Large Scale Structure and Cannibal Dark Matter

Manuel Buen-Abad, BU
Razieh Emami, HKUST
Martin Schmaltz, BU
1803.08062
Outline

1. data matter power spectrum $\sigma_8$

2. model partially cannibalistic dark matter
The large upward shift in the temperature spectrum fitted to the absolute calibration spectrum is complicated to check at the sub-percentage level. None of the conclusions in this paper (including those based on CMB Commander, Planck Collaboration XI, and other analyses) would differ from those presented herein if the full "TT,TE,EE" likelihoods were used instead of the cross-half-mission likelihood, with foreground and other nuisance parameters determined from separate analyses. Theoretical simulations cannot model the foregrounds and instrumental noise, Galactic dust, treatment of relative calibrations, and multipole limits applied to each spectrum. The sky coverage used in this likelihood is identical to that used for the full-mission data. The sky coverage used in this likelihood is 94% of the sky. The best-fit base likelihood of Fig. 1 is plotted in the upper panel. Residuals with respect to this theoretical model are shown in the lower panel in each plot. The error bars show uncertainties.

However, the two likelihoods differ in their treatment of systematic effects, correlations, and priors. The lowP best-fit model of Fig. 3, cross-half-mission likelihood, with foreground and other nuisance parameters determined separately, is of interest because this parameter is sensitive to small differences in the theoretical predictions. The most highly developed of the best-fit models is the CDM cosmology (see Sect. 2.3). The most highly developed of the base models is the Planck 2015 temperature power spectrum. At multipoles $\ell > 1500$, particularly with the large upward shift in the amplitude of the matter fluctuations at low redshift, will be important when we come to discuss possible tensions between the amplitude of the matter fluctuations at low redshift and the temperature spectrum computed from the Planck Collaboration XI 2015 temperature power spectrum. At multipoles $\ell > 1500$, particularly with the large upward shift in the amplitude of the matter fluctuations at low redshift, will be important when we come to discuss possible tensions between the amplitude of the matter fluctuations at low redshift and the temperature spectrum computed from the Planck Collaboration XI 2015 temperature power spectrum.
Planck 2016 (TT,TE,EE,LowP)

“Cosmic Concordance”

\( \Omega_b h^2 \) .............. 0.02225 ± 0.00016
\( \Omega_c h^2 \) .............. 0.1198 ± 0.0015
100\( \theta_{MC} \) .............. 1.04077 ± 0.00032
\( \tau \) ...................... 0.079 ± 0.017
\( \ln(10^{10} A_s) \) ........ 3.094 ± 0.034
\( n_s \) ..................... 0.9645 ± 0.0049
\( H_0 \) ..................... 67.27 ± 0.66
Planck 2016 (TT,TE,EE,LowP)

“Cosmic Concordance”

\[
\begin{align*}
\Omega_b h^2 & \quad 0.02225 \pm 0.00016 \\
\Omega_c h^2 & \quad 0.1198 \pm 0.0015 \\
100\theta_{MC} & \quad 1.04077 \pm 0.00032 \\
\tau & \quad 0.079 \pm 0.017 \\
\ln(10^{10} A_s) & \quad 3.094 \pm 0.034 \\
n_s & \quad 0.9645 \pm 0.0049 \\
H_0 & \quad 67.27 \pm 0.66
\end{align*}
\]

\[H_0 = 73.24 \pm 1.74 \text{(Riess)}\]
Planck 2016 (TT,TE,EE,LowP)

“Cosmic Concordance”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02225 \pm 0.00016$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1198 \pm 0.0015$</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04077 \pm 0.00032$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.079 \pm 0.017$</td>
</tr>
<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>$3.094 \pm 0.034$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9645 \pm 0.0049$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$67.27 \pm 0.66$</td>
</tr>
</tbody>
</table>

$\sigma_8$ .................. $0.831 \pm 0.013$

$\sigma_8 = \text{moment of the matter power spectrum}$
energy density fluctuations

\[ \rho(\mathbf{x}, t) = \bar{\rho}(t) \left( 1 + \delta(\mathbf{x}, t) \right) \]

Fourier transform \[ \delta(\mathbf{k}, t) = \hat{a}(t) \]

Matter power spectrum

\[ \langle \delta \delta \rangle \equiv P(k, a) \]
Matter power spectrum from weak lensing

This is also the case when combining with the Planck+ext combination. The results agree well with the DES SV constraints: combining DES SV constraints on small positive correlation between values of parameters (see Section 3). The purple contours in Figure 11 show constraints on parameters (see Section 3). The purple contours in Figure 11 show constraints on parameters (see Section 3).

The state of the art in cosmic shear, CFHTLenS, gives constraints on the dark energy equation of state: $w<0$ at 95% confidence. There is a preference for slightly higher values of $w$, with a preference for lower $w$.

Discussions that while Planck CMB temperature data alone do not strongly constrain $w$, they do appear to show close to a 1 region. The constraints on $w$ from DES SV ($\Delta w<0.06$), which we measure to $\Delta w<0.06$, give a preference for $w<0$.

The Dark Energy Survey Collaboration

MNRAS 2015b
Matter power spectrum \(\rightarrow \sigma_8\)

![Graph showing matter power spectrum vs. wavenumber k.](image)
KiDS-450: weak lensing power spectrum

\[ S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3} \]

- \( \Lambda \text{CDM} + A_{\text{IA}} + A_{\text{bary}} + \Sigma m_{\nu} + \text{noise}; 2 \text{ z-bins} \)
- \( \Lambda \text{CDM} + A_{\text{IA}} + A_{\text{bary}} + \Sigma m_{\nu} + \text{noise}; 3 \text{ z-bins} \)

- KiDS-450, CF, fiducial (Hildebrandt et al. 2017)
- KiDS-450, CF, \( \xi_+ \) large scales (Hildebrandt et al. 2017)
- Deep Lens Survey, CF (Jee et al. 2016)
- CFHTLenS, QE, \( \Lambda \text{CDM} + \text{all} \) (Köhlinger et al. 2016)
- DES-SV, CF (DES Collaboration 2016)
- CFHTLenS re-analysis, CF (Joudaki et al. 2016)
- \( \text{Planck} \), TT+lowP (Planck Collaboration 2016)
- \( \text{Planck} \) re-analysis (Spergel et al. 2015)
- Pre-\( \text{Planck} \) CMB (Calabrese et al. 2013)
- WMAP 9-year (Hinshaw et al. 2013)
Predicting the matter power spectrum

DM is a gravitating fluid, GR fluid equations

$\delta$ small $\rightarrow$ different k decouple
growth of perturbations

$k=0.2 \ Mpc^{-1}$

$\delta_{DM}$

Potentially interesting effects at small scales!
MPS

- Sensitive to new long range interactions (another talk)
- DM must be cold to cluster

\[ \frac{T}{M} = \frac{v^2}{v_{\text{escape}}} \]
DM naturalness problem

- particle DM
- abundance determined by standard mechanism

\[ M_{\text{DM}} \ll M_{\text{Planck}} \]
Solutions:

1. $M_{DM}$ related to scales of "SM":
   - WIMP
   - $m_{\nu}$
   - GUT ...

2. New scale from dimensional transmutation:
   \[ M_{DM} \sim M_{pl} e^{-\frac{1}{4d}} \]
Simplest natural dark sector

non-Abelian (pure) gauge theory

\[ L_D \sim \frac{1}{g_D^2} F_D^2 + \frac{H^\dagger H F_D^2}{M_{pl}^2} + \ldots \]

no flavors \hspace{1cm} \text{dim} \geq 6

automatically decoupled from SM
dark dynamics

$T_D$

$\Lambda_D$

$M_{DM}$

dark gluons

"radiation"

glueball masses

dark glueballs

"matter"
massive particle thermal history

\[ T \sim \frac{1}{a} \quad \text{radiation} \]

\[ T \sim \frac{1}{a^2} \quad \text{cold matter} \]
mistake: ignored interactions of glueballs

\[ n \sim \langle \sigma \eta \rangle \]

thermal equilibrium
mistake: ignored interactions of glueballs

\[ \times \sim \langle \sigma n \rangle n \]

thermal equilibrium

"cannibalism" heat source

\[ \Rightarrow \text{chemical equilibrium} \]
behavior to cannibalism at $T/m \approx 1/3$. The ratio of scale factors between start and end of the cannibalistic phase $a_{nr}/a_{can} \approx 10^5$ depends on the strength of the interaction. We will be interested in models where $\alpha$ is strong (between 1 and $4\times 10^{-6}$); then the duration of cannibalism $a_{nr}/a_{can}$ is between $10^{-4}$ and $10^{-5}$ with only a mild dependence on other model parameters.

**FIG. 1:** Temperature to mass ratio as a function of scale factor $a$ for the minimal cannibal (MC) model. The temperature drops like $1/a$ while the particles are relativistic, it drops logarithmically in $a$ while the particles cannibalize, and it drops like $1/a^2$ after the cannibalizing interaction decouples and the particles cool like ordinary non-relativistic matter. The temperature curve shown here was found by solving the background equations (A30) numerically and includes the decoupling of $3\times 2$ interactions.

From preceding discussions it is clear that we can choose parameters in the cannibal sector such that the cannibalistic phase overlaps with the matter-dominated era of the universe. This choice of parameters is the most interesting because then the cannibals suppress the matter power spectrum. We dedicate most of this paper to its study. In Fig. 2 we show the evolution of the energy density of the cannibal fluid (green) in a model where the cannibal transition happens at $a_{c} \approx 10^{-5}$ and decoupling at $a_{nr} \approx 1$. For comparison we show the total energy density in the $\cdm$ components (black) with its radiation-, then matter-,
natural cannibals do not cluster

⇒ cannot be all DM
growth of perturbations in cannibals

\[ \ddot{\delta}_{\text{can}} + \mathcal{H} \dot{\delta}_{\text{can}} + k^2 c_s^2 \delta_{\text{can}} = -k^2 \psi \]
However, as we will show in Sec. IV this constraint is relaxed in UV completions of the MC model because the energy density in radiation in the UV is reduced in such models.

![Graph showing growth of DM perturbations in presence of cannibals](image)

**FIG. 4:** Evolution of the perturbation $\delta_{\text{cdm}}$ for wave number $k = 0.2 \, h\, \text{Mpc}^{-1}$ in the presence of cannibals compared to its value in $\cdm$, for three different choices of model parameters. Models were chosen to give a 10% suppression in the MPS today (i.e. $R = 0.9$). The three choices of $m$ and $S_{\text{can}}$ are also indicated as red, green, and blue points in Fig. 5.

The black contours showing the values for $R(k)$ were calculated for $\epsilon = 4\pi$. Since the value of $\epsilon$ determines the scale factor at which the $3 \to 2$ interactions decouple and cannibalism ends, we expect some dependence of the predicted MPS on $\epsilon$. However, within the range of parameters in Fig. 5 this dependence is very weak. The two main effects are that cannibal perturbations stop oscillating and start catching up to the dark matter perturbation after decoupling. If they have enough time to grow they can have a non-negligible impact on the MPS via the second term in Eq. (25) and they contribute to the gravitational potential. However for the points that we are interested in the cannibal perturbations remain too small to be important. A numerically more significant effect is that when the cannibal fluid stops cannibalizing its energy density transitions from scaling like $1/(a^3 \log a)$ to $1/a^3$. Thus a model in which the $\Lambda$ particles stop cannibalizing earlier will have more energy density in cannibals and therefore more Hubble friction. This effect is somewhat more important but still small. For example, choosing $m$ and $S_{\text{can}}$ as for the blue dot in Fig. 5 but choosing $\epsilon = 1$ and $\epsilon = 1/8$ (i.e. no decoupling of the $3 \to 2$ interactions) we obtain $R = 0.92$ and $R = 0.902$ for the MPS ratio respectively, a very small effect.
Varying parameters:
Fraction of DM that cannibalizes

\[ \frac{S_{\text{can}}^{1/3}}{m} \approx 6 \times 10^{-8} \quad (a_{\text{can}}=10^{-6.5}) \]

- \( f_{\text{can},0} = 1\% \) (\( m_{\text{can}} = 4.4 \times 10^{-12} \text{eV}^4 \))
- \( f_{\text{can},0} = 1.8\% \)
- \( f_{\text{can},0} = 3.2\% \)
- \( f_{\text{can},0} = 5.6\% \)
- \( f_{\text{can},0} = 10\% \) (\( m_{\text{can}} = 4.4 \times 10^{-11} \text{eV}^4 \))
Fig. 8 shows the dependence of the MPS on the decoupling scale $a_{nr}$. For fixed $a_{eq} = 4 \pi$, we have roughly $a_{nr} \sim 10^5 a_{can} \sim 10^6 S_1 / m_{can}$, thus $a_{nr}$ depends on the ratio of $S_1 / m_{can}$. This scale is when cannibalism stops, therefore any wave mode $k$ which enters the (sound) horizon after this scale cannot be affected by the cannibal fluid oscillations and will take on the same value as in $\Lambda$CDM. Thus $a_{nr}$ can be understood to determine the smallest values of $k$ which are suppressed by cannibalism. Therefore changing the ratio $S_1 / m_{can}$ which changes $a_{nr}$ is equivalent to shifting the MPS suppression curve in the horizontal $k$ direction. For the purposes of this plot we fixed the fraction of the energy density in the cannibal fluid today relative to the ordinary dark matter energy density to $f_{can,0} = 0.01$ for all models. The $\Lambda$CDM reference power spectrum which we compare to (the denominator of $R(k)$) has 1% of additional dark matter instead of the cannibal fluid so that all models being compared have the same value of $H_0$. This removes the background effect of the additional energy density in the cannibal fluid.

![Varying parameters: When cannibalism stops](image)

- $f_{can,0} = 1\%$
- $a_{nr} = 10.$
- $a_{nr} = 1.$
- $a_{nr} = 0.1$
- $a_{nr} = 0.01$
- $a_{nr} = 0.001$
issues not discussed

- $M, T \sim S^3$ parameter space
- glueball spectrum dependence
- global fit: CLASS, MontePython
**M, T ~ S^{y_3}** parameter space

![Graph showing the parameter space with contours and points indicating different values. The graph is labeled with logarithmic scales on both axes, representing mass in units of m/eV and entropy ratio log_{10}[S_{can}/S_{SM}].](image)

- **FIG. 5:** $m$ versus $S_{can}/S_{SM}$ parameter space where $S_{SM} = 2.2 \times 10^{11} \text{eV}^3$ is the entropy in the Standard Model today. The black lines are contours of the ratio of the MPS in the presence of cannibal dark matter to that of $\cdots CDM$. The brown dotted curves correspond to constant $f_{can}$.

- The green band is an estimate for the suppression that gives a $\ldots$ within 1 of the value quoted in [4]. The orange region corresponds to MC models that enter the cannibalistic phase after matter-radiation equality, while the blue one corresponds to those for which cannibalism ends before $a = 10^{2.7}$. In red are those models whose $\cdots$ contributes to $N_e |_{BBN} > 0.66 [45]$ when they are in their radiation phase.

- Having shown that the presence of cannibals suppress the MPS by numerically solving the equations for the perturbations, we devote the rest of this Section to understanding this result from Eqs. (21)-(24). We will only be interested in $k$ modes which are well inside the horizon during matter domination, i.e. modes for which $k \gg \omega_{eq} \sim 0.01 \text{Mpc}^{-1}$.

- Let us start with the cannibal perturbations. For modes deep inside the horizon the gravitational potential is approximately constant so that we can ignore derivatives of $\omega$. In addition, we can use $w_{can} \ddot{\omega}_{can} \dddot{t} = \dot{\omega}_{can} \dddot{t} \text{od r o p s u b l e a d i n g t e r m s i n E q s .( 2 1 )a n d( 2 2 ) .}$
We have studied the possibility that a subdominant component of the dark matter might be made of glueball states. For the very strongly first-order phase transition, we match a UV theory of two massless bosonic degrees of freedom and a jump in entropy (increasing from $m/\Lambda_{SM} \approx 2$ (dashed green) lines respectively.}

The energy densities of the heavier glueball states. The MPS ratio is less

\[ \frac{\alpha^{3} \rho}{[eV]} \]

\[ a \]

\[ \Lambda_{CDM} \]

\[ \phi \text{ model} \]

\[ N=2, M/m=3 \]

\[ N=2, M/m=1.25 \]

\[ N=7, M/m=3 \]

\[ N=7, M/m=1.25 \]
global fit: CLASS, MontePython
Conclusions

- future MPS measurements are precision tests of ΛCDM
- non-standard DM models can predict different MPS shapes
- partially cannibalistic DM suppresses MPS → solution to Ω problem?
back up!
Galaxy Power Spectrum, SDSS-DR7, “straight up”

Power Spectrum

\[ P(k) \left( \frac{h^{-3} \text{Mpc}^3}{k^3} \right) \]

\[ k \left( h \cdot \text{Mpc}^{-1} \right) \]

\( \Lambda \)CDM  

iDM 1  

iDM 2  

Galaxy Power Spectrum, SDSS-DR7, “straight up”
Galaxies don’t track dark matter perfectly

“Galaxy bias”

\[ P_{\text{DM}}(k) = P_{\text{gal}}(k) (a + b \, k + c \, k^2) \]

Power Spectrum

\[ P(k)/(f^{-3} \cdot \text{Mpc}^3) \]

No bias

\[ k/(h \cdot \text{Mpc}^{-1}) \]
Galaxy Power Spectrum, SDSS-DR7

Power Spectrum

\[ P(k)(h^{-3}\text{Mpc}^3) \]

\[ k/(h\cdot\text{Mpc}^{-1}) \]

\[ \Lambda\text{CDM} \quad \text{iDM} \]

with bias