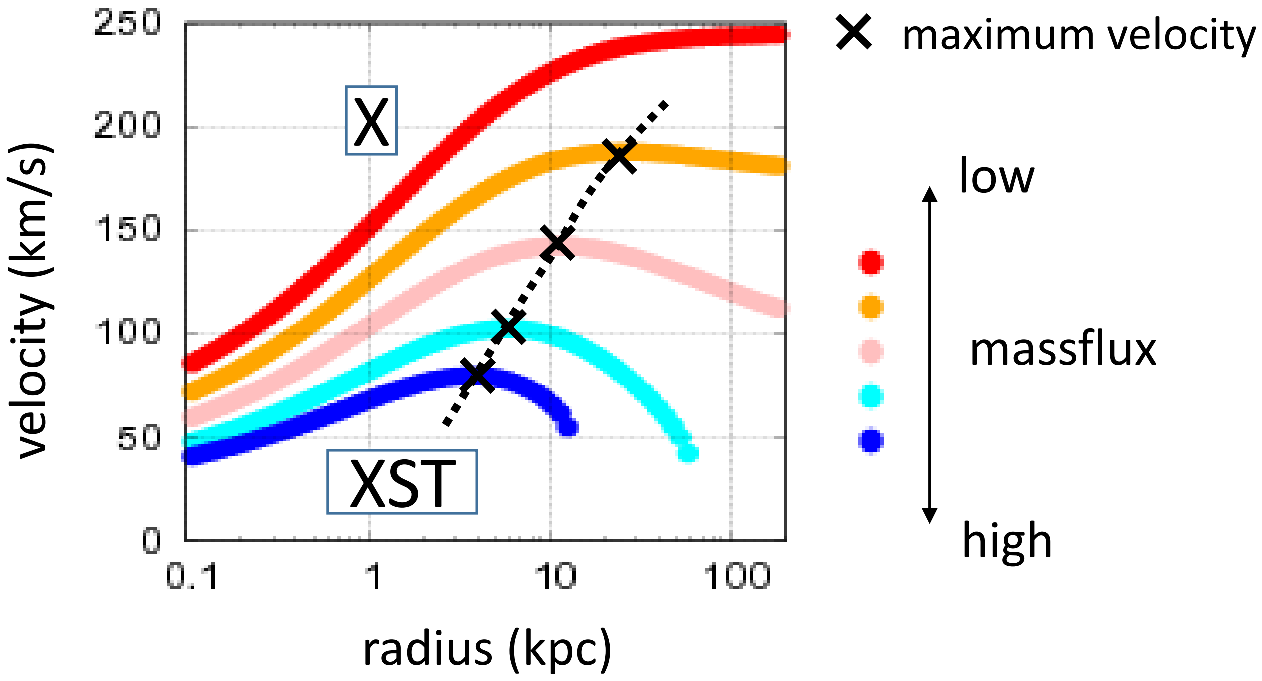
$$\rho_{DMH}(r) = \frac{\rho_{dmh} r_{dmh}^3}{r(r+r_{dmh})^2}$$

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

Result: velocity profile to mass loading factor (MLF)

$\boxed{\mathrm{MLF} = \dot{M} / \mathrm{SFR}}$

example: stellar mass = $10^{8.6}\,M_\odot$
(dark halo mass = $10^{10.96}\,M_\odot$)
SFR = 10 $M_\odot$/yr



Massflux corresponds to maximum velocity (larger than terminal velocity)

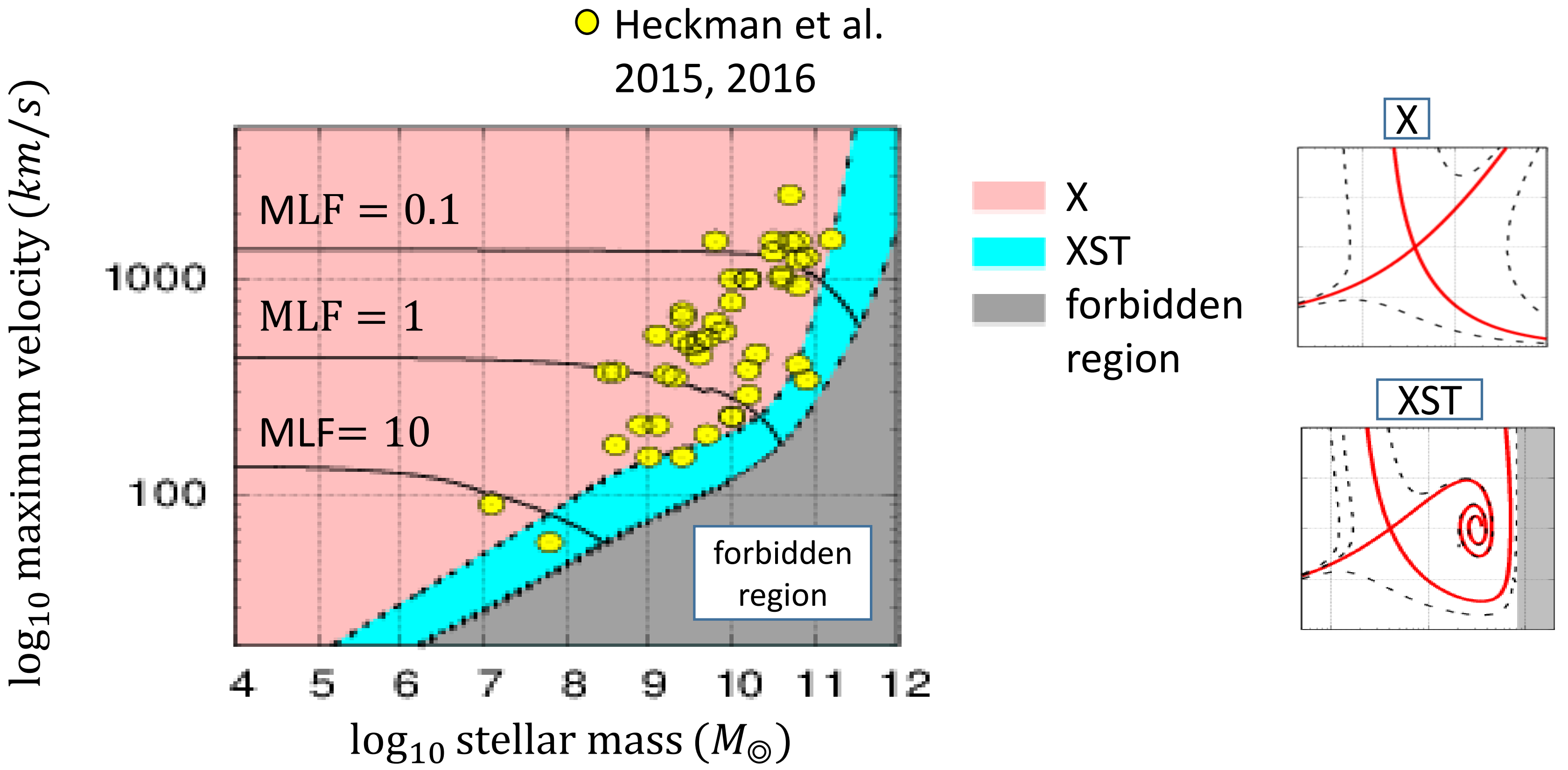
⇩

Maximum velocity corresponds to MLF

assume dark halo mass and effective radius from stellar mass and redshift (Behroozi et al. 2010, 2013; Bullock et al. 2001; Munoz-Cuartas et al. 2011; Shibuya et al. 2015).

Result: velocity profile to mass loading factor (MLF)

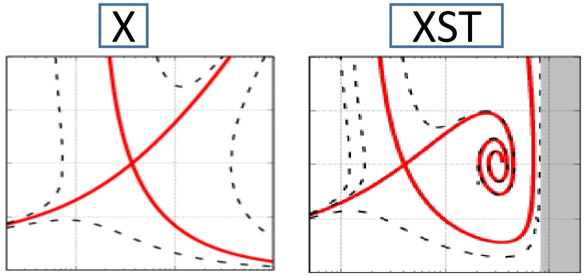
$\boxed{\mathrm{MLF} = \dot{M}\ /\ \mathrm{SFR}}$



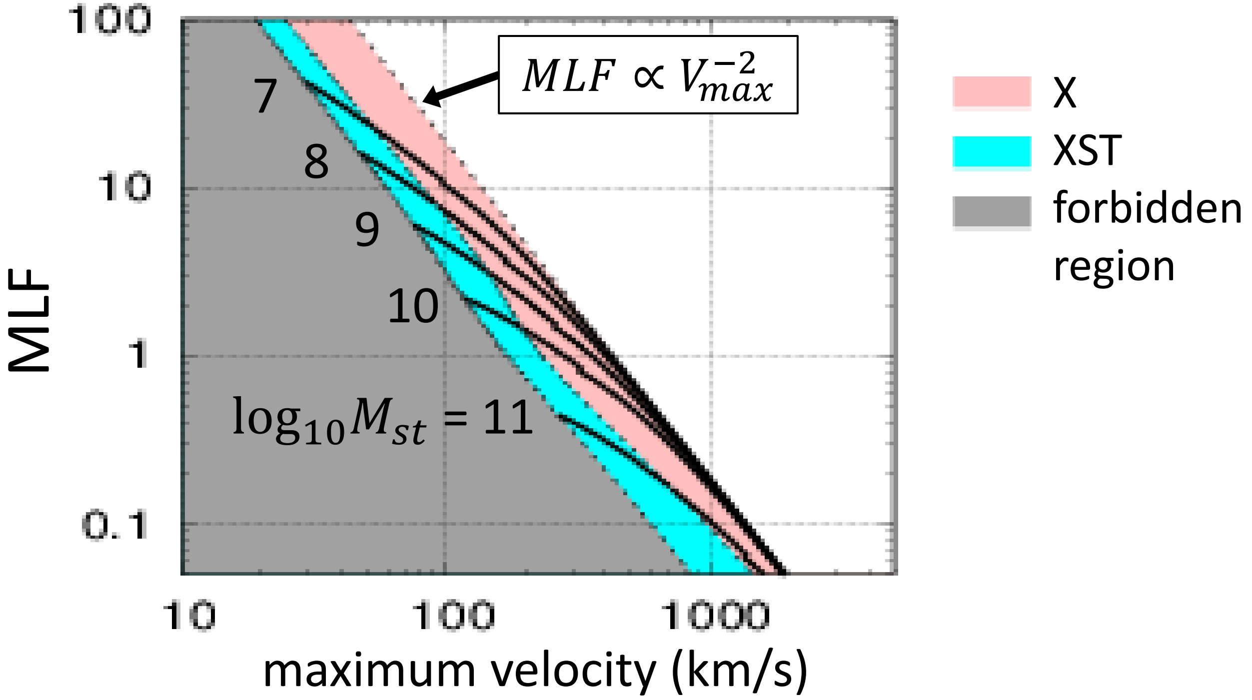
We can estimate massflux with transonic outflow model from observed velocity

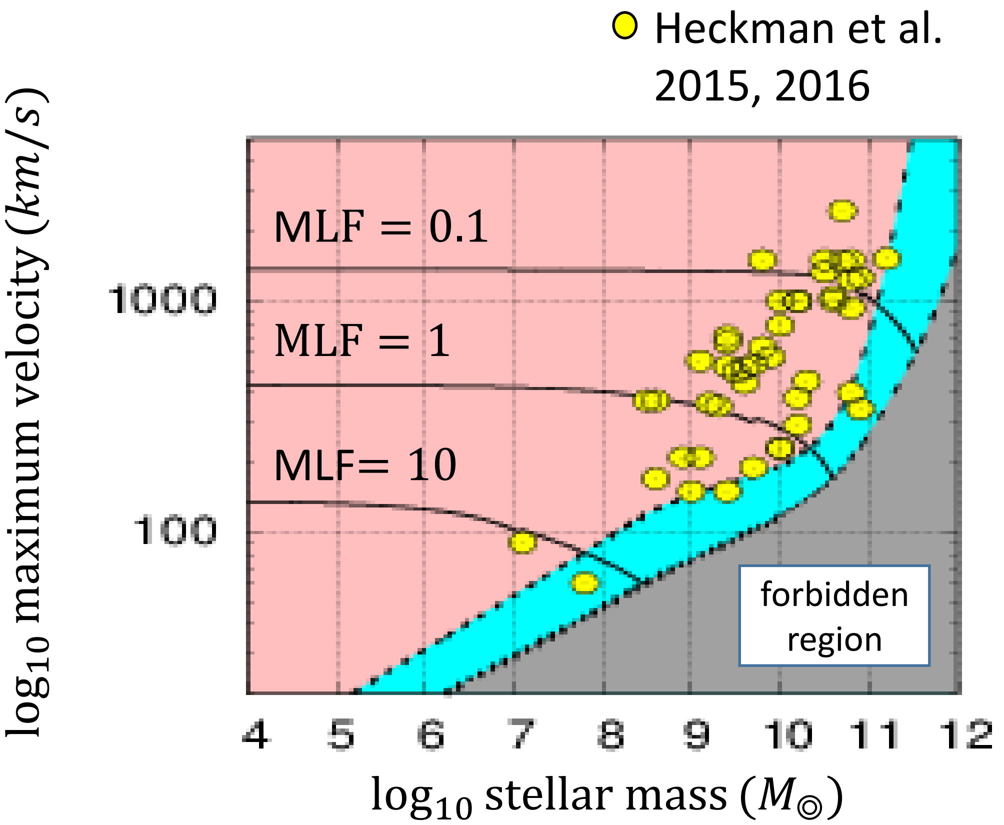
Result: velocity profile to mass loading factor (MLF)

$$\boxed{\mathrm{MLF} = \dot{M}\ /\ \mathrm{SFR}}$$



Maximum velocity to MLF (and stellar mass)

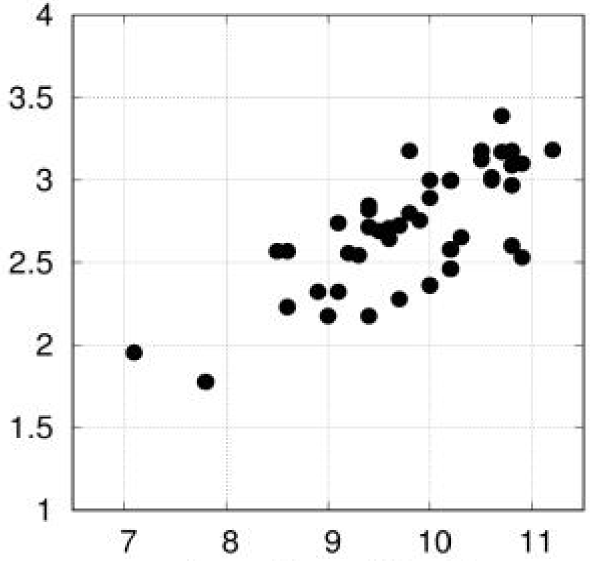




⇨ We can estimate massflux with transonic outflow model from observed velocity

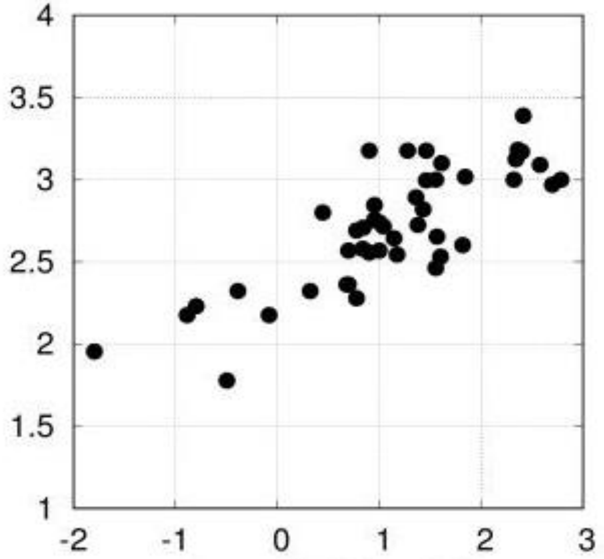
outflow velocity

(Heckman 2015, 2016)



$\log_{10}$ maximum velocity (km/s)

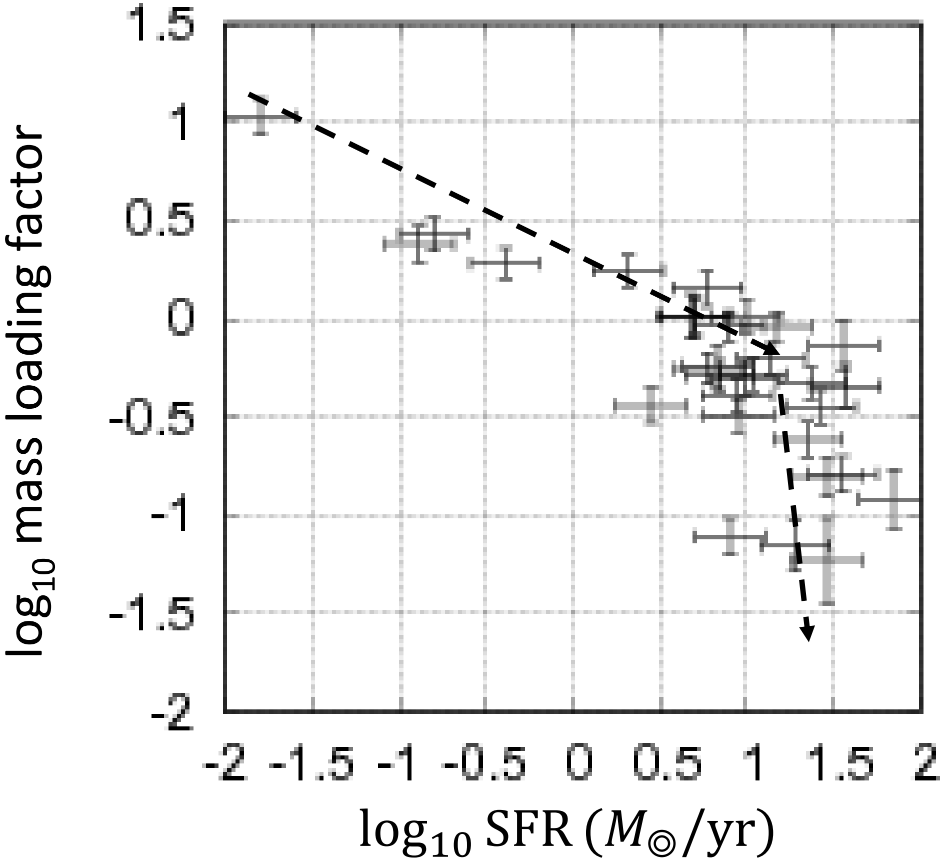
$\log_{10}$ stellar mass $(M_{\odot})$



$\log_{10}$ maximum velocity (km/s)

$\log_{10}$ SFR $(M_{\odot}/\text{yr})$

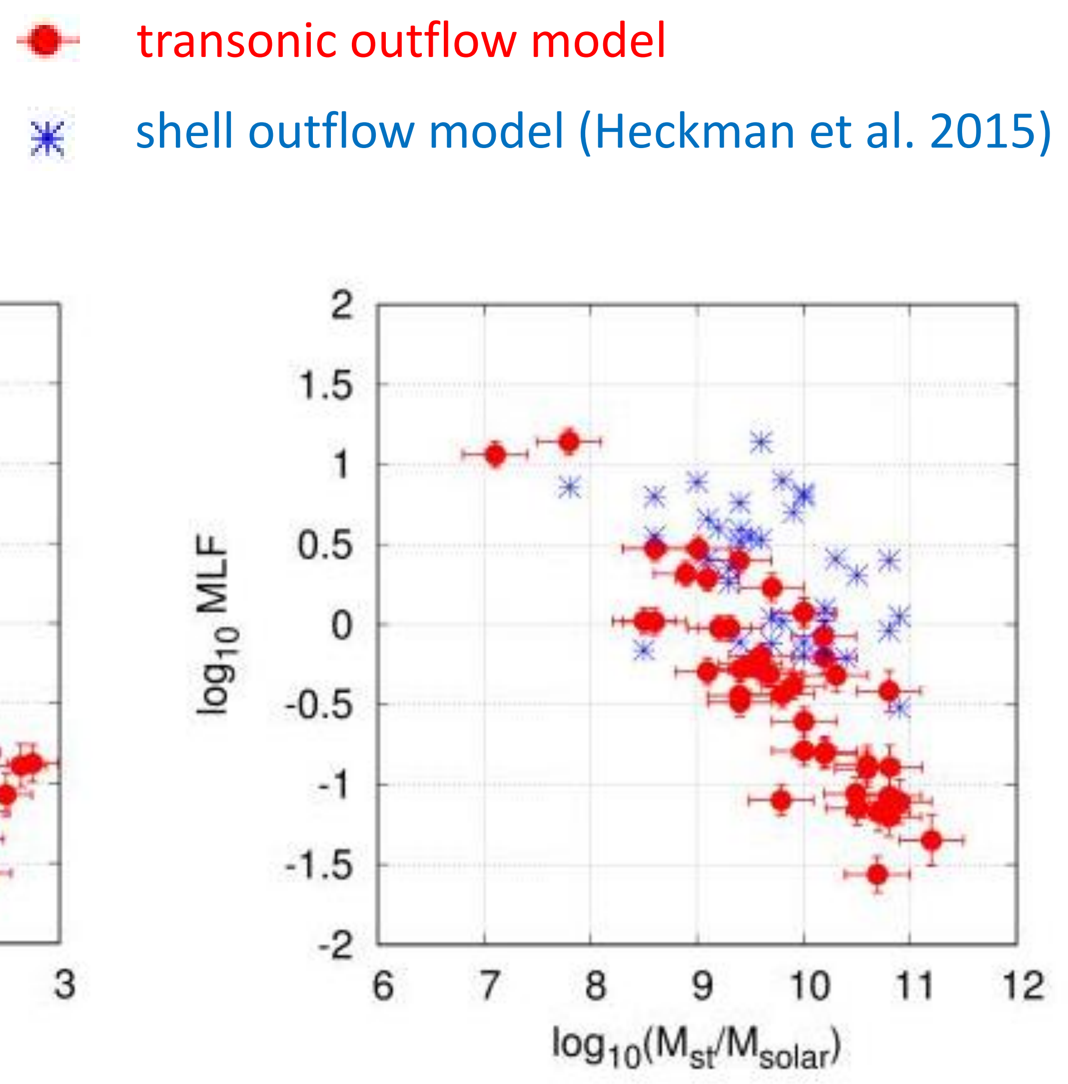
discussion



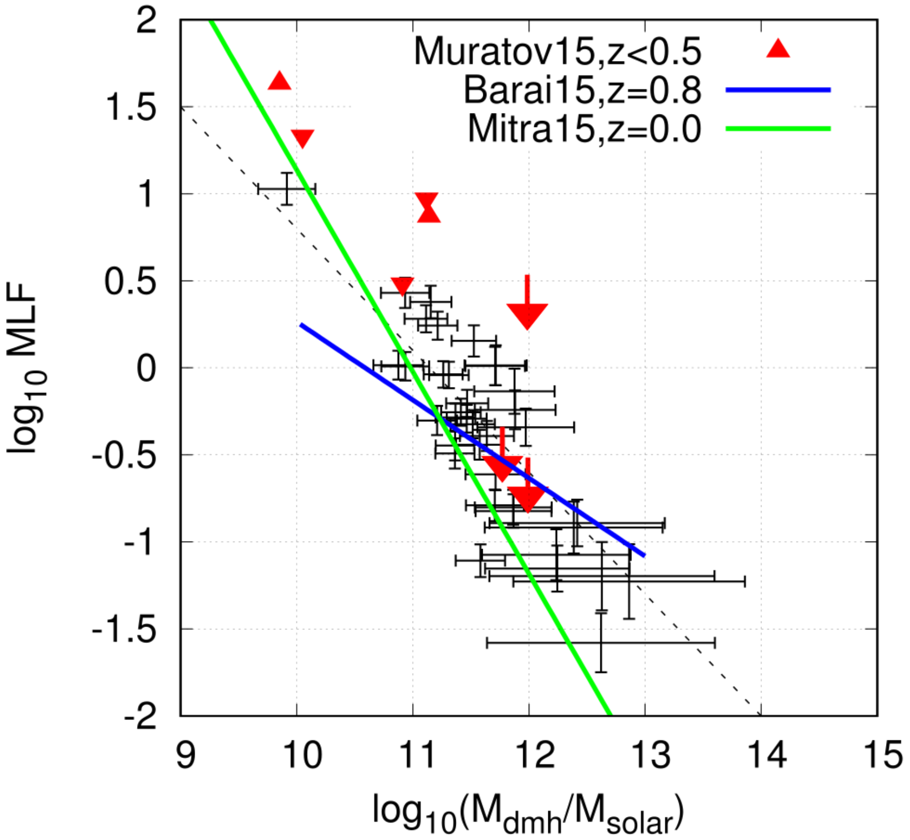
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
$\log_{10}$ mass loading factor
$\log_{10}$ SFR ($M_{\odot}$/yr)

Result: Shell outflow model との比較

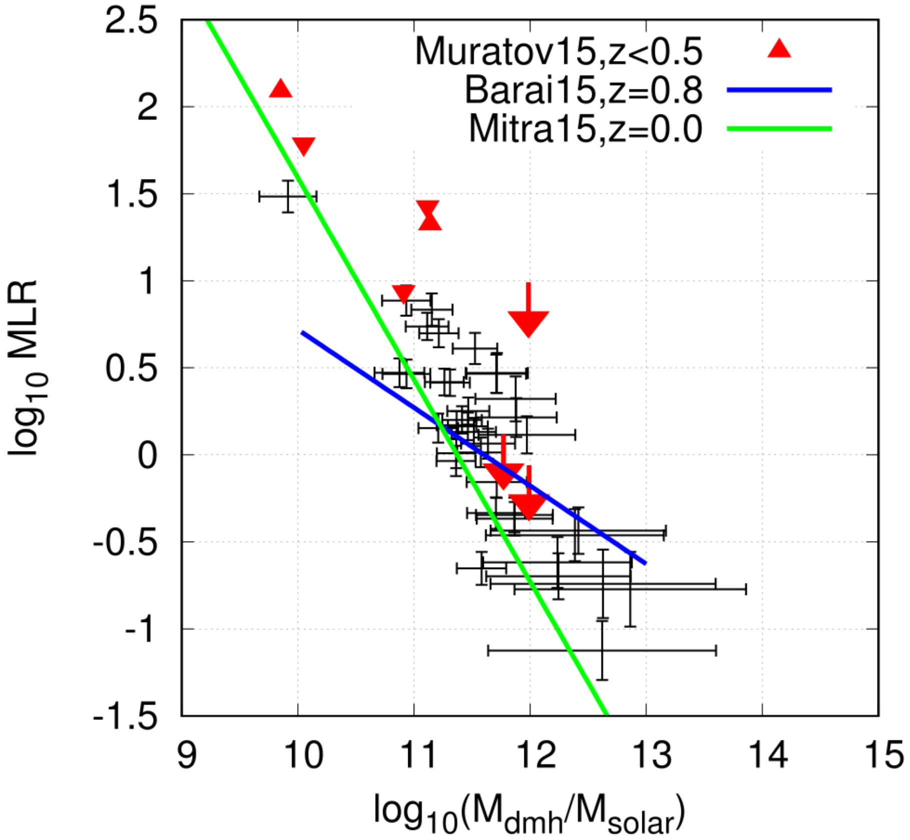
$\boxed{\mathrm{MLF} = \dot{M}\ /\ \mathrm{SFR}}$



数値実験との比較



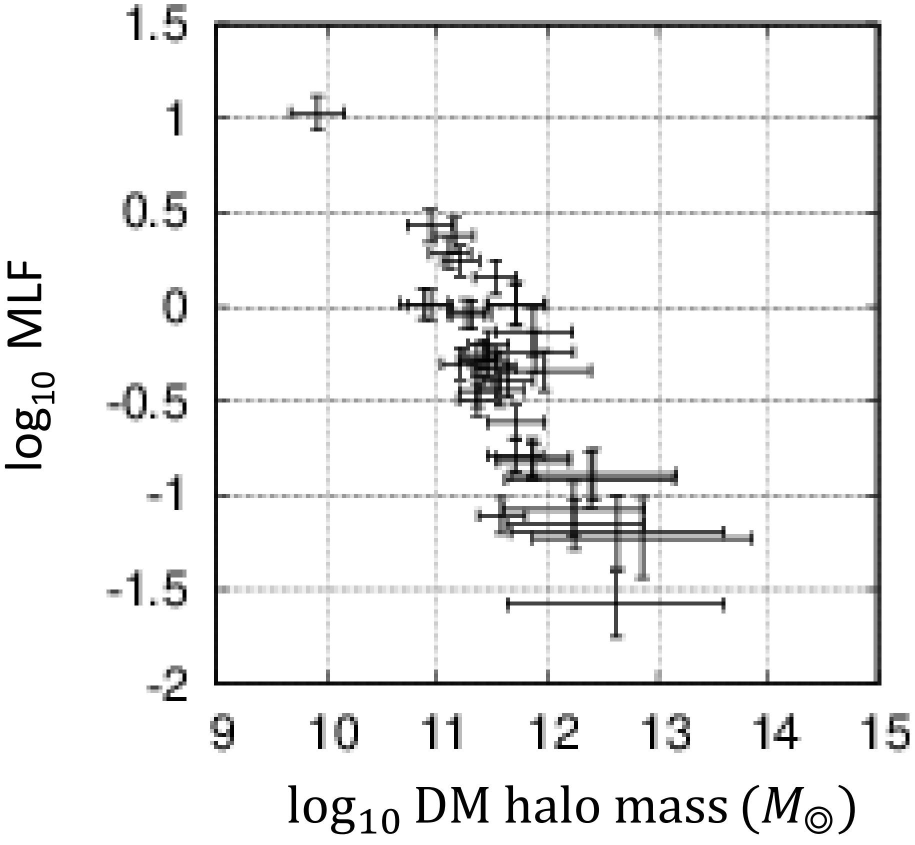
Muratov15,z<0.5
Barai15,z=0.8
Mitra15,z=0.0
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
9
10
11
12
13
14
15
$\log_{10}$ MLF
$\log_{10}(M_{dmh}/M_{solar})$



Muratov15,z<0.5
Barai15,z=0.8
Mitra15,z=0.0
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
9
10
11
12
13
14
15
$\log_{10}$ MLR
$\log_{10}(M_{dmh}/M_{solar})$

Result: ダークマターハロー質量への依存性

$$\begin{cases} \dot{M}_{SNeII} = 0.35\ \mathrm{SFR} \\ MLF = \dot{M}/SFR \end{cases} \rightarrow \frac{\dot{M}}{\dot{M}_{SNeII}} = \frac{\mathrm{MLF}}{0.35}$$



$M_{DMH} \ll 10^{11.5} M_{\odot}$: MLF $\gg 0.35$

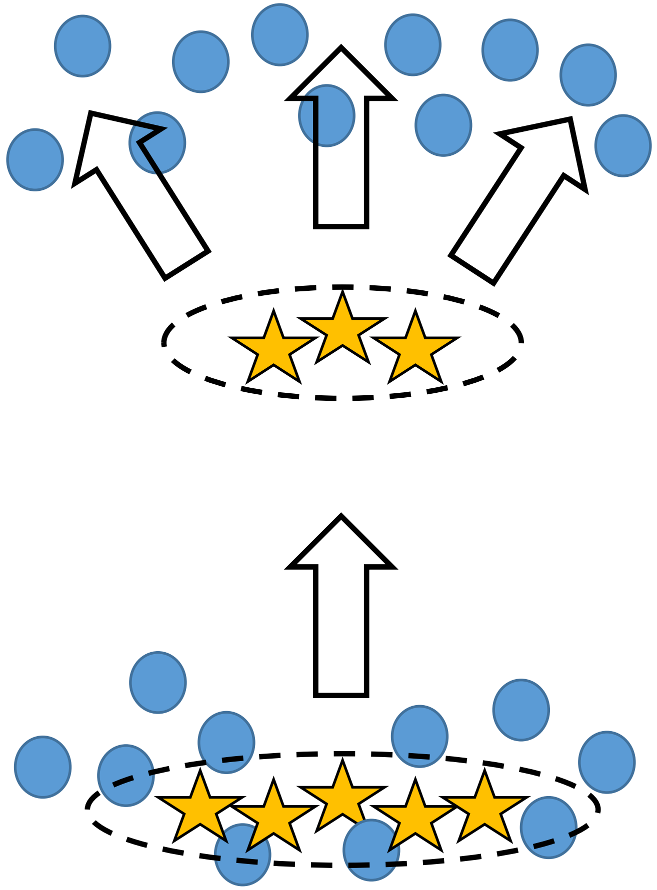
小質量銀河でガス流出の効率が高い
(星形成が抑制されやすい)

$M_{DMH} \sim 10^{11.5} M_{\odot}$: MLF ~ 0.35

SNeII から放出されたガスが
そのまま出てくる

($M_{DMH} \gg 10^{11.5} M_{\odot}$: MLF $\ll 0.35$)

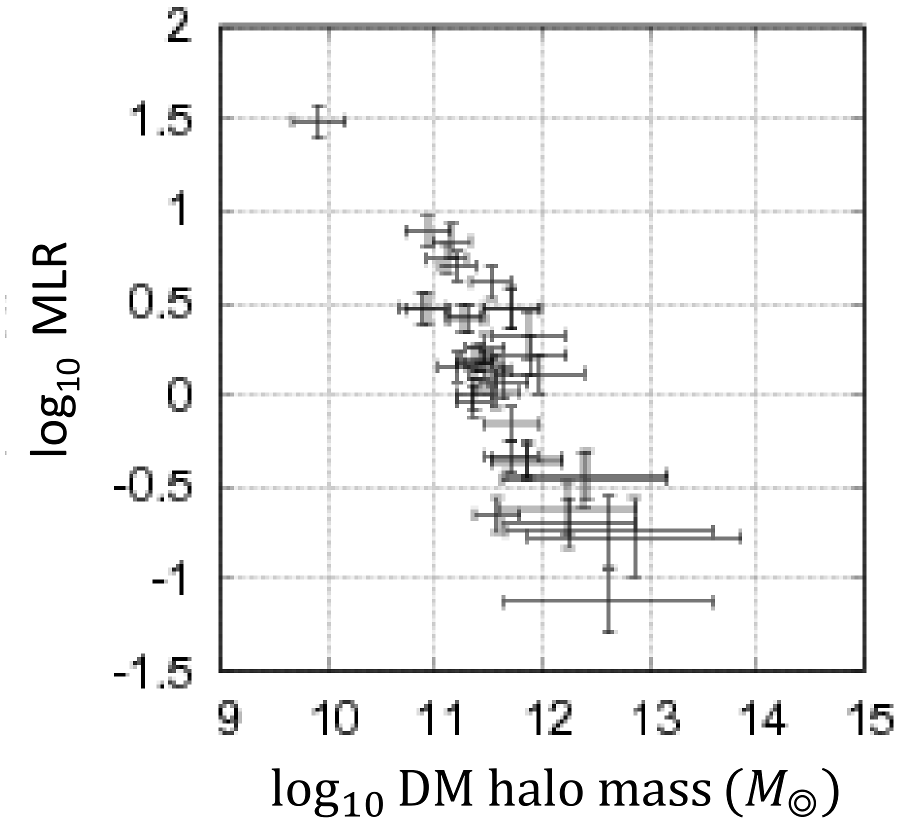
(ガス流出の効率が低い)



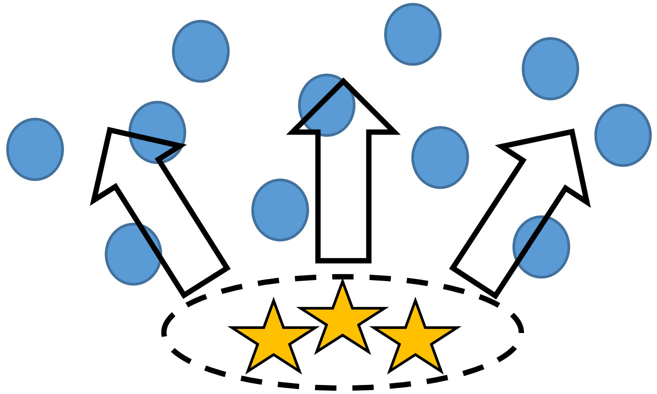
Result: ダークマターハロー質量への依存性

mass loading rate (MLR):　SNeII からの ejected mass と massflux の比
星間ガスの流出効率を示す

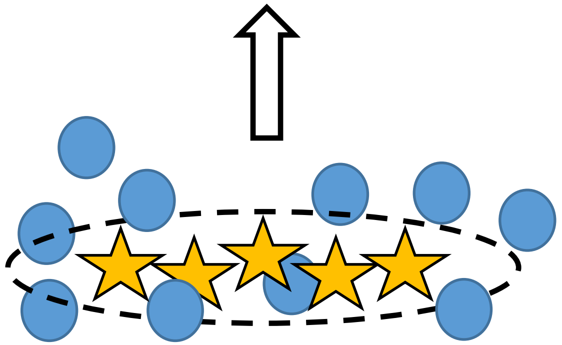
$\boxed{\mathrm{MLR} \equiv \dot{M} \,/\, \dot{M}_{SNeII}\ (\propto \mathrm{MLF})}$　($\dot{M}_{SNeII}$ $\propto$ SFR)



$M_{DMH} \ll 10^{11.5} M_{\odot}$: MLR $\gg$ 1
星間ガスの流出効率が高い
(星形成が抑制されやすい)

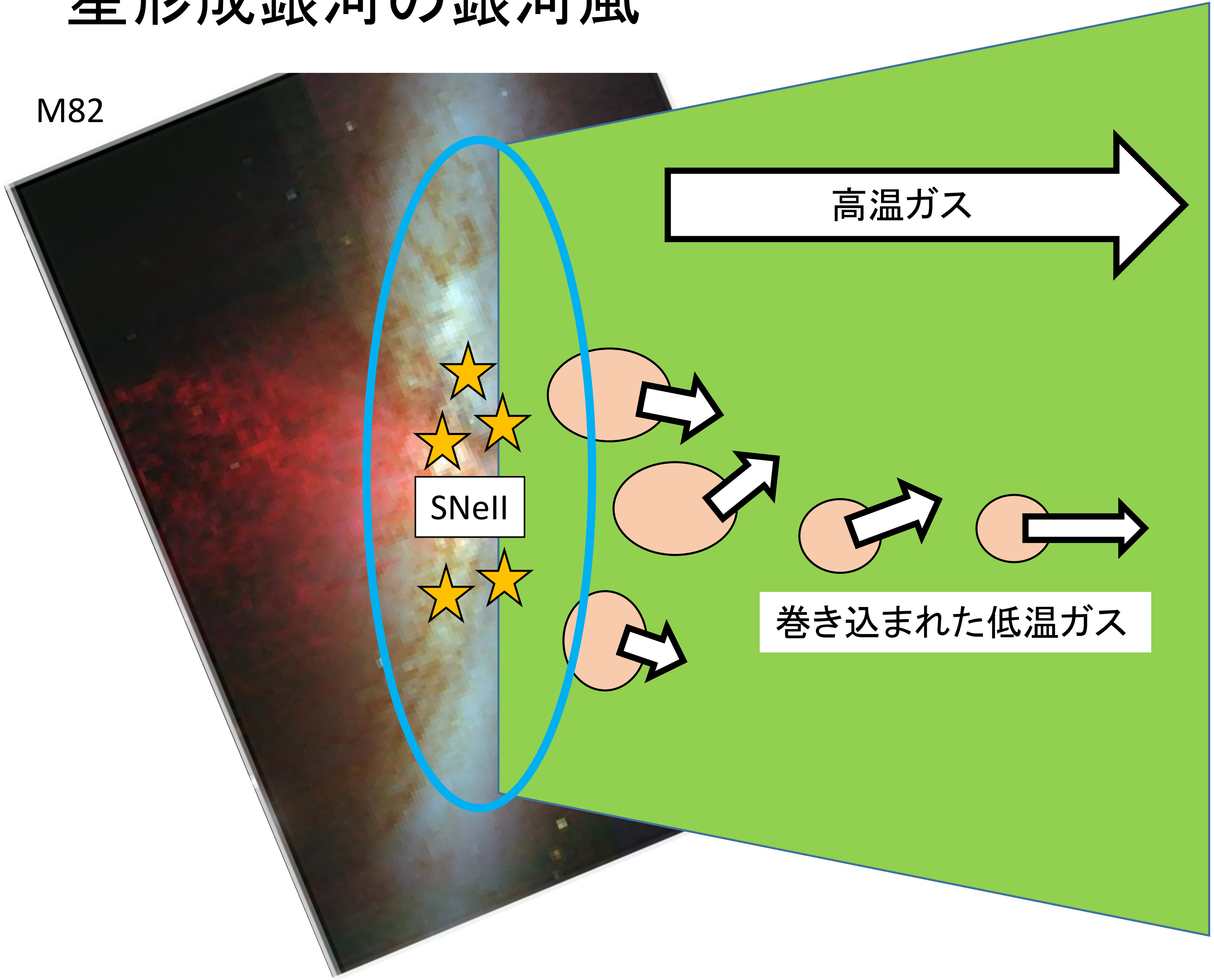


$M_{DMH} \sim 10^{11.5} M_{\odot}$: MLR ~ 1
SNeII からの ejected mass が
そのまま出てくる



$M_{DMH} \gg 10^{11.5} M_{\odot}$: MLR $\ll$ 1
ガス流出の効率が低い

星形成銀河の銀河風



高い星形成率

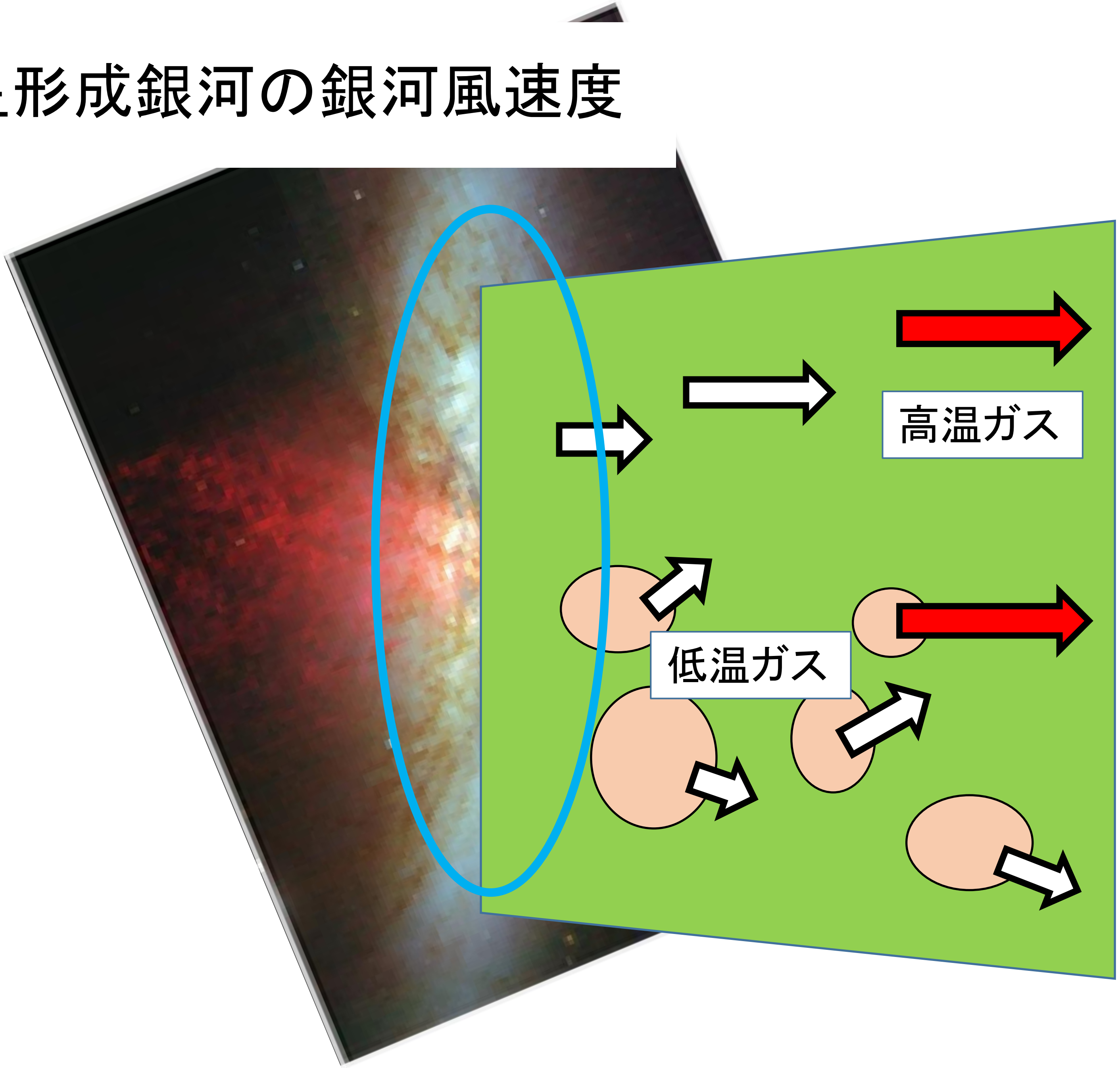
→ 星間ガスにエネルギー注入

→ 銀河風で星間ガスが流出

⇩

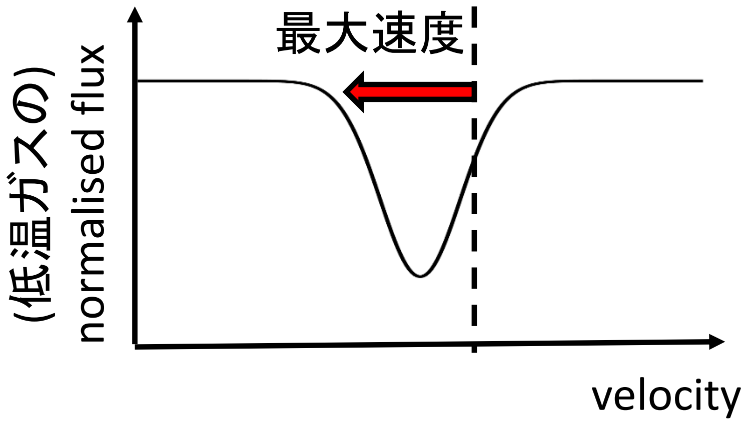
1. 星形成の抑制
2. 銀河間空間の重元素汚染

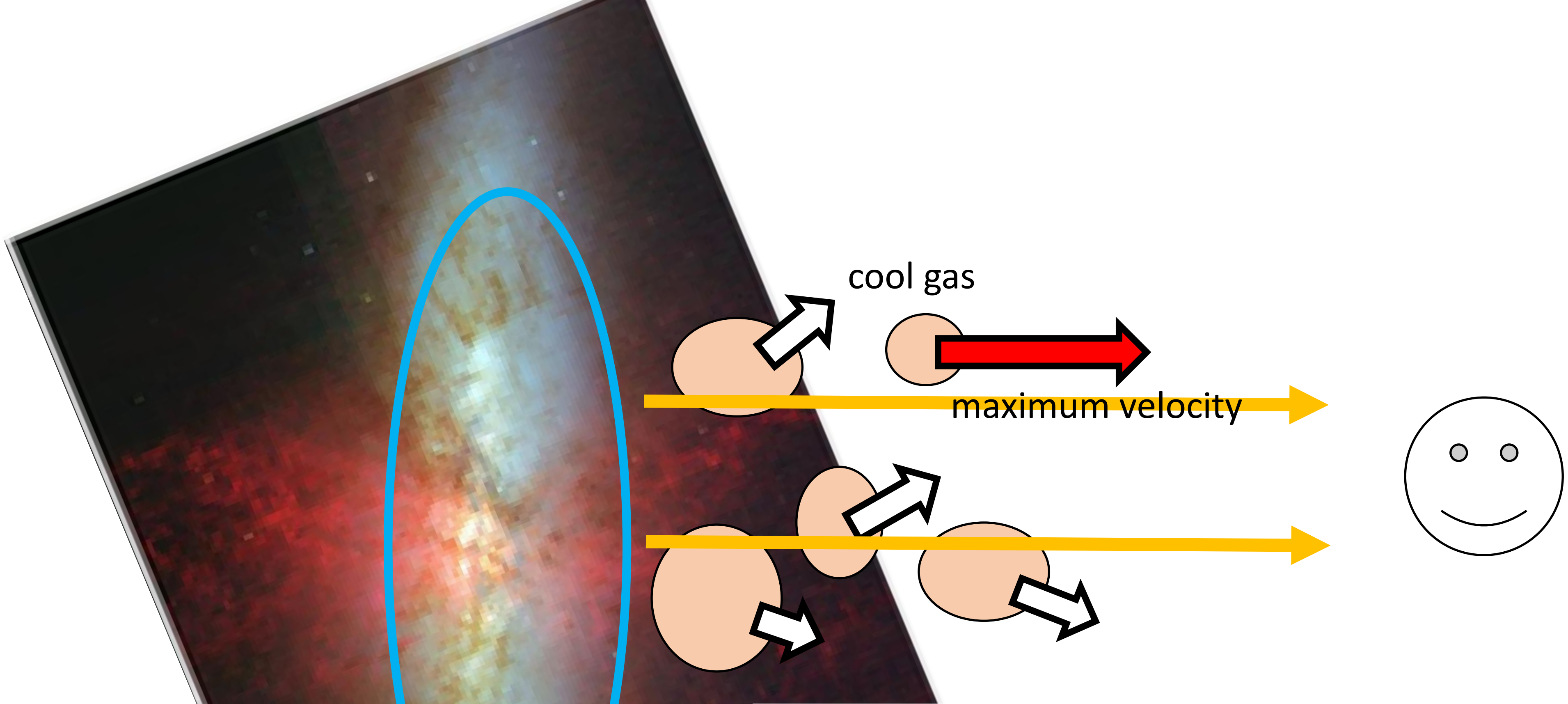
星形成銀河の銀河風速度



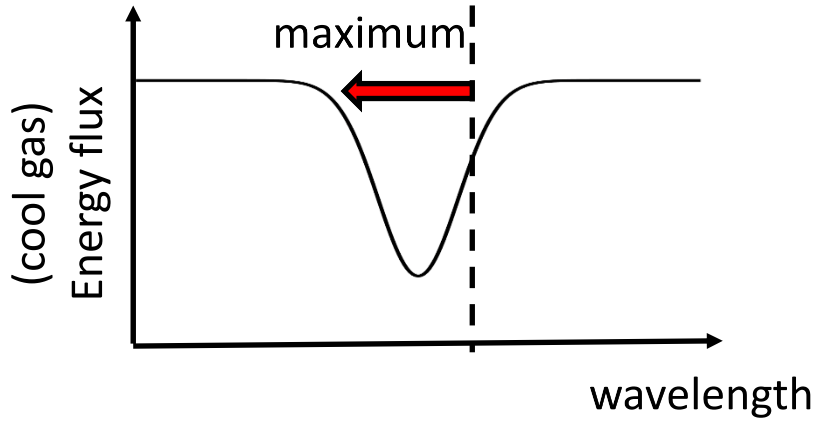
高温ガスの流れによって低温ガスが加速

低温ガスの最大速度
≀
高温ガスの最大速度(の下限)





Cool gas contains various velocity components.



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

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

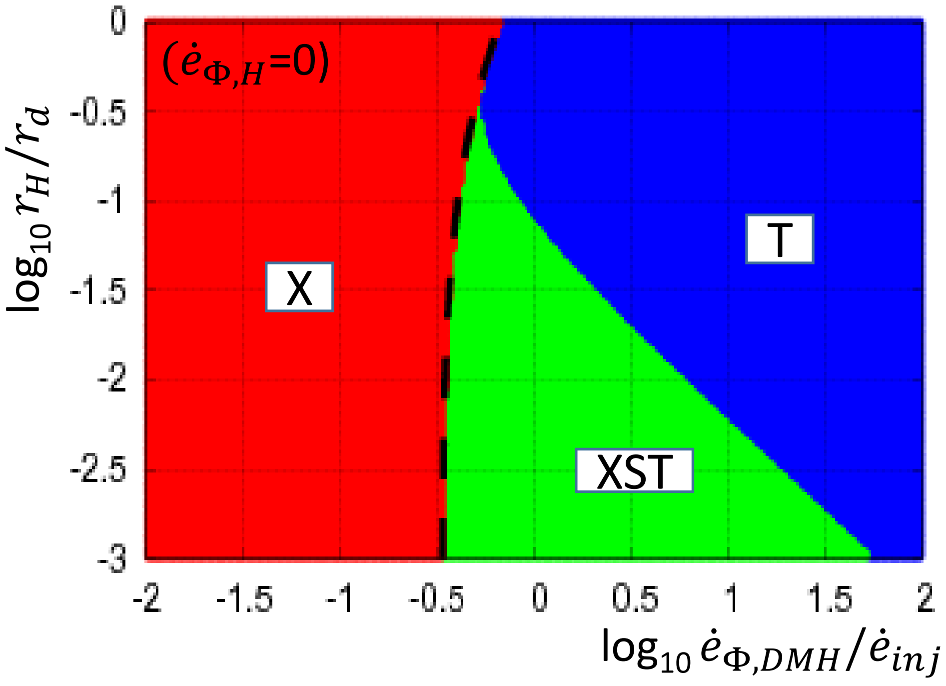
$$-\frac{\Gamma M^2+1}{2}\frac{\dot{e}_n - 2\dot{m}_n\Phi_n}{\dot{e}_n - \dot{m}_n\Phi_n}\frac{1}{\dot{m}_n}\frac{d\dot{m}_n}{dx} - \frac{\Gamma M^2+1}{2}\frac{1}{\dot{e}_n - \dot{m}_n\Phi_n}\frac{d\dot{e}_n}{dx}$$

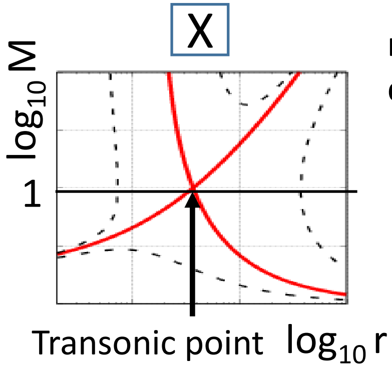
$$\Phi_n \equiv \frac{\Phi}{\dot{e}_{inj}/\dot{m}_{inj}} \qquad \dot{m}_n \equiv \frac{\dot{m}}{\dot{m}_{inj}} \qquad \dot{e}_n \equiv \frac{\dot{e}}{\dot{e}_{inj}}$$

Classification of transonic solutions

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

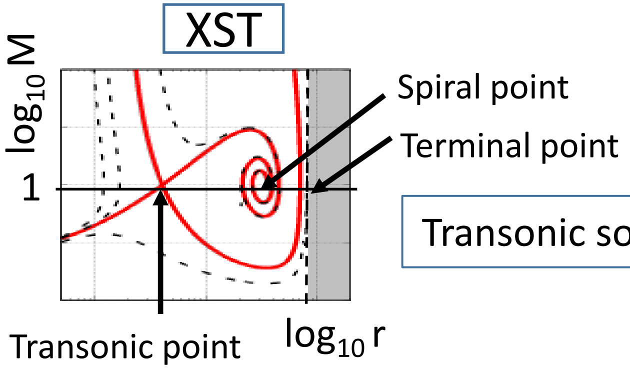
There are 3 patterns of transonic solutions.



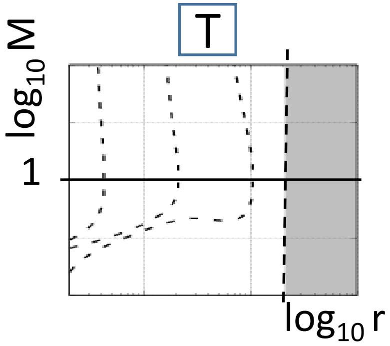


red : transonic solution
dashed : other solution

Transonic solution expands to infinity.



Transonic solution stops.

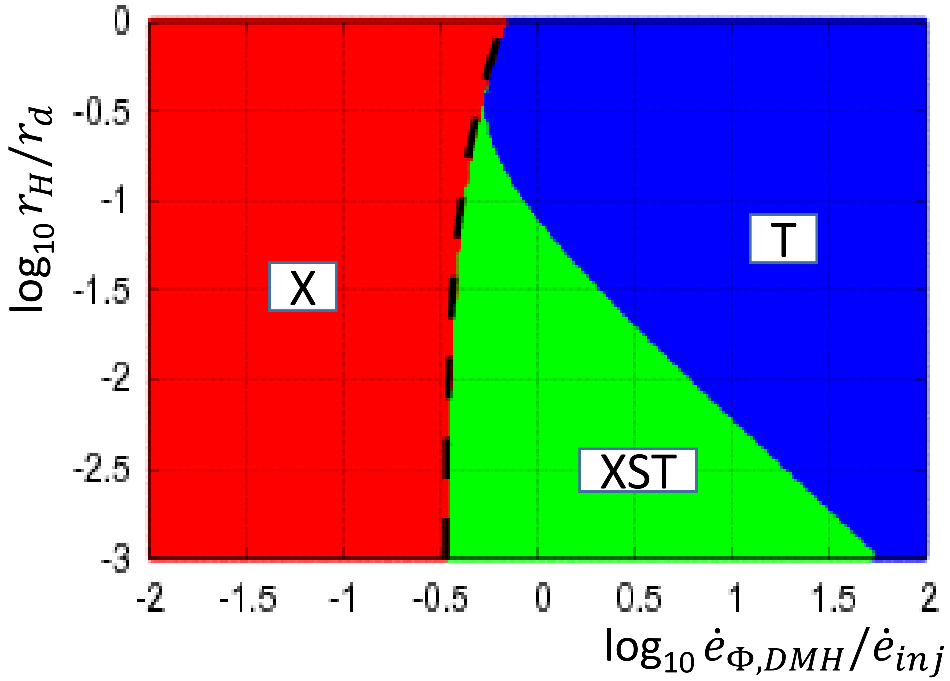


No transonic solution

Classification of transonic solutions

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

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



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

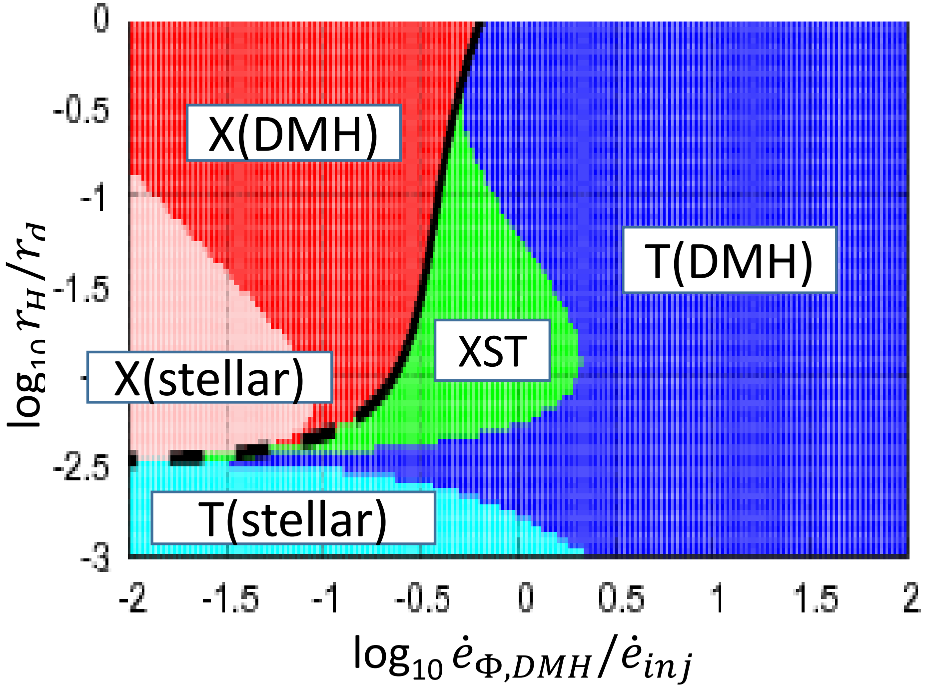
$$\dot{e} - \dot{m}\Phi = 0$$

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

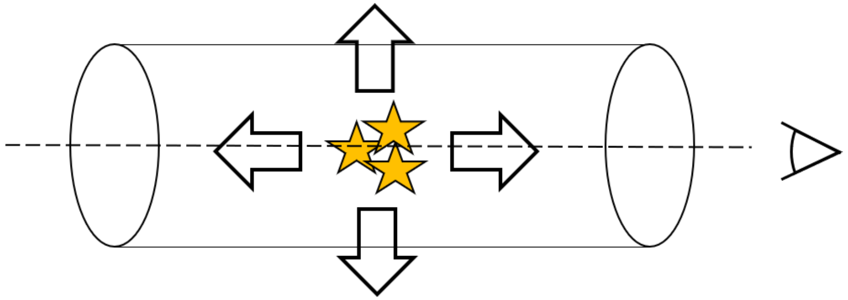
Classification of transonic solutions

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

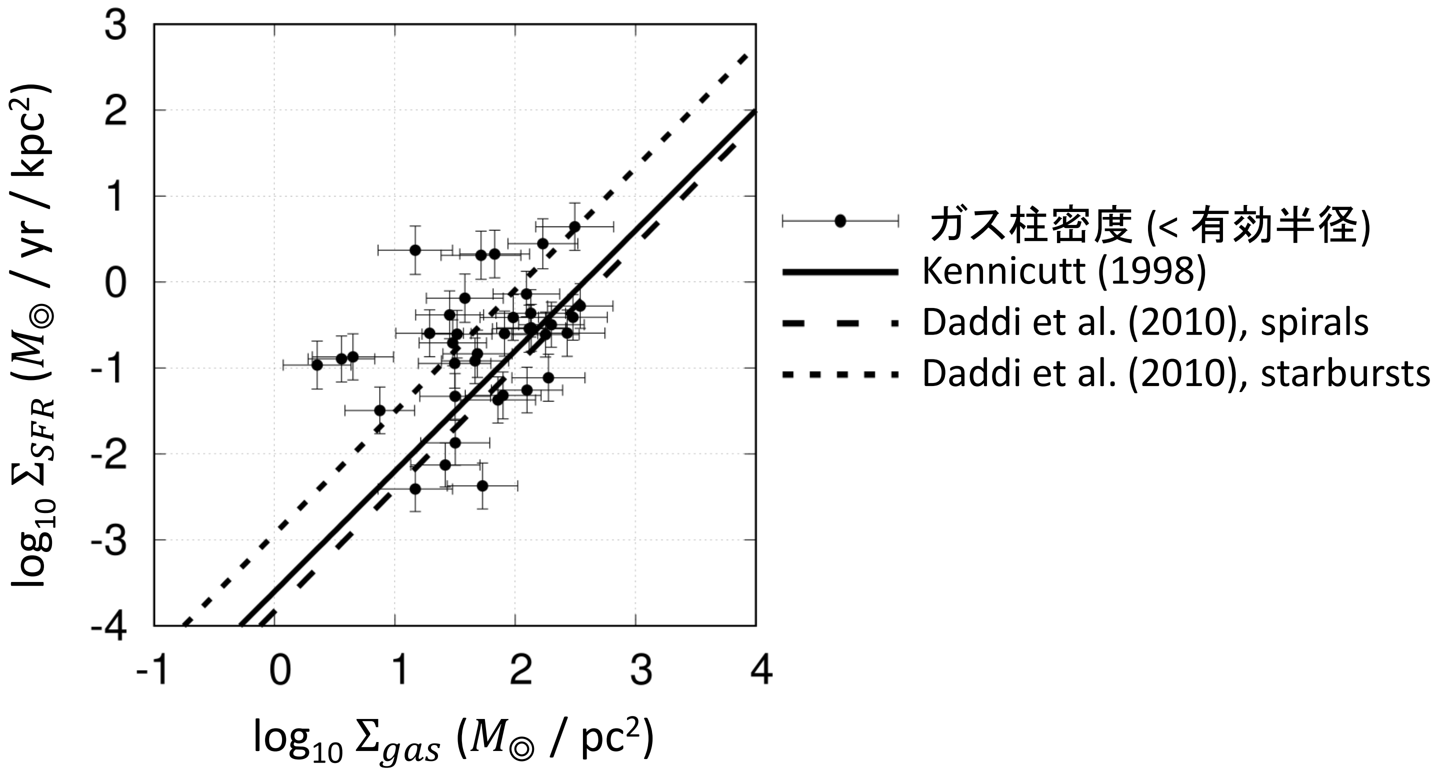
($\log_{10} \dot{e}_{\Phi,H}/\dot{e}_{inj}$ = -2)



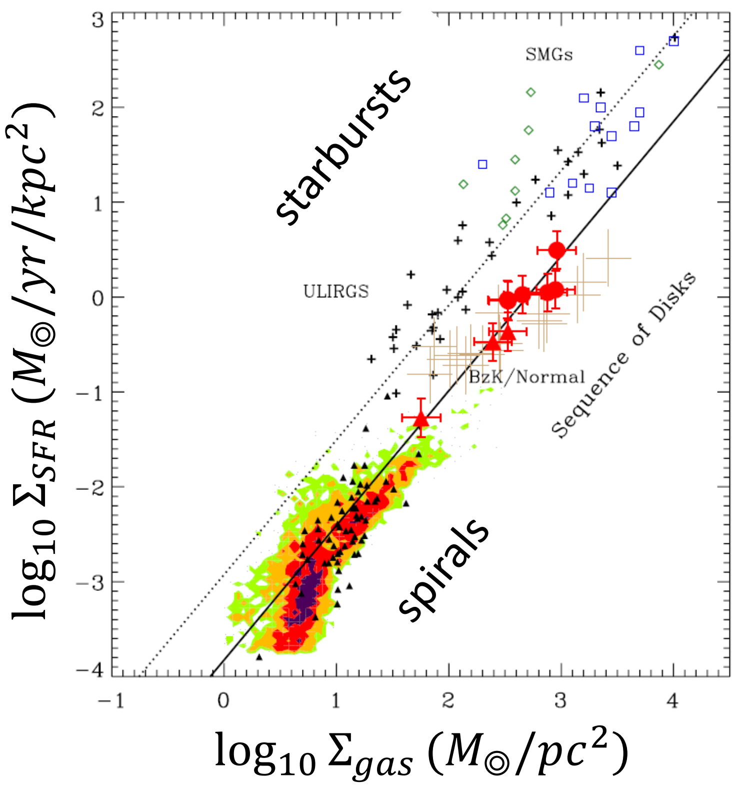
discussion: ガス柱密度



質量流束からガス柱密度が予想できる
Kennicutt-Schmidt law と比較

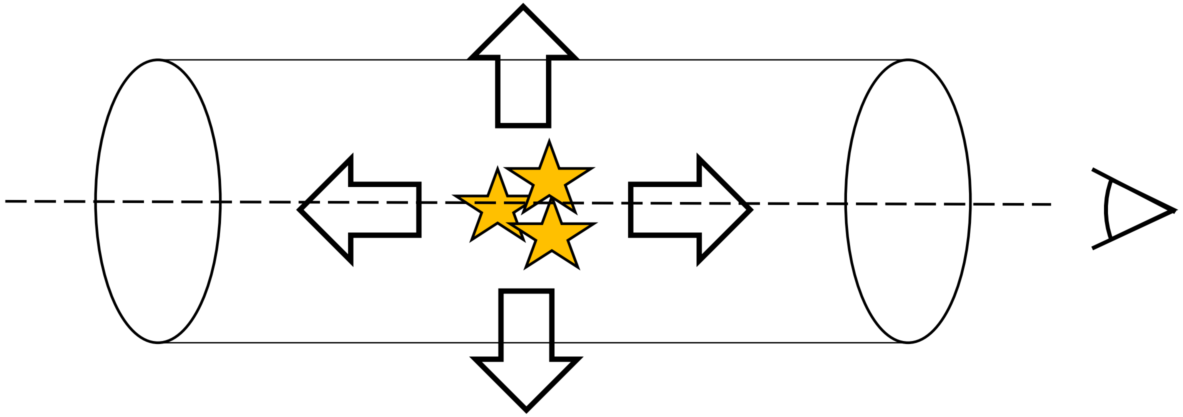


Kennicutt-Schmidt law for
spirals and starbursts
(Daddi et al. 2010)

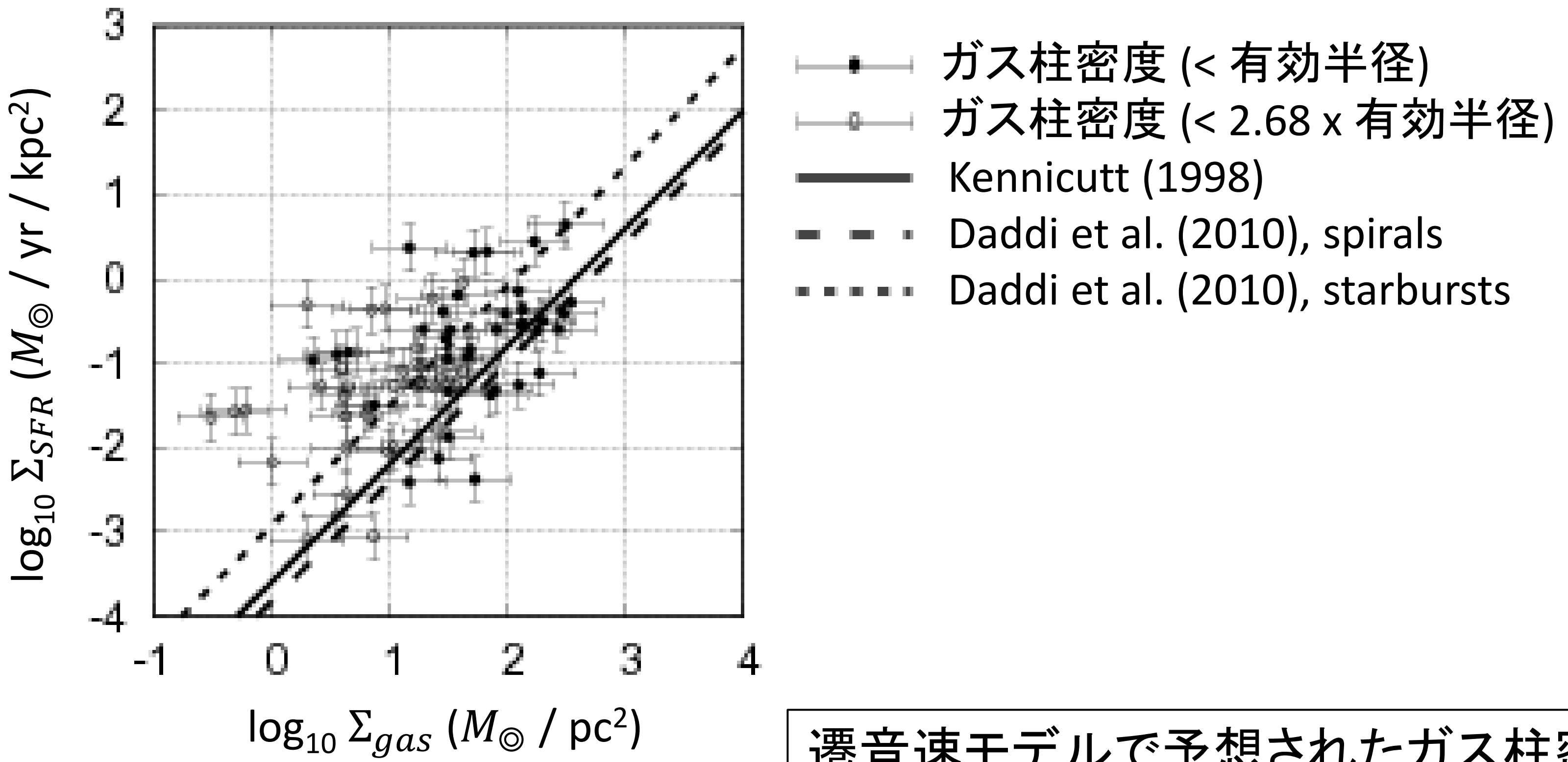


遷音速モデルで予想されたガス柱密度は (starburst galaxies の) Kennicutt-Schmidt law と矛盾しない

discussion: ガス柱密度



質量流束からガス柱密度が予想できる
Kennicutt-Schmidt law と比較



遷音速モデルで予想されたガス柱密度は (starburst galaxies の) Kennicutt-Schmidt law と矛盾しない

discussion: ガス柱密度

質量流束からガス柱密度を評価
Kennicutt-Schmidt law と比較