The high-z interplay between annihilating DM and the IGM

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ACP Seminar, IPMU, University of Tokyo,
Kashiwanoha, Japan, June 16th 2011

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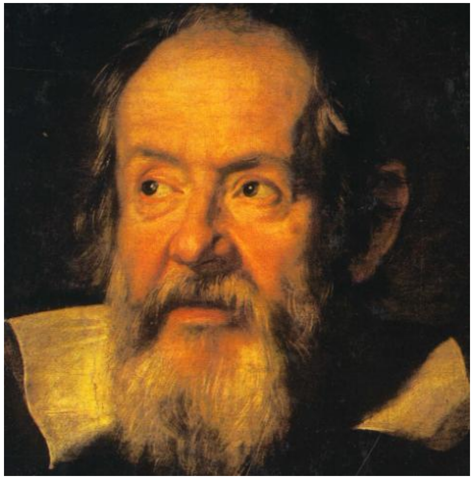

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DAVID

The Dark Ages VIrtual Department

http://www.arcetri.astro.it/twiki/bin/view/DAVID/WebHome

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Outline:

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

- MEDEA, past achievements, improvements, prospects
- Future work and conclusions

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

- HI 21 cm line, CMB
- DM trace on the high-z HI 21 cm background

3. How do overdensities enhance the 21 cm signal?

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

a keV electron

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Secondary energy cascade − I

- Complex issue, interest in a precise calculation
- Monte Carlo code to follow in detail the secondary processes arising from an energetic primary electron or photon; 1000 realizations.
- Previous results by Shull 1979, Shull & van Steenberg 1985 (S79 and SVS85)

Improvements

↓

- More precise cross sections now available
- Important processes need to be included
- Following individual photons is essential

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Secondary energy cascade – II

Assumption: the keV photon ionizes an atom ⟶ *primary electron*

Once the primary electron is injected into the IGM the code calculates the cross sections relative to a list of possible processes:

(I) H, He, HeI ionization ⟶ *two electrons*

↓

followed separately as they interact further with the gas.

Assumption: electrons with energy $T < 10.2$ eV are deposited as heat. Requires assumption that $T_K < 10^4$ K or electrons with $T < 1$ eV could even cool the gas.

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Secondary energy cascade – III

(II) H, He excitation
(III) Collisions with thermal electrons
(IV) Free-free interactions ionized atoms
(V) Recombinations

→ Ensemble of secondary photons:
(i) have h■ < 10.2 eV and escape freely in the IGM
(ii) interact further with the gas

SVS85 derive the amount of energy which is deposited in excitations but does not give details about the individual photons.

↓

We precisely estimate the amount of energy going into Lyα photons.

(i) Lyα photons affect 21 cm signal by WF effect.

(ii) Lyα photons by scattering resonantly off HI cool or heat the gas, depending on whether they enter the resonance from its red (*injected*) or blue wing (*continuum*) respectively

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Secondary energy cascade – IV

Additional feature of our model with respect to SVS85: inclusion of two-photon forbidden transition $2s \rightarrow 1s$

• direct: collisional excitation cross section to the $2s$ level
• indirect: collisional excitation to a level $n \geq 3$ can results in a cascade through the $2s$ level rather than through $2p$ - most probable decay channel (Hirata 2005, Chuzhoy & Shapiro 2007)

Emission of two photons below the Lyα energy that do not further interact with the gas.

• We separate *injected* Lyα photons from those with lower energy.
• The calculations include processes that can produce continuum photons, such as recombinations and Bremsstrahlung free-free interactions of electrons with ionized atoms $\longrightarrow$ negligible.

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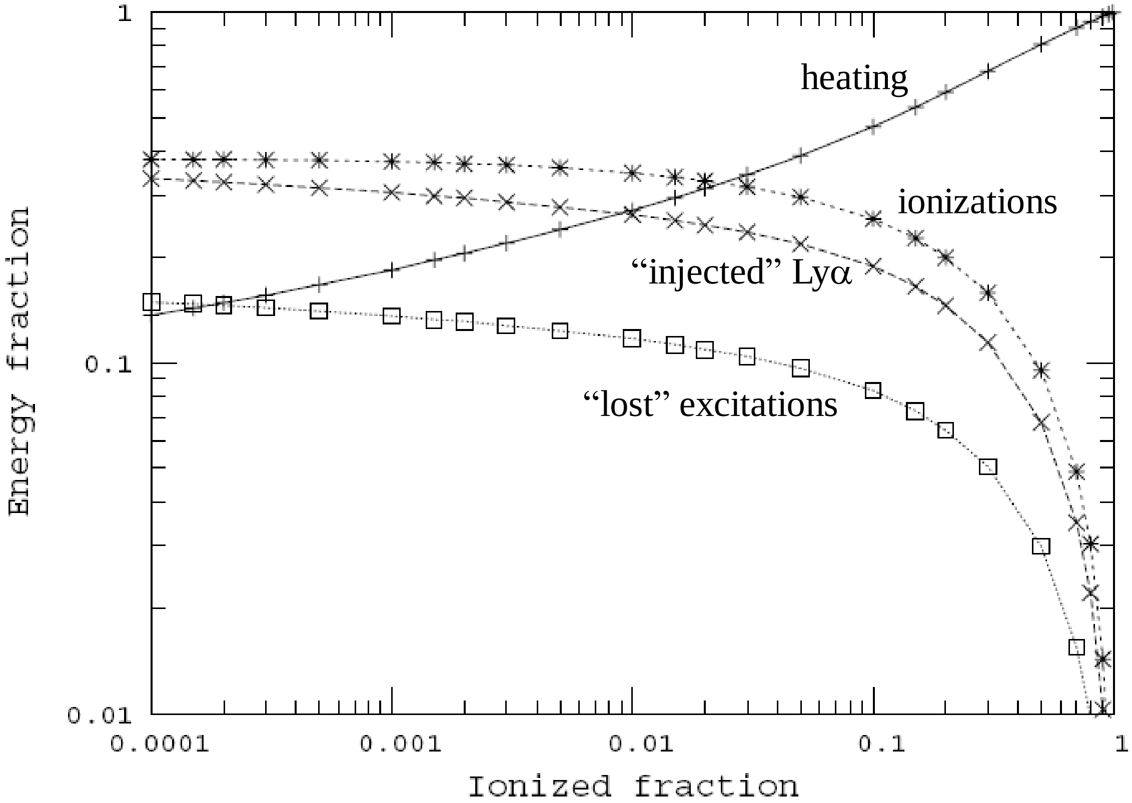
Results – I



$$f_h = 1.0 - 0.8751\,(\,1.0 - x^{0.4052})$$

$$f_\alpha = 0.3484\,(\,1.0 - x^{0.3065})^{0.9533}$$

$$f_i = 0.3846\,(\,1.0 - x^{0.5420})^{1.1952}$$

$$f_c = 0.1537\,(\,1.0 - x^{0.3224})$$

Valdés & Ferrara 2008

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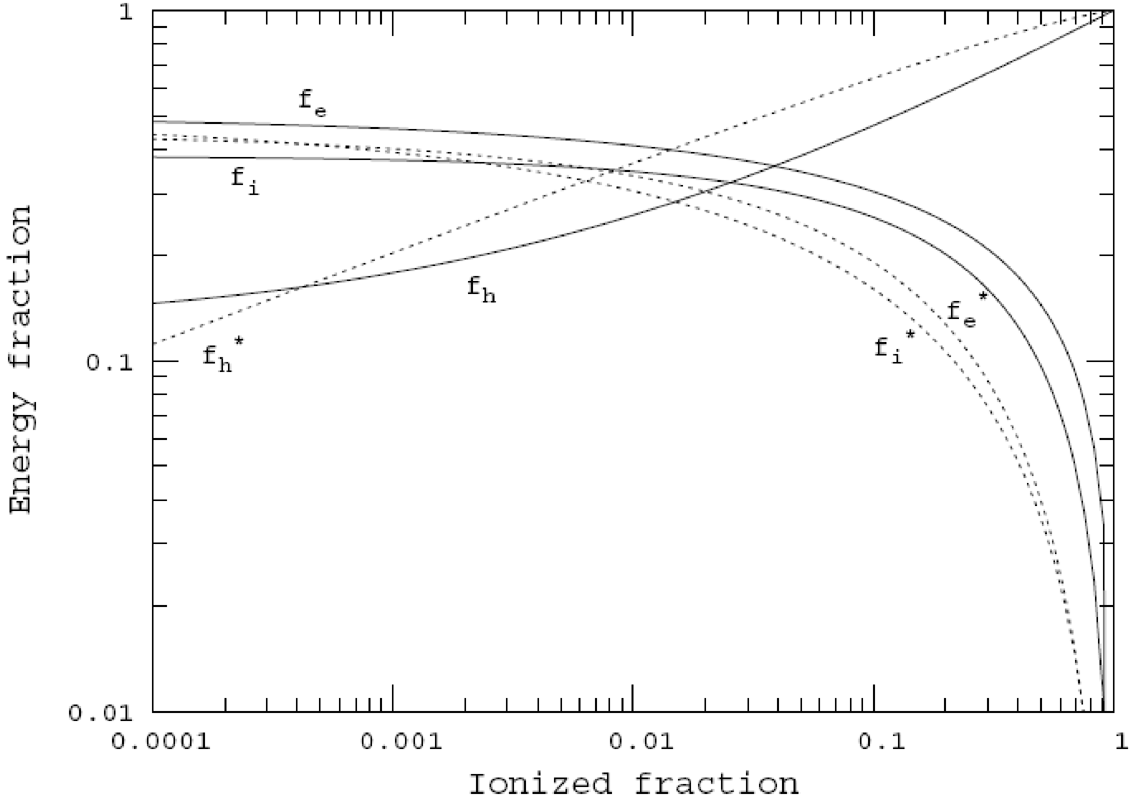
Results – II



Differences substantial, e.g. $f_i > f_i^*$ by a factor ~ 2 for $x_e = 0.2$

Valdés & Ferrara 2008

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

a TeV electron

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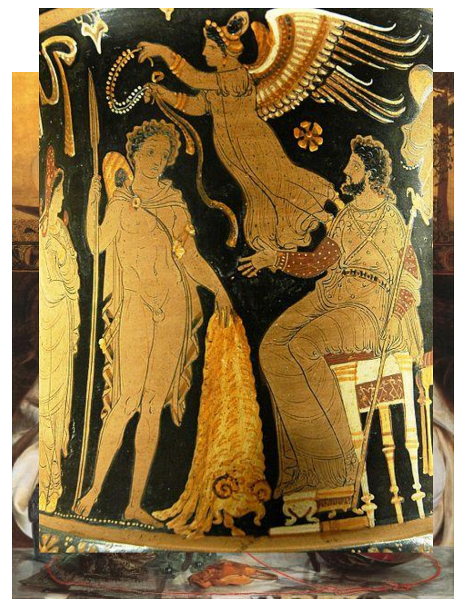
MEDEA – Monte Carlo Energy DEposition Analysis

MEDEA - 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 relativistic electron up to 1 TeV (previous works did up to 10 keV – Shull 1979, Valdés & Ferrara 2008, Furlanetto 2010)



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Particle energy cascade in the intergalactic medium

Valdés & Ferrara, 2008

Valdés, Evoli C. & Ferrara A., 2009

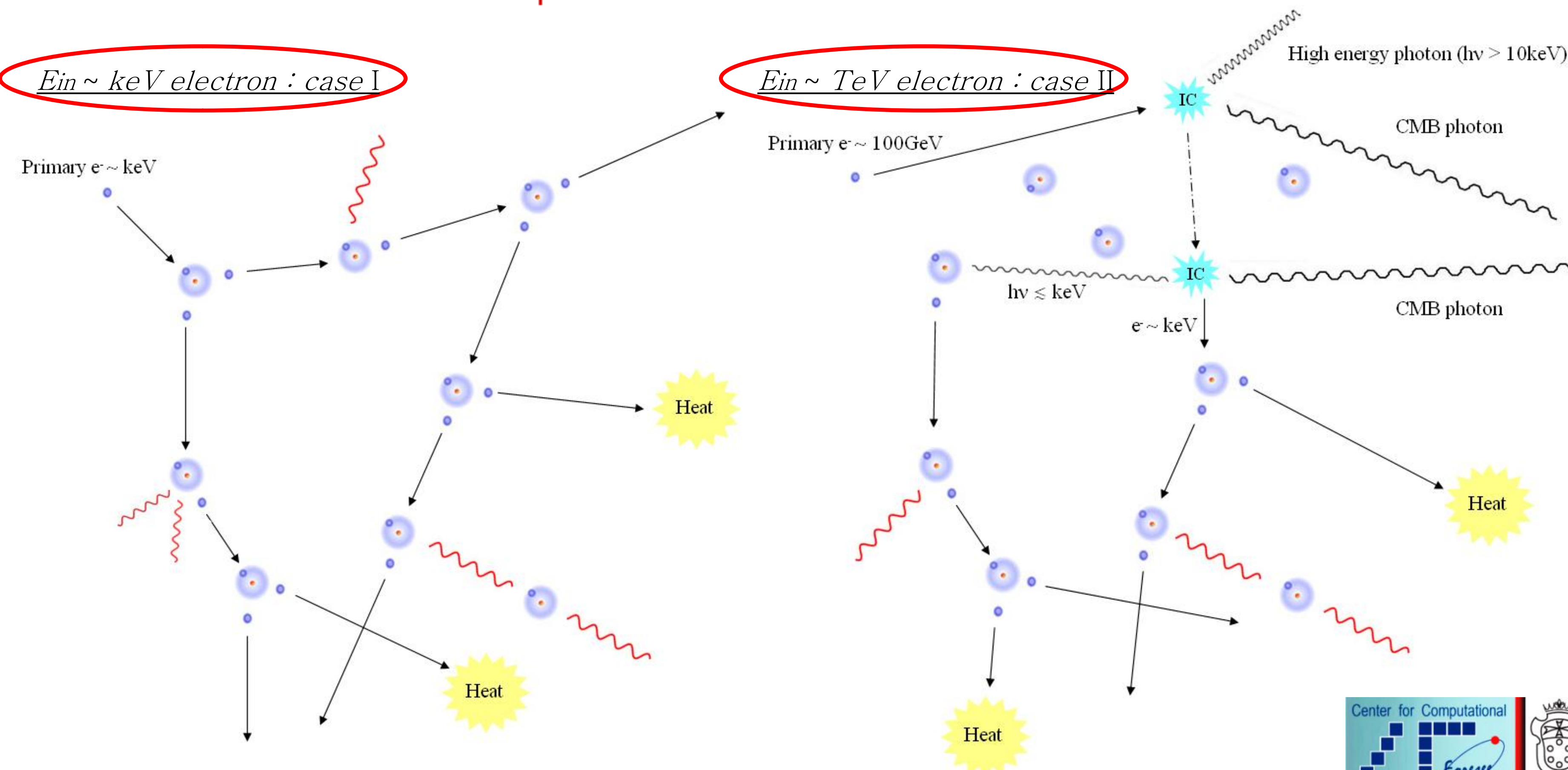
LE
- (I) H, He, HeI ionization
- (II) H, He *excitation*
- (III) *Collisions with thermal electrons*
- (IV) *Recombinations*

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



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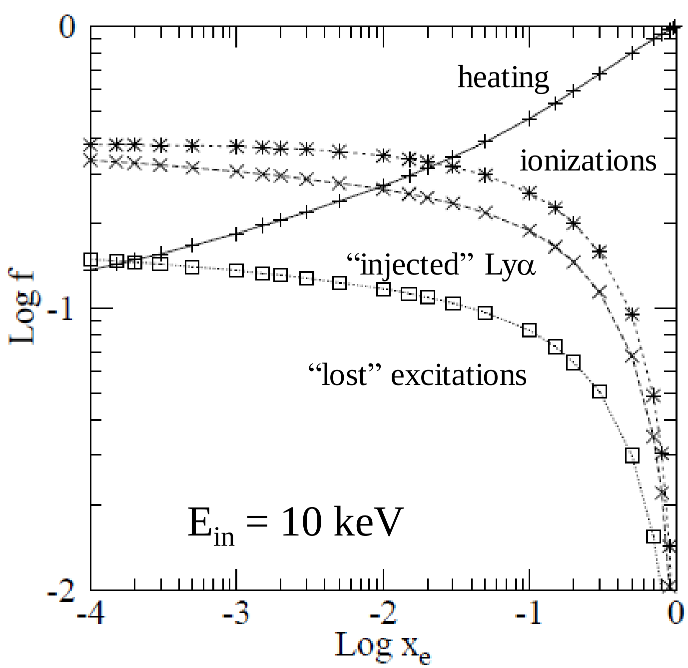
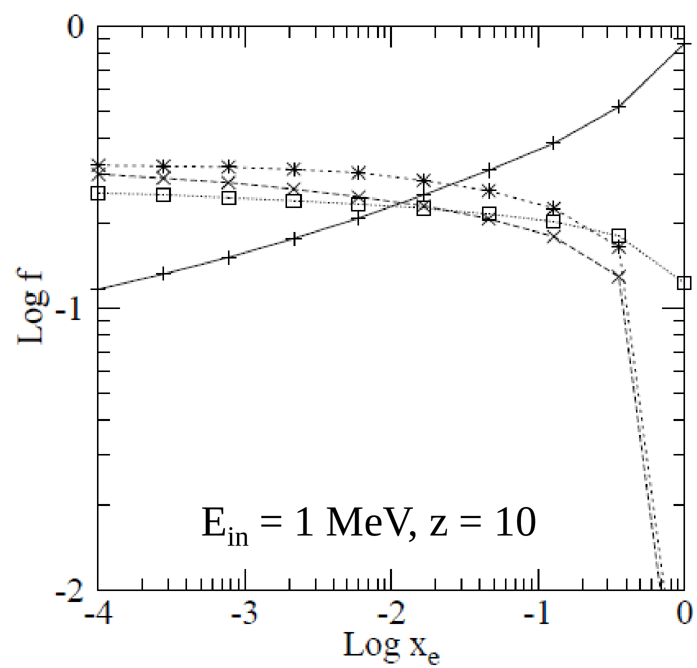
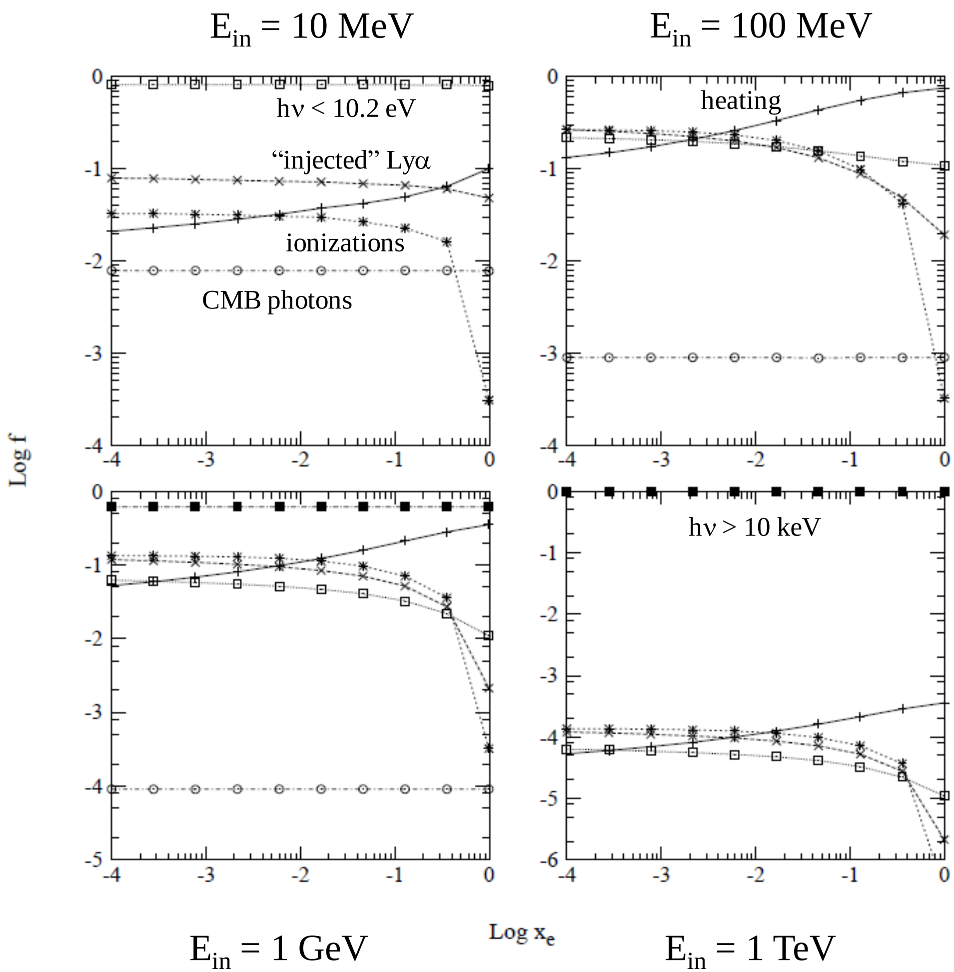
MEDEA results – I

- 10 keV case as in VF08 vs E_{in} = 1 MeV
- Calculation for 9 different choices of x_e
- f_c is increased in the 1 MeV plot… why? IC is already dominant, but upscattered photon energy is 0.00259 eV ≤ h■ ≤ 0.0905 eV!
- IC virtually independent from x_e ~ f_c increased by constant ~ 0.12 step





MEDEA results – II



10 MeV

* very high $f_c \sim 0.8$
* IC max energy ~ 5 eV
* $f_a > f_i$ some IC ~ 10.2 eV - 13.6 eV

100 MeV

* like 10 keV case: IC > 13.6 eV

1GeV

* IC > 10 keV, less scatters
* f_{HE} appears, and strong ~ 0.6

1 TeV

* $f_{HE} \sim 0.99$
* still 100 MeV into IGM

Results- table example

x_e (ionized fraction)	Gas Heating	Excitations (Lyman-α)	Ionizations (H, He, HeII)	Excitations ($E < 10.2$ eV)	HE photons ($E > 10$ keV)	Energy from CMB
1.000e-04	1.1683e-01±6e-04	2.9872e-01±1e-03	3.2137e-01±1e-03	2.5601e-01±1e-03	0.0000e-00±0e-00	7.2476e-03±6e-05
2.779e-04	1.3206e-01±3e-04	2.8895e-01±9e-04	3.1907e-01±1e-03	2.5273e-01±5e-04	0.0000e-00±0e-00	7.3315e-03±0e-00
7.725e-04	1.5127e-01±8e-04	2.7870e-01±2e-04	3.1644e-01±1e-03	2.4660e-01±1e-03	0.0000e-00±0e-00	7.2354e-03±8e-05
2.147e-03	1.7655e-01±9e-04	2.6434e-01±1e-03	3.1123e-01±8e-04	2.4079e-01±1e-03	0.0000e-00±0e-00	7.2713e-03±1e-04
5.968e-03	2.0875e-01±1e-03	2.4811e-01±1e-03	3.0218e-01±1e-03	2.3371e-01±8e-04	0.0000e-00±0e-00	7.3170e-03±1e-05
1.658e-02	2.5211e-01±1e-03	2.3070e-01±1e-03	2.8374e-01±1e-03	2.2626e-01±5e-04	0.0000e-00±0e-00	7.3188e-03±1e-05
4.610e-02	3.0845e-01±1e-03	2.0764e-01±1e-03	2.6096e-01±5e-04	2.1570e-01±6e-04	0.0000e-00±0e-00	7.3151e-03±1e-05
1.281e-01	3.8448e-01±3e-03	1.7929e-01±2e-03	2.2604e-01±1e-03	2.0289e-01±1e-03	0.0000e-00±0e-00	7.3018e-03±2e-05
3.561e-01	5.1813e-01±8e-03	1.2930e-01±3e-03	1.6469e-01±3e-03	1.8054e-01±1e-03	0.0000e-00±0e-00	7.3347e-03±1e-05
9.900e-01	8.6428e-01±1e-04	2.3276e-03±5e-05	3.0192e-03±7e-05	1.2297e-01±5e-05	0.0000e-00±0e-00	7.3925e-03±0e-00

Table A1. Fraction of the energy $E_{\rm in}$ of a 1 MeV primary electron that is deposited into heat, ionizations, Lyα line radiation, photons with energy $E < 10.2$ eV, photons with energies $E > 10$ keV due to Inverse Compton. The last column shows the total energy from the CMB photons before they were upscattered as a test of energy conservation. We consider here redshift $z = 10$.

http://www.arcetri.astro.it/twiki/bin/view/DAVID/MedeaCode

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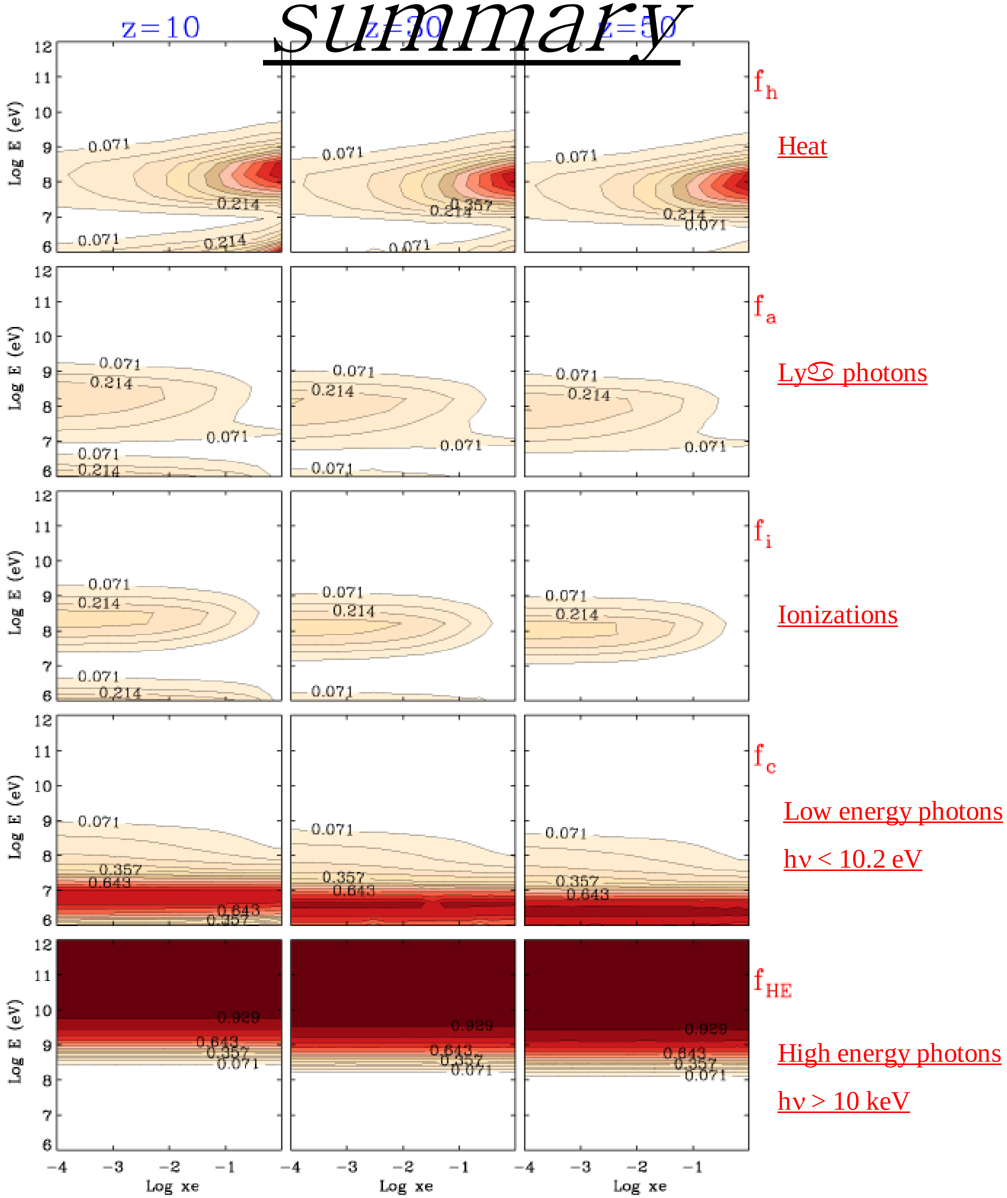
MEDEA results summary



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

DM energy deposition

* Problem is tricky, tackled by several authors in literature.

* If we want to consider the effects from decaying/annihilating particles it is crucial to calculate precisely their interaction with the IGM by a Monte Carlo calculation that includes all the relevant processes.

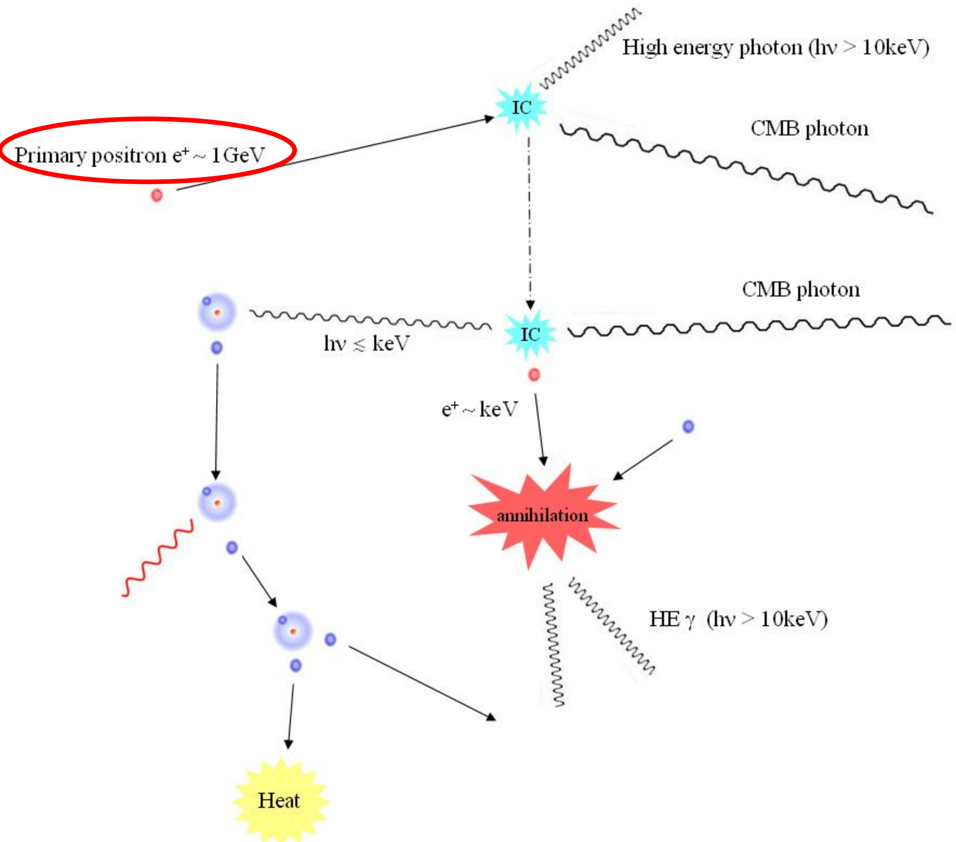
↓

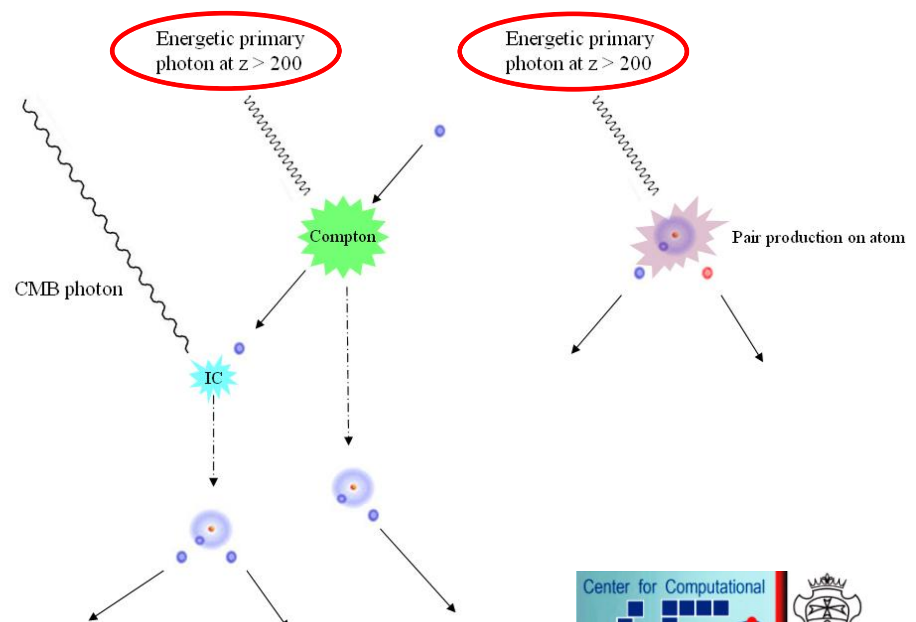
* Many applications since Active Galactic Nuclei, Stellar flares, Gamma Ray Bursts, Pulsar Wind Nebulae, Supernova Remnants, Intracluster radio relics (etc…) house shock accelerated electrons

The energy spectrum from DM annihilations (Evoli, Valdes, Ferrara, Yoshida 2011 in prep)

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*
**Positron-electron annihilations*





MEDEA2 – new physical processes

Positrons behave like electrons but annihilate

Photons instead…

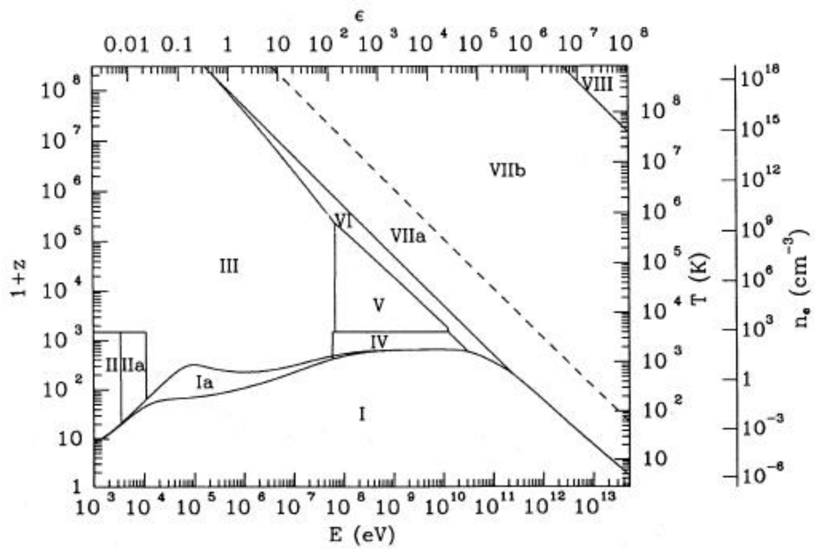


FIG. 4.—The plane $\epsilon - z$ divided into regions of dominance of the various absorption and scattering processes. The regions labeled from I to VIII correspond to I, τ(scattering and absorption) < 1; I + Ia, τ(energy loss and absorption) < 1; II, photoionization dominant over Compton scattering; II + IIa, photoionization dominant over Compton energy loss; III, dominant Compton scattering; IV, pair production on atoms; V, pair production on ions and free electrons; VI, photon-photon scattering; VIIa, b, single photon-photon pair productions; VIII, double pair production. The cosmological parameters are the same as in Fig. 1. See § VIII*b* for discussion.

Zdziarski & Svensson 1989

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MEDEA2 – new physical processes

a) Pair Production on Atoms

Pair production on atoms is generally calculated using a statistical Thomas-Fermi approach assuming the number of electrons per atom to be large (see Joseph and Rohrlich 1958; Motz, Olsen, and Koch 1969 for reviews). A more exact treatment using detailed wavefunctions is required for light atoms such as H and He. The cross section for pair production on He was calculated by Knasel (1968), who included both coherent (nuclear) and incoherent (electronic) pair production as well as screening. A simple fit accurate to 5% for $\epsilon > 6$ is

$$\sigma_{\mathrm{He}} = \alpha_f r_0^2 \, 8.76 \ln\left(\frac{513\epsilon}{\epsilon + 825}\right) . \tag{5.1}$$

The cross section approaches the constant value $\sigma_{\mathrm{He}} = 54.7\alpha_f r_0^2$ in the full screening regime ($\epsilon \gg 1/\alpha_f$). For hydrogen we use

$$\sigma_{\mathrm{H}} = \alpha_f r_0^2 5.4 \ln\left(\frac{513\epsilon}{\epsilon + 825}\right) , \tag{5.2}$$

knowing approximately the asymptotic high-energy limit $\sigma_{\mathrm{H}}/\alpha_f r_0^2 \simeq 34 \pm 2$ (Joseph and Rohrlich 1958) and assuming the same energy dependence as for He.

The absorption probability for pair production in neutral matter with mass fractions of H and He being 75% and 25%, respectively, is

$$\frac{d\tau}{d\ell} = \tau_0 (1 + z)^3 \ln\left(\frac{513\epsilon}{\epsilon + 825}\right) , \qquad \epsilon > 6 , \tag{5.3}$$

where

$$\tau_0 = 5.3 n_e^0 \alpha_f r_0^2 \frac{c}{H_0} = 1.4 \times 10^{-5} \Omega_{0.1} h_{50} . \tag{5.4}$$

$\varepsilon = E/(m_e c^2)$

MEDEA2 – new physical es

$$\sigma_{\mathrm{KN}} \cong 8\pi r_e^2 \, \frac{(1+2k+1.2k^2)}{3(1+2k)^2}$$

$$k = E / mc^2$$

*Compton, E is photon energy

$$E' / E = 1/[1+k(1-\cos\theta)]$$

X-ray photon energy loss

The annihilation in flight of a positron and electron is described by the cross section formula of Heitler

$$\sigma(Z,E) = \frac{Z\pi r_e^2}{\gamma+1}\left[\frac{\gamma^2+4\gamma+1}{\gamma^2-1}\ln\left(\gamma+\sqrt{\gamma^2-1}\right) - \frac{\gamma+3}{\sqrt{\gamma^2-1}}\right]$$

where

E = total energy of the incident positron

γ = E/mc^2

r_e = classical electron radius

*Positron-electron annihilations

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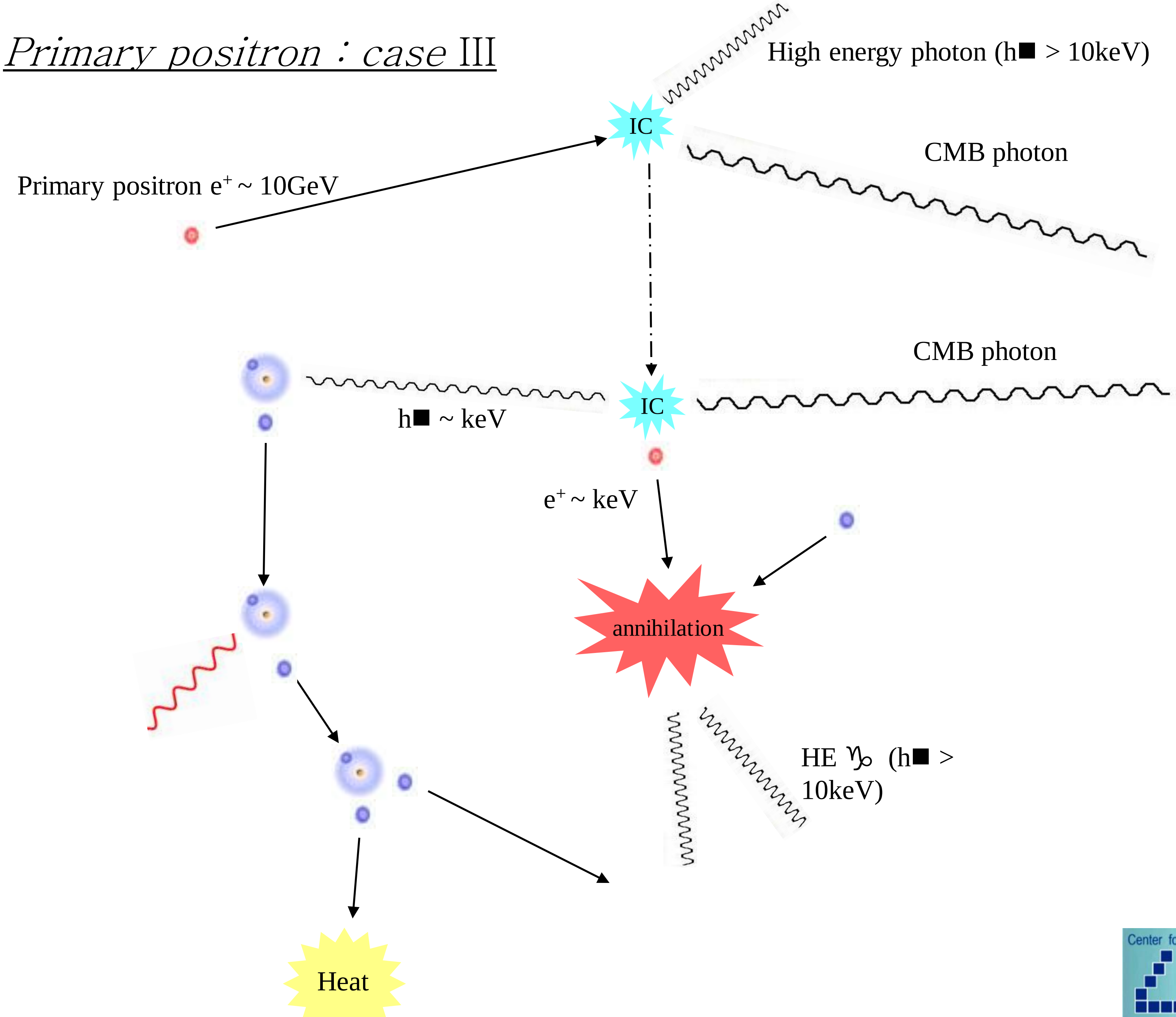
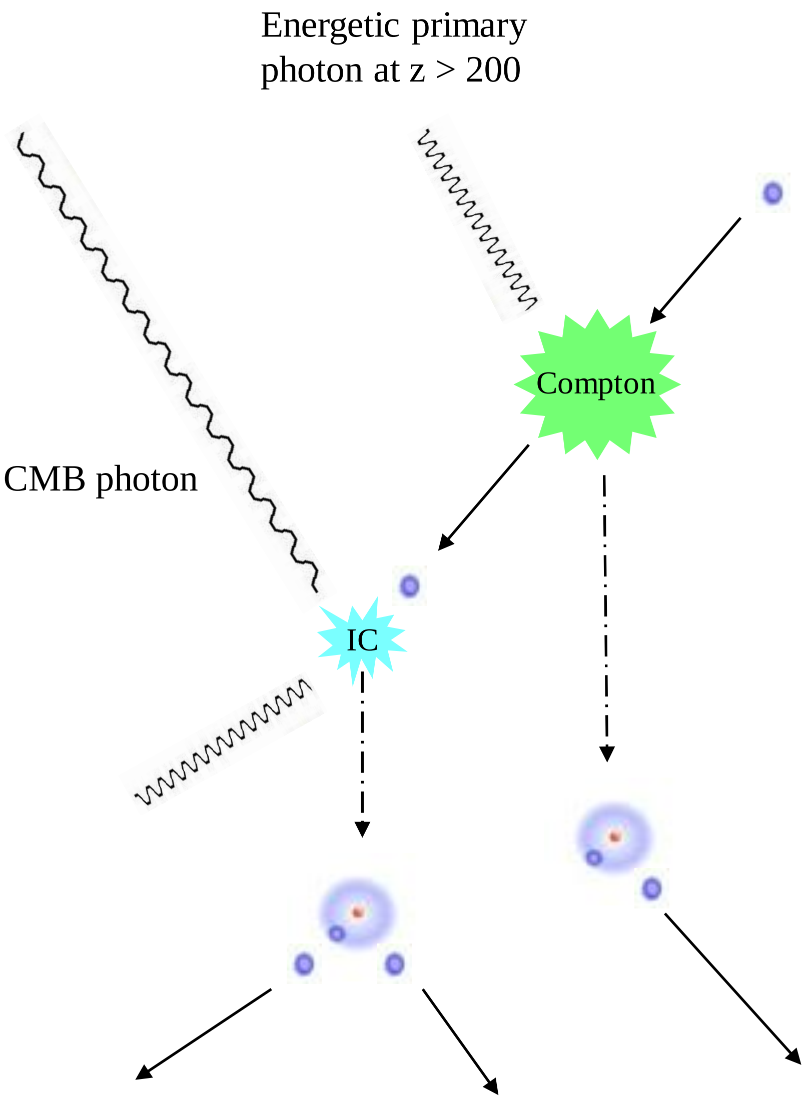
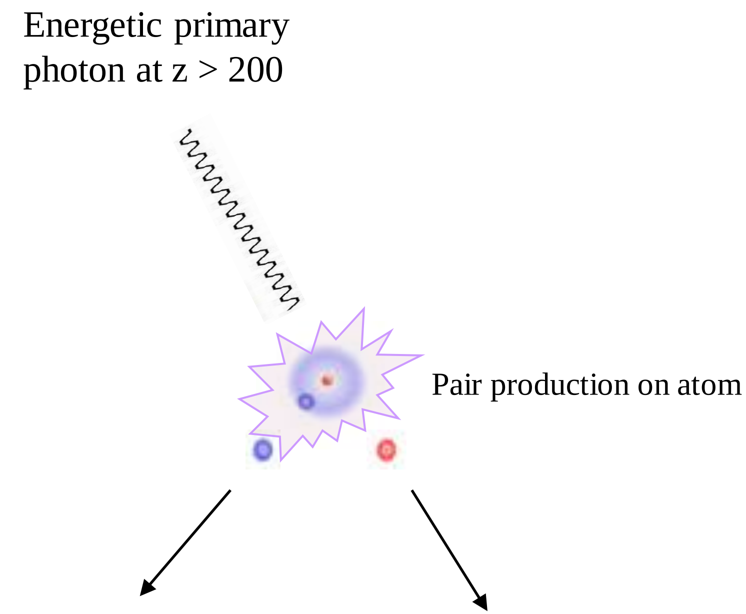
Primary positron : case III



Primary energetic photon : cases IV–V





Annihilating DM candidates – I

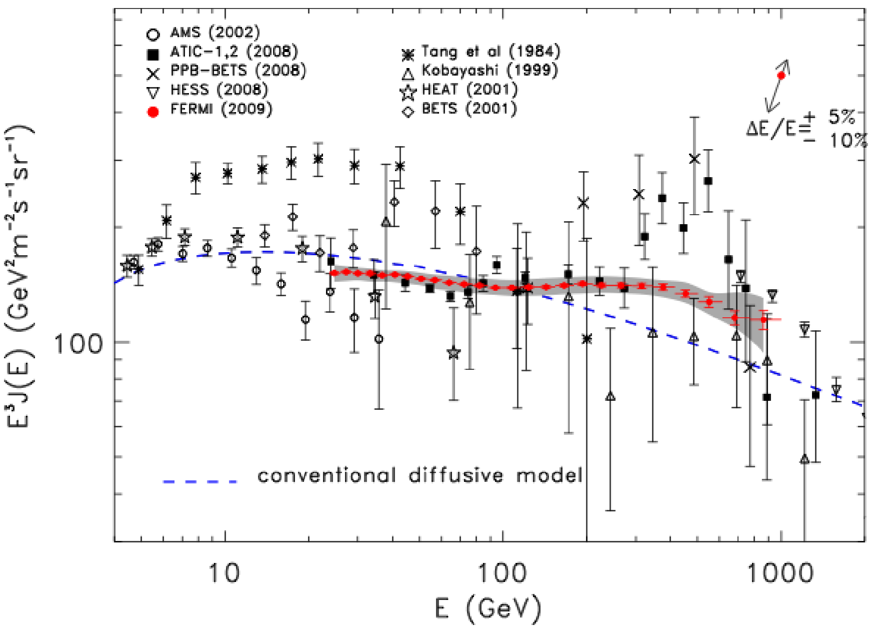
A number of recent observations has put stringent contrains on the nature of DM:

•Pamela showed an excess of positrons over the expected background generated by interactions between cosmic-ray nuclei and interstellar matter in the energy range between 10 and 100 GeV.

•ATIC reported a ...) - 800 GeV.

•The later observ ... nario again, not confirming the p ... antly harder than previously belie ...

•A DM particle ... r annihilates dominantly in le ... ess observed by PAMELA and th ...



Annihilating DM candidates – II

* 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.

•We study three DM candidates following Linden et al. (2010)

- (i) a 40 GeV bino-like neutralino with a soft energy injection spectrum;
- (ii) a heavy 1.5 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.

* *To do so we couple our code MEDEA2 to DarkSusy which gives the input spectral energy distribution of eletrons positrons and photons for the DM candidates of choice*

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Dark Susy

Dark SUSY

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Internal pages (password restricted)

Dark SUSY

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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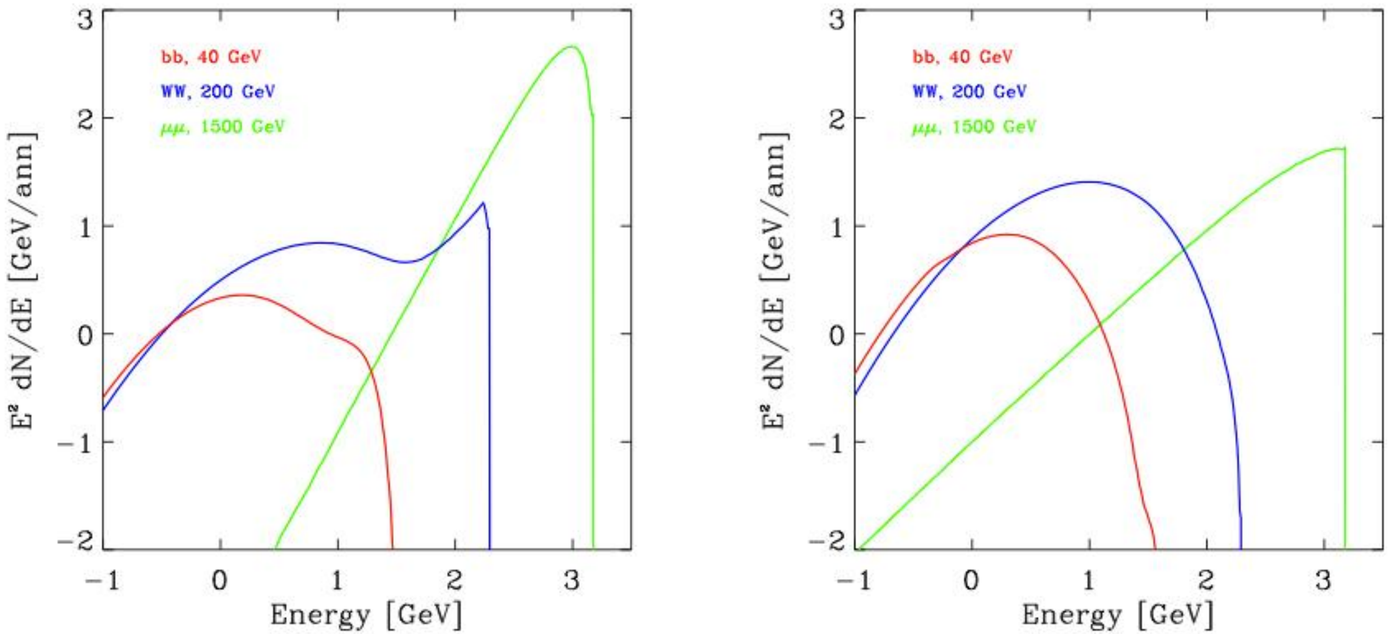
Input spectra



* DarkSusy generated spectral energy distributions for electrons/positrons (left panel) and photons (right panel). We use these distributions as input for MEDEA2

Evoli, Valdés, Ferrara, Yoshida 2011 in prep.

Mean free paths

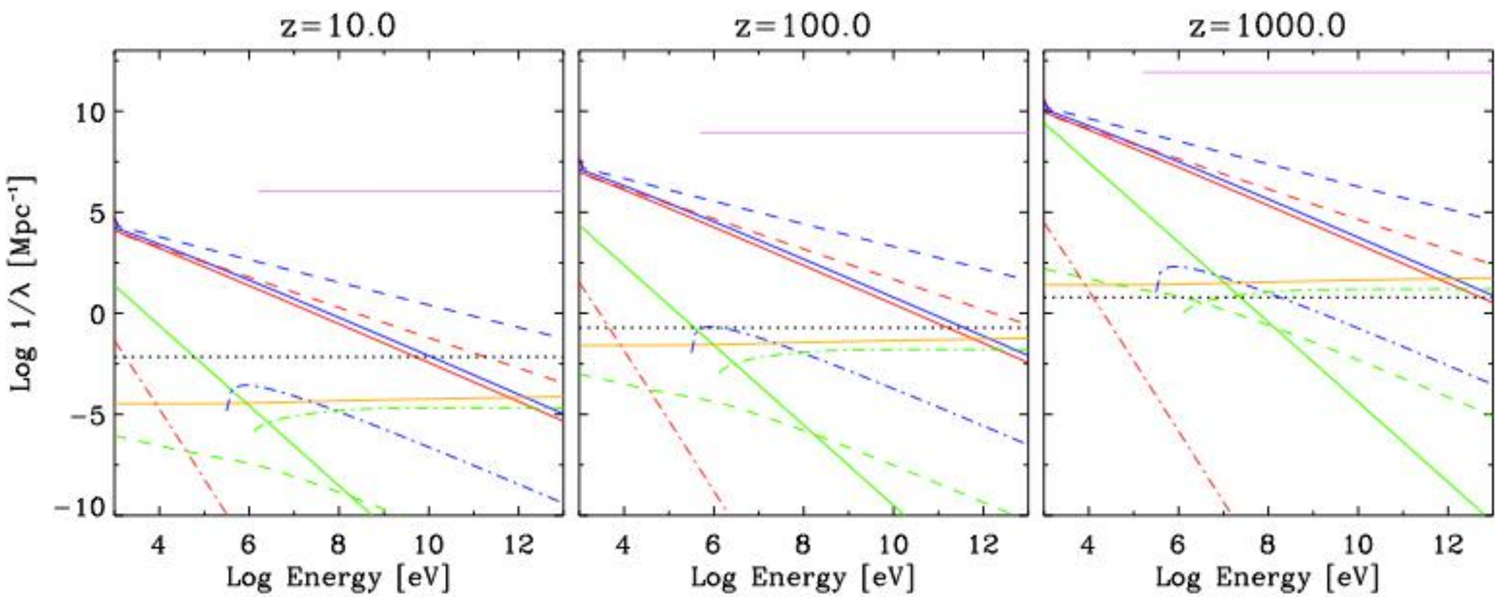


Figure 3. The inverse of the mean free paths of electrons, positrons and photons in the IGM. Electron interactions (solid): ionizations (red), excitations (blue), ee (green), Bremsstralungh (orange), IC (violet). Positron interactions (dashed): ionizations (red), excitations (blue), annihilations (green). 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.

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Electrons/positrons

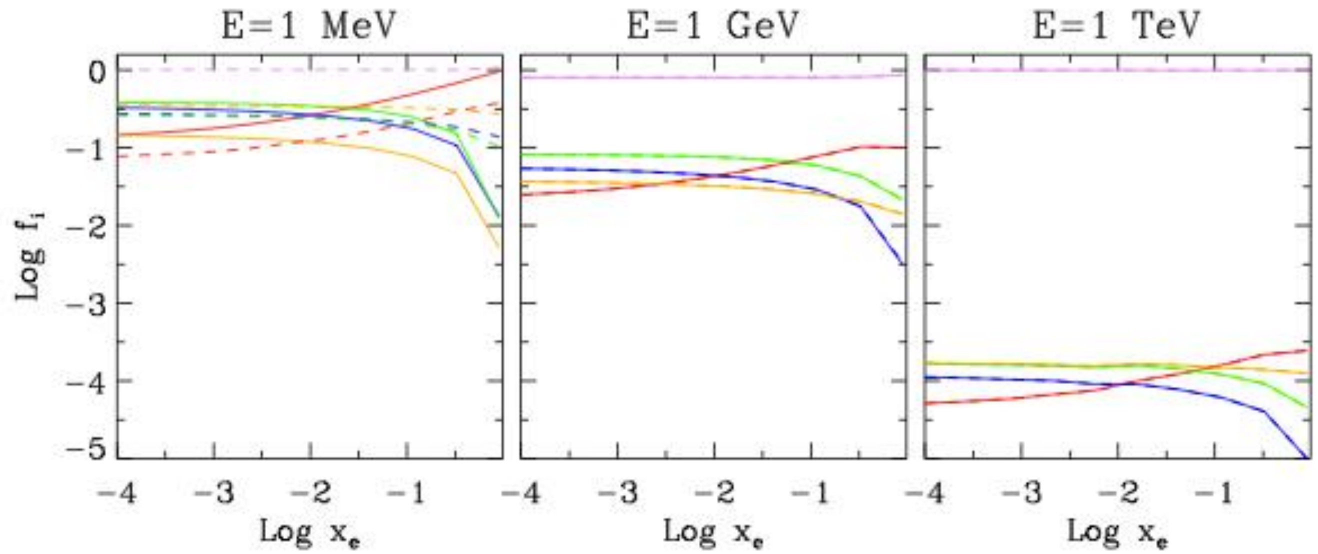

Figure 4. The energy deposition fractions for a single electron (solid line) and positron (dashed line) of different initial energies ($E = 10^6$, 10^9, 10^{12} eV at $z = 10$. The curves represent the energy fraction that goes into gas heating (f_h, red line), Lyα photons (f_α, green line), ionizations (f_{ion}, blu line), photons with $E < 10.2$ eV (f_c, orange line) and photons with higher energy that free stream to the observer (f_{HE}, purple line).

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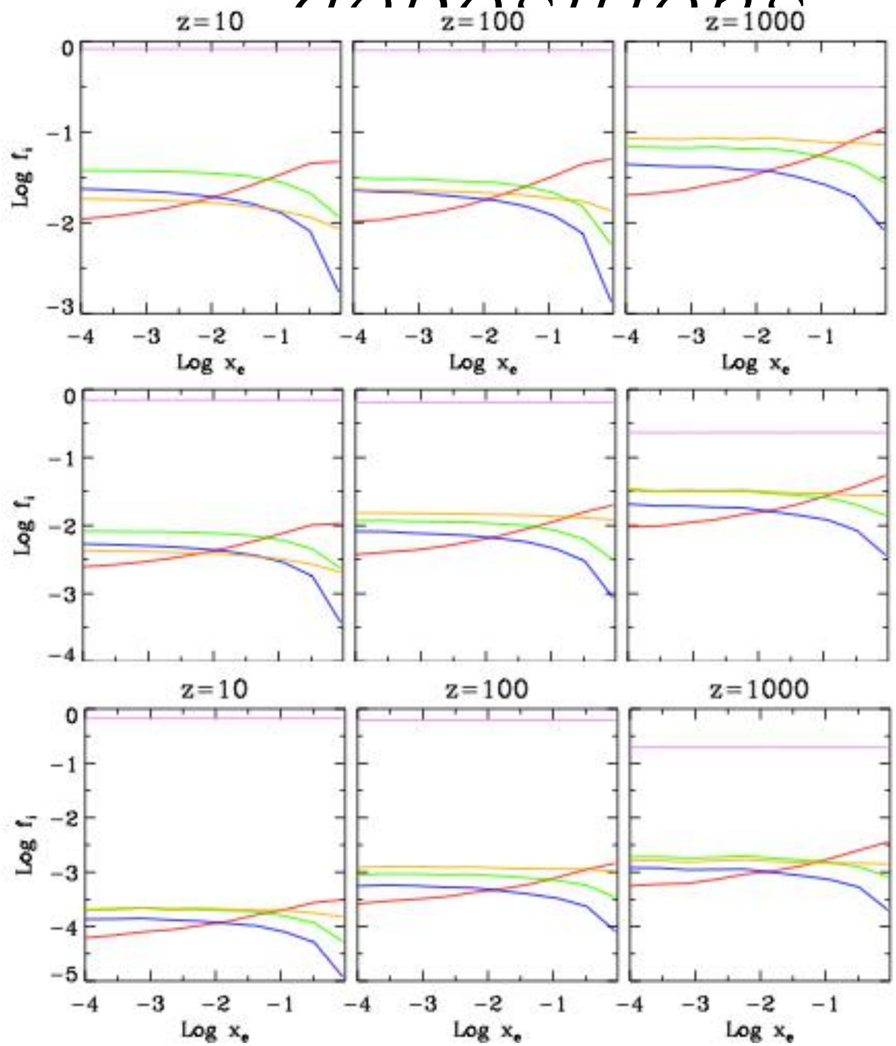
The DM energy depositions



40 GeV

200 GeV

1.5 TeV

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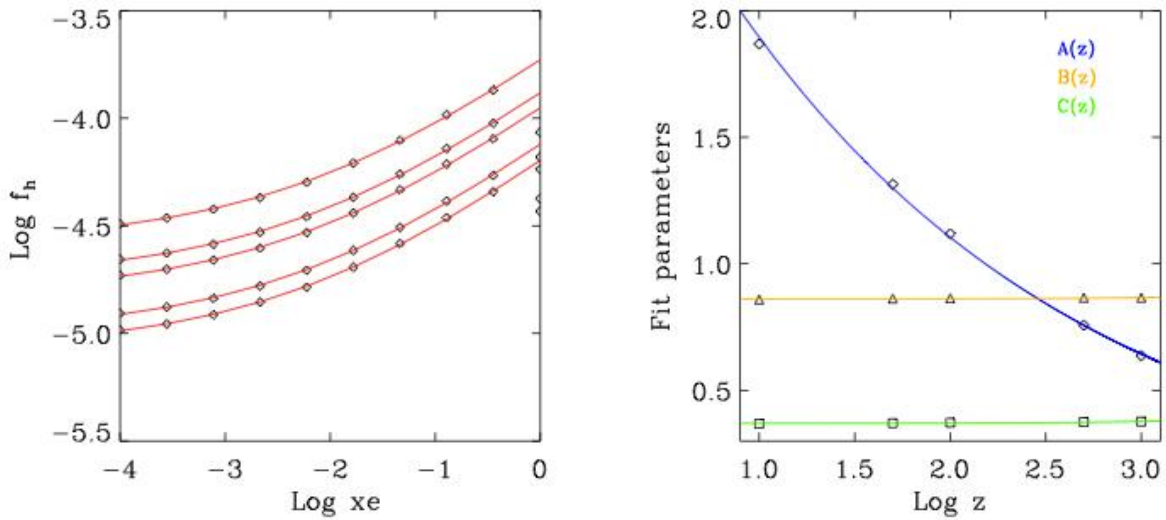
The fitting functions



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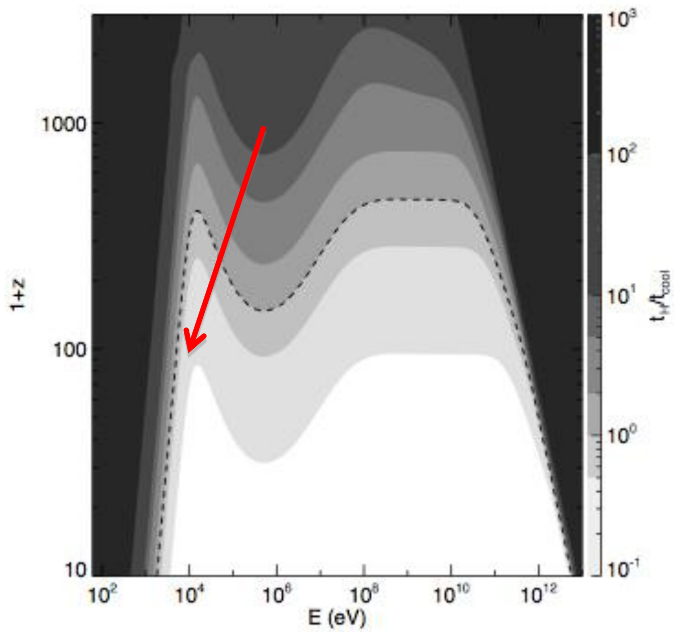
Some comparisons and questions

Slatyer 2009



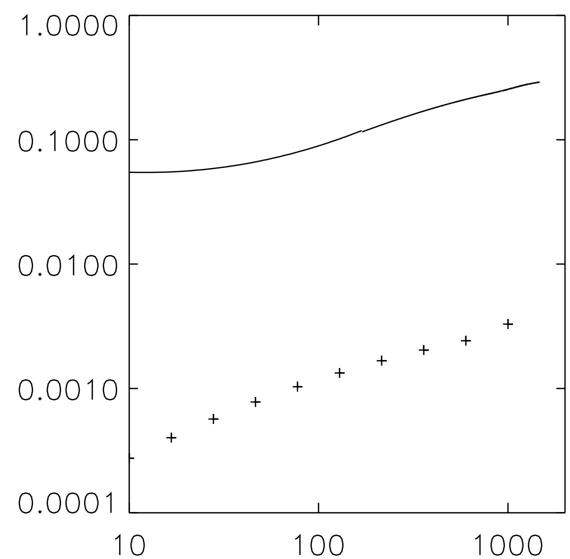


FIG. 2: A comparison of the photon cooling time (from all processes) to the Hubble time over the entire redshift range of interest. The plot assumes a He mass fraction of 1/4, with a baryon density of 2.57×10^{-7} amu / cm^3 today, and the standard ionization history and fiducial cosmology. The dashed line corresponds to $t_{\rm cool} = t_H$. There is a discrepancy between this figure and Fig. 2 in the originally published version of [37]: the authors of that paper have advised us that upon revising their calculation, their results now agree with ours.

Discrepancy due to different treatment

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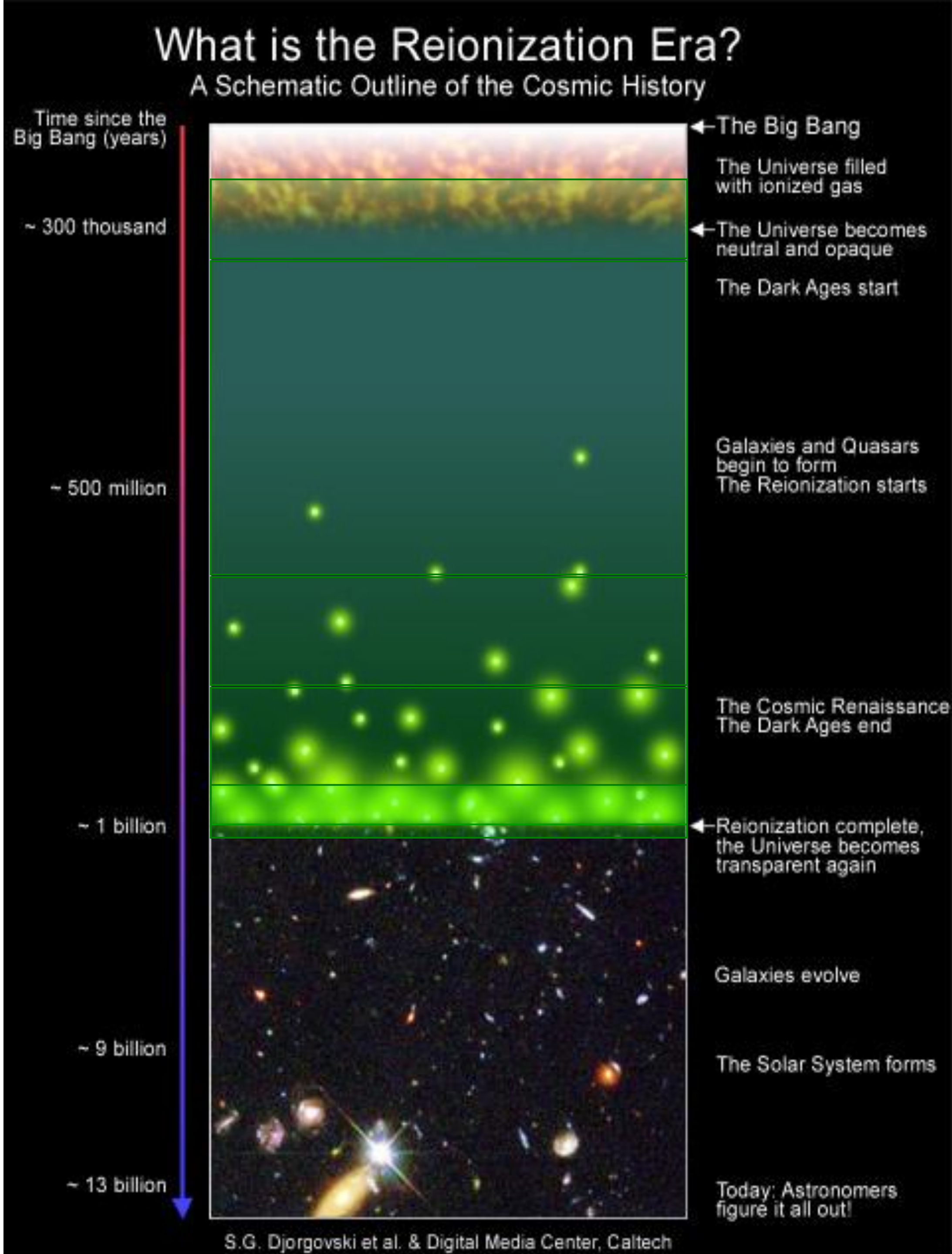
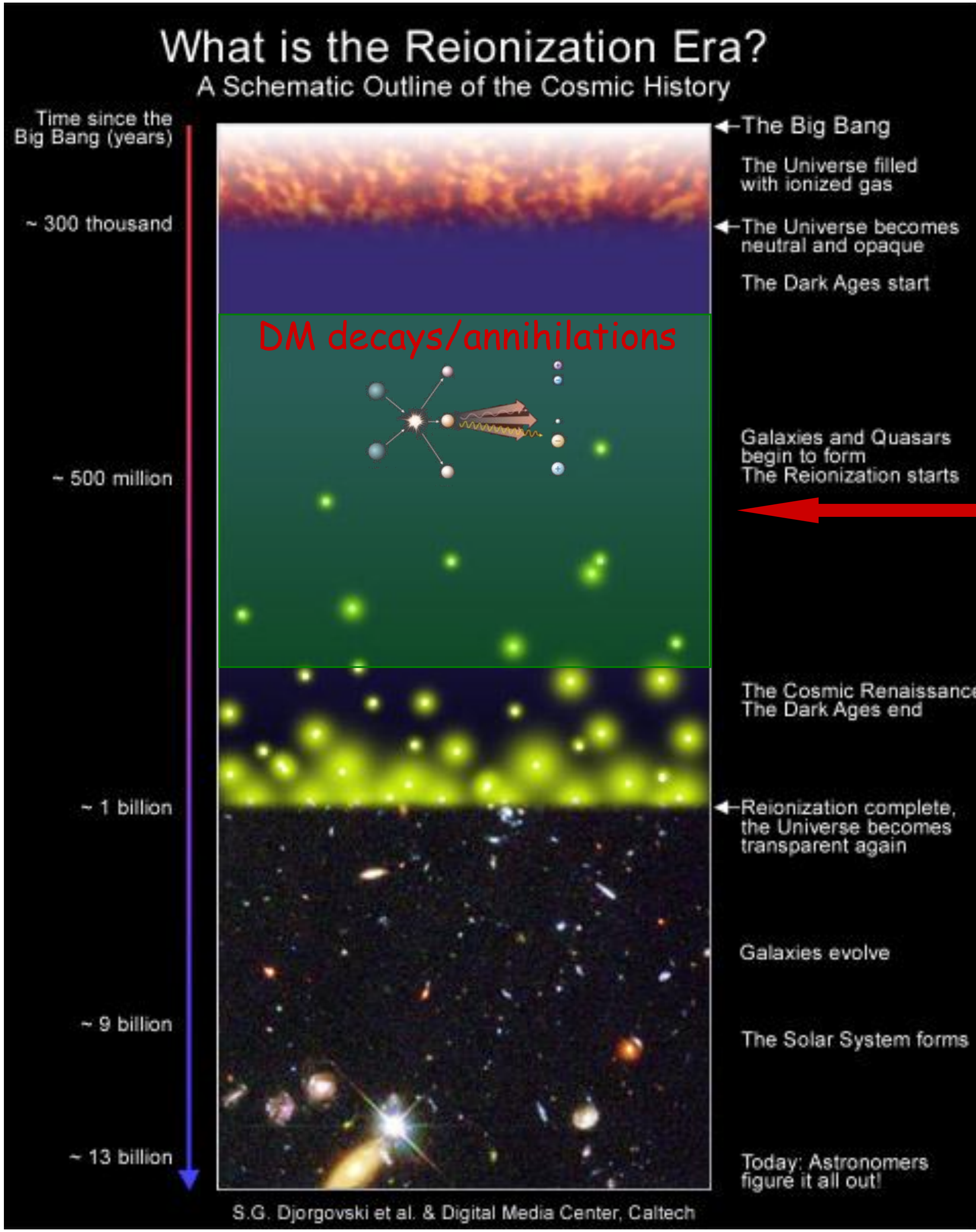
2. How does DM affect the high-z IGM?

Sequence of Events

- At z ~ 1100 the Universe cools down to 3300K . Hydrogen becomes neutral ("Recombination")
- "Dark Ages"
- At z ~ 30 the first "PopIII" stars form
- At 6 < z < 20 galaxies gradually photo-ionize the hydrogen in the IGM
- "Reionization" is complete by z ~ 6-10





Dark Ages

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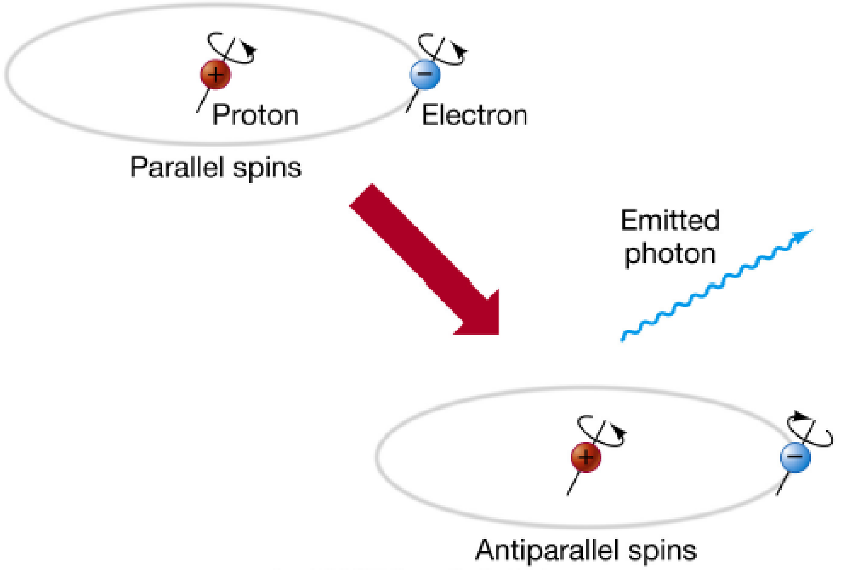
HI 21 *cm hyperfine transition*



$\nu_0 = 1420.405751$ 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 (~ 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 Ly♋ 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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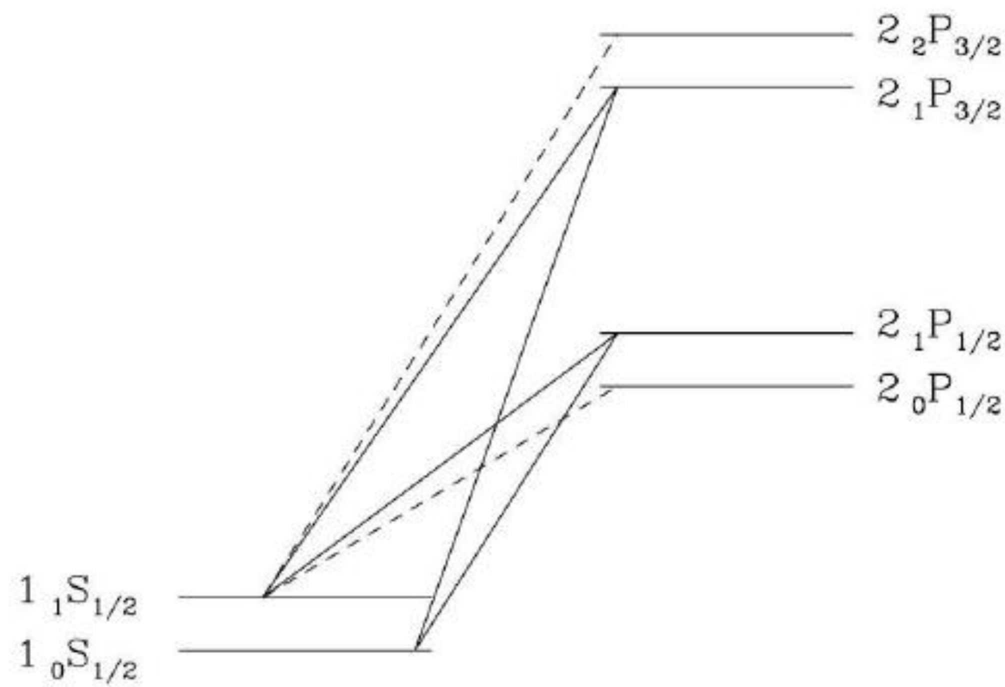
HI 21 *cm line – WF process*

F = total angular momentum of the atom

☟F = 0, ±1 ¥ 0 → 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



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:

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

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

Requirements for succesful high-z HI 21 cm detection:

1. A low frequency interferometer (■ ~ 10 – 240 MHz)
2. An exceptional sensitivity (≏T_b ~ 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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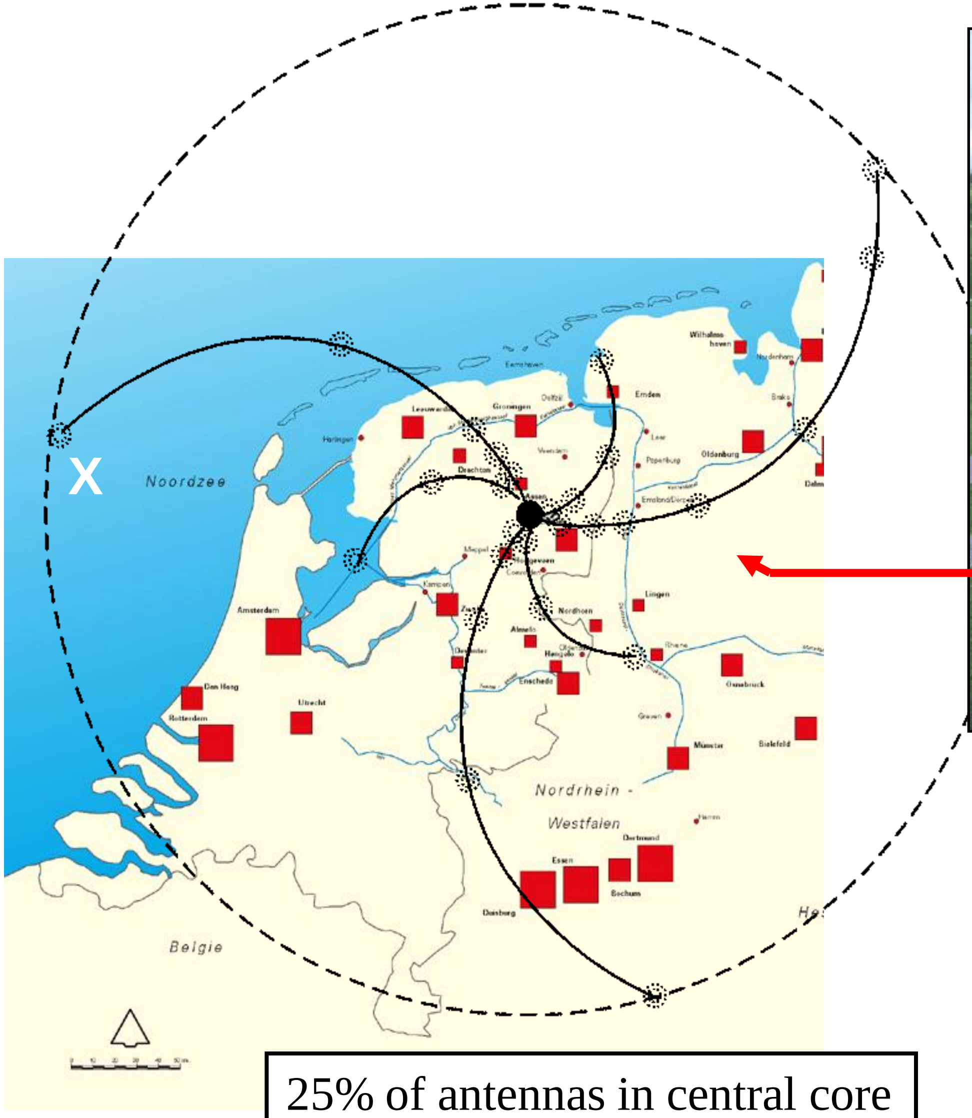
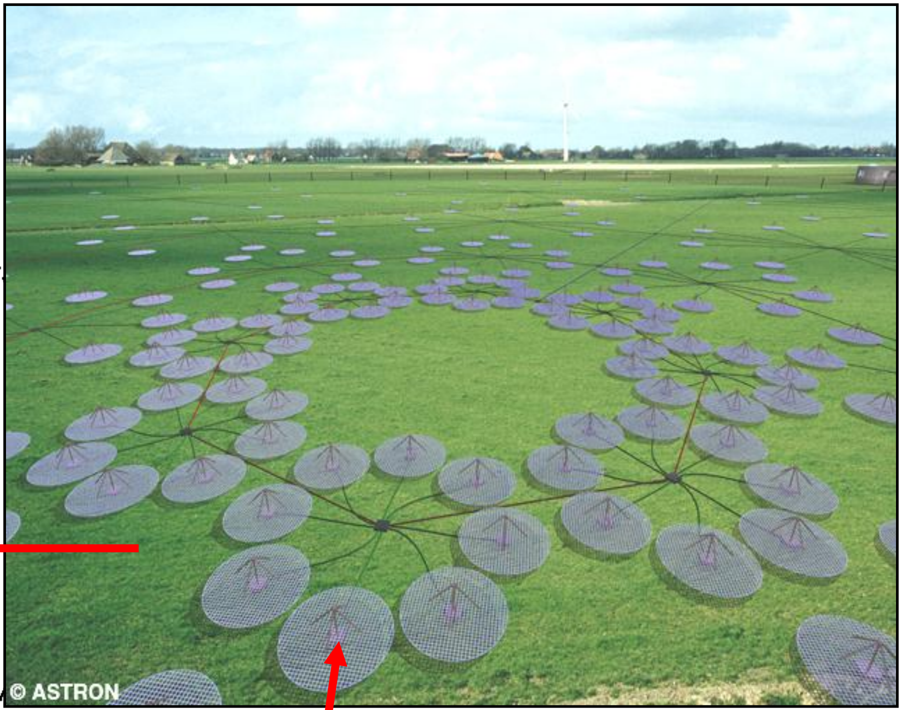
LOFAR Radio Telescope





25% of antennas in central core

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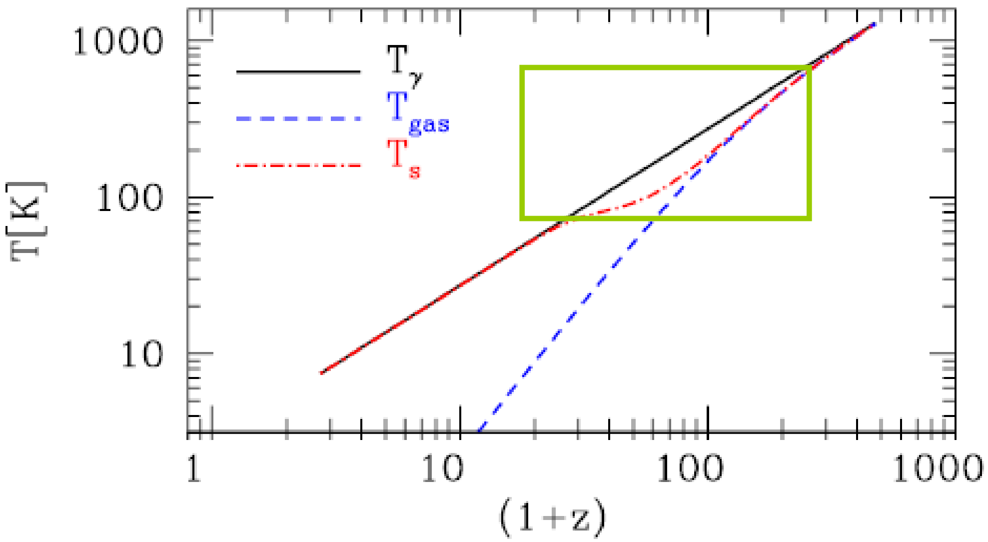
"Standard" T_S history



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

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

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

- 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:

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

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

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

We assume, for LDM and sterile neutrinos respectively:

$$n_{\rm DM,0} \sim 446, \;\; \tau_{\rm DM} = 4 \times 10^{25}\ {\rm s}, \;\; {\rm and} \;\; \langle \sigma v \rangle \sim 2.4 \times 10^{-28}\ {\rm cm}^3\ {\rm s}^{-1}$$

$$\tau_{\rm DM} = 9.67 \times 10^{25}\ {\rm s} \;\; {\rm and} \;\; n_{\rm DM,0} = 1.88 \times 10^5$$

IGM evolution

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

- Solve diff. eqs. describing redshift evolution of x_e, T_k, J_α
- Compute new values of ♎T_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*

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

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

T_S → ♎T_b

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DM candidates - light

Sterile neutrinos

* Warm dark matter candidate, can decay into an active neutrino and a photon.

* Mass and lifetime can be constrained by X-ray observations of galaxy clusters, galaxies, background.

* We consider 25 keV neutrinos (maximal contribution to heating/ ionization).

LDM

* LDM particles are all those with mass between 1-100 MeV. Can decay or annihilate, producing photons, neutrinos and pairs.

* Observations constrain mass to be < 20 MeV.

* We consider 10 MeV LDM particles (most efficient heating/ ionization).

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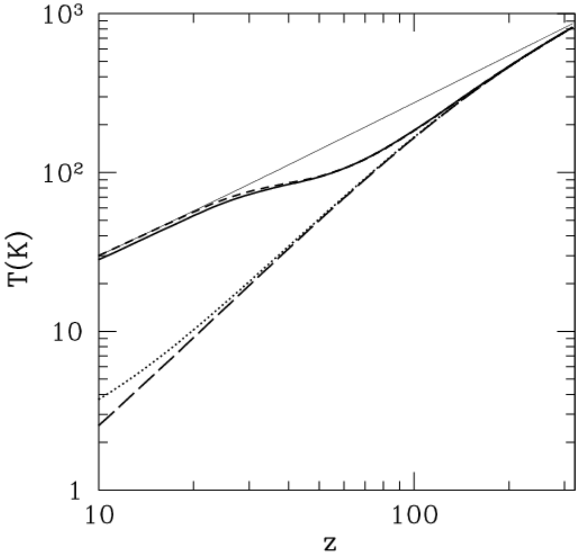
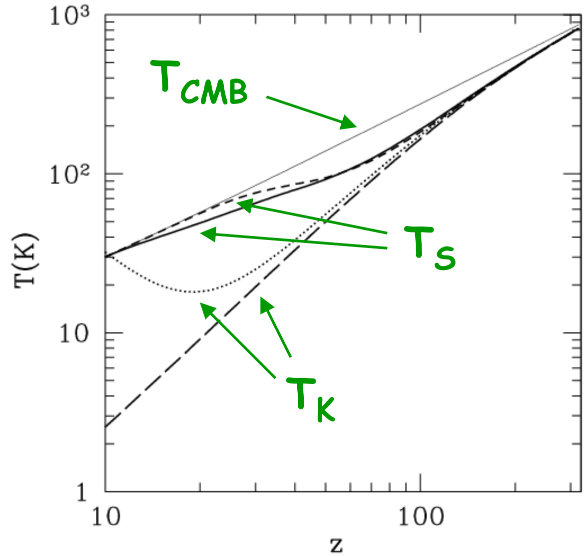
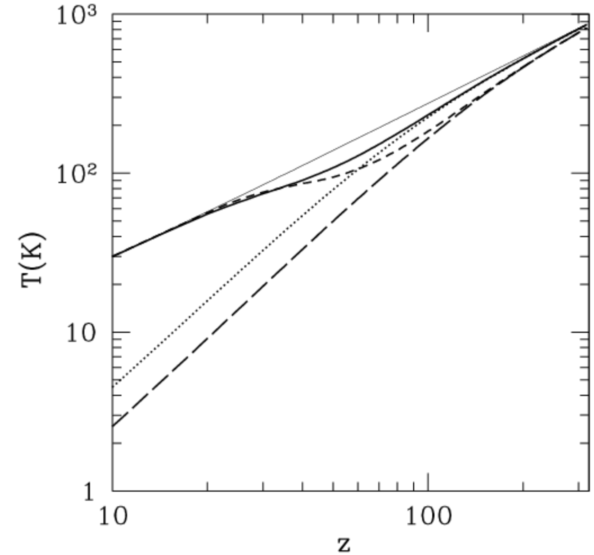
Results : spin



Sterile neutrinos



LDM decays



LDM annihilations

- WDM: effect very modest in comparison with “standard” case, $T_s - T_{CMB}$ remains extremely small

- LDM_D: T_k decouples from standard behavior already at z ~ 50, rising sharply below z ~ 25; $T_s < T_{CMB}$ for a much longer redshift interval → extended frequency range to observe IGM in absorption (f_{abs} larger of a factor 10 with respect to sterile neutrinos down to z = 30)

- LDM_A: T_k deviates from “standard” evolution already at z ~ 200; annihilation process depends on the square of the DM density → effect vanishes at lower z

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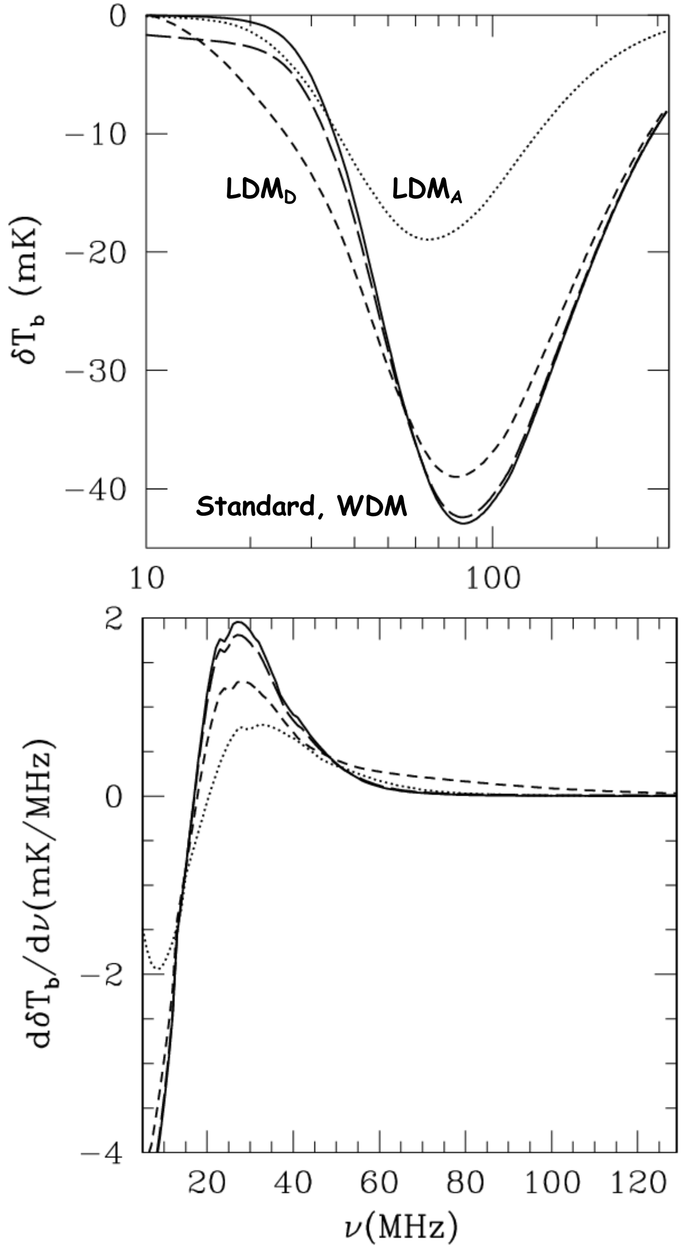
21 cm background imprint from DM



1. *Sterile neutrinos*: at 30 < z < 300 the HI 21 cm background signal only slightly modified: max difference ~ 2mK at z ~ 10−40.

2. *Decaying LDM*: larger deviation. Max difference ~ −(5−8) mK at z ~ 20−40. LOFAR, SKA should observe the signal.

3. *Annihilating LDM*: give largest deviations in the entire range z ~ 40−200. ≏T_b is forced to values > −20mK.

• Challenge: foreground removal.

• Exploit 21cm background spectral features to separate signal from foregrounds.

Valdés et al. 2007

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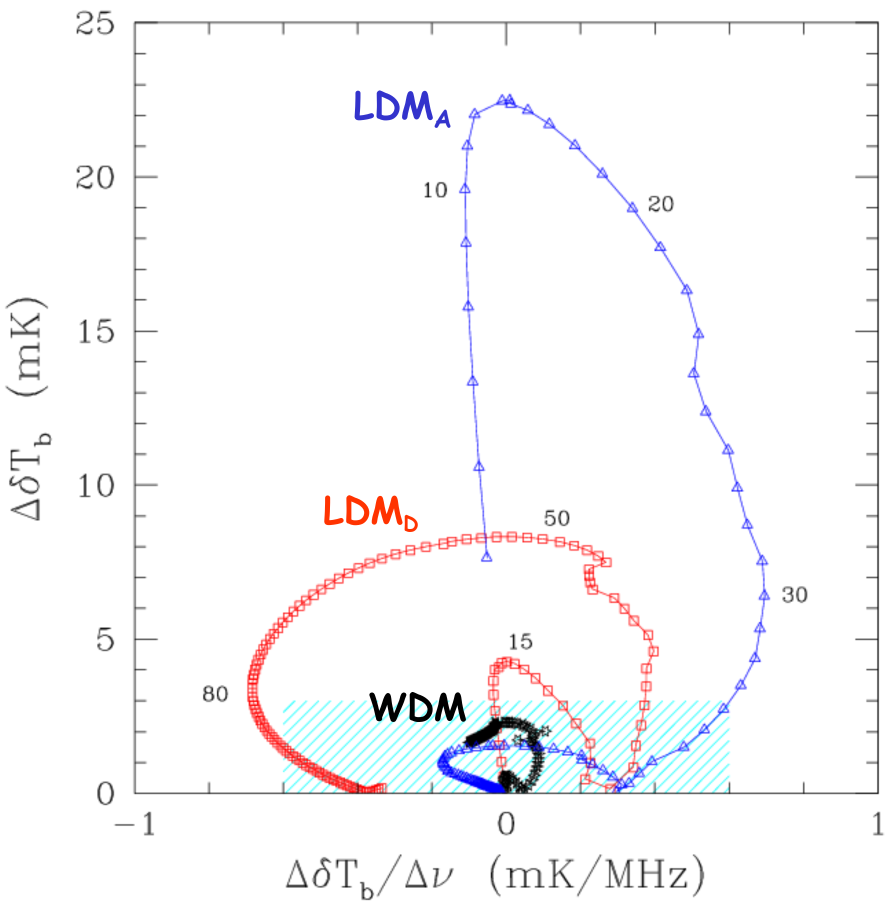
Future Observations



How to discriminate among DM candidates?

Observations need to distinguish with respect to the standard scenario:

* difference in brightness temperature

* difference in its gradient

1. *Sterile neutrinos*: the points lie within the shaded area → hard to detect.
2. *Decaying LDM*: ideal frequencies to study are 40−80 MHz where $\Delta\delta T_b$ ~4 mK and 80−90 MHz where $\Delta\delta T_b/\Delta\nu$ ~ 0.6 mK/MHz.

$$\Delta\delta T_b = \delta T_b - \delta {T_b}^0$$

$$\Delta\delta T_b/\Delta\nu = d\delta T_b/d\nu - d\delta {T_b}^0/d\nu$$

frequencies 10−30 MHz where $\Delta\delta T_b$ ~ 6 mK (peak of 20 mK).

Valdés et al. 2007

DM candidates – heavy

- **Those that we studied with MEDEA2**!

  - (i) a 40 GeV bino-like neutralino with a soft energy injection spectrum;

  - (ii) a heavy 1.5 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.

* *Coupling MEDEA2 to DarkSusy gives us the precise energy depositions*

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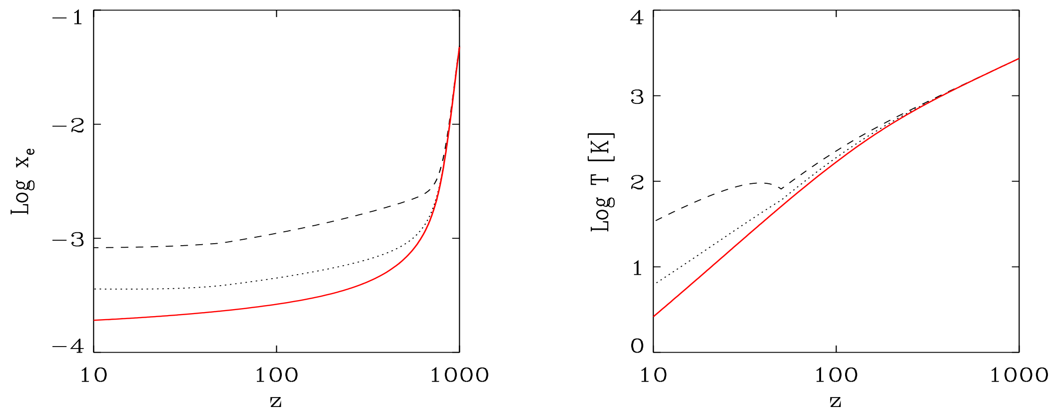
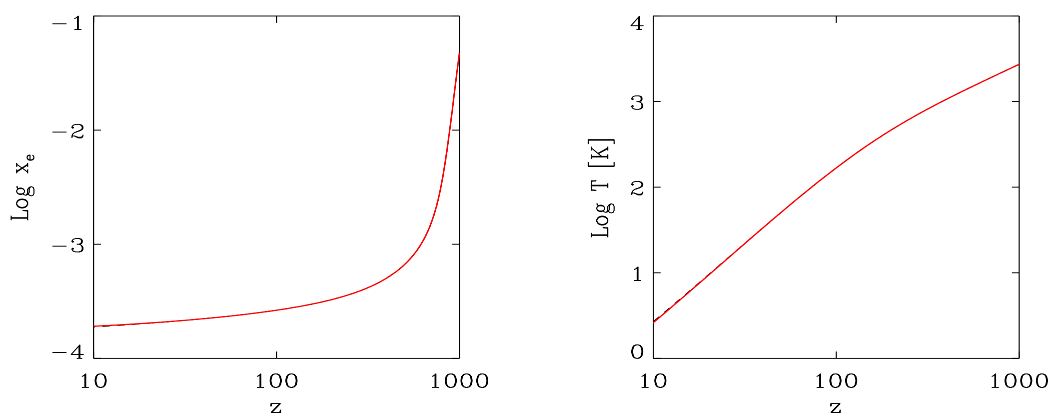
IGM evolution

CosmoRec



40 GeV case, f = 1, f = 10



1.5 TeV case, f = 1

Valdés, Evoli, Ferrara, Yoshida 2011 in prep.

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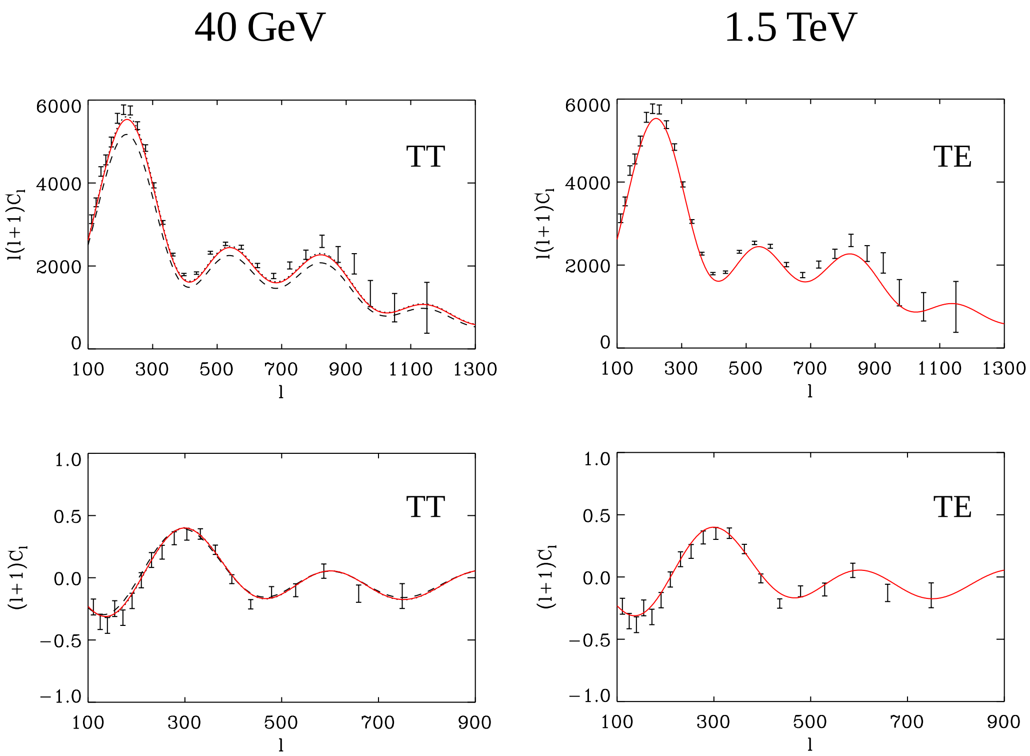
CMB constrains



CAMB + CosmoRec: Temperature-temperature (top panel) and temperature-polarization (bottom panel) power spectra.

→DM suppression of the spectrum is lower than previously found.

Will Planck observe the signal?

Valdés, Evoli, Ferrara, Yoshida 2011 in prep.

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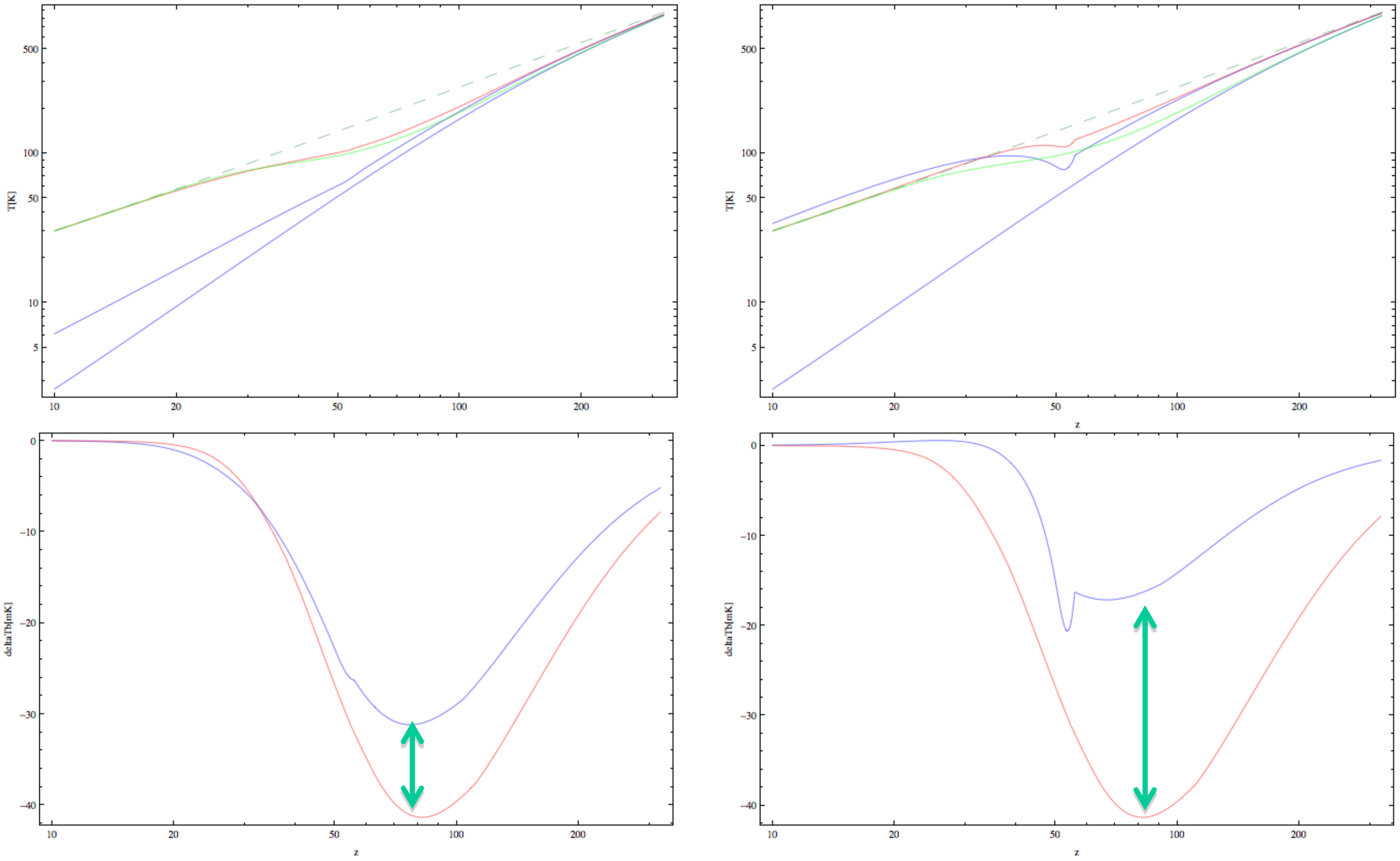
HI 21 cm constrains



LOFAR, SKA may detect the signal

Valdés, Evoli, Ferrara, Yoshida 2011 in prep.

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Preliminary heavy DM results

- Energy absorbed by IGM *smaller* than previously thought
- Constrains to be recalculated
- CMB power spectra in particular are less suppressed
- Heavier candidates don't affect thermal IGM history → X and Gamma ray constrains
- GeV scale particles can be detected by 21cm observations

3. How do overdensities enhance the 21 cm signal?

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Enhanced effects by clumping

* Clumping can enhance the effects of DM decays/annihilations on the IGM.

* To calculate properly the differences with respect to a homogeneous sky-averaged signal, a *cosmological simulation* is the natural tool.

* We start our study with the least promising candidate on a “HI 21 cm point of view”, *sterile neutrinos of mass 5 keV* as recently favoured by observational constrains.

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Simulations: DM physics

Do we have to solve a system of DE for every simulated cell???

Not if the timescale associated to DM heating $T_{DM} << T_{hubble}$

→ steady state solution an excellent approximation

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

0

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

0

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

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

0

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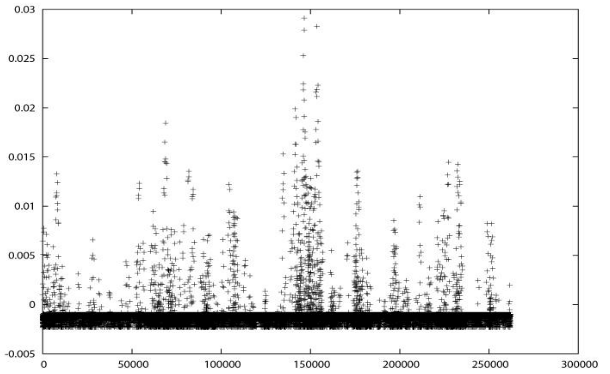
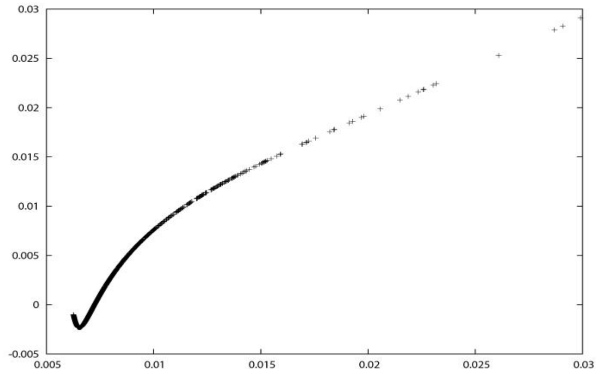
Inhomogeneous case: gas properties

z = 20

ΔT_b (mK)



Grid cells



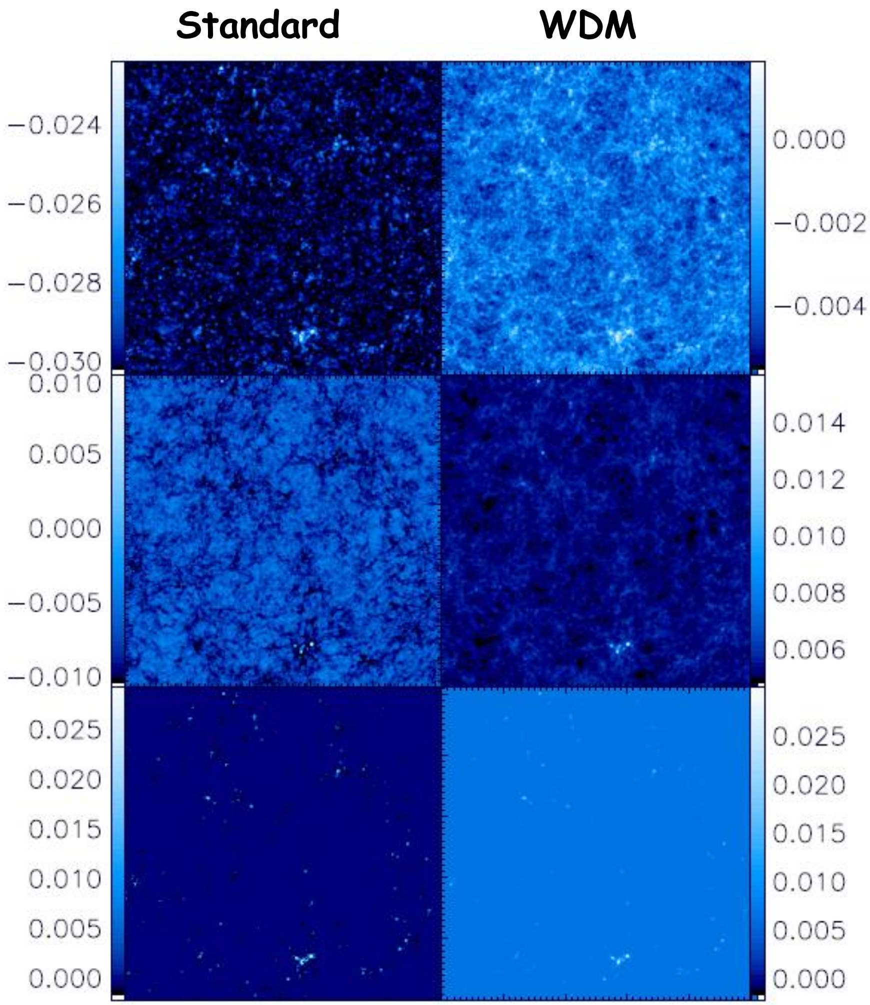
ΔT_b^* (mK)

GADGET simulation
768^3 particles, 512^3 grid
Box size= 10 h^{-1} cMpc
Particle mass = $1.4 \times 10^5 M_\odot$

* Lyα pumping is enhanced in the overdensities, resulting in better coupling of T_S to T_K.

* The energy absorbed fraction is higher in the overdensities. We assume $f_{abs} = 0.2$.

<u>*Inhomogeneous case: 21 cm maps*</u>



Differential brightness temperature, ΔT_b [mK]

<u>z = 40</u>: WDM turns the pure absorption scenario to a partial emission one.

<u>z =30</u>: the right panel presents an average emission of ~ 5 mK

<u>z = 20</u>: global step of ~ 10 mK: observable?

<u>Calculation for heavier annihilating DM candidates to follow soon, now that we have MEDEA2 energy depositions</u>

Valdés, Yoshida, Shimizu, Ferrara 2011 in prep.

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Conclusions

• To observationally constrain DM you need the energy depositions

→ MEDEA2 is a powerfull tool for DM studies

• Decaying/annihilating DM can affect the properties of high-z IGM

→21cm observations: a clean test of DM nature
→constrains from CMB seem hard given our low f_i

• Including structure formation enhances the DM effects

<u>NEXT:</u> → Study more DM candidates via MEDEA2
→ Gamma and X-ray constrains TBD soon
→ Simulations with effects on structure formation
→ Dark Stars