Gravitational Interactions of Matter and Dark Matter

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with Jordi Salvado, Ben Stefanek, arxiv:1505:04789

Evidence of Dark Matter

there is no doubt that dark matter has gravitational interaction

the question for this talk: how precise we know dark matter gravitational interaction strength?

Dark Matter Direct Detection

3

Gravitational Interaction Floor

101: How much we know the Newton's Constant for all matter?

• A well known fact: the gravitational acceleration of a probing body of mass m depends only on the product of Newton's Constant G_N and the central body mass M

$$
a_{\rm grav} = -\frac{G_N M}{r^2}
$$

- To break this degeneracy and measure G_N , an additional force is required to define the central body mass
- A variety of methods has been adopted including terrestrial origin: torsion-balance and atom interferometry
- Current value from CODATA 2010 has

 $G_N = 6.67384(80) \times 10^{-11} \,\mathrm{m}^3 \mathrm{kg}^{-1} \mathrm{s}^{-2}$

a relative error of 1.2×10^{-4}

Terrestrial Measurement of G_N <u>transiectories is of the industrial results in analysis of the experimental results in an in</u> analysis in analy $\frac{1}{2}$ and $\frac{1}{2}$ the value of the atomic clouds, and at $\frac{1}{2}$ ation, lead to a combined relative uncertainty α **PRESULTER COMPARED WITH THE VALUES OF COMPARED WITH THE VALUE SOF COMPARED WITH THE VALUE SOF** $\overline{}$

A large discrepancies among different experiments

Cosmological Measurement of G_N

- Existing studies in the literature have used data from the primordial abundances of light elements synthesized by BBN and cosmic microwave background (CMB) anisotropies to measure *G^N*
- Zahn and Zaldarriaga, astro-ph/0212360, pointed out this possibility
- Umezu, Ichiki, Yahiro, astro-ph/0503578, constrained G_N at the level of ~5% using BBN
- Galli, Melchiorri, Smoot, Zahn, arxiv:0905.1808, obtained a similar constraint using WMAP+BBN data
- We use the latest available cosmological data including: Planck, ACT, SPT, Lensing, BAO, HST and BBN

Cosmology with a Modified Gravitational Constant

- Introducing λ_G to quantify deviations of the gravitational constant from G_N (as measured in Earth based laboratory experiments) $G = \lambda_G^2 G_N$
- The Friedmann equation is: $H^2 =$ $\int \dot{a}$ *a* \setminus^2 = 8π 3 a^2 λ_G^{-2} G_N $\bar{\rho}$
- Unphysical for the background evolution (zeroth order)
- change the "expansion clock" $\tau \to \lambda_G \tau$

$$
H^2 = \left(\frac{a'}{a}\right)^2 = \frac{8\pi}{3}a^2 G_N \bar{\rho}
$$

• next check the first-order linear order equations

1'st Order Fluid Perturbations (DM)

• From energy-momentum conservation (hydrodynamical equations)

$$
T^{\mu\nu}_{\quad \ ;\mu}=\partial_{\mu}T^{\mu\nu}+\Gamma^{\nu}_{\ \alpha\beta}T^{\alpha\beta}+\Gamma^{\alpha}_{\ \alpha\beta}T^{\nu\beta}=0
$$

• For pressureless dark matter fluid (in the conformal Newtonian gauge)

$$
\dot{\delta}_D = -\theta_D + 3\dot{\phi}
$$

$$
\dot{\theta}_D = -\frac{\dot{a}}{a}\theta_D + k^2\psi
$$

 $\delta_D \equiv \delta \rho_D / \bar{\rho}_D$ $\theta_D \equiv i k_j v_D^j$ $ds^2 = a^2(\tau) \{-(1+2\psi)d\tau^2 + (1-2\phi)dx^idx_i\}$

- change the "expansion clock" $\tau \to \lambda_G \tau$
- rescale the wavenumber by $k \rightarrow k/\lambda_G$
- first order DM perturbation equations are also invariant

1'st Order Fluid Perturbations (baryon)

- For baryons, the electromagnetic interaction makes the parameter λ_G physical
- EM force can be used to define the inertial mass of baryon; then one can use gravitational force to measure *G*

$$
\dot{\delta}_b = -\theta_b + 3\dot{\phi}
$$

$$
\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_s^2 k^2 \delta_b + \frac{4\bar{\rho}_{\gamma}}{3\bar{\rho}_b} a \, n_e \, \sigma_T (\theta_{\gamma} - \theta_b) + k^2 \psi
$$

• Equations are no longer invariant under

$$
\tau \to \lambda_G \,\tau \qquad k \to k/\lambda_G
$$

• Varying λ_G now yields an observable change in cosmological evolution

CMB Temperature Power Spectrum

• Cosmological equations integrated and CMB spectra computed using the publicly available CLASS code

CMB EE Power Spectrum

• Cosmological equations integrated and CMB spectra computed using the publicly available CLASS code

Why at High Multipole Moments?

• If λ_G is increased (decreased), recombination takes place over a longer (shorter) period of time

• For λ_G > 1, the photon visibility function broadens. Photons the visibility function of conformal time. The axes have been rescaled using the secon last scatter over a longer period of time. This damps anisotropy on scales smaller than the photon mean free path.

Analysis Method Analysis Method

- Markov Chain Monte Carlo (MCMC) using the publicly available MontePython code (written to work with CLASS) MontePython code (written to work with CLASS). Markov Chain Monte Chain M
And the public lynnicly available public lynnicles available publicly available publicly available publicly av Markov Chain Monte Carlo (MCMC) using **Example : ishise, ye.ish: space** \overline{y} , compute observables using the using order
- For a given point in parameter space θ_i , compute observables using our modified CLASS code $\lim_{n \to \infty} \frac{1}{n}$ Obscribables asing our inounical CLASS code
- Obtain $\mathcal{L}(D|\theta_i)$ using the package provided by the Planck collaboration which compares the output of the CLASS computation to the data Obtain 2000 and package provided by the package provided by the package provided by the planck of the planck o
Distribution were planted by the planted by the planck of the planted by the Planck of the Planck of the plante Obtain $\mathcal{L}(D|\theta_i)$ using the package provided by the Planck $P(\theta_i|D) = \frac{\mathcal{L}(D|\theta_i)\pi(\theta_i)}{\int \mathcal{L}(D|\theta_i)d\theta_i}$

Posterior Probability for the Parameters

Posterior Probability for the Parameters *ⁿ^s* ⁰*.*⁹⁶⁸⁵ ⁰*.*9676+0*.*⁰⁰⁹¹ 0*.*⁰⁰⁹¹ ⁰*.*⁹⁴⁹² ⁰*.*⁹⁸⁵⁸

 $\label{eq:Planck+ACT/SPT+Lensing+BAO+HST}$ \quad Figure 3. 68% and 95% likelihood contour plots on the *ns^G* plane using the

We show the constraints on G from different compiled compiled compiled and different computations of datasets in G

Results

 $G(\text{cosmological}) = \lambda_G^2 \, G_N(\text{CODATA}) = 7.26^{+0.27}_{-0.27} \times 10^{-11} \, \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$

Scalar-mediated Date Congress Direct Matter Force of the Direct Matter Section 2.1 σ which has a relative error of 3.7% and the cosmological measured value is roughly consistent which has a roughly consistent which **Example 12 Different from CODATA at 2.2 sigma**

Will update the analysis once Planck 2015 data is public

Does dark matter have the same gravitational interaction strength as ordinary matter?

Breaking of Weak Equivalence Principle

- The equivalence principle is the principal assumption on which general relativity has been built
- Weak equivalence principle is to check whether:

 $m_{\text{grav.}} \doteq \dot{m}_{\text{inertial}}$?

• One introduces a long-range fifth force to change the effective gravitational potential/force

$$
V(r) = -\frac{G_N m_1 m_2}{r} \left(1 + \alpha_f e^{-m_\phi r} \right)
$$

Breaking of WEP for Baryons EF IOF DATYONS

tueiberger, Frecker, Fverson \blacksquare Schlamminger, et. al., arxiv:0712.0607
hep-ph/0307284 hep-ph/0307284 a review, Adelberger, Heckel, Nelson

baryon 11 Schlamminger et al arxiv⁻0712.0607

using other test-body materials and improving the sensi-

a of ordinary mattor are very S have substantial in the limits of the limits of the limits of the limits of the limits on the limits on the limits on the limits of th stringent at the cosmological scales constraints on the fifth force of ordinary matter are very

Breaking of WEP for Dark Matter

- \bullet The tidal disruption of the • The tidal disruption of the Sagittarius dwarf galaxy orbiting the Milky way
- e N-hody simulation using disruption or the structure. The structure is internal structure. The distribution of σ rupted stars will act like purely baryonic test particles, and the stars will baryonic test particles, and the • N-body simulation using
- Fortunately, the Sagittarius (Sgr) dwarf galaxy, the • This constraints additional $t = \frac{1}{2}$ is nearly ideal for our purposes. In the output of our purposes, it is nearly ideal for our purposes. dark matter force weaker streams observed by the Two-Micron All Sky Survey **Example 28 and than 10% of gravity**

14−36 M⊙/L⊙, and Sgr orbit with period and Sgr orbit with period and Sgr orbit with period and Sgr orbit with p
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Kesden and Kamionkowski, astro-ph/0606566 resden and Namionkowski, astro-ph/0600000

figure shows that for $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are determined for $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$

Long-range Force only for Dark Matter \overline{a} 2 @*µ*@*µ* ¹ $\overline{\mathbf{r}}$ **222**
2000 - 2001 : Contract *f m* ¯ *.* (3.1)

matter is to internet is to internet internet and ultra light space and only couples to dark matter, which we ultra light scalar mediator, which only coupled and an ultra light scalar mediator, which only coupled and an ul • The ultra-light scalar field could be a Pseudo-Nambu Goldstone Boson to mediate the macroscopic forces Here, the ultra-light pseudo Nambu-Goldstone boson could be associated with spontaneous **breaking of some global symmetry at the symmetry at the sequel-training**

Hill and Ross, PLB 203 (1988), 125

^f ⇢*^c ^a*² *.* (3.4)

$$
\mathcal{L} \supset \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} m_{\phi}^2 \phi^2 + \bar{\chi} i \gamma_{\mu} \partial^{\mu} \chi - \left(1 + \frac{\phi}{f} \right) m_{\chi} \bar{\chi} \chi
$$

• Only dark matter feels the additional force *Itter feels the add* $\frac{1}{2}$

$$
V(r) = -\frac{G_N m_{D_1} m_{D_2}}{r} \left(1 + \alpha_f e^{-m_\phi r}\right) \qquad \alpha_f \equiv \frac{M_{\rm pl}^2}{f^2}
$$

• The Friedmann equation is modified: Mediated by the new light scalar field, two dark matter particles with masses *mD*¹ and The light scalar field can also contribute to the energy-momentum tensor and the energy-momentum tensor and therefore α

$$
\mathcal{H}^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} a^2 G_N \left[\rho + \frac{\phi}{f} \rho_c + \frac{1}{2} \frac{\dot{\phi}^2}{a^2} + V(\phi)\right]
$$

r , (3.2) Nusser, Gubser, Peebles, astro-ph/0412586; Bean, Flanagan, Laszlo, Trodden, 0808.1105 Frieman and Gradwohl, PRL 67(1991) 2926; Bean, astro-ph/0104464

⁼ ¹

¨ + 2 *^H* ˙ ⁺ *^a*² *^m*²

Conditions to Ignore the Scalar Background parameter space where we can ignore the contribution to the background evolution (*i.e.*, C *Onditio r* **ng to Ignore the Scalar Background**

• For an ultra-light scalar satisfying:

$$
m_\phi^2 \ll \frac{1}{a^2} \left(\frac{\ddot{\phi}}{\phi} + 2 \mathcal{H} \frac{\dot{\phi}}{\phi} \right)
$$

- $\phi = 1 \phi^2$ ✓*M*Pl ◆ *H*² 0⌦⁰ *^cM*Pl Z *da* 8⇡ **R**equi \log $\frac{\phi}{c}$ $\frac{\varphi}{f}$ ρ_c + 1 2 $\dot{\phi}^2$ $\frac{\gamma}{a^2} + V(\phi)$ • Requiring $\frac{\varphi}{f} \rho_c + \frac{1}{2} \frac{\varphi}{a^2} + V(\phi)$ << $\bar{\rho}$
- *^H* ⁺ homogens is an integration of the following equation for the following background evolution for density can denote the current time, respectively. Starting from a radiation-dominated universe with the contract of the contr • We can ignore the ϕ particle contribution to the

$$
f \gg 4 M_{\rm pl}
$$
 or $\alpha_f \ll 0.06$
 $m_{\phi} \ll 0.2 H_0 \approx 10^{-34} \text{ eV}$

Linear Perturbation Equations 3.2 Linear Perturbation Equation Equations (2002) To derive the linear perturbation equations, we expand the scalar field into **Extending the Secondary Perfumbation Fountions of** *hinear Perfumbation Fountions* with 0(⌧) as the background field and '(*x,* ⌧) as the first order perturbation function. Per- α is a constant from Eq. (3.8), we have the following initial init **n Equations** hati

• Dark matter can source scalar field $\phi(x,\tau) = \phi_0(\tau) + \varphi(x,\tau)$ *h* $\overline{f(x^2, y^2)}$ $\overline{f(0, y^2)}$ $\varphi_0(\tau) + \varphi(x,\tau)$

$$
\ddot{\varphi}+2\,\mathcal{H}\,\dot{\varphi}+(k^2+a^2m_{\phi}^2)\varphi=-\frac{1}{2}\dot{h}\,\dot{\phi_0}-\frac{1}{f}\,\rho_c\,\delta_c\,a^2
$$

• The scalar field modified the gravitational potential a *ii*banica die gravitational potential

$$
k^2 \eta - \frac{1}{2} \mathcal{H} \dot{h} = 4\pi G_N a^2 \delta T^0 \qquad \delta T^0_{\ 0}(\phi) = -\frac{\rho_c}{f} [\varphi + \phi_0 \delta_c] - \frac{\dot{\varphi} \phi_0}{a^2} - m_\phi^2 \phi_0 \varphi
$$

• In synchronous gauge:
$$
\dot{\delta}_c = -\frac{1}{2} \dot{h}
$$

field. Deep in the radiation epoch, keeping the radiation epoch, and neglecting terms in powers of and neglecting terms in and neglecting terms in powers of and neglecting terms in powers of and neglecting terms in powers • In synchronous gauge: $\dot{\delta}_c = -\frac{1}{2}\dot{h}$ and **a** / www.android.com/and noticing that \mathbf{a} $\frac{1}{2}$ **k** $\frac{1}{2}$ *i* $\frac{1}{2}$ *i* $\frac{1}{2}$ *j* $\frac{1}{2}$ *j h* $\frac{1}{2}$ $\frac{1$ *ⁱ ,* (3.19) • In synchronous gauge: $\dot{\delta}_c = -\frac{1}{2}\dot{h}$ $\frac{1}{2}\dot{h}$

12 M

iki

*T*⁰

ⁱ() = ¹

*a*2 ˙

- ty nart ⁰ ⌧ *,* '˙ ⁼ ¹ • Dark matter density perturbation is affected by the scalar
field rturbation is affected by the sc *ⁱ*() = ³ *a*2 ˙ ⁰ '˙ ³ *^m*² which agree with the formulas in Ref. [13]. The formulas in Ref. [13]. The dark matter density perturbation still obeys in Ref. [13]. The dark matter density perturbation still obeys in Ref. [13]. The dark matter density p change the values of the values of the change the through the dark matter density perturbations, the first mat
The through the density perturbations, the dark matter density perturbations, the dark matter density perturba • Dark matter density perturbation is affected by the scalar field
	- I *k*² integrated Sachs-Wolfe (ISW), which main ⁰ *,* (3.17) *k*2 potential or integrated sacris-violie (is vv), which mainly changes the power for low multipole moments The first-order perturbed Einstein equations are \mathbf{z} ntegrated Sachs-Wolfe (ISW), which mainly ower for low multipole moments $\rm cct$ is the late time variati 3.3 Constraints on ↵*^f* ⌘ *^M*² pl*/f* ² ϵ choice of an interest of ϵ in ϵ of ϵ and ϵ mediator evolutions for ϵ s_{sc} and s_{sc} for s_{sc} force s_{sc} from the perturbation part r_{sc} • The main effect is the late time variation of the gravitational potential or integrated Sachs-Wolfe (ISW), which mainly changes the power for low multipole moments

^h¨ + 6¨⌘ + 2 *^H* (*h*˙ +6˙⌘) ²*k*² ⌘ = 24⇡*G^N ^a*²(ˆ

^k^j ¹

ˆ *^k^j* ¹

ij)(*Tⁱ*

Change of Gravitational Potential and from Fig. 4, one can see that increasing the value of ↵*^f* leads to a larger gravitational

A larger value of α_f leads to a larger gravitational potential and a more dramatic ISW effect **values of the fifth force strength and at the current time.**

Effect for CMB Power Spectrum

Figure 4. Left panels: the derivative of the gauge-invariant scalar metric perturbation as a function as a function as $\frac{1}{2}$ data from Planck 2013

Constraints on the Fifth Force Strength anticipate that the CMB temperature anisotropies can constrain *m* in the regime where the **CONSTIGNUMER CONDITION CONDITION IN EXAMPLE 11**

$$
\alpha_f \equiv M_{\rm pl}^2 / f^2 \le 1.62 \times 10^{-4} \quad (95\% \text{ C.L.})
$$

Caveat and Other Approach Caveat and Other Approach

- The previous fifth-force discussion is still in the general relativity frame, which equivalence principe is embedded
- The fifth-force can only mimic the potential breaking of WEP $\mathsf{V} \mathsf{V} \mathsf{E} \mathsf{P}$ and $\mathsf{V} \mathsf{E} \mathsf{P}$ and $\mathsf{V} \mathsf{E} \mathsf{P}$ and $\mathsf{V} \mathsf{E} \mathsf{P}$
- The real sign of WEP breaking is that gravitational mass is not equal to the inertial mass and the difference between iner-In this section, we use cosmological data to constrain the difference between inertial and τ fire real sign of vver breaking is that gravitational mass is tial and gravitation and the 1013 level is 2013 level is 2013 level [11] (see also [11]

$$
\lambda_D = m_D^{\rm grav}/m_D^{\rm inertial} \neq 1
$$

• Consequently, we have different gravitational forces among two matter particles and two dark matter particles such that the ratio of dark matter gravitational to inertial mass is given by *^D* = *m*grav dictor *C*onsequently, we have different gravitational forces among particles *D*¹ and *D*2, the gravitational forces in terms of the particle inertial masses are

$$
F_{b_1,b_2}=-\frac{G_Nm_{b_1}m_{b_2}}{r^2},\quad F_{b_i,D_j}=-\lambda_D\frac{G_Nm_{b_i}m_{D_j}}{r^2},\quad F_{D_1,D_2}=-\lambda_D^2\frac{G_Nm_{D_1}m_{D_2}}{r^2}
$$

As pointed out in the text book $\overline{\mathcal{I}}$, one can derive part of the Friedmann and linear and li

Two-Fluid Description that may encode the se deviations is beyond the second that work. The second the scope of this work is this work. centers located at the same point. The same point of the mass density of the mass density of the same point of the mass density of the same point. The mass density of the same assumed the same point of the same point of th

• Two expanding spheres with the same center; one can check the probing matter or dark matter radius changes CriceR are probing matter or dark matter radius changes **diagraphs** check the probing matter o *P M*^{*b*} *r***₂ and** *Center***: one cand** *D***^{***r***}** masses *mb*, *M^b* and *M^D* are inertial masses. Similarly, for a probing dark matter particle with ark matter radius changes

$$
m_b \frac{d^2 r_b}{dt^2} = -\frac{G_N m_b M_b(r_b)}{r_b^2} - \lambda_D \frac{G_N m_b M_D(r_b)}{r_b^2}
$$

$$
m_D \frac{d^2 r_D}{dt^2} = -\lambda_D \frac{G_N m_D M_b(r_D)}{r_D^2} - \lambda_D^2 \frac{G_N m_D M_D(r_D)}{r_D^2}
$$

– 12 – • Requiring the radii proportional to the scale factors other. So, to match to the Friedmann equations, we need to introduce two scale factors, *a*(*t*) In time the tage proportional to the search actors **D** \overline{D} **D** \overline{D} **D** \overline{D} **D** \overline{D} \overline{D} In general, the two radius functions in time *rb*(*t*) and *rD*(*t*) could be independent of each

$$
r_b(t) \, = \, r_b^0 a(t) / a^0 \qquad \qquad r_D(t) = r_D^0 a_D(t) / a_D^0
$$

• Two coupled "Friedmann equations" *^D*. We then rewrite Eqs. (4.2)(4.3) as $R = \frac{1}{2}$ to the scale factor θ or the scale factors, we have θ • Two coupled "Friedmann equations" Requiring the radii proportional to the scale factors, we have *rb*(*t*) = *r*⁰ wo coupled Friedmann equations

$$
\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G_N}{3} \left[\rho_b(a) + \lambda_D \rho_D(a_D) \right] \qquad \frac{1}{a_D}\frac{d^2a_D}{dt^2} = -\frac{4\pi G_N}{3} \left[\lambda_D \rho_b(a) + \lambda_D^2 \rho_D(a_D) \right]
$$

corresponds to the number of dark matter masses present in the interaction, *e.g.* a dark matter

corresponds to the number of dark matter masses present in the interaction, *e.g.* a dark matter

 $\frac{4}{3}$

• In the limit of $\lambda_D = 1$, back to the normal case *^D/aD*(*t*)]3. The equations in Eq. (4.4) describe the acceleration of baryonic \overline{D} \overline{D} \overline{D} \overline{D} and \overline{D} and \overline{D} accelerations of \overline{D} *^D/aD*(*t*)]3. The equations in Eq. (4.4) describe the acceleration of baryonic and dark matter particles, when the dark matter sector violates the WEP. The power of *^D* and ⇢*^D* = ⇢⁰ *D*[*a*⁰ *^D/aD*(*t*)]3. The equations in Eq. (4.4) describe the acceleration of baryonic If the limit of $\lambda_D = 1$ back to the normal case \mathbf{a} and \mathbf{a} \mathbf{b} \mathbf{b} \mathbf{c} \mathbf{b} \mathbf{b} and \mathbf{c} and \mathbf{b} and \mathbf{c} and \mathbf{c} • In the limit of $\lambda_D = 1$, back to the normal case

Two-Fluid Description limit where the WEP is restored (*D is restormand and a the UP is also and the usual Friedmann and where we were the usual Friedmann and the usual Friedmann and the usual Friedmann and the usual Friedmann and the usual Fri* 2 *^D*⌦*^D* \dot{a}

Example of Assemption
• We add in the other species by assuming they couple to gravity in the same way as the baryons <u>R and district the same way as the beyone</u> Blavity in the same way as the +
+ *a*3 *D .* (4.6) 1 Here, we introduce the parameter *H*e⁰ to draw a distinction from the ordinary Hubble constant, *a^D d*2*a^D dt*² ^{they} c \overline{a} 22 J *Dl* **∪**
; Teoria estadounidense
boroom *^a*³ ⁺

$$
\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{\widetilde{H}_0^2}{2}\left[\frac{\Omega_b}{a^3} + \frac{2\Omega_R}{a^4} + (1+3w)\frac{\Omega_\Lambda}{a^{3w+3}} + \frac{\lambda_D\Omega_D}{a^3}\right],
$$

$$
\frac{1}{a_D}\frac{d^2a_D}{dt^2} = -\frac{\widetilde{H}_0^2}{2}\left[\lambda_D\left(\frac{\Omega_b}{a^3} + \frac{2\Omega_R}{a^4} + (1+3w)\frac{\Omega_\Lambda}{a^{3w+3}}\right) + \frac{\lambda_D^2\Omega_D}{a_D^3}\right]
$$

 \bullet Two more initial conditions • Two more initial conditions *dt |*today, at the current universe. For *^D* = 1 with a single scale factor, we have \blacksquare second-order differential equation, which requires two more initial conditions. A simple way in initial conditions. A simple way in initial conditions was a simple way in initial conditions. A simple way in the simple way Compared to ordinary cosmology with a single scale factor, we have one additional

at some time a some time and the dark we are all the dark we are the some time the dark we as the dark we are the dark we are the dark we are the dark we assume that the dark we are the dark we are this time, we are the da

two scale factors, we will keep as a free parameter.
The film will keep her a free parameter.

evolves as a separate fluid according to a dark scale factor *aD*.

$$
a_D = a \text{ and } da/dt = da_D/dt
$$

at a dark WFP hreak turning time: $z_T = a^{-1} - 1$ $\mathbf{S} = \mathbf{S} \mathbf$ at a dark WEP break turning time: $z_T = a_{\text{init}}^{-1}$ where some interaction coupling data that standard matter to the Standard Model falls out of equilibrium. The S
Which is a standard matter to the Standard Model falls out of equilibrium in the Standard Model falls of each $\frac{-1}{\text{init}} - 1$

to fix the dark matter scale factor initial conditions is to have *a^D* = *a* and *da/dt* = *daD/dt* • I will skip here the modified first order equations parametrized by the parametrized by *z*
1980 - Andrew Standard Standard Barbara (2002)
1980 - Andrew Standard Standard Standard Barbara (2002) a single scale factor and the dark matter of the dark matter of the dark matter decouples from the other compo
The dark matter of the second was the dark matter component and the components and the second components and th a single state factor and the dark matter of the dark matter of the dark matter and the other components and the
After and the dark matter and the other components and the other components and the other components and the

Before the transition redshift *z^T* , everything evolves as a one-component fluid described by

where the some interaction coupling to the some to the Standard Model falls of the Standard Model falls out of the Standard Model falls of

Evolution of the Scale Factors

the Universe is not flat with *dark* WFP hreaking with the current observed Hubble constant. the Universe is not flat with dark WEP breaking

Changes on the CMB Power Spectrum

Constraints on WEP Breaking

dark WEP breaking is constrained to be smaller than 10^{-6} panel: 68% and 95% and two dark matter particles is modified by the presence of an ultra light scalar, which mediates \mathbf{u} a long range at the main of the main of the main of the main of the decay of the decay of the decay of the decay the decay of the d

May Explain the Tension of H0

- ★ The cosmological measurement of the Newton's constant for all matter is at 3% precision level and differs by \sim 2 sigma from the lab-based values
- ★ Additional fifth force for dark matter particles is constrained to be weaker than 10^{-4} of the gravitational force
- ★ We introduce a post-Newtonian two-fluid description to explicitly break the WEP by introducing a difference between dark matter inertial and gravitational masses
- \star The ratio of the dark matter gravitational mass to inertial mass is constrained to be unity at the 10^{-6} level

