Modeling dust in large-scale simulations: *first attempts*

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Large-scale Dust Questions

- dust mass function
- cosmic dust density
- dust rich high redshift galaxies
- dust-to-gas ratios
- dust-to-stellar-mass ratios

→ constraining galaxy formation models

multi zone models of galaxy formation coupled to dust physics:
no cosmological context, no detailed galaxy formation physics, no large scale statistics

e.g., Dwek & Scalo 1979, 1980, Dwek 1998, Lisenfeld & Ferrara 1998, Hirashita 1999, Edmunds 2001, Inoue 2003, Calura+ 2008, Asano+ 2013, Zhukovska & Henning 2013, Rowlands+ 2014

→ **Goal: large-scale galaxy formation simulations with dust physics**

ingredients of a most simplistic dust model for large-scale cosmological hydrodynamical galaxy formation simulations:

1) **dust production** in stellar outflows (low mass stars) and stellar ejecta (high mass stars)

2) **dust growth** in ISM as gas-phase atoms collide with existing grains

3) **dust destruction** in ISM through SN shocks

approach:

McKinnon+ 2016 **[M16 model]**

- implement dust model in Arepo
  Springel 2010
- incorporate dust production into stellar evolution code of Illustris model
  Vogelsberger+ 2013, Torrey+2013, Vogelsberger+2014, Genel+2014, Sijacki+2014
- implement sub-resolution models for small-scale dust physics
- dust as passive scalar
- study isolated Milky Way-like galaxies and compare to observational data
  Springel 2010, Marinacci+ 2013

1) Dust Production: during stellar evolution a certain amount of mass of a given chemical species is assumed to condense into dust; the rest goes into the gas phase

AGB dust production:

$$\Delta M_{i,\mathrm{dust}} = \begin{cases} \delta_{\mathrm{C}}^{\mathrm{AGB,C/O}>1}(\Delta M_{\mathrm{C}} - 0.75\,\Delta M_{\mathrm{O}}) & \text{if } i = \mathrm{C} \\ 0 & \text{else,} \end{cases}$$

C/O > 1

~ carbon type

$$\Delta M_{i,\mathrm{dust}} = \begin{cases} 0 & \text{if } i = \mathrm{C} \\ 10 \sum_{j=\mathrm{Mg,\ Si,\ Fe}} \delta_j^{\mathrm{AGB,C/O}<1} \Delta M_j/\mu_j & \text{if } i = \mathrm{O} \\ \delta_i^{\mathrm{AGB,C/O}<1} \Delta M_i & \text{else,} \end{cases}$$

C/O < 1

~ silicate type

SN dust production:

$$\Delta M_{i,\mathrm{dust}} = \begin{cases} \delta_{\mathrm{C}}^{\mathrm{SN}} \Delta M_{\mathrm{C}} & \text{if } i = \mathrm{C} \\ 10 \sum_{j=\mathrm{Mg,\ Si,\ Fe}} \delta_j^{\mathrm{SN}} \Delta M_j/\mu_j & \text{if } i = \mathrm{O} \\ \delta_i^{\mathrm{SN}} \Delta M_i & \text{else,} \end{cases}$$

δ = condensation efficiencies

e.g. Draine 1990, Dwek 1998

2) Dust Growth: mass of dust in the ISM increases over time as gas-phase atoms collide with grains

atom dust collisions $\longrightarrow$ $$\frac{dN_{d,A}}{dt} = (\alpha \pi a^2 v) n_g n_{d,A}$$ growth equation for specific element A

$N_{d,A}$: # density of atoms within dust
n_g : # density of atoms in gas
n_d : # density of dust

α sticking probability (*P* for particle to stick to dust after collision)
a size (cross section = area; affected by shattering/coagulation)
v mean thermal velocity at given gas temperature *T* $(8kT/\pi m_A)^{1/2}$

Within each cell integrate for each element:

$$\boxed{\left(\frac{\mathrm{d}M_{i,\mathrm{dust}}}{\mathrm{d}t}\right)_{\mathrm{g}} = \left(1 - \frac{M_{i,\mathrm{dust}}}{M_{i,\mathrm{metal}}}\right)\left(\frac{M_{i,\mathrm{dust}}}{\tau_{\mathrm{g}}}\right)}$$

where the local growth time scale is given by:

$$\tau_{\mathrm{g}} = \tau_{\mathrm{g}}^{\mathrm{ref}} \left(\frac{\rho^{\mathrm{ref}}}{\rho}\right)\left(\frac{T^{\mathrm{ref}}}{T}\right)^{1/2}$$

silicate:

$$\tau = 1.61 \times 10^8 \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)\left(\frac{Z}{Z_\odot}\right)^{-1}\left(\frac{n_\mathrm{H}}{10^3\,\mathrm{cm}^{-3}}\right)^{-1} \times \left(\frac{T_\mathrm{gas}}{10\,\mathrm{K}}\right)^{-1/2}\left(\frac{S}{0.3}\right)^{-1}\,\mathrm{yr}$$

graphite:

$$\tau = 0.993 \times 10^8 \left(\frac{a}{0.1\,\mu\mathrm{m}}\right)\left(\frac{Z}{Z_\odot}\right)^{-1}\left(\frac{n_\mathrm{H}}{10^3\,\mathrm{cm}^{-3}}\right)^{-1} \times \left(\frac{T_\mathrm{gas}}{10\,\mathrm{K}}\right)^{-1/2}\left(\frac{S}{0.3}\right)^{-1}\,\mathrm{yr}$$

Hirashita 2012

$\longrightarrow$ straightforward to extend to depend on arbitrary local cell properties

e.g., Drain 1990, Dwek 1998, Hirashita 1999, Yozin & Bekki 2014, Zhukovska 2014, Bekki 2015

3) Dust Destruction: SN shocks are the dominating mechanism for dust destruction in the ISM

Within each cell integrate for each element:

$$\boxed{\left(\frac{\mathrm{d}M_{i,\mathrm{dust}}}{\mathrm{d}t}\right)_{\mathrm{d}} = -\frac{M_{i,\mathrm{dust}}}{\tau_{\mathrm{d}}}}$$

where the local destruction time scale is given by:

$$\tau_{\mathrm{d}} = \frac{M_{\mathrm{g}}}{\epsilon\,\gamma\,M_{\mathrm{s}}(100)}$$

M_{g} : gas mass in cell

γ : local SN II rate based on stellar evolution model

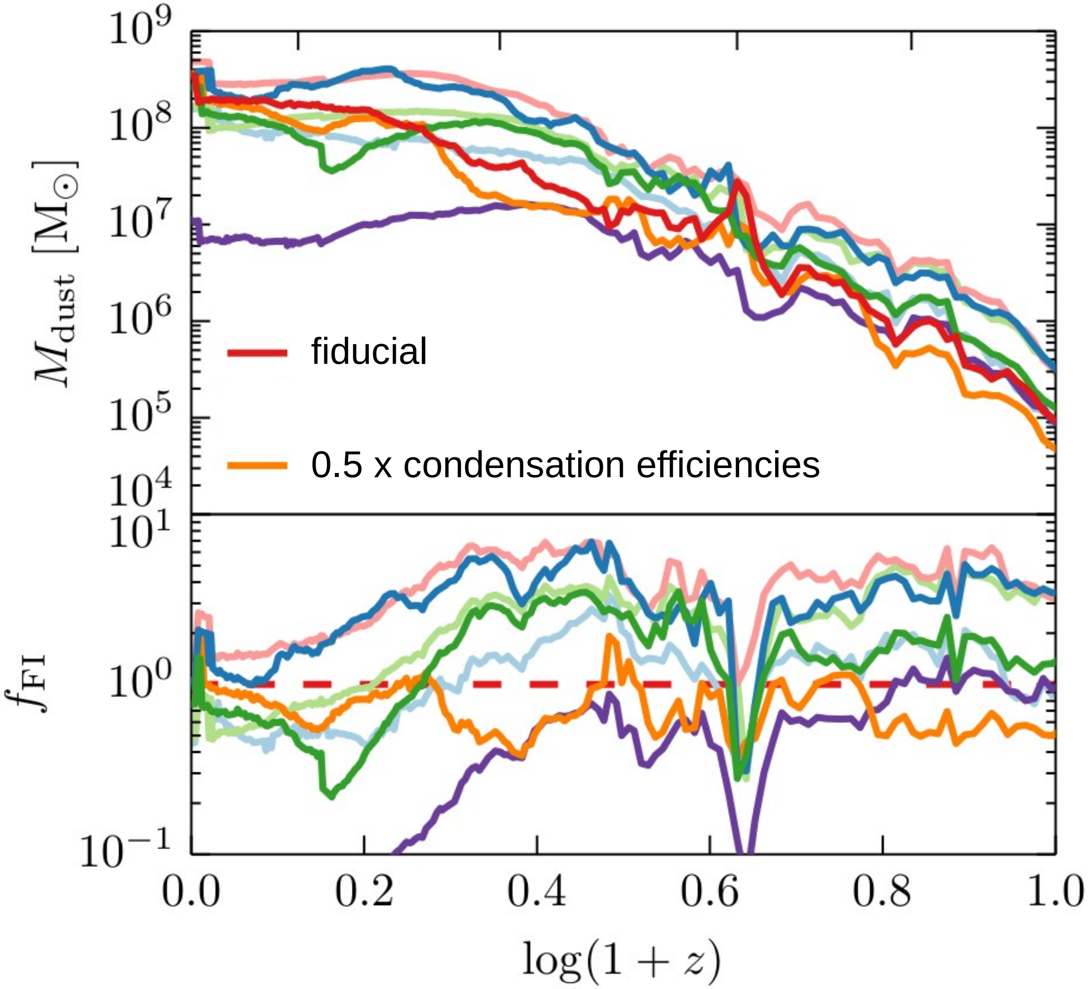
$M_{\mathrm{s}}(100)$: gas mass shocked to at least 100 km/s

ϵ : average effective shock destruction efficiency

$$\longrightarrow \quad \epsilon M_s(100) = \int \widetilde{\epsilon}(v_s)\, dM(v_s)$$

e.g., Seab & Shull 1983, Seab 1987, McKee 1989, Draine 1990, Jones+ 1994, Jones & Nuth 2011

Dust Model Variations

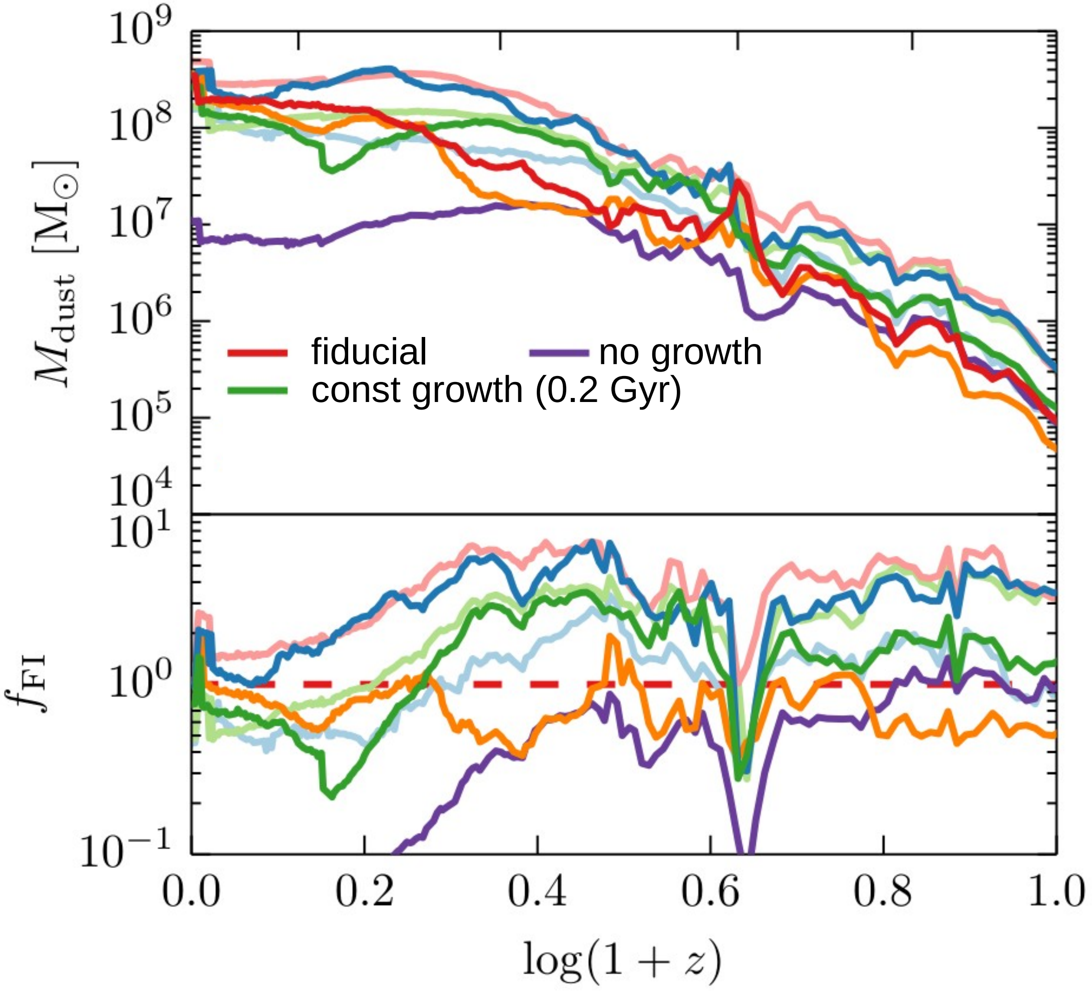


dust condensation coefficients

- dust mass evolution of fiducial model similar to that of the model with decreased dust condensation efficiencies
- at low z good agreement; at large z some small differences

→ insensitive to exact δ values (at least within this model and for the galaxies simulated here)

Dust Model Variations

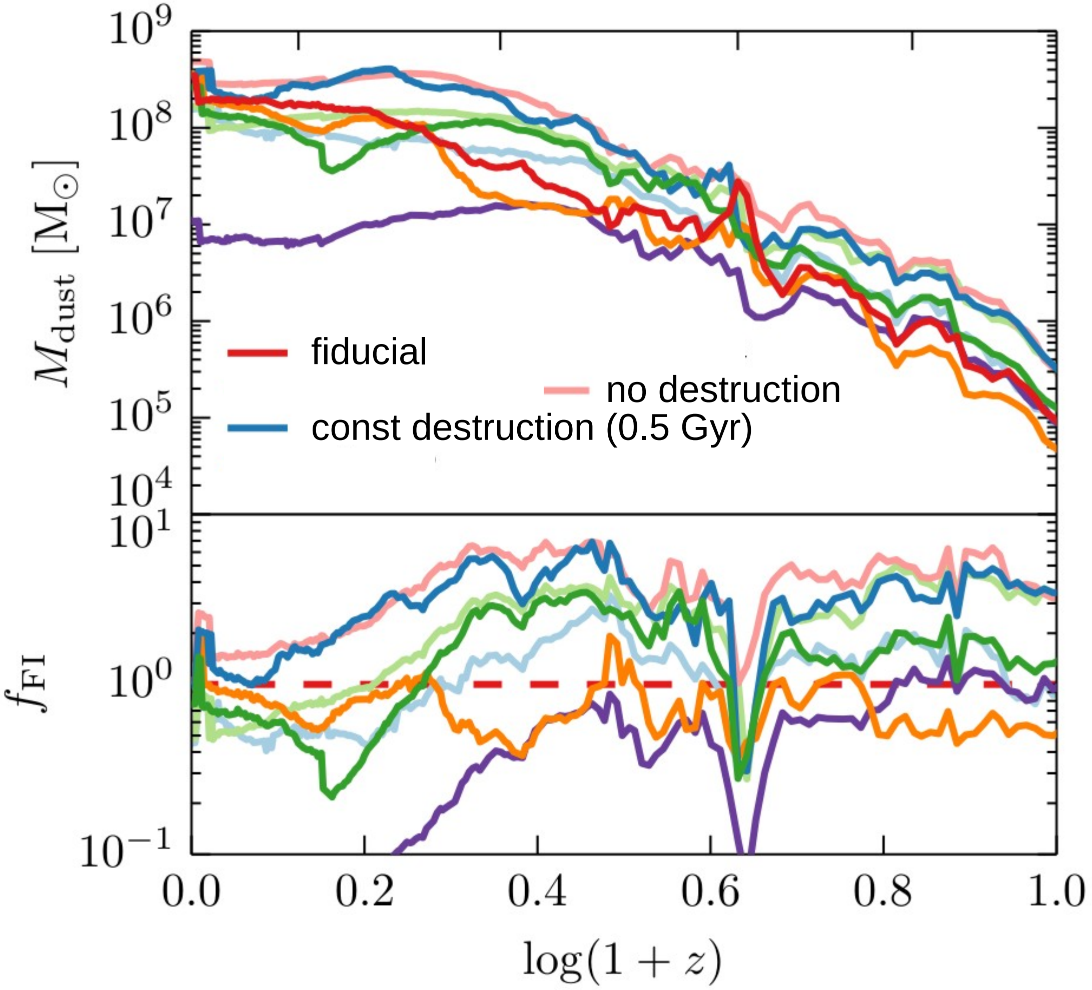


growth timescale

- dust mass evolution of fiducial model differs significantly from a constant growth model for intermediate redshifts
- no growth model clearly underestimates the z=0 dust mass by more than an order of magnitude

→ non-constant growth timescale important

Dust Model Variations



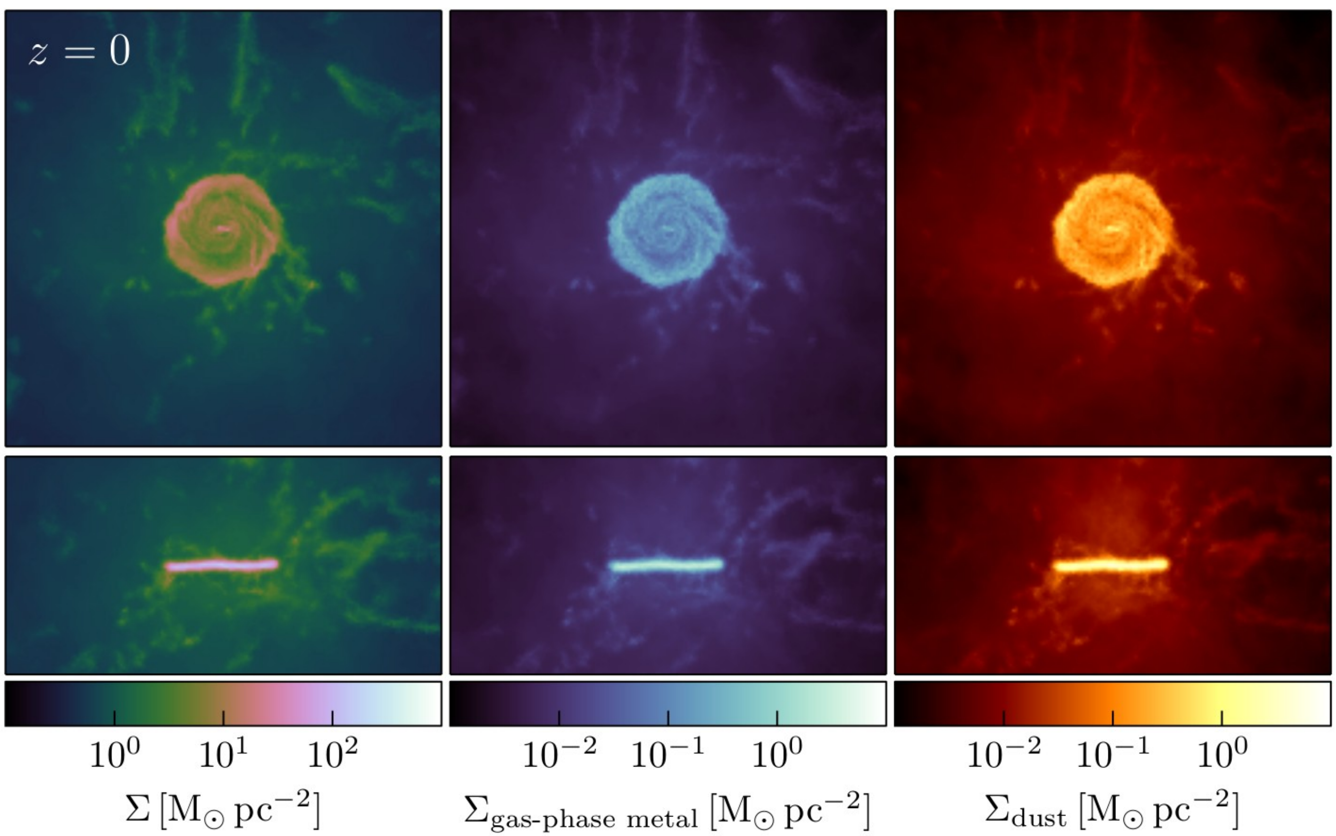
destruction timescale

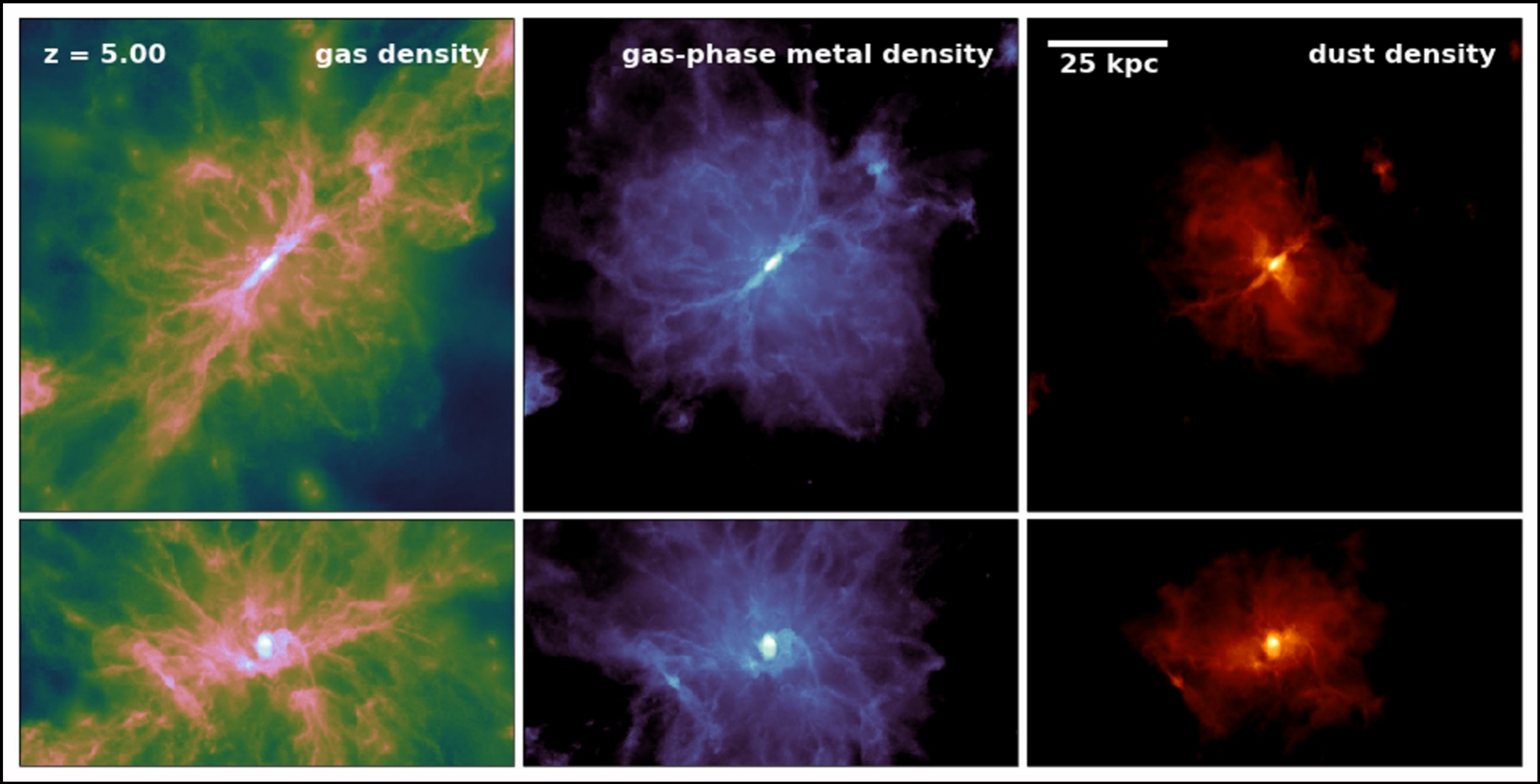
- no destruction and constant destruction lead to significant dust overproduction at higher redshift
- the overproduction is less severe at z=0, but still substantial

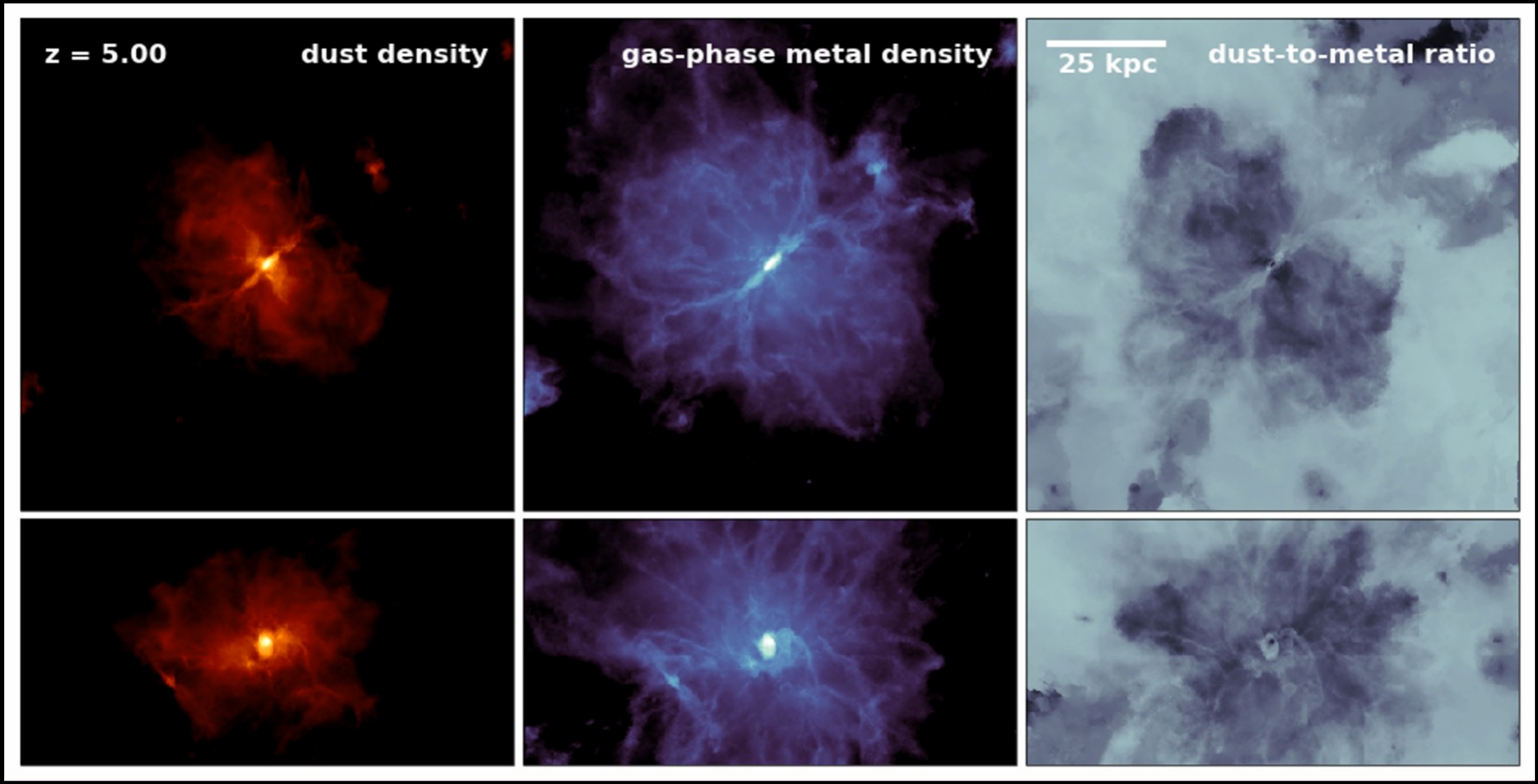
non-constant destruction timescale crucial

Milky Way-like Halos: Aquarius ICs Springel+ 2008, Marinacci+ 2014

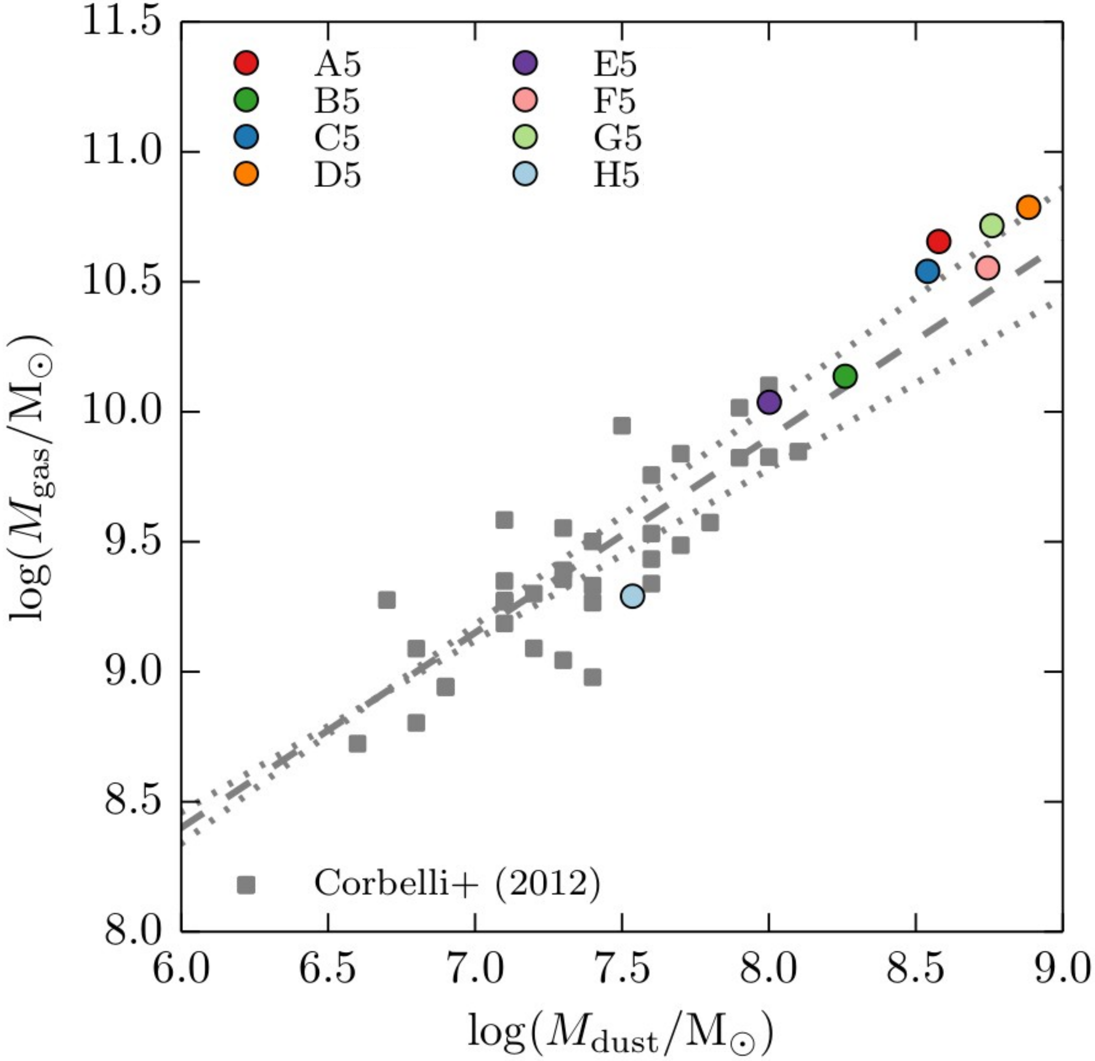
Run	R_{200} [kpc]	$M_{\rm gas}$ [10^{10} M$_\odot$]	$M_{\rm dm}$ [10^{10} M$_\odot$]	$M_{\rm dust}$ [10^8 M$_\odot$]	$M_{\rm gas,disc}$ [10^{10} M$_\odot$]	$M_{\rm dust,disc}$ [10^8 M$_\odot$]	$N_{\rm gas}$	$N_{\rm dm}$	$m_{\rm gas}$ [10^5 M$_\odot$]	$m_{\rm dm}$ [10^5 M$_\odot$]
A5	237.5	11.62	182.29	5.61	4.52	3.79	211527	690478	5.03	26.40
B5	183.0	4.22	78.18	3.48	1.37	1.82	119386	518981	3.35	17.59
C5	233.5	11.11	175.93	5.98	3.47	3.47	253836	814834	4.11	21.59
D5	240.7	15.18	195.56	12.20	6.12	7.66	319074	846419	4.40	23.10
E5	206.7	6.14	114.16	5.35	1.09	1.00	179039	652270	3.33	17.50
F5	208.0	9.26	113.67	9.48	3.58	5.55	375068	942365	2.30	12.06
G5	201.9	9.94	95.99	7.78	5.20	5.74	317798	769854	2.83	14.88
H5	180.1	2.61	76.24	1.67	0.20	0.34	87369	588050	2.96	15.56
C4	232.5	6.82	159.19	3.89	1.44	1.76	1265814	5898234	0.51	2.70
C6	235.6	13.92	179.84	6.91	4.97	4.54	39592	104118	32.90	172.73




z = 5.00
gas density
gas-phase metal density
25 kpc
dust density

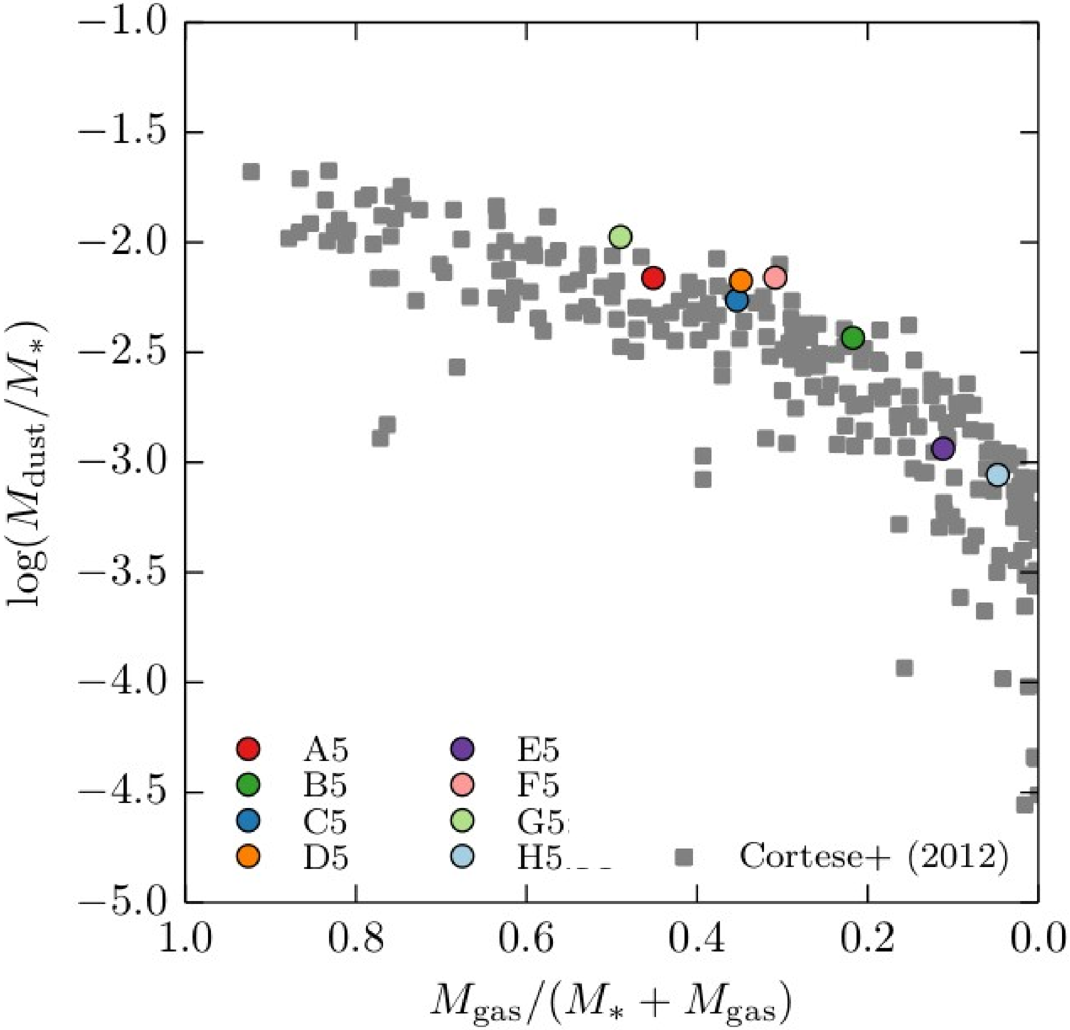

z = 5.00
dust density
gas-phase metal density
25 kpc
dust-to-metal ratio

Basic Dust Scaling Relations for 8 MW-like Halos

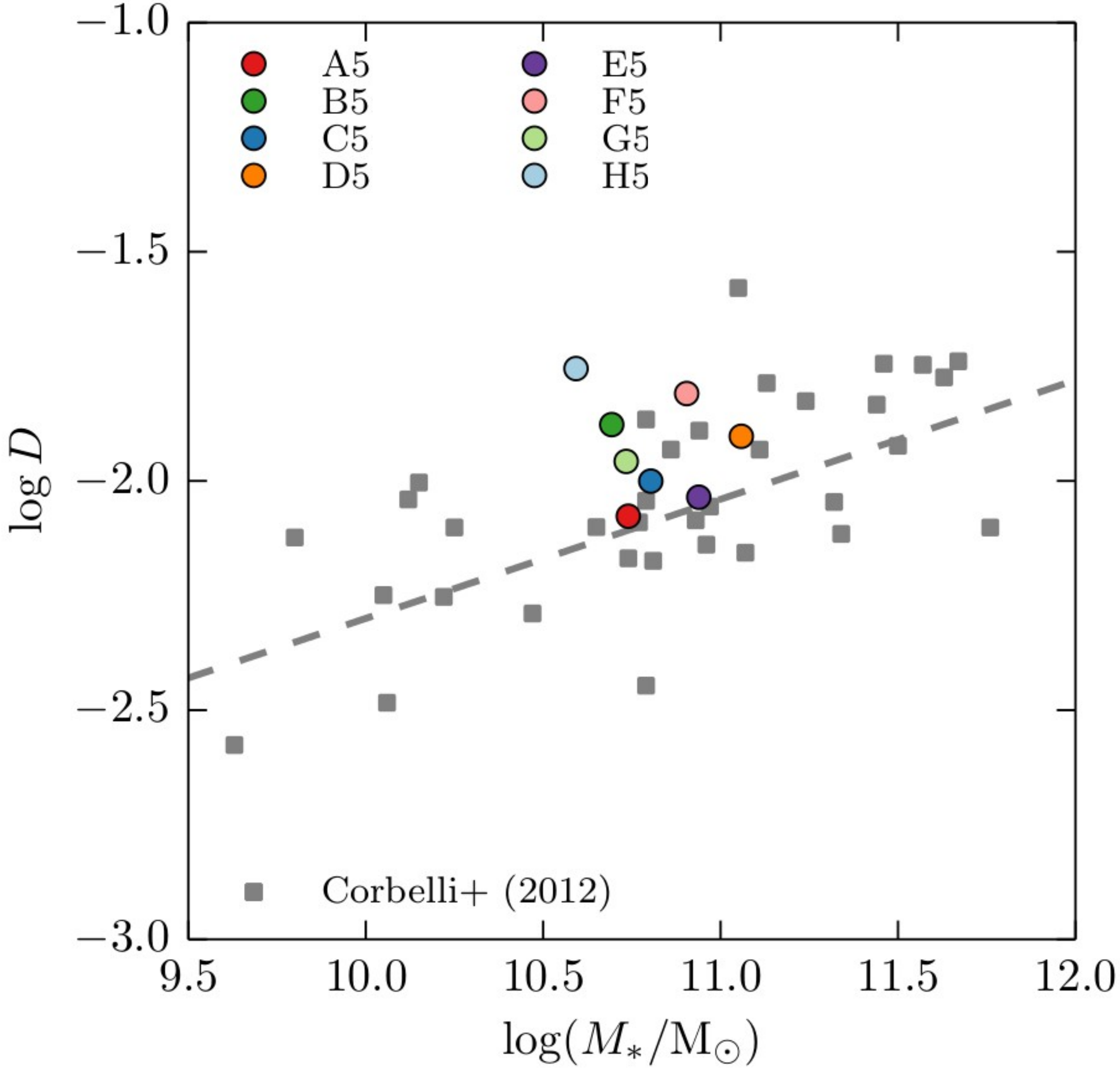


gas mass vs. dust mass

Basic Dust Scaling Relations for 8 MW-like Halos



dust mass vs. gas fraction

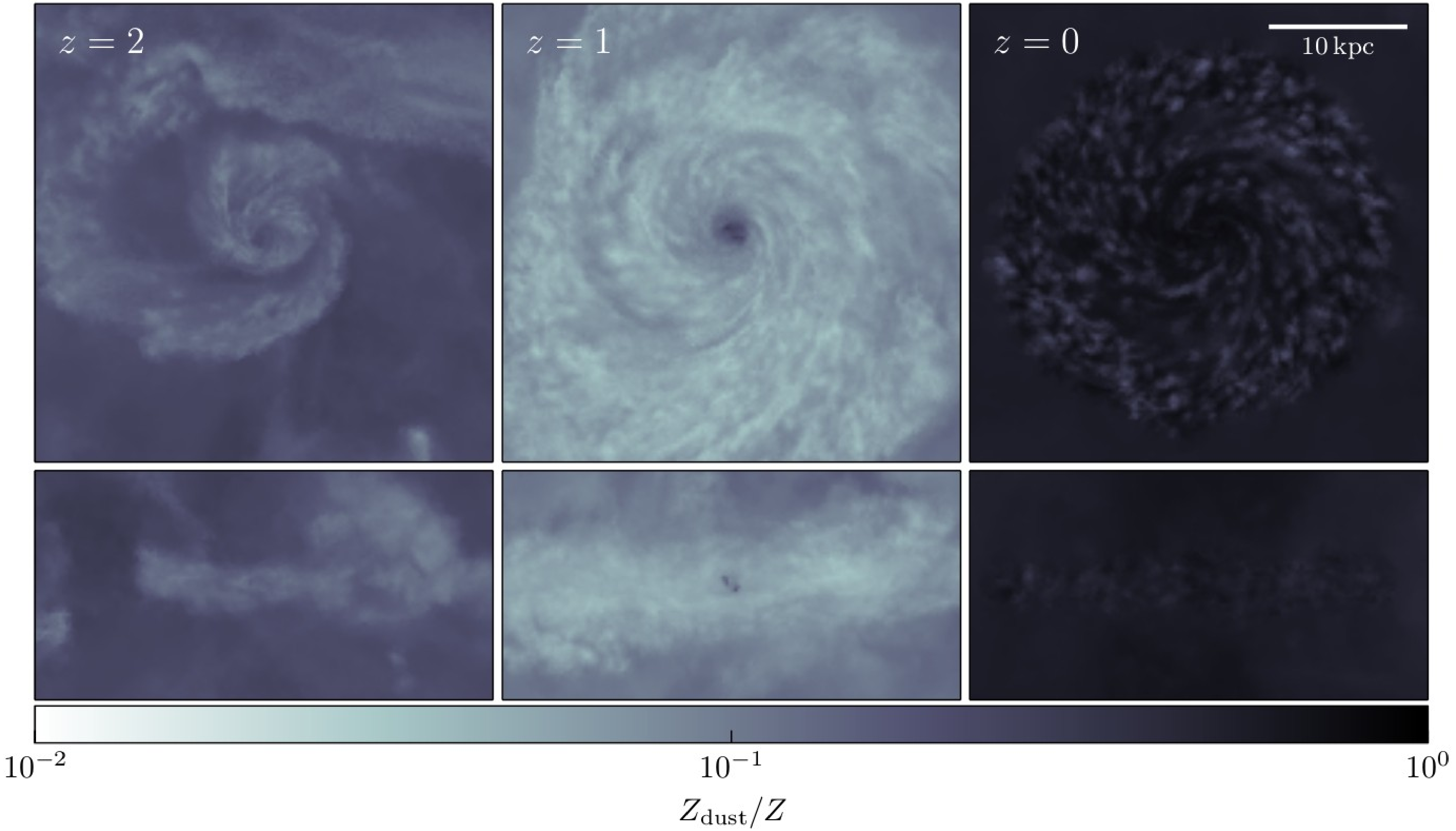


Basic Dust Scaling Relations for 8 MW-like Halos

dust-to-gas ratio vs. stellar mass

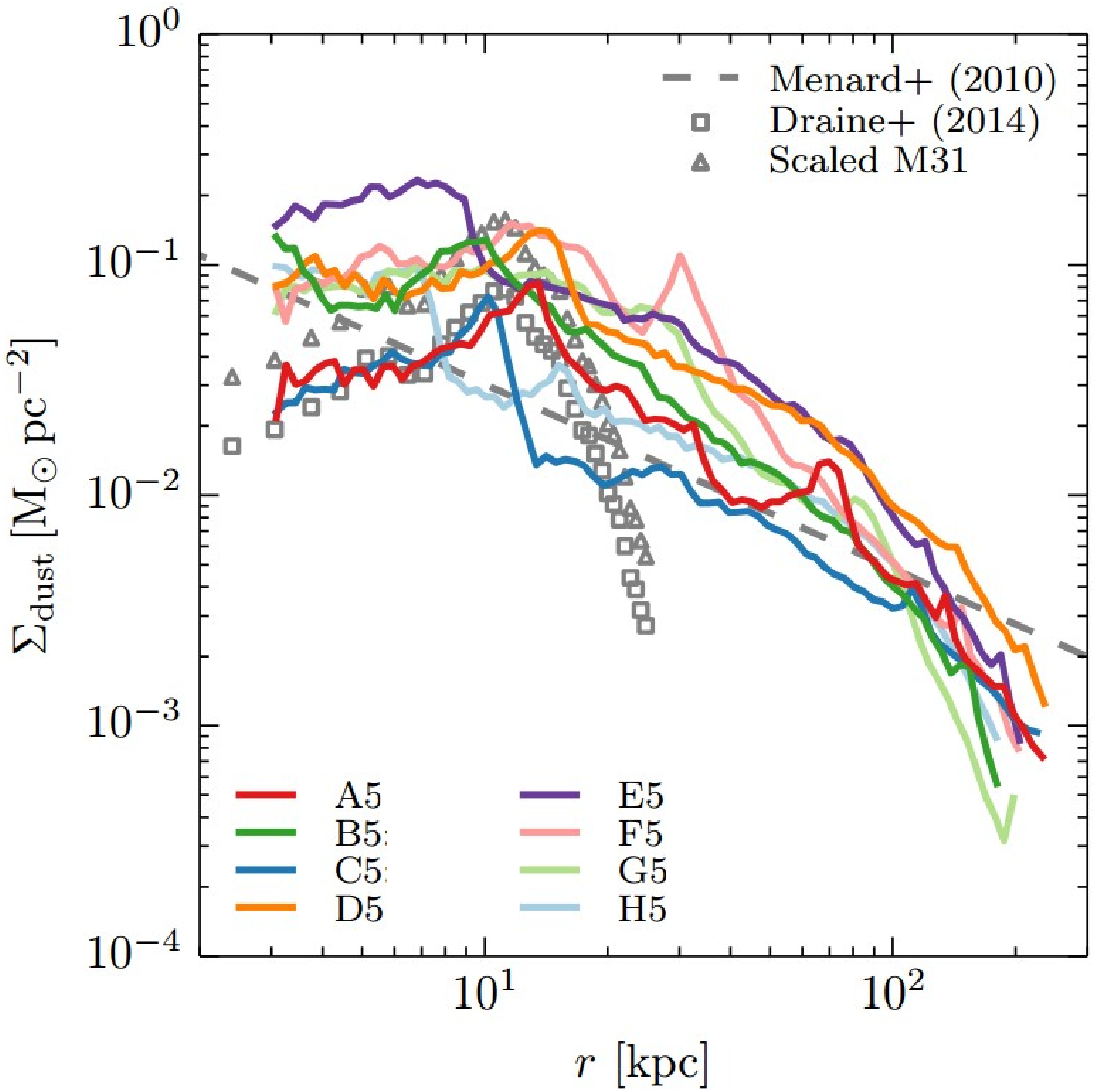
reasonable agreement between model M16 and various dust scaling relations

Dust-to-Metal Ratio

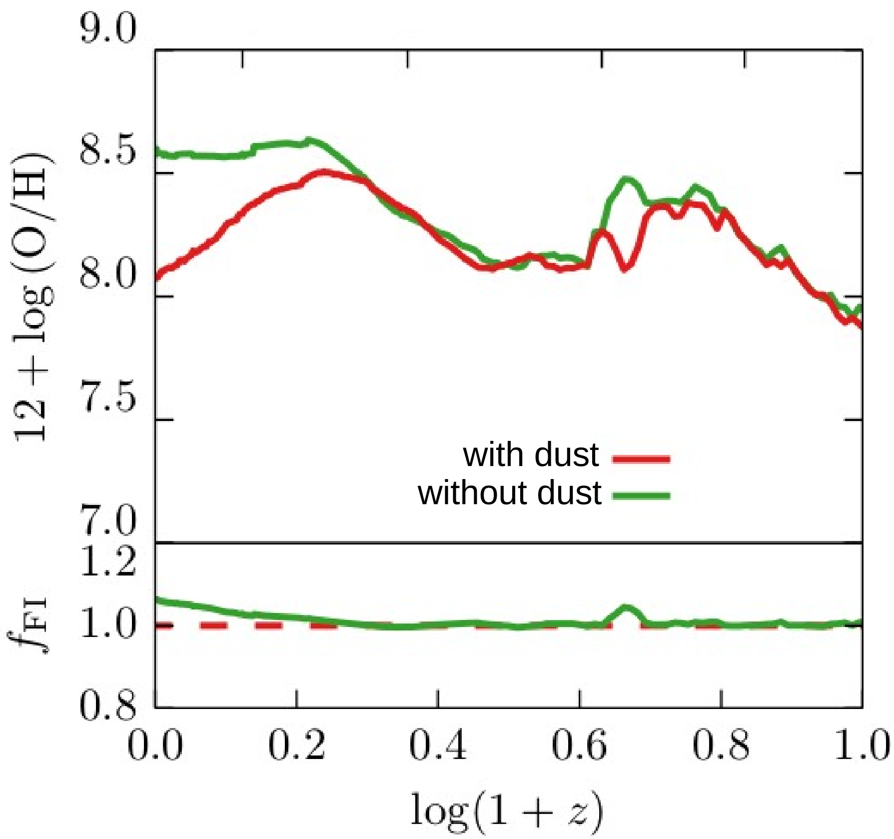


- at low z, there are small pockets of varying dust-to-metal ratio
- at higher z, also large-scale variation of dust-to-metal ratio
- overall: dust-to-metal ratio not constant/uniform

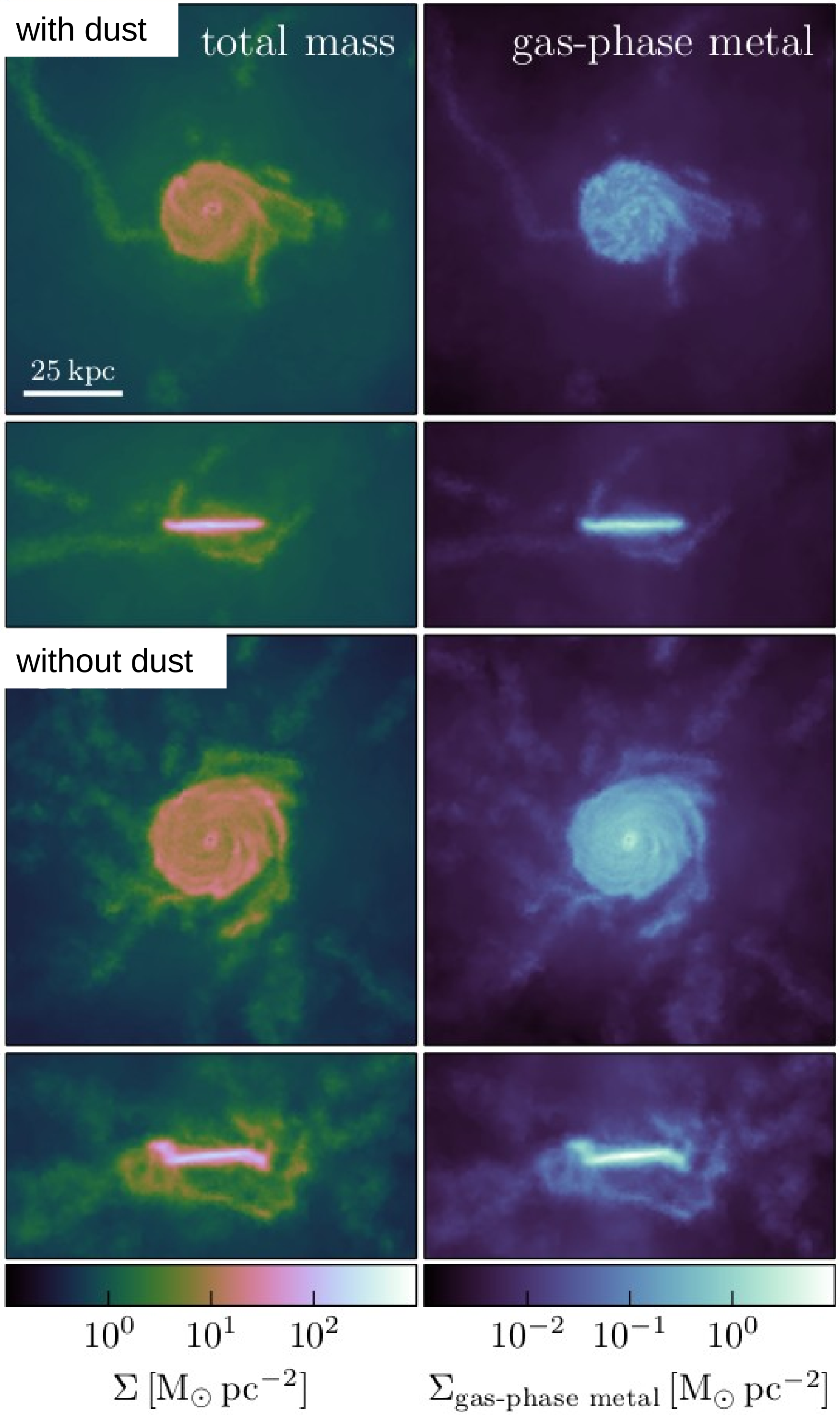
Dust Surface Density



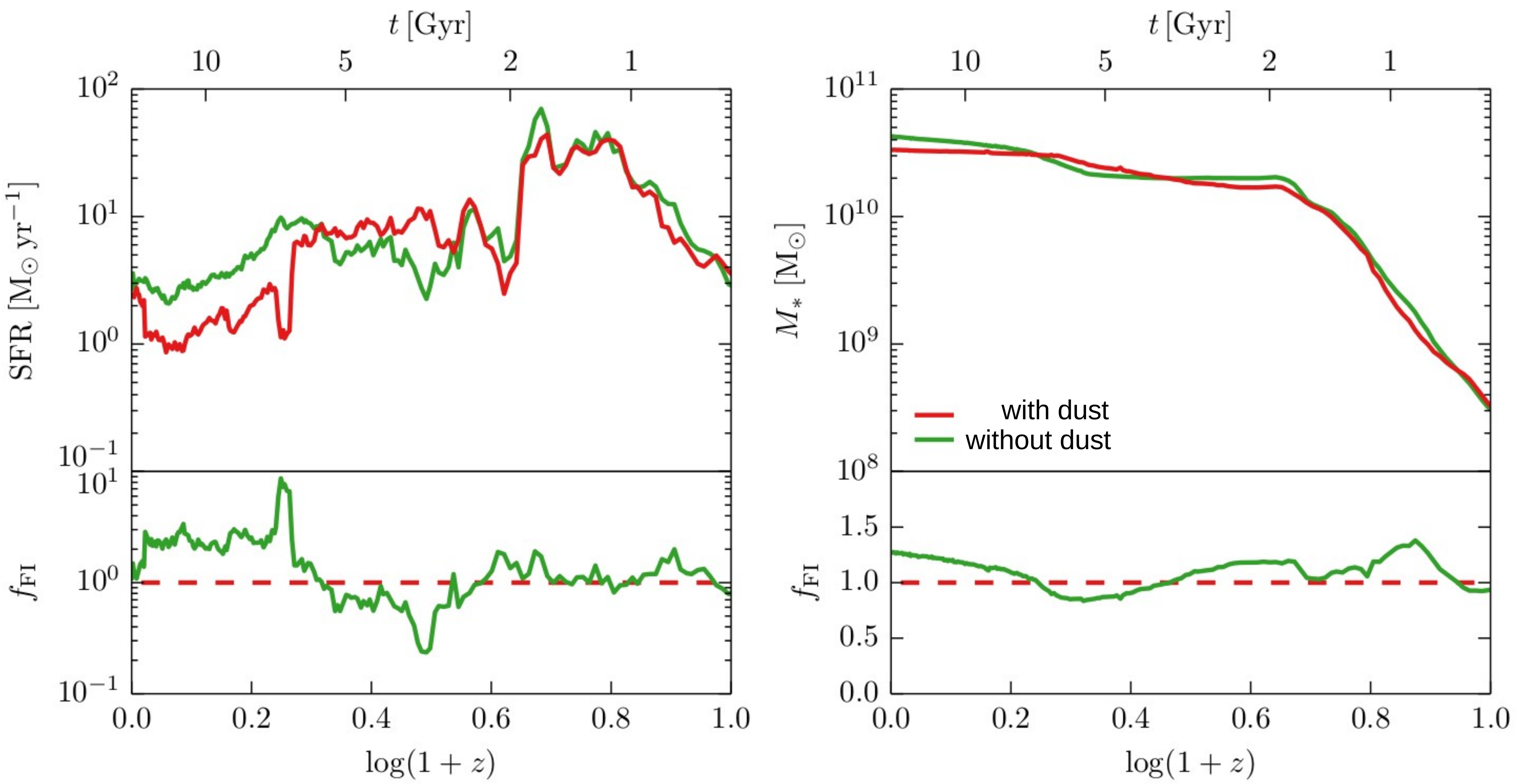
Consequences of Dust Formation



- dust formation reduces gas phase metal abundance:
  O/H reduced by ~0.5 dex at z=0
- reduces metal line cooling

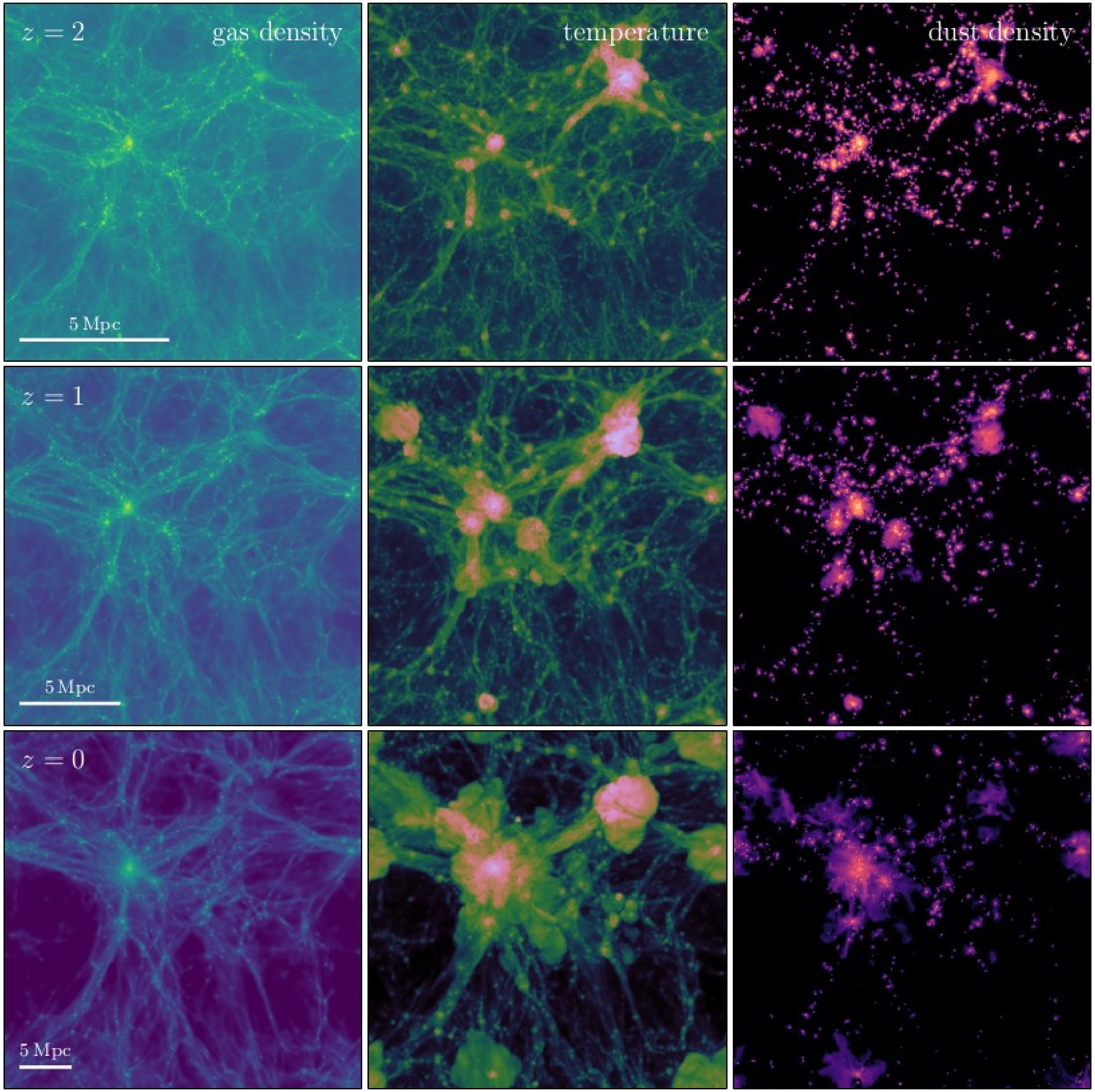


Consequences of Dust Formation: 'higher order' implications



reduced metal line cooling also affects the star formation rates and final stellar mass:
(depends on details of dust model)

- ~ factor 2-3 reduction in star formation rate at late times
- ~30% reduction of star mass at z=0



Beyond Galactic Mass Scale: Global Dust Statistics

what do globally integrated dust properties like the cosmic dust density as a function of redshift look like?

dust within and between galactic halos (not just ISM) has to be modeled reliably

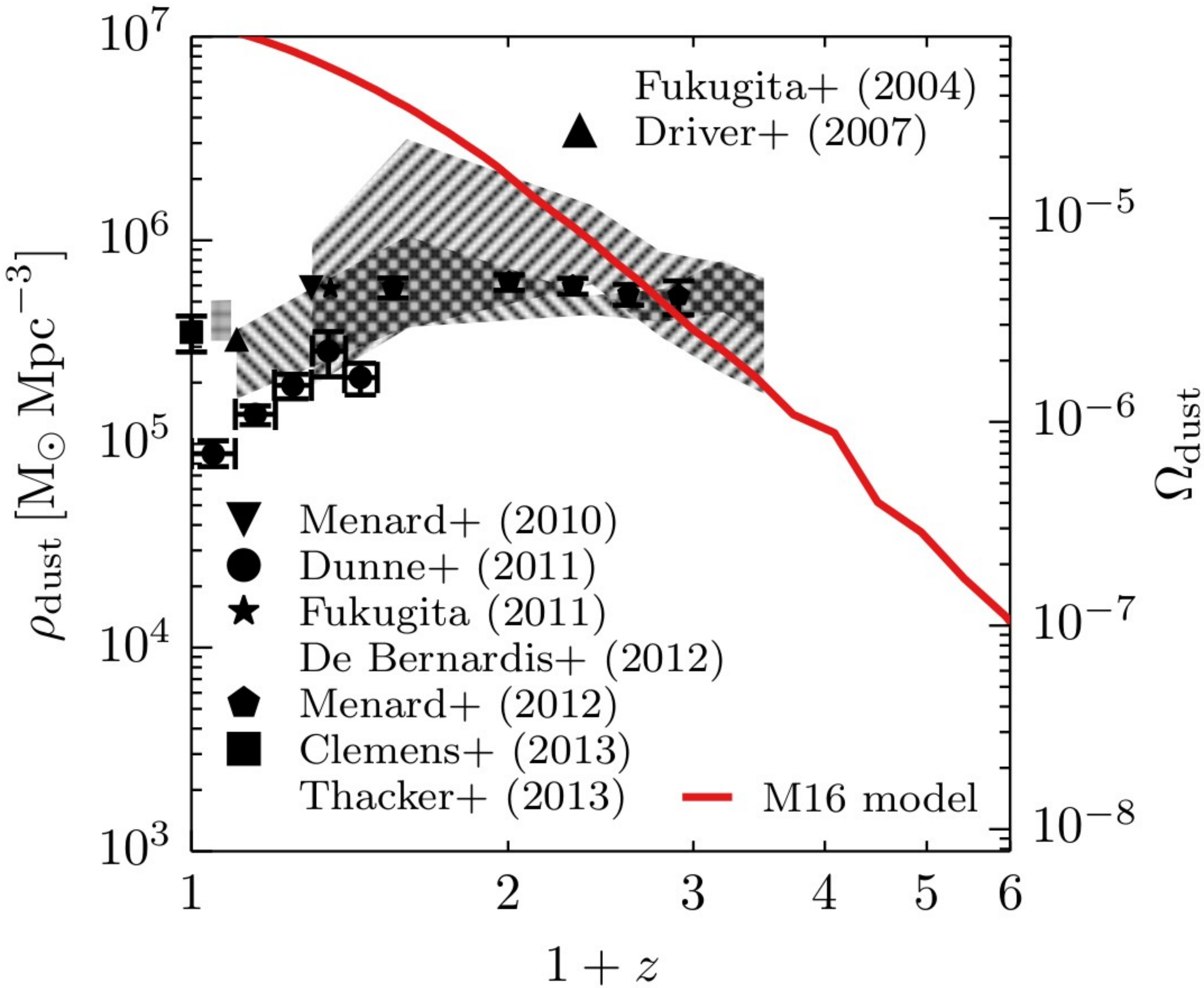
explore simple M16 model beyond the MW mass scale

Name	Volume $[(h^{-1}\,\mathrm{Mpc})^3]$	N	ϵ $[h^{-1}\,\mathrm{kpc}]$	m_{dm} $[h^{-1}\,\mathrm{M}_\odot]$	m_{gas} $[h^{-1}\,\mathrm{M}_\odot]$	physics
L25n128	25^3	2×128^3	2.5	5.26×10^8	9.82×10^7	fiducial
L25n256	25^3	2×256^3	1.25	6.58×10^7	1.23×10^7	fiducial
L25n512	25^3	2×512^3	0.625	8.22×10^6	1.53×10^6	fiducial

preliminary

McKinnon+ (in prep)

Cosmic Dust Density



wrong redshift dependence and two orders of magnitude too much integrated dust at z=0

although MW scale ISM dust content is modeled correctly, the model fails in describing global dust statistics

Dust Destruction: thermal sputtering of dust grains due to ion collisions within hot gas

$$\frac{\mathrm{d}N_{\rm sp}}{\mathrm{d}t} = 2\pi a^2 \sum_i n_i \langle Y_i v \rangle \longrightarrow \frac{\mathrm{d}m}{\mathrm{d}t} = -\, 4\pi a^2 \rho_{\rm g} \frac{\mathrm{d}a}{\mathrm{d}t} \longrightarrow \frac{\mathrm{d}a}{\mathrm{d}t} = -\, \frac{n_{\rm H} m_{\rm sp}}{2\rho_{\rm g}} \sum_i A_i \langle Y_i v \rangle$$

$N_{\rm sp}$: # of particles sputtered off dust surface

Y_i : sputtering yield of species i

n_i : # density of species i

$m_{\rm sp}$: mass of particle sputtered off surface

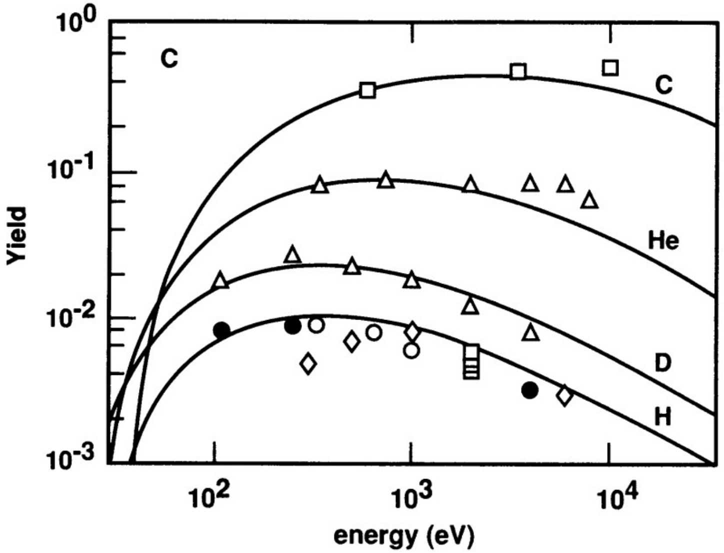
$n_{\rm H}$: # density of H

A_i : abundance of species i

$\rho_{\rm g}$: material dust density

m : mass of dust grain

e.g., Burke & Silk 1974, Barlow 1978,
Draine & Salpeter 1979, Tielens+ 1994



$$\frac{\mathrm{d}a}{\mathrm{d}t} = -\tilde{h}\left(\frac{\rho}{m_{\rm p}}\right)\left[\left(\frac{T_0}{T}\right)^{\omega} + 1\right]^{-1}$$

density and temperature dependent fitting formula

$$\tau_{\rm sp} = a\left|\frac{\mathrm{d}a}{\mathrm{d}t}\right|^{-1} = \left(\frac{a}{\tilde{h}}\right)\left(\frac{m_{\rm p}}{\rho}\right)\left[\left(\frac{T_0}{T}\right)^{\omega} + 1\right]$$

$$\approx 0.17\left(\frac{a}{0.1\,\mu{\rm m}}\right)\left(\frac{10^{-27}\,{\rm g\,cm^{-3}}}{\rho}\right)\left[\left(\frac{T_0}{T}\right)^{\omega} + 1\right]\,{\rm Gyr}$$

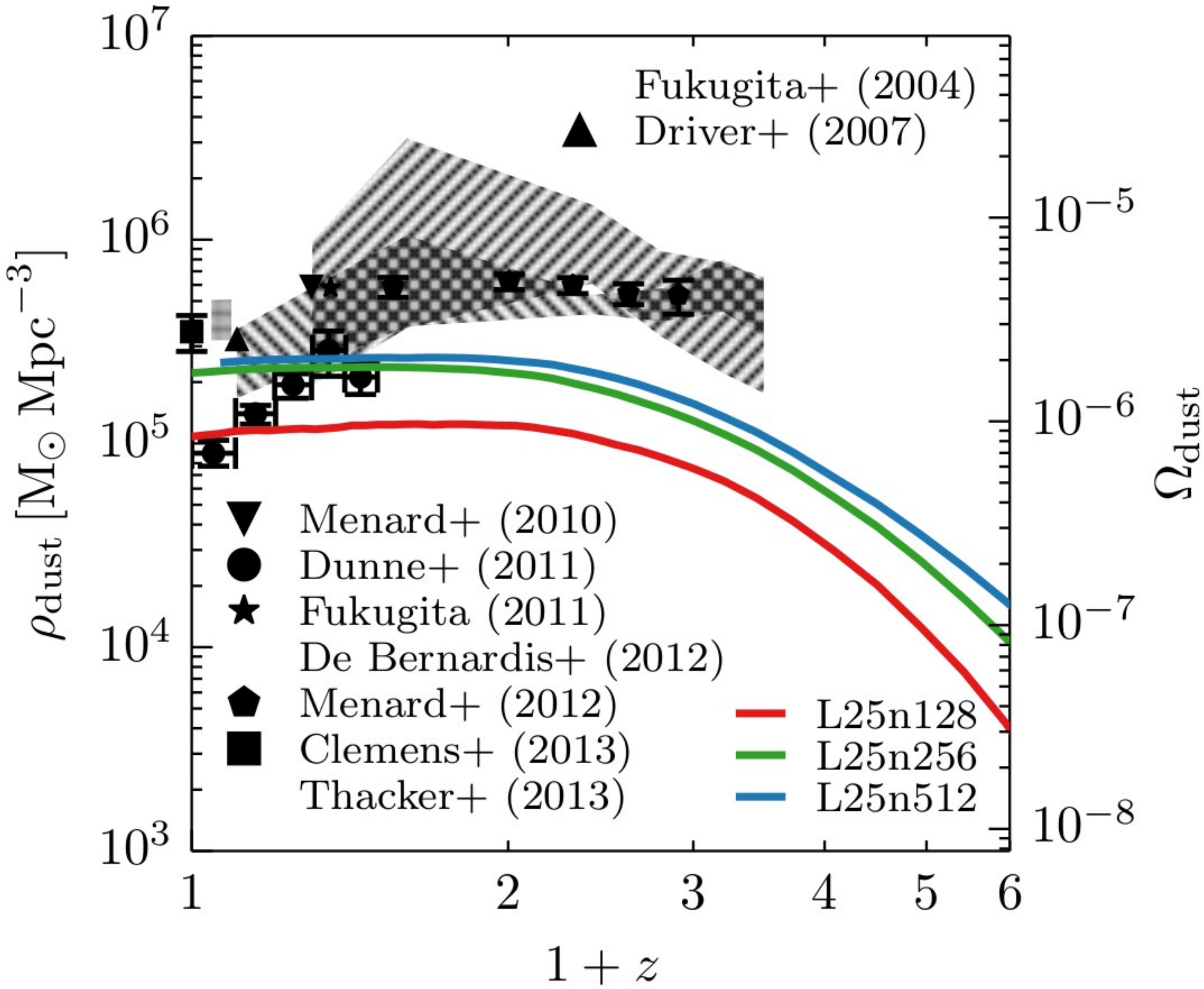
sputtering time scale

Tsai & Mathews 1995, Hirashita+ 2015

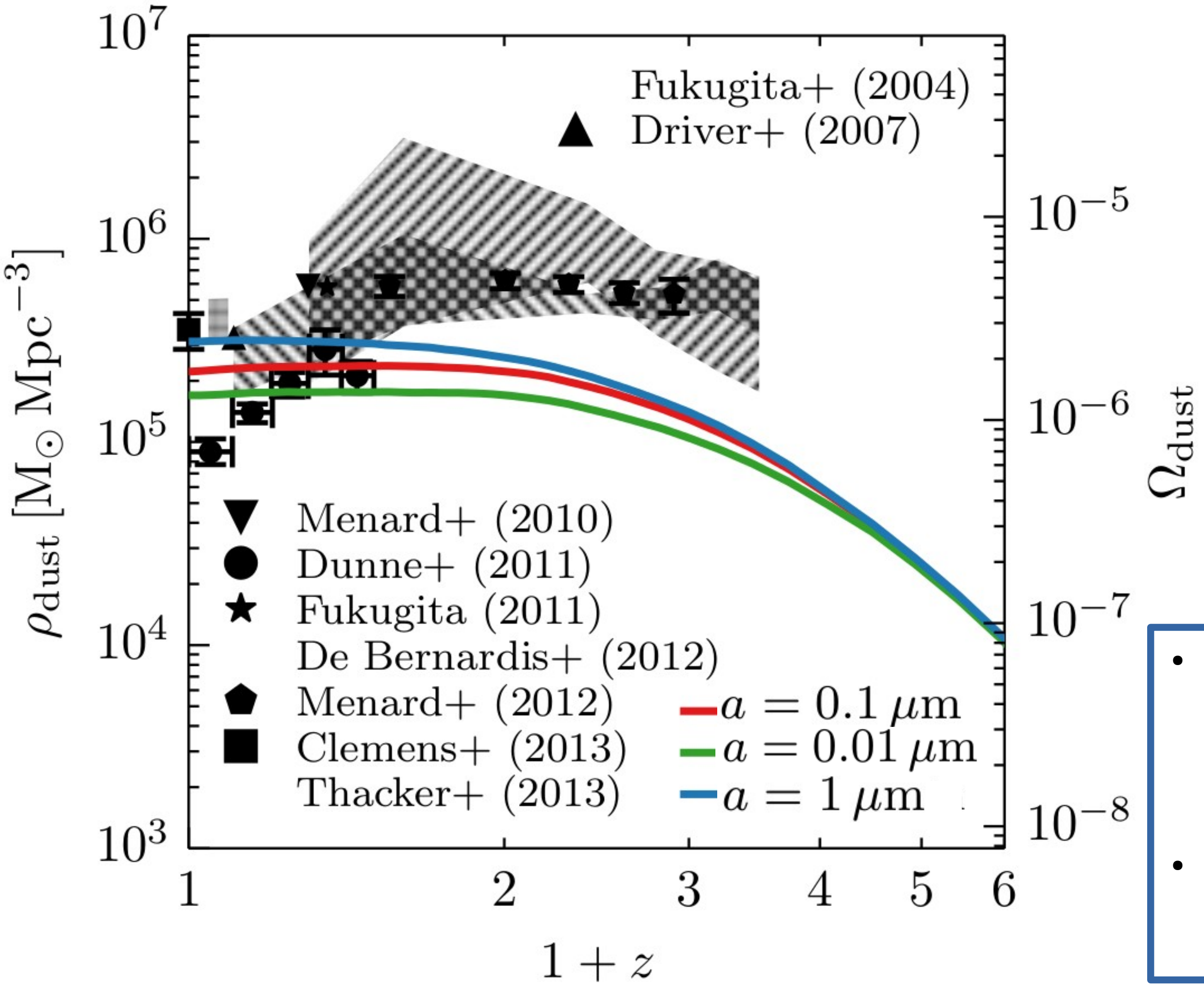
Within each cell integrate for each element:

$$\boxed{\left(\frac{\mathrm{d}M_{i,\rm dust}}{\mathrm{d}t}\right)_{\rm sp} = -\frac{M_{i,\rm dust}}{\tau_{\rm sp}/3}}$$

Cosmic Dust Density for Improved Model

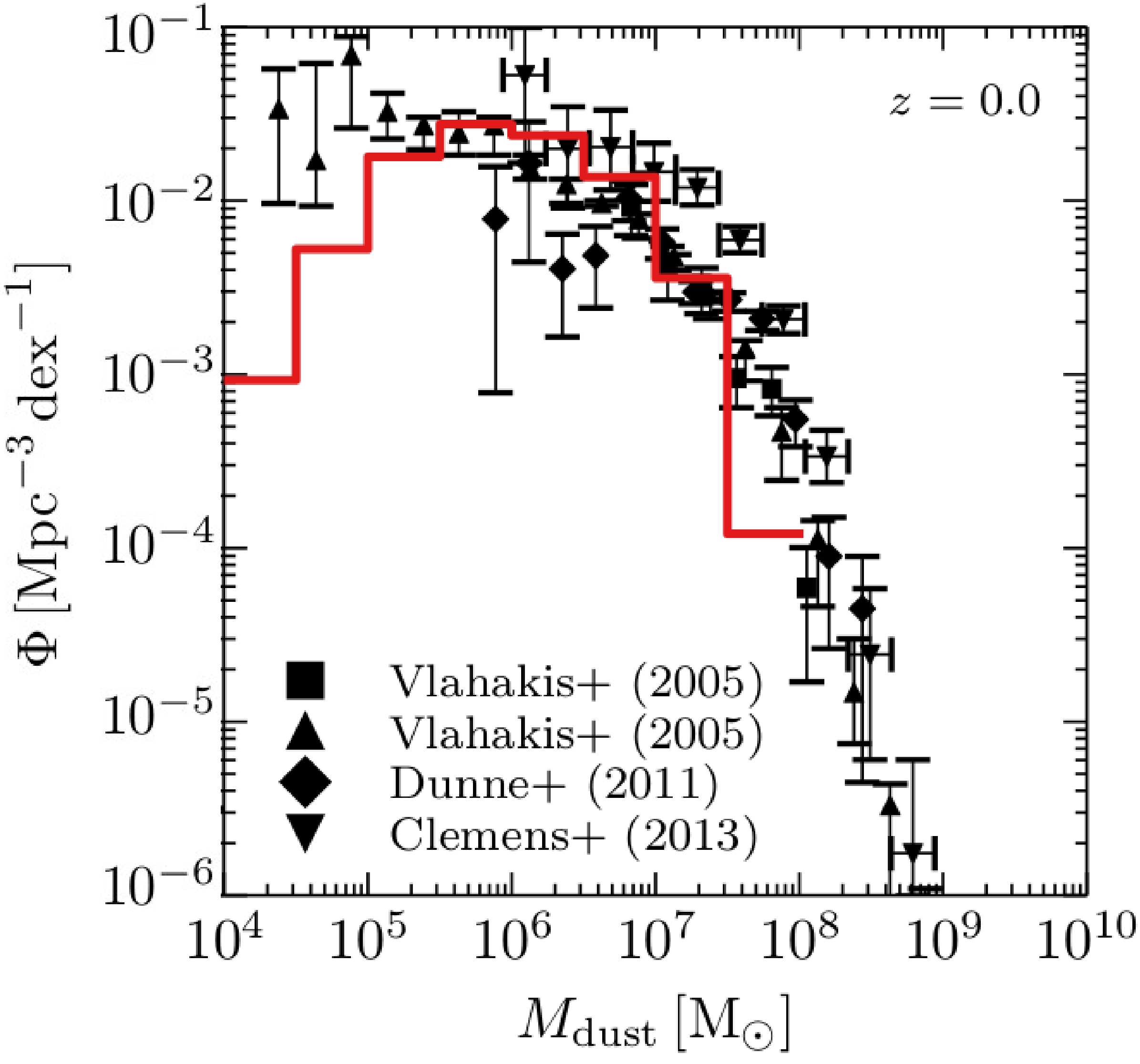


Impact of Dust Grain Size for Improved Model



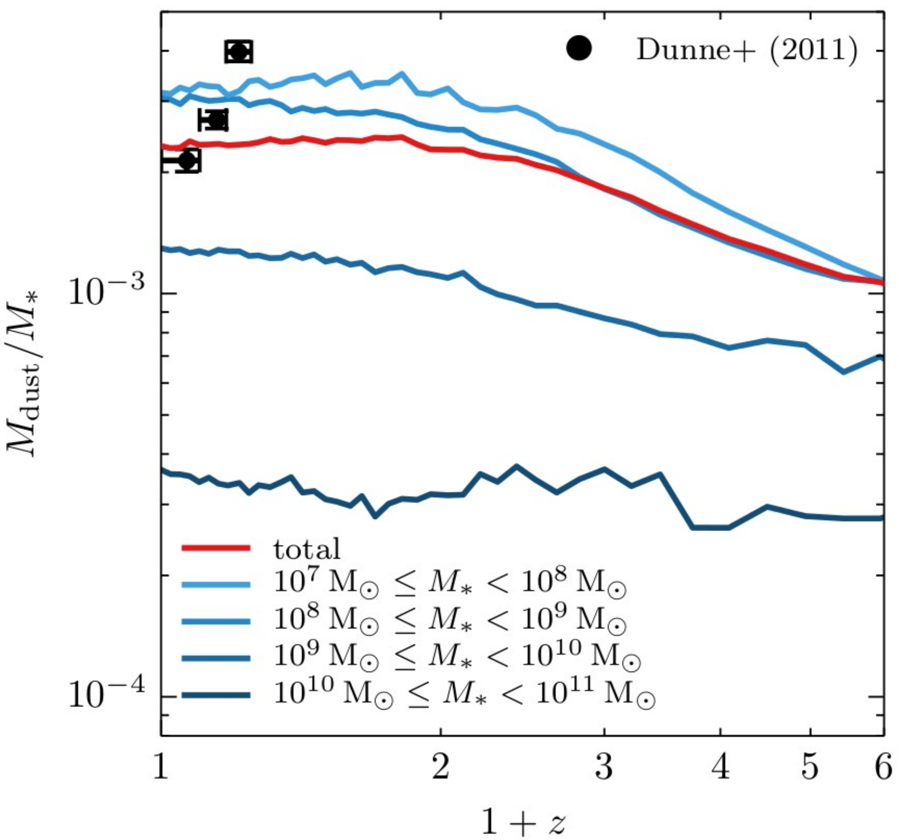
- differences only significant for lower redshifts once sufficient hot gas is available for thermal sputtering to destroy grains
- a factor of 100 in grain size leads to a factor ~2 different cosmic dust densities at z=0

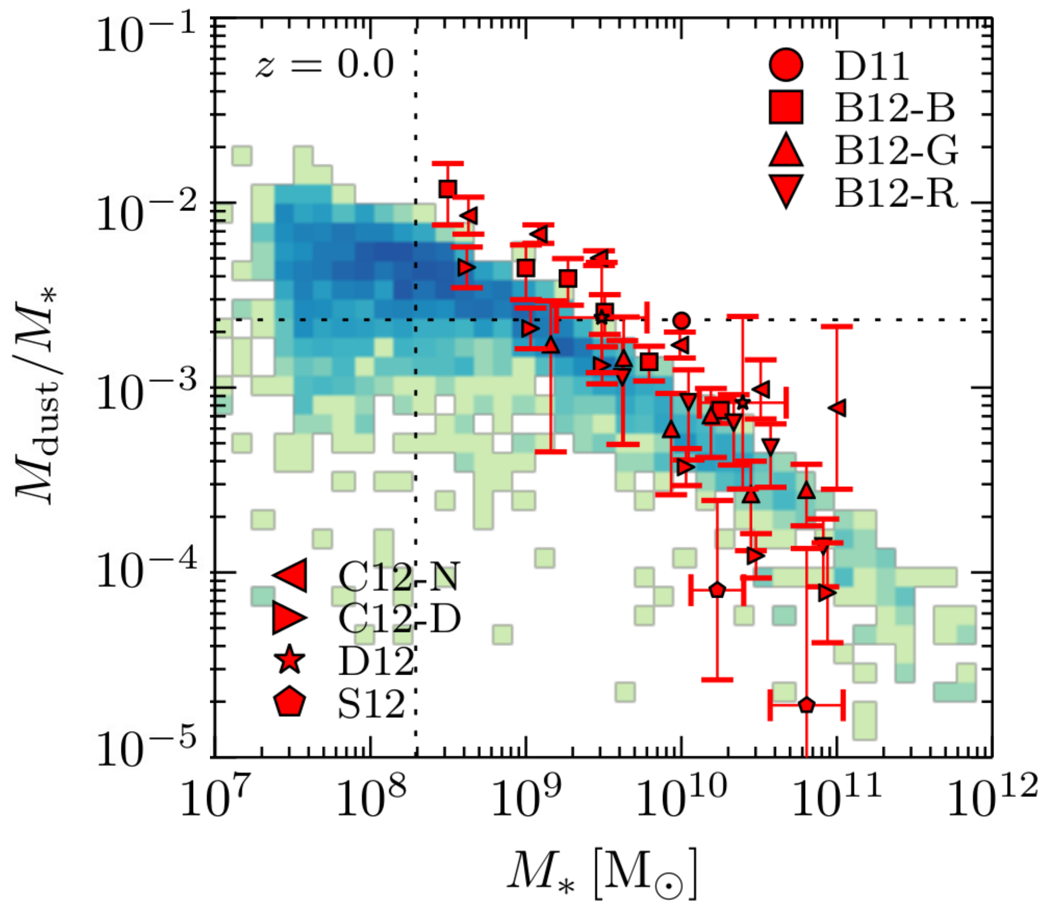
Dust Mass Function



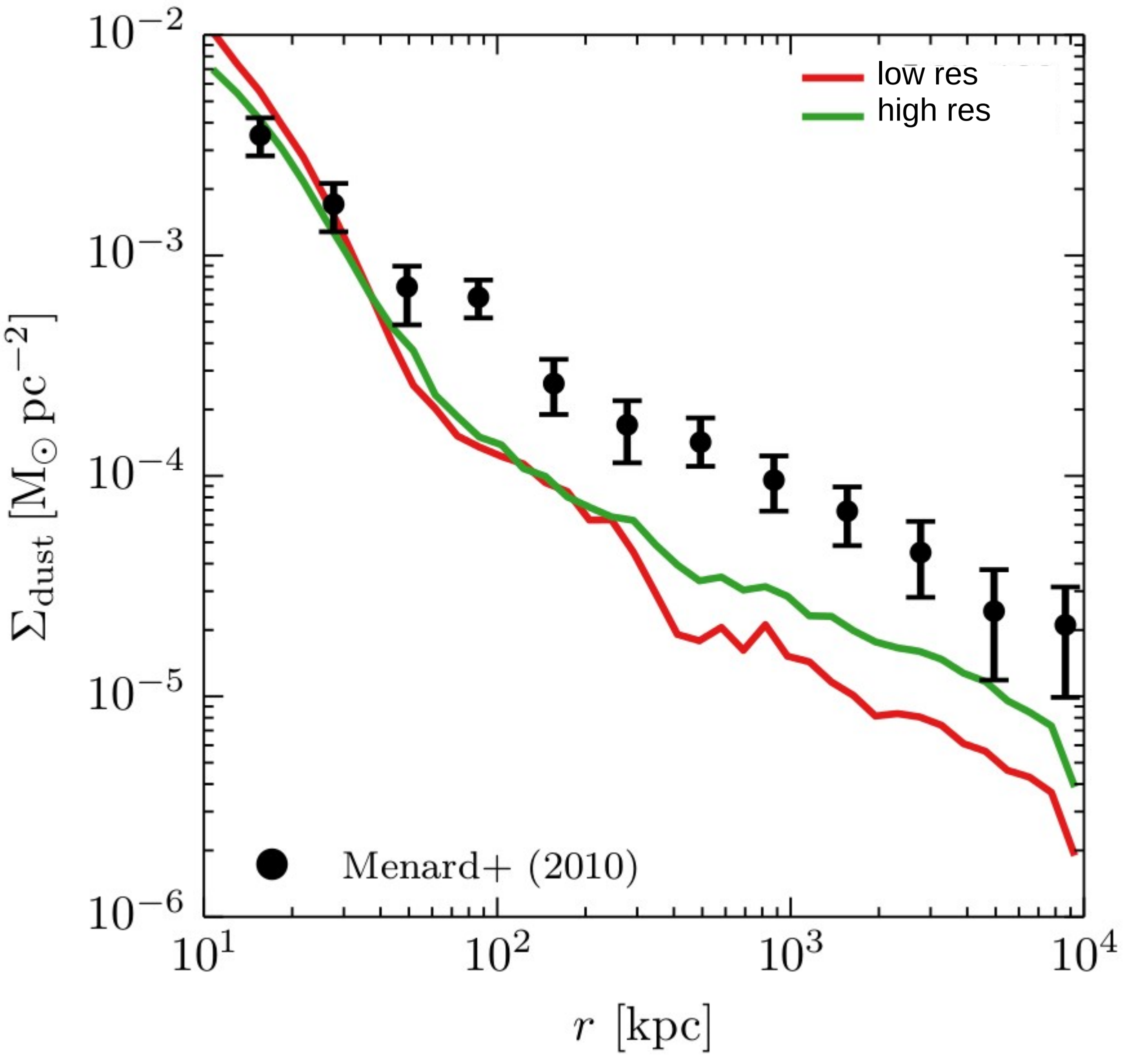
- redshift zero dust mass function is in reasonable agreement with data
- simulation volume too small to sample very dusty galaxies
- resolution too low to converge towards lower dust masses

Dust-to-Stellar-Mass Ratio





Dust Surface Density Profile

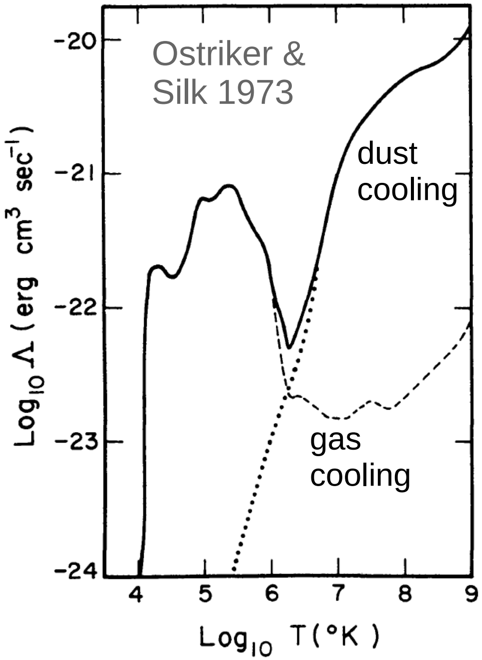


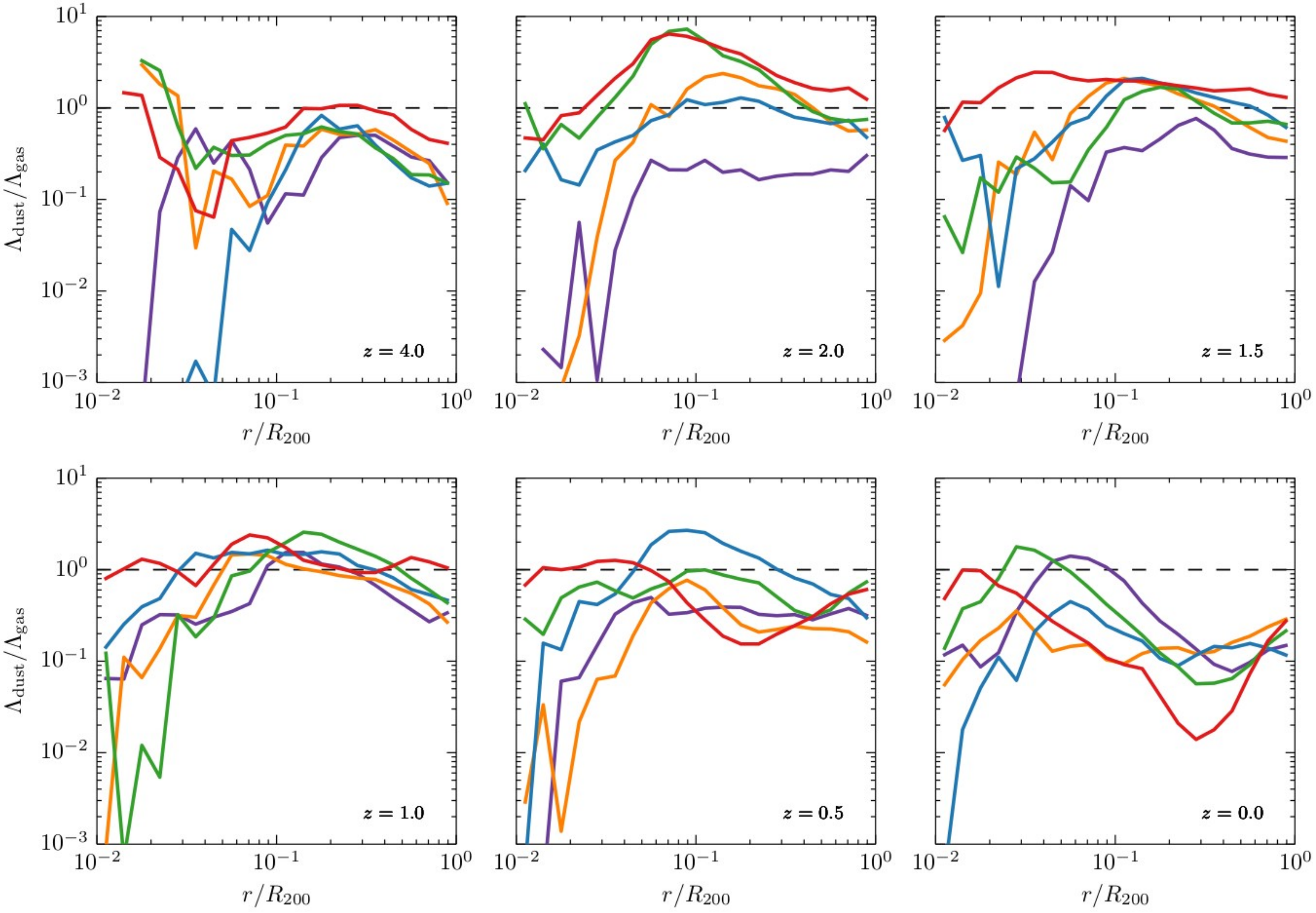
dust surface density profile as a function of projected radial distance in physical units around galactic centers at z = 0.3

simulated dust surface density profiles well-converged out to r ~ 300 kpc; higher resolution runs showing slightly greater dust surface density out to Mpc scales

Note: High Temperature Dust Cooling

- competition between thermal sputtering and dust replenishment
- if there is sufficient dust the cooling rates increase



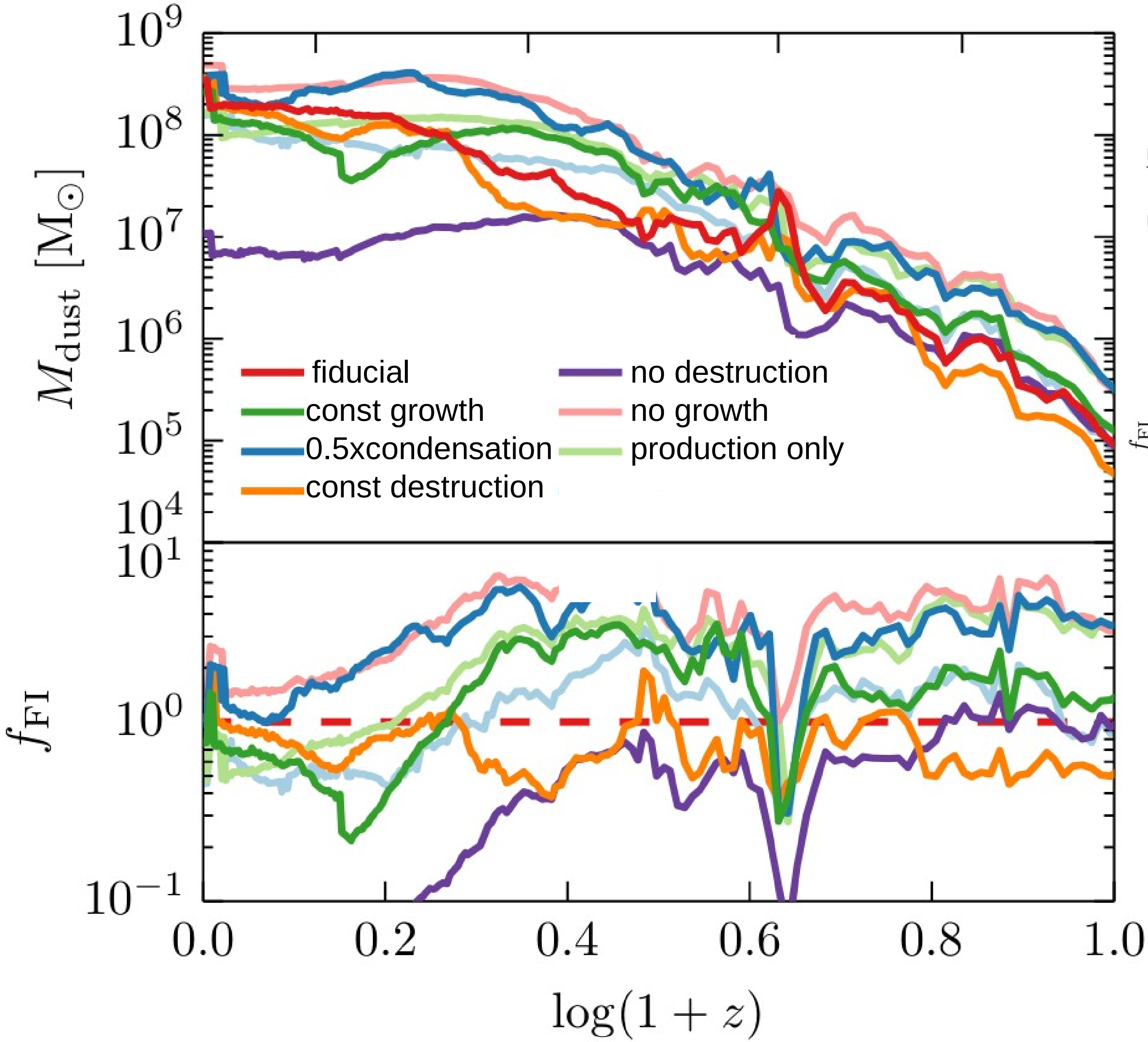


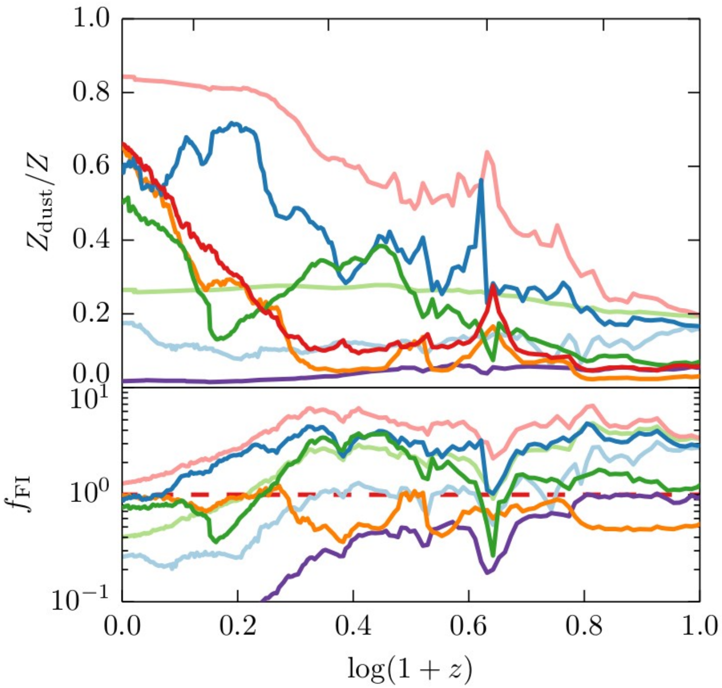
Some Potential Next Steps:

- variations of grain size distribution (e.g., shattering, coagulation)
- dust interaction with radiation (e.g., radiation pressure)
- more detailed dust destruction (e.g., grain-grain collisions, detailed sputtering yields, cosmic rays)
- dust growth refinements (e.g., more detailed treatment of sticking probabilities)
- dust heating/cooling (e.g., hot gas cooling)
- dust production (e.g., condensation efficiency refinements)
- hydro-dust coupling (e.g. active dust particles using tracer particles)
- ...

- most of this has already been studied in a variety of small-scale simulations
- how does their interplay affect the dust content of the galaxies population?

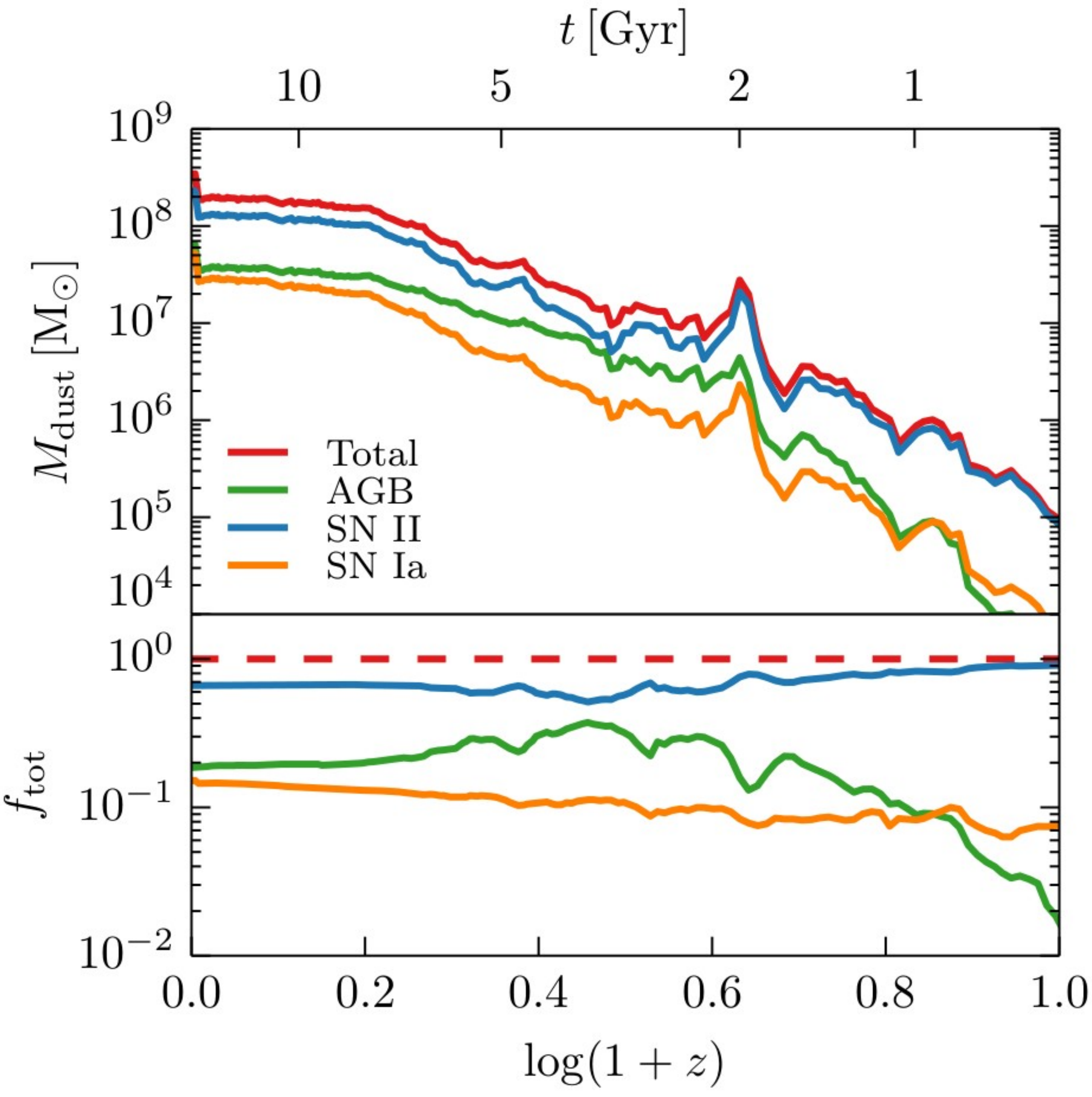
Overview: Variations of Dust Model





- dust mass can vary by up to ~2 orders of magnitude for different dust model parameters
- dust to metal ratio can vary by a factor up to ~5 for different dust model parameters

Variable	Fiducial Value	Description
$\delta_i^{\mathrm{AGB,C/O}\,>\,1}$	0.0 for $i = \mathrm{H}$, He, N, O, Ne, Mg, Si, Fe, 1.0 for $i = \mathrm{C}$	dust condensation efficiency for species i in AGB stars with C/O > 1 in ejecta
$\delta_i^{\mathrm{AGB,C/O}\,<\,1}$	0.0 for $i = \mathrm{H}$, He, N, C, Ne, 0.8 for $i = \mathrm{O}$, Mg, Si, Fe	dust condensation efficiency for species i in AGB stars with C/O < 1 in ejecta
δ_i^{SN}	0.0 for $i = \mathrm{H}$, He, N, Ne, 0.5 for $i = \mathrm{C}$, 0.8 for $i = \mathrm{O}$, Mg, Si, Fe	dust condensation efficiency for species i in SNe
$\tau_{\mathrm{g}}^{\mathrm{ref}}$	0.2	reference dust growth timescale, in units of [Gyr]
ϵ	0.3	SN destruction efficiency



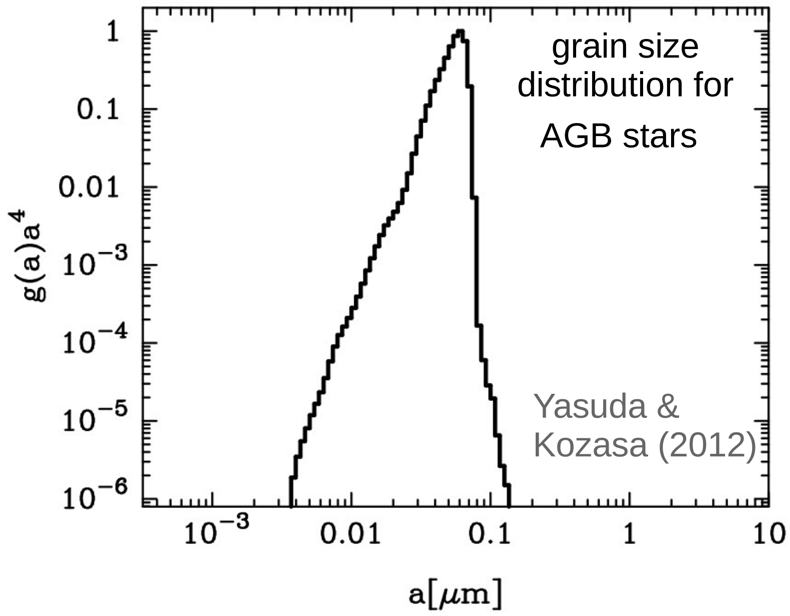
Dust Contributions

for simulated MW systems:

- >80% of dust originated in SNII for z>5
- AGB contribution peaks around z~2 with a contribution of around 40%
- at z=0 about 20% of dust are due to AGB stars

→ for M16 model and MW like galaxies most of the dust is coming from SNII

grain size distribution

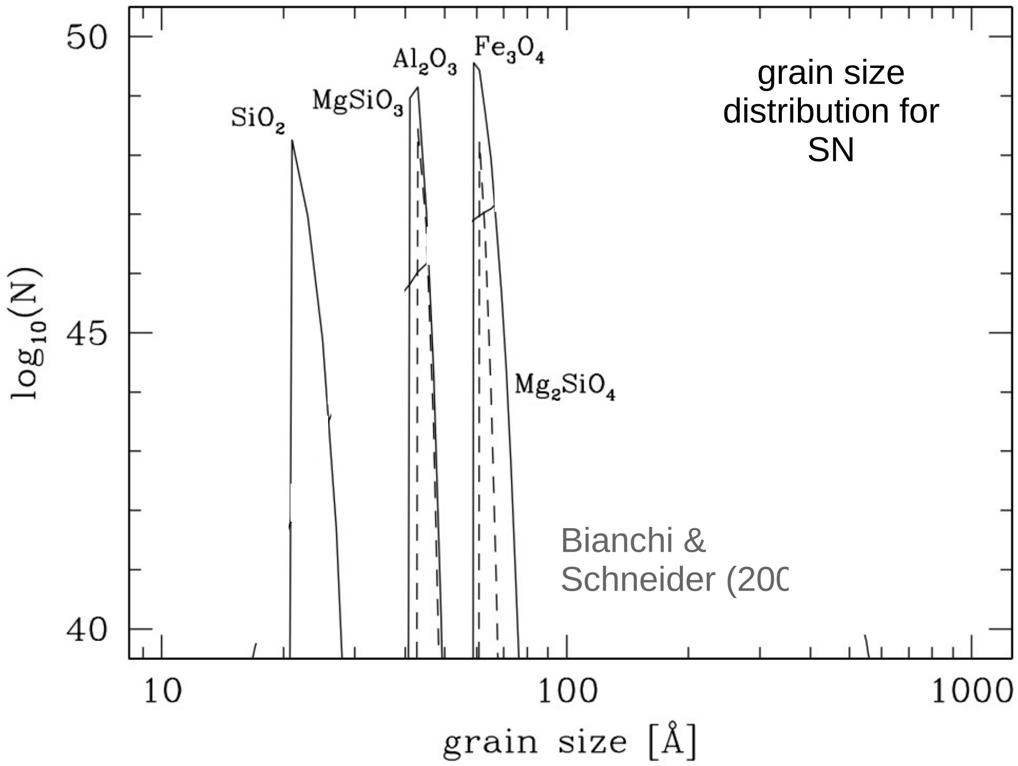


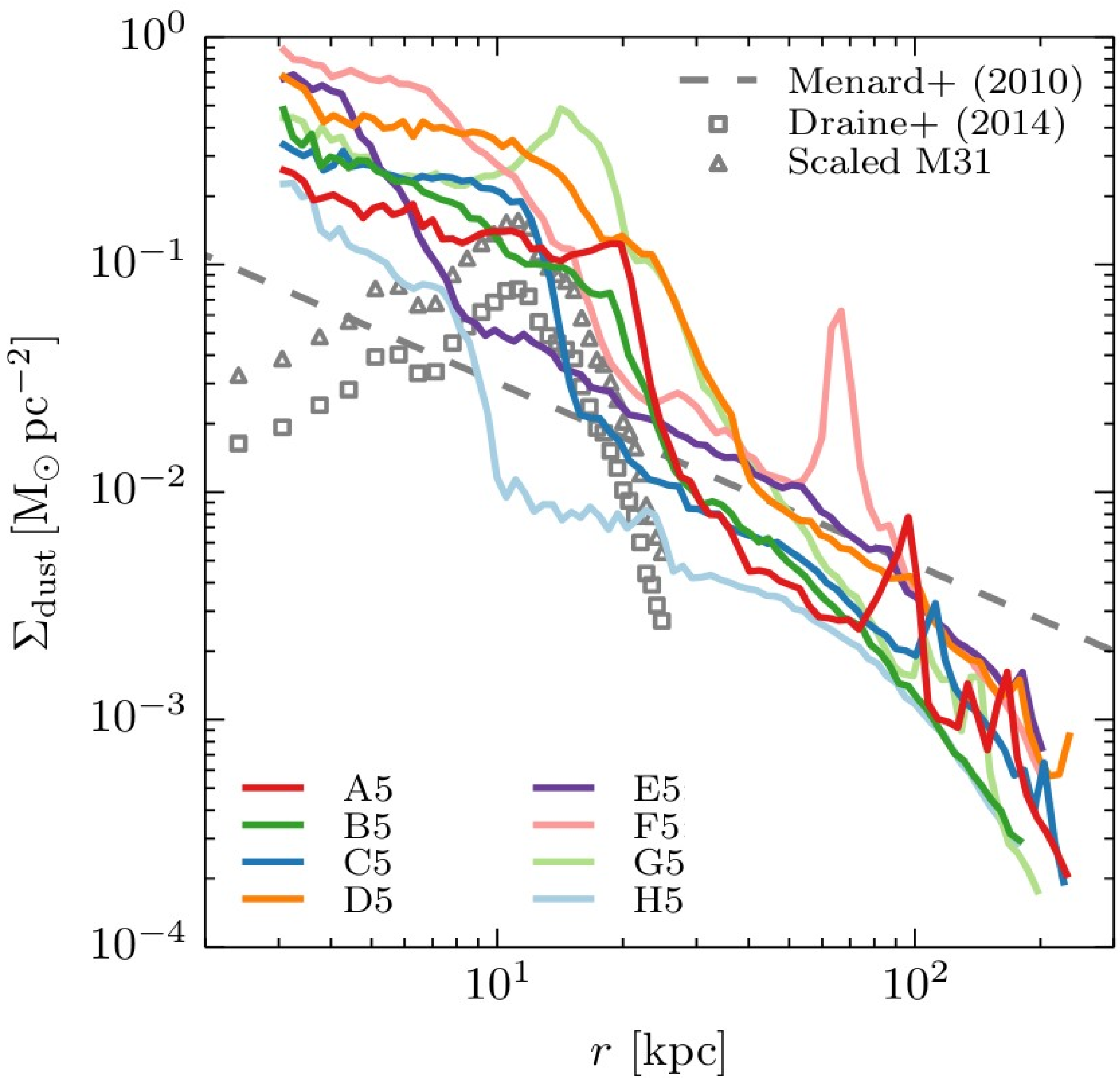
Thermal sputtering rate depends linearly on grain size. Currently, we do not follow the evolution of grain sizes; we therefore use a fixed grain size for our fiducial model.

fiducial model: $a = 0.1\,\mu\mathrm{m}$

Note: implementing grain size distributions is straightforward: similar to having IMF for macroscopic stellar particles

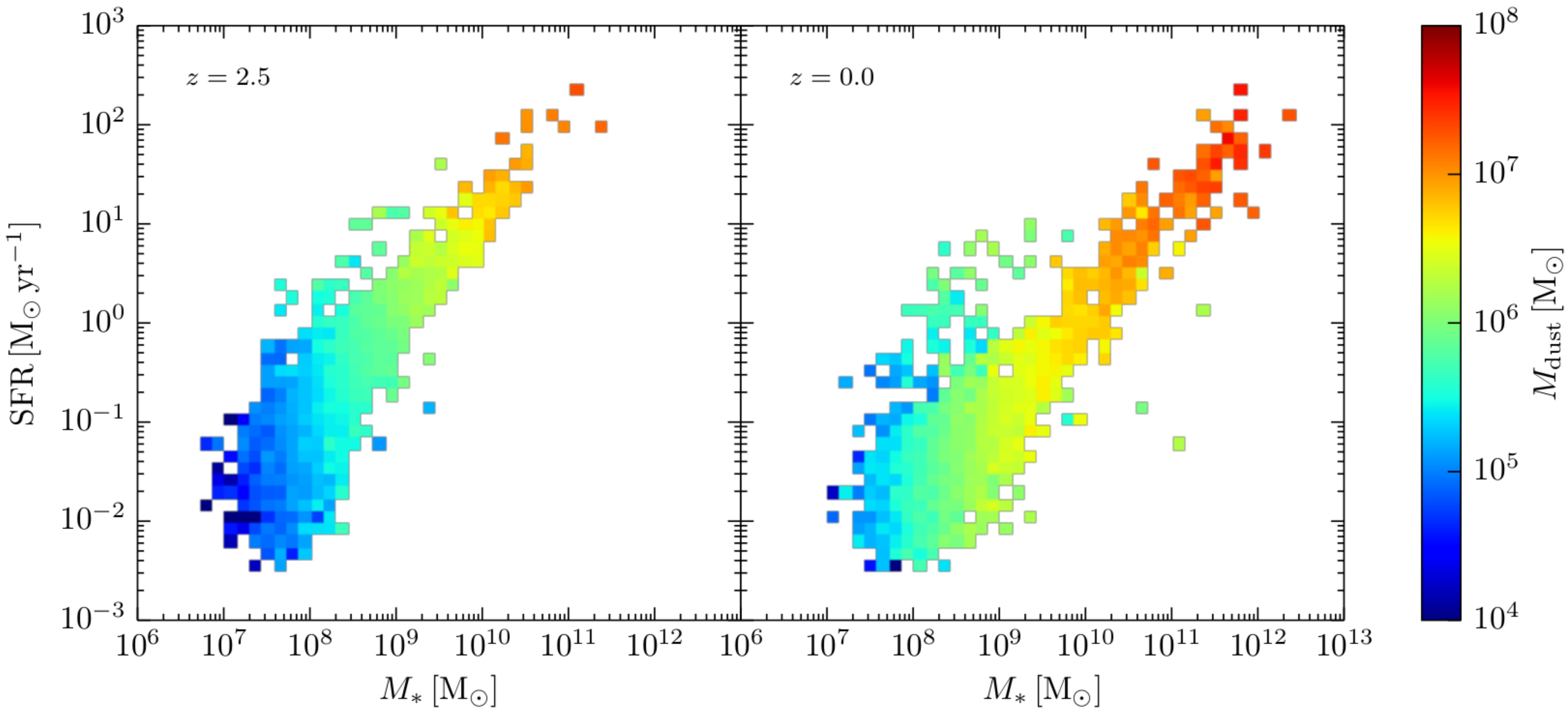
reasonable approximation since grain size distributions are typically sharply peaked





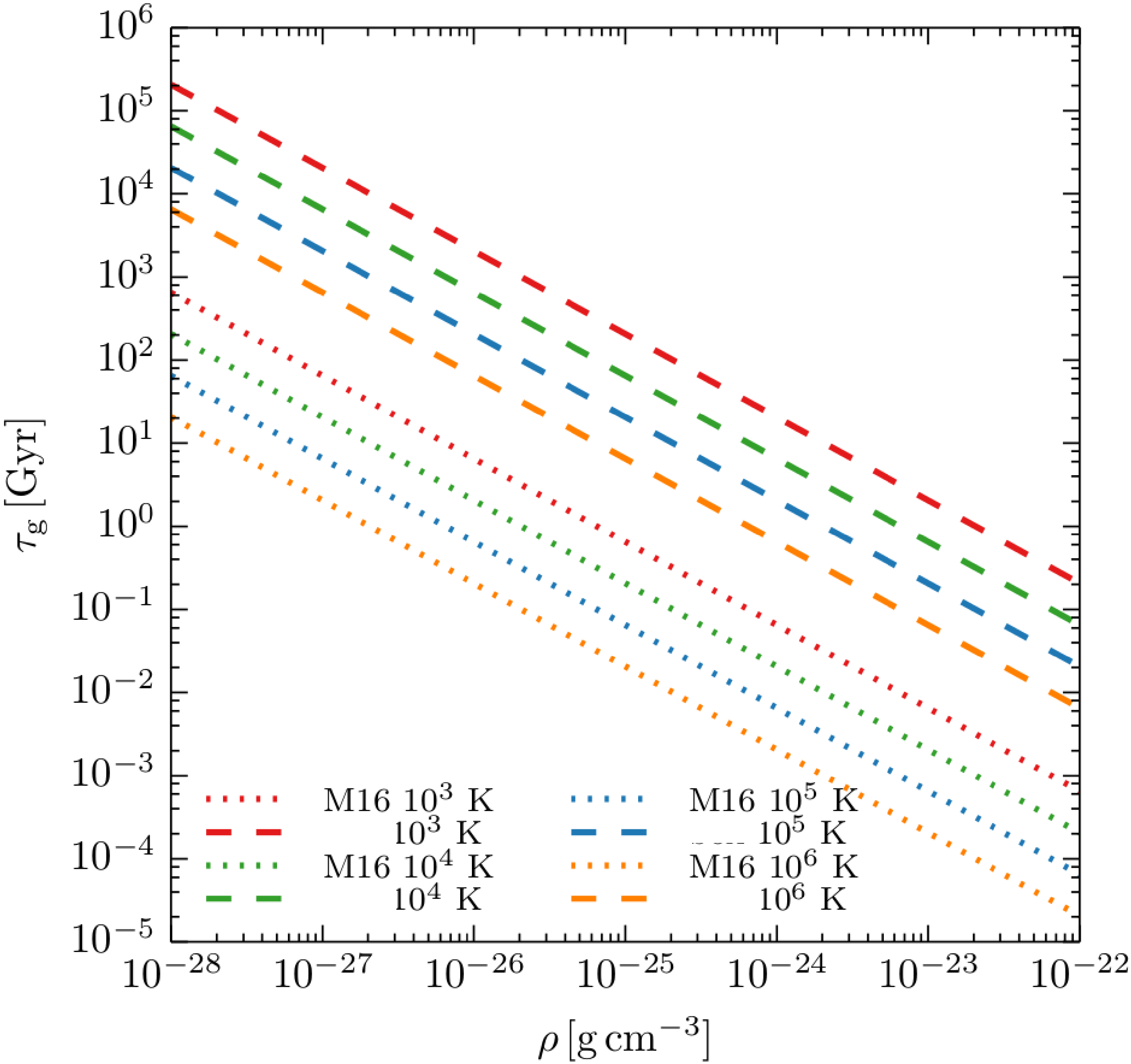
- surface density of dust as a function of radial distance
- comparison to M31 and MW measurements and SDSS
- sharp rise of dust density towards galaxy reproduced
- SDSS r^{-8} scaling roughly reproduced
- central drop of dust density not reproduced. Why?

Dust along the Star Formation Main Sequence



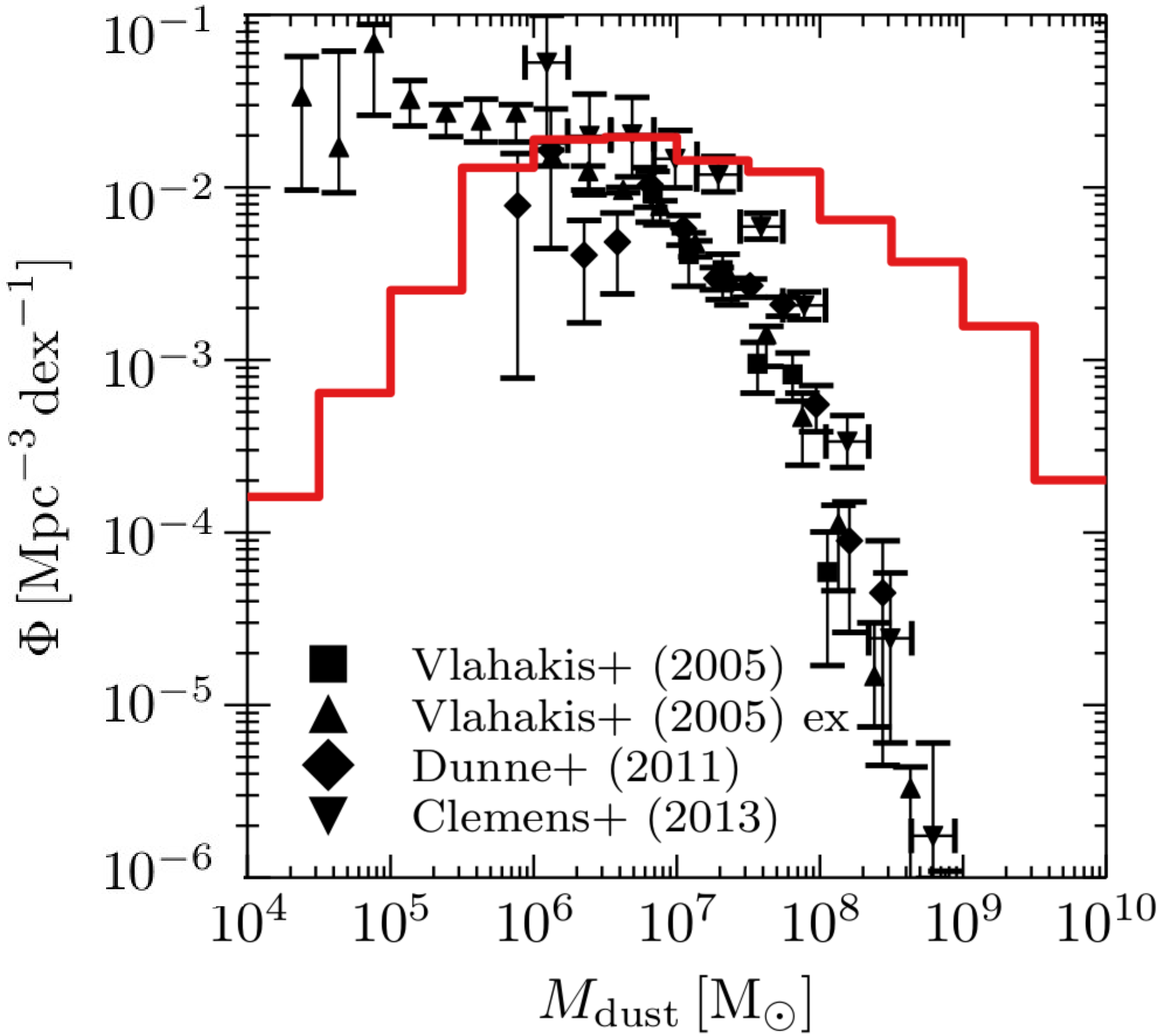
dustiest galaxies are those with the highest star formation rates

Dust Growth:



reduce dust growth

dust mass function



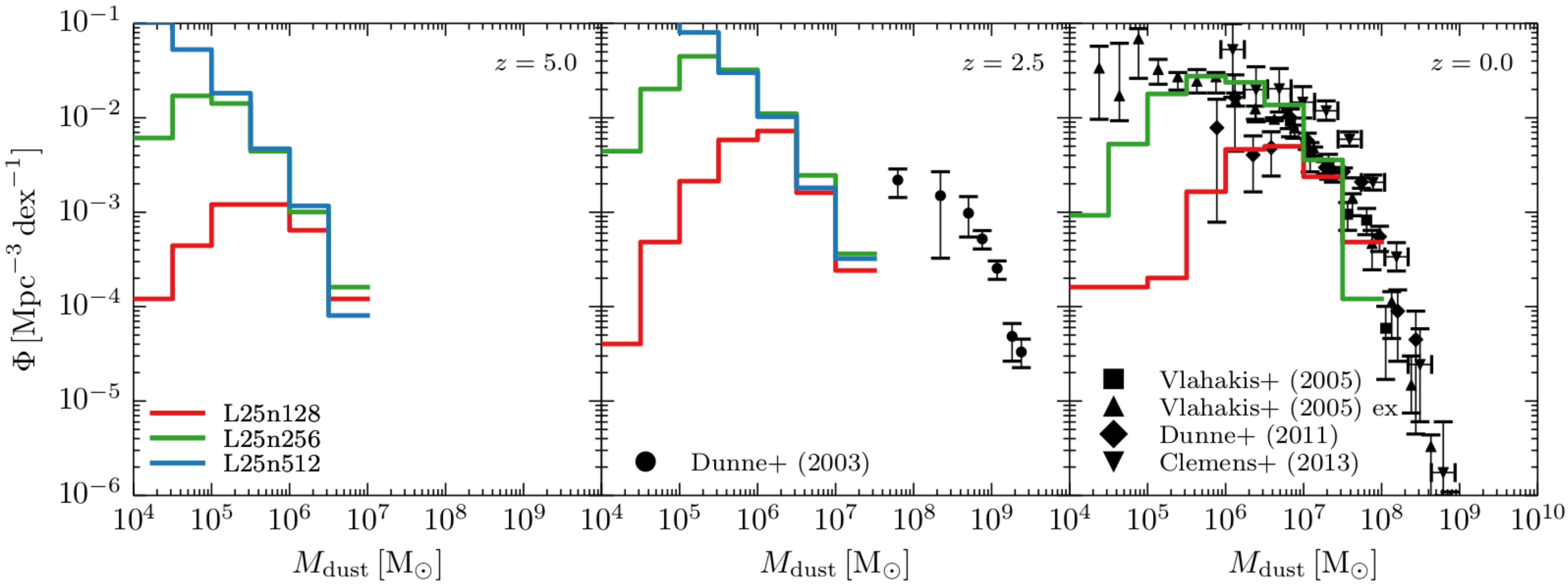
predicted dust mass function of simple M16 model

too many galaxies >10^8 solar masses; at 10^9 solar masses, the number densities are off by more than three orders of magnitude

abundance of galaxies with ~ MW type dust content approximately correct within M16, but not for more massive systems

M16 either too much dust production or too little dust destruction

Remaining Issues: Redshift Evolution



- dust grows in monotonic fashion, which is wrong
- the nature of dust processes makes the dust mass function behave in a much more dynamic way than the galaxy stellar mass function.
- a dust growth mechanism that allows for more variation among galaxies may be needed to form dust-rich galaxies at high redshift but also avoid overproducing dust at low redshift.