Momentum Injection by Supernovae in the ISM

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2014. 7. 2.

Gravity's Loyal Opposition: The Physics of Star Formation Feedback@ KITP

Classical Evolutionary Stages

- Free expansion (of ejecta): constant velocity and mass

$$p_{\rm free} = M_{\rm ej} v_{\rm ej} = 10^4 M_\odot \, {\rm km \, s^{-1}} (M_{\rm ej}/M_\odot)^{1/2} E_{51}^{1/2}$$

- Sedov-Taylor: point source explosion. energy conserving.

- Pressure Driven Snowplow: overpressured hot gas pushes shell.

- Momentum Conserving Snowplow: no push. no addition of momentum

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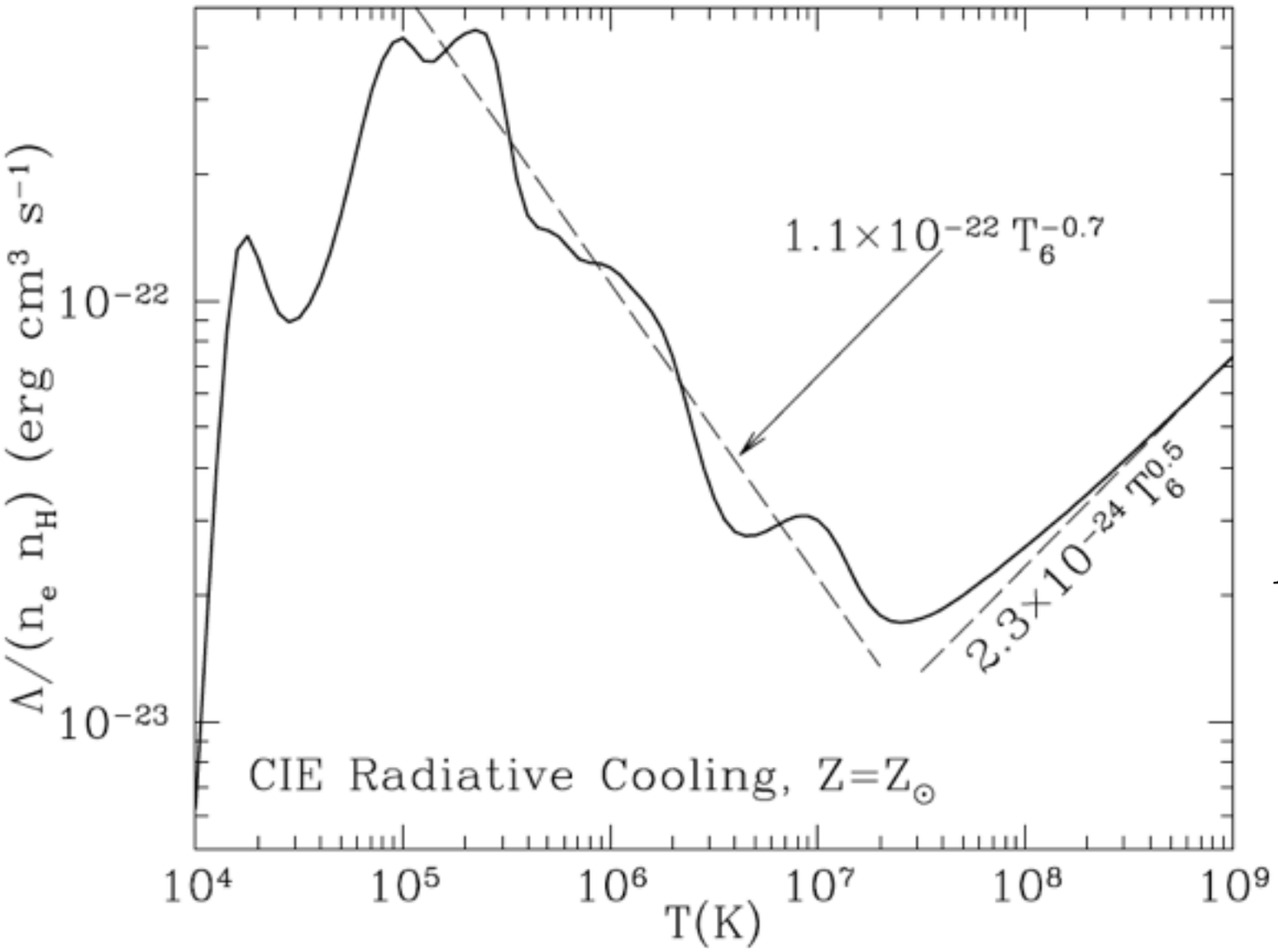

$$t_{\rm sf} = 4.4 \times 10^4 {\rm yr}\, E_{51}^{0.22} n_0^{-0.55}$$

$$r_{\rm sf} = 23 {\rm pc}\, E_{51}^{0.29} n_0^{-0.42}$$

$$M_{\rm sf} = 1.7 \times 10^3 M_\odot\, E_{51}^{0.87} n_0^{-0.26}$$

Draine (2011)

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$$p_{\rm PDS} \propto t^{1/7} \quad \text{for adiabatic expansion with } \gamma = 5/3$$

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Numerical Simulations

- Athena code
- 3D HD simulations with cooling (KI02 + SD93)
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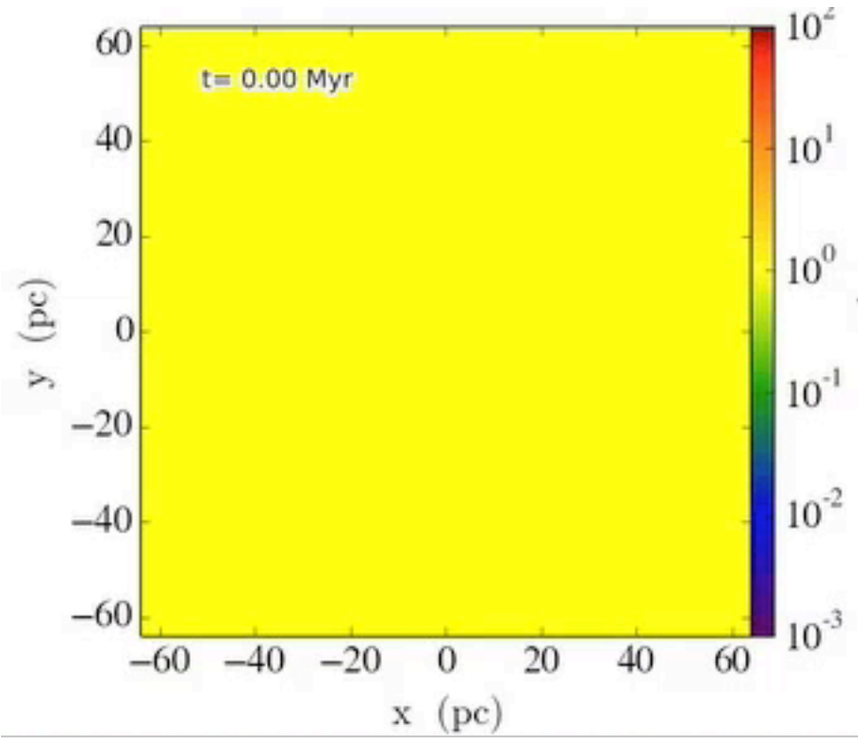
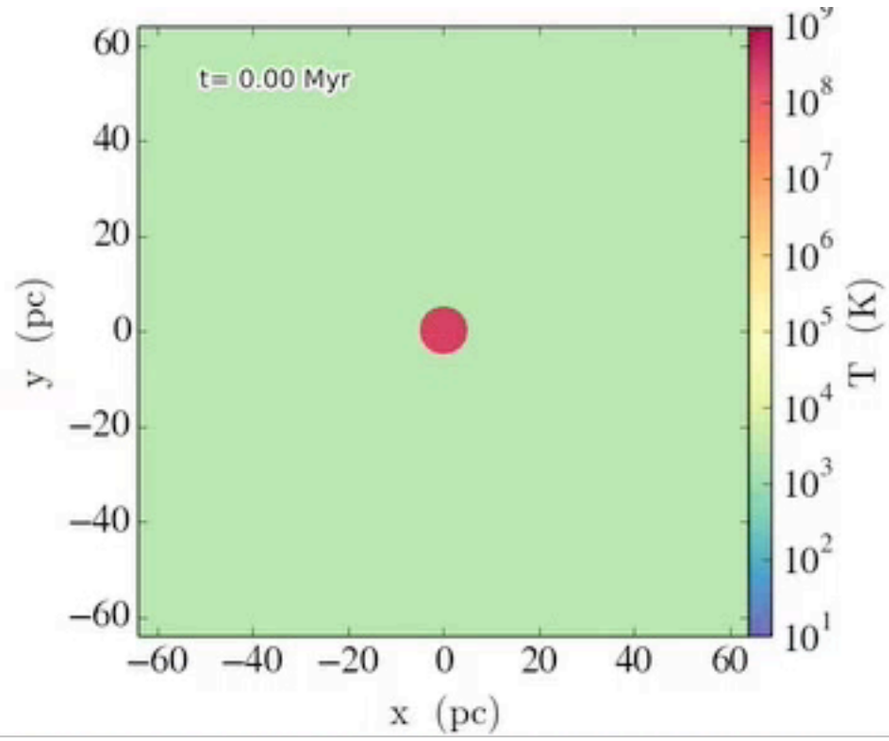
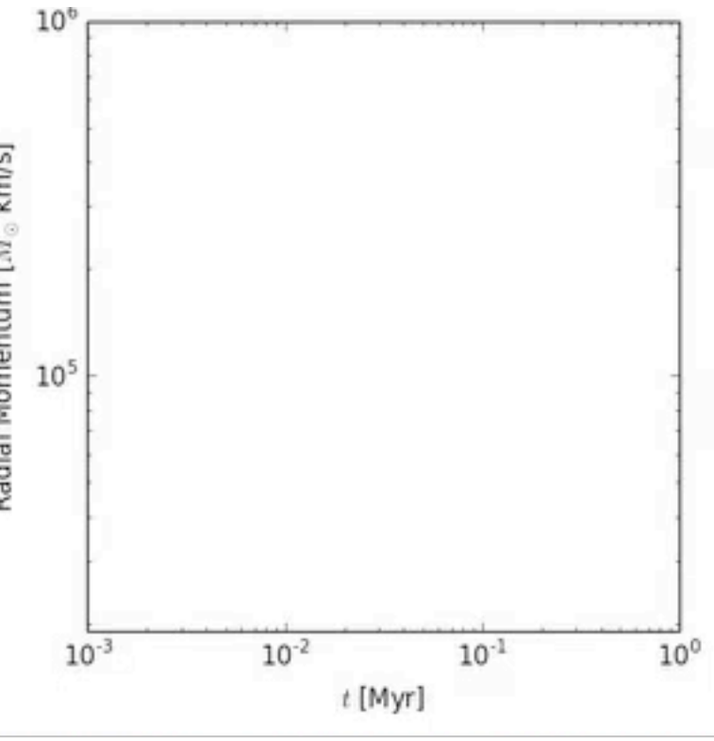
- 3D HD simulations with cooling (KI02 + SD93)
- no CR, no conduction, CIE cooling with Z_{sun}
- 1D spherical simulations
  - Chevalier (1974) and many others: early results
  - Cioffi et al. (1988): develop complete evolutions for a single SN
  - Thornton et al. (1998): parameter space study including Z

Single SN/Uniform Background







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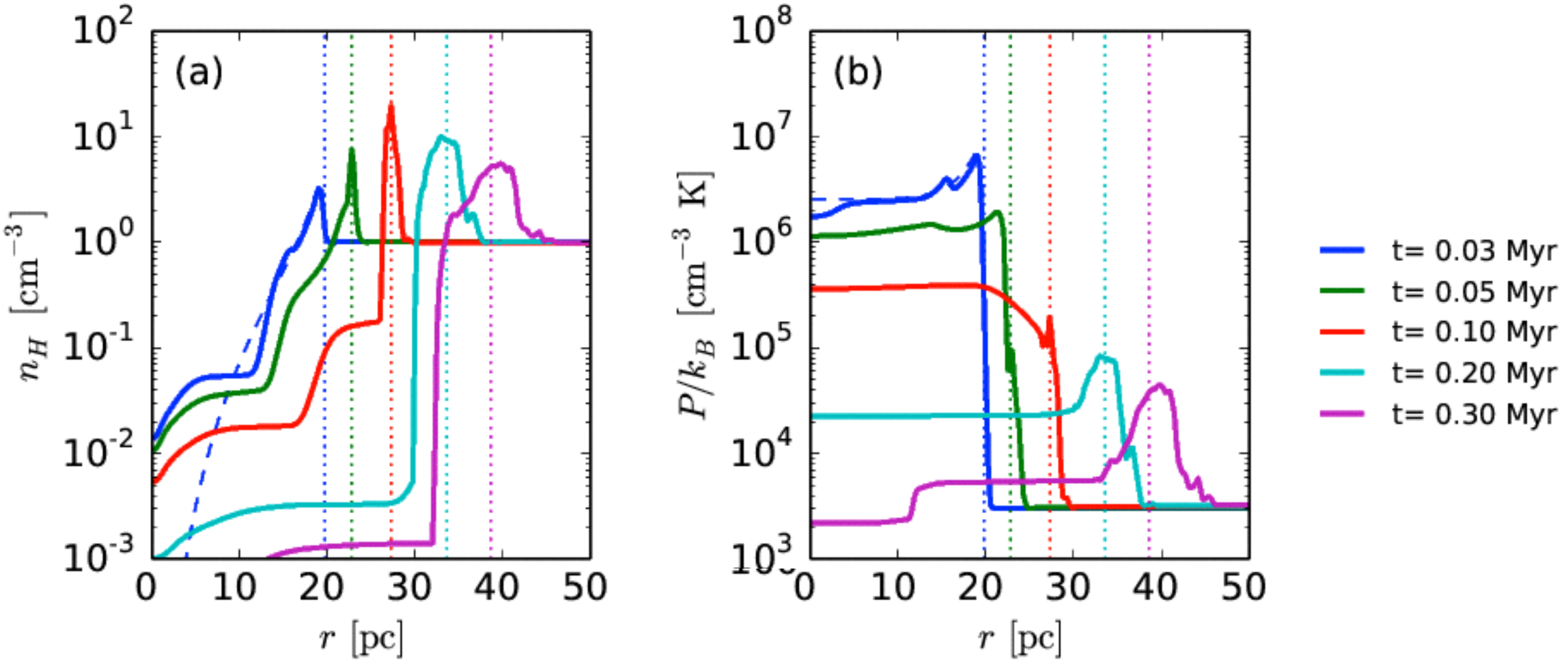
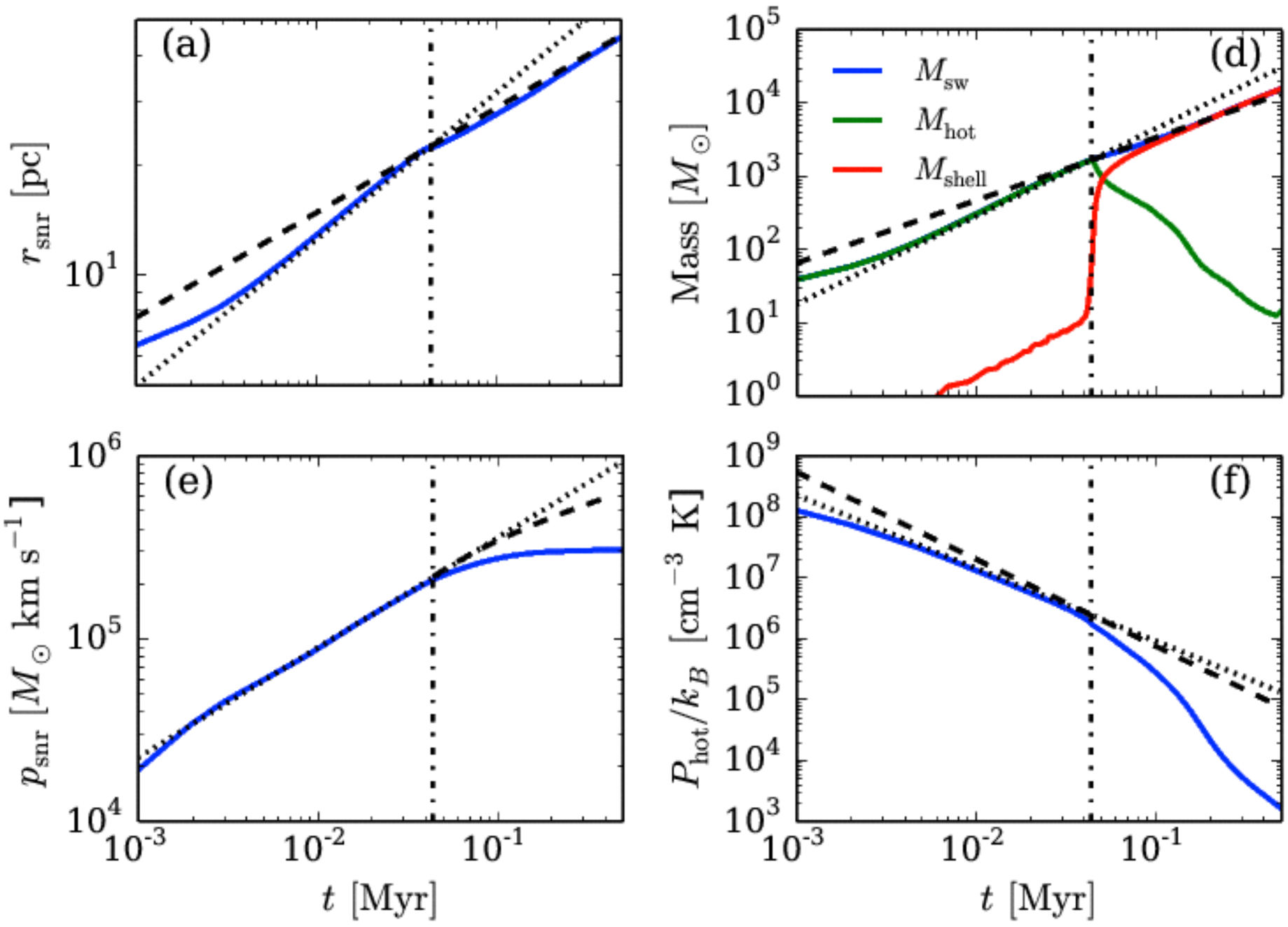


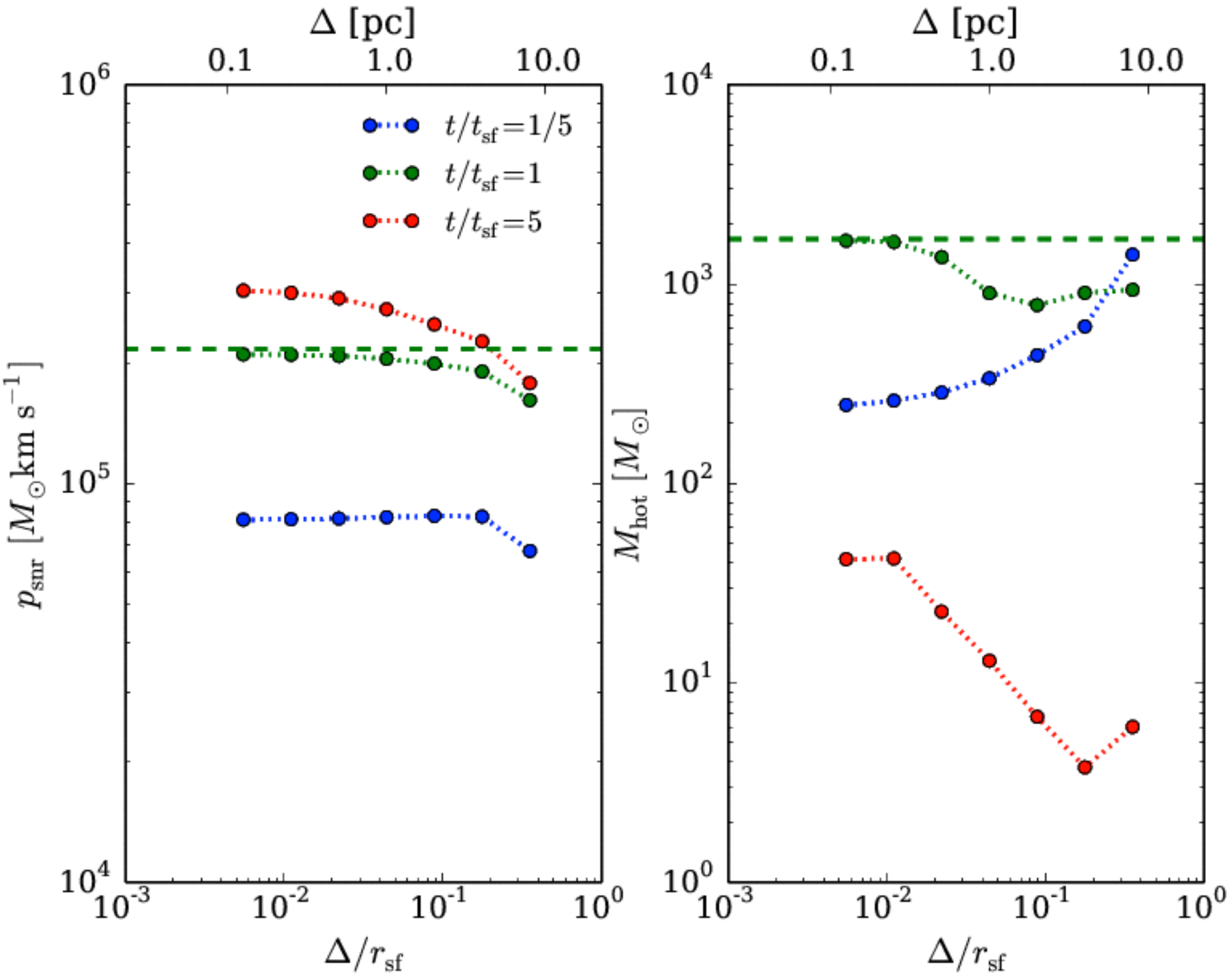
Good agreement with the spherical models (e.g., Cioffi et al. 1988)

Single SN/Uniform Background



Pressure drops faster than adiabatic expansion by radiative cooling (see Cioffi et al. 1988)
Less additional momentum after shell formation. ($dp/p_{sf}<1$)

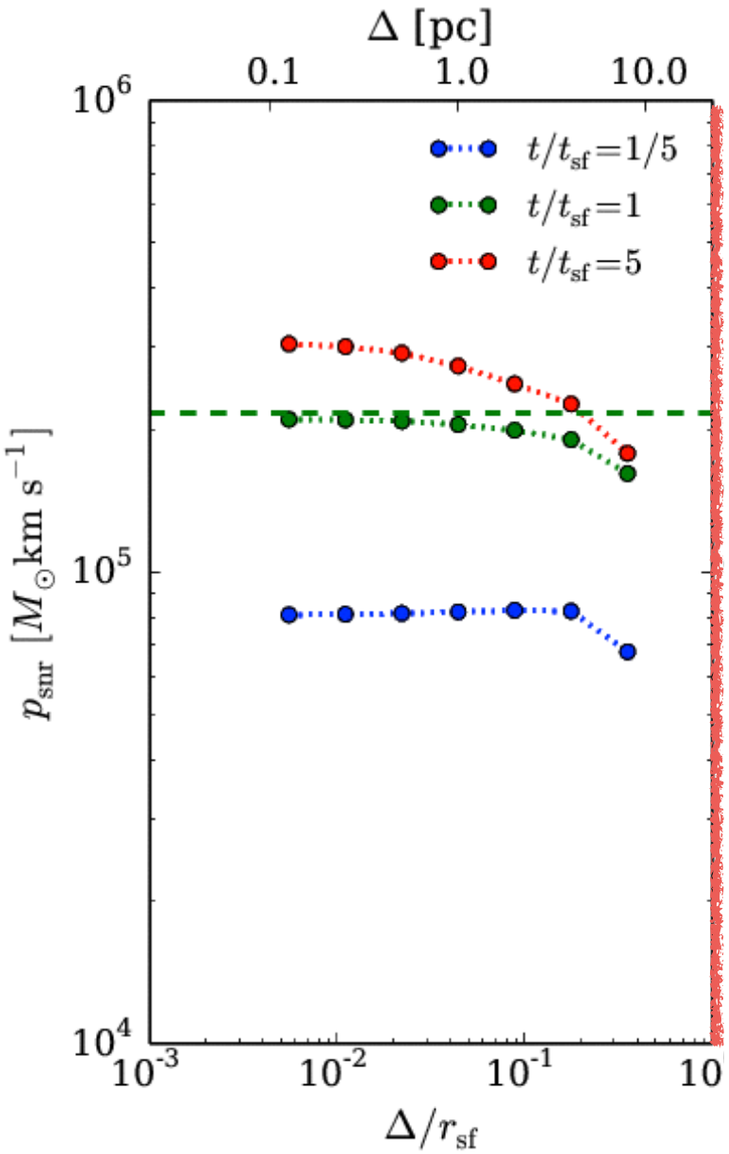
Single SN/Uniform Background



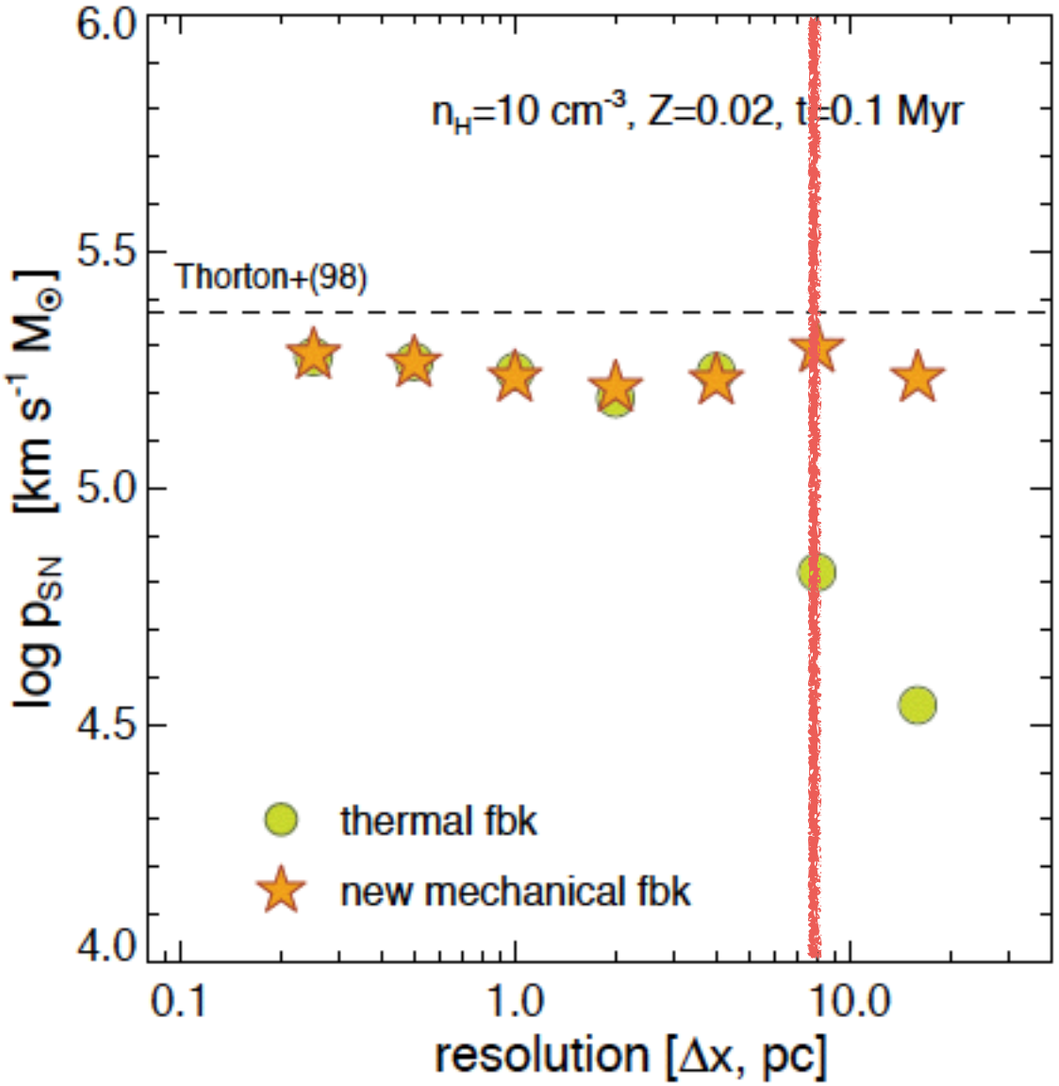
n_0=1cm^{-3}
E_{SN}=10^{51}erg
r_{init}=5pc

Single SN/Uniform Background

t_{sf}=0.012Myr



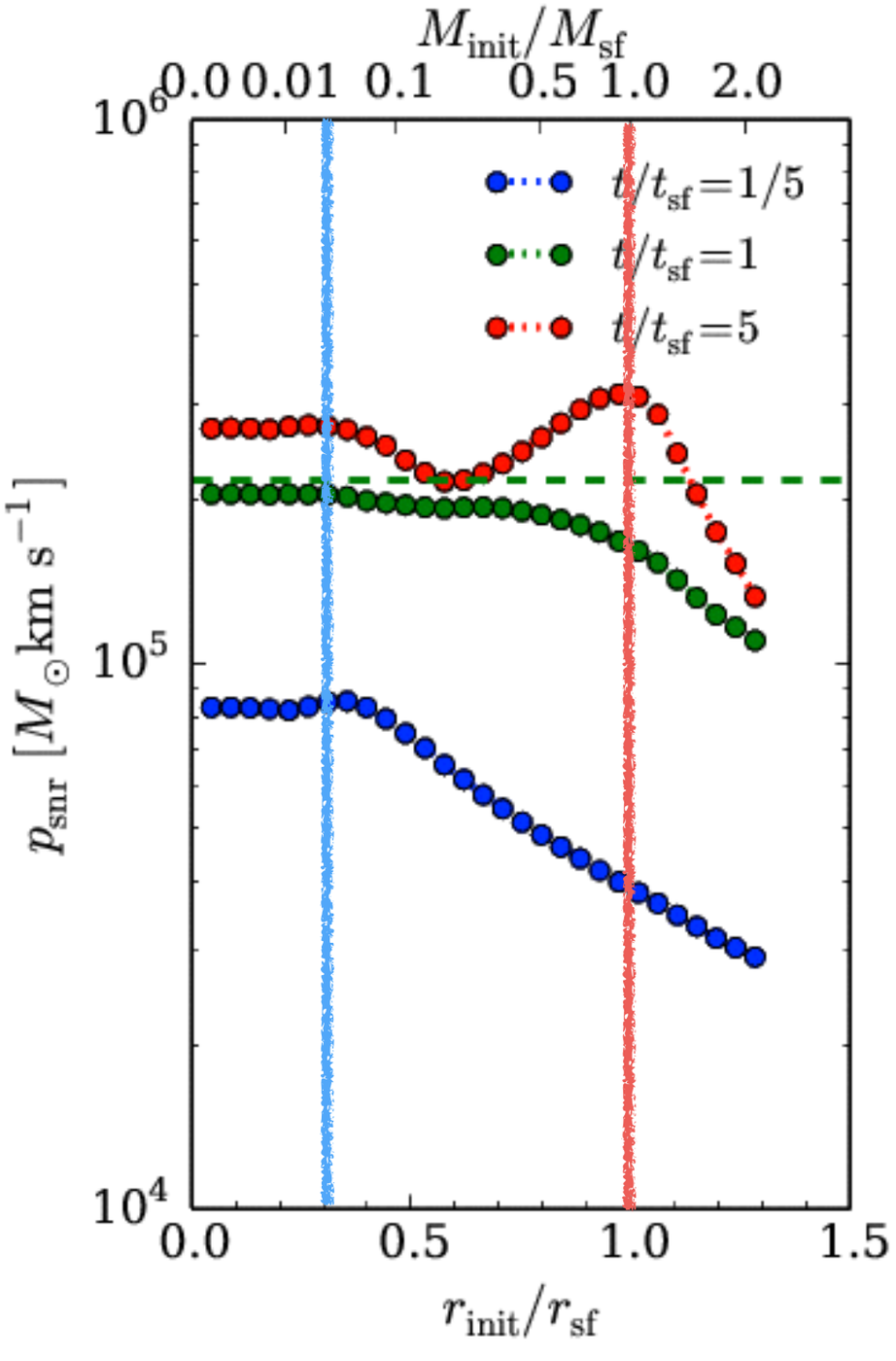
Kimm & Cen (2014)

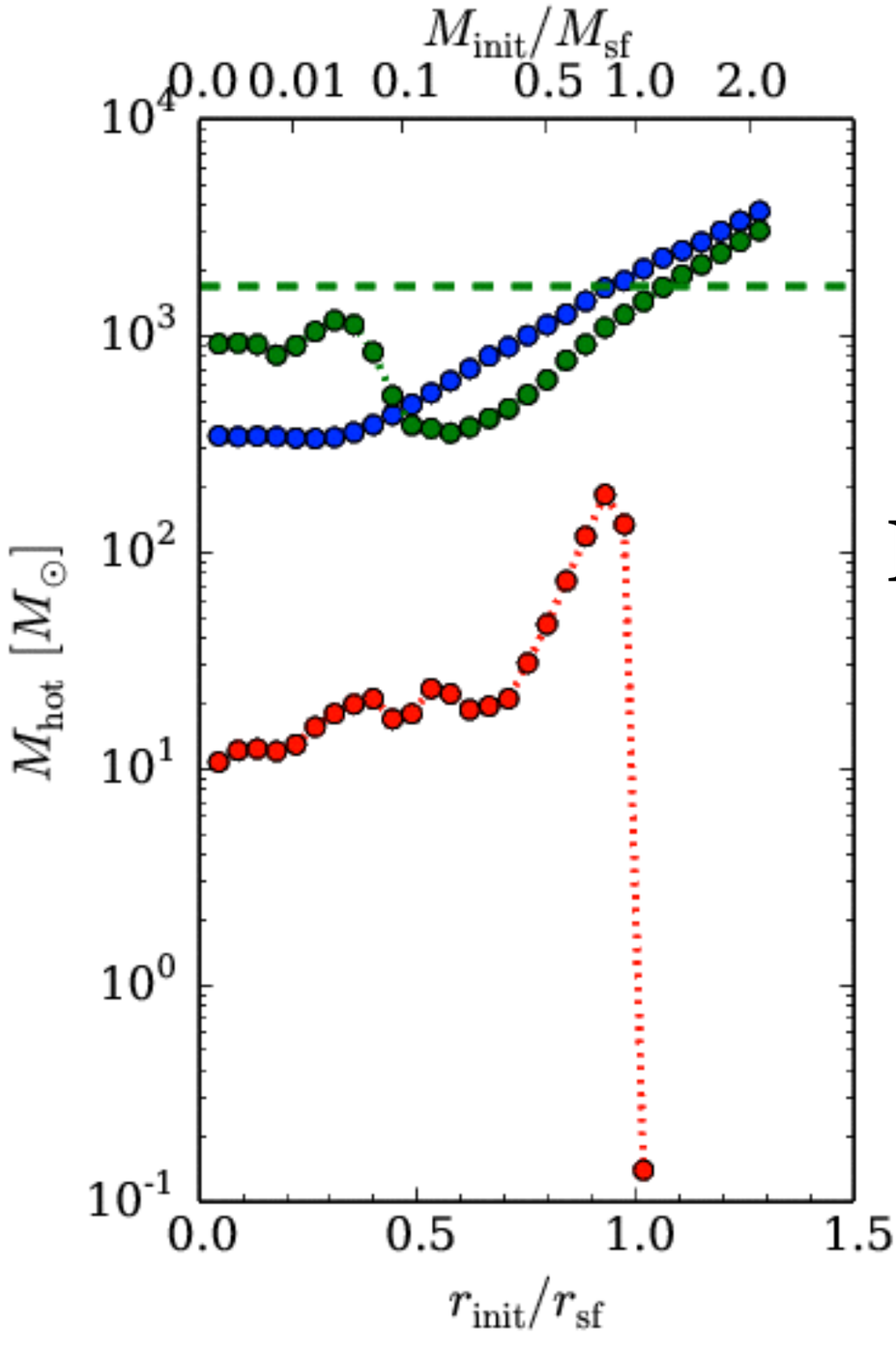


There is no hope (for hot gas) if you use very poor resolution (dx>r_{sf})

Correct momentum can be injected by using “mechanical feedback”

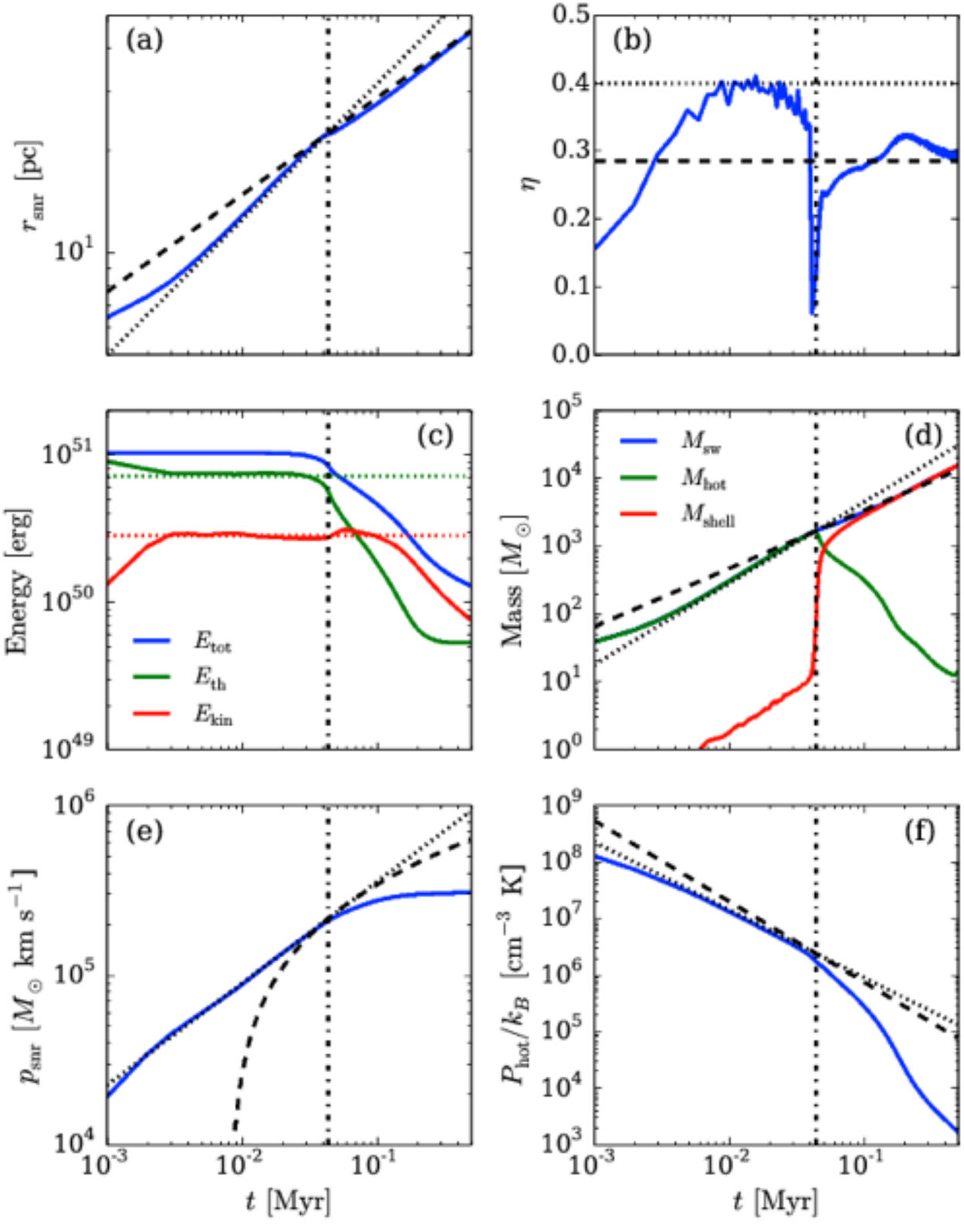
Single SN/Uniform Background

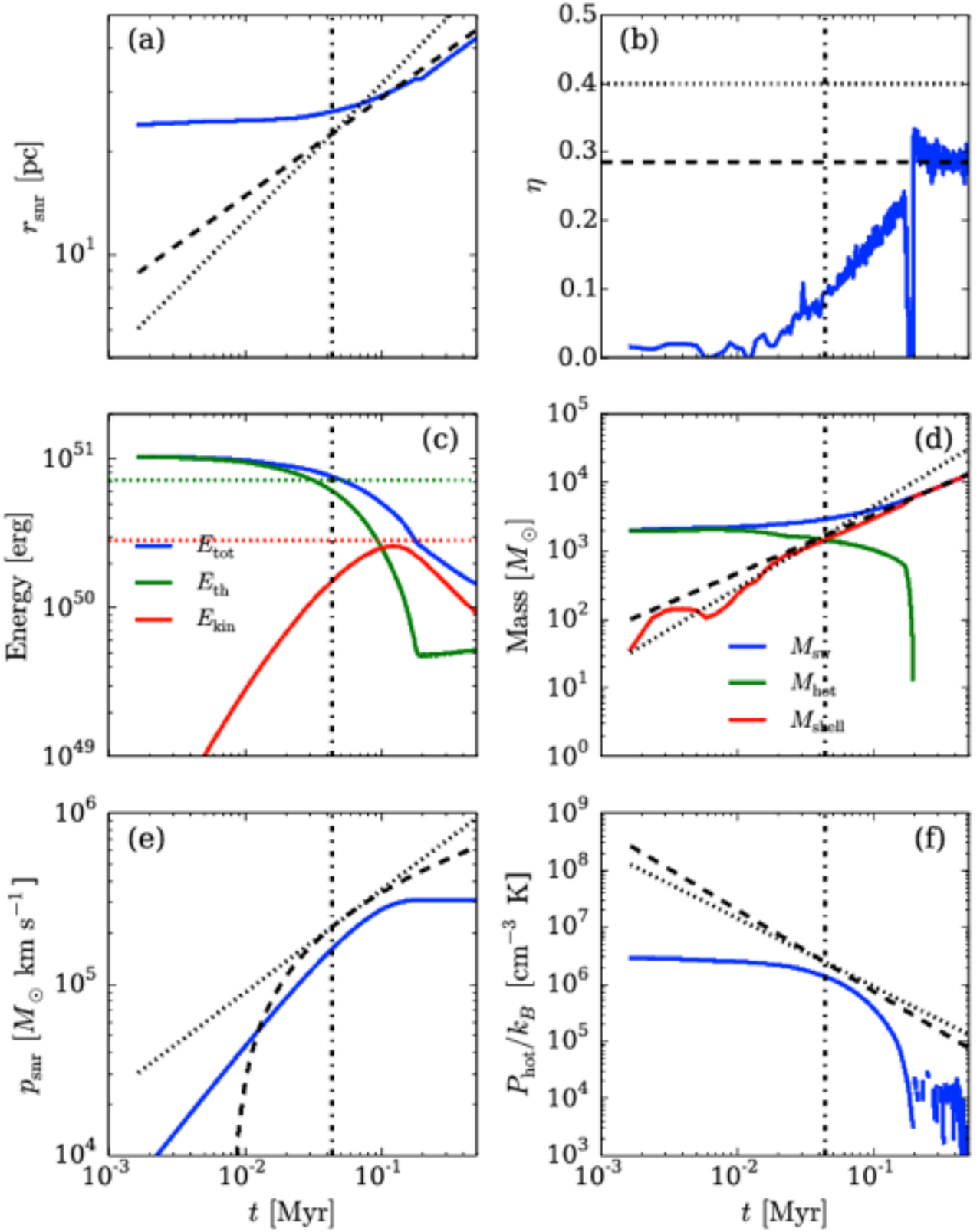




n_0=1cm^{-3}
E_{SN}=10^{51}erg
dx=1pc

r_{init}/r_{sf}=1, dx=1pc





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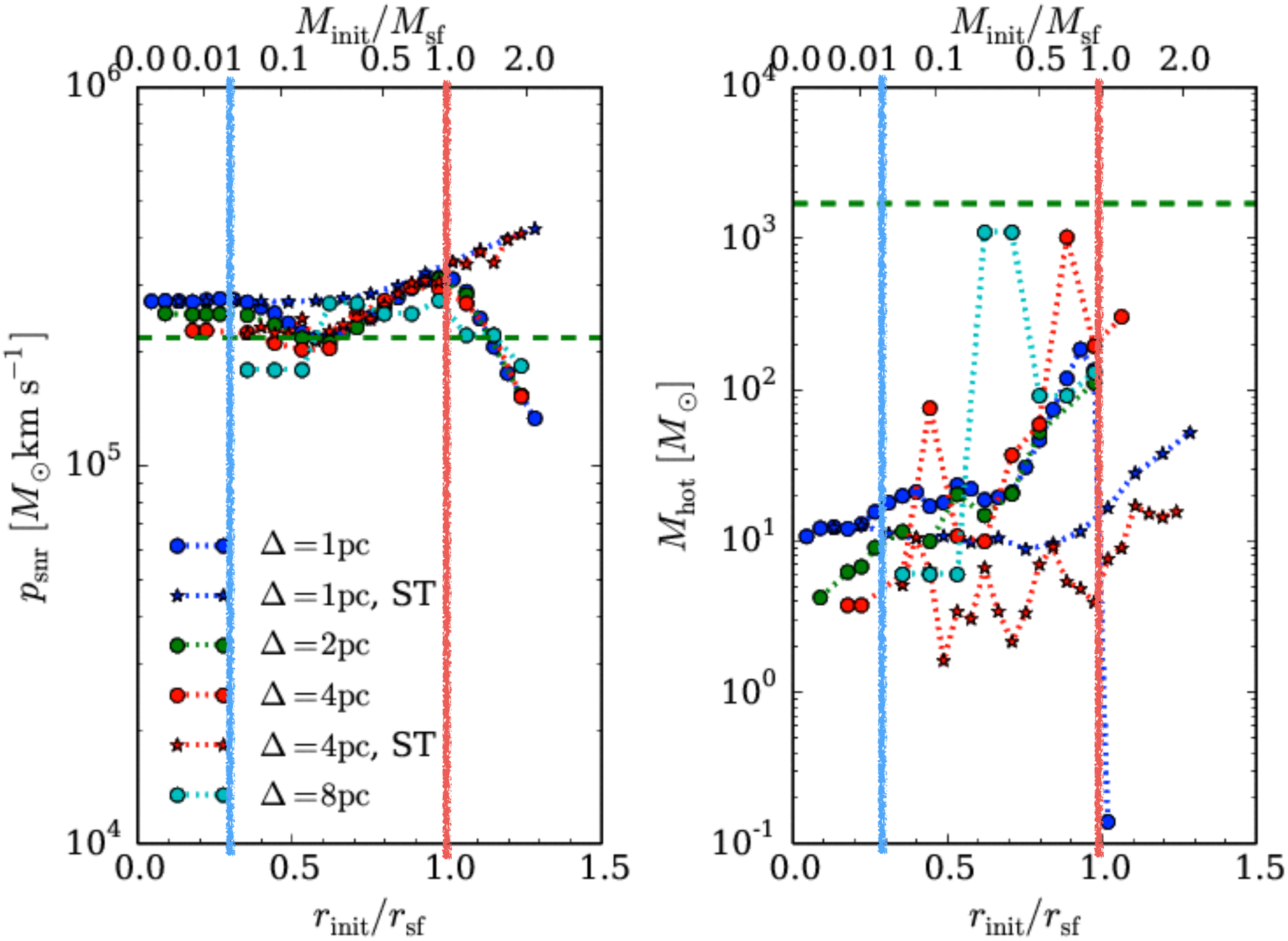
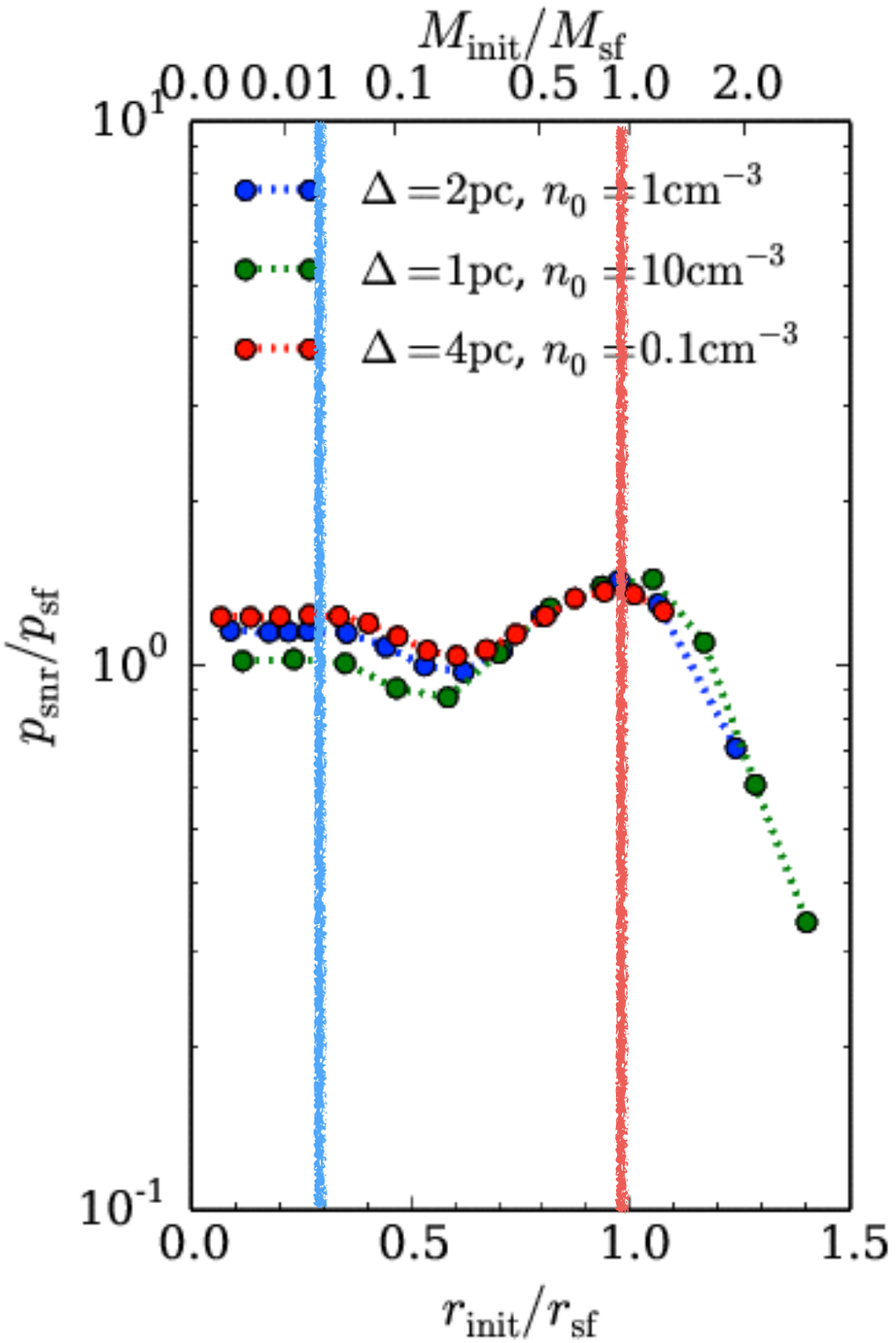
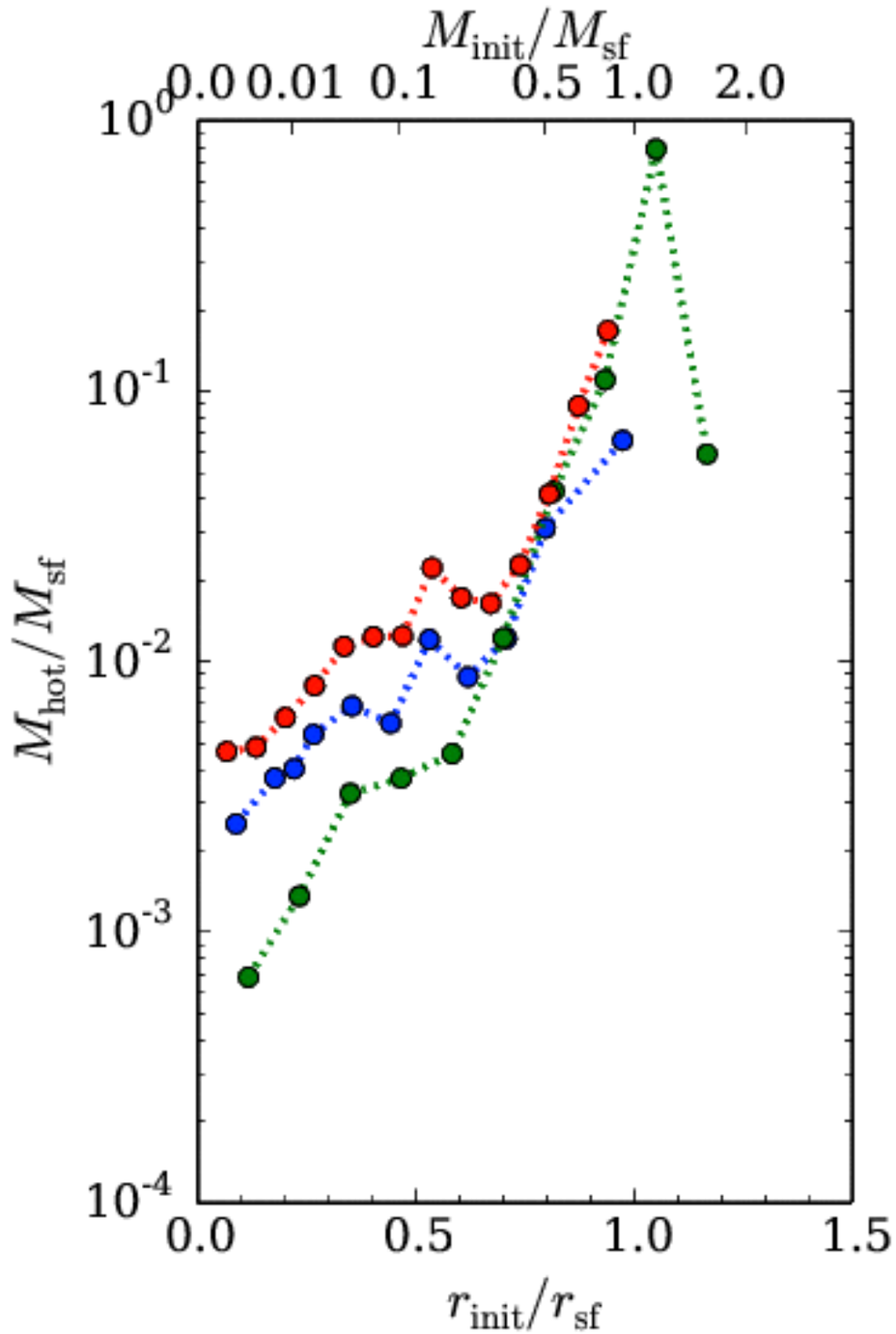


Single SN/Uniform Background

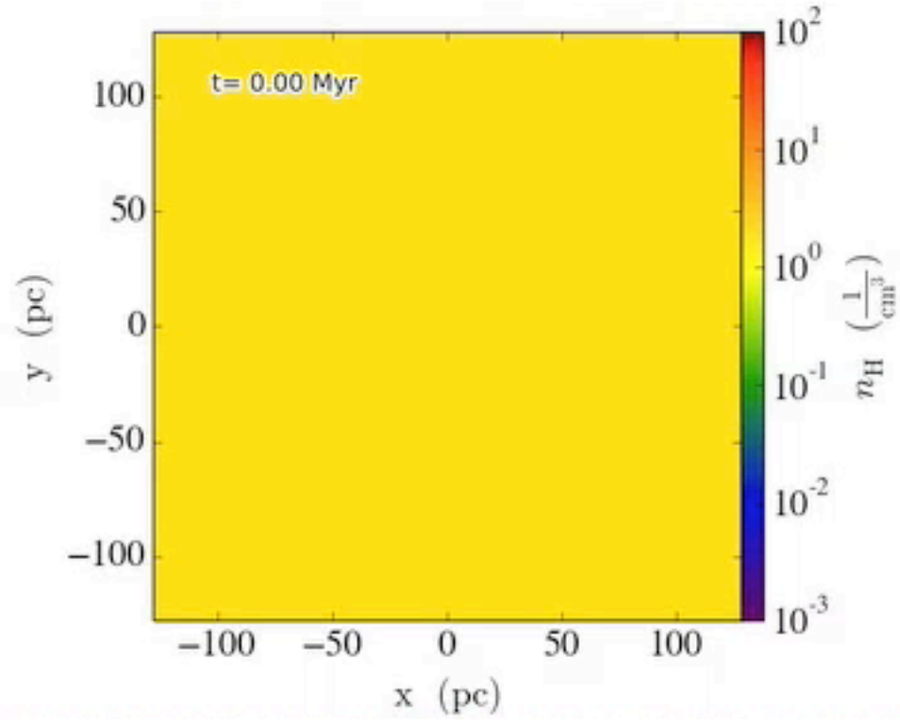


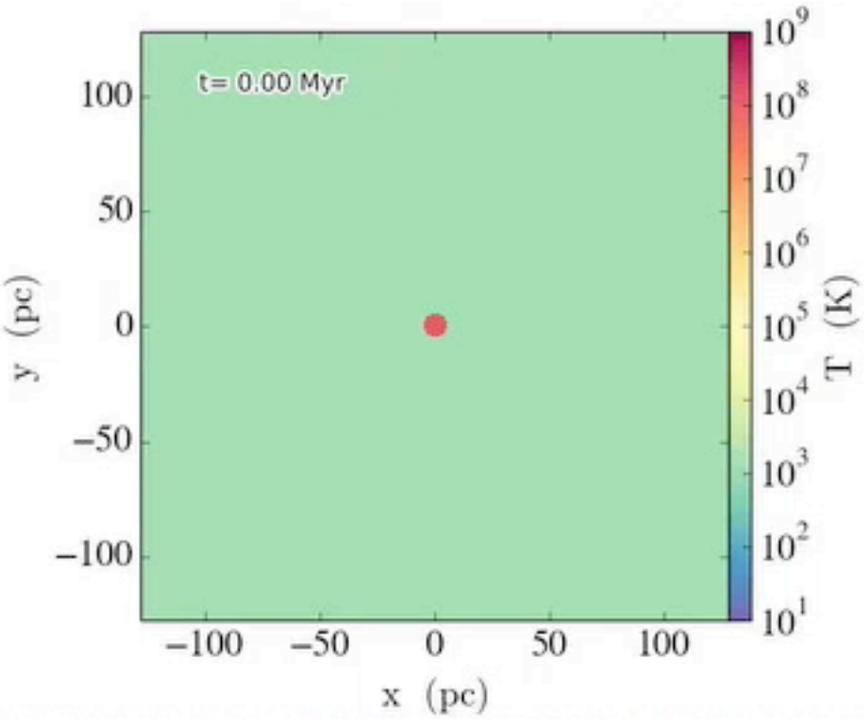


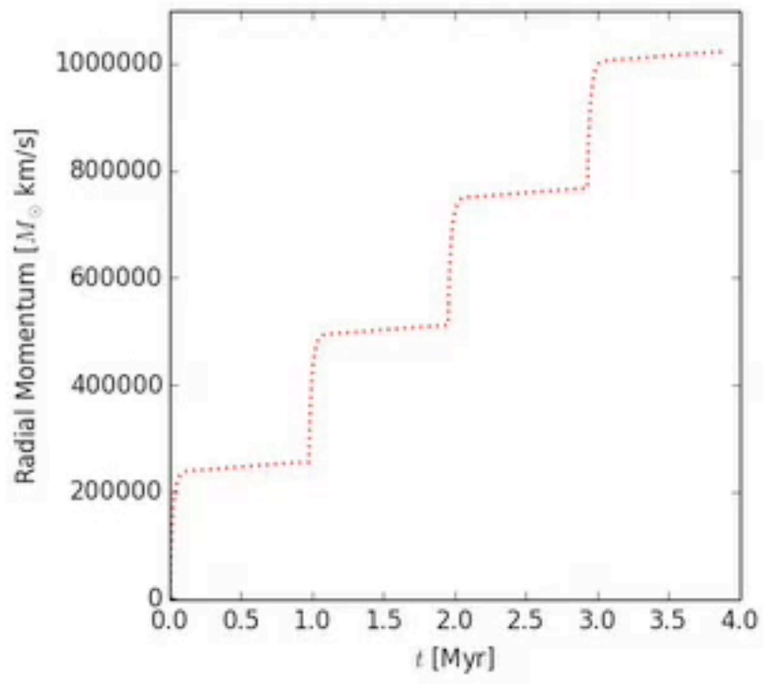
Criteria for Correct SN feedback

- **dx & $r_{init} < (r_{sf}/3)$:**
  - "conservative criterion" to resolve correct ST phase and correct time evolution
    - M_{sf} is insensitive to n_o: $M_{init}<(M_{sf}/27)\sim 60M_{sun}$ will be useful in practice
- **$dx < (r_{init}/2)$ & $r_{init} < r_{sf}$:**
  - no ST phase, incorrect history
  - right momentum
  - okay if SN is initially realized by ST solution

Multiple SNe/Uniform Background







$n_0=2cm^{-3}$

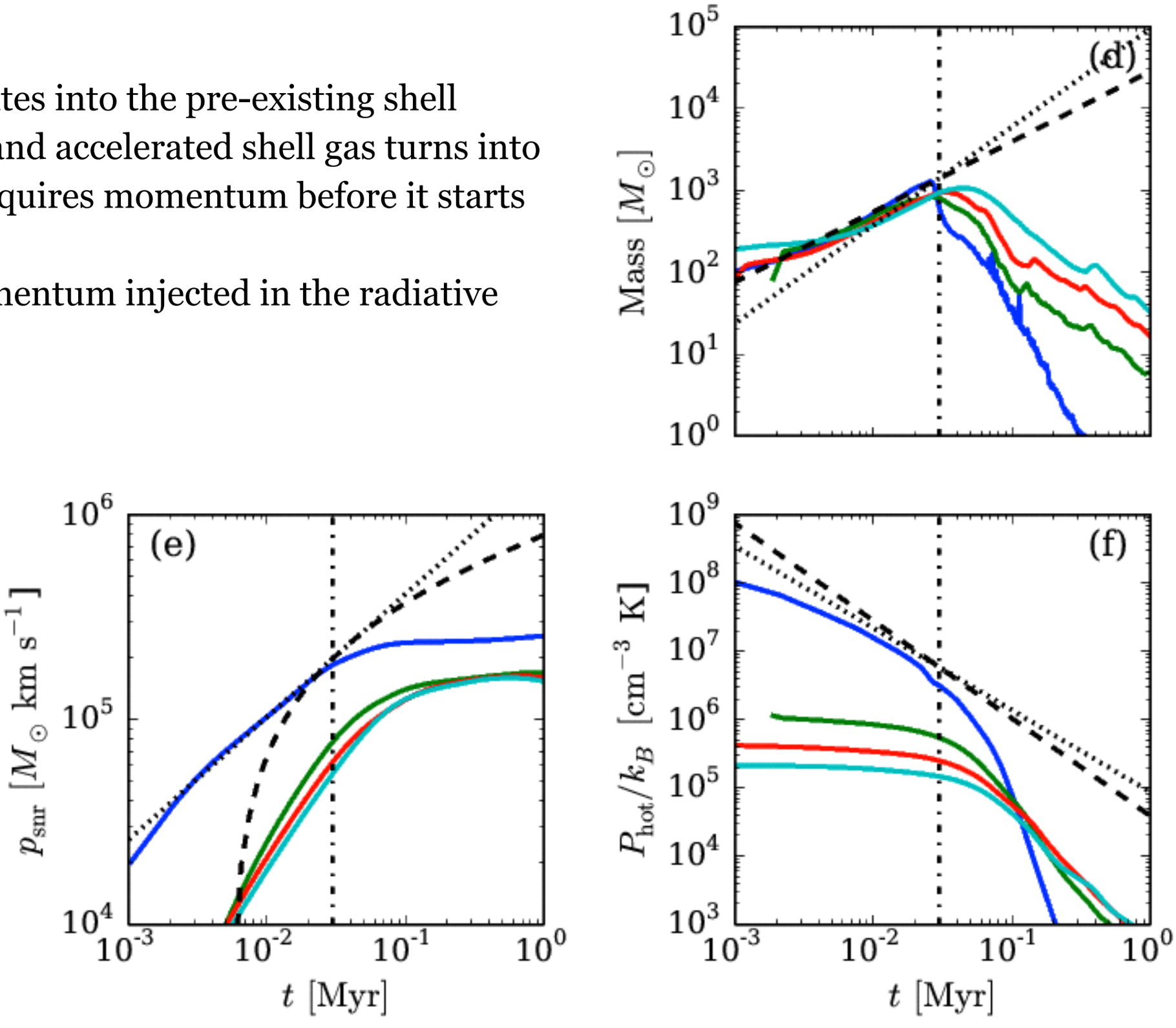
$E_{SN}=10^{51}erg$

dx=1pc

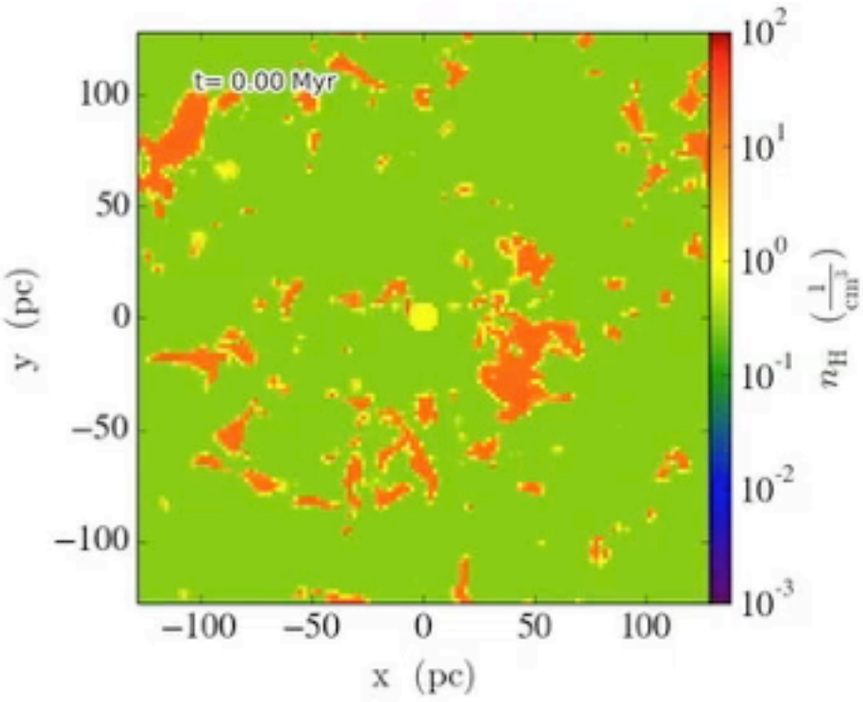
$dt_{SN}=1Myr$

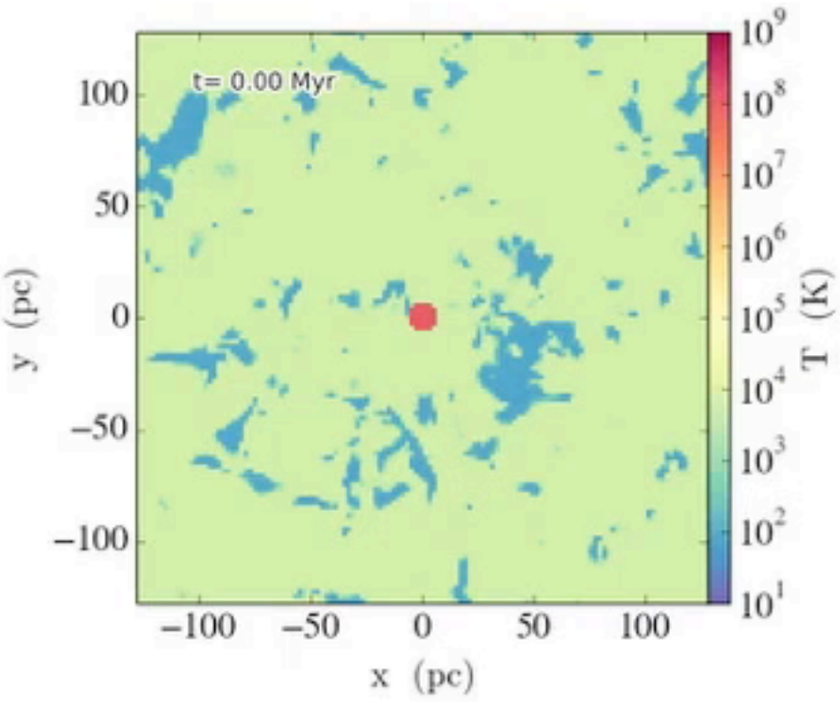
Multiple SNe/Uniform Background

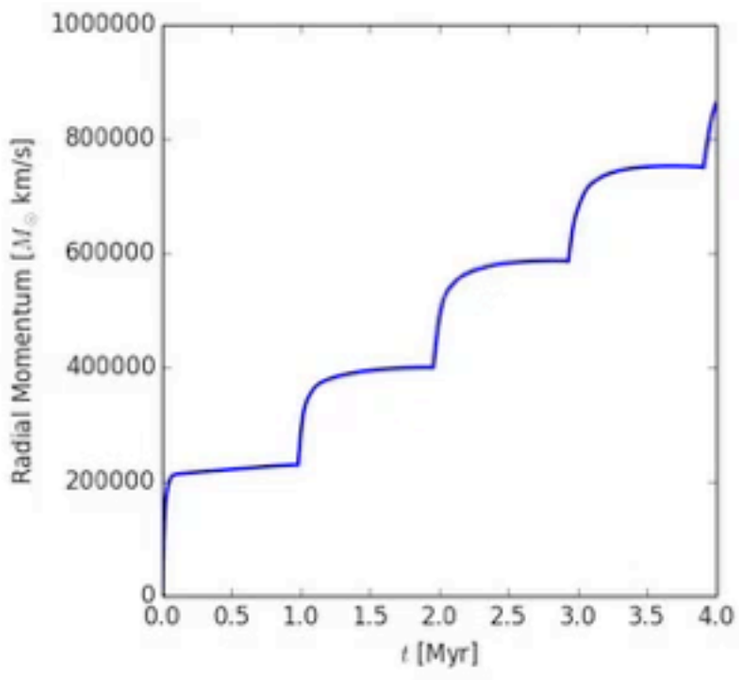
1. shock propagates into the pre-existing shell
2. shock heated and accelerated shell gas turns into hot gas and acquires momentum before it starts to cool
3. not much momentum injected in the radiative PDS stage

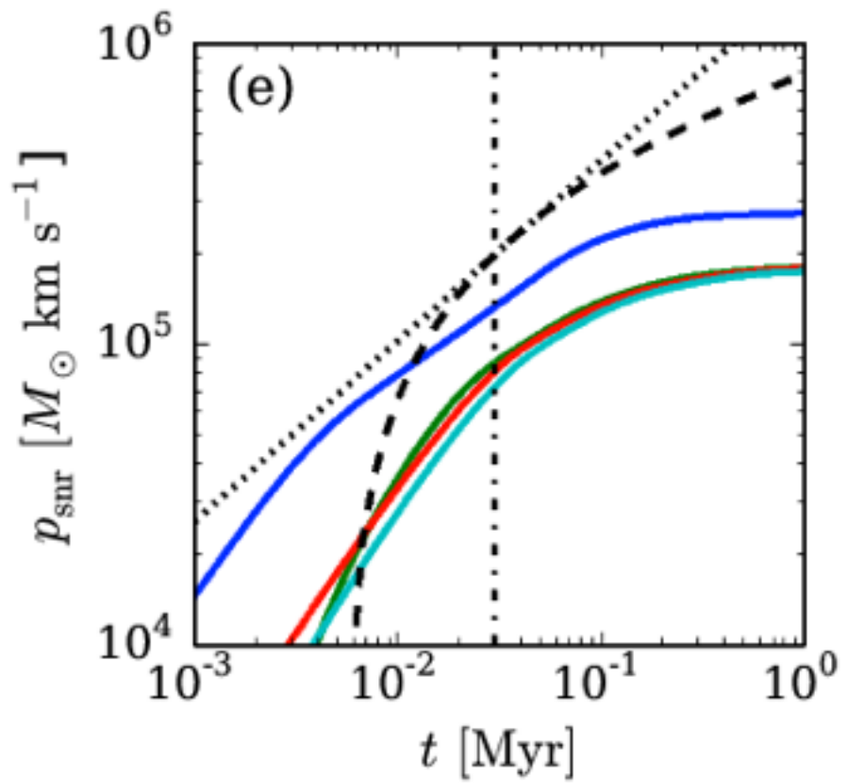


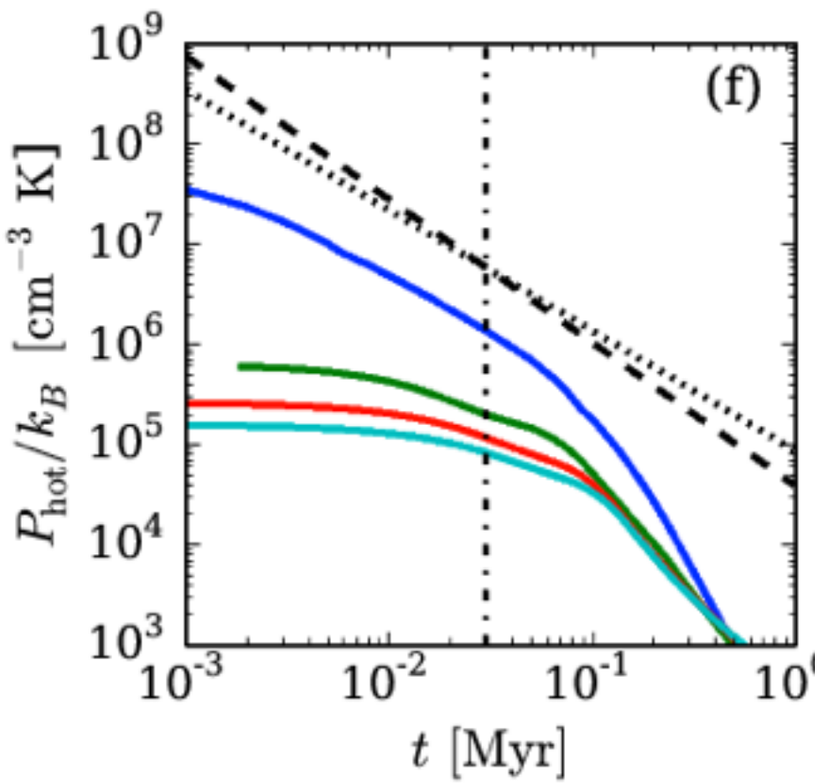
Multiple SNe/Multiphase ISM

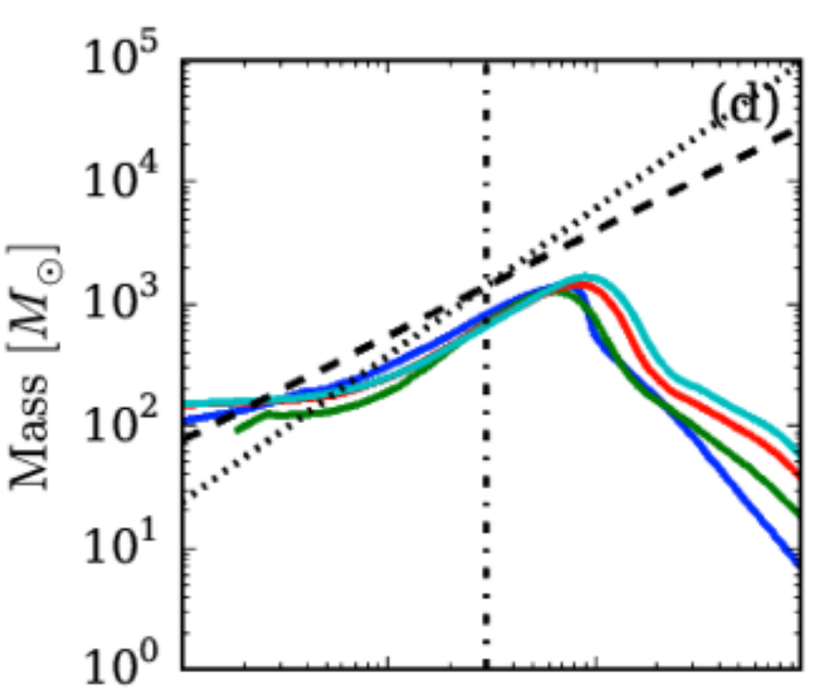












Multiple SNe

- Momentum injection can be lower than a single high energy SN.

$$p_{\rm ST}(t_{\rm sf}) = 2.1\times10^5 M_\odot\,{\rm km\,s^{-1}} E_{51}^{0.93} n_0^{-0.13}$$

- To maintain a hot bubble, SN time interval need to be shorter than or comparable to t_{sf}.

- dt_{SN}~1Myr ($10^3 M_{sun}/M_{SC}$) vs. $t_{\rm sf} = 4.4\times10^4{\rm yr}\,E_{51}^{0.22} n_0^{-0.55}$