“Signatures of clumpy dark matter in the global 21 cm background signal”

D.T. Cumberland, M. Lattanzi, and J.Silk

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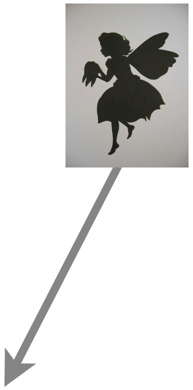
Daniel Grin
Ay. Journal Club
1/23/2009



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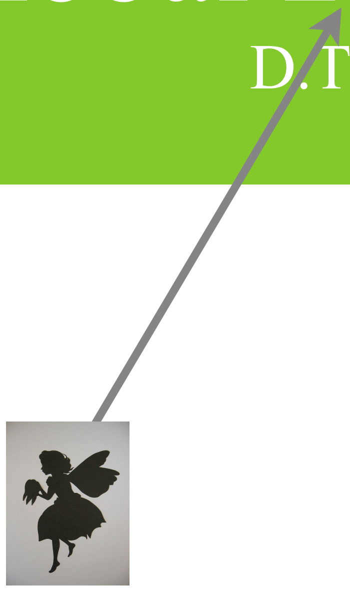

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Outline

- Dark matter candidates
- Clumping and dark matter annihilation
- Dark matter annihilation and IGM heating
- 21 cm physics and D.M. annihilation

Dark matter

- WIMPs (Weakly interacting massive particles):

$$10\ \text{GeV} \lesssim M_\chi \lesssim 1\ \text{TeV}$$

- Axions:

$$10^{-5}\ \text{eV} \lesssim m_{\text{a}} \lesssim 10^{-3}\ \text{eV OR } 1\ \text{eV} \lesssim m_{\text{a}} \lesssim 20\ \text{eV}$$

CAST, PVLAS, ADMX, stellar ev. constraints, telescope searches, γeV

- MACHOS
- Sterile Neutrinos: x-ray background, $\text{Ly}\alpha - \text{forest}$
- Light dark matter: INTEGRAL 511 keV excess, WMAP haze $\text{M}_{\text{DM}} \sim \text{MeV}$

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WIMPs

- Cold WIMPs can be all the dark matter (WIMP Miracle)

$$\Omega_x = \frac{5.5 \times 10^{-27}\ \mathrm{cm}^3 s^{-1}}{\langle \sigma v \rangle} \times \text{Function of slowly varying logarithms}$$

- SuSy solves hierarchy/gauge unification problem
- SuSy doubles SM particle number: LSP could be the dark matter
- Neutralinos: $\chi = A^B \tilde{B} + A^W \tilde{W}^3 + A_1^H \tilde{H}_1 + A_2^H \tilde{H}_2$
- Gravitinos: supersymmetric partner of graviton
- Experiments: COUPP, CDMS, ZEPLIN, DAMA, XENON, LHC, Fermi, EGRET, PAMELA, WMAP haze

Light dark matter

- Experimental motivation: unexplained excess of e^+e^- pairs detected at the galactic center through the 511 keV line measurements with INTEGRAL
- Coupling could be through a new U(1) boson that mediates SM interactions
- INTEGRAL +relic density constraints demand MeV scale dark matter with s-wave suppressed interactions

$$\sigma v \propto v^2$$

- Smaller-scale structure is suppressed (free-streaming):

$$R \lesssim R_{\mathrm{F}} = 7.4 \times 10^{-6} m_{\mathrm{MeV}}^{-4/3} \left(\frac{\Omega_m}{0.28}\right)^{1/3} \left(\frac{h}{0.72}\right)^{5/3} h^{-1}\ \mathrm{Mpc}$$

Dark matter annihilation and energy deposition into IGM

- Dark matter annihilates: $\chi\chi \rightarrow \mathrm{stuff}$
- Rest-mass energy of DM thermalized. Homogeneous specific heating rate:

Mass of DM particle

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

Efficiency of IGM absorption
Thermally averaged DM annihilation cross section

- This work includes enhancement in annihilation rate due to DM inhomogeneities

Halo clumping and IGM energy deposition by DM

- IGM energy deposition depends on halo population:

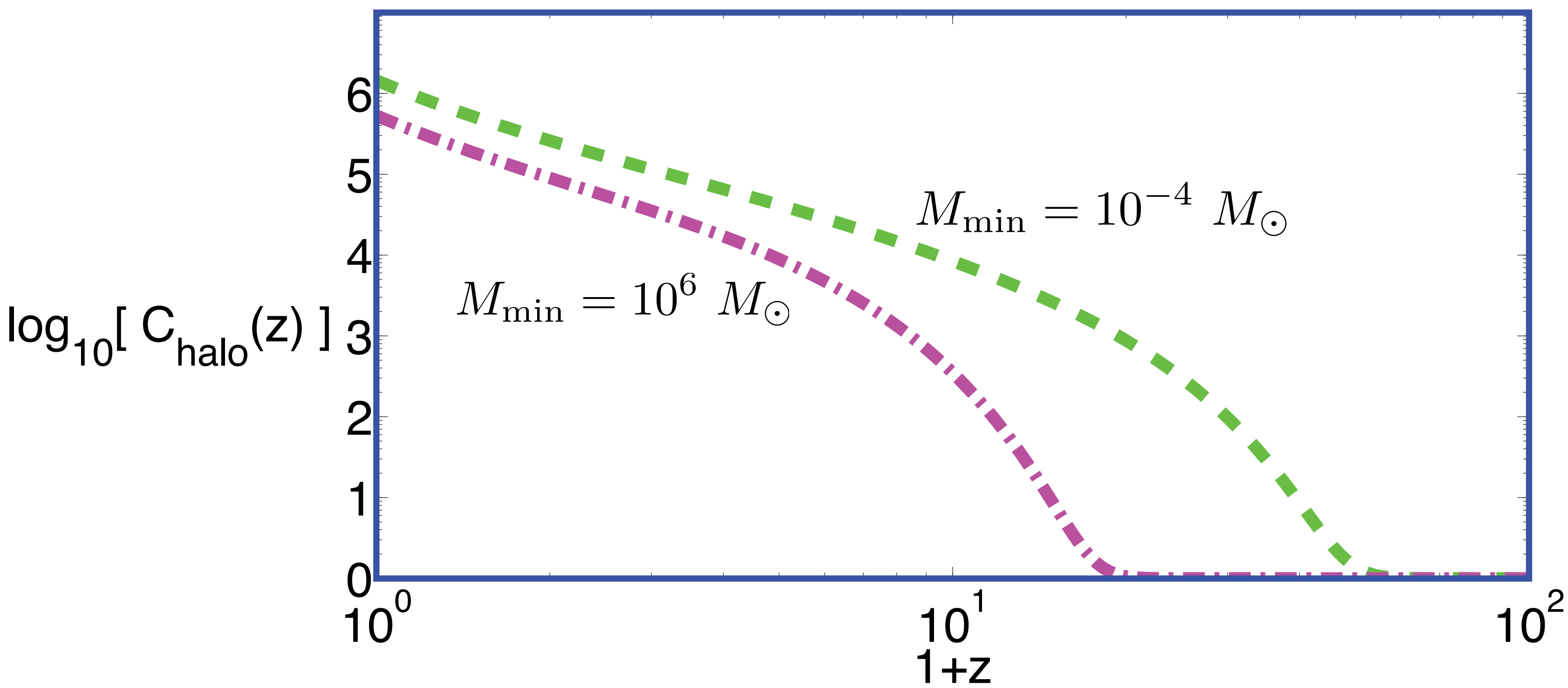
$$\Gamma(z) = (1+z)^3 \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}(M,z) R(M,z)$$

- IGM energy deposition depends on halo density profile:

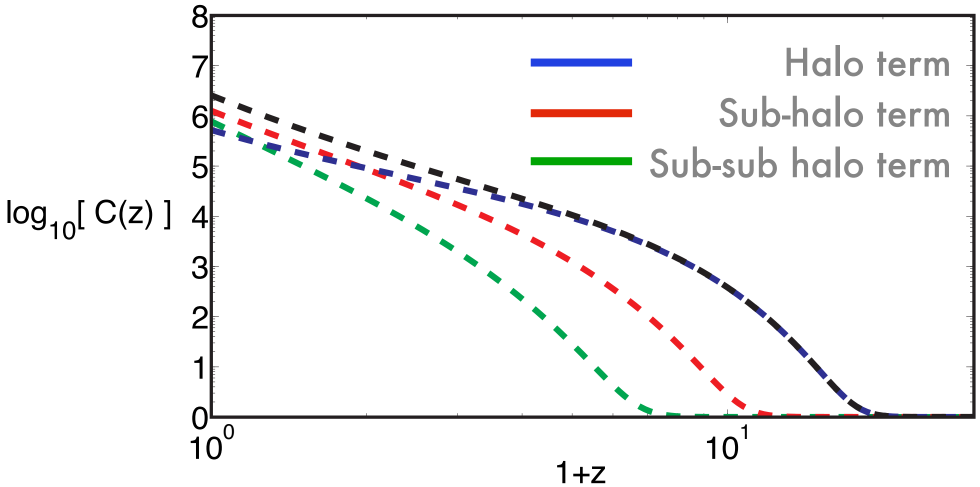
$$R(M,z) = \frac{\langle \sigma v \rangle}{m_{\rm DM}^2 \overline{n}_b(z)} \int_0^{r_{\rm vir}(M,z)} \rho^2(r) 4\pi r^2 dr$$

$$C(z) \equiv 1 + \frac{\Gamma(z)}{\overline{\rho}_{\rm DM}^2(z)/(m_{\rm DM}^2 \overline{n}_b(z))}$$

Halo clumping and IGM energy deposition by DM



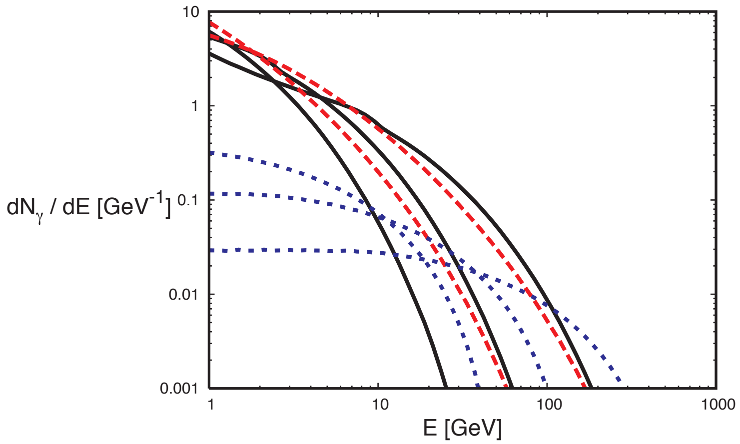
The effect of halo substructure

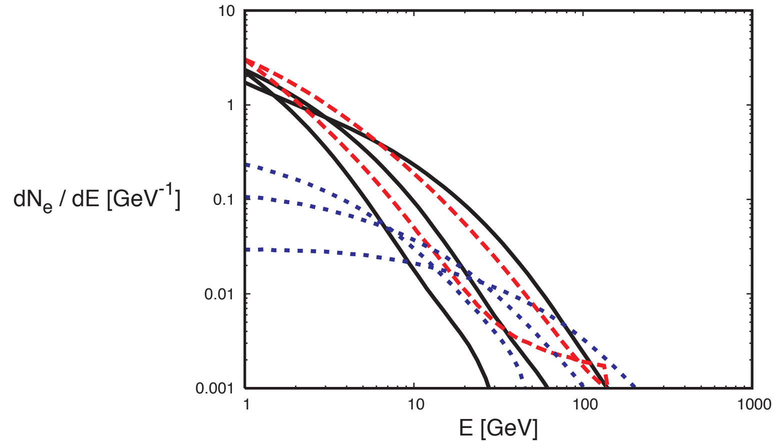


- VL II simulations show a hierarchy of substructure in halos with mass function $\dfrac{dN(M)}{dM_s} \propto M_s^{-2}$
- Substructure halos are more concentrated by a factor of ~ 3
- Rate due to substructure annihilation given by

$$R_{\rm sub}(M,z) = \frac{\langle \sigma v \rangle}{2m_{\rm DM}^2} \int dM_s \frac{dN(M, F_{\rm sub})}{dM_s} \int_0^{r_{\rm vir}(r,M_s)} \rho^2(r, c^{\rm sub}, M_s, z) 4\pi r^2 dr$$

Energy injection spectra





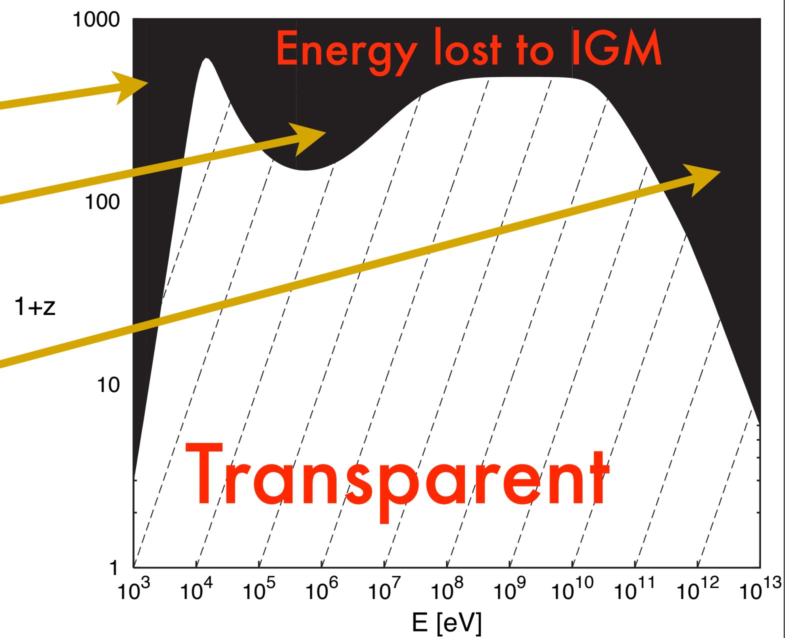
- WIMPs self annihilate $\chi\chi \rightarrow t\bar{t}, b\bar{b}, \tau^+\tau^-, W^+W^-$
- Decay products interact strongly, weakly, hadronize:
- Continuum radiation is produced: $\gamma, e^+, e^-, p,$ and ν
- LDM (3 and 20 MeV) annihilates into monochromatic e^+e^- pairs

Energy deposition into IGM by photons

- Absorption channels:

Dominant {
  - Photo-ionization
  - Compton scattering
  - Pair production on CMB photons

  - Scattering on CMB photons
  - Pair production on atoms/electrons/nuclei



- Simple criterion for absorption (not a real radiative transfer treatment):

$$\Gamma_{\rm abs}(z) > H(z)$$

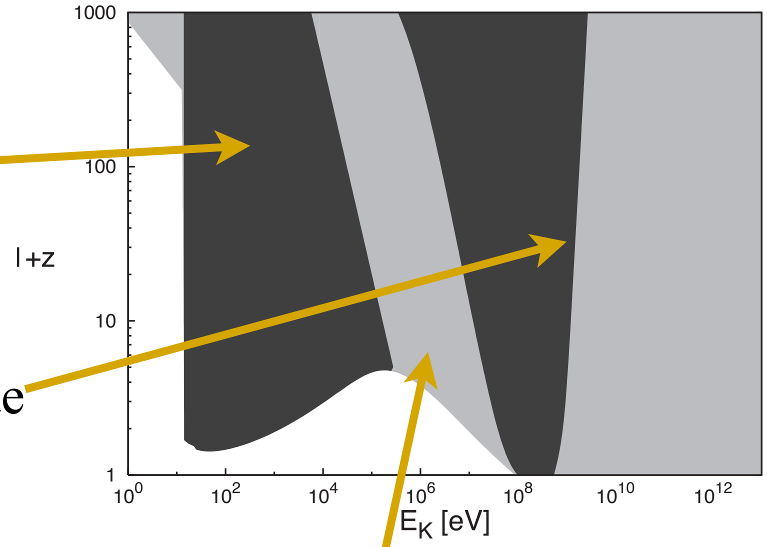
Absorption region

$$\mathrm{f_{abs}} = \frac{\sum_i \int_{A_i(z)} E \frac{dN_i}{dE} dE}{2 m_{\rm dm} c^2}$$

Energy deposition into IGM by e+e- pairs

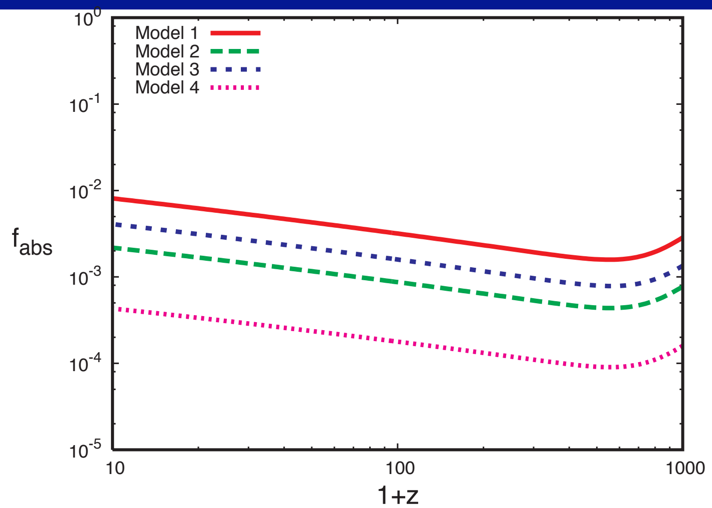
- Absorption channels:

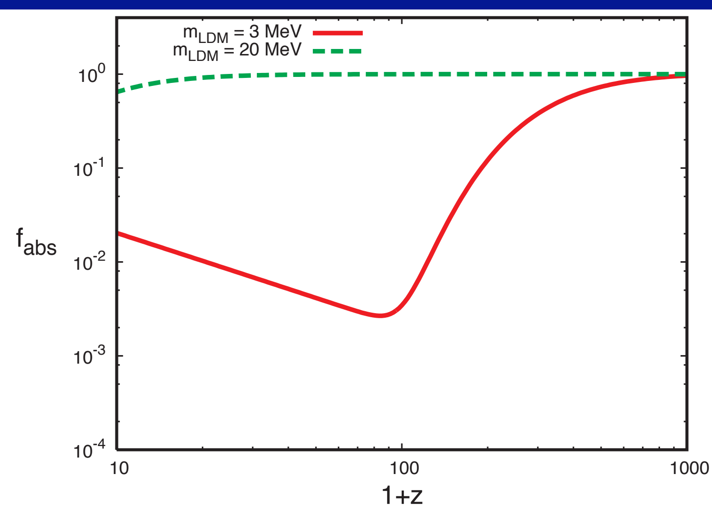
Dominant {
- Collisional ionization
- Compton scattering off CMB:
    - Then absorbed as on previous slide
}
- Annihilation with thermal e
- Synchrotron radiation



Compton photons in transparency window

Where does the energy go?

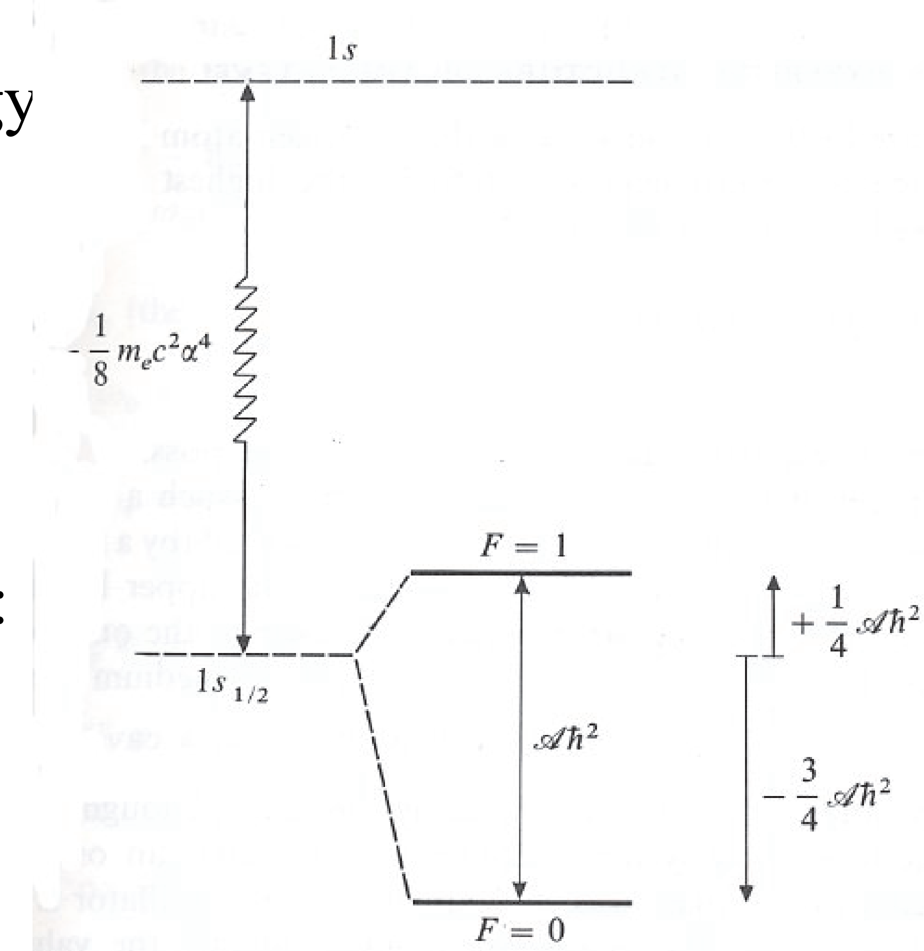




- Model 1: 50 GeV neutralino: $B_{b\bar{b}} = 0.96, B_{\tau^+\tau^-=0.04}$
- Model 2: 150 GeV, same branching
- Model 3: 150 GeV, $B_{W^+W^-} = 0.58, B_{ZZ} = 0.42$
- Model 4: 600 GeV, $B_{b\bar{b}=0.87}, B_{\tau^+\tau^-} = 0.13$
- Results of Chen, Kamionkowski (2004) used to determine how much energy goes to heat, ionization, evolution of $T_{\rm K}$

21 cm line physics: The basics

- Fine structure: SO and SR lower energy of HI ground state
- Hyperfine splitting: F=1 state less affected by SO interaction, higher energy than F=0 state
- Magnetic dipole transition, 21 cm line: $\nu = 1420.405751768 \pm 1$ Mhz



The 21 cm spin temperature

- Spin temperature defined by
  $$\frac{n_1}{n_0} \equiv 3e^{-hc/(\lambda k T_s)}$$
- Photon absorption couples T_s and T_α: Wouthuysen-Field effect
- Collisions couple T_k and T_s
- Resonant scattering couples T_k and T_α
- Quasi-static approx yields

$$T_s = \frac{T_\gamma + (y_\alpha + y_c)T_k}{1 + y_\alpha + y_c}$$

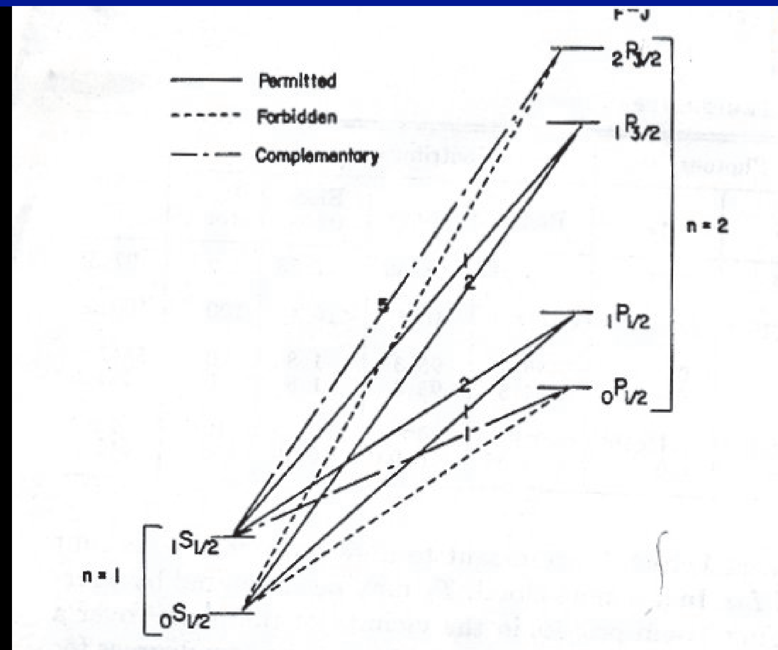


Fig. 3—The 1S and 2P levels of hydrogen, showing the particular transitions in the $L\alpha$ line which excite the triplet (dark lines). The numbers in the center are relative strengths.

$$T_* \equiv hc/k\lambda_{21\ \mathrm{cm}}$$

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

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

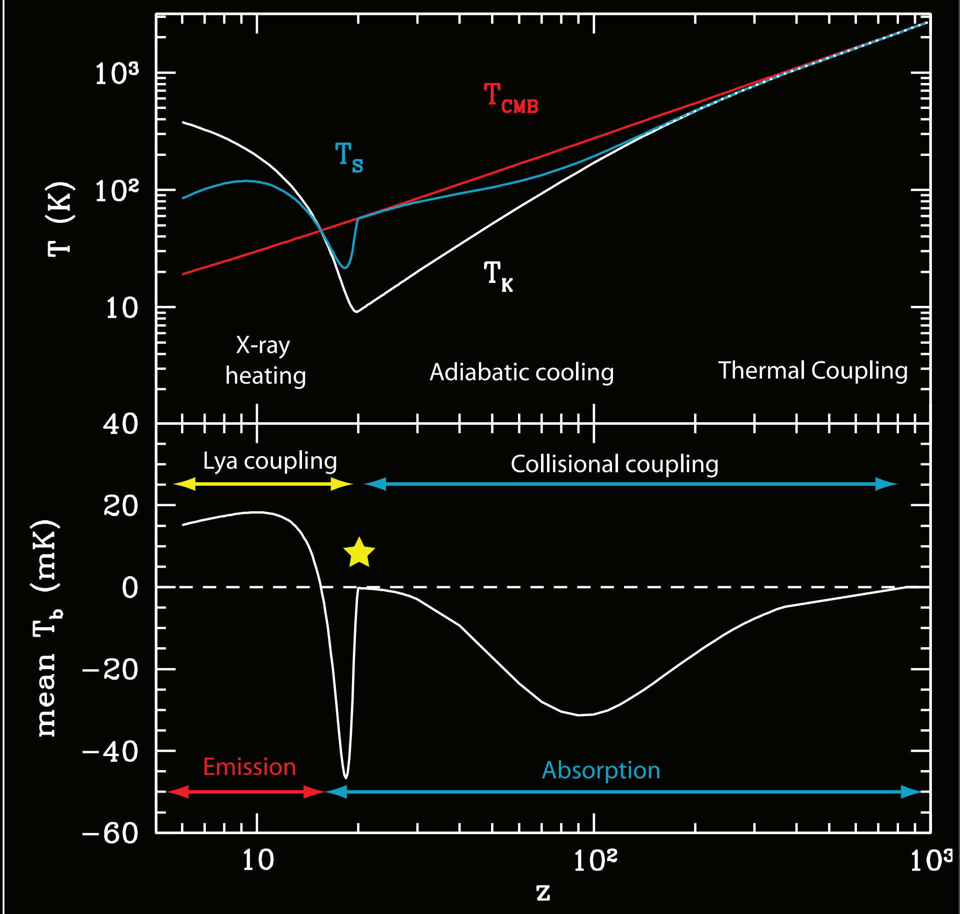
P_{10}: Wouthuysen effect rate

C_{10}: Collisional excitation rate of F=1 state

A_{10}: Spontaneous hyperfine rate

Evolution of the spin temperature

- Residual Compton scat. locks T_γ and T_k for z>200
- T_s then follows T_k until z<70, when hyperfine radiative transitions take over
- First sources turn on, heating neutral hydrogen



- Observable is

$$T_b = 26\ \mathrm{mK}\ x_{\mathrm{HI}} \left(1 - \frac{T_{\mathrm{CMB}}}{T_s}\right)\left(\frac{\Omega_{\mathrm{b}} h^2}{0.02}\right) \times \left[\left(\frac{1+z}{10}\right)\left(\frac{0.3}{\Omega_M}\right)\right]^{1/2}$$

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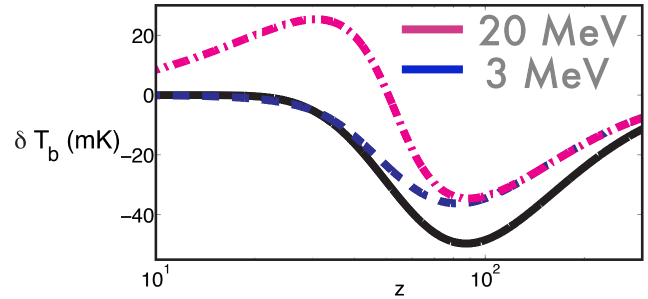
'Observable' 21 cm signal

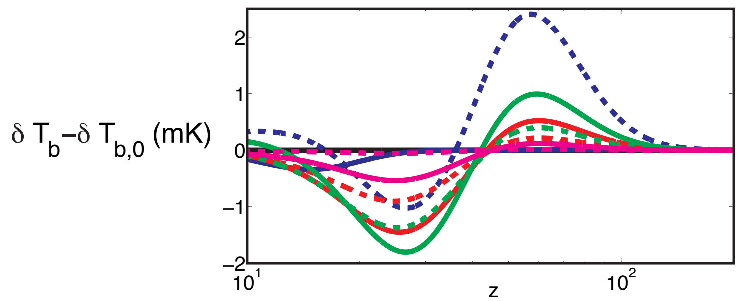
Parameters chosen to avoid early reionization

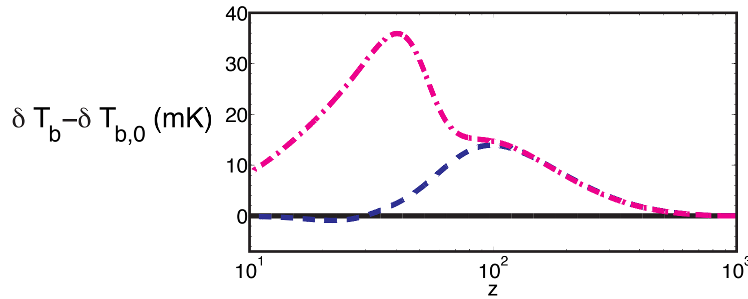
- Particle physics held fixed
- Density profile varied
- Sub(-sub)structure mass fraction varied

Used most optimistic parameters consistent with measurements of diffuse gamma-ray background (EGRET, COMPTEL) and diffuse X-ray background (INTEGRAL)

- LOFAR sensitivity is ~ $\delta T_b \simeq 1\ \mathrm{mK}$







Conclusions

- Proof of concept
- Standard neutralino models are marginally detectable
- More novel DM candidates stand a better chance
- SUSY parameter space should be more robustly explored
- Realistic (not optimistic) density profiles should be used, particularly for evaluation of clumping factors: Millenium/VL/VLII/Aquarius simulations?
- Sub-structure mass hierarchy may not be self-similar (see Aquarius)
- It would be useful to see realistic comparisons with LOFAR sensitivity