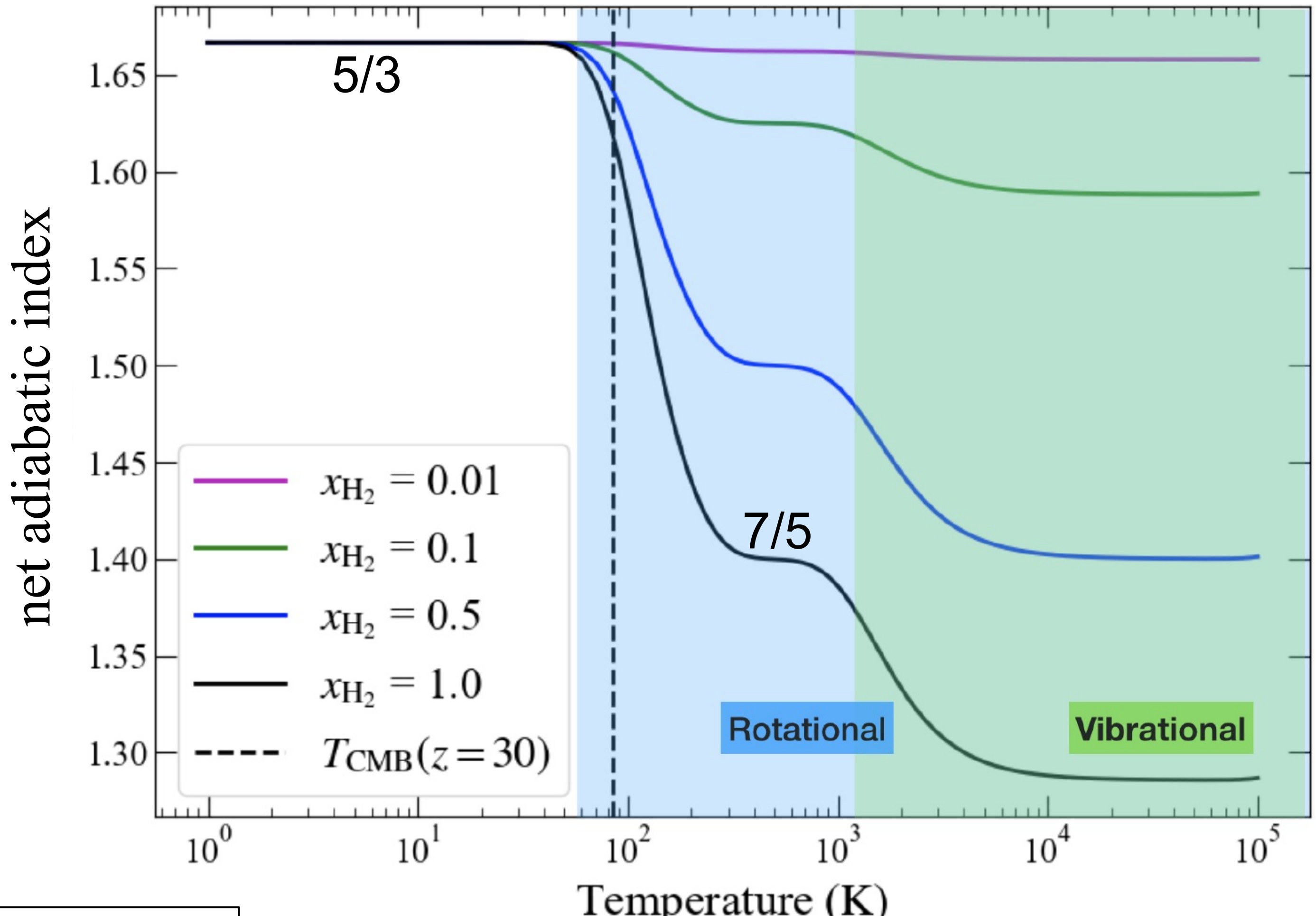
Astrophysical Gas Dynamics

TODAY:

- *The Equation of State (EOS) (→ recap notes)*
- *Implications/Modelling of the EOS (chemistry, heating, cooling)*
- *The validity of the gas/fluid approximation*
- *Gas/fluid instabilities (today: gravitational instability)*

Adiabatic Index

Temperature dependence of the adiabatic index (γ)



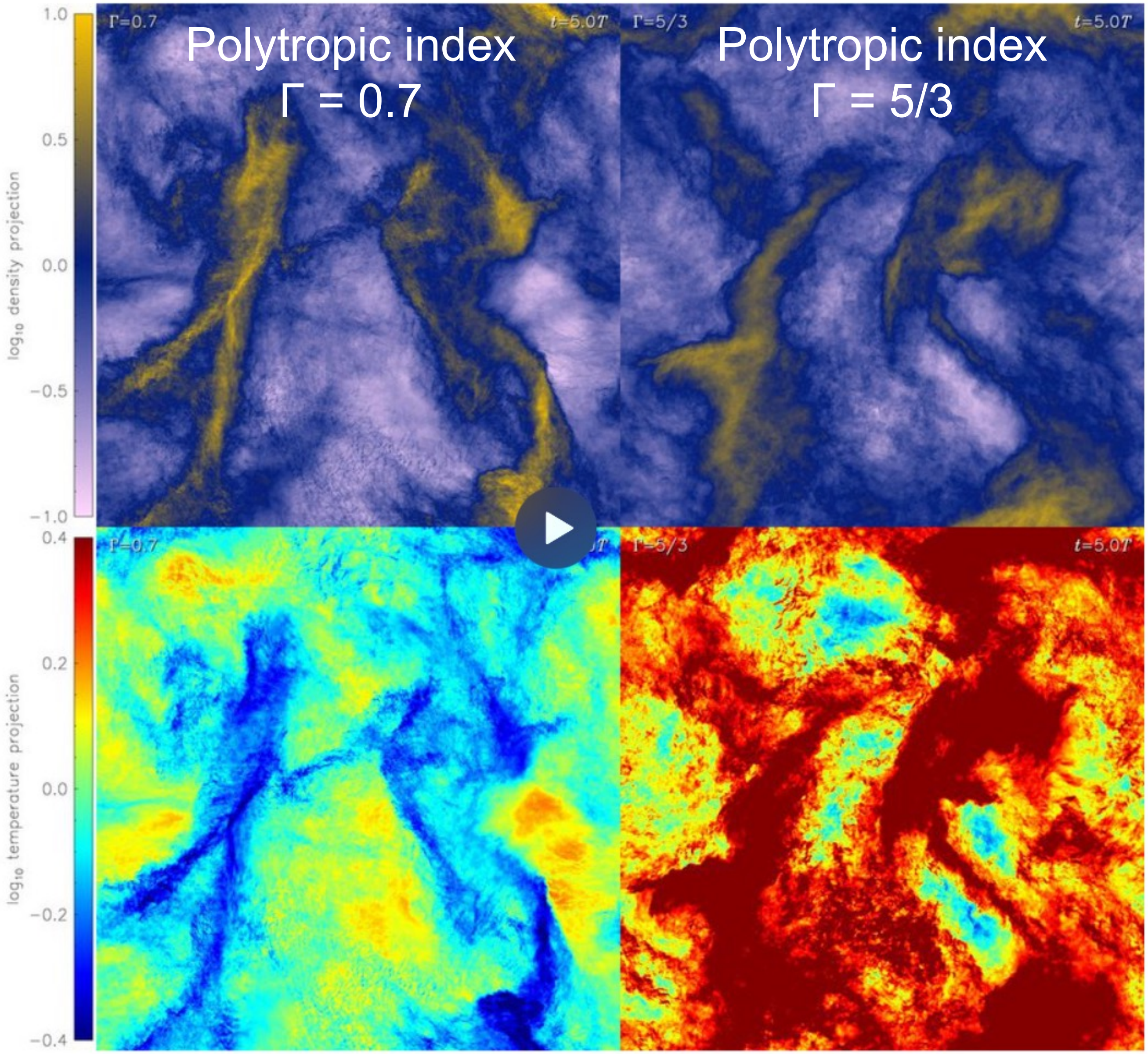
$\gamma = c_P/c_V = 1+2/f$

Number of degrees of freedom (f) depends on excitation of rotational and vibrational states (partition functions: T-dependence).

Sharda et al. (2019)

Equation of State – Polytropic EOS

$$P_{\mathrm{th}} = K\rho^{\Gamma}$$



Density

Temperature

Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/polytropic/polytropic.html

Federrath & Banerjee (2015)

Energy equation with heating and cooling

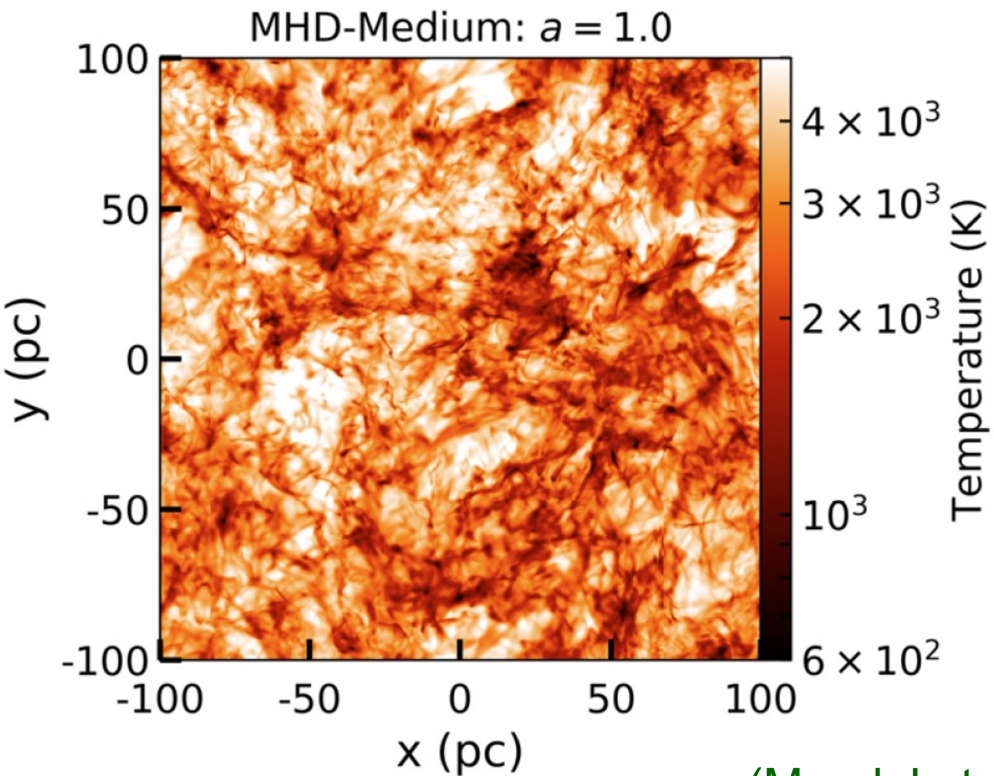
$$\frac{\partial}{\partial t}e_{\rm tot} + \nabla\cdot\left[(e_{\rm tot} + P_{\rm tot})\boldsymbol{v} - \frac{1}{4\pi}(\boldsymbol{B}\cdot\boldsymbol{v})\boldsymbol{B}\right] = \frac{1}{\rho}\left[\frac{\rho}{\mu m_{\rm H}}\Gamma - \left(\frac{\rho}{\mu m_{\rm H}}\right)^2\Lambda(T)\right]$$

Heating:

$$\Gamma = 2\times10^{-26}\ {\rm erg\ s^{-1}}$$

Cooling:

$$\frac{\Lambda(T)}{\Gamma} = 10^7\exp\left(\frac{-1.184\times10^5}{T+1000}\right) + 1.4\times10^{-2}\sqrt{T}\exp\left(\frac{-92}{T}\right)\ {\rm cm^3}$$



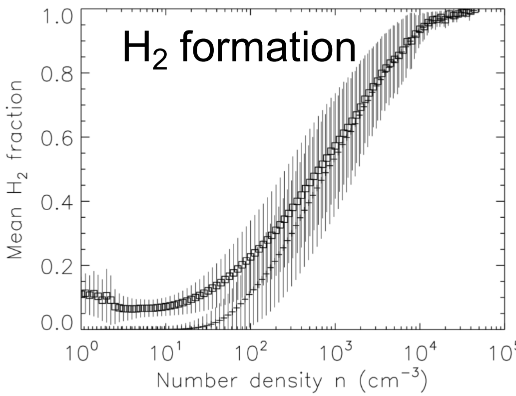
- Photoelectric heating from small grains and polycyclic aromatic hydrocarbons (PAHs)
- Heating and ionization from cosmic rays and X-rays
- H_2 formation and destruction
- Atomic and molecular line cooling

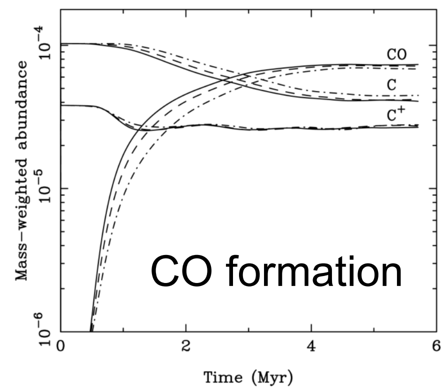
(Sutherland & Dopita 1993; Koyama & Inutsuka 2002; Vazquez-Semadeni et al. 2007)

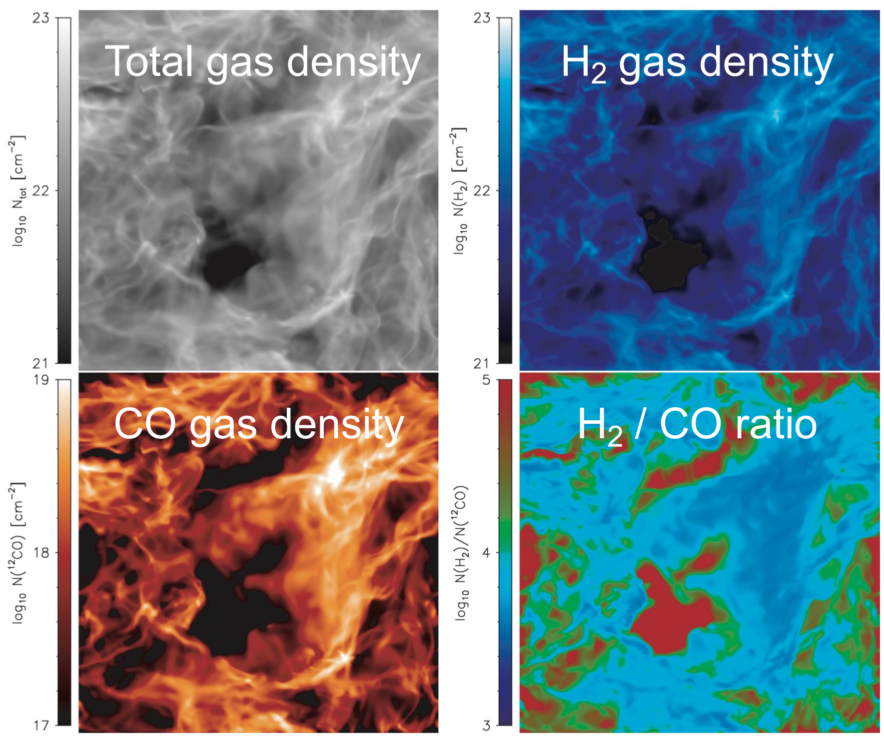
(Mandal et al. 2020)

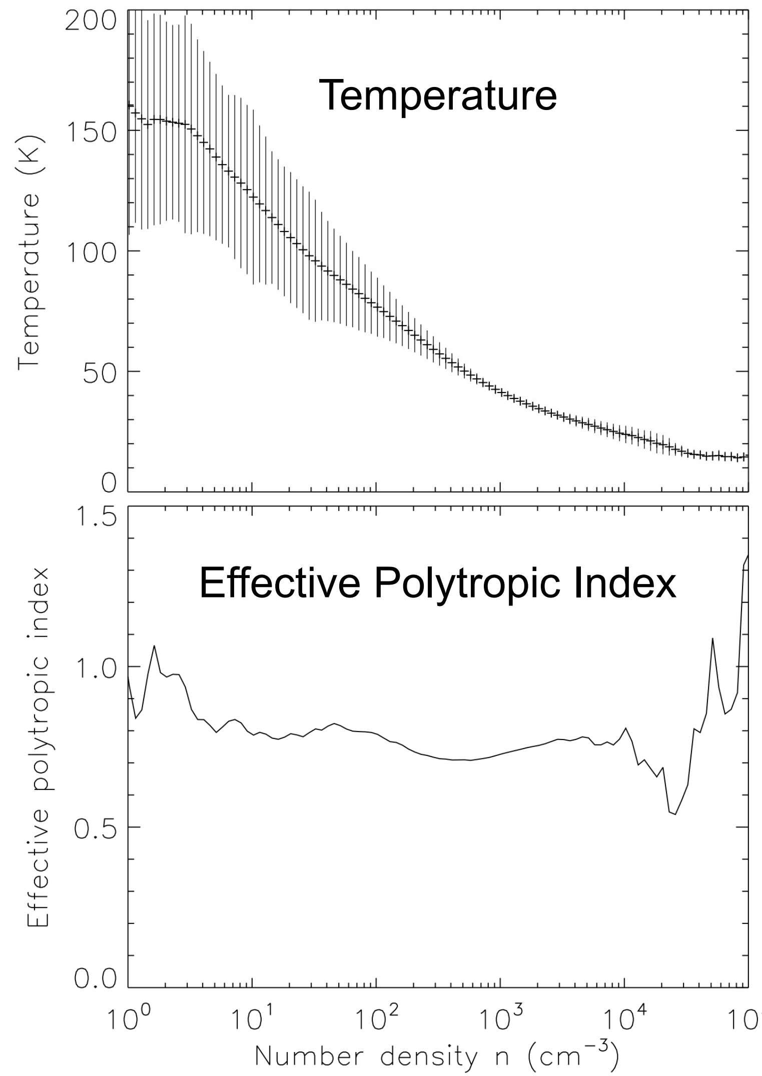
Equation of State – Chemistry / Heating / Cooling

Chemistry / Heating / Cooling: (Glover et al. 2007, 2010)



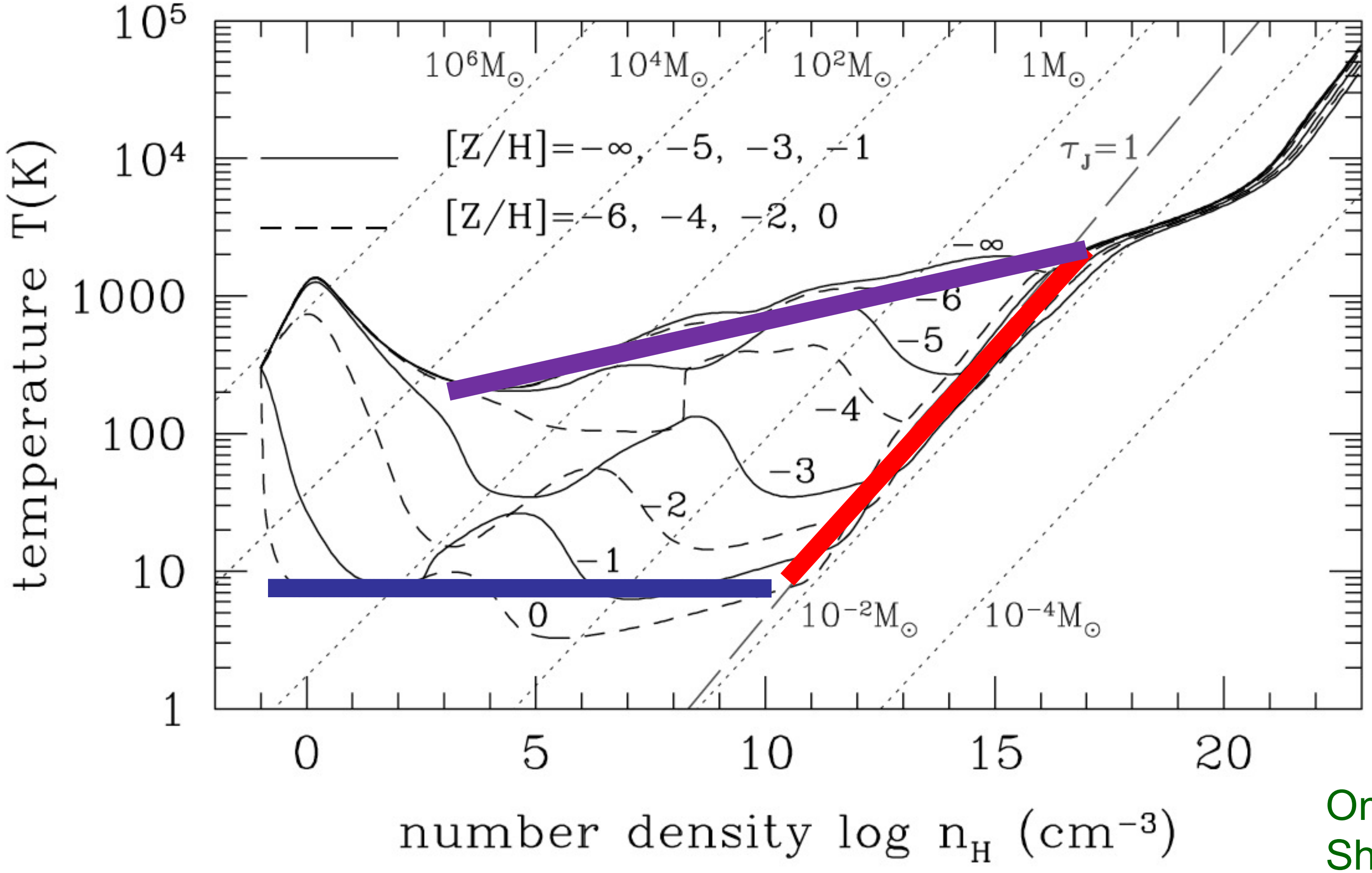






Equation of State – Chemistry / Heating / Cooling

Chemistry / Heating / Cooling: (Glover+2007, 2010, Micic+2012, Clark+2012)



Omukai et al. (2005);
Sharda et al. (2020)

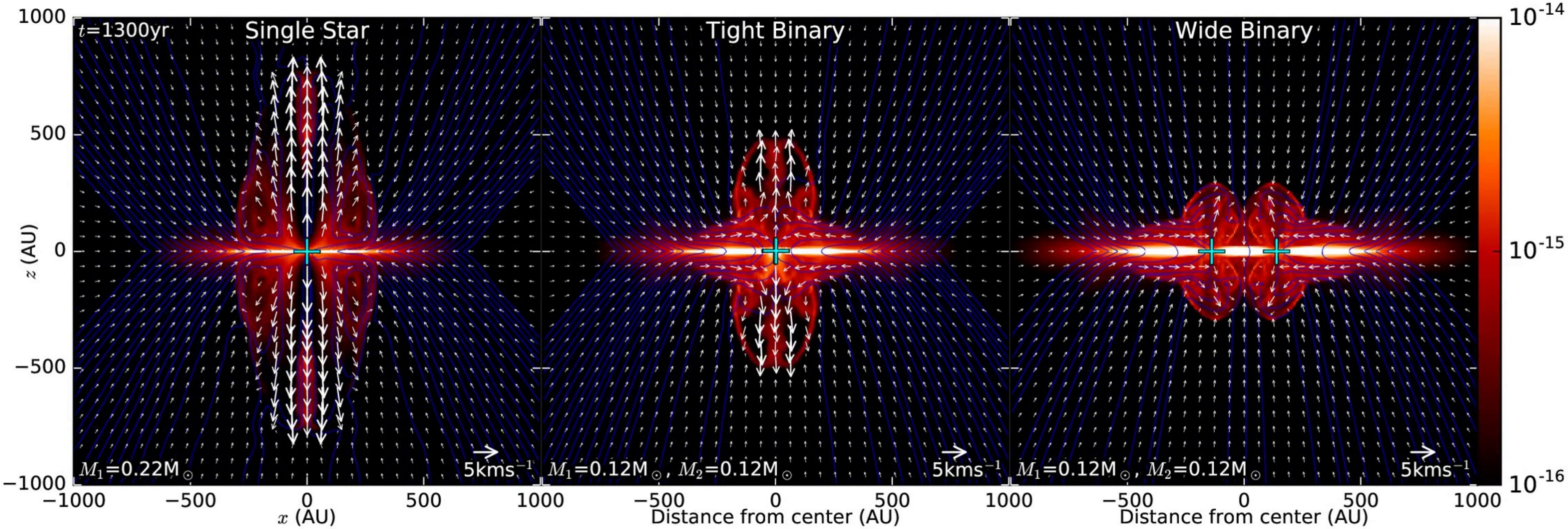
Molecule formation in high-density gas: $t_{form} \sim 1/n$

Micic et al. (2012),
Hollenbach et al. (1971)

Equation of State – Polytropic EOS for Star Formation

$$P_{\rm th} = K\rho^{\Gamma} \quad \text{with} \quad \Gamma = \begin{cases} 1 & \text{for} \quad \rho \le \rho_1 \equiv 2.50 \times 10^{-16}\,\mathrm{g\,cm^{-3}}, \\ 1.1 & \text{for} \quad \rho_1 < \rho \le \rho_2 \equiv 3.84 \times 10^{-13}\,\mathrm{g\,cm^{-3}}, \\ 1.4 & \text{for} \quad \rho_2 < \rho \le \rho_3 \equiv 3.84 \times 10^{-8}\,\mathrm{g\,cm^{-3}}, \\ 1.1 & \text{for} \quad \rho_3 < \rho \le \rho_4 \equiv 3.84 \times 10^{-3}\,\mathrm{g\,cm^{-3}}, \\ 5/3 & \text{for} \quad \rho > \rho_4 . \end{cases}$$

Movies available:
https://www.mso.anu.edu.au/~chfeder/pubs/binary_jets/binary_jets.html



Kuruwita et al. (2017); Gerrard et al. (2018)

Equation of State – Chemistry / Heating / Cooling

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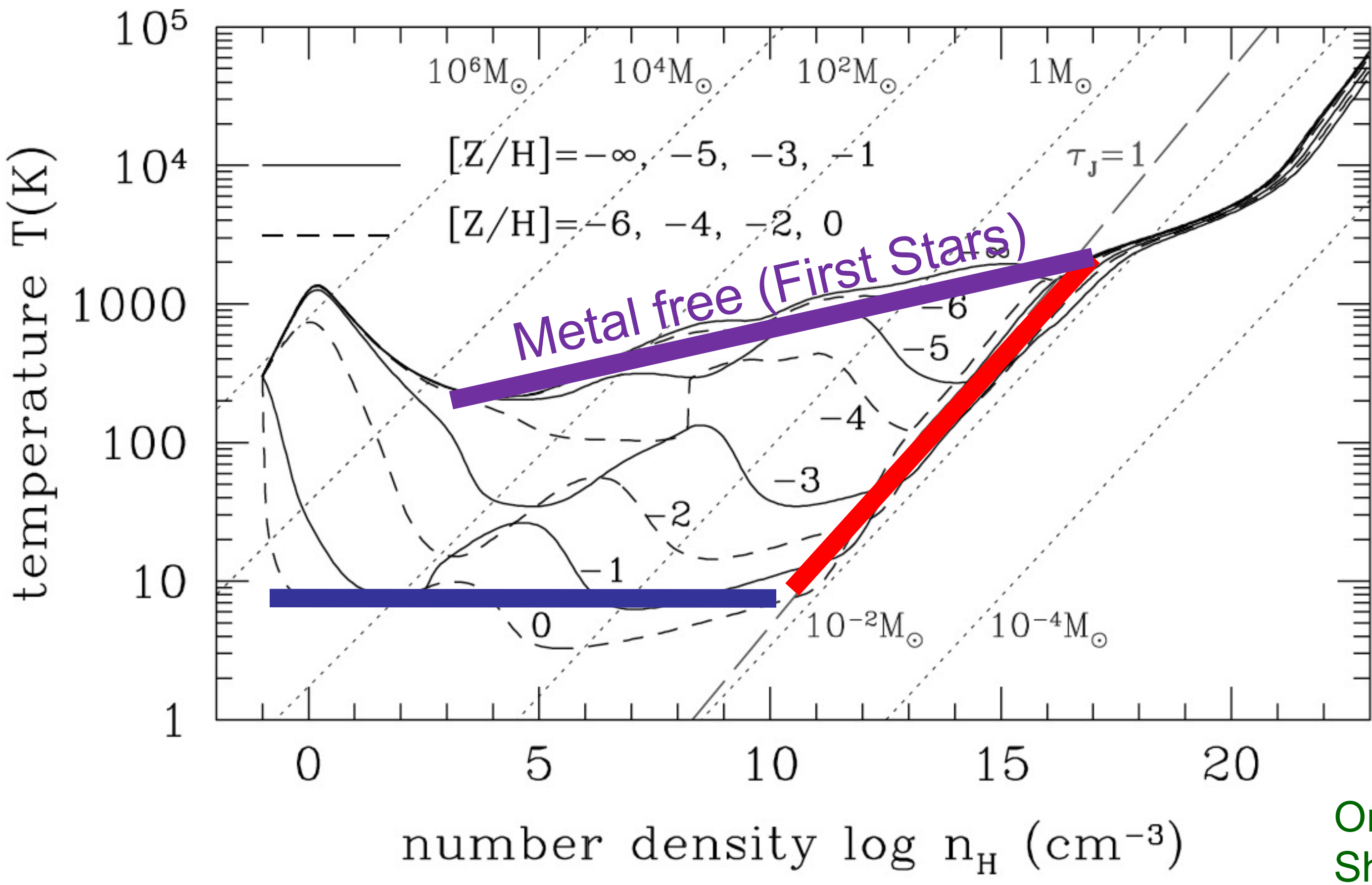

Omukai et al. (2005); Sharda et al. (2020)

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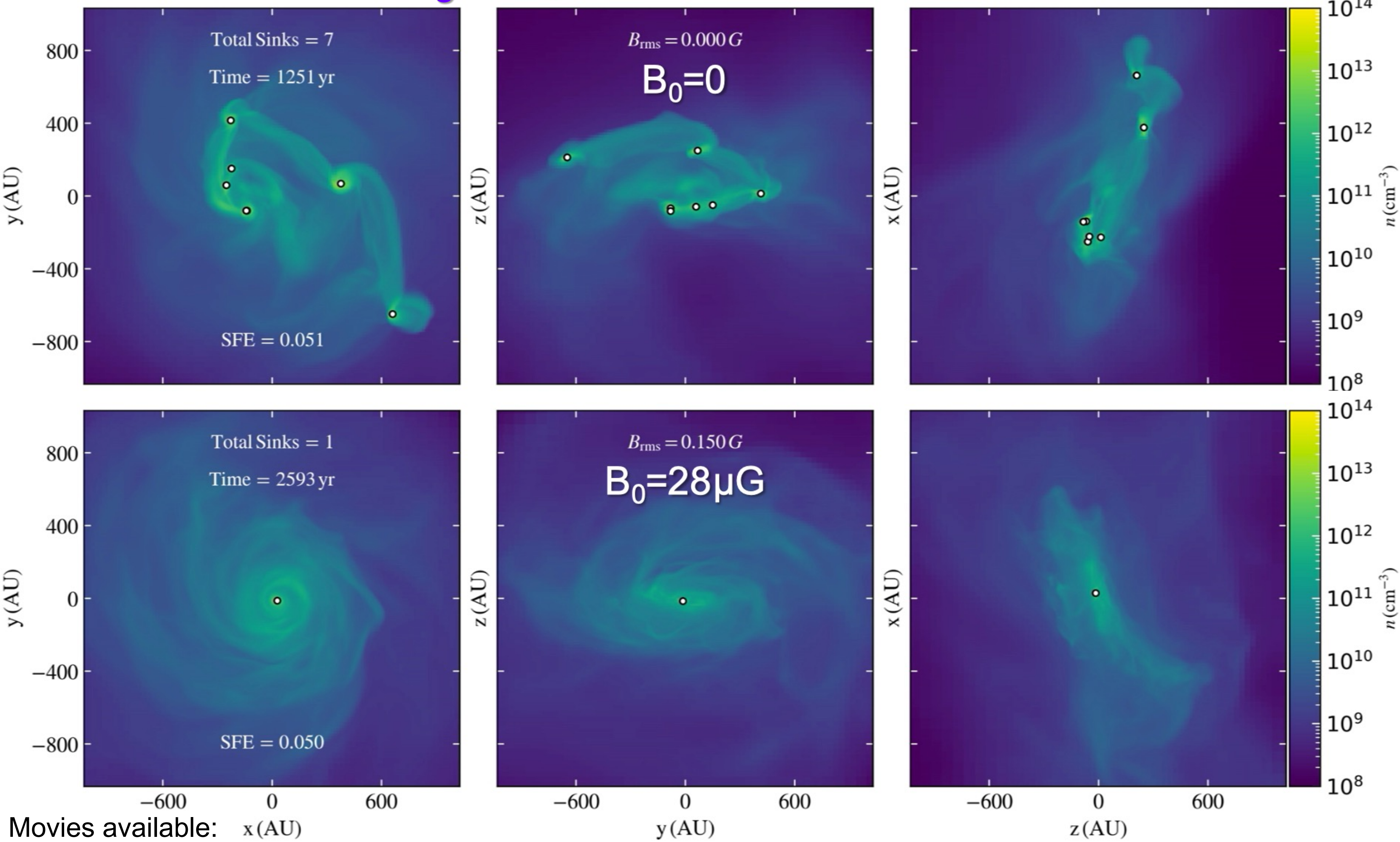
Primordial Star Formation (First Stars)

The role of magnetic fields for the formation of the First Stars



Movies available:
https://www.mso.anu.edu.au/~chfeder/pubs/first_stars/first_stars.html

Sharda et al. (2020)

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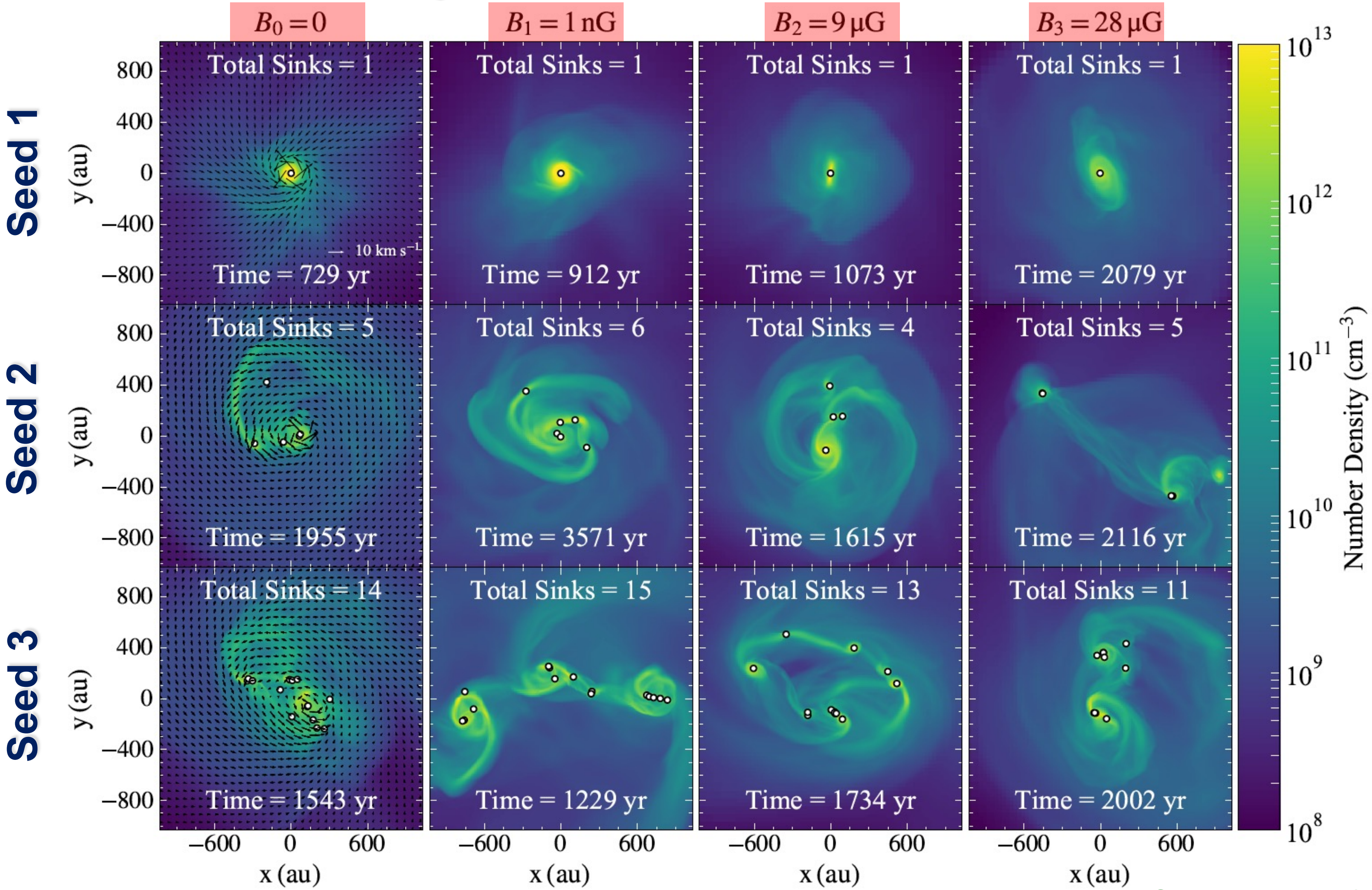

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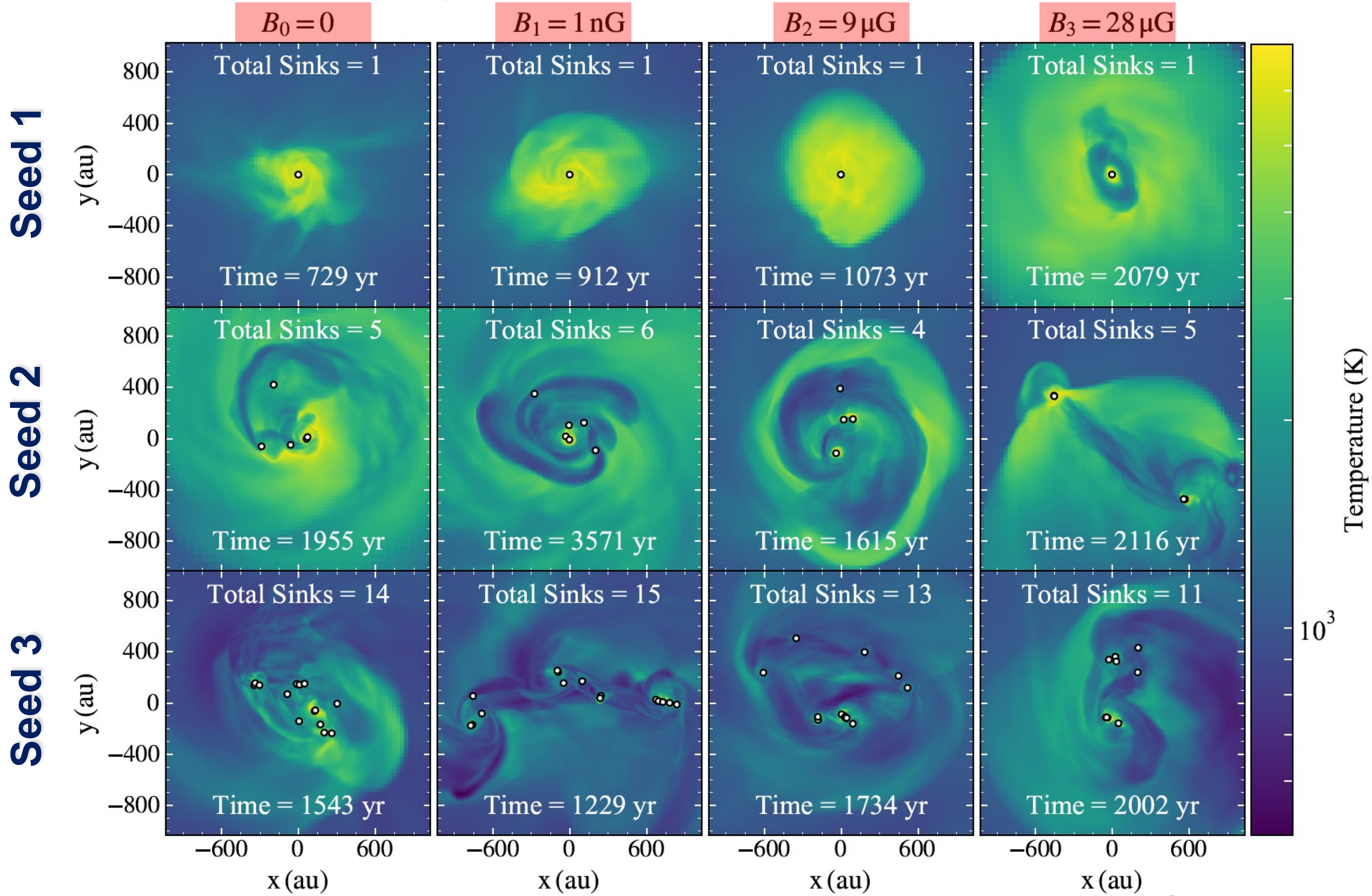

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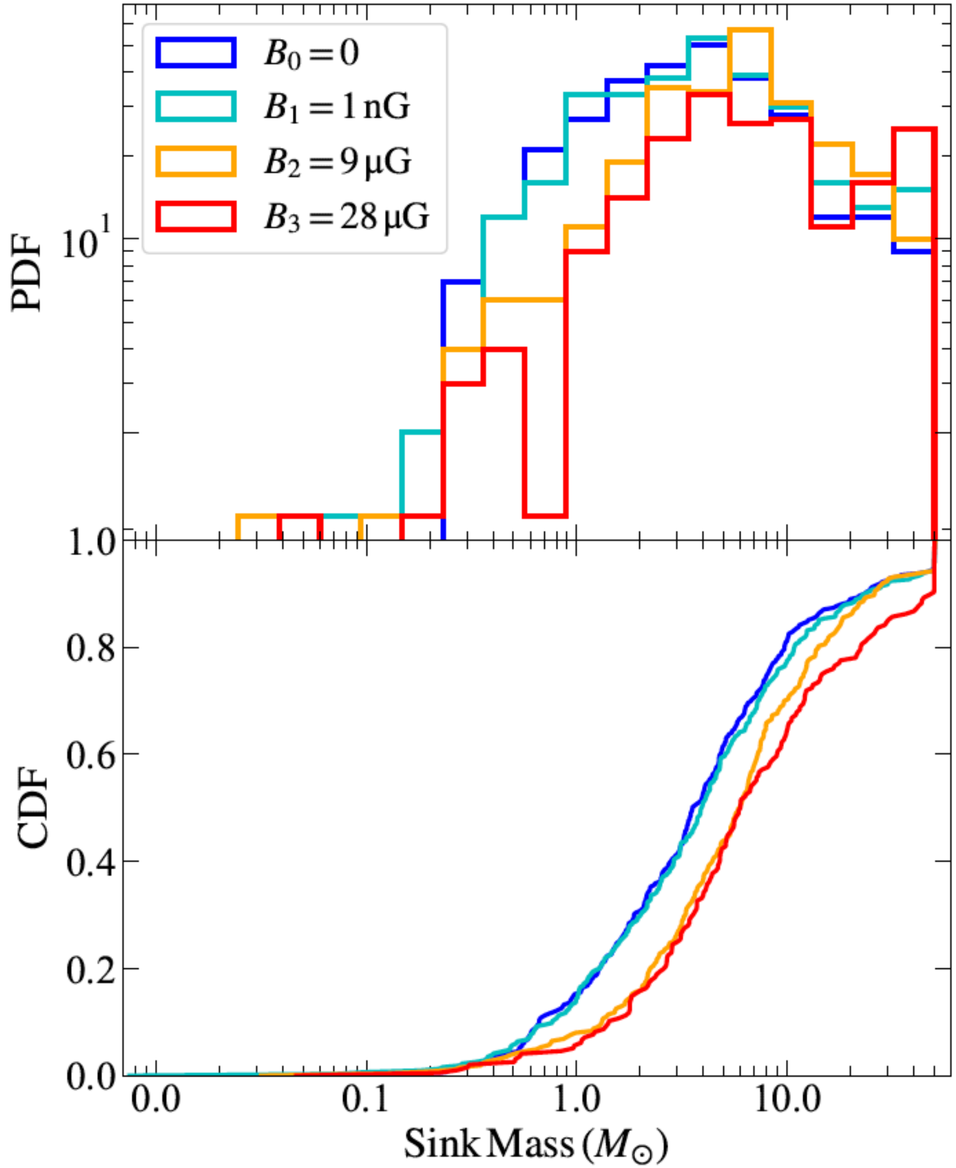

→ B field tends to suppress fragmentation, but also stochasticity

Sharda et al. (2020)

Astrophysical Gas Dynamics

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Validity of the Gas/Fluid Approach

Gas/Fluid approximation only valid if particle mean free path much less than scales of interest

(particle collisions are sufficiently frequent on microscopic level)

Medium	Particle mean free path	Size scale
Water	9×10^{-9} cm	...
Air	5×10^{-6} cm	...
Solar core	2×10^{-8} cm	$\sim R_{sol}/4 \sim 2 \times 10^{10}$ cm
Solar corona	1×10^{8} cm	$\sim R_{sol} \sim 7 \times 10^{10}$ cm
Solar wind	1×10^{13} cm	$\sim$ AU $\sim 1.5 \times 10^{13}$ cm
Interstellar medium	$1 \times 10^{5-15}$ cm	$\sim$ pc $\sim 3 \times 10^{18}$ cm
Galaxy cluster (intracluster medium)	1×10^{23} cm	$\sim$ Mpc $\sim 10^{24}$ cm

If the gas/fluid approximation breaks down, kinetic treatment is required.

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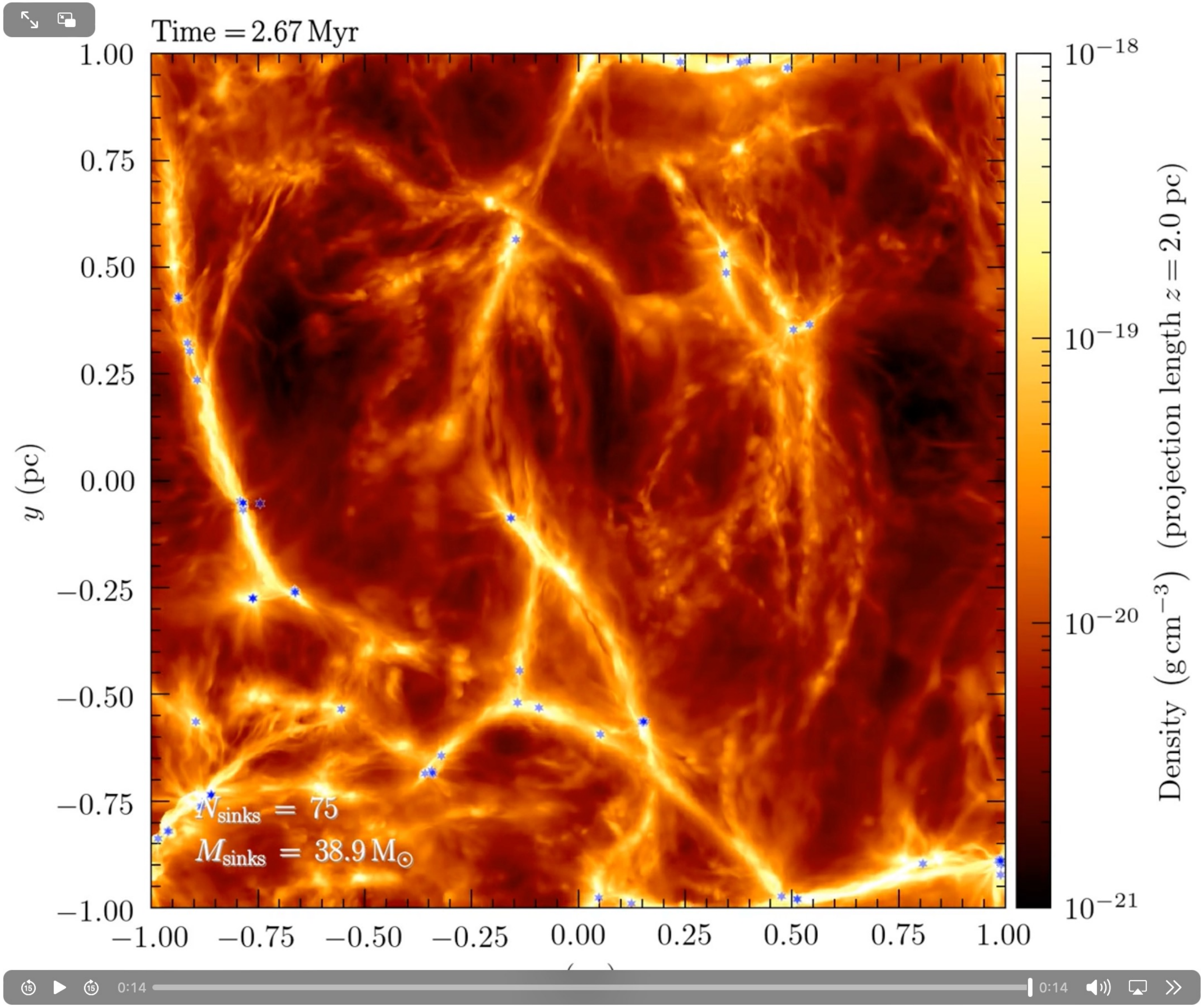
Image credit: M. S. Povich

Jeans fragmentation

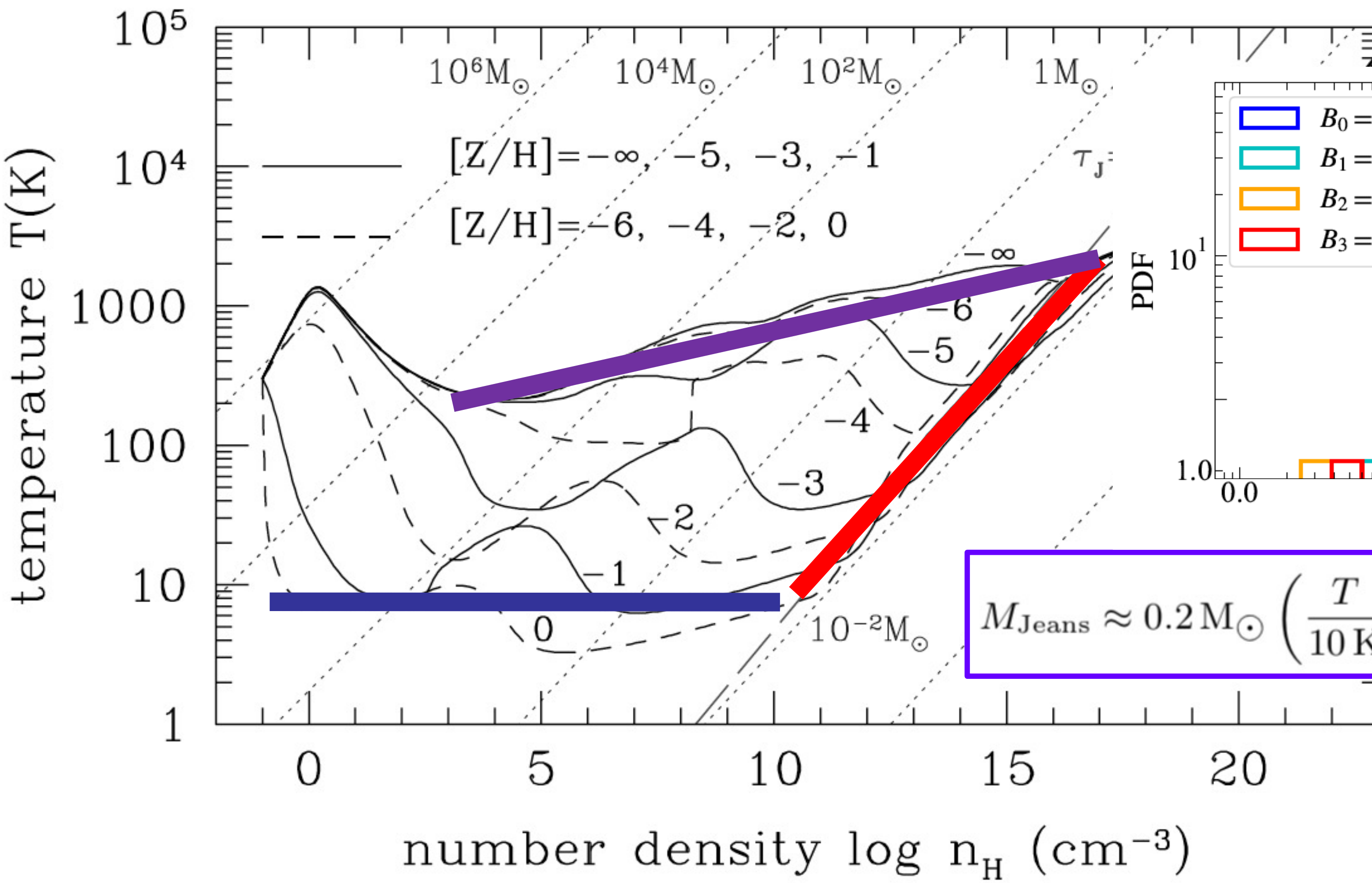
(Federrath 2015 MNRAS)

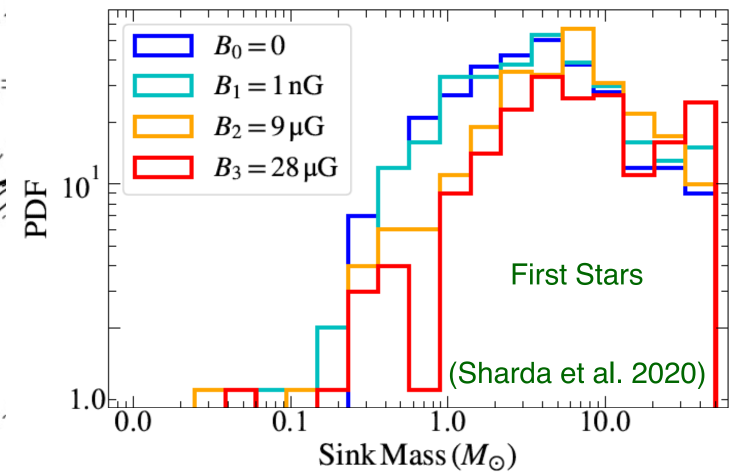
Movies available: http://www.mso.anu.edu.au/~chfeder/pubs/ineff_sf/ineff_sf.html



Equation of State – Chemistry / Heating / Cooling

Chemistry / Heating / Cooling: (Glover+2007, 2010, Micic+2012, Clark+2012)





$$M_{\rm Jeans} \approx 0.2\,{\rm M}_\odot \left(\frac{T}{10\,{\rm K}}\right)^{3/2} \left(\frac{n}{10^5\,{\rm cm}^{-3}}\right)^{-1/2}$$

Omukai et al. (2005);
Sharda et al. (2020)

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Toomre (gravitational disc) instability

Condition for disc instability

$$\frac{c_s \kappa}{\pi G \Sigma} < 1$$

c_s is the speed of sound

κ is the epicyclic frequency

Σ is the surface density

(Toomre 1964; Romeo et al. 2010)

For Jeans instability, we basically compare thermal pressure versus gravity.
For Toomre, we compare thermal pressure + rotation versus gravity.

Notes:

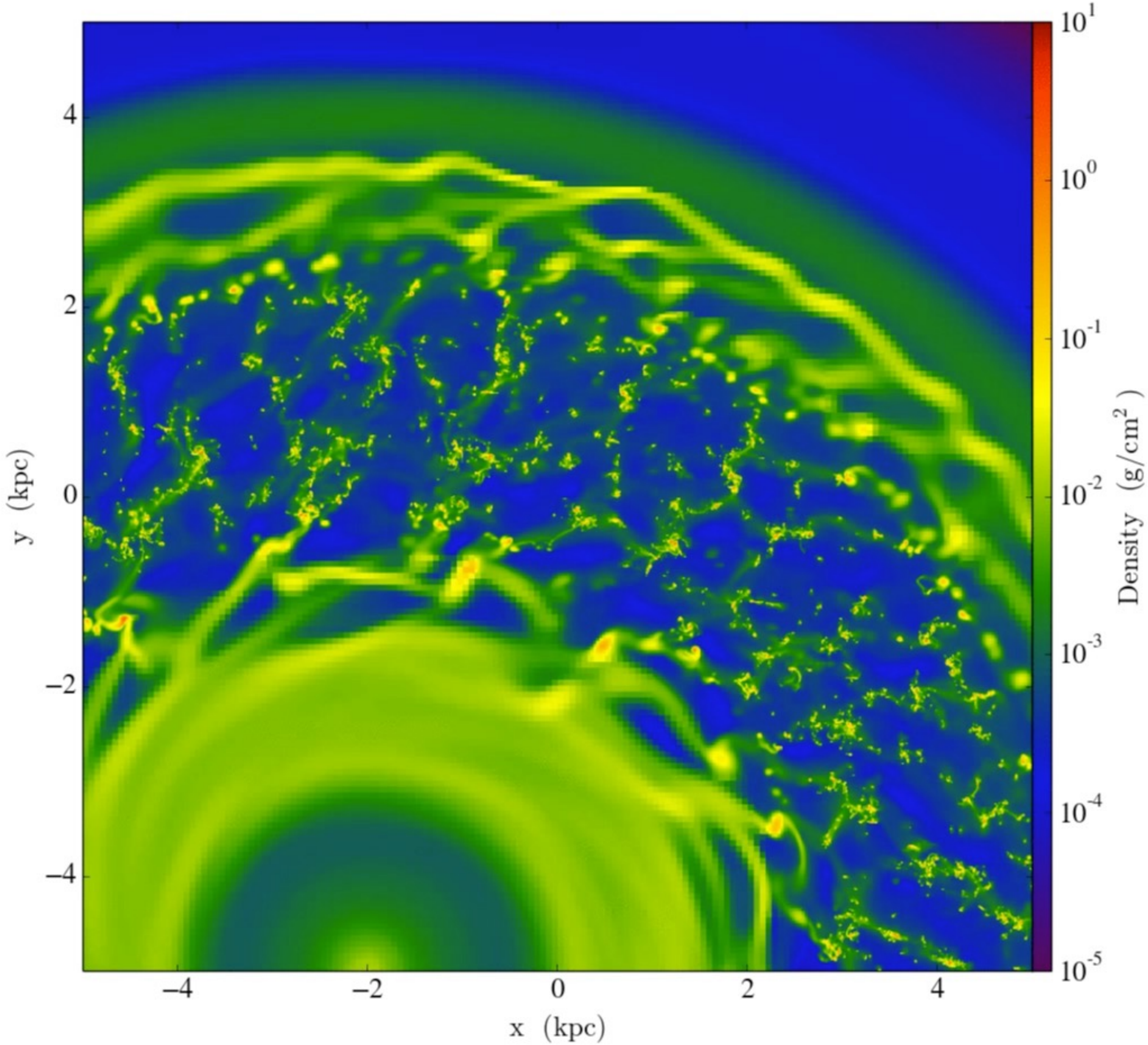
- Surface density can have gas and star contribution
- Sound speed could be modified to include turbulence and/or magnetic pressure (e.g., turbulent, magnetic Jeans length)

(Federrath & Klessen 2012)

Toomre (gravitational disc) instability

Movies available: https://www.mso.anu.edu.au/~chfeder/pubs/turb_driv_gal/turb_driv_gal.html

For example, simulations of disc galaxies:



(Jin et al. 2017)

Astrophysical Gas Dynamics

NEXT TIME:

- *Gas/fluid instabilities: Kelvin-Helmholtz instability*

Image credit: M. S. Povich