Title: Testing gravity on cosmic scales

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Abstract: While the properties of gravity, and its consistency with General Relativity (GR), are well tested on solar system scales, within our system and the decay of binary pulsar orbits, they are, by comparison, poorly tested on cosmic scales. This is of particular interest as we try to understand the origins of cosmic acceleration, and whether they are a signature of deviations from GR. Using the latest measurements of the universe's expansion history, twinned with the evolution of large scale structure, we discuss the current constraints on gravity's behavior on the largest scales observable today.

Why test gravity on cosmic scales?

How might one modify gravity?

What is the effect on the growth of inhomogeneities?

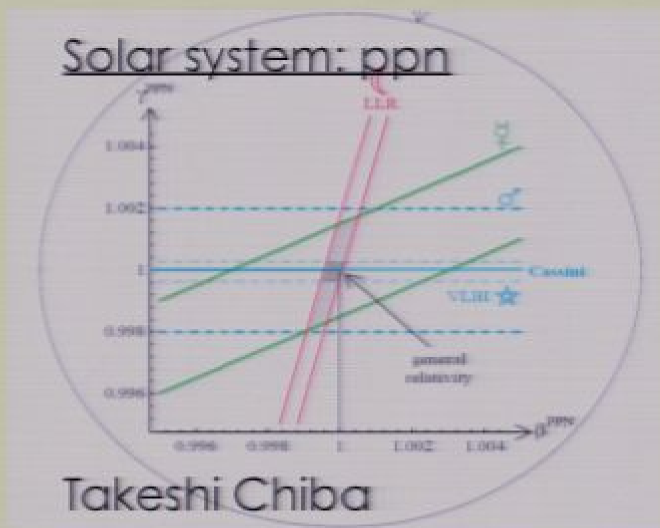
What effect does modifying gravity have on observations?

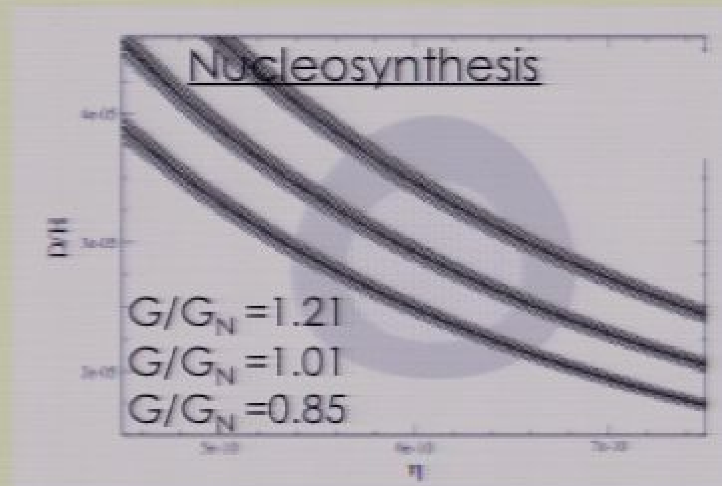
What are the current constraints?

What about the future?

Testing gravity's properties on cosmic scales

- Testing gravity on cosmic scales is a complementary endeavor to precisions tests of GR in the solar system and at early times





Copi, Davis, Krauss 2003

- As we've been hearing, a current motivation for investigating deviations from GR is as an explanation of cosmic acceleration
  - Key differentiator between dark energy and modified gravity on cosmic scales is latter's effect on growth of structure
  - Especially in light of upcoming push for deeper and wider surveys

Why modify gravity?

- Cosmic acceleration could signify a modification to the left and/or right hand side of Einstein's equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Modified gravity?

New matter? interactions?

Λ?

Inhomogeneous universe?

Can we distinguish whether acceleration evidence for modified gravity, Λ or a new type of matter?

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Why modify gravity?

- IR modifications to GR an active area of theoretical investigation
  - Variety of instructive models are being considered

GR $$S = \int d^4x \sqrt{-g} \frac{1}{16\pi G} R$$

Why modify gravity?

- Cosmic acceleration, just like Λ, could signify a modification to the left or right hand side of Einstein's equations
  - GR + normal matter (P>0) implies deceleration

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m)$$

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  - Modifying LHS allows acceleration and P>0 to not be inconsistent

$$f(g_{\mu\nu}, R, R_{\mu\nu}) + G_{\mu\nu} = 8\pi G T^{mat}_{\mu\nu} \qquad stuff + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m)$$

  - Example: f(R) gravity

$$H^2 + \frac{f}{6} + H\dot{f}_R = \frac{\kappa^2}{3}\rho$$

$$\frac{\ddot{a}}{a} - H^2 f_R + \frac{a^2}{6} f + \frac{3}{2} H\dot{f}_R + \frac{1}{2}\ddot{f}_R = -\frac{\kappa^2}{6}(\rho + 3P)$$

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Describing the growth of structure : the perturbed metric

- Consider cosmic evolution not only of homogeneous background expansion but also of inhomogeneities

- Homogenous and isotropic space described by FRW metric

$$ds^2 = -a(\tau)^2 d\tau^2 + a(\tau)^2 d\mathbf{x}^2$$

- Complication in how one defines the inhomogeneous coordinate system because there is a freedom or "gauge choice"
  - An example: a perturbed FRW metric in the Newtonian gauge

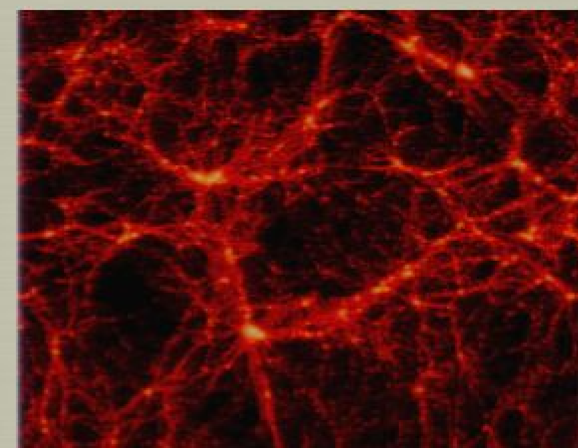
$$ds^2 \;=\; -a(\tau)^2[1 + \underline{2\psi(\mathbf{x},t)}]d\tau^2 + a(\tau)^2[1 - \underline{2\phi(\mathbf{x},t)}]d\mathbf{x}^2$$

  - ϕ, ψ describe the fluctuations in how space and time are related

Describing the growth of structure : the perturbed matter

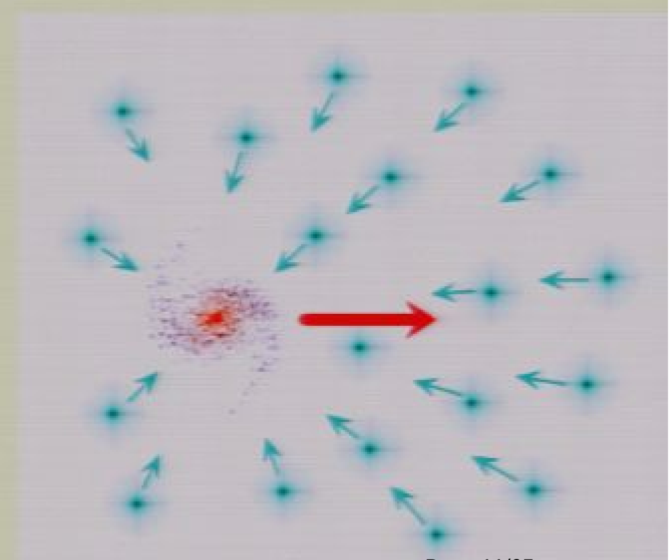
In the real universe:

- Matter collects into clumps, and leaves voids: "density fluctuations"



$$\delta(\mathbf{x},t) \equiv \frac{\rho(\mathbf{x},t)}{\bar{\rho}}$$

- Matter has motion over and above the Hubble expansion: "peculiar velocity fluctuations"



$$\frac{d}{d\tau}(a\mathbf{x}) = \mathcal{H}(a\mathbf{x}) + a\mathbf{v}$$

$$\theta \equiv \nabla \cdot \mathbf{v}$$

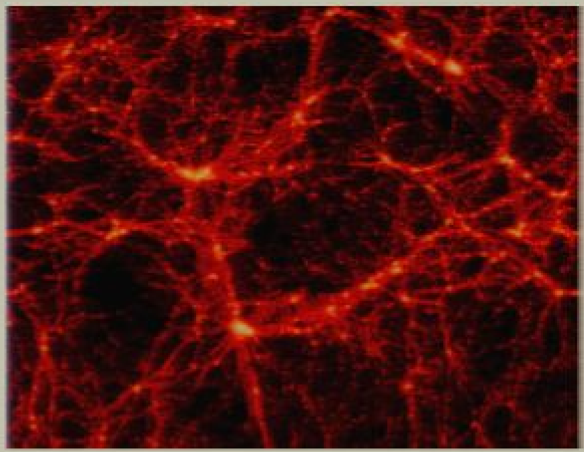
Describing the growth of structure : the perturbed matter

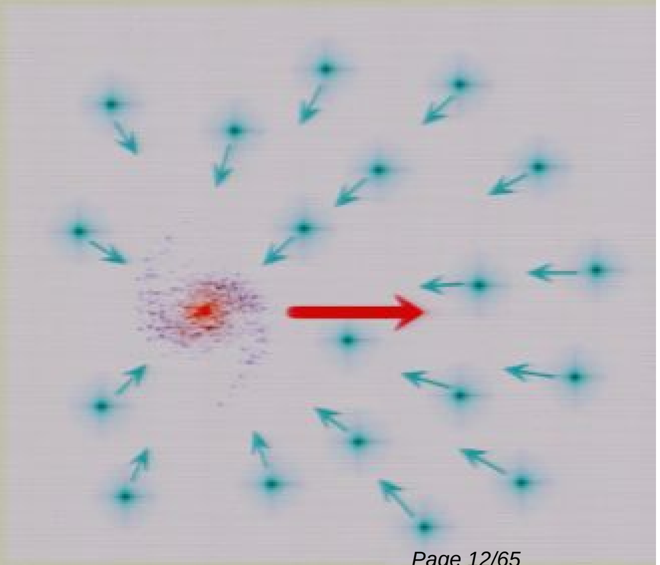
- Conservation of energy and momentum tells us how matter and velocities evolve over time "the fluid equations"

$$\dot{\delta} = -\theta + 3\dot{\phi}$$

$$\frac{1}{a}\frac{d(a\theta)}{d\tau} = k^2\psi$$

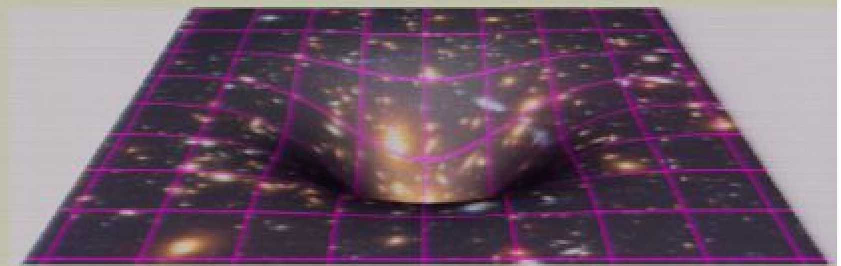
- If we just modify how gravity behaves these are unchanged





Perturbed Einstein equations: how the matter and metric fluctuations are related

- Perturbed (modified/unmodified) Einstein equations tell us how metric and matter fluctuations related



- Poisson equation:
  How potential related to local density

$$k^2\phi \;=\; -4\pi G a^2 \sum_j \rho_j \Delta_j$$

Δ = density fluctuation in the rest frame (v=0)

$$\Delta \;=\; \delta + 3\mathcal{H}(1+w)\frac{\theta}{k^2}$$

- Relationship between two potentials:
  In absence of shear stresses

$$k^2\psi = k^2\phi$$

A modified growth model

- f(R), scalar tensor, higher dimensional gravity have broadly similar phenomenological properties:

1) A modification to Poisson's equation

$$k^2\phi = -4\pi G Q a^2 \rho \Delta$$

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Q≠1: can be mimicked by

- additional (dark energy?) perturbations,
- modified dark matter evolution (e.g. non-minimal coupling between matter and dark energy)

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2) An inequality in Newton's potentials

$$k^2\psi = k^2 R\phi - shear\ stresses$$

R≠1: potential smoking gun for modified gravity?

- Significant and lasting shear stresses are exceptionally hard to create in non-relativistic fluids e.g. dark matter and dark energy.

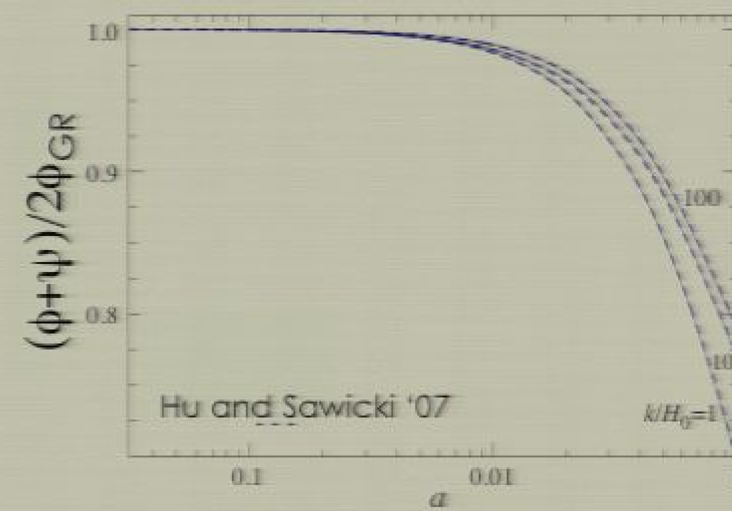
A modified growth model – Theoretical examples

- DGP: Scale independent modifications

$$R(a) = \frac{2}{3\beta(a) - 1}$$

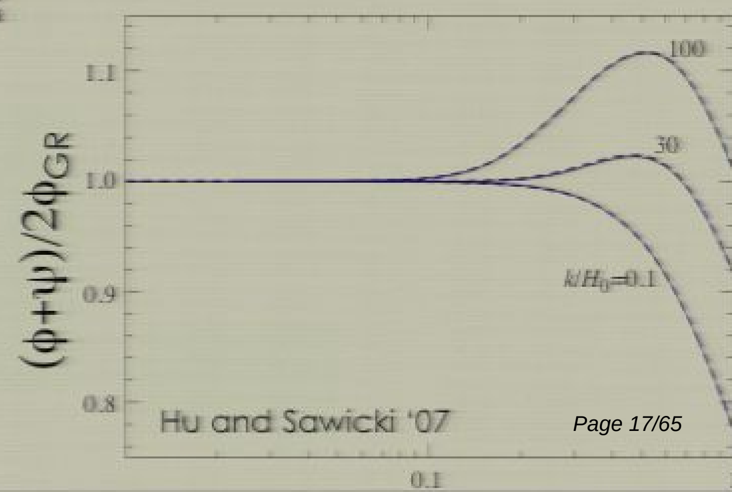
$$Q(a) = 1 - \frac{1}{3\beta(a)}$$

$$\beta(a) = 1 - \frac{2H(a)^2 l_c^2}{2H(a) l_c - 1} \qquad l_c = \frac{m_p^{(4)2}}{2m_p^{(5)3}}$$



- f(R) gravity : scale dependent modifications

$$Q(a) = \left(1 + \frac{df}{dR}\right)^{-1}$$



Constraints on cosmic growth - prospective surveys

- Recent work considers constraints for future surveys e.g. Zhang, Bean, Liguori & Dodelson '07/'08, Zhao et al 2008, Guzik, Jain & Takada 2009
  - LSST
  - DES
  - Future JDEM mission
- Using phenomenological models to investigate predictive power of future surveys
- But what are the current constraints with publicly available data?

Constraints on cosmic growth - a current benchmark

- Considering constraints on modified growth history f(R) in a standard expansion history
  - f(R) and scalar tensor theories can reconstruct an expansion history degenerate with ΛCDM but with differing growth history

- Consider simple, phenomenological power law deviations from GR

$$Q(k,a) = 1 + (Q_0 - 1)a^s e^{-k/k_c}$$

$$R(k,a) = 1 + (R_0 - 1)a^s e^{-k/k_c}$$

  - For s=0: constant modification to G, as it affects the growth
  - For s>0: At early times, GR recovered, late time modification to gravity
  - Modified for $k<k_c$, recovers GR $k>>k_c$

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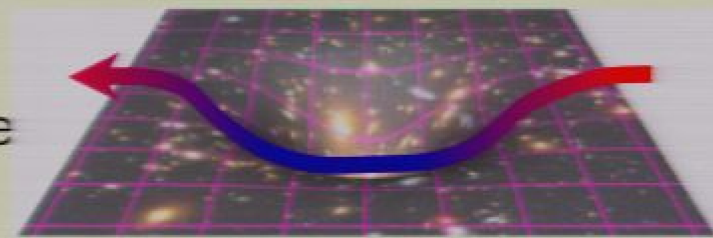
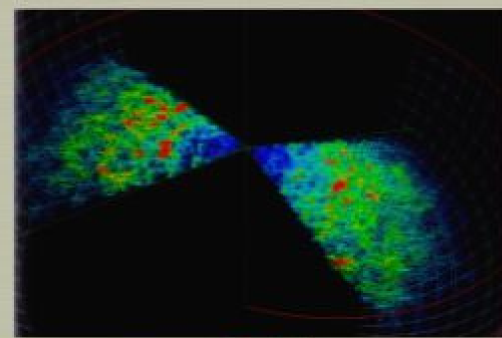
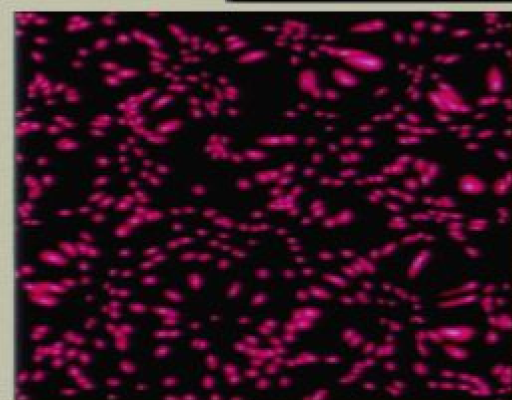
What about extra galactic constraints?

- Three primary sources at present:
  - Amplitude of the Integrated Sachs Wolfe (ISW) effect in the Cosmic Microwave Background (CMB)





  - Evolution in the number of galaxies
  - Amplitude of the weak lensing shear



- Can include both auto and cross-correlations between these sources

Extra galactic constraints with publicly available data

- Three classes of observations of increasing utility in testing gravity

I: Background expansion

CMB angular diameter distance (WMAP 5 '08)

Supernovae luminosity distance (Union SCP data + Hicken et al CfA '08)

BAO angular scale (SDSS DR7 release + 2dF Percival et. al. '09)

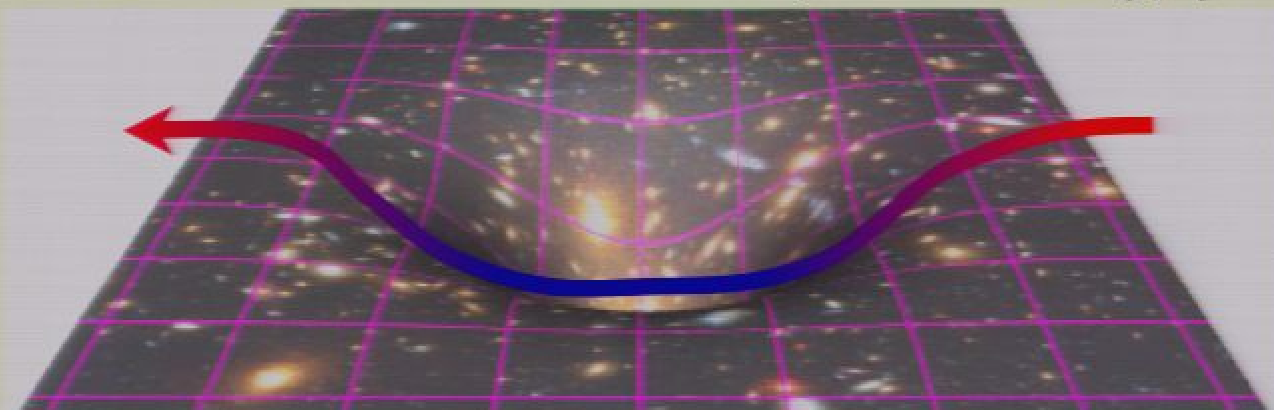
Extra galactic constraints with publicly available data

- Three classes of observations of increasing utility in testing gravity

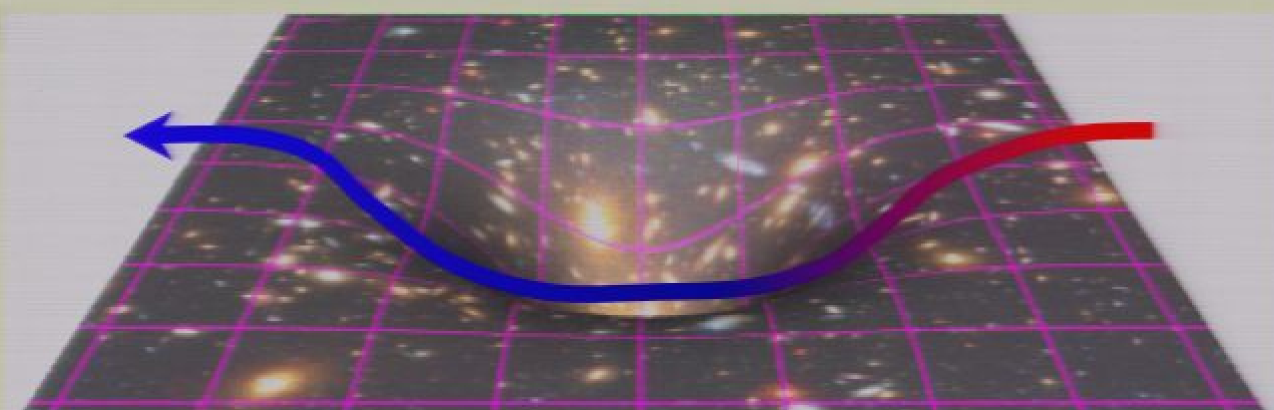
I: Background expansion	II: Growth, up to some (unknown) bias	III: Growth, independent of bias
CMB angular diameter distance (WMAP 5 '08)	Galaxy autocorrelations (SDSS DR7 Reid et al. '09)	CMB ISW autocorr (WMAP5 '08)
Supernovae luminosity distance (Union SCP data + Hicken et al CfA '08)	Galaxy – ISW x-corrln (Ho et. al. '08: SDSS DR5 LRG+ 2MASS with WMAP5)	Weak lensing autocorr (COSMOS survey '07)
BAO angular scale (SDSS DR7 release + 2dF Percival et. al. '09)		

The Integrated Sachs-Wolfe (ISW) effect

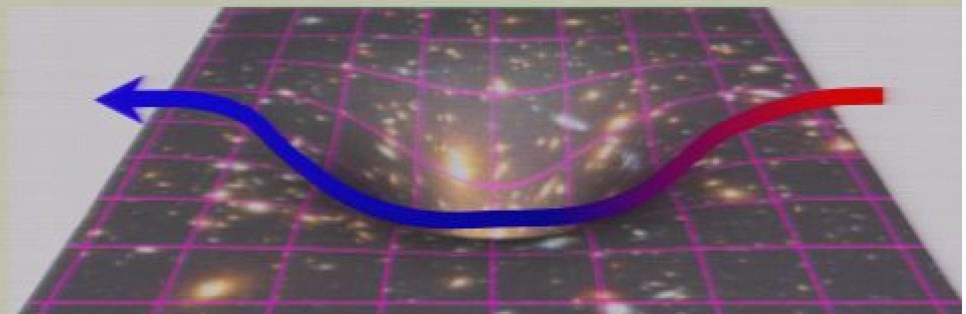
- As photons fall into (climb out of) a potential well they are blue (red) shifted
- If potential constant no net boost to photon energy (no ISW)



- If potential is decaying as photon transits, the photons energy is boosted (ISW)



How is ISW affected?

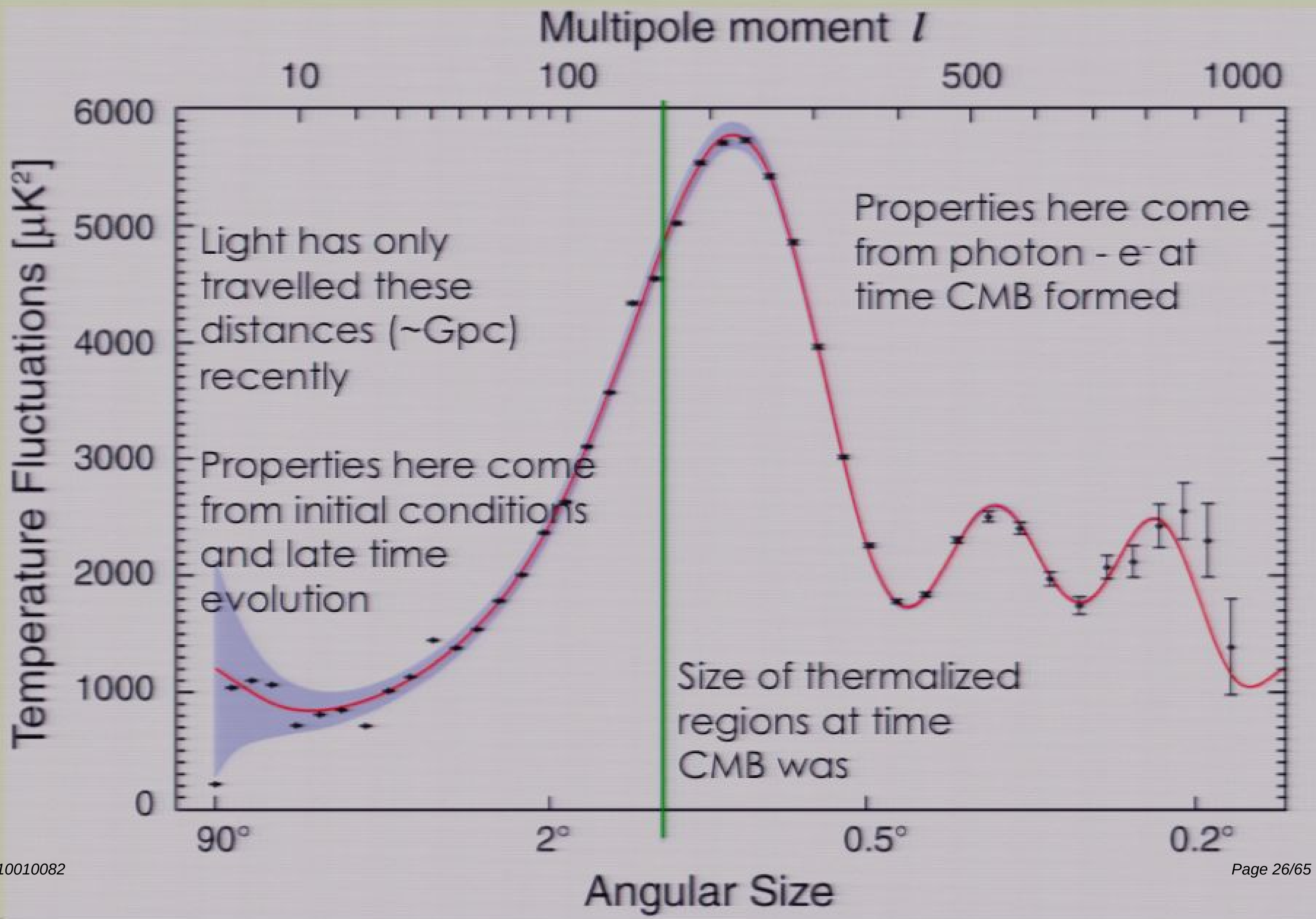


- ISW sensitive to evolution of potentials

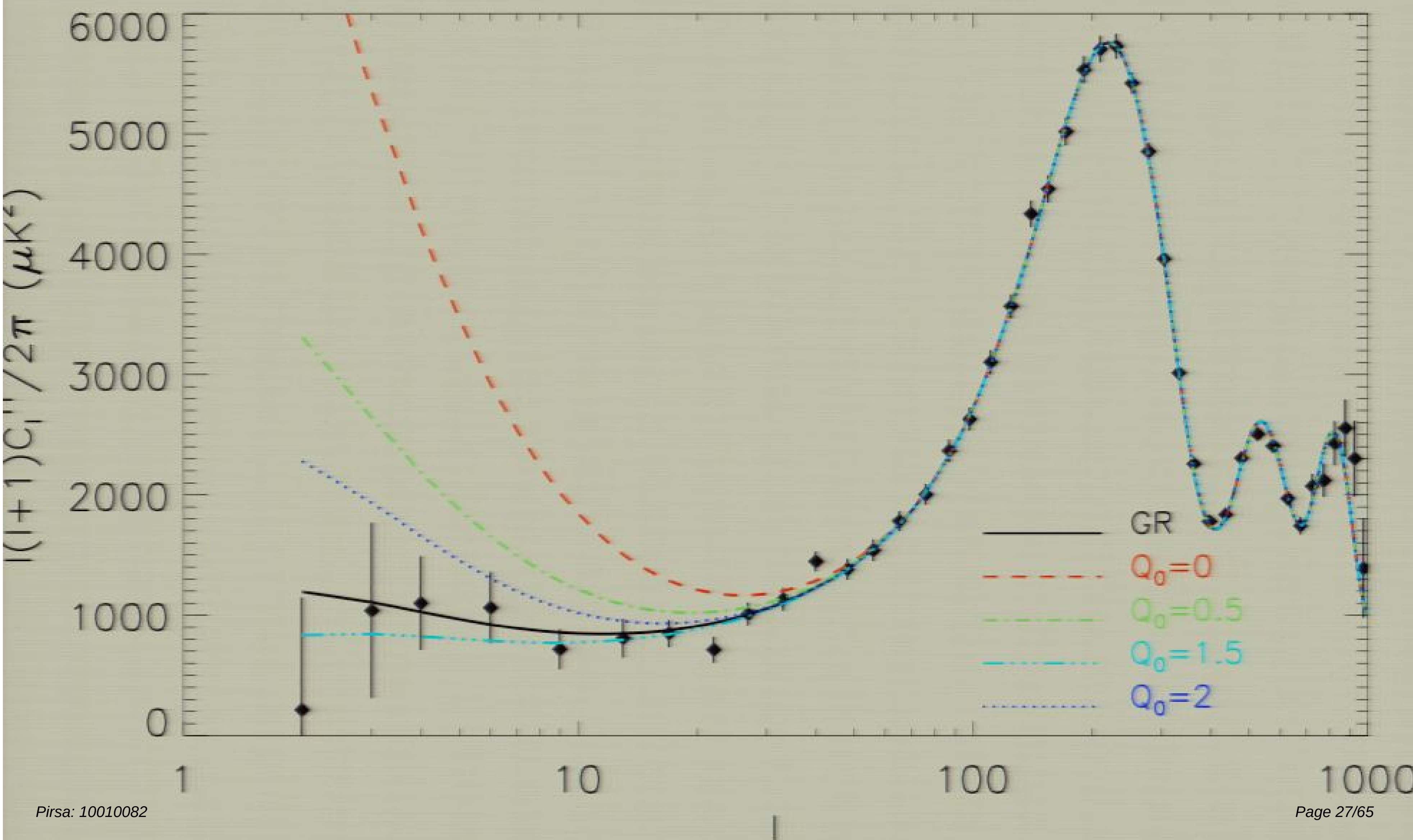
$$\frac{\Delta T}{T} \propto \dot{\phi} + \dot{\psi}$$

- Accelerated expansion suppresses growth
  - Photons warmer in overdense regions
- As Q,R increase
  - growth boosted
  - photons become cooler, $\Delta T \to 0$ then negative
  - $C_l \sim \Delta T^2$ falls then increases
- Scales ~ horizon at time effected
  - Late time evolution =>late time ISW on large scales
  - Constant Q,R => can effect early time ISW on smaller scales too

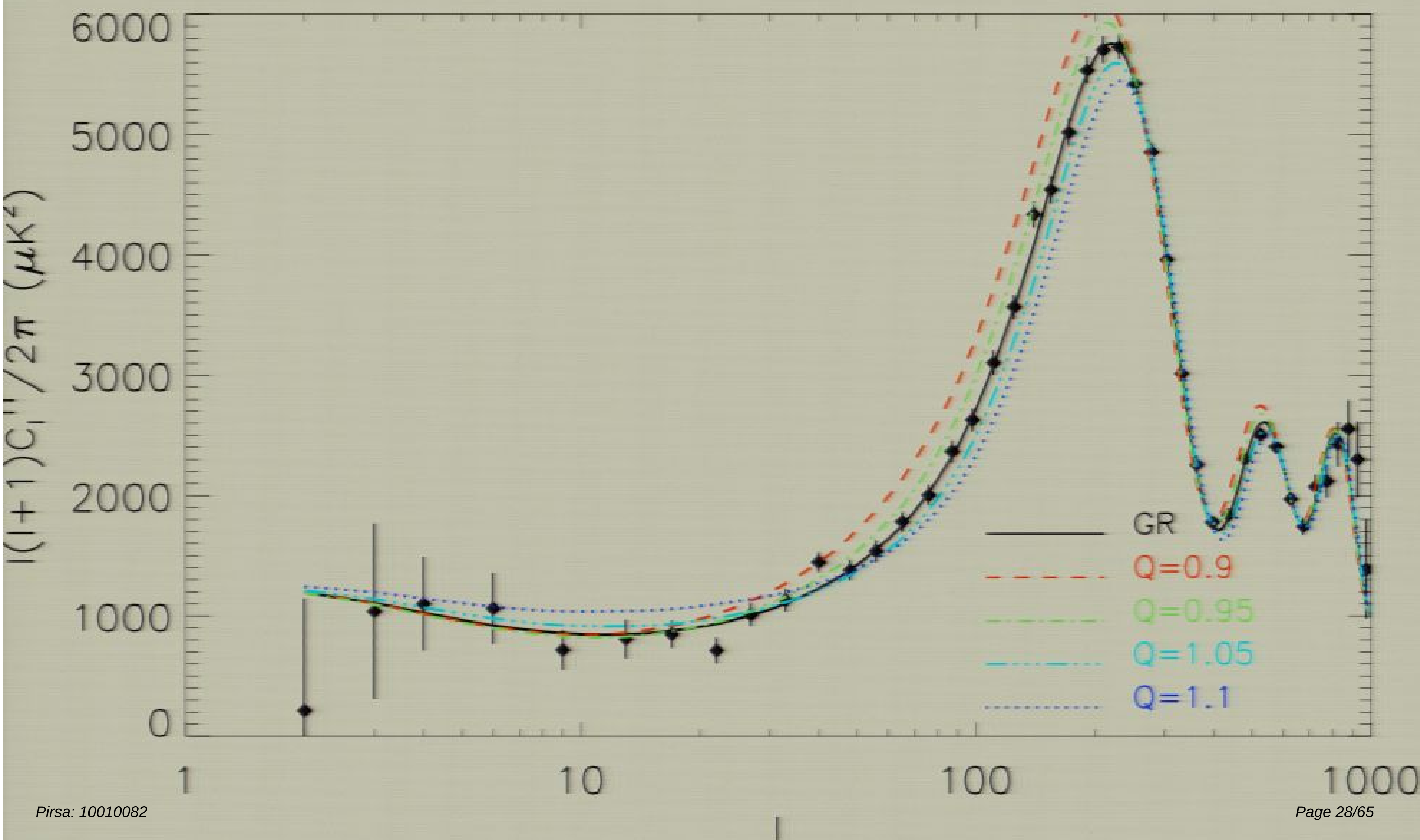
Dissecting the CMB power spectrum



Effect on CMB of late time modifications e.g. Q~ a^3



Effect on CMB of constant modifications e.g. Q~ constant



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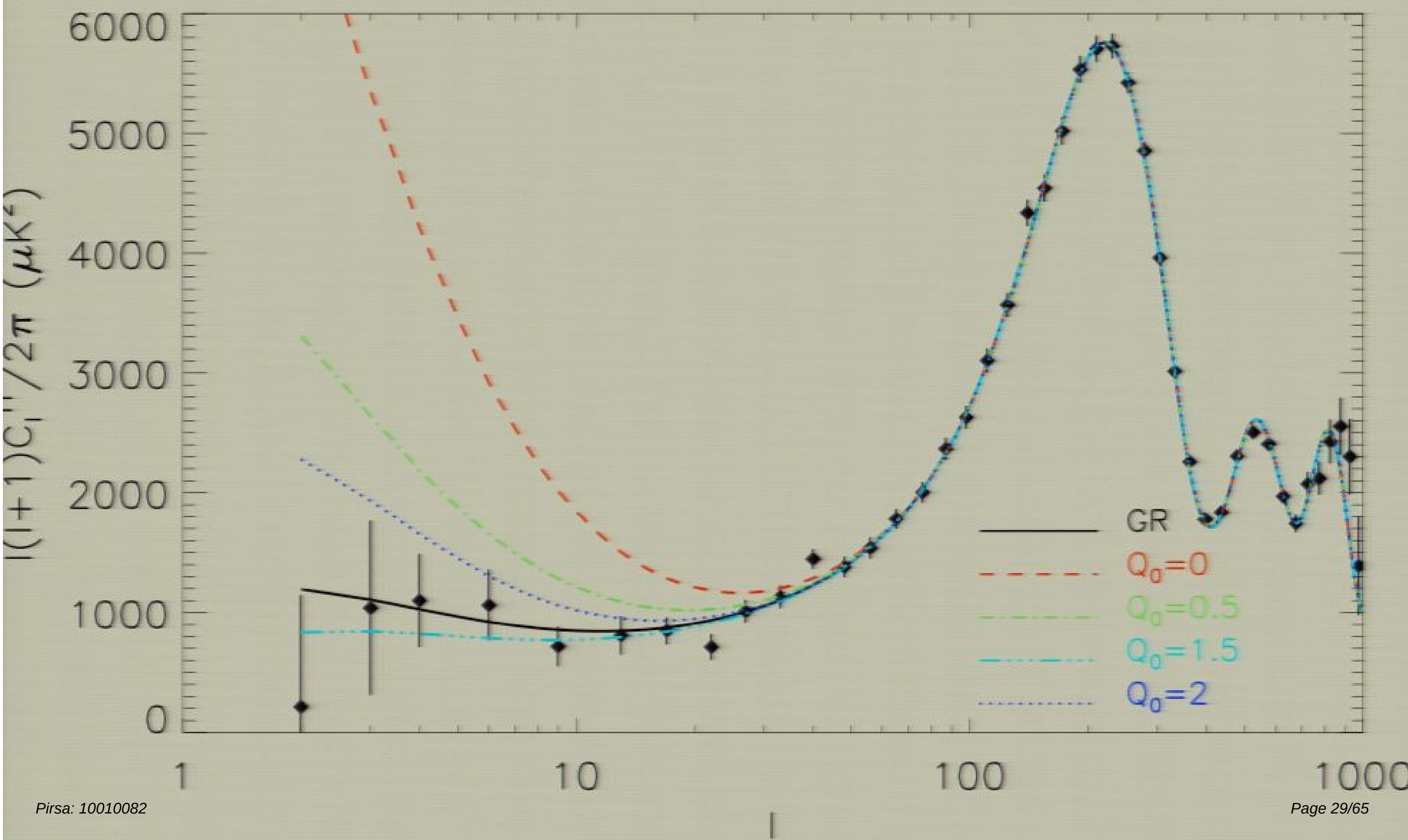


$$k^2 \Phi = -4\pi G a^2 Q \Delta.$$

$$\Psi = R\Phi - \frac{\text{Shear stresses}}{k^2}$$

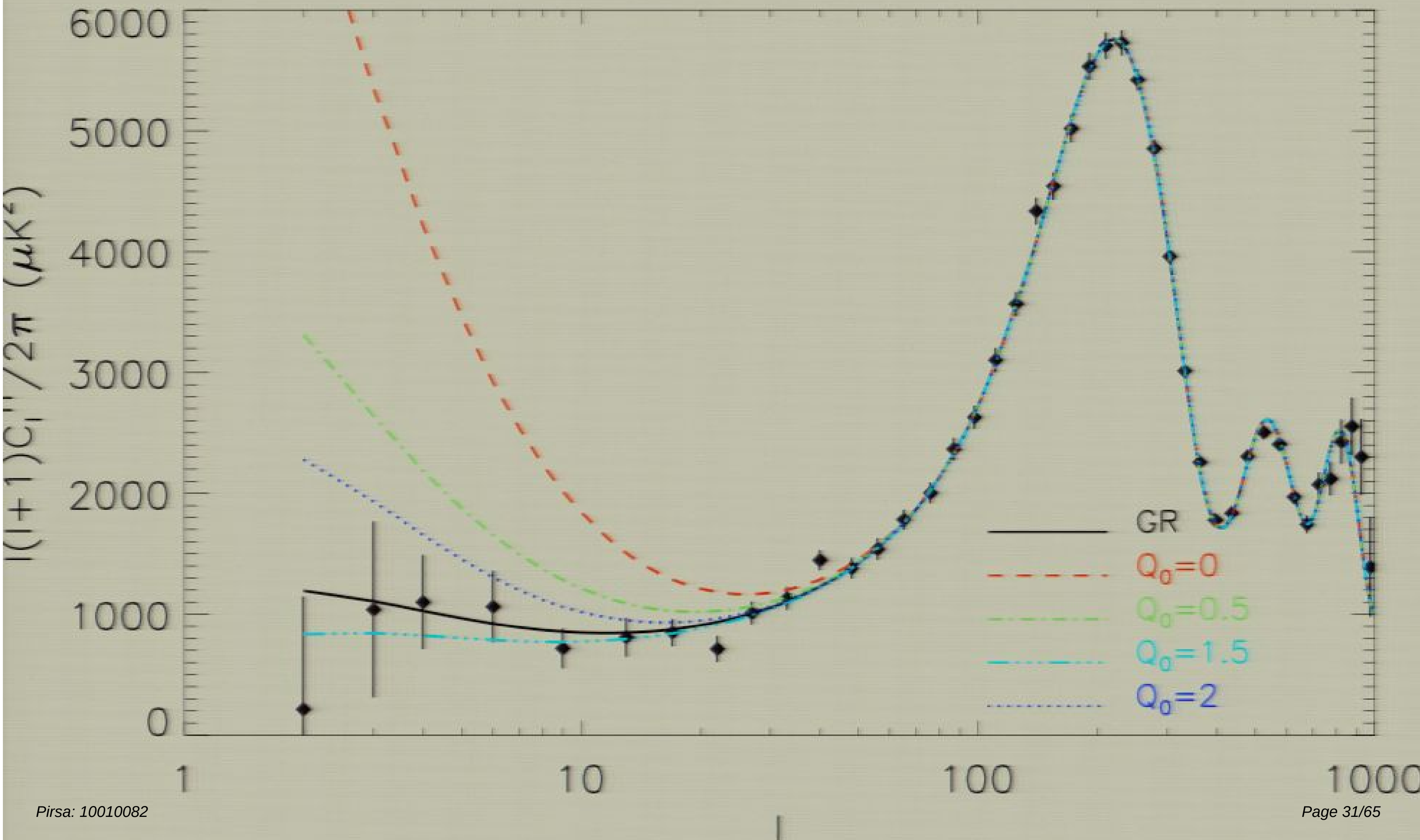
→ 0 @ late times.

$$R = 1 + (R_0 - 1)\, a^s e^{-k/k_c}$$

$$Q = 1 + (Q_0 - 1)\, a^s e^{-k/k_c}$$

$$R_0 = Q_0 = 1 \Rightarrow GR$$

Effect on CMB of late time modifications e.g. $Q \sim a^3$



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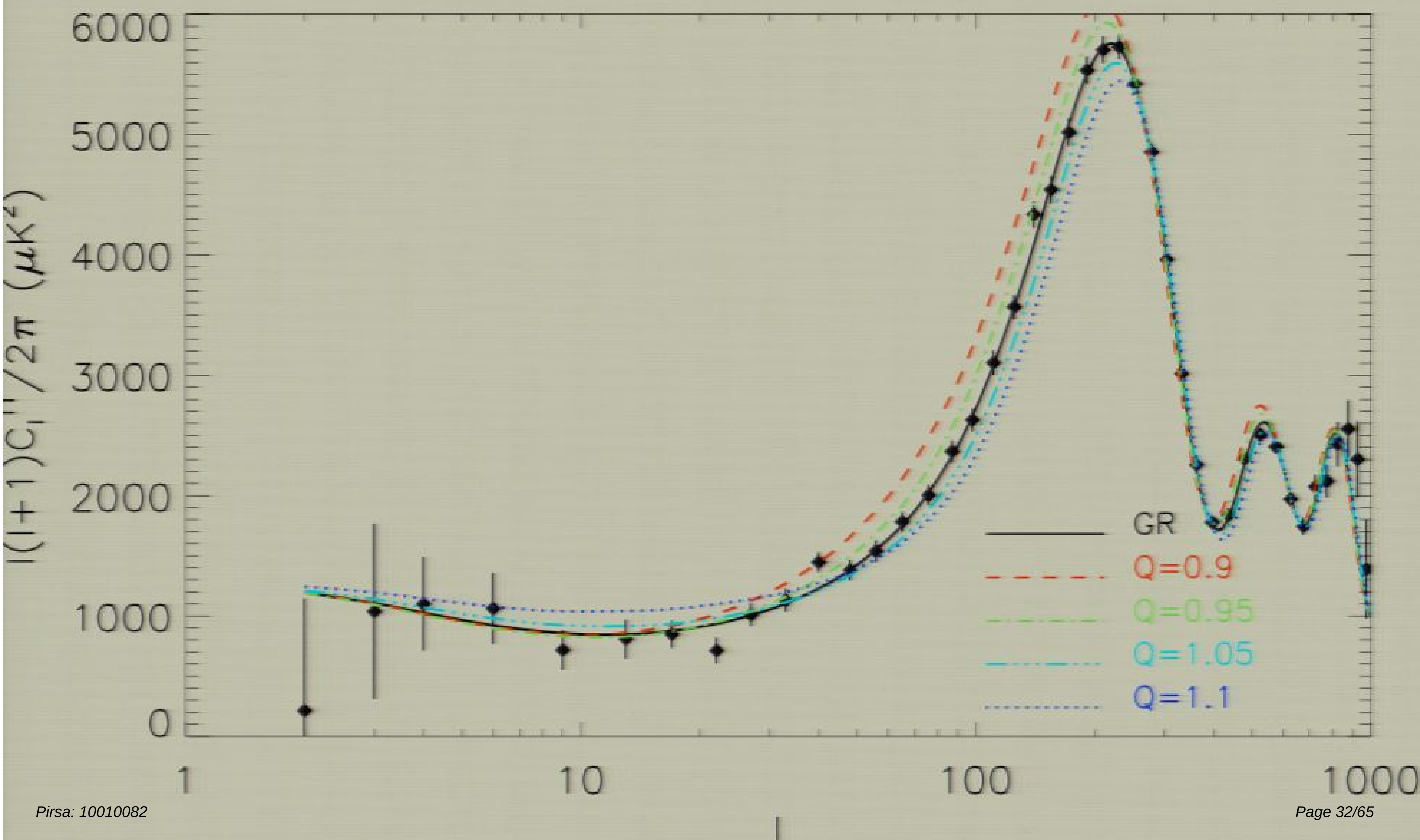

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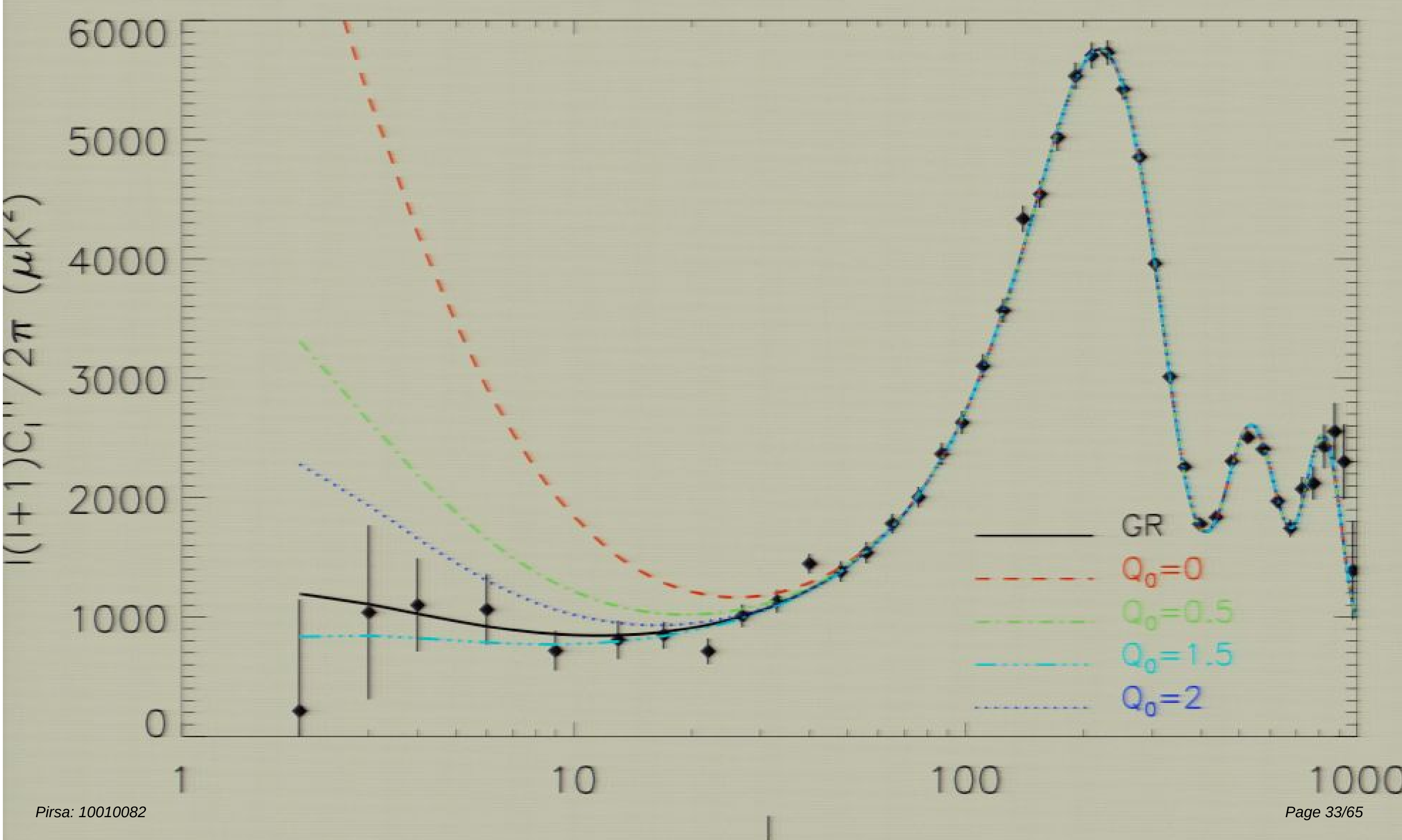

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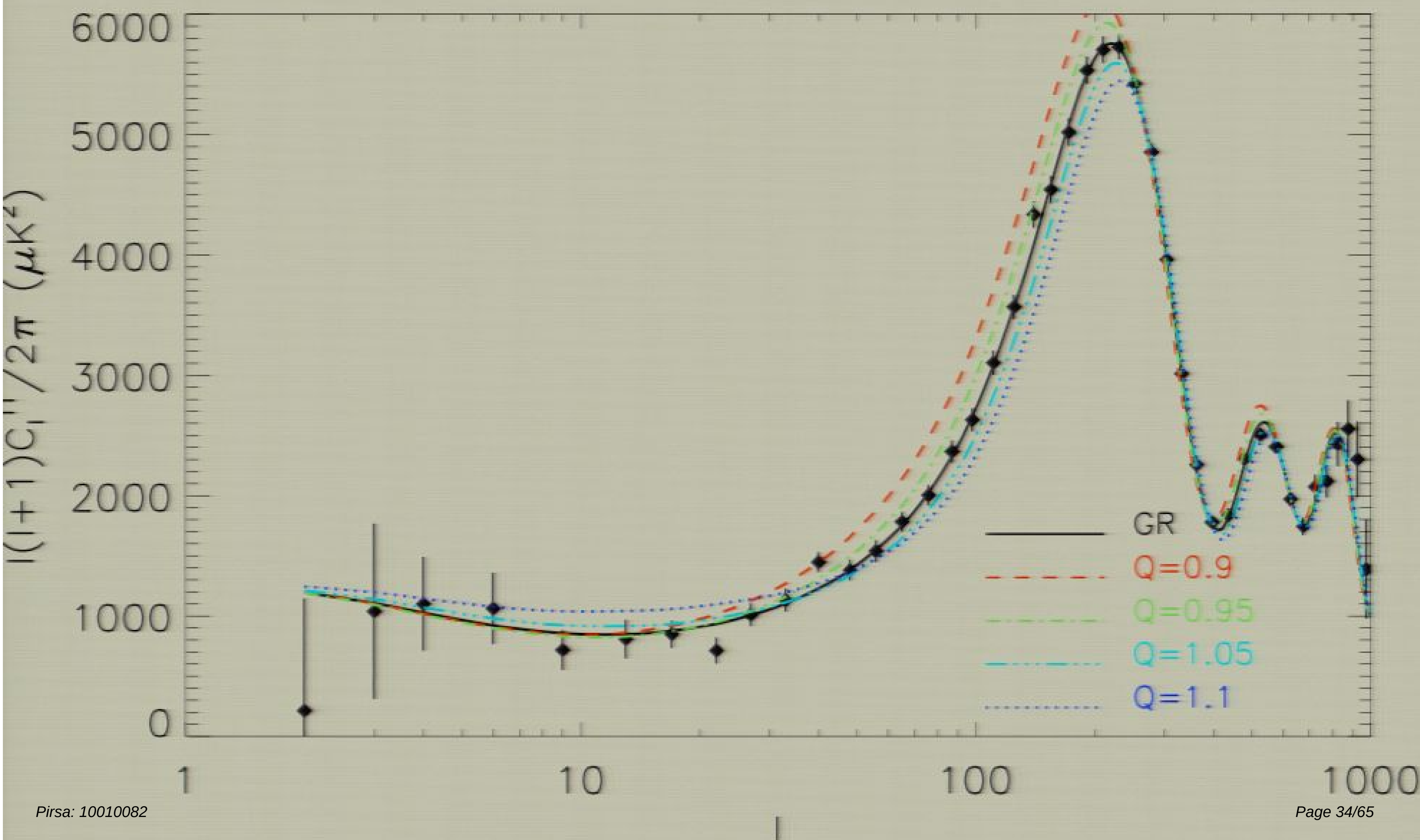
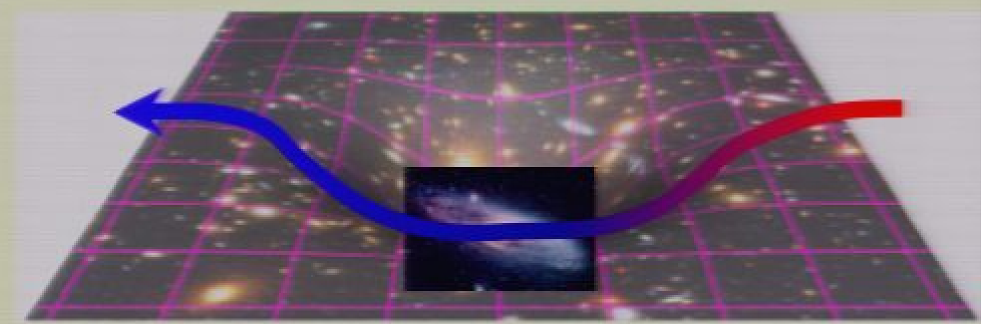


How are ISW - galaxy cross-correlations affected?



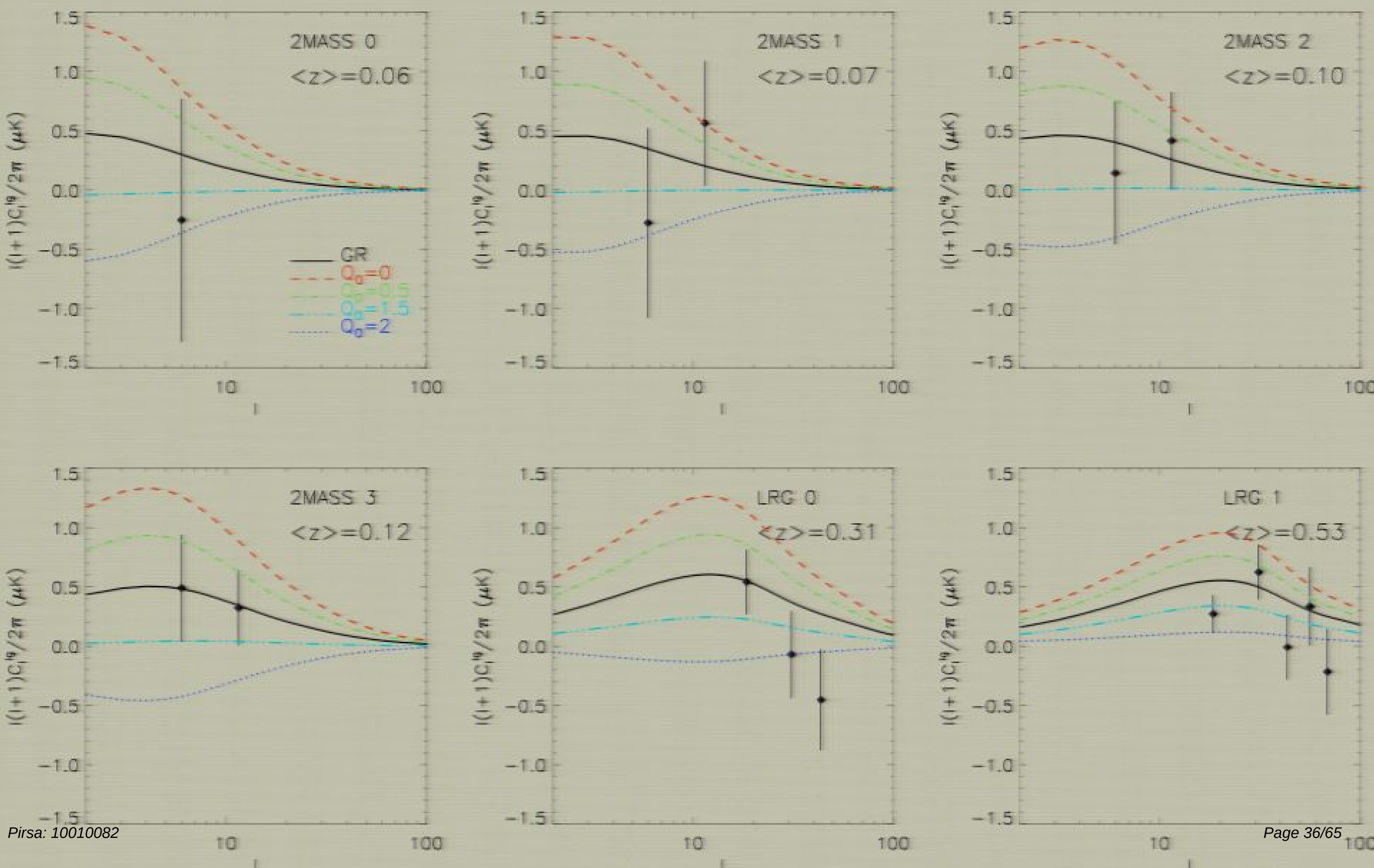
- Galaxy formation dependent on ϕ
- Monotonic & degenerate with Q,R

Potential decaying (GR, or Q,R <1)
- Decay => boost ISW
- ISW-galaxy correlation

Potential growing (Q,R>1)
- Growth => suppresses ISW
- galaxy anti-correlation

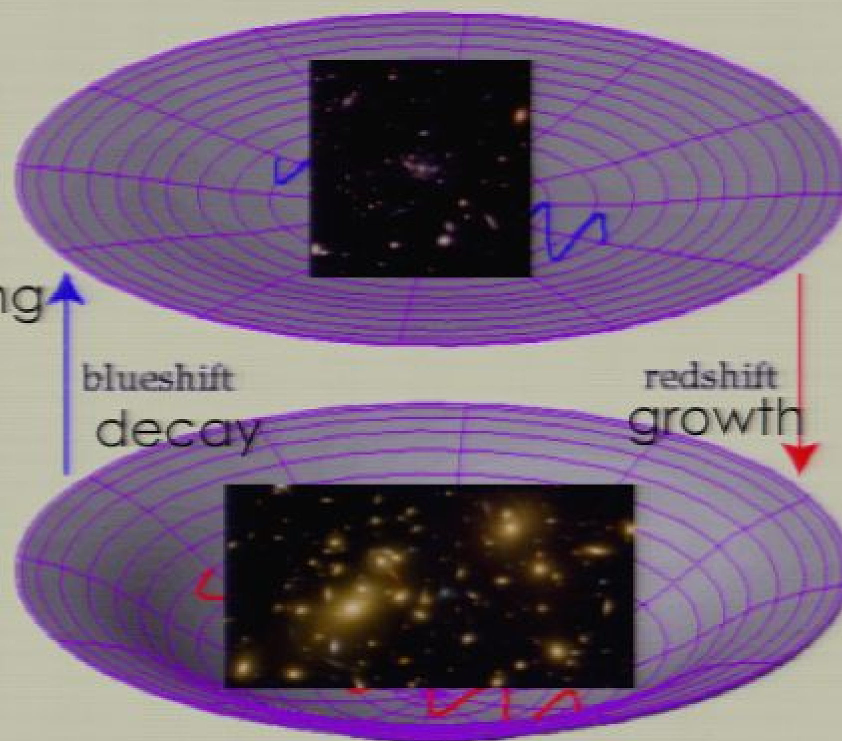
- Mass-to-light bias has is a factor (hindrance)
  - z-dependence calibrated of luminosity
  - z-independent factor analytically marginalized over
  - decreases sensitivity of growth constraints

Effect on ISW-galaxy cross-correlations of Q, R~ a^3



How is weak lensing affected?

- Lensing dependent on $\phi+\psi$
- Consider in current data
- Auto-correlation monotonic with Q,R
  - Q,R >0 boosts growth in $\phi+\psi$ and lensing
- No mass-to-light bias factors to consider
- Again degeneracy between Q,R



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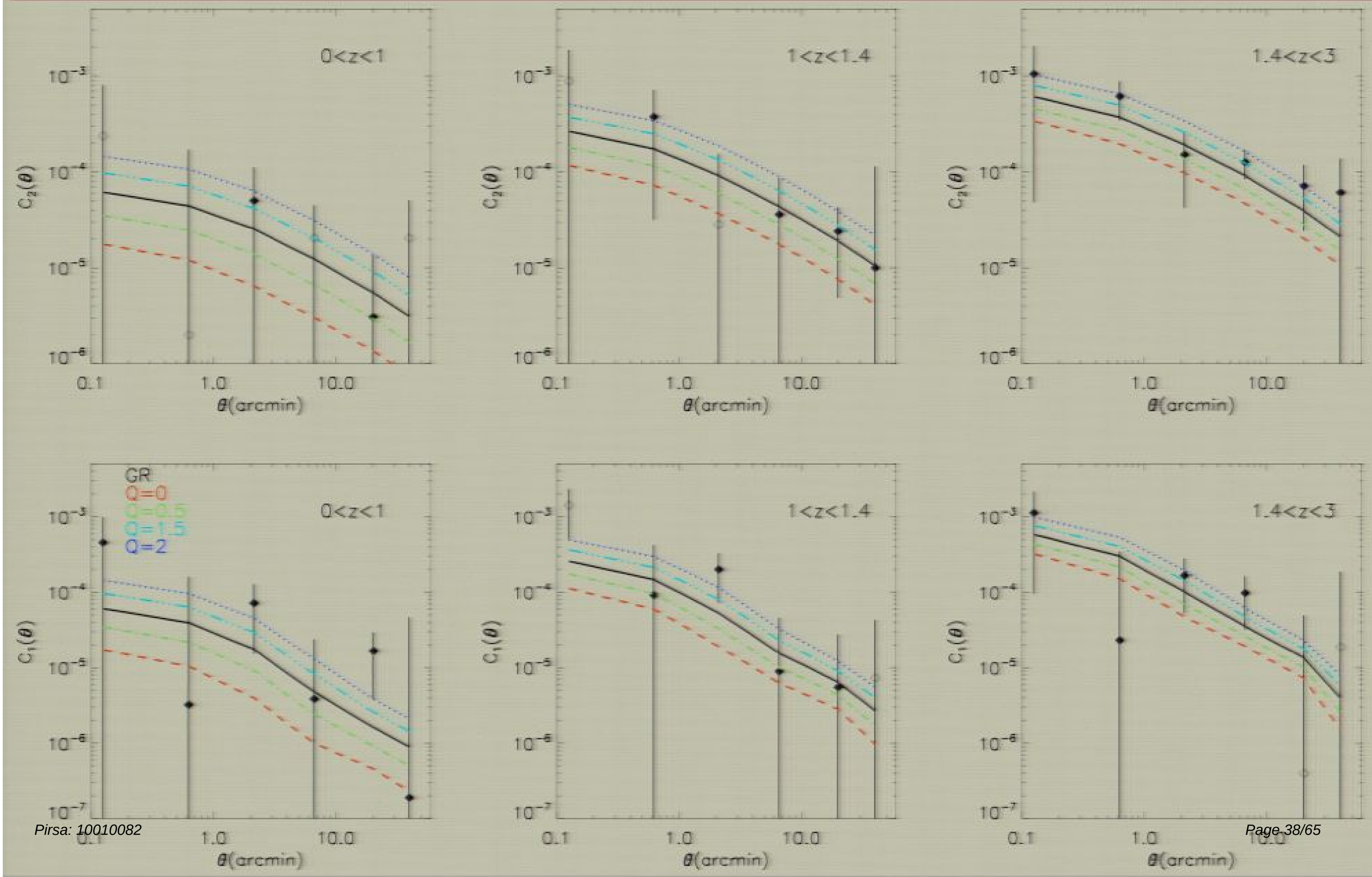

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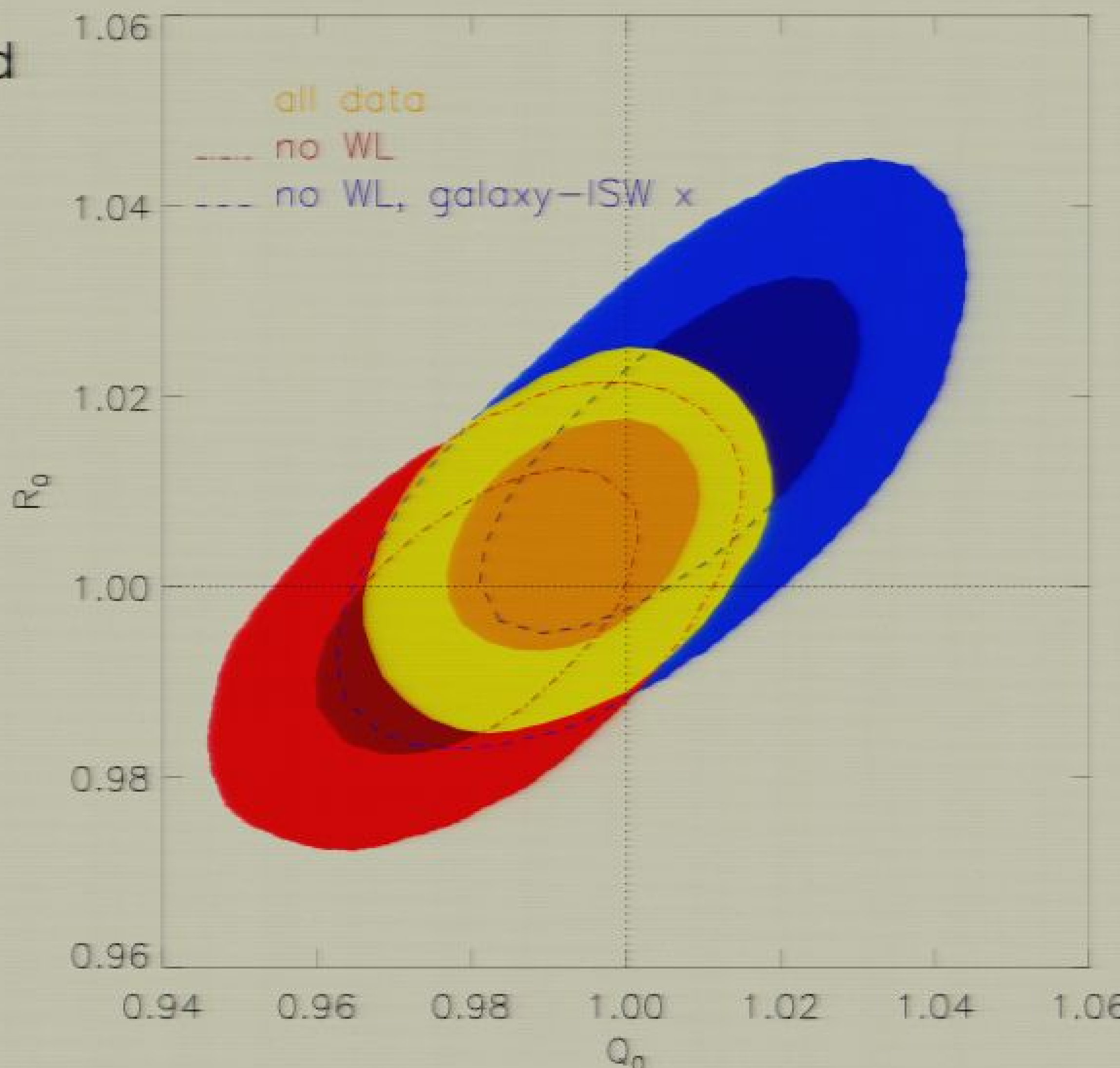
Scale and time-independent modifications

- Q and R tightly constrained to ~ 2%
- Driven by early ISW constraints



Bean & Tangmatitham in prep

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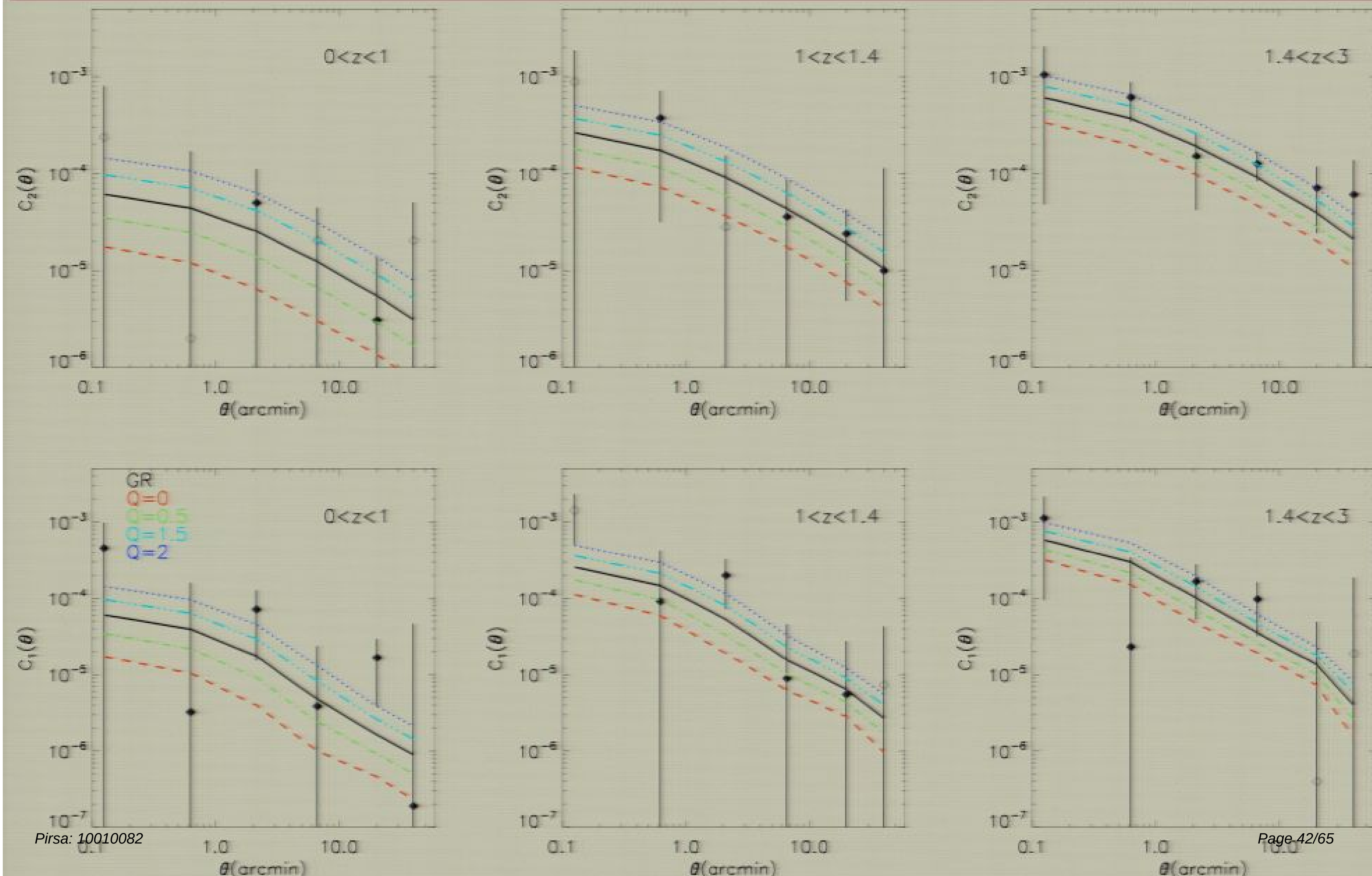

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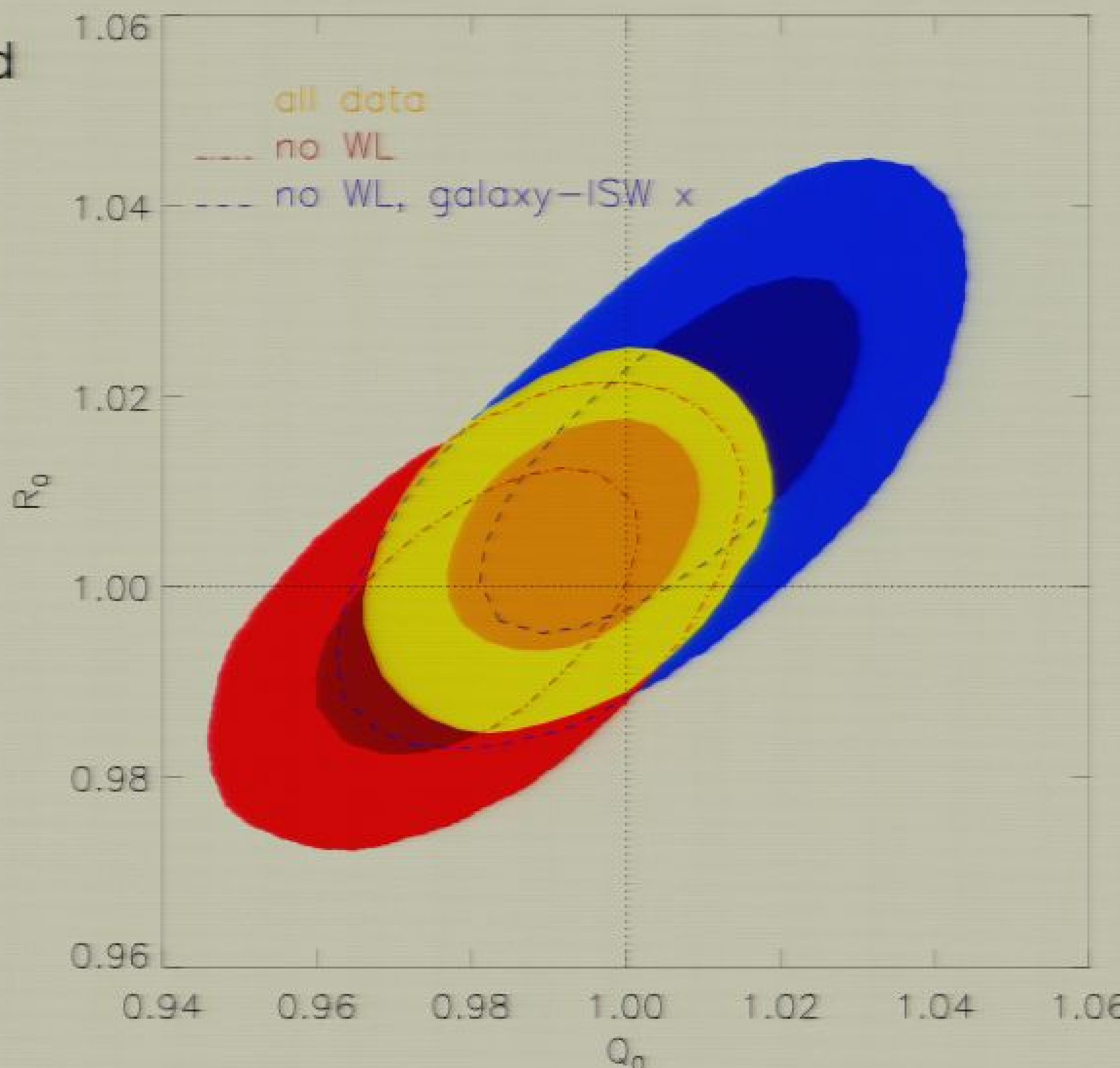

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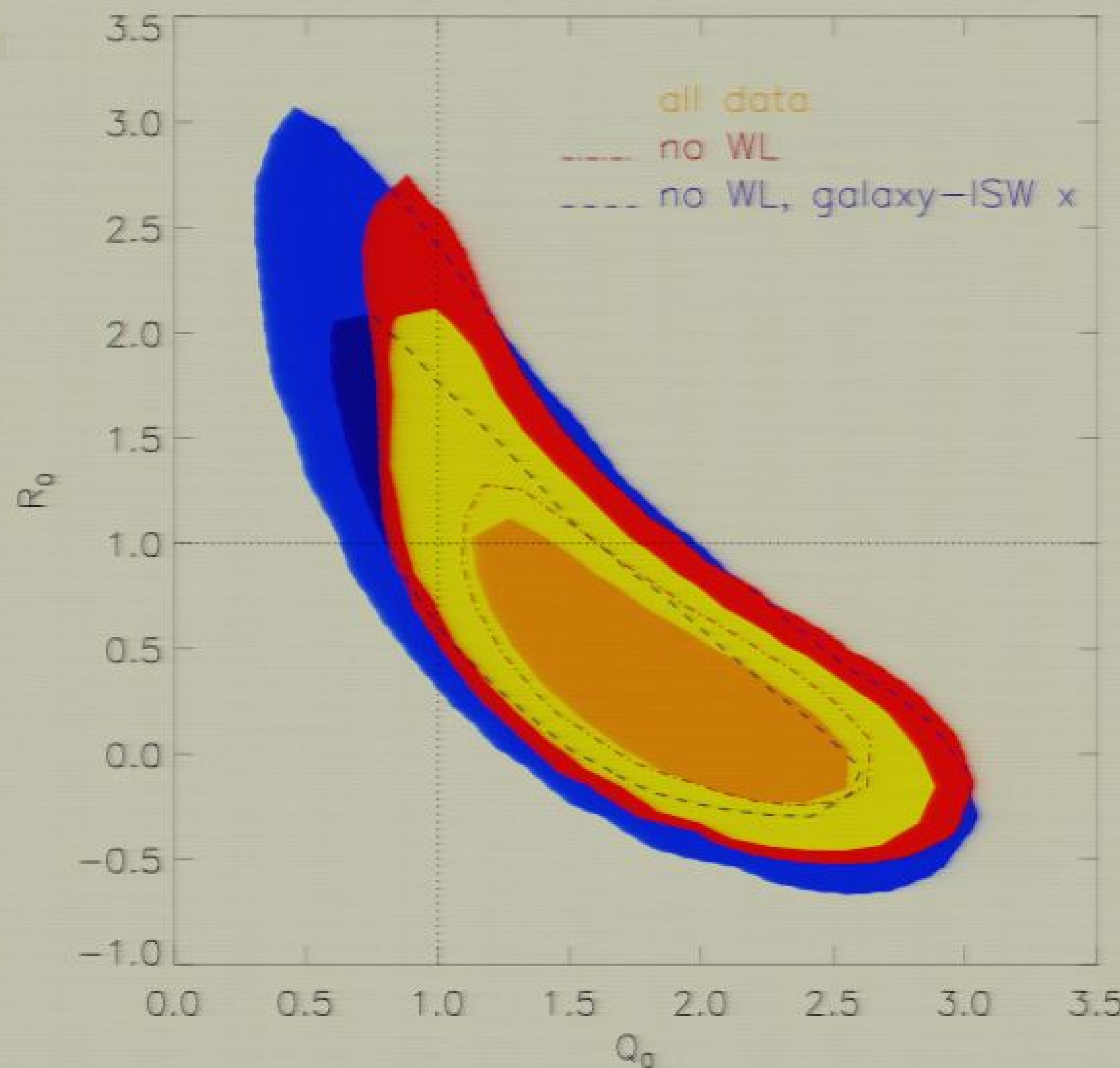
Time-dependent modifications

- Late time evolution allowed far more lee-way
- ISW and ISW-galaxy correlations



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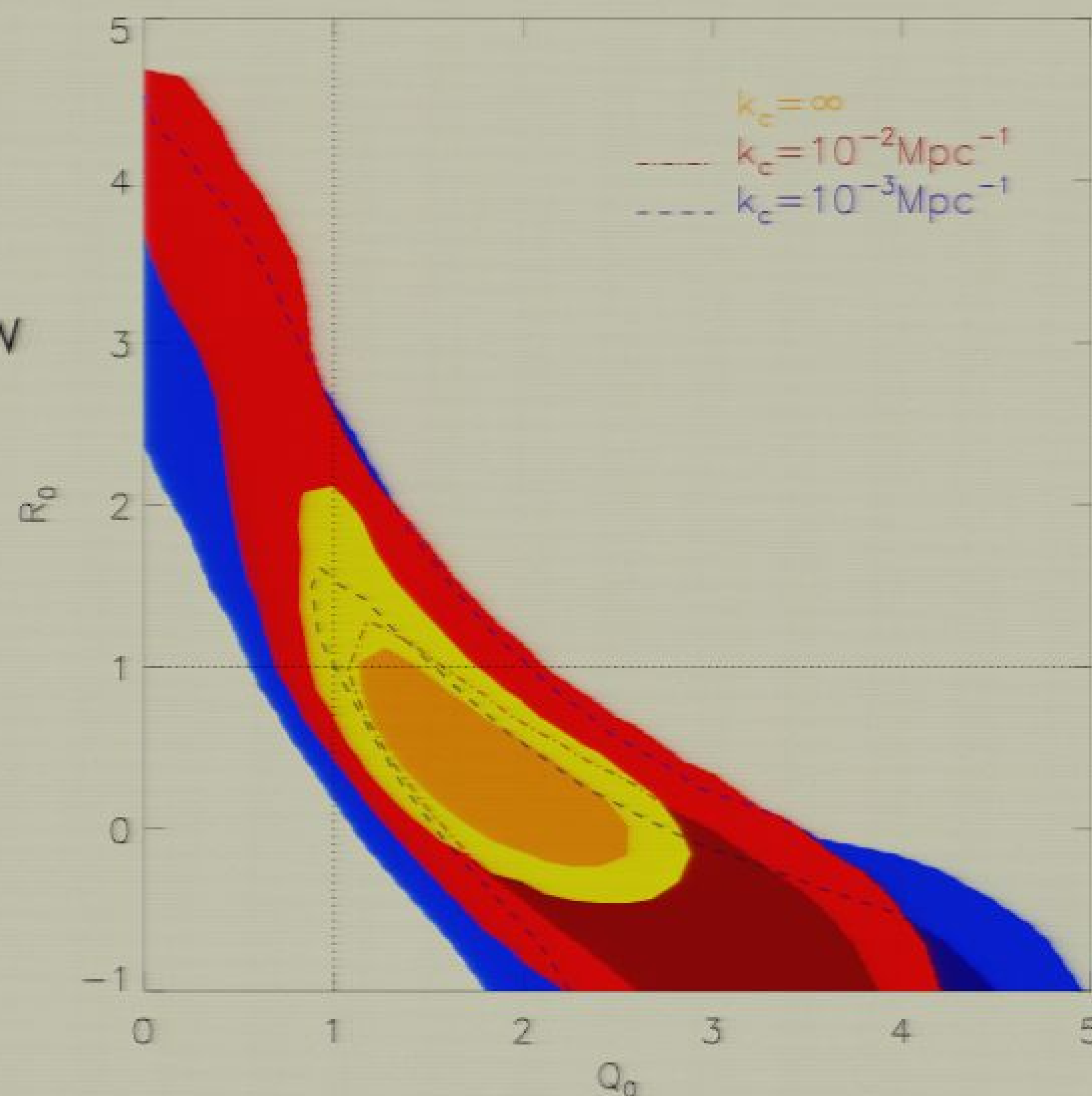
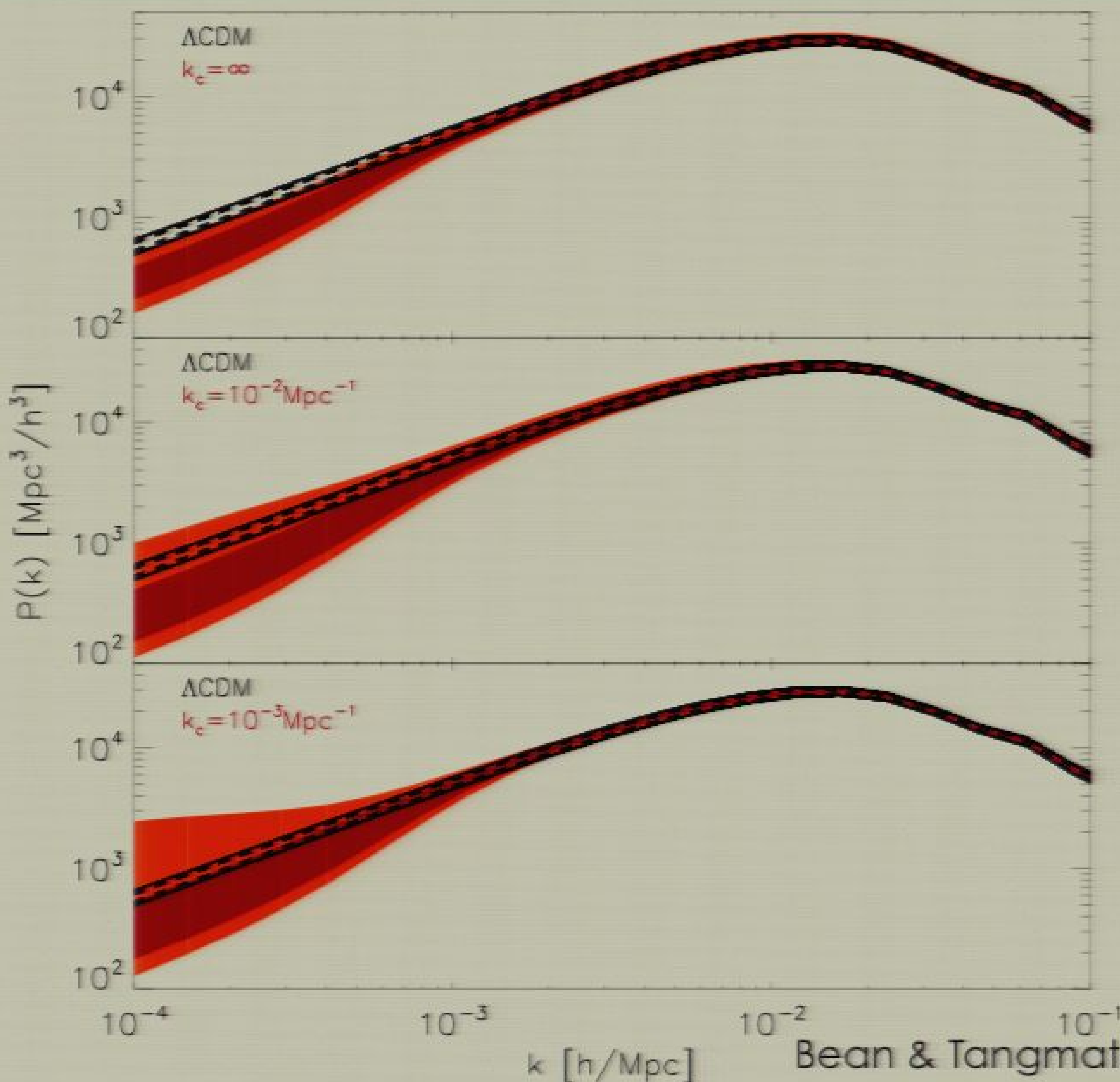
Scale-dependent modifications

- Decouples the modified evolution from ISW-galaxy and lensing data
- Degeneracy in late time ISW translates into broad constraints on Q,R



Constraints on the matter power spectrum



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Mimicking modified gravity

- What if an additional dark component has fluctuations in its density or modifies how dark matter clusters?

  - Could mimic a modified Poisson equation

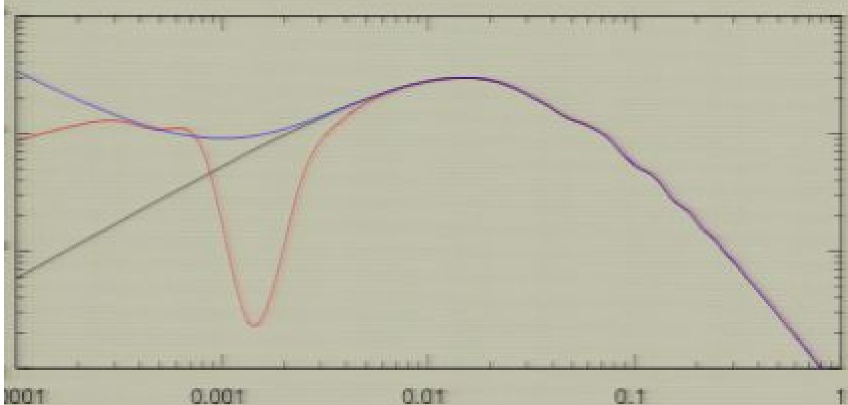
$$\begin{aligned} k^2\phi &= -4\pi G a^2 \left(\rho_m \Delta_m + \rho_x \Delta_x\right) \\ &= -4\pi G\, Q_{eff}\, a^2 \rho_m \Delta_m \end{aligned}$$

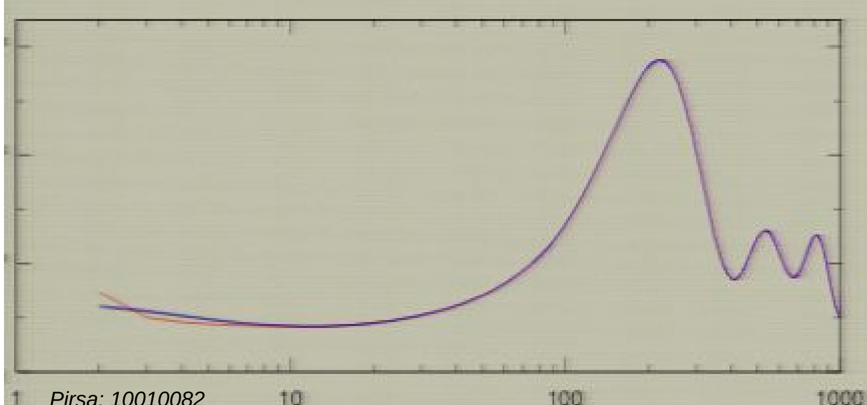
- Investigate this with another phenomenological model

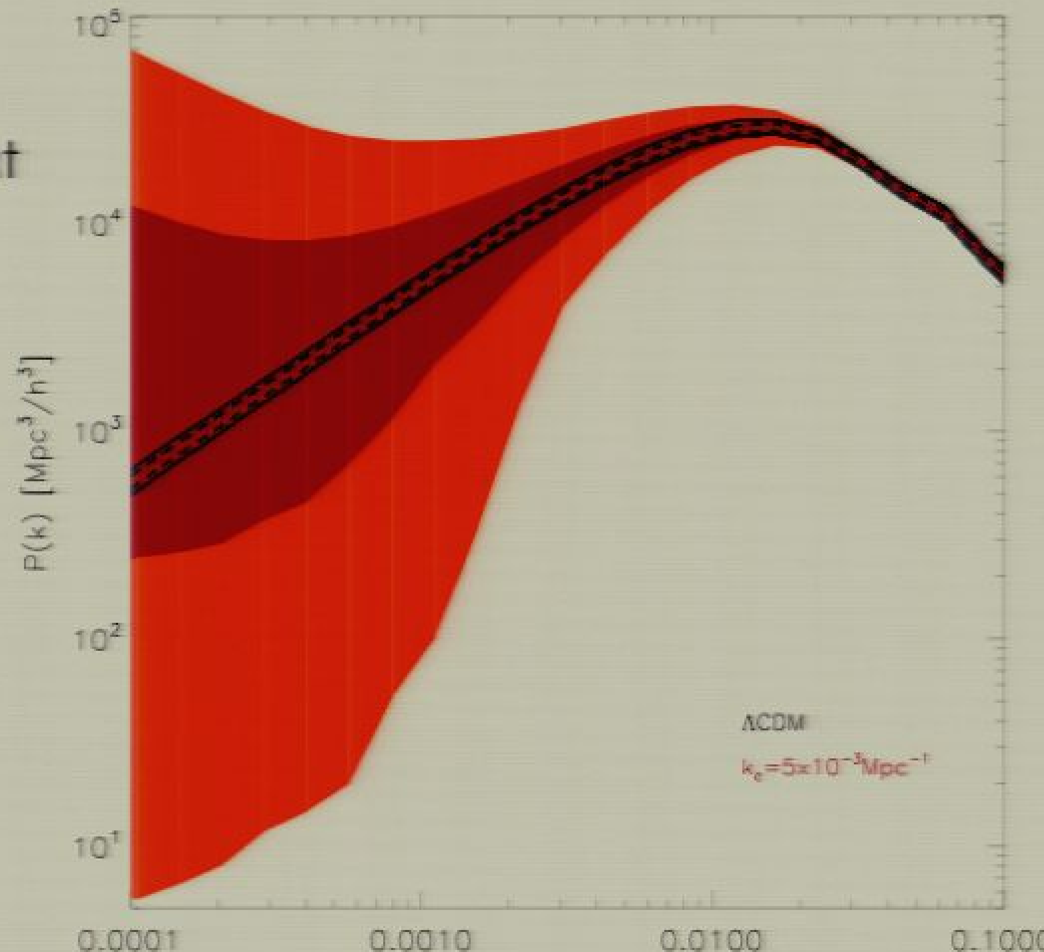
$$\Delta_x(k,a) = \Delta_{xH} \left(\frac{k}{\mathcal{H}}\right)^{n_x} a^s e^{-k/k_c}$$

Constraints on matter power spectrum with additional fluctuations

- Cancellation of CDM and extra perturbations can lead to dramatic changes in P(k) at large scales







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General parameterizations of growth

- Number of ways to describe growth and assess ability of future instruments to constrain the growth history

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Growth factor
Relative to early epoch

$$G(a) \equiv \frac{\delta_c(a)}{\delta_c(a_{ref})};$$

Reference point well before dark energy dominated era

Growth factor
Relative to today

$$G_0(a) \equiv \frac{\delta_c(a)}{\delta_c(a=1)}$$

Measurable with astrophysical observations

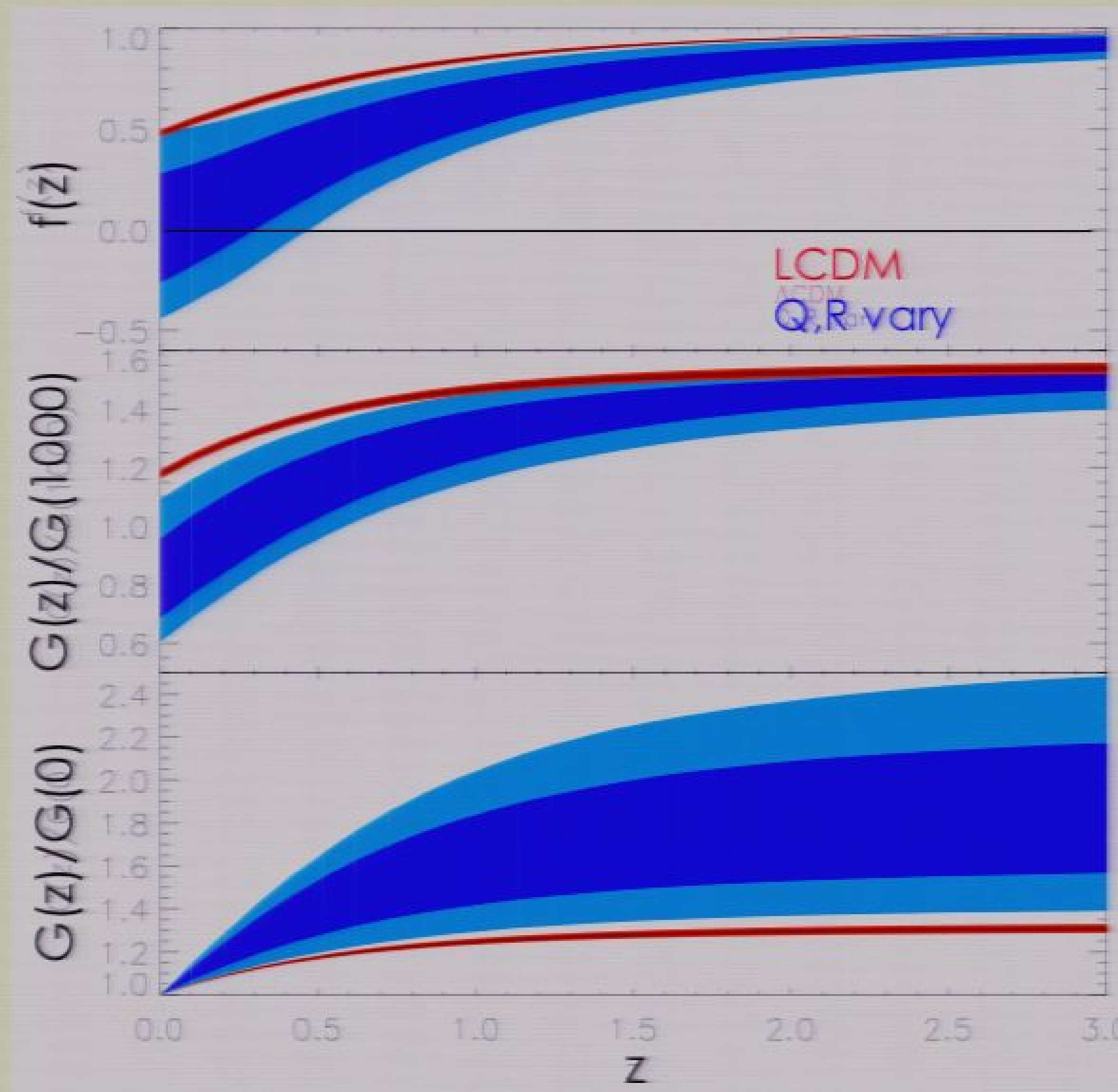
General parameterizations of growth

- Number of ways to describe growth and assess ability of future instruments to constrain the growth history

Growth factor Relative to early epoch	$G(a) \equiv \frac{\delta_c(a)}{\delta_c(a_{ref})};$	Reference point well before dark energy dominated era
Growth factor Relative to today	$G_0(a) \equiv \frac{\delta_c(a)}{\delta_c(a=1)}$	Measurable with astrophysical observations
Growth exponent	$f(a) \equiv \frac{d \ln \delta_c}{d \ln a};$	Extracts out simple power law behavior
Growth index	$\gamma(a) \equiv \frac{\ln f(a)}{\ln \Omega_m(a)}$	~0.55 for GR considered as sensitive discriminator to test for modifications to gravity

Constraints on growth parameters

- Growth rate, f(z), can be negative => commonly used γ parameter undefined
- γ could be poor choice of parameter to describe modified growth histories in light of current constraints…



Bean & Tangmatitham in prep

General parameterizations of growth

- Number of ways to describe growth and assess ability of future instruments to constrain the growth history

Growth factor Relative to early epoch	$G(a) \equiv \frac{\delta_c(a)}{\delta_c(a_{ref})};$	Reference point well before dark energy dominated era
Growth factor Relative to today	$G_0(a) \equiv \frac{\delta_c(a)}{\delta_c(a=1)}$	Measurable with astrophysical observations
Growth exponent	$f(a) \equiv \frac{d \ln \delta_c}{d \ln a};$	Extracts out simple power law behavior
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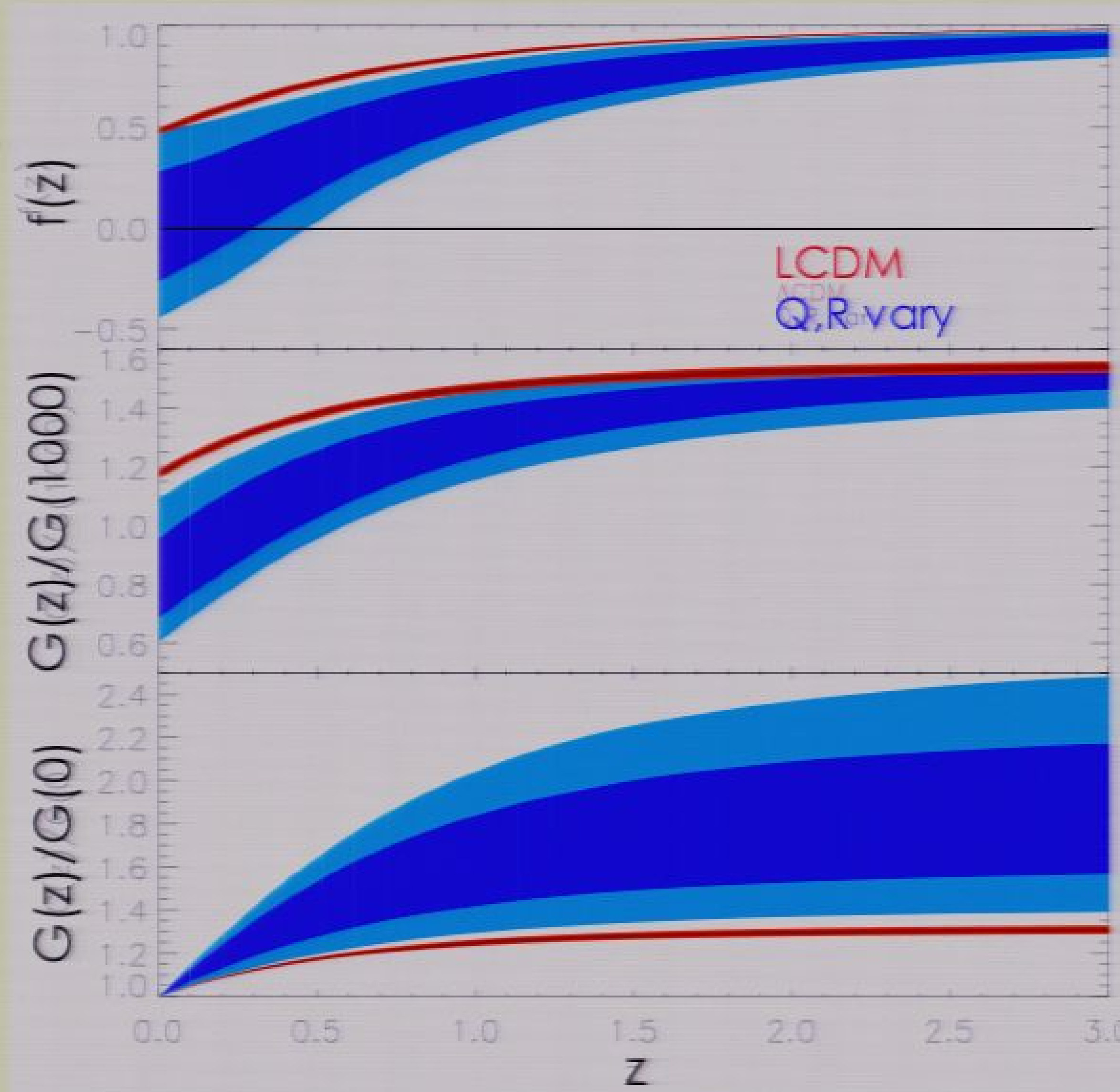
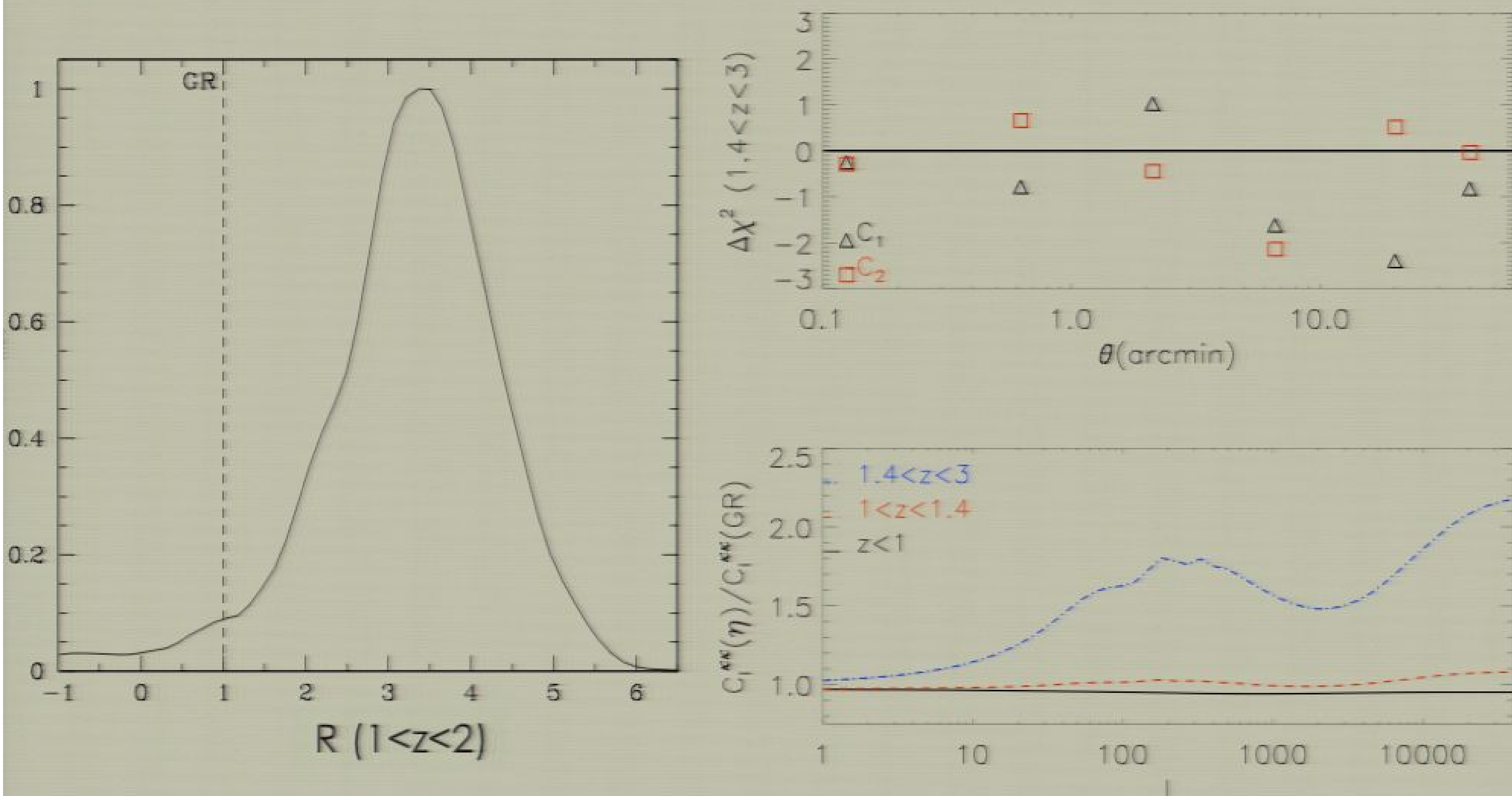


Bean & Tangmatitham in prep

A parable on the perils of systematic errors…

R and the highest z lensing COSMOS data



Bean 0909.3853

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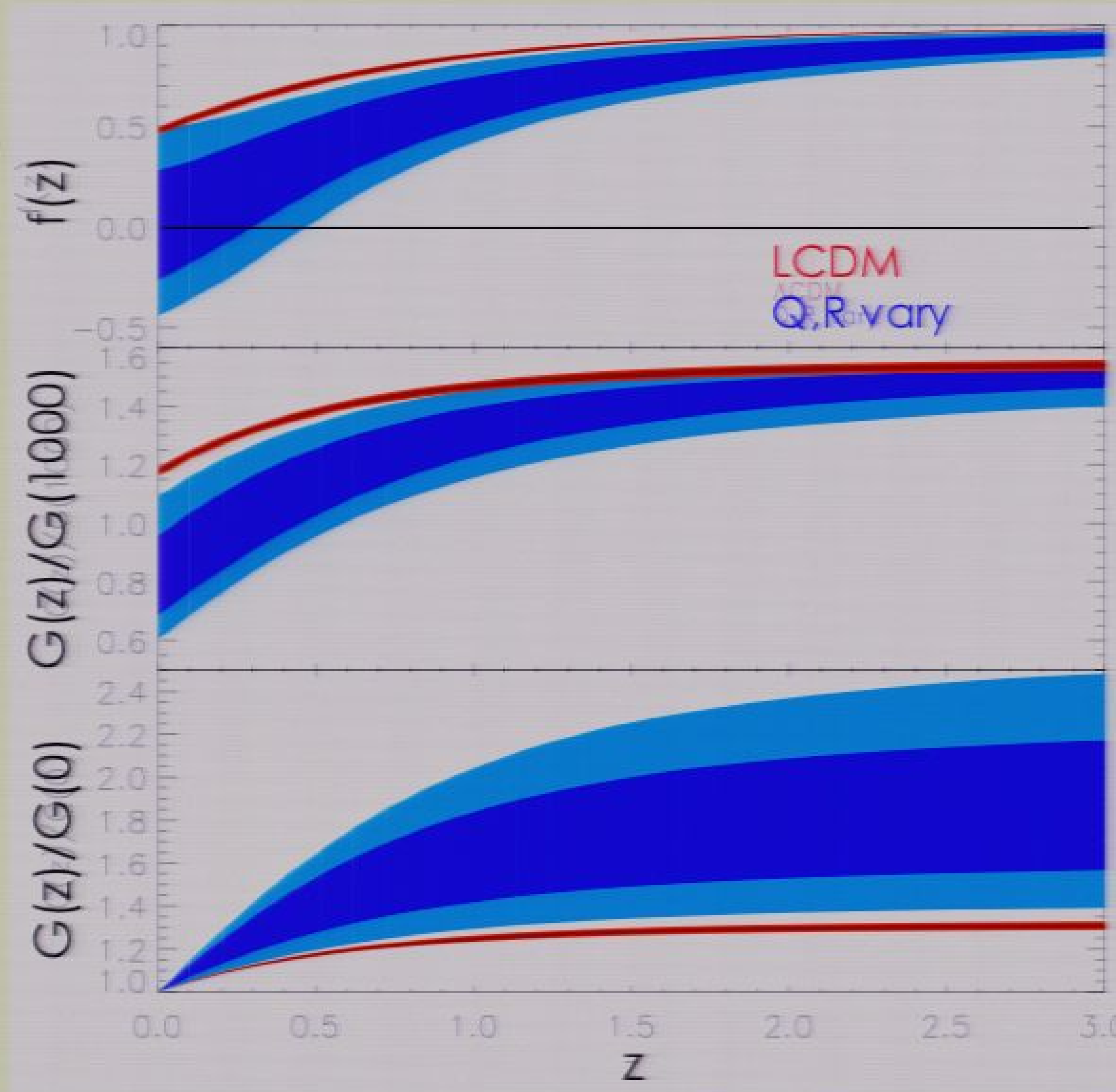

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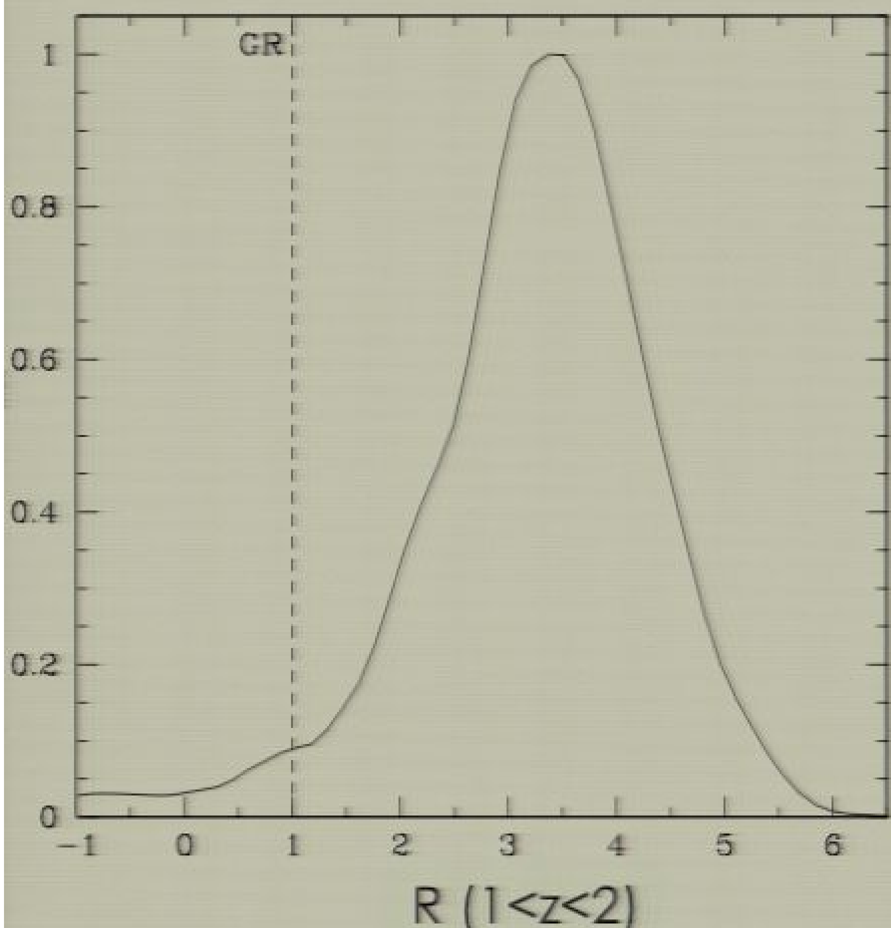
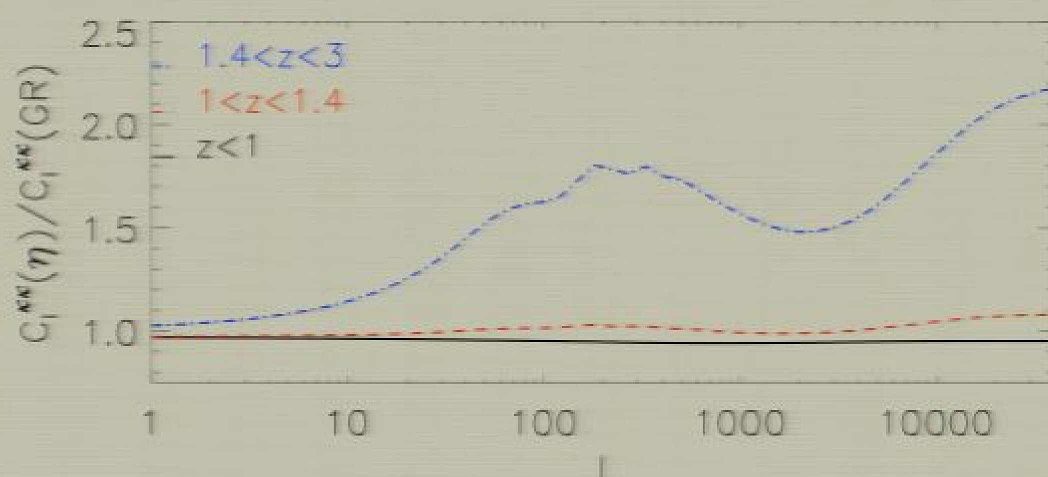
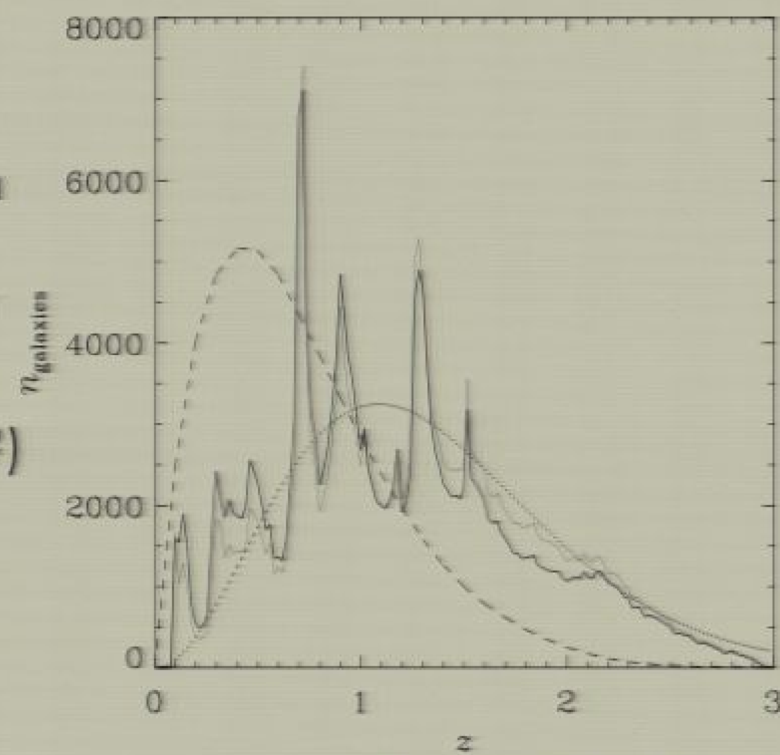




Bean 0909.3853

A parable on the perils of systematic errors…

- Errors included in the analysis, based on COSMOS team simulations
  - 6% calibration uncertainty on overall shear
  - 5% relative calibration uncertainty between bins
  - 10% catastrophic photometric redshift error



Massey et al. '07

- But it appears their errors likely (significantly?) underestimated…
  - Significant B-modes contaminating data
  - Photometric redshift errors distort window functions

- Analysis out a few weeks back, Schrabback et al. 0911.0053 does better analysis of systematics, though they've not released their data publicly pretty sure the effect is gone

Why test gravity on cosmic scales?

- Galaxy number counts - φ –> Q
- Peculiar velocities - ψ => QR

- By using cross correlations aim is to
  - Remove key systematics (photometric redshifts, bias)
  - Break the degeneracy between Q and R

- An example Zhang, Liguori, RB, Dodelson PRL 2007
  - Ratios of lensing, galaxy count and peculiar velocity correlations

$$\hat{E}_G \propto \frac{\text{lensing} - \text{galaxy correlation}}{\text{velocity} - \text{galaxy correlation}}$$

$$\hat{E}_G = \left. \frac{\nabla^2(\Psi + \Phi)}{3H_0^2 \frac{d\delta}{d\ln a}} \right|_{k=\frac{l}{\chi},\bar{z}}$$

In the future…
Distinguishing between modified gravity and Λ

- Different observations measure different quantities
  - Weak lensing distortions – $\phi+\psi$ => $Q(1+R)$
  - Galaxy number counts - ϕ => Q
  - Peculiar velocities - ψ => QR

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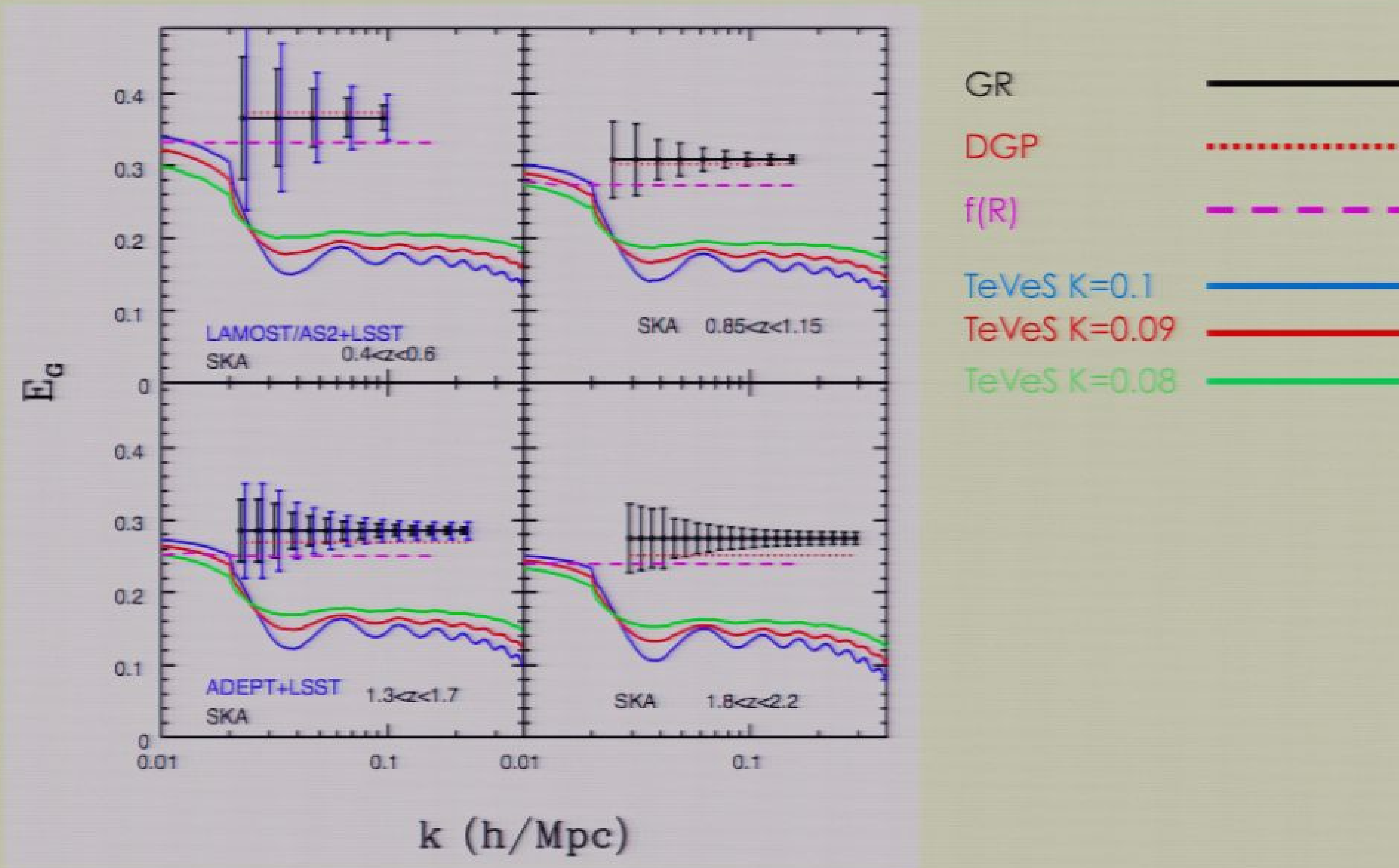
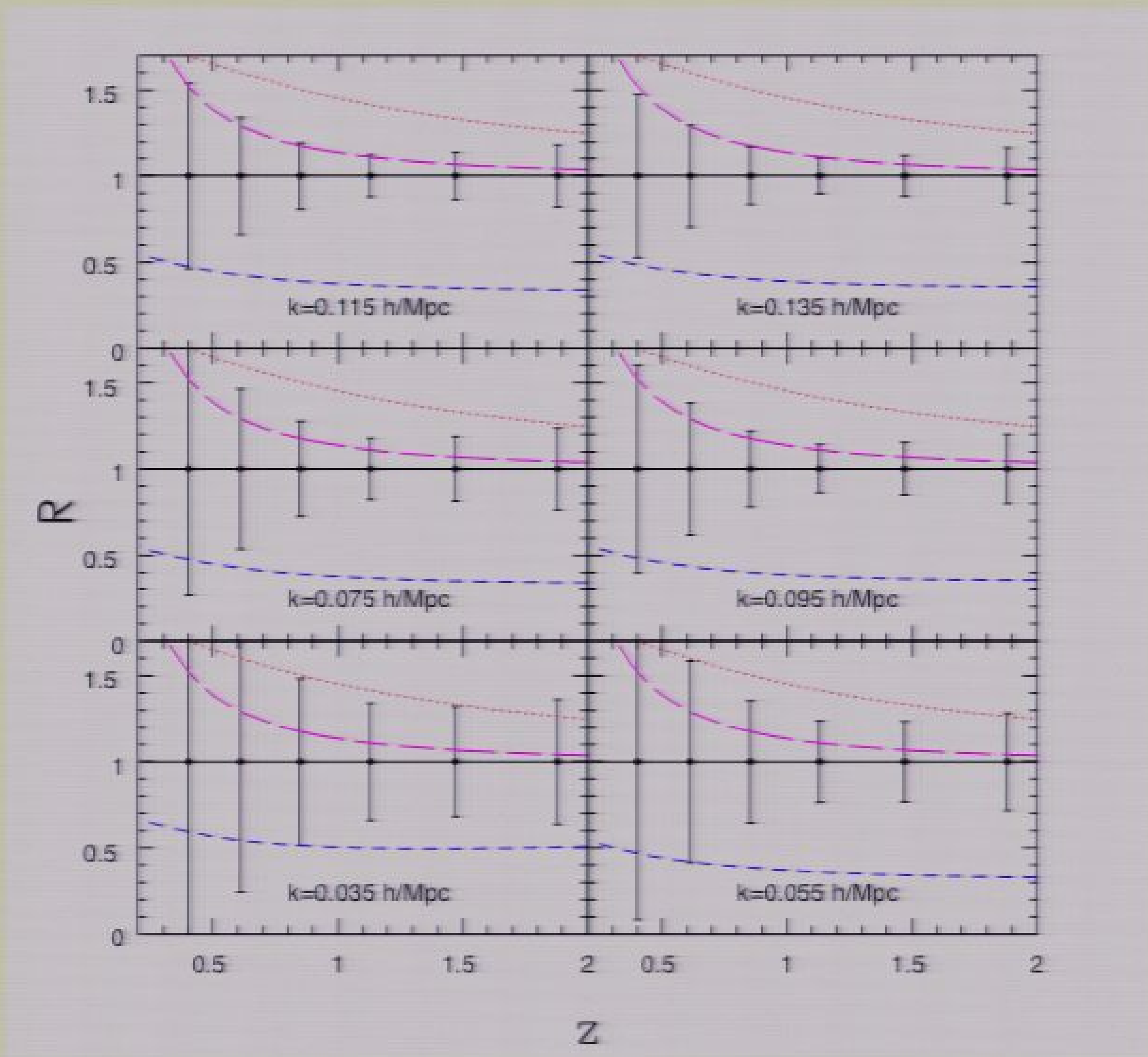
Distinguishing between modified gravity and Λ



Zhang, Liguori, RB, Dodelson PRL 2007

Measuring R



GR

DGP

shear~ a^3

TeVeS K=0.08

Error bars for SKA.

ADEPT, HSHS 21cm, and LSST could provide more immediate constraints

Zhang, RB, Liguori, Dodelson '08

Controlling systematics crucial for testing gravity using these techniques

- Photometric redshift errors
  - Can be significant effect on predictions of lensing shear evolution especially hi z to lo z mapping. Self-calibration approach could address this (Zhang, Pen & Bernstein '09).
- Intrinsic alignments
  - Galaxy/IA correlations potentially confuse measurement of Q and R? (Bean, Bridle, Kirk, Laszlo in prep)
- Peculiar velocities
  - Galaxy- velocity cross correlations could be useful however velocities to date modeled with simplistic models, need non-linear fitting and better characterization of systematics (Scoccimarro '04)

Conclusions

- Cosmic acceleration may indicate a modification of General Relativity on cosmic scales
- Modifications to gravity typically alter both the growth and expansion histories
- Current CMB (ISW), galaxy-ISW correlations, and weak lensing observations can place constraints on the modifications to gravity
- Combining peculiar velocity, weak lensing and galaxy distribution data from upcoming surveys offers tantalizing method to isolate modifications gravity
- However systematics are a major concern (e.g. peculiar velocity modeling, photometric redshift errors and intrinsic alignments)