PART V

Stellar Feedback

1. What Escapes From Stars

$$\textit{Energy:} \quad E_{\rm tot} = E_{\rm SNII} + E_{\rm SNIa} + E_{\rm wind}$$

$$\textit{Momentum:} \quad p_{\rm tot} = p_{\rm SNII} + p_{\rm wind} + p_{\rm rad}$$

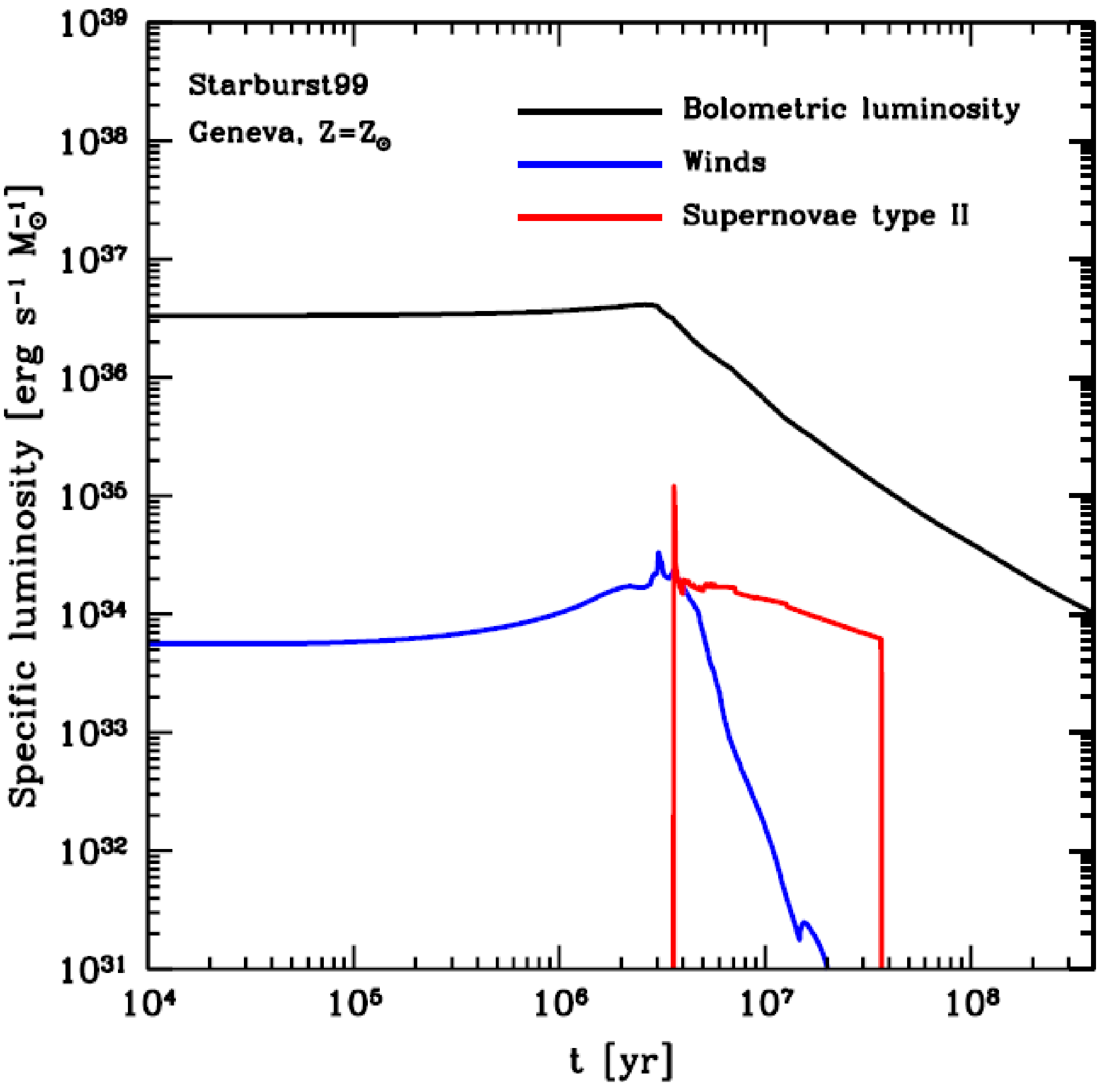
$$\textit{Mass loss:} \quad m_{\rm tot} = m_{\rm SNII} + m_{\rm SNIa} + m_{\rm wind} + m_{\rm loss}$$

$$\textit{Metals:} \quad m_{\rm Z,tot} = m_{\rm Z,SNII} + m_{\rm Z,SNIa} + m_{\rm Z,wind} + m_{\rm Z,loss}$$

(+ dust)

(+ cosmic rays)

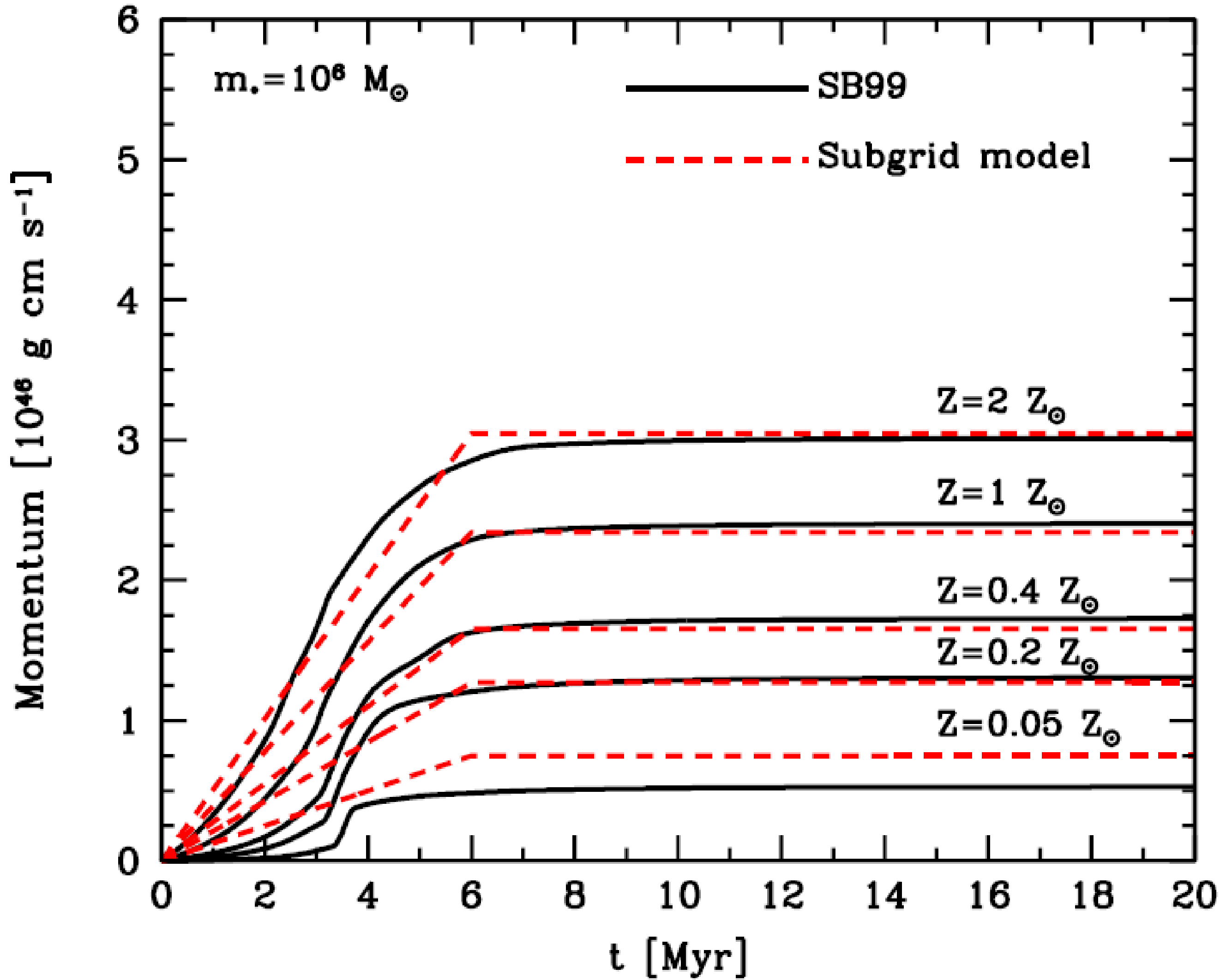
Two Things That Matter: Energetics And Timing



- *Important fact:* the largest (by far) energy output of stars is in light!
- *Hands-on exercise*: add other important lines on this plot.

Stellar Winds

- Wind power roughly scales as $Z^{0.4}$.



Radiation Pressure

- For heavily obscured stars most of their light is absorbed; since photons have momentum, absorbing all light from a star/star cluster of luminosity L injects momentum into the surrounding gas:

$$\dot{p}_1 = \frac{L}{c}$$

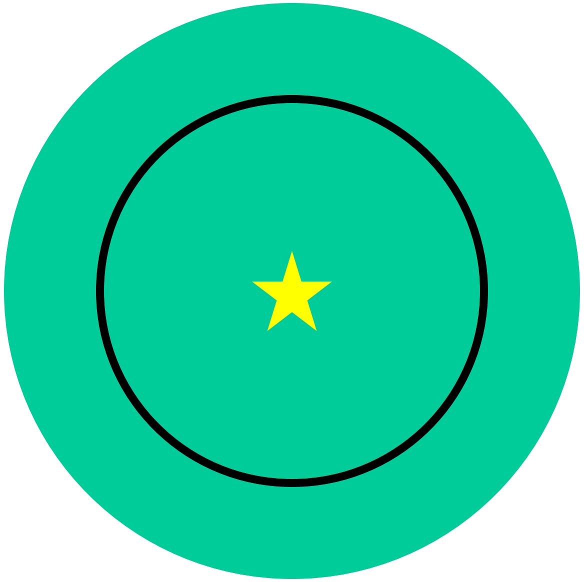
- However, energy is conserved – the absorbed energy is irradiated by dust in the IR. If there is enough dust, it will be optically thick to its own IR radiation. That IR radiation does work on (=injects extra momentum into) the gas.

$$\dot{p}_{\rm tot} = \left(1 - e^{-\tau_{\rm UV}} + \tau_{\rm IR}\right) \frac{L}{c}$$

The τ_{IR} Term: Calculus

- The extra $\tau_{\rm IR}$ term can be derived easily: since energy is conserved, the radiation flux at each radius R is still

$$F_R = \frac{L}{4\pi R^2}$$

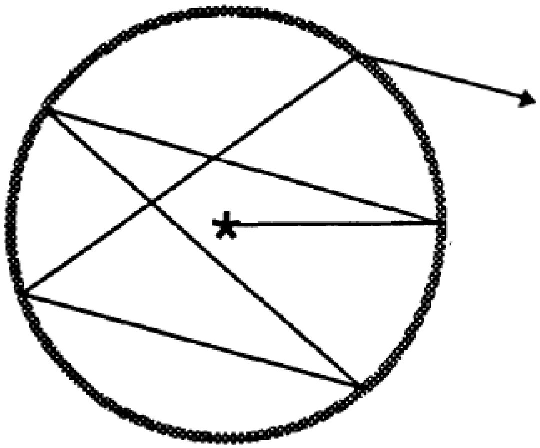


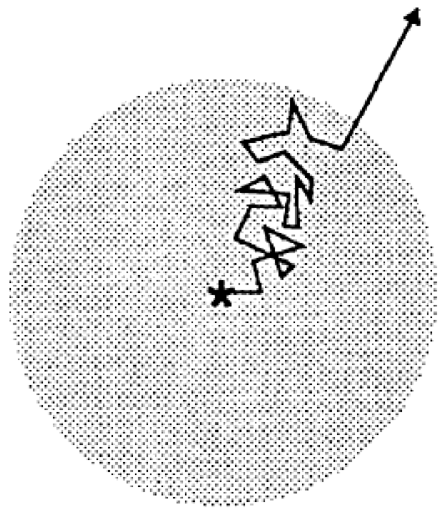
- Hence, the momentum imparted between R and $R + dR$ is

$$d\dot{p}_{\rm IR} = 4\pi R^2 \frac{F_R}{c} \kappa dR = \frac{L}{c} d\tau$$

$$\dot{p}_{\rm IR} = \tau_{\rm IR} \frac{L}{c}$$

The τ_{IR} Term: Geometry



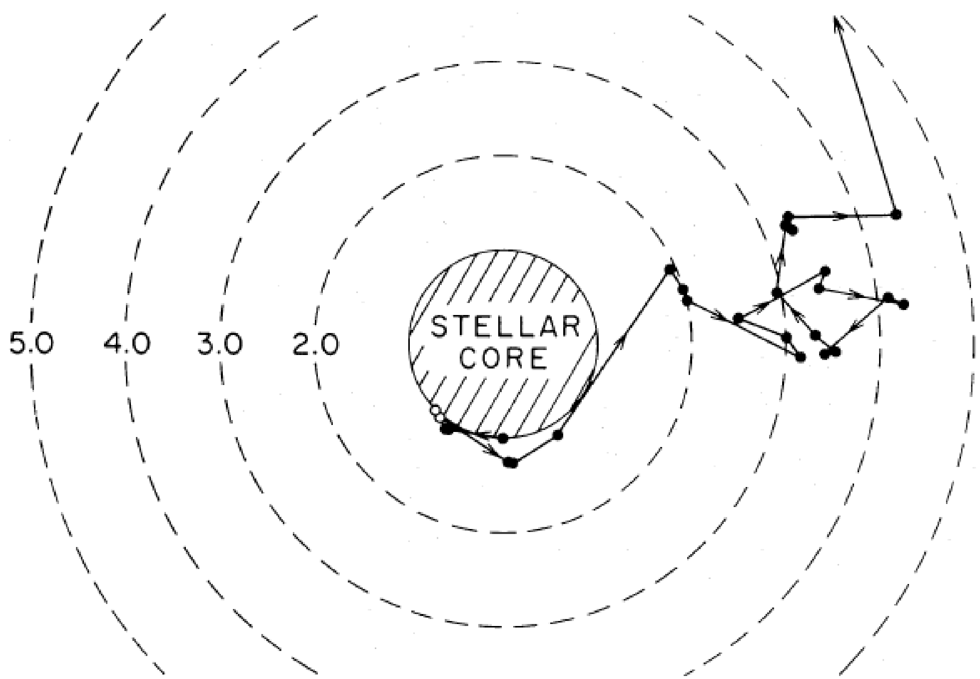


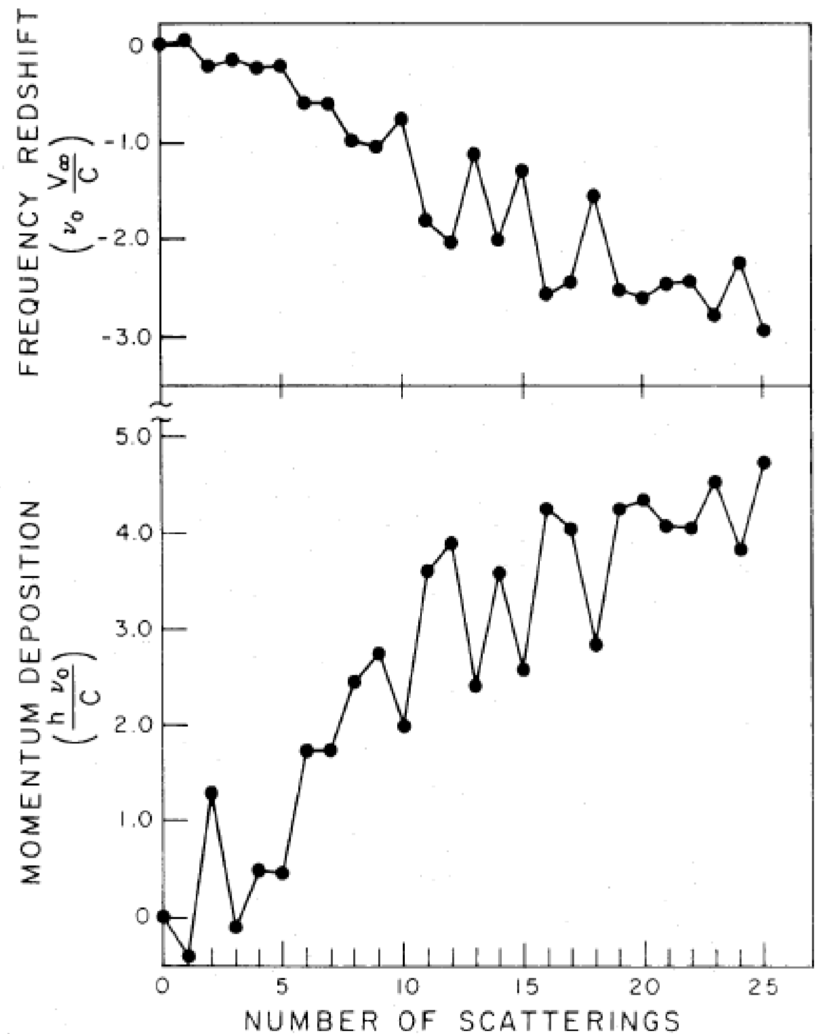
- For a thin shell of optical depth τ there is a clear geometric explanation.
- What about a real case (continuous medium)?

- Recall: “ogres are like onions”. That applies to spherical clouds too.

The τ_{IR} Term In Action

- An example of photon scattering:





- Note: number of scatterings is τ^2, not τ.

Radiation Pressure

- What about $\tau_{\rm IR}$?

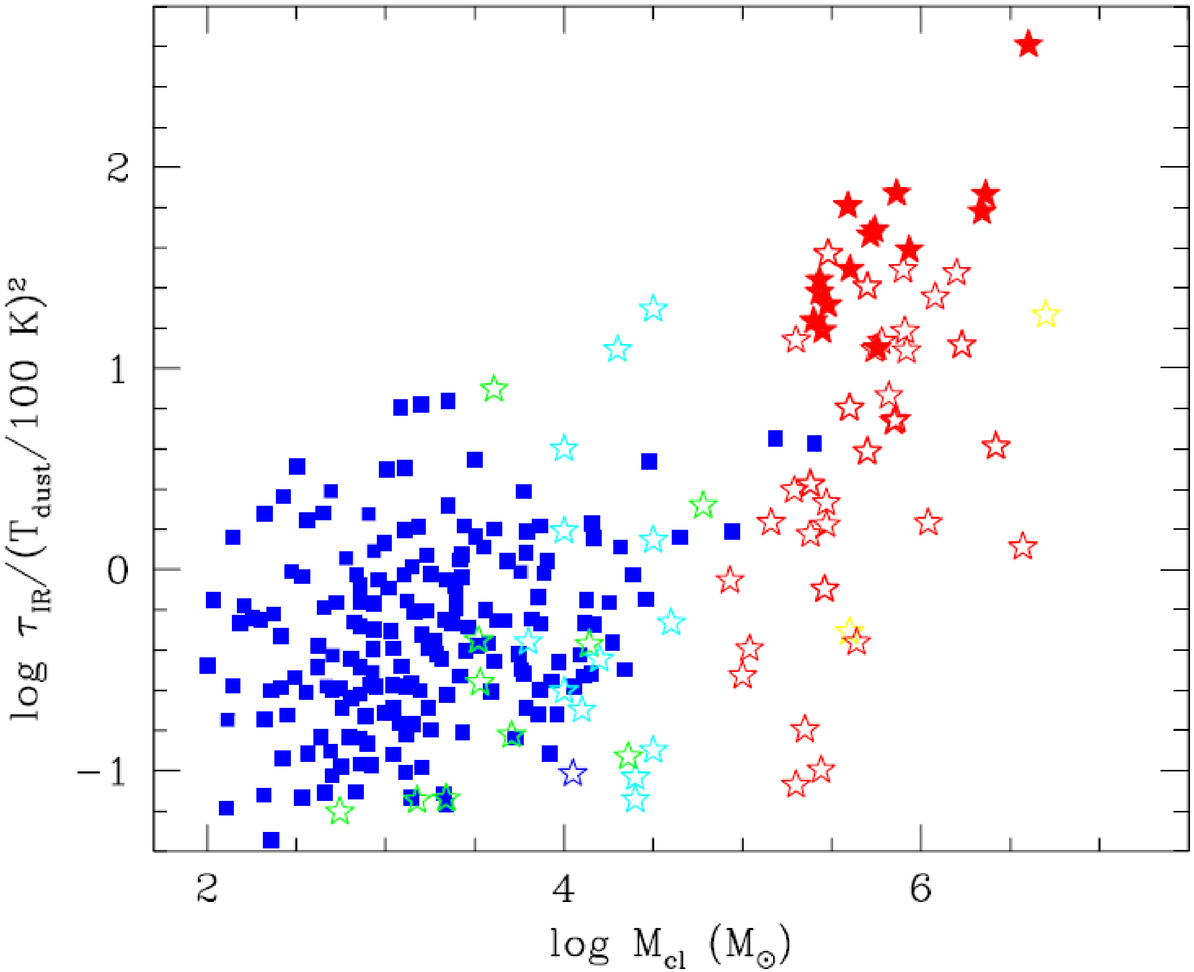
$$\tau_{\rm IR} = \varkappa_{\rm IR}\Sigma_g$$

$$\varkappa_{\rm IR} \approx 3\frac{\rm cm^2}{\rm g}\left(\frac{T_d}{100{\rm K}}\right)^2$$

- (Hot dust absorbs way more).

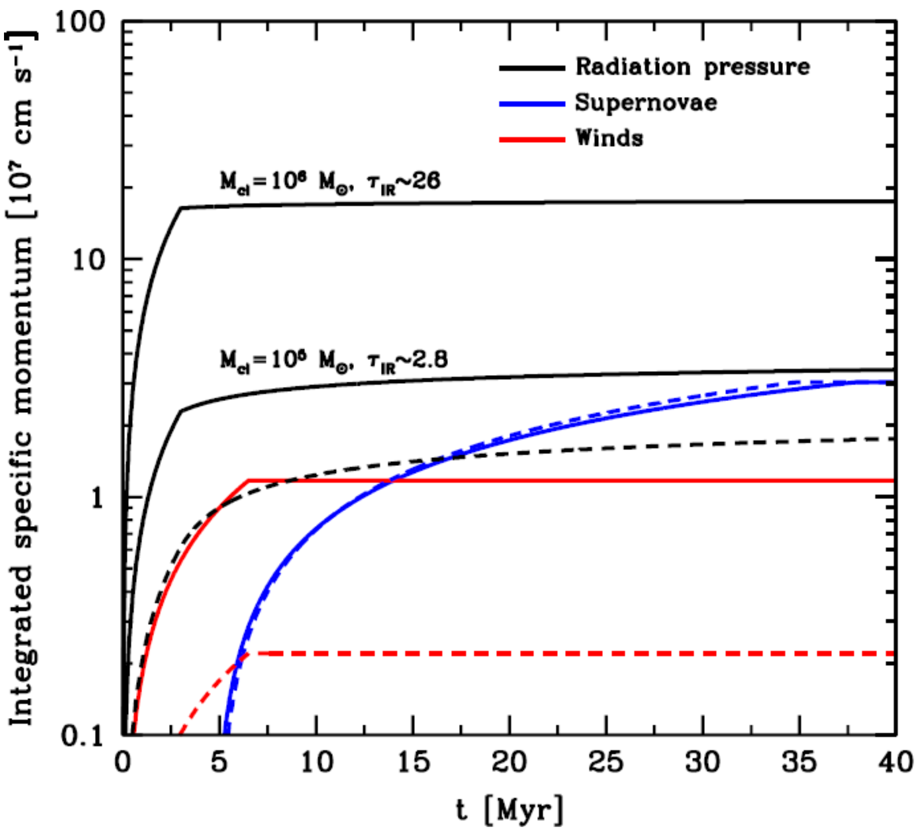
Radiation Pressure

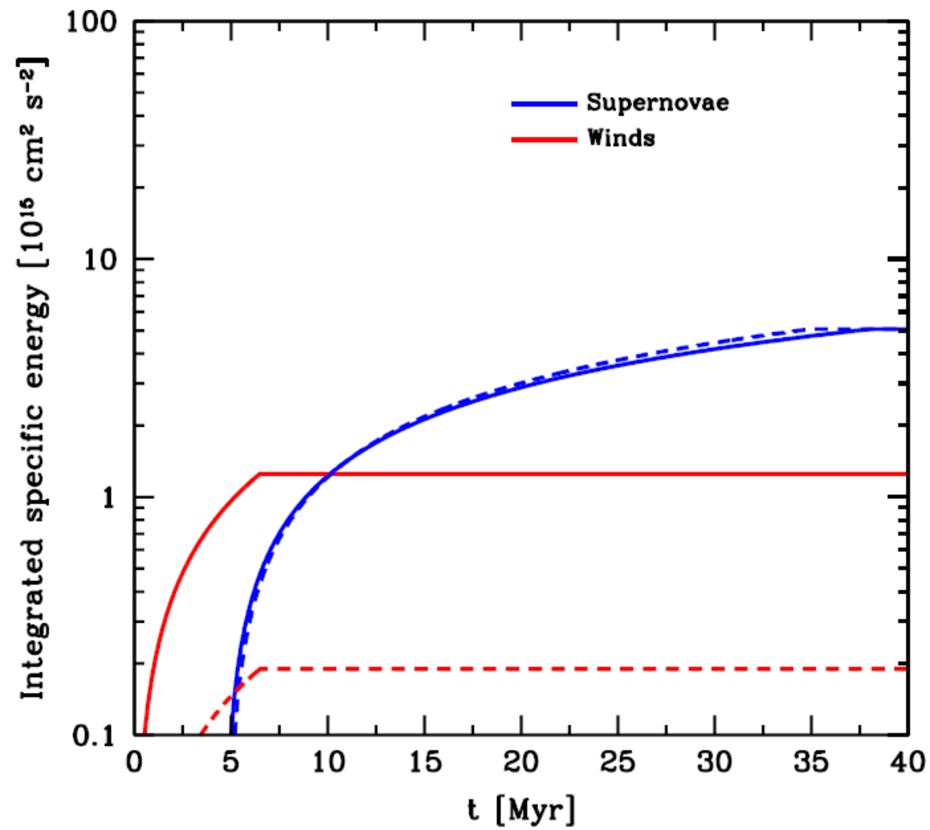
- Radiation pressure is particularly important for large stellar clusters.



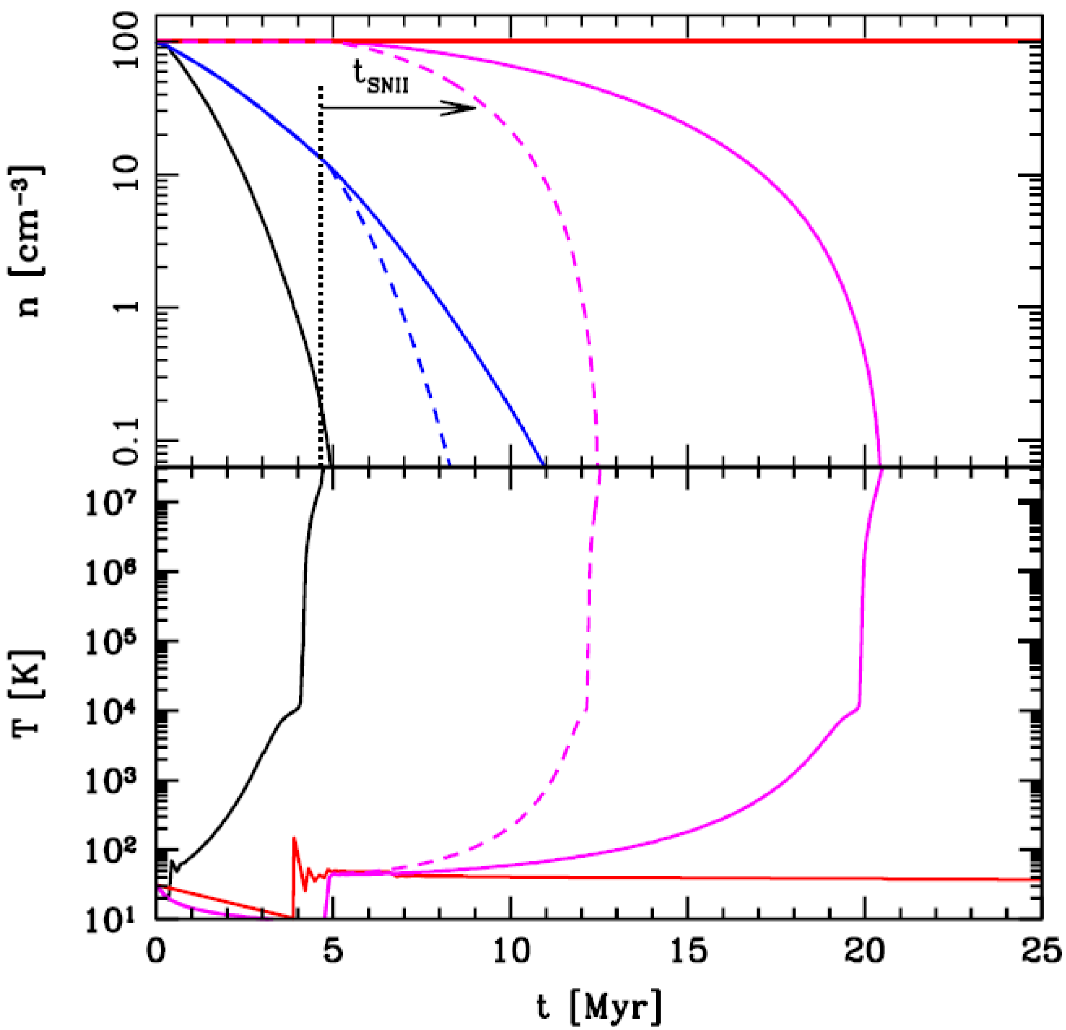
All Feedback Together

- Important lesson: supernovae go off after most of other feedback already did its share.
- For destroying molecular clouds SNe are irrelevant.





Now, Let's Simulate!



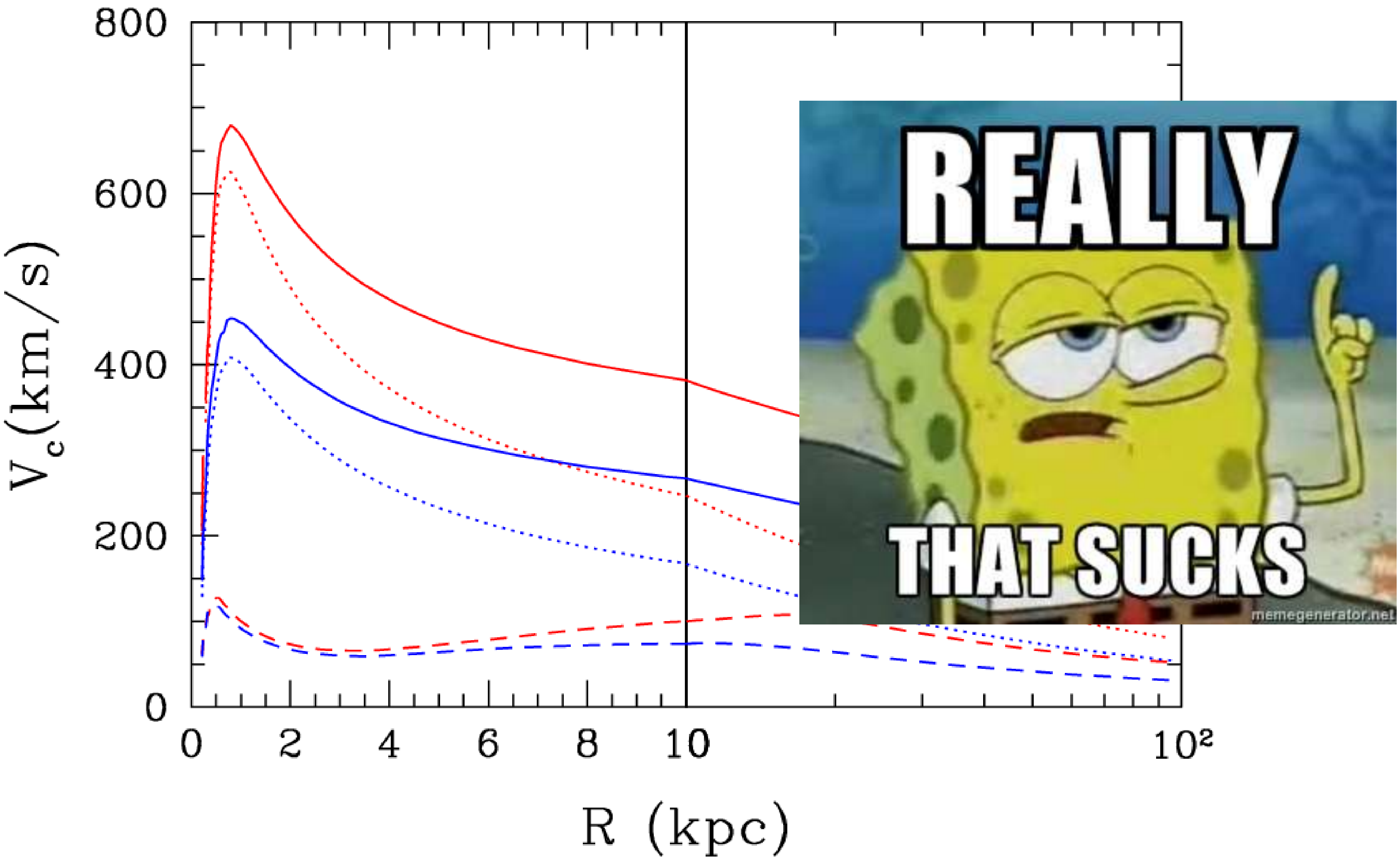
- All feedback together
- Momentum only
- SNe only (E & p)
- Energy only

2. Unconventional Marriage: Feedback & SF

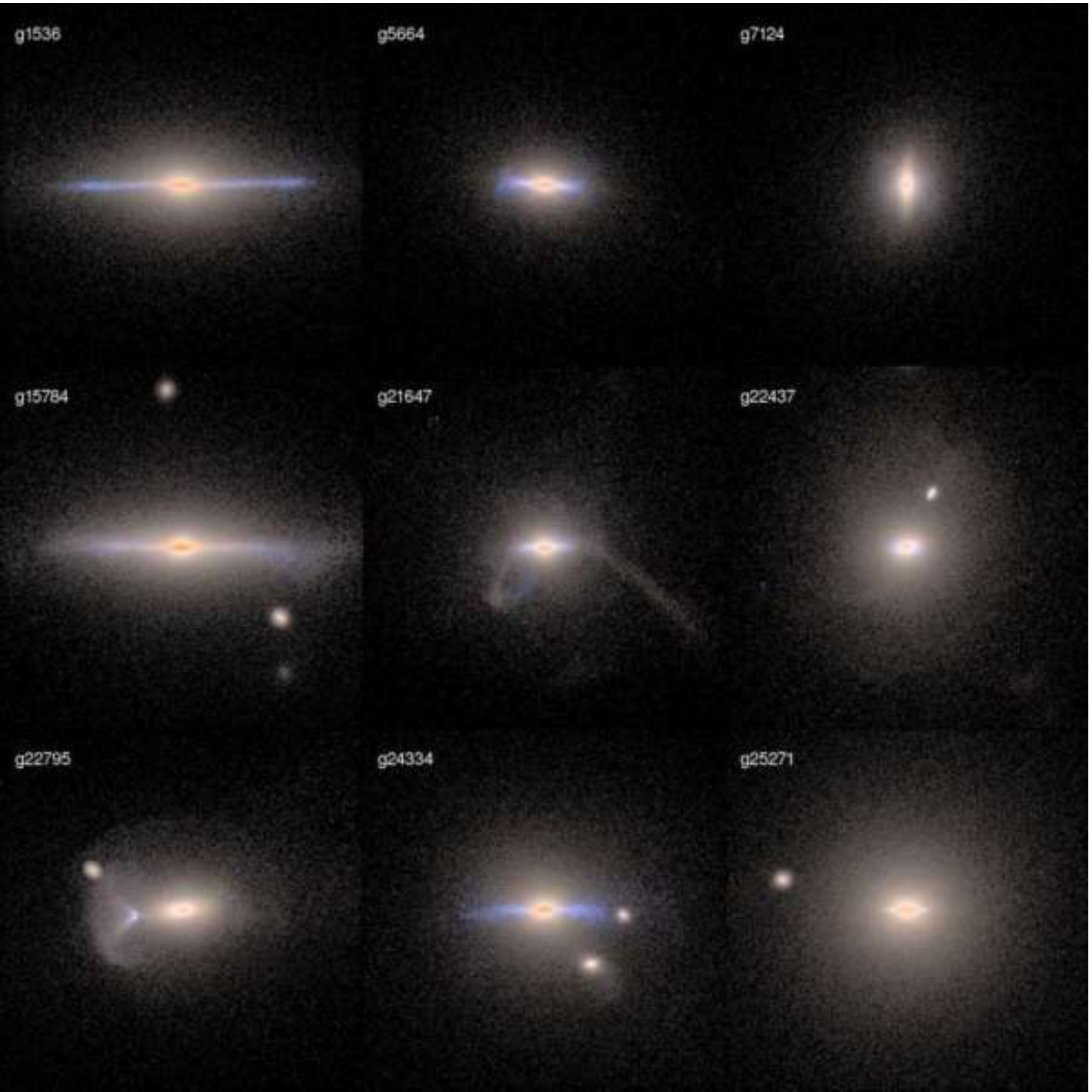
- Recall: $\tau_{\rm SF}$ is long (~ 1 Gyr), while molecular clouds are short lived (10-20 Myr).
- Hence, star formation is *inefficient* – only a small fraction of all molecular gas goes into stars in a molecular cloud during its lifetime.
- A natural conclusion: since feedback comes from stars, it should be inefficient too.

How About This?

- The same galaxy that has the right gaseous halo profile...



Simulated Galaxies…

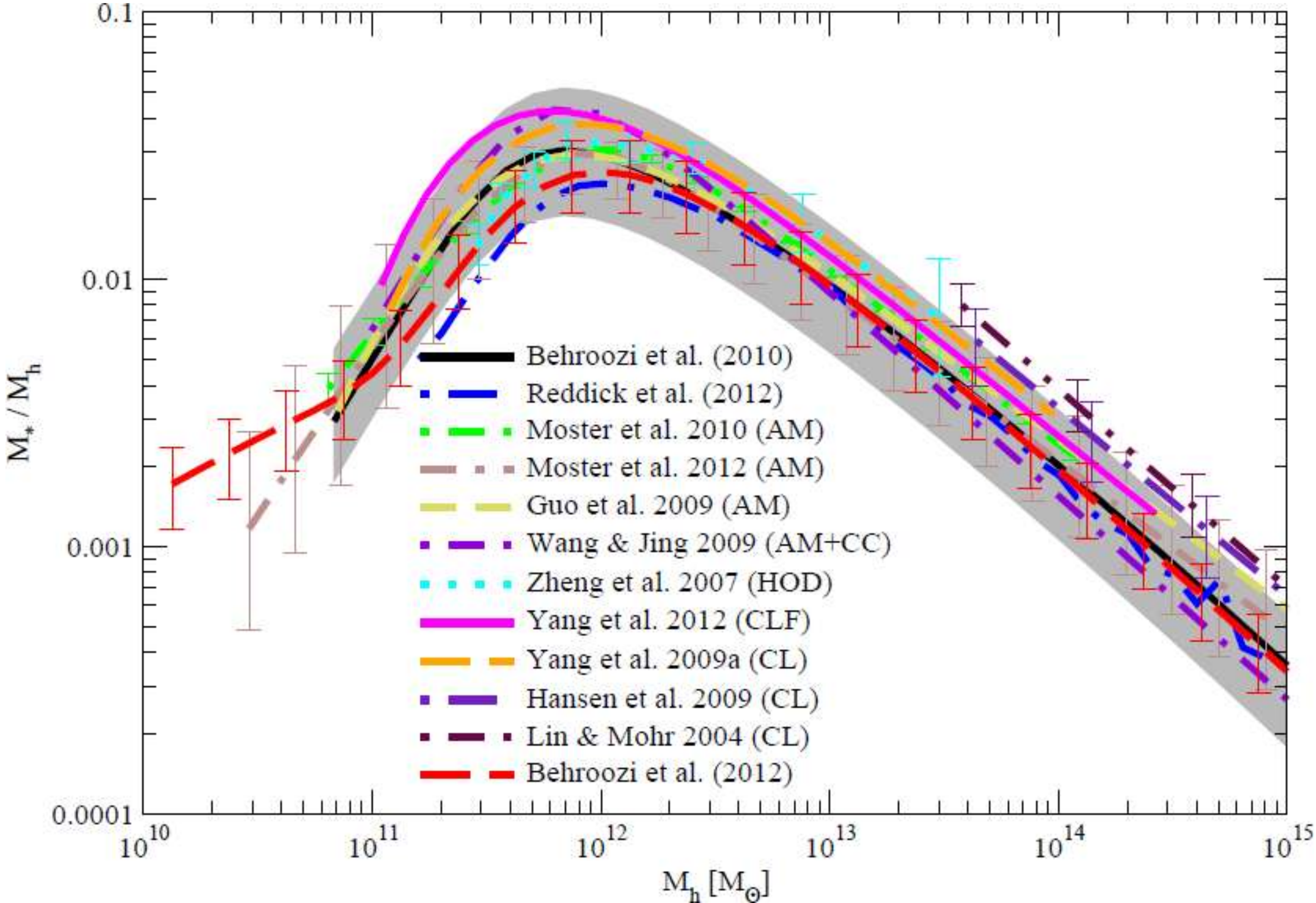


- MUGS galaxies (Stinson et al 2010)
- All simulated galaxies have large bulges.

...And Real Ones

- Hey, who stole my bulge?

Galaxies Are Inefficient Star-Formers



SF-Feedback Dilemma

- The challenge in understanding star formation and feedback is that star formation is inefficient, but feedback must be efficient in expelling a significant fraction of baryons from MW-like galaxies and even larger fractions for low and higher mass galaxies.

3. Miracles Do Happen

- Historically, there were many attempts to model feedback in cosmological and galactic simulations with *sub-grid* models.
- None of them was particular successful...

A Sub-grid Model #Next

- Yepes et al 1997

$$\left(\frac{\mathrm{d}\rho_*}{\mathrm{d}t}\right)_{\text{star formation}} = \frac{(1-\beta)\rho_c}{t_*}.$$

$$\left(\frac{\mathrm{d}\rho_h}{\mathrm{d}t}\right)_{\text{star formation}} = \frac{\beta\rho_c}{t_*}.$$

$$\left(\frac{\mathrm{d}\rho_h}{\mathrm{d}t}\right)_{\text{evap}} = -\left(\frac{\mathrm{d}\rho_c}{\mathrm{d}t}\right)_{\text{evap}} = \frac{A\beta\rho_c}{t_*}$$

Correspondingly, the net energ
phase by supernovae is

$$\left(\frac{\mathrm{d}\rho_h\varepsilon_h}{\mathrm{d}t}\right)_{\text{SN}} = \frac{\beta\rho_c}{t_*}[\varepsilon_{\text{SN}} + (A+1)\varepsilon_c].$$

A Sub-grid Model #Next

- Gnedin 1998

$$\frac{d\rho_*}{dt} = \left(\frac{d\rho_*}{dt}\right)_0 (1 - f_{\rm hot}),$$

$$f_{\rm hot} = 1 - \exp(-Q),$$

where (McKee 1990; Silk 1997)

$$v = q\frac{4\pi}{3}R_{\rm S}^3 t_{\rm S},$$

$$Q = v\frac{1}{m_{\rm SN}}\frac{d\rho_*}{dt}.$$

$$R_{\rm S} = 25.7\ {\rm pc}\ \frac{E_{51}^{31/98}}{\xi^{5/98} n_0^{18/49} v_{100}^{3/7}},$$

$$t_{\rm S} = 7.57 \times 10^4\ {\rm yr}\ \frac{E_{51}^{31/98}}{\xi^{5/98} n_0^{18/49} v_{100}^{10/7}}.$$

A Sub-grid Model #Next

- Springel & Hernquist 2003

$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = \frac{\rho_\mathrm{c}}{t_\star} - \beta\frac{\rho_\mathrm{c}}{t_\star} = (1-\beta)\frac{\rho_\mathrm{c}}{t_\star}.$$

$$\frac{\mathrm{d}\rho_\mathrm{c}}{\mathrm{d}t} = -\frac{\rho_\mathrm{c}}{t_\star} - A\beta\frac{\rho_\mathrm{c}}{t_\star} + \frac{1-f}{u_\mathrm{h}-u_\mathrm{c}}\Lambda_\mathrm{net}(\rho_\mathrm{h}, u_\mathrm{h}),$$

$$\frac{\mathrm{d}\rho_\mathrm{h}}{\mathrm{d}t} = \beta\frac{\rho_\mathrm{c}}{t_\star} + A\beta\frac{\rho_\mathrm{c}}{t_\star} - \frac{1-f}{u_\mathrm{h}-u_\mathrm{c}}\Lambda_\mathrm{net}(\rho_\mathrm{h}, u_\mathrm{h}).$$

A Sub-grid Model #Next

- Teyssier et al 2013

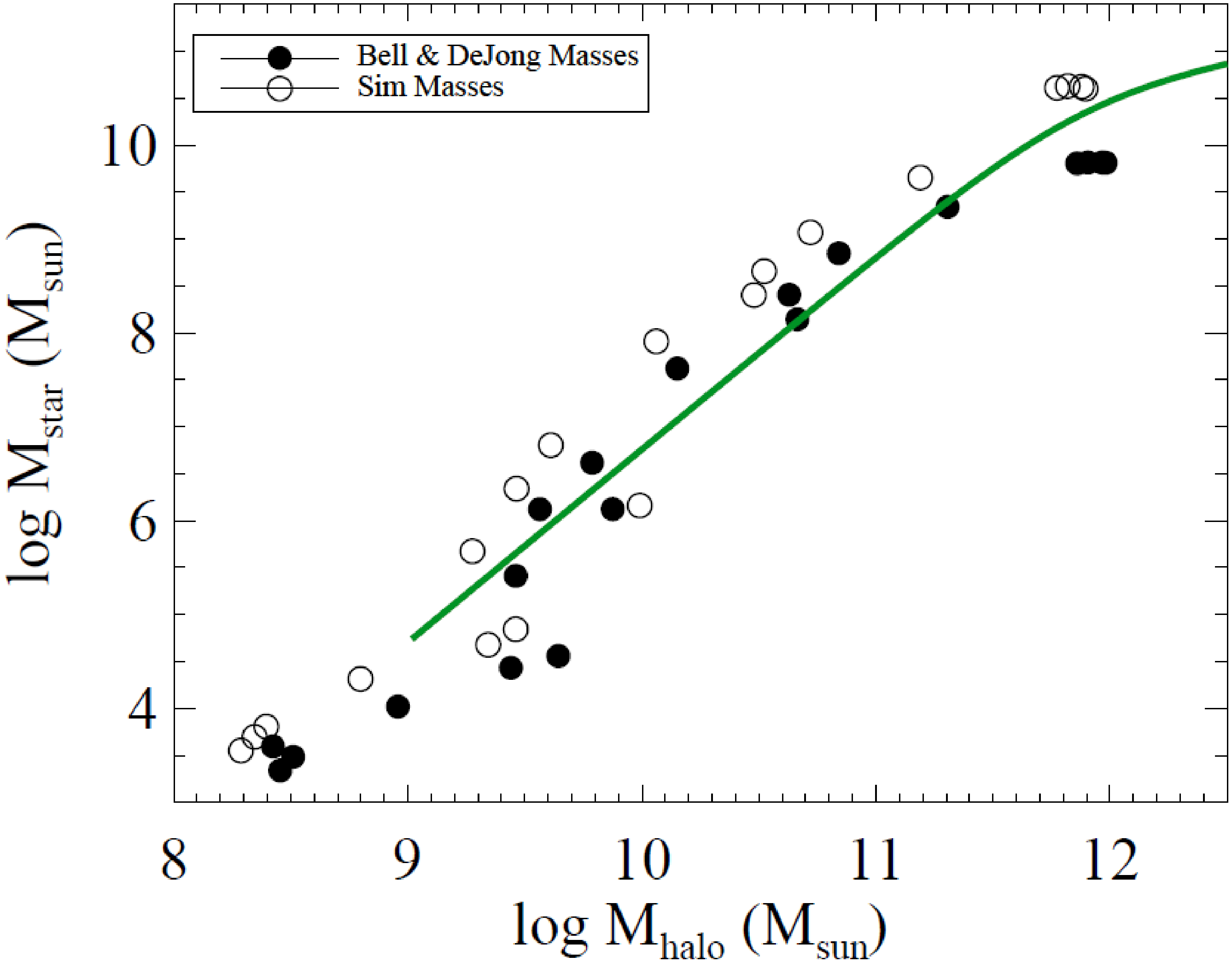
$$\dot{\rho}_* = \epsilon_* \frac{\rho_{\rm gas}}{t_{\rm ff}} \quad {\rm if} \quad \rho_{\rm gas} > \rho_* .$$

$$\rho \frac{D\epsilon_{turb}}{Dt} = \dot{E}_{inj} - \frac{\rho\epsilon_{turb}}{t_{\rm diss}}$$

$$\rho \frac{D\epsilon_{\rm thermal}}{Dt} = \dot{E}_{\rm inj} - P_{\rm thermal} \nabla \cdot \mathbf{v} - n_H^2 \Lambda$$

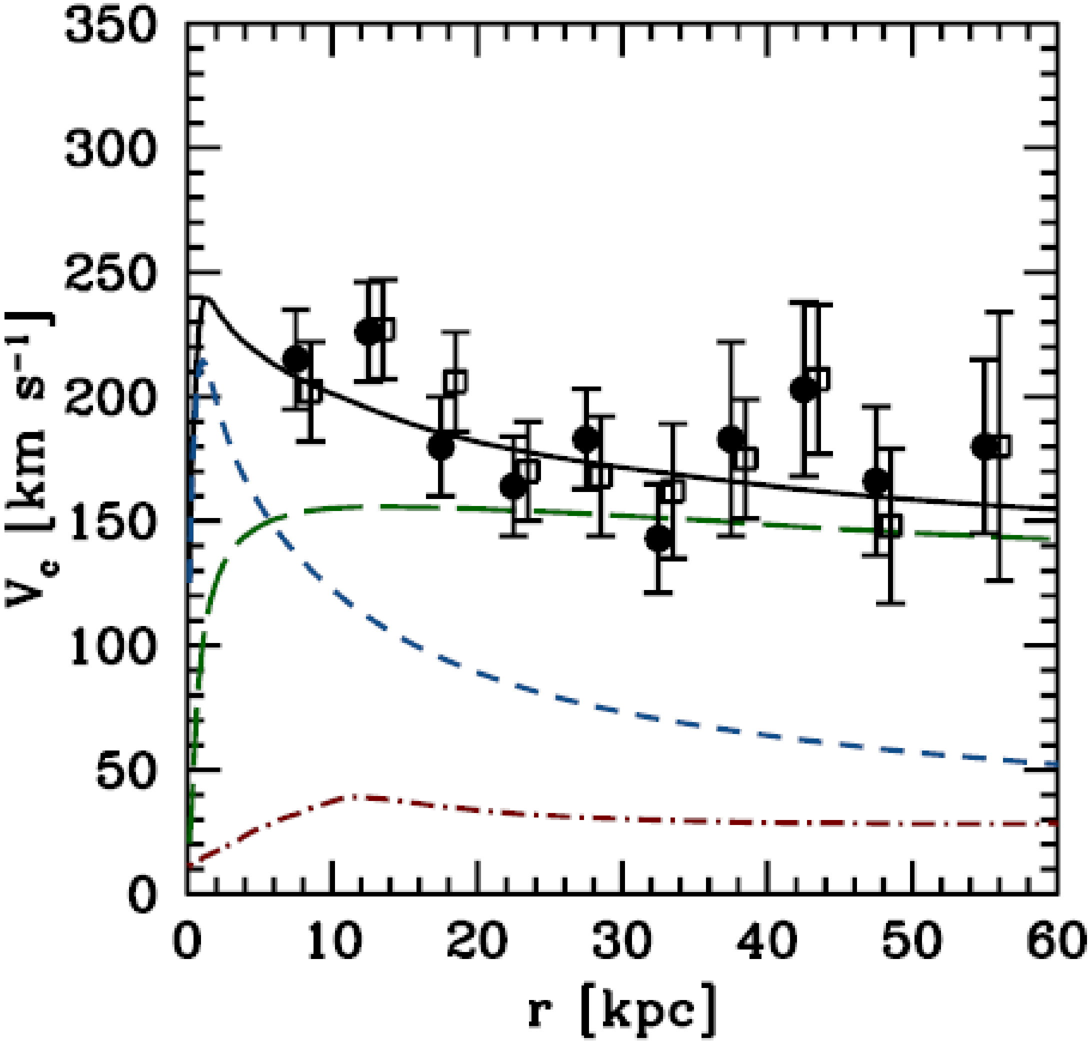
The World Is Full Of Magic

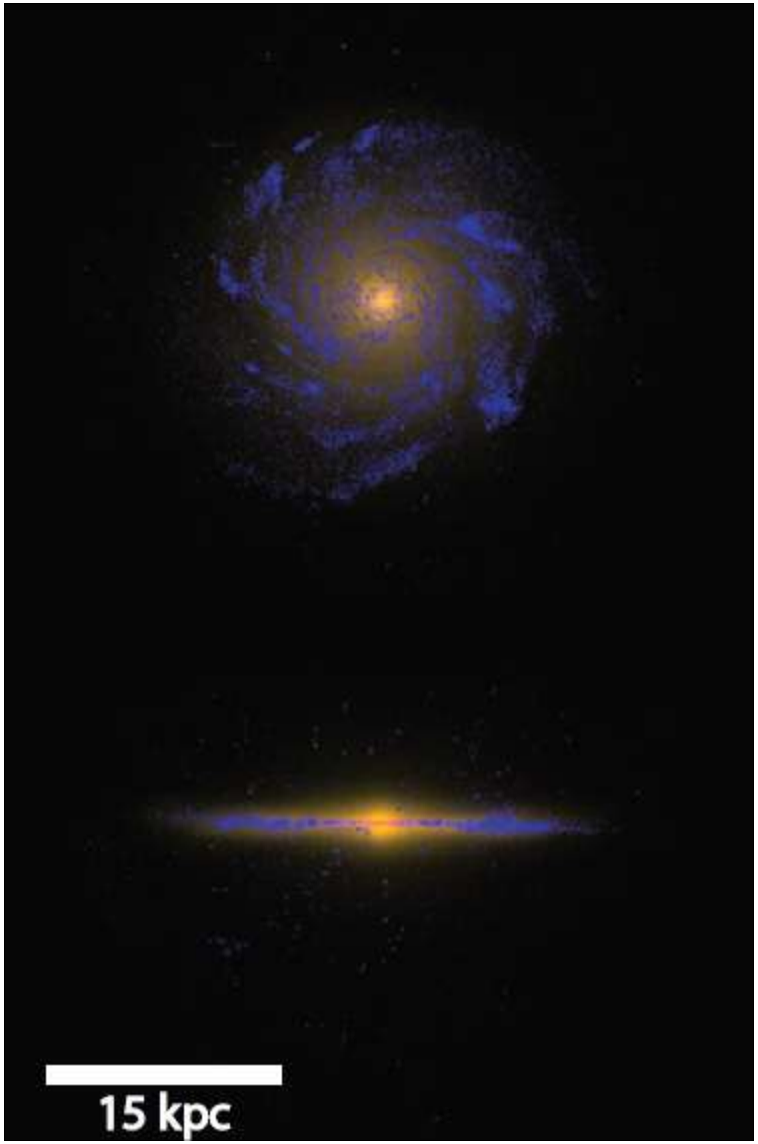
- Munshi et al 2012 (Gasoline team):



The World Is Full Of Magic

- "Eris": virtual Milky Way





And The Magic Is…

- *All one needs to do to make a realistic galaxy in a cosmological simulation is to switch off cooling in a star forming region for ~10 Myr.*
- Things to note:
  - As such, it is a trick, it has no physical justification.
  - The fact that it works may be a pure coincidence.
  - Alternatively, it can be a manifestation of a real physical process that operates on <1pc scales, but its consequences on ~100pc appear as *if cooling was switched off*.

Nature Of Delayed Cooling

Quiz: Which small-scale physical process behaves as delayed cooling on large scales:

A. Radiation pressure - massive (=bright) stars live for ~10 Myr.
B. Thermal pressure of coronal gas - cooling time of coronal gas ~10 Myr.
C. Kinetic energy of internal motions inside molecular clouds - molecular cloud lifetimes are ~10 Myr.
D. Cosmic Ray pressure – cosmic ray energy loss time in molecular clouds ~10 Myr.

4. Star Formation Model And Feedback

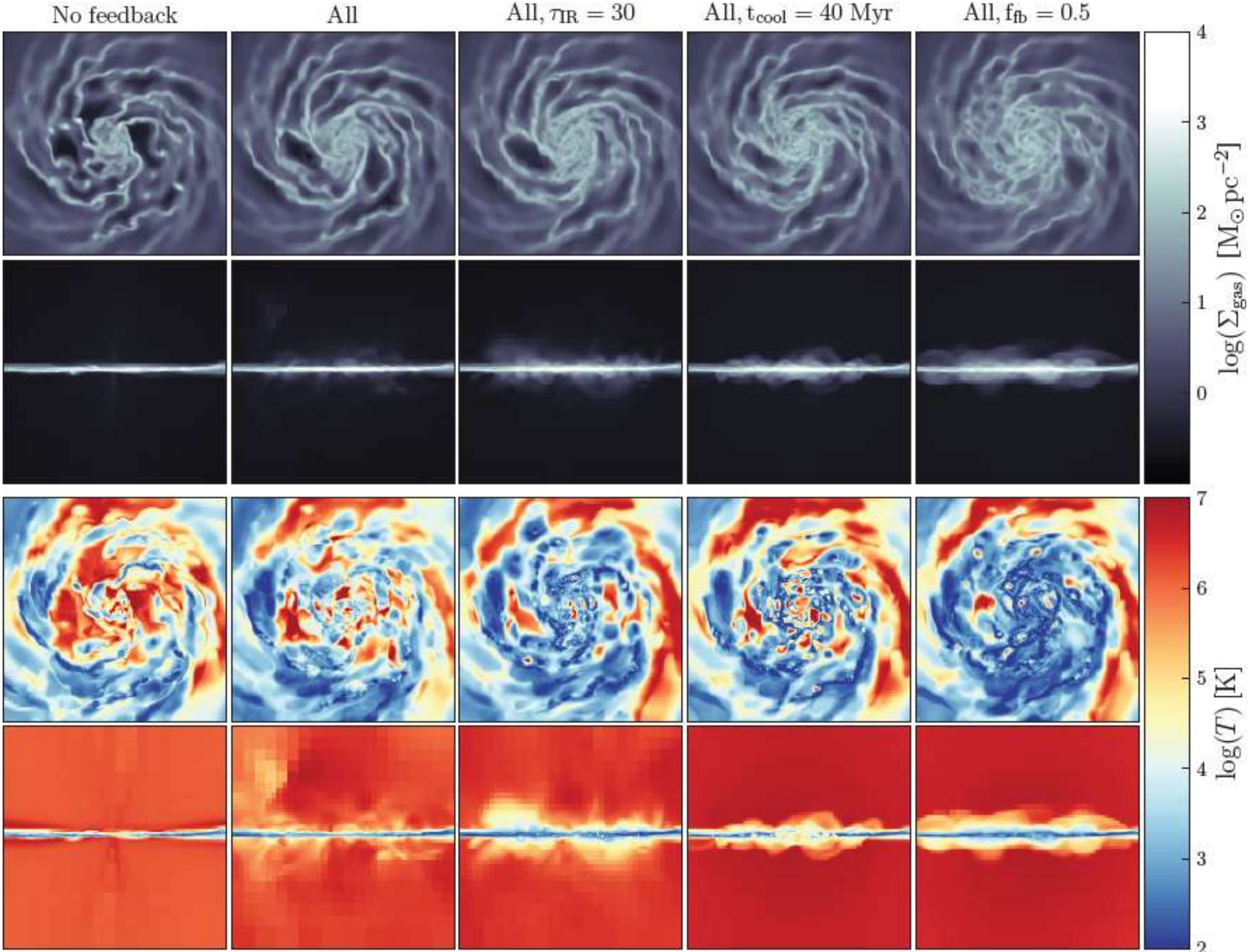
- The efficiency of the feedback does depend on your adopted star formation model:
- The canonical $\tau_{\rm SF} = \tau_{\rm ff}/\epsilon_{\rm ff}$ model ($\dot{\rho}_* \propto \rho_{\rm mg}^{3/2}$) converts gas into stars too fast at early times, and requires extra "early" feedback on top of delayed cooling.
- The modern $\tau_{\rm SF} = {\rm const}$ model ($\dot{\rho}_* \propto \rho_{\rm mg}$) avoids the need for early feedback, but does not concentrate feedback enough.
- Looks like existing SF models actually ran out of steam…

5. Towards The Future

- We need SF folks to tell us how/which/when molecular gas makes stars – looks like not all gas makes stars equally well.

- Different feedback modes do produce significant differences in the details of modeled galaxies.

- The challenge now is to figure out which one(s) of several possible physical mechanisms is/are the primary stellar feedback channel.



No feedback
All
All, $\tau_{\rm IR} = 30$
All, $t_{\rm cool} = 40$ Myr
All, $f_{\rm fb} = 0.5$
$\log(\Sigma_{\rm gas})$ [$M_\odot\,{\rm pc}^{-2}$]
4
3
2
1
0
$\log(T)$ [K]
7
6
5
4
3
2

The End

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