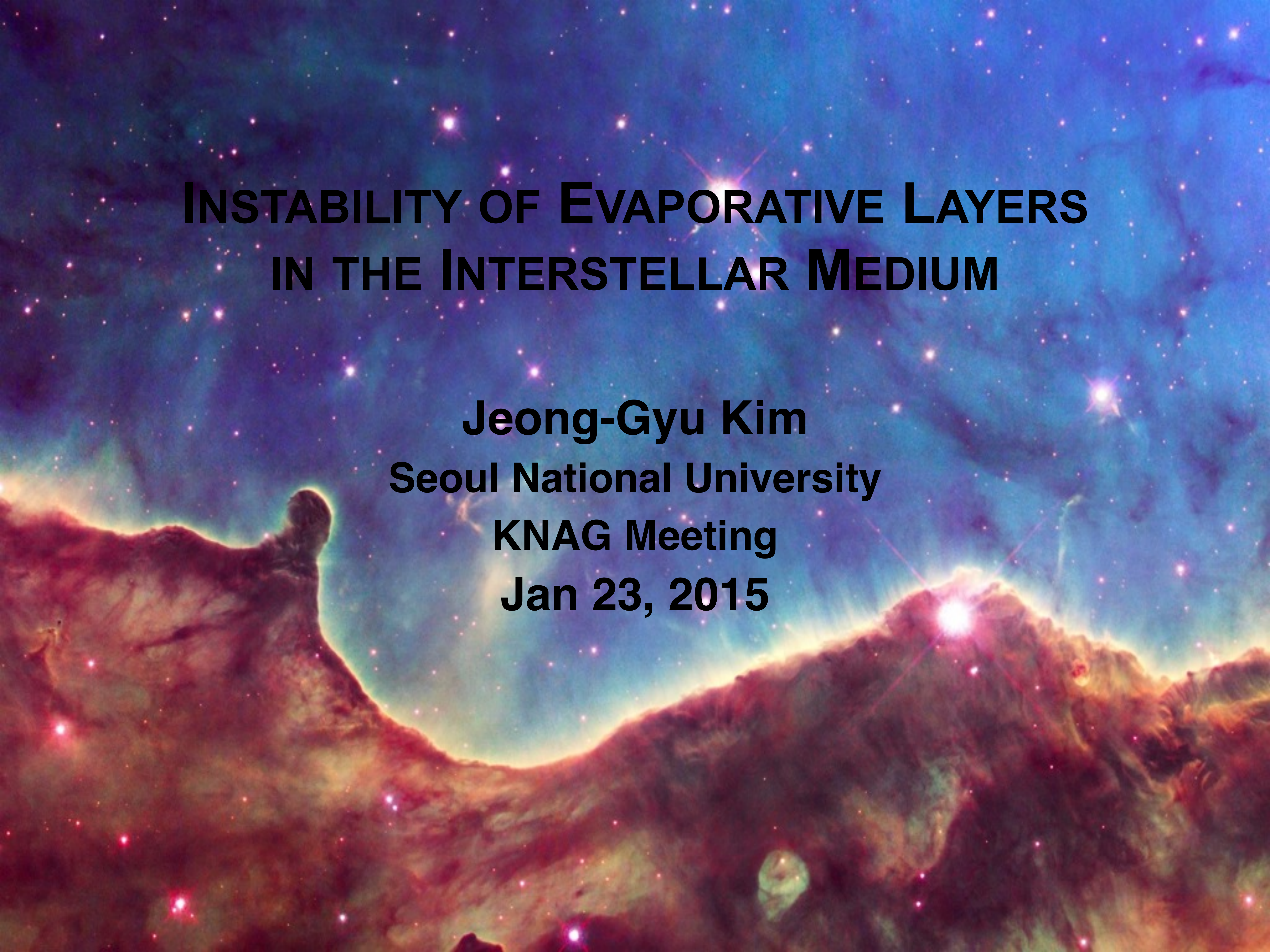

Instability of Evaporative Layers in the Interstellar Medium

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KNAG Meeting

Jan 23, 2015

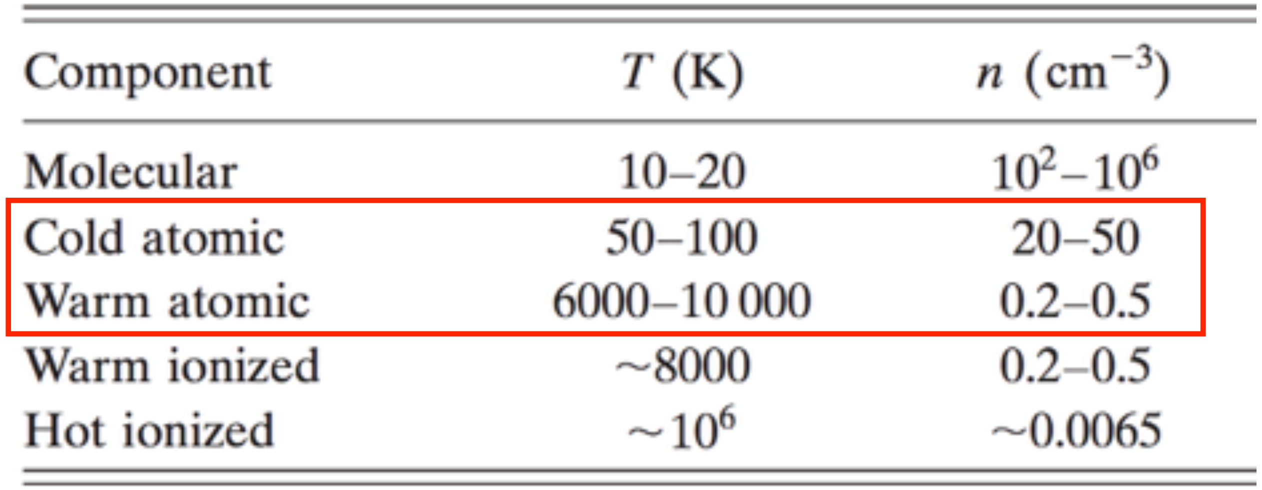
1. Instability of Evaporation Fronts in Neutral Atomic ISM

Kim and Kim (2013)

2. Instability of Magnetized Ionization Fronts

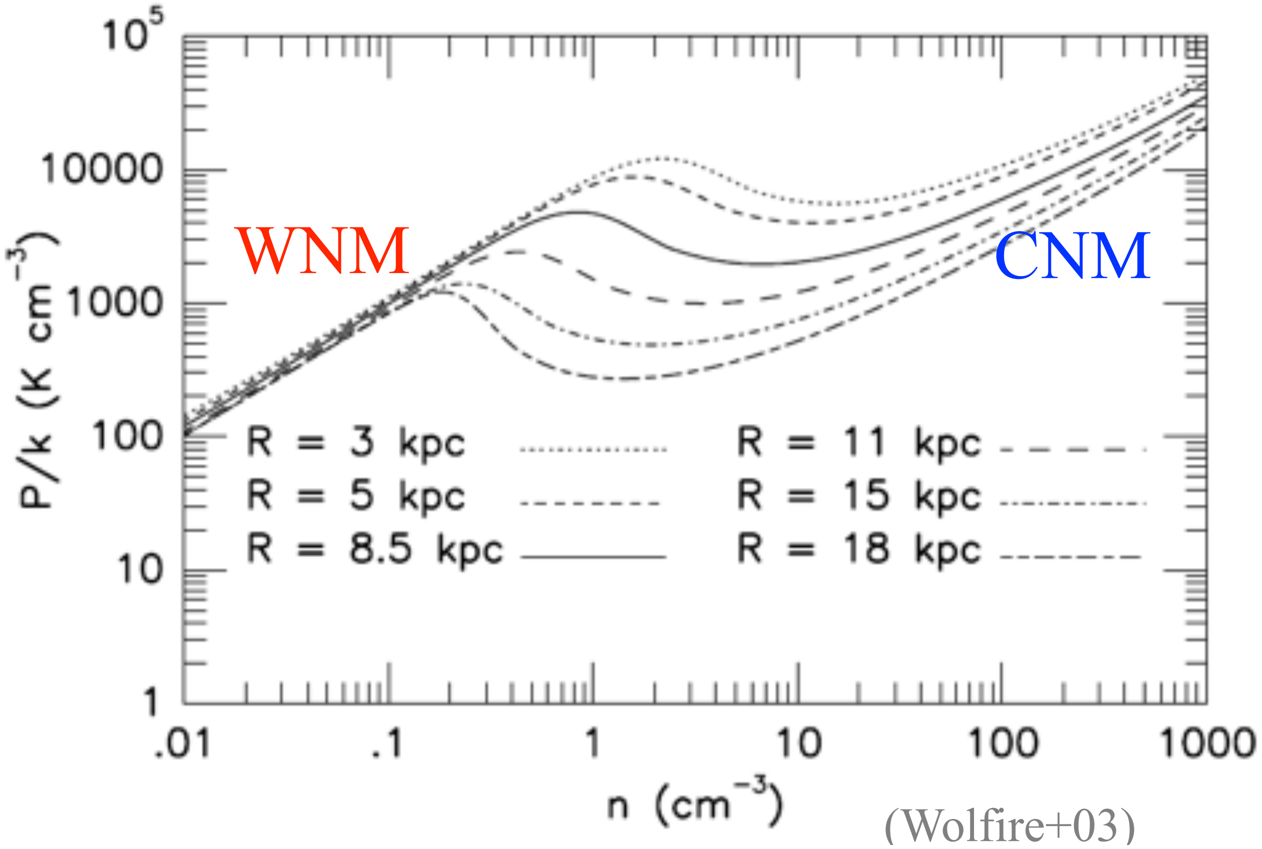
Kim and Kim (2014)

Two-phase Model for Neutral ISM



Component	T (K)	n (cm^{-3})
Molecular	10–20	10^2–10^6
Cold atomic	50–100	20–50
Warm atomic	6000–10 000	0.2–0.5
Warm ionized	~8000	0.2–0.5
Hot ionized	~10^6	~0.0065

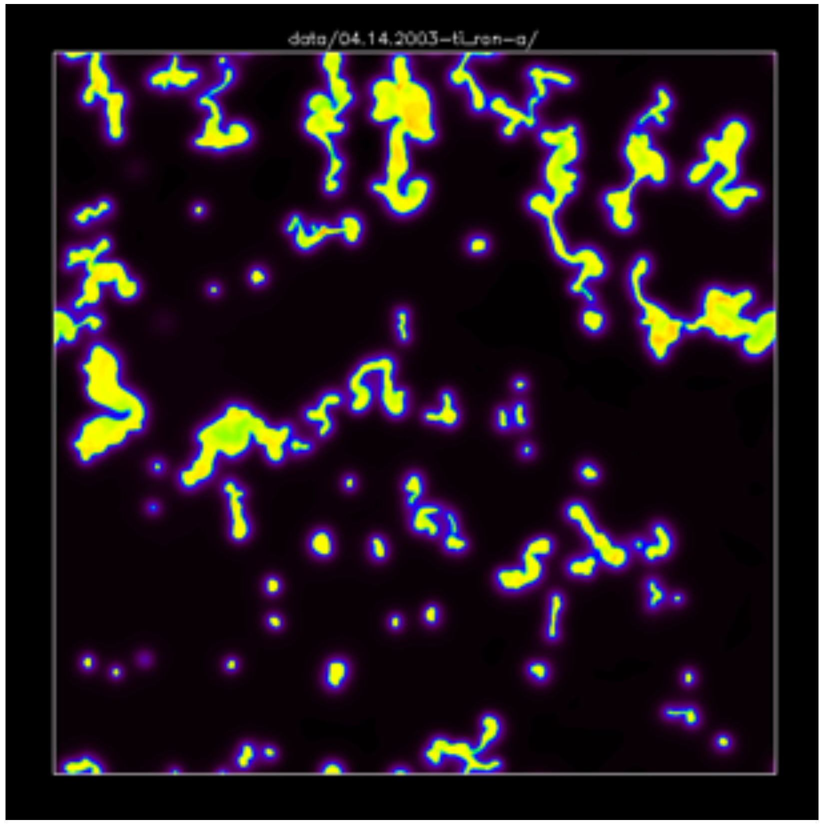
(Ferriere 01)



(Wolfire+03)

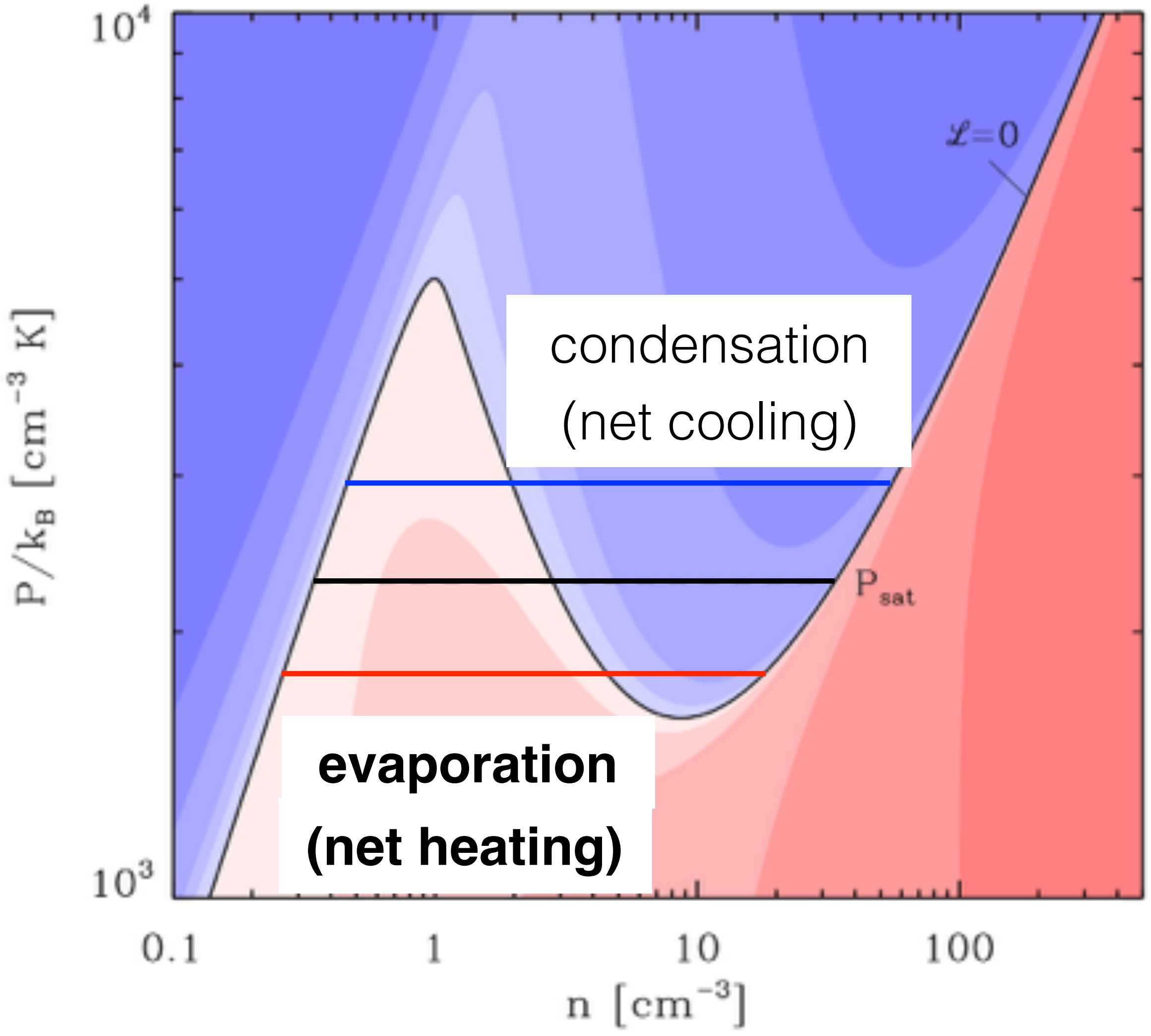
- Neutral gas segregates into a cold neutral medium (CNM) and a warm neutral medium (WNM) by thermal instability (Field+69)
- In rough pressure equilibrium even in supersonic turbulence as long as

  $t_{\rm shock} > t_{\rm cool}$ (Wolfire+69)
- **Thermal fronts** are phase transition layers connecting CNM and WNM



(Piontek+04)

Structure of Steady Thermal Fronts



condensation
(net cooling)

evaporation
(net heating)

- **P_{eq} determines density jump and type of thermal fronts**

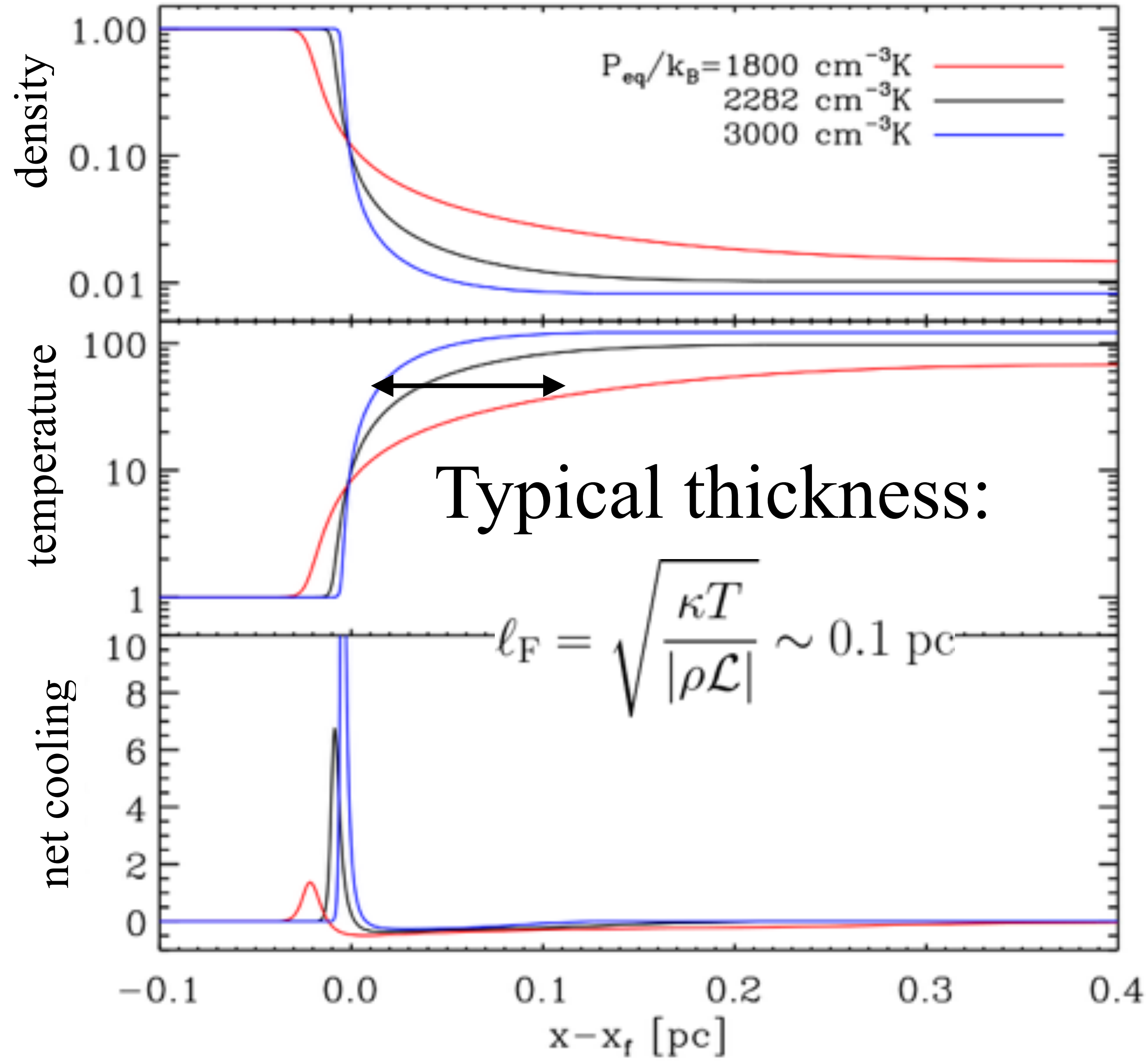
(e.g., Zeldovich69, Penston+70)

$$j_{x0} \equiv \rho v_x = \text{constant},$$

$$P + \rho v_x^2 = \text{constant},$$

$$\kappa \frac{d^2T}{dx^2} = j_{x0} c_P \frac{dT}{dx} + \rho\mathcal{L}(T).$$

CNM(1) **WNM(2)**



Typical thickness:

$$\ell_F = \sqrt{\frac{\kappa T}{|\rho\mathcal{L}|}} \sim 0.1\ \text{pc}$$

Density jump
(or expansion factor)

$$\alpha \equiv \frac{\rho_1}{\rho_2} = \frac{v_2}{v_1} > 1$$

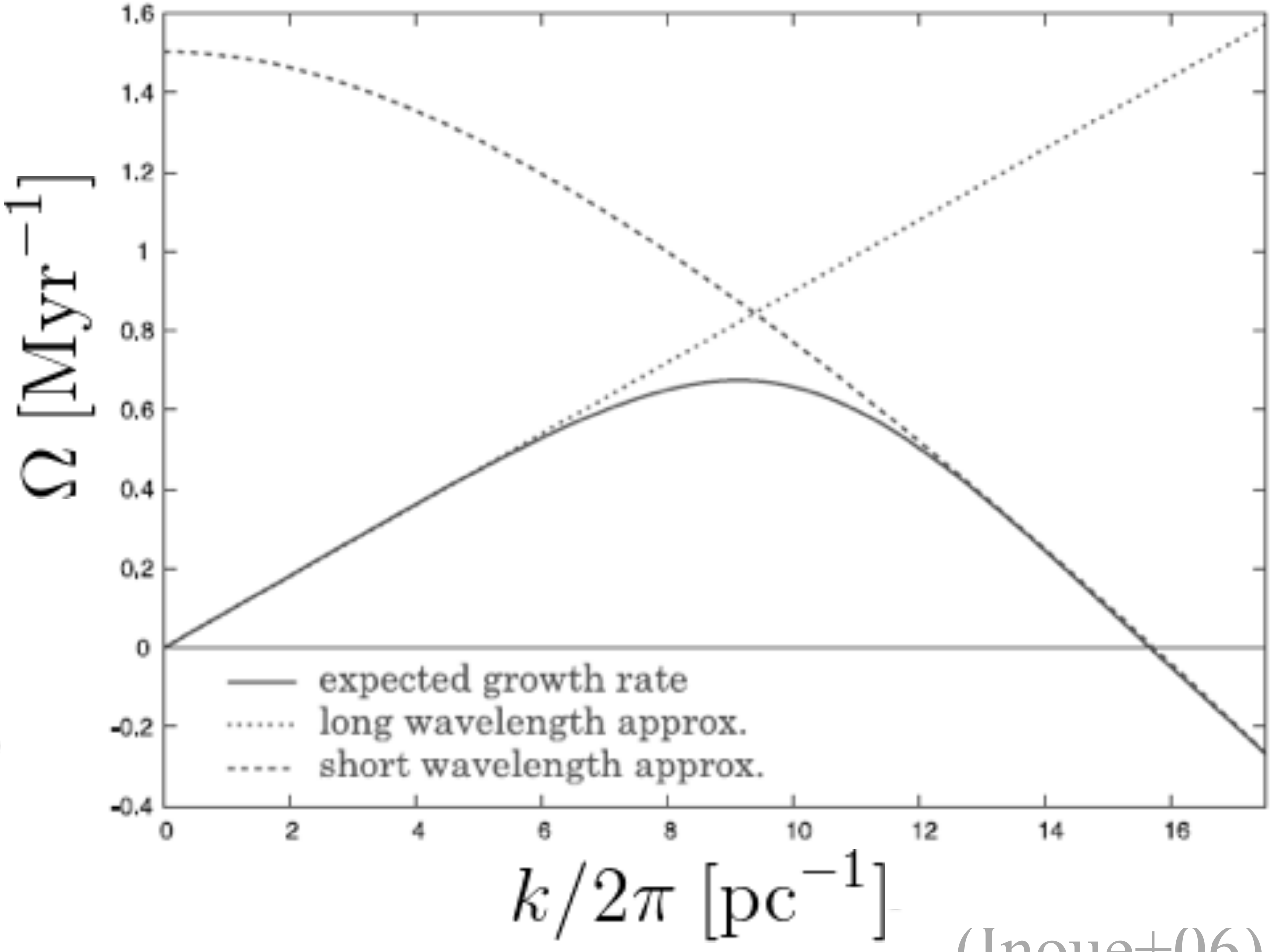
Instability of Evaporation Fronts

- Evaporation fronts are unstable to distortional perturbations (e.g., Inoue+06, Stone+09)
- Without conduction

$$\Omega_0 \simeq \sqrt{\alpha} k v_{x1}$$

- With conduction, maximum growth at

$$\lambda_{\rm max} \sim 0.1 \ {\rm pc} \quad t_{\rm max} \sim 0.3 \ {\rm Myr}$$



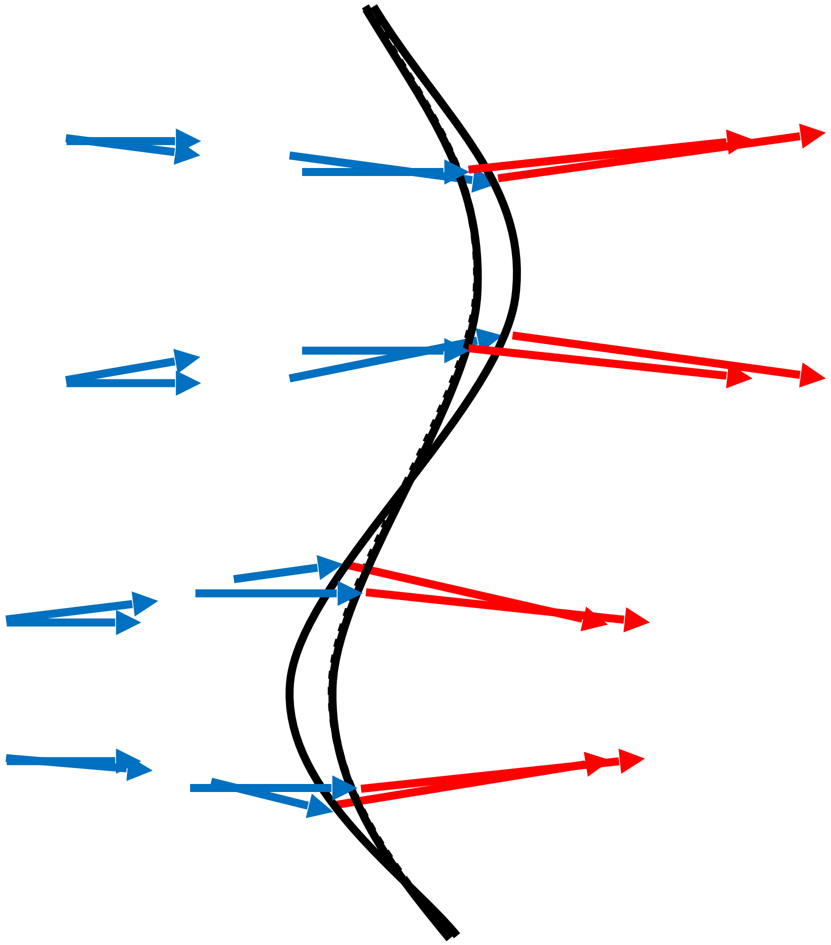
(Inoue+06)

Outstanding Questions

- What determines the characteristic length and time scales of the instability?
- Can the instability in nonlinear regime drive small-scale turbulence in the diffuse ISM?

Instability Mechanism

1. After passing the distorted front, the flow is **refracted toward the normal** to the front due to expansion.
2. Normal velocity increases at the parts convex towards the downstream, **increasing the mass flux** there.
3. Since the **local evaporation rate through the front remains constant**, the front should advance further downstream.

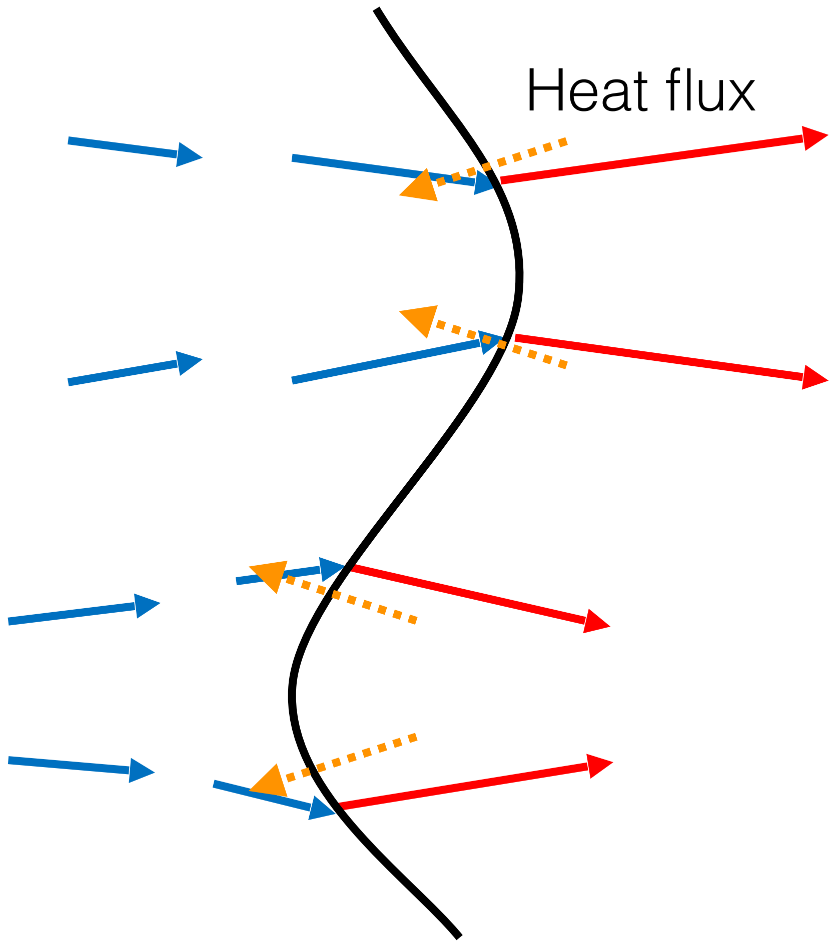


$$\Omega = kv_1 \times \sigma(\alpha)$$

↑

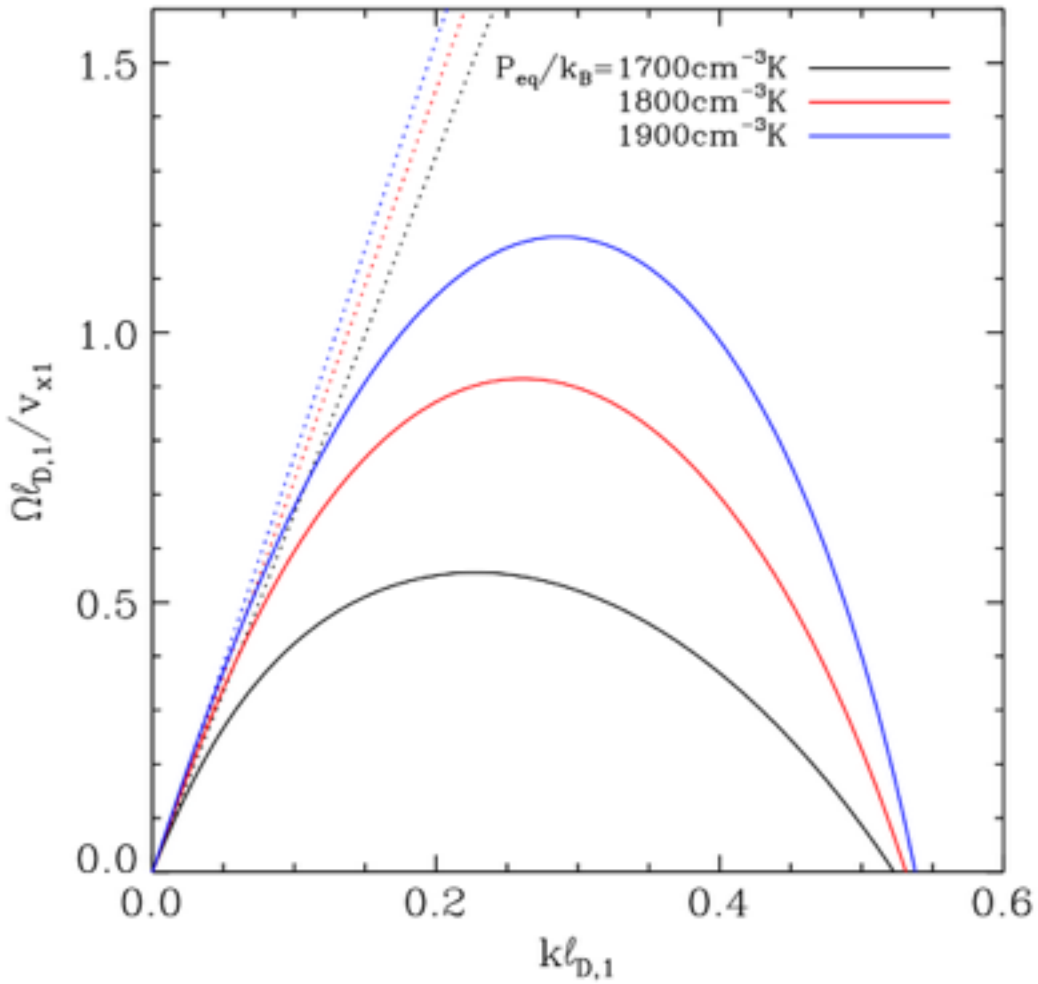
the only relevant (inverse of) time scale
that can be constructed out of
physical parameters of the problem

Stabilization by Conduction



- **Conduction-mediated heat enhances evaporation rate**, reducing a need for the front to advance further.
- Typical length, times scales are

$$\ell_D = \frac{\kappa/\rho c_P}{v} \qquad t_D = \frac{\ell_D}{v}$$

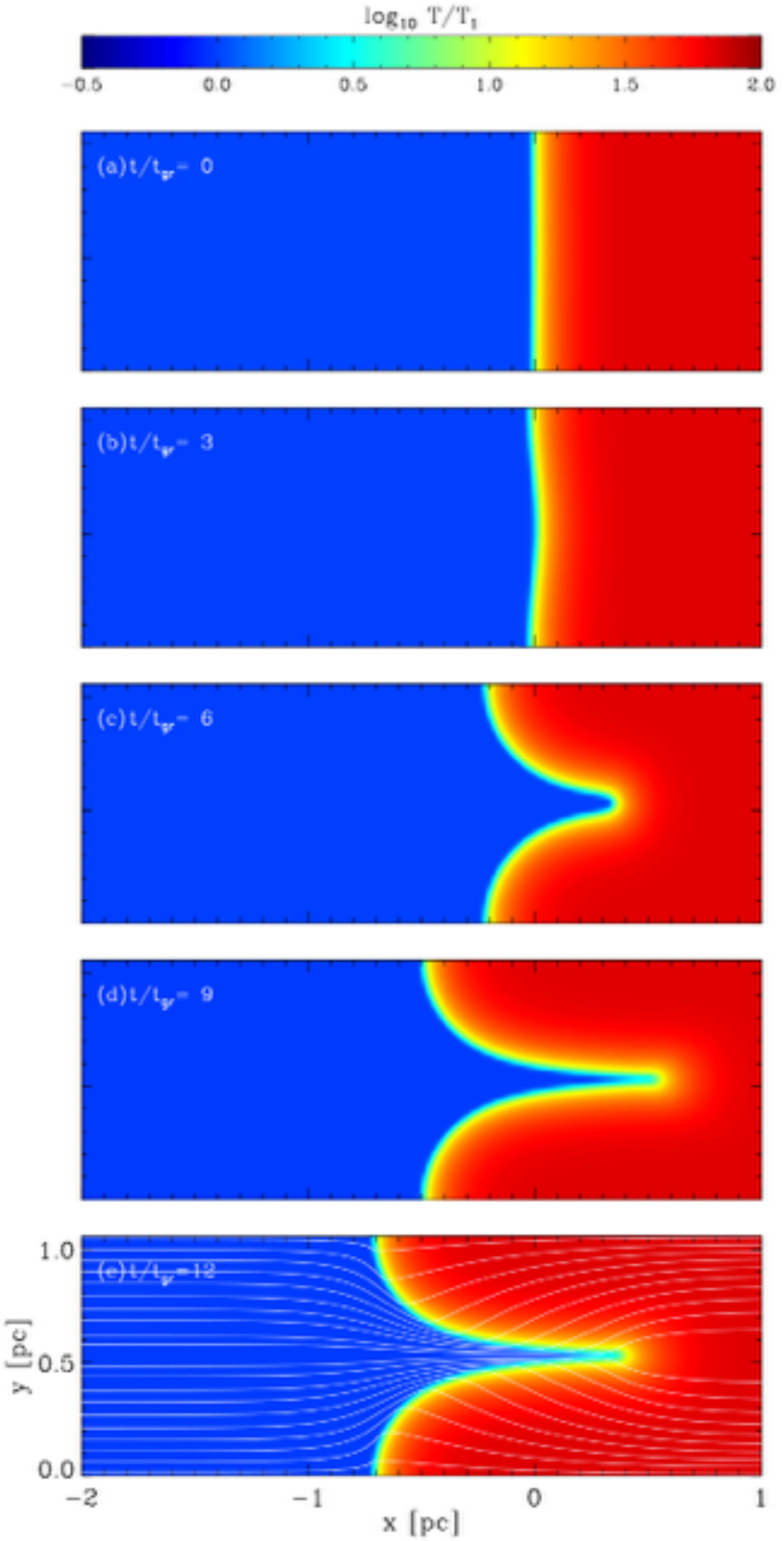


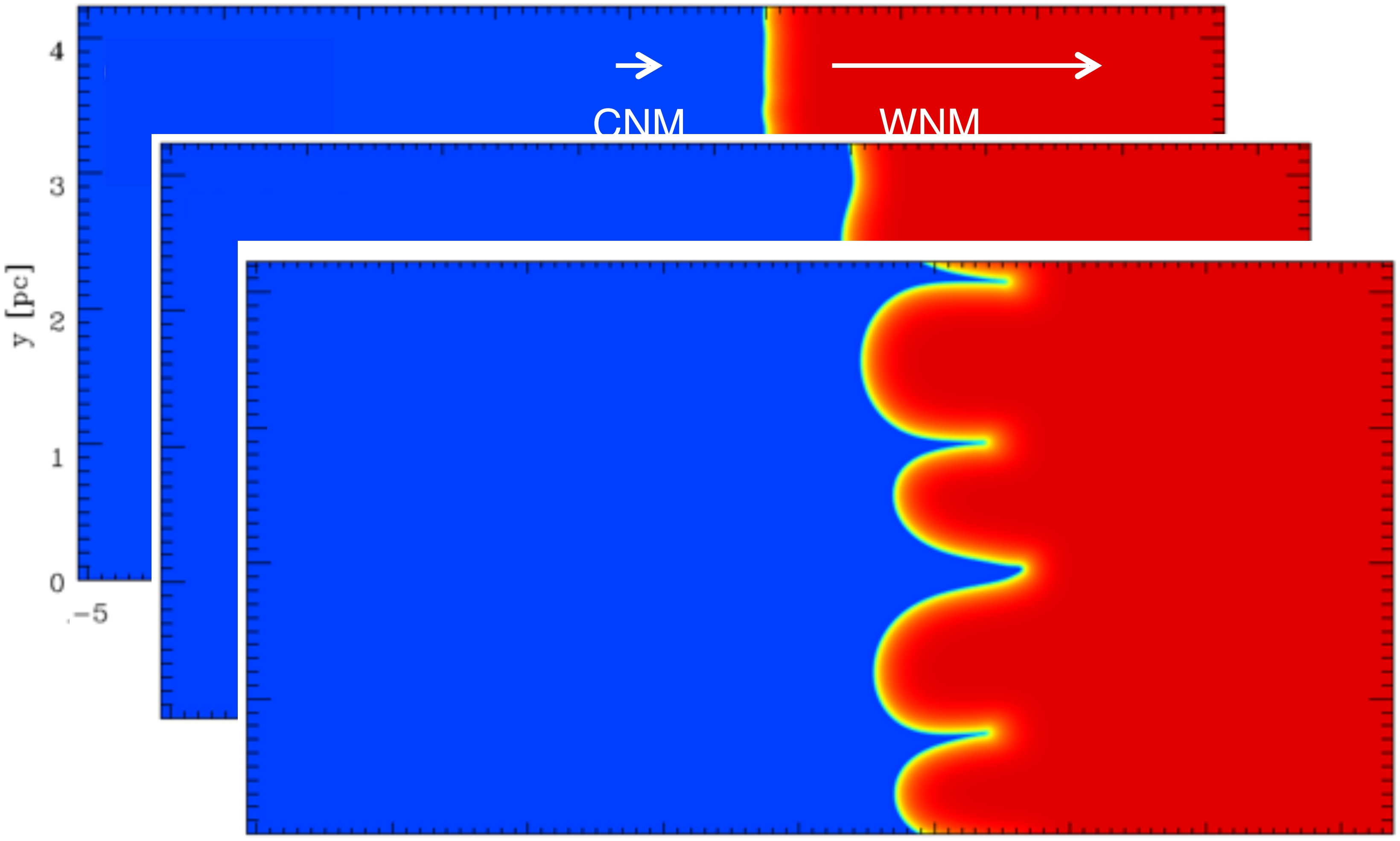
- Full stability analysis gives

$$\lambda_{\max} \approx 0.2\,\mathrm{pc}\left(\frac{v_1}{10\,\mathrm{m\,s^{-1}}}\right)^{-1}\left(\frac{n_1}{10\,\mathrm{cm^{-3}}}\right)^{-1}\left(\frac{\kappa}{10^5\,\mathrm{erg\,s^{-1}\,cm^{-1}\,K}}\right)$$

$$t_{\max} \approx 0.92\,\mathrm{Myr}\left(\frac{v_1}{10\,\mathrm{m\,s^{-1}}}\right)^{-2}\left(\frac{n_1}{10\,\mathrm{cm^{-3}}}\right)^{-1}\left(\frac{\kappa}{10^5\,\mathrm{erg\,s^{-1}\,cm^{-1}\,K}}\right)$$

2D Numerical Simulations





- Front saturates to a steady state with a finger-like shape pointing toward the WNM.
- **Flow remains laminar, without generating turbulence**

1. Instability of Evaporation Fronts in Neutral Atomic ISM

Kim and Kim (2013)

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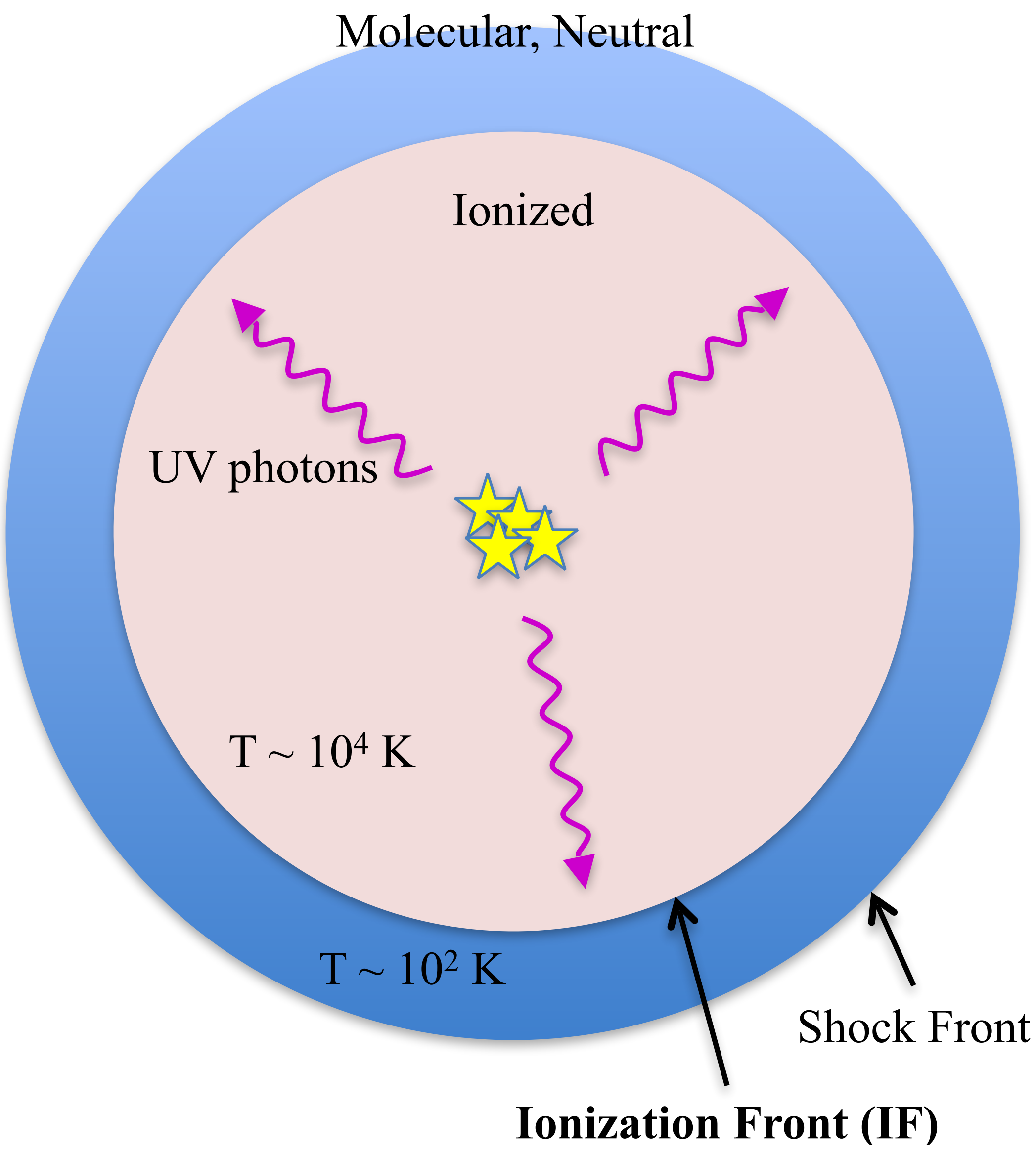
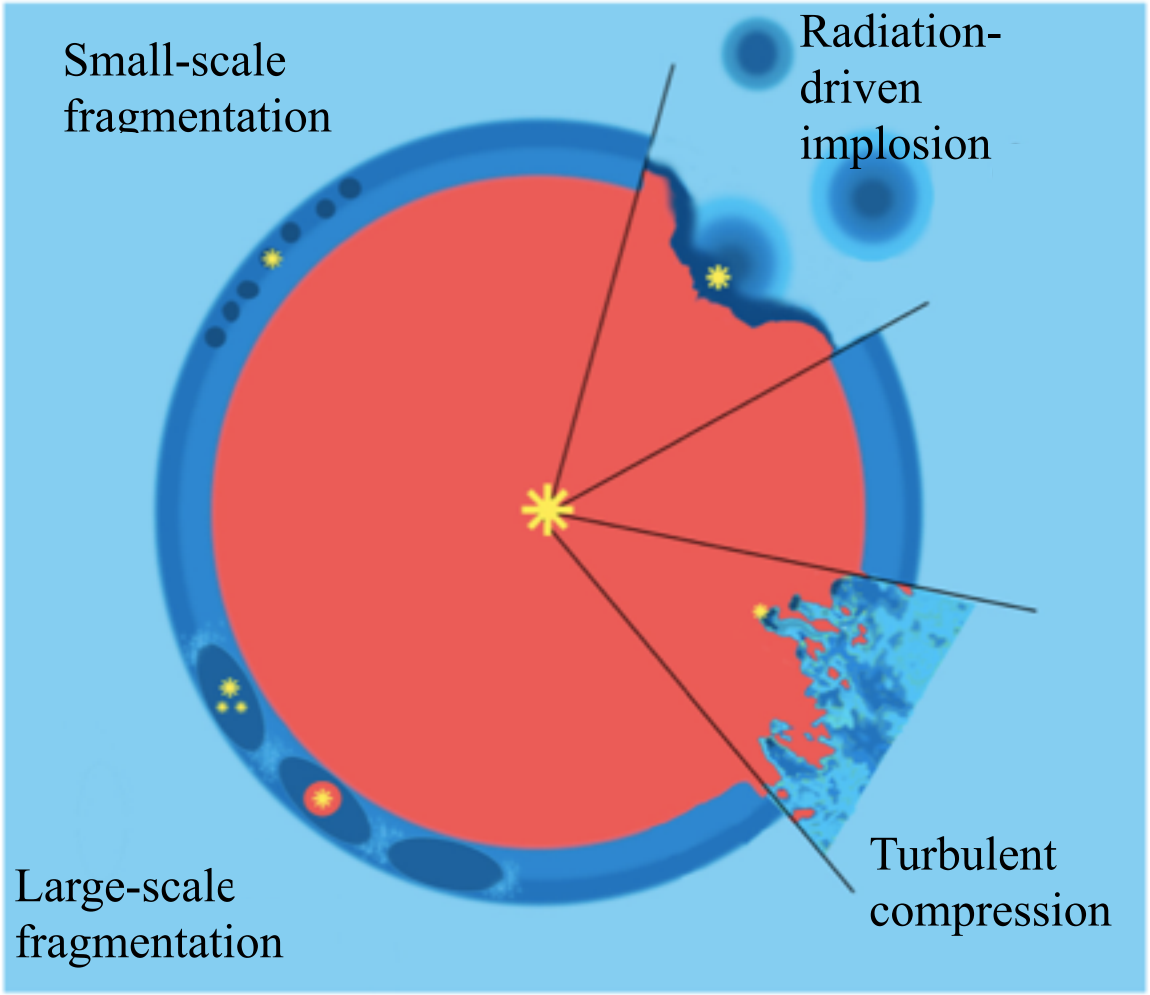


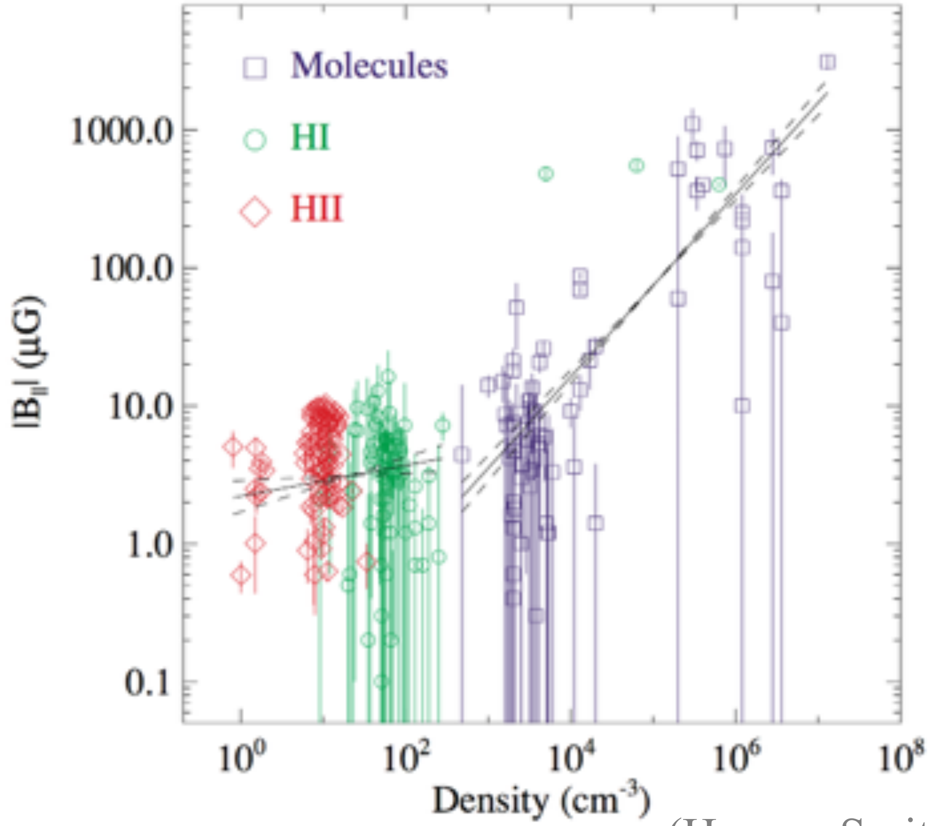


Deharveng et al. (2011)

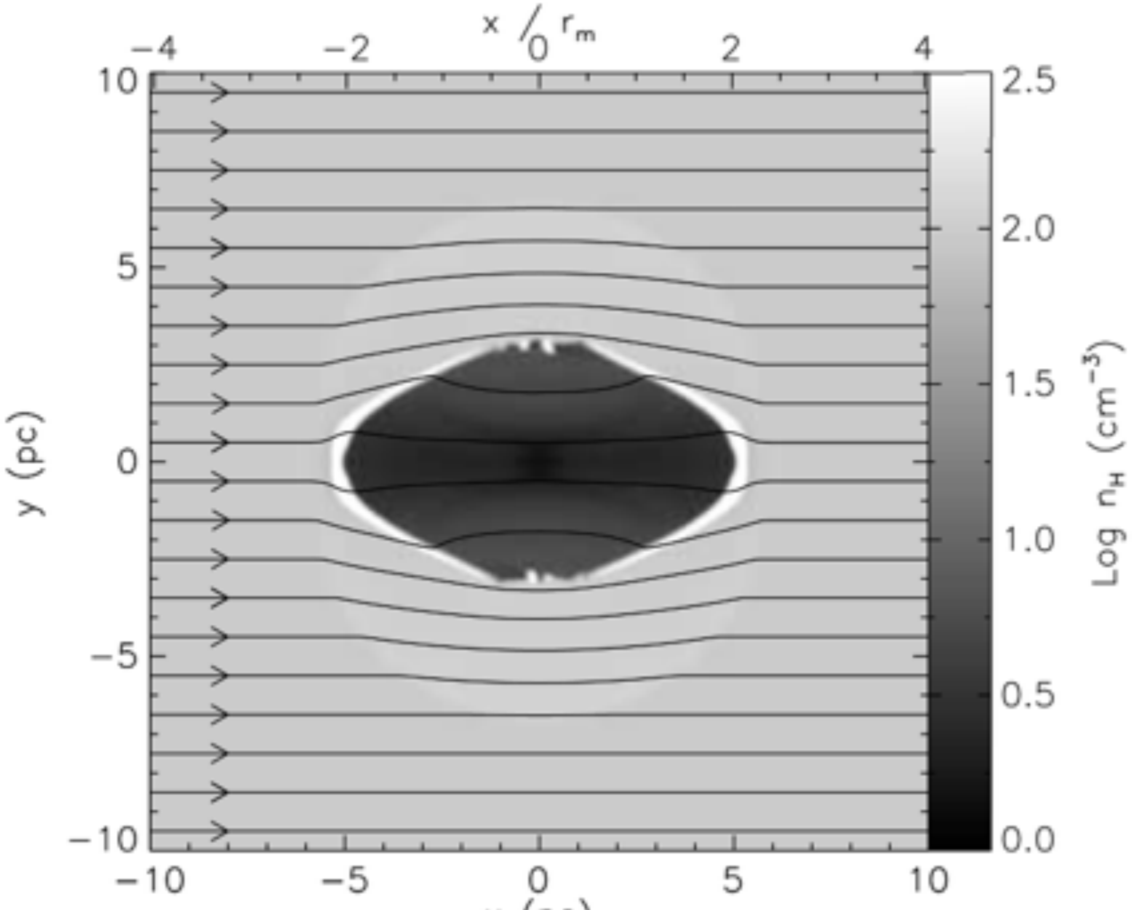
- Evolution of IF for embedded H II regions
  - R-type ⇒ R-Critical ⇒ D-Critical + Shock ⇒ **D-type**
- H II regions are rich in substructures such as globules, filaments, pillars (or “elephant trunks”)
- Dynamical instabilities in IFs
  - **IF instability** (Vandervoort62, Axford64, Williams+02)
  - Rayleigh-Taylor instability (Spitzer+54, Ricotti+13, Park+14)
  - Thin-shell instability (Giuliani79, Vishniac83, Garcia-Segura+96, Whalen+08)

Magnetized H II regions

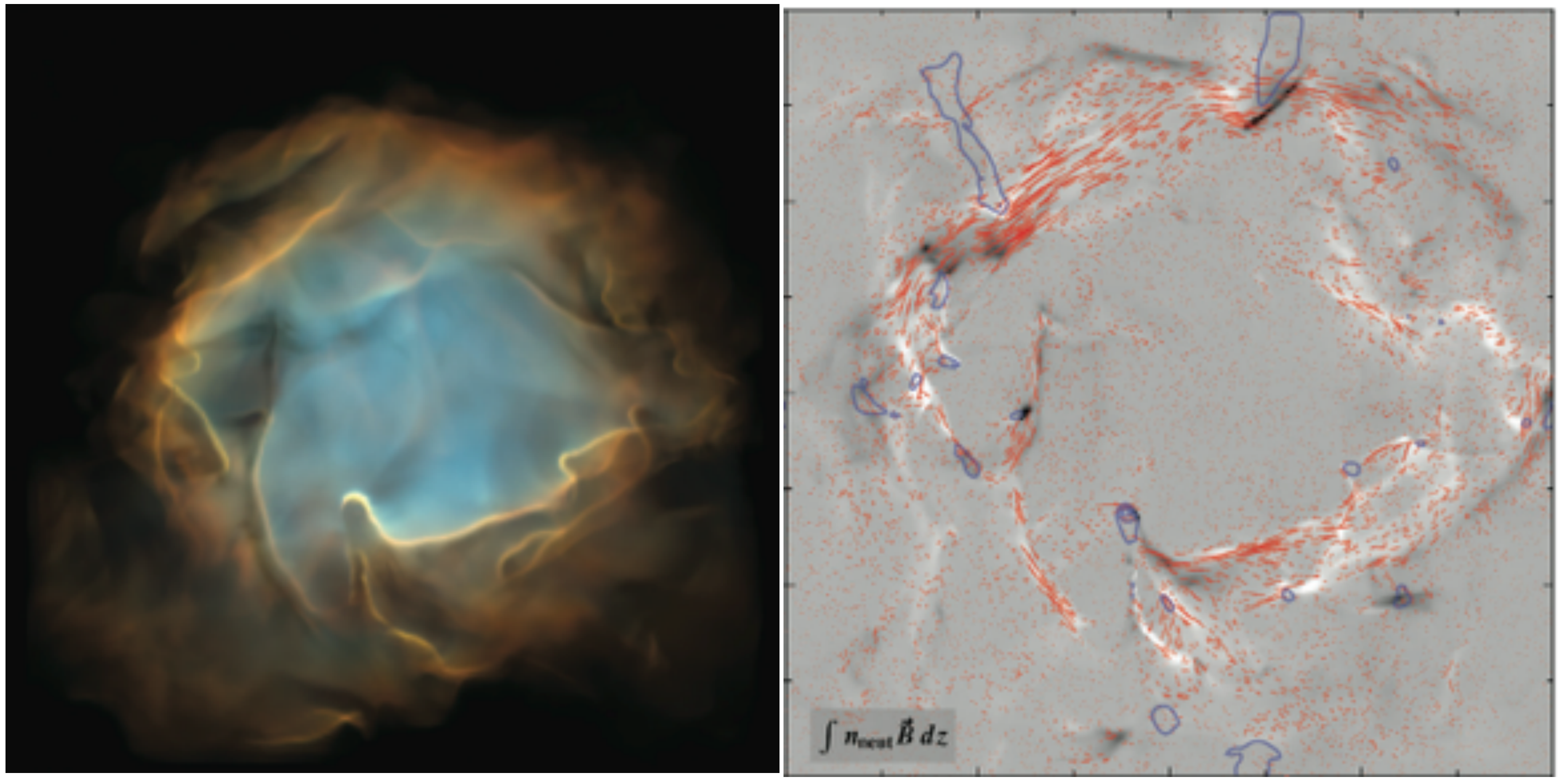
- Observed thermal-to-magnetic pressure ratio β
  - β ~ 2-20 (HII) (Heiles+81, Harvey-Smith+11, Rodriguez+12)
  - β ~ 0.04-0.3 (HI or molecular) (Brogan+99, Crutcher99, Heiles+05)



(Harvey-Smith+11)

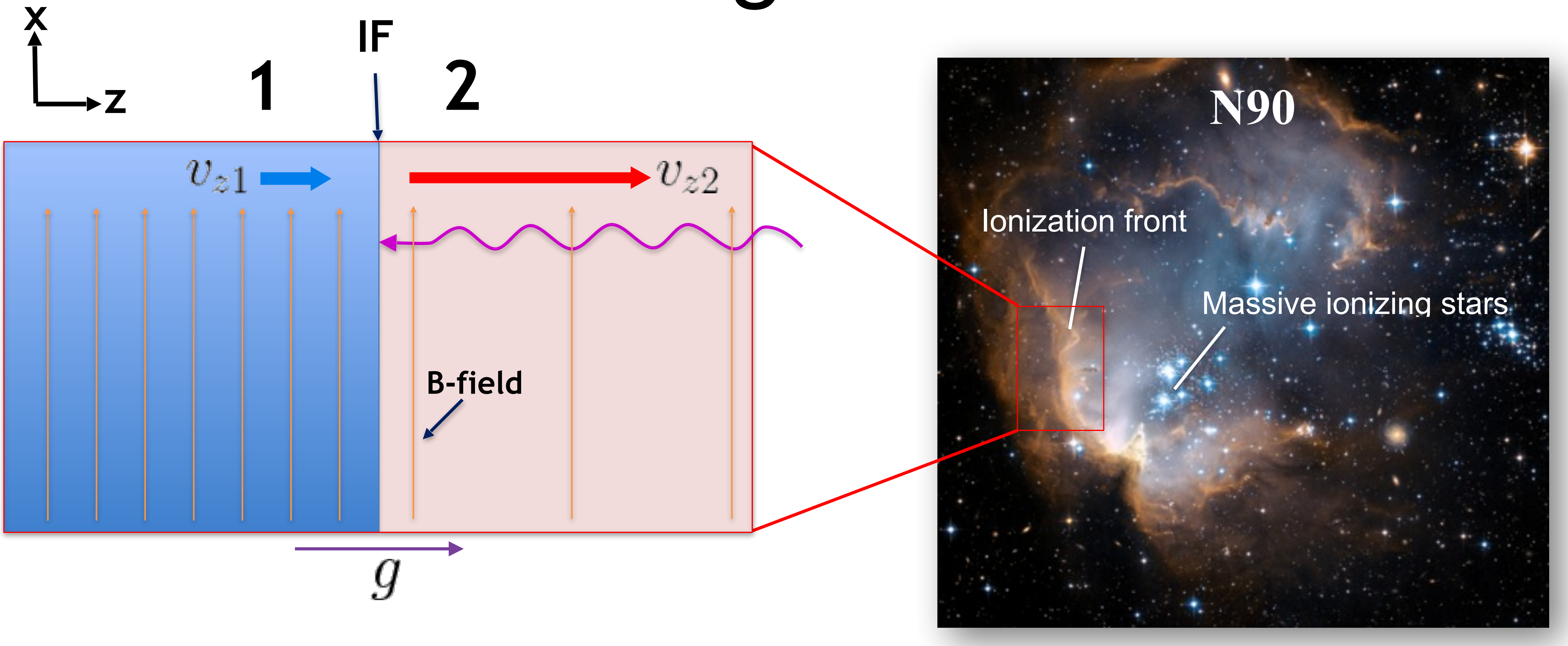


(Krumholz+07)



(Arthur+11)

Local Background State



- Solve for the density contrast in terms of
  - Heating factor: $T_2/T_1 \approx 100$
  - Plasma beta: $\beta = c^2/v_{\rm A}^2$
  - Mach number: $\mathcal{M}_{\rm M} = v/(c^2+v_{\rm A}^2)^{1/2}$

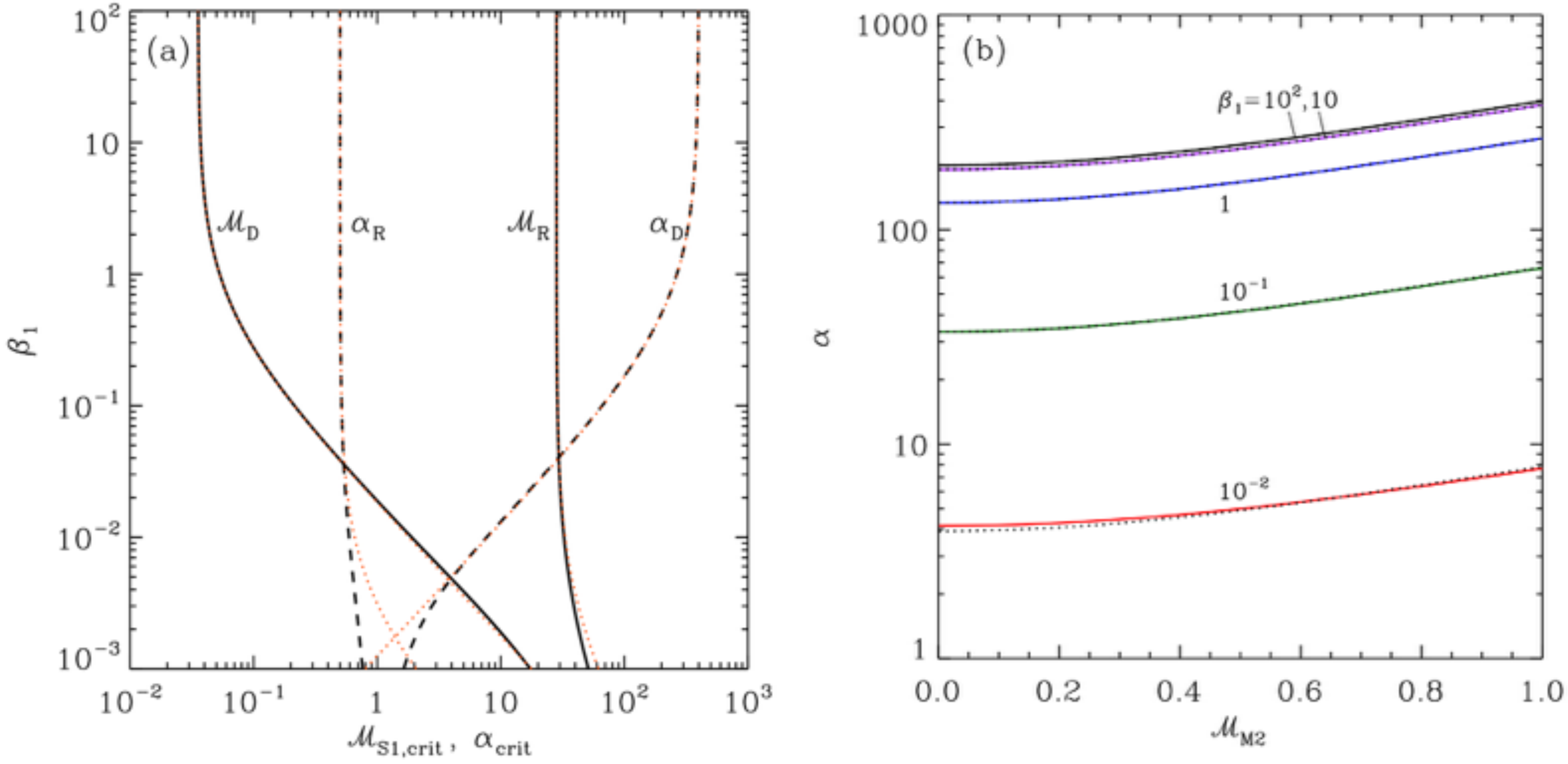
$$j_z \equiv \rho_1 v_{z1} = \rho_2 v_{z2} = m_{\rm H} F_{\rm ph}\,,$$

$$P_1 + \rho_1 v_{z1}^2 + \frac{B_{x1}^2}{8\pi} = P_2 + \rho_2 v_{z2}^2 + \frac{B_{x2}^2}{8\pi}\,,$$

$$B_{x1} v_{z1} = B_{x2} v_{z2}\,.$$

Jump Conditions for Magnetized IFs

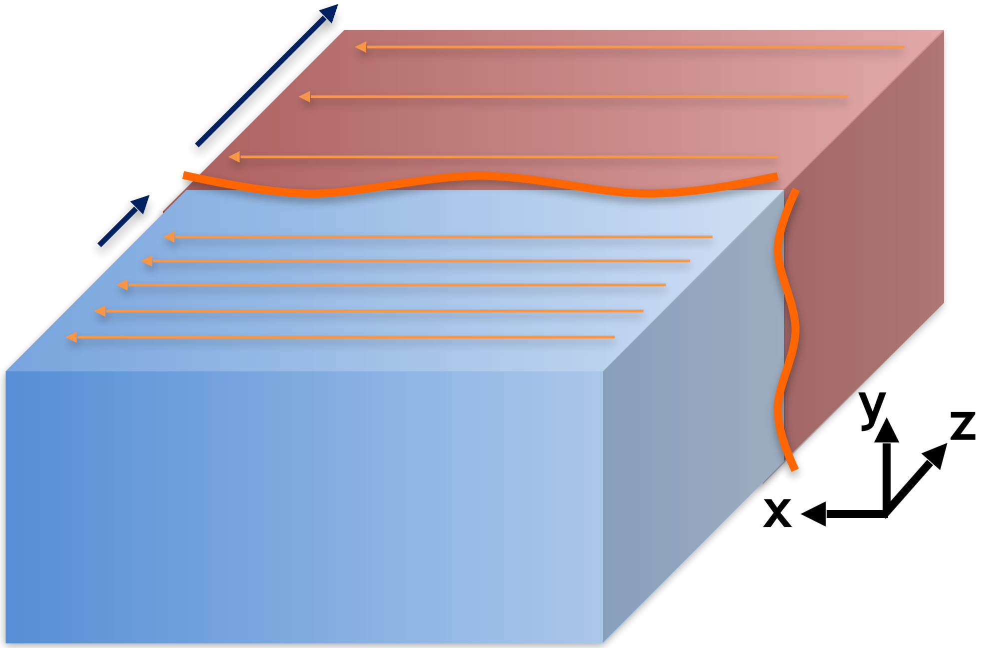
(e.g., Redman+98, Williasms+00, Draine 11)



- For B-fields parallel to IF
  - Critical IFs always have $\mathcal{M}_{M2} = 1$
  - R-critical = D-critical + Isothermal MHD shock
  - Strong B-fields tends to reduce expansion factor of weak D-type IFs by a factor of $(1 + 1/(2\beta_1))$

Linear Analysis: Method

- Decompose perturbations into Fourier modes of the form $\propto \exp(i\mathbf{k}\cdot\mathbf{x}+\Omega t)$
- Find MHD waves that are evanescent away from the IF
- Determine growth rate and amplitudes of waves that fulfills perturbed jump conditions across the IF



$$\Delta\left[\rho v_{\mathrm{n}}\right]=0\,,$$

$$\Delta\left[\rho v_{\mathrm{n}}\mathbf{v}_{\mathrm{t}}-\frac{B_{\mathrm{n}}\mathbf{B}_{\mathrm{t}}}{4\pi}\right]=0\,,$$

$$\Delta\left[\rho v_{\mathrm{n}}^{2}+P+\frac{B_{\mathrm{t}}^{2}}{8\pi}\right]=-\Delta\left[\rho\right]g\zeta\,,$$

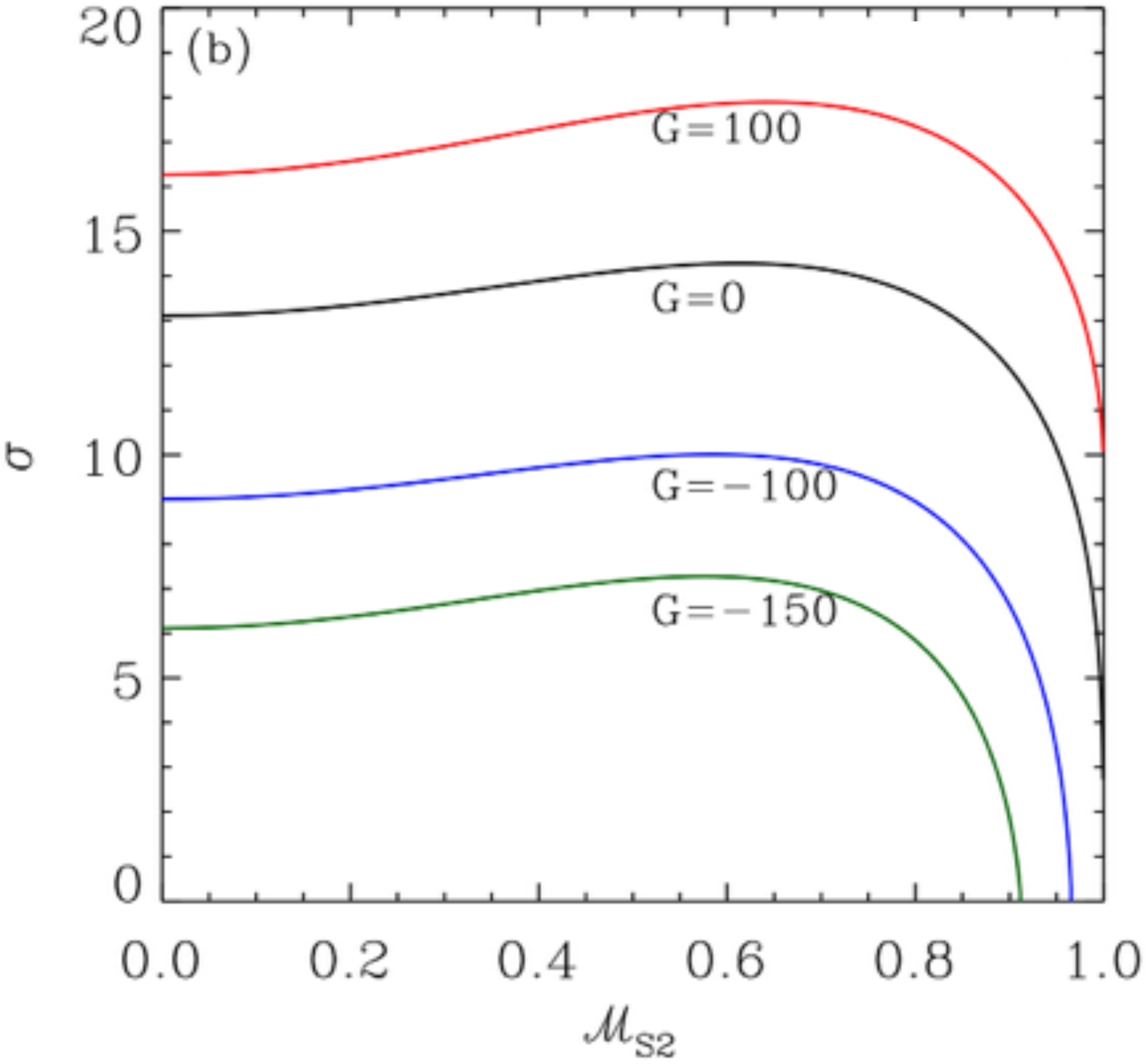
$$\Delta\left[v_{\mathrm{n}}\mathbf{B}_{\mathrm{t}}-B_{\mathrm{n}}\mathbf{v}_{\mathrm{t}}\right]=0\,,$$

$$\Omega = kv_1 \times \sigma(\alpha, \beta_1, \mathcal{M}_{\mathrm{M}}; G)$$

$$k = (k_x^2 + k_y^2)^{1/2}$$

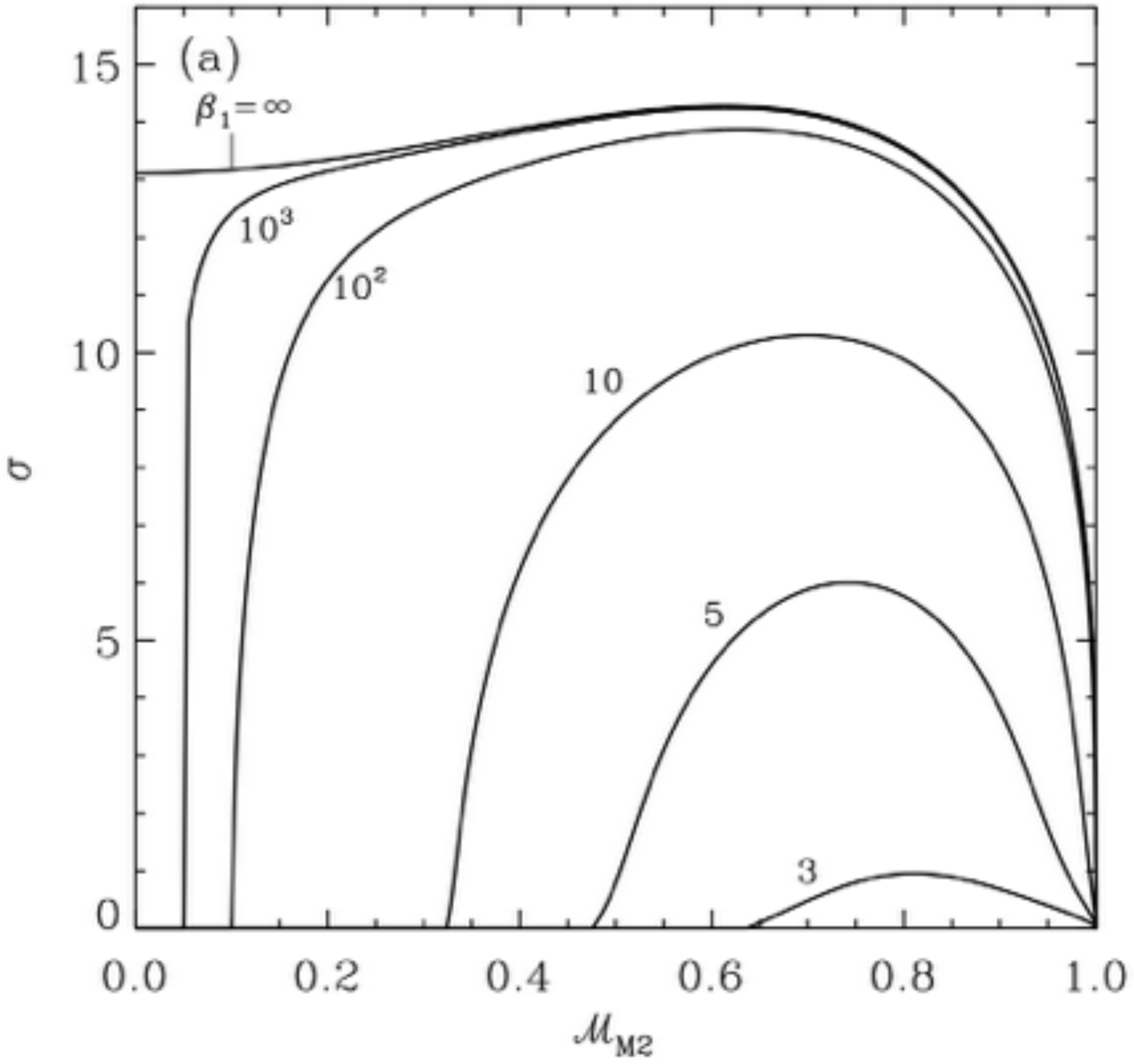
Dispersion Relations

$$\beta \rightarrow \infty, g \neq 0$$



- IF instability either cooperates with RTI (g>0) or becomes suppressed by buoyancy (g<0)

$$k_x \neq 0, k_y = 0$$



- Stabilized by magnetic tension

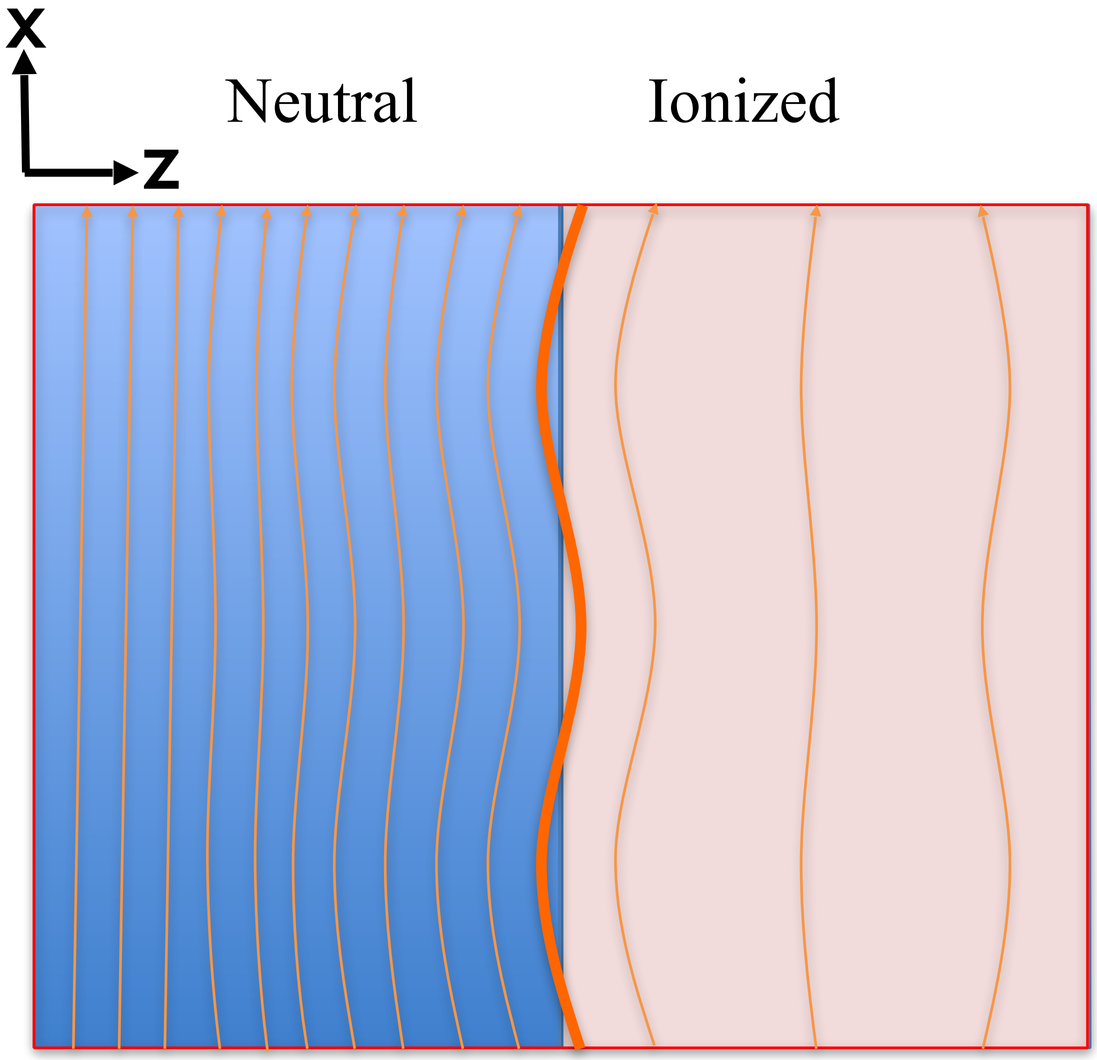
$$\mathcal{M}_{\rm M2} < \left(\frac{2}{2\beta_1 - 1}\right)^{1/2}, \quad \text{for stability,}$$

Effects of magnetic tension

- Magnetic tension reduces mass flux

$$B'_z/B_x \sim k\zeta$$

$$|v'_{\rm A}| \sim |B_z|'/\sqrt{4\pi\rho} \sim v_{\rm A}k\zeta$$



- **Flows with small Alfvén-Mach number are stablized.**

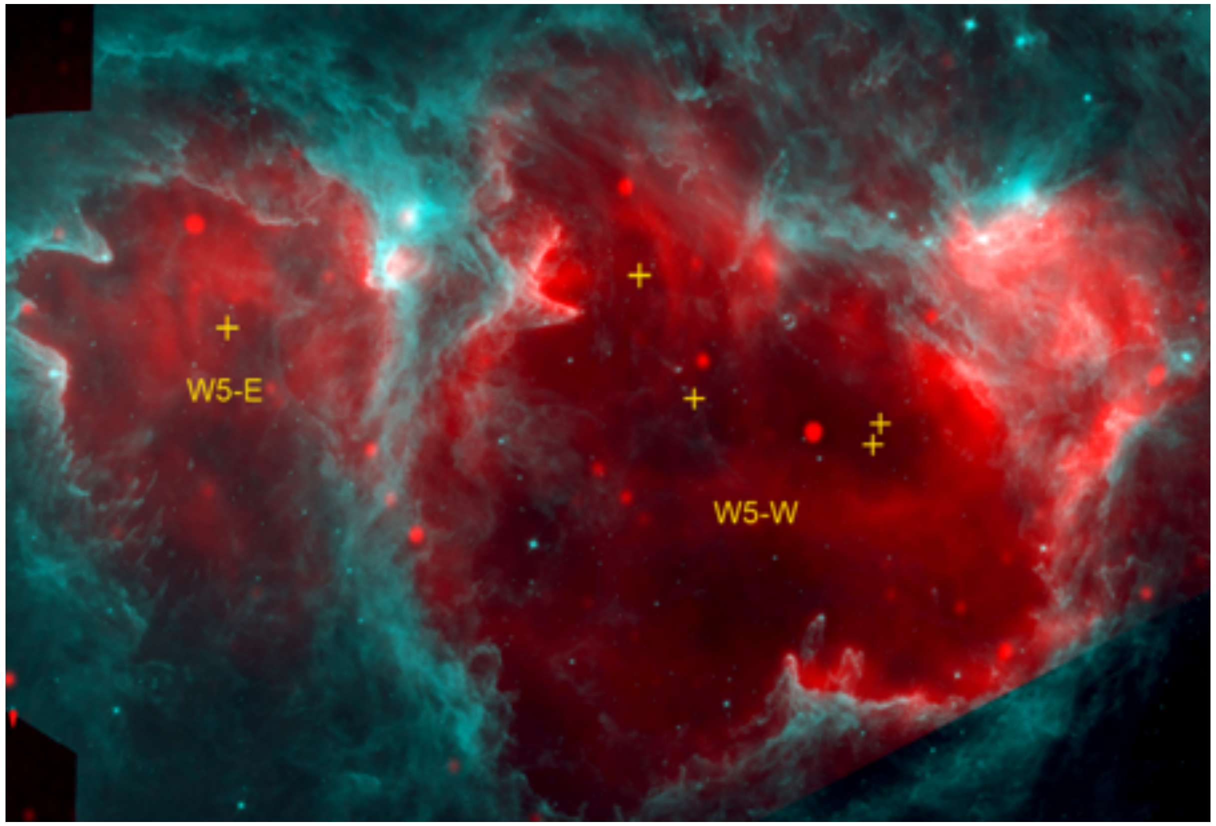
Discussion

- IF instability growth time:

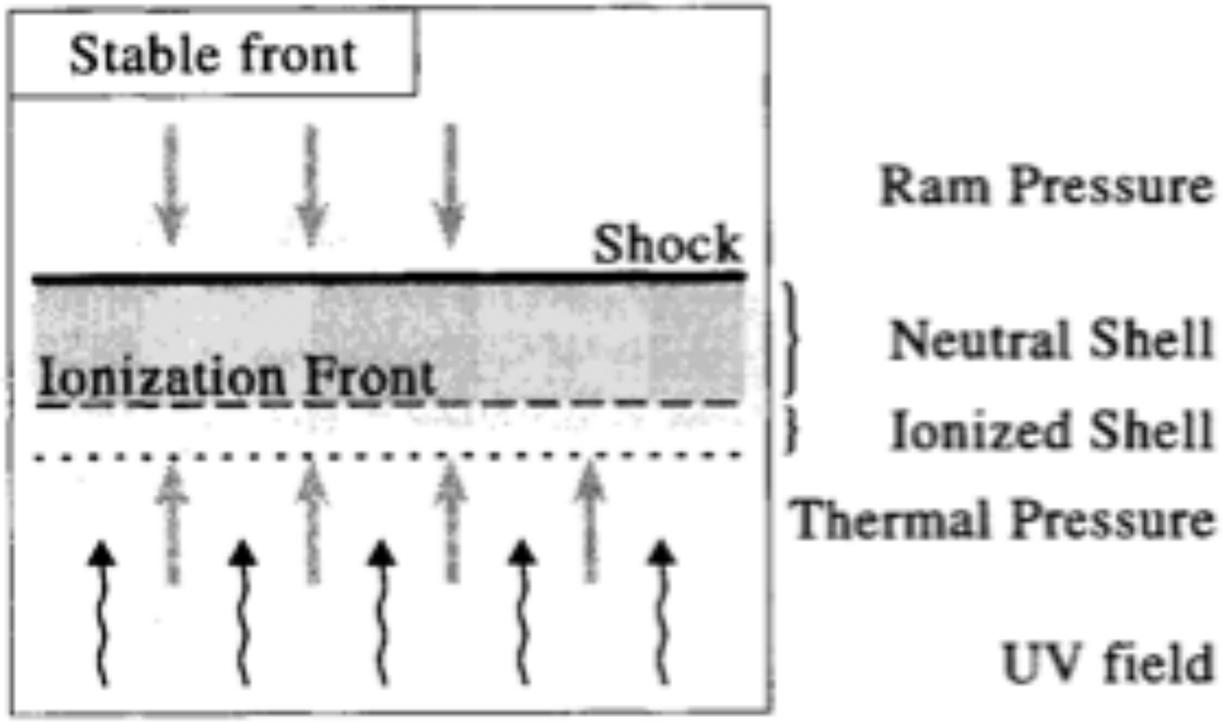
$$\Omega^{-1} \approx 1.5 \times 10^4 \frac{(1+\beta_1^{-1})^{1/2}}{\mathcal{M}_{\rm M1}\sigma} \left(\frac{\lambda}{0.1\,{\rm pc}}\right) \quad {\rm yr}$$

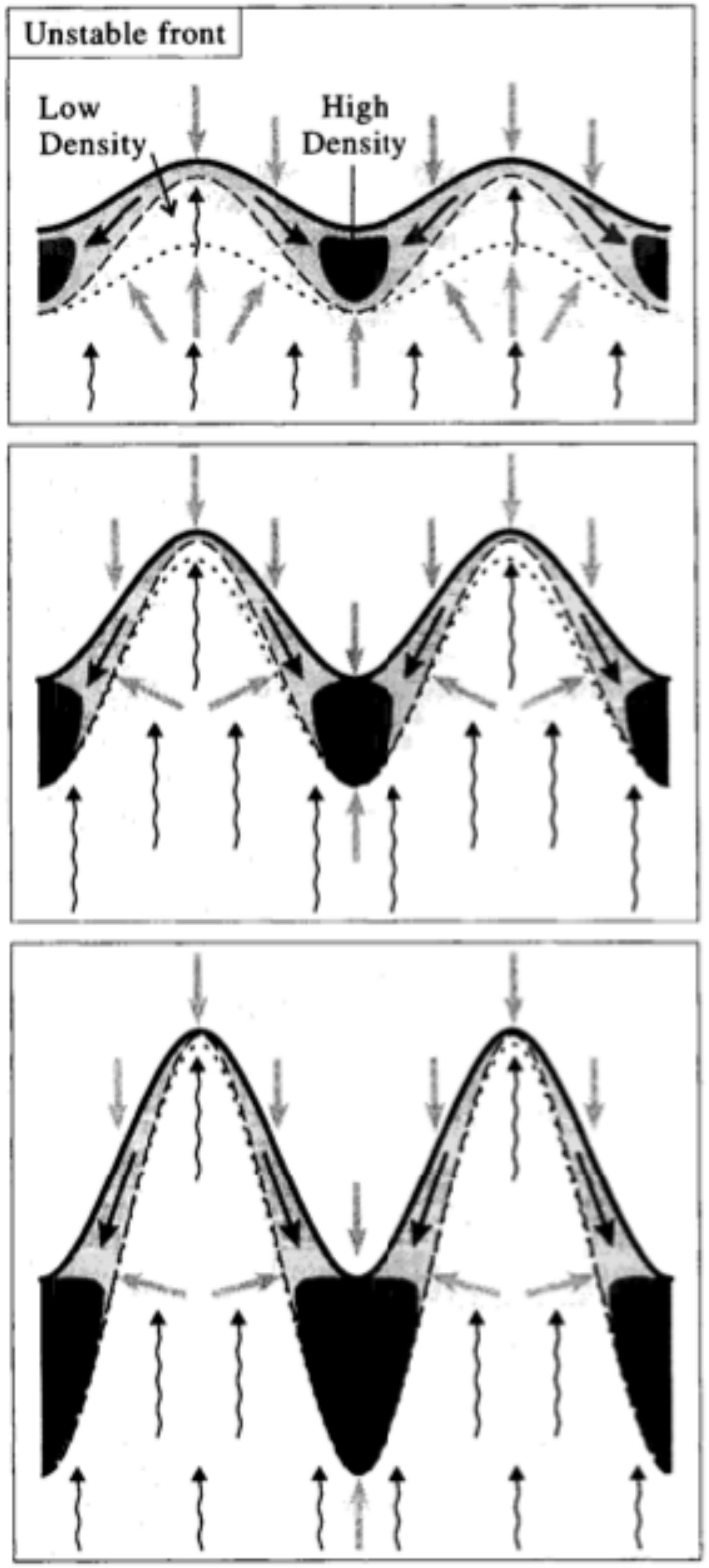
- Completely stabilized by tension for $\beta_1 < 1.5$
  - Photodissociation regions supported by magnetic pressure
- Can IF instability manifest in simulations of H II regions?
  - For ~ 0.01pc resolution, perturbations with wavelength < 0.1pc would be damped by numerical diffusion
- Caveats of the simplified model
  - Steady state, plane-parallel, uniform background
  - Presence of shock front
    - How IF instability would affect and interact with large-scale RTI, thin-shell instability
    - Gas ahead of IF is subject to non-steady heating/cooling

Thank you!



Thin-shell instability





Adopted from Garcia-Segura+96

Compressibility effect

- Compressible flow: $v_2 \sim c_2$

$$\rho'/\rho \sim \mathcal{M}_s^2 P'/P \qquad j' = \rho' v + \rho(v' - \Omega\zeta) = 0$$

- σ decreases as M_{s2} increases
- Instability is suppressed for $M_{s2} = 1$ (D-critical)