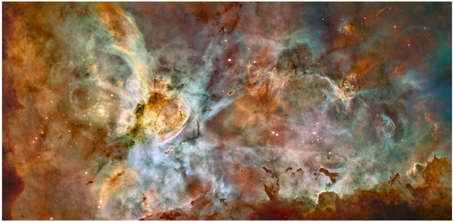
Galaxy formation simulations including local radiation fields

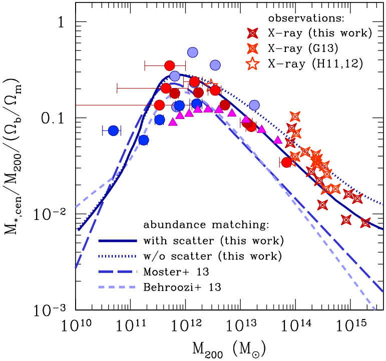


Rahul Kannan (MPIA)
G. Stinson, A.V. Macciò
J. F. Hennawi, S. Cantalupo

Quenching & Quiescence
17 July 2014

Why is star formation inefficient?

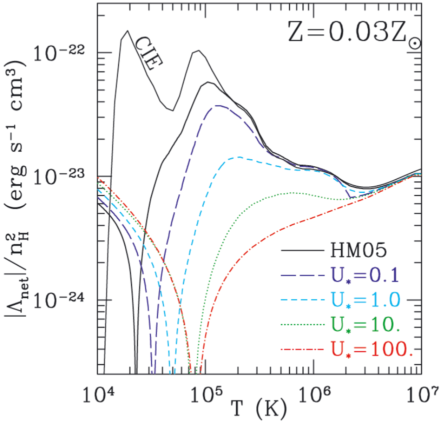
- Gas overcooling problem in simulations
- High Star formation efficiency
- Need to invoke various feedback mechanisms
  - SNe feedback invoked at the low mass end
  - AGN feedback invoked at the low mass end
  - Decreasing the cooling rate can also regulate star formation (see P. Hopkins and S. Cantalupo talk)



Kravtsov+14

Is gas cooling calculated correctly?

- Only extragalactic UV background considered in calculations of gas cooling rate
- Local sources such as stellar winds from O & B stars and SNe shocks produce ionizing radiation
- Cantalupo 2010, argues that this effect is important in MW mass galaxies
- Important for low mass galaxies (S. Cantalupo's Talk)



Heat Equation

$$\frac{D\varepsilon}{Dt} = -\frac{P}{\rho}\vec{\nabla}.\vec{u} + \frac{H - \Lambda}{\rho} \tag{1}$$

where ε = specific internal energy, H = Heating rate, Λ = Cooling rate and

$$\frac{H - \Lambda}{\rho} = f(n_i, T, U) \tag{2}$$

where n_i = density of each species, U = incident radiation field but

$$n_i = f(n_{i,j}, T, U) \tag{3}$$

Effect of ionizing radiation

- The photoionization rate - Γ_γ depends on the incident radiation field

$$\Gamma_{\gamma,i} = \int_{\nu_T}^{\infty} \frac{4\pi J_\nu}{h\nu} \sigma_i \, d\nu \tag{4}$$

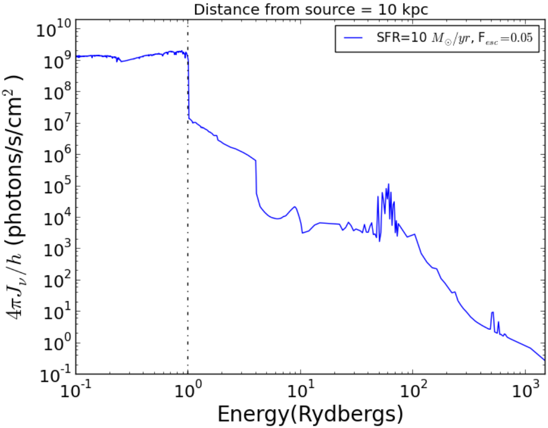
- σ_i is the photoionization cross section for species 'i'
- This cross section is highest at threshold freqeuncy
- In addition to ionizing the gas, high energy photons can also heat the gas
- The photoheating rate - ε_i is given by

$$\varepsilon_i = \int_{\nu_T}^{\infty} \frac{4\pi J_\nu}{h\nu} \sigma_i (h\nu - h\nu_T) \, d\nu \tag{5}$$

- High energy photons inject more energy into gas, but the cross section for interaction is less

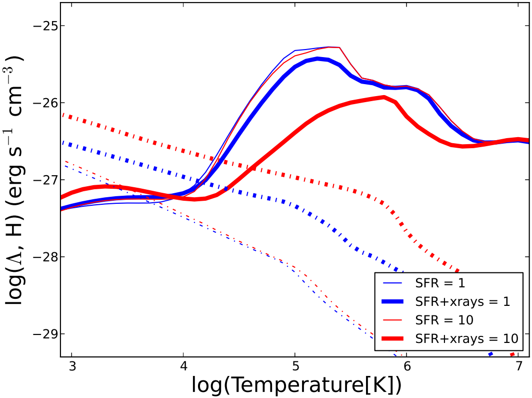
Young stars+X rays

- Cervino+2002 considered X-rays from shock heated SNe gas
- Corelates well with the SF in the galaxy
- Assumption - 5% of mechanical energy of supernova converted into thermal
- Empirical SED derived, quantified by the SFR of the galaxy



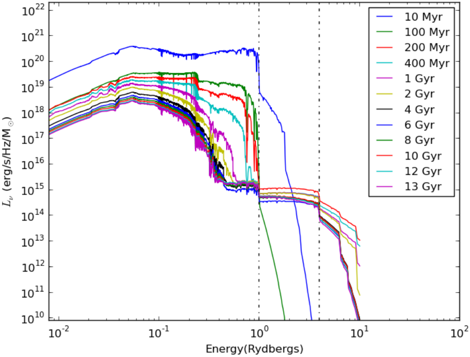
Young stars+X rays

- Distance = 1 kpc, $n_H = 0.01 cm^{-3}$, Z=Z$_\odot$
- High ionization state metal cooling suppressed along with total quenching of H, He cooling
- Becomes important at low redshifts, where the metallicity of incoming gas has been increased due to successive bursts of star formation



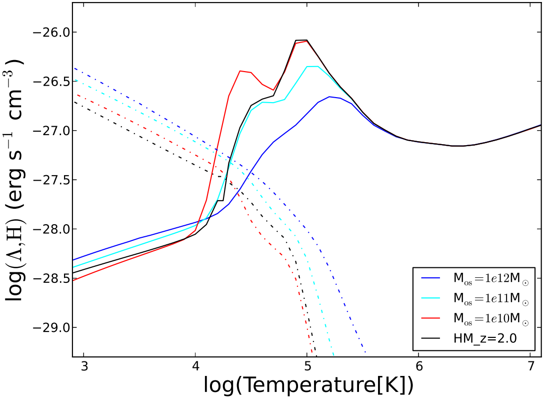
Contribution from old stars

- Bruzual & Charlot SSP models
- Accumulation of post-AGB stars contribute to ionizing flux
- The SED is almost constant after 200 Myrs
- Low level of hydrogen flux, but a harder spectrum extending up to 10 Rydbergs



Effect of radiation form old stars

- Distance = 10 kpc, $n_H = 0.01 cm^{-3}$, Z=0.01$Z_\odot$
- Helium cooling affected more than H cooling



Attempts at including local radiation sources in simulations

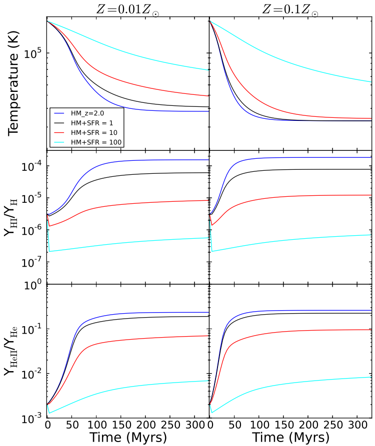
- All previous simulations have calculated gas cooling in the presence on UV background
- Local sources not accounted for
- Some exception : Radiative transfer (RT) embedded in galaxy formation code (Gnedin 2008, Petkova & Springel 2009)
  - Computationally expensive
  - Cannot simulate beyond z=4
- RT in post process (Fumagalli +2011, Rahmati+2013)
  - Can only probe the diagnostics like distribution of DLAs
  - Cannot asses the effect on the dynamics

Basic Assumptions

- Simplifying assumptions need to be made in order to include local sources and simulate the galaxies down to z=0
- The surrounding hot halo gas is optically thin which makes RT becomes an inverse square problem
  - The distance r is directly taken form the gravity tree calculation (computationally efficient)
  - $$F_\nu(r) = \frac{F_\nu(r_1) r_1^2}{r^2} \quad (6)$$
- Absorption at source
  - 95 % of flux in Lyman Limit frequencies absorbed by birth cocoon of new stars
  - Old stars are considered field stars and hence the escape fraction is unity

Test particle runs in GASOLINE

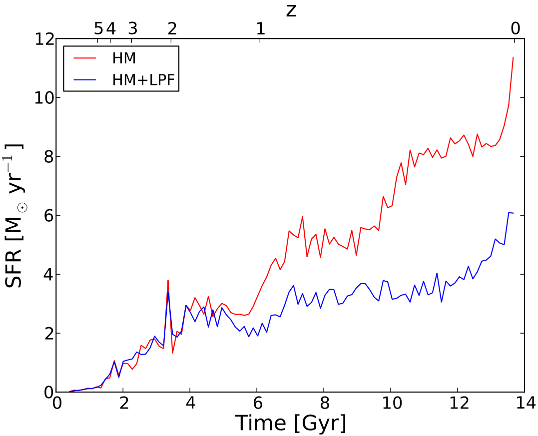
- $n_H = 0.001 cm^{-3}$
- Initial Temperature = 2×10^5 K
- Variaiton in cooling times only due to change in ionization state
- Less cooling as metallicity increases



Simulation of MW galaxy

- Halo mass - 6.5×10^{11} $M_\odot$
- SNe Feedback + Early Stellar feedback - Stinson+2013
- Gas particle mass - 2×10^{5} $M_\odot$, Softening - 310 pc
- Metal cooling
  - Only UV background - HM run
  - UV background + local photoionizing radiation sources - HM+LPF run

Star Formation History



Phase Space Diagrams

- Cold phase of ISM suppressed
- Gas accretion onto the disk is also suppressed

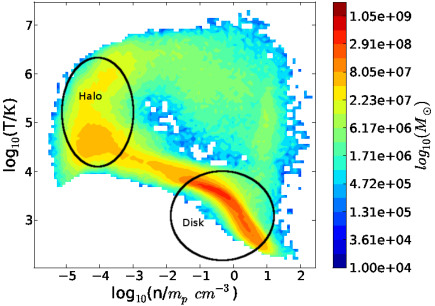


Figure : HM

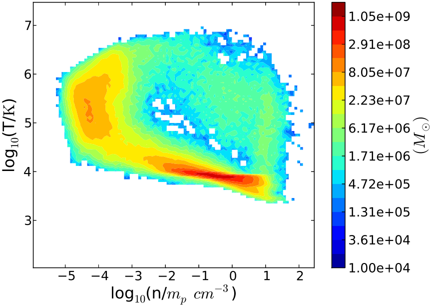
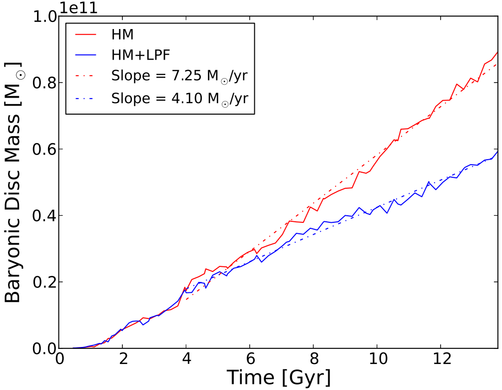


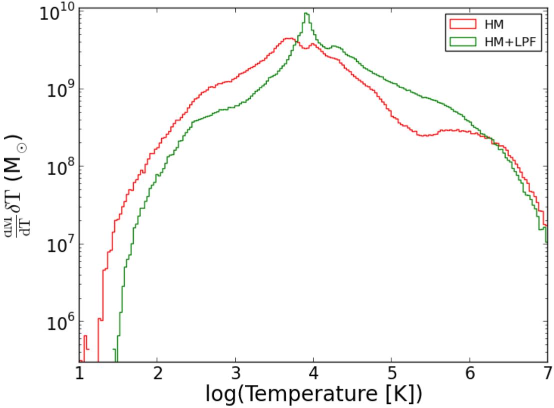
Figure : HM+LPF

Gas Accretion rate

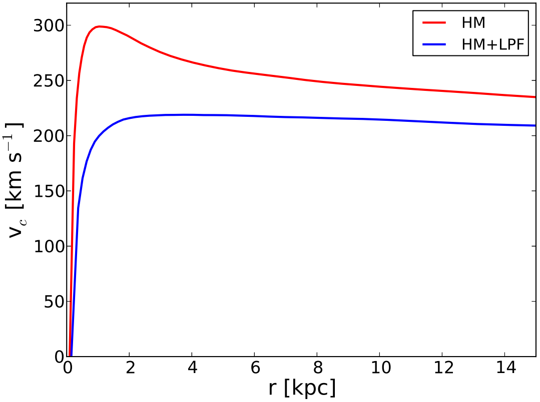
- Gas accretion rate onto the disk of the central galaxy
  - HM = $7.25 M_{\odot}/yr$
  - HM+LPF = $4.10 M_{\odot}/yr$



Temperature histogram



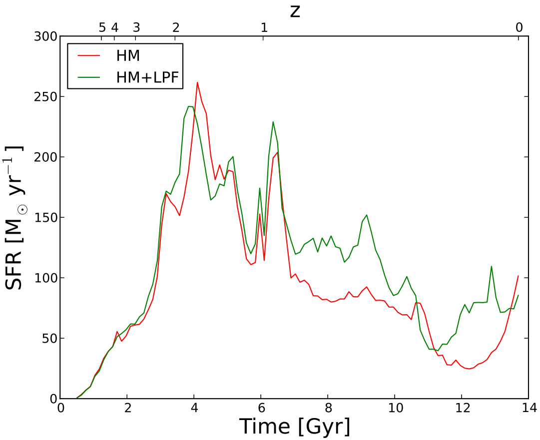
Rotation Curves



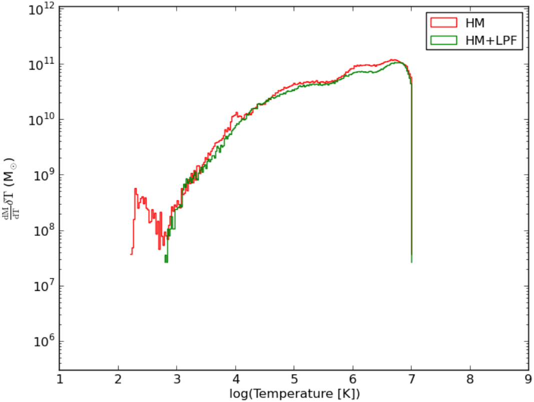
Simulation of high mass galaxy

- Halo mass - 10^{13} $M_\odot$
- SNe Feedback + Early Stellar feedback - Stinson+2013
- Metal cooling
  - Only UV background - HM run
  - UV background + local photoionizing radiation sources - HM+LPF run

Rotation curves



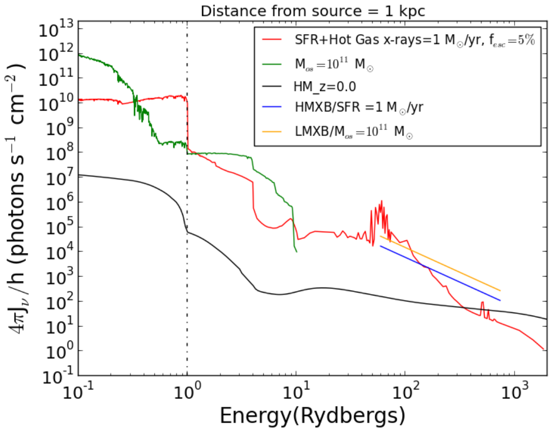
Temperature histogram



X-ray binaries (See also M. Gilfanov's Talk)

- Obervationally for both LMXB and HMXB
  - $\frac{dL}{dE} = AE^{-2}$
- Observationally for HMXB's - Mineo+14
  - $(L_x)\big|_{0.5}^{8} = 2.5 \times 10^{39}\ \ \mathrm{erg/s}$ for a SFR of $1\ \mathrm{M_\odot/yr}$
- For LMXB's - Gilfanov 2004
  - $(L_x)\big|_{0.5}^{8} = 1 \times 10^{40}\ \ \mathrm{erg/s}$ per $10^{11}\mathrm{M_\odot}$

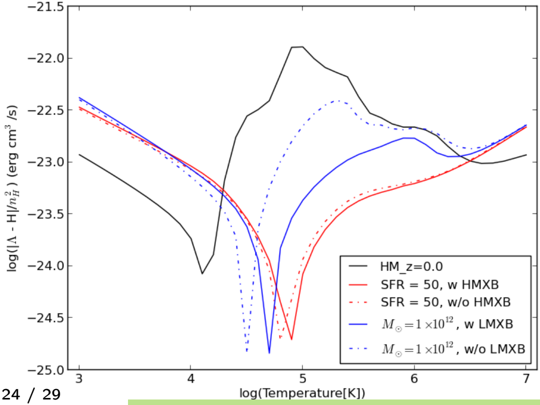
X-ray binaries



X-ray binaries

$n_H = 0.001 cm^{-3}$, $Z = 0.1 Z_\odot$, Distance = 3 kpc

Low mass x-ray binaries have larger effect - Additional source in the x-ray regime

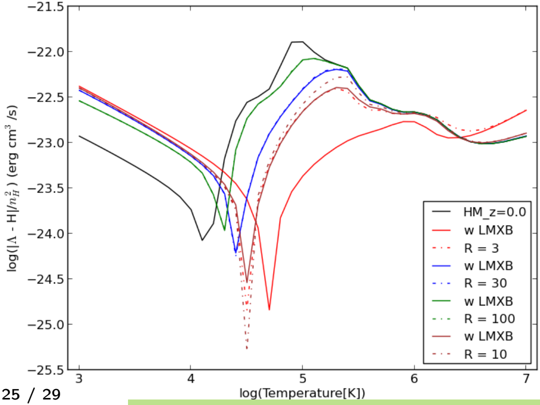


X-ray binaries - LMXBs

$n_H = 0.001 cm^{-3}$, $Z = 0.1 Z_{\odot}$

Low impact at large distances

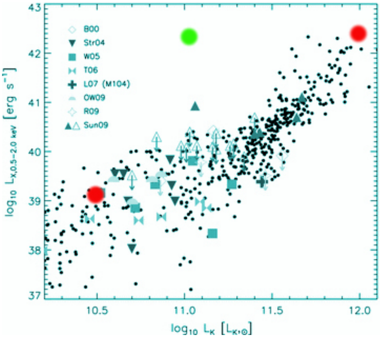
Need to know the soft x-ray emission form binaries



Hot Halo Emission

- Consider only free-free emission form hot gas
- $j_\nu^{ff} = 5.44 \times 10^{-39} Z^2 g_{ff} T^{-1/2} e^{-h\nu/k_B T} n_e n_i \;\; erg/s/cm^3/Hz/ster$

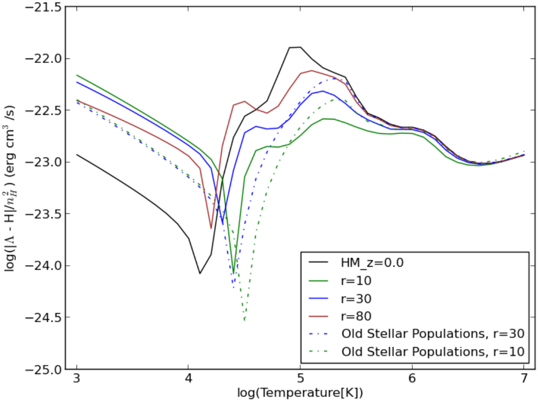
- Lower mass simulation ($6.5 \times 10^{11} M_\odot$) predicts correct L_x value
- Overcooling problem in high mass halos ($10^{13} M_\odot$) also linked with higher L_x



Crain + 10

Effect of boosted cooling radiation

$n_H = 0.001 cm^{-3}$, $Z = 0.1 Z_\odot$



Conclusions

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- MW mass galaxy simulation shows
  - 67% reduction in SFR at late times
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  - Slowly rising rotation curves

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- Novel new method introduced to include the effects of local photoionizing radiation field in cosmological simulations (Kannan et al. 2014b)
- MW mass galaxy simulation shows
  - 67% reduction in SFR at late times
  - ~ 40% reduction in total stellar mass of galaxy
  - Slowly rising rotation curves
- Two different effects of LPF as seen in phase diagram
  - Stops gas accretion onto the disk thereby reducing fuel for star formation - Preventive feedback
  - Stops gas in the disk from getting cold - stabilising the disk through pressure support
- *Preventive* feedback mechanism

Conclusions

- Does not work for high mass galaxies

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- Does not work for high mass galaxies
- Additional radiation sources might have an impact on high mass galaxy formation
    - HMXB's - slight increment in the hard X-ray regime
    - LMXB's - Source of X-rays from old stellar populations - promising but need to figure out the soft x-ray component
    - Cooling radiation from hot halo - very low impact even with boosted radiation fields
    - Accreting White Dwarfs ? (see M. Gilfanov's talk)
    - AGN - Low duty cycle (Vogelsberger+13), might need to account for non-equilibrium effects (Oppenheimer & Schaye 2013 a,b)