What regulates the growth of *low mass* galaxies?

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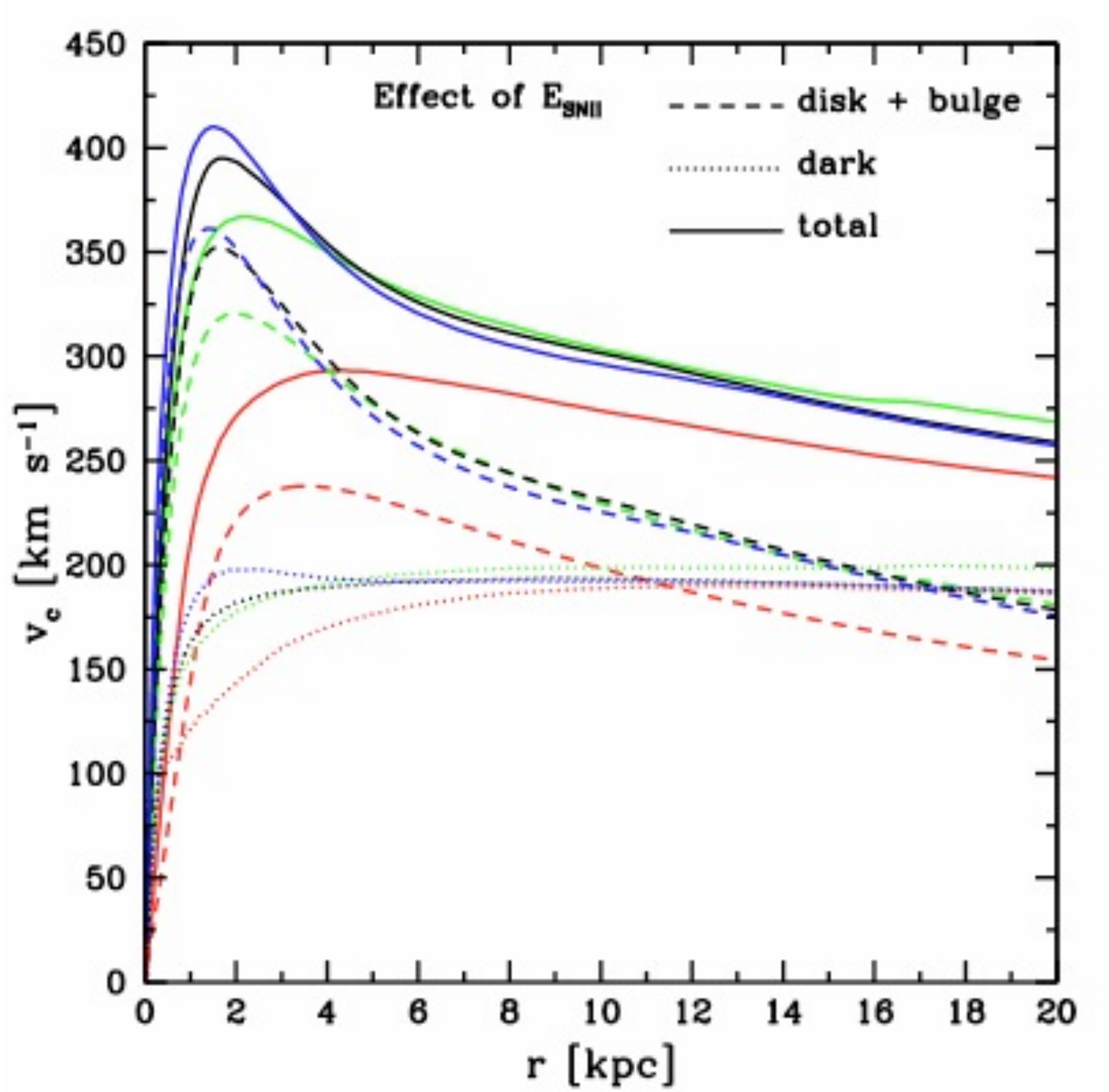
Trujillo-Gomez et al. (in prep.) & *Ceverino et al. (2013, submitted)*

Santa Cruz Galaxy Workshop - UCSC - August 16, 2013

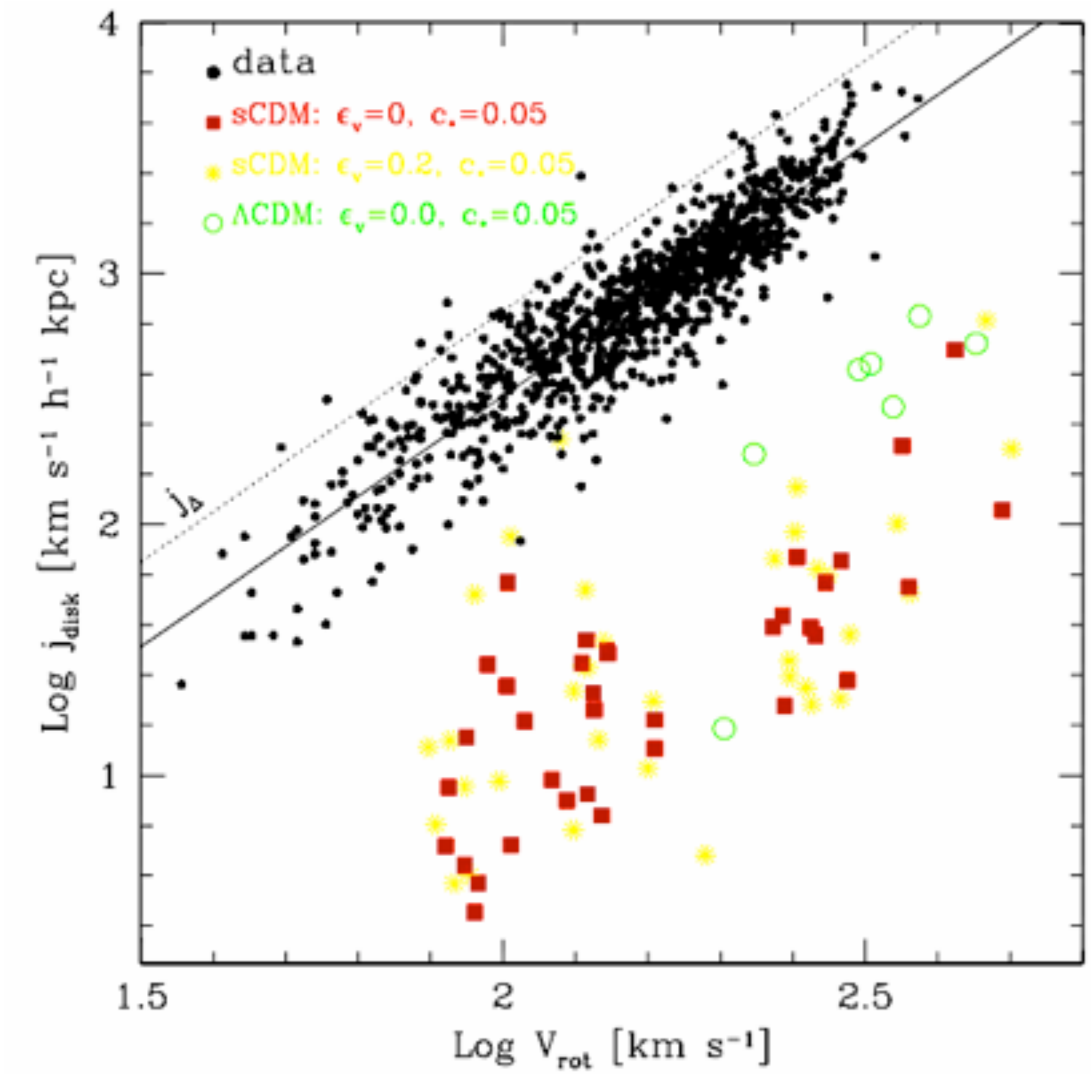
Motivation

- overcooling problem:
  galaxies experience runaway collapse of all their gas to high densities -> conversion of most baryons to stars



Agertz+2010

- angular momentum catastrophe:
  simulated disks lose too much angular momentum, become too concentrated



Navarro+2000

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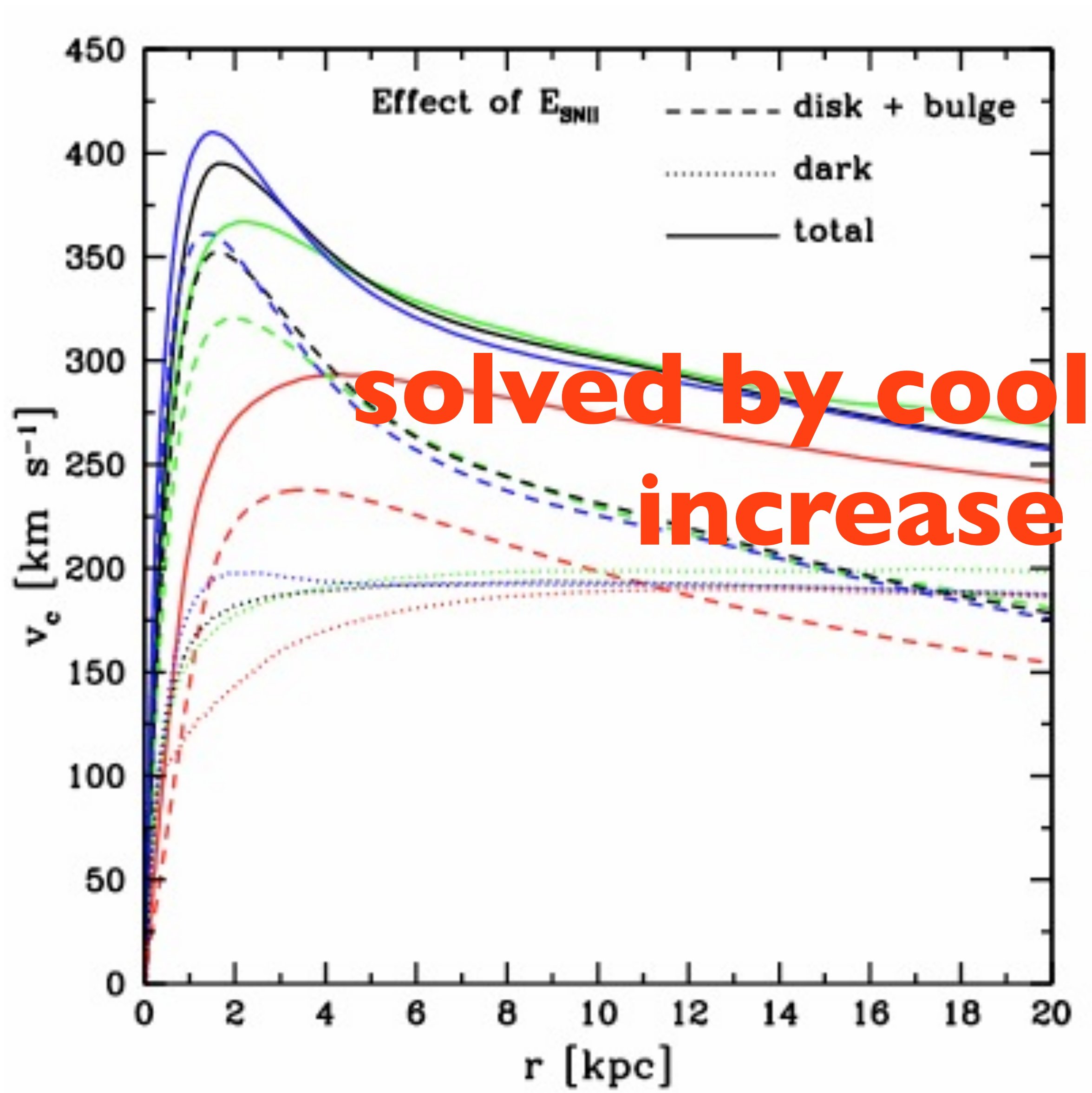
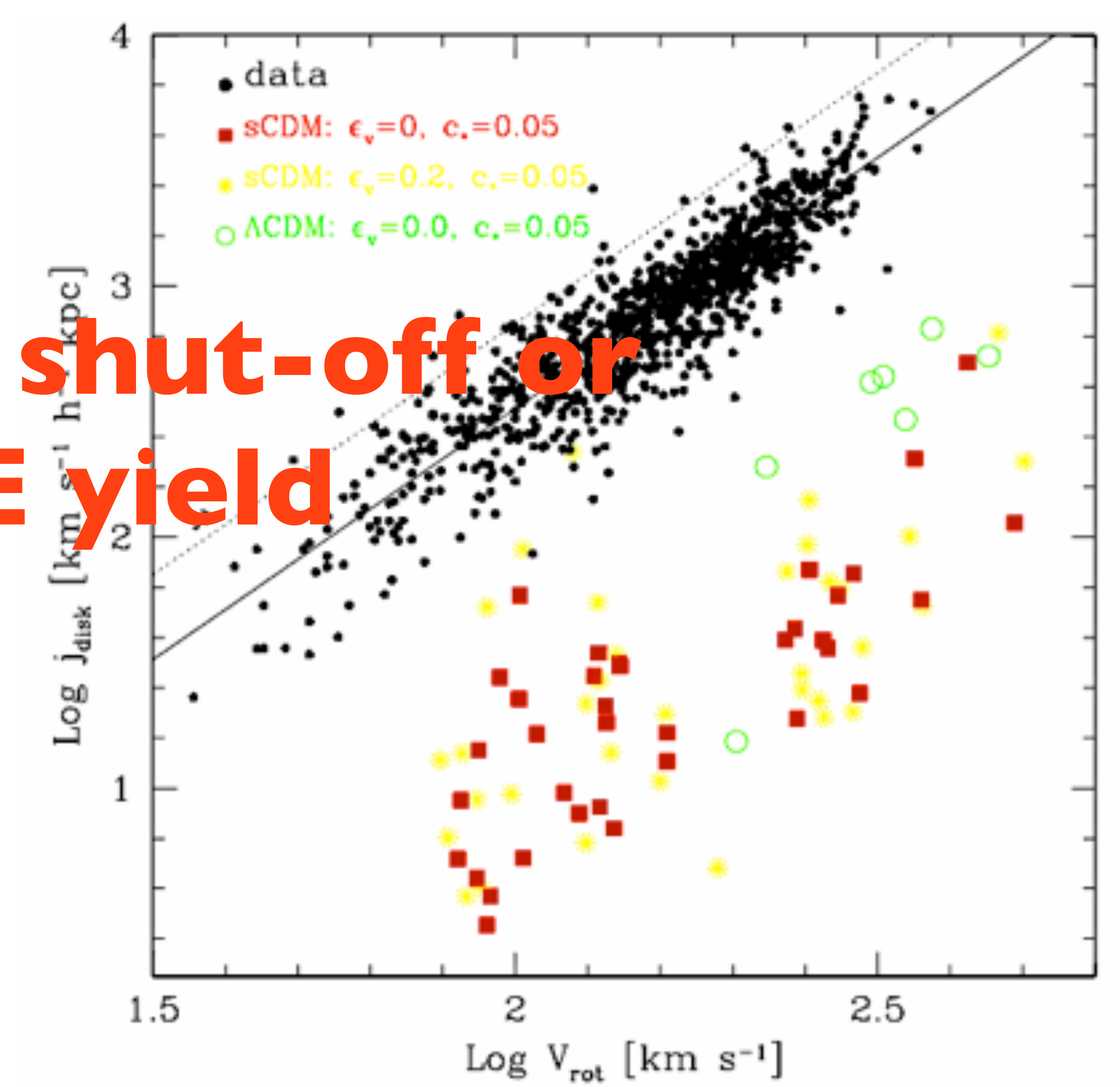


Agertz+2010

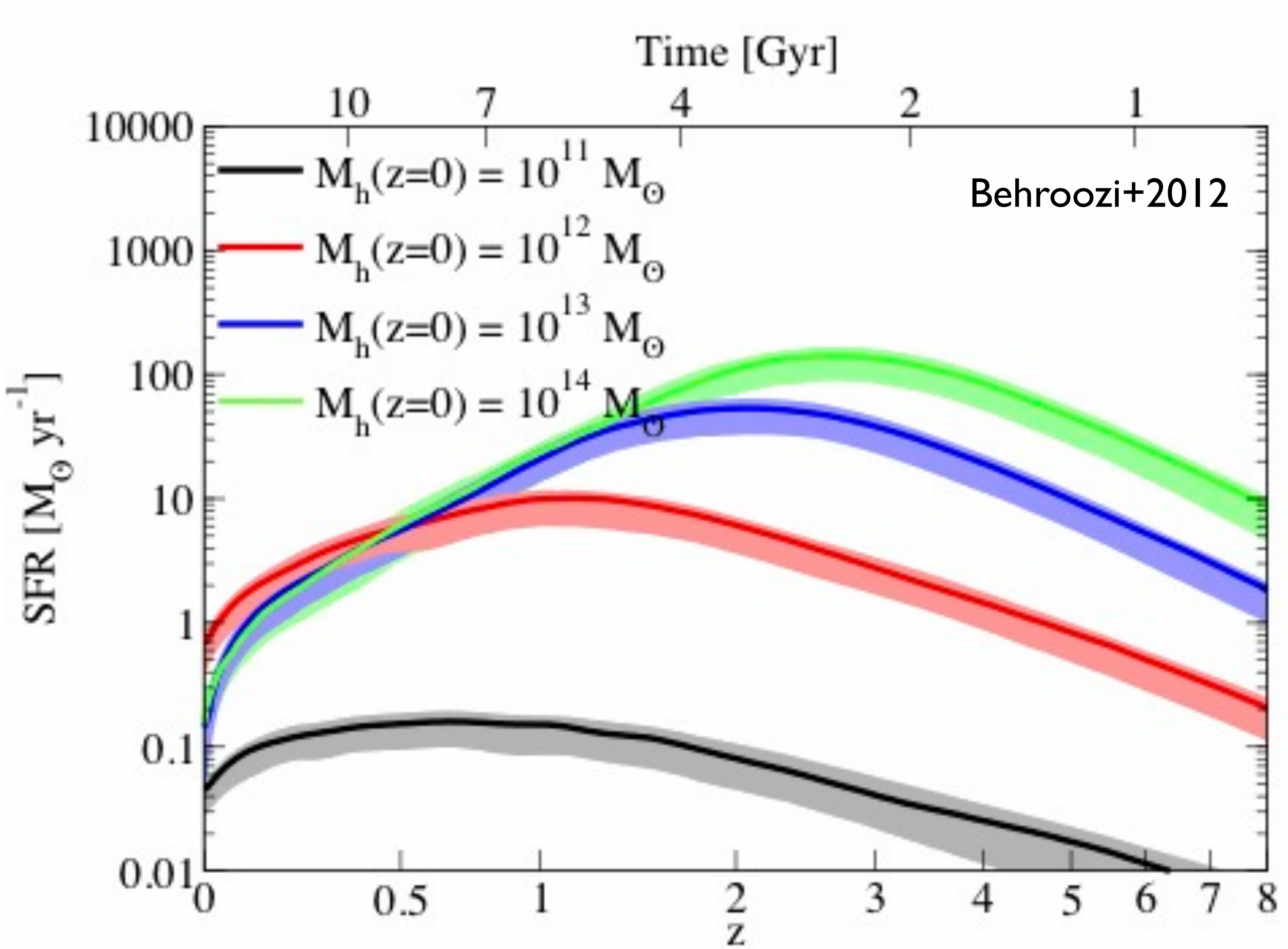


Navarro+2000

solved by cooling shut-off or increase in E yield

Motivation

observations + ΛCDM prior



why do we care to get SFH correct at high z?

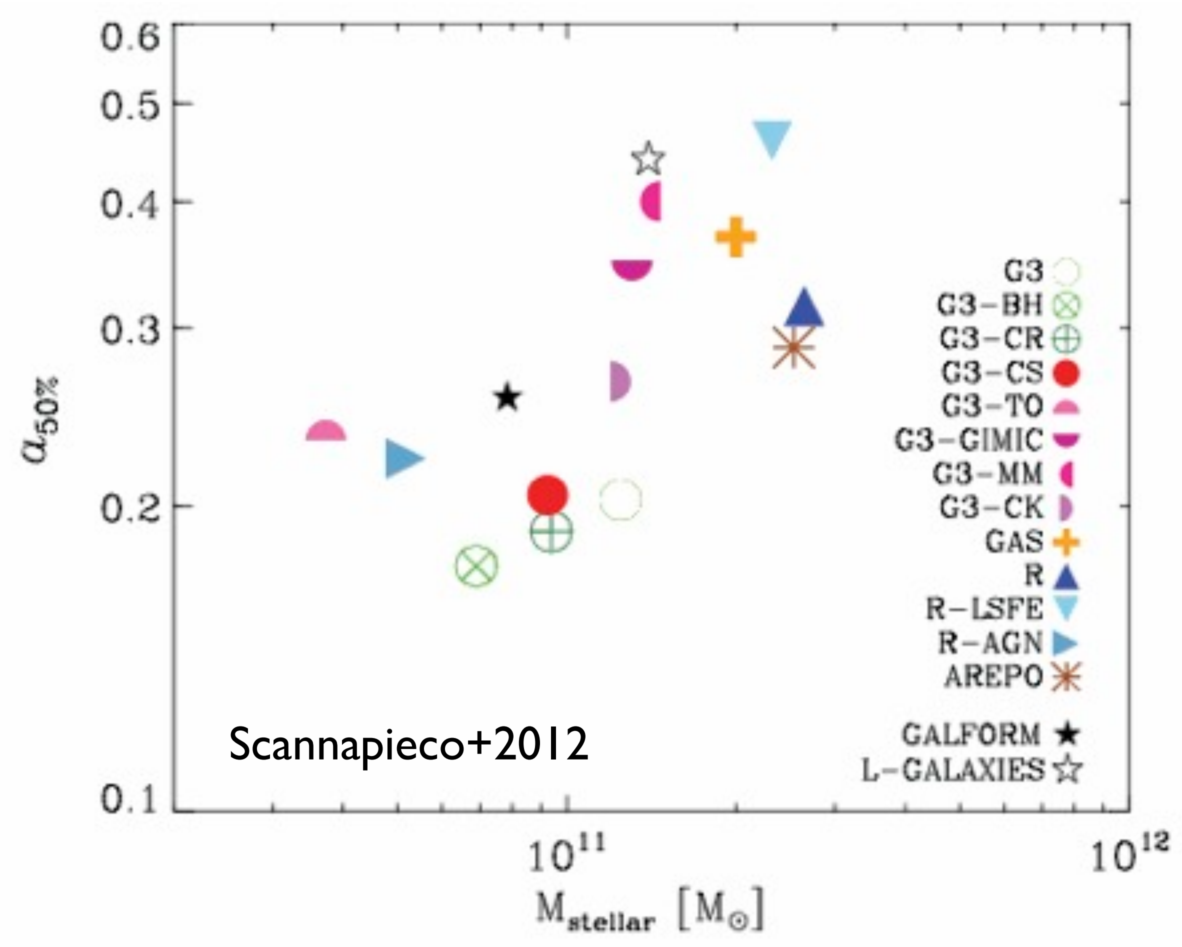
➡ **enrichment of stellar populations**

➡ **amount of baryons in CGM/IGM sensitive to stellar energy budget**

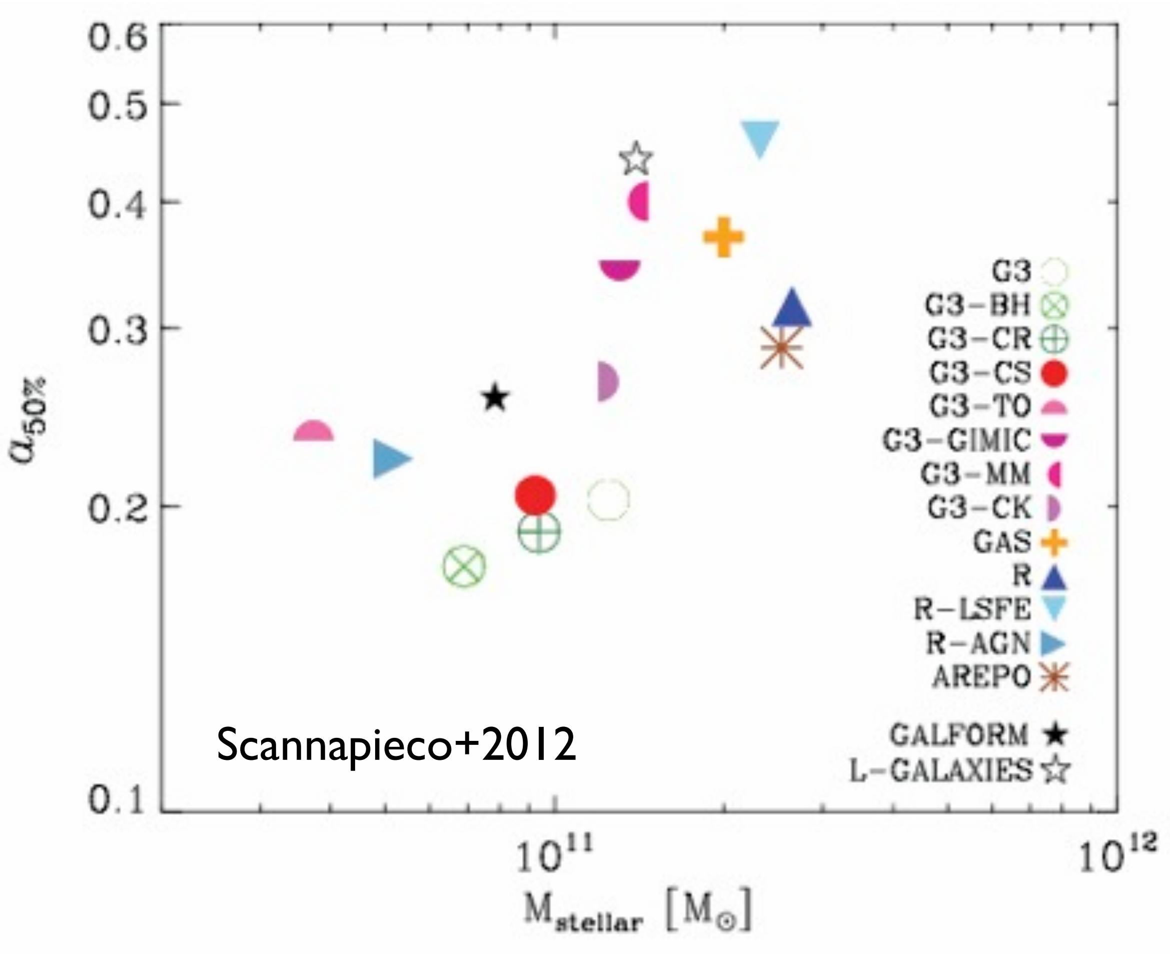
➡ **metals enrichment/ ionization conditions in CGM (see C. Churchill's talk)**

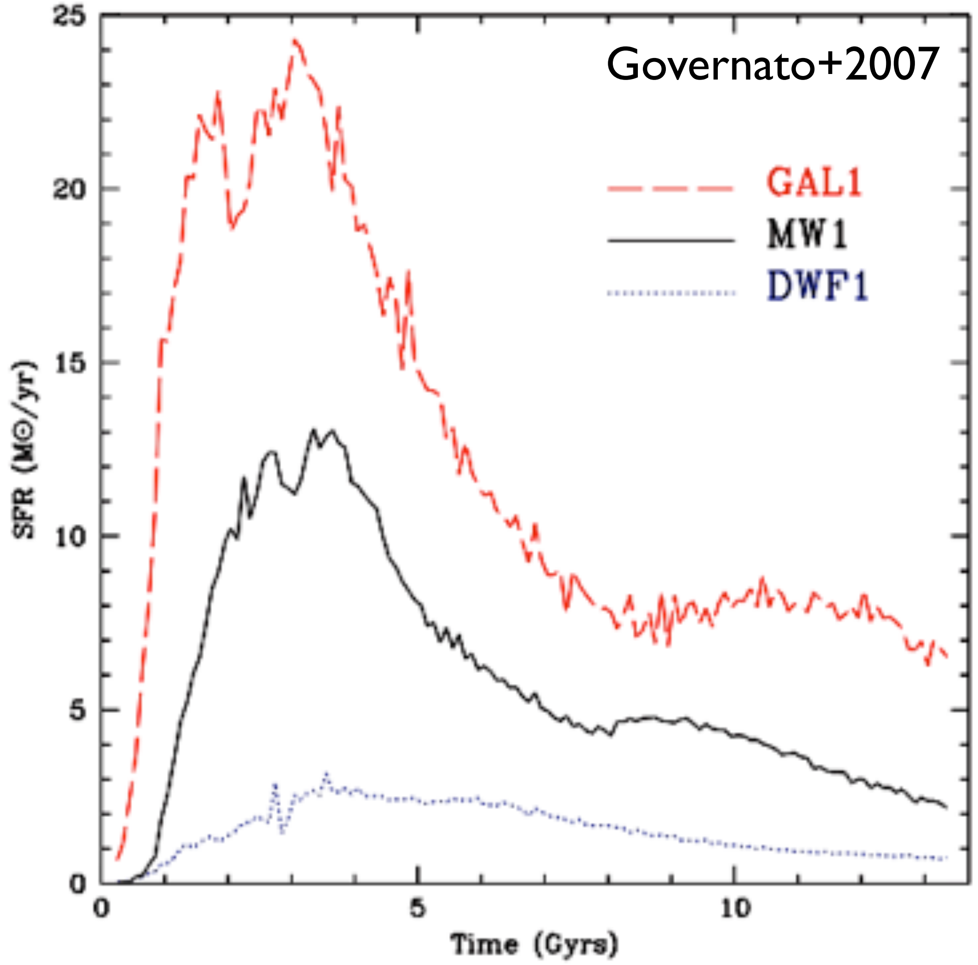
➡ **structural components of galaxies have different ages**

simulations & semi-analytics



simulations & semi-analytics





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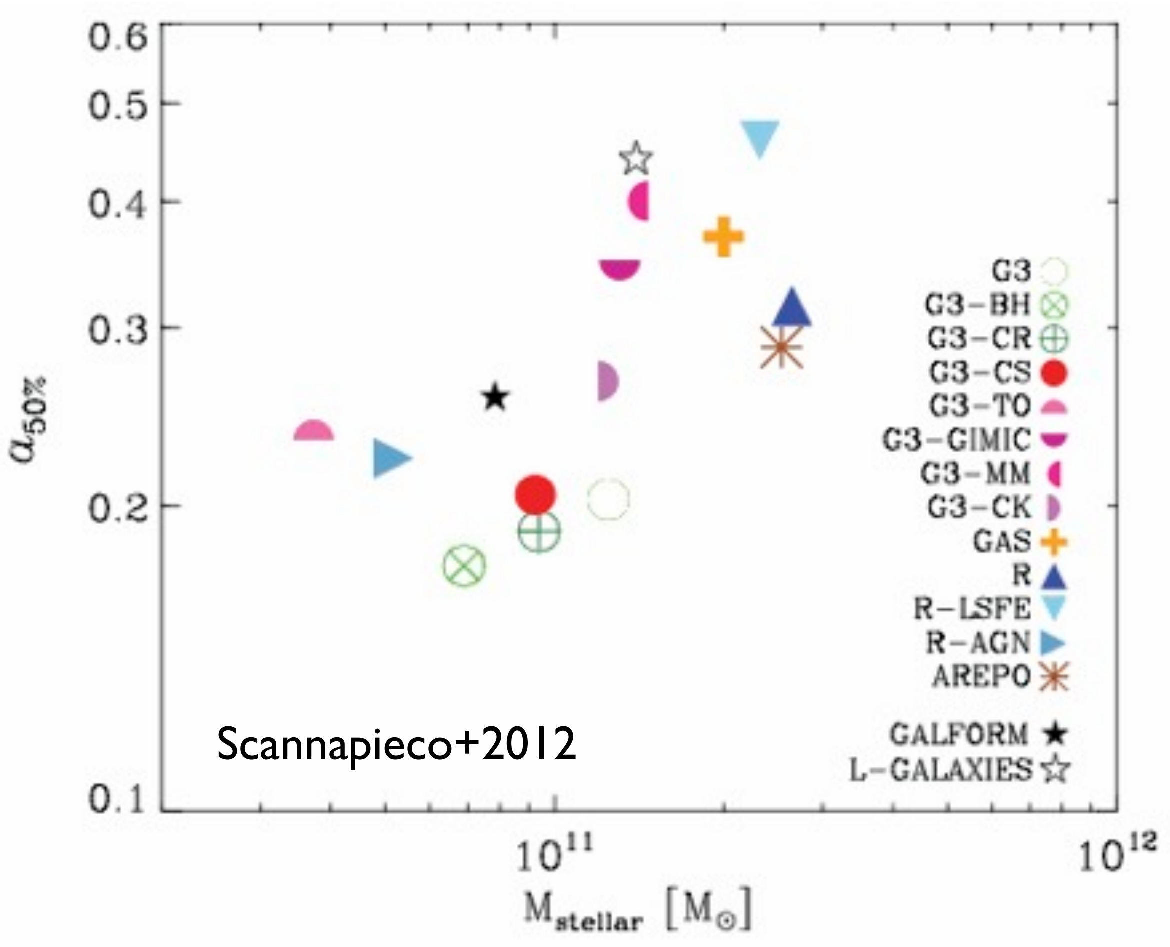
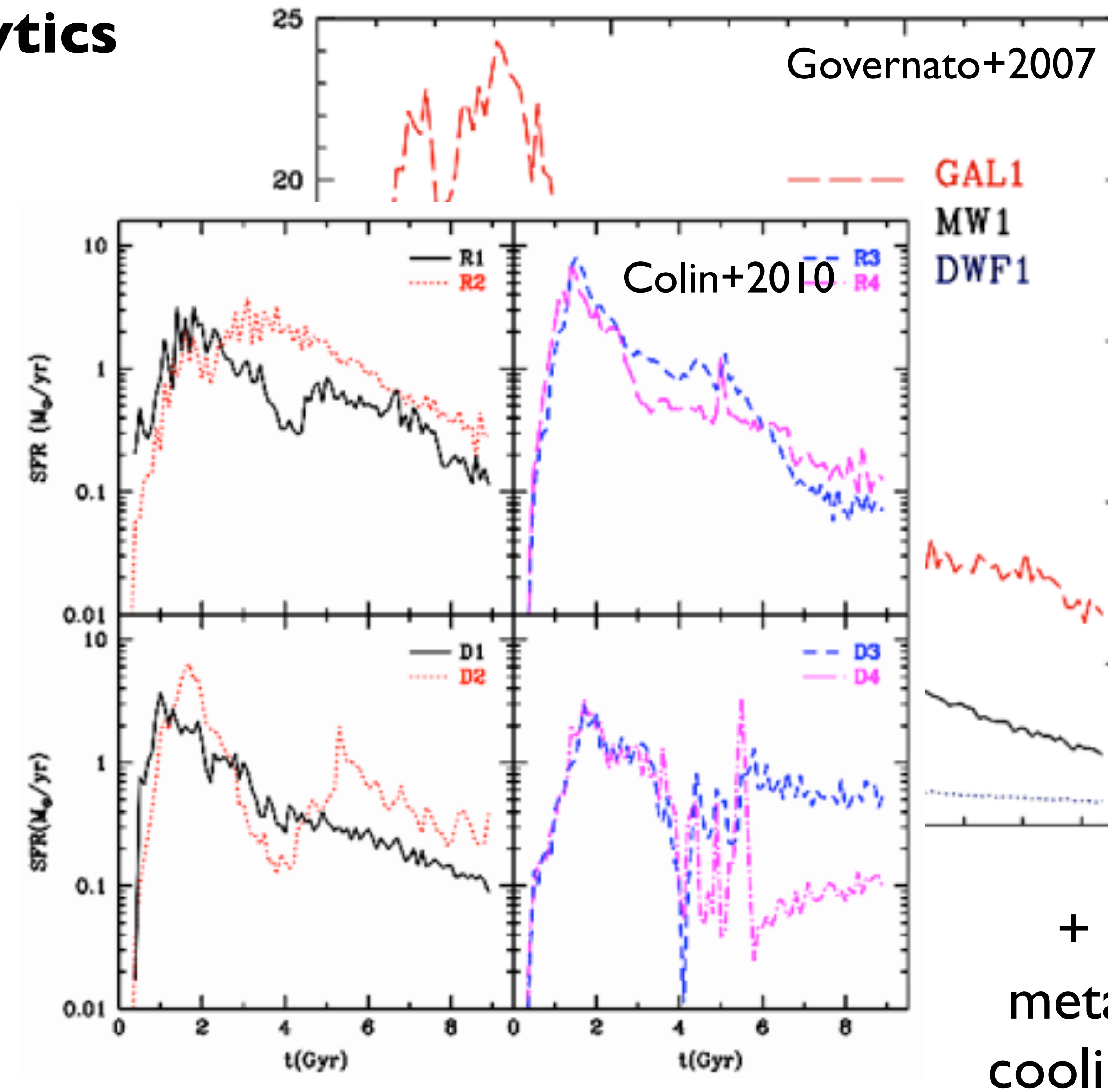
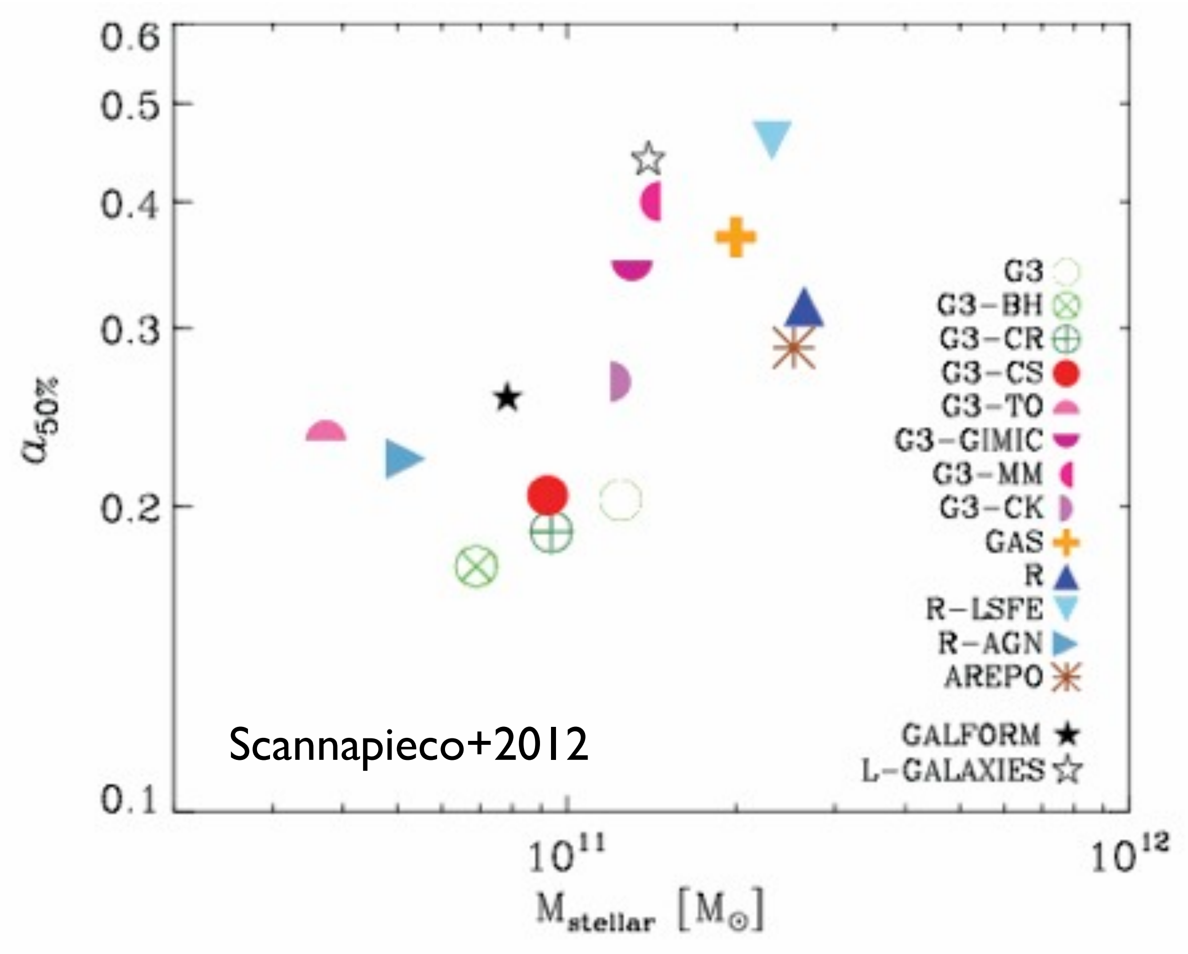
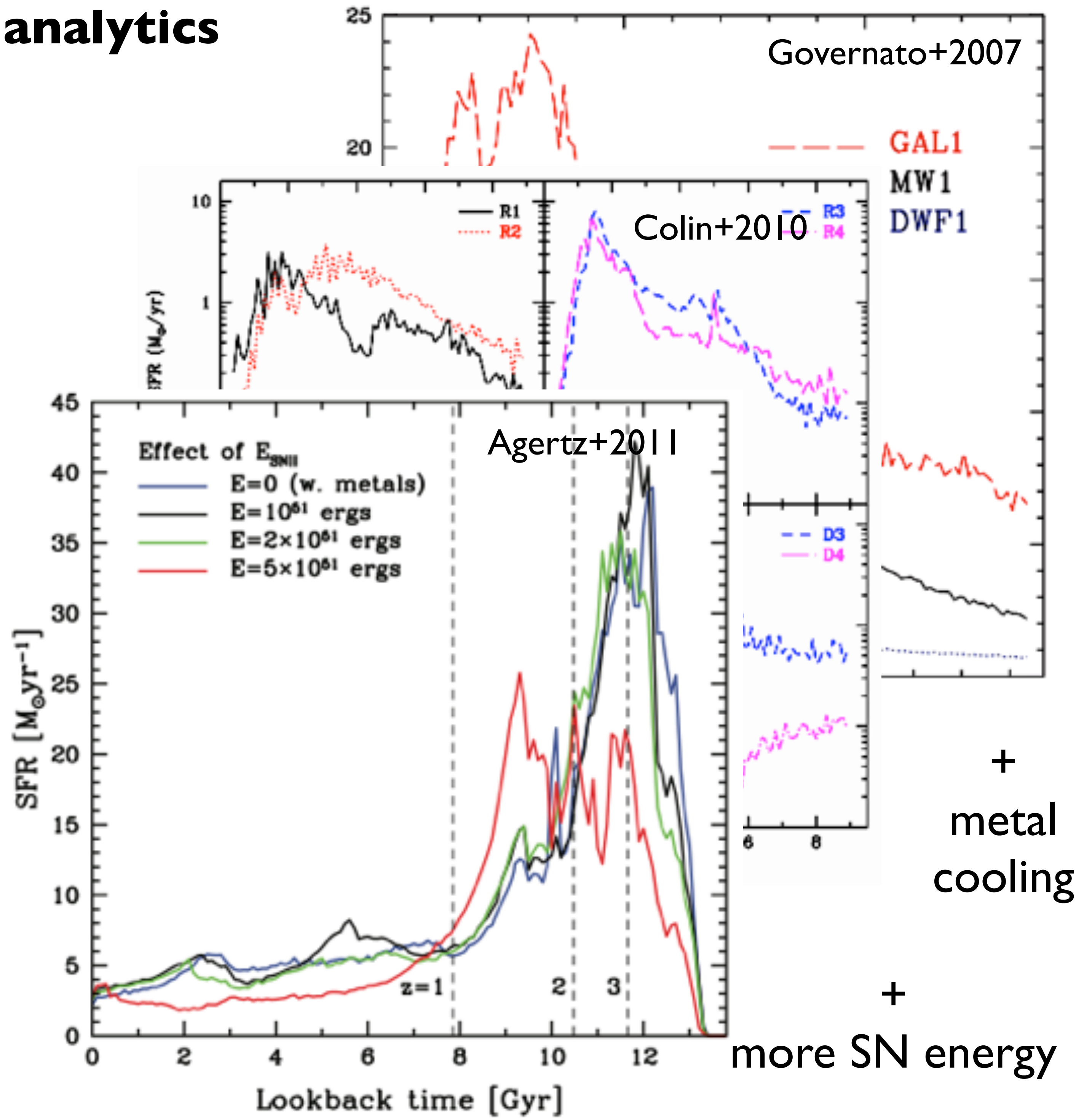




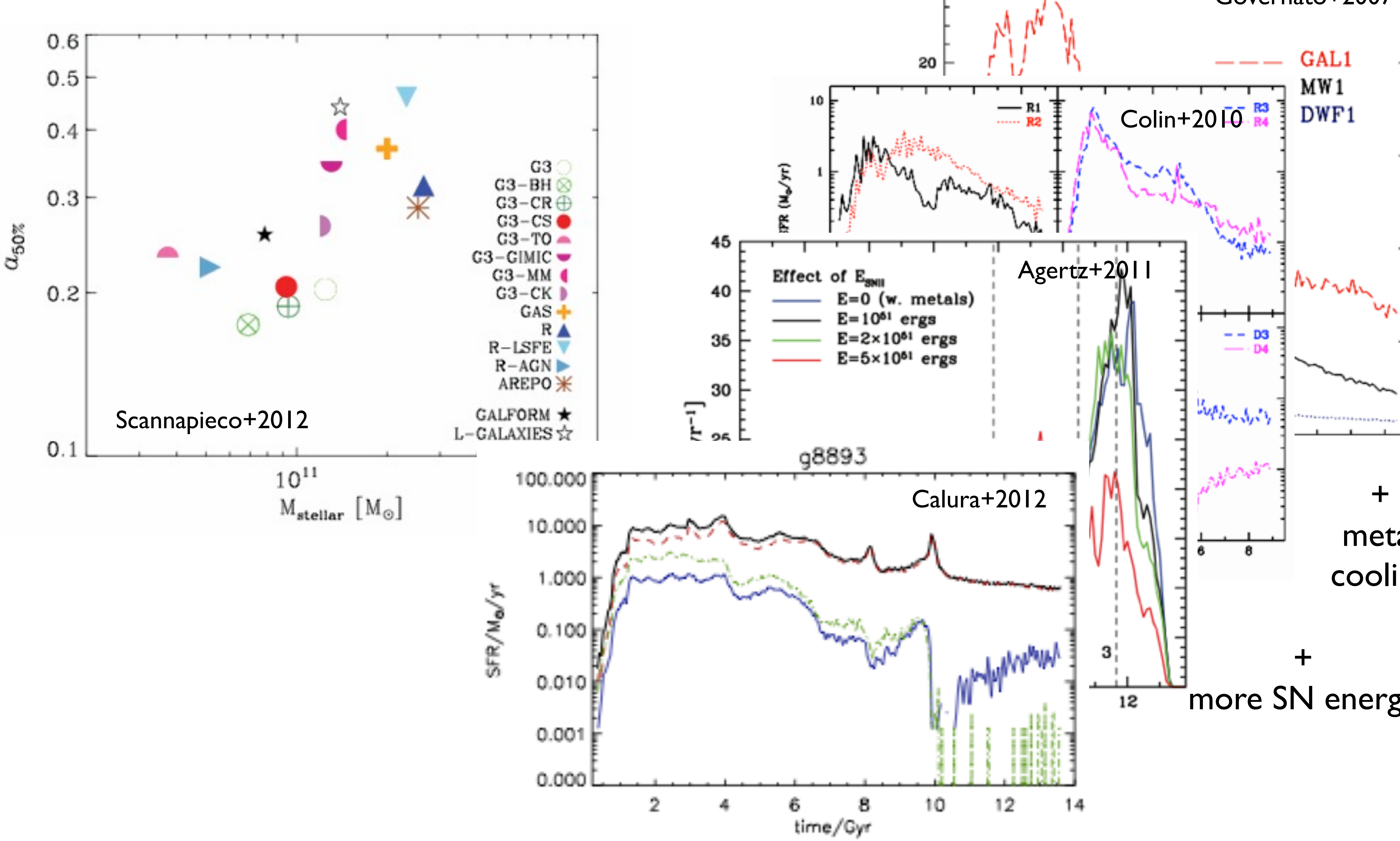
+
metal
cooling

simulations & semi-analytics





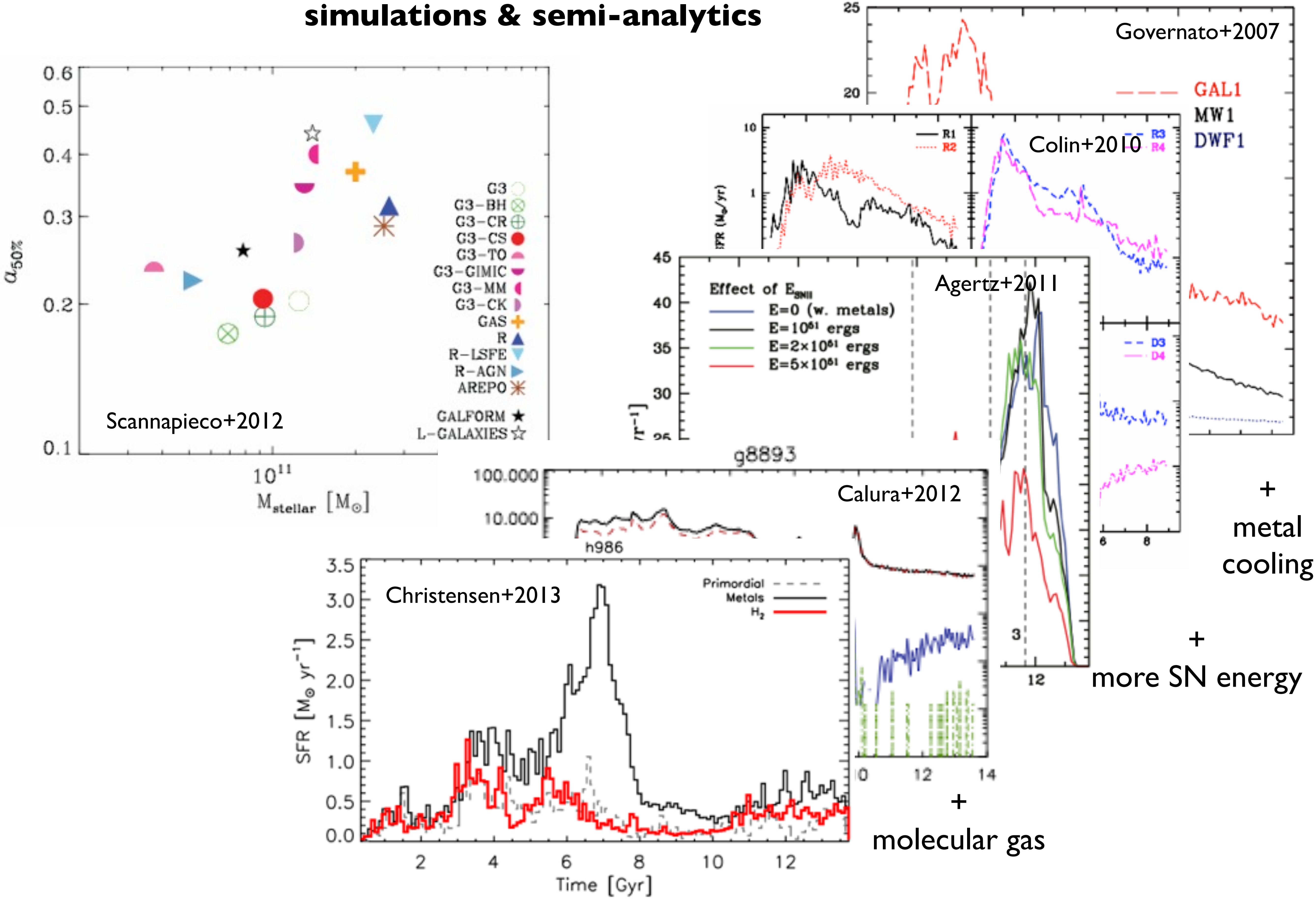
simulations & semi-analytics



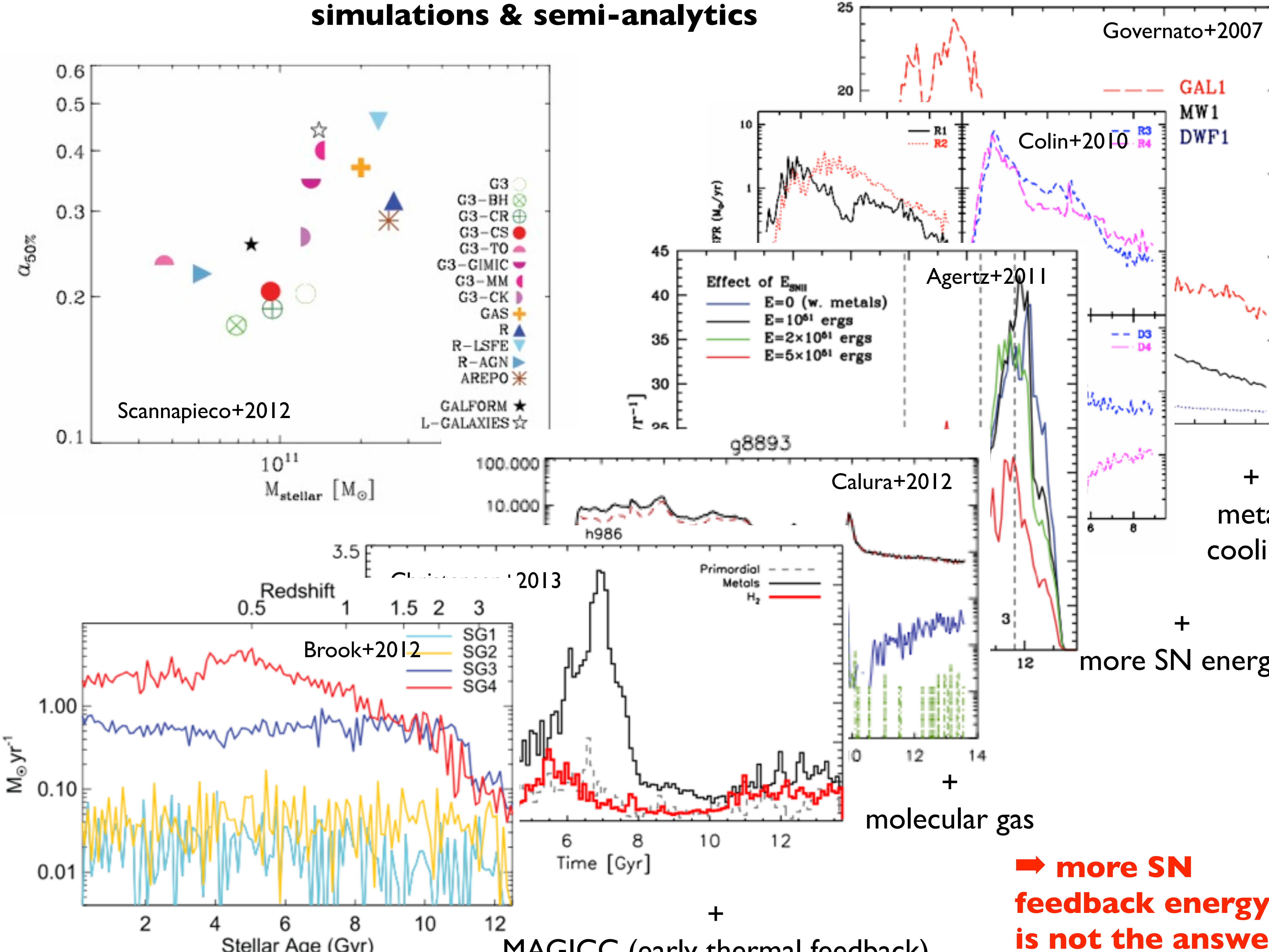
+ metal cooling

+ more SN energy

simulations & semi-analytics



simulations & semi-analytics



+ metal cooling

+ more SN energy

+ molecular gas

+ MAGICC (early thermal feedback)

➡ more SN feedback energy is not the answer

Radiation pressure alone may not be enough to launch massive galactic outflows (Mark's talk)

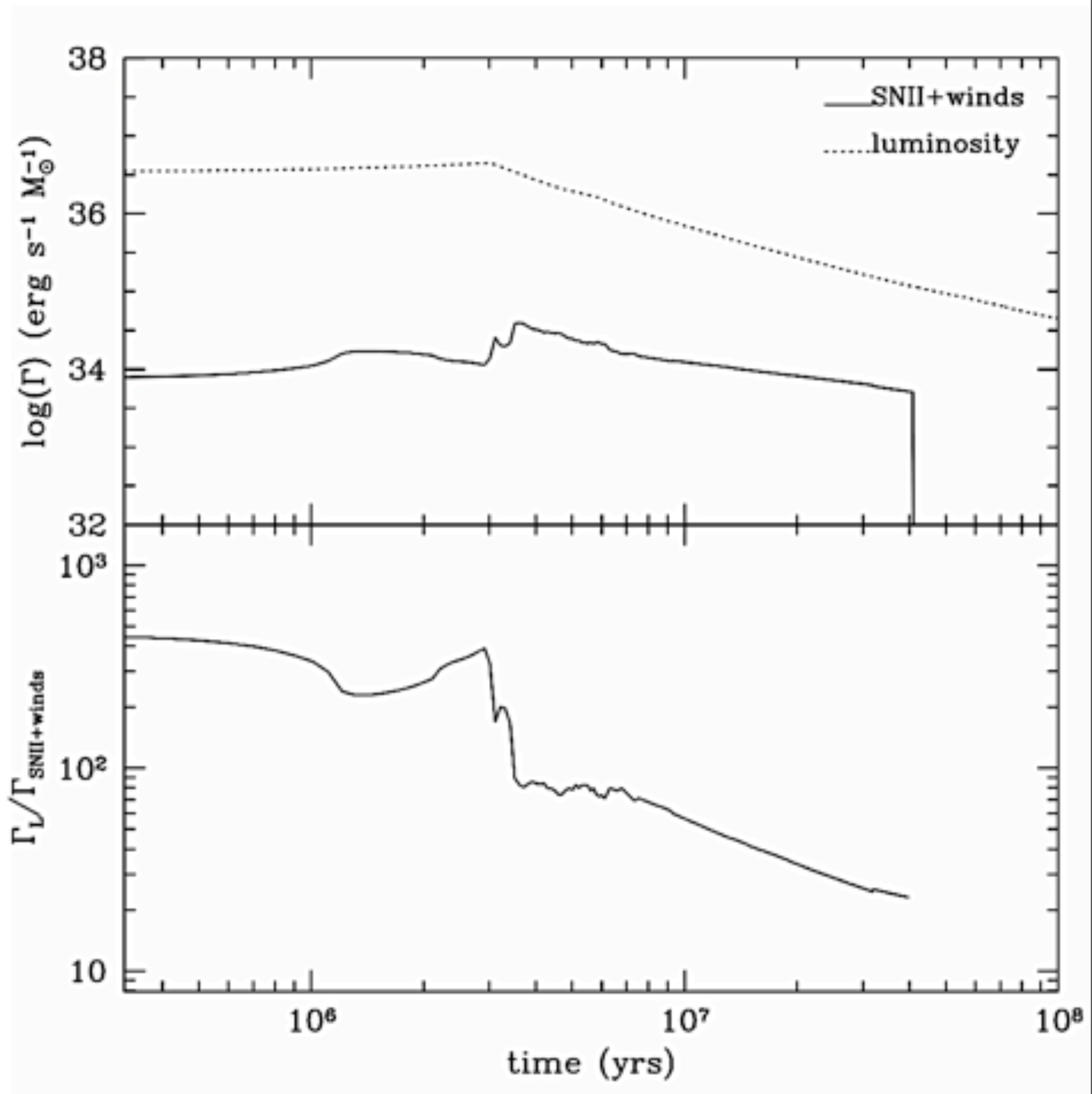
SN + RP may be necessary (see Phil's talk)

radiative feedback implementation:

$$\dot{p}_{\rm rad}(t) = (\tau_{\rm UV} + \tau_{\rm IR})\frac{L(t)}{c}$$

$$P_{\rm rad}(t) = \frac{\dot{p}_{\rm rad}(t)}{6\Delta x^2}$$

(Murray+10, Hopkins+11a, Agertz+13)



Trujillo-Gomez et al. (in prep.)

this is different from thermal "early feedback" of MAGICC simulations

L ~ 250*P_{SN} per solar mass for < 3Myr (STARBURST99)

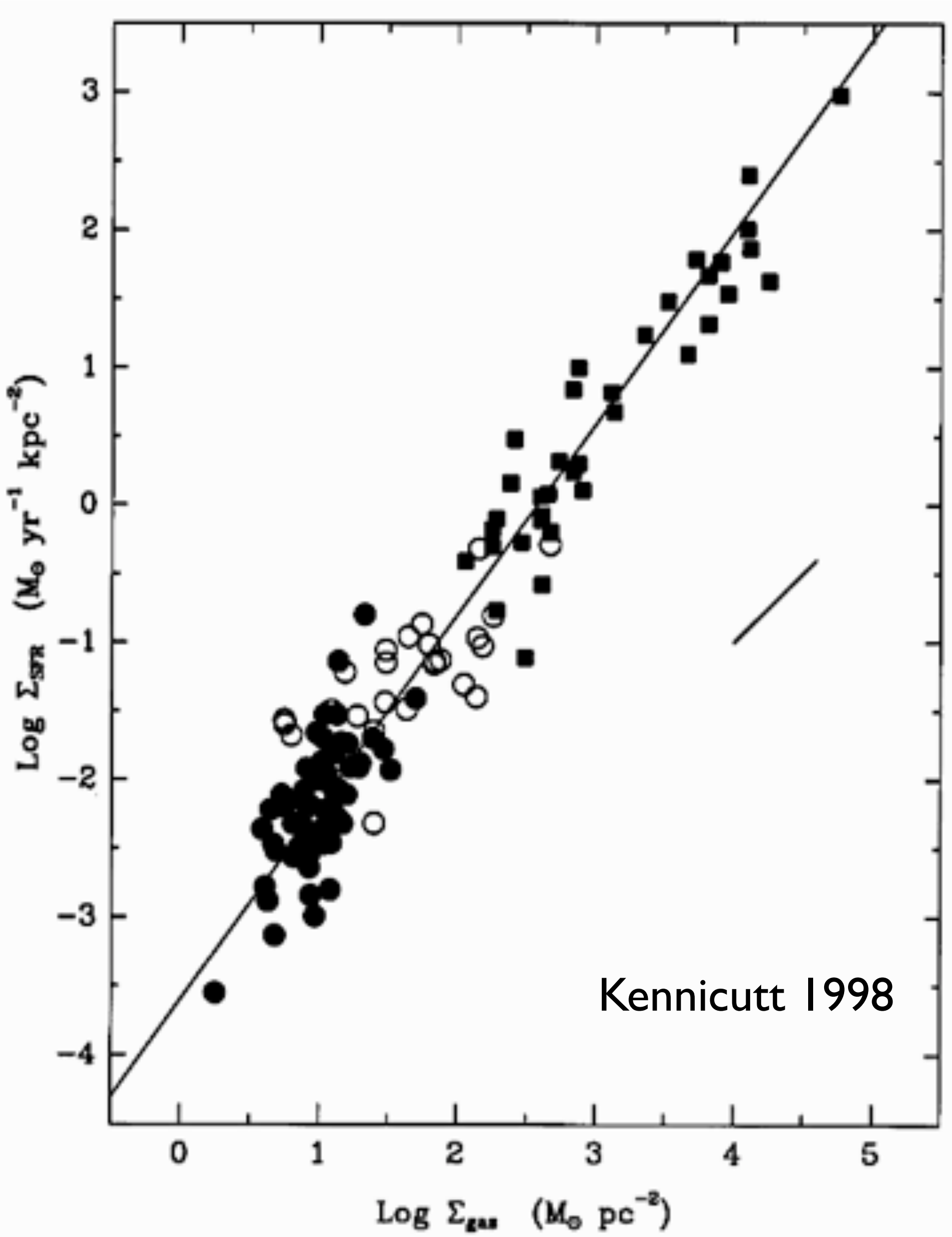
effect of RP on ISM is *not* equivalent to stronger SN feedback (Agertz+2013)

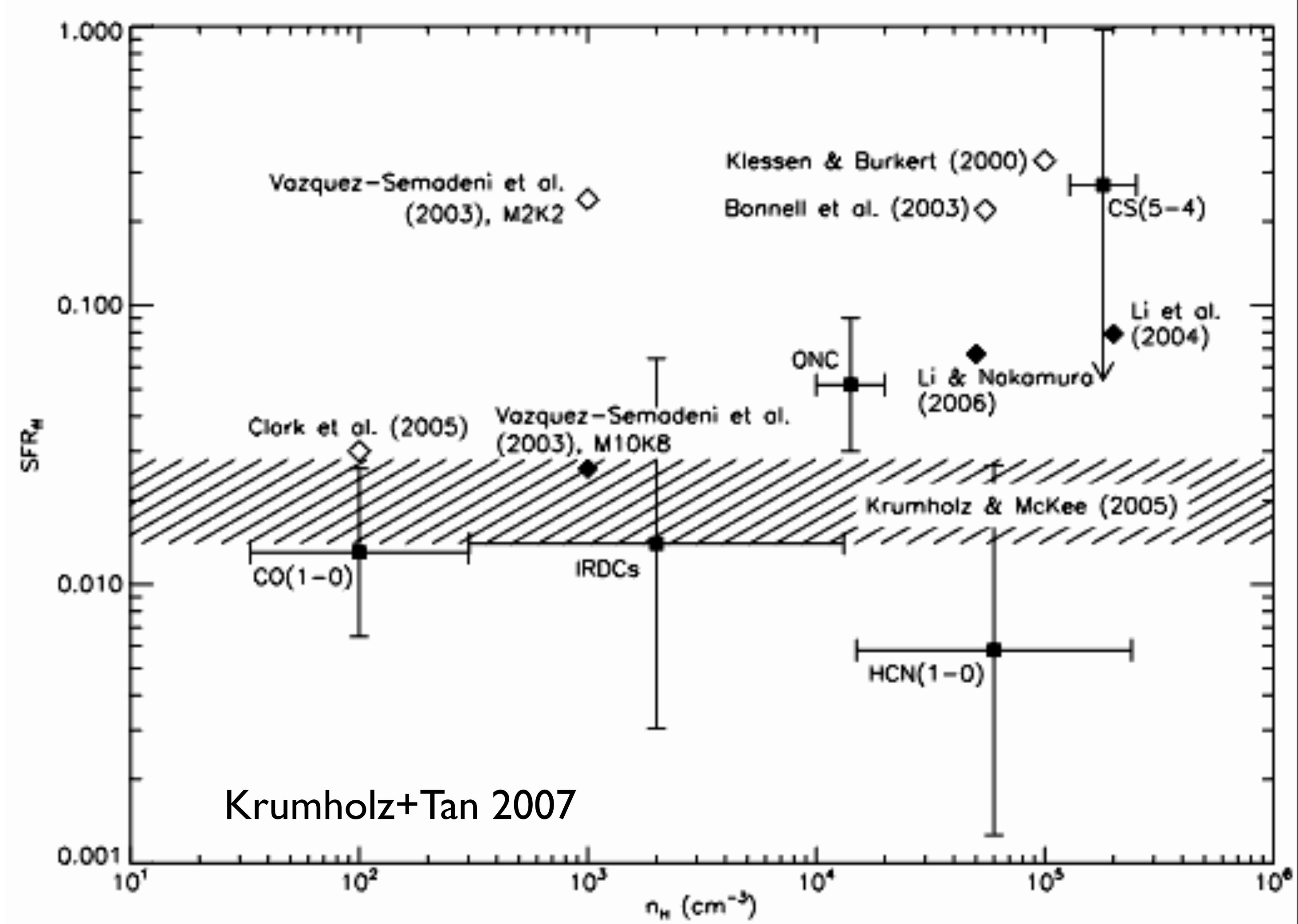
The physical model - local star formation

Global SF
(~kpc scales)

vs.

Local SF
(~pc scales)





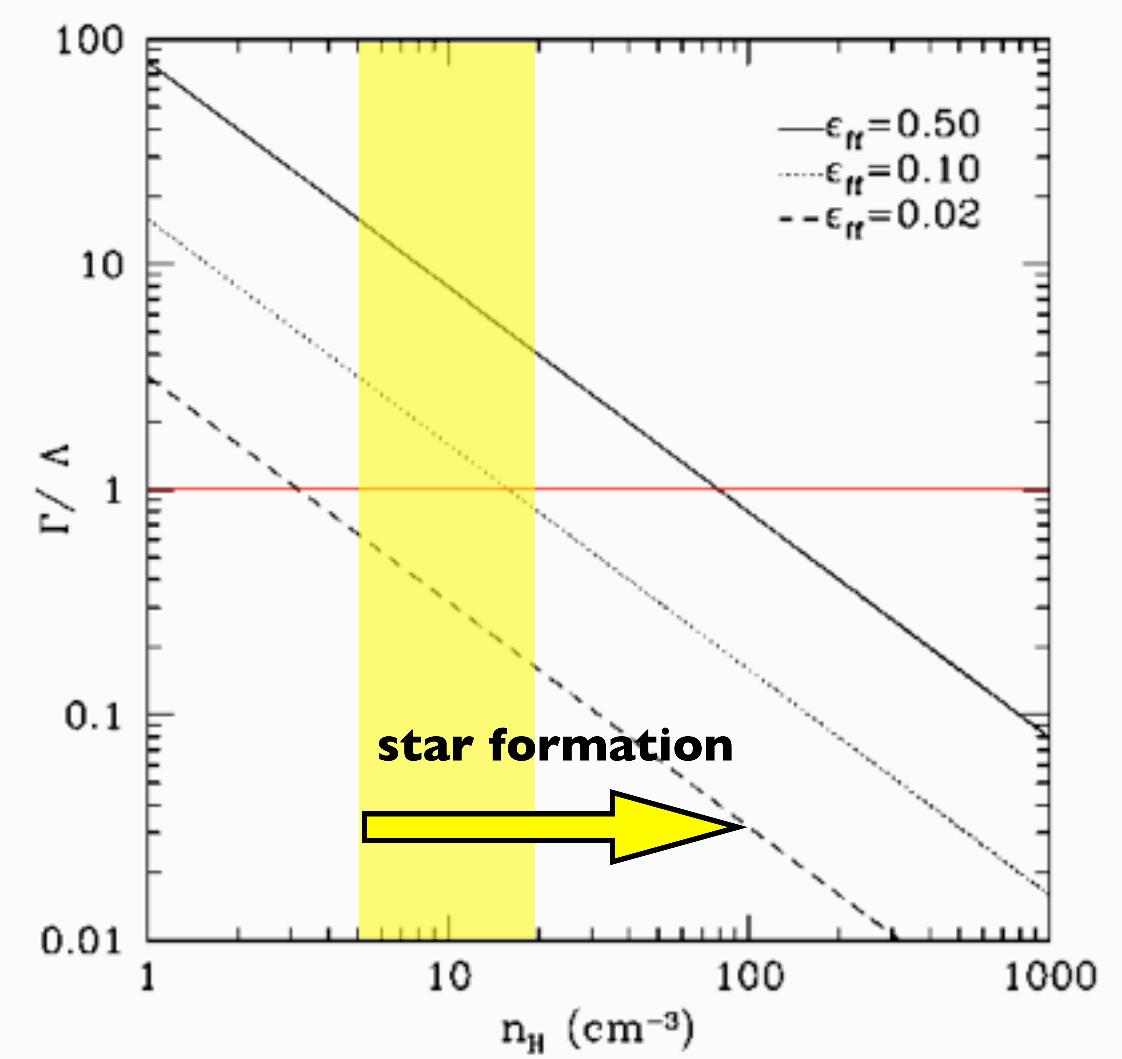
$$\Sigma_{\rm SFR} = A\Sigma_{\rm gas}^{N}$$

$$\frac{d\rho_*}{dt} = \epsilon_{\rm ff}\frac{d\rho_{\rm gas}}{dt}$$

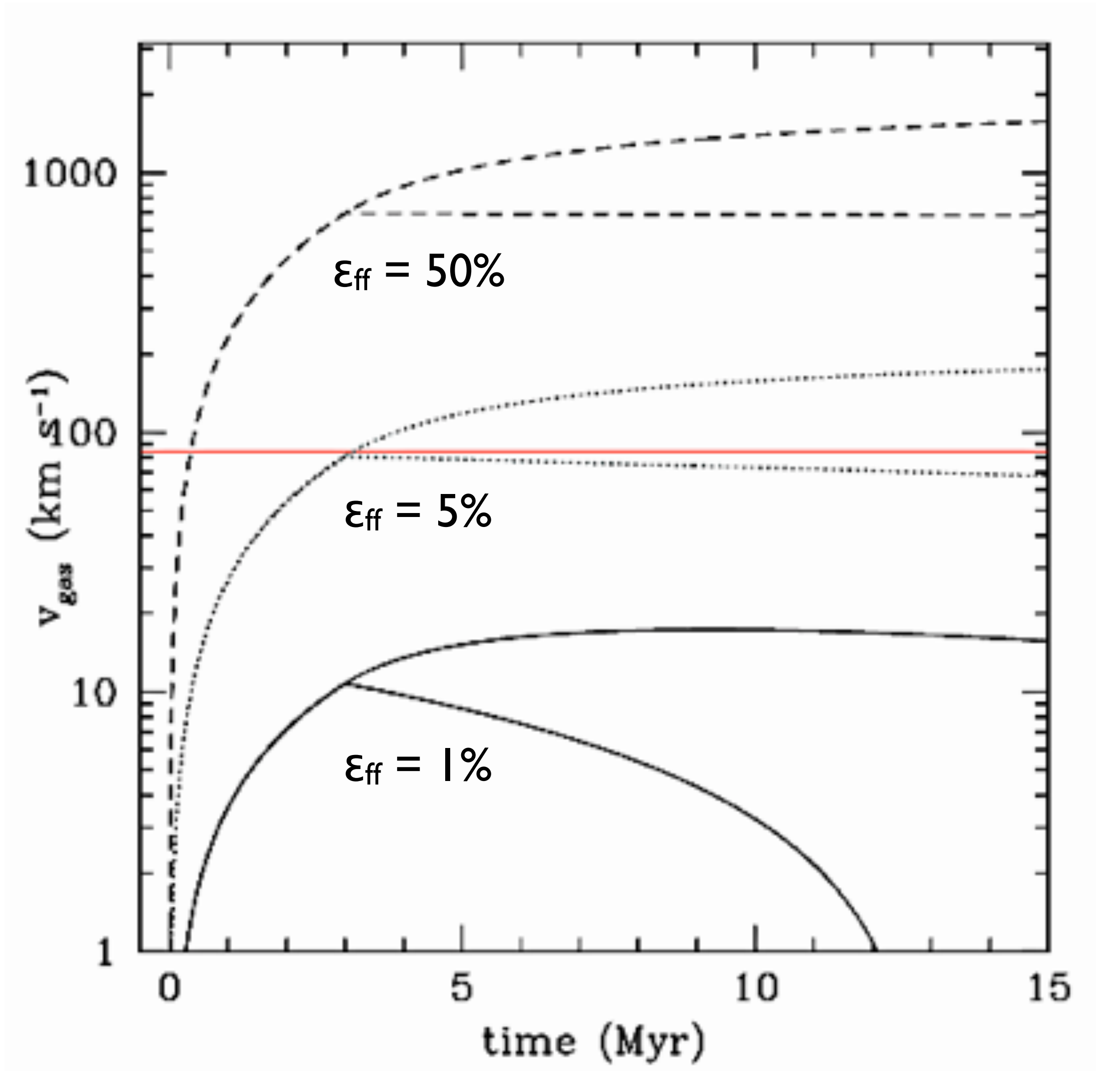
many ways to obtain K-S relation without local SF
(*most simulations do so*)

effects of local SF on feedback

feedback effects depend on local SF efficiency



SN heating/cooling in cloud vs. gas density



RP gas outflow velocity vs. time

local SF efficiency has large effect on feedback and stellar mass assembly

The simulations

in a cosmological setting, does radiation pressure:

1. regulate stellar mass assembly?
2. prevent formation of a massive bulge?
3. reduce the baryon fraction?
3. drive cold massive outflows?

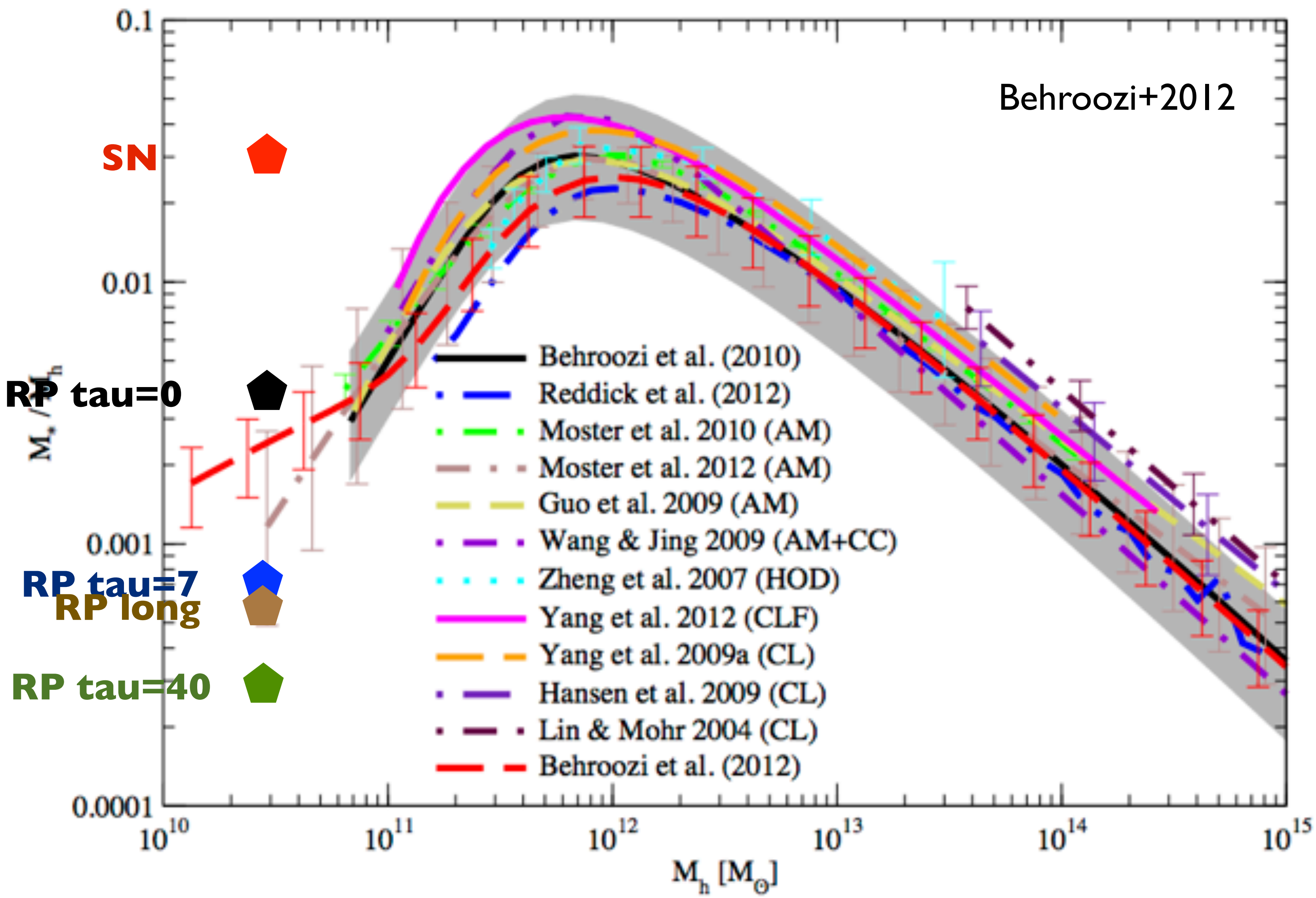
$\tau_{IR} \sim 0$: momentum conserving limit (no photon trapping)
(Krumholz+2013)

run	redshift	halo mass	R_{vir} (proper)	resolution (proper)	SF model	feedback model	τ_{UV}	τ_{IR}	RP density threshold
SN	z=0	$\sim 3\times10^{10}\ M_s$	~80 kpc	38 pc/h	2%	SN	-	-	-
RP tau=0					5%	SN+RP	1	0	10^{-1}
RP tau=7					2%	SN+RP	1	7	10^{-1}
RP long					2%	SN+RP	1	0	10^{-2}
M33_no	z~1 (still running)	$\sim 2\times10^{11}\ M_s$	~80 kpc	76 pc/h	2%	SN	-	-	-
M33_0						SN+RP	1	0	10^{-1}
M33_40						SN+RP	1	5	10^{-1}
M33_long						SN+RP	1	0	10^{-2}

-> we are testing the effect of SF and feedback without fine tuning to produce realistic galaxies

dwarf: global properties

	Model	redshift	M_{vir} ($M_\odot$)	M_* ($M_\odot$)	M_{gas} ($M_\odot$)	$M_{gas,cold}$ ($M_\odot$)	M_*/M_{vir}	$M_{gas,cold}/M_*$	f_{bar}
SN	dwarf_no	0	3.0×10^{10}	8.1×10^8	8.1×10^8	5.5×10^8	2.7×10^{-2}	0.68	0.0540
RP tau=0	dwarf_0	0	3.2×10^{10}	1.3×10^8	2.1×10^9	1.4×10^9	4.1×10^{-3}	10.8	0.0697
RP tau=7	dwarf_IR	0	2.8×10^{10}	2.1×10^7	5.5×10^8	1.2×10^8	7.5×10^{-4}	5.70	0.0204
RP tau=40	dwarf_40	0	2.7×10^{10}	7.5×10^6	1.9×10^8	1.3×10^7	2.8×10^{-4}	1.73	0.0073
RP long	dwarf_long	0	2.9×10^{10}	1.6×10^7	7.4×10^8	6.2×10^7	5.5×10^{-4}	3.88	0.0261



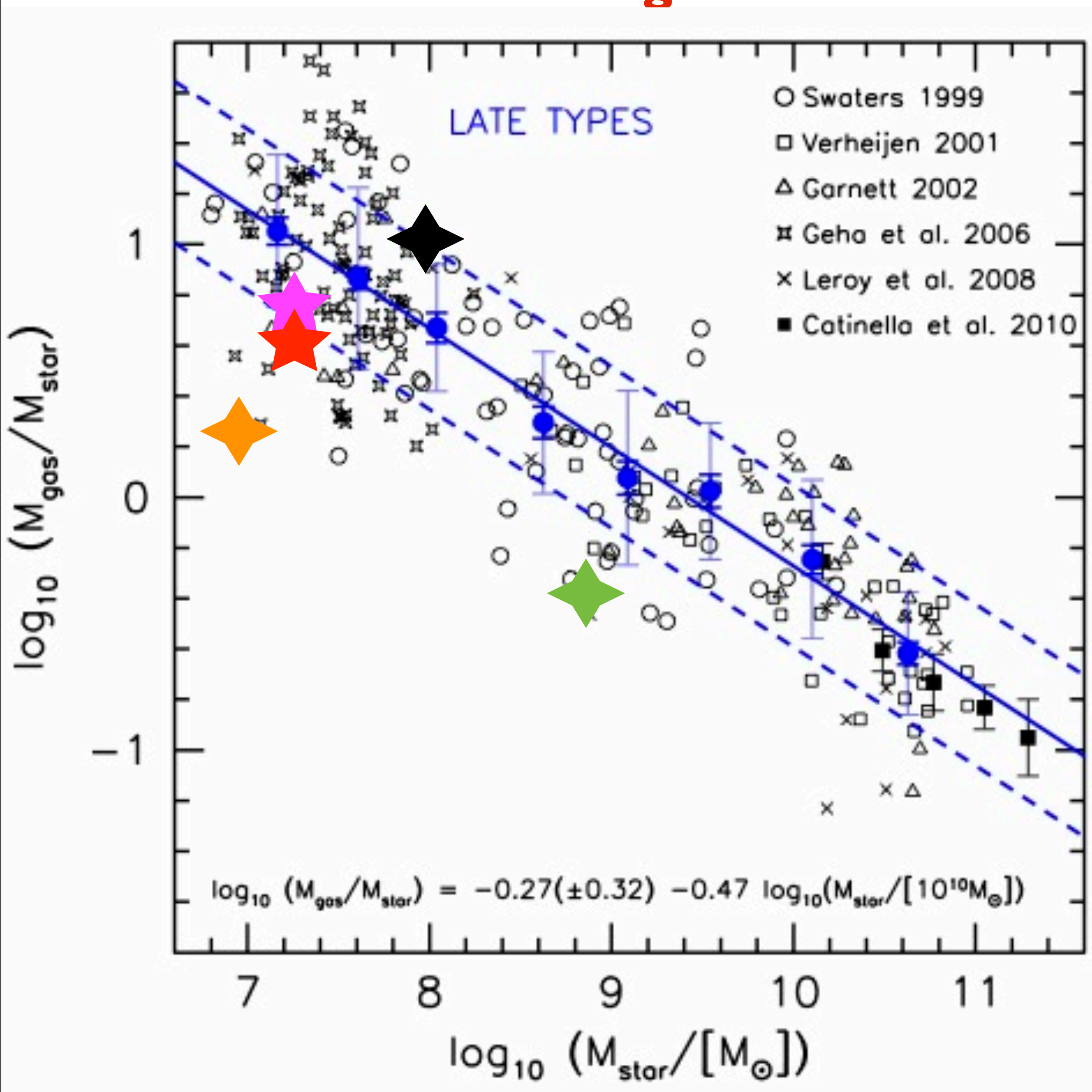
-> all radiative feedback models consistent within a factor of ~3 (modulo changes in epsilon)

scatter at low mass in observations > systematics

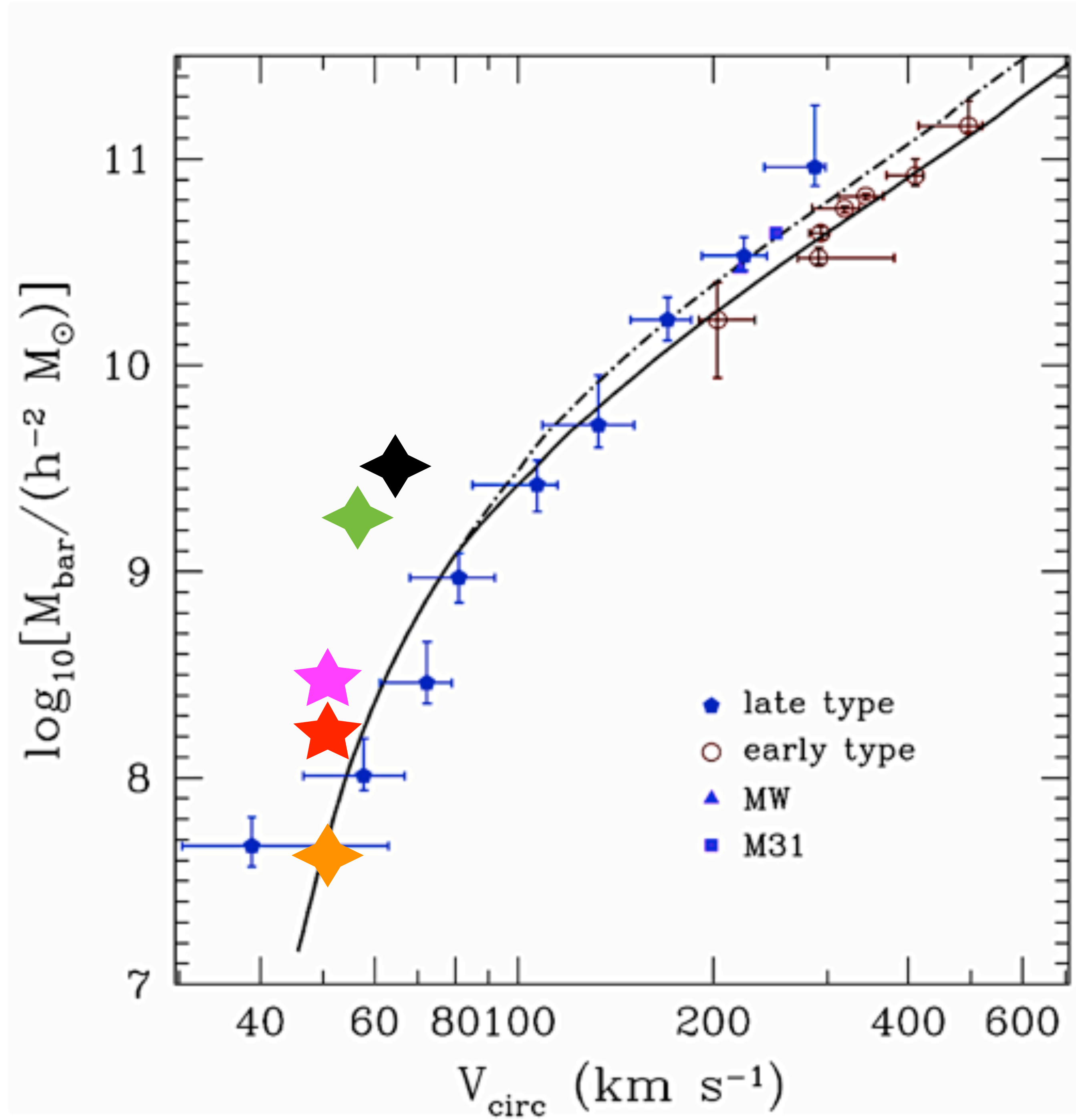
dwarf: scaling relations

SN

RP tau=0
RP tau=7
RP tau=40
RP long



Dutton+2010

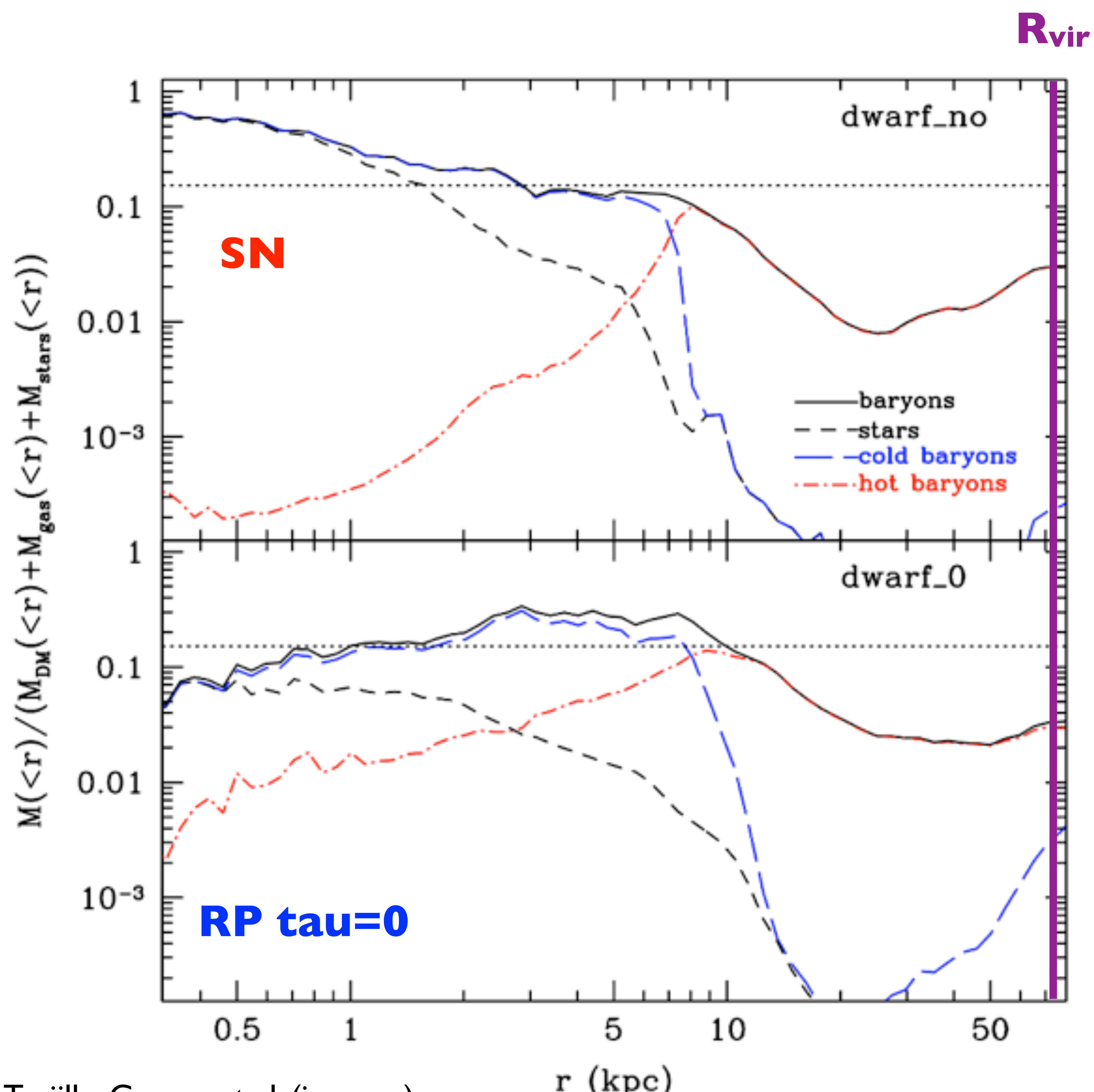


Trujillo-Gomez+2011

SN produces overly massive galaxy at same V_{circ}

RP models cluster within scatter in baryonic T-F relation

dwarf: galaxy formation efficiency



Trujillo-Gomez et al. (in prep.)

Overall, RP does not modify f_{bar}, but:

within ~2 kpc:

SN well above cosmic, mostly locked in stars

RP reduces f_{bar} ~ cosmic mean, dominated by cold gas (consistent with THINGS)

within CGM:

both ~ 20% of cosmic, dominated by hot gas

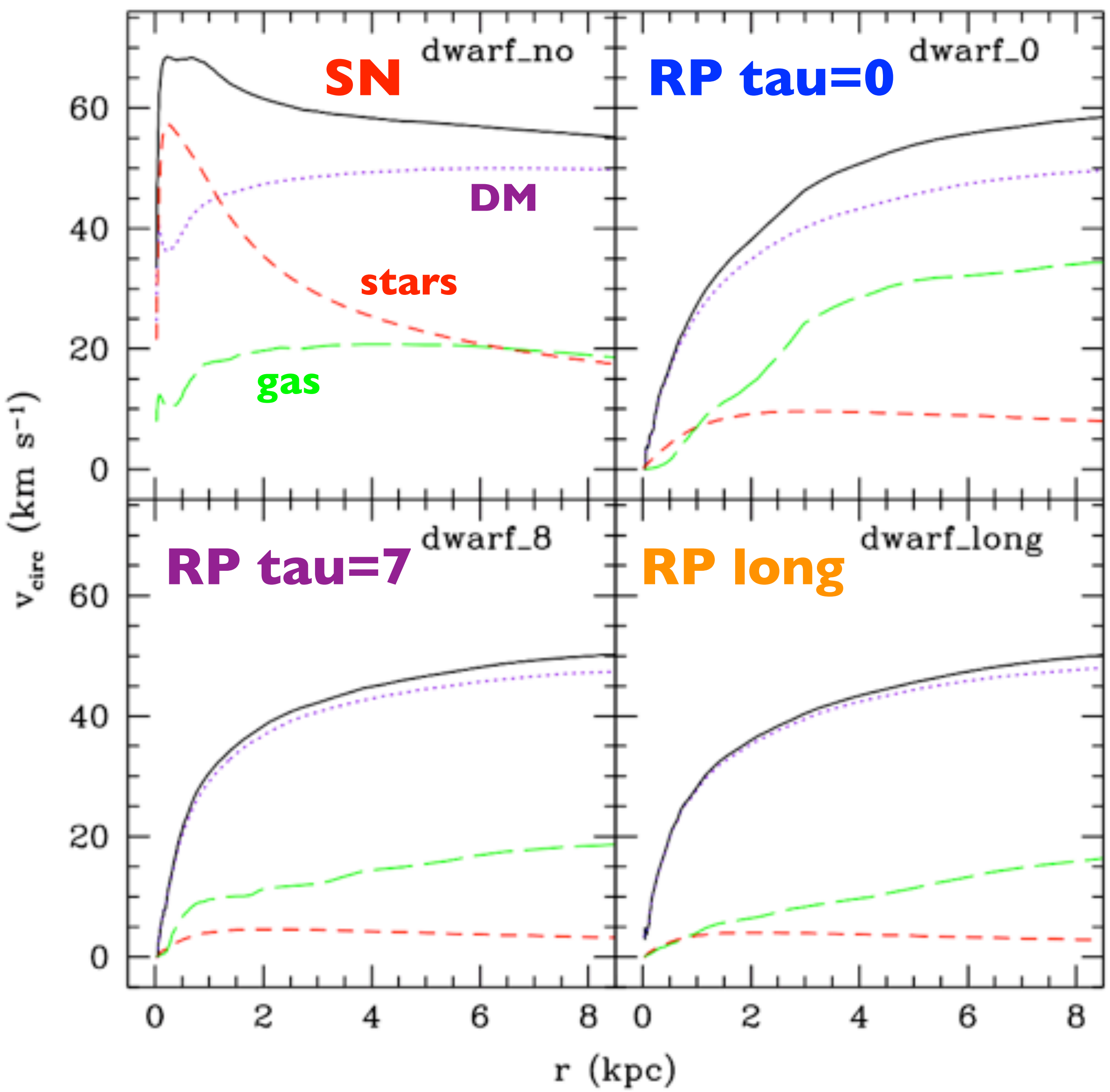
note that there is no need to blow baryons out of halos! observations mostly see cold baryons

1. RP regulates conversion of cold gas into stars
2. RP increases hot gas in galaxy and increases cold gas in CGM

dwarf: mass distribution

-> all radiative feedback models show very similar mass distributions:

slowly rising, DM dominated at all radii



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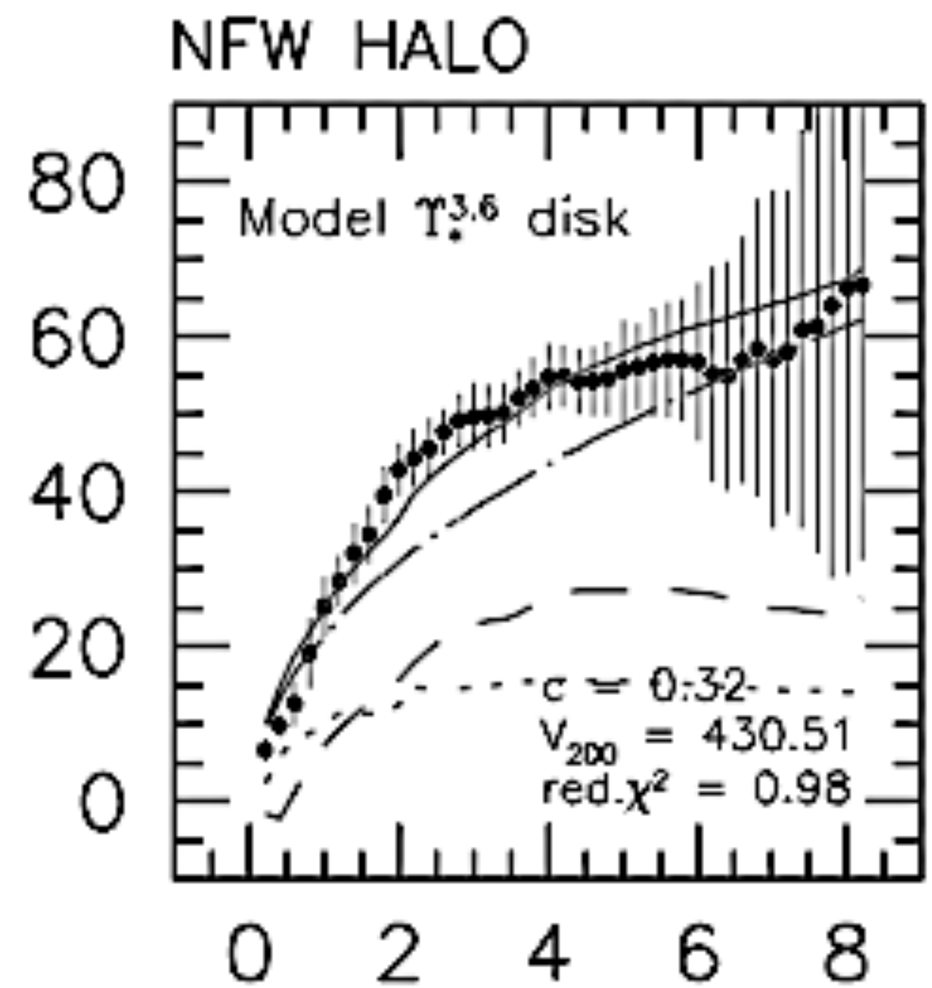
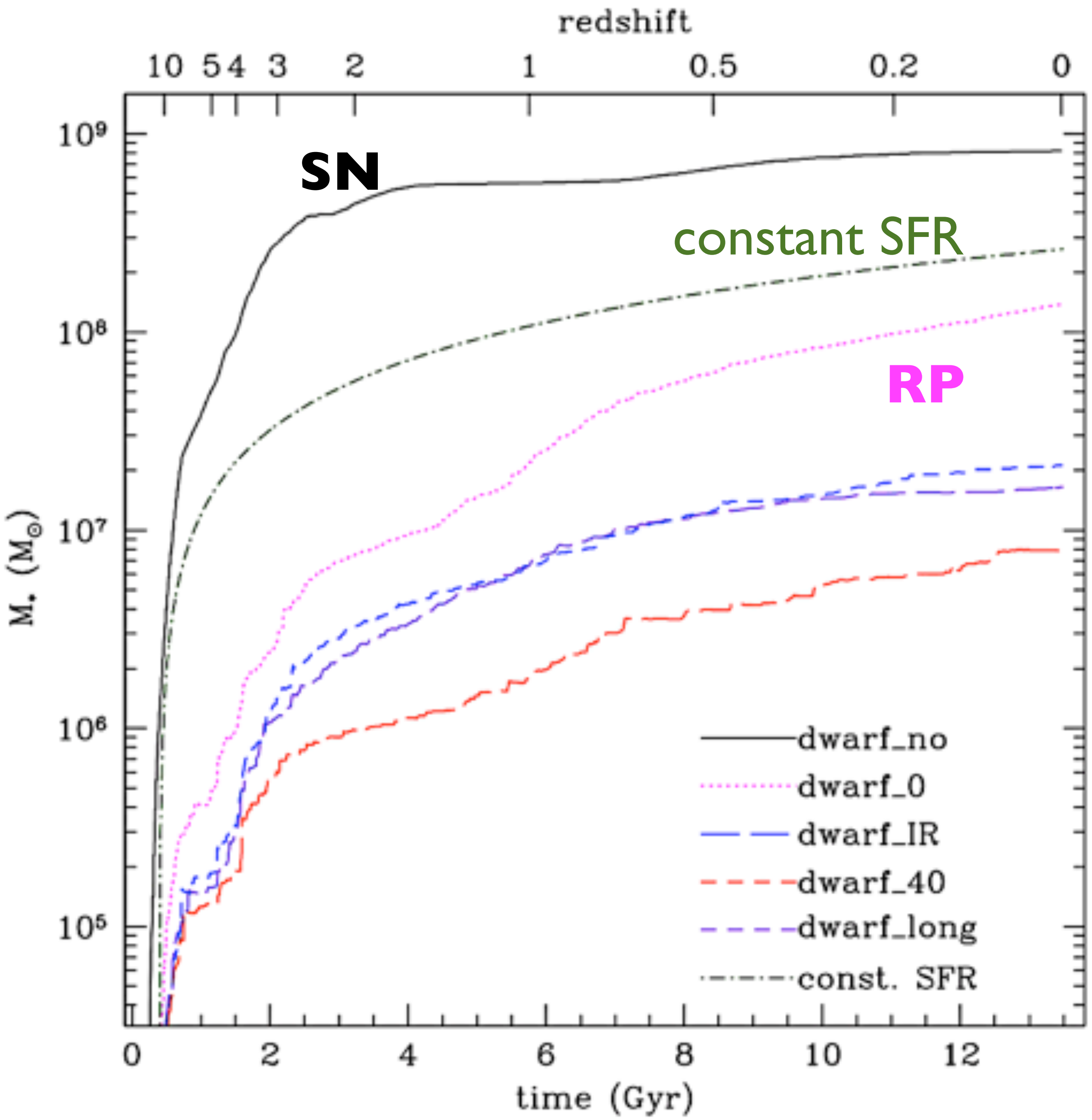


NGC2366 (Oh+2011)

galaxy dominated by rotation -> $V_{circ} \sim V_{rot}$

dwarf: stellar mass assembly



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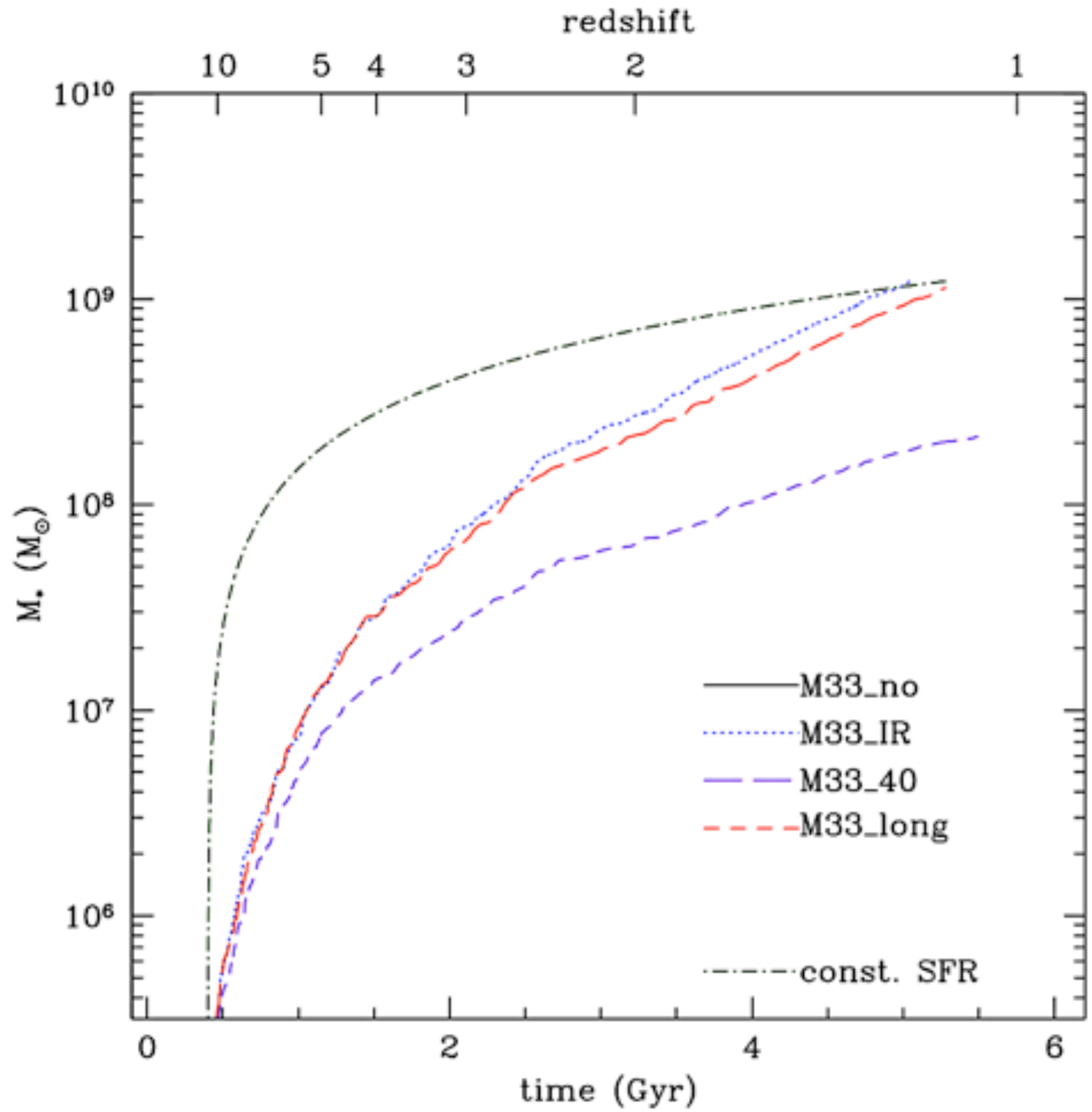
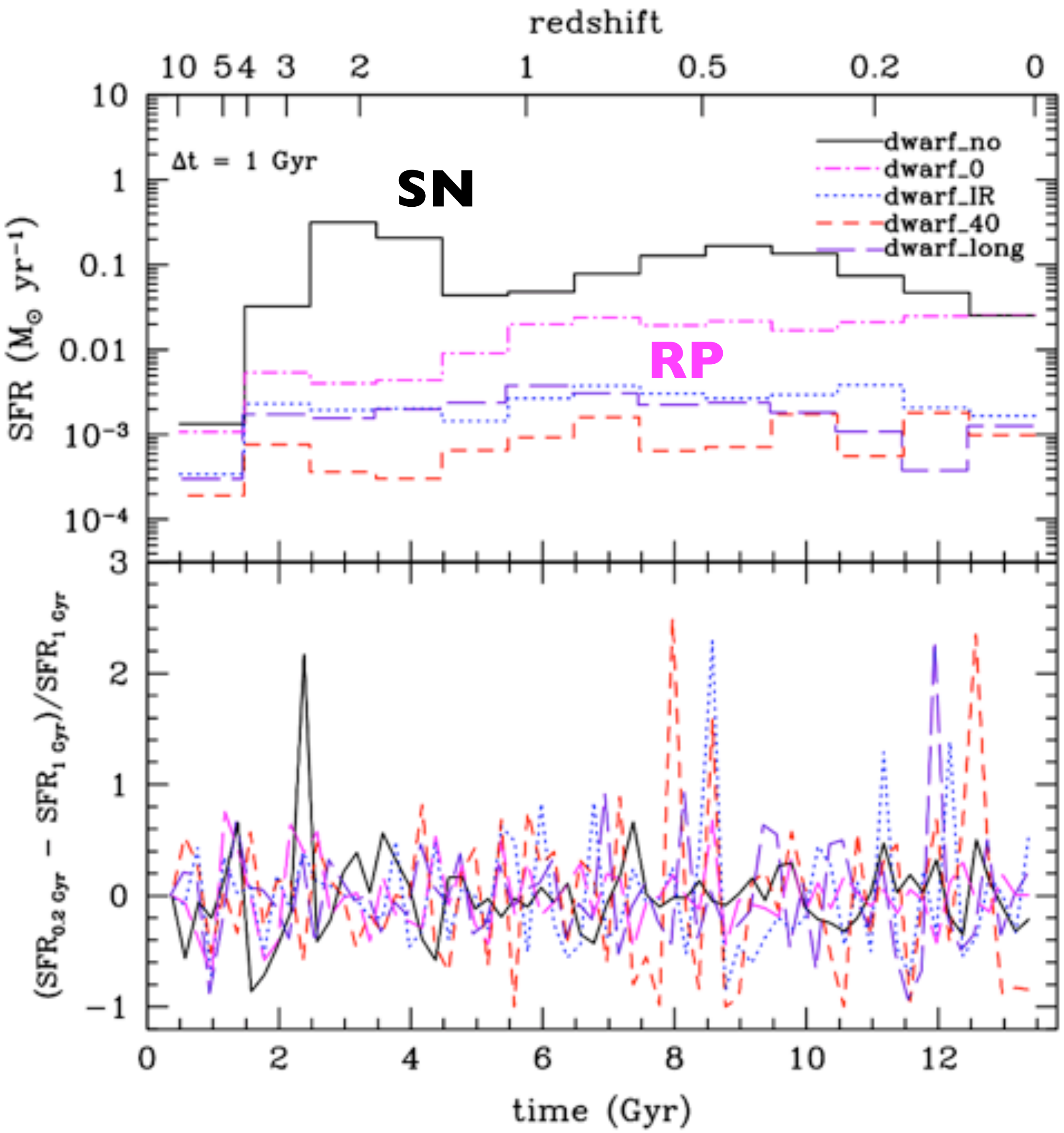


Trujillo-Gomez et al. (in prep.)

SN: ~80% of stellar mass assembled by z=2

RP: ~50% of stellar mass assembled in last 5-7 Gyr

dwarf: star formation history



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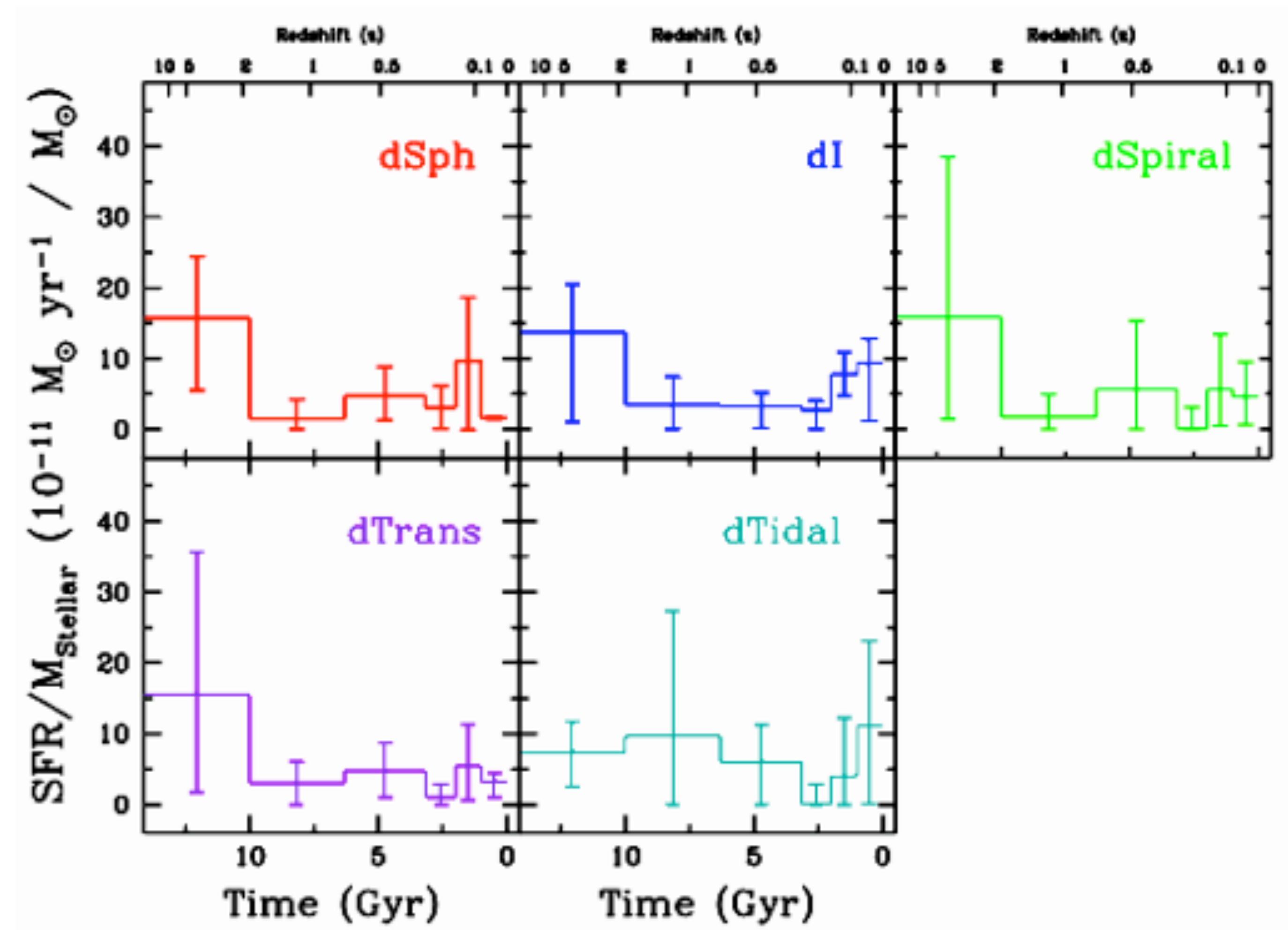


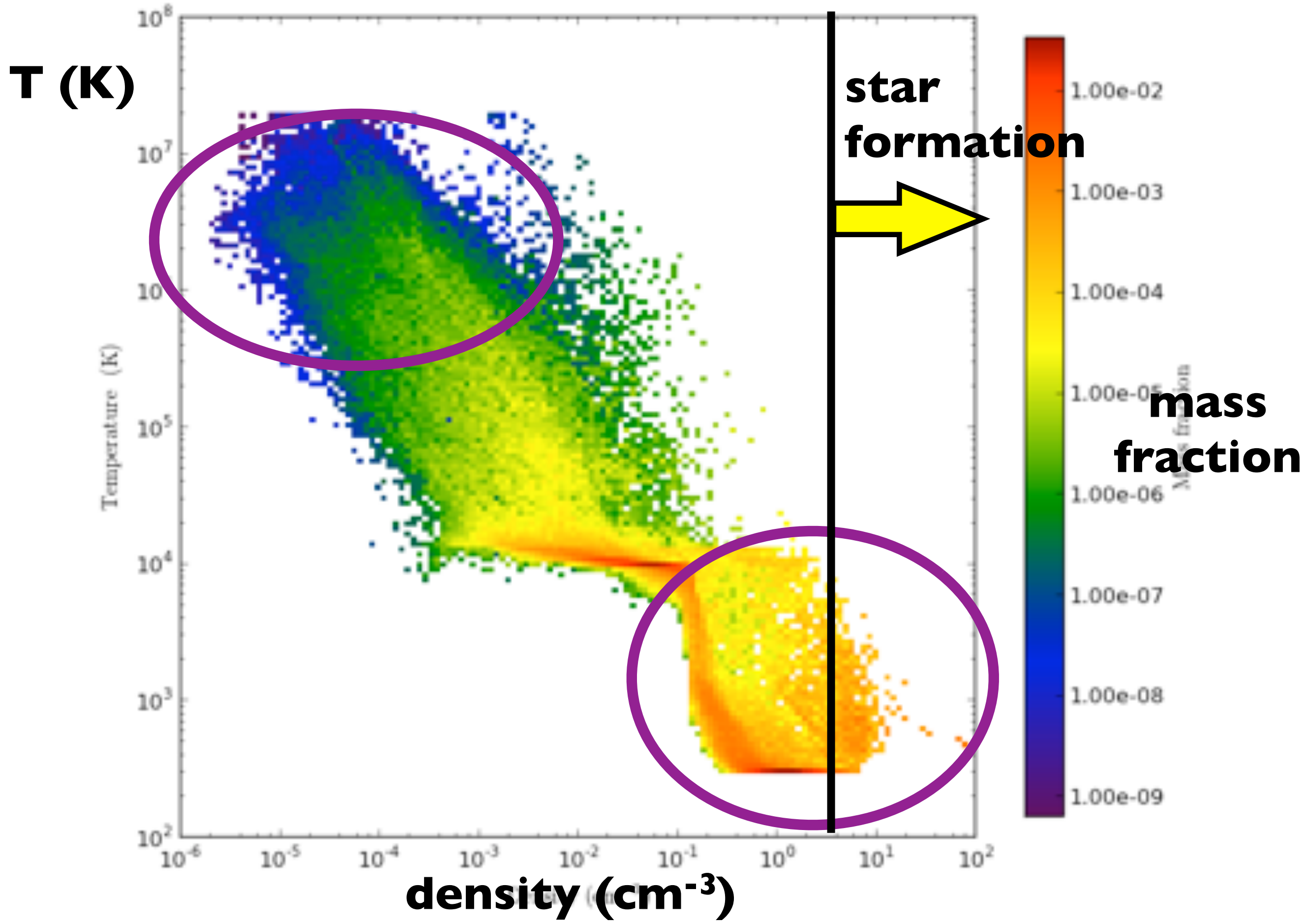
Weisz+2011: 60 dwarfs from ANGST

SFR_{RP} ~ 10^{-3} M_{sol}/yr

~100x smaller than SFR_{SN} at z~2

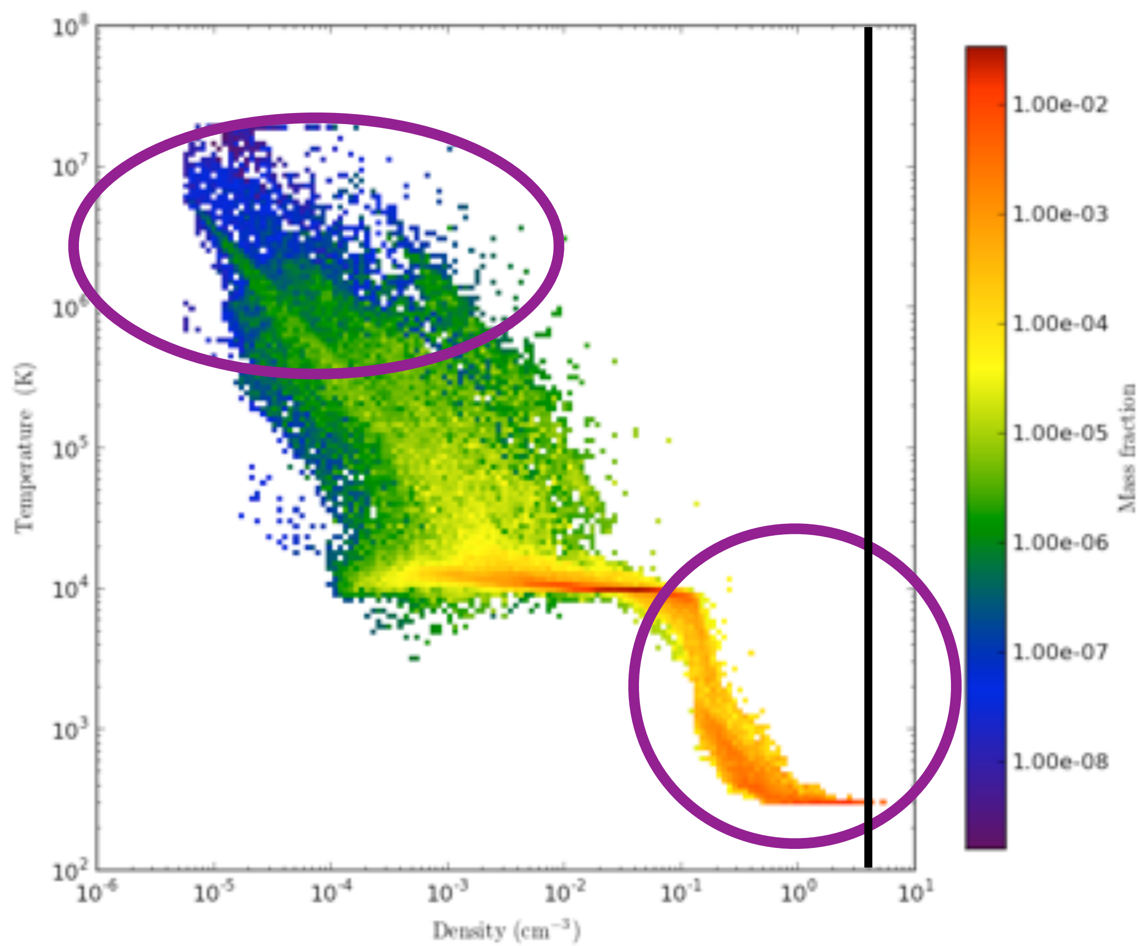
dwarf: gas thermodynamics

SN



SN feedback more effective in heating gas in ISM & CGM

RP tau=7



RP feedback reduces cold+dense star forming gas in galaxy

➡ again, effect of RP is *not* equivalent to strong SN feedback

see S. Shen's talk for importance to CGM enrichment

dwarf: gas properties - infall & outflows

in galaxy:

SN:

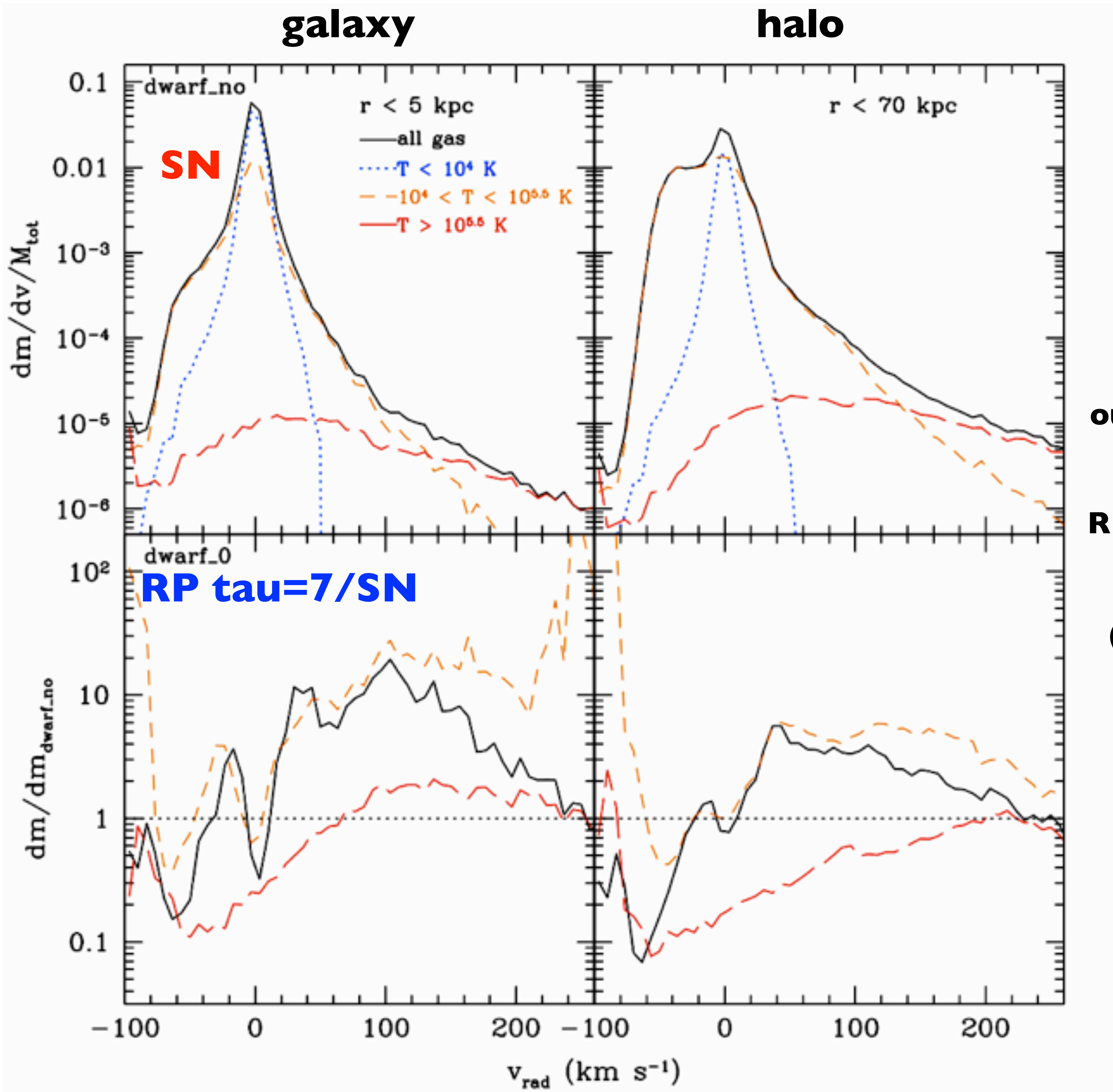
most outflowing gas is warm/hot

RP:

increases outflow mass ~10x at high velocities

~10x more warm gas

~5x reduced hot infall



Trujillo-Gomez et al. (in prep.)

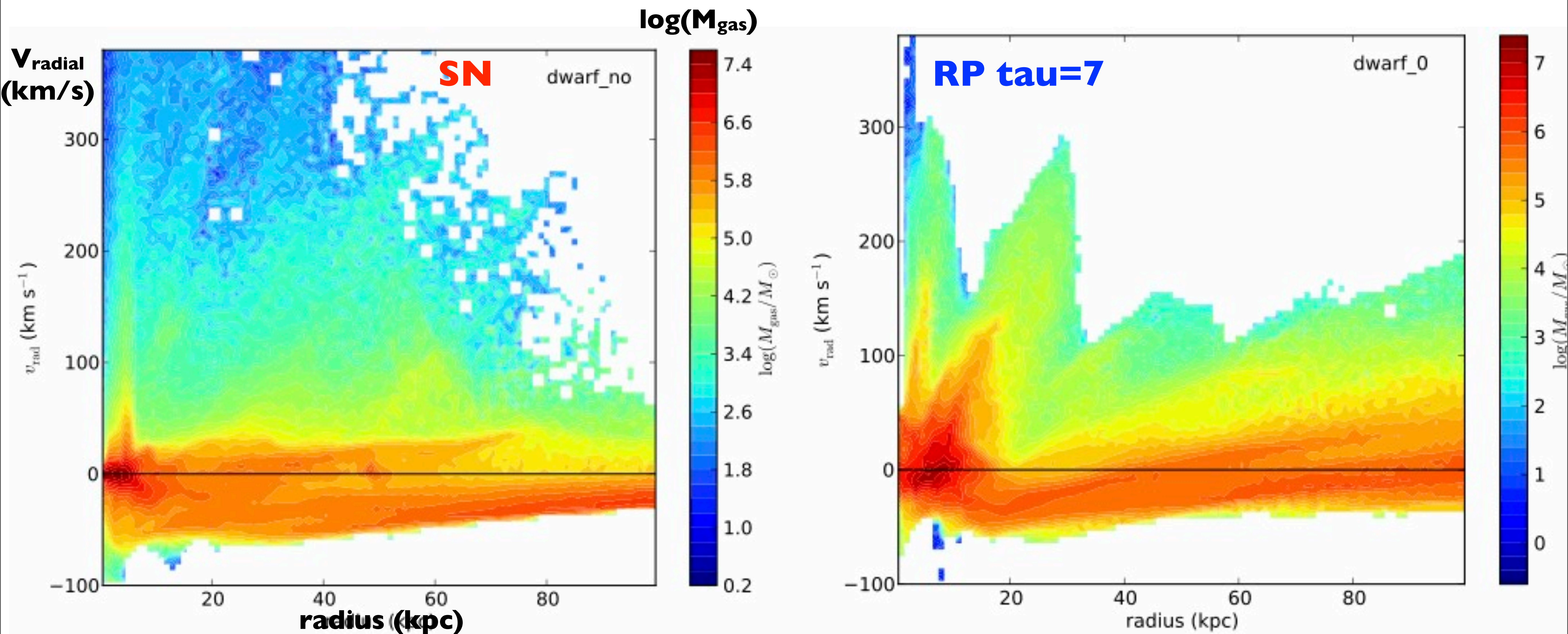
in halo:

both produce outflows out to R_{vir}

RP enhances warm, reduces hot

***(recycled)* infall is reduced ~10x**

dwarf: gas properties - infall & outflows



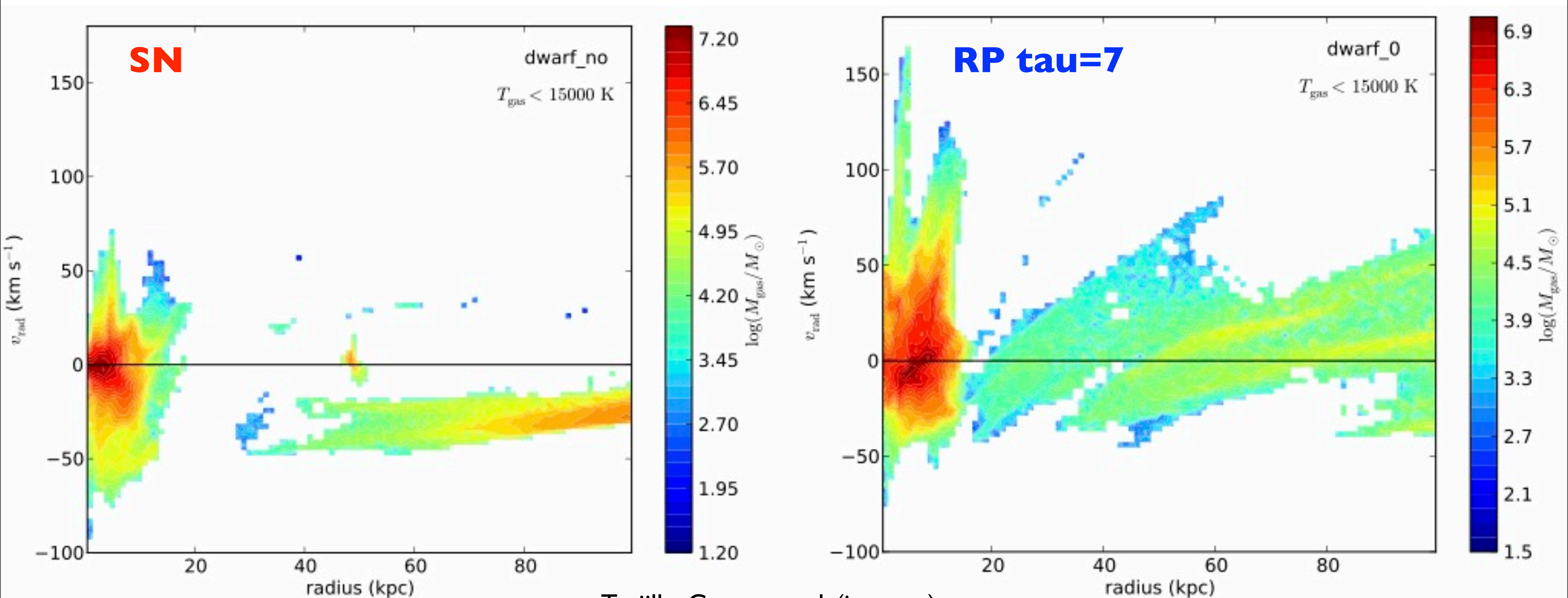
Trujillo-Gomez et al. (in prep.)

SN:
larger SFR gives larger speeds near galaxy but small mass loading

RP:
much larger mass with escape speed near galaxy and out beyond R_{vir}

dwarf: gas properties - cold infall & outflows

QSO absorption should constrain amount of metals and ionization state of CGM



Trujillo-Gomez et al. (in prep.)

SN stirs up cold gas in the ISM but produces no cold outflows beyond ~20 kpc

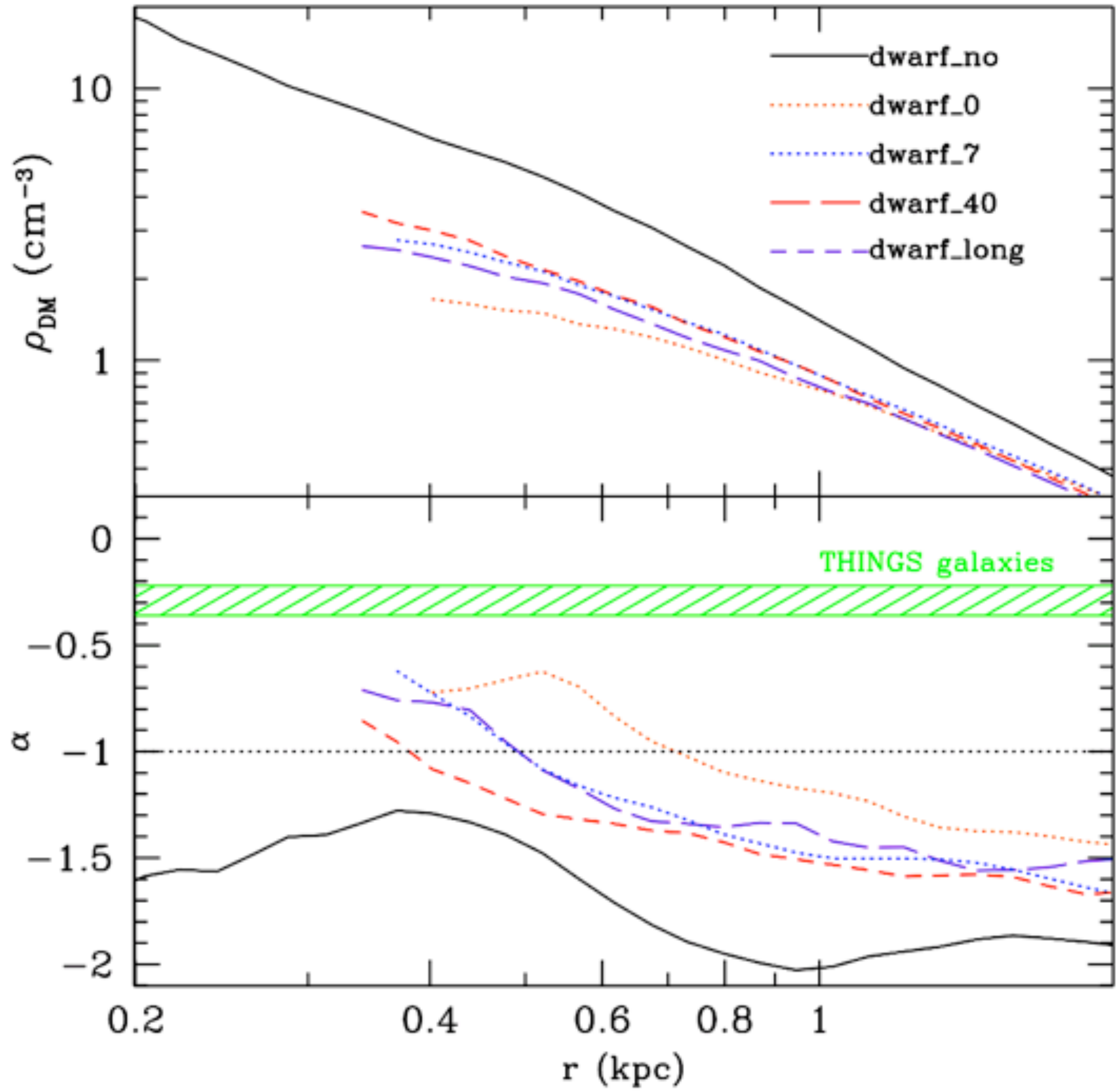
RP produces cold winds with v > v_{escape}

RP: cold outflows entrained in warm gas & survive into CGM and past R_{vir}

➡ again, effect of RP is *not* equivalent to stronger SN feedback

this may be a way to increase the covering fraction of cold gas to match observations (see Michele's talk)

DM distribution - cusps or cores?



Trujillo-Gomez et al. (in prep.)

no detectable cores in ~3e10 M_{sun} dwarfs but not so clear for ~2e11 M_{sun}

Conclusions

in a cosmological setting, does radiation pressure:

1. regulate early SF?

✓ RP reduces the early SFR and leads to a late buildup of the stellar component in low-mass halos

2. prevent formation of a massive bulge?

✓ yes, RP reduces concentration of stellar component. mass profiles are consistent with observations.

3. reduce the baryon fraction?

✓ RP reduces the fraction of cold baryons within R_{vir} by ~20x

4. drive massive outflows?

✓ RP produces *cold+warm* outflows at large velocities that can escape the halo

➡ effect of RP is *not* equivalent to stronger SN feedback: RP does not overheat gas + produces cold outflows

✓ RP dilutes and ejects cold dense gas from galaxy

✓ RP dwarfs show *clear break* from SN models

✓ RP models show similar global properties *regardless of implementation*

✓ RP produces *less hot gas* in galaxy and CGM

✓ RP produces weak DM cores