Gravitational Interactions of Matter and Dark Matter

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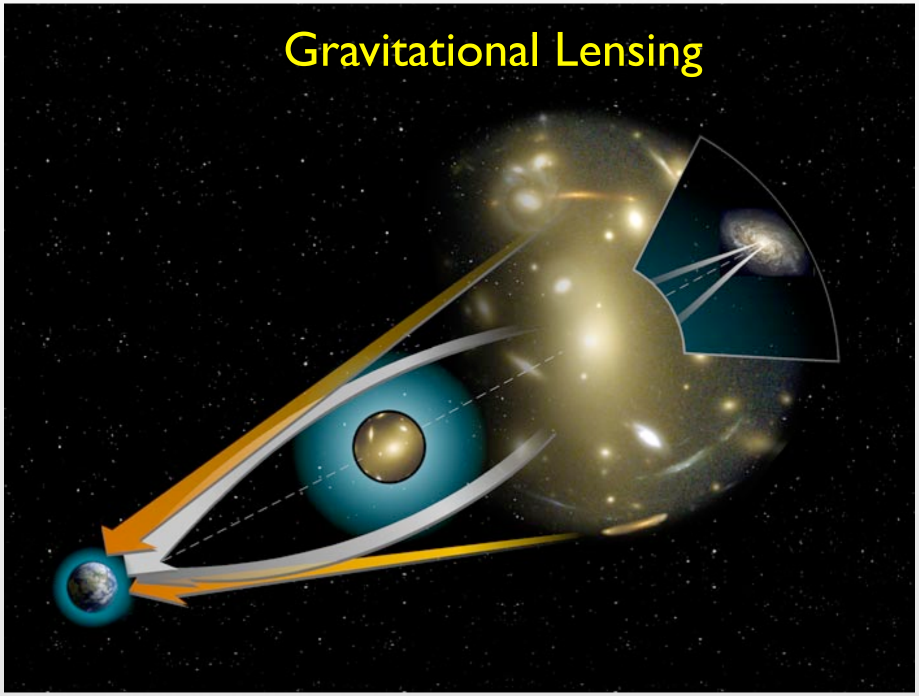
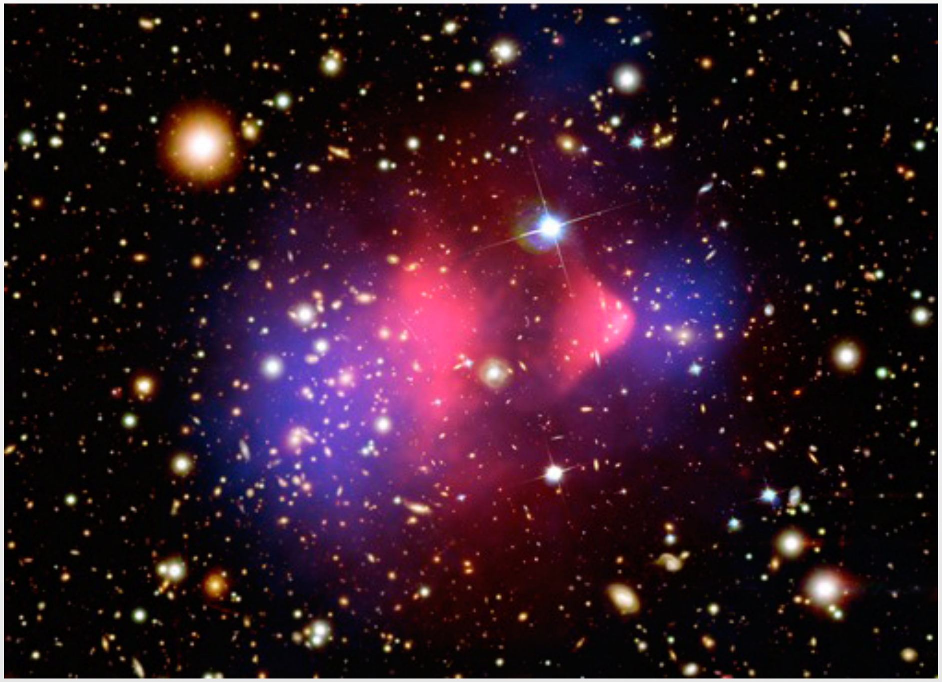
Beyond WIMPs@Hagoshrim, Israel, May 31, 2015

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

Evidence of Dark Matter

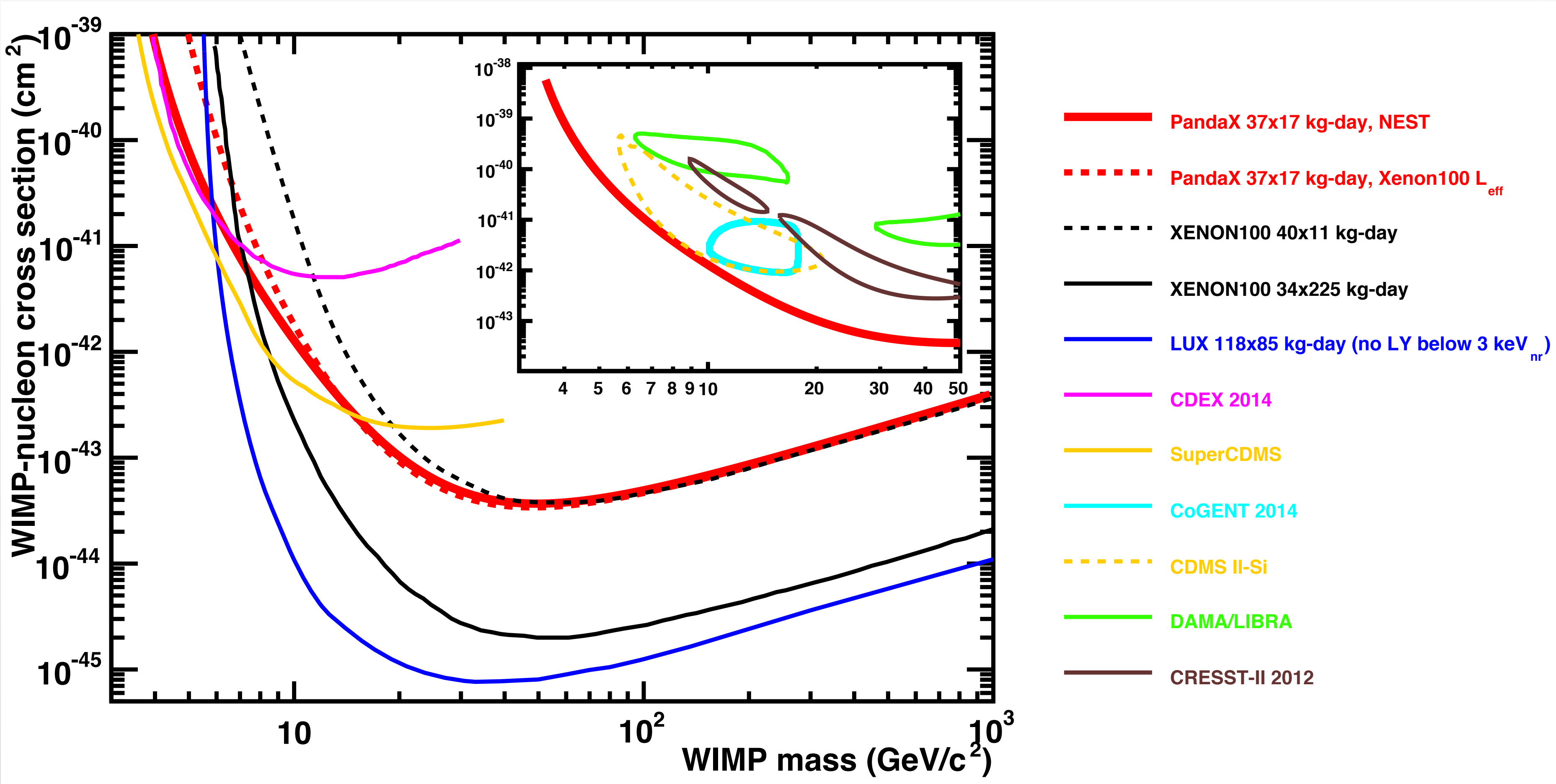




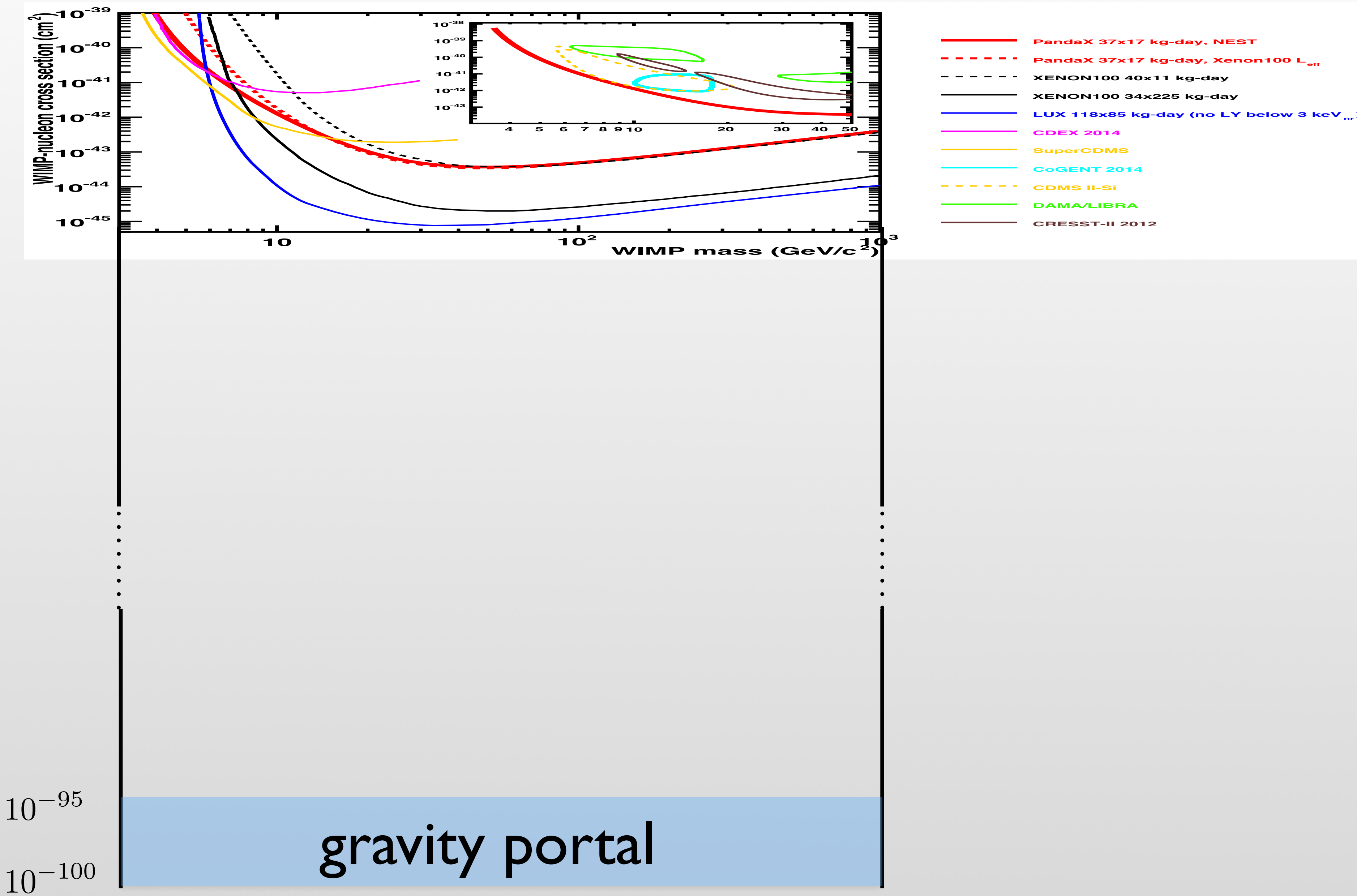
there is no doubt that dark matter has gravitational interaction

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

Dark Matter Direct Detection



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

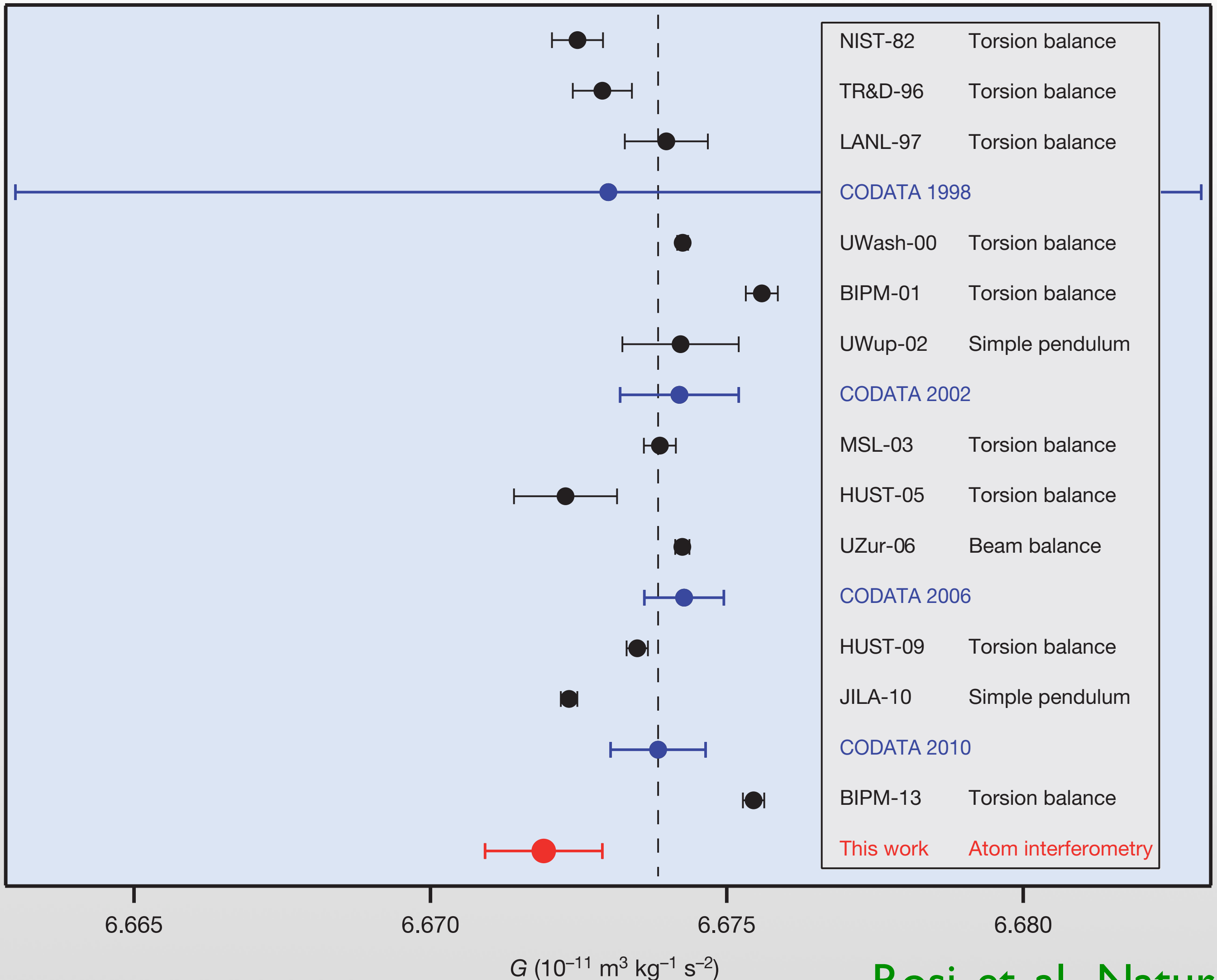
$$a_{\rm grav} = -\frac{G_N M}{r^2}$$

- 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

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

a relative error of 1.2×10^{-4}

Terrestrial Measurement of G_N



Rosi, et. al., Nature 510 (2014)

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: $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} a^2 {\lambda_G}^2 G_N \bar{\rho}$
- Unphysical for the background evolution (zeroth order)
- change the "expansion clock" $\tau \rightarrow \lambda_G \tau$

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

- next check the first-order linear order equations

I'st Order Fluid Perturbations (DM)

- From energy-momentum conservation (hydrodynamical equations)

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

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

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

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

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

- change the "expansion clock" $\tau \to \lambda_G \, \tau$
- rescale the wavenumber by $k \to k/\lambda_G$
- 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

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

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

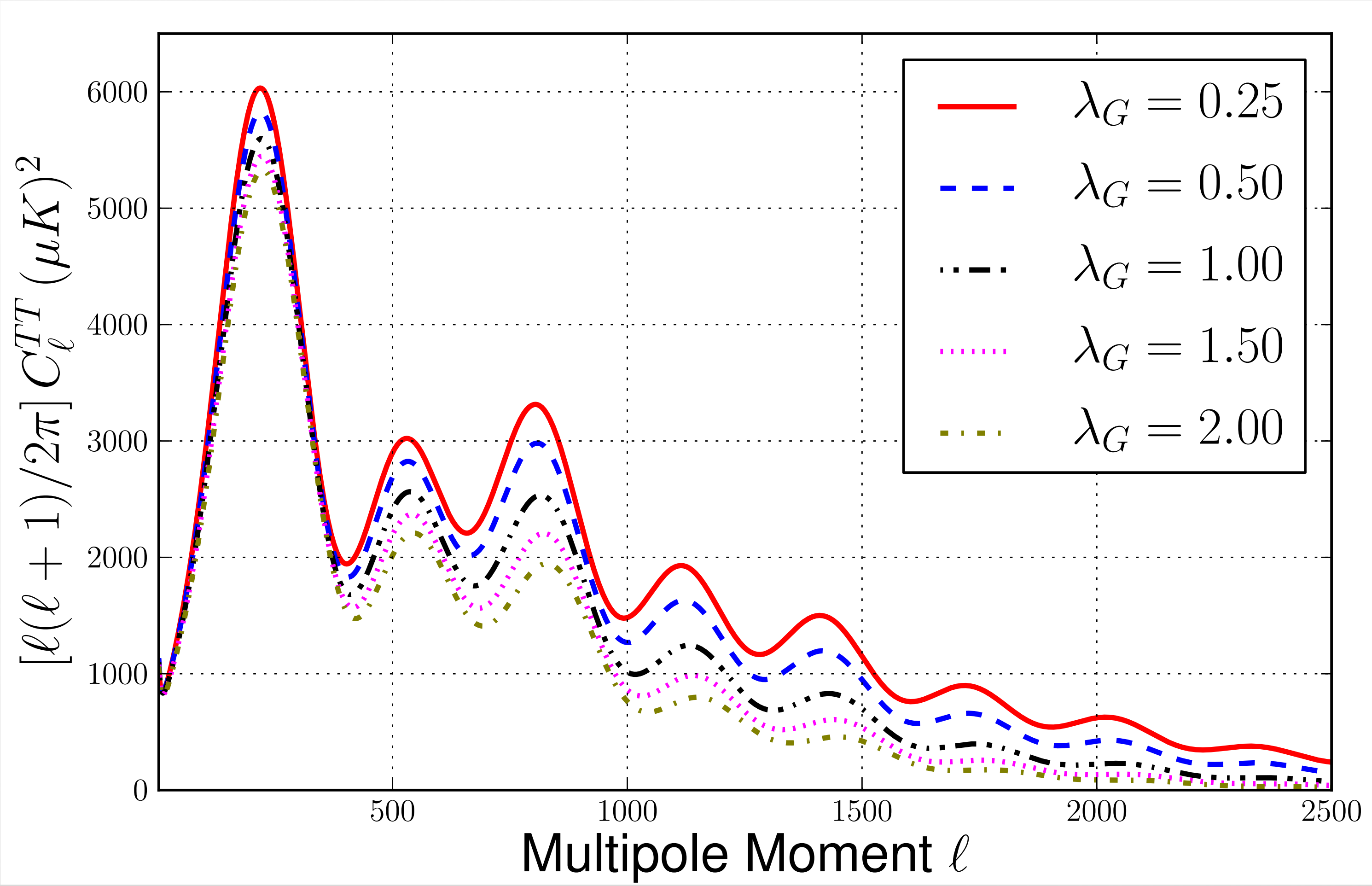
- Equations are no longer invariant under

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

- Varying λ_G now yields an observable change in cosmological evolution

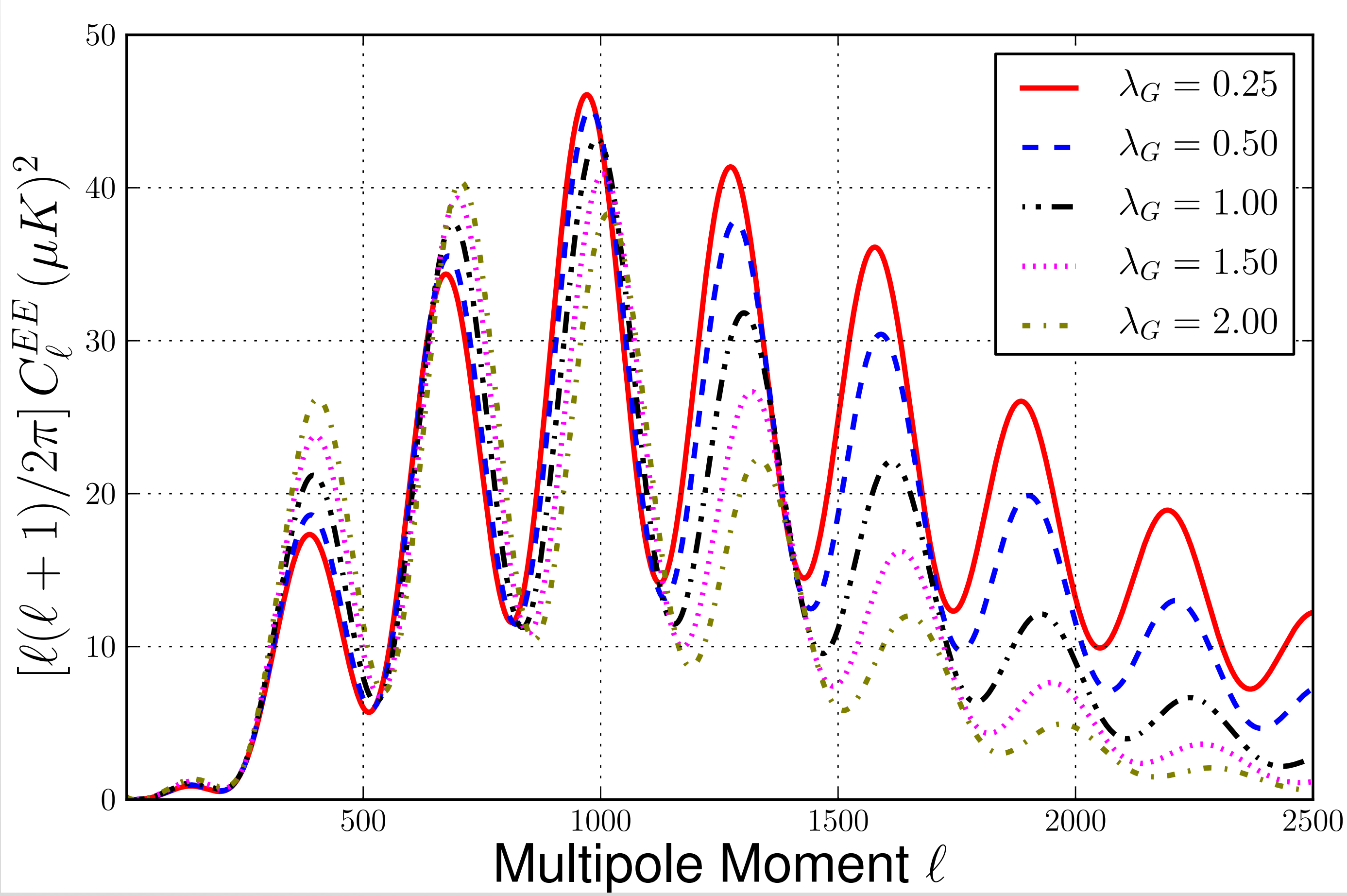
CMB Temperature Power Spectrum

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



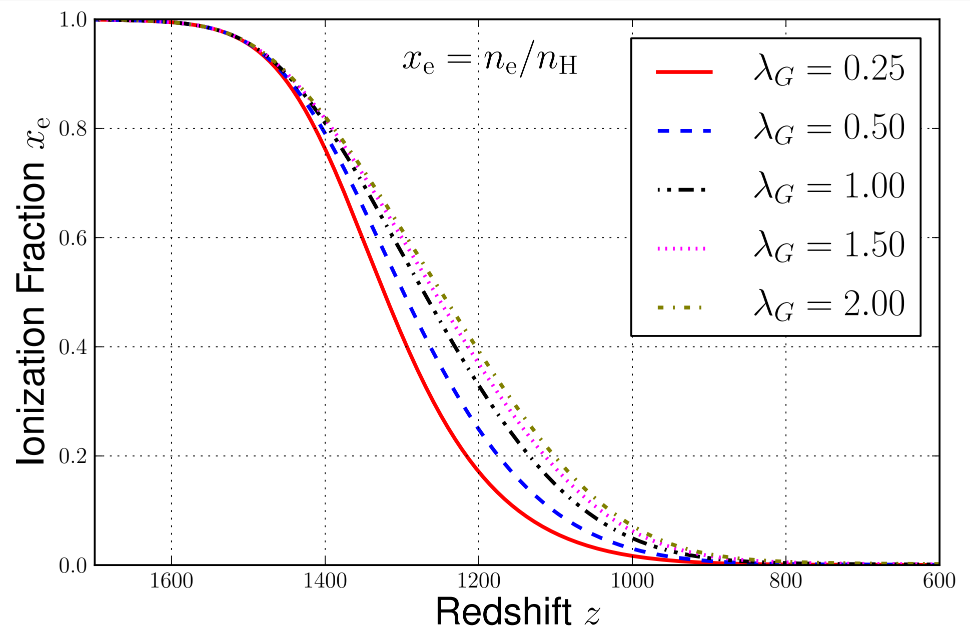
CMB EE Power Spectrum

- 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

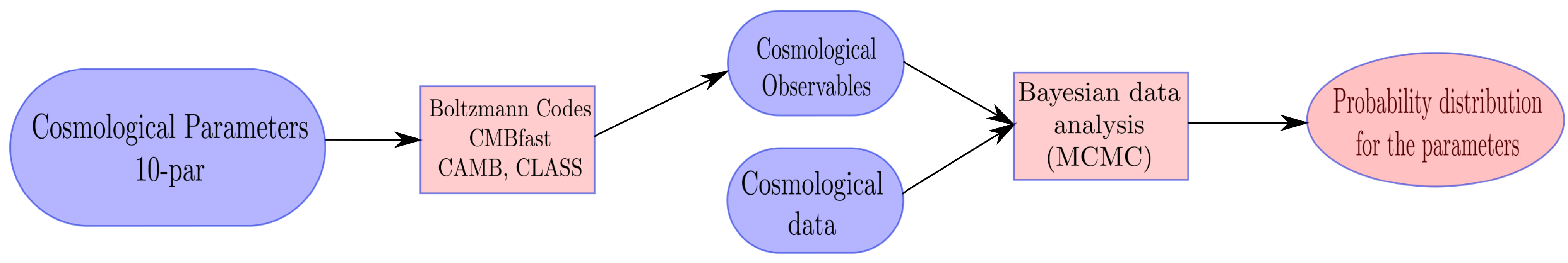


- For $\lambda_G > 1$, the photon visibility function broadens. Photons last scatter over a longer period of time. This damps anisotropy on scales smaller than the photon mean free path.

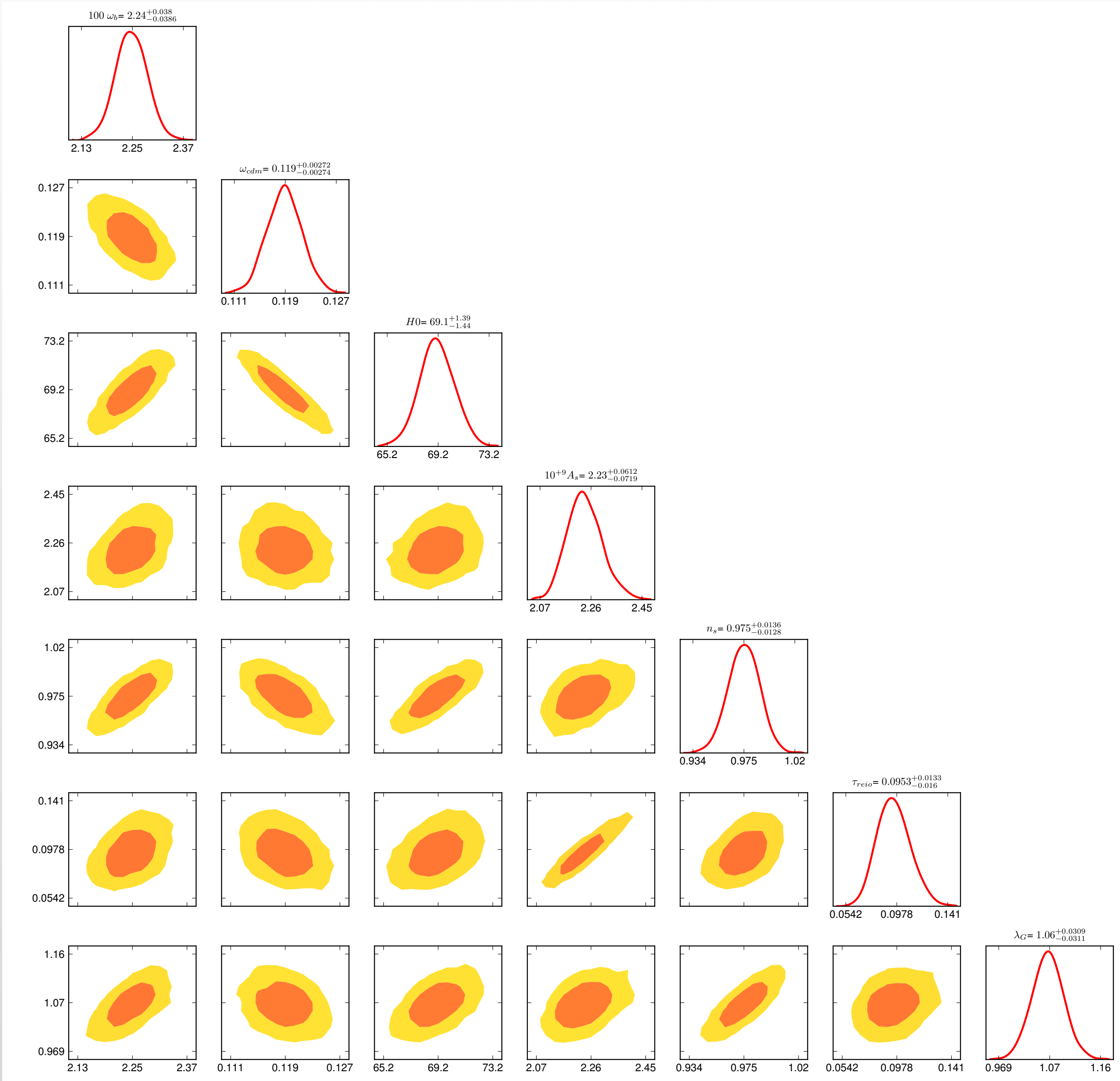
Analysis Method

- Markov Chain Monte Carlo (MCMC) using the publicly available MontePython code (written to work with CLASS)
- For a given point in parameter space θ_i, compute observables using our modified 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

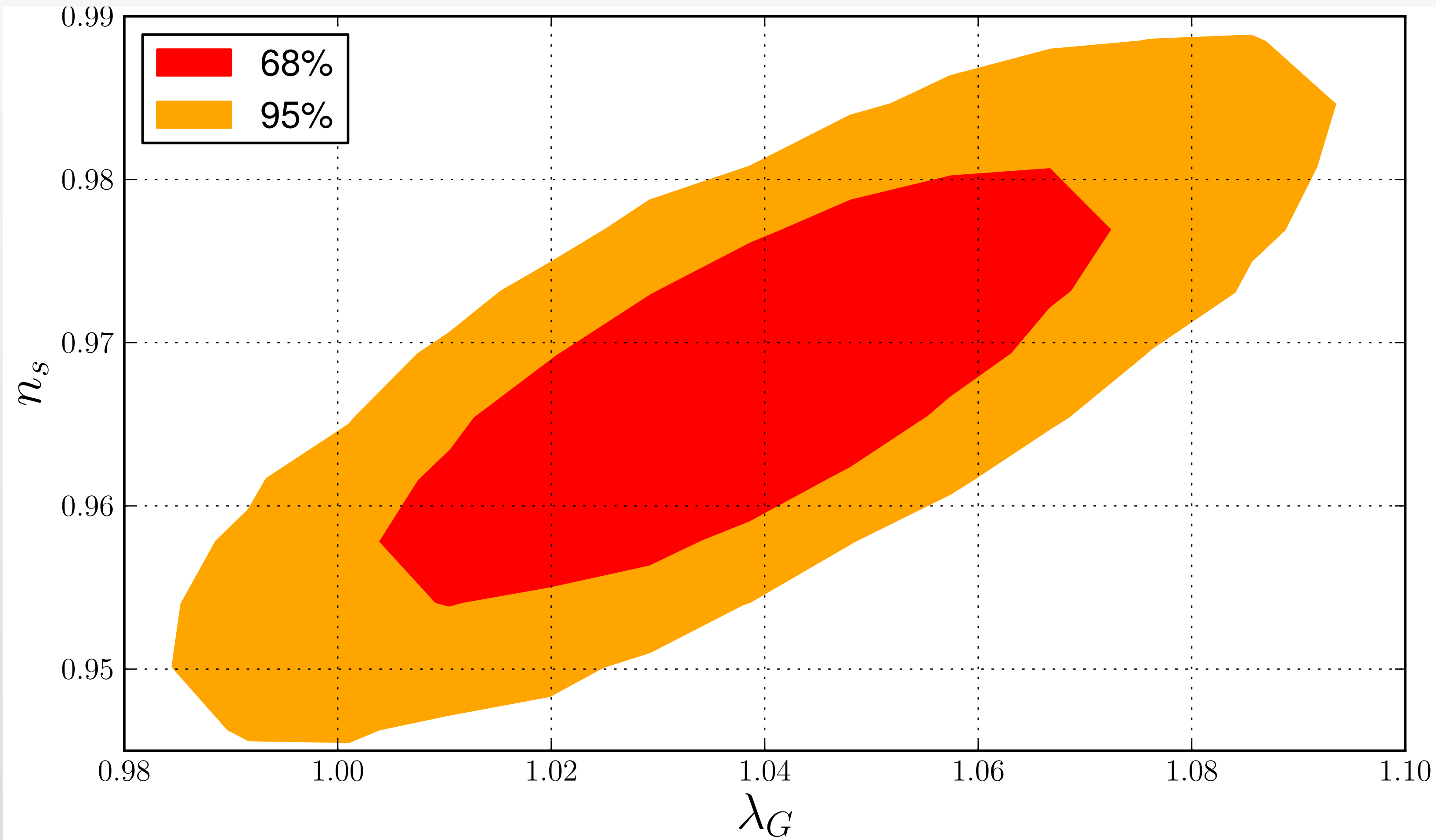
$$P(\theta_i|D) = \frac{\mathcal{L}(D|\theta_i)\pi(\theta_i)}{\int \mathcal{L}(D|\theta_i)d\theta_1..d\theta_N}$$



Posterior Probability for the Parameters



Posterior Probability for the Parameters



Planck+ACT/SPT+Lensing+BAO+HST

Results

Data	λ_G
Planck (2013)	$1.062^{+0.031}_{-0.031}$
Planck+Lensing+BAO	$1.041^{+0.024}_{-0.027}$
Planck+Lensing+BAO+HST	$1.046^{+0.026}_{-0.027}$
Planck+Lensing+BAO+BBN	$1.046^{+0.021}_{-0.021}$
Planck+ACT/SPT	$1.046^{+0.025}_{-0.028}$
Planck+ACT/SPT+Lensing+BAO+HST	$1.038^{+0.022}_{-0.023}$
Planck+ACT/SPT+Lensing+BAO+HST+BBN	$1.043^{+0.019}_{-0.019}$

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

A relative error of 3.7%

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

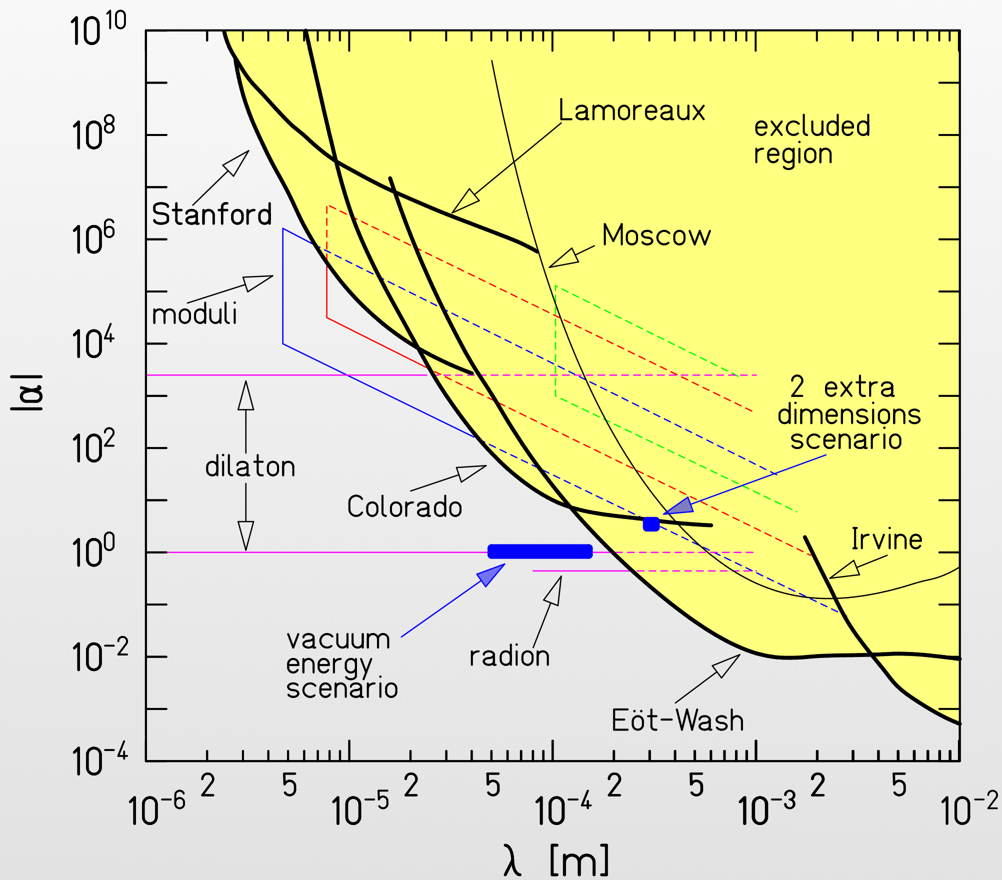
- The equivalence principle is the principal assumption on which general relativity has been built
- Weak equivalence principle is to check whether:

$$m_{\text{grav.}} \stackrel{?}{=} m_{\text{inertial}}$$

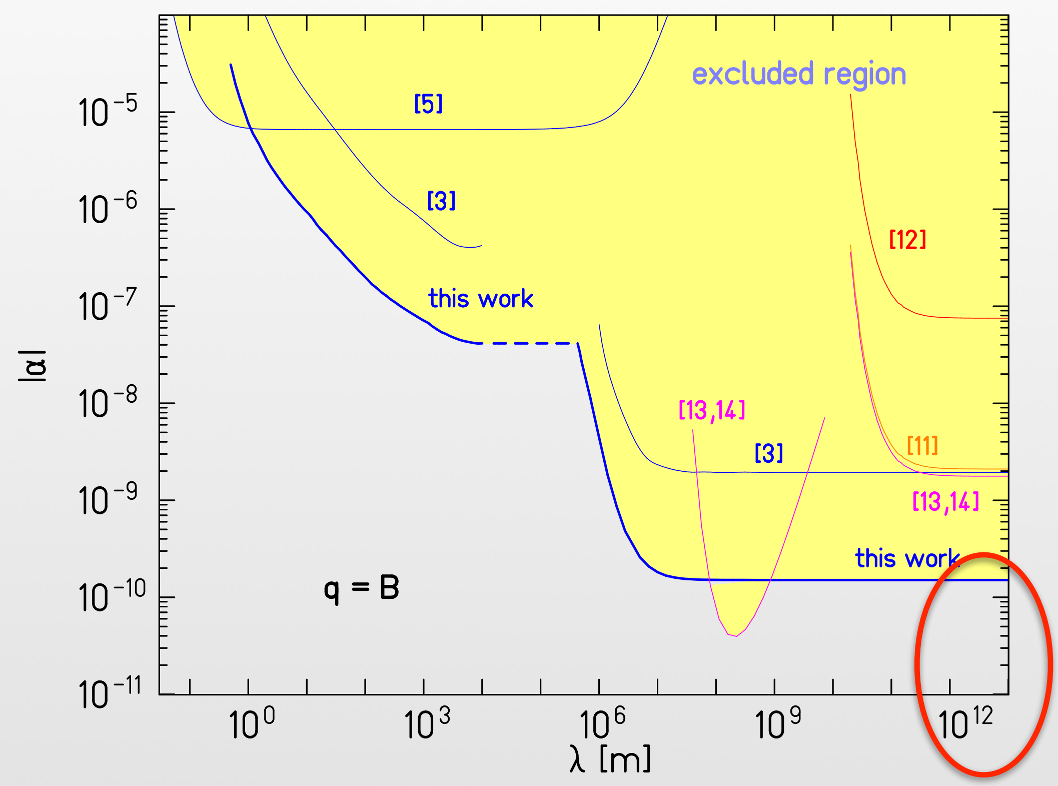
- One introduces a long-range fifth force to change the effective gravitational potential/force

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

Breaking of WEP for Baryons



a review, Adelberger, Heckel, Nelson
hep-ph/0307284



Schlamminger, et. al., arxiv:0712.0607

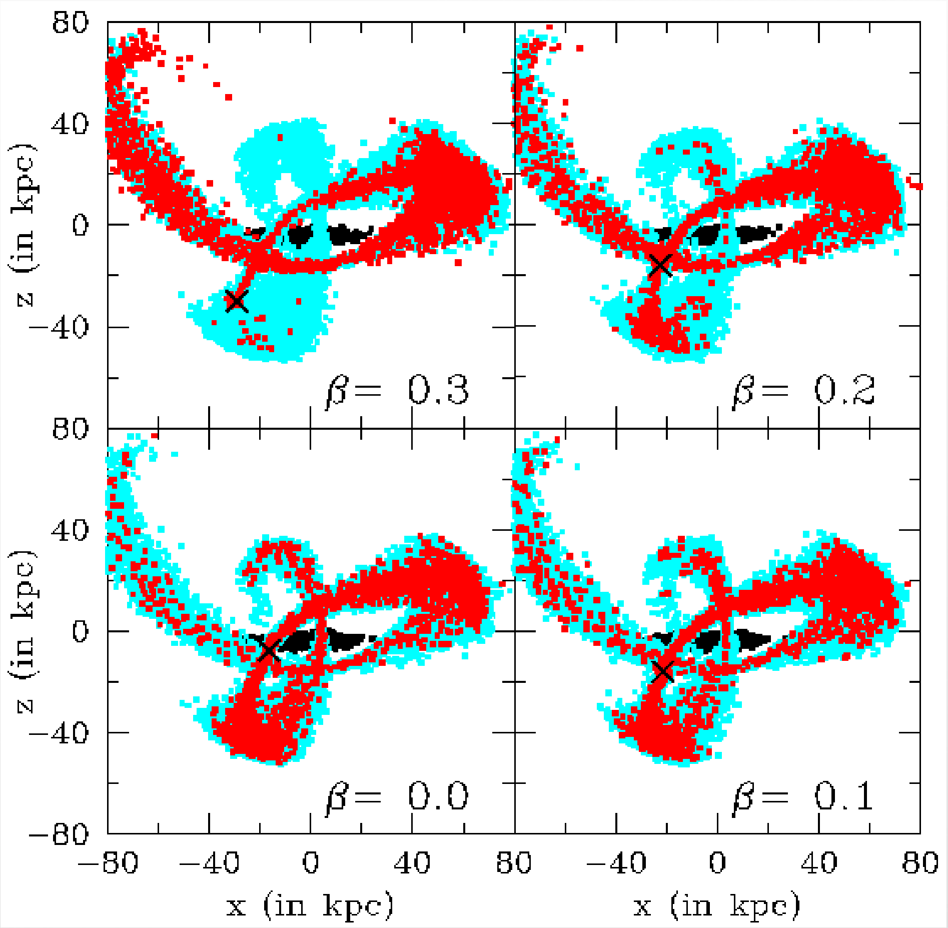
constraints on the fifth force of ordinary matter are very stringent at the cosmological scales

Breaking of WEP for Dark Matter

- The tidal disruption of the Sagittarius dwarf galaxy orbiting the Milky way

- N-body simulation using GADGET

- This constraints additional dark matter force weaker than 10% of gravity



$$\alpha_f = \beta^2$$

Kesden and Kamionkowski, astro-ph/0606566

Long-range Force only for Dark Matter

- The ultra-light scalar field could be a Pseudo-Nambu Goldstone Boson to mediate the macroscopic forces

Hill and Ross, PLB 203 (1988), 125

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

- Only dark matter feels the additional force

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

- The Friedmann equation is modified:

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

Frieman and Gradwohl, PRL 67(1991) 2926; Bean, astro-ph/0104464

Nusser, Gubser, Peebles, astro-ph/0412586; Bean, Flanagan, Laszlo, Trodden, 0808.1105

Conditions to Ignore the Scalar Background

- For an ultra-light scalar satisfying:

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

- Requiring $\frac{\phi}{f}\rho_c + \frac{1}{2}\frac{\dot{\phi}^2}{a^2} + V(\phi)$ << $\bar{\rho}$

- We can ignore the ϕ particle contribution to the background evolution for

$$f \gg 4\,M_{\rm pl} \quad \text{or} \quad \alpha_f \ll 0.06$$

$$m_\phi \ll 0.2\,H_0 \approx 10^{-34}\,\text{eV}$$

Linear Perturbation Equations

- Dark matter can source scalar field $\phi(x,\tau) = \phi_0(\tau) + \varphi(x,\tau)$

$$\ddot{\varphi} + 2\mathcal{H}\dot{\varphi} + (k^2 + a^2 m_\phi^2)\varphi = -\frac{1}{2}\dot{h}\,\dot{\phi}_0 - \frac{1}{f}\rho_c\,\delta_c\,a^2$$

- The scalar field modified the gravitational potential

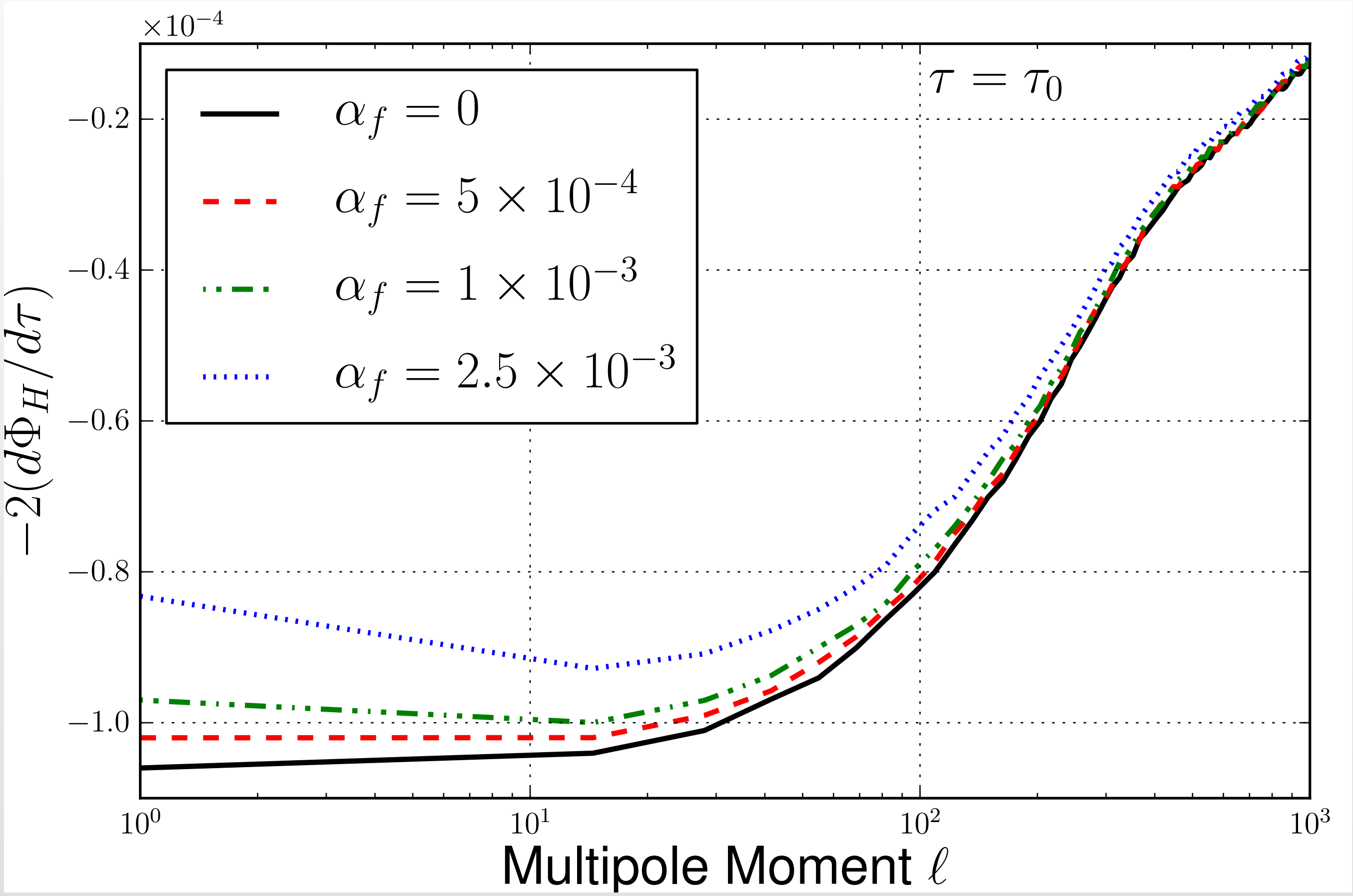
$$k^2\eta - \frac{1}{2}\mathcal{H}\,\dot{h} = 4\pi G_N\,a^2\,\delta T^0{}_0 \qquad \delta T^0{}_0(\phi) = -\frac{\rho_c}{f}\left[\varphi + \phi_0\,\delta_c\right] - \frac{\dot{\varphi}\,\phi_0}{a^2} - m_\phi^2\,\phi_0\,\varphi$$

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

- Dark matter density perturbation is affected by the scalar field

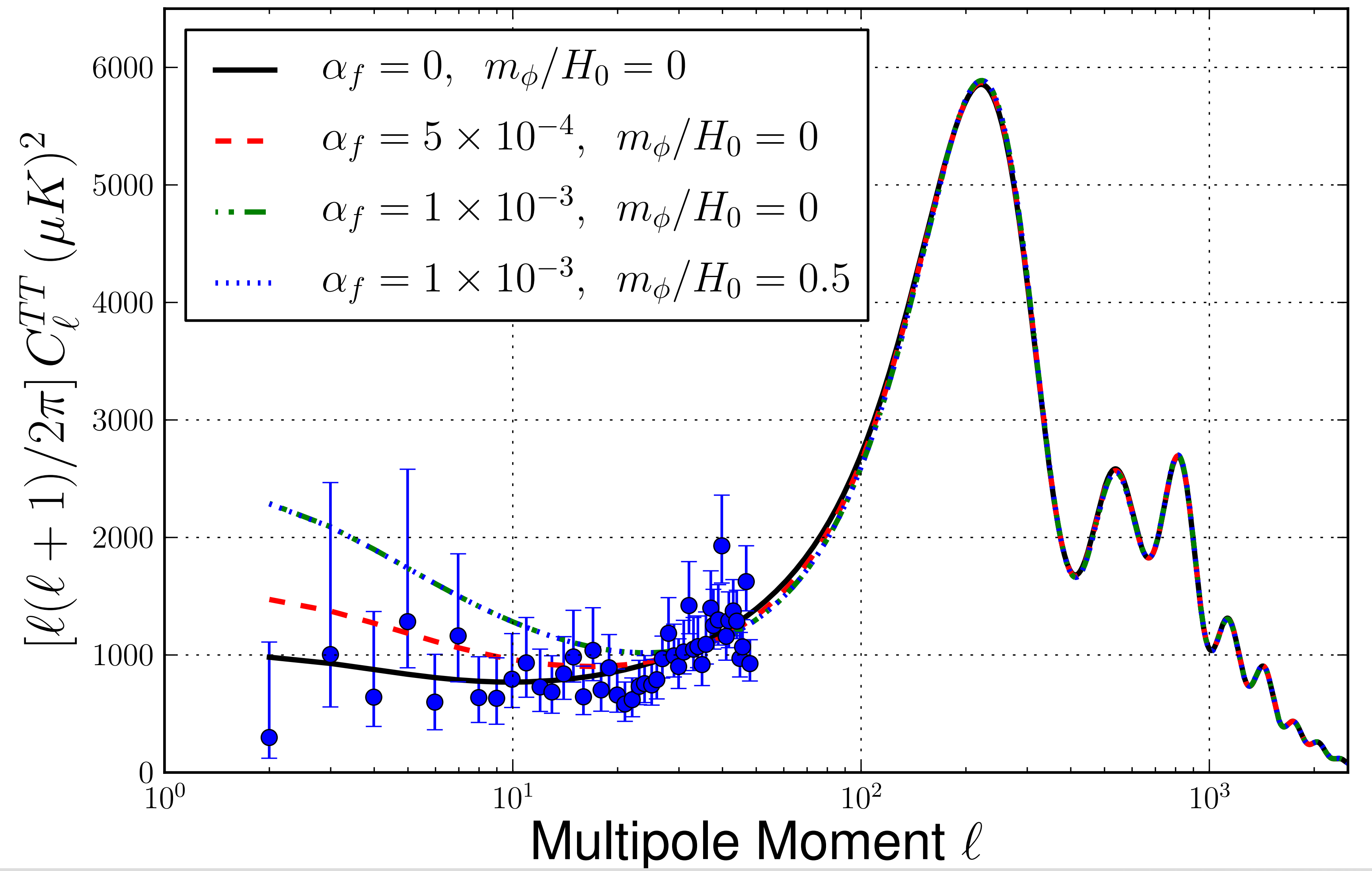
- The main effect is the late time variation of the gravitational potential or integrated Sachs-Wolfe (ISW), which mainly changes the power for low multipole moments

Change of Gravitational Potential



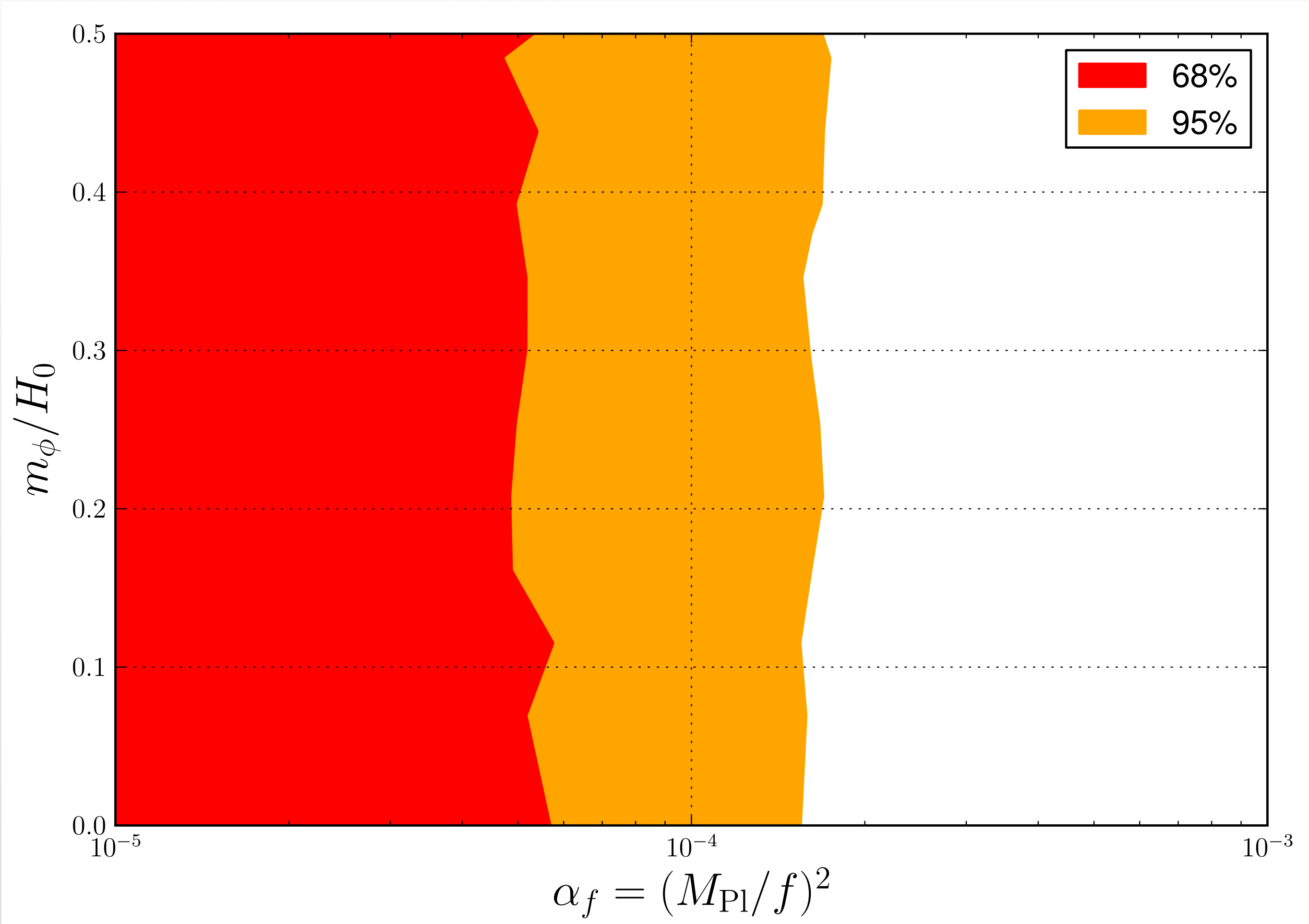
A larger value of α_f leads to a larger gravitational potential and a more dramatic ISW effect

Effect for CMB Power Spectrum



data from Planck 2013

Constraints on the Fifth Force Strength



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

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

- The real sign of WEP breaking is that gravitational mass is not equal to the inertial mass

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

- Consequently, we have different gravitational forces among two matter particles and two dark matter particles

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

Two-Fluid Description

- Two expanding spheres with the same center; one can check the probing matter or dark matter radius changes

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

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

- Requiring the radii proportional to the scale factors

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

- Two coupled "Friedmann equations"

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

- In the limit of $\lambda_D = 1$, back to the normal case

Two-Fluid Description

- We add in the other species by assuming they couple to gravity in the same way as the baryons

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

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

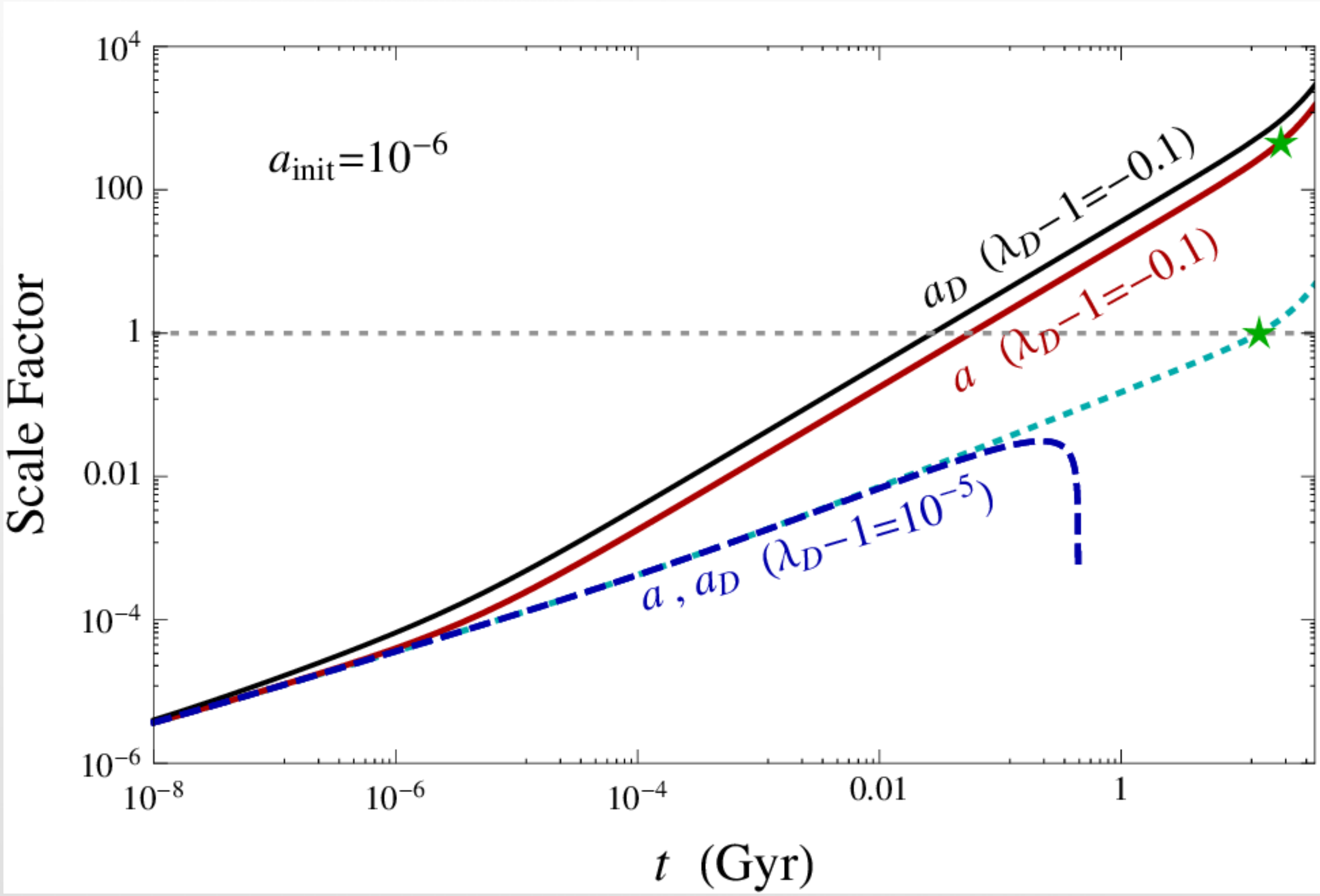
- Two more initial conditions

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

at a dark WEP break turning time: $z_T = a_{\rm init}^{-1} - 1$

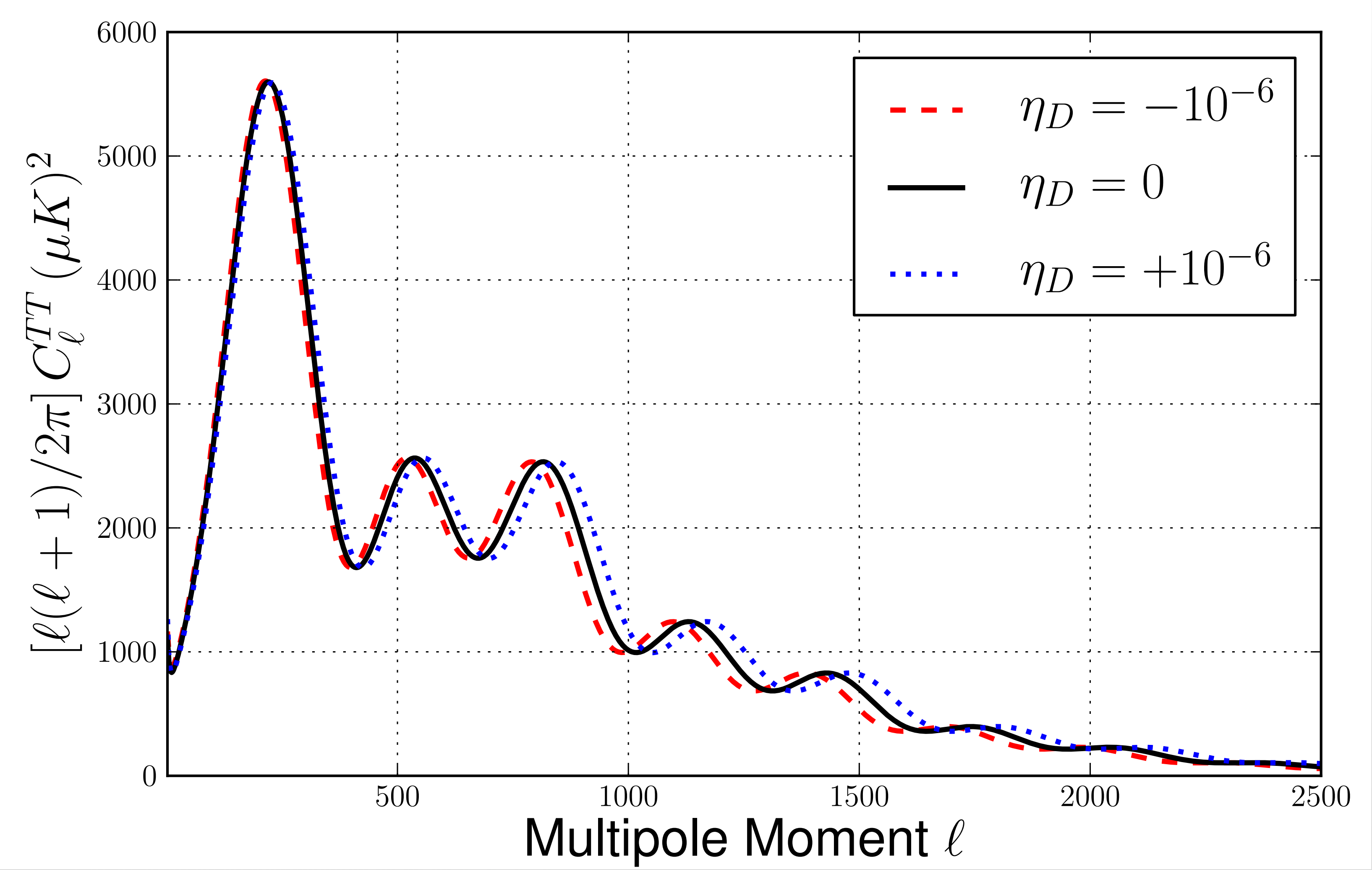
- I will skip here the modified first order equations

Evolution of the Scale Factors

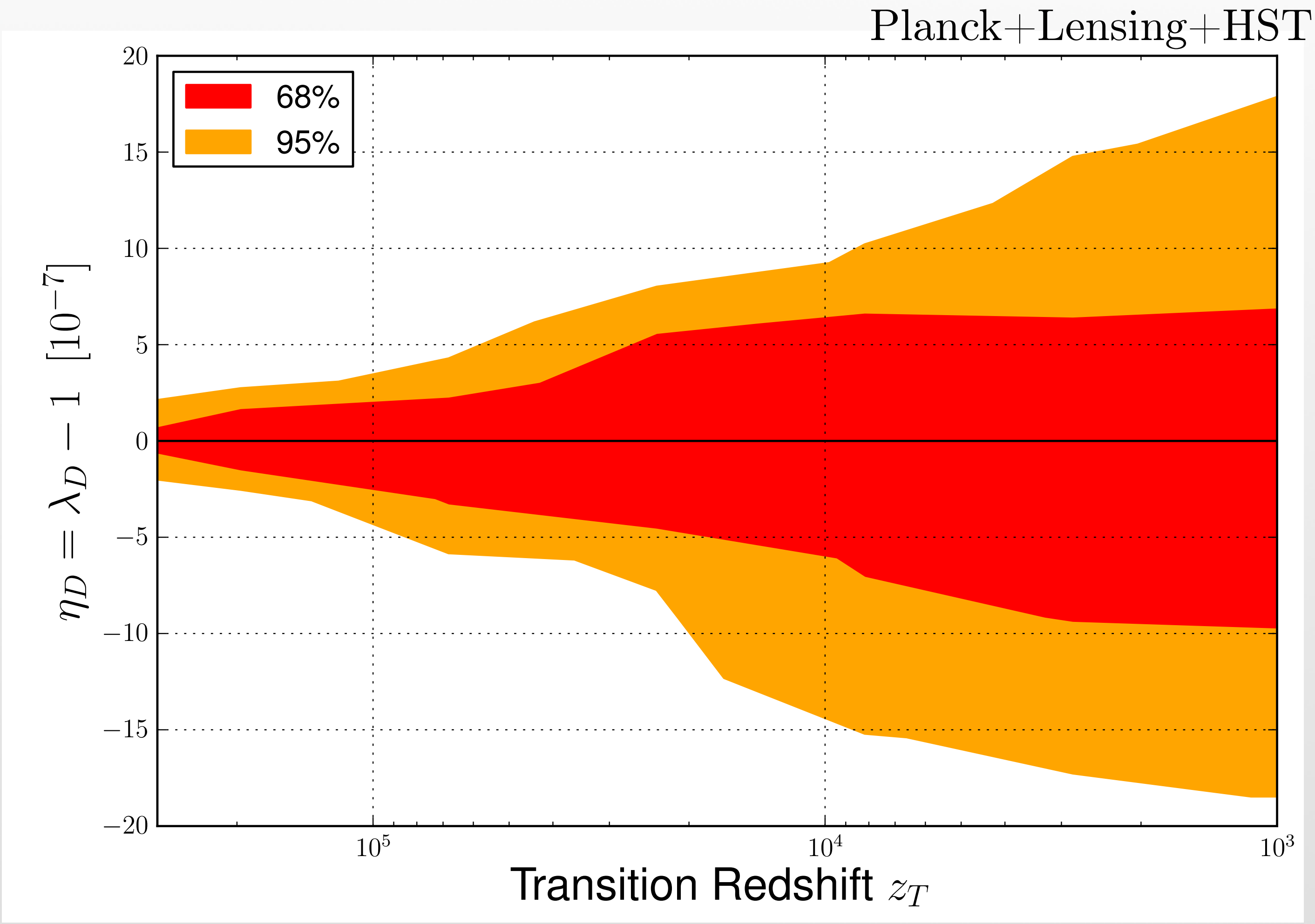


the Universe is not flat with dark WEP breaking

Changes on the CMB Power Spectrum

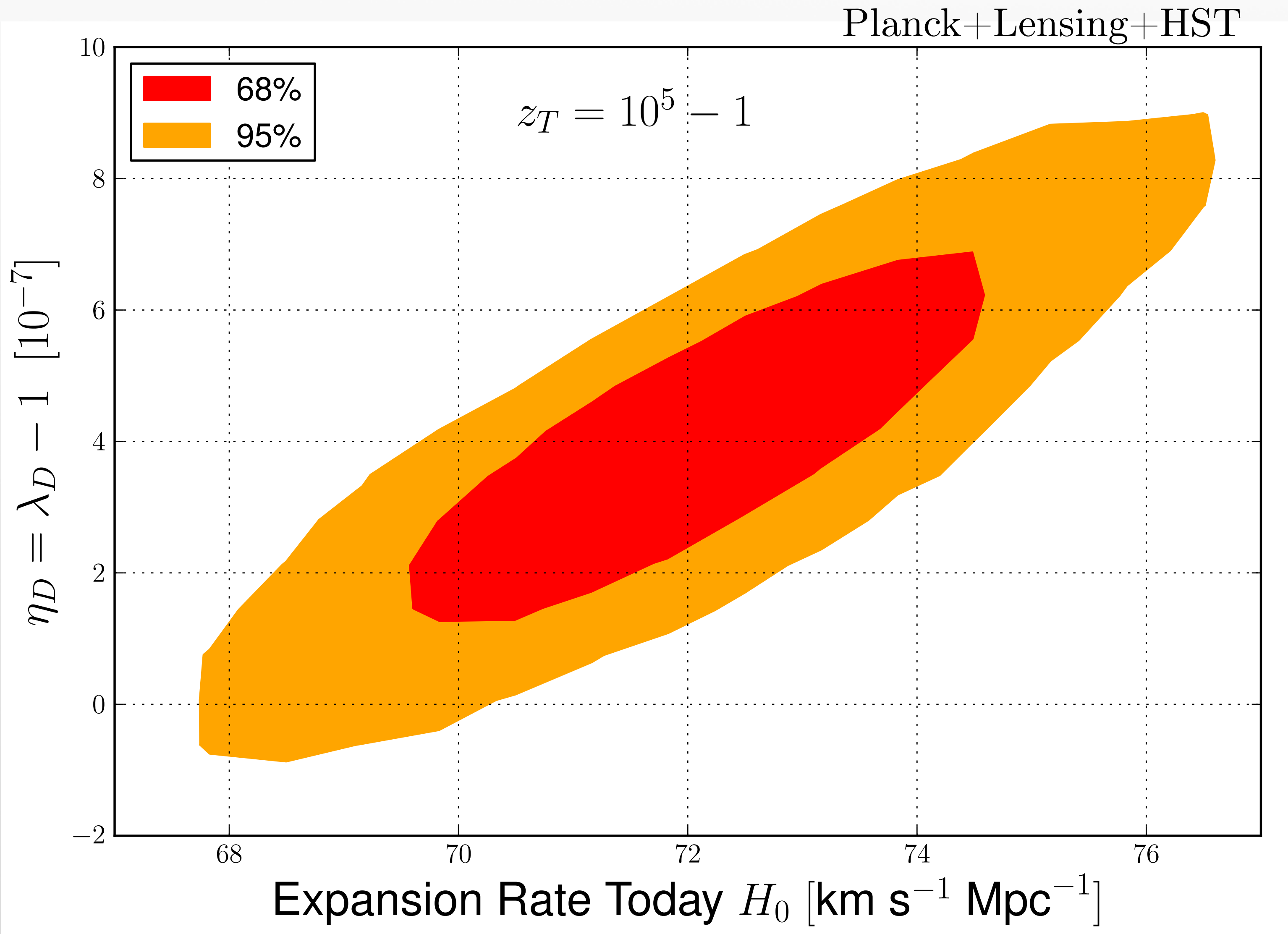


Constraints on WEP Breaking



dark WEP breaking is constrained to be smaller than 10^{-6}

May Explain the Tension of H0



Conclusions

- ★ The cosmological measurement of the Newton's constant for all matter is at 3% precision level and differs by ~ 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
- ★ The ratio of the dark matter gravitational mass to inertial mass is constrained to be unity at the 10^{-6} level

Thanks