The Radio Universe @ Ger's (wave)-length

Groningen, November 4-7 2013

The Epoch of Reionization:

Theoretical overview

Benedetta Ciardi

Max Planck Institute for Astrophysics

Modelling of cosmic reionization: ingredients

✧ Model of galaxy formation

Semi-analytic models

$$M\frac{dn}{dM} = \left(\frac{2}{\pi}\right)^{1/2} \frac{-d(\ln\sigma)}{d(\ln M)} \frac{\rho_0}{M} \upsilon_c e^{-\upsilon_c^2/2}$$

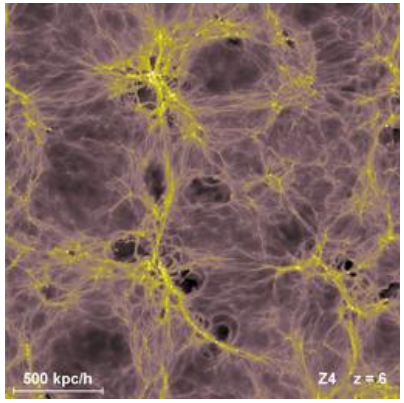
$$M_*^{\&} = \alpha \frac{dM}{dt}$$

$$t_{cool} < t_{dyn}$$

...

+

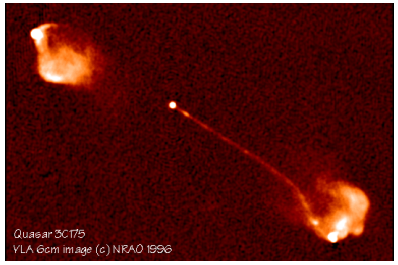
Numerical simulations



✧ Properties of the sources of ionizing radiation

Stellar type

Quasars



DM annihilation/decay

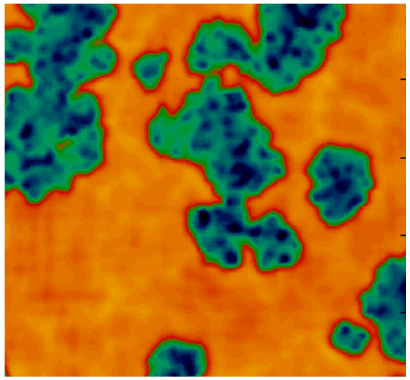
light dark matter

neutralinos

gravitinos

sterile neutrinos

...



✧ Evolution of the HII regions

Model of galaxy formation

- ✧ Semi-analytic models

Model of galaxy formation

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- ✧ Numerical simulations: hydro, L=533 cMpc/h, mDM=2d8 Msun (e.g. DeGraf+ 2012)
  Nbody, L=425 cMpc/h, mDM=5d7 Msun (e.g. Hannes+ 2013)

Model of galaxy formation

- ✧ Semi-analytic models
- ✧ Numerical simulations: hydro, L=533 cMpc/h, mDM=2d8 Msun (e.g. DeGraf+ 2012)
  Nbody, L=425 cMpc/h, mDM=5d7 Msun (e.g. Hannes+ 2013)
- ✧ Semi-numeric models: e.g. Mesinger & Furlanetto 2007; Zahn+ 2007; Geil & Wyithe 2008; Santos+2008

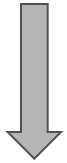
Mini/small halos

- ✧ Mini halos: H2 cooling, $M < 10^8\ M_{sun}$
- ✧ Small halos: H cooling, $10^8\ M_{sun} < M < 10^9\ M_{sun}$

Mini/small halos

- ✧ Minimum mass of star forming halos
- ✧ Feedback effects on their formation/evolution

Ciardi & Ferrara 2005 (and 2008 update on arXiv)

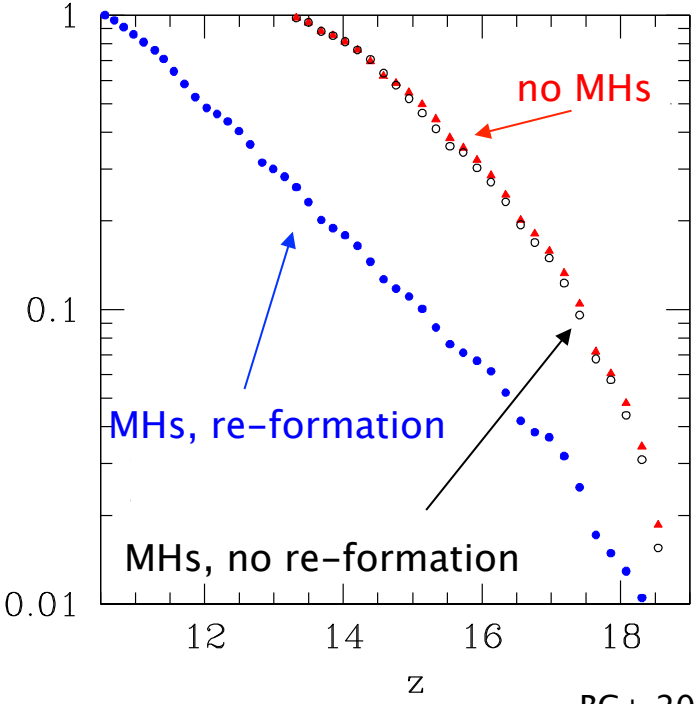


Sinks or sources of ionizing photons?

Haiman, Rees & Loeb 1997
Ciardi, Ferrara & Abel 2000
Ciardi+ 2000
Haiman, Abel & Rees 2000
Susa & Kitayama 2000
Haiman, Abel & Madau 2001
Kitayama+ 2000, 2001
Machacek, Bryan & Abel 2001
Ricotti, Gnedin & Shull 2002
Yoshida+ 2003
Dijkstra+ 2004
Shapiro, Iliev & Raga 2004
Susa & Umemura 2004
Alvarez, Bromm & Shapiro 2006
Mesinger, Bryan & Haiman 2006
Ahn & Shapiro 2007
Ciardi & Salvaterra 2007
Johnson, Greif & Bromm 2008
McGreer & Bryan 2008
Mesinger & Dijkstra 2008
Whalen+ 2008
Hasegawa, Umemura & Susa 2009
Mesinger, Bryan & Haiman 2009
Pawlik & Schaye 2009
Wang+ 2009
Wolcott-Green, Haiman, Bryan 2011
Safranek-Shrader+ 2012

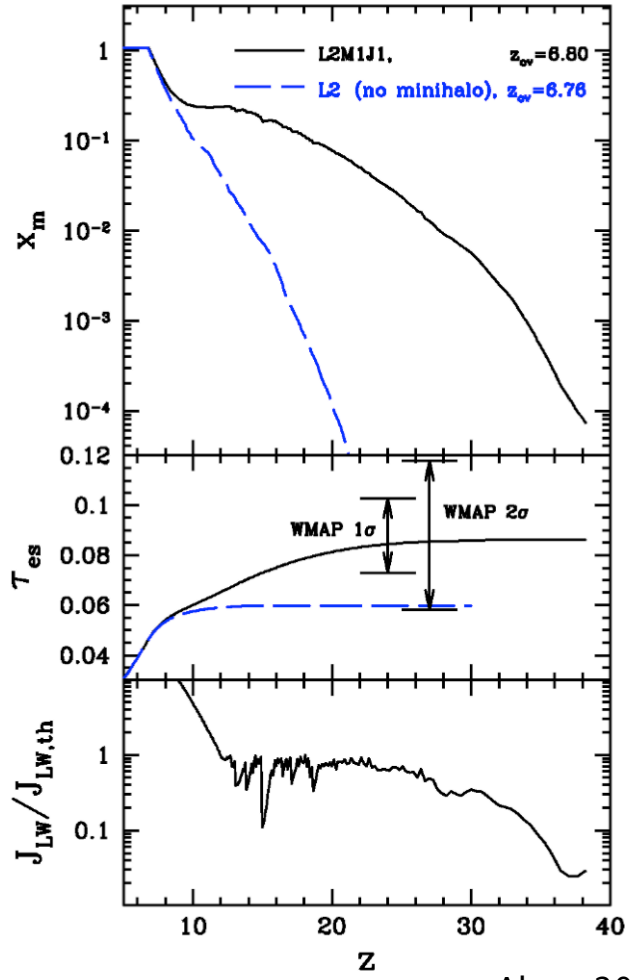
Effect of mini/small halos

H volume averaged ionization fraction



BC+ 2006

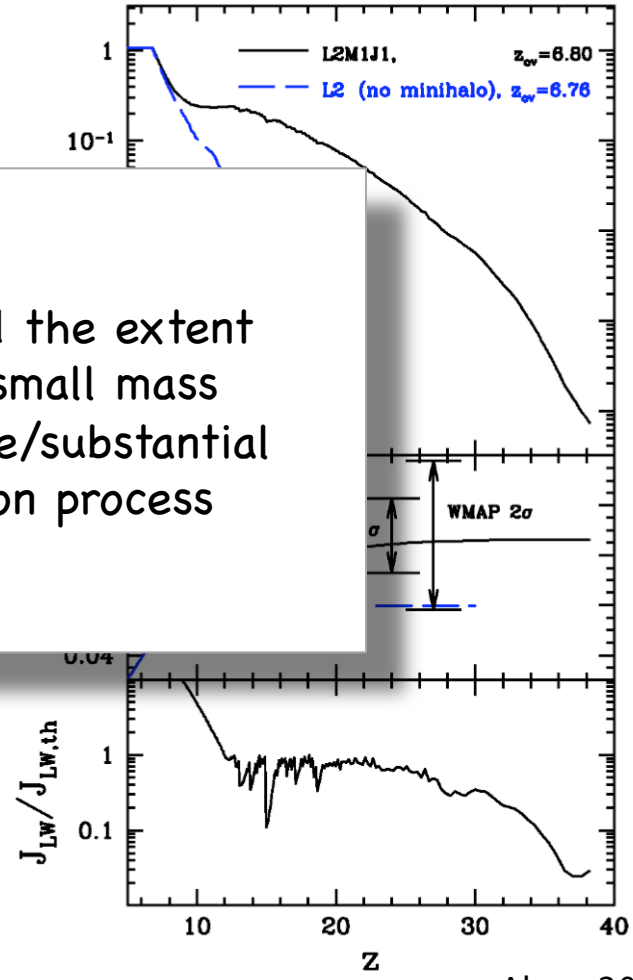
H mass averaged ionization fraction



Ahn+ 2012

Effect of mini/small halos

H mass averaged ionization fraction



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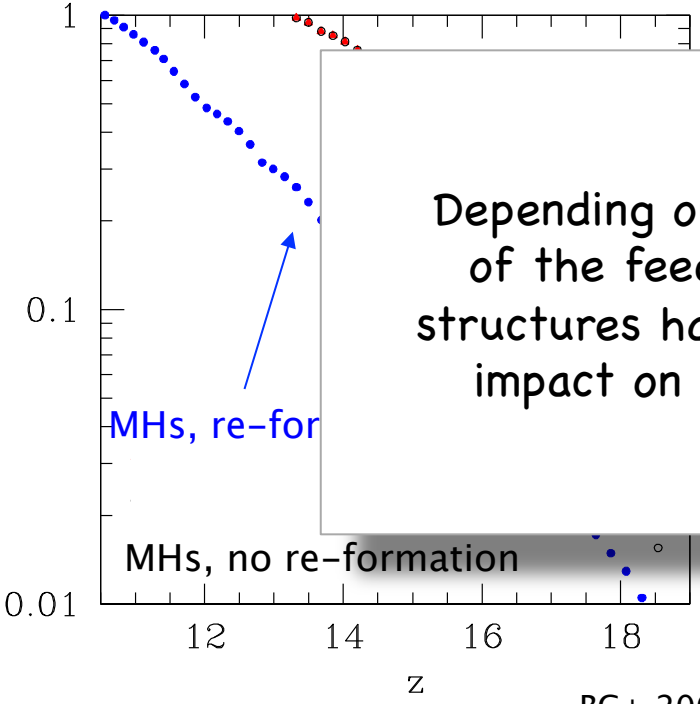
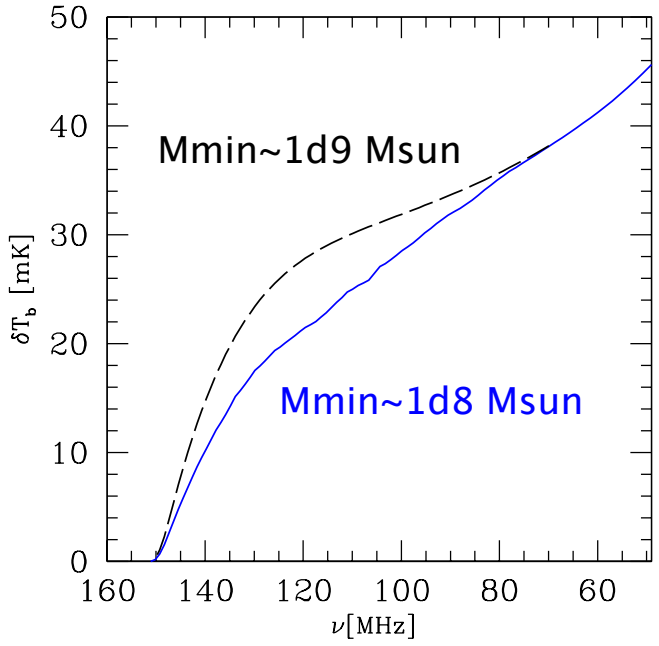


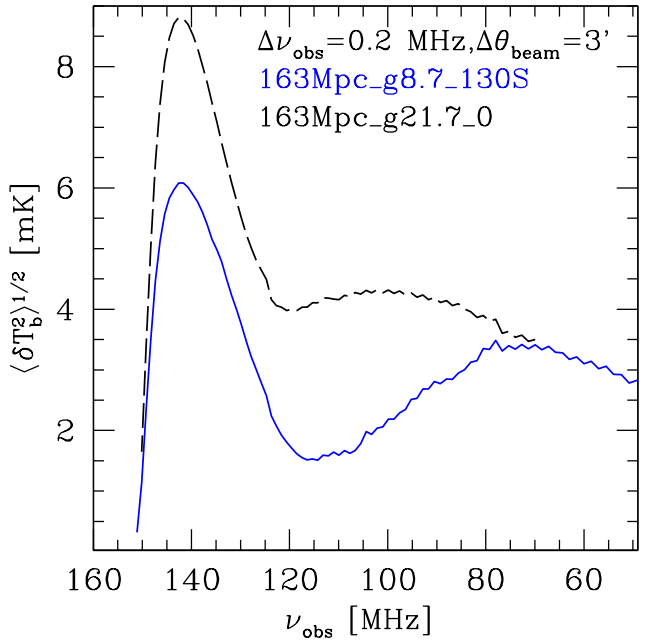
BC+ 2006

Depending on the sign and the extent of the feedback effect, small mass structures have a negligible/substantial impact on the reionization process

Effect of mini/small halos on 21cm signal

Differential brightness temperature and its rms





Iliev+ 2012

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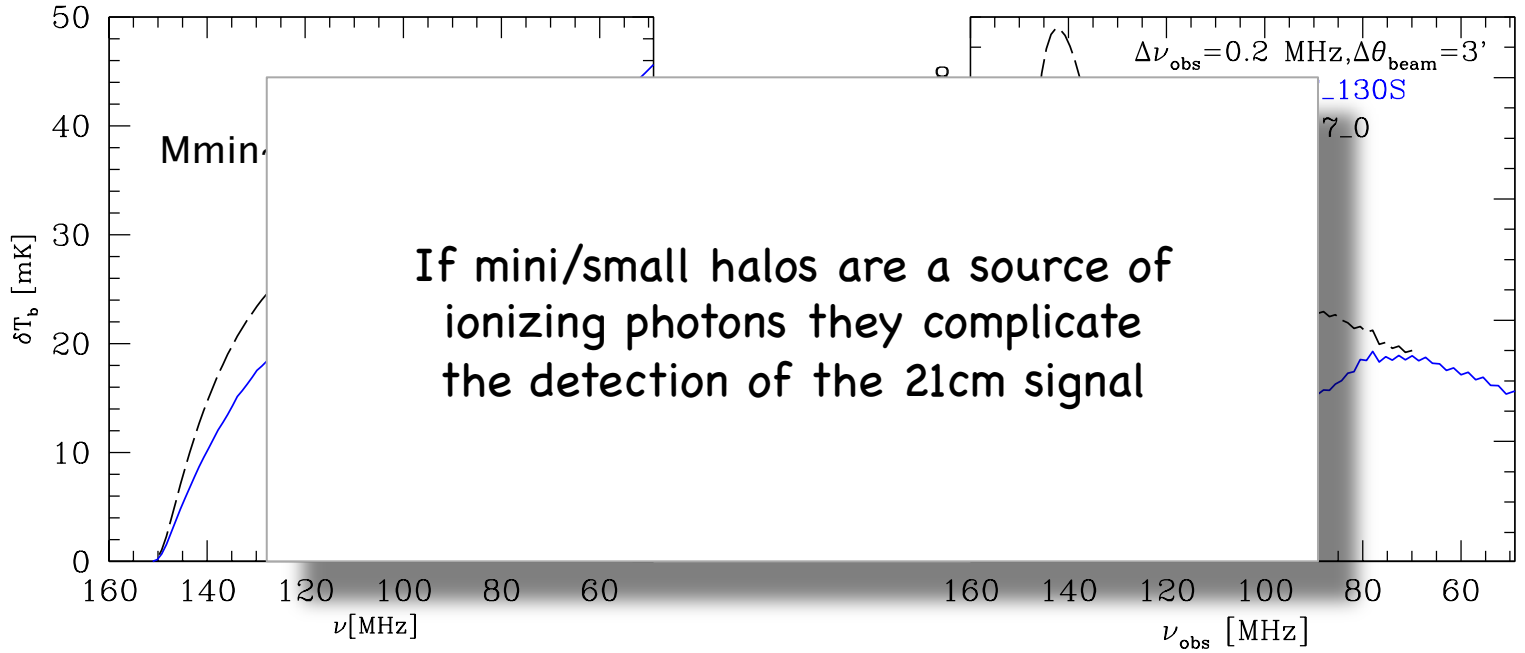

Iliev+ 2012

Stream velocity

✧ Relative velocity of dark matter and baryonic fluids

Effect of stream velocity

- ✧ The abundance/distribution of DM halos is changed
- ✧ Star formation is delayed/suppressed in small mass halos

Tseliakhovich, Hirata 2010
Dalal, Pen, Seljak 2010
Maio, Koopmans, Ciardi 2011
Stacy, Bromm, Loeb 2011
Greif et al 2011
Tseliakhovic, Barkana, Hirata 2011
O'Leary & McQuinn 2012
McQuinn & O'Leary 2012
Naoz, Yoshida & Gnedin 2012
Visbal et al 2012
Fialkov et al 2012
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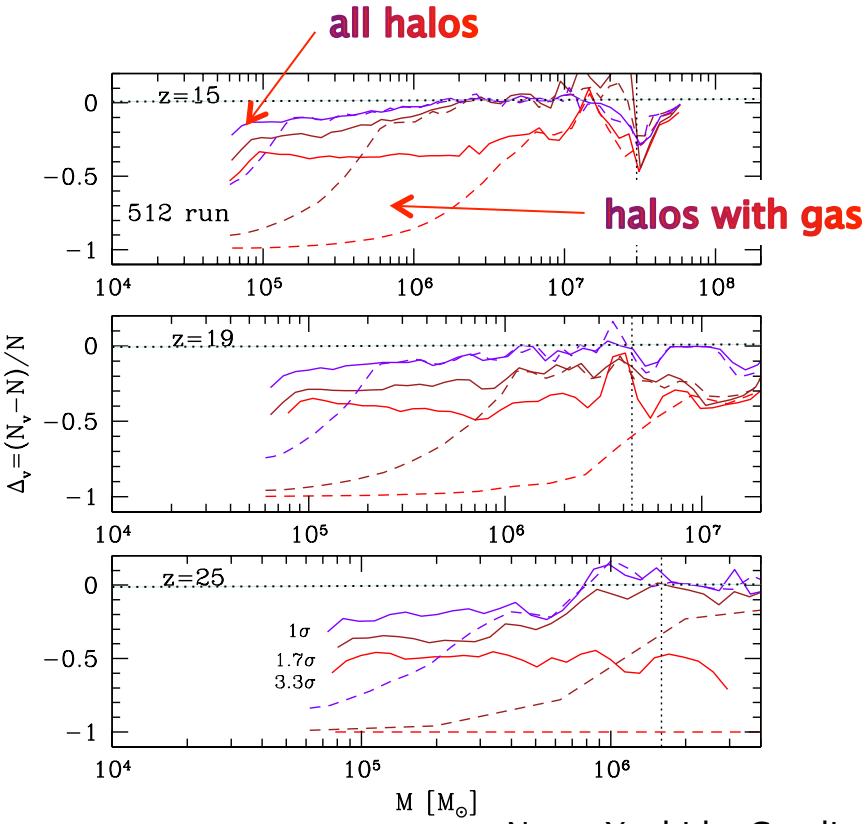
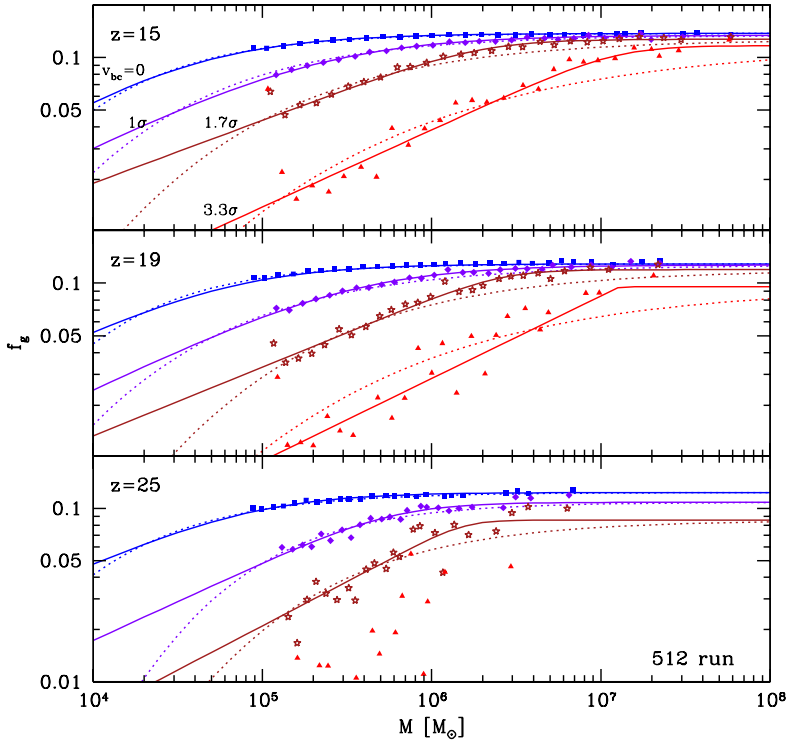


Naoz, Yoshida, Gnedin 2012



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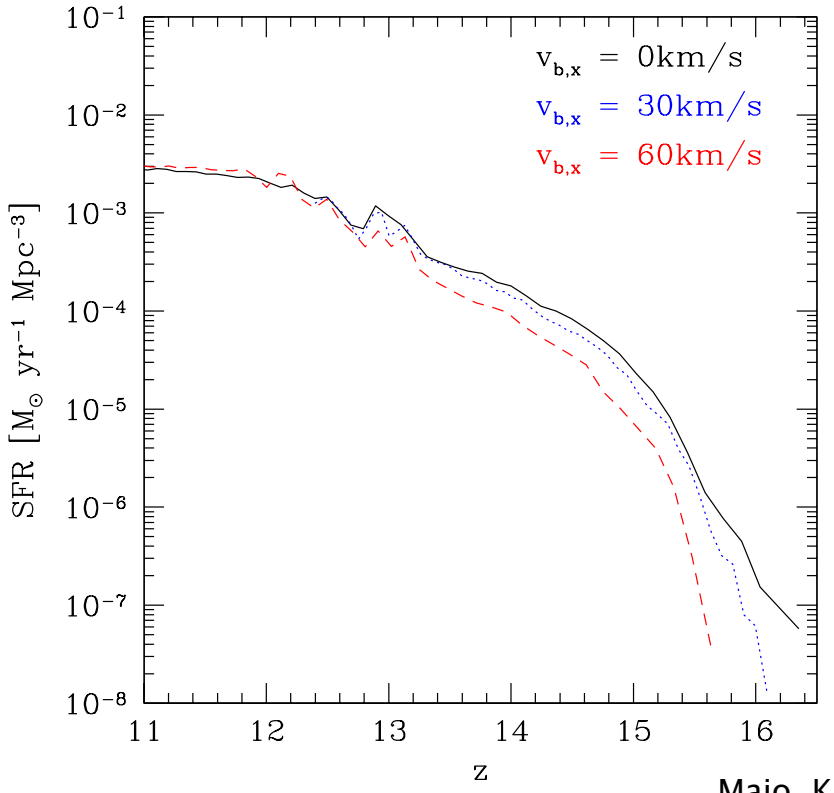

Maio, Koopmans, BC 2011

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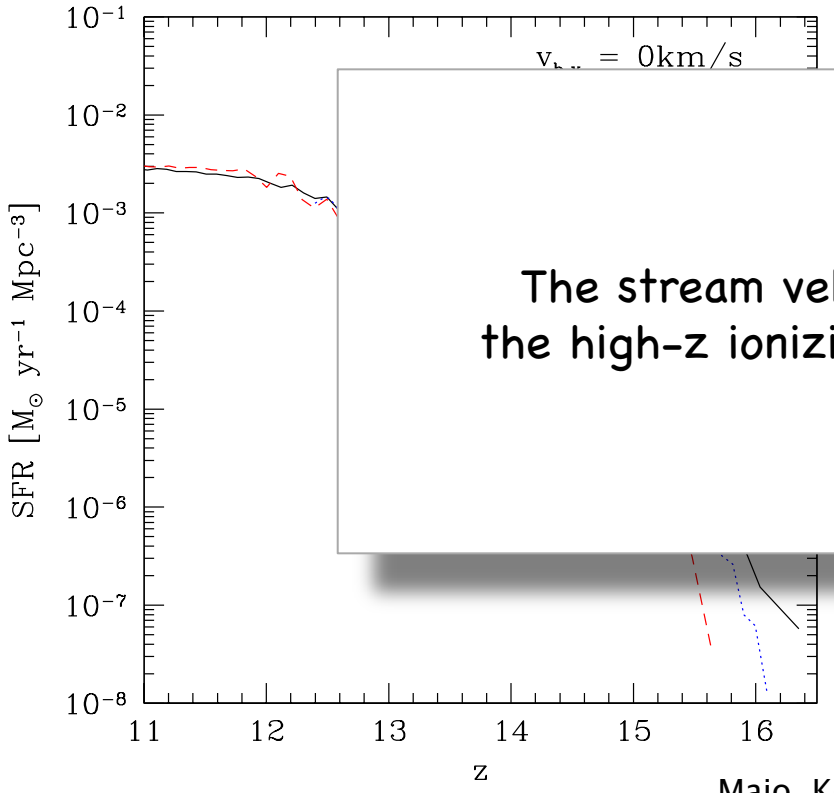
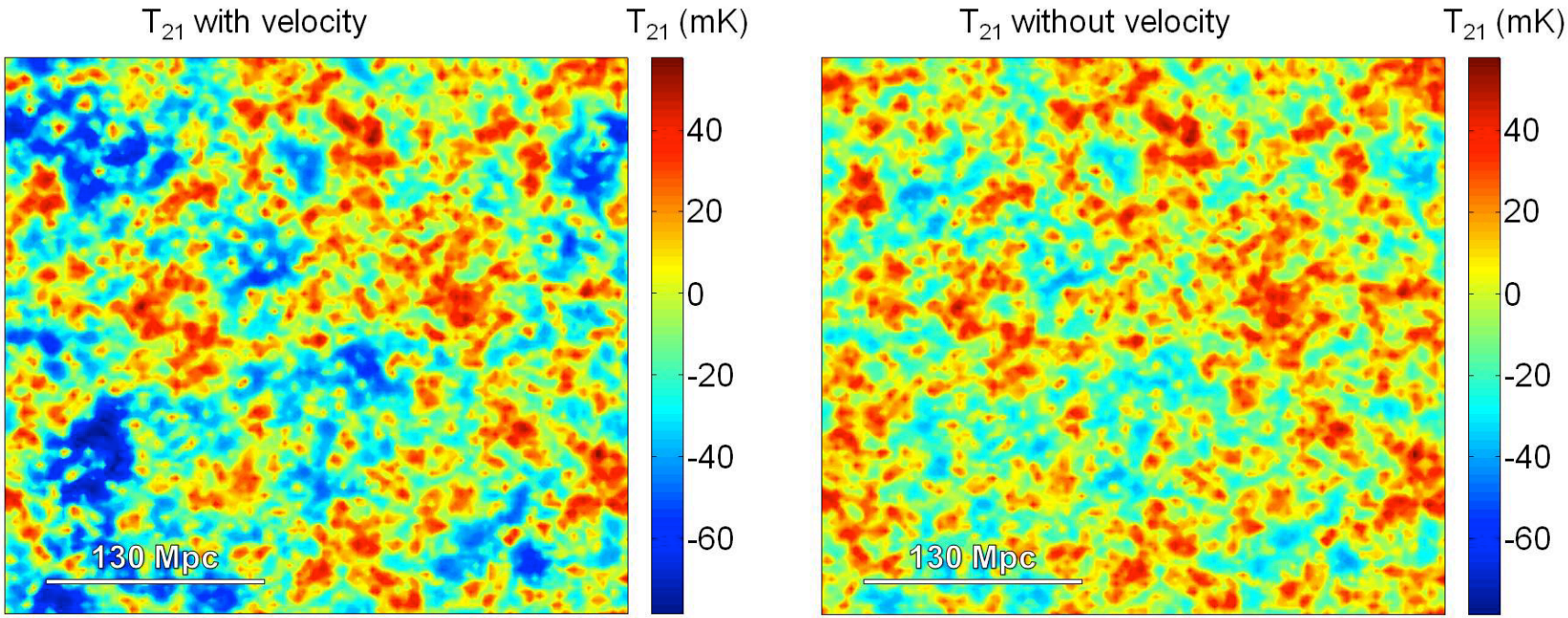


The stream velocity can change the high-z ionizing photons' budget

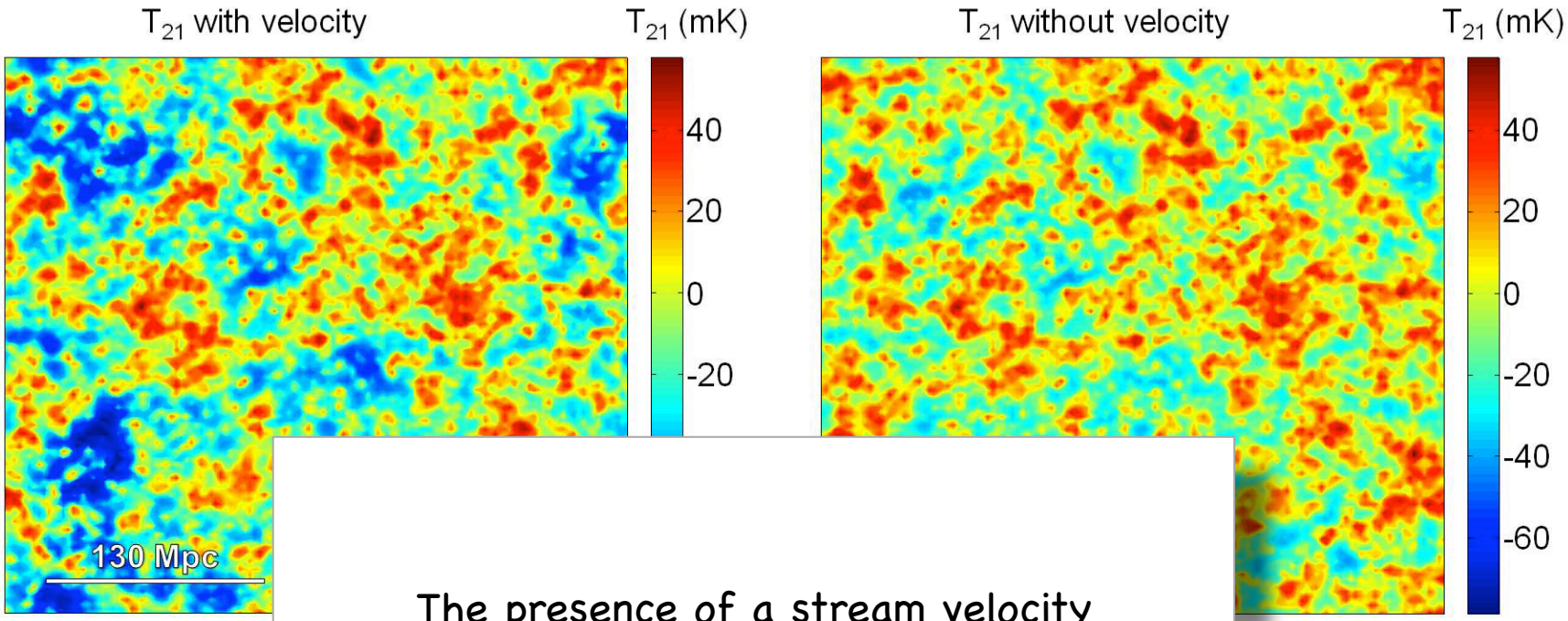
Maio, Koopmans, BC 2011

Effect of stream velocity on 21cm signal



Visbal+ 2012

Effect of stream velocity on 21cm signal



The presence of a stream velocity could increase the chances of 21cm signal detection at high-z

Visbal+ 2012

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✧ Model of galaxy formation

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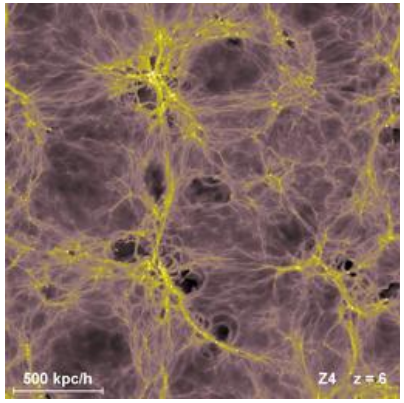
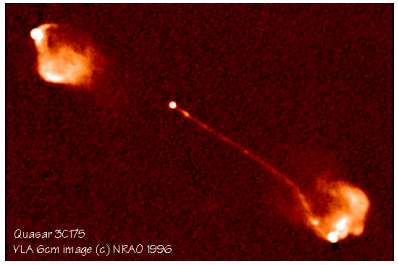


✧ Properties of the sources of ionizing radiation

Stellar type

Quasars



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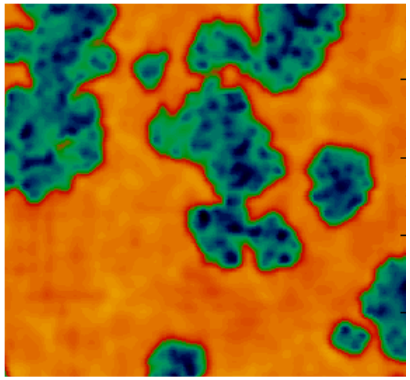


✧ Evolution of the HII regions

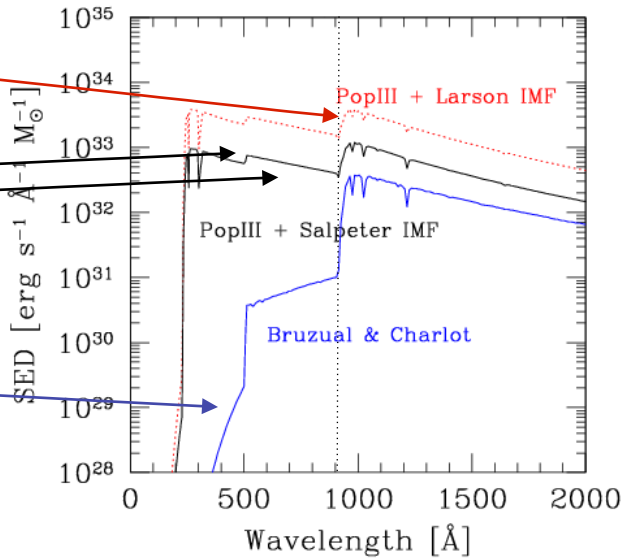
Stellar type sources

✧ Initial Mass Function and spectrum

Salpeter or Larson IMF?

Zero or higher metallicity?

Spectral Energy Distribution



Stellar type sources

✧ Initial Mass Function and spectrum

✧ Primordial (PopIII) → standard (PopII/I) star formation: metallicity threshold

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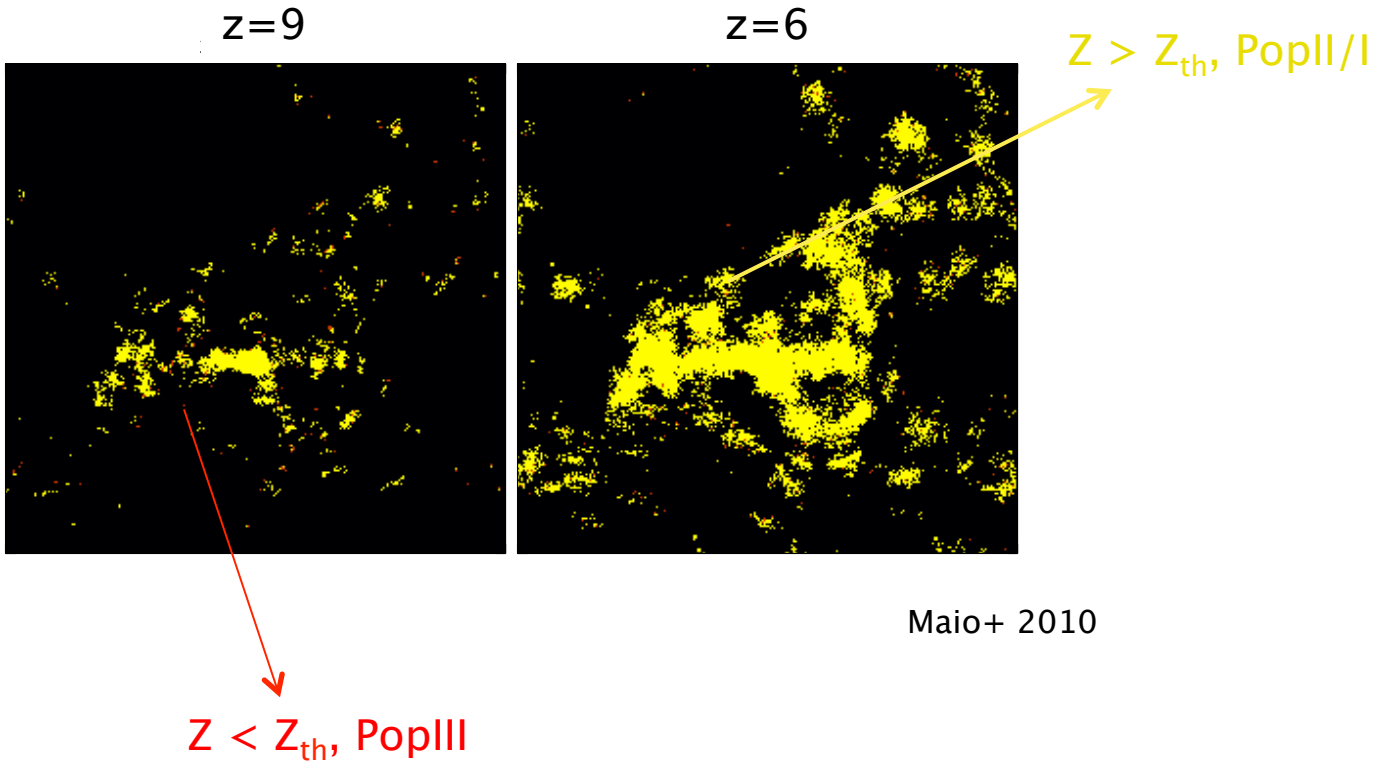


Maio+ 2010

Stellar type sources

✧ Initial Mass Function and spectrum

✧ Primordial (PopIII) → standard (PopII/I) star formation: metallicity threshold

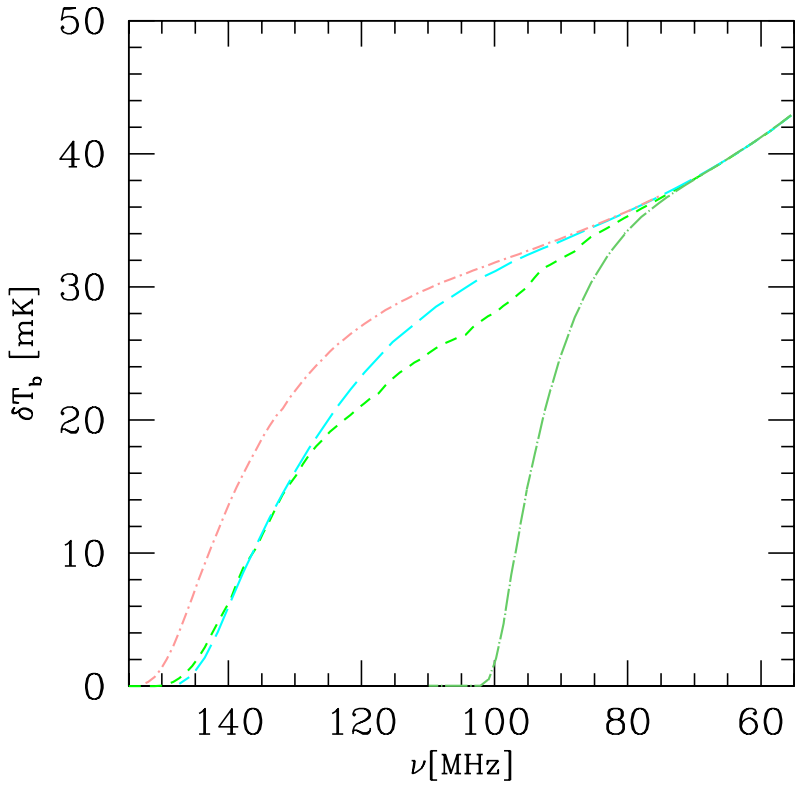
✧ Escape fraction

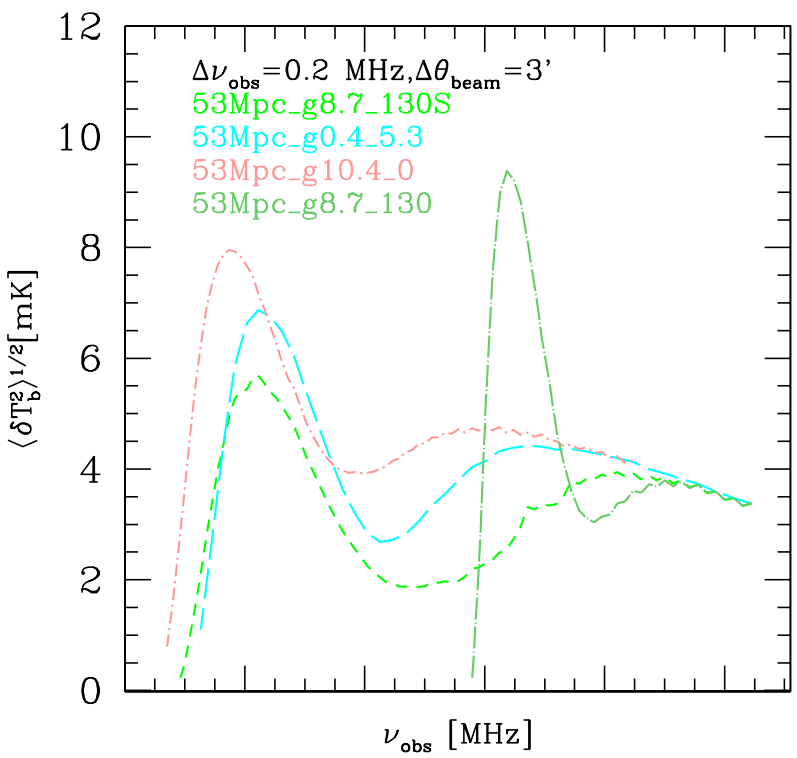
Fesc <20% but there is a big variation in the number both theoretically & observationally

Fesc > 70% for primordial, very-massive stars

Effect of stellar type sources on 21cm signal

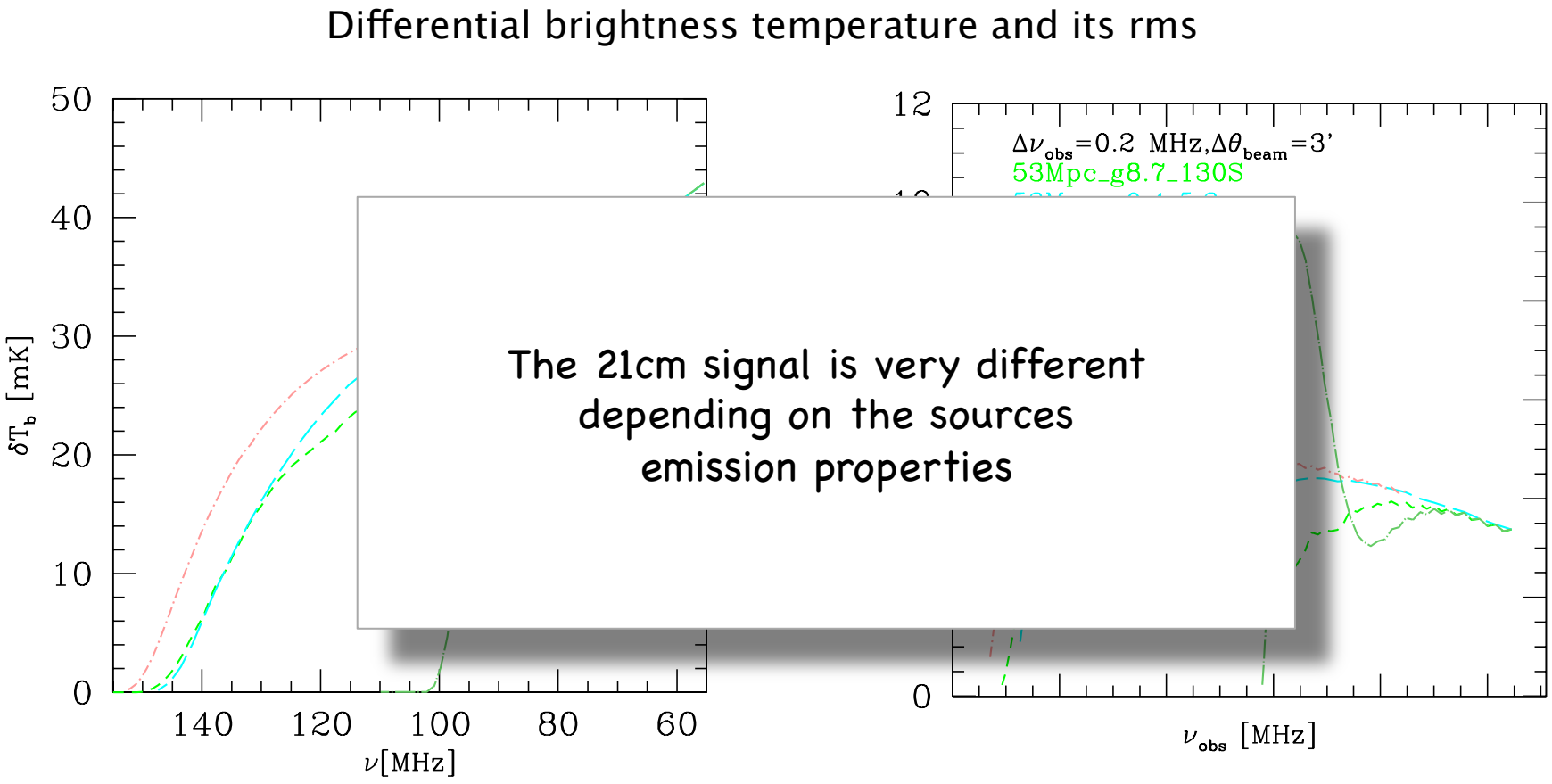
Differential brightness temperature and its rms





Iliev+ 2012

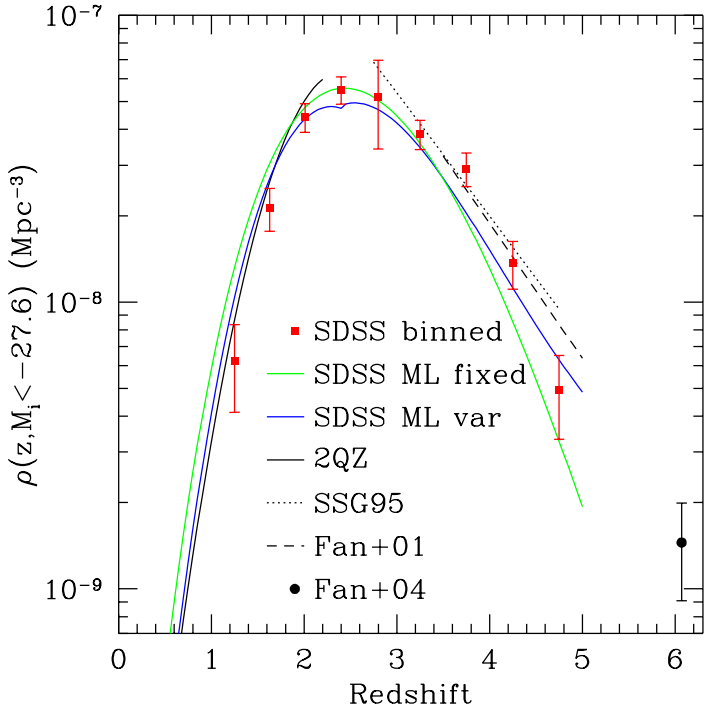
Effect of stellar type sources on 21cm signal



Iliev+ 2012

Quasars

✧ Quasars' abundance falls rapidly at high-z

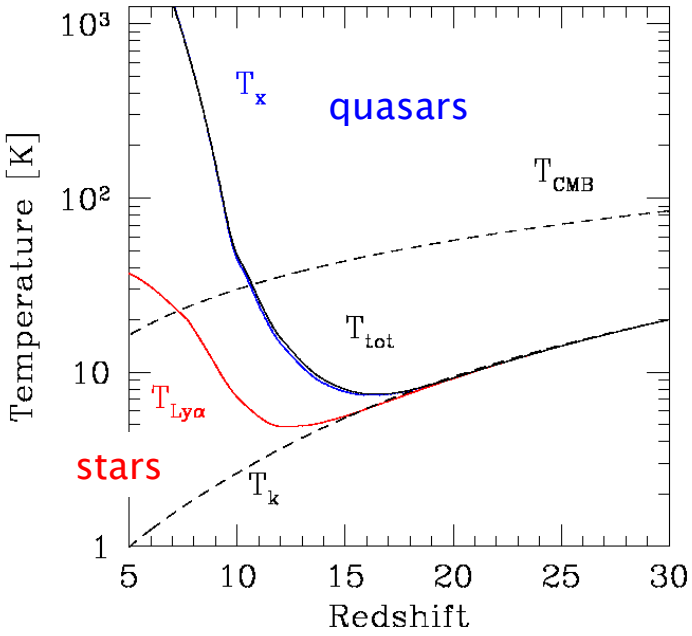


Richards+ 2006

✧ HeII late reionization requires spectral softening with increasing z

Effect of quasars

✧ Energy input into the IGM



Pelupessy, Di Matteo, BC 2007
BC, Salvaterra, Di Matteo 2009

Pritchard & Furlanetto 2007
Srbinovsky & Wyithe 2007
Shull & Venkatesan 2008
Thomas & Zaroubi 2008
Geil & Wyithe 2009
Volonteri & Gnedin 2009
Baek+ 2010
McQuinn 2012
Mesinger+ 2013

Effect of quasars

✧ Energy input into the IGM

Pritchard & Furlanetto 2007
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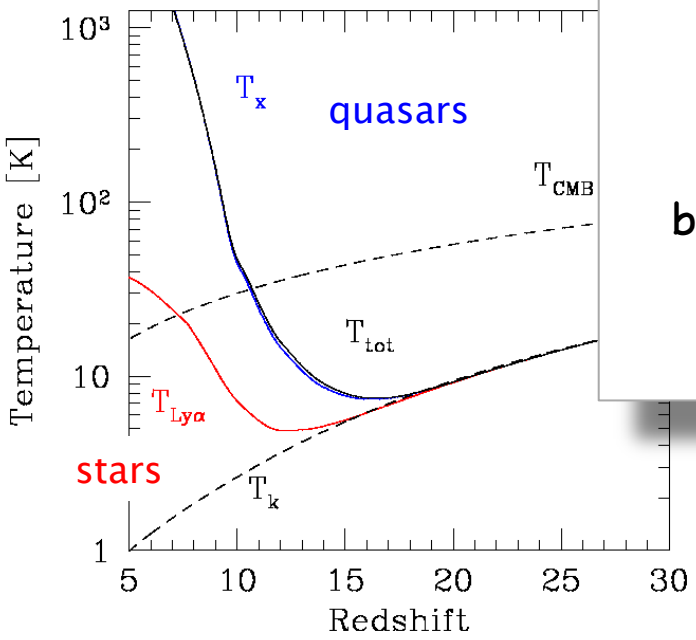
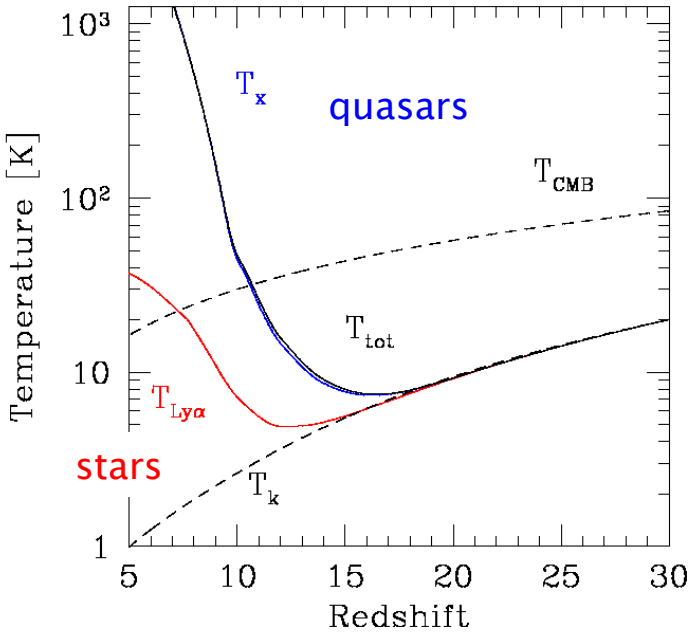


Quasars do not contribute substantially to the ionization budget at high-z, but they could dominate the energy input

Pelupessy, Di Matteo, BC 2007
BC, Salvaterra, Di Matteo 2009

Effect of quasars on 21cm signal



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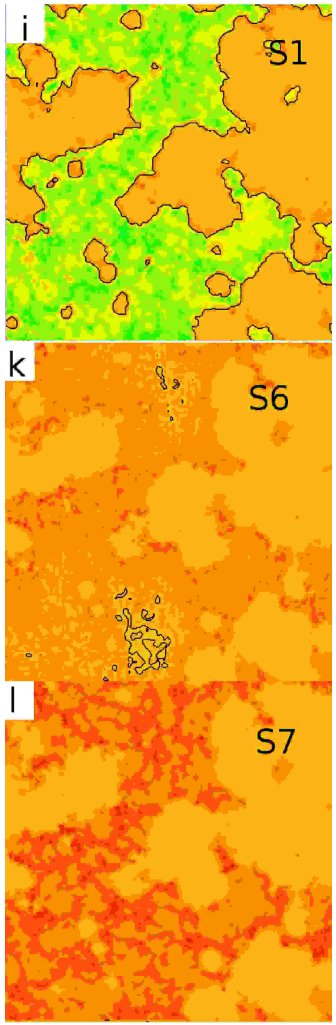
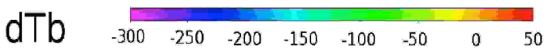


100% stars

99% stars
1% qsos

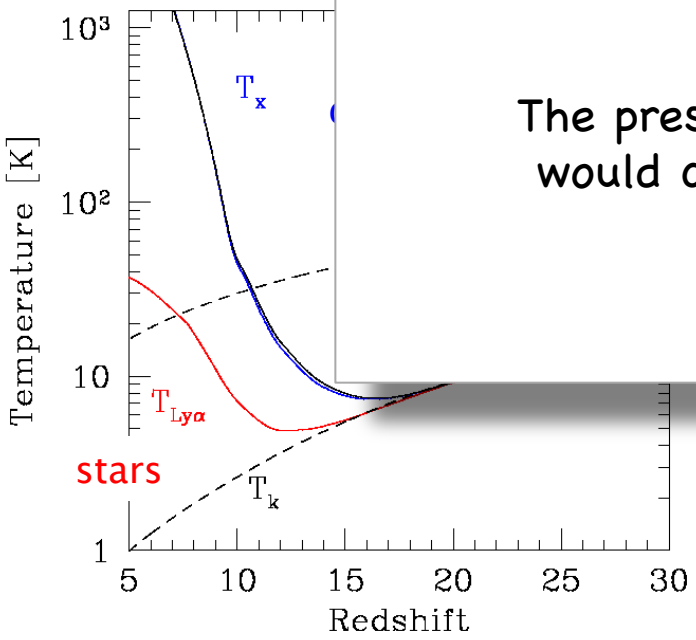
90% stars
10% qsos



Baek+ 2010

Effect of quasars on 21cm signal

The presence of high-z quasars would change the 21cm signal



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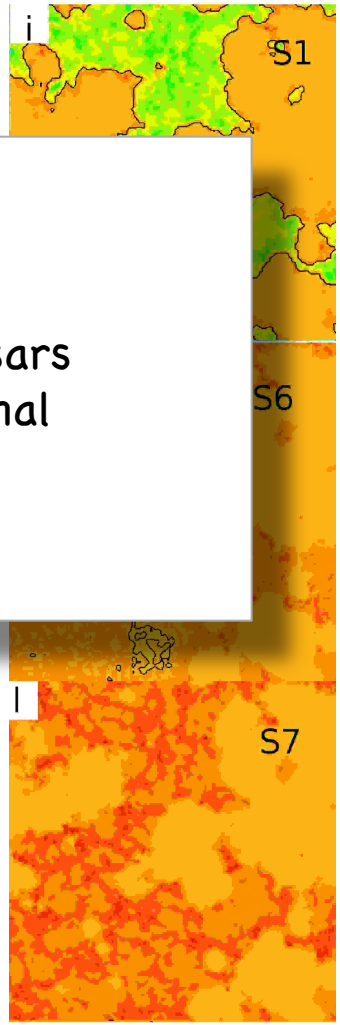

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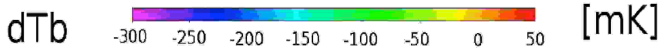
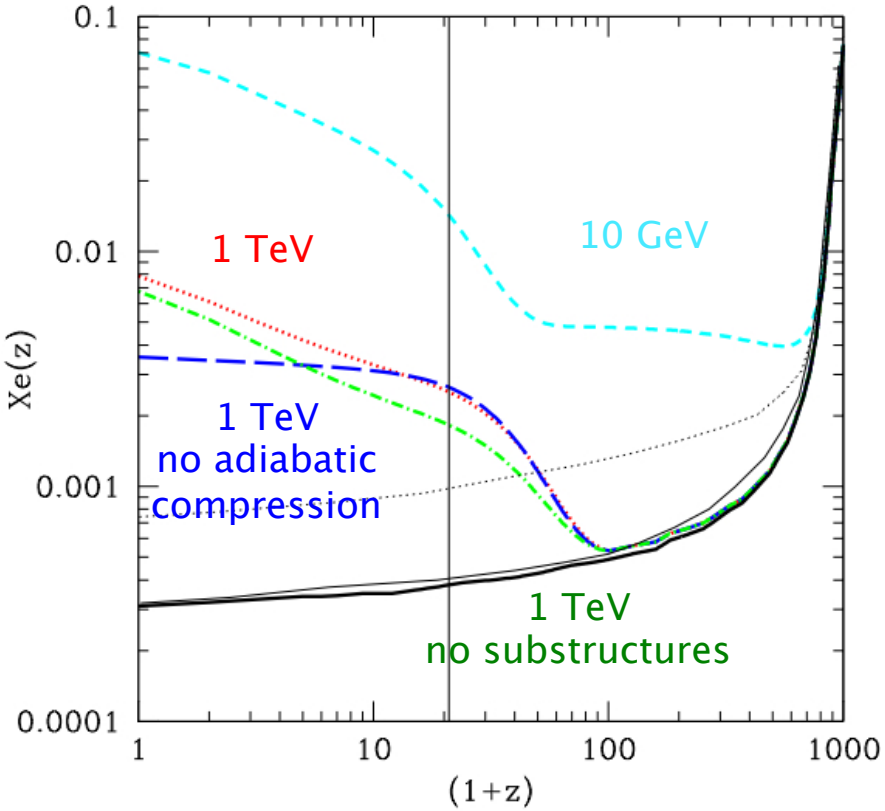


Baek+ 2010

Dark Matter annihilation effect

✧ can provide a floor of HII and heat the IGM



Araya & Padilla 2013

Avelino& Barbosa 2004
Chen & Kamionkowski 2004
Hansen & Haiman 2004
Kasuya, Kawasaki & Sugiyama 2004
Kasuya & Kawasaki 2004
Furlanetto, Oh, Pierpaoli 2006
Mapelli, Ferrara & Pierpaoli 2006
Ripamonti, Mapelli & Ferrara 2007
Valdes+ 2007
Chuzhoy 2008
Natarajan & Schwarz 2008
Schleicher, Banerjee & Klessen 2008
Natarajan & Schwarz 2009
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Valdes+ 2013

Dark Matter annihilation effect on 21cm signal

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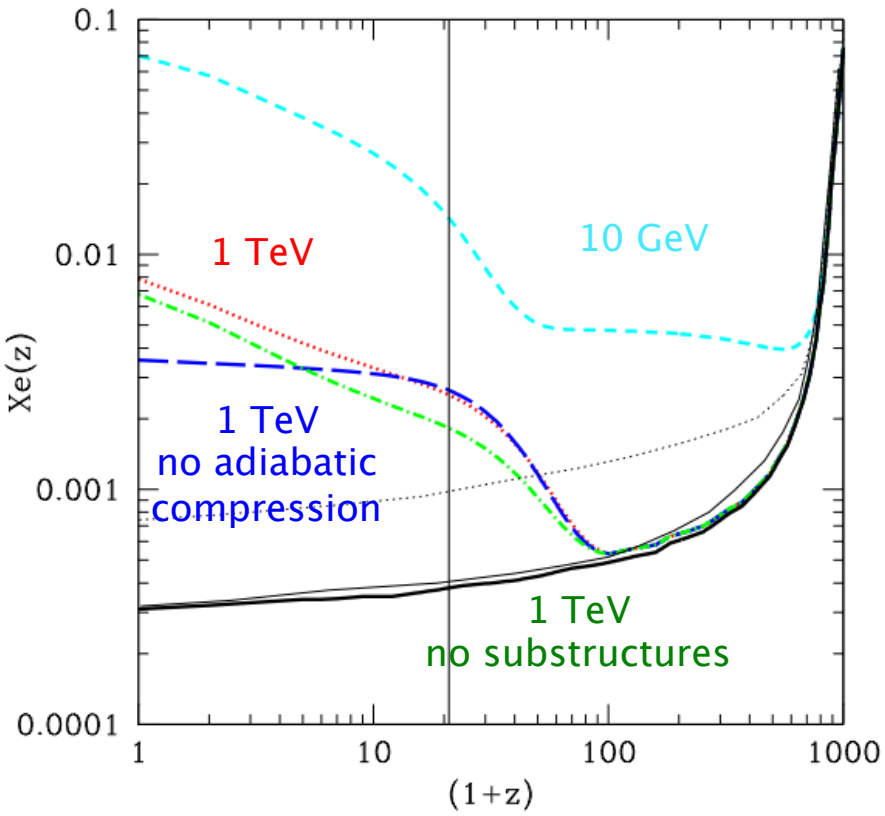

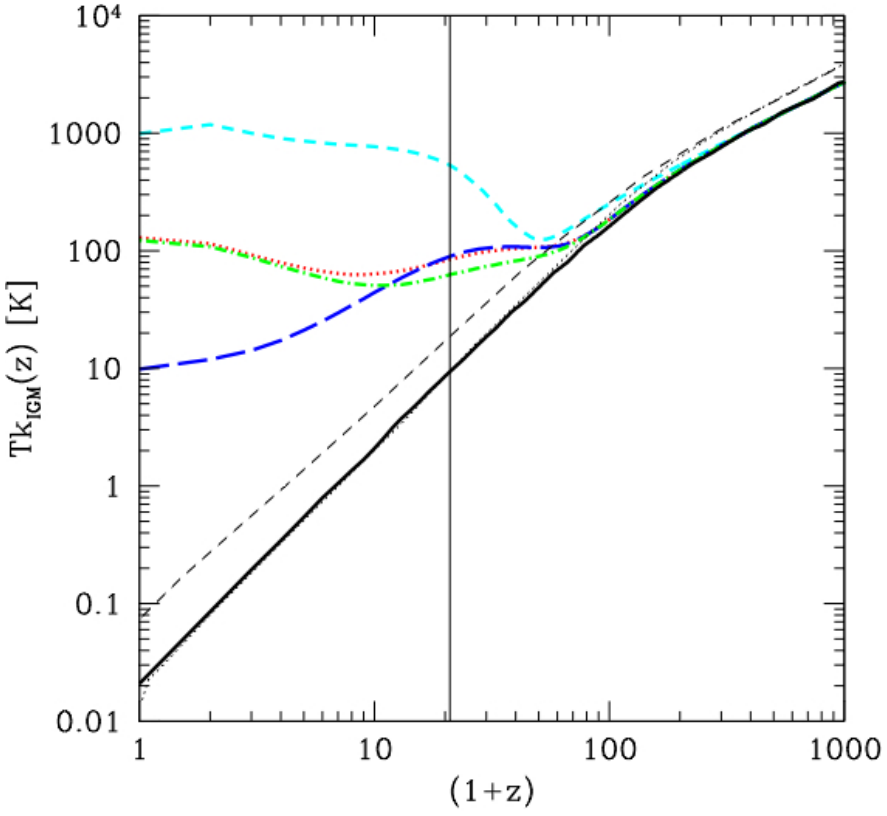

Araya & Padilla 2013

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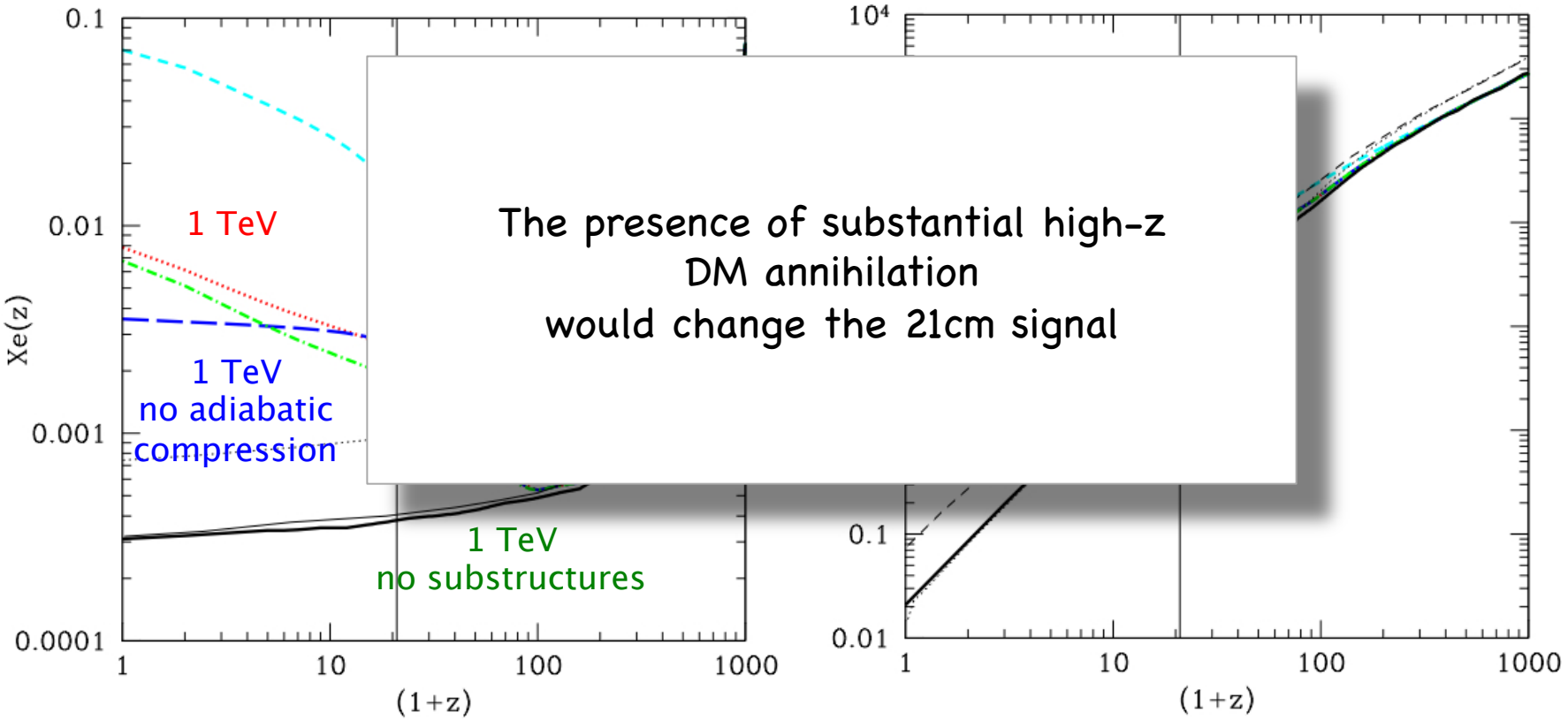

The presence of substantial high-z
DM annihilation
would change the 21cm signal

Araya & Padilla 2013

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✧ Model of galaxy formation

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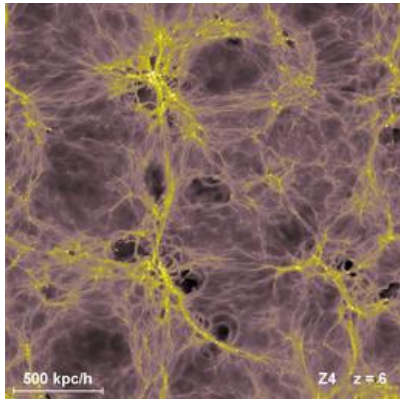

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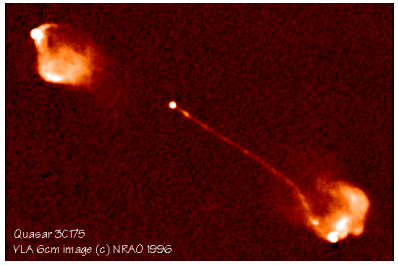

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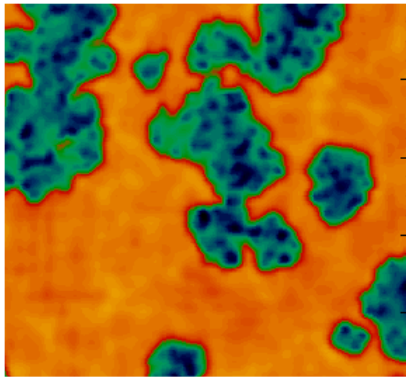


✧ Evolution of the HII regions

Evolution of the HII regions

✧ Semi-analytic approach

✧ Radiative transfer calculation (1D-3D)

Ciardi+ 2001
Gnedin & Abel 2001
Maselli, Ferrara & Ciardi 2003
Mellema+ 2006
Ahn & Shapiro 2007
Norman+ 2007
Aubert & Teyssier 2008
Pawlik & Schaye 2008
Thomas & Zaroubi 2008
Baek+ 2009
Finlator, Ozel & Dave' 2009
Gnedin, Tassis & Kravtsov 2009
Petkova & Springel 2009
Cantalupo & Porciani 2011
Partl+ 2011
Althay & Theuns 2013
Rosdahl+ 2013

Evolution of the HII regions

✧ Semi-analytic approach

✧ Radiative transfer calculation (1D-3D)

✧ Semi-numeric approach

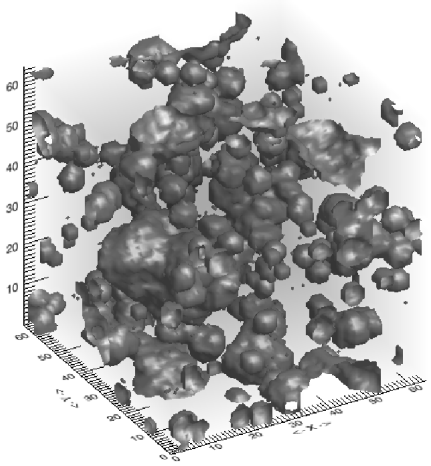
Ciardi+ 2000
Zhang, Hui & Haiman 2007
McQuinn+ 2007
Mesinger & Furlanetto 2007
Choudhury, Haehnelt & Regan 2009
Geil & Wyithe 2009
Thomas+ 2009
Santos+ 2010

Evolution of the HII regions

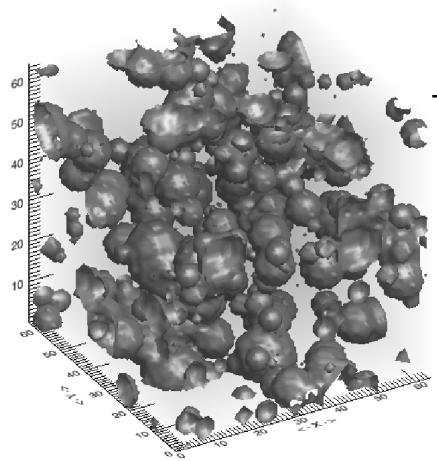
- ✧ Semi-analytic approach
- ✧ Radiative transfer calculation (1D-3D)
- ✧ Semi-numeric approach

CRASH

BC+ 2001;
Maselli, Ferrara & BC 2003;
Maselli, BC & Kanekar 2009;
Partl+ 2011;
Graziani, Maselli, BC 2012



12.5 Mpc/h com.



12.5 Mpc/h com.

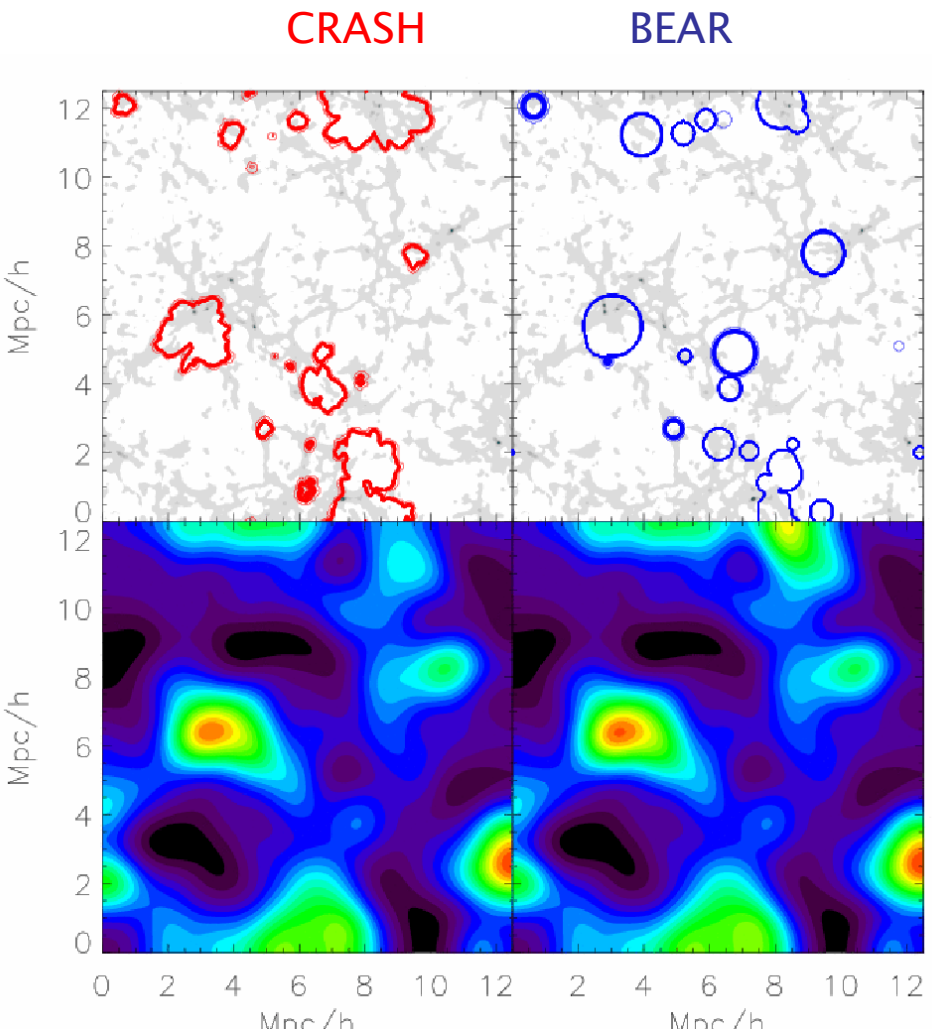
BEAR

Thomas & Zaroubi 2008

Thomas+ 2009

Evolution of the HII regions

- ✧ Semi-analytic approach
- ✧ Radiative transfer calculation (1D-3D)
- ✧ Semi-numeric approach

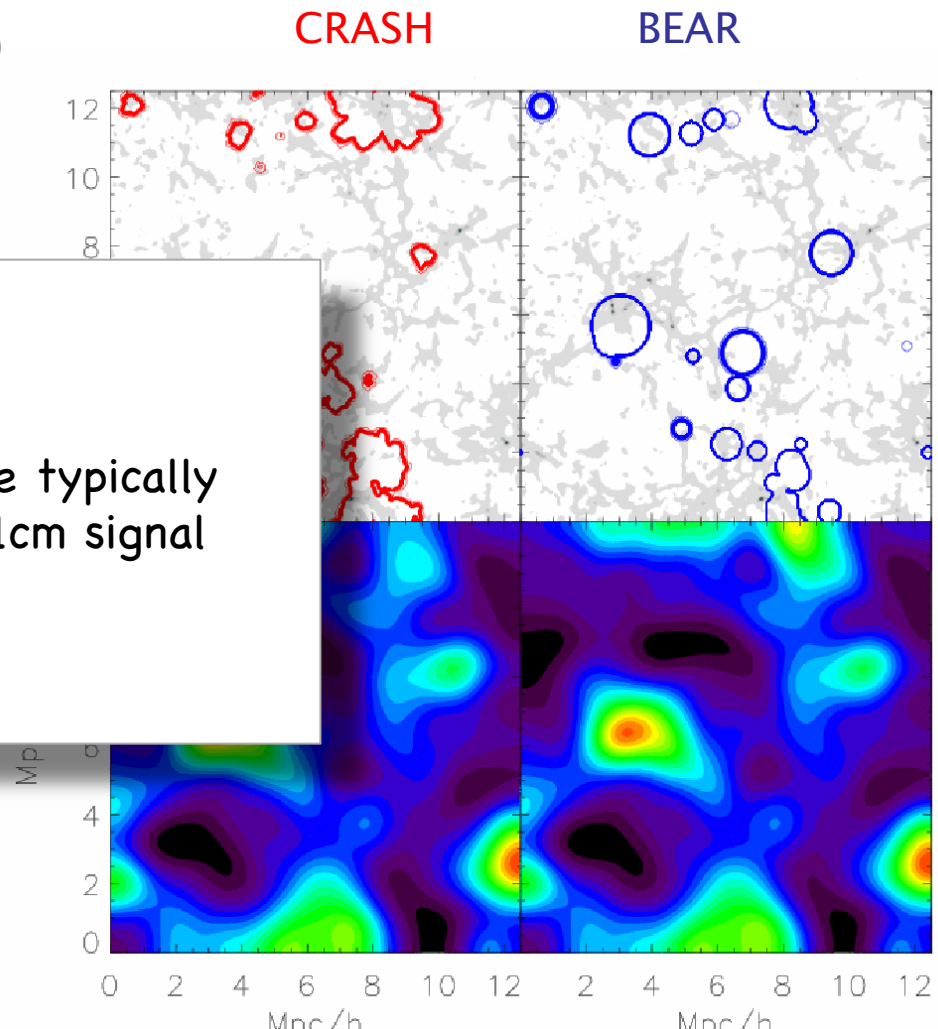


Thomas+ 2009

Evolution of the HII regions

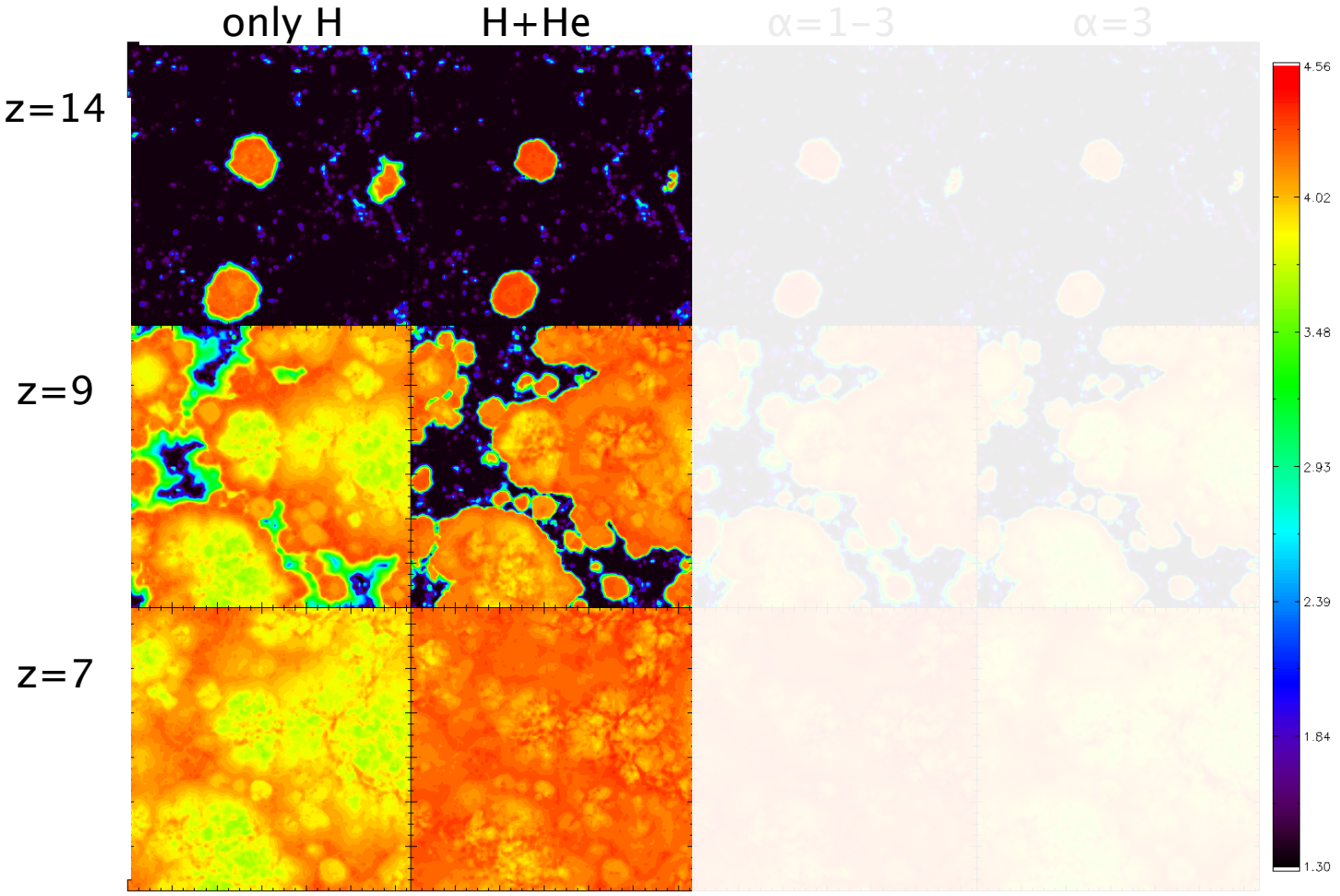
- ✧ Semi-analytic approach
- ✧ Radiative transfer calculation (1D-3D)
- ✧ Semi-numeric approach

Semi-numeric approaches are typically appropriate for studies of 21cm signal



Thomas+ 2009

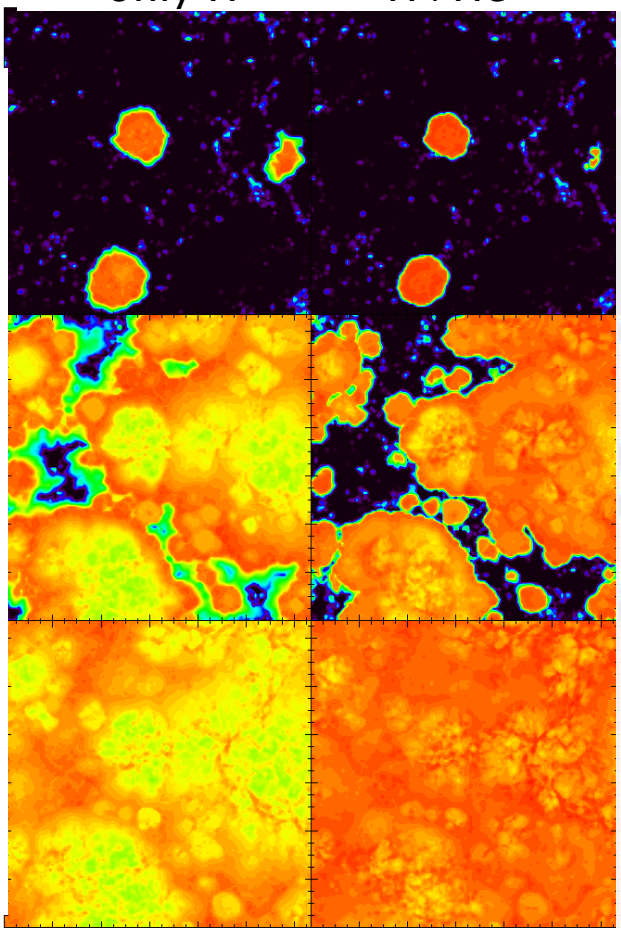
Evolution of the HII regions

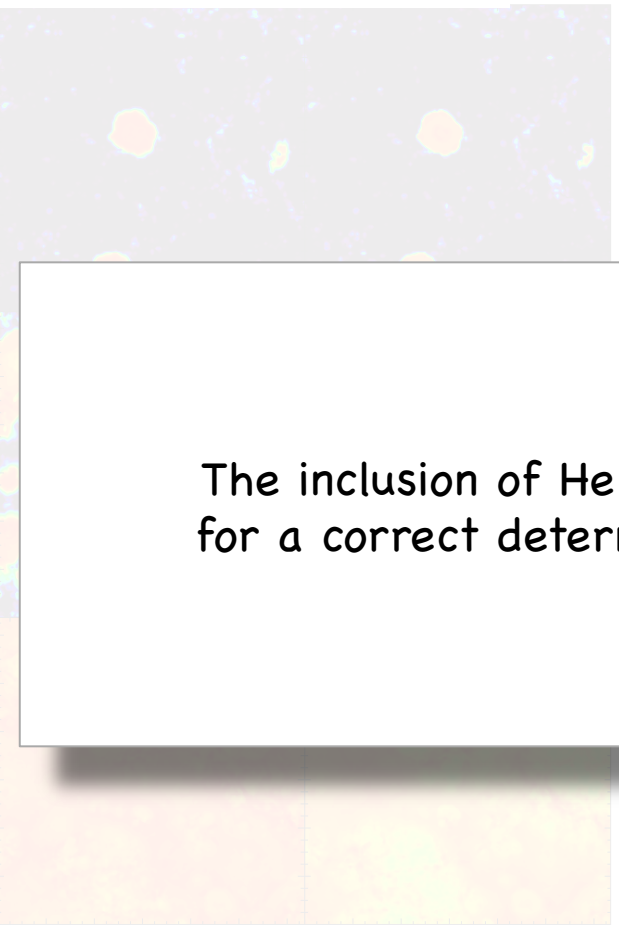


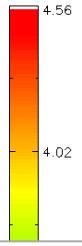
Temperature [K]

BC+ 2012

Evolution of the HII regions







Temperature [K]

The inclusion of He is important for a correct determination of T

BC+ 2012

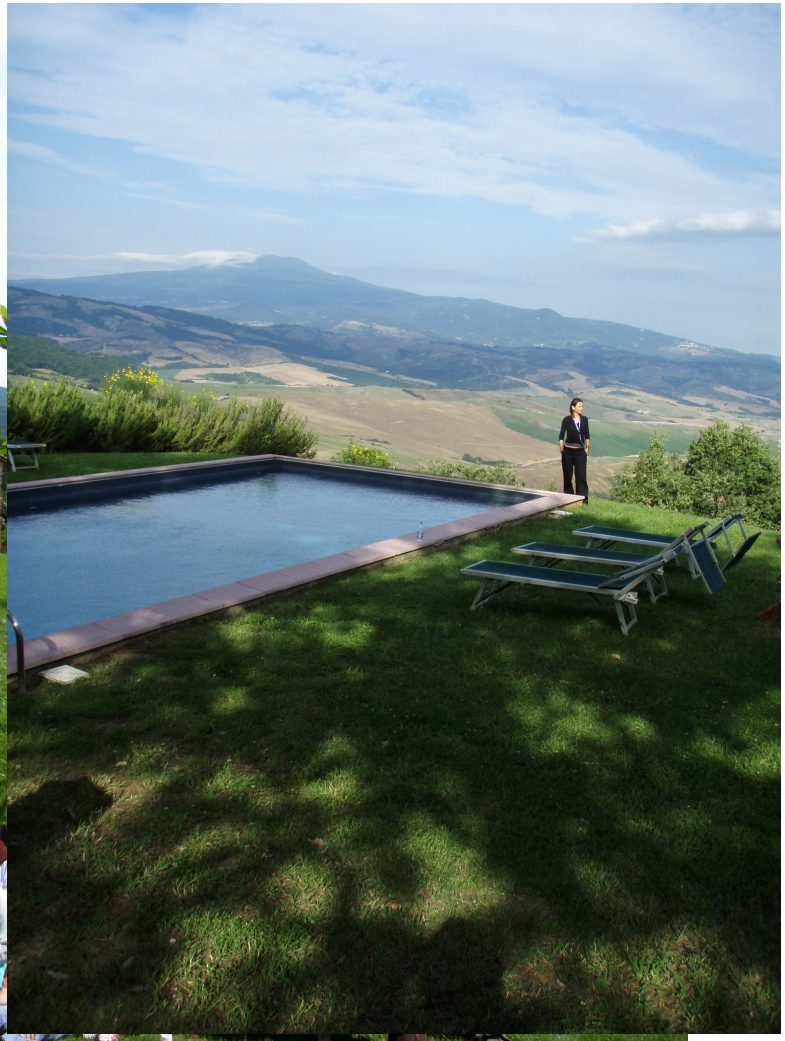
Conclusions

Elba 2002

Spineto 2007

Spineto 2007

Spineto 2007



Spineto 2007

Spineto 2007

Spineto 2007

Spineto 2007