Constraining Modified Growth Patterns with Tomographic Surveys

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Alessandra Silvestri

in collaboration with: Levon Pogosian, GongBo Zhao, Joel Zylberberg
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Outline

- Cosmic Acceleration: Λ? Modified Gravity ? Dark Energy?
- Can we distinguish between them?

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Large Scale Structure!

- ***f(R) theories*** : as a learning-ground for signatures of modifications

Background:

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degenerate with LCDM

Growth of Structure:

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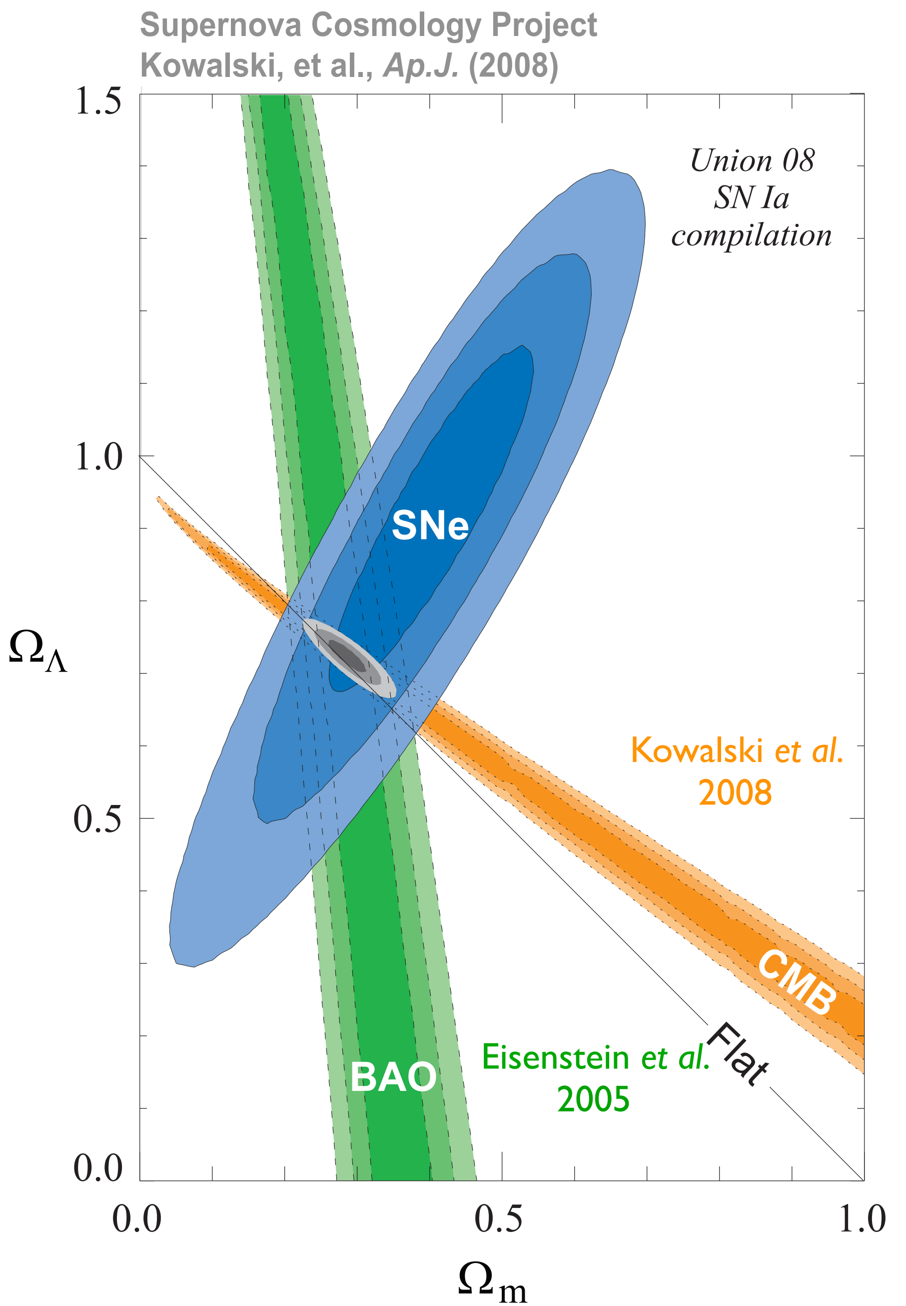
the dynamics is changed, leading to a characteristic scale-dependent pattern

- ***Searching for modified growth patterns***

Cosmic Acceleration



SNeIa, CMB, LSS

+

standard GR applied to a homogeneous and isotropic Universe

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$$\Omega_m^0 \approx 0.3$$

$$\Omega_X^0 \approx 0.7$$

$$\left(\Omega_m^0 \equiv \frac{\rho^0}{3H_0^2 M_P^2} = \frac{\rho^0}{\rho_{cr}^0} \right)$$

Cosmic Acceleration

A very good fit to all these data is a Universe in which 70% of the energy budget is in the COSMOLOGICAL CONSTANT, LCDM

Anyhow it is important to explore the whole space of explanations that fit these data and could have testable features...

Dark Energy		Modified Gravity
$G_{\mu\nu} = \frac{1}{M_P^2} \tilde{T}_{\mu\nu}$	⟷	$\tilde{G}_{\mu\nu} = \frac{1}{M_P^2} T_{\mu\nu}$
X matter fields with dynamics such as to cause the late universe to accelerate (quintessence, k-essence, ...)		modification of GR on large scales, admitting self-accelerating solutions

Generalized Dark Energy + Modified Gravity	vs.	LCDM (or uncoupled DE)

What do we learn from f(R) gravity ?

f(R) Gravity

$$S = \frac{M_P^2}{2} \int dx^4 \sqrt{-g}\,[R + f(R)] + \int d^4x \sqrt{-g}\mathcal{L}_m[\chi_i, g_{\mu\nu}]$$

(S.Capozziello, S.Carloni & A.Troisi, astro-ph/0303041
S.Carroll, V.Duvvuri, M.Trodden & M.S.Turner, Phys.Rev.D70 043528 (2004))

$$\begin{cases} (1+f_R)R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}(R+f) + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)f_R = \frac{T_{\mu\nu}}{M_P^2} \\ \nabla_\mu T^{\mu\nu} = 0 \end{cases}$$

$$f_R \equiv \frac{df}{dR}$$

The Einstein equations are fourth order.

The trace-equation becomes:

dynamical !

$$(1 - f_R)R + 2f - 3\Box f_R = \frac{T}{M_P^2}$$

Background Viability

There is an extra scalar d.o.f.: the scalaron f_R

$$\lambda_C \equiv \frac{2\pi}{m_{f_R}} \approx 2\pi\sqrt{\frac{3f_{RR}}{1+f_R}}$$

...extra dynamics and fifth-force...

to have a stable high-curvature regime, i.e. to go through a standard matter era, to have a positive effective Newton constant, and to satisfy LGC

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$$w_{\rm eff} \simeq -1$$

(Dolgov & Kawasaki, Phys.Lett.B 573 (2003), Navarro et al. gr-qc/0611127, Sawicki and Hu astro-ph/0702278
Starobinsky astro-ph/0706.2041, Chiba, Smith, Erickcek astro-ph/0611867
Amendola et al. astro-ph/0603703-0612180, Amendola & Tsujikawa astro-ph/0705.0396)

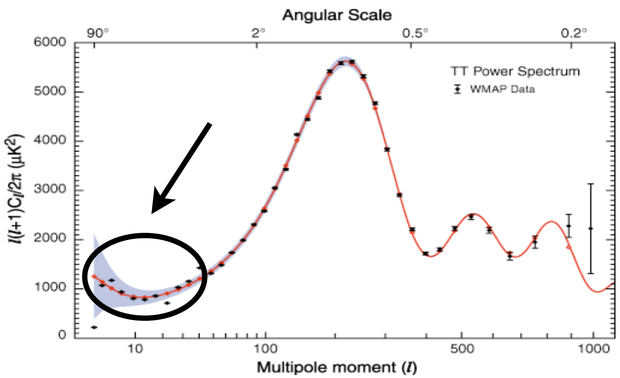
Can we distinguish them from LCDM?

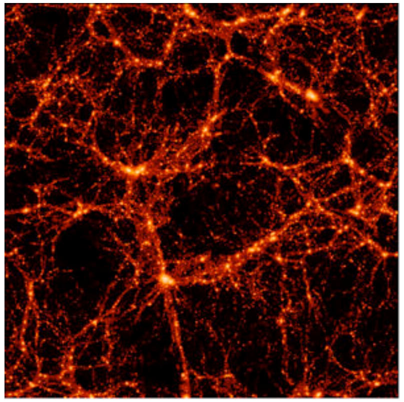
While at the background level viable f(R) must closely mimic LCDM, the difference in their prediction for the growth of large scale structure can be significant

The scalaron sets a transition scale, inducing a characteristic scale-dependent pattern

coupled DE

On scales below the Compton wavelength of the scalaron, the modifications contribute a slip between the Newtonian potentials and the growth is enhanced by the fifth-force





ISW, P(k), ISW-galaxy & WL

Dynamics of Linear Perturbations....Sub-Horizon

$$\delta_m'' + \left(1 + \frac{H'}{H}\right)\delta_m' + \frac{k^2}{a^2H^2}\Psi = 0$$

$$k^2\Psi = -\frac{3}{2}\,\frac{1}{F}\,\frac{1+4\frac{k^2}{a^2}\frac{f_{RR}}{F}}{1+3\frac{k^2}{a^2}\frac{f_{RR}}{F}}\,E_m\delta_m$$

time and scale dependent rescaling of Newton constant

$$\frac{k^2}{a^2}\frac{f_{RR}}{F} = \frac{k^2}{a^2}\frac{1}{m^2}$$

$$\frac{\Phi}{\Psi} = \frac{1+2\frac{k^2}{a^2}\frac{f_{RR}}{F}}{1+4\frac{k^2}{a^2}\frac{f_{RR}}{F}}$$

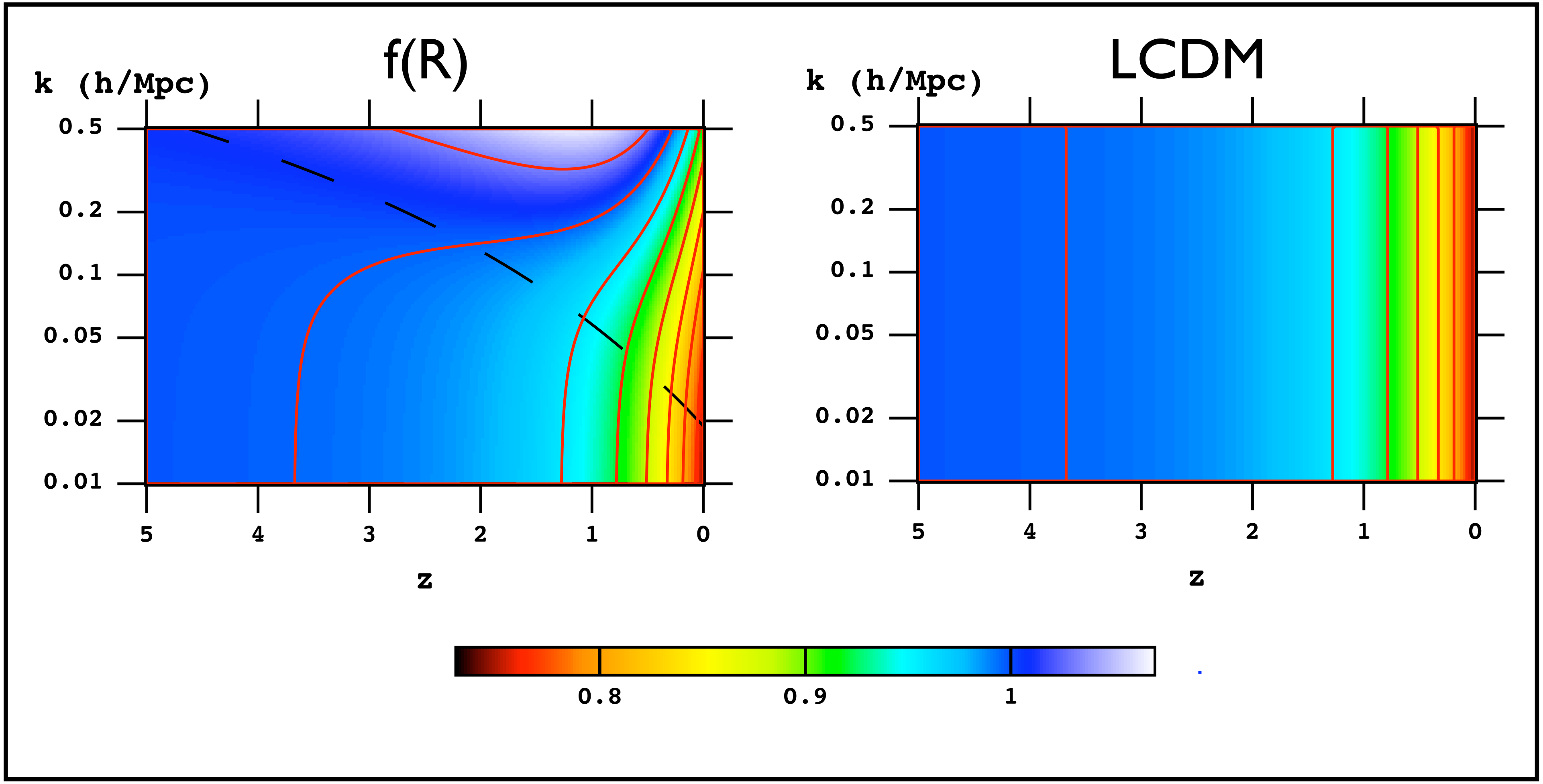
β

$$\frac{G_{\rm eff}}{G} = \frac{1+\frac{4}{3}\frac{k^2}{a^2m^2}}{1+\frac{k^2}{a^2m^2}} \qquad \frac{\Phi}{\Psi} = \frac{1+\frac{2}{3}\frac{k^2}{a^2m^2}}{1+\frac{4}{3}\frac{k^2}{a^2m^2}}$$

$w_{eff} = -1$
$f_R^0 = -10^{-4}$

$$\frac{\Delta_m(a,k)/a}{\Delta_m(a_i,k)/a_i}$$

$$\left(\frac{\Phi_+(a,k)}{\Phi_+(a_i,k)}\right)$$



Characteristic signatures

Overall we observe a scale-dependent pattern of growth.

The modifications introduced by f(R) models are similar to those introduced by more general scalar-tensor theories and models of coupled DE-DM

The dynamics of perturbations is richer, and different observables are described by different functions, not by a single growth factor!

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combining different measurements we can build discriminating probes of gravity

What is the potential of current and upcoming tomographic surveys to detect departures from GR *(LCDM,quintessence)* **in the growth of structure?**

Parametrization

- slip between Newtonian potentials: $\gamma(a,k) \equiv \frac{\Phi}{\Psi}$
- effective Newton constant: $G \to G \cdot \mu(a,k)$

in standard GR : $\gamma(a,k) = 1$
$\mu(a,k) = 1$

Parametrization: inspired by scalar-tensor theories / massive coupled quintessence

$$\frac{G_{\text{eff}}}{G} = \frac{1+\beta\frac{k^2}{a^2m^2}}{1+\frac{k^2}{a^2m^2}} \longleftrightarrow \Phi_{\text{Yuk}} \sim \frac{1}{r}\left[1+(\beta-1)e^{-r/\lambda}\right]$$

$$\boxed{\mu(a,k) \equiv \frac{1+\beta_1\lambda_1^2\,k^2a^s}{1+\lambda_1^2\,k^2a^s}} \qquad \boxed{\gamma(a,k) \equiv \frac{1+\beta_2\lambda_2^2\,k^2a^s}{1+\lambda_2^2\,k^2a^s}}$$

Fisher analysis for the parameters: $\{s, \beta_1, \beta_2, \lambda_1^2, \lambda_2^2\}$

Observables: theoretical predictions

$$\begin{cases} \Delta_m'' + \mathcal{H}\Delta_m' + k^2\Psi = 0 \\ k^2\Psi = -\dfrac{a^2}{2M_P^2} G \cdot \mu(a,k)\Delta_m \\ \Phi = \gamma(a,k) \cdot \Psi \end{cases}$$

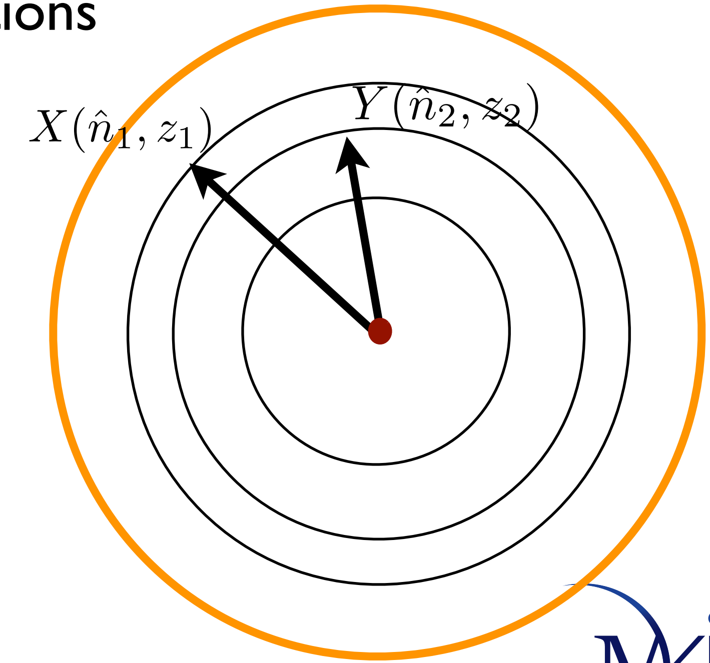
$\Rightarrow$ OBSERVABLES

We wish to combine multiple-redshift information on Galaxy Count, Weak Lensing, CMB and their cross correlations

Therefore the observables are the ANGULAR POWER SPECTRA:

$$C_l^{XY}(\theta) = 4\pi \int \frac{dk}{k} \Delta_{\mathcal{R}}^2 I_l^X(k) I_l^Y(k)$$

$$I_l^X(k) = c_{x\mathcal{R}} \int_0^{z_*} dz\, W(z) j_l[kr(z)] \tilde{X}(k,z)$$



Surveys

background: SNeIa (SNAP) + CMB (Planck)

Galaxy Count (GC) & Weak Lensing (WL): DES (Dark Energy Survey, Sept. 2009, $0.1 < z < 1.3$)

DARK ENERGY SURVEY

LSST (Large Synoptic Survey Telescope, proposed, $z \sim 3$)

CMB: Planck (ESA, $\frac{\Delta T}{T} \sim 2 \times 10^{-6}$, $\theta \sim 5'$)

Large Synoptic Survey Telescope

Fiducials

$$\mu(a,k) \equiv \frac{1+\beta_1\lambda_1^2\, k^2 a^s}{1+\lambda_1^2\, k^2 a^s}$$

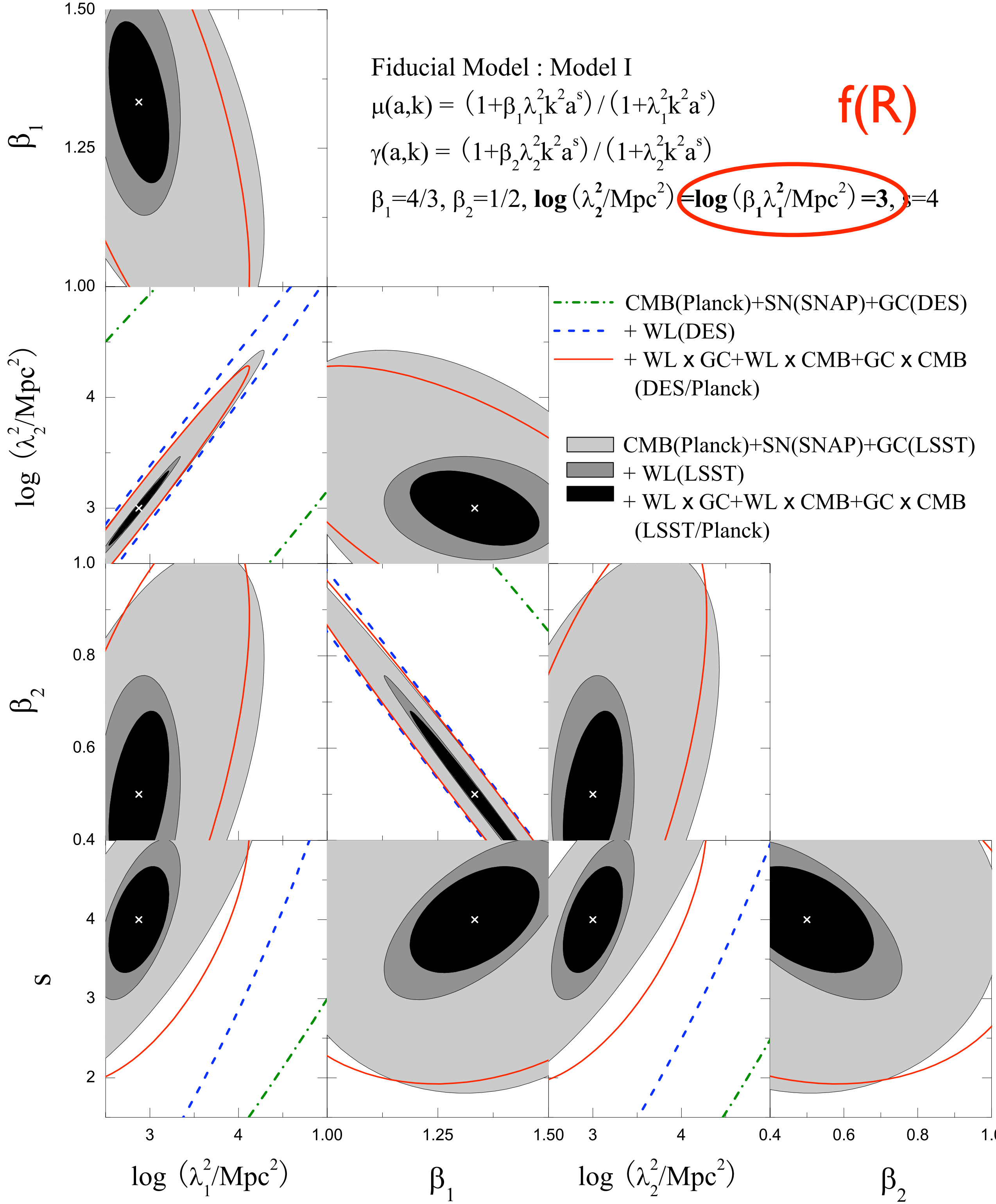
$$\gamma(a,k) \equiv \frac{1+\beta_2\lambda_2^2\, k^2 a^s}{1+\lambda_2^2\, k^2 a^s}$$

<u>f(R) fiducials:</u>

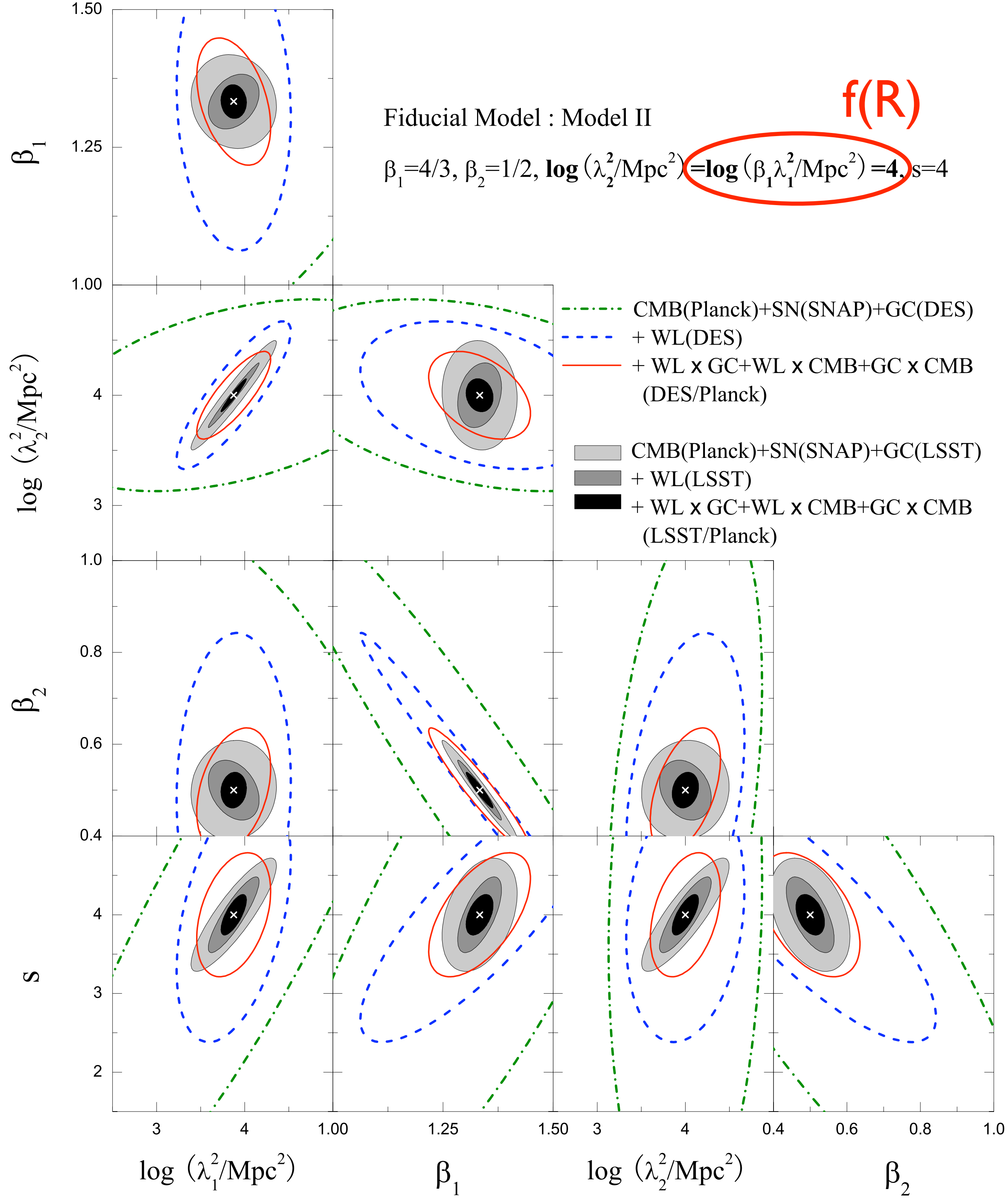
- fixed coupling: $\beta_1 = \frac{4}{3}\,,\ \beta_2 = \frac{1}{2}$
- mass evolution: $\frac{1}{m^2} \sim f_{RR} \propto a^{-6} \longrightarrow \quad s \sim 4$
- mass scale today: $\lambda_1 \lesssim O(10)\,\mathrm{Mpc}$ (LGC)

  $\lambda_1 \lesssim O(10^3)\,\mathrm{Mpc}$ ~~(LGC)~~

68% Confidence Contours for the 5 modified-growth parameters



Fiducial Model : Model I
μ(a,k) = (1+β1λ1²k²a^s) / (1+λ1²k²a^s)
γ(a,k) = (1+β2λ2²k²a^s) / (1+λ2²k²a^s)
β1=4/3, β2=1/2, log (λ2²/Mpc²) =log (β1λ1²/Mpc²) =3, s=4
f(R)
CMB(Planck)+SN(SNAP)+GC(DES)
+ WL(DES)
+ WL x GC+WL x CMB+GC x CMB (DES/Planck)
CMB(Planck)+SN(SNAP)+GC(LSST)
+ WL(LSST)
+ WL x GC+WL x CMB+GC x CMB (LSST/Planck)
β1
log (λ2²/Mpc²)
β2
s
log (λ1²/Mpc²)
β1
log (λ2²/Mpc²)
β2



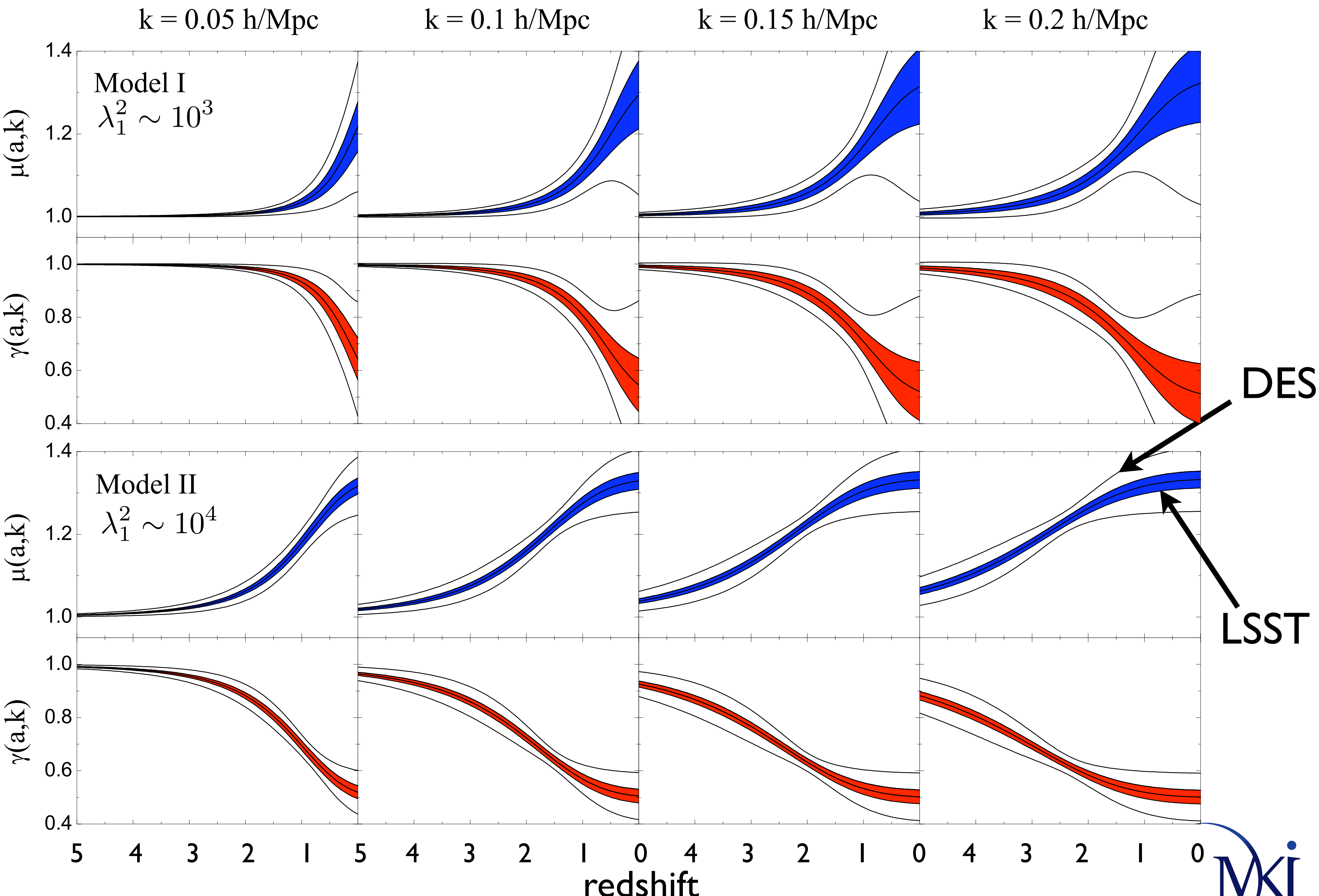
f(R)
Fiducial Model : Model II
β1=4/3, β2=1/2, log (λ2²/Mpc²) =log (β1λ1²/Mpc²) =4, s=4
CMB(Planck)+SN(SNAP)+GC(DES)
+ WL(DES)
+ WL x GC+WL x CMB+GC x CMB (DES/Planck)
CMB(Planck)+SN(SNAP)+GC(LSST)
+ WL(LSST)
+ WL x GC+WL x CMB+GC x CMB (LSST/Planck)
β1
log (λ2²/Mpc²)
β2
s
log (λ1²/Mpc²)
β1
log (λ2²/Mpc²)
β2

Relative Errors

P	Model I		Model II	
	DES	LSST	DES	LSST
$\log(\lambda_1^2/\mathrm{Mpc}^2)$	34%	9%	18%	4%
β_1	20%	6%	9%	2%
$\log(\lambda_2^2/\mathrm{Mpc}^2)$	33%	9%	18%	4%
β_2	68%	20%	26%	4%
s	53%	14%	30%	6%

with all data combined

Reconstructed G and gravitational slip



Summary

The degeneracy among models of cosmic acceleration is broken at the level of Large Scale Structure.

Weak Lensing (WL), Galaxy Count (GC), the Integrated Sachs Wolfe effect (ISW) & their cross-correlations offer a powerful testing ground for GR on large scales.

We have learned that upcoming and future surveys can place non trivial bounds on modifications of the growth of structure even in the most conservative case, i.e. considering only linear scales.

These results are model-dependent, but they motivate us to pursue model-independent methods such as PCA (Principal Component Analysis)

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results coming soon, stay tuned :-)

THANK YOU !