The formation of the earliest structures as a probe of dark matter and primordial small-scale power

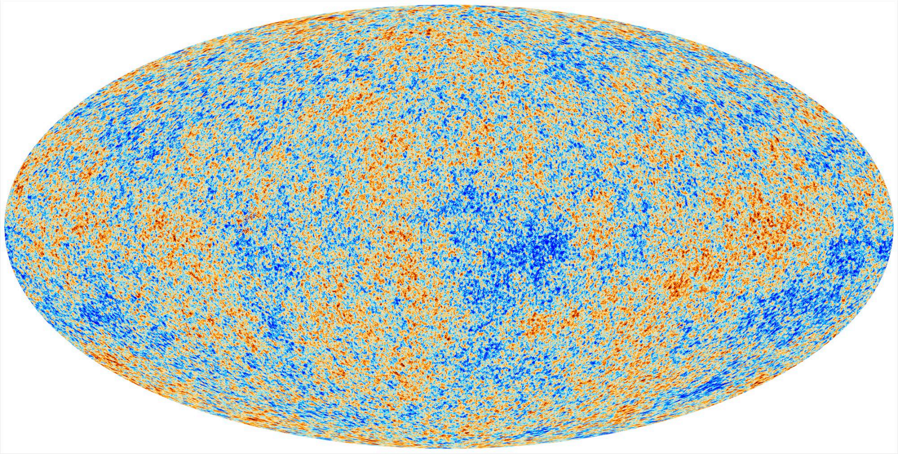
Andrei Mesinger

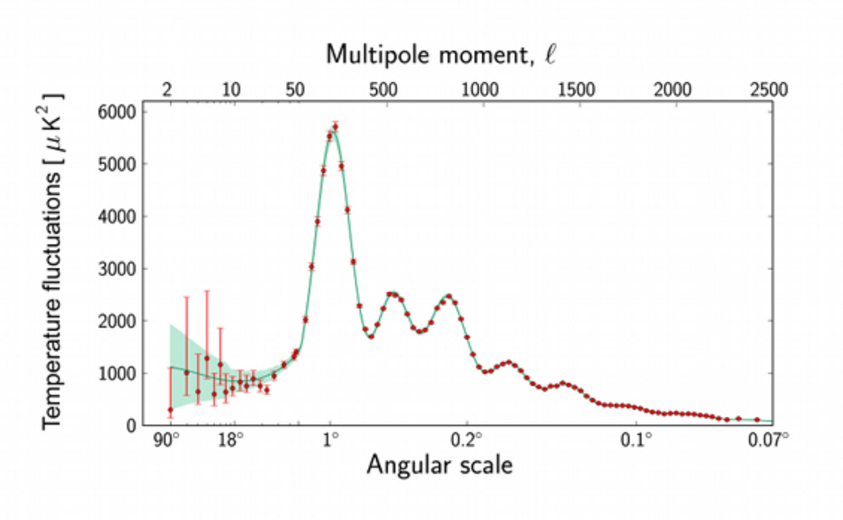
Scuola Normale Superiore, Pisa

Concordance LCDM has been remarkably successful on large scales

- CMB, large-scale structures through galaxy surveys, cluster abundance, cosmic web

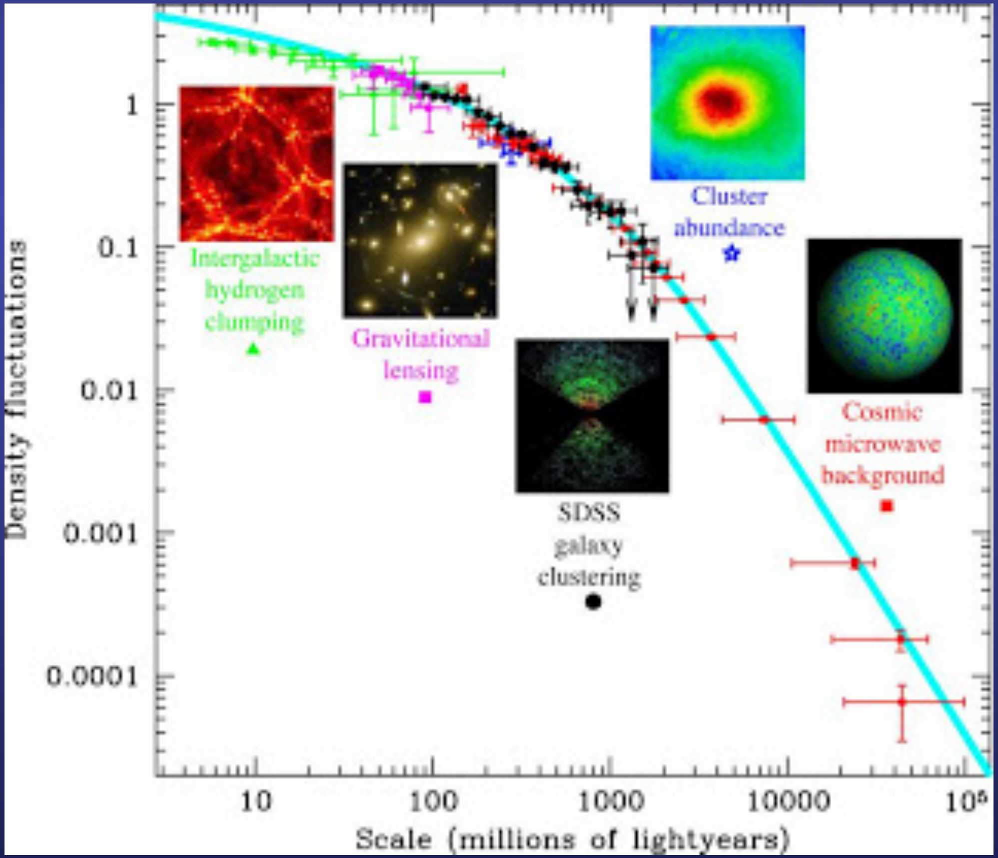
CMB by Planck





However the scales probed are fairly large

- Direct observations of matter fluctuations on linear to quasi-linear scales, >~ few cMpc

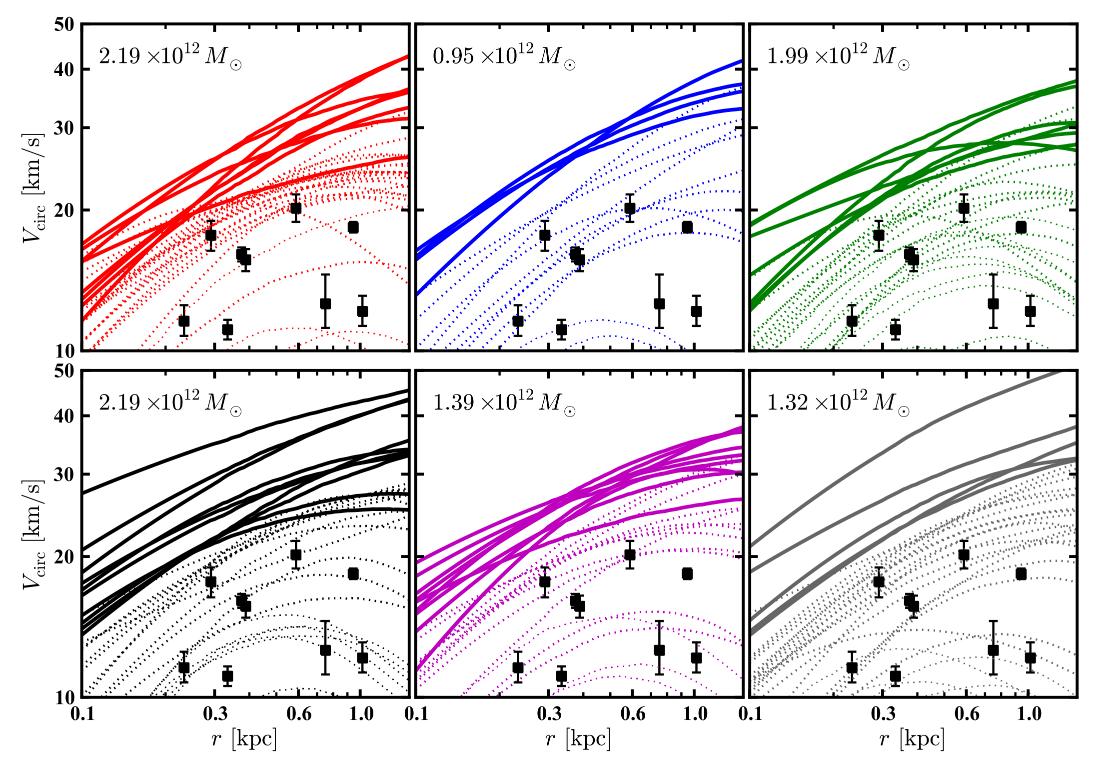


SDSS collaboration

Interestingly, CDM seemingly doesn't do so well on small-scales

for example:

- Galactic halos are kinematically inconsistent with CDM: missing population of dense, massive satellites (Boylan-Kolchin+ 2012)



Interestingly, CDM seemingly doesn't do so well on small-scales

for example:

- Galactic halos are kinematically inconsistent with CDM: missing population of dense, massive satellites (Boylan-Kolchin+ 2012)
- Inner profiles of individual dwarf galaxies are too shallow (Moore+1994; de Blok+2001; Maccio+2012; Governato+2012)
- Number of satellite galaxies in Milky Way (Moore+1999; Klypin+1999) and in the field (ALFALFA survey; Papastergis+2011; Ferrero+2012) is too low
- … (see Sellwood & Kosowsky 2001; Menci+ 2012; Boylan-Kolchin+2012)

Appeal to baryons?
maybe…

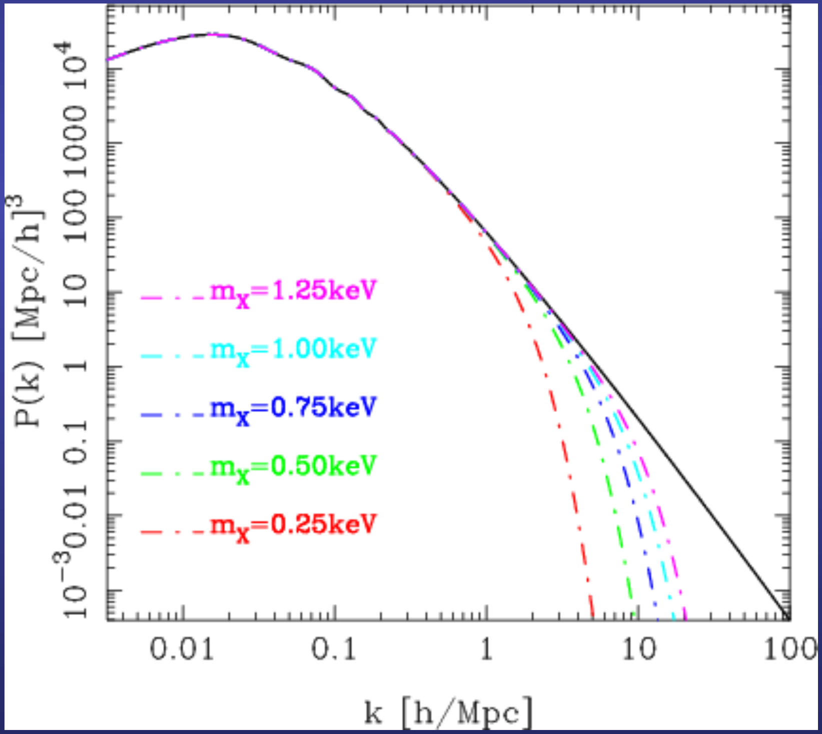
- SNe, reionization and ram pressure stripping can reduce baryon content, smearing out some DM along with them
- But simulations have difficulties in reproducing all properties even with a "tuning-knob" approach to feedback (e.g. Boylan-Kolchin+2012; Garrison-Kimmel et al. 2013; Teyssier et al. 2013)

What about suppressing primordial power, e.g. Warm Dark Matter

1. Free-streaming: particles stream out of primordial potential wells, truncating power on scales below the distance traveled up to ~ radiation-matter equality (Bode+ 2001):

$$R_S \approx 0.31\left(\frac{\Omega_X}{0.3}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{\mathrm{keV}}{m_X}\right)^{1.15} h^{-1}\ \mathrm{Mpc}\ .$$

thermal relic)



Smith+2011

Modification of the transfer function

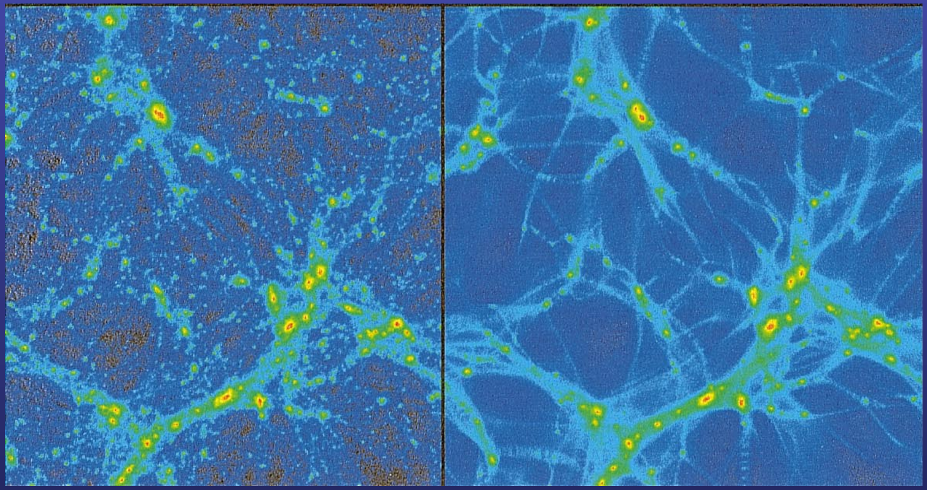
$$T(k) \rightarrow T(k)\left[1+(\epsilon k \lambda_{\mathrm{s}})^{2\nu}\right]^{-\eta/\nu}$$

What about suppressing primordial power, e.g. Warm Dark Matter

1. Free-streaming: particles stream out of primordial potential wells, truncating power on scales below the distance traveled up to ~ radiation-matter equality (Bode+ 2001):

$$R_s \approx 0.31 \left(\frac{\Omega_X}{0.3}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} \left(\frac{\mathrm{keV}}{m_X}\right)^{1.15} h^{-1}\ \mathrm{Mpc}\ .$$

CDM WDM, m_x= 0.35 keV



Bode+ 2001

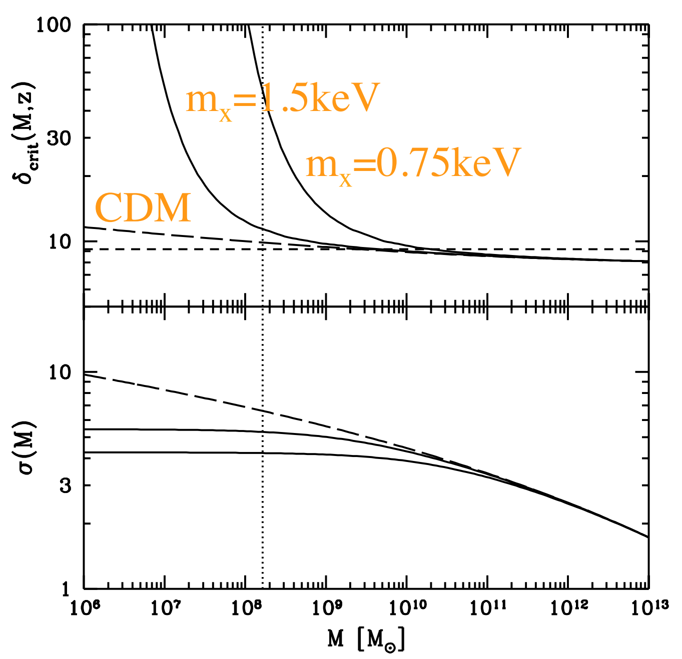
Modification of the transfer function

$$T(k) \rightarrow T(k)\left[1 + (\epsilon k \lambda_{\mathrm{s}})^{2\nu}\right]^{-\eta/\nu}$$

What about suppressing primordial power, e.g. Warm Dark Matter

1. Free-streaming: particles stream out of primordial potential wells, truncating power on scales below the distance traveled up to ~ radiation-matter equality (Bode+ 2001).
2. Residual particle velocities: act as an “effective pressure”, preventing the growth of early perturbations below a WDM “Jeans scale” (Barkana+ 2001)

$$\begin{aligned} M_{\rm J} &= 3.06\times10^{8}\left(\frac{1+z_{\rm eq}}{3000}\right)^{1.5}\left(\frac{\Omega_{\rm M}h_0^2}{0.15}\right)^{1/2} \\ &\times\left(\frac{g_{\rm X}}{1.5}\right)^{-1}\left(\frac{m_{\rm X}}{1.0\ {\rm keV}}\right)^{-4}\ {\rm M}_\odot, \end{aligned}$$



1D hydro collapse sims:
gas analogy to WDM pressure
(Barkana+2001)

Current constraints

- Lyman alpha forest: $m_x > 1\text{-}3$ keV (Viel+ 2006; 2008)
- Reproducing stellar mass function and Tully-Fisher relation: $m_x > 0.75$ keV (Kang+ 2013)
- Reionization occurring by $z \sim 6$: $m_x > 1$ keV (Barkana+ 2001)

Current constraints

- Lyman alpha forest: $m_x > 1\text{-}3$ keV (Viel+ 2006; 2008)
- Reproducing stellar mass function and Tully-Fisher relation: $m_x > 0.75$ keV (Kang+ 2013)
- Reionization occurring by z~6: $m_x > 1$ keV (Barkana+ 2001)

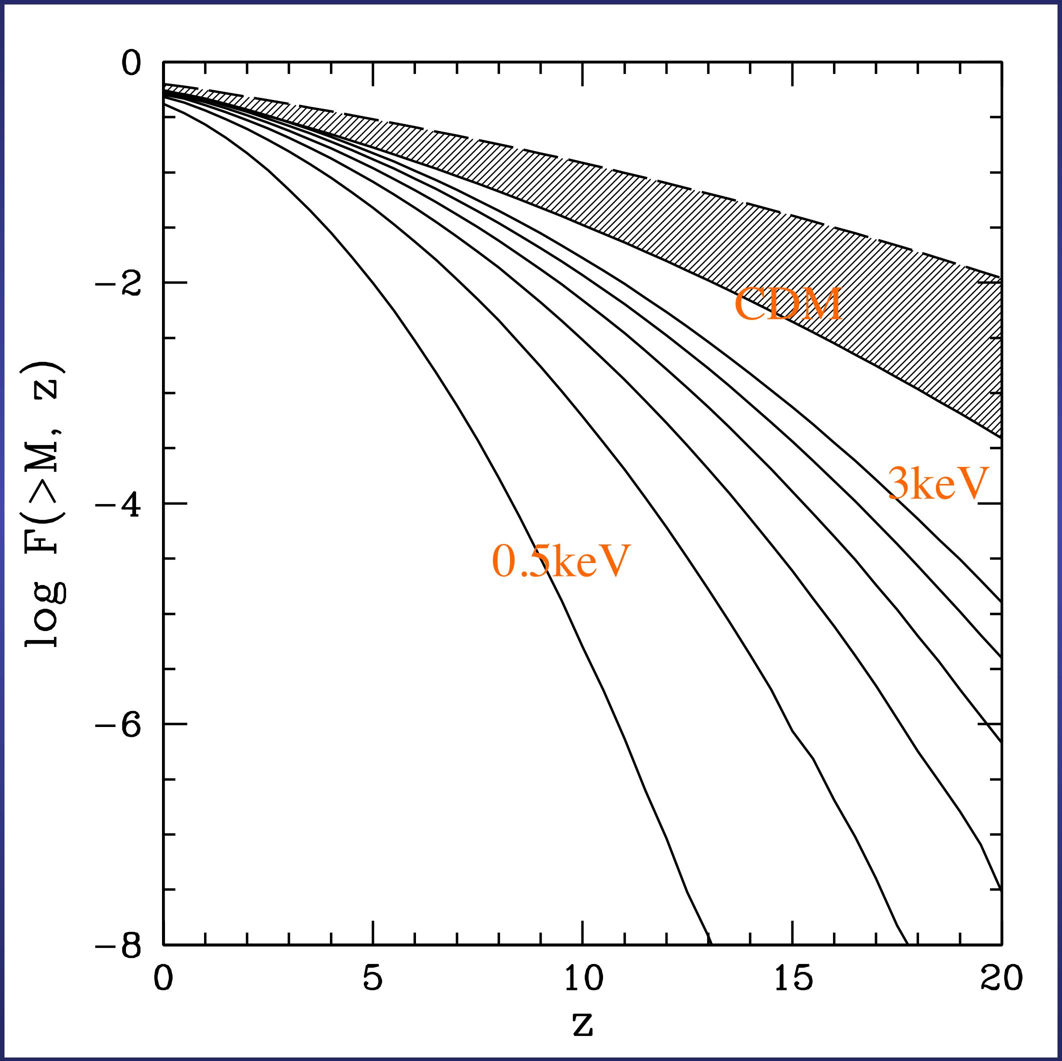
Difficulty is always in degeneracy with astrophysics!

New and upcoming constraints on DM properties (i.e. belated outline for this talk)

- Constraints from high-z abundances
  - z~10 lensed galaxies (from CLASH survey)
  - Swift GRB distributions
- Future potential with the physics-rich redshifted 21cm line
  - 21cm into
  - Modeling the signal (21cmFAST commercial)
  - WDM delay vs astrophysics
  - Robust imprint of WDM decay and CDM annihilation in thermal history

Always minimizing degeneracy with astrophysics.
Robust, robust, robust!

High-z is the place to be

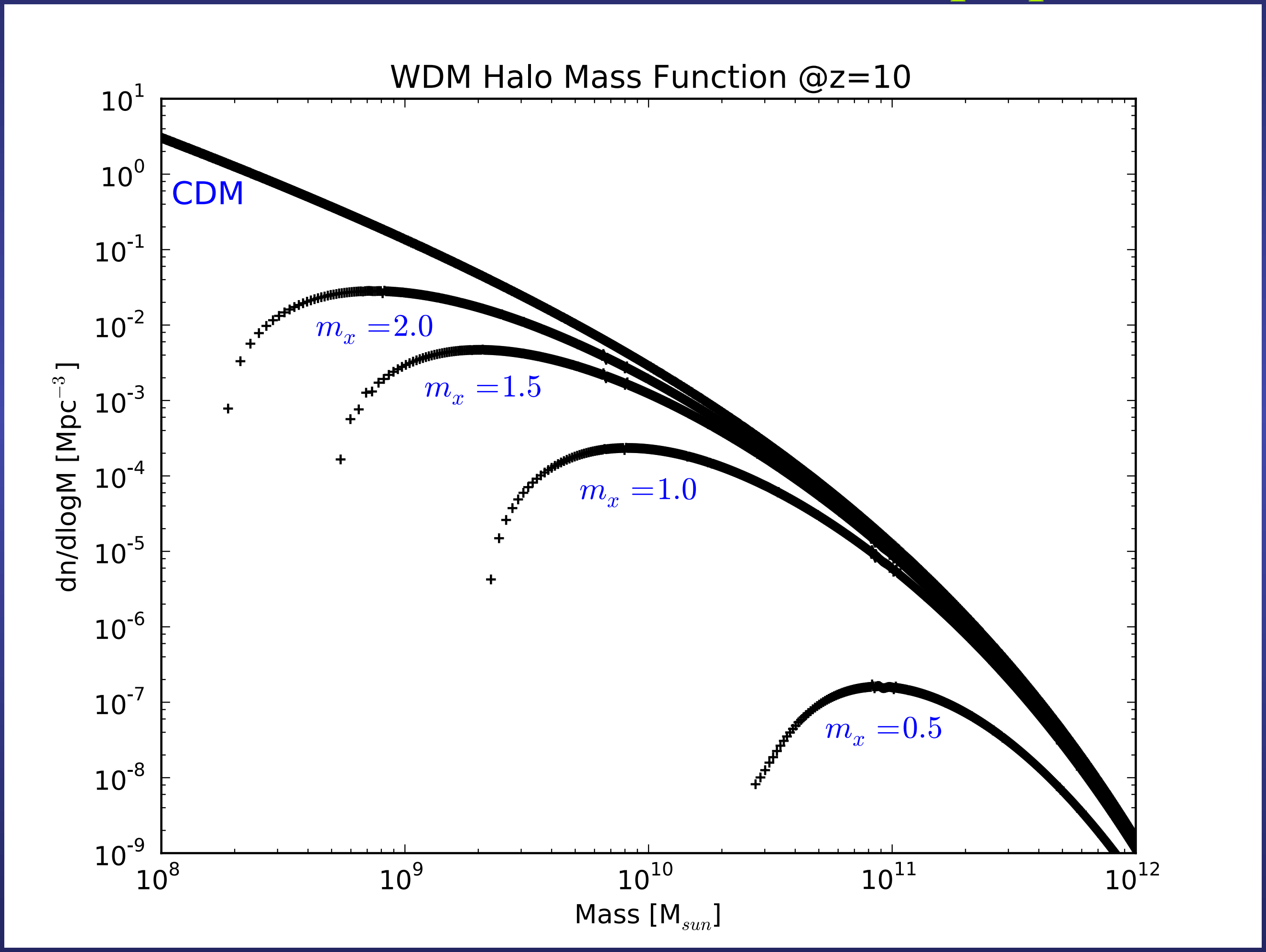


Mesinger+2005

Due to heirarchal structure formation, in WDM it is empty!

Sharp suppression in small-mass halos

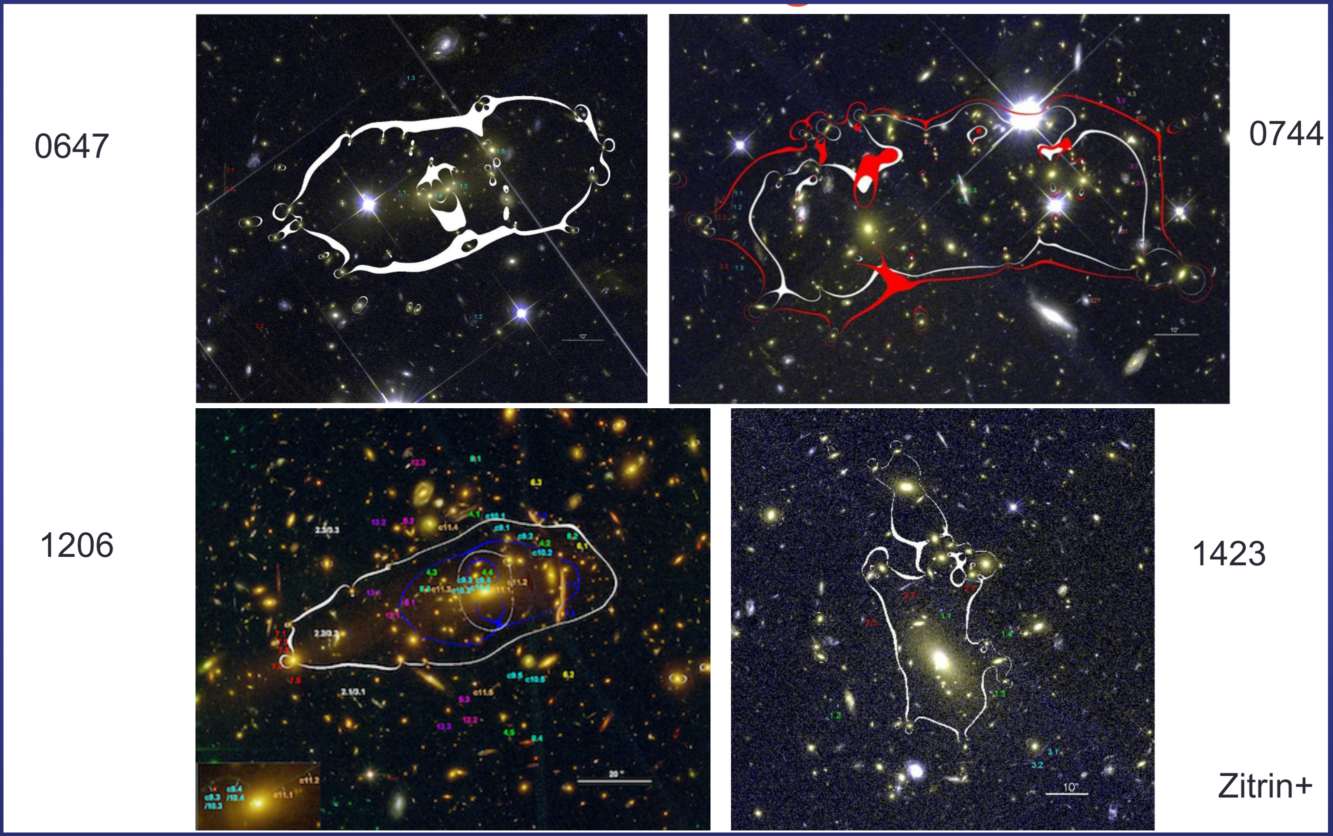
Pacucci, AM, Haiman, in-prep



Following analytic approach of Benson+2013
accounts for (i) free streaming; (ii) residual velocities (ala Barkana+2001)

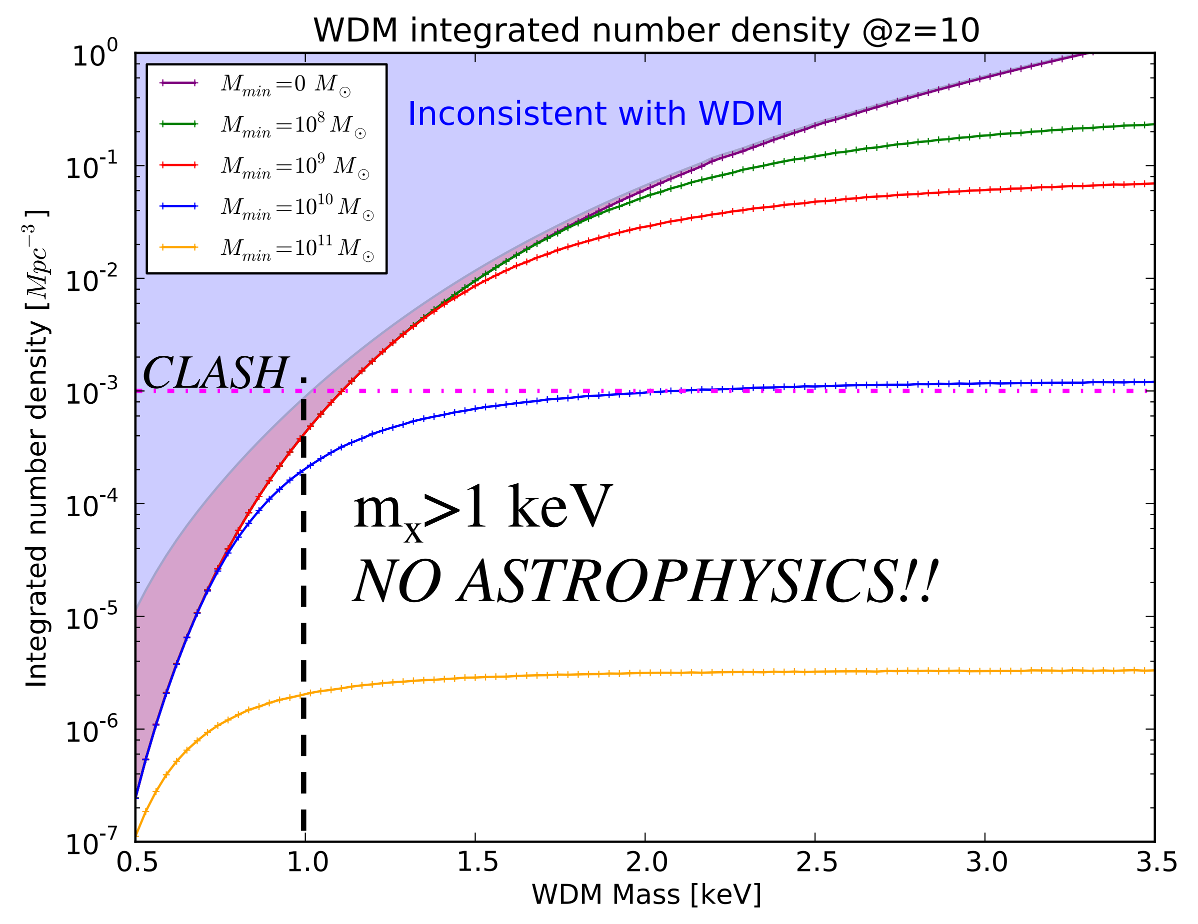
Cluster Lensing And Supernova survey with Hubble (CLASH)

Will cover 25 lensing clusters (currently 12 processed)



Already has 2 candidates (one with multiple images) at z=10 in tiny ~10^3 Mpc volume! → high number density of halos!

Halo number density constraint from CLASH

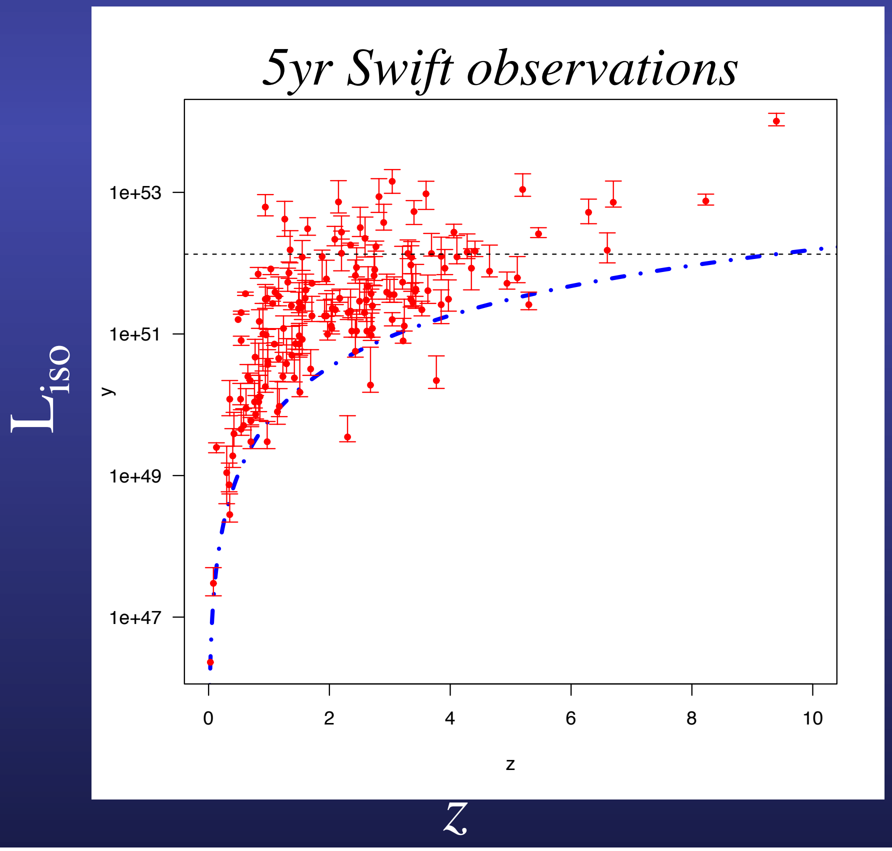


Limits can improve dramatically with future detections

Pacucci, AM, Haiman, in prep

Larger sample of high-z objects would be better

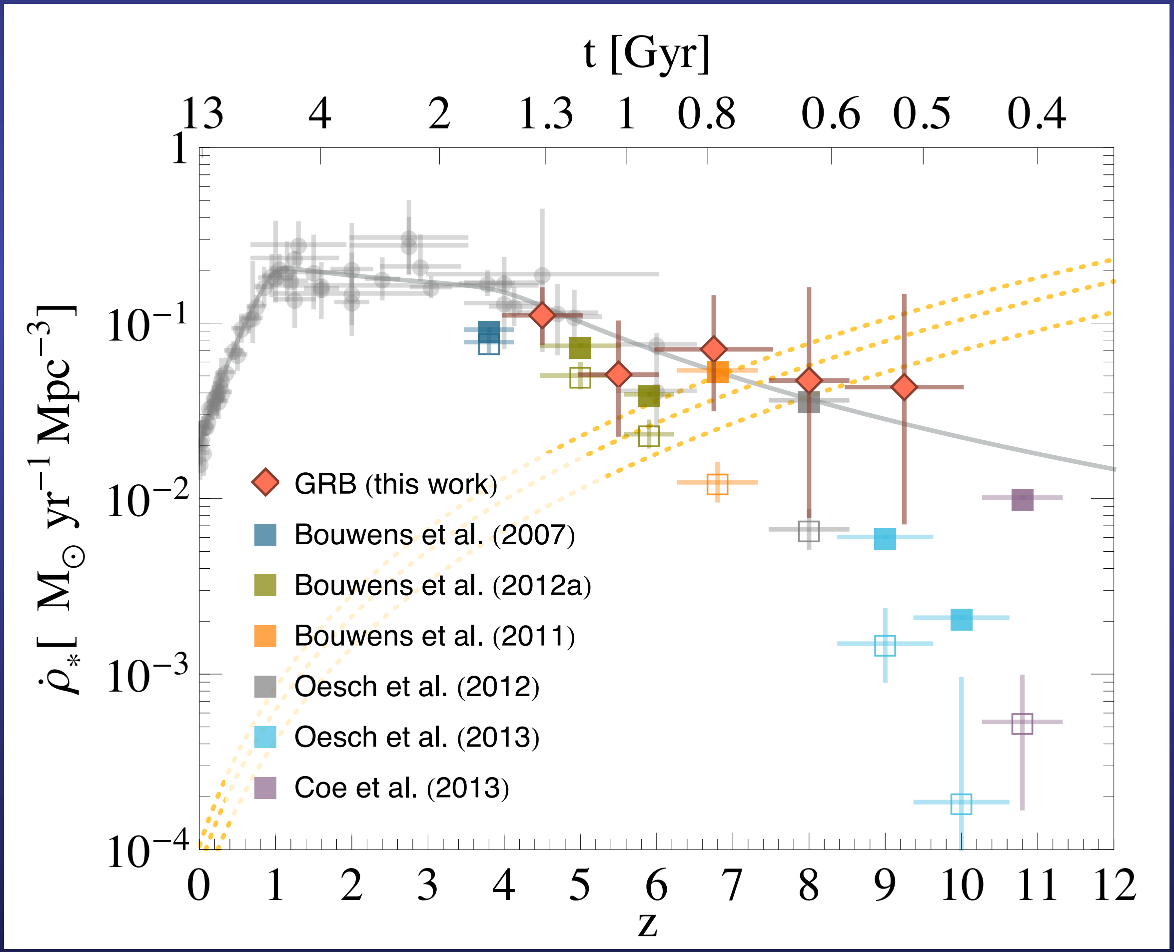
- How about gamma-ray bursts (GRBs): brightest events in the Universe; can be seen to very high-redshifts tracing the earliest/smallest structures. Many have accurate redshift determinations (not the case for LBG candidates).



de Souza, AM+ (2013)
Robertson & Elis (2012)

GRBs let us see the small guys where the interesting things are happening

- GRBs do not suffer from incompleteness like LBG candidates
- GRB derived SFR shows a flatter redshift evolution, consistent with Lyα forest

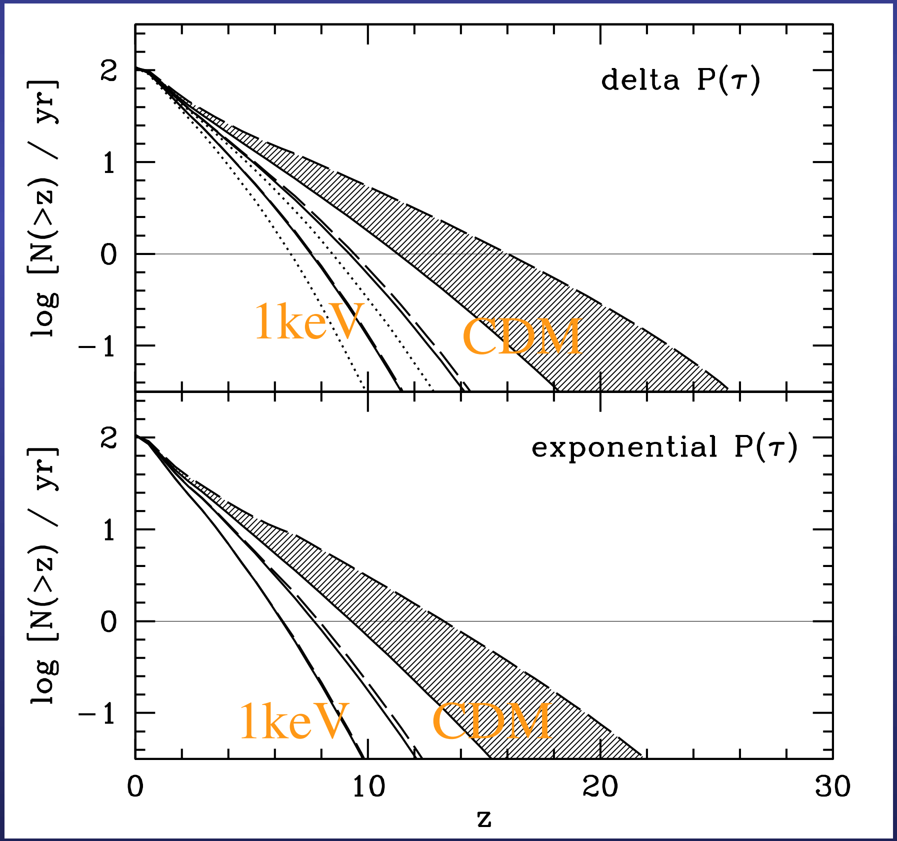


Kistler+2013

Early work pointed out their use for WDM

- However, it assumed a constant SFR→ GRB rate conversion.

Predicted SWIFT detection rates



AM+2005

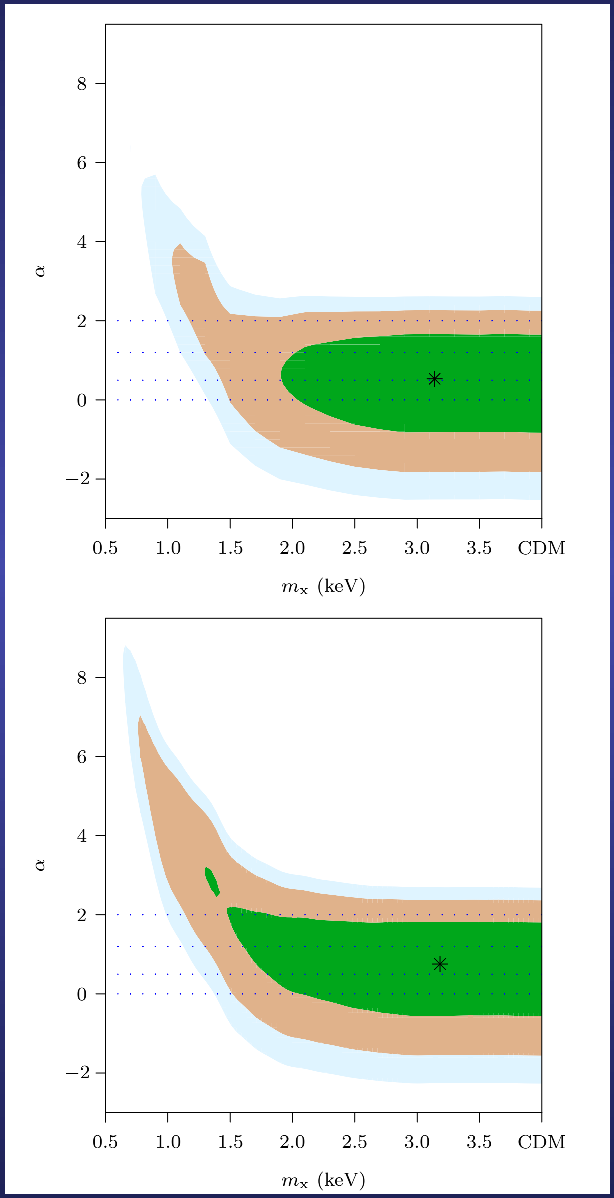
Must be more robust!

de Souza, AM+ 2013

- Use latest GRB dataset with well-determined redshifts
- Allow arbitrary redshift evolution in astrophysics:

  GRB rate ~ SFR $(1+z)^{\alpha}$
- Present results for two different samples: (i) LF constructed at low z; (ii) luminosity complete subsample
- Quantify constraints in Bayesian framework

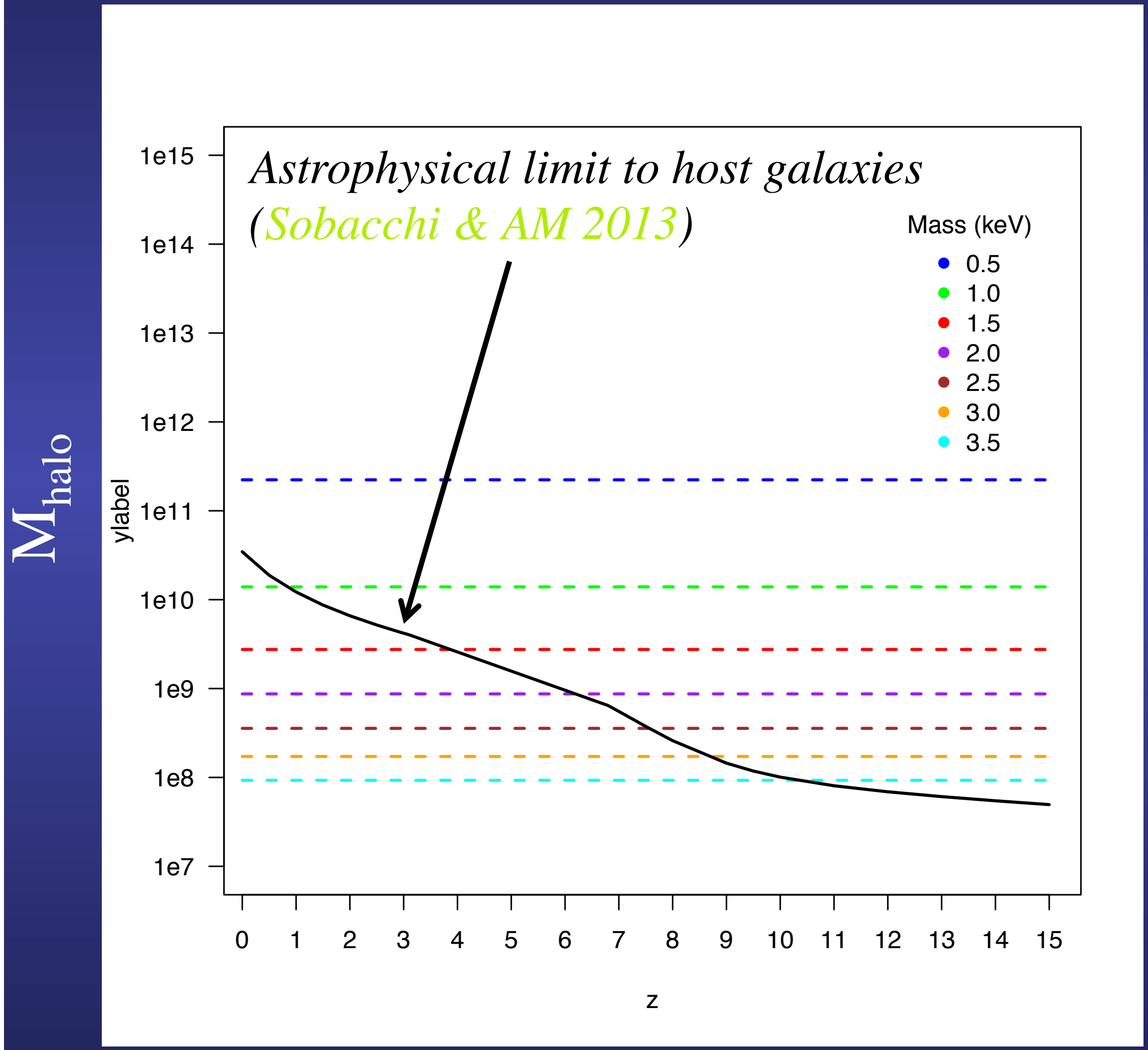
Results from GRBs



de Souza, AM + 2013

Marginalizing over a (flat prior) results in **robust** limits of $m_x > 1.6$-1.8 keV (95% C.L.)

Where do we do from here?



Impossible to do better than m_x>3keV at z<10 from galaxy abundances.

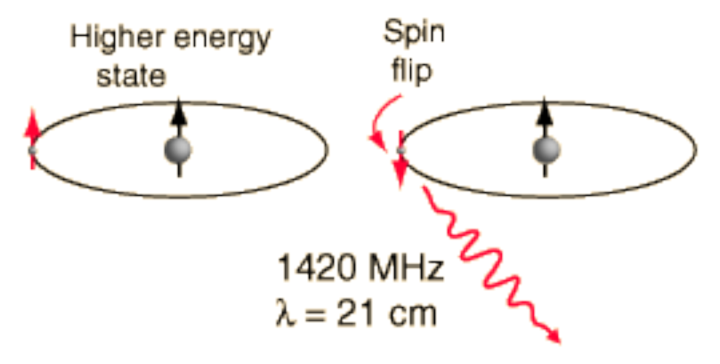
-go to higher redshifts
-find other metrics less sensitive to gastrophysics

de Souza, AM + 2013

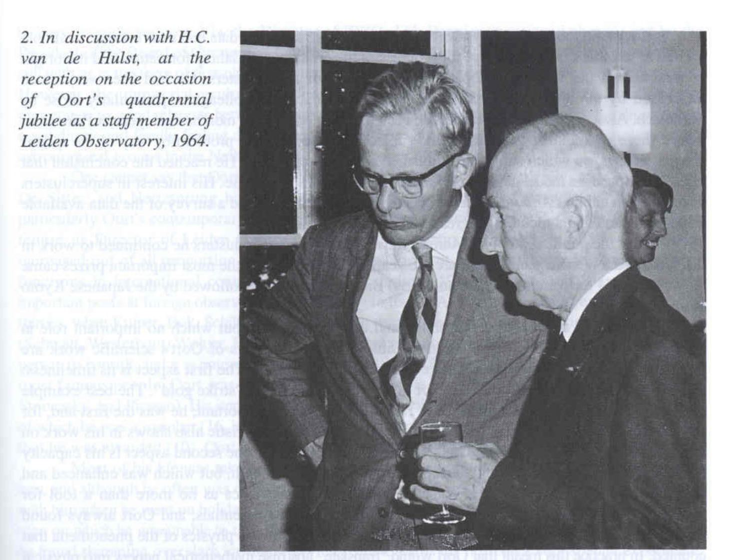
The most powerful probe of this epoch is the redshifted 21cm line!

Probes ionization AND thermal history of the Universe!

21 cm line from neutral hydrogen



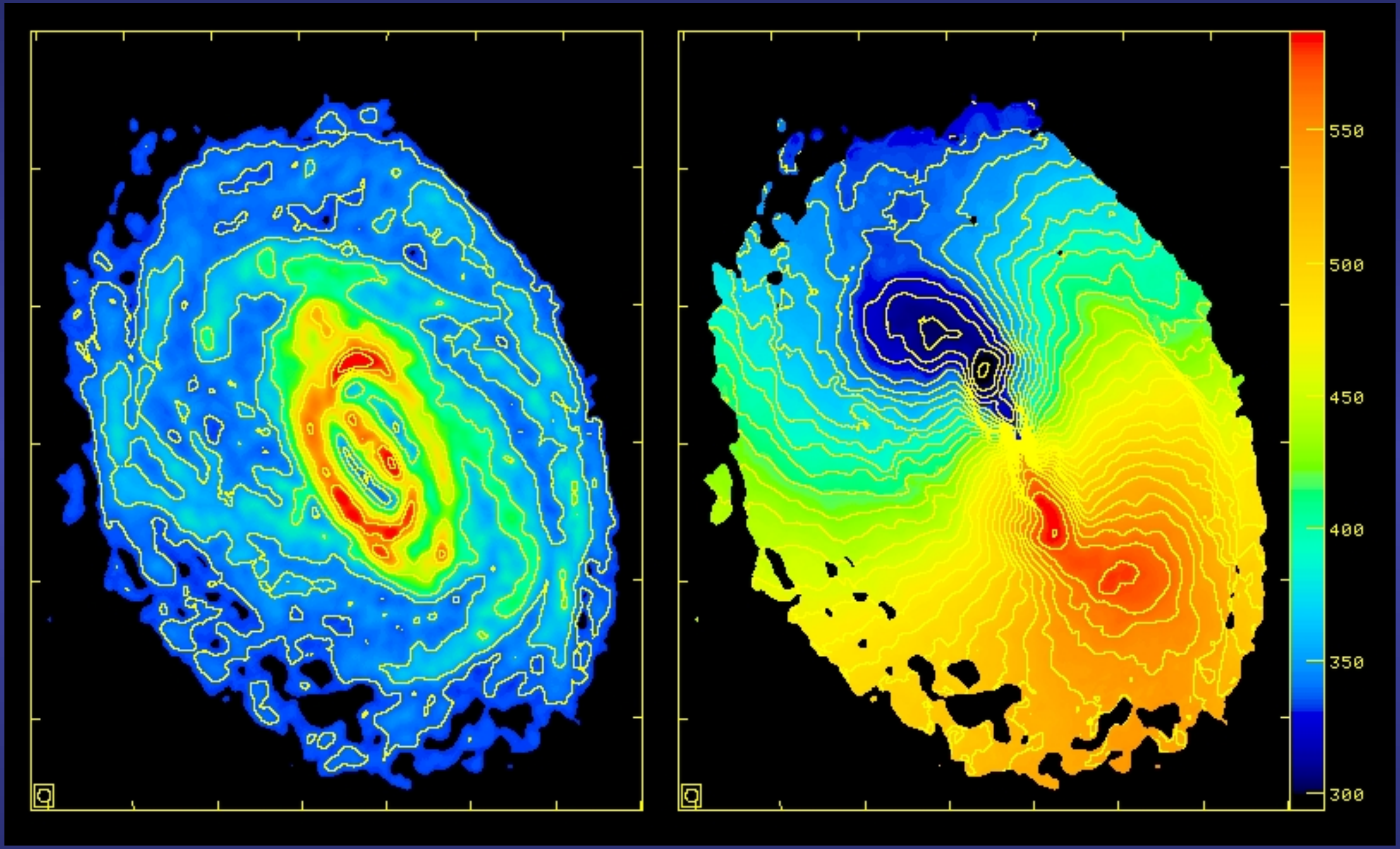
Hyperfine transition in the ground state of neutral hydrogen produces 21cm line.



2. In discussion with H.C. van de Hulst, at the reception on the occasion of Oort's quadrennial jubilee as a staff member of Leiden Observatory, 1964.

Predicted by van den Hulst when Oort told him to find unknown radio lines to study our galaxy

Now widely used to map the HI content of nearby galaxies

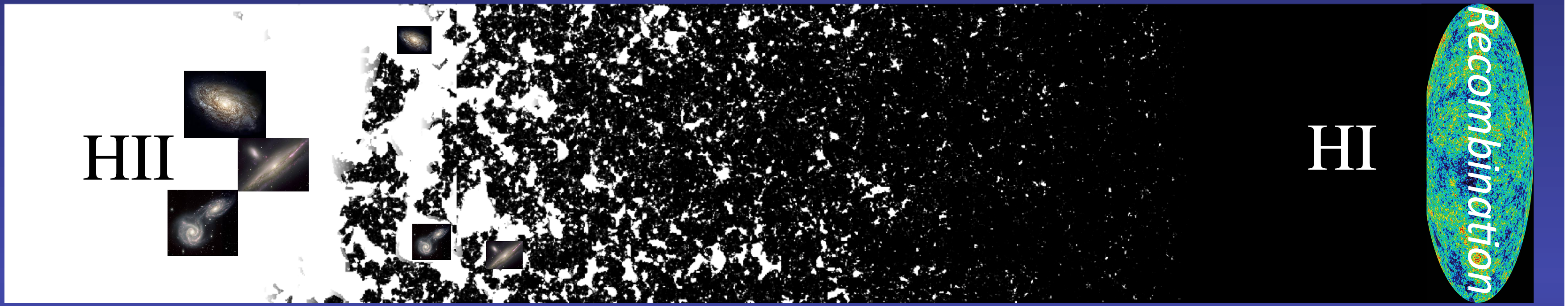


Circinus Galaxy

ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).

Once upon a time, HI was much more abundant

Reionization *Dark Ages*



$z = 0$ $z \sim 6$ $z \sim 20$ $z \sim 1100$

$t_{age} \sim 14$ Gyr $t_{age} \sim 1$ Gyr $t_{age} \sim 150$ Myr $t_{age} \sim 0.4$ Myr

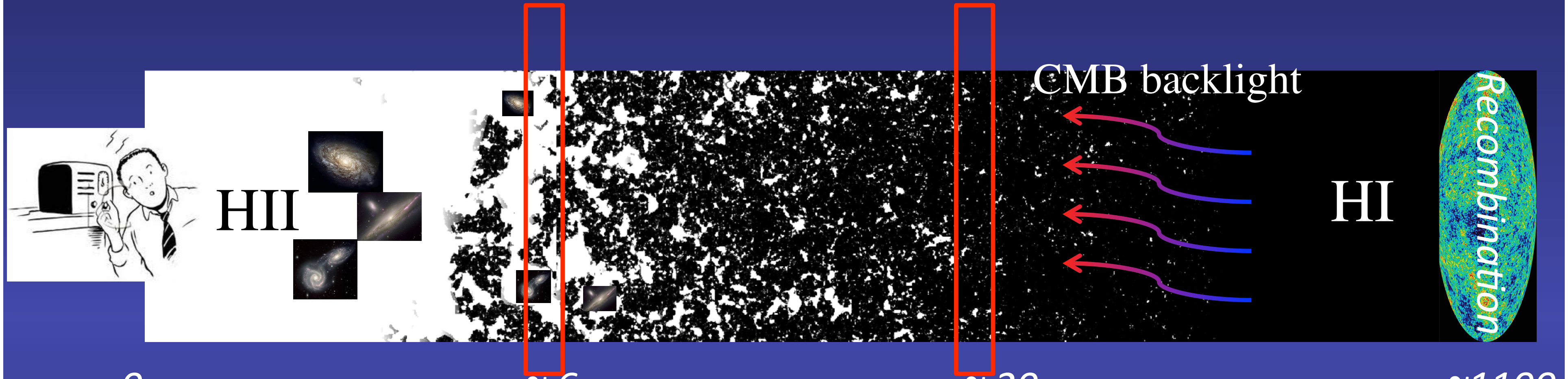
Once upon a time, HI was much more abundant

Redshifted 21cm signal.

tune radio to:

υ_{21}~ 200 MHz

υ_{21}~ 70 MHz



z = 0

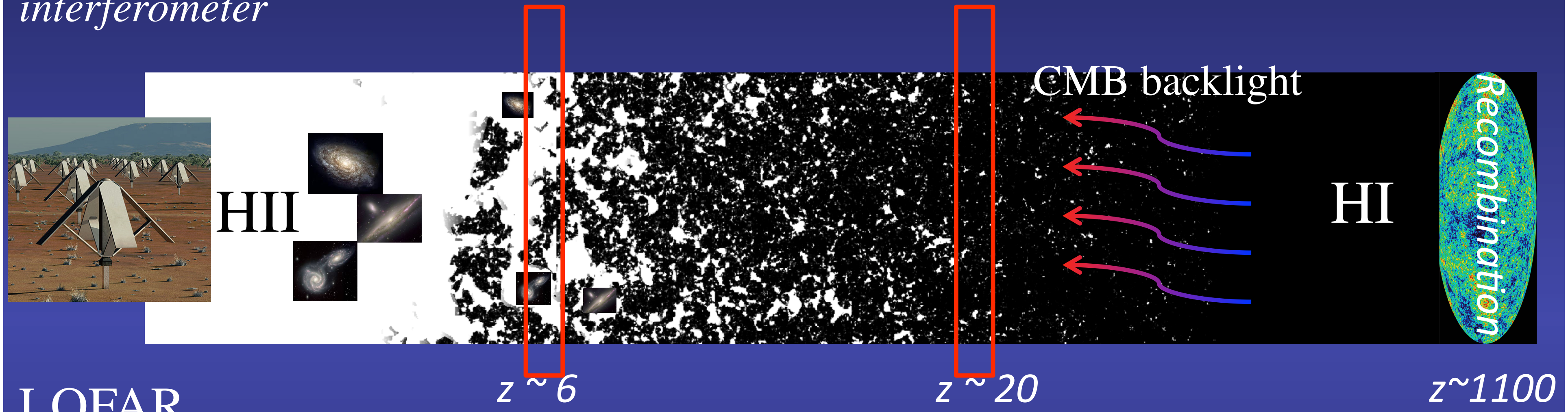
z ~ 6

z ~ 20

z~1100

Once upon a time, HI was much more abundant

Redshifted 21cm signal.
tune r✖io to:
interferometer

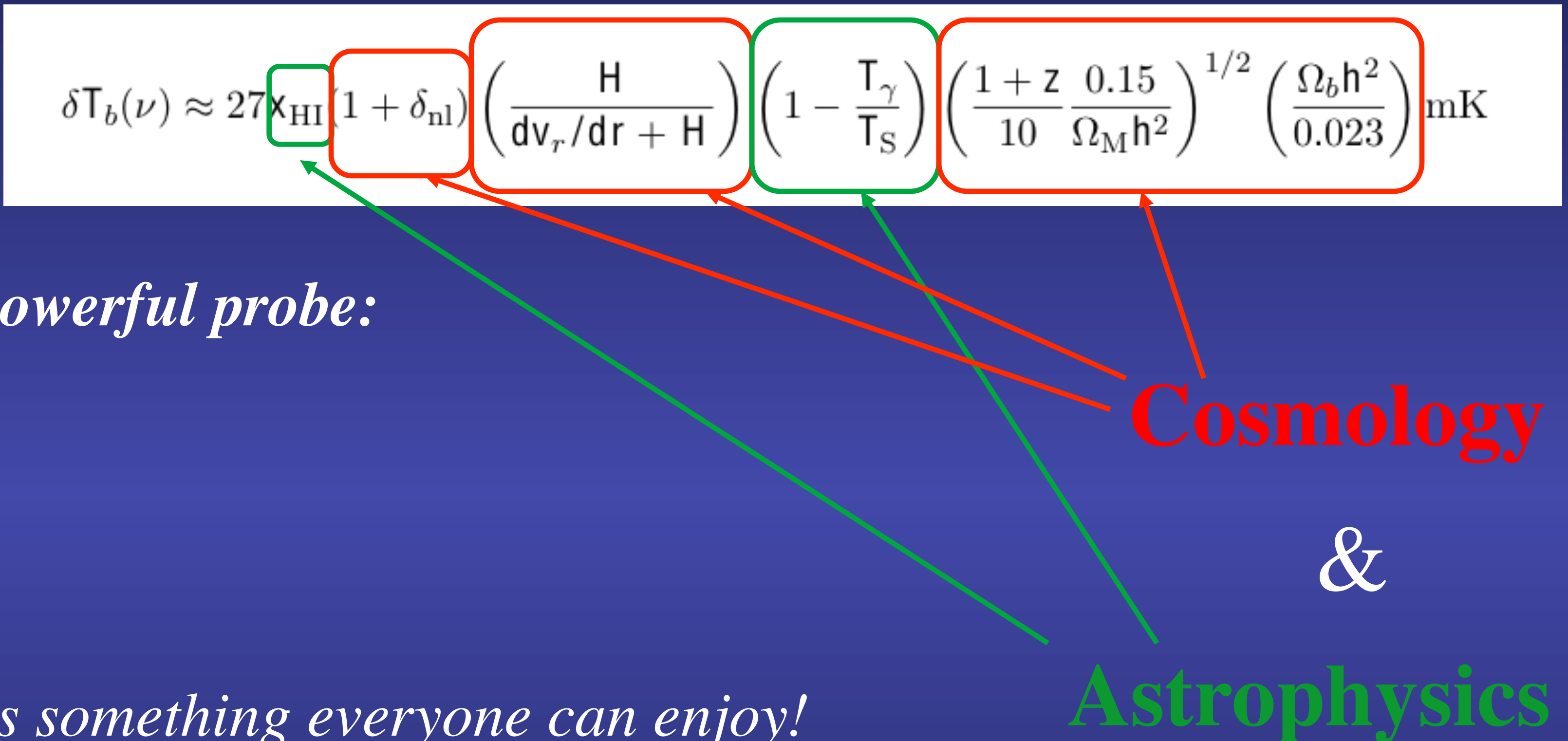


LOFAR,
MWA,
PAPER,
21CMA,
GMRT
2nd gen: SKA

Cosmological 21cm Signal

$$\delta T_b(\nu) \approx 27 \underbrace{\boxed{x_{\rm HI}}}_{\text{neutral fraction}} \underbrace{\boxed{(1+\delta_{\rm nl})}}_{\text{gas density}} \underbrace{\boxed{\left(\frac{H}{dv_r/dr + H}\right)}}_{\text{LOS velocity gradient}} \underbrace{\boxed{\left(1 - \frac{T_\gamma}{T_S}\right)}}_{\text{spin temperature}} \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \,\mathrm{mK}$$

Cosmological 21cm Signal



$$\delta T_b(\nu) \approx 27\boxed{x_{\rm HI}}\boxed{(1+\delta_{\rm nl})}\boxed{\left(\frac{H}{dv_r/dr + H}\right)}\boxed{\left(1-\frac{T_\gamma}{T_S}\right)}\boxed{\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)}\,\mathrm{mK}$$

Powerful probe:

Cosmology

&

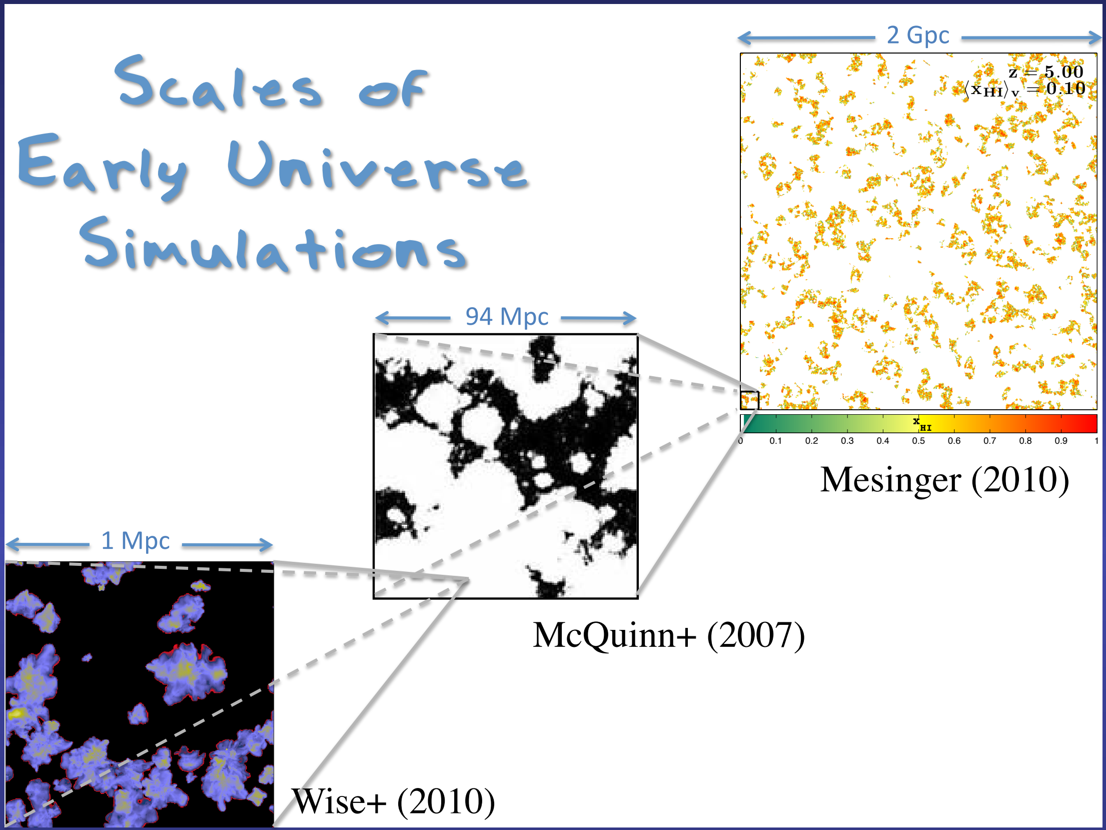
Astrophysics

Has something everyone can enjoy!

The trick is to disentangle the components:

- *separation of epochs and/or*
- *accurate, efficient modeling (21cmFAST) and/or*

How to understand the signal?



~ FoV of 21cm interferometers

- *Dynamic range required is enormous: single star --> Universe*
- *We know next to nothing about high-z --> ENORMOUS parameter space to explore*
- *Numerical simulations are computationally expensive: not good for parameter studies*
- *Most relevant scales are in the linear to quasi-linear regime*

--> use the right tool for each task!

21cmFAST

semi-numerical simulation (AM, Furlanetto, Cen 2011)

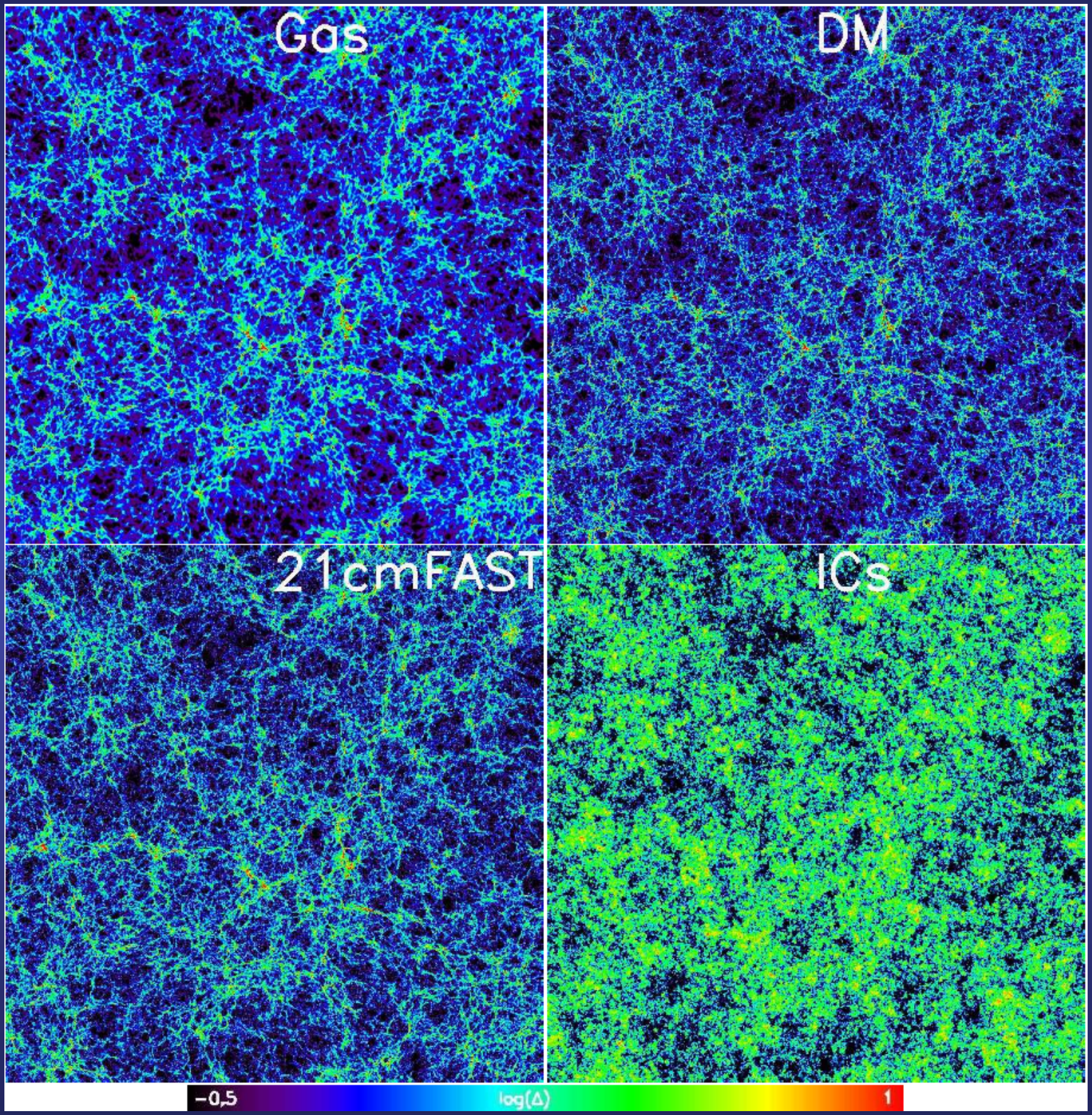
- Combines excursion-set approach with perturbation theory for efficient generation of large-scale density, velocity, halo, ionization, 21cm brightness fields
- Portable and FAST! (if it's in the name, it must be true…)
  - A realization can be obtained in ~ minutes on a single CPU
  - *New* parallelized version, optimized for parameter studies
- Run on arbitrarily large scales
- Optimized for the 21cm signal
- Vary many independent free parameters; cover wide swaths of parameter space
- Tested against state-of-the-art hydrodynamic cosmological simulations (Trac & Cen 2007; Trac+ 2008)
- Publically available: http://homepage.sns.it/mesinger/Sim

Previous halo-based version, DexM (Mesinger & Furlanetto 2007),
has been used to interpret LAEs, QSO spectra, LLS distribution,

Density Fields

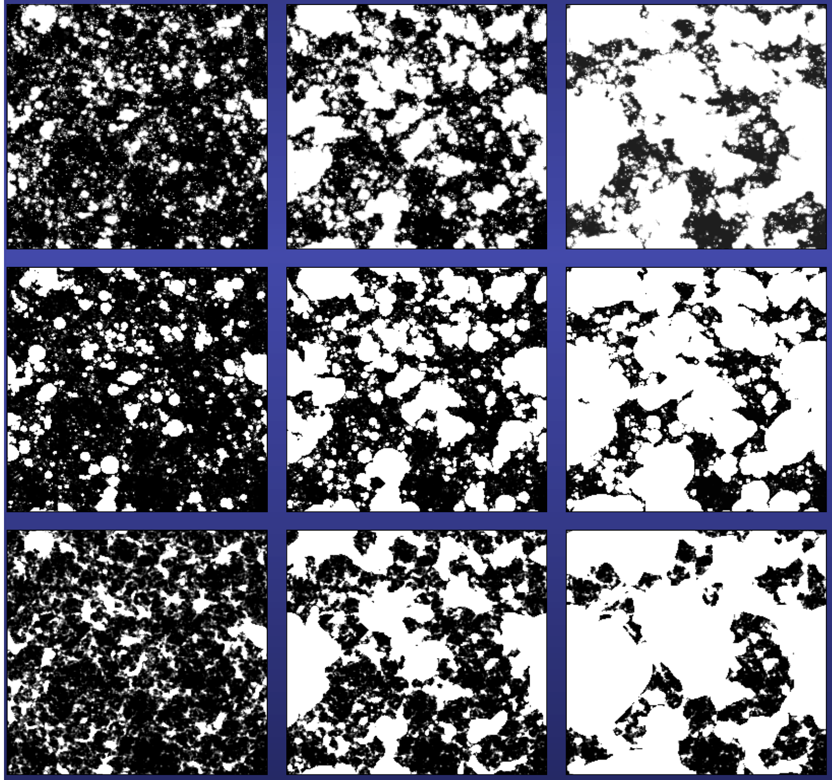
z=7

0.19 Mpc cells



143 Mpc

Ionization fields



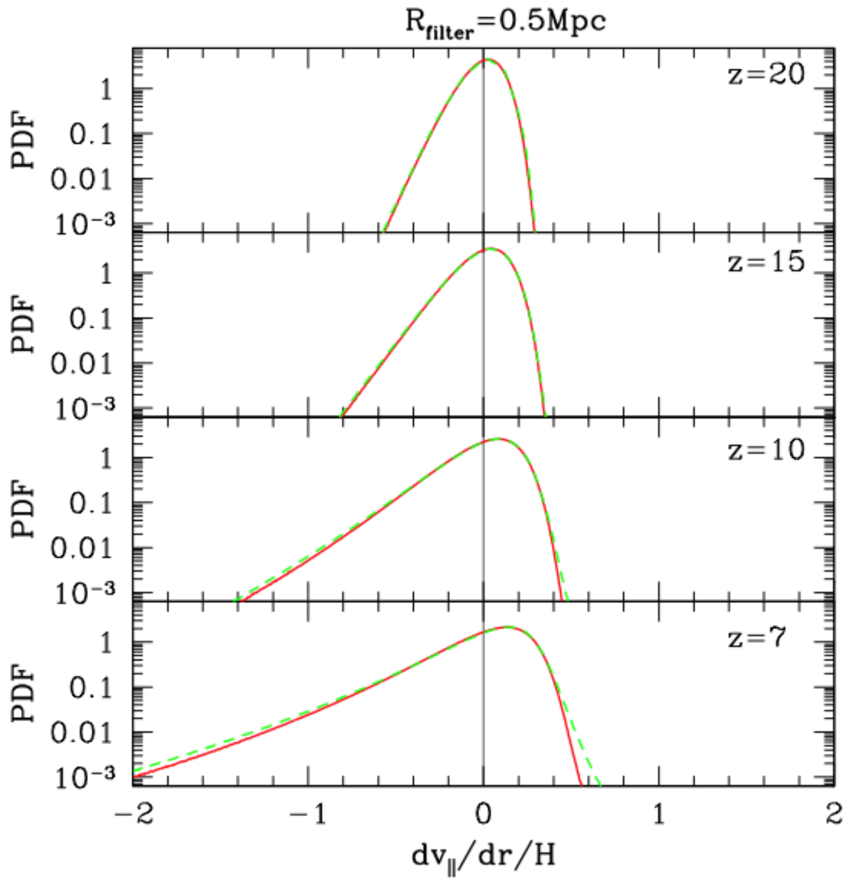
Trac & Cen (2007)

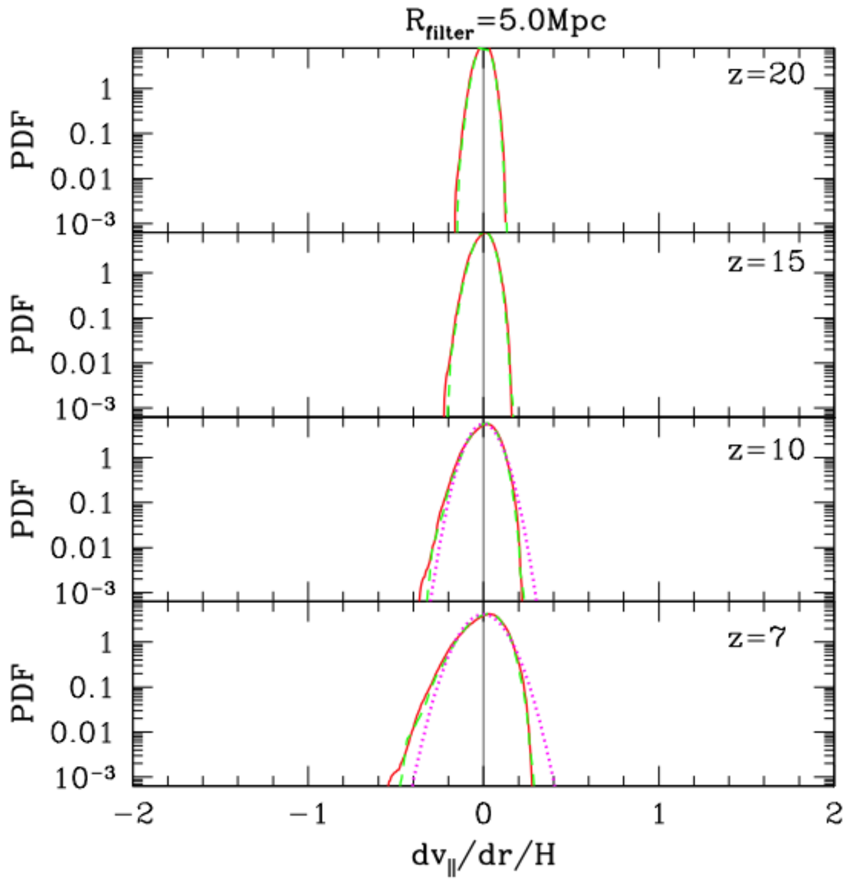
DexM (with halos;
Mesinger & Furlanetto; 2007)

21cmFAST (Mesinger+ 2011)

Zahn+ (2010)

Redshift space distortions (sorry no pics)

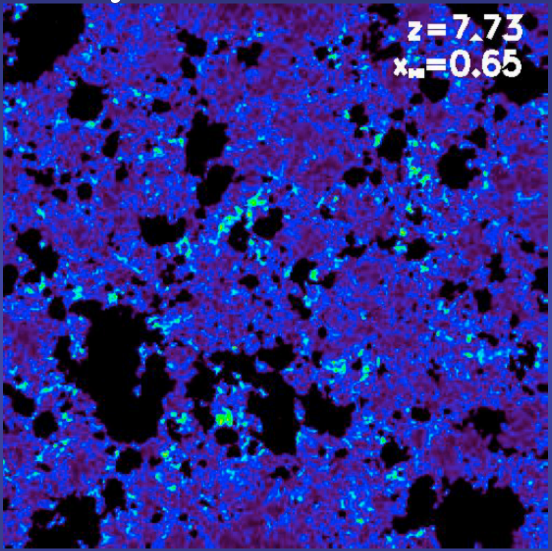




nonlinear structure formation creates an asymmetric velocity gradient distribution

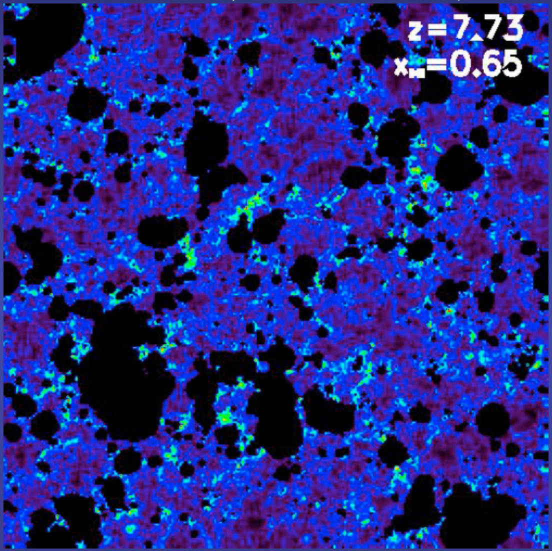
Full 21cm comparison (without spin temperature)

hydro+DM+RT



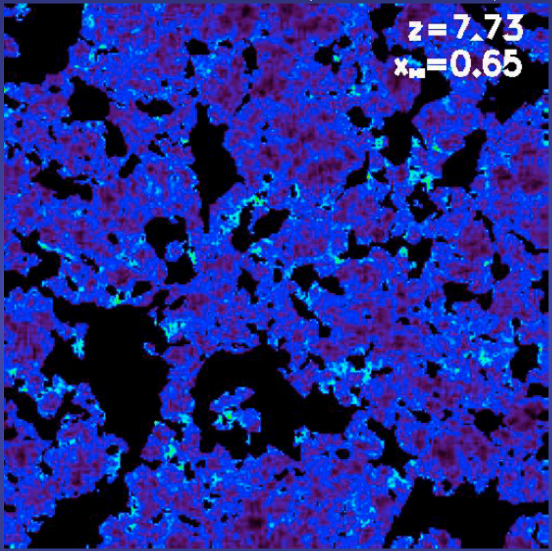
~ 1 week on 1536 cores

DexM (with halos)



← 100 Mpc/*h* →

21cmFAST (no halos)



~ few min on 1 core

Get on board!

http://homepage.sns.it/mesinger/Sim

In just over 2 years, 21cmFAST is being used by researchers in 12 countries, and most of the 1st gen. 21cm experiments: LOFAR, MWA, 21CMA

Thermal evolution: pre-reionization signal

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}})\left(\frac{H}{dv_r/dr+H}\right)\boxed{\left(1-\frac{T_\gamma}{T_S}\right)}\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\,\mathrm{mK}$$

spin temperature

defined in terms of the ratio of the number densities of electrons occupying the two hyperfine levels:

$$n_1/n_0 = 3\ e^{-0.068\ \mathrm{K}/T_s}$$

Pre-reionization signal

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}}) \left(\frac{H}{dv_r/dr + H}\right) \boxed{\left(1 - \frac{T_\gamma}{T_S}\right)} \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$

spin temperature:

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

T_γ – temperature of the CMB
T_K – gas kinetic temperature
T_α – color temperature ~ T_K

the spin temperature interpolates between T_γ and T_K

The spin temperature interpolates between T_γ and T_K

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

two coupling coefficients:

$$x_c = \frac{0.0628\ \mathrm{K}}{A_{10} T_\gamma} \left[n_{\mathrm{HI}} \kappa_{1-0}^{\mathrm{HH}}(T_{\mathrm{K}}) + n_e \kappa_{1-0}^{\mathrm{eH}}(T_{\mathrm{K}}) + n_{\mathrm{p}} \kappa_{1-0}^{\mathrm{pH}}(T_{\mathrm{K}}) \right]$$

collisional coupling

requires high densities

effective in the IGM at z>40

$$x_\alpha = 1.7 \times 10^{11} (1+z)^{-1} S_\alpha J_\alpha$$

Wouthuysen-Field (WF)

uses the Lyα background

effective soon after the first sources ignite

The spin temperature approaches the kinetic temperature if either coefficient is high. Otherwise, the spin temperature approaches the CMB temperature: NO SIGNAL!

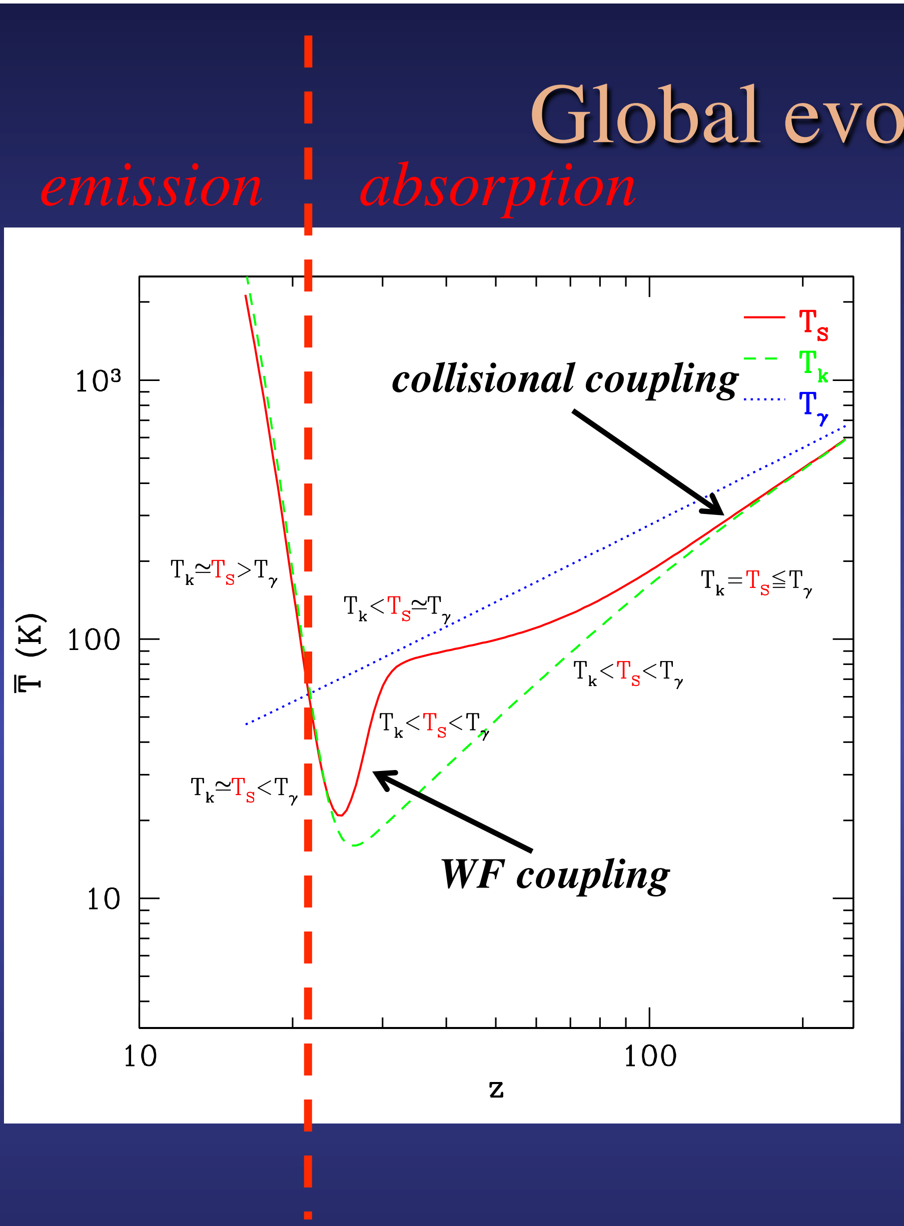
What do the temperatures do?

T_γ – CMB temperature decreases as (1+z)

T_K – coupled to the CMB at high z ~>250. Then after decoupling adiabatically cools as ~$(1+z)^2$. When first astrophysical sources ignite, they heat the IGM through their X-rays.

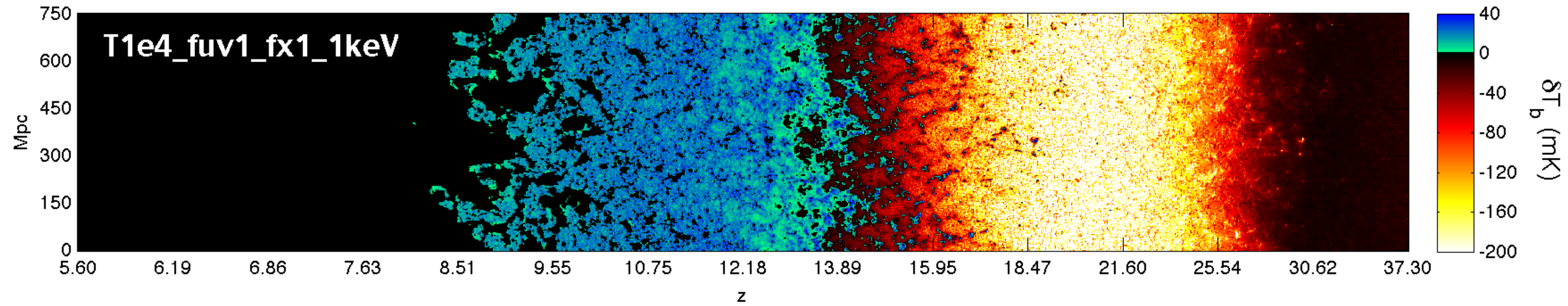
Global evolution: T_S, T_K, T_{CMB}

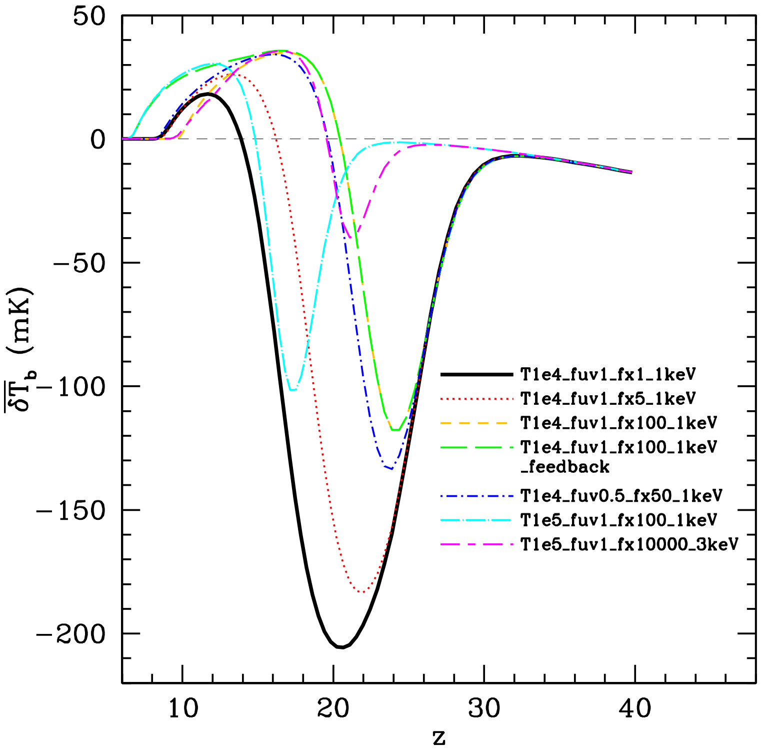
emission *absorption*



Global evolution: dT_b

$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ \mathrm{mK}$$



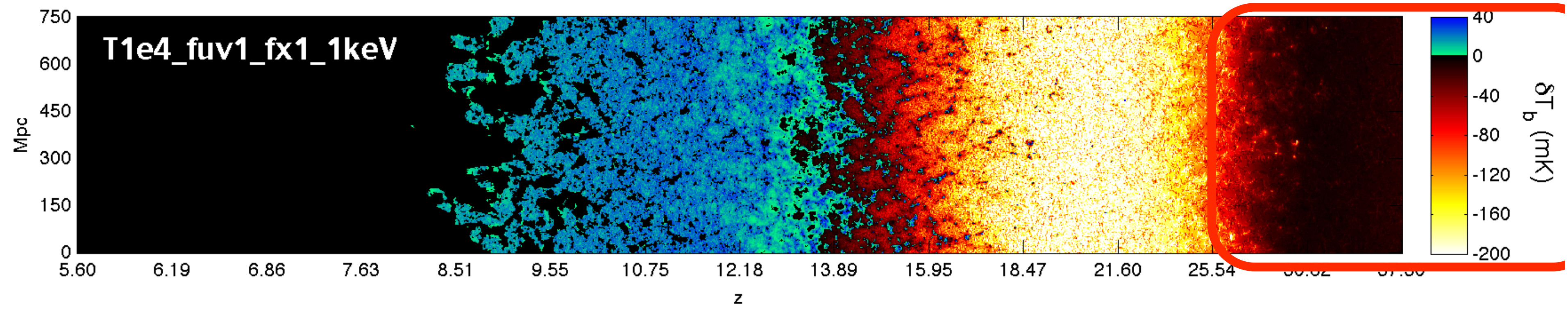


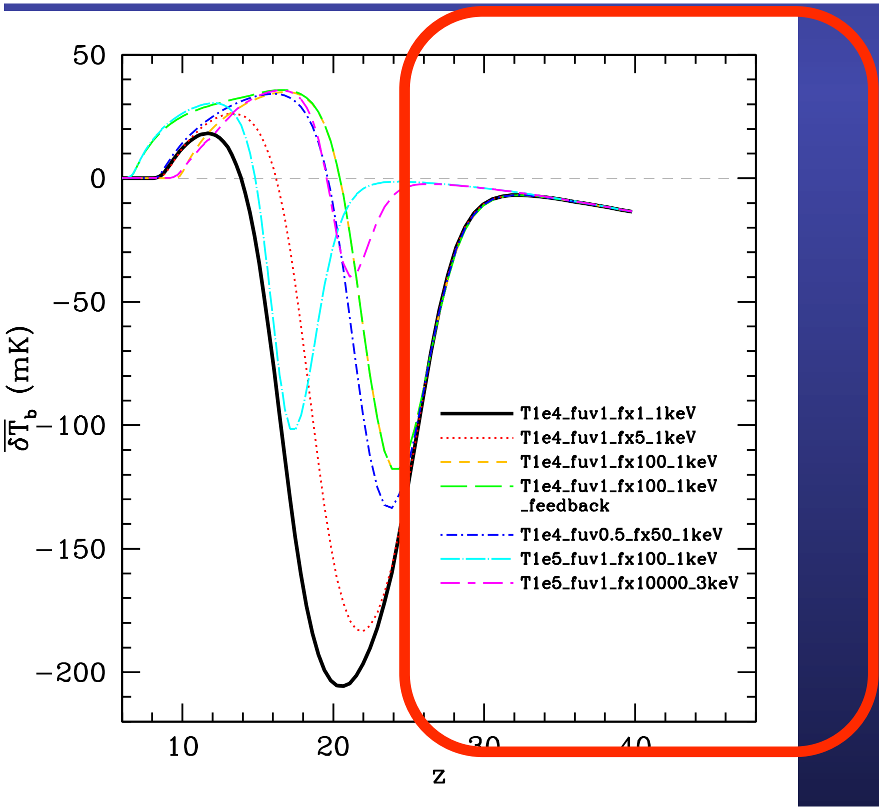
Main stages:

- Collisional coupling (z>~100)

Global evolution: dT_b

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}})\left(\frac{H}{dv_r/dr+H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\mathrm{mK}$$



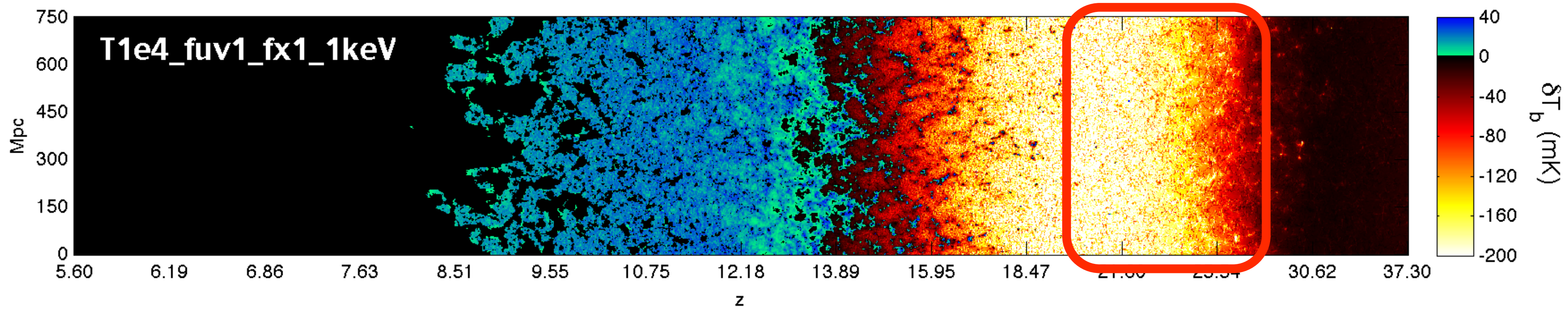


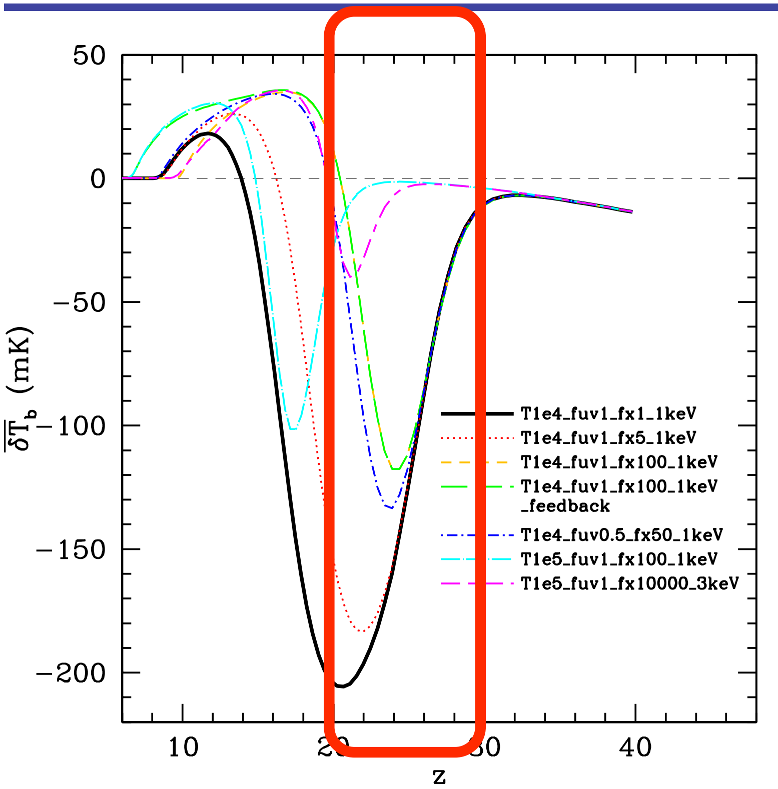
Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)

Global evolution: dT_b

$$\delta T_b(\nu) \approx 27 x_{\mathrm{HI}}(1+\delta_{\mathrm{nl}})\left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\,\mathrm{mK}$$



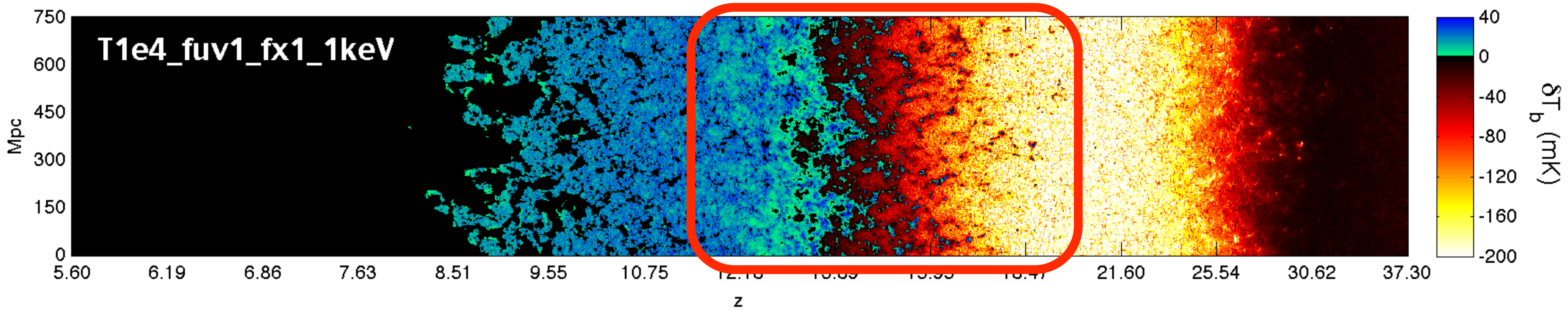


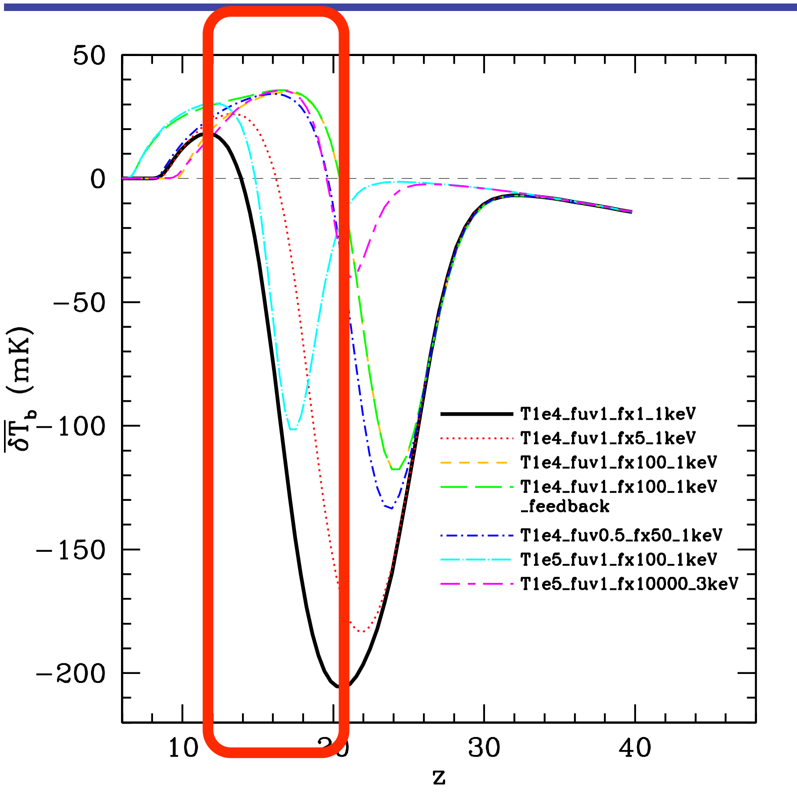
Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)
- WF coupling (Lyα pumping)

Global evolution: dT_b

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$



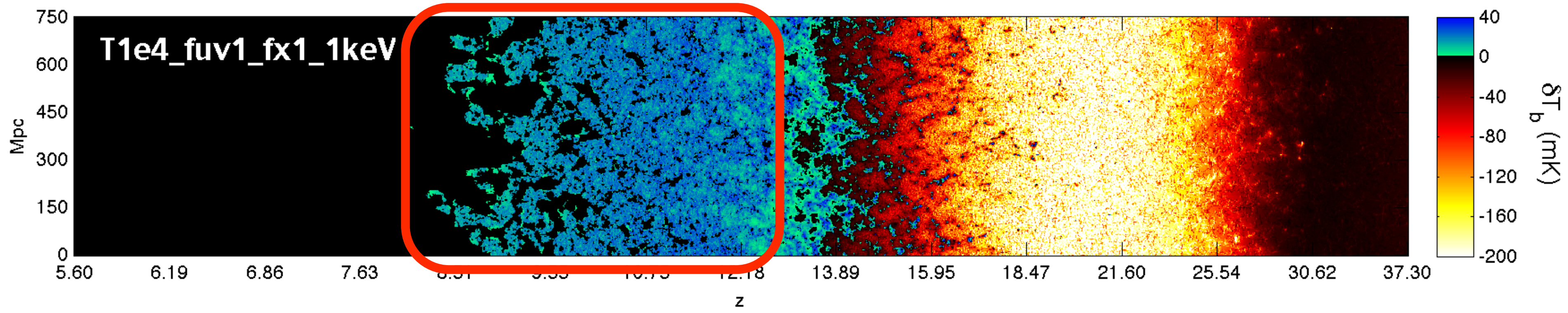


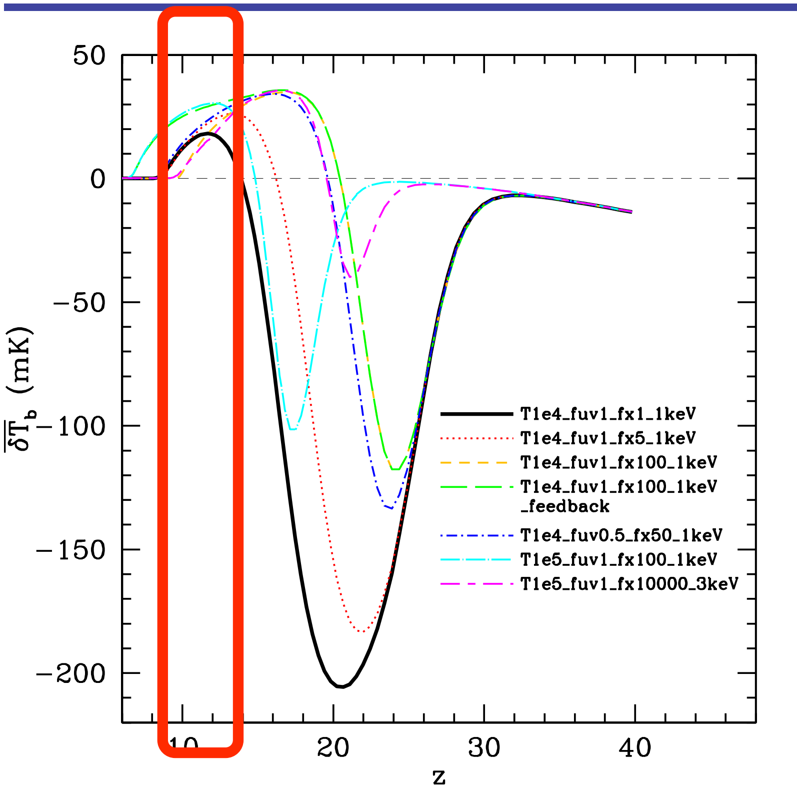
Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)
- WF coupling (Lyα pumping)
- IGM heating (X-rays)

Global evolution: dT_b

$$\delta T_b(\nu) \approx 27 x_{HI}(1+\delta_{nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \mathrm{mK}$$



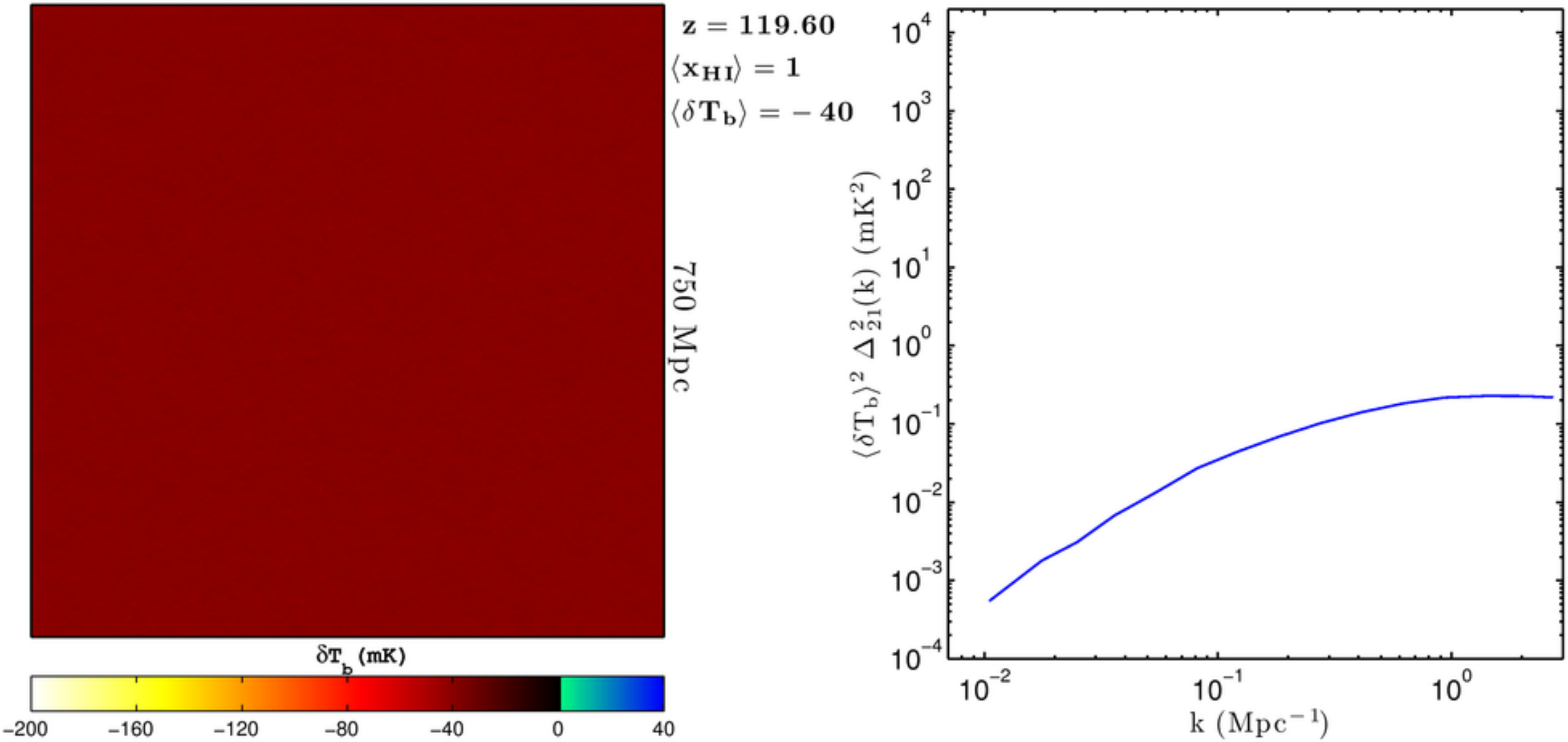


Likely overlap!

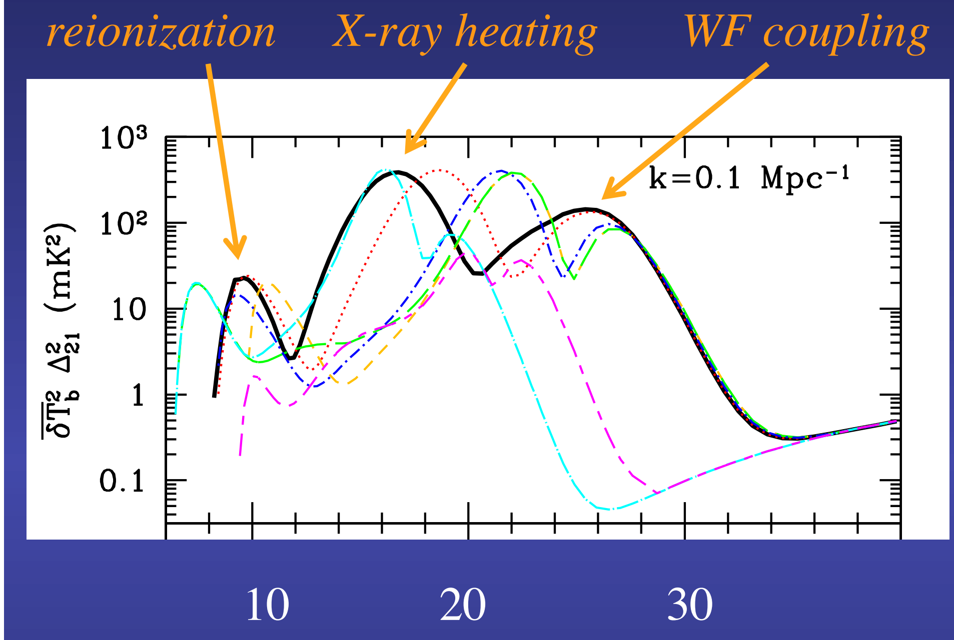
Main stages:

- Collisional coupling (z>~100)
- Collisional decoupling (25<z<100)
- WF coupling (Lyα pumping)
- IGM heating (X-rays)
- Reionization

http://homepage.sns.it/mesinger/21cm_fiducial.mov



dT_b Power spectra



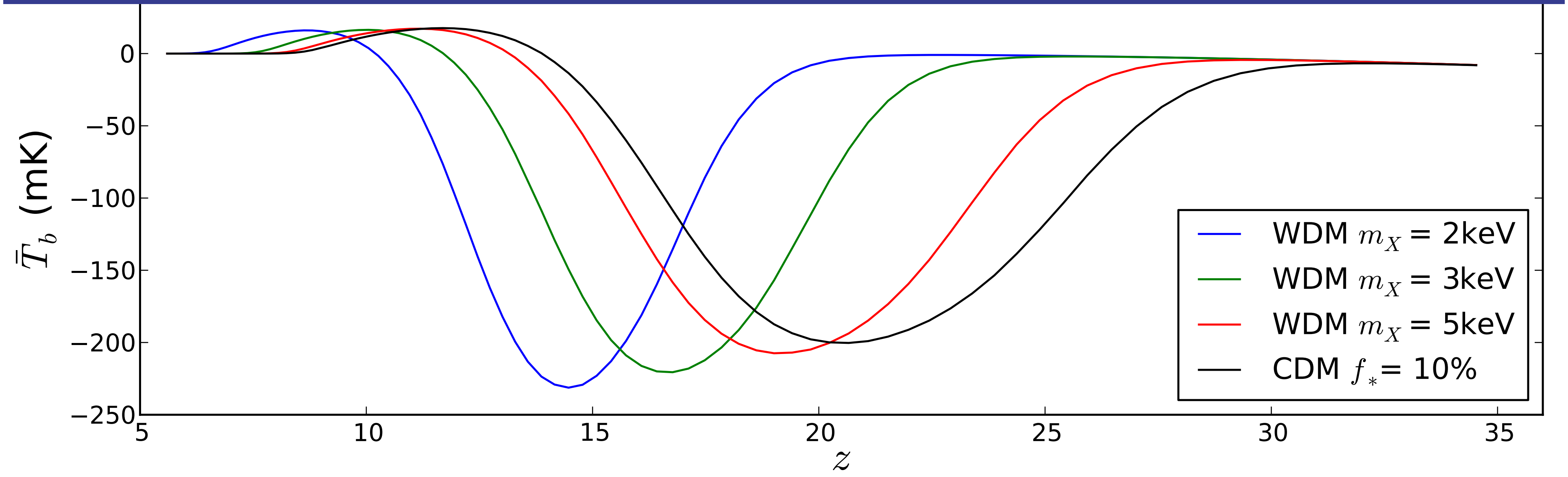
AM+2013

generic 3 peaked evolution of large-scale power

Highest peak is always X-ray heating.

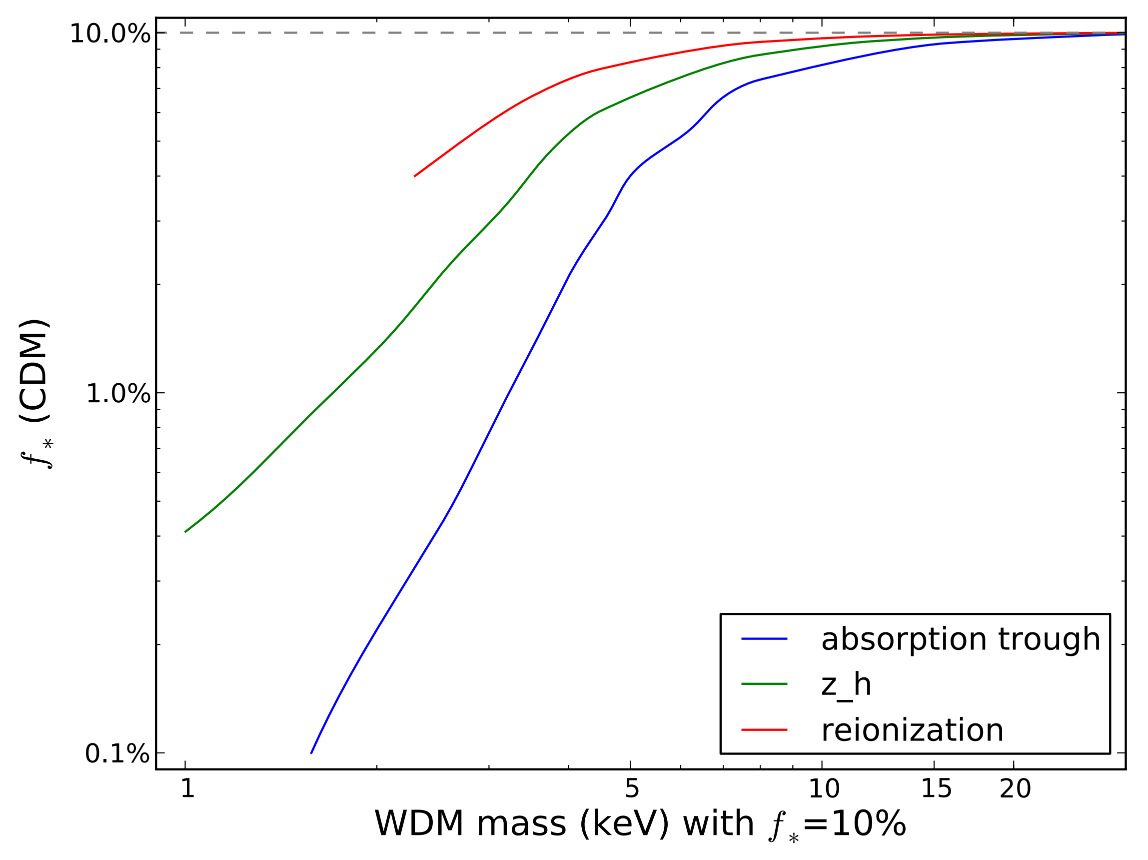
How does WDM affect signal?

- From its suppression of halo abundances, the relevant epochs are delayed, and then accelerated



Sitwell+, in prep

But this is degenerate with star formation



Sitwell+ in prep

- *Best bet is high-z regime (heating epoch)*
- *For $m_x > 5$keV, we must know astrophysics to better than a factor of 2*
- *For $m_x > 3$keV, order of magnitude is sufficient*

How does WDM affect signal?

- From its suppression of halo abundances, the relevant epochs are delayed, and then accelerated

but also…

- Can contribute to the epoch of IGM heating through WDM particle decay (or through annihilations for CDM)

Thermal history pre-reionization is a powerful probe

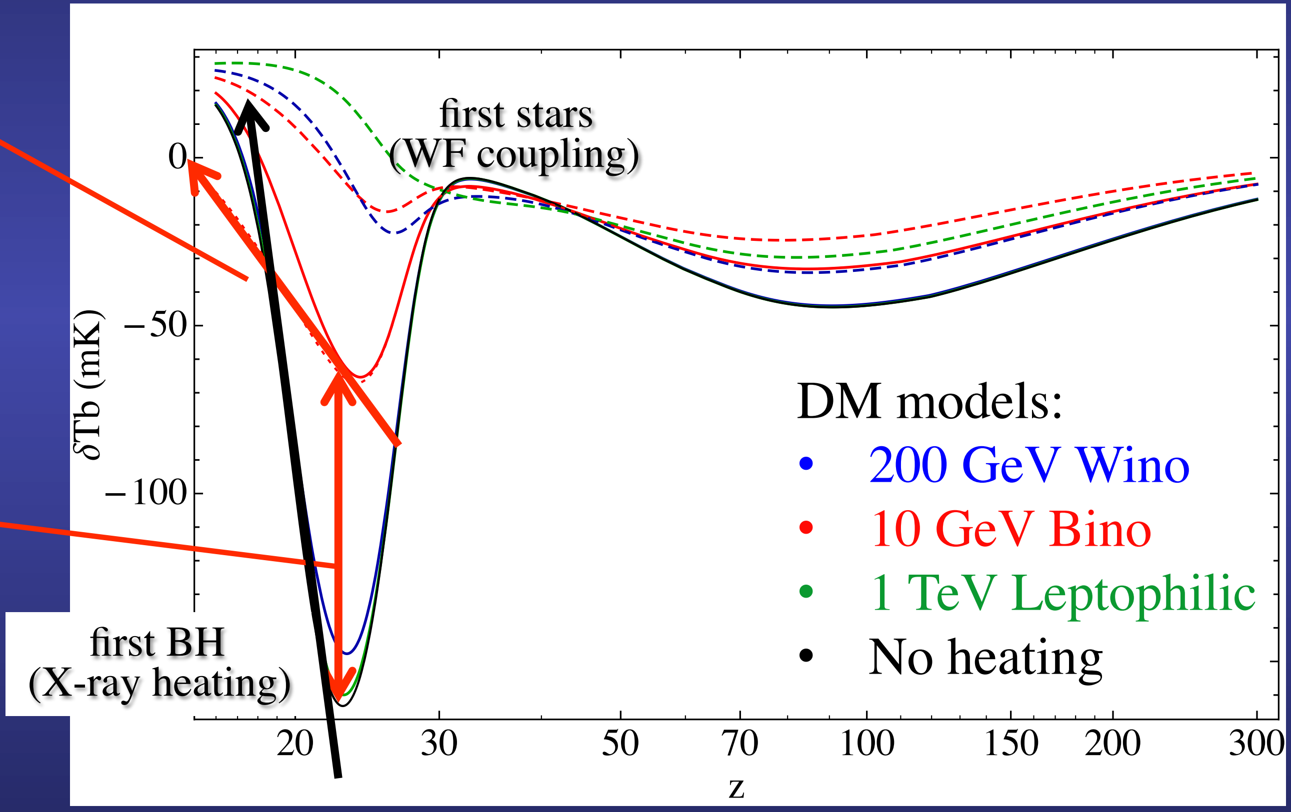
DM heating can affect the global signal

DM heating is slower than X-ray heating (extremely weakly degenerate with astro!)

AND

DM heating suppresses absorption trough (degenerate with more abundant X-rays)

DM annihilation heating +“fiducial” astrophysics



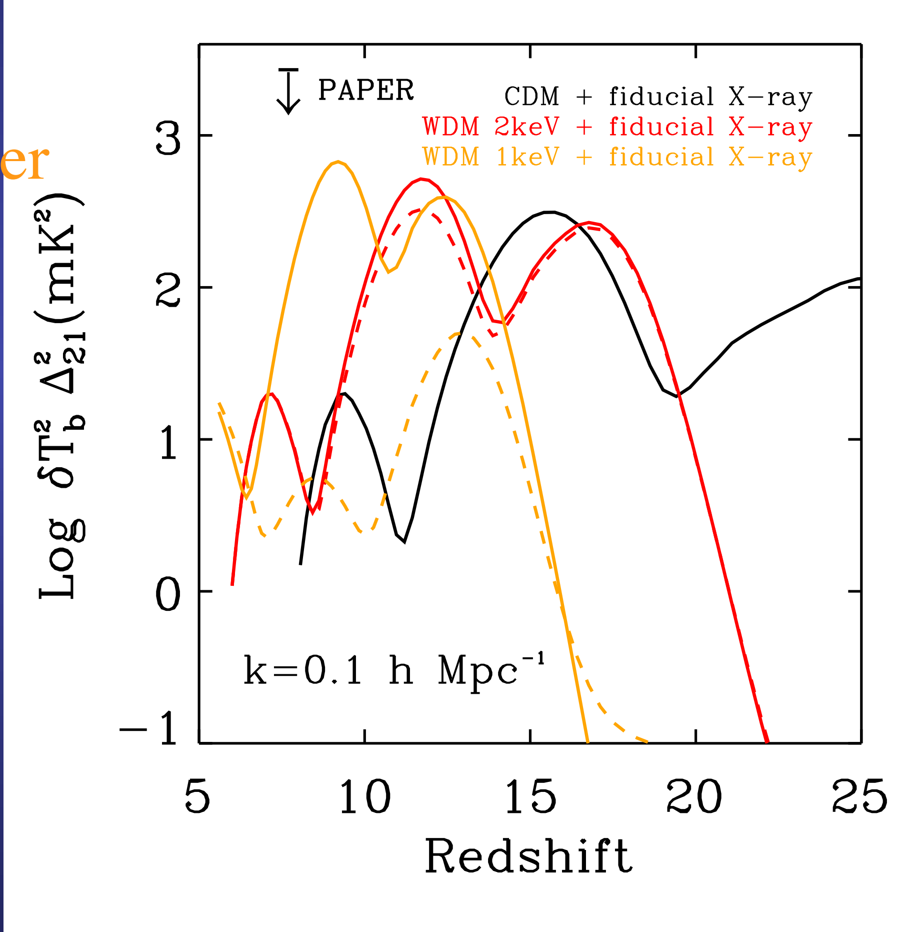
Valdes+2013

annihilation heating computed with MEDEA2 (Evoli+)

DM heating has a more exciting impact on 21cm power-spectra

WDM, decaying sterile neutrino

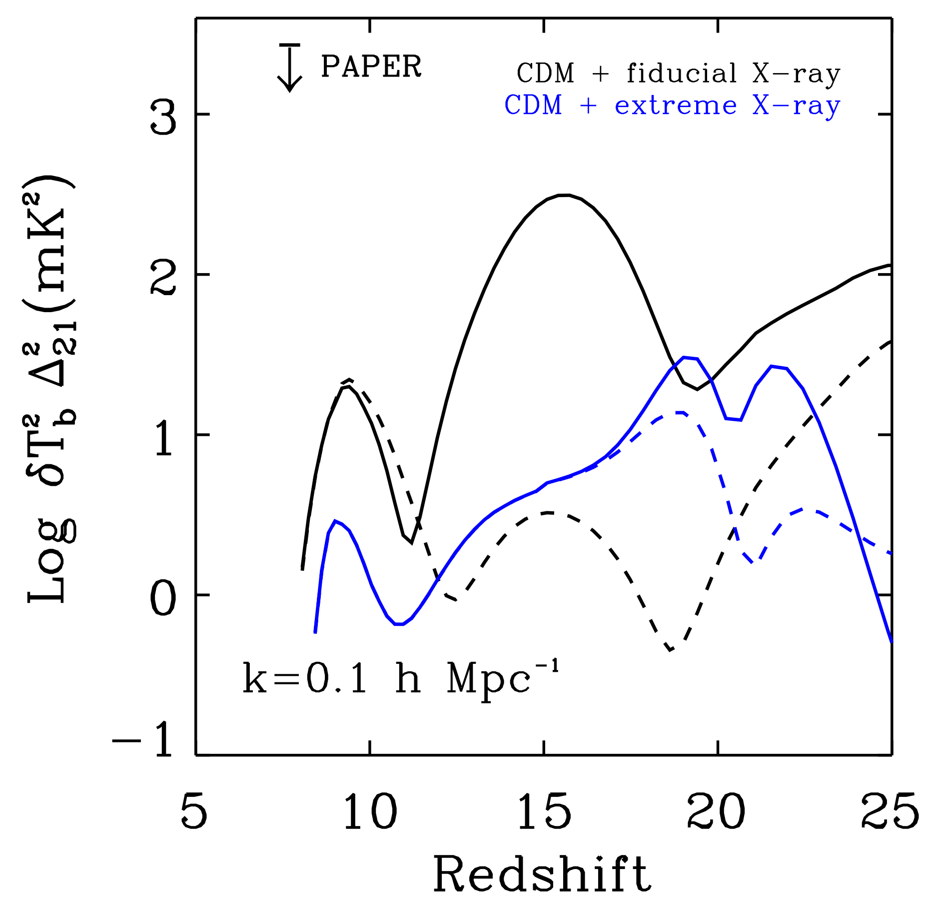
~1 keV
suppresses power



Evoli & AM, in prep

DM heating has a more exciting impact on 21cm power-spectra

CDM, annihilating 10GeV Bino, thermal cross-sec



Evoli & AM, in prep

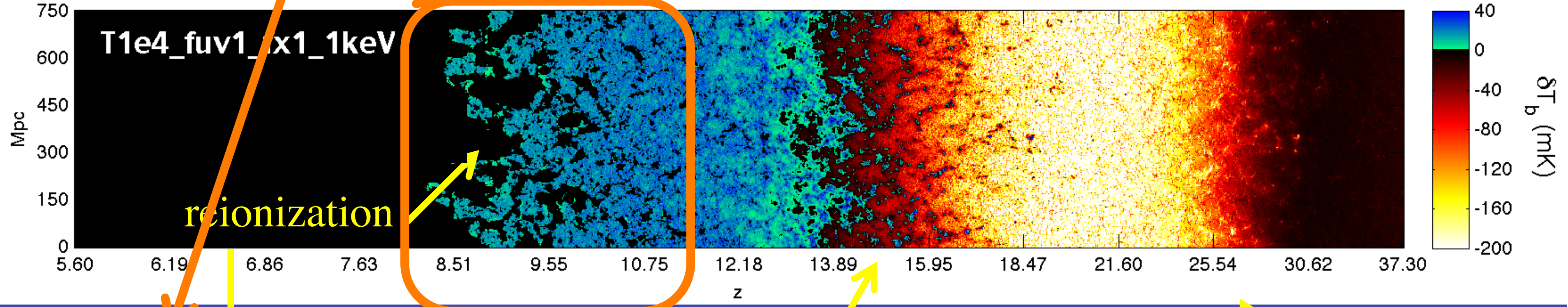
DM heating is more uniform than astrophysical → heating peak is LOWEST of the three

This cannot be reproduced with astrophysics

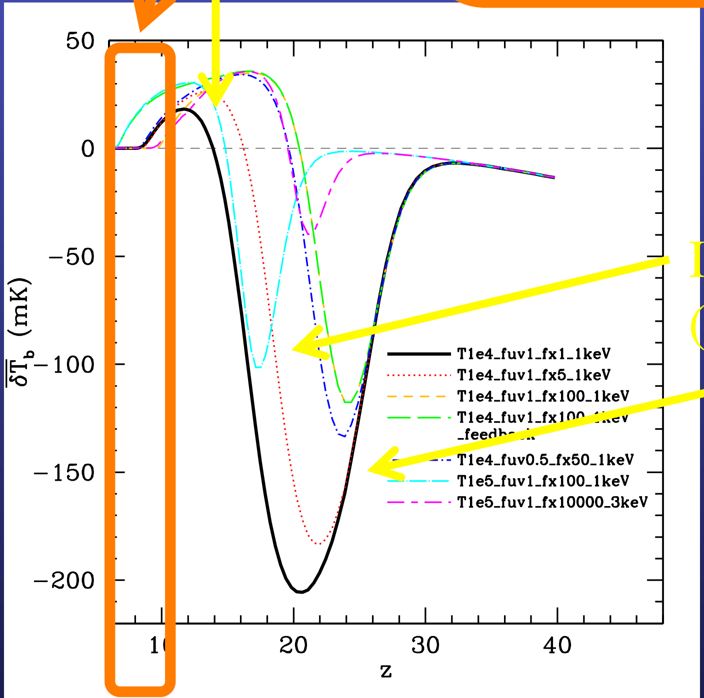
Rich physics of the early Universe

1st gen.: LOFAR, MWA, PAPER

Cosmology:
DM heating, BAO, matter power spectrum



reionization

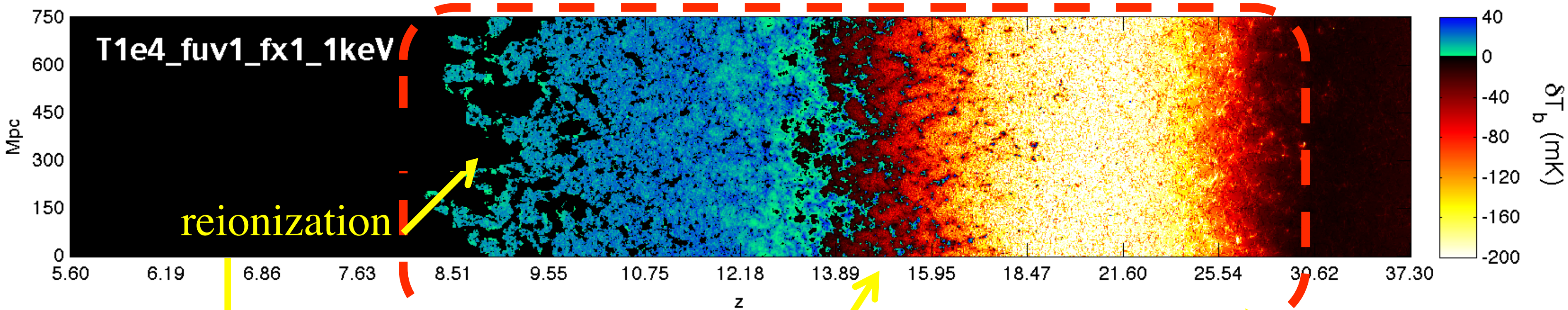


IGM heating
(first BH, DM)

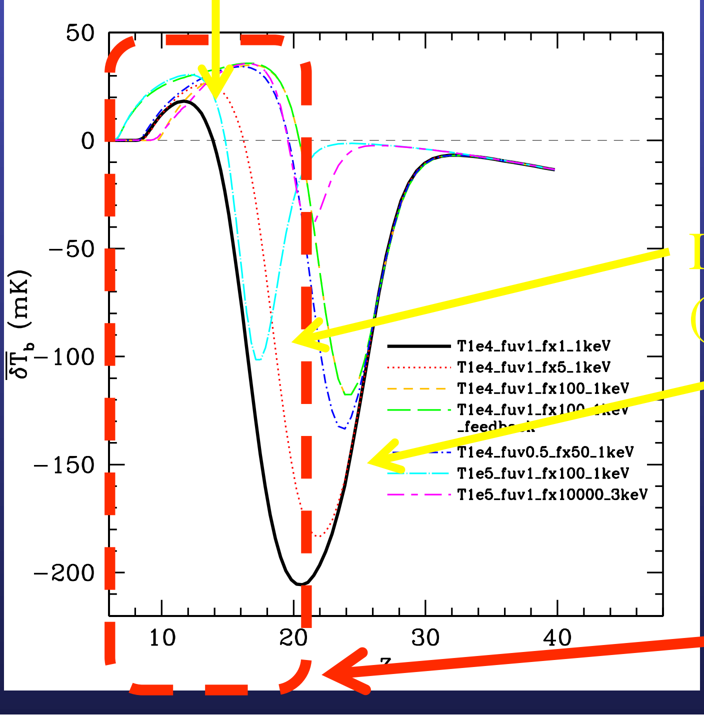
spin T coupling
(first stars)

Rich physics of the early Universe

Cosmology:
DM heating, BAO, matter power spectrum



reionization



IGM heating
(first BH, DM)

spin T coupling
(first stars)

2^{nd} gen.: SKA, LUNAR

(see upcoming SKAI WB)

Conclusions

- The early Universe is a great test-bed for models involving a suppression of small-scale power, like WDM
- Challenge in disentangling signal from uncertain astrophysics: look for robust probes/techniques
- Lensed galaxies have the potential to offer the most robust constraints, without any astrophysics! Current limits from CLASH: $m_x > 1$ keV
- GRBs offer improved statistics, at the cost of some astrophysical modeling. Swift 5yr data sets very conservative limits of $m_x > 1.6$-1.8 keV
- The most powerful upcoming probe of the early Universe will be the cosmological 21cm line, including both astrophysical and cosmological components
  - We need efficient modeling tools to interpret data: 21cmFAST
  - The evolution of the signal would be delayed and more rapid in WDM models
  - The additional heating from some models of WDM decay and DM annihilation can have a robust, unique footprint: (i) slower evolution; (ii) much more uniform with very little power on large (k~0.1/Mpc) scales
  - Italy is a founding member of SKA! We have the responsibility to support the rich science returns.