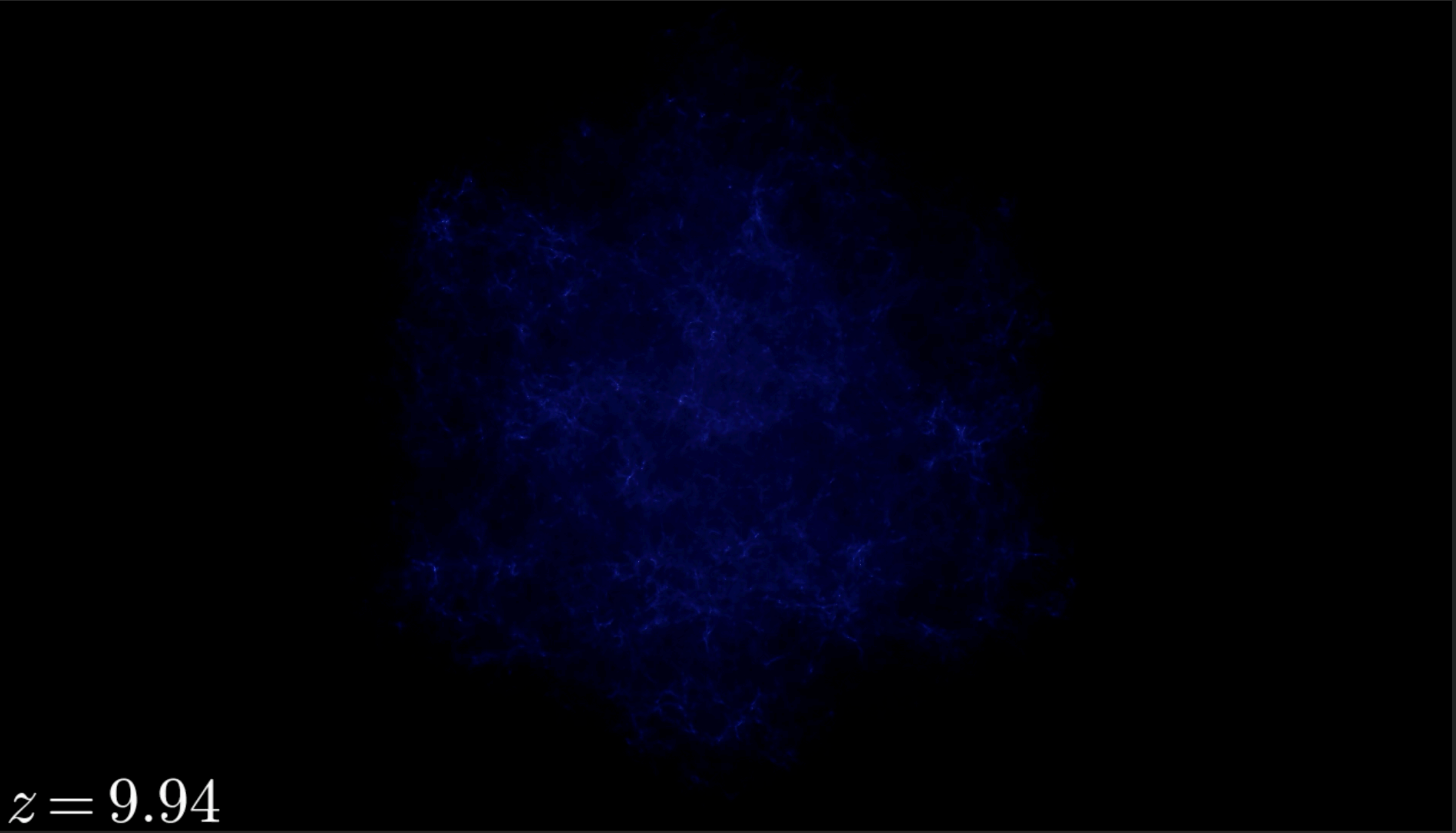
Dust in Galaxy Formation Simulations: A Review



Desika Narayanan

PART 1: HOW DO WE SIMULATE GALAXIES?

PART 2: HOW DO WE SIMULATE DUST?

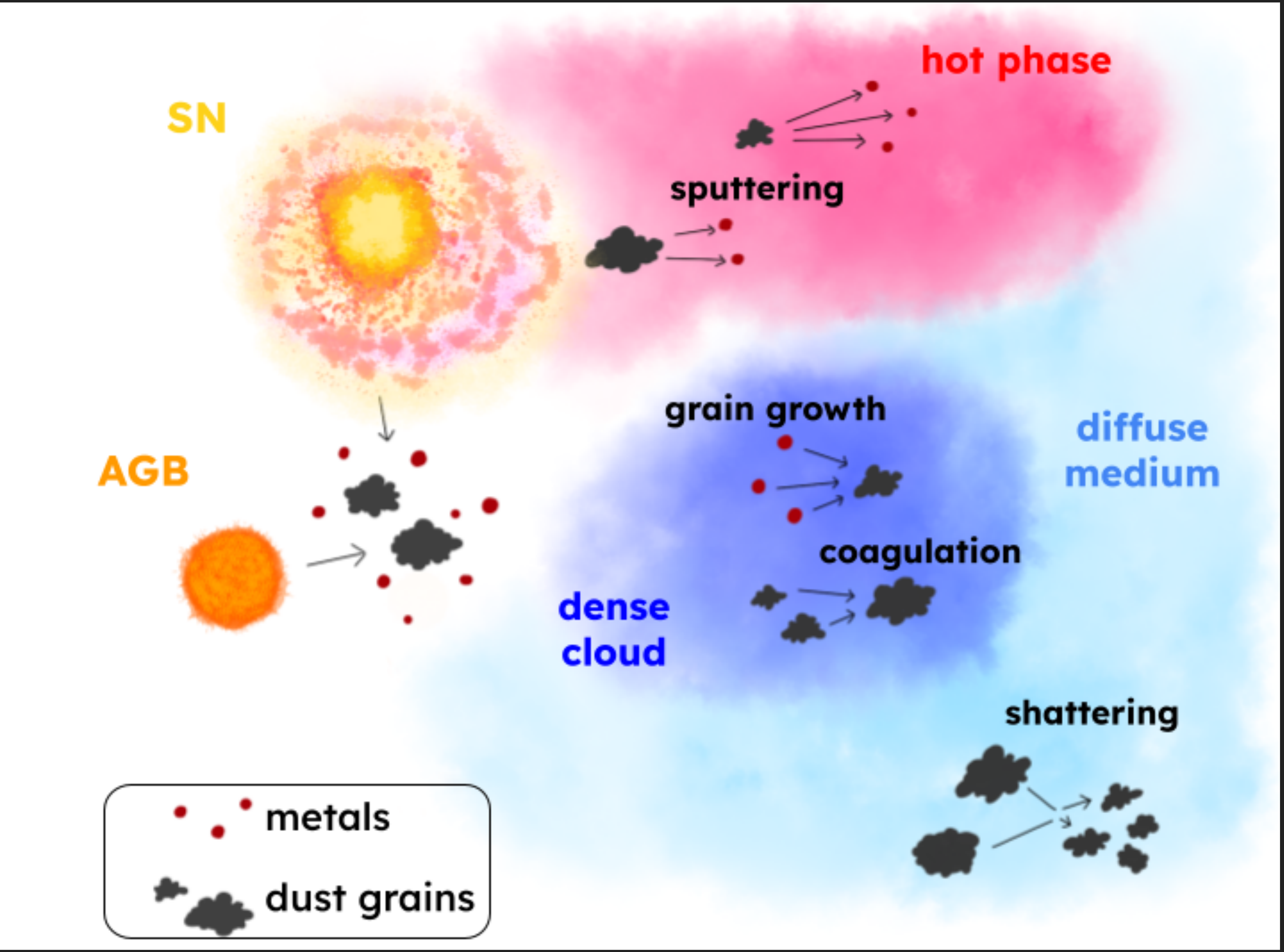
PART 3: SUCCESSES AND FAILURES

PART 4: AN EXAMPLE [MAYBE]

PART 5: WHAT DO WE NEED GOING FORWARD?

PART 1: HOW DO WE SIMULATE GALAXIES?

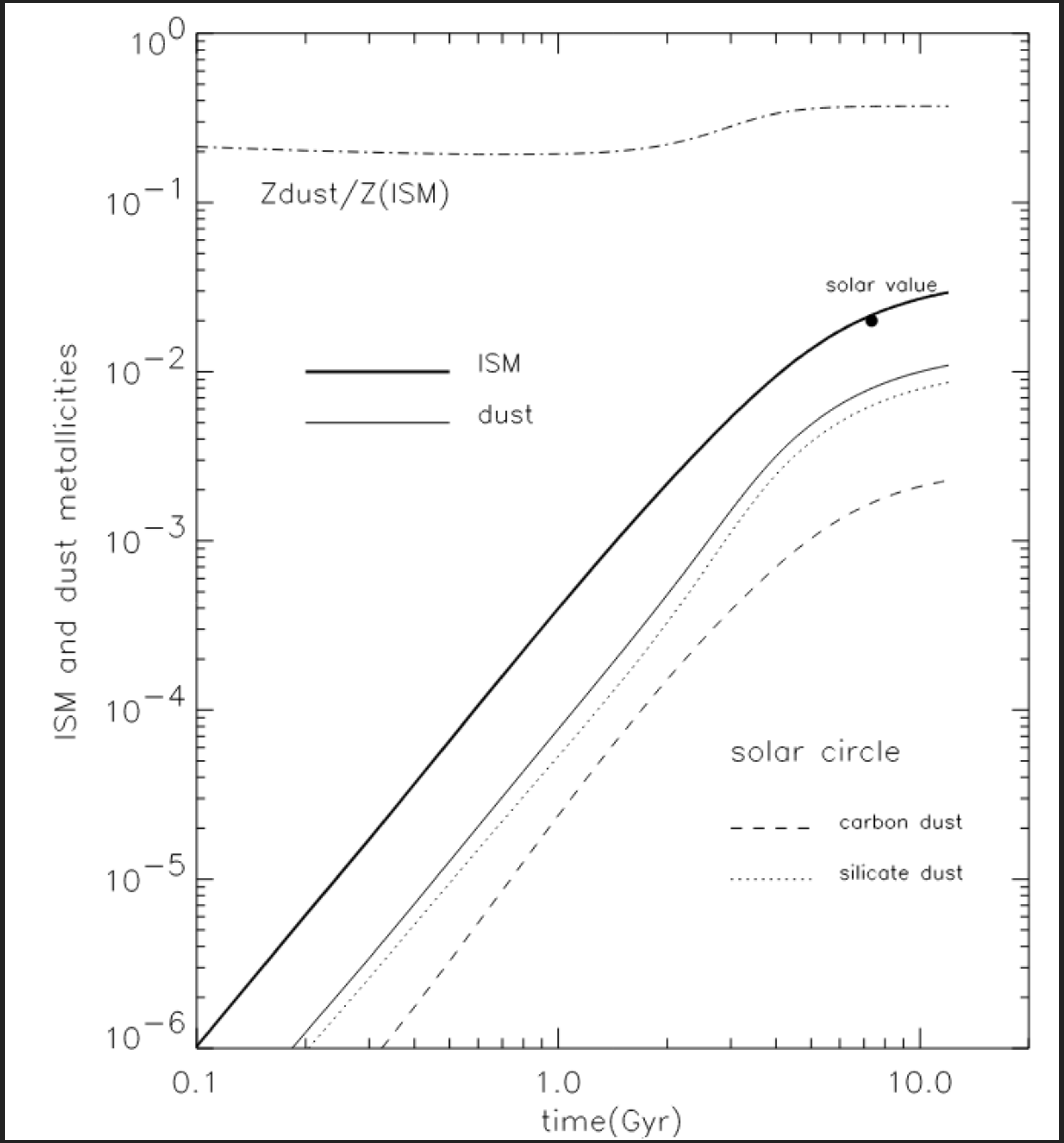
What do we care about (for dust)



Parente, 2025

PART 1: HOW DO WE SIMULATE GALAXIES?

$$\dot{M}_{dust} = M^{stars}_{dust}(t) - \frac{M_{dust}}{M_{gas}}\psi + M^{growth}_{dust}(\tau_{gg}) - M^{SNdes}_{dust}(\tau_{SNdes}) - \dot{M}^{outflow}_{dust}.$$



Dwek 1998
Dwek & Cherchneff 2011

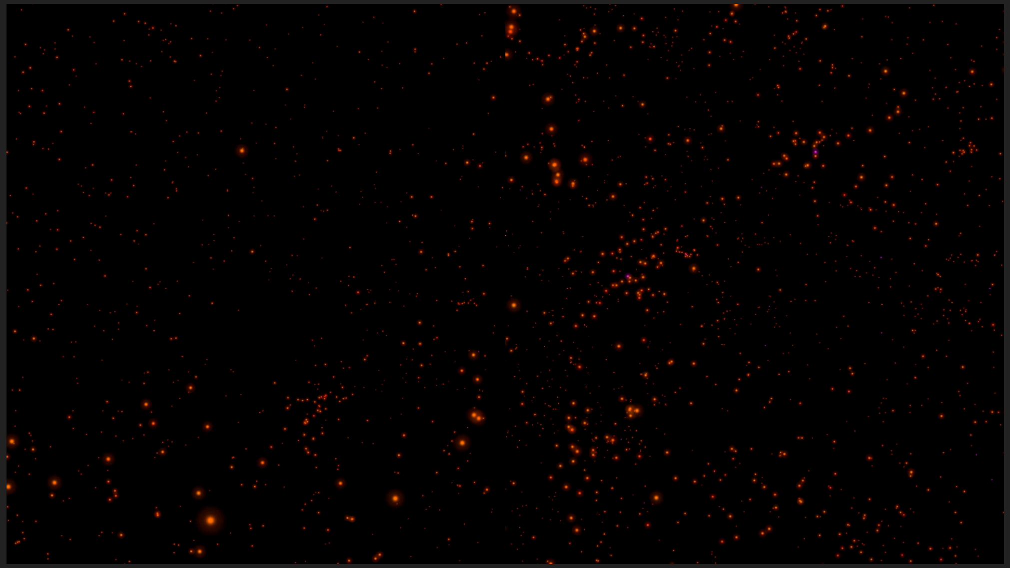
PART 1: HOW DO WE SIMULATE GALAXIES?

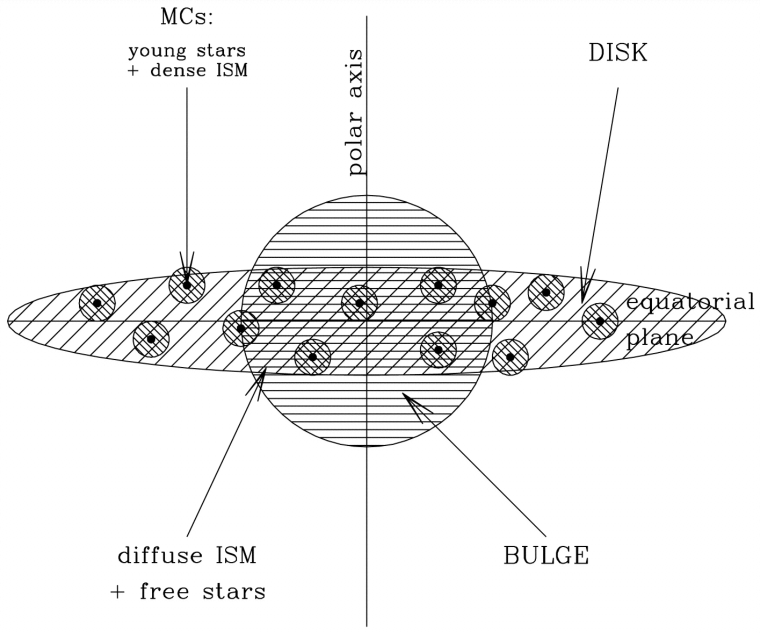
Semi Analytic Models

Idealized Simulations

Cosmological Simulations

Zoom Simulations





Granato et al. 2000

Advantages

- Speed
- Can search parameter spaces efficiently
- Can isolate driving physical processes

Drawbacks

- Highly simplistic view of galaxies (Fluid processes not simulated)
- Structure of Galaxies not simulated
- Subresolution scale at the scale of dark matter halos

Codes/Campaigns

- Durham SAM (`GALFORM`)
- L-Galaxies
- Santa Cruz SAM

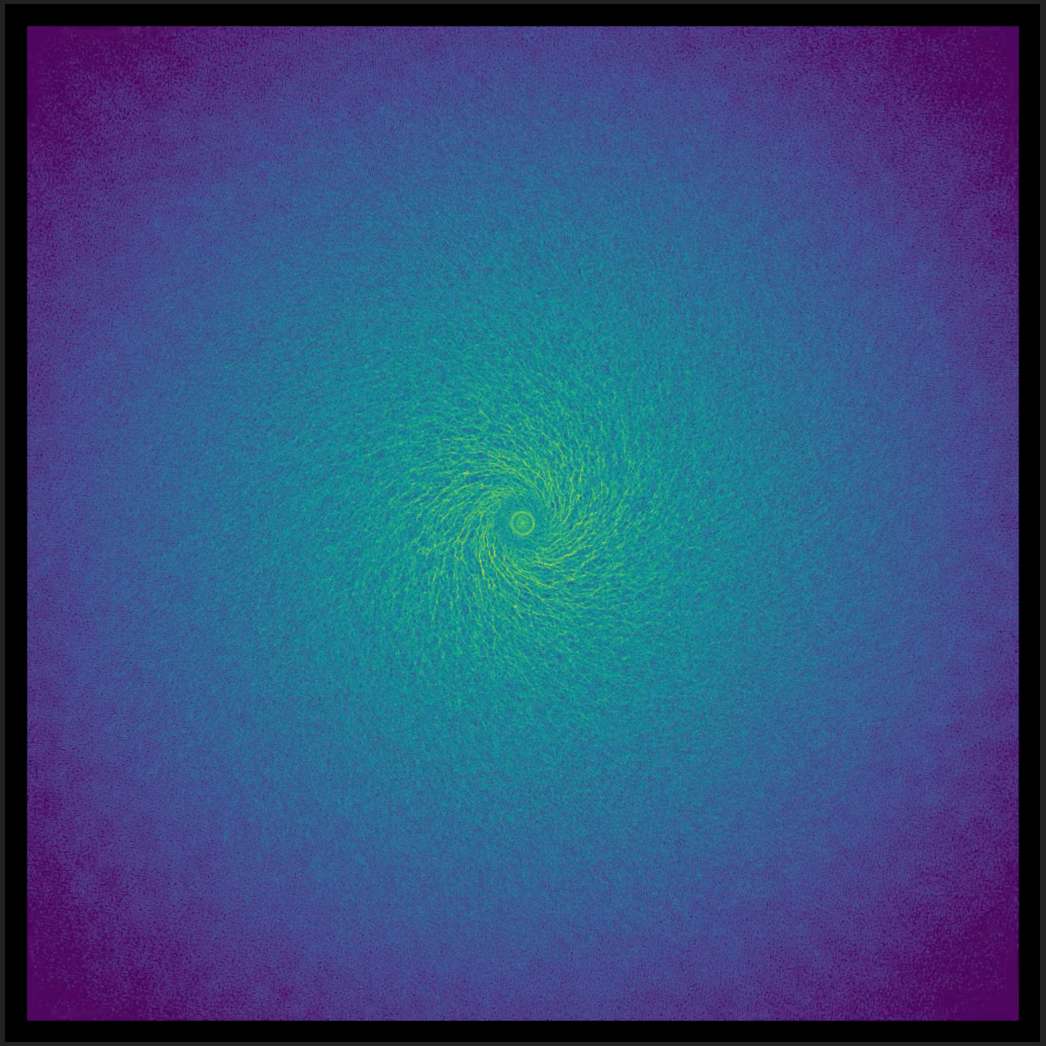
PART 1: HOW DO WE SIMULATE GALAXIES?

Semi Analytic Models

Idealized Simulations

Cosmological Simulations

Zoom Simulations



Advantages

- Highest possible resolutions of all the methods
- Relatively fast to run
- Can run radiative transfer
- Can isolate internal processes

Drawbacks

- Non cosmological (no environment)
- Early phases dominated by ICs and lack physical information
- Not obvious how to simulate statistics

Codes/Campaigns

- Gadget/GIZMO
- Ramses
- Gasoline
- Arepo/SMUGGLE

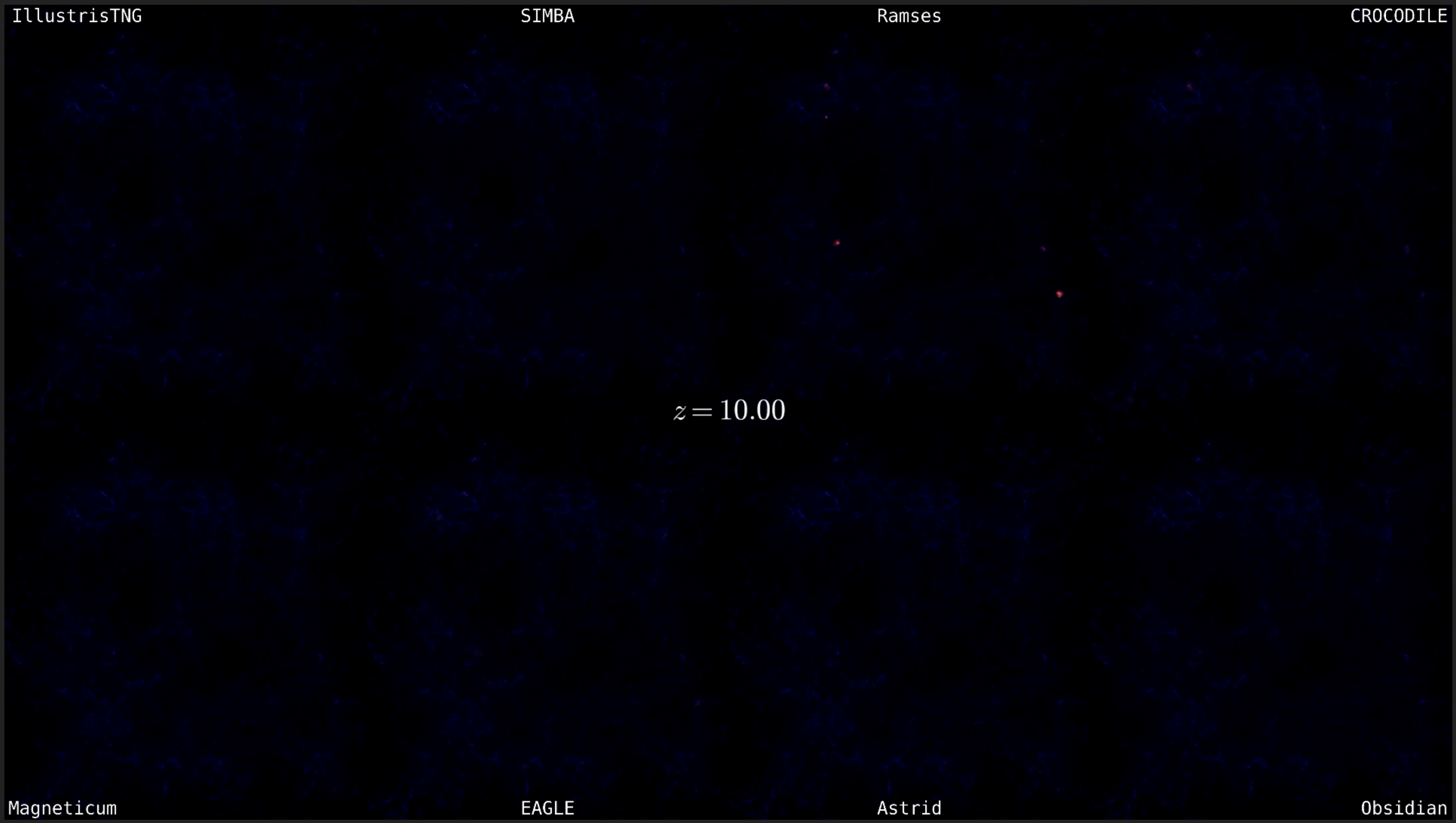
PART 1: HOW DO WE SIMULATE GALAXIES?

Semi Analytic Models

Idealized Simulations

Cosmological Simulations

Zoom Simulations



Advantages

- Numerous halos/galaxies
- Cosmic environment included
- Can simulate deep fields

Drawbacks

- Even state of the art resolution is relatively poor (~10^5 M⊙)
- Can be quite slow
- Not obvious you can resolve ISM enough to run RT

Codes/Campaigns

- EAGLE/COLIBRE
- SIMBA
- Illustris

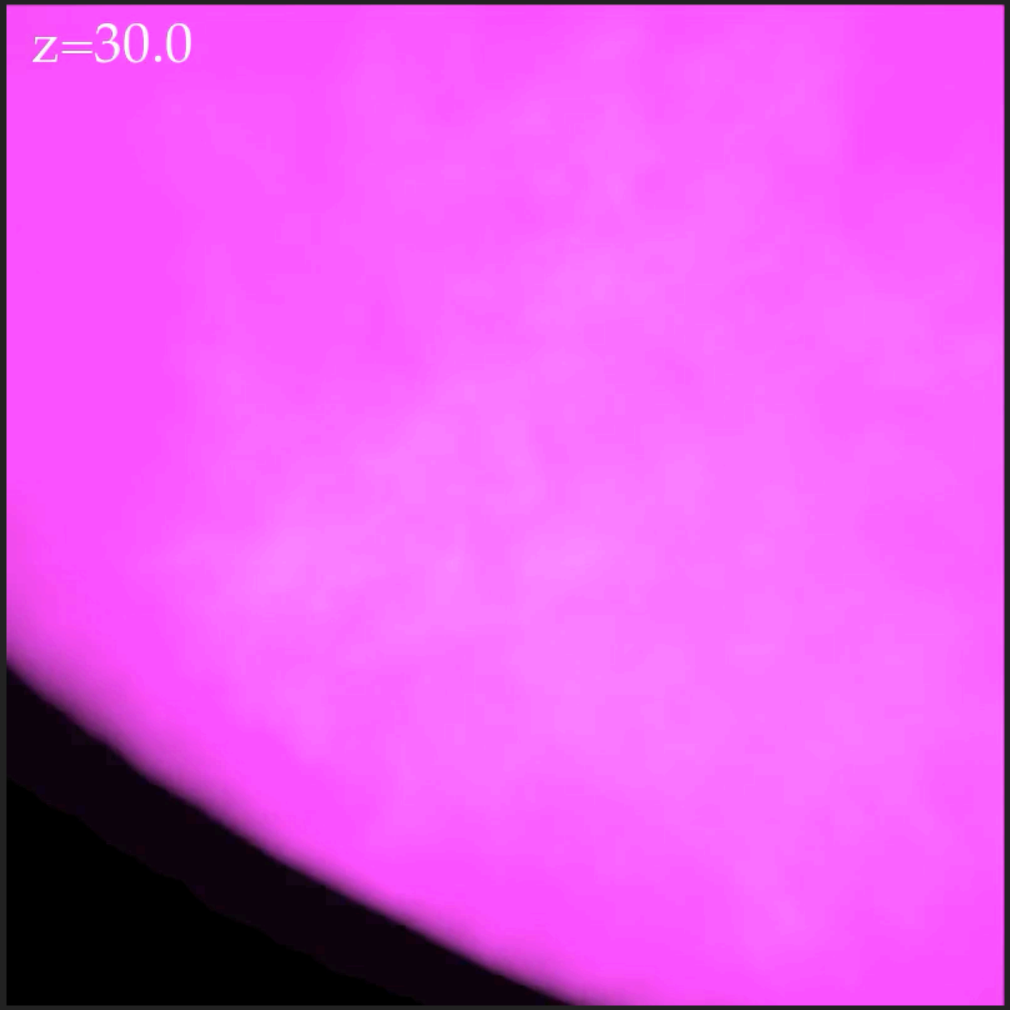
PART 1: HOW DO WE SIMULATE GALAXIES?

Semi Analytic Models

Idealized Simulations

Cosmological Simulations

Zoom Simulations



Advantages

- Resolution can approach that of idealized
- Cosmic environment included
- Better ISM resolution
- Best of both (hydro) worlds

Drawbacks

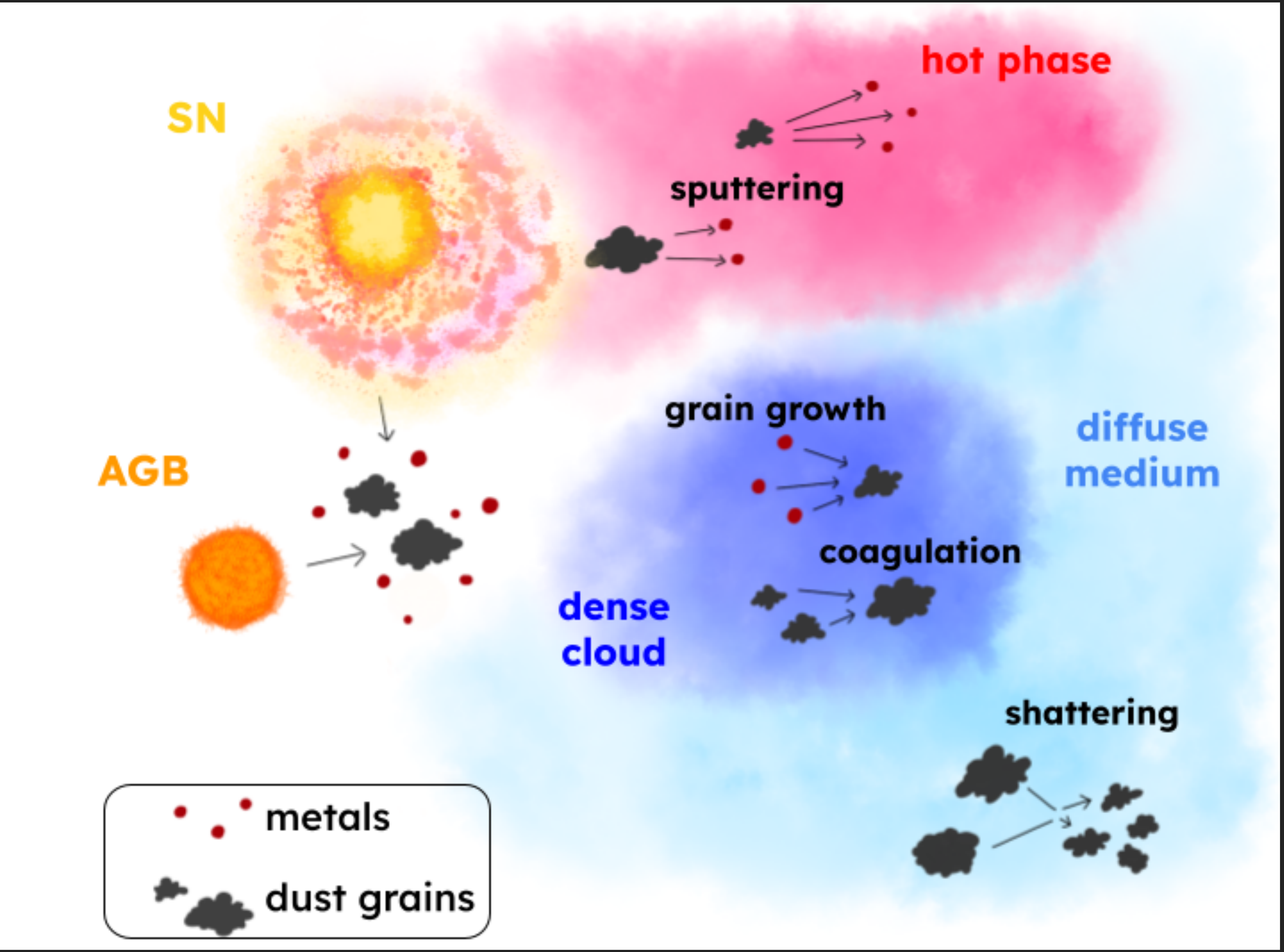
- Pretty Slow.
- The most technically challenging out of the four methods
- Not obvious how to simulate statistics

Codes/Campaigns

- FIRE
- Arepo/Smuggle
- CHANGA

PART 2: HOW DO WE SIMULATE DUST?

What do we care about (for dust)

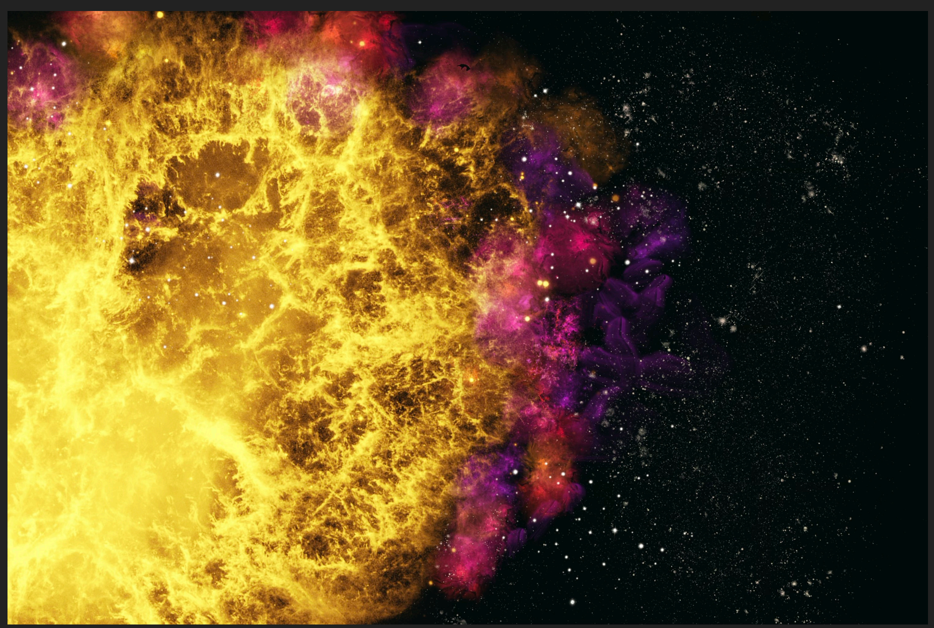


Parente, 2025

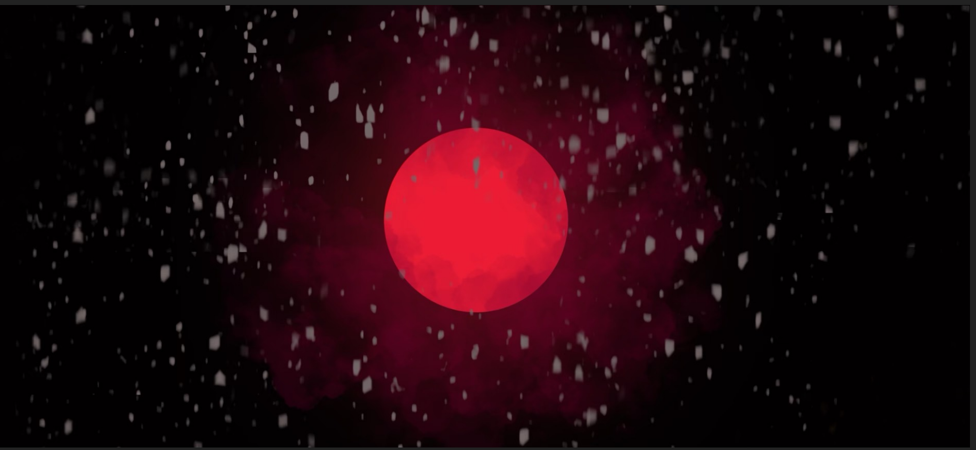
PART 2: HOW DO WE SIMULATE DUST?

Dust Formation: Composition, Condensation Efficiencies, Size Distribution

SNe Dust Formation



AGB Dust Formation



C>O

$$m_{i,d}^{AGB} = \begin{cases} \delta_C^{AGB}(m_{C,ej}^{AGB} - 0.75 m_{O,ej}^{AGB}), & i = C \\ 0, & \text{otherwise,} \end{cases}$$

C<O

$$m_{i,d}^{AGB} = \begin{cases} 0, & i = C \\ 16 \sum_{i=Mg,Si,S,Ca,Fe} \delta_i^{AGB} m_{i,ej}^{AGB}, & i = O \\ \delta_i^{AGB} m_{i,ej}^{AGB}, & \text{otherwise,} \end{cases}$$

Dwek 1998

Uncertain Values:

$\delta_{\mathrm{SNII,AGB}}$

0.15 ⟷ 1

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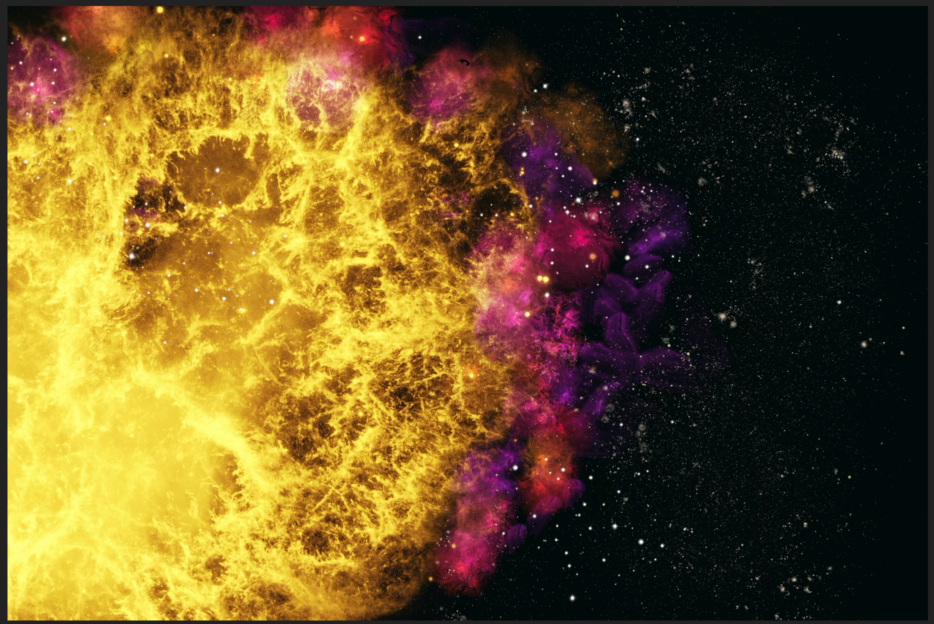
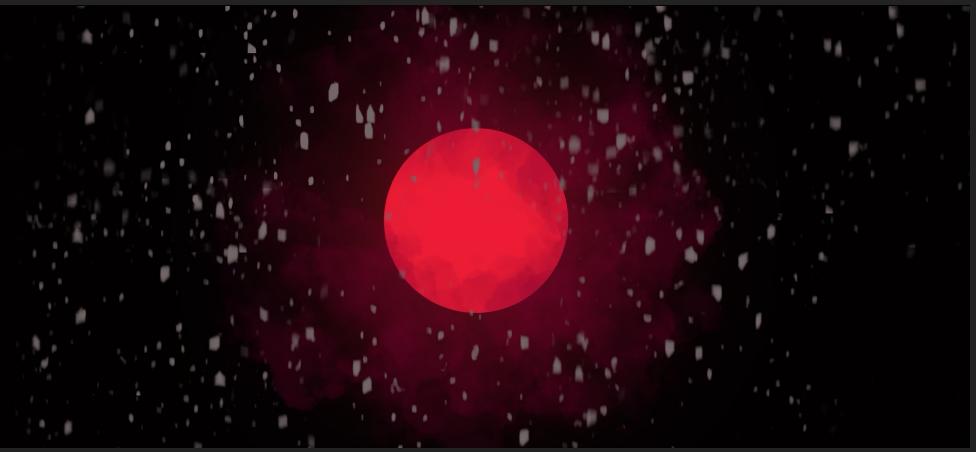
SNe Dust Formation



AGB Dust Formation



C>O

$$m_{i,d}^{AGB} = \begin{cases} \delta_C^{AGB}(m_{C,ej}^{AGB} - 0.75 m_{O,ej}^{AGB}), & i = C \\ 0, & \text{otherwise}, \end{cases}$$

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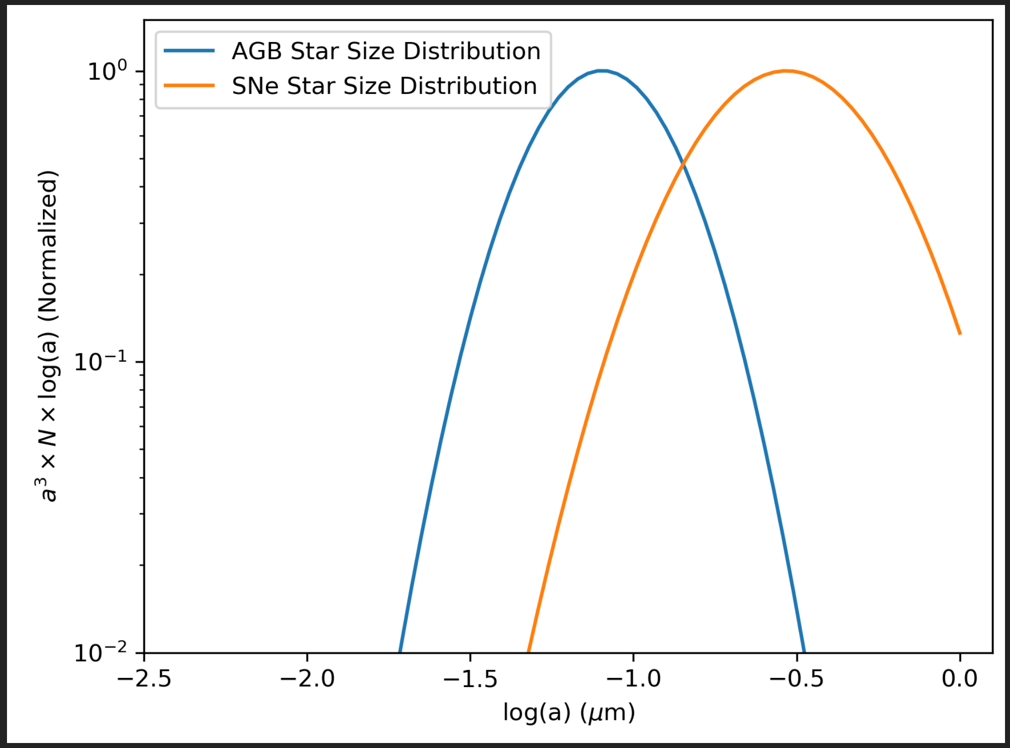
Uncertain Values:

$$\frac{\partial n}{\partial a} = \frac{C}{a^P} \exp\left(-\frac{\ln^2(\mathrm{a}/\mathrm{a}_0)}{2\sigma^2}\right)$$

Initial Size Distribution

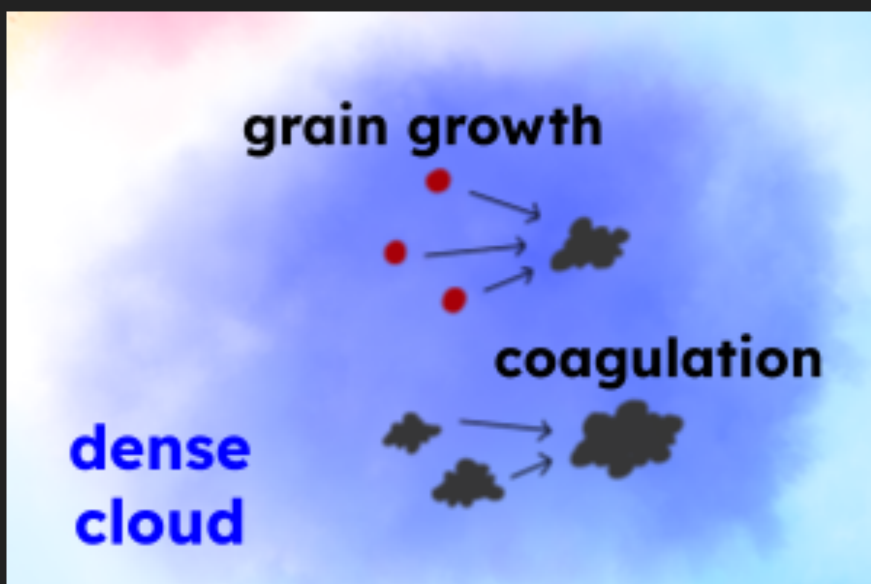


PART 2: HOW DO WE SIMULATE DUST?

Dust Growth: Timescale Dependencies, Clumping, Abundance Limitations, & Coulomb Enhancement

$$\frac{dM}{dt} \propto \frac{M}{\tau_{\rm accr}} \qquad \tau_{accr} = \tau_{ref}\left(\frac{a}{a_{ref}}\right)\left(\frac{\rho_{ref}}{\rho_g}\right)\left(\frac{T_{ref}}{T_g}\right)^{1/2}\left(\frac{Z_{ref}}{Z_g}\right)\left(\frac{S_{ref}}{S}\right).$$

Dwek 1998



Uncertainties: τ_{ref}

1 Myr ⟷ 100 Myr

McKinnon+2017, Popping+2018

- Clumping Factors [effectively, impact reference values]
- Temperature dependent sticking factors (Zhukovska et al. 2014)
- Size dependence

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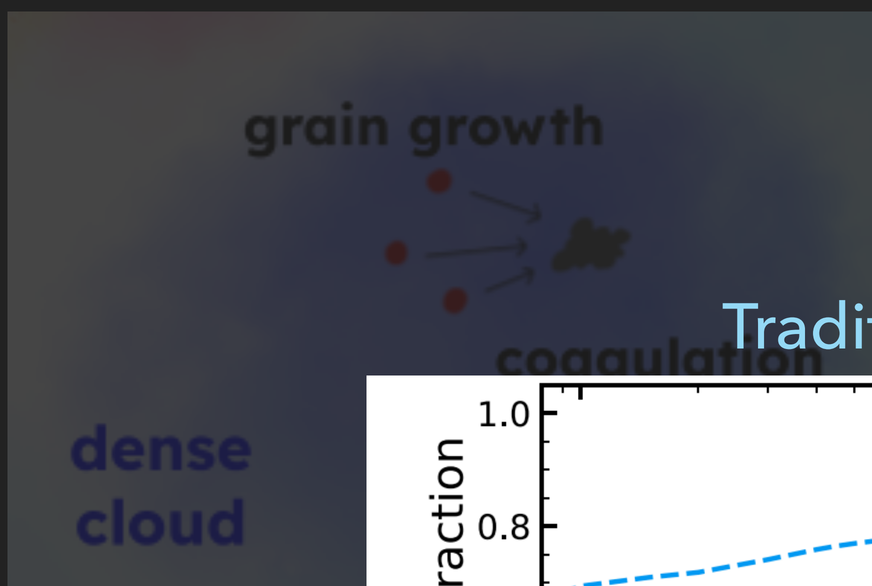
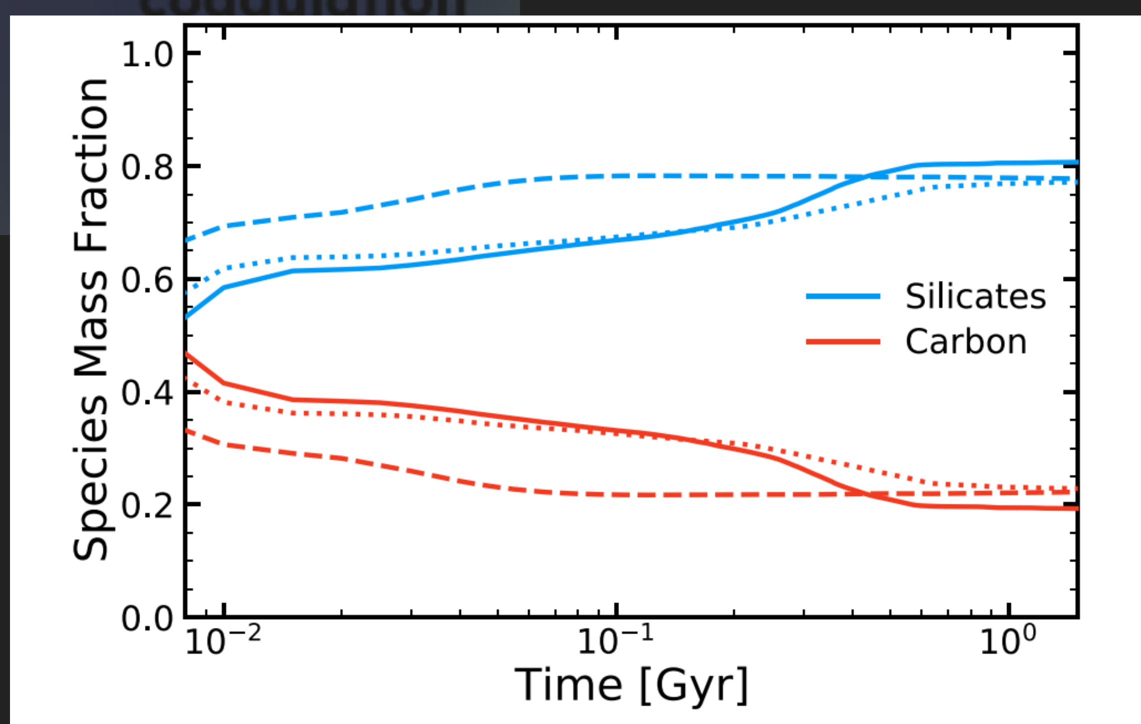
Dwek 1998

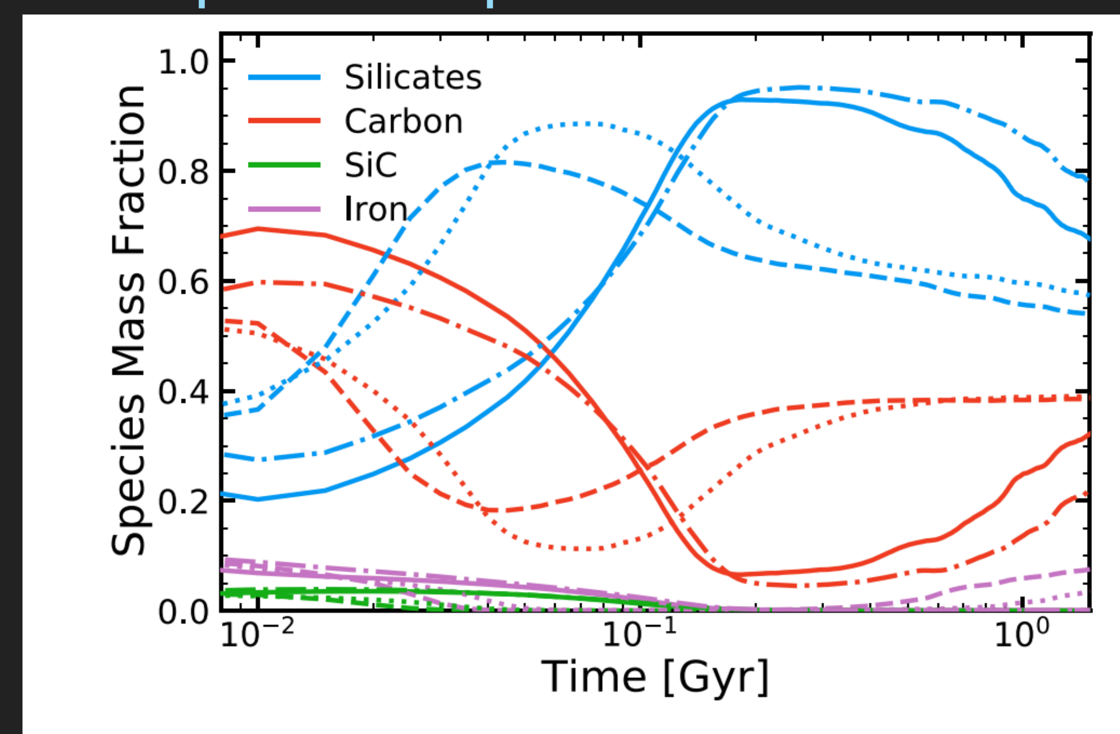


Uncertainties: Species-dependent accretion rates

Traditional Accretion



Species-dependent rate limiters



Choban et al. 2022

PART 2: HOW DO WE SIMULATE DUST?

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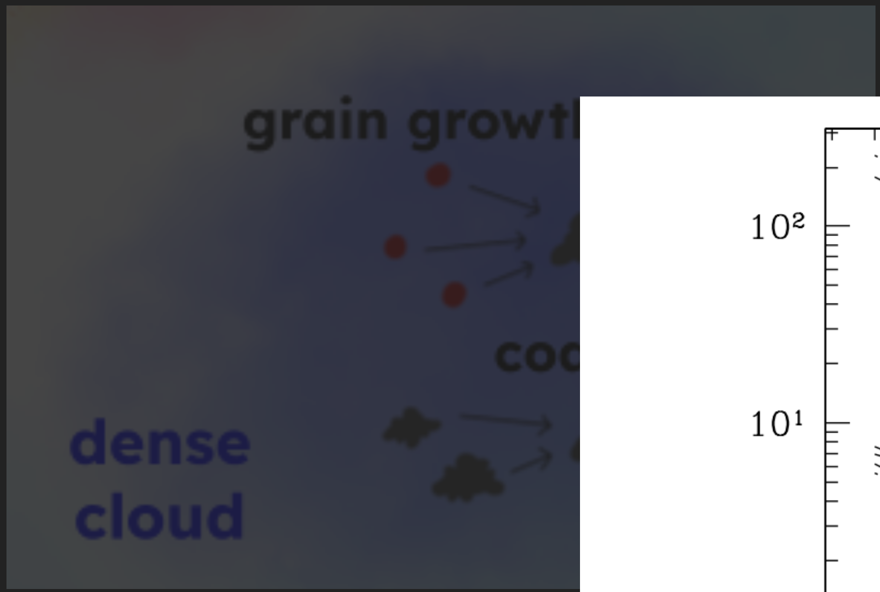
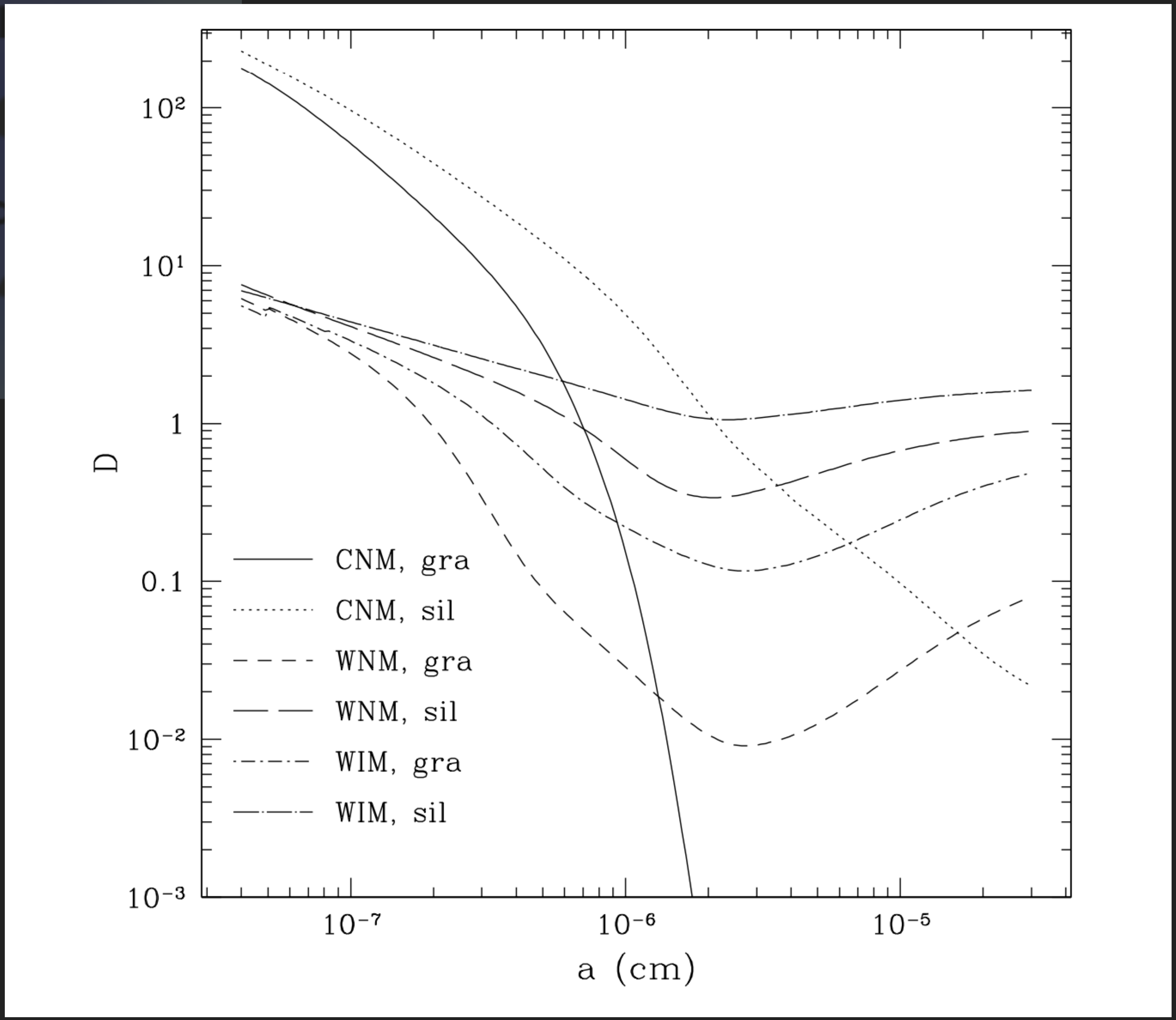
Coulomb-Enhancement of Charged Grains

Dwek 1998





Weingartner & Draine 1999

PART 2: HOW DO WE SIMULATE DUST?

Dust Shattering and Coagulation

v<vthresh

v>vthresh

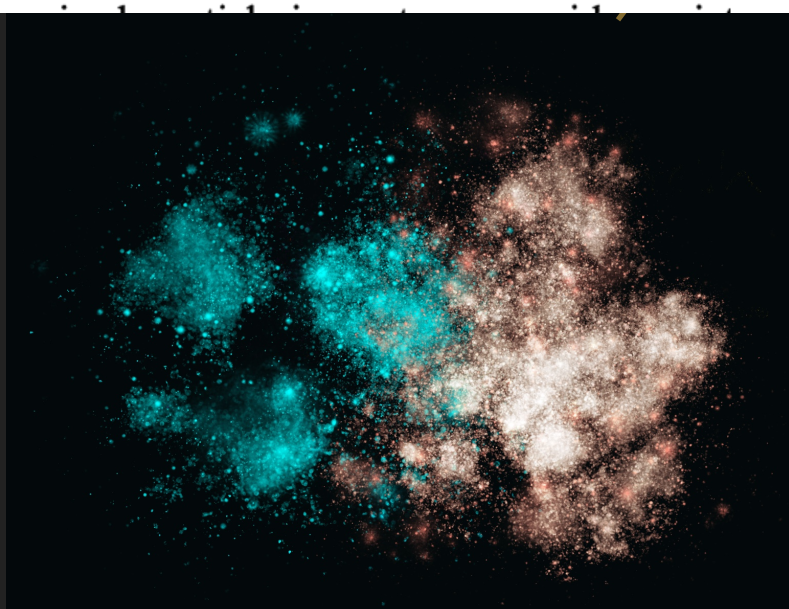
GRAIN SHATTERING IN SHOCKS: THE INTERSTELLAR GRAIN SIZE DISTRIBUTION

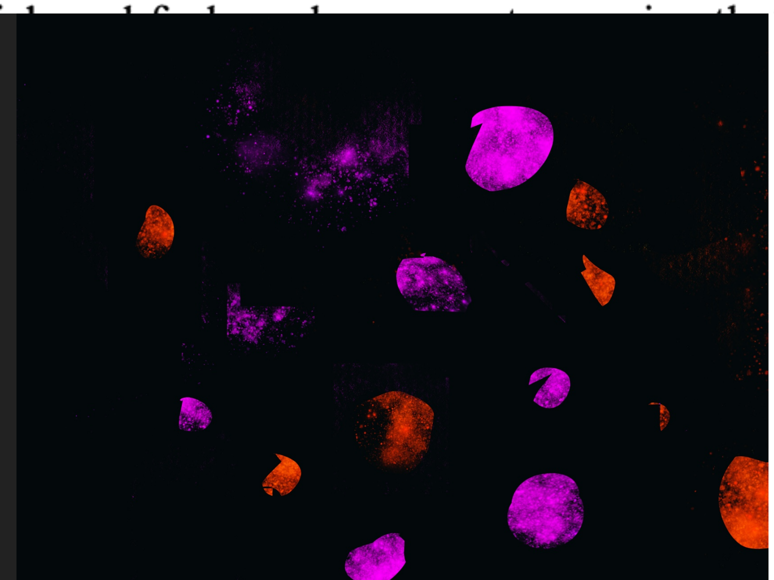
A. P. JONES,[1,2] A. G. G. M. TIELENS,[2] AND D. J. HOLLENBACH[2]

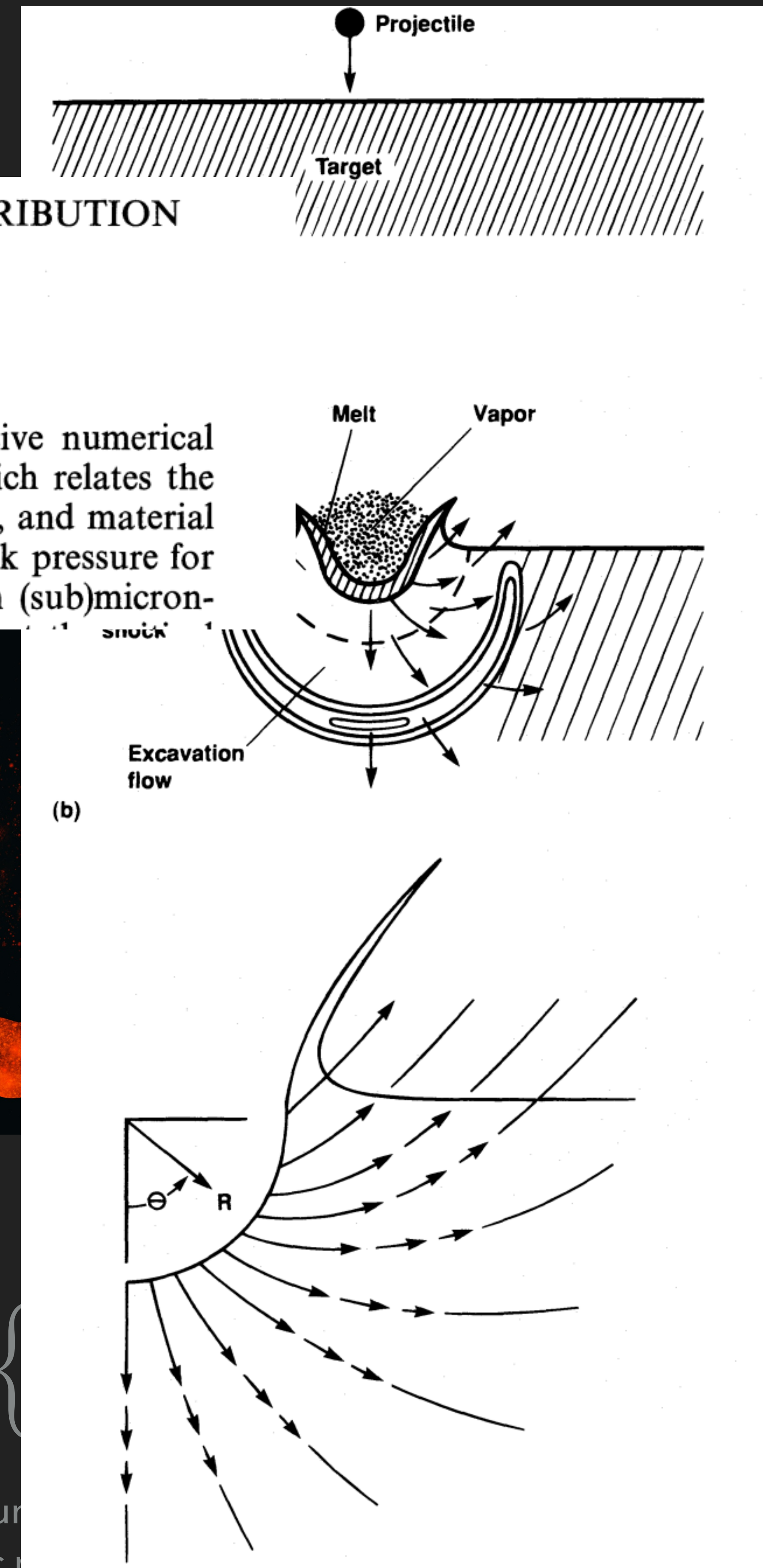
Received 1996 January 12; accepted 1996 April 10

ABSTRACT

We have studied the effects of shattering in grain-grain collisions. Based upon extensive numerical simulation of surface explosions and impacts, an analytical model has been developed which relates the final crater mass and fragment size distribution to the relative collision velocity, grain sizes, and material properties of projectile and target. Our model contains one free parameter, the critical shock pressure for shattering. We have compared the calculated crater masses to laboratory experiments on (sub)micron-







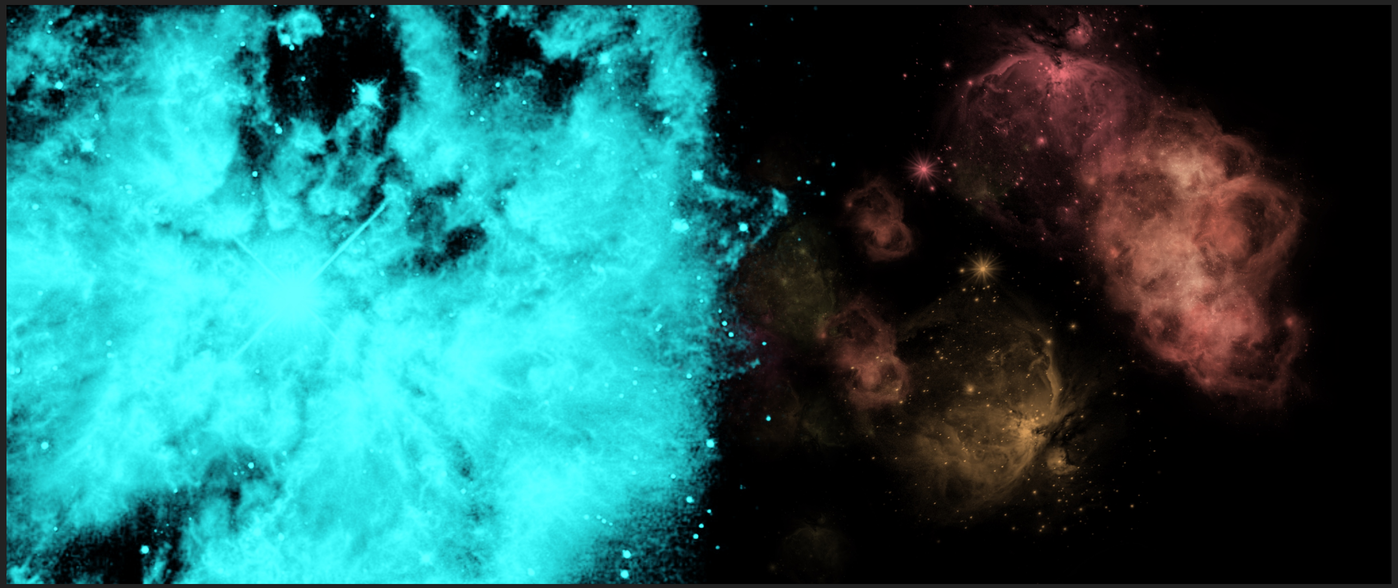
$v_{\rm thresh} = \{$

Based on nu

and analytic

PART 2: HOW DO WE SIMULATE DUST?

Dust Destruction in SNe Shocks



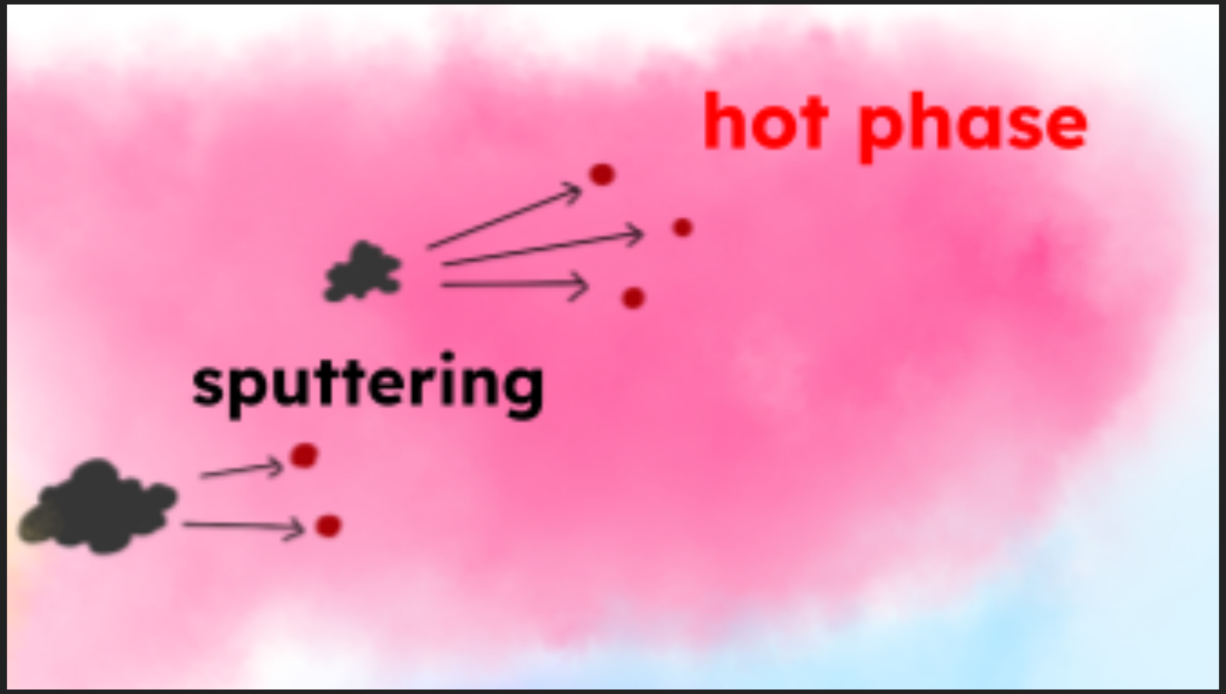
$$\tau_{des,SN} \propto \frac{1}{R_{SN}\dot{M}_{sw}\epsilon},$$

ϵ

0.1 SNe destruction Efficiency 0.5

McKee 1989

Thermal Sputtering



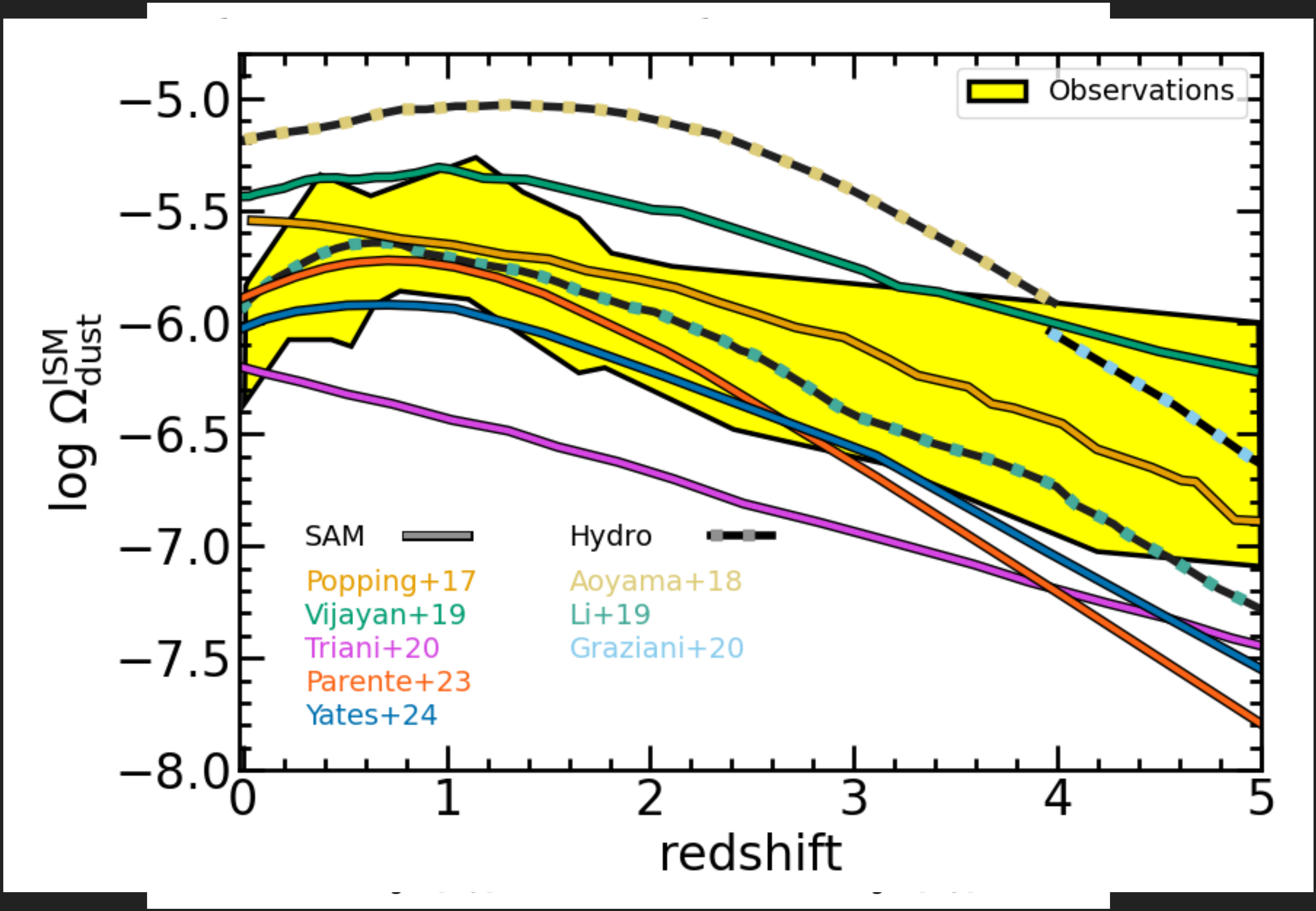
Parente, 2025

$$\tau_{d,SN} = 6.8 \times 10^3 \left(\frac{M_h}{10^6 M_\odot}\right)\left(\frac{1}{R_{SN}}\right),$$

$$\tau_{d,PISN} = 36.3 \left(\frac{M_h}{10^6 M_\odot}\right)\left(\frac{1}{R_{PISN}}\right).$$

Graziani et al. 2020

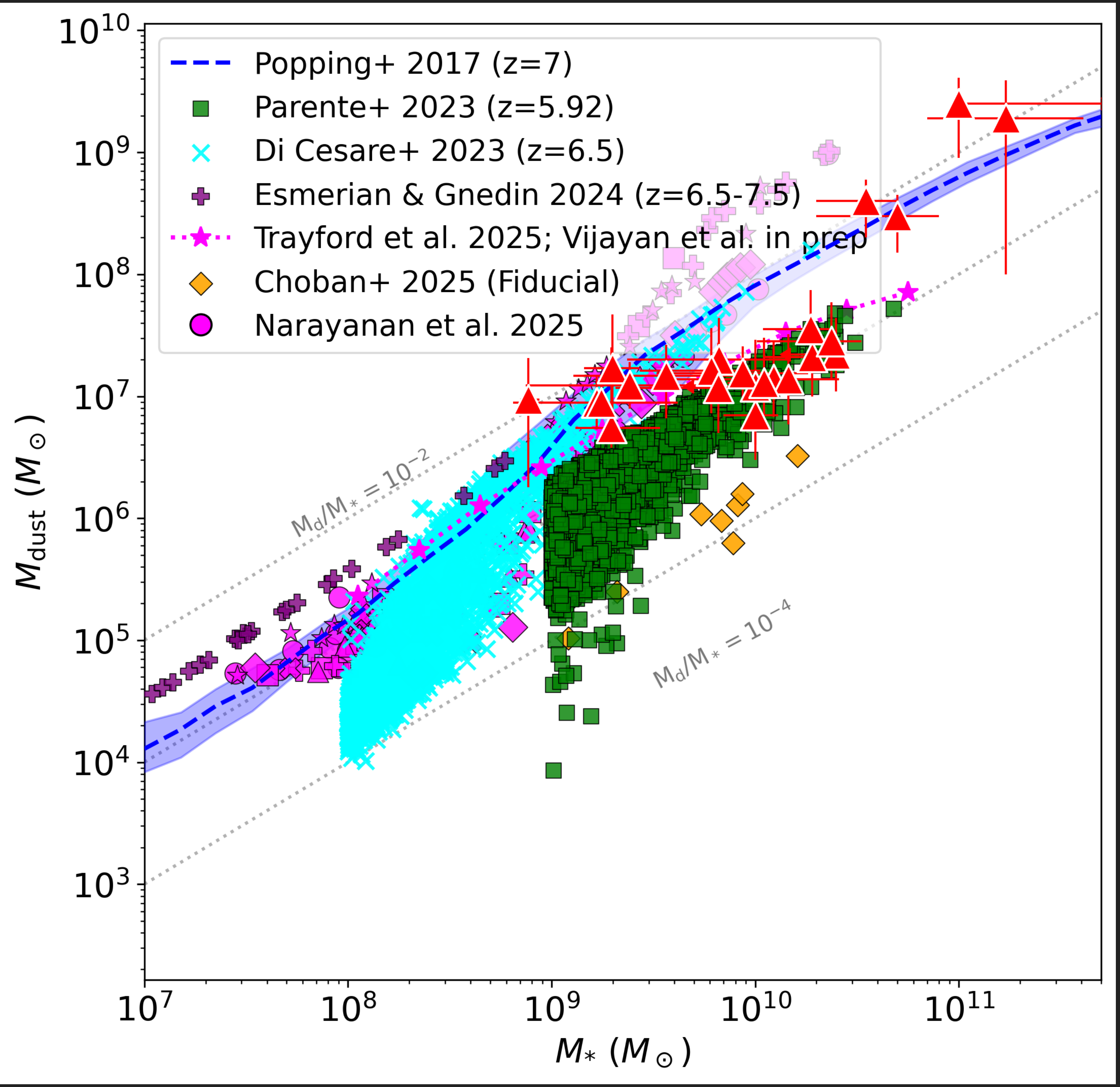
PART 3: SUCCESSES AND CHALLENGES



Parente, 2025

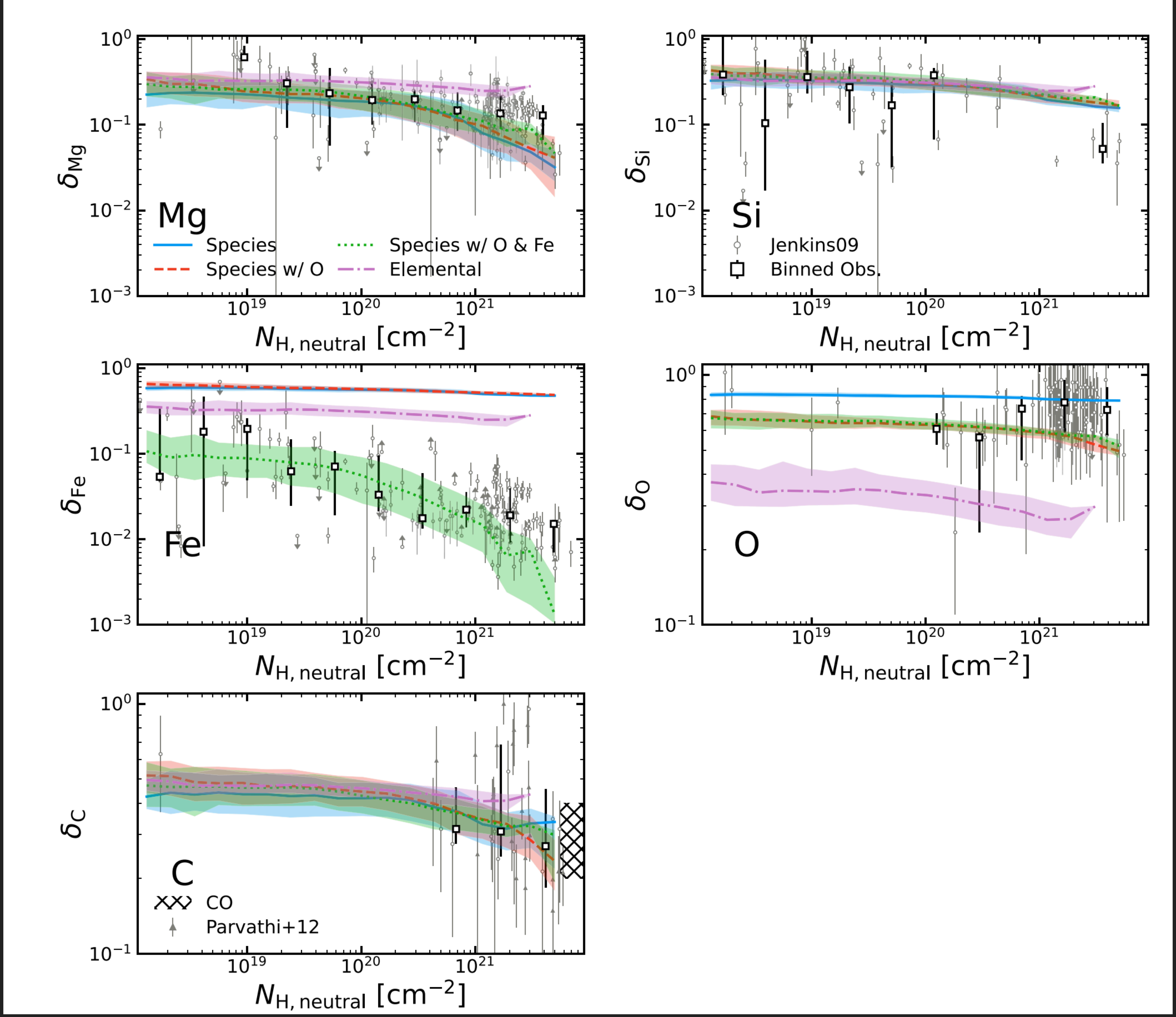
PART 3: SUCCESSES AND CHALLENGES

z~6-7



No citation - just made for this talk

PART 3: SUCCESSES AND CHALLENGES



Choban et al. 2022

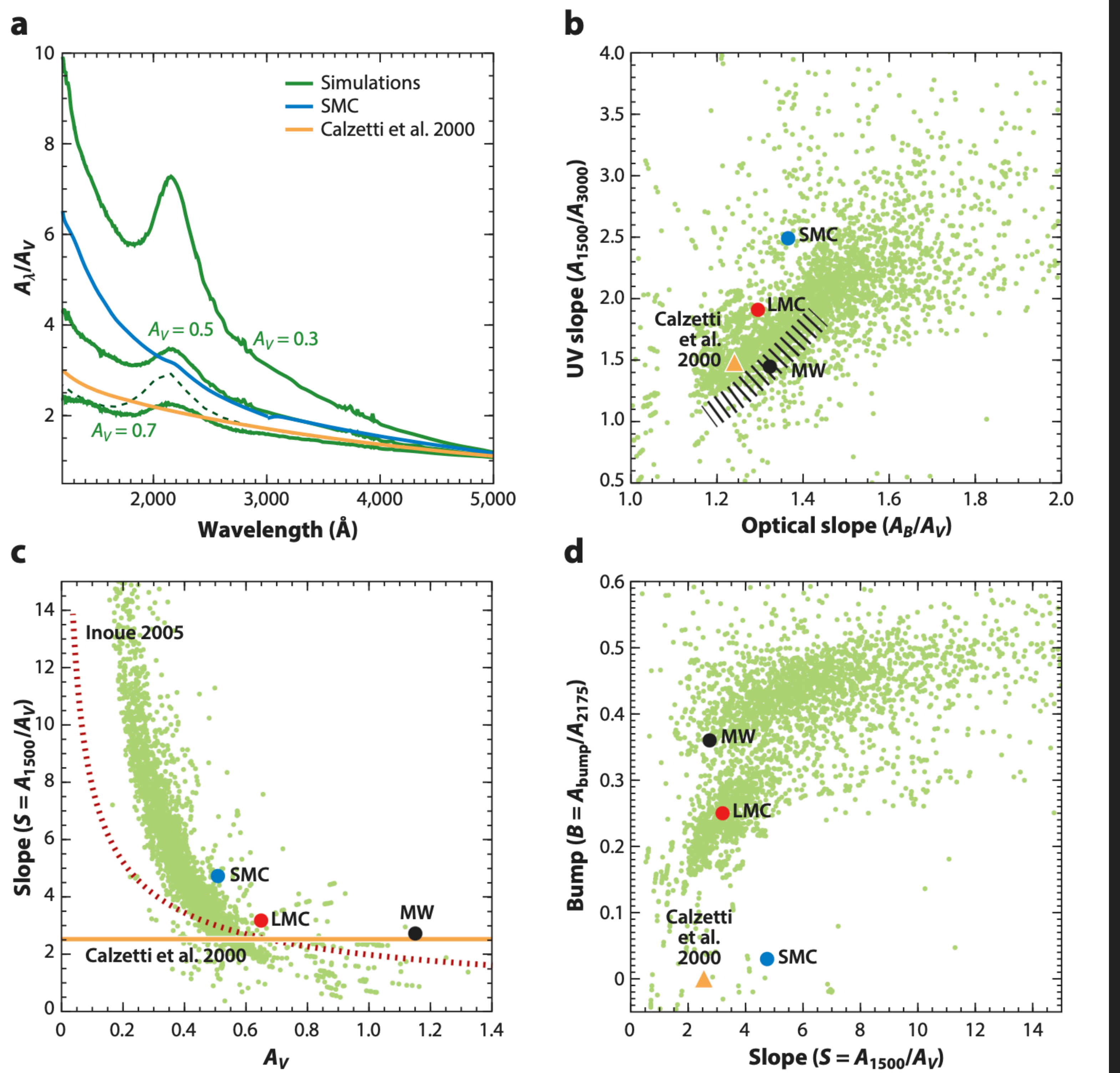
see also Trayford et al. 2025

PART 3: SUCCESSES AND CHALLENGES

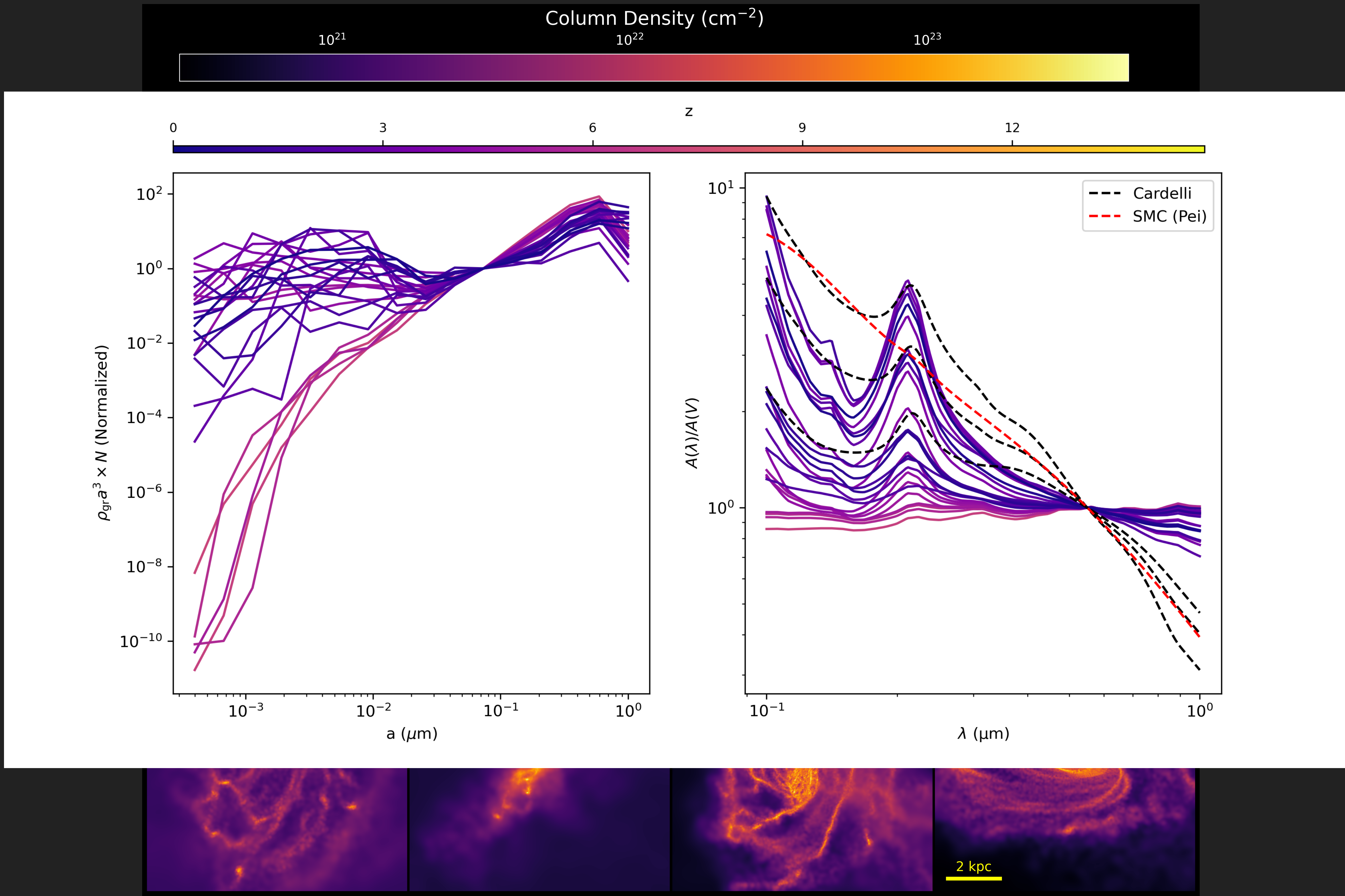
Annual Review of Astronomy and Astrophysics

The Dust Attenuation Law in Galaxies

Samir Salim[1] and Desika Narayanan[2,3]

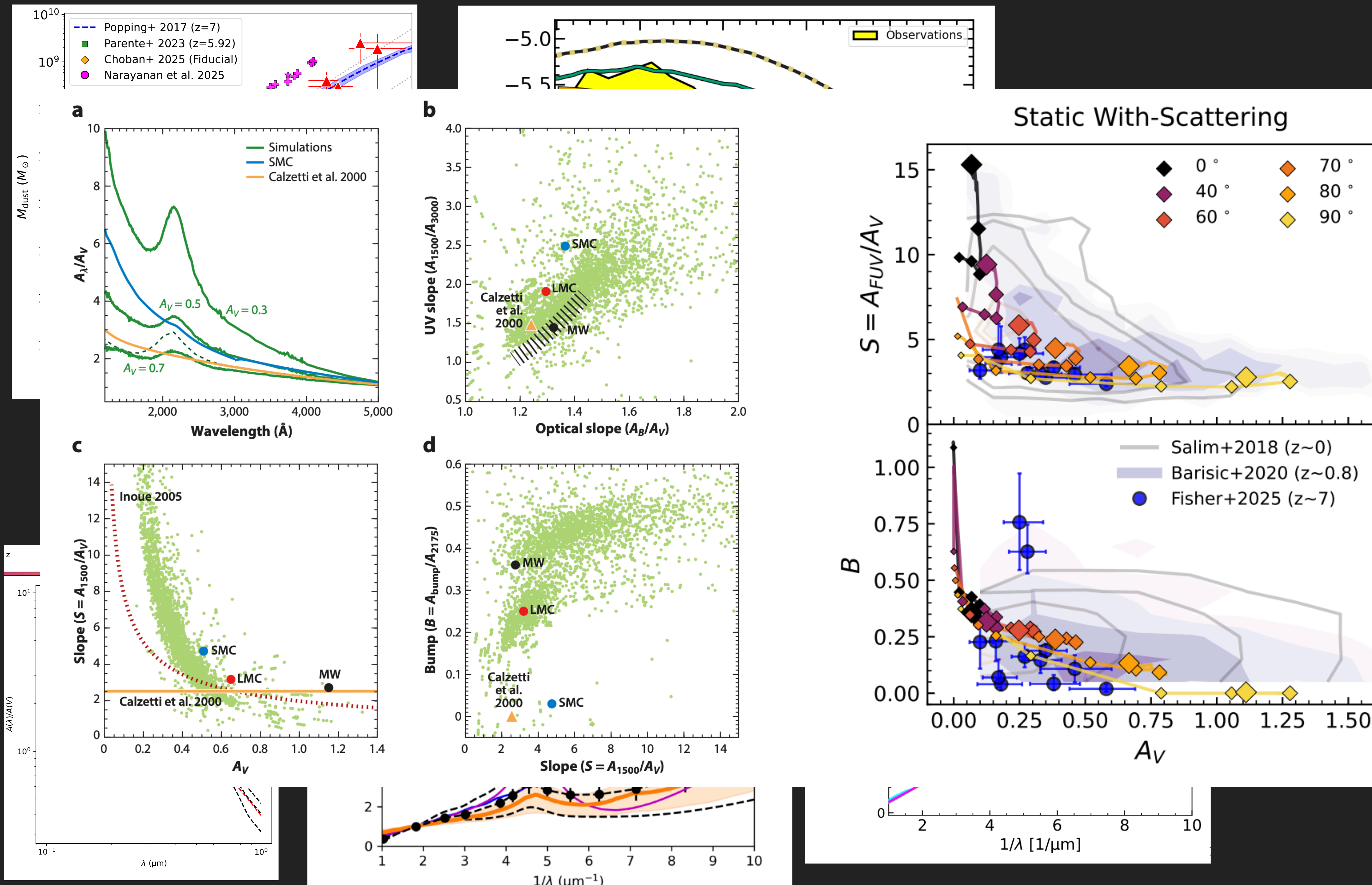


PART 3: SUCCESSES AND CHALLENGES



Q. Li, Narayanan, Torrey & Dave 2020
Matsumoto et al. 2025

PART 4: WAYS FORWARD [AKA WHY DO THINGS WORK AT ALL?]

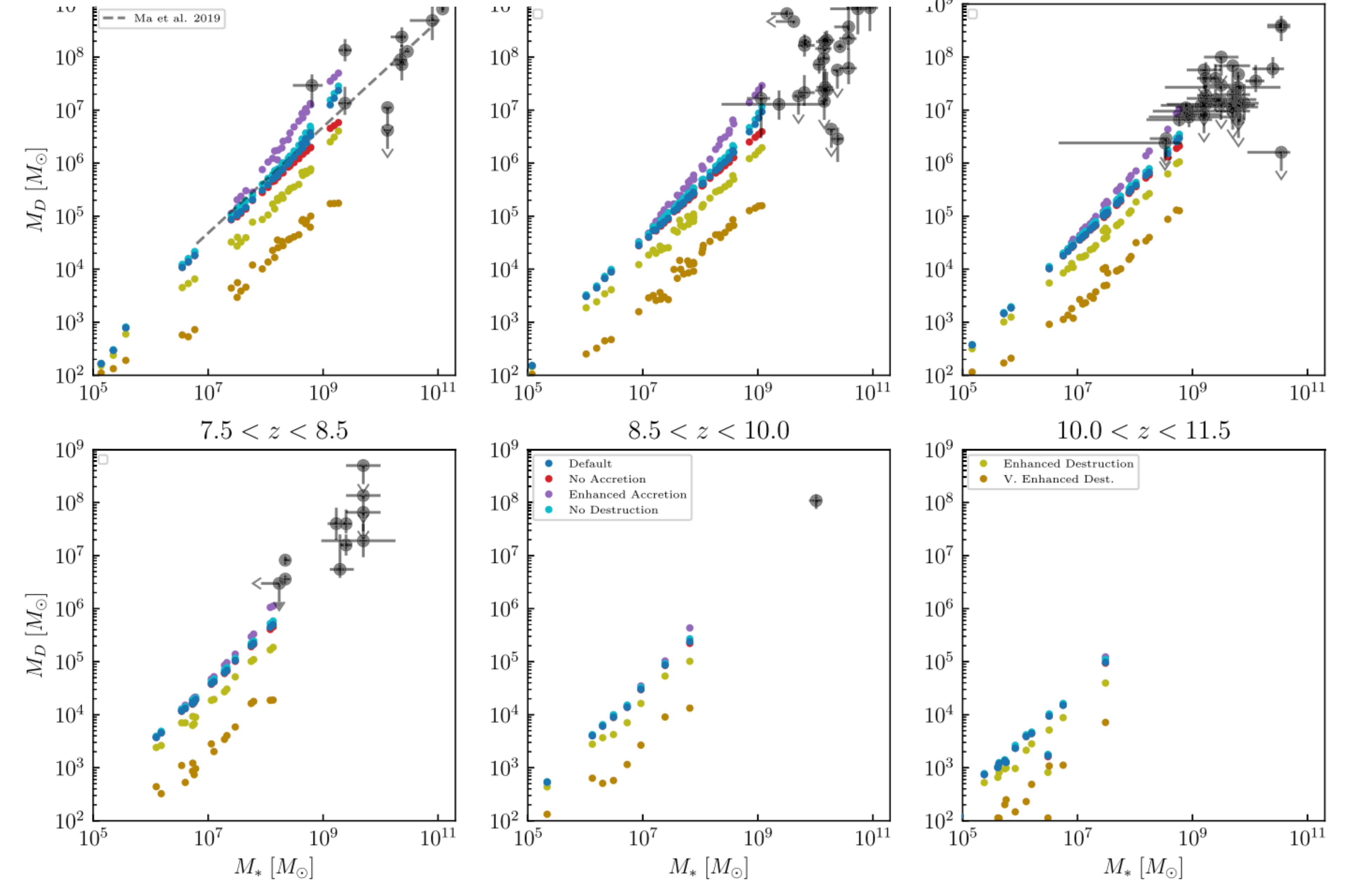


Li et al. 2020

Matsumoto et al. 2025

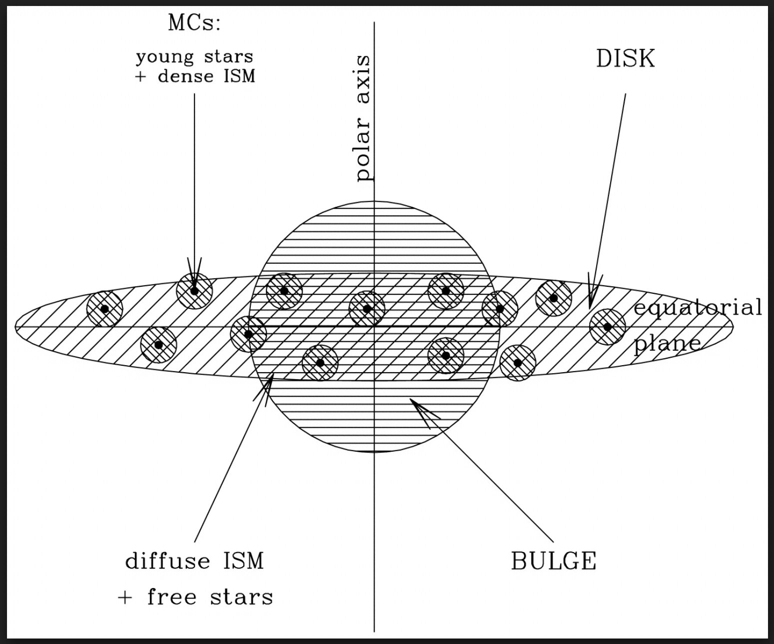
PART 4: WAYS FORWARD [AKA WHY DO THINGS WORK AT ALL?]

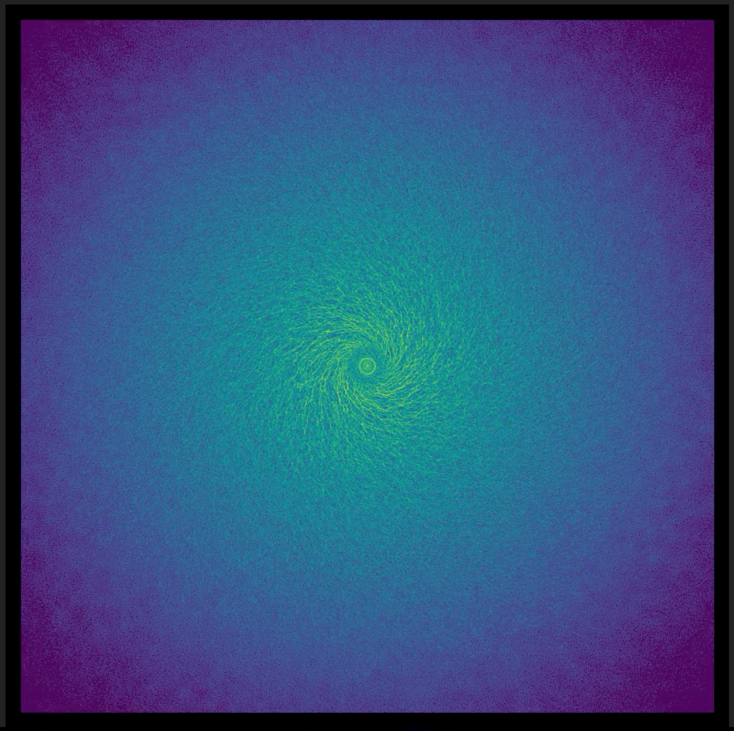
Model Name	Key Parameters	Description	Color in Figures
Default	$y_{D,\mathrm{SN}} = y_{D,\mathrm{AGB}} = 0.1$, $\tau_{\mathrm{accr}} = 3 \times 10^8\mathrm{yr}$, $C_{\mathrm{dest}} = 1$	Default from Esmerian & Gnedin (2022), parameters based on Dwek (1998); Feldmann (2015).	blue
No Accretion	$\tau_{\mathrm{accr}} = \infty$	No grain growth due to gas-phase accretion in cold ISM	red
Enhanced Accretion	$\tau_{\mathrm{accr}} = 0.1\tau_{\mathrm{accr,Default}}$	Enhanced grain growth due to gas-phase accretion in cold ISM	purple
No Destruction	$C_{\mathrm{dest}} = 0$	No grain destruction in hot gas due to SNRs	cyan
Enhanced Destruction	$C_{\mathrm{dest}} = 10C_{\mathrm{dest,Default}}$	Enhanced grain destruction in hot gas due to SNRs	yellow-green
Very Enhanced Destruction	$C_{\mathrm{dest}} = 100C_{\mathrm{dest,Default}}$	Very enhanced grain destruction in hot gas due to SNRs	dark yellow
Low SN Production	$y_{D,\mathrm{SN}} = 0.1y_{D,\mathrm{SN,Default}}$	Suppressed dust yield from SN	orange
No SN Production	$y_{D,\mathrm{SN}} = 0$	SN do not produce dust	magenta
Very Low SN Production, No AGB Production	$y_{D,\mathrm{SN}} = 0.1y_{D,\mathrm{SN,Default}}$, $y_{D,\mathrm{AGB}} = 0$	Very suppressed dust yield from SN, AGB do not produce dust	brown

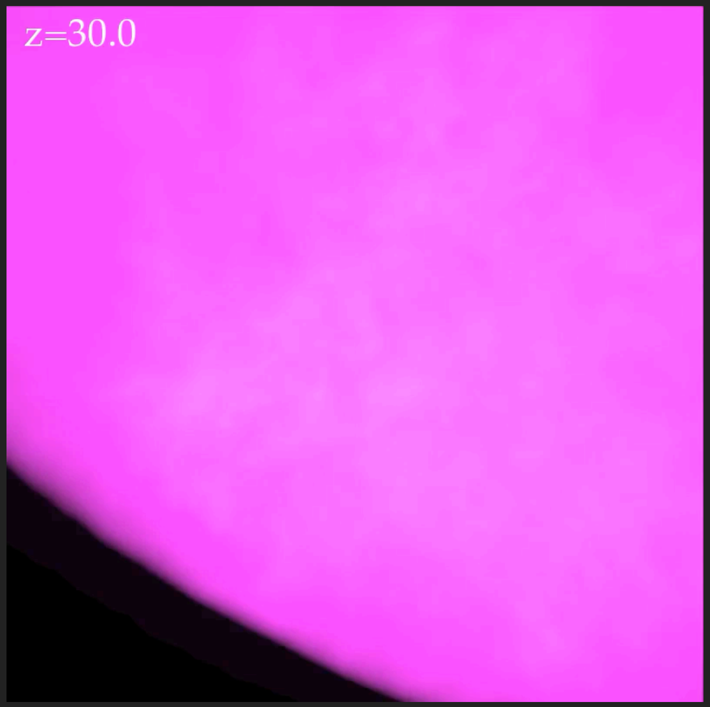


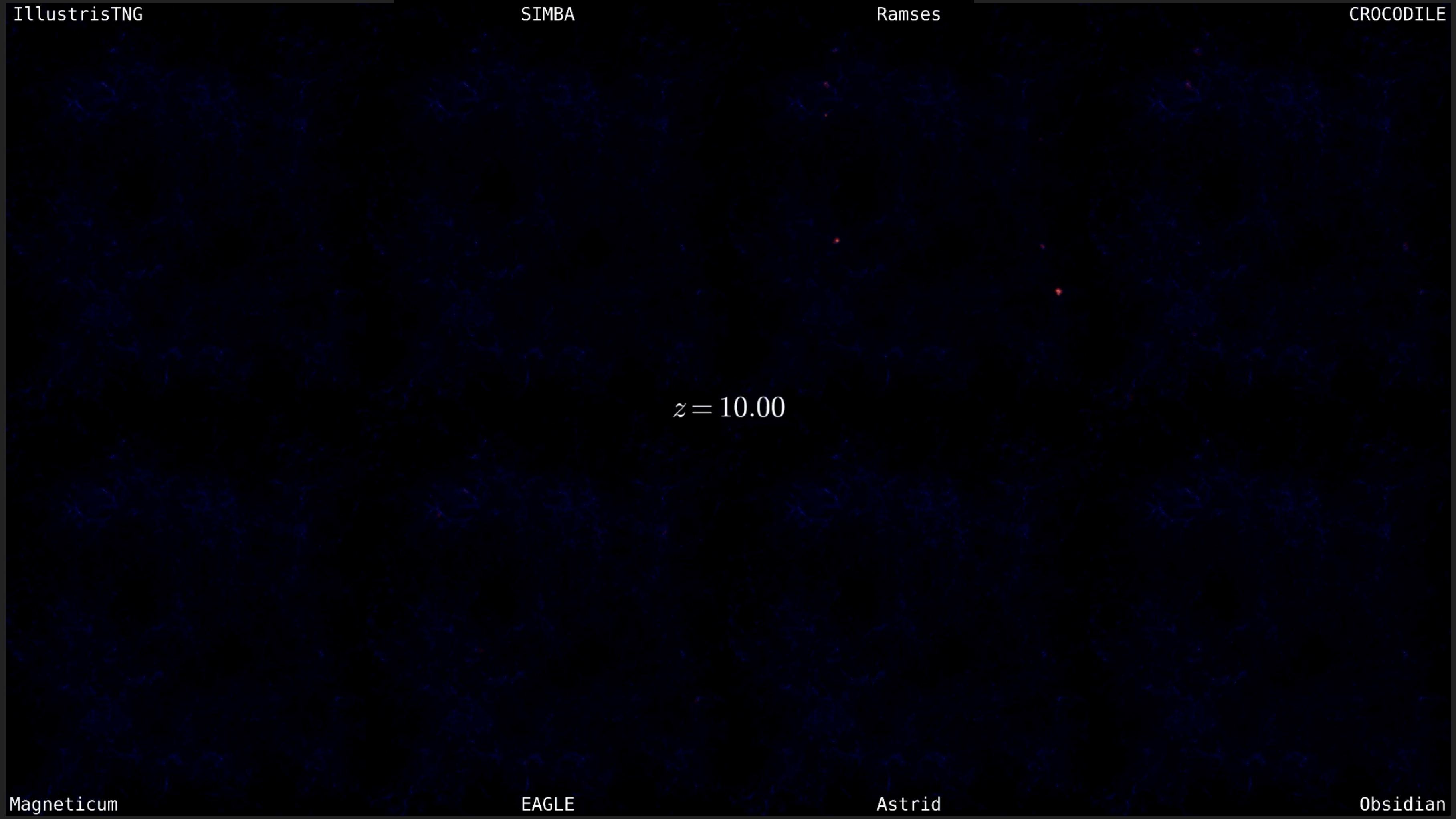
Esmerian & Gnedin 2024

GALAXY SIMULATIONS + DUST SHOULD BE THOUGHT OF AS NUMERICAL EXPERIMENTS, NOT FUNDAMENTAL THEORY



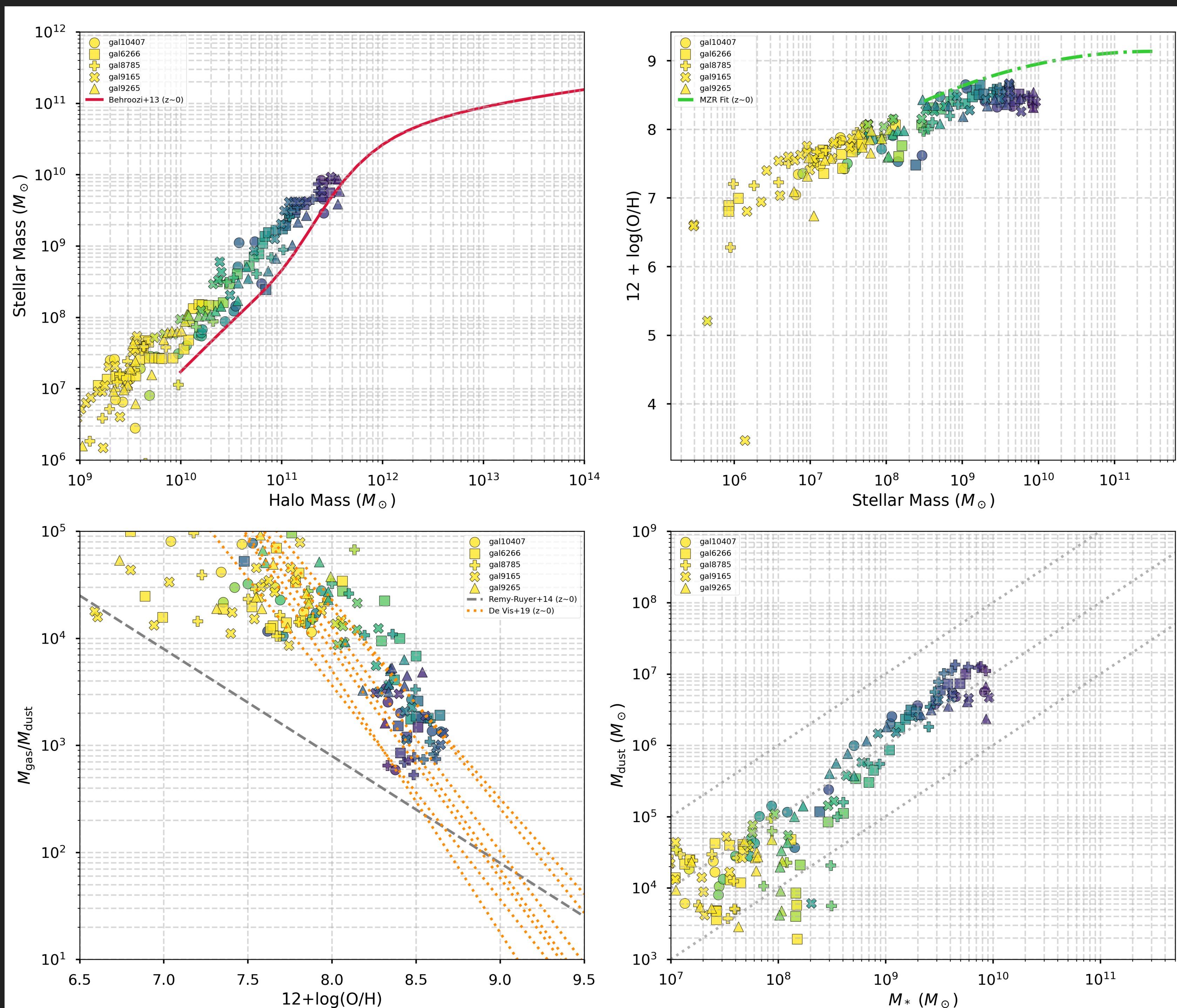


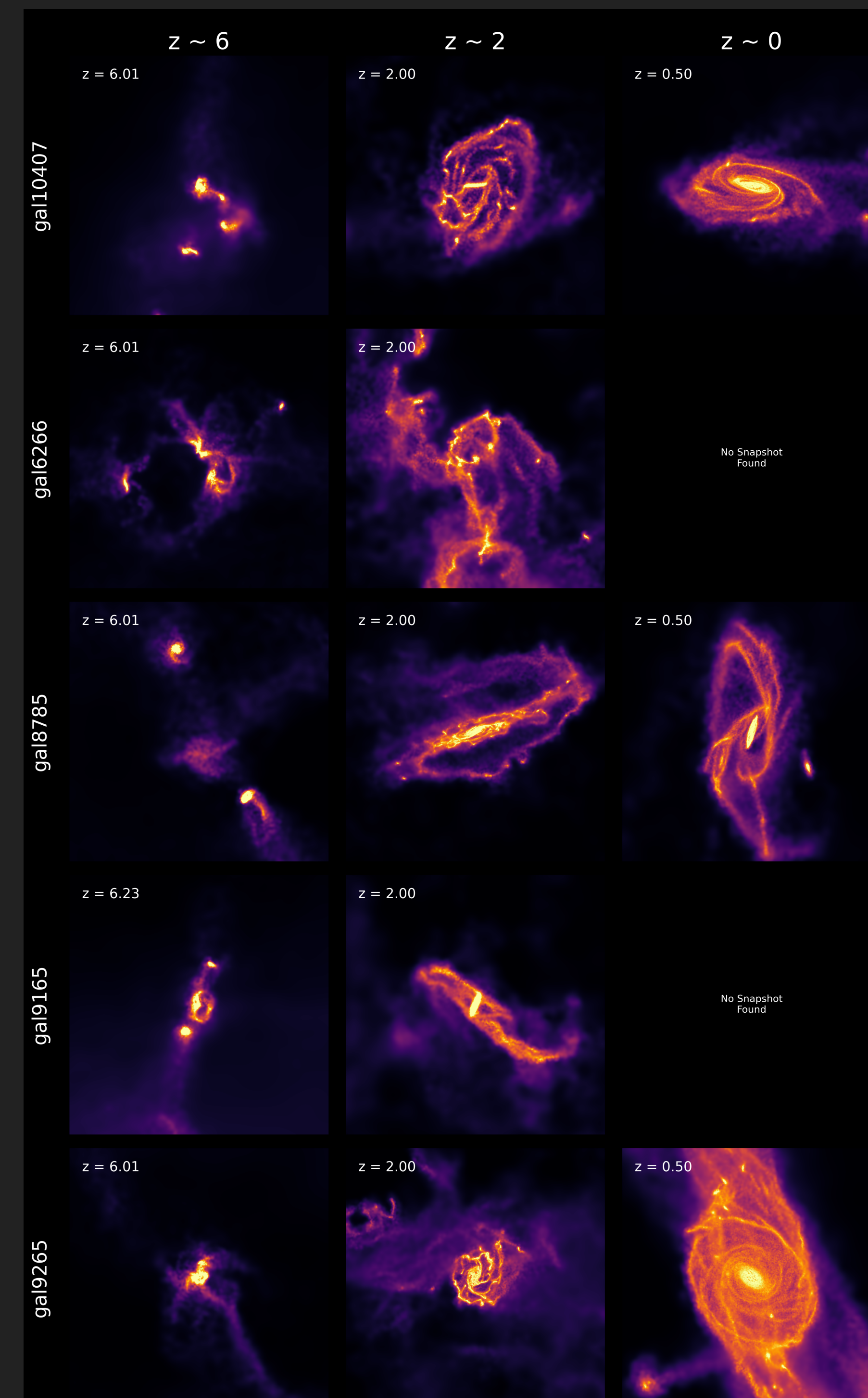




GALAXY SIMULATIONS + DUST SHOULD BE THOUGHT OF AS NUMERICAL EXPERIMENTS, NOT FUNDAMENTAL THEORY

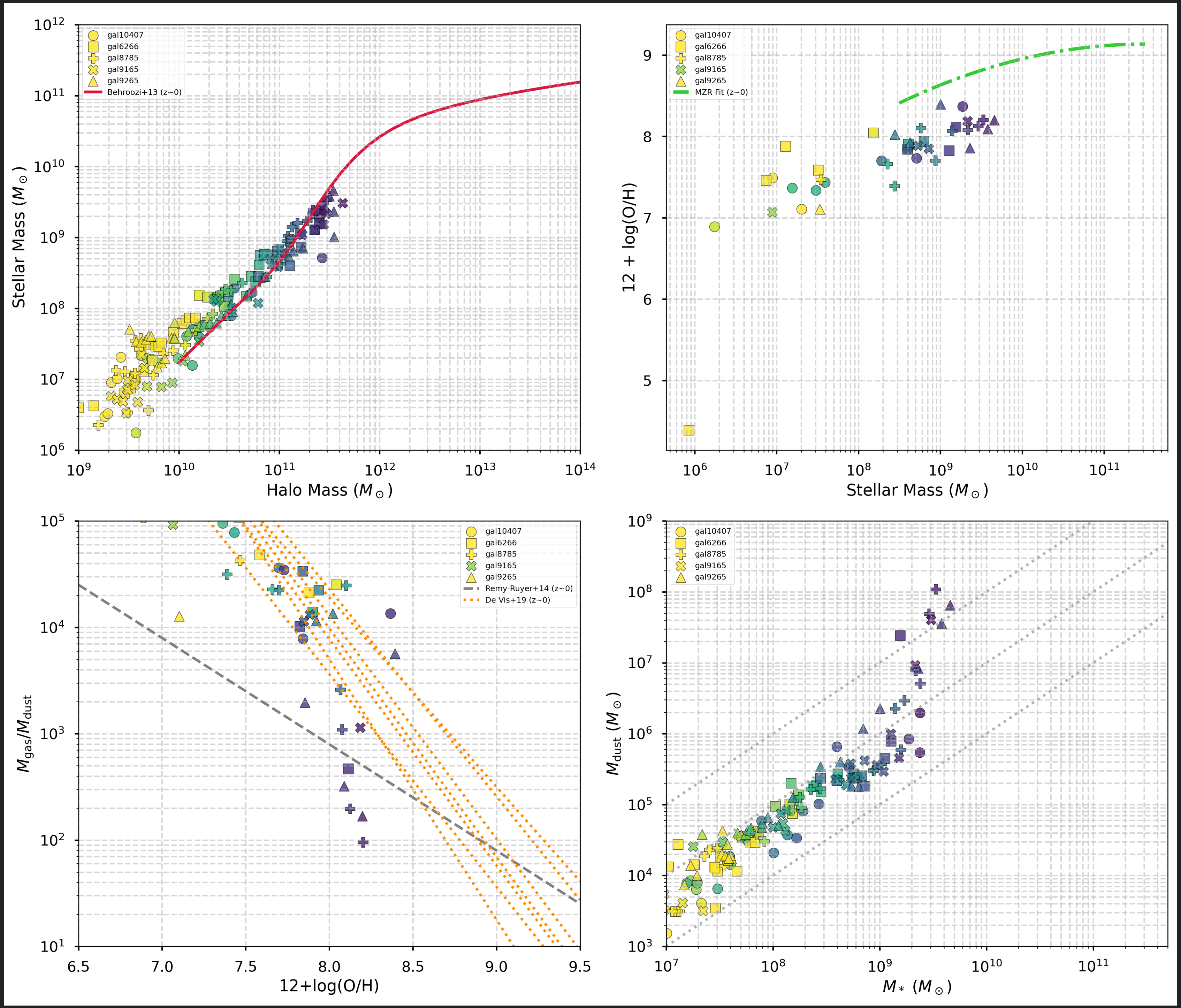
Parameter Set 44

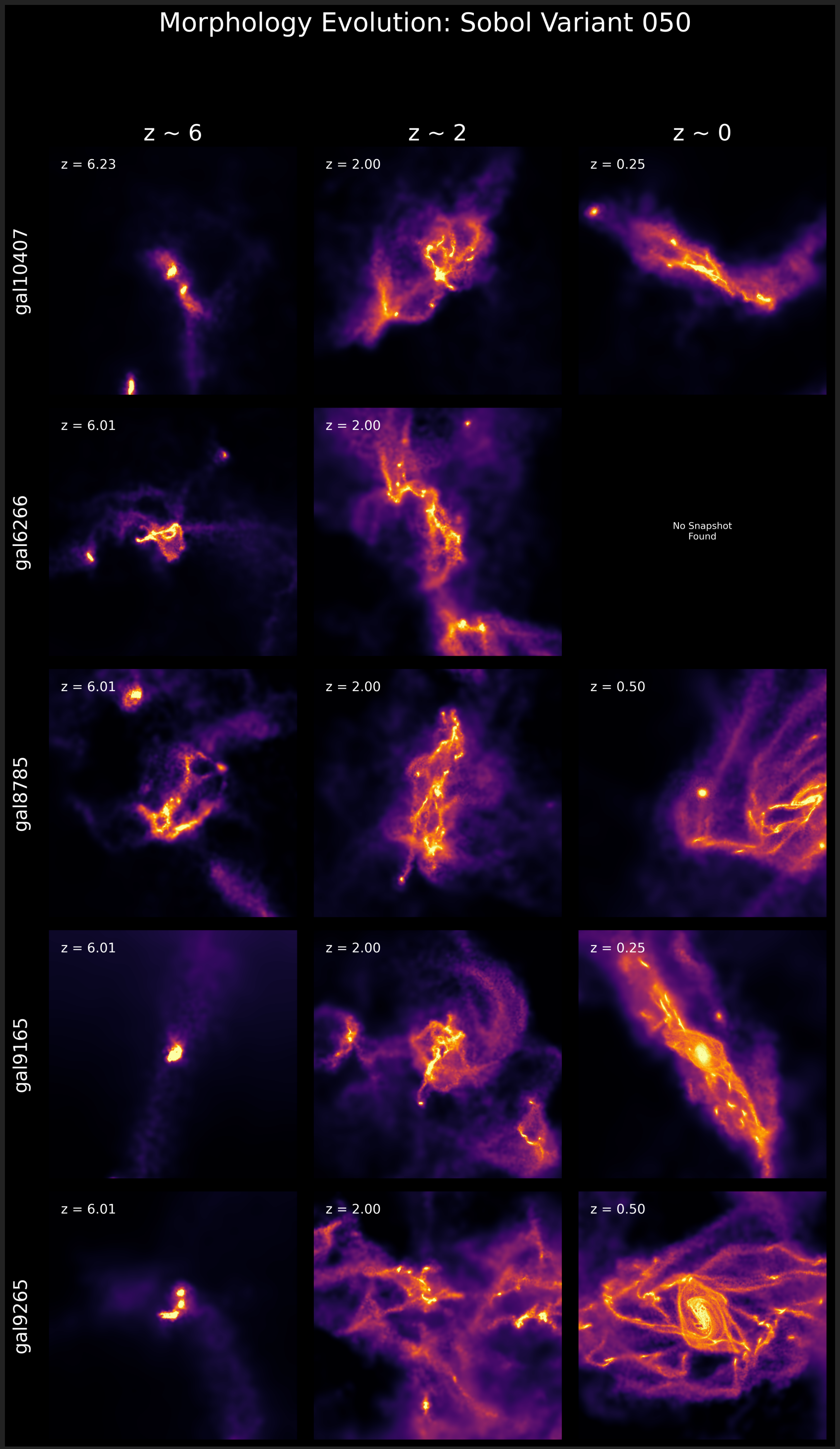




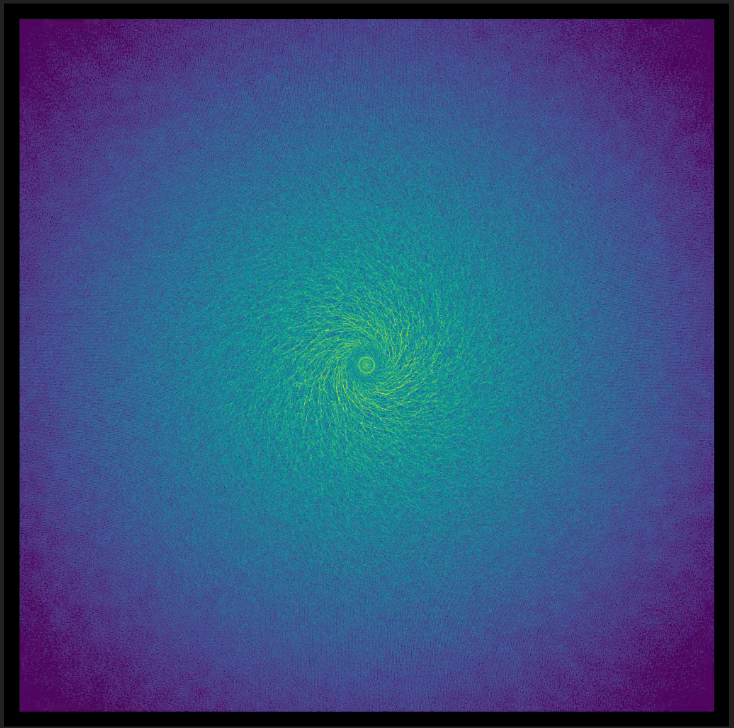
GALAXY SIMULATIONS + DUST SHOULD BE THOUGHT OF AS NUMERICAL EXPERIMENTS, NOT FUNDAMENTAL THEORY

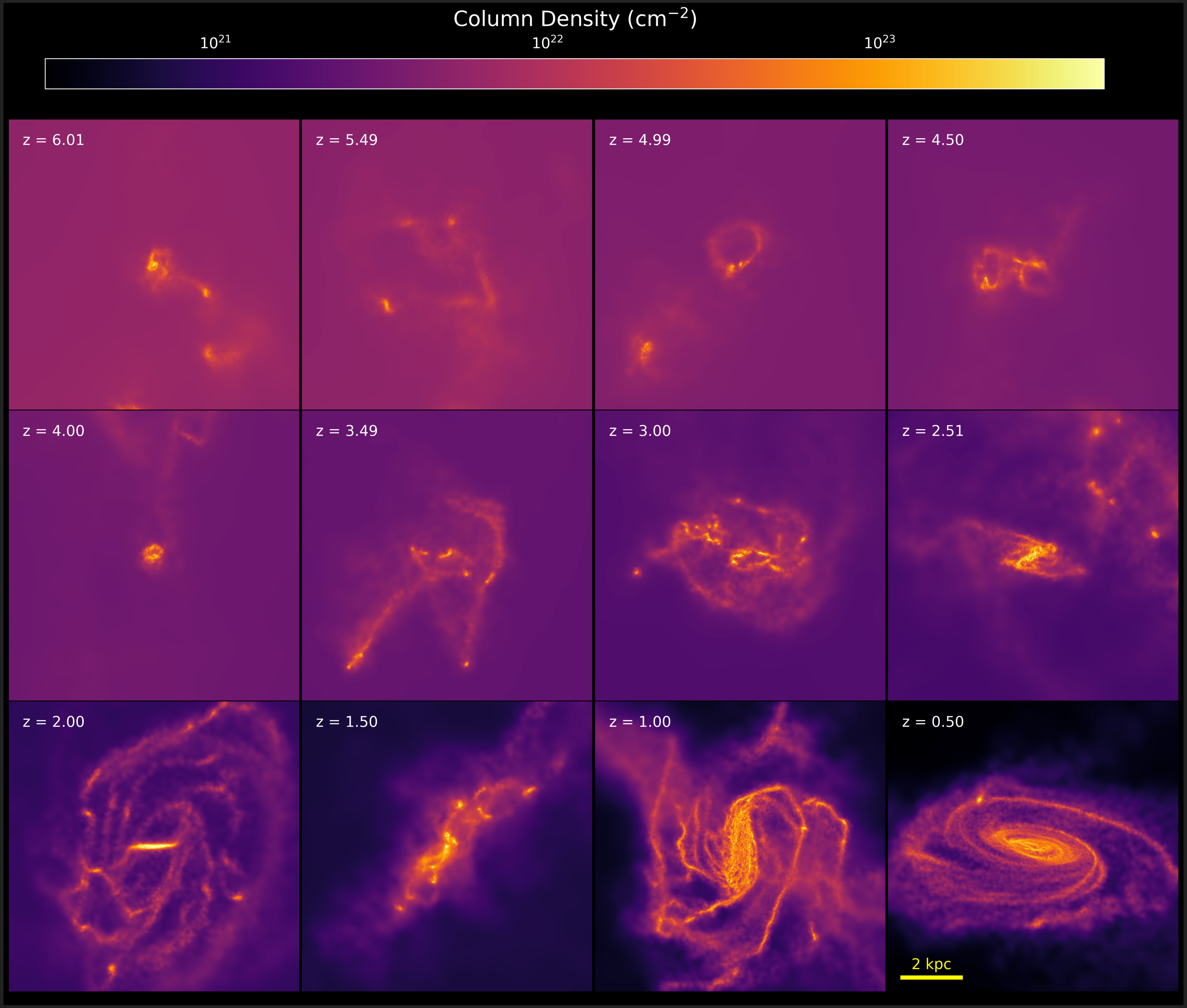
Parameter Set 50



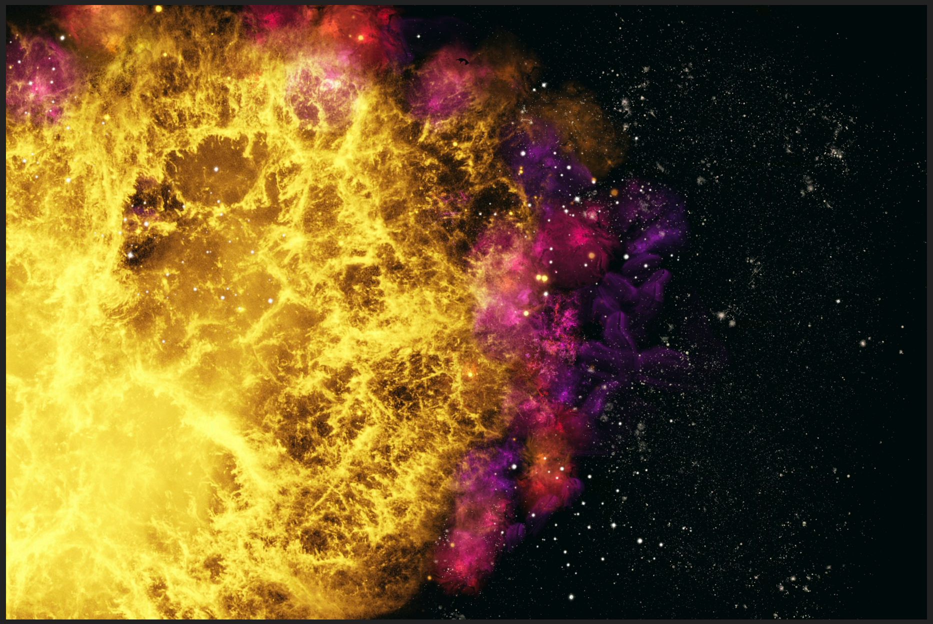


PART 5: DUST EVOLUTION IN ZOOM SIMULATIONS

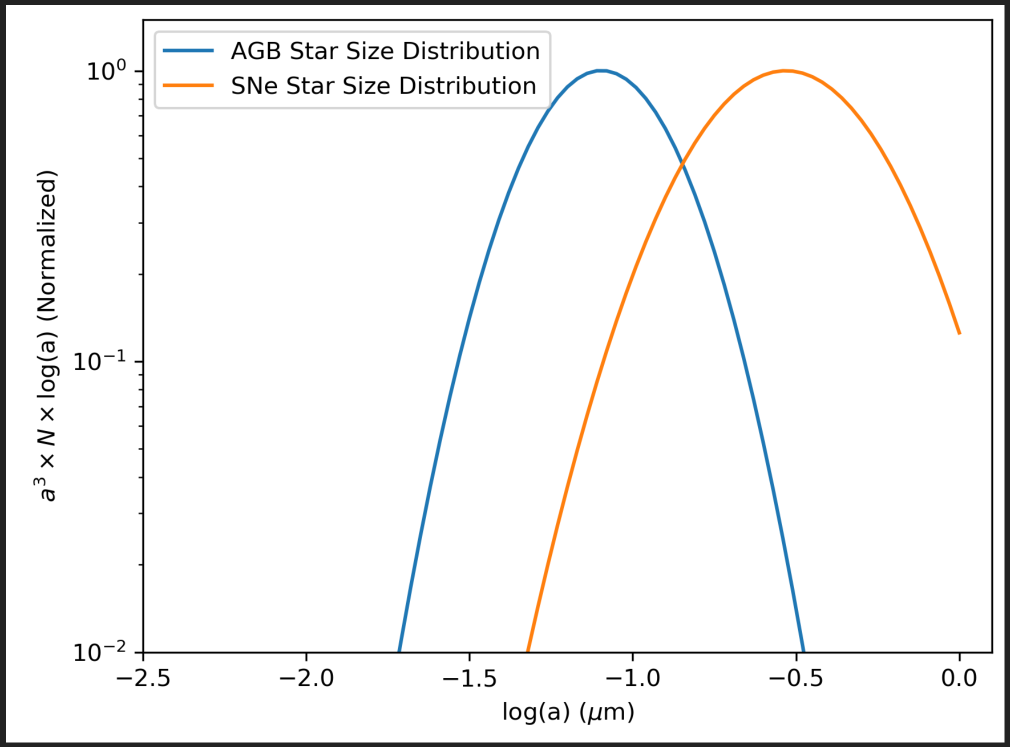


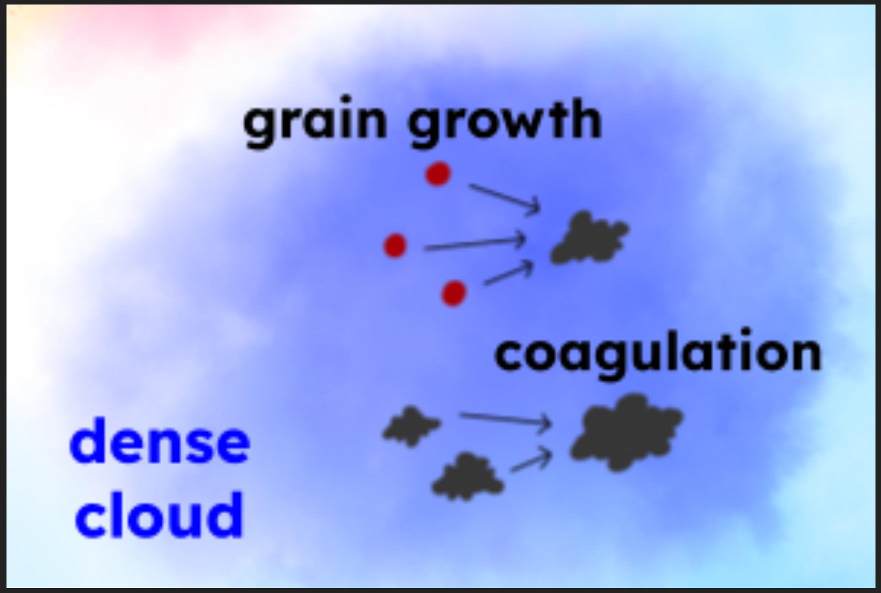


KEY ASPECTS OF THIS NUMERICAL EXPERIMENT



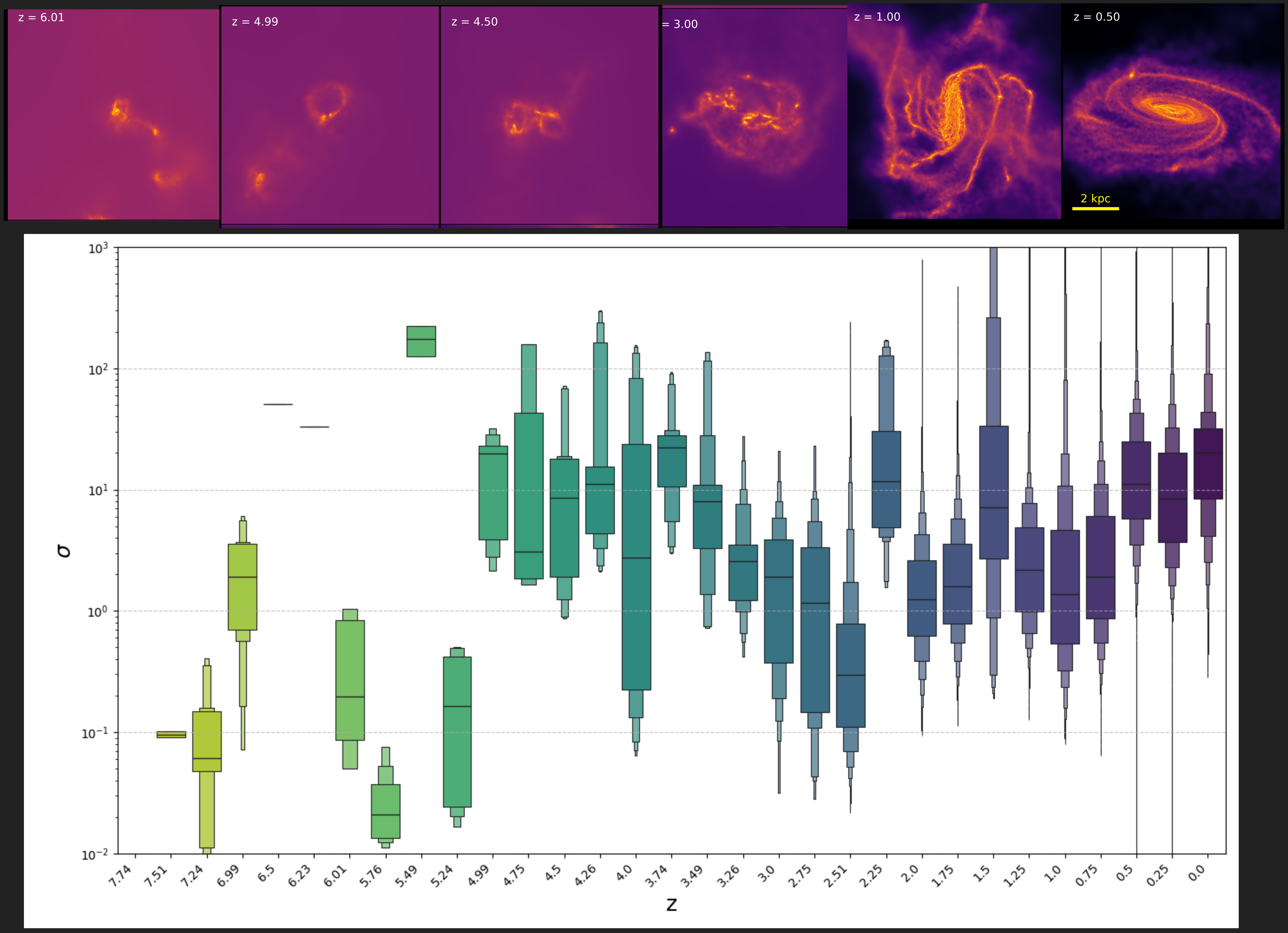
Initial Size Distribution



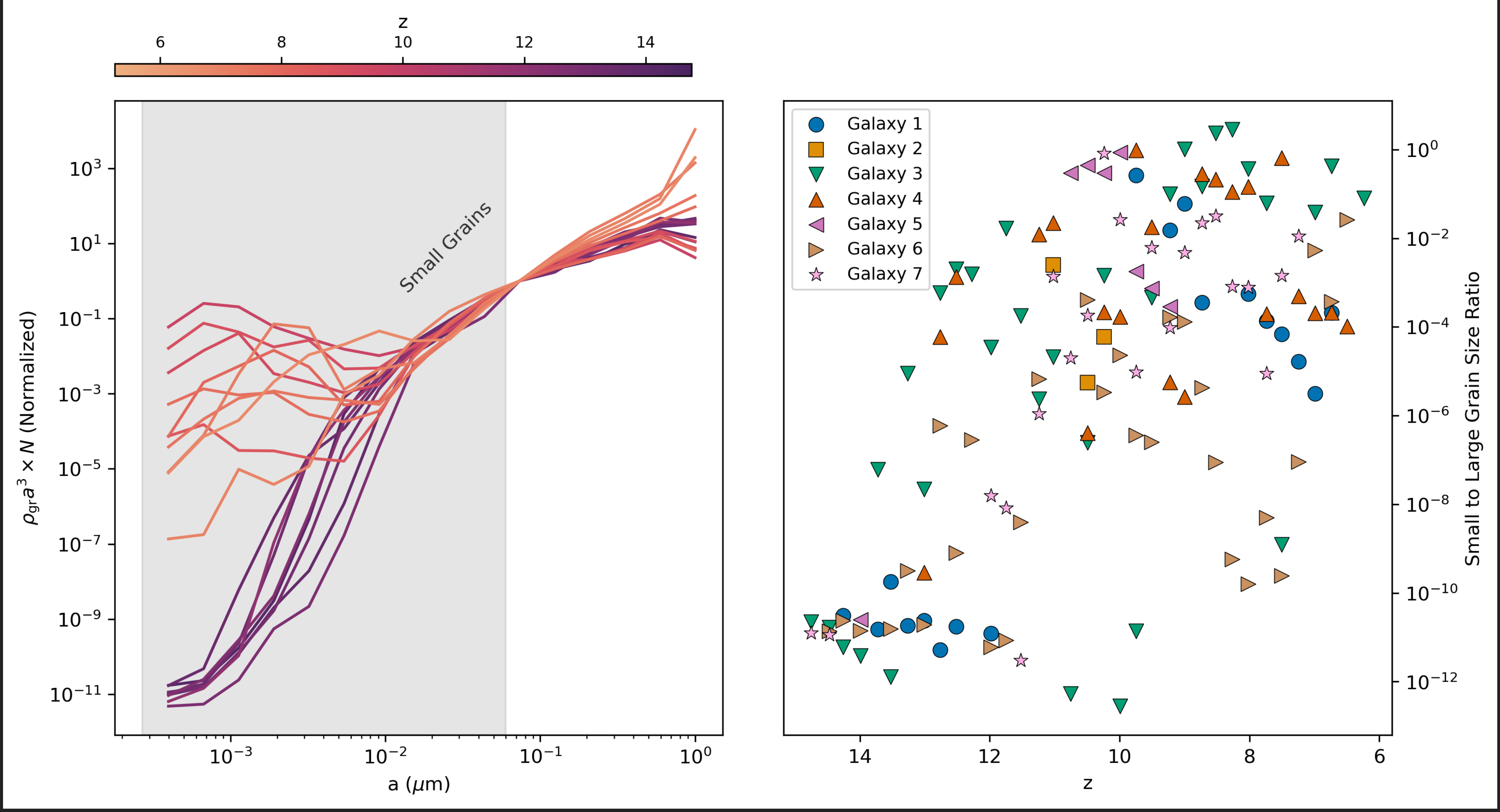


$$\frac{dM}{dt} \propto \frac{M}{\tau_{\rm accr}} \qquad \tau_{accr} = \tau_{ref}\left(\frac{a}{a_{ref}}\right)\left(\frac{\rho_{ref}}{\rho_g}\right)\left(\frac{T_{ref}}{T_g}\right)^{1/2}\left(\frac{Z_{ref}}{Z_g}\right)\left(\frac{S_{ref}}{S}\right).$$

$$v_{\rm thresh} = \begin{cases} 2.7\ \mathrm{km/s} & \text{silicates} \\ 1.2\ \mathrm{km/s} & \text{carbonaceous} \end{cases}$$

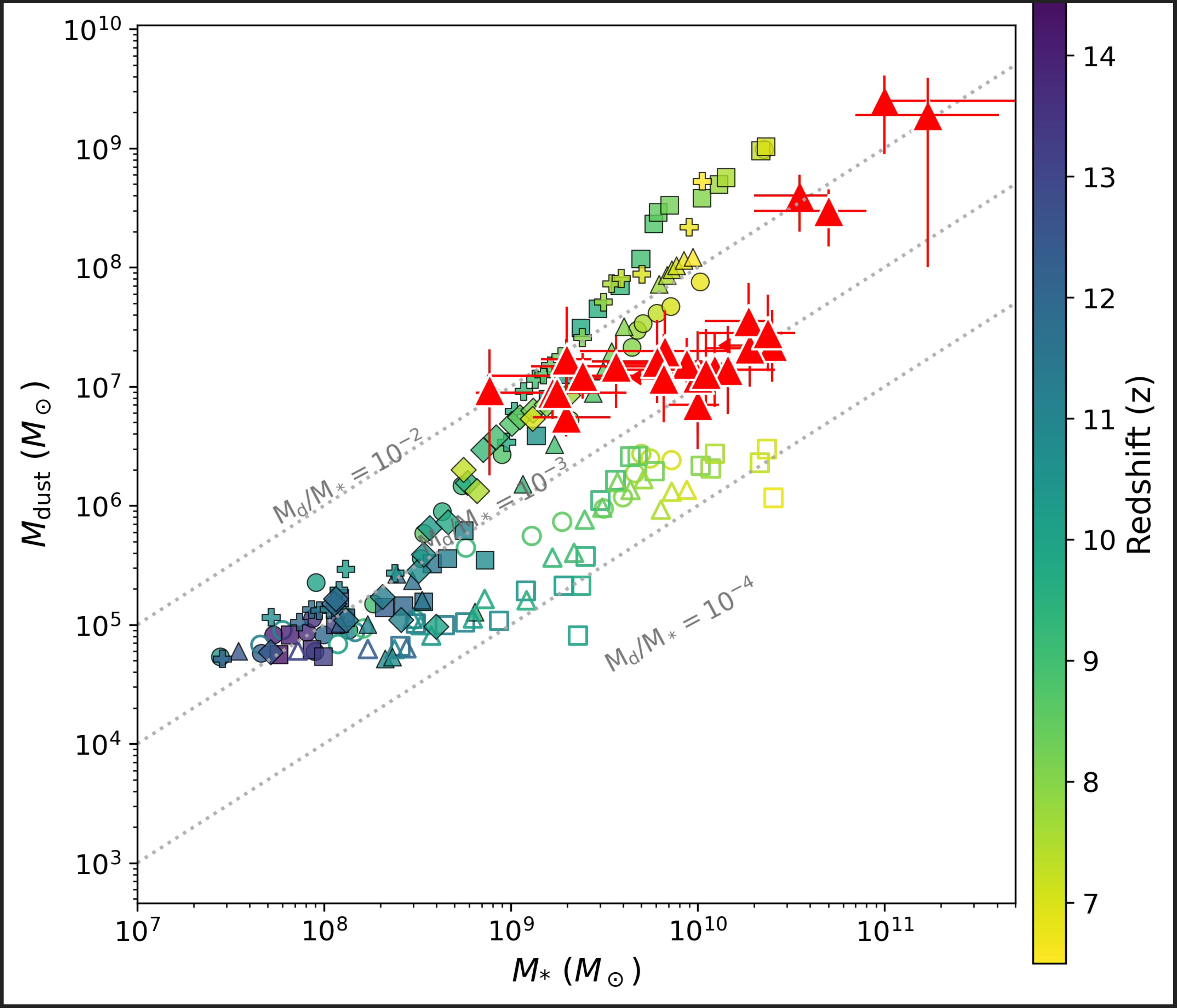


z = 6.01
z = 4.99
z = 4.50
= 3.00
z = 1.00
z = 0.50
2 kpc
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
σ
7.74 7.51 7.24 6.99 6.5 6.23 6.01 5.76 5.49 5.24 4.99 4.75 4.5 4.26 4.0 3.74 3.49 3.26 3.0 2.75 2.51 2.25 2.0 1.75 1.5 1.25 1.0 0.75 0.5 0.25 0.0
z



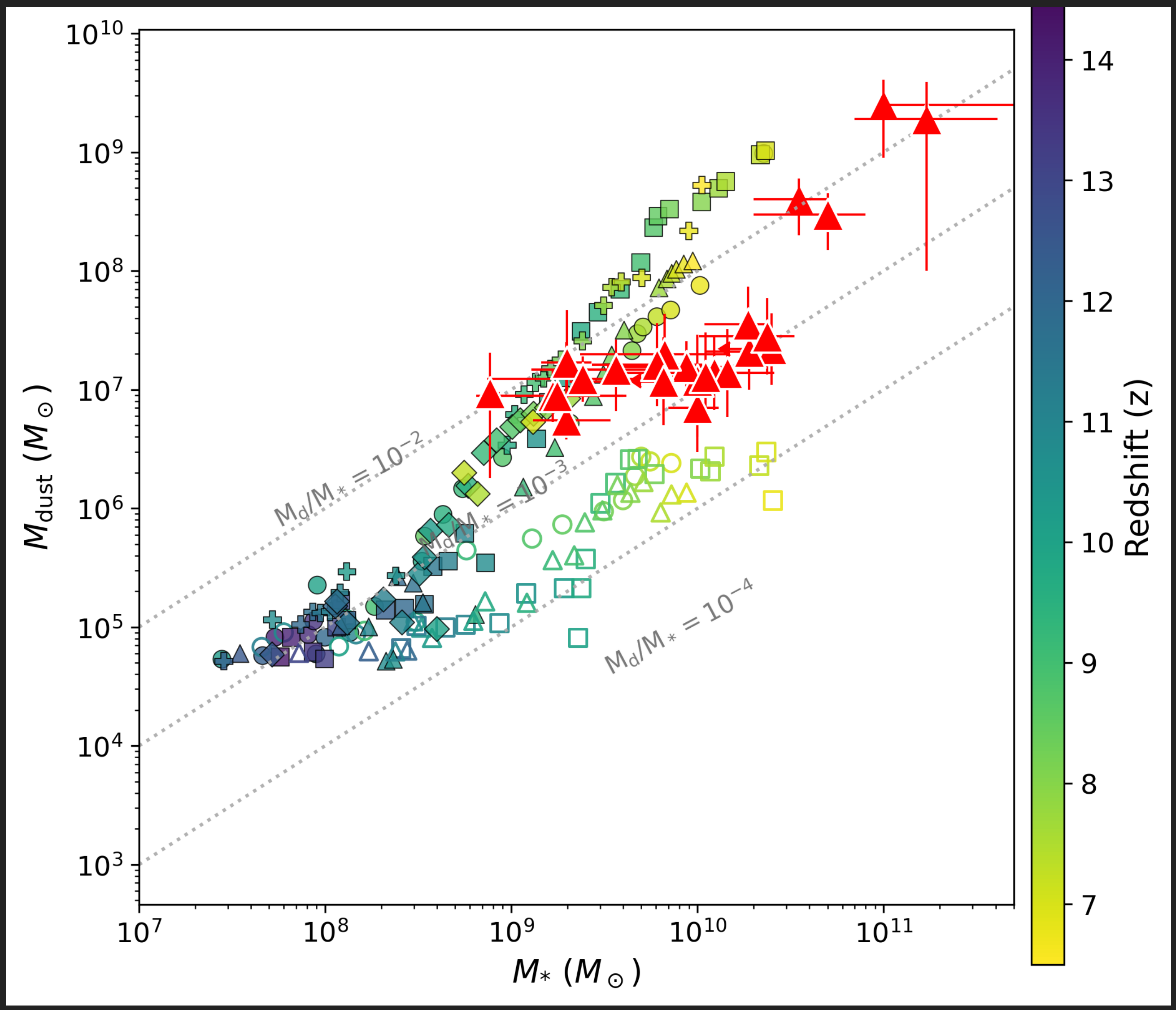
Narayanan, Torrey, Stark et al. 2025

The formation of the first dusty galaxies: Growth takes over at z=10 (or so)

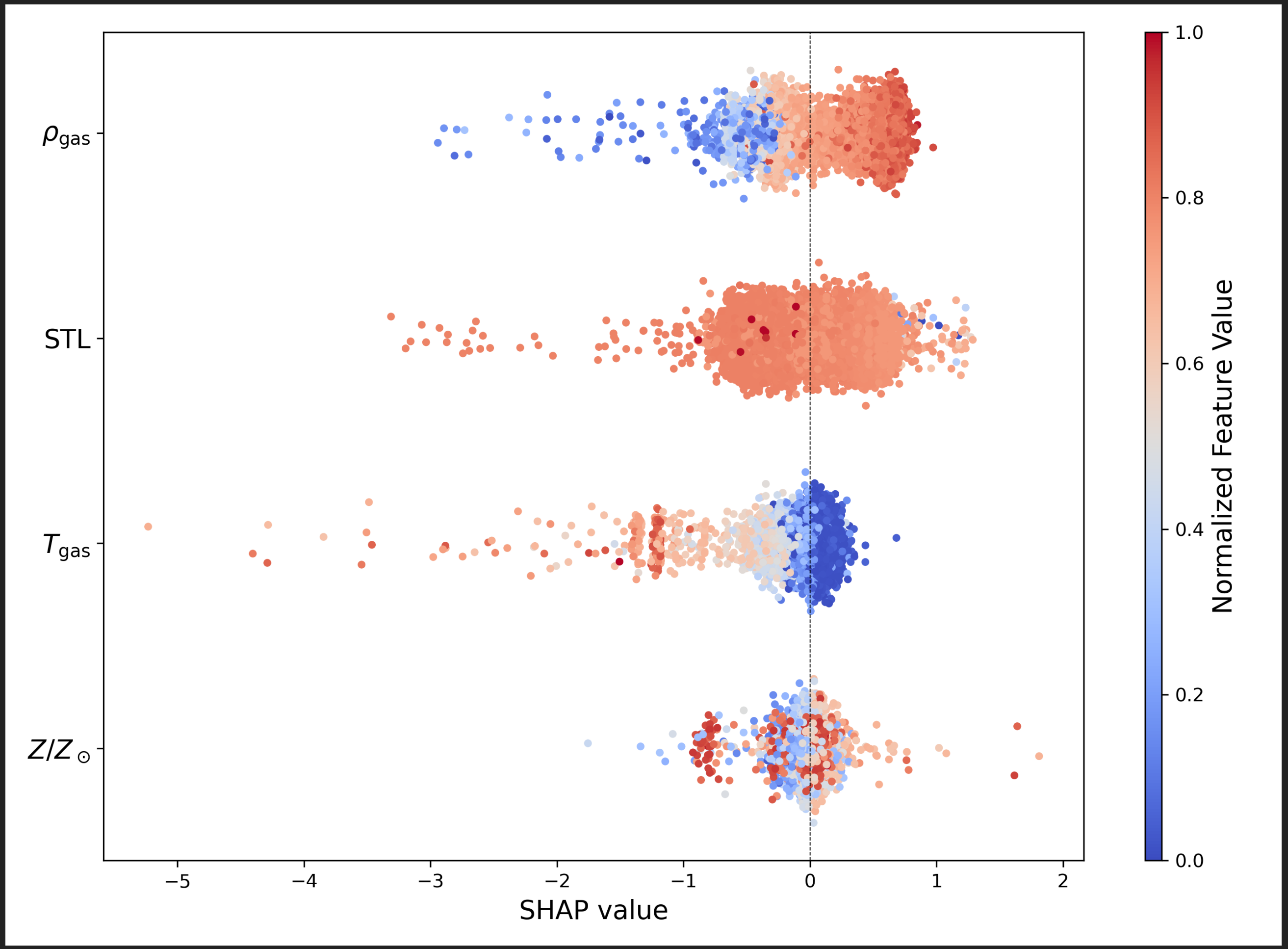


Narayanan, Torrey, Stark et al. 2025

The formation of the first dusty galaxies: Growth takes over at z=10 (or so)



$$\tau_{accr} = \tau_{ref}\left(\frac{a}{a_{ref}}\right)\left(\frac{\rho_{ref}}{\rho_g}\right)\left(\frac{T_{ref}}{T_g}\right)^{1/2}\left(\frac{Z_{ref}}{Z_g}\right)\left(\frac{S_{ref}}{S}\right).$$



Narayanan, Torrey, Stark et al. 2025

The curious case of “blue monsters”

A&A, 694, A286 (2025)
https://doi.org/10.1051/0004-6361/202452707

Astronomy & Astrophysics

Blue monsters at $z > 10$: Where all their dust has gone

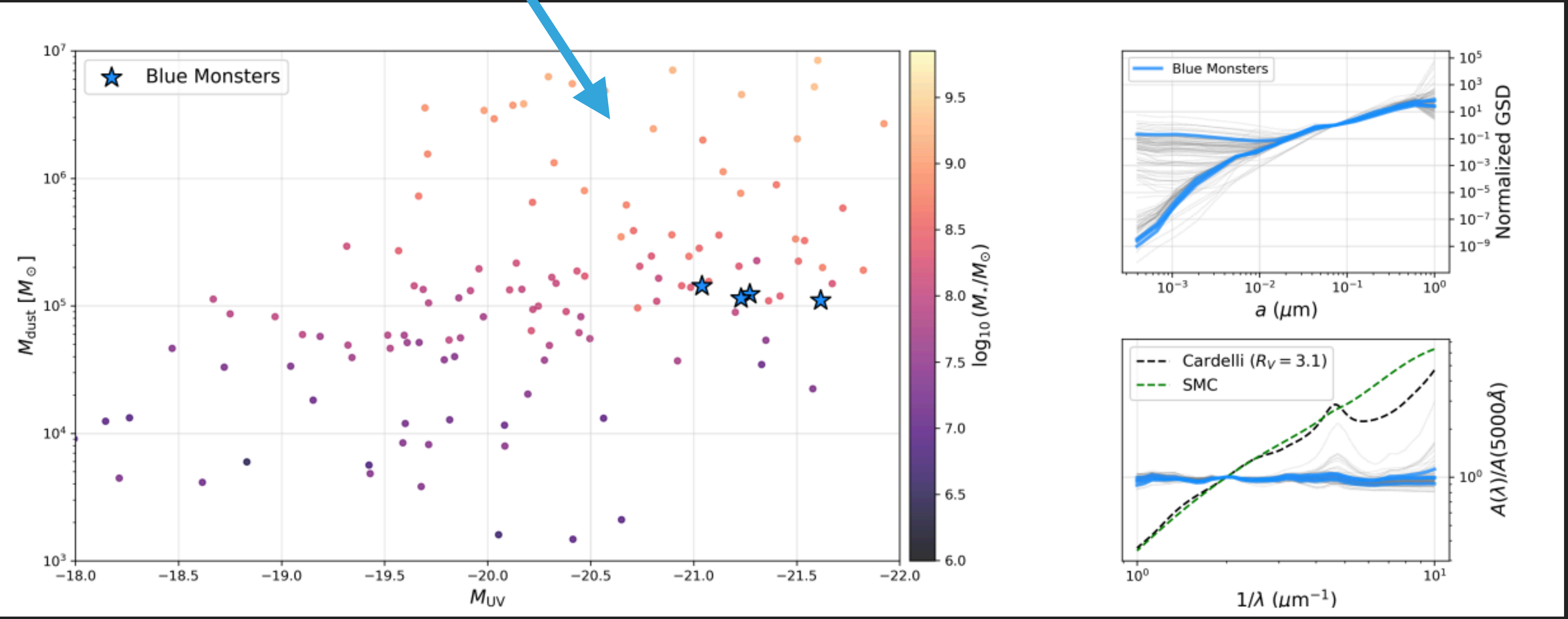
A. Ferrara[1,★], A. Pallottini[1], and L. Sommovigo[2]

Table 1. Relevant properties of spectroscopically confirmed super-early galaxies at $z > 10$.

ID (1)	Redshift (2)	A_V [mag] (3)	$\log(Z/Z_\odot)$ (4)	r_e [pc] (5)	$\log(M_d/M_\odot)$ (6)	$\log(M_\star/M_\odot)$ (7)	$\log \xi_d$ (8)
CEERS2-7929 [(a)]	10.10	$0.14^{+0.29}_{-0.14}$	–	520^{+127}_{-127}	$5.2^{+10.9}_{-5.2} \times 10^4$	$8.50^{+0.30}_{-0.40}$	$-3.78^{+0.99}_{-0.99}$
MACS0647-JD [(b)]	10.17	<0.01	$-0.90^{+0.09}_{-0.09}$	70^{+24}_{-24}	$<6.7 \times 10^1$	$7.50^{+0.10}_{-0.10}$	<-5.67
UNCOVER-37126 [(c)]	10.25	$^{(*)}0.18^{+0.14}_{-0.14}$	–	426^{+40}_{-42}	$4.5^{+3.5}_{-3.5} \times 10^4$	$8.16^{+0.08}_{-0.07}$	$-3.51^{+0.35}_{-0.35}$
GS-z10-0 [(d)]	10.38	$0.05^{+0.03}_{-0.02}$	$-1.91^{+0.25}_{-0.20}$	<62	$<2.6 \times 10^2$	$7.58^{+0.19}_{-0.20}$	<-5.16
GN-z11 [(e)]	10.60	$0.17^{+0.03}_{-0.03}$	$-0.92^{+0.06}_{-0.05}$	64^{+20}_{-20}	$9.6^{+3.4}_{-3.4} \times 10^3$	$8.73^{+0.06}_{-0.06}$	$-5.75^{+0.17}_{-0.17}$
CEERS2-588 [(a)]	11.04	$0.10^{+0.11}_{-0.07}$	$-0.84^{+0.16}_{-0.12}$	<477	$<3.1 \times 10^4$	$8.99^{+0.54}_{-0.22}$	<4.49
Maisie [(f)]	11.44	$0.07^{+0.09}_{-0.05}$	–	340^{+14}_{-14}	$1.1^{+1.4}_{-1.1} \times 10^4$	$8.40^{+0.30}_{-0.40}$	$-4.35^{+0.69}_{-0.69}$
GS-z11-0 [(d)]	11.58	$0.18^{+0.06}_{-0.06}$	$-1.87^{+0.28}_{-0.18}$	$^{(\dagger)}77^{+8}_{-8}$	$1.5^{+0.5}_{-0.5} \times 10^3$	$8.67^{+0.08}_{-0.13}$	$-5.50^{+0.20}_{-0.20}$
GHZ2 [(g)]	12.34	$0.04^{+0.07}_{-0.03}$	$-1.40^{+0.27}_{-0.24}$	105^{+9}_{-9}	$6.1^{+10.6}_{-6.1} \times 10^2$	$9.05^{+0.10}_{-0.25}$	$-6.27^{+0.80}_{-0.80}$
UNCOVER-z12 [(c)]	12.39	$0.19^{+0.17}_{-0.10}$	$-1.34^{+0.60}_{-0.42}$	426^{+40}_{-42}	$4.7^{+4.2}_{-4.2} \times 10^4$	$8.35^{+0.14}_{-0.18}$	$-3.67^{+0.43}_{-0.43}$
GS-z12-0 [(d)]	12.63	$0.05^{+0.03}_{-0.02}$	$-1.44^{+0.23}_{-0.22}$	$^{(\dagger)}144^{+15}_{-15}$	$1.4^{+0.9}_{-0.9} \times 10^3$	$7.64^{+0.66}_{-0.39}$	$-4.49^{+0.71}_{-0.71}$
UNCOVER-z13 [(c]	13.08	$0.04^{+0.08}_{-0.03}$	$-1.57^{+0.35}_{-0.28}$	309^{+110}_{-74}	$5.2^{+10.7}_{-5.2} \times 10^3$	$8.13^{+0.11}_{-0.15}$	$-4.41^{+0.89}_{-0.89}$
GS-z13-0 [(d)]	13.20	$0.05^{+0.03}_{-0.02}$	$-1.69^{+0.28}_{-0.31}$	<52	$<1.9 \times 10^2$	$7.95^{+0.19}_{-0.29}$	<-5.68
GS-z14-1 [(h)]	13.90	$0.20^{+0.11}_{-0.07}$	$-1.10^{+0.60}_{-0.50}$	<160	$<7.0 \times 10^3$	$8.00^{+0.40}_{-0.30}$	<-4.15
GS-z14-0 [(h)]	14.18	$0.31^{+0.14}_{-0.17}$	$-0.75^{+0.03}_{-0.03}$	260^{+2}_{-2}	$1.2^{+0.3}_{-0.3} \times 10^4$	$8.84^{+0.09}_{-0.10}$	$-4.76^{+0.14}_{-0.14}$

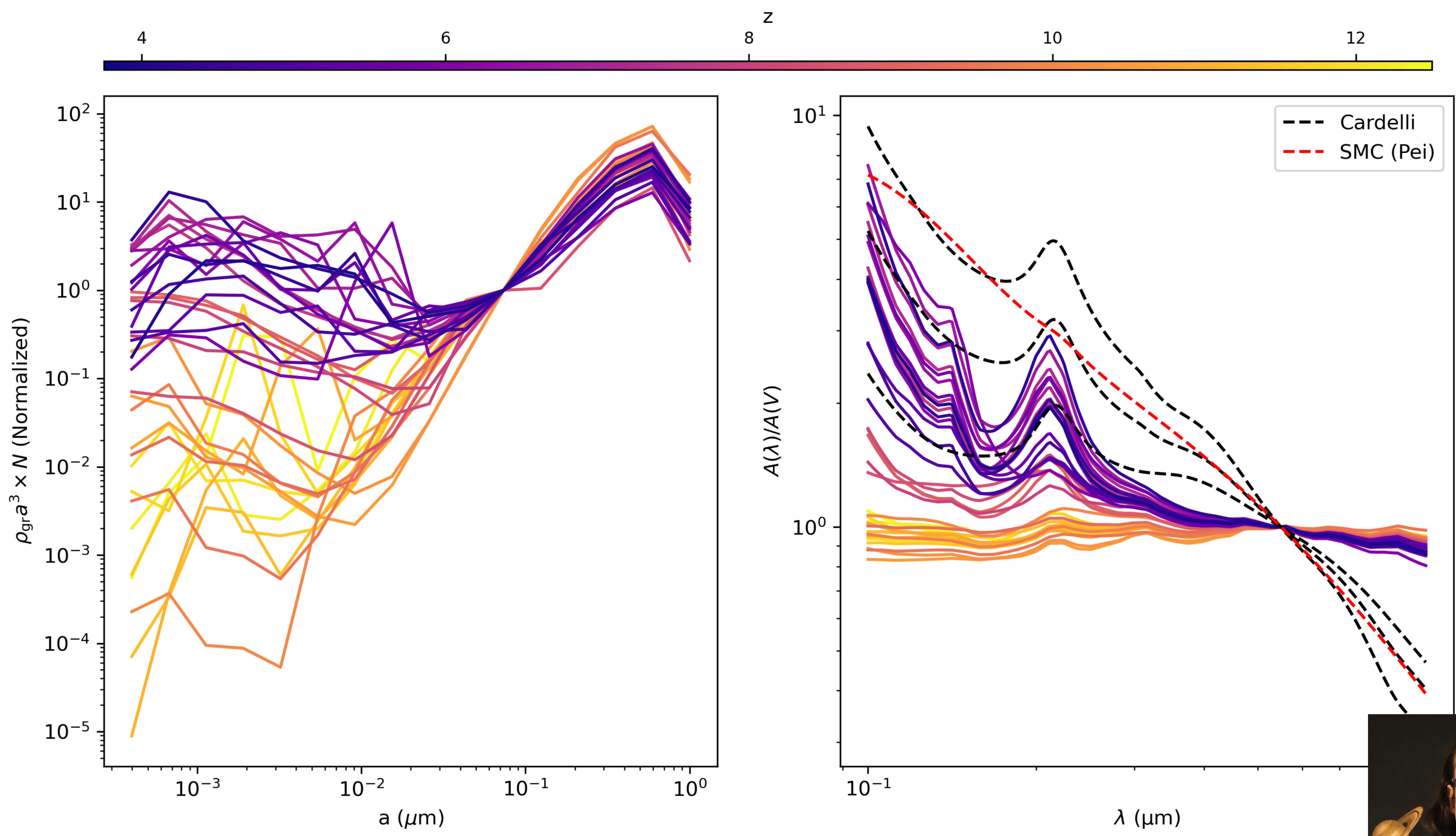
The curious case of "blue monsters": the dust is there.. you just can't see it.

Blue Monsters: here, z>10, MUV < -20



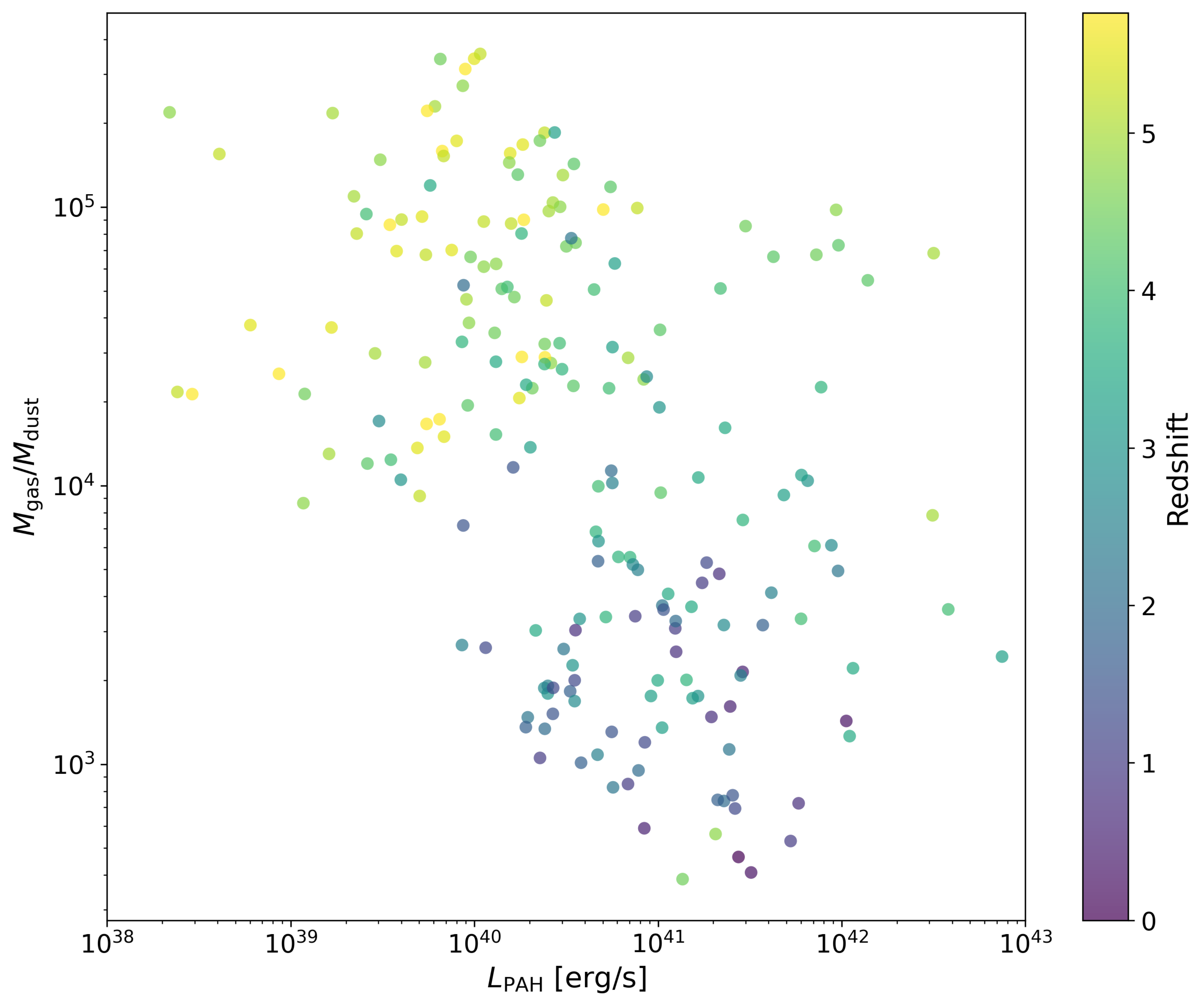
Narayanan, Torrey, Stark et al. 2025

SHATTERING AT EARLY TIMES LEADS TO PRONOUNCED 2175 AT Z=7

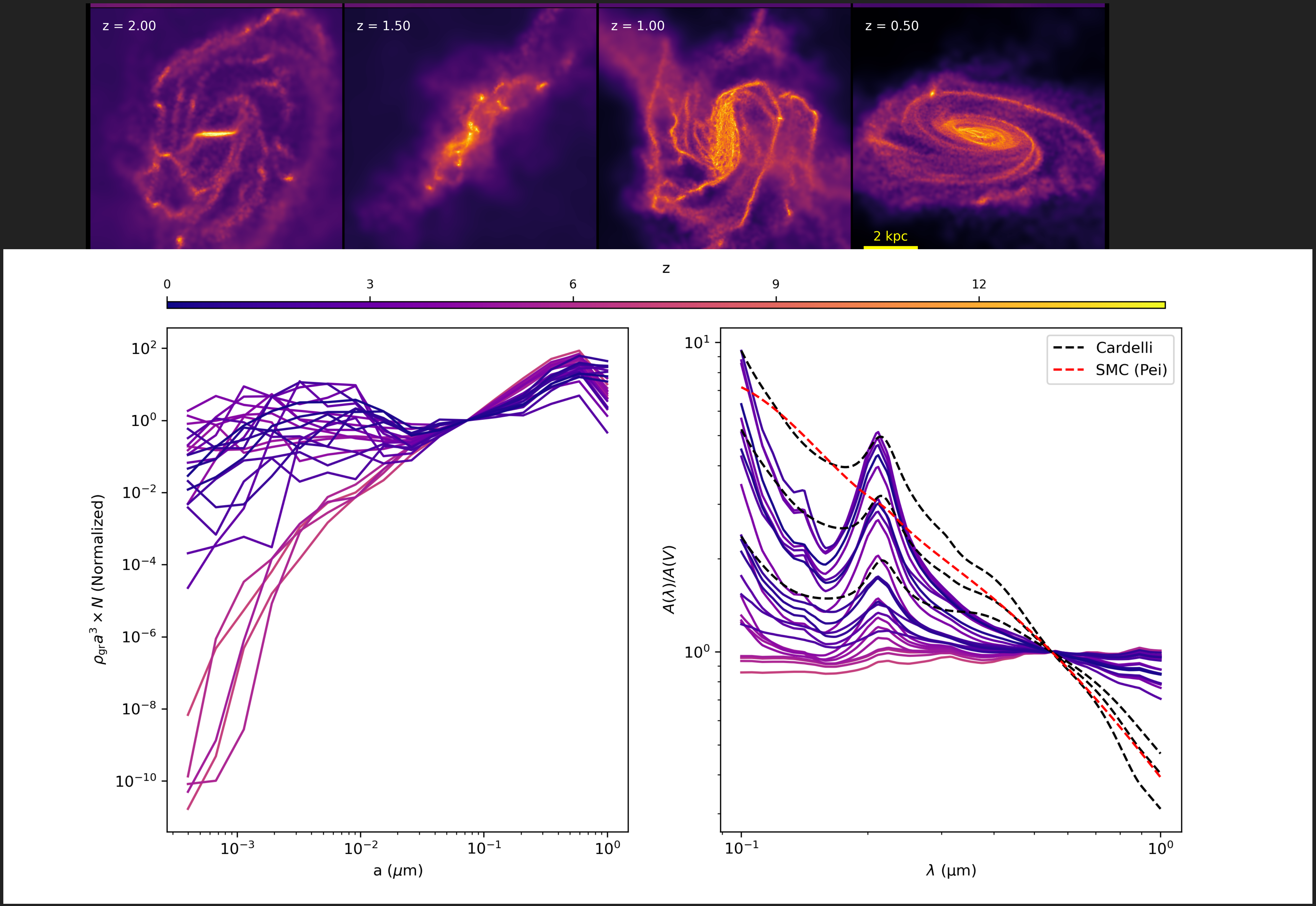


E. Savitch, Narayanan et al. [in prep]

I LITERALLY ONLY MADE THIS SLIDE FOR KARL GORDON



SHATTERING RESULTS IN AN A STEEPENING OF THE EXTINCTION LAW WITH TIME

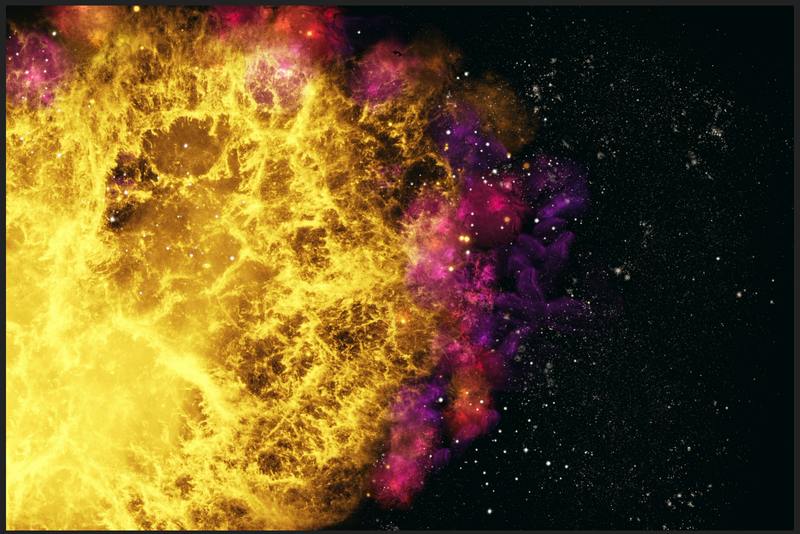


DN, Torrey+ in prep.

Q. Li, Narayanan, Torrey & Dave 2020
Matsumoto et al. 2025

CONCLUDING THOUGHTS AND WAYS FORWARD

Dust Formation

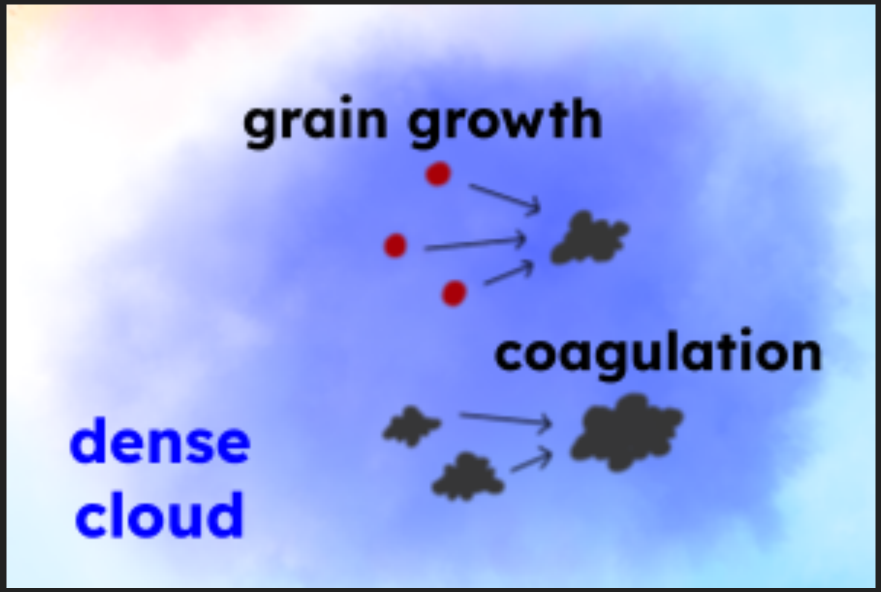


Yields, condensation efficiencies, Size Distributions

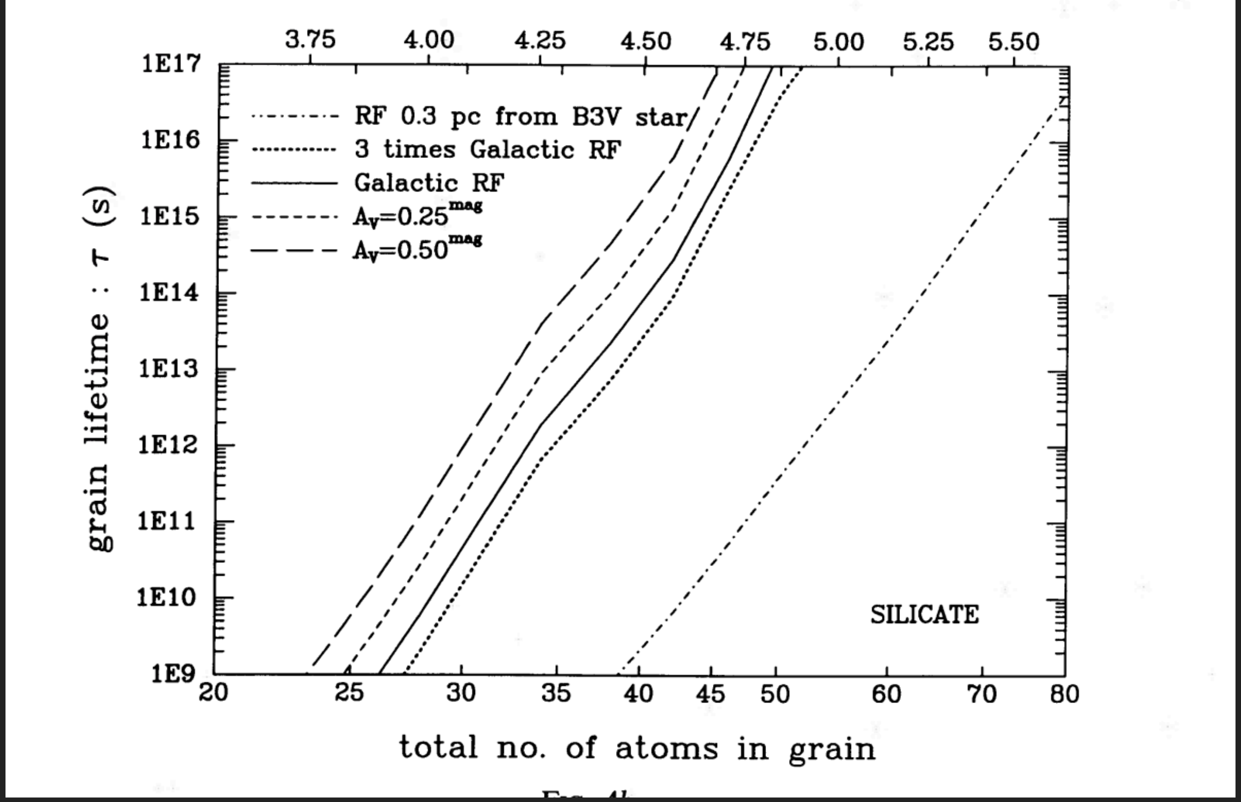
Grain Collisions

Threshold Velocities and outcome [Esmerian talk]

Dust Growth



Sticking Coefficients, Species-dependent growth rates, Coulomb Enhancement Factors



How do we handle interaction with radiation? [Guhathakurta & Draine 1989]