Title: Cosmological Constraints on theories of Modified Gravity

Date: Oct 16, 2014 11:00 AM

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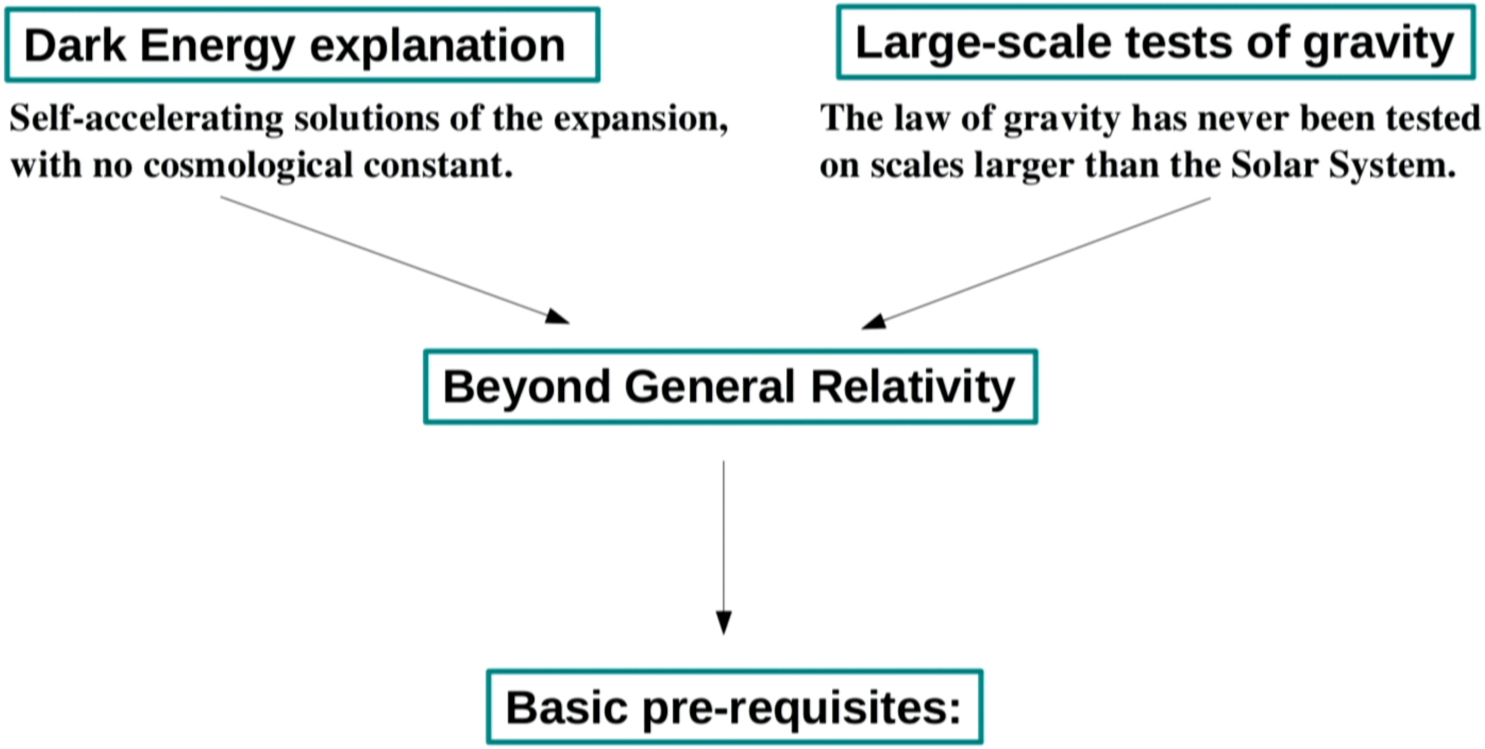
Abstract: <span>Recently, research in cosmology has seen a growing interest in theories of gravity beyond General Relativity (GR). From an observational point of view, there are two main reasons for this. Firstly, the law of gravity has never been directly tested on scales larger than the Solar System. Hence, by understanding better the various signatures that different gravity models can leave on cosmological observables, one can improve the chances of identifying any departures from GR, or alternatively, extend the model's observational success into a whole new regime. Secondly, theories of modified gravity can arise also as an alternative to the cosmological constant (or any other form of dark energy) to explain the current accelerated expansion of the Universe. Using my results from suitably modified Boltzmann, N-body codes and semi-analytical models of structure formation, I will describe the way modified gravity models typically impact a series of cosmological observables. I will use two popular models as examples, which are known as Galileon and Nonlocal Gravity. In the Galileon model, the modifications to gravity on large scales are driven by nonlinear derivative interactions of a scalar field, which can nevertheless be suppressed in the Solar System by means of a mechanism known as Vainshtein screening. This model can provide a good fit to the latest CMB, BAO and SNIa data, although with different cosmological parameters than the standard LCDM model. Specifically, unlike LCDM, the Galileon model predicts nonzero neutrino masses (over 5sigma) and the constraints on the Hubble rate are compatible with its local determinations. The results from my N-body simulations and Halo Occupation Distribution analysis also show that the model can describe the measured clustering amplitude of Luminous Red Galaxies and that the screening mechanism can be very efficient in "hiding" the modifications to gravity on small scales. However, these results also show that the observational viability of the model may be under pressure due to the combined constraints derived from the sign of the ISW effect and from Solar System tests. In the Nonlocal model, the acceleration of the universe is driven by terms that involve the inverse of a derivative operator acting on curvature tensors. This model is also likely to pass large-scale structure constraints with the same flying colors as Galileon gravity, but the lack of a screening mechanism in this model makes it unclear on whether or not it is able to satisfy Solar System constraints. These steps I will describe for the cases of the Galileon and Nonlocal models can be viewed as guidelines for one to place constraints on other (or not yet invented) models of modified gravity. References: The results I will describe are based on the following papers: arXiv:1208.0600, arXiv:1302.6241, arXiv:1306.3219, arXiv:1308.3699, arXiv:1401.1497, arXiv:1404.1365, arXiv:1406.0485, arXiv:1408.1084

Why modified gravity



Dark Energy explanation

Self-accelerating solutions of the expansion, with no cosmological constant.

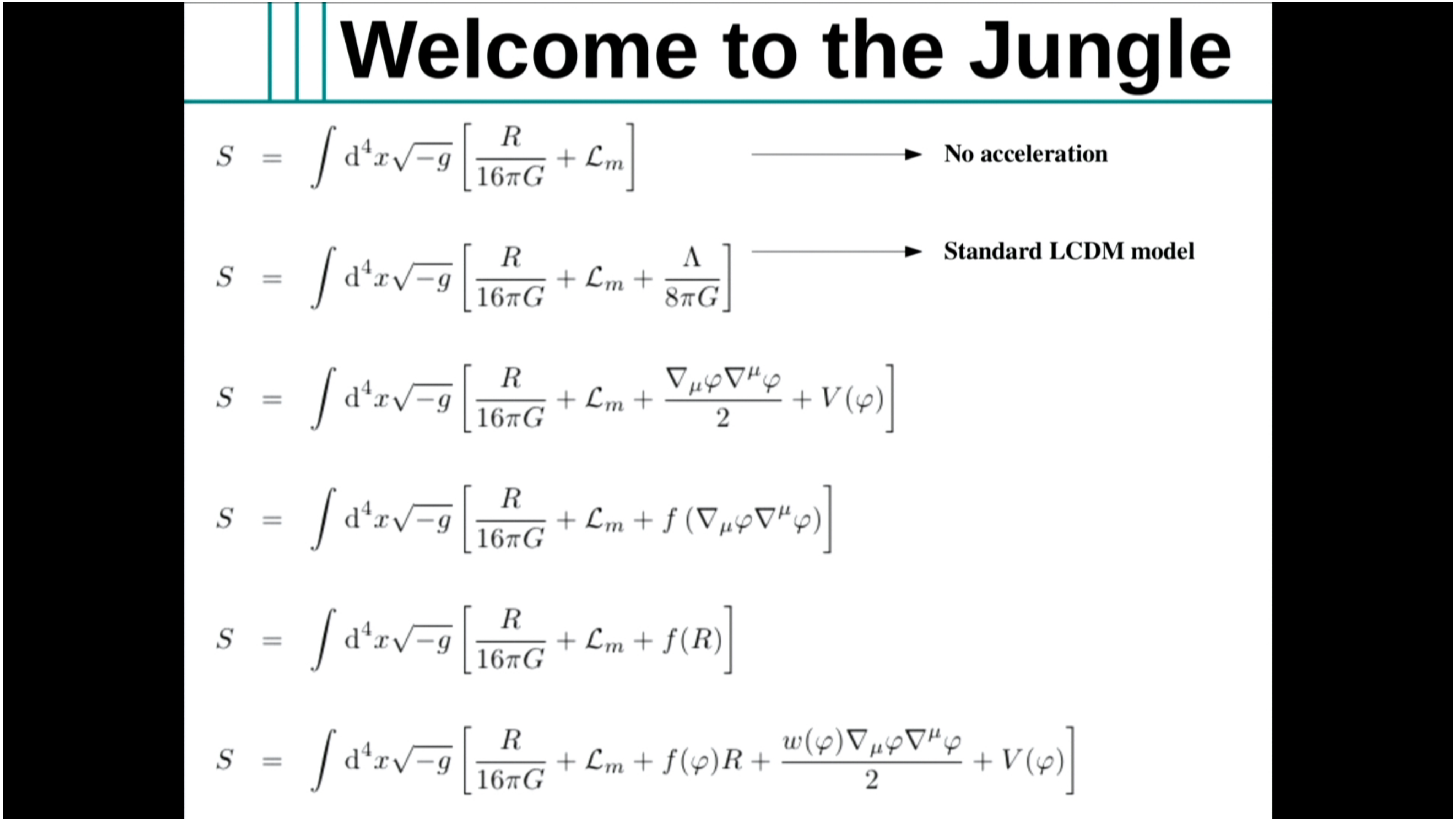
Large-scale tests of gravity

The law of gravity has never been tested on scales larger than the Solar System.

Beyond General Relativity

Basic pre-requisites:

- Preserve past inflationary, radiation and matter dominated eras.
- Modifications have to be small in the Solar System, where GR is very successful.



Welcome to the Jungle

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m\right]$$ → **No acceleration**

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\Lambda}{8\pi G}\right]$$ → **Standard LCDM model**

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f\left(\nabla_\mu\varphi\nabla^\mu\varphi\right)\right]$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(R)\right]$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(\varphi)R + \frac{w(\varphi)\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

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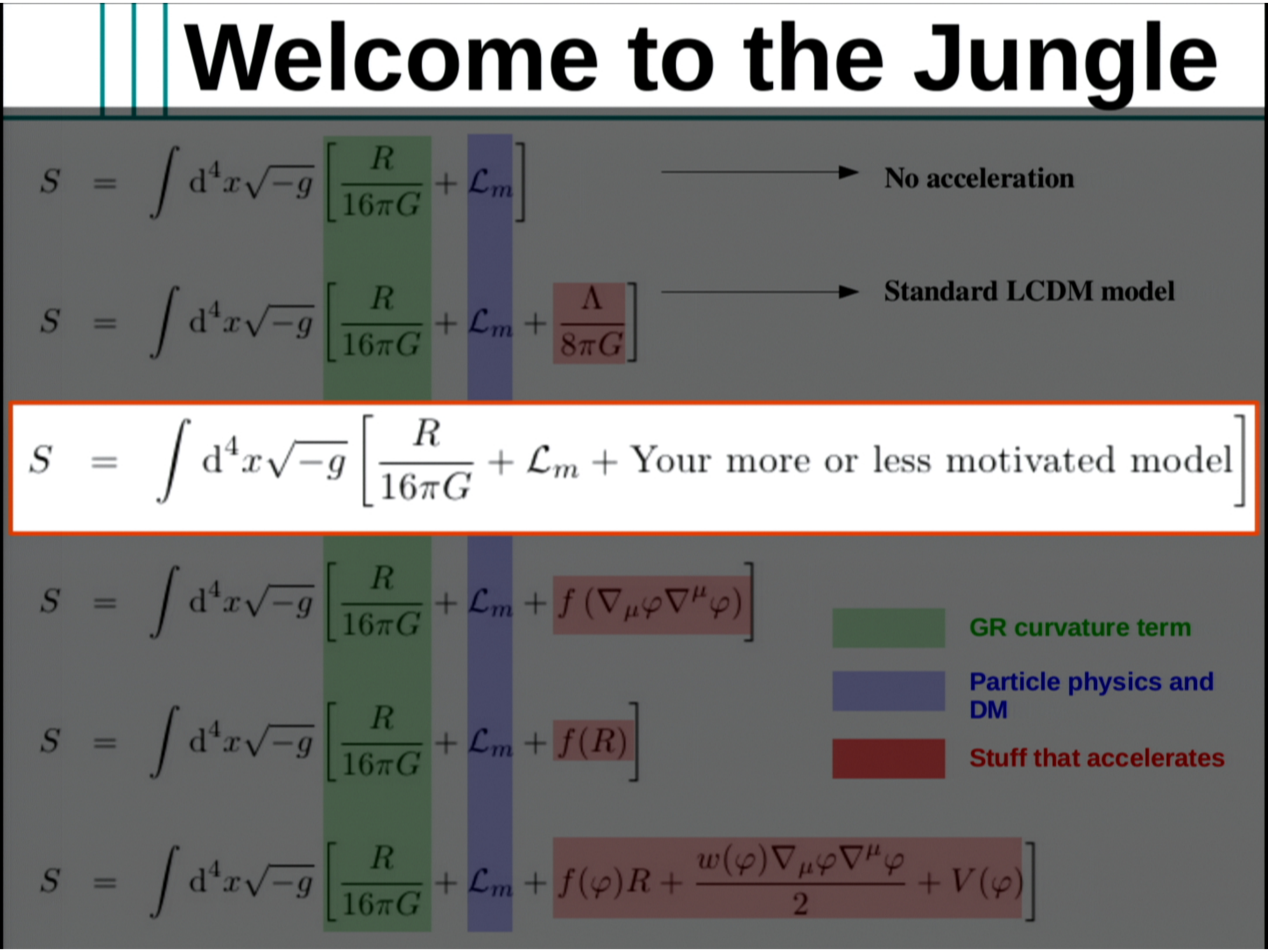
🟩 GR curvature term

🟦 Particle physics and DM



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$$\boxed{S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \text{Your more or less motivated model}\right]}$$

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f\left(\nabla_\mu\varphi\nabla^\mu\varphi\right)\right]$$

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🟩 GR curvature term

🟦 Particle physics and DM

🟥 Stuff that accelerates

Galileon origins

Galilean shift transformation

$$\boxed{\partial_\mu \varphi \longrightarrow \partial_\mu \varphi + b_\mu}$$

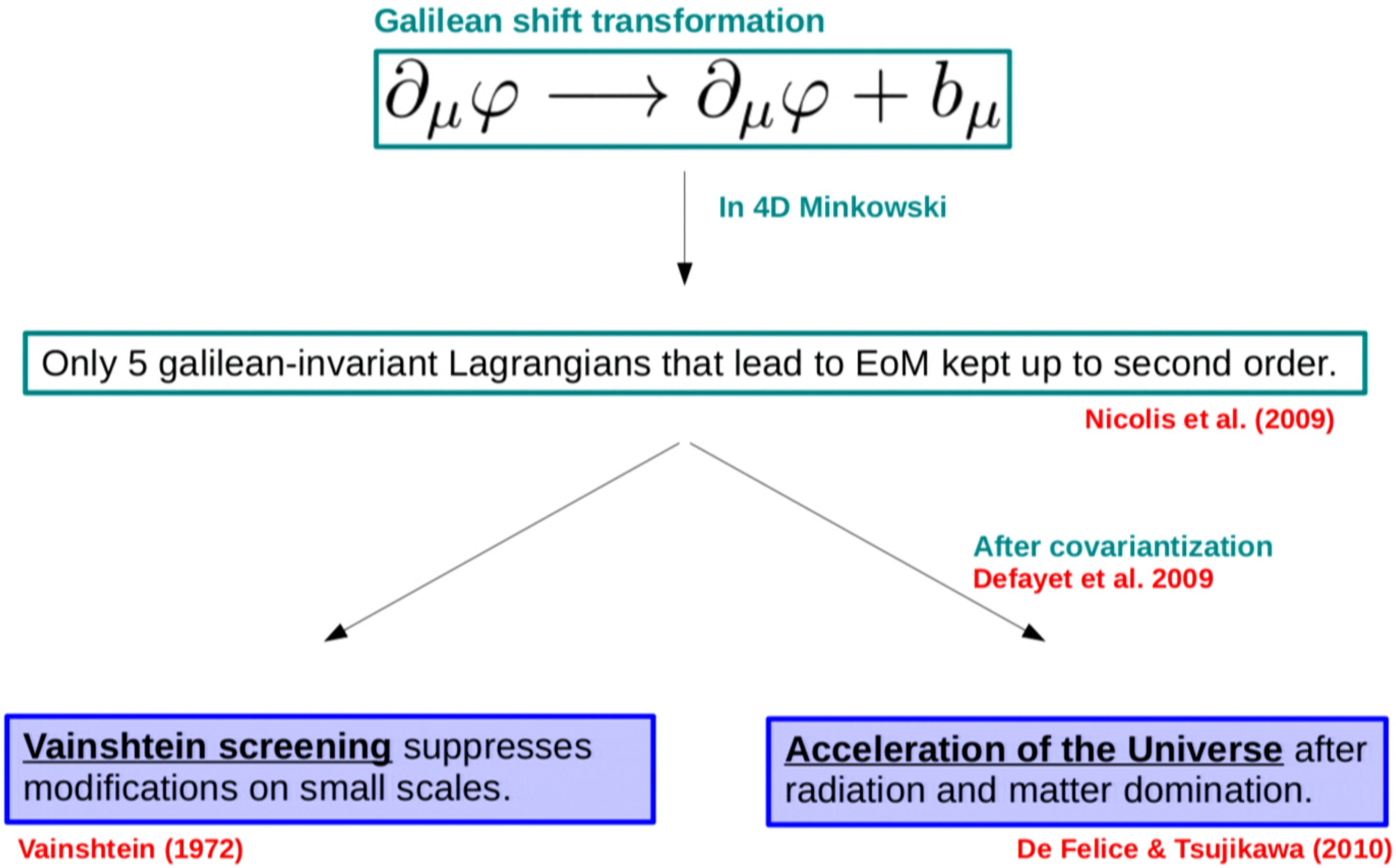
In 4D Minkowski

$\downarrow$

Only 5 galilean-invariant Lagrangians that lead to EoM kept up to second order.

Nicolis et al. (2009)

Galileon origins



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Nicolis et al. (2009)

After covariantization
Defayet et al. 2009

<u>Vainshtein screening</u> suppresses modifications on small scales.

Vainshtein (1972)

<u>Acceleration of the Universe</u> after radiation and matter domination.

De Felice & Tsujikawa (2010)

The Galileon Model

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\sum_{i=1}^{5} c_i\mathcal{L}_i - \mathcal{L}_m\right] \qquad M^3 \equiv M_{\rm Pl}H_0^2$$

$$\begin{aligned}
\mathcal{L}_1 &= M^3\varphi, \\
\mathcal{L}_2 &= \nabla_\mu\varphi\nabla^\mu\varphi, \\
\mathcal{L}_3 &= 2\Box\varphi\nabla_\mu\varphi\nabla^\mu\varphi/M^3,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_4 &= \nabla_\mu\varphi\nabla^\mu\varphi\left[2(\Box\varphi)^2 - 2(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi)\right. \\
&\quad \left.-R\nabla_\mu\varphi\nabla^\mu\varphi/2\right]/M^6, \\
\mathcal{L}_5 &= \nabla_\mu\varphi\nabla^\mu\varphi\left[(\Box\varphi)^3 - 3(\Box\varphi)(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi)\right. \\
&\quad +2(\nabla_\mu\nabla^\nu\varphi)(\nabla_\nu\nabla^\rho\varphi)(\nabla_\rho\nabla^\mu\varphi) \\
&\quad \left.-6(\nabla_\mu\varphi)(\nabla^\mu\nabla^\nu\varphi)(\nabla^\rho\varphi)G_{\nu\rho}\right]/M^9.
\end{aligned}$$

Kinetic Braiding

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\sum_{i=1}^{5}\right]$$

In flat space, need explicit coupling to introduce fifth forces.

$$\mathcal{L} = -\frac{c_2}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{c_3}{\mathcal{M}^3}\partial^2\varphi\partial_\mu\varphi\partial^\mu\varphi + \frac{g}{M_{\rm Pl}}\varphi T^\mu_\mu$$

$$\frac{c_2}{2}\partial^2\varphi + \frac{2c_3}{\mathcal{M}^3}\left[\left(\partial^2\varphi\right)^2 - \partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi\right] \propto \frac{g}{M_{\rm Pl}}T^\mu_\mu$$

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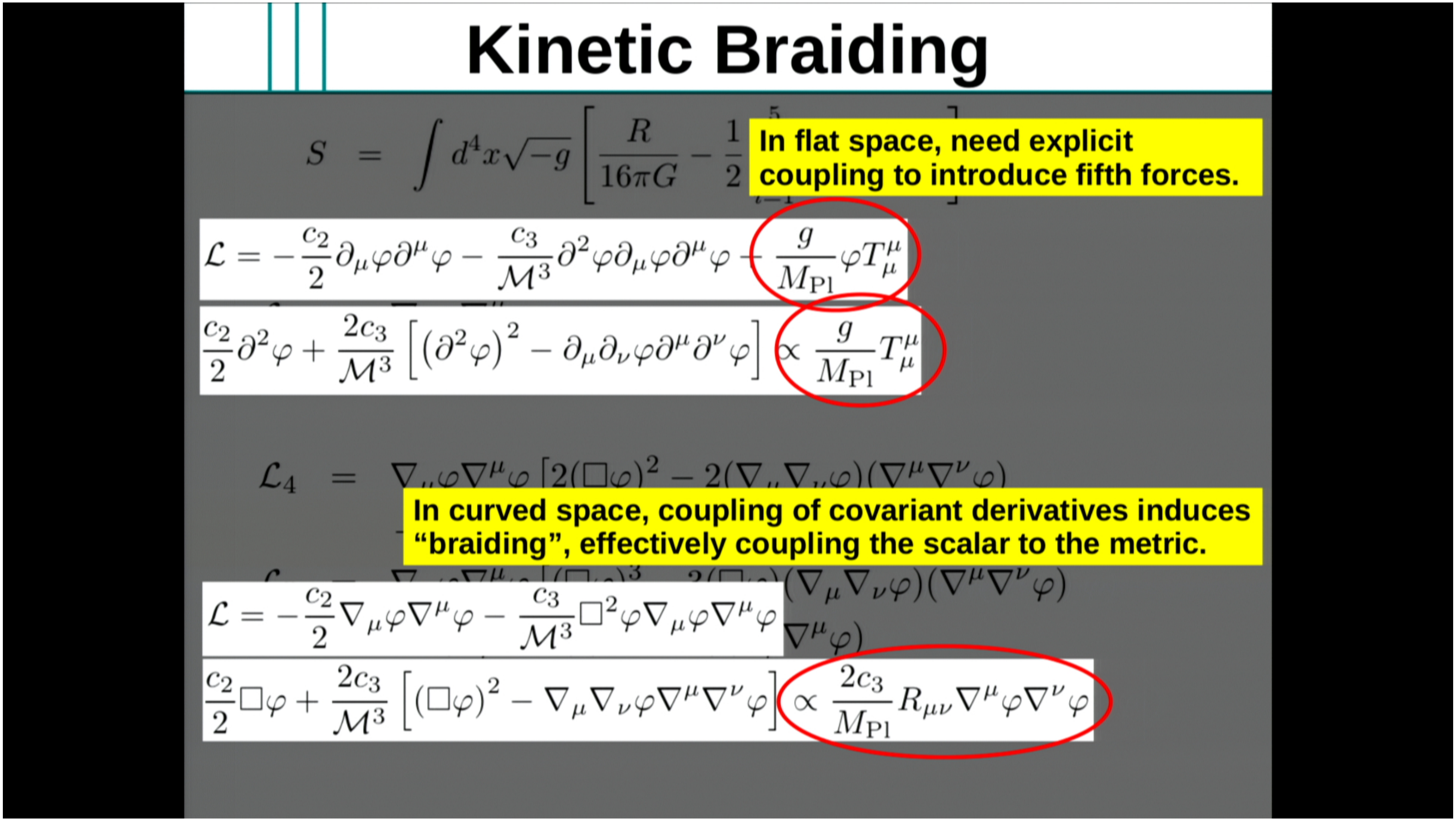
\end{aligned}$$



Kinetic Braiding

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\right]$$

In flat space, need explicit coupling to introduce fifth forces.

$$\mathcal{L} = -\frac{c_2}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{c_3}{\mathcal{M}^3}\partial^2\varphi\partial_\mu\varphi\partial^\mu\varphi + \frac{g}{M_{\rm Pl}}\varphi T^\mu_\mu$$

$$\frac{c_2}{2}\partial^2\varphi + \frac{2c_3}{\mathcal{M}^3}\left[\left(\partial^2\varphi\right)^2 - \partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi\right] \propto \frac{g}{M_{\rm Pl}}T^\mu_\mu$$

$$\mathcal{L}_4 = \nabla_\mu\varphi\nabla^\mu\varphi\left[2(\Box\varphi)^2 - 2(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi)\right)$$

In curved space, coupling of covariant derivatives induces "braiding", effectively coupling the scalar to the metric.

$$(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi)$$

$$\mathcal{L} = -\frac{c_2}{2}\nabla_\mu\varphi\nabla^\mu\varphi - \frac{c_3}{\mathcal{M}^3}\Box^2\varphi\nabla_\mu\varphi\nabla^\mu\varphi$$

$$\frac{c_2}{2}\Box\varphi + \frac{2c_3}{\mathcal{M}^3}\left[(\Box\varphi)^2 - \nabla_\mu\nabla_\nu\varphi\nabla^\mu\nabla^\nu\varphi\right] \propto \frac{2c_3}{M_{\rm Pl}}R_{\mu\nu}\nabla^\mu\varphi\nabla^\nu\varphi$$

The Galileon Model

$$S \;=\; \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G}-\frac{1}{2}\sum_{i=1}^{5}c_i\mathcal{L}_i-\mathcal{L}_m\right] \qquad M^3 \;\equiv\; M_{\rm Pl}H_0^2$$

$$\begin{aligned}
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~~$\mathcal{L}_1 = M^3\varphi,$~~ **Potential term; not interested.**

$$\begin{aligned}
\mathcal{L}_2 &= \nabla_\mu\varphi\nabla^\mu\varphi, \\
\mathcal{L}_3 &= 2\Box\varphi\nabla_\mu\varphi\nabla^\mu\varphi/M^3, \\
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\end{aligned}$$

Cubic Galileon (c4=c5=0)

$$\begin{aligned}
\mathcal{L}_4 &= \nabla_\mu\varphi\nabla^\mu\varphi\left[2(\Box\varphi)^2 - 2(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi)\right. \\
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\end{aligned}$$

Quartic Galileon (c5=0)

$$\begin{aligned}
\mathcal{L}_5 &= \nabla_\mu\varphi\nabla^\mu\varphi\left[(\Box\varphi)^3 - 3(\Box\varphi)(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi)\right. \\
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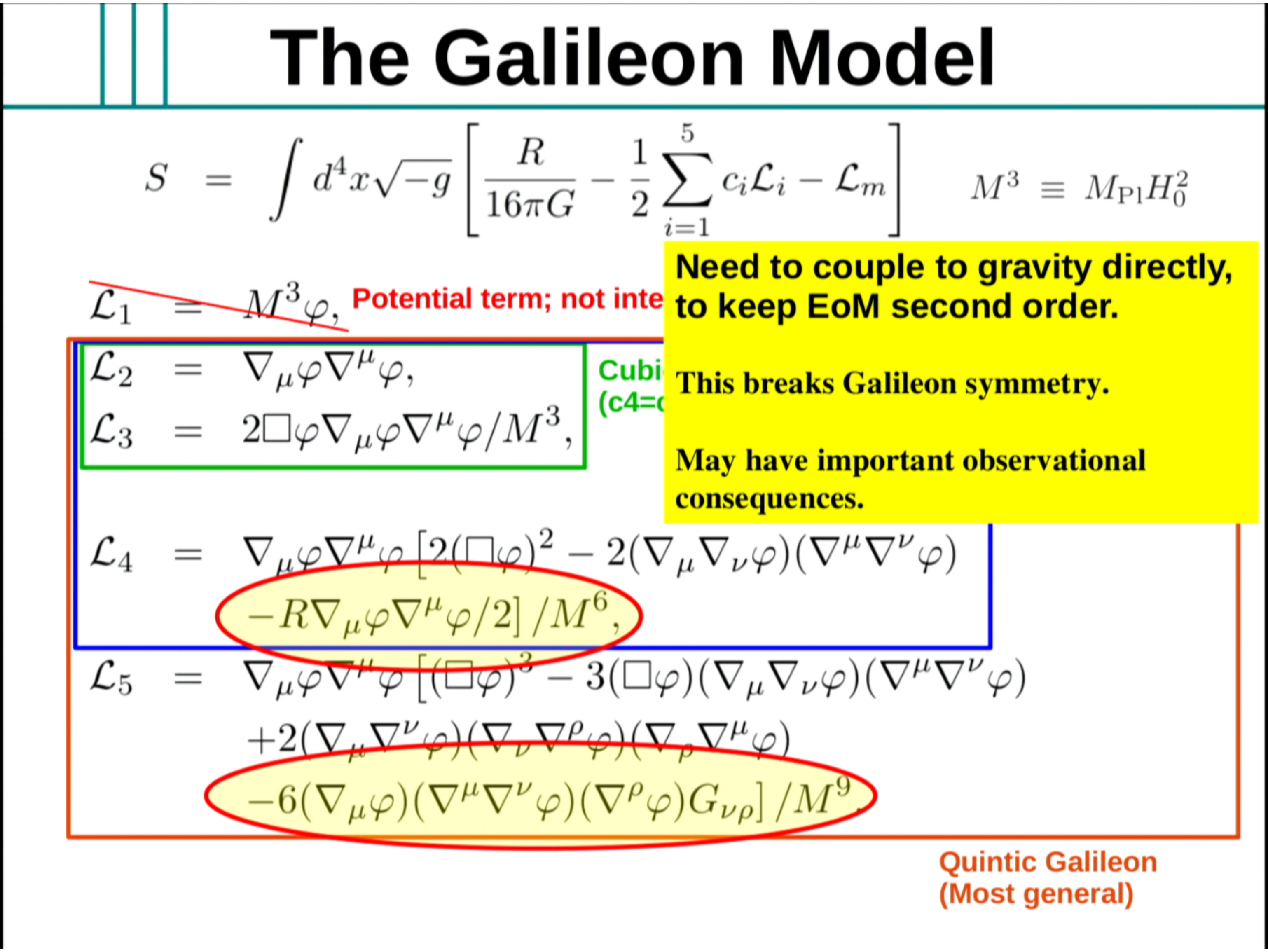
\end{aligned}$$

Quintic Galileon (Most general)



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$$\cancel{\mathcal{L}_1 = M^3\varphi,}$$

Potential term; not inte

Need to couple to gravity directly, to keep EoM second order.

This breaks Galileon symmetry.

May have important observational consequences.

$$\begin{aligned}
\mathcal{L}_2 &= \nabla_\mu\varphi\nabla^\mu\varphi,\\
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Cubi
(c4=c

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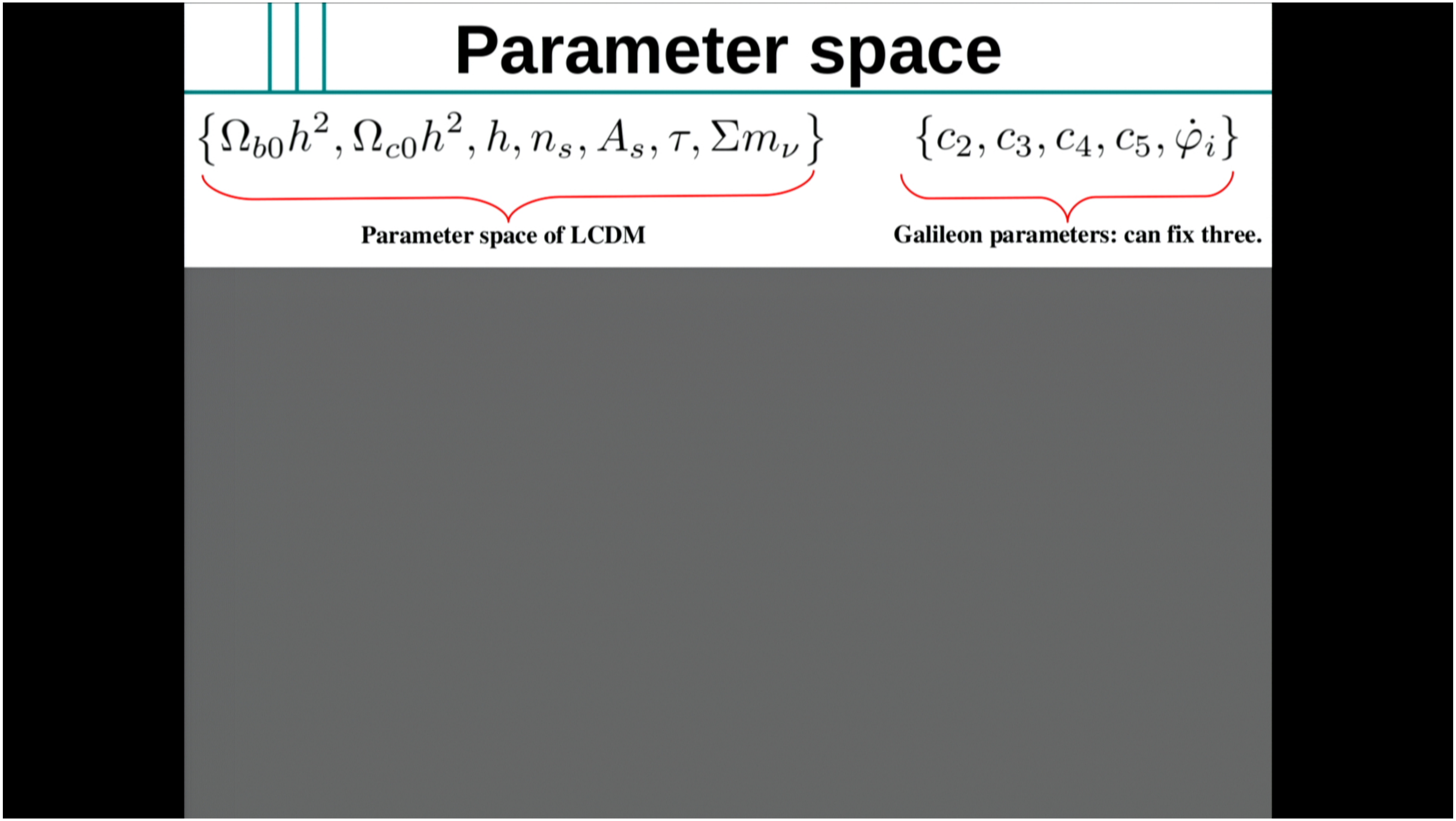

Parameter space

$$\underbrace{\{\Omega_{b0}h^2, \Omega_{c0}h^2, h, n_s, A_s, \tau, \Sigma m_\nu\}}_{\text{Parameter space of LCDM}} \qquad \underbrace{\{c_2, c_3, c_4, c_5, \dot{\varphi}_i\}}_{\text{Galileon parameters: can fix three.}}$$

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Background density of the Galileon field:

$$\boxed{\bar{\rho}_\varphi \propto \frac{1}{2}c_2\dot{\bar{\varphi}}^2 + 6\frac{c_3}{H_0^2}\dot{\bar{\varphi}}^3 H + \frac{45}{2}\frac{c_4}{H_0^4}\dot{\bar{\varphi}}^4 H^2 + 21\frac{c_5}{H_0^6}\dot{\bar{\varphi}}^5 H^3}$$

$$\begin{aligned} c_2 &\longrightarrow c_2/B^2 \\ c_3 &\longrightarrow c_3/B^3 \\ c_4 &\longrightarrow c_4/B^4 \\ c_5 &\longrightarrow c_5/B^5 \\ \varphi &\longrightarrow \varphi B, \end{aligned}$$

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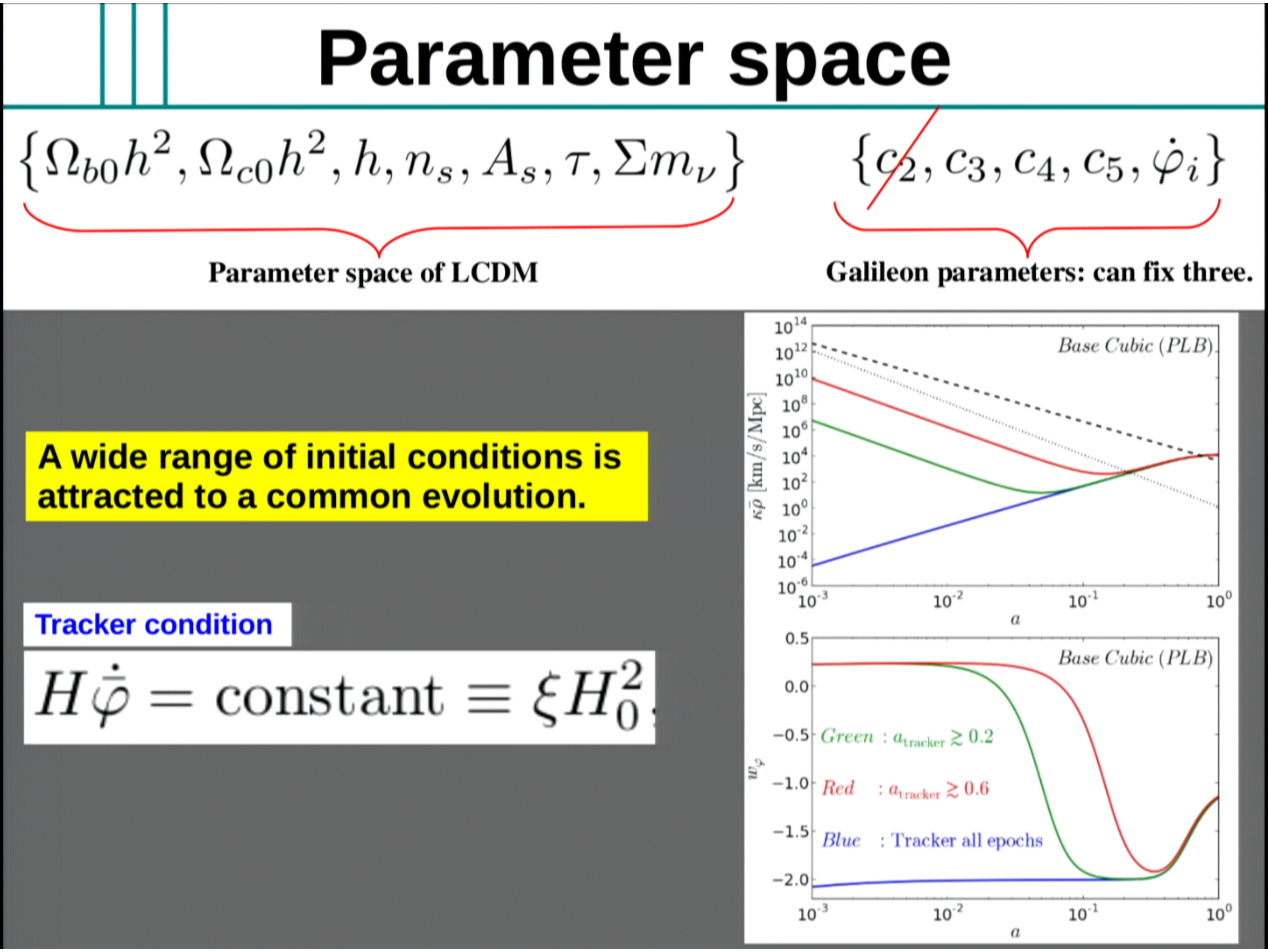
Physics do not change under these scalings.

Can simply fix one of the parameters.

$$c_2 = -1$$



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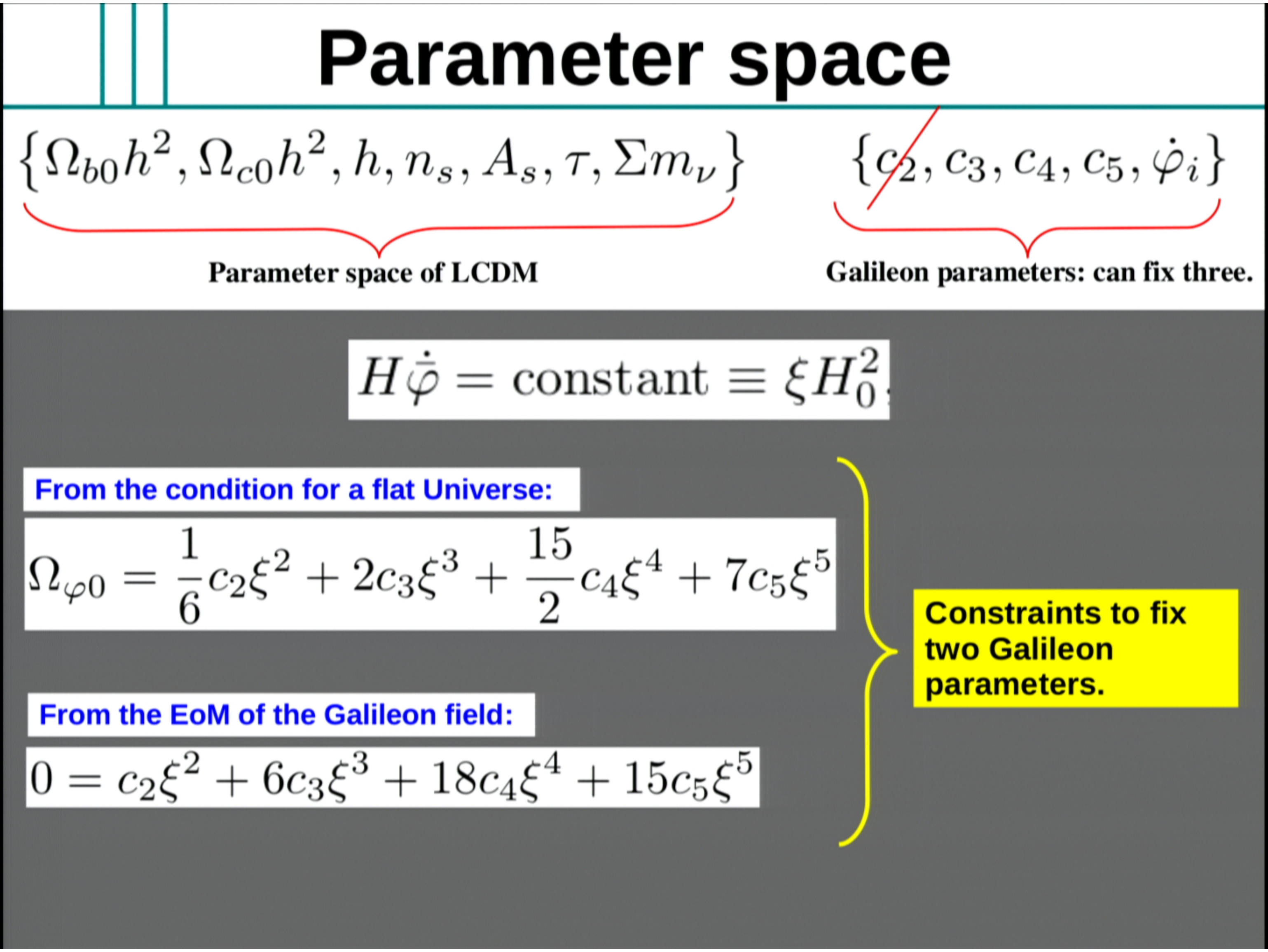
A wide range of initial conditions is attracted to a common evolution.

Tracker condition

$$H\dot{\bar{\varphi}} = \text{constant} \equiv \xi H_0^2$$



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$$\underbrace{\{\Omega_{b0}h^2, \Omega_{c0}h^2, h, n_s, A_s, \tau, \Sigma m_\nu\}}_{\text{Parameter space of LCDM}} \qquad \underbrace{\{\cancel{c_2}, c_3, c_4, c_5, \dot{\varphi}_i\}}_{\text{Galileon parameters: can fix three.}}$$

$$H\dot{\varphi} = \text{constant} \equiv \xi H_0^2$$

From the condition for a flat Universe:

$$\Omega_{\varphi 0} = \frac{1}{6}c_2\xi^2 + 2c_3\xi^3 + \frac{15}{2}c_4\xi^4 + 7c_5\xi^5$$

From the EoM of the Galileon field:

$$0 = c_2\xi^2 + 6c_3\xi^3 + 18c_4\xi^4 + 15c_5\xi^5$$

Constraints to fix two Galileon parameters.

Parameter space

$$\underbrace{\{\Omega_{b0}h^2, \Omega_{c0}h^2, h, n_s, A_s, \tau, \Sigma m_\nu\}} \qquad \underbrace{\{\cancel{c_2}, c_3, c_4, c_5, \dot{\varphi}_i\}}$$

- **7-dimensional cosmological parameter space**

$$\{\Omega_{b0}h^2, \Omega_{c0}h^2, h, n_s, A_s, \tau, \Sigma m_\nu\}$$

From the condition for a flat Universe:

- **2-dimensional Galileon parameter space**

$$\{c_3, c_4, c_5(c_3, c_4), \xi(c_3, c_4)\}$$

From the EoM of the Galileon field:

$$0 = c_2\xi^2 + 6c_3\xi^3 + 18c_4\xi^4 + 15c_5\xi^5$$

Methodology

Derive the **fully linearly perturbed** Einstein and Galileon equations

No screening (linear study)

Barreira et al. (PRD) arXiv:1208.0600

Cosmological predictions from modified version of the ***CAMB* code**

Lewis & Challinor (1999)

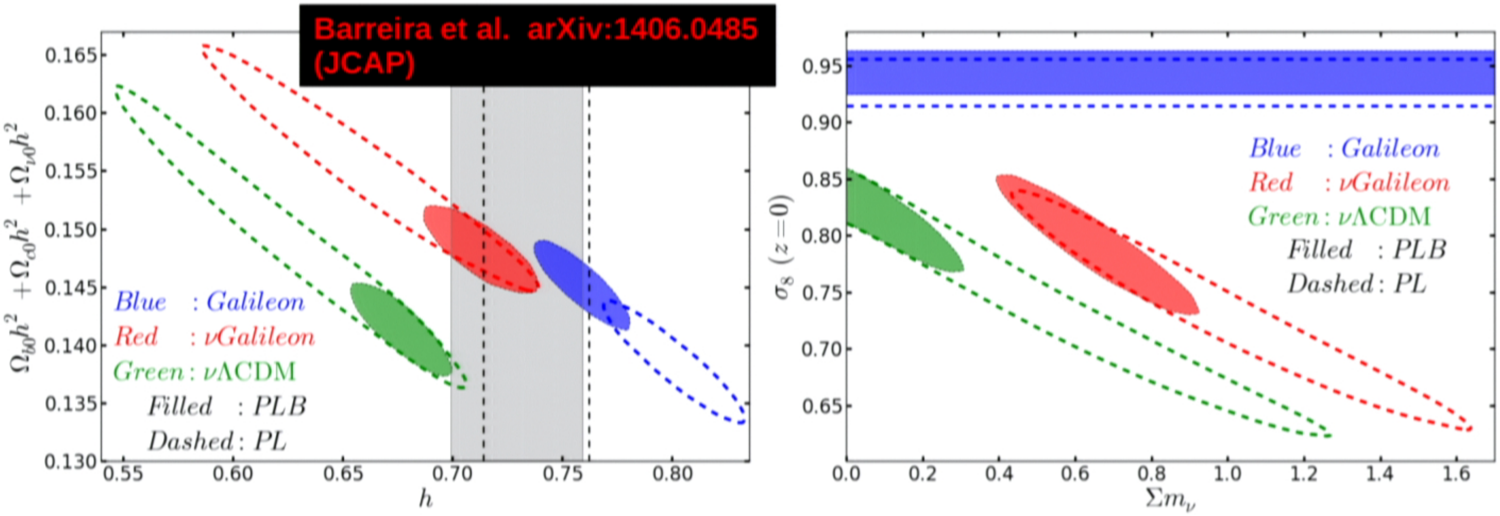
Monte Carlo exploration of the parameter space with the ***CosmoMC* code**

Lewis & Bridle (2002)

Likelihood determined by the data:

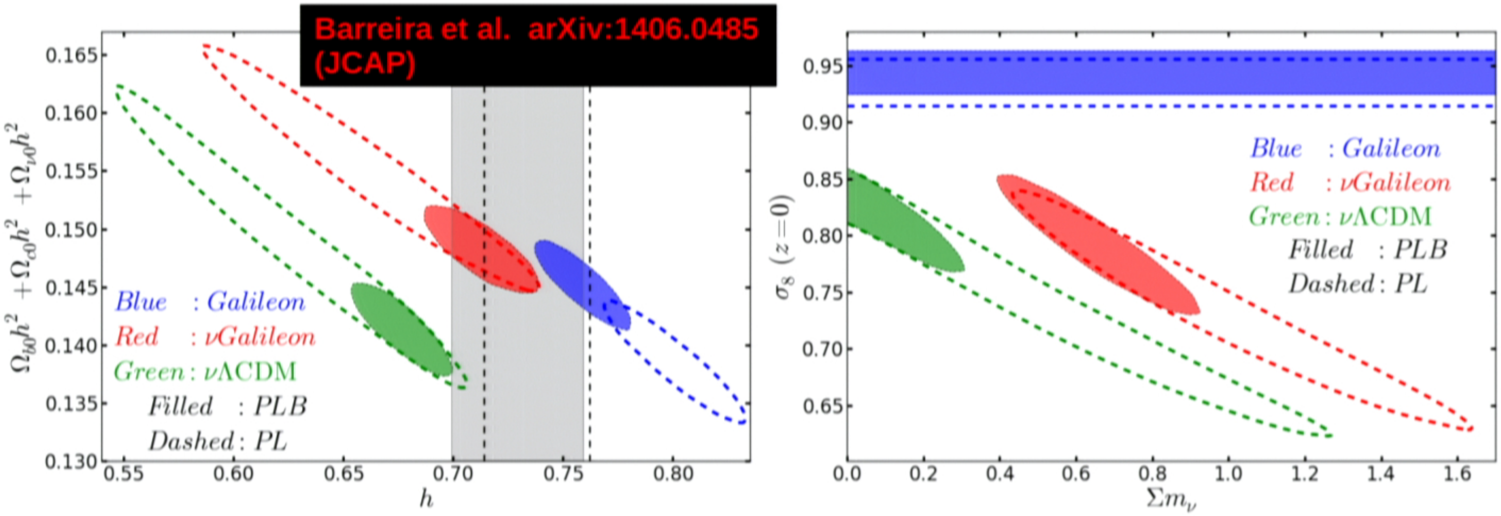
- Full **Planck TT** spectrum data;
- Planck **CMB lensing** power spectrum;
- **BAO** feature from 6df, SDSS, BOSS, WiggleZ

Linear theory constraints



Barreira et al. arXiv:1406.0485 (JCAP)

Linear theory constraints



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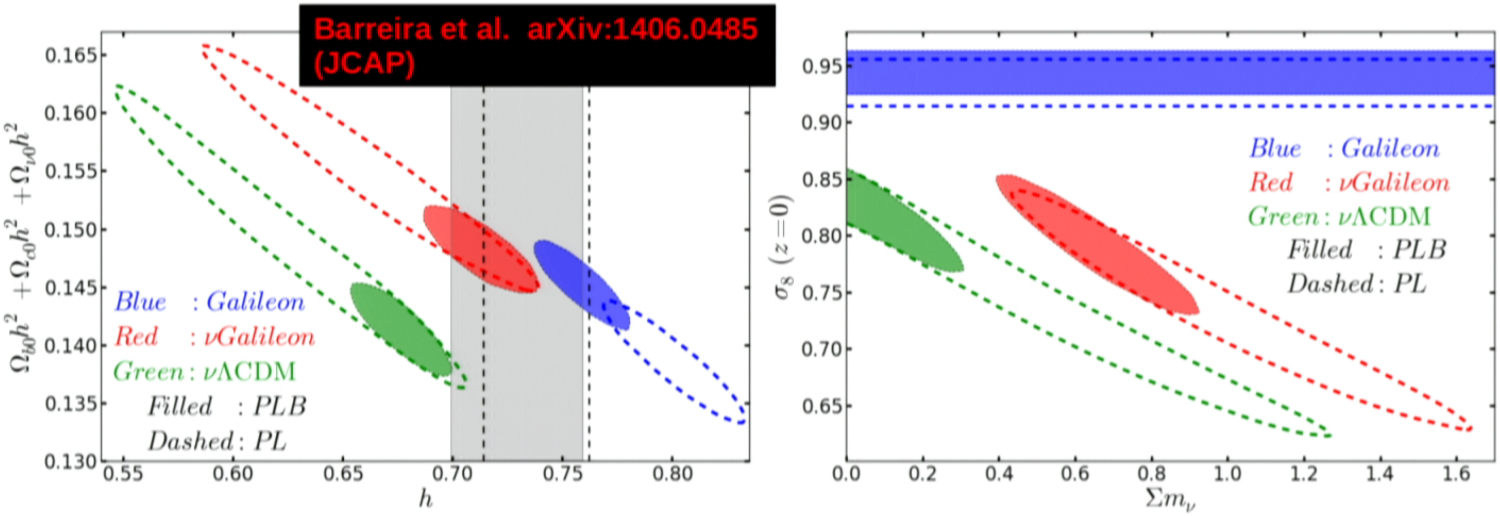
Massive neutrinos

- Over 6-sigma evidence;
- Driven by tension in H0 from CMB and BAO peaks;
- Earth-based neutrino experiments (KATRIN e.g.) can say more.

Linear theory constraints



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Massive neutrinos

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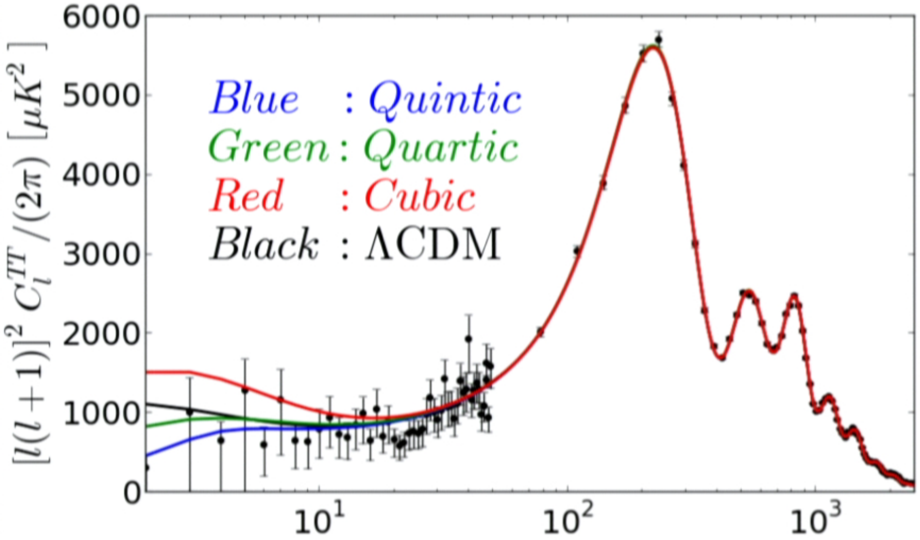
H0 compatibility

- Unlike LCDM, the constraints are compatible with local determinations (see vertical bars).

Low clustering amplitude

- Despite enhanced gravity, clustering can be weaker than in LCDM;
- Mainly due to massive neutrino fraction.

Best-fitting cosmologies

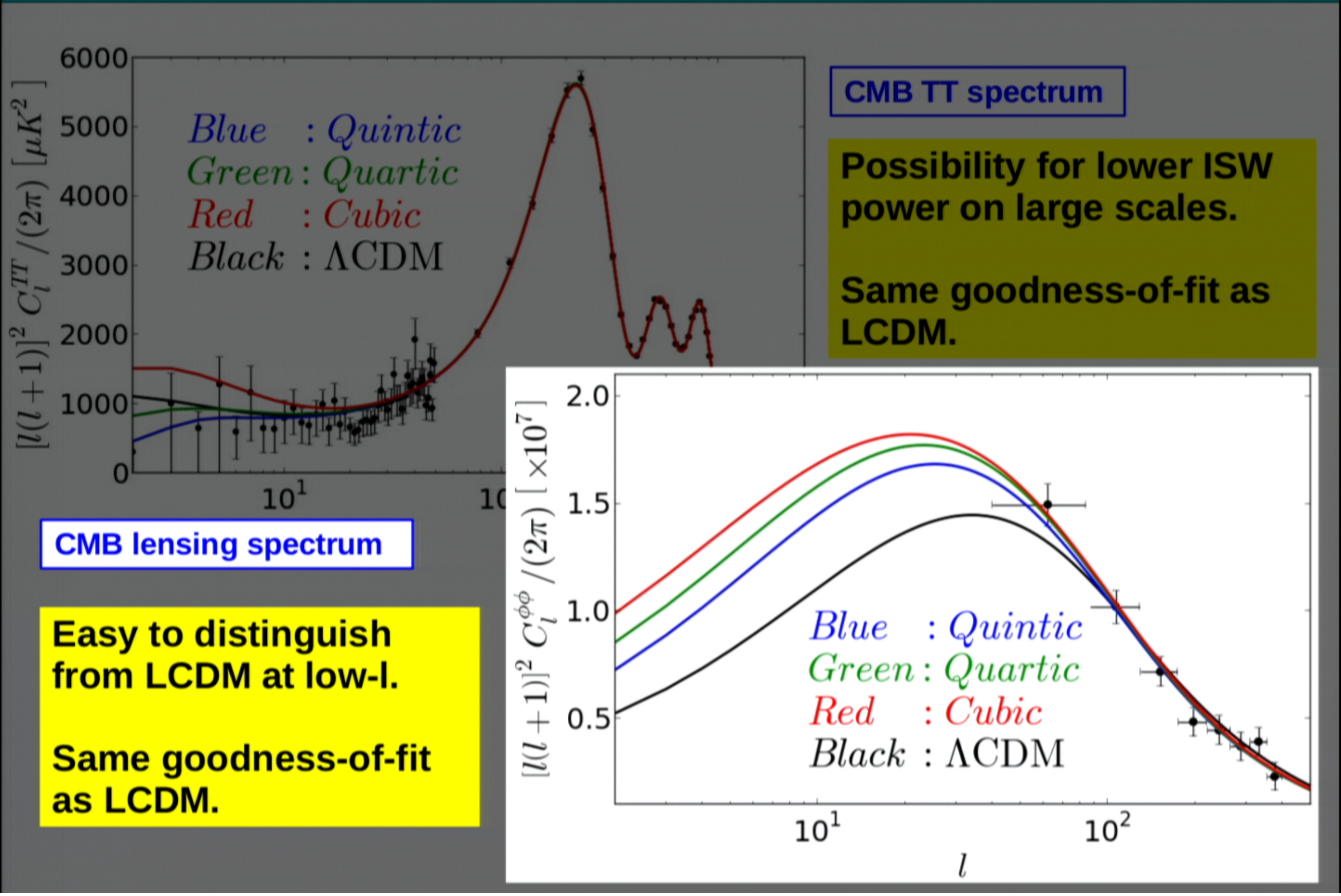


CMB TT spectrum

Possibility for lower ISW power on large scales.

Same goodness-of-fit as LCDM.

Best-fitting cosmologies



CMB TT spectrum

Possibility for lower ISW power on large scales.

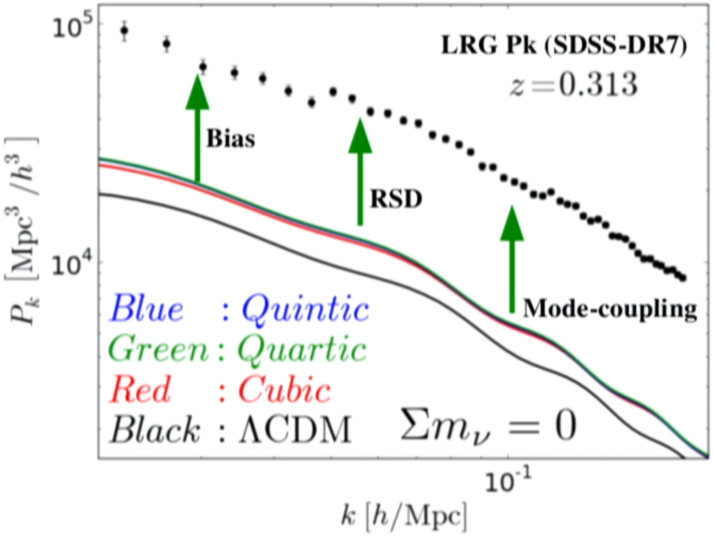
Same goodness-of-fit as LCDM.

CMB lensing spectrum

Easy to distinguish from LCDM at low-l.

Same goodness-of-fit as LCDM.

Growth of structure



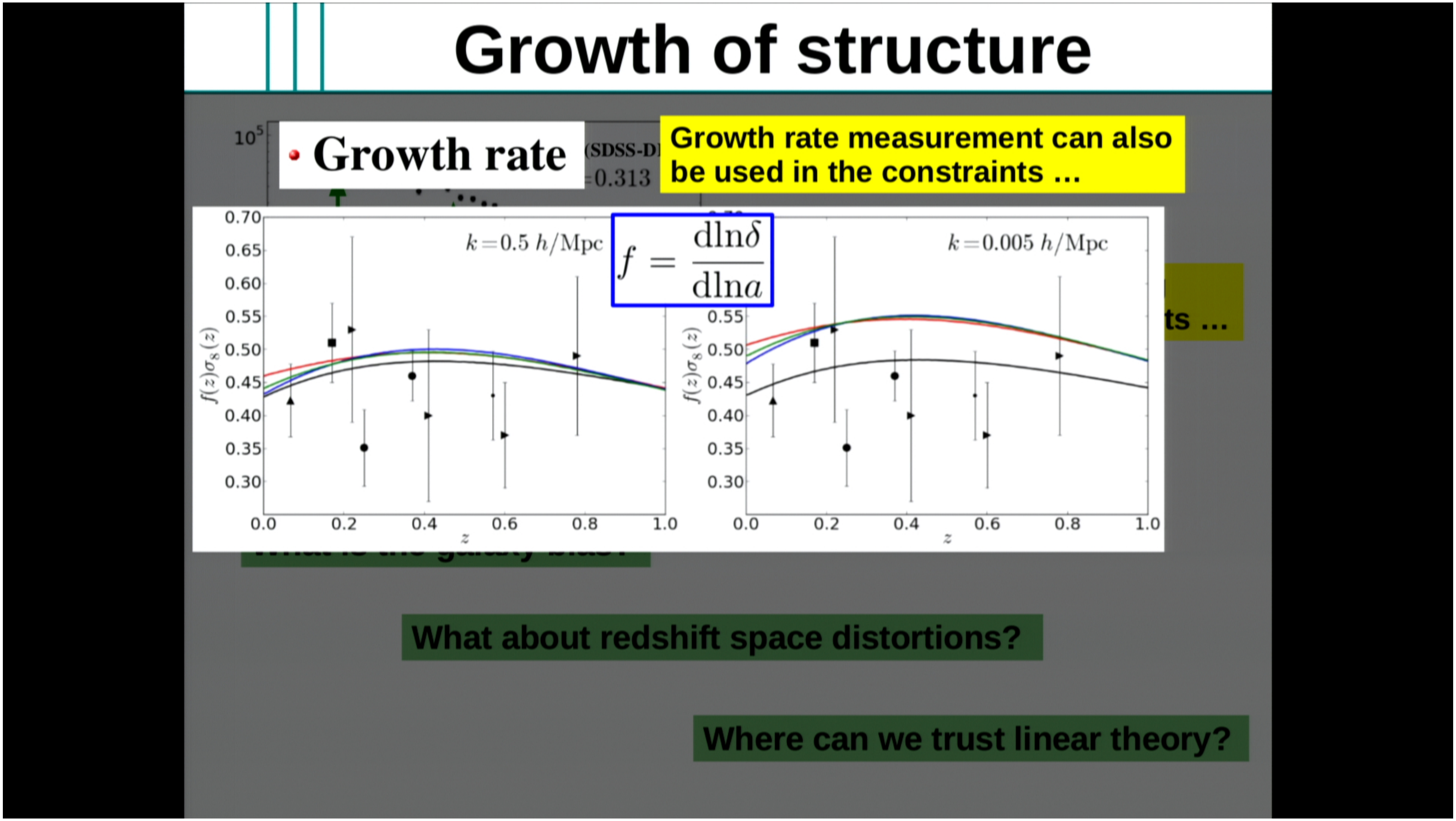
- **Galaxy clustering**

Amplitude of galaxy clustering may be added to the constraints …

What is the galaxy bias?

What about redshift space distortions?

Where can we trust linear theory?



Growth of structure

- Growth rate

Growth rate measurement can also be used in the constraints …

$$f = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a}$$

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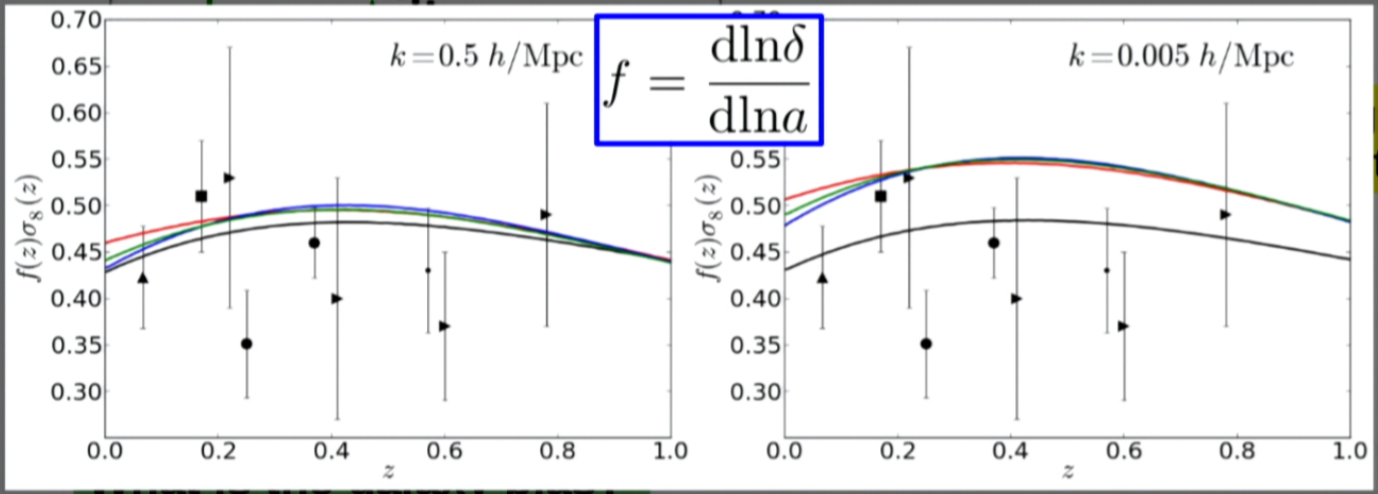
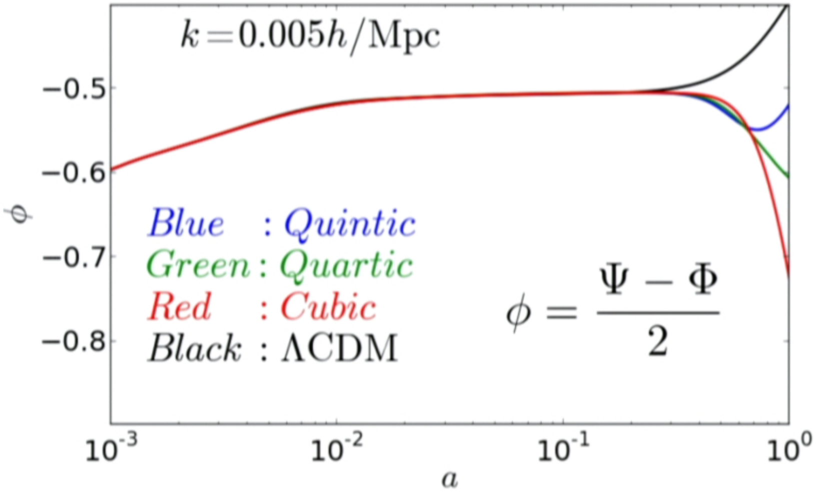


$$f = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a}$$

Data assumes scale-independent growth, which does not hold for large massive neutrino fractions, even on linear scales.

Where can we trust linear theory?

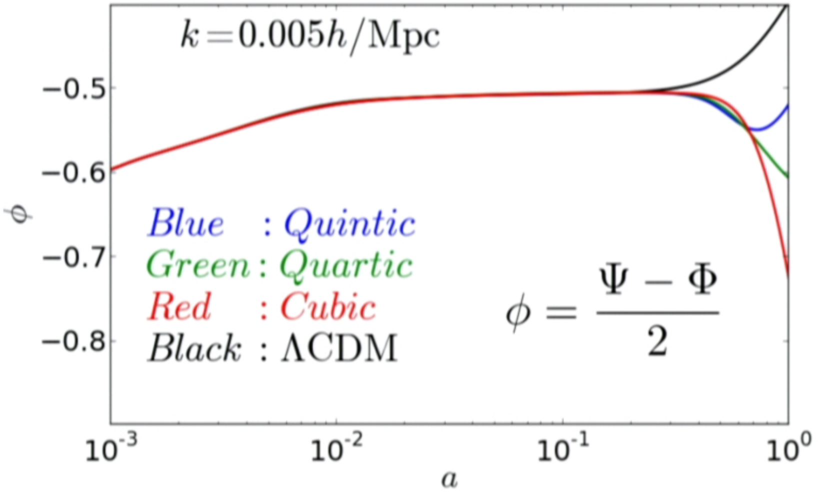
Tension with ISW effect



Lensing potential deepens at late times, contrary to LCDM.

The ISW effect is therefore negative in Galileon gravity.

Tension with ISW effect



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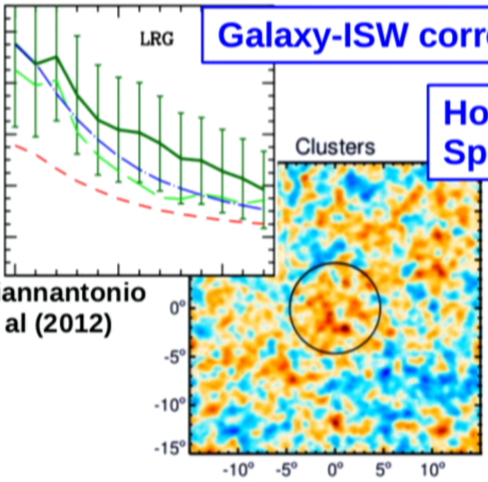


Galaxy-ISW correlation

Hot and Cold Spots

Giannantonio et al (2012)

Planck colla. ISW (2013)

CMB temperature-lensing correlation

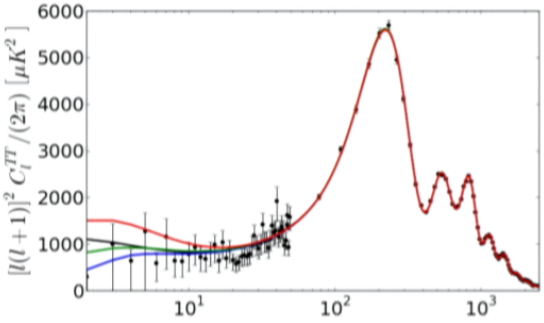
Data suggests a positive ISW;

Galileon models in TENSION ?

Thus far …

CMB + BAO constraints

- Galileon model with massive neutrinos fits the data with the same flying colors as LCDM;



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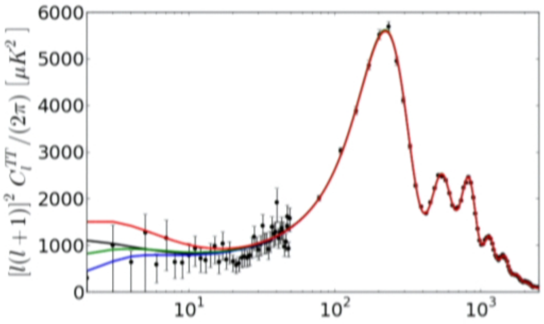

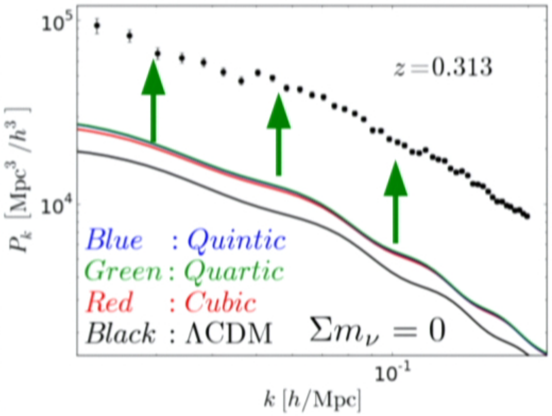

Use of galaxy clustering data

- Requires proper modeling of nonlinear structure formation;

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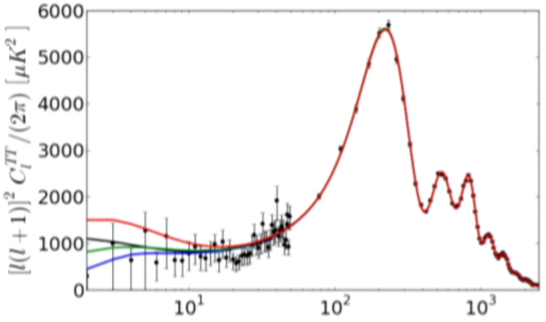

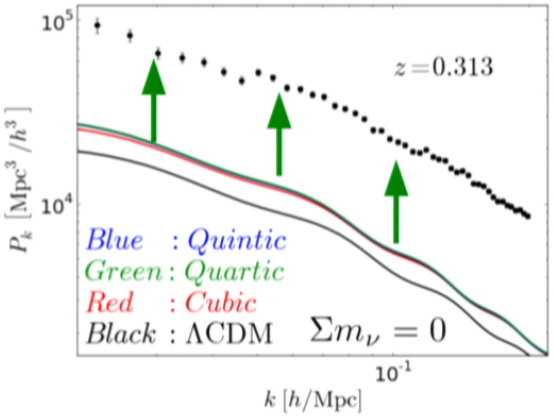

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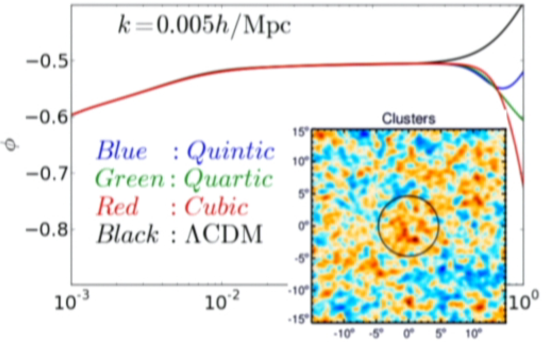


Negative ISW effect

- At odds with current observations;

Galileon gravity:

Targeted tests with spherical symmetry

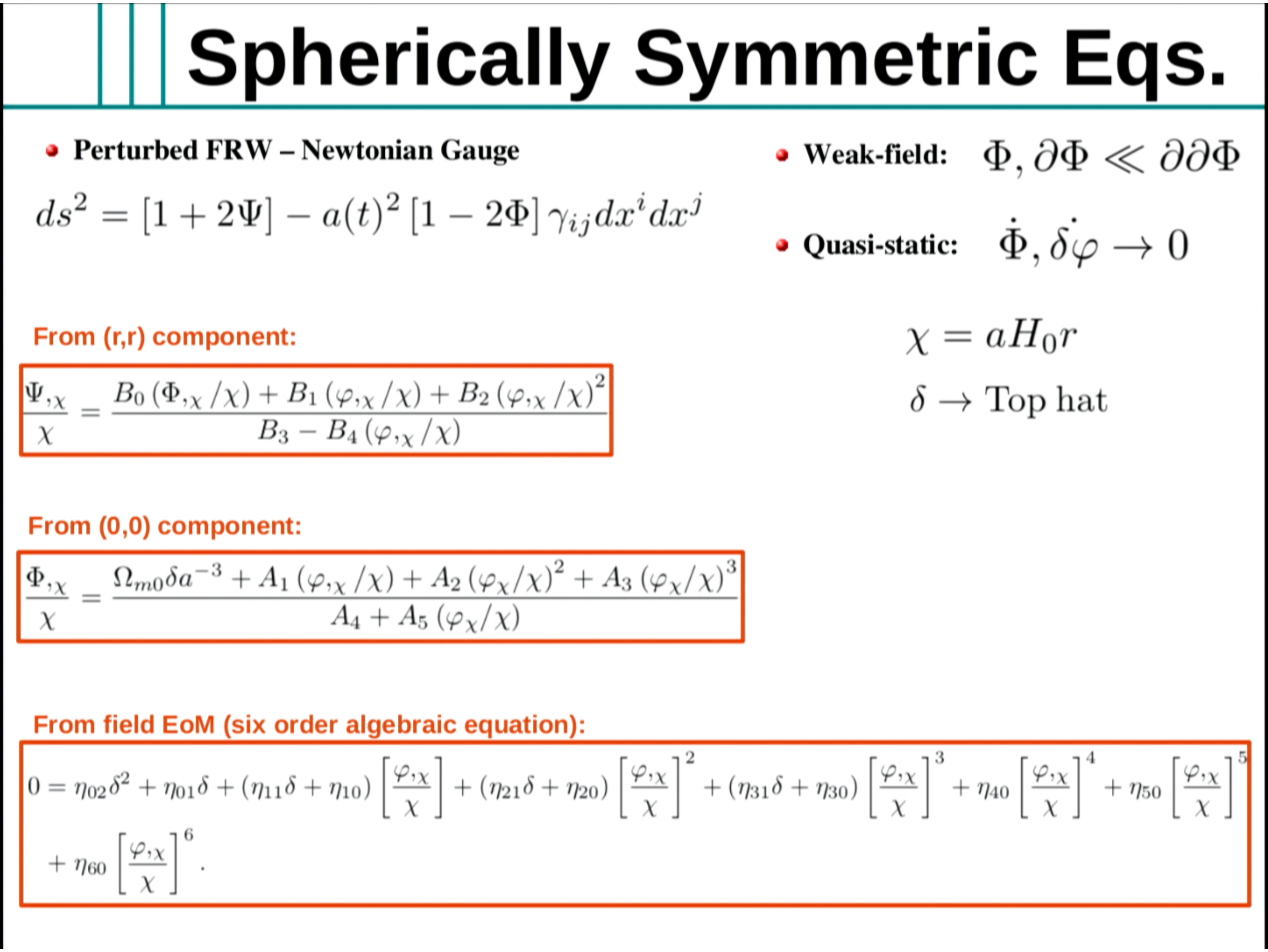
Barreira et al. arXiv:1308.3699 (JCAP)
Barreira et al. arXiv:1401.1497 (JCAP)

Spherically Symmetric Eqs.

- **Perturbed FRW – Newtonian Gauge**

$$ds^2 = [1+2\Psi] - a(t)^2\,[1-2\Phi]\,\gamma_{ij}dx^i dx^j$$

- **Weak-field:** $\Phi, \partial\Phi \ll \partial\partial\Phi$
- **Quasi-static:** $\dot{\Phi}, \dot{\delta\varphi} \to 0$



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$$\chi = aH_0 r$$

$$\delta \to \text{Top hat}$$

From (r,r) component:

$$\boxed{\frac{\Psi_{,\chi}}{\chi} = \frac{B_0 (\Phi_{,\chi}/\chi) + B_1 (\varphi_{,\chi}/\chi) + B_2 (\varphi_{,\chi}/\chi)^2}{B_3 - B_4 (\varphi_{,\chi}/\chi)}}$$

From (0,0) component:

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From field EoM (six order algebraic equation):

$$\boxed{\begin{aligned}0 &= \eta_{02}\delta^2 + \eta_{01}\delta + (\eta_{11}\delta + \eta_{10}) \left[\frac{\varphi_{,\chi}}{\chi}\right] + (\eta_{21}\delta + \eta_{20}) \left[\frac{\varphi_{,\chi}}{\chi}\right]^2 + (\eta_{31}\delta + \eta_{30}) \left[\frac{\varphi_{,\chi}}{\chi}\right]^3 + \eta_{40} \left[\frac{\varphi_{,\chi}}{\chi}\right]^4 + \eta_{50} \left[\frac{\varphi_{,\chi}}{\chi}\right]^5 \\ &+ \eta_{60} \left[\frac{\varphi_{,\chi}}{\chi}\right]^6 .\end{aligned}}$$

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🟥 Normal gravity term

🟩 Spatial gradient terms

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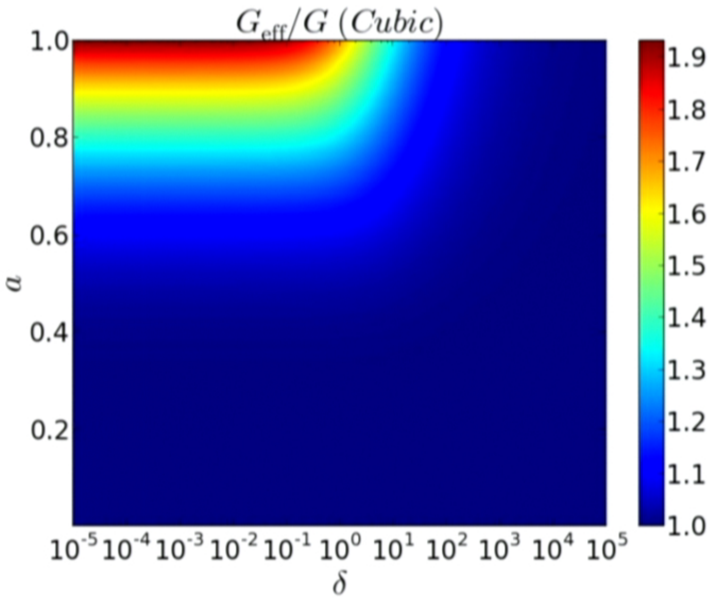
Cubic Galileon

$$\frac{G_{\rm eff}}{G}(a,\delta) = \frac{\Psi,_{\chi}/\chi}{\Psi,_{\chi}^{\rm GR}/\chi}$$



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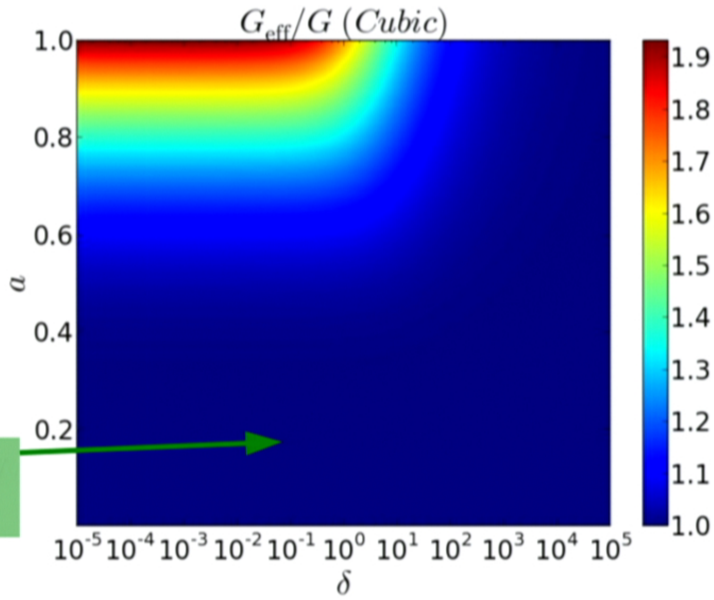

At early times, gravity is unchanged.

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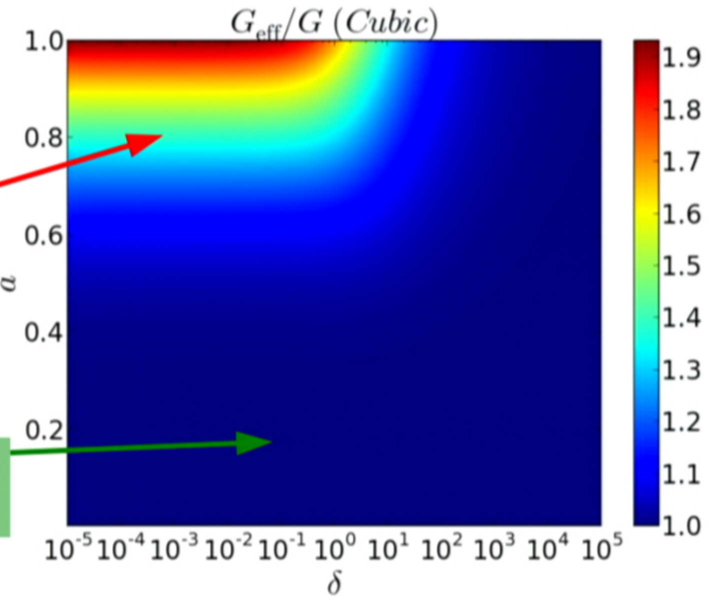

Stronger gravity at late times and when density is low.

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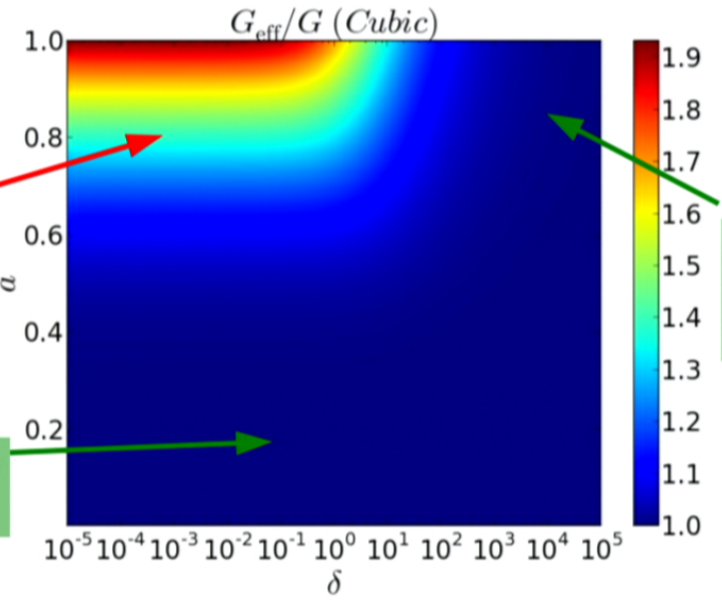

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Gravity remains unchanged if density is high.

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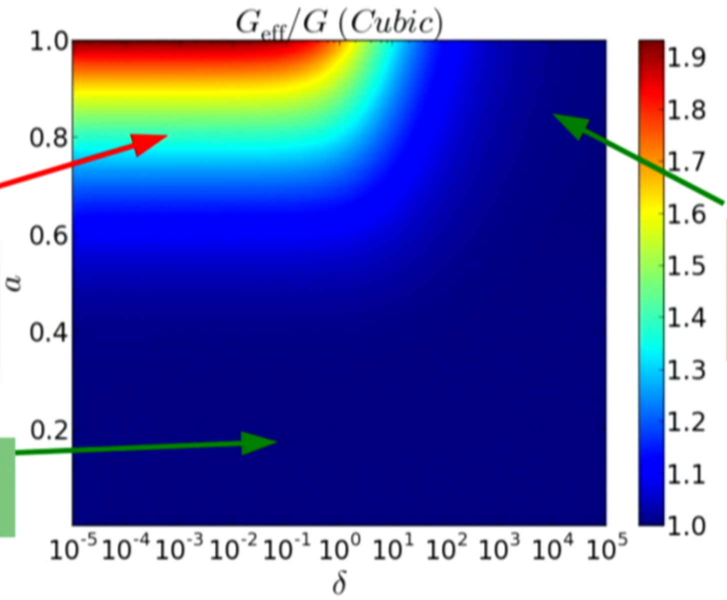

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$$\frac{\Psi_{,\chi}}{\chi} = \frac{\Omega_{m0}\delta}{2}a^{-3} + \frac{A_1}{2}\left[\frac{\varphi_{,\chi}}{\chi}\right]$$

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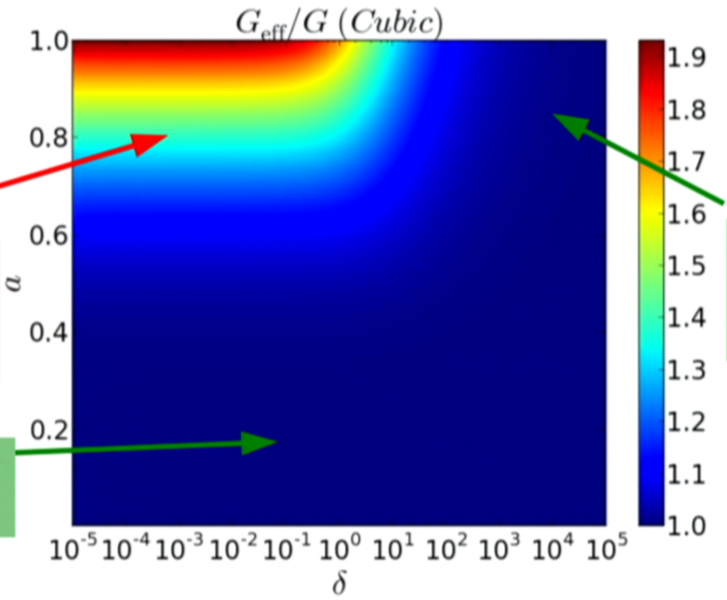

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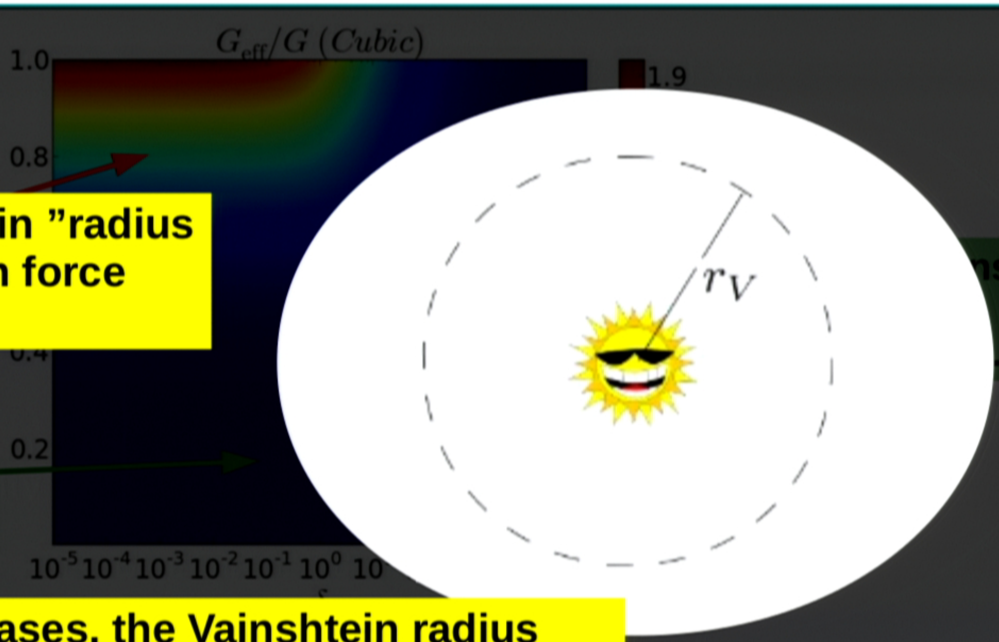
Fifth force term gets suppressed since it grows slower with the density.

Cubic Galileon

$$\frac{G_{\rm eff}}{G}(a,\delta) = \frac{\Psi_{,\chi}/\chi}{\Psi_{,\chi}^{\rm GR}/\chi}$$

There is a “Vainshtein ”radius below which the fifth force becomes negligible.

density is low.



At early times, gravity is unchanged.

As the density increases, the Vainshtein radius increases, which suppresses the fifth force inside the overdensity.

$$\frac{\Psi_{,\chi}}{\chi} = \frac{\Omega_{m0}\delta}{2}a^{-3} + \frac{A_1}{2}\left[\frac{\varphi_{,\chi}}{\chi}\right] \quad \left[\frac{\varphi_{,\chi}}{\chi}\right] \sim \sqrt{\delta}, \quad \delta \gg 1$$

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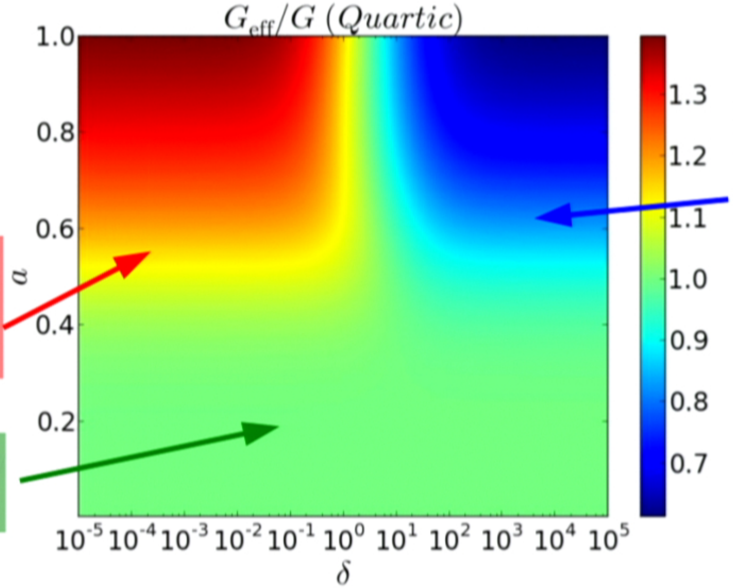

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Gravity becomes weaker in high-density regions.

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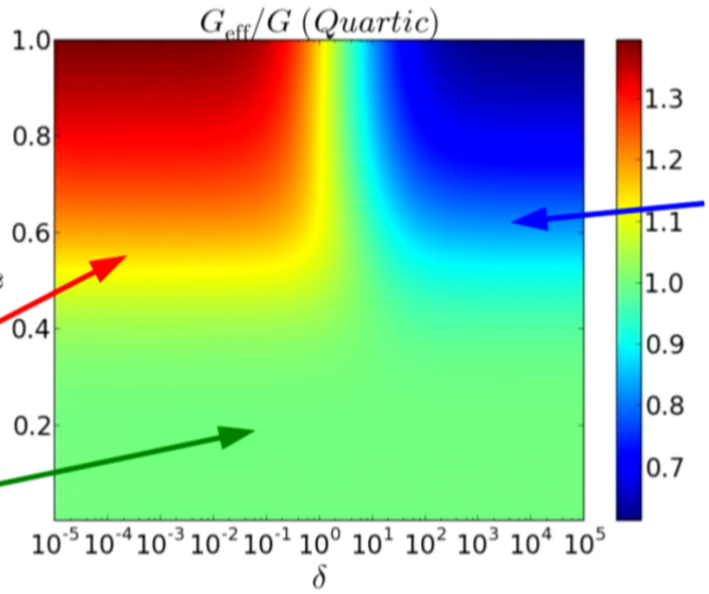

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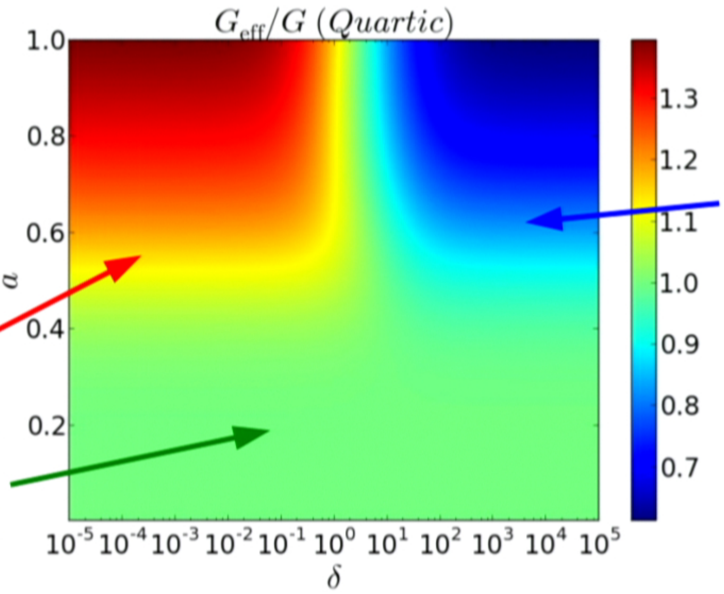

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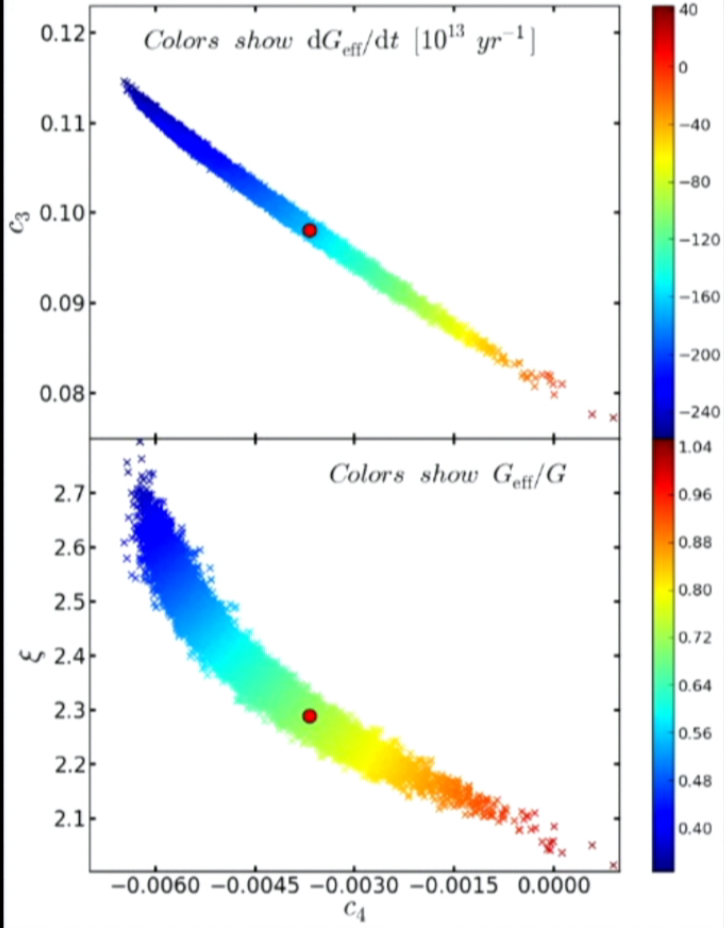
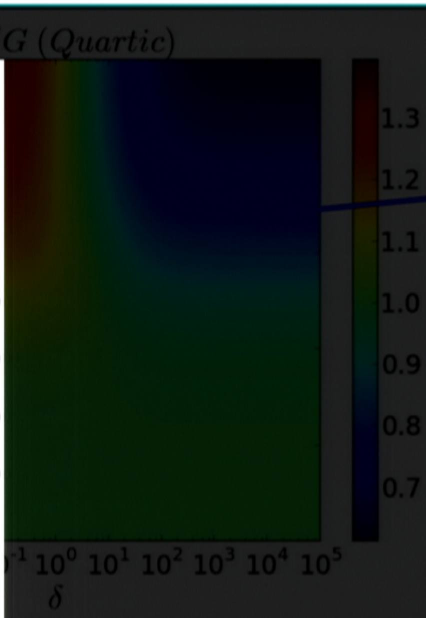
$$\mathcal{L}_4 \sim R\nabla_\mu\varphi\nabla^\mu\varphi$$

Multiplicative terms remain, after suppression of Galileon gradients.

Solar System constraints





Gravity becomes weaker in high-density regions.

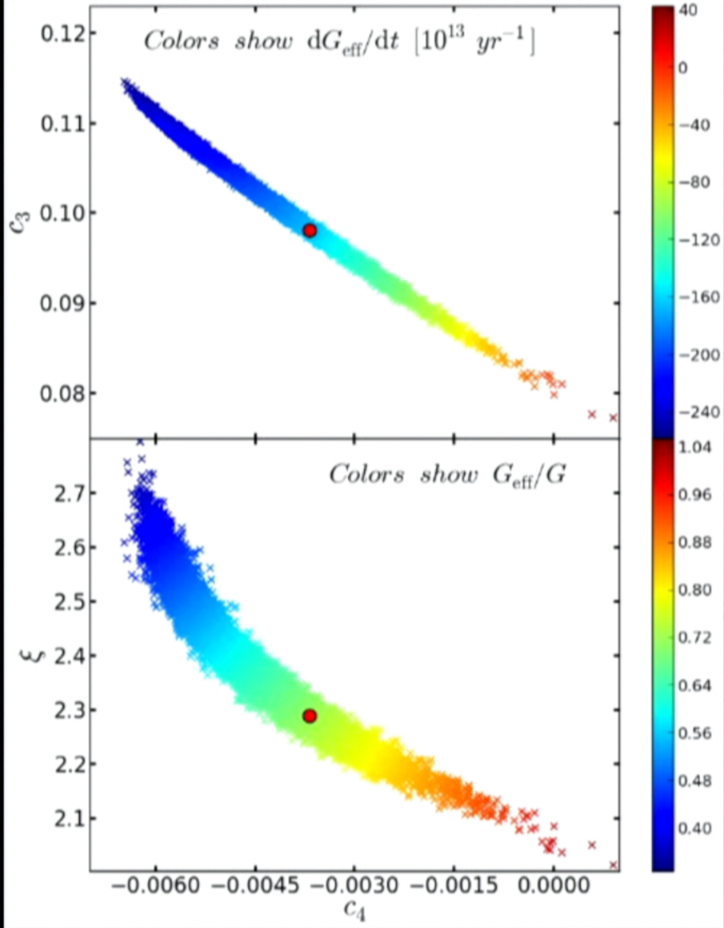
cover GR:

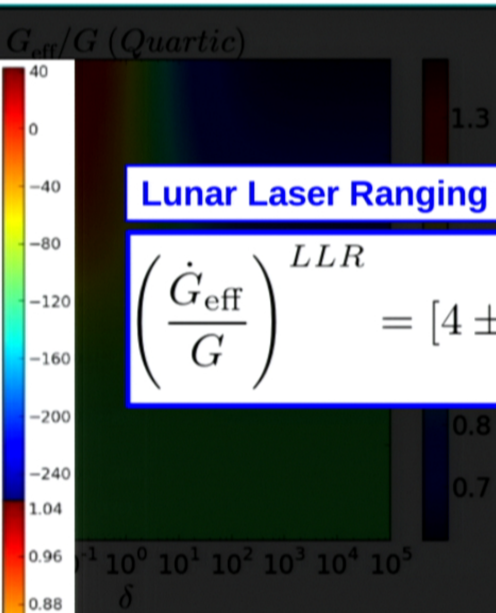
$$\varphi_\chi/\chi)^2 + A_3\,(\varphi_\chi/\chi)^3$$

$$/\chi)$$

tive terms remain, after suppression n gradients.

Solar System constraints





Lunar Laser Ranging Constraints

$$\left(\frac{\dot{G}_{\rm eff}}{G}\right)^{LLR} = [4 \pm 9] \times 10^{-13}\ \mathrm{yrs}^{-1}$$

Gravity becomes weaker in high-
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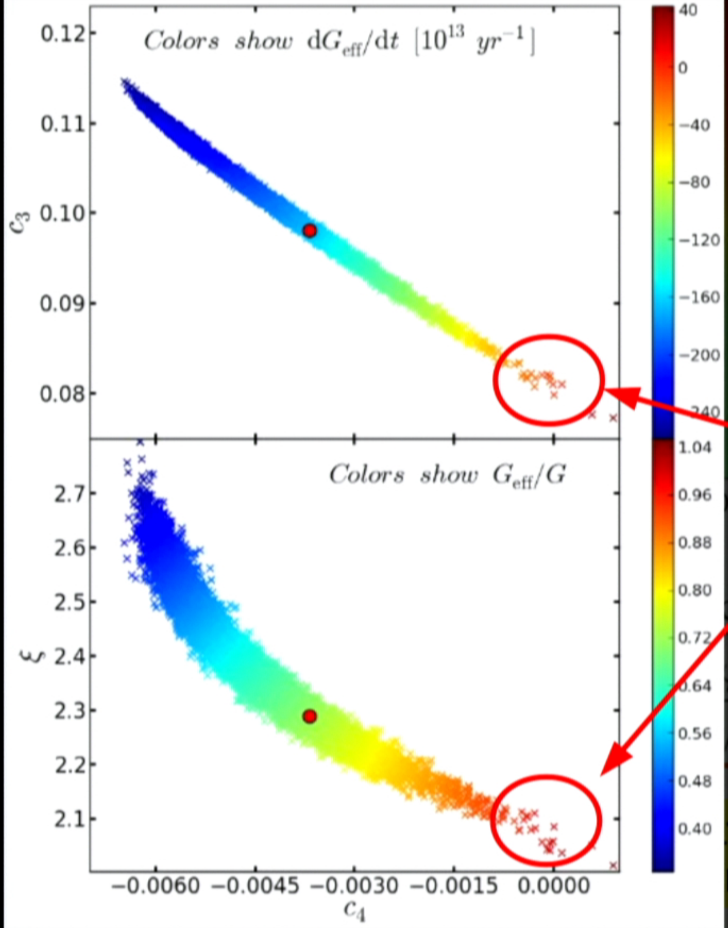

Lunar Laser Ranging Constraints

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The only viable regions are those with c4 ~ 0.

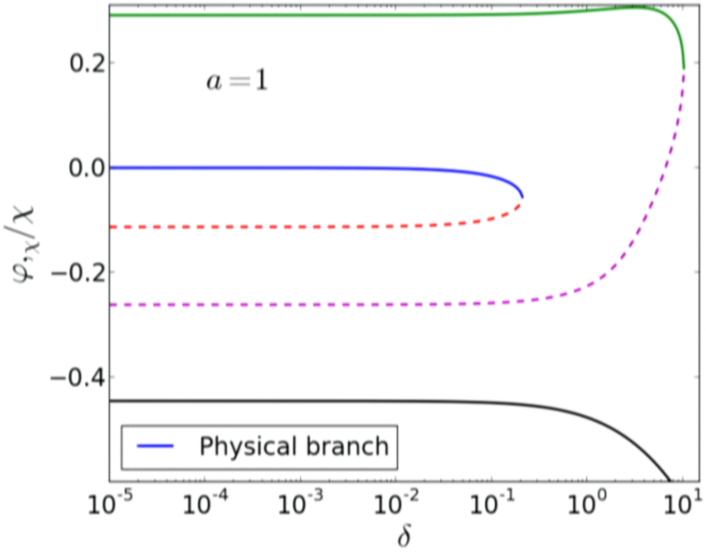
Recover the Cubic Galileon

Quintic Galileon

From field EoM (six order algebraic equation):

$$0 = \eta_{02}\delta^2 + \eta_{01}\delta + (\eta_{11}\delta + \eta_{10})\left[\frac{\varphi,_\chi}{\chi}\right] + (\eta_{21}\delta + \eta_{20})\left[\frac{\varphi,_\chi}{\chi}\right]^2 + (\eta_{31}\delta + \eta_{30})\left[\frac{\varphi,_\chi}{\chi}\right]^3 + \eta_{40}\left[\frac{\varphi,_\chi}{\chi}\right]^4 + \eta_{50}\left[\frac{\varphi,_\chi}{\chi}\right]^5 + \eta_{60}\left[\frac{\varphi,_\chi}{\chi}\right]^6 .$$

- **Density-dependence of the Galileon gradient today**



Physical branch

$$\frac{\varphi,_\chi}{\chi}(\delta \to 0) \to 0$$

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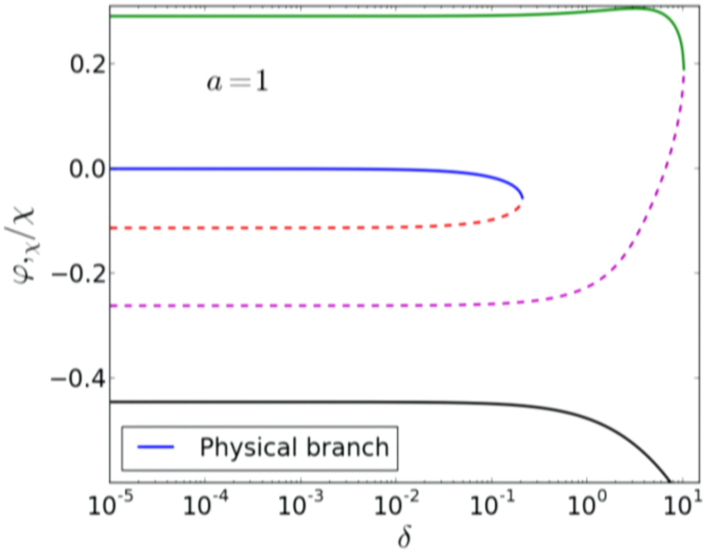


Physical branch

$$\frac{\varphi_{,\chi}}{\chi}(\delta \rightarrow 0) \rightarrow 0$$

Physical solution becomes a complex number !!

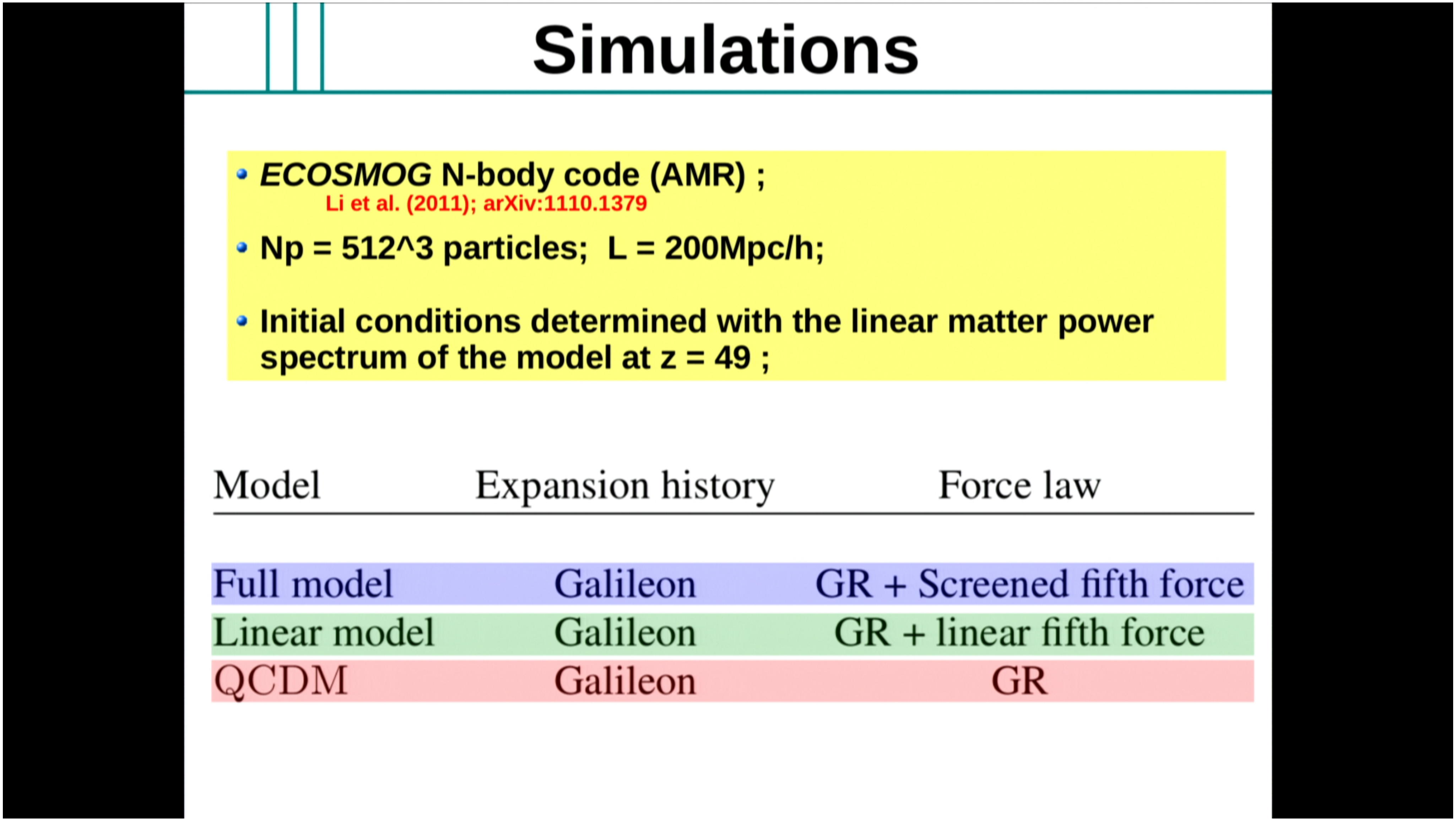
1) Breakdown of the weak-field or quasi-static limits?

2) Breakdown of the model?

Galileon gravity:

Targeted tests with N-body simulations

Barreira et al. arXiv: 1306.3219(JCAP)
Li & Barreira, et al. arxiv: 1308.3491 (JCAP)
Barreira et al. arXiv: 1401.1497(JCAP)

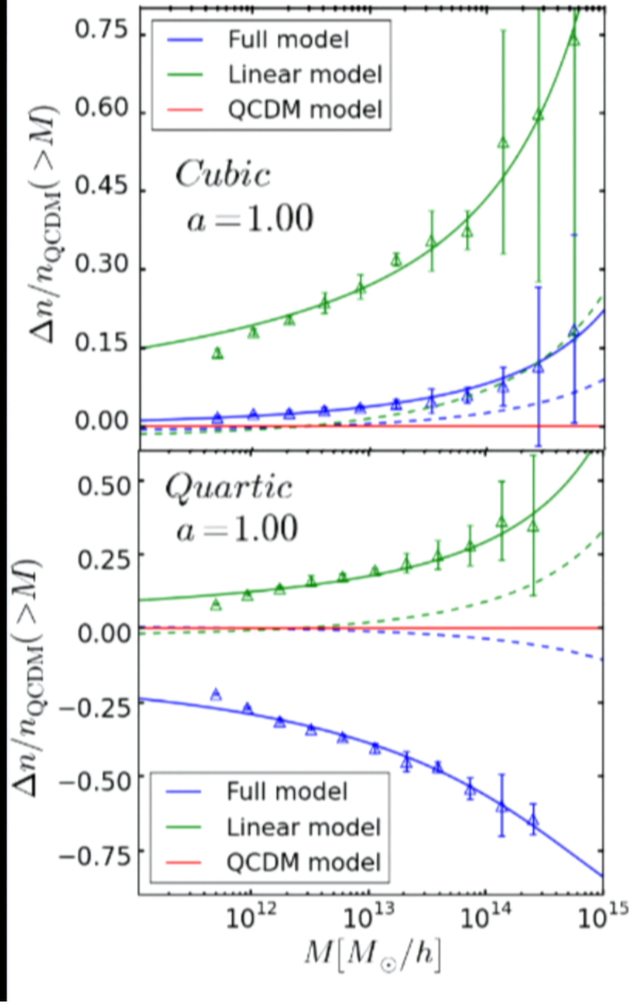


Simulations

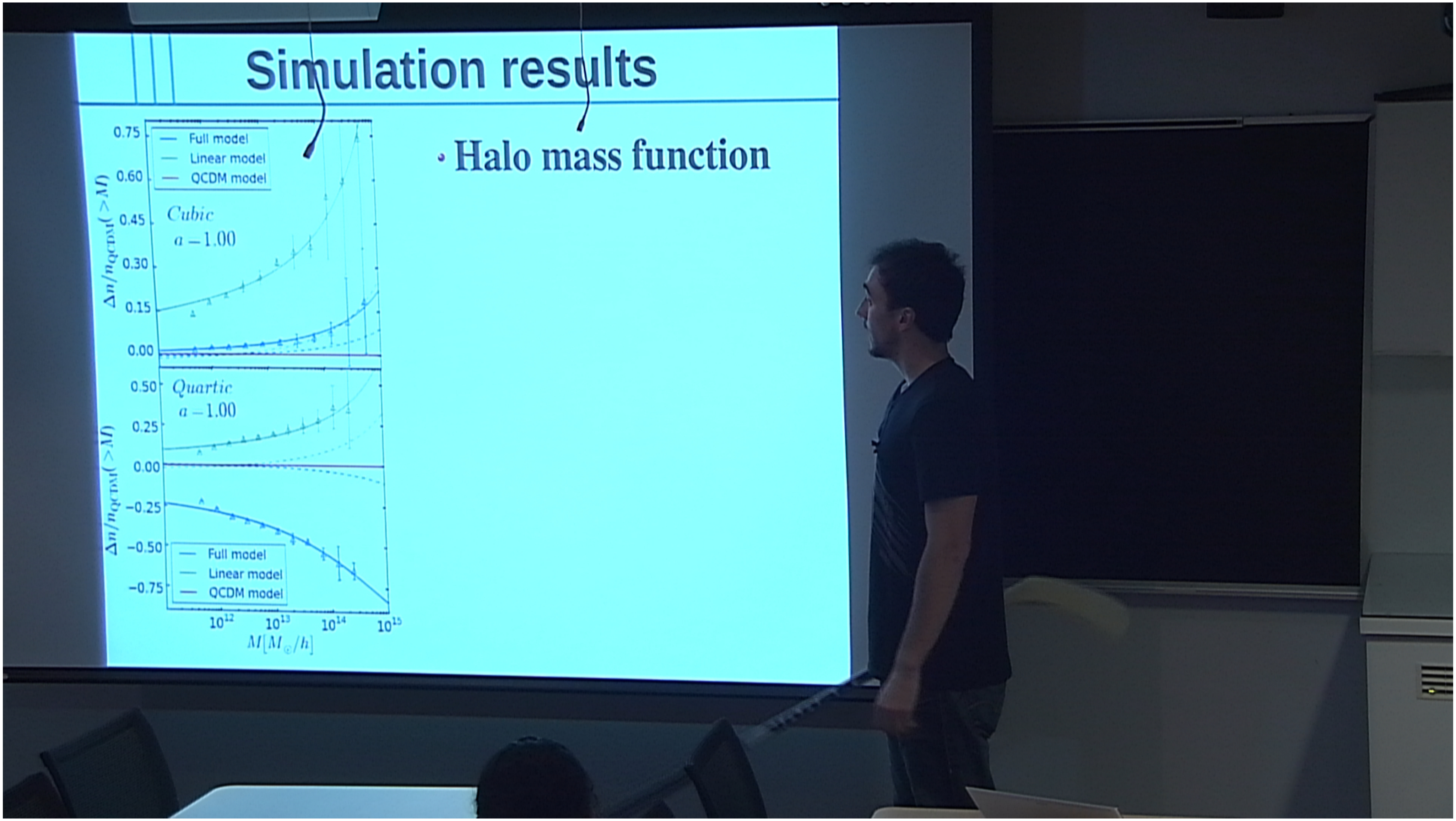
- ***ECOSMOG*** **N-body code (AMR) ;**
  Li et al. (2011); arXiv:1110.1379
- **Np = 512^3 particles; L = 200Mpc/h;**
- **Initial conditions determined with the linear matter power spectrum of the model at z = 49 ;**

Model	Expansion history	Force law
Full model	Galileon	GR + Screened fifth force
Linear model	Galileon	GR + linear fifth force
QCDM	Galileon	GR

Simulation results



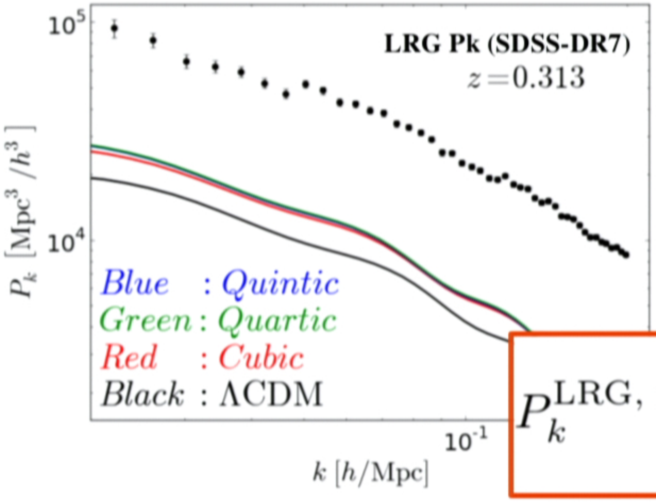
- **Halo mass function**



Simulation results

- **Halo mass function**

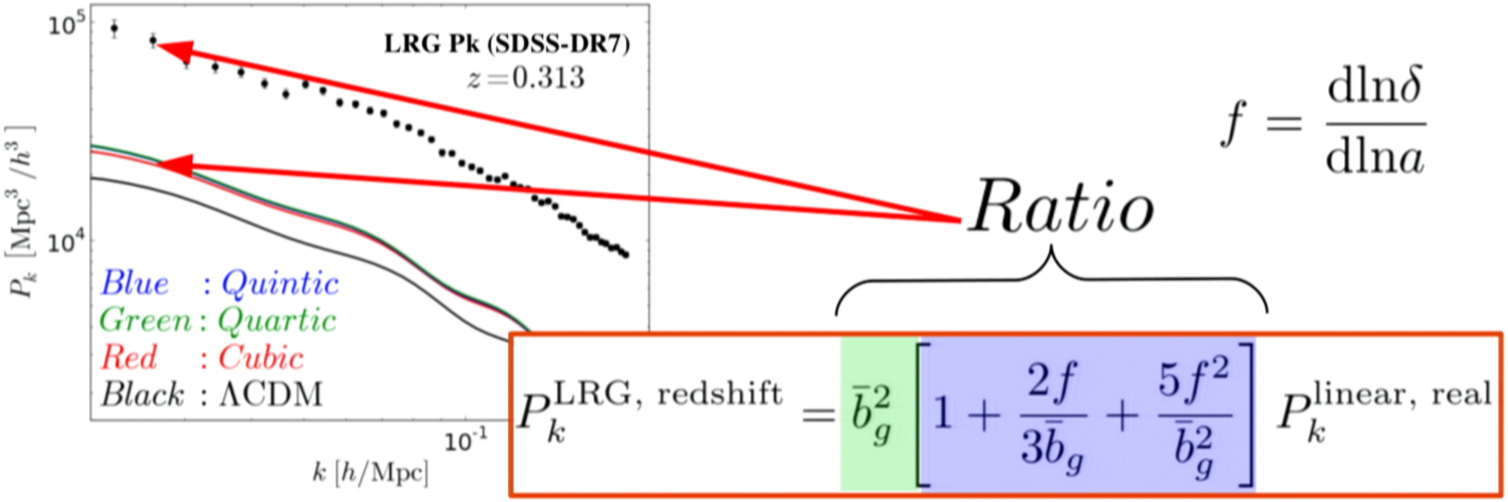
Halo Occupation Distribution



$$P_k^{\mathrm{LRG,\ redshift}} = \bar{b}_g^2 \left[1 + \frac{2f}{3\bar{b}_g} + \frac{5f^2}{\bar{b}_g^2} \right] P_k^{\mathrm{linear,\ real}}$$

LRG bias

Halo Occupation Distribution



$$f = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a}$$

$$P_k^{\text{LRG, redshift}} = \overbrace{\bar{b}_g^2 \left[1 + \frac{2f}{3\bar{b}_g} + \frac{5f^2}{\bar{b}_g^2}\right]}^{Ratio} P_k^{\text{linear, real}}$$

LRG bias

Redshift space distortions (Kaiser term)

Cubic & Quartic

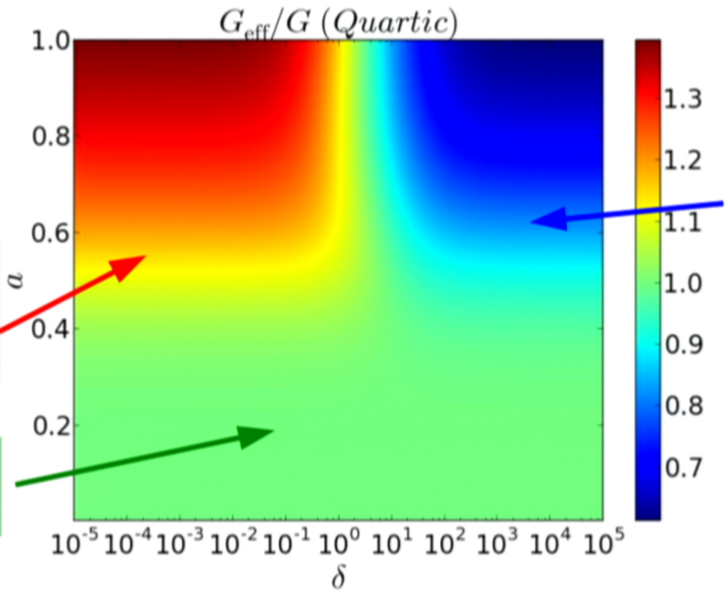
$$\boxed{\bar{b}_g \approx 1.6}$$

LCDM

$$\boxed{\bar{b}_g \approx 2.0}$$

Quartic Galileon

$$\frac{G_{\rm eff}}{G}(a,\delta) = \frac{\Psi_{,\chi}/\chi}{\Psi_{,\chi}^{\rm GR}/\chi}$$



Stronger gravity at late times and when density is low.

At early times, gravity is unchanged.

Gravity becomes weaker in high-density regions.

- **Vainshtein mechanism alone does not recover GR:**

$$\frac{\Phi_{,\chi}}{\chi} = \frac{\Omega_{m0}\delta a^{-3} + A_1\left(\varphi_{,\chi}/\chi\right) + A_2\left(\varphi_{\chi}/\chi\right)^2 + A_3\left(\varphi_{\chi}/\chi\right)^3}{\boxed{A_4} + A_5\left(\varphi_{\chi}/\chi\right)}$$

$$\mathcal{L}_4 \sim R\nabla_\mu\varphi\nabla^\mu\varphi$$

Multiplicative terms remain, after suppression of Galileon gradients.

Halo Occupation Distribution

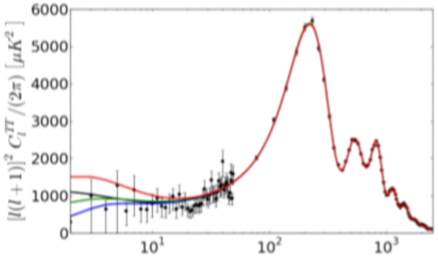
- **Postulate shape for the mean number of galaxies, N, in haloes of mass M.**

$$\langle N|M\rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log_{10}\left(M/M_{\mathrm{min}}\right)}{\sigma_{\log_{10}M}}\right)\right]$$

Galileon Summary

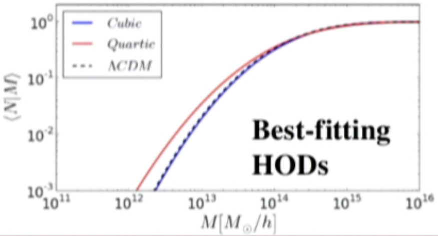
CMB + BAO constraints

- Good fit to CMB and BAO data with strong evidence for massive neutrinos.

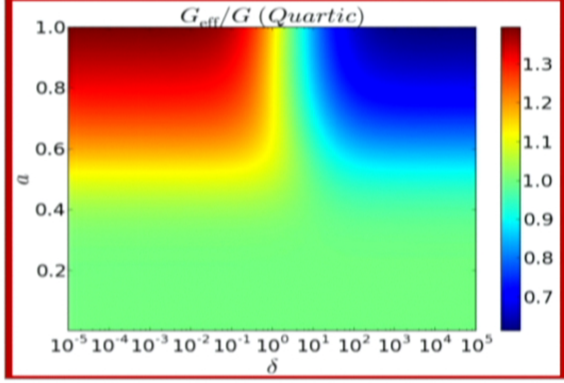


Galaxy halo distributions

- Degeneracies between enhanced linear growth, halo abundances and halo bias can keep galaxy distribution unchanged.

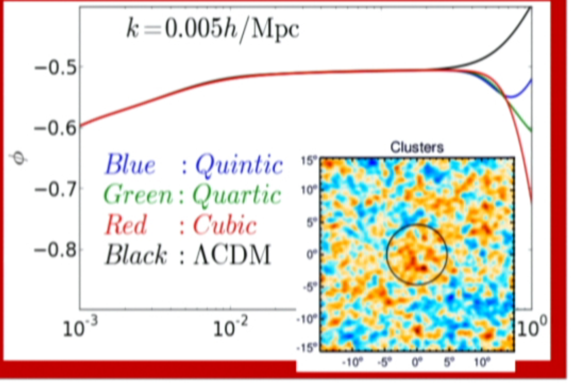


Local time variation of the gravitational strength



Hard to reconcile theory with observations.

Negative ISW at odds with observations



The Maggiore&Mancarella model

Nonlocal action (Maggiore&Mancarella 2014)

$$\boxed{A = \frac{1}{2\kappa}\int \mathrm{d}x^4\sqrt{-g}\left[R - \frac{m^2}{6}R\Box^{-2}R - \mathcal{L}_m\right]}$$

Auxiliary scalar quantities

$$\boxed{U = -\Box^{-1}R, \quad S = -\Box^{-1}U}$$

Integral (nonlocal) solutions

$$\boxed{U(x) = U_{\mathrm{hom}}(x) - \int \mathrm{d}y^4\sqrt{-g(y)}G(x,y)R(y)}$$

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Impose “by hand” that these are retarded operators, to keep causality.

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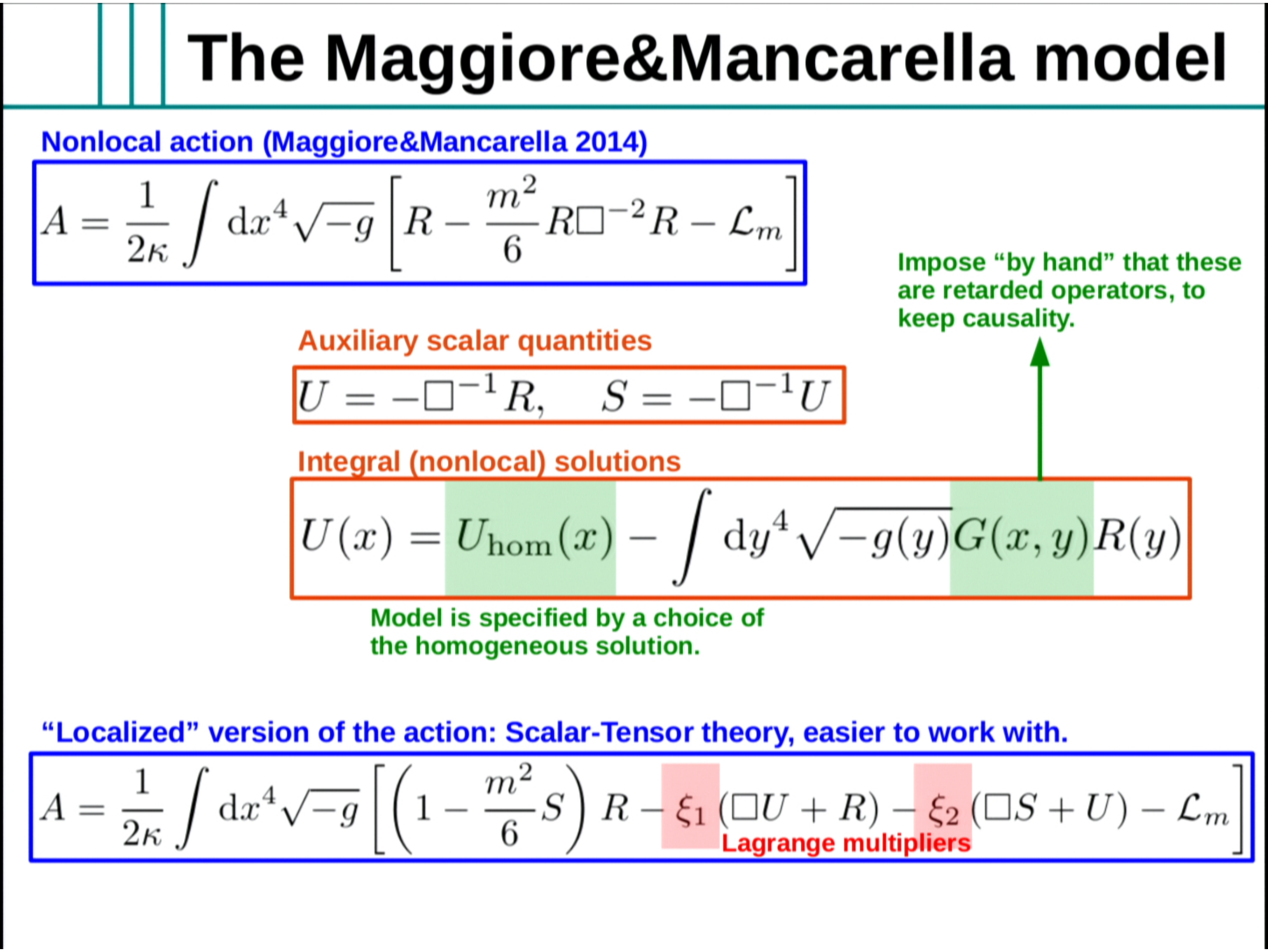
Model is specified by a choice of the homogeneous solution.



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Model is specified by a choice of the homogeneous solution.

"Localized" version of the action: Scalar-Tensor theory, easier to work with.

$$A=\frac{1}{2\kappa}\int \mathrm{d}x^4\sqrt{-g}\left[\left(1-\frac{m^2}{6}S\right)R-\xi_1\left(\Box U+R\right)-\xi_2\left(\Box S+U\right)-\mathcal{L}_m\right]$$

Lagrange multipliers

Structure formation equations

- **Perturbed FRW – Newtonian Gauge**

$$ds^2 = [1+2\Psi] - a(t)^2\,[1-2\Phi]\,\gamma_{ij}dx^i dx^j$$

- **Weak-field:** $\Phi, \partial\Phi \ll \partial\partial\Phi$
- **Quasi-static:** $\dot{\Phi}, \delta\dot{\varphi} \to 0$

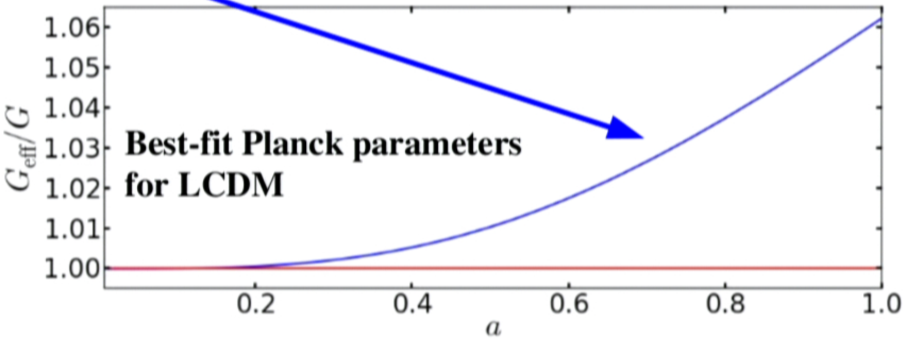
From (0,0)-cpt:

$$\nabla^2\Phi = 4\pi G\left[1-\frac{m^2\bar{S}(a)}{3}\right]^{-1}\delta a^2$$

From (i,i)-cpt:

$$\Phi = \Psi$$

Gravity is ~6% stronger today ..



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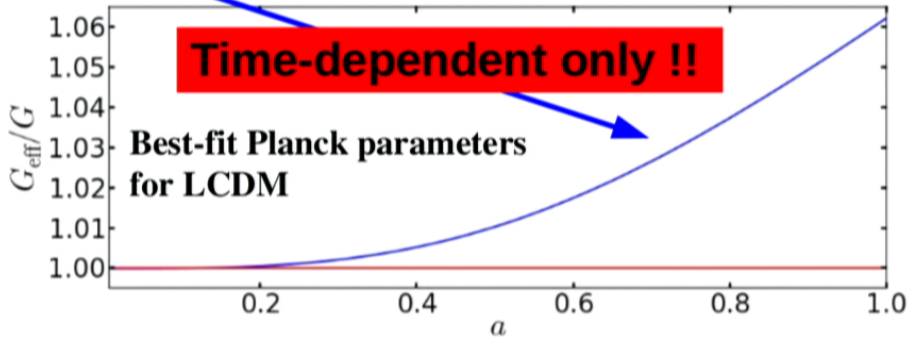
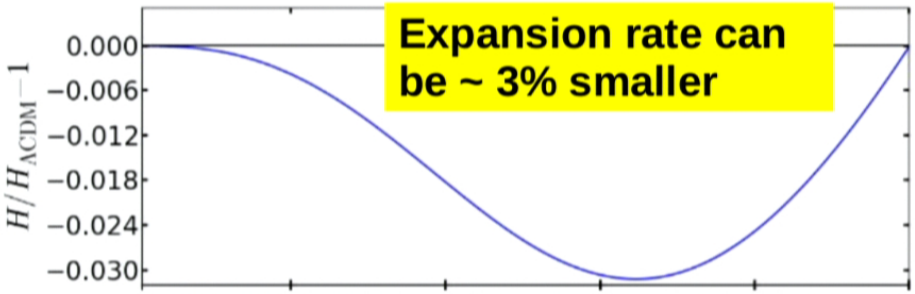


Nonlocal: Prospect constraints



Expansion rate can be ~ 3% smaller

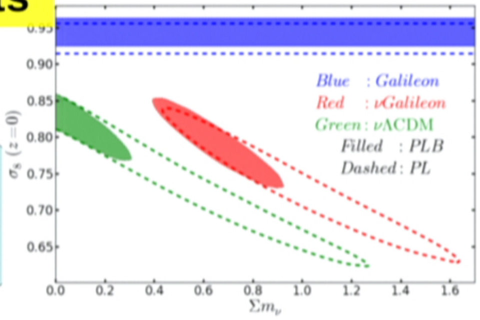
Barreira et al. arXiv: 1408.1084 (JCAP)

Take Home

1) Expansion history and linear theory constraints

- Determine the parameters that best-fit the “holy-grail” of cosmological data;
- Identify differences in parameter values compared to LCDM;

$$\boxed{\Sigma m_\nu}$$



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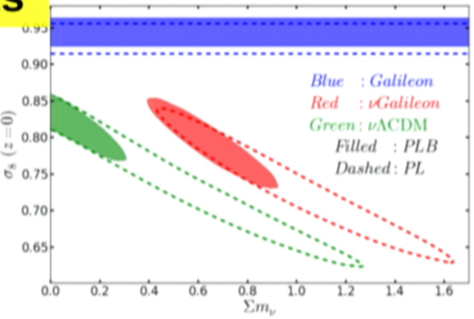

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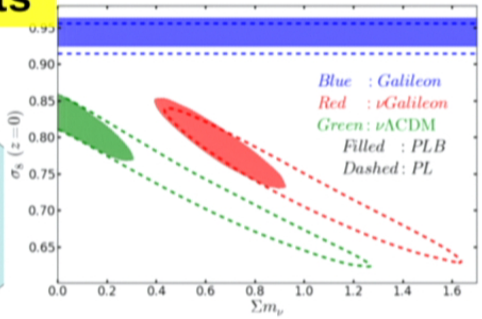

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2) Targeted tests of gravity: growth of structure on smaller scales

- Focus N-body simulations on the best-fitting parameters and look at:

Galaxy distribution/velocities

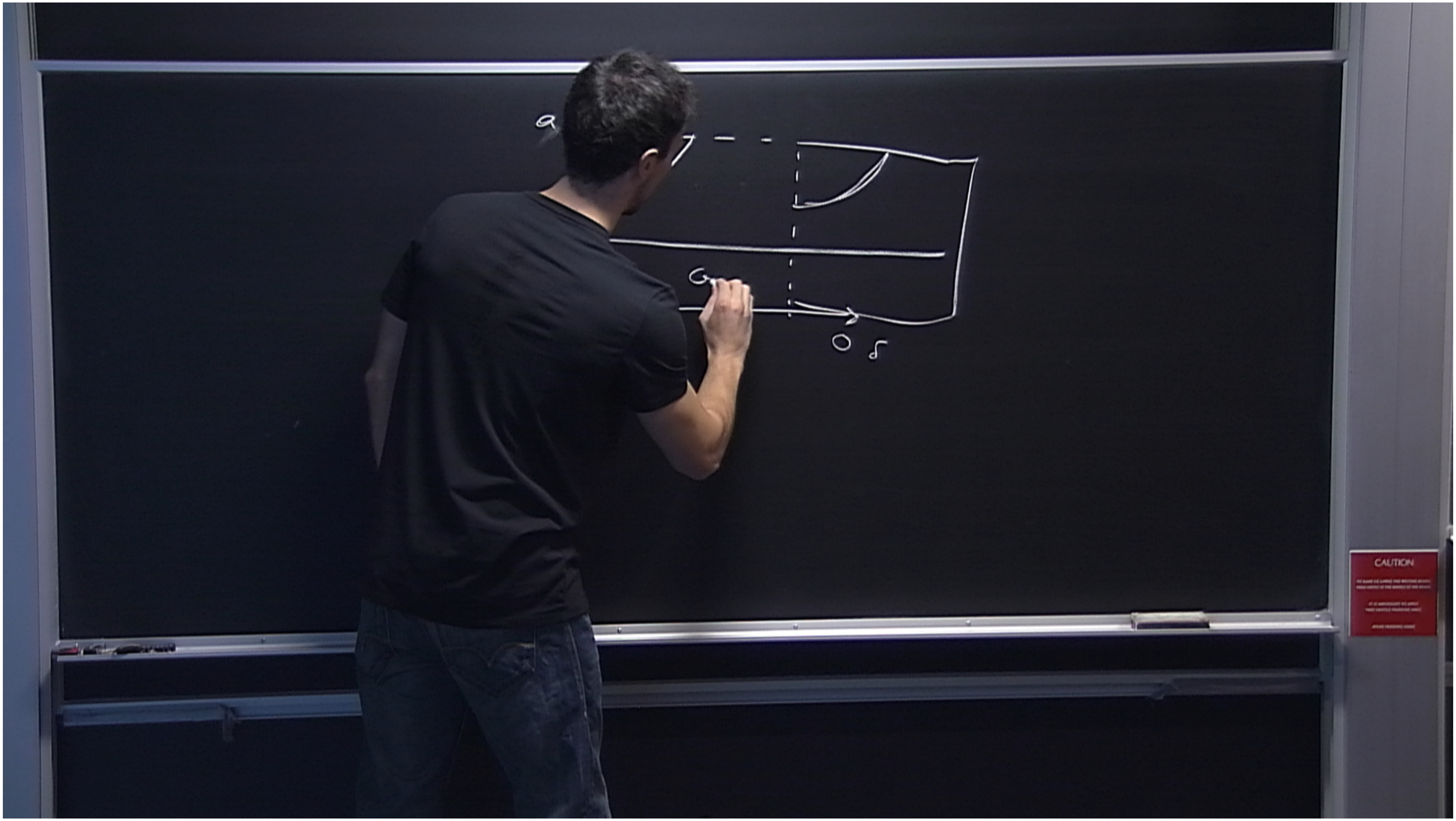
Time-evolving potentials/ISW

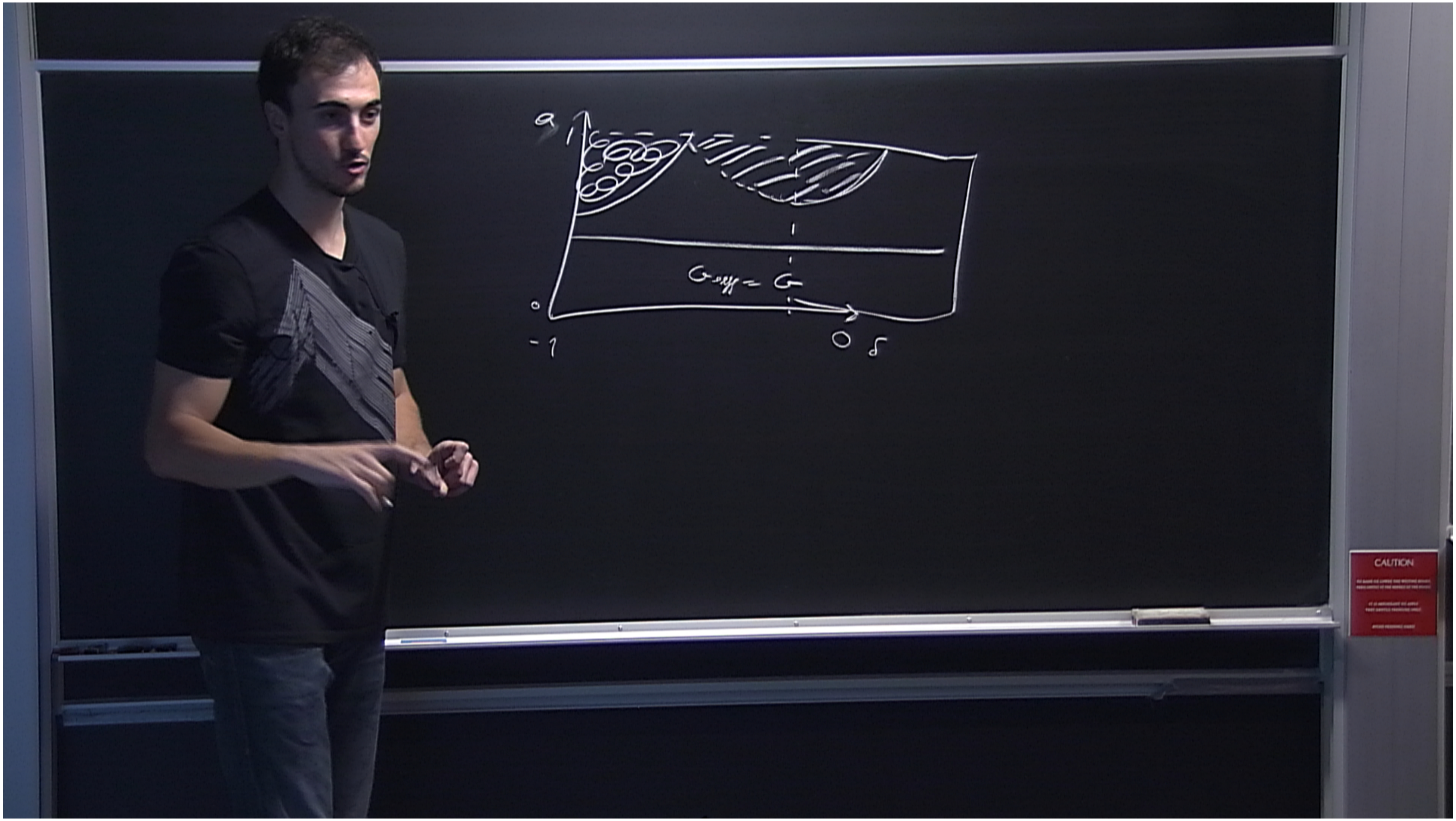
Cluster shapes

Growth rate

Lensing

Solar System


a
0
δ


a
1
0
-1
G_eff = G
0
δ
CAUTION

Spherically Symmetric Eqs.

rbed FRW – Newtonian Gauge

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- Quasi-static: $\dot{\Phi}, \dot{\delta}, \dot{\varphi} \rightarrow 0$

$\chi = aH_0 r$

$\delta \rightarrow$ Top hat

r) component

Normal gravity term

0,0) component

n field EoM (six order algebraic equation)

Take Home

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