DUSTY | PRISM

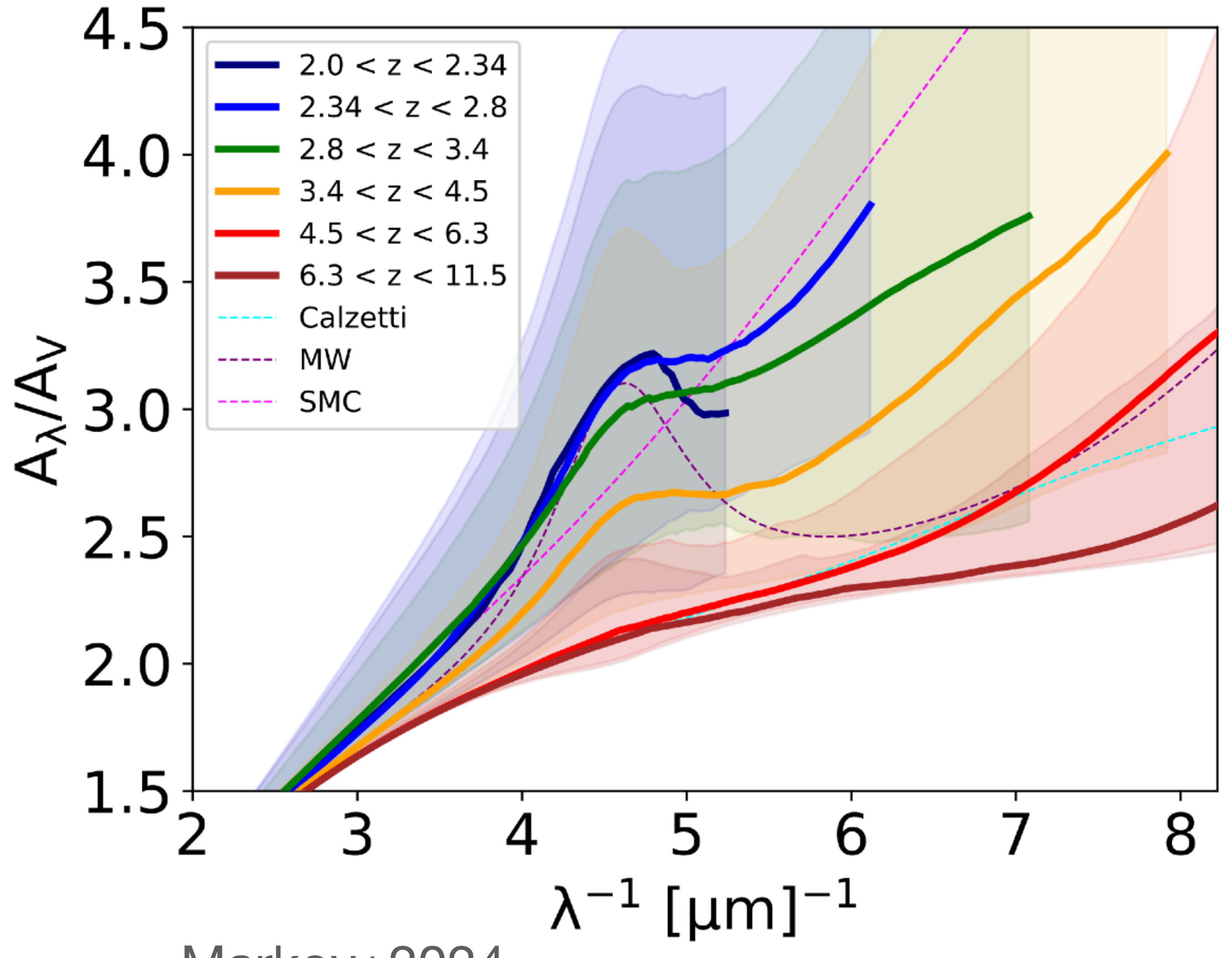
Predicting the evolution of dust and PAHs across cosmic time for PRIMA with radiation-hydrodynamics

Francisco (Curro) Rodríguez Montero - Dusting Off the Secrets of the COSMOS with PRIMA IR Space Telescope

1. The need for forward modelling

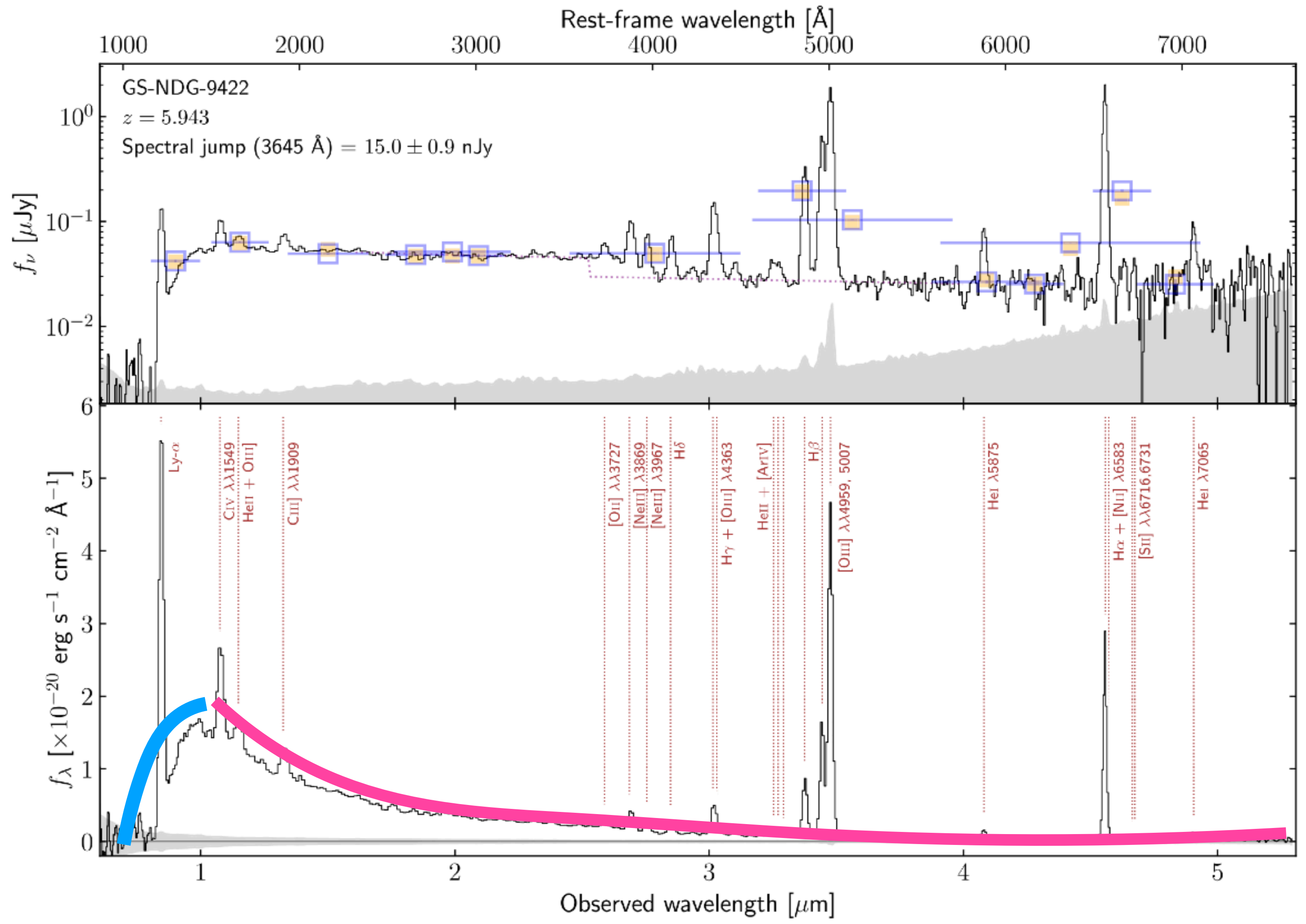
Studying galaxy formation at **all redshifts** relies heavily on **SED modelling**…

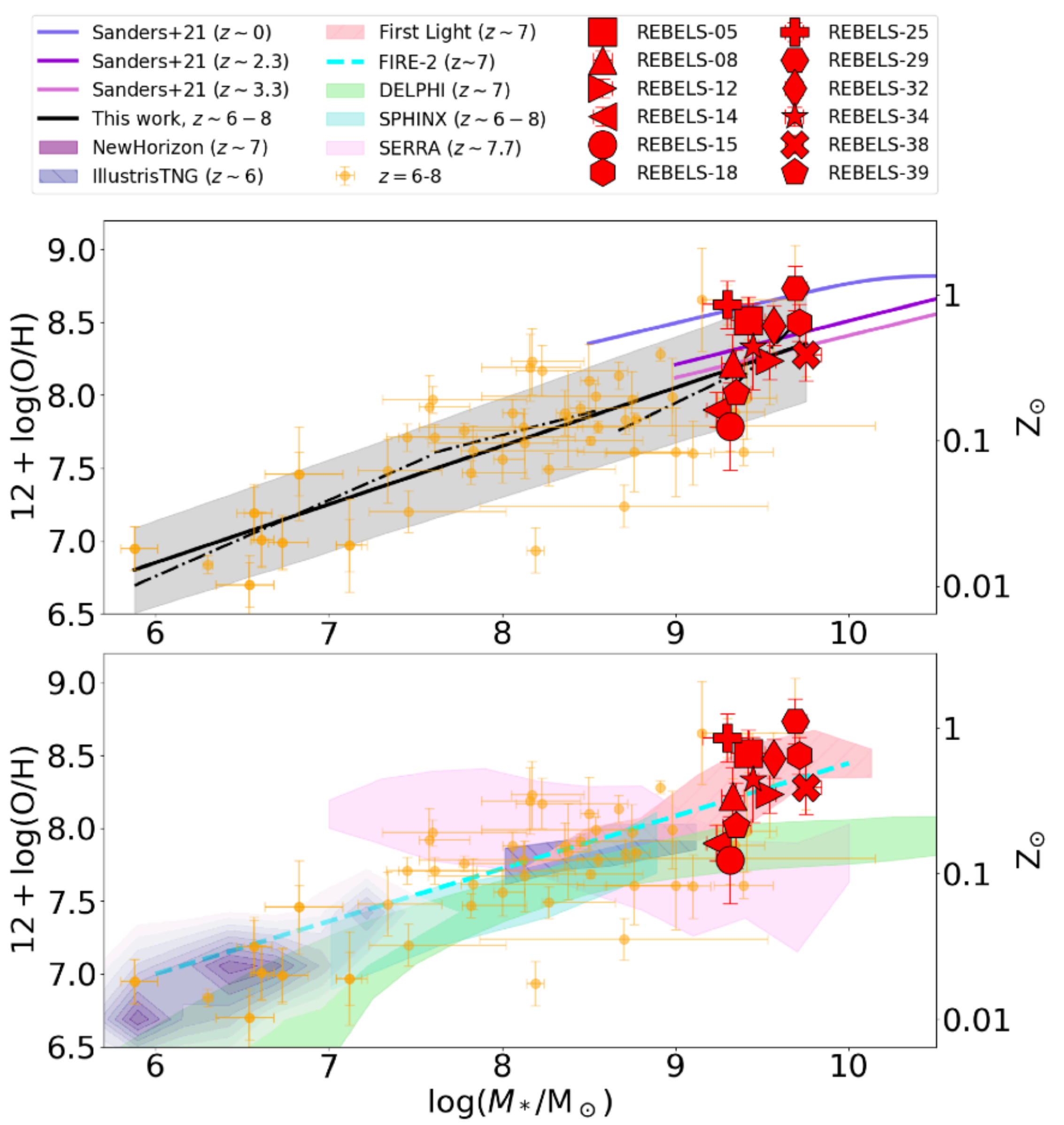
…but these rely on **unclear assumptions** and **extrapolations**



Markov+2024

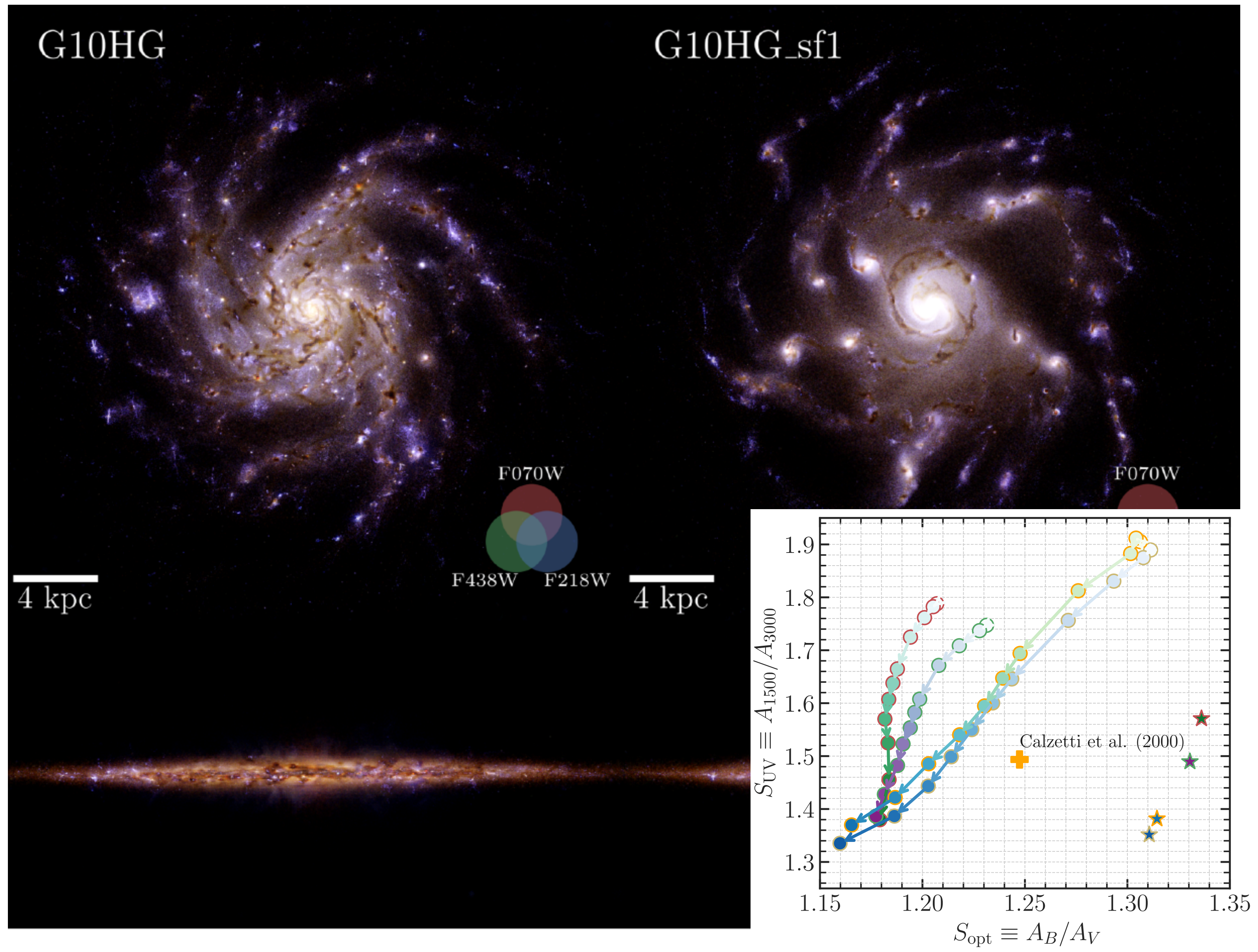
Cameron+2024

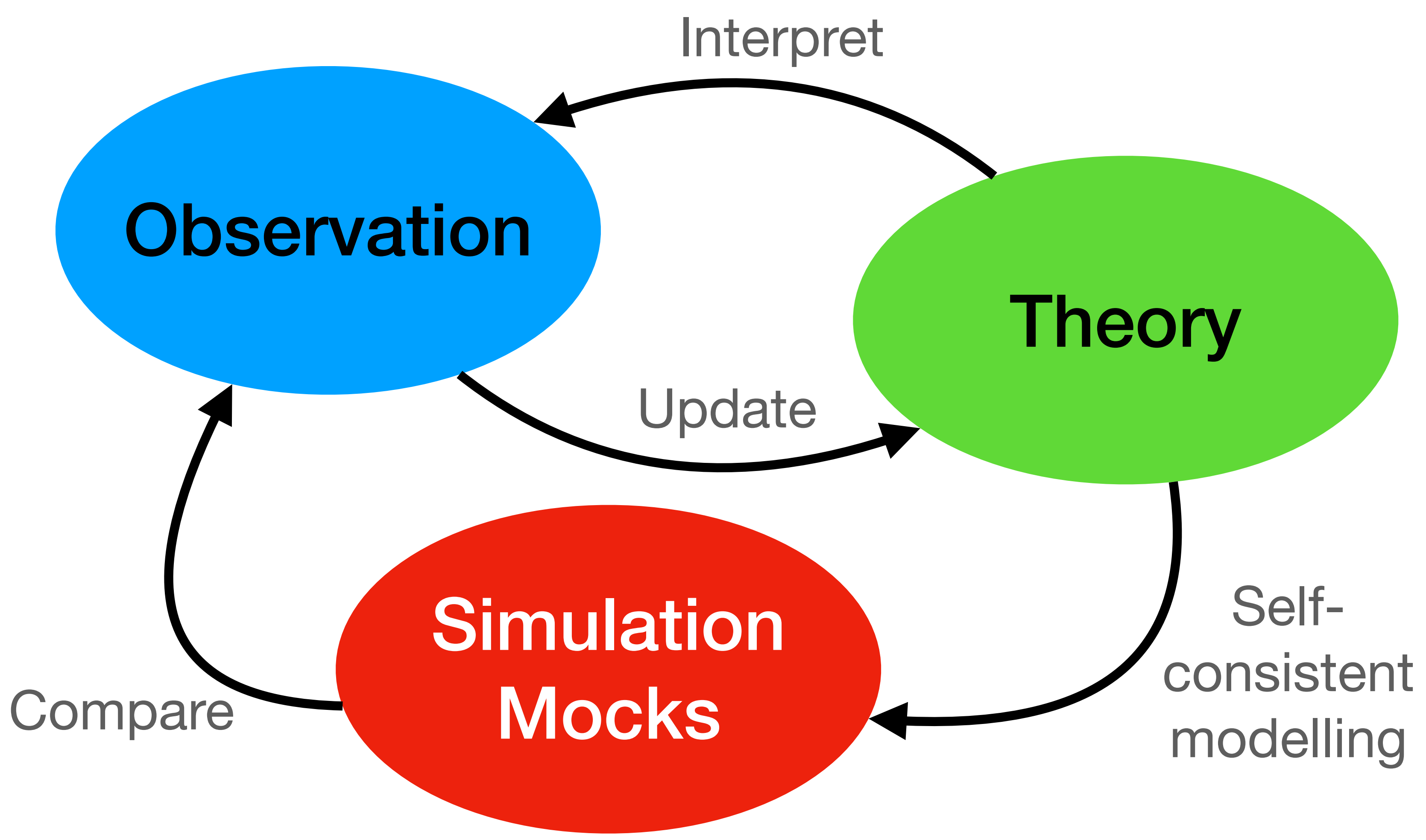




Rowland+2025

Dubois, RM, in prep.

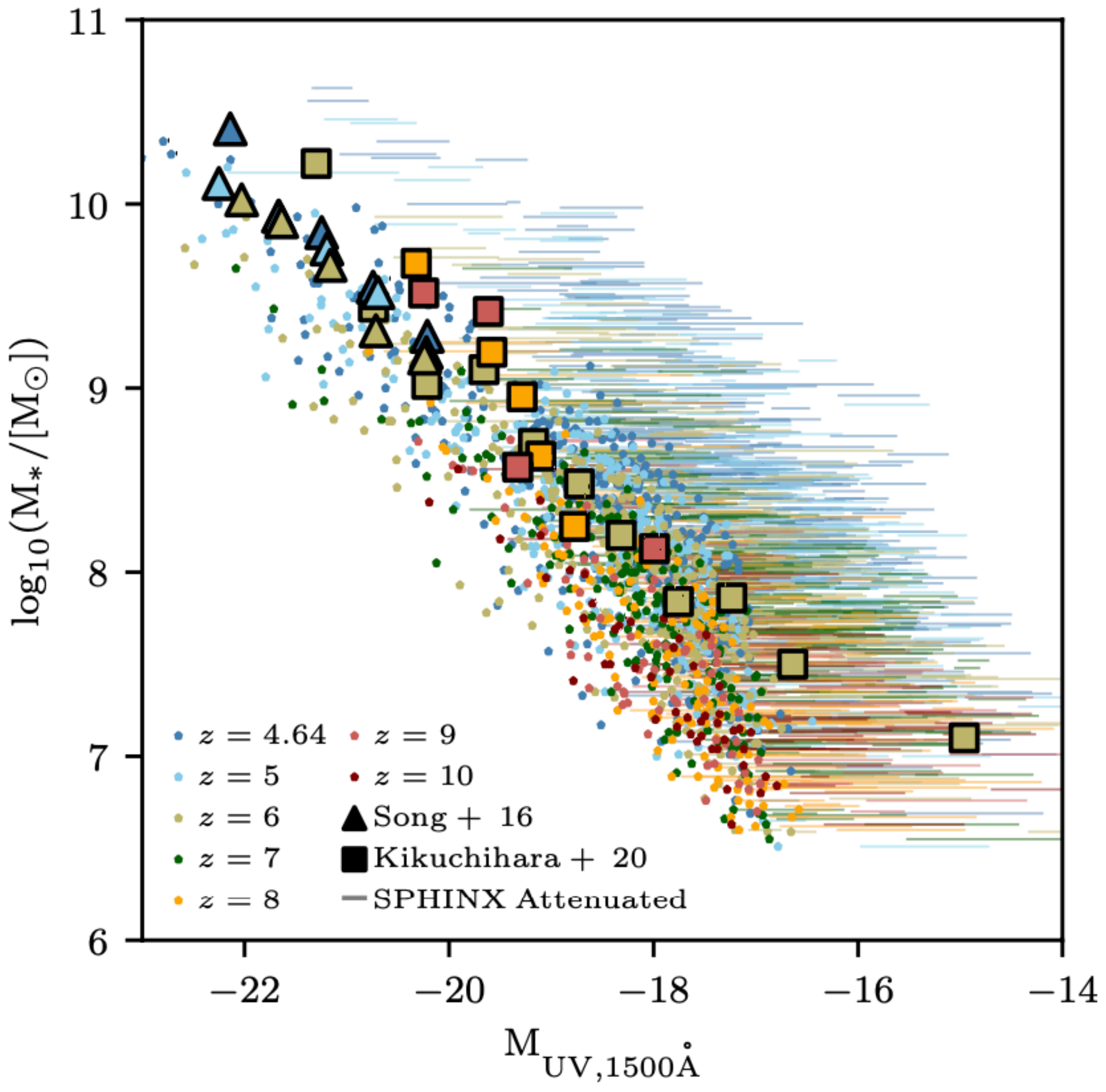




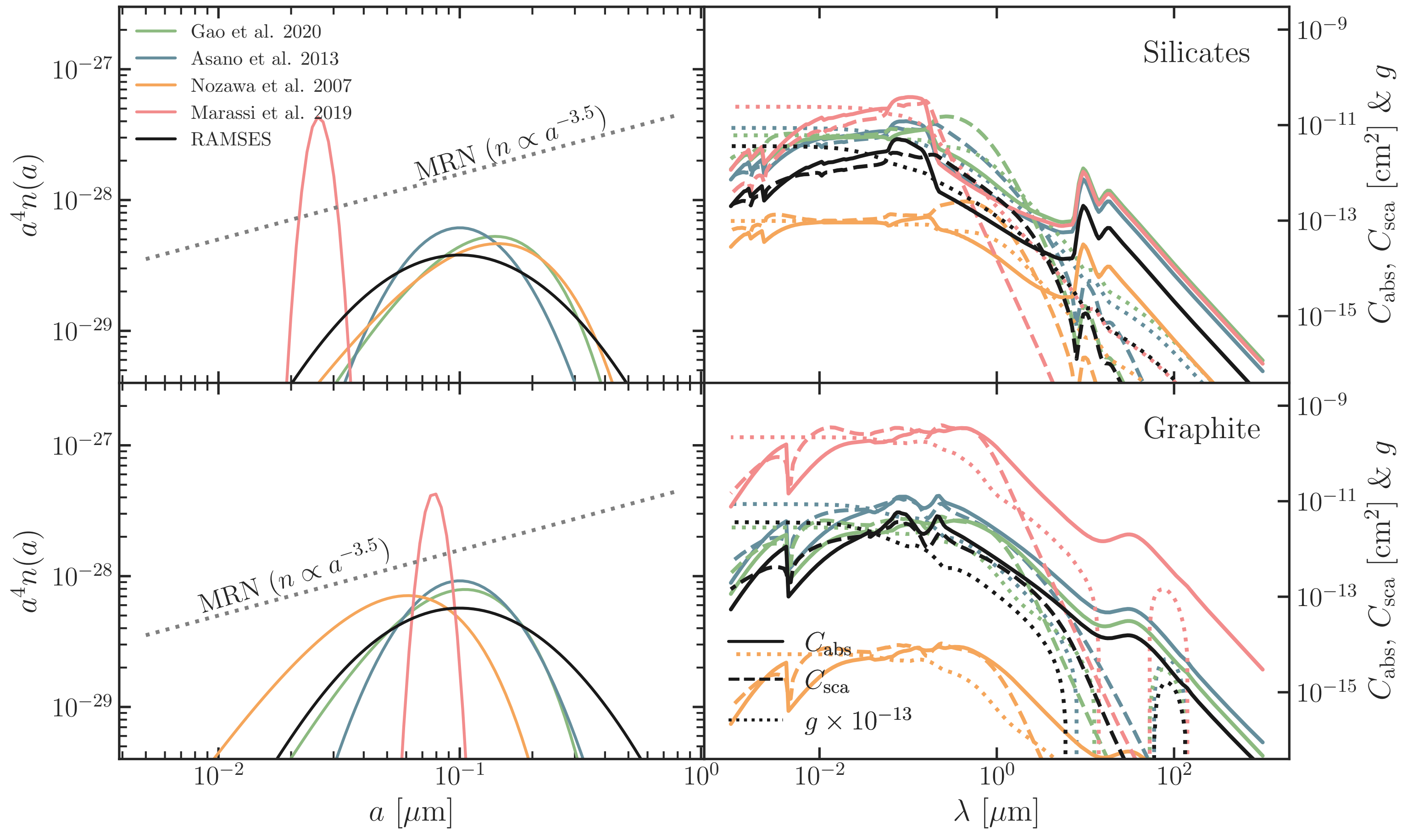
2. Why an on-the-fly dust model

UV-calibrated simulations have too **massive** and too **dusty** galaxies

Katz+2023

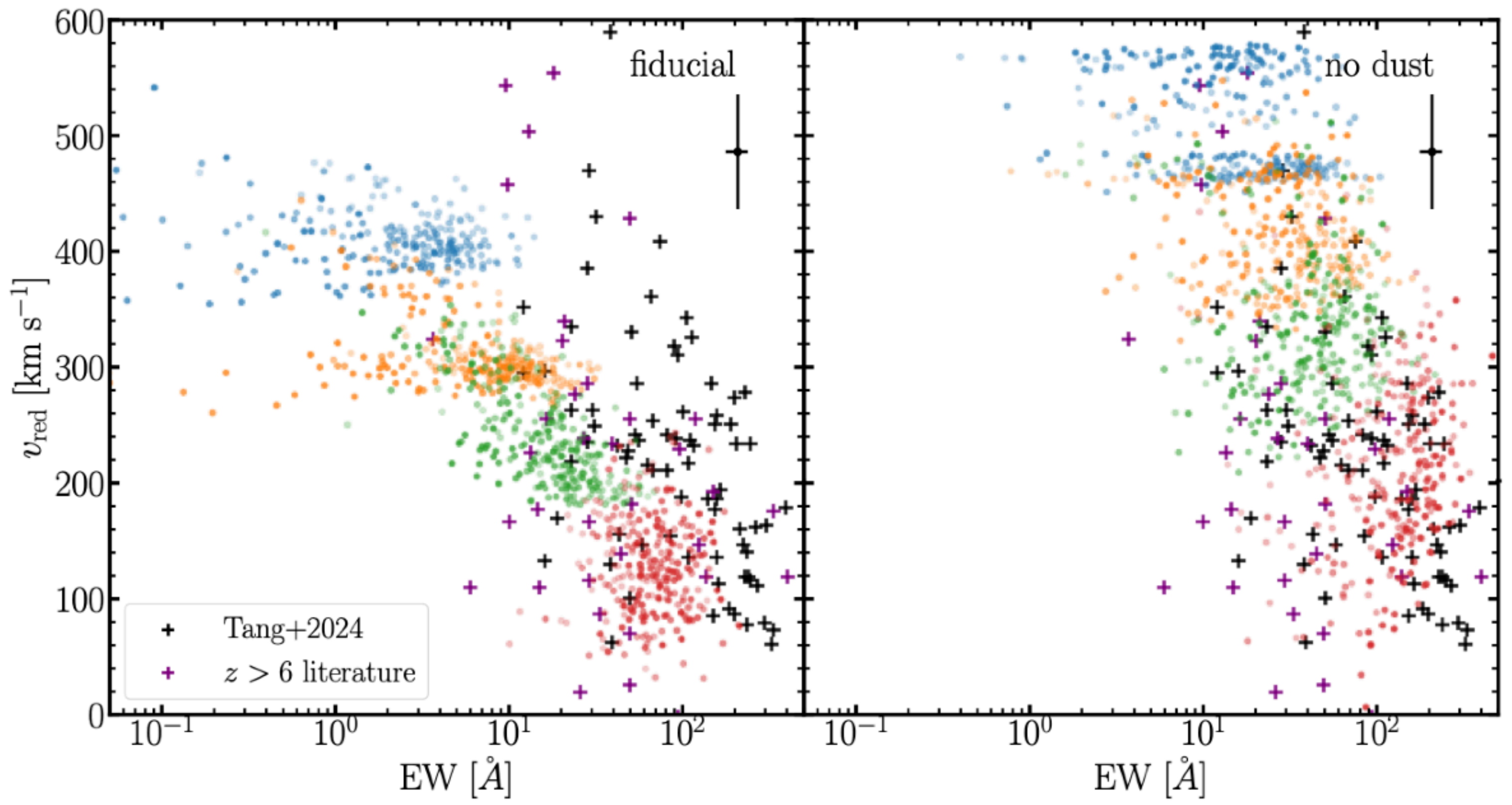


Rodríguez Montero+,in prep.

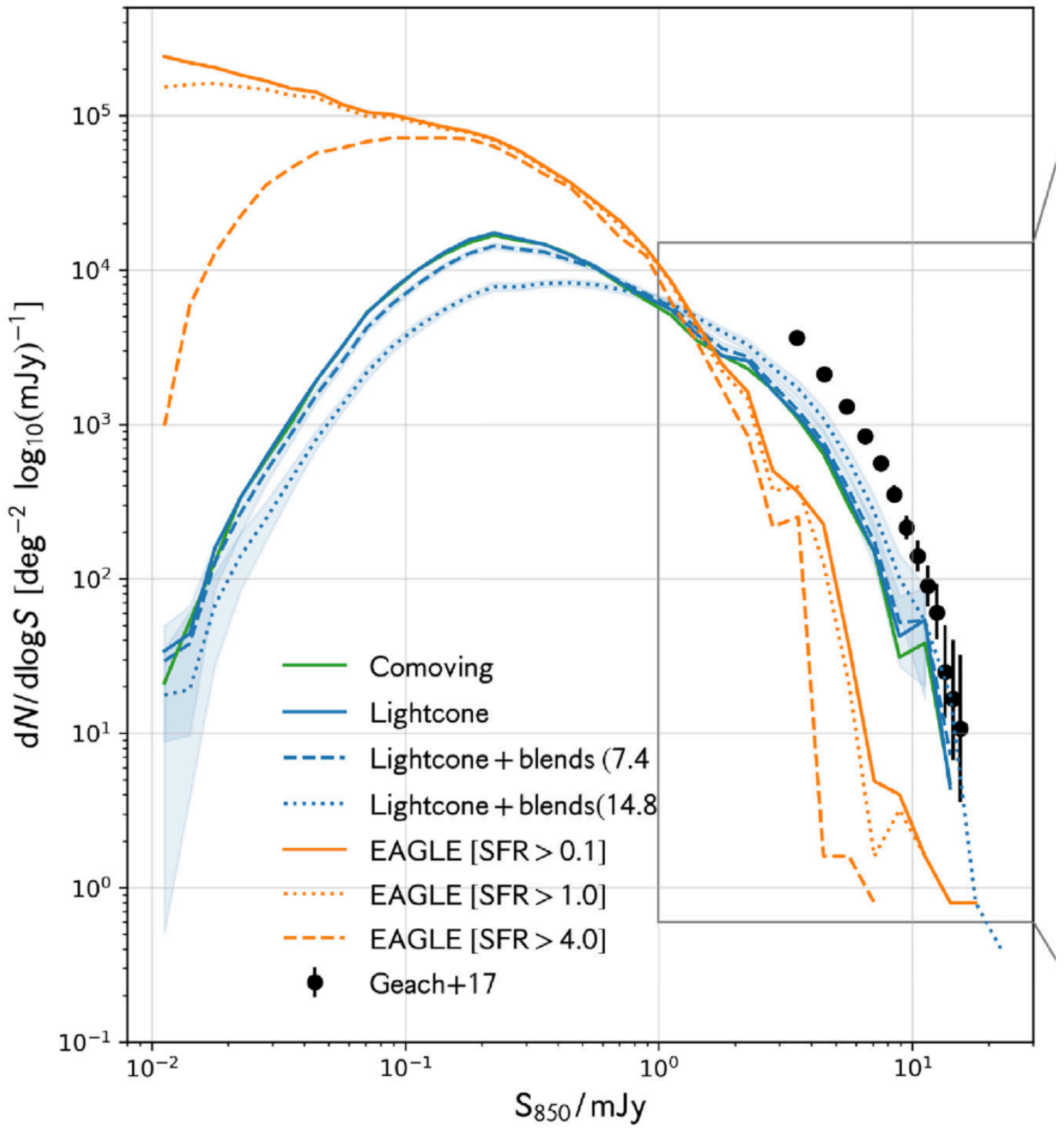


Simple dust models **incapable of predicting Lya** observables, even with additional physics

Yuan+2025

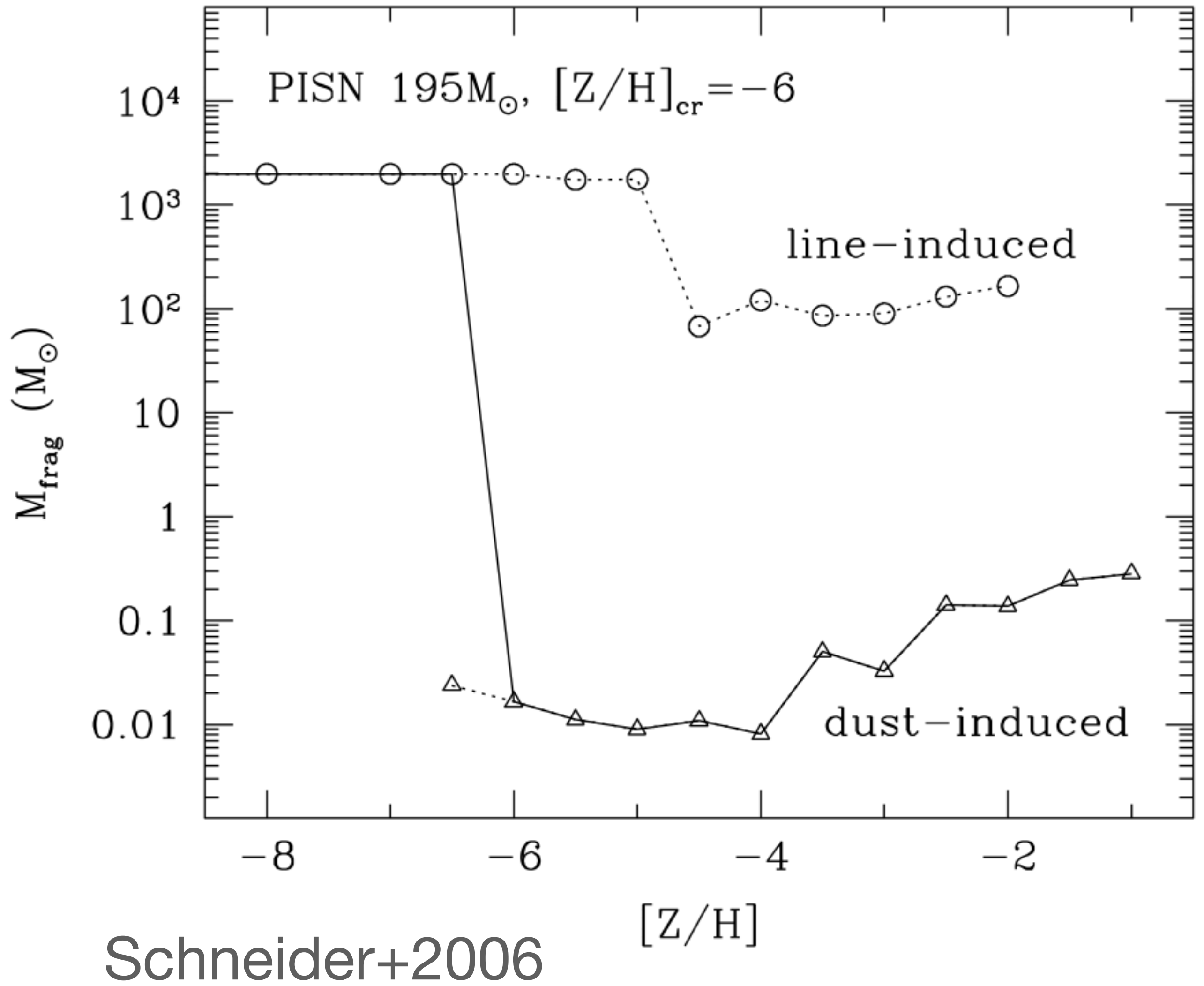


Lovell+2021



Dust modelling needs to go **hand in hand with ISM modelling**

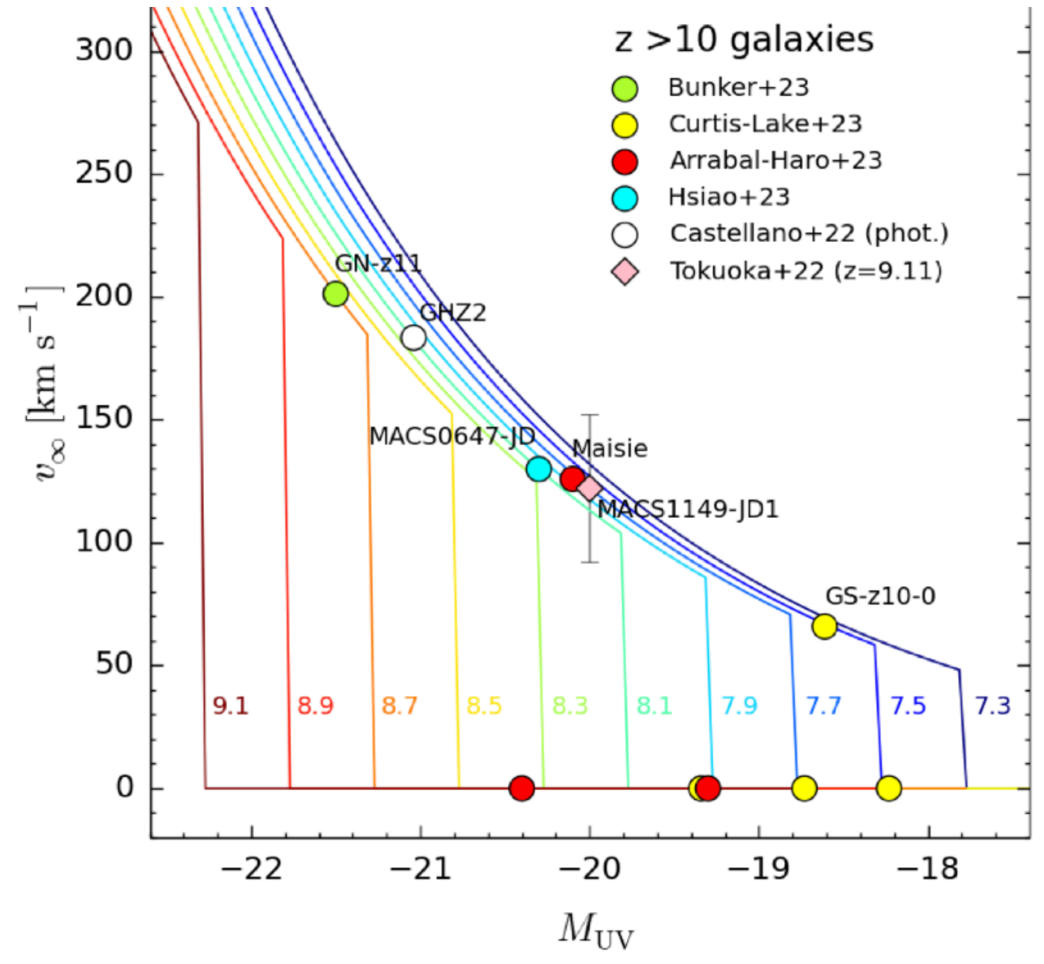
2. Why an on-the-fly dust model



Schneider+2006

Dust physics have **timescales similar** to fundamental **ISM**, making **post-processing challenging**

Ferrara2024



Cloud fragmentation enriched by Pop III

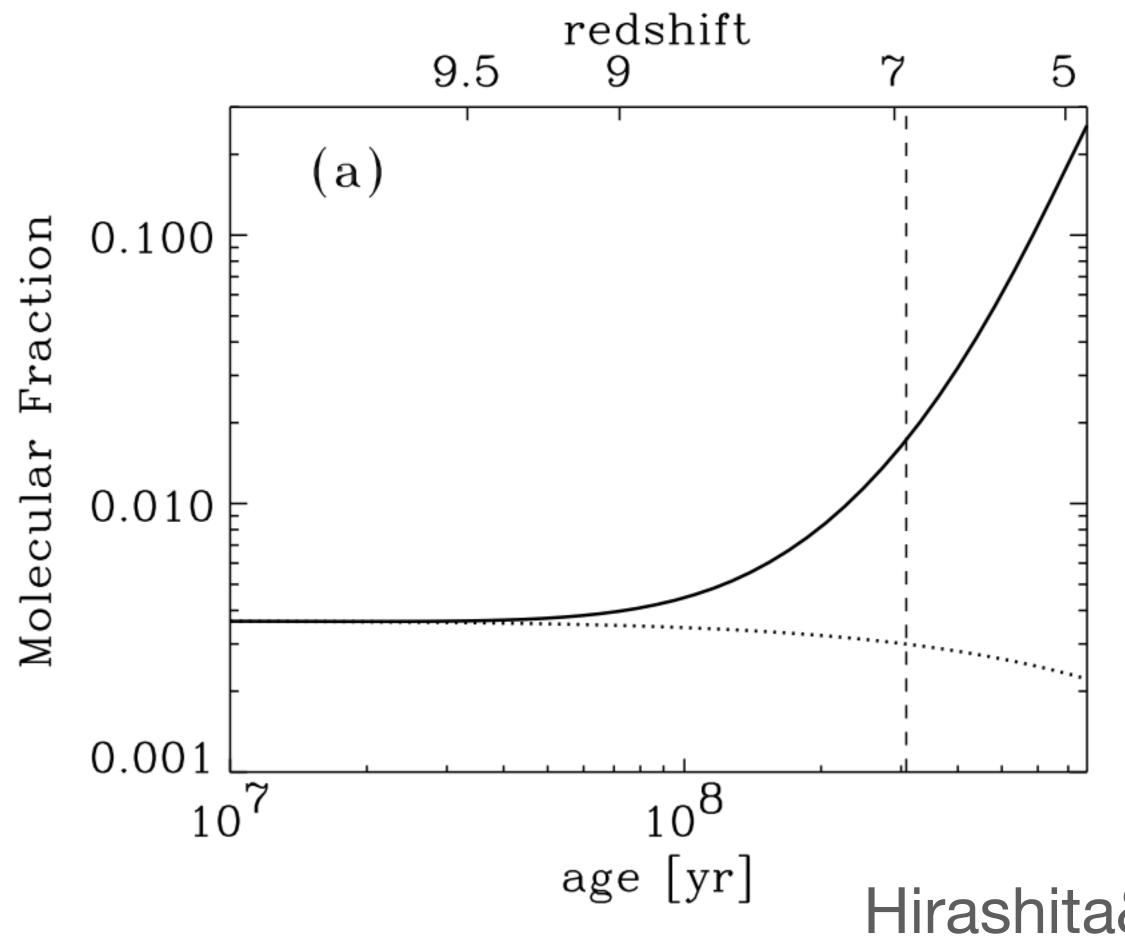
Radiation pressure

Just ~1% of the ISM mass, but a lot of influence!

Elemental abundances and enrichment

Ionisation properties of HII regions

Katz,RM+2022



Hirashita&Ferrara2001

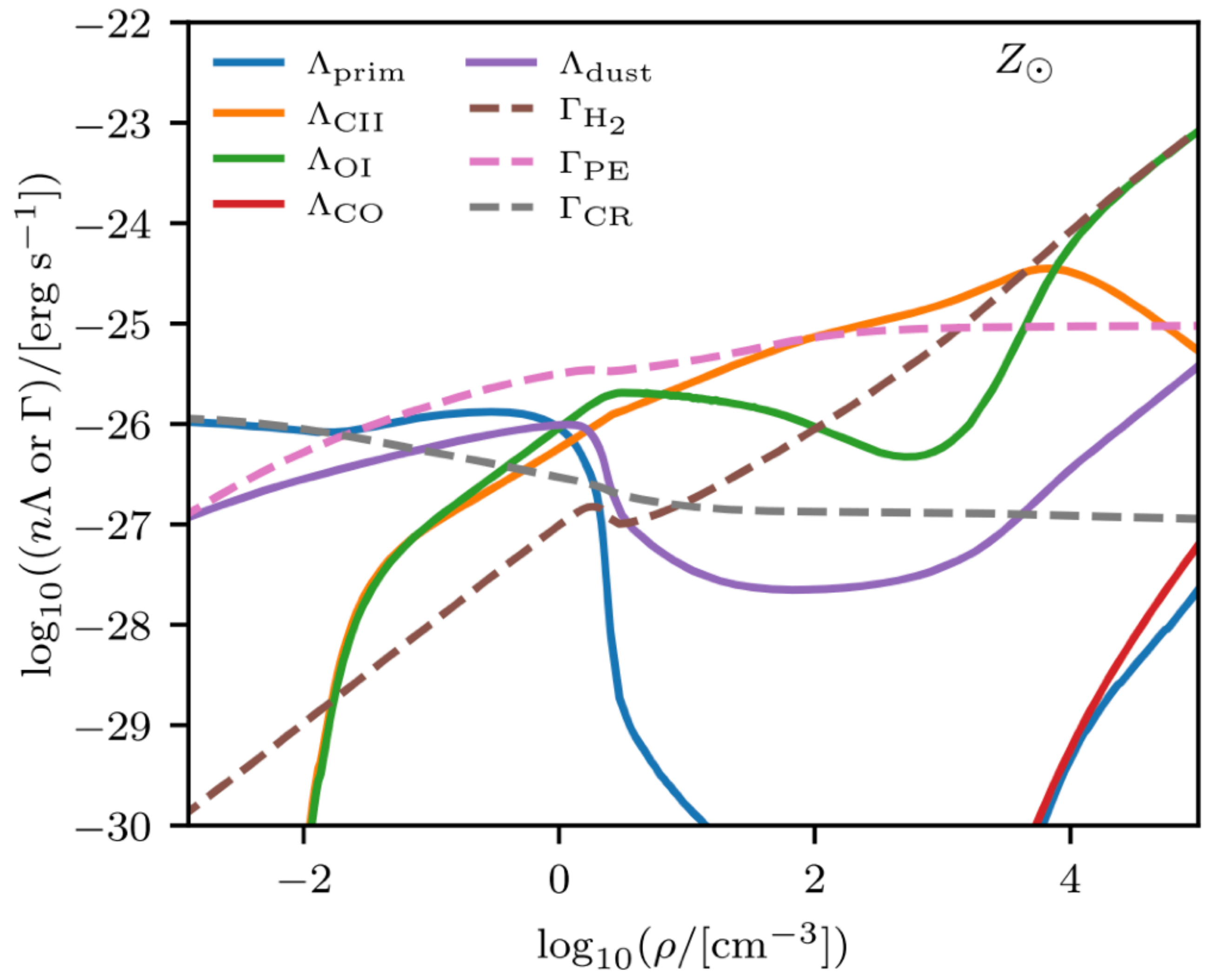
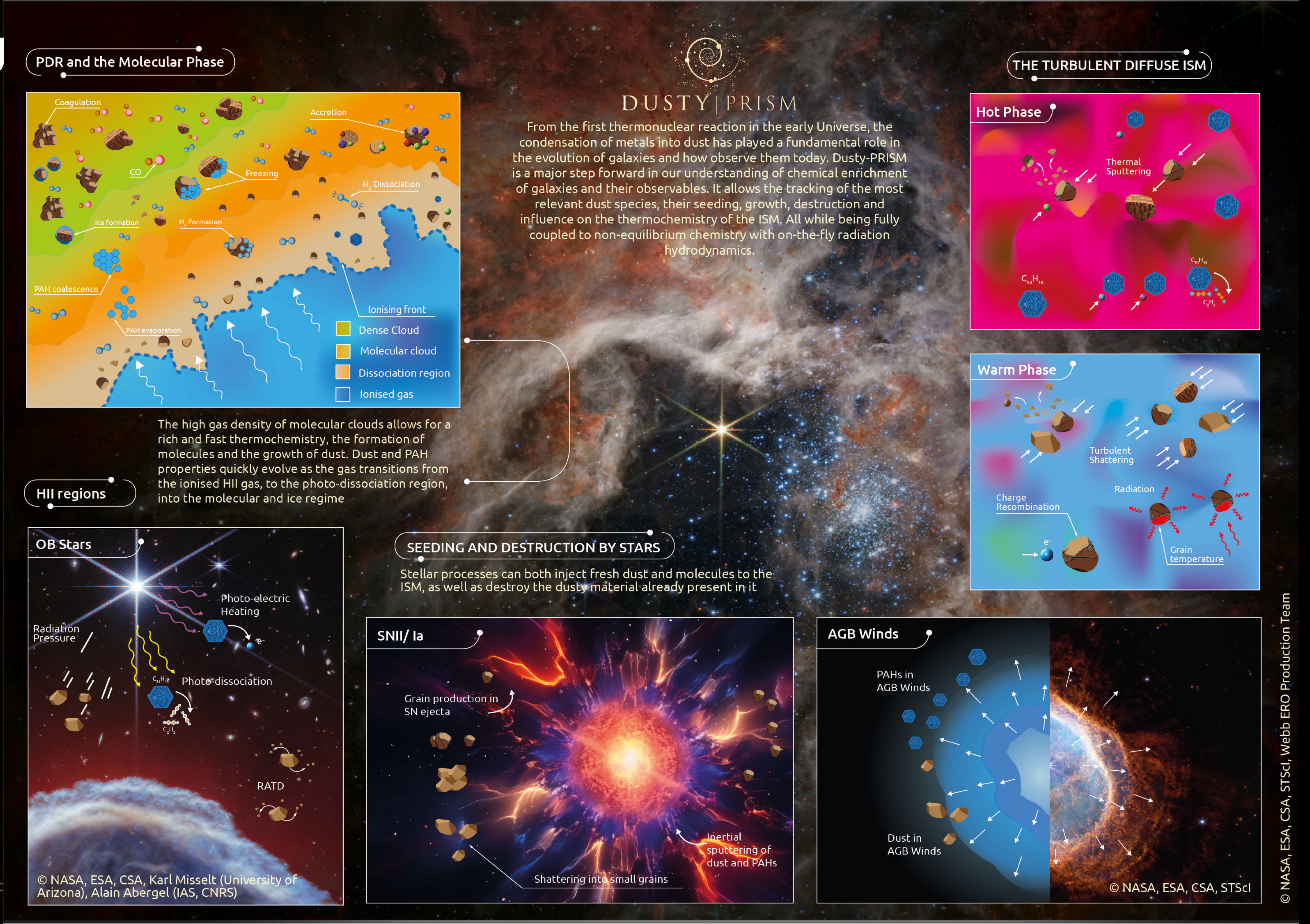


Photo-electric heating

Shielding from UV radiation

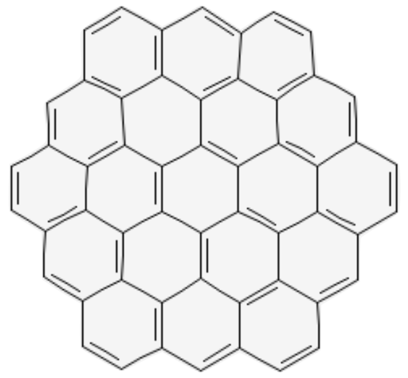
Molecule catalysis

3. Introducing Dusty-PRISM



3. Introducing Dusty-PRISM

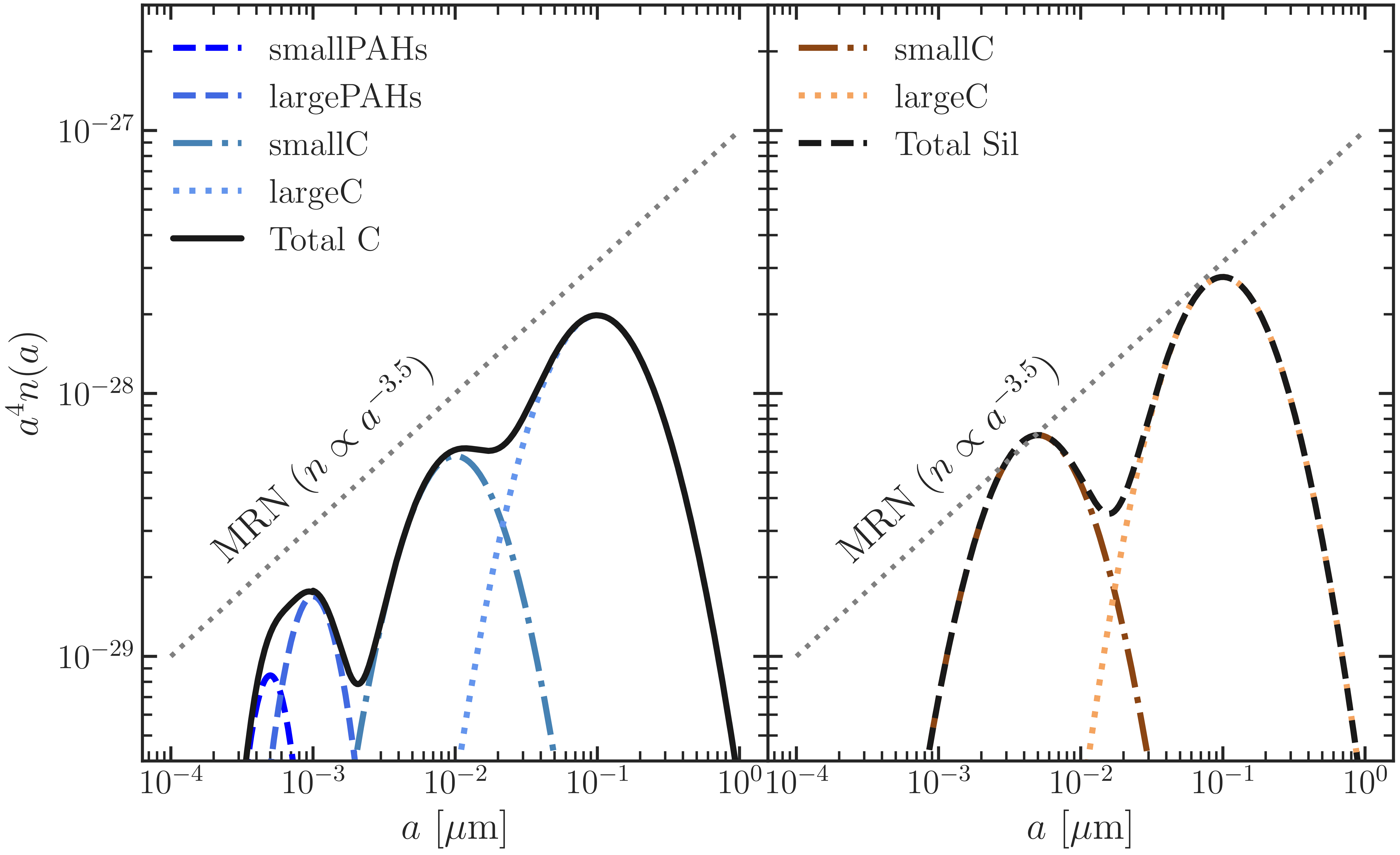
Extending the GSD into the molecular regime


Circumcoronene (C54H18)

Why smalls AND large?

- Strong polarisability = strong bonding between aromatic planes
- Clusters may be the carrier of the mid-IR plateau
- Variation in band ratios
- Link between molecules and amorphous grains

	s [g cm^{-3}]	N_C	a_0 [μm]	a_{min} [μm]	a_{max} [μm]
small PAHs	2.0	54	5×10^{-4}	3×10^{-4}	1×10^{-3}
large PAHs	2.0	418	1×10^{-3}	3×10^{-4}	9×10^{-3}
small C	2.2	-	1×10^{-2}	1×10^{-3}	1×10^{-1}
large C	2.2	-	1×10^{-1}	5×10^{-3}	1.0
small Sil	3.3	-	5×10^{-3}	5×10^{-4}	1×10^{-1}
large Sil	3.3	-	1×10^{-1}	5×10^{-3}	1.0



3. Introducing Dusty-PRISM

Building a dynamical, molecular ISM

diffusion length

(Gas-dust fully coupled) $L_{\rm D} = 5\left(\frac{a_{\rm gr}}{0.1\mu{\rm m}}\right)\left(\frac{n}{1{\rm cm}^{-3}}\right)^{-1}\left(\frac{\sigma_{\rm gr}}{c_{\rm s}}\right)$ pc

Implementation in the RAMSES code:

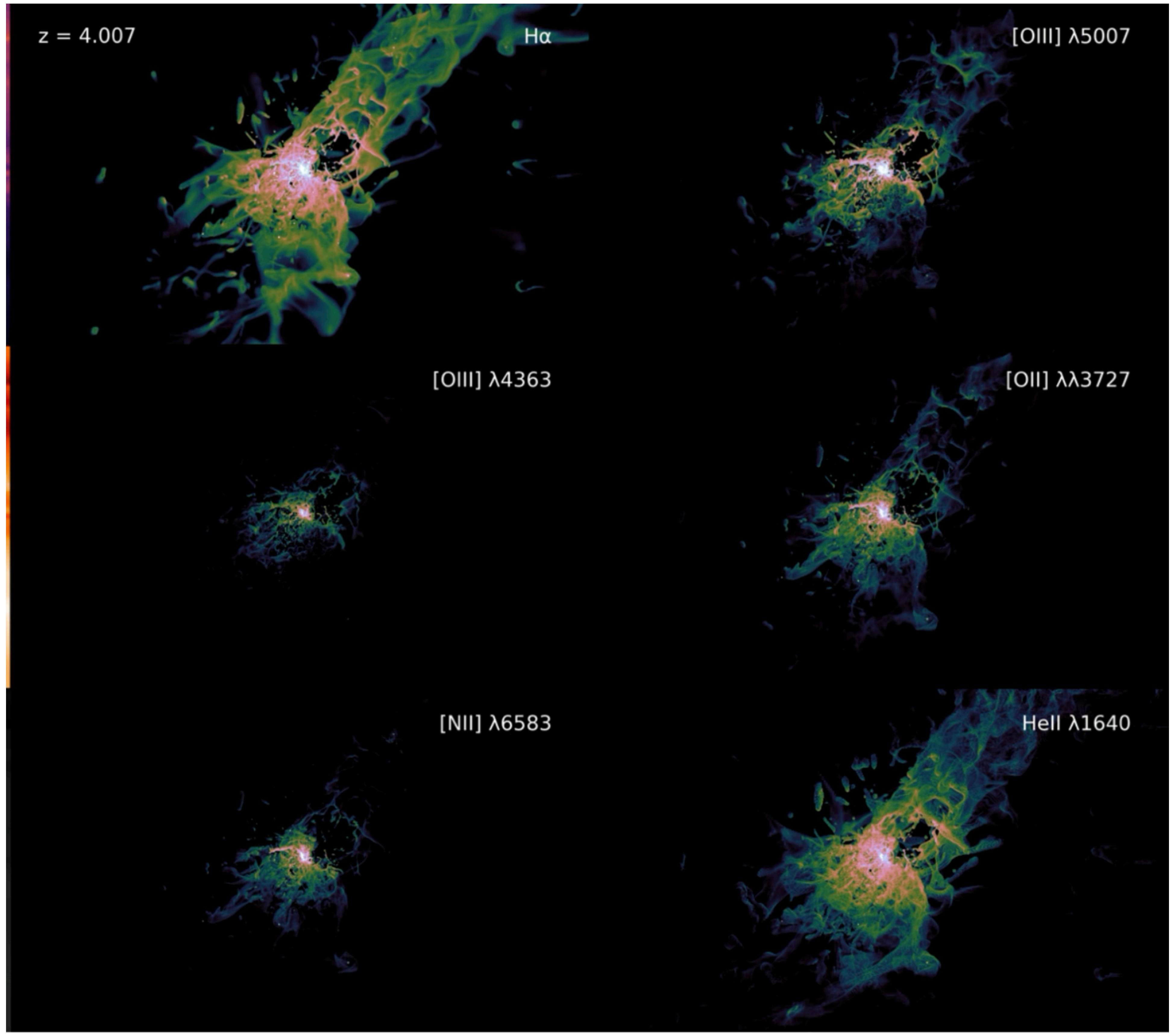
radiation transfer hydrodynamics code with magnetic fields and cosmic ray transport

ISM Physics

- M1 multi-band on-the-fly radiation transfer
- Full non-eq chemistry network tracking the population of ~150 ions, H_2 and CO
- H/He and metal cooling
- H_2 heating and cooling
- Photo-heating
- Photo-electric heating
- Charge transfer
- Cosmic ray heating

Dust physics

- 6 grain species
- Tracking of ice formation
- Turbulent model for shattering and coagulation
- Size-dependent sputtering and collisional cooling
- H_2 formation
- RAT-D
- Sublimation
- Charge-mediated accretion
- Recombination cooling and photoelectric heating



3. Introducing Dusty-PRISM

Coupling to on-the-fly multi-bin RT and non-eq chemistry

(Optical properties based on the NASA AMES PAH Database)

Photo-electric heating (PEH)

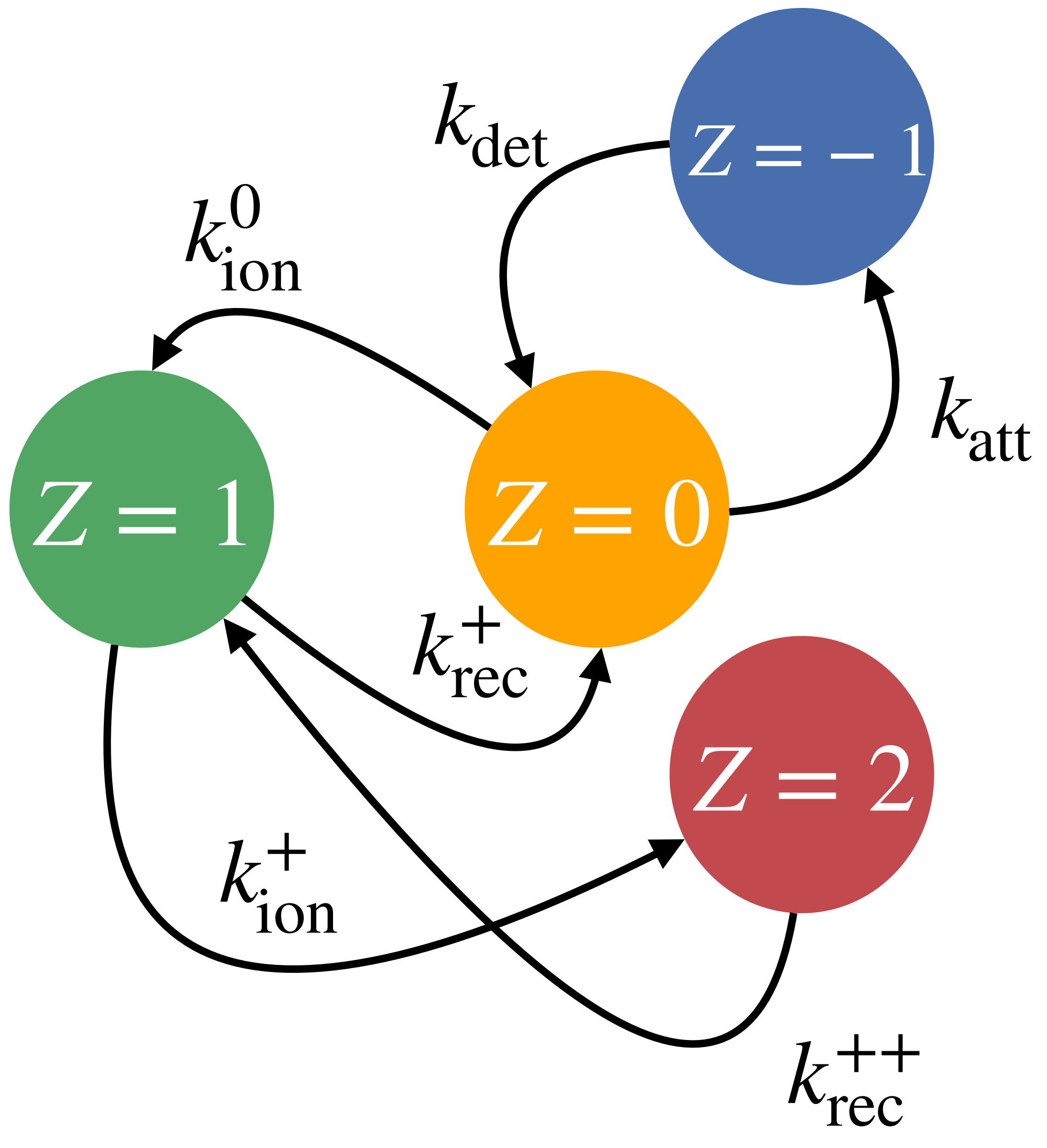
Consider at every position and time:
Photo-ionisation
+ Recombination
+ Electron attachment
+ Electron detachment

Self-consistent local heating!!

Photo-dissociation

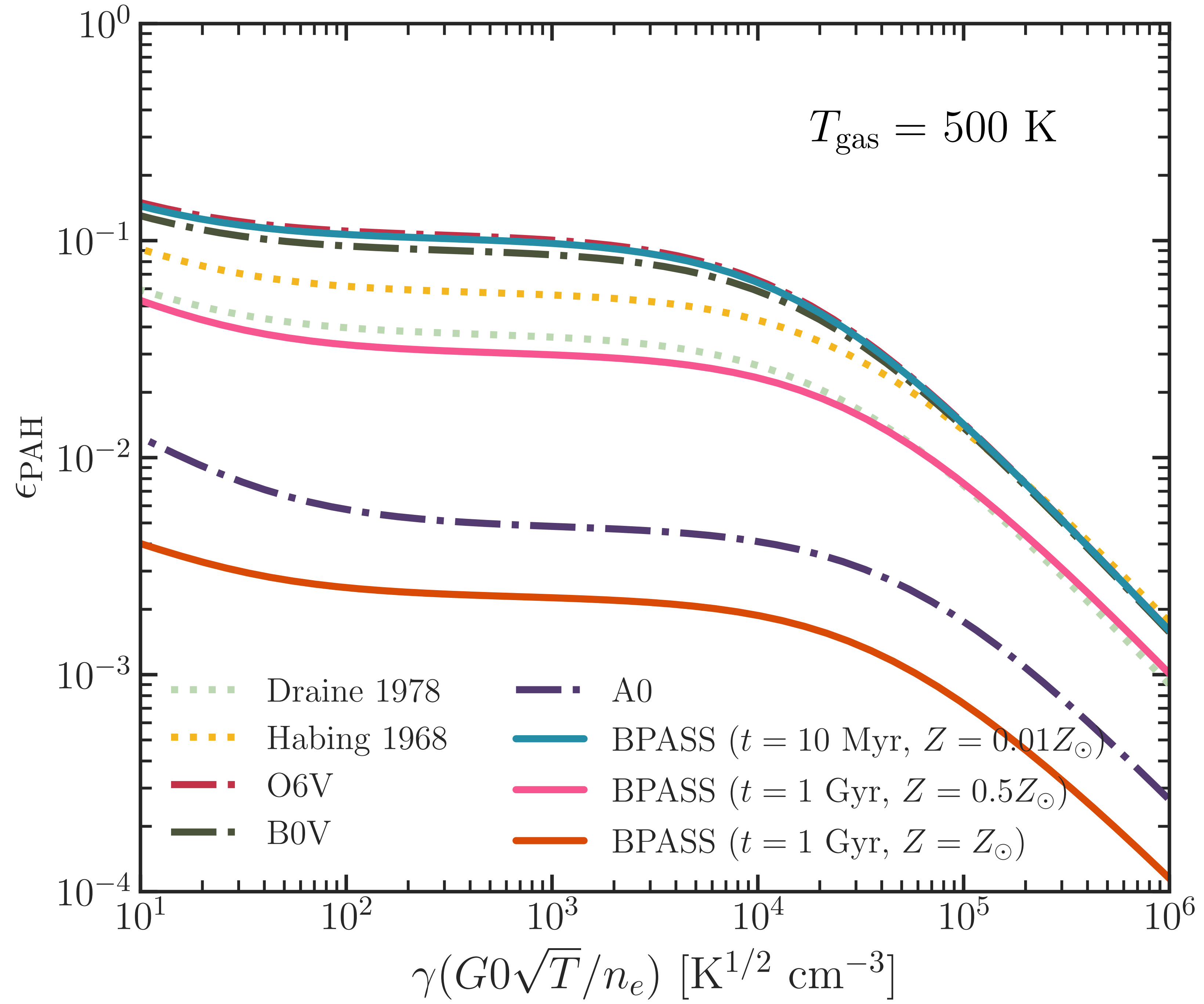
$$P^{C_2H_2}_{\rm diss}(E) = \frac{k^{C_2H_2}_{\rm diss}(E)}{k^{C_2H_2}_{\rm diss}(E) + k_{\rm IR}/(n_{\rm max} - 1)}$$

$$R^{C_2H_2}_{\rm diss}(G_0) = \int_{6\,{\rm eV}}^{13.6,{\rm eV}} \chi_{\rm dH}\sigma_{\rm PAH}(E) P^{C_2H_2}_{\rm diss}(E)\frac{F(E)}{E}{\rm d}E$$



Only for de-hydrogenated PAHs!

(For the diffuse ISM $\sim 4.7 \times 10^{-17} [s^{-1}]$, ~10x faster than Allain+1996)



PEH depends on the shape of the spectrum, which is not consider in state-of-the-art ISM models (Wolfire+2003, Bialy & Sternberg2019, Kim+22)

3. Introducing Dusty-PRISM

Thermal and non-thermal destruction

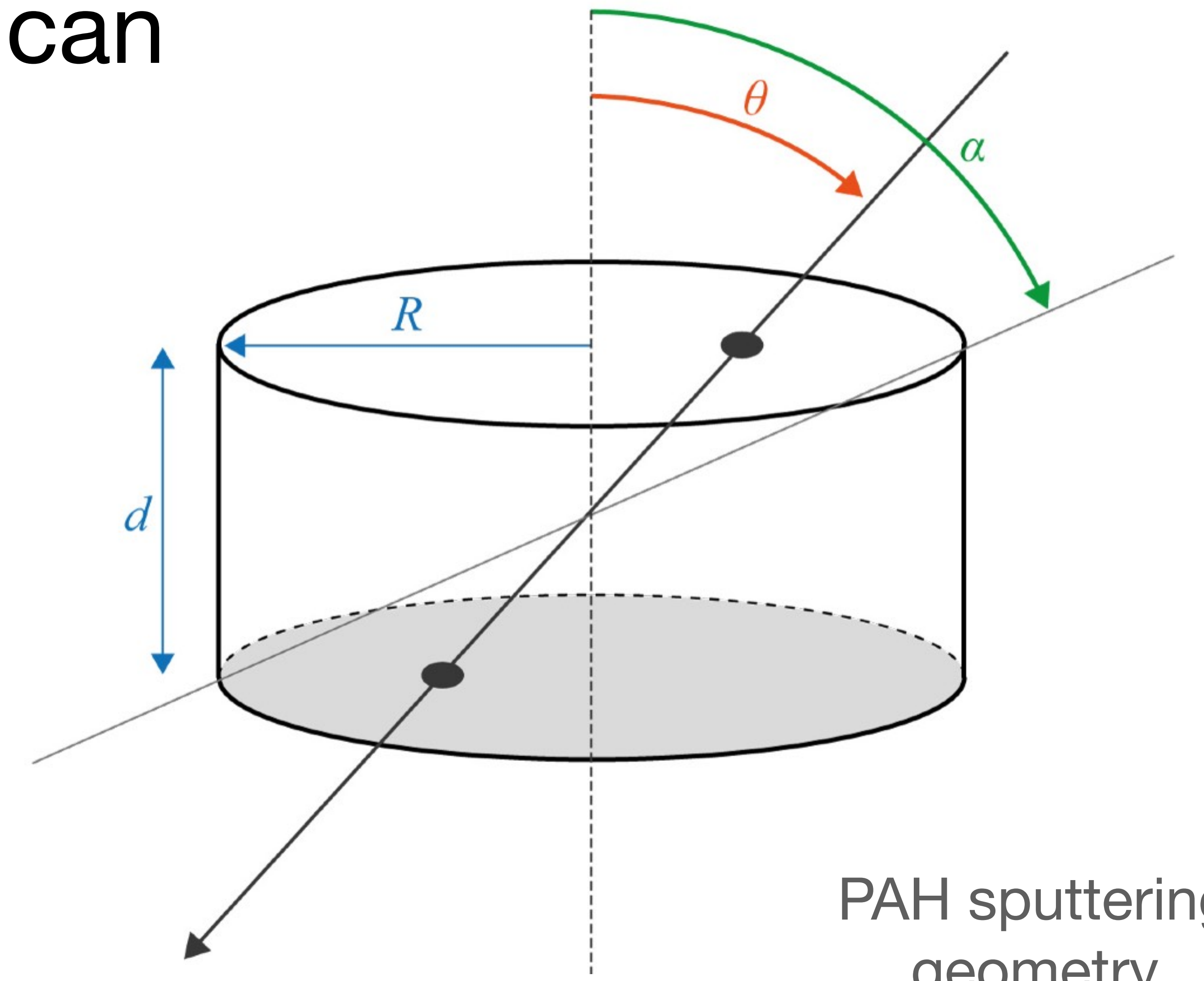
We follow also the RRKM theory as for photo-dissociation + data from the work of Micelotta+2010a

Collisions are dominated by e-, H, He and C

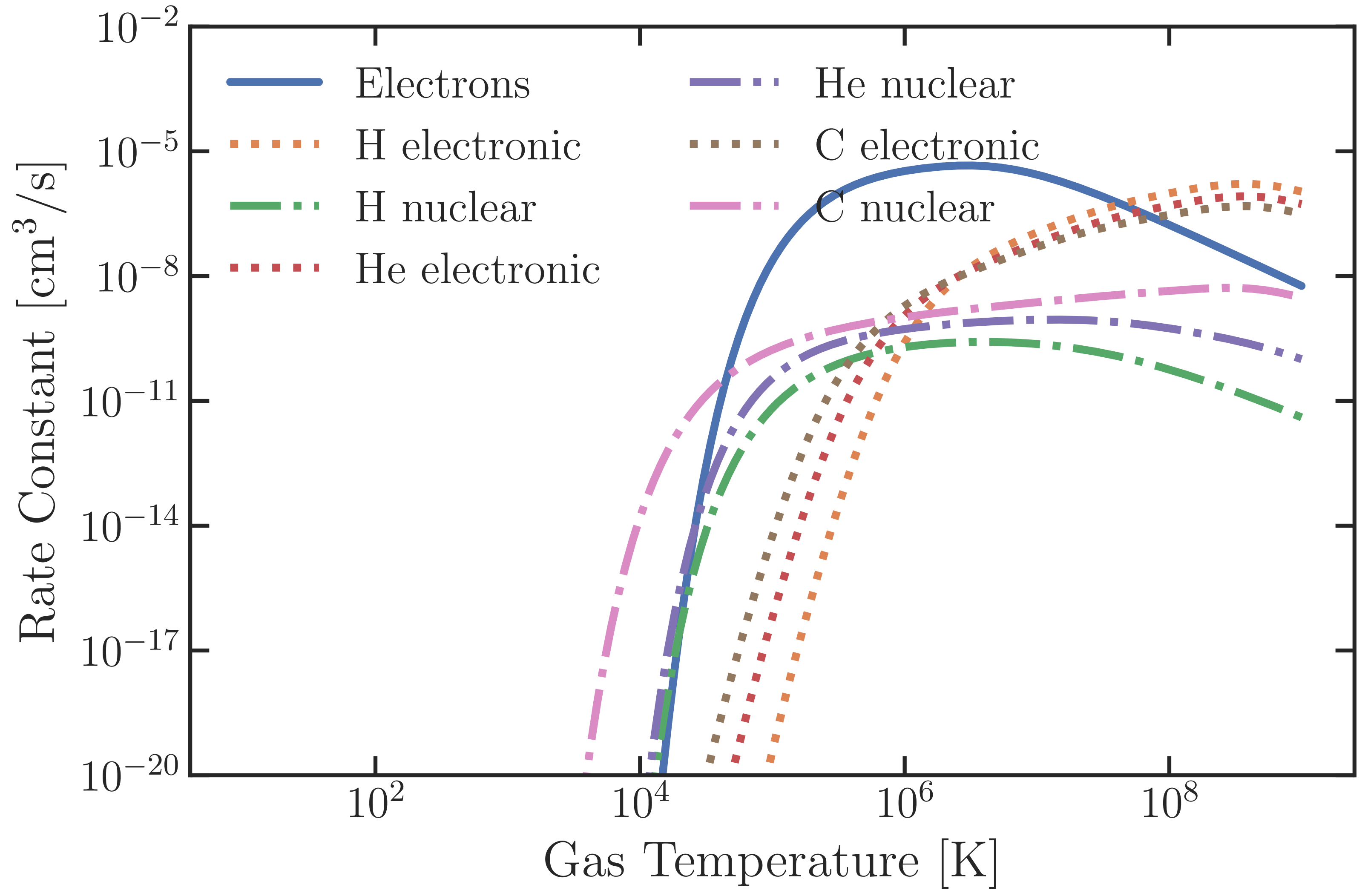
We consider sputtering when acetylene (C_2H_2) dissociation is achieved

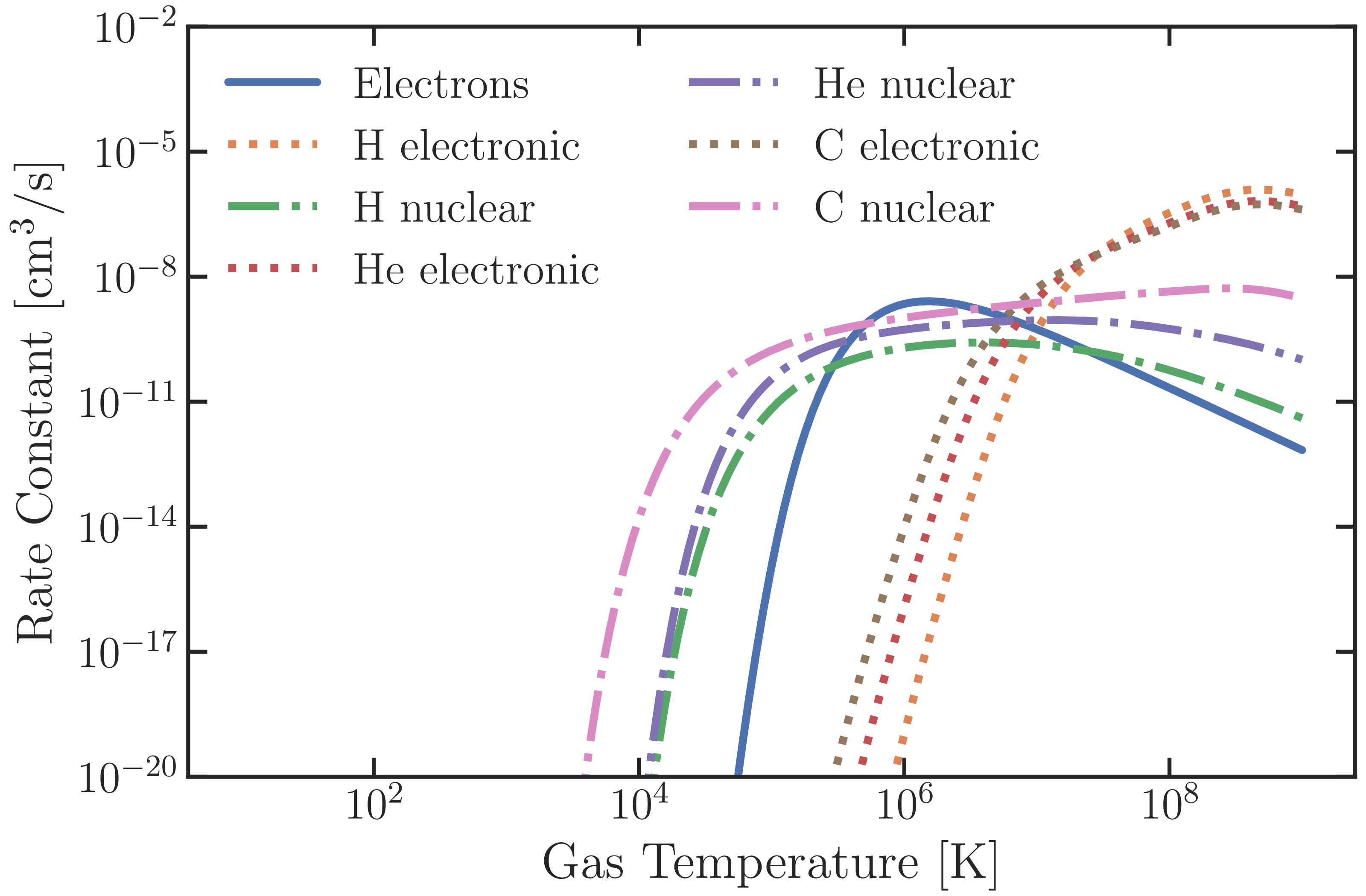
Upon collision, the excited state can decay via:

- IR emission
- Ionisation
- Thermionic emission
- Fragmentation



PAH sputtering geometry

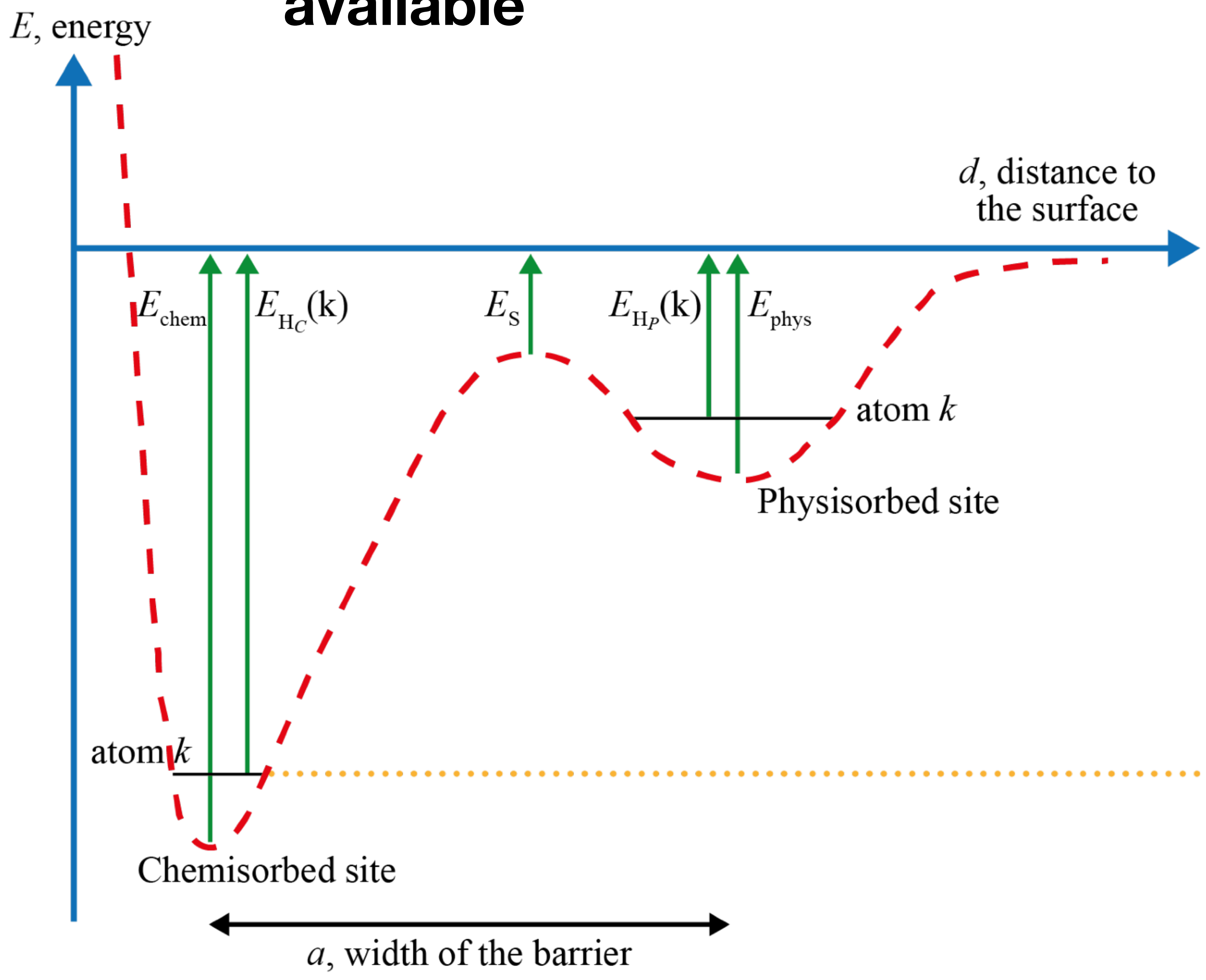




3. Introducing Dusty-PRISM

PAHs as a chemical catalyst

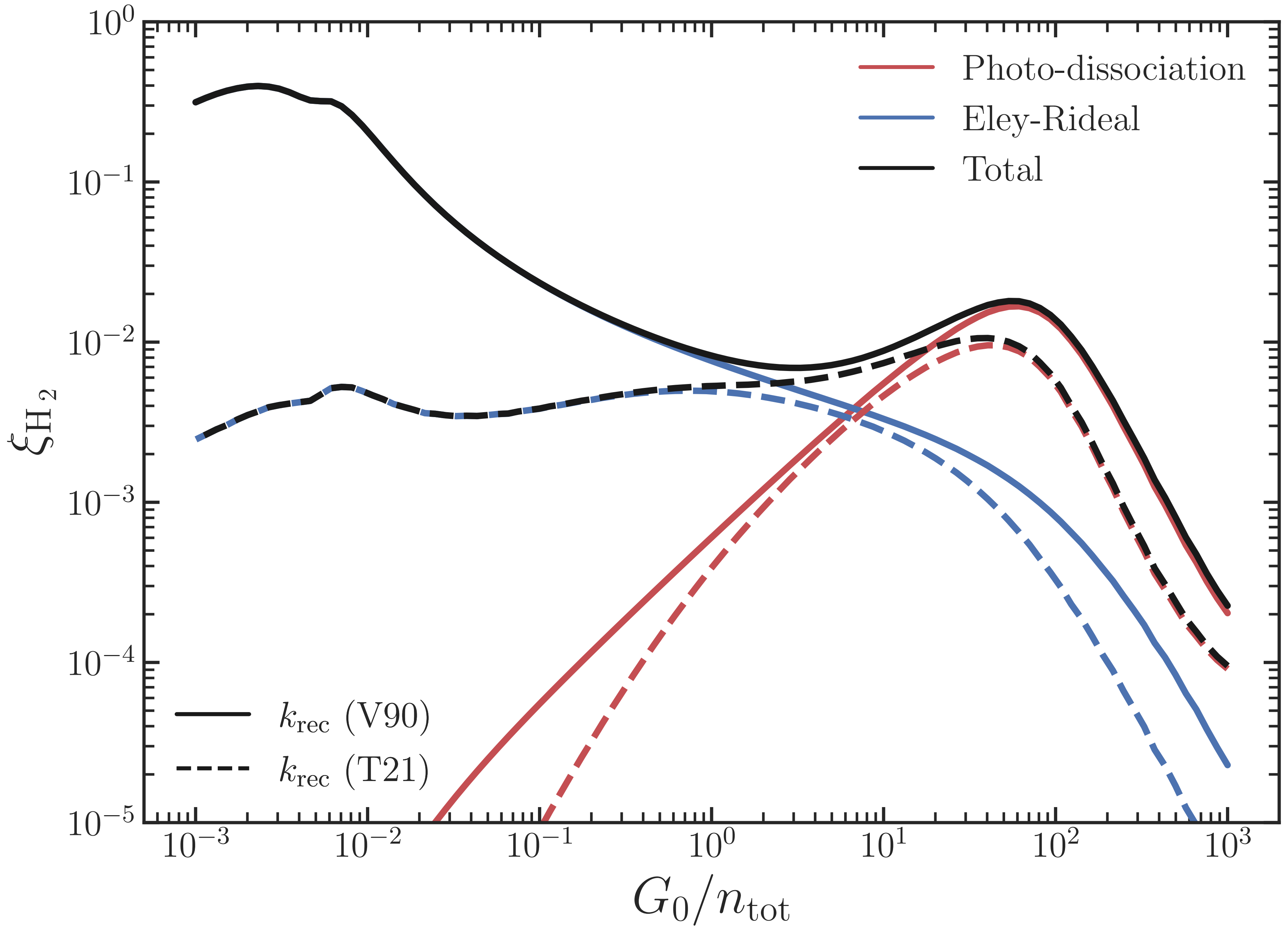
Beyond ~20 K, physisorbed site **no longer available**



Large **drop in H_2 formation efficiency**, in stark contrast to observations of PDRs (Habart+2003b,Allers+2005)

We consider:

- H covalent bond then abstracted by another H
- Photo-desorption of H_2 by a super-hydrogenated PAH

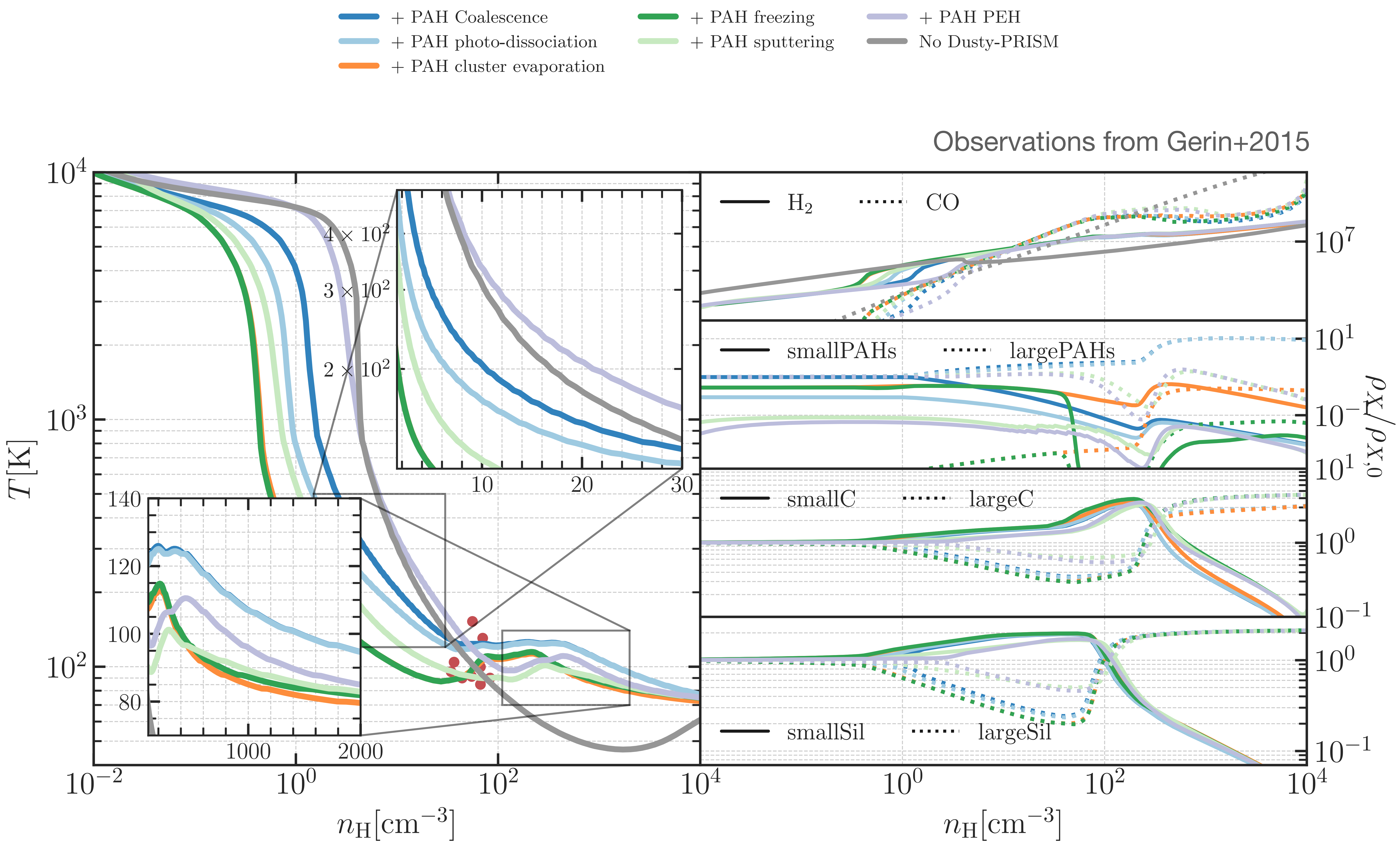


3. Introducing Dusty-PRISM

G8 simulation: low metallicity, dwarf galaxy

3. Introducing Dusty-PRISM

How different PAH processes affect the equilibrium curve in the ISM



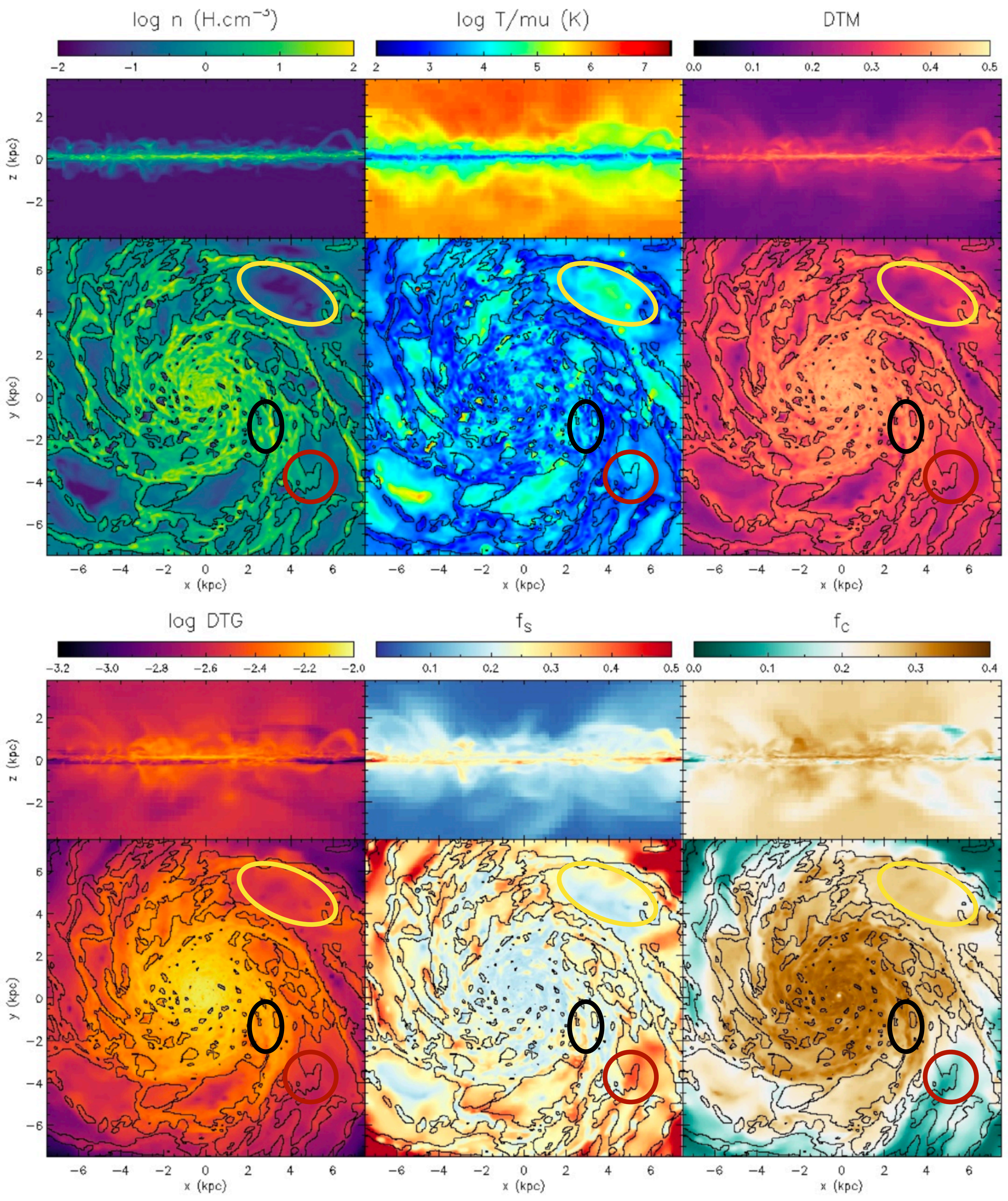
- Fix PAH fraction predicts too much heating
- Photo-dissociation reduces the abundance in the diffuse gas and close to the cooling instability
- Cluster evaporation allows for higher small PAH abundance, but little effect in the cooling
- Similar for freezing
- Sputtering destroys PAHs that could be forming H_2, hence less cooling
- Consistent PE Heating recovers the cooling instability of the no-dust simulations

4. What gives rise to the extinction curve of the Local Group?

The G8, G9 and G10 suite of isolated galaxy simulations

- Hydro simulations with adaptive mesh refinement code **RAMSES** (*Teyssier 02*)
- **Isolated disc** initial conditions
- **Halo mass** 10^{10},10^{11},10^{12} M_{sun}
- **Stellar mass** $2x10^8$ M_{sun}, $2x10^9$ M_{sun}, $2x10^{10}$ M_{sun} (B/D=0.2)
- Disc **gas fraction** 10 or 50%
- Initial <$\mathbf{Z_{gas}}$>=[0.1,0.3,0.8,1.6] Z_{sun}
- Initial **Solar composition** of elements
- 10^6 star particles + 10^6 DM particles
- Mass resolution ($8x10^3$ M_{sun}) + Jeans length refinement
- **Δx_{min}=20 pc** (also 10, 40, 80 pc)
- *Initial stars do not contribute to the overall feedback/metals/dust*

- Gas cooling down to T_{min}=10 K
- Star formation with $\dot{\rho}_\star = \varepsilon_{ff}\rho_g/t_{ff}$ and gravo-turbulent efficiency: $\varepsilon_{ff} = f(\mathcal{M}_{turb}, \alpha_{vir})$
- SNII feedback + SNIa+ stellar winds



Dubois,RM+2024

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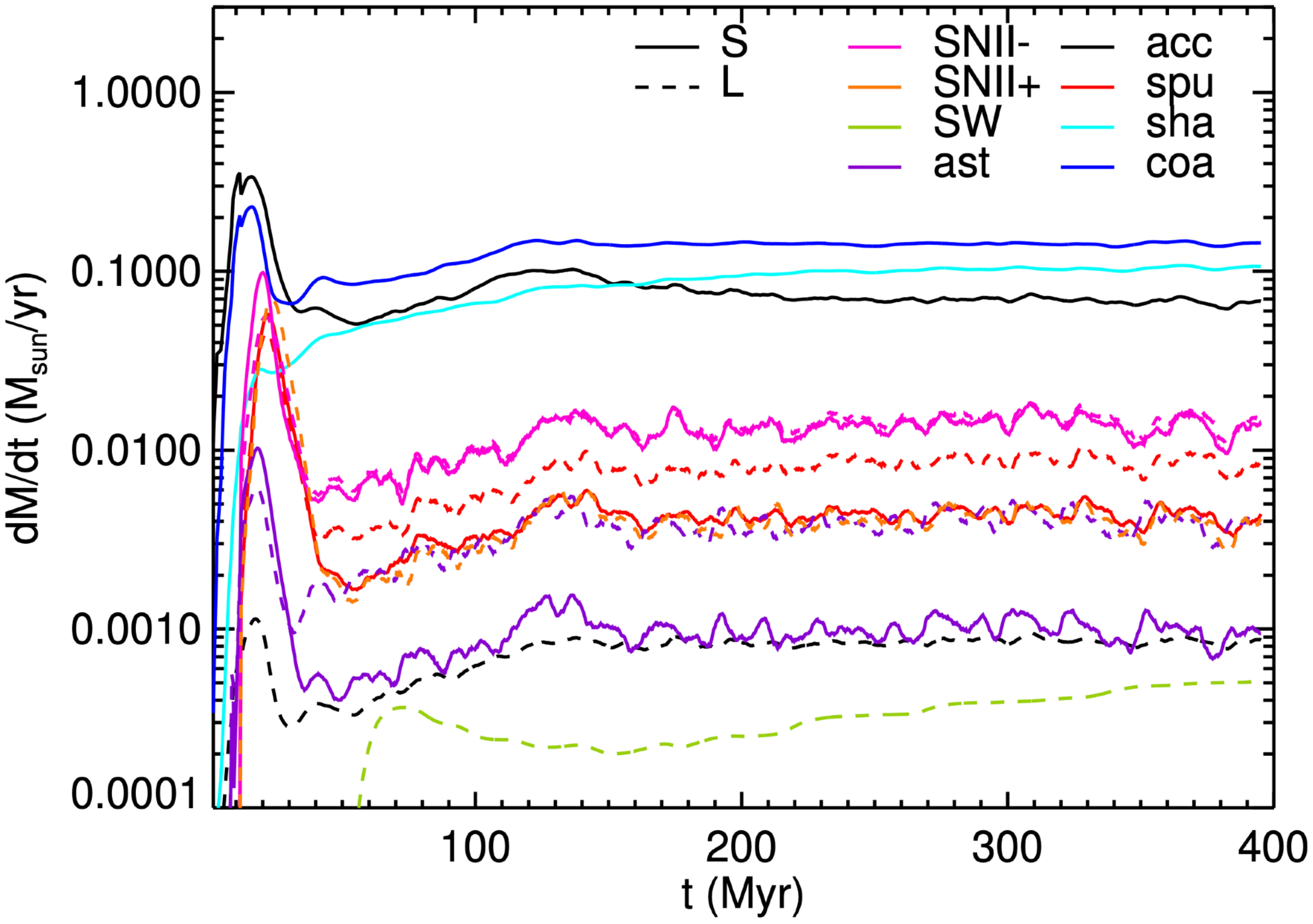
The G8, G9 and G10 suite of isolated galaxy simulations



$t_{acc,Sil} \simeq 2\,\mathrm{Myr}$ $\bar{n} \simeq 30\,\mathrm{H\,cm^{-3}}$

$t_{acc,C} \simeq 10\,\mathrm{Myr}$ $\mathcal{M} = \sigma_{turb}/c_s \simeq 3$

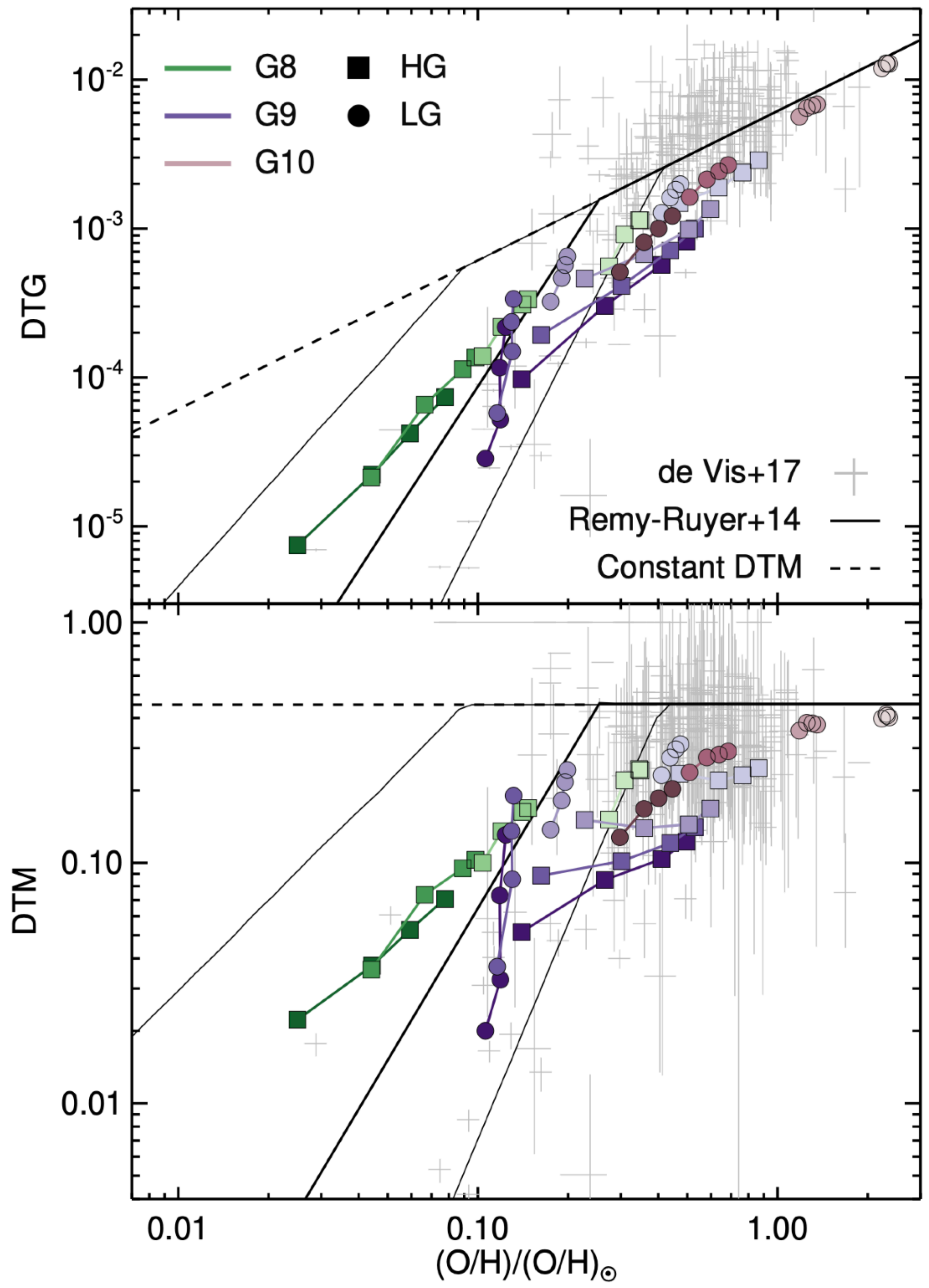
$t_{ff} \simeq 8\,\mathrm{Myr}$

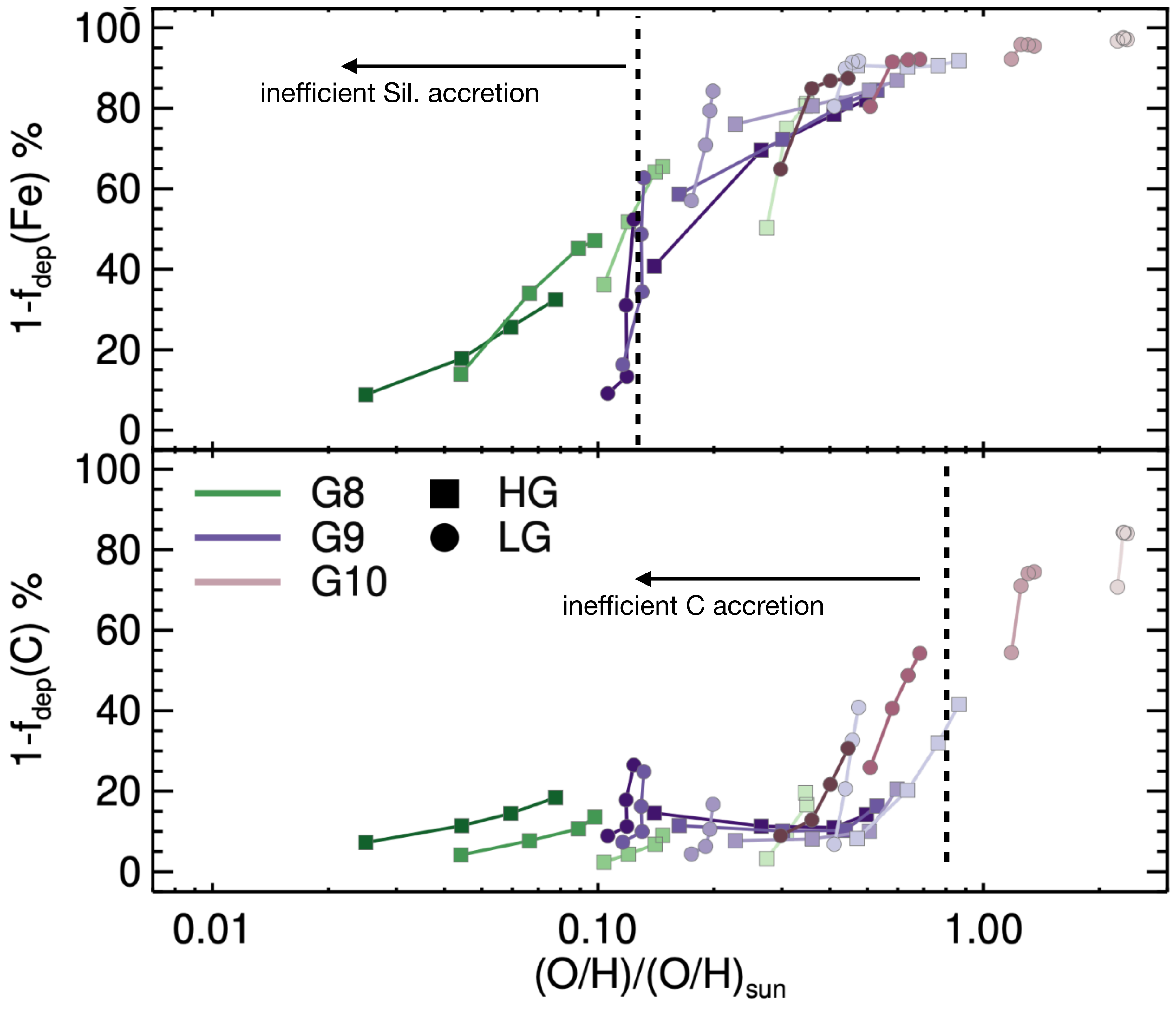
MW-like galaxy
$M_{halo}=10^{12}\ M_{sun}$
$f_{gas}=10\%$

- Accretion from ISM on grains (small grains) more efficient than stellar ejecta
- Coagulation and shattering very strong ➡shape the size distrib.
- Direct destruction by SNII is the dominant destruction process
- Astration and AGB winds negligible

4. What gives rise to the extinction curve of the Local Group?

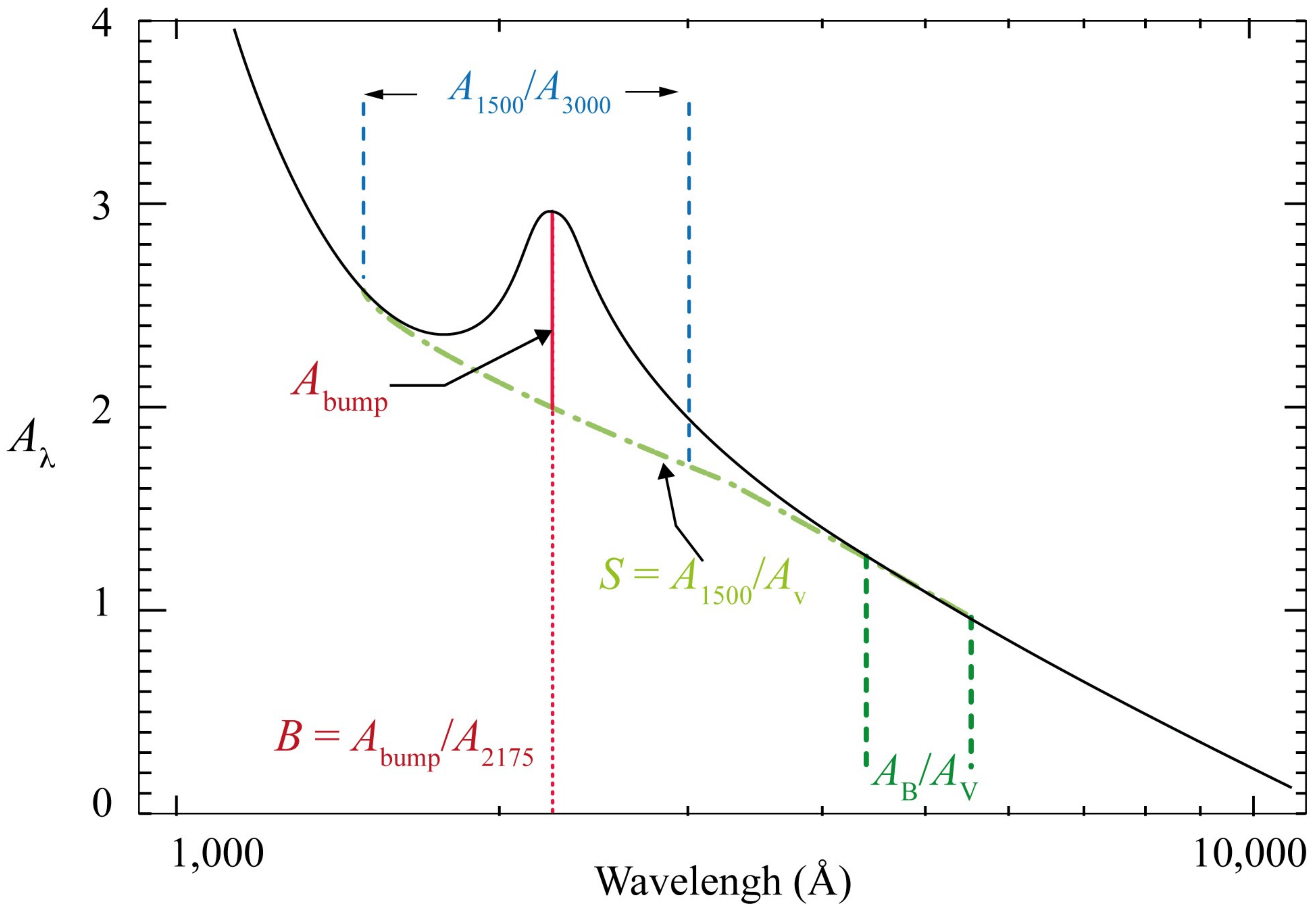
DTM/DTG variation with metallicity

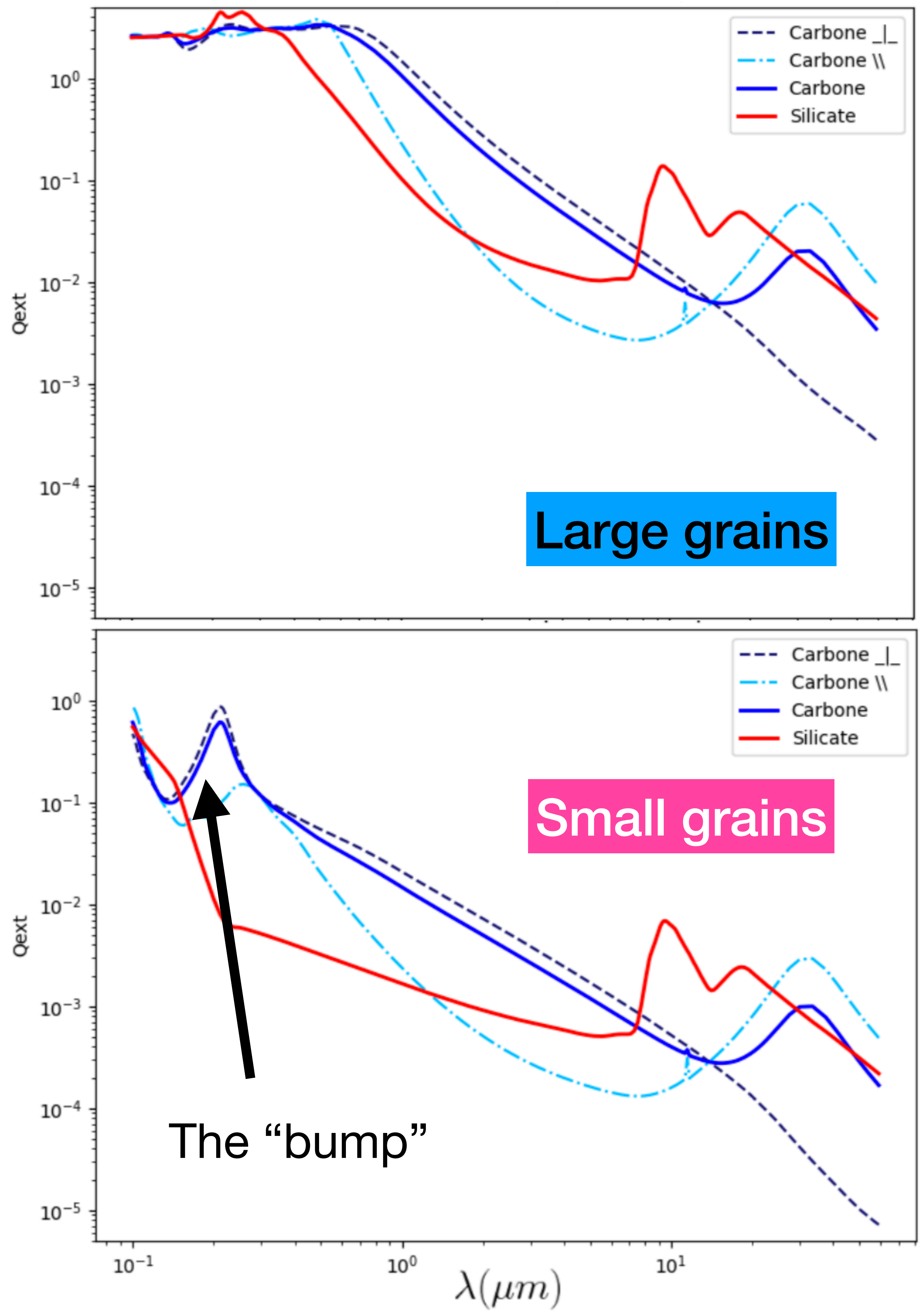




4. What gives rise to the extinction curve of the Local Group?

Evolution of extinction curve parametrisation





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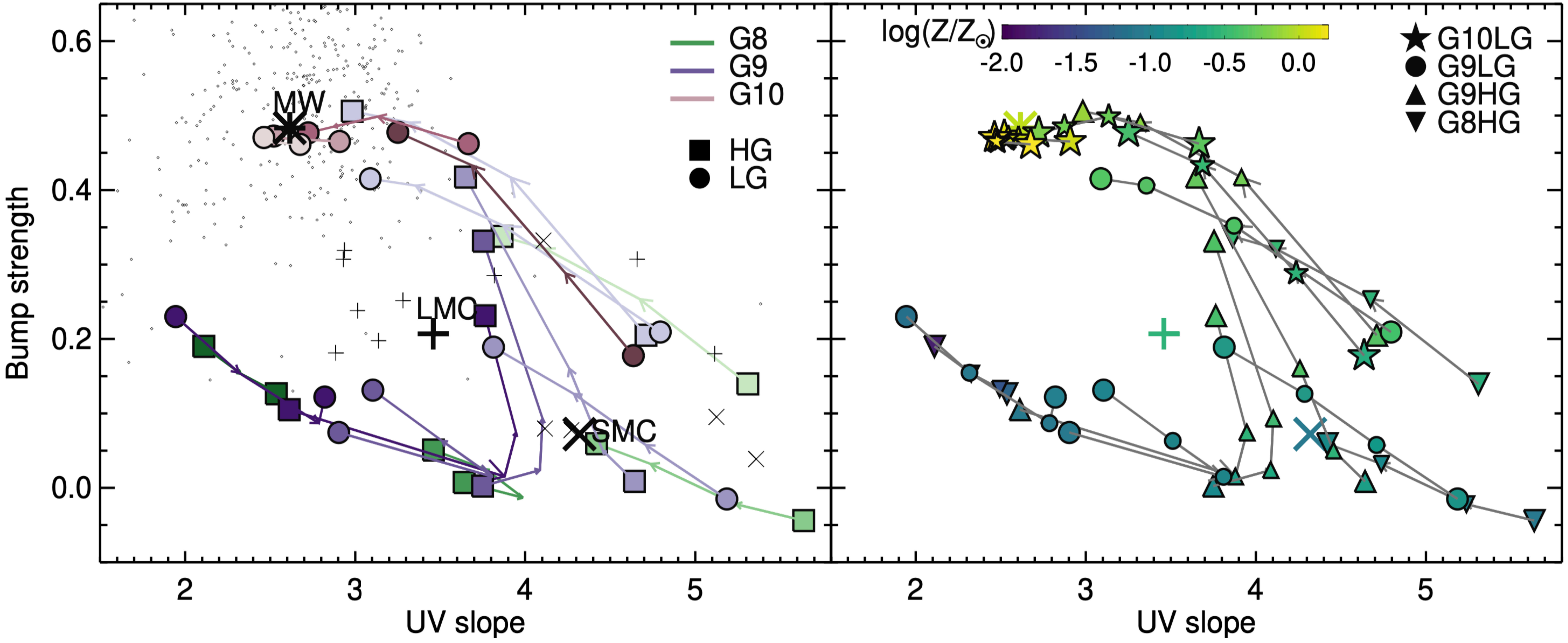

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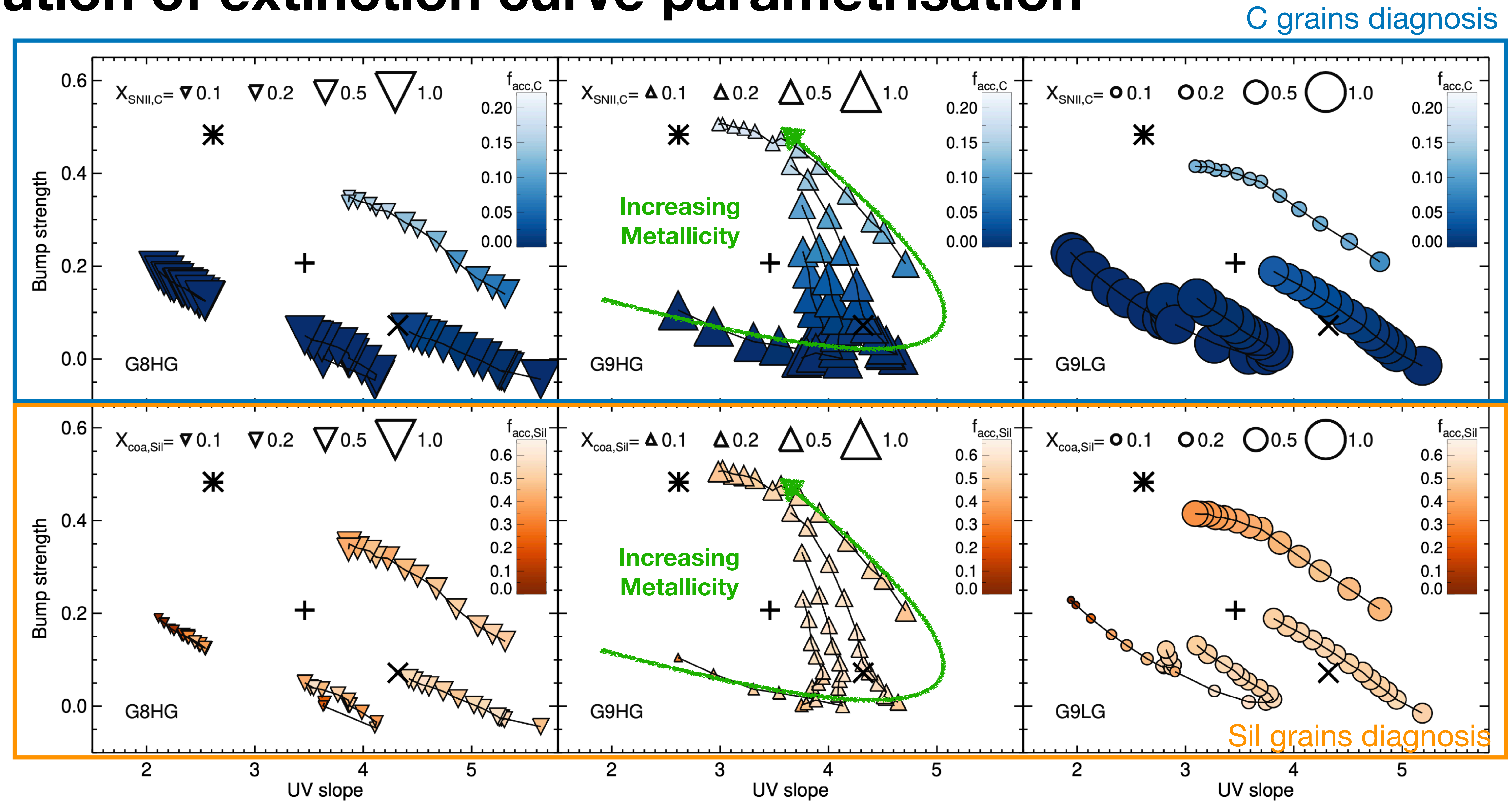
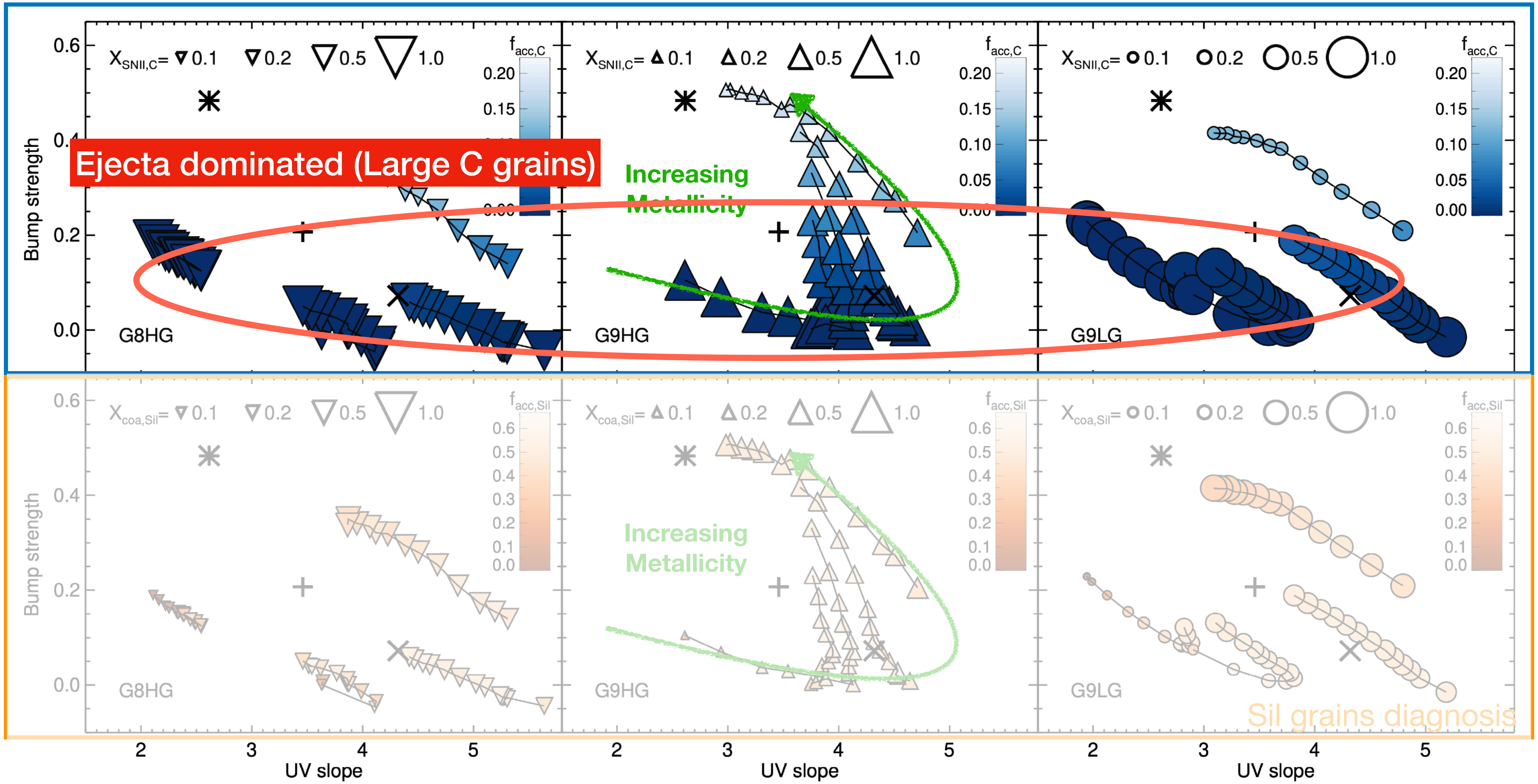


Francisco Rodríguez Montero - PRIMA Conference, Marseille 2025

4. What gives rise to the extinction curve of the Local Group?

Evolution of extinction curve parametrisation

C grains diagnosis



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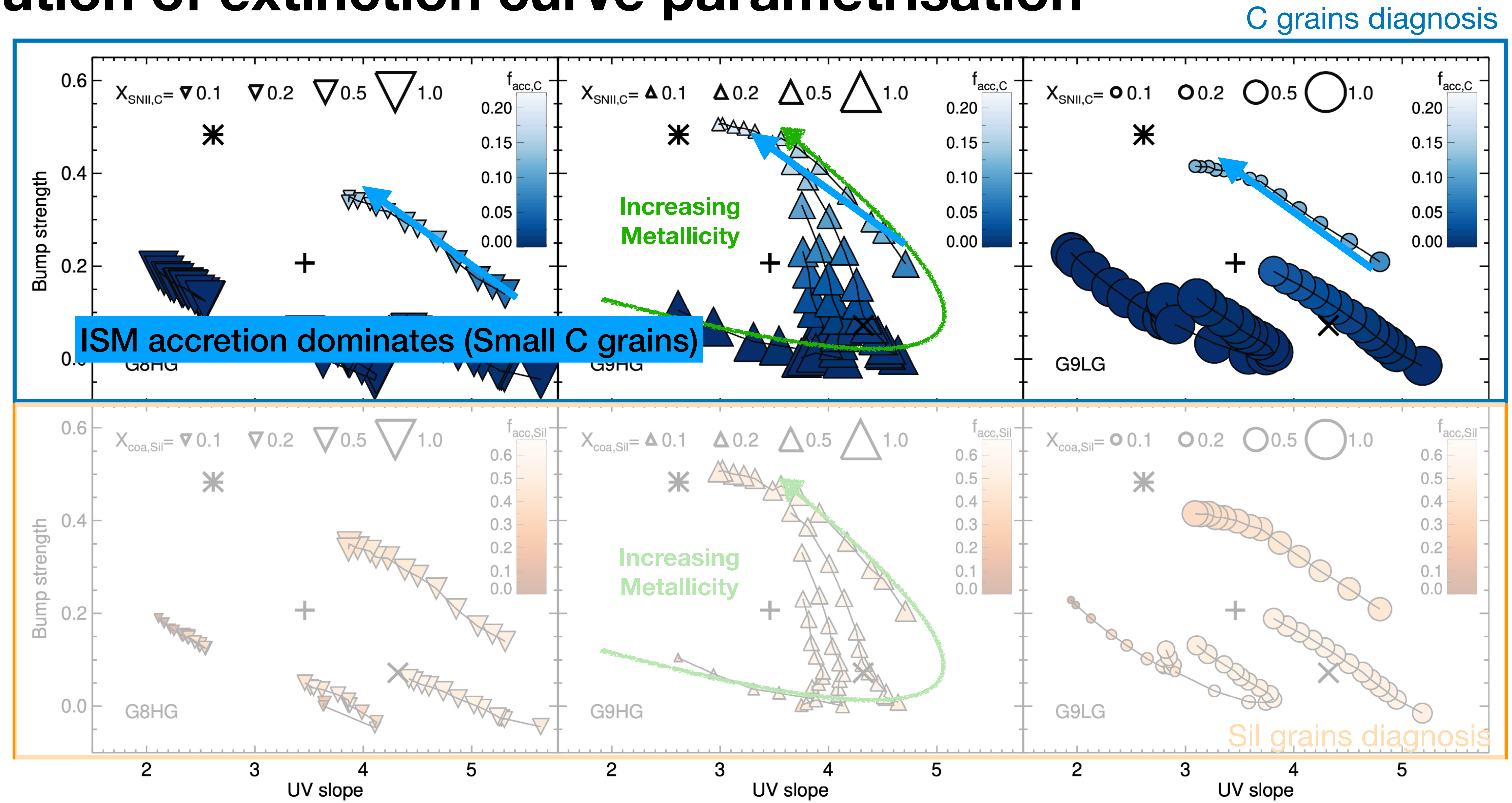

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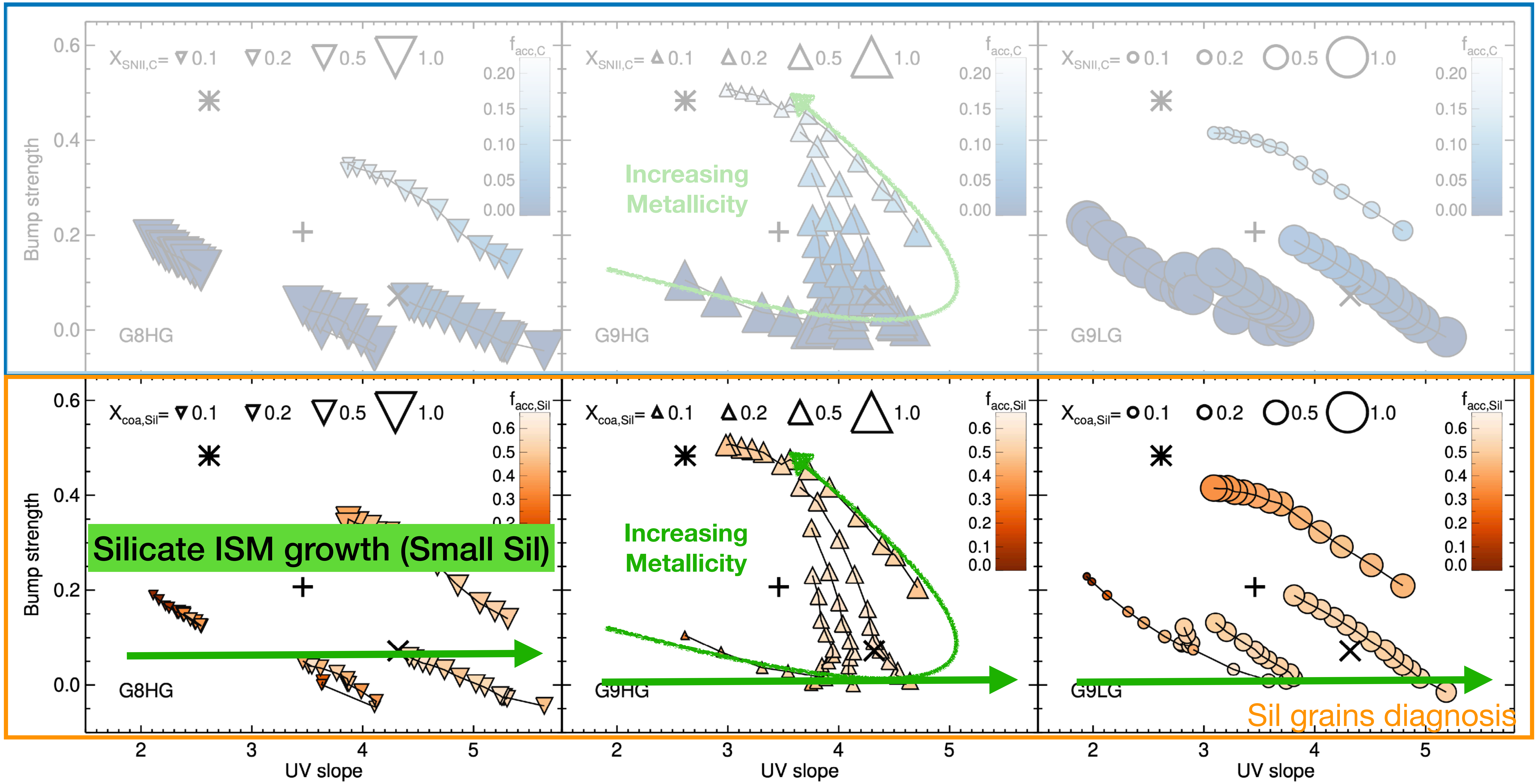

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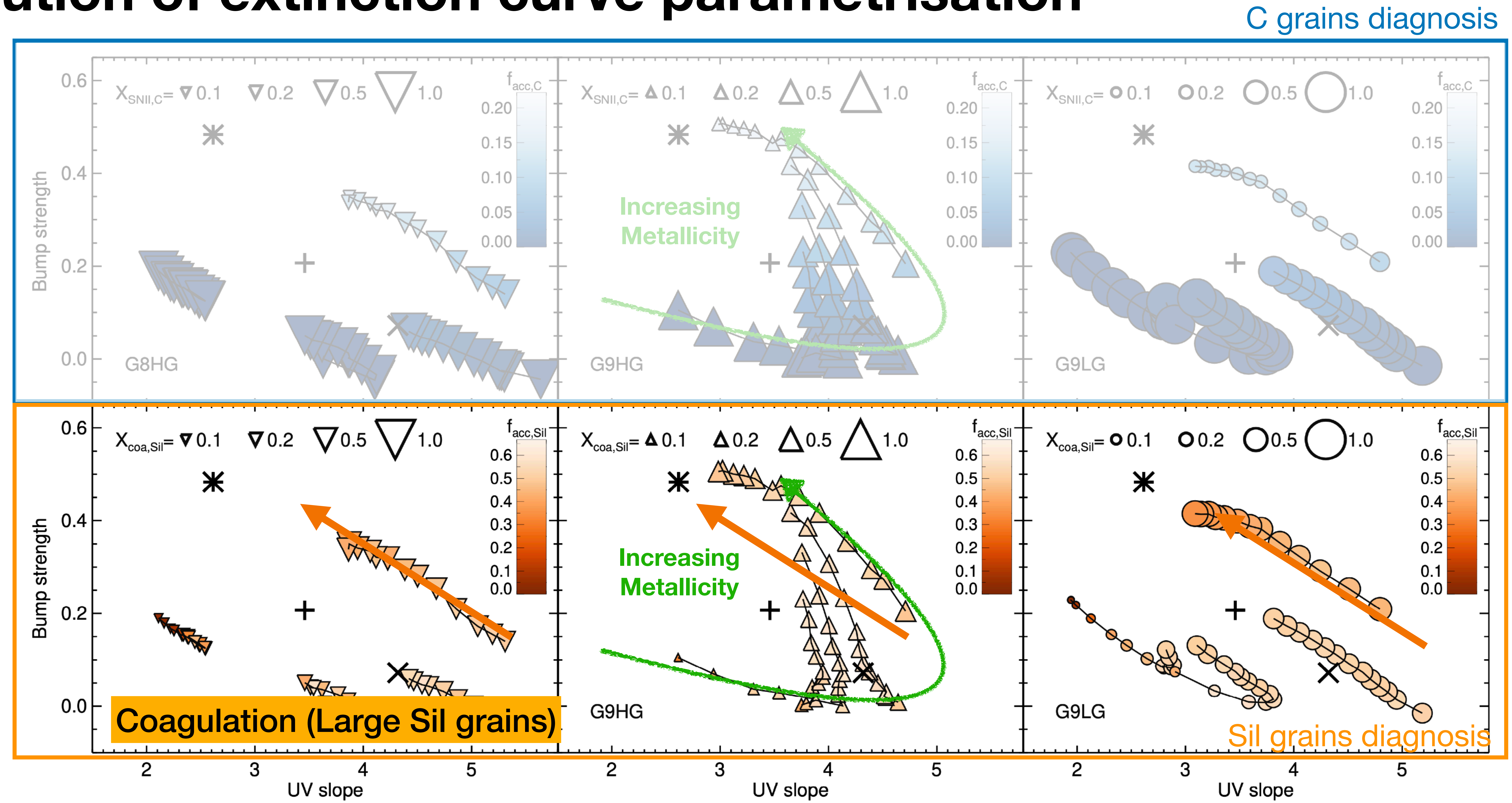

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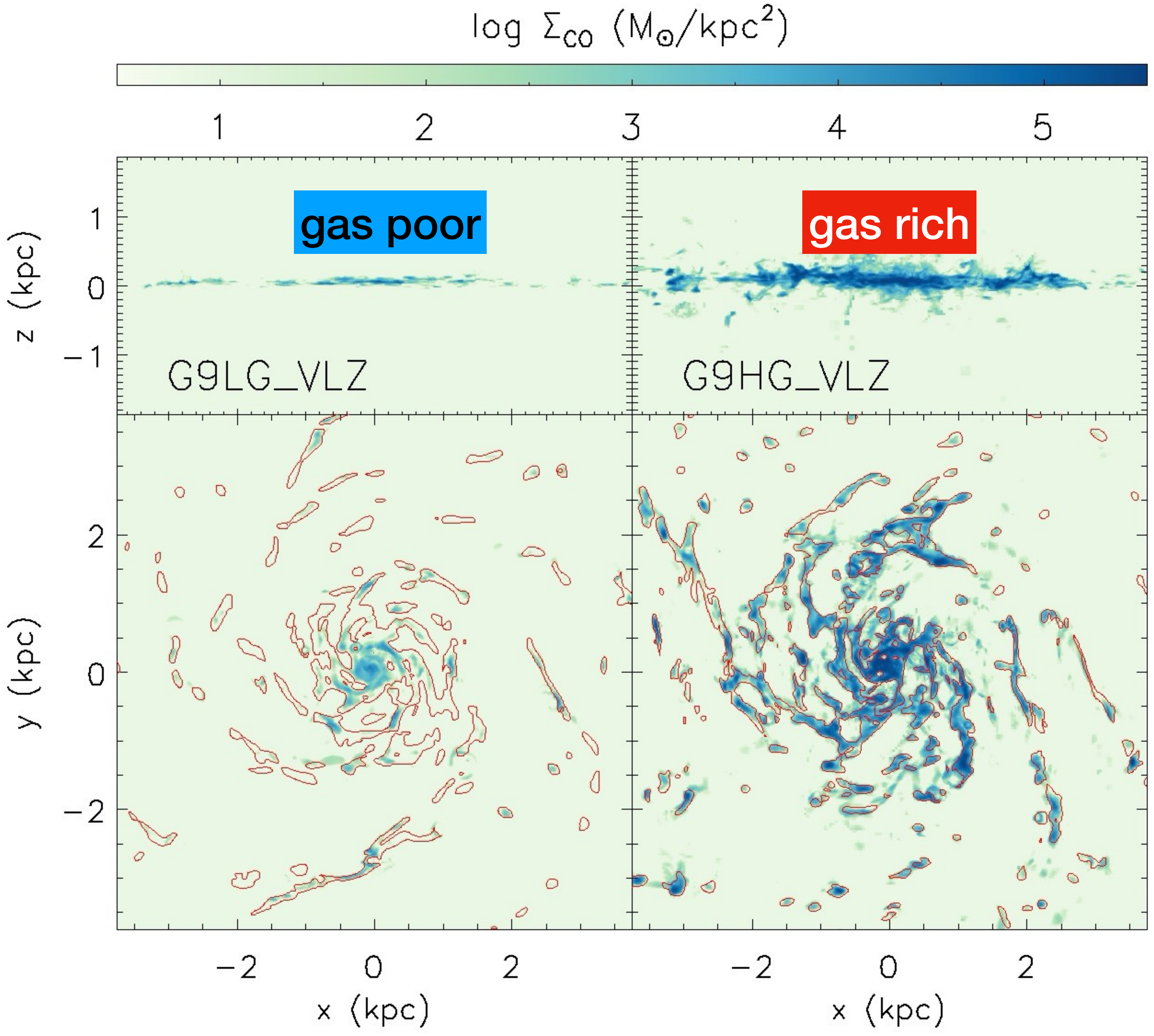
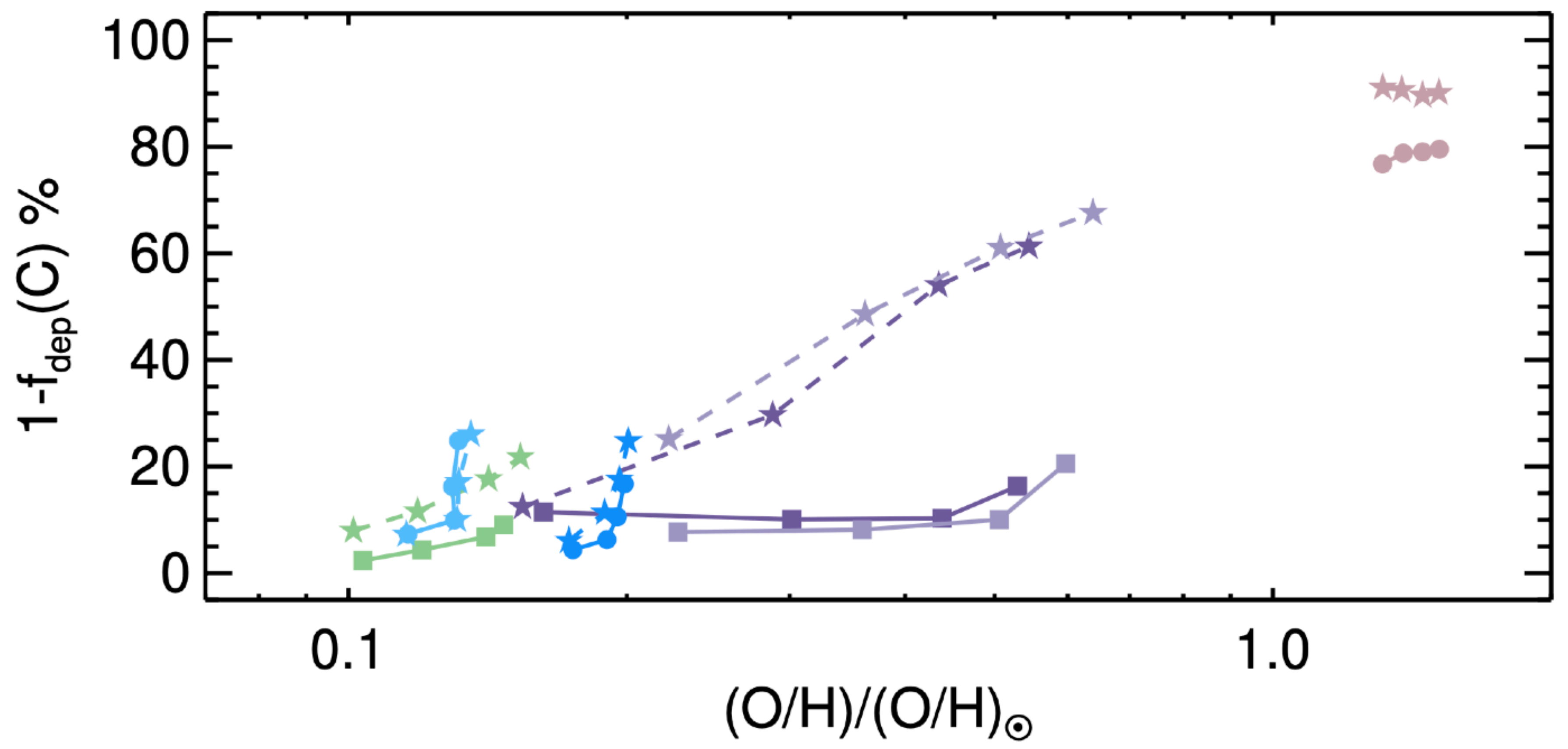
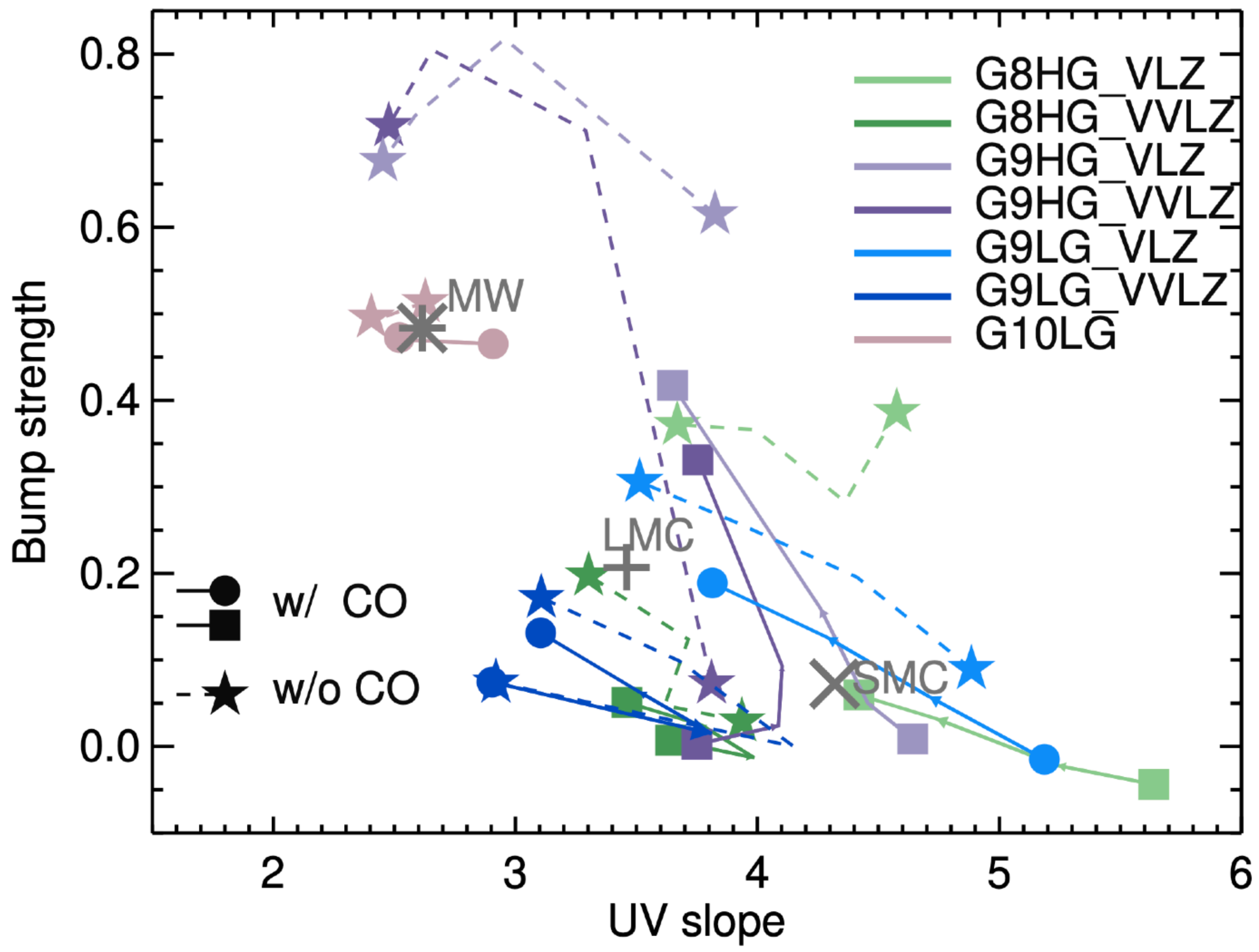
The need for CO formation

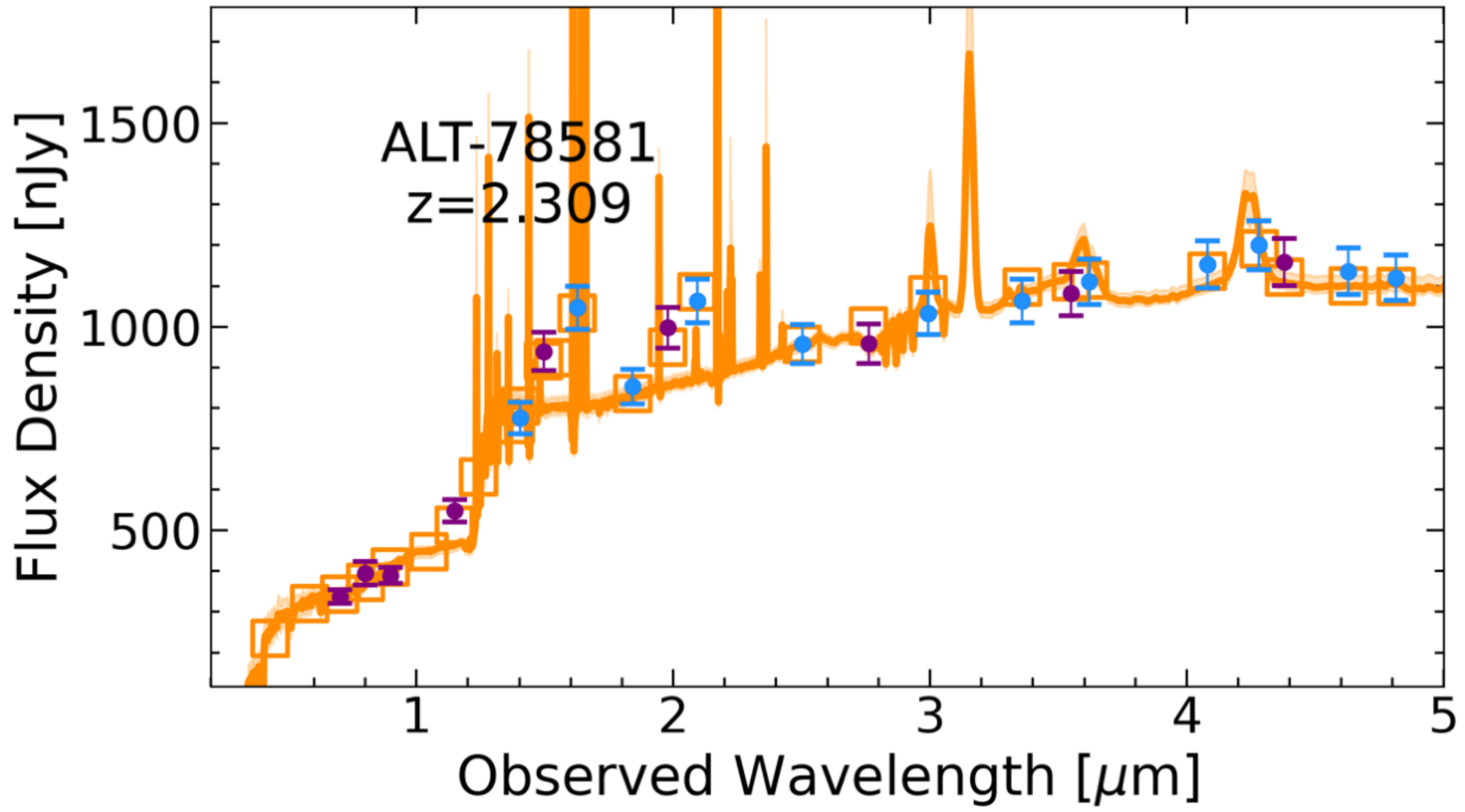


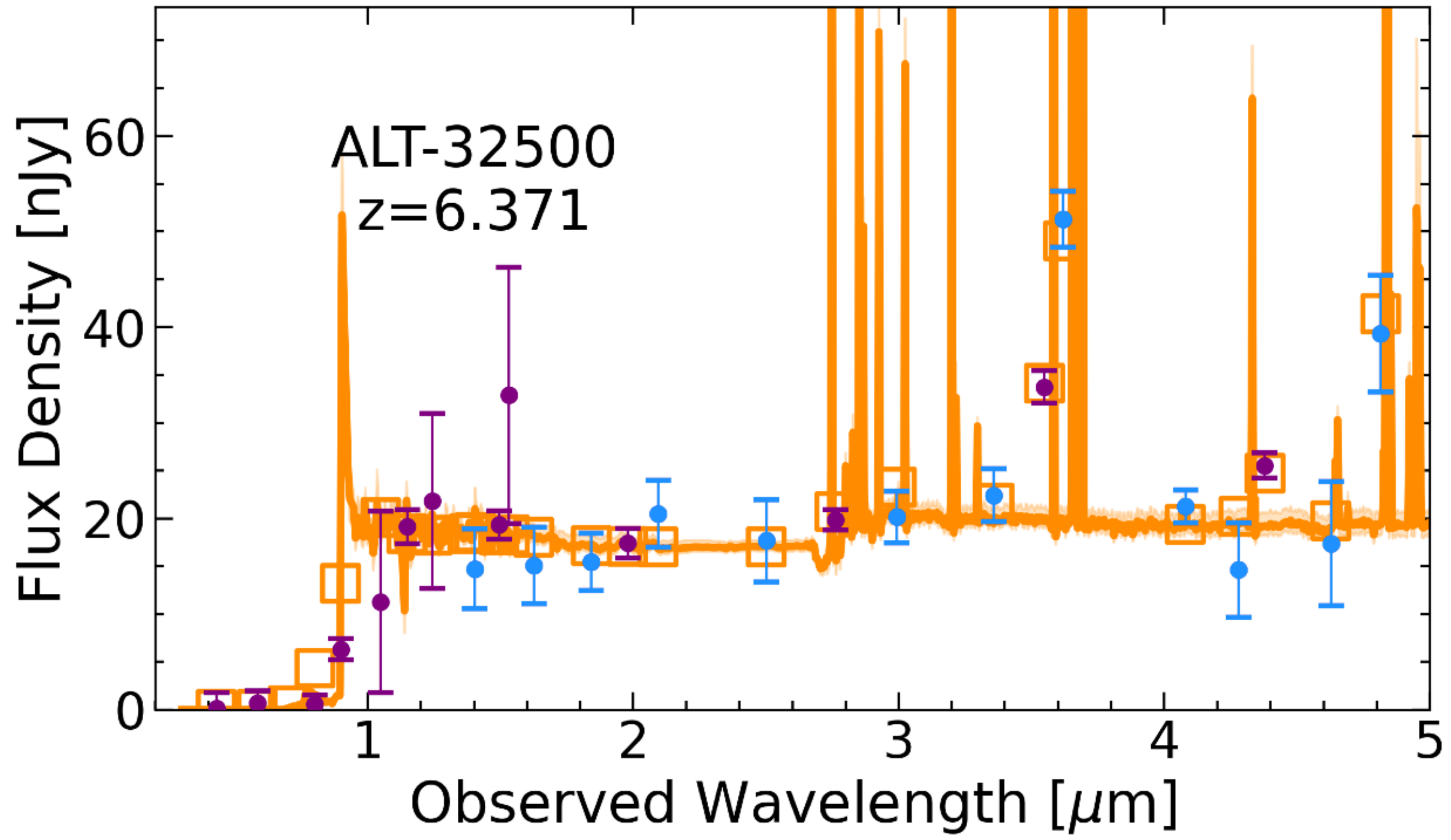




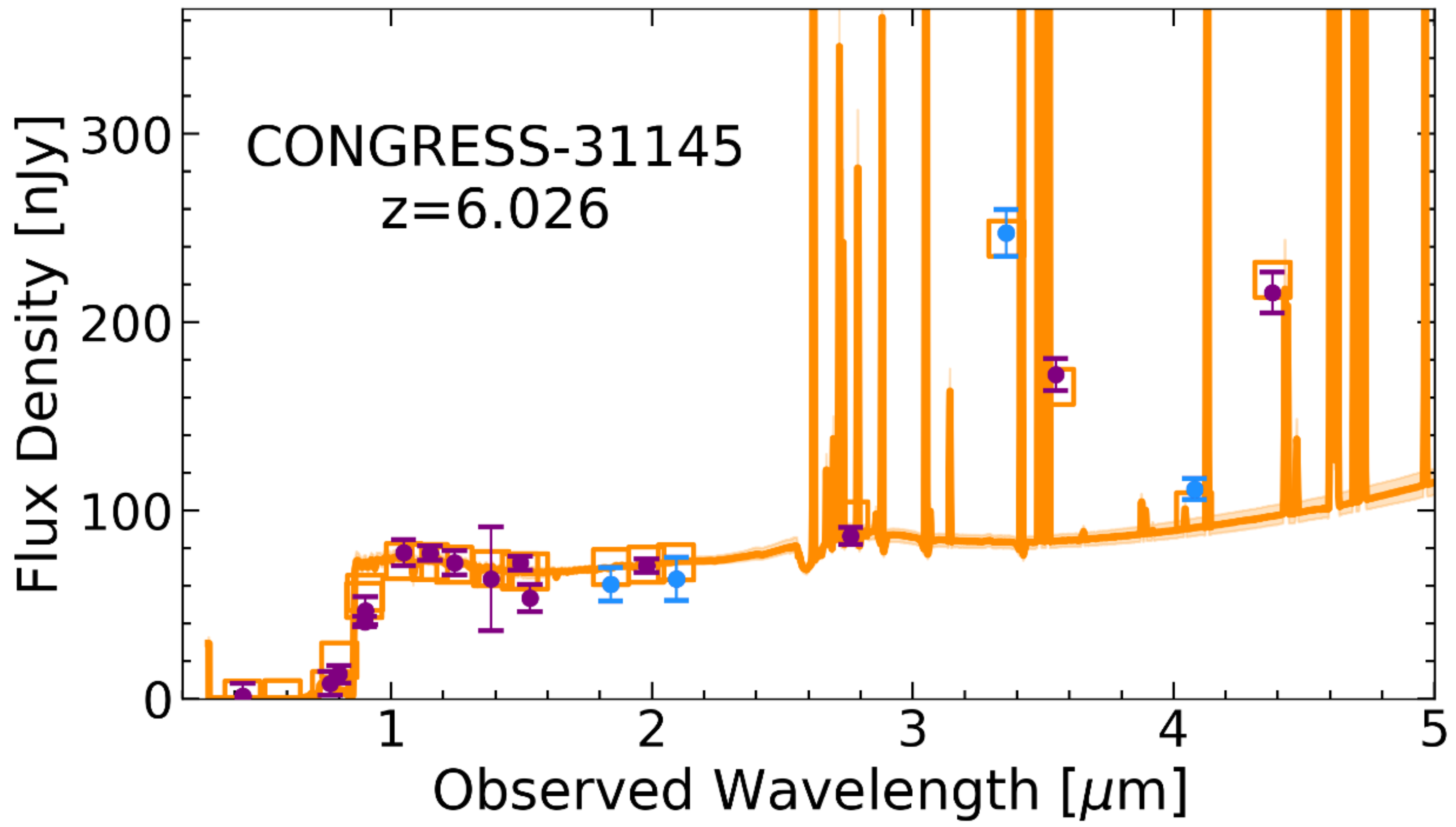
5. Predicting attenuation curves across cosmic time

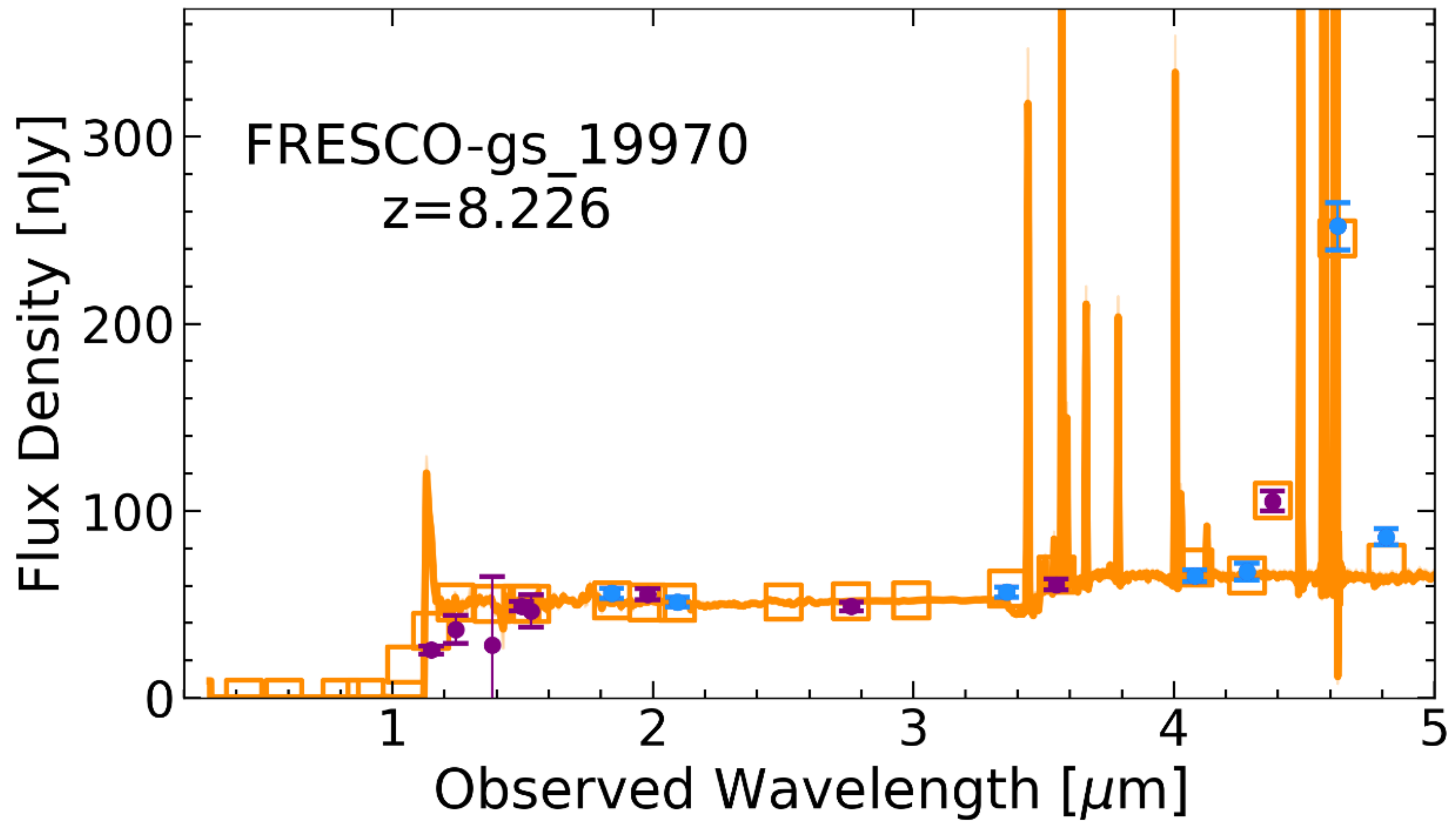
Three large grism campaigns: **FRESCO** (PI: Oesch), **ALT** (PIs: Matthee, Naidu), **CONGRESS** (PIs: Egami, Sun)





(Plot credits: Irene Shivaei)





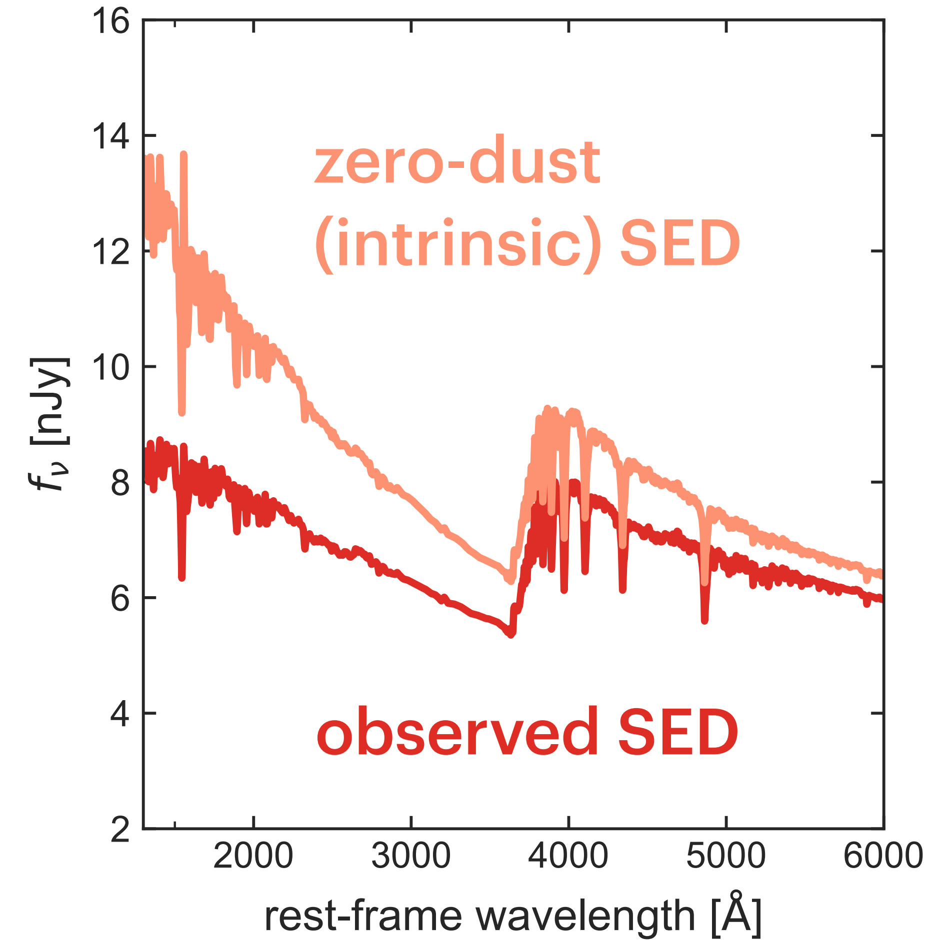
- Two component dust model (Charlot & Fall 2000): Birth-cloud and diffuse ISM dust

$$\hat{\tau}_\lambda(t') = \begin{cases} \hat{\tau}_\lambda^{\mathrm{BC}} + \hat{\tau}_\lambda^{\mathrm{ISM}} & \text{for } t' \leqslant t_{\mathrm{BC}}, \\ \hat{\tau}_\lambda^{\mathrm{ISM}} & \text{for } t' > t_{\mathrm{BC}}, \end{cases}$$

- Flexible attenuation curve slope for the ISM dust

$$k_{\lambda,\mathrm{mod}} = k_{\lambda,\mathrm{Cal}} \frac{R_{V,\mathrm{mod}}}{R_{V,\mathrm{Cal}}} \left(\frac{\lambda}{5500\text{Å}} \right)^{\delta} + D_\lambda,$$

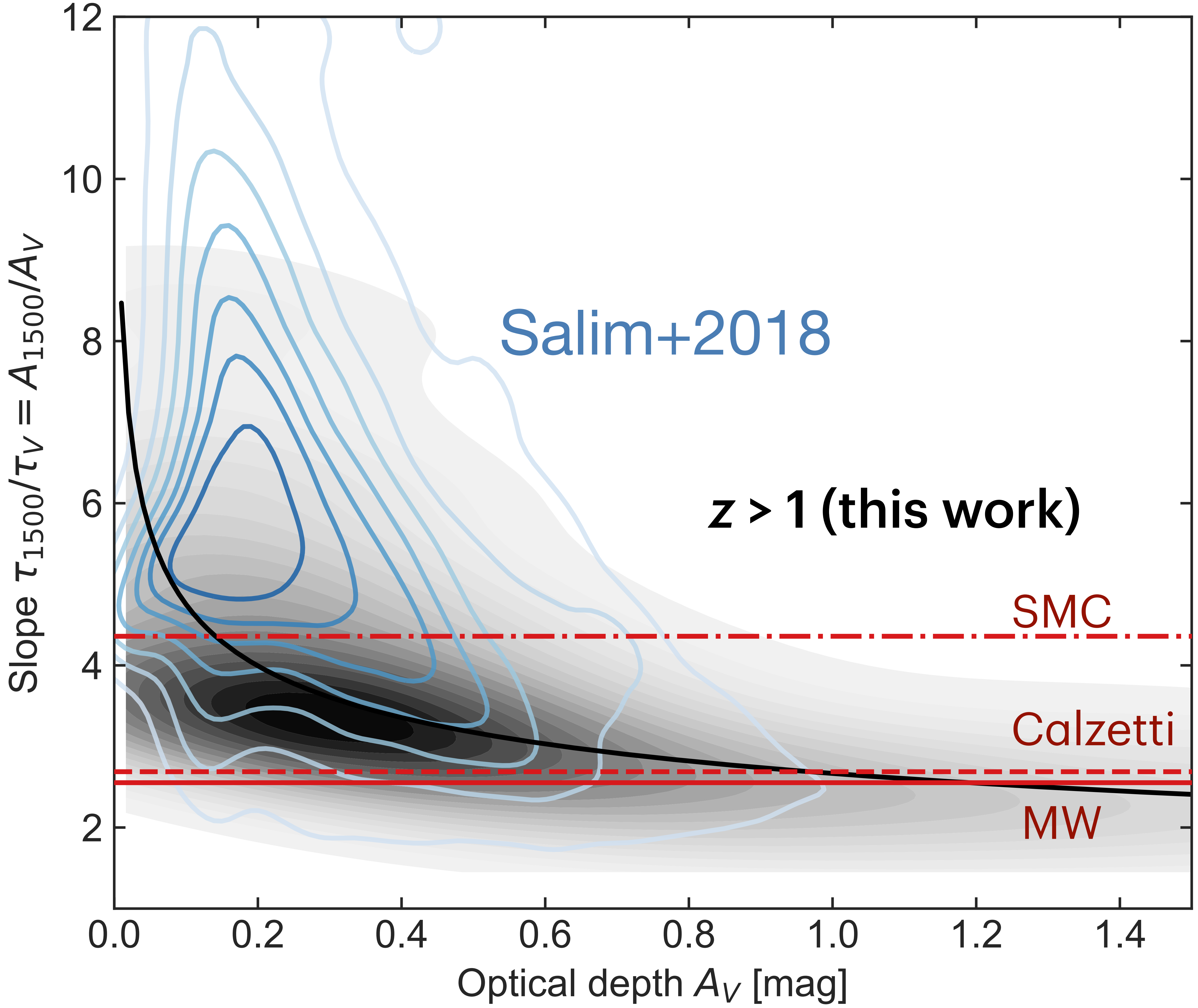
$$L_{\lambda,\mathrm{obs}}(t) = L_{\lambda,0}(t)\, 10^{-0.4 A_\lambda}$$



5. Predicting attenuation curves across cosmic time

(Plot credits: Irene Shivaei)

Shallower slopes at fixed optical depth



5. Predicting attenuation curves across cosmic time

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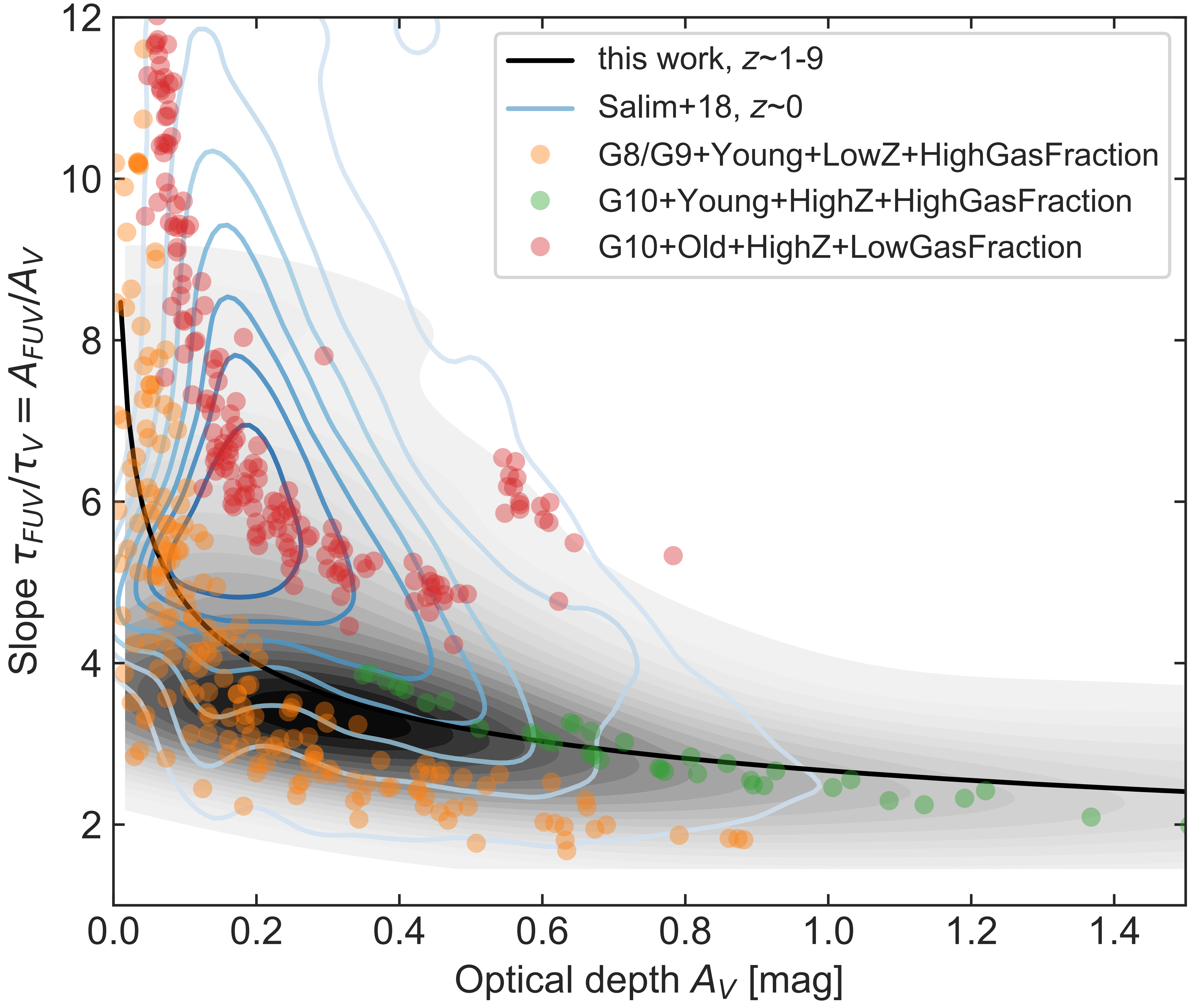


Dusty-PRISM suite of isolated disks, post-processed with SKIRT

Two channels for dust production:

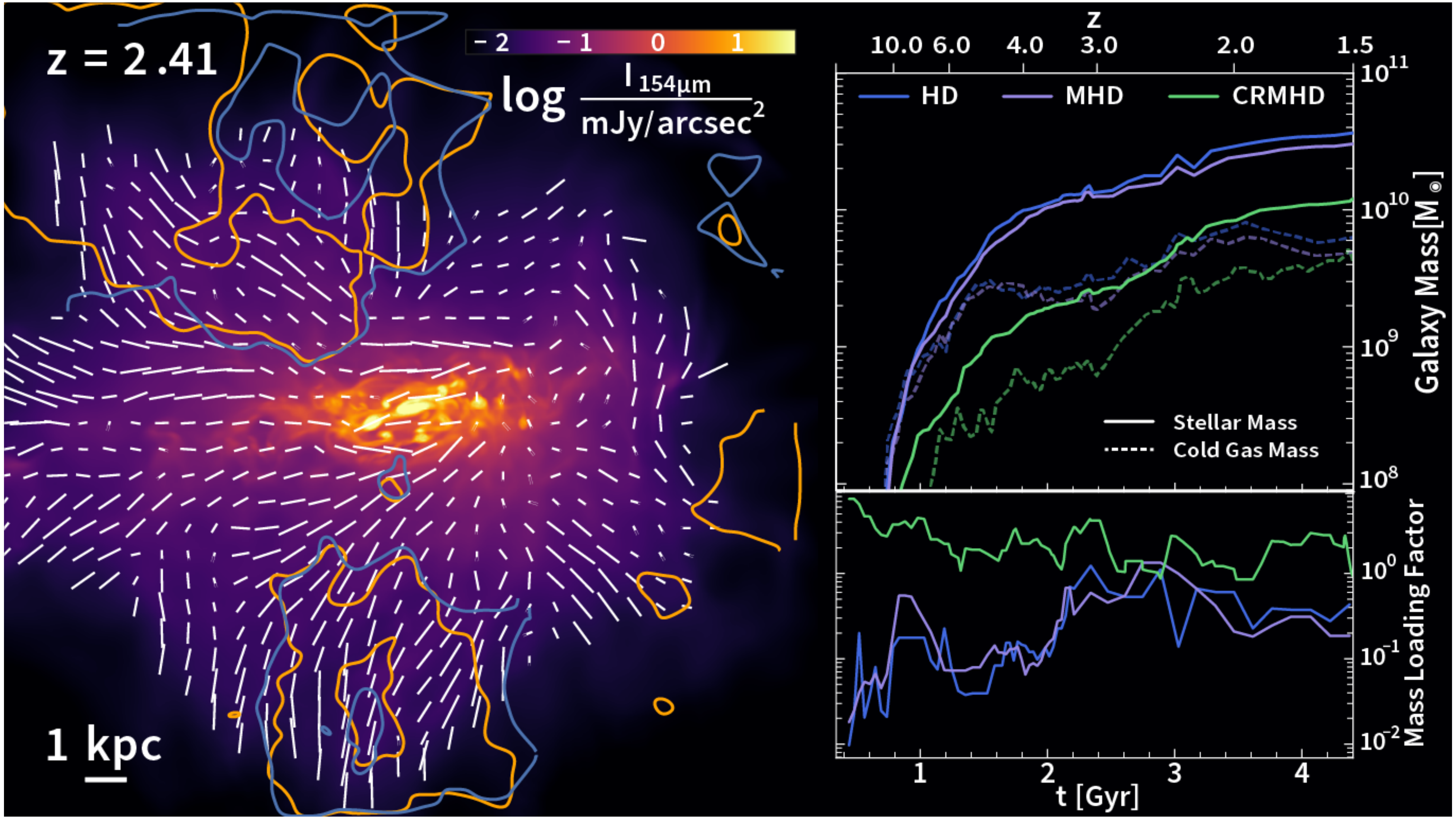
★ ISM growth (metal accretion from gas phase) - small grains

★ Stellar origin (SN ejecta) - large grains

>> dominant primordial stellar dust

(Inefficient gas accretion, dominant large dust grain population originating from SN ejecta)

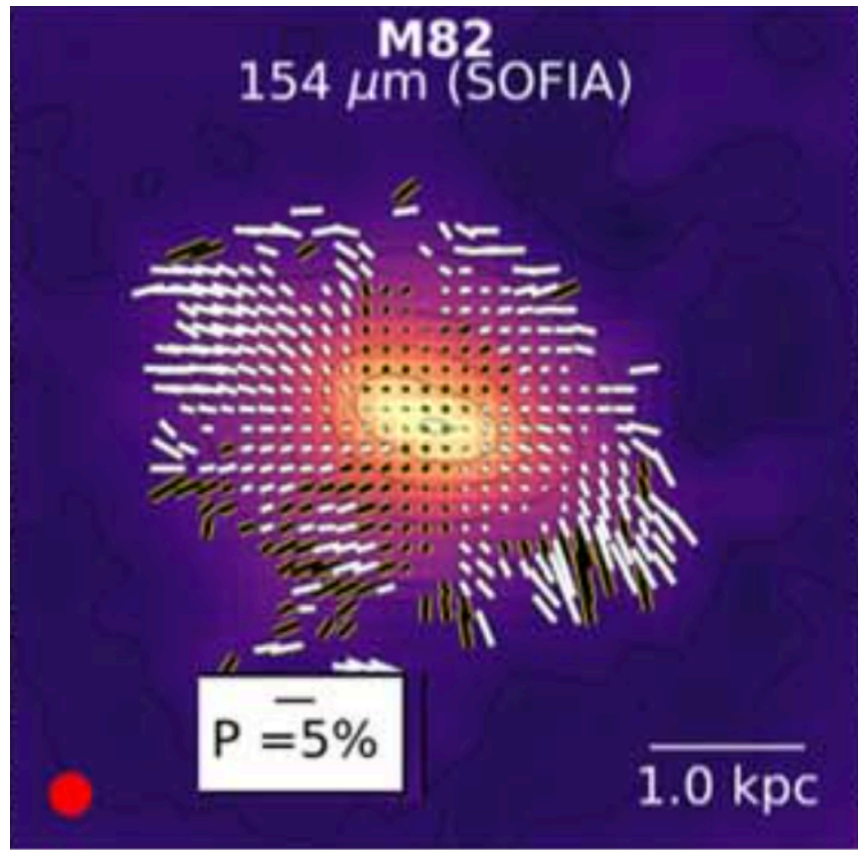
6. Dusty outflows in starburst galaxies



Adding CRs decreases the stellar mass by ~1 dex at high redshift and a factor 4 at lower redshift

Large depletion of cold gas compared to HD and MHD (lower star formation efficiency)

High mass loading outflows in the presence of CRs, which are cooler and observed in **FIR polarised emission**

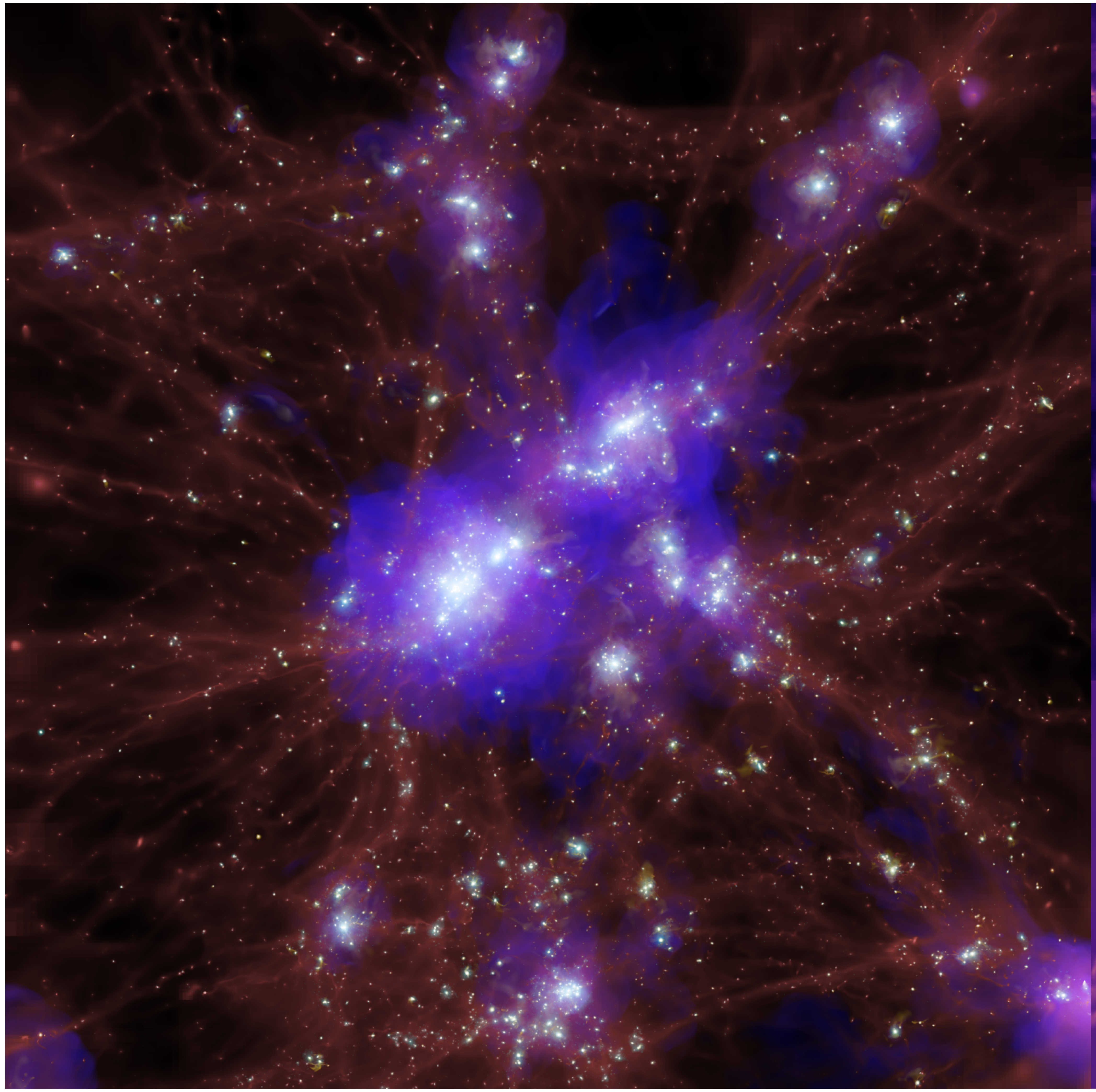


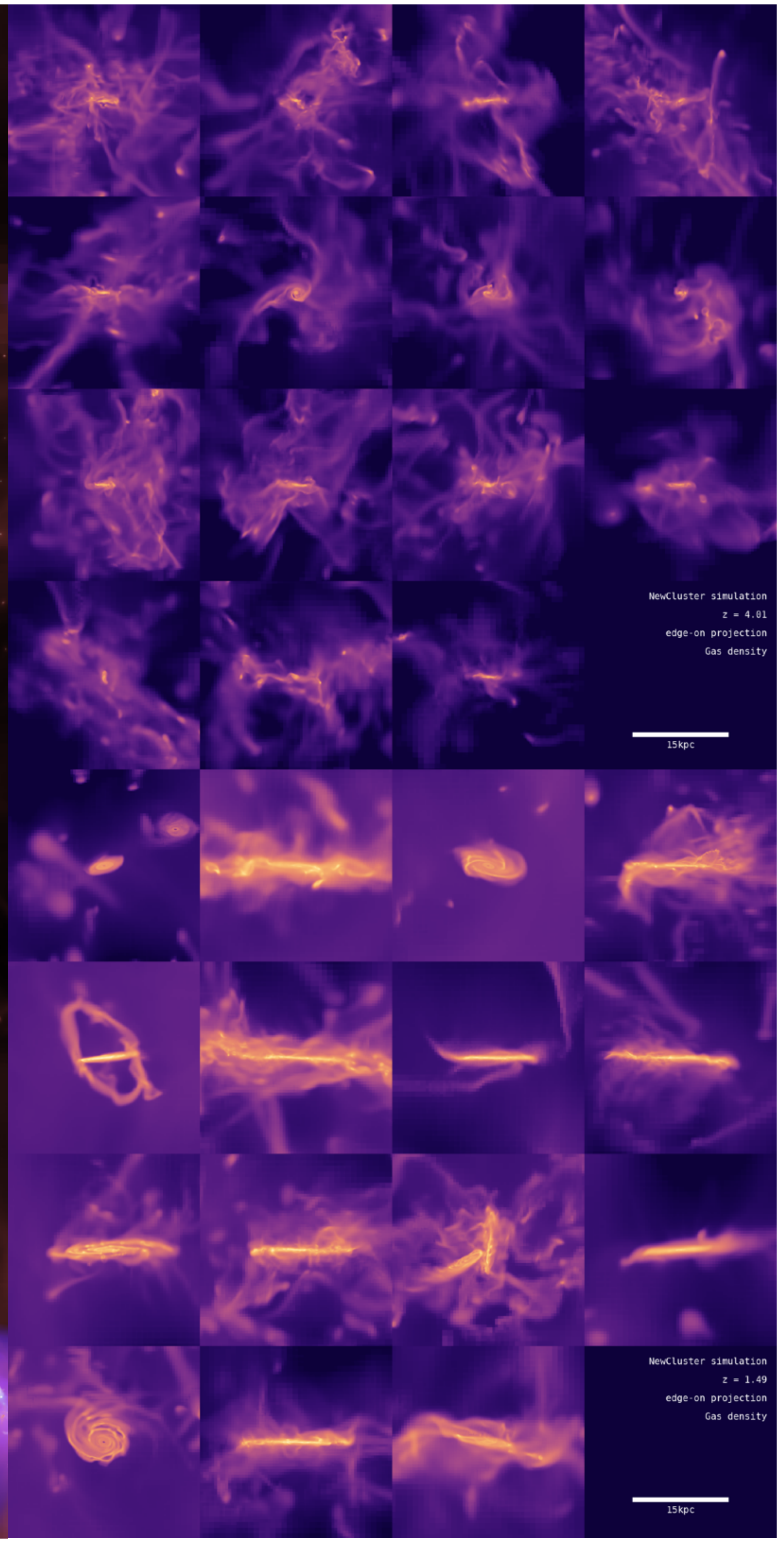
Lopez-Rodriguez2023

7. Ongoing projects using Dusty-PRISM

NewCluster

NewCluster simulation (Han, Yi+, in prep.)
Massive halo zoom-in simulation with <100 pc spatial resolution including the new dust model



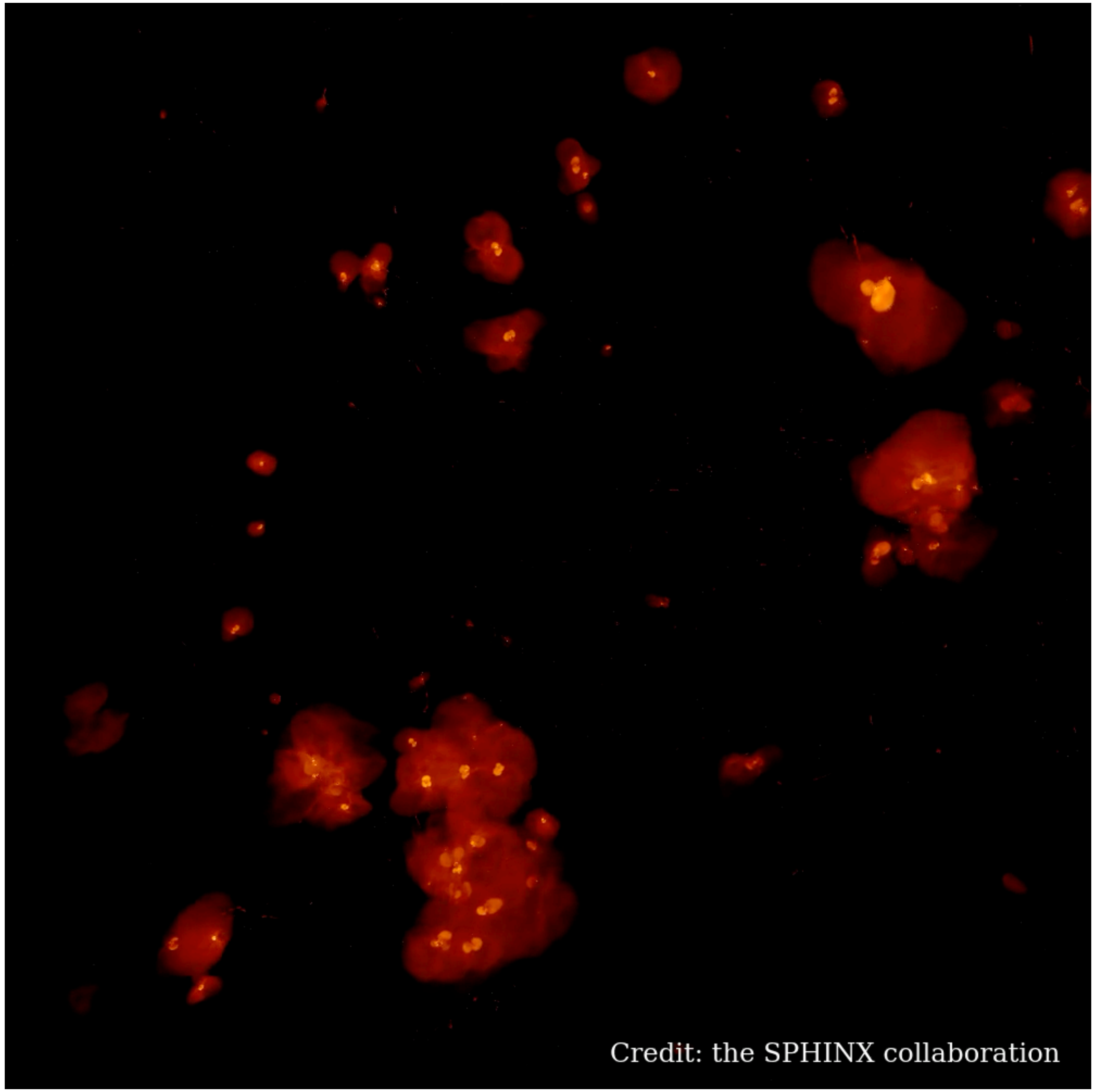


7. Ongoing projects using Dusty-PRISM

Dusty-SPHINX

Reionisation-era cosmological simulation with resolved ISM, radiation transfer and multi-grain dust evolution

PI: Dubois, RM, Rosdahl



8. Conclusions

- A new model of dust and chemistry evolution for galaxy and ISM simulations
- Multiphase ISM can help in constraining dust+PAH physics
- We can reproduce Local Group extinction curves
- SMC-like curves arise from inefficient gas accretion onto C grains (LMC) and also onto Sil grains (SMC) due to lower metallicity
- Low metallicity, young galaxies can reproduce observations at high-z
- Dust + additional physics (CRs) results in more realistic galaxies

The synergy between Dusty-PRISM and future PRIMA observations

- Dusty-PRISM can be used from small-scale cloud predictions all the way to large cosmological volumes
- On-the-fly dust and PAH evolution allows for quantitative analysis of the spatial and temporal variability of dust properties and observables
- Multi-grain prescription and state-of-the-art stellar evolution models will provide an understanding of the evolution of dust properties with cosmic time
- Direct coupling with non-thermal physics (radiation, magnetic fields and cosmic rays) provides an unprecedented predictive power for galaxy formation models
- Trivially extendable to different dust models/ properties

Very exciting times ahead!

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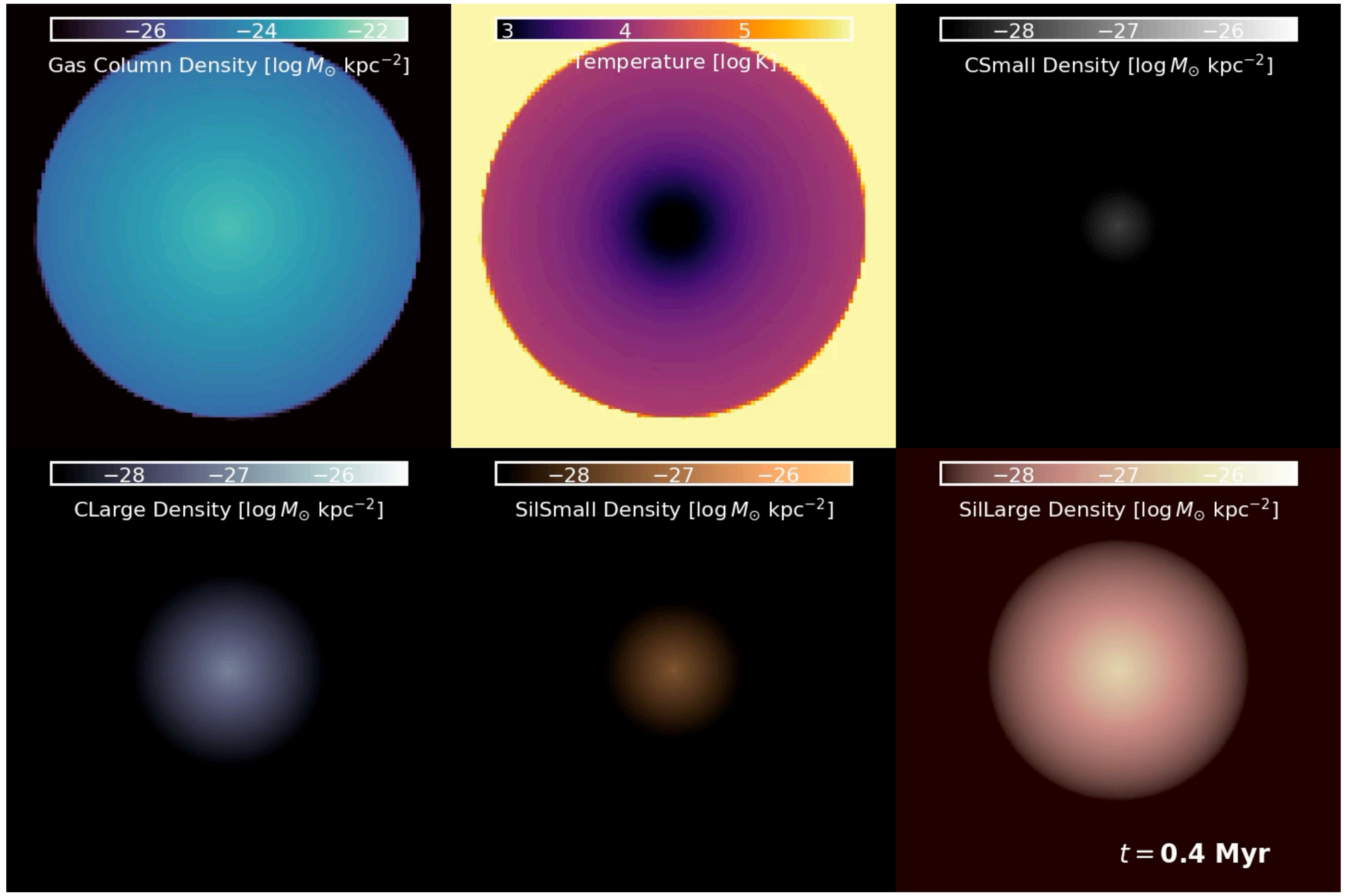
THANK YOU

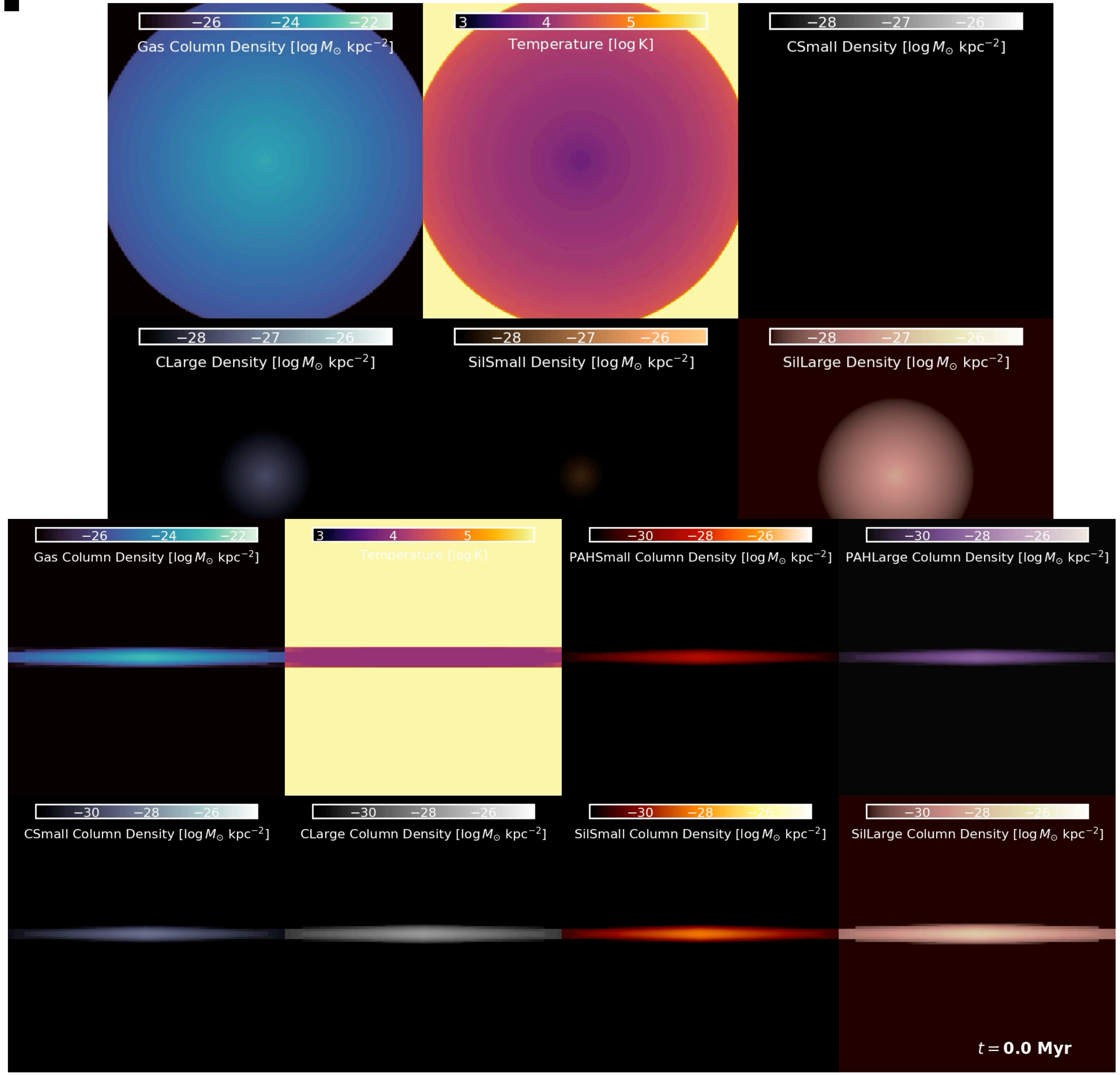
Francisco (Curro) Rodríguez Montero - Dusting Off the Secrets of the COSMOS with PRIMA IR Space Telescope

Testing Dusty-PRISM

Testing Dusty-PRISM

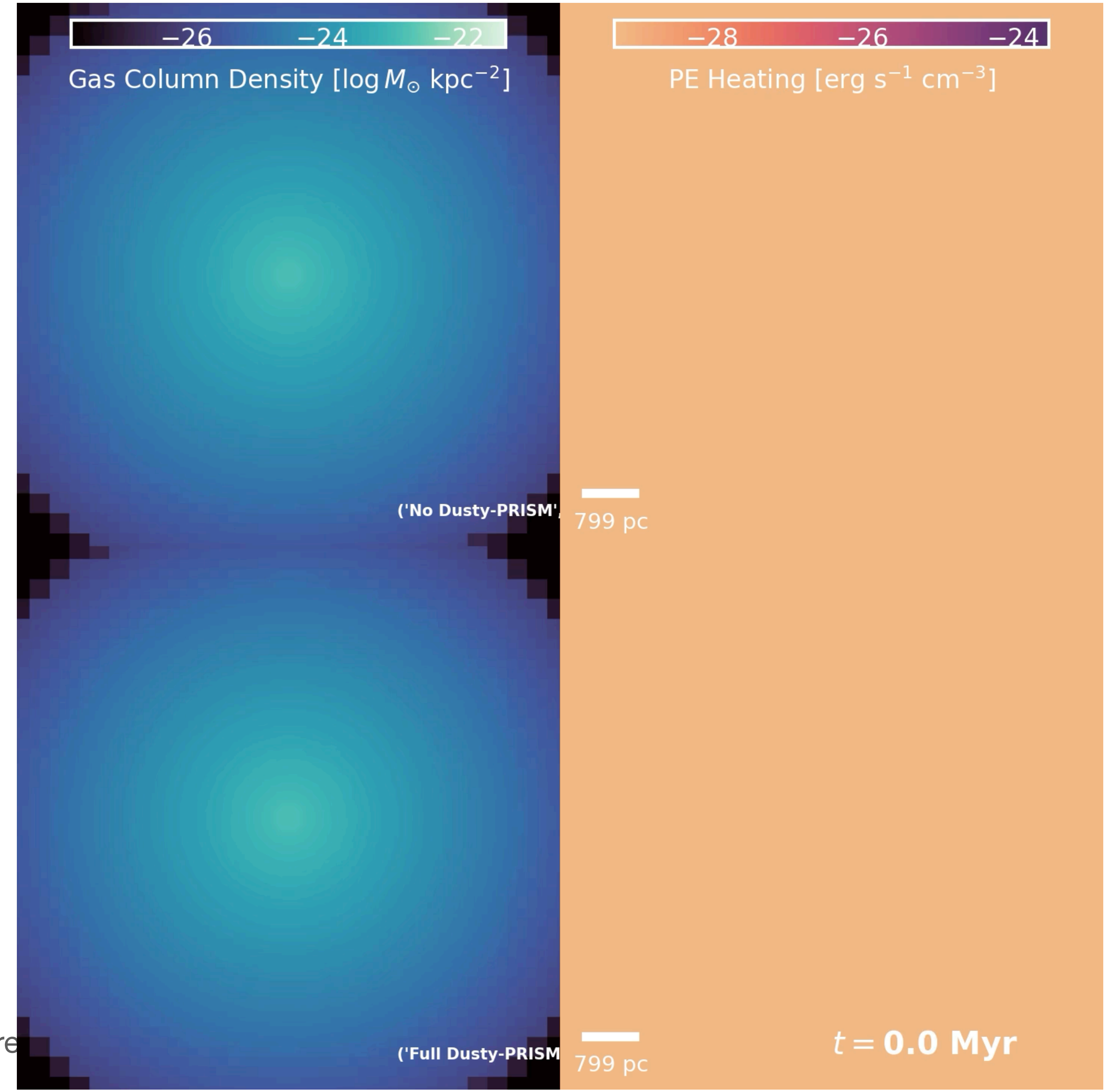
Isolated galaxy simulations





Testing Dusty-PRISM

Photo-electric heating



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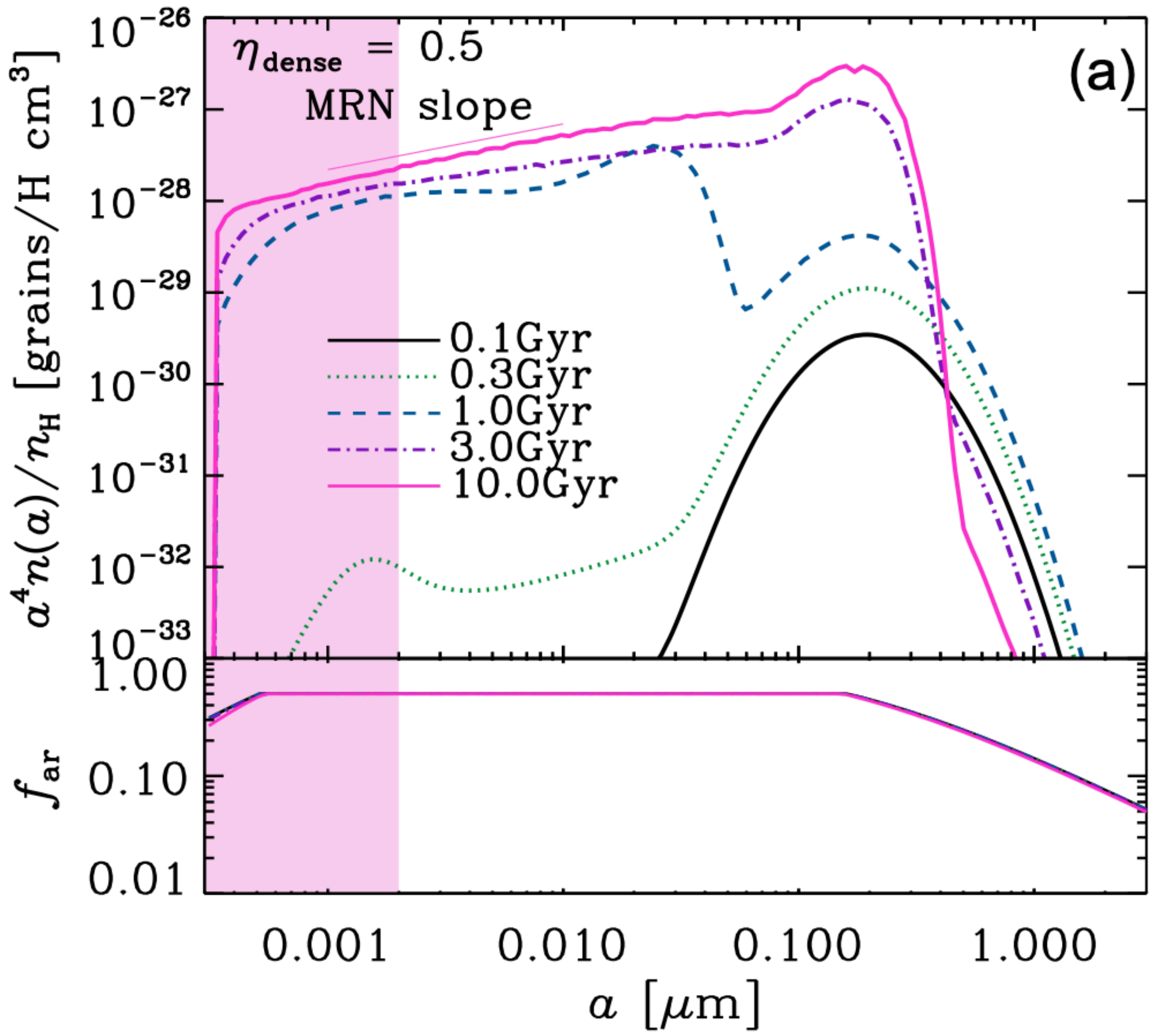
…and what about?

Where do PAHs come from??

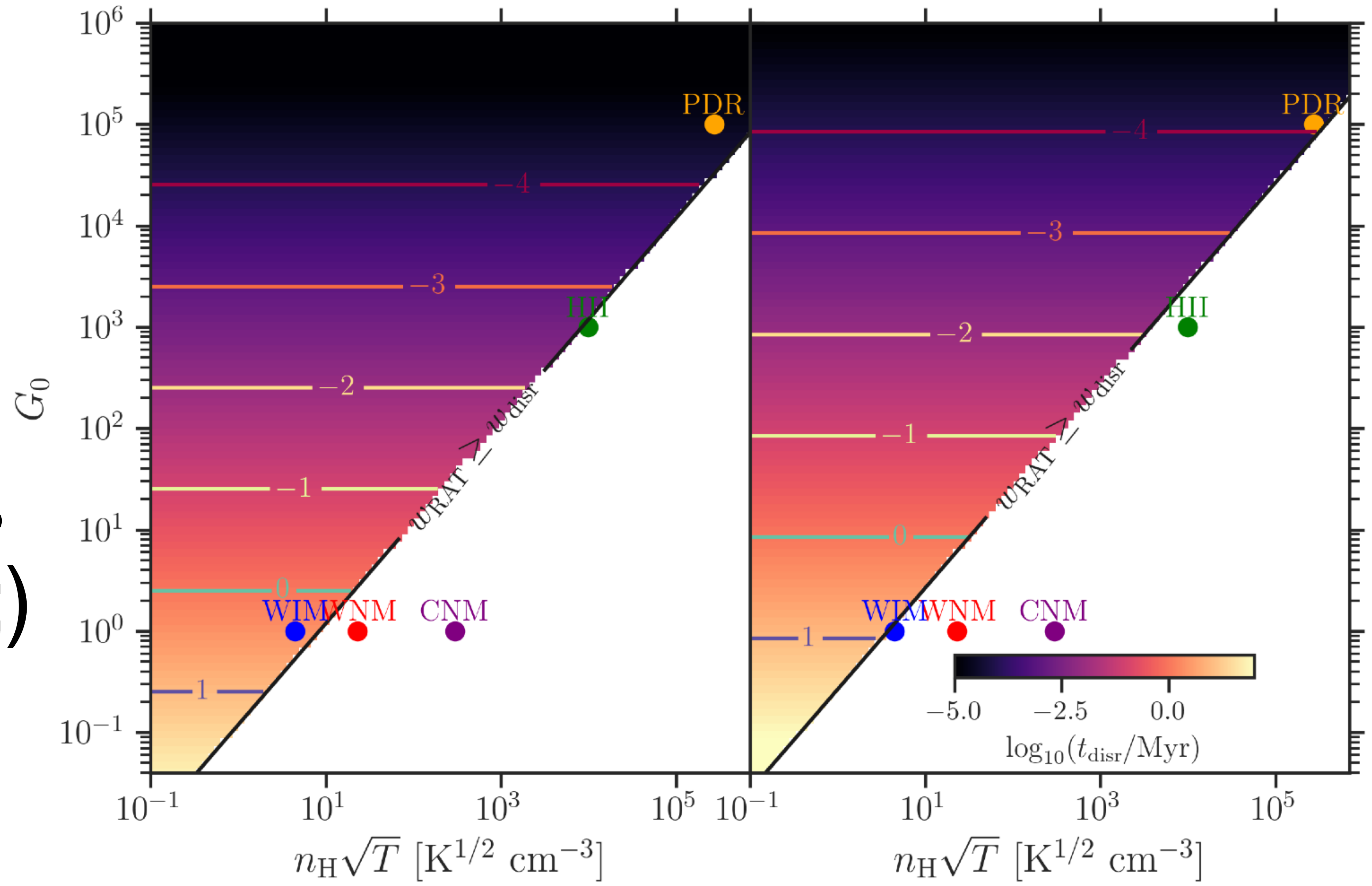
Shattering cascade and quick aromatisation?



Hirashita&Murga2020, Narayanan+2023

Fragmentation during radiative torque disruption?

Hoang+2021ab,Hirashita&Hoang2020



I propose we discuss this the next few day ;)

Allamandola+1989

AGB winds?

Combustion-like reactions in clouds?

Wang+97, Frenklach+02, Shukla+12, Zhao+18ac,Kaiser+15, Gavilan Marin+20, Cherchneff+1992, Cau2002

Graphene etching on dust surface?

Formation of ethane (C_2H_6) on dust ice mantels → Formation of benzene (C_6H_6) → Phenyl radical (C_6H_5) → **Naphthalene!!**

Formation of acetylene (C_2H_2) → Vinylacetylene → **Naphthalene!!**

Sub-grid turbulent model

$$\Delta V^{\mathrm{B}}_{i,j} = \sqrt{\frac{8 k_{\mathrm{B}} T_{\mathrm{gas}} (m_i + m_j)}{\pi m_i m_j}}.$$

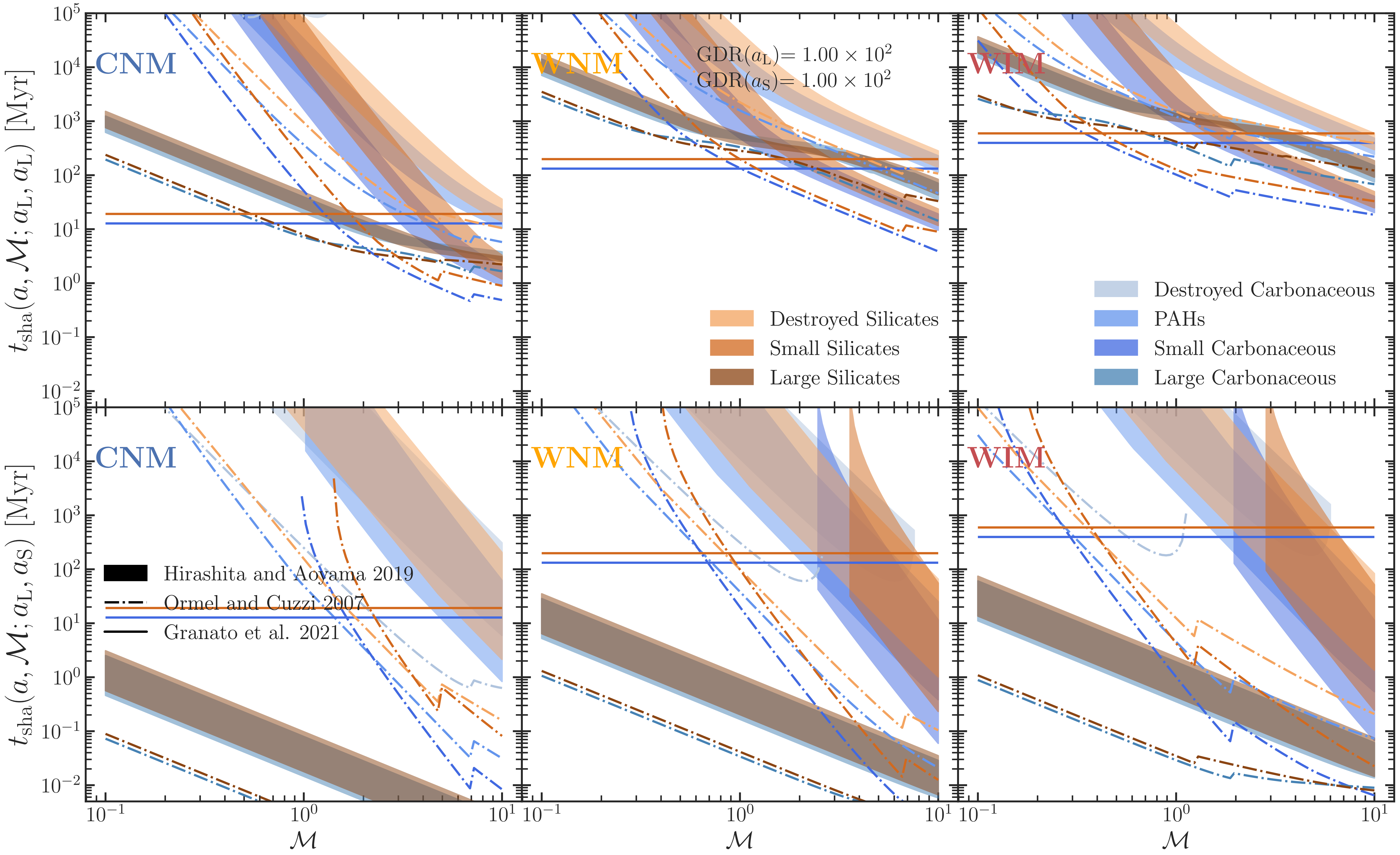
$$\Delta V^{\mathrm{T}}_{i,j} = \begin{cases} \sqrt{\frac{3}{2}}\sigma \sqrt{\frac{\mathrm{St}_i - \mathrm{St}_j}{\mathrm{St}_i + \mathrm{St}_j}} \sqrt{\frac{\mathrm{St}_i^2}{\mathrm{St}_i + \mathrm{St}_{\mathrm{min}}} - \frac{\mathrm{St}_j^2}{\mathrm{St}_j + \mathrm{St}_{\mathrm{min}}}}, & \text{if } \tau_\eta > t_{\mathrm{s}}^i, \\ \sqrt{\frac{3}{2}}\sigma \sqrt{f\left(\frac{\mathrm{St}_j}{\mathrm{St}_i}\right) \mathrm{St}_i}, & \text{if } \tau_\eta \le t_{\mathrm{s}}^i < \tau_{\mathrm{L}}, \\ \sqrt{\frac{3}{2}}\sigma \sqrt{\frac{1}{1+\mathrm{St}_i} + \frac{1}{1+\mathrm{St}_j}}, & \text{if } \tau_{\mathrm{L}} \le t_{\mathrm{s}}^i, \end{cases} \tag{46}$$

with the function f given by

$$f(x) = 3.2 - (1+x) + \frac{2}{1+x}\left(\frac{1}{2.6} + \frac{x^3}{1.6+x}\right), \tag{47}$$

and $\mathrm{St}_{\mathrm{min}} \equiv \tau_\eta / \tau_{\mathrm{L}} = 1/\sqrt{\mathrm{Re}}$. The final relative velocity is obtained by combining the Brownian and turbulent contributions:

$$\Delta V_{i,j} = \sqrt{(\Delta V^{\mathrm{B}}_{i,j})^2 + \Delta V^{\mathrm{T}}_{i,j})^2}. \tag{48}$$



Testing Dusty-PRISM