



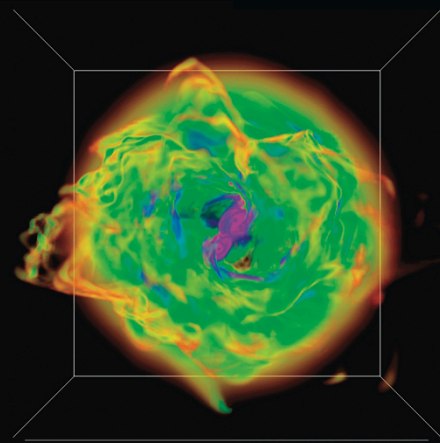
UC-HIPACC's
International Summer School
on AstroComputing presents:

ISSAC 2013: STAR & PLANET FORMATION

July 22 - August 9, 2013
University of California, Santa Cruz

visit us on the web: hipacc.ucsc.edu/ISSAC2013.html

Description: Star and planet formation are central drivers in cosmic evolution: they control generation of radiation, synthesis of heavy elements, and development of potential sites for life. Because star and planet formation involve numerous physical processes operating over orders of magnitude in length and time scale, simulations have become essential to progress in the field. The objective of the 2013 UC-HIPACC AstroComputing Summer School is to train the next generation of researchers in the use of large-scale simulations in star and planet formation problems. The school will cover many of the major public codes in use today, including tutorials and hands-on experience running and analyzing simulations. Students will receive accounts on the new 3,000-core supercomputer Hyades on the UCSC campus for the duration of the school.



Volume rendering of the gas density in a simulation of the formation of a 70 Solar mass binary system. Krumholz

The school is directed by Prof. Mark Krumholz (UCSC), and is funded primarily by UC-HIPACC (Prof. Joel Priemack, UCSC, director). Additional funds are being sought from NSF for student support and from DOE for infrastructure support. Students will be housed on the UCSC campus (approximately \$50/night). UC-HIPACC will cover lodging at UCSC for all accepted students and also travel for UC-affiliated students. Some financial assistance for travel may be available for other students.

Students must apply by filling in the online form at http://hipacc.ucsc.edu/ISSAC2013_Application.php

Applications are due March 16, 2013, although it may be possible to consider late applications. We aim to tell students who apply on time whether they are admitted by April 2, 2013. Upon acceptance all students who plan to attend will pay a registration fee of \$500. Week day lunches, coffee breaks, the school banquet, and a special excursion will be provided for attendees.

Director: Mark Krumholz (UCSC)

Speakers and Topics will include:

Main lecturers

(5 lectures each and lead afternoon workshops)

Robi Banerjee (U. Hamburg, FLASH)
Paul Clark (U. Heidelberg, GADGET / SEREN)
Patrick Hennebelle (CEA/Saclay, RAMSES)
Stella Offner (Yale, RADMC / HYPERION / CASA)
Tom Quinn (U. Washington, GASOLINE / CHANGA)
Jim Stone (Princeton, ATHENA)

Additional Lecturers

Tom Abel (Stanford, first stars, ENZO)
Neal Evans (U. Texas Austin, observations of massive star formation)
Alyssa Goodman (Harvard, observations of low-mass star formation)
Phil Hopkins (Caltech, the IMF)
Meredith Hughes (Wesleyan, observations of protoplanetary disks)
Kaitlin Kratter (U. Colorado, binary formation)
Mark Krumholz (UC Santa Cruz, massive star formation)
Chris McKee (UC Berkeley, star formation rates)
Eve Ostriker (Princeton, the ISM/star formation connection)
Joel Primack (UC Santa Cruz, star formation and galaxy evolution)

APPLY BY MARCH 16, 2013. For updated information and to apply: <http://hipacc.ucsc.edu/ISSAC2013.html>

Star Formation and Feedback

III: The Physics of Stellar Feedback

Mark Krumholz, UC Santa Cruz

30th Jerusalem Winter School on
Theoretical Physics

January 2, 2013

Outline

- Why feedback?
- Energy versus momentum-limited feedback
- Feedback budgets
- Feedback taxonomy
 - Photoionization
 - Radiation pressure
 - Stellar winds
 - Supernovae
- “Metallicity feedback”

Why Feedback?

UK Astrophysical
Fluids Facility

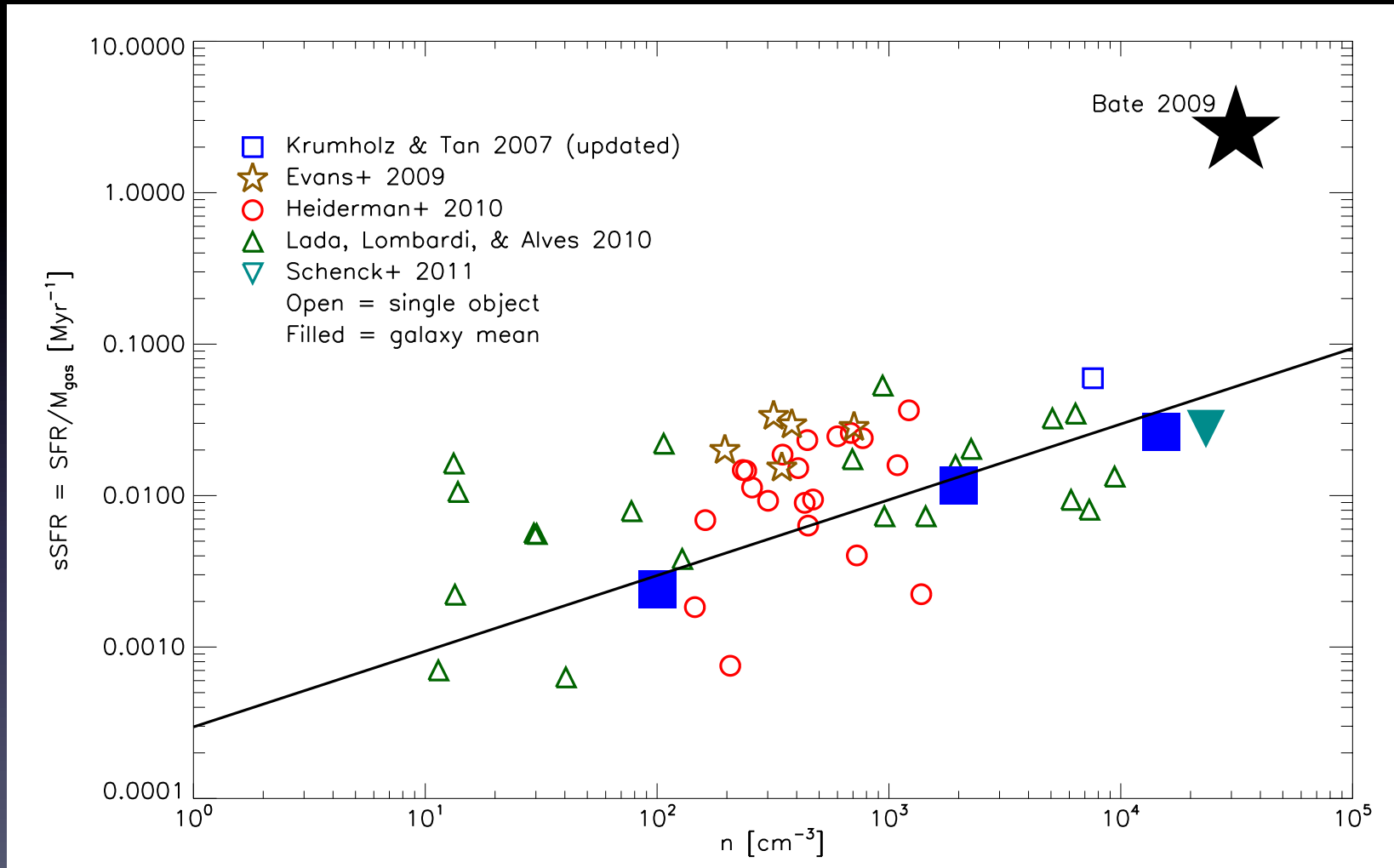


Matthew Bate 

Bate (2009)

What's included: hydrodynamics, gravity

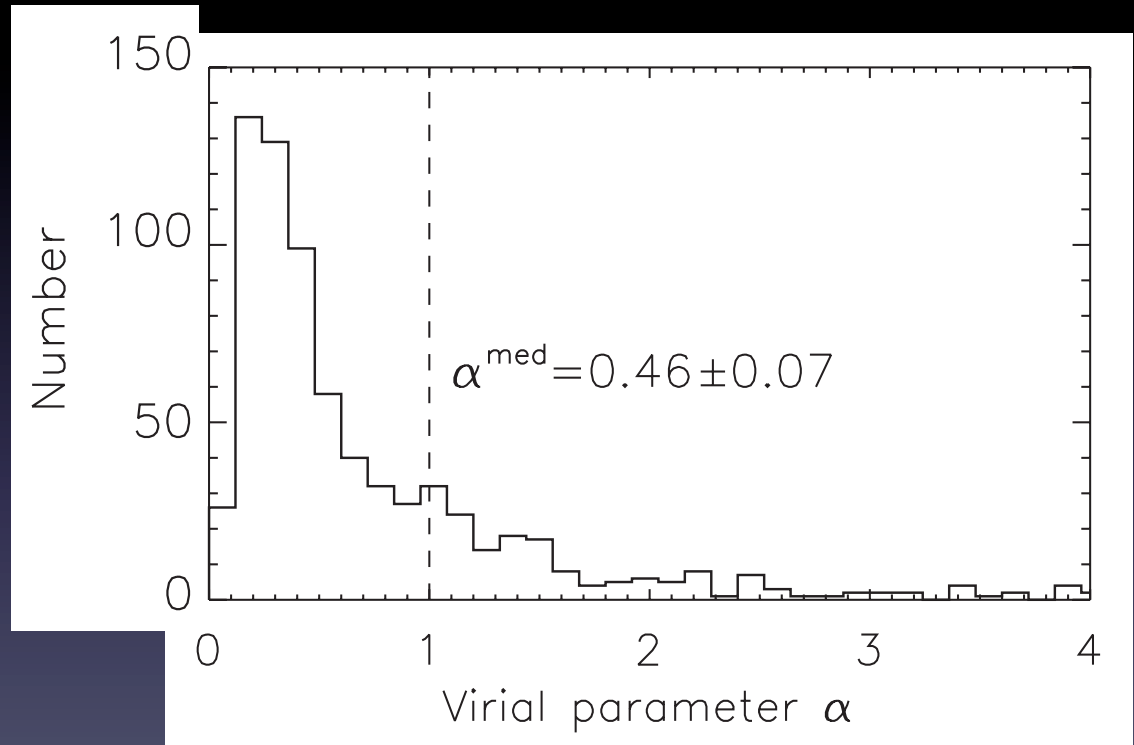
Star Formation Too Fast



Data compilation from Krumholz, Dekel, & McKee (2012); KTo7 updated with HCN effective density from Schenck+ (2011), new Orion data from Regianni + (2011), da Rio+ (2012)

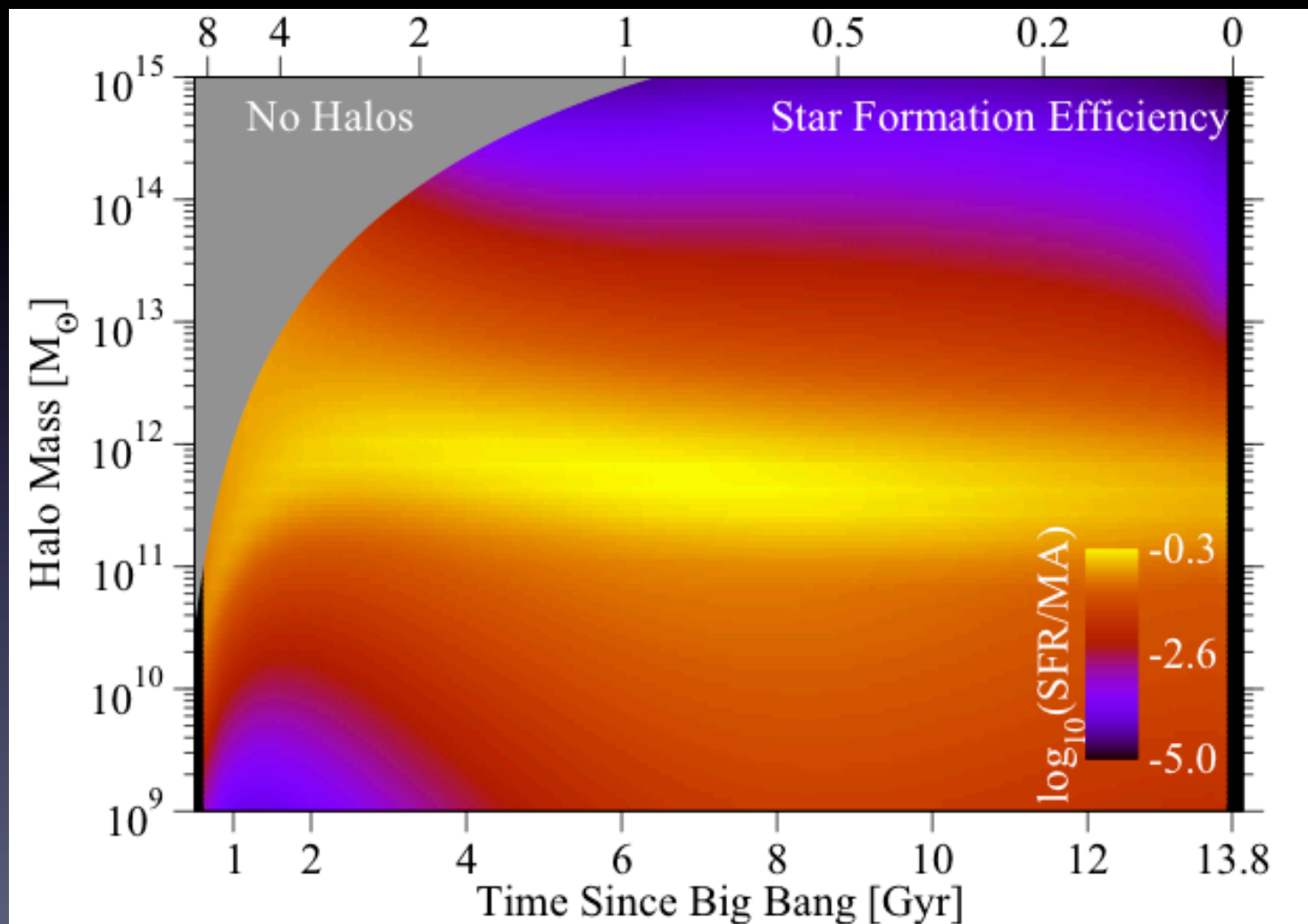
Star Formation Too Efficient

- Without feedback, bound clouds \rightarrow bound clusters
- Most GMC mass bound; proto-clusters ($n > 10^4 \text{ cm}^{-3}$) bound
- Why don't most stars form in bound clusters?



Virial ratio distribution of GMCs (Roman-Duval+ 2010)

Galaxy Formation Too Efficient

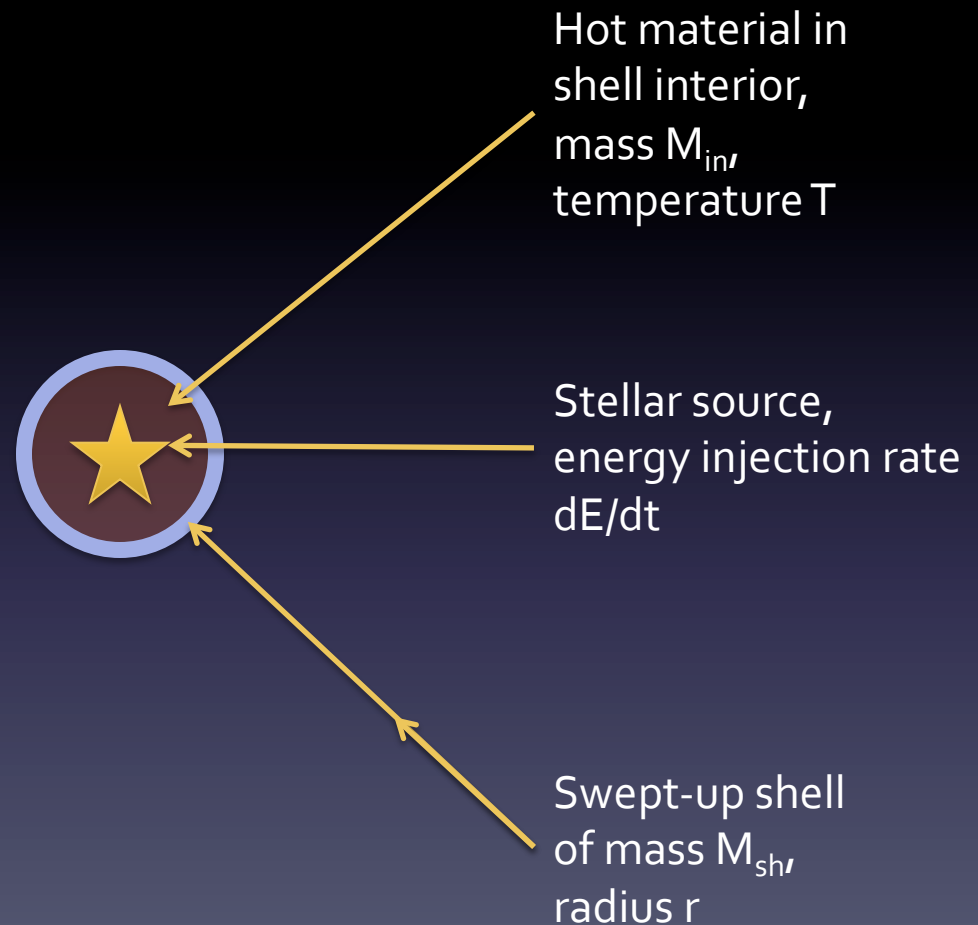


Behroozi+ (2013)

The Solution...



Energy-Conserving Feedback



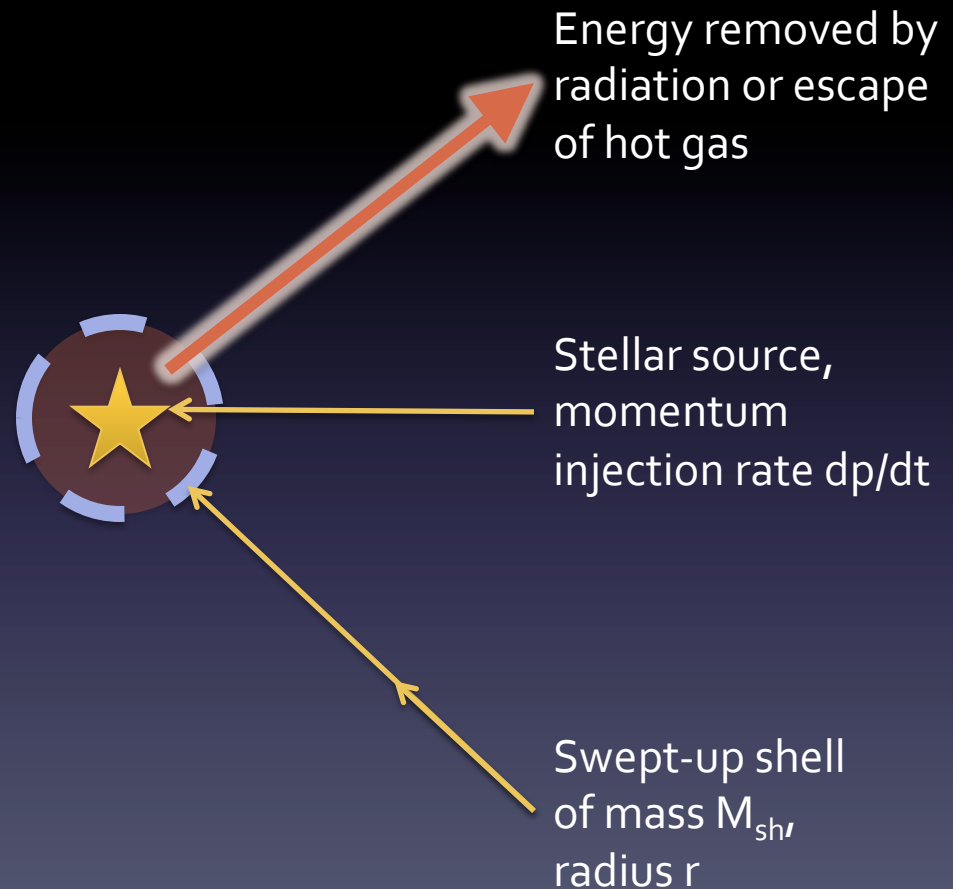
Shell radius
set by energy
conservation:

$$\dot{E}t \sim M_{sh}\dot{r}^2 + M_{in}k_B T \sim 2M_{sh}\dot{r}^2$$

Momentum-Conserving Feedback

Shell radius
set by
momentum
conservation:

$$\dot{p}t \sim M_{\text{sh}} \dot{r}$$



What's the Difference?

- Consider a source w/mass flux dM/dt , velocity v ; after time t , shell has mass M , radius r
- Energy-conserving case: $M_E \dot{r}_E^2 \sim \dot{M} v^2 t$
- Momentum-conserving case: $M_p \dot{r}_p \sim \dot{M} v t$
- Ratio of energies, momenta at equal times:

$$\frac{M_E \dot{r}_E^2}{M_p \dot{r}_p^2} \sim \frac{v}{\dot{r}_p} \gg 1 \quad \frac{M_E \dot{r}_E}{M_p \dot{r}_p} \sim \sqrt{\frac{M_E}{\dot{M} t}} \gg 1$$

- Define $f_{\text{trap}} = \frac{M \dot{r}}{\dot{M} v t} - 1$, i.e. $p/p_{\text{source}} - 1$

Feedback Budgets

- Let IMF be $\xi(m) = dn/d\ln m$, $\int \xi dm = 1$
- Mean star mass is $\bar{m} = 1 / \int \xi d\ln m$
- Consider a quantity Q , production rate $q(m, t)$ known from stellar evolution
- For stellar population of age t , production rate is $q(t) = M \int \xi q(m, t) d\ln m$
- Total amount of quantity produced over all time is $Q = M \int \xi \int q(m, t) dt d\ln m$

Feedback Budgets II

- From these results, define IMF-averaged production rate, yield by

$$\left\langle \frac{q}{M} \right\rangle_t \equiv \int \xi q(m, t) d \ln m$$

$$\left\langle \frac{Q}{M} \right\rangle \equiv \int \xi \int q(m, t) dt d \ln m$$

- RHS can be computed from stellar evolution and the IMF alone (e.g. by starburst99)

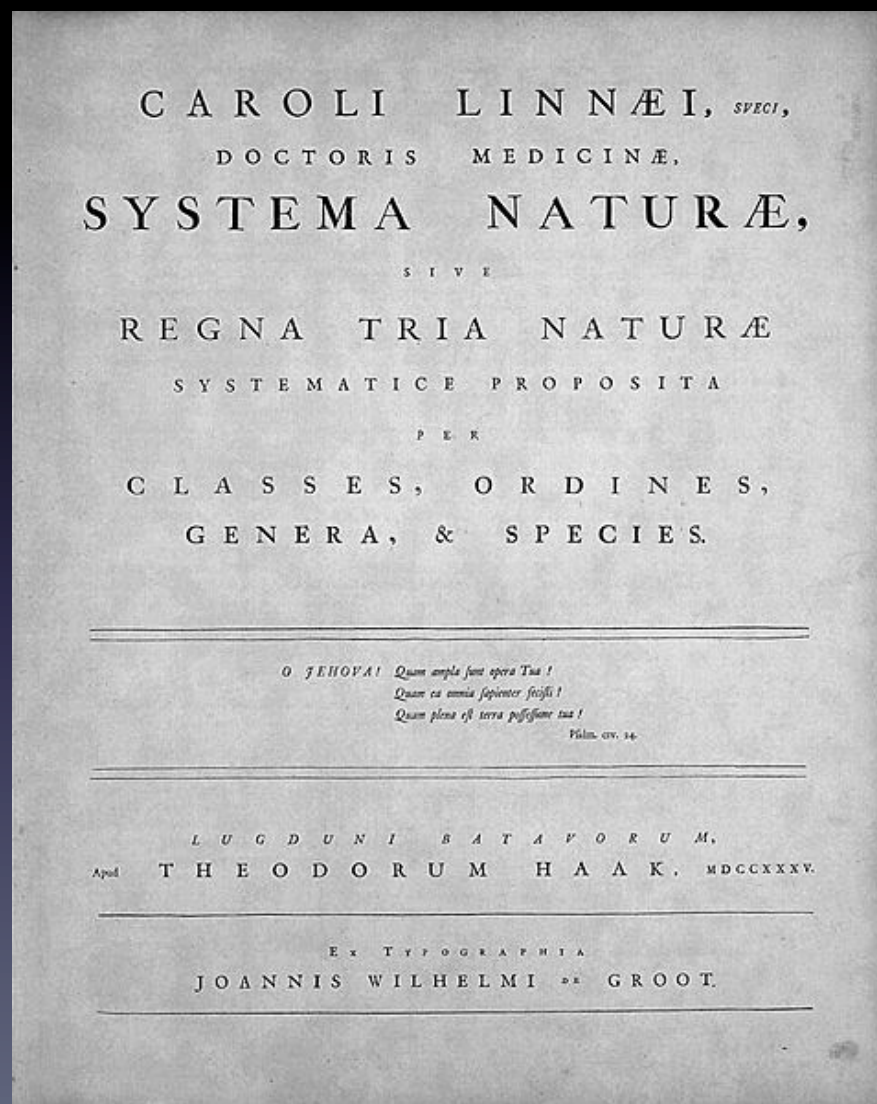
Feedback: What is Needed

- Consider an object with escape speed v_{esc}
- Momentum injection rate required to drive galactic wind with $(dM/dt)_{\text{wind}} \sim (dM_*/dt)$ is

$$\left\langle \frac{p}{M} \right\rangle > v_{\text{esc}}$$

- NB: this is a lower limit, assuming no losses
- SFE $< \sim 0.5$ in galaxies with $v_{\text{esc}} > 200 \text{ km s}^{-1} \rightarrow$
sum of feedbacks $\gg 200 \text{ km s}^{-1}$ on galactic scales

Feedback Taxonomy



Ionizing Radiation

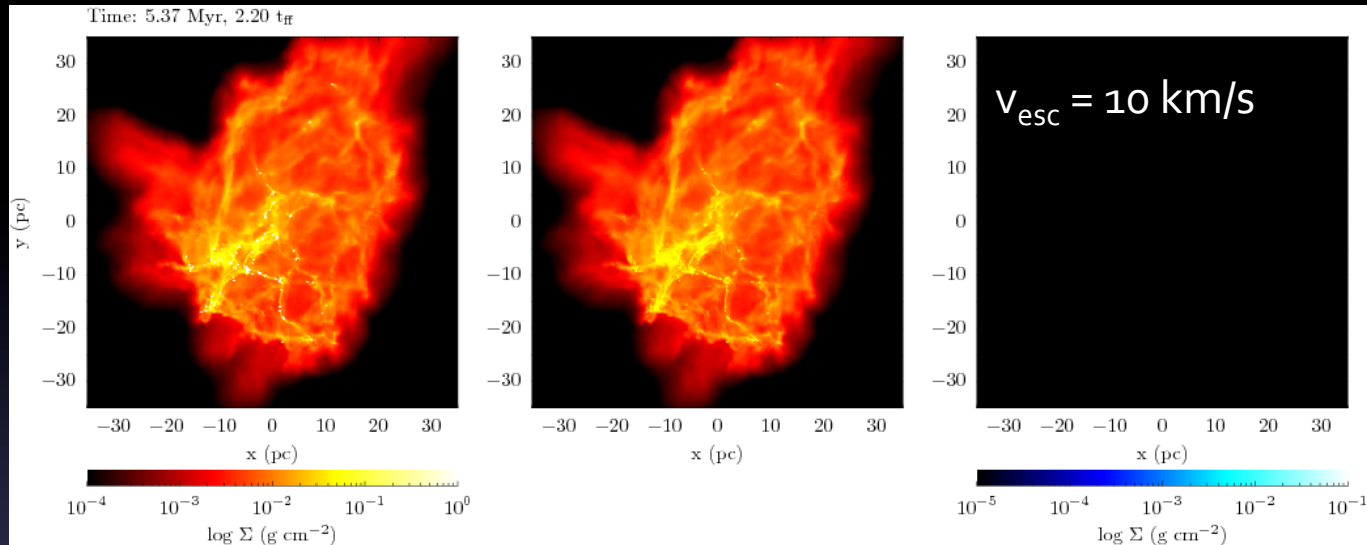


- Ionizing photons heat ISM to $\sim 10^4$ K ($c_s \sim 10$ km s $^{-1}$)
- Can't launch galactic winds, but can regulate SF
- Similar to momentum-conserving case, since gas temp fixed
- Budget:

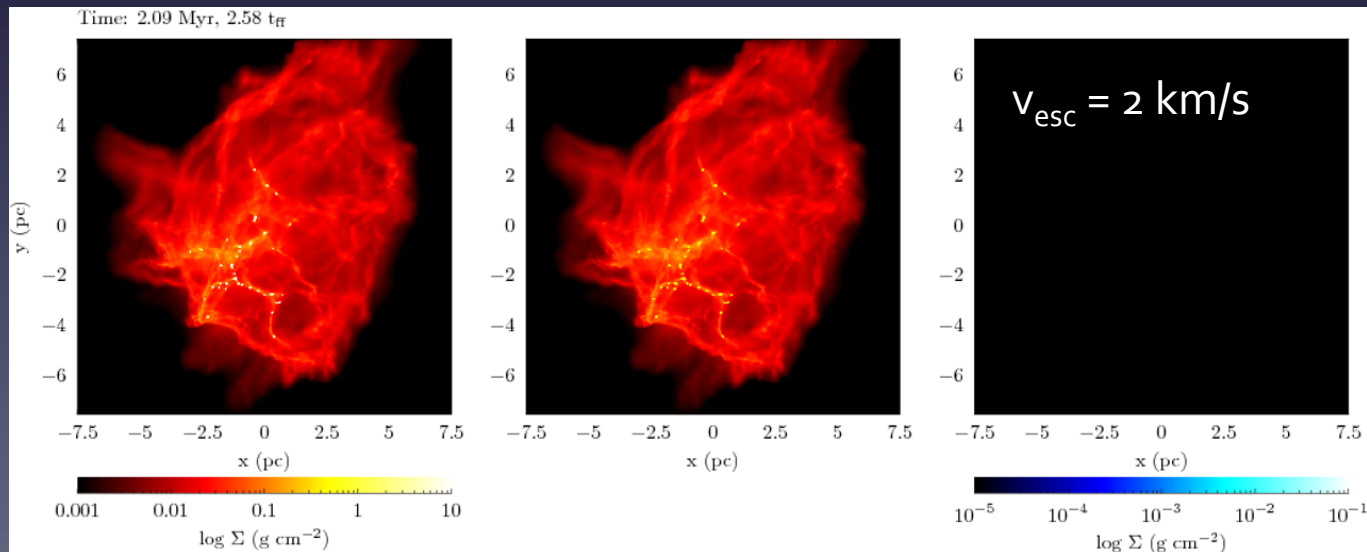
$$\left\langle \frac{Q(\text{H}^0)}{M} \right\rangle = 6.2 \times 10^{46} \text{ photons s}^{-1} M_{\odot}^{-1}$$

$$\left\langle \frac{Q(\text{H}_{\text{tot}}^0)}{M} \right\rangle = 4.2 \times 10^{60} \text{ photons } M_{\odot}^{-1}$$

Ionizing Radiation: Disruption



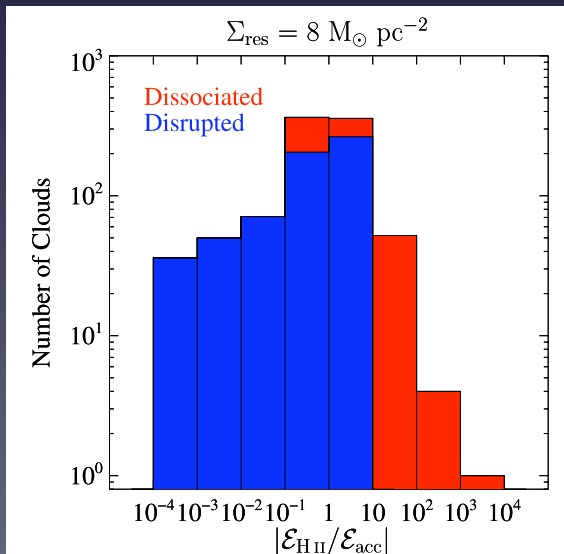
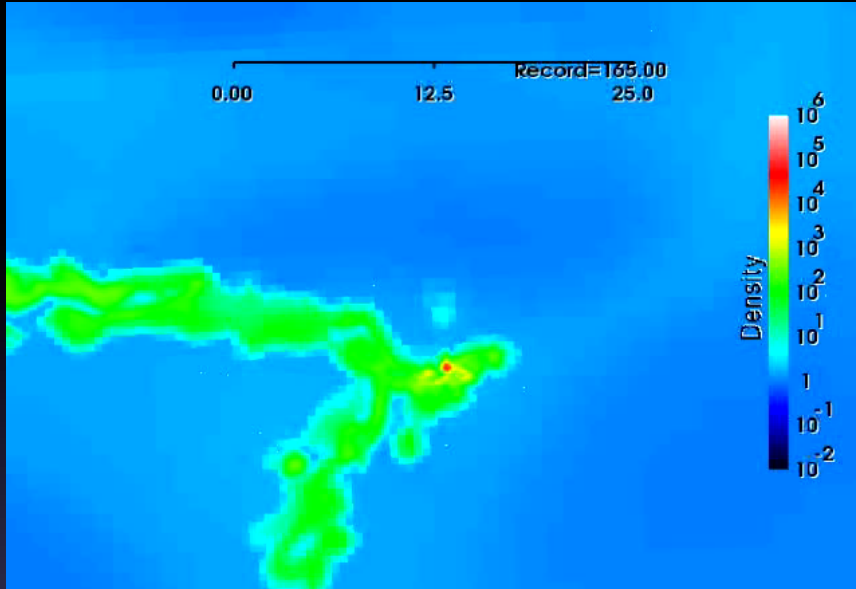
HII regions
disrupt
clouds with
 $v_{\text{esc}} < \sim \text{few}$
km/s, but
not larger



ones (Krumholz+
2006, 2009, Murray+
2010, Fall+2010,
Goldbaum+ 2011)

Dale+ (2012); What's
included: hydro,
gravity, ionizing
radiation

Ionizing Radiation: SF Regulation



Above: Vazquez-Semadeni+ 2010;
included: hydro,
gravity, approx.
ionization

Left: semi-analytic
GMC models,
Goldbaum+ 2011

- HII regions keep ϵ_{ff} , SFE low
(Gritschneider+ 2009,
Vazquez-Semadeni+ 2010,
Peters+ 2010, 2011,
Goldbaum+ 2011)
- After accretion ends, may disrupt clouds
- Probably the dominant SF regulator today

Radiation Pressure

- For a Kroupa IMF, instantaneous (zero-age) and total radiation production are (from sb99)

$$\left\langle \frac{L}{M} \right\rangle = 1140 L_{\odot} M_{\odot}^{-1} = 2200 \text{ erg g}^{-1}$$

$$\left\langle \frac{E_{\text{rad}}}{M} \right\rangle = 1.1 \times 10^{51} \text{ erg } M_{\odot}^{-1} = 6.2 \times 10^{-4} c^2$$

- Corresponding radiation momenta:

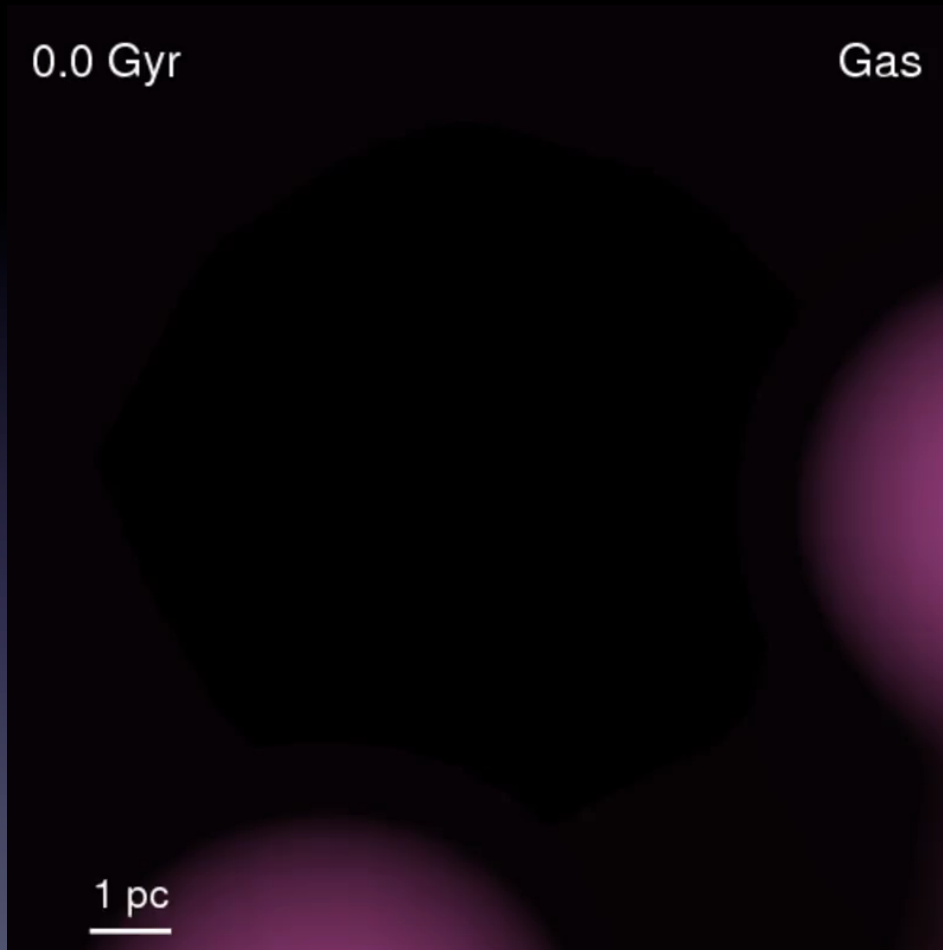
$$\left\langle \frac{\dot{p}_{\text{rad}}}{M} \right\rangle = 23 \text{ km s}^{-1} \text{ Myr}^{-1}$$

$$\left\langle \frac{p_{\text{rad}}}{M} \right\rangle = 190 \text{ km s}^{-1}$$

When is RP Important?

- Momentum budget $\sim 200 \text{ km s}^{-1} \rightarrow$ cannot launch winds in large galaxies unless $f_{\text{trap}} \gg 1$
- Can be important for early dwarfs and sub-galactic objects with $v_{\text{esc}} \ll 200 \text{ km s}^{-1}$ even if $f_{\text{trap}} \sim 1$ (Krumholz & Matzner 2009; Wise+ 2012)
- RP significant if $(f_{\text{trap}} L/c) t_{\text{ff}} > M v_{\text{vir}}$; with some manipulation, this gives (Fall+ 2010)
$$\Sigma < f_{\text{trap}} \cdot 1 \text{ g cm}^{-2}$$
- Key question: what is f_{trap} ?

Effects of f_{trap}



Hopkins+ (2012); What's included: hydro, gravity, RP subgrid model with $f_{\text{trap}} \sim \tau_{\text{IR}}$

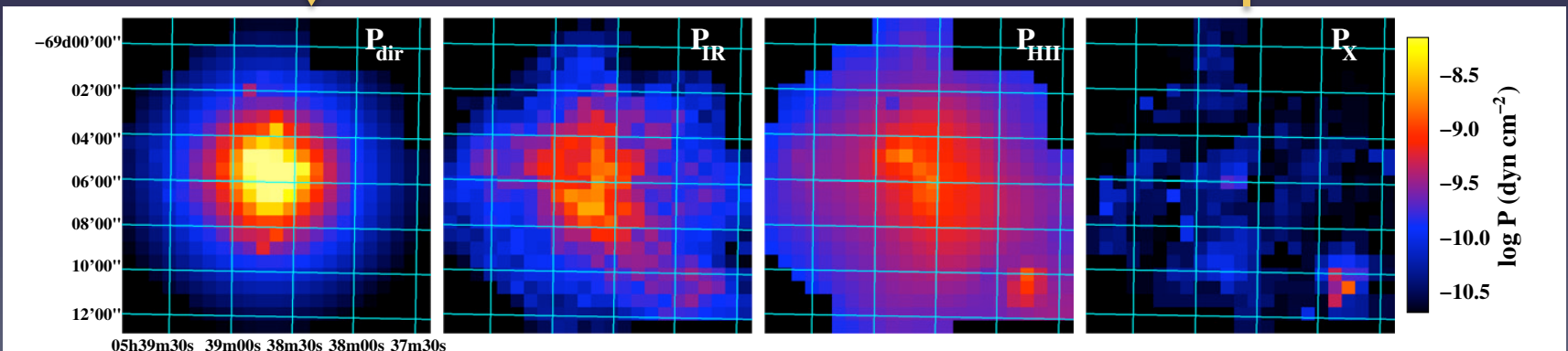
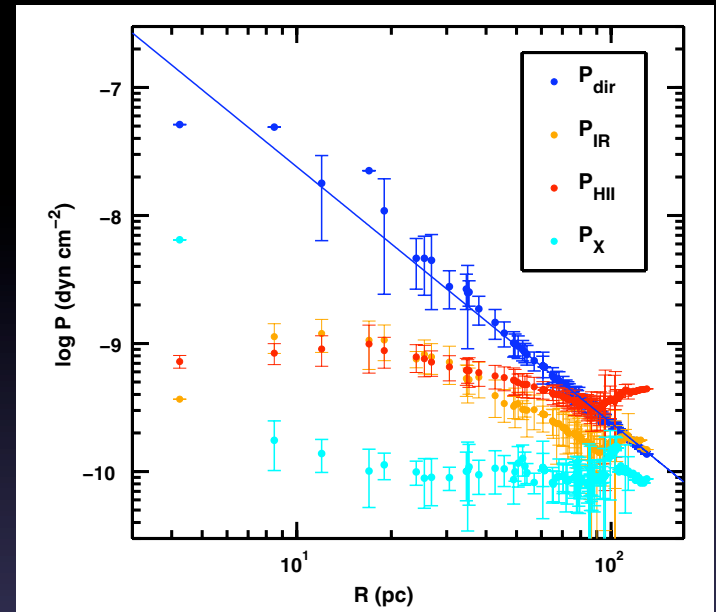
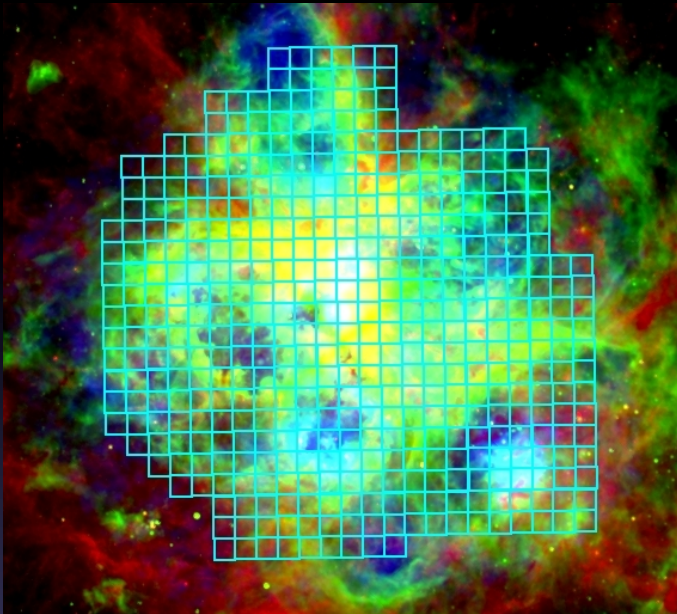
If $f_{\text{trap}} \sim \tau_{\text{IR}} \dots$ (Murray+ 2010, 2011, Hopkins+ 2012a,b,c,d)

- RP disrupts all clusters, launches galactic winds

If $f_{\text{trap}} \sim 1 \dots$ (Krumholz & Matzner 2009, Fall+ 2010, Krumholz & Dekel 2010)

- RP important only in some clusters, small dwarfs

Observations of f_{trap}



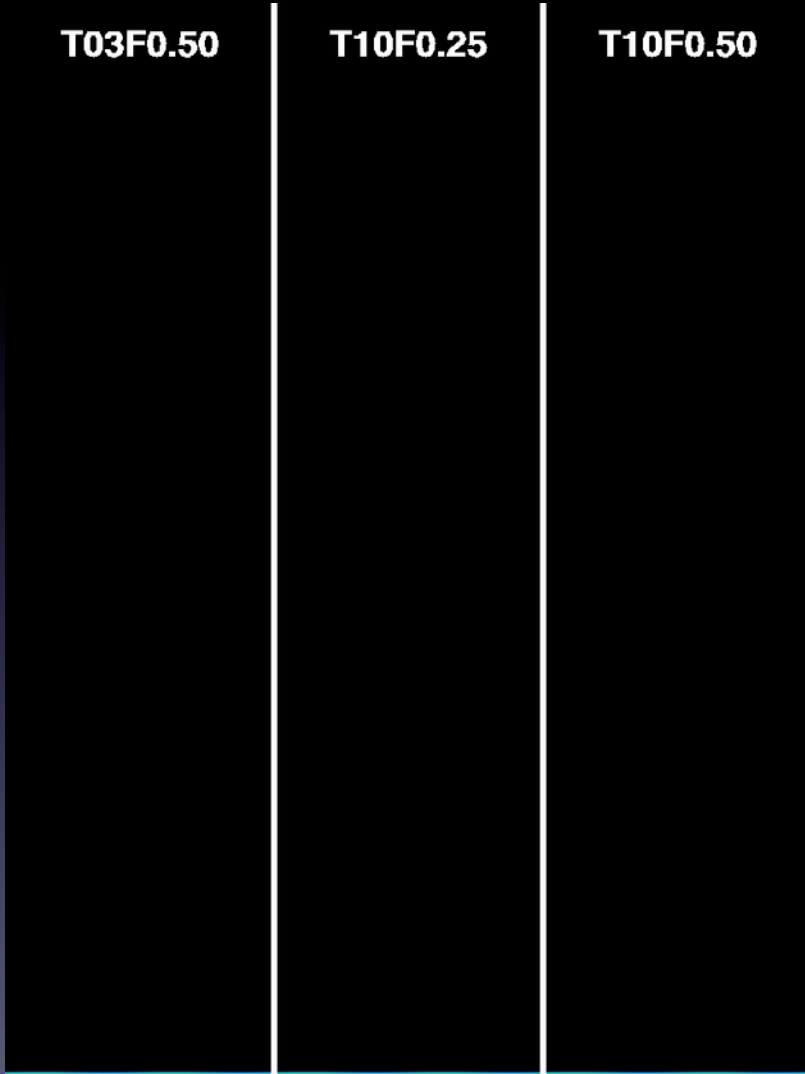
Pressures of direct starlight, reprocessed IR, warm gas, hot gas in 30 Dor (Lopez+ 2011)

Numerical Measurement of f_{trap}

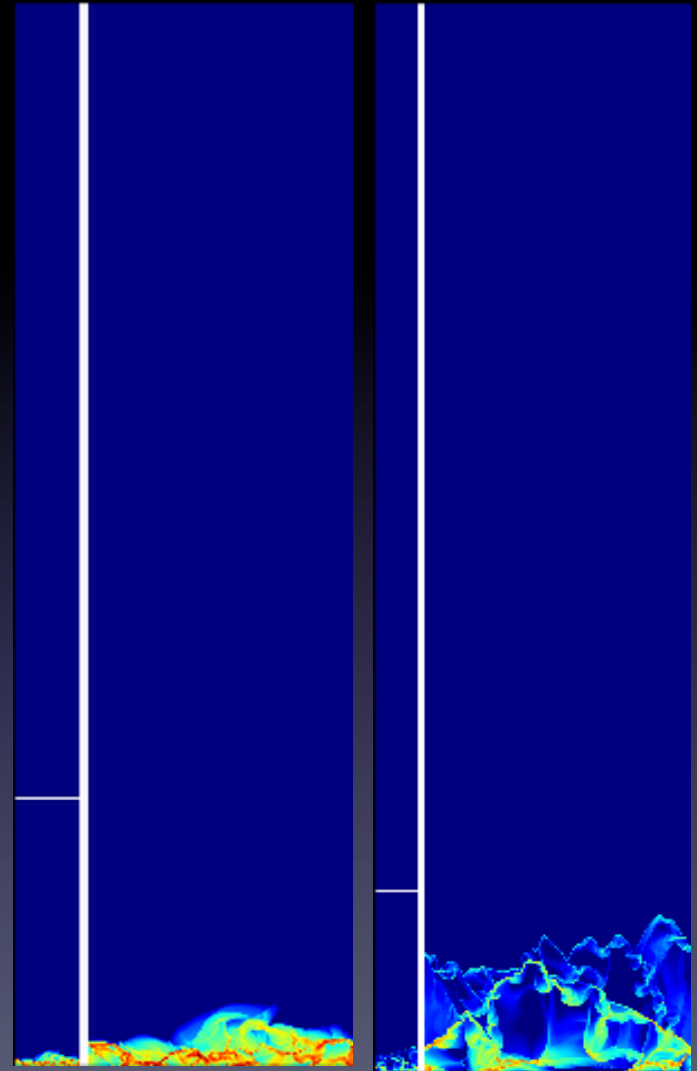
T03F0.50

T10F0.25

T10F0.50

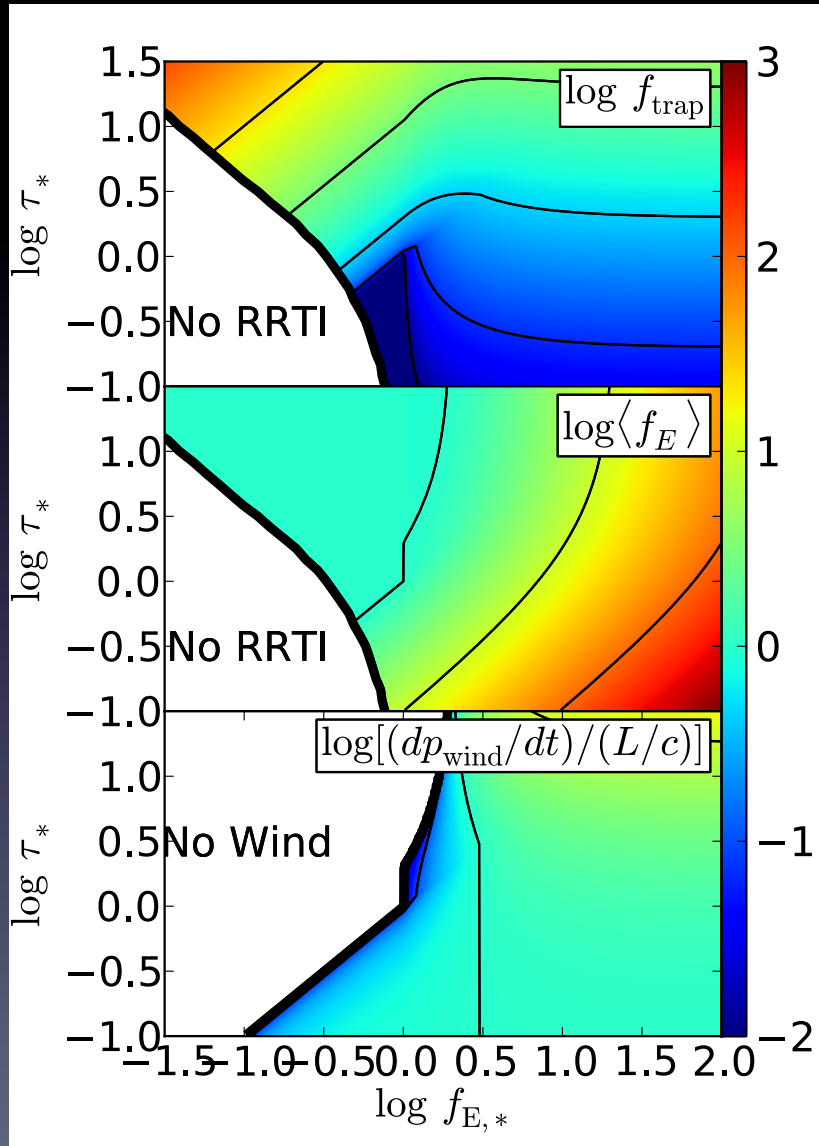


Gravity-confined, radiatively-driven shells (Krumholz & Thompson 2012)



Freely-expanding, radiatively-driven shells (Krumholz & Thompson 2013)

Numerical Results



- If radiation force < gravity at dust photosphere, no wind
- If radiation force > gravity at dust photosphere, wind, but with $f_{\text{trap}} \sim 1$
- Conclusion: RP may affect sub-galactic objects, but cannot produce galactic winds

Krumholz & Thompson (2013)

Stellar Winds

- For a Kroupa IMF, instantaneous (zero-age) and total wind production are (from sb99)

$$\left\langle \frac{L_{\text{wind}}}{M} \right\rangle = 2.0 L_{\odot} M_{\odot}^{-1} = 3.8 \text{ erg g}^{-1}$$

$$\left\langle \frac{E_{\text{wind}}}{M} \right\rangle = 2.3 \times 10^{48} \text{ erg } M_{\odot}^{-1} = 1.3 \times 10^{-6} c^2$$

- Approximate wind momenta:

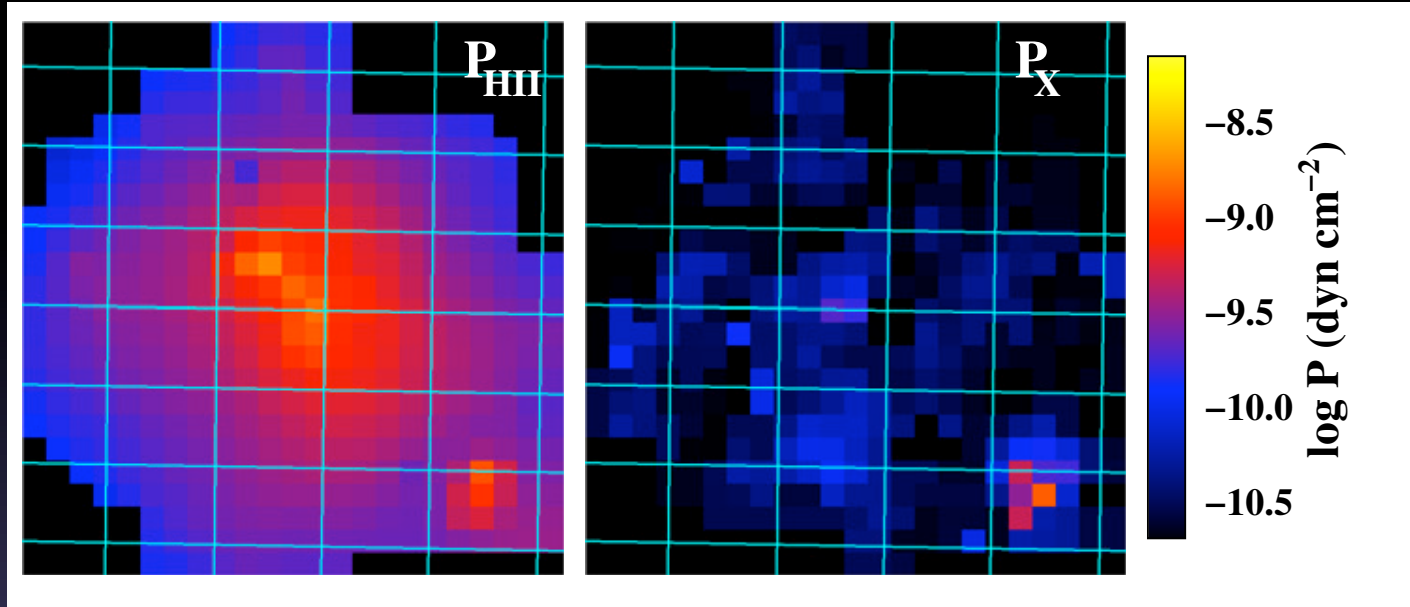
$$\left\langle \frac{\dot{p}_{\text{wind}}}{M} \right\rangle = 7.0 \text{ km s}^{-1} \text{ Myr}^{-1}$$

$$\left\langle \frac{p_{\text{wind}}}{M} \right\rangle = 113 \text{ km s}^{-1}$$

Winds vs. Radiation

- Stellar winds add $\sim(25\%, 50\%)$ to (zero-age, total) radiation momentum output – due to wind-luminosity relation (Kudritzki+ 1999, Repolust+ 2004)
- Implication: winds just add a little to radiation unless $f_{\text{trap,wind}} \gg f_{\text{trap,rad}}$

Observational Diagnosis



P_{HII} vs. P_{wind} in
30 Dor, Lopez
+ (2011)

- Can estimate pressure of shocked stellar wind gas via x-ray observations
- If shocked gas is trapped, $P_X \gg P_{\text{HII}}$ (Castor+ 1975)
- Observed L_X implies wind is *not* trapped: $P_X \ll P_{\text{HII}}$ (Harper-Clark & Murray 2009; Lopez+ 2011; Yeh & Matzner 2012)

Supernovae

- To compute budget, let $q(m,t) = E_0 \delta(t-t_1(m))$,
 $E_0 \approx 10^{51}$ erg, for all stars above mass m_{\min} :

$$\left\langle \frac{E_{\text{SN}}}{M} \right\rangle = E_0 \int_{m_{\min}}^{\infty} \xi d \ln m = E_0 \left\langle \frac{N_{\text{SN}}}{M} \right\rangle$$

- Result:

$$\left\langle \frac{N_{\text{SN}}}{M} \right\rangle = 0.011 M_{\odot}^{-1}$$

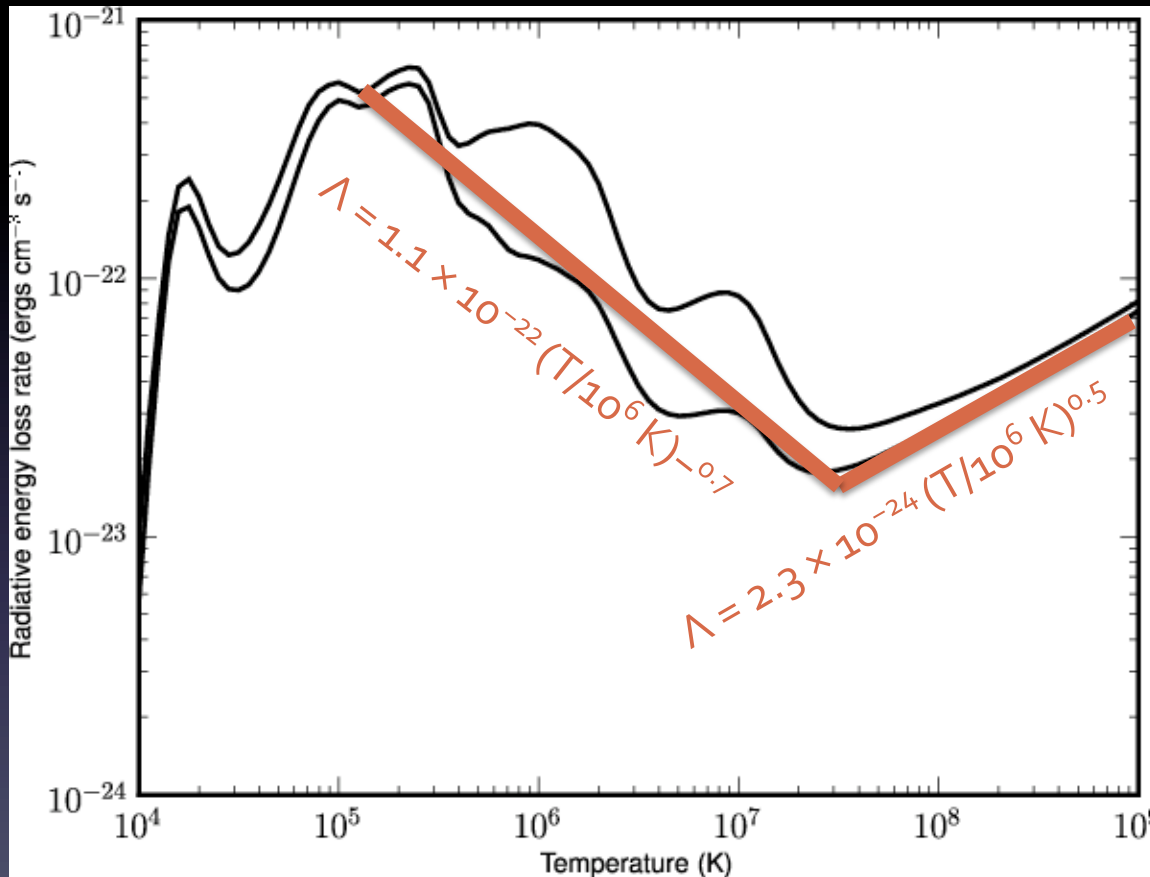
$$\left\langle \frac{E_{\text{SN}}}{M} \right\rangle = 1.1 \times 10^{49} \text{ erg } M_{\odot}^{-1} = 6.1 \times 10^{-6} c^2$$

$$\left\langle \frac{p_{\text{SN}}}{M} \right\rangle = \frac{2}{v_{\text{ej}}} \left\langle \frac{E_{\text{SN}}}{M} \right\rangle = 55 \left(\frac{10^4 \text{ km s}^{-1}}{v_{\text{ej}}} \right) \text{ km s}^{-1}$$

Supernovae vs. Winds, Radiation

- Compared to radiation, SN have $\sim 100 \times$ less energy, $\sim 6 \times$ less momentum
- Compared to winds, SN have $\sim 5 \times$ more energy, $\sim 2 \times$ less momentum
- So why are SN potentially so important?
- Answer: because while radiation, winds are close to momentum-conserving, SNe are much closer to energy-conserving!

Why Are SNe Energy-Conserving?



Radiative cooling rate for solar metallicity gas (lower curve) in collisional ionization equilibrium (Dere+ 2009)

- Post-shock temp. for SN ejecta moving at 10⁴ km s⁻¹ is ~10¹⁰ K
- Cooling time $t_{\text{cool}} \sim nkT / \Lambda n^2 \sim 60 \text{ Myr } (n/\text{cm}^{-3})^{-1}$
- Time to escape galaxy t_{esc} at 10⁴ km s⁻¹ is $\ll 1 \text{ Myr}$
- $t_{\text{cool}} \gg t_{\text{esc}}$ initial expansion is adiabatic

Sedov-Taylor Expansion

- During energy-conserving phase, SN blast follows Sedov-Taylor (ST) similarity solution

$$R_s(t) = 1.2 \left(\frac{E_0}{\rho_0} t^2 \right)^{1/5} \quad T_s(t) = \frac{\mu R_s(t)^2}{k_B t^2}$$

$$x = \frac{r}{R_s} \quad \rho(r) = \rho_0 f(x) \quad T = T_s j(x)$$

- Radiation rate is $\frac{dE}{dt} = \int_0^{R_s} 4\pi r^2 \Lambda n^2 dr$
- Energy conserving-phase ends when at time

t_{rad} defined by

(NB: see Thornton et al. 1998 for much more accurate calculation)

$$\int_0^{t_{\text{rad}}} \frac{dE}{dt} dt' \sim E_0$$

Momentum Budget

- Initial momentum $p_i = 2E_o / v_{ej} \approx 10^4 M_\odot \text{ km s}^{-1}$
- At t_{rad} , $p_{\text{rad}} = (4\pi/3)\rho_0 R_s^3 \dot{R}_s|_{t_{\text{rad}}}$
- Numerical evaluation:

$$t_{\text{rad}} = 49 E_{51}^{0.22} n_0^{-0.55} \text{ kyr}$$

$$R_s(t_{\text{rad}}) = 24 E_{51}^{0.29} n_0^{-0.42} \text{ pc}$$

$$\dot{R}_s(t_{\text{rad}}) = 190 E_{51}^{0.07} n_0^{-0.13} \text{ km s}^{-1}$$

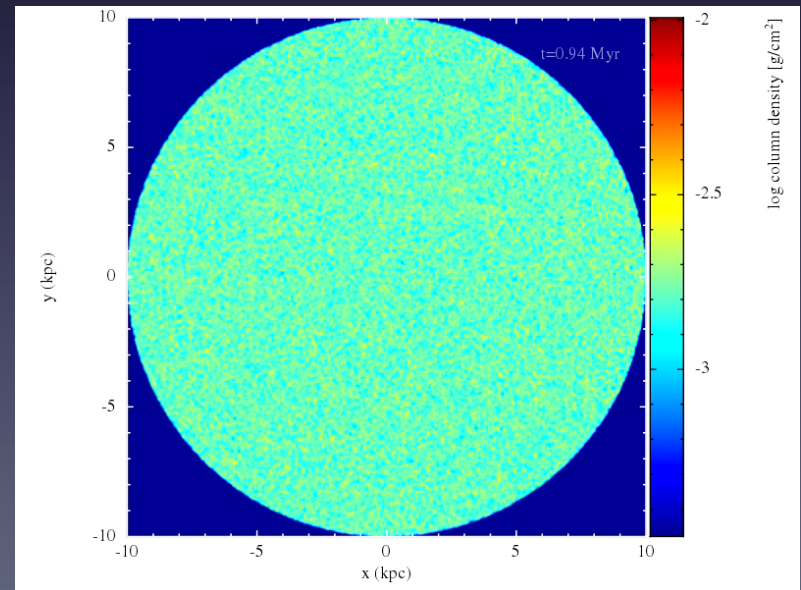
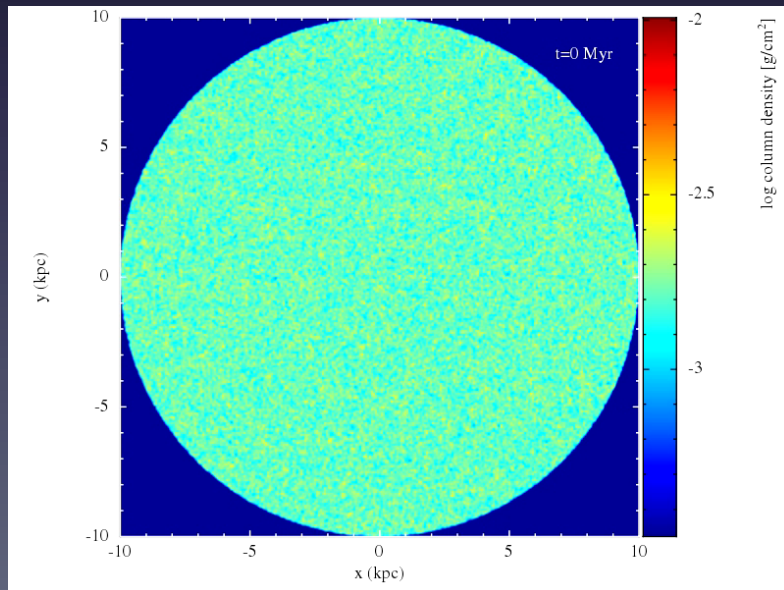
$$p_{\text{rad}} = 3.6 \times 10^5 E_{51}^{0.94} n_0^{-0.39} M_\odot \text{ km s}^{-1}$$

$$1 + f_{\text{trap}} = \frac{p_{\text{rad}}}{p_i} = 36 E_{51}^{-0.06} n_0^{-0.39}$$

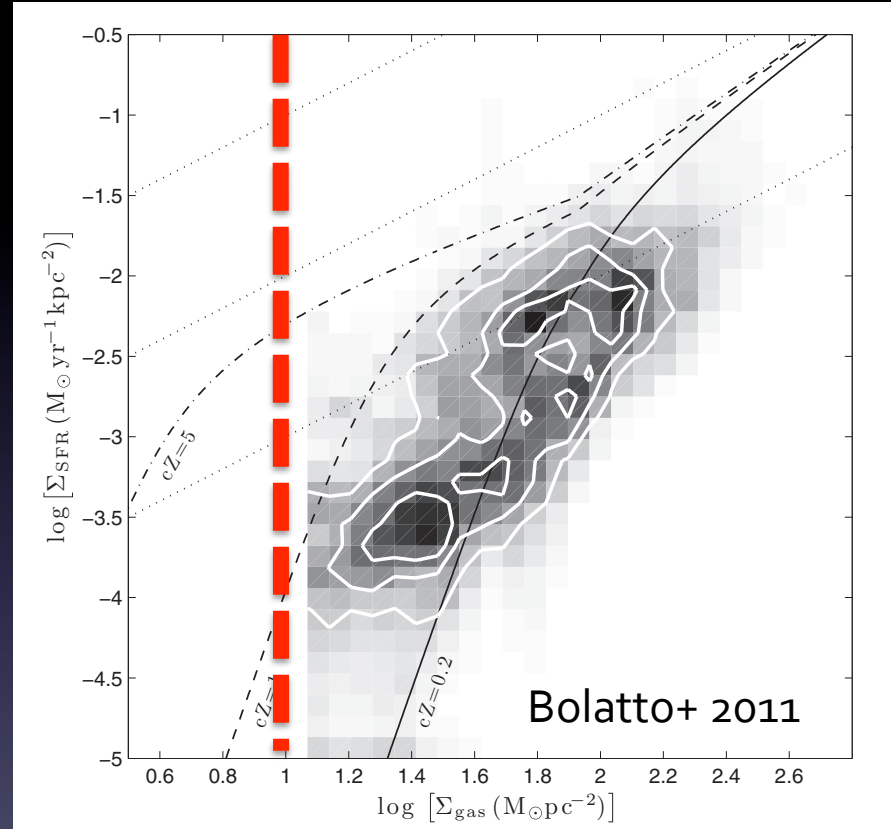
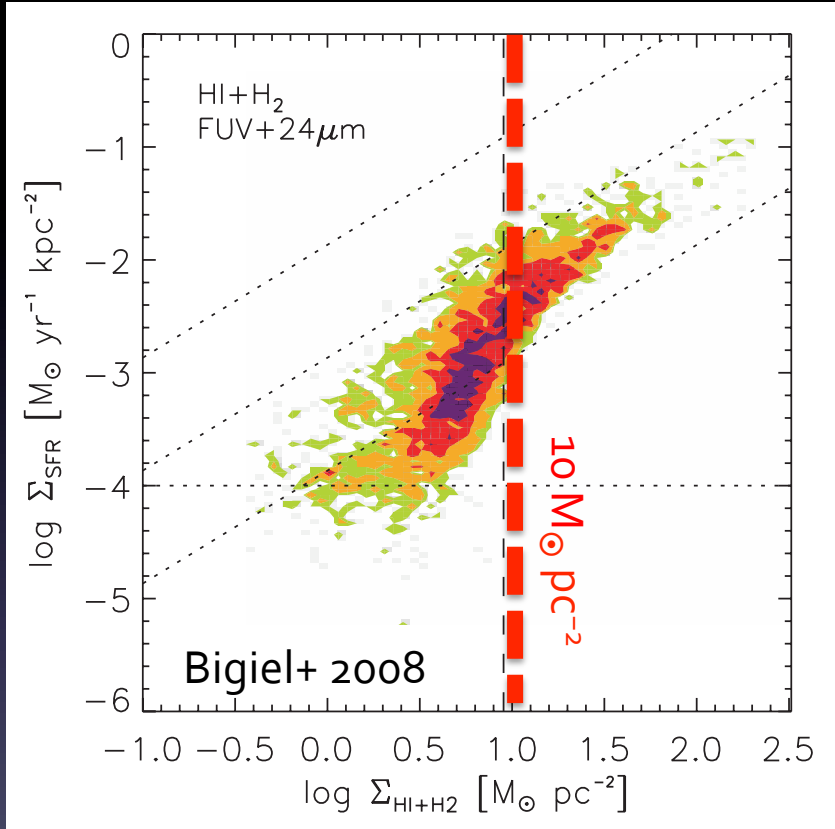
Implications

- SN can dominate momentum budget *if* n_0 is small enough \rightarrow other feedbacks critical
- Hard to simulate: must include FB that lowers n_0 before SN, and resolve ST phase

Below: two simulations w/strong, weak SNe (Dobbs+ 2011)

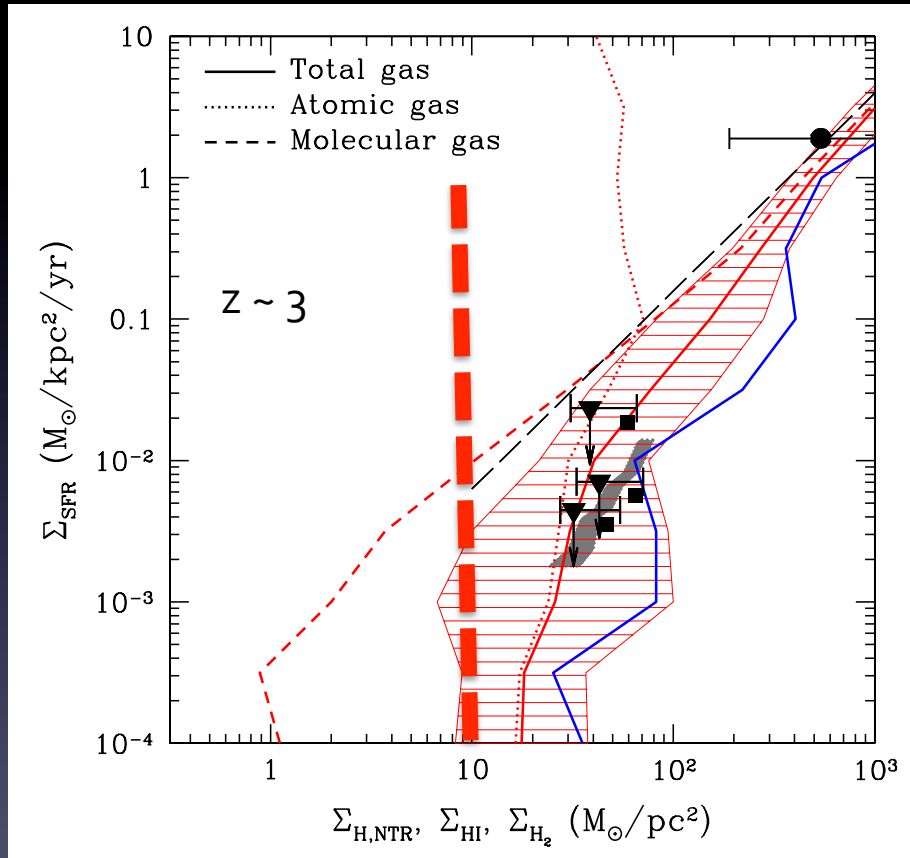


“Metallicity Feedback”

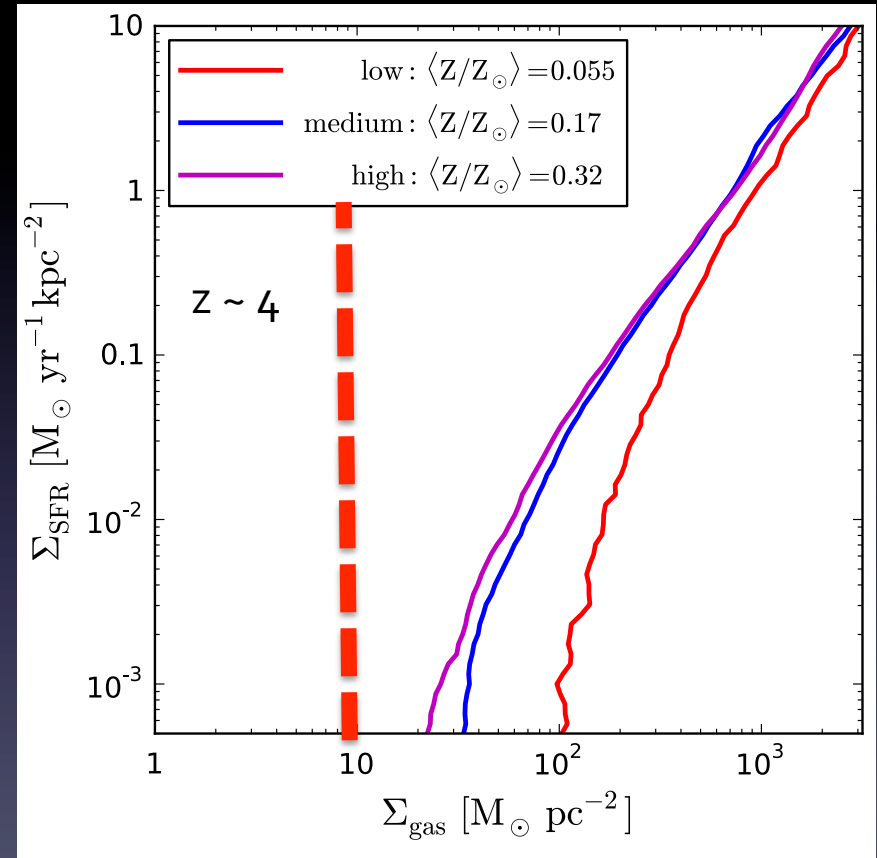


- Metallicity changes SF law, and stars produce metals
- Effect non-negligible in dwarfs and in early universe, because $t_{\text{SF}} > t_{\text{H}}$

SF Laws in High-z Galaxies

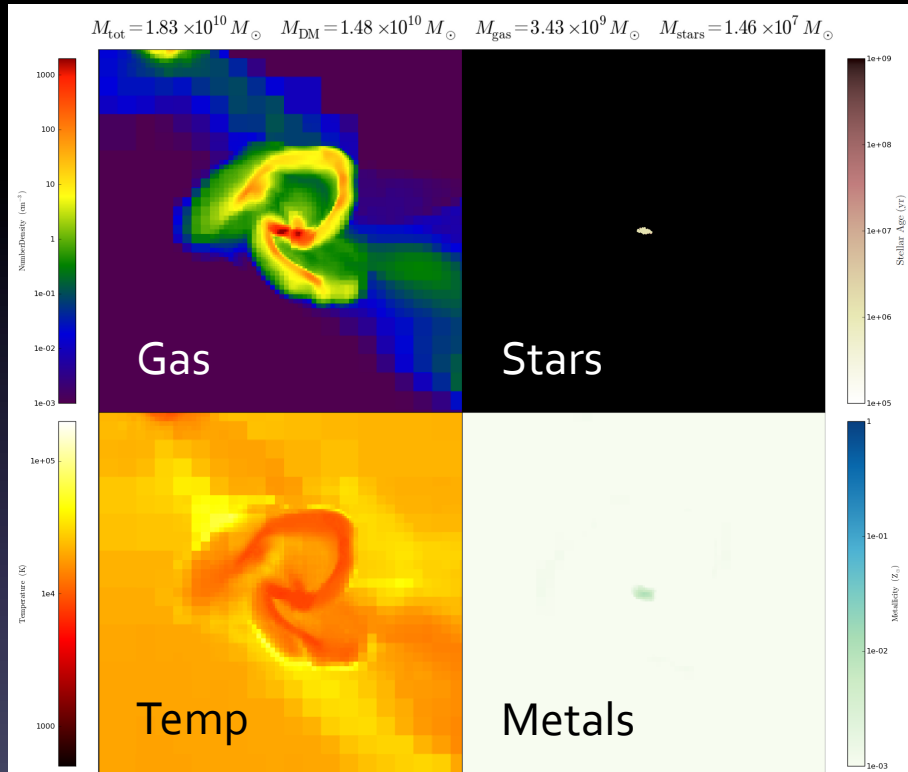


Gnedin & Kravtsov 2010

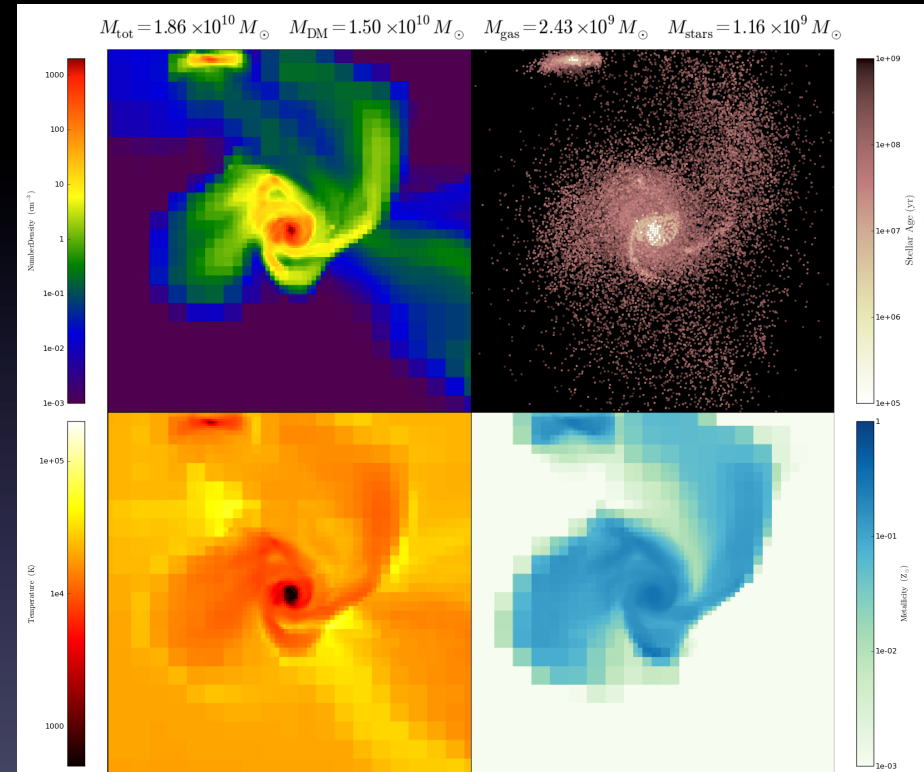


Kuhlen+ 2012

Metallicity-Regulated SF



Metallicity-dependent SF

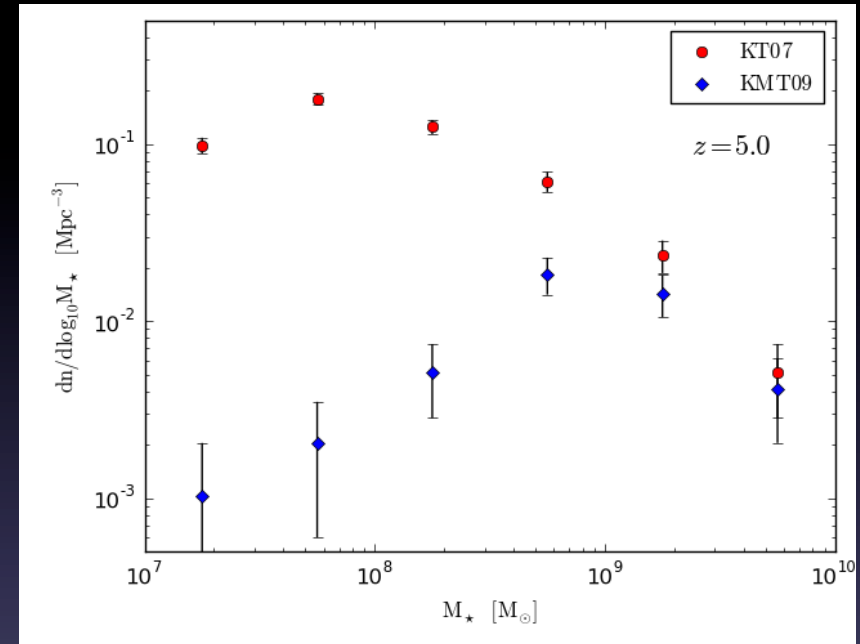
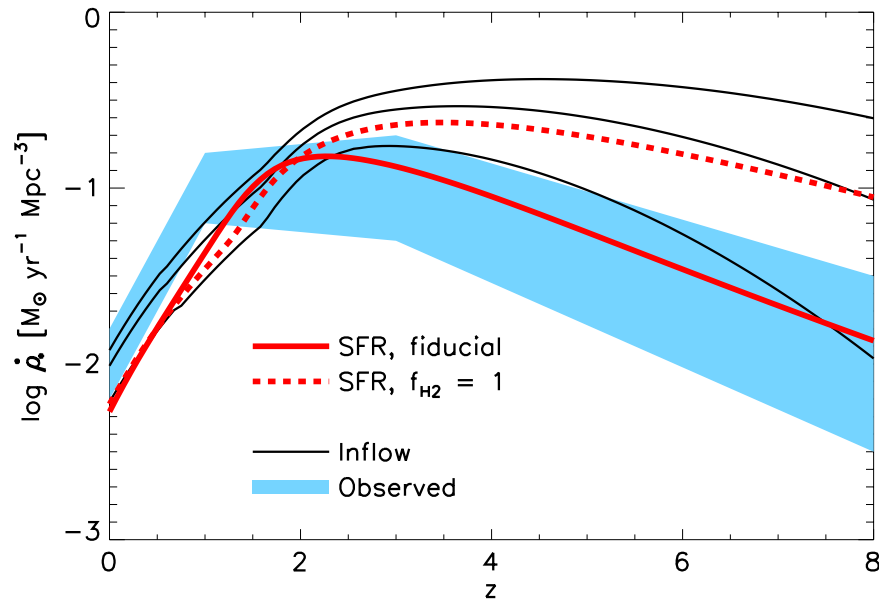


Metallicity-independent SF

Same halo ($\sim 10^{10} M_{\odot}$, $z \sim 5$) in two simulations with different SF recipes (Kuhlen+ 2012)

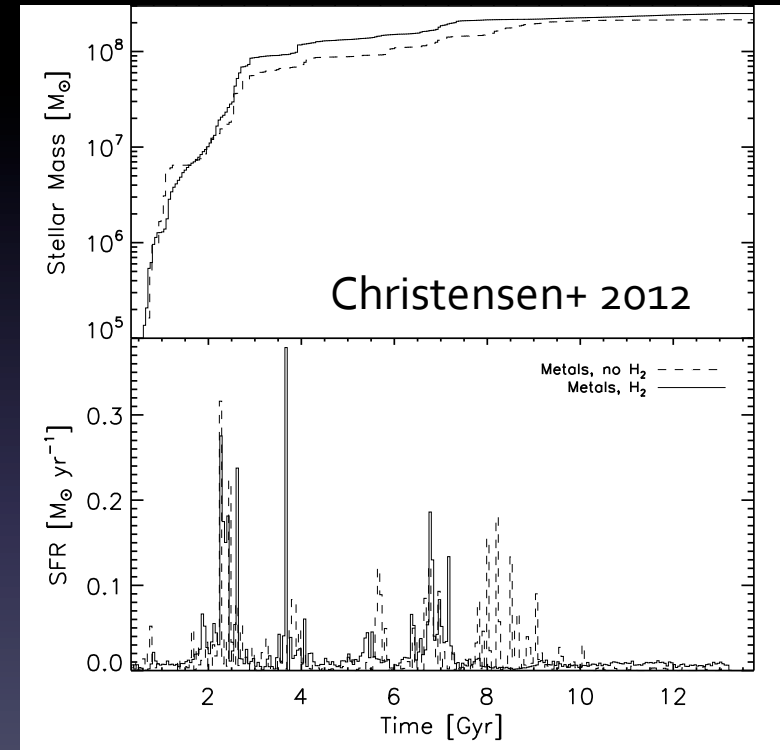
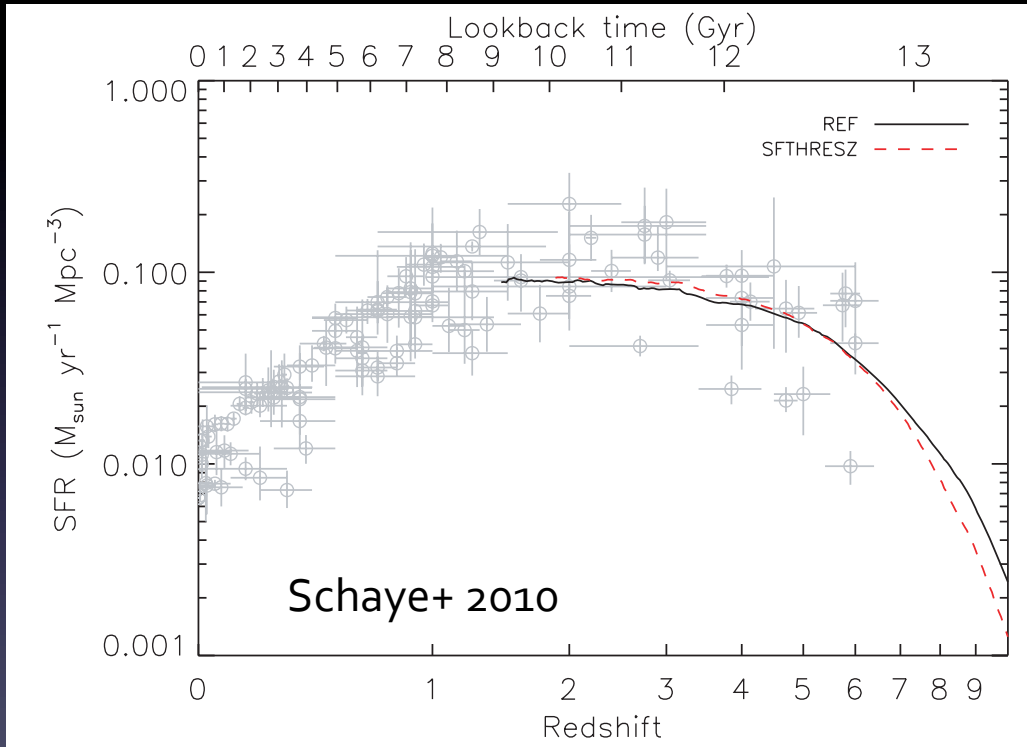
Mass Function and SF at High z

Krumholz & Dekel 2012



Kuhlen+ 2012

Not Quite So Simple



Why different than Kuhlen+, Krumholz & Dekel?
Probably feedback.

Implications

- Metallicity-dependent star formation makes no difference in MW-sized galaxies, but makes a large difference at SMC scales
- Metal ejection, IGM mixing, re-accretion make a big difference; this needs numerical work