The stellar IMF at very low metallicities

Gustavo Dopcke,
Paul Clark, Simon Glover,
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Outline

- Physical mechanisms that shape the IMF
- Low metallicity coolants
- Simulations that address the problem
- Building up the IMF

Physical mechanisms that shape the IMF

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- Mechanical: Turbulence and Rotation

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- Thermal: dependent on the chemical composition and mechanic history
- B-Field: Equipartition can be reached quickly even in the metal-free case (see talk by J. Schober)
- Feedback: jets, accretion luminosity, young stars radiation

Physical mechanisms that shape the IMF

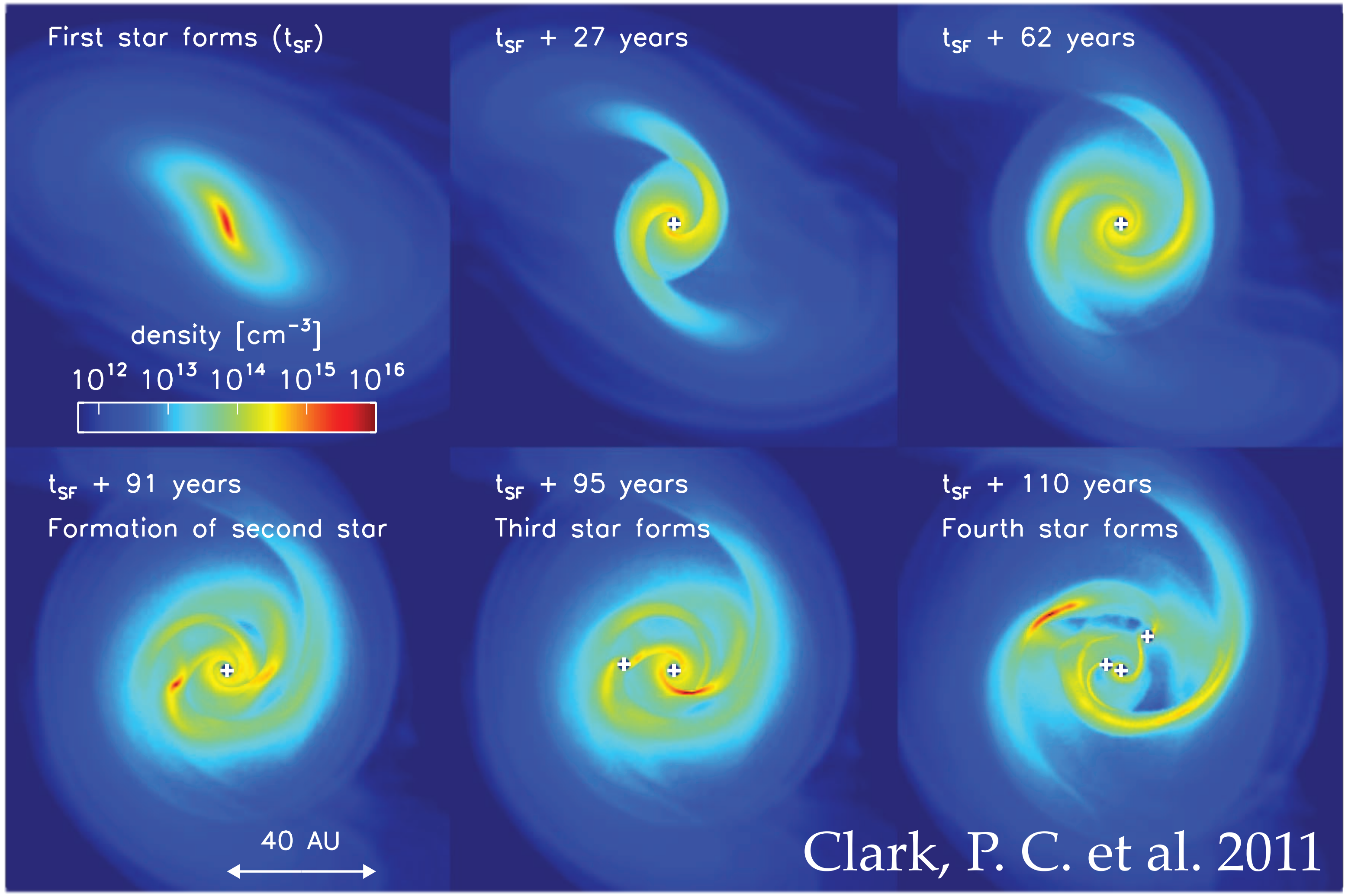
- Mechanical: Turbulence and Rotation
- Thermal: dependent on the chemical composition and mechanic history

The stellar IMF

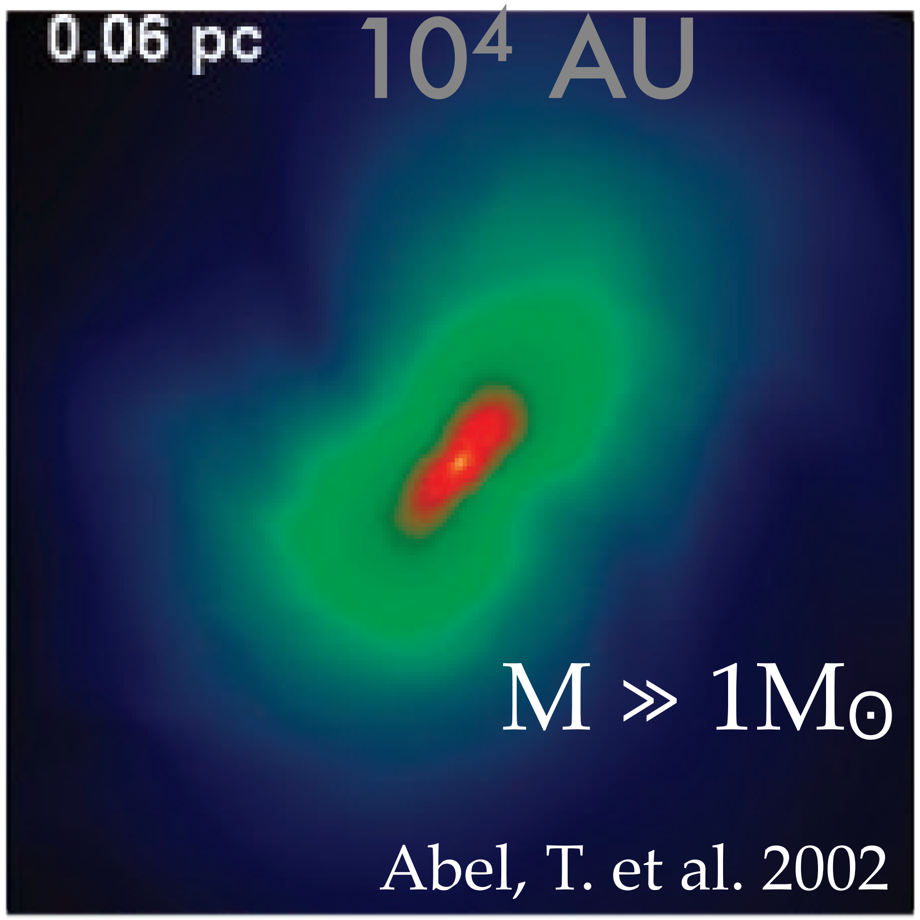
- for Z=0, $M >> M_\odot$
- otherwise, IMF = Chabrier & Kroupa
- Z_{crit}

Pop III

- Pop III IMF is top heavy (Abel, Bromm, Clark, Greif, O'Shea, Norman, Yoshida, etc.)



Clark, P. C. et al. 2011

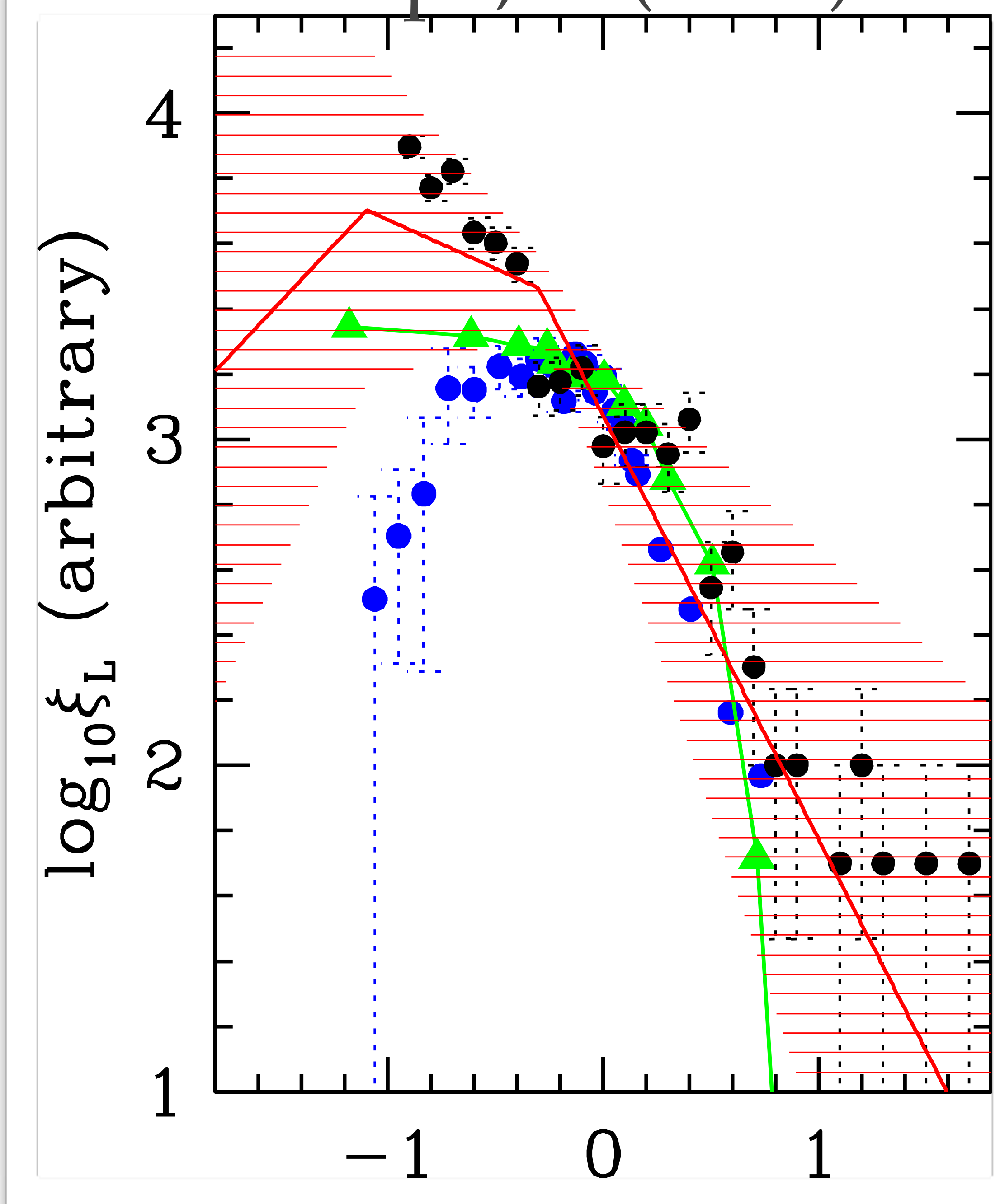


Abel, T. et al. 2002

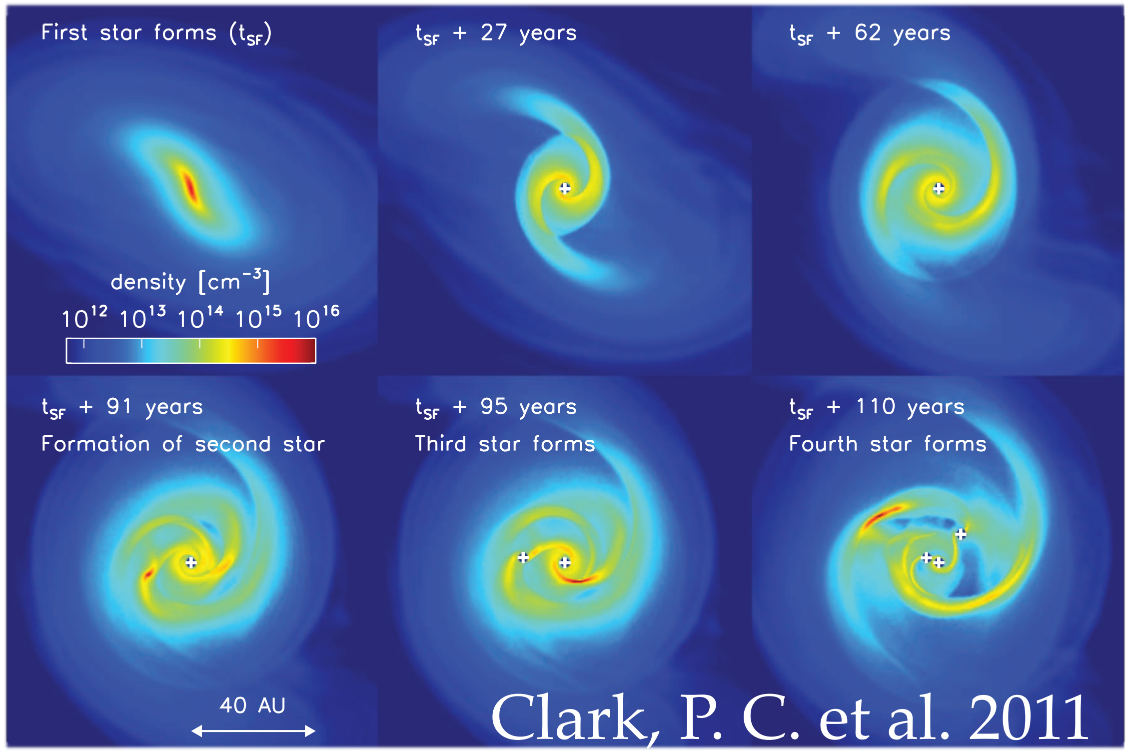
Present day IMF

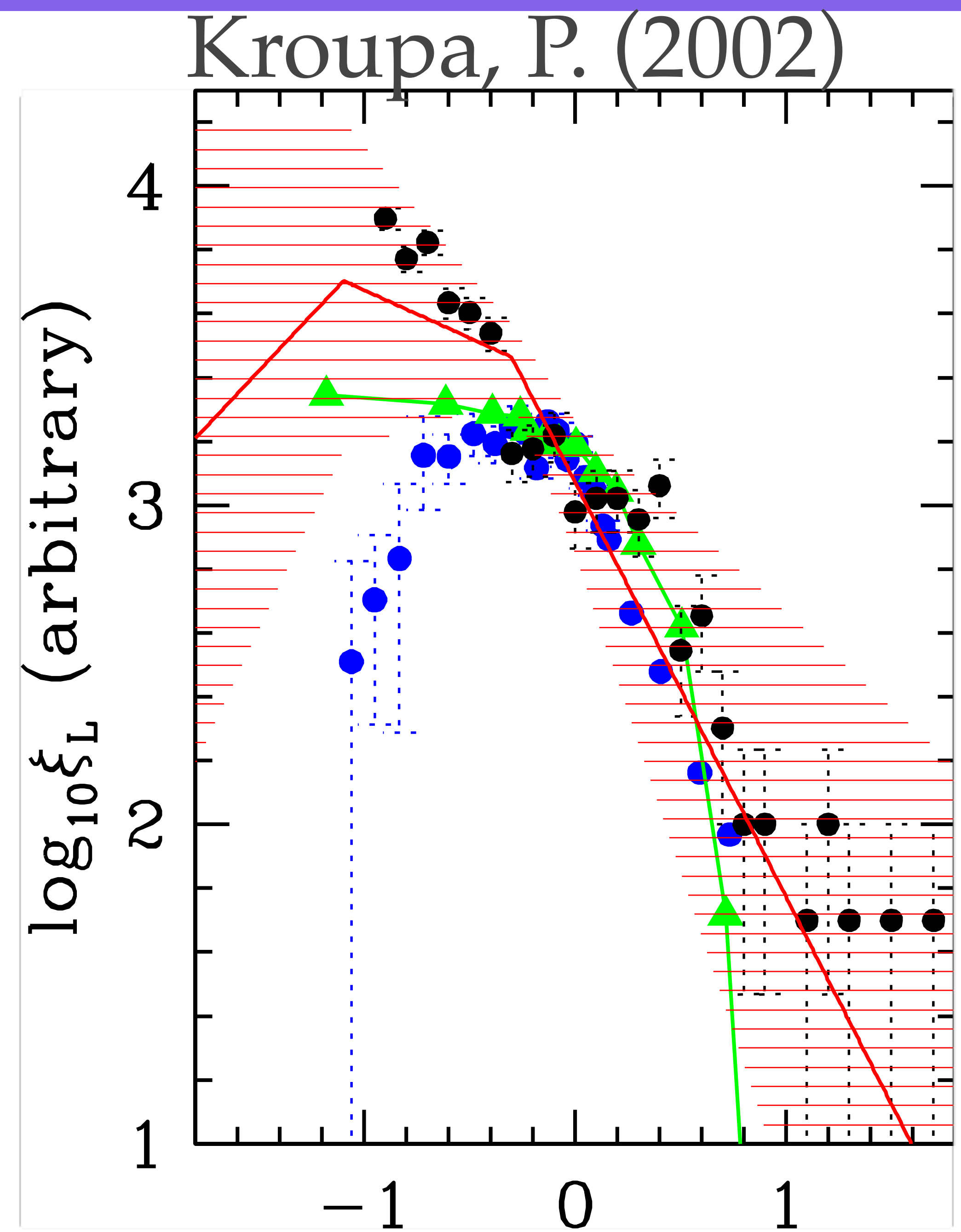
- Present day IMF favours masses < 1M☉ (Kroupa, Chabrier, etc.)

Kroupa, P. (2002)

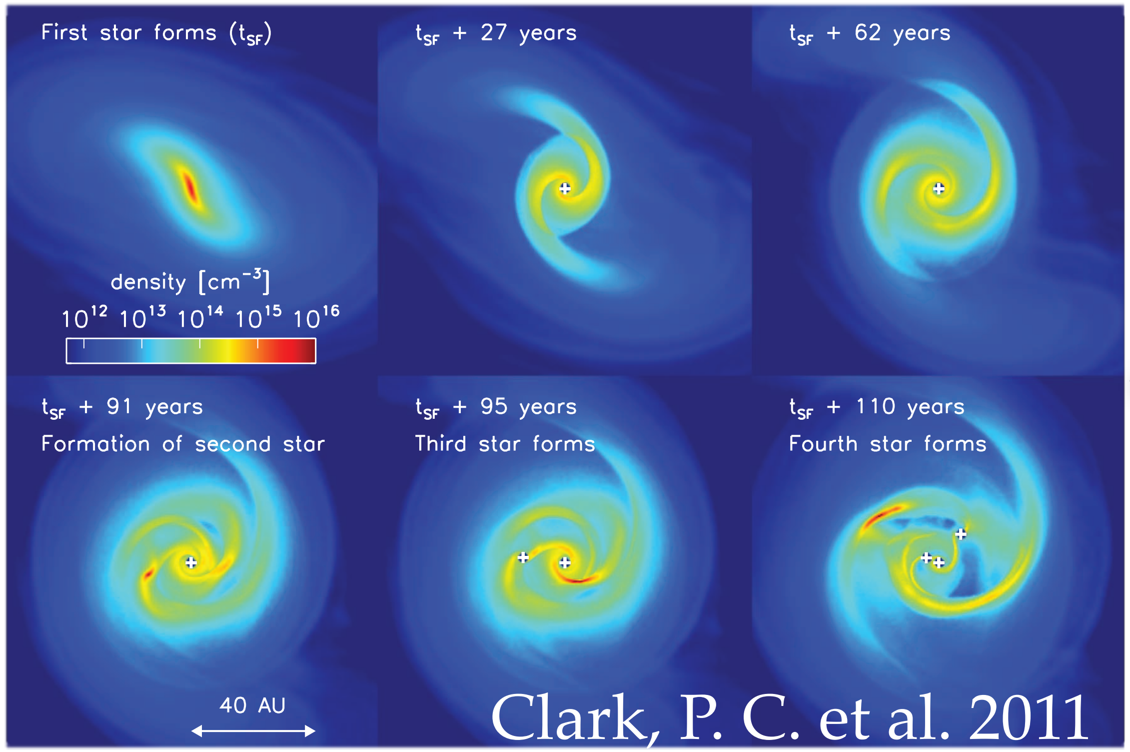


Pop III - Pop II/I

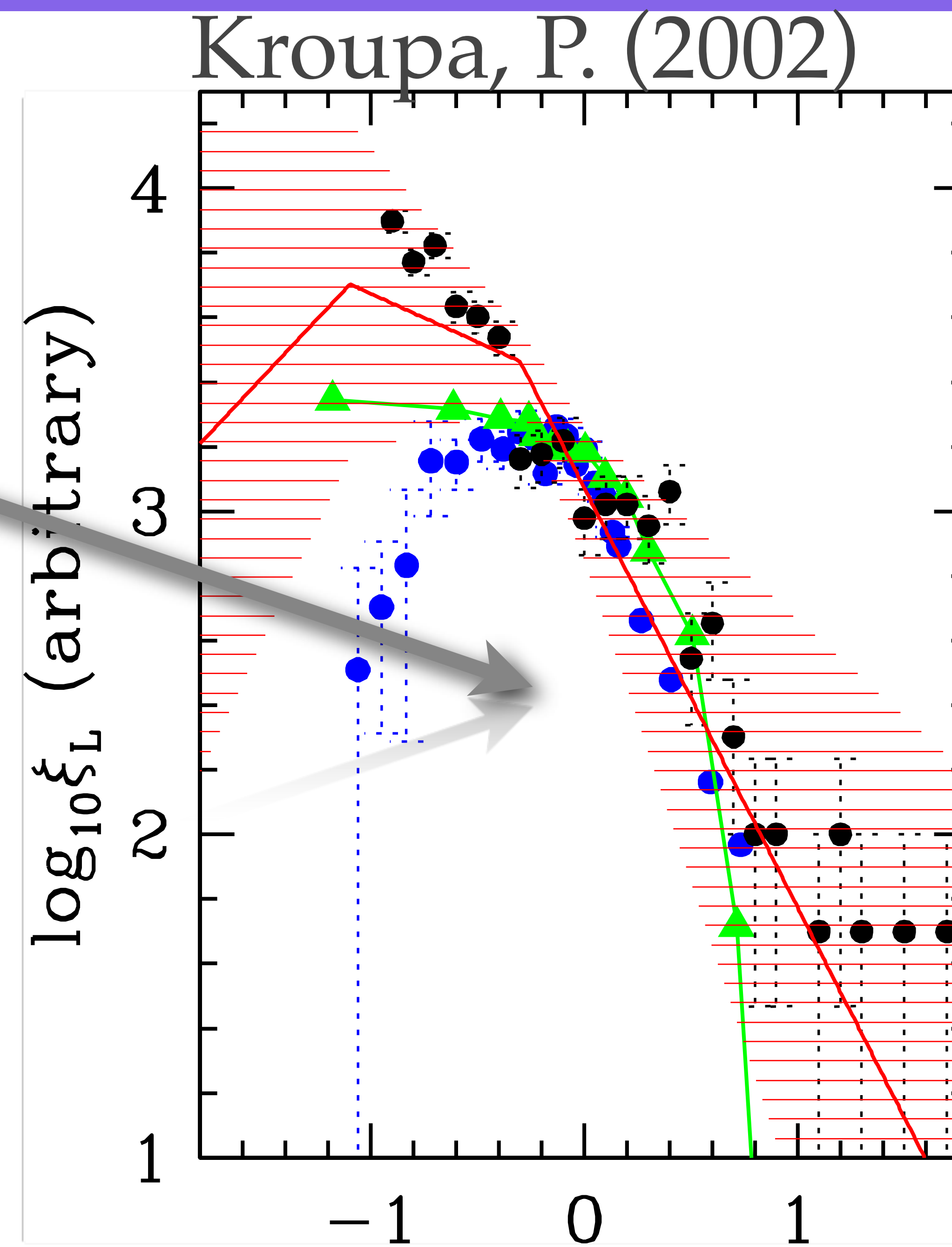




Pop III - Pop II/I



?



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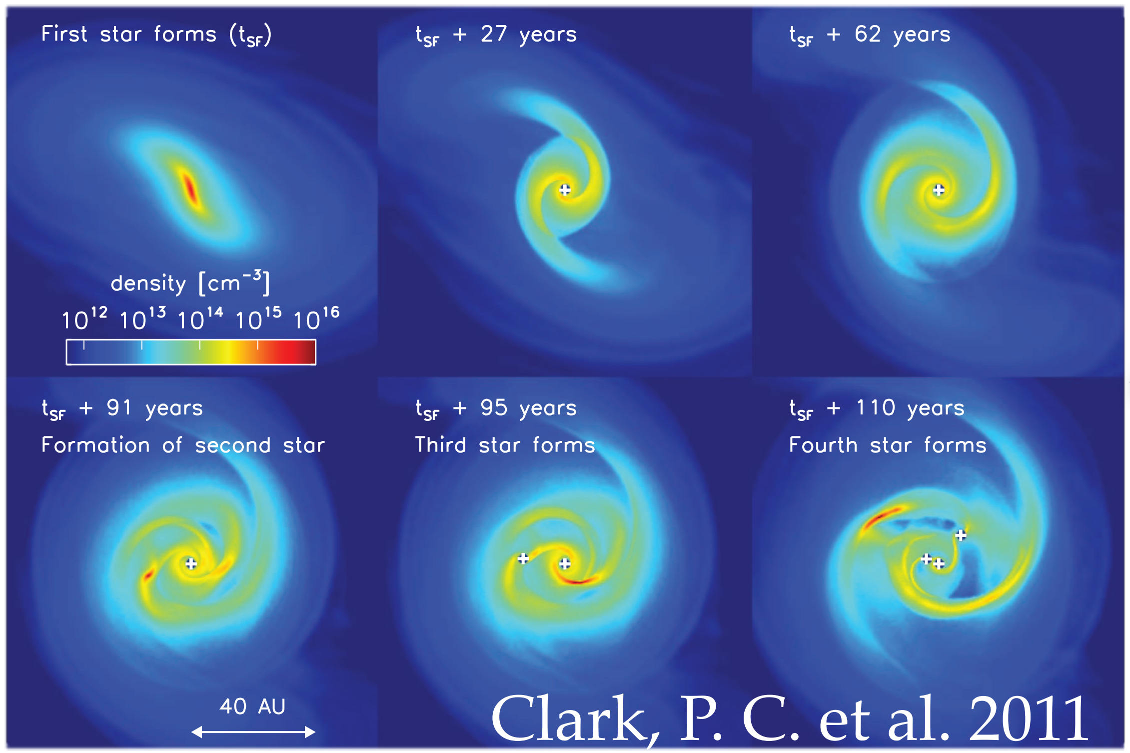
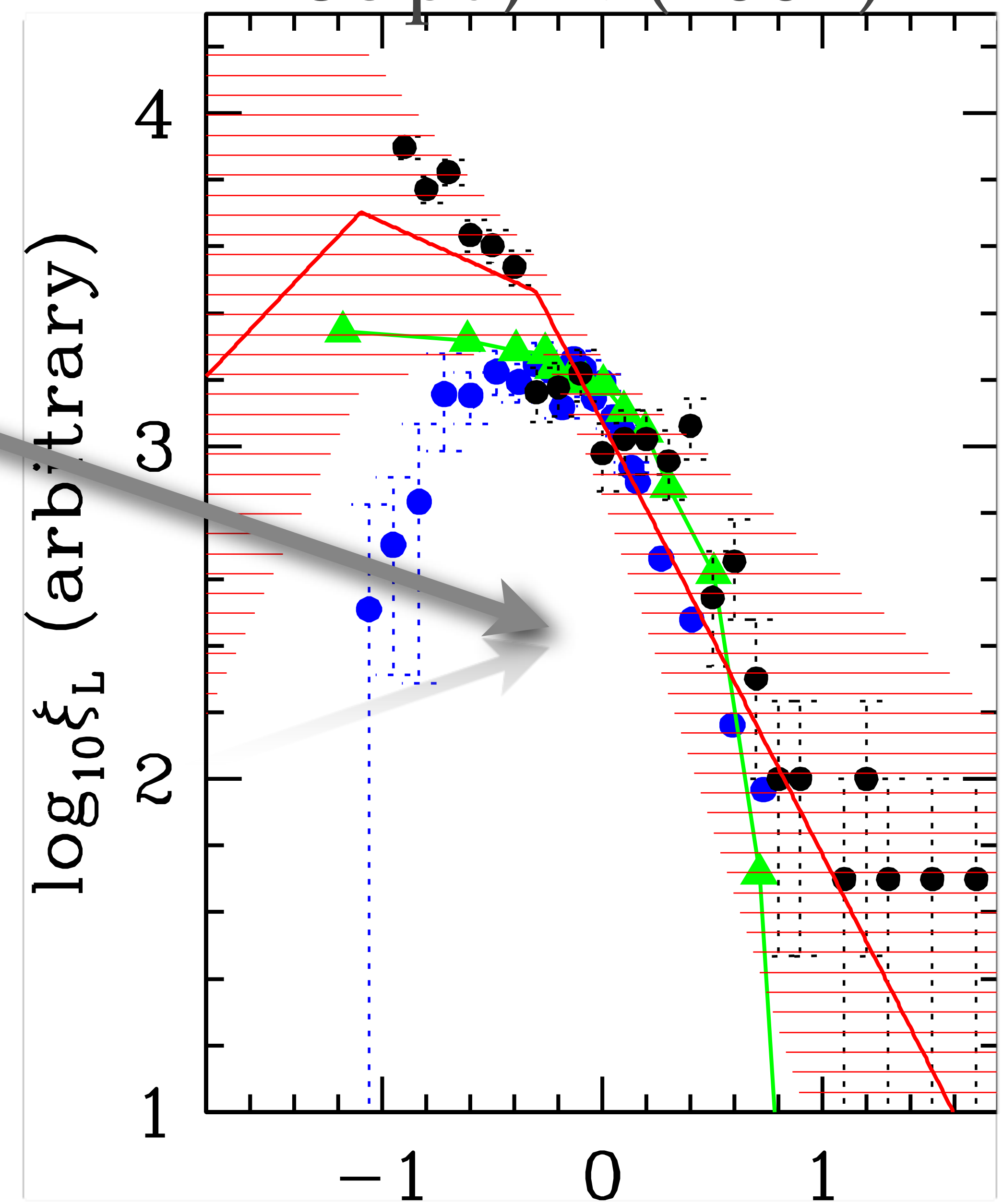


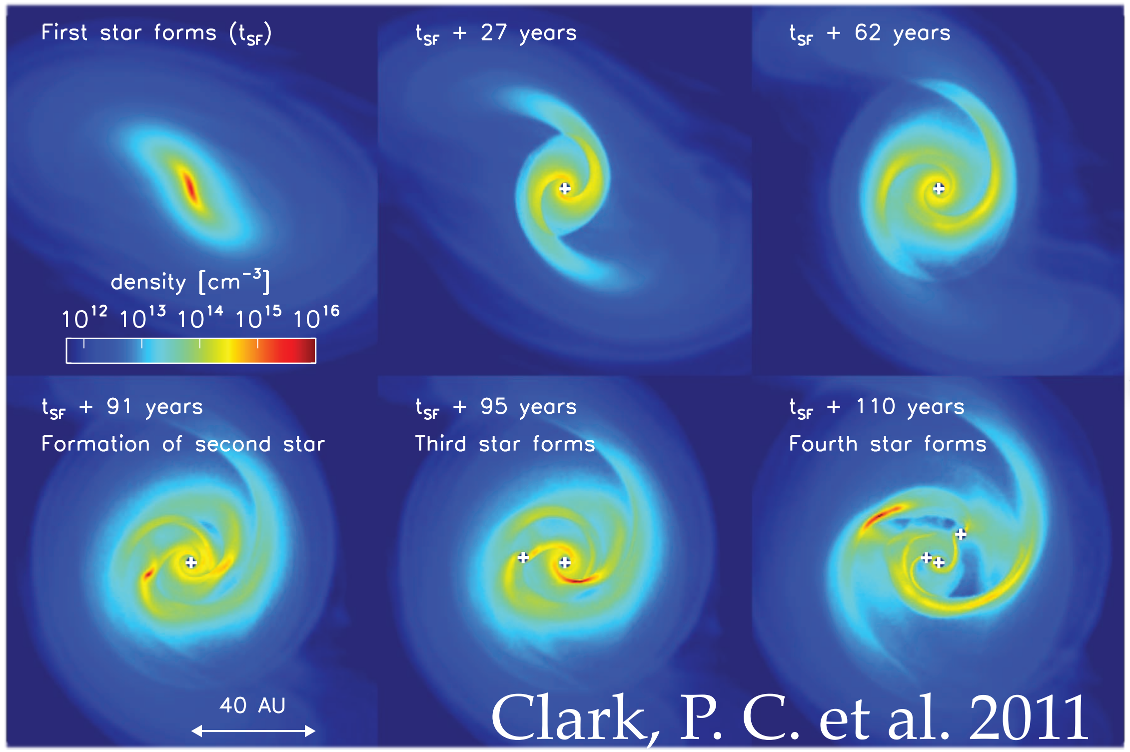
Z ↑

Metals

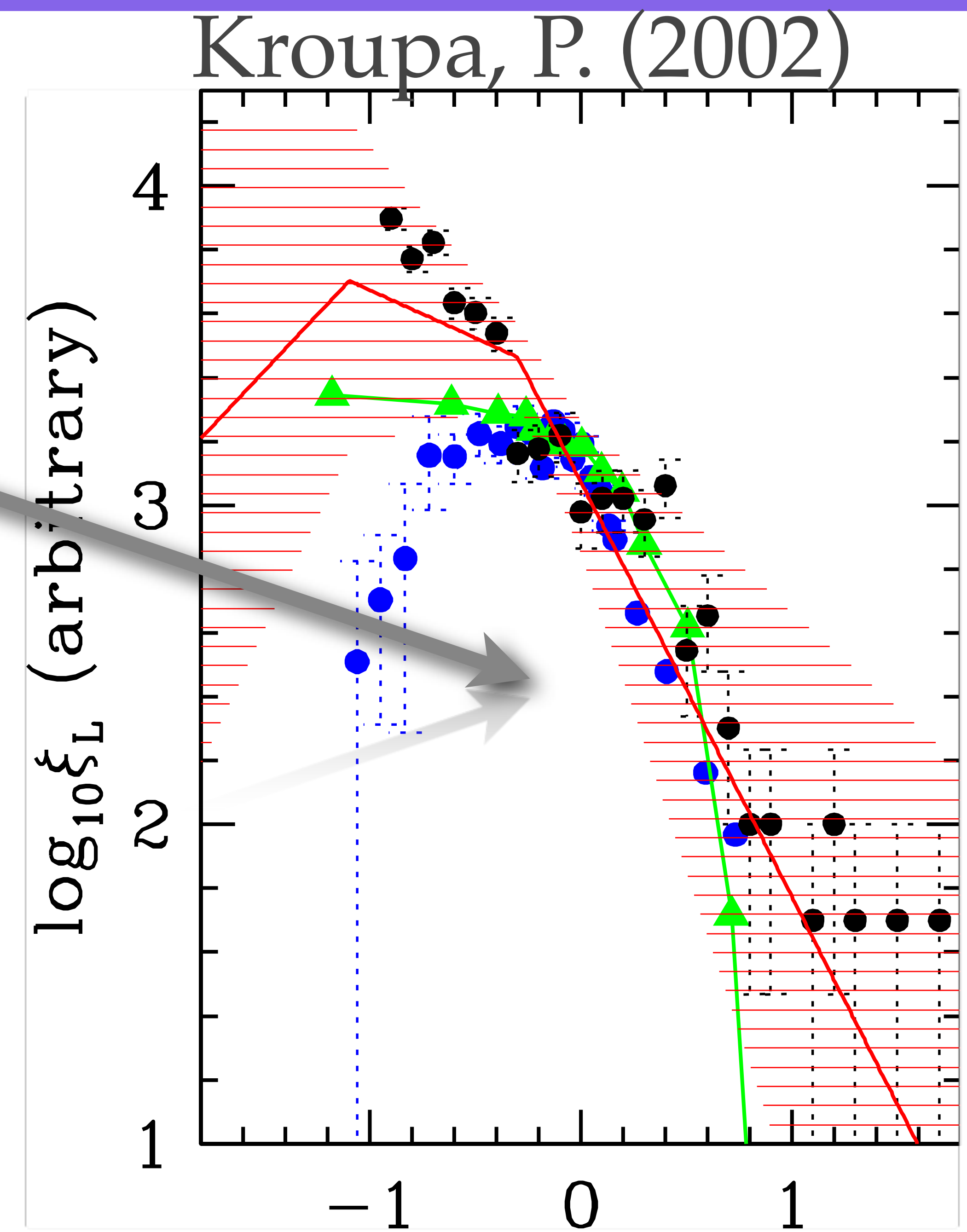
Kroupa, P. (2002)



Pop III - Pop II/I



Z ↑



Metals

Most important coolants for very low metallicity:

H_2 and **dust**

Pop III - Pop II/I

- What is the driving mechanism responsible for the change in the IMF shape?

Simulations: ICs

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- $E_{tub}/E_{grav} = 10\%$ and $E_{rot}/E_{grav} = 2\%$

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- $Z/Z_\odot = 0, 10^{-6}, 10^{-5}, 10^{-4}$

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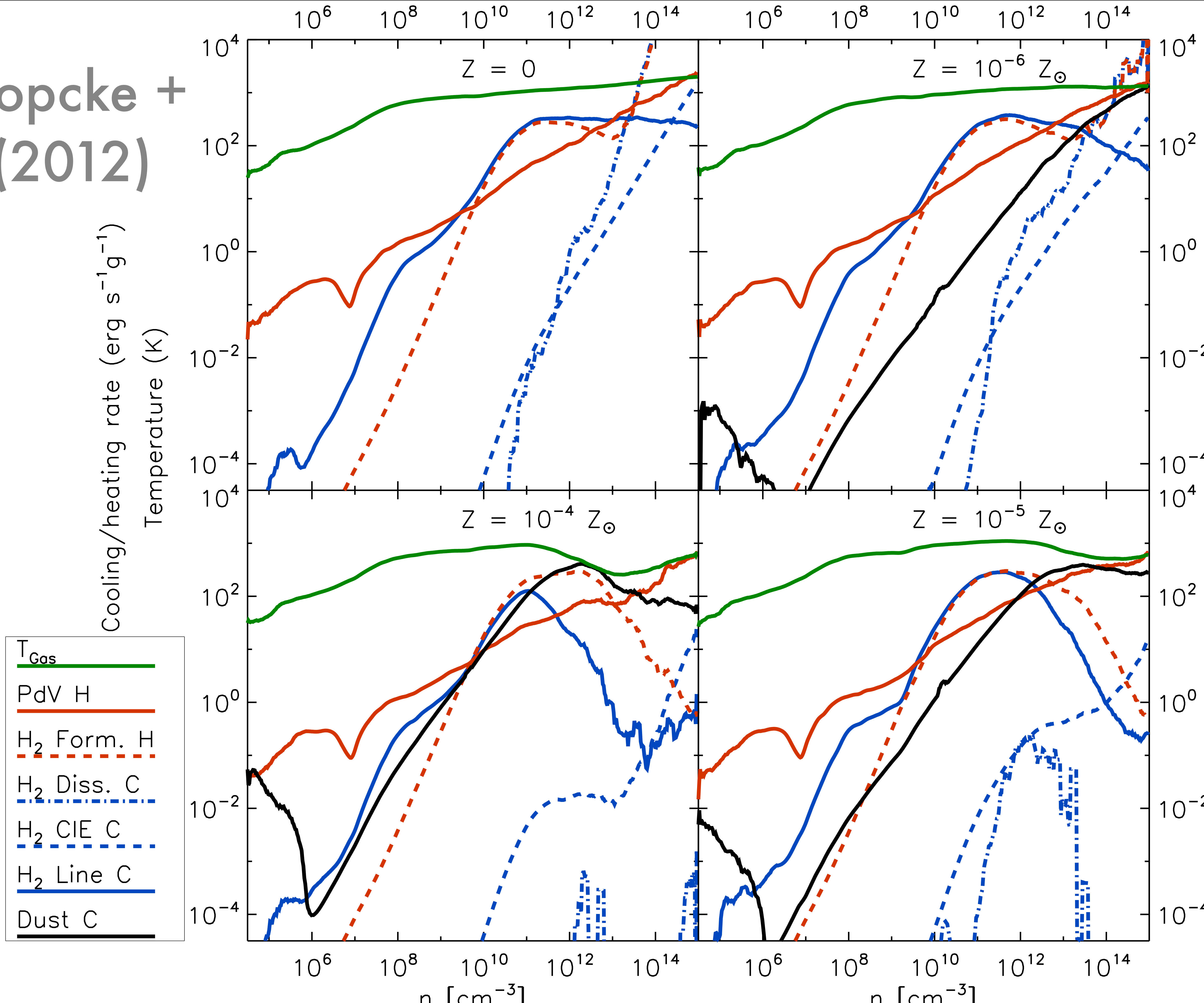
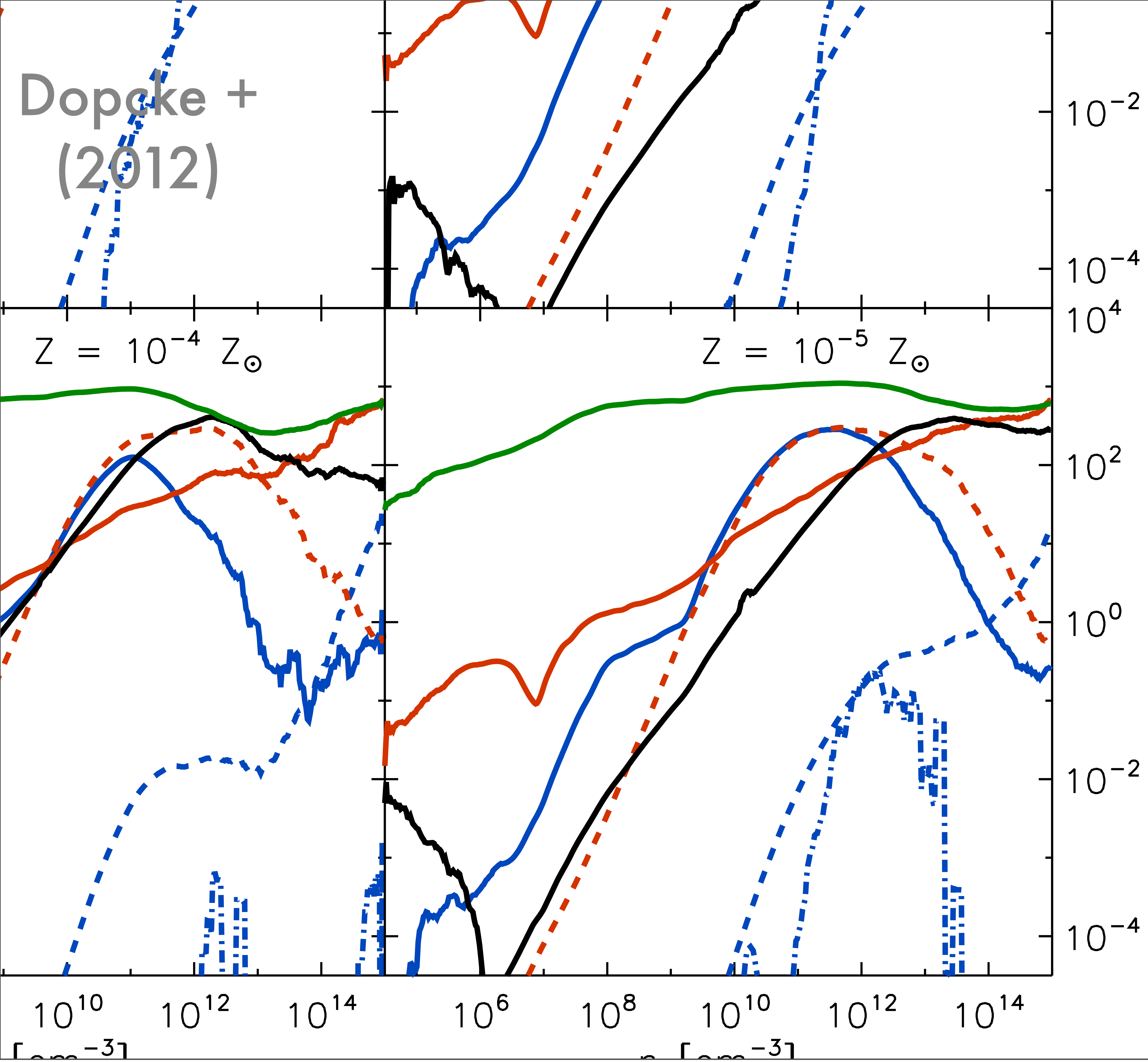
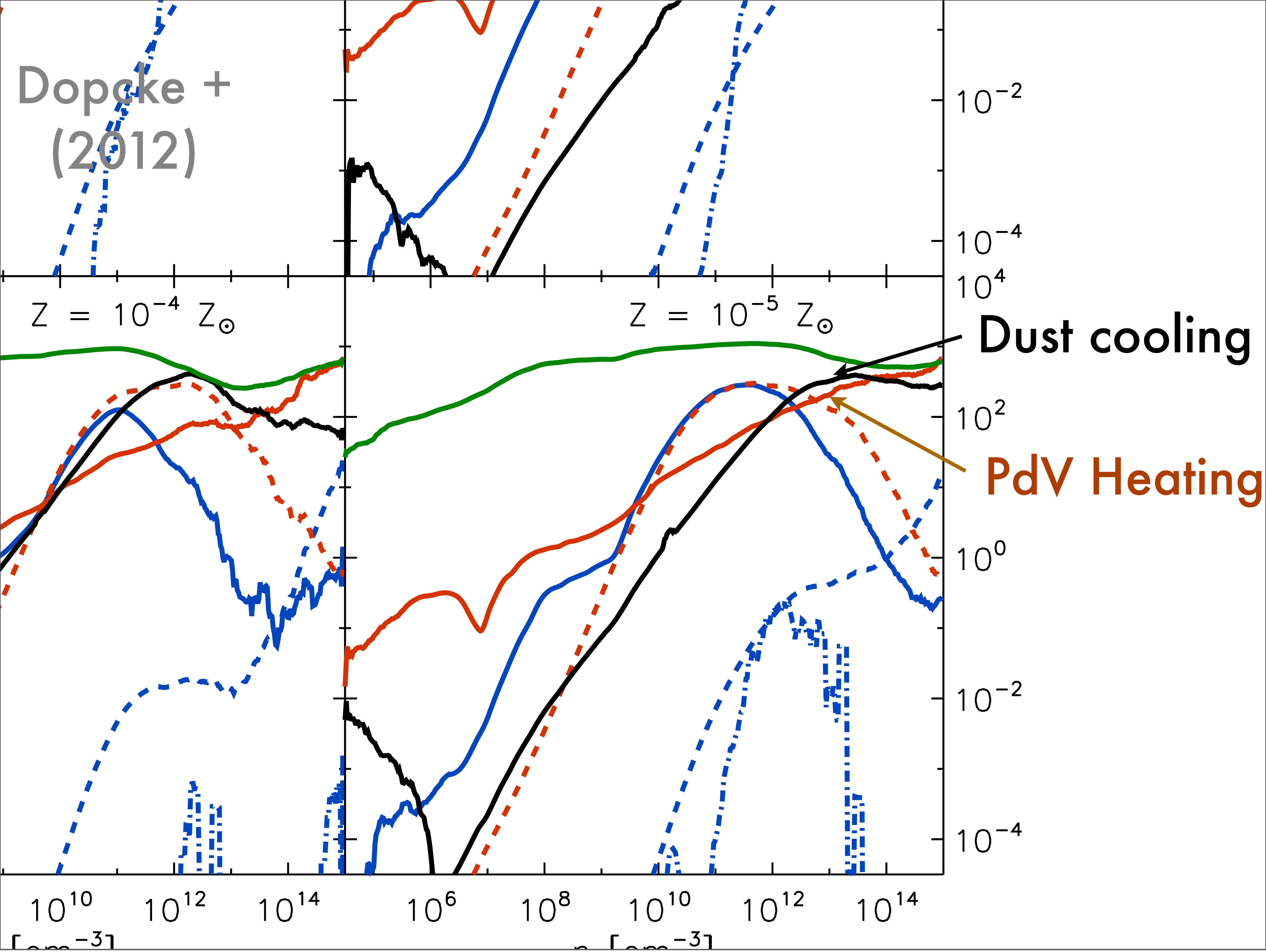
H_2 is the main gas-phase coolant

Dopcke + (2012)

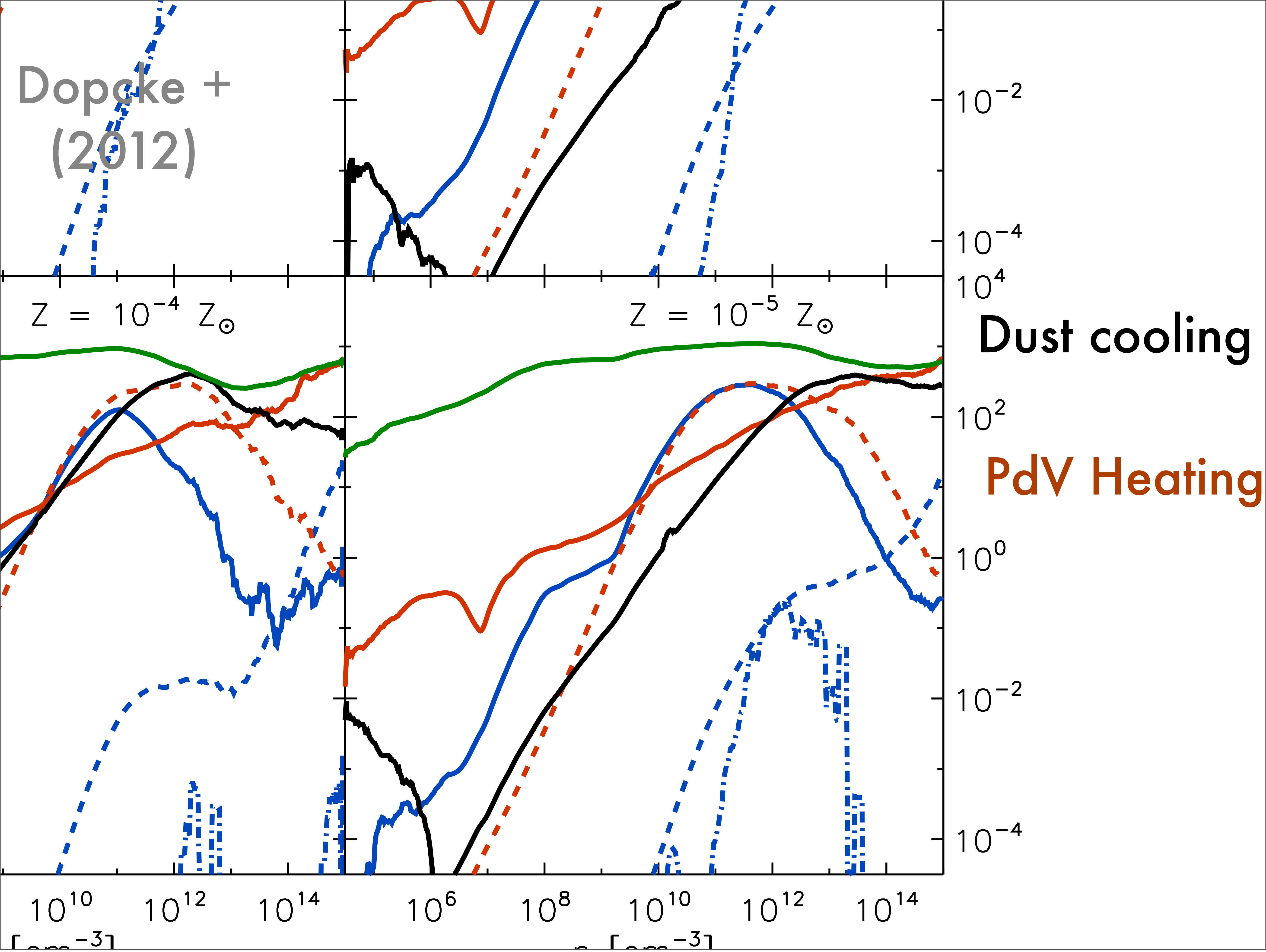


Z = 0
Z = 10^{-6} $Z_\odot$
Z = 10^{-4} $Z_\odot$
Z = 10^{-5} $Z_\odot$
Cooling/heating rate (erg $s^{-1}g^{-1}$)
Temperature (K)
n [cm^{-3}]
T_{Gas}
PdV H
H_2 Form. H
H_2 Diss. C
H_2 CIE C
H_2 Line C
Dust C

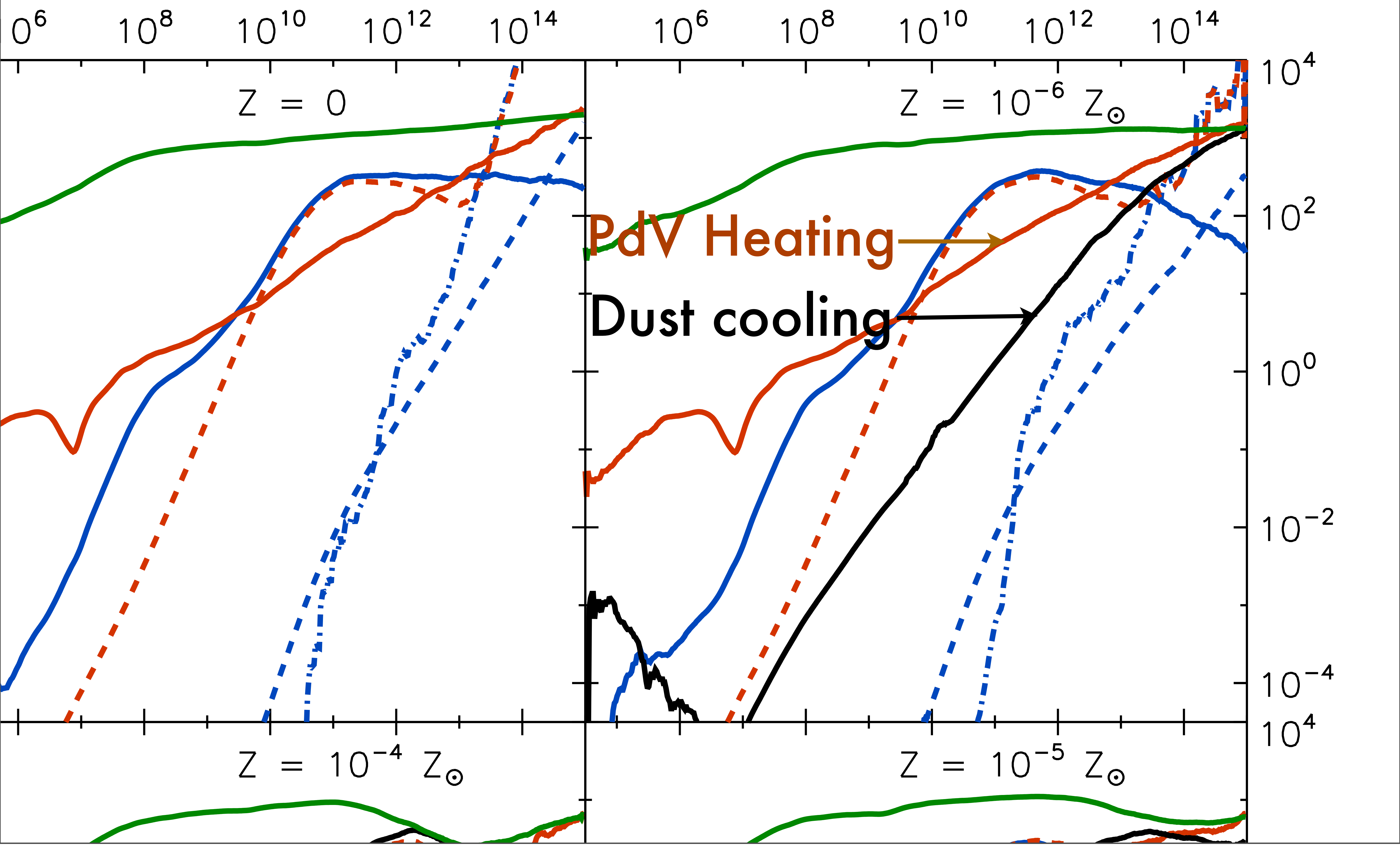

Dopcke + (2012)
Z = 10^-4 Z⊙
Z = 10^-5 Z⊙
10^-2
10^-4
10^4
10^2
10^0
10^-2
10^-4
10^10
10^12
10^14
10^6
10^8
10^10
10^12
10^14



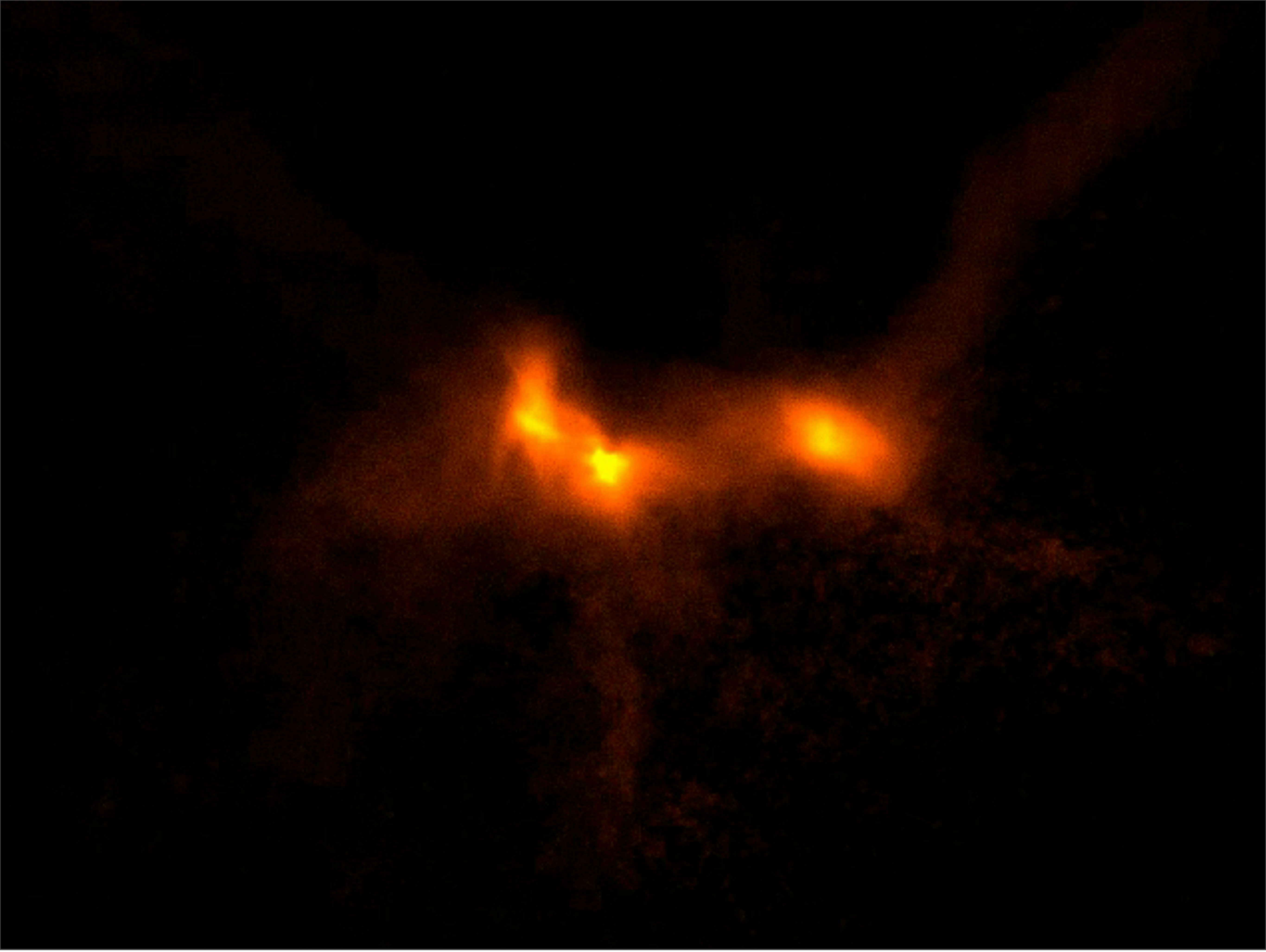
Tuesday, October 9, 2012

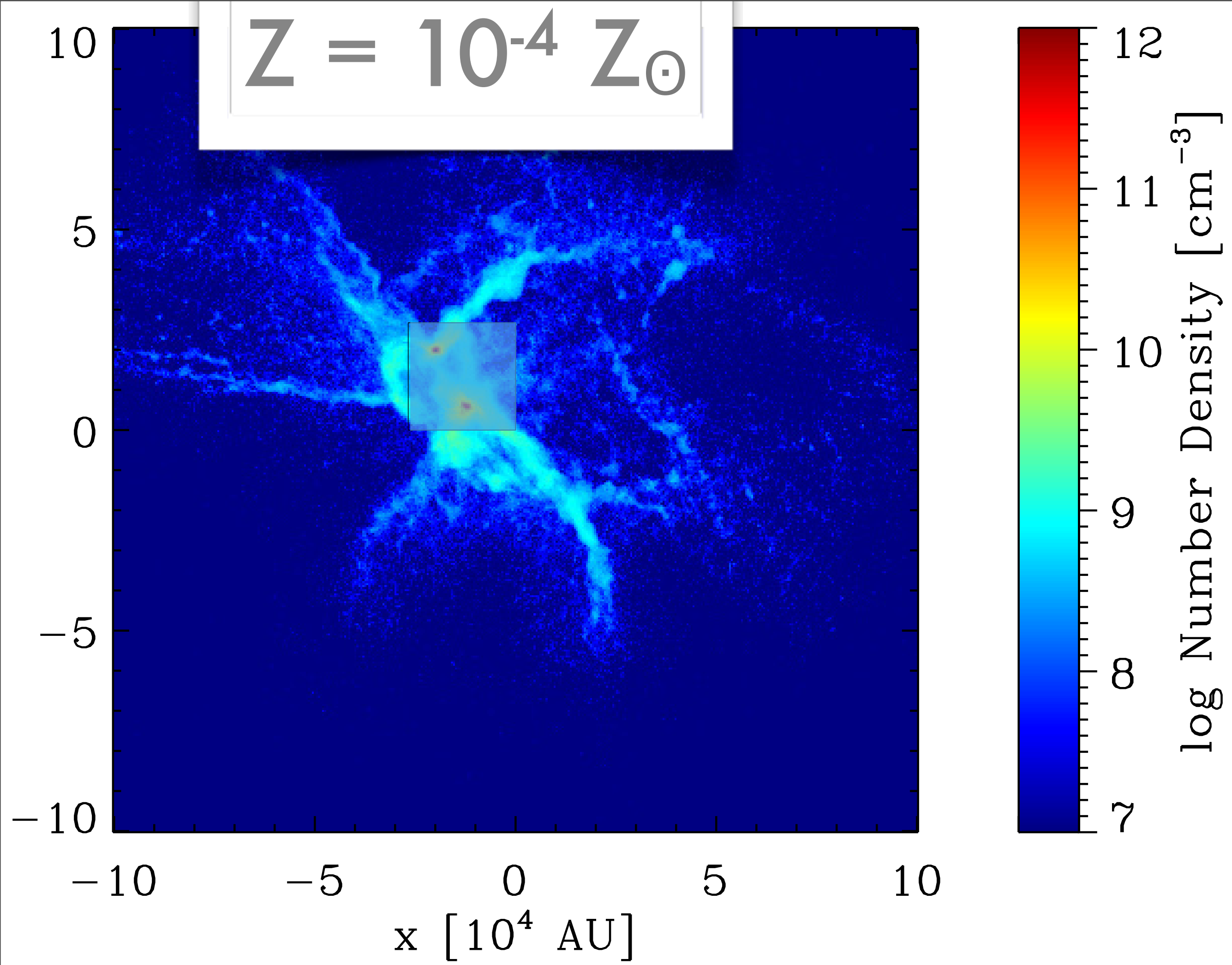

Dopcke + (2012)
$Z = 10^{-4} Z_\odot$
$Z = 10^{-5} Z_\odot$
Dust cooling
PdV Heating
10^{-2}
10^{-4}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{10} 10^{12} 10^{14}
10^{6} 10^{8} 10^{10} 10^{12} 10^{14}

Dopcke + (2012)

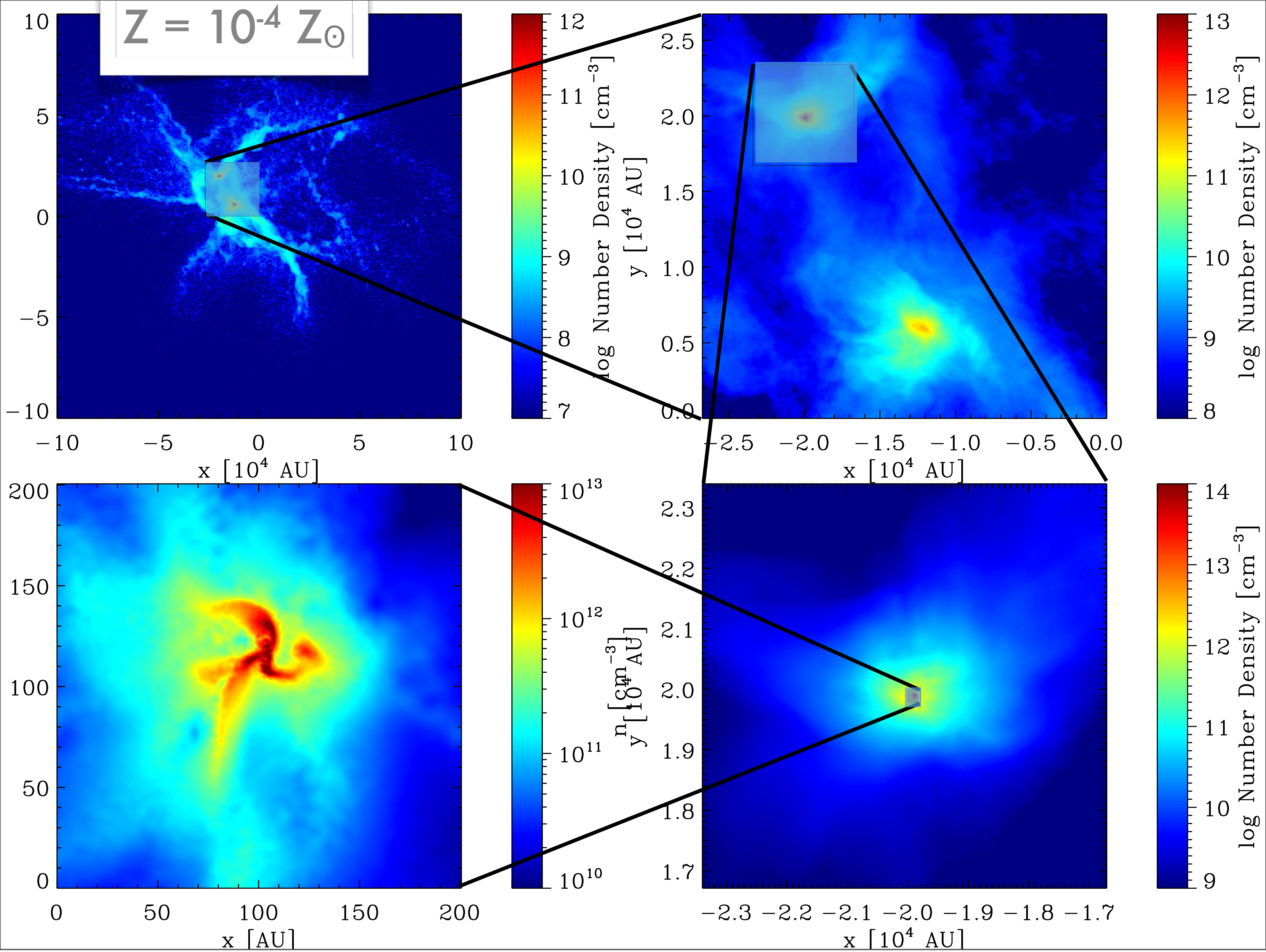


PdV Heating
Dust cooling
Z = 0
Z = 10^−6 Z⊙
Z = 10^−4 Z⊙
Z = 10^−5 Z⊙
10^6
10^8
10^10
10^12
10^14
10^4
10^2
10^0
10^−2
10^−4





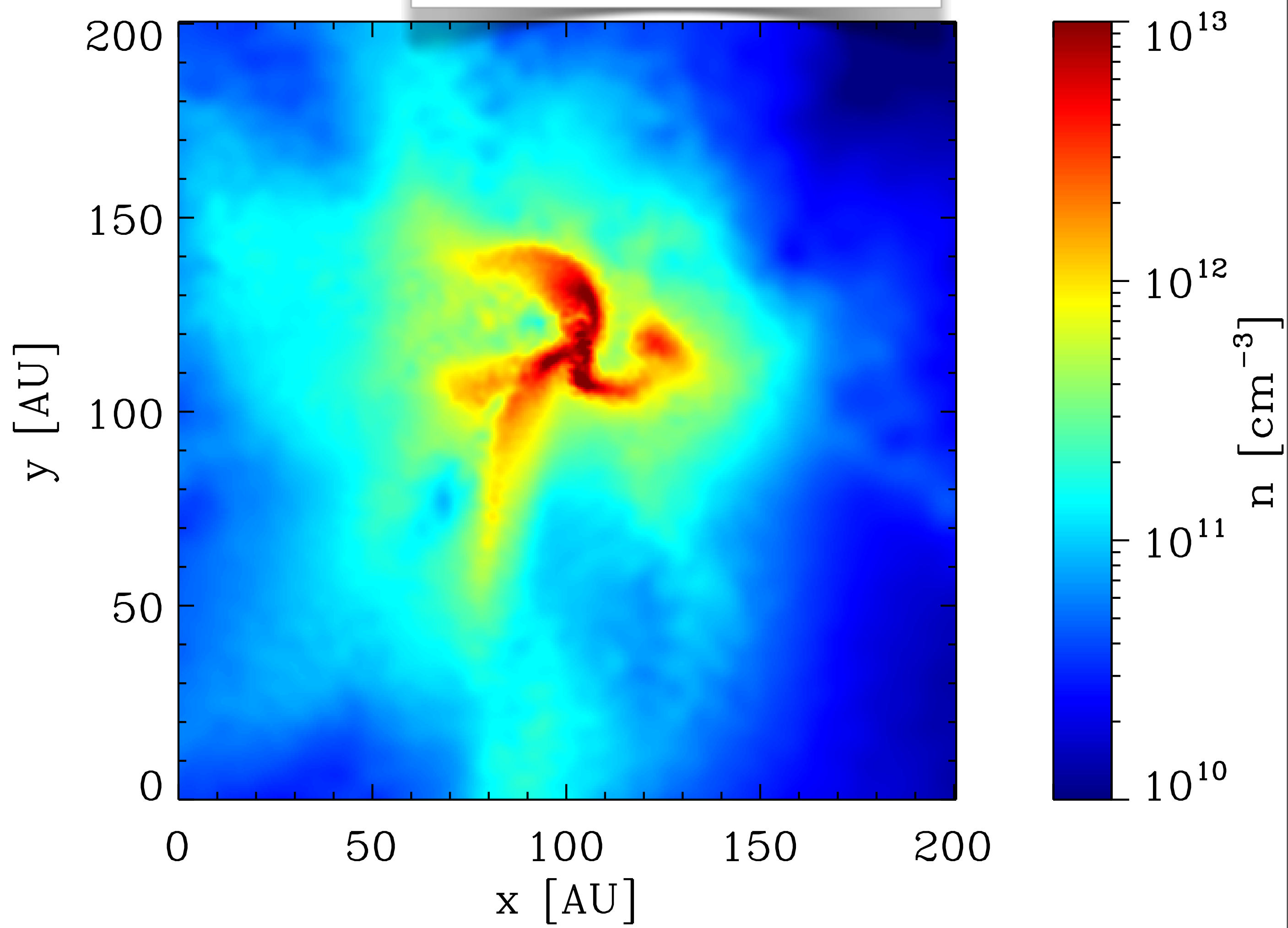
Z = 10-4 Z⊙
10
5
0
−5
−10
−10
−5
0
5
10
x [10⁴ AU]
12
11
10
9
8
7
log Number Density [cm⁻³]



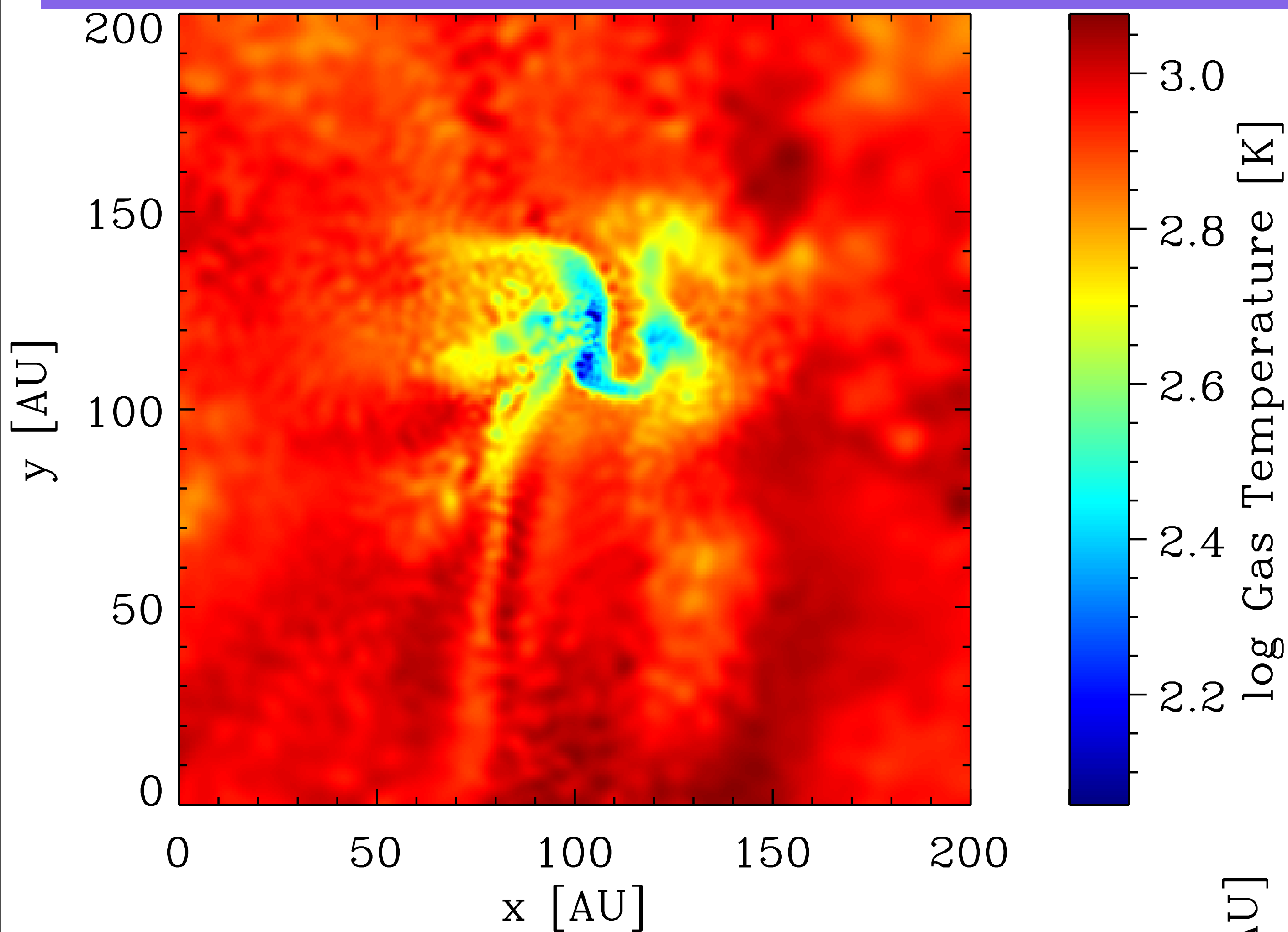
Z = 10-4 Z⊙
log Number Density [cm-3]
y [104 AU]
x [104 AU]
x [AU]
n [cm-3]
log Number Density [cm-3]

Density and Temperature Maps

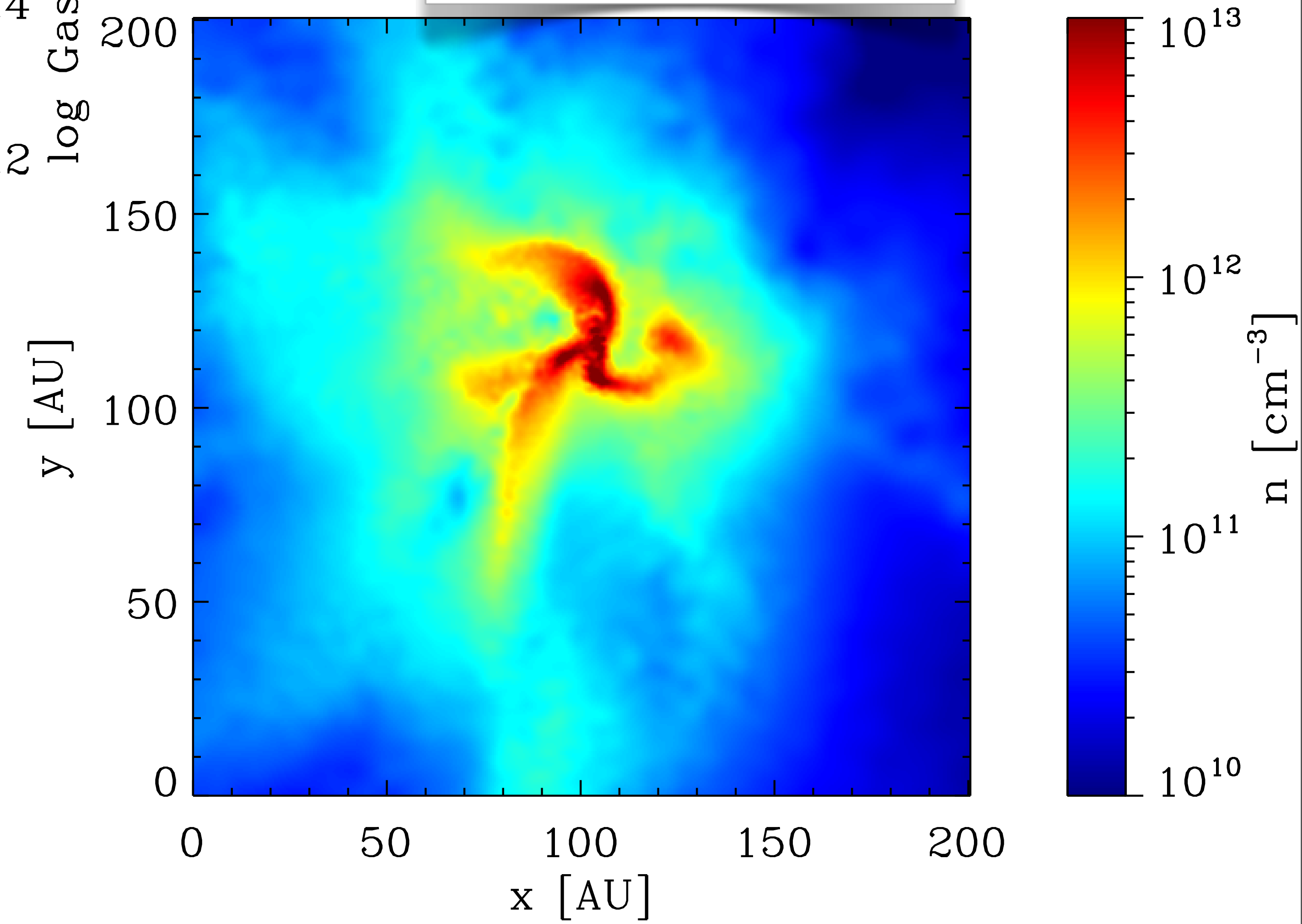
$Z = 10^{-4}\ Z_{\odot}$

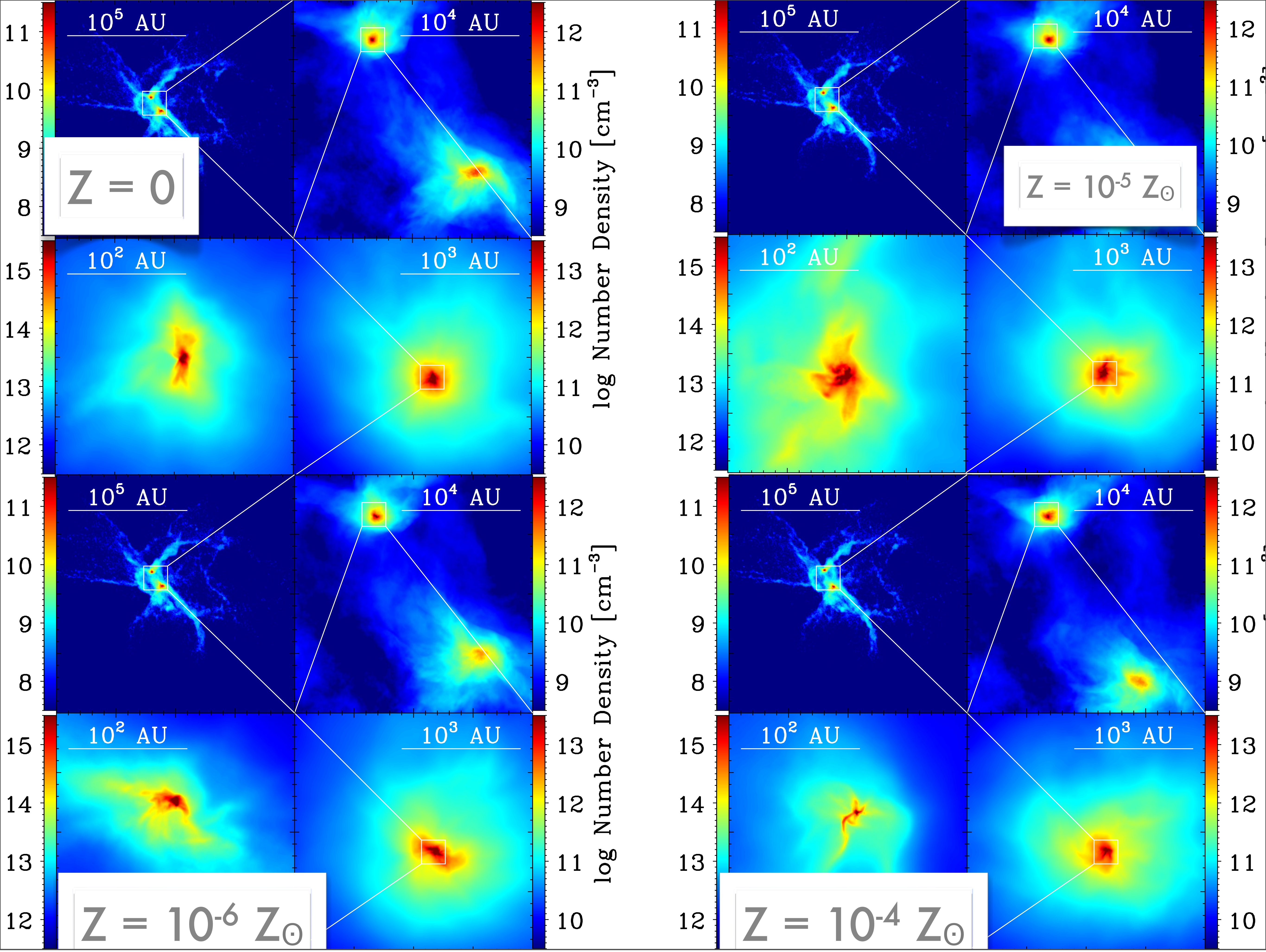


Density and Temperature Maps

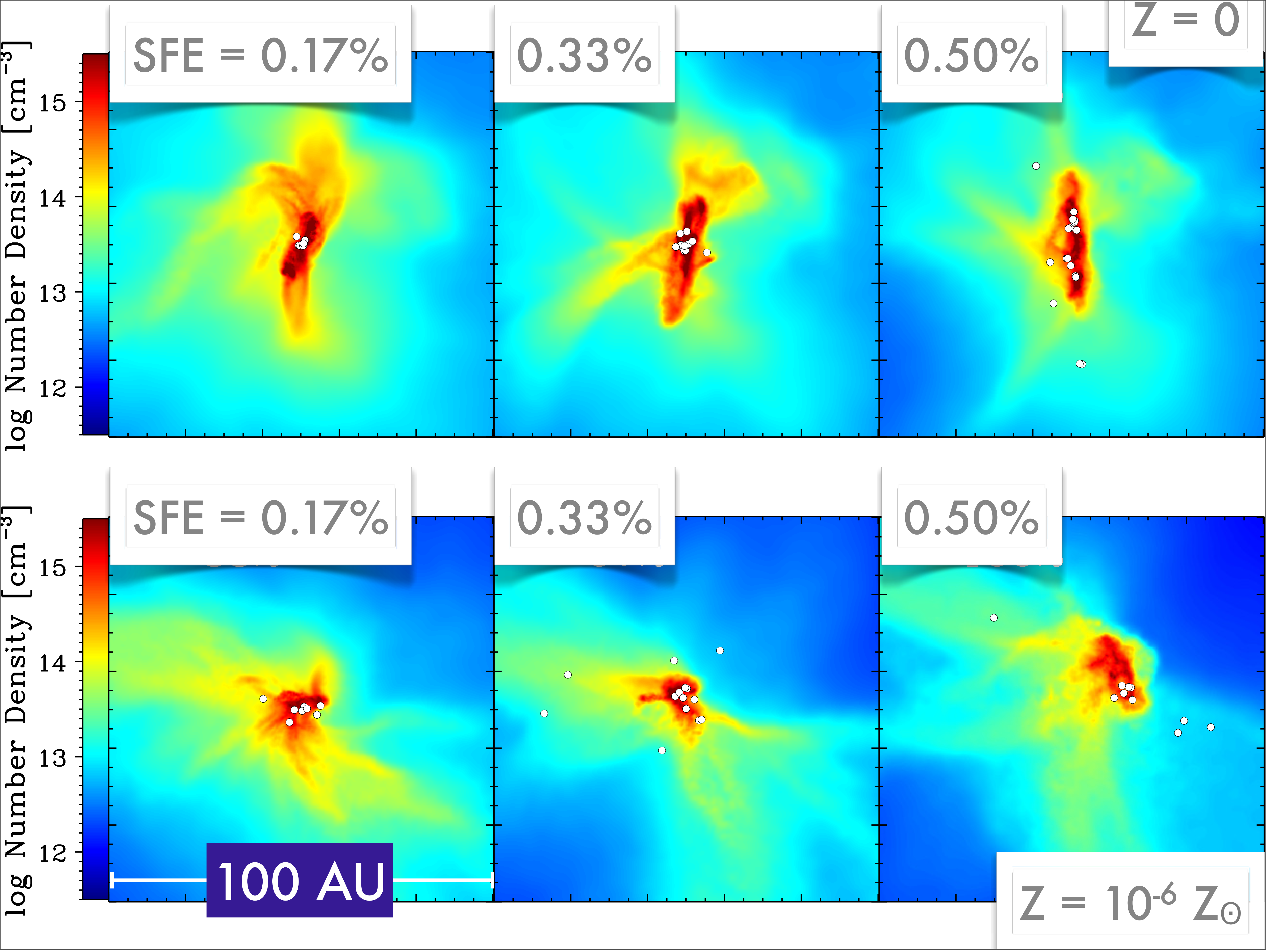


$Z = 10^{-4}\ Z_{\odot}$





10^5 AU
10^4 AU
10^3 AU
10^2 AU
Z = 0
$Z = 10^{-5}\ Z_\odot$
$Z = 10^{-6}\ Z_\odot$
$Z = 10^{-4}\ Z_\odot$
log Number Density [cm^{-3}]



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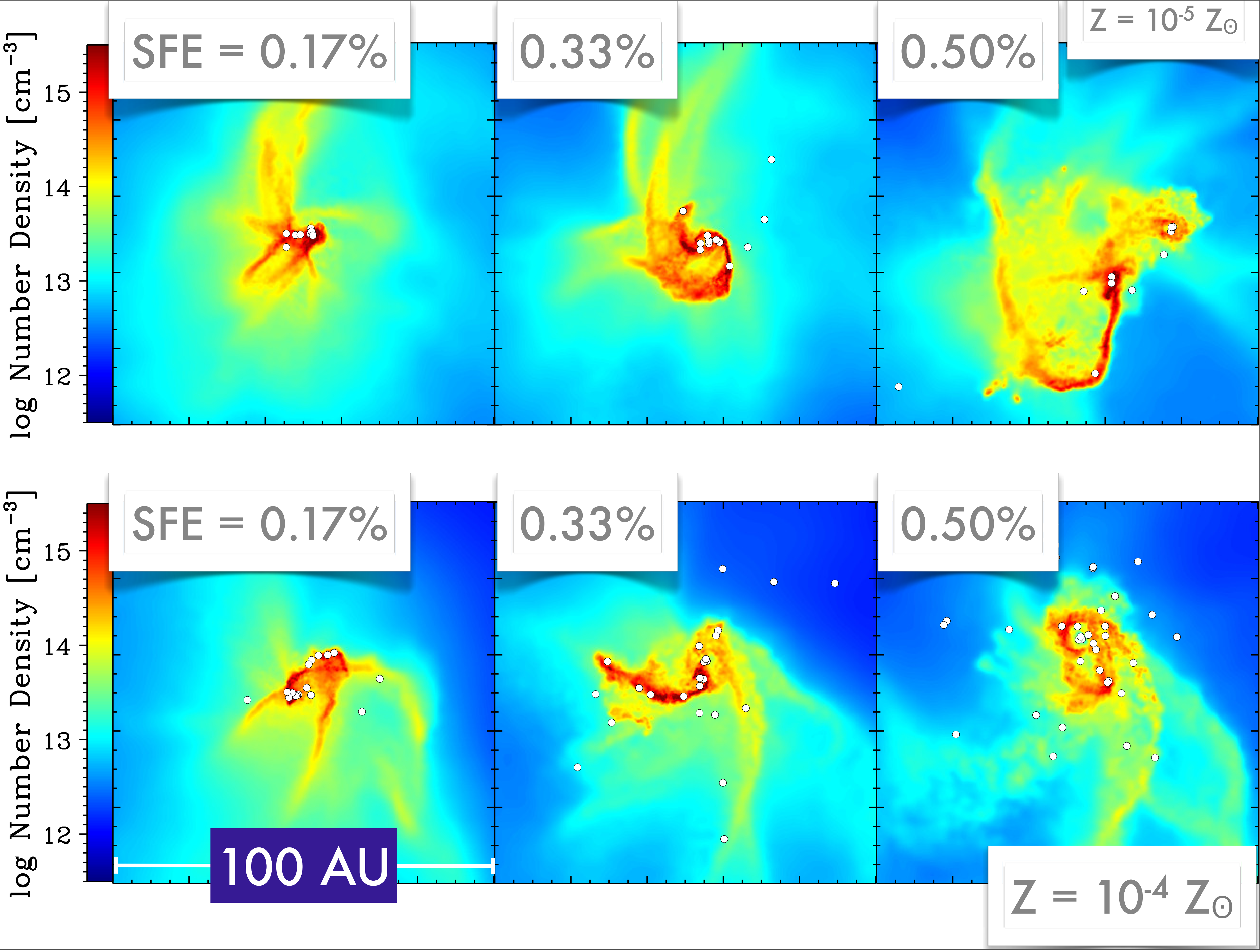
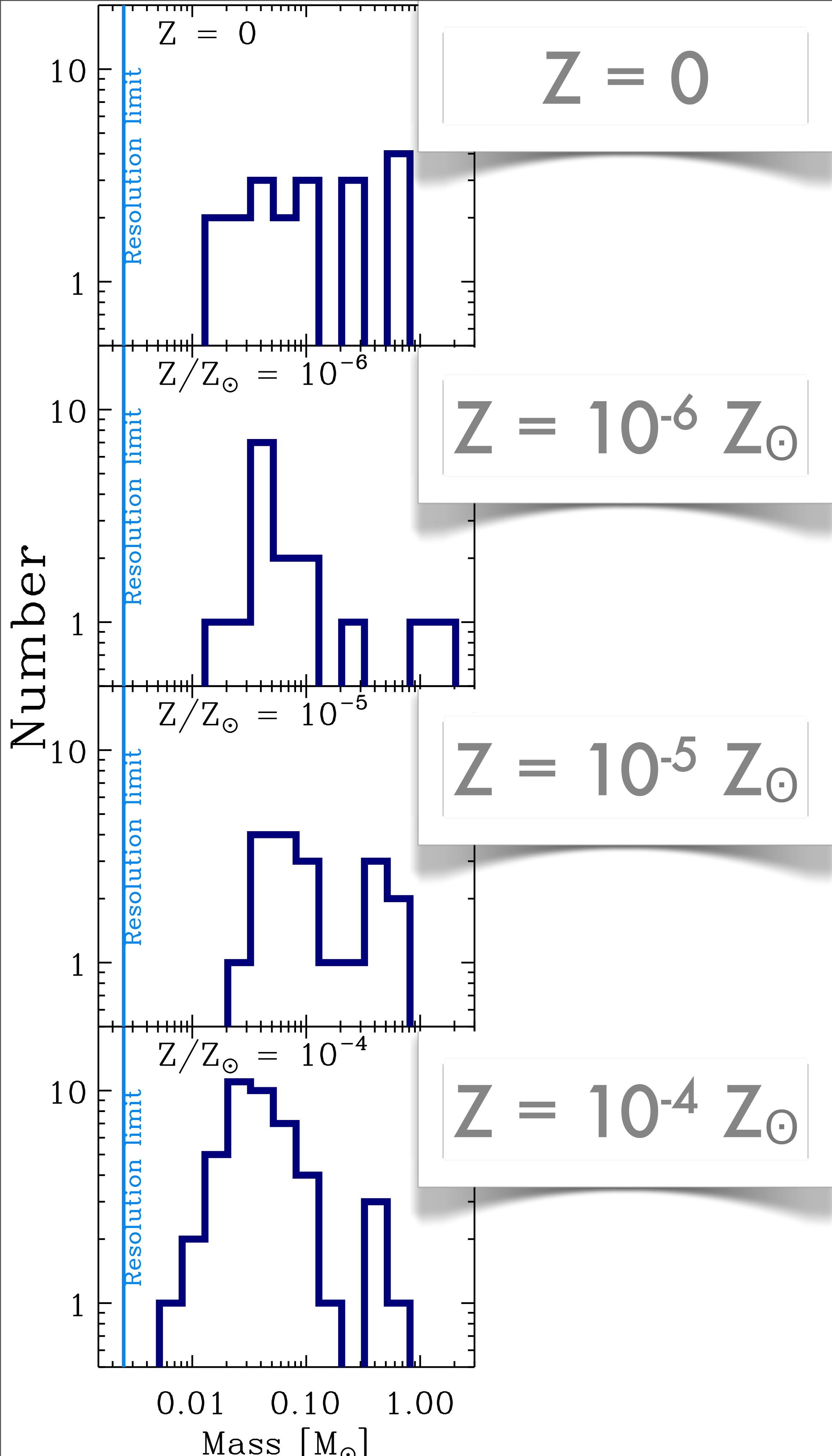
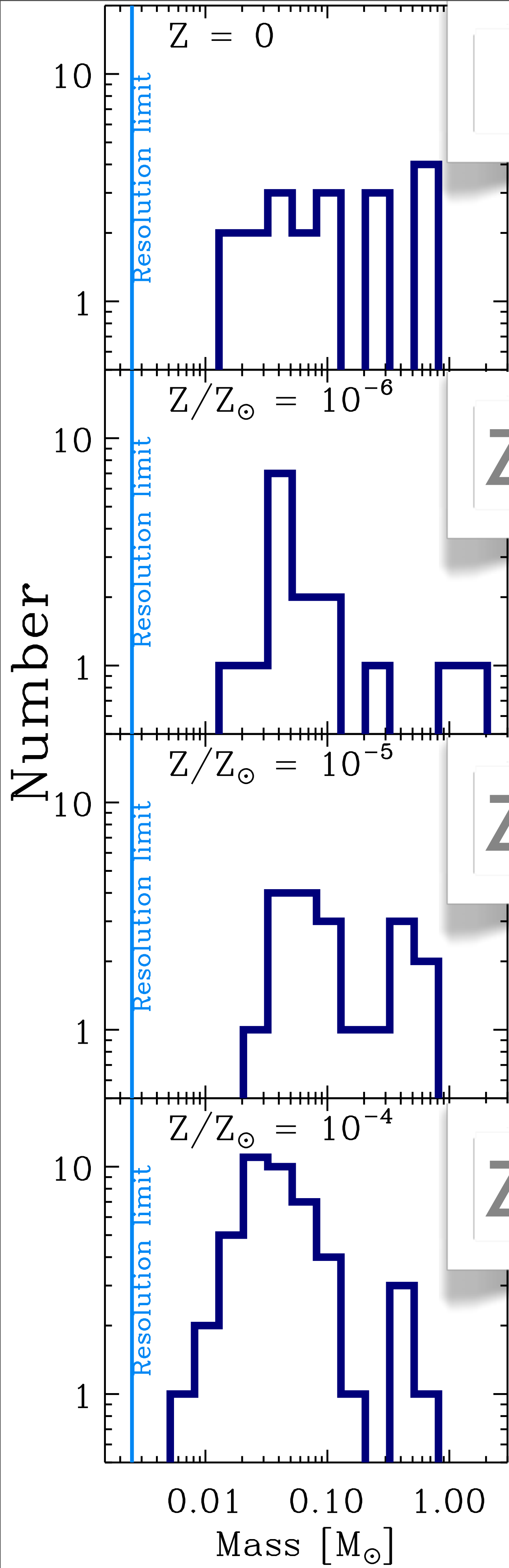


log Number Density [cm^{-3}]
15
14
13
12
SFE = 0.17%
0.33%
0.50%
Z = 10^{-5} Z$_\odot$
log Number Density [cm^{-3}]
15
14
13
12
SFE = 0.17%
0.33%
0.50%
100 AU
Z = 10^{-4} Z$_\odot$

Sink Mass Function



Sink Mass Function



$Z = 0$

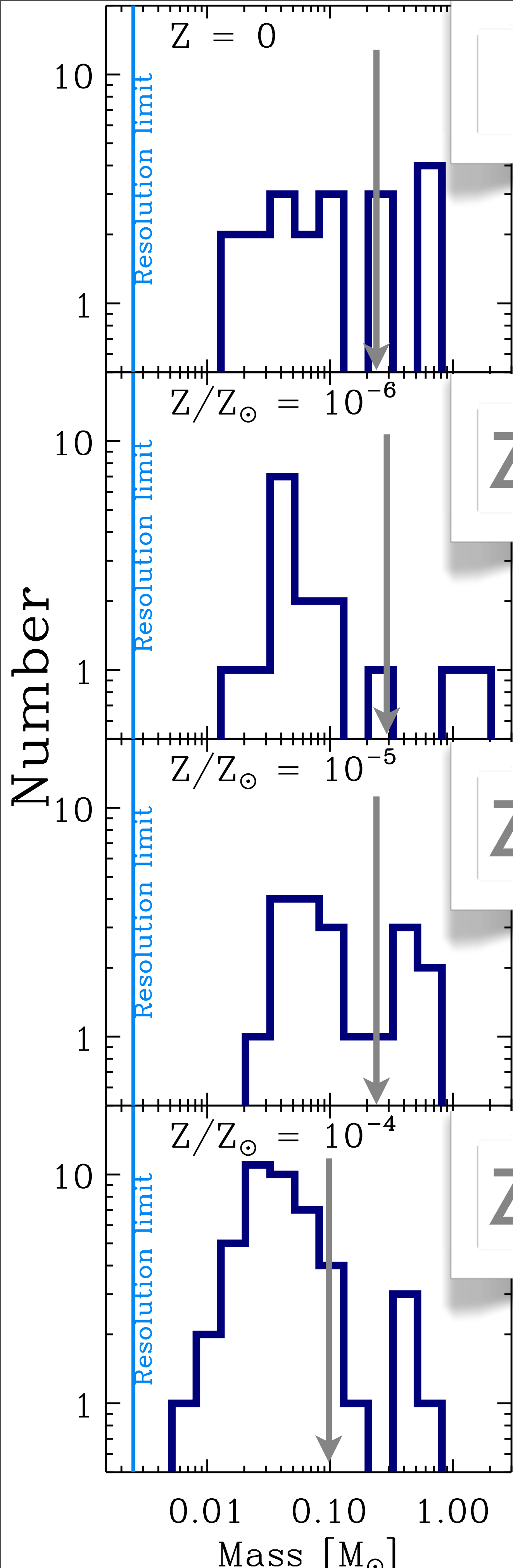
$Z = 10^{-6}\,Z_\odot$

$Z = 10^{-5}\,Z_\odot$

$Z = 10^{-4}\,Z_\odot$

$5M_\odot$

Sink Mass Function



Z = 0

Z = 10^{-6} $Z_\odot$

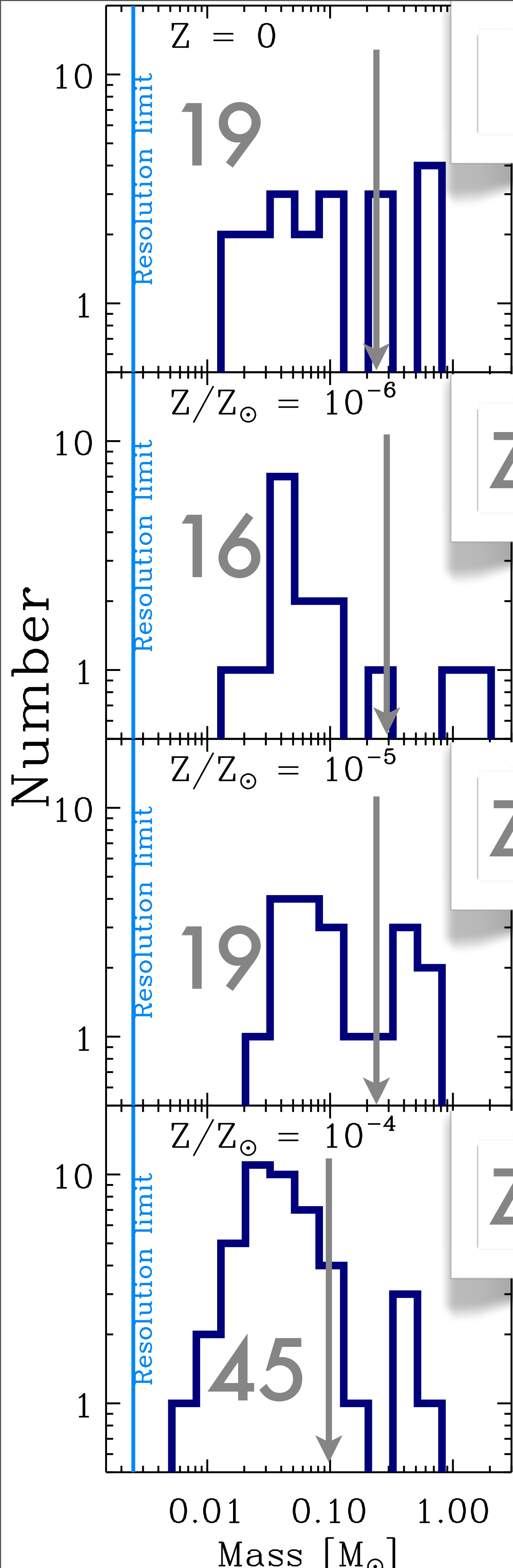
Z = 10^{-5} $Z_\odot$

Z = 10^{-4} $Z_\odot$

mean sink mass

$5M_\odot$

Sink Mass Function



Z = 0

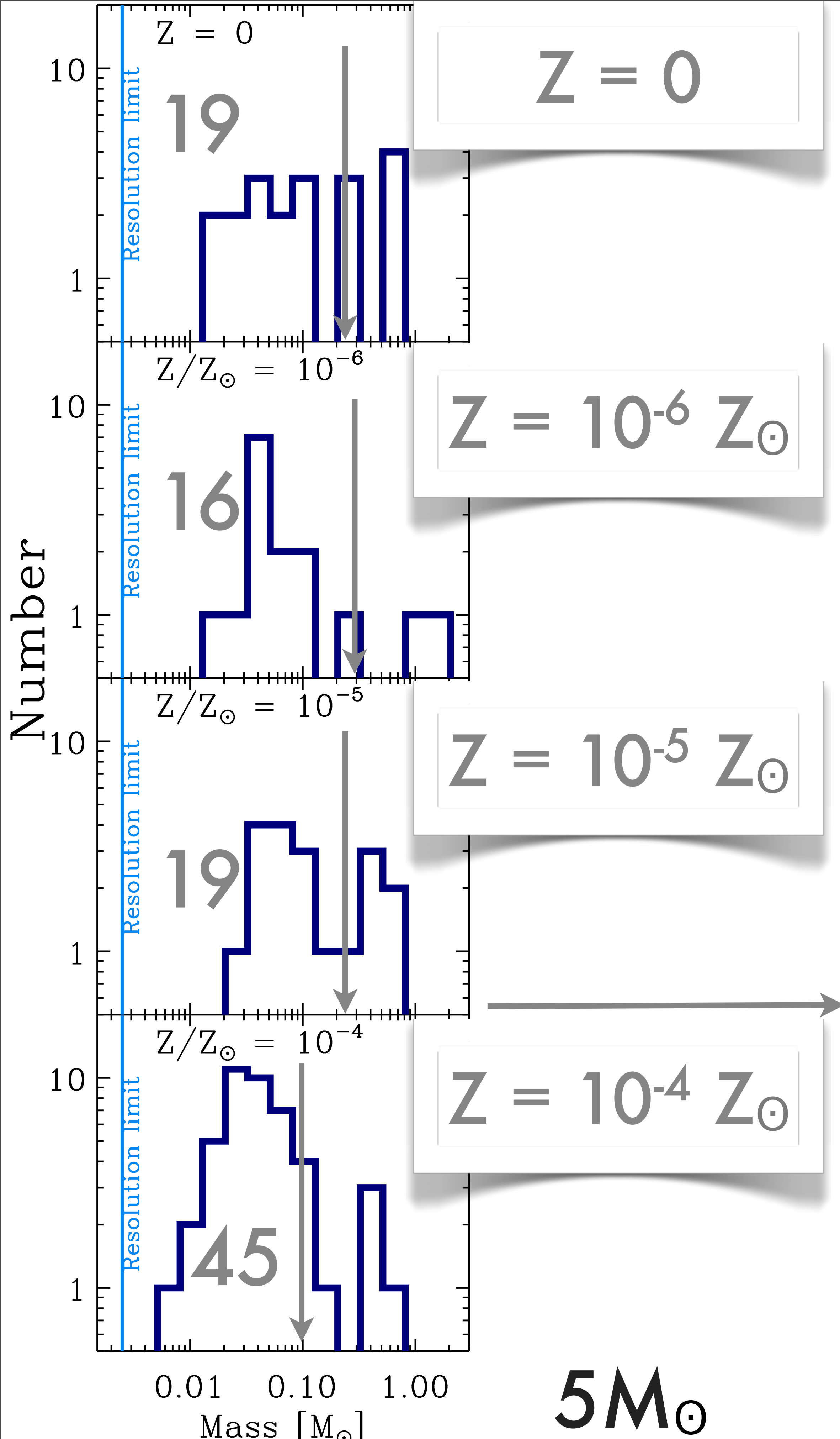
$Z = 10^{-6}\, Z_\odot$

$Z = 10^{-5}\, Z_\odot$

$Z = 10^{-4}\, Z_\odot$

mean sink mass

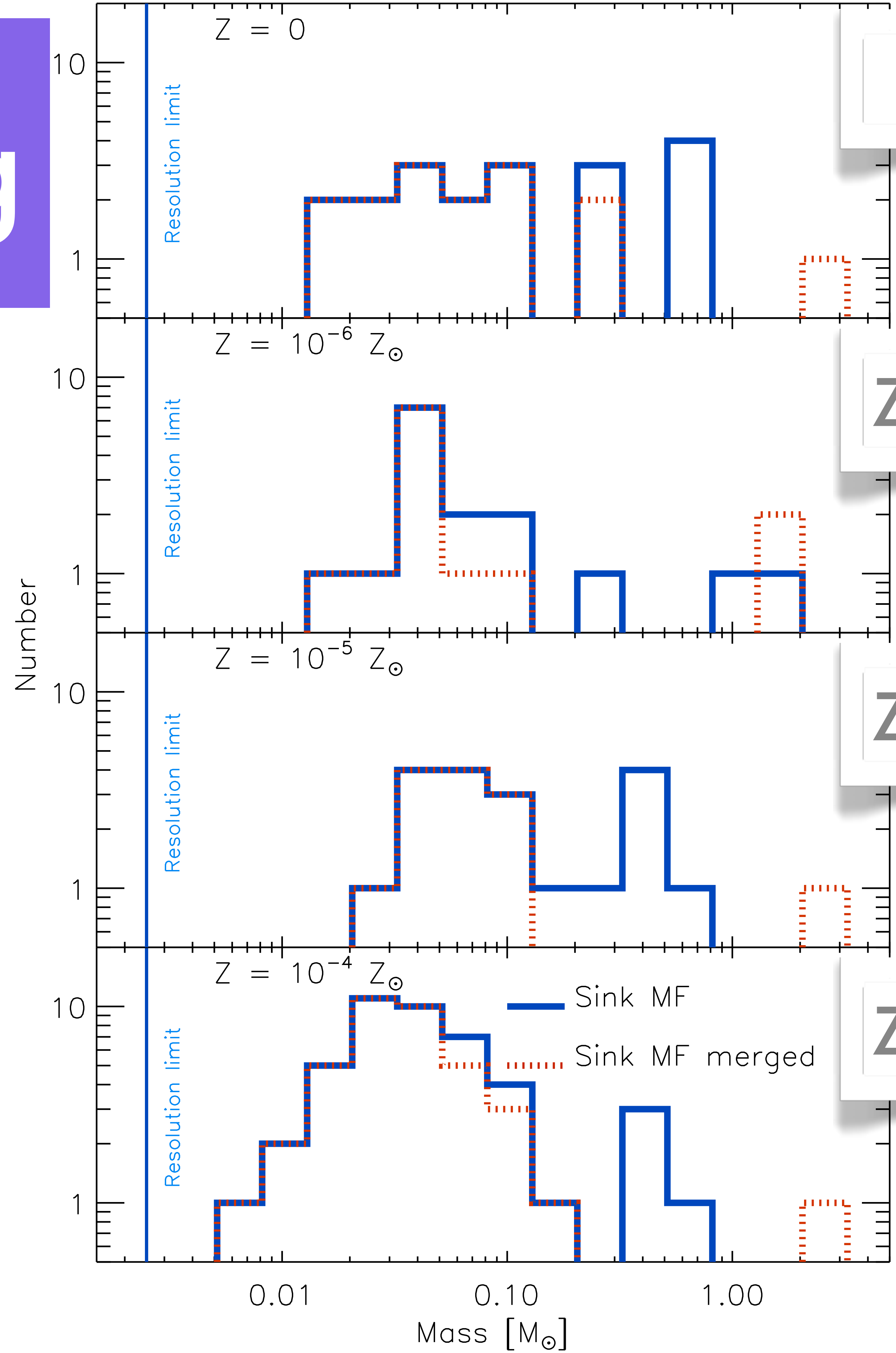
$5 M_\odot$



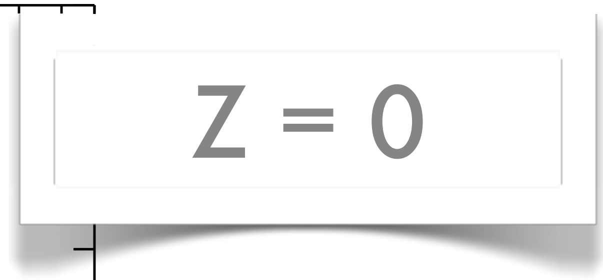
Sink Mass Function

- Mode of star formation changes
- Favors lower mass objects

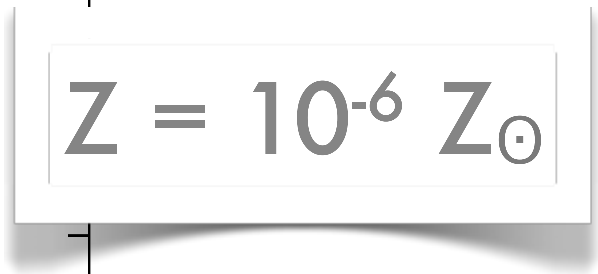
Merging



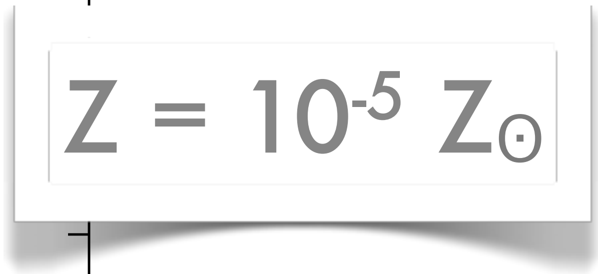
Z = 0
Z = 10^{-6} $Z_\odot$
Z = 10^{-5} $Z_\odot$
Z = 10^{-4} $Z_\odot$
Resolution limit
Sink MF
Sink MF merged
Number
Mass [$M_\odot$]
0.01
0.10
1.00
10
1



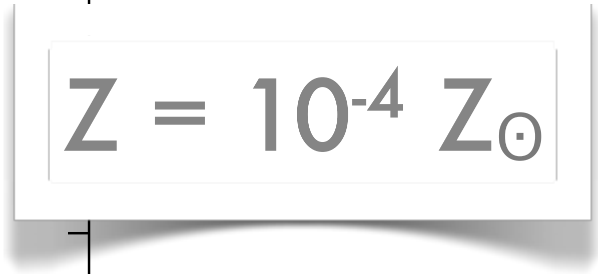
Z = 0



Z = 10^{-6} $Z_\odot$

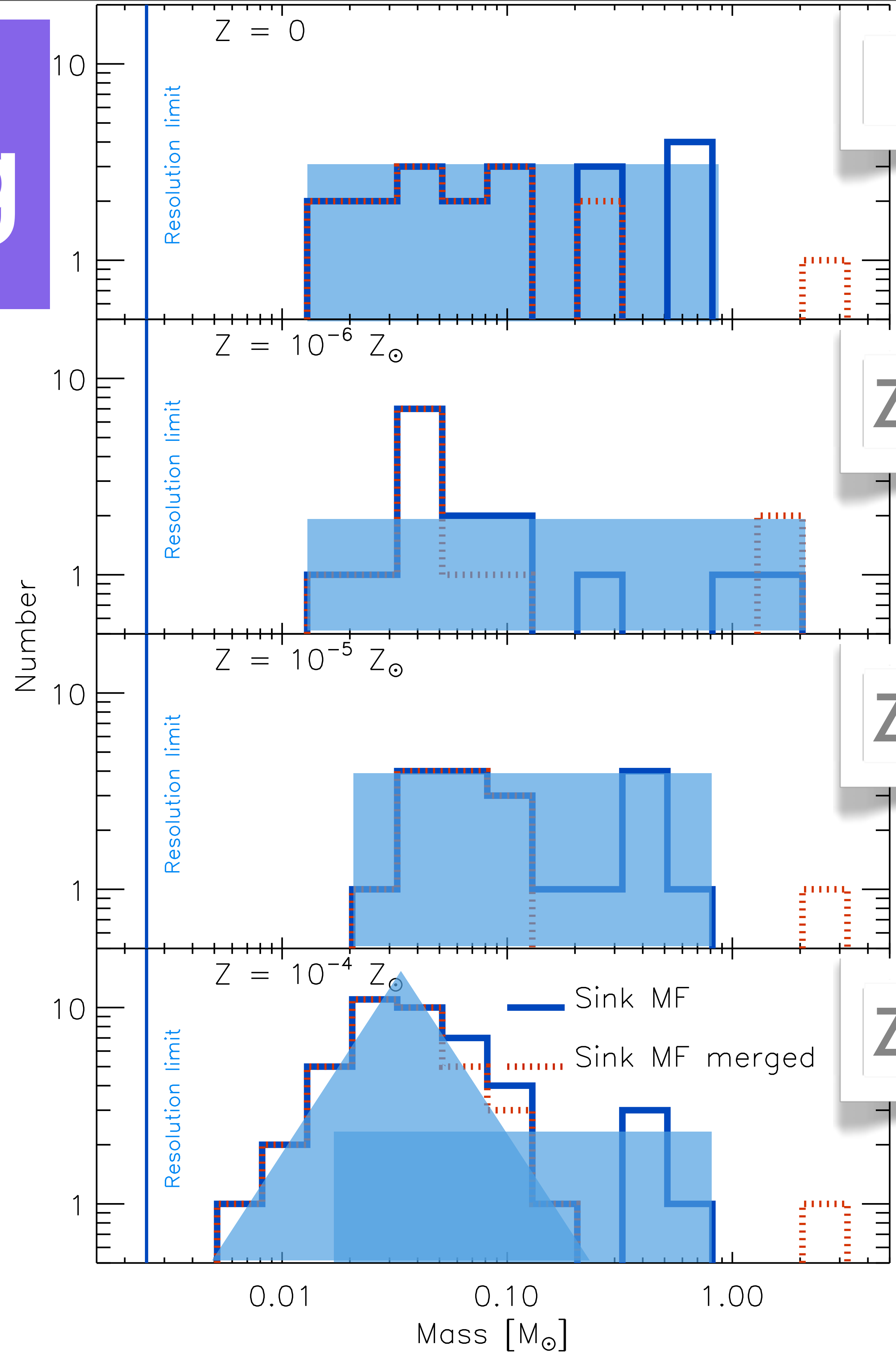


Z = 10^{-5} $Z_\odot$



Z = 10^{-4} $Z_\odot$

Merging



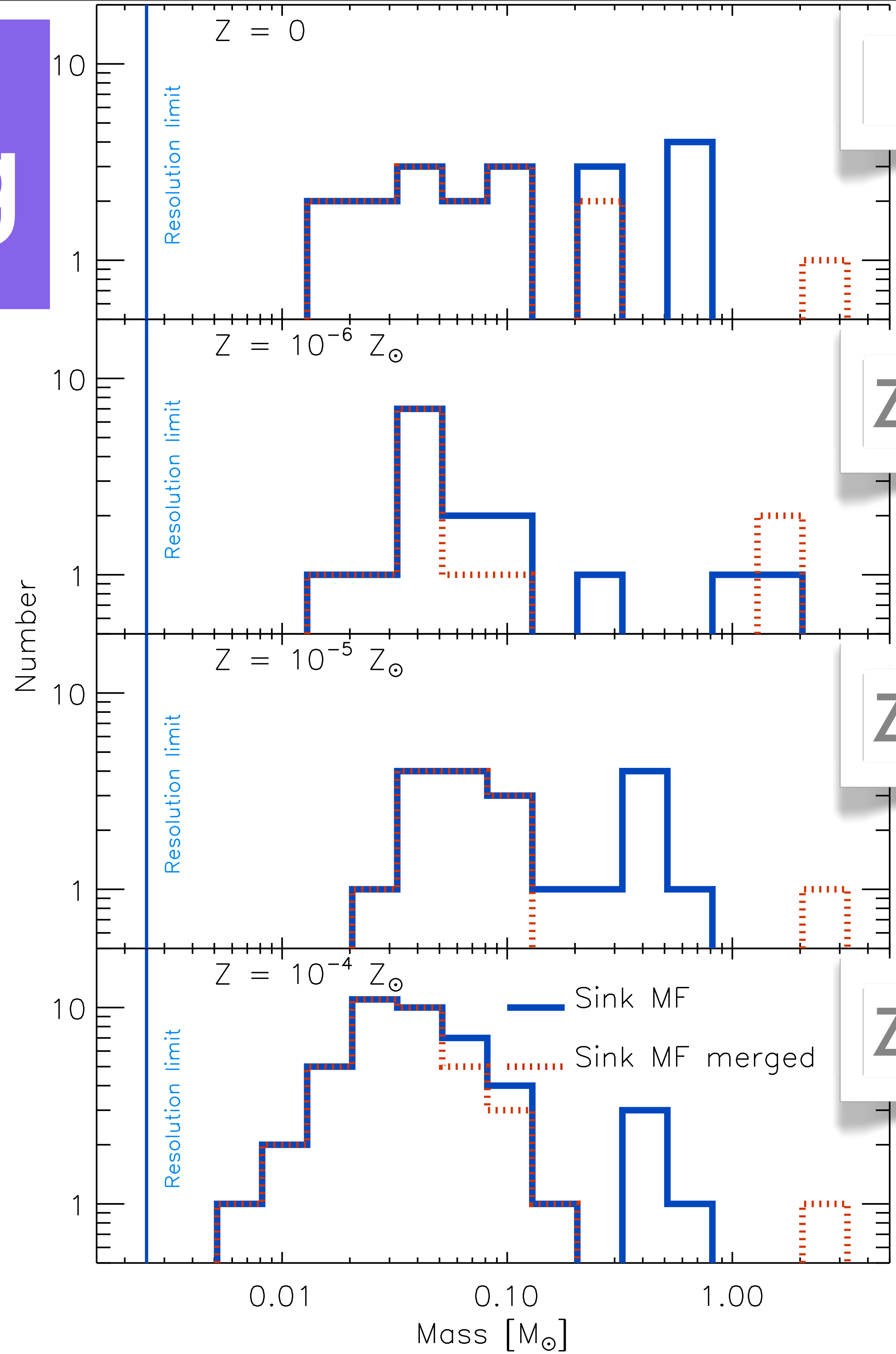
Z = 0

Z = 10^{-6} $Z_\odot$

Z = 10^{-5} $Z_\odot$

Z = 10^{-4} $Z_\odot$

Merging



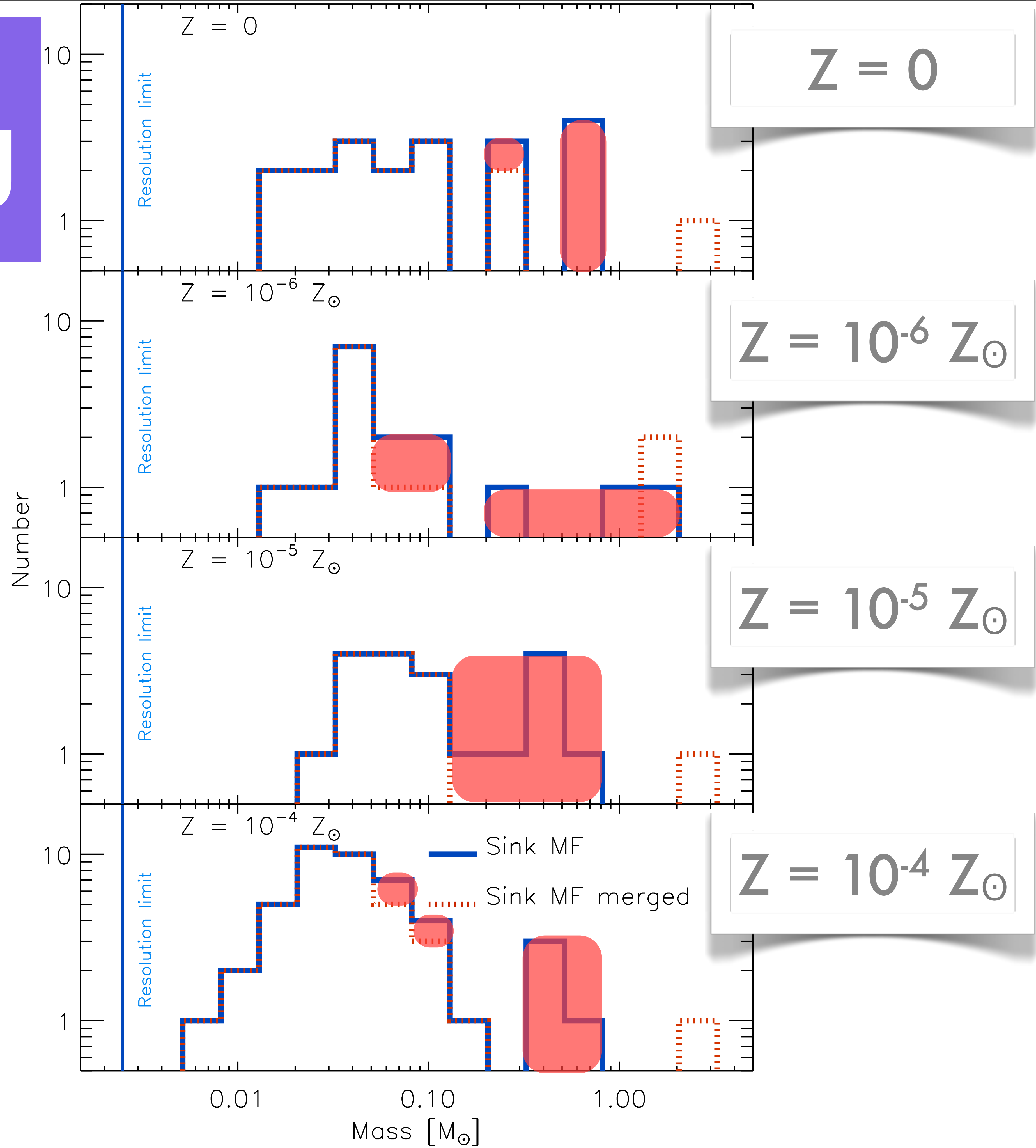
Z = 0

Z = 10^{-6} $Z_\odot$

Z = 10^{-5} $Z_\odot$

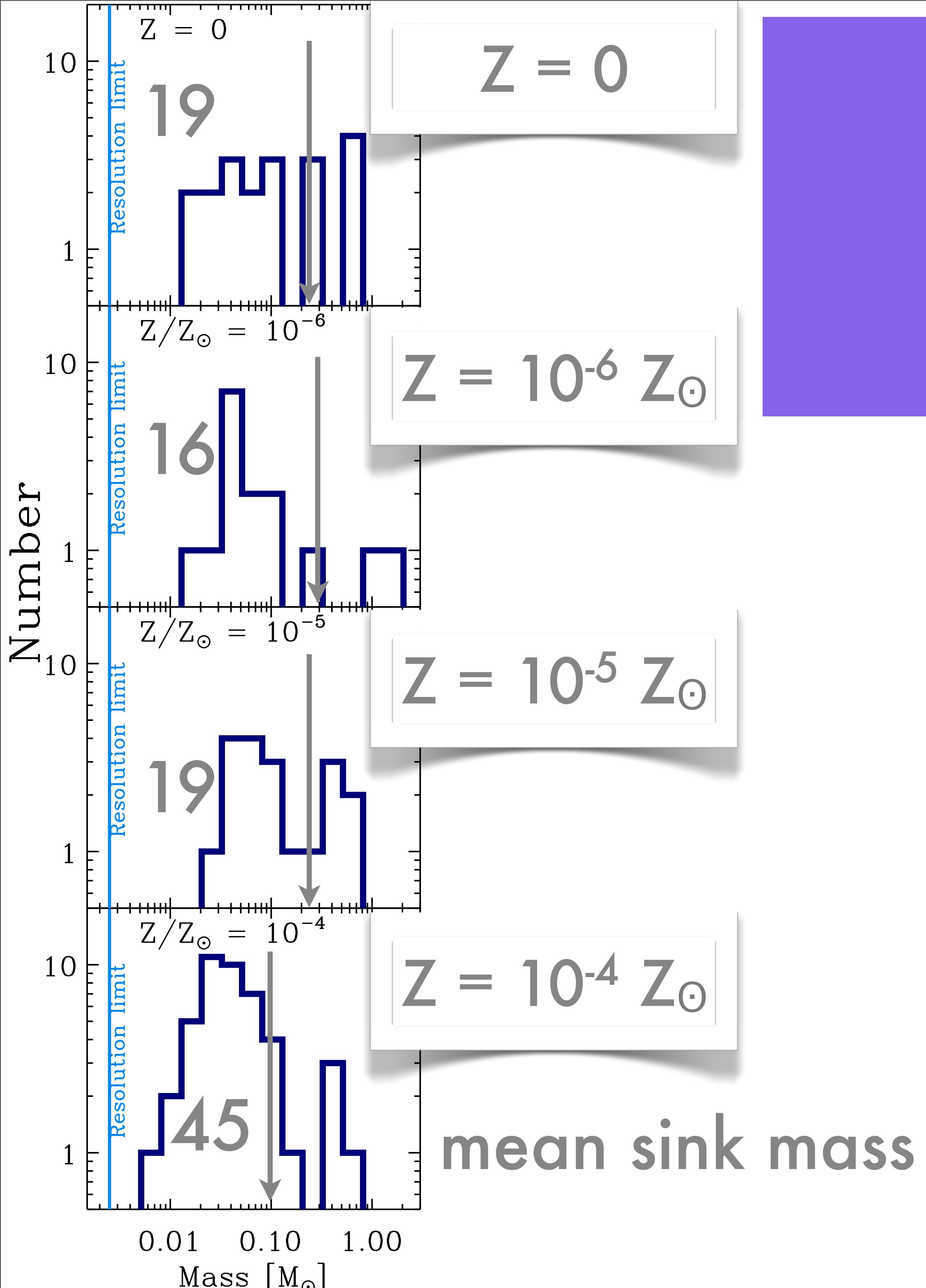
Z = 10^{-4} $Z_\odot$

Merging

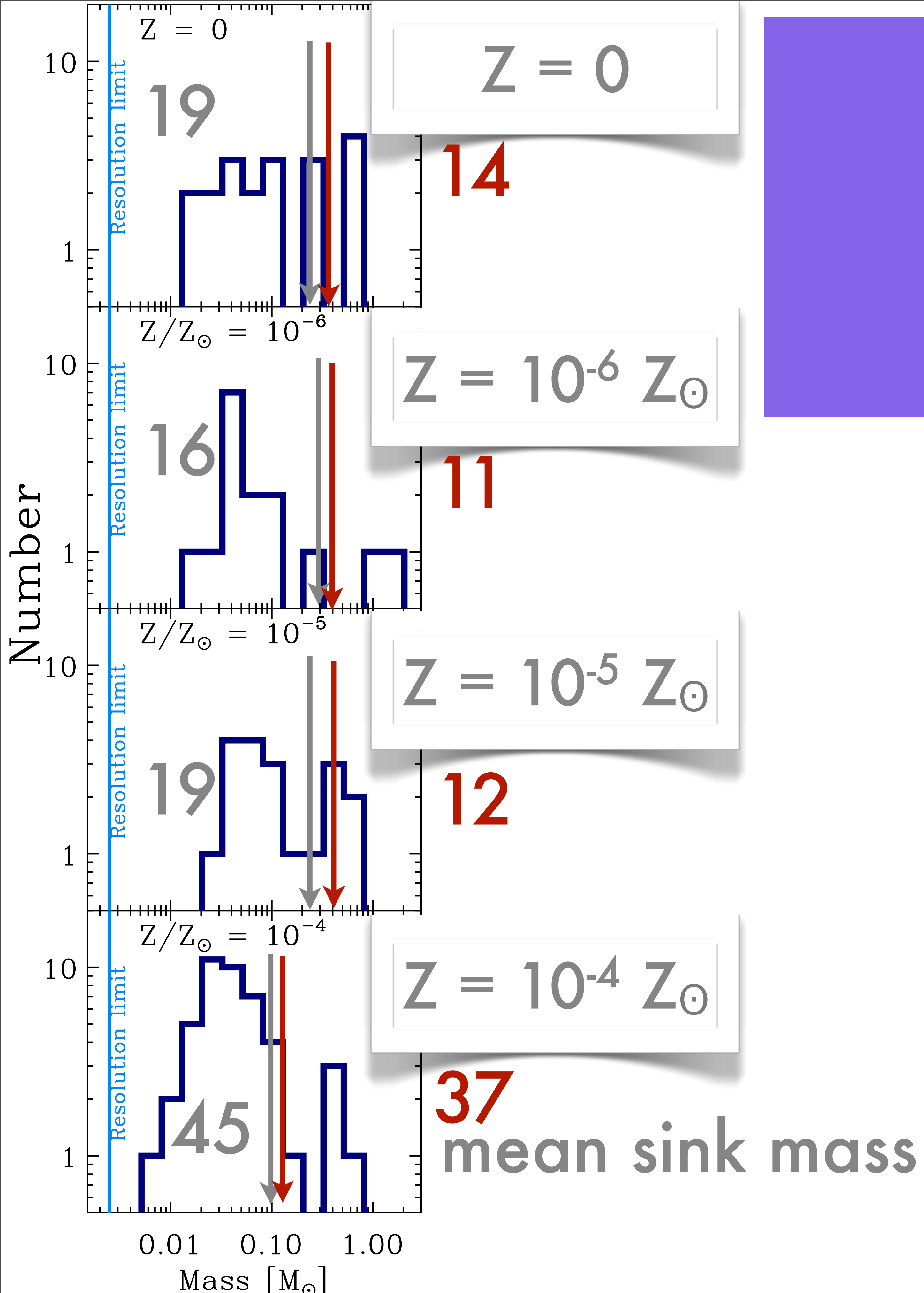


Z = 0
Z = 10^{-6} $Z_\odot$
Z = 10^{-5} $Z_\odot$
Z = 10^{-4} $Z_\odot$
Resolution limit
Sink MF
Sink MF merged
Number
Mass [$M_\odot$]
0.01
0.10
1.00
1
10

Sink Mass Function

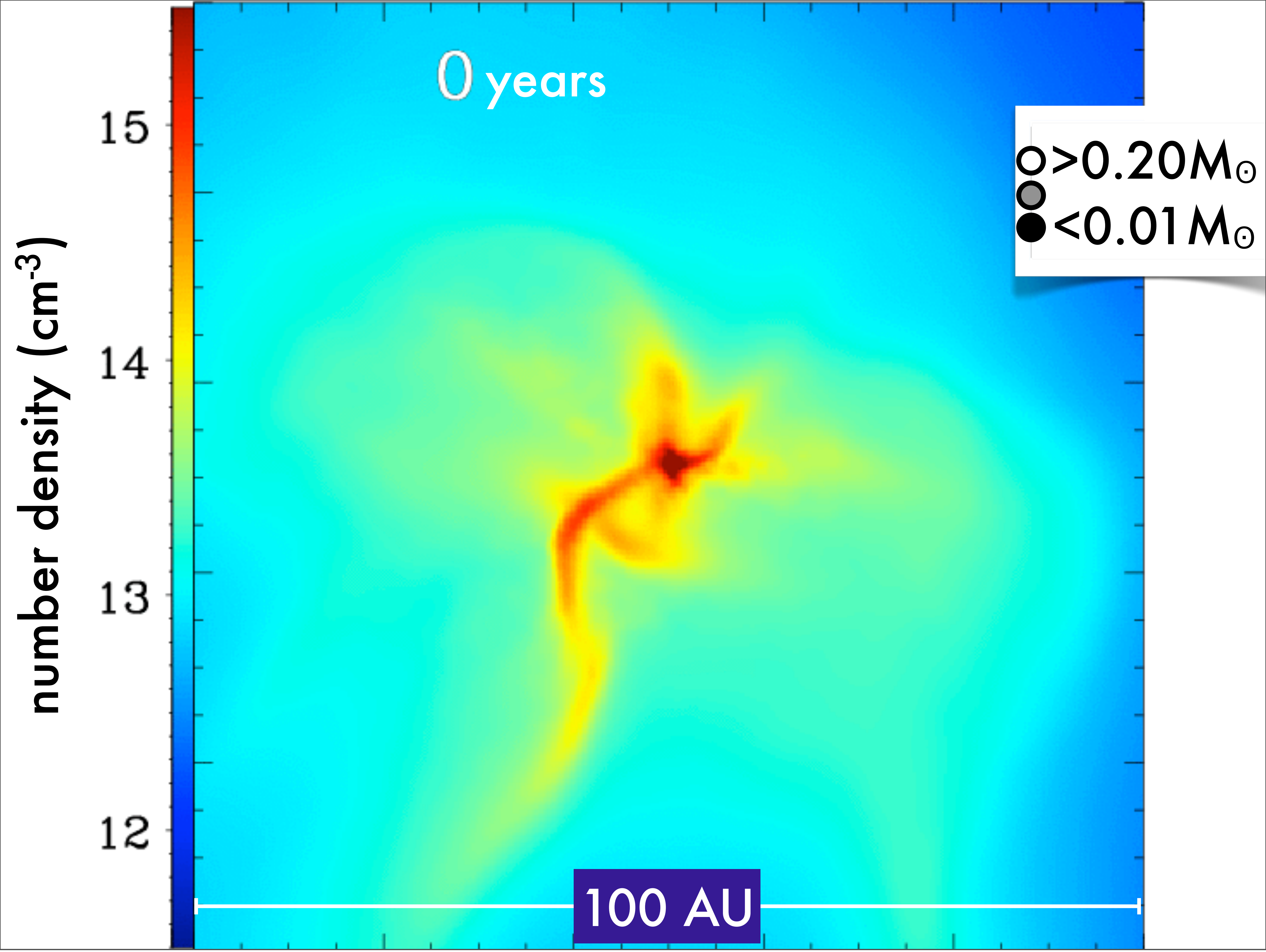


Sink Mass Function

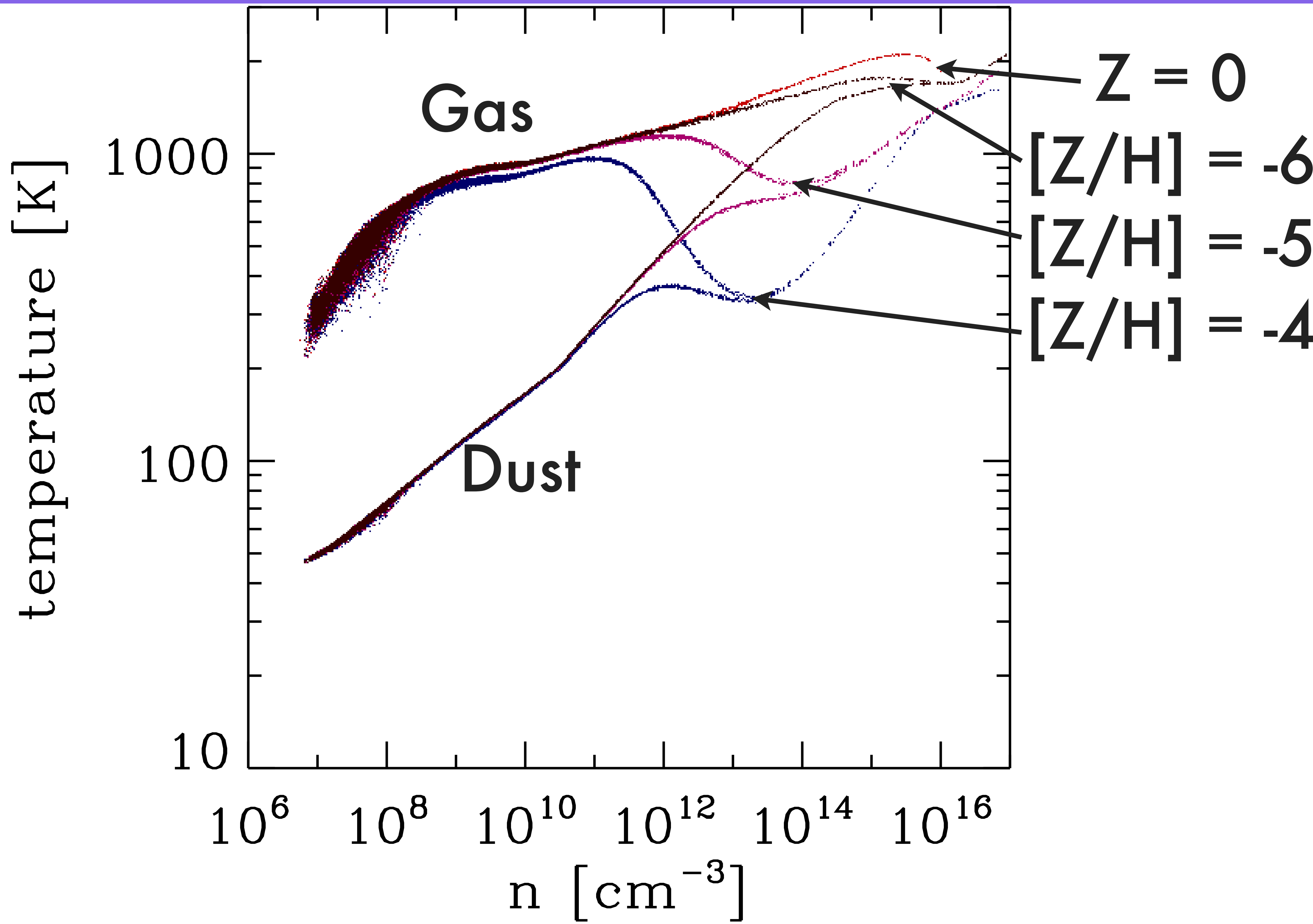


Conclusions

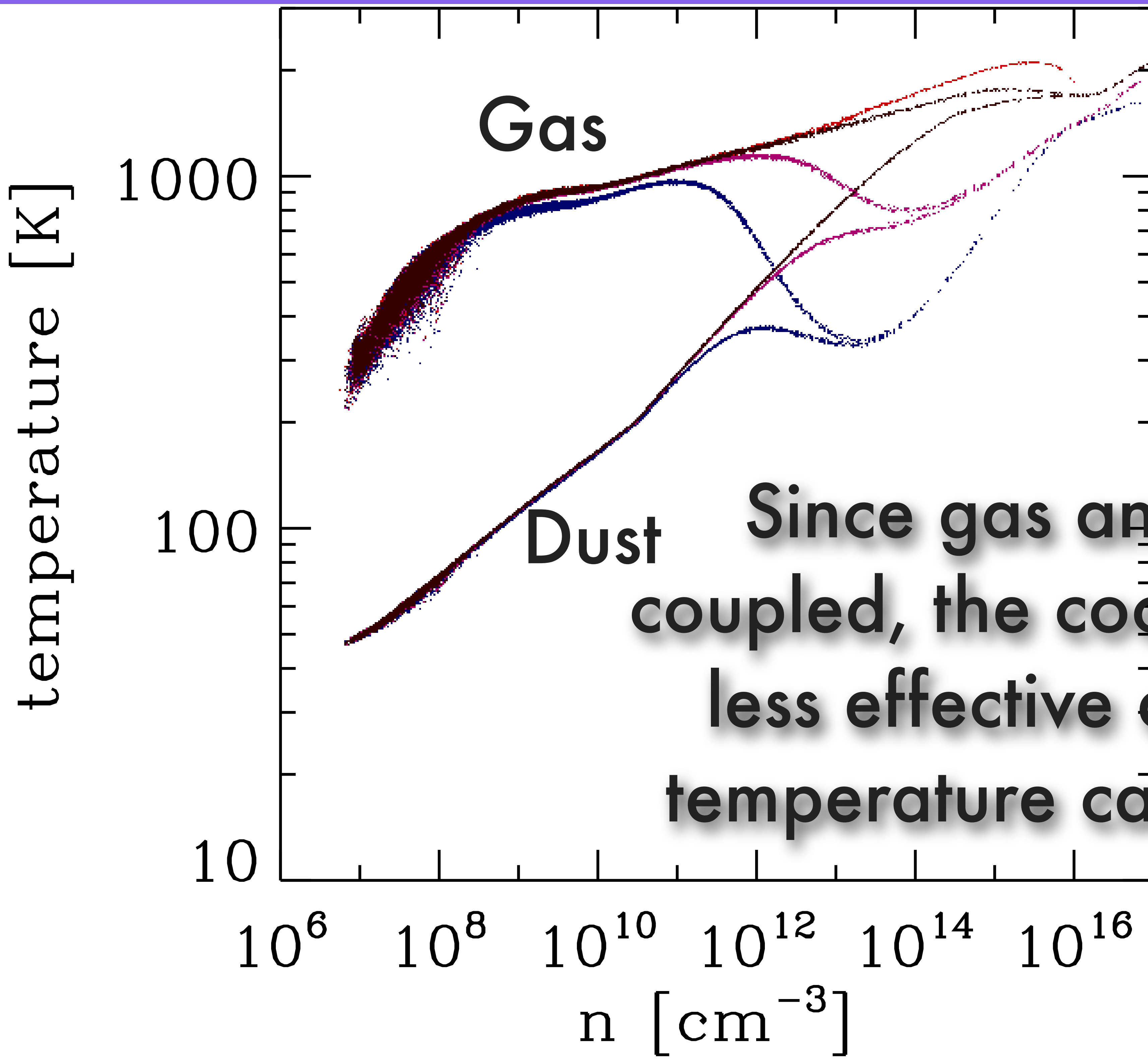
- Dust is an efficient coolant
- At $Z \sim 10^{-4} Z_{solar}$, dust plays an important role in causing fragmentation
- And on the evolution of the stellar IMF


0 years
>0.20M⊙
<0.01M⊙
number density (cm-3)
15
14
13
12
100 AU

Dust cooling



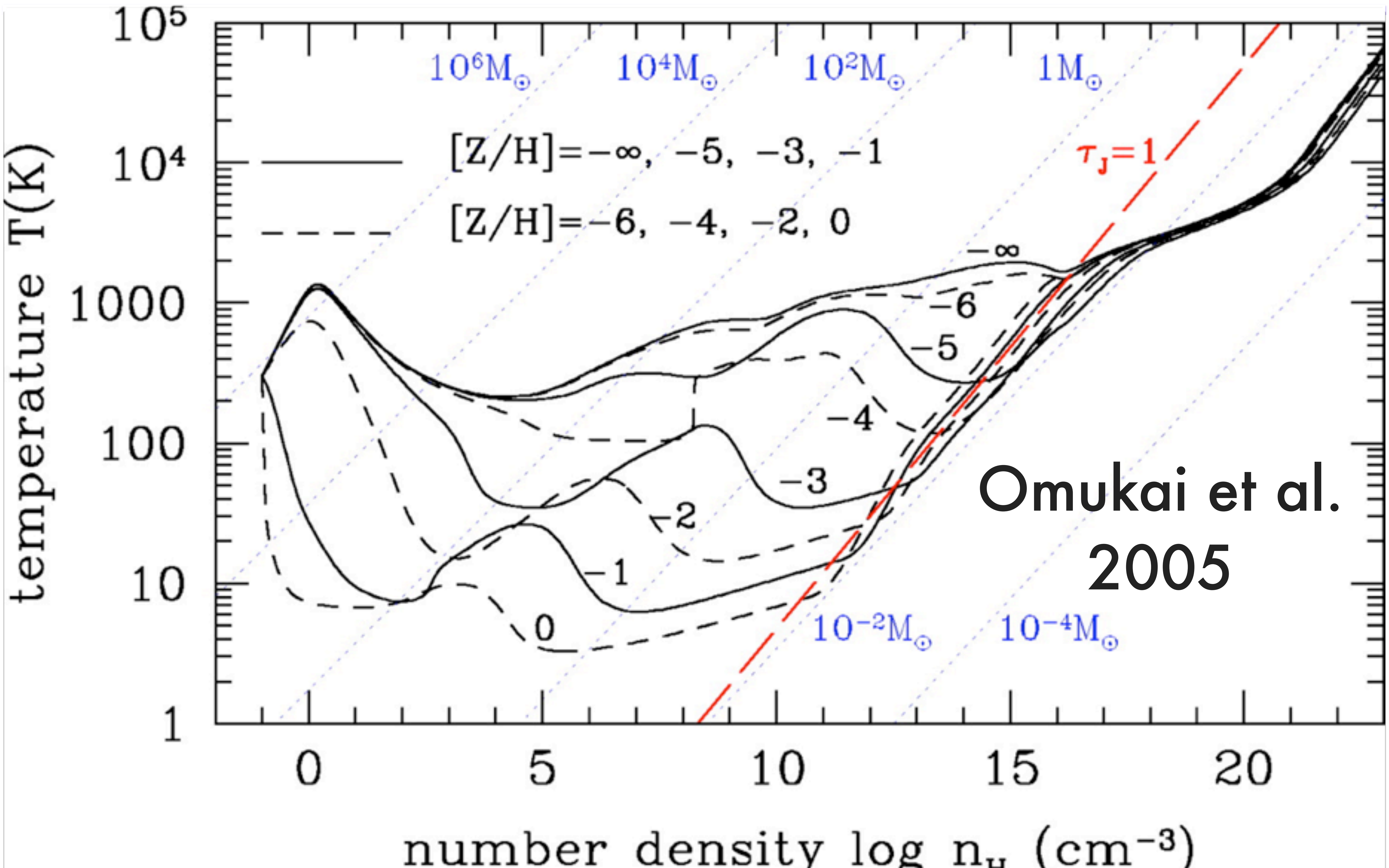
Dust cooling



Z = 0
[Z/H] = -6
[Z/H] = -5
[Z/H] = -4

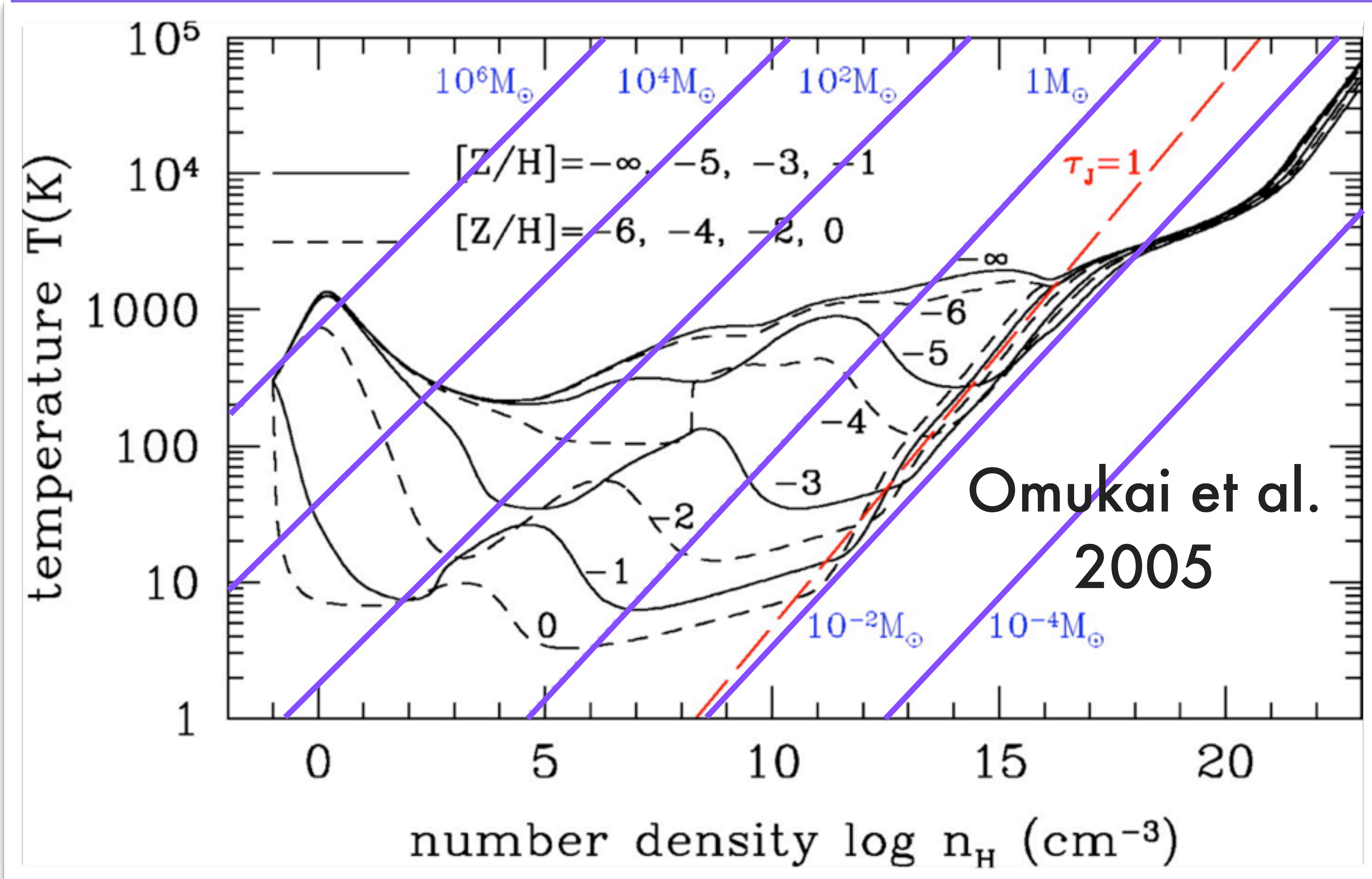
Since gas and dust are coupled, the cooling becomes less effective and the gas temperature can rise again.

Fragmentation

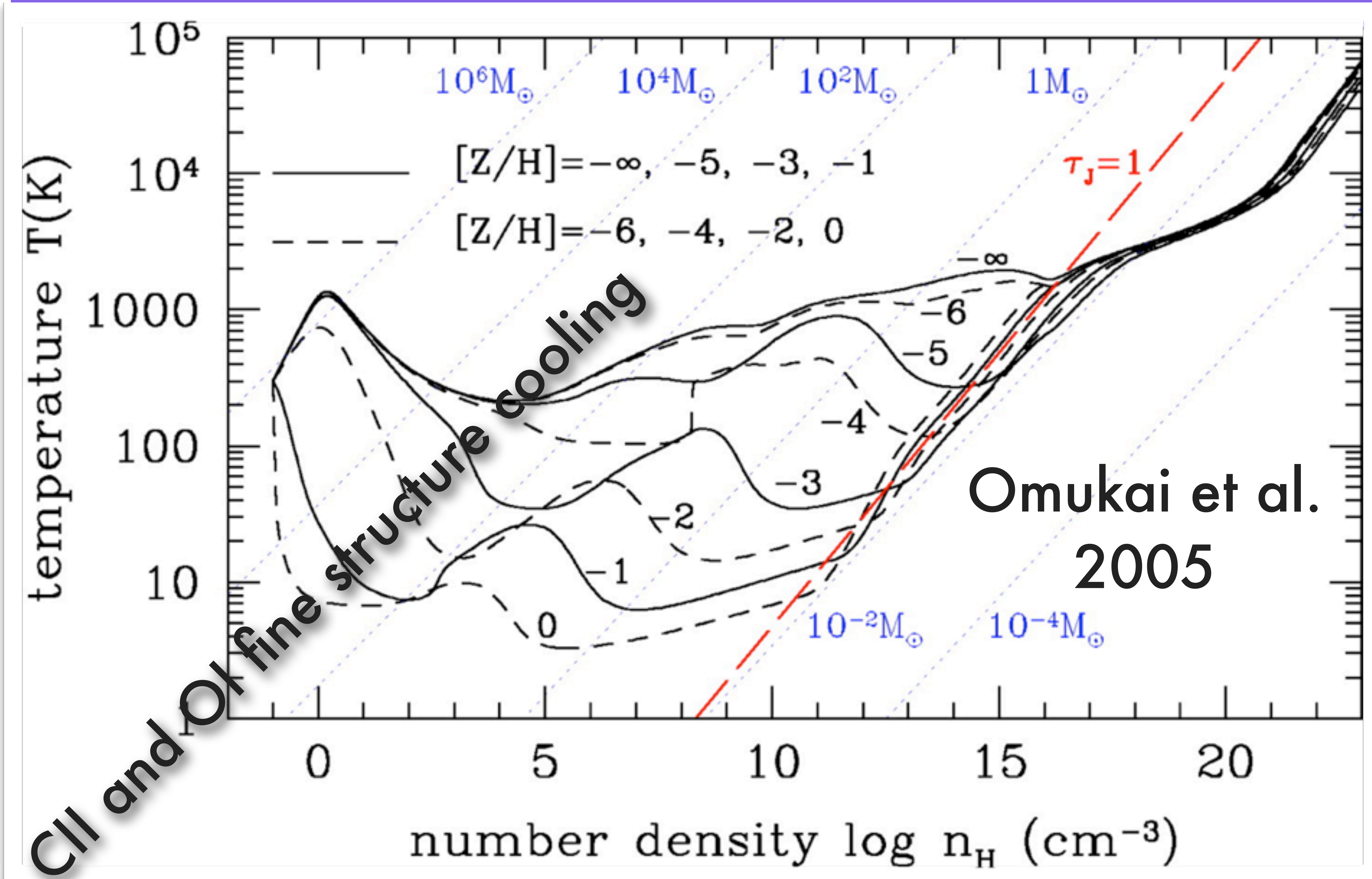


Omukai et al. 2005

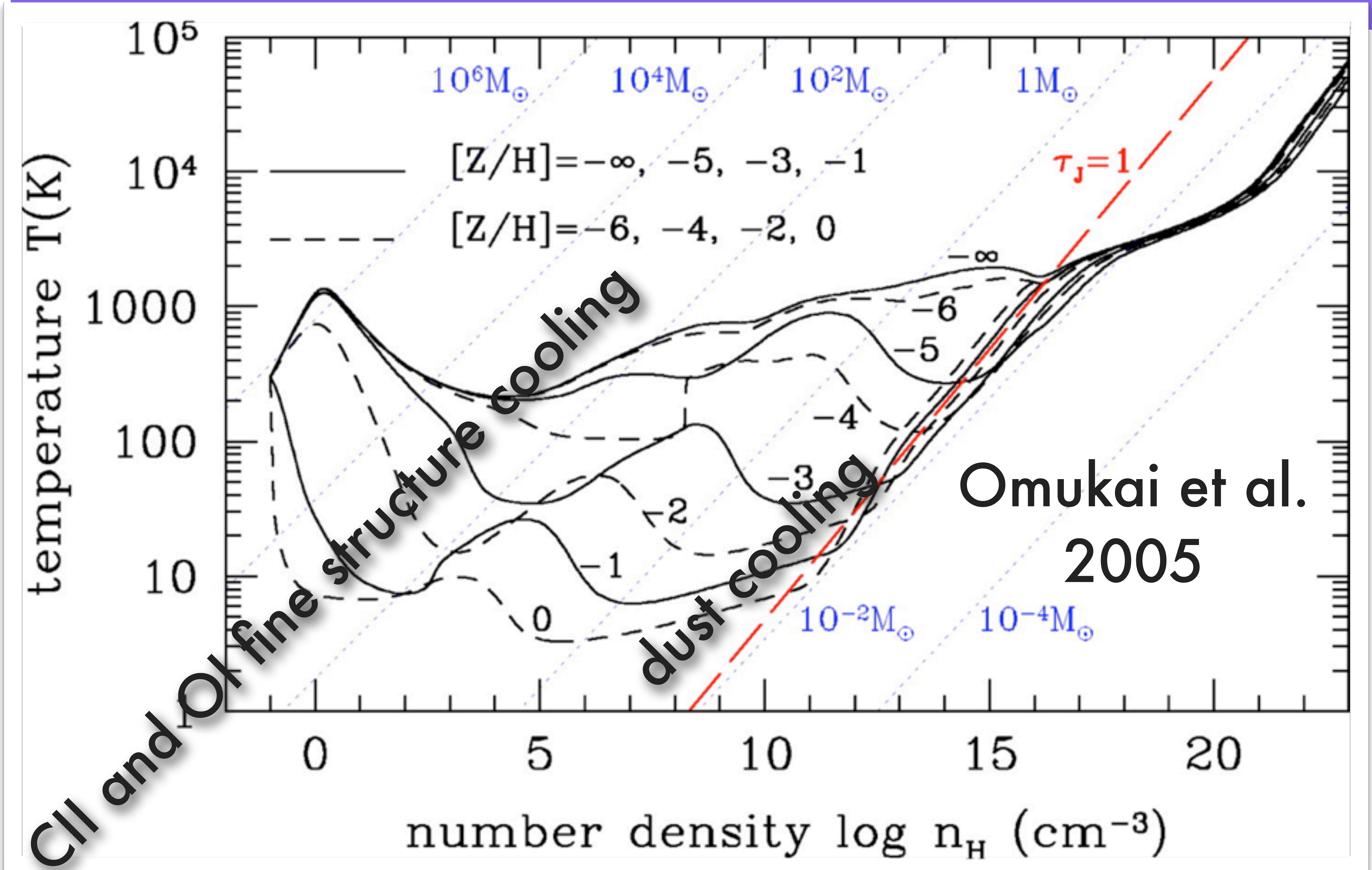
Fragmentation



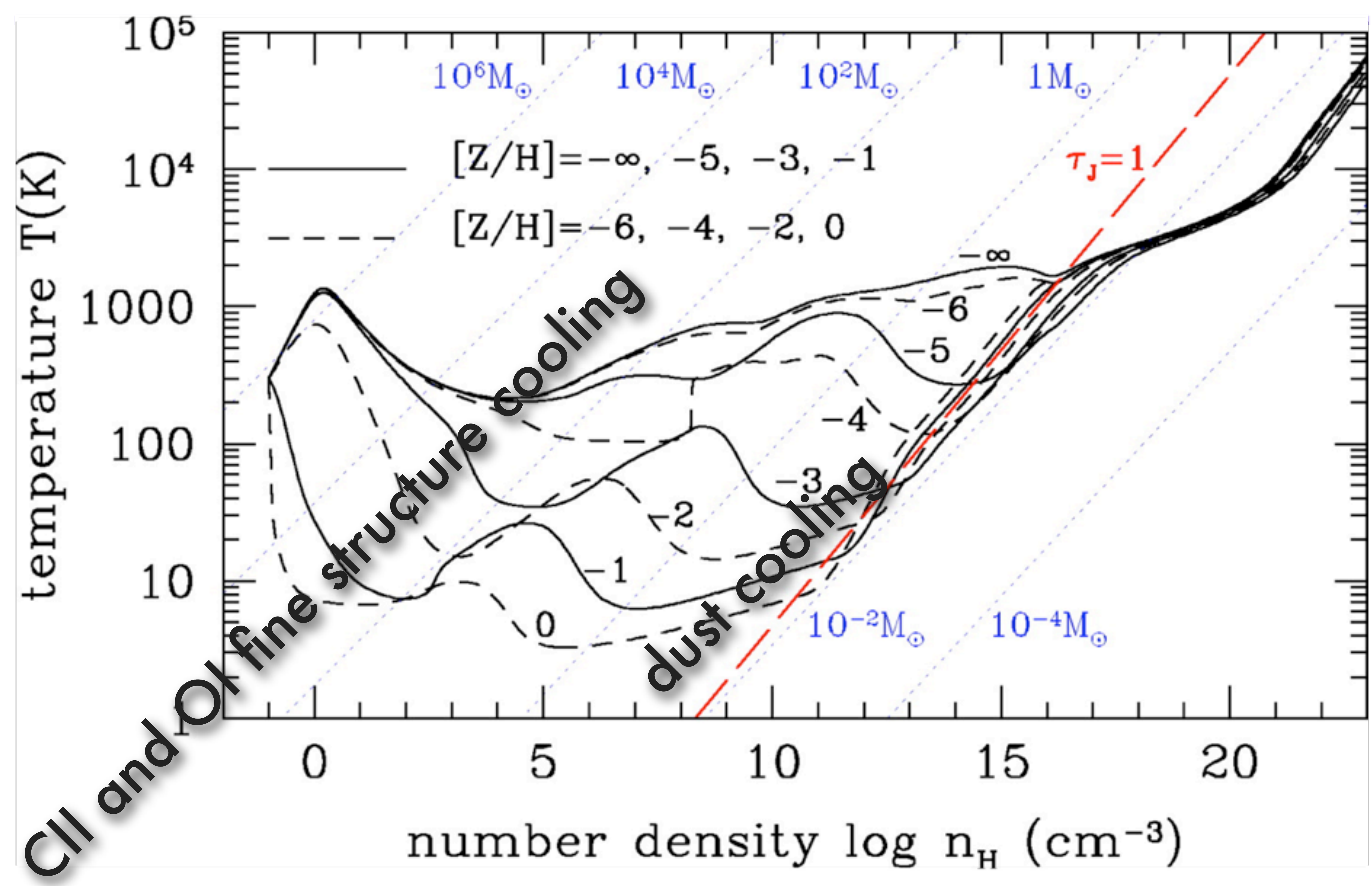
Fragmentation



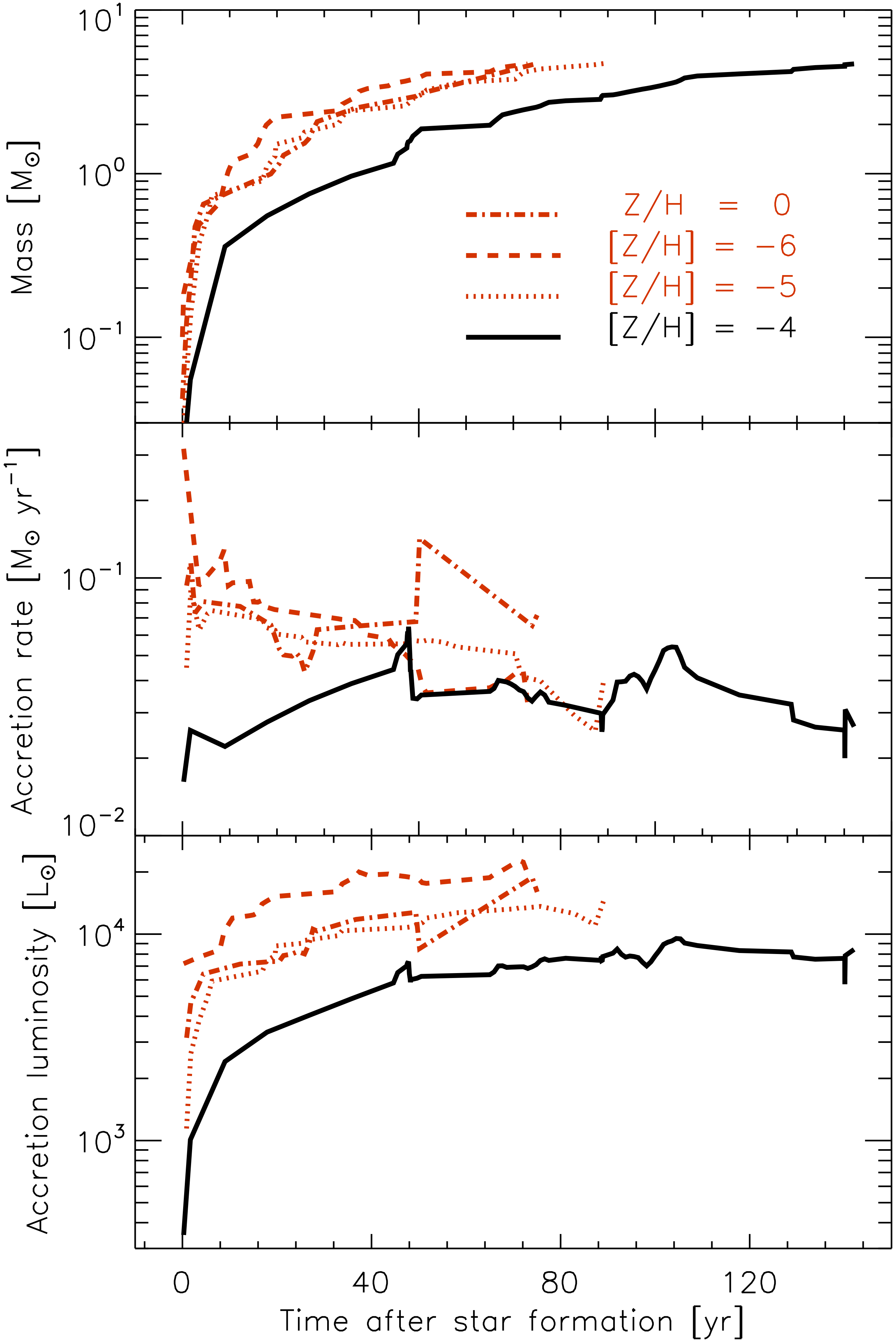
Fragmentation



Fragmentation



Future work

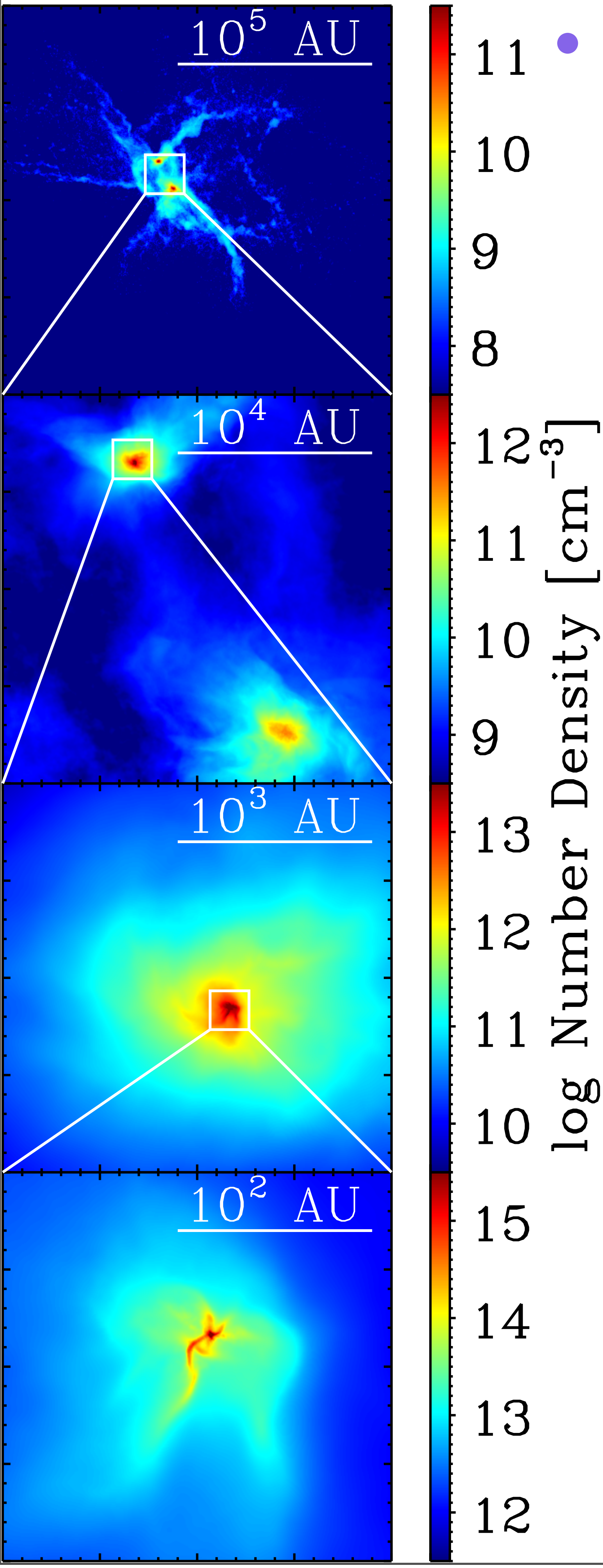


Accretion Rate

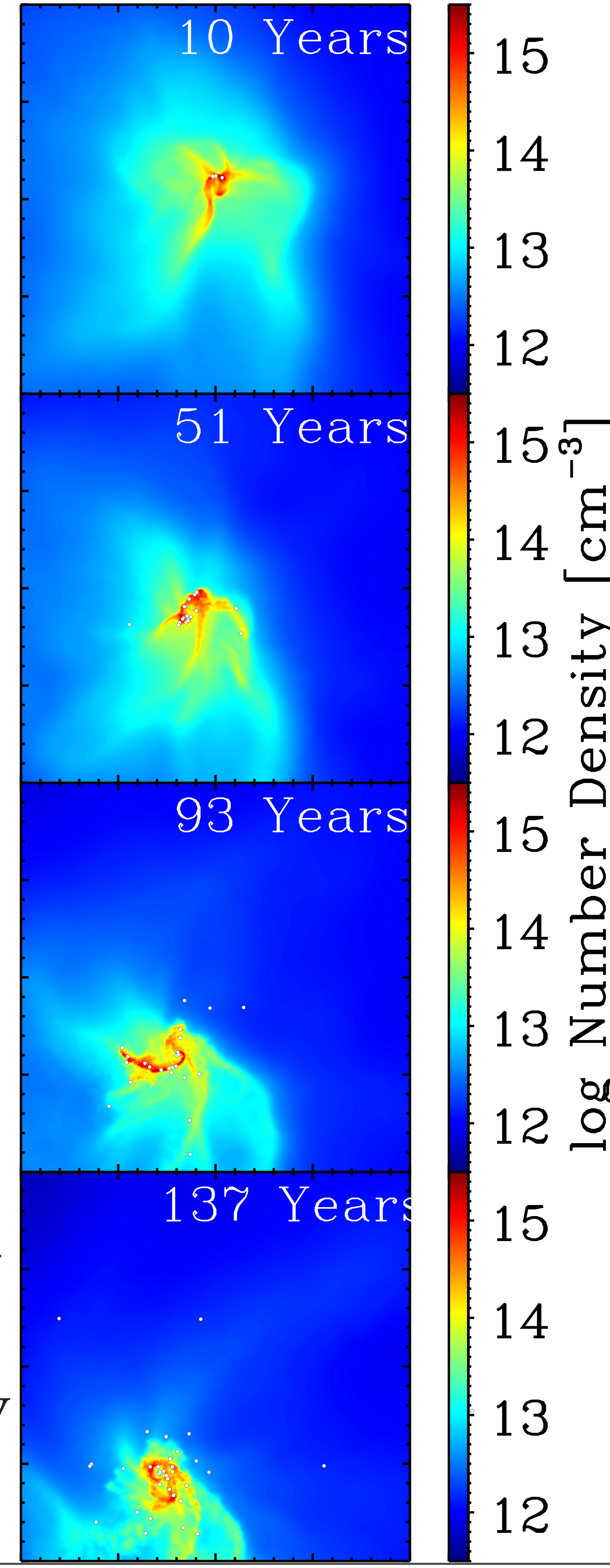
$$L_{acc} = \frac{GM_*\dot{M}}{R_*}$$

$$R_* = 66.8\left(\frac{M_*}{M_\odot}\right)^{0.27}\left(\frac{\dot{M}}{10^{-2}M_\odot \mathrm{yr}^{-1}}\right)^{0.41} R_\odot$$

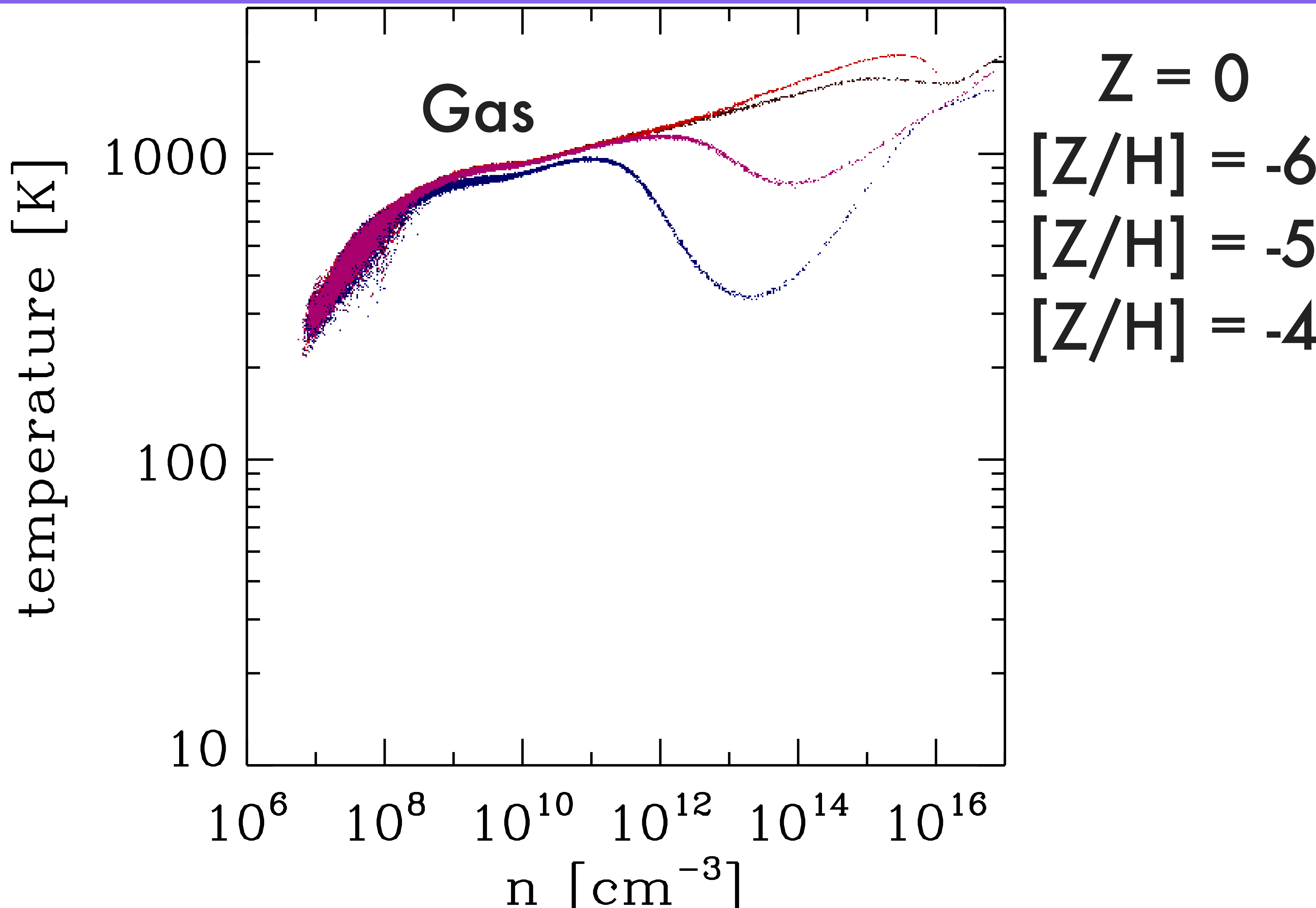
$$\Gamma_{acc} = \kappa_P\left(\frac{L_{acc}}{4\pi r^2}\right)\mathrm{erg\ s^{-1}g^{-1}}$$



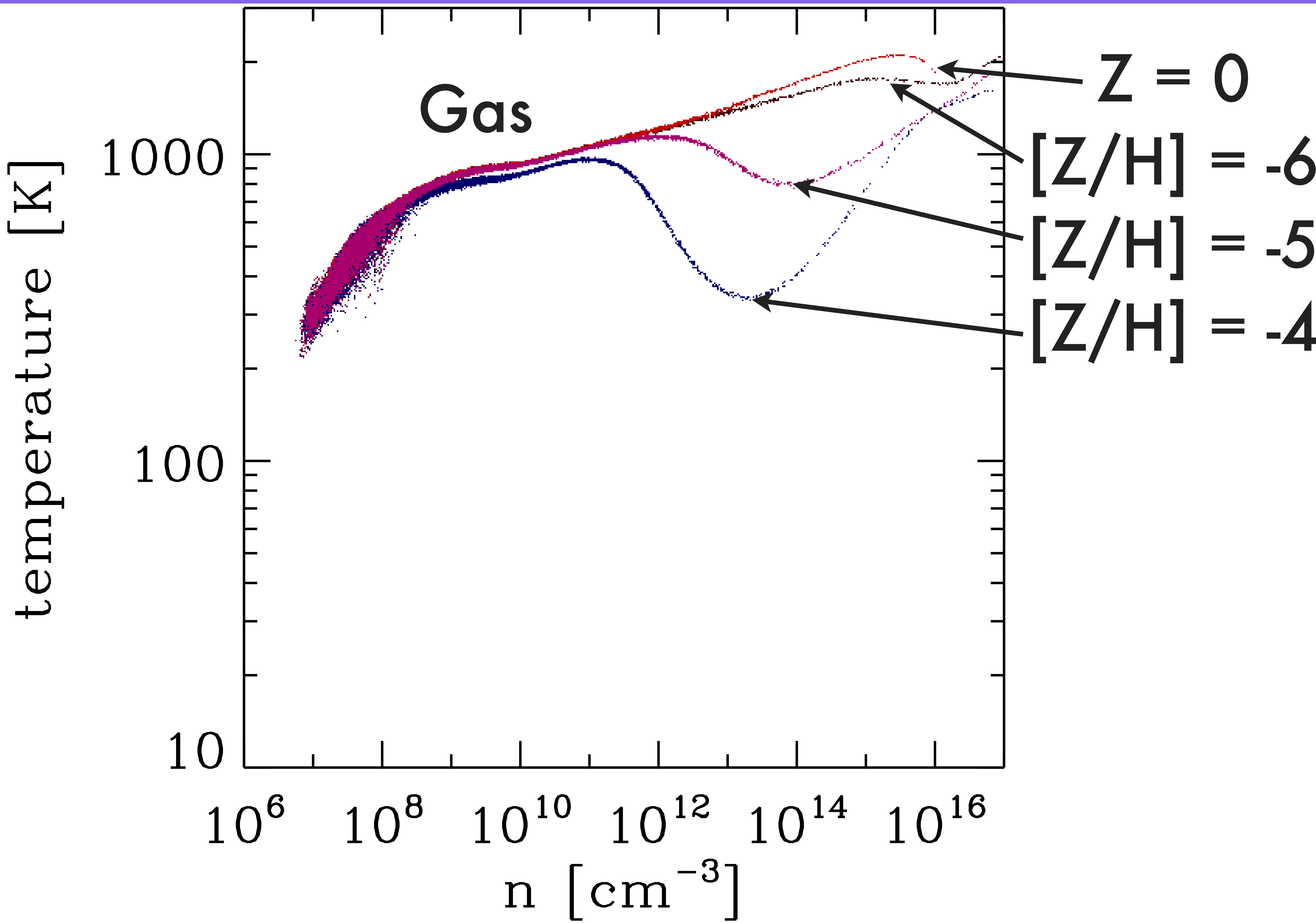
- Sink particle
  - continue beyond the formation of the first very high density, protostellar core
  - Replace high density region by a non-gaseous, simple particle
  - Contains all the mass in the region and accretes any infalling mass (Bate 1995)
  - Formed once the SPH particles are bound, collapsing, and within an accretion radius, $\mathbf{h_{acc} = 1.0}$ **AU**
  - The threshold number density for creation is $\mathbf{5.0 \times 10^{13}\ cm^{-3}}$



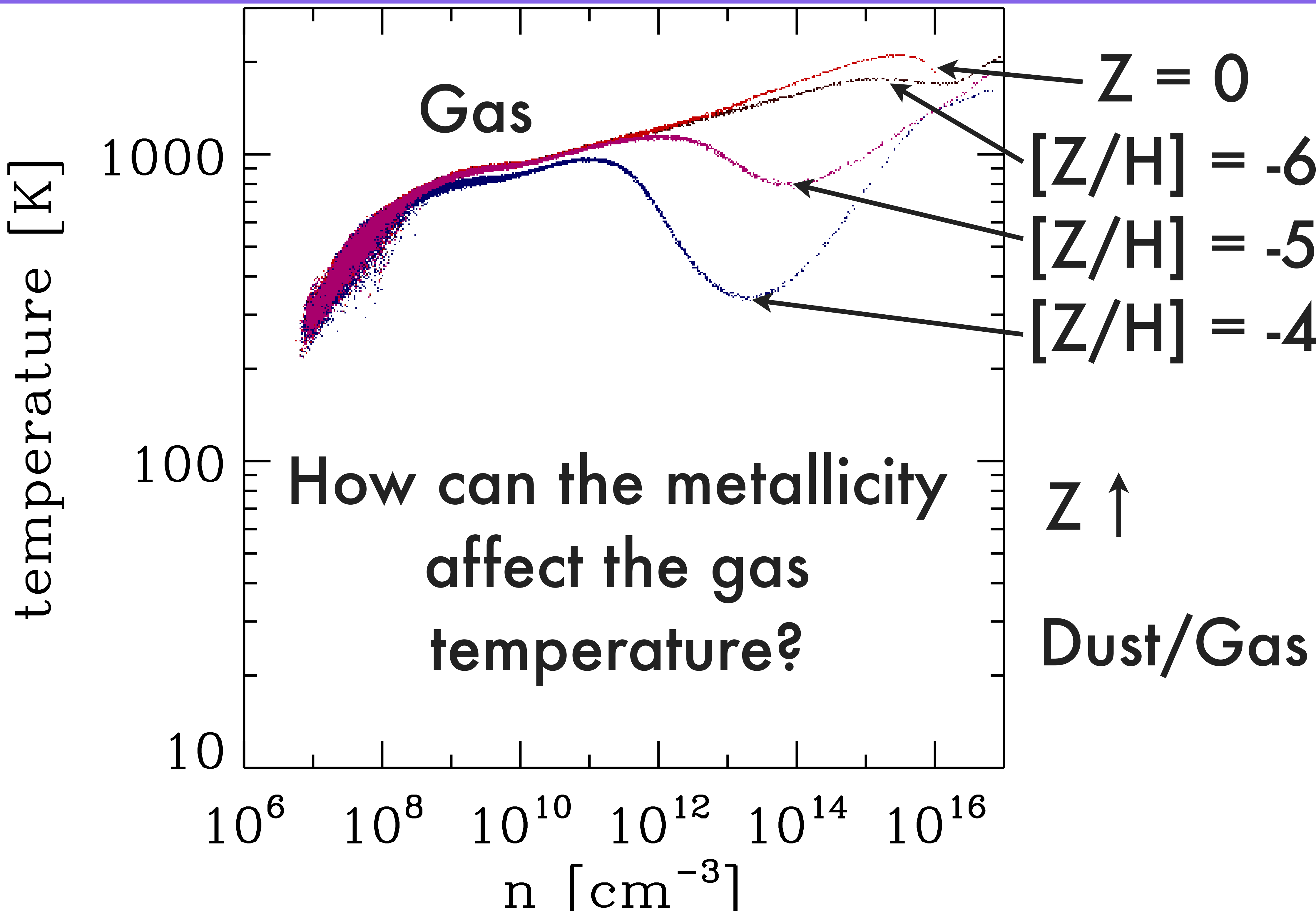
Dust cooling



Dust cooling



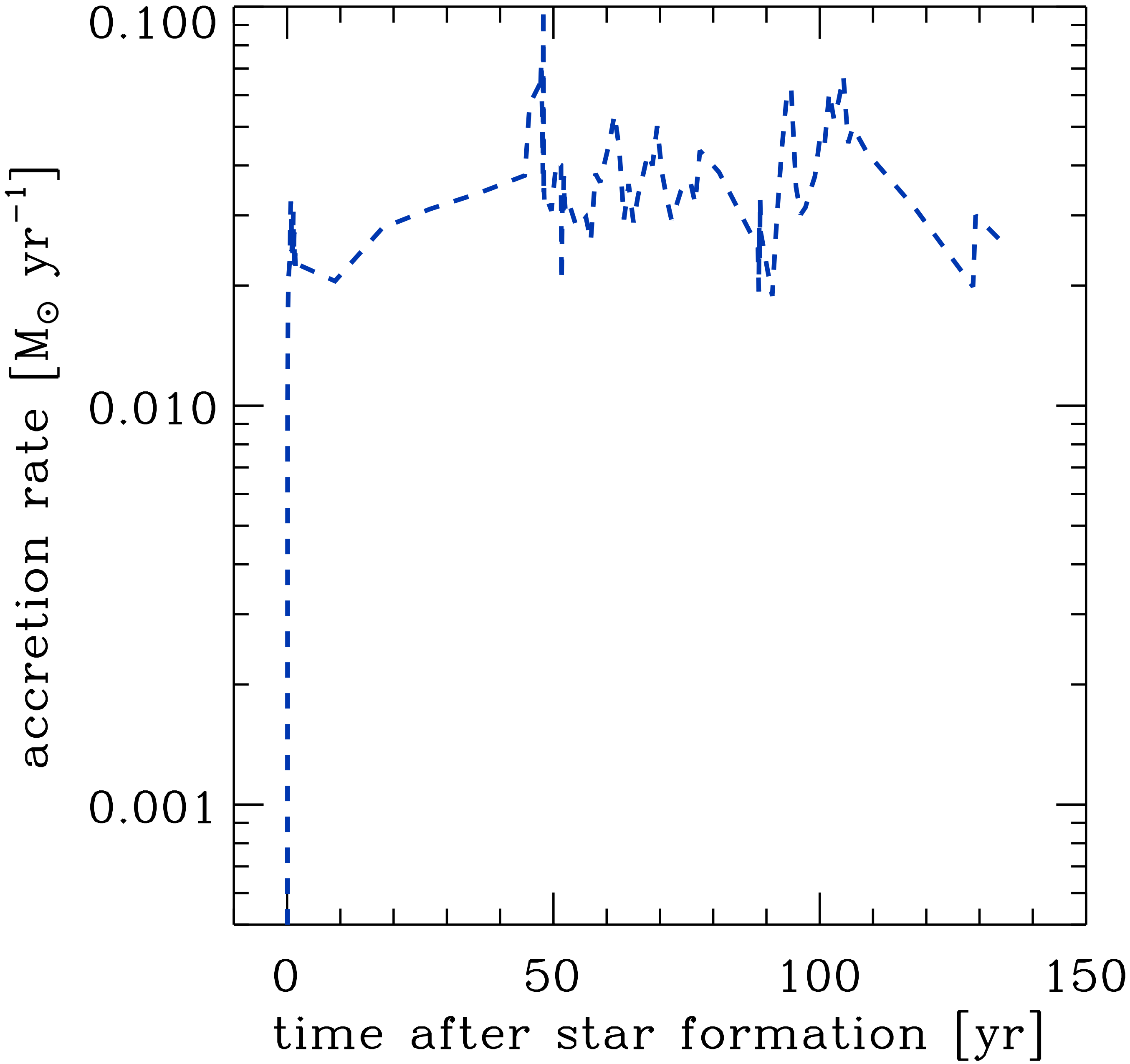
Dust cooling



Z ↑

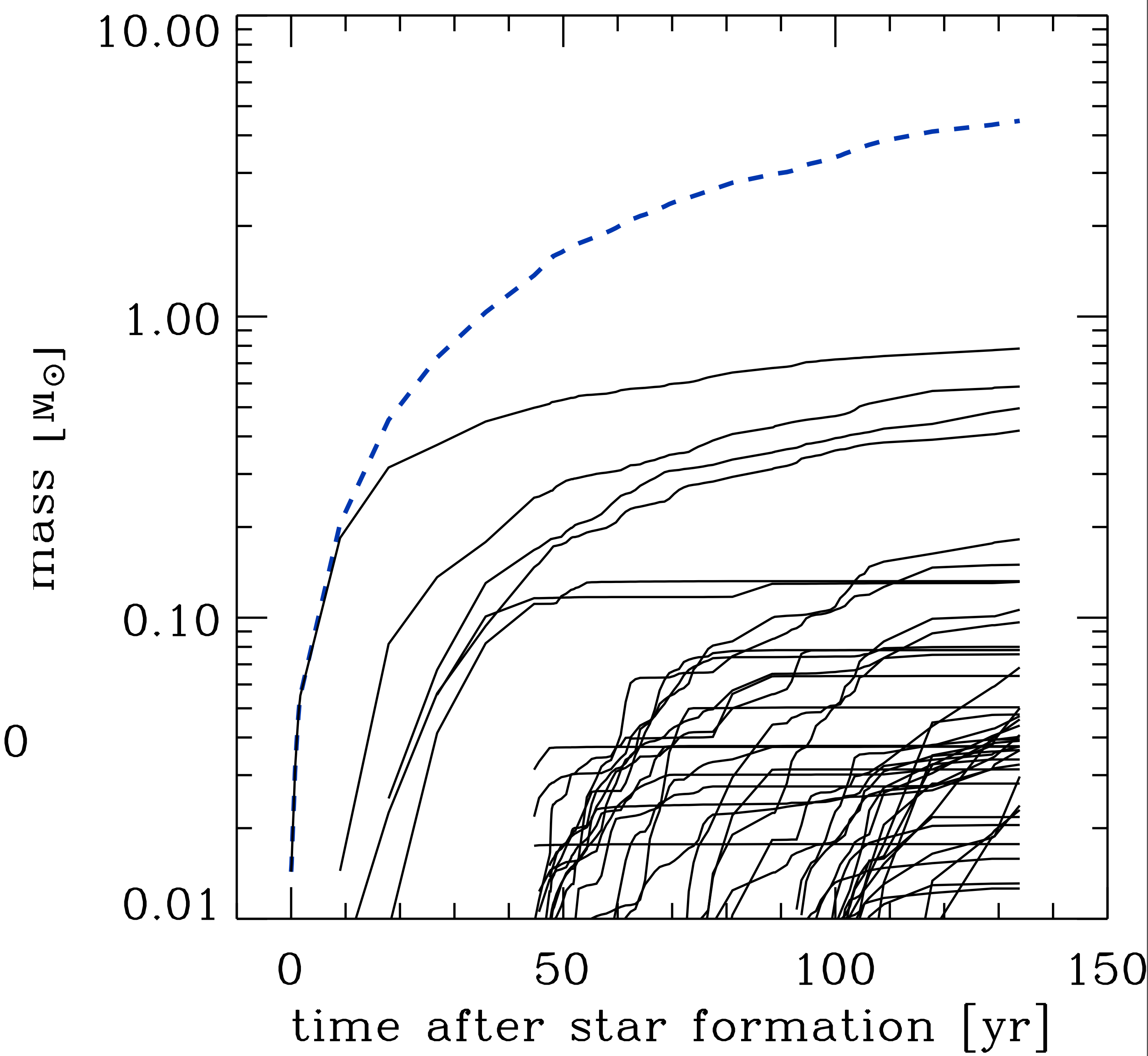
Dust/Gas ↑

Accretion Rates

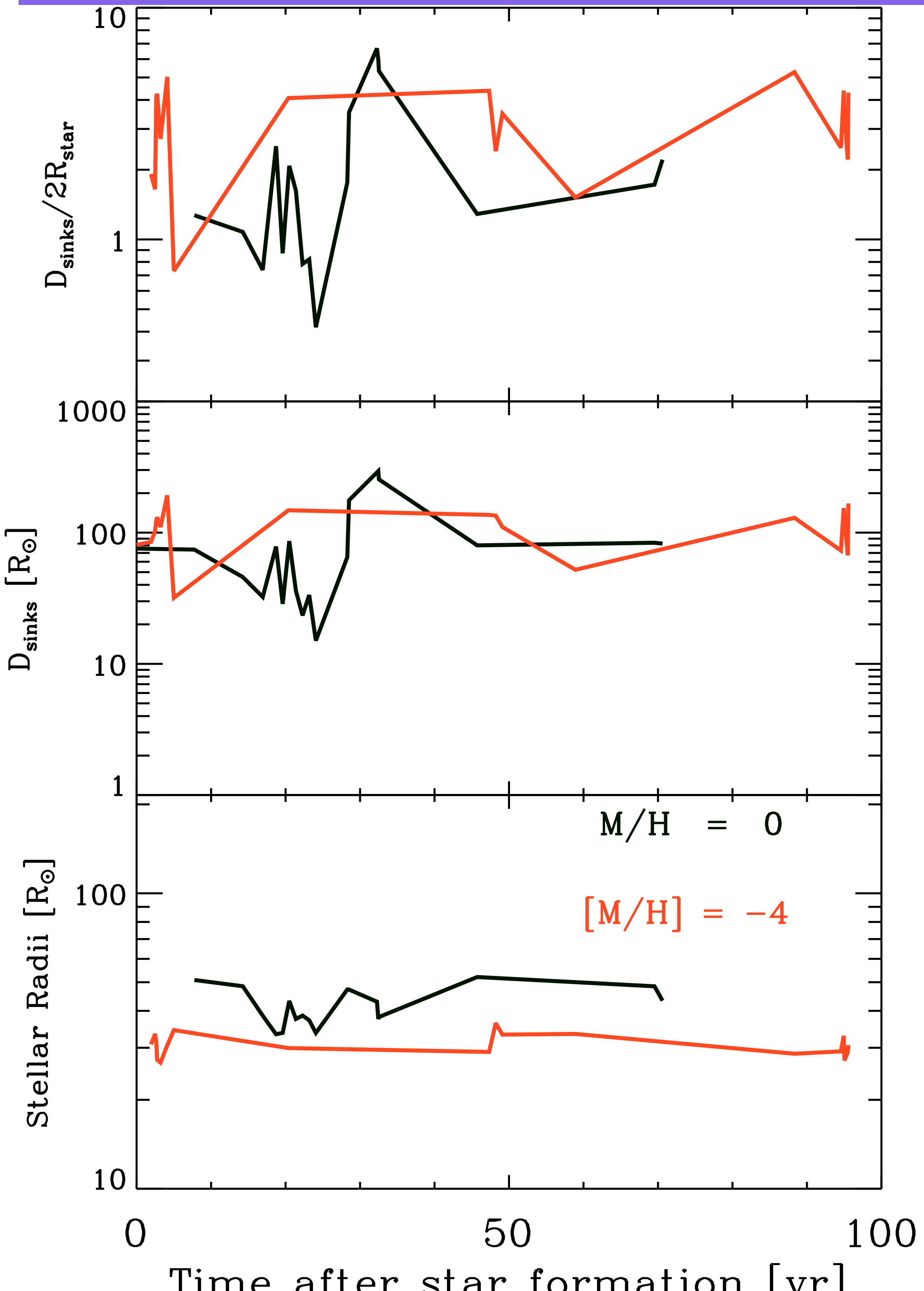


$Z = 10^{-4} Z_{\odot}$

Episodic formation

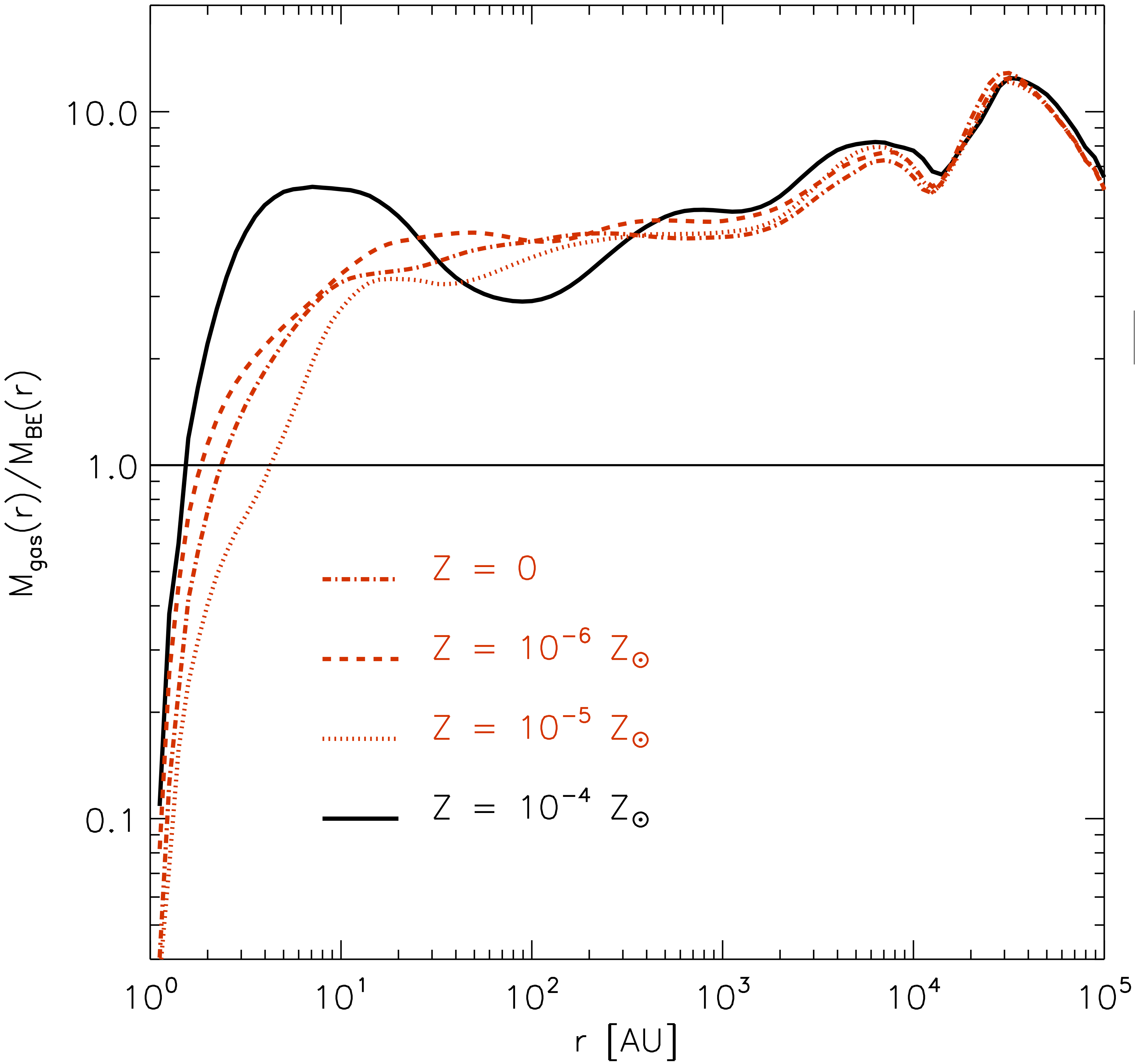


Encounters



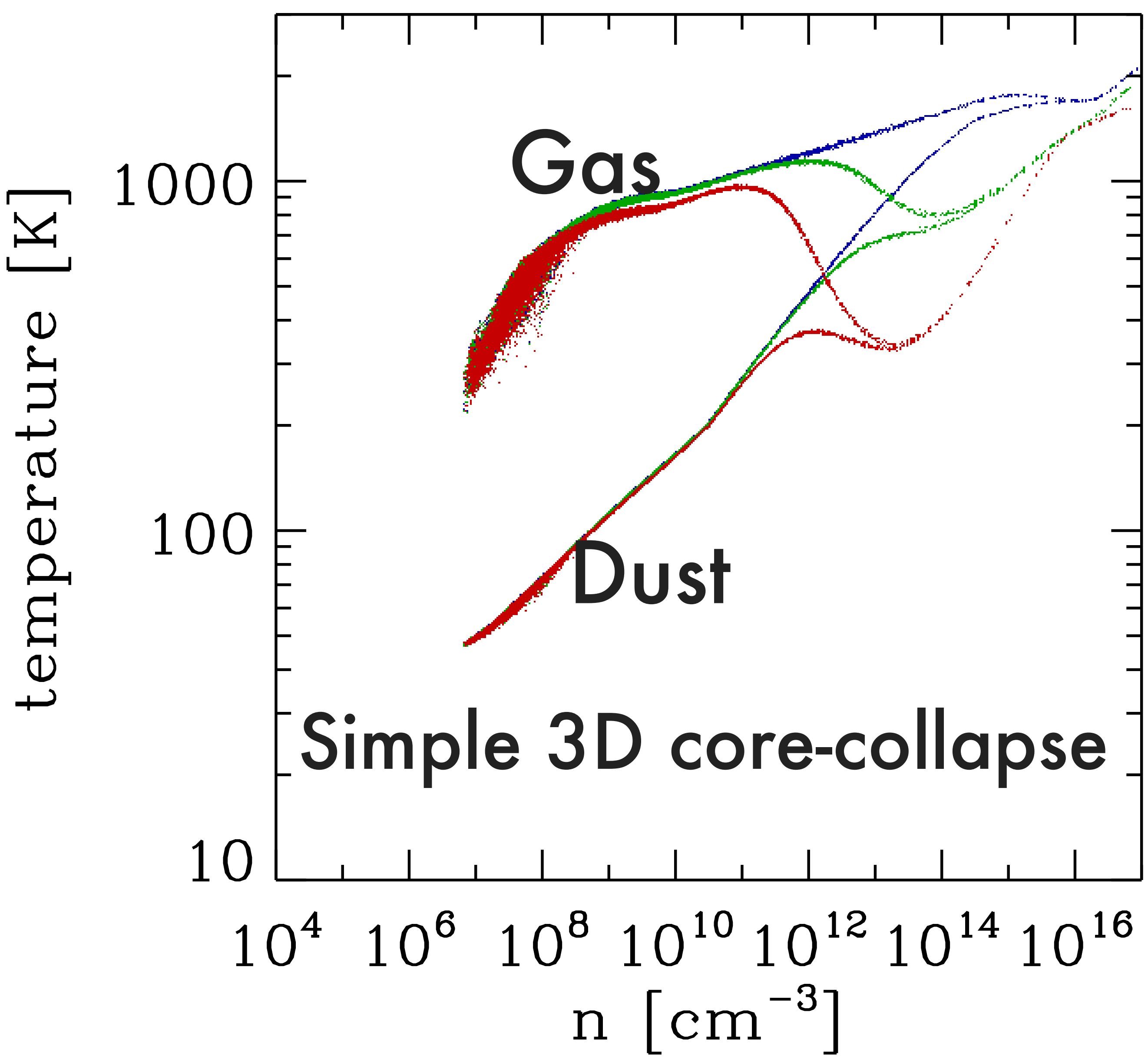
10
1
$D_{sinks}/2R_{star}$
1000
100
10
1
D_{sinks} $[R_\odot]$
M/H = 0
[M/H] = −4
100
10
Stellar Radii $[R_\odot]$
0
50
100
Time after star formation [yr]

Level of Instability

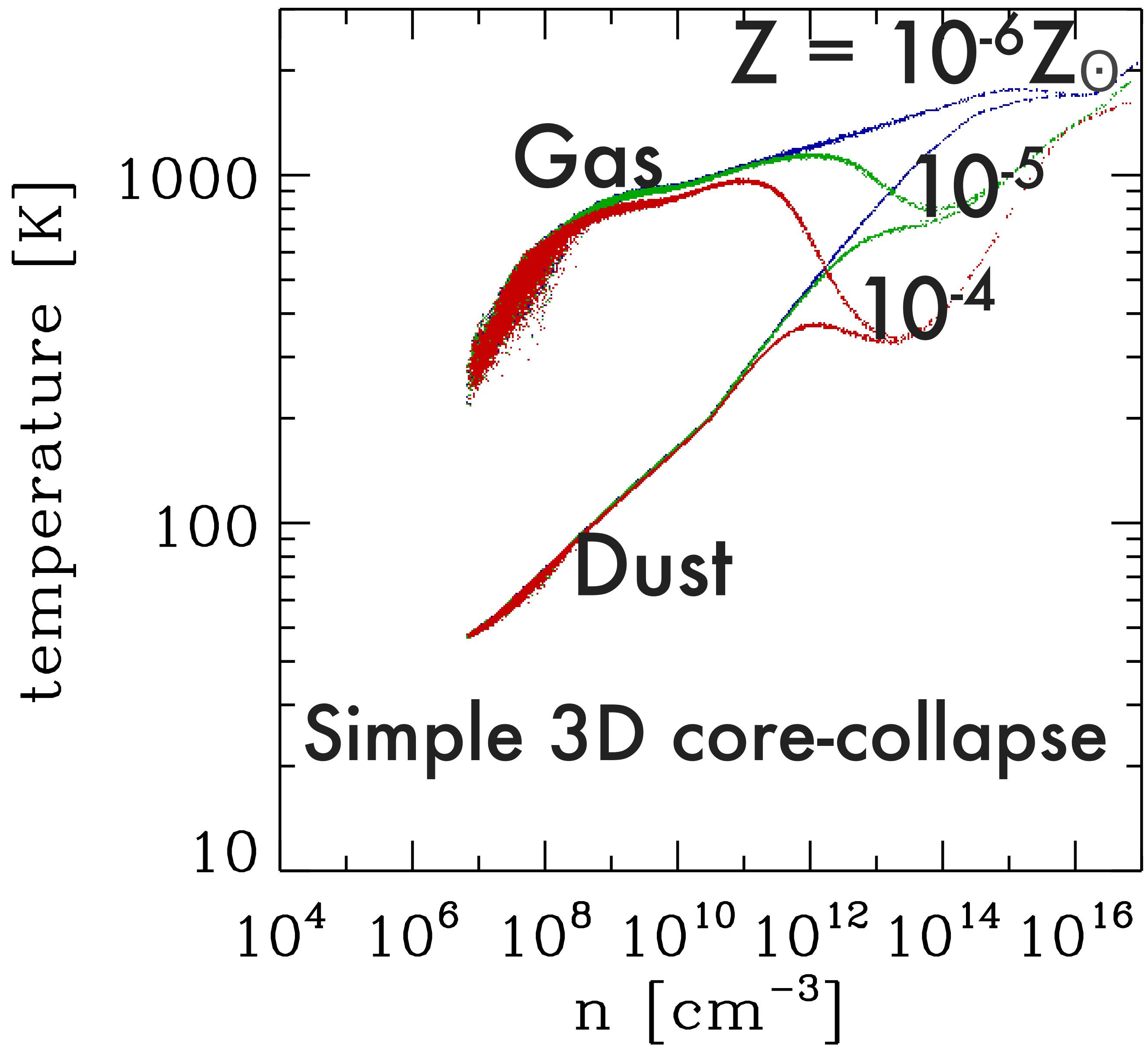


For $Z = 10^{-4} Z_\odot$: Due to the efficient dust cooling, it got more unstable

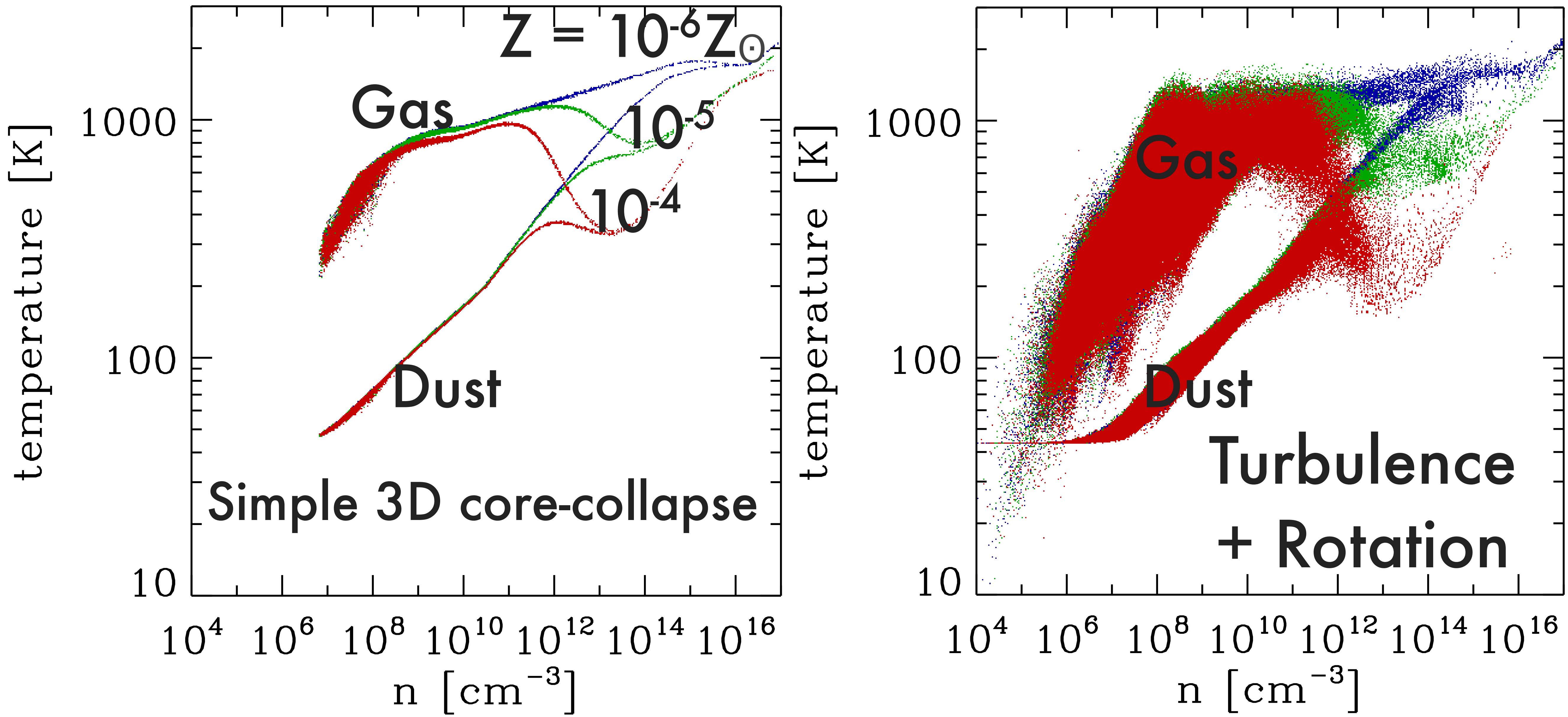
3D Simulation



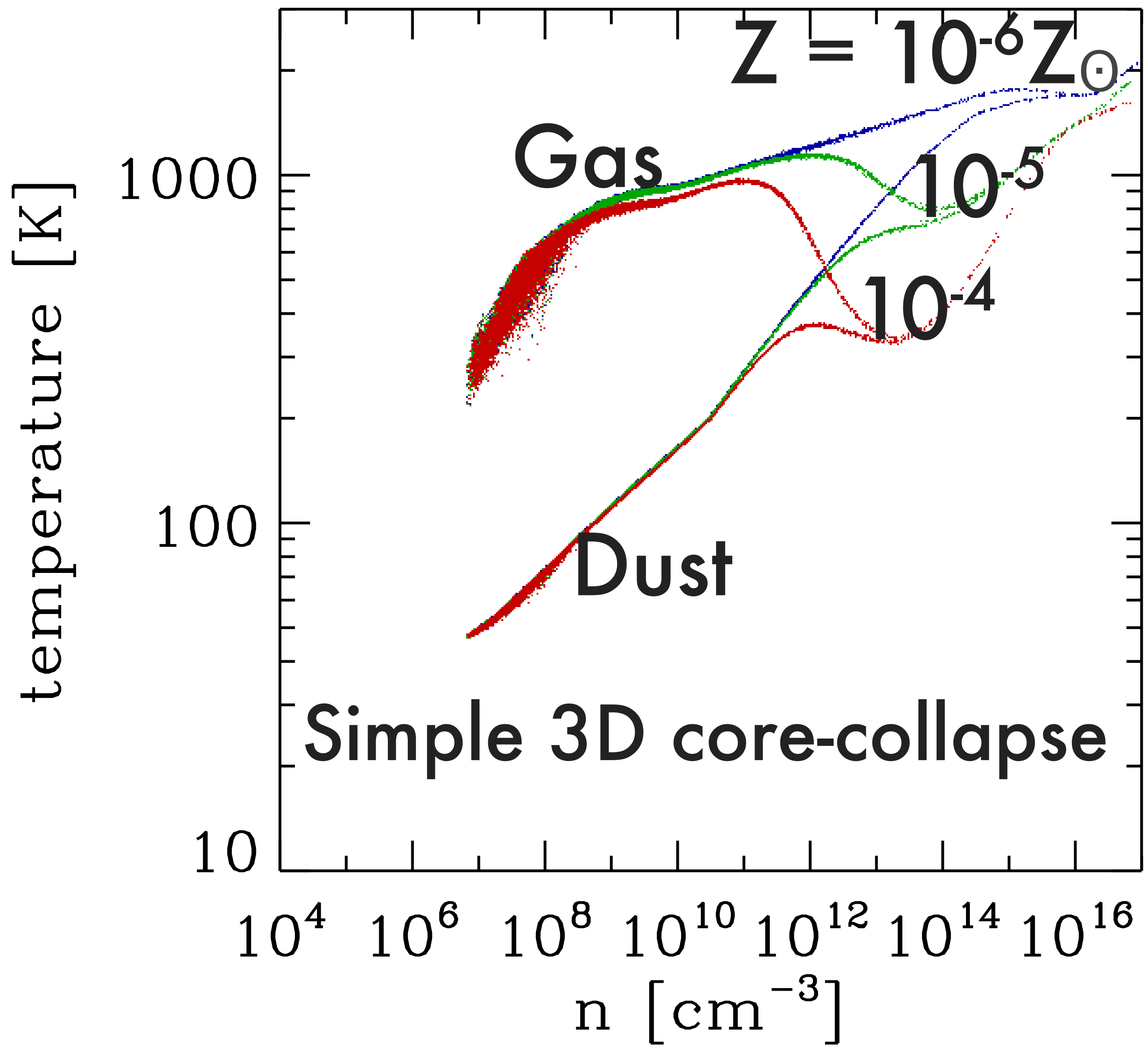
3D Simulation

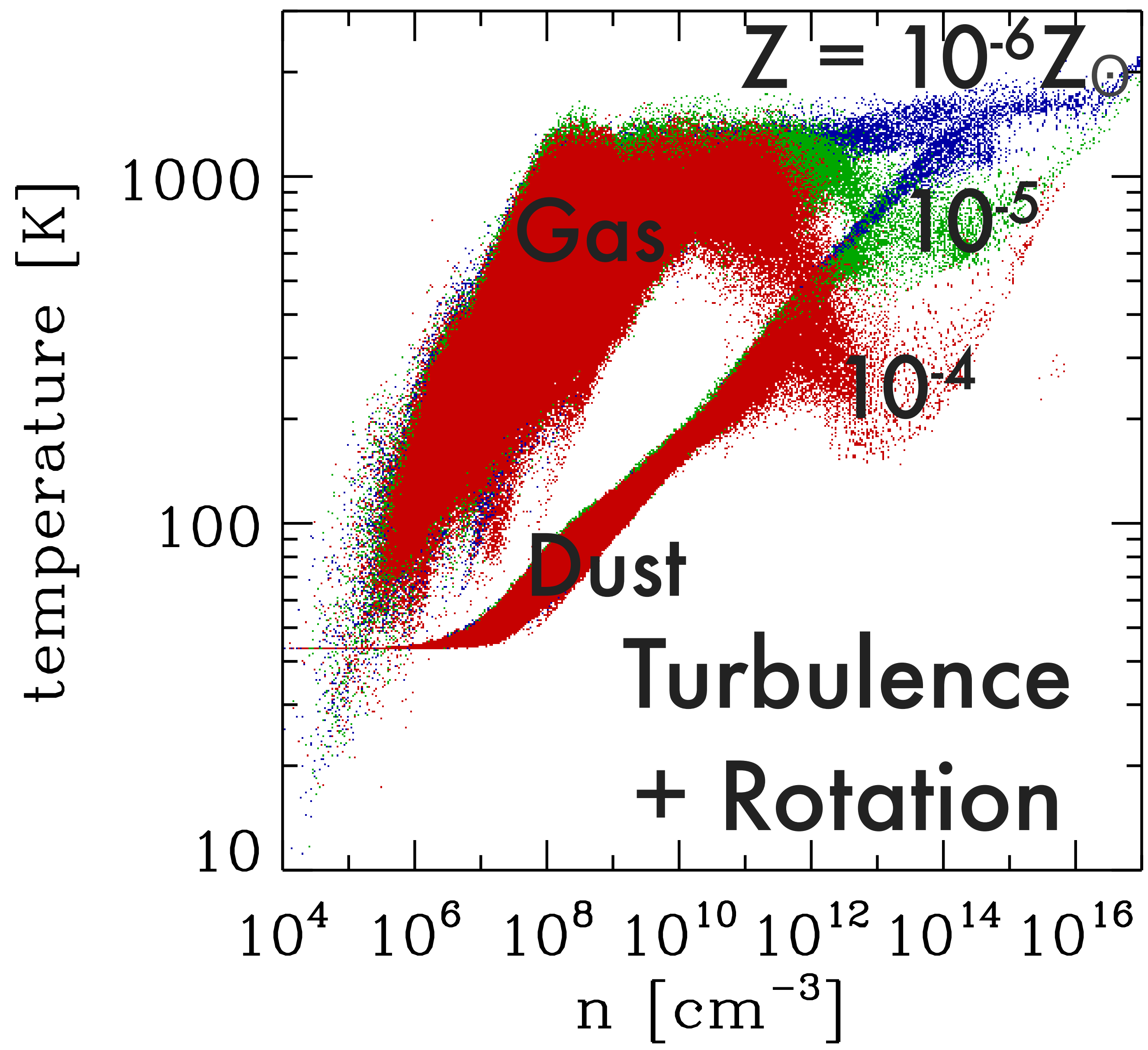


3D Simulation

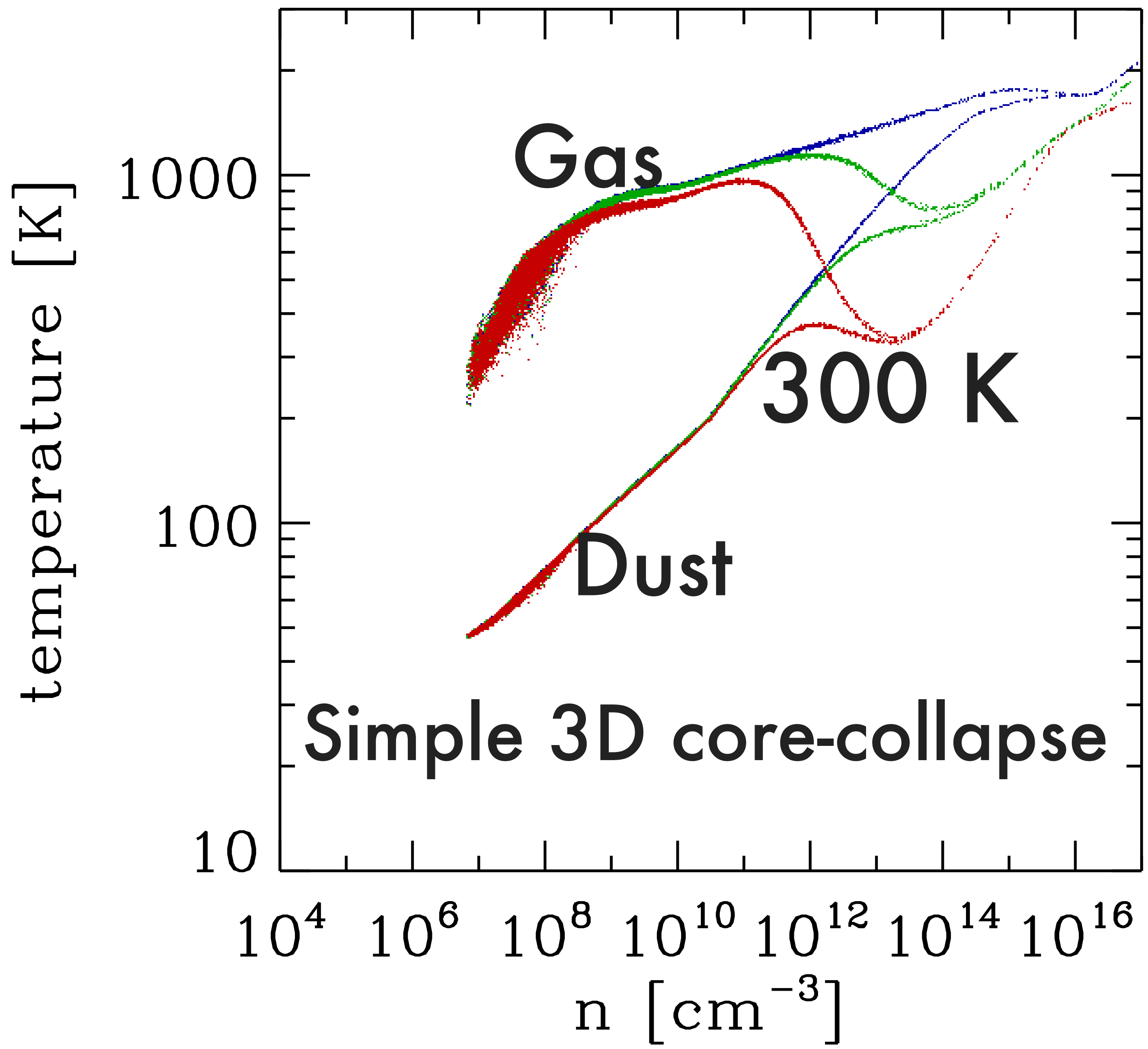


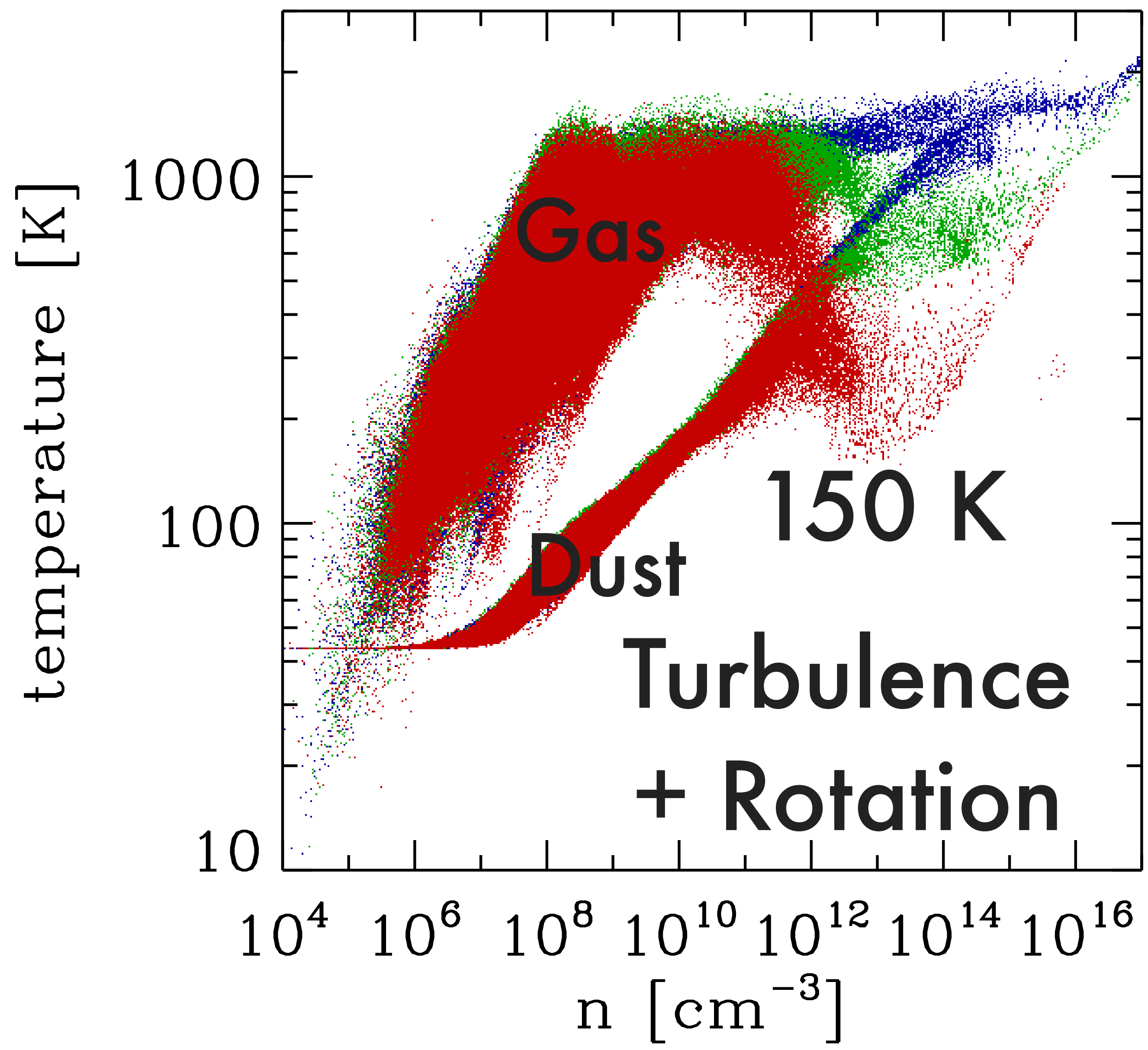
3D Simulation



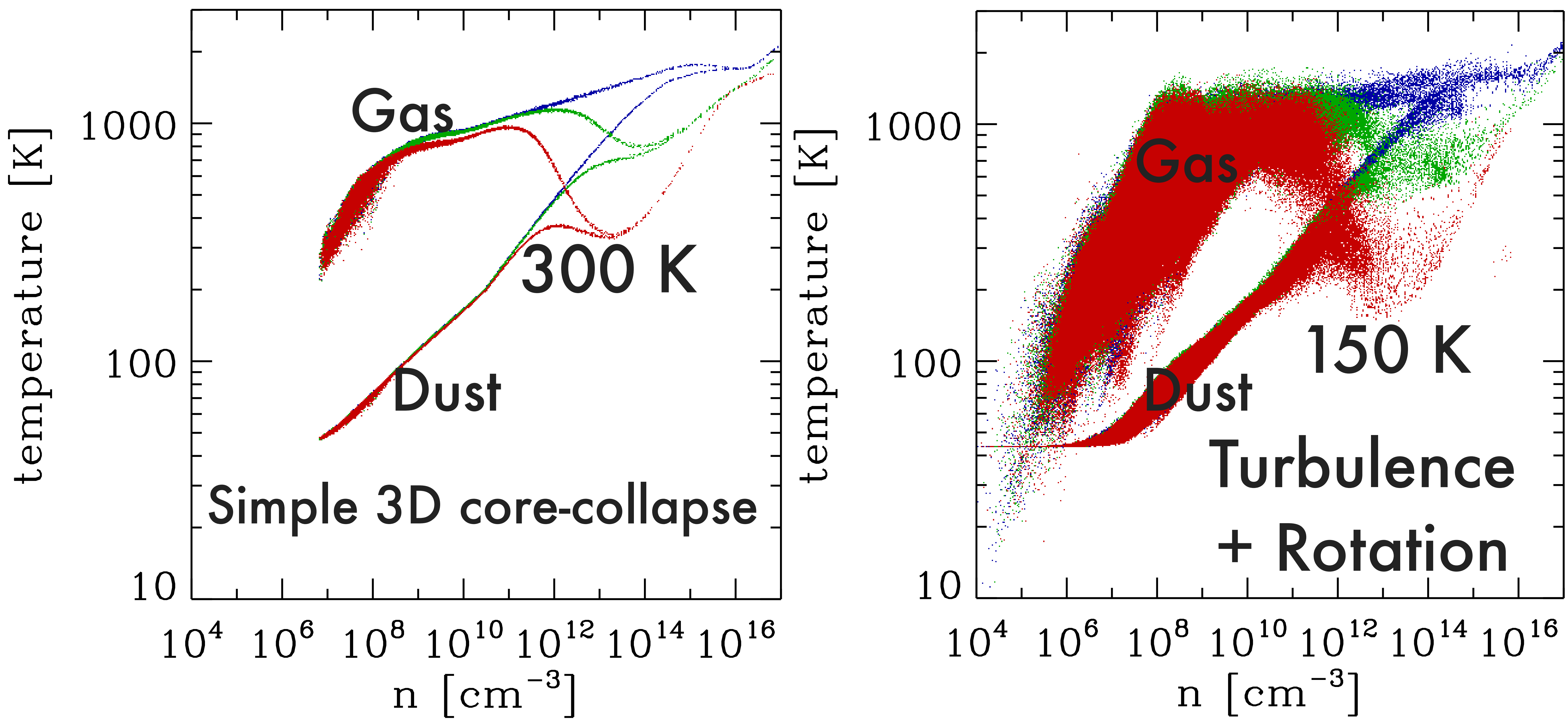


3D Simulation



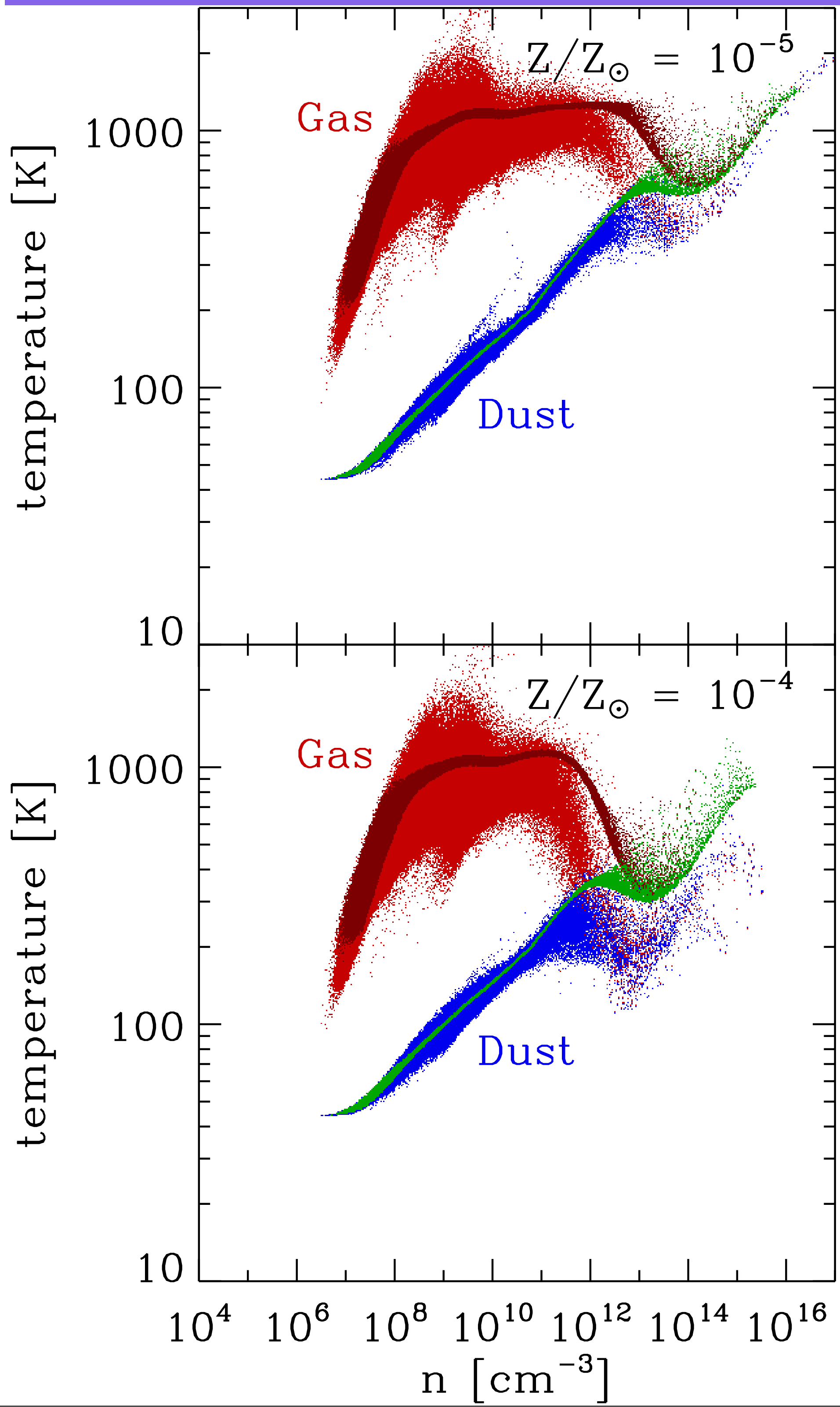


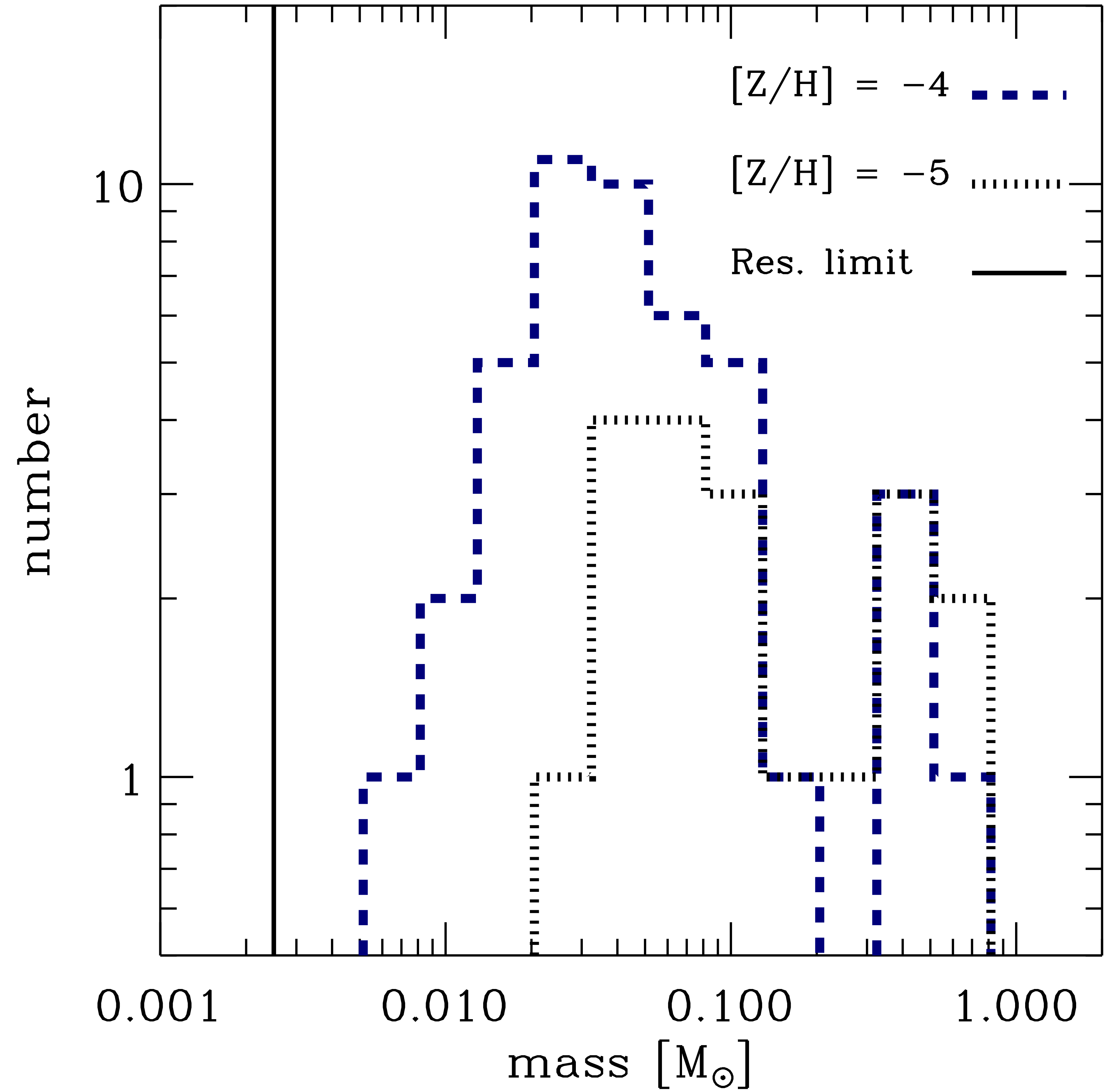
3D Simulation



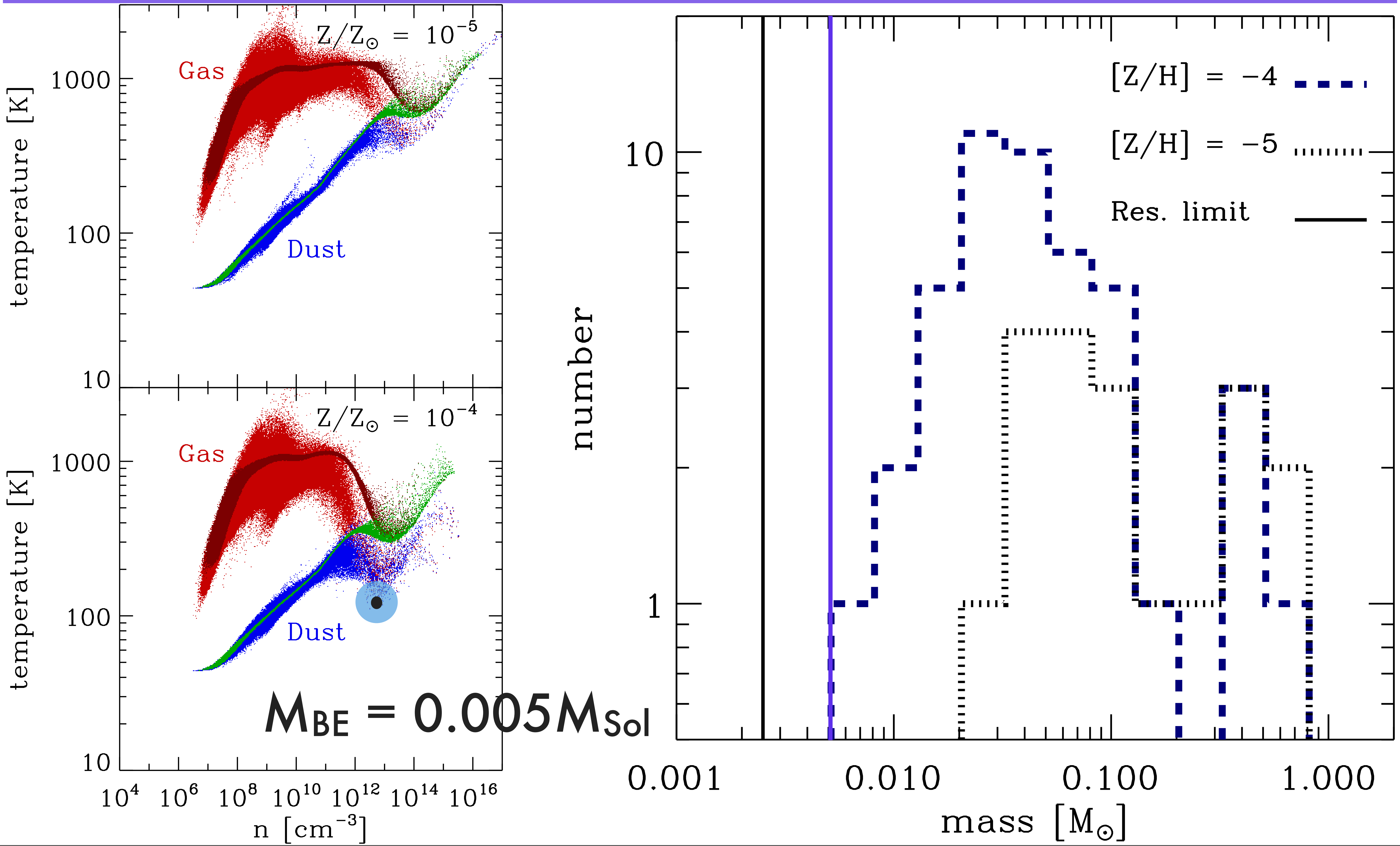
Difference due to PdV heating

Sink Mass Function



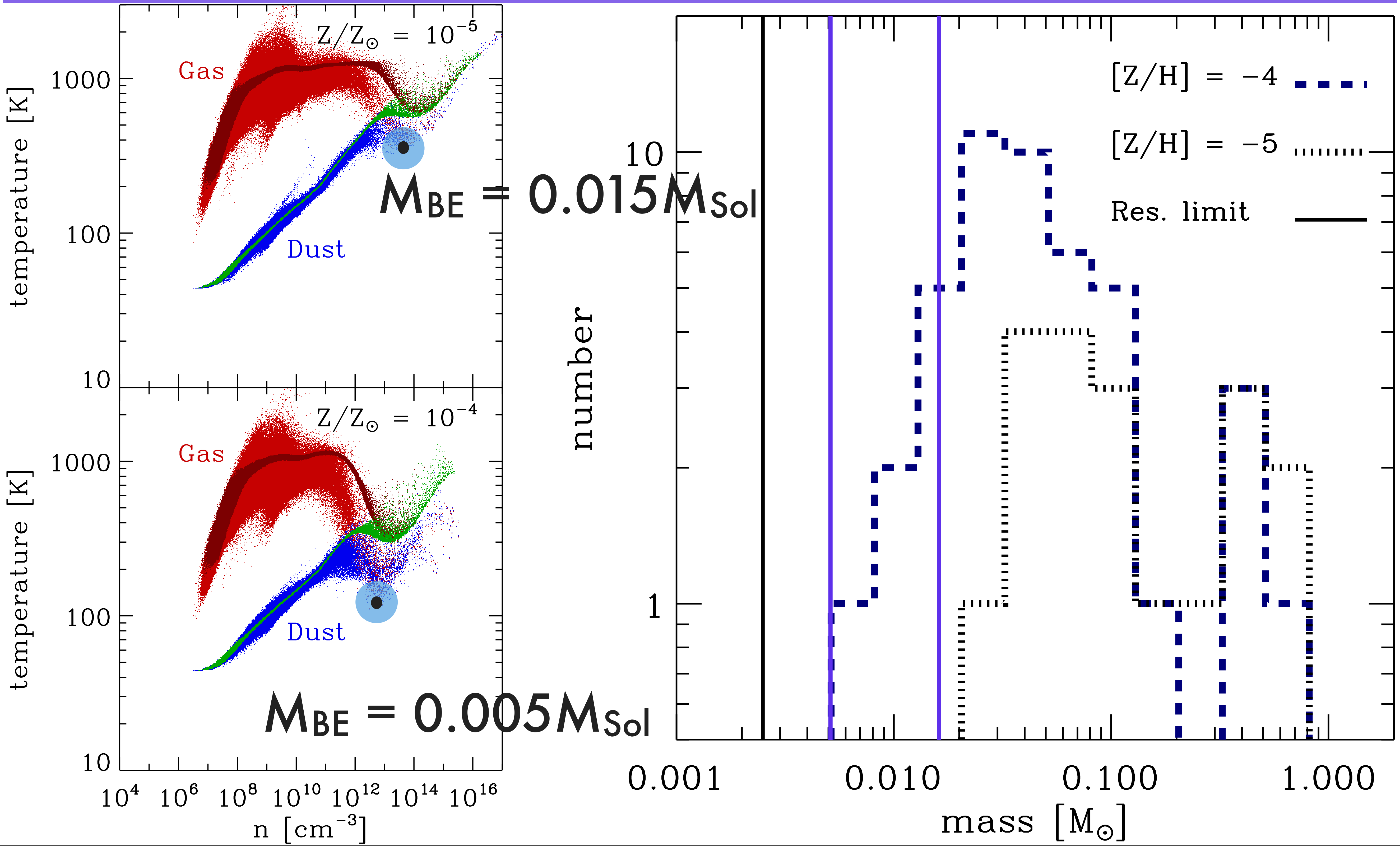


Sink Mass Function



$M_{BE} = 0.005 M_{Sol}$

Sink Mass Function

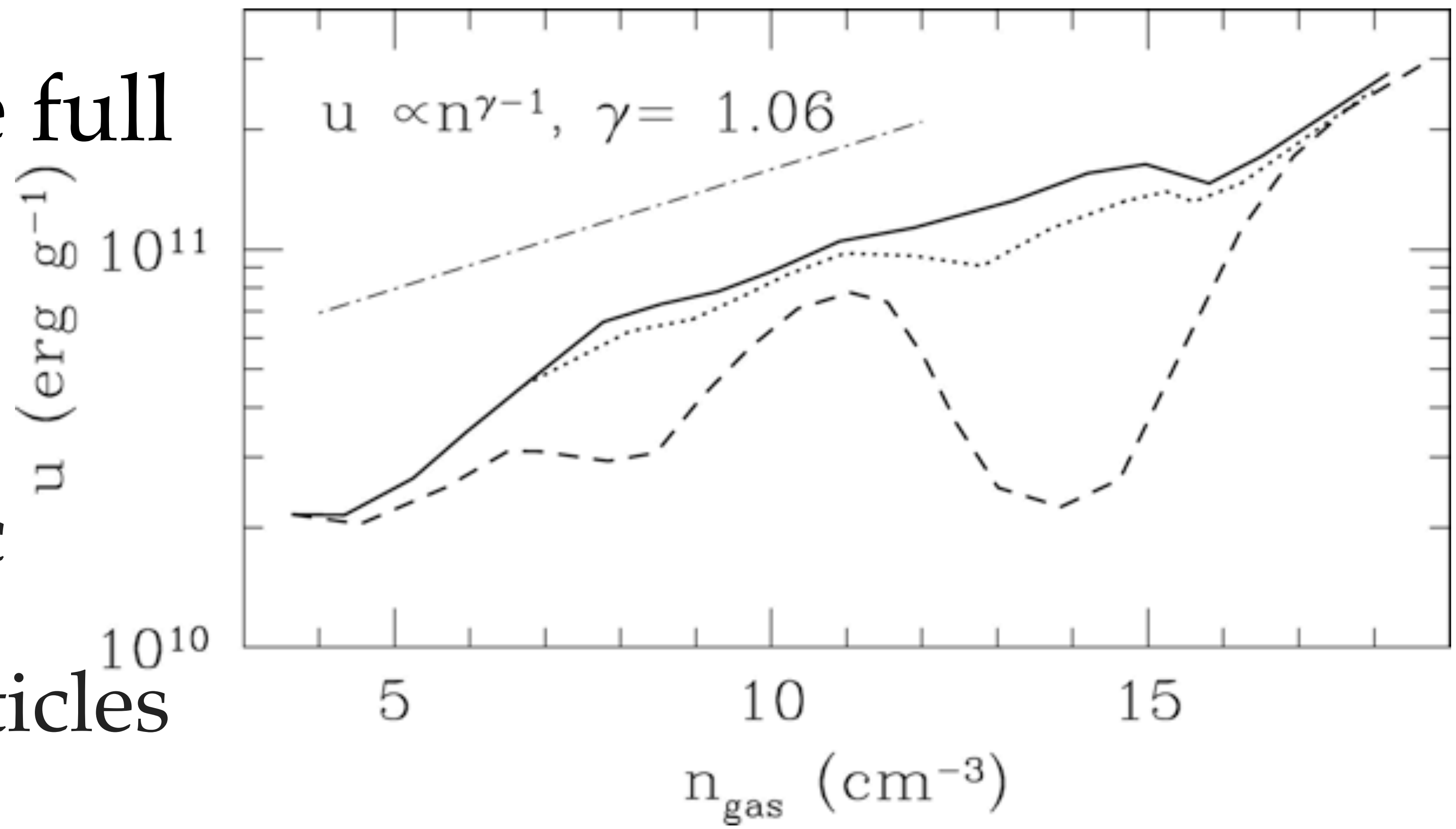


Future work

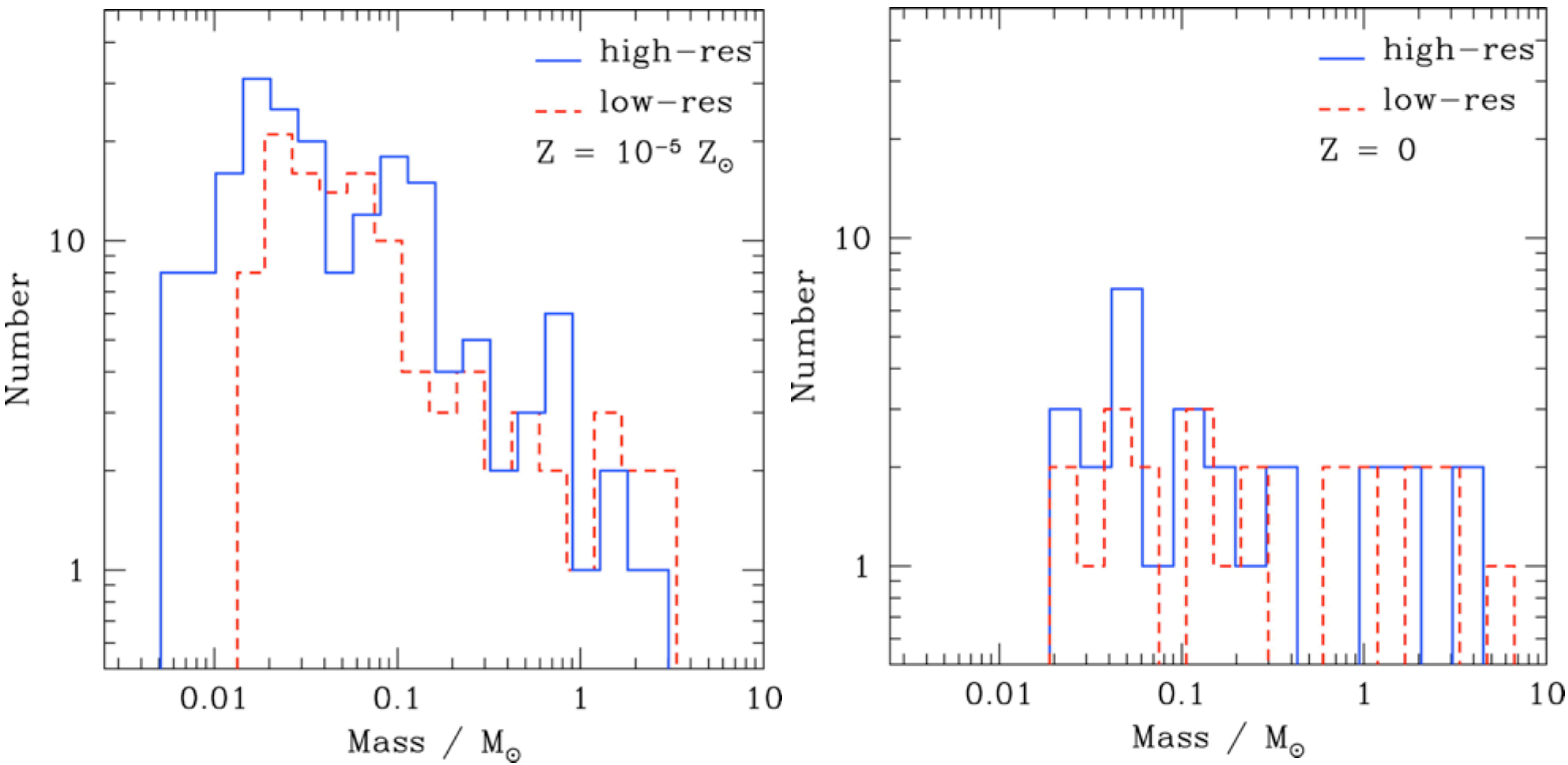
- Change dust properties
- Add accretion luminosity feedback

Clark et al. 2008

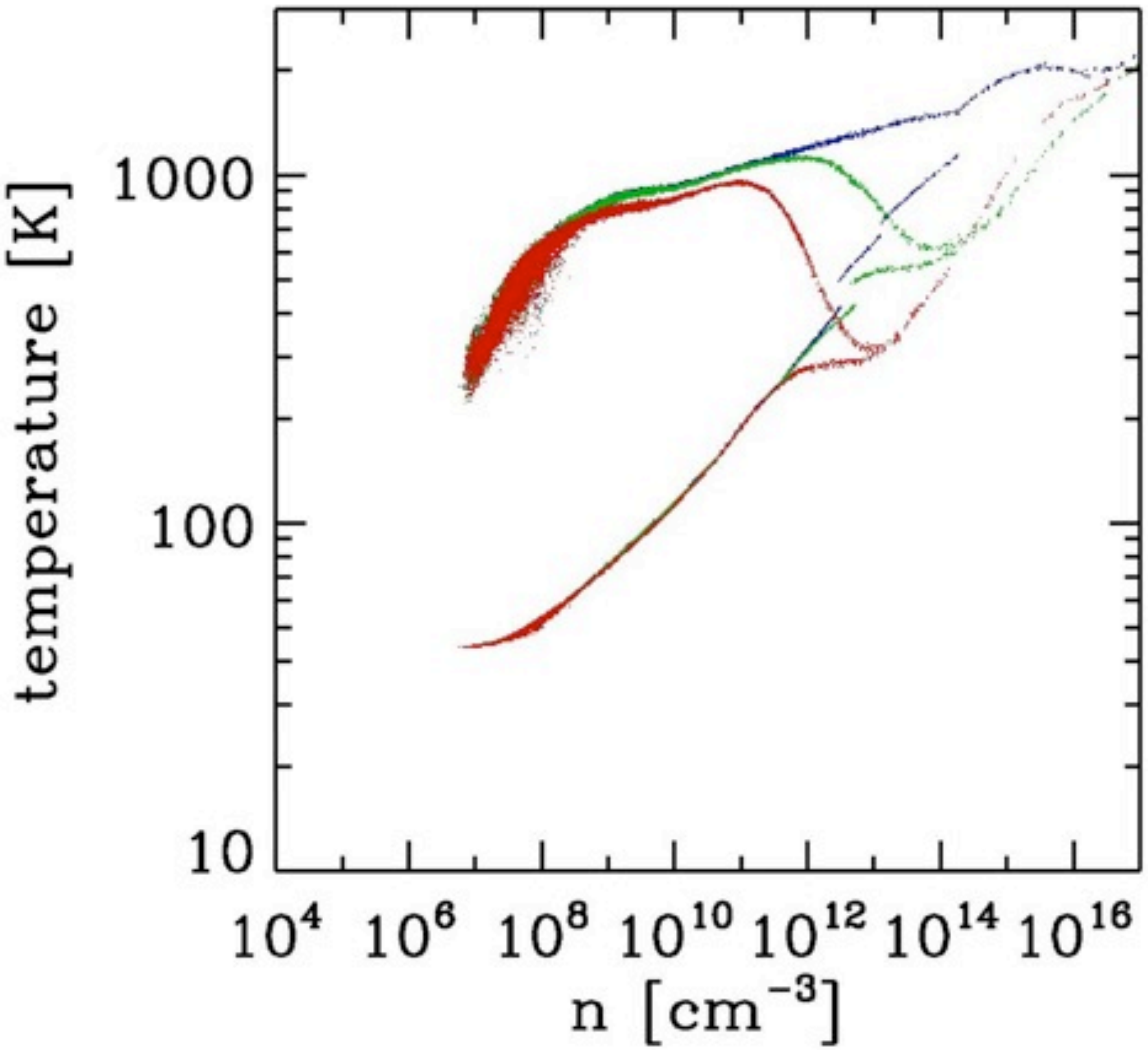
- Used a tabulated EOS
- P(n) and u(n)
- Avoid solving the full thermal energy equation
- 500 M_{sol} and 0.17 pc
- 25 million SPH particles
- Rotation and turbulence



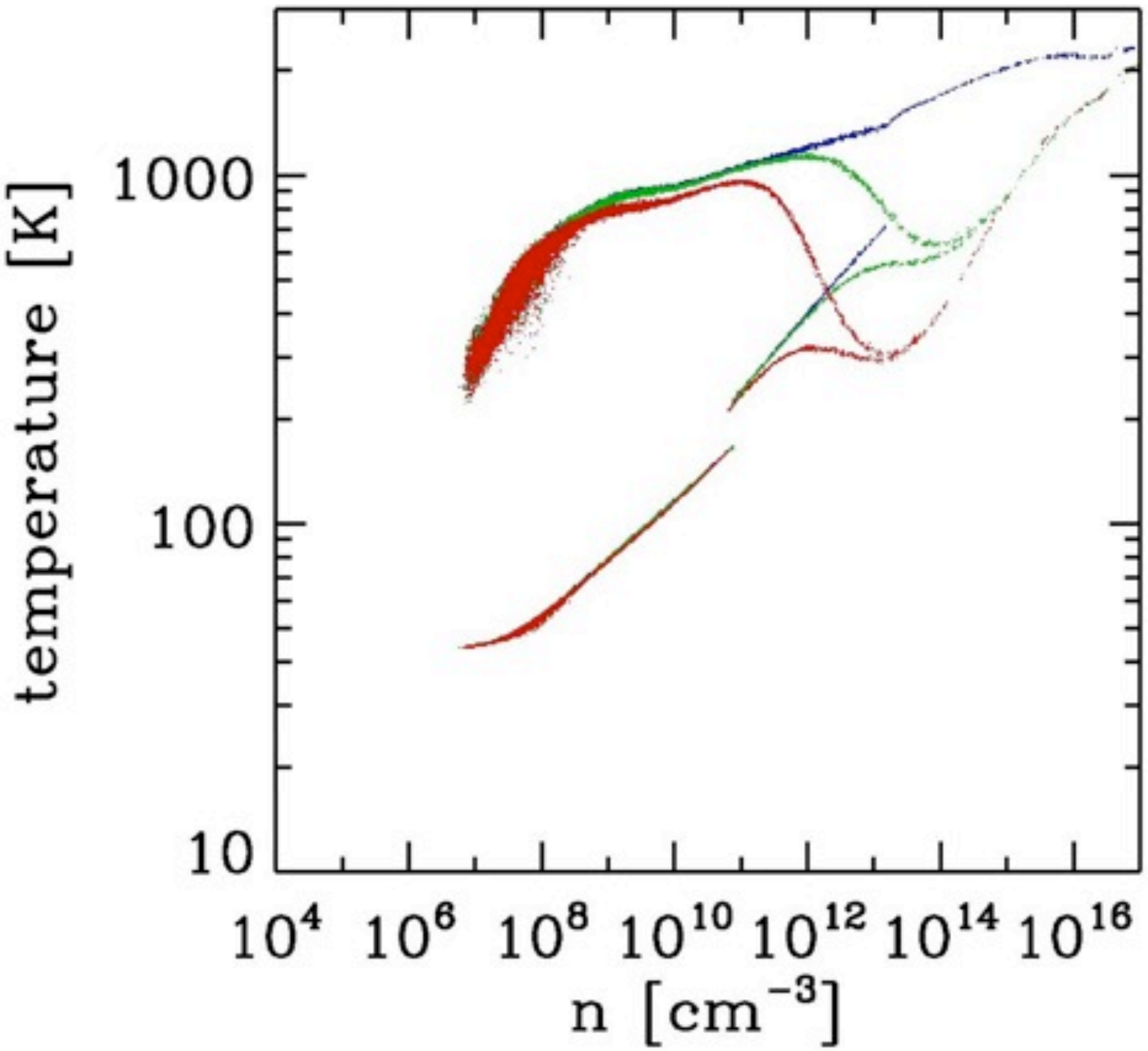
Clark et al. 2008



Different Dust Opacity Models

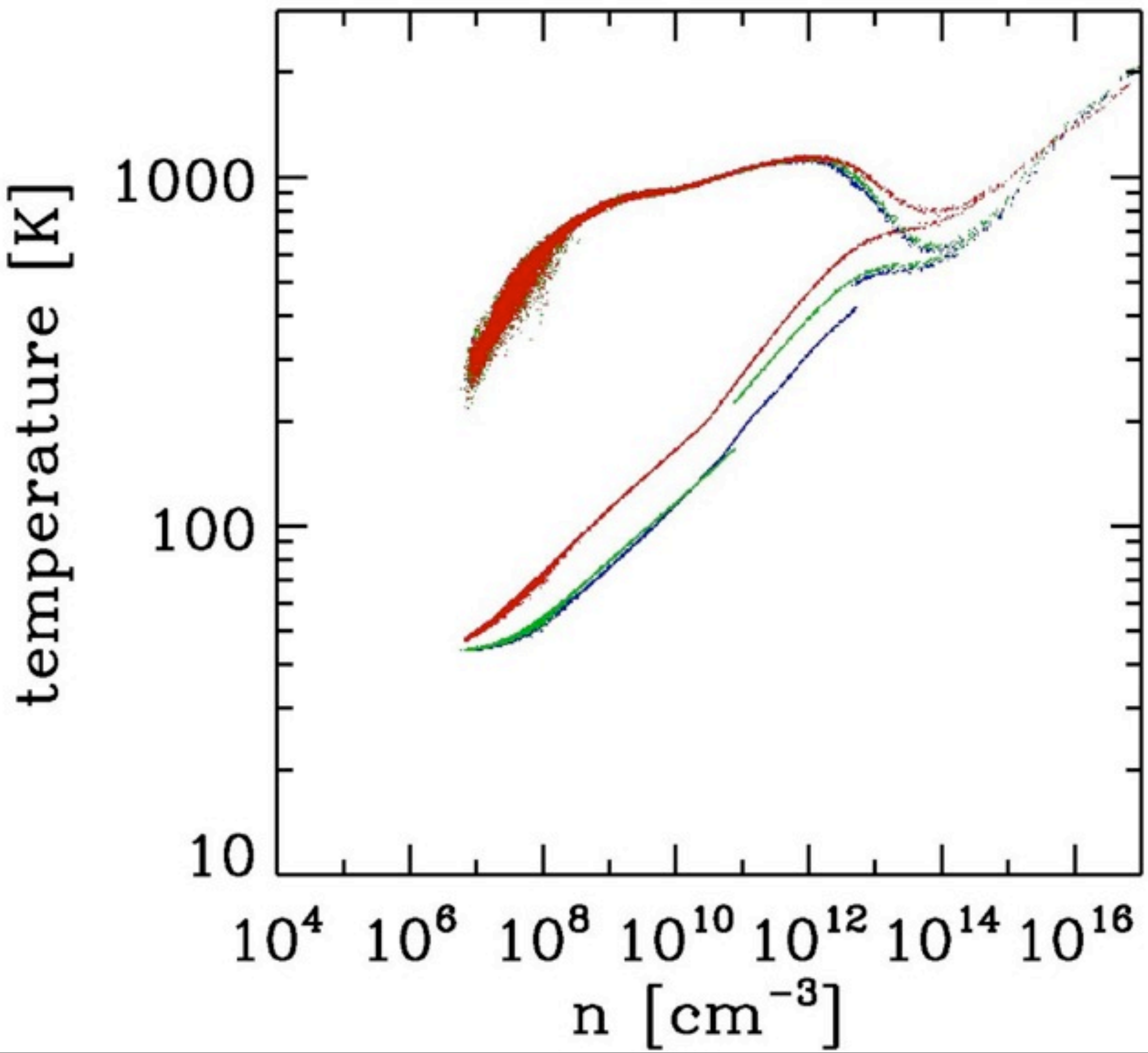


Semenov



Bell & Lin

Different Dust Opacity Models



[Z/H] = -5