Testing the CDM paradigm with the CMB

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in collaboration with
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Outline

(0) Motivation

(1) Generalised dark matter (GDM),
   - 3 new parameters (2 for pressure, 1 for viscosity) for 3 d.o.f.
   - CMB with $\Lambda$-GDM. Constraints from Planck:
     - old) all 3, but constant. new) only 1, but time-dependent.
   - Both cases consistent with $\Lambda$CDM. No hints for “beyond CDM”.

(2) Parametrized Post Friedmann (PPF) frame work,
   - Special case: 2 new parameters, no d.o.f. associated with DM.
   - Bad fit to CMB. DM phenomenon requires degrees of freedom.
Believing in dark matter

- Extensions of the standard model of particle physics (SM). Yet no detection.

- Cold dark matter (CDM) gives concordant picture within General Relativity (GR). Some tensions.

- Modified gravity?:
  - GR’s success for over a century
  - Lack of working alternatives

\[ T^\mu_\nu = T_{\text{cdm}}^\mu_\nu + T_\Lambda^\mu_\nu + T_{\text{SM}}^\mu_\nu = (8\pi G_N)^{-1} G^\mu_\nu \]
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\[
T^\mu_\nu = \left[ T_g + T_\Lambda + T_{SM} \right] = \left( 8\pi G_N \right)^{-1} G^\mu_\nu \\
g \text{ for GDM}
\]
Believing in dark matter

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\[ T^\mu_\nu = T^\Lambda_{\mu\nu} + T^\text{SM}_{\mu\nu} = (8\pi G_N)^{-1} \left( G^\mu_\nu + \mathbf{U}^\mu_\nu \right) \]
Dark matter fluid

\[ T_{\mu\nu} = \rho u_\mu u_\nu + P(g_{\mu\nu} + u_\mu u_\nu) + \Sigma_{\mu\nu} \]

- Cold and Collisionless particles in the continuum limit are described before shell crossing as pressureless perfect fluid (=CDM in *camb* and *CLASS*)

\[
\text{Planck 2015 XX, 1502.02114} \quad \beta_{c,\text{iso}} < 0.038 \\
\text{Planck 2015 XIII, 1502.01589} \quad \omega_c = 0.12 \pm 0.0027
\]

- General fluid has pressure \( P = P(\rho, \phi, \nabla_\mu u_\nu, f(x,p), \ldots) \).

- Shear \( \Sigma_{\mu\nu}(\rho, \nabla_\mu u_\nu, g_{\mu\nu}, f(x,p), \phi, \ldots) \), spatial and traceless

⇒ More DM properties that we can potentially measure!
⇒ Test the CDM paradigm
1) **Generalised Dark Matter**

Linear scalar perturbation

- Perturbed stress-energy-momentum tensor
  \[
  T_{g\mu}^{\nu} = \rho_g u_{g\mu} u_{g\nu} + P_g (\delta^{\mu}_{\nu} + u_{g\mu} u_{g\nu}) + \Sigma_{g\nu}^{\mu}
  \]

- \( \delta_g = \delta \rho_g / \bar{\rho}_g \)
- \( u_{g\mu} = -a \partial_{\mu} \theta_g \)
- \( w = \bar{P}_g / \bar{\rho}_g \)
- \( \Pi_g = \delta P_g / \bar{\rho}_g \)

- \( \nabla_{\mu} T_{g\mu}^{\nu} = 0 \) perturbed conservation equation
1) Generalised Dark Matter

Linear scalar perturbation

- **Perturbed stress-energy-momentum tensor**

\[ T_{g \nu}^\mu = \rho_g u_{g \mu} u_{g \nu} + P_g (\delta_{g \mu} + u_{g \mu} u_{g \nu}) + \Sigma_{g \mu} \]

- **Perturbed stress-energy balance**

\[ \delta_g = \frac{\delta \rho_g}{\bar{\rho}_g} \]

\[ u_{g i} = -a \partial_i \theta_{g} \]

\[ \Pi_g = \delta P_g / \bar{\rho}_g \]

- **Perturbed conservation equation**

\[ \nabla_\mu T_{g \mu \nu} = 0 \]

- **GDM parameters**

  - \( w(\tau) \)
  - \( c_s^2(k, \tau) \)
  - \( c_{\text{vis}}^2(k, \tau) \)
  - \( c_a^2 = \frac{\dot{P}_g}{\bar{\rho}_g} = w - \frac{\dot{w}}{3 \mathcal{H}(1 + w)} \)

- **GDM closure equations**

\[ \Pi_g = c_a^2 \delta_g + (c_s^2 - c_a^2) \hat{\Delta}_g \]

- **Non-adiabatic pressure** \( \Pi_{\text{nad}} \) vanishes if \( P_g = P_g(Q_g) \)

\[ \dot{\Sigma}_g = -3 \mathcal{H} \Sigma_g + \frac{4}{(1 + w) \bar{\rho}_g} c_{\text{vis}}^2 \hat{\Theta}_g \]

\[ \text{made-up by W. Hu 1998 ApJ 506} \]

\[ \text{Blas et al 2011 JCAP 7} \]

\[ \text{Newtonian} \]
GDM from...

**Particles** (Boltzmann equation)
- Freely streaming **warm dark matter**
  - Armendariz-Picon, Neelakanta, JCAP 2014
- Specific models, like **self interacting massive neutrinos and dark atoms + dark photons**
  - Oldengott et al, JCAP 2015
  - Cyr-Racine, Sigurdson, PRD 2013

**Fields** (effective or fundamental)
- **Axion condensates.**
  - Sikivie, Yang, PRL 2009
- **Effective theory of large scale structure:** Landau-Lifshitz type energy momentum tensor for **CDM** due to small scale nonlinearities
  - Baumann et al, JCAP 2012
- **K-essence** and more general **constrained-norm scalar field theories.**
  - Scherrer, PRL 2004
  - Ballesteros, JCAP 2015

**Fluids** (imperfect, or coupled perfect)
- Kopp et al, 1605.00649
Rough estimates

\[ w \approx c_s^2 \approx c_{\text{vis}}^2 \]

GDM with constant parameters
Thomas et al, 1601.05097

Freely streaming CDM, warmed-up by non-linearities, EFTofLSS
Baumann et al, JCAP 2012

Freely streaming warm dark matter
Armendariz-Picon et al, JCAP 2014

CDM neutralino \(10^{-24}\)

Upper limit from CMB+Ly-\(\alpha\)

Upper limit from CMB+Ly-\(\alpha\)

Ruled out by Planck
Extending $\Lambda$CDM into $\Lambda$-GDM: Imprints on the CMB and Constraints from Planck

Based on a modified CLASS code Lesgourgues 2011, MCMC 6+3 params with montepython

Constraints
(99.7% c.l.)

$w < 2.4 \times 10^{-3}$
$w > -0.9 \times 10^{-3}$

$c_s^2 < 3.21 \times 10^{-6}$
$c_{\text{vis}}^2 < 6.06 \times 10^{-6}$

Thomas et al, 1601.05097

Similar studies:
Mueller, PRD 71 2005
Calabrese et al, PRD 80 2009
Xu, Chang, PRD 88, 2013

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Kunz et al, 1604.05701
Tutusaus et al, 1607.08016
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Data: Planck 2015, SDSS-III 2013

$$a^3 \bar{\rho}_g \propto \omega_g^{(0)} (1 + 3w \ln(1 + z))$$

- Changes $q_{\text{rad}}/q_{\text{matter}}$ during recombination: peak heights
- Angular diameter distance to last scattering: peak positions

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\[
k_{\text{decay}}^{-1} H \simeq \sqrt{c_s^2 + 0.5 c_{\text{vis}}^2}
\]

- Potentials \( \Phi, \psi \) decay below \( k_{\text{decay}} \): less CMB lensing
- \( c_s^2, c_{\text{vis}}^2 \) are uncorrelated with \( w \). Setting \( c_s^2 = c_{\text{vis}}^2 = 0 \) gives same constraints on \( w \).

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\[\text{(99.7\% c.l.)}\]
CMB constraints on time-dependent $w(a)$

Simultaneous constraints on 8 piecewise constant $w$-bins.
Based on a modified CLASS code Lesgourgues 2011. MCMC 6+8 params with montepython

- $c_s^2, c_{vis}^2$ are uncorrelated with $w$ $\Rightarrow$ safe to fix $c_s^2 = c_{vis}^2 = 0$
- 8 bins give rise to a sufficiently general time dependence

Kopp et al, 1802.09541
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- conservative way to test coldness of DM

\( \frac{\text{var-}w}{\text{ const-}w} \) PPS, PPS+BAO, PPS+HST

99% contours

- Planck power spectra (PPS)
- 6dF and SDSS-III BOSS surveys (BAO)
- Hubble Space Telescope (HST)
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- conservative way to test coldness of DM

$w=0$, constant $w$ and varying $w$ are nested $\Rightarrow$ CDM favoured
CMB constraints on DM abundance

Derived from constraints on $8 w_i$ and $\omega_g^{(0)}$

- $c_s^2, c_{vis}^2$ are uncorrelated with $w$  ➞  safe to fix $c_s^2 = c_{vis}^2 = 0$
- 8 bins give rise to a sufficiently general time dependence
- conservative way to test abundance of DM at different epochs

$$\omega_g(a) \equiv a^3 \bar{\rho}_g \frac{8\pi G}{3 \times (100 \text{ km/s/Mpc})^2}$$

$$\frac{d \ln \omega_g(a)}{d \ln a} = -3 w(a)$$

$$\omega_g(a = 1) = \omega_g^{(0)}$$

DM abundance is:
- Nonzero at all times
- Tightly constrained around equality
- Well constrained around $a = [0.2-0.4]$
$w(a)$ degeneracies

68% and 95% contours of 2D marginalised posteriors

$a_0 = 1$

- Loss of constraining power at late times in the var-w model since the late Universe behaviour disassociates from the early Universe.
- Adding BAO or HST data thus strongly affects contours
- $\omega_g$ is anticorrelated with $\Omega_\Lambda$ since combination of CDM and $\Lambda$ can be modeled by wDM.

$a_6 = 10^{-3.75} = 0.00018$

- Strong constraining power at early times. Nearly as good as const w or CDM
- $\omega_g$ is better constrained then $w$. Causes correlations.
Summary (GDM)

- ‘Generalized dark matter’ GDM with 3 new parameters allows to constrain dark matter properties and thus to **test the CDM paradigm**.

- For the first time the **DM equation of state** is constrained in 8 redshift bins throughout cosmic history between $z=10^5$ and $z=0$ with **Planck** likelihood + BAO or HST prior: strongest constraints in the pre-recombination universe and **consistent with $w=0$ (CDM) at all times**.

- Derived constraints on **abundance DM**: it is non-negative at all times and nearly as strongly constrained at matter-radiation equality as the CDM abundance.

- Expect our constraints on $w(a)$ to be **valid for any alternative to CDM**.

**Ongoing**

- Exploring **nonlinear regime** with extensions of GDM. Halo model construction shows that constraints are robust. Apply to WiggleZ, CFHTLenS, Ly-α
- Add neutrino mass as free parameter
- Forecasts for combination of Euclid-like data combined with Planck CMB
- Constrain **scale and time dependent sound speed and viscosity**. Constrain isocurvature modes.

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Kopp et al, 1605.00649
Thomas et al, 1601.05097
Kopp et al, 1802.09541
Thomas, Markovic et al, 180x.xxxxx
2) **Parametrized Post Friedmann**

Linear scalar perturbations

Skordis, PRD 79, 2009

1. Correct number of **time derivatives** in constraint Eqs.

2. Modification should lead to **gauge invariant field Eqs.**

3. Satisfy linearized **Bianchi identity** (such that $\nabla_\mu T^{\mu \nu} = 0$)

   - Full **control** of number of propagating dof
     (connection to non-perturbative parent theory)
   - **Consistently implement numerics** in any gauge
   - **Reduces number of free parameters** to two, if number of extra d.o.f is zero. $P_0(k, \tau), P_1(k, \tau)$
PPF without extra d.o.f.

CDM Background $w=0$

- We assume a CDM background: effective equation of state of this (tentative) modification of gravity is $w=0$.

- Question: can we choose $P_0(k, \tau), P_1(k, \tau)$ to exactly mimic CDM perturbatively?

Yes we can!

\[
P_{0}^{\text{cdm}}(\tau, k) = - \frac{9 \Omega_X}{2} \frac{\mathcal{H} \Theta_{\text{cdm}}}{\dot{\Phi}} \bigg|_{\text{GR+cdm}}
\]

\[
P_{1}^{\text{cdm}}(\tau, k) = - \frac{3 \Omega_X}{2} \frac{\Delta_{\text{rest frame}}}{\dot{\Phi}} \bigg|_{\text{GR+cdm}}
\]

"Parameters"?

should be solution-independent

used in GR+PPF without CDM
determined from GR+CDM without PPF
PPF: CMB

Based on a modified CLASS code Lesgourgues 2011

Characteristic effect of CDM: even-odd asymmetry of the peaks disappears.

Kopp et al, 180x.xxxx
PPF: CMB

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Potential freeze, but too low amplitude.
Non-oscillatory source missing.

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Modified gravity without extra d.o.f. cannot fit CMB

(assumptions: non-linearities negligible, conservation of matter energy-momentum, adiabatic initial conditions)
Summary (PPF)

• ‘Parametrized Post Friedmann’ PPF is a flexible framework that allows to test the dark matter paradigm beyond the fluid picture if one replaces CDM in linear perturbation theory.

• Without adding new degrees of freedom, modified gravity cannot fit the CMB without fine tuning.

Ongoing

• Allow 1 extra S0(3)-scalar perturbative d.o.f, but impose spatial locality: 5 free purely time-dependent functions.

• Find useful parametrizations and constrain with CMB.

Skordis, 0806.1238 (2009)
Baker et al, 1209.2117
Kopp et al, 180x.xxxxx