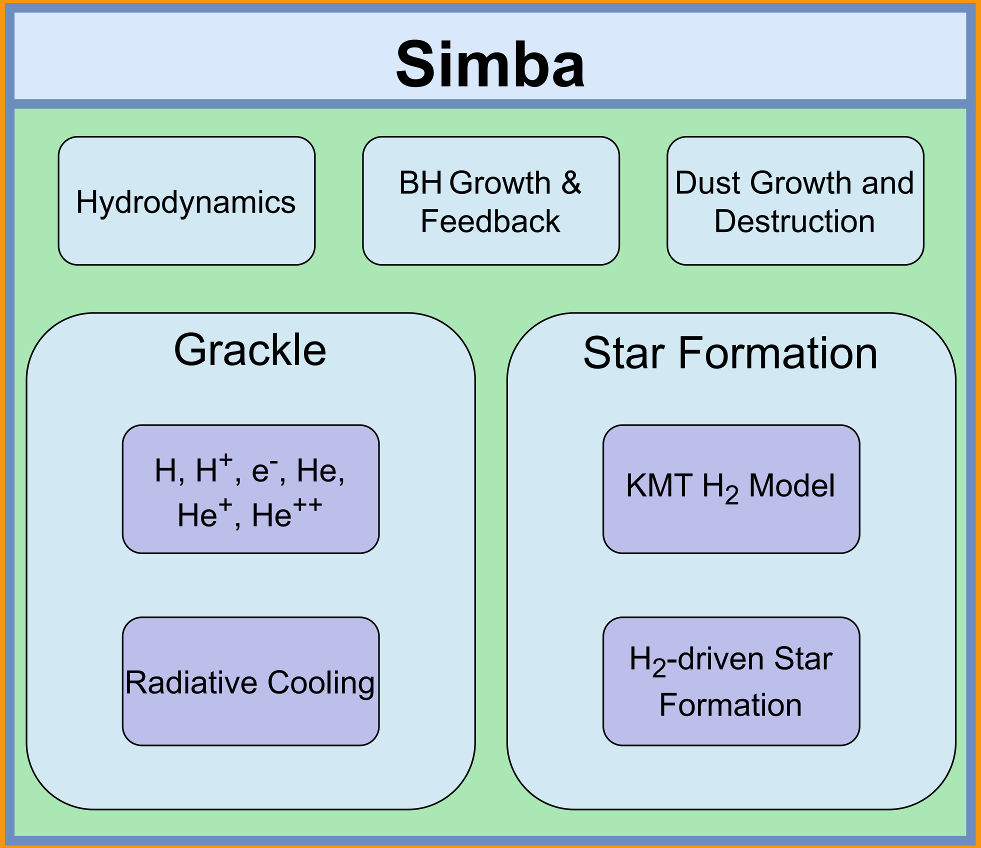
Improved ISM Modelling in Simba

Ewan Jones, Britton Smith & Romeel Davé

What is Simba?

- Smoothed-particle hydrodynamics simulation suite (GIZMO)
- Galaxy formation & evolution
- Advanced sub-grid modelling (BH feedback, winds etc.)
- Chemistry and cooling is off-loaded to Grackle



Simba

Hydrodynamics

BH Growth & Feedback

Dust Growth and Destruction

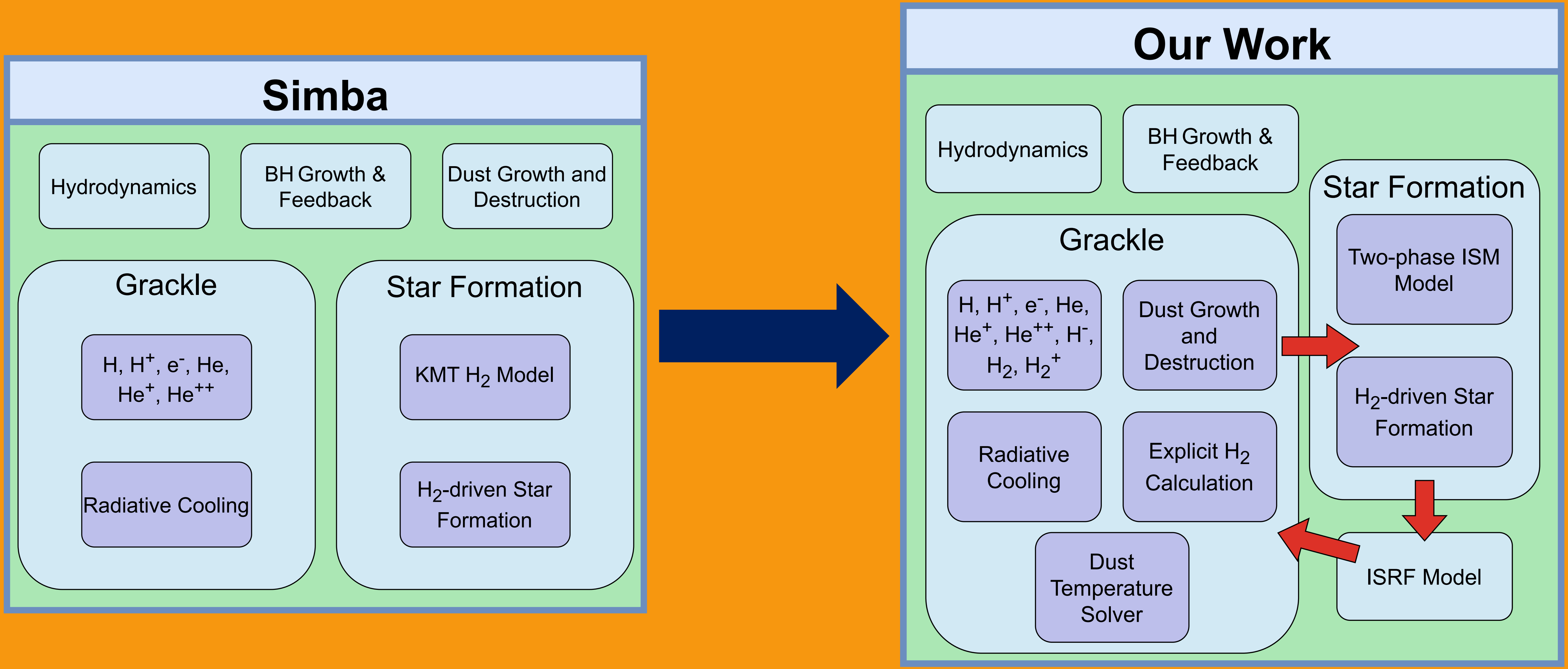
Grackle

- H, H^+, e^-, He, He^+, He^{++}
- Radiative Cooling

Star Formation

- KMT H_2 Model
- H_2-driven Star Formation

Updating Simba's star formation



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Our Work

Hydrodynamics

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$H, H^+, e^-, He, He^+, He^{++}, H^-, H_2, H_2^+$

Dust Growth and Destruction

Radiative Cooling

Explicit H_2 Calculation

Dust Temperature Solver

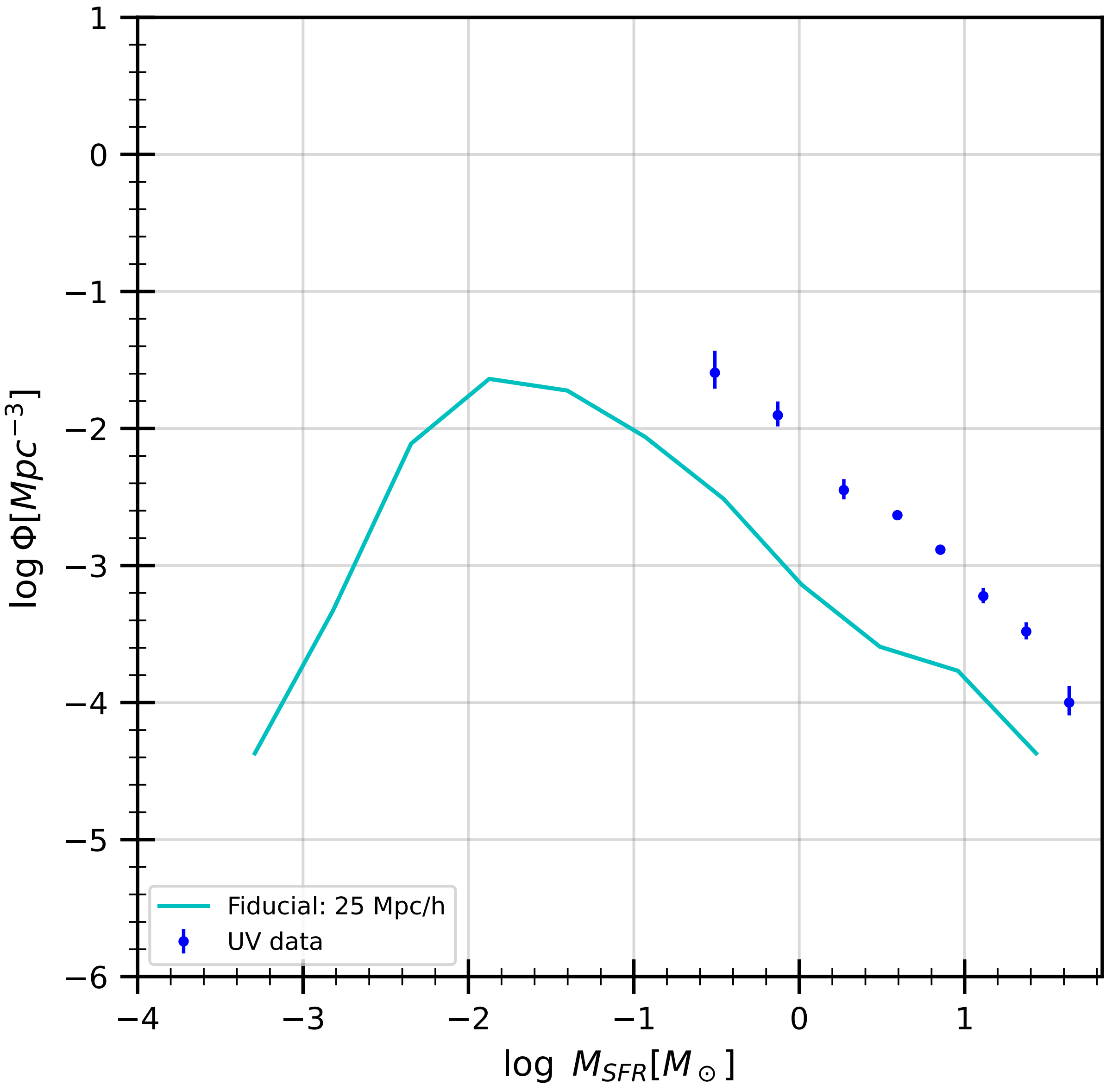
Star Formation

Two-phase ISM Model

H_2-driven Star Formation

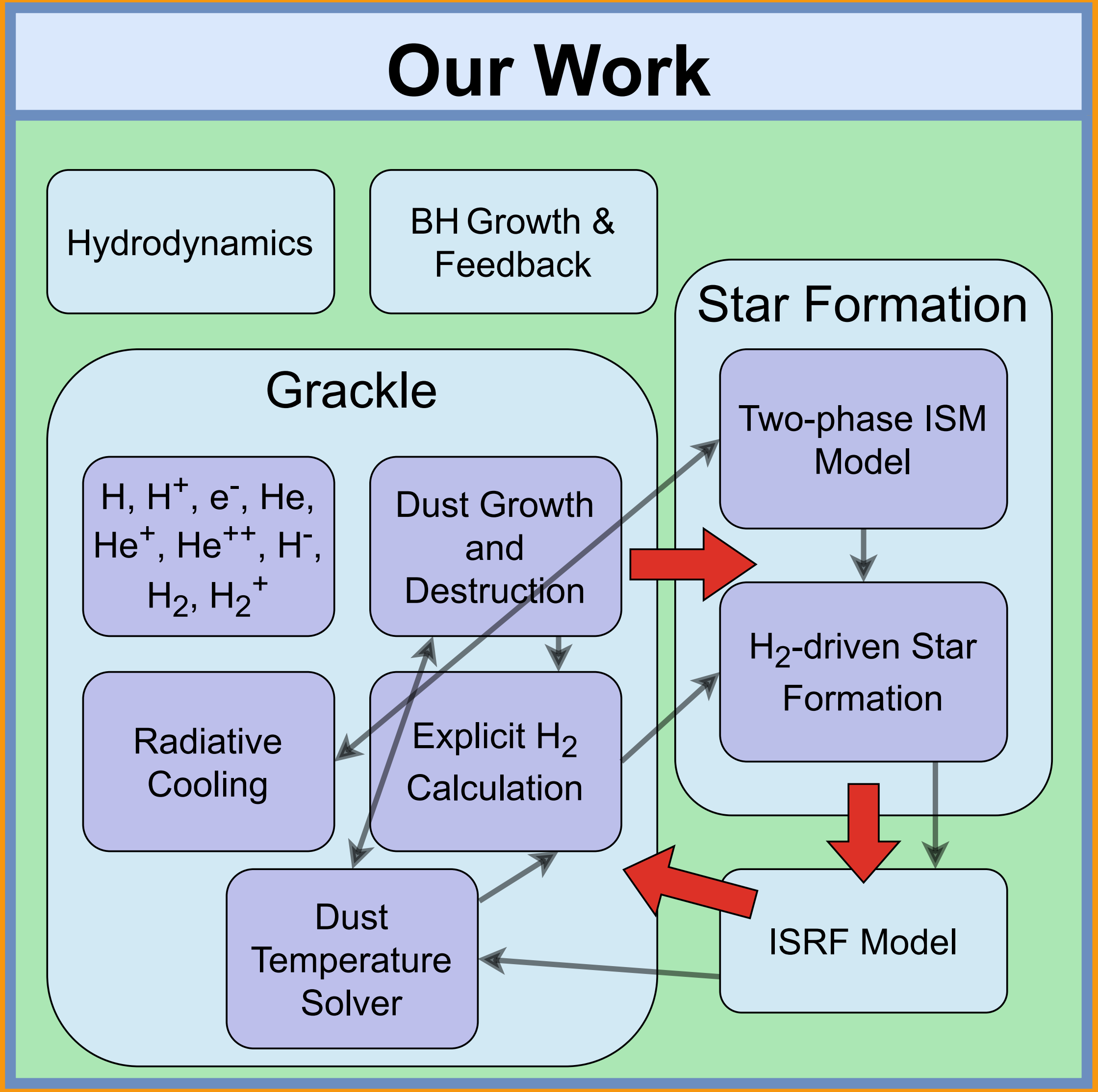
ISRF Model

Why?



(Data from Bouwens et al., 2015)

What affects star formation?



Primarily:

Molecular hydrogen drives star formation

Secondary Processes:

1. Dust catalyses the formation of molecular hydrogen
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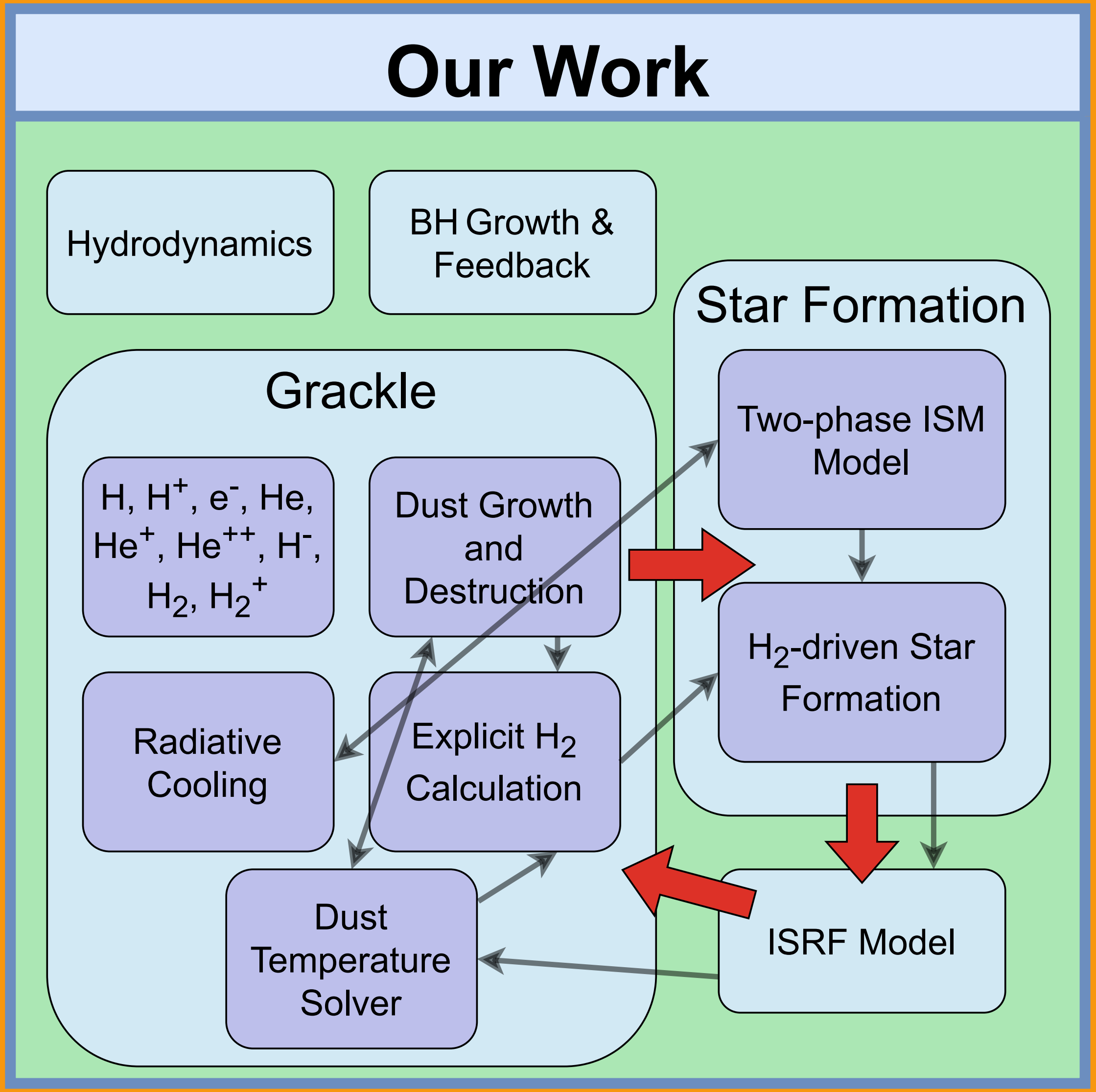

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Star Formation Rate

Particle density

Molecular
hydrogen
fraction

$$\frac{dM_\star}{dt} = \epsilon_\star \frac{\rho f_{H_2}}{t_{\mathrm{dyn}}}$$

Star formation
efficiency
~0.02

Dynamical time
$1/\sqrt{\rho G}$

Star Formation Rate

How do we calculate the molecular hydrogen fraction?

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KMT

The Setup:

- Spherical cloud of gas
- Exposed to isotropic, dissociating radiation field
- Assume atomic to molecular transition occurs in infinitely thin shell

The Inputs:

- Metallicity
- Dust column density

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Computationally fast

Very simple

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Chemical Network

The Setup:

- Add three new chemical species to the network in Grackle: H^-, H_2, H_2^+
- Pass the abundance of each species to Simba

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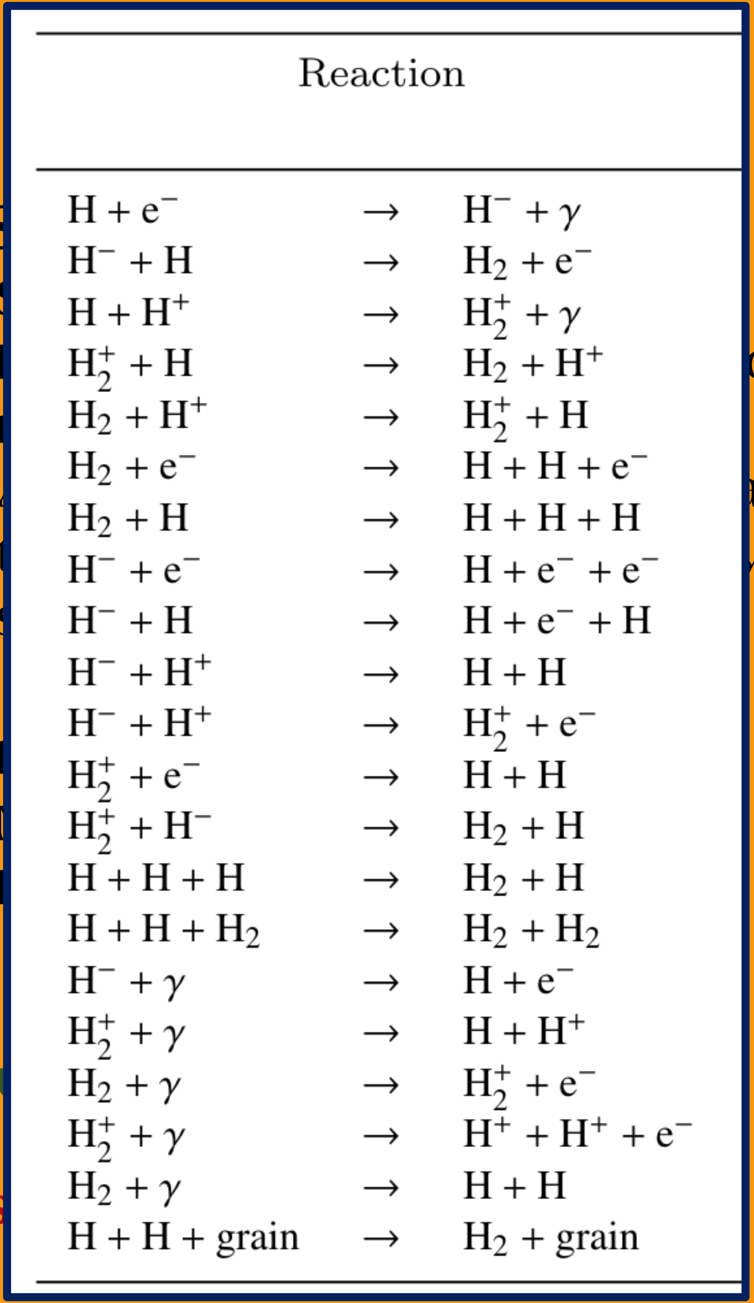

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$H^- + H$	→	$H_2 + e^-$
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$H + H + \text{grain}$	→	$H_2 + \text{grain}$

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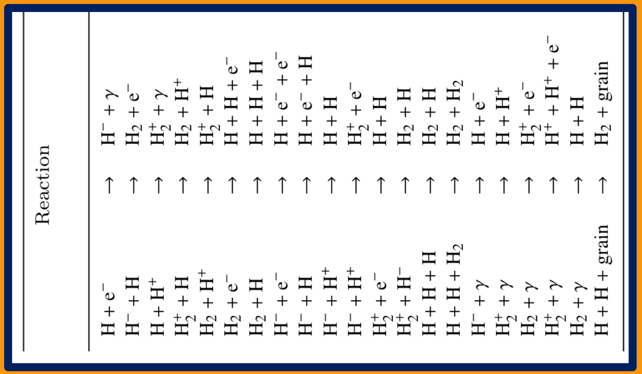

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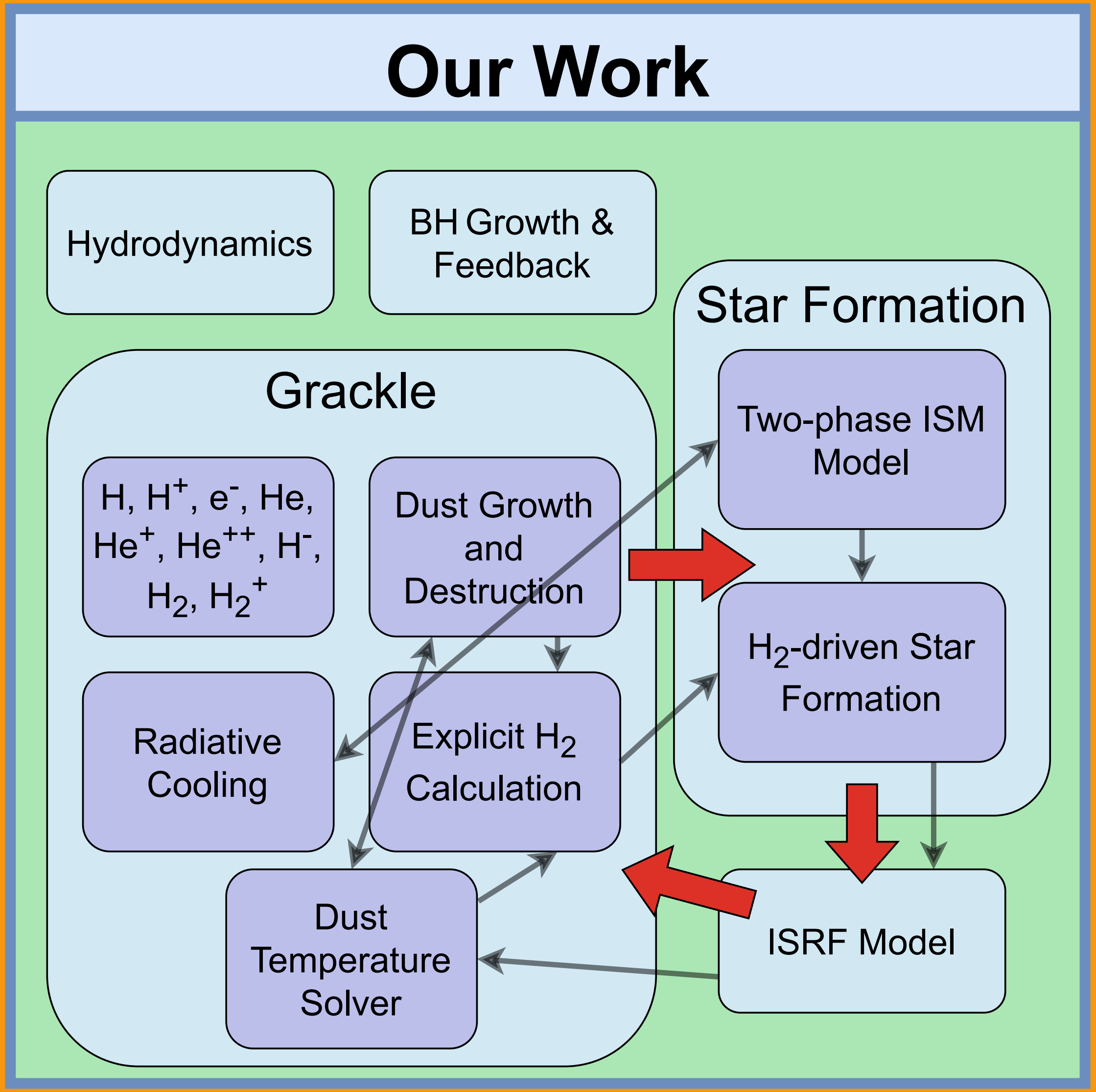
$H + H + \text{grain} \rightarrow H_2 + \text{grain}$

Explicitly solves chemistry for each particle

Much slower than KMT

What affects star formation?



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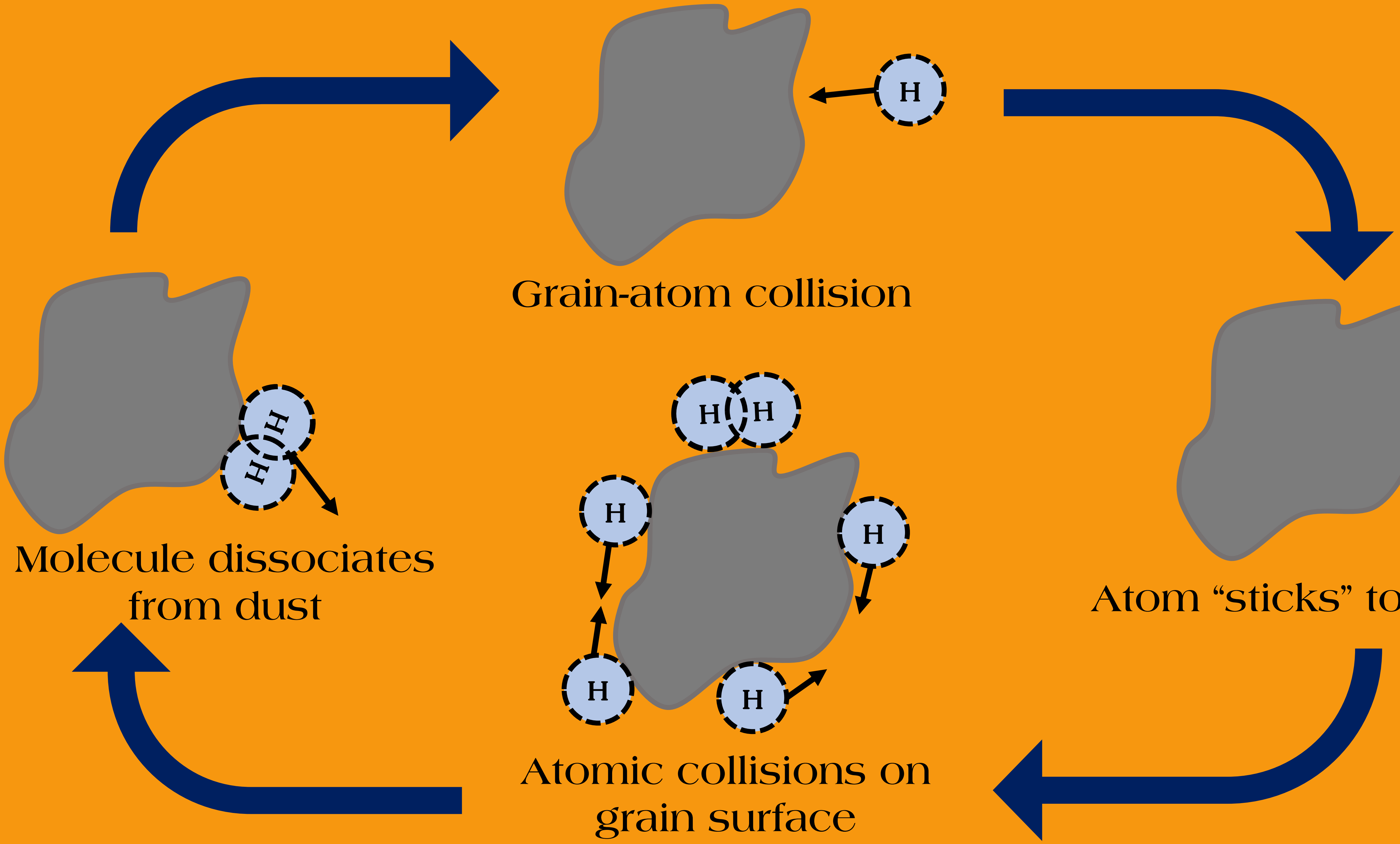


Grain-atom collision

Atom “sticks” to dust

Atomic collisions on grain surface

Molecule dissociates from dust

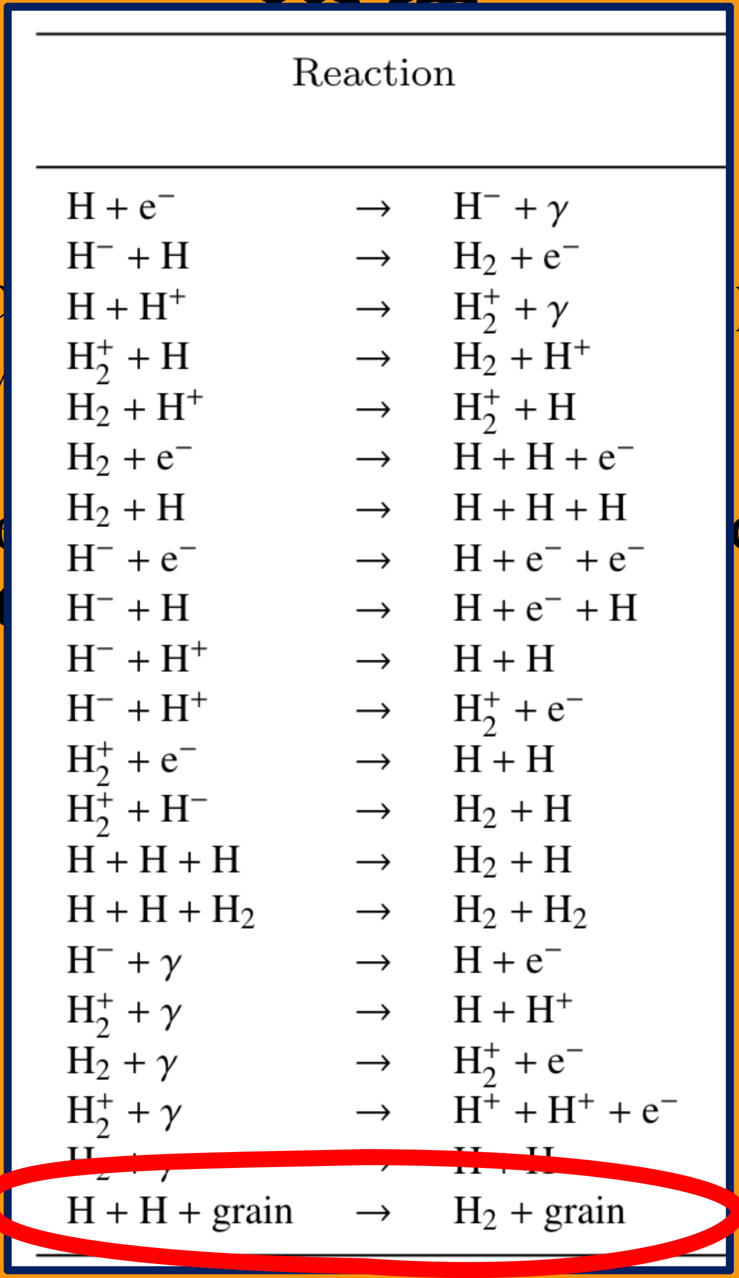
KMT

Dust column density is an input to the KMT model

No specific models for different formation pathways

Dust c put to the KM

No spe ent format



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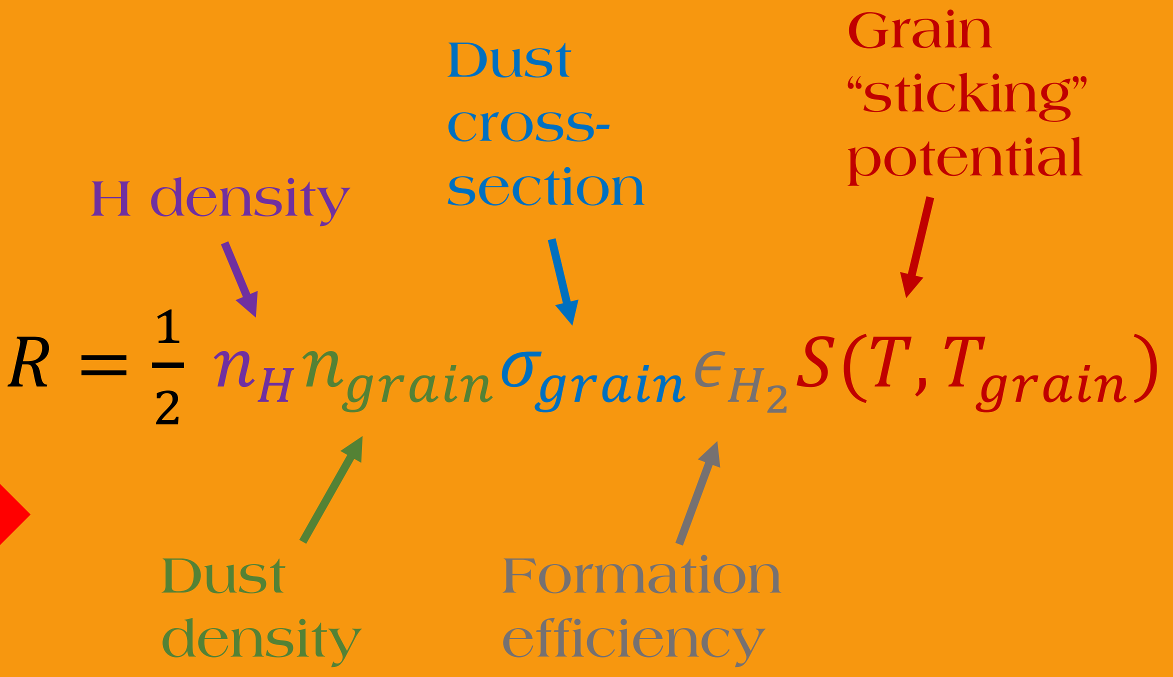
(Schneider et al., 2006)

Grackle



Grain "sticking" potential

Dust cross-section

H density

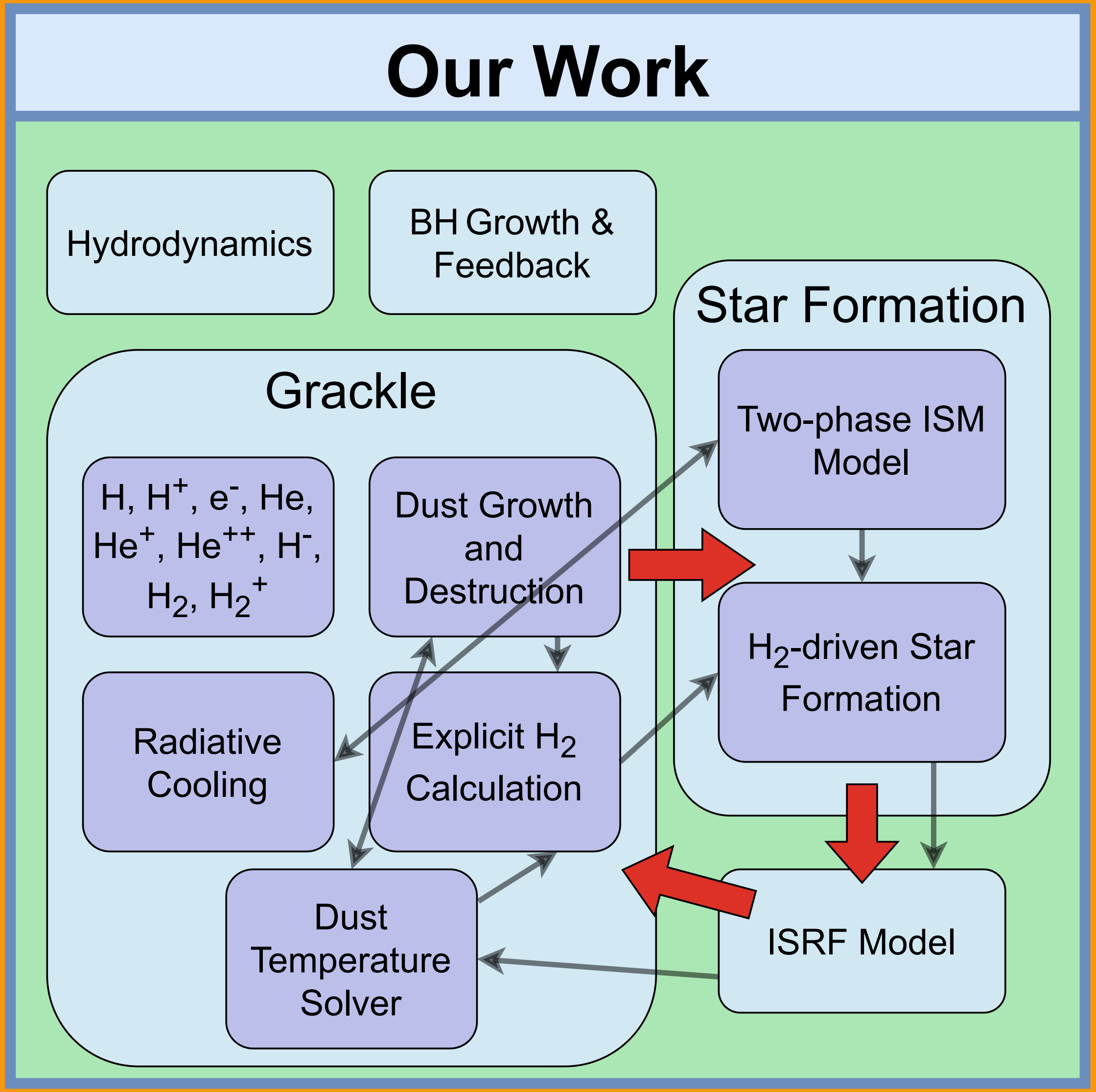
$$R = \frac{1}{2} n_H n_{grain} \sigma_{grain} \epsilon_{H_2} S(T, T_{grain})$$

Dust density

Formation efficiency

Explicit calculation – much more accurate!

What affects star formation?



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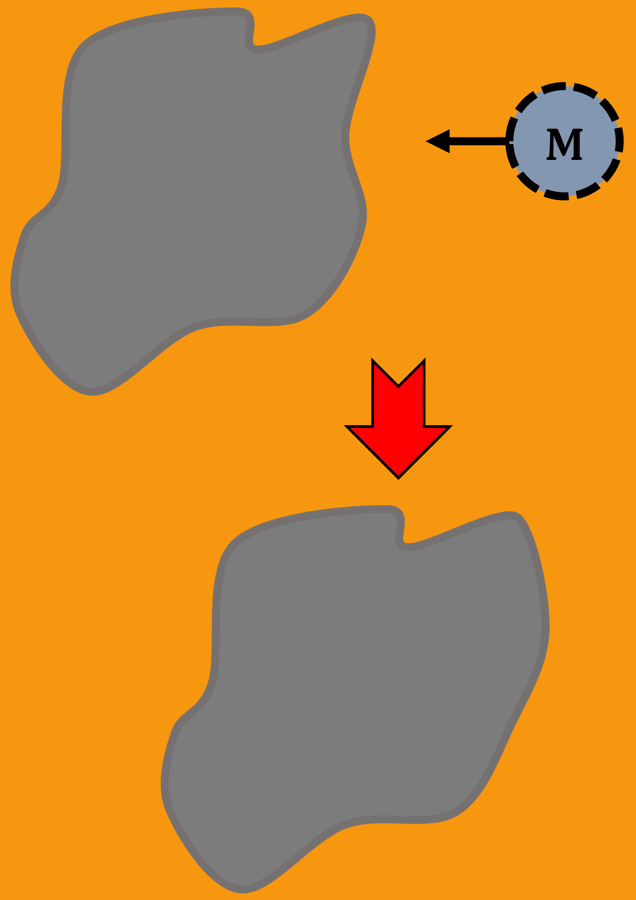
Dust Growth and Destruction

(Li et al., 2019)

Grains grow through accretion of gas-phase metals



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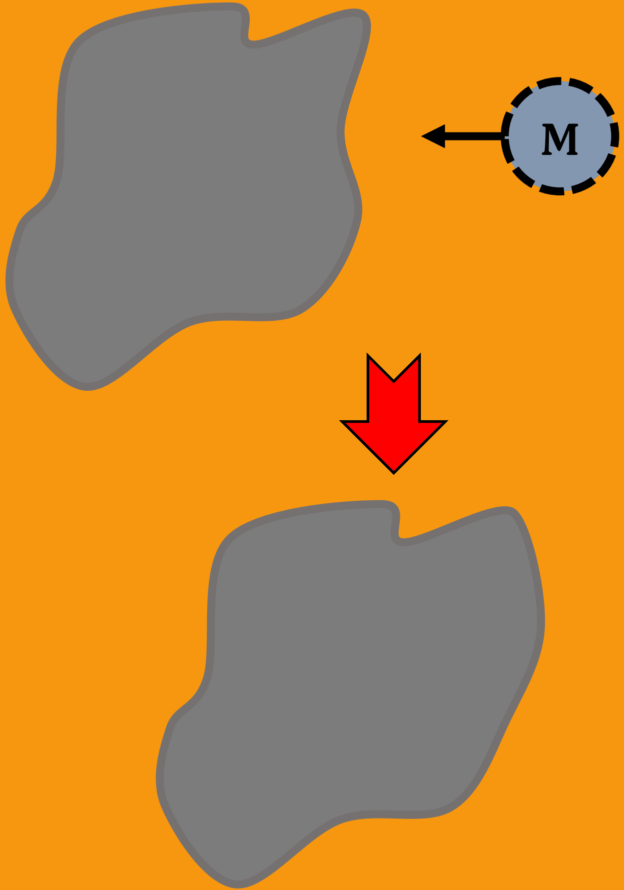
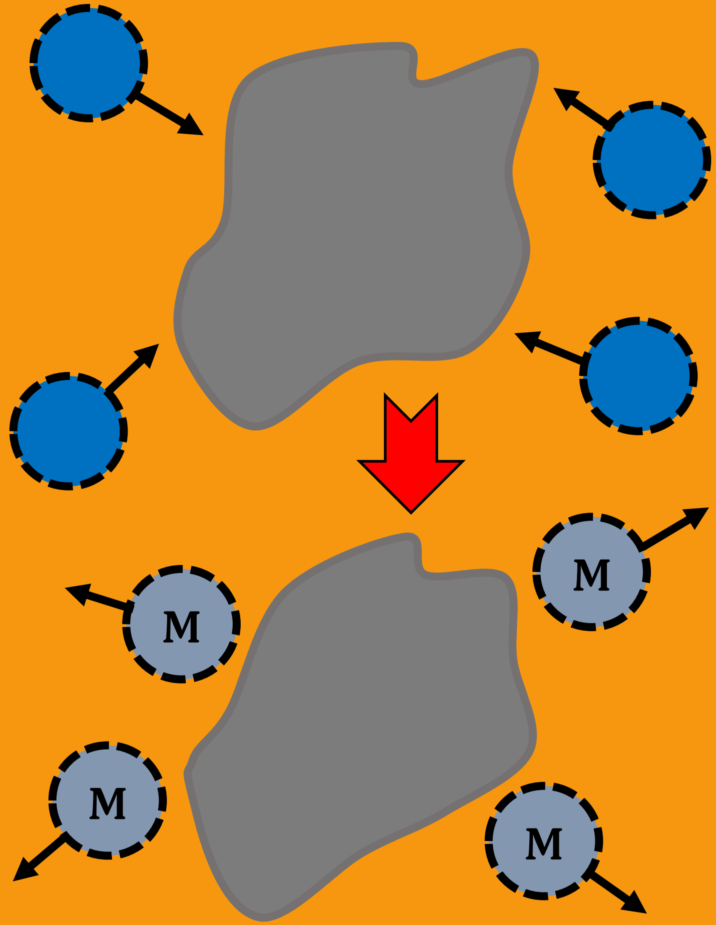


Grains abraded by thermal sputtering



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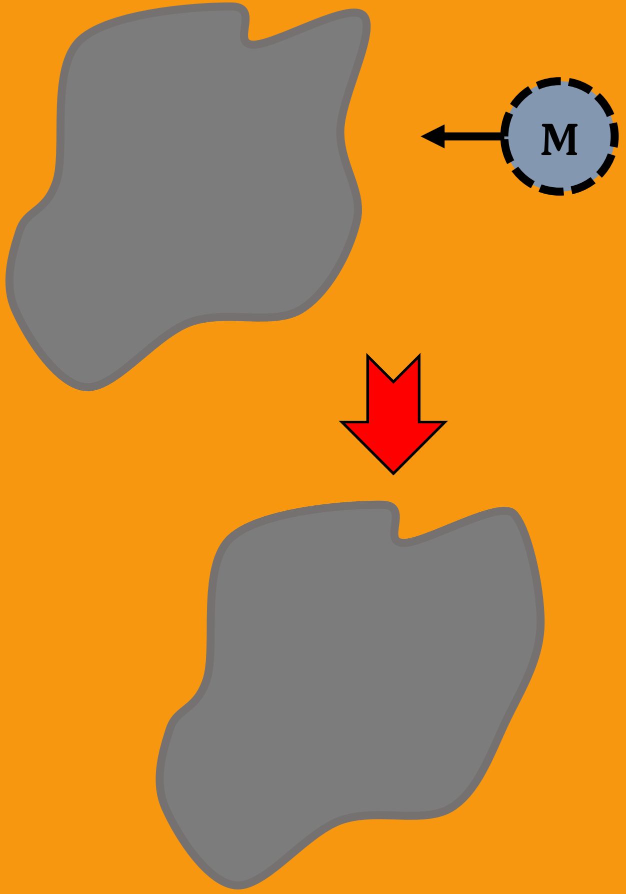

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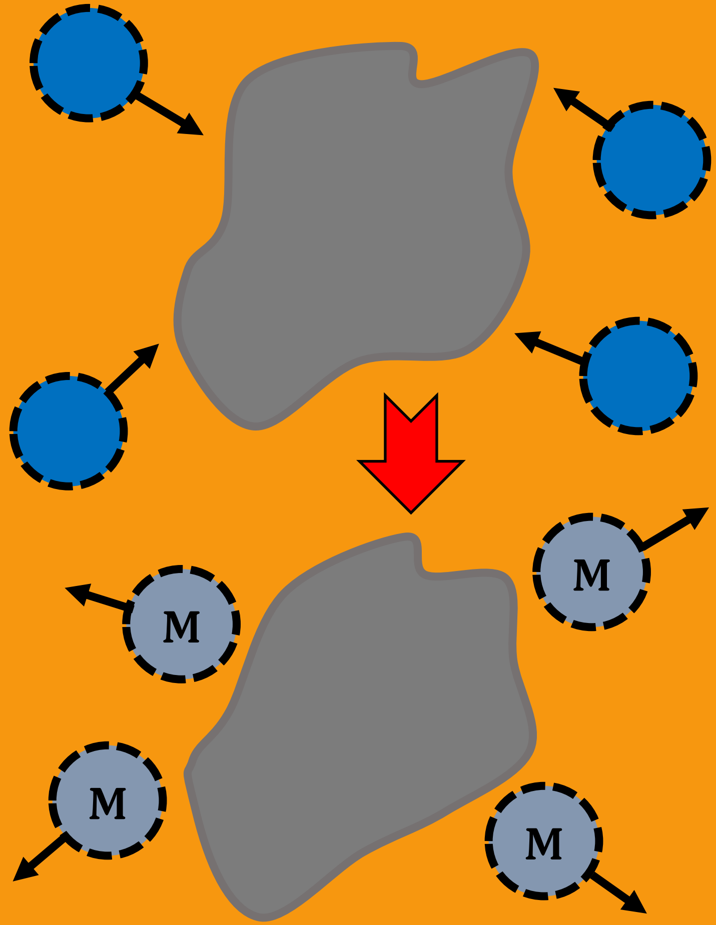
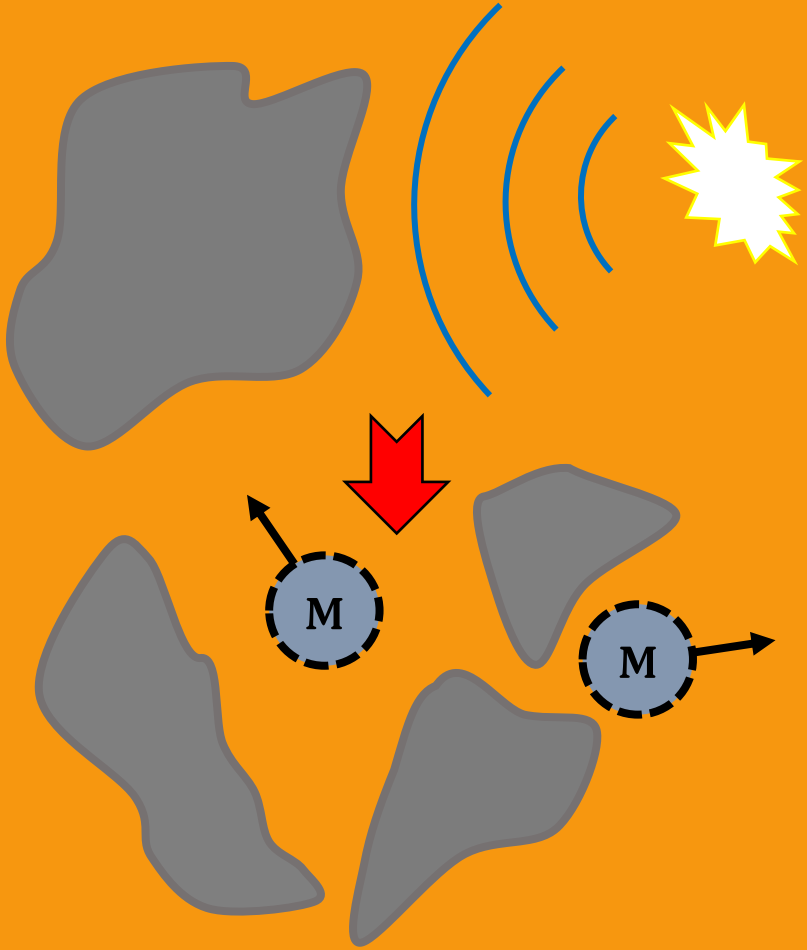


Grains destroyed by shocks



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Simba

Growth and destruction rates characterised by timescales:

$$\left(\frac{dM_{grain}}{dt}\right)_i \propto \frac{1}{\tau_i}$$

The accretion timescale:

$$\tau_{accr} = \tau_{ref}\left(\frac{T_{ref}}{T_{gas}}\right)\left(\frac{\rho_{ref}}{\rho_{gas}}\right)\left(\frac{Z_{\odot}}{Z_{gas}}\right)$$

Reference parameters are tuned:

$$T_{ref} = 20\ \mathrm{K}$$

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Our Work

Solve gas-grain heat balance for dust temperature:

$$\underbrace{4\sigma T_{gr}^4 \overset{\substack{\text{Grain opacity}\\ \downarrow}}{\kappa_{gr}}}_{\text{Radiative cooling}} = \underbrace{4\sigma T_{CMB}^4 \kappa_{gr} + \overset{\substack{\text{Rate of heat transfer}\\ \text{between gas and dust}\\ \downarrow}}{\Lambda_{gas-grain}}}_{\text{Heating}}$$

Replace reference temperature:

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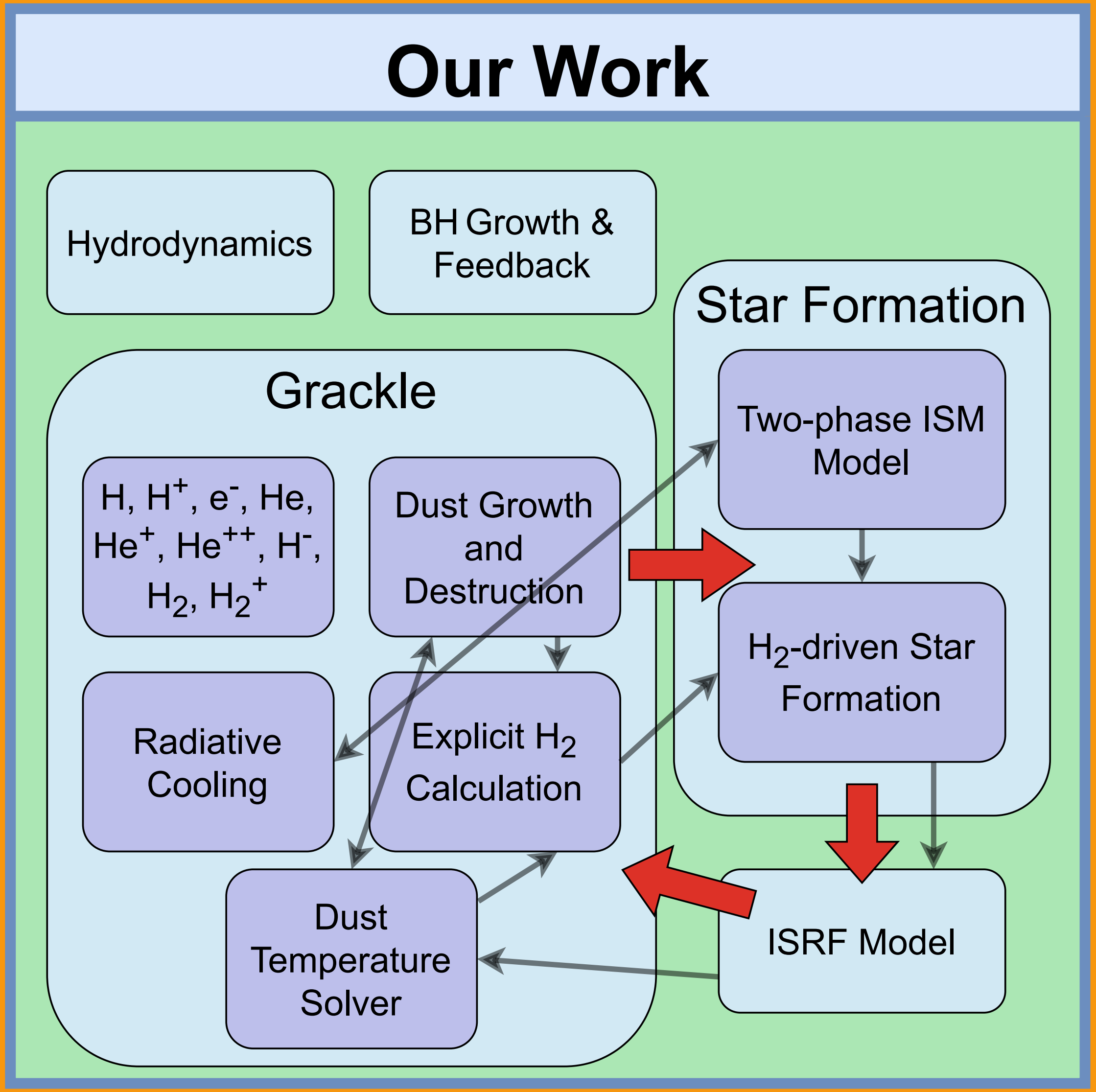
Dust model integrated into chemical network

What affects star formation?



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BH Growth & Feedback

Star Formation

Two-phase ISM Model

H_2-driven Star Formation

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Dust Growth and Destruction

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Explicit H_2 Calculation

Dust Temperature Solver

ISRF Model

Primarily:

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Secondary Processes:

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Isolated Case

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Dust model integrated into chemical network

External Radiation Field

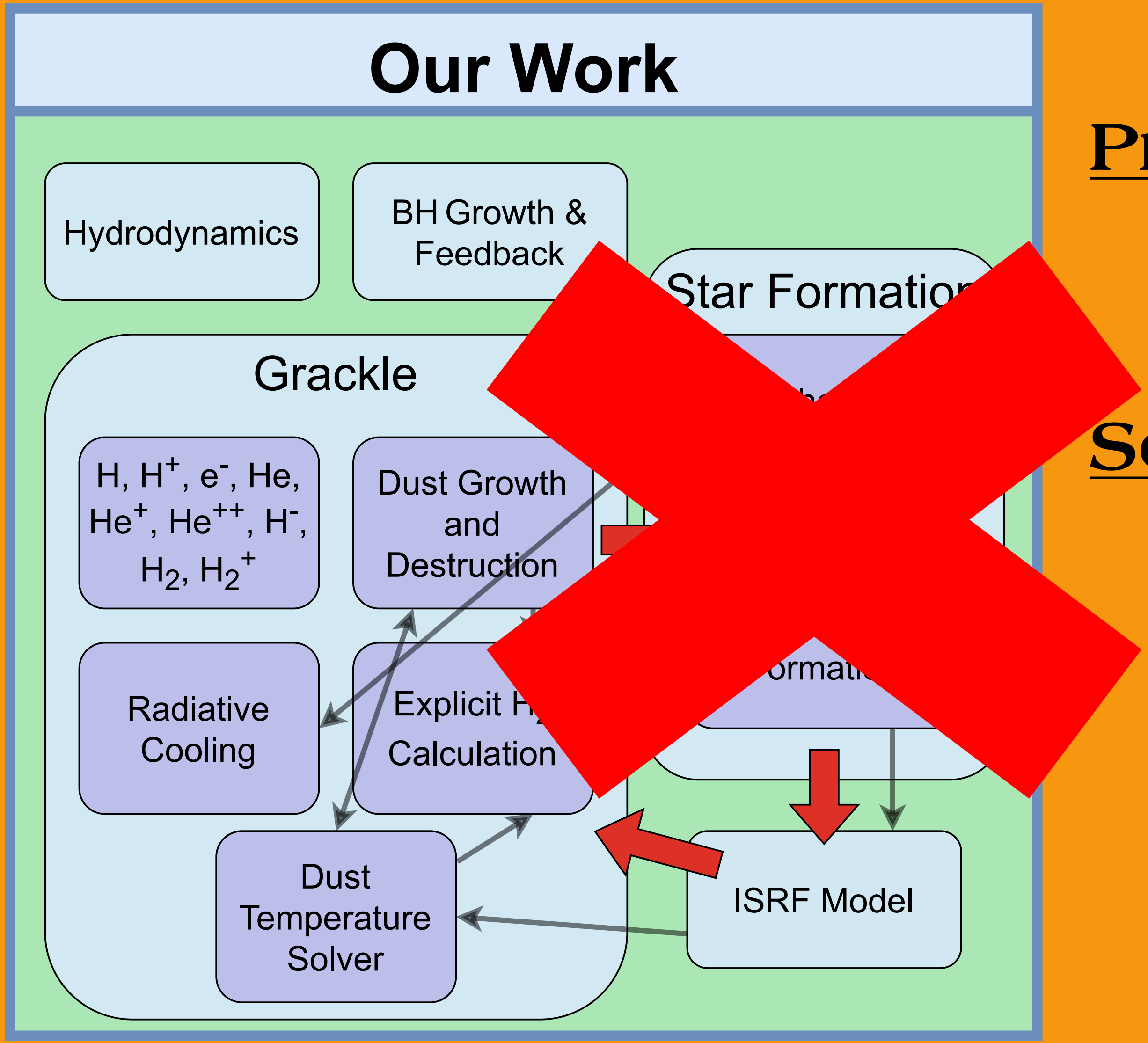
Interstellar radiation field heats dust:

$$4\sigma T_{gr}^4 \kappa_{gr} = 4\sigma T_{CMB}^4 \kappa_{gr} + \Lambda_{gas-grain} + \underset{\text{Dust heating rate}}{\Gamma_{\mathrm{ISRF}}}\,\underset{\text{ISRF strength}}{G_0}$$

Estimate ISRF from star formation in local environment:

$$G_0 = \frac{G_{0,MW}}{\underbrace{\Sigma_{MW}}_{\text{Milky-way values}}}\,\overset{\text{Star formation rate density}}{\Sigma}$$

What affects star formation?



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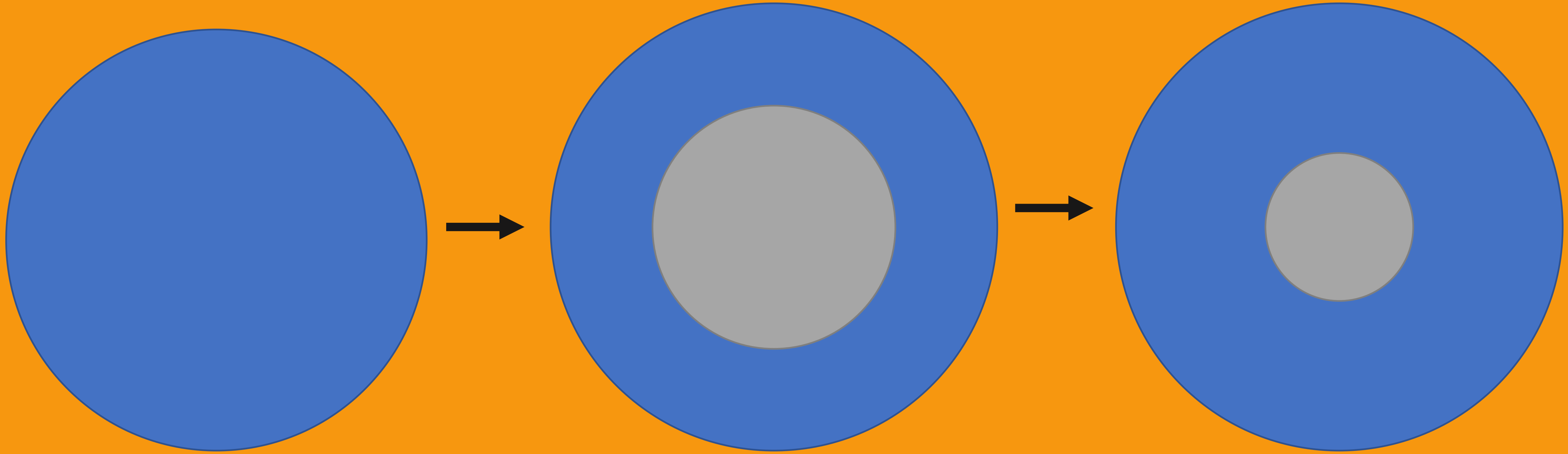
Modelling Changes

- Removal of KMT model left star formation unresolved

- Implement sub-grid model to fix this:
  1. Gas reaches sufficiently high density → Treat as two phases
  2. Only cool the molecular phase → Update its density to maintain pressure equilibrium

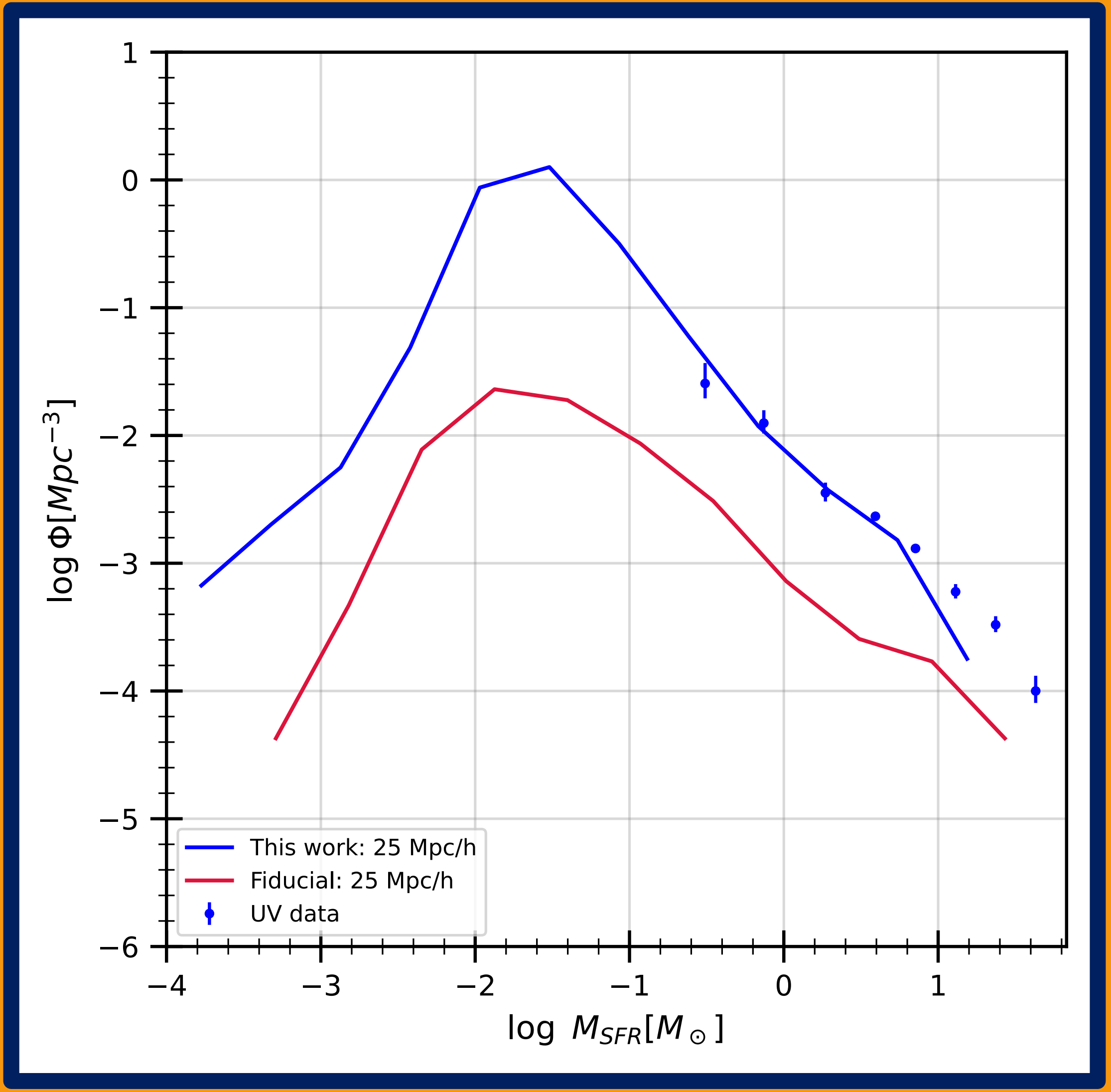


Our Simulations

- Two production simulations completed on Cirrus:
  - 50 Mpc/h box – 1024^3 particles
  - 25 Mpc/h box – 1024^3 particles

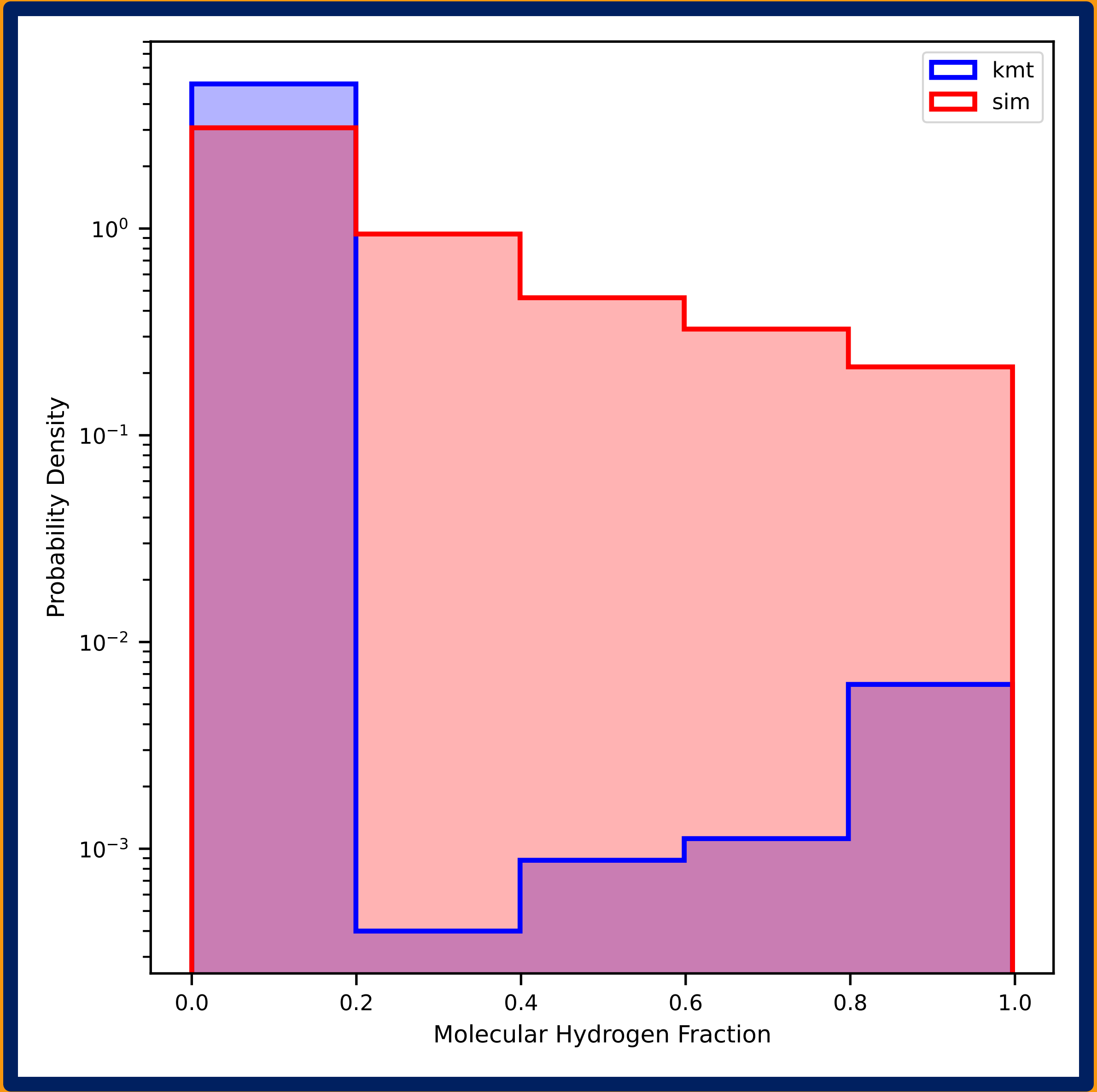
- Evolved from redshift 99 to 6

Mass Functions: SFR



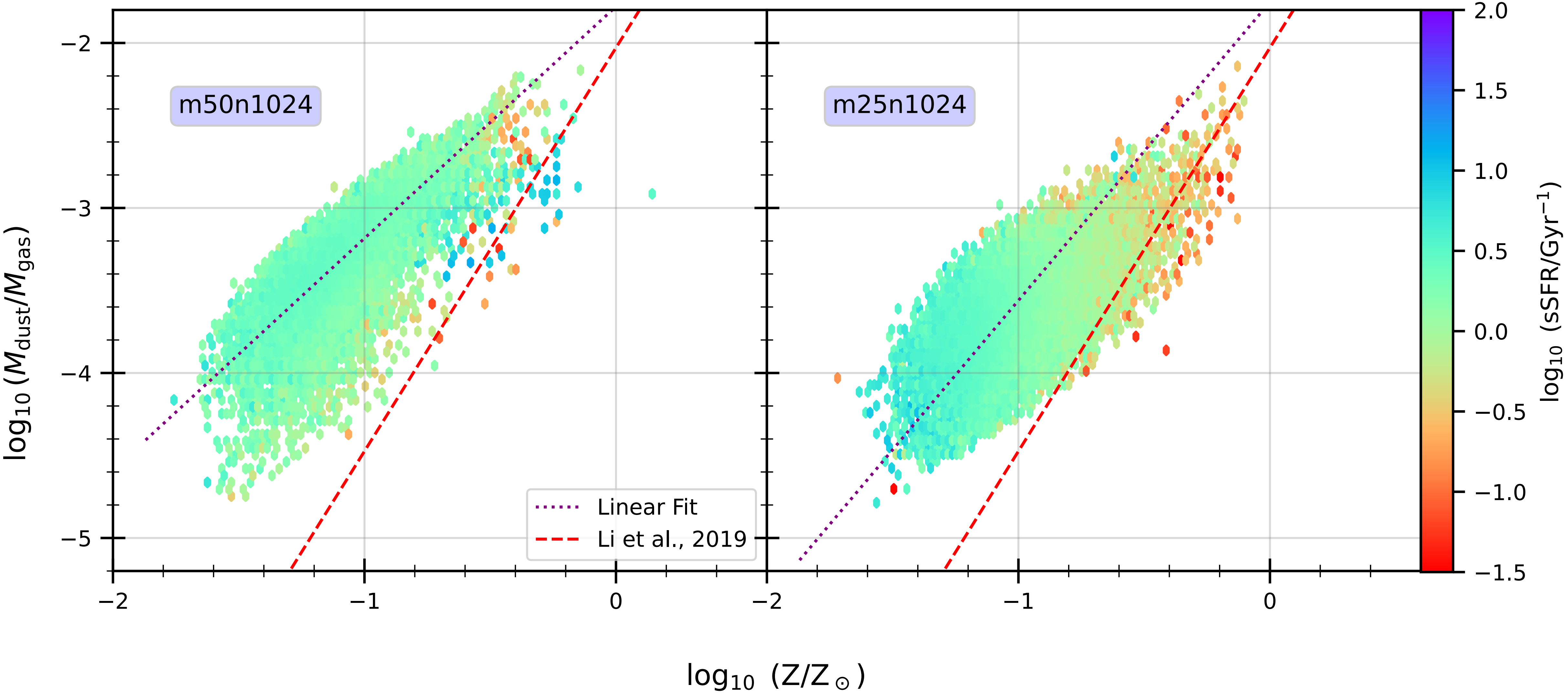
25 Mpc/h

Molecular Hydrogen Fraction

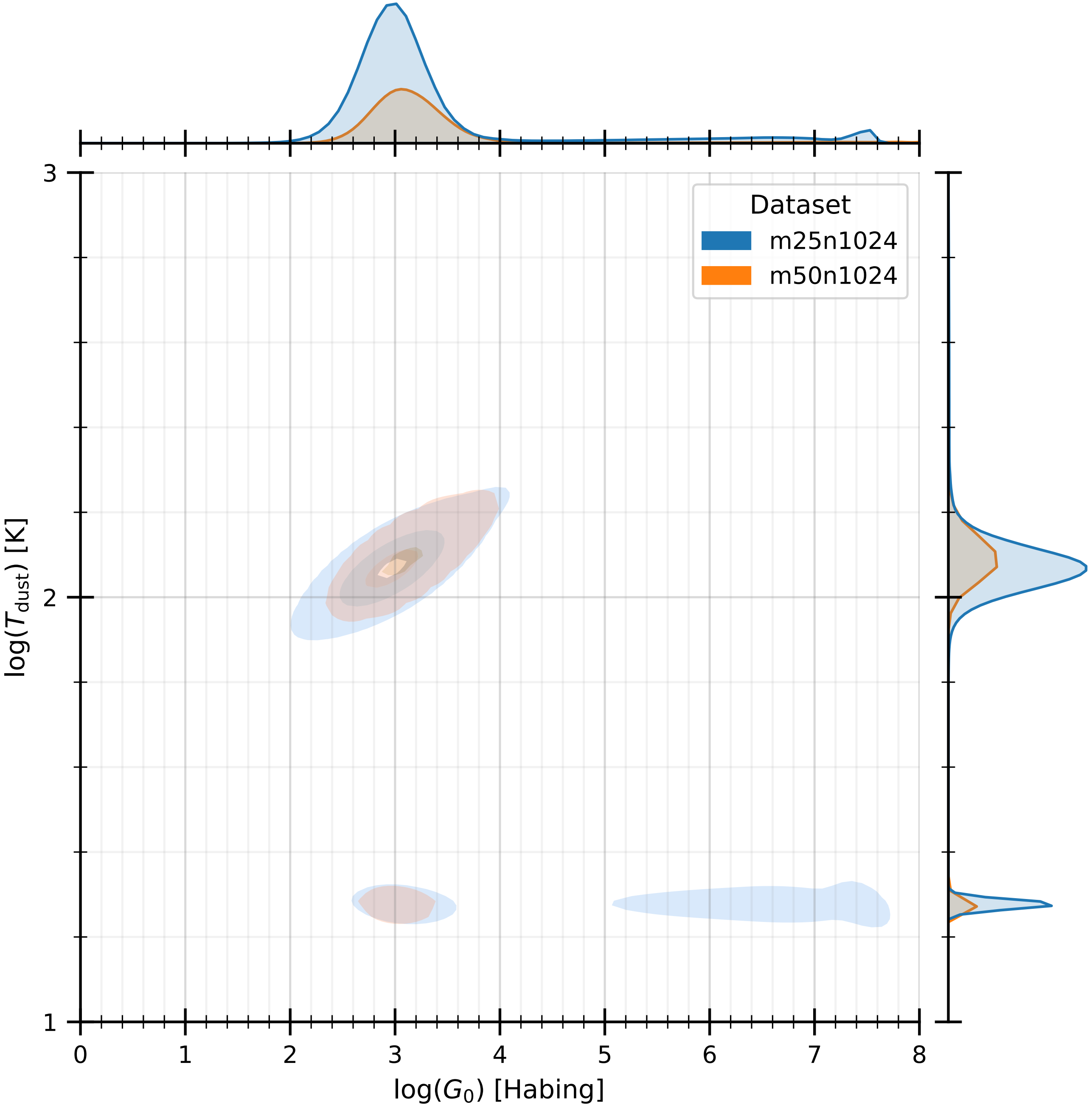


(25 Mpc/h)

Dust-to-Gas Ratio



Dust Temperature



- Contours containing 10%, 50%, 80% and 95% of the data

Summary

What we've done

Improvements:

- Extended chemical network
- Solving for dust temperature
- Molecular hydrogen calculation

Additions:

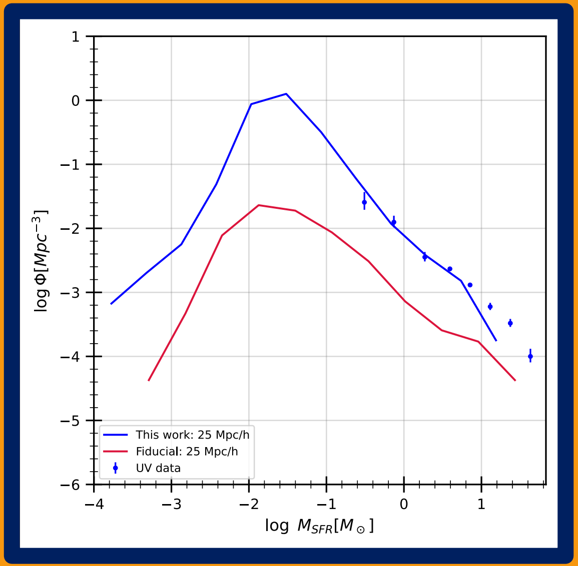
- ISRF model
- Two-phase sub-grid model

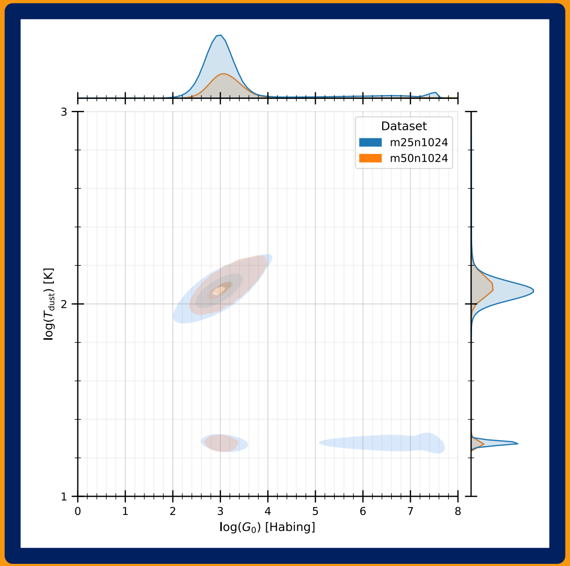
What we've seen

- Good agreement with fiducial Simba
- Improved SFR
- Interesting results to look into!

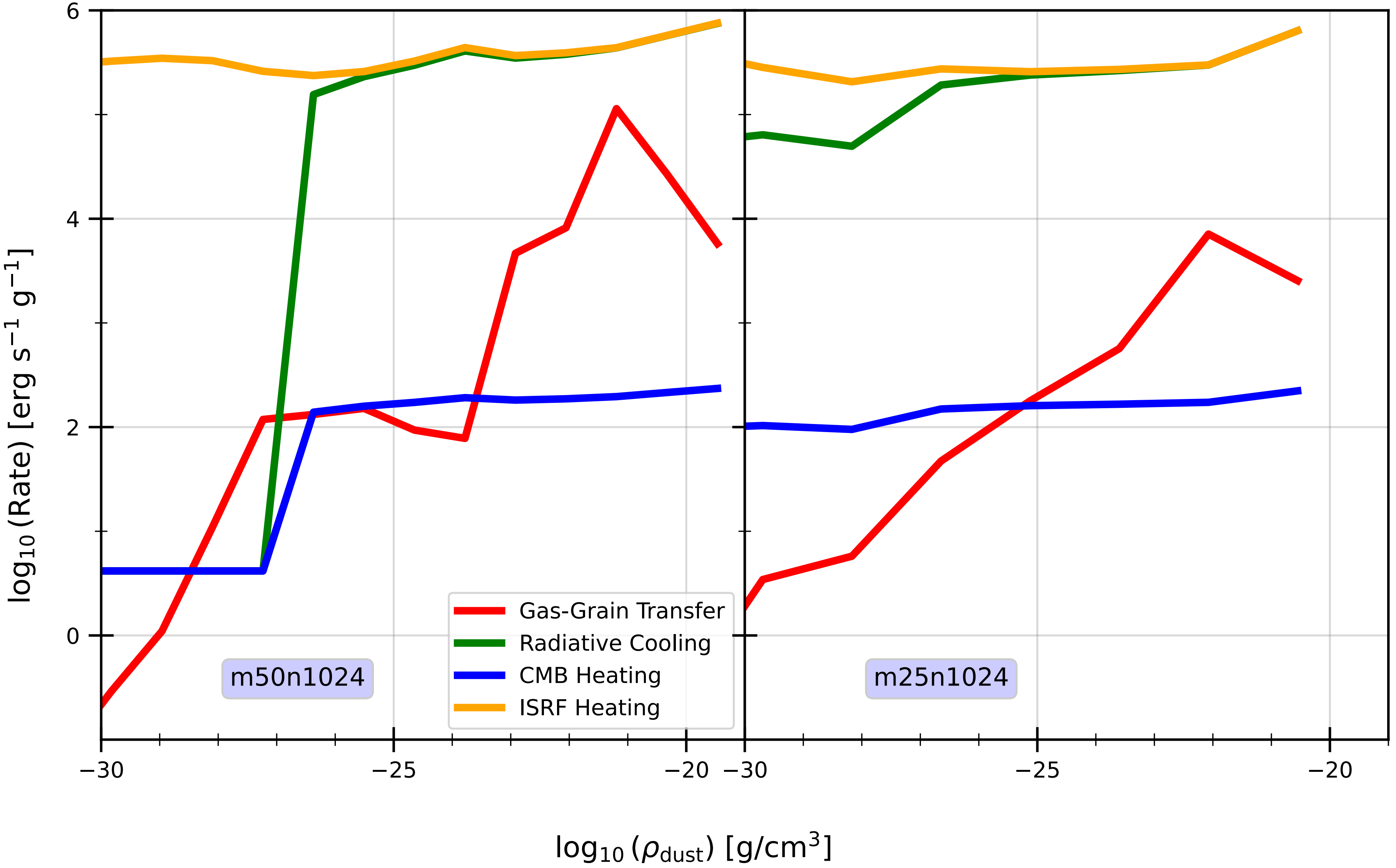
What's next?

- Run to lower redshifts
- Comparison to new observational data
- Higher resolutions (zooms)

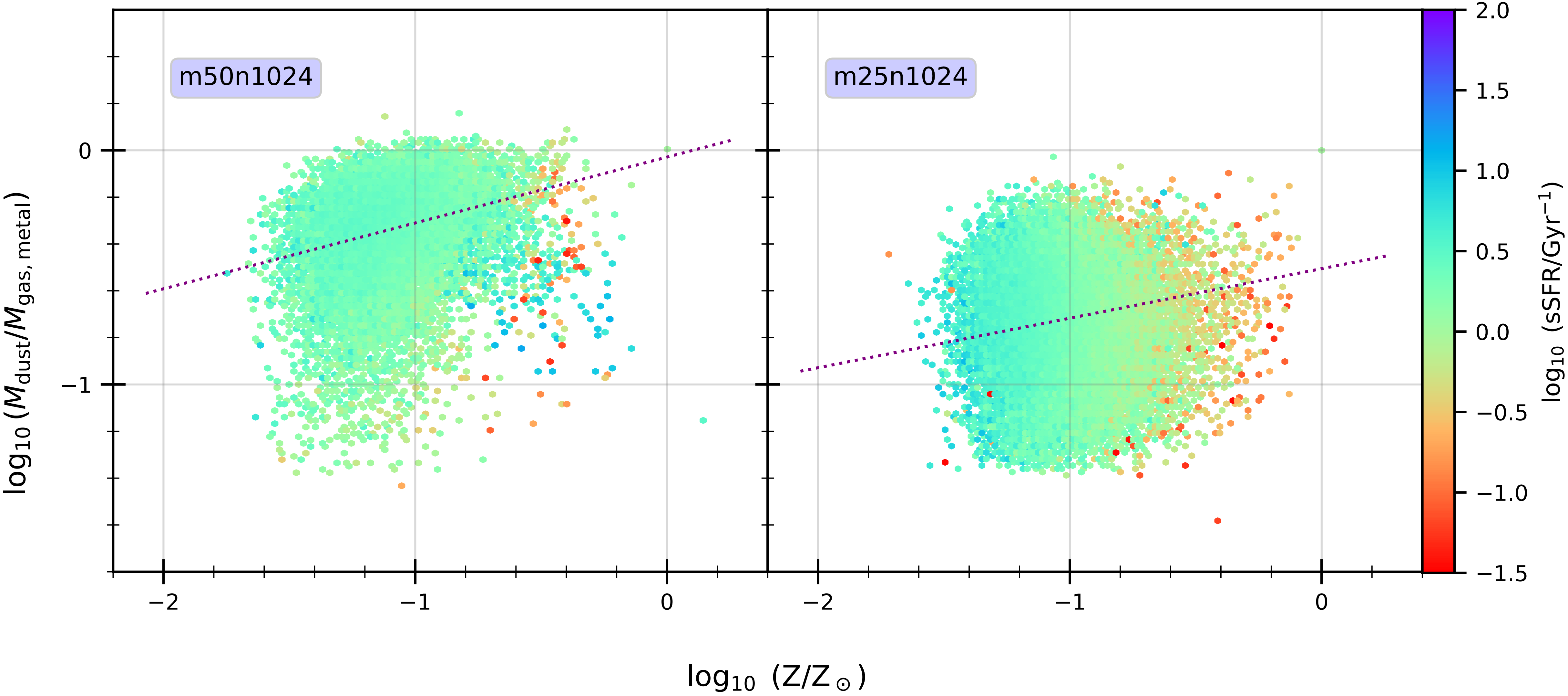


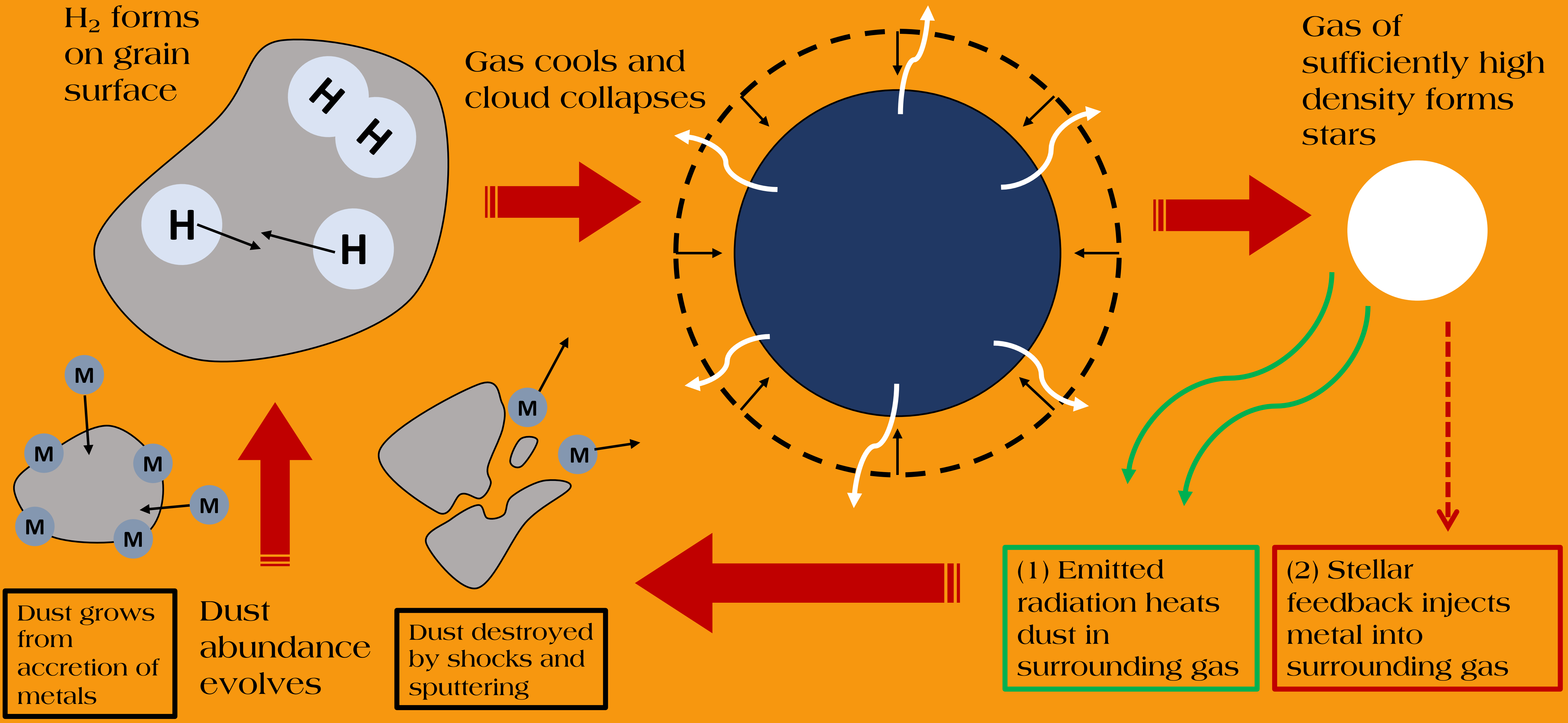


Dust Heating Rate



Dust-to-Metal Ratio





H_2 forms on grain surface

Gas cools and cloud collapses

Gas of sufficiently high density forms stars

(1) Emitted radiation heats dust in surrounding gas

(2) Stellar feedback injects metal into surrounding gas

Dust destroyed by shocks and sputtering

Dust abundance evolves

Dust grows from accretion of metals