DUSTY GALAXIES AT HIGH REDSHIFT

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How do you include dust in galaxy simulations?
SIMBA: the descendent of MUFASA

**Numerics:**
GIZMO: Gadget gravity+meshless hydro
Grackle-3.1 cooling with metals and self-shielding

**Physics (SF/Dust):**
KMT H$_2$-based star formation
9 metal-chemical enrichment from SNe, AGB
*On the fly Dust formation/destruction*

**Physics (other):**
Black hole growth/AGN feedback
Kinetic winds based on FIRE scalings

Davé, Anglés-Alcázar, Narayanan, Li et al. 2019
SIMBA: Model Verification

Davé, Anglés-Alcázar, Narayanan, Li et al. 2019

**z=0 gas MZR**

![z=0 gas MZR](image)

**z=2 gas MZR**

![z=2 gas MZR](image)

**z=0 stellar MZR**

![z=0 stellar MZR](image)
HOW DUST USED TO BE INCLUDED

\[ M_{\text{dust}} = 0.4 \times M_{\text{metals}} \]

Dwek 1998
Vladilo 1998
Watson 2011
A NEW GENERATION OF DUST IN GALAXY FORMATION SIMULATIONS

Visualization: Ben Kimock (University of Florida)

Formation
- Type II SNe
- AGB Stars

Growth
- Accretion of metals

Destruction
- Sputtering
- SNe blast waves
- Consumption by SF

See also: Popping et al. (2017), McKinnon et al. (2016), C.-Y. Hu et al 2019, Choban et al. in prep., Hou et al. (2019), Hirashita et al. (2018)
**TUNING TO THE DUST MASS FUNCTION**

\[
m_{i,d}^{\text{SNII}} = \begin{cases} 
16 \sum_{i=\text{Mg, Si, S, Ca, Fe}} \delta_i^{\text{SNII}} m_{i,ej}^{\text{SNII}}, & i = \text{O} \\
\delta_i^{\text{SNII}} m_{i,ej}^{\text{SNII}}, & \text{otherwise},
\end{cases}
\]

\[
\left( \frac{dM_{\text{dust}}}{dt} \right)_{\text{grow}} = 1 - \frac{M_{\text{dust}}}{M_{\text{metal}}} \left( \frac{M_{\text{dust}}}{\tau_{\text{accr}}} \right)
\]

\[
\tau_{\text{accr}} = \tau_{\text{ref}} \left( \frac{\rho_{\text{ref}}}{\rho_{g}} \right) \left( \frac{T_{\text{ref}}}{T_{g}} \right) \left( \frac{Z_{\odot}}{Z_{g}} \right).
\]

Dwek 1998

Asano et al. 2013

Davé, Anglés-Alcázar, Narayanan, Li et al. 2019

Li, Narayanan & Davé 2019 in prep.
TUNING TO THE DUST MASS FUNCTION

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\frac{dM_{\text{dust}}}{dt} \bigg|_{\text{grow}} = 1 - \frac{M_{\text{dust}}}{M_{\text{metal}}} \left(\frac{M_{\text{dust}}}{\tau_{\text{accr}}}\right)
\]

Dwek 1998

\[
m_{i,d}^{\text{SNII}} = \begin{cases} 
16 \sum_{i=\text{Mg,Si,S,Ca,Fe}} \delta_{i}^{\text{SNII}} m_{i,ej}^{\text{SNII}}, & i = 0 \\
\delta_{i}^{\text{SNII}} m_{i,ej}^{\text{SNII}}, & \text{otherwise},
\end{cases}
\]

Asano et al. 2013

\[
\tau_{\text{accr}} = \tau_{\text{ref}} \left(\frac{\rho_{\text{ref}}}{\rho_{g}}\right) \left(\frac{T_{\text{ref}}}{T_{g}}\right) \left(\frac{Z_{\odot}}{Z_{g}}\right).
\]
The impact of on the fly dust physics: $z=0$ (25 Mpc)$^3$ SIMBA volume

Quenched Galaxies
APPLICATION 1: THE ORIGIN OF HIGH-REDSHIFT DUSTY GALAXIES
APPLICATION 1: A UNIVERSE OF DUSTY GALAXIES: WHAT PHYSICS IS IMPORTANT?

Grain growth and sputtering dominate dust mass function

Narayanan, Li, Davé 2019 (in prep)
THE RISE OF DUSTY STAR FORMING GALAXIES AT HIGH-REDSHIFT

The graph shows the normalized quantities of various parameters over redshift (z). The parameters include SFR/2.6e+03 (M⊙/yr), M_{dust}/5.1e+9 (M⊙), and L_{IR}/1.3e+13 (L⊙). The axes represent normalized quantities on the y-axis and redshift on the x-axis.
DIVERSE MORPHOLOGICAL STRUCTURES OF DSFGS

\[ \text{SFRs} = 300-1500 \, M_\odot \, \text{yr}^{-1} \]
THE COMPLEX GEOMETRIES ASSOCIATED WITH HIGH-REDSHIFT GALAXIES

Narayanan, Turk, Feldmann et al. 2015, Nature
DIVERSITY IN SEDS AT Z=2: SFRS = \([300-1500 \, M_\odot/\text{YR}]\)
**EXTINCTION AND ATTENUATION**

- **2175 Å bump**
- **1 μm**
- **1000 Å**

More optically obscured
A UNIVERSE OF ATTENUATION LAWS

Narayanan, Conroy, Davé Johnson & Popping 2018b
WHAT DRIVES THE DIVERSE RANGE OF OBSERVED ATTENUATION LAWS?
WHAT DRIVES THE DIVERSE RANGE OF OBSERVED ATTENUATION LAWS?
WHAT ABOUT THE BUMP?

Kriek & Conroy 2013

Bump Strength

(DN, Conroy, Davé, Johnson & Popping 2018b)
WHAT DRIVES THE DIVERSE RANGE OF OBSERVED ATTENUATION LAWS?
GEOMETRY + STELLAR AGE DISTRIBUTION DRIVES VARIATIONS IN THE IRX-β PLANE AS WELL.
1. New SIMBA cosmological simulations self-consistently model the formation, growth, and destruction of dust in large volumes.

2. DSFGs at high-redshift are a “main mode” of galaxy formation – mergers unimportant. A dusty galaxy at high-z is just a plain old massive galaxy.

3. Attenuation laws (slopes and bump strengths) show dramatic variations between galaxies due primarily to star-dust geometries (for a fixed extinction law).