The formation of exponential star-forming disk and the corresponding metal-enrichment

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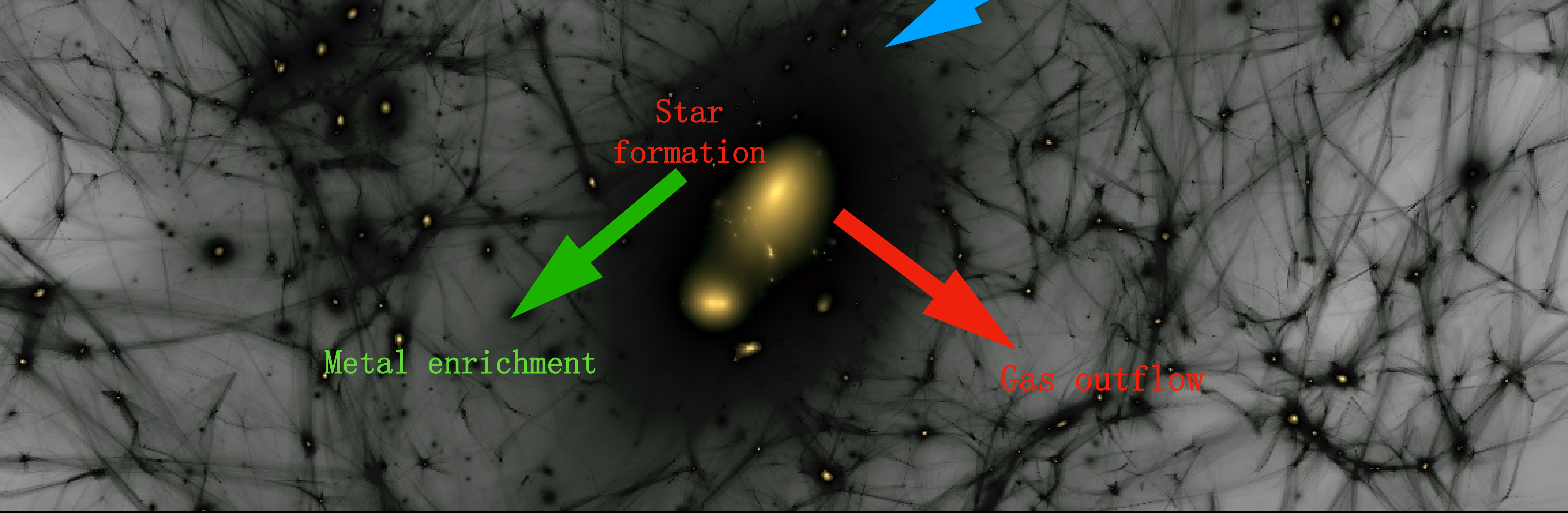
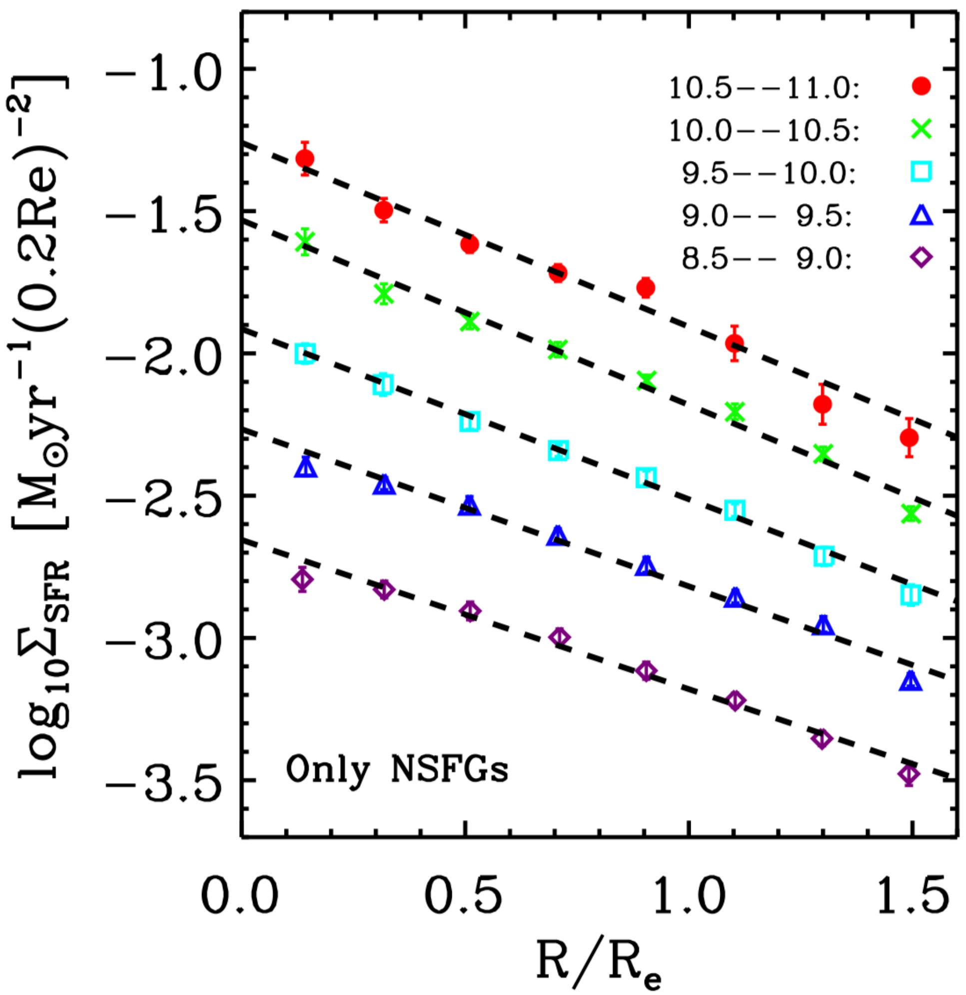
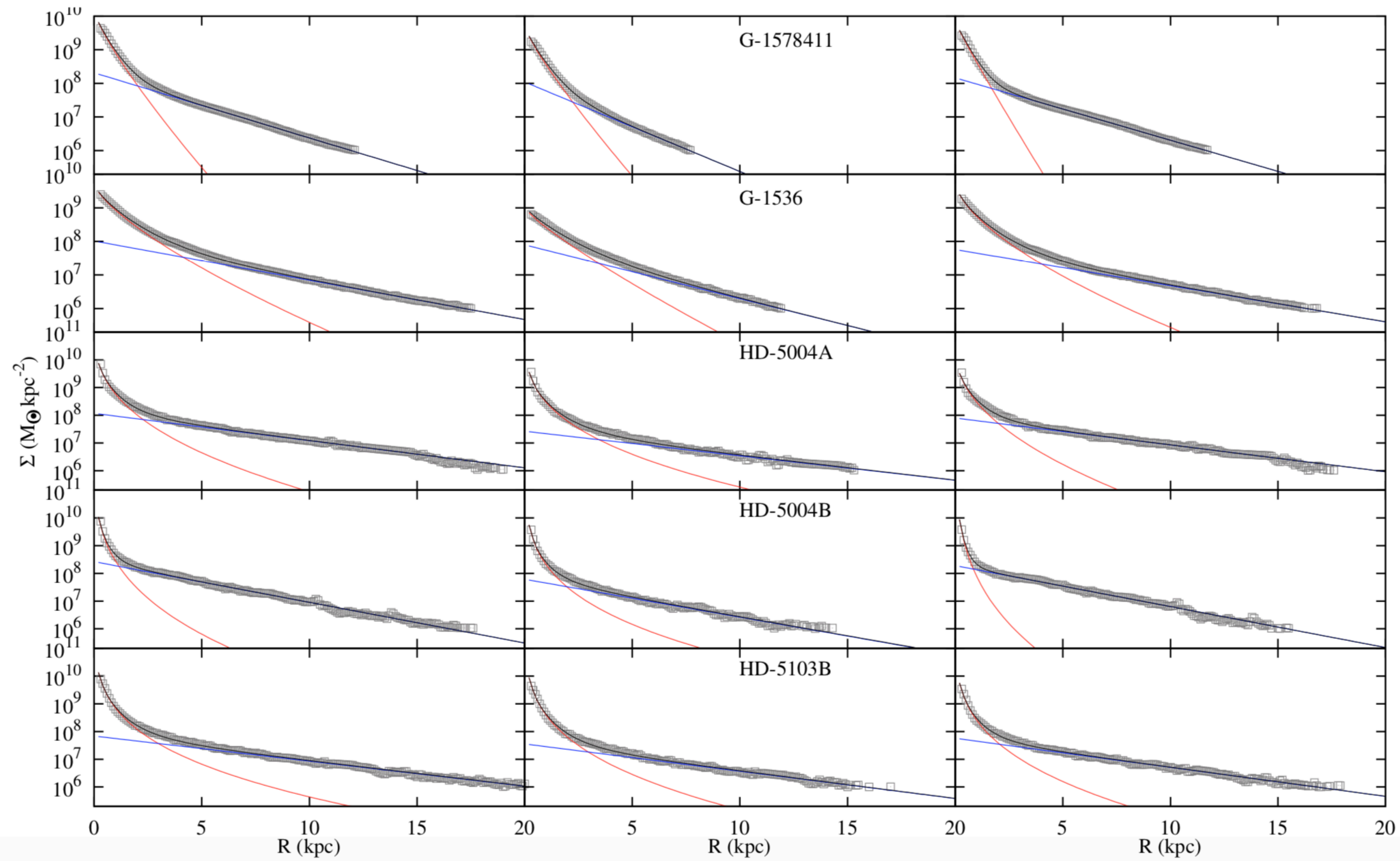
Basic continuity equation:

$$\dot{M}_{gas} = \dot{M}_{inflow} - \dot{M}_{SF} - \dot{M}_{outflow}$$



The exponential star-forming disk





Wang et al. 2019

Obreja et al. 2013

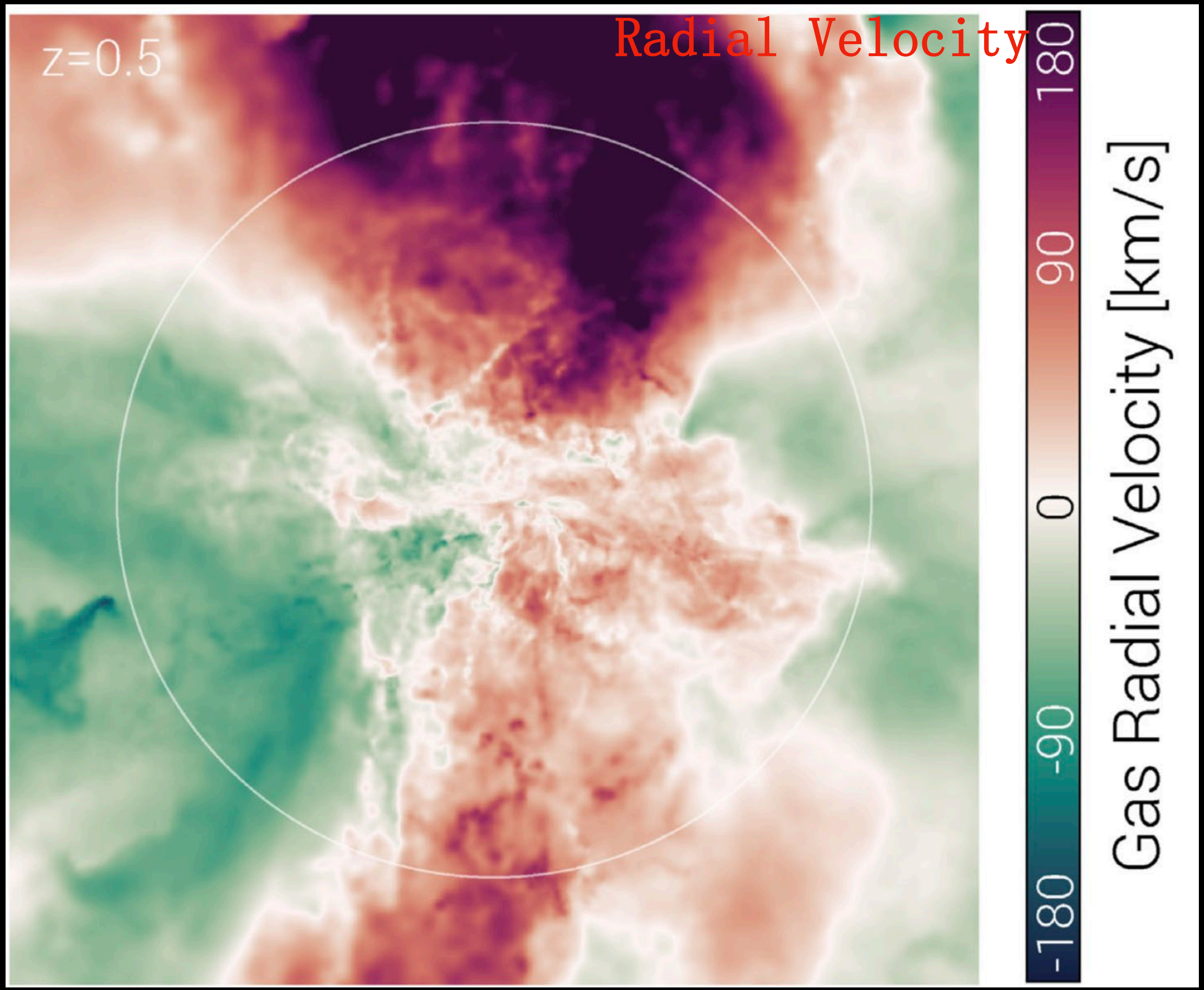
e SF galaxies usually have a Sersic core and exponential disk up to a few scalelength.

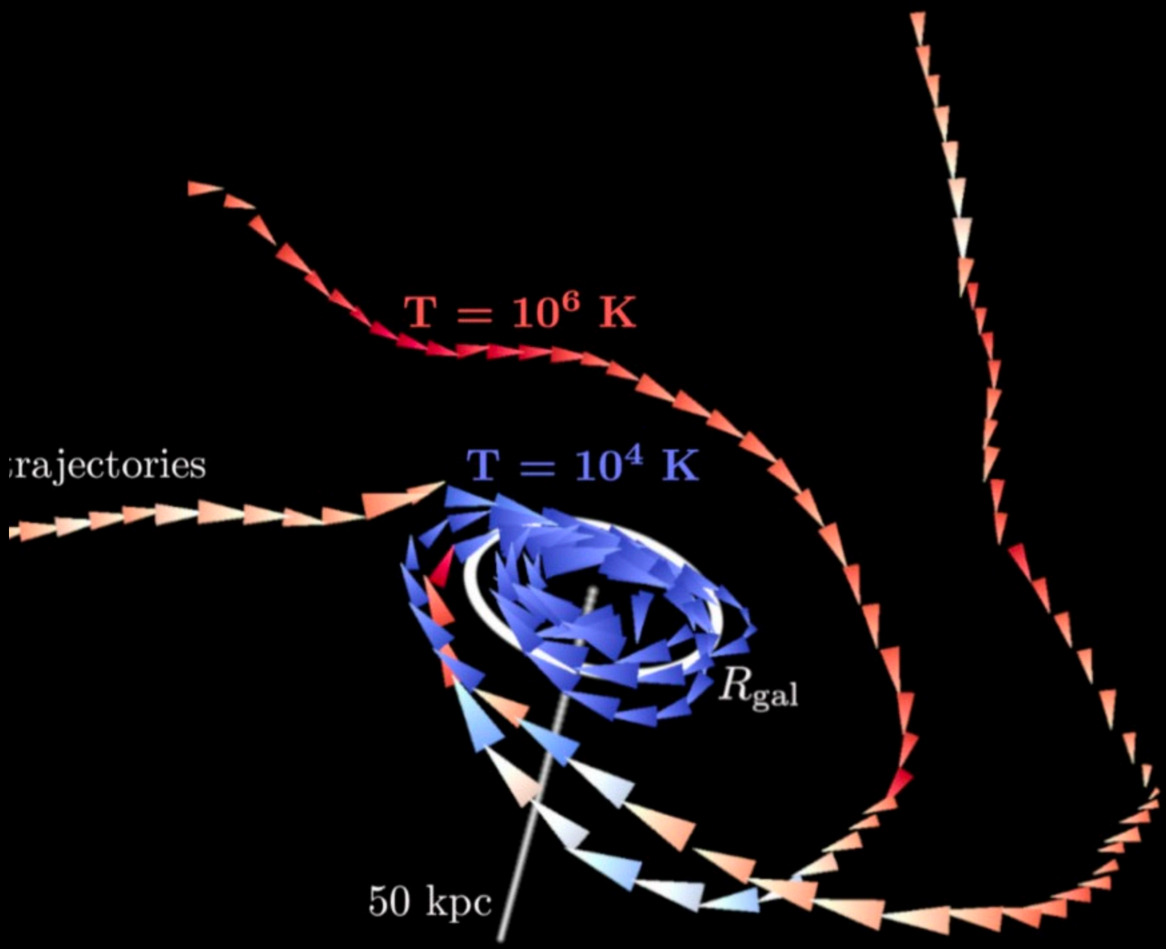
ne exponential disk is seen in both stars and SFR surface density.

Previous ideas for this:

- the redistribution of stars
- specifying the angular momentum of inflowing gas
- the redistribution of cold gas in the disk via viscosity

How gas is accreted on to galactic disk?



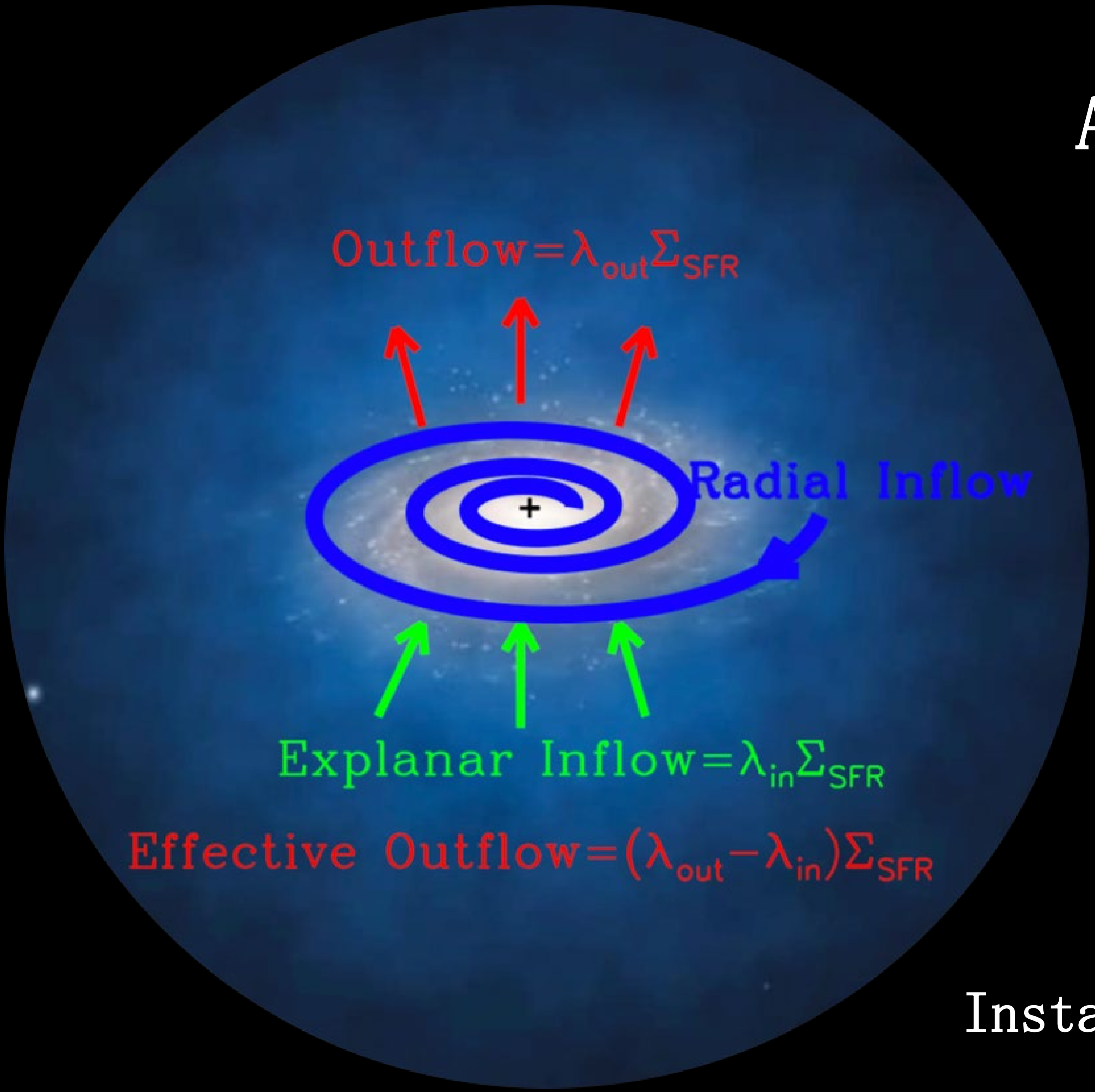


Peroux et al. 2020 with TNG50
(Also see Nelson et al. 2019)

Hafen et al. 2022 with FIR

The inflowing gas is preferentially coplanar, and that the outflowing gas is preferentially along the direction perpendicular to the disk.

The modified accretion disk



Assumptions:

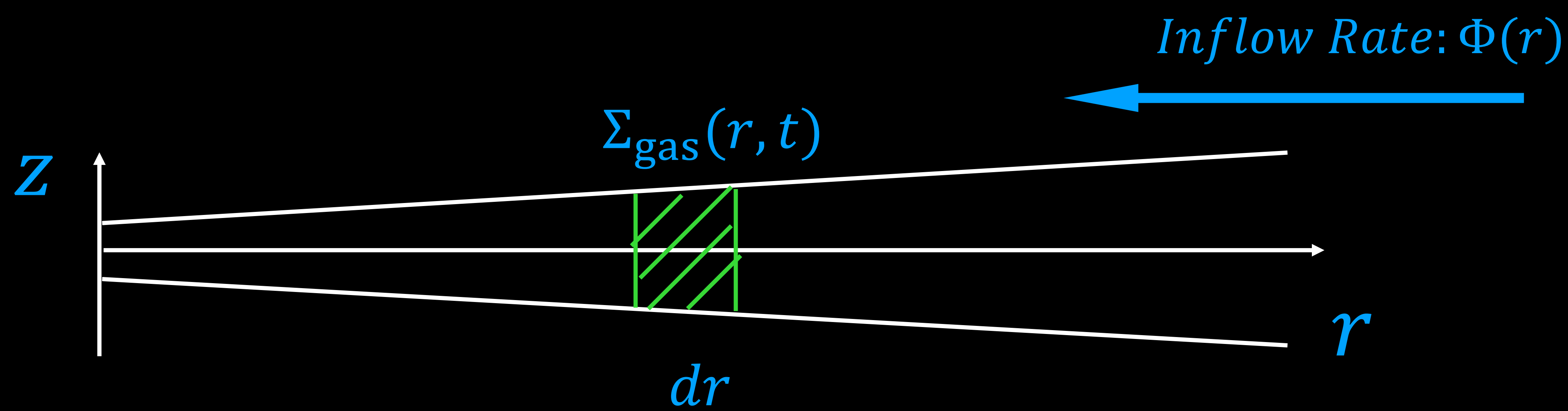
Radial gas inflow
- Co-planar
- Dominates the inflow

Outflow by stellar winds
- Ex-planar
- Scaled by SFR

Rotationally-supported

Instantaneous metal-enrichment

The basic equations



Continuity equation:

$$\frac{\partial \Sigma_{gas}}{\partial t} = \frac{\partial \Phi}{2\pi r \partial r} - (1 - R + \lambda) \cdot \Sigma_{SFR}$$

Radial inflow — Outflow and SF

$$\frac{\partial (Z \cdot \Sigma_{gas})}{\partial t} = \frac{\partial (\Phi \cdot Z)}{2\pi r \partial r} - Z \cdot (1 + \lambda)\Sigma_{SFR} + y \cdot \Sigma_{SFR}$$

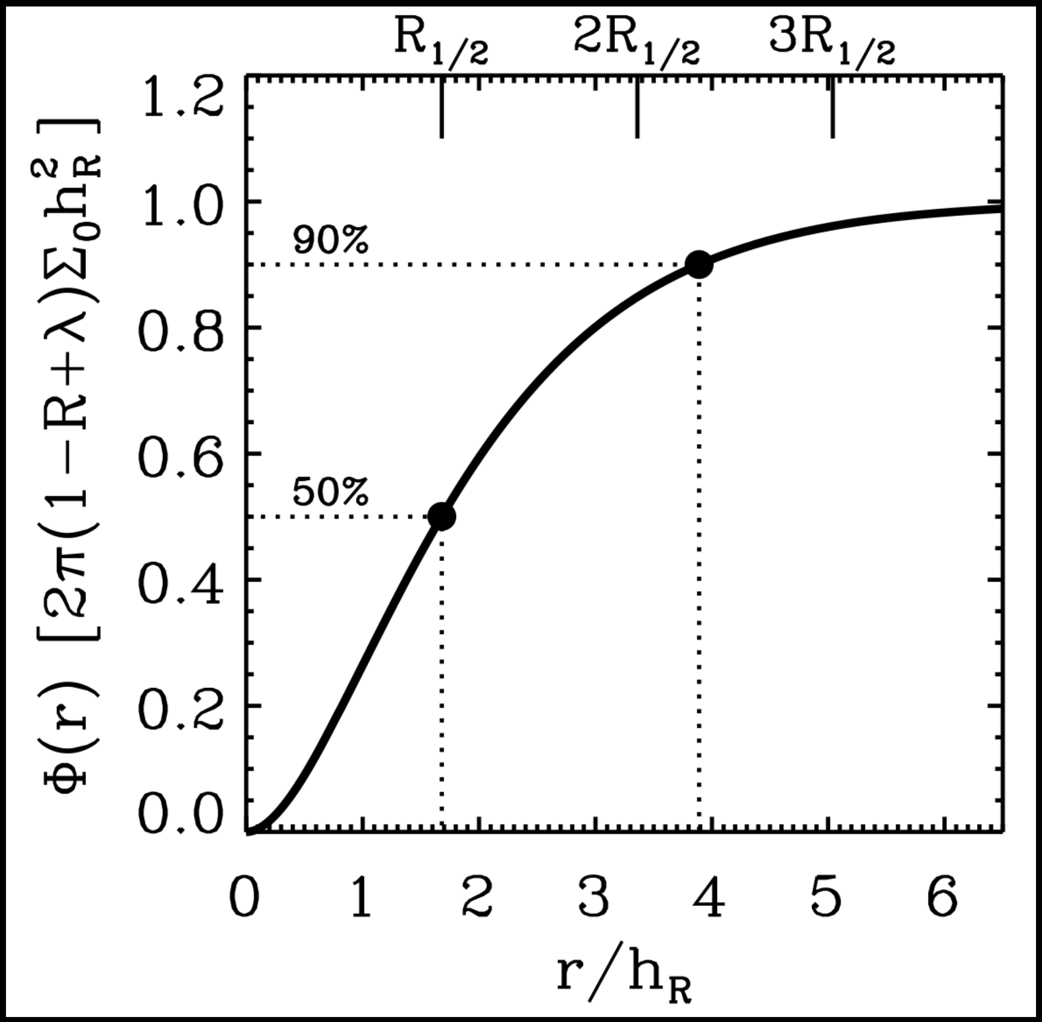
Radial inflow — Outflow and SF — Produce by SF

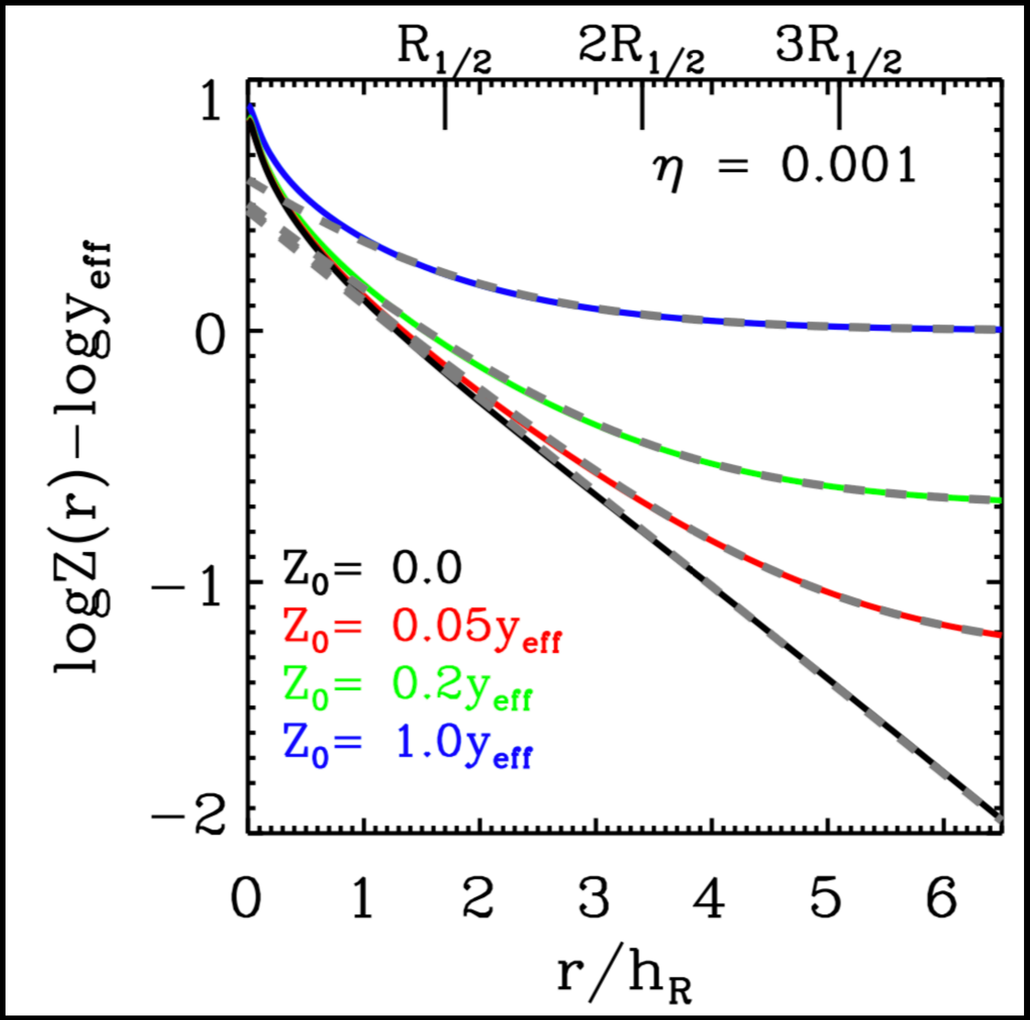
At the equilibrium: $\frac{\partial \Sigma_{gas}}{\partial t} = 0, and\ \frac{\partial Z}{\partial t} = 0$

$$\Phi(r) = \Phi(+\infty) - \int_r^{+\infty} 2\pi r' \cdot (1 - R + \lambda)\Sigma_{\rm SFR}(r') dr'.$$

$$Z(r) = Z(+\infty) + \int_r^{+\infty} \frac{2\pi r' \cdot y \cdot \Sigma_{\rm SFR}(r')}{\Phi(r')} dr'$$

The metallicity profile predicted by this model





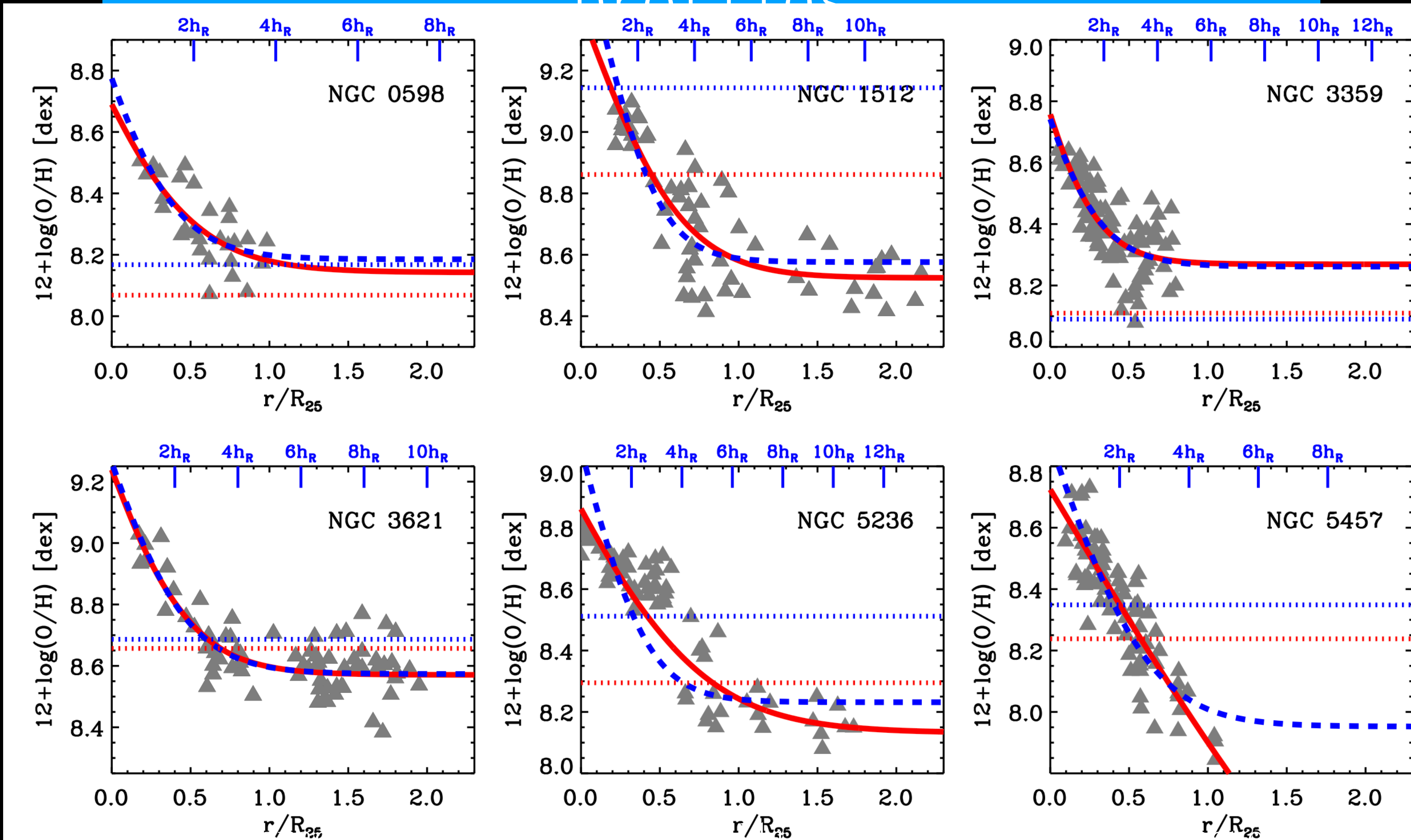
Assumption of exponential disk: $\Sigma_{SFR} = \Sigma_0 \cdot exp(-r/h_R)$

$$\frac{\Phi(r)}{1-R+\lambda} = \mathrm{SFR} \cdot [1+\eta-(x+1)\cdot\exp(-x)], \qquad x = r/h_R$$

$$Z(r) = -y_{\rm eff}\cdot\ln\left(1-\frac{x+1}{\eta+1}\cdot e^{-x}\right)+Z_0, \qquad y_{\rm eff} = y/(1-R+\lambda).$$

h_R *and* $y_{\rm eff}/Z_0$

Fit the observed metallicity profiles



the radial inflow of cold gas which is continuously enriched by in-situ star formation.

The continuity equation of angular momentum

$$\frac{\partial(\Sigma_{gas} r^2 \Omega)}{\partial t} = \frac{\partial(\Phi r^2 \Omega)}{2\pi r \partial r} - r^2\Omega(1 - R + \lambda)\Sigma_{SFR} - \frac{\partial T}{2\pi r \partial r}$$

Radial inflow — Outflow and SF — Torque by viscosity

$$T = 2\pi r^2 W$$

Viscous stress: defined as viscous force per unit length around the circumference

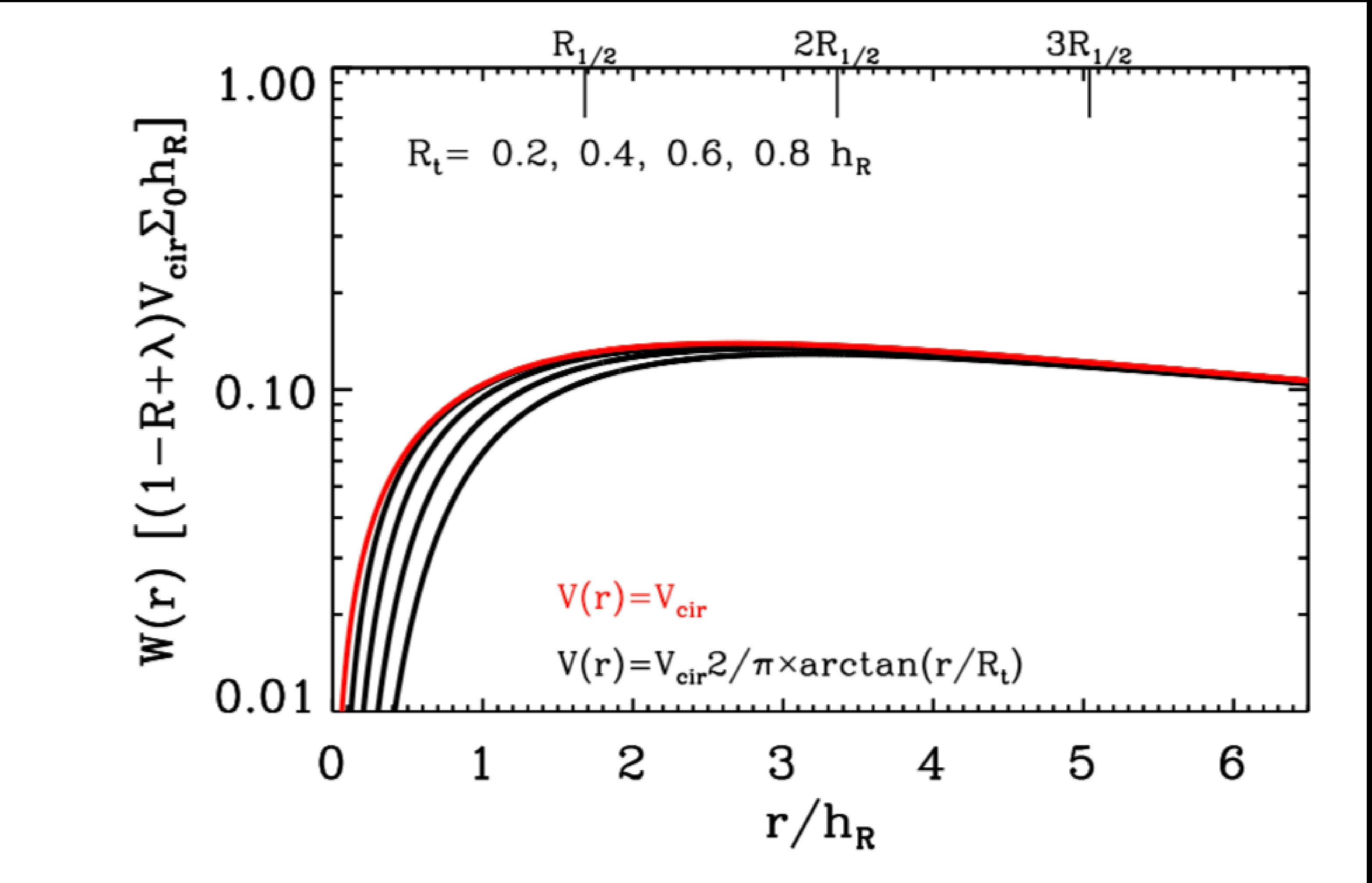
ssuming steady-state, exponential SF disk and constant circular velocity:

$$\frac{\partial \Sigma_{\rm gas}}{\partial t} = 0, \text{and} \frac{\partial \Omega}{\partial t} = 0 \qquad \Sigma_{SFR} = \Sigma_0 \cdot exp(-r/h_R) \qquad \Omega = V_{\rm cir}/r$$

The solution of viscous stress:

$$\frac{W(r)}{1 - R + \lambda} = V_{\rm cir}\Sigma_0 h_{\rm R} \cdot x^{-2} \cdot [(1+\eta)x + (2+x)\cdot e^{-x} - 2]$$

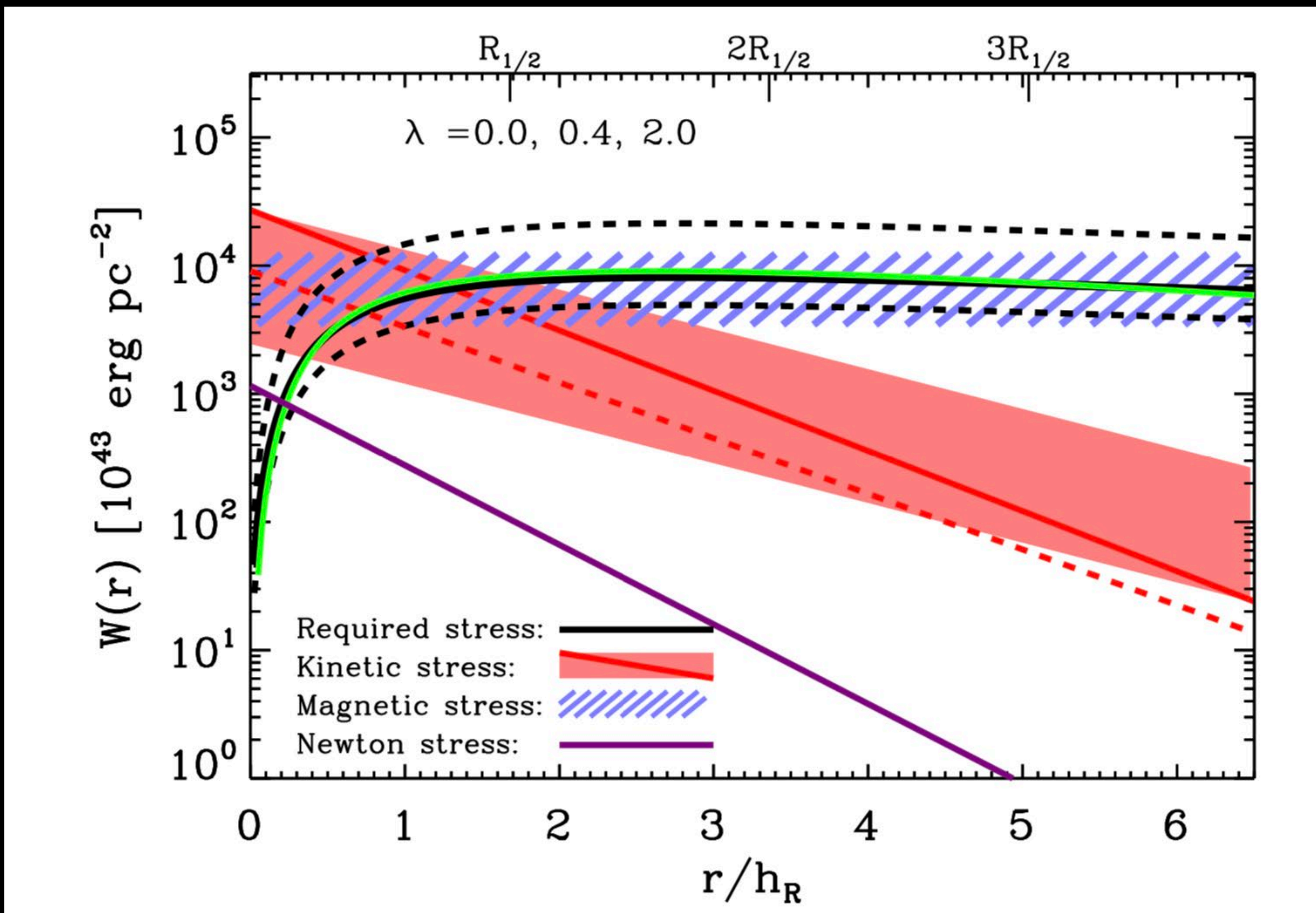
$$x = r/h_R$$



Searching for the source of viscous process

Three main effects (Balbus & Papaloizou 1999):

- Turbulence of the gas in the disk (Reynolds stress or kinematic stress)
- The magnetic field. (Maxwell stress or magnetic stress)
- Peculiar motions due to the gravitational collapse of gas (Newton stress)



Viscous stress tensor:

$$W_{r\phi} = \langle u_r u_\phi + u_{Gr} u_{G\phi} - u_{Ar} u_{A\phi} \rangle,$$

$$where\, \mathbf{u}_A = \frac{\mathbf{B}}{\sqrt{4\pi\rho}}, and$$

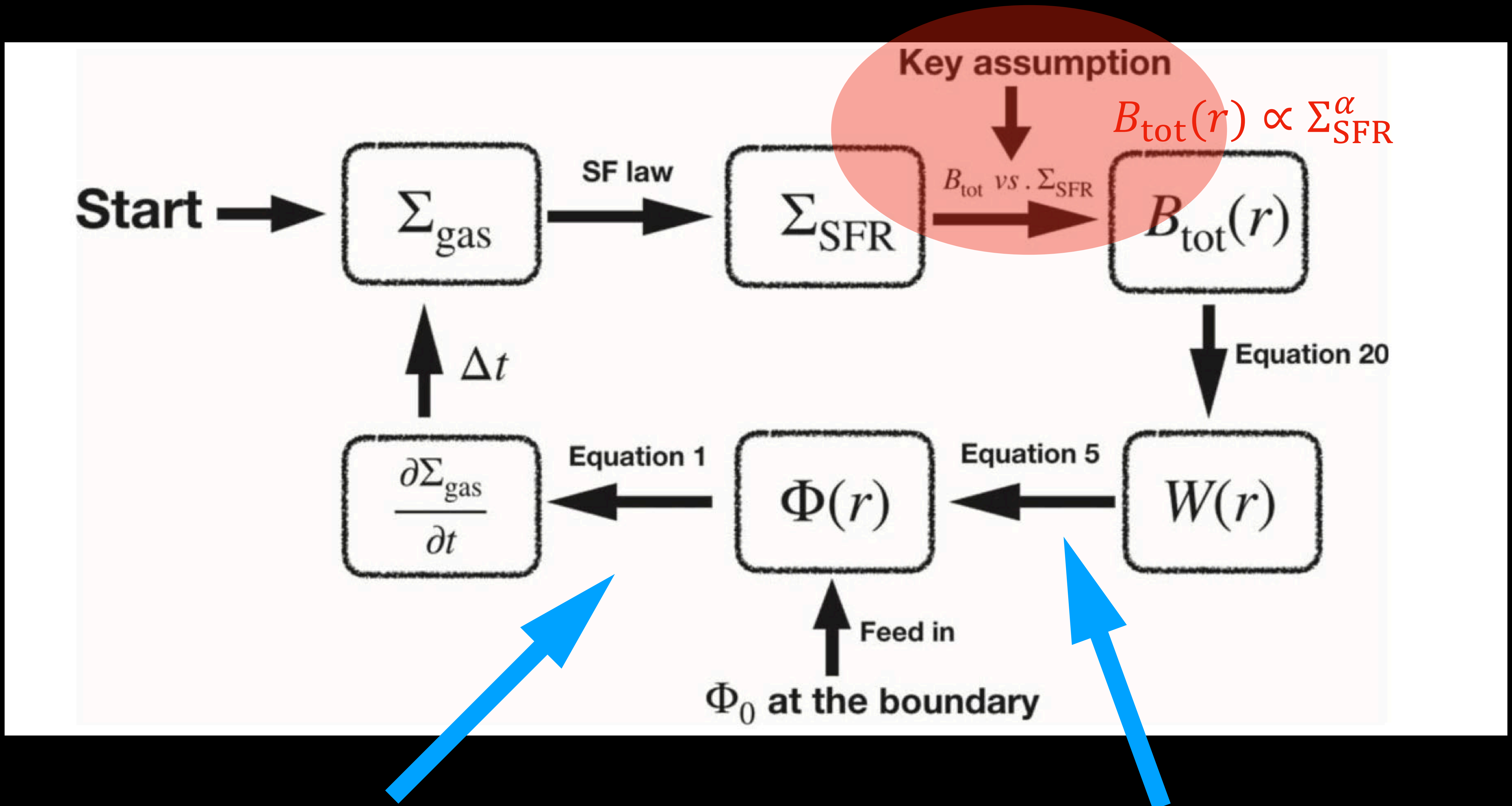
$$\mathbf{u}_G = \frac{\nabla \phi_s}{\sqrt{4\pi G\rho}}.$$

$$W = \Sigma_{gas} \cdot W_{r\phi}.$$

Magnetic filed is taken fro Seta & Beck (2019).

The MRI (magneto-rotational instability) is the most plausible source of viscosity.

Construct a model to understand whether or how it works



$$\frac{\partial \Sigma_{gas}}{\partial t} = \frac{\partial \Phi}{2\pi r \partial r} - (1 - R + \lambda) \cdot \Sigma_{SFR}$$

$$\frac{\partial (\Sigma_{gas} r^2 \Omega)}{\partial t} = \frac{\partial (\Phi r^2 \Omega)}{2\pi r \partial r} - r^2 \Omega (1 - R + \lambda) \Sigma_{SFR} - \frac{\partial T}{2\pi r \partial r}$$

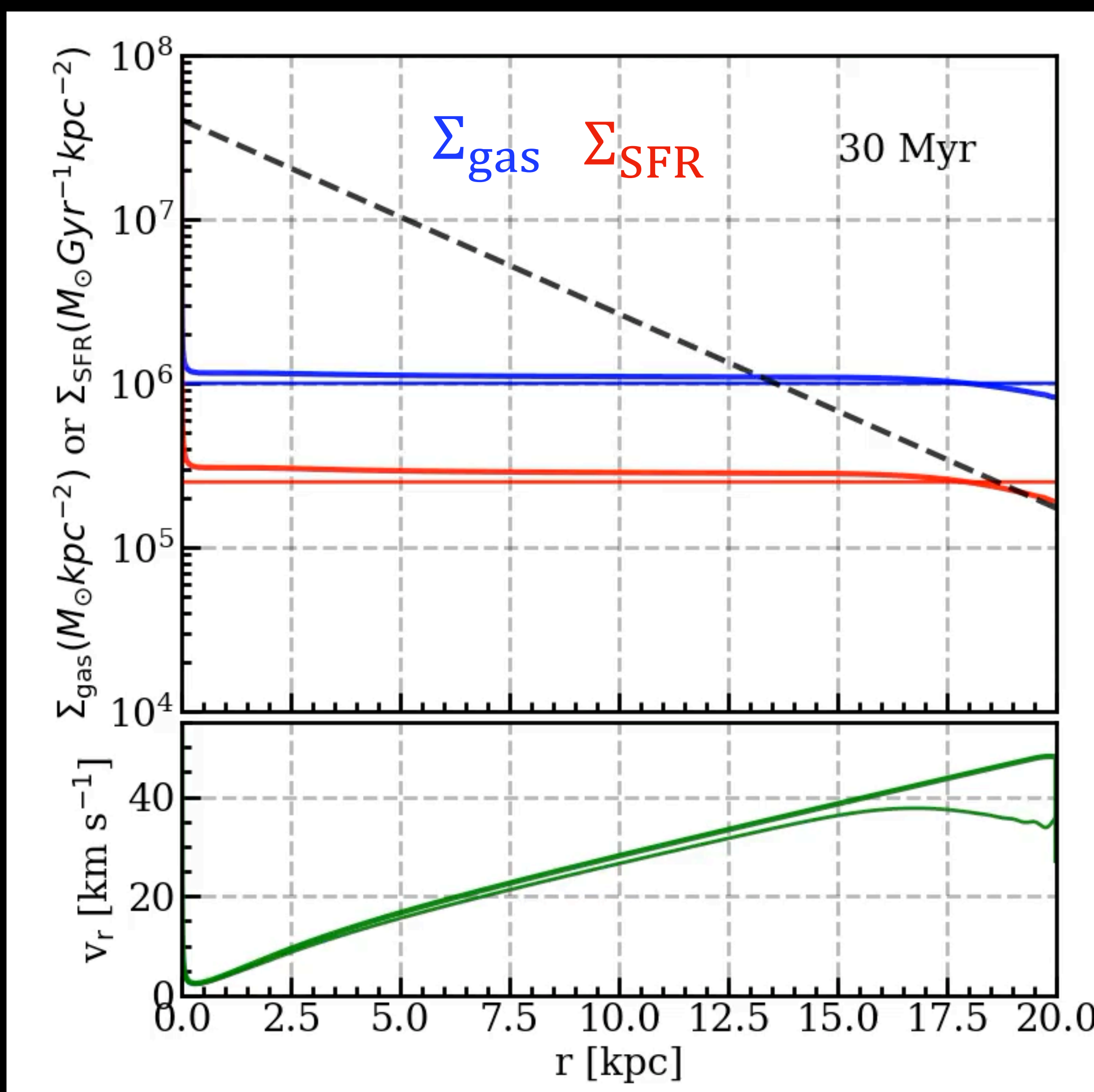
The key assumption is the magnetic field is regulated by the instantaneous SFR surface density.

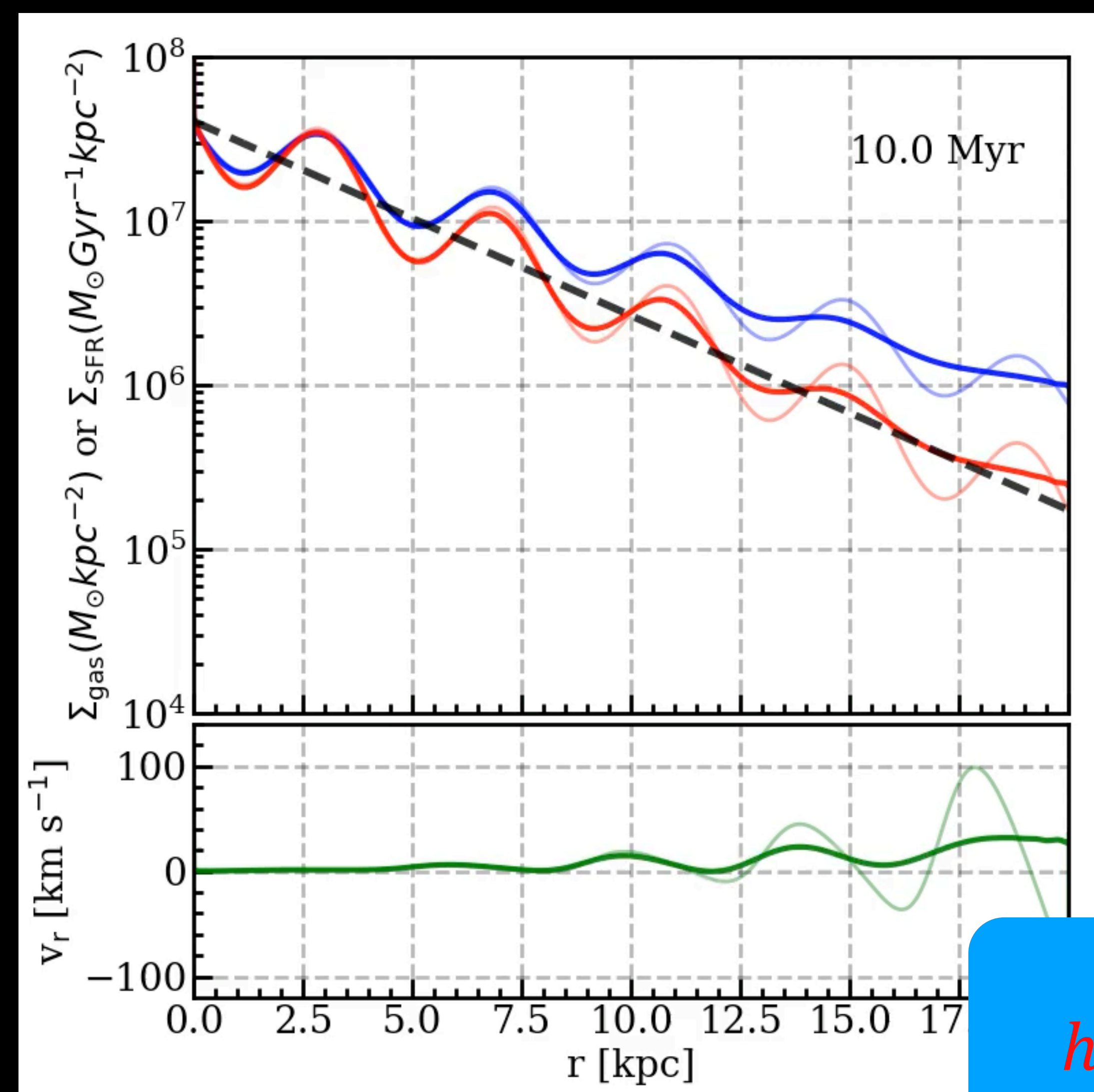
The output of the model

With the assumption of energy equipartition between the magnetic field and cosmic rays, observations indicate that (Heesen et al. 2014, Beck et al. 2019):

$$B_{\rm tot}(r) = 19.1\mu G \cdot \left(\frac{\Sigma_{\rm SFR}}{0.01 {\rm M_\odot yr^{-1} kpc^{-2}}}\right)^{0.15}.$$

Fiducial run: $\Phi_0 = 3.5 M_\odot yr^{-1}$

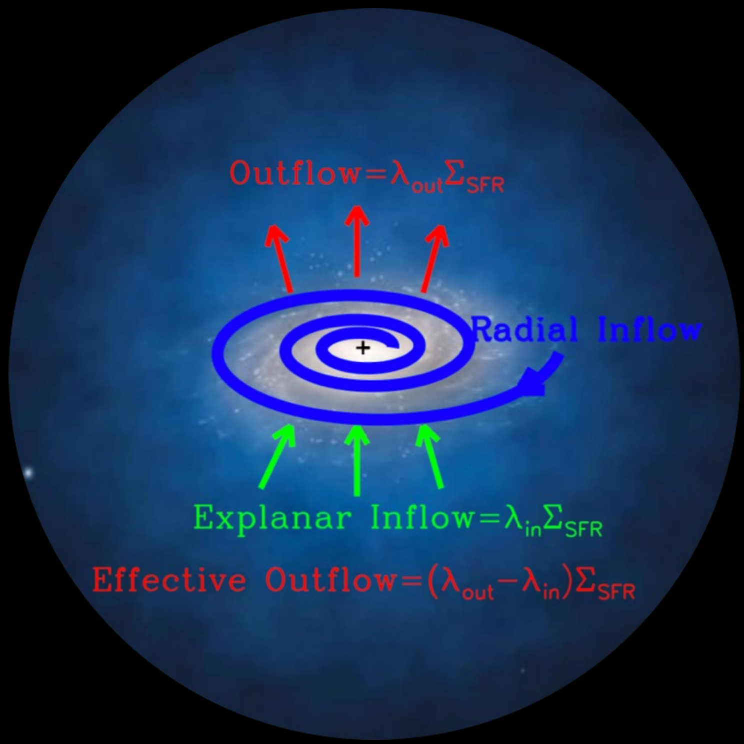


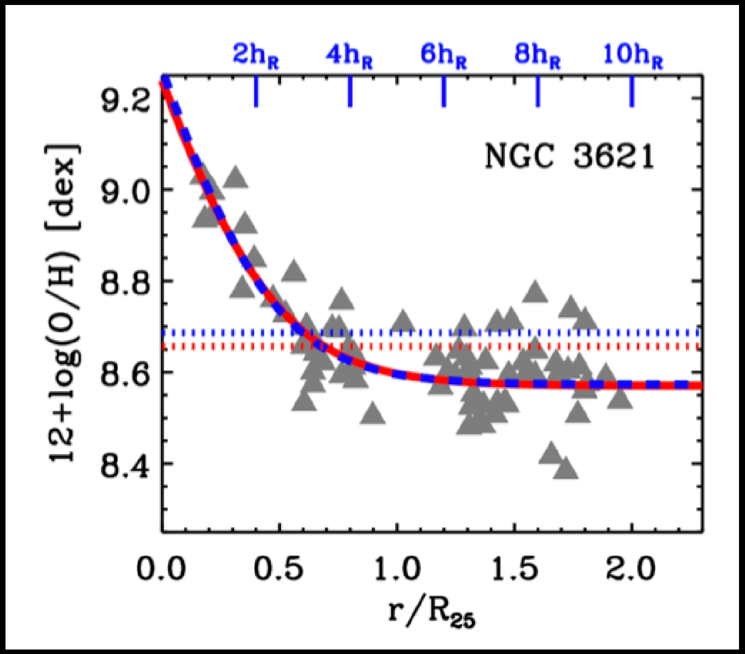


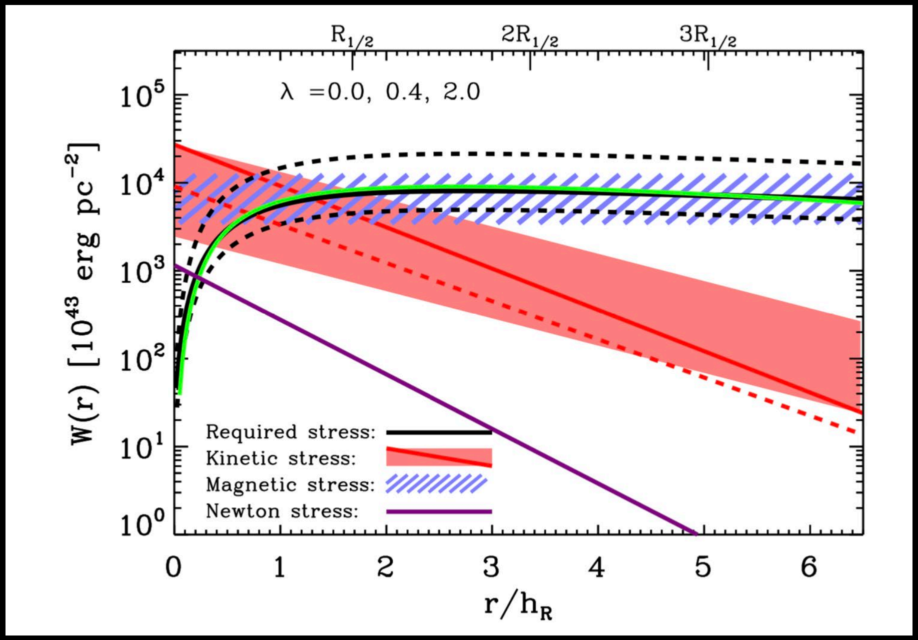
$h_R = 4kpc$

The viscous process is powerful enough to redistribute the angular momentum.

Conclusion







Gas disk of SF galaxies can be treated as a leaky accretion disk, suggested from the hydro-simulations.

The radial gradient of metallicity is a nature consequence of co-planar gas inflow which is continuously enriched by in-situ star formation.

The magnetic field is the most plausible source of viscosity that is responsible for the formation of exponential star-forming disk.

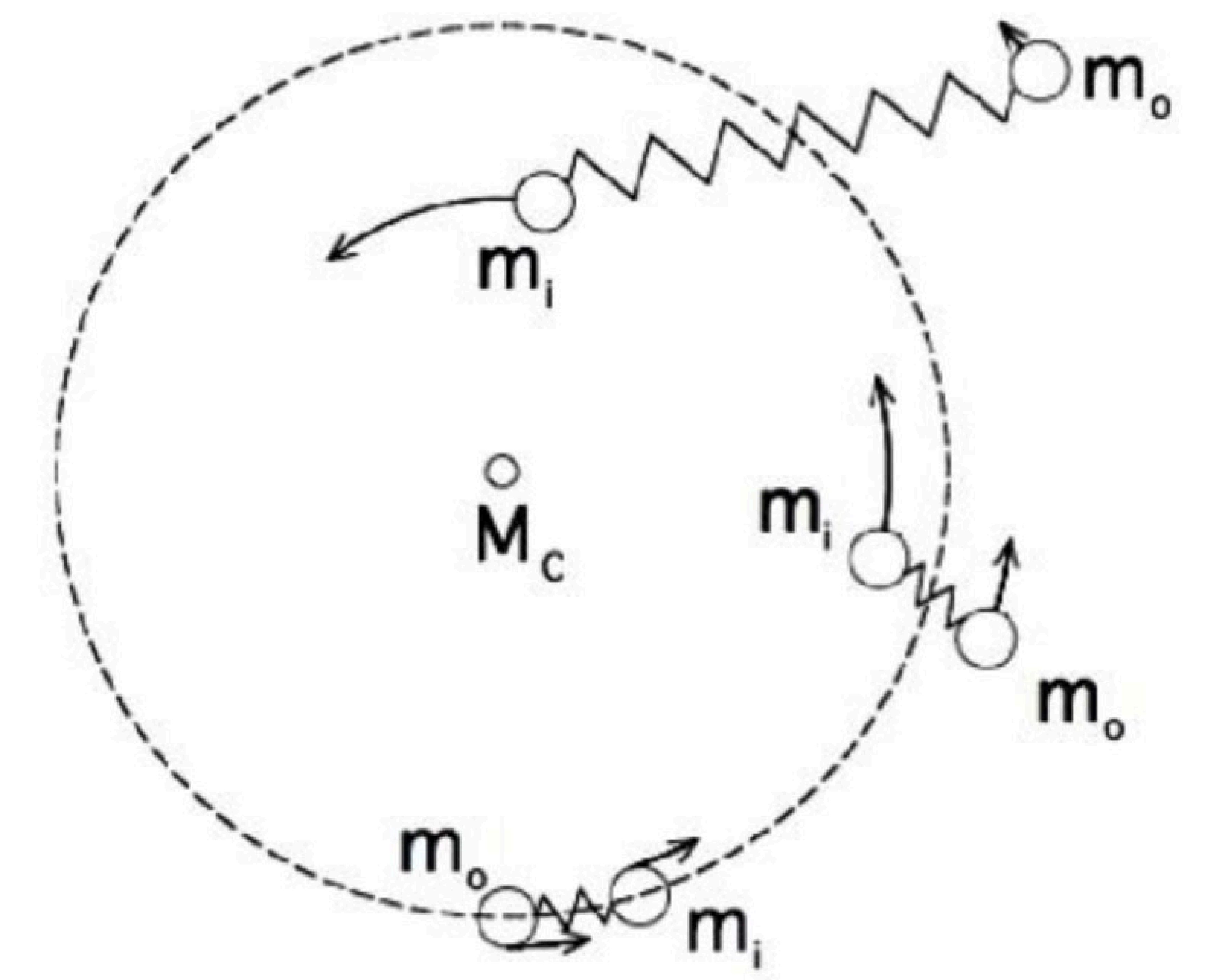
Wang, E., Lilly, S. J., Pezzulli, G., & Matthee, J. 2019, ApJ, 877, 132

Wang, E., & Lilly, S. J. 2022a, ApJ, 927, 217

Wang, E., & Lilly, S. J. 2022b, ApJ, 929,95

Wang, E., & Lilly, S. J. 2023, ApJ, 944, 143

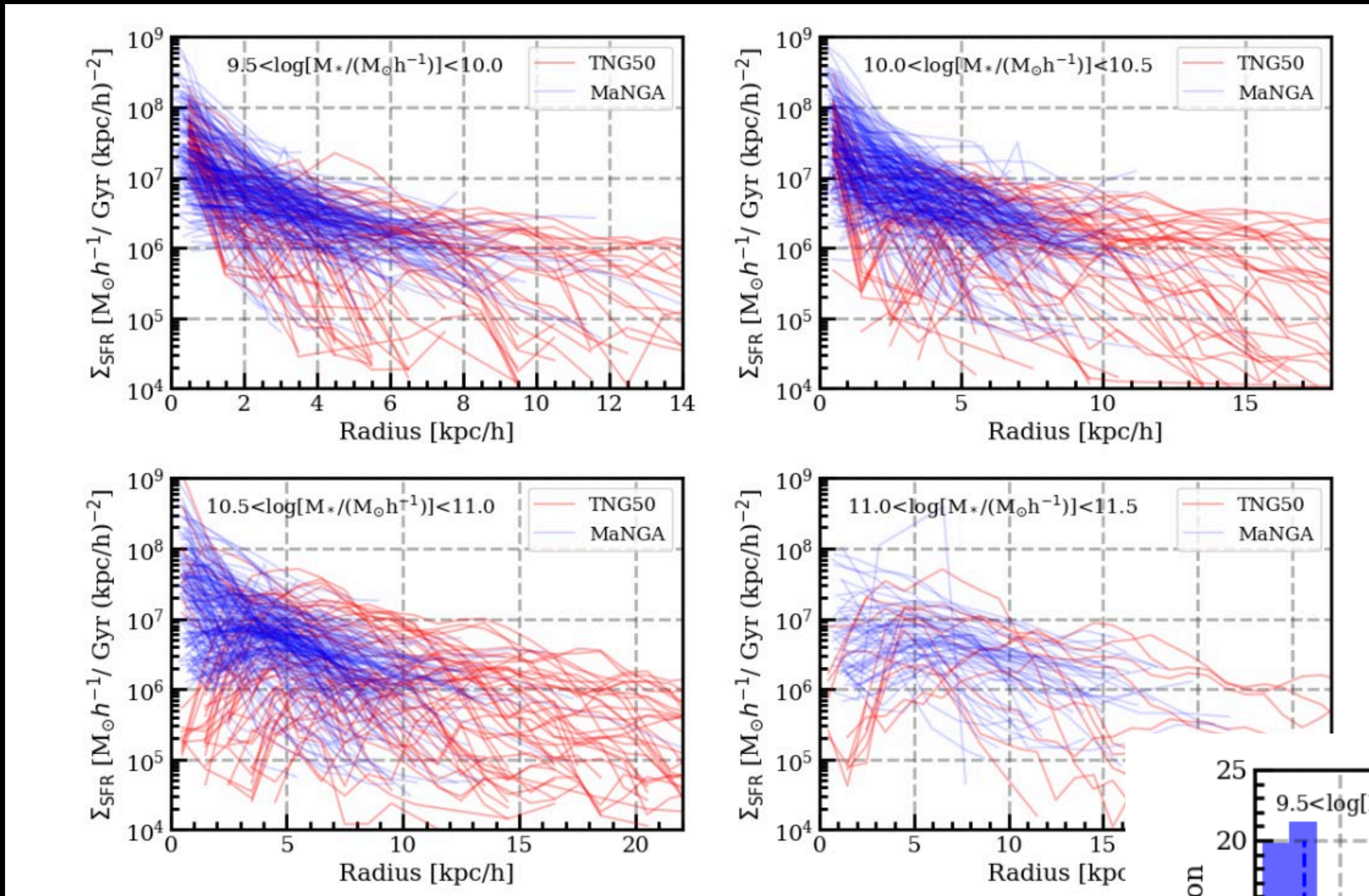
What is the magneto-rotational instability?



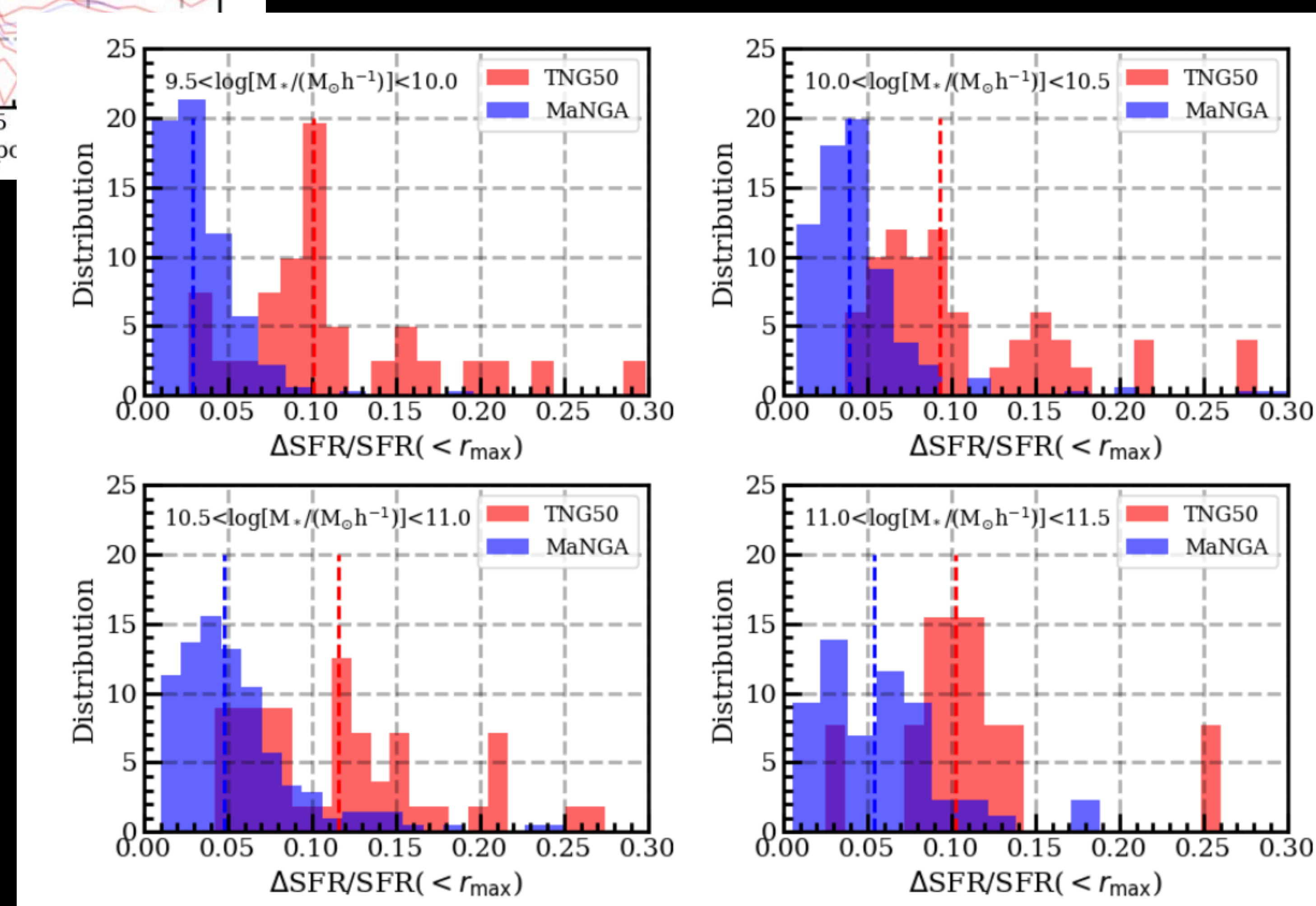
works like a weak string, and any weak magnetic field can cause the instability.

MRI instability (Balbus-Hawley-1991)

Whether IllustrisTNG can produce exponential SF profile?



Disk galaxies in TNG show larger size of star-forming disk than MaNGA galaxies.



Disk galaxies in TNG show larger deviation from the exponential star-forming disk than MaNGA galaxies.

Wang & Lilly 2023 (submitted)

Other non-essential assumptions

Star formation law:

$$\Sigma_{\rm SFR} = 2.5 \times 10^{-4} \cdot (\frac{\Sigma_{\rm gas}}{1{\rm M_\odot pc^{-2}}})^{1.4} {\rm M_\odot yr^{-1} kpc^{-2}}$$

Scale height of gas disk:

$$h_{\rm z} = 150{\rm pc} \times (\frac{r}{R_{\rm z}} + 1.0), R_z = 10kpc$$

Rotation curve:

$$V_\phi(r) = V_{\rm cir} \cdot \frac{2}{\pi} \arctan(r/R_{\rm t}), R_t = 2kpc$$

The shear-to-vorticity factor:

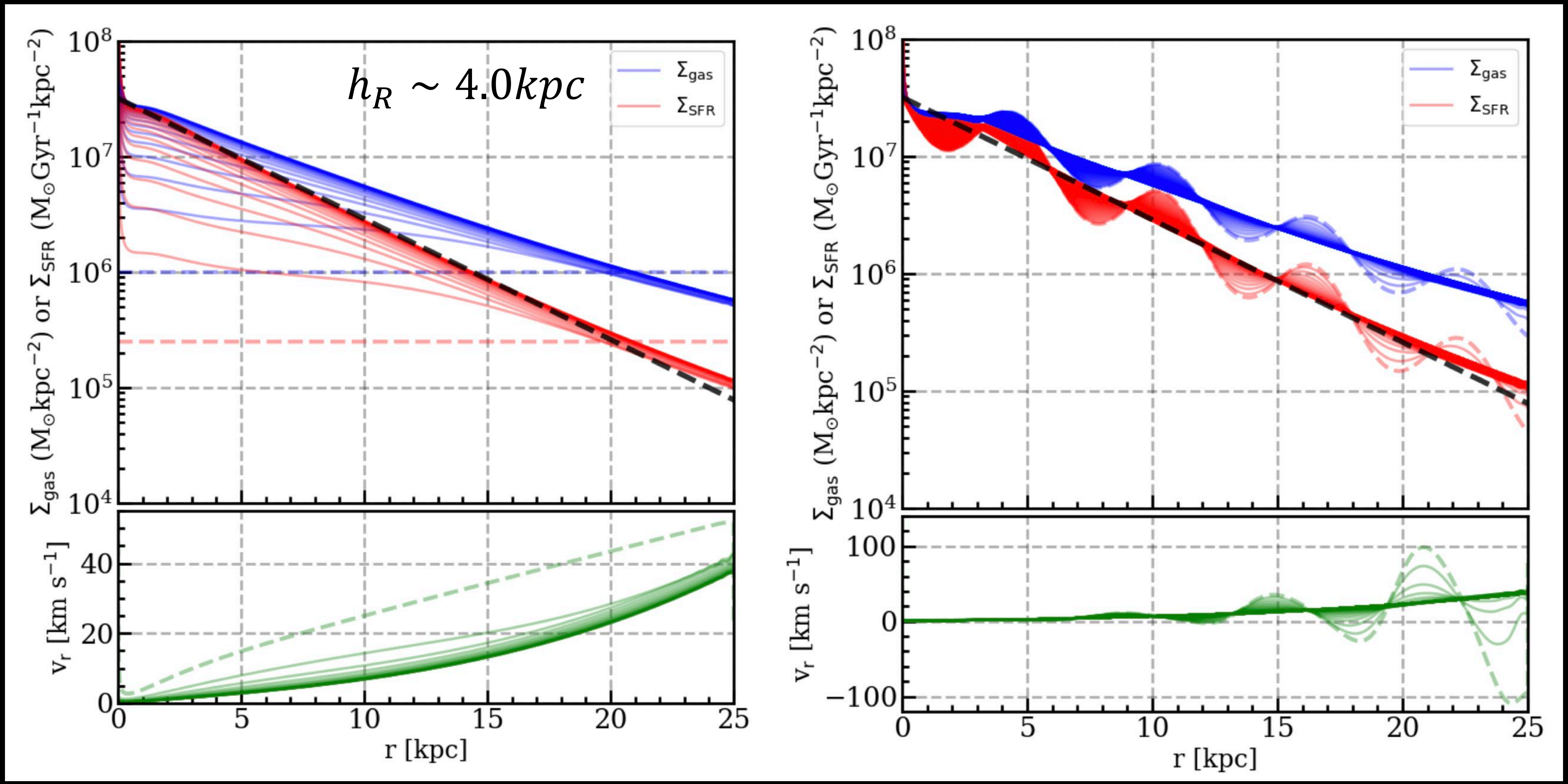
$$f_{\rm s/v} = q/(2-q), \qquad q = -\frac{\partial \ln \Omega}{\partial \ln r}.$$

The output of the model

With the assumption of energy equipartition between the magnetic field and cosmic ra

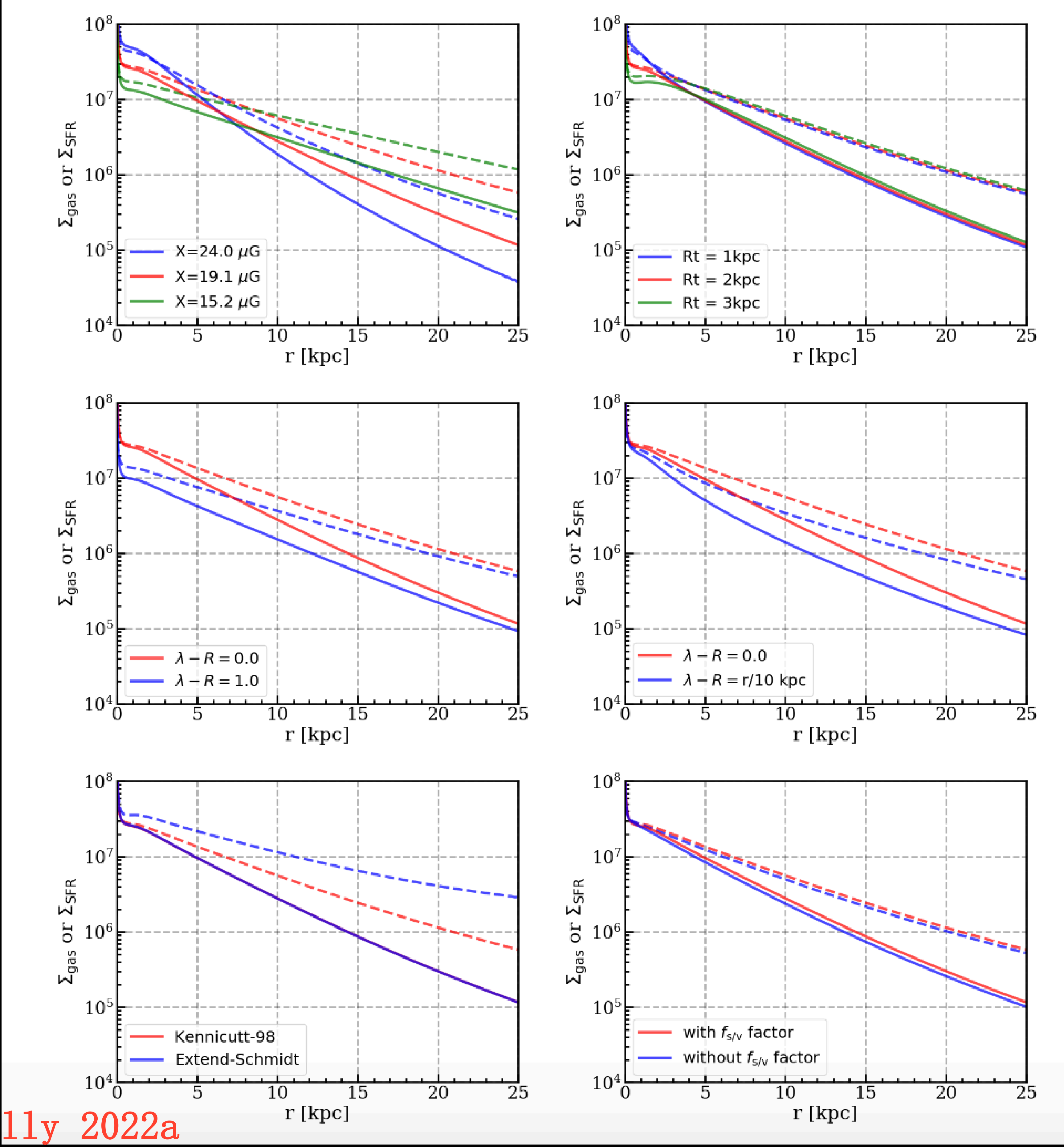
$$B_{\rm tot}(r) = 19.1\mu G \cdot (\frac{\Sigma_{\rm SFR}}{0.01{\rm M_\odot yr^{-1}kpc^{-2}}})^{0.15}.$$

iducial run: $\Phi_0 = 3.5 M_\odot yr^{-1}$



The viscous process is powerful enough to redistribute the angular momentum.

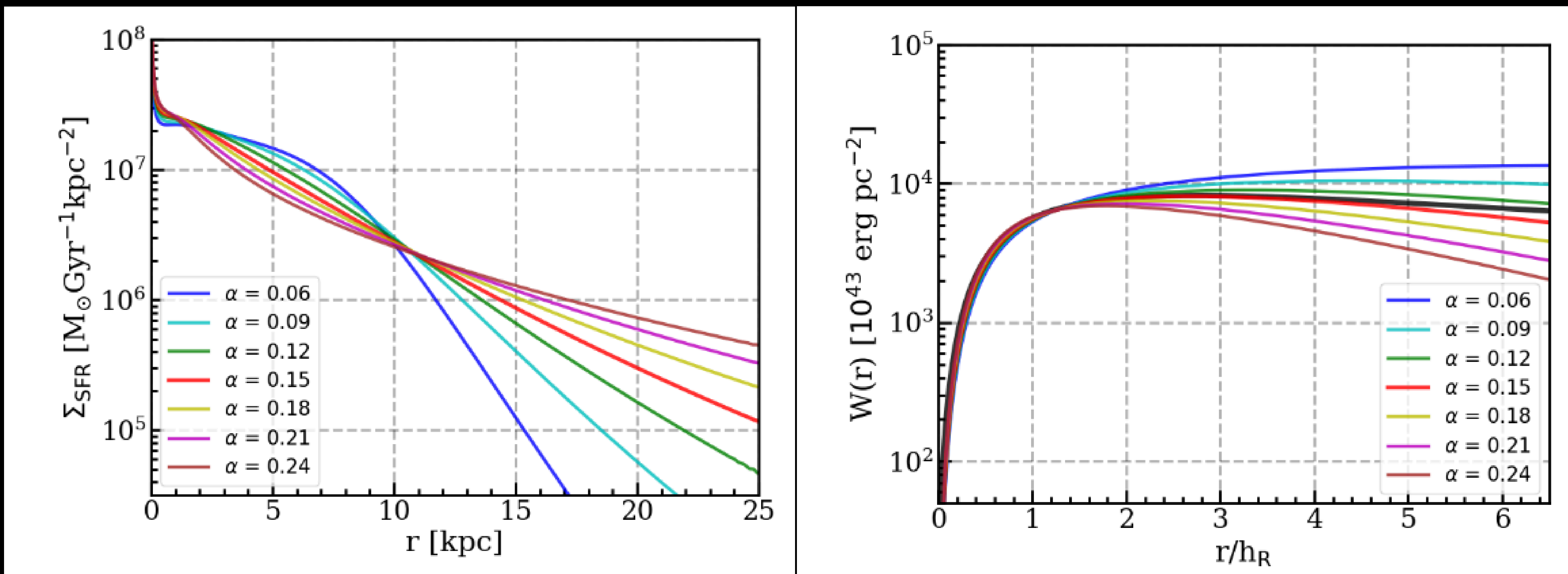
Check the dependence of the parameter settings



Wang & Lilly 2022a

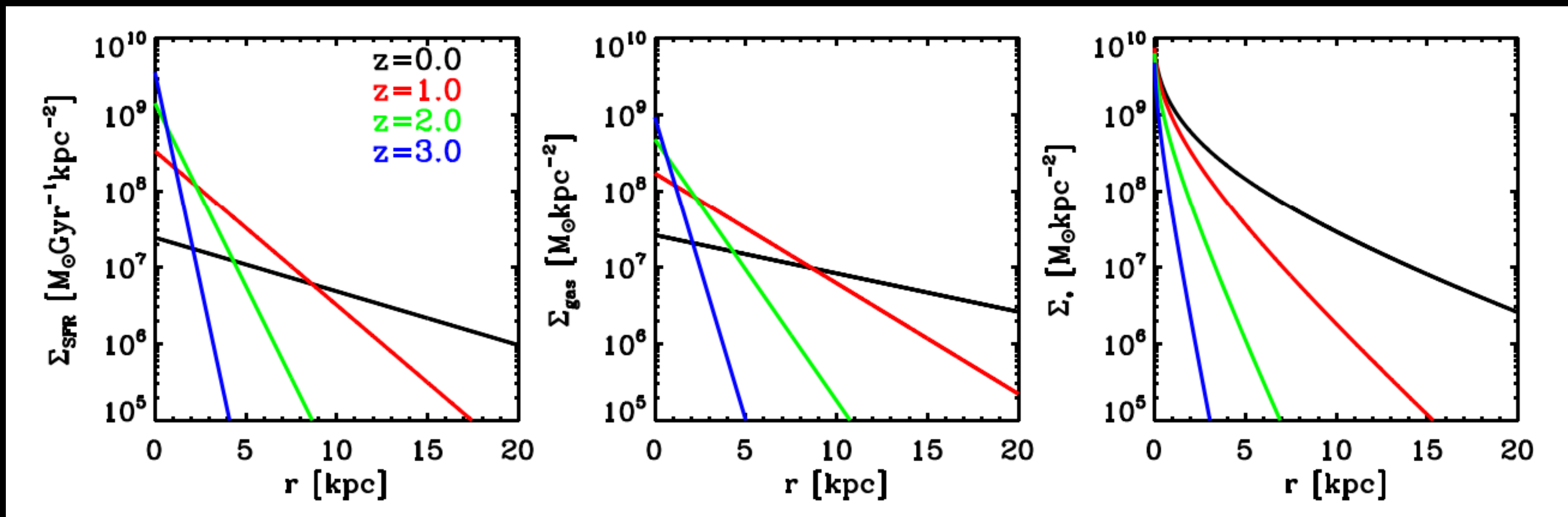
The dependence of alpha

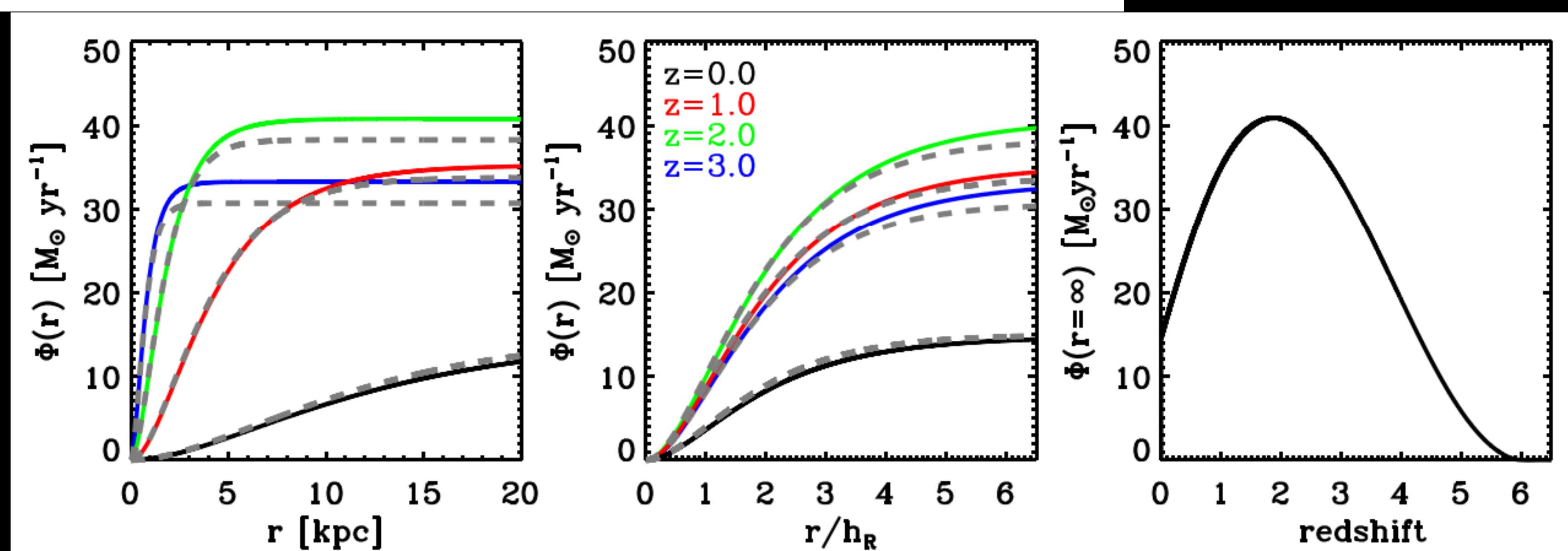
$$B_{\rm tot}(r) = 19.1\mu G \cdot \left(\frac{\Sigma_{\rm SFR}}{0.01 {\rm M_\odot yr^{-1} kpc^{-2}}}\right)^{0.15}.$$

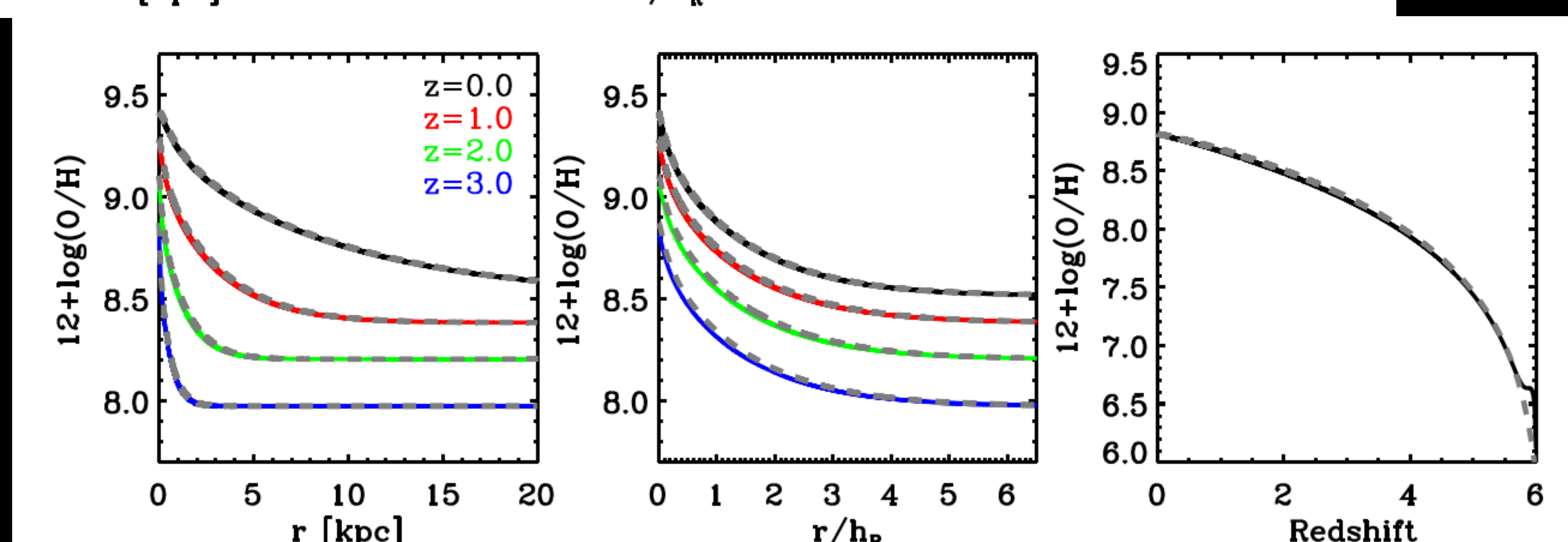


Wang & Lilly 2022a

Considering the cosmic evolution

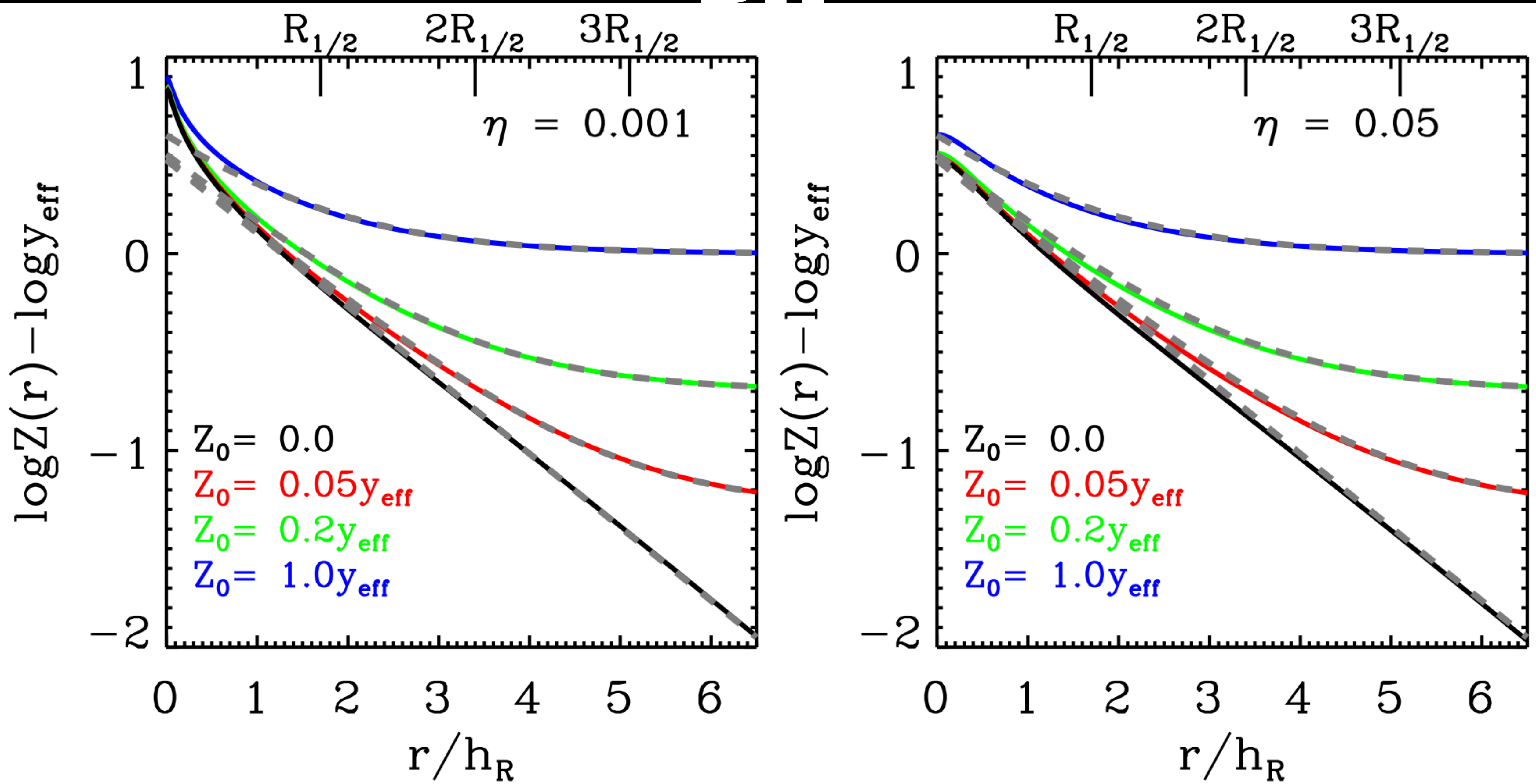






Wang & Lilly 2022b

Central gas sink into BH



$$Z(r) = -y_{\mathrm{eff}} \cdot \ln\left(1 - \frac{x+1}{\eta+1} \cdot e^{-x}\right) + Z_0, y_{\mathrm{eff}} = y/(1 - R + \lambda).$$

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The diffusion of metals

Equation (2). Then the continuity equation of metal mass can then be written as

$$\Sigma_{\rm gas} \cdot \frac{\partial Z}{\partial t} = \Phi \cdot \frac{\partial Z}{2\pi r \partial r} + y \cdot \Sigma_{\rm SFR} + \frac{\partial}{r\partial r}\left(\nu_{\rm D} \Sigma_{\rm gas} r \frac{\partial Z}{\partial r}\right), \tag{15}$$

where $\nu_{\rm D}$ is the diffusion coefficient. The turbulence-driven $\nu_{\rm D}$ is proportional to the squared of the turbulent velocity and the dissipation timescale (Karlsson et al. 2013):

$$\nu_{\rm D} \sim \sigma_{\rm turb}^2 \cdot \tau_{\rm D}. \tag{16}$$

We note that the $\sigma_{\rm turb}$ in Equation (16) reflects the turbulent velocity in the radial direction only, as opposed to the three-dimensional turbulent velocity, since we are only concerned with the radial dimension in the current work.

We assume the $\tau_{\rm D} = 10$ Myr (Wada et al. 2002; Mac Low & Klessen 2004), which roughly corresponds to a turbulent scale length of 100 pc for $\sigma_{\rm turb} = 10$ km s^{-1}. Observationally, the

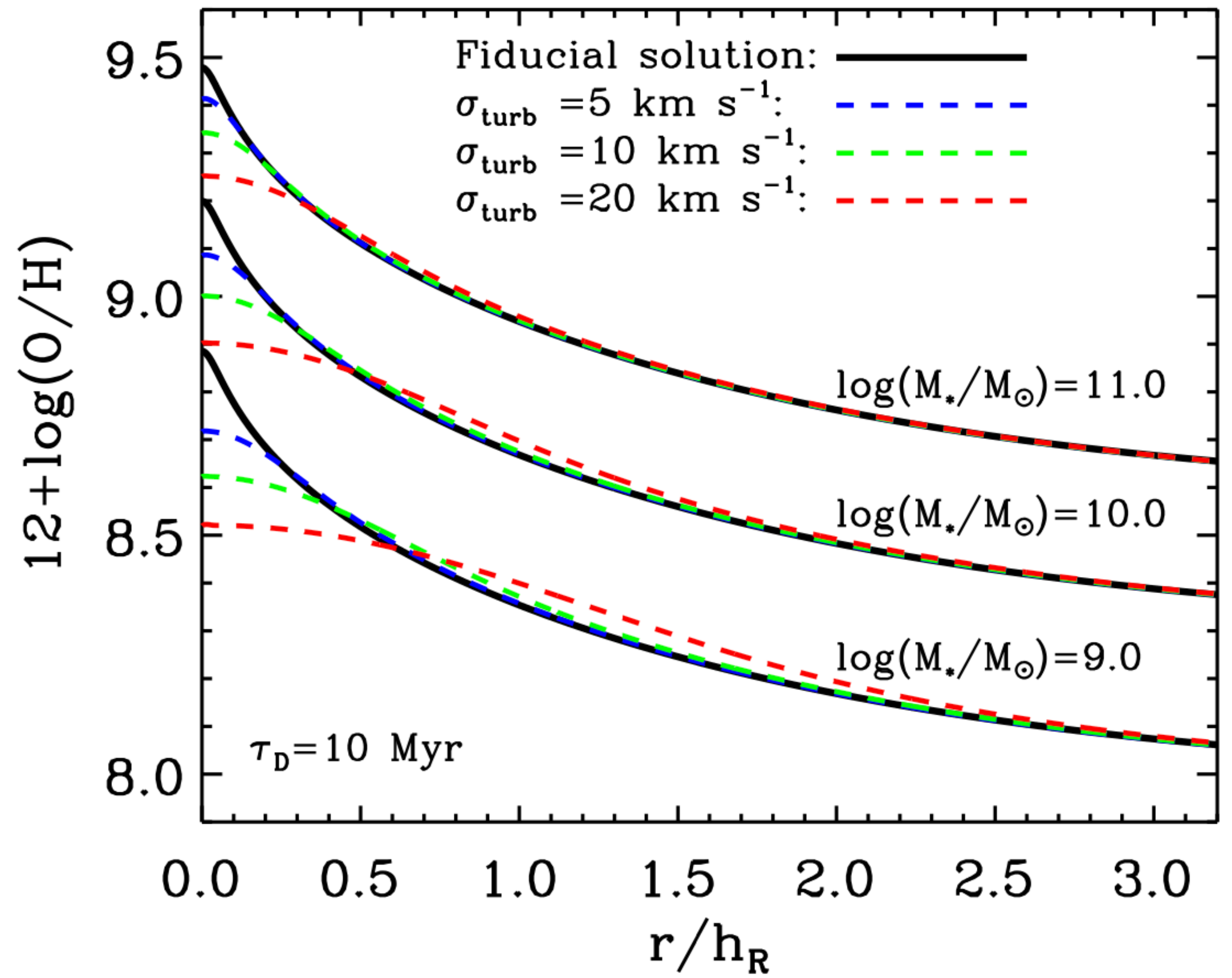

Figure 2. Effect of diffusion on the metallicity profile for three typical main-sequence galaxies of different masses. The colored dashed lines show the numerical solutions of oxygen abundance for three different $\nu_{\rm D}$, as denoted in the top of the panel. For comparison, we show the metallicity profile without any diffusion as the black solid lines (also see Equation (12)).

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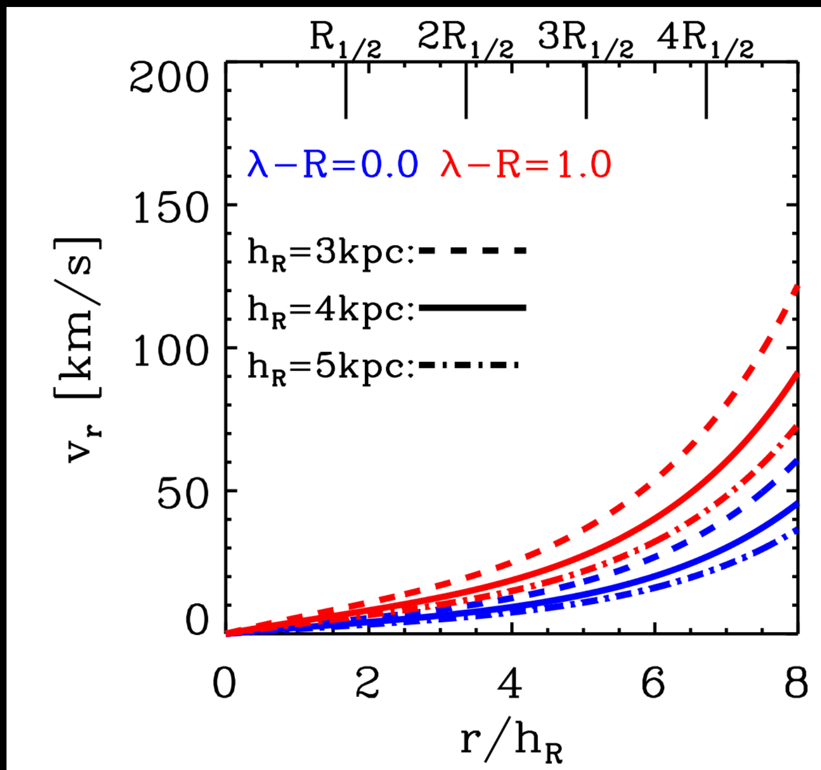
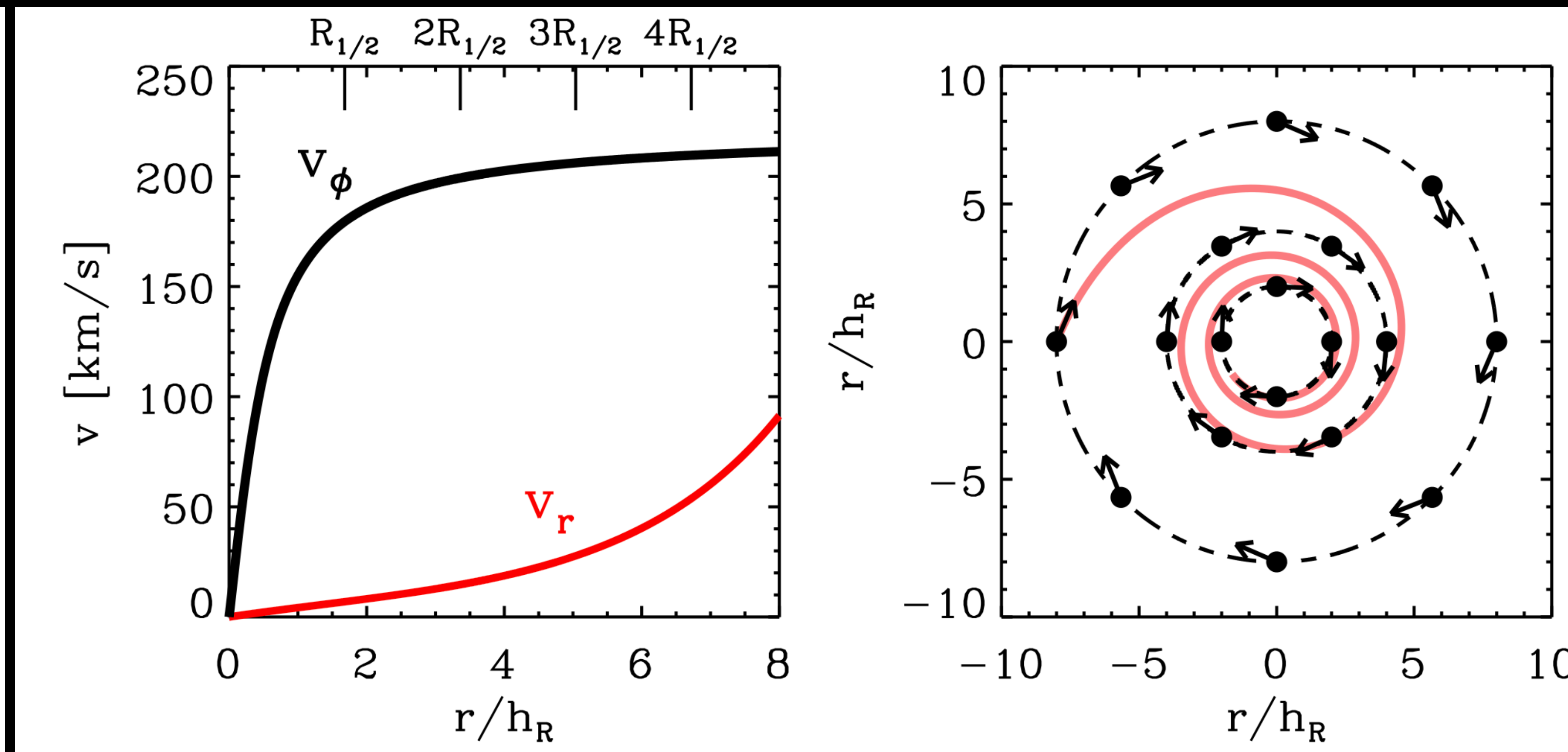
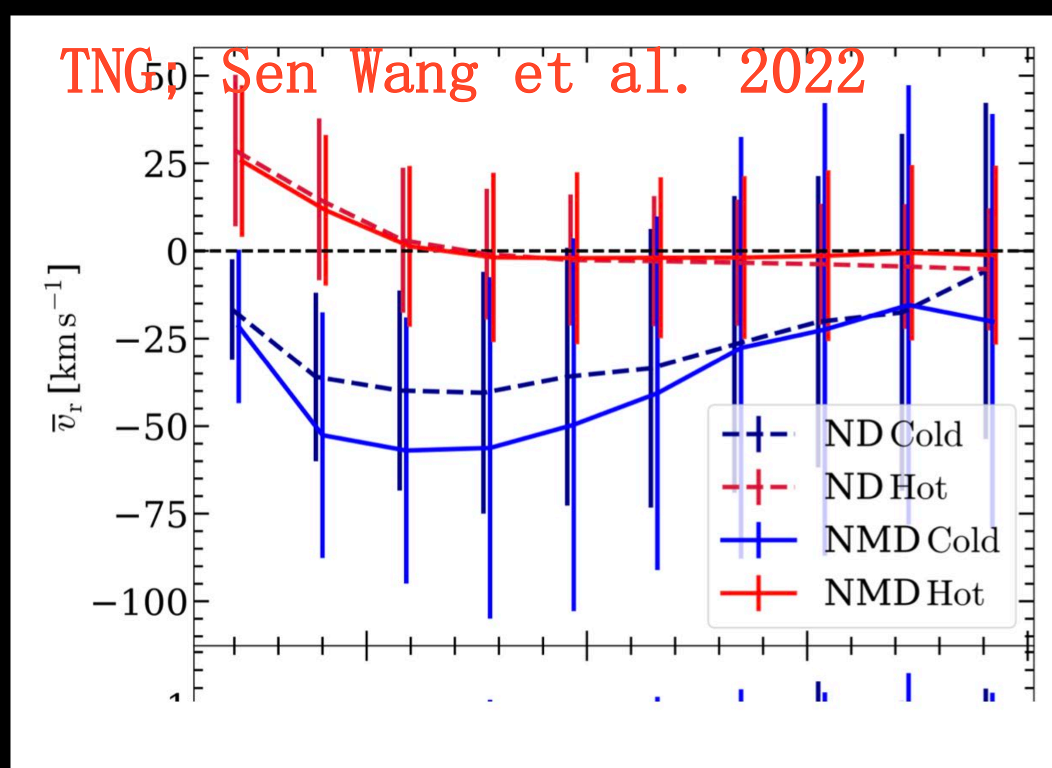
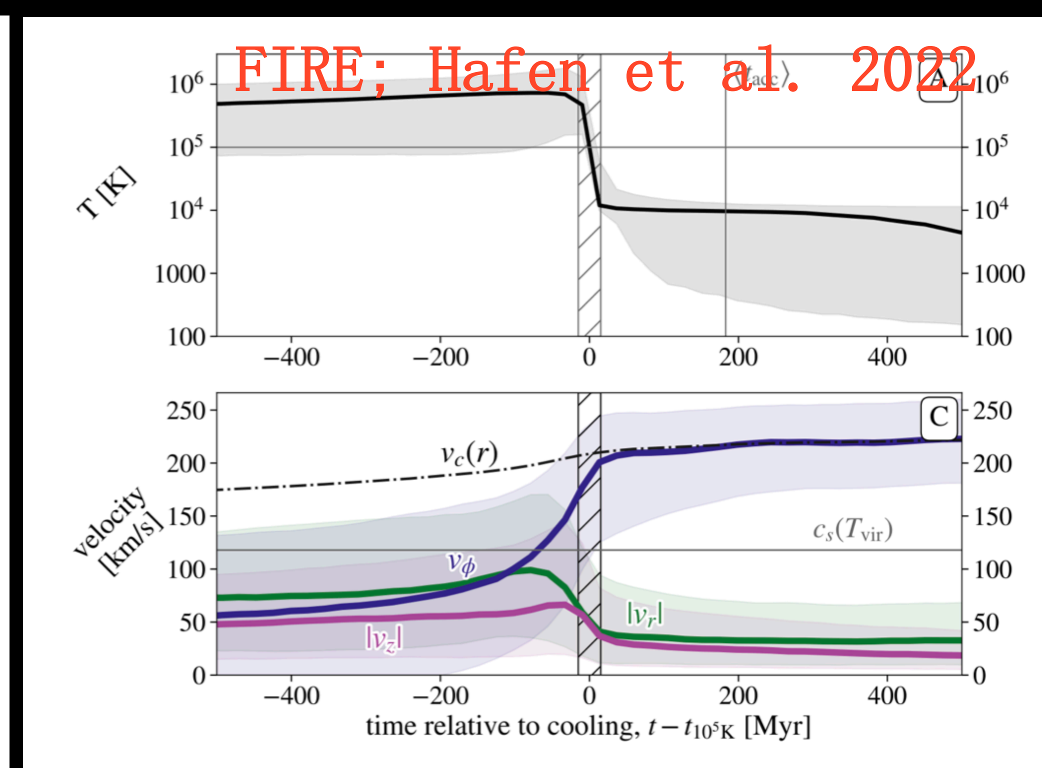
Gas inflow velocity









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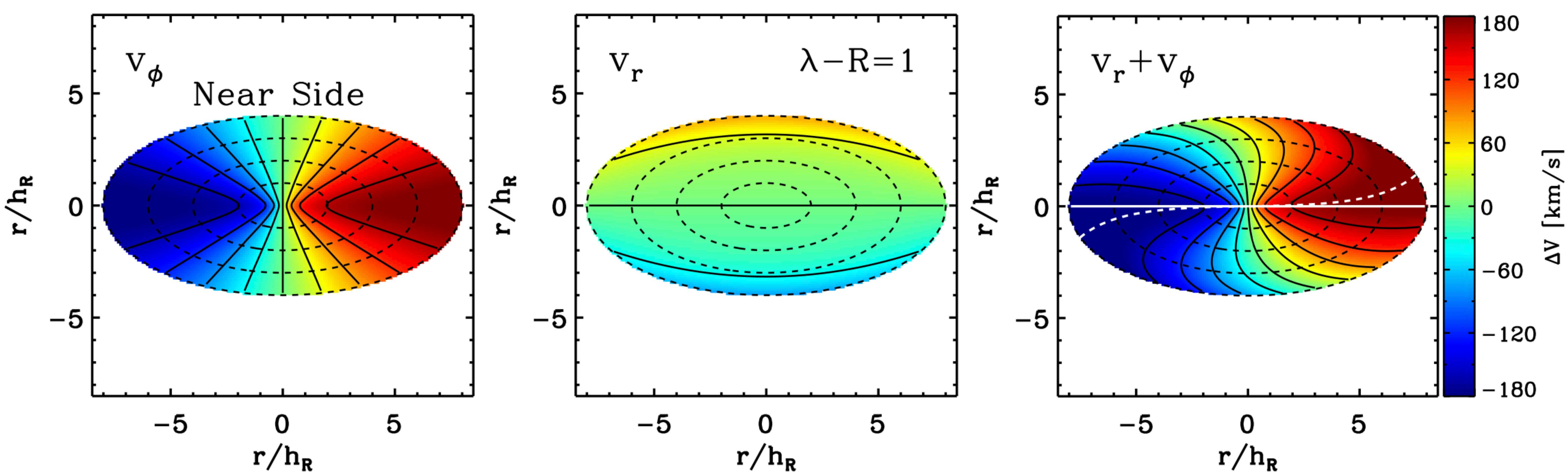
The problem of previous method to extract radial motion



The degeneracy on the kinematic maps for the warps and radial motion

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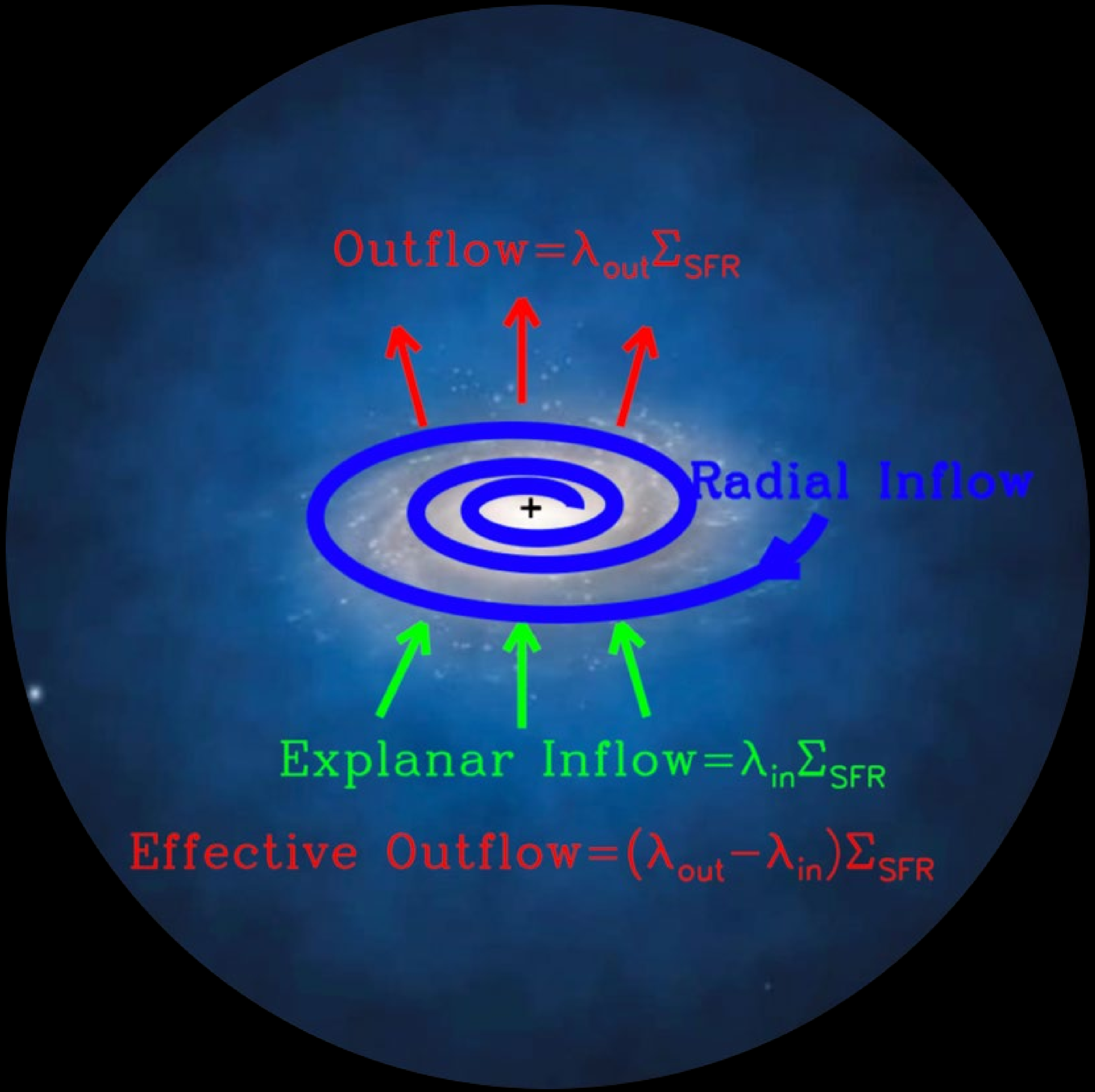

Outflow=$\lambda_{out}\Sigma_{SFR}$
Radial Inflow
Explanar Inflow=$\lambda_{in}\Sigma_{SFR}$
Effective Outflow=$(\lambda_{out}-\lambda_{in})\Sigma_{SFR}$