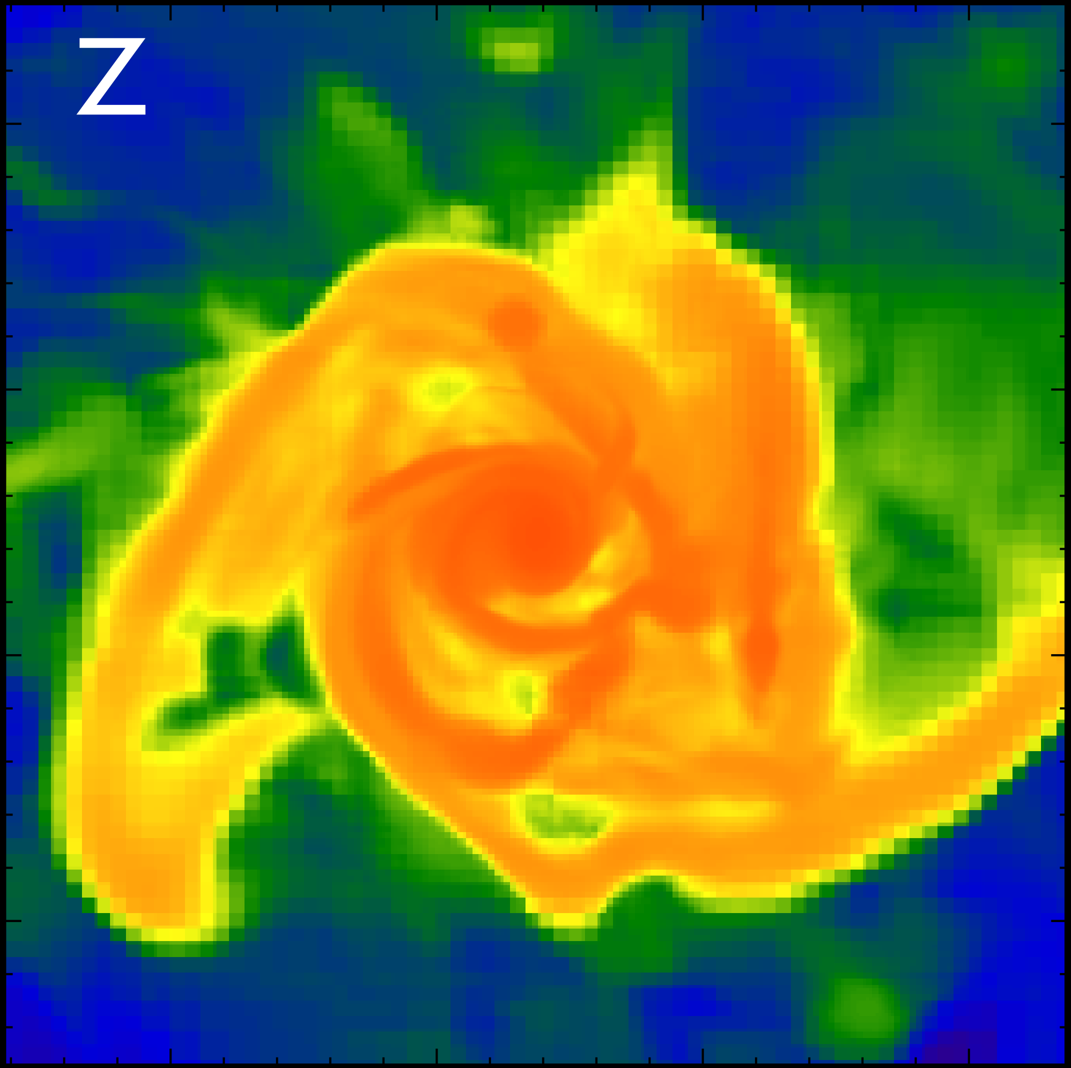
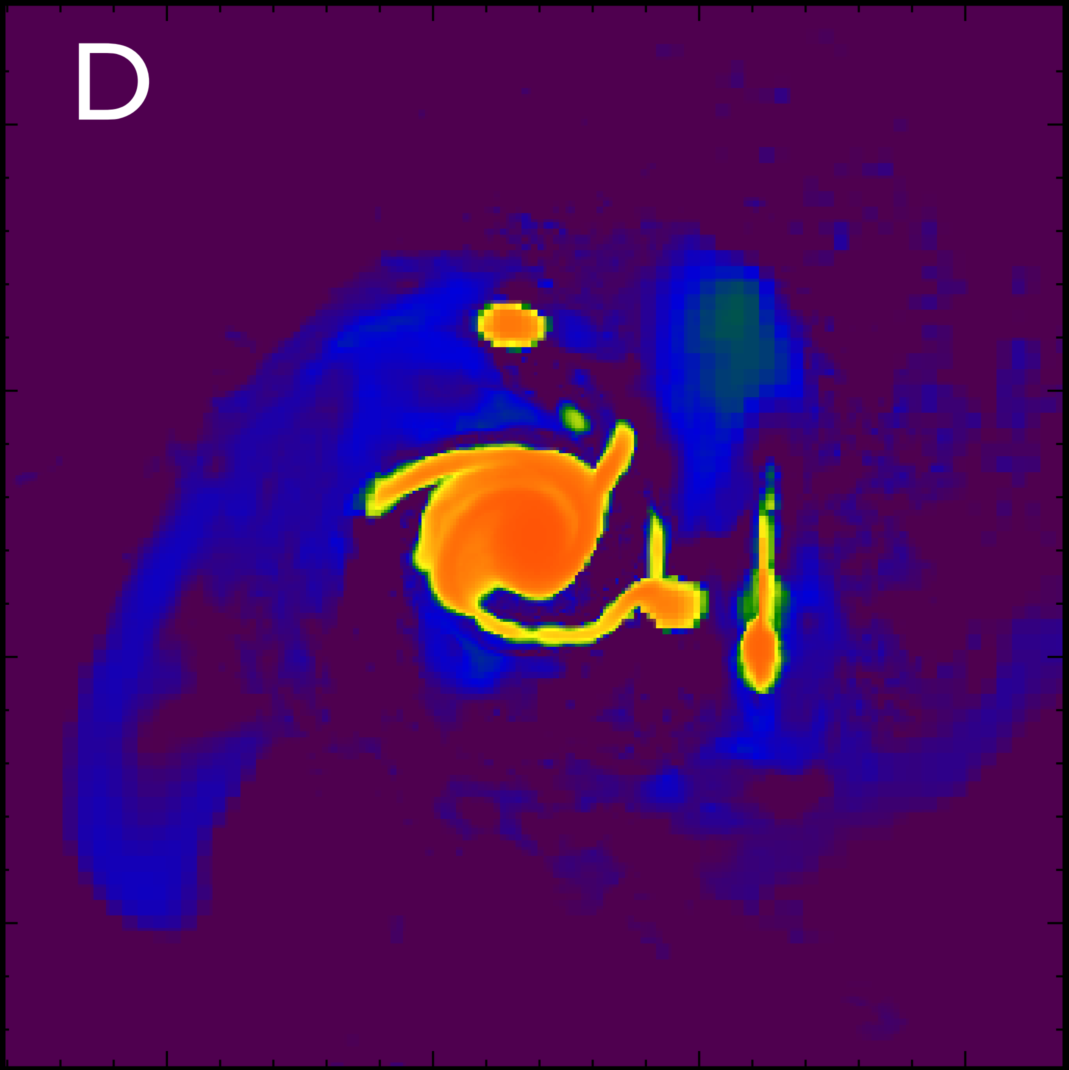
What drives low dust-to-gas and dust-to-metal ratios in galaxies?





based on
Feldmann 2015, MNRAS, 449,
arxiv:1412.2755

Robert Feldmann
UC Berkeley

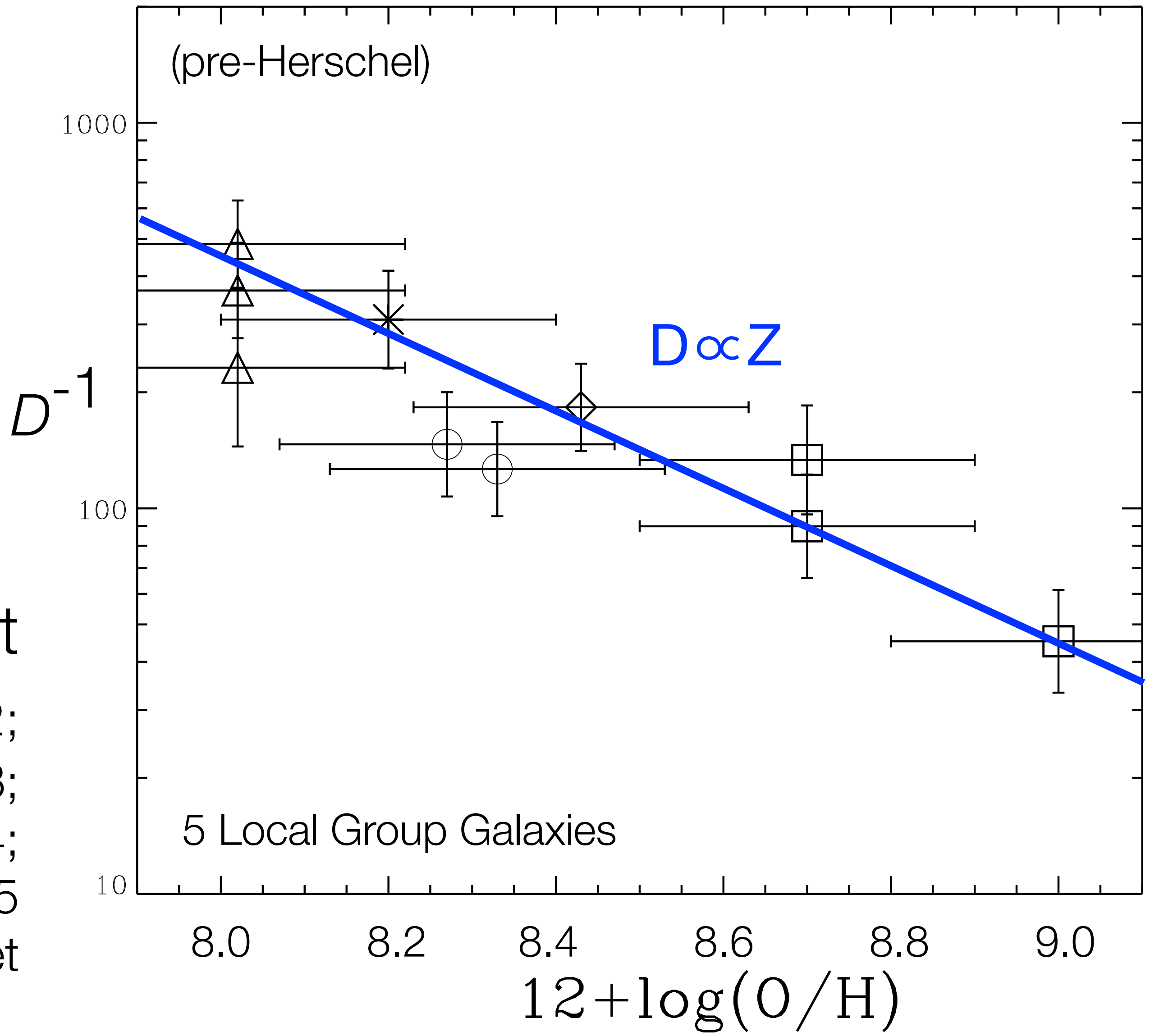
What sets the dust abundance in galaxies?

- observations show $D \sim 0.5 \times Z$ for many nearby galaxies

- similar result at intermediate z (QSO, GRB; e.g. de Cia+13, Zafar & Watson 13)

- How dusty are high-redshift galaxies? e.g., Walter et al. 2012; Kanekar et al. 2013; Ouchi et al. 2013; Ota et al. 2014; Gonzalez-Lopez et al. 2014; Maiolino et al. 2015; Schaerer et al. 2015 Cooray et al. 14, Capak et al. 15, Watson et al. 15, Scoville et al. 2015

Leroy et al. 2011



- clear deviation from linear relation for nearby dwarf galaxies
  - prototypical example: low Z, dwarf galaxies such as I Zw 18 (e.g., Galametz et al. 2011, Herrera-Camus et al. 2012)
  - larger samples with Herschel (e.g., Remy-Ruyer et al. 2014)

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Rémy-Ruyer et al. 2014

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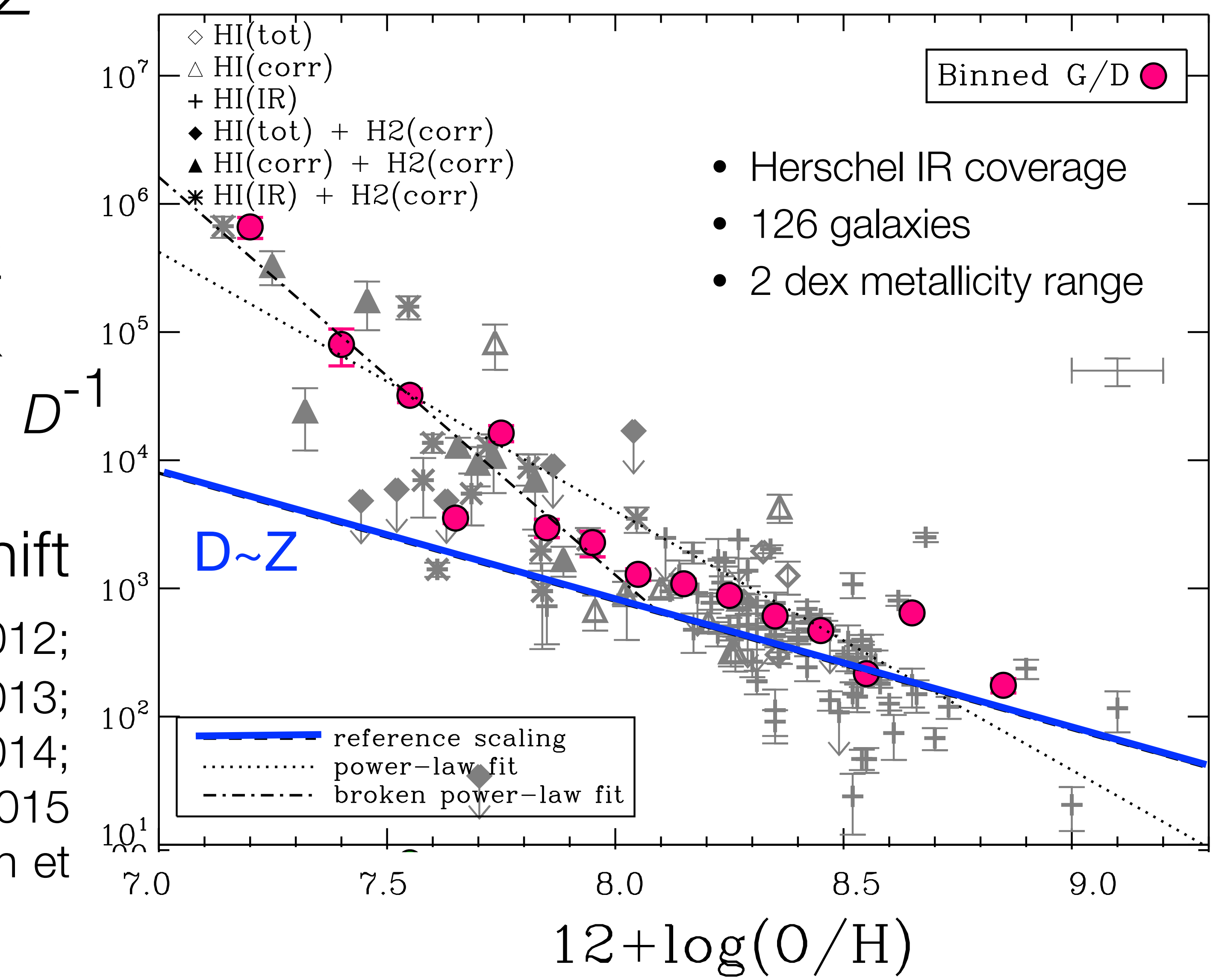

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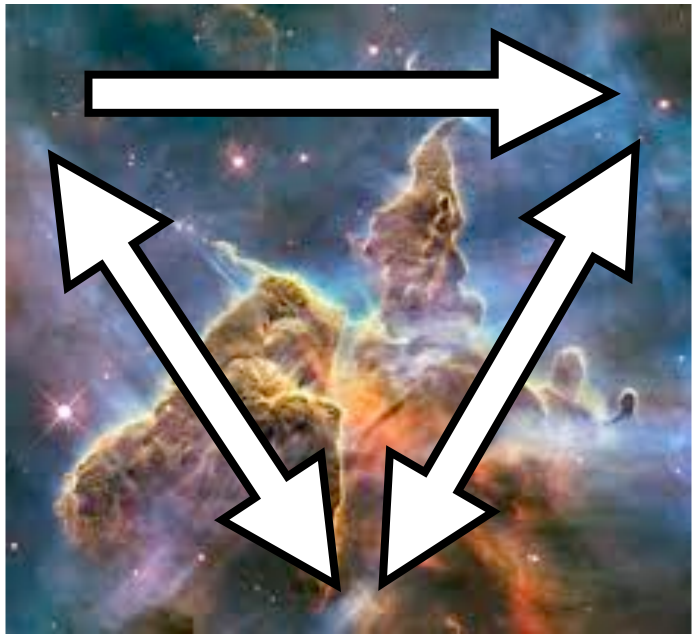
What does it tell us about the physics of dust?

- importance of grain growth in the cold ISM
- stellar dust production / destruction
- role of dust-poor inflows & dusty outflows

Extract information about the chemical cycle of the ISM?

Metals

- primary cooling agent
- required for ISM chemistry



Dust

- shielding agent
- cooling/heating
- catalysts for H_2 formation
- radiation pressure

Star formation

- metal & dust production
- dust destruction

How to analyze the dust evolution of galaxies?

Complexity

- one-zone chemical model with equilibrium ansatz
- dynamical, one-zone model with empirical constraints
- cosmological, hydrodynamical simulation with live dust model

e.g., Bekki 2015, McKinnon et al. 2015,
Feldmann & Gnedin in prep

Dust production & destruction:

- dust production by stars (AGB stars, SN) [$\propto$ metal production]
- dust destruction by SN shockwaves
- dust removal via star formation
- dust removal in outflows
- inflows from the cosmic web

- dust growth in the interstellar medium: $\dot{M}_{\rm dust} \propto M_{\rm dust}/t_{\rm acc}$
  - here: $t_{acc} \sim t_{acc,\odot}\, Z_\odot / Z$ (e.g., Inoue+11, Asano+13)
  - can be calculated directly (collision theory, e.g., Dwek 1998, Weingartner & Draine 1999), but uncertain parameters

  => t_{acc} rather uncertain: 10^5 yr (Dwek 1998) – 10^8 yr (Hirashita 2000)

One-zone models

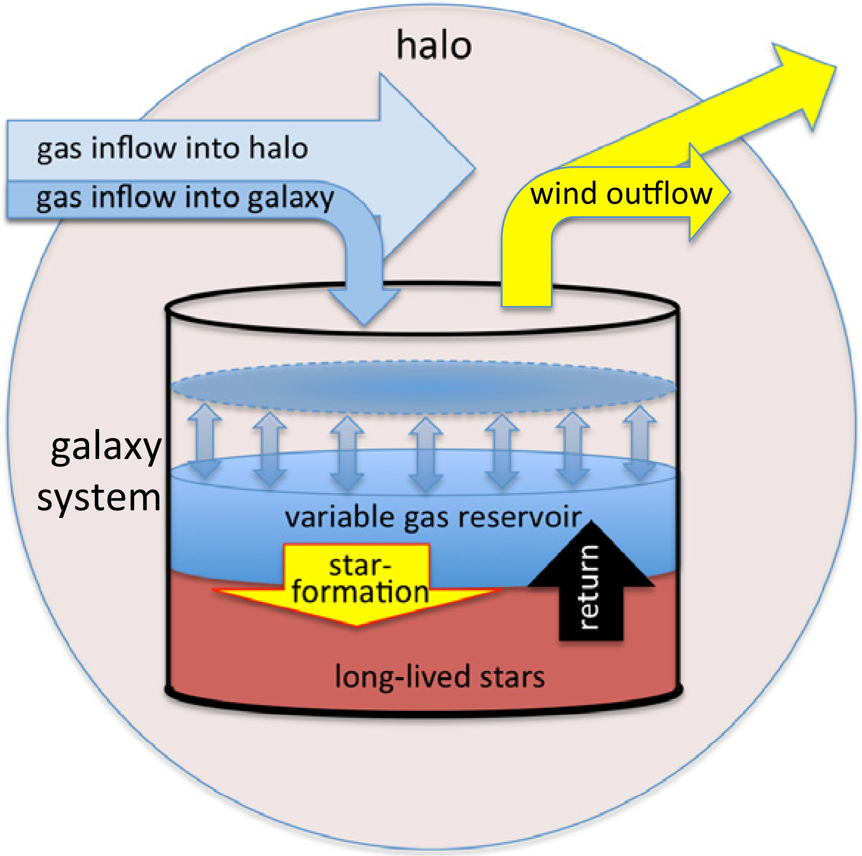
- treat galaxies as a single zone
- average over spatial variations

$$\dot{M}_{\rm g} = \dot{M}_{\rm g,in} - (1-R)\,{\rm SFR} - \epsilon_{\rm out}\,{\rm SFR}$$

change in ISM mass | inflow | star formation | outflows

- similar equations for
  - metal masses in the ISM (y)
  - dust masses (y_d, t_{acc}, $\epsilon_{\rm SN}$)
- extensively used to study chemical (dust/metals) evolution:

e.g., Dwek & Scalo 1980, Wang 1991, Dwek 1998, Hirashita & Ferrara 2002, Galliano, Dwek & Chanial 2008, Gall, Andersen & Hjorth 2011, Inoue 2011, Asano et al. 2013, Feldmann 2013, Lilly et al. 2013, Zhukovska 2014, Zahid et al. 2014, ...

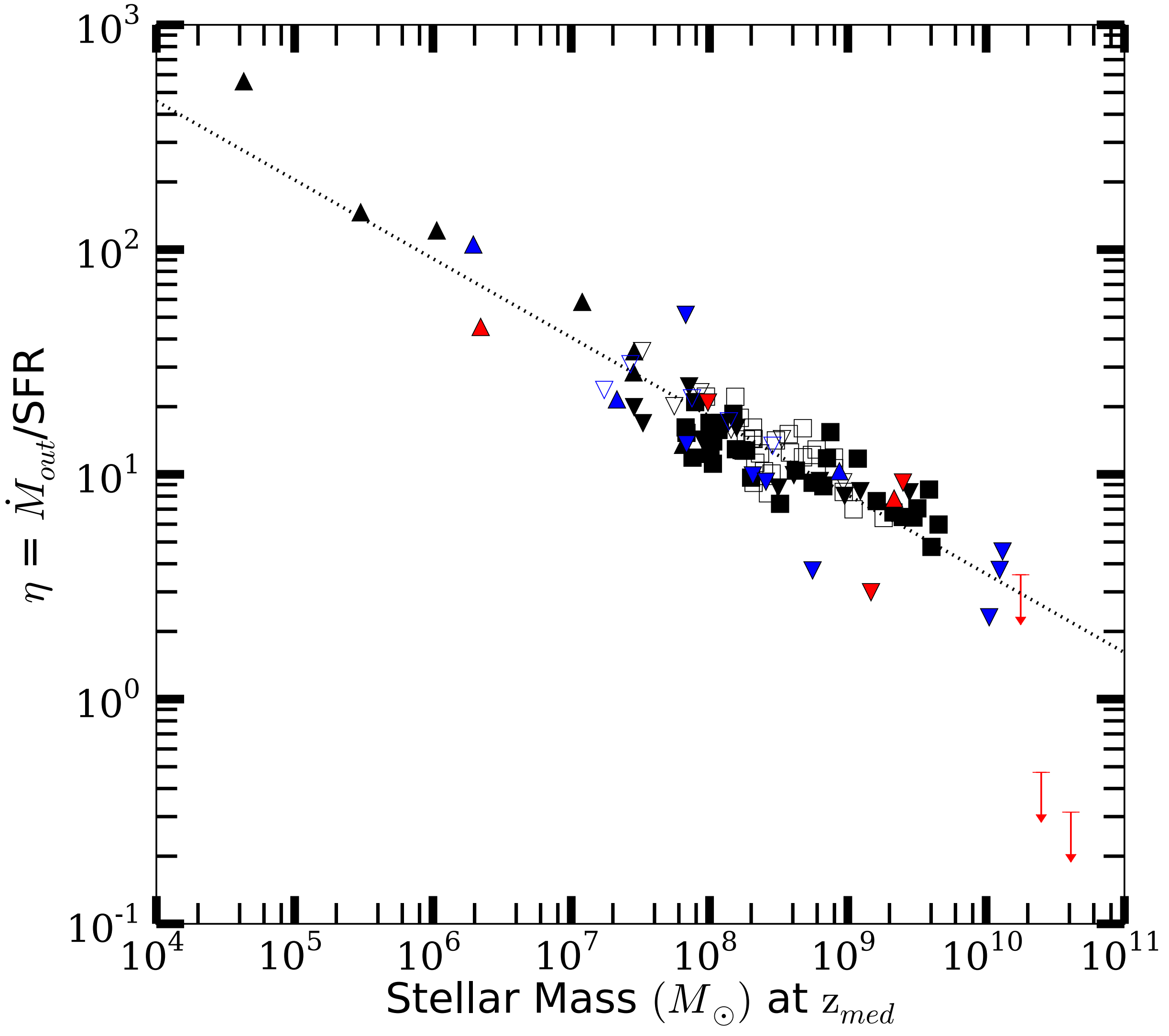


Lilly et al. 2013

Outflows

mass loading factor $\epsilon_{\rm out} = \frac{\dot{M}_{\rm gas,out}}{\rm SFR}$

Muratov et al. 2015



- hydrodynamical simulations find mass loading increases with decreasing stellar mass (e.g., Hopkins et al. 2011, Shen et al. 2012, Muratov et al. 2015)

$$\epsilon_{\rm out} \propto M_*^{-[0.3,0.5]}$$

- consistent with observations of outflows (~10^4 K gas) from galaxies in the nearby Universe (e.g., Chisholm et al. 2014)

Equilibrium Model

Equilibrium ansatz: Z and D change only "slowly"

gas mass / gas accretion rate ≲ t_{age}
(see Feldmann 2015)

metal yield

1. $$\langle Z \rangle \sim y \frac{\mathrm{SFR}}{\dot{M}_{\mathrm{gas,in}}}$$

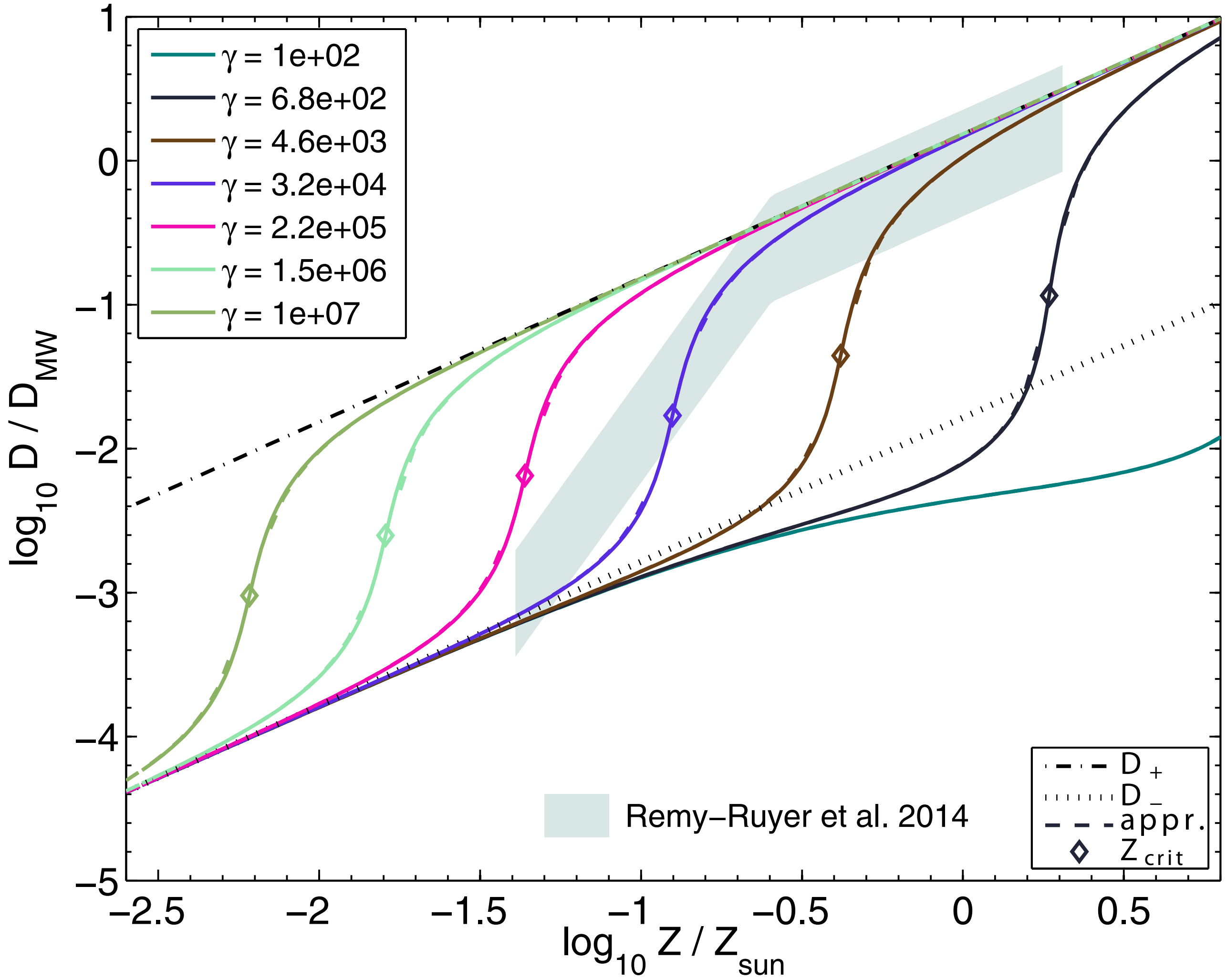
$$\left(\frac{\mathrm{SFR}}{\dot{M}_{\mathrm{gas,in}}} \right)^{-1} = \epsilon_{\mathrm{out}} + (1 - R) + \dot{M}_{\mathrm{gas}}/\mathrm{SFR}$$

outflows — star formation — changing ISM masses

2. $$\langle D \rangle = f\left(Z, \frac{\mathrm{SFR}}{\dot{M}_{\mathrm{gas,in}}}, \ldots\right) \Rightarrow \langle D \rangle (Z, \ldots)$$

model parameters, e.g., y, y_d, ...

Equilibrium prediction for the dust-to-gas ratio



$$\gamma = \frac{t_{\mathrm{dep,H_2}}}{t_{\mathrm{acc},\odot}\, Z_\odot}$$

$$\gamma \sim 3 \times 10^4$$

$$\Rightarrow \boxed{t_{\mathrm{acc},\odot} \sim 1 - 3 \times 10^6\, \mathrm{yr}}$$

- 3 regimes:
  - small *D/Z:* $D \sim \frac{y_\mathrm{d}}{y} Z$ — D set by stellar dust production
  - large *D/Z:* $D \sim \mathcal{O}(1)\, Z$ — D depletion limited
  - critical metallicity: $Z_\mathrm{crit} \sim \sqrt{y/\gamma}$ — balance: dust production & dust dilution by gas-poor inflows
- form of the D - Z relation constrains y_D/y & t_{dep}/t_{acc}

Main motivation:

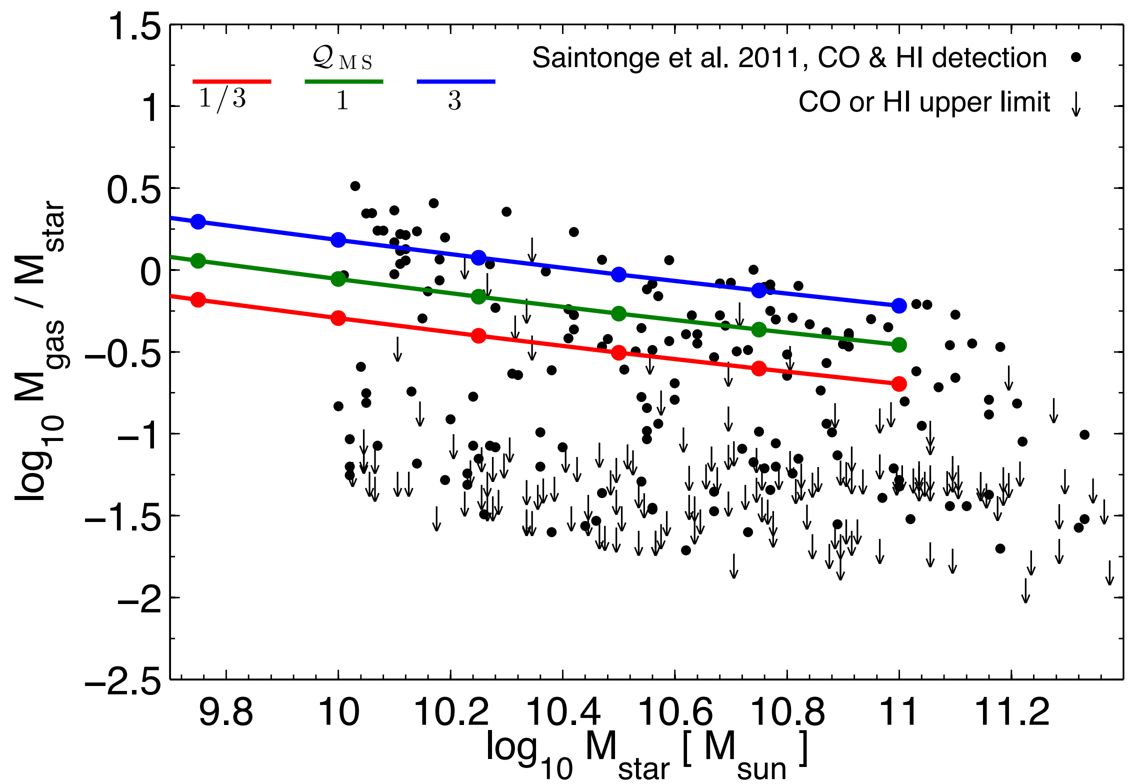
- to test validity / accuracy of the equilibrium ansatz
- to study which processes (outflows, star formation, evolving ISM masses, ...) drive low D/Z ratios
- to gain additional insights in the evolution of properties not captured by the equilibrium ansatz

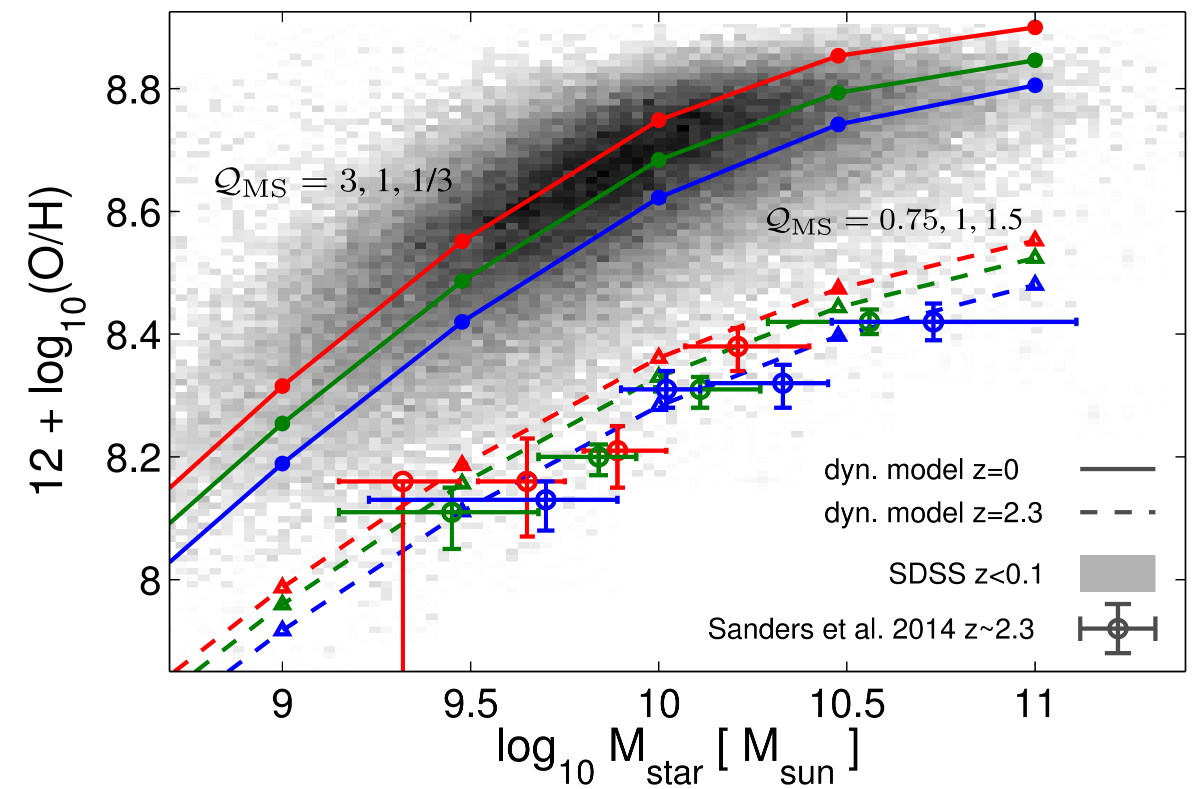
Method:

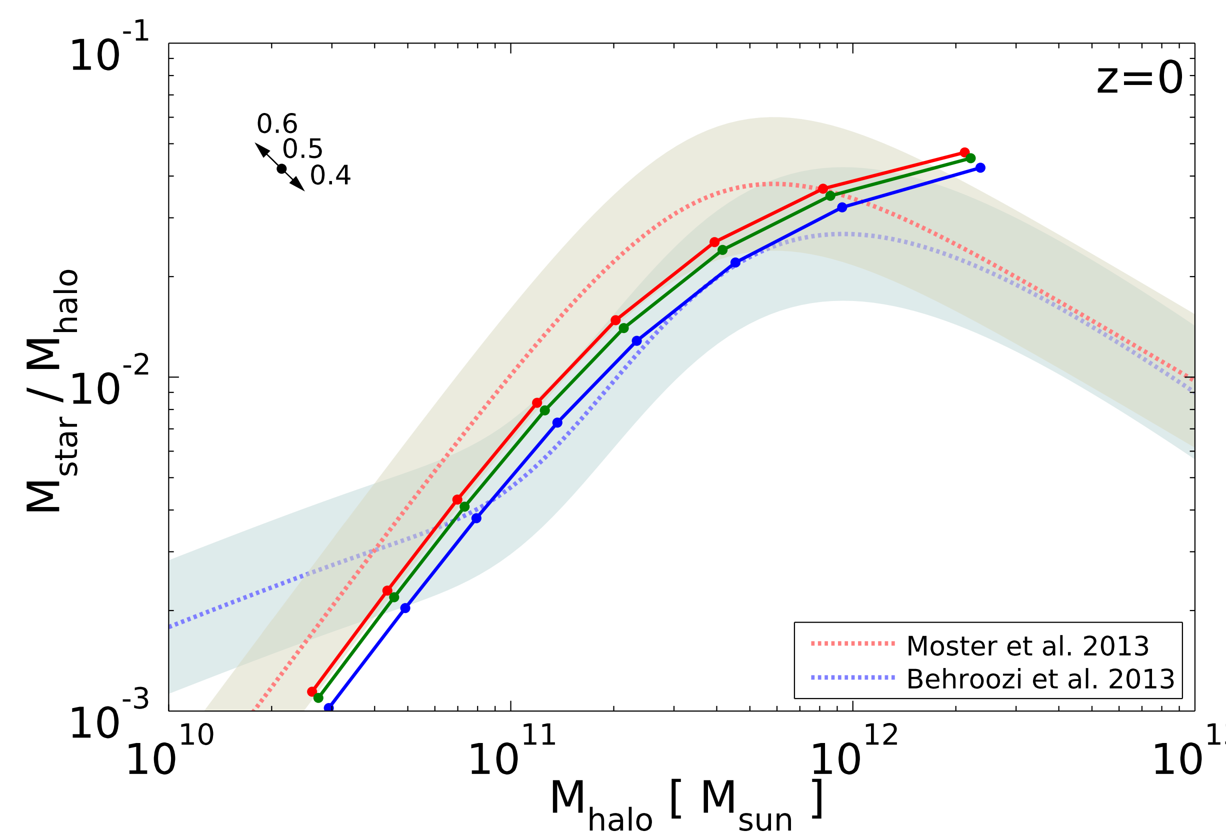
- pick z=0 galaxy of certain stellar mass
- evolve the observed sSFR(t) backward in time — Lilly et al. 2013
- obtain $M_{\rm g}(t), \dot{M}_{\rm g}(t)$ from observed depletion times — Genzel et al. 2014
- mass loading factor from simulations & observations — Hopkins et al. 2011, Chisholm et al. 2015
- mass conservation equation provides $\dot{M}_{\rm g,in}(t)$
- evolve model forward with Z and D network

$$\dot{M}_{\rm g} = \dot{M}_{\rm g,in} - (1-R)\,{\rm SFR} - \epsilon_{\rm out}\,{\rm SFR}$$

The dynamical model reproduces scaling relations





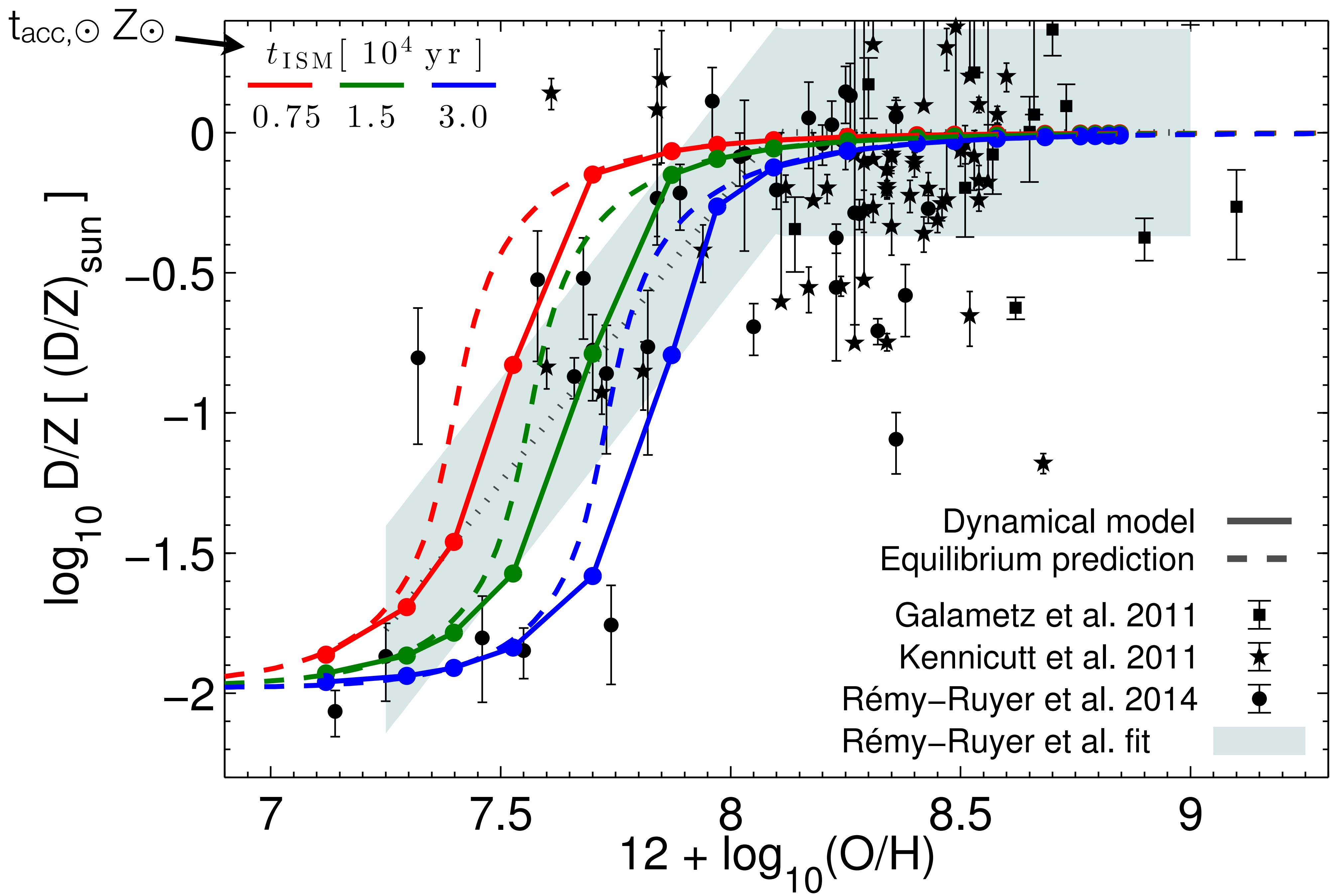


Dynamical model matches:

- total/molecular f_{gas}, gas-to-stellar ratios
- mass – metallicity relation and its evolution
- stellar mass – halo mass relation and its evolution (for $M_{halo} < 10^{12}\,M_\odot$)

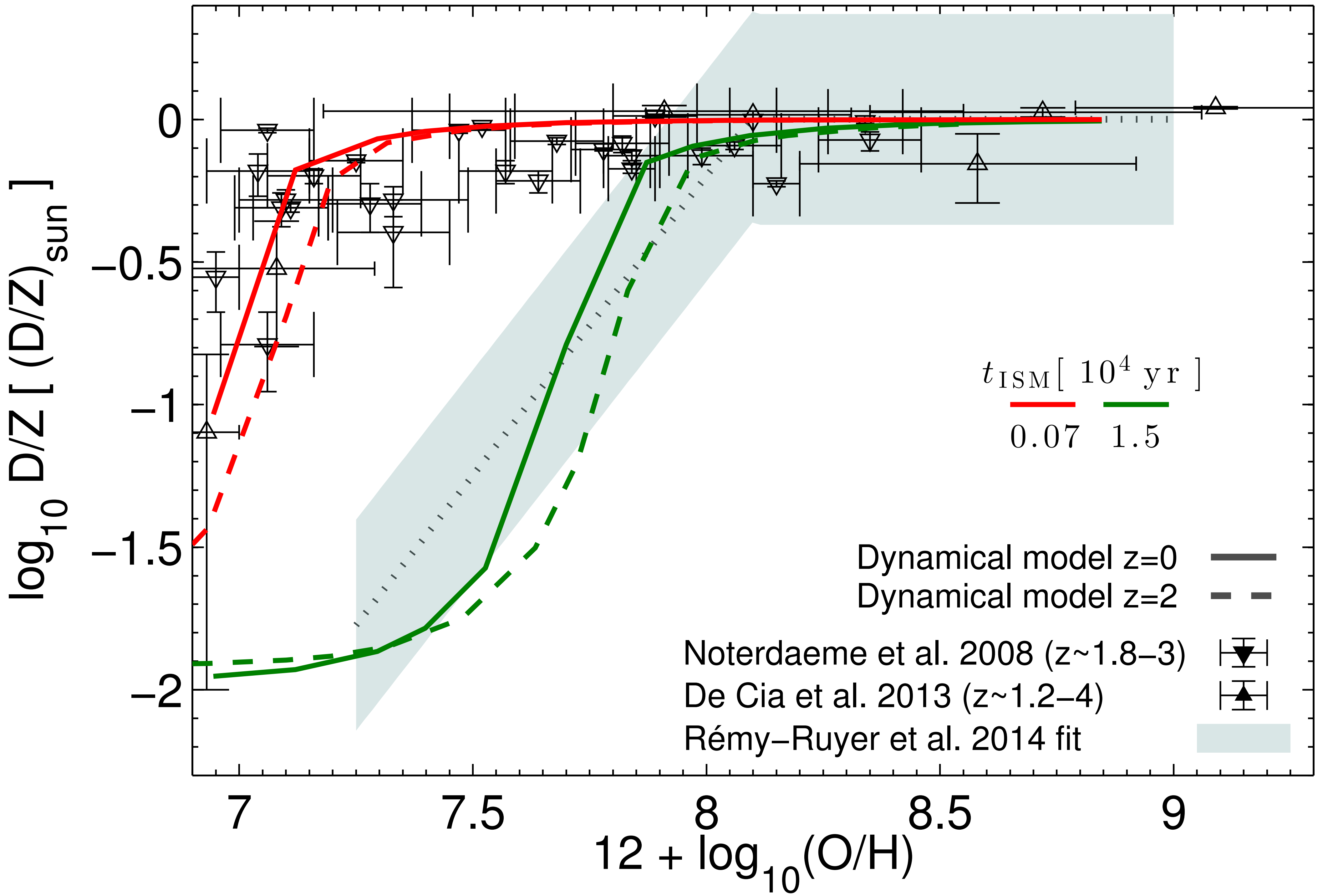
By construction:

- main sequence evolution



- Equilibrium ansatz describes the Z - D relation qualitatively correct
- Some difference to dynamical model during the transition
- $t_{acc,\odot} \sim 10^6$ yr

The Z - D relation at higher redshift



- little difference expected unless model parameters evolve strongly with z
- intriguing: QSO & GRB observations indicate ~MW D/Z ratios even at low Z

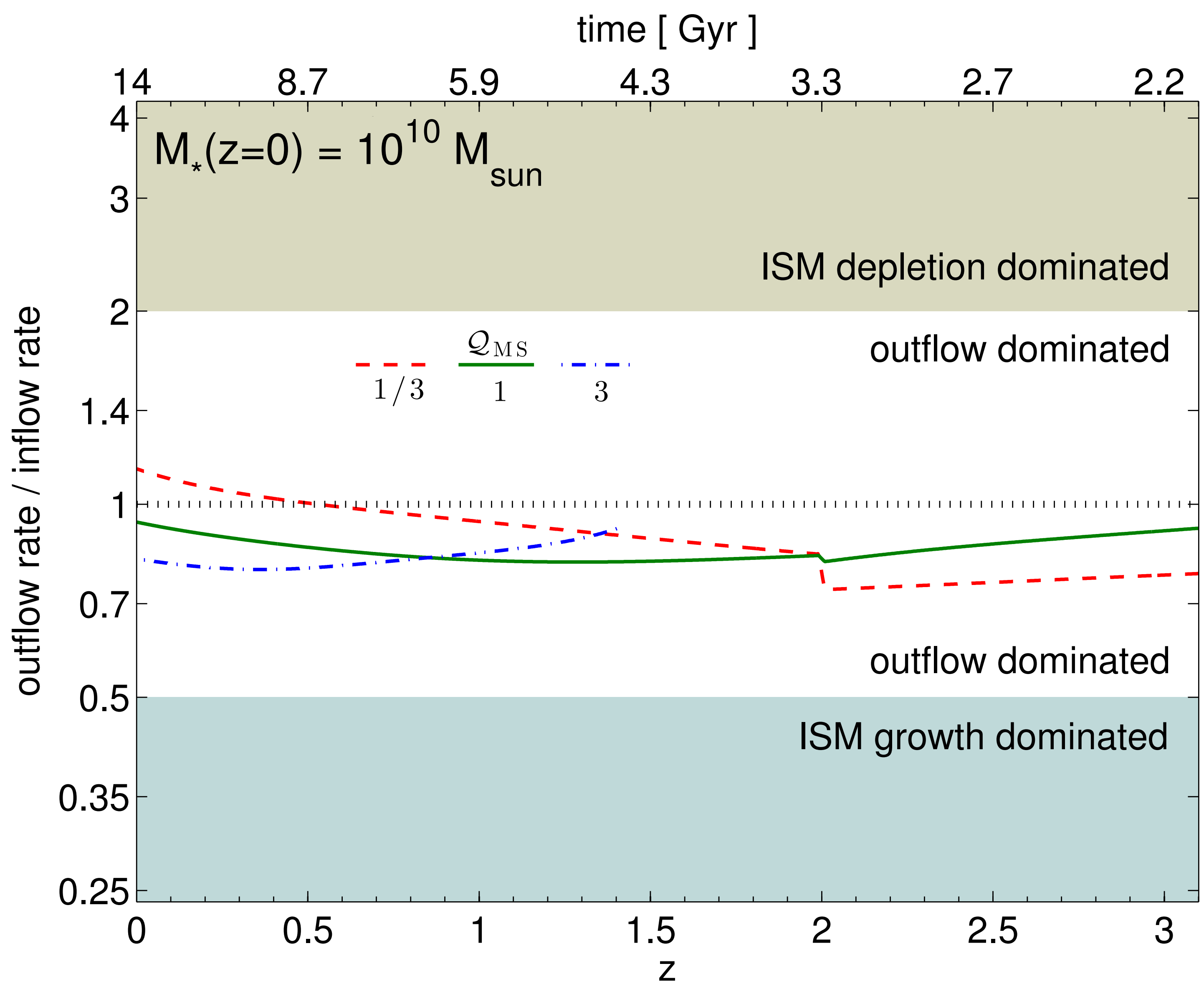
Outflow rate ~ Inflow rate

outflows ~ inflows at all times

$$\frac{\text{outflow rate}}{\text{inflow rate}} = \frac{\epsilon_{\rm out}\,{\rm SFR}}{\dot{M}_{\rm gas,in}}$$

$$\sim \frac{\epsilon_{\rm out}}{\epsilon_{\rm out} + \dot{M}_{\rm gas}/{\rm SFR}}$$

⇨ $\dot{M}_{\rm gas}/{\rm SFR} \ll \epsilon_{\rm out}$



$$\left(\frac{\rm SFR}{\dot{M}_{\rm gas,in}}\right)^{-1} = \epsilon_{\rm out} + (1-R) + \dot{M}_{\rm gas}/{\rm SFR} \quad \& \quad \langle Z \rangle \sim y \frac{\rm SFR}{\dot{M}_{\rm gas,in}}$$

⇨ (low) Z set by (large) value of mass loading factor

How does it all fit together?

Low mass galaxy:

- large outflow mass loading
- large outflow & large inflow rates (~equilibrium)
- inflow of metal-poor, dust-poor gas
  => dilution of pre-existing dust & metals
- $Z << Z_{crit}$; grain growth unimportant
- D/Z small

High mass galaxy:

- low outflow mass loading
- dilution of gas metallicity is small => $Z >> Z_{crit}$
- grain growth efficient
- D/Z near the depletion limit

Conclusions

- D & Z of galaxies can be modeled based on an equilibrium ansatz:

$$\dot{D} \equiv 0 \text{ \& } \dot{Z} \equiv 0$$

- Naturally predicts low D/Z at low Z and high D/Z at high Z
- critical metallicity: grain growth balanced by dust dilution (SN destruction only secondary effect)
- Empirical dynamical model reproduces several core observations
- Good agreement between dynamical model and equilibrium approach
- The stellar mass dependence of galactic outflows drives the evolution of Z, D, and D/Z in galaxies.

see Feldmann 2015, MNRAS, 449 [arxiv: 1412.2755]

Thank you!