High redshift 21 cm signal as a dark matter probe

Marcos Valdés (Scuola Normale Superiore di Pisa)

A. Ferrara, C. Evoli, A. Mesinger, N. Yoshida

Kavli IPMU, Tokyo University, June 7th 2012

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Outline:

1. How does DM deposit its energy into the IGM?

- MEDEA I, MEDEA II codes

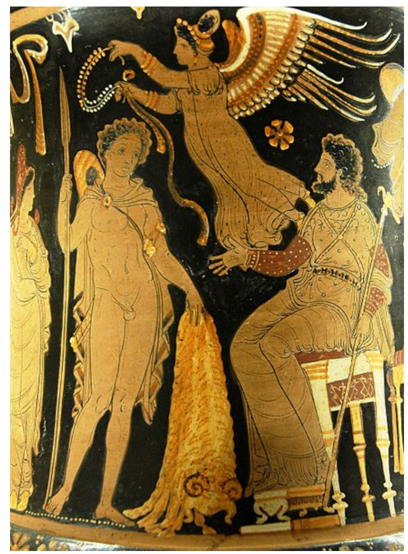
2. How does DM affect the high-z IGM?

- Investigate DM trace on the high-z HI 21 cm and on the CMB

1. How does DM deposit its energy into the IGM?

MEDEA - Monte Carlo Energy DEposition Analysis

MEDEAI - Monte Carlo Energy DEposition Analysis: repeated random sampling of the relevant physical quantities and processes, i.e. *cross-sections and interaction probabilities* to follow the evolution of a fast electron up to 1 TeV (previous works did up to 10 keV – Shull 1979, Valdés & Ferrara 2008, Furlanetto 2010)



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MEDEA I – electron energy deposition

Valdés & Ferrara, 2008

Valdés, Evoli C. & Ferrara A., 2010

LE
- (I) H, He, HeI ionization
- (II) H, He *excitation*
- (III) *Collisions with thermal electrons*
- (IV) *Recombinations*

HE
- (V) *Bremsstrahlung*
- (VI) *Inverse Compton*

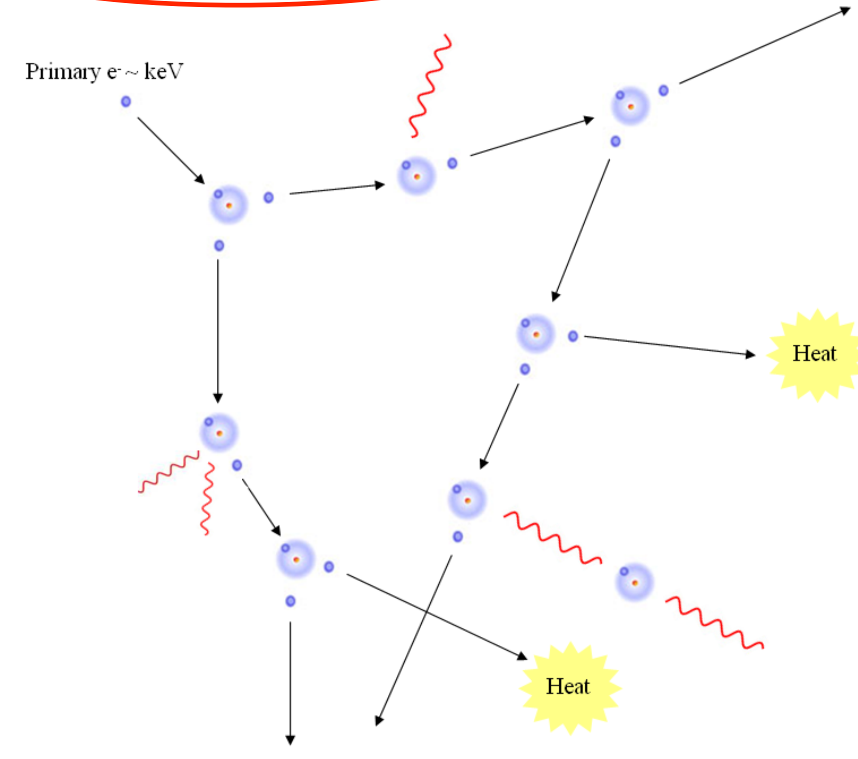
→ Ensemble of secondary photons and electrons which can interact further with the gas. Start with one particle → end up with many!

Thresholds:

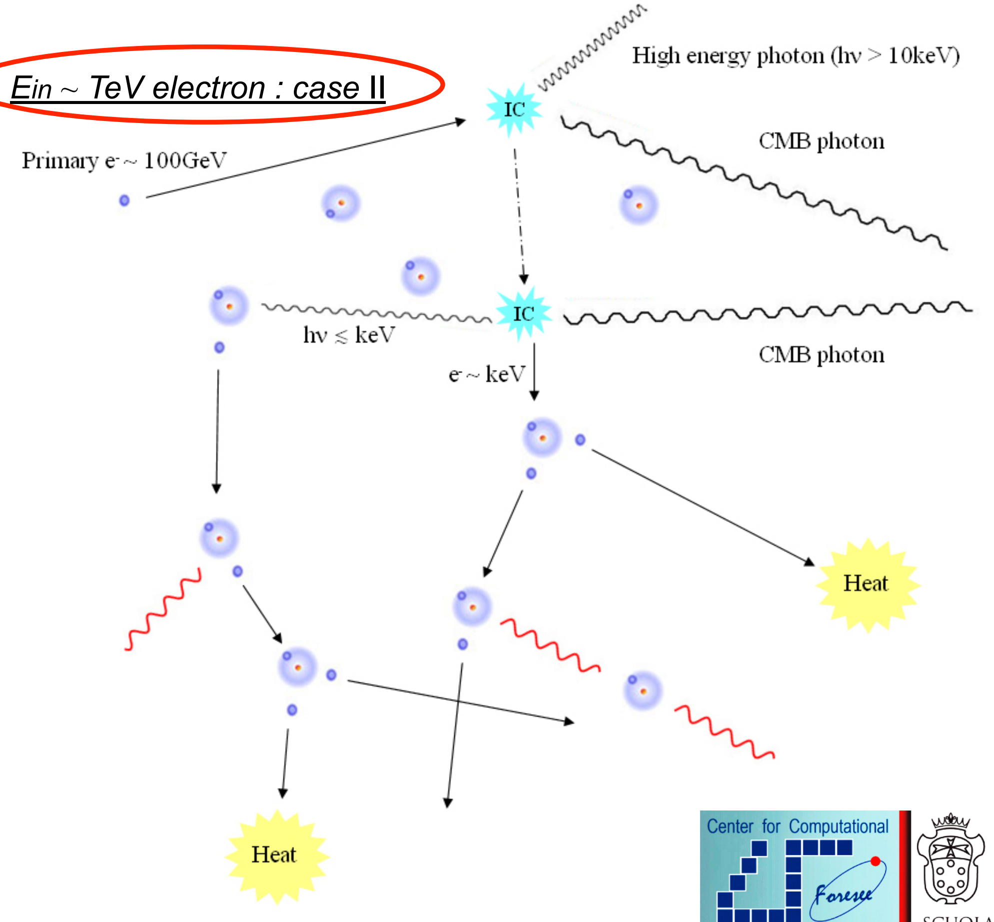
* 10.2 eV and 10keV for photons

* 10.2 eV for electrons – heat the gas

Ein ~ keV electron : case I



Ein ~ TeV electron : case II



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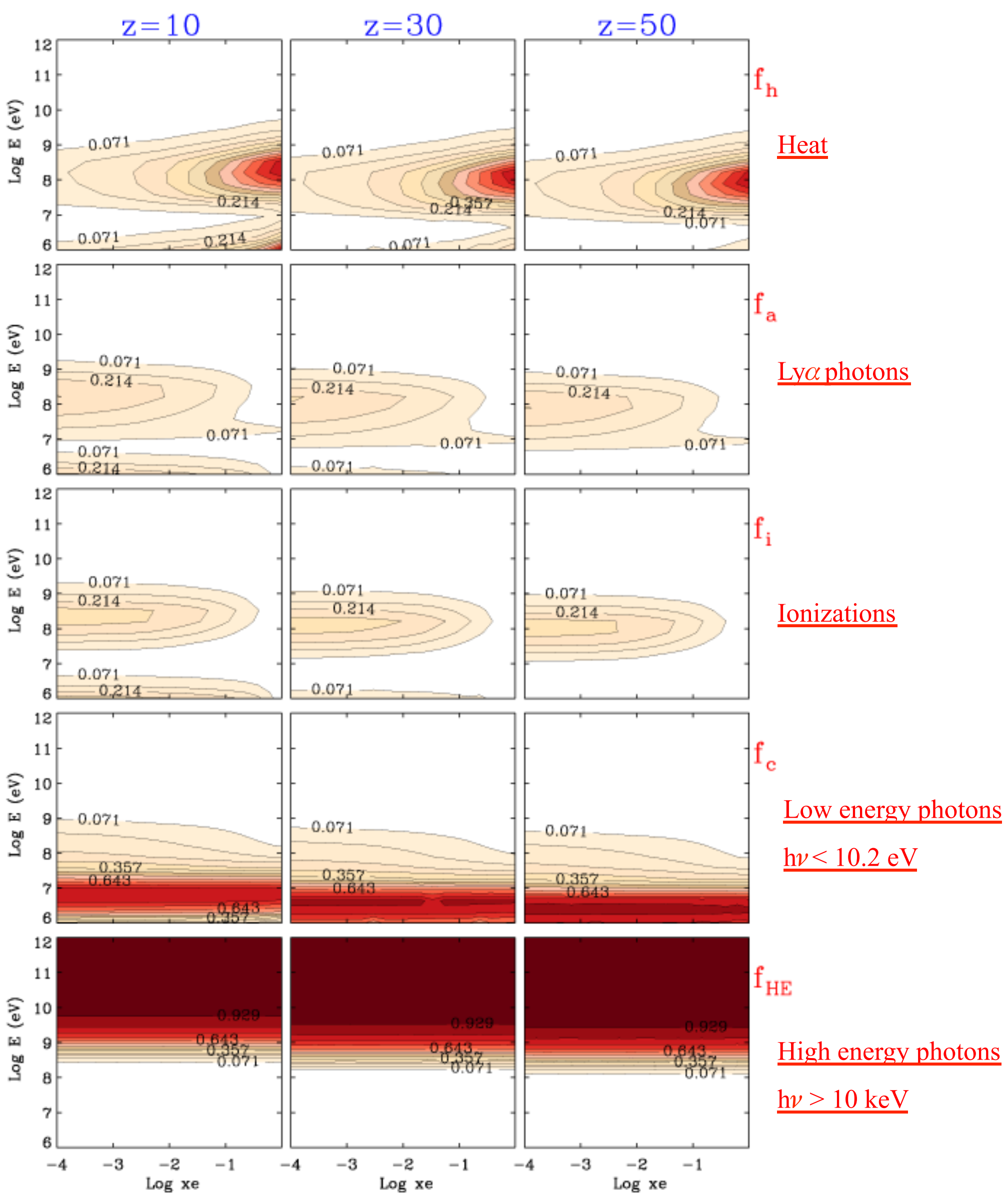
MEDEA I results



Energy depositions isocontours

- f_h heating grows with x_e
- f_i , f_a , f_h present a "double peak", with very low values for 10 MeV… f_c absorbs ~ 80% of the energy!
- f_{HE}, f_c independent from x_e vary slow with z
- f_{HE} dominant over 1 GeV

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MEDEA II (Evoli, Valdes, Ferrara, Yoshida 2011)

Input	MEDEA1	MEDEA2
Primary e^-	√	√
Primary e^+	×	√
Primary γ	×	√
Single particle	√	√
Particle distribution	×	√
Energy range	1 MeV $< E_{\rm in} <$ 1 TeV	1 MeV $< E_{\rm in} <$ 1 TeV
Redshift range	$10 < z < 50$	$10 < z < 1000$

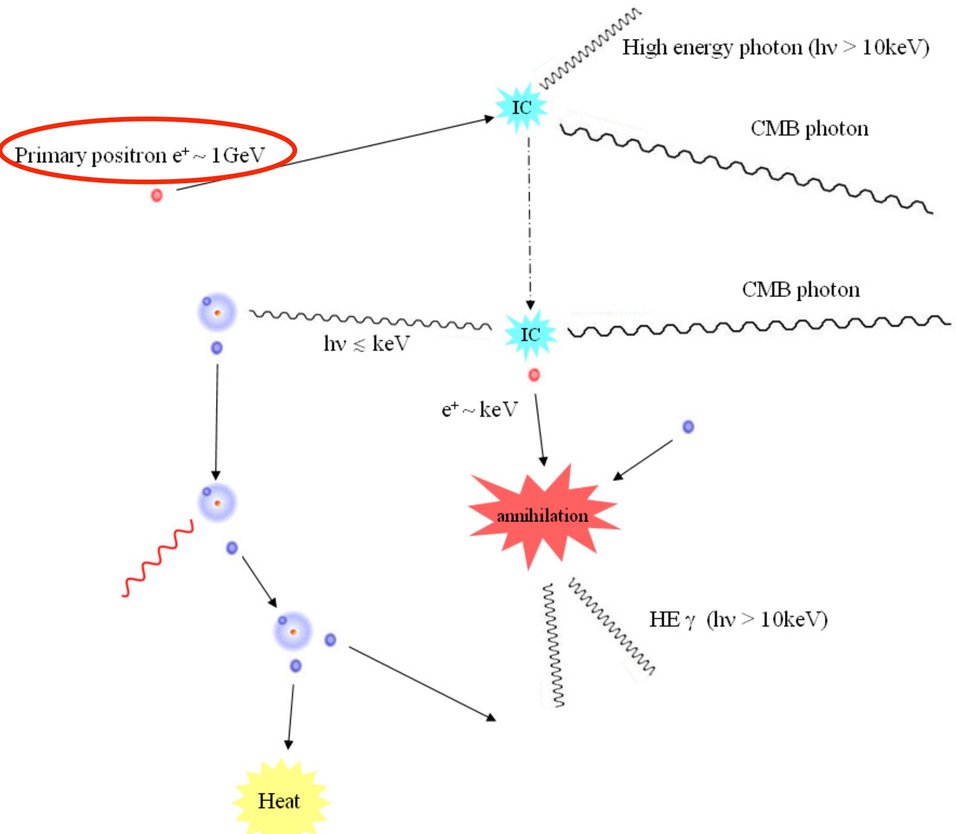
MEDEA2 is an extension of the code to follow a distribution of electrons, positrons and photons rather than a single primary electron → more applications.

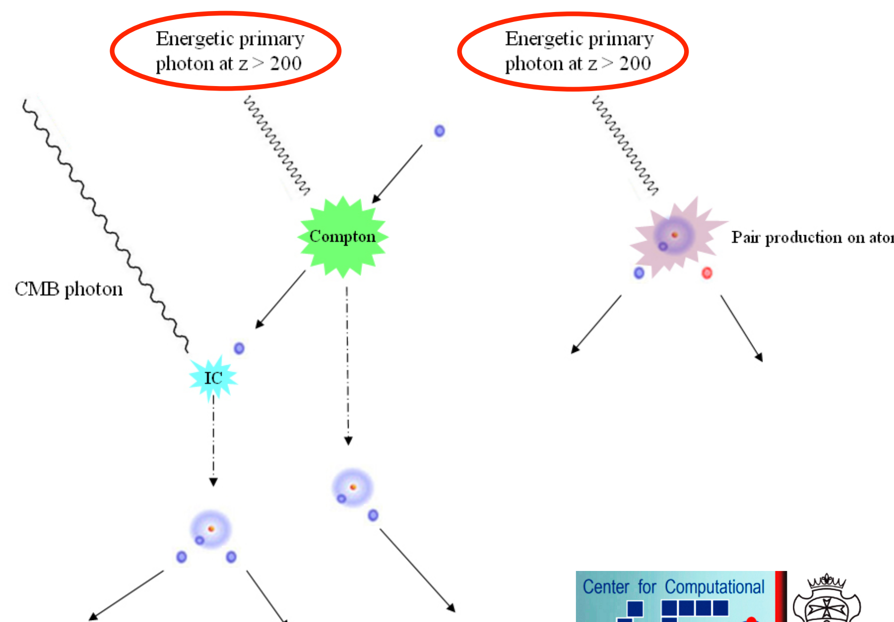
Additional processes implemented in the code:

**Compton*

**Pair production on atoms and photons*

**Positron-electron annihilations*





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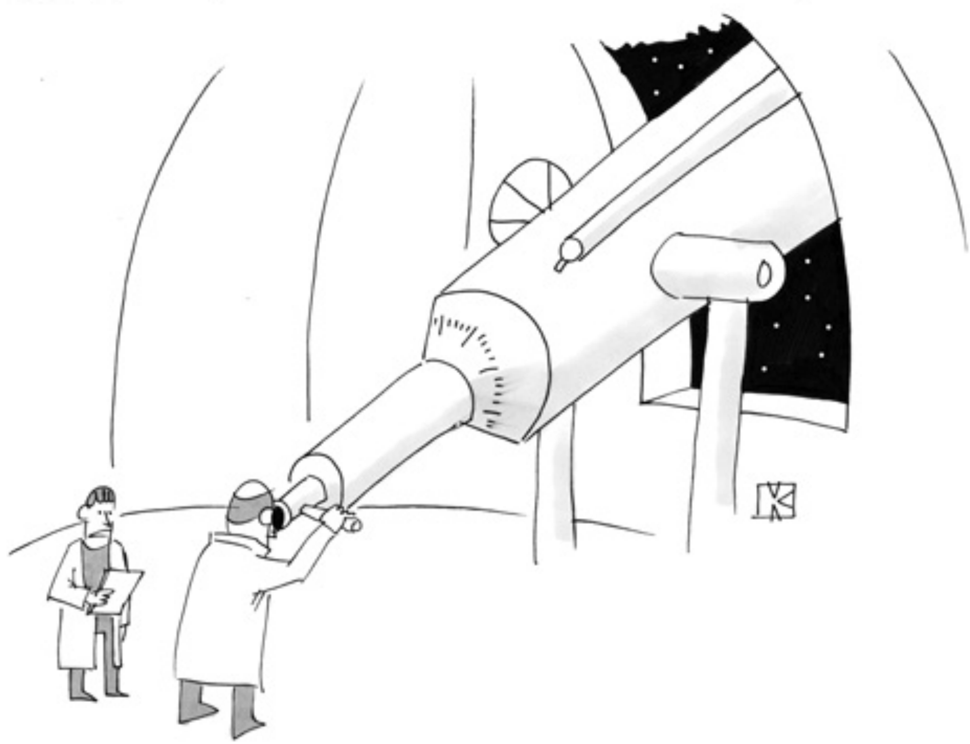
Considered DM candidates

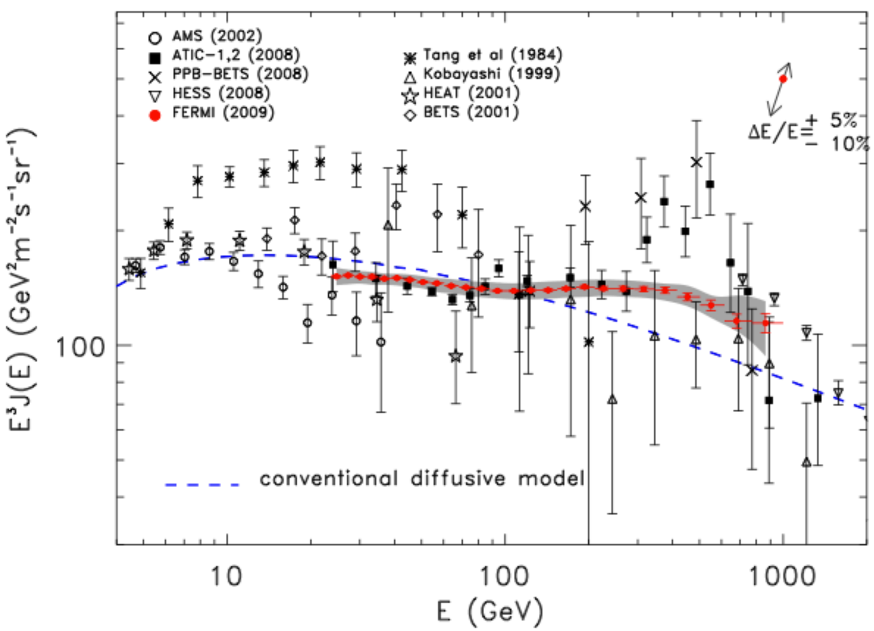


“That isn’t dark matter, sir—you just forgot to take off the lens cap.”

Heavy annihilating DM candidates

A number of recent observations has put stringent contrains on the nature of DM:

- WIMPs hav ion with ordinary matter and t via elastic collision with the nuc Nal, CDMS-II, EDELWEIS
- Pamela show ground generated by interactions in the energy range between 10
- ATIC report 300 - 800 GeV.
- The later obs scenario again, not confirming t ificantly harder than previously b



→ General consensus that a WIMP with mass 10 GeV < m_{DM} < 1 TeV that annihilates dominantly in leptonic channels is the strongest DM candidate

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Heavy annihilating DM candidates

- We study three promising DM candidates:

  - (i) a 10 GeV bino-like neutralino with a soft energy injection spectrum;
  - (ii) a heavy 1 TeV DM candidate that annihilates into muons and gives a hard energy spectrum in agreement with Pamela and Fermi-LAT;
  - (iii) an intermediate mass 200 GeV wino-like neutralino with a pair-annihilation into W^+W^- pairs.

* The distribution of photons, electrons and positrons generated by a DM pair annihilation event depends on the annihilation channel, cross section and on the particle mass.

* *To be consistent we couple our code MEDEA2 to DarkSusy, a package for supersymmetric DM calculations which gives the input spectral energy distribution of eletrons positrons and photons for the DM candidate of choice*

Dark Susy

Dark SUSY

Overview

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Documentation

Logos

DarkSUSY online

Internal pages (password restricted)

DarkSUSY Home Page

Welcome to DarkSUSY's home on the web!

DarkSUSY is a fortran package for supersymmetric dark matter calculations. It is written by Paolo Gondolo, Joakim Edsjö, Lars Bergström, Piero Ullio, Mia Schelke, Ted Baltz, Torsten Bringmann and Gintaras Duda. On these pages you will find information about DarkSUSY and you can also download the package.

If you use DarkSUSY, please refer to the following publication describing DarkSUSY:

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke and E.A. Baltz,**
> **JCAP 07 (2004) 008** [astro-ph/0406204]

Please also cite this web page as

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann and G. Duda, http://www.darksusy.org.**

Note. You should also refer to the original physics work on which DarkSUSY is based and which DarkSUSY uses. Most notably, DarkSUSY is interfaced (and uses) the following codes:

- FeynHiggs - for Higgs masses and widths
- HiggsBounds - for Higgs boson constraints from accelerators
- ISAJET/ISASUGRA -for mSUGRA/CMSSM RGE running
- SLHALIB - for reading/writing SLHA2 files

and can (for the experienced user) be configured to run with

- Galprop - for cosmic ray propagation (not used by default).

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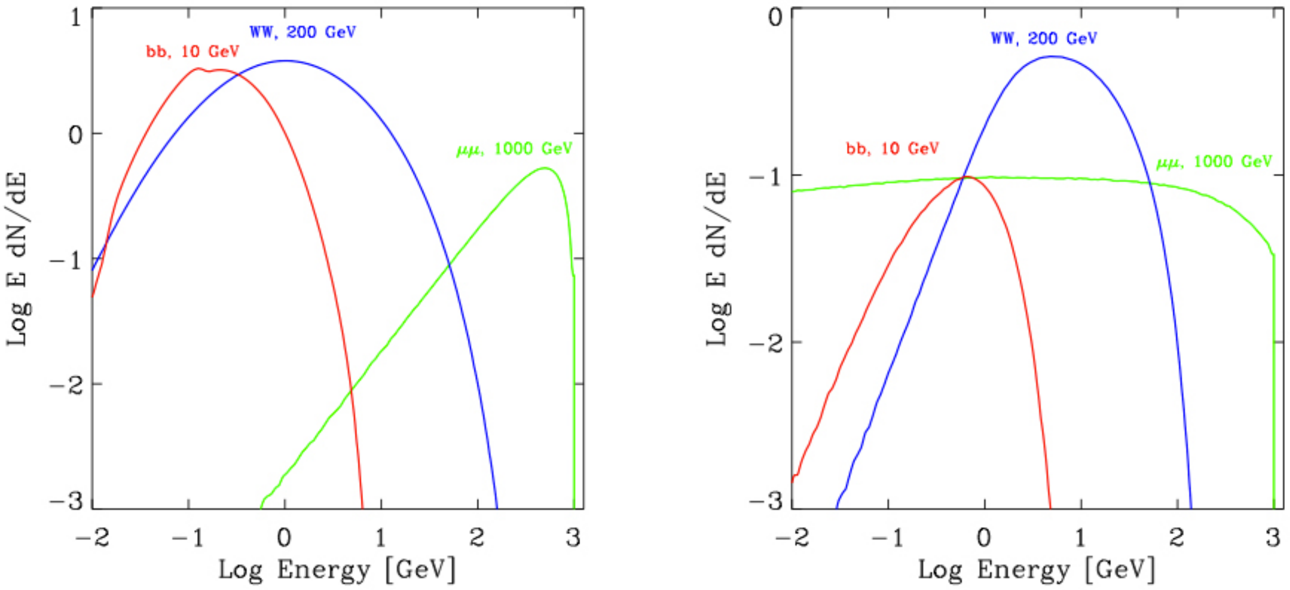
Input spectra



DM annihilation spectra for electrons+positrons (*left panel*) and photons (*right panel*).

Evoli, Valdés, Ferrara, Yoshida 2012

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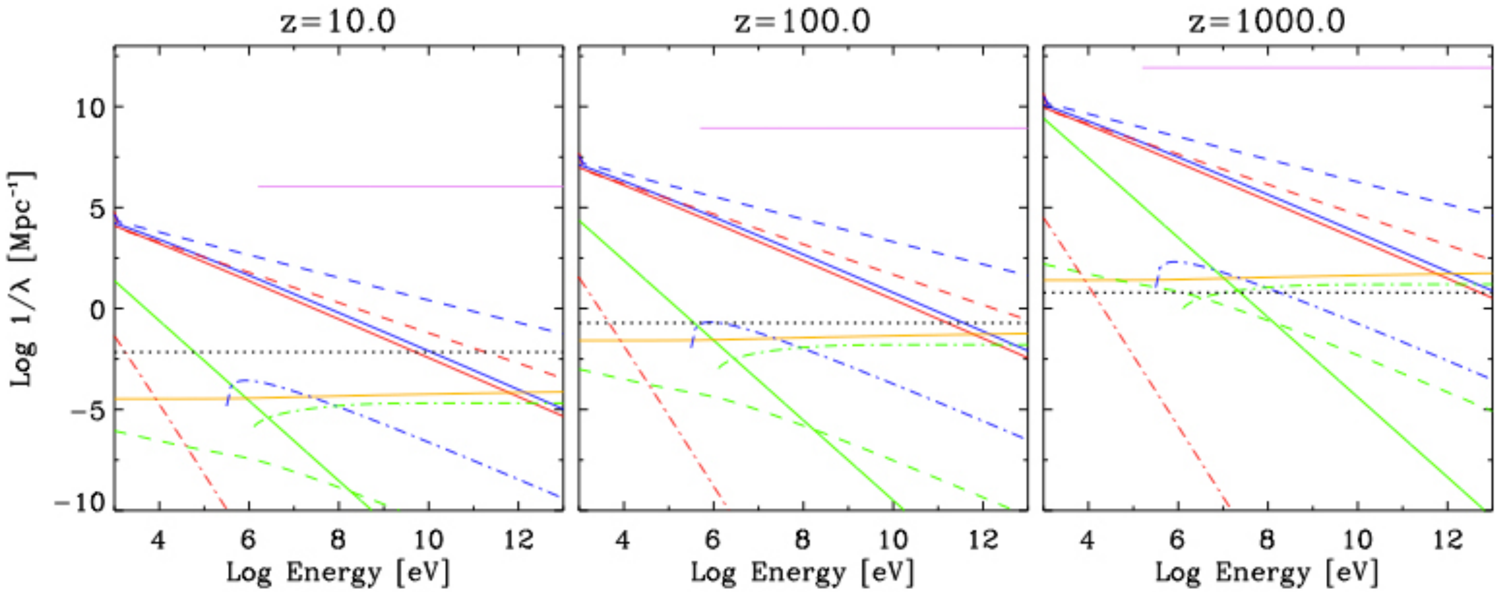
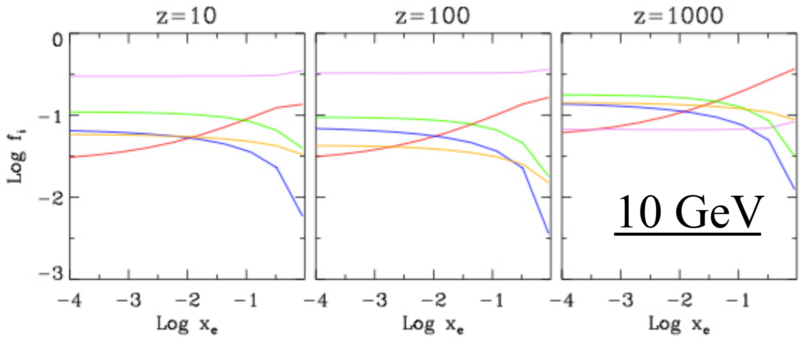
Mean free paths

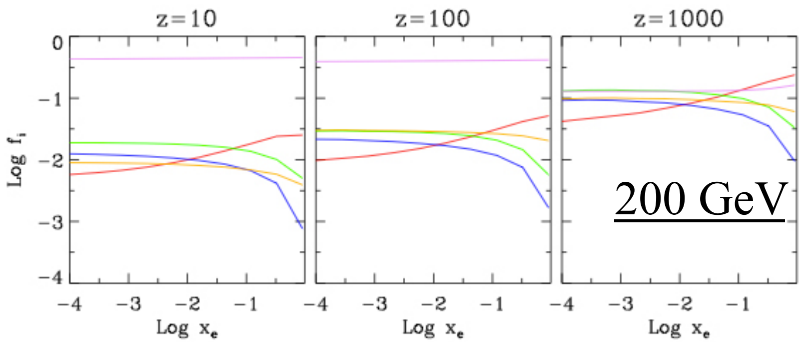


The inverse of the mean free paths of electrons, positrons and photons in the IGM. Electron interactions (solid): ionizations (red), excitations (blue), ee (green), Bremsstralungh (orange), IC (violet). Positron interactions (dashed): ionizations (red), excitations (blue), annihilations (green). Photon interactions (dot-dashed): photo-ionization (red), Compton (blue), pair-production (green). The dotted-black line shows the inverse of the Hubble radius at the considered redshift.

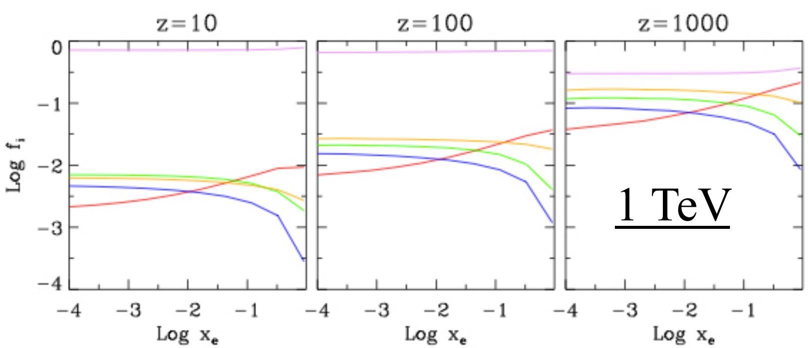
Evoli, Valdés, Ferrara, Yoshida 2012



Fractional depositions from DM annihilation of a 10 GeV $b\bar{b}$ DM candidate. Line colors as in Fig. 4.

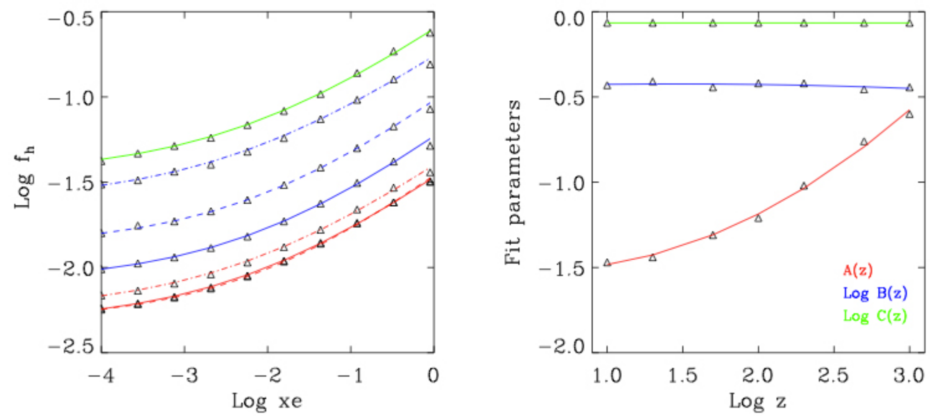


Fractional deposition from DM annihilation of a 200 GeV W^+W^- DM candidate.



Fractional deposition from DM annihilation of a 1 TeV $\mu^+\mu^-$ DM candidate.

Evoli, Valdés, Ferrara, Yoshida 2012



The functional parameters fitting for $f_h(x_e, z)$ in the considered case of W^+W^- DM candidate.

$$
\begin{aligned}
f_h(x_e, z) &= 10^{A(z)} * (1 - C(z) * (1 - x_e^{B(z)})) \\
f_a(x_e, z) &= 10^{A(z)} * (1 - x^{B(z)})^{C(z)} \\
f_{ion,H}(x_e, z) &= 10^{A(z)} * (1 - x^{B(z)})^{C(z)} \\
f_{ion,He}(x_e, z) &= 10^{A(z)} * (1 - x^{B(z)})^{C(z)}
\end{aligned}
$$

$$
\begin{aligned}
A(z) &= A_0 + A_1 * \log z + A_2 * (\log z)^2 \\
B(z) &= B_0 + B_1 * \log z + B_2 * (\log z)^2 \\
C(z) &= C_0 + C_1 * \log z + C_2 * (\log z)^2
\end{aligned}
$$

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2. How does DM affect the high-z IGM?

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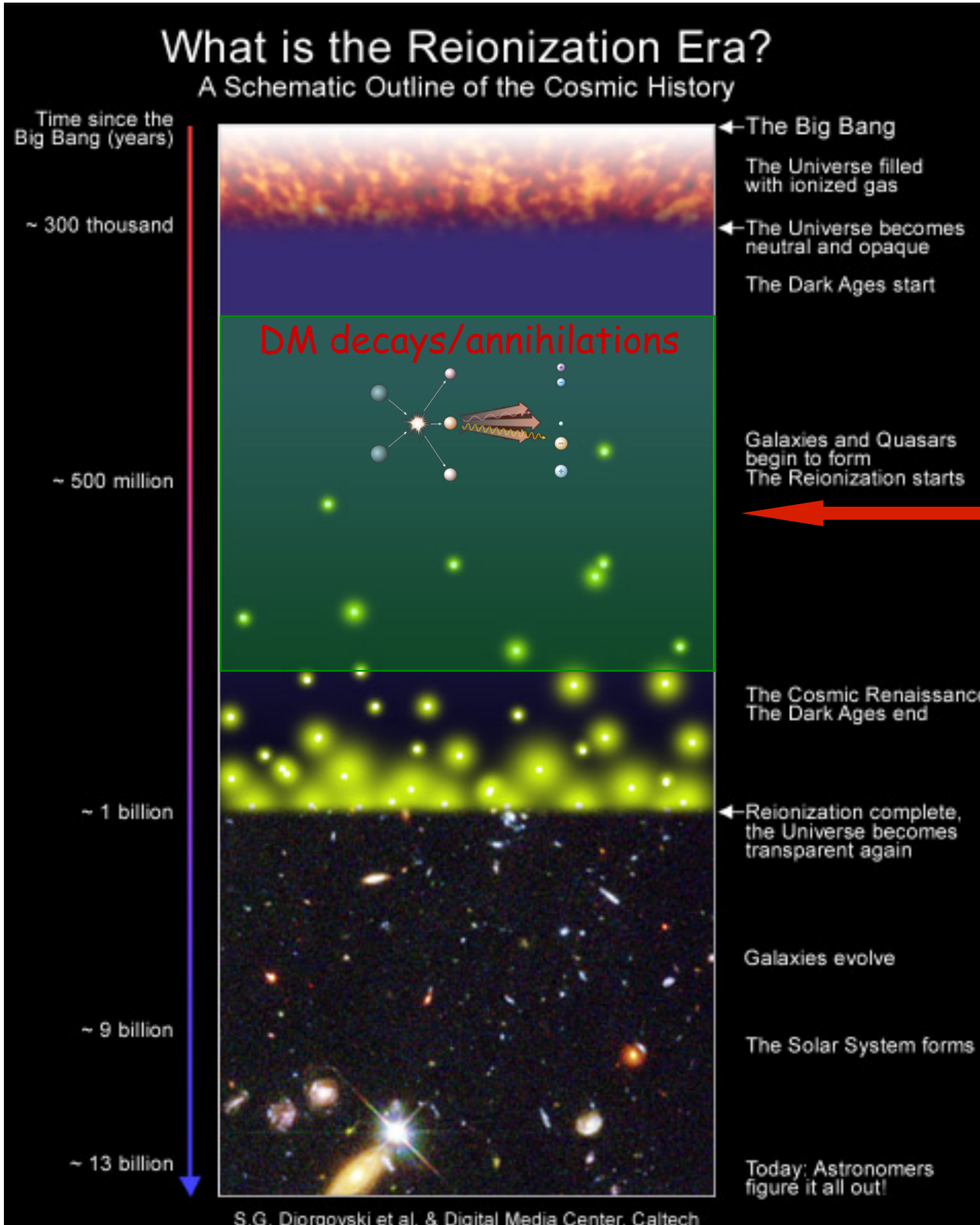

Dark Ages

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Smoking gun

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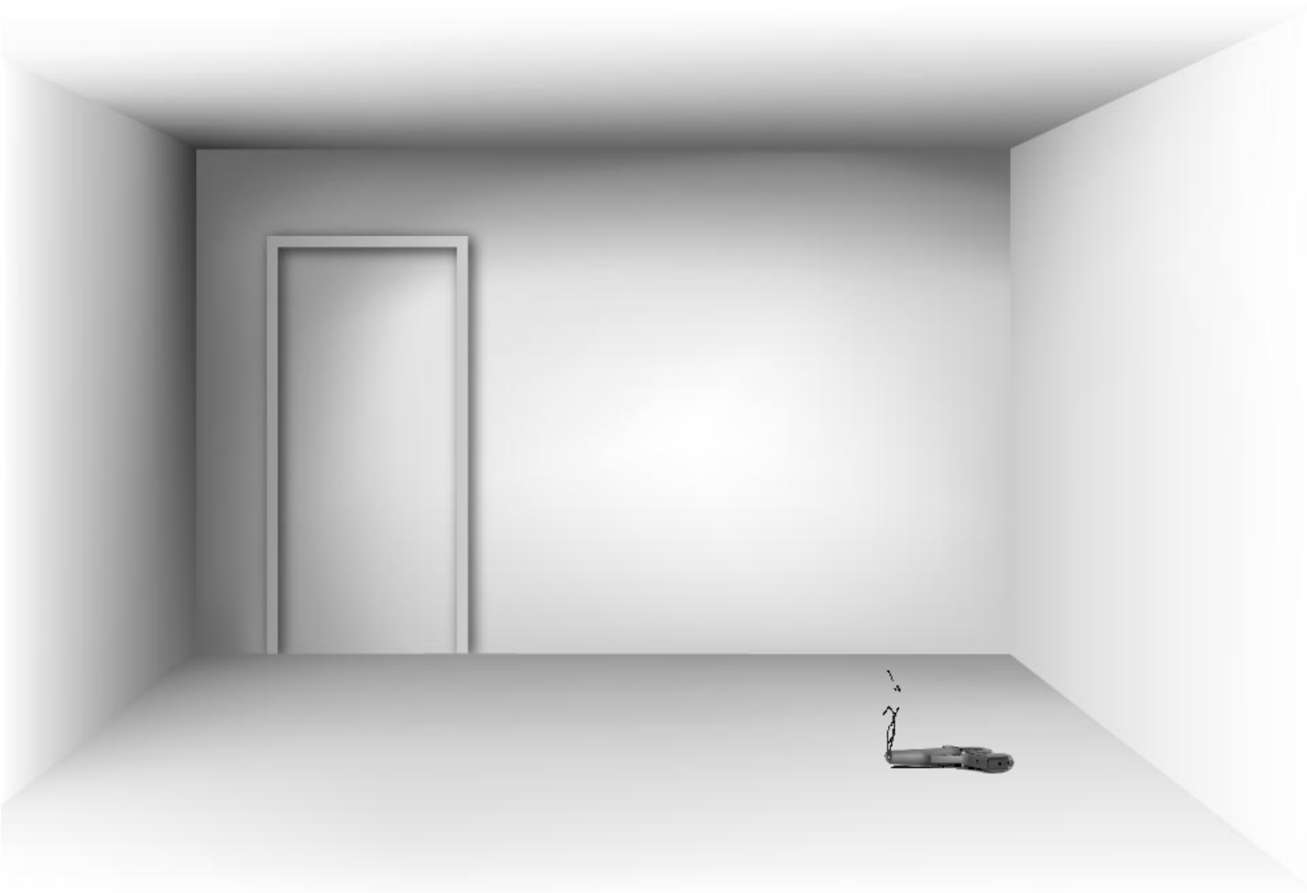
Smoking gun



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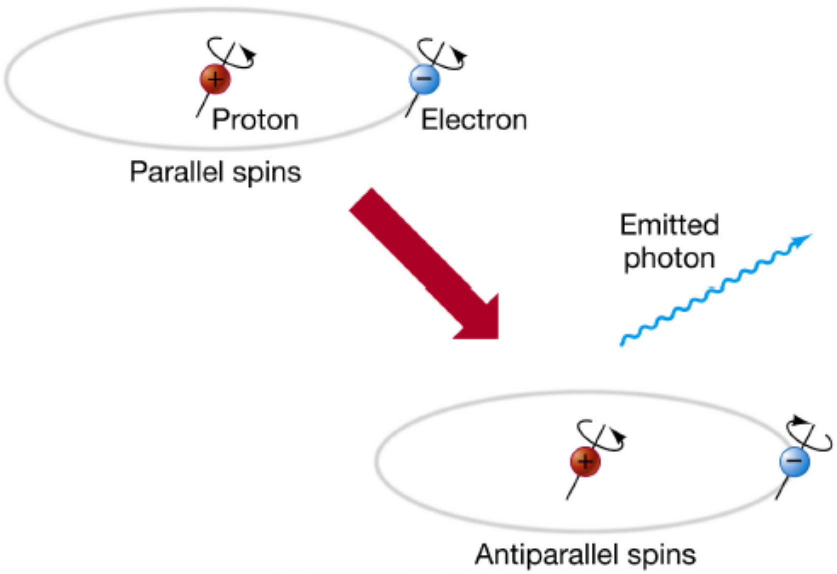
HI 21 *cm hyperfine transition*



$n_0 = 1420.405751$ MHz
$A_{10} = 2.85 \times 10^{-15}\ s^{-1}$

- Visualization of the two energy states of the ground level of neutral hydrogen, in which the electron has its spin either parallel or anti-parallel to that of the proton.
- The parallel state has an energy higher by ~ 5.9×10^{-6} eV, so a transition to the anti-parallel state results in the emission of a HI 21 cm photon

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HI 21 *cm line*

HI 21 cm tomography: a powerful tool for future observations

Emission/absorption of 21cm photons governed by the HI spin temperature T_s

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

CMB radiation forces $T_s \sim T_{CMB}$ on a short timescale ($\sim 10^4$ yr).

HI will not emit nor absorb

Two mechanisms can decouple T_s from T_{CMB} :

- Collisions (effective at z > 70 due to the higher mean gas density)
- Scattering by Lyα photons , Wouthuysen-Field (WF) process

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

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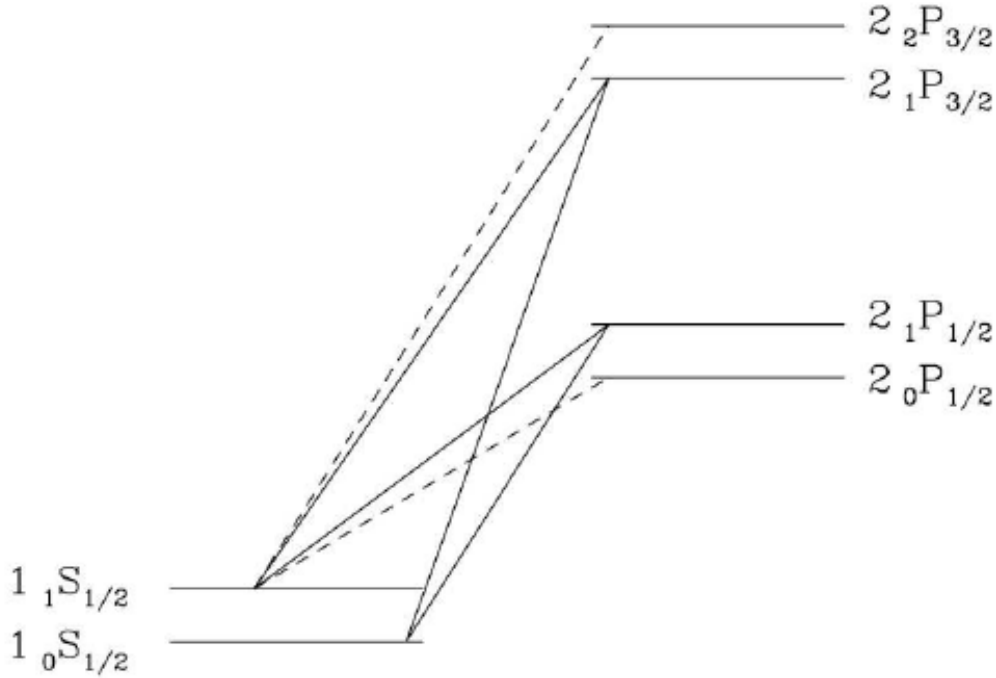
HI 21 *cm line – WF process*

F = total angular momentum of the atom

$\Delta F = 0, \pm 1 \setminus 0 \rightarrow 0$ (electric dipole selection rules)

An H atom in the singlet ground level that absorbs a Lyα photon and jumps to the 2p state is allowed to re-emit the Lyα photon and end up in the triplet ground level



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HI 21 *cm line* – δT_b

$$y_\alpha = \frac{P_{10} T_*}{A_{10} T_k}$$

$$y_c = \frac{C_{10} T_*}{A_{10} T_k}$$

- A_{10} : spontaneous decay rate of the hyperfine transition of hydrogen
- P_{10} : indirect de-excitation rate of the triplet via absorption of a Lyα photon = 4/27 the rate at which Lyα photons are scattered by HI
- C_{10} : collisional de-excitation rate

Once T_s has been determined we can obtain the 21 cm radiation intensity which can be expressed by the differential brightness temperature between a neutral hydrogen patch and the CMB:

$$\delta T_b \simeq \frac{T_S - T_{CMB}}{1+z}\tau$$

$$\tau \simeq \frac{3c^3 h_p A_{10}}{32\pi k_B \nu_0{}^2 T_S H(z)} \mathcal{N}_{\rm HI}$$

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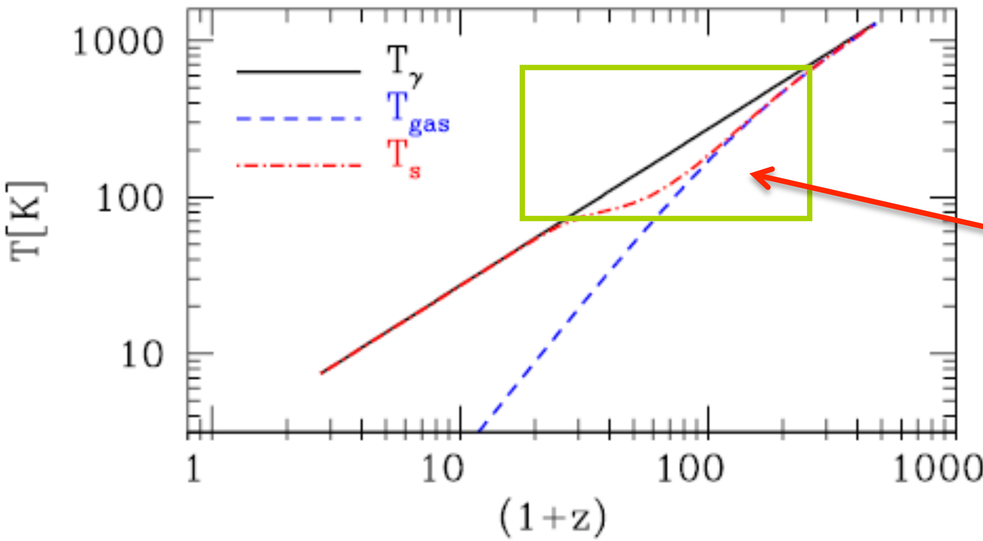
"Standard" T_S history



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

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

$$\delta T_b \simeq \frac{T_S - T_{CMB}}{1+z}\tau$$

$$\tau \simeq \frac{3c^3 h_p A_{10}}{32\pi k_B \nu_0{}^2 T_S H(z)} \mathcal{N}_{\rm HI}$$

- Both T_s and T_k track T_{CMB} down to z ~ 300
- Collisions are efficient at coupling T_s and T_k down to z ~ 70
- At z < 70 radiative coupling to the CMB becomes dominant and T_s tracks T_{CMB}
- The predicted 21cm absorption feature at the redshift window at 20 < z < 300 could be modified by decaying/annihilating DM

DM energy input

The rate of energy transfer per baryon to the IGM is:

overdensities!

$$\dot{E}_x(z) = f_{abs}(z)\,\dot{n}_{\rm DM}(z)\, m_{\rm DM}\, c^2 (1 + B(z))$$

The decrease rate of the number of DM particles per baryon for annihilations is:

$$\dot{n}_{\rm DM}(z) \simeq \frac{1}{2}\, n^2_{\rm DM,0}\, \mathcal{N}_{\rm b}(0)\, \langle \sigma\, v \rangle (1+z)^3$$

- **Those that we studied with MEDEA2 → we have precise energy depositions**!

- (i) a 10 GeV bino-like neutralino with a soft energy injection spectrum;
- (ii) a heavy 1 TeV DM candidate that annihilates into muons and gives a hard energy spectrum in agreement with Pamela and Fermi-LAT;
- (iii) an intermediate mass 200 GeV wino-like neutralino with a pair-annihilation into W^+W^- pairs.

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IGM evolution

DM decays/annihilations affect the thermal and ionization history of the IGM

- We solve diff. eqs. describing redshift evolution of x_e, T_k, J_a
- Compute new values of δT_b

$$-\frac{dx_e}{dz} = \frac{1}{H(z)(1+z)}[R_s(z) - I_s(z) - I_x(z)]$$ ← *ionization*

$$(1+z)\frac{dT_k}{dz} = 2T_k + \frac{l_\gamma x_e}{H(z)(1+f_{He}+x_e)}(T_k - T_{CMB})$$ ← *gas temperature*

$$-\frac{2\chi_h \dot{E}_x}{3k_b H(z)(1+f_{He}+x_e)}$$

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

$$\rightarrow T_S \rightarrow \delta T_b$$

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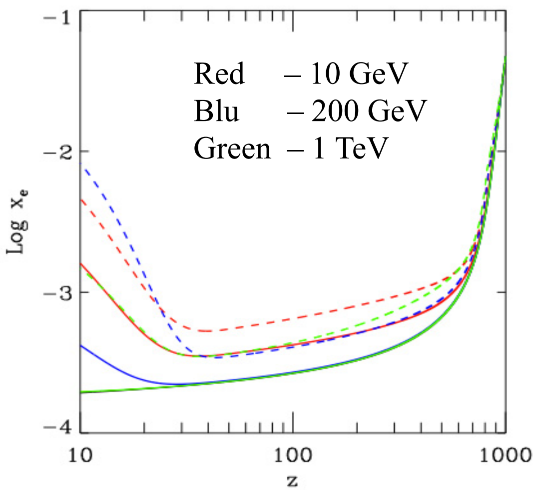
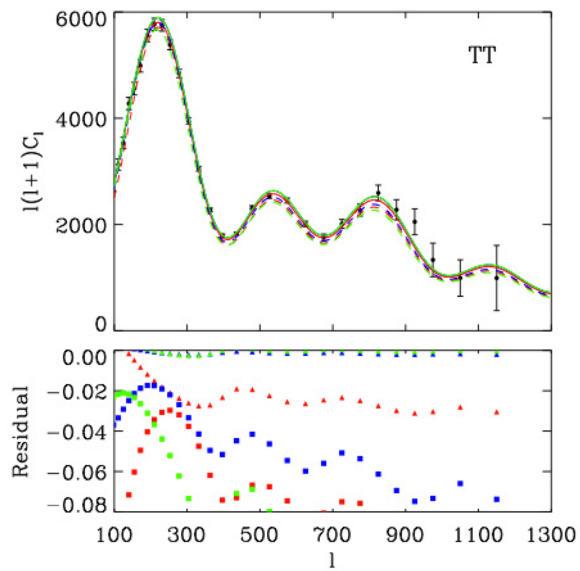
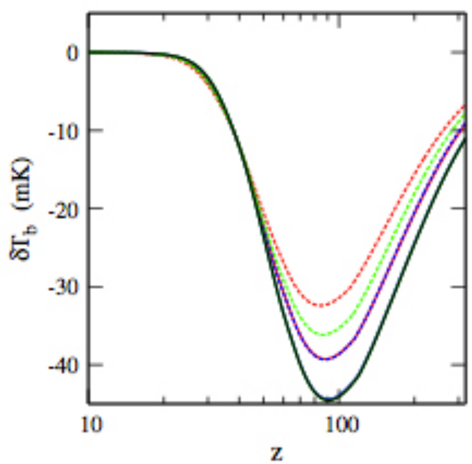
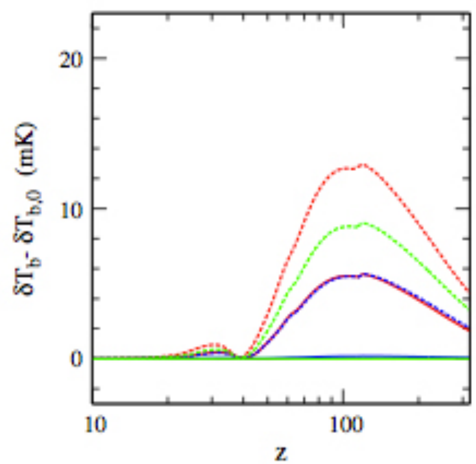
DM constrains from CMB









- Ionizations from DM increase the integrated Thomson optical depth and affect the CMB power spectra.
- We use CAMB (Code for Anisotropies in the Microwave Background – Lewis & Challinor)
  → Temperature-temperature (TT) and temperature-polarization (TE) CMB power spectra and τ calculation
- *We can verify that results are consistent with WMAP7 and put limits on the annihilation cross section.*

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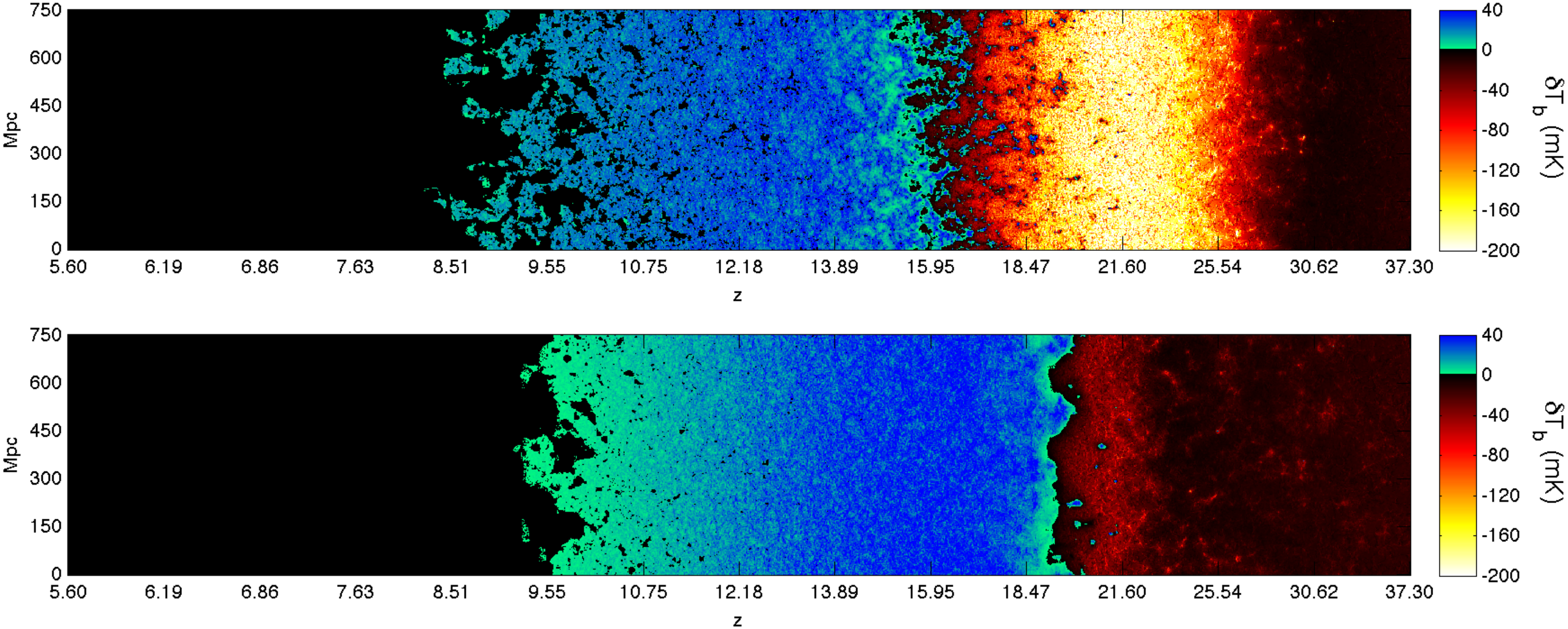
21cmFAST prescription for sources

Fiducial model (1 X-ray photon per stellar baryon)



Extreme model (2000 times more X-rays)

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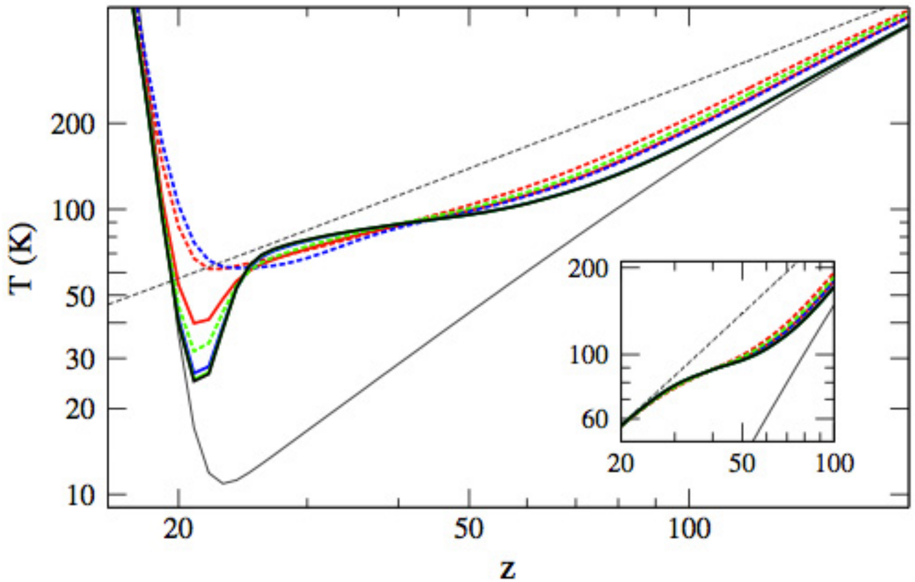
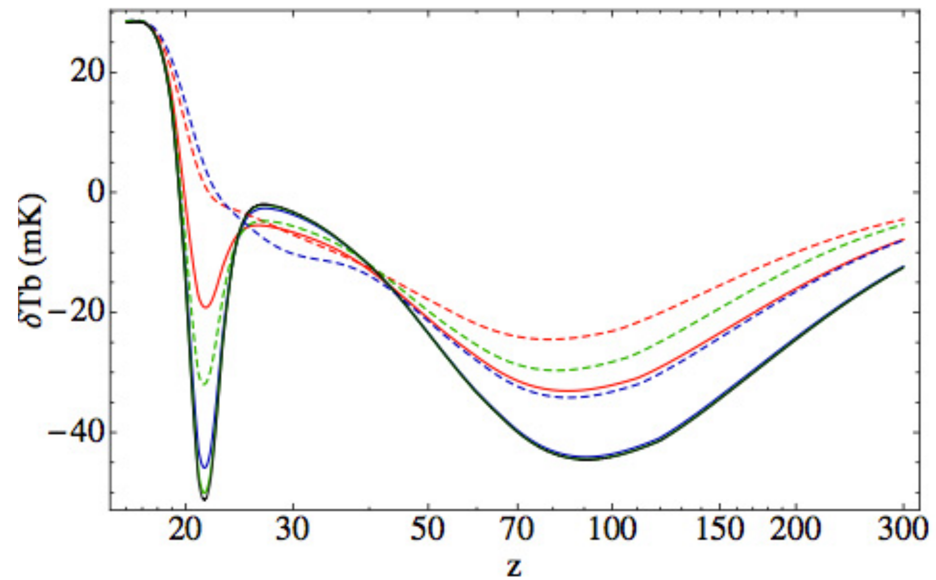
HI 21 cm results

Extreme model





Valdés, Evoli, Mesinger, Ferrara, in prep

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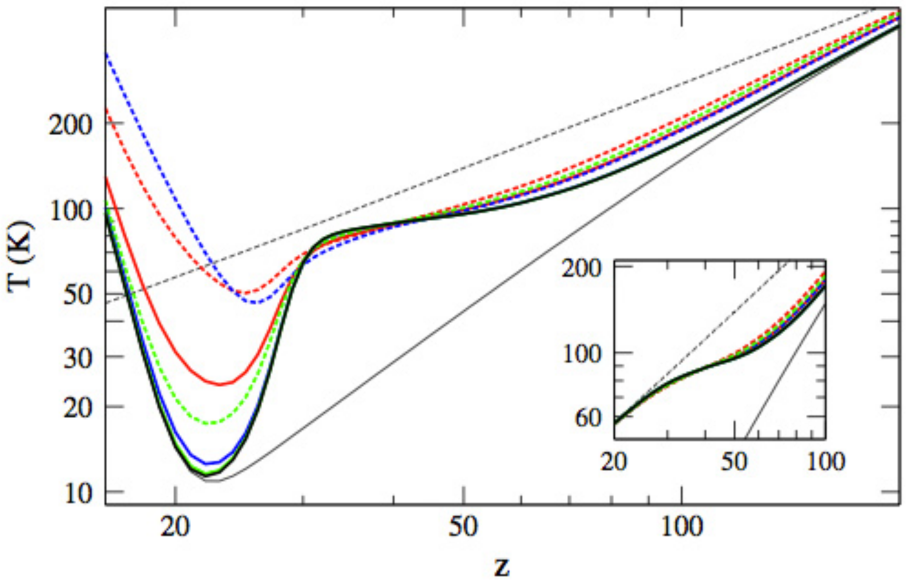
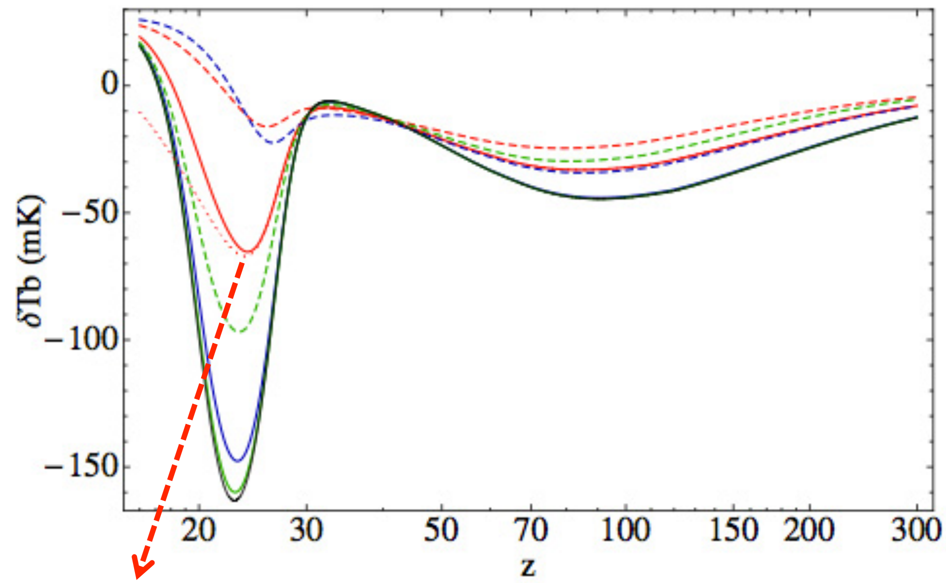
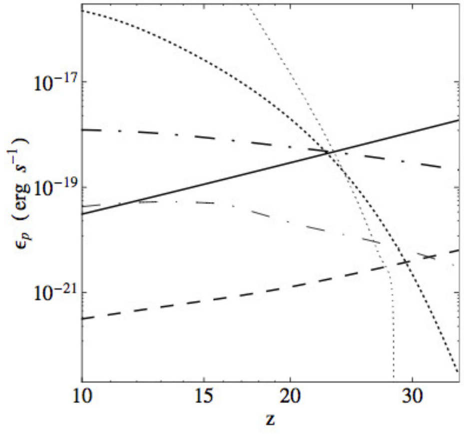
HI 21 cm results

Fiducial model

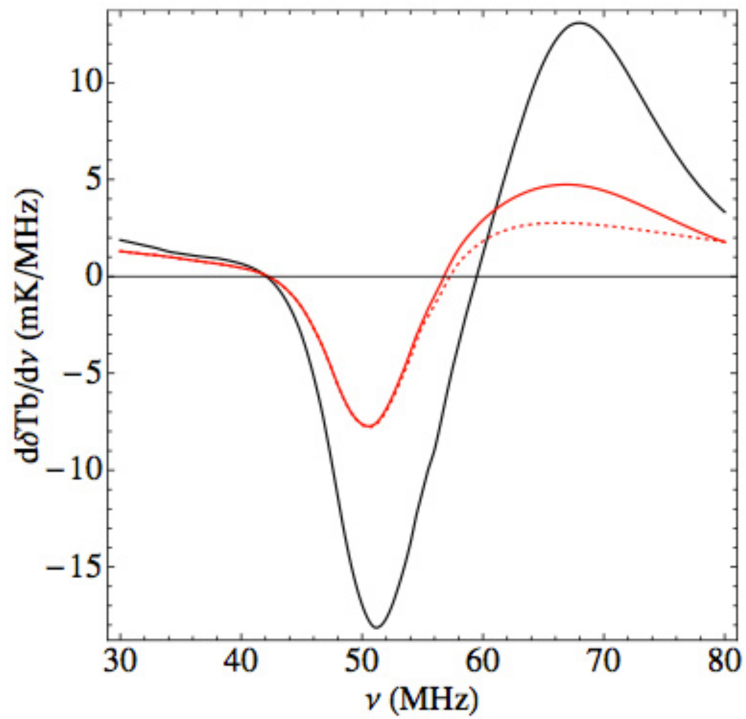






Valdés, Evoli, Mesinger, Ferrara, in prep

DM signal gradient



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Requirements for succesful high-z HI 21 cm detection:

1. A low frequency interferometer ($\nu \sim 10 - 240$ MHz)
2. An exceptional sensitivity ($\delta T_b \sim$ mK on arcmin scales)
3. Big part of the effective aperture has to be on "short" distances (~ Km)

Technical challenges:

1. Radio interference (VHF band is "crowded")
2. High dinamic range (removal of brightest sources)
3. Foregrounds
4. Ionosphere variations
5. Enormous data flows (25 Tb/s)

21CMA, GMRT, LOFAR, MWA, SKA

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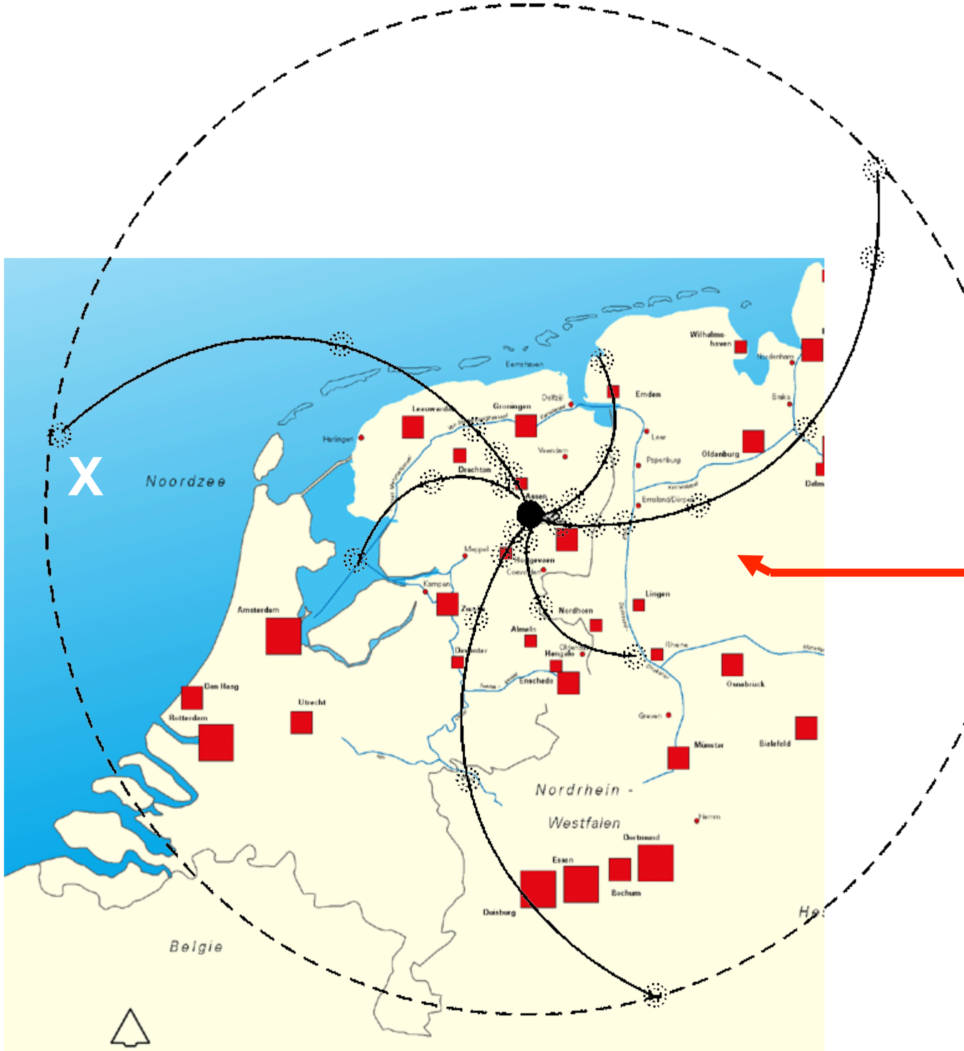
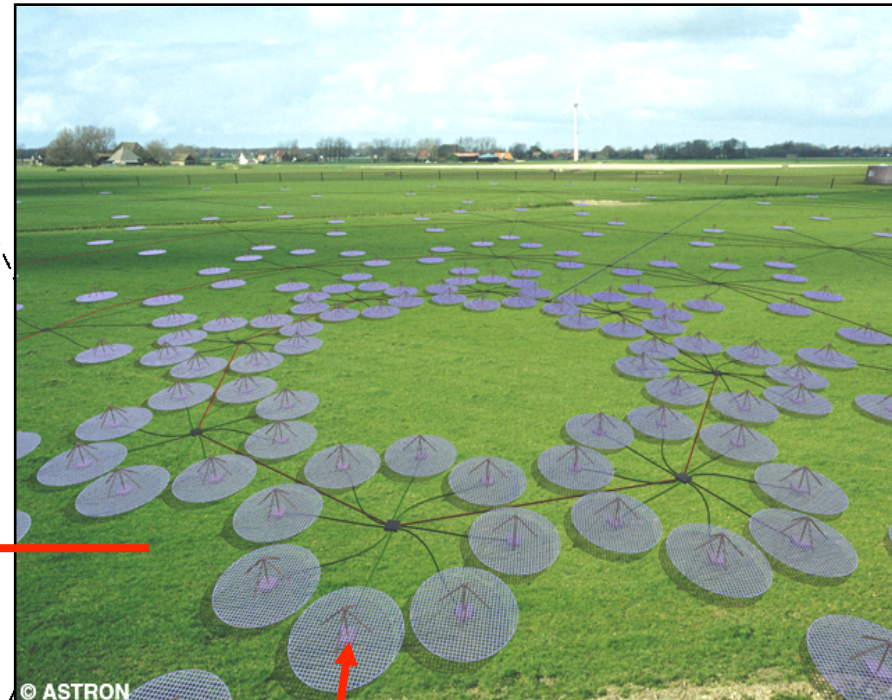
LOFAR Radio Telescope



25% of antennas in central core



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Summary

Obs. constrains

→ DM_0

+DarkSUSY

+MEDEA2

$f_i\ (x_e,z)$

+ CAMB

DM_1

+21cmFAST recipe

+ Our 21cm code

δT_b

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Conclusion

1. MEDEA2 a strong tool for DM studies

2. HI 21 cm line a probe of DM

3. Including galaxies actually *increases* the DM signal

4. A plateau in the signal gradient at frequencies $\nu \sim 60-80$ MHz would be a clear indicator of a phase in which the IGM is heated mainly by DM annihilations.

5. Some degeneracy but ways to avoid it.

6. Next few years will be crucial for observations

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