Where are the baryons in the universe? Theoretical perspective

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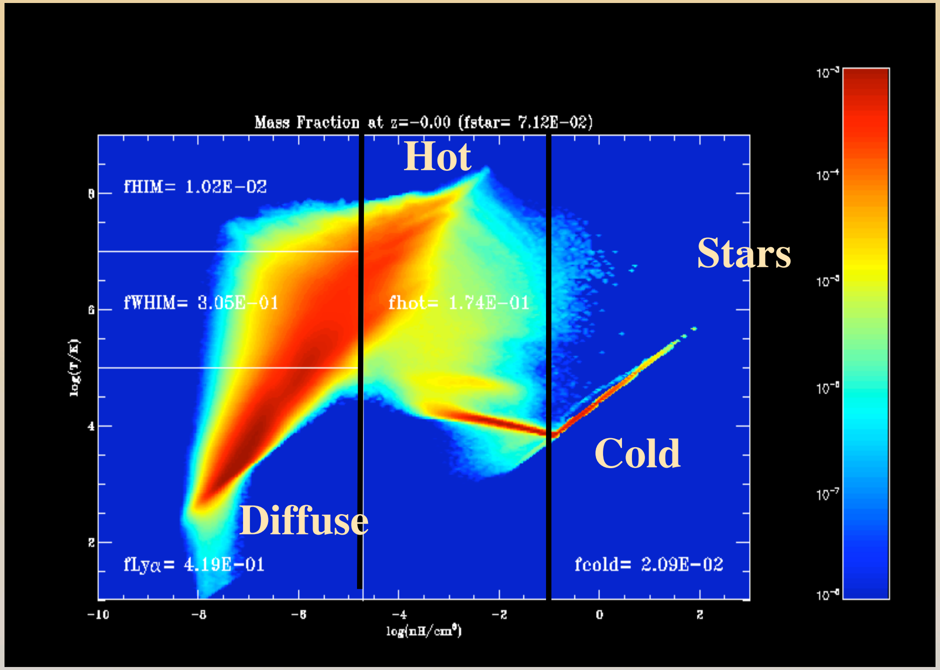
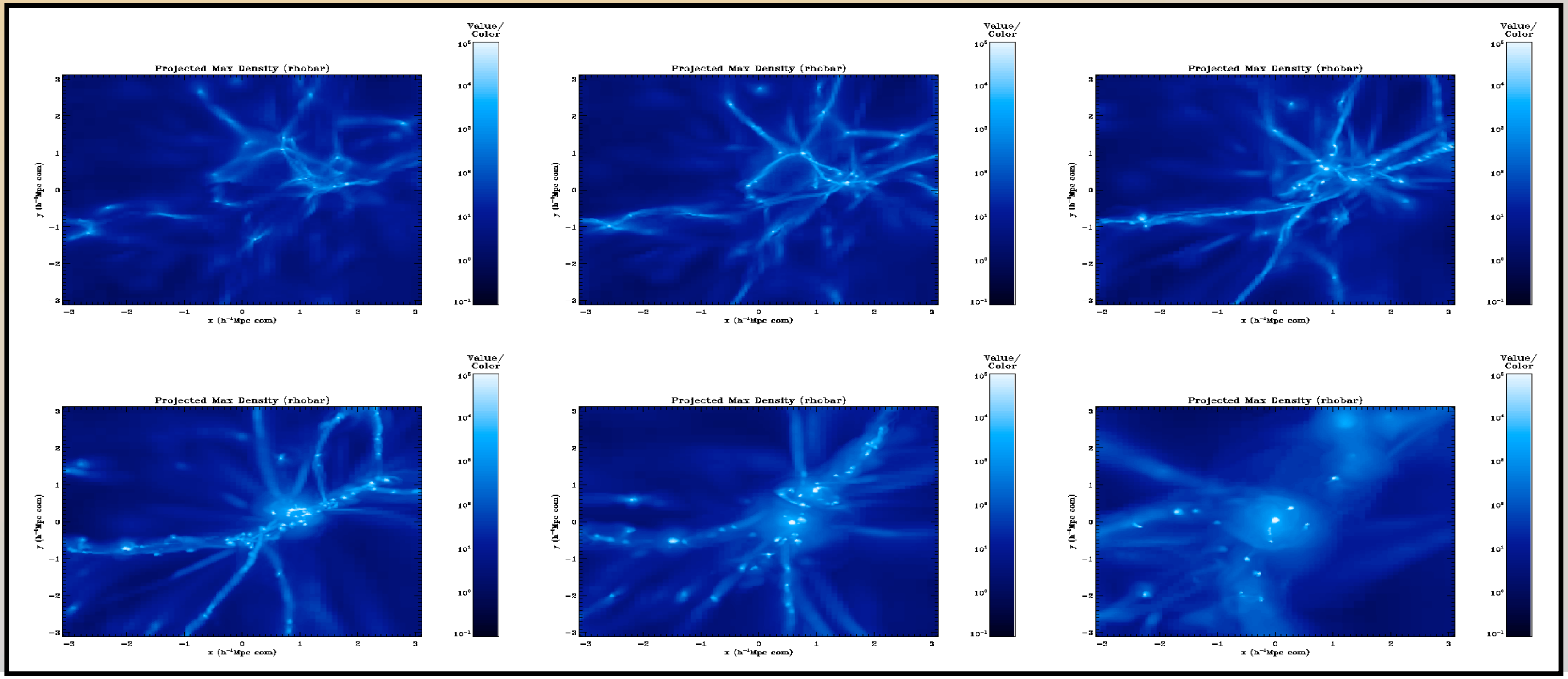


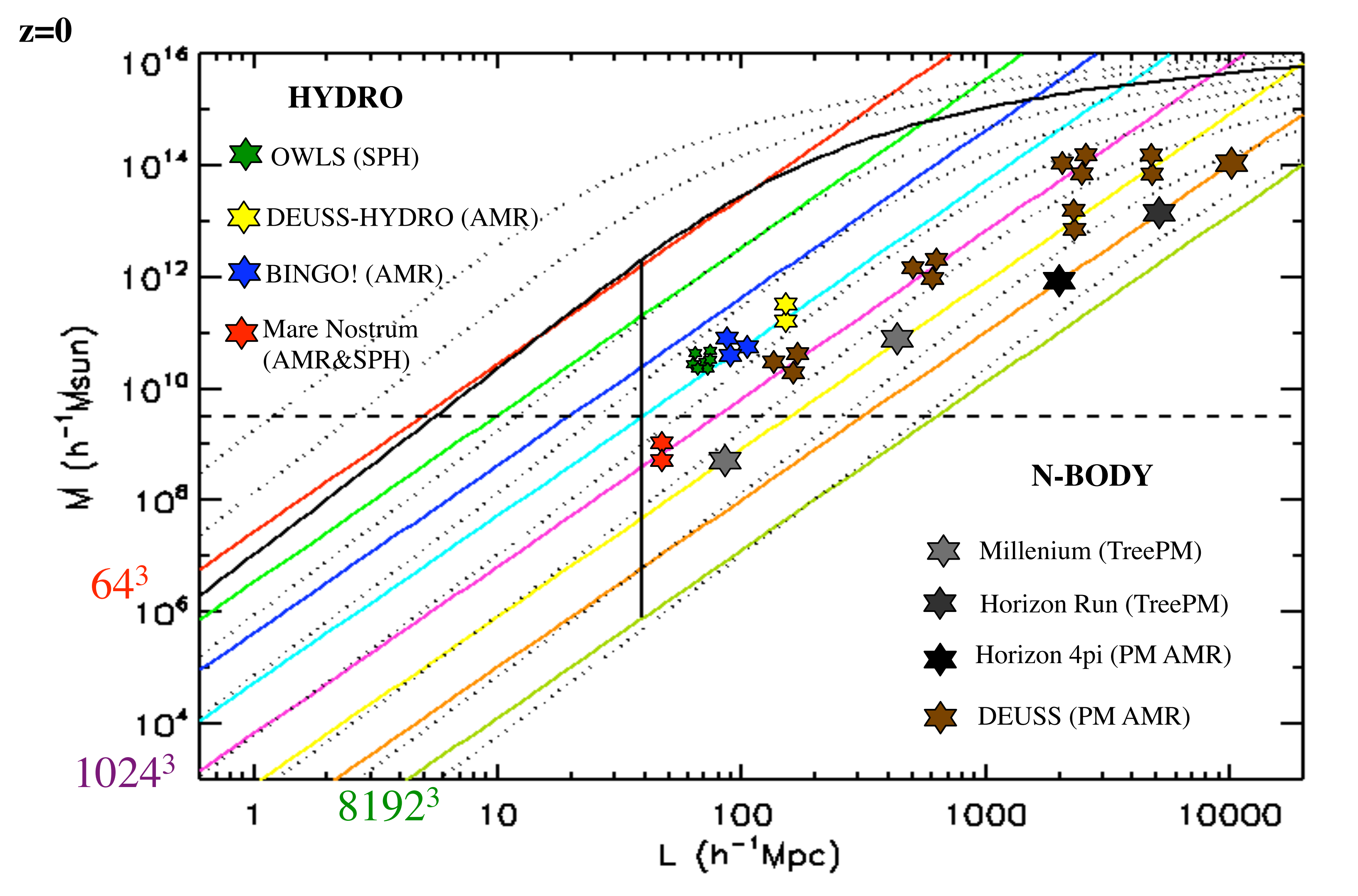
OUTLINE

- **What we probably know: Accretion**
- **What we might know: Cooling**
- **What we would like to know? Star formation and feedback**

- **Hierarchical model of galaxy formation**:
  - Cold Dark Matter framework
  - Small primordial fluctuations + gravitational instability
  - Gas falls into dark matter halos (streams) to form galaxies
  - Galaxies merge and grow
- **CODE (Romain Teyssier and collaborators)**
  - RAMSES (evolves DM+gas+stars under gravity, cooling, heating, star formation and AGN or SN feedback from z of order 100 to z=0)



Mass limitations of simulations



✶Typical Volume Simulations: 10TB

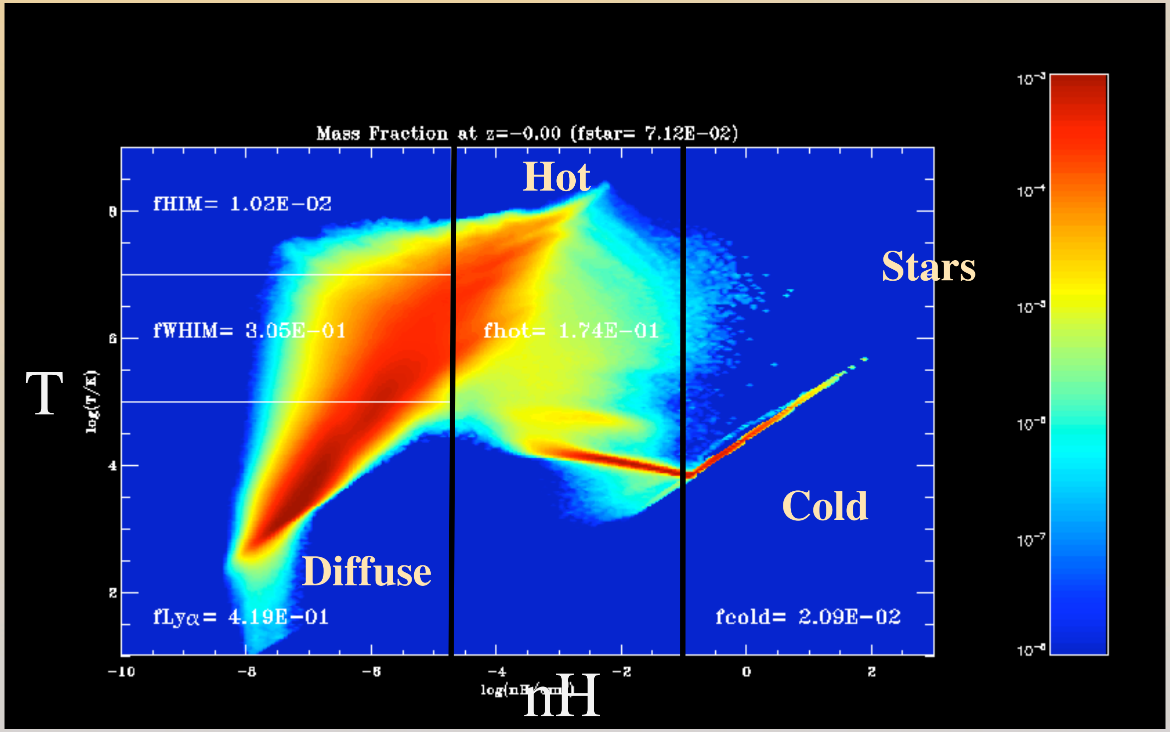
✶Typical mono-cpu time: 1 000 000h

✶Typical number of processus: 5 000

✶Typical memory: 10 TB

✶Model: phases definition in the density-temperature plane

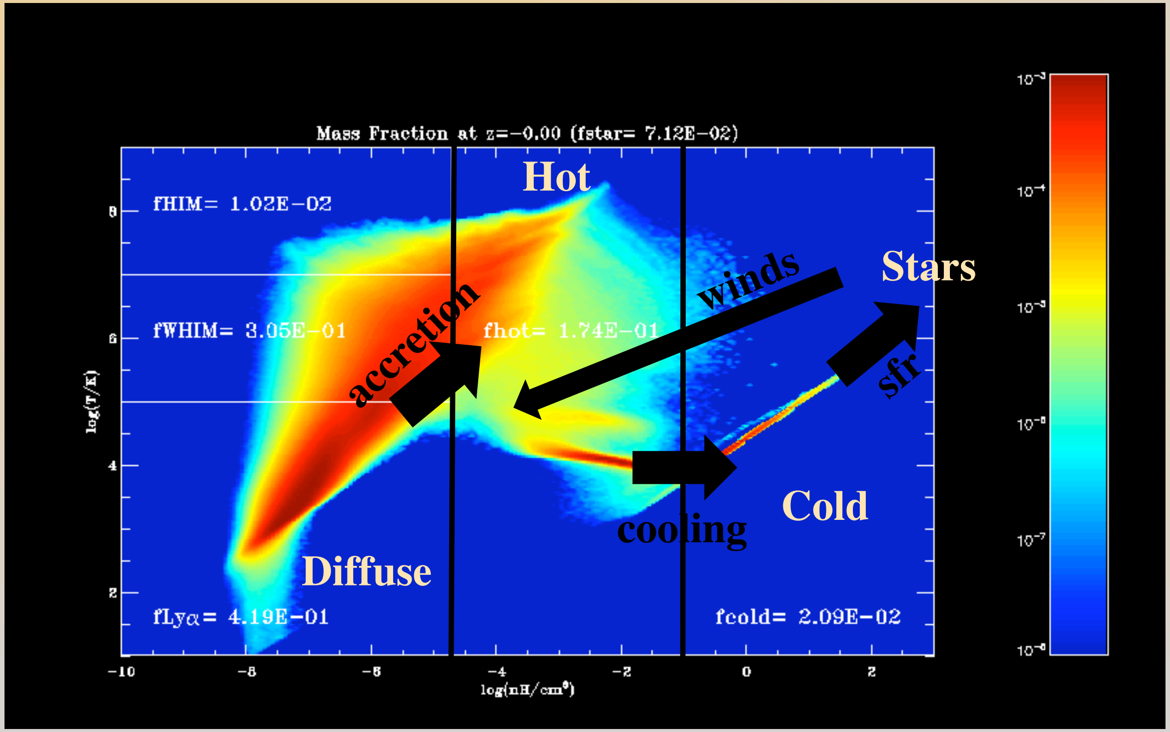
- **Diffuse background :** Lyalpha (delta<100, T<10^5K), WHIM (delta<100, 10^5K<T<10^7K), HIM (delta<100, T>10^7K)
- **Hot** : CGM(delta>100, nH<0.1at/cm^3), winds, streams
- **Cold** : star forming gas (nH>0.1at/cm^3)
- **Stars** : stars, remnants, recycled gas



✶Model: average baryon transfer rates (Rasera&Teyssier, 2006)

- **Accretion rate: ?**
- **Cooling rate: ?**
- **Star formation rate: ?**
- **Winds rate: ?**

Where are the winds going?



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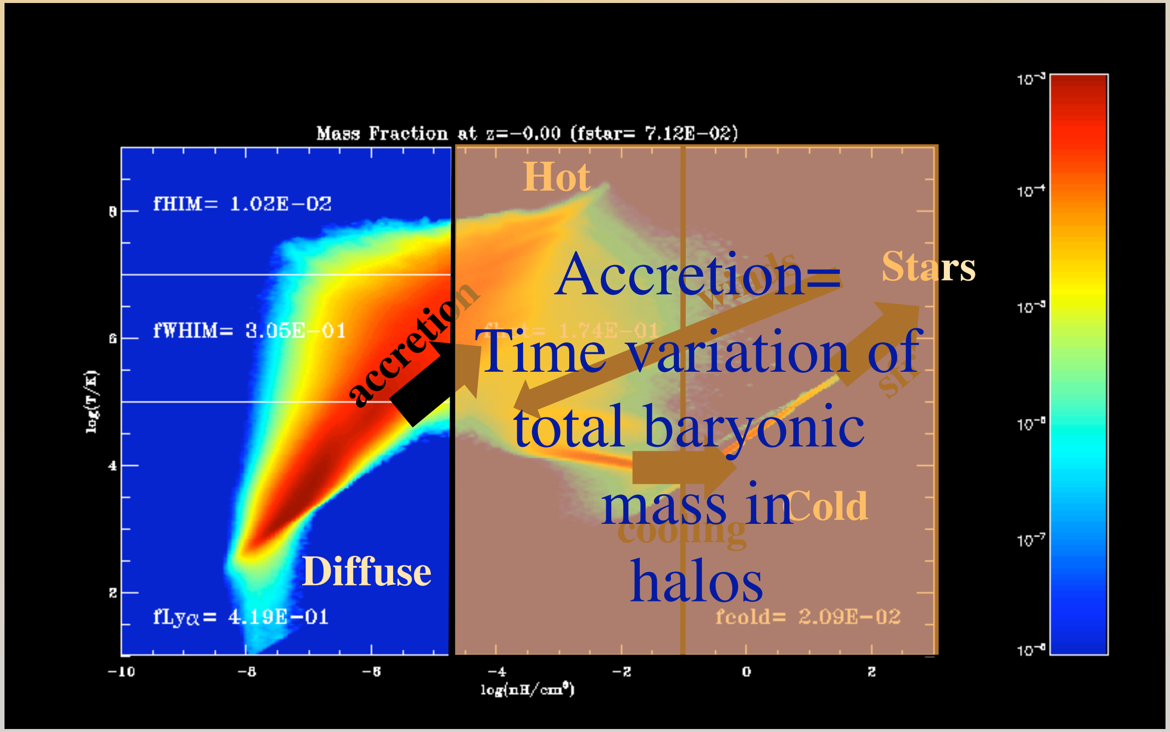
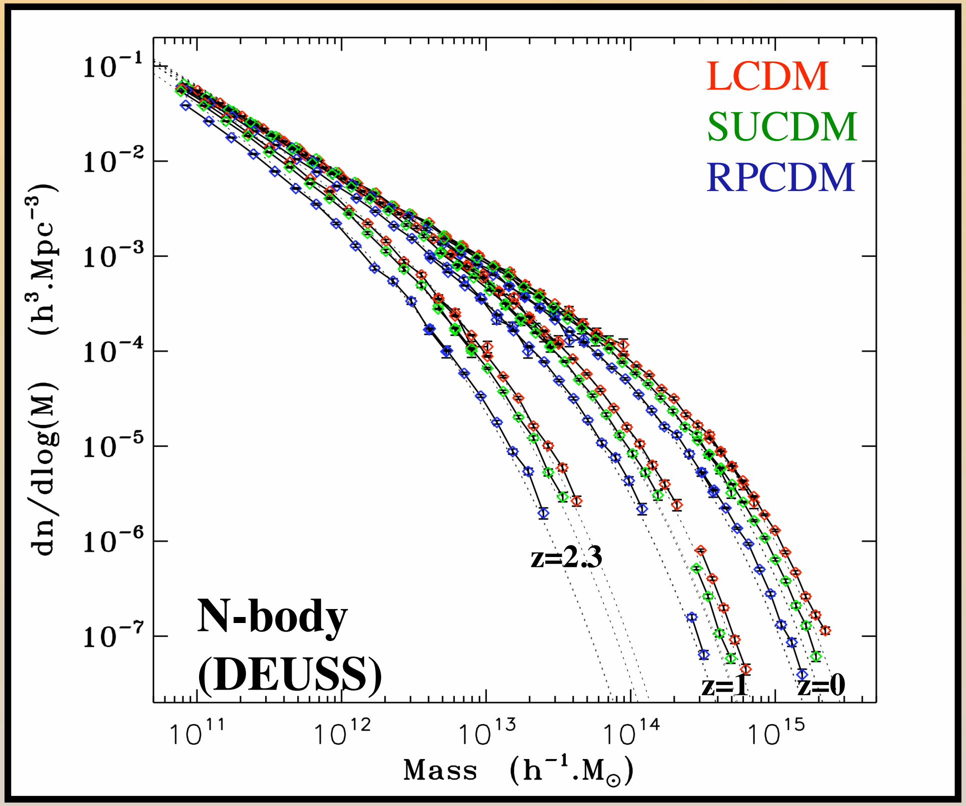
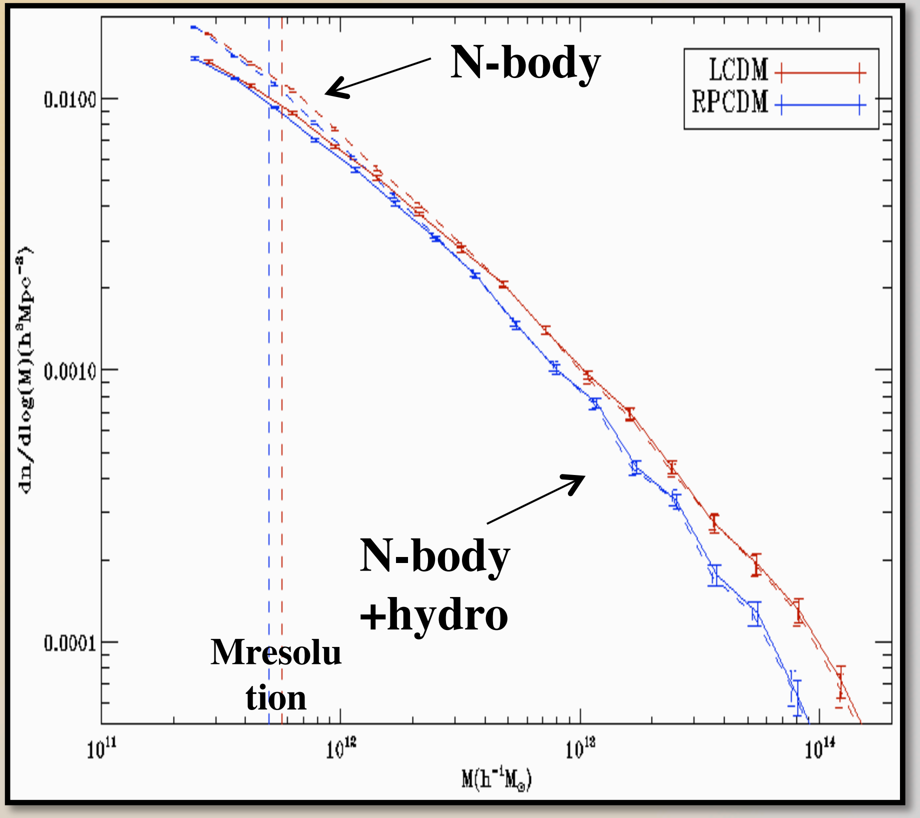


Ingredients:
Dark matter halo mass function +
baryonic fraction+
Mass threshold

Dark matter halo mass function

✶N-body simulations/N-body+hydro simulations





Total halo mass function (M_{200})varies very little with baryons

Needs further studies for small mass haloes

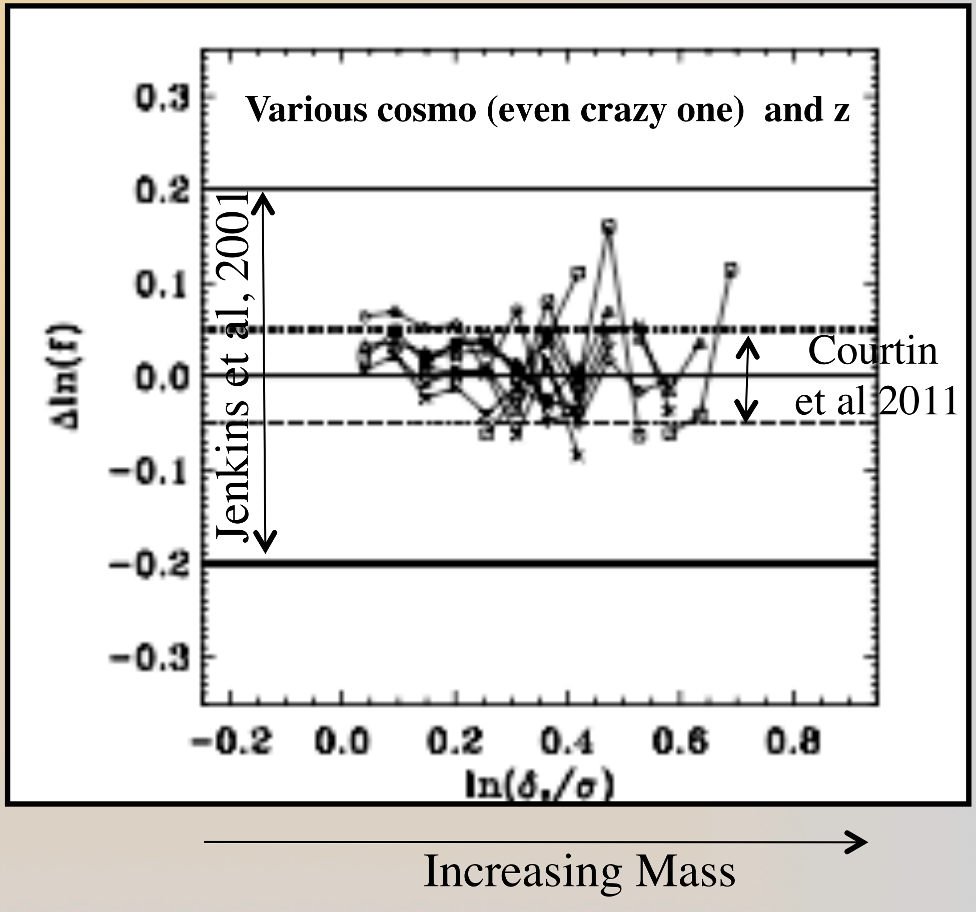
Dark matter halo mass function

- ✶Excursion Set Theory (Corasaniti&Achitouv 2011)
- ✶Cosmology-dependant threshold deltac
- ✶Halos are not spherical => proper halo finder (FOF, HOP,…)
- ✶Cosmology-dependant ENCLOSED (ie. not spherical) overdensity deltavir

⇒**5% accuracy (Courtin et al, 2011, More et al, 2011)**

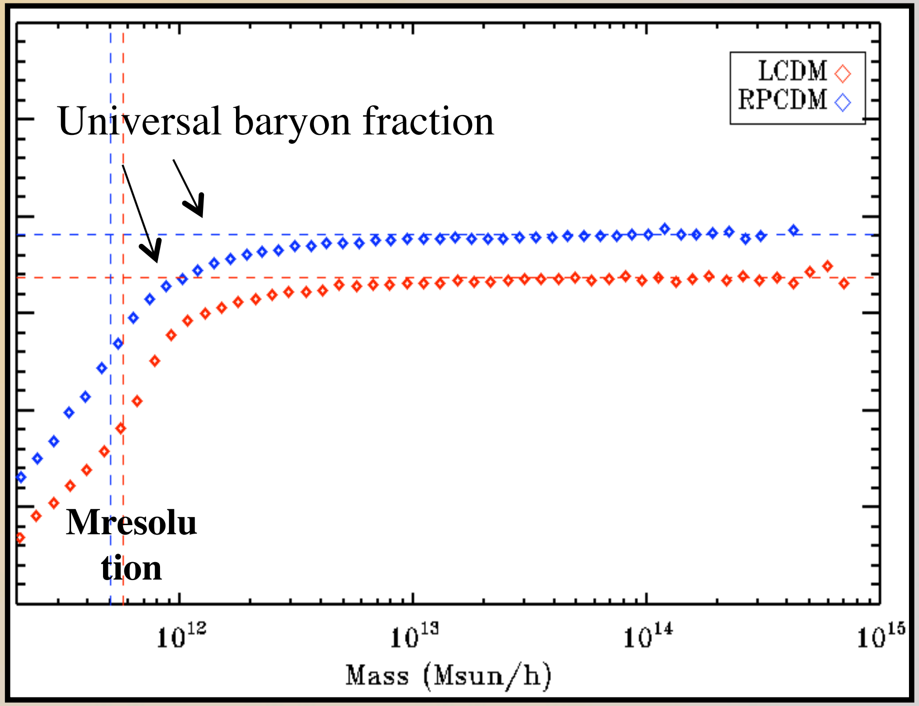
Otherwise 20% deviation depending on redshift/cosmology

DEVIATION FROM THEORY

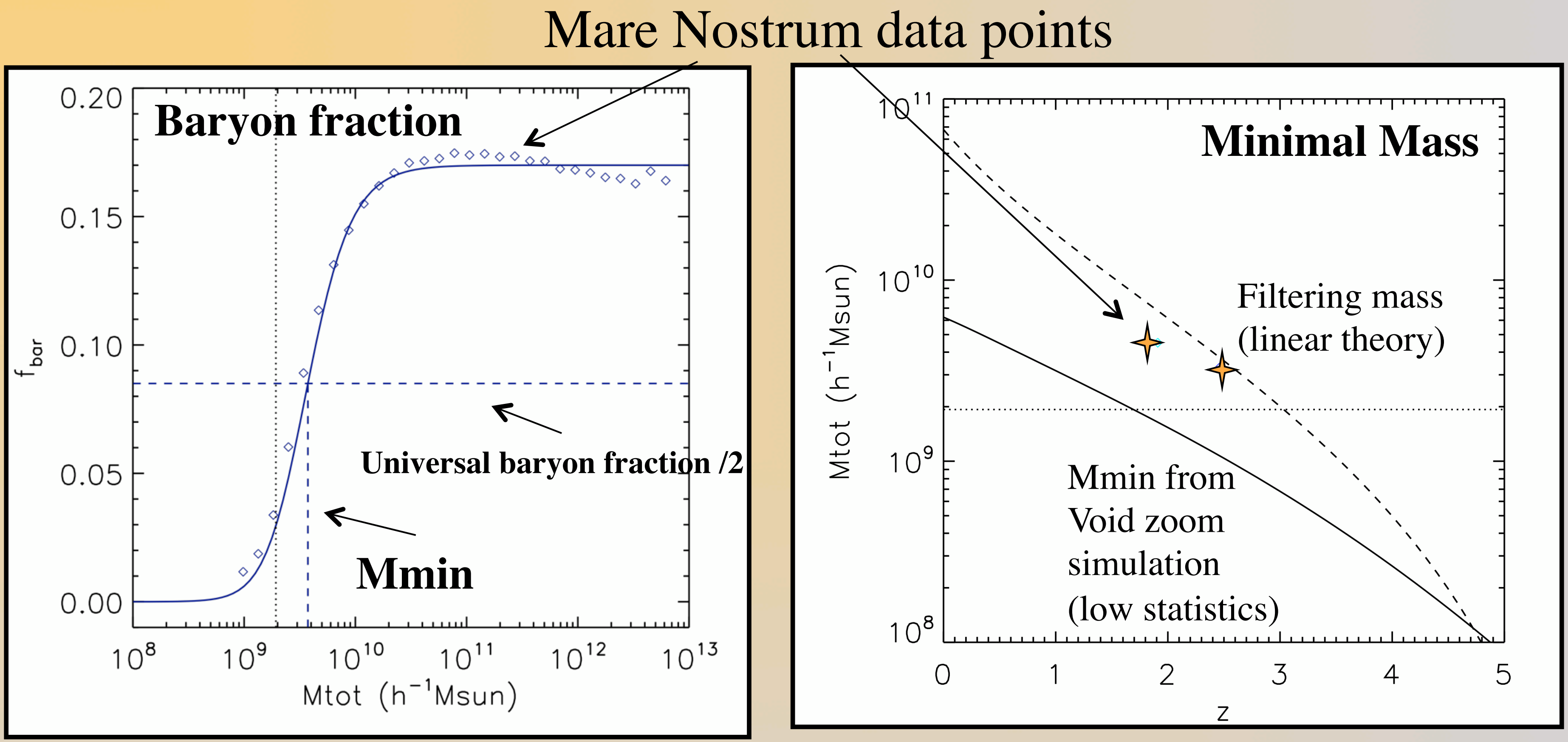


Baryon fraction

- ✶Close to universal baryon fraction Ωb/Ωm for high mass halos
- ✶Increase slightly with cooling
- ✶Decrease slightly with winds

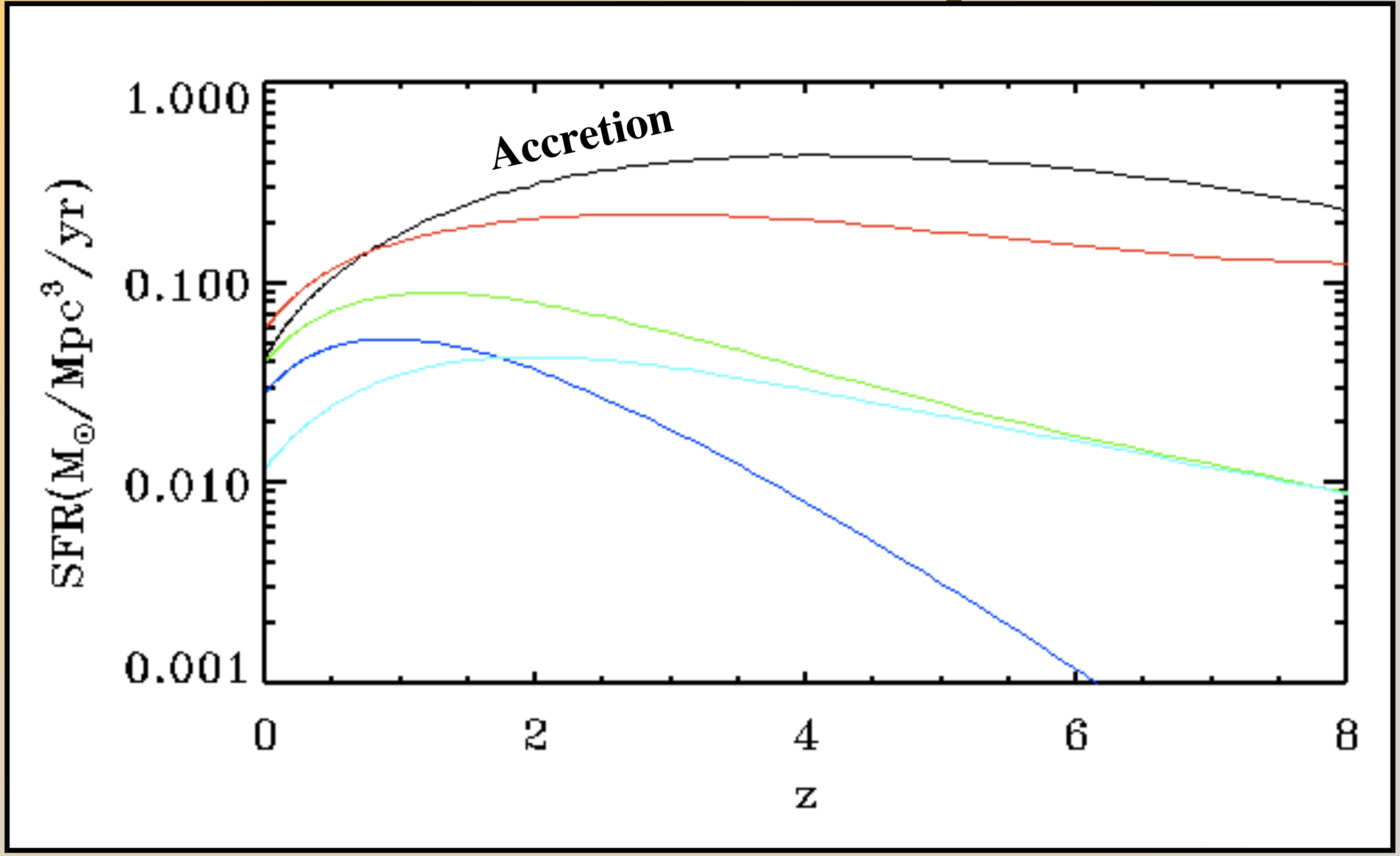


Minimal mass of star forming halos



- ✶Baryonic fraction drops near the Minimal mass for star forming halo Mmin
- ✶Evolution of Mmin close to filtering mass (Jeans mass) but a bit below

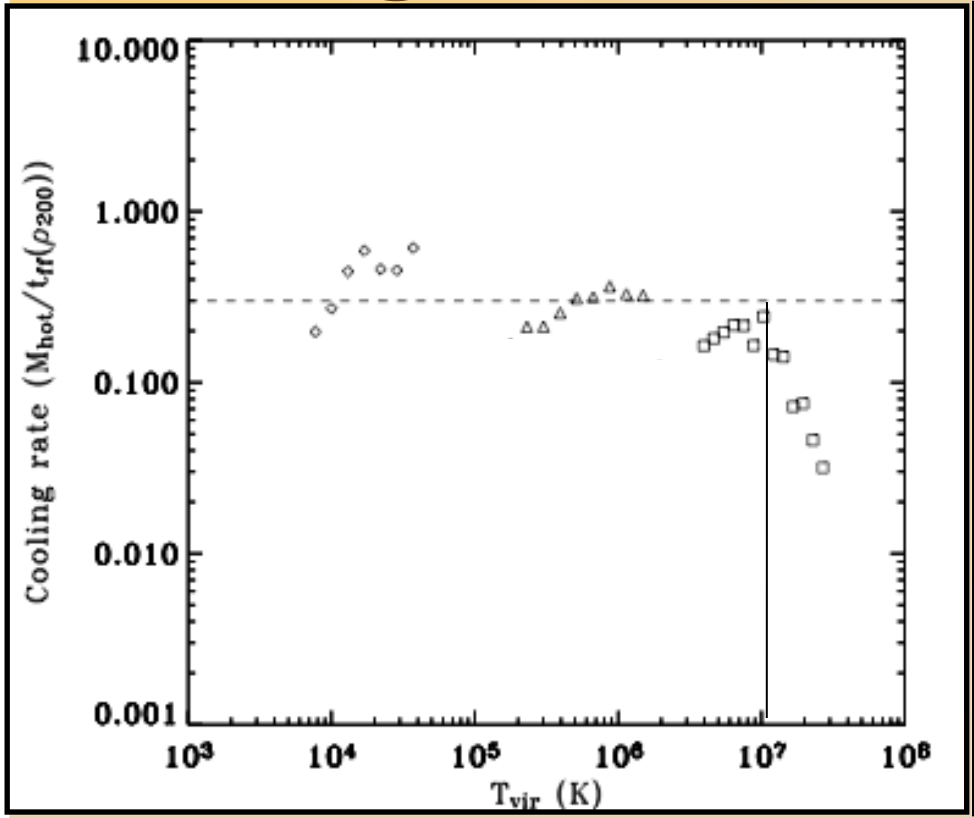
Accretion or the envelope of CSFR

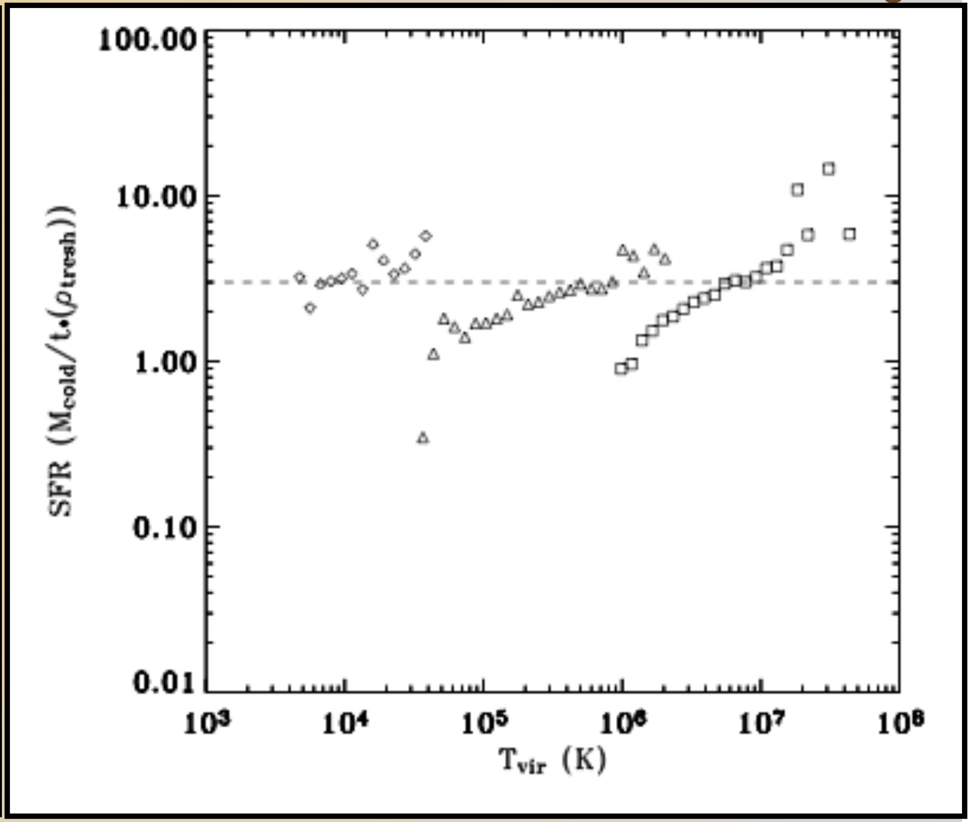


- Accretion can be computed easily

$$\frac{\dot{M}_{acc}}{M_{200}} = f_{bar} \frac{dF(> T_{min})}{dt}$$

Cooling and star formation efficiency





✶Cooling is calibrated on simulation: governed by free-fall time

$$\dot{M}_{cool} = \frac{M_{hot}}{<t_{cool}>}$$

✶Halo SF efficiency governed by local SF efficiency

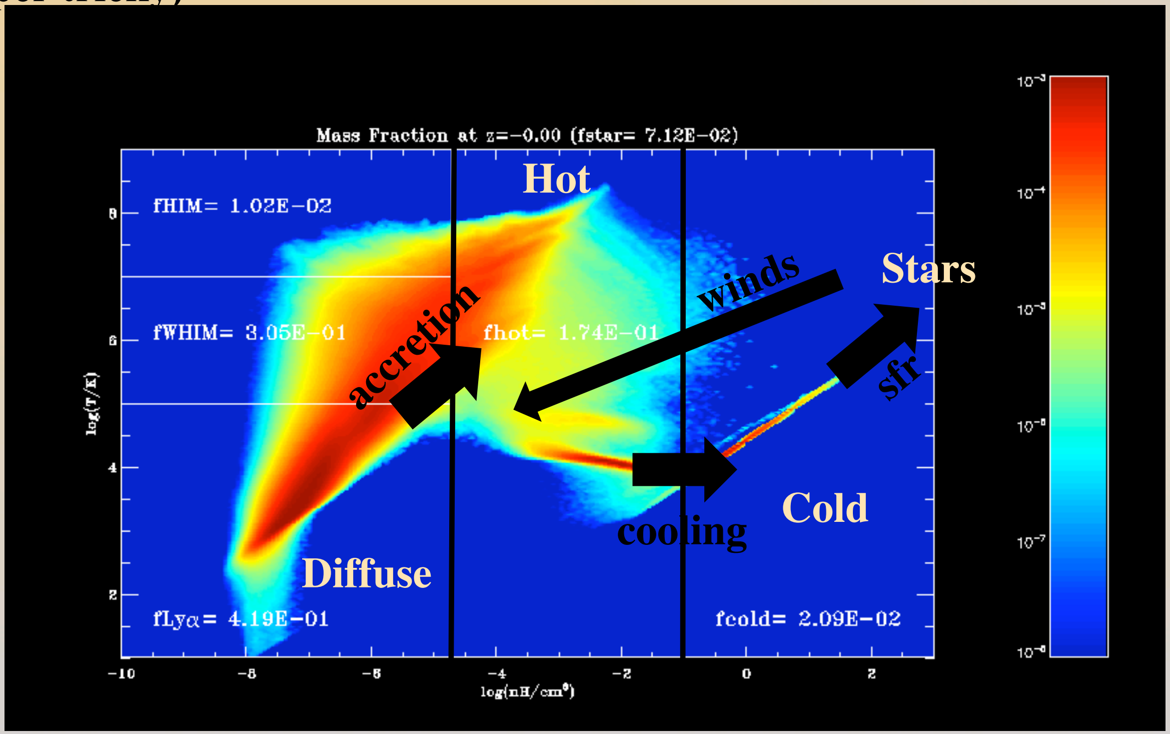
$$\dot{M}_{*} = \frac{M_{disc}}{<t_{*}>}$$

Average over all halos (important role of mass function)

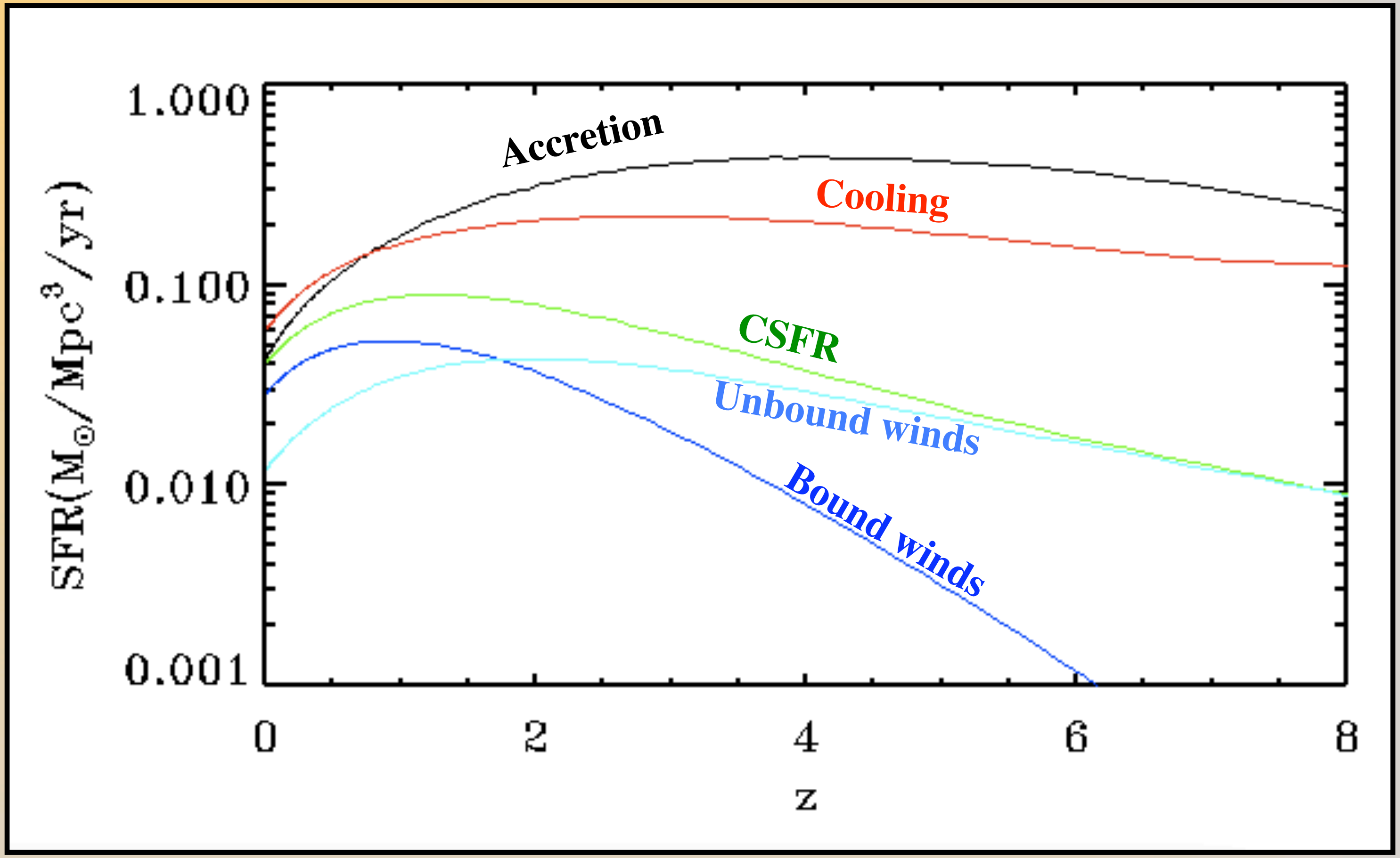
✶Model: average baryon transfer rates (we refer here to Rasera&Teyssier, 2006 and don't go in the details)

- **Accretion rate:** $\frac{\dot{M}_{acc}}{M_{200}} = f_{bar}\frac{dF(>T_{min})}{dt}$ **(robust)**
- **Cooling rate:** $\dot{M}_{cool} = \frac{M_{hot}}{<t_{cool}>}$ **(roughly ok)**
- **Star formation rate:** $\dot{M}_{*} = \frac{M_{disc}}{<t_{*}>}$ **(bof)**
- **Winds rate:** $\dot{M}_{wind} =< \eta_w > \dot{M}_{*}$ **(tricky)**

Where are the winds going? For halos smaller than T_w, in the background, otherwise in the hot phase (super tricky)



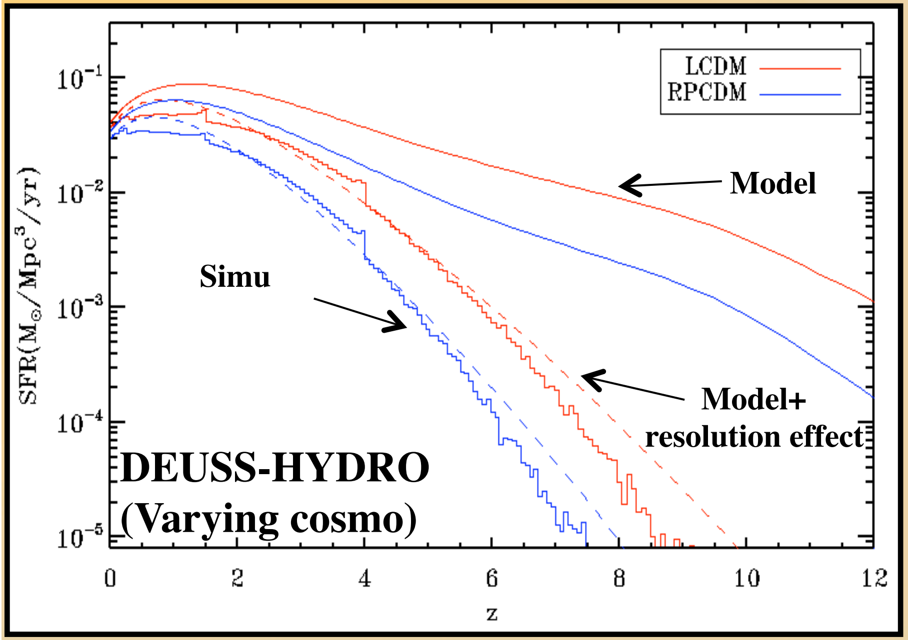
Transfer rates

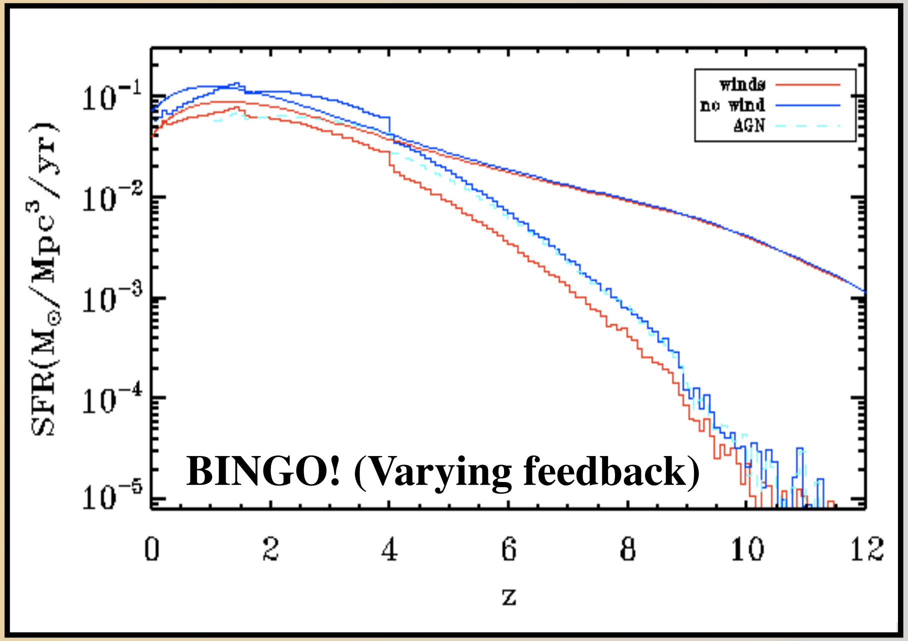


- ✶ Accretion can be computed easily

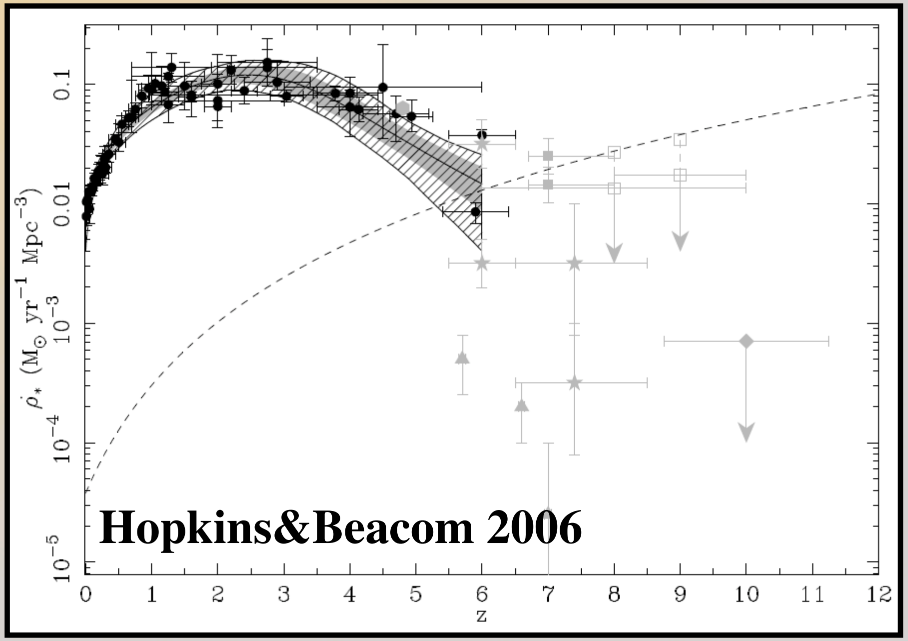
$$\frac{\dot{M}_{acc}}{M_{200}} = f_{bar} \frac{dF(> T_{min})}{dt}$$

✶Cosmic Star Formation Rate

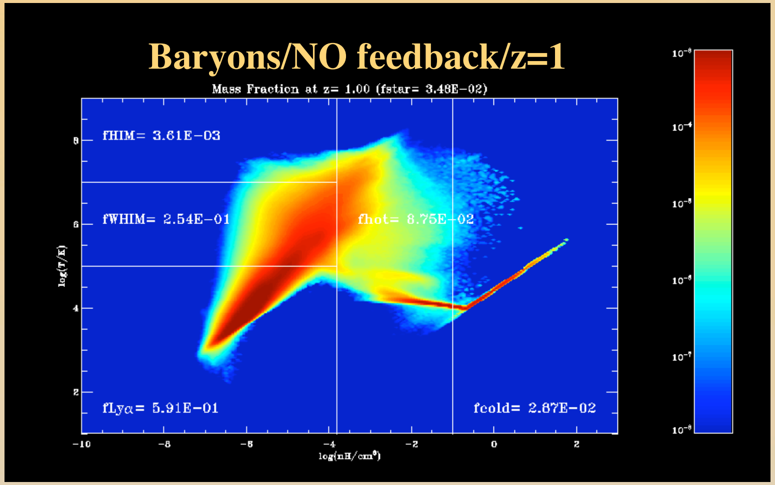


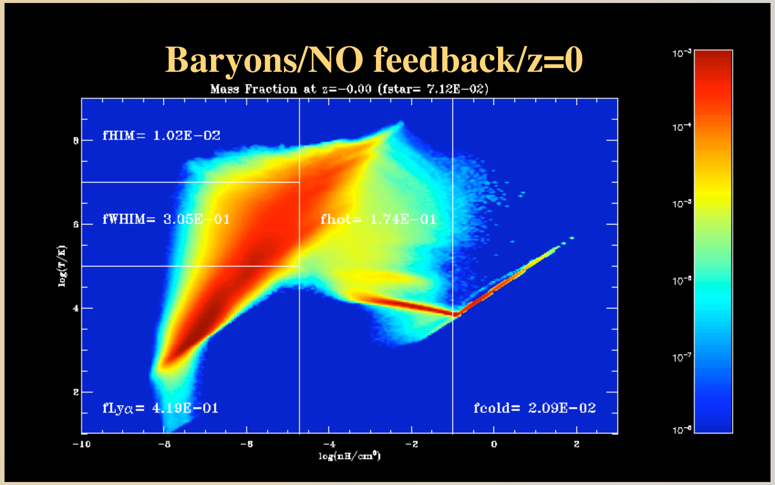


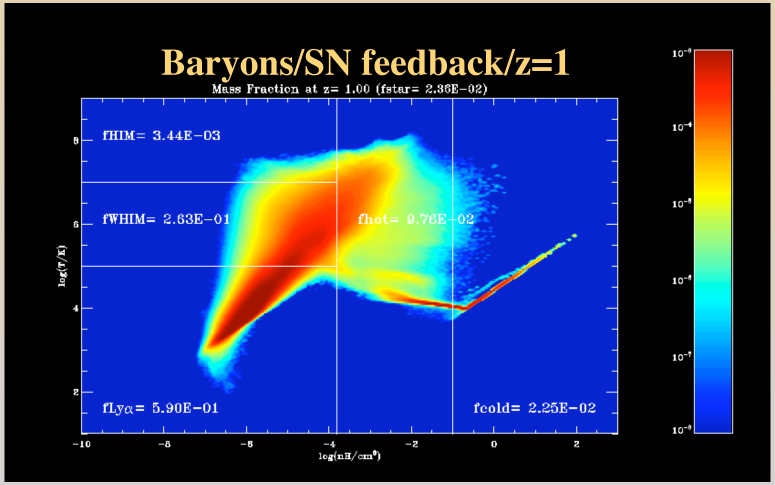
- Agreement simu/model (cross-validation)
- Allow to extrapolate SFR
- DEUSS-HYDRO (V. Reverdy): 2 cosmological models calibrated on SNIa and CMB gives different SFR
- BINGO!&Y.Dubois: AGN feedback required at low redshift. Simu in progress.
- What about high redshift?

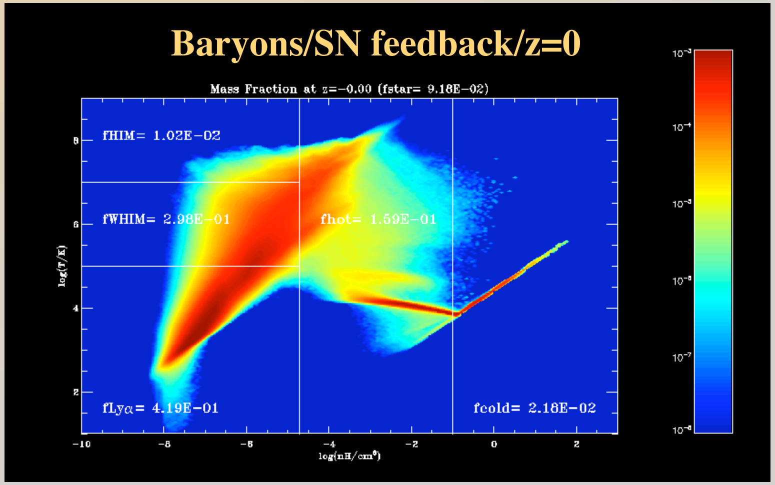


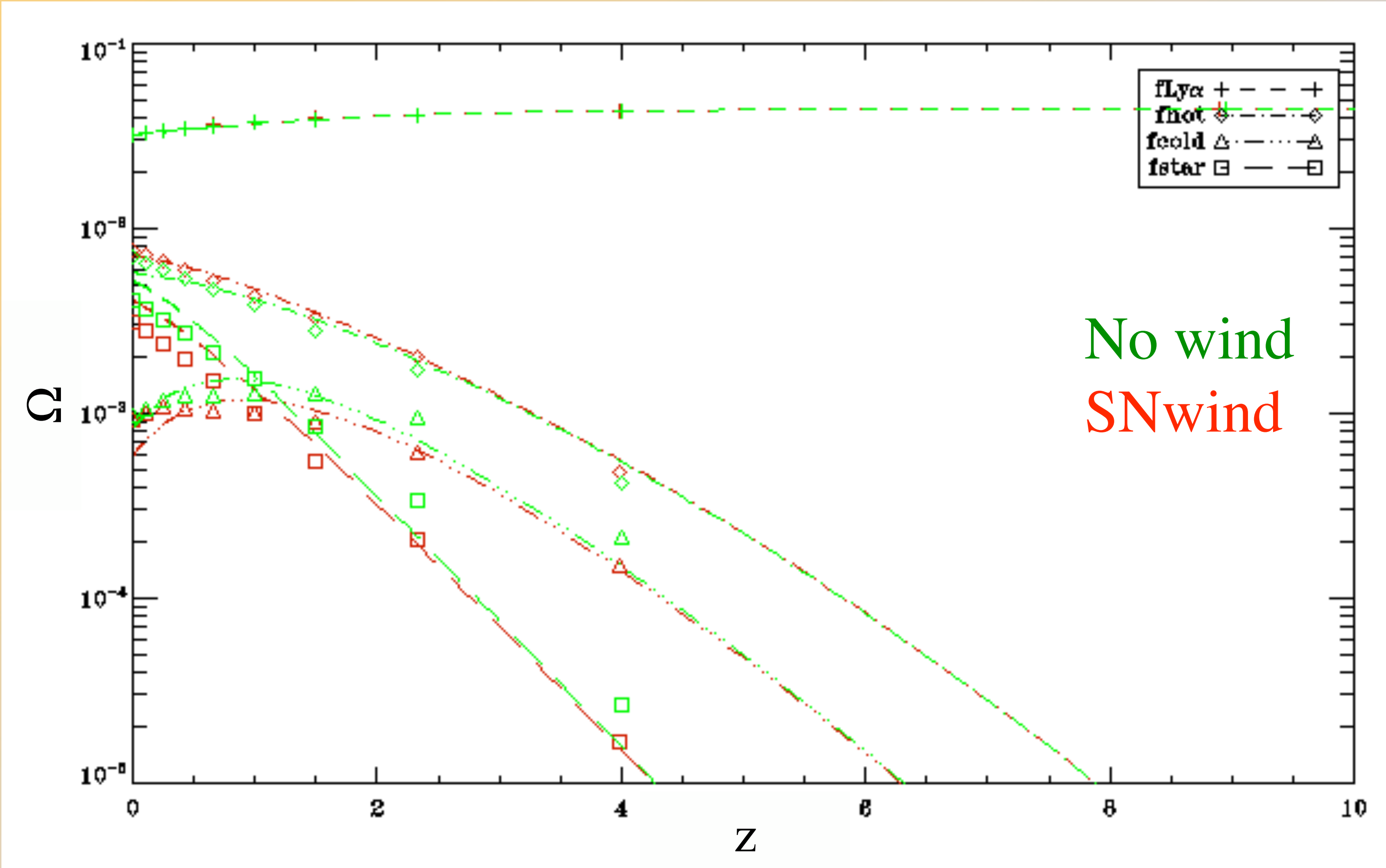
✶Global baryon budget: histograms



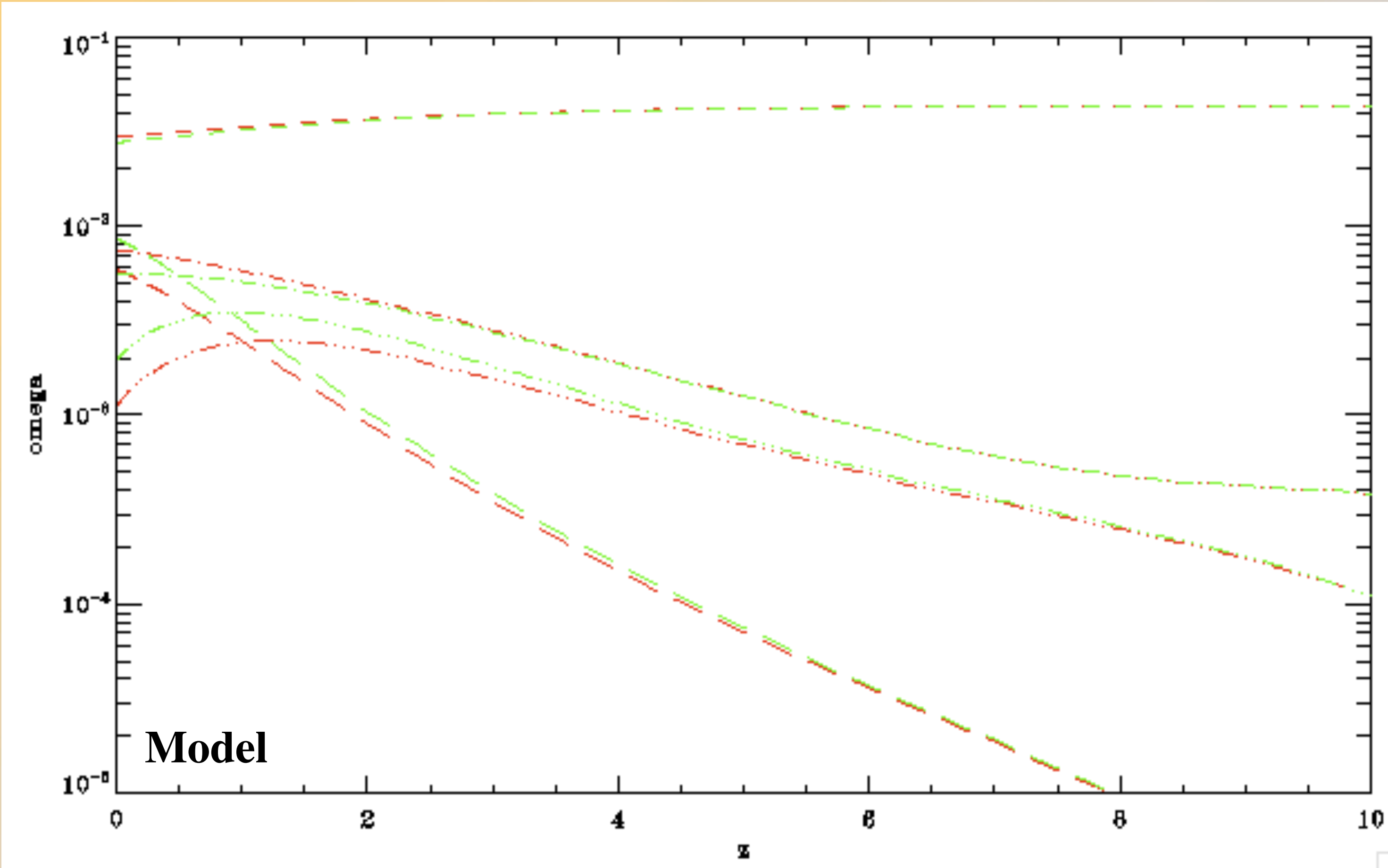








• Good agreement between simu and models
• Extrapolation of baryon budget with model
• SN winds have little effect on the baryon budget (unlike unrealistic winds Springel&Hernquist,2003)
• AGN feedback should change this



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Conclusion

✶ Cosmological simulations+analytical models

- Allow to understand evolution of baryons in universe
- Accretion controls available gas for star formation
- Cosmology can change amplitude of CSFR
- SN winds not powerful enough to change baryon budget
- we can use the same formalism and methods for metals budget
- we can use the same formalism and methods for halos

✶ Next

- Studies the fate of winds in more details (important for metals)
- Finish jet AGN simulations
- Analytical models for AGN jet

★High resolution (billion cells) AMR cosmological simulation with jets from (Credits: Y. Dubois & BINGO!)

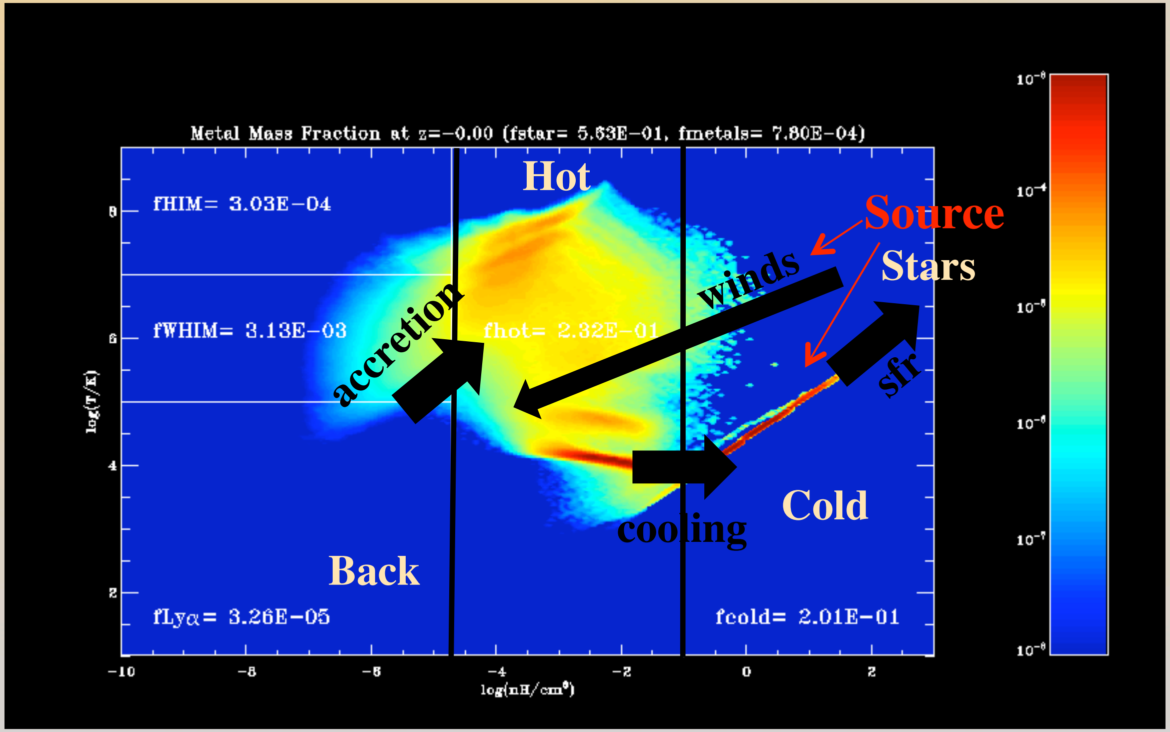
green: gas density

red:gas temperature

blue: gas metallicity

✶Model: average **METAL** transfer rates

- **Advection:** same as for baryons (black arrows)
- **Source term (SN):** $\dot{M}_Z = \eta_{sn} \times yield \times \dot{M}_*$
- Consequence: total amount of metals is not constant (but easy to compute from SFR)
- Issues: Which fraction goes to cold, hot and background phase? **Budget very sensitive!!!**
- Adopted solution: assume given wind metallicity Z_w
- Fraction of metal in wind (ie hot+back), $f_Z^w = \eta_w/\eta_{sn} \times Z_w/yield$ and in cold $f_Z^{cold} = 1 - f_Z^w$



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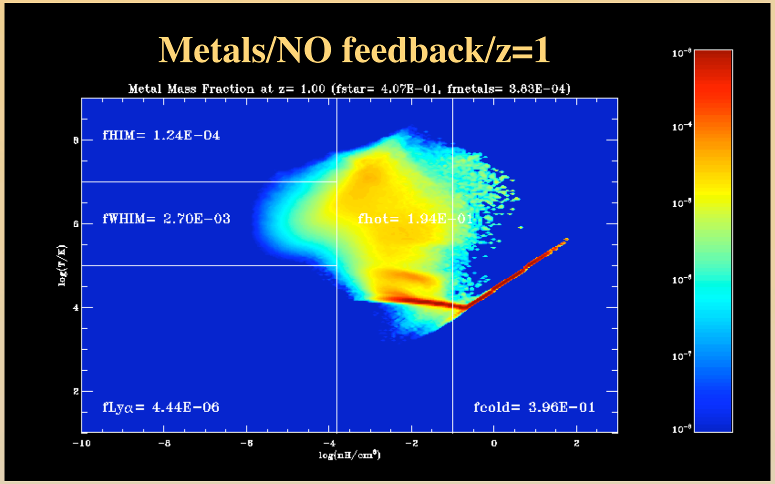
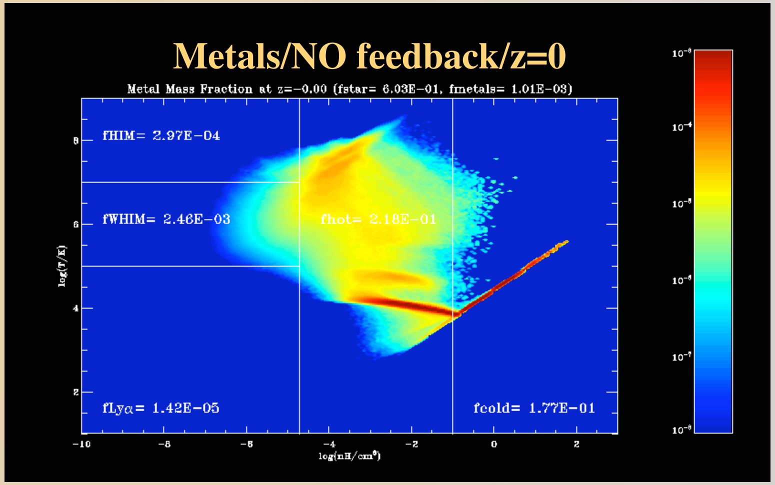
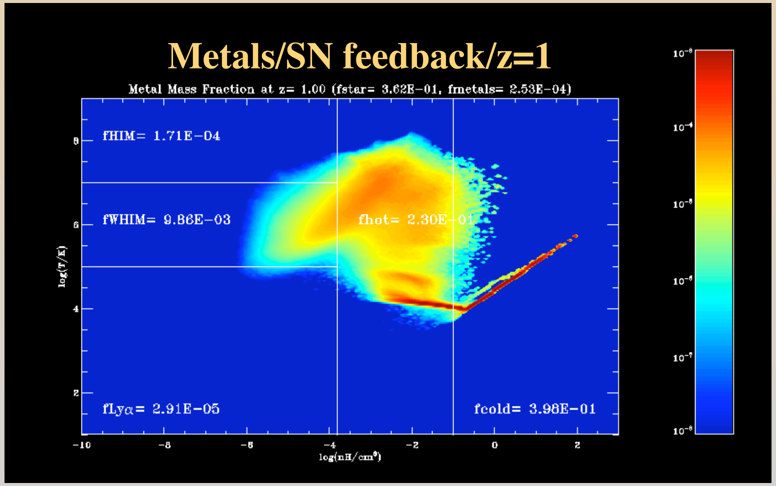
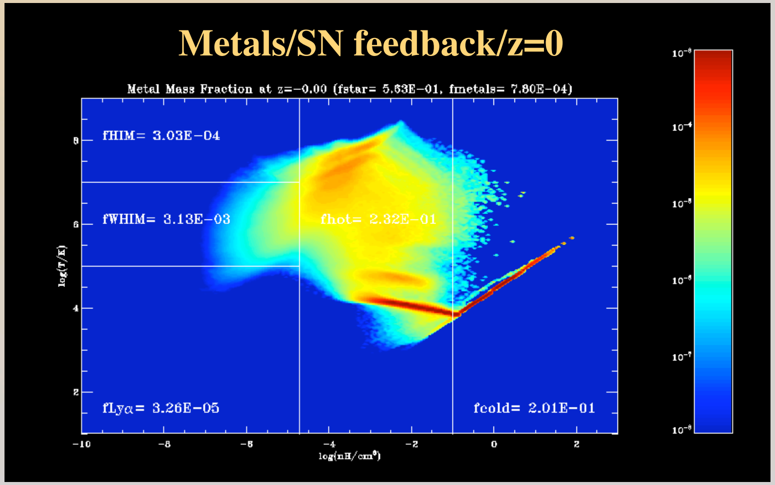
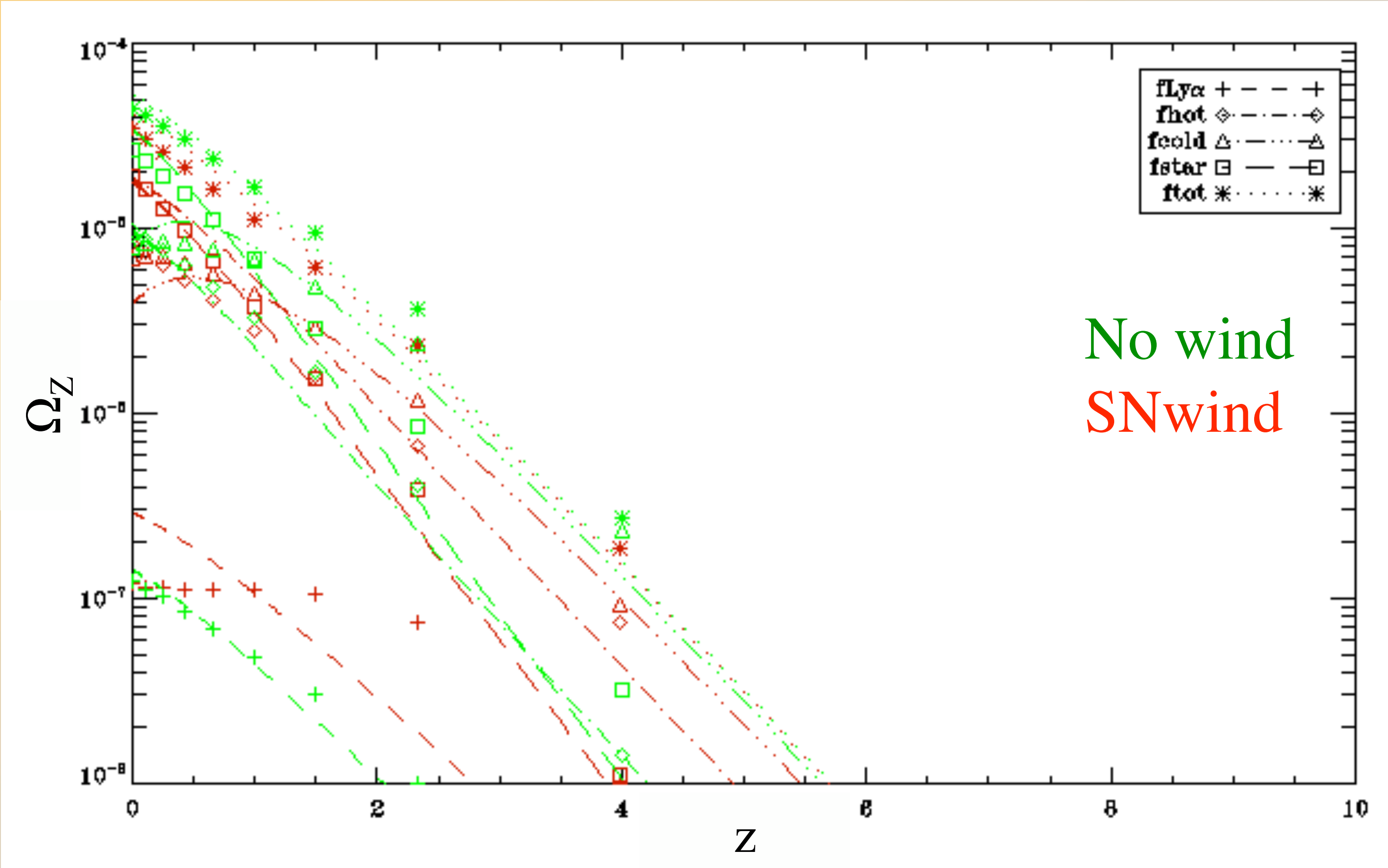






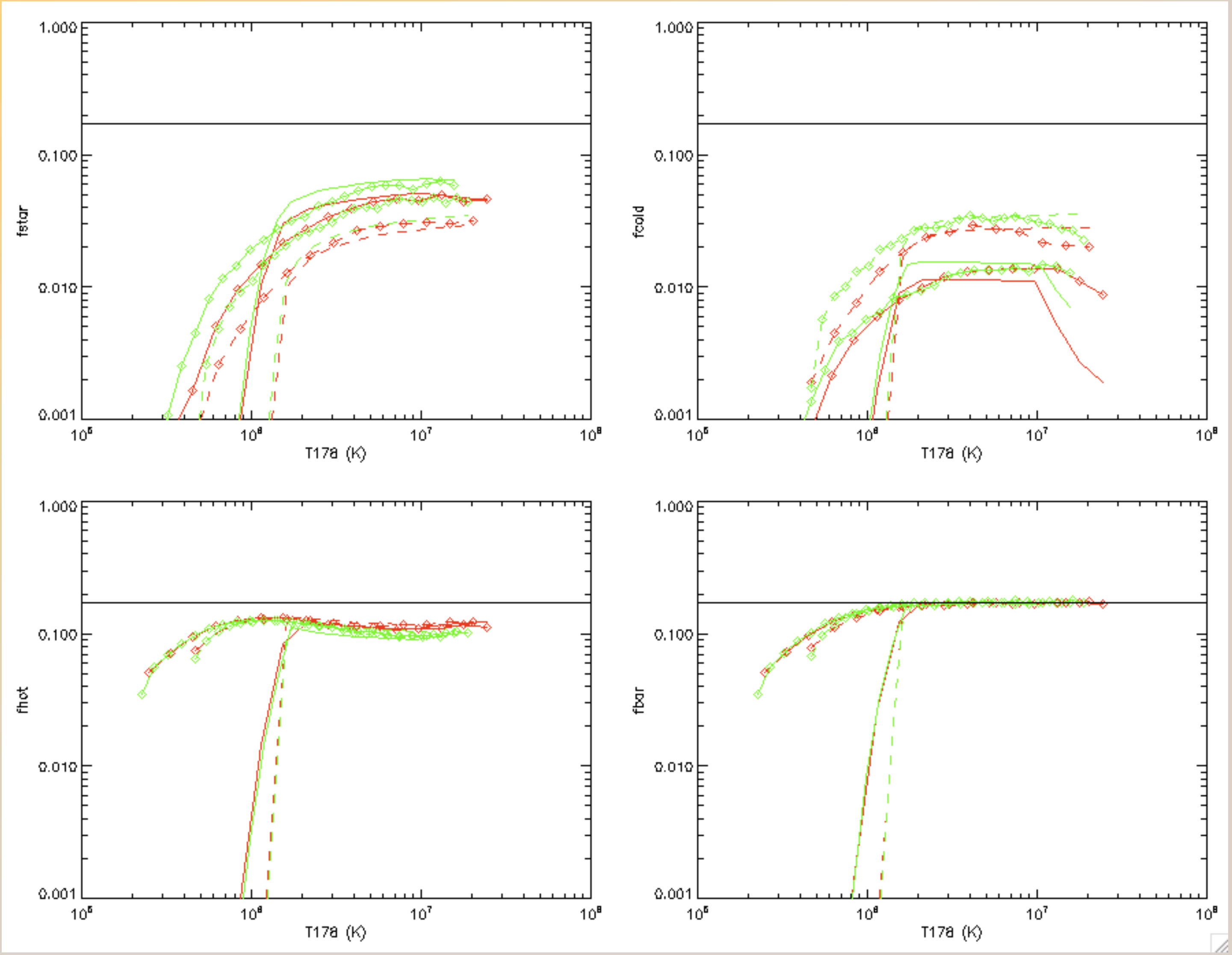


✶Global metal budget: evolution (don't worry I will make the plot nicer!)

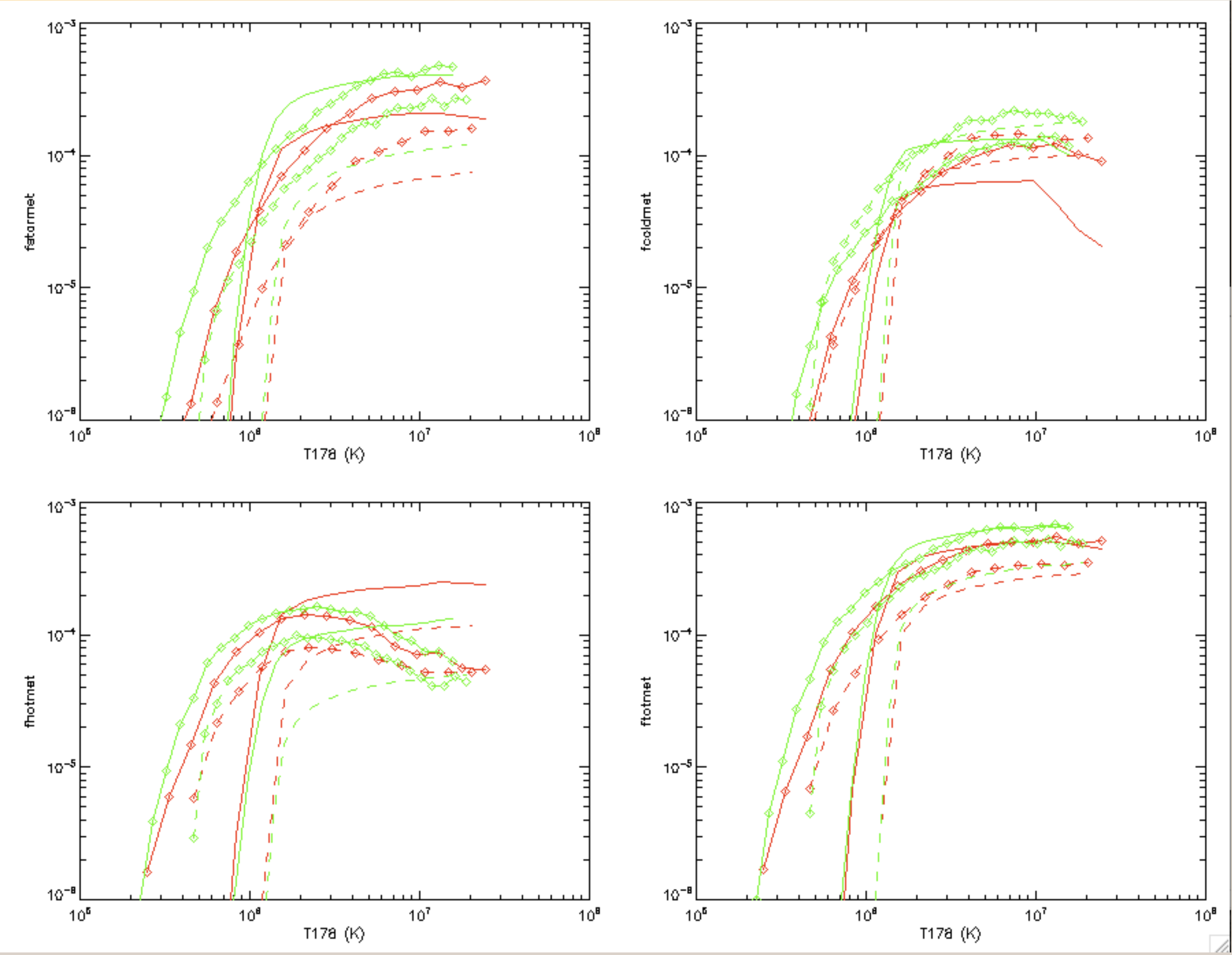


- Need to take T_w=7.5 10^5 K (to reproduce the amount of metals in background)
- Assume Z_w=0.15 Zsun (0.5 Zsun everything in wind, 0 Zsun everything in cold)
- Issue with **hot and background in the SN wind case** !!! Why? Is is because of rbubble? Or physical phenomenon? Need better constraint using halo metal budget

✶Halo baryon budget



✶Halo metal budget (preliminary)



- Main discrepancy: metals amount in hot gas is dropping in large halo
- Solution: take into account ram pressure of infalling material (Teyssier&Dubois, 2008)
- Direct measurement of winds: shell method