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Cosmology with long-lived charged massive particles (CHAMPs)

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Based on

A. Kamada, Kohri, T. Takahashi, N. Yoshida, arXiv:1604.07926 [astro-ph.CO]

Abstract

- We have some strong motivations to consider a long-lived charged massive particle (CHAMP), e.g., NLSP stau with weak scale masses and so on.
- CHAMPs are severely constrained by BBN
- CHAMPs may solve the ``Missing Satellite Problem''
- CHAMPs can be constrained by cosmological observations such as CMB or LSS

Introduction

What is Dark Matter?

- Massive ($\rho \propto a^{-3}$)
- Relatively stable ($\tau \gg 10^{18}$ sec)
- It does not scatter off photons so much
- It is almost neutral (forming a bound state?)
- The velocity dispersion is small [in order to become cold dark matter (CDM)]

$$\underline{k_{FS}^{-1} < \sim O(1) \text{ Mpc}}$$

Structure formation with CDM

Cold Dark Matter (CDM) has an essential role for formation of Large Scale Structure (LSS), i.e, galaxies and clusters of galaxies

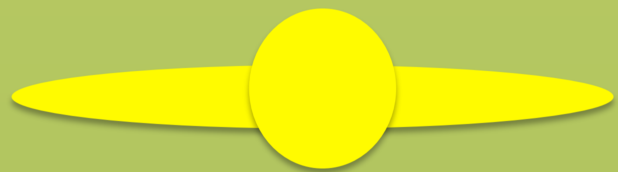
- Only pure fluctuation of baryon is too small to produce LSS because of acoustic oscillation and Silk damping
- CDM fluctuation evolves after matter-radiation equality epoch, which is ahead of baryon fluctuation

$$\delta \propto a(t)$$

- Baryon fluctuation catches up with CDM fluctuation after recombination

Time-evolution of the fluctuation to produce a galaxy

First, dark matter halo was produced in the early universe



Then a galaxy (made by baryons) is produced inside the CDM halo due to the gravity of dark matter

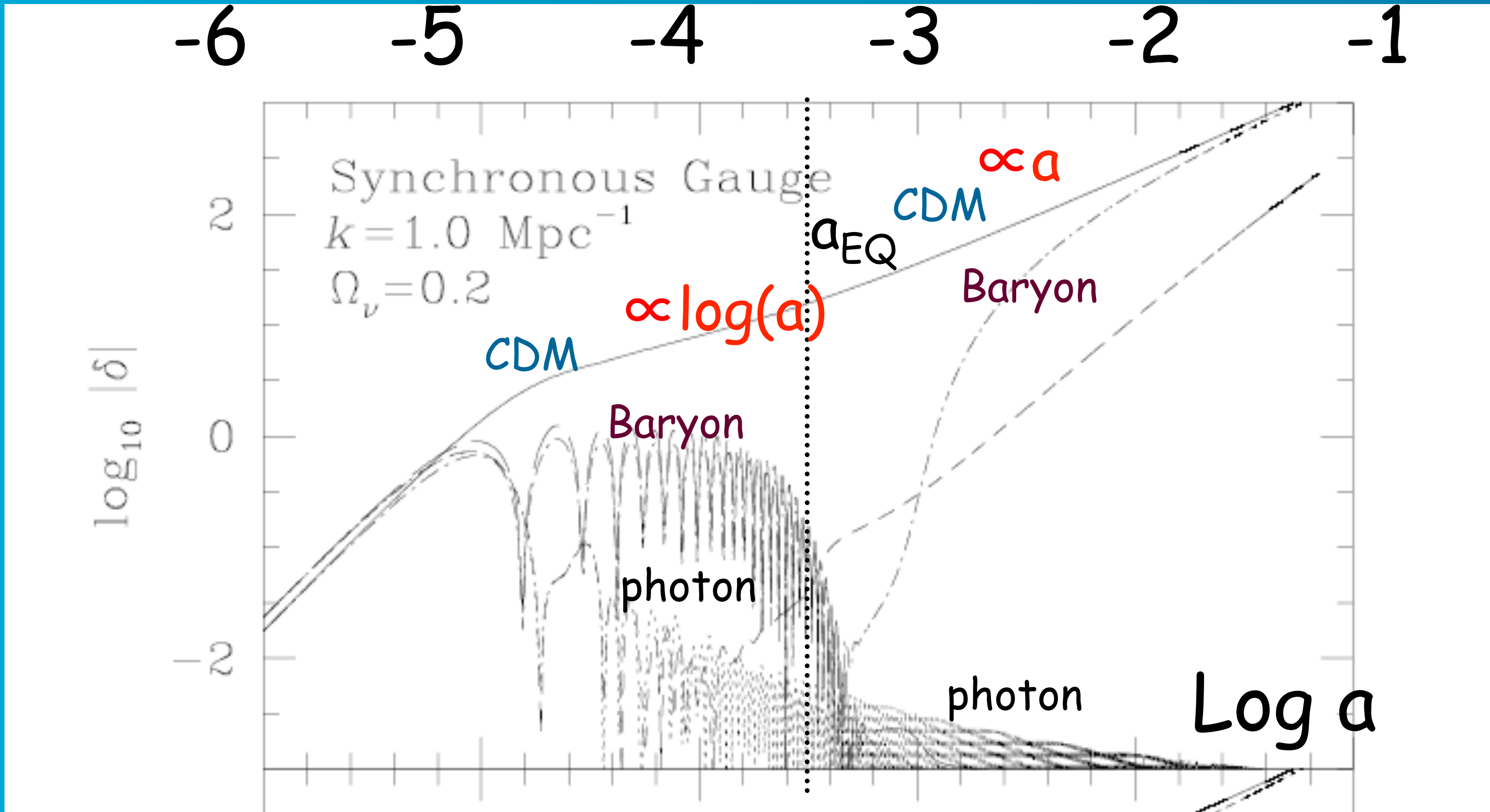
We need $\frac{\rho_{DM}}{\rho_{baryon}} \sim 5$

Evolution of density perturbation

- Before the horizon reentry, there is no evolutions of the density perturbations
- Perturbations within a horizon scale can evolve after the matter-radiation equality (called "stagspansion")
- Only after the recombination, baryon perturbations can evolve

Time-evolution of fluctuation

Horizon reentry before matter-radiation equality epoch



$z_{EQ} \sim 3000$

$z_{rec} \sim 1000$

Ma and Bertschinger (95)

CHAMPs with BBN

CHAMPs with BBN

Cahn and Glashow (1981)

Kohri and Takayama, hep-ph/0605243

CHAMPs may recombine with light elemcts

$E_{bin} \sim \alpha^2 m_i \sim 100\text{keV}$, $a_{Bohr} \sim (\alpha m_i)^{-1}$

$T_c \sim E_{bin}/40 \sim 10\text{keV}$ ($t \sim 10^3$ sec)

See standard recombination between electron and proton,

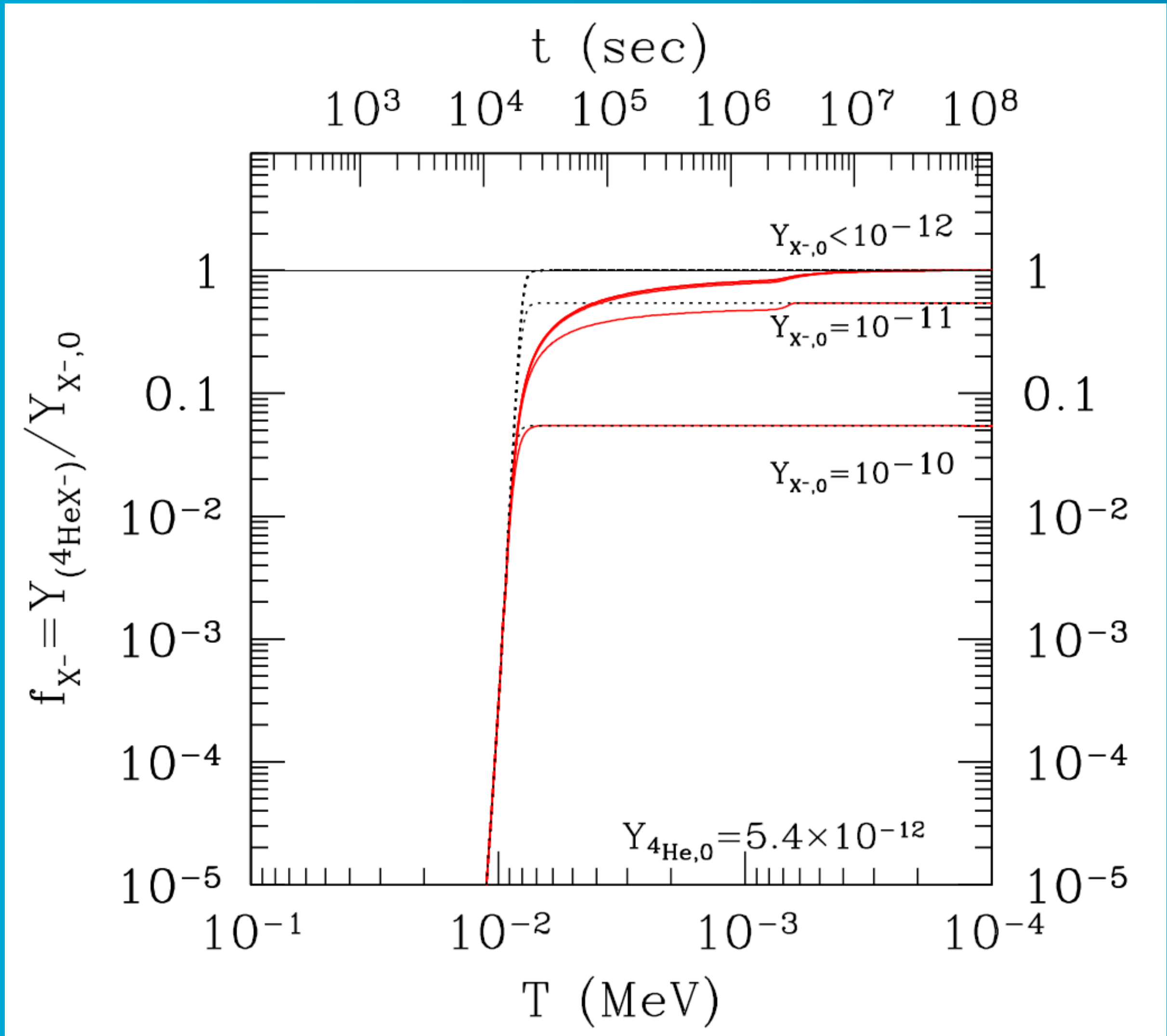
($E_{bin} \sim \alpha^2 m_e \sim 13.6\text{eV}$, $a_{Bohr} \sim (\alpha m_e)^{-1}$

$T_c \sim E_{bin}/40 \sim 0.1\text{eV}$, $t \sim 10^{13}$ sec)

Bound states (C,^{4}He) changes the nuclear reaction rates dramatically in BBN

Fraction of bound state with ^{4}He

Kohri and T. Takahashi (2009)



Most of CHAMPs are included into He4 for

$Y = n/s < 10^{-12}$

They are still positively-charged!

Pospelov's effect

Pospelov (2006),**hep-ph/0605215**

- CHAMP bound state with ^{4}He enhances the rate $D + {}^4He \rightarrow {}^6Li + \gamma$

$$D + ({}^4He, C^-) \rightarrow {}^6Li + C^-$$

- Enhancement of cross section

$$\sim (\lambda_\gamma / a_{Bohr})^5 \sim (30)^5 \sim 10^{7-8}$$

Confirmed by Hamaguchi et al (07), hep-ph/0702274

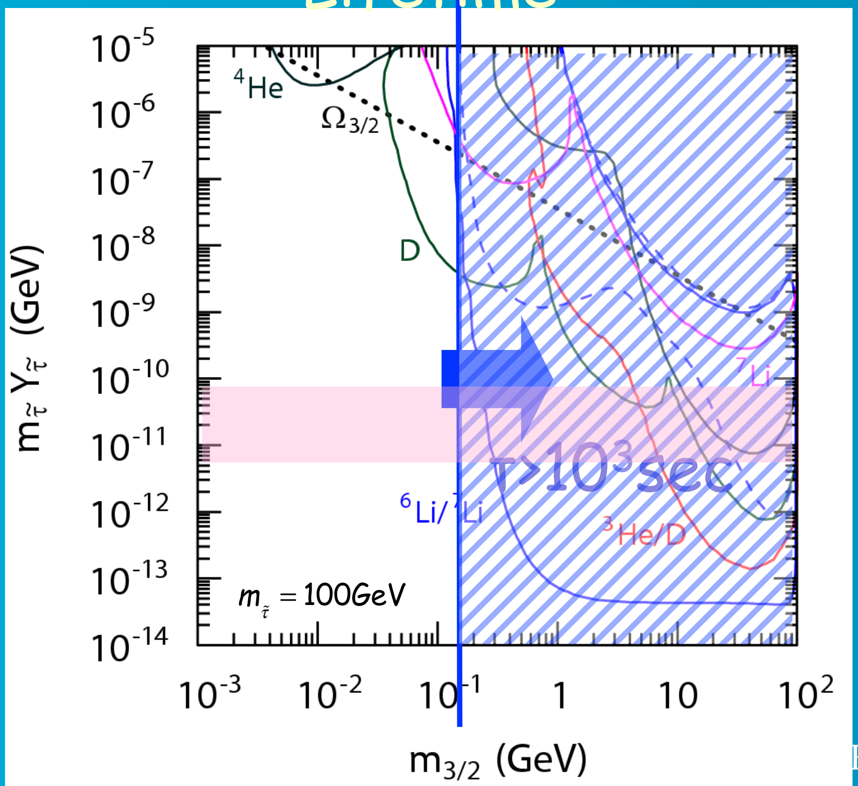
Stau NLSP and gravitino LSP Scenario in gauge mediation

Kawasaki, Kohri, Moroi PLB 649 (07) 436

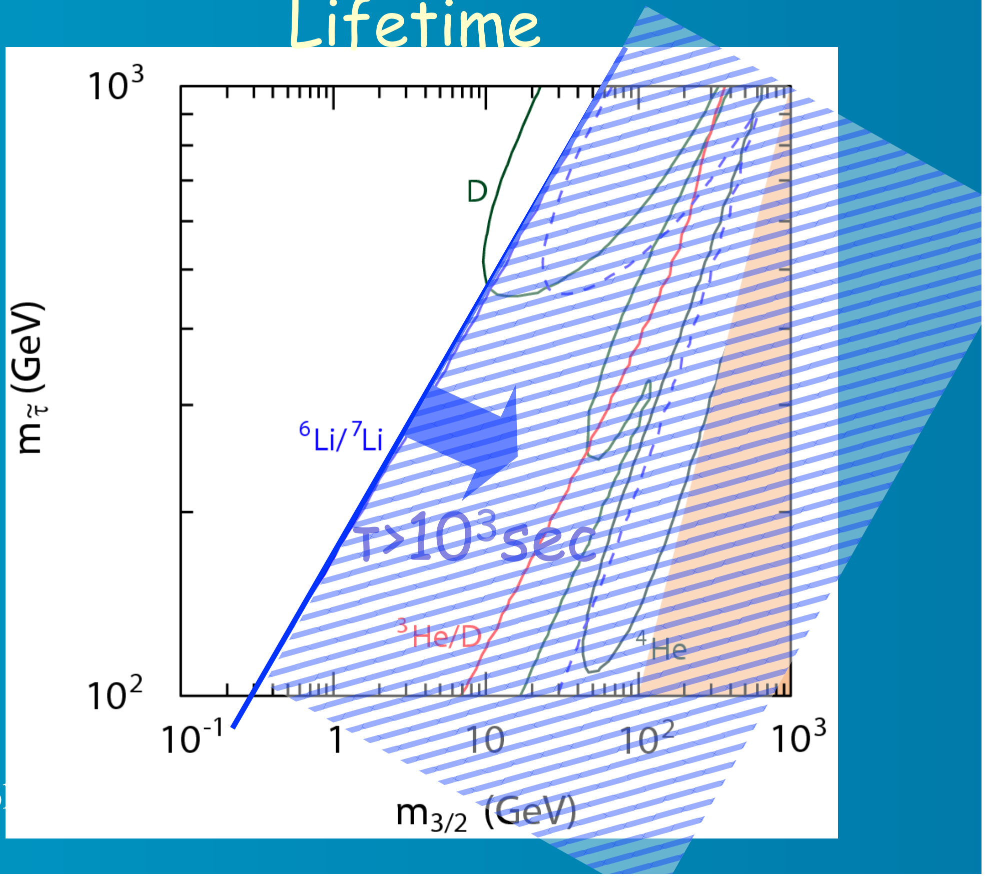
Relic abundance

$$Y_{\tilde{\tau}} \simeq 7 \times 10^{-14} \times \left(\frac{m_{\tilde{\tau}}}{100\ \mathrm{GeV}}\right)$$

Lifetime



Lifetime



Suppression of density perturbation by long-lived charged massive particle (CHAMP)

Large-scale structure (LSS)

Shigurdson and Kamionkowski (04)

Kohri and Takahashi (09)

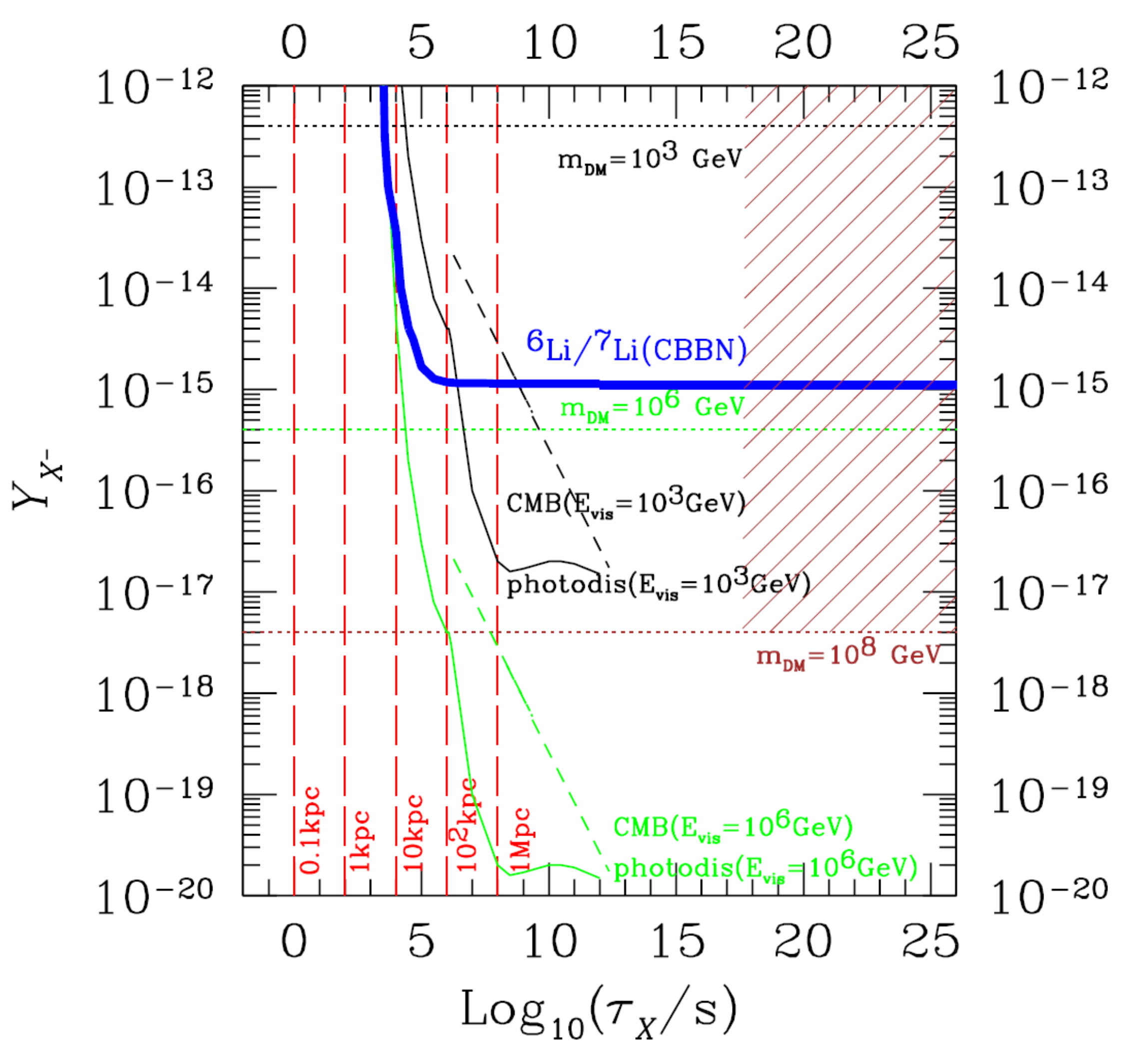
- The perturbation of CDM could evolve without interacting background plasma of photon, proton and electron

- Acoustic oscillation of CHAMP-radiation fluid could have suppressed the density perturbation of galaxy scale at its decay time $k_{\rm Ch} = aH|_{t=\tau_{\rm Ch}}$

$$k_{Ch}^{-1} \sim 1\ \mathrm{Mpc}\left(\tau_{Ch}/10^{8}s\right)^{1/2}$$

Constraint from Large-Scale Structure

Kohri and Takahashi (09)



←BBN allows long-lived CHAMP with >10^6 GeV

←Massive stable CHAMPs DM (>10^8 GeV) can be allowed by the sea water experiments?

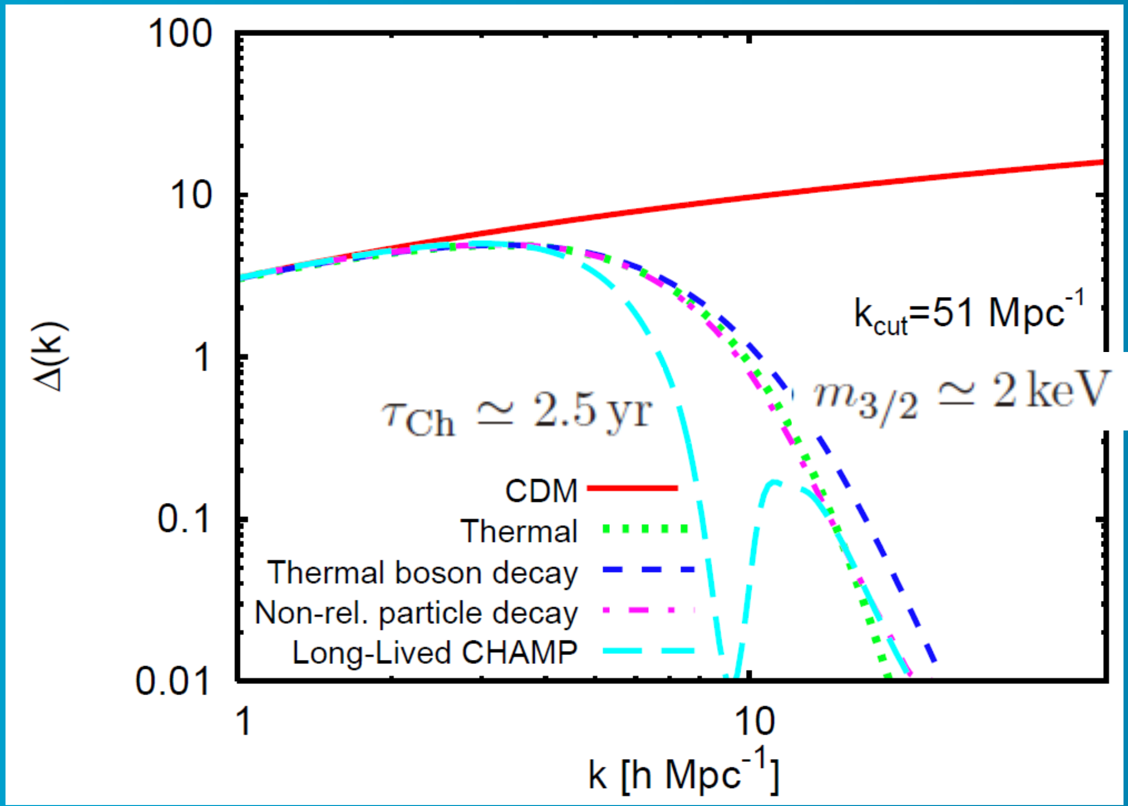
From now on, let us assume that the electromagnetic visible energy can be negligible for a decaying CHAMP for simplicity

Missing satellite problem

- The number of observed satellite galaxies in our galaxy (O(10) is much smaller than the predictions by N-body simulations (~O(100) or more)

Power spectrum

$$k_{\rm cut} \equiv k_{\rm J} \simeq 45\, k_{\rm Ch}$$



A.Kamada, Yoshida, KK, T.Takahashi (2013)

N-body simulation

A.Kamada, Yoshida, KK, T.Takahashi (2013)

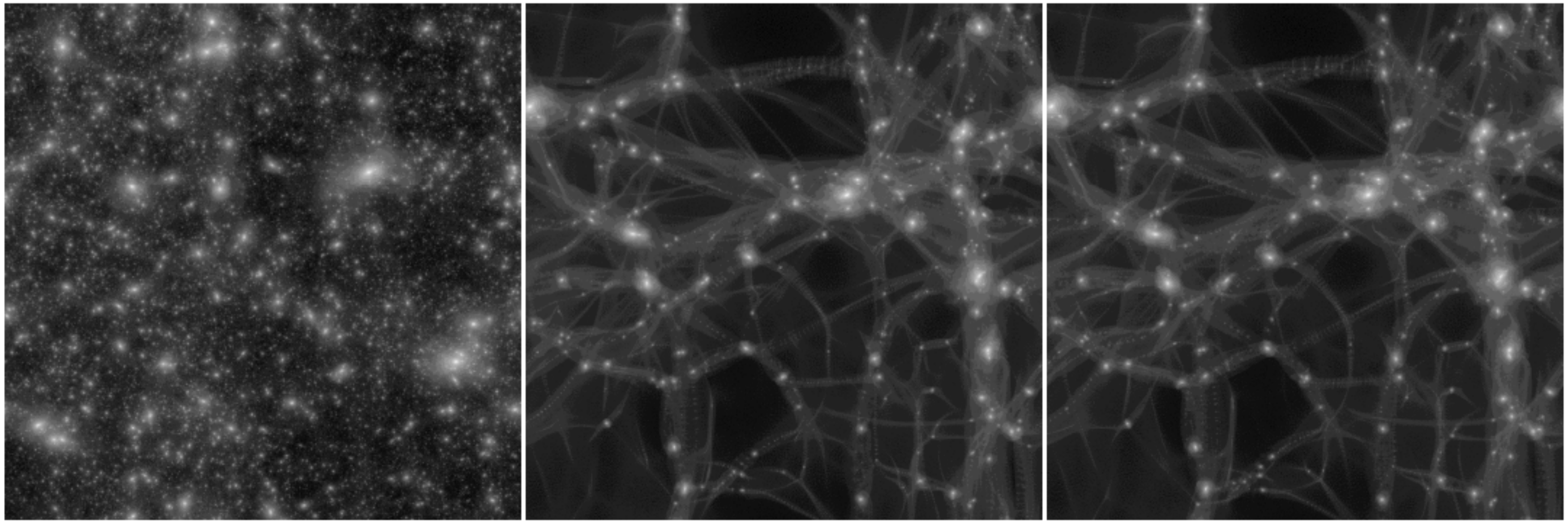
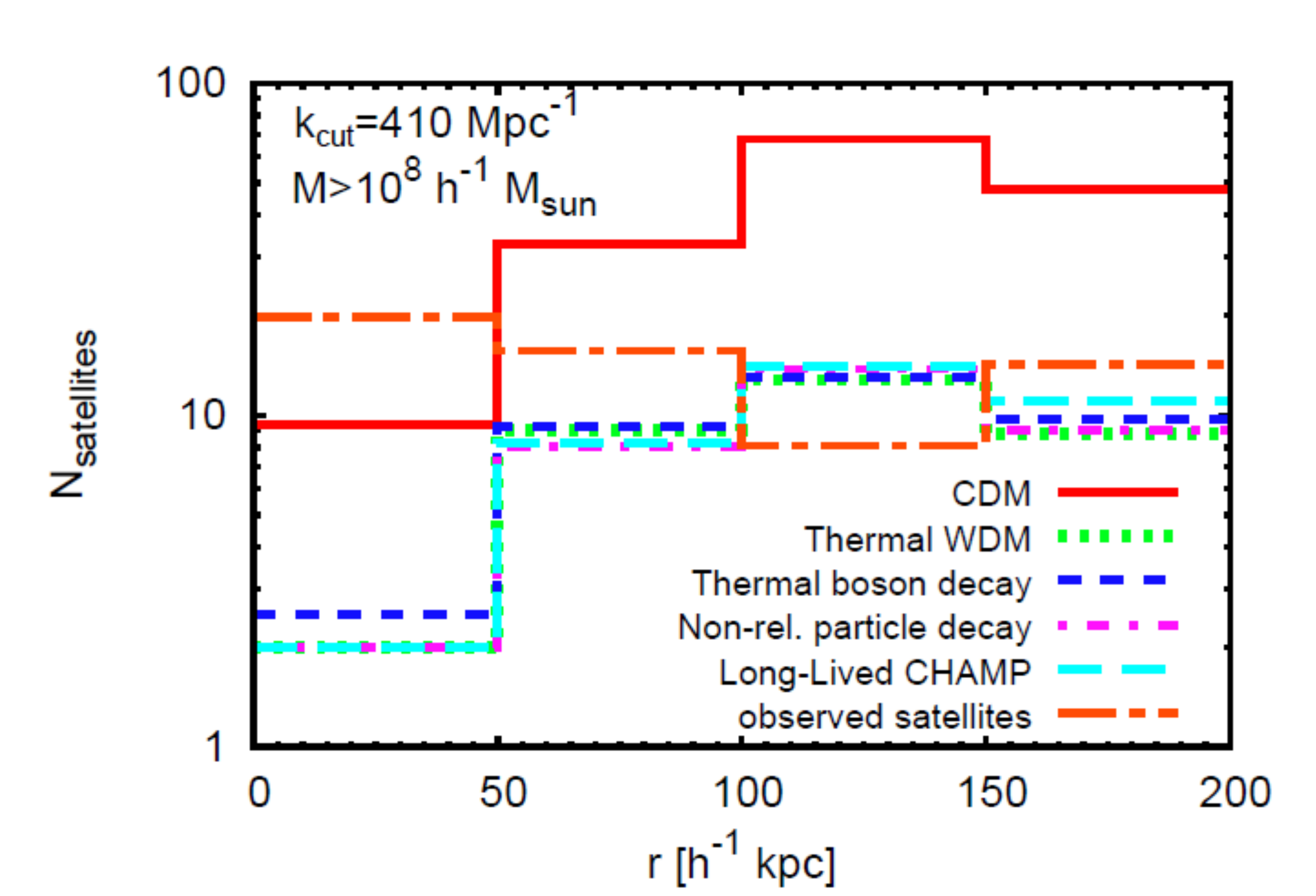


Fig. 3.— *The projected matter distribution in the CDM model (left panel), in the Thermal WDM model (middle panel) and in the Long-Lived CHAMP model (right panel). For the Thermal WDM model and for the Long-Lived CHAMP model, we take the same cut-off scale* $k_{\rm cut} = 51\,{\rm Mpc}^{-1}$ *as in Fig. 2. One side of the plotted region is* $L = 10\,h^{-1}\,{\rm Mpc}$. *Brighter regions denote higher matter densities.*

Litetime τ~ O(1) year

Number count

A.Kamada, Yoshida, KK, T.Takahashi (2013)



$m_{3/2} \simeq 9.5\,\mathrm{keV}$ $\tau_{\mathrm{Ch}} \simeq 0.04\,\mathrm{yr}$

Kinetic "re-coupling"

A. Kamada, Kohri, T. Takahashi, N. Yoshida (2016)

- For a large mass CHAMP (> 10^{11} GeV), it can decouple from thermal plasma after e+e- annihilation (T < ~ m_e /23)

- On the other hand, a CHAMP with its mass 10^{10} -- 10^{11} GeV can "re-couple" with thermal plasma, which can be checked by cosmological observations such as CMB and LSS.

Momentum transfer rate to CHAMPs

$$\gamma = \sum_{b=e^{+/-},p^+,\mathrm{He}^{2+}} \frac{1}{6m_{\mathrm{Ch}}T_b} \sum_{s_b} \int \frac{d^3\mathbf{p}_b}{(2\pi)^3} f_b^{\mathrm{eq}}(1 \mp f_b^{\mathrm{eq}}) \int_{-4\mathbf{p}_b^2}^{0} dt(-t)\frac{d\sigma}{dt}v$$

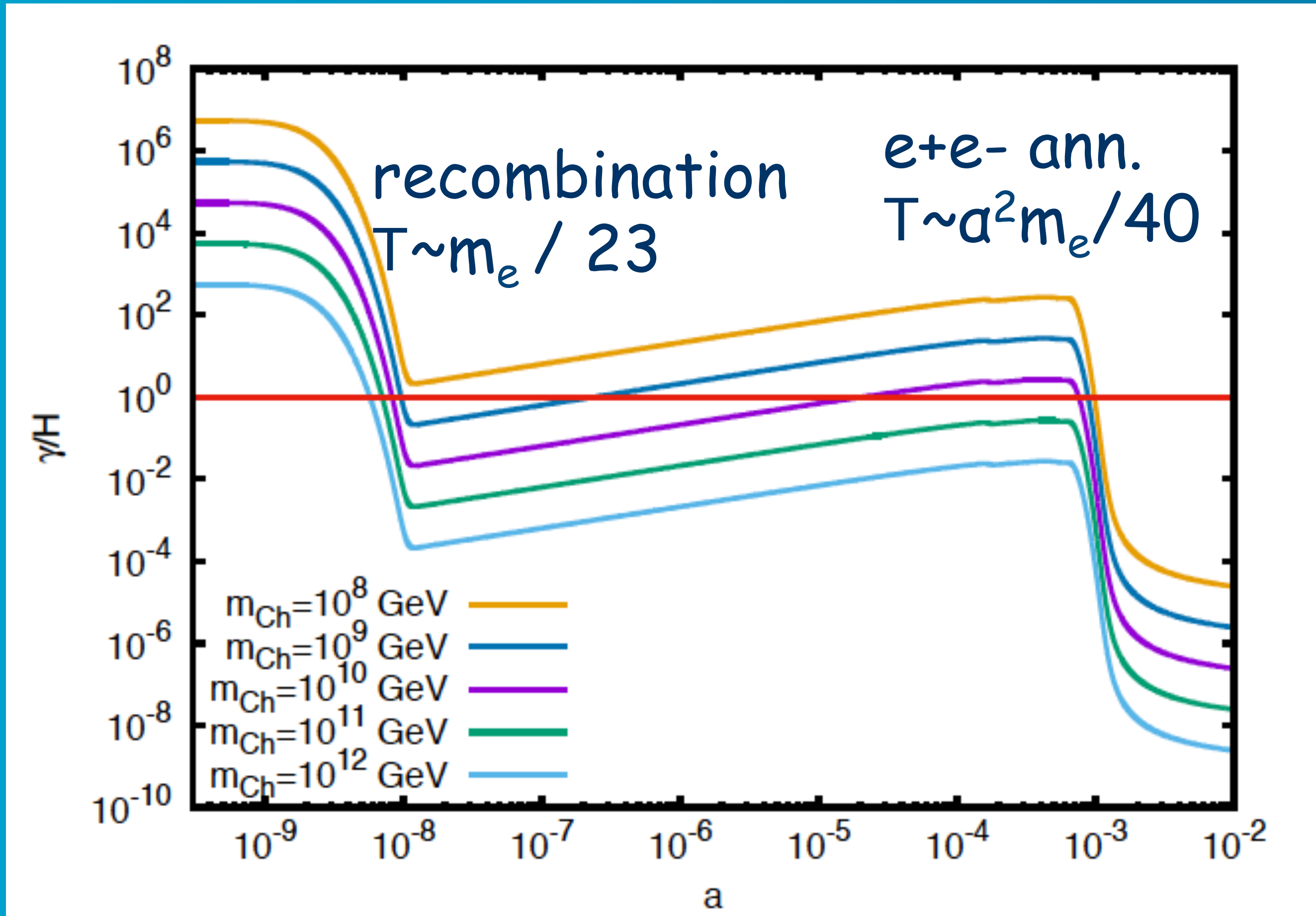
$$\simeq \sum_b \frac{1}{6m_{\mathrm{Ch}}T_b} 8\pi\alpha^2 Z_b^2 \int \frac{d^3\mathbf{p}_b}{(2\pi)^3} f_b^{\mathrm{eq}}(1 \mp f_b^{\mathrm{eq}}) \frac{E_b}{|\mathbf{p}_b|} \ln\left(\frac{4\mathbf{p}_b^2}{k_{\mathrm{D}}^2}\right)$$

- $T \gg m_e$ $\quad p_e \propto T_e \quad \gamma \propto T_b^2/m_{\mathrm{Ch}}$
- $T \ll m_e$ $\quad p_e \propto \sqrt{T_e} \quad \gamma \propto Z_b^2\sqrt{m_b}n_b/(T_b^{3/2}m_{\mathrm{Ch}})$
  $\propto T_b^{3/2}$
- Hubble rate in radiation dominated era $\quad H \sim \dfrac{T^2}{m_{\mathrm{pl}}}$

Momentum transfer rate / Hubble rate

A. Kamada, Kohri, T. Takahashi, N. Yoshida (2016)

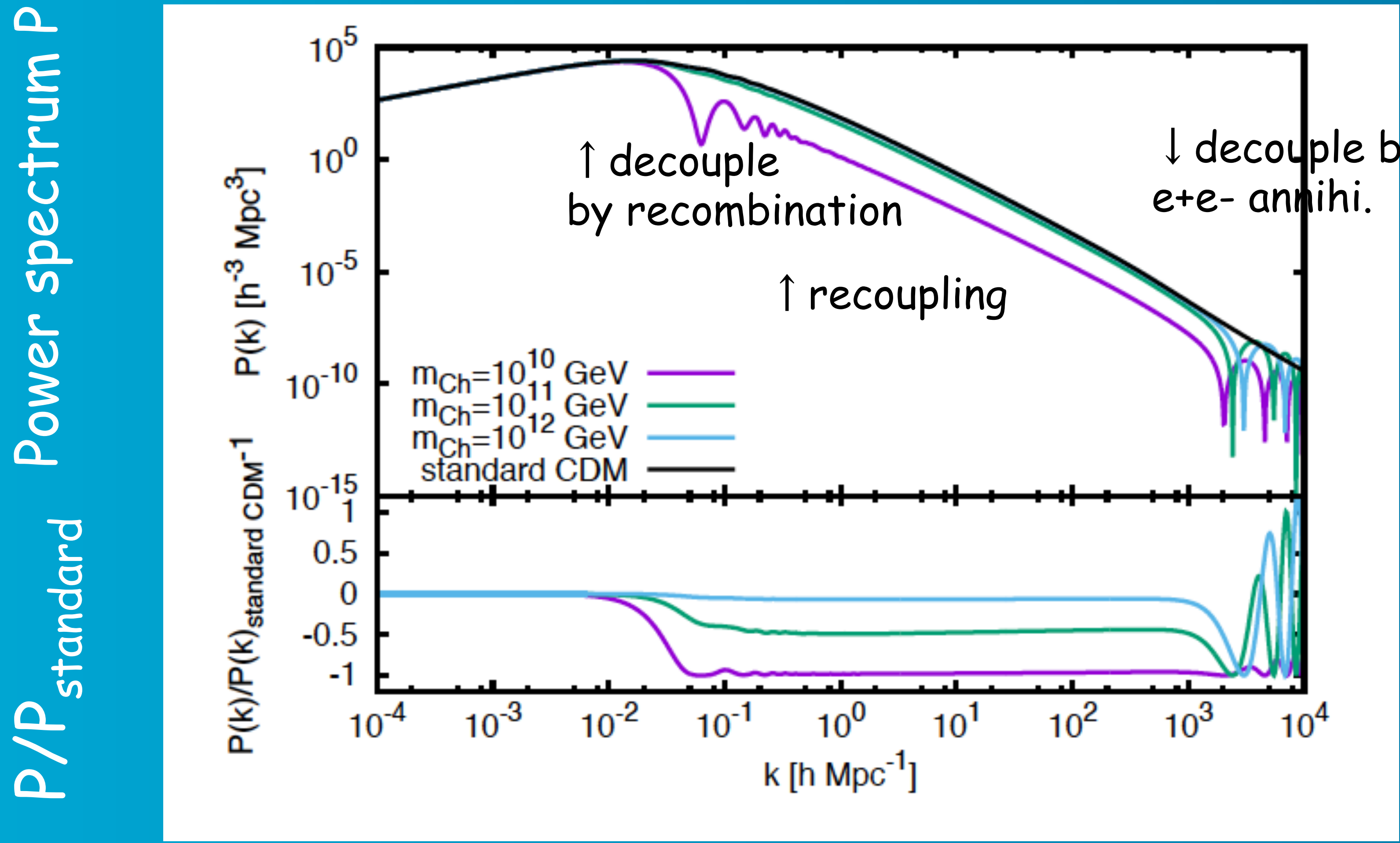
γ / H



$\tau_C > 4 \times 10^5$ years

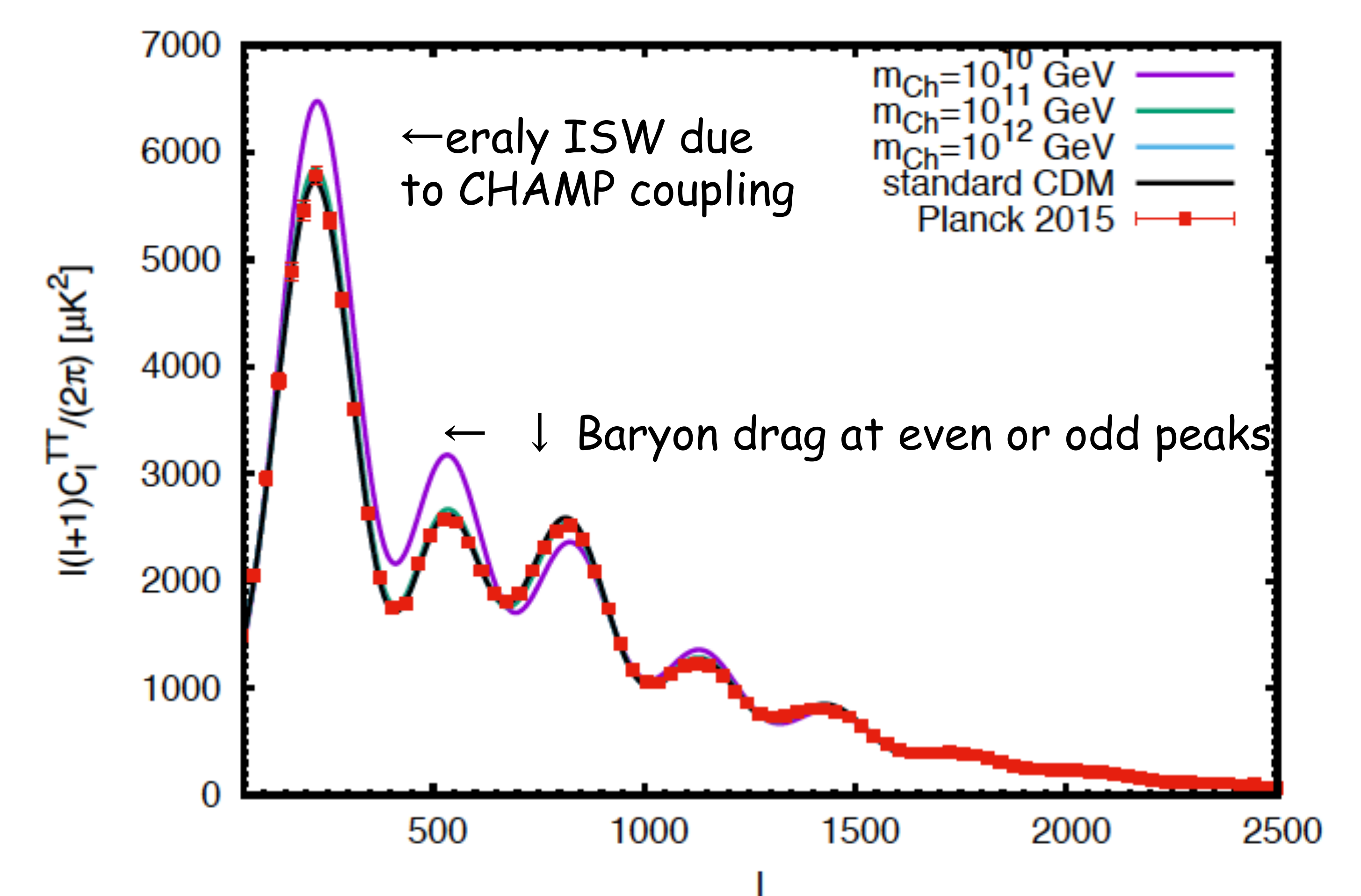
Matter power spectrum

A. Kamada, Kohri, T. Takahashi, N. Yoshida (2016)



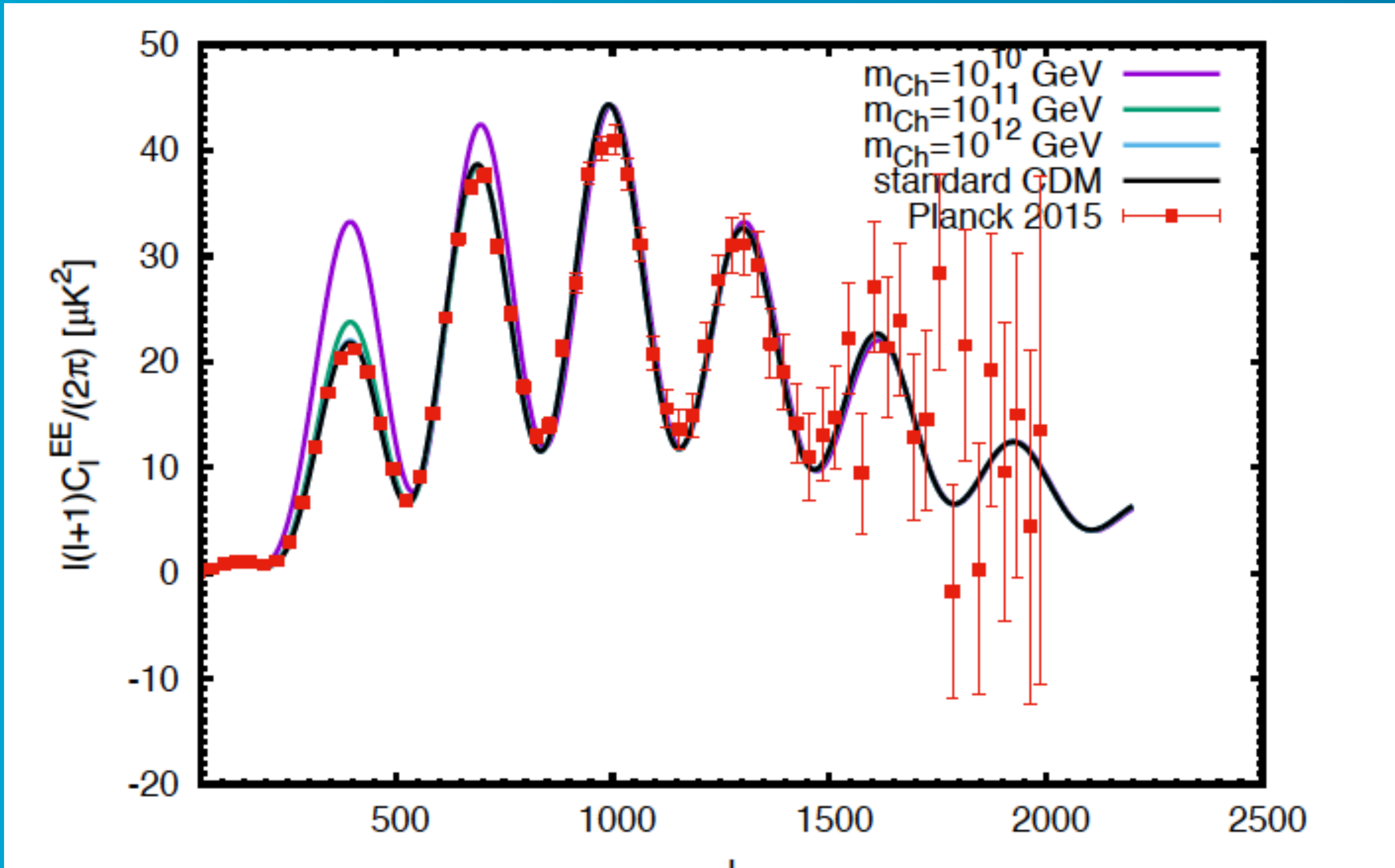
Temperature-Temperature angular correlation of CMB

A. Kamada, Kohri, T. Takahashi, N. Yoshida (2016)



EE correlation of CMB polarization

A. Kamada, Kohri, T. Takahashi, N. Yoshida (2016)



Summary

- CHAMPs coupled with thermal plasma suppress the density perturbation
- CHAMPs can solve missing satellite
- For large mass CHAMPs (> 10^{11} GeV), the CHAMP can decouple from thermal plasma after e+e- annihilation ($T < m_e/23$)
- On the other hand, CHAMPs with masses 10^{10} -- 10^{11} GeV, can recouple with thermal plasma, which can be checked by observations (The obtained bound is $>10^{11}$ GeV)
- For a milli-charged particle with its charge ε, the bound is rescaled to be

$$m_{\rm Ch}/\epsilon^2 > 10^{11}\,\mathrm{GeV}$$