Turbulence in the multi-phase ISM

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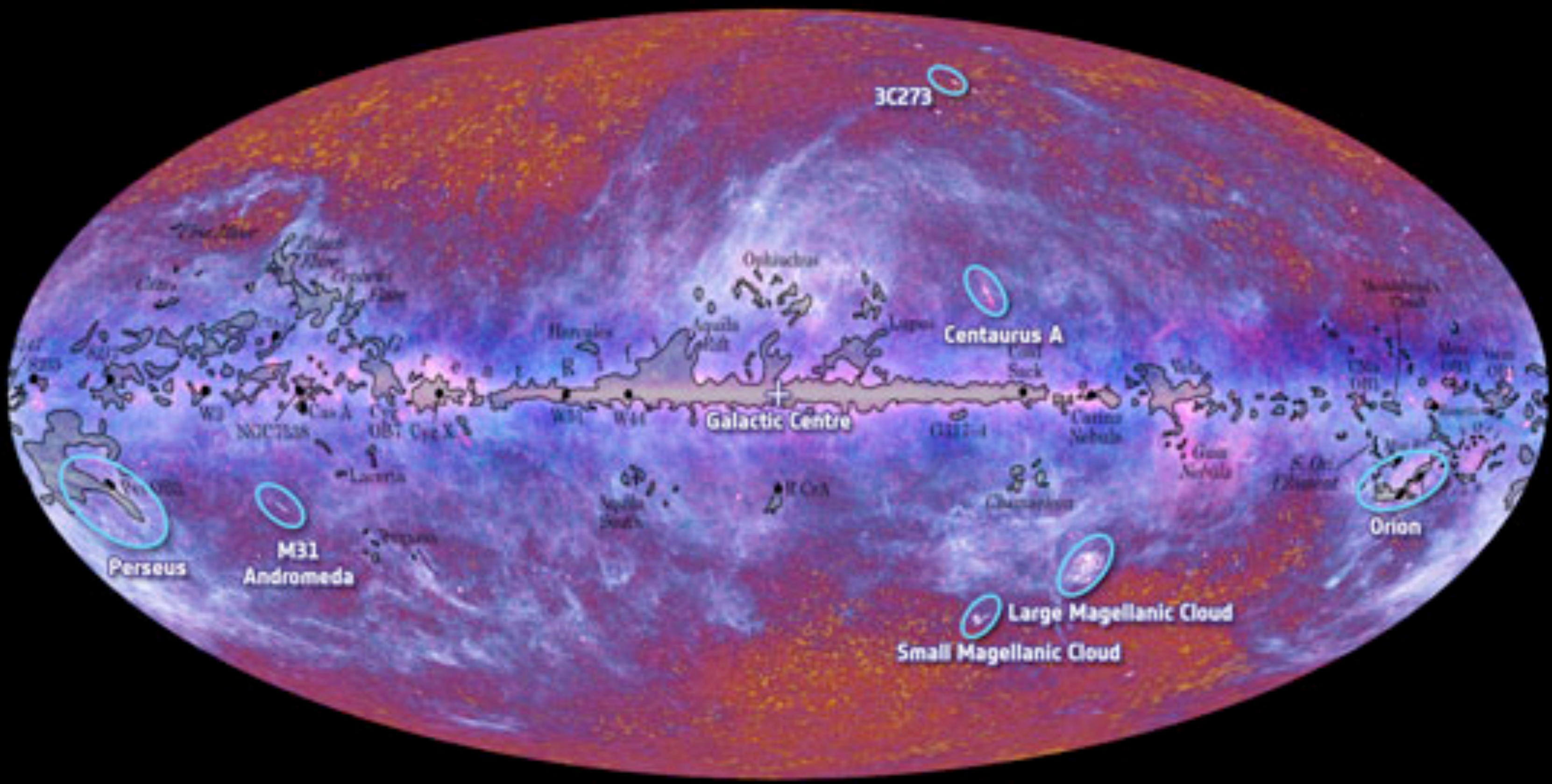
Multi-phase ISM: HI and molecular gas

superimposed: CO survey (Dame et al. 2001)



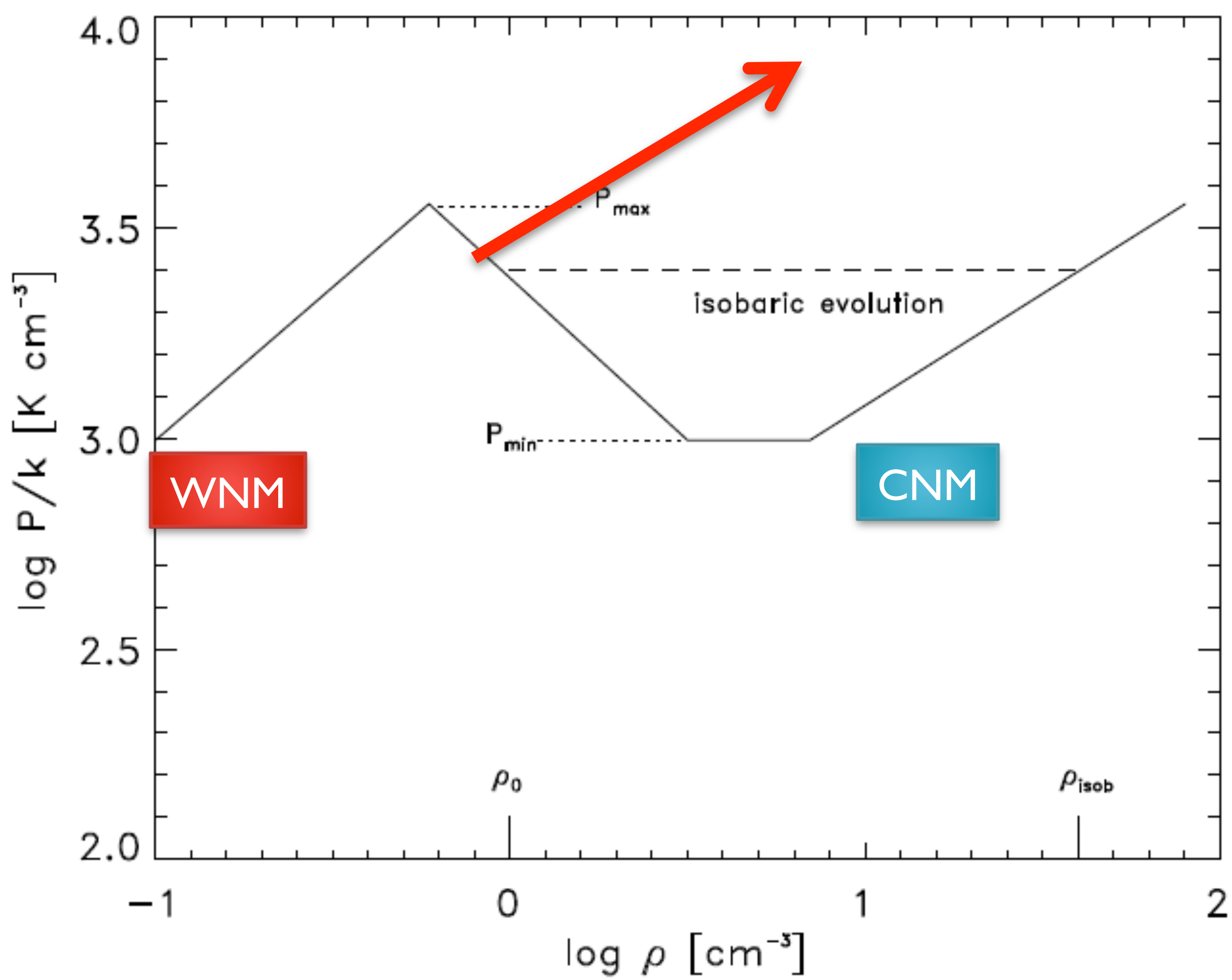
Parameters influencing the formation of cold gas

4 main parameters:

1. Density
2. Metallicity
3. Heating by background rad (UV + CR)
4. Velocity Dispersion (v_{rms})
5. Driven/Decaying turbulence?
6. Non-equilibrium chemistry?

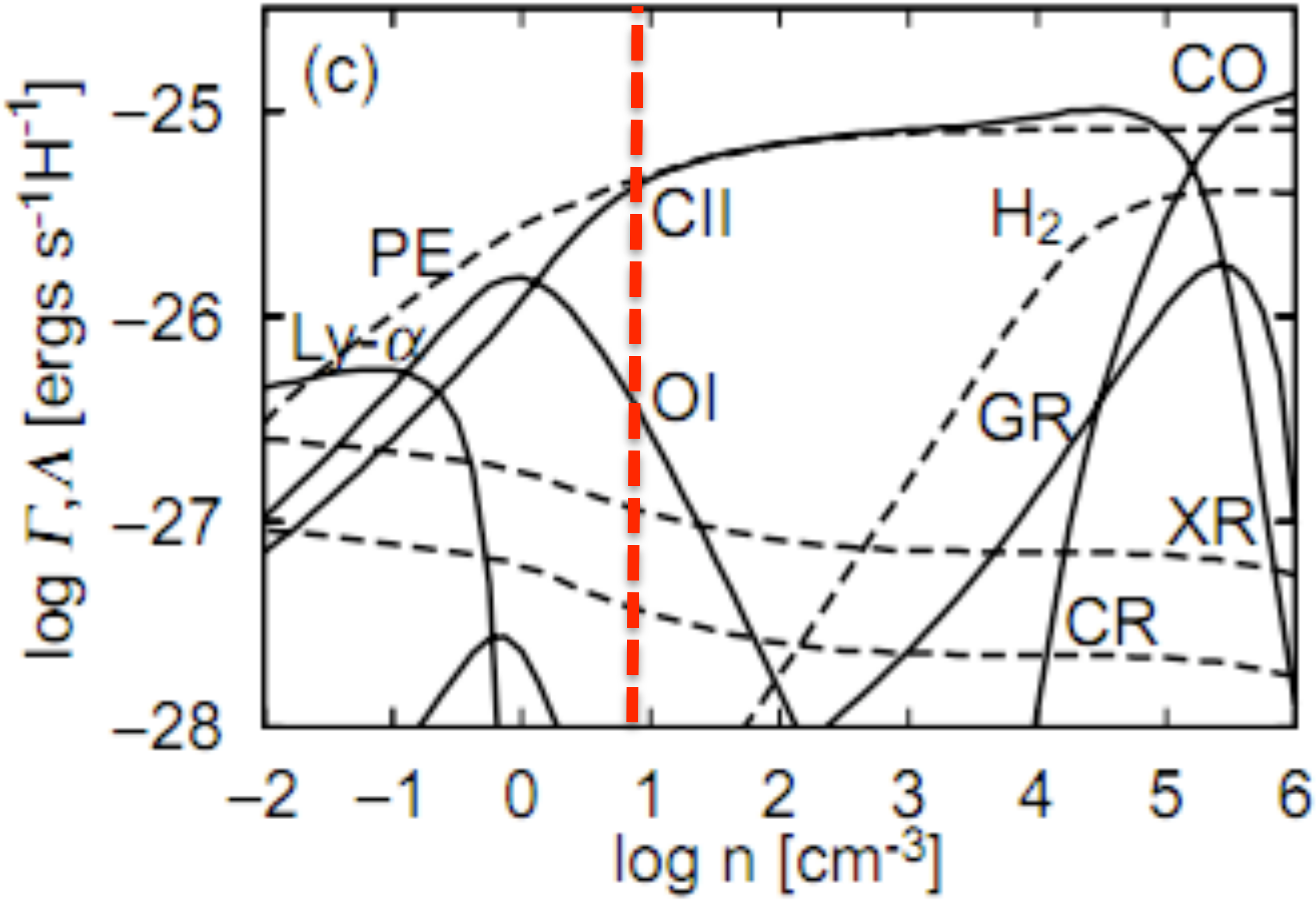
Walch et al. 2011 arXiv: 1101.2894

Multi-phase ISM



From Sanchez-Salcedo 2002

Heating & Cooling



From Koyama & Inutsuka 2000

Gas Chemistry & Implementation

- Simplified version of Glover et al. (2009):
- Only major coolants (see Wolfire 1995, 2003)
  - ➢ COOLING for (T>8000K): excitation of H, He, etc resonance lines (tabulated Sutherland & Dopita 1993) + recombination of e^- with dust (Wolfire 2003)
  - ➢ COOLING in WNM (T~ 8000K): Ly α emission from H, e^- recombination with small grains, O fine-structure emission, also Si^+; CNM (T < 300K): C^+ fine-structure emission, also O;
  - ➢ HEATING: Photoelectric emission from dust => determined by UV background, dust-to-gas ratio, e^- abundance. Also X-Rays, Cosmic Rays
- Only one additional field variable: ionisation degree (e^- abundance).
- Self-consistently follows chemical rate equations as well as radiative and compressional heating and cooling.
- Gas dynamics and gas chemistry are strongly coupled and should be solved at the same time.
- Time step for chemistry: $\Delta t_{cool}=0.3\, e/|\Lambda|$
- Subcycling where necessary.
- Glover et al. (2007a,b, 2009) are focussed on treating the formation of molecules within dense regions. Thus, they are always in a regime where the cold neutral medium dominates, and the two-phase behaviour does not occur.
- Standard solar abundances (e.g. Sembach et al. 2000):

  $X_C=1.4 \bullet 10^{-4}$; $X_O=3.2 \bullet 10^{-4}$; $X_{si}=1.5 \bullet 10^{-5}$

Gas Chemistry & Implementation in FLASH

- Equation to solve in chemically reactive flow for H and H^+:

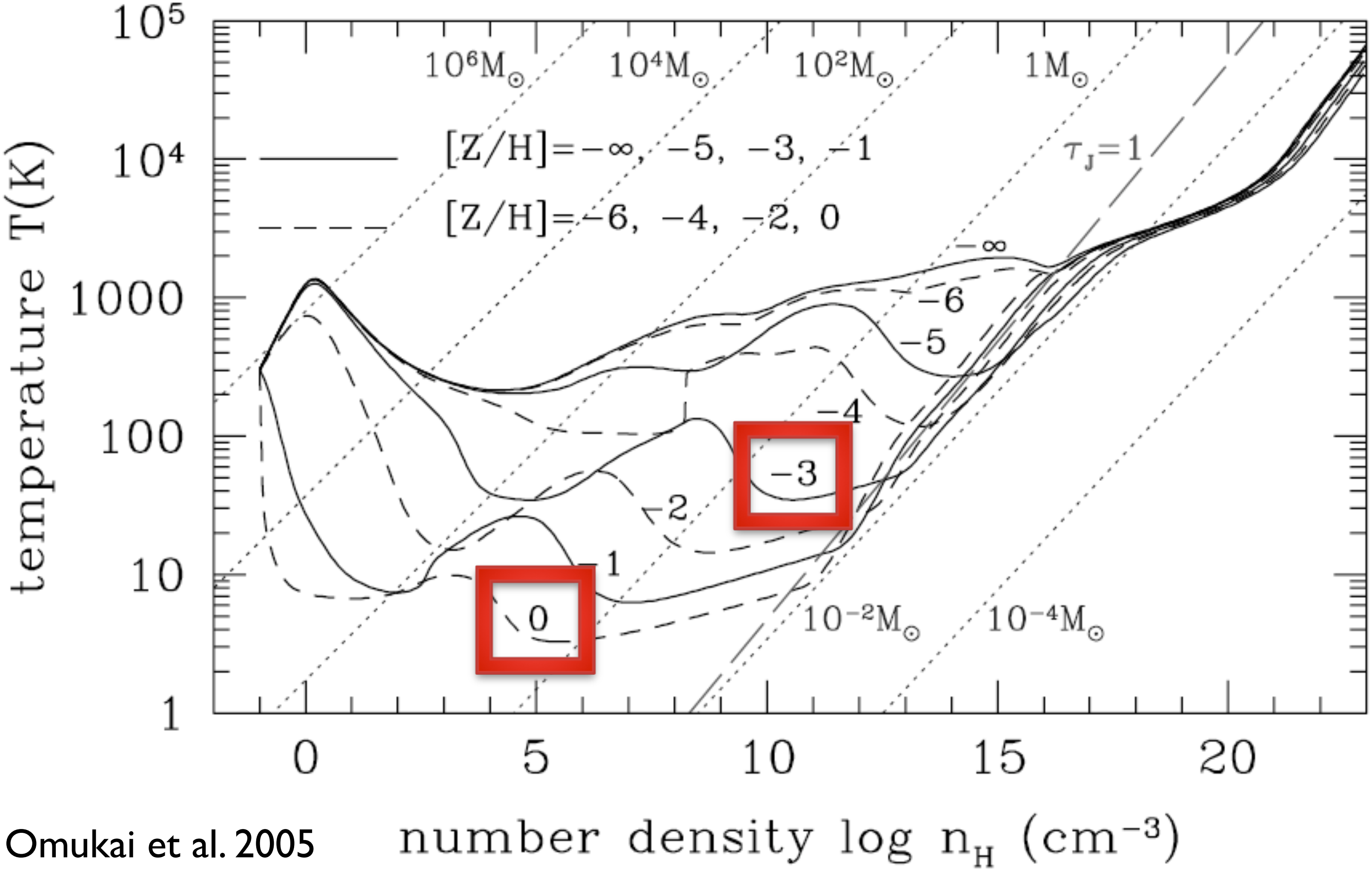
$$\frac{D\rho_i}{Dt} = -\rho_i \nabla \cdot \boldsymbol{v} + C_i - D_i,$$

- And modified energy equation:

$$\frac{\partial e}{\partial t} = -p\nabla \cdot \boldsymbol{v} - \Lambda.$$

- Solved in implicit form
- $\Lambda = \Lambda_{cool} - T_{heat}$ is net heating/cooling rate

Influence of gas metallicity



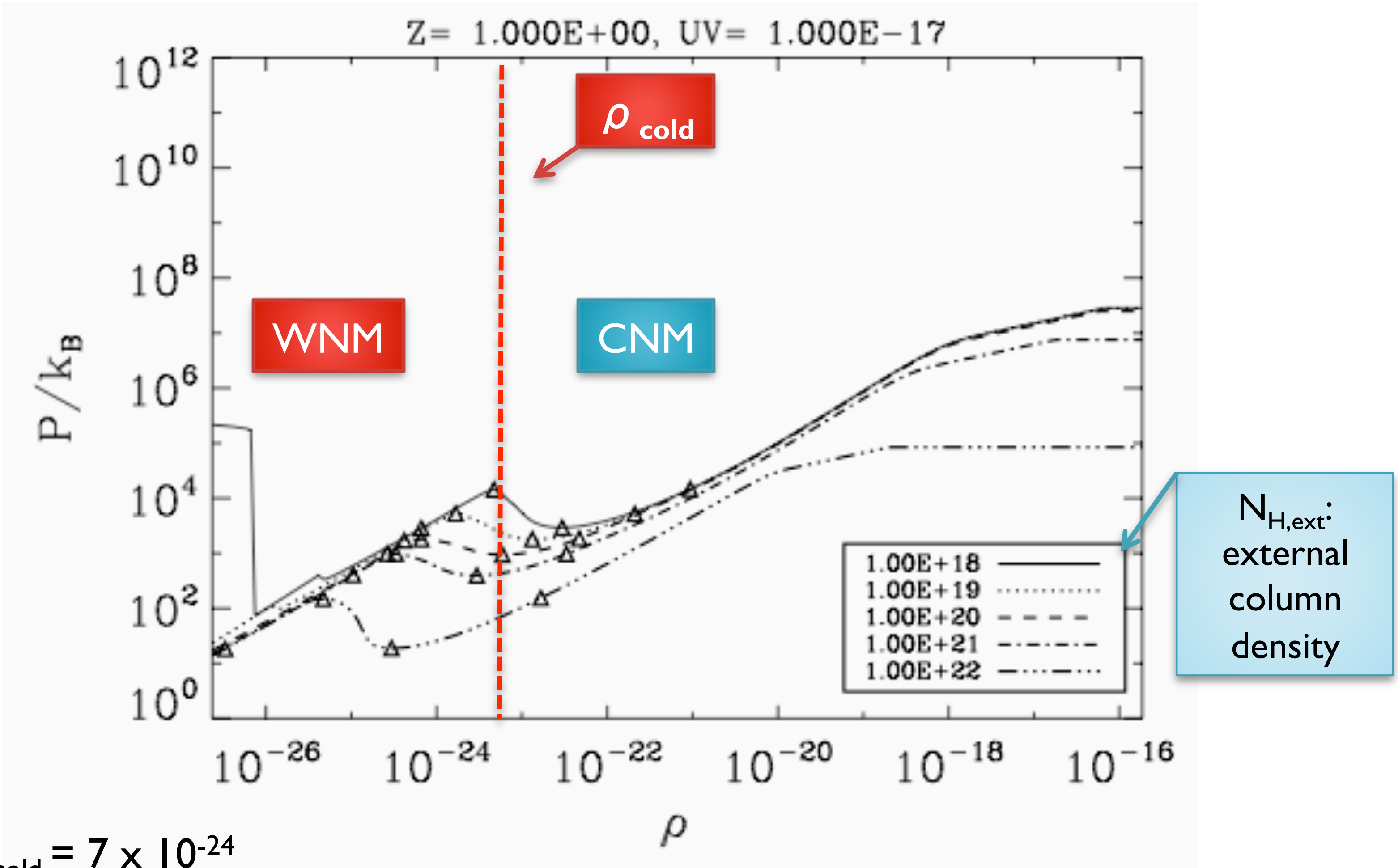
Omukai et al. 2005

Influence of gas metallicity

- Cooling function depends on metal abundance in gas
- Depending on the strength of the UV background radiation, lower gas metallicities ($< 0.01 Z_{solar}$) influence heating/cooling balance so much that development of a bi-stable phase can be fully suppressed (see semi-analytical estimates by Spaans & Carollo, 1997; Spaans & Norman, 1997, or estimates of star formation in the outer regions of galactic disks: Schaye)

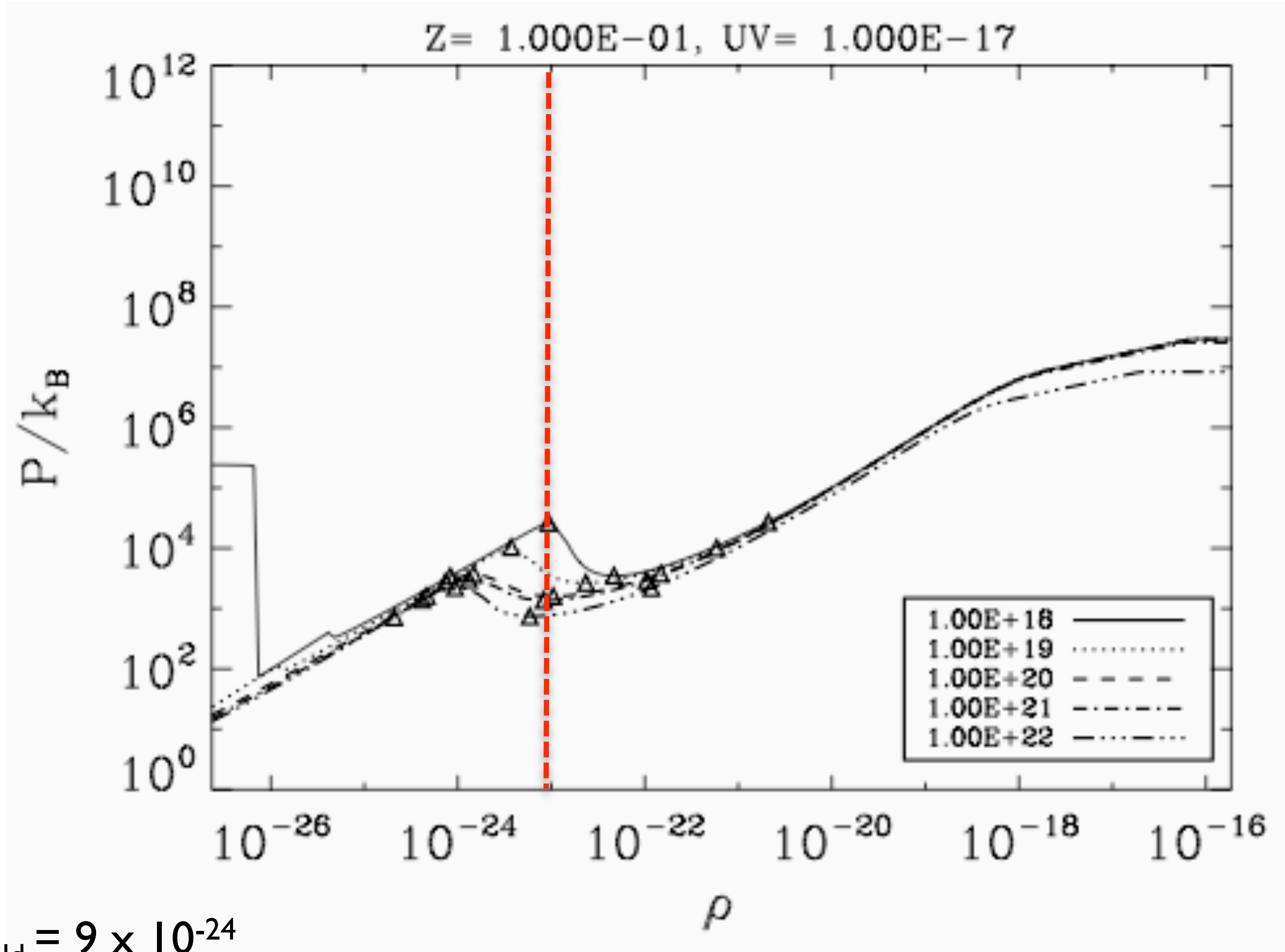
- Models of primordial star formation (Elmegreen &Klessen 2008, Myers 2011, Clarke 2010) find similar fragmentation properties & IMFs => Is metallicity important for star formation or not??

Parameters influencing the formation of cold gas



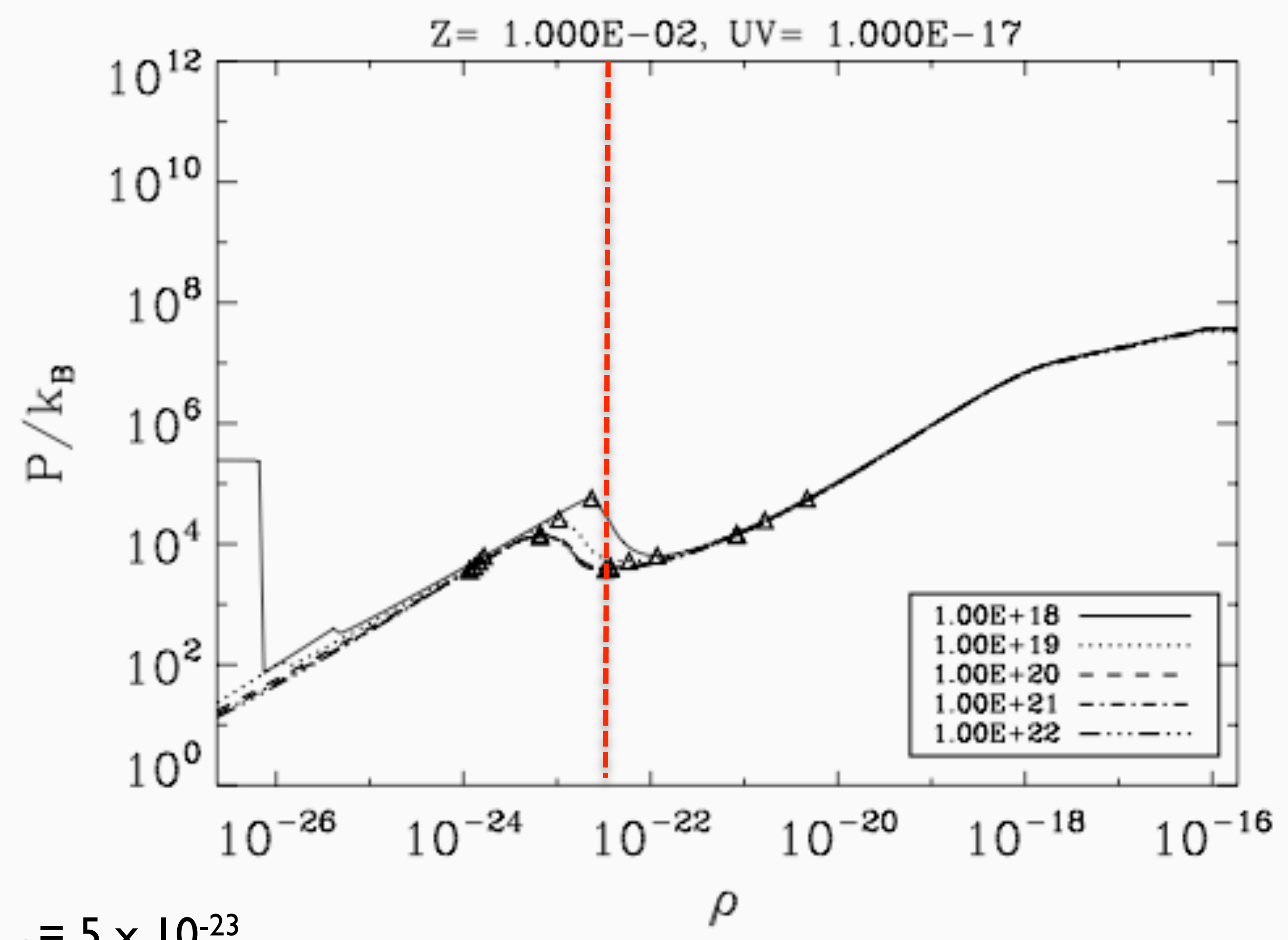
$\rho_{cold} = 7 \times 10^{-24}$

Parameters influencing the formation of cold gas



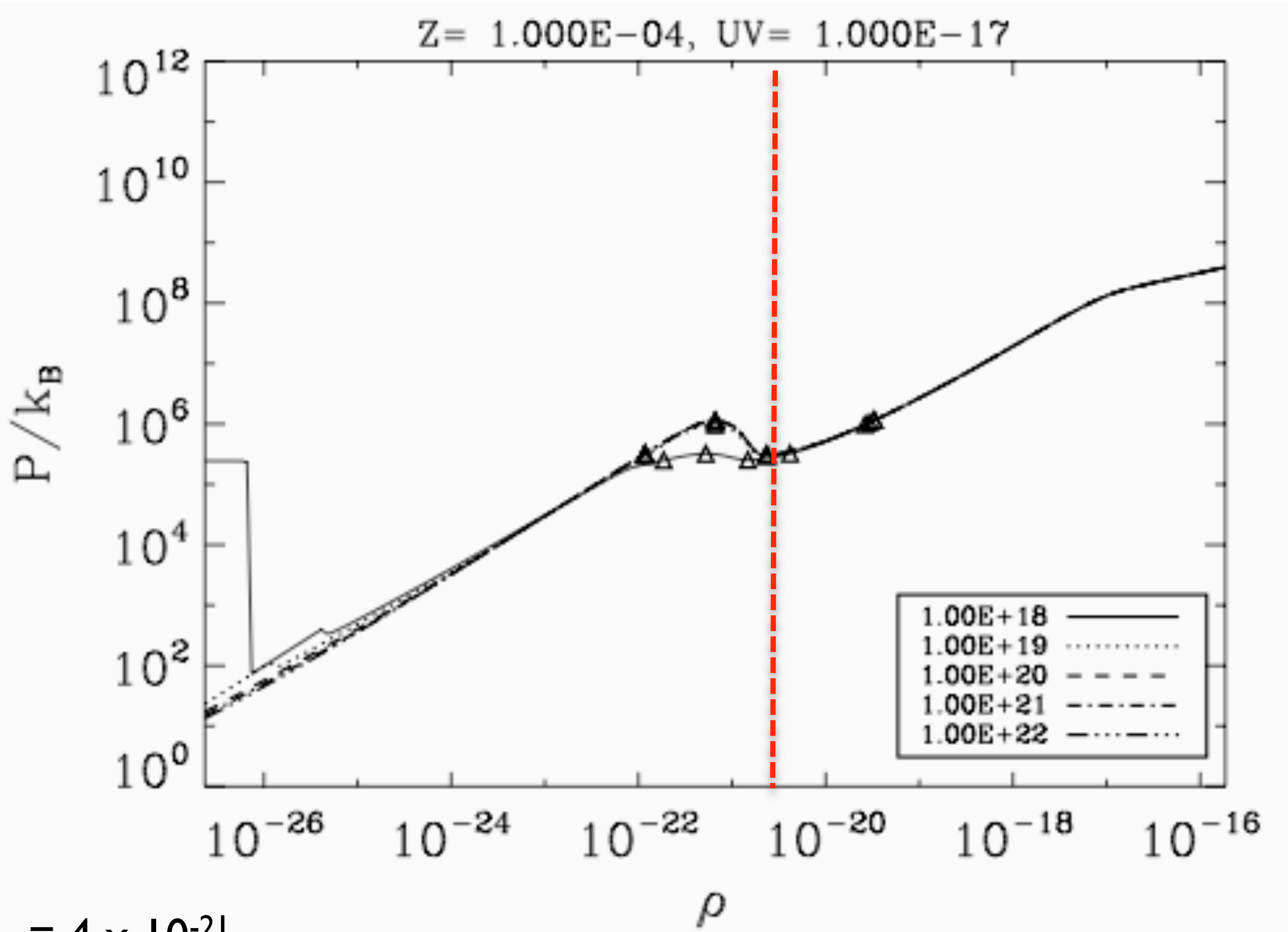
$\rho_{cold} = 9 \times 10^{-24}$

Parameters influencing the formation of cold gas



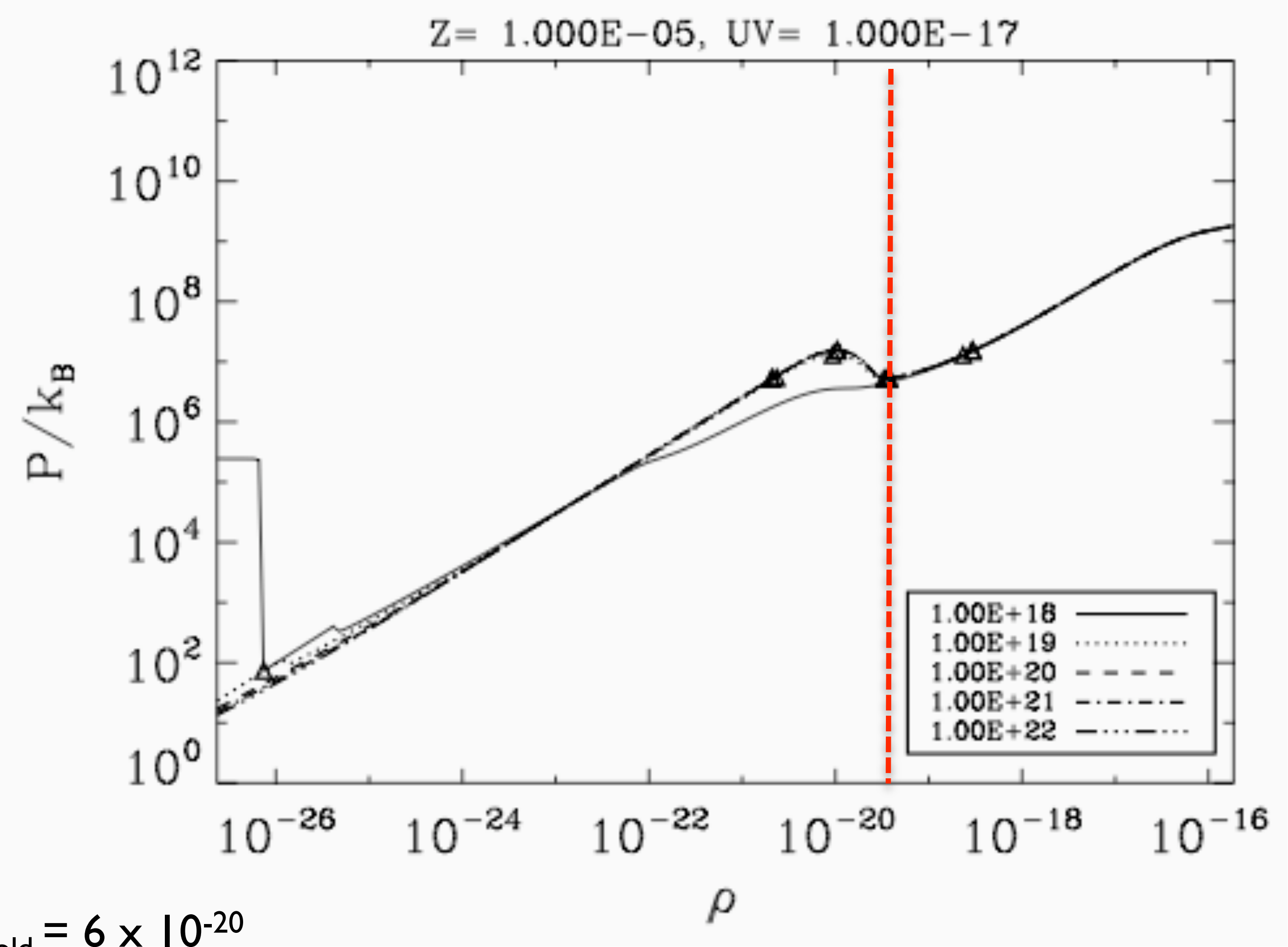
$\rho_{cold} = 5 \times 10^{-23}$

Parameters influencing the formation of cold gas



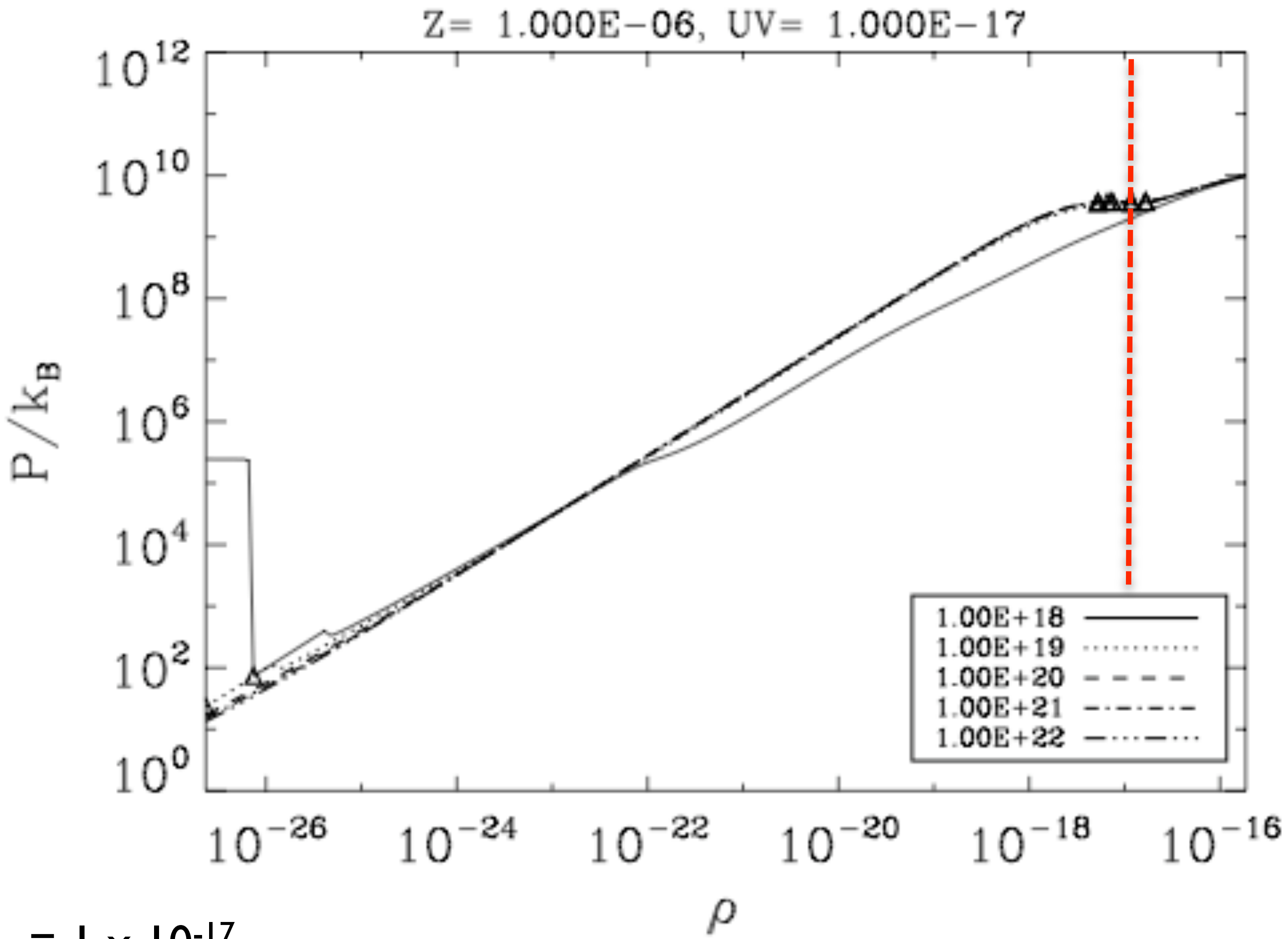
$\rho_{cold} = 4 \times 10^{-21}$

Parameters influencing the formation of cold gas



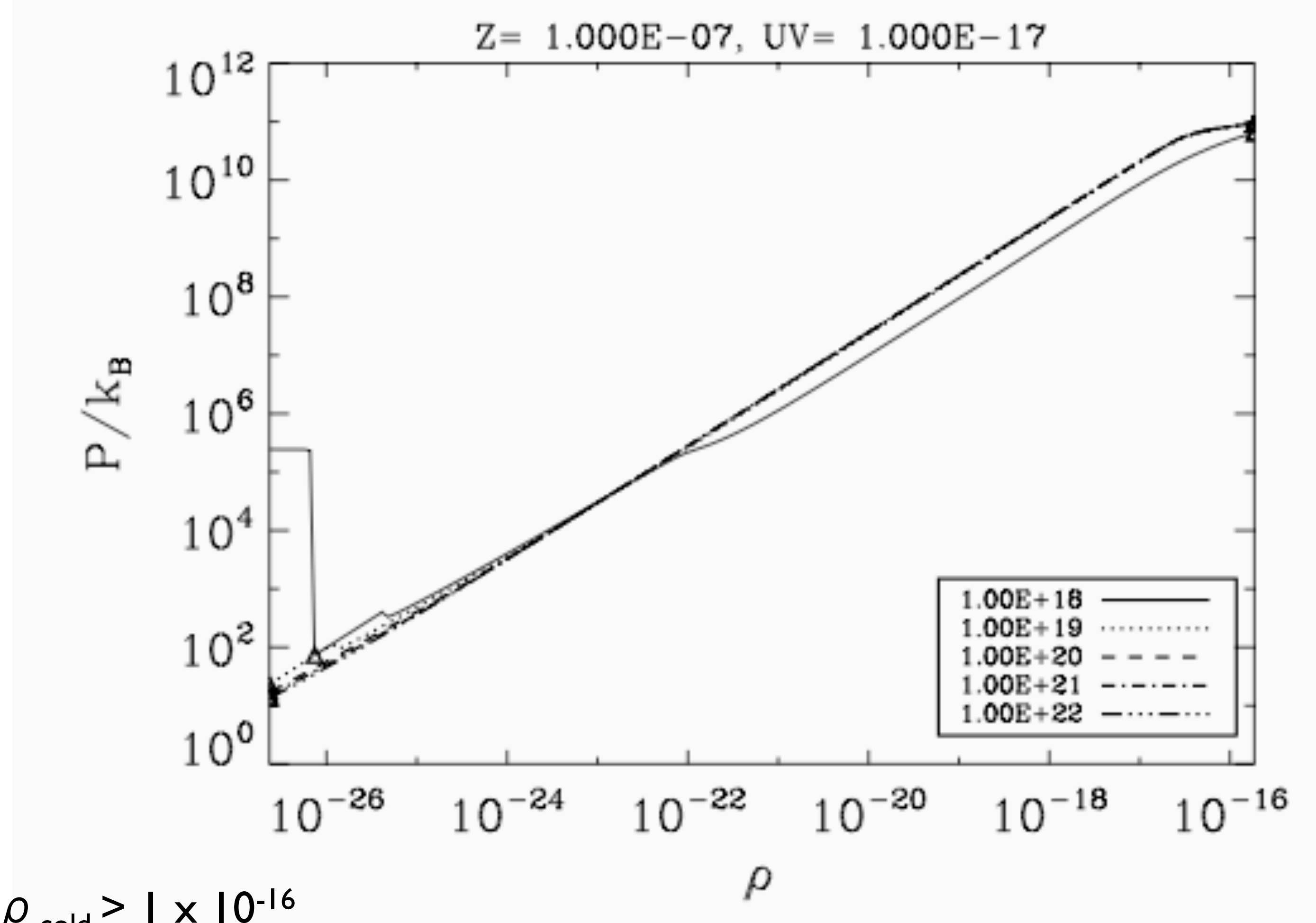
$\rho_{cold} = 6 \times 10^{-20}$

Parameters influencing the formation of cold gas



$\rho_{cold} = 1 \times 10^{-17}$

Parameters influencing the formation of cold gas



$\rho_{cold} > 1 \times 10^{-16}$

Parameters influencing the formation of cold gas

From the equilibrium curves:

- Strong influence of metallicity for $Z < 0.1\ Z_{sun}$
- Below $10^{-6}\ Z_{sun}$ the 2-phase medium might not exist because the pressure dip dissapears!
- Influence of background heating rate strong for 'high' metallicity ($Z > 10^{-2}\ Z_{sun}$):

  ρ_{cold} varies approximately by 0.5 dex per dex of $N_{H,ext}$
- We expect the formation of cold gas to strongly depend on metallicity

Introducing turbulence…

To self-consistently model the development of a two-phase medium we study simulations of driven and decaying turbulence with FLASH.

Walch et al. 2011, ApJ 733, 47, OR arXiv: 1101.2894

Multi-phase ISM (Heating & Cooling)

3 issues to address:

- Gas metallicity
- Development (turbulence and driving)
- When is non-equilibrium chemistry important?

Why is turbulence interesting?

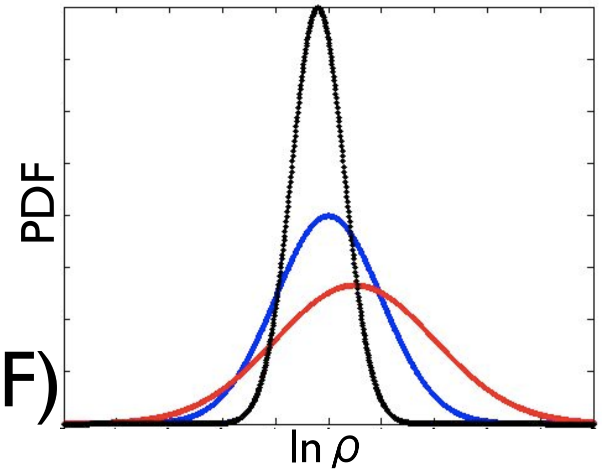
Molecular clouds are subject to supersonic turbulence.

Relationship turbulence and

⇔Width of density PDF

⇔Mass distribution of stars (IMF)

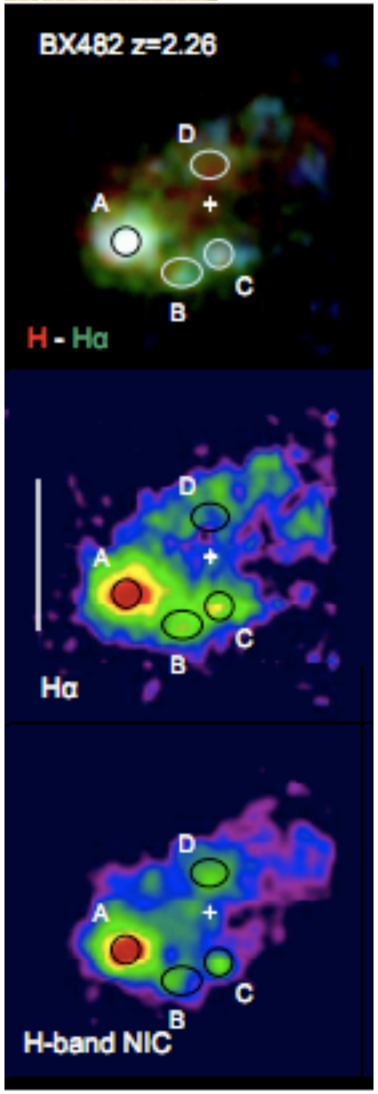
(Hennebelle & Chabrier 2008)



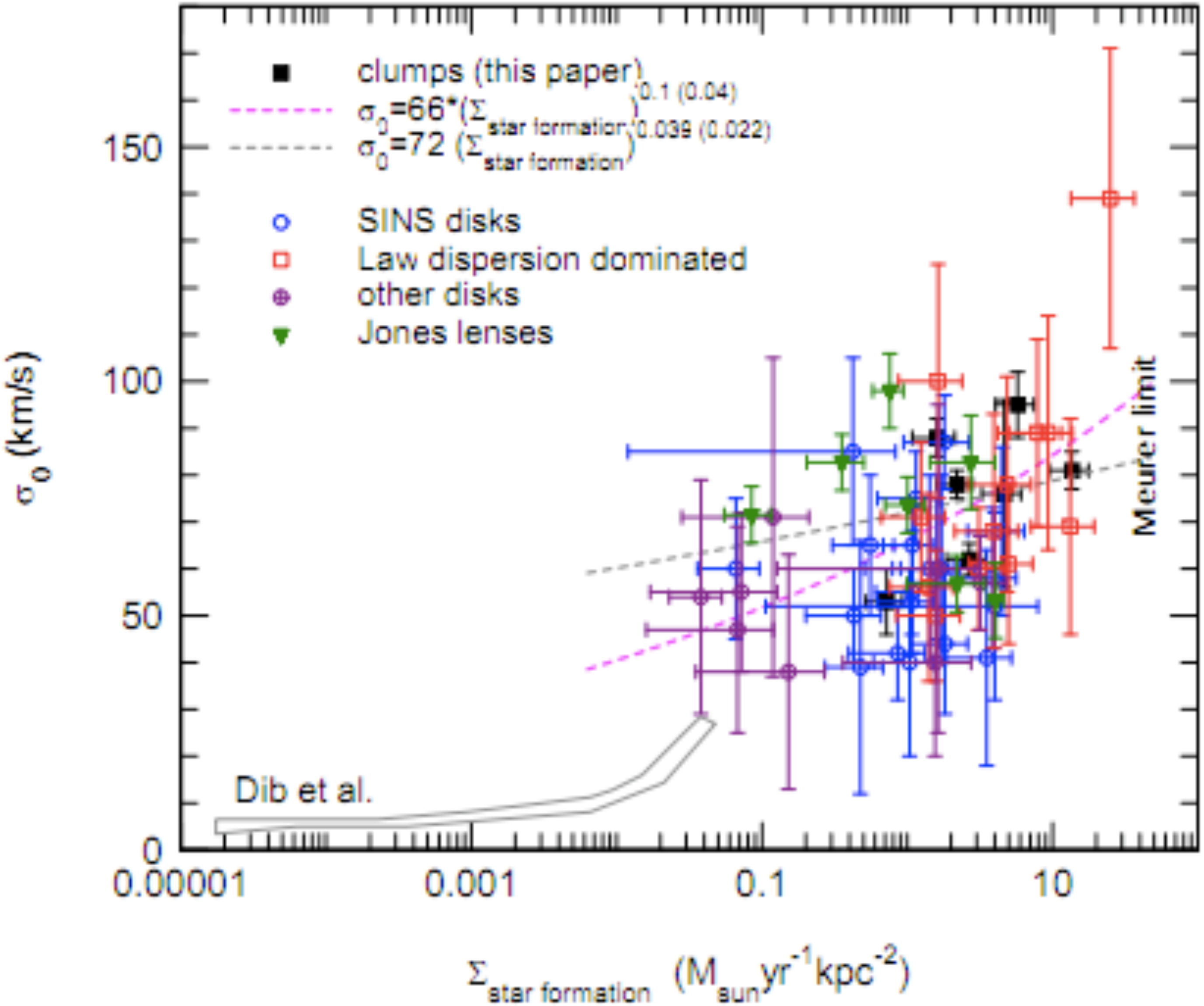
Observed velocity dispersions:

- In local galaxies: few – 10km/s
- High redshift star forming galaxies: up to 80 km/s?!

Why is turbulence interesting?



Genzel et al.

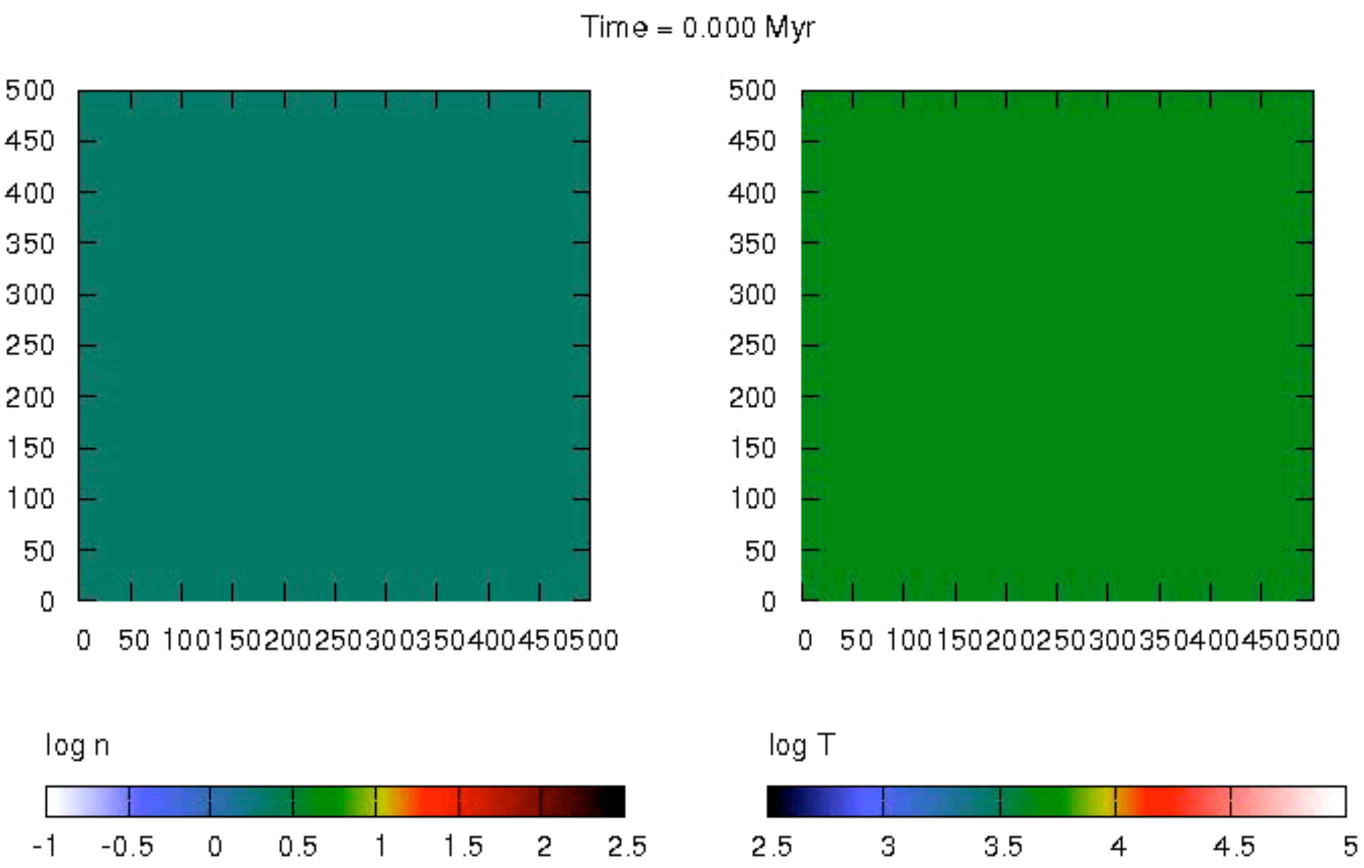


Driven Turbulence with FLASH

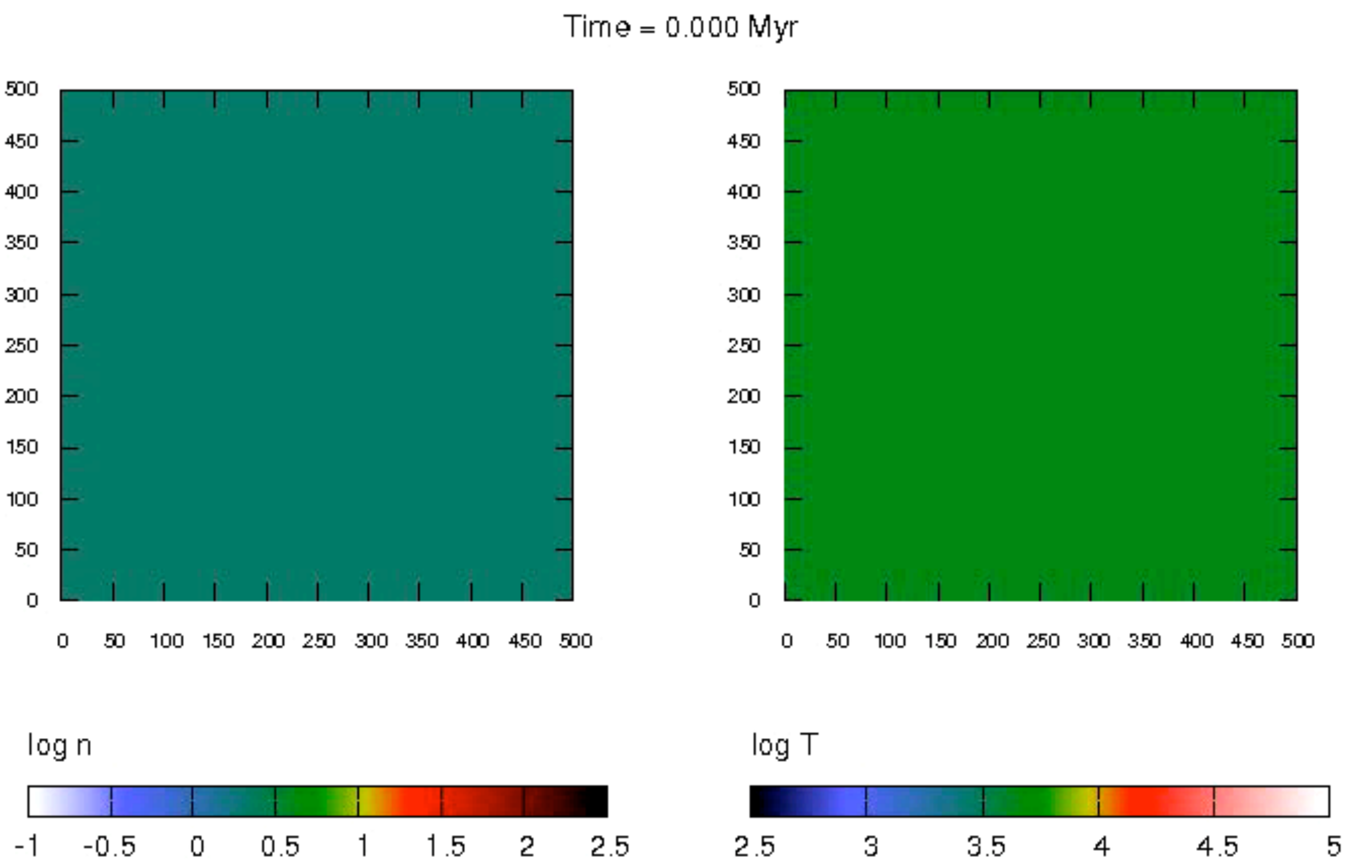
Parameters:

- Resolution = 512^3
- Box size = 500 pc
- Box mean density = 3 particles/cc
- Driving time = 50 Myr
- Driving rms velocity = 50 km/s
- Mach number = 5 for hot gas
- Driving on large scales (k=1…3)
- No imposed power law: P(k)=const
- Results at different gas metallicity:
  a) 1 Z_{solar}
  b) 10^{-3} Z_{solar}

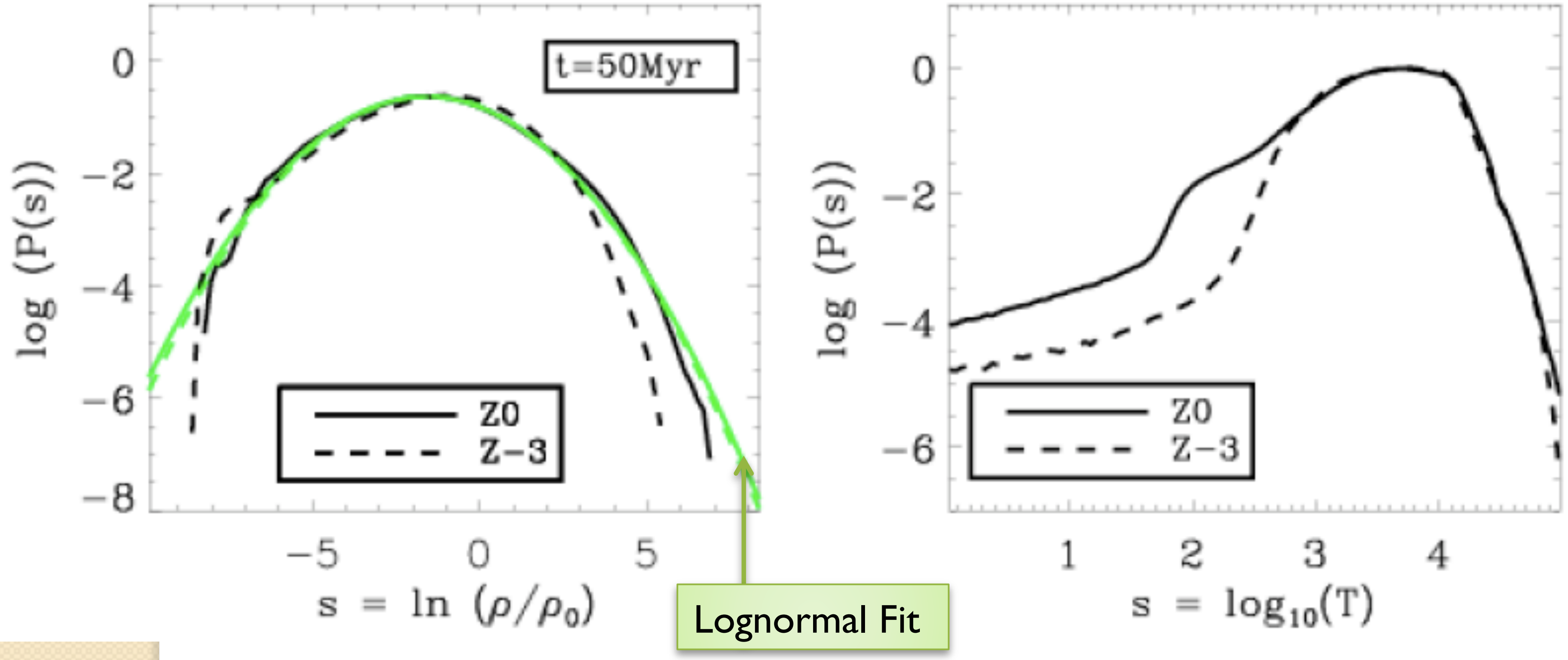
a) Solar metallicity



b) 10^{-3} Solar metallicity



Density & Temp PDFs



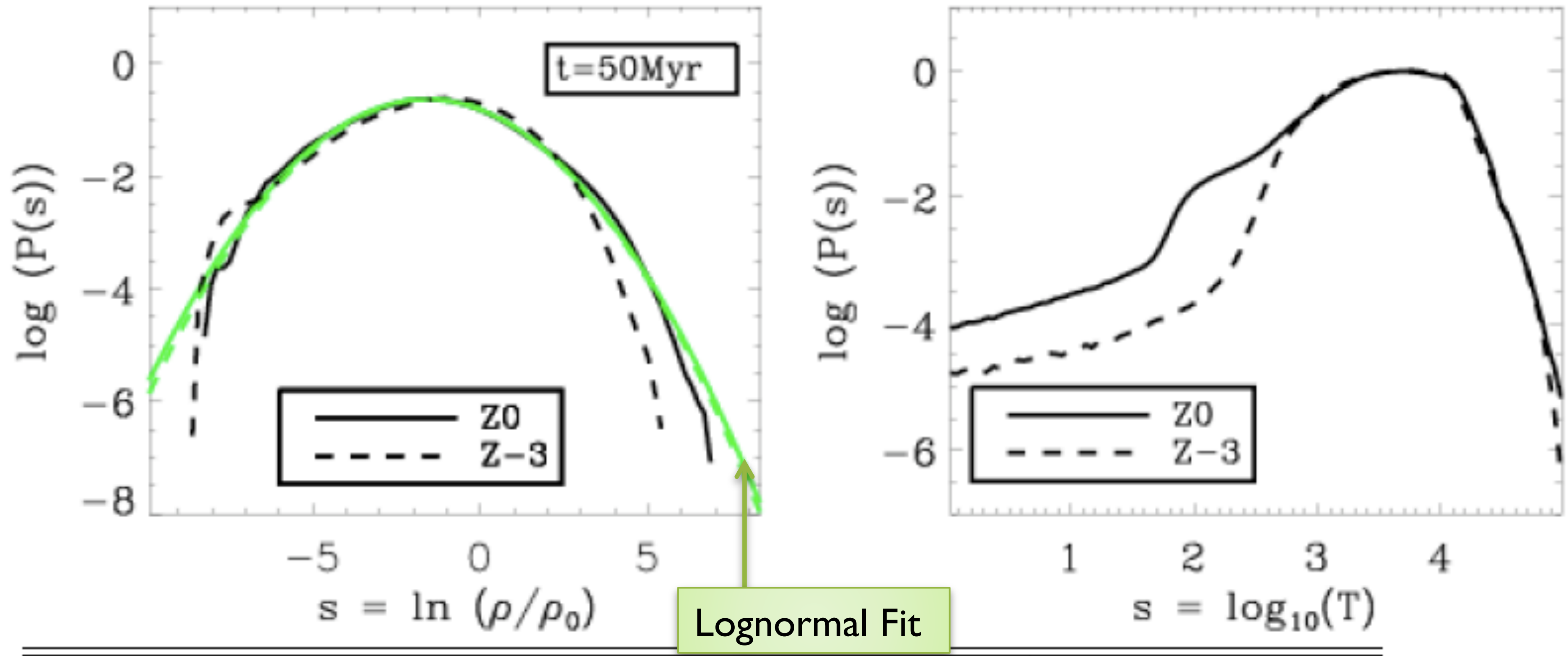
$$p(s)ds = \frac{1}{\sqrt{2\pi\sigma^2}} \exp -\frac{(s-s_0)^2}{2\sigma^2} ds.$$

Width of distribution in agreement with previous findings

$$\sigma^2 = \ln\left(1 + b^2 M^2\right)$$

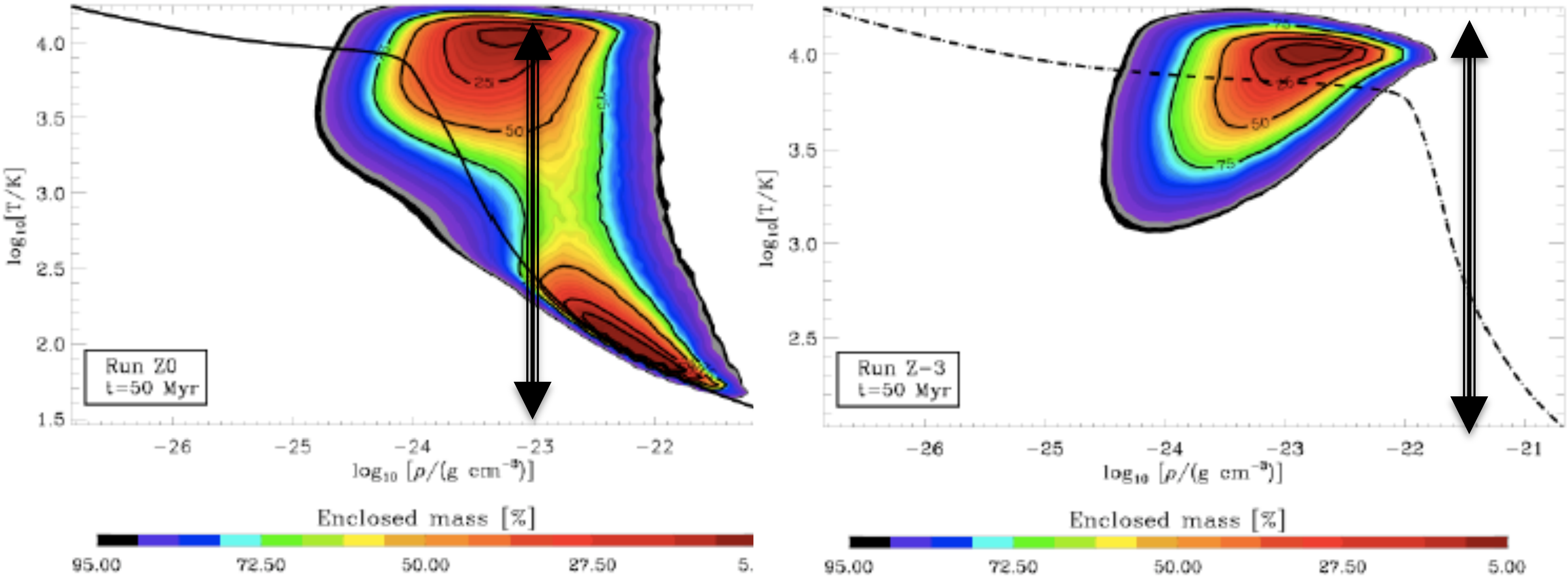
$\sigma \sim 1.7$

Density & Temp PDFs



Run	time [Myr]	Max [g cm^{-3}]	Mean warm [g cm^{-3}]	Mean cold [g cm^{-3}]	Fit $\rho(s_0)$	Fit σ
Z0	50	2.4×10^{-21}	1.65×10^{-24}	3.35×10^{-23}	4.4×10^{-25}	1.73
Z-3	50	3.2×10^{-22}	2.07×10^{-24}	7.33×10^{-25}	4.6×10^{-25}	1.70
Z0	100	1.0×10^{-21}	5.83×10[illegible]	1.22×10[illegible]	6.3×10^{-25}	0.22
					8.2×10^{-24}	0.93
Z-3	100	1.2×10^{-23}	9.27×10^{-25}	–	1.9×10^{-24}	0.31

Mass distribution in T- ρ -plane



Contours denote percentage of enclosed mass at a certain T- ρ -level

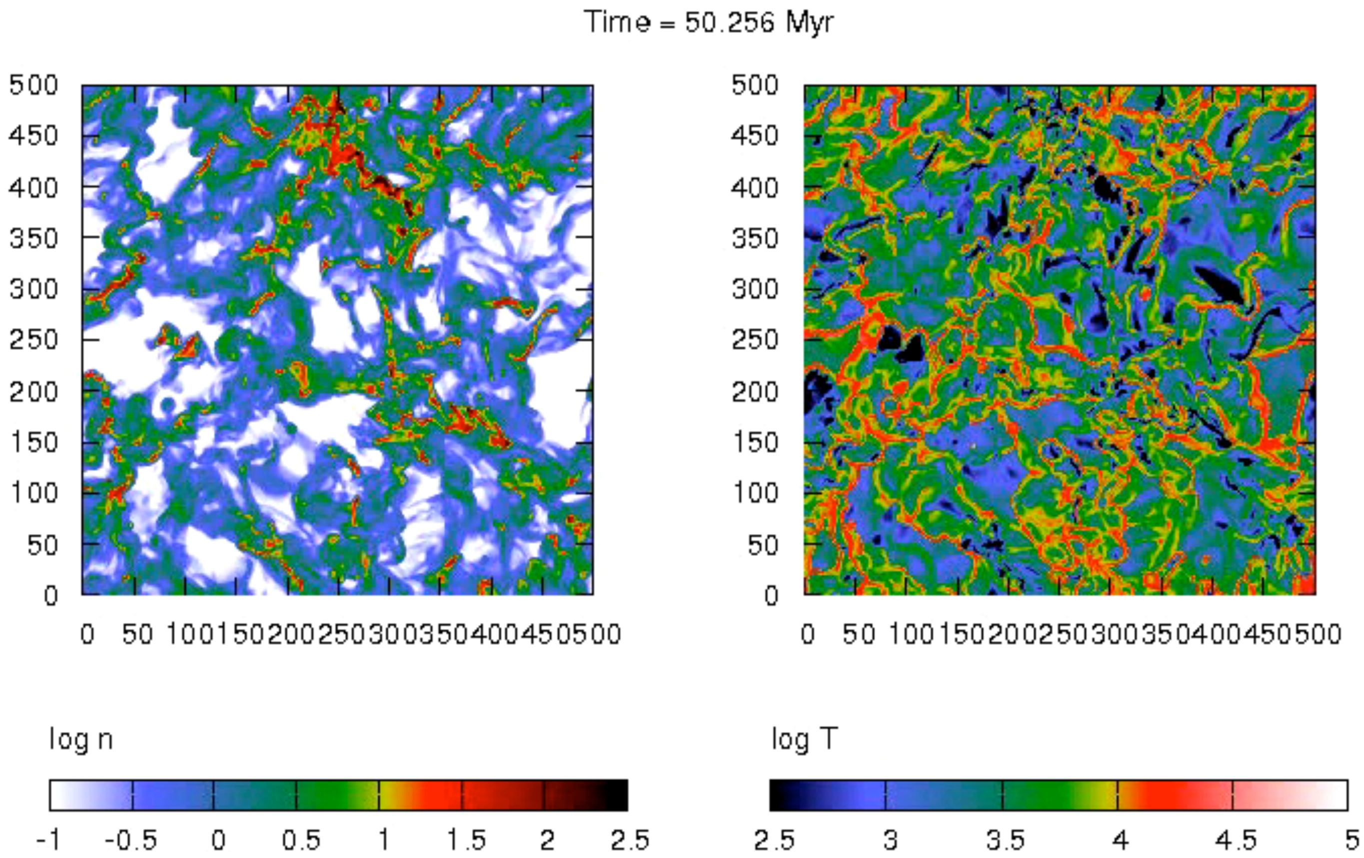
Threshold density ρ_{thres}, where T=300K:
Z= Z$_{sun}$: ρ_{thres} ~9 x 10^{-24}
Z=0.001 Z$_{sun}$: ρ_{thres} ~ 5 x 10^{-22}

Decaying turbulence

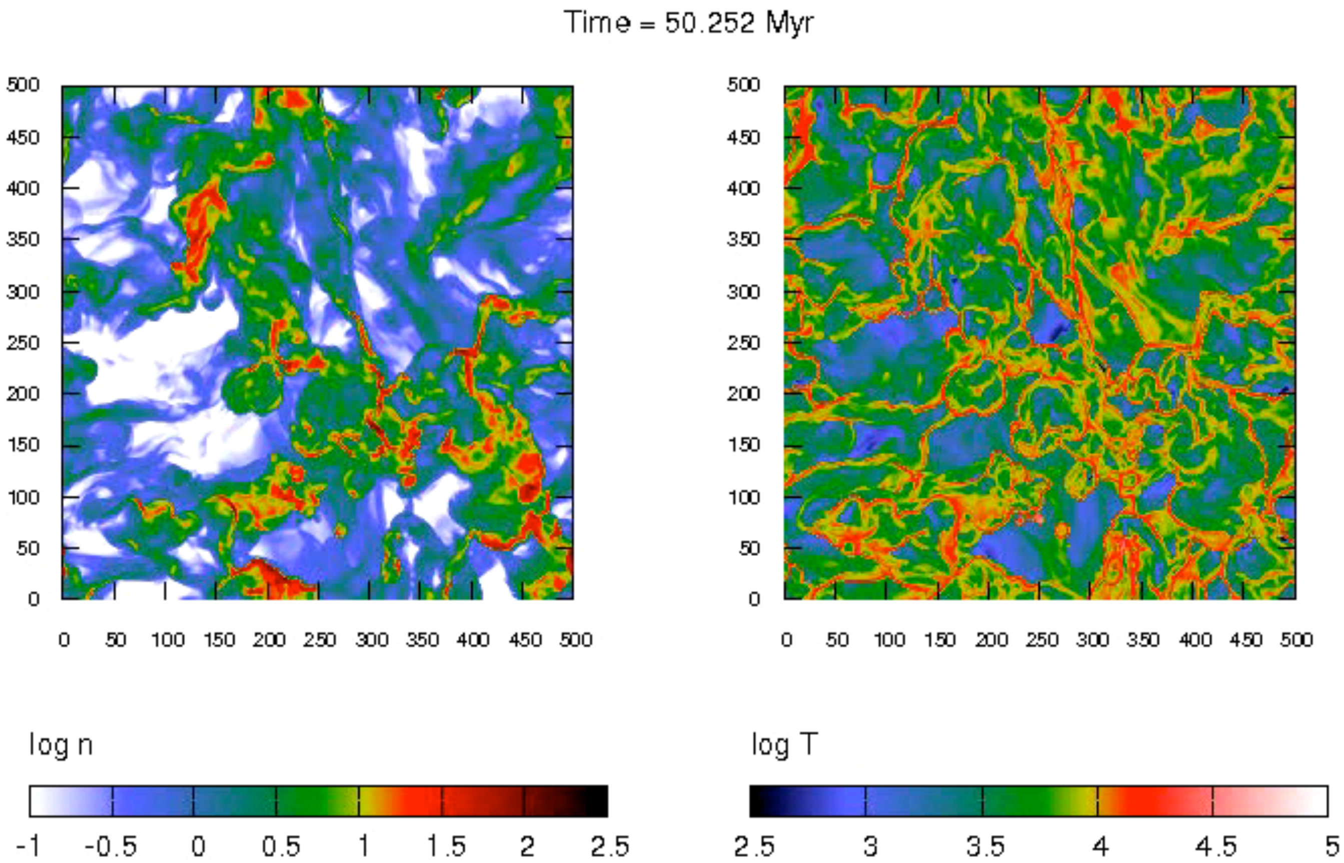
Parameters:

- Starting from final snapshot of driven cases (after 50Myr = 1 crossing time).
- Evolution for 50Myr.
- Results at different gas metallicity:
  a) Z_{solar}
  b) $10^{-3}\,Z_{solar}$

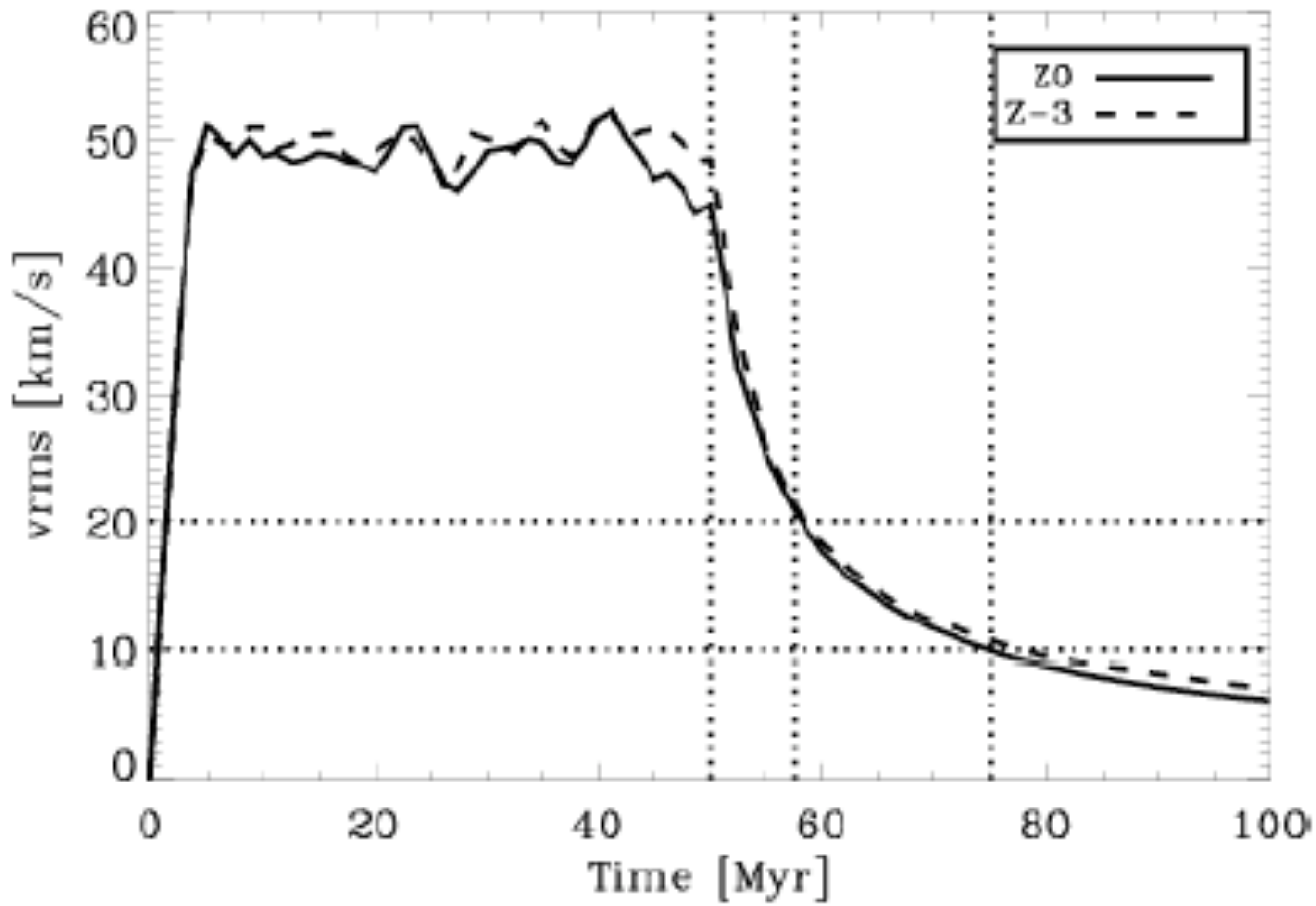
a) Solar metallicity



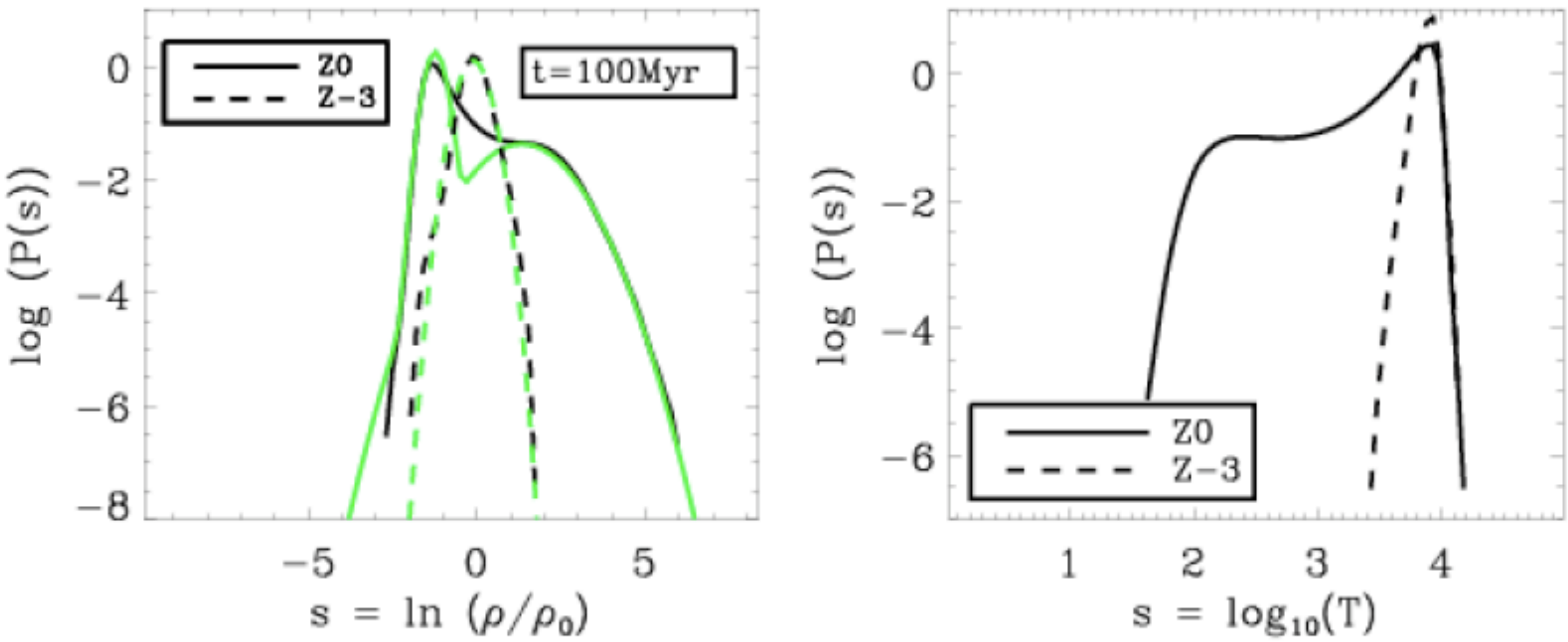
a) 10^{-3} Solar metallicity



Decay: RMS Velocity

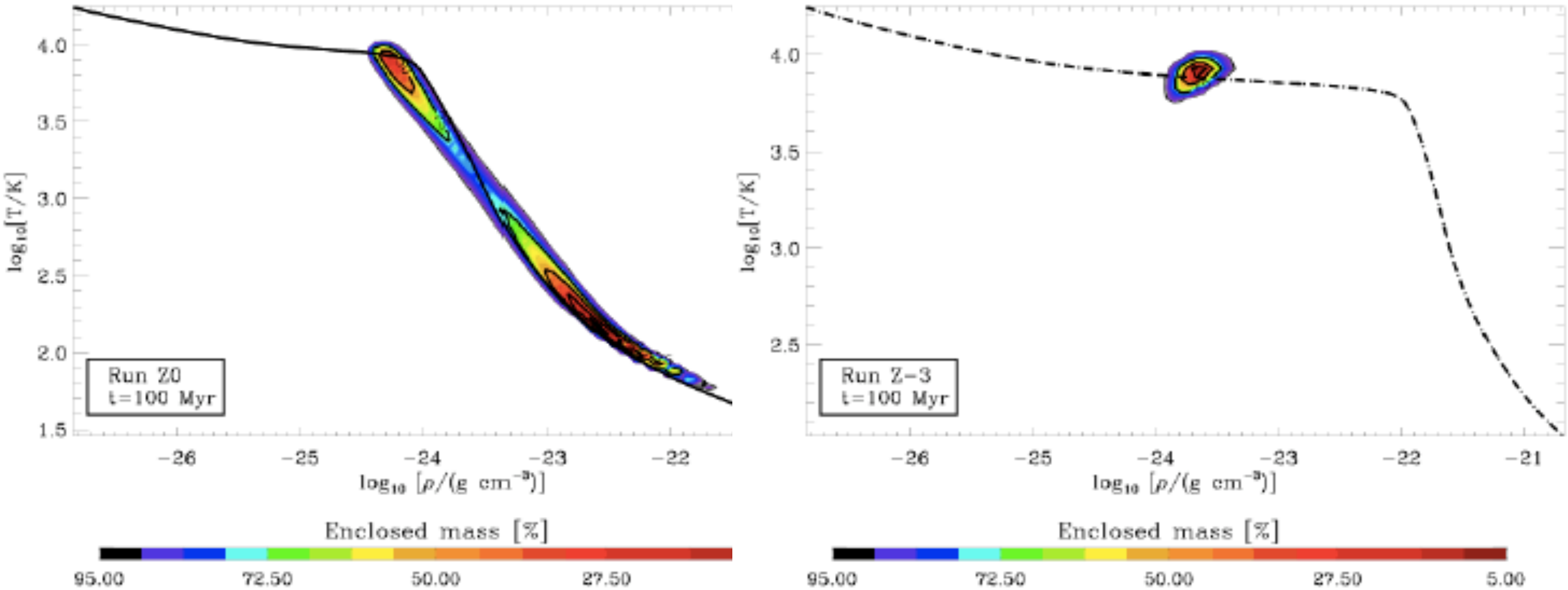


Density & Temp PDFs



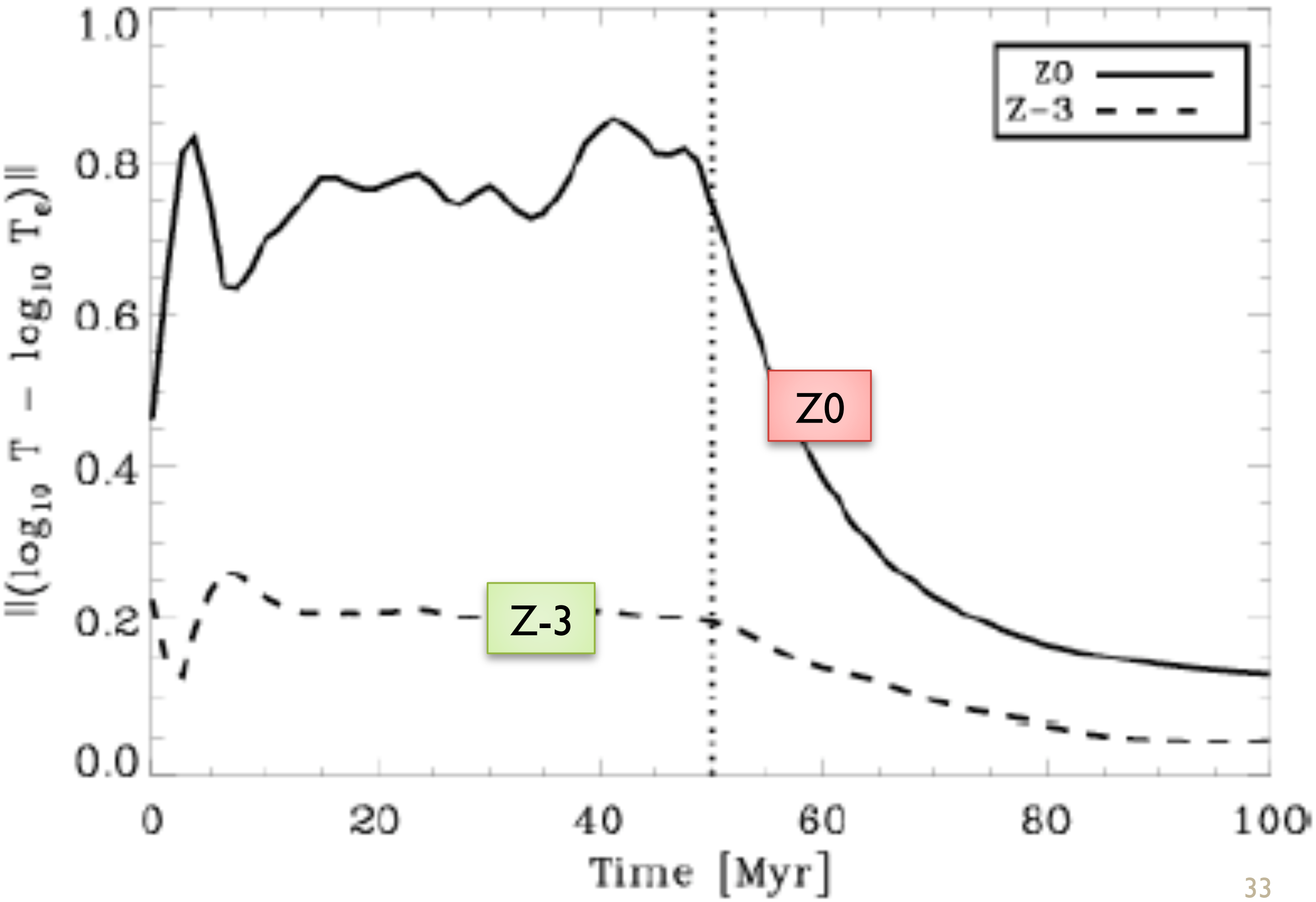
Formation of a bimodal ISM in case of solar metallicity;
Return to a single phase in case of low metallicity.

Mass distribution in the T- ρ -plane



Influence of non-equilibrium ionisation: Actual temp vs. equil. temp

Non-equilibrium chemistry especially important in solar metallicity gas??

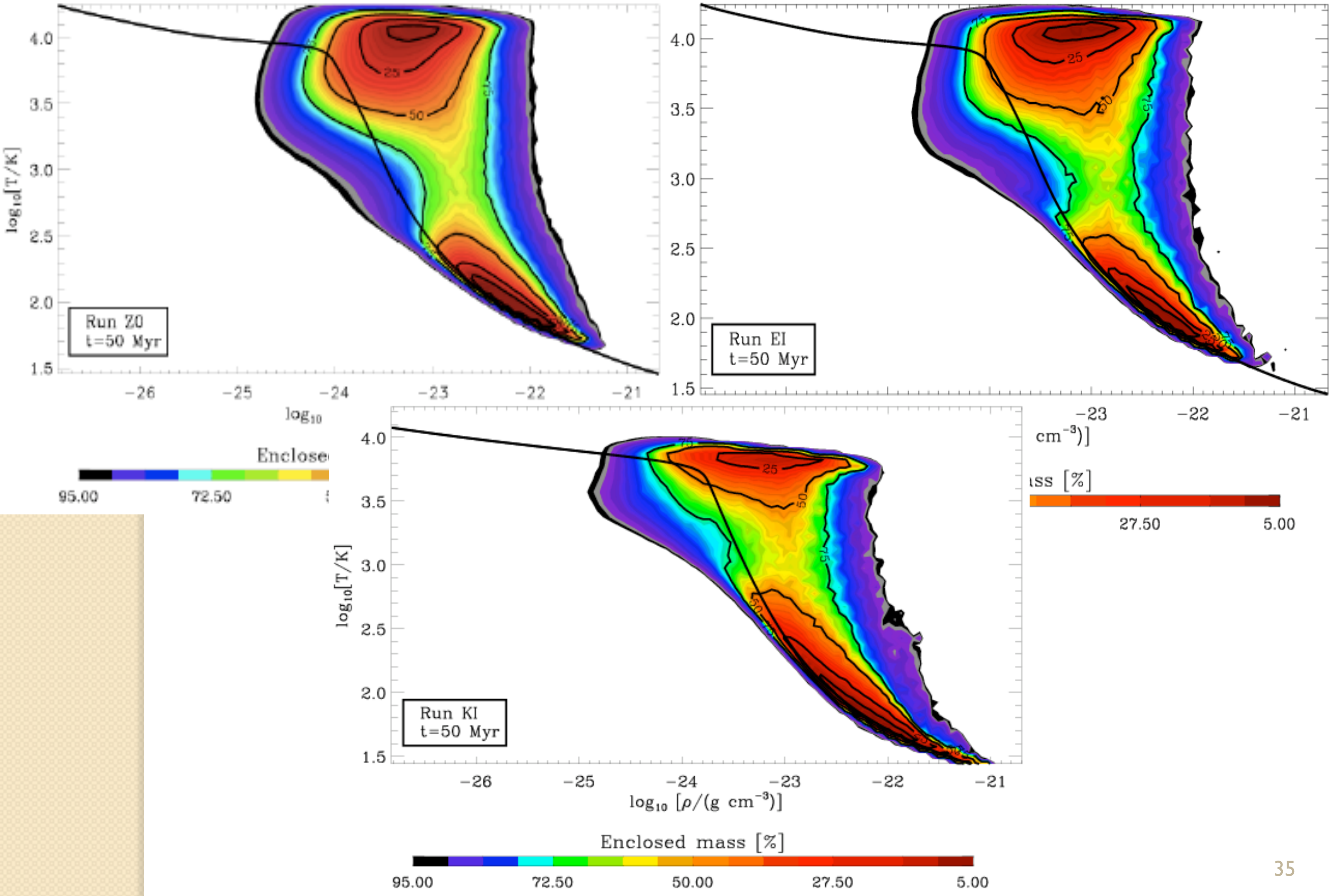


To test the influence of non-equilibrium chemistry we did 2 comparison runs at solar metallicity:

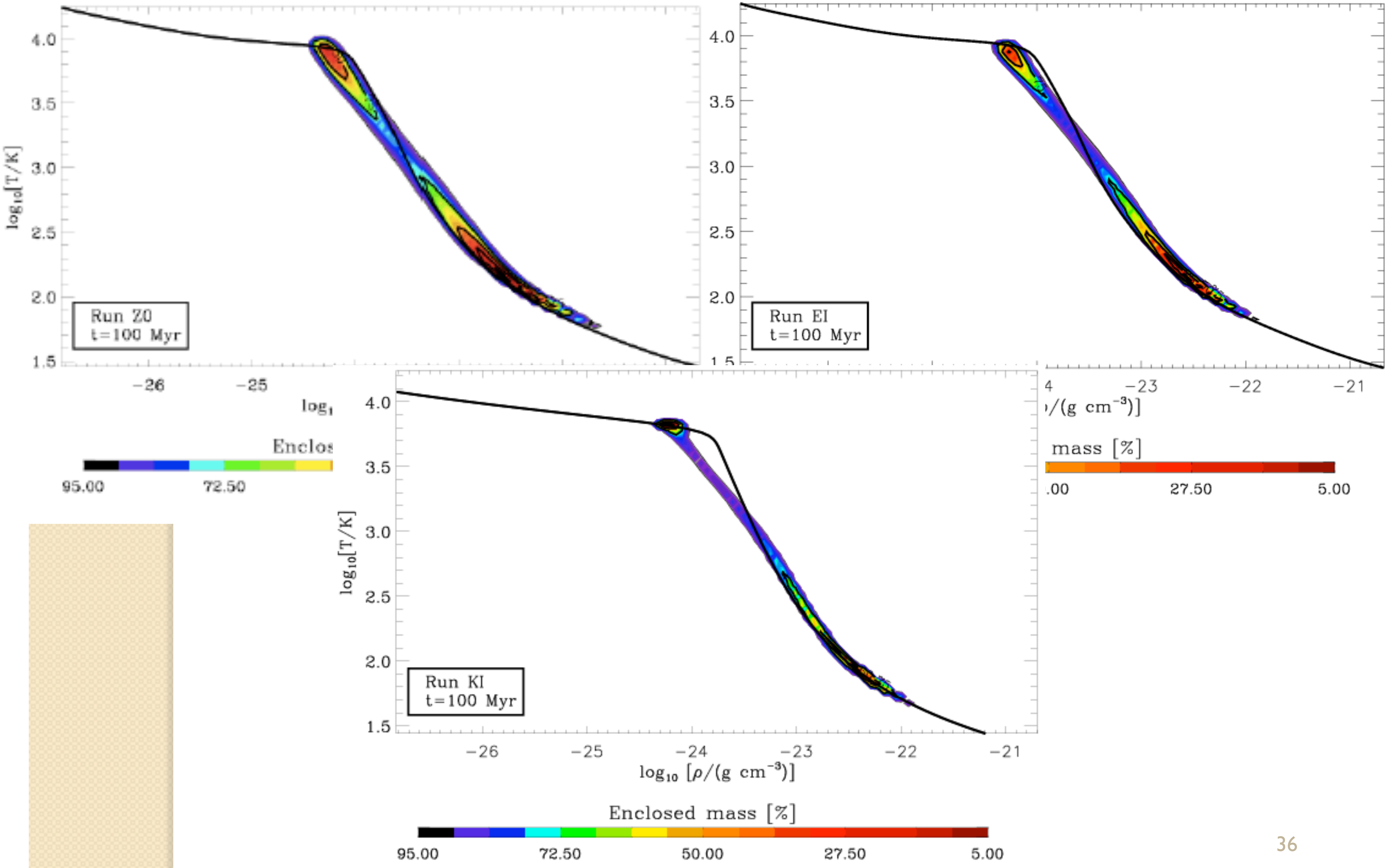
1. Run 'EI' with the detailed cooling by Glover et al. and with equilibrium ionisation

2. Run 'KI' without detailed cooling etc. Instead we use the parameterized cooling function by Koyama & Inutsuka 2002.

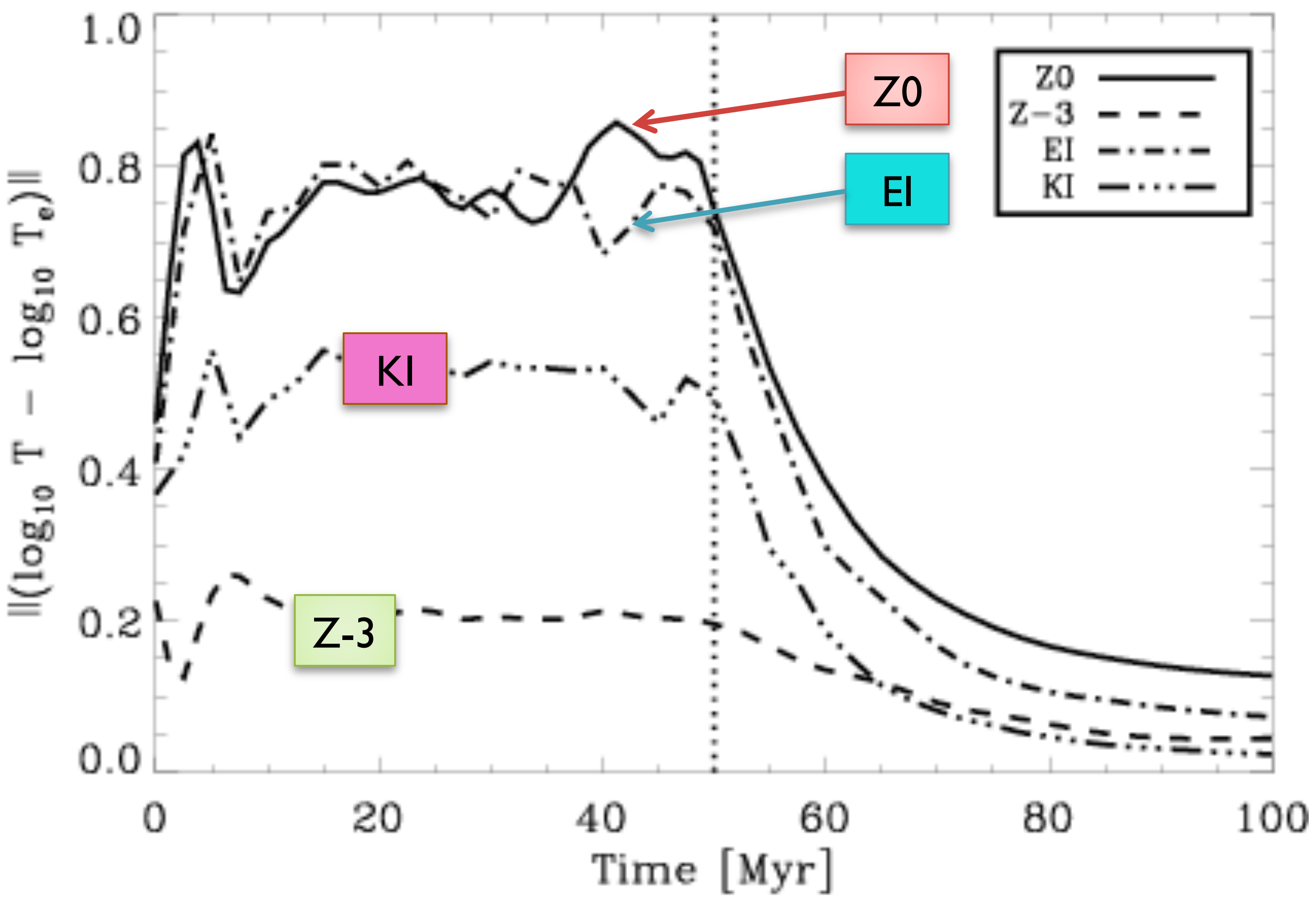
Comparison of ρ -T-diagrams



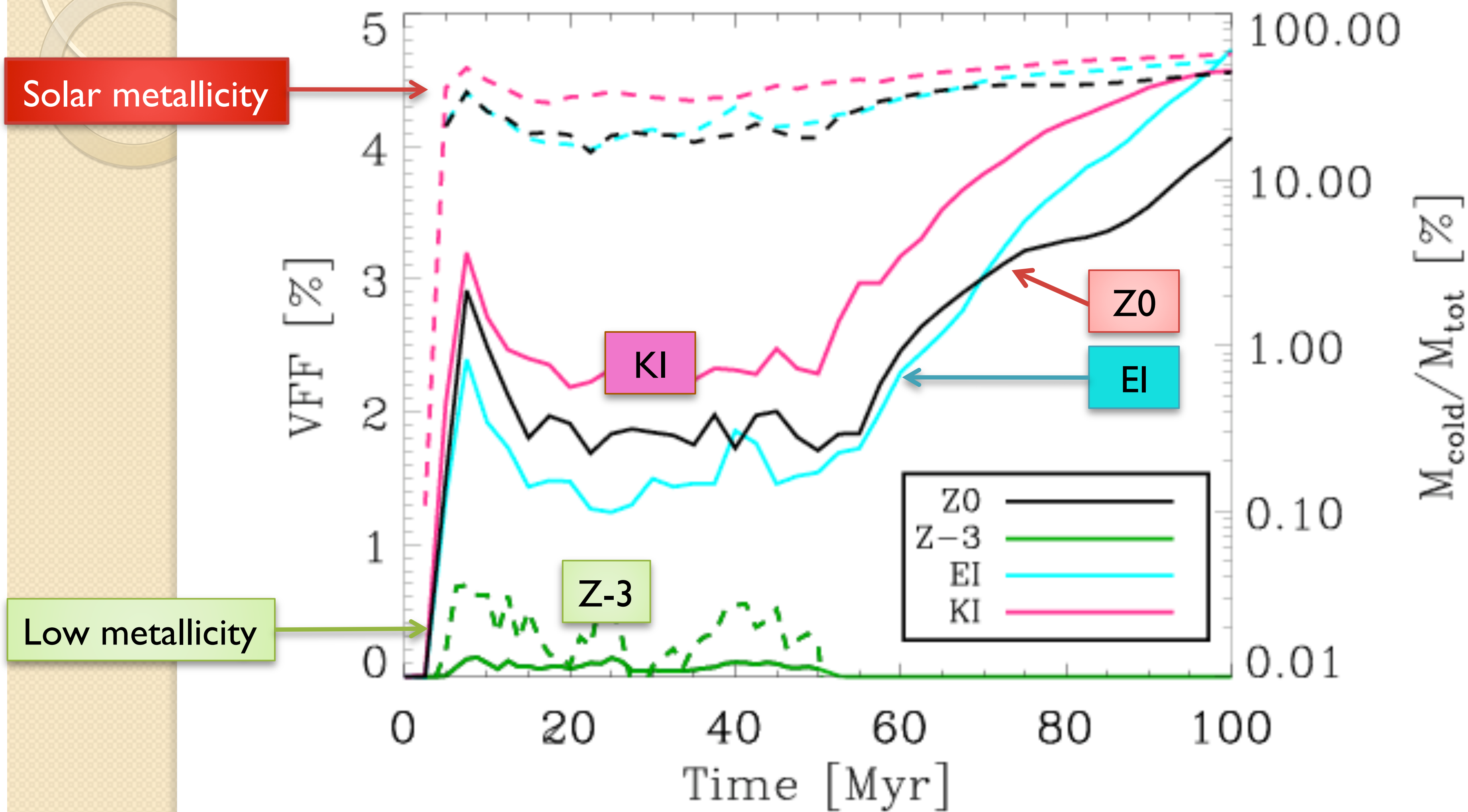
Comparison of ρ -T-diagrams



In T-Tequi diagram



VFF & Mass in cold gas

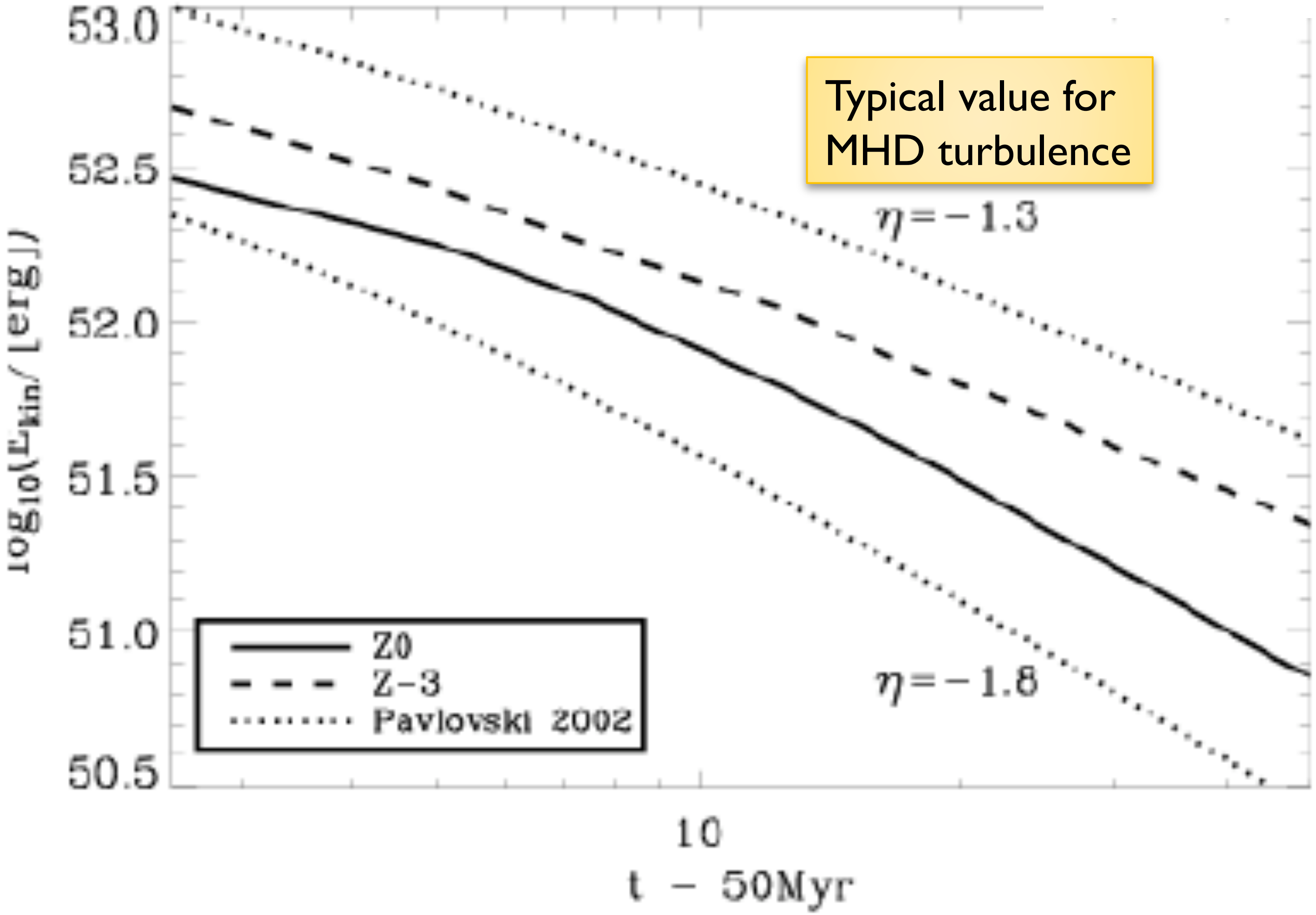


Solid lines: Volume filling factor (VFF) of the cold gas.

Dashed line: Mass in cold gas

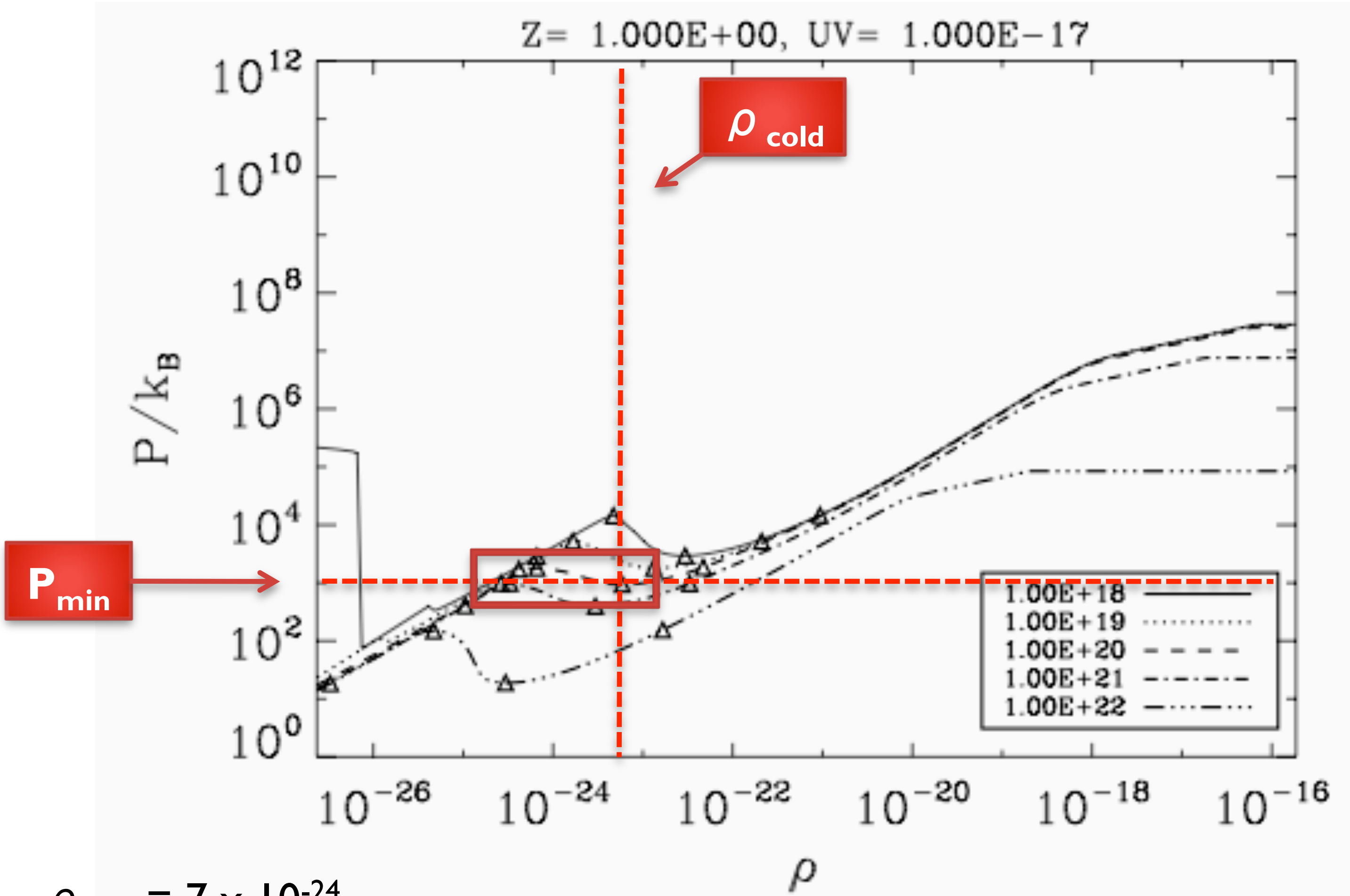
Decay: kinetic energy

$$E_k(t) \approx E_0\left(\frac{t}{t_0}\right)^{-\alpha}$$



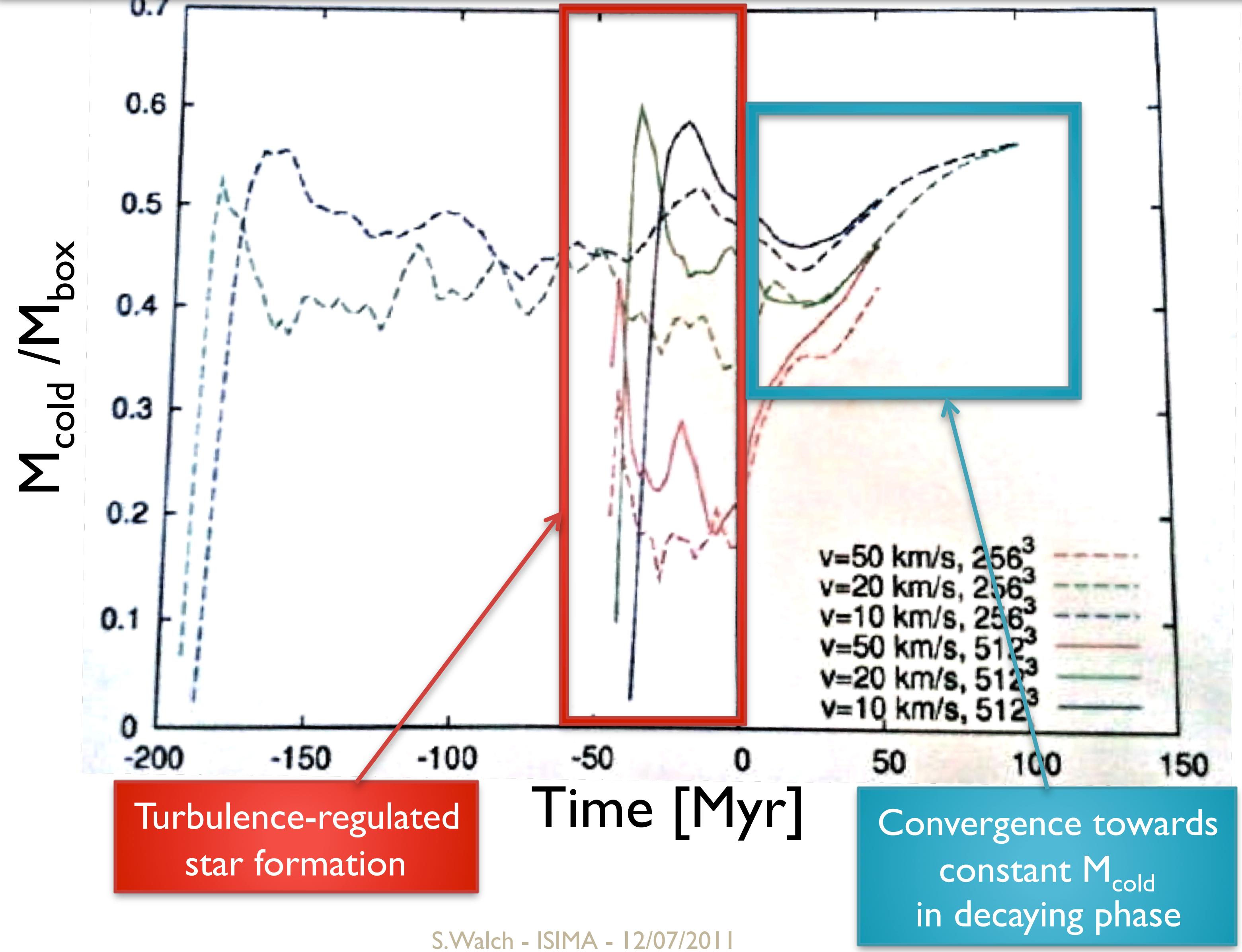
For comparison: In Kitsionas et al. (2009) we find η =-1 with FLASH for decaying isothermal supersonic turbulence.

Where does the gas settle down?



$\rho_{cold} = 7 \times 10^{-24}$

Note that this behaviour is not captured in a single log-normal density PDF where σ increases with M



Conclusions

Driven turbulence:

- PDFs similar; single peaked => turbulence dominant
- BUT: much more (~1000x) gas in dense & cold regions in case of solar metallicity as compared to $Z=10^{-3}Z_{solar}$.
- Gas in Z_{solar} case truly undergoes thermal instability

Decaying turbulence:

- PDF double peaked in case of solar metallicity
- Dense regions only survive for solar metallicity, where 2 stable phases are developed!
- The only way to form cold gas with low metallicity is to increase your gas density!
- This implies that the evolution of the ISM at different metallicities causes systematic changes in the initial conditions for star formation and should strongly affect the global star formation efficiency of a galaxy
- Cooling seems to be enhancing the decay of supersonic turbulence!

Conclusions

Non-equilibrium chemistry:

- Initially not important; systems out of equilibrium due to the efficient thermalization of turbulent energy.
- Not very important at low metallicity.
- Becomes increasingly more important at low turbulent velocities ($v_{rms} \leq 13$km/s)

Turbulence-regulated cold gas formation?

- In driven case: M_{cold} depends on v_{rms}^{-n}, where n will be defined in our parameter study => SF is turbulence regulated
- Trend opposite! More cold gas for smaller Mach numbers (not predicted by density PDF based theory)
- In decaying phase: M_{cold} converges against $M_{cold,max}$, independent of v_{rms} => Set upper limit for cold gas available to SF

Implications

<u>Observations:</u>

- Metal-poor dwarfs have very low SFR
- and usually complex SF histories with short episodes of burst-like SF

<u>Predictions:</u>

- SFR in galaxy mergers can be high, independent of gas metallicity
- Metal-poor galaxies could slowly accrete a lot of gas without efficiently forming stars, hence they acquire star-burst potential.