SFDE 2017

Dispersal of Molecular Clouds by Photoionisation and Radiation Pressure

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Slow and Inefficient SF

- **SF is slow:**

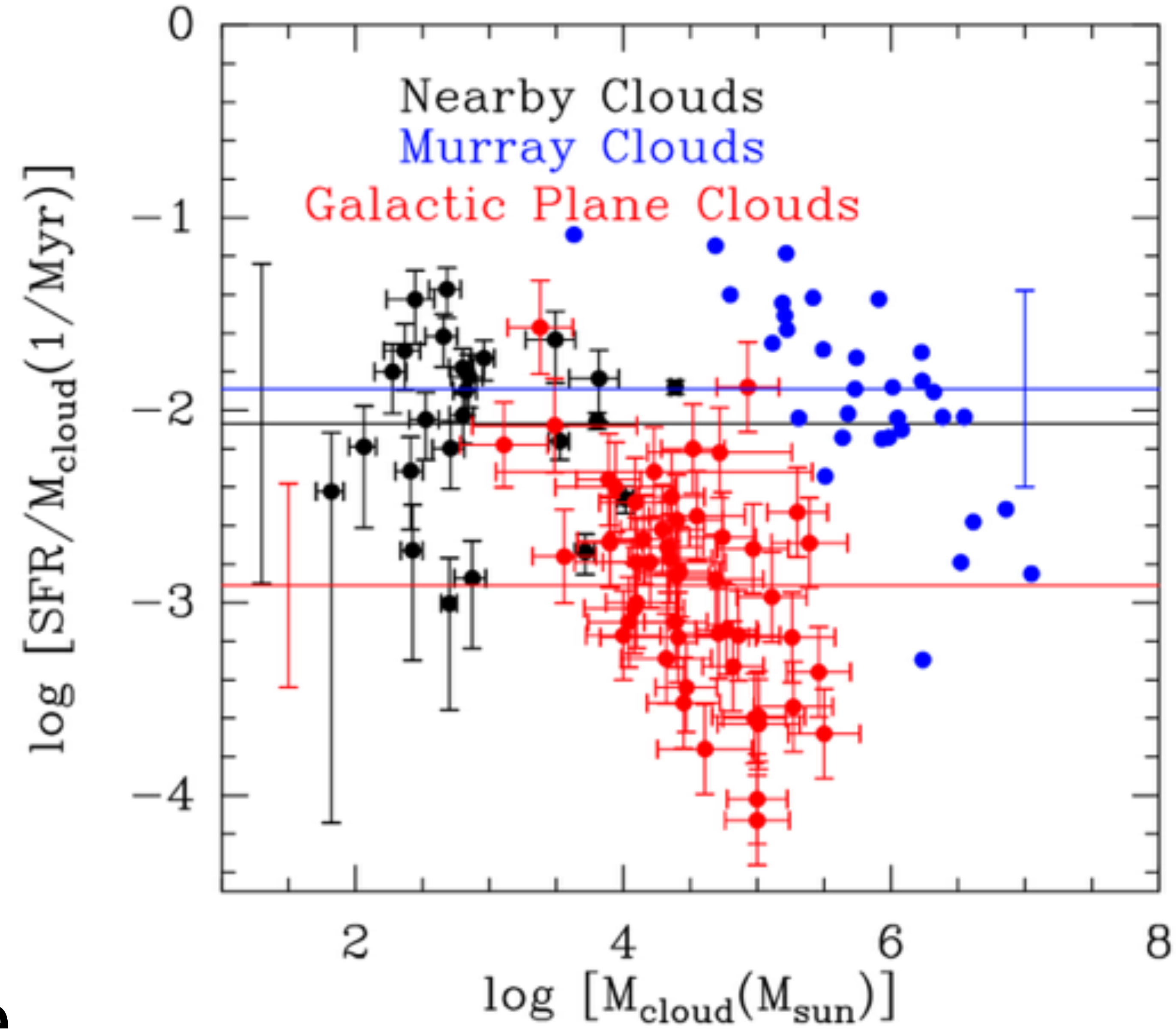
$$t_{\text{dep}} = M_{\text{cl}}/\text{SFR}$$
$$\gg t_{\text{ff}} \sim \text{1-10 Myr}$$

(Bigiel+08, Kennicutt+12, Leroy+13)

- **SF is inefficient:**

$$\text{SFE} = \frac{M_*}{M_* + M_{\text{cl}}}$$

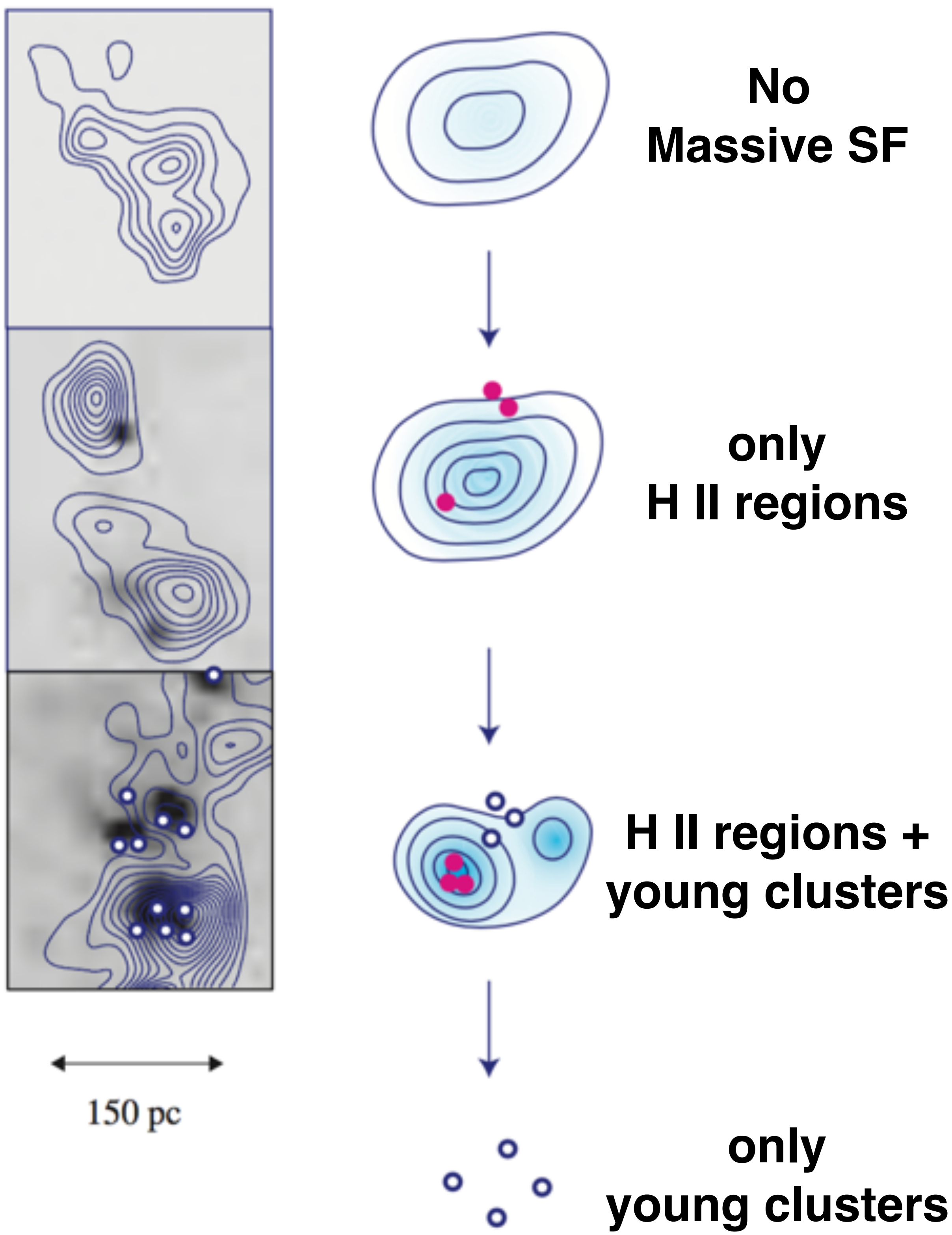
Vutisalchavakul+16



  - Star-forming clouds in the Milky Way have SFE ~ 0.002-0.2, a few % on average (Myers+86, Williams+97, Carpenter00, Murray+11, Garcia+14)

- Shorter t_{dep}, higher SFE in dese, high-Σ environments (Meier+02, Turner+15; Leroy+13, 15)

Lifetime and Disruption of GMCs



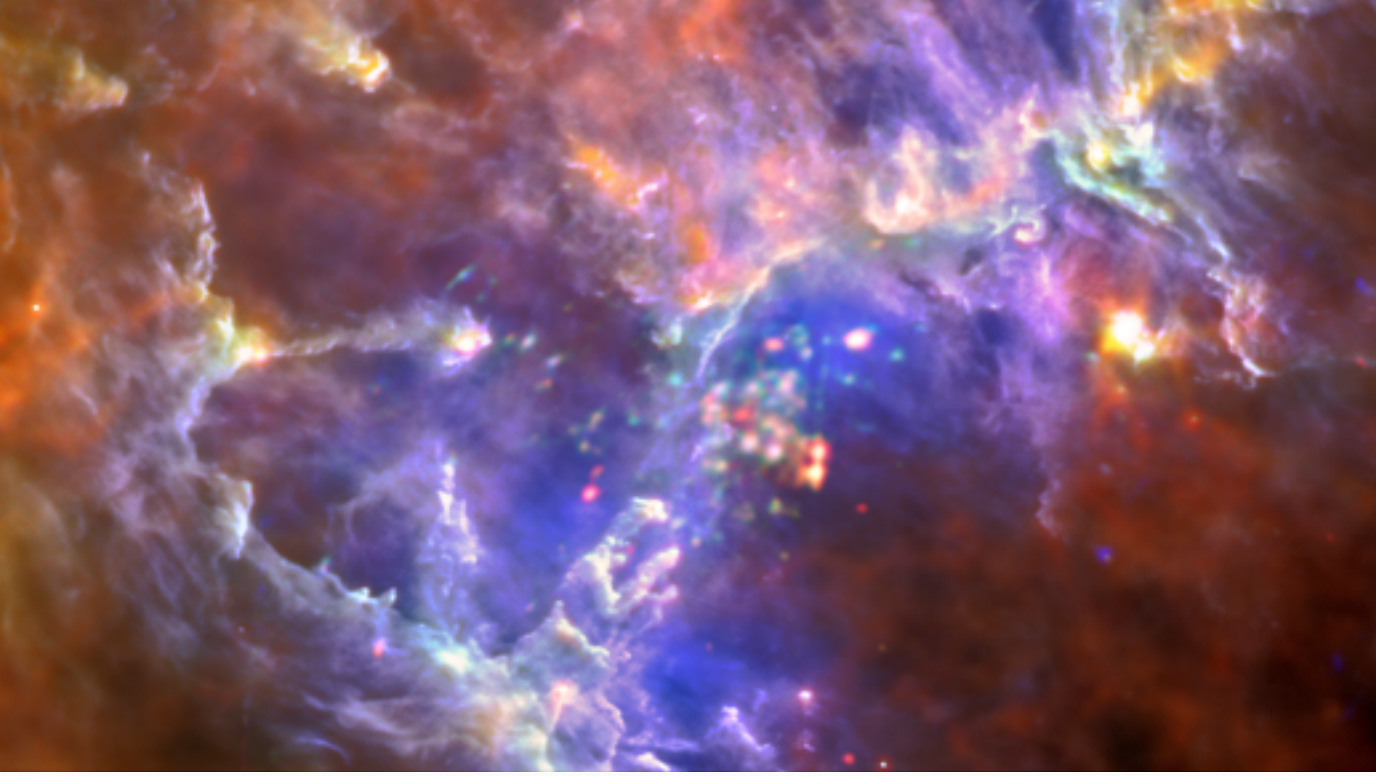
Blitz+07; Kawamura+09

- Final (or net) SFE for steady SFR

$$\mathrm{SFE}_{\mathrm{final}} = \frac{\mathrm{SFR} \times t_{\mathrm{cl}}}{M_{\mathrm{cl}}} = \frac{t_{\mathrm{cl}}}{t_{\mathrm{dep}}}$$

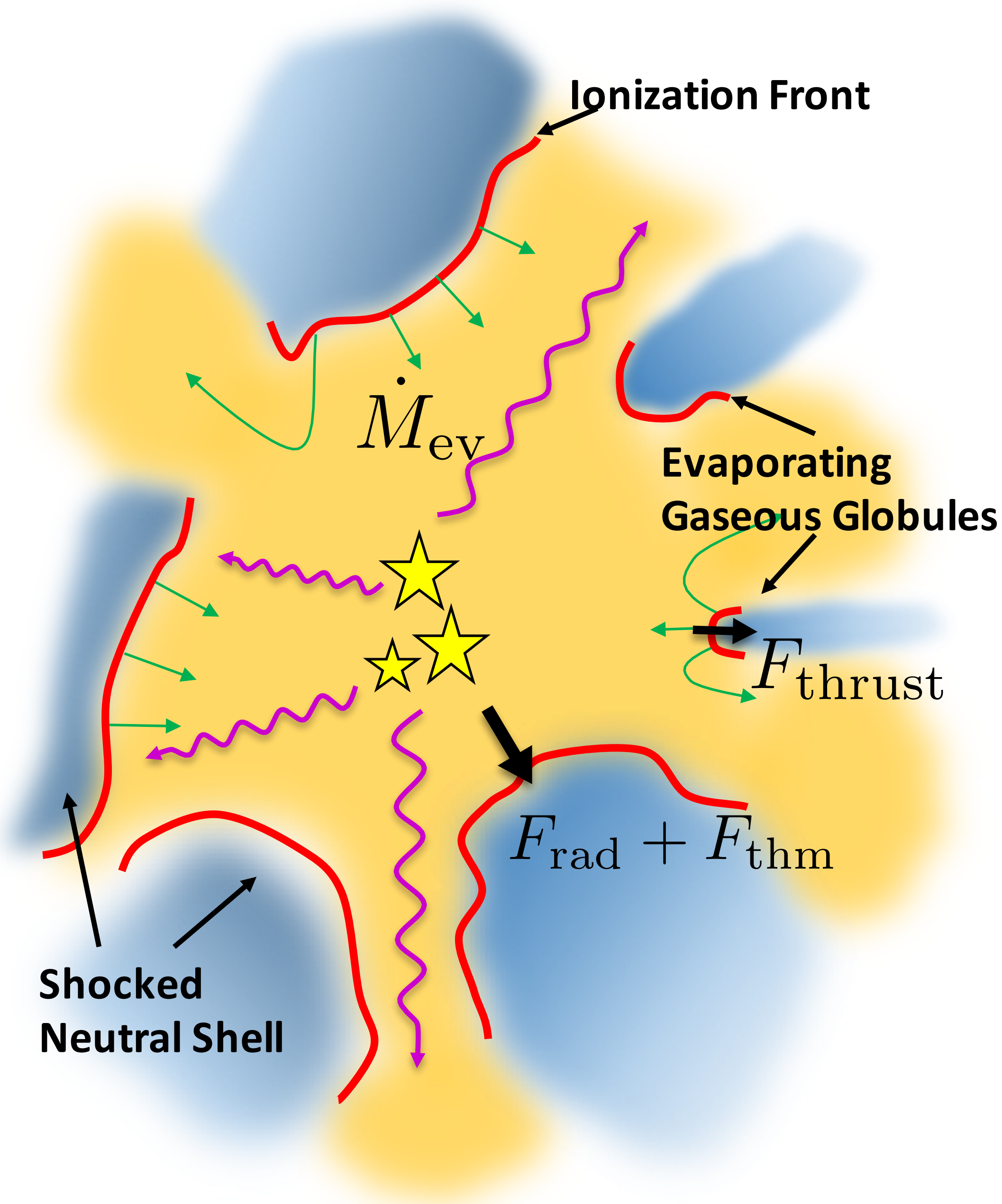
- H II regions and young star clusters seen with GMCs
- Each type represents evolutionary sequence
- **Lifetime of GMCs: 20-30 Myr**

(see also Murray+11, Miura+12, Meidt+15)




Radiation feedback can remove residual gas around young star clusters, controlling SFE and lifetime of molecular clouds.


Destructive Effects of UV Radiation

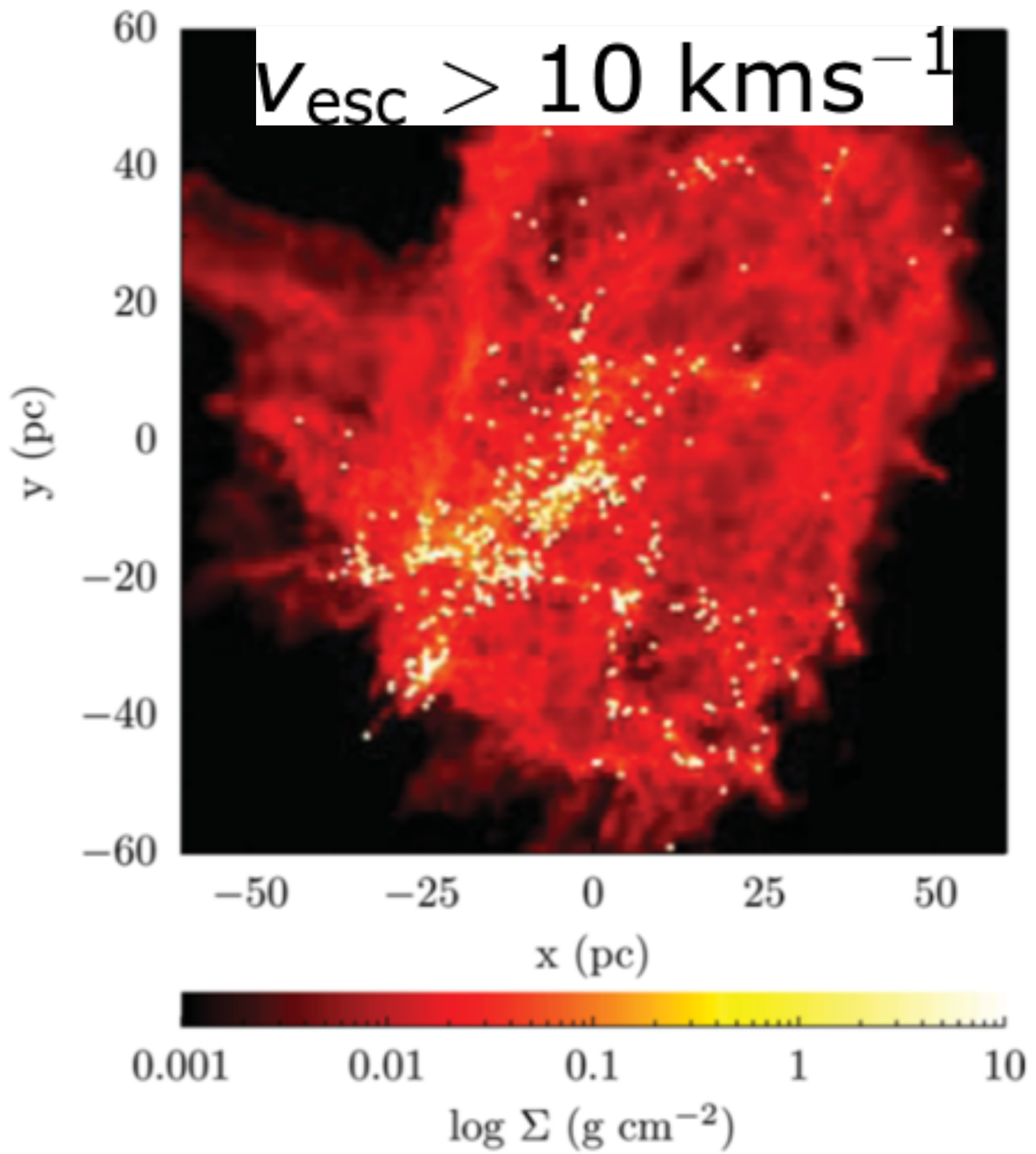


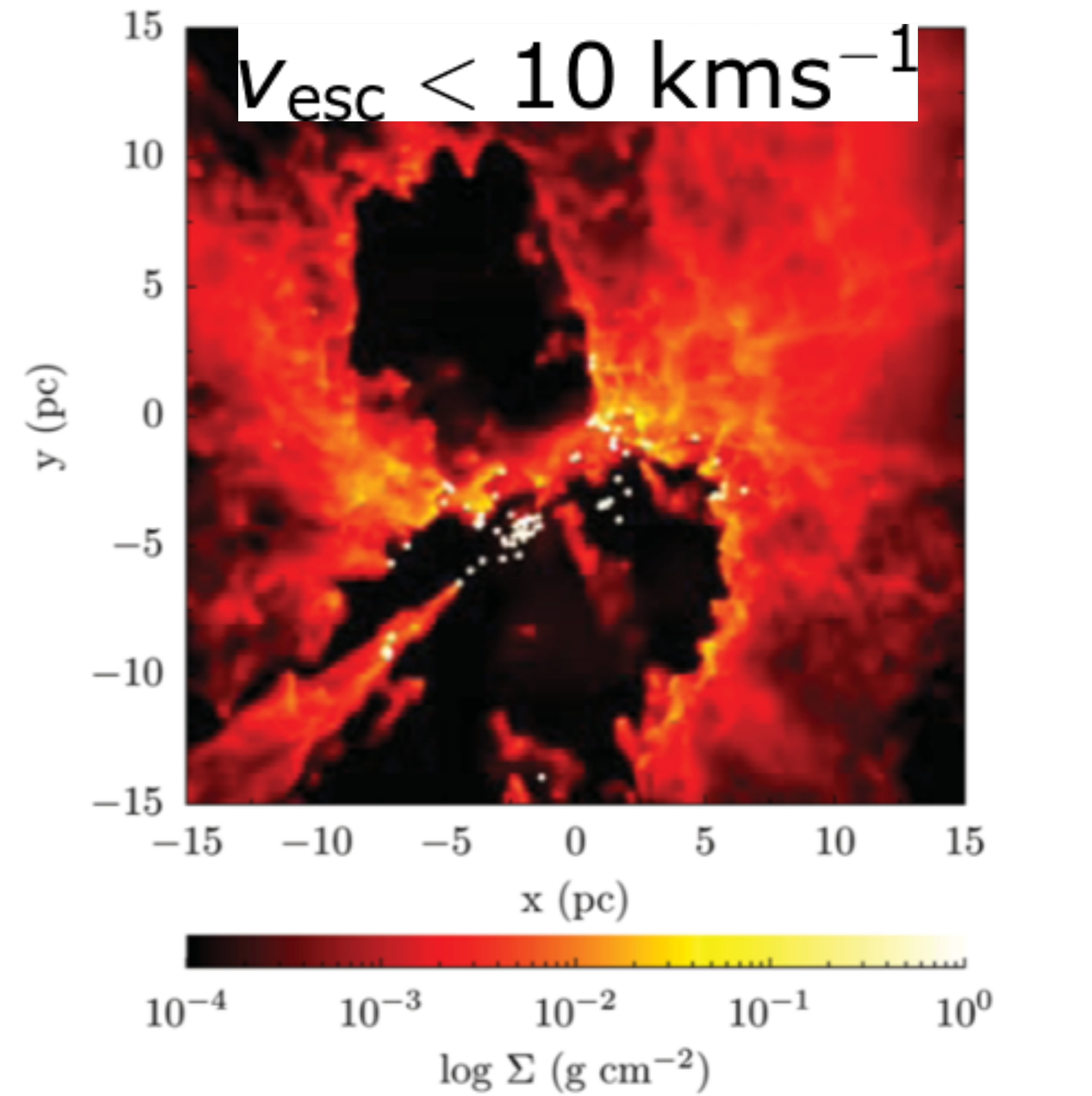
- **Photoionization**
  - Photoevaporation
  - Thermal pressure
  - Rocket effect
- **Radiation pressure on dust**
  - Important in massive, high-Σ clouds

(Whitworth+79, Franco+94, Williams+97, Matzner+02, Krumholz+06, Krumholz+09, Murray+10, Goldbaum+11, Lopez+11, Zamora-Aviles+12, Kim+16)

Previous Models on Cloud Disruption

Photoionization only (Dale+12, 13)

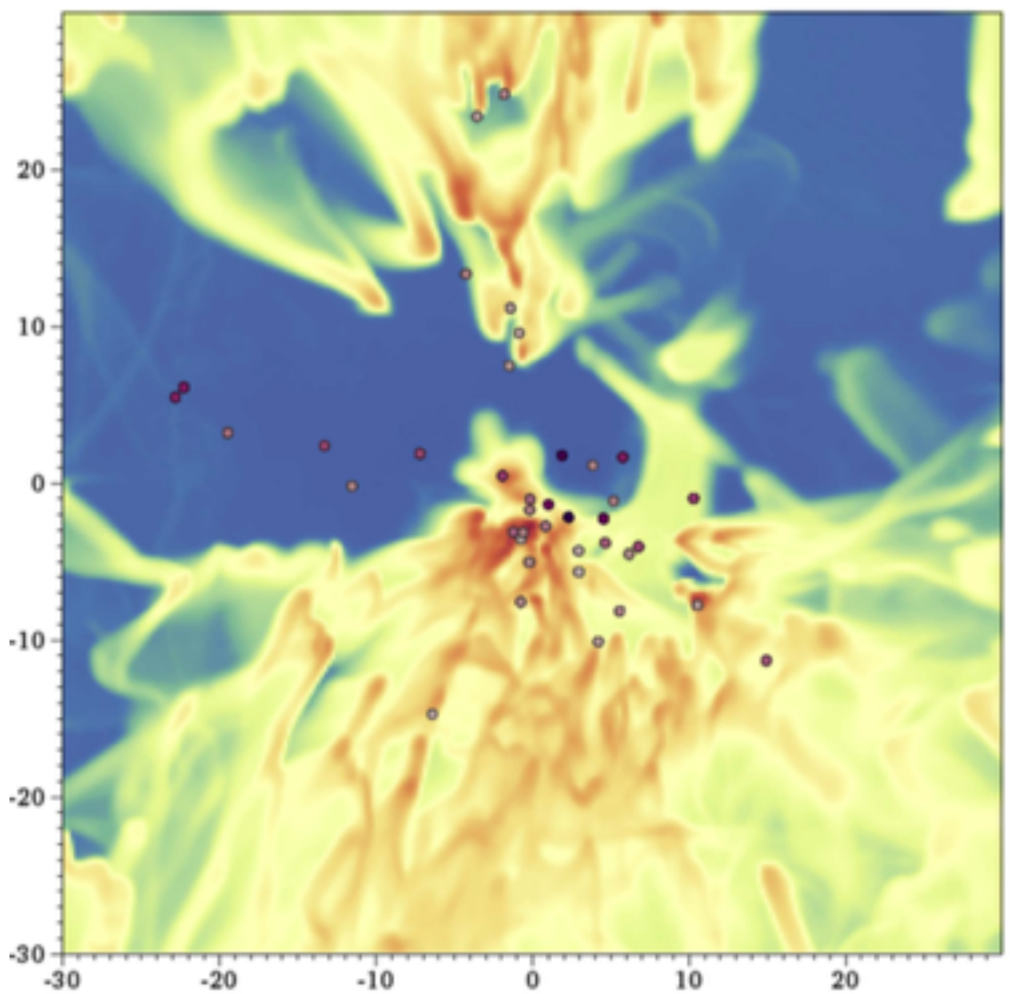


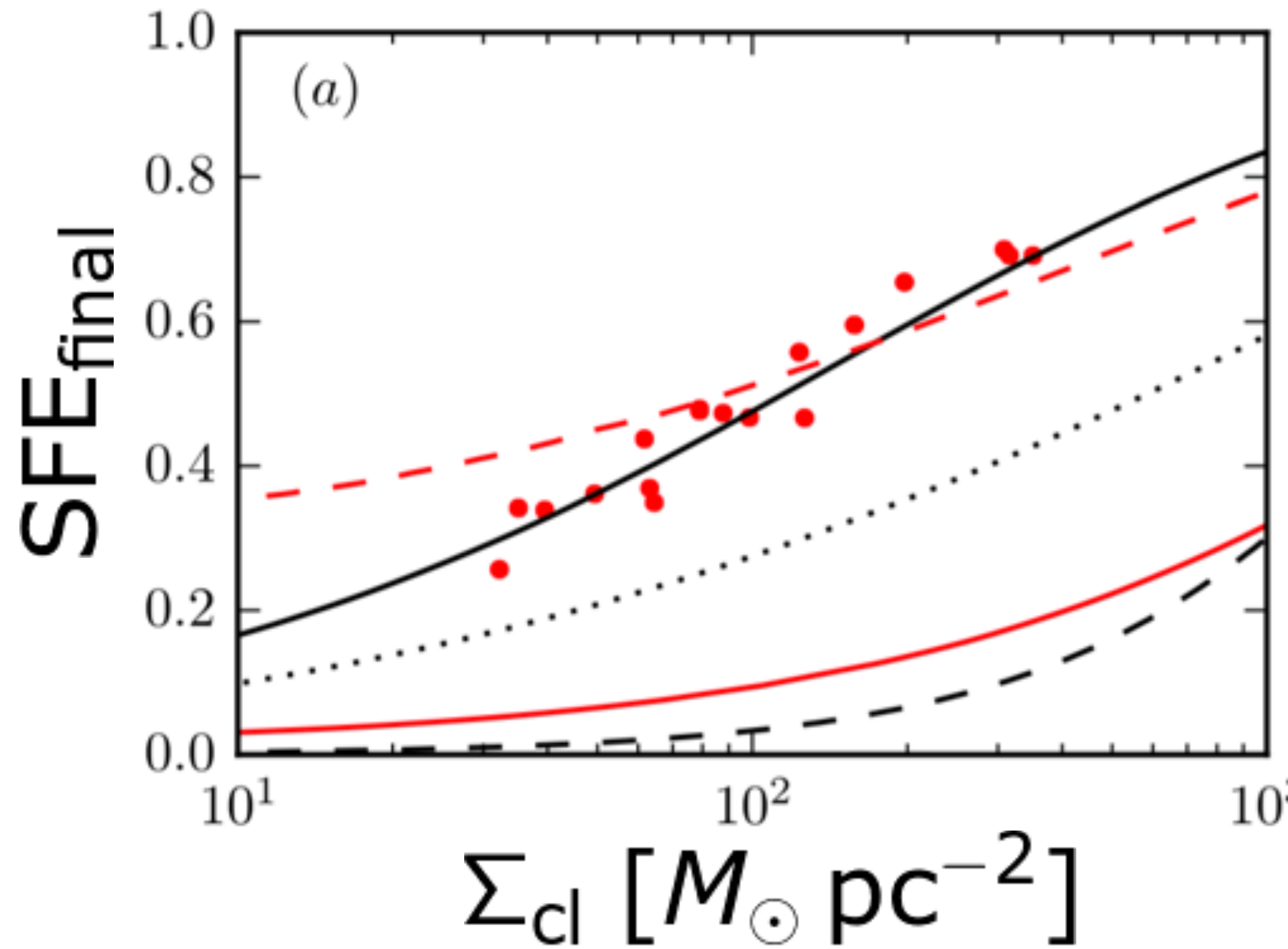


(see also Walch+12; Geen+15, 16, 17; Howard+16, 17; Gavagnin+17)

Previous Models on Cloud Disruption

Radiation pressure only (Raskutti+16)





- $\mathrm{SFE_{final}}$ of radiation pressure-regulated clouds depend on (the distribution of) Σ_{cl}

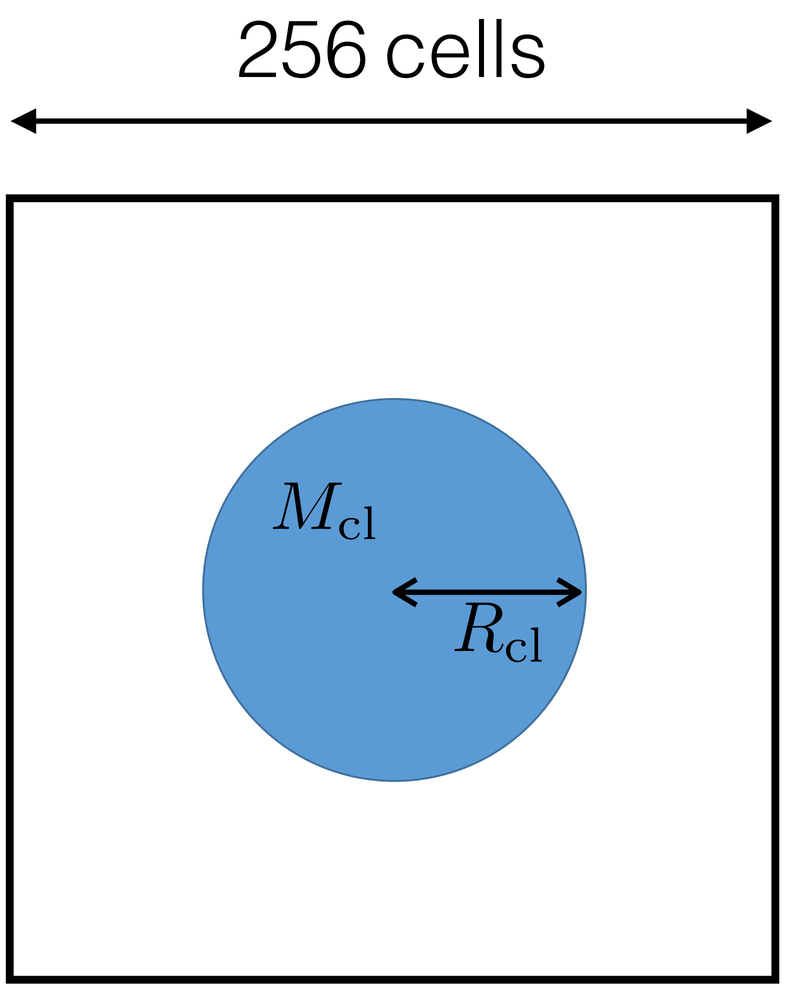
(Fall+10, Thompson+16, Kim+16, Raskutti+16, Grudic+17)

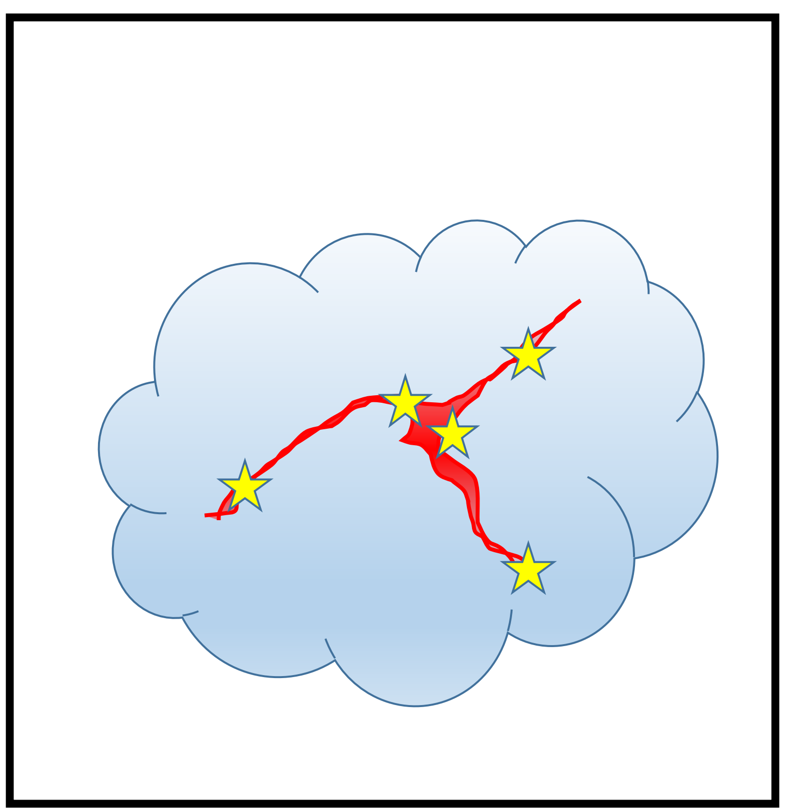
Key Issues

- Can UV radiation feedback sustain cloud turbulence or completely destroy cloud?
- **Can UV radiation feedback explain low SFE of GMCs?**
- **What is the timescale for gas dispersal?**
- **Relative importance of mass loss mechanisms**
  - Photoevaporation
  - Dynamical ejection
- Escape fraction of ionizing radiation
- Boundedness of star clusters

3D radiation hydrodynamic simulations of star cluster formation in turbulent clouds including both photoionization and radiation pressure

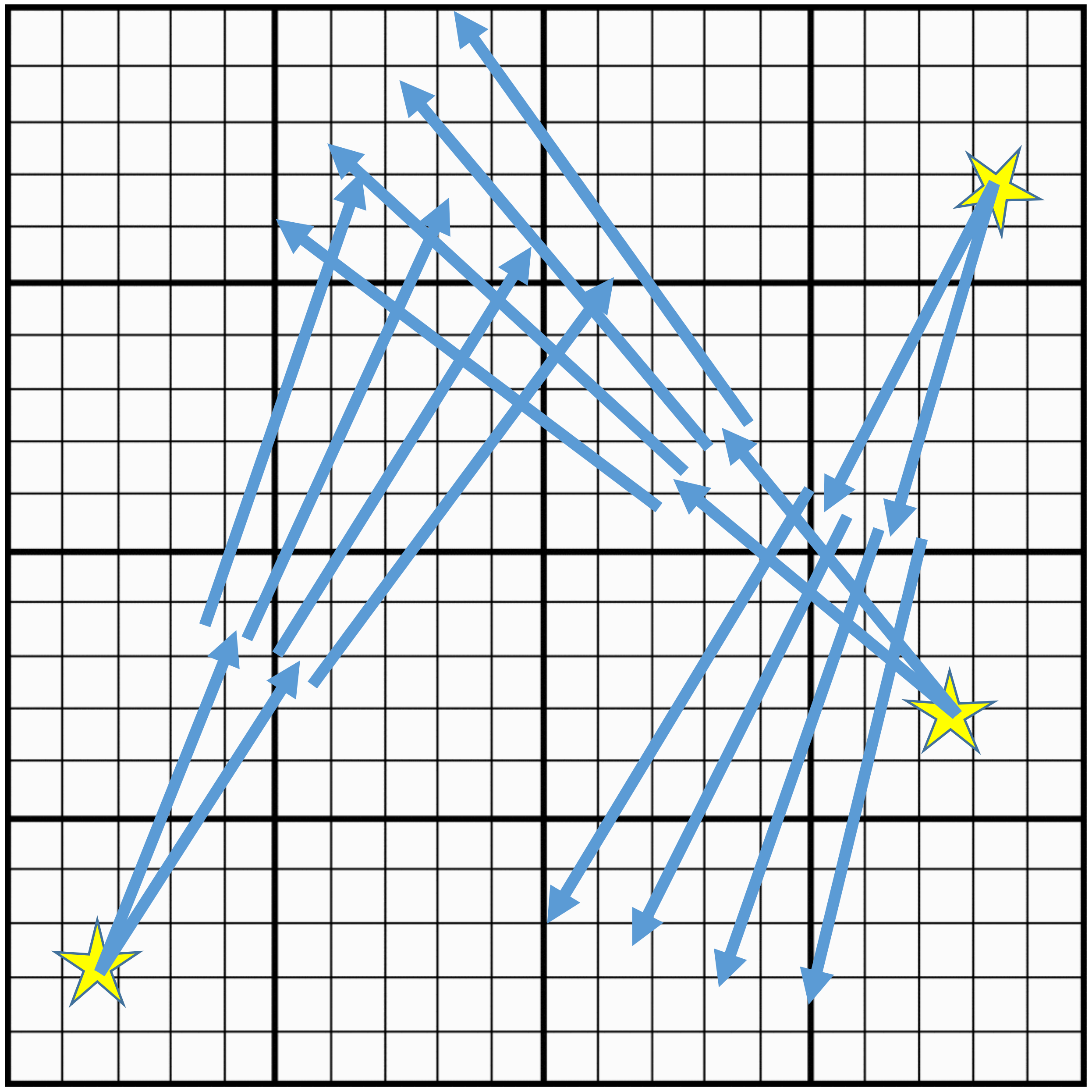
Numerical Method





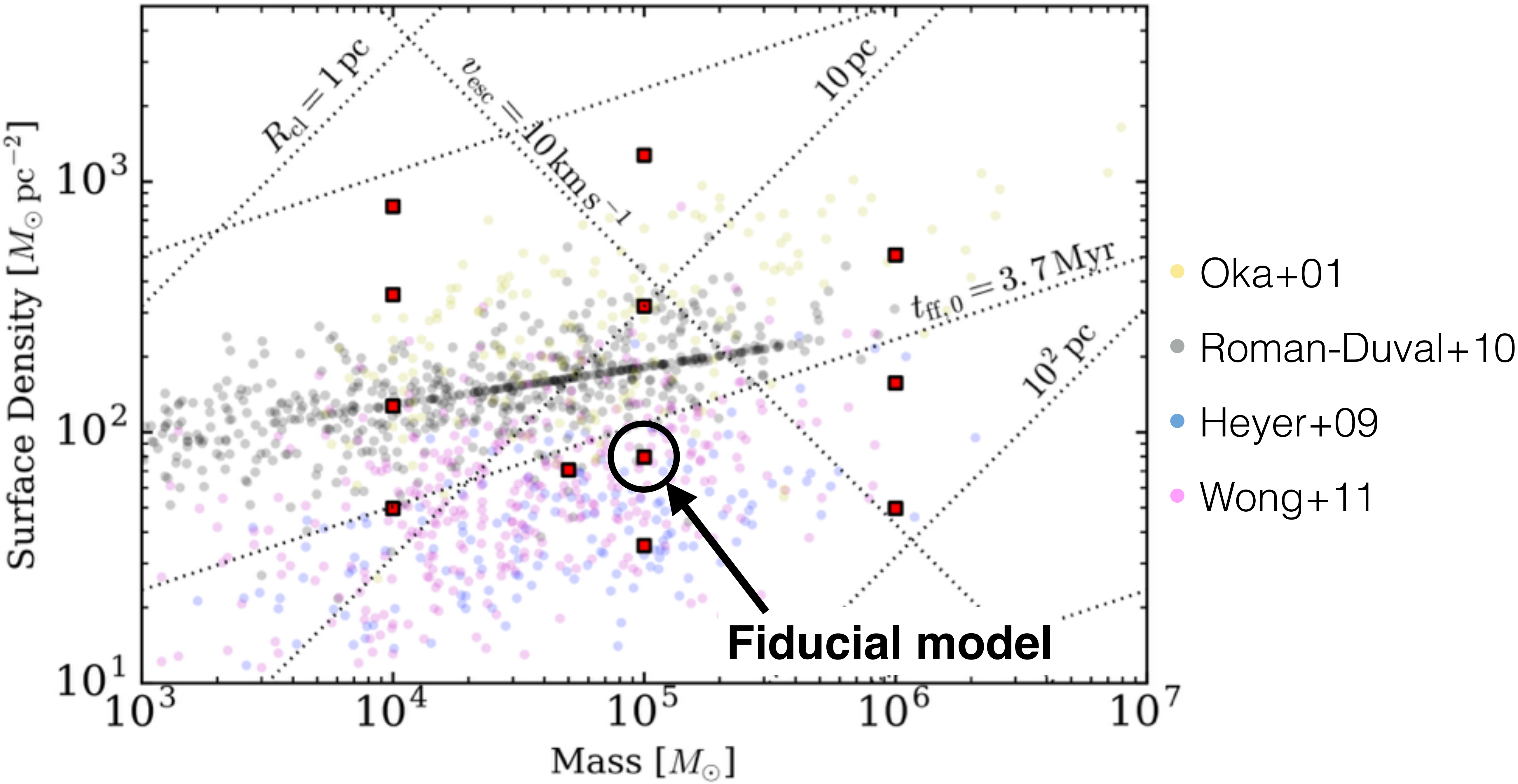
- Grid-based code *Athena* (Stone+08)
- Uniform density sphere with initial injection of turbulence (Stone+98)
- Marginally bound with $\alpha_{\rm vir} = 2$
- Star formation and accretion via sink particle method (Gong+13)
- Temperature as a function of H-ionization fraction (20 K < T < 8000 K)

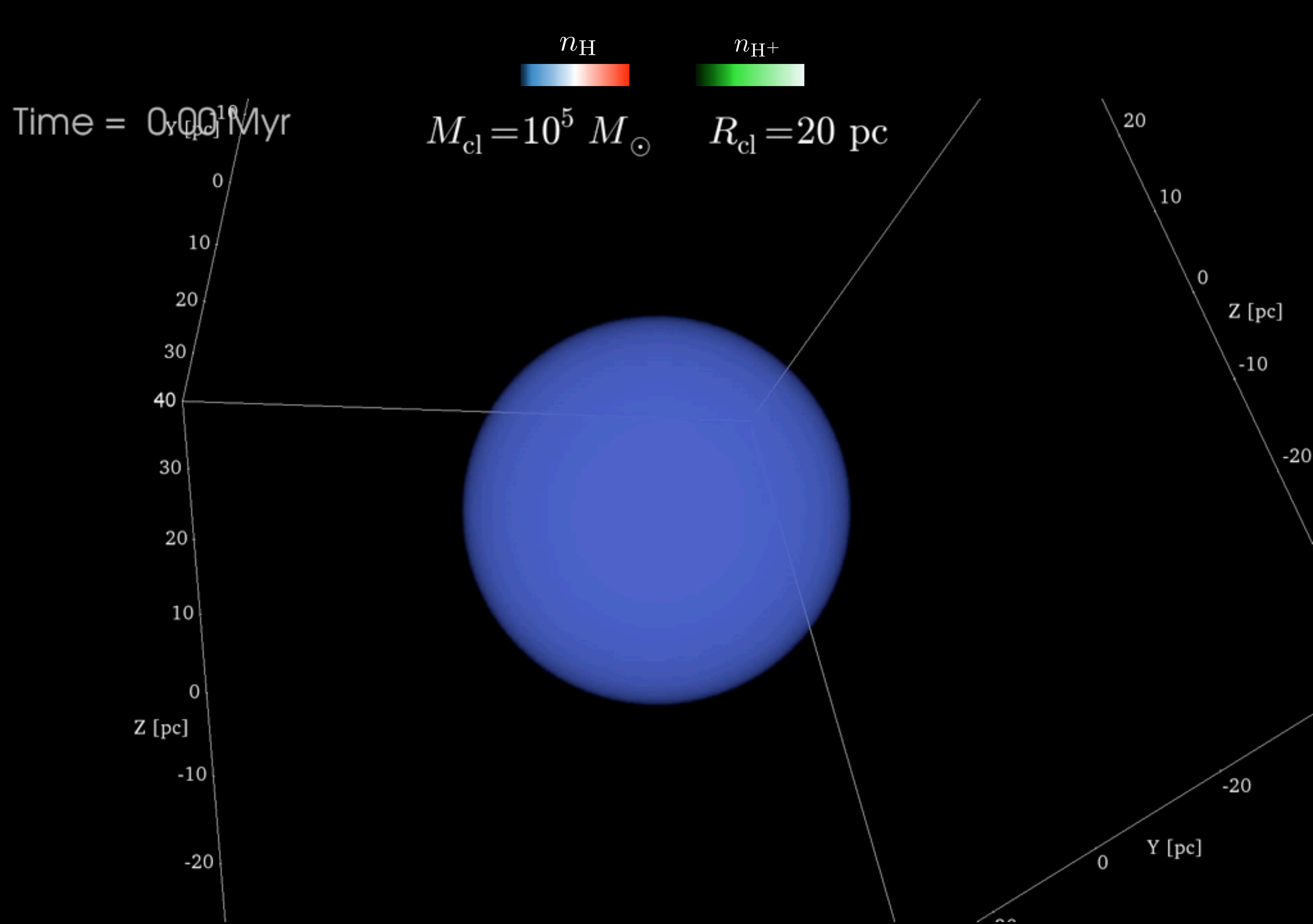
Radiative Transfer for Multiple Moving Point Sources



- Sink particles representing subclusters emit ionizing and non-ionizing radiation.
- Adaptive ray tracing (Abel+02) with improved parallel performance (Rosen+17, Kim+17, submitted)

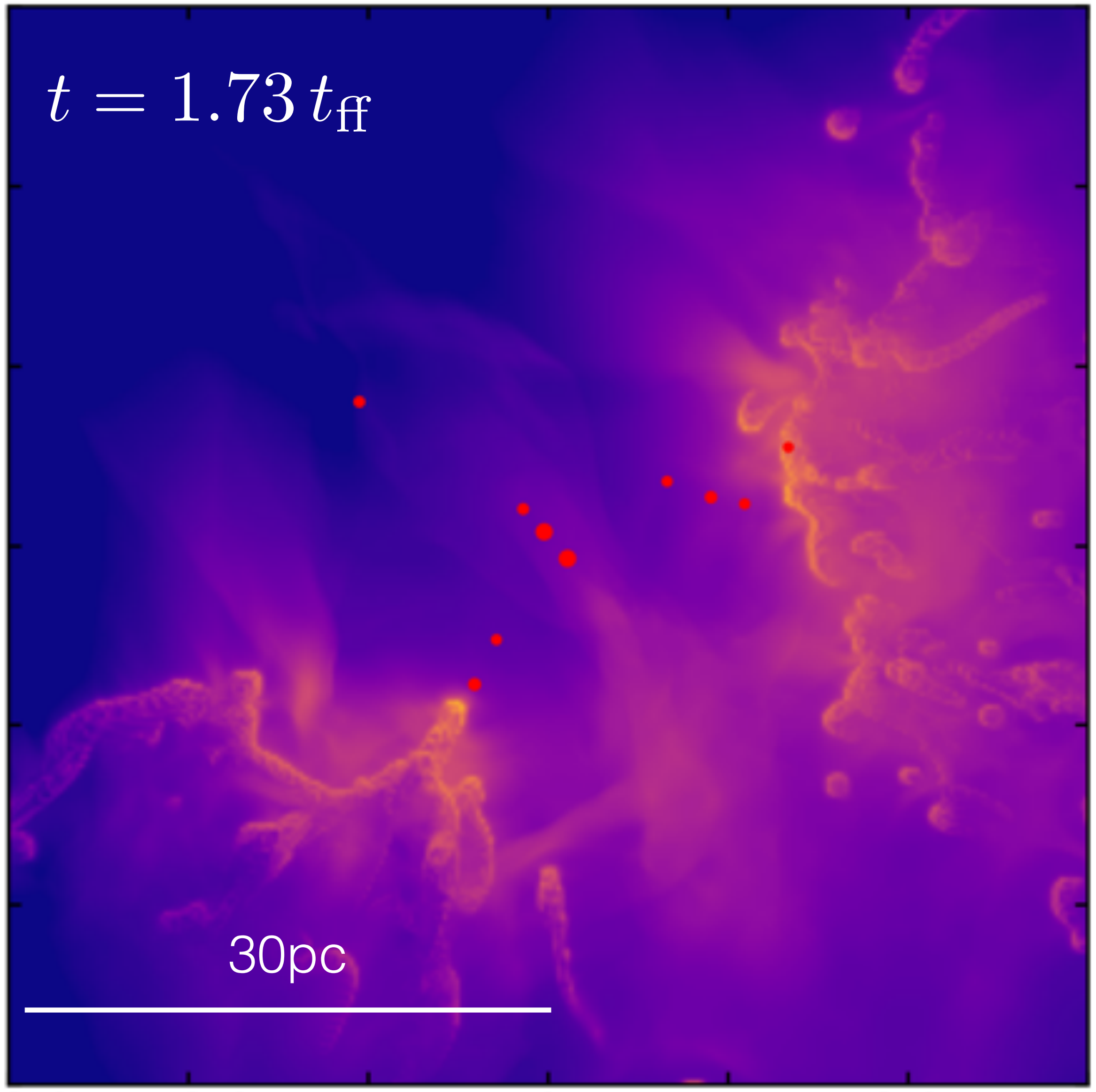
Cloud Parameters

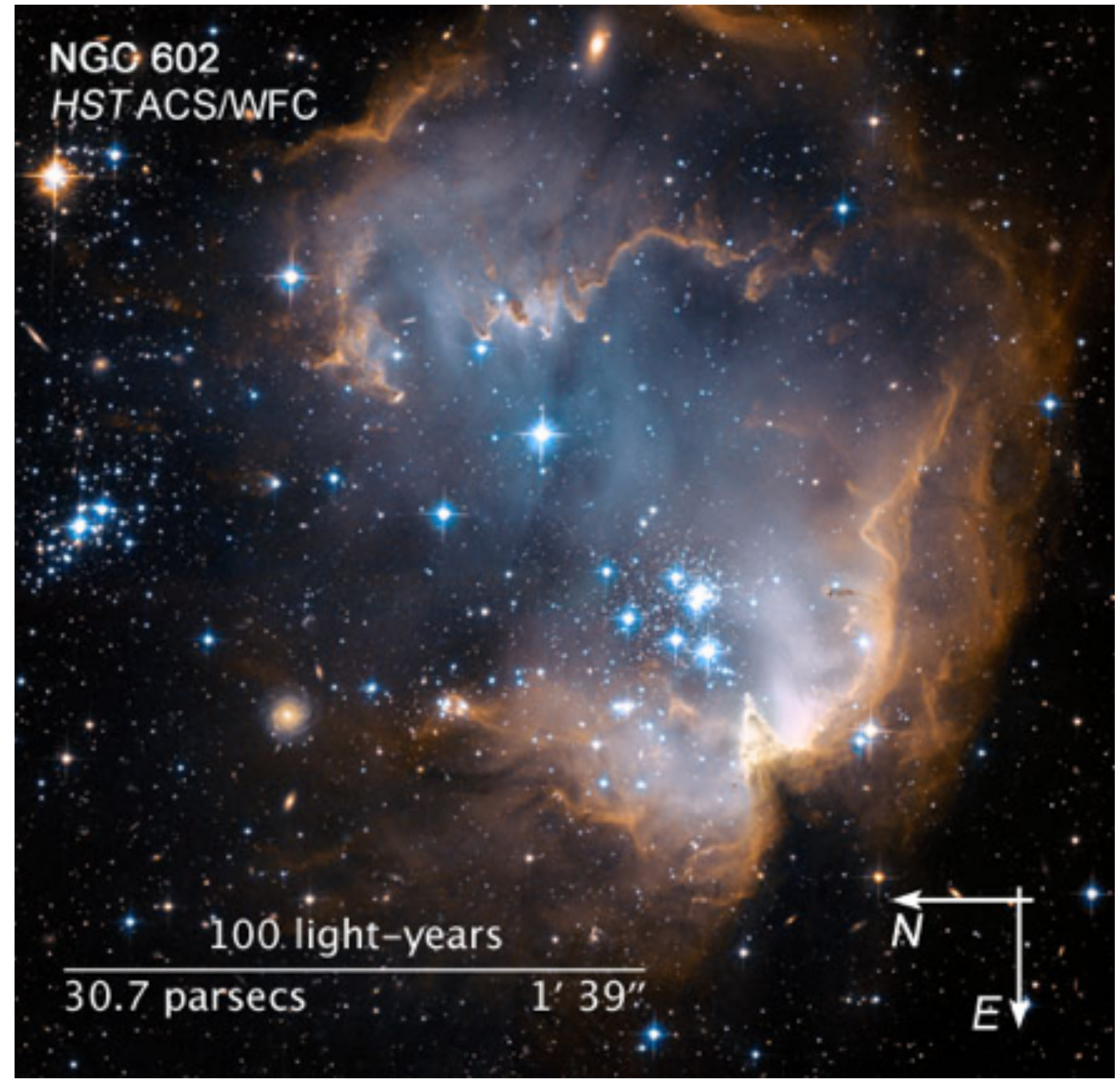




n_{H}
$n_{\mathrm{H+}}$
Time = 0.00 Myr
$M_{\mathrm{cl}} = 10^5\ M_\odot$
$R_{\mathrm{cl}} = 20$ pc
Z [pc]
Y [pc]
Z [pc]

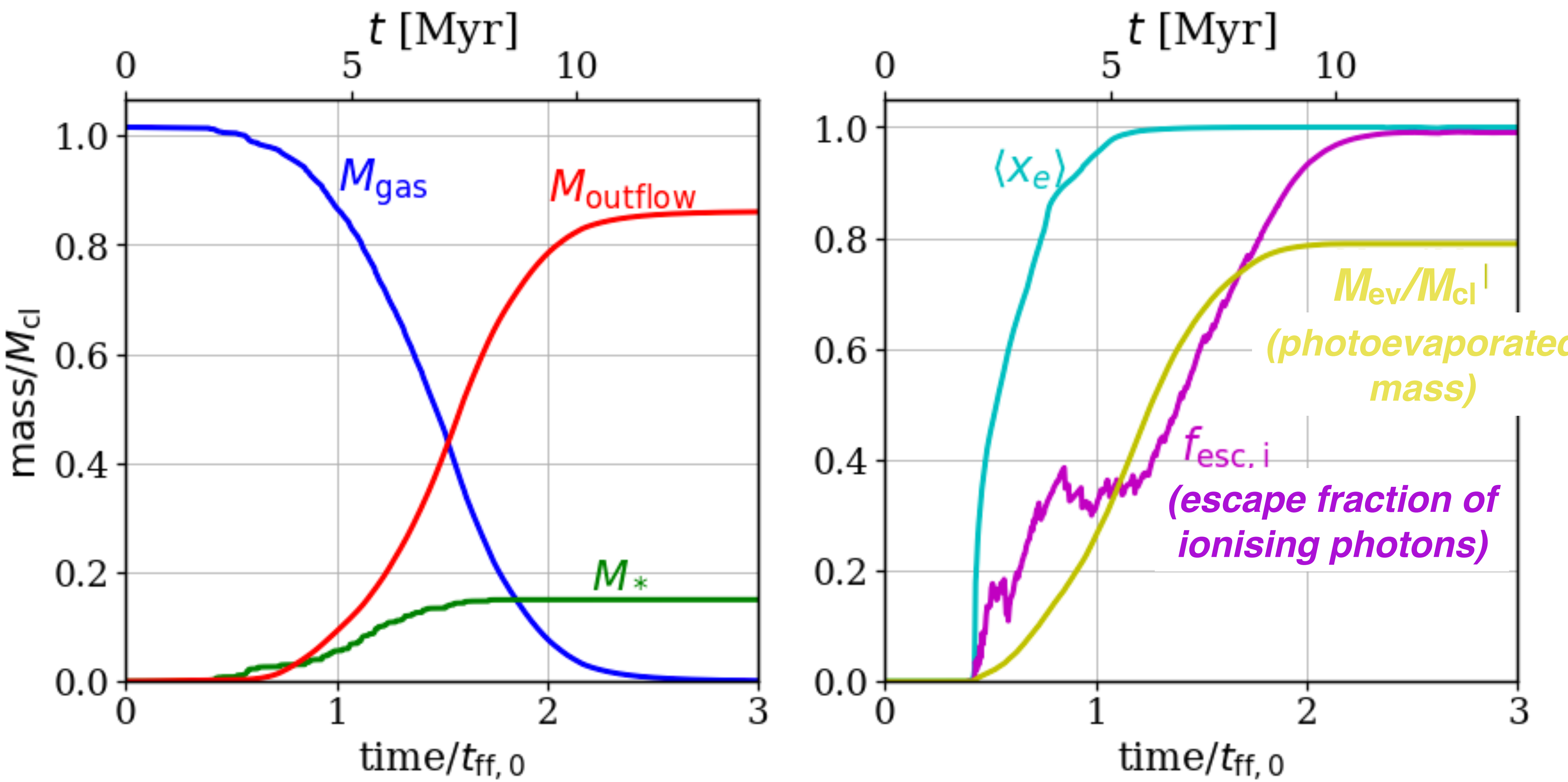
Emission measure (Simulation) **NGC 602 (HST image)**





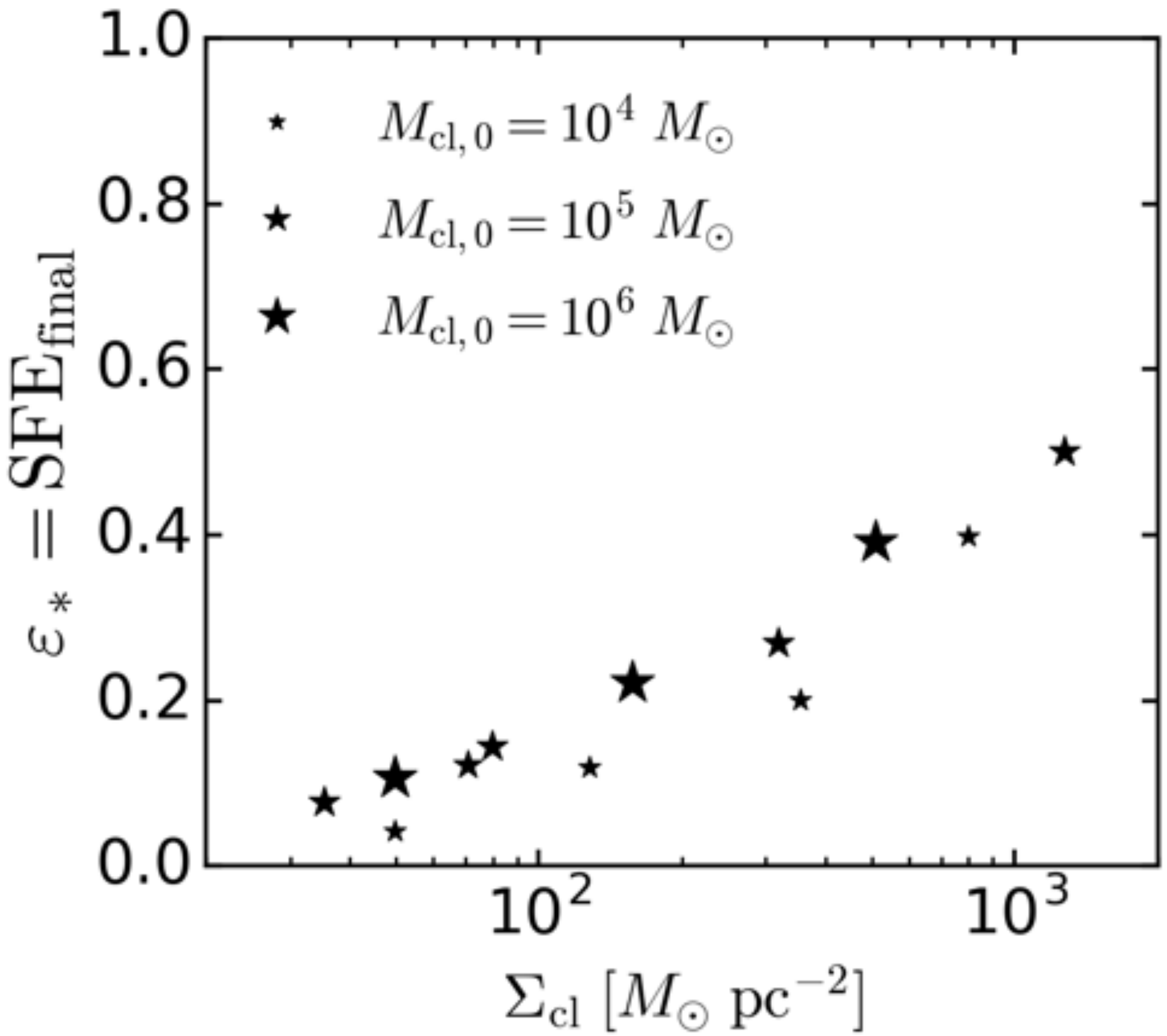
- Irregular structures such as “fingers”, “elephant trunks” naturally arise from turbulent density field sculpted by UV radiation
  (e.g., Mellema+06, Arthur+11,Tremblin+12, Gritschneder+09, 10)

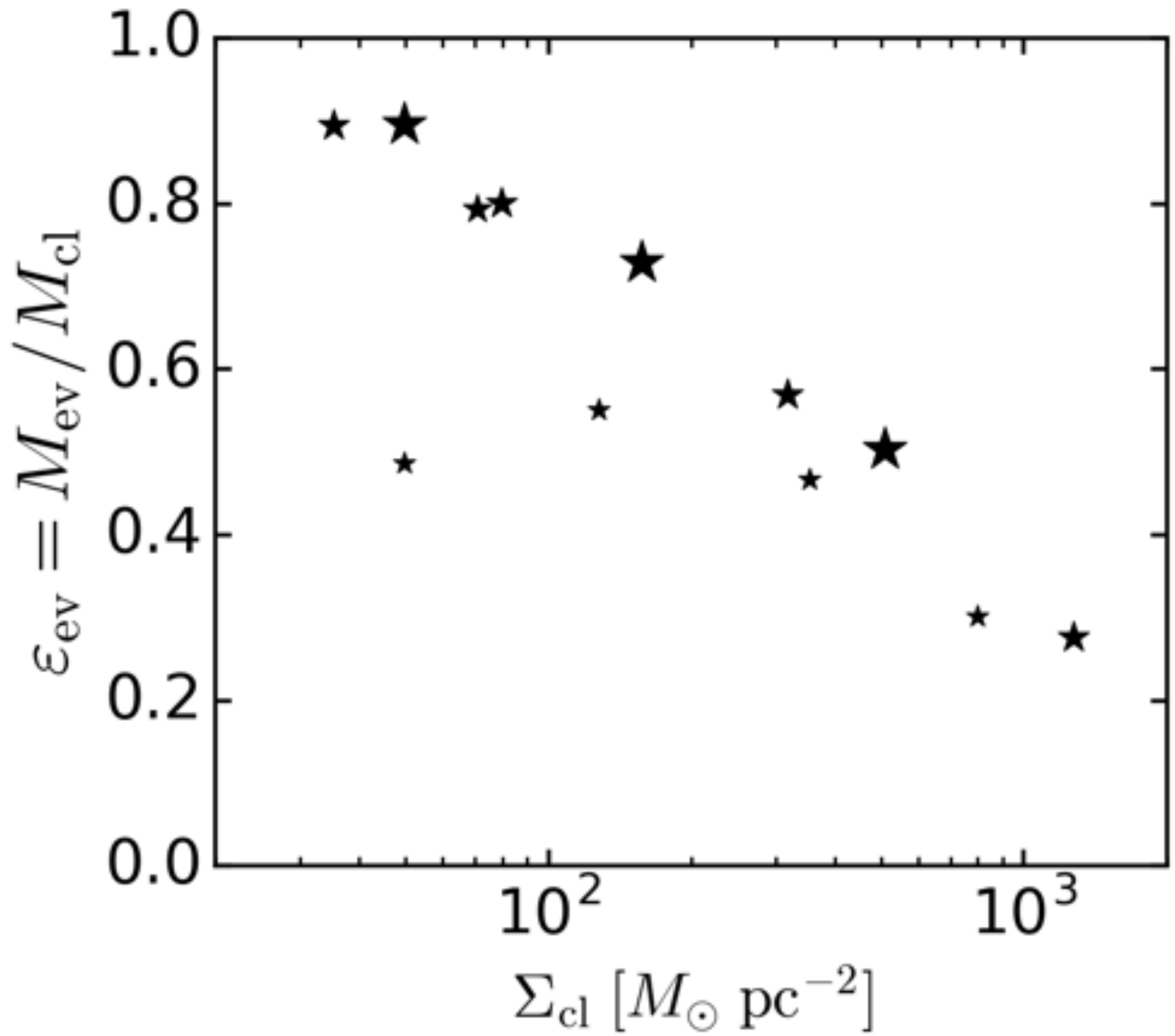
Evolution of Key Characteristics



- SFE_{final}: 15%
- Photoevaporation is the dominant mass loss mechanism ($M_{ev}/M_{cl} \sim 0.8$)

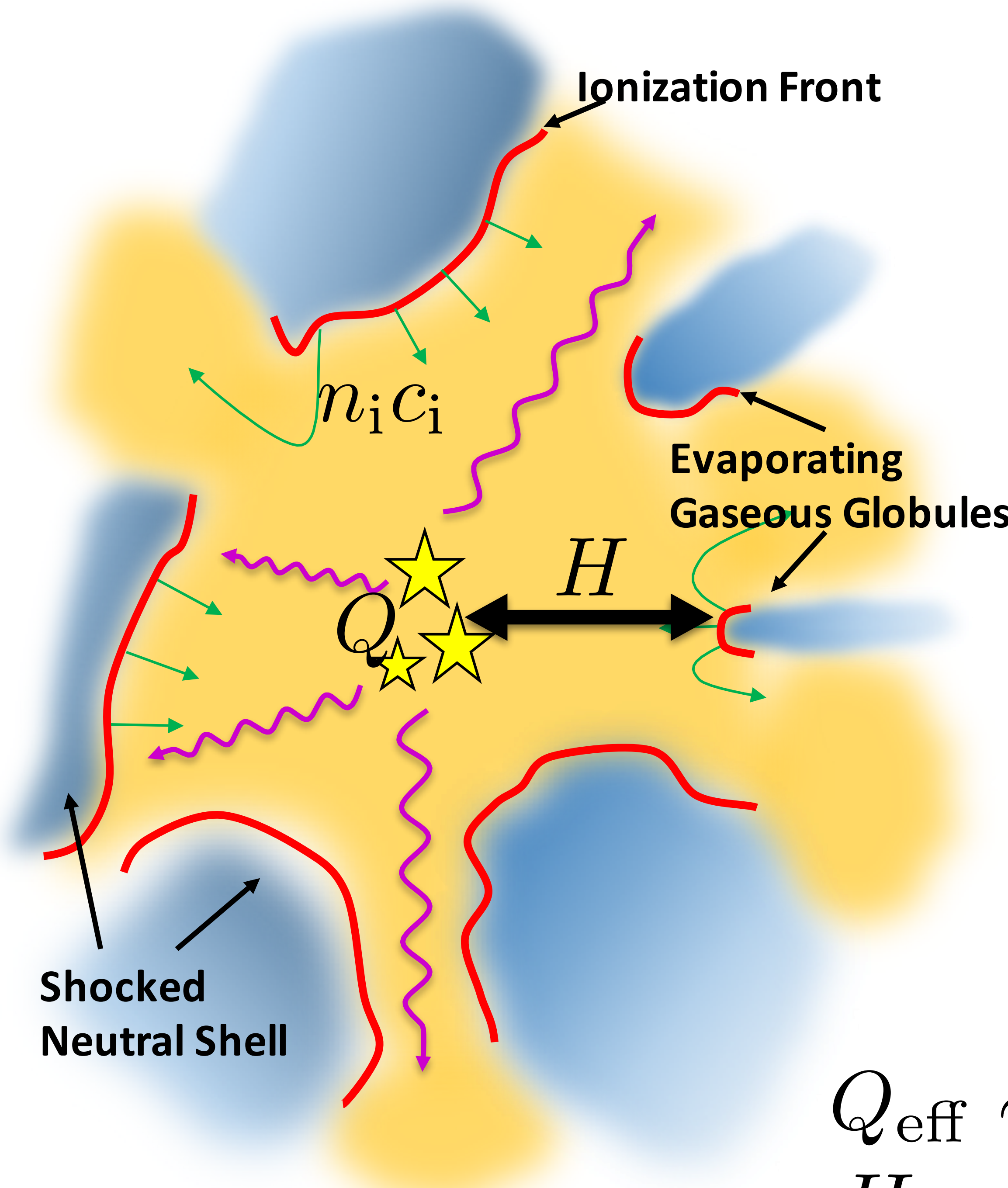
Final SFE and Evaporation Efficiency





- $\mathrm{SFE}_{\rm final}$ and evaporation efficiency depend primarily on the initial cloud surface density

Characterizing Mass Loss by Photoevaporation



- Ionization-recombination balance

$$Q_{\rm eff} \approx \alpha_{\rm i} n_{\rm i}^2 AH$$

$Q_{\rm eff}$: ionizing photon absorption rate
A : area of ionization front
H : thickness of recombination layer

- Mass loss rate

$$\dot{M}_{\rm ev} = (\mu n_{\rm i} c_{\rm i}) \times A$$

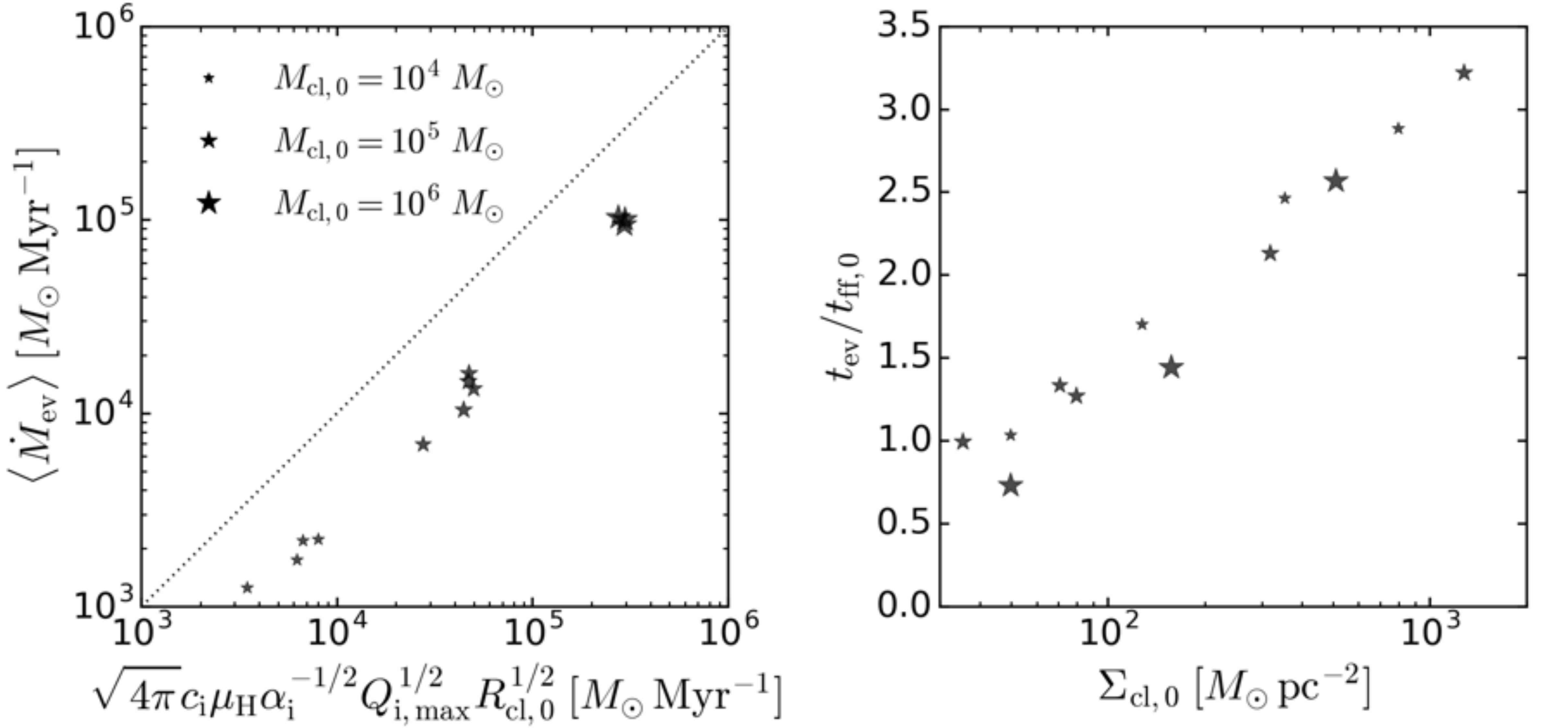
$$= \mu c_{\rm i} \left(\frac{Q_{\rm eff}}{\alpha_{\rm i} AH} \right)^{1/2} \times A$$

$$\propto (Q_{\rm eff} A/H)^{1/2}$$

$$\propto Q^{1/2} R_{\rm cl}^{1/2}$$

$$Q_{\rm eff} \sim Q$$
$$H \sim R_{\rm cl}$$
$$A \sim 4\pi R_{\rm cl}^2$$

Mass Loss Rate and Evaporation Time Scale



- Mass loss rate $\propto Q_{\rm i}^{1/2} R_{\rm cl}^{1/2}$
- Evaporation timescale (measured in units of free-fall time) depends primarily on $\Sigma_{\rm cl}$

Control of SFE by Photoevaporation

- Stellar mass required to photoevaporate $M_{\rm ev} = M_{\rm cl} - M_*$

$$\begin{aligned} M_{\rm cl} &= M_* + M_{\rm ev} \\ &= M_* + \langle \dot{M}_{\rm ev} \rangle t_{\rm ev} \\ &= M_* + \frac{\mu_{\rm H} c_{\rm i}}{\alpha_{\rm i}^{1/2}} \left\langle \frac{Q_{\rm eff}^{1/2} A^{1/2}}{H^{1/2}} \right\rangle t_{\rm ev} \end{aligned}$$

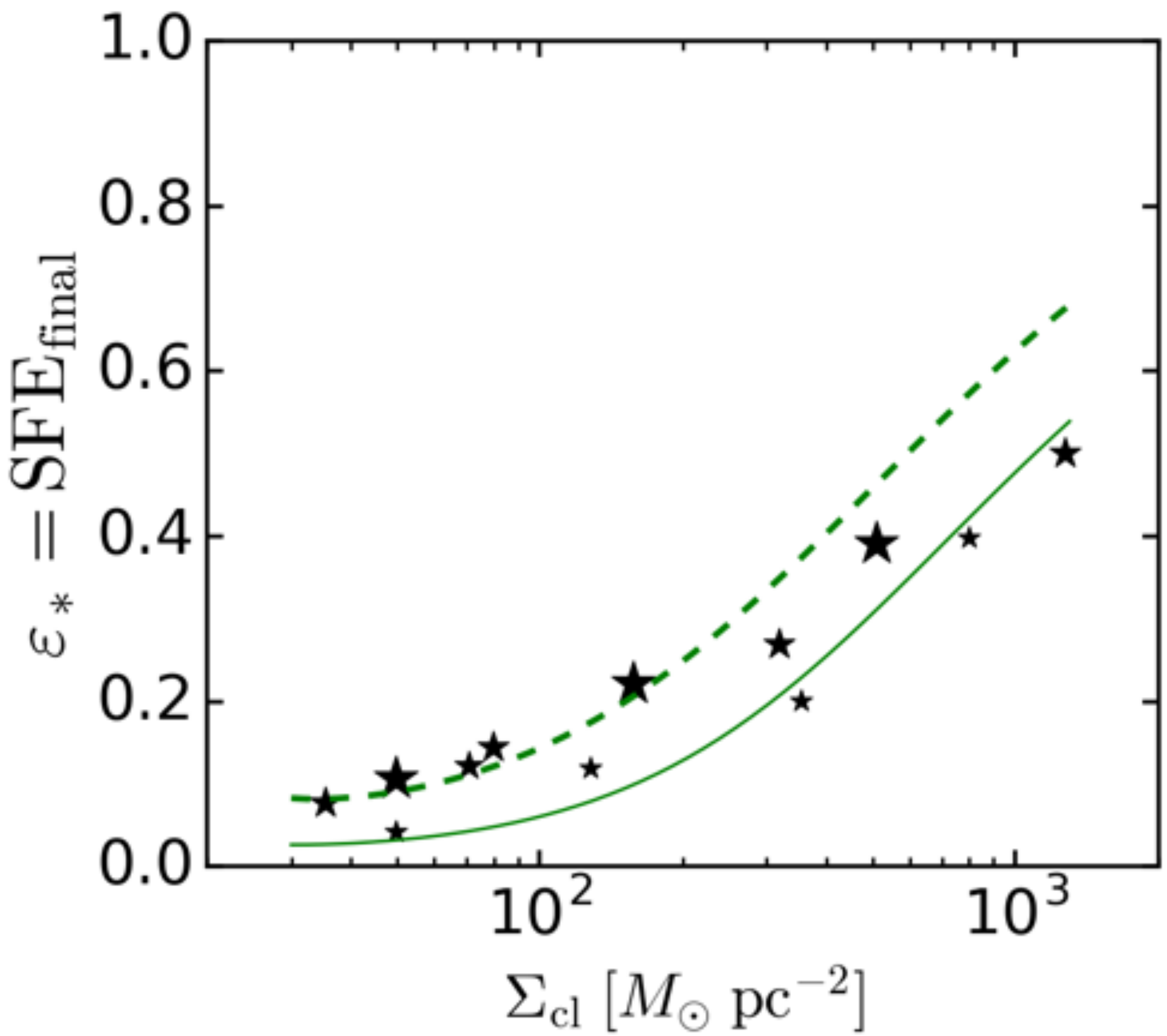
- Dividing by $M_{\rm cl}$

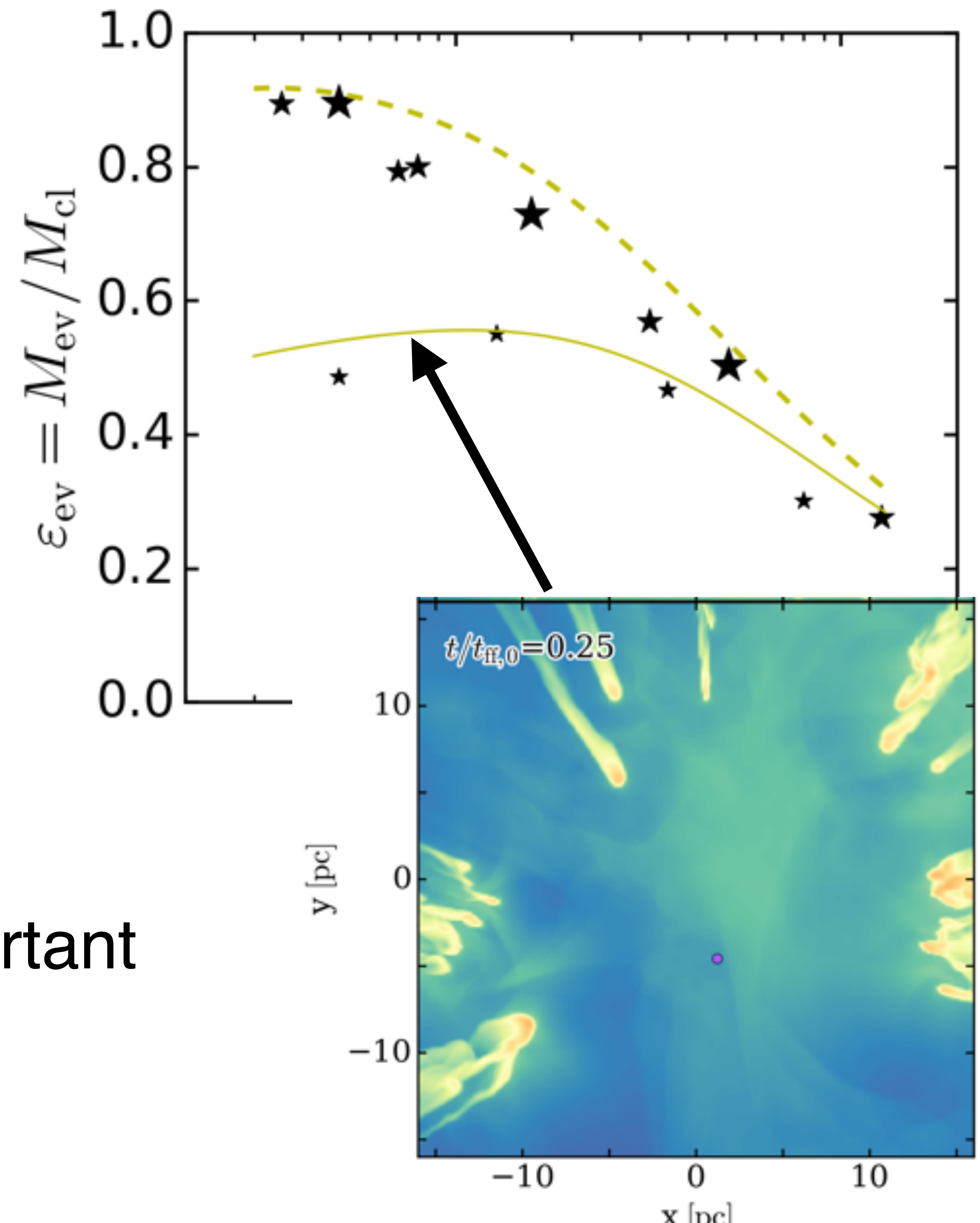
$$1 = \varepsilon_* + \phi \left(\frac{t_{\rm ev}}{t_{\rm ff,0}} \right) \left(\frac{\Sigma_{\rm cl}}{500\ M_\odot {\rm pc}^{-2}} \right)^{-1} \varepsilon_*^{1/2}$$

~0.3

$$\phi_t = -1.65 + 1.55 \log_{10} \Sigma_{\rm cl,0}$$

Final SFE and Evaporation Efficiency





- Rocket effect becomes important for low-mass clouds with

$$M_{\mathrm{ej}} v_{\mathrm{esc}} \propto M_{\mathrm{ev}} c_{\mathrm{i}}$$

Discussion

- **t_{ev} is a good measure of the timescale for gas dispersal after the onset of massive SF for photoevaporation-dominated cases**
  - t_{ev} ranges between ~1-3 t_{ff} or 2-10 Myr
  - $t_{dep} \sim t_{cl}/\mathrm{SFE}_{final} \sim t_{ev}/\mathrm{SFE}_{final} \sim$ 10-100 Myr

- **Possible reasons for higher SFE and shorter t_{dep} than observed?**
  - Artificial initial condition
  - Neglect of stellar winds and supernovae
  - Absence of magnetic support
  - Unresolved, subgrid-scale physical processes
    - Need for a subgrid model for sink particles? (Howard+14,16)

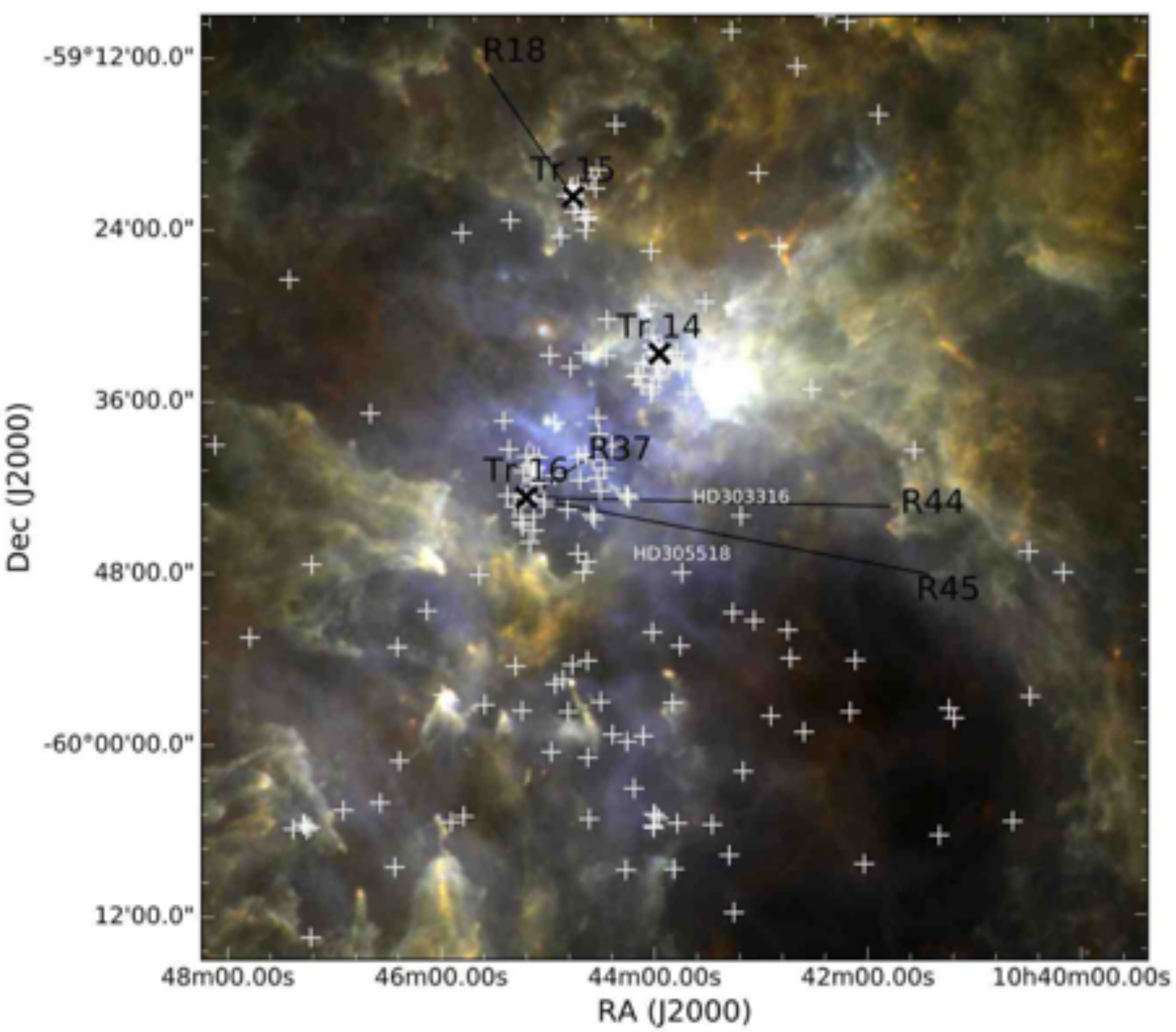
Mass Loss Rate of Evaporating Pillars

$$\dot{M}_{\rm ev,obs} = \pi r^2 m_{\rm H} n_{\rm H} v$$

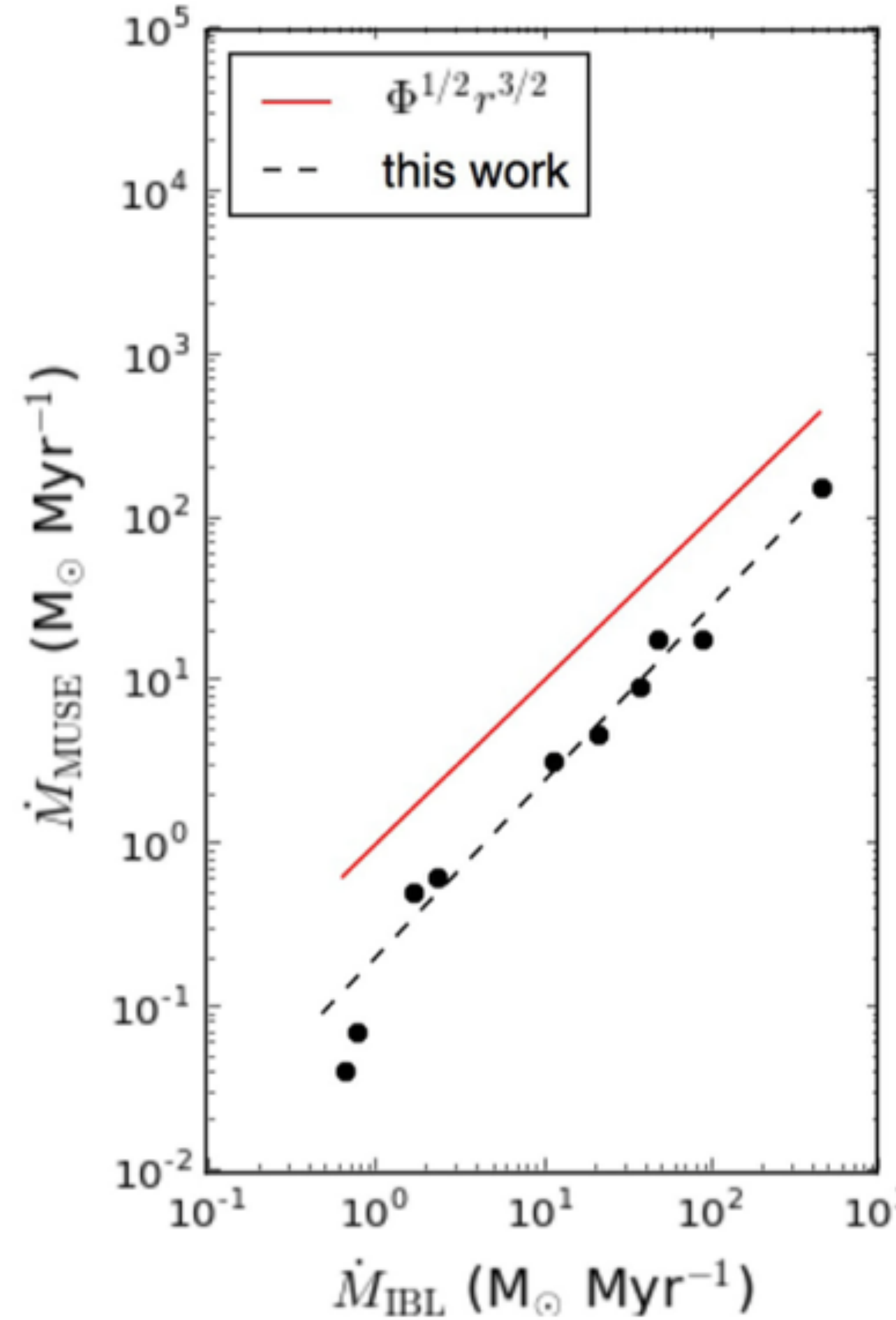
$$\dot{M}_{\rm ev,theory} \propto \Phi^{1/2} A r^{-1/2}$$

$$\propto \Phi^{1/2} r^{3/2}$$

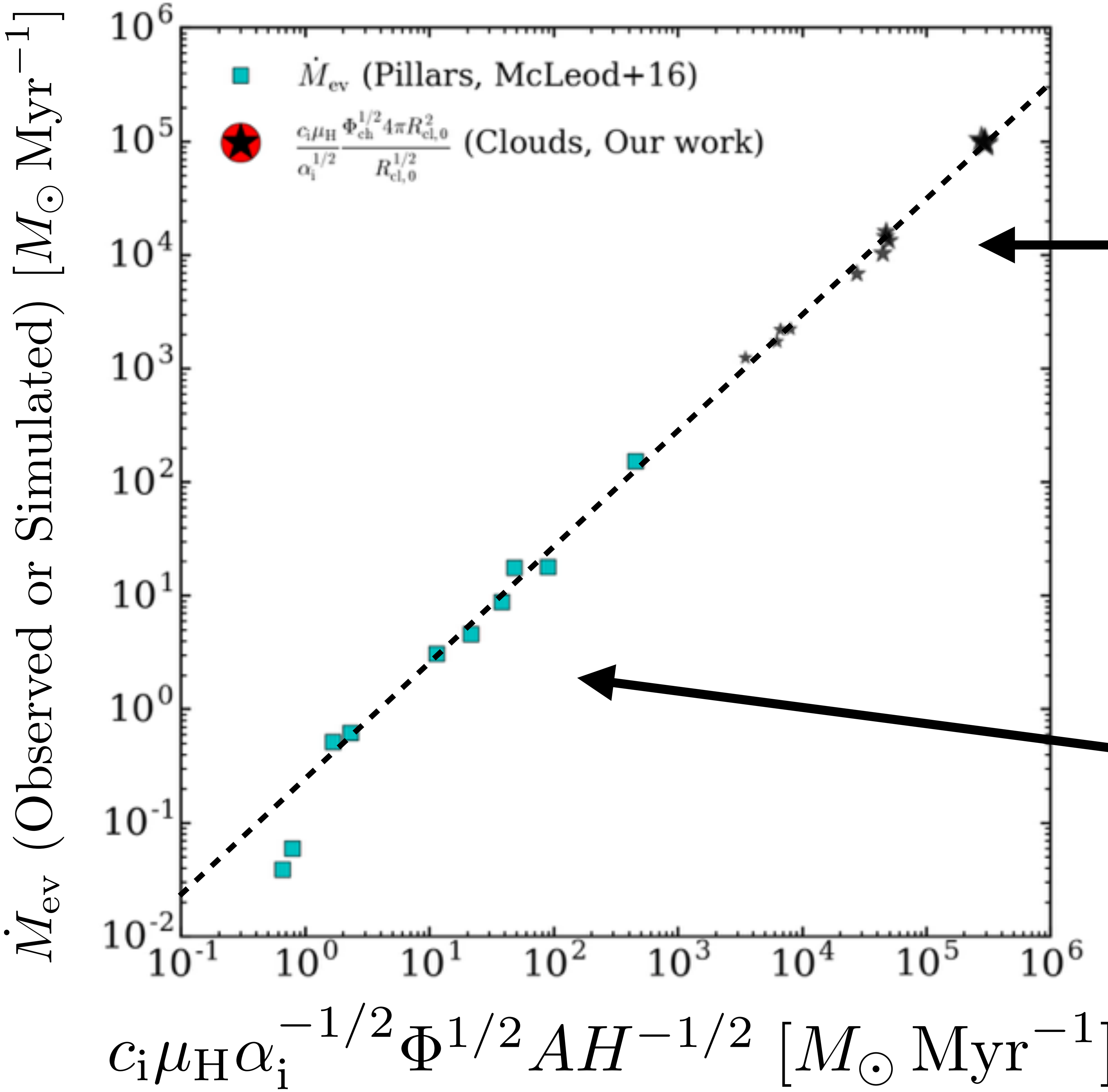
(e.g., Kahn+69, Bertoldi89,+90, Lefloch+94)

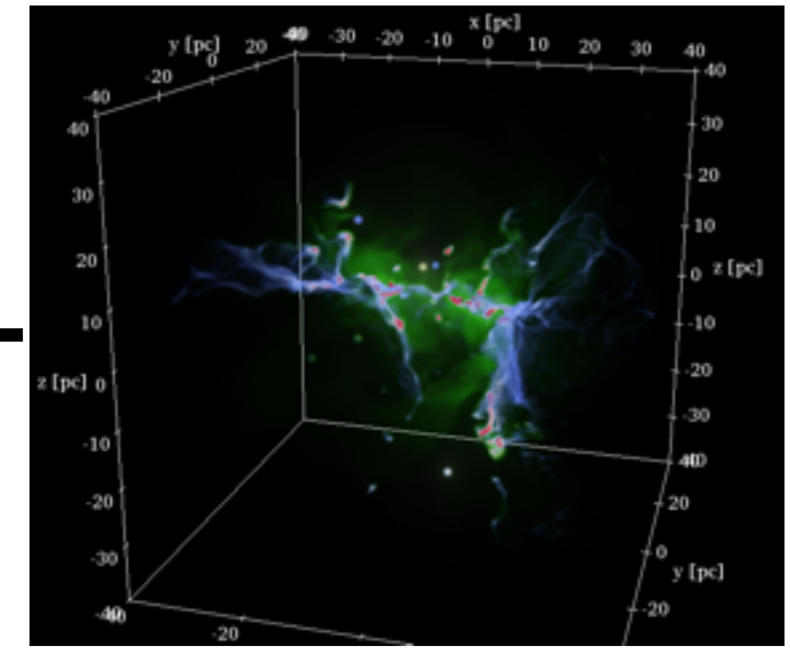


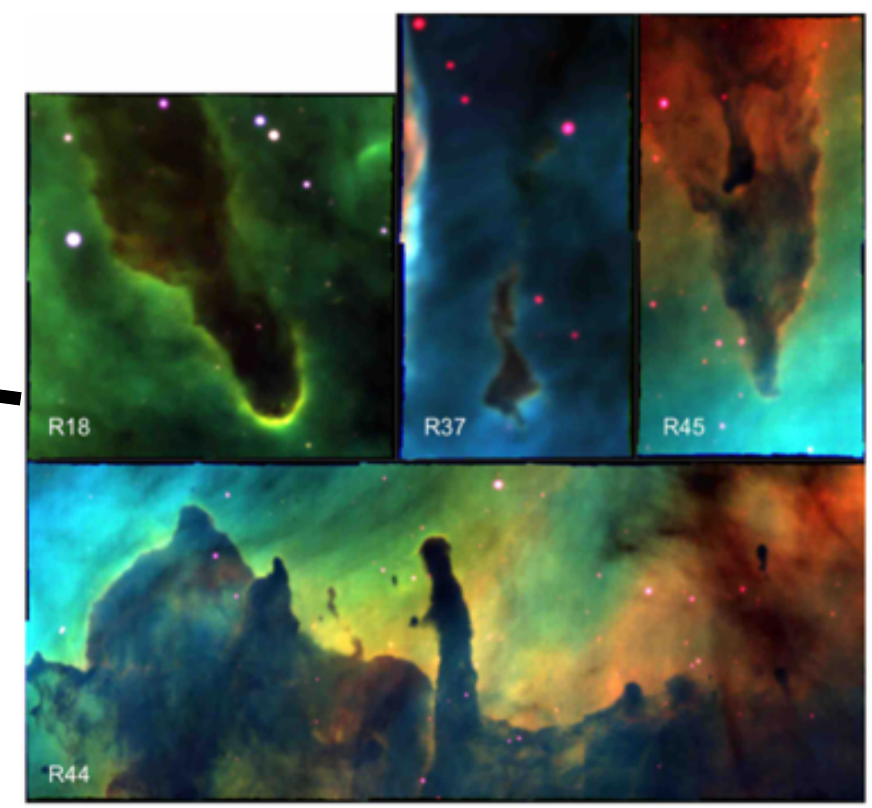
McLeod+16



Analogy between Pillars and Clouds







Summary

- Radiation hydrodynamic simulations of star cluster formation in turbulent GMCs
    1. **Photoevaporation plays a dominant role** in the disruption of GMCs typical of the MW.
    2. **High $\mathrm{SFE}_{\mathrm{final}}$ for high-Σ clouds**
    3. Cloud destruction occurs within **a few dynamical timescales once sufficiently luminous H II regions form**.