Unveiling the nature of Dark Matter in the LOFAR sky

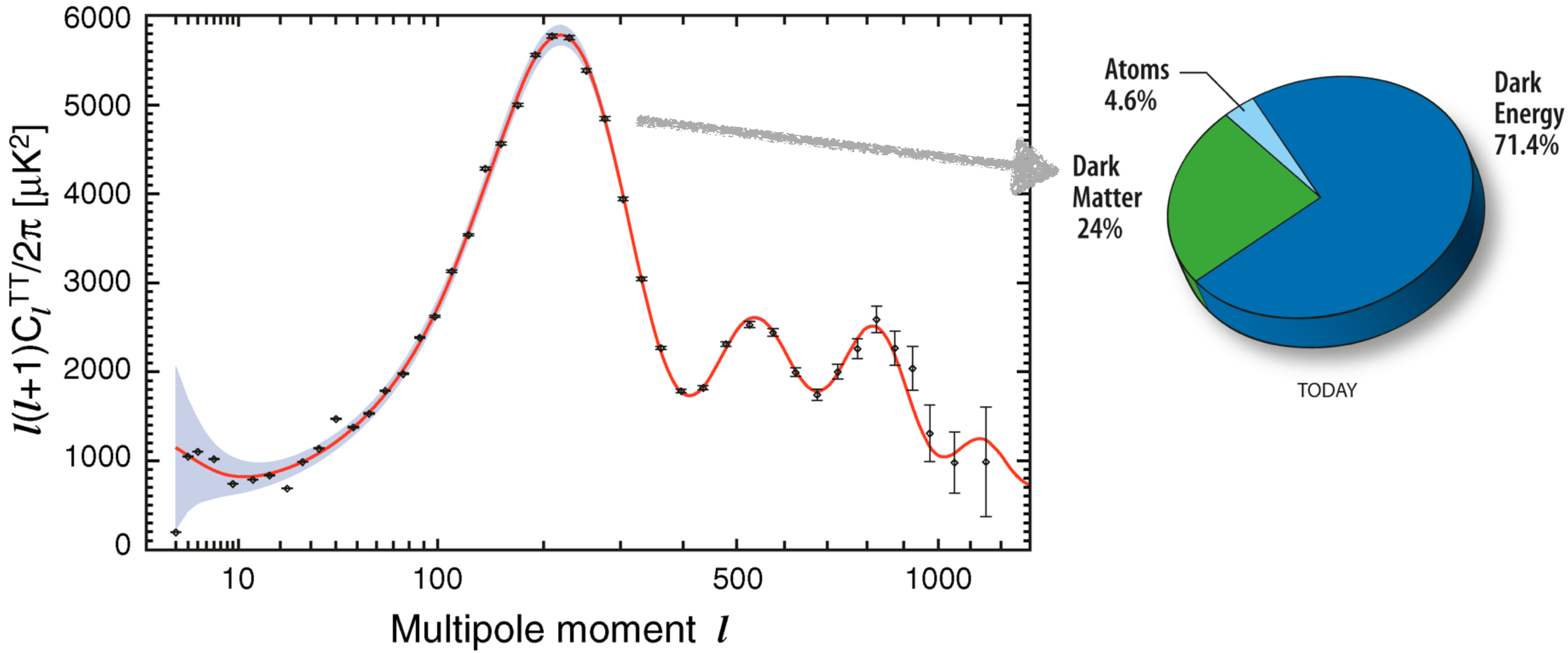
Carmelo Evoli (Universität Hamburg)

HELMHOLTZ ASSOCIATION

Alliance for Astroparticle Physics

Dark-MALT | Munich | 18th of February 2015

Dark Matter on cosmological scales



- Dark Matter (DM) needed on all scales.
- DM model requires electrically neutral particles moving (almost)non-relativistically when structures formed.
- Therefore, Standard Model is not a complete and fundamental theory.

Dark Matter on galactic scales

THE ASTRONOMICAL JOURNAL VOLUME 86, NUMBER 12 DECEMBER 1981

21-CM LINE STUDIES OF SPIRAL GALAXIES. II. THE DISTRIBUTION AND KINEMATICS OF NEUTRAL HYDROGEN IN SPIRAL GALAXIES OF VARIOUS MORPHOLOGICAL TYPES

A. Bosma[a)]
Kapteyn Astronomical Institute, University of Groningen, Groningen, The Netherlands

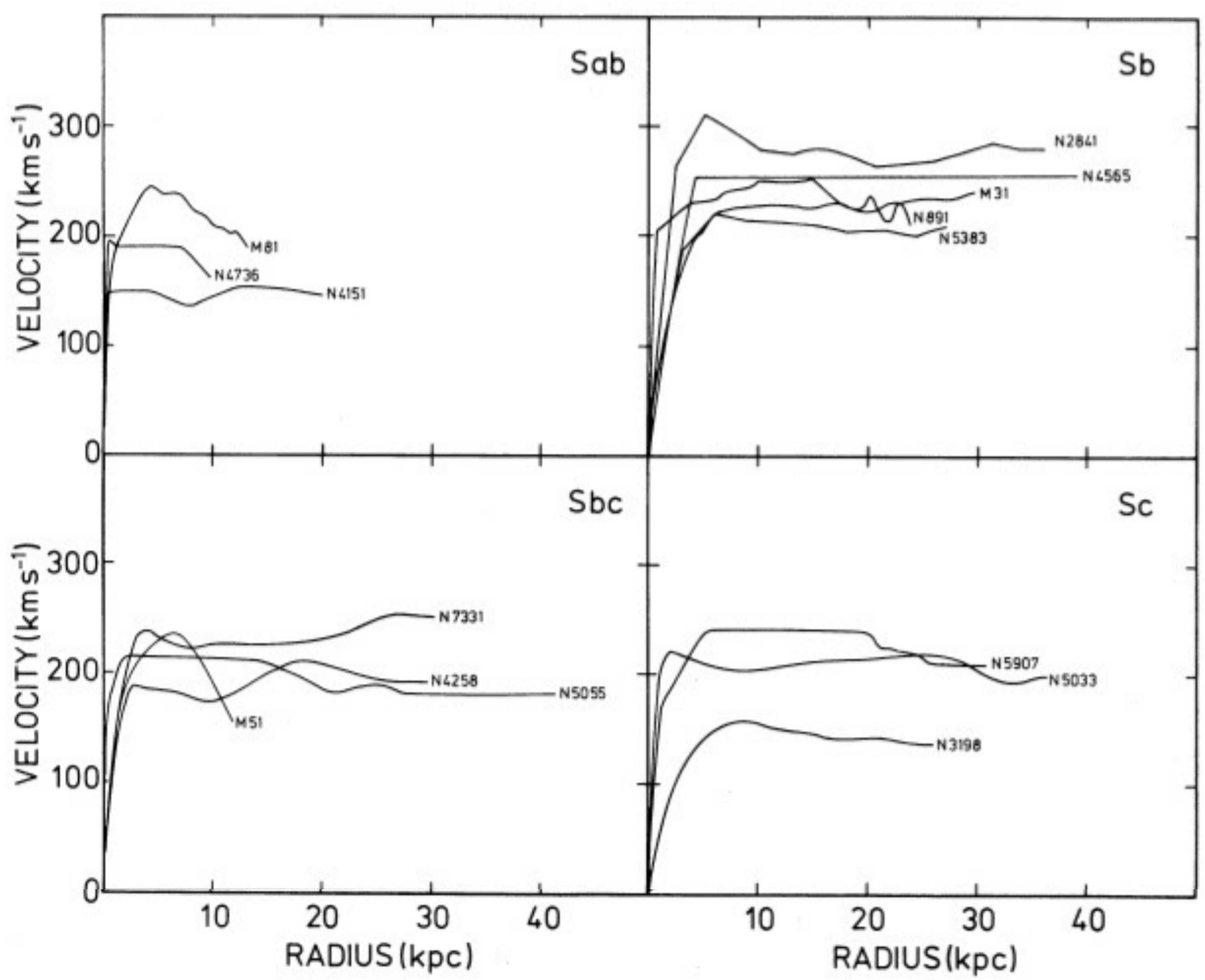


Fig. 3. Rotation curves of galaxies of various Hubble types.

The WIMP "miracle"

E. Kolb and M. Turner, "The Early Universe" (1994)

Let χ be a stable particle carrying a non-zero charge under the SM gauge group:

$$\chi\bar{\chi} \to q\bar{q} \tag{1}$$

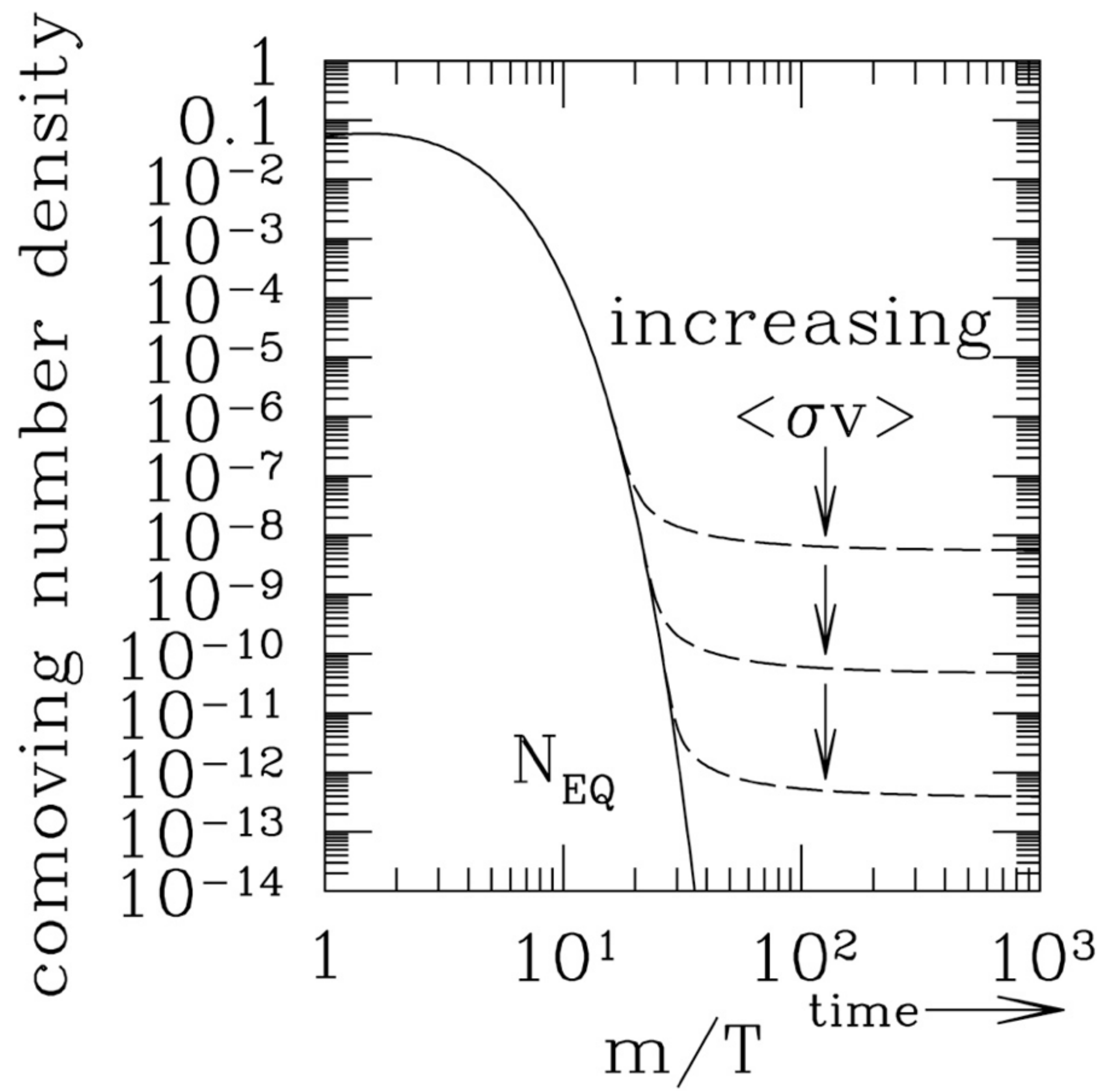
The evolution of the number density is described by the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle_T\left[(n_\chi)^2 - (n_\chi^{\mathrm{eq}})^2\right] \tag{2}$$

At freeze-out, when $\Gamma \ll H$, the number density per comoving volume becomes constant. For a species which is not-relativistic at freeze-out:

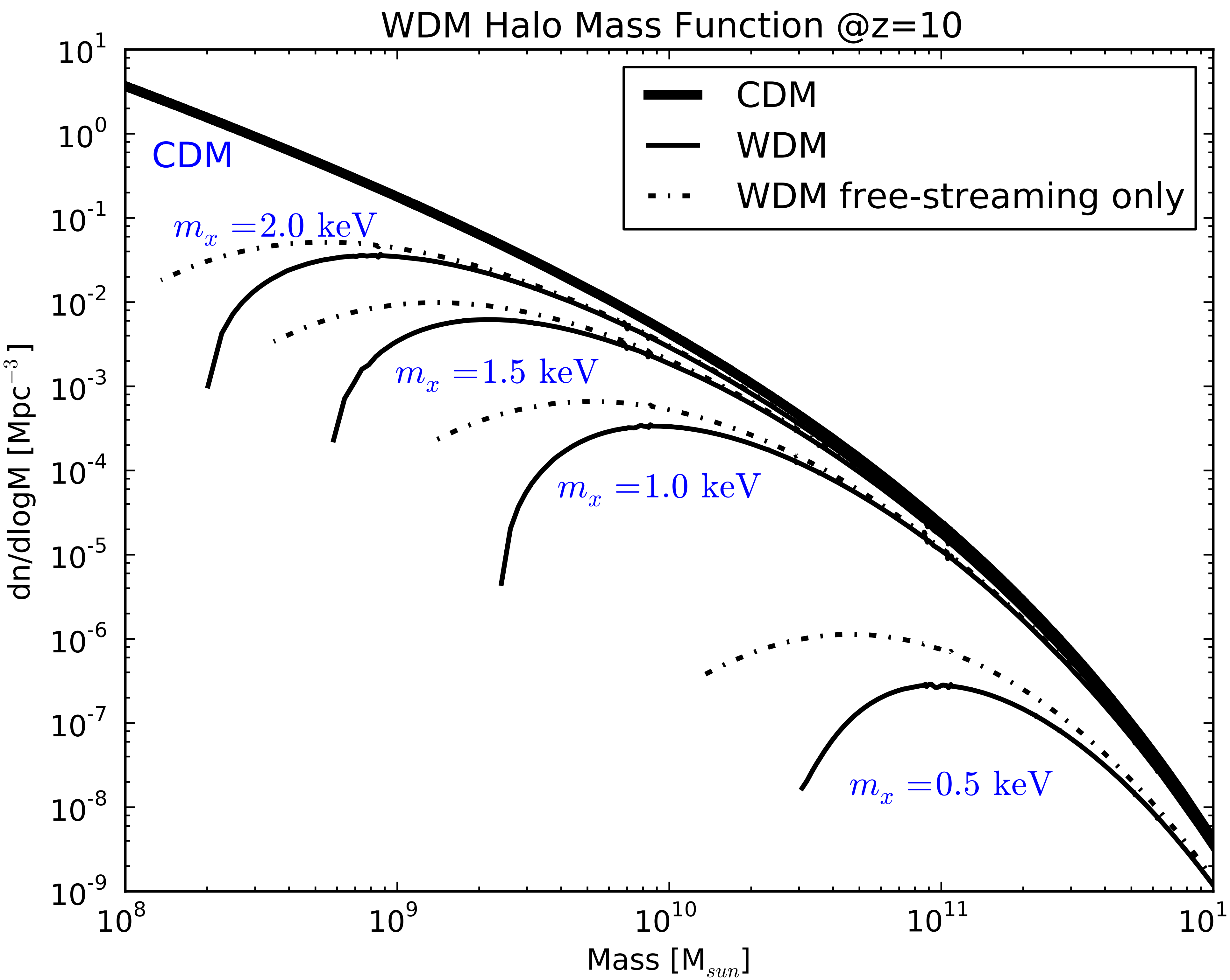
$$\boxed{\Omega h^2 \sim \frac{3\times10^{-27}\,\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle_{T=T_f}}} \tag{3}$$

The WIMP recipe to embed a DM candidate in a SM extension foresees an extra particle χ that is stable, massive and weakly-interacting!

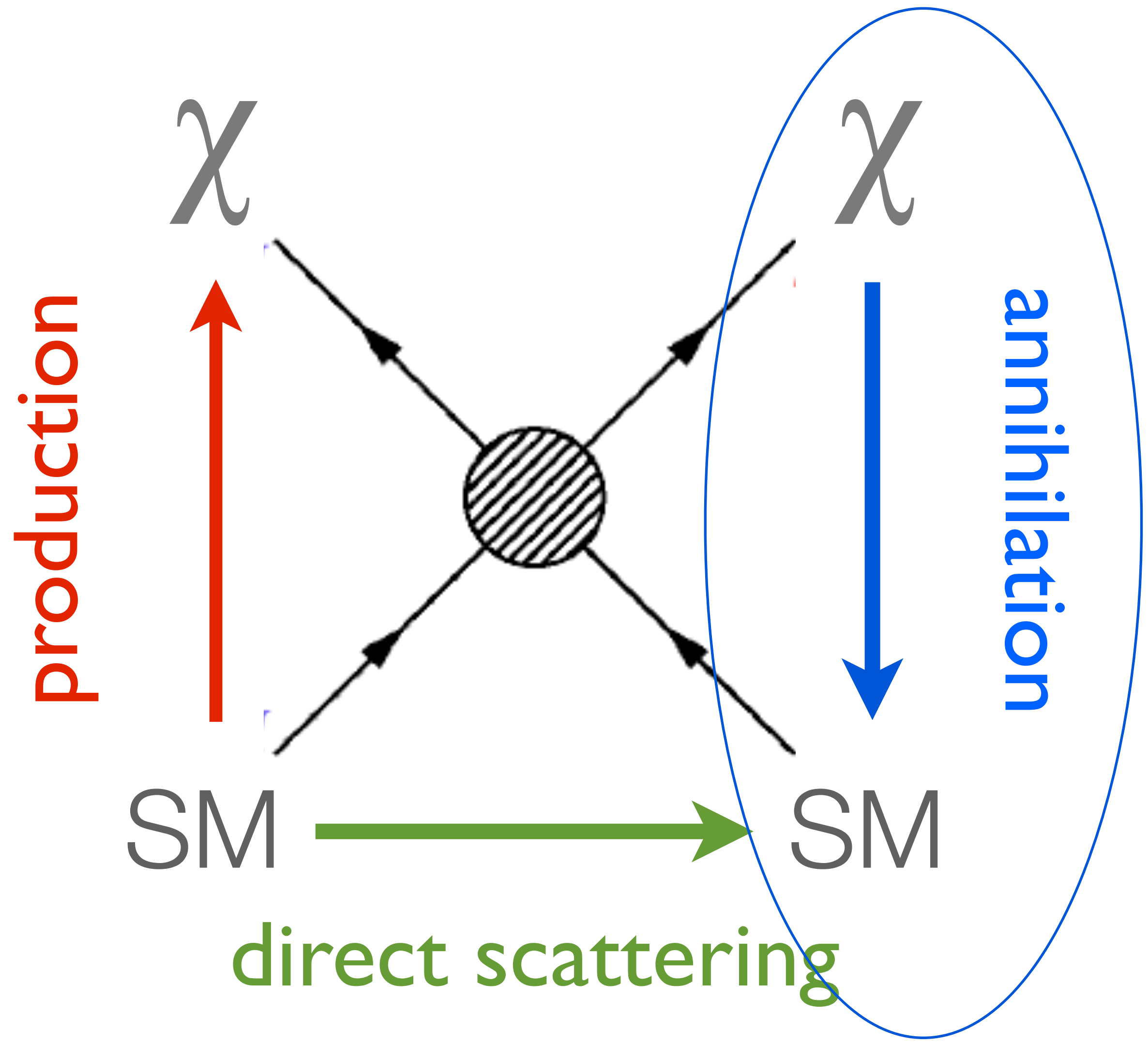


How Cold Is Cold Dark Matter?

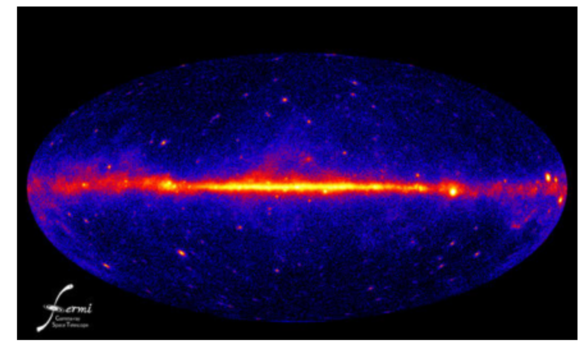
F. Pacucci, A. Mesinger and Z. Haiman, MNRAS, 2013



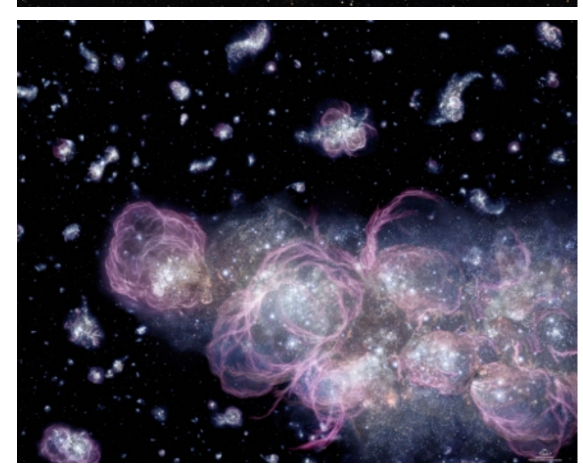
WIMPs detection strategies



$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$


Galactic Center

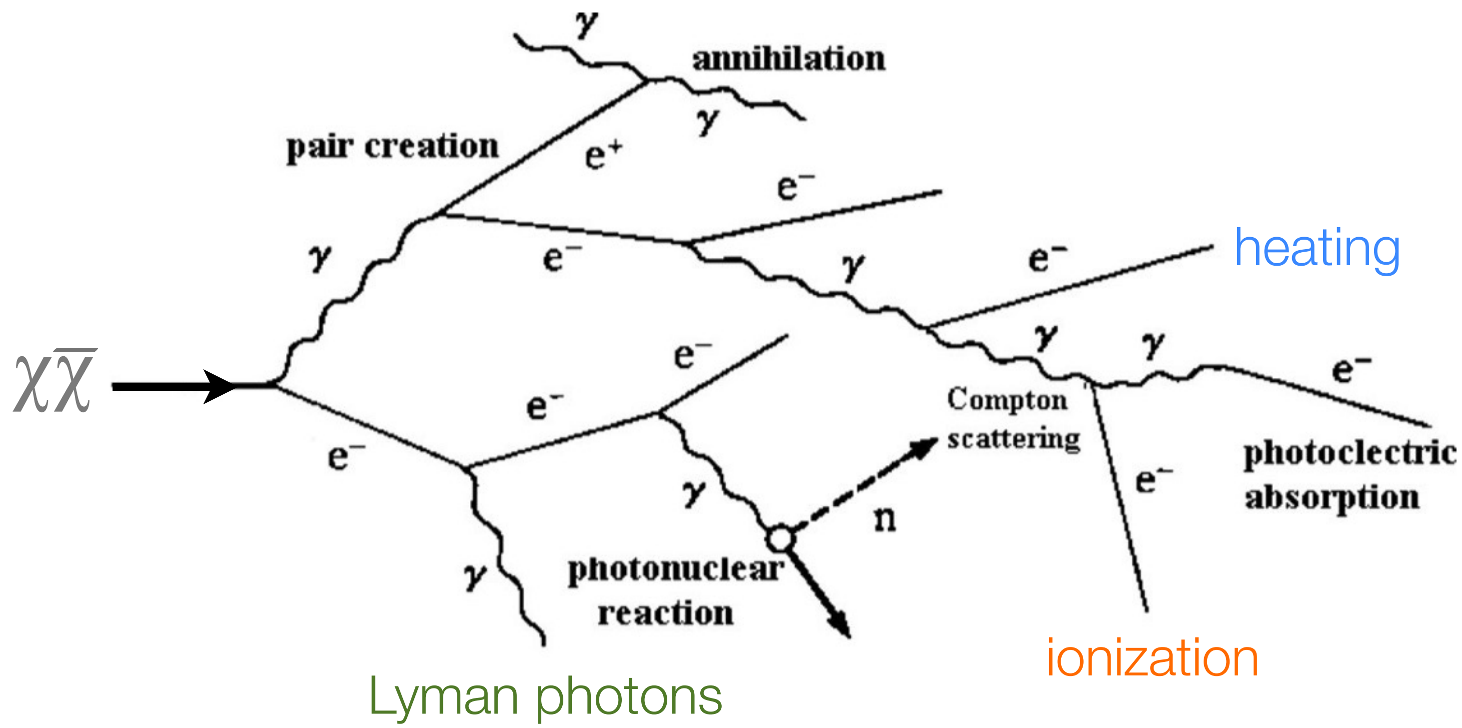

Dwarf galaxies


Early Universe

All these approaches are complementary!

DM during Dark Ages

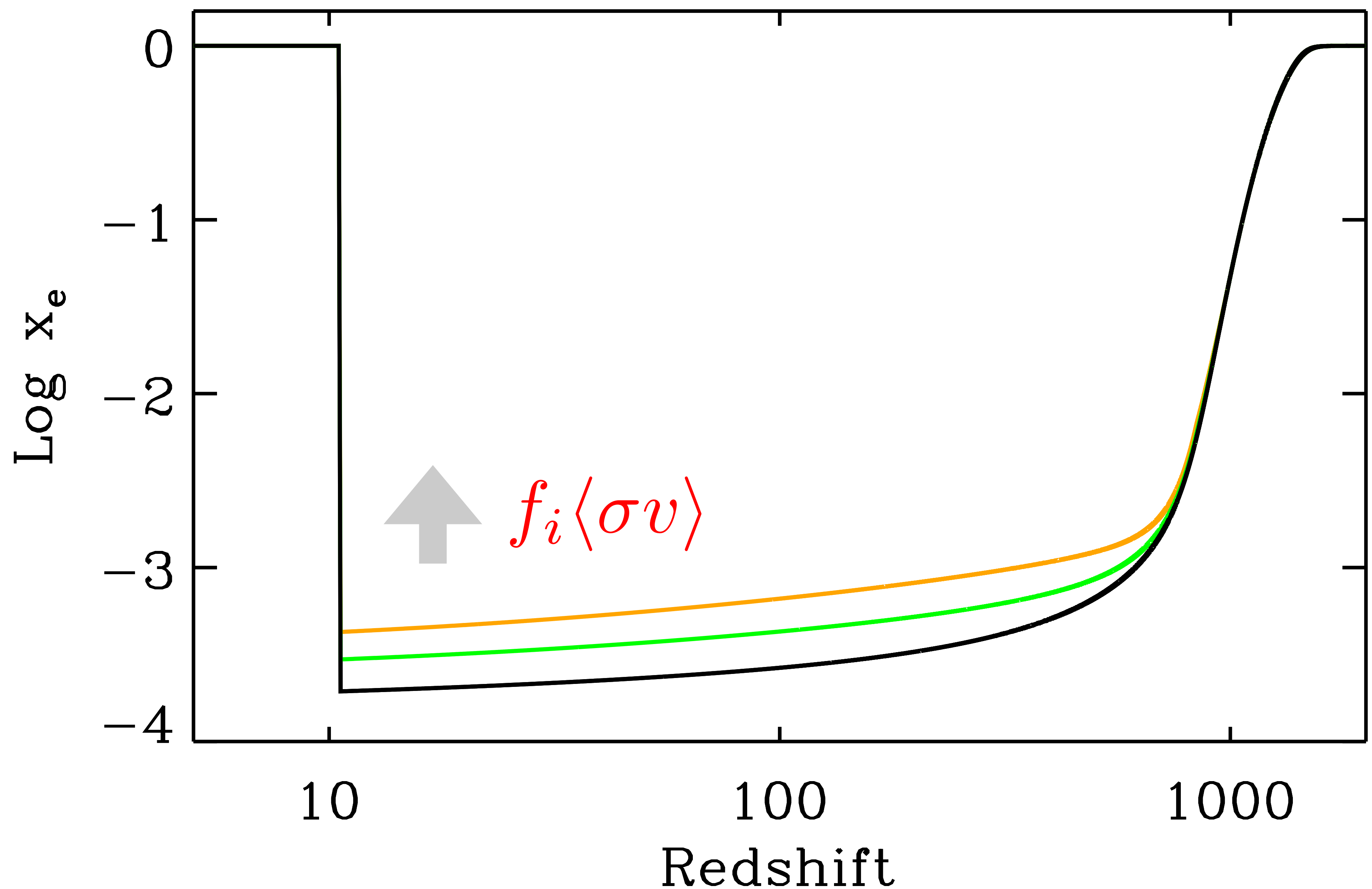
CE, M.Valdés, A.Ferrara, N. Yoshida, MNRAS, 2012



- WIMP annihilation produce gamma-rays, cosmic-rays, anti-matter: release energy which, in principle, **ionize**/**heat** up baryonic gas.
- Energy released enormous: **1 GeV** energy is sufficient to ionize **~10^8 hydrogen atoms**, only a tiny fraction of DM decay/annihilate is enough to affect ionization history.
- By looking for departures from the “standard recombination” scenario, we can place limits on energy injection at ***z=100-1000*** and translate these limits to exclusions in WIMP parameter space (e.g. the cross-section / mass plane, etc.).

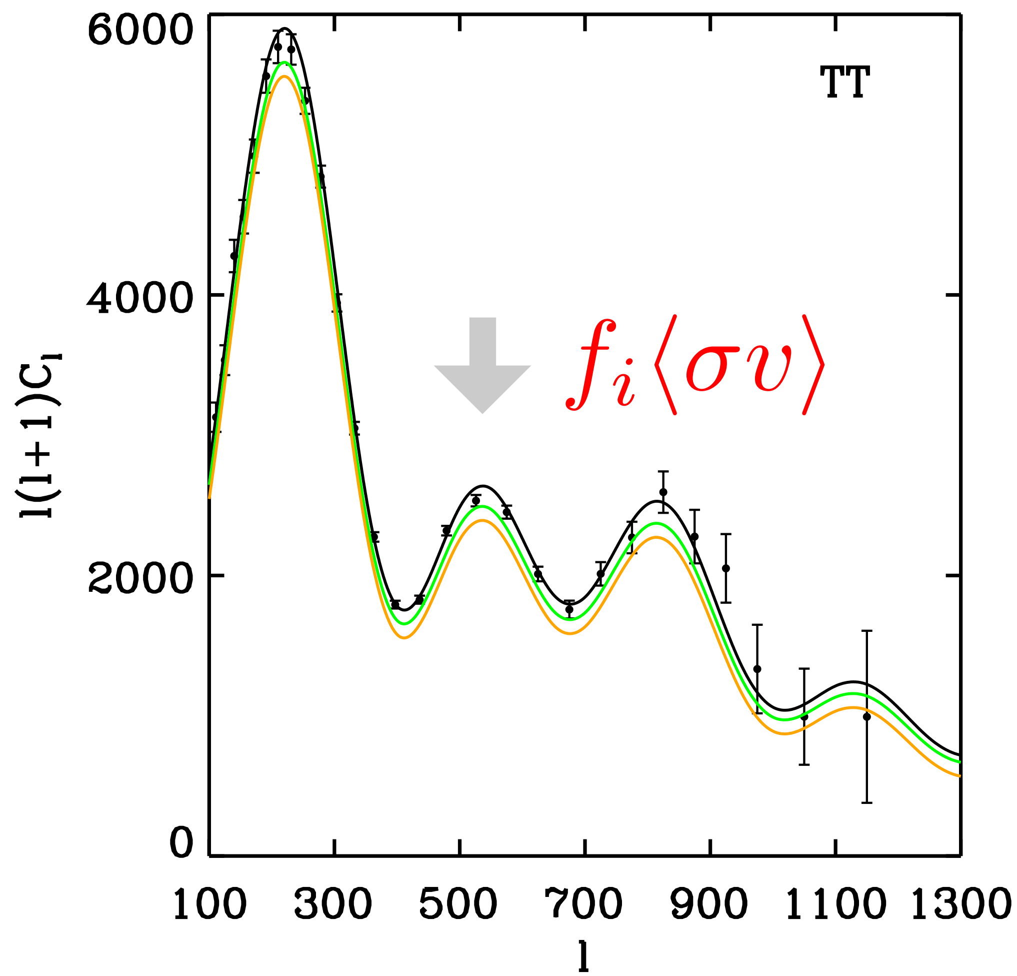
Baryon history in the Universe

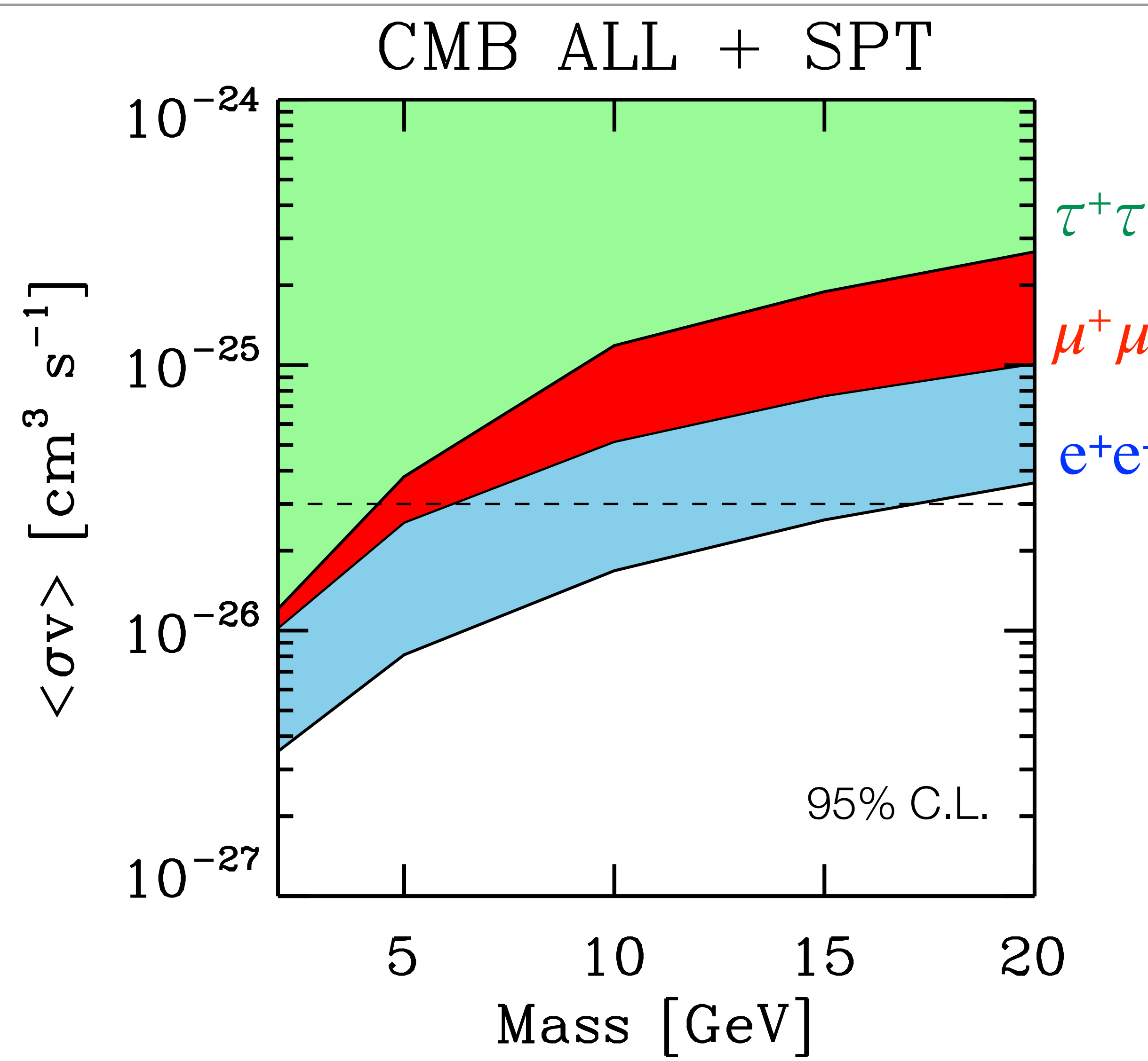
$$\frac{dE_\chi}{dt} = 2M_\chi f_i \langle \sigma v \rangle n_\chi^2$$



CMB constraints

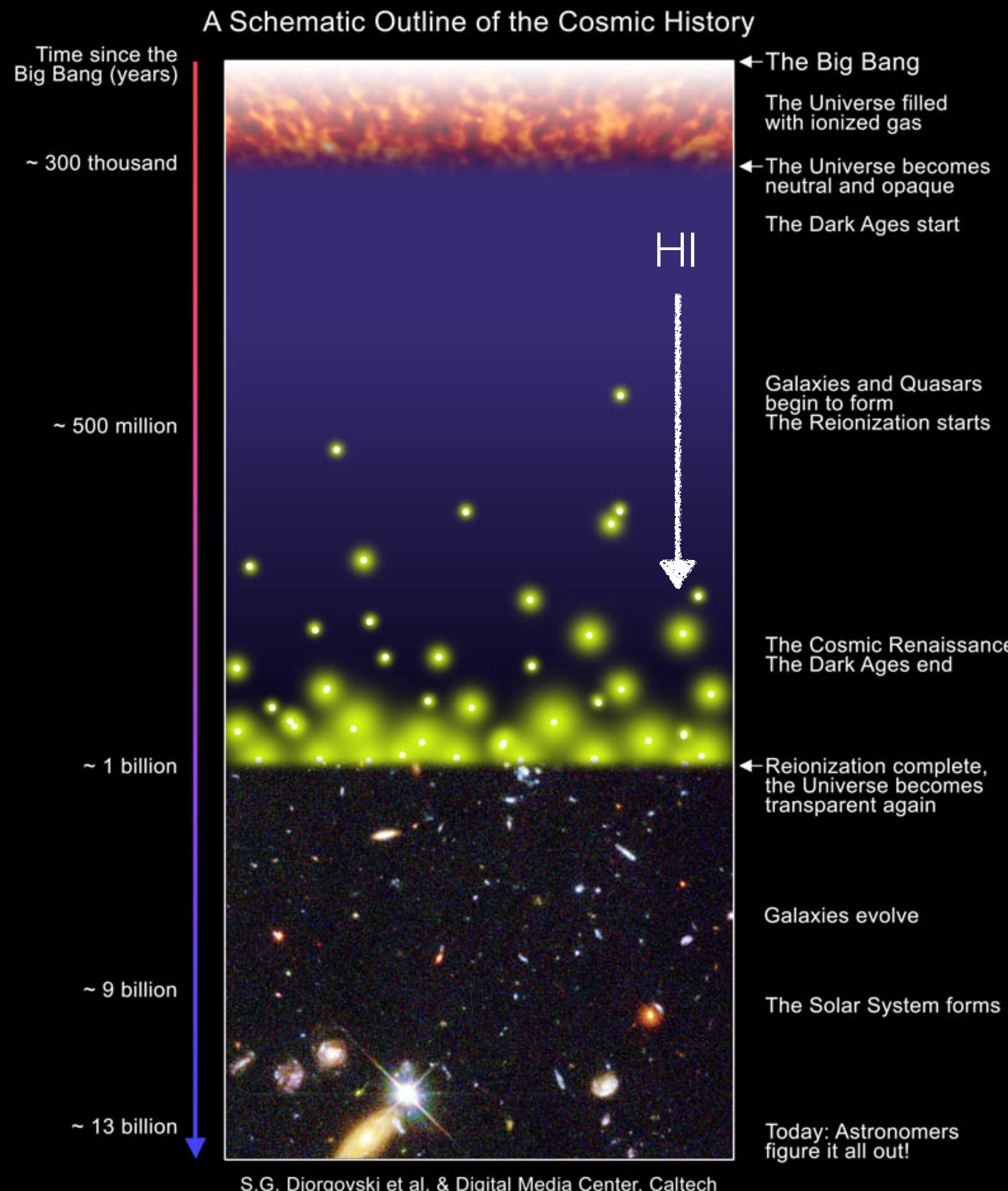
CE, S.Pandolfi and A.Ferrara, MNRAS, 2013





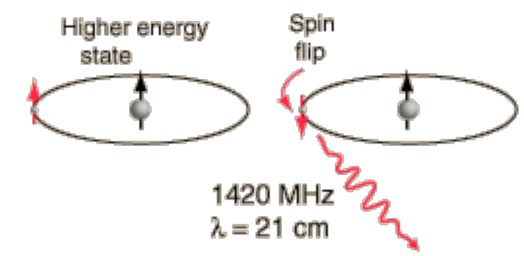
- more **free electrons** survive at low redshift after recombination compared to the standard case. Increase the width of the LSS, and consequently the width of the visibility function.
- these results are quite robust since we understand recombination and the **CMB** quite well and astrophysical backgrounds are less relevant with respect to constraints based on, e.g., annihilations in late-time halos.

“Dark Ages”


A Schematic Outline of the Cosmic History
Time since the Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion
HI
The Big Bang
The Universe filled with ionized gas
The Universe becomes neutral and opaque
The Dark Ages start
Galaxies and Quasars begin to form
The Reionization starts
The Cosmic Renaissance
The Dark Ages end
Reionization complete, the Universe becomes transparent again
Galaxies evolve
The Solar System forms
Today: Astronomers figure it all out!
S.G. Djorgovski et al. & Digital Media Center, Caltech

21cm physics in a nutshell

J.Pritchard and A.Loeb, arXiv:1109.6012



- H I emission (predicted by van de Hulst in 1945, student of Oort):

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{T_{21\mathrm{cm}}}{T_S}\right)$$

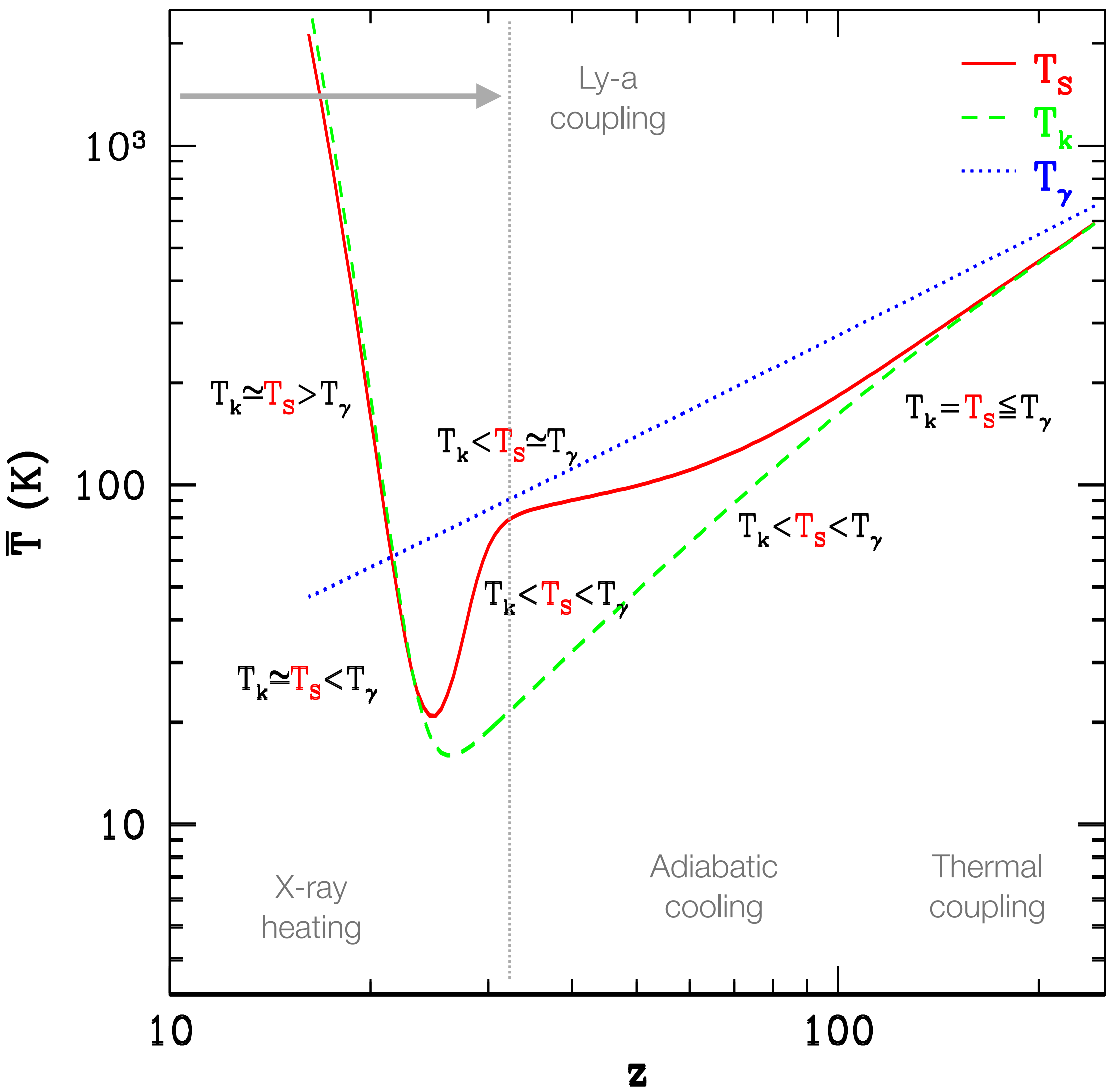
- 21 cm brightness temperature of an IGM gas parcel at a redshift z, relative to the CMB:

$$\delta T_b \sim 25\, x_{\mathrm{HI}}\,(1+\delta)\left(\frac{1+z}{10}\right)^{1/2}\left[\frac{T_{\mathrm{S}} - T_{\mathrm{CMB}}}{T_{\mathrm{S}}}\right]\ \mathrm{mK}$$

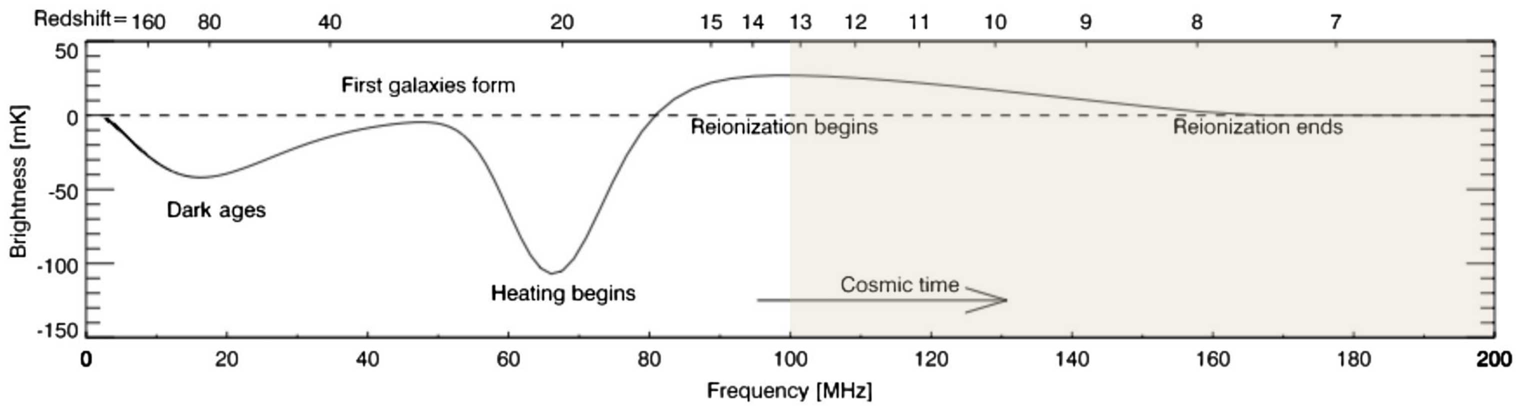
- In *emission* if $T_{\mathrm{S}} > T_{\mathrm{CMB}}$; in *absorption* if $T_{\mathrm{S}} < T_{\mathrm{CMB}}$

- In the absence of coupling mechanisms: $T_{\mathrm{S}} = T_{\mathrm{CMB}}$.
But! Two mechanisms couple T_S to T_K: collisions and Lyα pumping (also known as Wouthuysen-Field Effect):

$$T_{\mathrm{S}} = \frac{T_{\mathrm{CMB}} + y_\alpha T_k + y_c T_k}{1 + y_\alpha + y_c}$$



The LOFAR EoR experiment



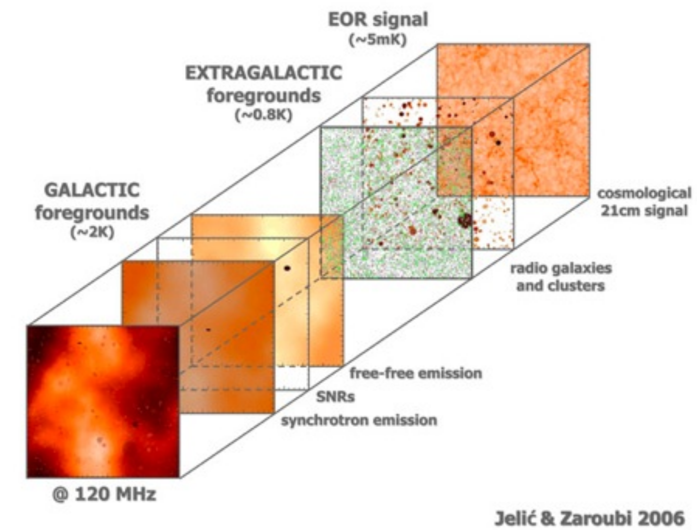
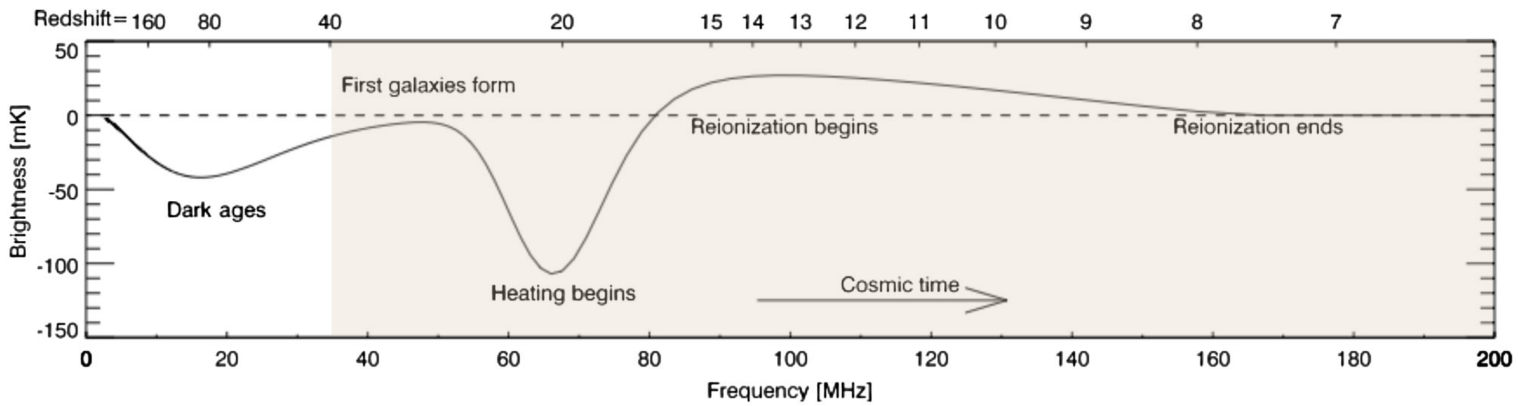


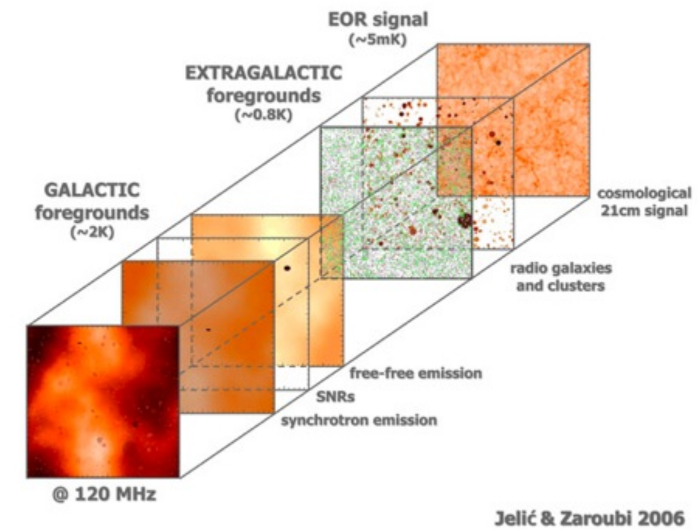
Fig. 19 *Left hand panel*: An artists impression of the layout of the LOFAR telescope over Western Europe. For the EoR, only the central part of the telescope is relevant. (courtesy of Peter Prijs). *Right hand panel*: The very central area of LOFAR. This circular area is know as the superterp and is the heart of the LOFAR core. The high-band array stations (covered in black blastic sheets) are clearly seen in this picture. In between one can also see the Low-Band Array antennas

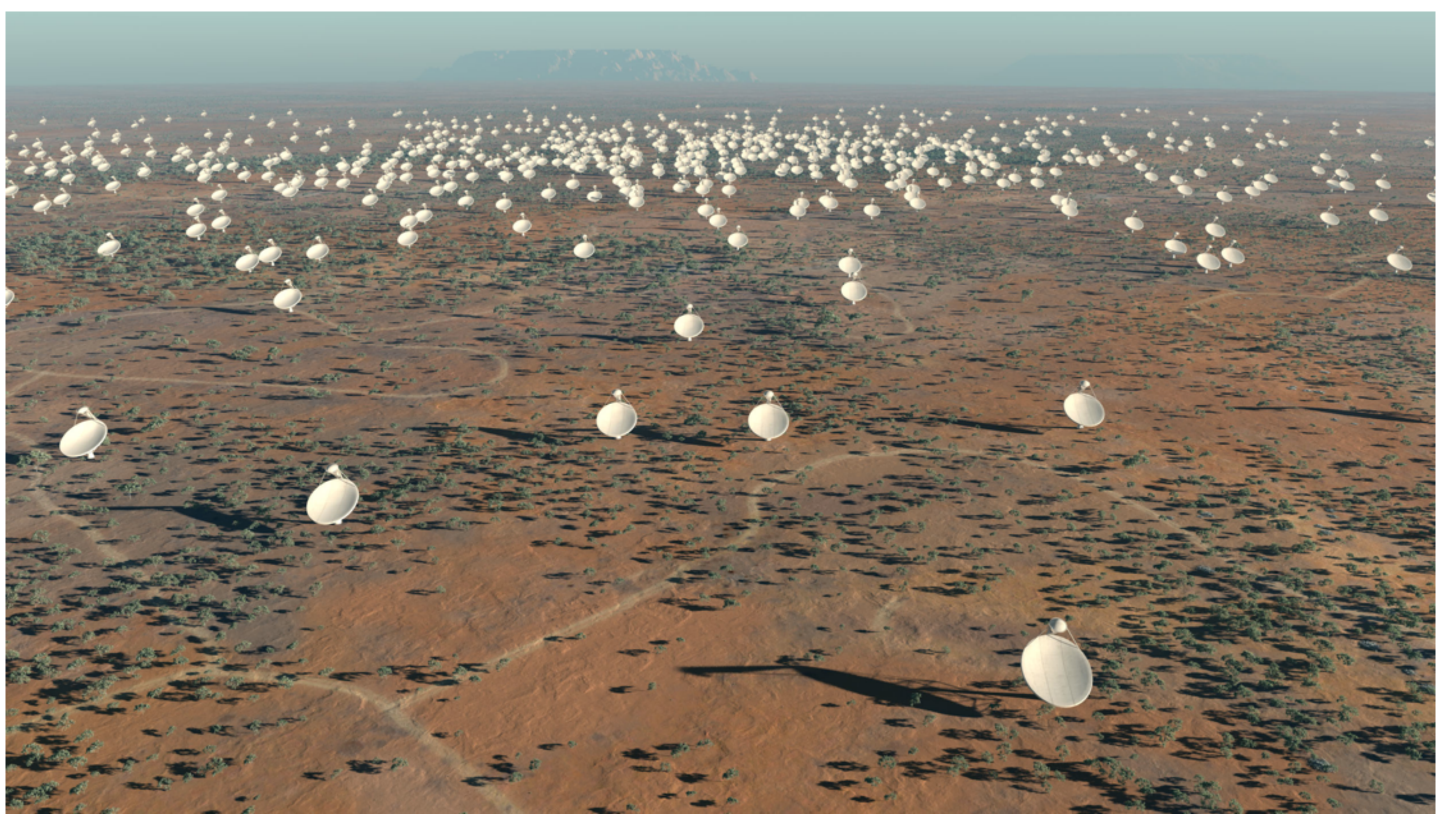
(Zaroubi, 2013)

frequency coverage: 120-240 Mhz
site: Netherlands
angular resolution: 5”-3”
effective area: 93,479 m^2
already in data-taking

Square Kilometer Array (SKA)







(artistic view)

frequency coverage: 40-30,000 Mhz
site: Australia + South Africa
angular resolution: <0.1”
effective area: 1,000,000 m^2
first light in 2020!

DM annihilation effects on 21 cm

S.R.Furlanetto, S.P.Oh & E.Pierpaoli, PRD, 2006 ; A.Natarajan & D.J.Schwarz, PRD, 2009

$$T_S = \frac{T_{CMB} + y_\alpha T_k + y_c T_k}{1 + y_\alpha + y_c},$$

$$(1+z)\frac{\mathrm{d}T_k}{\mathrm{d}z} = 2T_k + \frac{l_\gamma x_e}{H(z)(1 + f_{He} + x_e)}(T_k - T_{CMB}) - \frac{2\chi_h \dot{E}_x}{3k_b H(z)(1 + f_{He} + x_e)},$$

$$J_\alpha(z) = \frac{\mathcal{N}_H^2 hc}{4\pi H(z)}\left[x_e x_p \alpha_{2P}^{\mathrm{eff}} + x_e x_{H\,I}\gamma_{eH} + \frac{\chi_\alpha \dot{E}_x(z)}{\mathcal{N}_H h\nu_\alpha}\right],$$

heating fraction

Lya fraction

M.E.DE.A. code

M.Valdés, CE, A.Ferrara, MNRAS, 2011

- Several astrophysical and cosmological sources produce high energy particles through different acceleration processes:
  how is this energy transferred to the surrounding environment?

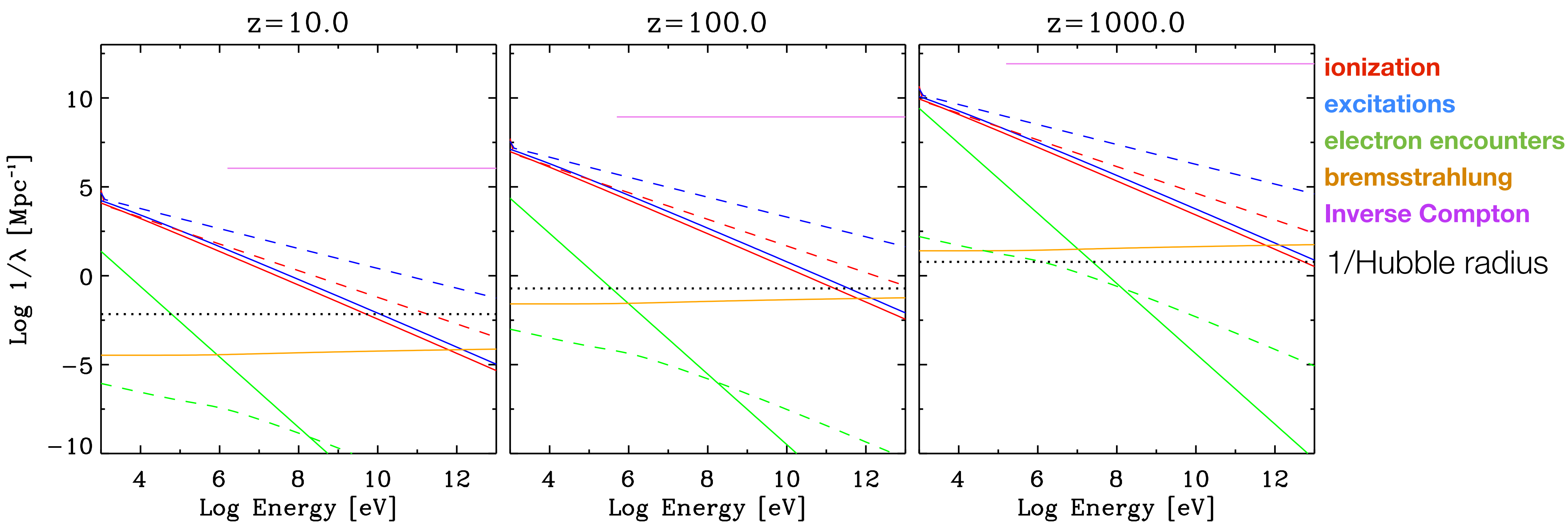
- **Monte Carlo method**: repeated random sampling of the relevant physical quantities and processes (i.e. cross-sections and interaction probabilities) to follow the evolution of a relativistic electron.

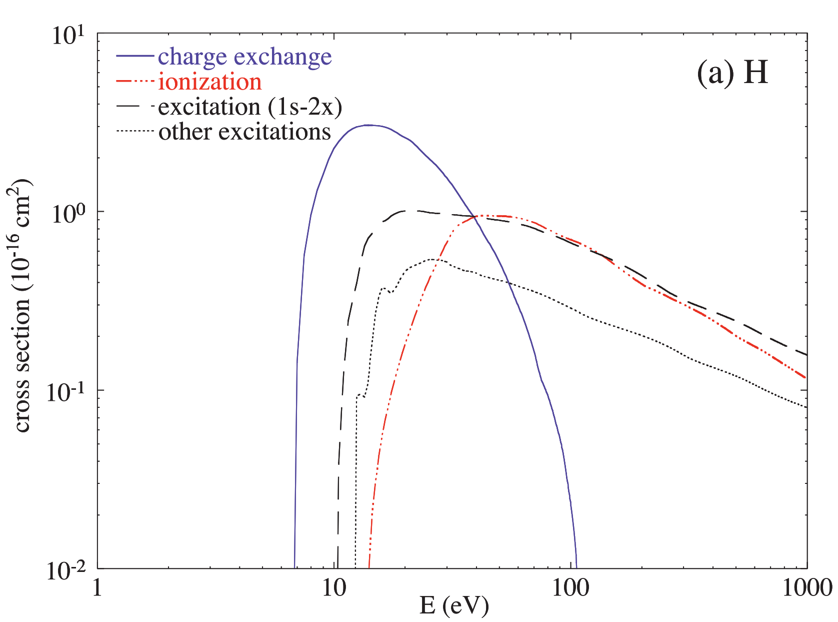
- An high energy electron in the IGM produces a chain of reactions: start with one particle, end up with many → the code calculates for every particle the probability of the main interaction channels and then selects one by a random number generator, until the energy is deposited into the IGM.

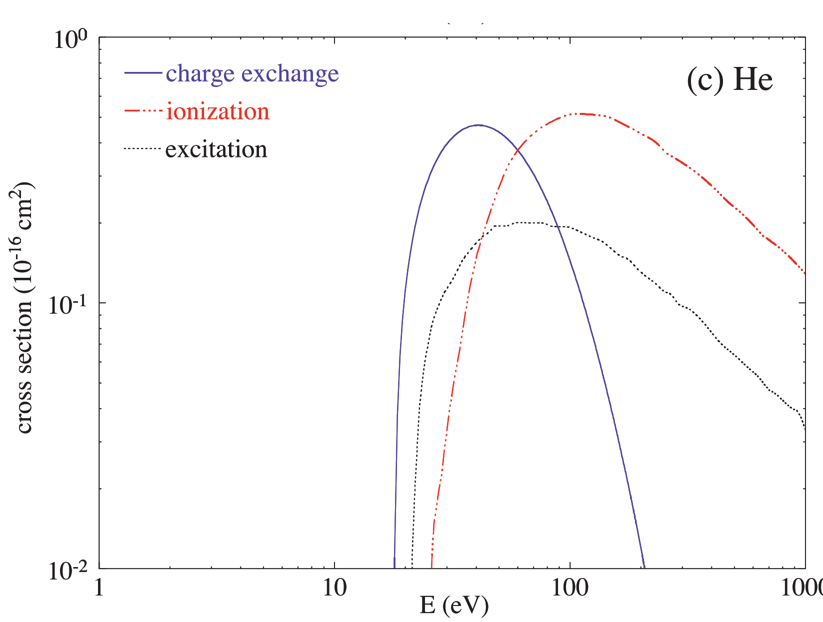
- **M**ontecarlo **E**nergy **DE**position **A**nalysis.

Lepton interactions

N.Guessoum et al., A&A, 2005 ; CE, M.Valdés, A.Ferrara and N.Yoshida, MNRAS, 2012



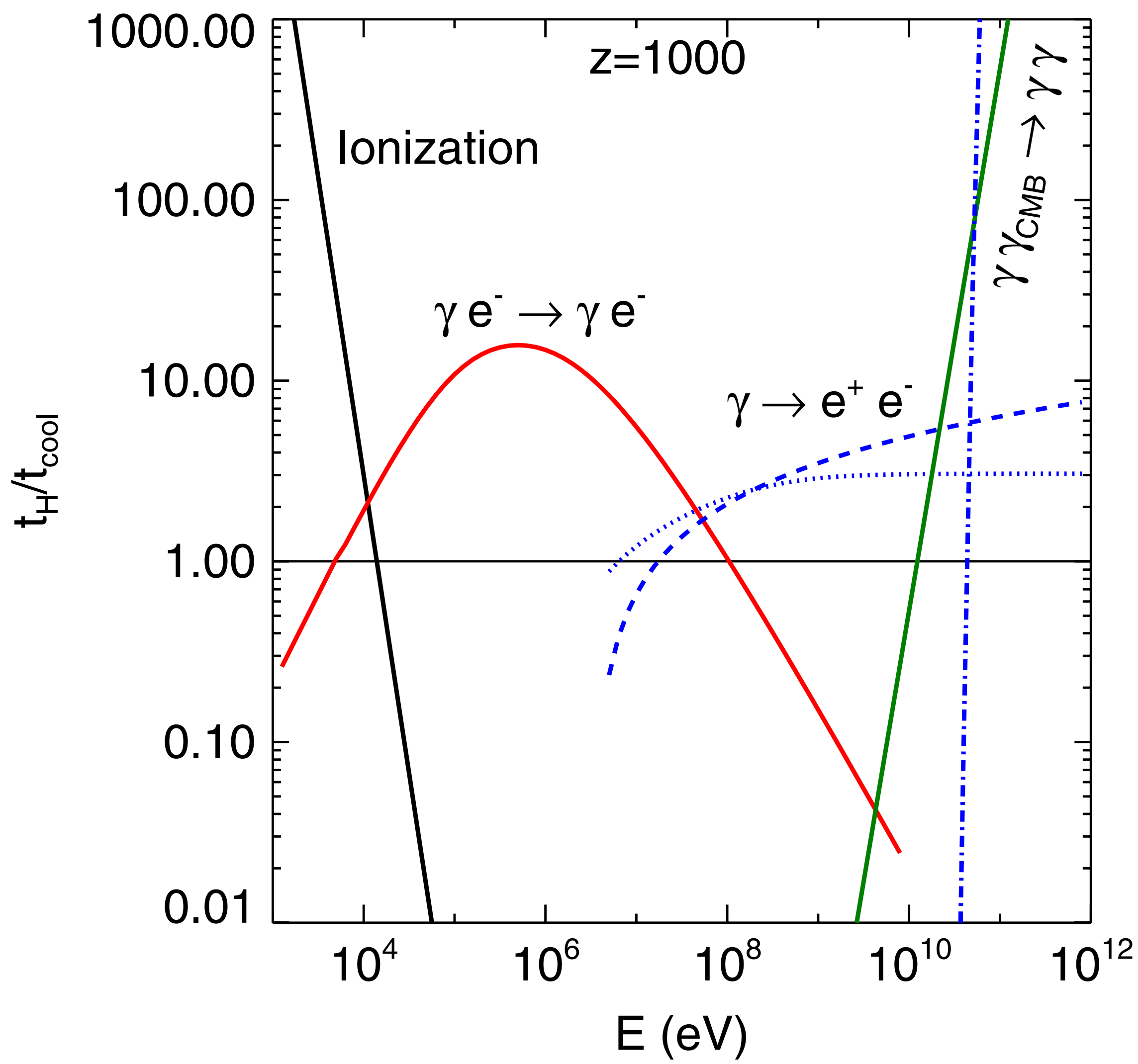


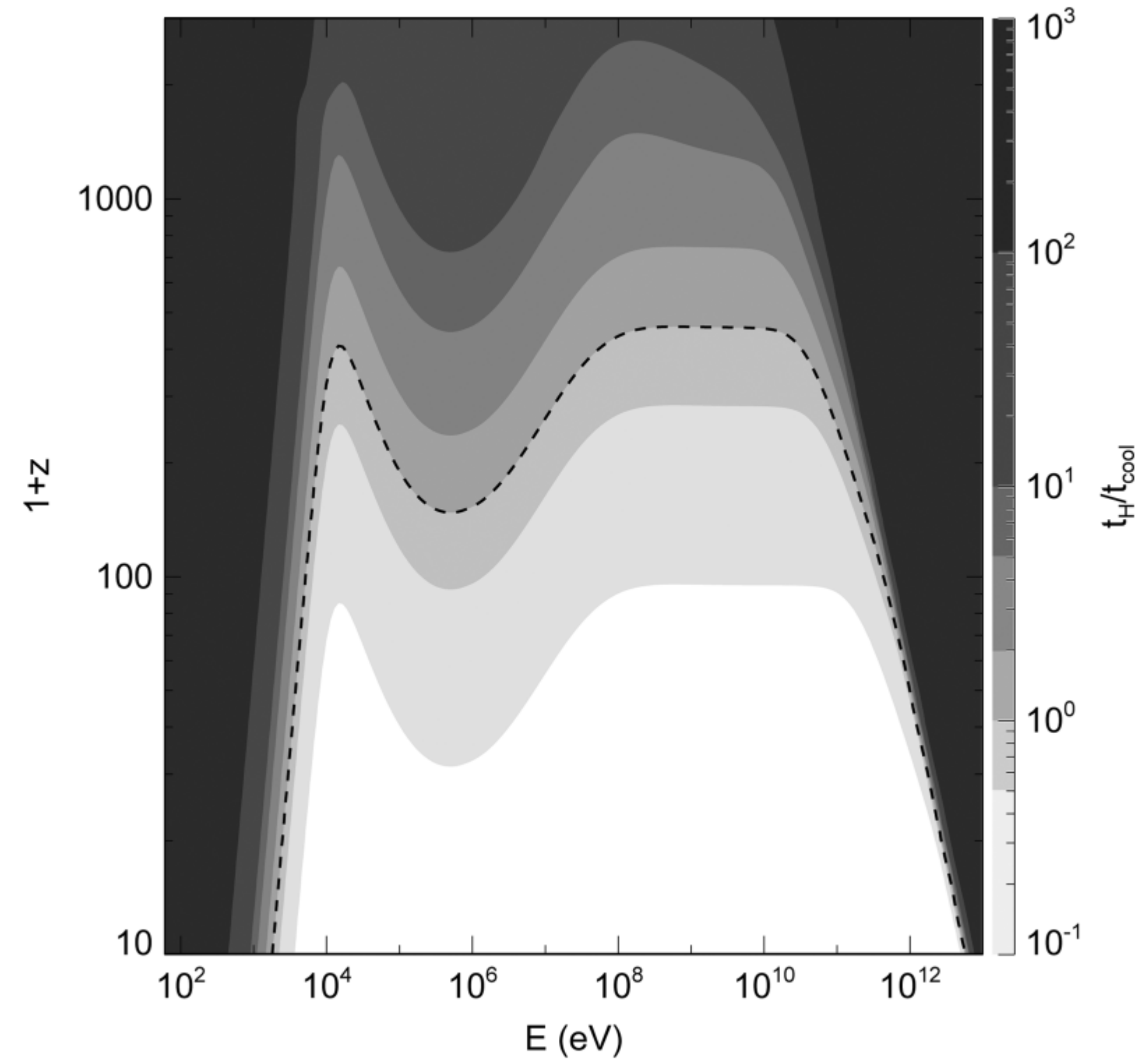


- IC dominant down to a O(MeV) energy
- Positronium formation in positron collision with H and He.

Photon interactions

A.A.Zdziarski and R.Svensson, APJ, 1989 ; T.Slatyer et al., PRD, 2009



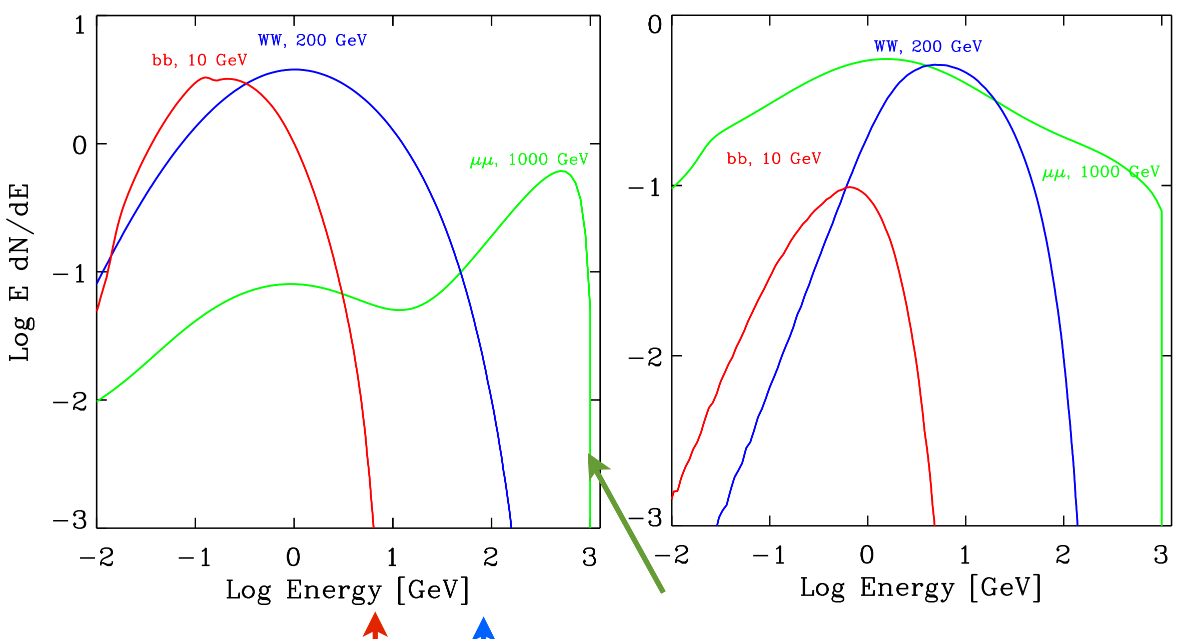


- There is a z-dependent transparency window.
- In the z ~ 100 - 1000 region energy deposition is almost “local” (as for electrons).

DM energy depositions

CE, M.Valdés, A.Ferrara and N.Yoshida, MNRAS, 2012

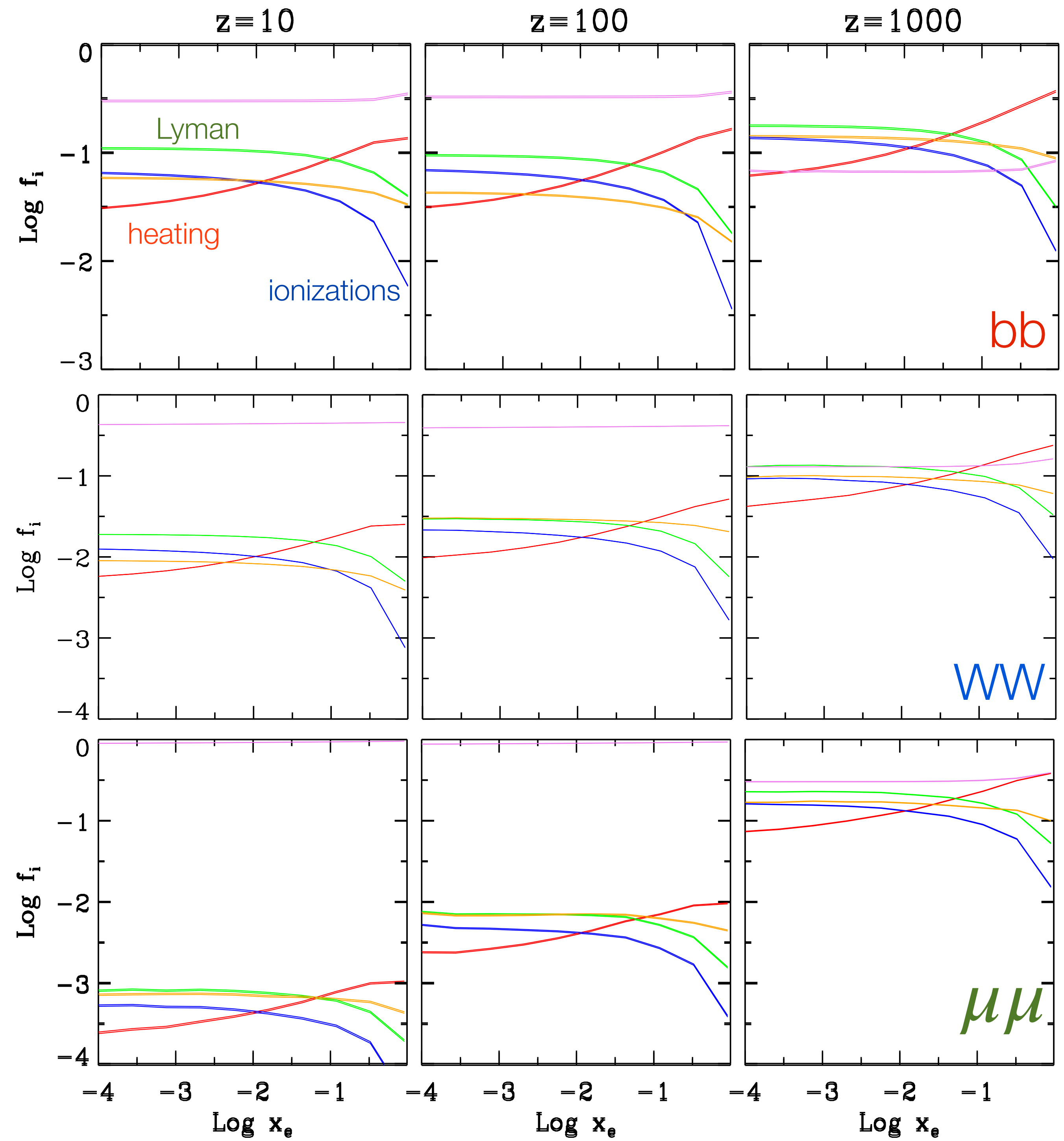
lepton spectra   photon spectra



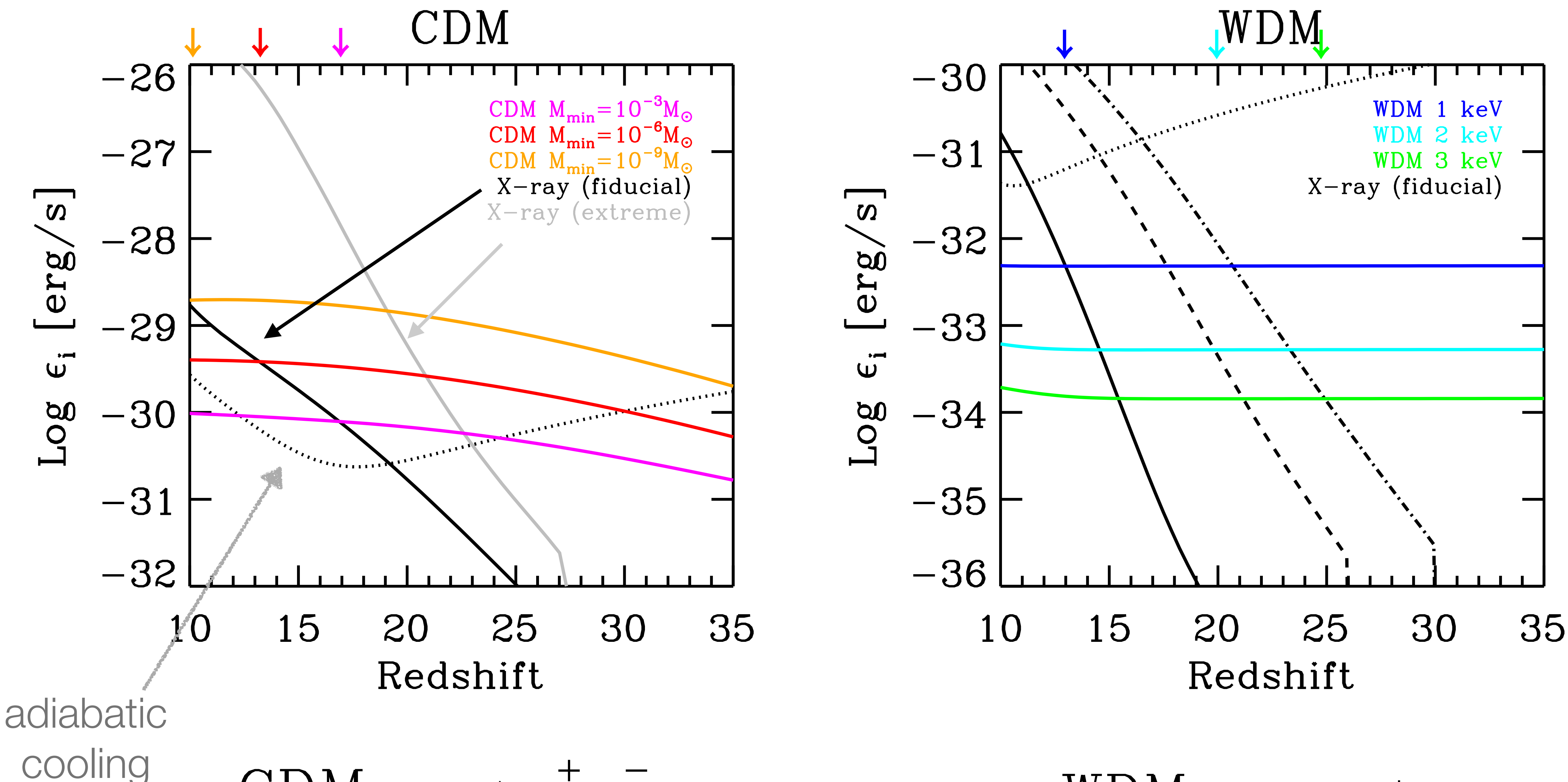
Ciafaloni et al., JCAP, 2011

DarkSUSY v.5.0.5

- heating grows with $\mathbf{x_e}$
- ionizations and Lyman photons grows with $\mathbf{x_H}$
- “high”-energy photons dominate energy depositions above 1 GeV
- “low”-energy photons dominate energy depositions below 10 MeV



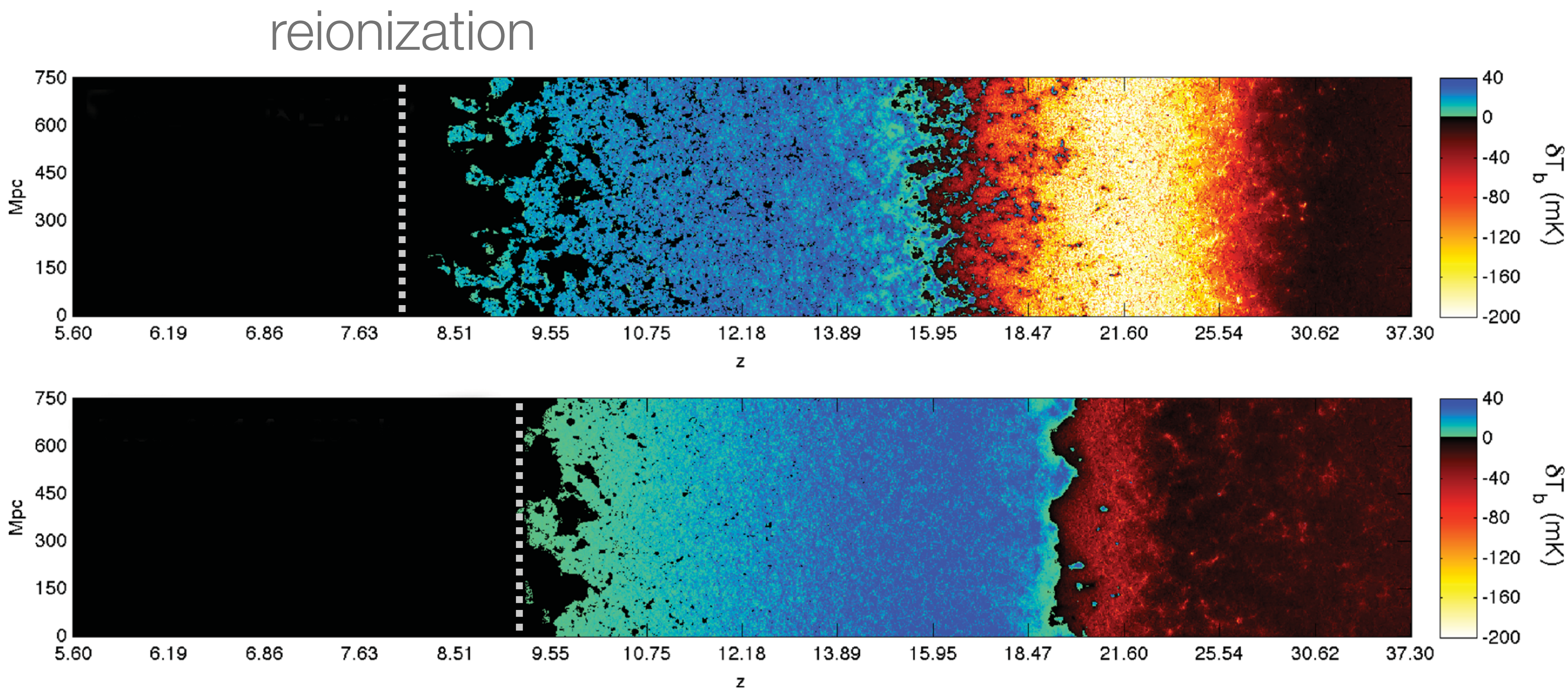
Energy deposition rates



CDM $\chi\chi \to e^+e^-$

WDM $\nu_s \to \nu_a + \gamma$

Reionization models



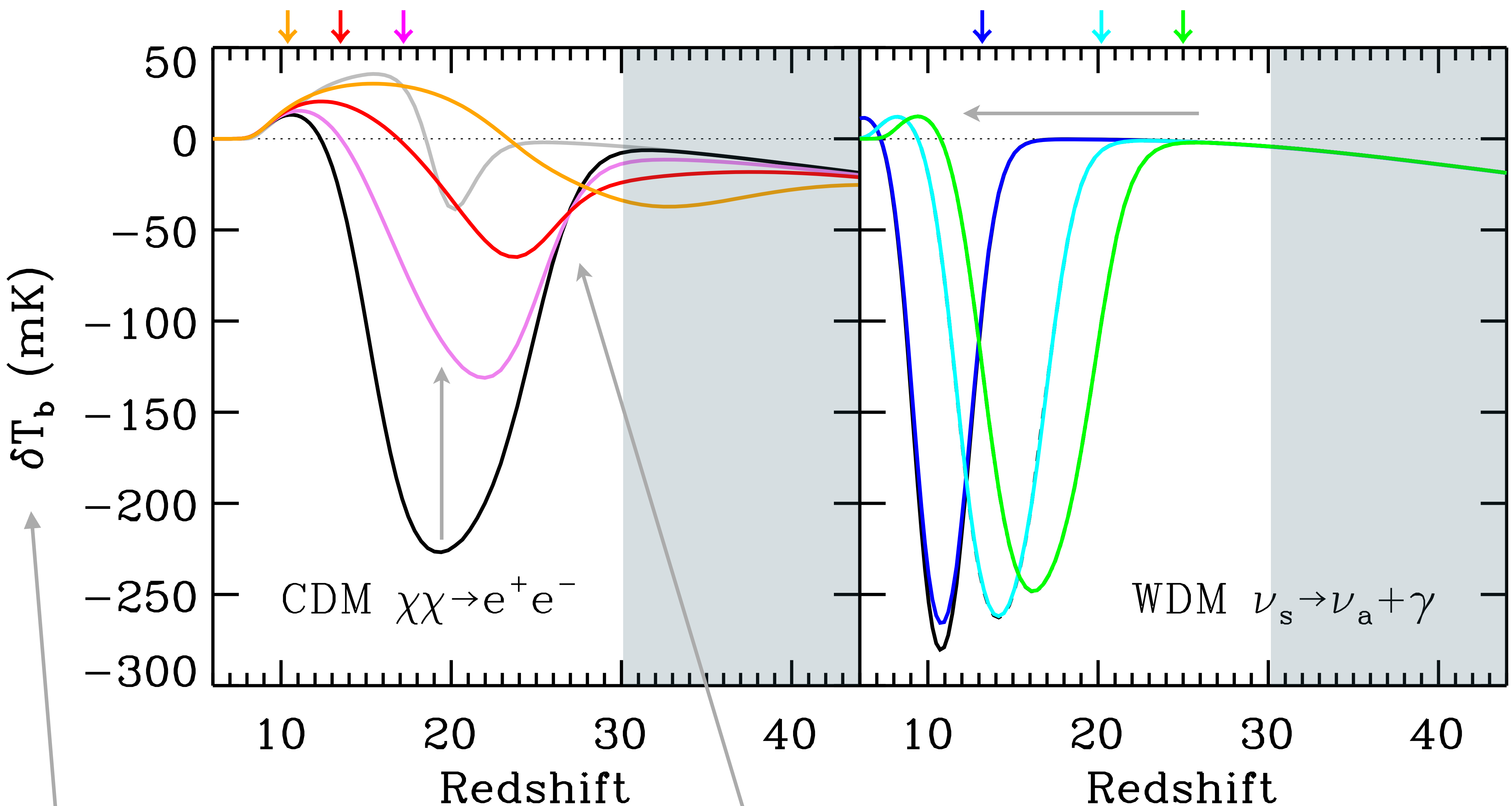
fiducial (0.2 X-ray per stellar baryon, UV dominated)

vs

extreme (4000 X-ray per stellar baryon, X-ray dominated)

The 21 cm global signal

M.Valdés, CE, A.Mesinger, A.Ferrara & N.Yoshida, MNRAS, 2013

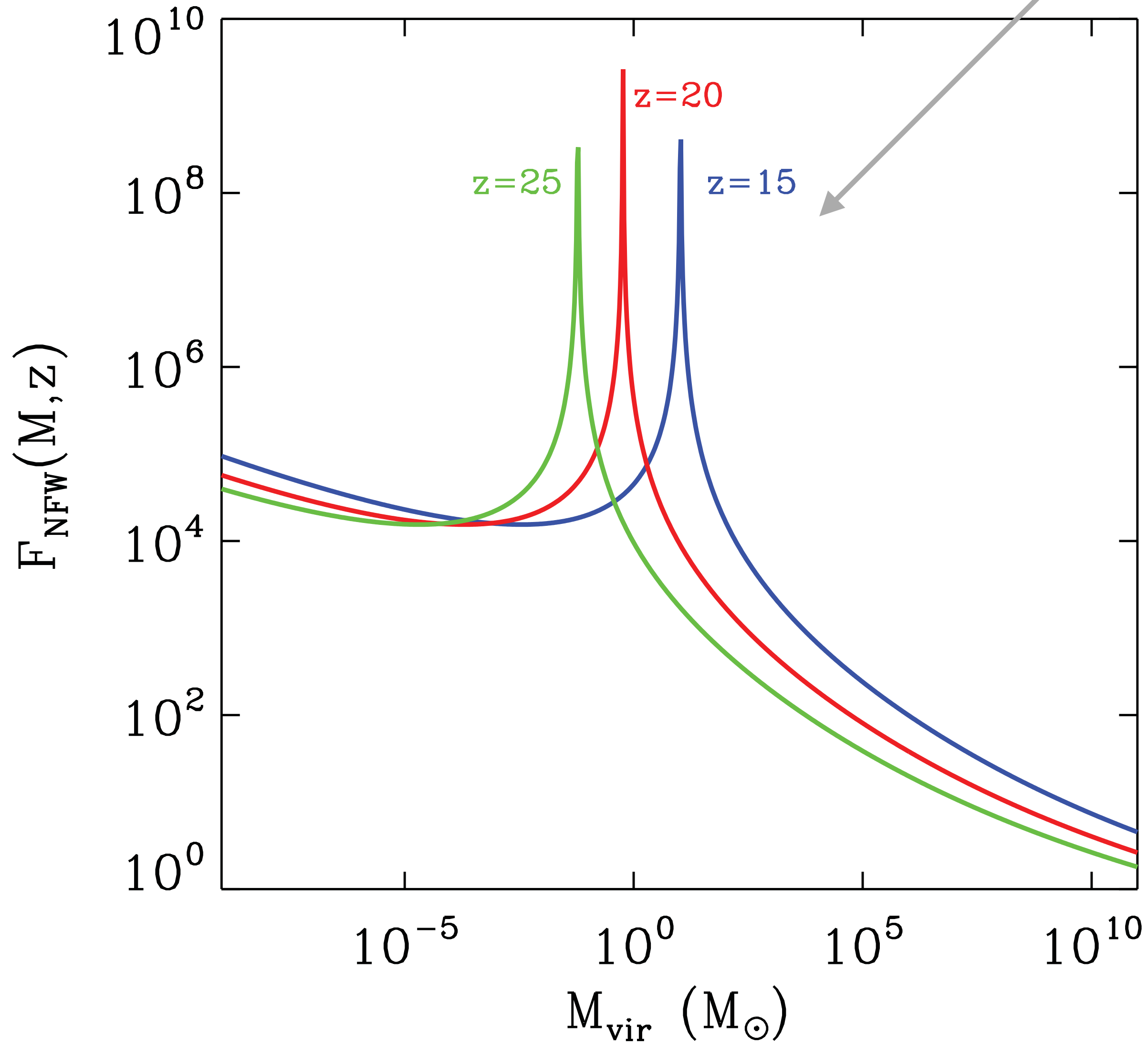


differential brightness
Temperature

DM Ly-a couples
Ts->Tk earlier

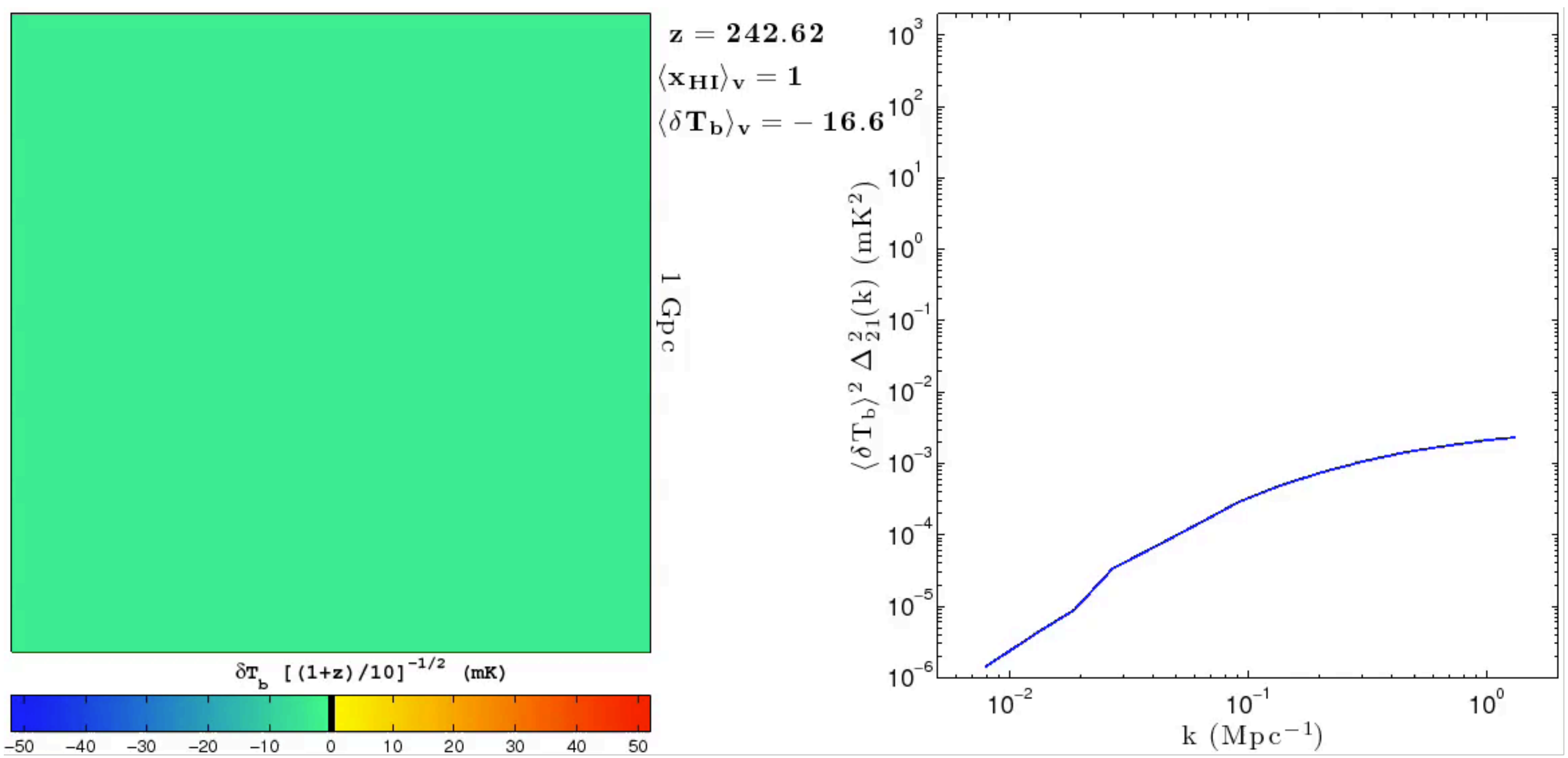
DM heating is uniform

$$A^{\rm struct}(z) = \frac{\langle \sigma v \rangle}{2\, m_\chi^2} \int dM \, \frac{dn}{dM}(z, M)\, (1+z)^3 \boxed{\int dr\, 4\pi r^2\, \rho_i^2(r, M(z))}$$



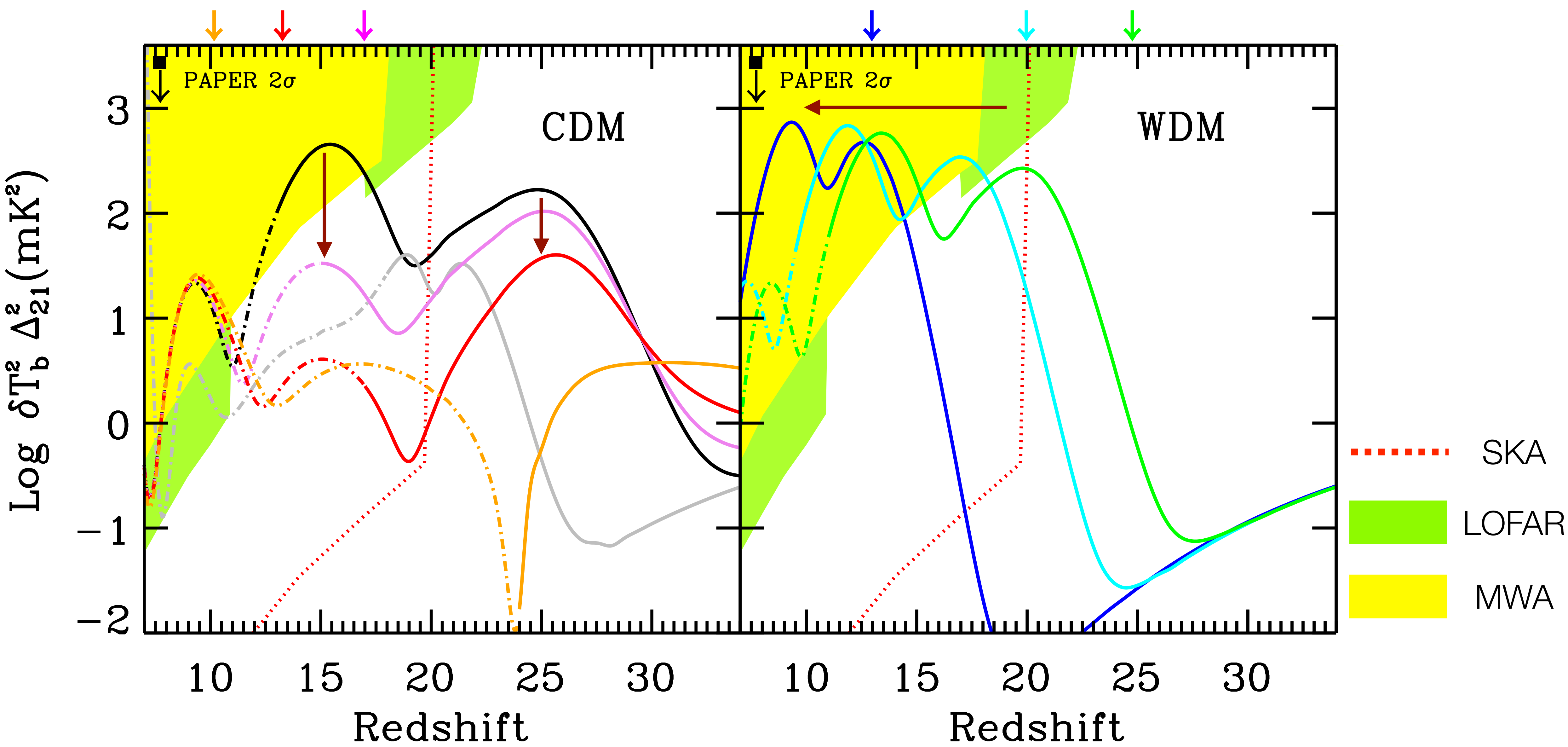
Astrophysical heating sources are biased

21cmFAST code



Power-spectrum

CE, A.Mesinger and A.Ferrara, *to be finished soon*



- *Robust* DM identification:
- when DM: the “heating” peak is lower than the “Ly-alpha” peak.
- when DM: the “heating” peak is in emission.

Conclusions

- Energy injection by DM annihilation at z ~ 100-1000 can be properly constrained after accounting for degeneracies with cosmological parameters.

- We have developed a new model, which includes lepton and photon interactions with the IGM, allowing us to compute the energy partition into heating, excitations and ionizations as a function of the **electron initial energy**, the **ionization fraction** and the **redshift**.

- Our results can be applied to calculate DM contribution to the 21 cm cosmological evolution. Observations of the 21 cm signal from the *Dark Ages* could eventually detect a **robust** signal of exotic processes like DM decays or annihilations.