Gravitino, Axino, Kaluza-Klein Graviton Warm and Mixed Dark Matter and Reionization

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Stable particle dark matter may well originate during the decay of long-lived relic particles, as recently extensively examined in the cases of the axino, gravitino, and higher-dimensional Kaluza-Klein (KK) graviton. It is shown that in much of the viable parameter space such dark matter emerges naturally warm/hot or mixed. In particular, decay produced gravitinos (KK-gravitons) may only be considered cold for the mass of the decaying particle in the several TeV range, unless the decaying particle and the dark matter particle are almost degenerate. Such dark matter candidates are thus subject to a host of cosmological constraints on warm and mixed dark matter, such as limits from a proper reionization of the Universe, the Lyman- α forest, and the abundance of clusters of galaxies.. It is shown that constraints from an early reionsation epoch, such as indicated by recent observations, may potentially limit such warm/hot components to contribute only a very small fraction to the dark matter.

The nature of the ubiquitous dark matter is still unknown. Dark matter in form of fundamental, and as yet experimentally undiscovered, stable particles predicted to exist in extensions of the standard model of particle physics may be particularly promising. For a scale of the new physics around 1 TeV, as preferred by theoretical arguments, such dark matter abundances produced either during freeze-out of stable particles from equilibrium, or freeze-out of meta-stable particles and their subsequent decay into stable particles, may come tantalizingly close to the abundance required by cosmology. For this reason, a number of candidate dark matter particles, including also stable axinos produced in decays of next-to-lightest supersymmetric particles (NLSP); binos or staus [\[1,](#page-5-0) [2,](#page-5-1) [3,](#page-5-2) [4\]](#page-5-3), stable gravitinos produced via NLSP bino, stau, or sneutrino decays [\[5,](#page-5-4) [6,](#page-5-5) [7,](#page-5-6) [8,](#page-5-7) [9\]](#page-5-8), or stable KK-gravitons produced via the decay of KK $U(1)$ hypercharge gauge bosons [\[5](#page-5-4)], have been recently considered/reconsidered. For details and the theoretical motivation for the possible existence of such particles we refer the reader to the orginal literature.

In this note we consider the fact that particle dark matter (DM) produced by the decay of a relic population of metastable particles is often warm or even hot. This has been known for some time [\[10](#page-5-9)], but has escaped entering into the conlusions of some recent studies. This effect is also known to exist in the context of dark matter production by cosmic string evaporation [\[11\]](#page-5-10). Nevertheless, very recently the very same observation has been rediscovered in the studies by Cembranos et al. [\[12](#page-5-11)] and Kaplinghat [\[13\]](#page-5-12). These latter papers concentrate on the possible resolution of a number of alleged deviations between the observed sub-structure of galactic halos and structure of dwarf galaxies and that predicted in structure formation with a purely cold DM particle, whereas our study focusses mostly on constraining such warm- or mixed- dark matter models by reionization. In any case, for a complete view the reader is referred to the above studies as well.

Decay produced particle dark matter is often warm/hot, i.e. is endowed with primordial free-streaming velocities leading to the early erasure of small-scale perturbations [\[14](#page-5-13)], due to the kinetic energy imparted on the decay product during the decay process itself. Since axinos, gravitinos, and KK-gravitons are superweakly interacting, they will not thermalise after decay, and inherit as kinetic energy a good fraction of the rest mass energy of the mother particle. For decay $\chi \to \gamma + G$ of a massive particle χ to an essentially massless particle γ (with $m_{\gamma} \ll m_{\chi}$) and the dark matter particle \tilde{G} , with $m_{\chi} > m_{\tilde{G}}$ one finds for the instantaneous post-decay momentum of G

$$
p_{\tilde{G}}^i = \frac{(m_\chi^2 - m_{\tilde{G}}^2)}{2m_\chi} \,. \tag{1}
$$

The momentum of particles of arbritrary relativity redshifts with the scale factor of the Universe, and insisting for the particle to be non-relativistic at the present epoch, one may compute the present free-streaming velocity of the DM particle

$$
v_{DM}^0 = \left(\frac{m_{\chi}^2 - m_{\tilde{G}}^2}{2m_{\chi}m_{\tilde{G}}}\right) \frac{T_0}{T_d} \left(\frac{g_0}{g_d}\right)^{1/3},\tag{2}
$$

where T and g are cosmic temperarture and statistical weight of the plasma at the present '0' and particle decay ′d′ epochs, respectively. It has been shown that a sudden decay approximation, approximating all particles to decay at the same T_{d} , is excellent [\[3\]](#page-5-2), provided one uses the relation $t_d \simeq \Gamma_d^{-1}$ with $t = (2H)^{-1}$ in the early radiation dominated Universe, where t is cosmic time, Γ_d is the decay width of the particle, and H the Hubble constant, respectively. Using the above one finds

$$
v_{DM}^0 \simeq 4.57 \times 10^{-5} \frac{\text{km}}{\text{s}} \left(\frac{m_{\chi}^2 - m_{\tilde{G}}^2}{2m_{\chi}m_{\tilde{G}}} \right) g_d^{-1/12} \left(\frac{\tau_d}{1 \text{s}} \right)^{1/2}.
$$
\n(3)

Free-streaming velocities may become appreciable for either light DM particles (i.e. $m_{\tilde{G}} \ll m_{\chi}$) or late decay, a condition satisfied for much of the axino-, gravitino-, and KK-graviton- DM parameter space.

Cosmological constraints on warm dark matter deriving, for example, from the Lyman- α forest or cosmological reionization, are often formulated as lower limits on the mass of a hypothetical gravitino DM particle. Such limits assume a relativistically freezing out gravitino, leading thereby to a well-specified relation $v_{\rm rms} \simeq 0.044 \rm{kms}^{-1} (\Omega_{\tilde{G}} h^2/0.15)^{0.34} (m_{\tilde{G}}/1 \, keV)^{-1.34}$ [\[15](#page-5-14)] between gravitino mass and root-mean-square present day gravitino velocity (cf.e.g. to [\[16](#page-5-15), [17\]](#page-5-16)). However, it is rather the latter quantity, $v_{\rm rms}$, which is, without further assumptions about the nature and production mechanism of the dark matter, constrained by cosmology. Free-streaming particles erase primordial dark matter perturbations between very early times and the epoch of matter-radiation equality (EQ), after which further erasure becomes inefficient. Up to which scale perturbations have been erased than depends essentially only on v_{rms} and the time of EQ (determined itself by Ω_m , the total non-relativistic matter density), such that one finds [\[17\]](#page-5-16)

$$
R_c^0 \simeq 0.226 \text{Mpc} \left(\frac{\Omega_m}{0.15}\right)^{-0.14} \left(\frac{v_{\text{rms}}}{0.05 \text{ km/s}}\right)^{0.86}, \quad (4)
$$

by detailed Boltzman-equation simulations [\[18\]](#page-5-17). Here $\tilde{R}_c^0 \equiv 1/k_c$ defines the wave vector k_c for which the primordial power spectrum is suppressed by a factor two [\[19](#page-5-18)] when compared to the same cosmological model, but with cold dark matter. Armed with a relation between $v_{\rm rms}$ and gravitino mass, as well as Eq. [\(3\)](#page-0-0), we may now translate in the literature existing limits on relativistically freezing out gravitino warm dark matter, into limits on warm dark matter generated by particle decay. Here we employ decay widths as calculated in the original literature [\[20\]](#page-5-19).

We note here that the equivalence between traditional warm dark matter, described by a Fermi-Dirac distribution, and metastable particle decay produced dark matter, with a velocity distribution given by exponential decay, is not entirely perfect. This is due to the differing velocity distributions. Kaplinghat [\[13](#page-5-12)] computes the tansfer function for decay produced dark matter and finds differences in the damping tails between decay produced dark matter and warm dark matter. Nevertheless, given current measurement and theoretical uncertainties in cosmology, such as for example in the determination of the epoch of reionization, both types of DM should be considered as having equivalent effects on structure formation as long as they have an identical second moment of the distribution, i.e. an identical root-mean-square velocity.

There exists a large number of observable cosmological differences between scenarios with warm- (WDM) and cold- dark matter (CDM). It has even been argued that WDM has phenomelogical advantages over CDM, potentially resolving possible difficulties of CDM scenarios in explaining a scarce of substructure in Milky-Way type halos or the existence of cores in dwarf galaxies. Nevertheless, counterarguments in favor of CDM have also been presented, such that the situation is not resolved. We will here only focus on three cosmological implications of WDM or mixed dark matter (MDM) scenarios; namely the optical depth in the Lyman- α forest of mildly non-linear fluctuations on smaller scales ~ 1 Mpc [\[21\]](#page-5-20), the successful reionization of the Universe at high redshift (probing perturbations on the smallest scales \sim $10 - 100 \,\text{kpc}$ [\[17,](#page-5-16) [22\]](#page-5-21), and for the case of MDM, the abundance of clusters at close to the present epoch [\[23\]](#page-5-22). A recent analysis of the matter power spectrum as implied by observations of the Lyman- α forest and the cosmic microwave background anisotropies (CMBR) by the WMAP mission has yielded a 2σ lower limit on the WDM gravitino mass of $550 \, eV$ [\[21](#page-5-20)]. Using the above this may be translated to a limit $v_{\text{rms}}^0 \lesssim 0.1 \text{ km s}^{-1}$. One year of observations of polarization of the CMBR by the WMAP sattelite have revealed a high optical depth $\tau \approx 0.17 \pm 0.04$ [\[24](#page-5-23)] for Thomson scatterings of CMBR photons on electrons. The recently presented three year WMAP analysis has led to a downward revision of this value to $\tau \approx 0.09 \pm 0.03$ [\[25\]](#page-5-24), where error bars are one sigma and a ΛCDM concordance model has been assumed. This implies a fairly complete reionization of the Universe at redshift $8.5 \, \frac{<}{<} \, z \, \frac{<}{<} \, 15$ (at 95% confidence level) seemingly consistent with CDM scenarios. Such scenarios predict an early reionization of the Universe due to the early formation of sub-galactic halos and massive stars therein. The situation is different in WDM scenarios due to the lack of small-scale power and the concomitant late formation of the first stars. If the fairly high optical depth is indeed due to the first stars, rather than due to some 'exotic' mechanism, reionization places very stringent limits on the warmness of the DM. In particular, Yoshida et al. [\[22\]](#page-5-21) have shown that even for WDM with $m_{\tilde{G}} \approx 10 \,\text{keV}$ reionization is far from substantial at redshift $z \sim 17$ (appropriate to the τ central value of the one year WMAP analysis). This corresponds to $v_{\rm rms}^0 \lesssim 0.002 \,{\rm km \, s^{-1}}$. In the numerically expansive study of Yoshida et al WDM scenarios with $m_{\tilde{G}} > 10 \,\text{keV}$ have not been considered. As the case $m_{\tilde{G}} = 10 \,\text{keV}$ fails, even larger $m_{\tilde{G}}$ could potentially fail. Nevertheless, uncertainties in these calculations exist due to the modeling of the physics of gas cooling, radiation transport, and star formation. We thus regard such limits as preliminary.

Scenarios of DM due to decaying metastable particles often may come in the flavor of mixed dark matter when only a component of the DM is due to decay, with the other component possibly due to thermal scatterings at high temperature. Such scenarios of MDM scenarios may also be constrained by the abundance of clusters of galaxies [\[23\]](#page-5-22). Nevertheless, MDM may only be constrained by these means, in case the warm component is warm/hot enough to erase primordial perturbations on the scale of a cluster of galaxies. For $\lambda_c \equiv 2\pi/k \approx 20$ Mpc we find that a half wavelength roughly encompasses $10^{14}M_{\odot}$, the

FIG. 1: Contour plots of constant present-day free-streaming velocities in a variety of scenarios where the dark matter \tilde{G} is generated by the late decay of a non-relativistic primary $\chi \rightarrow \tilde{G} + \gamma$ (cf. Eq. 1). Results are shown in the plane of $m_{\tilde{G}}$ and $\Delta m \equiv m_{\chi} - m_{\tilde{G}}$ (all in GeV). The scenarios are bino-decay into gravitinos (red-solid), slepton decay into gravitinos (bluedotted), and B^1 decays into KK-gravitons (green-dashed). Shown are the contours of velocities (from top to bottom) $v = 0.002, 0.1,$ and 1 km s⁻¹, respectively. Also shown, by the thin dotted lines, are the contours where the effects of small-scale suppression due to the coupling of a charged slepton to the CMBR decaying later into a gravitino are similar to warm dark matter with $v = 0.002, 0.1$, and 1 km s⁻¹, respectively (see text for details).

approximate mass of a typical cluster. In order to erase perturbations on the scale λ_c the present day DM velocity has to exceed $v_{\text{rms}}^0 \gtrsim 1 \text{ km s}^{-1}$. If this is the case, however, only a fraction between $10-20\%$ of all the DM may be warm/hot [\[23](#page-5-22)] (cf. also to [\[21\]](#page-5-20) for similar limits from the Lyman- α forest).

In Fig. 1 WDM limits on gravitino DM produced by metastable particle decay are shown in the parameter space spanned by the mass splitting between the gravitino and the NLSP $\Delta m \equiv m_{\text{NLSP}} - m_{\tilde{G}}$ and the gravitino mass itself. The respective limits of v_{rms}^0 = $0.002, 0.1$, and 1km s^{-1} , as discussed above, are indicated as heavy lines for the cases when either the bino (longdashed) or the stau or sneutrino (solid) is the NLSP. The order of the lines is such that v_{rms}^0 exceeds the limit in the parameter space below the lines, with lines at higher Δm corresponding to a limit with lower v_{rms}^0 . It is seen that most of the parameter space results in WDM, potentially already in conflict with, at least, the high optical depth as inferred by WMAP. In particular, only for excessively large $m_{\rm NLSP} \,{}^>_\sim\, 5 \, \rm TeV$ decay produced gravitino dark matter may be considered almost cold. The limit may be less stringent when only a small component $\lesssim 10\%$ of the gravitino DM is due to decay, as then masses $m_{\rm NLSP} \, {\buildrel > \over {_{\sim}}} \, 100 \, {\rm GeV}$ ascertain that the decayproduced component is not too hot to delay the formation of clusters of galaxies.

We note here, however, that for gravitino masses not too small $(m_{\tilde{G}}^{\lt}\sim 0.1\,$ GeV for a bino NLSP and $m_{\tilde{G}}^{\lt}\sim 10$ GeV for a stau NLSP [\[7](#page-5-6), [8](#page-5-7)]) very stringent constraints on such scenarios apply from a disruption of Big Bang nucleosynthesis (BBN) with smaller mass splittings Δm preferentially constrained by the effects of electromagnetic energy injection after the epoch of BBN and distortion of the CMBR blackbody spectrum and larger Δm by hadronic three-body decays during and after BBN. In particular, ⁶Li [\[26\]](#page-5-25) production as well as significant perturbations of the ³He/D [\[27](#page-6-0)] ratio potentially rule out much of the parameter space at larger $m_{\tilde{G}}$. If such constraints are combined with the requirement of having the supersymmetric potential bounded from below, only very little parameter space remains, at least in the constrained minimal supersymmetric standard model (CMSSM) and for small tri-linear couplings A [\[28\]](#page-6-1). These limits are not shown in Fig. 1.

Fig.1 shows also analogous results for a $KK-B^1$ decaying into a photon and KK-graviton, with constraints indicated by the dotted line. It is seen that constraints from the warmness are not quite as stringent as in the gravitino case, yet, for m_{G^1} around the weak scale, $m_{B^1} \gtrsim 1 \,\text{TeV}$ is still required for a sucessful reionization by star formation. Only for much smaller $m_{G^1} \mathop{}_{\textstyle \sim}^{\textstyle <} 1 \, \text{GeV}$ may decay of lighter $m_{B^1} \stackrel{<}{_{\sim}} 300 \,\text{GeV}$ result in CDM. However, it is rather expected for the mass difference between the KK- $B¹$ and KK-graviton to be small, since it should be only due to radiative corrections. Almost degenerate $B¹$ and $G¹$ are then constrained by limits from BBN. It has recently been pointed out that a generation of dark matter by particle decay may lead to an additional suppression of small-scale power provided the decaying particle is charged [\[29](#page-6-2)]. Since the charged 'primary' is coupled to the CMBR sub-horizon perturbations in the primaryphoton fluid are below the Jeans mass. Perturbations may thus only start growing by the gravitational instability when decoupled from the CMBR, i.e. after the decay of the primary. In particular, it was found in Ref. [\[29,](#page-6-2) [30](#page-6-3)] that for a charged particle decay time of $\tau_d = 3.5 \text{ yr}$ the wavevector k_d where the power is reduced by half, when compared to a CDM scenario, is approximately $k_d \approx 3 \,\text{Mpc}^{-1}$ (assuming $h = 0.7$). Comparing this to Eq.[\(4\)](#page-1-0) one may infer a velocity $v_{\text{rms}}^0 \approx 0.078 \text{ km s}^{-1}$ which would yield a similar erasure of small-scale power due to finite DM velocities. An analogy between the net result of these two physically different small-scale power suppression mechanism may be established by noting that the damping scale due to charged particle decay is approximately the horizon scale at decay [\[29\]](#page-6-2), $\lambda_d \sim 0.265 \text{Mpc} (\tau/\text{yrs})^{1/2}$. Comparing this scale to Eq. [\(4\)](#page-1-0) the above limits of $v_{\text{rms}}^0 = 0.002, 0.1, \text{ and } 1 \text{km} \text{s}^{-1}$ translate to decay times $\tau_d \sim 3 \times 10^{-3}$, 2, and 125 yr, respectively. In Fig.1 the light lines are lines of constant decay time for the decay $\tilde{\tau} \to \tau + \tilde{G}$ with values as given above. Here shorter decay times are at higher Δm . It is seen that in the scenarios considered here the effects of free-streaming are generally more important than those of charged particle decay, though this may be different when other scenarios are considered [\[30\]](#page-6-3).

We now investigate the resulting free-streaming velocities in axino DM generation due to stau- $(\tilde{\tau} \to \tau + \tilde{a})$ and bino- $(B \to \gamma + \tilde{a})$ decays as proposed by Ref. [\[1](#page-5-0), [2](#page-5-1), [3,](#page-5-2) [4\]](#page-5-3). Taking the decay widths of the literature [\[31\]](#page-6-4) we find present root-mean-square velocities of

$$
v_0 \approx 14.7 \frac{\text{km}}{\text{s}} \left(\frac{m_{\tilde{a}}}{1 \text{ MeV}}\right)^{-1} \left(\frac{m_{\tilde{\tau}}}{100 \text{ GeV}}\right)^{1/2} \times \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right)^{-1} \left(\frac{f_a}{10^{11} \text{ GeV}}\right) (5)
$$

$$
v_0 \approx 1.68 \frac{\text{km}}{\text{s}} \left(\frac{m_{\tilde{a}}}{1 \text{ MeV}}\right)^{-1} \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right)^{-1} \left(\frac{f_a}{10^{11} \text{ GeV}}\right) (6)
$$

for stau- Eq. [\(5\)](#page-3-0) and bino- Eq. [\(6\)](#page-3-0) decay, respectively. Here m denote the masses for axino \tilde{a} , stau $\tilde{\tau}$ and bino \tilde{B} , and f_a , required to be in the range $10^{10} \text{GeV} \lesssim f_a \lesssim 10^{12} \text{GeV}$, is the scale where the chiral $U(1)$ -symmetry, related to the Peccei-Quinn symmetry is spontaneously broken. In the above we have neglected numbers of order unity and a very weak dependence on the statistical weight during decay. Velocities become excessively large for small $m_{\tilde{a}}$. It is evident that axinos generated by decay having masses $m_{\tilde{a}} \stackrel{<}{\sim} 10 \,(1) \,\text{GeV}$ should be considered as warm and may be in conflict with an early reionization by stars. However, since the decay contribution to the axino density $\Omega^{decay}_{\tilde{a}} = \Omega_{\tilde{B},\tilde{\tau}} m_{\tilde{a}}/m_{\tilde{B},\tilde{\tau}}$ becomes typically small when $m_{\tilde{a}}$ is small and moreover efficient production of "thermal" axinos during reheating is possible at low temperatures for small $m_{\tilde{a}}$ [\[33\]](#page-6-5), axino dark matter should be naturally mixed, rather than warm, with a small component of axinos with large velocities, and the rest essentially cold. Note that due to the relatively large decay width, suppression of small-scale power due to existence of a charged particle primary [\[29](#page-6-2)] is generally unimportant for axinos.

We have observed that constraints on warm dark matter from cosmic reionization may become very stringent, particularly if an early reionization epoch as indicated by the excessive low multipole CMBR polarization in the WMAP data [\[24](#page-5-23)] is confirmed. On the other hand, gravitino- and axino- dark matter scenarios often are coming as mixed dark matter scenarios with only a smaller fraction of the dark matter warm/hot. As we will see, even in this case future constraints could be very stringent.

The Universe is believed to have been reionised mostly due to UV-radiation by the first stars, with likely only a small contribution due to the UV-radiation emitted by quasars [\[17\]](#page-5-16). It has been shown [\[34\]](#page-6-6) that the collapse of the smallest halos and the stars which form therein actually impede further star formation as the principal cooling agent H_2 is photodissociated. Only when harder radiation $\sim 1 \,\text{keV}$ is emitted at the same time, cooling of baryons in small halos is still possible. Efficient star formation and reionization thus generally may only occur

4

FIG. 2: Contour plot of the redshift z when a fraction 10^{-2} of all baryons is collapsed within halos exceeding a virial temperature of 10^4 K. Results are shown depending on the warm/hot dark matter fractional contribution to the present critical density Ω_x and the present free-streaming velocity v_x in km s⁻¹ of the warm/hot component. The calculation assumes the remainder of the dark matter $\Omega_c = 0.26 - \Omega_x$ to be cold. The shown redshifts may be identified with the approximate reionsation redshift when a "standard" reionsation efficiency is assumed. For comparison, the WMAPIII results of optical depth $\tau = 0.09 \pm 0.03$ imply a reionization redshift within the Λ CDM concordence model between $z \approx 8.5 - 15$ at 95% confidence level. The star indicates a recent limit [\[21](#page-5-20)] on a small contribution of $m_{\tilde{G}} \stackrel{>}{\sim} 16\;$ eV thermal gravitinos to the dark matter ruled out by a combination of CMBR and Lyman- α forest data. Regions above and right of the dashed line should be ruled out by these considerations (see text).

FIG. 3: As Fig.2, but for a collapse fraction 10^{-4} , corresponding to a factor ∼ 100 more efficient reionization than inferred from present-day properties of star clusters and star formation.

FIG. 4: As Fig.2, but for a spectral index for the adiabatic primordial perturbations of $n_s = 1$.

when larger halos, with virial temperatures $T_{vir} \, \gtrsim 10^4 \text{K}$, may collapse as in such halos cooling is possible due to atomic hydrogen. The typical UV-radiation production for a star cluster at low metallicity and for an initial mass function close to that observed locally is estimated around $N_{\gamma} = 4000$ ionising photons per stellar proton. Since normally only a small fraction $f_{\star} \sim 10\%$ of the gas forms stars and moreover only a small fraction $f_{esc} \sim 10\%$ is capable of leaving the host galaxy, one may estimate around 40 ionising photons per collapsed and cooled baryon. This implies that the fraction of halos $F(T_{vir} > 10^4)$ with virial temperature larger than 10^4 K has to be rather large, $\geq 1/(N_{\gamma}f_{\star}f_{esc}) = 2.5 \times 10^{-2}$. Note that this conservatively neglects further recombinations. A virial temperature of 10^4 K corresponds to a mass scale of $M_{10^4} \approx 3 \times 10^7 M_{\odot}[(1+z)/11]^{-3/2}$ where z is redshift.

We have utilised CMBFAST in order to find the transfer function in models of mixed dark matter with varying warm/hot dark matter fractions Ω_x and root-meansquare velocity v_x . The transfer function allowed us to compute the collapsed mass fraction $F(M)$ as a function of redshift. Our models assume $\Omega_x + \Omega_c + \Omega_b = 0.3$, where Ω_c is the cold dark matter density parameter and Ω_b is the baryonic density parameter, and we assumed $\Omega_b = 0.04$ and a Hubble parameter of $h = 0.65$. Most of our calculations assume a red spectral index for scalar adiabatic perturbations $n_s = 0.951$ corresponding to the central value of the by the after three years of WMAP observations determined $n_s = 0.951^{+0.015}_{-0.019}$ within the ΛCDM concordance model. This model assumes a negligible contribution of primordial gravitational waves to the CMBR anisotropies. Gravitational waves due to an inflationary epoch mostly contribute to the CMBR anisotropies on large scales. If present, they may therfore also describe the WMAP data well, albeit with a lower normalisation of scalar perturbations on the largest scales and a larger spectral index n_s . As the two sigma upper limit on n_s from a combination of WMAP observations and large-scale structure surveys (and in the absence of a running spectral index) is close to one, we have also utilised a Harrison-Zeldovich spectrum $n_s = 1$ for one particular computation. This may be indicative of variations of our results with respect to the assumed cosmological model. All models are normalized on the present horizon scale (taking COBE-DMR results, i.e. Eq.(30) in Ref. [\[35\]](#page-6-7)), irrespective of if gravitational waves are present or not. Finally, the warm component was simulated by adding a massive "neutrino" to the fluid with a root-mean-square velocity of v_x , while keeping also the three massless standard model neutrinos.

In Fig. 2 we show the redshifts at which in a particular mixed model (defined by Ω_x and v_x) a fraction > 10⁻² of all baryons have collapsed within halos exceeding a virial temperature of 10^4 K. Assuming an essentially instantaneous baryon cooling and star formation [\[36\]](#page-6-8), and given the required $F(T_{vir} > 10^4) > 2.5 \times 10^{-2}$ as inferred in a "standard" reionization scenario, this redshift z may be approximately indentified with the epoch of reionization. It is seen that even for warm/hot dark matter fractions as small as $\Omega_x \sim 10^{-3} - 10^{-2}$ reionization with standard efficiencies may be problematic for redshifts larger than $z > 10$. This should be compared to the current estimate of $z_{reion} \approx 8.5-15$ as inferred by WMAP, indicating the potentially stringent nature of limits one could potentially derive on very small warm/hot dark matter fractions from reionization. Such limits, if holding up againts future observational tests, could severely constrain the nature of particle dark matter, by requiring it to be essentially exclusively cold.

However, it needs to be stressed here, that the results as shown in Fig. 2 (as well as in the figures which follow) are not intended by the authors to be employed to derive limits on mixed dark matter models. This is due to a variety of reasons, such as uncertainties in the reionization process and cosmological model (see below), but also due to the fact that we have not marginalized over all cosmological parameters entering the analysis. Furthermore, different constraints, not shown in the figures, may be of importance. For example, models with relatively large v_X and Ω_X , corresponding to a significant hot dark matter component, may potentially be ruled out simply by a relative mismatch between the predicted and observed powers on $8 \text{ Mpc} \, h^{-1}$ and the present horizon scale $3000 \,\mathrm{Mpc} \,h^{-1}$, respectively. This is due to the hot component erasing power on $8 \text{ Mpc} h^{-1}$ due to freestreaming.

Intrinsic uncertainties about the reionization process during the dark ages are still large enough to evade drastic conclusions. It may be that either the effiency of star forming regions to produce UV-radiation (by a topheavy initial mass function, for example) or the escape fraction/star formation effiency are substantially larger at early times than at the current epoch. Most of such

evolutionary effects should be testable, by, for example searches for very high redshift galaxies or heavy element abundances in the high redshift gas, by the NGST (nextgeneration space telescope). In Fig. 3 we show the redshifts where a much smaller fraction of 10^{-4} of the gas was able to collapse in virial halos with $T_{vir} > 10^4$ K. This corresponds to a factor 100 increase in "reionization" efficiency. It is seen that fairly early $z \sim 16$ reionsation epochs are possible except when Ω_x becomes large \geq 10⁻² and free-streaming velocities are not too small $v_x \stackrel{\text{>}}{_{\text{sim}}} 0.1 \text{ km s}^{-1}$. It is evident, that even with a factor ∼ 100 higher efficiency reionization than expected, and provided the reionization redshift is found to be larger than $z \geq 12$, limits from reionization on warm/mixed dark matter may be more stringent than those derived from the CMBR-Lyman- α forest. This conclusion is also in accord with the numerical simulations recently performed in Ref. [\[22\]](#page-5-21).

Both plots show by the star and the lines also the recently derived limit [\[21](#page-5-20)] on a small thermal warm/hot gravitino component from a combination of WMAP-CMBR data (probing perturbations on larger scales ∼ $10-3000$ Mpc) and the Lyman- α forest (probing perturbations on smaller scales $\sim 1 - 40 \,\text{Mpc}$. The models considered in Ref. [\[21\]](#page-5-20) are lying on the diagonal dotted line and are ruled out because of a too severe suppression of the power spectrum at small scales, at odds with observations of the Lyman- α forest. Models with the same Ω_X

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but even larger v_X than that indicated by the star, moving the power spectrum supression to even larger scales, should also be at odds with the observations. We have therefore added a vertical dotted line, such that the region in the right upper hand corner of the star (bounded by these dotted lines) should be ruled out.

Similarly, uncertainties in the prediction of the reionization redshift in mixed dark matter models are also due to uncertainties in the cosmological model and/or scalar spectral index n_s . In Fig. 4 we show the reionization redshift in our simple reionization model for the same required collapse fraction and virial halo temperatureas as in Fig. 2, but for a model which has a Harrison-Zeldovich n_s spectral index. It is seen that the requirement of early reionization is more easily satisfied for $n_s = 1$ than for $n_s = 0.951$. Nevertheless, the change is not big and amounts only to $\Delta z_{reion} \approx 2$. We have also varied the COBE normalization, moving it approximately two sigma upwards (resulting in a factor 1.14 larger perturbations) and have obtained very similar results to those shown in Fig. 4, i.e. approximately $\Delta z_{reion} \approx 2$. We conclude that the proper reionization of the Universe seems a promising alley in constraining warm and mixed dark matter scenarios. Finally we note that the potentially strong constraints on warm/mixed dark matter possible from a determination of the reionsation redshift have also been noted in the two very recent papers of Refs. [\[12,](#page-5-11) [13](#page-5-12)]

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