Constraining Dark Matter Models Through 21cm Observations

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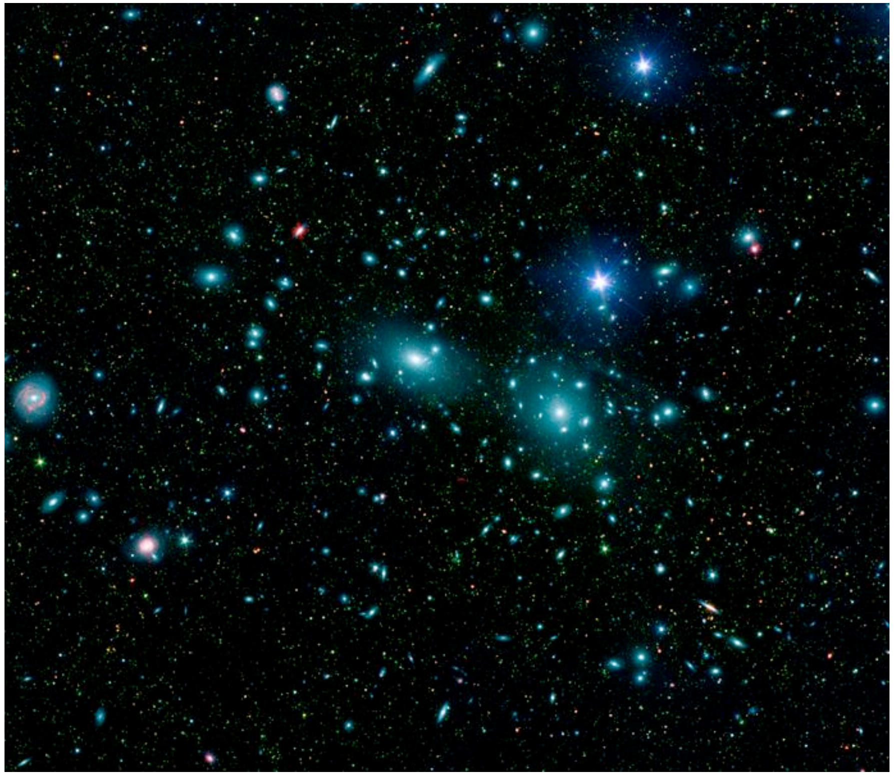
First hint for DM

The first hint to the existence of dark matter came in 1933, with F. Zwicky's estimation of the mass-to-light ratio in the Coma galaxy cluster, based on measurements of the galaxies' velocity.

The M/L ratio was ~100 times larger than expected.

The "missing mass problem" was born...

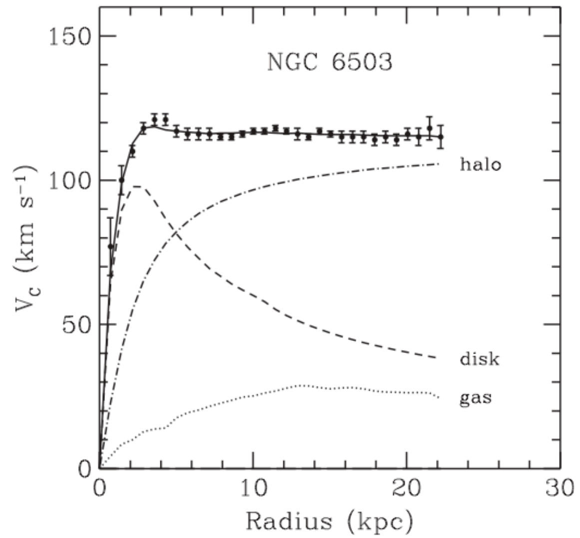


Zwicky proposed to explain this with the existence of an invisible ("dark") form of matter.

Galactic scales

75 years have passed, and observational evidence for the existence of dark matter has continued to accumulate over the time:

- On galactic scales:



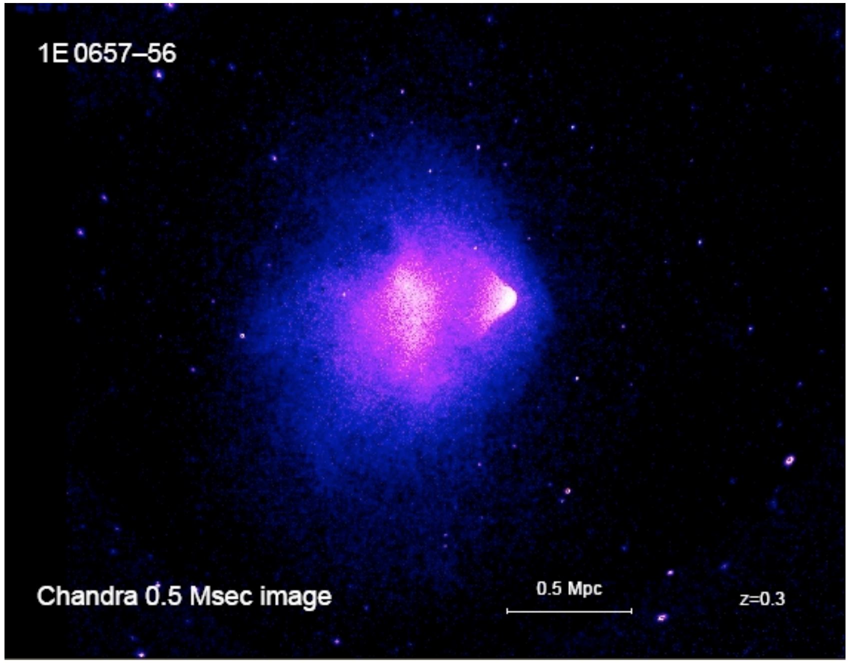
- **Rotation curves of galaxies;**
- **Weak gravitational lensing;**
- **Velocity dispersion of dwarf spheroidal galaxies;**
- **Velocity dispersion of spiral galaxy saltellites;**

Galaxy clusters scales

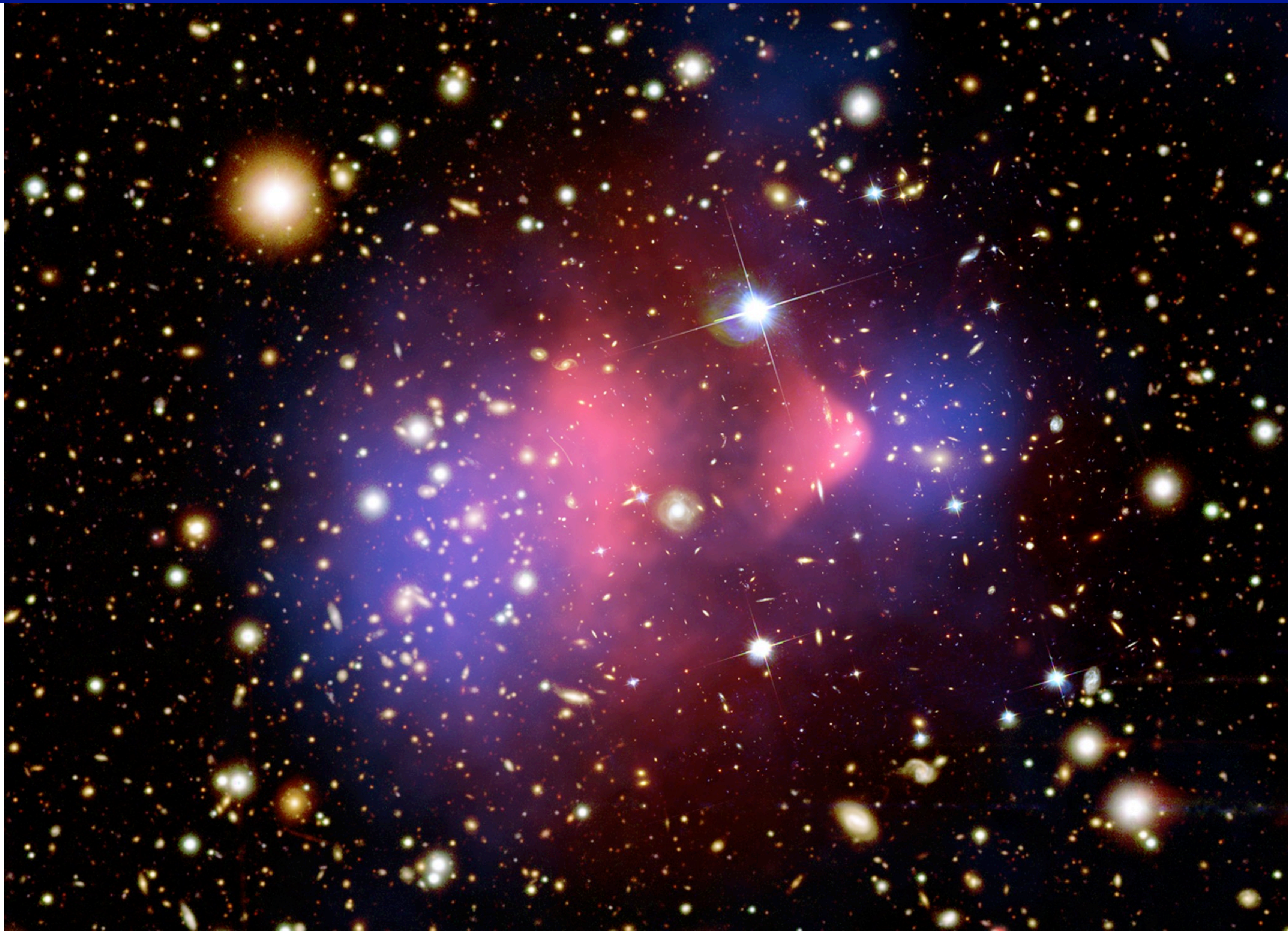
75 years have passed, and observational evidence for the existence of dark matter has continued to accumulate over the time:

- On the scale of galaxy clusters:

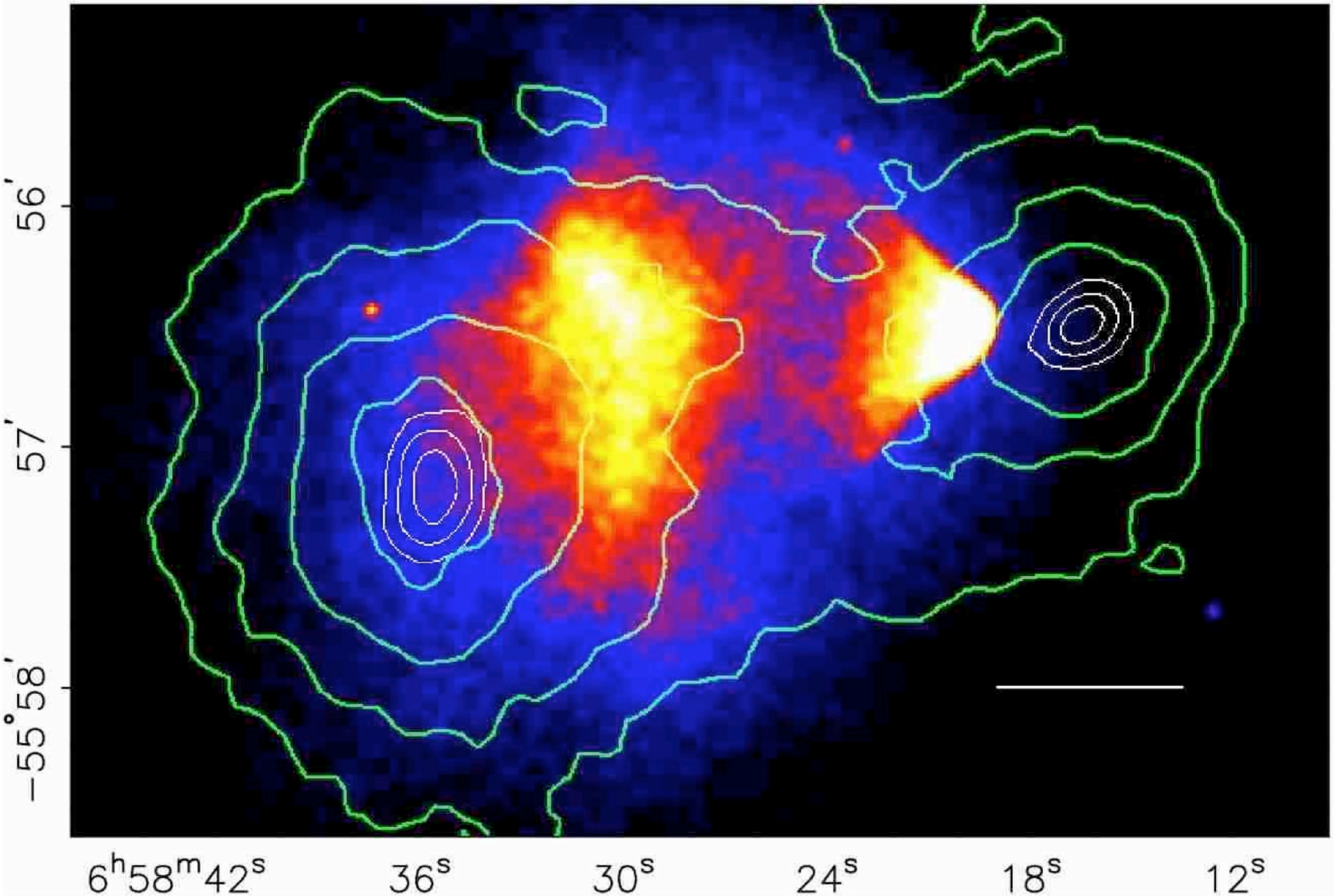
  - **Distribution of radial velocities;**
  - **Weak gravitational lensing**
  - **X-ray emission**



The Bullet Cluster



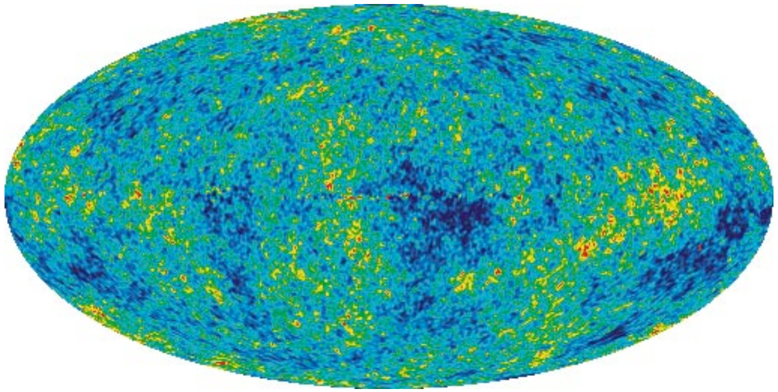
The Bullet Cluster



Cosmological scales

75 years have passed, and observational evidence for the existence of dark matter has continued to accumulate over the time:

- On cosmological scales:

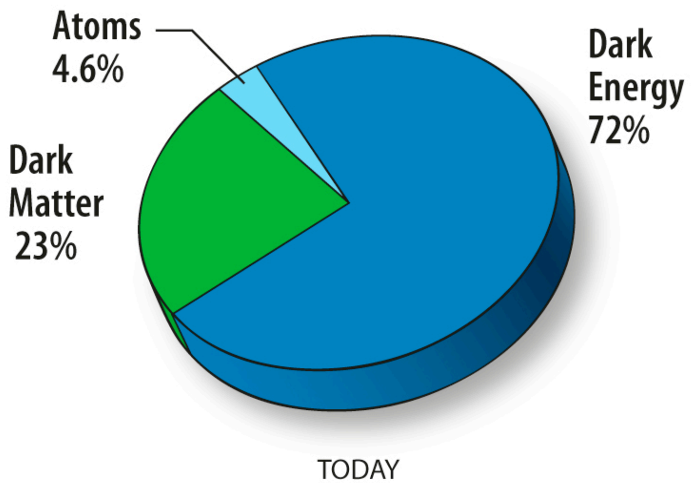


- CMB anisotropy spectrum and
- Matter power spectrum;

are both consistent with Ω_M=0.28

but CMB and BBN also give

Ω_b=0.05



.... What is the Dark Matter made of ?

POSSIBLE CANDIDATES FOR DM

- *Supersymmetric particles*
- *Kaluza Klein particles*
- *sterile neutrinos*
- *majorons*
- *light dark matter*
- *axions*
- *others (x-citing DM, little Higgs, wimpzillas, Q-balls…)*
- *+ non-standard theories of gravity (MOND, f(R), etc…)*

...Can we detect Dark Matter?

- *Direct detection experiments (DAMA-LIBRA, EDELWEISS, CDMS, ZEPLIN-I, ...) look for the interaction of DM particles with the nucleons in the detector*
  - *Elastic scattering;*
  - *Inelastic scattering;*
- *Indirect detection experiments observe the products of DM annihilations:*
  - *Gamma Rays (HESS, GLAST, EGRET, AGILE...)*
  - *Neutrinos (AMANDA, ANTARES, ICE CUBE...)*
  - *Positrons and antiprotons (HEAT, PAMELA, AMS...)*
- *Radio observations can probe the heating history of the IGM*

- *others (little Higgs, wimpzillas, Q-balls…)*

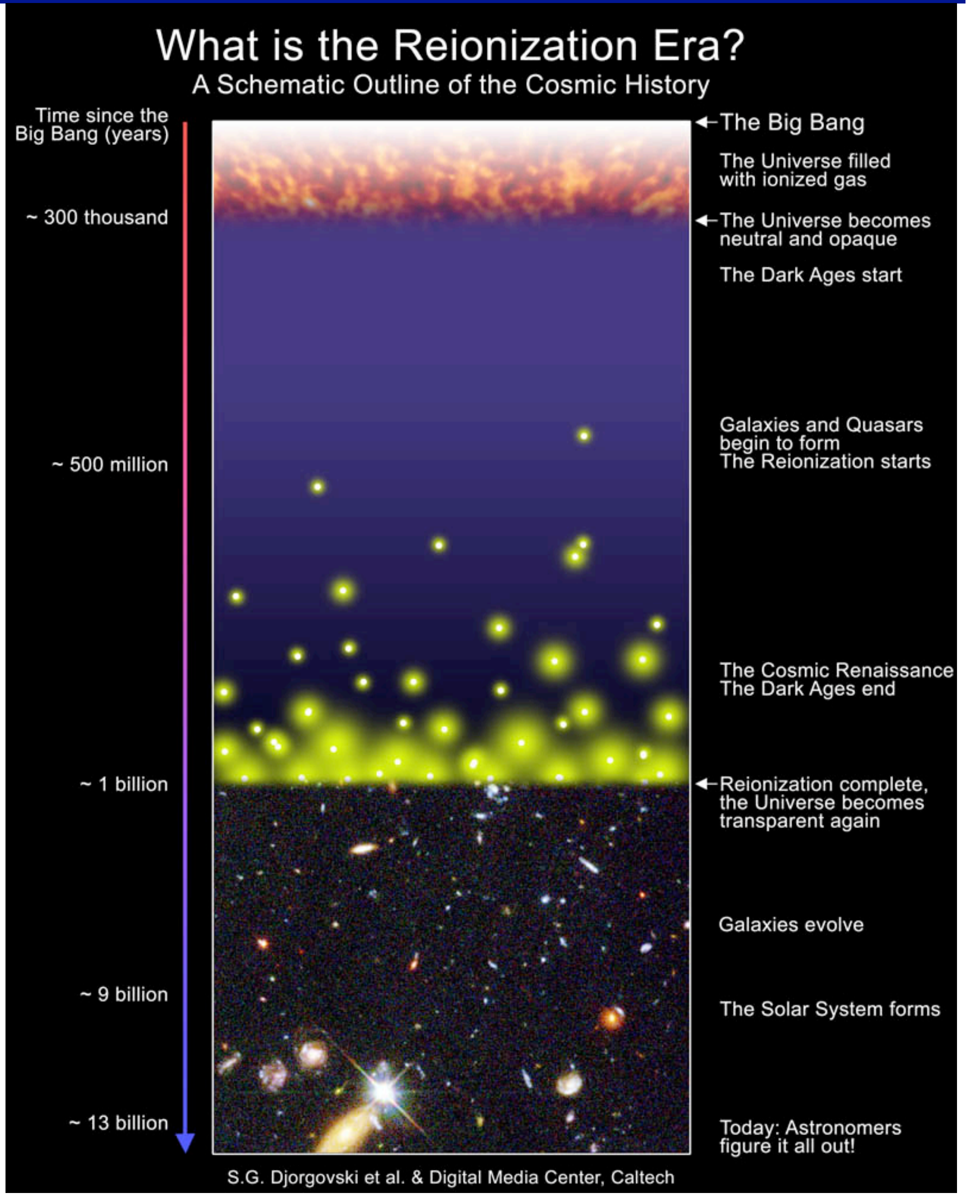
The Dark Ages

CMB decouples at z ~ 1100

First stars light up at z ~ 10

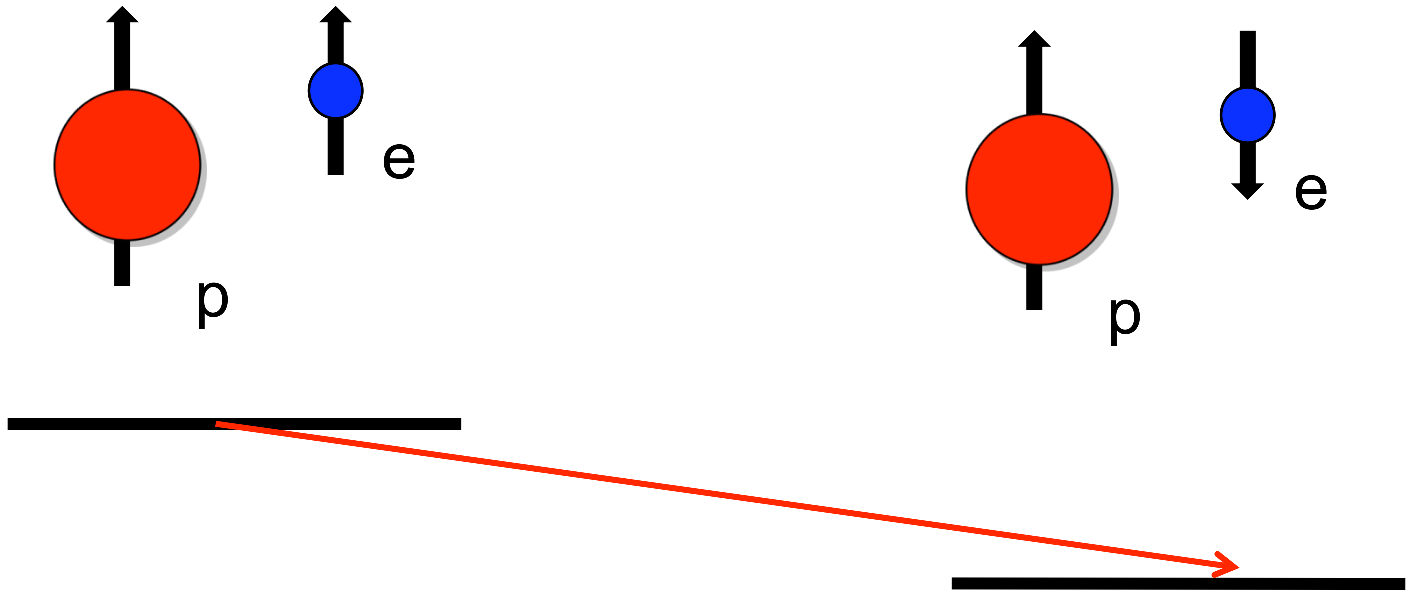
What happens in between?

How can we probe the DA?



The 21cm line

The abundance and density of neutral hydrogen can be probed by looking at the 21cm H line, associated to the hyperfine transition from the triplet to the singlet state



$$\Delta E = (21\text{cm})^{-1} = 1420 \text{ MHz} = 6 \times 10^{-6} \text{ eV} = 6.8 \times 10^{-2} \text{ K}$$

Generation of the 21cm signal

If the hyperfine levels of hydrogen are in equilibrium with the CMB, no 21cm signal will be observed.

However, some mechanisms exist than can decouple the two.

We should distinguish between:

T_{CMB}	*CMB temperature*
T_K	*Kinetic temperature of the H gas*
T_S	*Spin temperature of the H gas*

$$n_1/n_0 = 3\,\mathrm{Exp}[-T_*/T_S]$$

The 21cm line

If $T_{CMB}=T_S$, no 21cm signal can be observed.

The energy transfer from photons to electrons is effective until z~300, then $T_{CMB} = T_K = T_S$

At this point the gas starts to cool adiabatically: $T_K \sim a^{-2}$

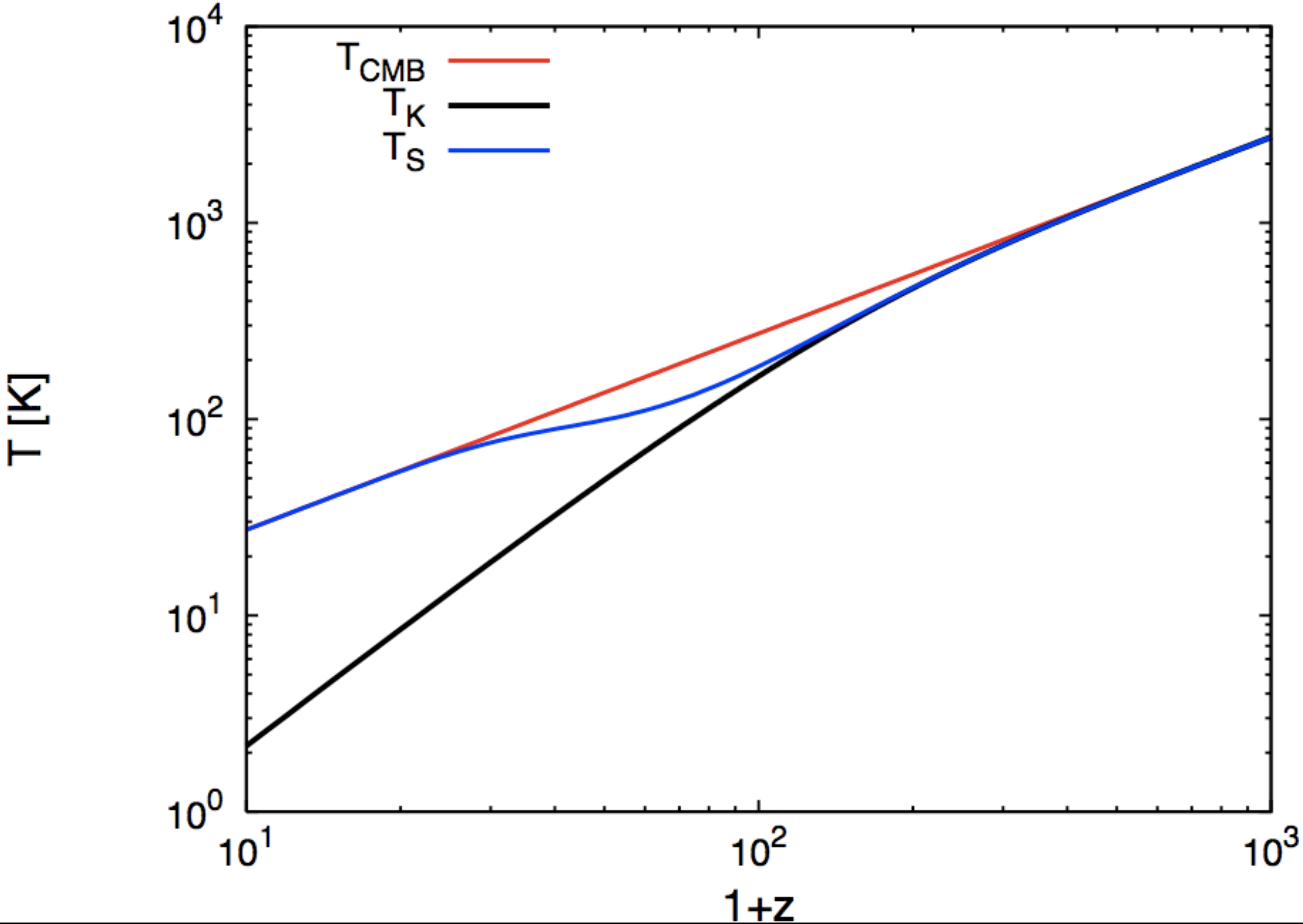
Atomic collisions and Ly-α photons (Wouthuysen-Field effect) drive the atomic energy levels to equilibrium with the gas temperature: $T_S \sim T_K < T_{CMB}$

$$T_S = \frac{T_{\rm CMB} + yT_K}{1+y}$$

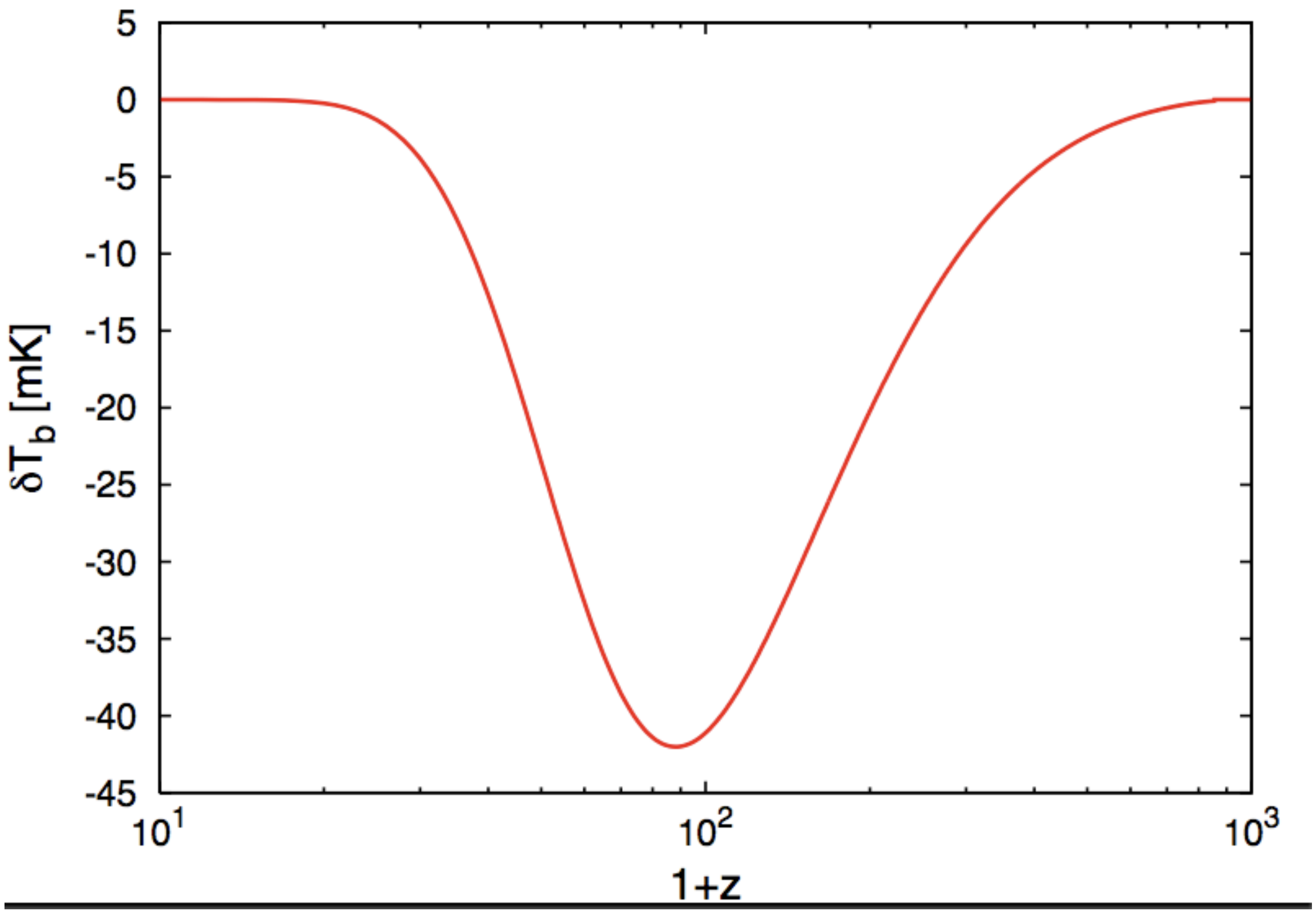
An absorption signal on the CMB is produced.

At z~30 the mechanisms that couple T_S and T_K become ineffective and then $T_S \sim T_{CMB}$

The 21cm line



The 21cm line



DM energy injection

Dark matter can inject energy into the IGM through its annihilation products.

$$\dot{\epsilon} = \frac{1}{2} \underline{f_{\mathrm{abs.}}} \frac{n_{\mathrm{DM},0}^2}{n_{\mathrm{H},0}} \langle \sigma_{\mathrm{ann.}} v \rangle m_{\mathrm{dm}} (1+z)^3 \, \underline{C(1+z)}$$

This will change the thermal and ionization history of the Universe, leading to a different 21cm signal.

The changes will depend on the spectrum of annihilation/decay products, and thus *will be different for different kinds of DM particles.*

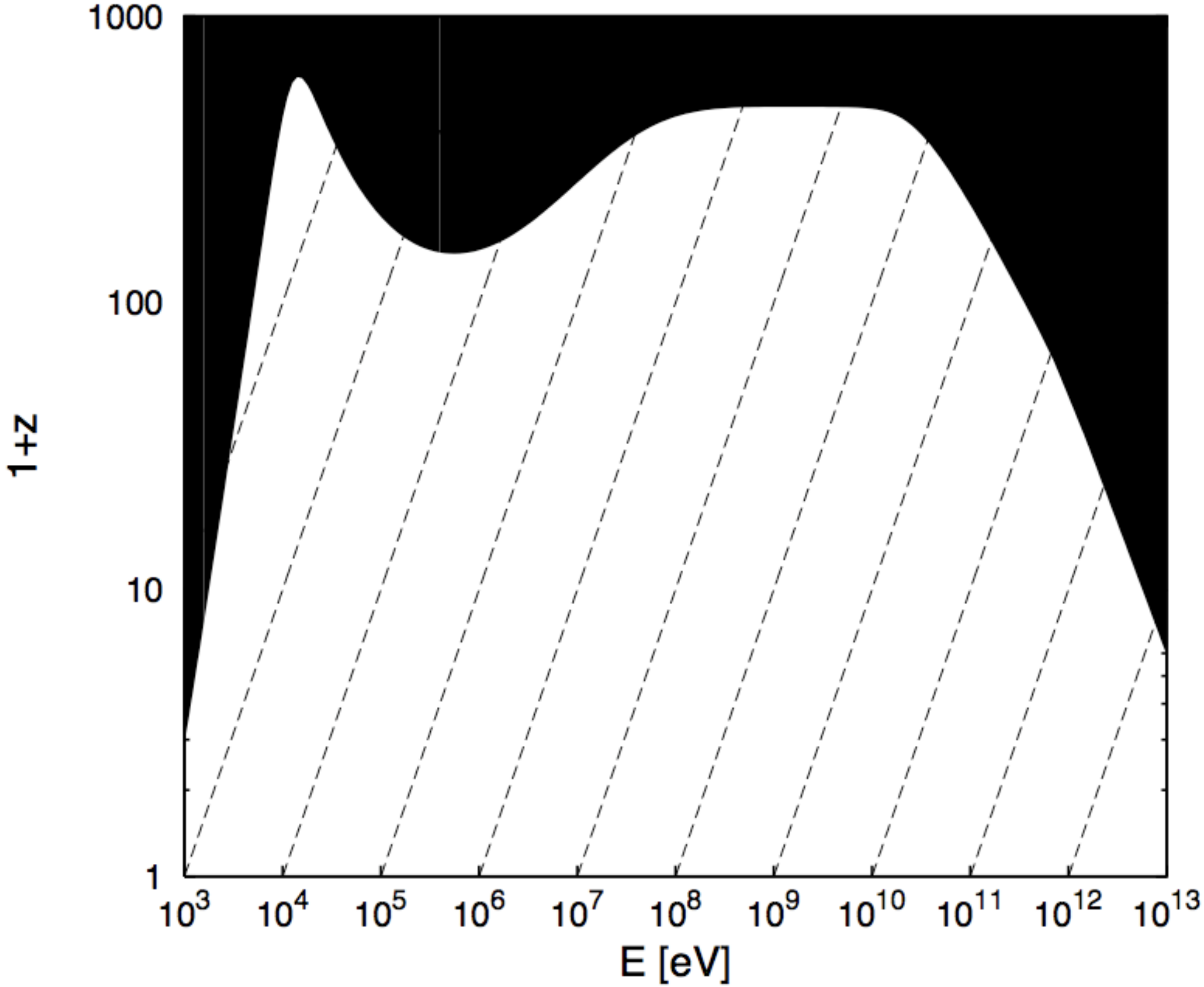
Before studying specific DM candidates, we discuss the absorption mechanism of the decay/annihilation products.

This products are usually photons, electron-positron pairs, protons, neutrons and neutrinos.

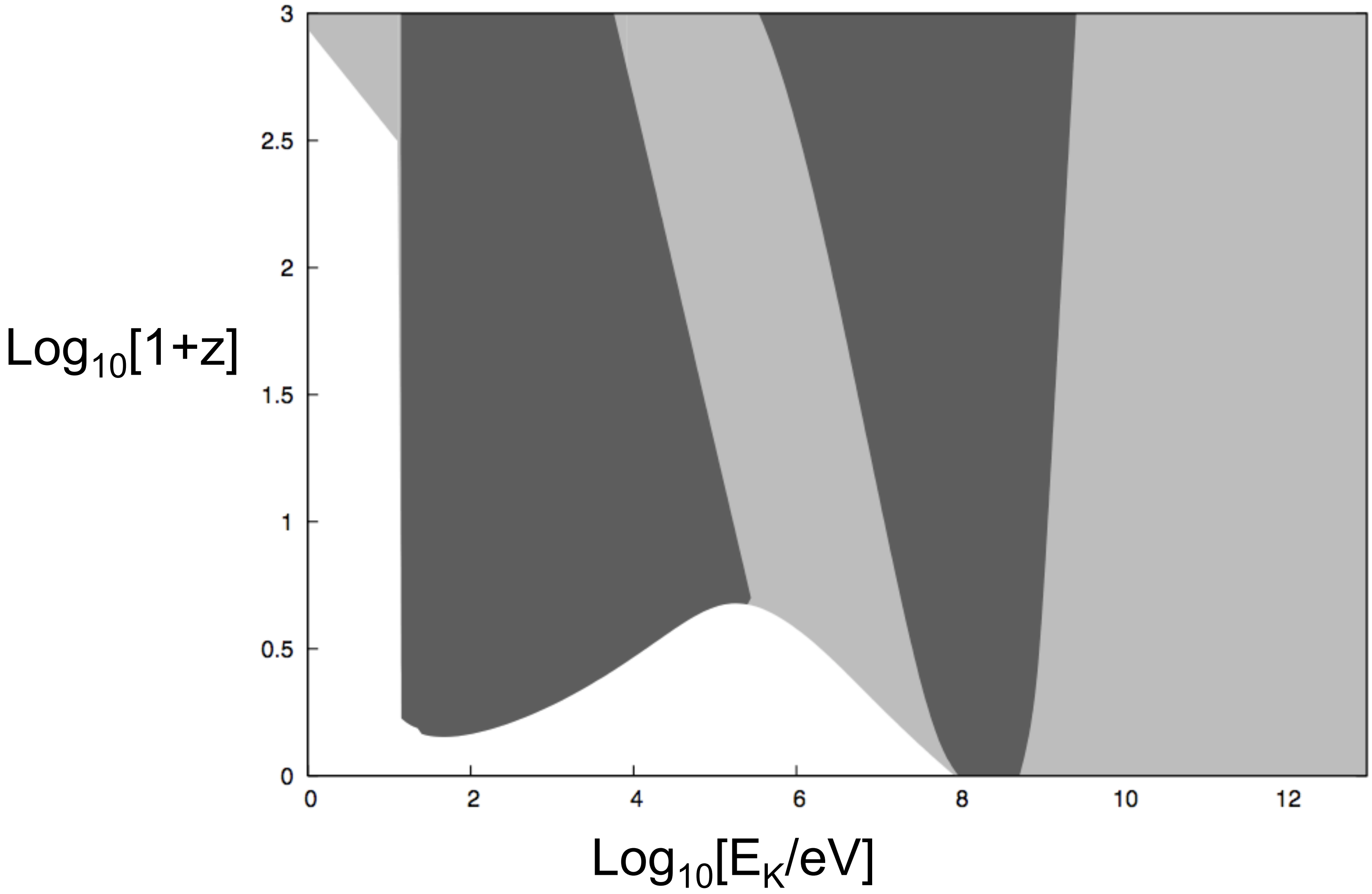
Relevant absorption processes include:

photoionisation	$\gamma\, A \rightarrow A^+\, e^-$
compton scattering	$\gamma\, e \rightarrow \gamma\, e$
pair production over atoms	$\gamma\, A \rightarrow A\, e^+\, e^-$
scattering over CMB photons	$\gamma\, \gamma_{CMB} \rightarrow \gamma\, \gamma_{CMB}$
pair production over CMB photons	$\gamma\, \gamma_{CMB} \rightarrow e^+\, e$
collisional ionisation	$e\, A \rightarrow A^+\, e^-\, e$
inverse compton over CMB photons	$e\, \gamma_{CMB} \rightarrow e\, \gamma_{CMB}$
pair production over IGM electrons	$e^+\, e^- \rightarrow \gamma\, \gamma$

Photon transparency window



Electron transparency window



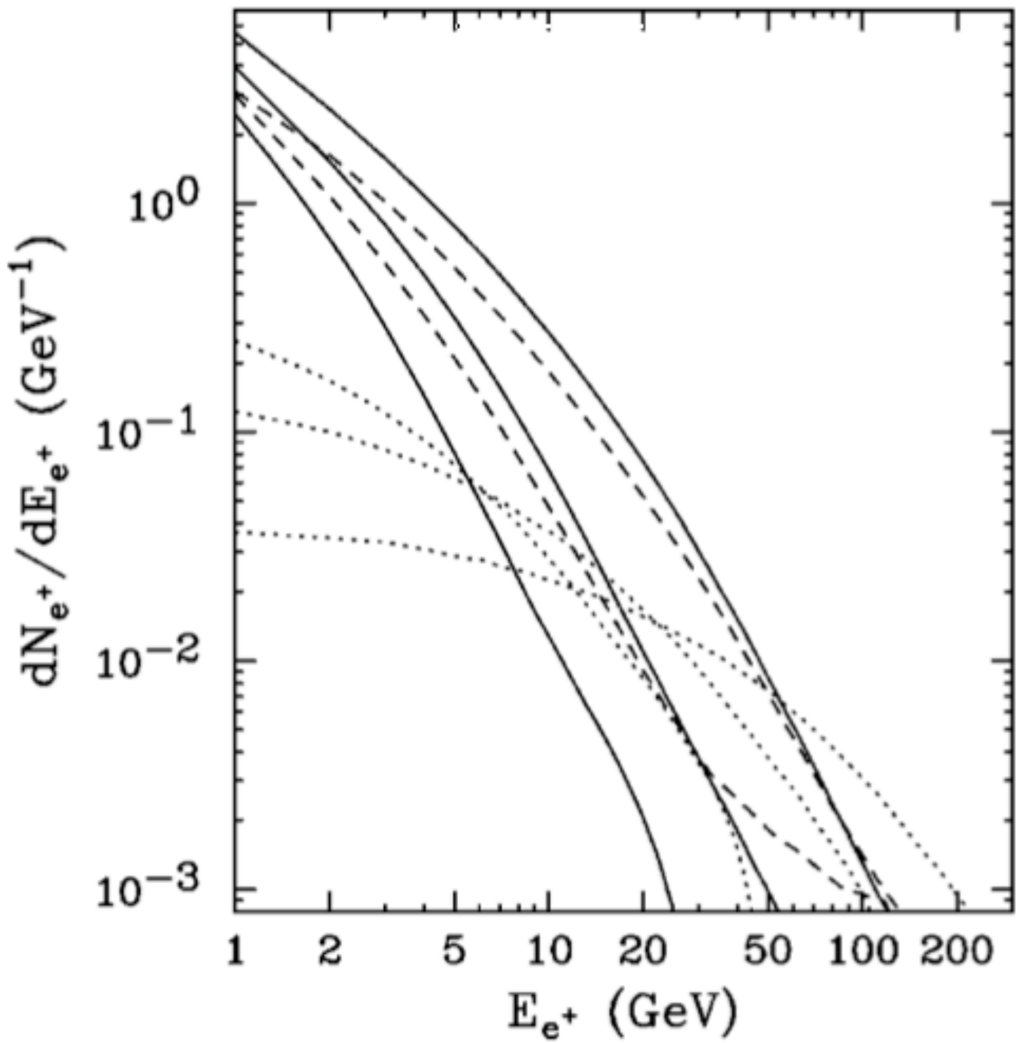
We consider two kinds of annihilating DM: neutralino DM and light DM.

The neutralino is (usually) the lightest supersymmetric particle (LSP) in SUSY theories. It is a superposition of higgsinos and gauginos.

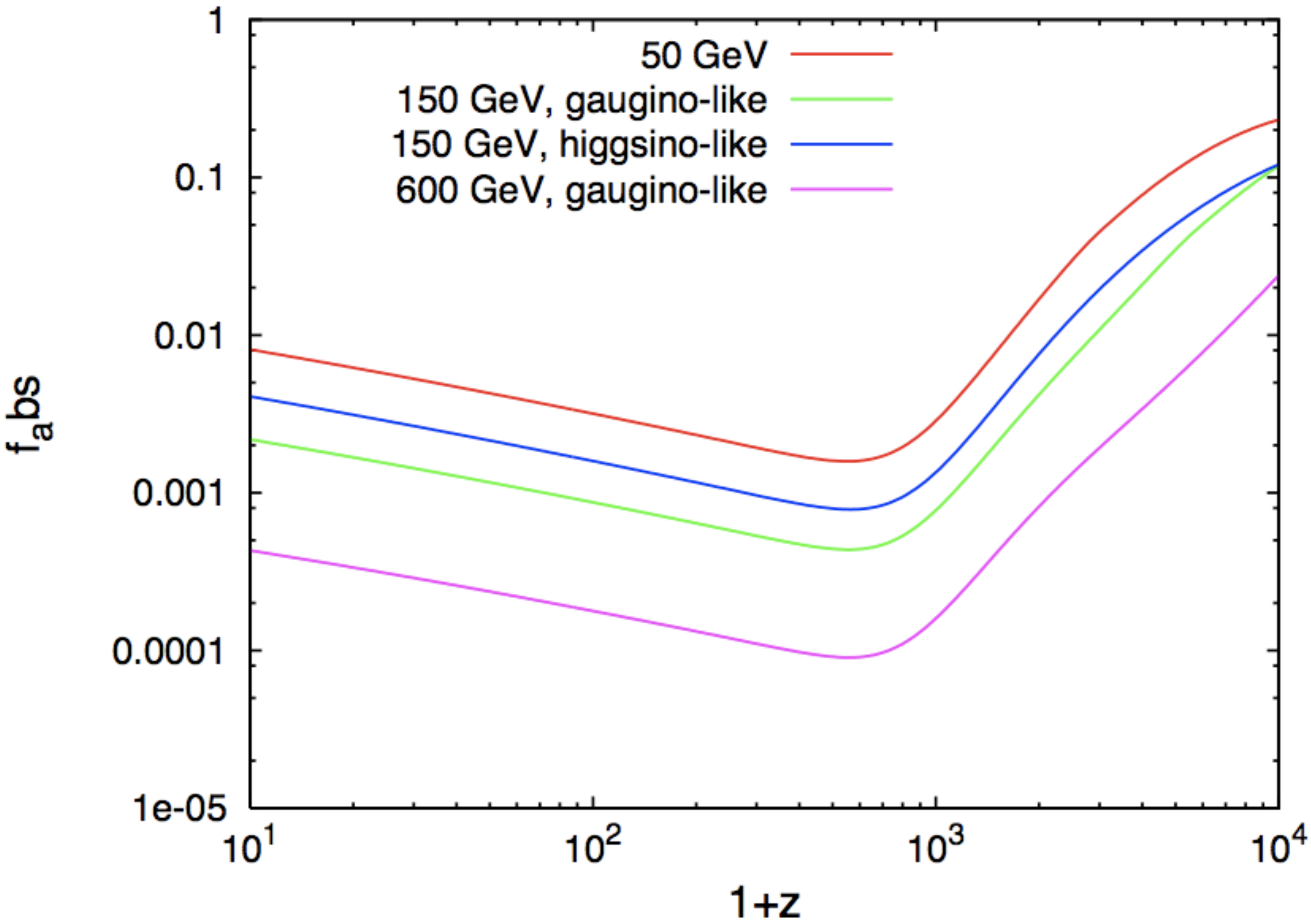
Neutralinos mainly annihilate to heavy quarks, W bosons, and tau leptons. The branching ratios depend on the gaugino fraction. We consider 4 different neutralino models with masses from 50 to 600 GeV.

Light dark matter is composed of scalar particles with mass in the MeV range. It was introduced to explain the INTEGRAL 511keV signal. We consider two cases m=3 and 20 MeV.

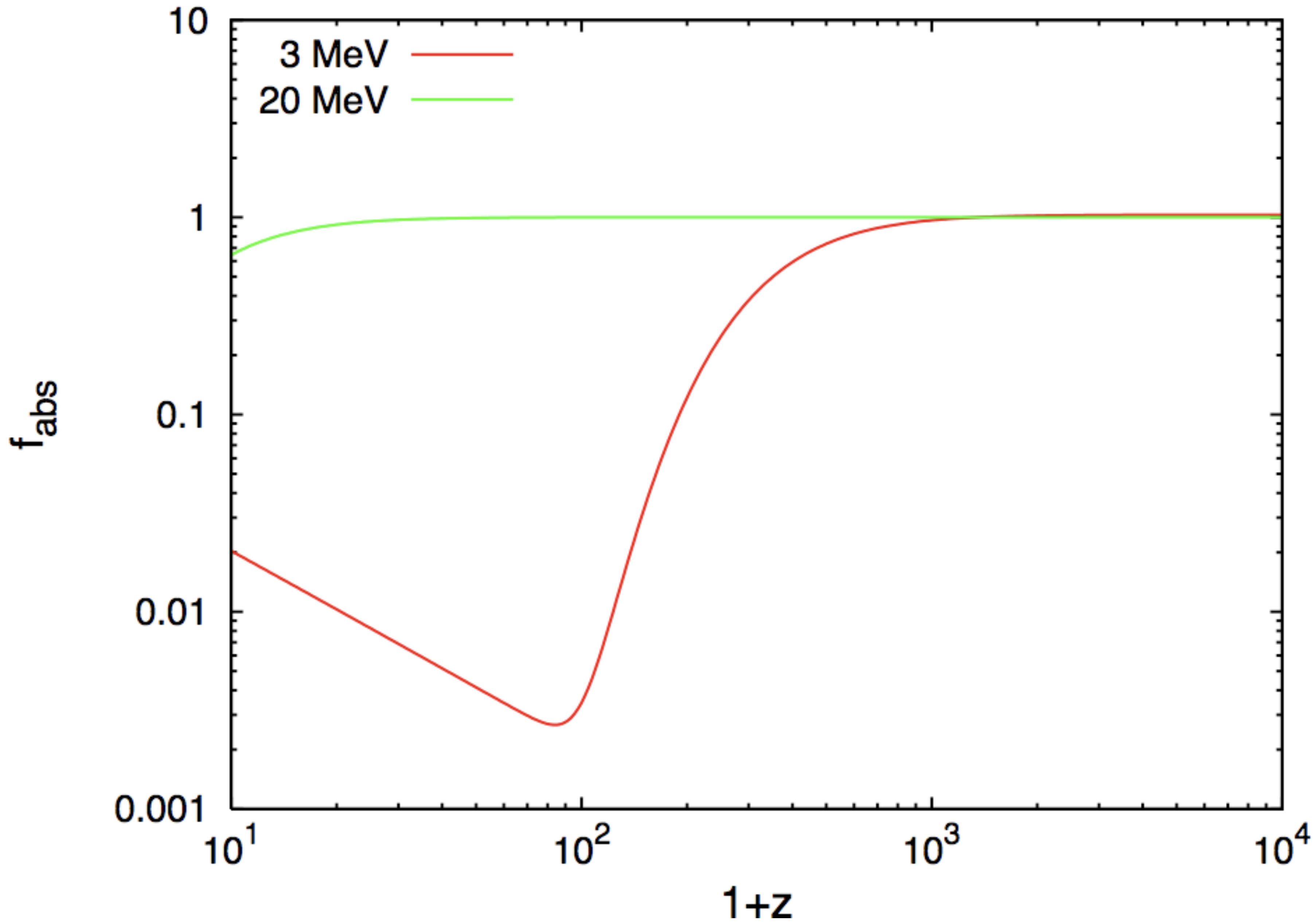
LDM annihilates directly to electron-positron pairs.



From Hooper, Taylor and Silk (2004)



50 GeV
150 GeV, gaugino-like
150 GeV, higgsino-like
600 GeV, gaugino-like
1
0.1
0.01
0.001
0.0001
1e-05
$f_a bs$
10^1
10^2
10^3
10^4
1+z



3 MeV
20 MeV
10
1
0.1
0.01
0.001
f_{abs}
10^1
10^2
10^3
10^4
1+z

The Clumping Factor

The annihilation rate scales like (density)^2

This means that the annihilation rate is enhanced in high density region (contrarily to what happens to decay rate).

The enhancement is proportional to $\langle\rho^2\rangle / \langle\rho\rangle^2$

We incorporate this effect into the ***clumping factor*** C(z).

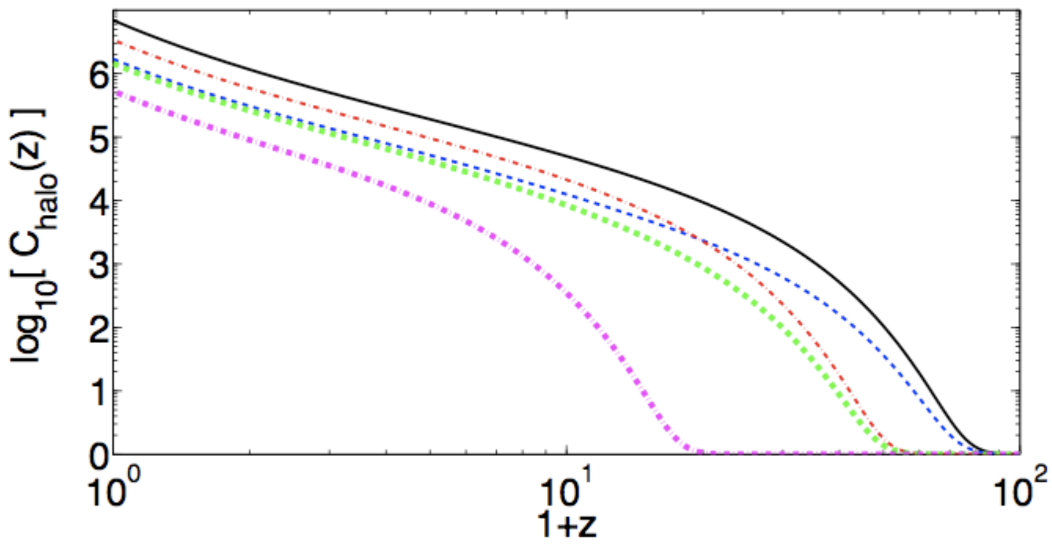
The CF depends on the halo mass function (i.e. on the mass distribution of halos) and on the halo density profile.

We used the recent results by Diemand et al. (2008)

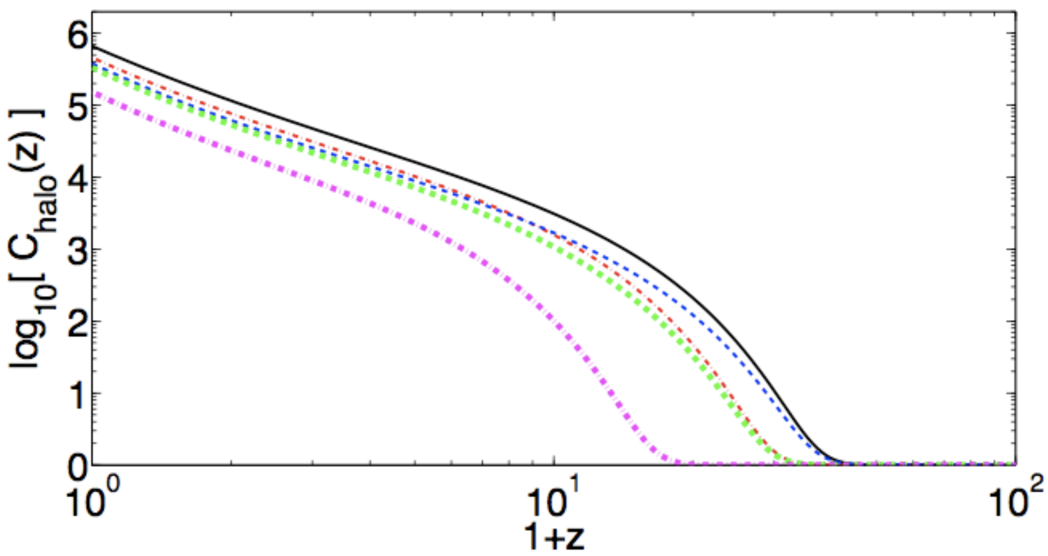
We take into account free streaming (for LDM)

We also take into account several generations of substructures inside halos.

The Clumping Factor



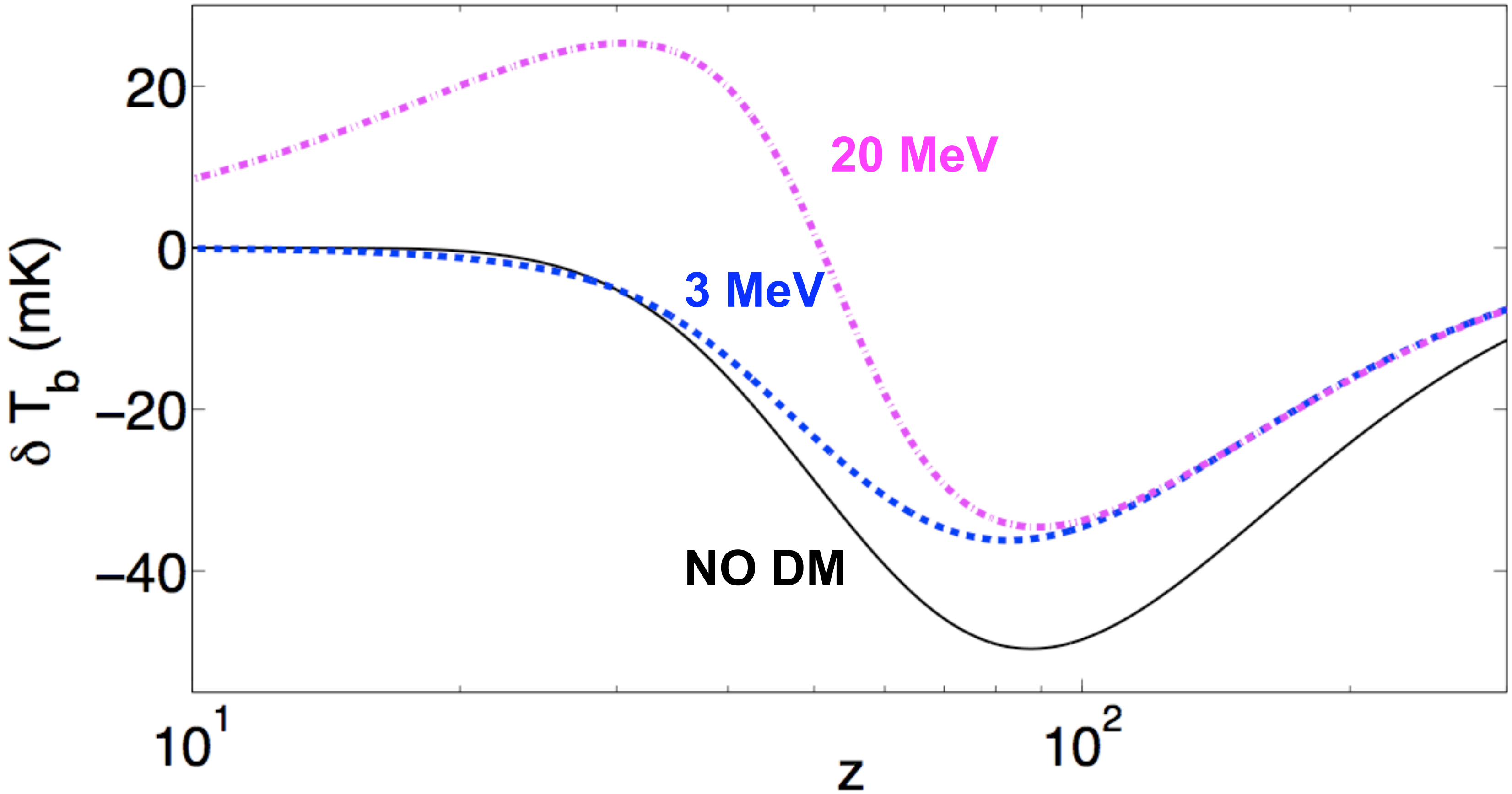
CDM (NFW profile)



WDM (Burkert profile)

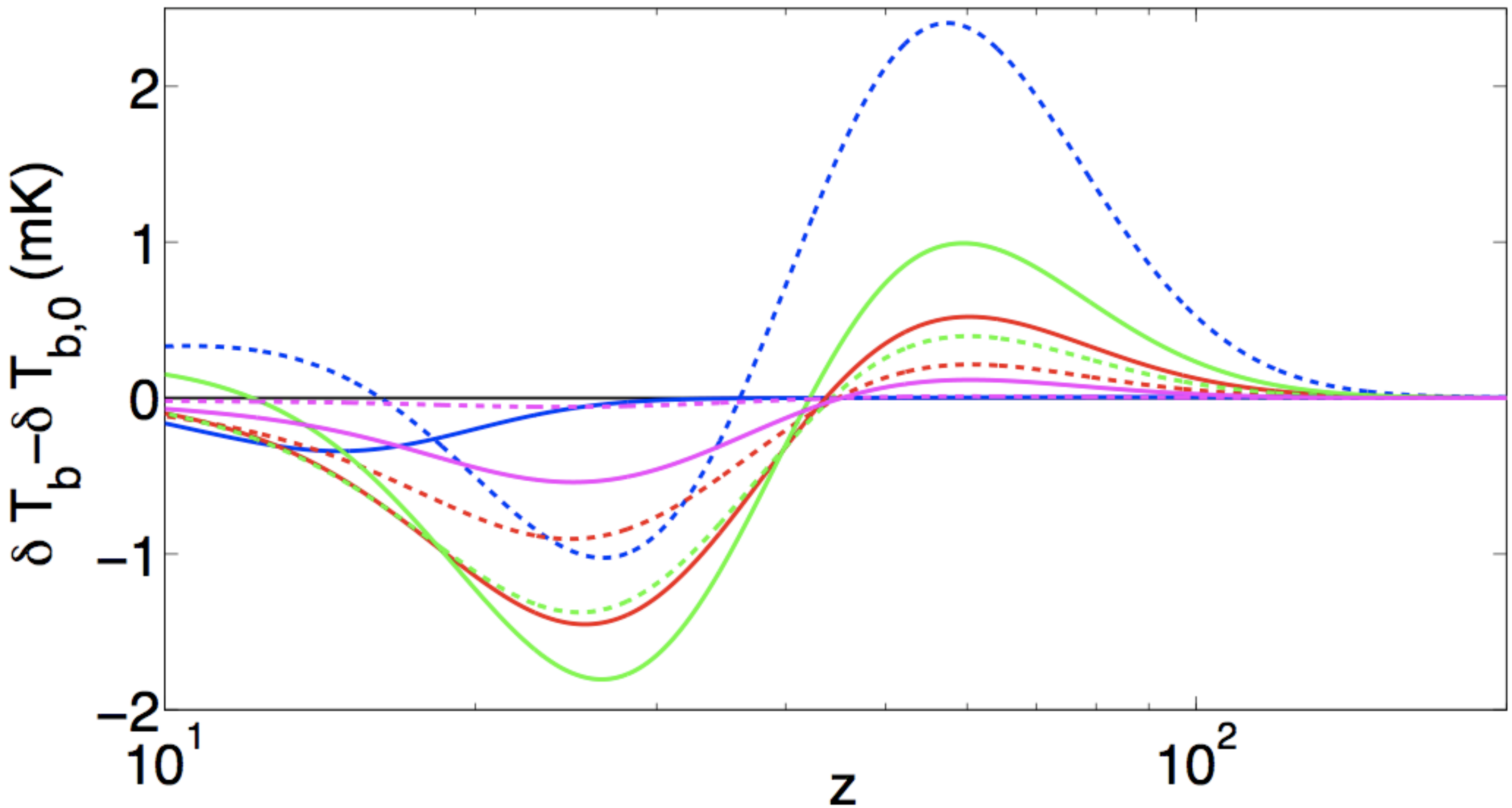
Brightness temperature

We use a modified version of the RECFAST code to compute the brightness temperature.



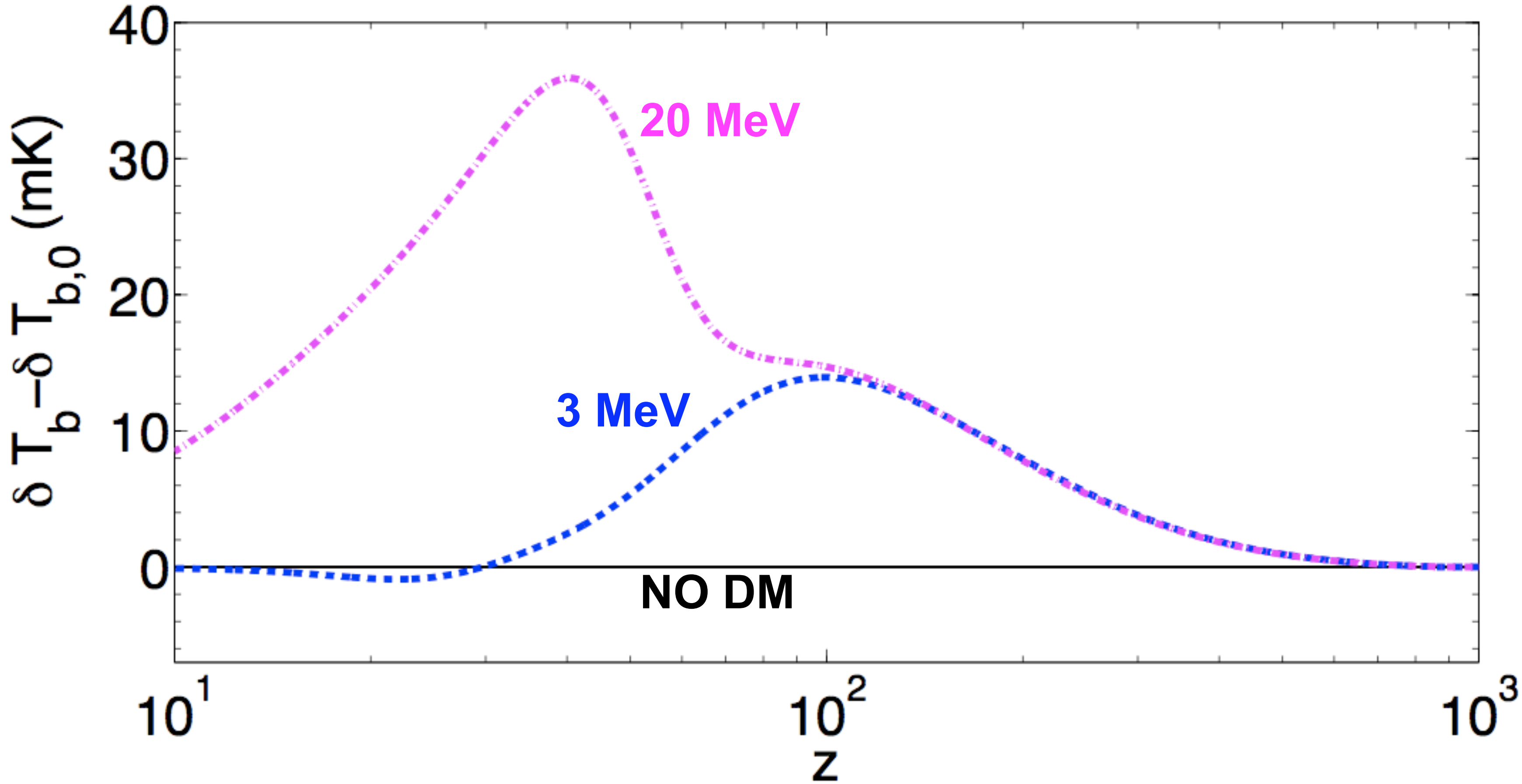
Brightness temperature

Neutralinos



Brightness temperature

LDM



Perspectives for Exp. detection

We have computed the deviations in the brightness temperature wrt the no DM case.

Will it be possible in the (near?) future to measure the differential brightness temperature to the necessary accuracy?

Future radio telescopes, like LOFAR, MWA, 21CMA,SKA,

can possess the necessary sensitivity

Perspectives for Exp. detection

The LOw Frequency ARray (LOFAR) uses an array of ~25000 omni directional antennas, arranged in clusters spread out over an area of 350km of diameter.

One of the key projects of LOFAR is the observation of the 21cm signal ("Epoch of reionization" project)

LOFAR will observe the 115-180 MHz range, corresponding to $6 < z < 12$

The cosmological signal is contaminated by many astrophysical and non-astrophysical components.

Preliminary results show however that it will be possible to reach a sensitivity of few mK at $z \sim 10$

Conclusions

- We have strong evidence for the existence of DM, from different observations at different energy scales;
- Many theoretically motivated candidates exist;
- Many experimets aim to detect DM directly, or its annihilation products;
- The 21cm signal probes the heating/ionisation history of the Universe, and can be affected by the presence of DM, giving characteristic signatures;
- LDM gives a signal that could be detected by LOFAR;
- Neutralino dark matter is beyond LOFAR reach... maybe in the future?