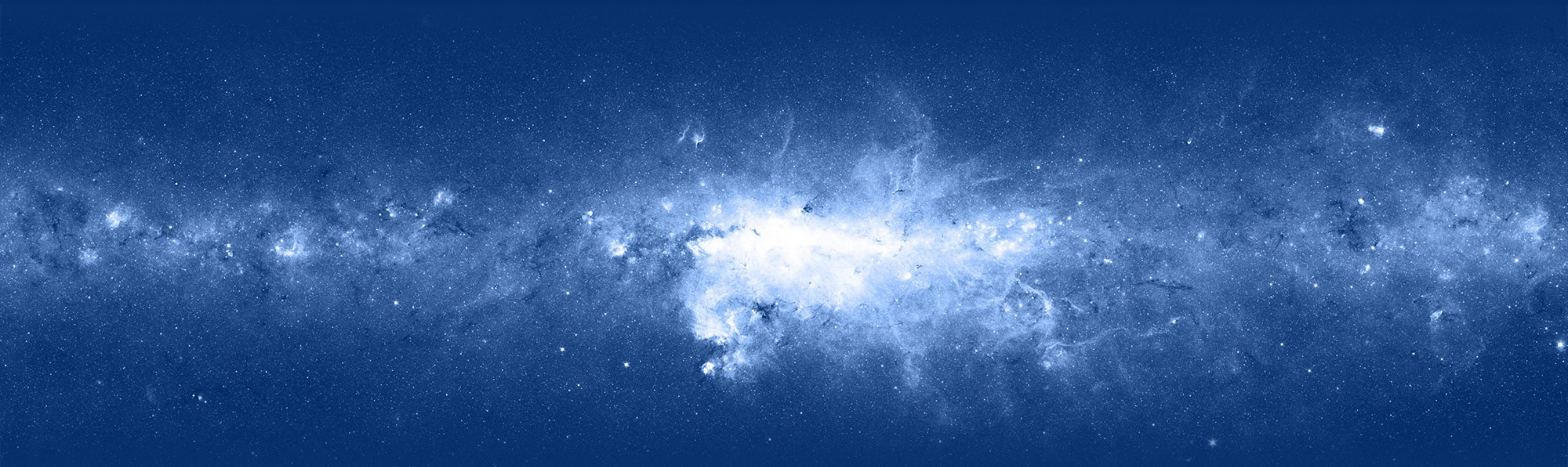
ASTR 670: Interstellar medium and gas dynamics

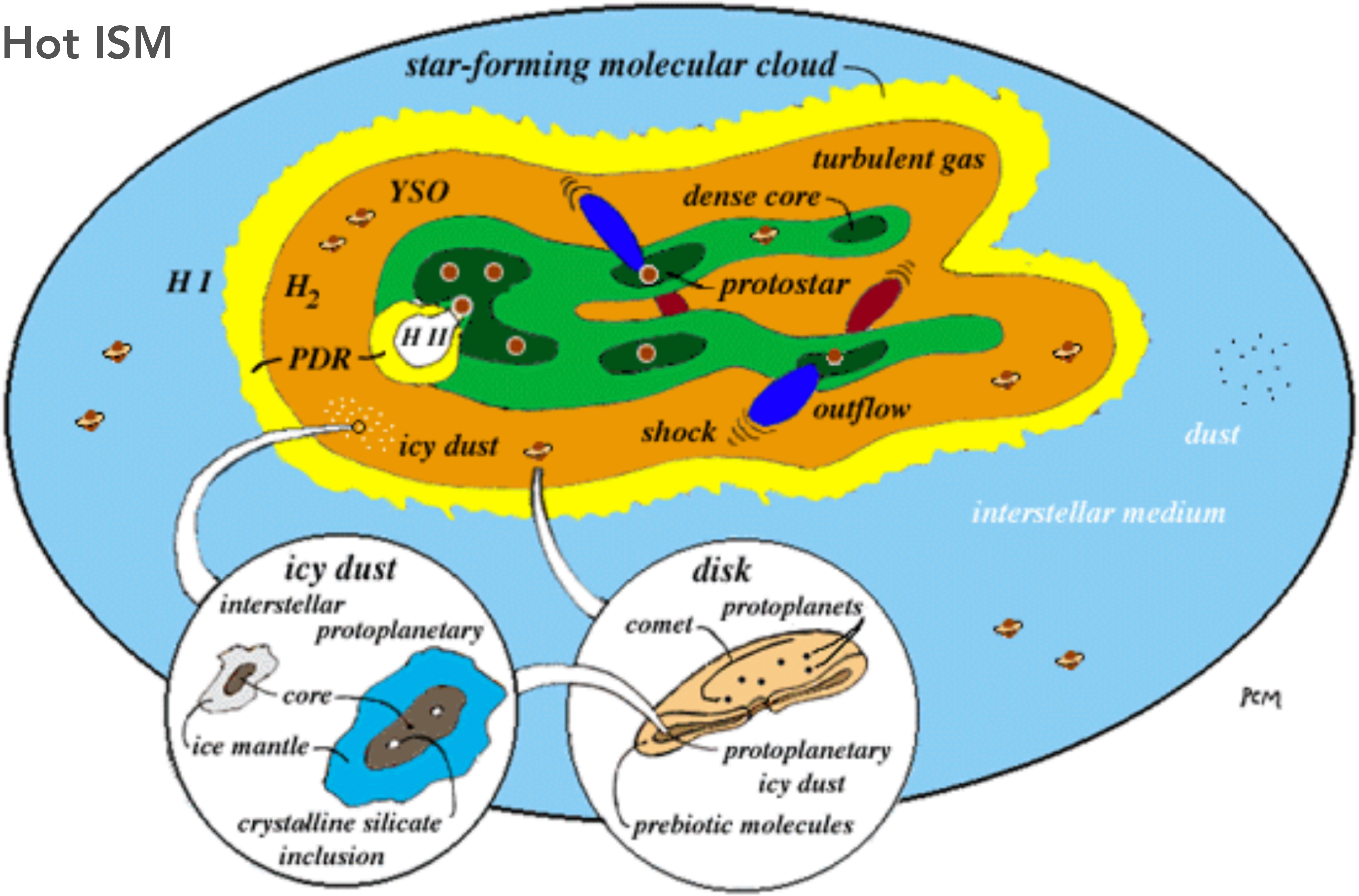
Prof. Benedikt Diemer



Chapter 10 • Global models of the ISM

Hydro vs. ISM

Hot ISM



star-forming molecular cloud
turbulent gas
YSO
dense core
H I
H_2
protostar
H II
PDR
outflow
shock
icy dust
dust
interstellar medium
icy dust
interstellar
protoplanetary
core
ice mantle
crystalline silicate
inclusion
disk
comet
protoplanets
protoplanetary
icy dust
prebiotic molecules
PCM

Gas phases (in the Milky Way)

	Phase	T (K)	n_H (cm^{-3})	f_V -	P/k_B (K/cm^3)	Comments
H II 23%	Hot ionized medium (HIM)	$10^{5.7}$	0.004	0.5	4400	Collisionally ionized, shock-heated by supernovae and stellar winds
	H II regions	10000	0.1-10^4	0.01	varies	Photo-ionized nebulae around stars; density and pressure vary across these bubbles
	Warm ionized medium (WIM)	8000	0.2	0.1	4400	Diffuse photo-ionized gas, large scatter in temperature and density
H I 60%	Warm neutral medium (WNM)	8000	0.5	0.4	4400	About 60% of HI by mass; in pressure equilibrium witn CNM
	Cool neutral medium (CNM)	100	40	0.01	4400	Significant fraction of the mass despite small volume filling fraction
H_2 17%	Diffuse molecular gas	50	150	0.001	4400	Self-shielded against dissociation, but not dense enough to form stars
	Molecular clouds	10-50	10^3-10^6	0.0001	>10000	The site of star formation; more or less gravitationally bound

§10.1 • Two-phase medium in thermal equilibrium

Pressure

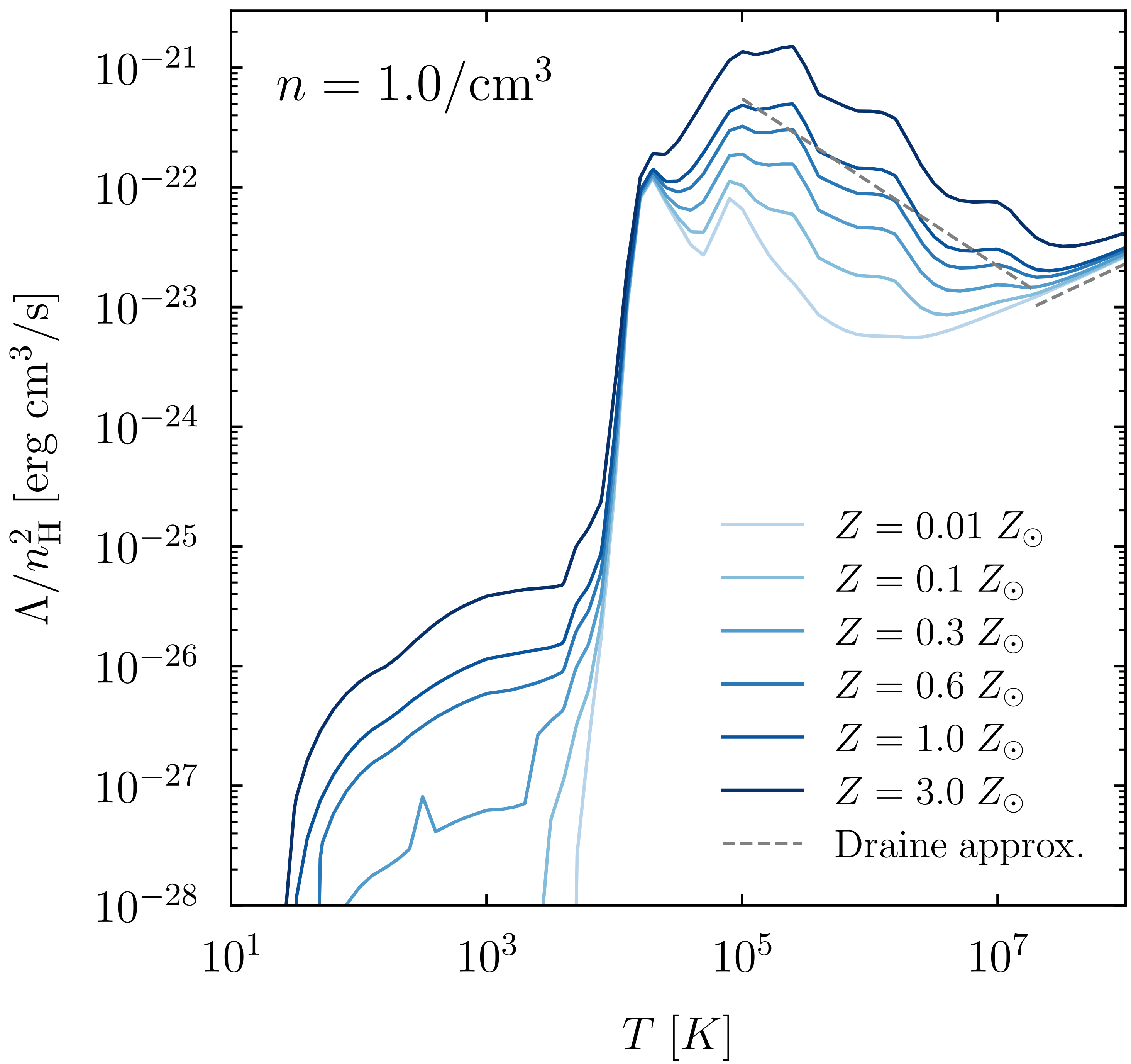
- Pressure is often expressed as P/kB

$$P = nk_\mathrm{B}T \implies \frac{P}{k_\mathrm{B}} = nT$$

- Typical pressure of hot gas in ISM is

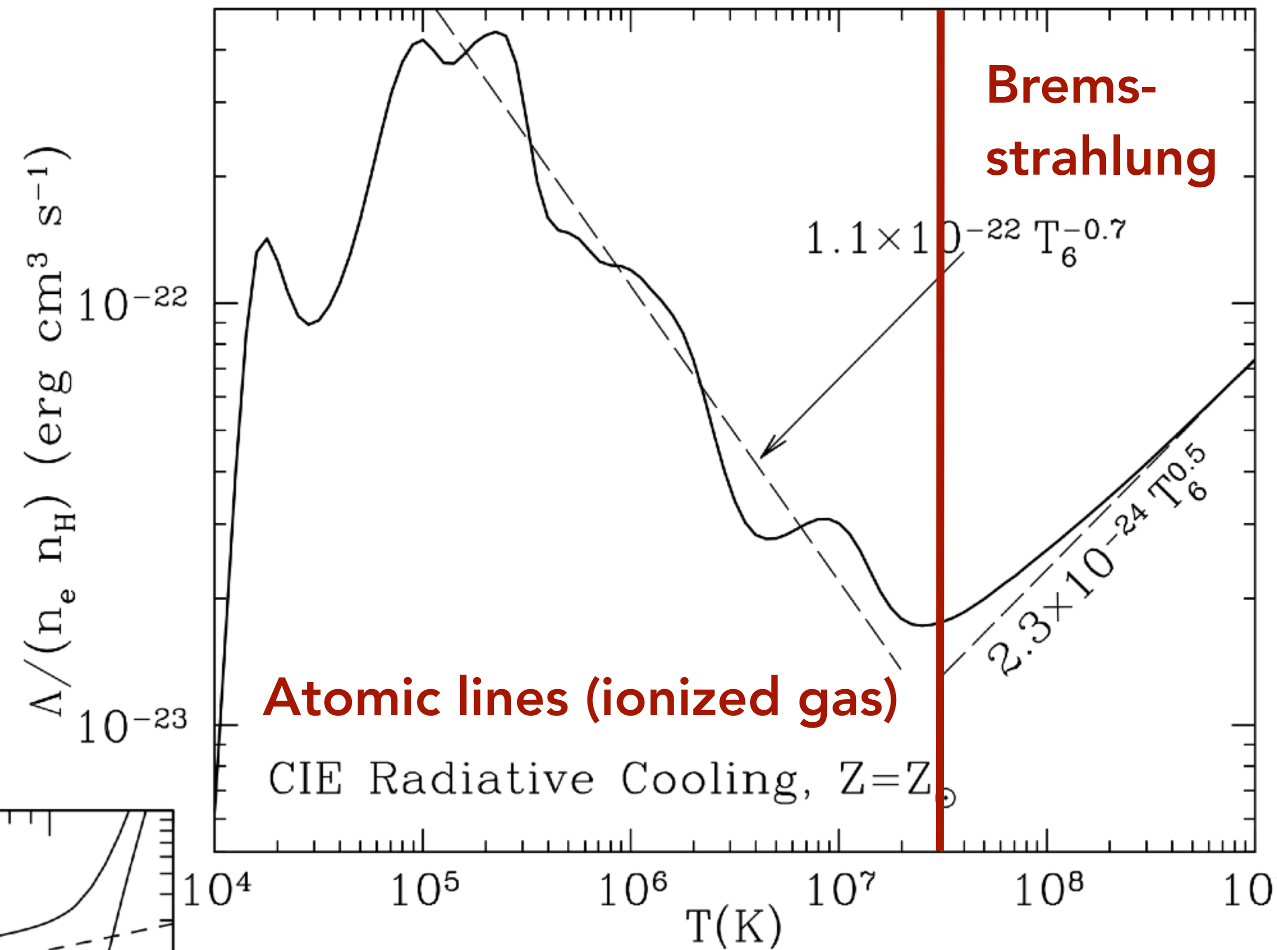
$$\frac{P}{k_\mathrm{B}} \approx 3000 - 5000\frac{\mathrm{K}}{\mathrm{cm}^3}$$

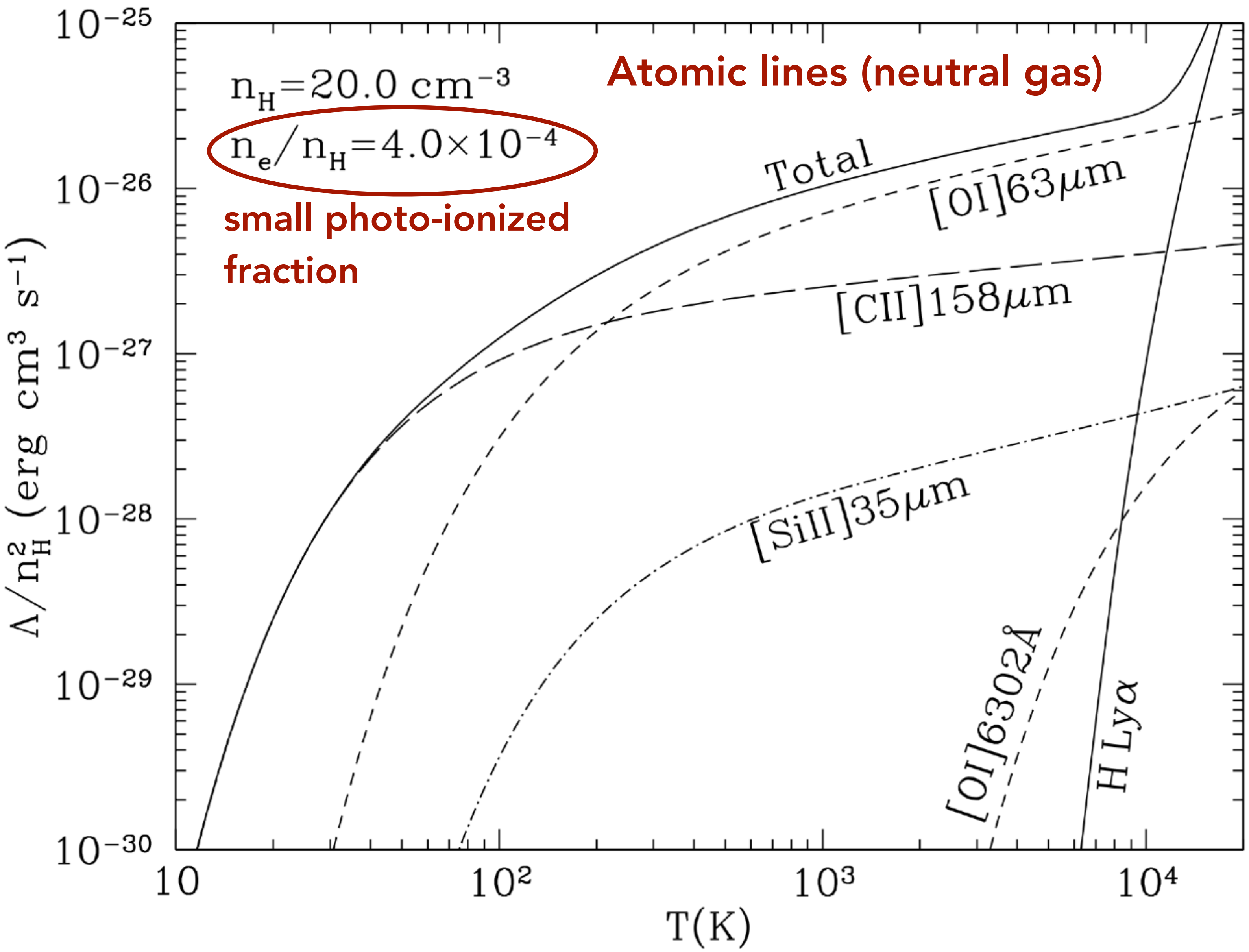
Cooling curves



Plöckinger & Schaye 2020

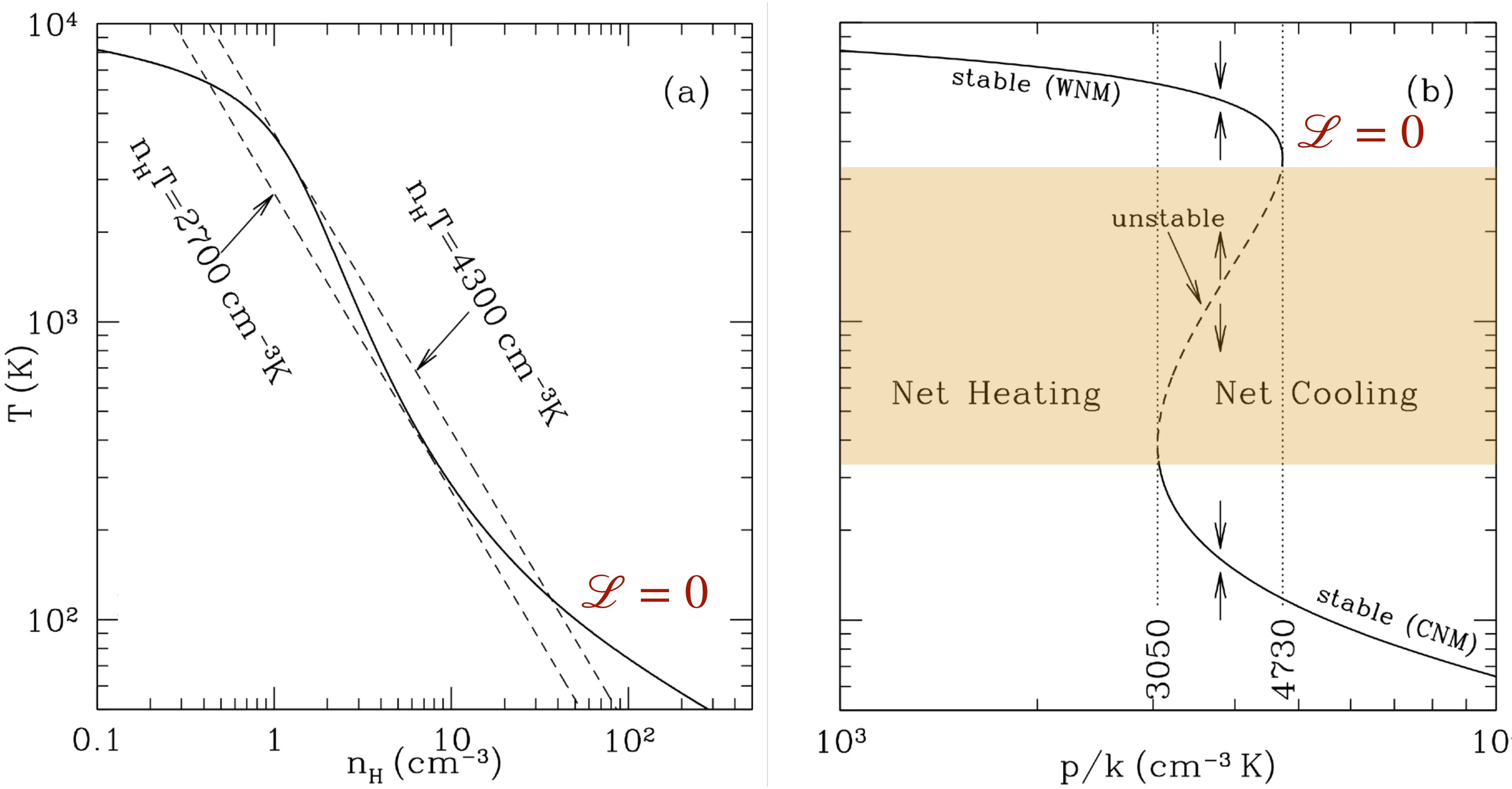
Cooling curve revisited





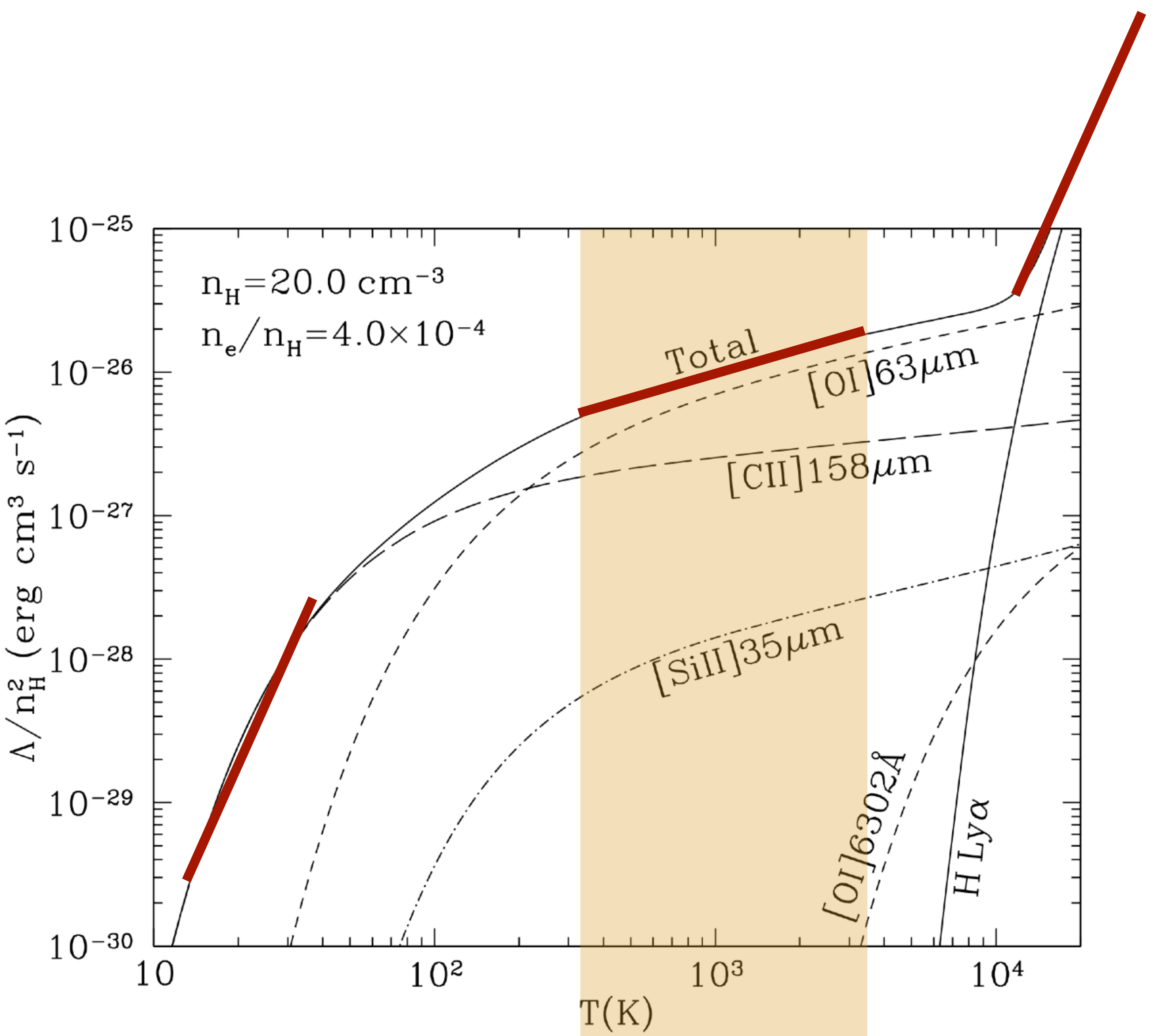
Draine §30.4, §34.1

Why is there a multi-phase ISM?

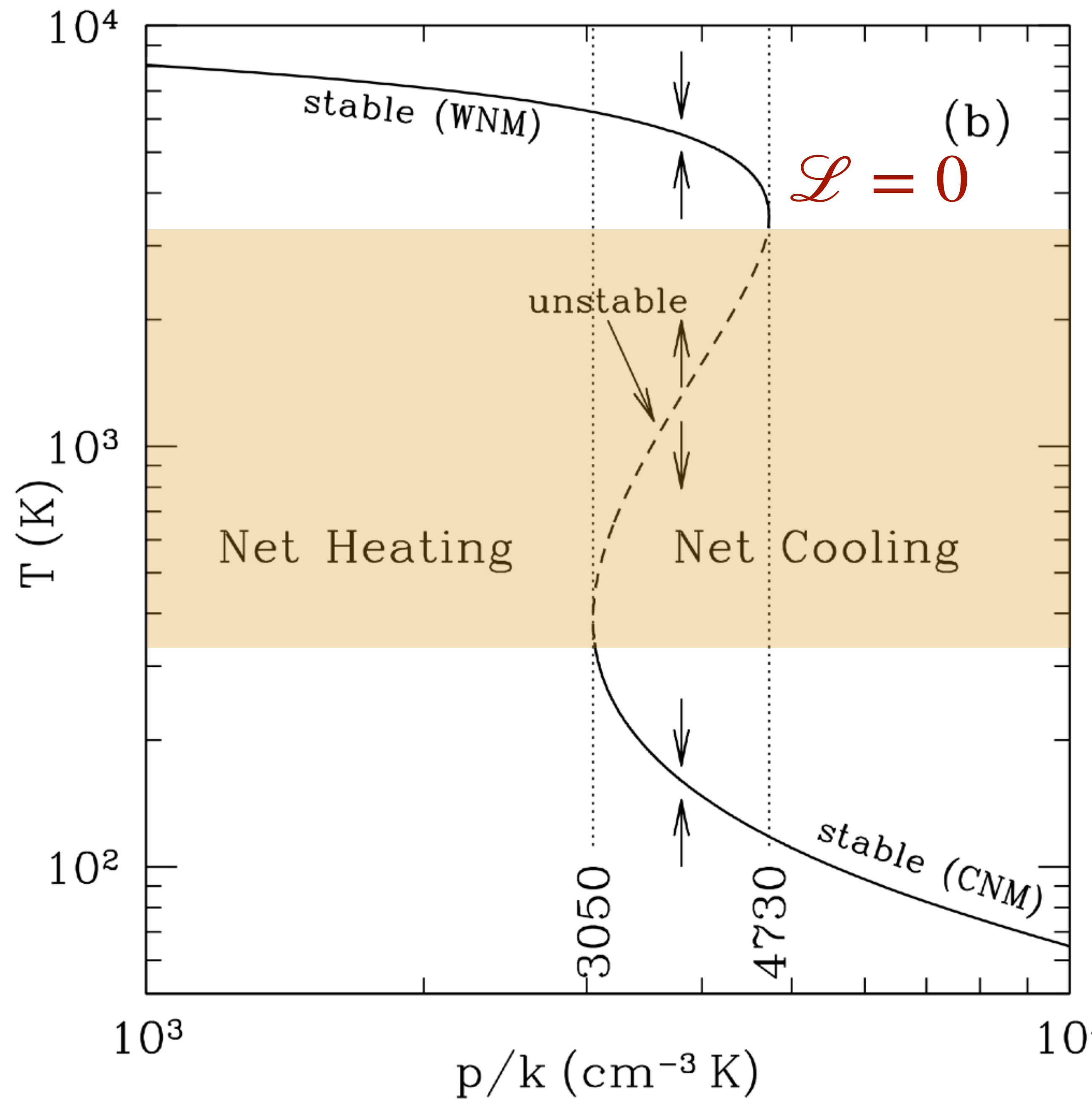


Draine §30.4 • Slide inspired by K. Sandstrom

Why is there a multi-phase ISM?

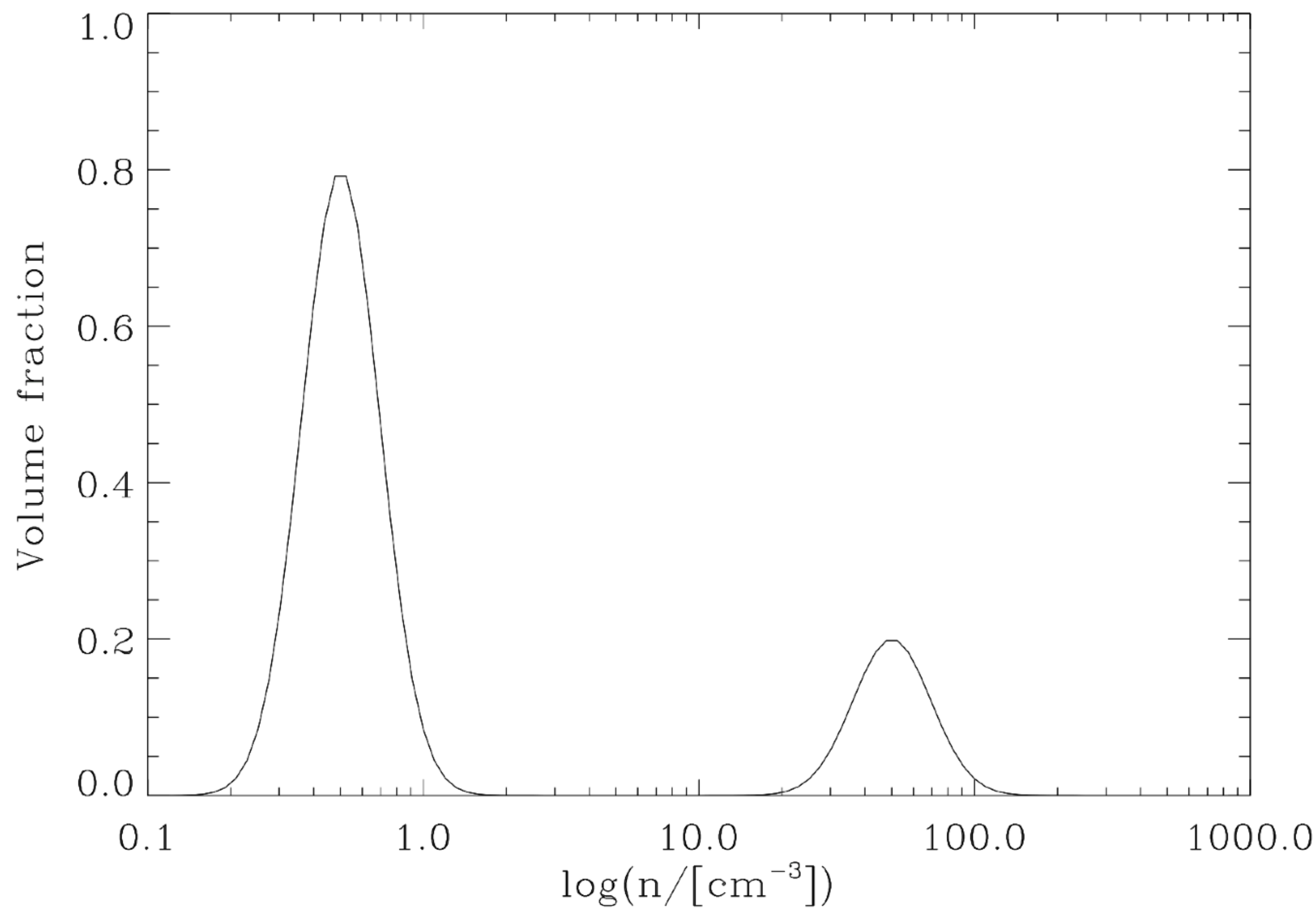


$$\left.\frac{\partial \mathscr{L}}{\partial T}\right|_P > 0 \qquad \left.\frac{\partial \mathscr{L}}{\partial T}\right|_P < 0 \qquad \left.\frac{\partial \mathscr{L}}{\partial T}\right|_P > 0$$



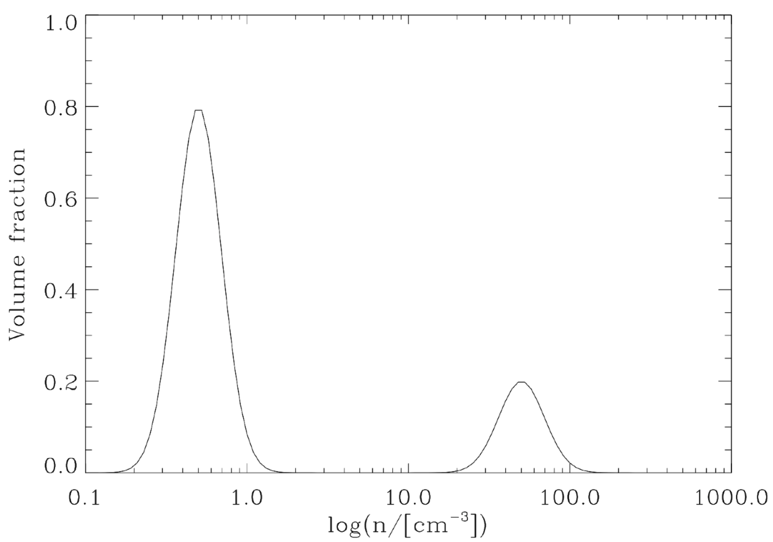
Draine §30.4 • Slide inspired by K. Sandstrom

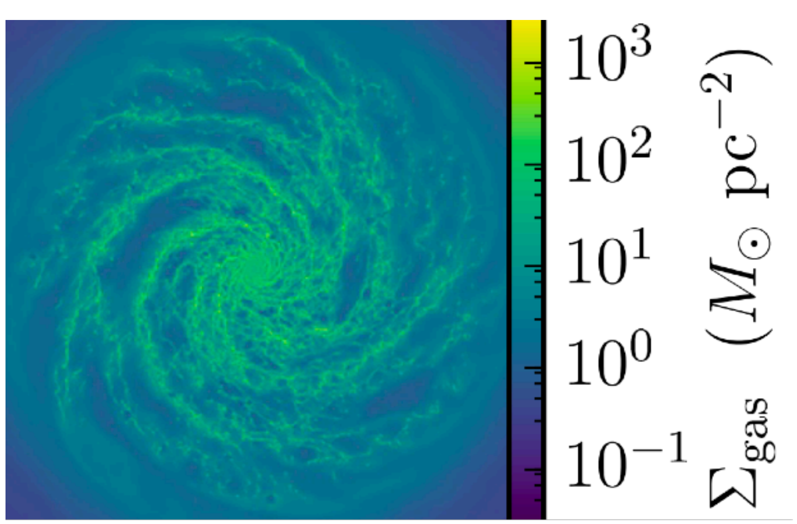
Is the model realistic?

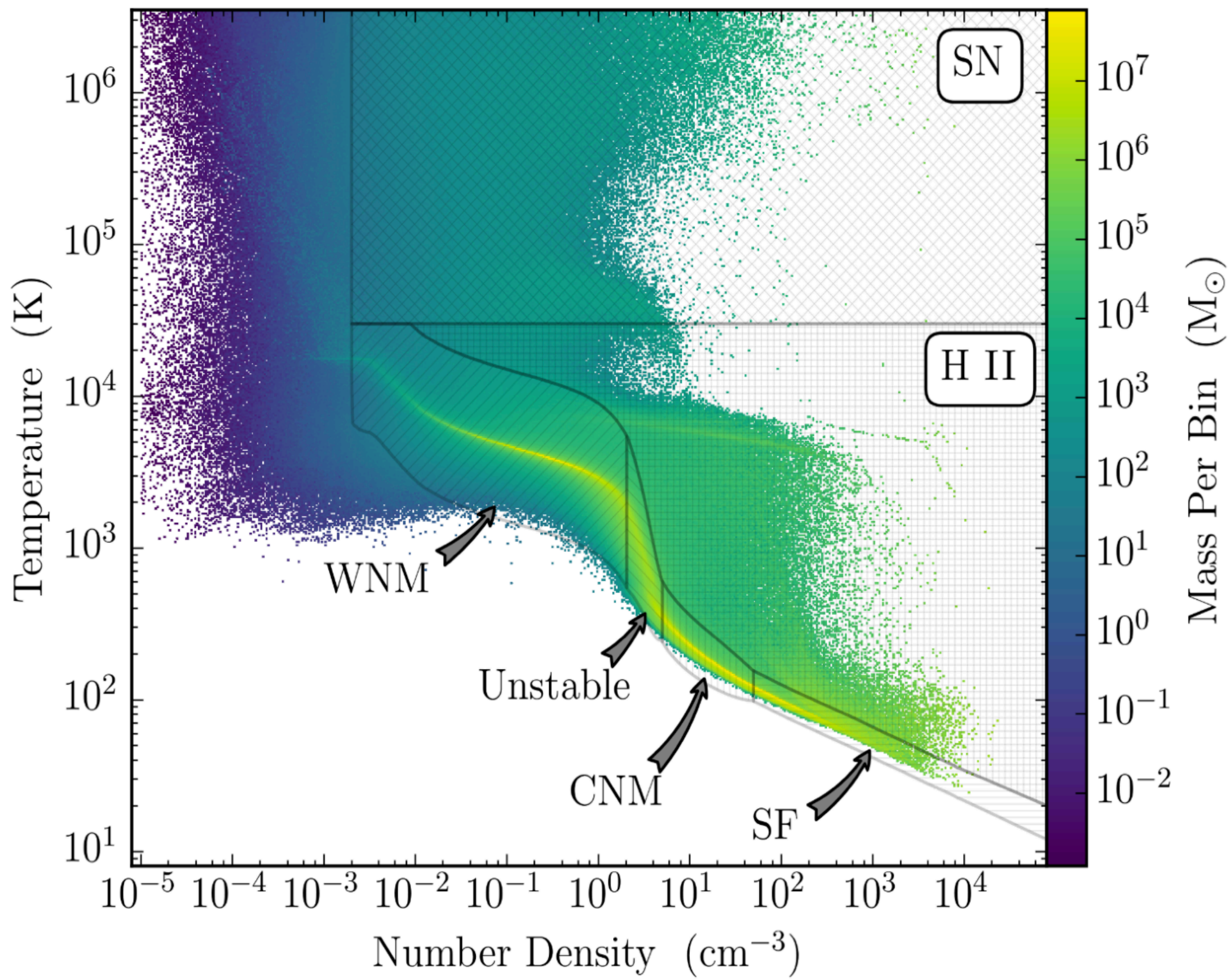


Vazquez-Semadeni 2009

Is the model realistic?







Vazquez-Semadeni 2009 • Goldbaum et al. 2016

§10.2 • Three-phase medium with supernovae as pressure regulators

Pressure equilibrium: an old idea

ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1956

ABSTRACT

The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

Spitzer 1956

A THEORY OF THE INTERSTELLAR MEDIUM: THREE COMPONENTS REGULATED BY SUPERNOVA EXPLOSIONS IN AN INHOMOGENEOUS SUBSTRATE

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Received 1977 February 3; accepted 1977 May 2

The conclusion is clear and rather surprising. *The standard two-phase model proposed by Field, Goldsmith, and Habing (1969) for which $(T_0, n_0) \sim (10^4\ \mathrm{K}, 10^{-1}\ \mathrm{cm}^{-1})$ cannot be maintained if our estimate of supernova rate S is reasonably accurate.* It would rapidly self-destruct (time $< 10^7$ years) as the relatively cool intercloud medium was swept up into dense shells and replaced by hot, low-density shock-heated gas. Thus we must consider anew the

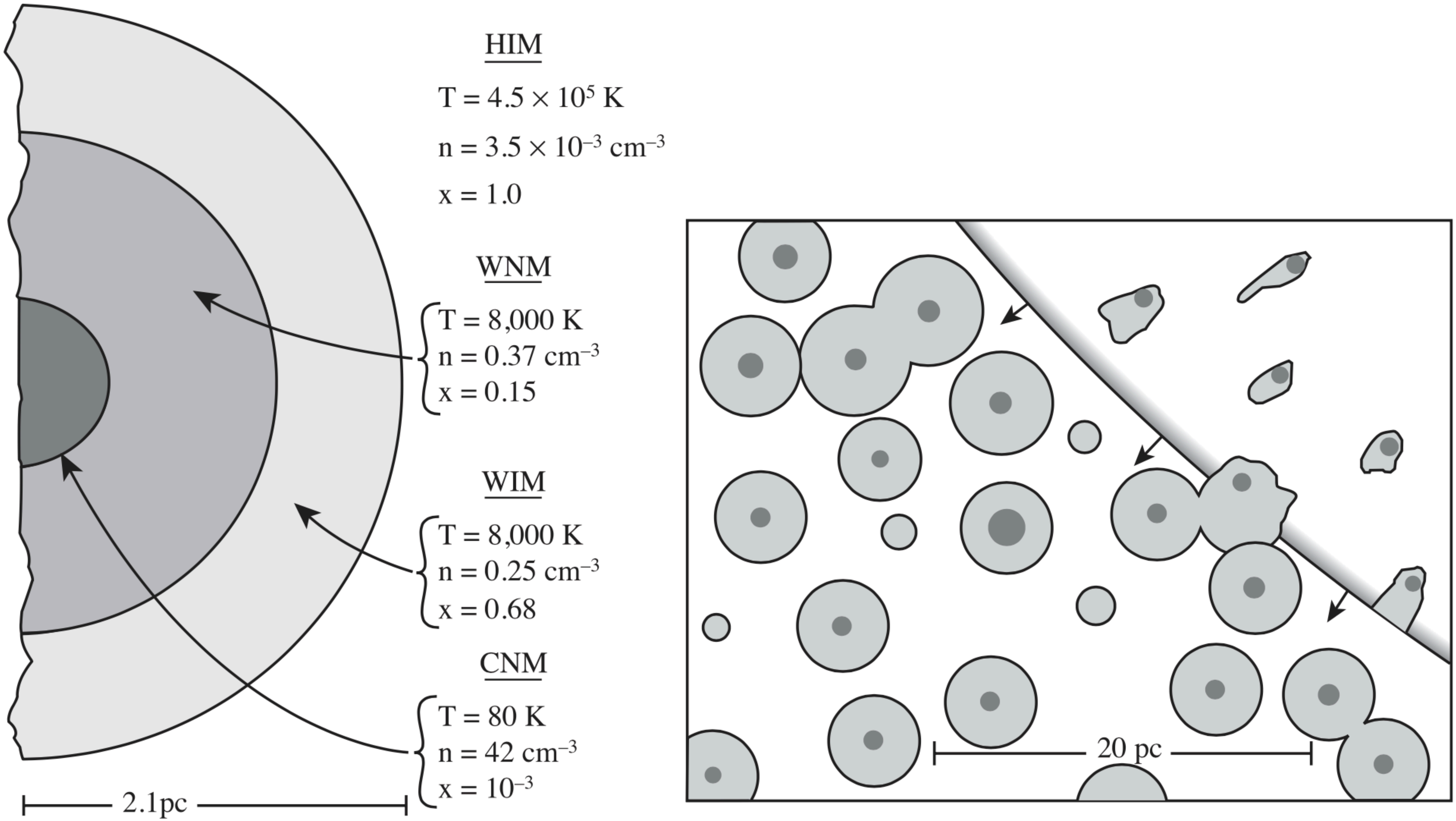
In summary, the model developed has three essential components. Most of the space is filled with a hot low-density medium (the HIM) with typical values of the density and temperature $(n, T) = (10^{-2.5}\ \mathrm{cm}^{-3}, 10^{5.7}\ \mathrm{K})$ which is moderately inhomogeneous [probability distributions for (n, T) are given] as blast waves from supernova explosions of various ages pass by a given point; the filling factor for this component f_{HIM} is 0.7 to 0.8. Embedded in the hot medium are cold, neutral, relatively dense clouds (CNM); the filling factor f_{CNM} is 0.02–0.04, and the internal density and temperature are $(10^{1.6}\ \mathrm{cm}^{-3}, 10^{1.9}\ \mathrm{K})$. Surrounding each cloud is a warm ($T \sim 8{,}000$ K) photoionized cloud corona. This component occupies a much larger volume than the cold clouds—the filling factor being ~ 0.2—but contains far less mass. In our simplified treatment we subdivide the cloud coronae into two regions, an outer one wherein the fractional ionization is ~ 0.7 maintained by hot (B) stars, which we designate the warm ionized medium (WIM), and an inner layer of smaller volume which is nearly neutral having fractional ionization ~ 0.1 maintained by the very soft X-rays ($h\nu \sim 60$ eV) emitted by supernova remnants, which we designate WNM.

All components are in rough pressure equilibrium; and the interchange of material between the phases due to the processes of cloud evaporation, photoionization, thermal instabilities, and hydrodynamic shocks is quite rapid, with the mass in a given volume element typically changing phase in a time less than 10^6 years. Molecular cloud complexes, ordinary Strömgren spheres, and other phenomena occurring in regions of active star formation are not treated in this paper.

$$Q_{\mathrm{SNR}} = 10^{-0.29} E_{51}{}^{1.28} S_{-13} n_0{}^{-0.14} \tilde{P}_{04}{}^{-1.30}, \qquad f_{\mathrm{SNR}} = 1 - \exp(-Q_{\mathrm{SNR}}).$$

McKee & Ostriker 1977

Three-phase model of the ISM



Draine §39.4 • McKee & Ostriker 1977

§10.3 • Hydrostatic balance

Know your Ostrikers!

Jerry Ostriker

Eve Ostriker

REGULATION OF STAR FORMATION RATES IN MULTIPHASE GALACTIC DISKS: A THERMAL/DYNAMICAL EQUILIBRIUM MODEL

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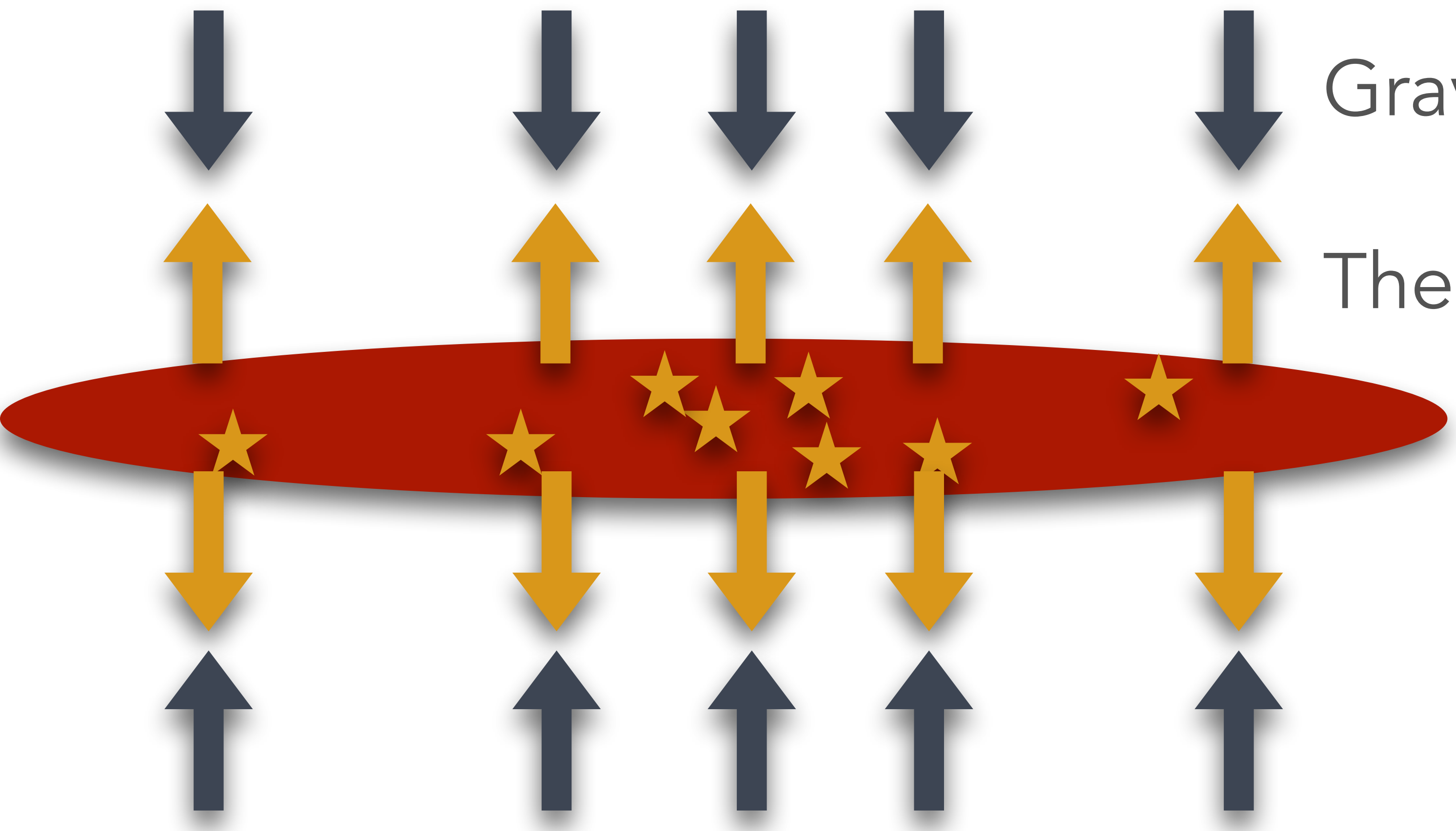
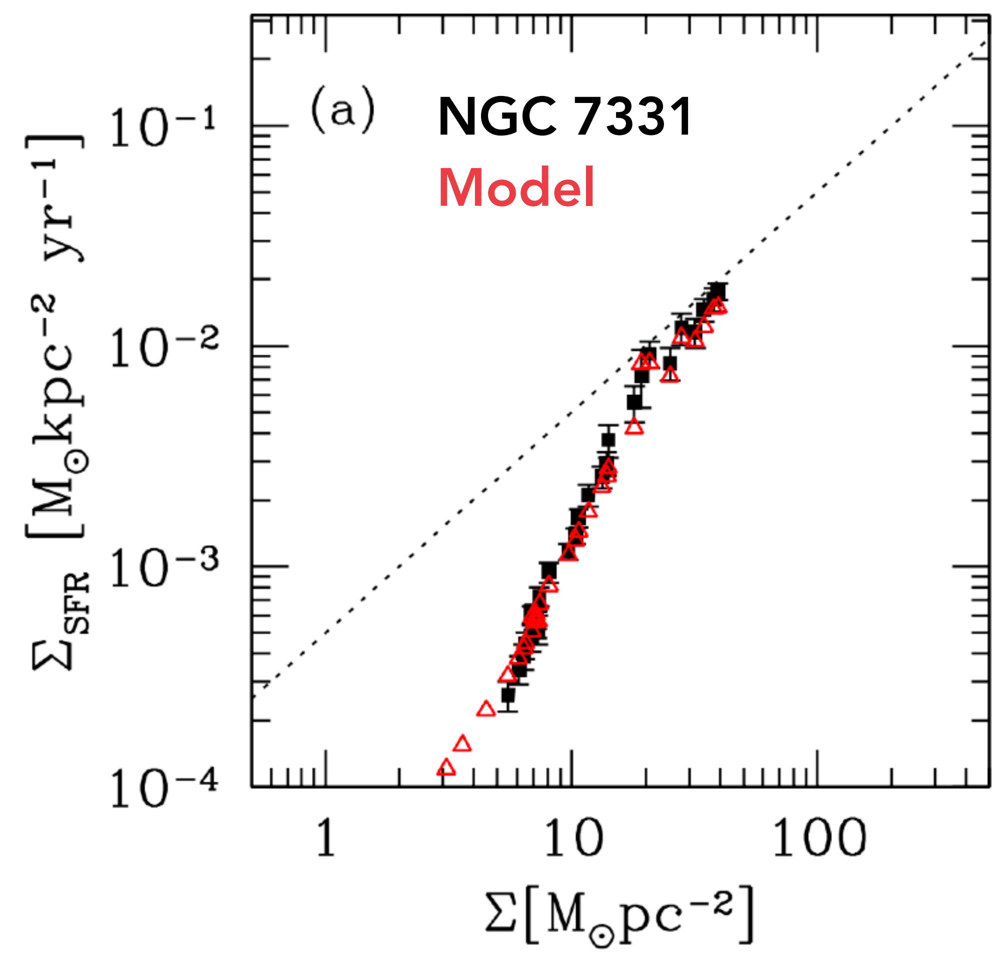
ABSTRACT

We develop a model for the regulation of galactic star formation rates Σ_{SFR} in disk galaxies, in which interstellar medium (ISM) heating by stellar UV plays a key role. By requiring that thermal and (vertical) dynamical equilibrium are simultaneously satisfied within the diffuse gas, and that stars form at a rate proportional to the mass of the self-gravitating component, we obtain a prediction for Σ_{SFR} as a function of the total gaseous surface density Σ and the midplane density of stars+dark matter ρ_{sd}. The physical basis of this relationship is that the thermal pressure in the diffuse ISM, which is proportional to the UV heating rate and therefore to Σ_{SFR}, must adjust until it matches the midplane pressure value set by the vertical gravitational field. Our model applies to regions

Ostriker et al. 2010

Hydrostatic balance





Ostriker et al. 2010 • Image: D. Hager & T. Grossmann

SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

Stefanie Walch
Philipp Girichidis
Thorsten Naab
Andrea Gatto
Simon C. O. Glover
Richard Wünsch
Ralf S. Klessen
Paul C. Clark
Thomas Peters
Dominik Derigs
Christian Baczynski

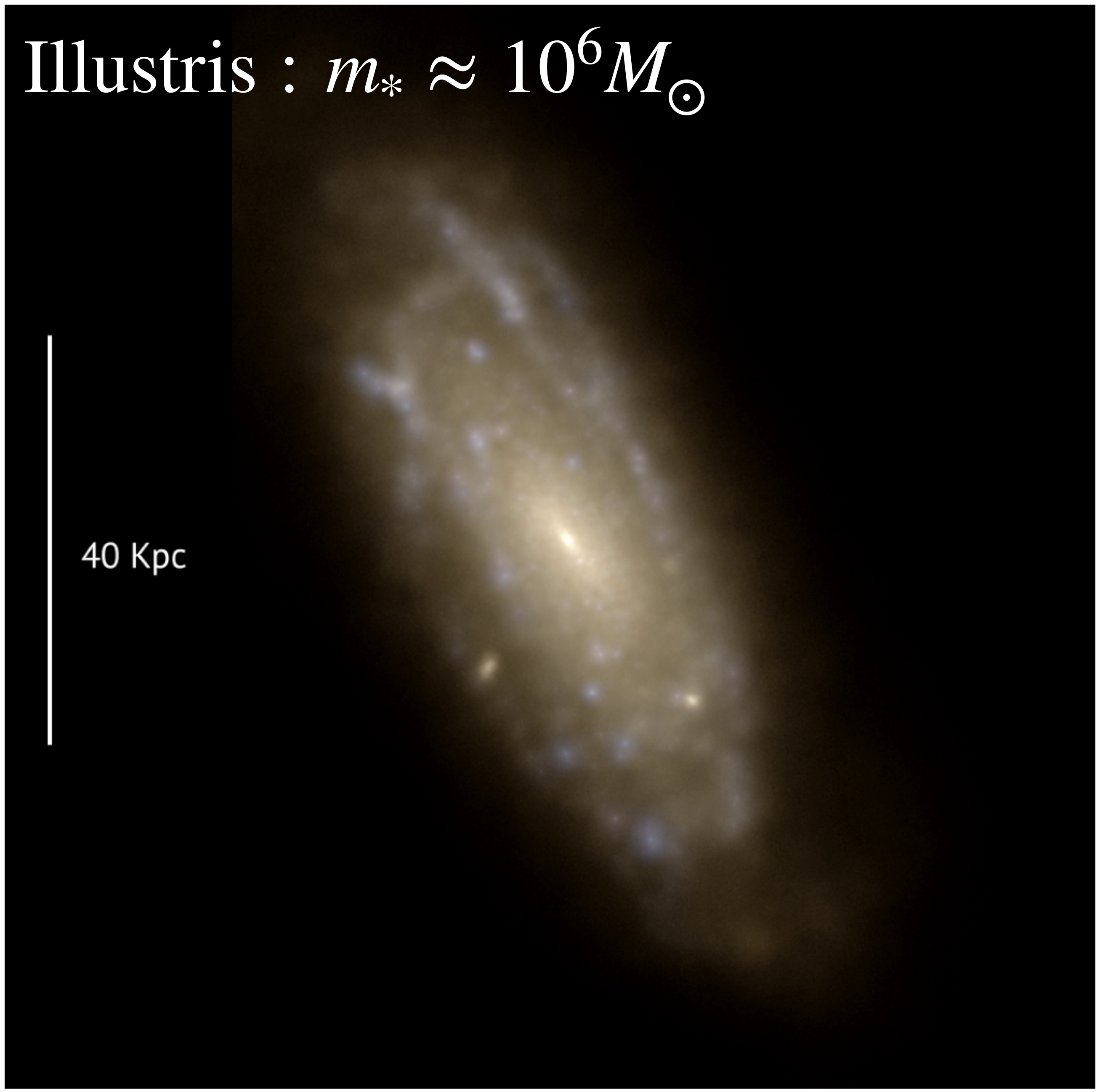
Walch et al., MNRAS 454, 238 (2015)
Girichidis et al., arXiv:1508.06646

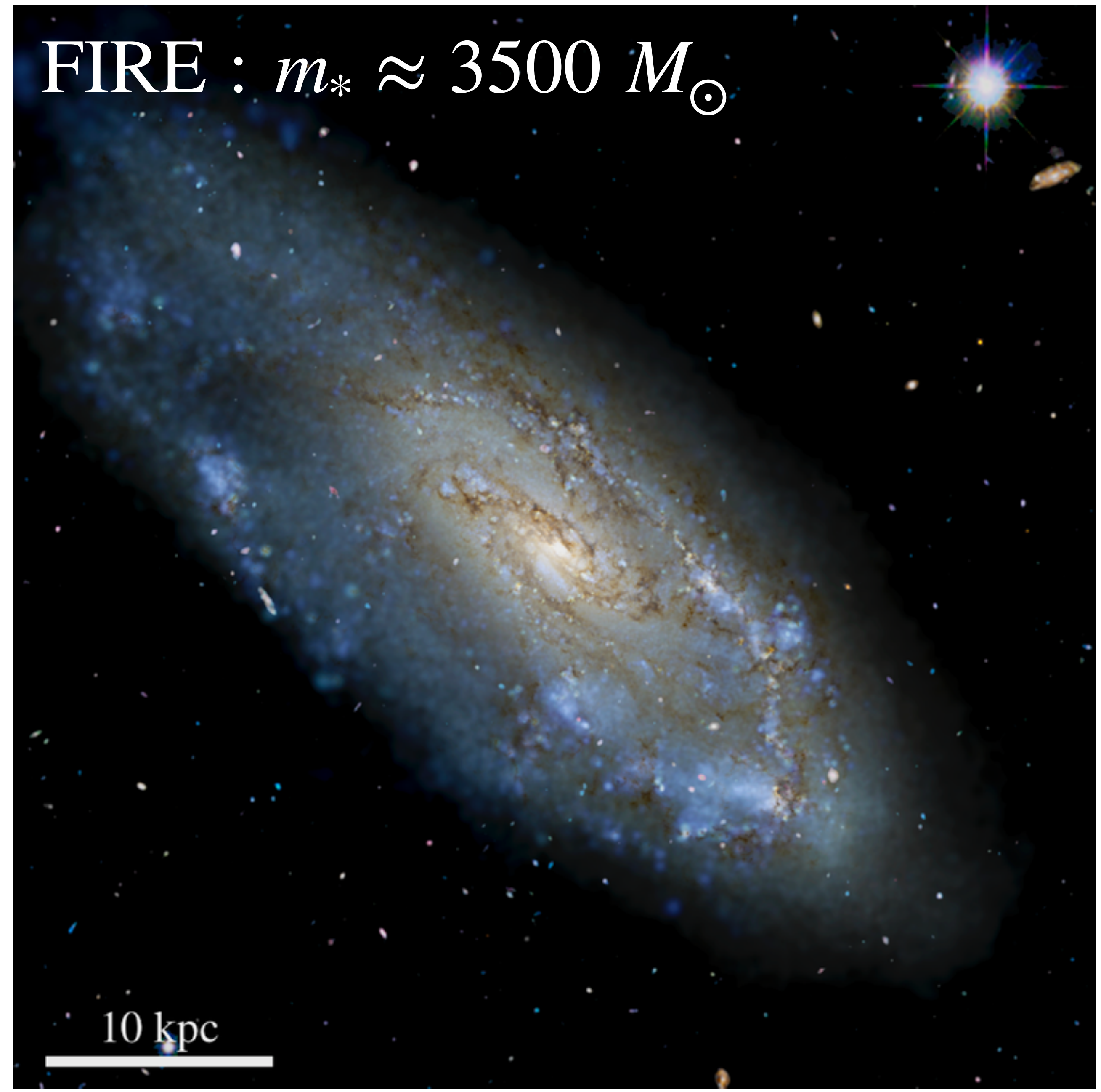
KS SN rate, random driving

SILCC project (website) • Walch et al. 2015

§10.4 • Feedback-regulated two-phase equilibrium

High resolution vs. large volume

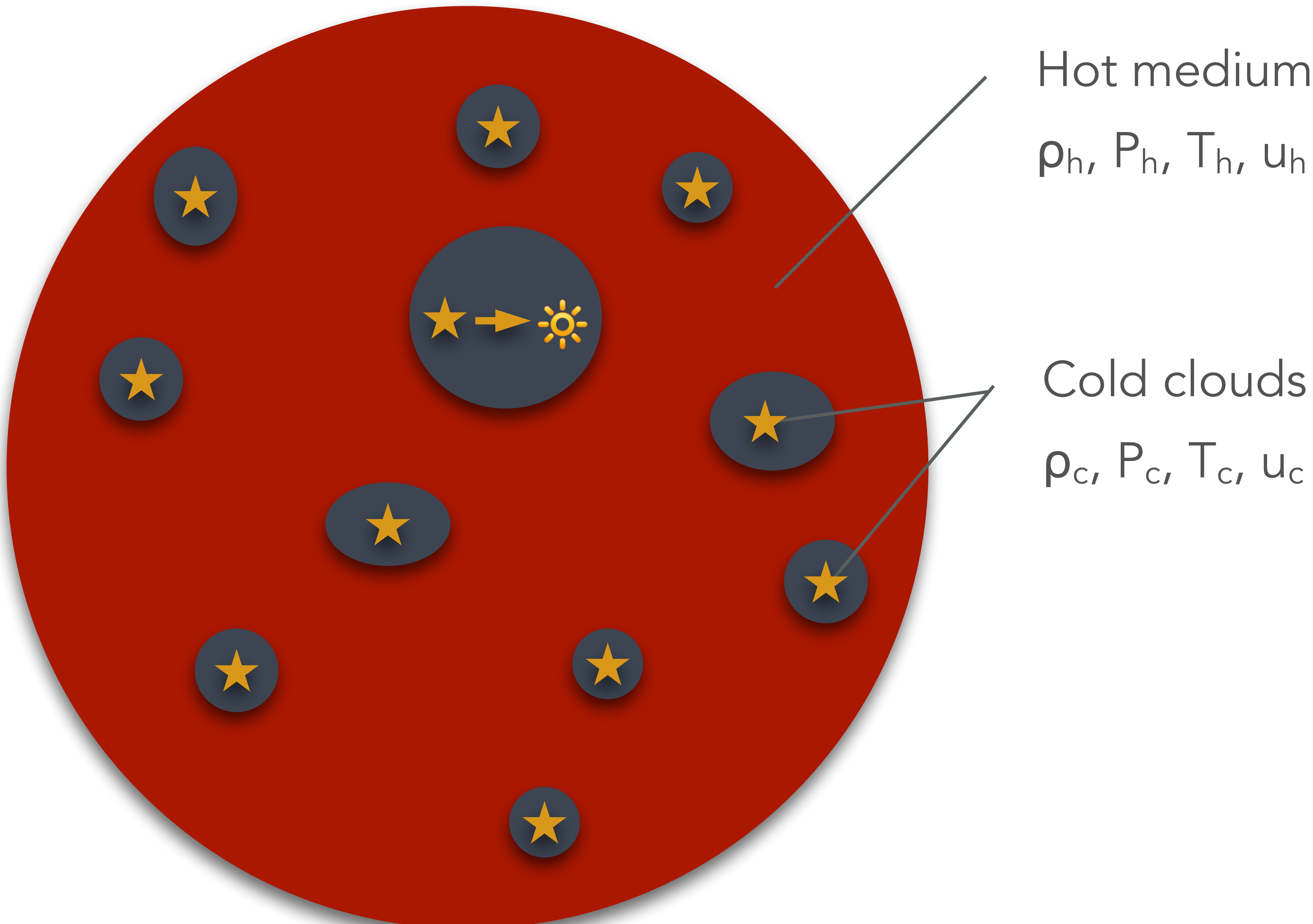




Illustris: Vogelsberger et al. 2013, 2014ab • **FIRE/FIRE-2:** Hopkins et al. 2014, 2017

The ISM model in Illustris

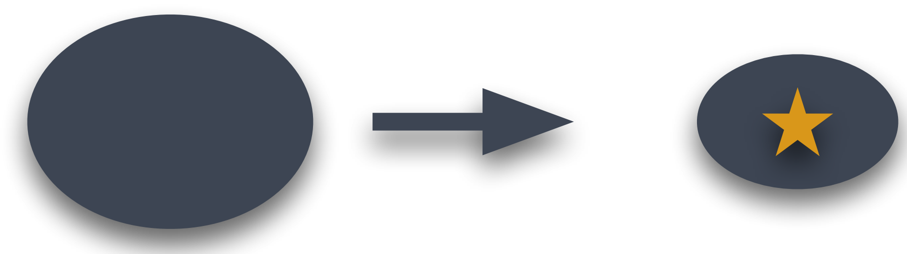
In each star-forming cell:



Springel & Hernquist 2003

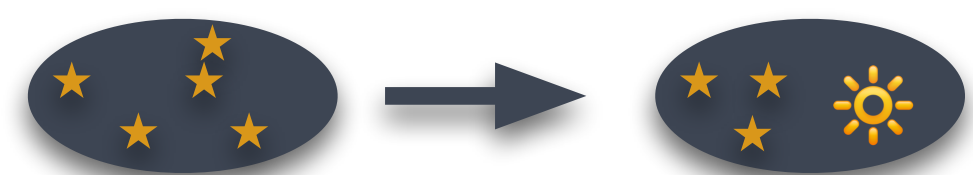
The ISM model in Illustris

Star formation: $\mathrm{SFR} = \frac{\rho_c}{t_\star}$



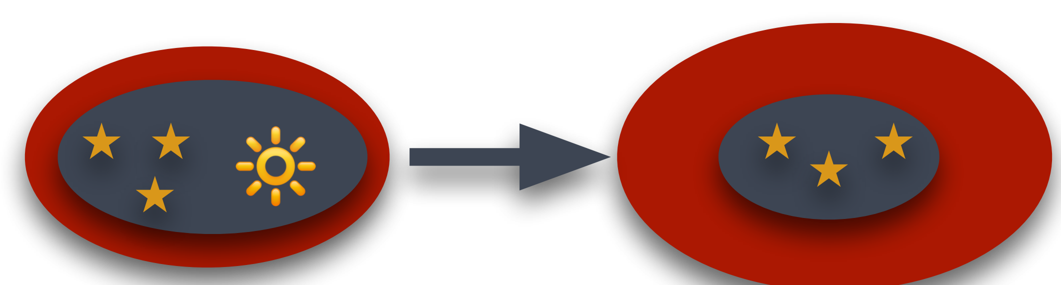
Supernovae:

$$\left.\begin{aligned}\frac{d\rho_\star}{dt} &= (1-\beta)\mathrm{SFR}\\ \frac{d}{dt}(\rho_h u_h) &= \beta \times u_{SN} \times \mathrm{SFR}\end{aligned}\right\}$$

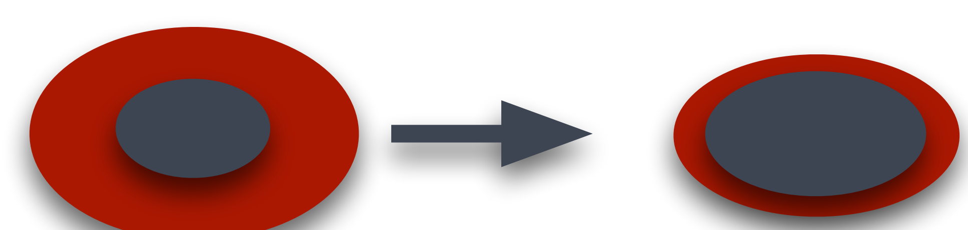


$$u_{SN} \equiv \frac{1-\beta}{\beta}\epsilon_{SN}$$

Cloud evaporation: $\frac{d\rho_c}{dt} = -A \times \beta \times \mathrm{SFR}$



Cooling: $\frac{d\rho_c}{dt} = \frac{\Lambda_{net}(\rho_c, u_h)}{u_h - u_c}$



Springel & Hernquist 2003

The SH03 model: equilibrium solution

Input / output

ρ → P, T, SFR

Energy of cold phase:

$$T_{\rm c} = const = 1000K \rightarrow u_{\rm c} << u_{\rm h}$$

Energy of hot phase:

$$\rho_{\rm h}\frac{du_{\rm h}}{dt} = \beta\frac{\rho_{\rm c}}{t_\star}\left[u_{\rm SN} + u_{\rm c} - u_{\rm h} - A(u_{\rm h} - u_{\rm c})\right] = 0$$

$$u_{\rm h} = \frac{u_{\rm SN}}{A+1} + u_{\rm c} \approx \frac{u_{\rm SN}}{A}$$

Total energy:

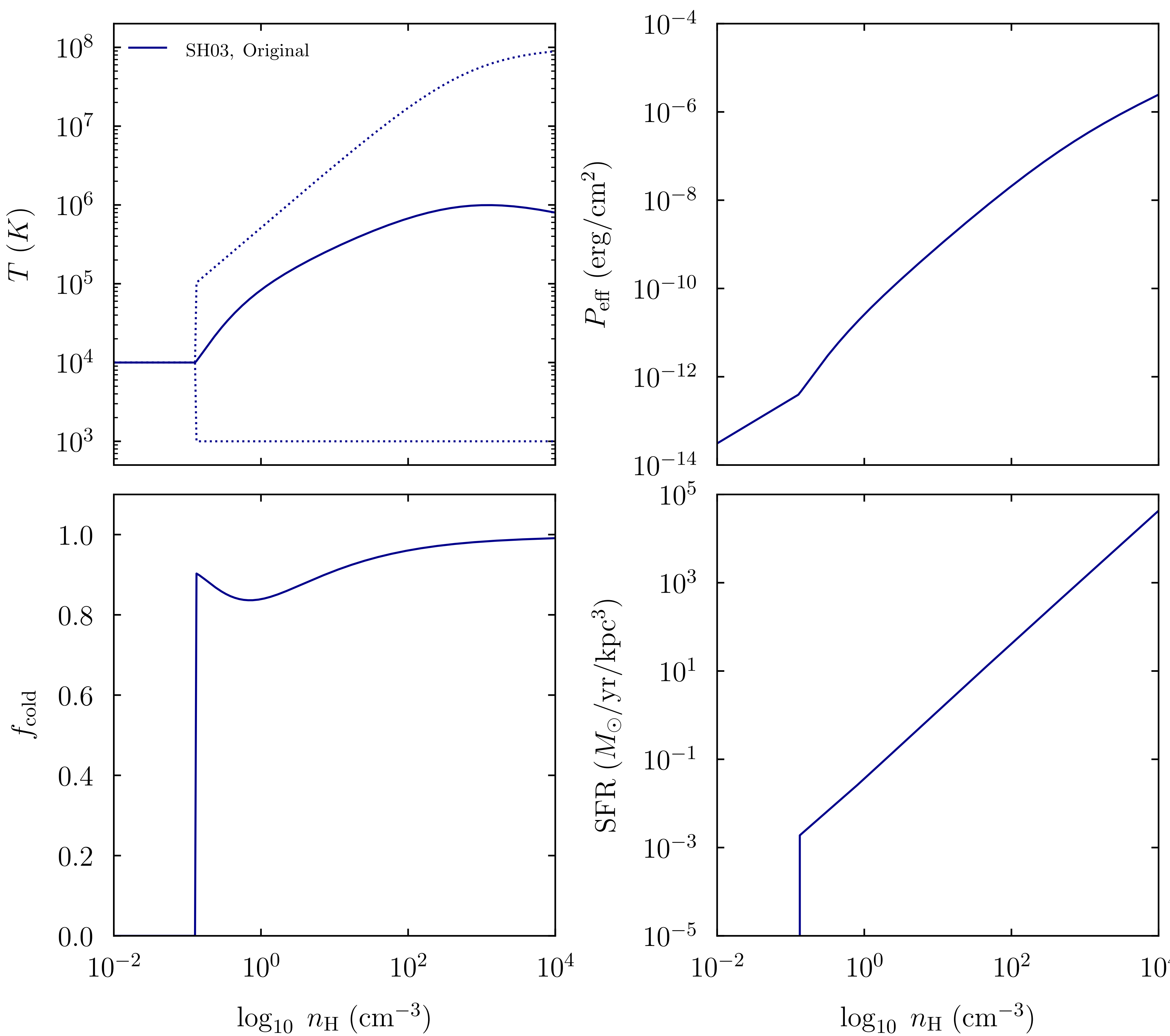
$$\frac{d}{dt}(\rho_{\rm h}u_{\rm h} + \rho_{\rm c}u_{\rm c}) = -\Lambda_{\rm net}(\rho_{\rm h}, u_{\rm h}) + \frac{\rho_{\rm c}}{t_\star}\beta u_{\rm SN} + (1-\beta)u_{\rm c}] = 0$$

$$\frac{\rho_{\rm c}}{t_\star} = \frac{\Lambda_{\rm net}(\rho_{\rm h}, u_{\rm h})}{\beta u_{\rm SN} - (1-\beta)u_{\rm c}}$$

$$x \equiv \frac{\rho_{\rm c}}{\rho} \qquad y \equiv \frac{t_\star\Lambda_{\rm net}(\rho, u_{\rm h})}{\rho\left[\beta u_{\rm SN} - (1-\beta)u_{\rm c}\right]} \qquad x = 1 + \frac{1}{2y} - \sqrt{\frac{1}{y} + \frac{1}{4y^2}}$$

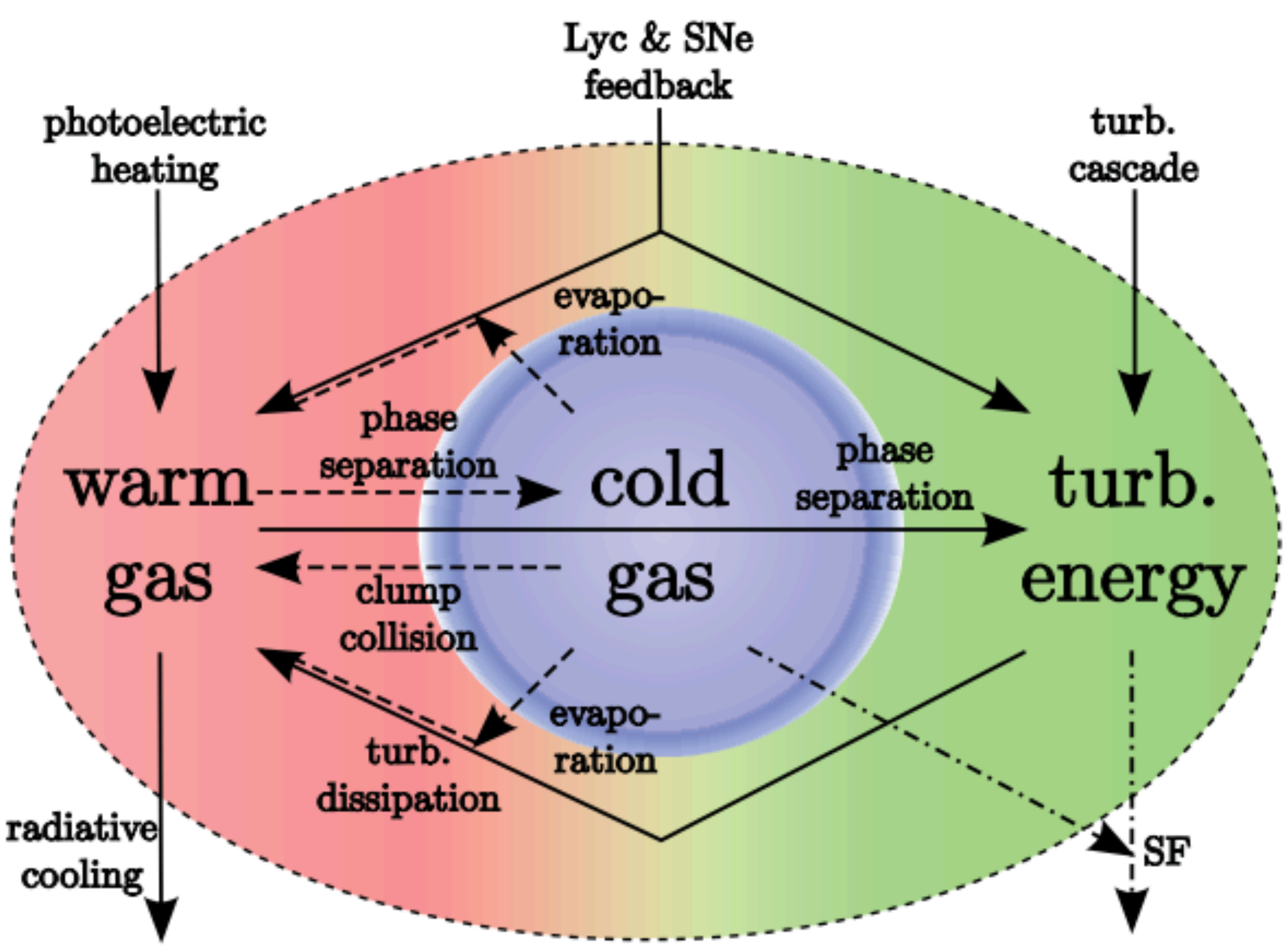
Springel & Hernquist 2003

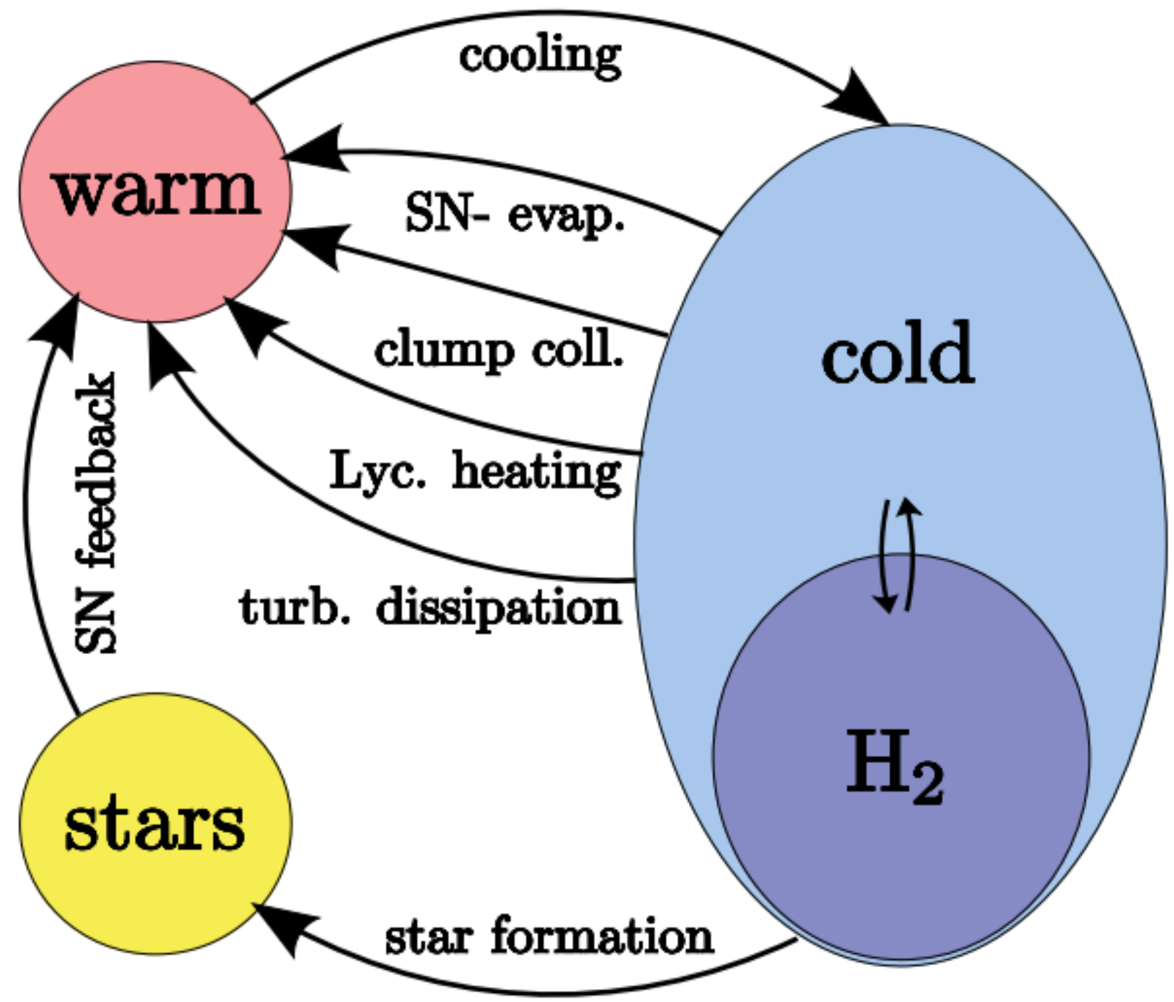
Predictions



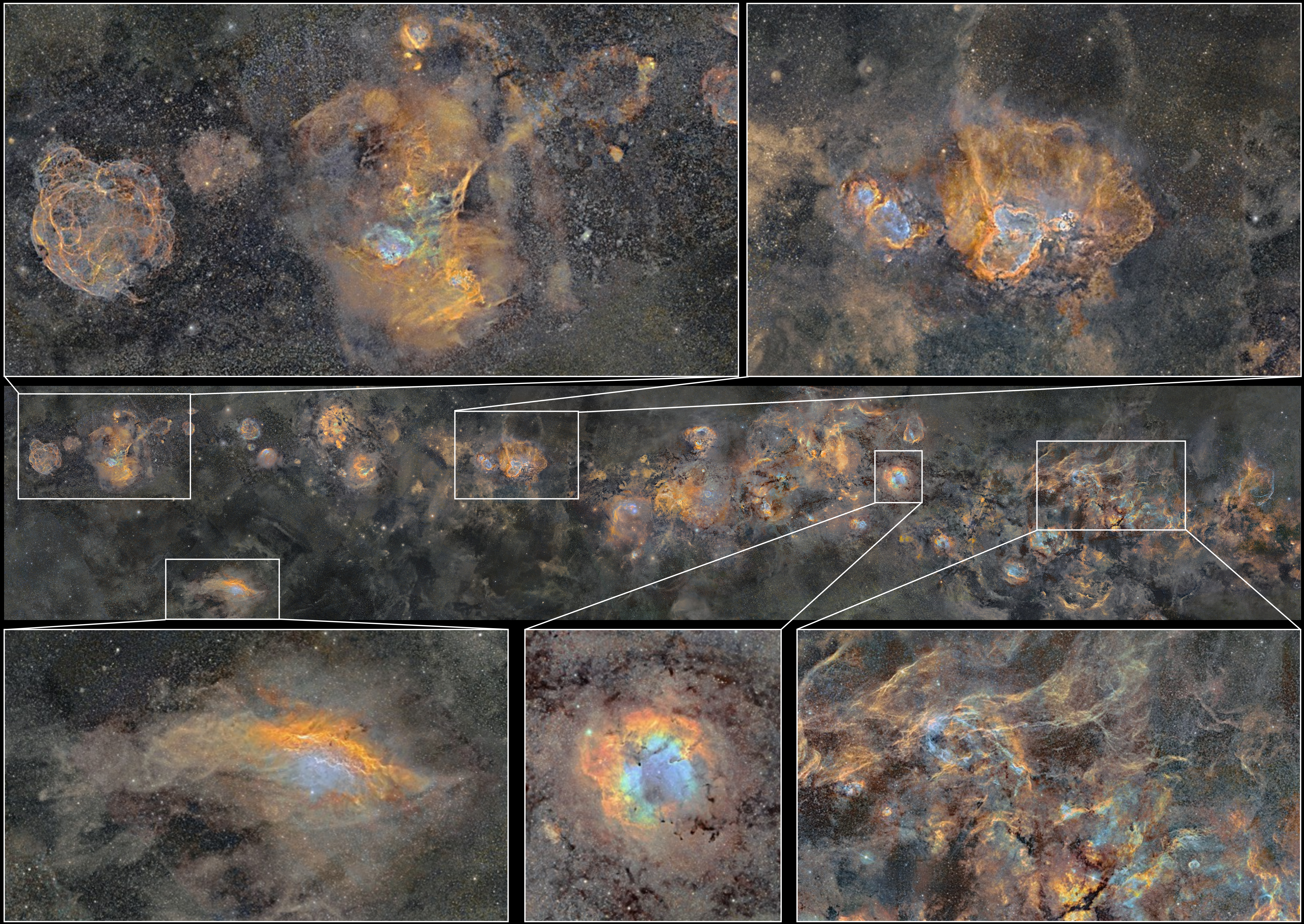
Springel & Hernquist 2003

How can we do better?





Braun & Schmidt 2012



J-P Metsavaino (amateur photography)

Reading

Draine

- §30.4
- §39.4