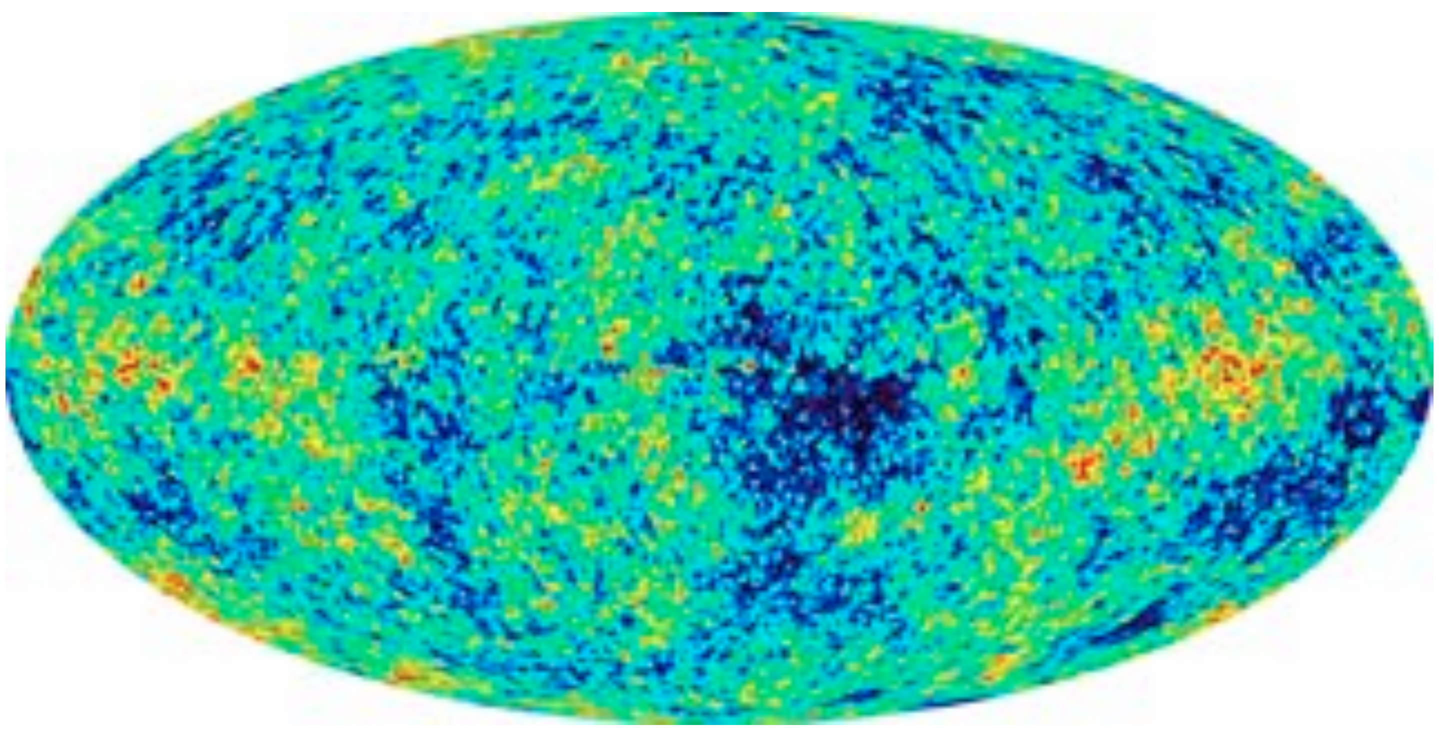
Testing Gravity with Cosmology
(a new Golden Age?)

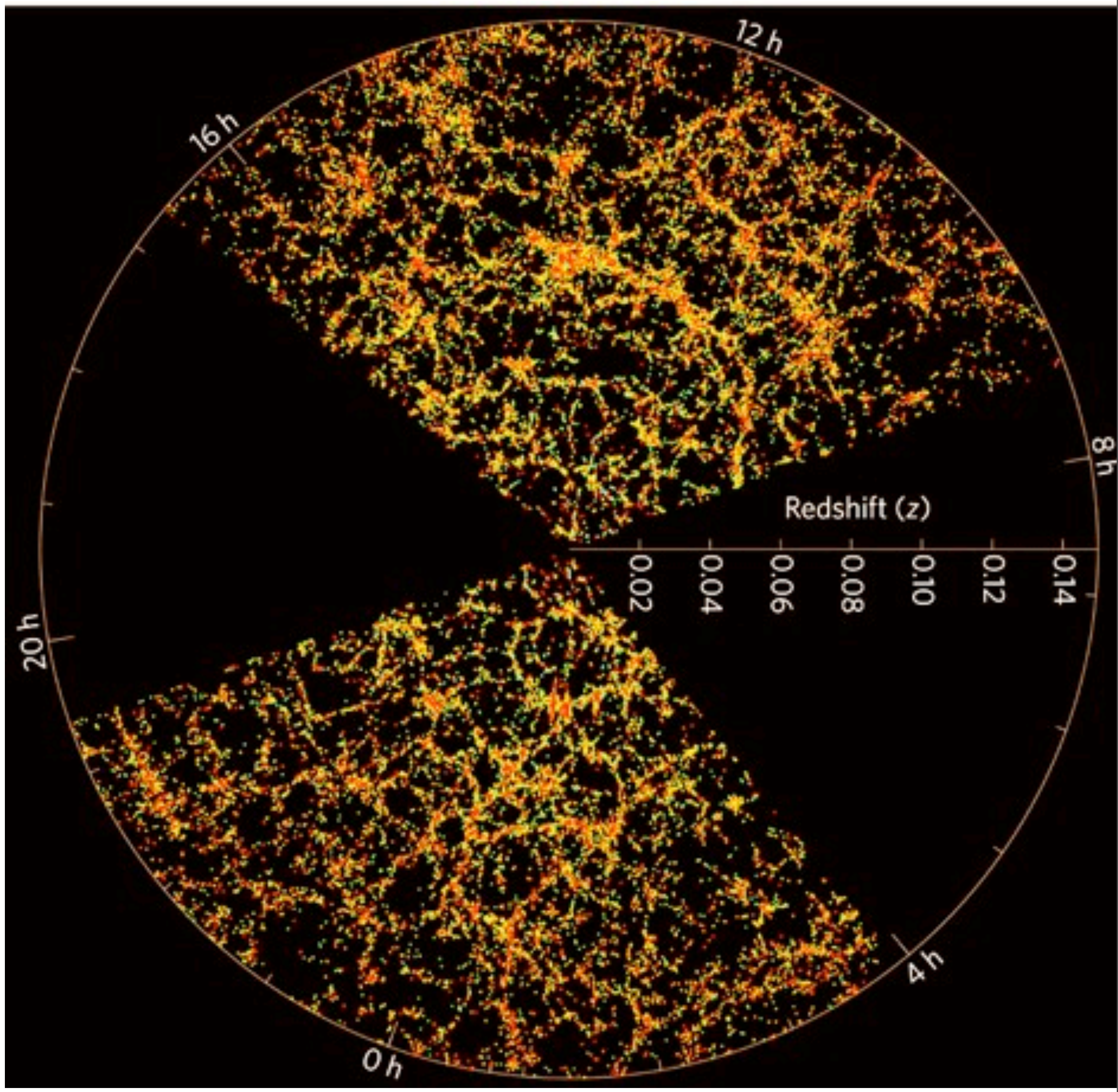
Pedro Ferreira
Oxford

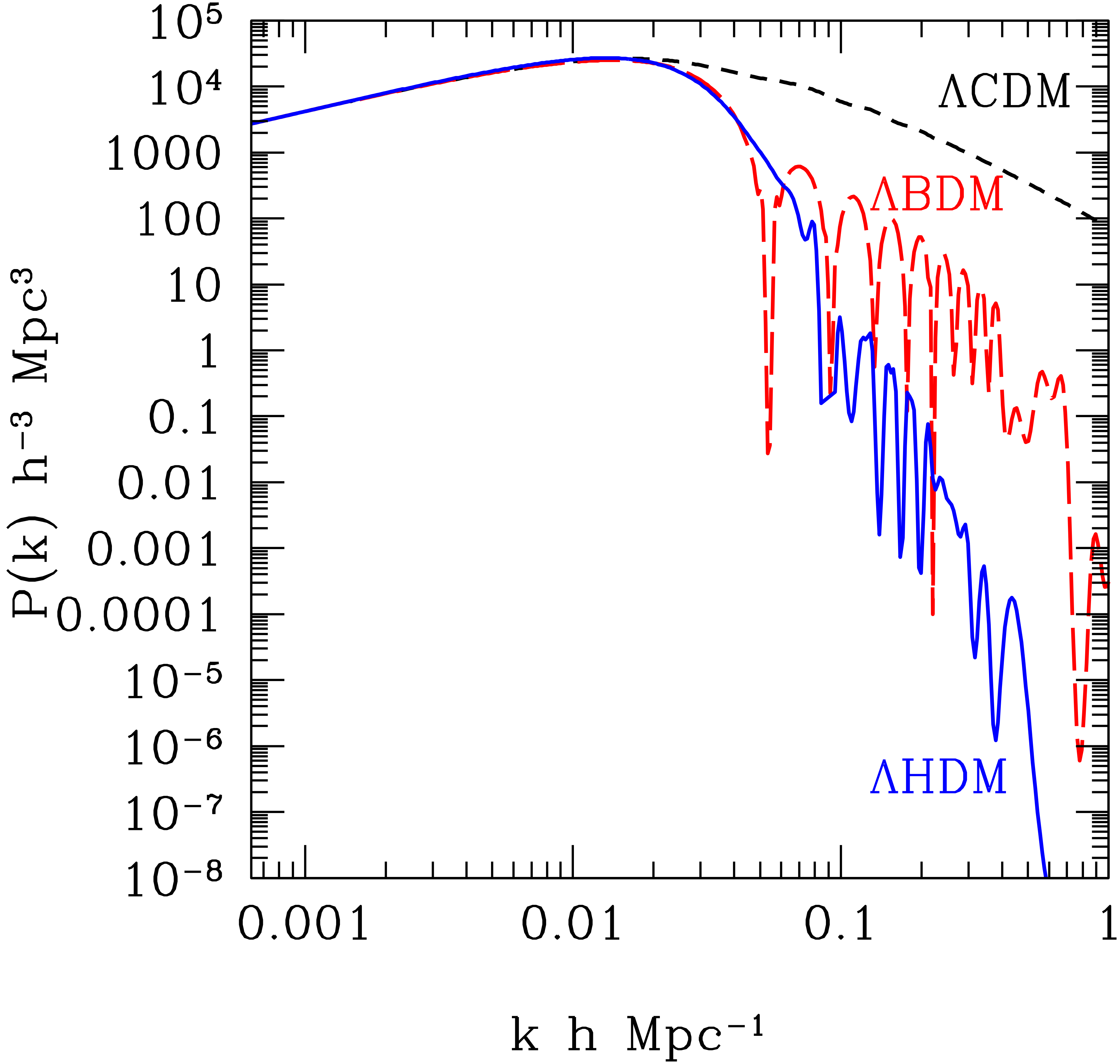
The Large Scale Structure of the Universe

WMAP

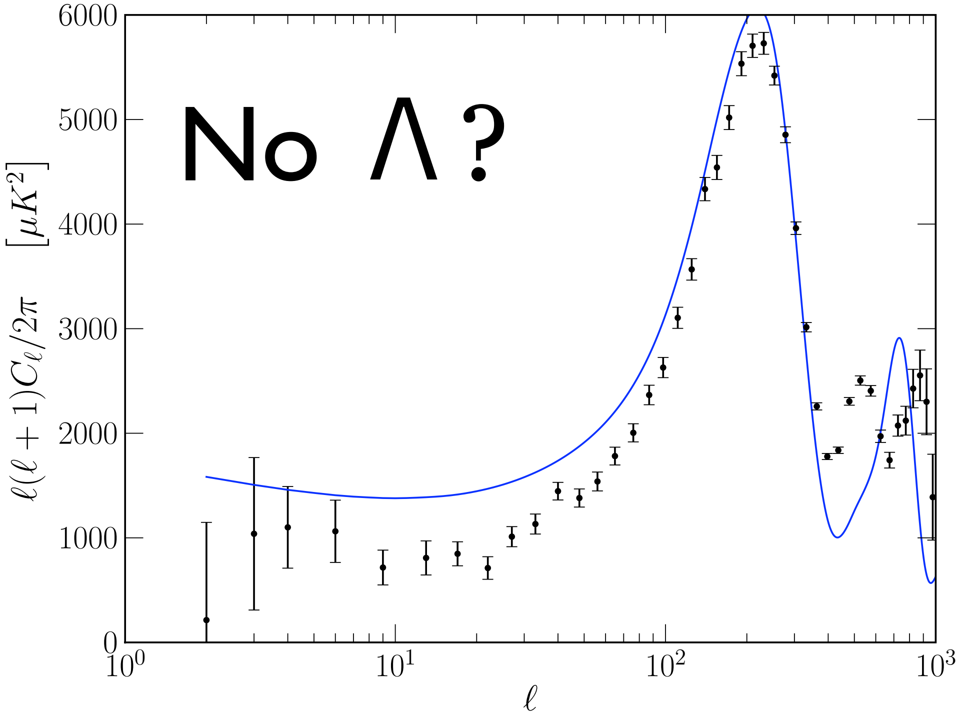


SDSS

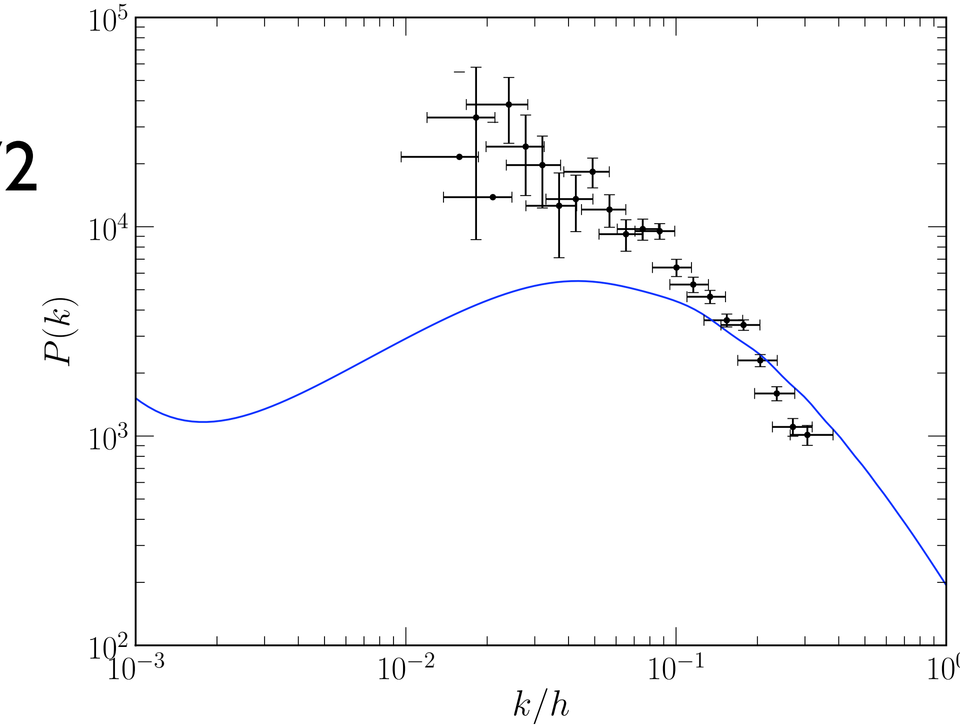


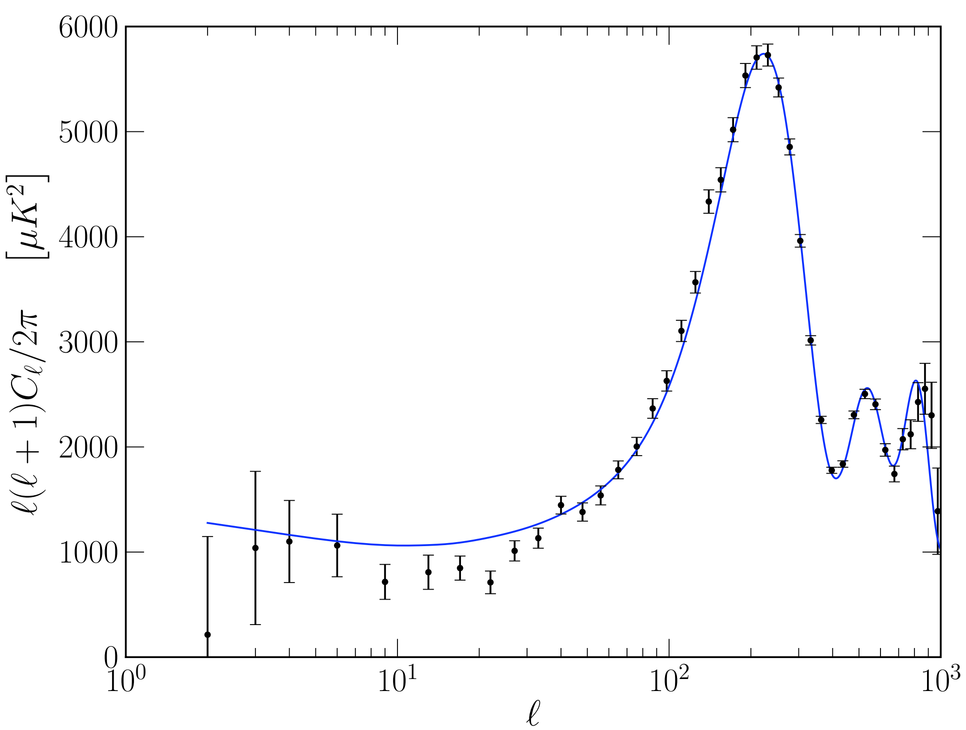


ΛCDM
ΛBDM
ΛHDM
P(k) h⁻³ Mpc³
k h Mpc⁻¹

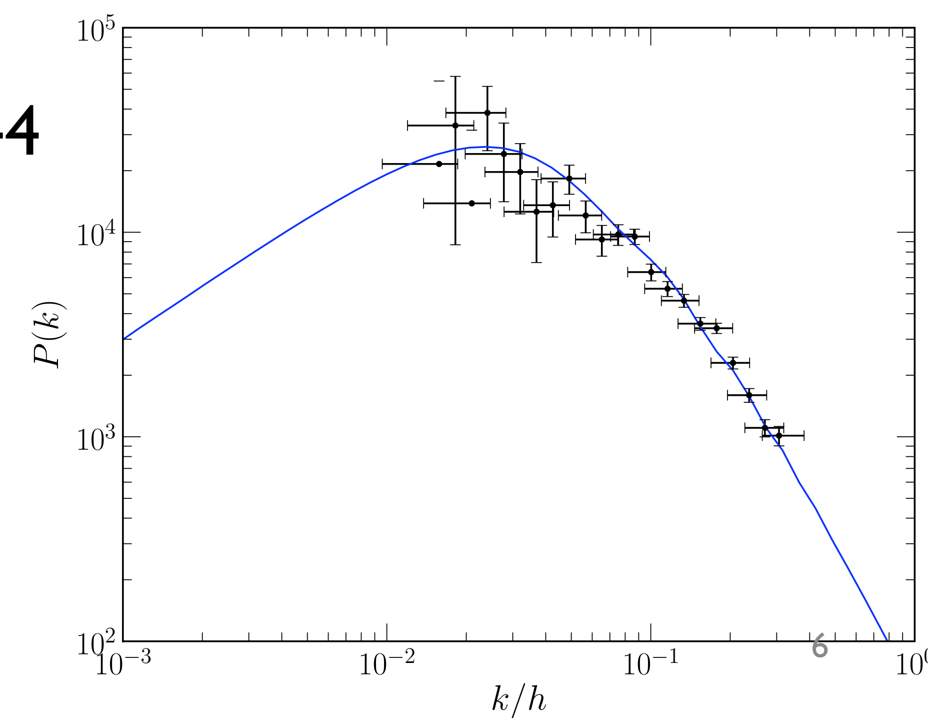

No Λ?
$\ell(\ell+1)C_\ell/2\pi \quad [\mu K^2]$
ℓ

H_0= 72


$P(k)$
k/h


$\ell(\ell+1)C_\ell/2\pi \quad [\mu K^2]$
ℓ

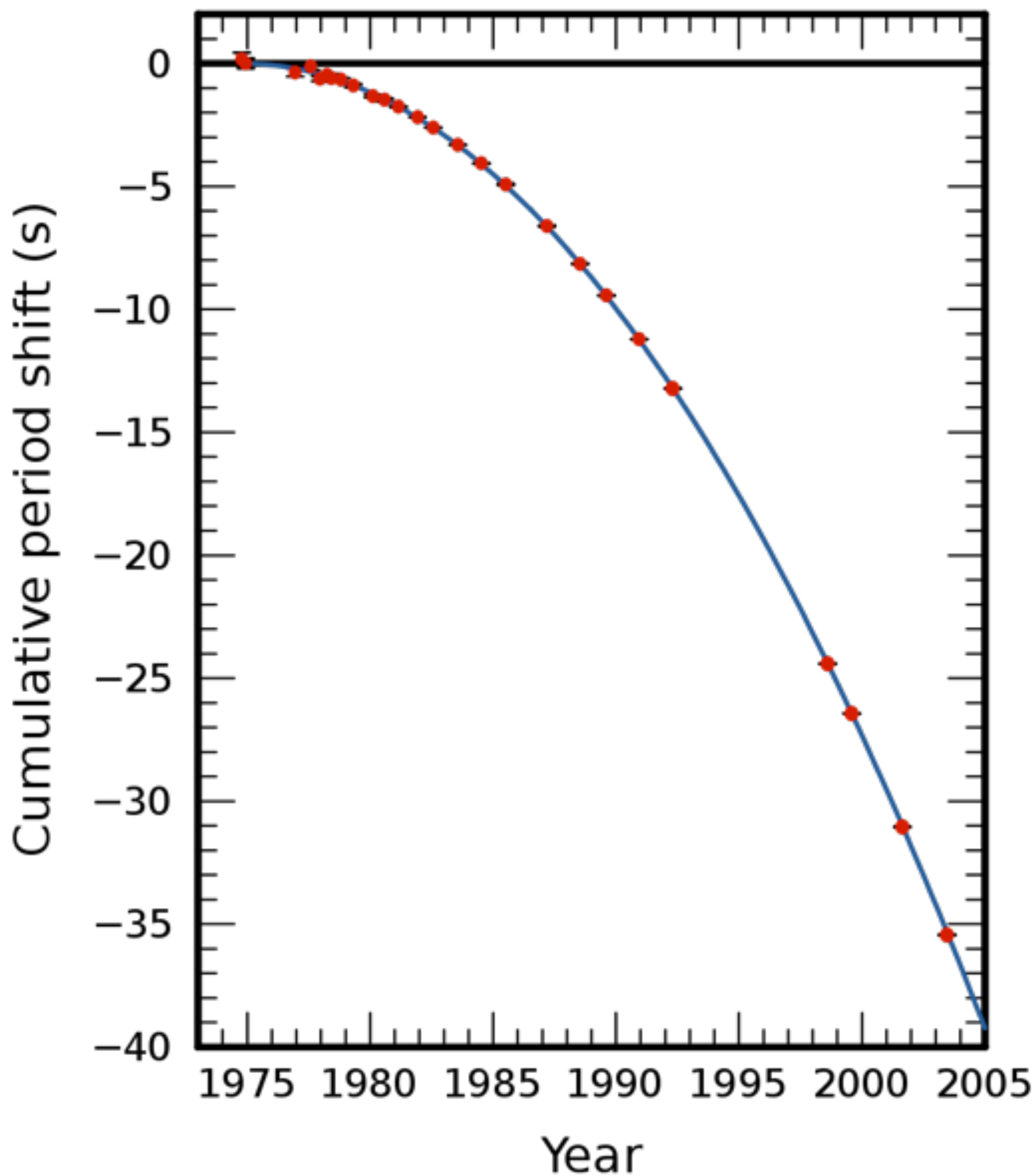
H_0= 44


$P(k)$
k/h

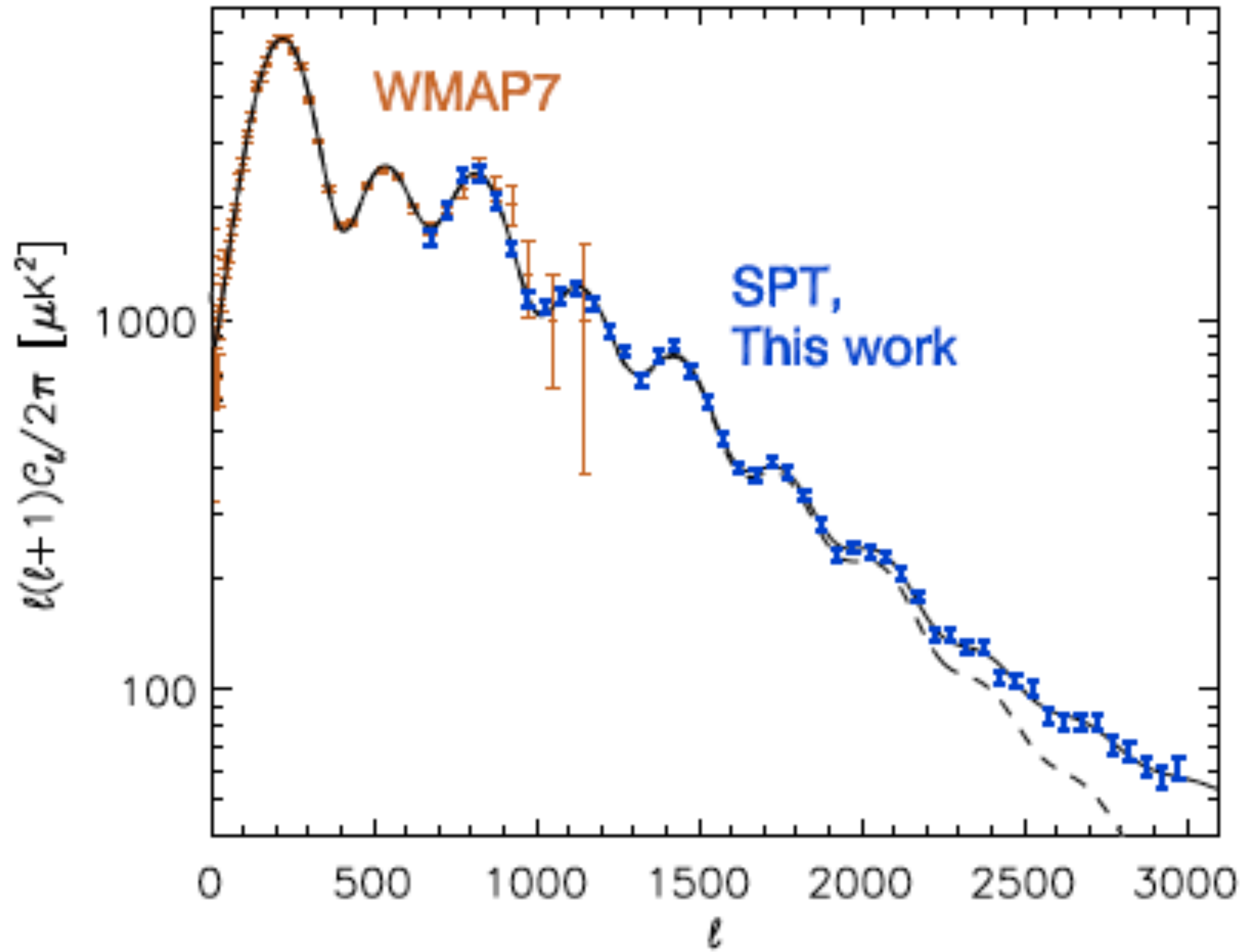
"The elegant logic of general relativity theory, and its precision tests, recommend GR as the first choice for a working model for cosmology. But the Hubble length is fifteen orders of magnitude larger than the length scale of the precision tests, at the astronomical unit and smaller, a spectacular extrapolation."

Jim Peebles, IAU 2000

Spin-down of the Hulse - Taylor binary pulsar



The Angular Power Spectrum of the CMB



Keisler et al 2011

$$\ell \simeq \frac{180^o}{\theta}$$

Outline

- The panorama of gravitation
- Cosmological linear perturbations
- How to parametrize the space of theories
- How to measure the parameters
- The future

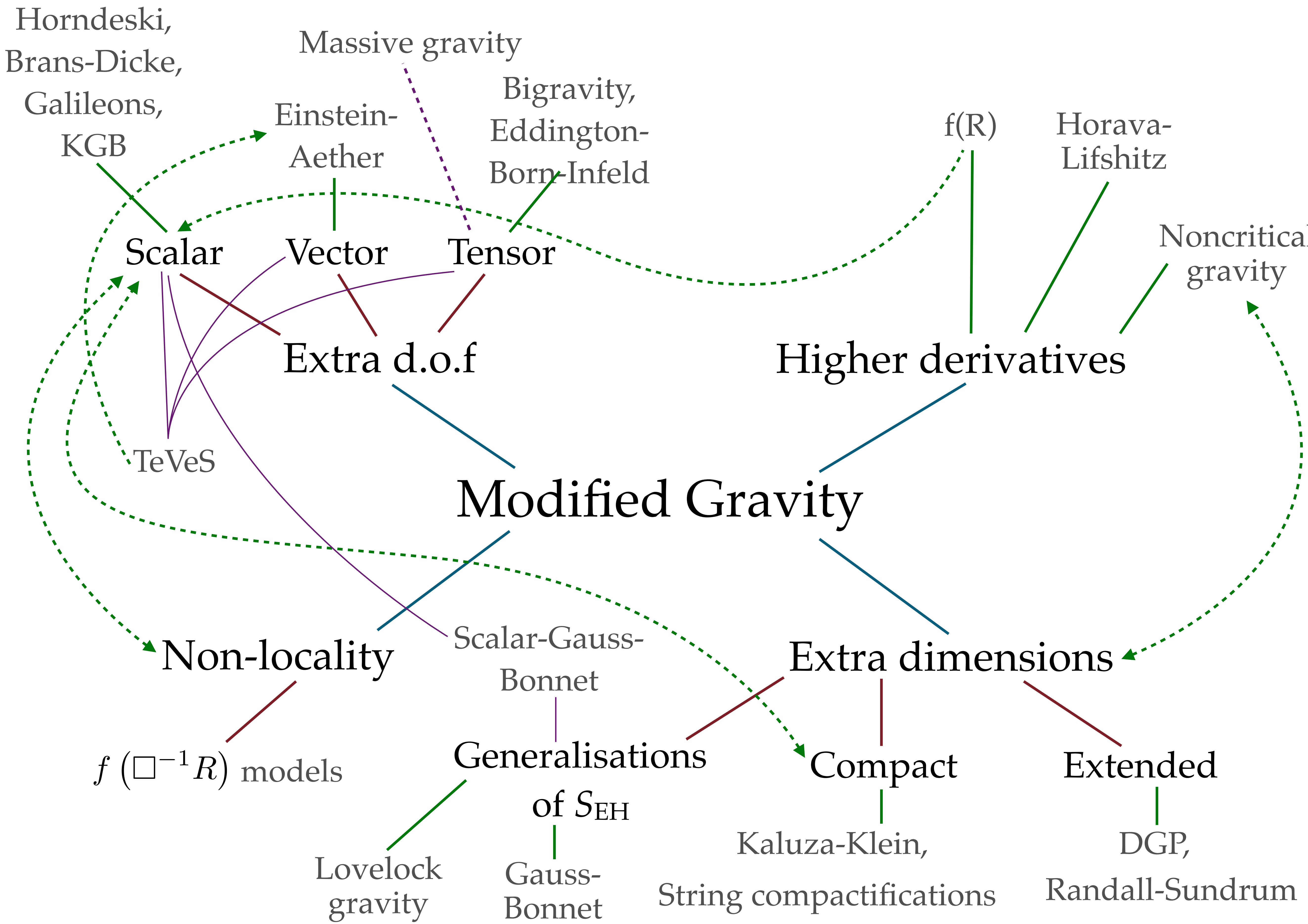
Einstein Gravity

Curvature

$$\frac{1}{16\pi G}\int d^4x\sqrt{-g}R(g)+\int d^4x\sqrt{-g}\mathcal{L}(g,\mathrm{matter})$$

Metric of space time

Lovelock's theorem (1971) :*"The only second-order, local gravitational field equations derivable from an action containing solely the 4D metric tensor (plus related tensors) are the Einstein field equations with a cosmological constant."*



ArXiv:1106.2476

Linear Perturbation Theory $(10 - 10,000 h^{-1} Mpc)$

$(\hat{\Phi}, \hat{\Psi})$

$$\delta G_{\alpha\beta} = 8\pi G \delta T_{\alpha\beta}$$

+ E.M. Conservation

Gauge invariant
Newtonian potentials

$$\hat{\Gamma} = \frac{1}{k}\left(\dot{\hat{\Phi}} + \mathcal{H}\hat{\Psi}\right)$$

$$\begin{aligned}
E_\Delta &= 2(\vec{\nabla}^2 + 3K)\hat{\Phi} - 6\mathcal{H}k\hat{\Gamma} - \frac{3}{2}\mathcal{H}EV && = 8\pi G a^2 \sum_i \rho_i \delta_i \\
E_\Theta &= 2\,k\hat{\Gamma} + \frac{1}{2}EV && = 8\pi G a^2 \sum_i (\rho_i + P_i)\theta_i \\
E_P &= 6k\frac{d\hat{\Gamma}}{d\tau} + 12\mathcal{H}k\hat{\Gamma} - 2(\vec{\nabla}^2 + 3K)(\hat{\Phi} - \hat{\Psi}) && \\
&\quad -3E\hat{\Psi} + \frac{3}{2}\left(\dot{E}_R - 2\mathcal{H}E_R\right)V && = 24\pi G a^2 \sum_i \rho_i \Pi_i \\
E_\Sigma &= \hat{\Phi} - \hat{\Psi} && = 8\pi G a^2 \sum_i (\rho_i + P_i)\Sigma_i
\end{aligned}$$

In fact- construct an algebraic equation: $(\nabla^2 + K)\hat{\Phi} = 4\pi G a^2 \sum_i \rho_i \Delta_i$

Simplest Approach

Zhang, Liguori, Bean and Dodelson
Caldwell, Cooray and Melchiorri
Amendola, Kunz and Sapone
Bertschinger and Zukin
Amin, Blandford and Wagoner
Pogosian, Silvestri, Koyama and Zhao
Bean and Tangmatitham

Poisson $-k^2\Phi = 4\pi G a^2 \rho\Delta$ $\quad (E_\Delta - 3\mathcal{H}E_\Theta)$

Slip $\Phi - \Psi = 0$ $\quad (E_\Sigma)$

$$-k^2\Phi = 4\pi G a^2 G a^2 \rho\Delta + F_1 \qquad F_1 = k^2 f_1 \Phi$$

$$\Phi - \Psi = F_2 \qquad F_2 = f_2 \Phi$$

Rearrange and rename:

$$-k^2\Phi = 4\pi G\mu a^2 \rho\Delta$$

$$\Psi = \gamma\Phi$$

$$-k^2(\Phi + \Psi) = 8\pi G\Sigma a^2 \rho\Delta$$

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Rearrange and rename:

$$-k^2\Phi = 4\pi G\mu a^2\rho\Delta$$

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Each function must be constrained on a grid of (a,k) using Principal Component Analysis .

- There are a few variants, e.g.

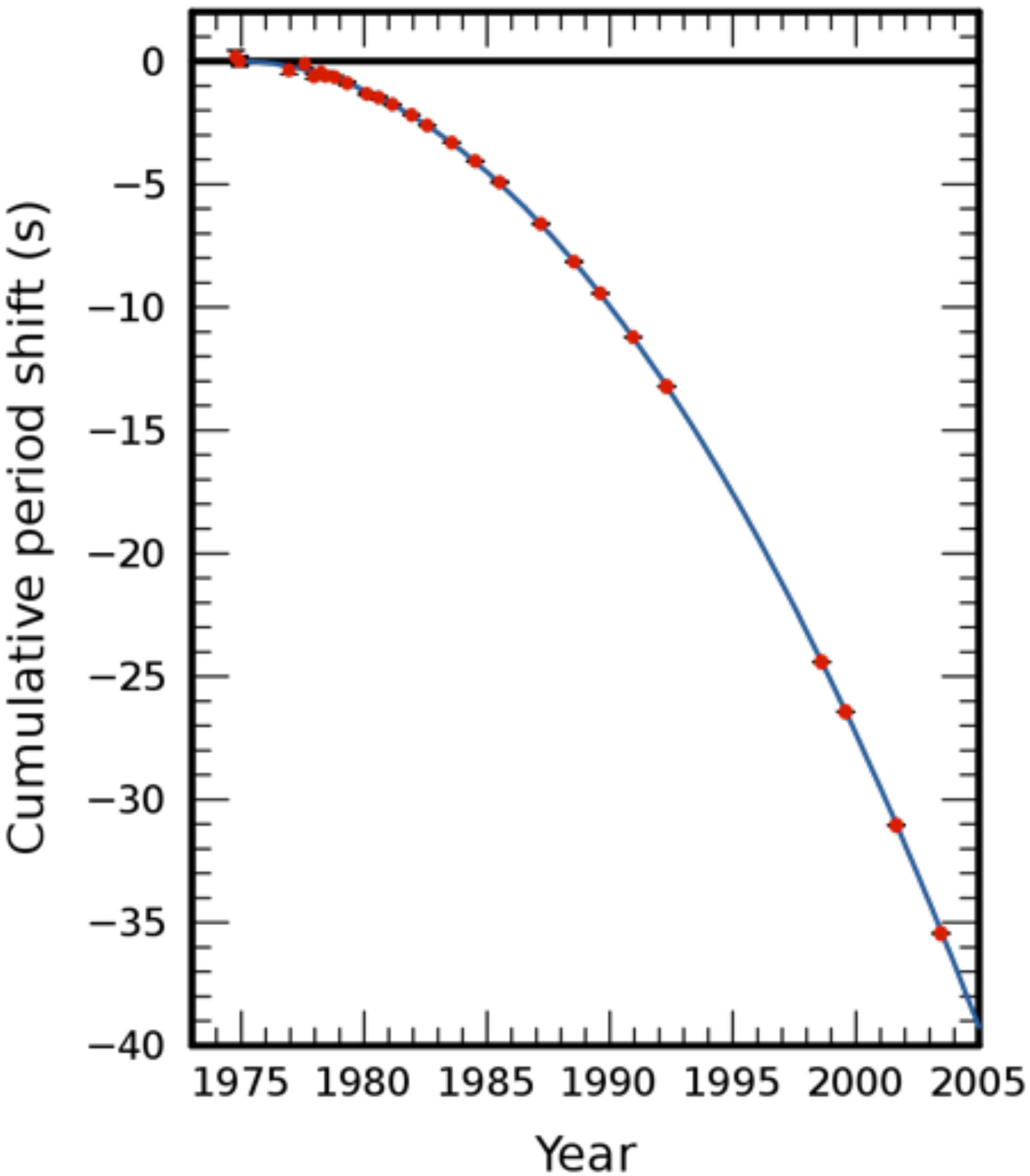
$$-k^2(\Phi + \Psi) = 8\pi G\Sigma a^2\rho\Delta$$

Lessons from PPN

		γ	β	ξ	α_1	α_2	α_3	ζ_1	ζ_2	ζ_3	ζ_4
	Einstein (1916) GR	1	1	0	0	0	0	0	0	0	0
Scalar-Tensor	Bergmann (1968), Wagoner (1970)		β	0	0	0	0	0	0	0	0
Scalar-Tensor	Nordtvedt (1970), Bekenstein (1977)		β	0	0	0	0	0	0	0	0
Scalar-Tensor	Brans-Dicke (1961)		1	0	0	0	0	0	0	0	0
Vector-Tensor	Hellings-Nordtvedt (1973)	γ	β	0	$\alpha1$	α_2	0	0	0	0	0
Vector-Tensor	Will-Nordtvedt (1972)	1	1	0	0	α_2	0	0	0	0	0
Bimetric	Rosen (1975)	1	1	0	0	$c_0/c_1 - 1$	0	0	0	0	0
Bimetric	Rastall (1979)	1	1	0	0	$\alpha2$	0	0	0	0	0
Bimetric	Lightman-Lee (1973)	γ	β	0	α_1	$\alpha2$	0	0	0	0	0
Stratified	Lee-Lightman-Ni (1974)	ac_0 / c_1	β	ξ	α_1	$\alpha2$	0	0	0	0	0
Stratified	Ni (1973)	ac_0 / c_1	bc_0	0	α_1	$\alpha2$	0	0	0	0	0
Scalar Field Theories	Einstein (1912) {Not GR}	0	0	0	-4	0	-2	0	-1	0	0
Scalar Field Theories	Whitrow-Morduch (1965)	0	-1	0	-4	0	0	0	-3	0	0
Scalar Field Theories	Rosen (1971)	λ		0	$-4-4\lambda$	0	-4	0	-1	0	0
Scalar Field Theories	Papetrou (1954a, 1954b)	1	1	0	-8	-4	0	0	2	0	0
Scalar Field Theories	Ni (1972) (stratified)	1	1	0	-8	0	0	0	2	0	0
Scalar Field Theories	Yilmaz (1958, 1962)	1	1	0	-8	0	-4	0	-2	0	-1
Scalar Field Theories	Page-Tupper (1968)	γ	β	0	$-4-4\gamma$	0	$-2-2\gamma$	0	ζ_2	0	ζ_4
Scalar Field Theories	Nordström (1912)	-1	β	0	0	0	0	0	0	0	0
Scalar Field Theories	Nordström (1913), Einstein-Fokker (1914)	-1	1	0	0	0	0	0	0	0	0
Scalar Field Theories	Ni (1972) (flat)	-1	$1-q$	0	0	0	0	0	ζ_2	0	0
Scalar Field Theories	Whitrow-Morduch (1960)	-1	$1-q$	0	0	0	0	0	q	0	0
Scalar Field Theories	Littlewood (1953), Bergman(1956)	-1	β	0	0	0	0	0	-1	0	0

Lessons from PPN

Spin-down of the Hulse - Taylor binary pulsar



Parameter	Bound	Effects	Experiment
$\gamma - 1$	2.3×10^{-5}	Time delay, light deflection	Cassini tracking
$\beta - 1$	2.3×10^{-4}	Nordtvedt effect, Perihelion shift	Nordtvedt effect
ξ	0.001	Earth tides	Gravimeter data
α_1	10^{-4}	Orbit polarization	Lunar laser ranging
α_2	4×10^{-7}	Spin precession	Solar alignment with ecliptic
α_3	4×10^{-20}	Self-acceleration	Pulsar spin-down statistics
ζ_1	0.02	-	Combined PPN bounds
ζ_2	4×10^{-5}	Binary pulsar acceleration	PSR 1913+16
ζ_3	10^{-8}	Newton's 3rd law	Lunar acceleration
ζ_4	0.006	-	Usually not independent

Extending Einstein's equations

$$\delta G_{\mu\nu} = 8\pi G_N \delta T^M_{\mu\nu} + \boxed{\delta U_{\mu\nu}} \text{ — ?}$$

METRIC **NEW D.O.F.**

$$\delta U_{\mu\nu} = \delta U^{\hat{\Phi}}_{\mu\nu} + \delta U^{\widehat{\delta\phi}}_{\mu\nu} + \text{gauge-form invariance fixing term}$$

Built from Bardeen potentials × function of background

Fixed by background equations

$$\delta(\nabla^\mu G_{\mu\nu}) = 0 \rightarrow \delta(\nabla^\mu U_{\mu\nu}) = 0$$

ArXiv:1209.2117

Adding New Scalars

$$-a^2\delta U^0_0 = U_\Delta = A_0 k^2\hat{\Phi} + F_0 k^2\hat{\Gamma} + \alpha_0 k^2\hat{\chi} + \alpha_1 k\dot{\hat{\chi}} + M_\Delta k^3 V$$

$$U_\Theta = B_0 k\hat{\Phi} + I_0 k\hat{\Gamma} + \beta_0 k\hat{\chi} + \beta_1\dot{\hat{\chi}} + M_\Theta k^2 V$$

$$a^2\delta U^i_i = U_P = C_0 k^2\hat{\Phi} + C_1 k\dot{\hat{\Phi}} + J_0 k^2\hat{\Gamma} + J_1 k\dot{\hat{\Gamma}} + \gamma_0 k^2\hat{\chi} + \gamma_1 k\dot{\hat{\chi}} + \gamma_2\ddot{\hat{\chi}} + M_P k^3 V$$

$$U_\Sigma = D_0\hat{\Phi} + \frac{D_1}{k}\dot{\hat{\Phi}} + K_0\hat{\Gamma} + \frac{K_1}{k}\dot{\hat{\Gamma}} + \epsilon_0\hat{\chi} + \frac{\epsilon_1}{k}\dot{\hat{\chi}} + \frac{\epsilon_2}{k^2}\ddot{\hat{\chi}}$$

Functions of background (a, k, φ_i...)

Gauge form-fixing term, zero in CN gauge.

ArXiv:1209.2117

$$\nabla_i U_\Theta = -a^2\delta U^0_i, \quad \left(\nabla^i\nabla_j - \frac{1}{3}\delta^i_j\nabla^2\right)U_\Sigma = a^2\delta U^i_j$$

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$$+\ \gamma_0 k^2\hat{\chi} + \gamma_1 k\dot{\hat{\chi}} + \gamma_2\ddot{\hat{\chi}} + \underbrace{M_P k^3 V}$$

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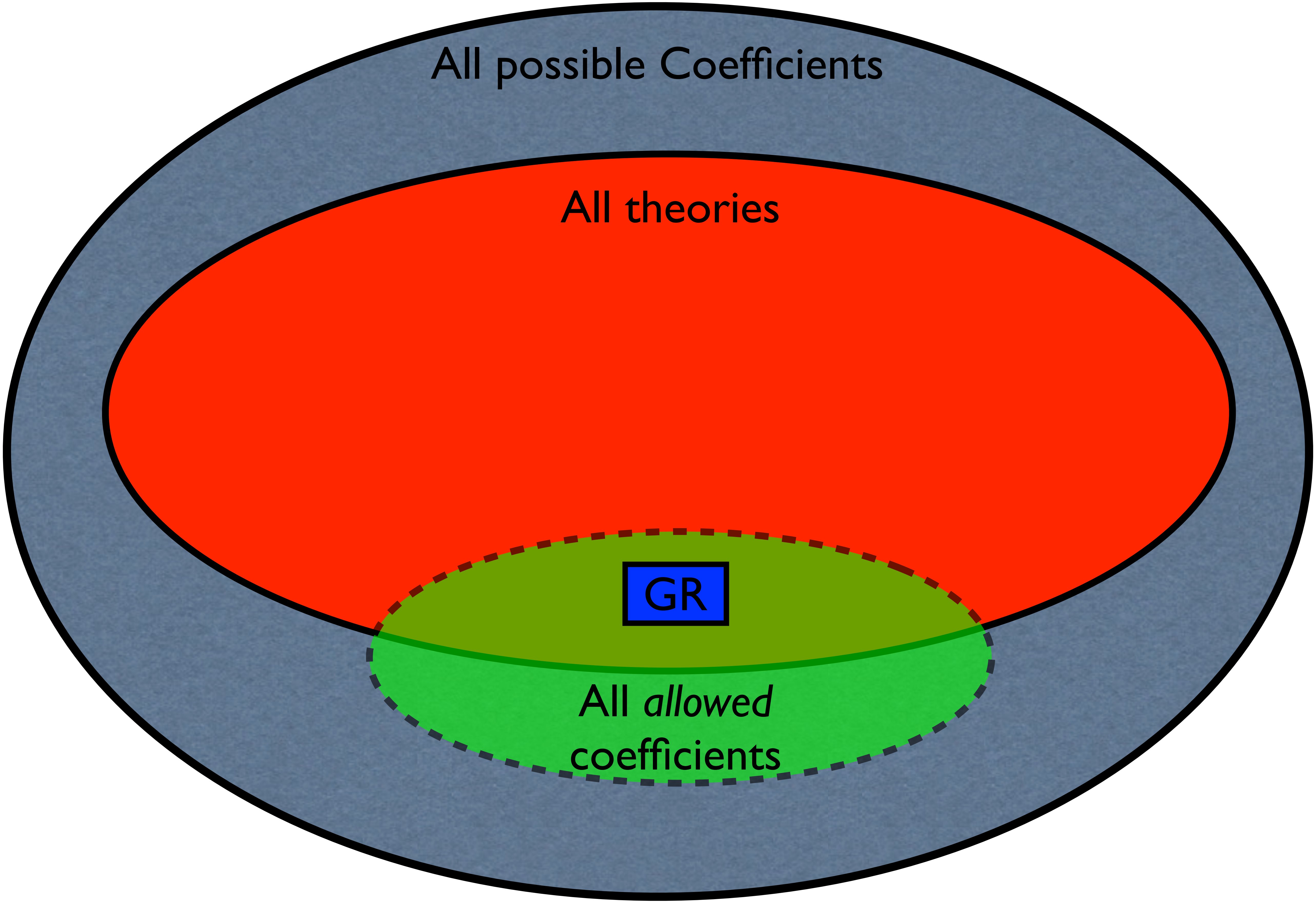
ArXiv:1209.2117

Category	Theory
Horndeski Theories	Scalar-Tensor theory (incl. Brans-Dicke)
	$f(R)$ gravity
	$f(\mathcal{G})$ theories
	Covariant Galileons
	The Fab Four
	K-inflation
	Generalized G-inflation
	Kinetic Gravity Braiding
	Quintessence (incl. universally coupled models)
	Effective dark fluid
Lorentz-Violating theories	Einstein-Aether theory
	Hořava-Lifschitz theory
>2 new degrees of freedom	DGP (4D effective theory)
	EBI gravity
	TeVeS

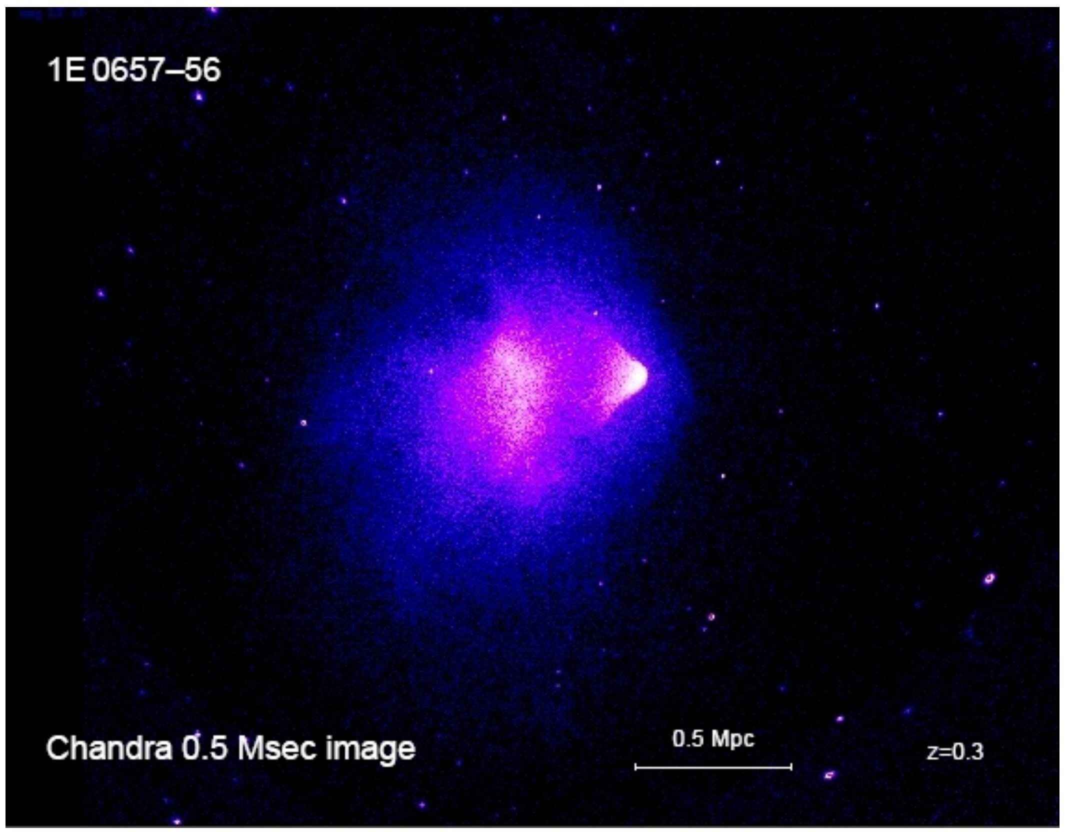
ArXiv:1209.2117

... and more to come.

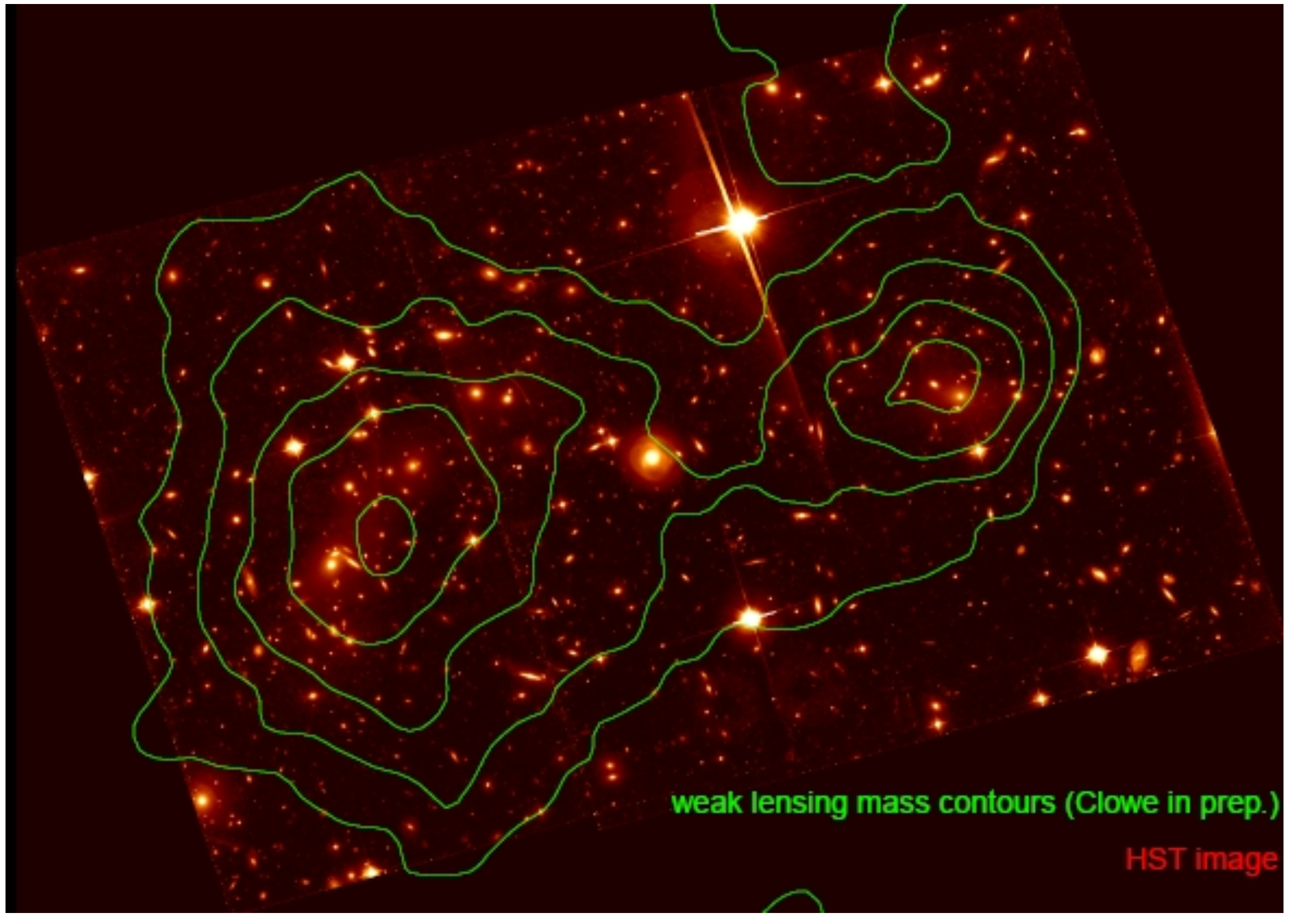

All possible Coefficients
All theories
GR
All *allowed* coefficients

What about the non-linear regime?

$$R \simeq 0.1 - 10h^{-1}Mpc$$



The Bullet Cluster



Clowe et al 2006

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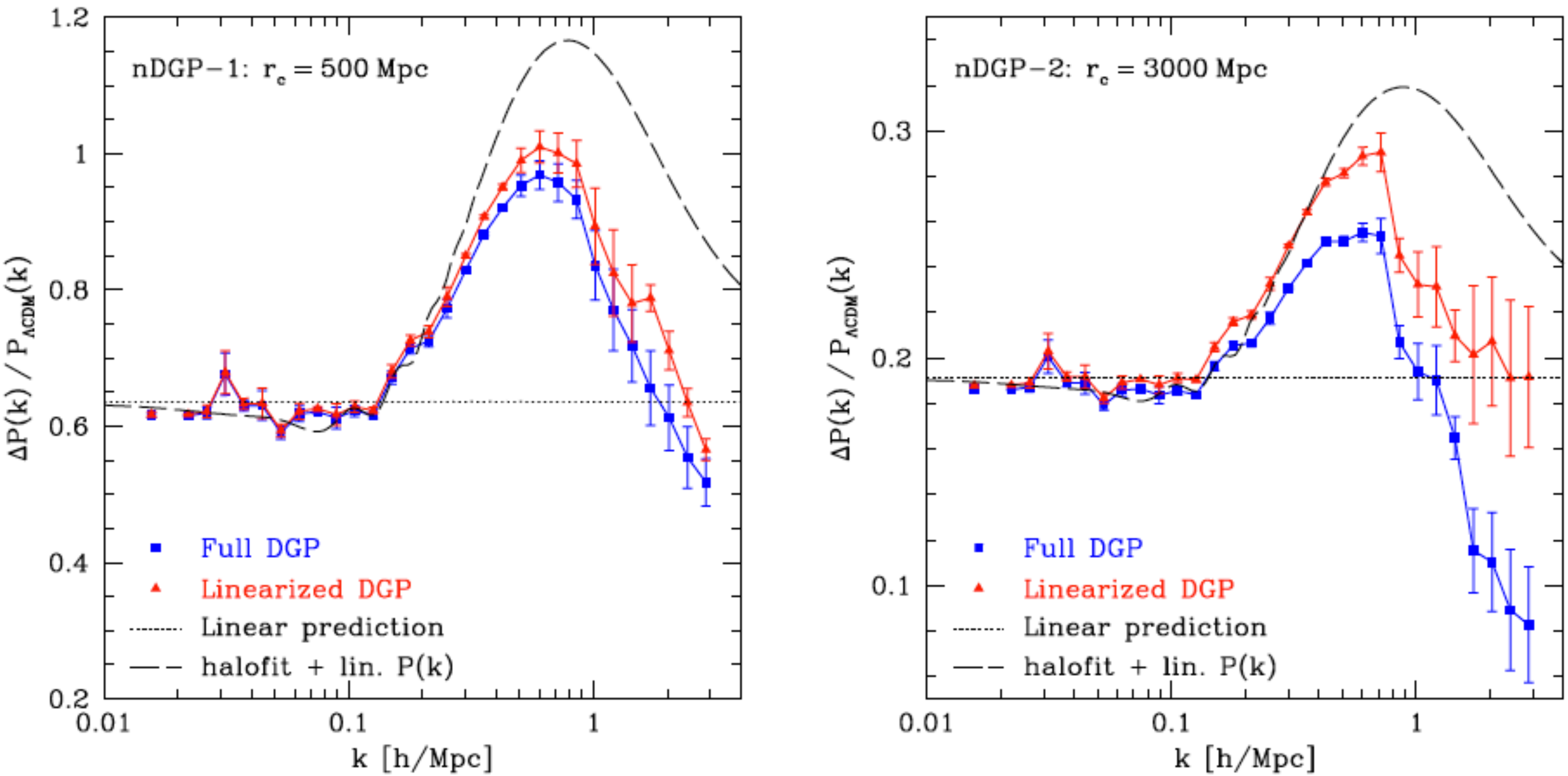


Schmidt 2009

Observables: Light vs. Matter

- For a perturbed line element of the form:

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

the equations of motion are:

$$\frac{1}{a}\frac{d(a\mathbf{v})}{d\tau} = -\nabla\Phi$$ (non-relativistic particles) → Growth of structure, RSDs and PVs.

$$\frac{d\mathbf{v}}{d\tau} = -\nabla_\perp(\Phi + \Psi)$$ (relativistic particles) → ISW, Lensing (CMB, weak)

Growth of Structure

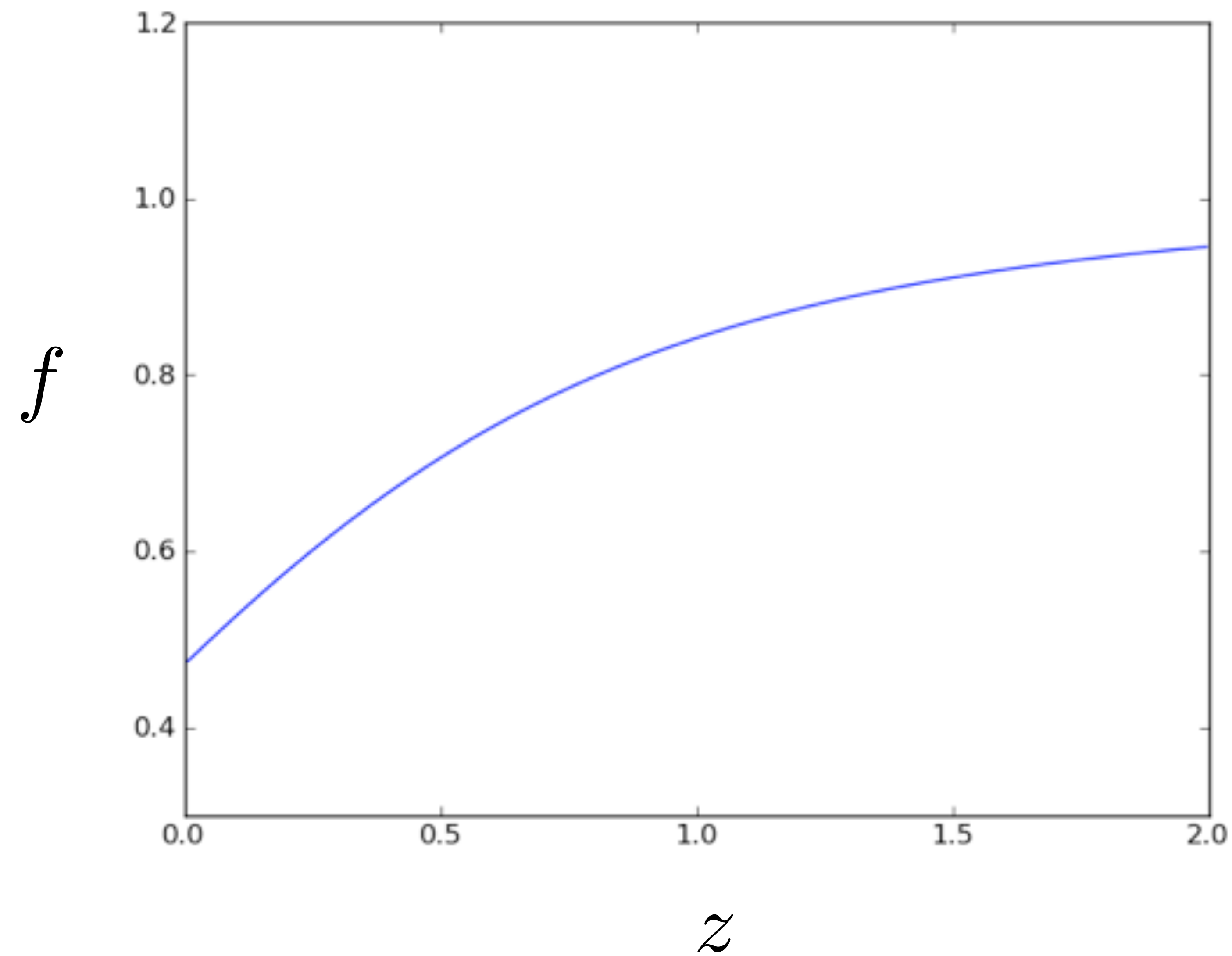
- Evolution of CDM energy density perturbations:

$$\ddot{\delta}_M + \mathcal{H}\dot{\delta}_M - 3\ddot{\Phi} - 3\mathcal{H}\dot{\Phi} + k^2\Psi = 0$$

- The growth rate of structure is quantified via *f* :

$$f(k,a) = \frac{d \ln \delta_M(k,a)}{d \ln a}$$

- In GR $\delta_M \propto a$ during matter domination, so $f = 1$ (independent of *k* for linear scales).



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$$\ddot{\delta}_M + \mathcal{H}\dot{\delta}_M - 3\ddot{\Phi} - 3\mathcal{H}\dot{\Phi} + k^2\Psi = 0$$

Relation to δ_M has changed. Relation to Φ has changed.

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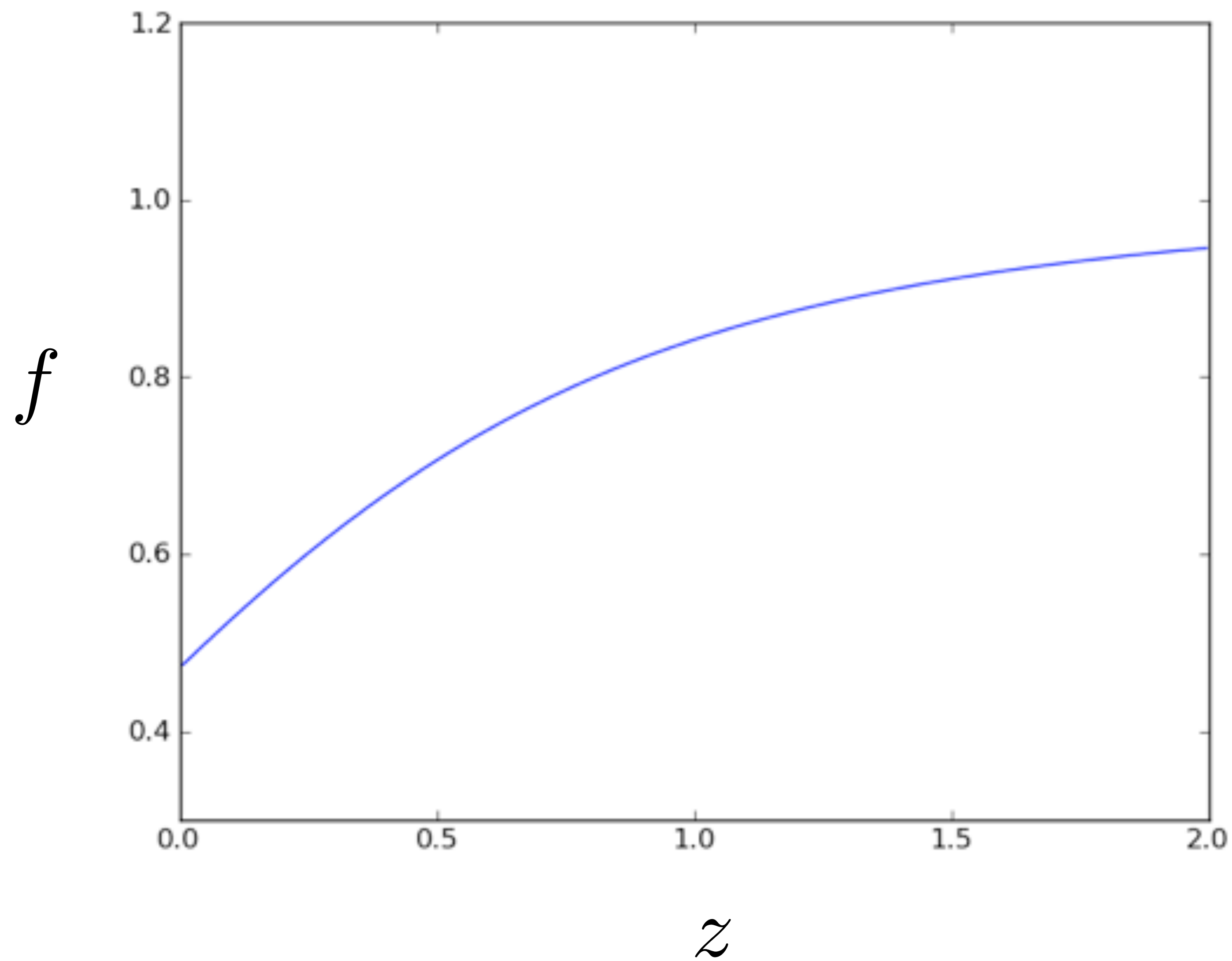
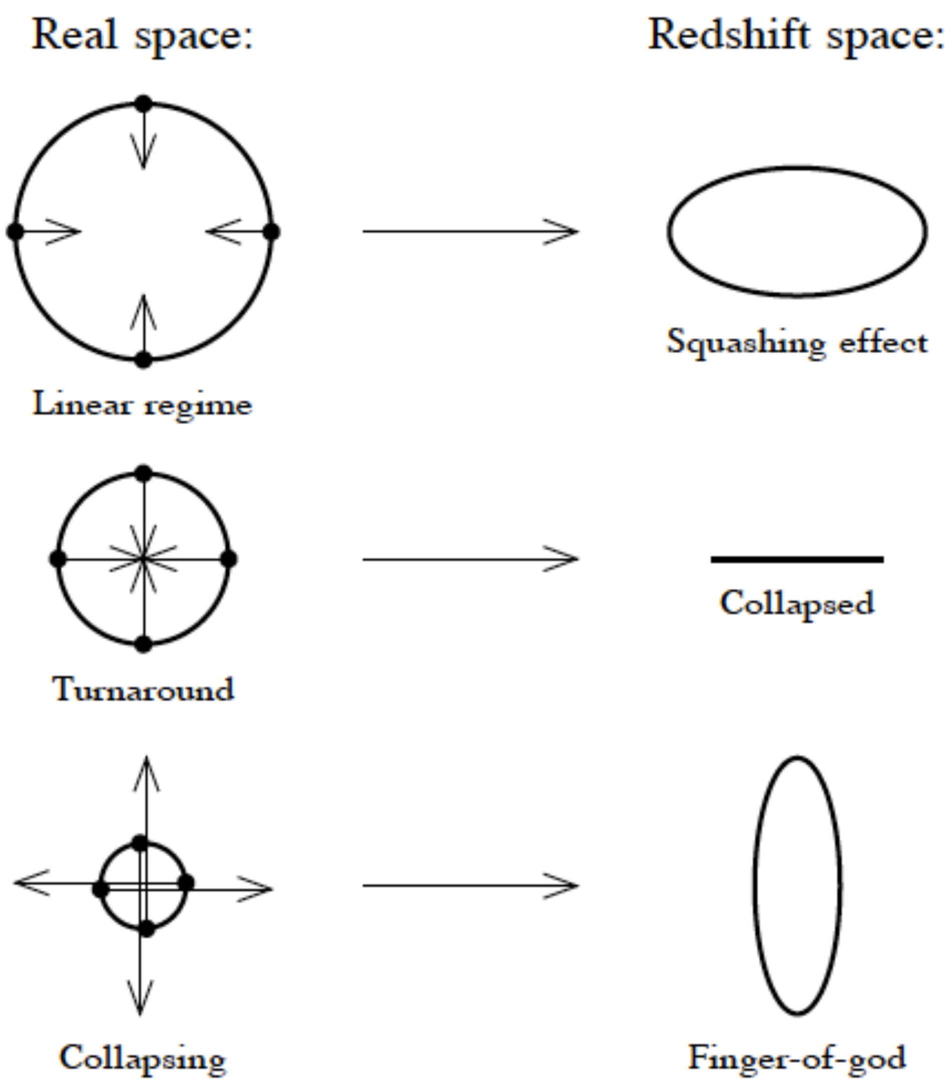
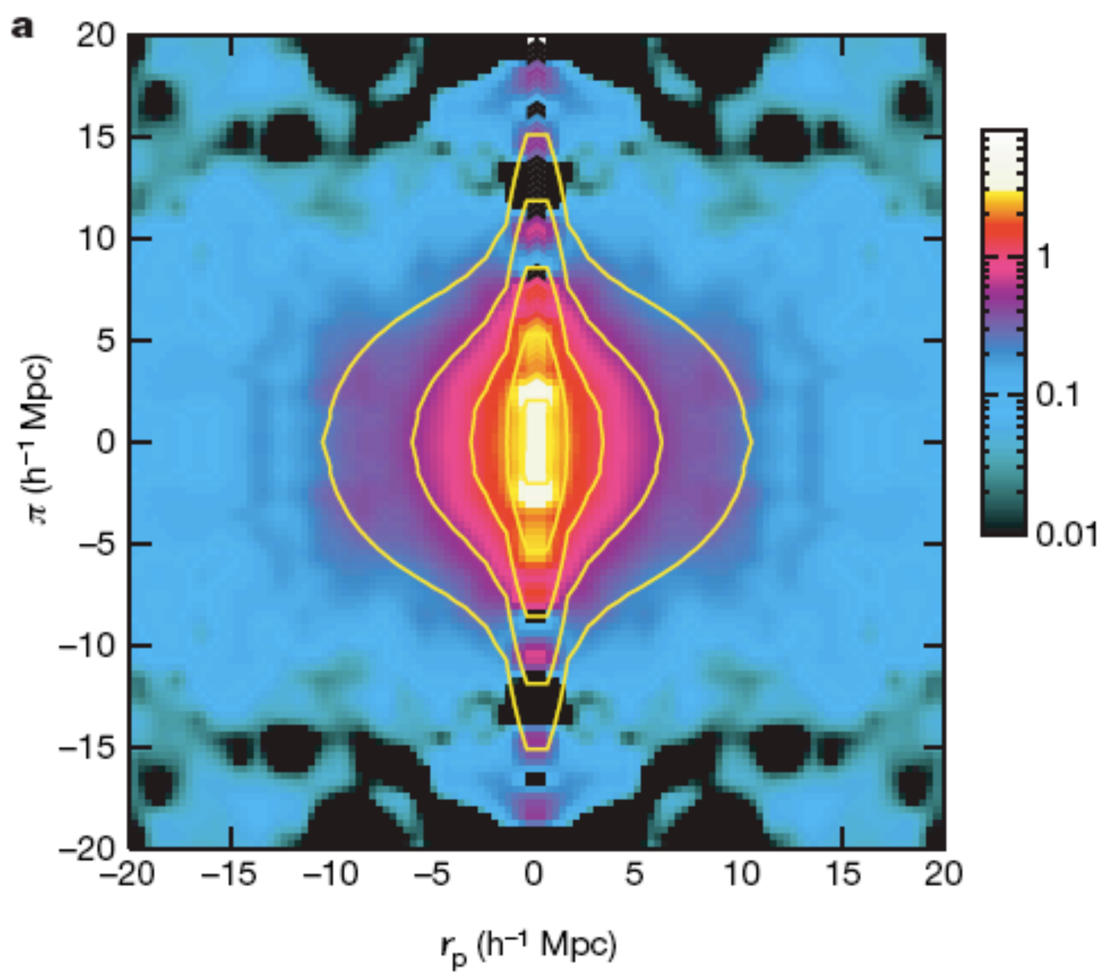
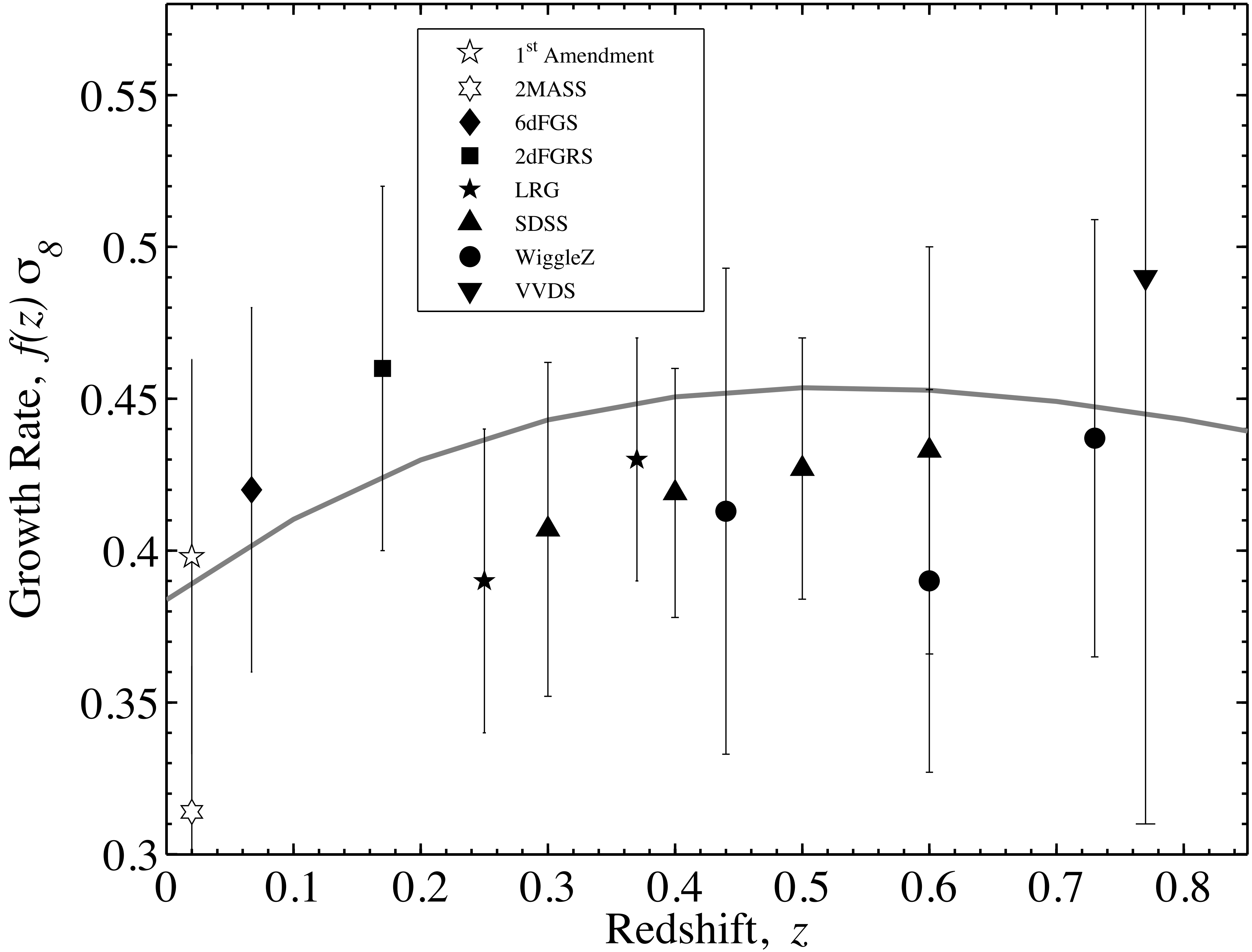


Redshift Space Distortions

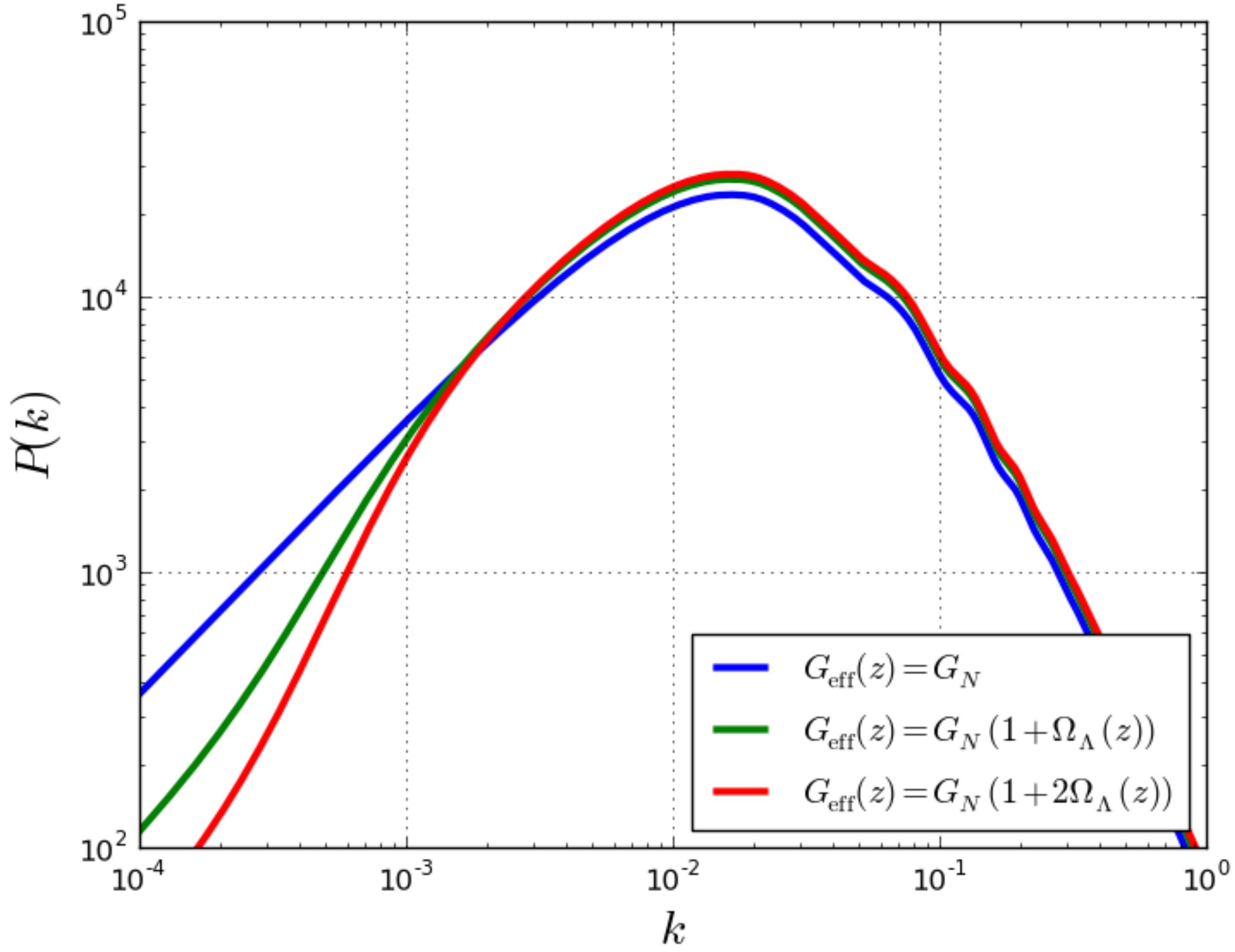


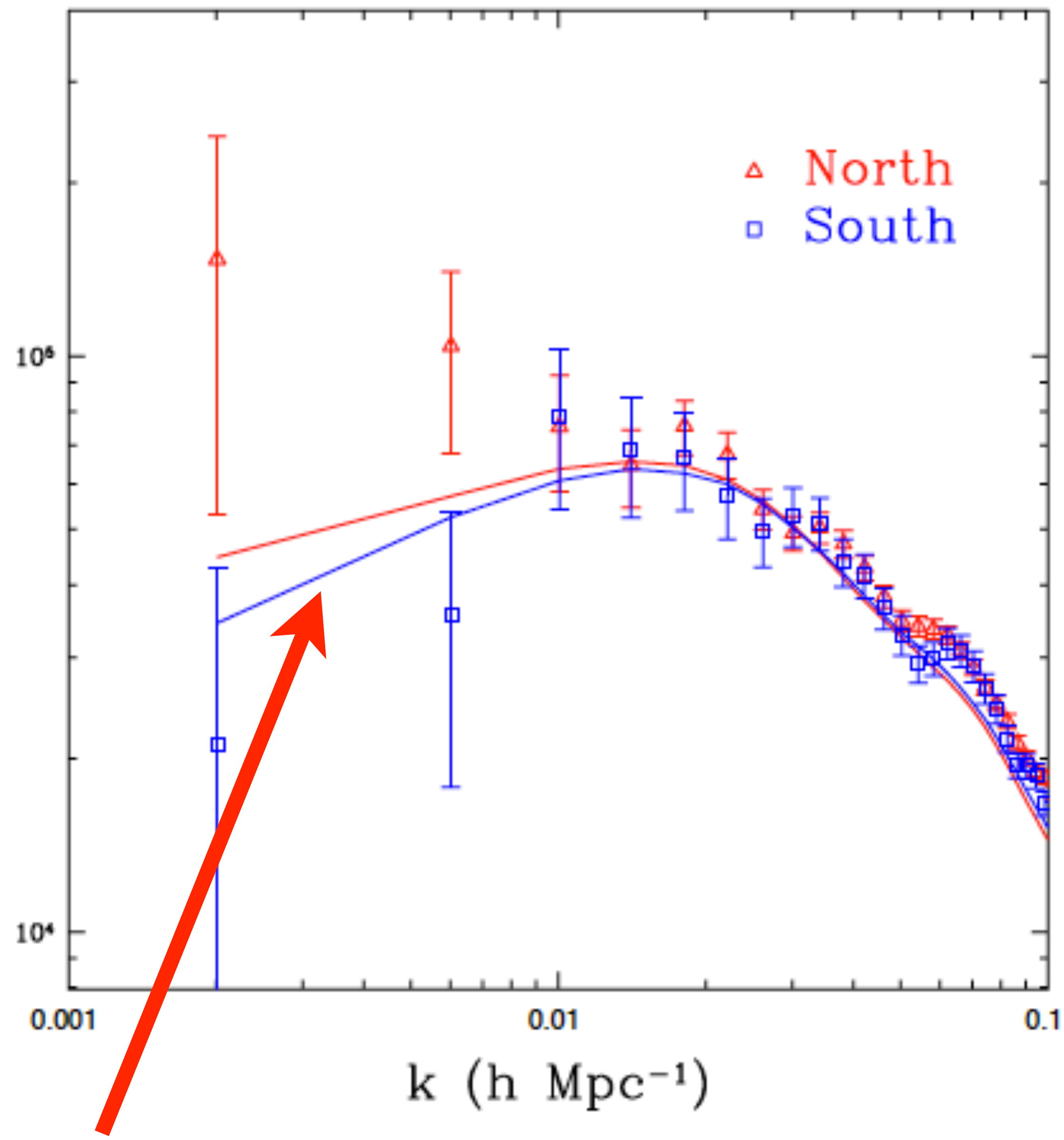


Guzzo et al 2008


1st Amendment
2MASS
6dFGS
2dFGRS
LRG
SDSS
WiggleZ
VVDS
Growth Rate, $f(z)\,\sigma_8$
Redshift, z
0.55
0.5
0.45
0.4
0.35
0.3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Ultra-large scale surveys

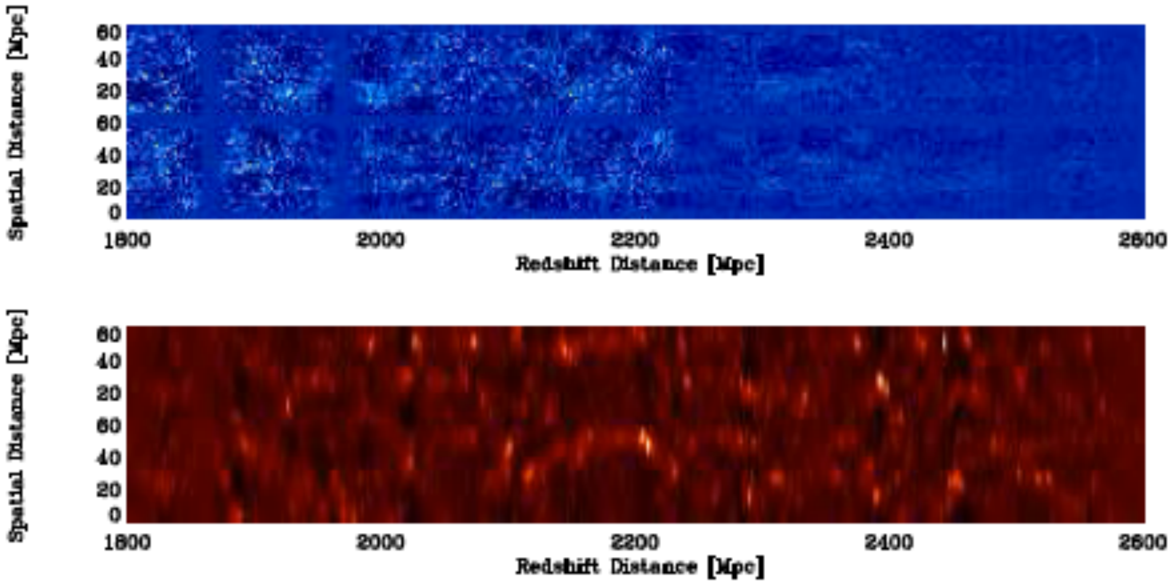


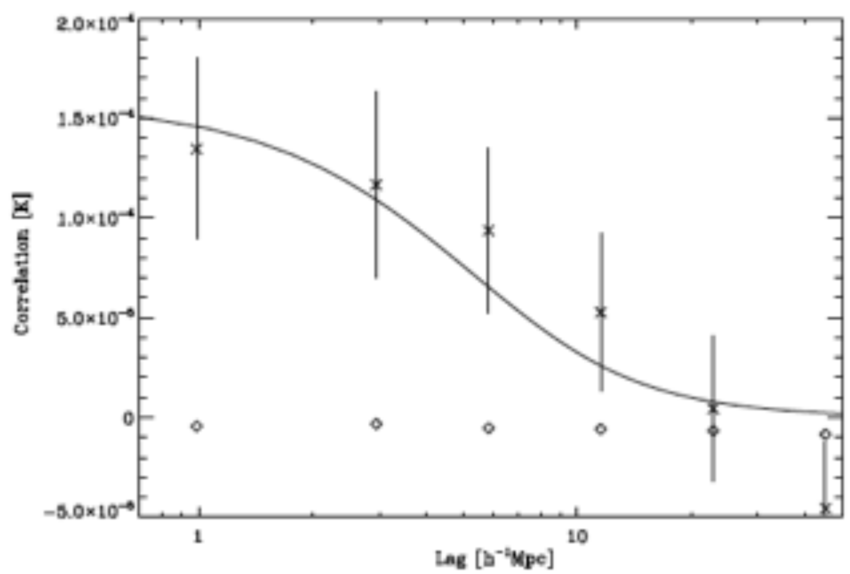


Systematic effect due to stellar densities

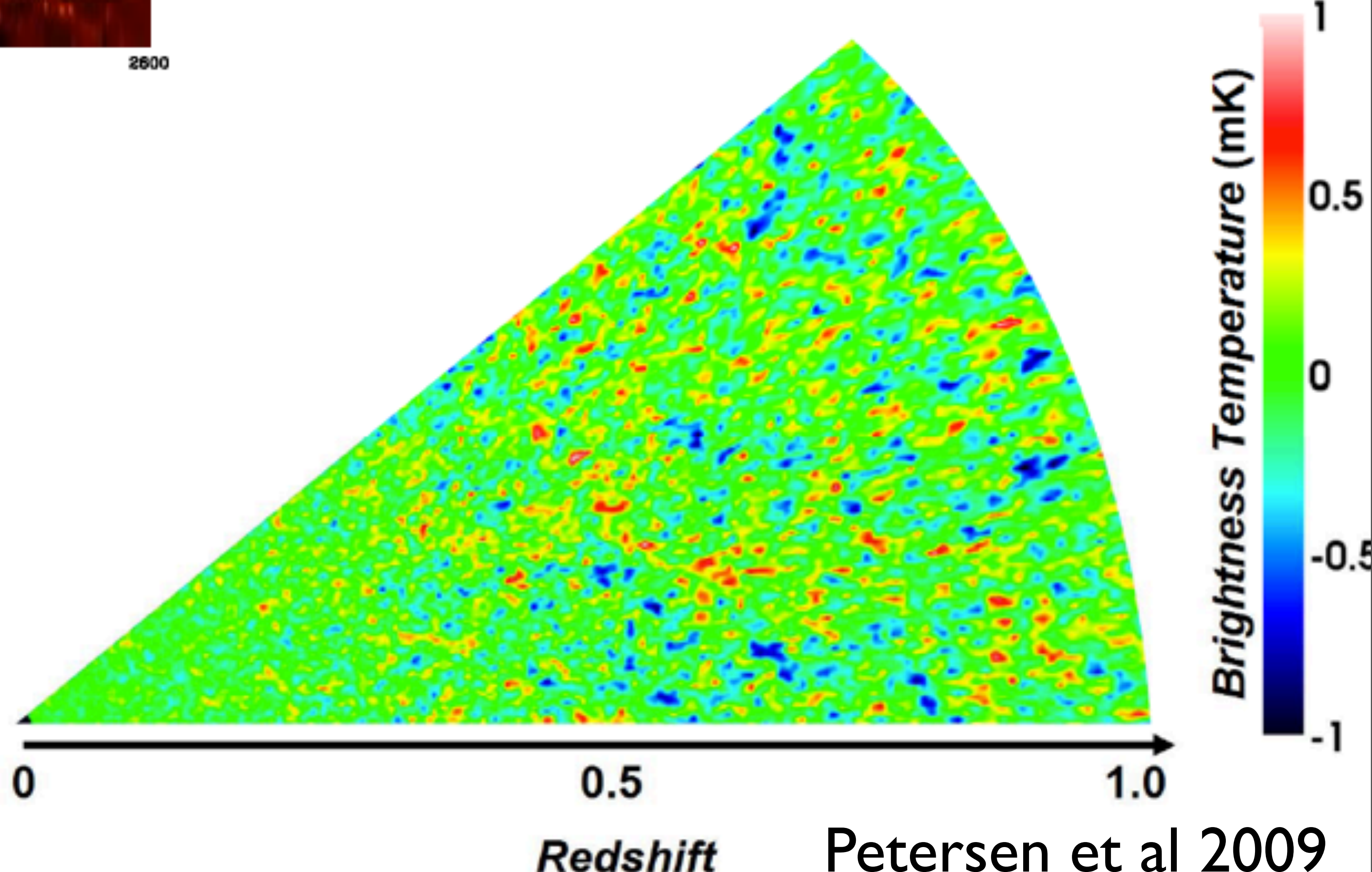
Ross et al (BOSS) 2012

Radio surveys and total intensity mapping



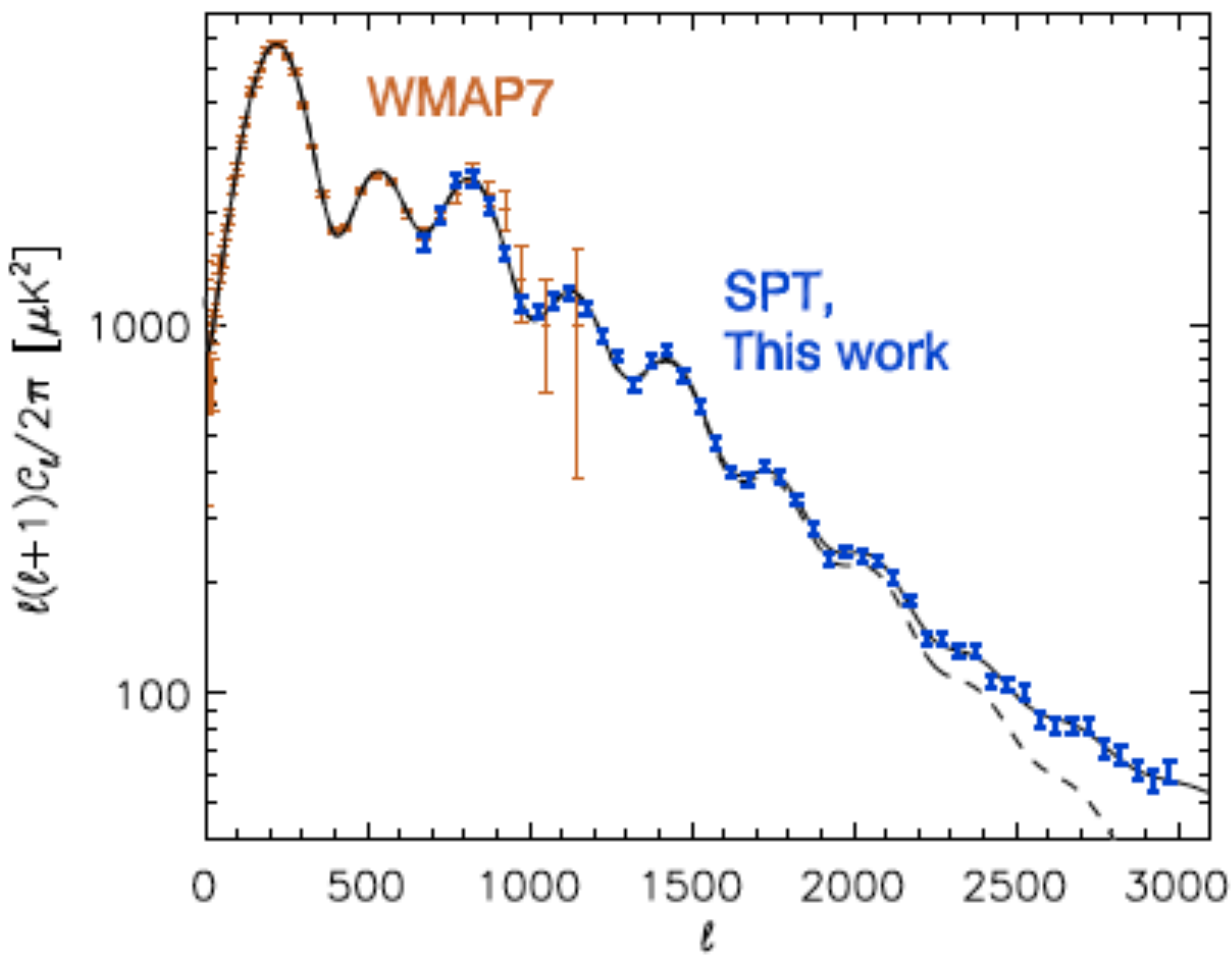


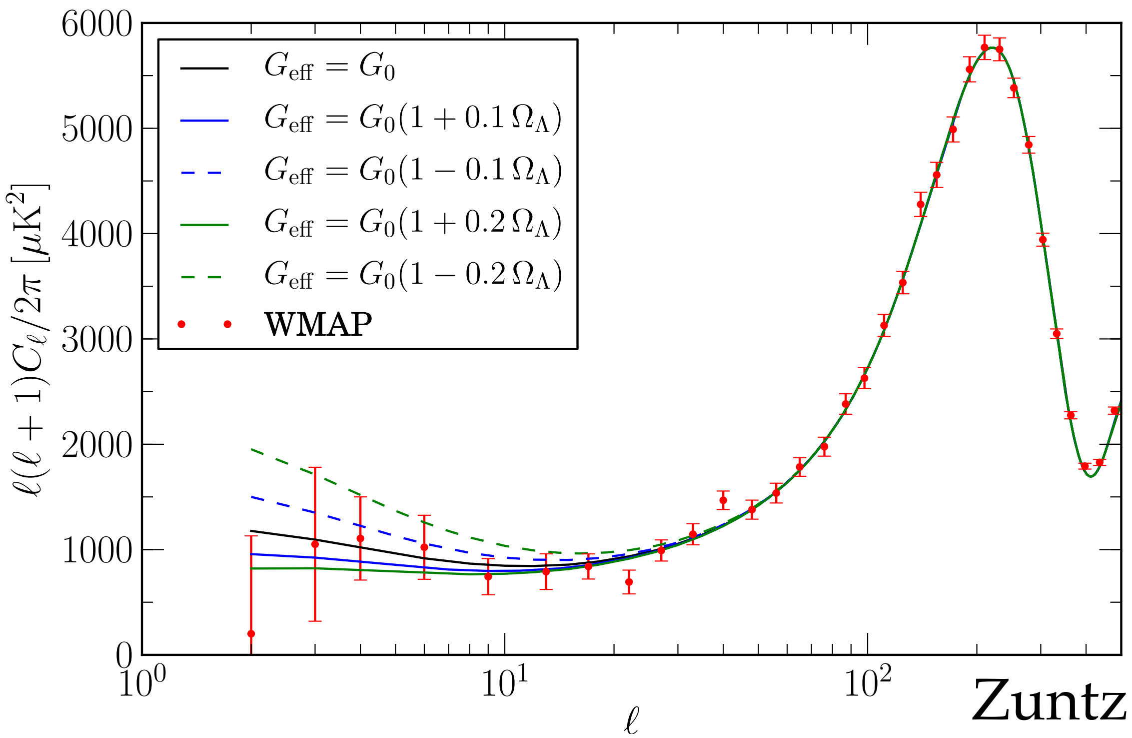
Chang et al 2010



Petersen et al 2009

The Angular Power Spectrum of the CMB





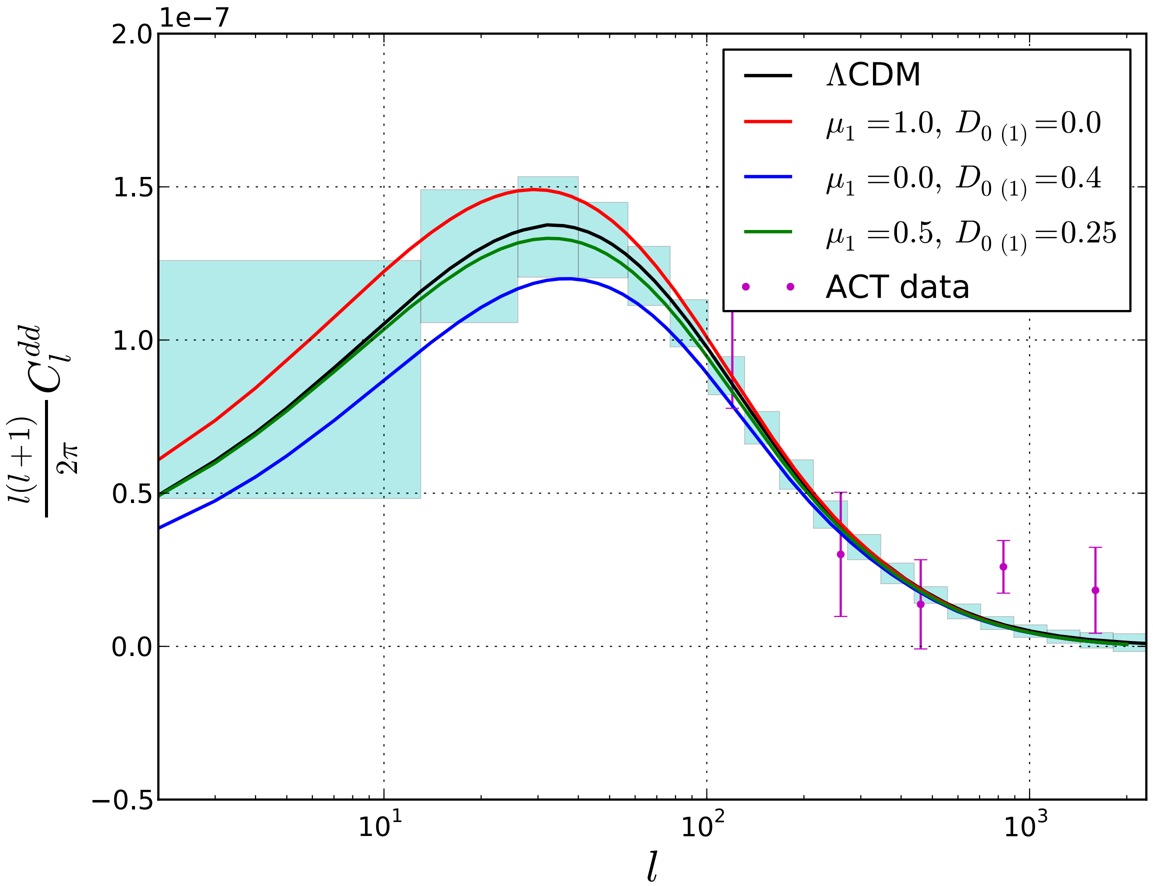
Zuntz *et al.* 2011

ISW- late time effects on large scales

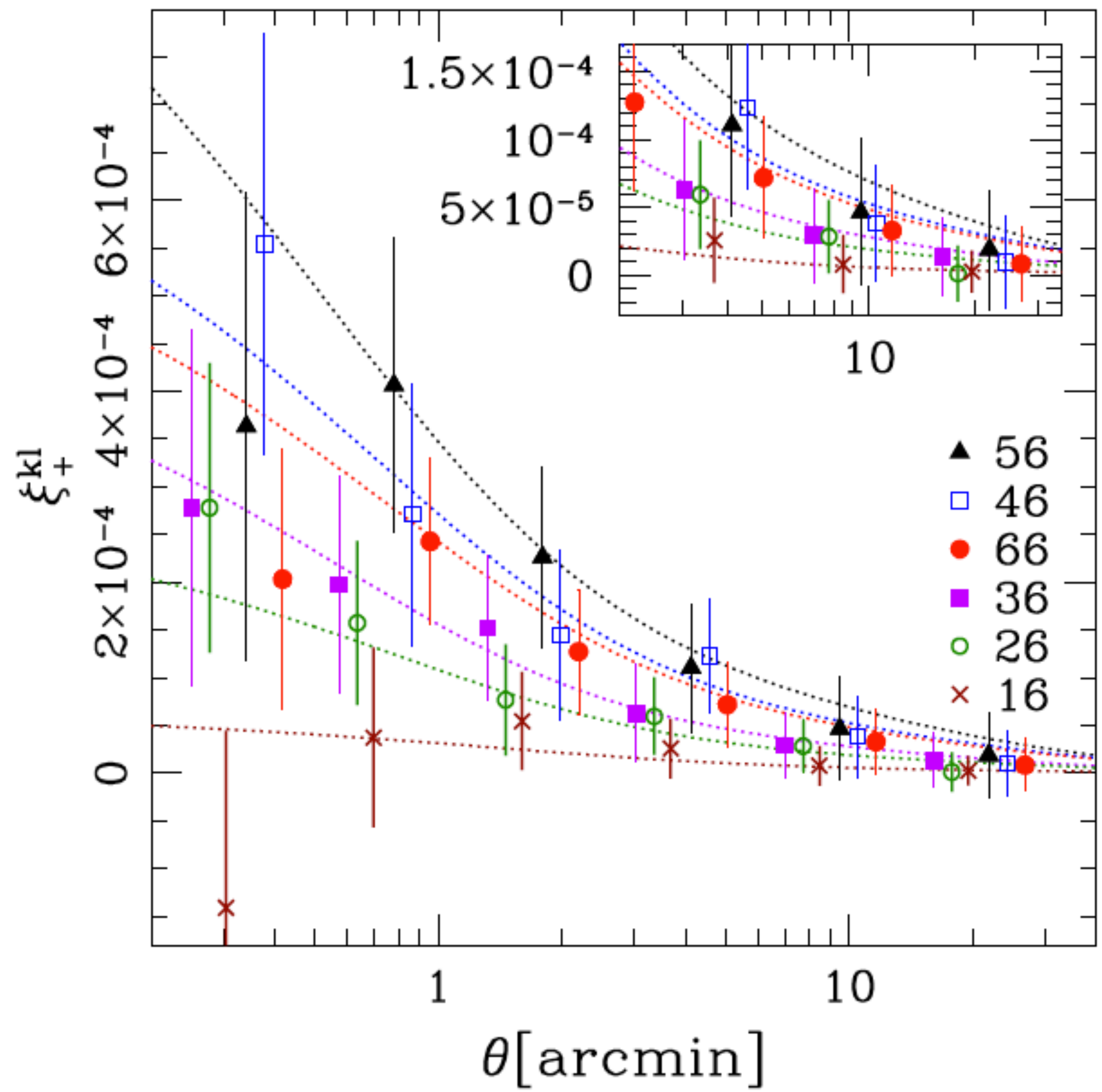
$$\propto \int (\dot{\Phi} + \dot{\Psi}) d\eta$$

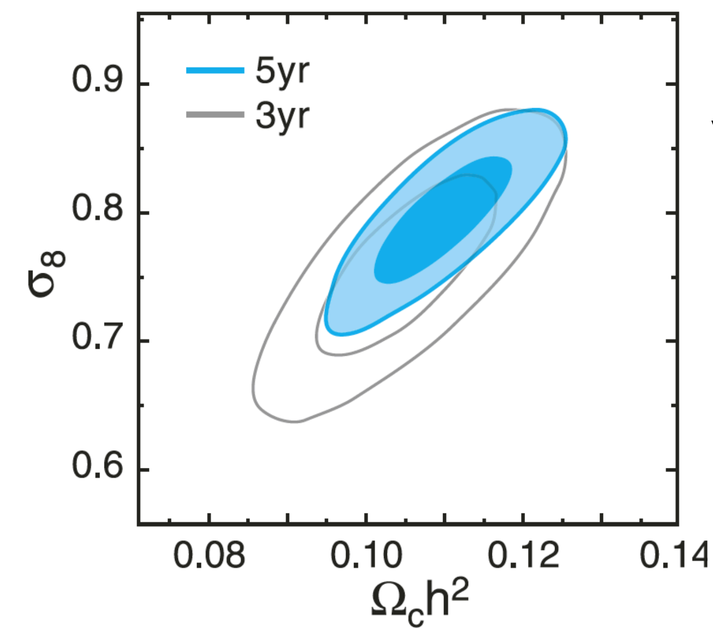
Weak lensing on small scales

$$\propto \int (\Phi + \Psi) d\eta$$

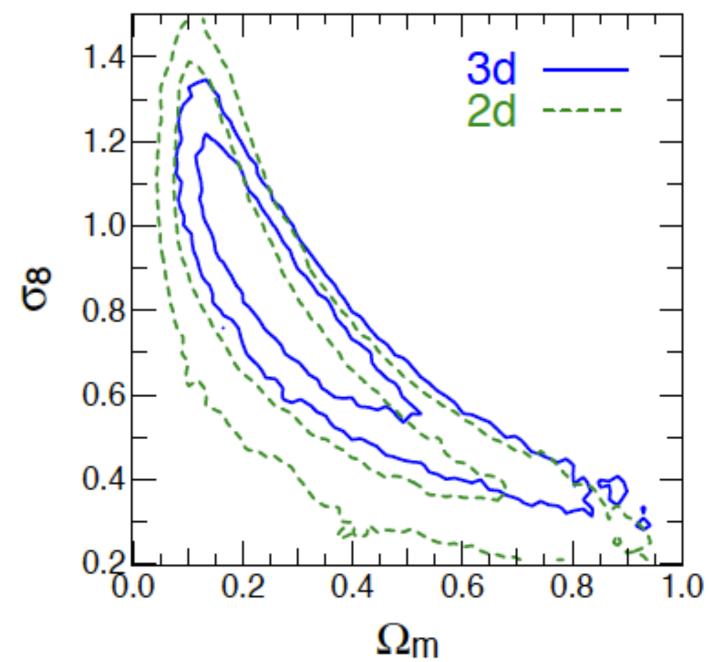


Weak Lensing: state of play



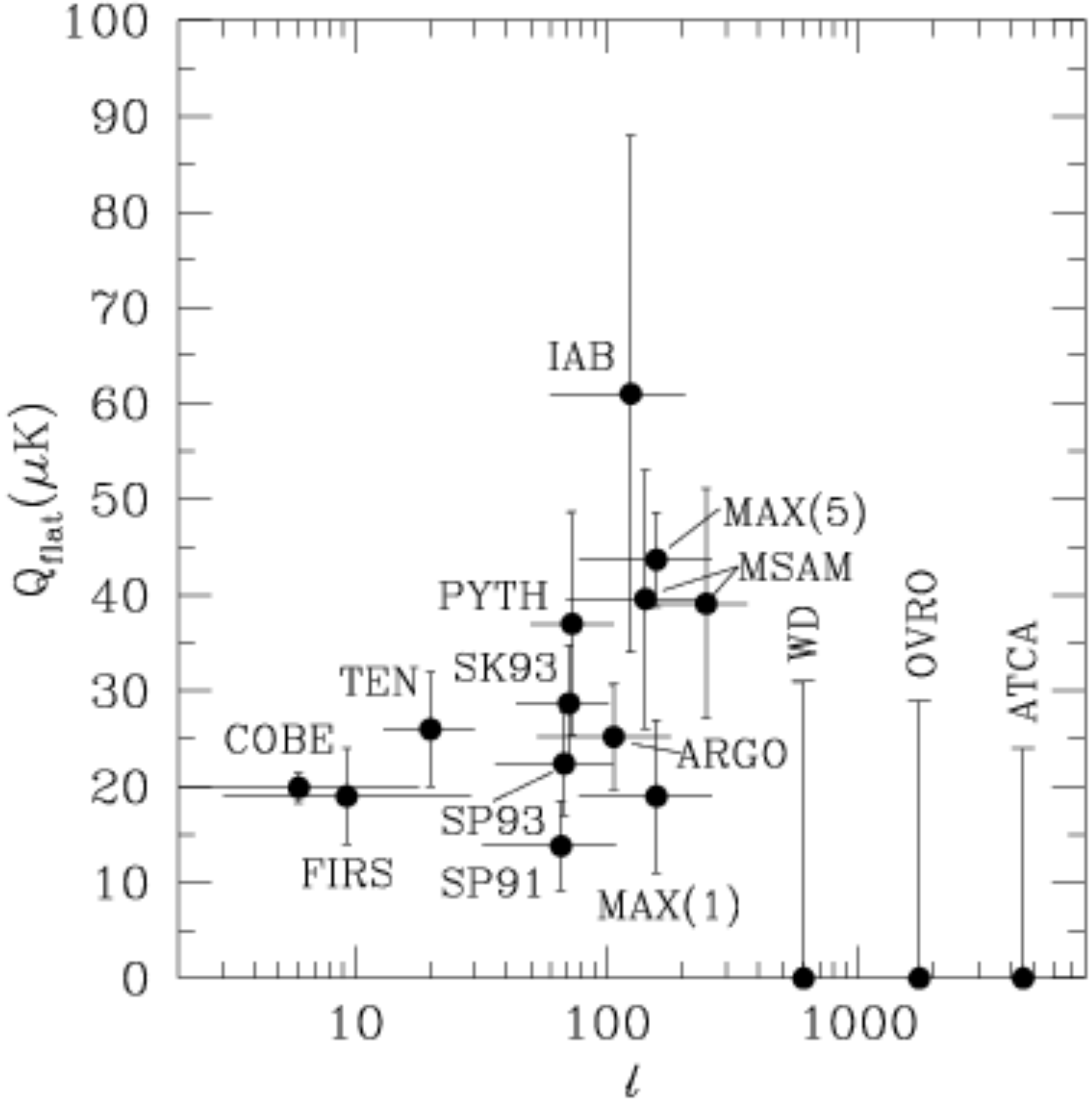


WMAP



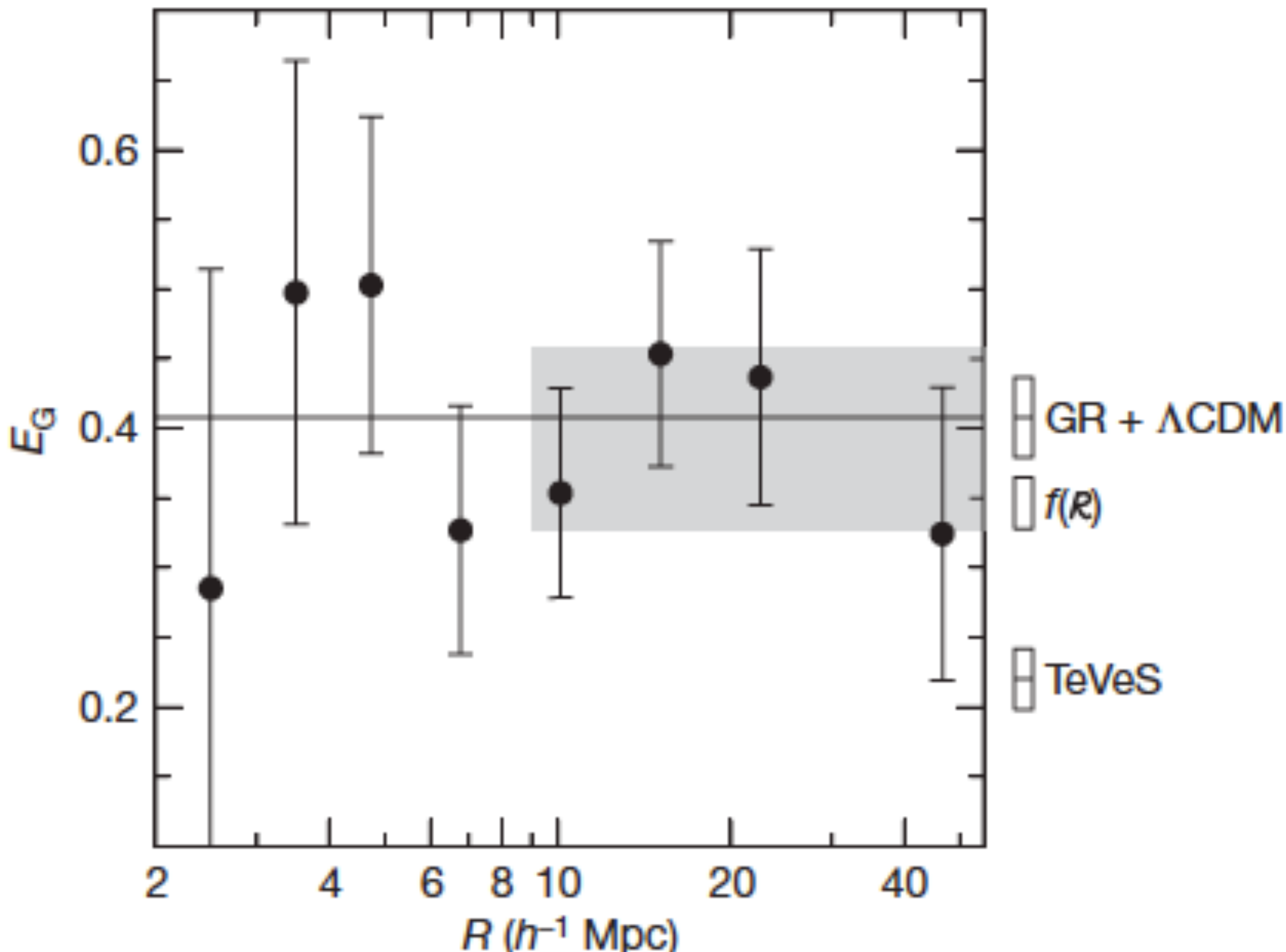
COSMOS: Schrabback et al 2010

CMB circa 1995



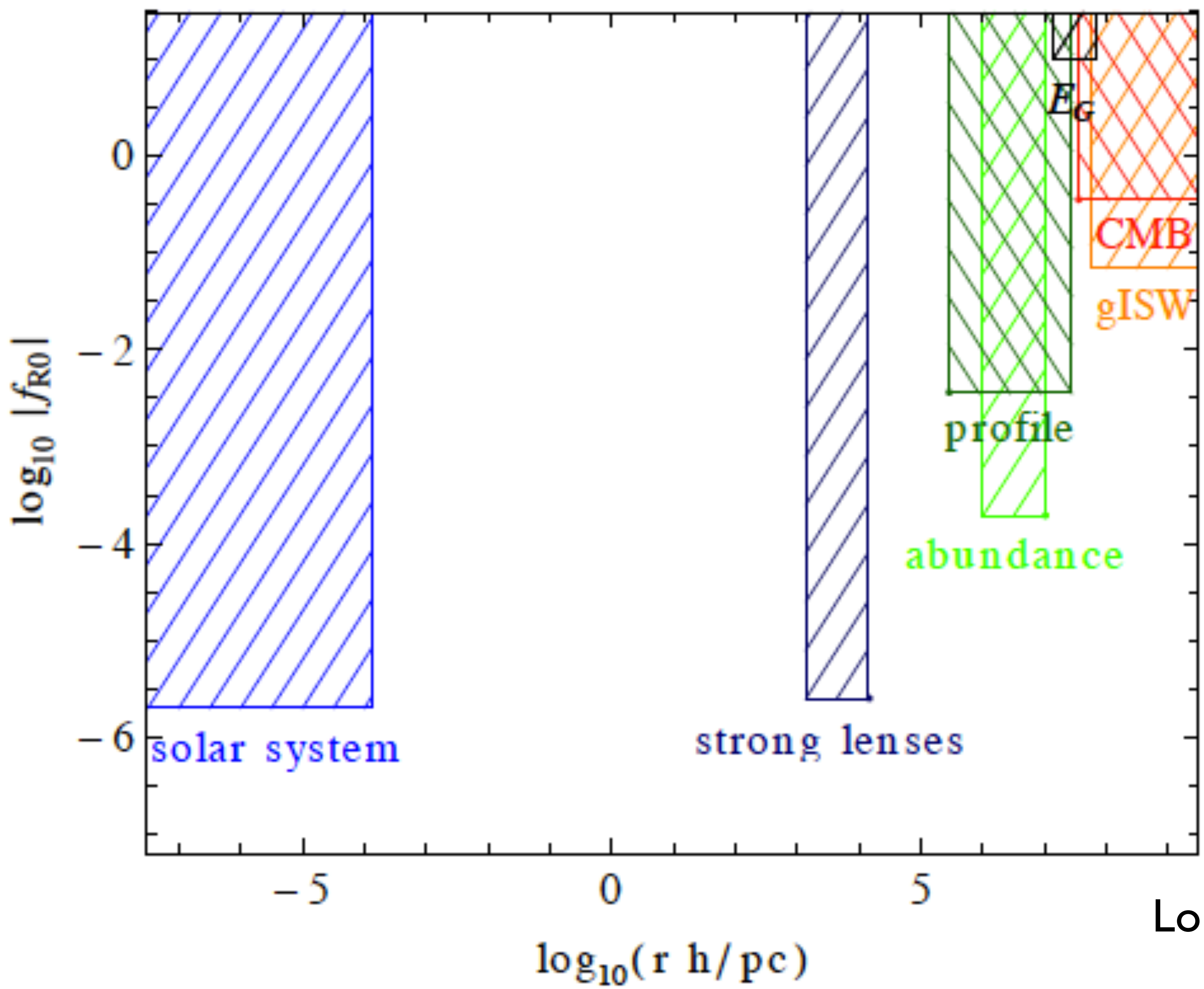
Scott 1995

Cross correlating data sets



Reyes et al 2010

Constraints on $F(R) = 1 + f(R)$



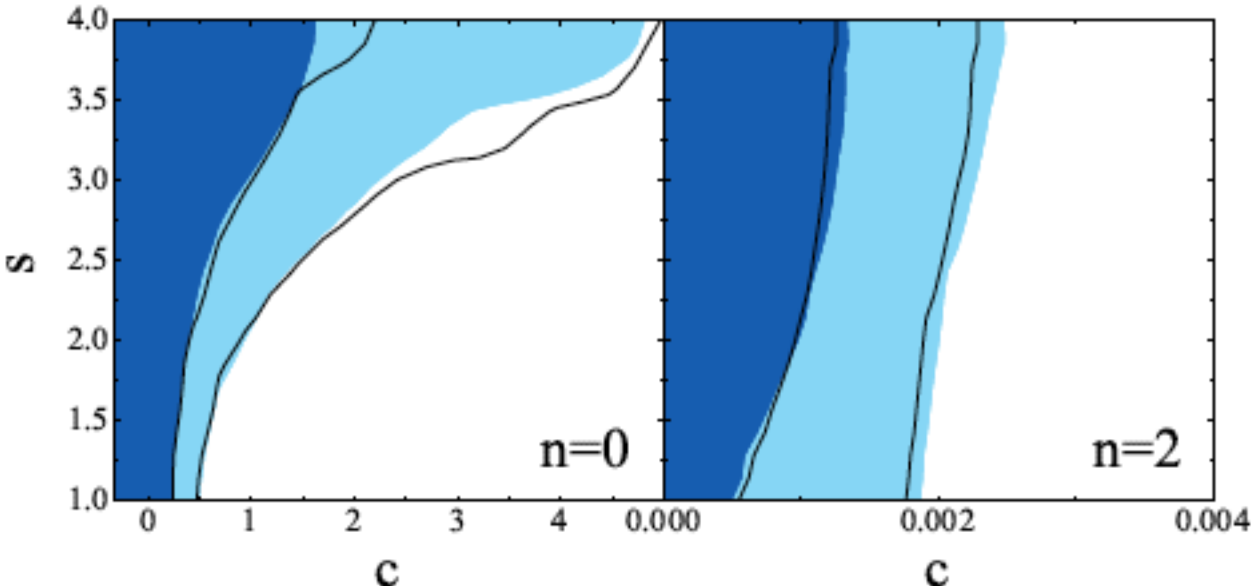
Lombriser et al 2012

Model Independent Constraints

$$-k^2\Phi = 4\pi G\mu a^2\rho\Delta$$

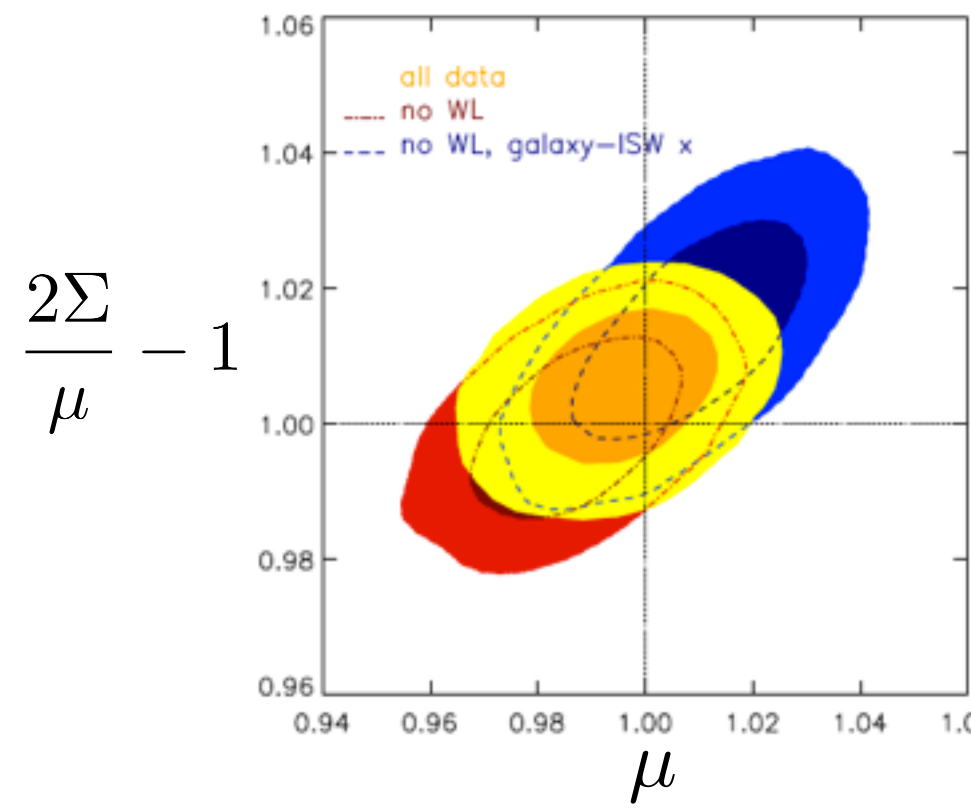
$$-k^2(\Phi+\Psi) = 8\pi G\Sigma a^2\rho\Delta$$

$$\mu = 1 + \frac{c a^s k_H^n}{1+3c a^s k_H^n}, \quad \Sigma = 1\,.$$



Zhao et al 2011

μ, Σ constant

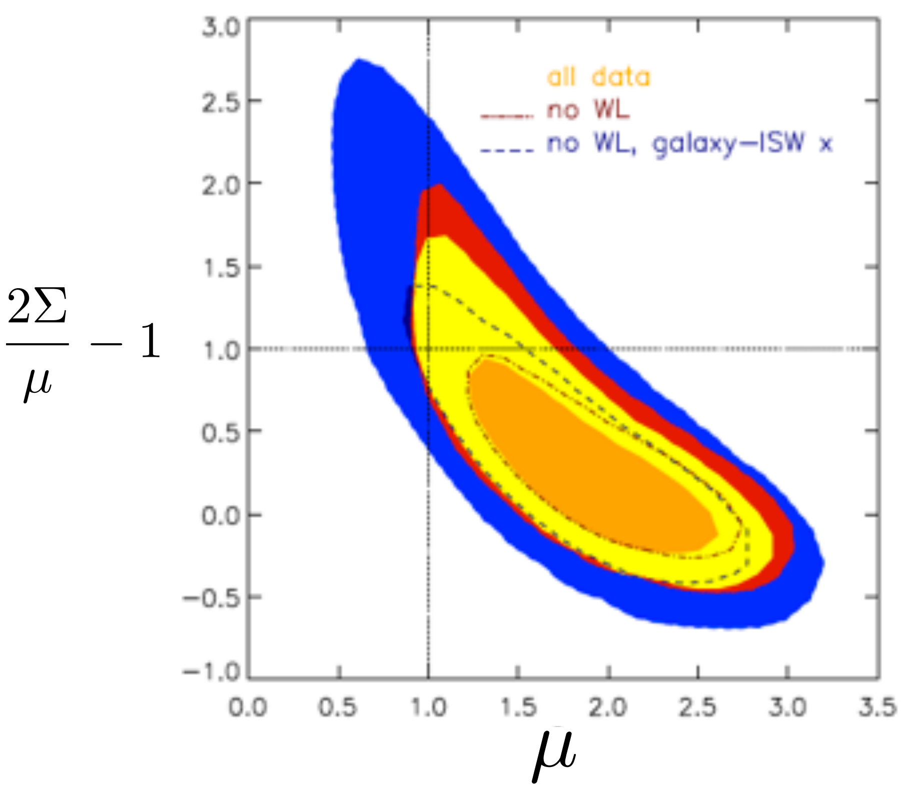


Bean and Tangmatitham 2011

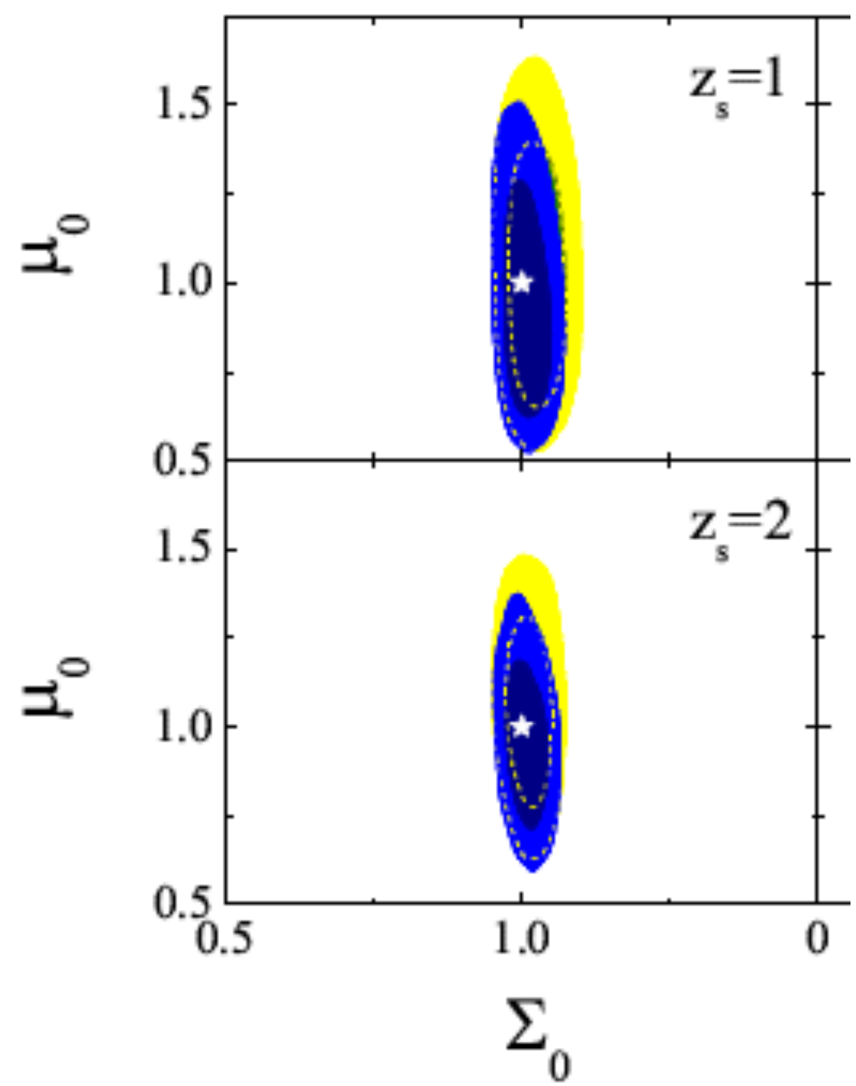
... are not that independent.

Model Independent Constraints

Time and spatial variations in μ, Σ



Bean and Tangmatitham 2011

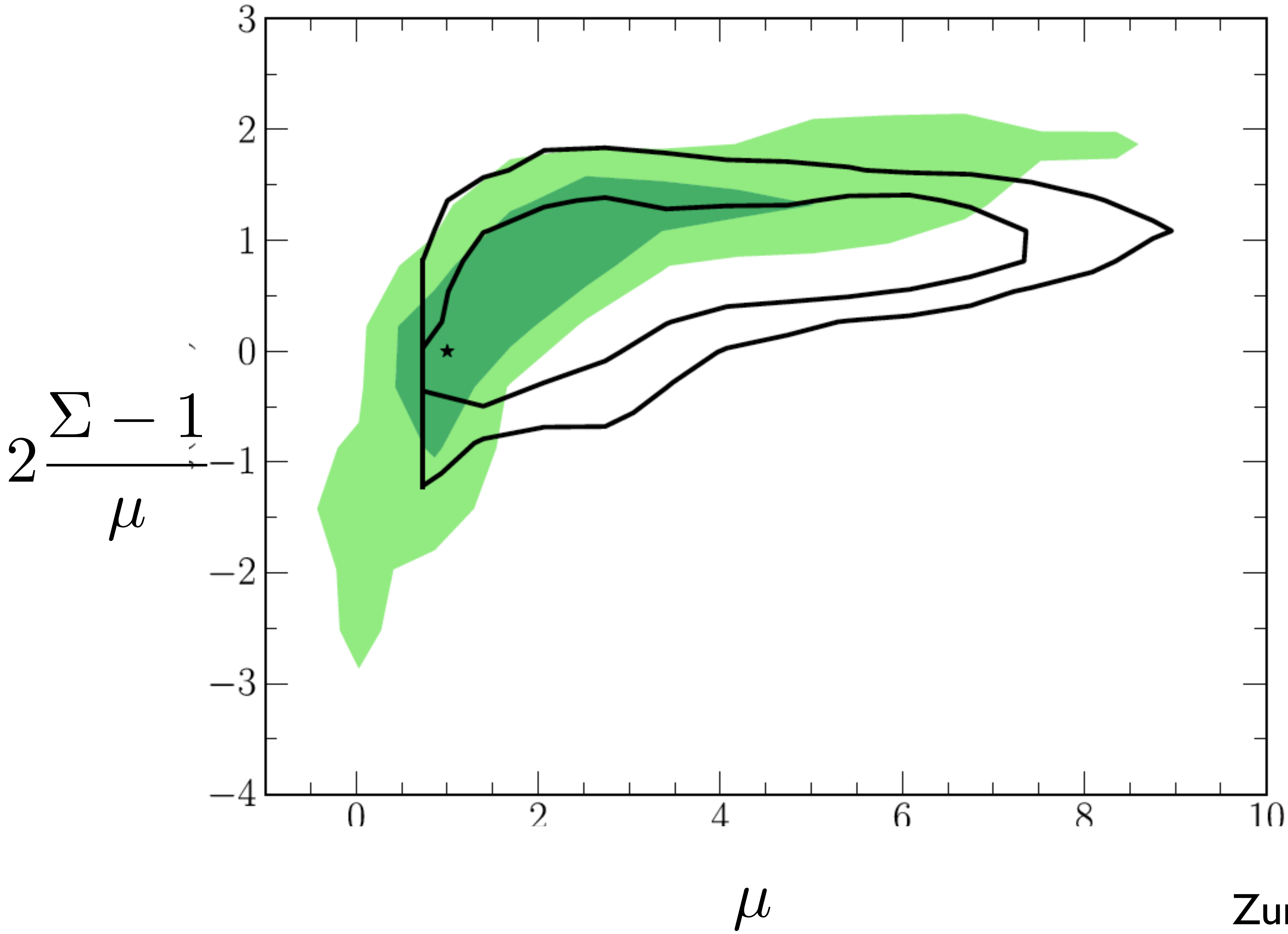


Zhao et al 2011

Dependent on parametrization and combination of data sets.

Friday, 5 October 12

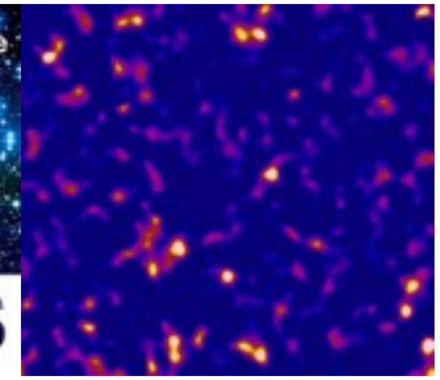
The State of Play



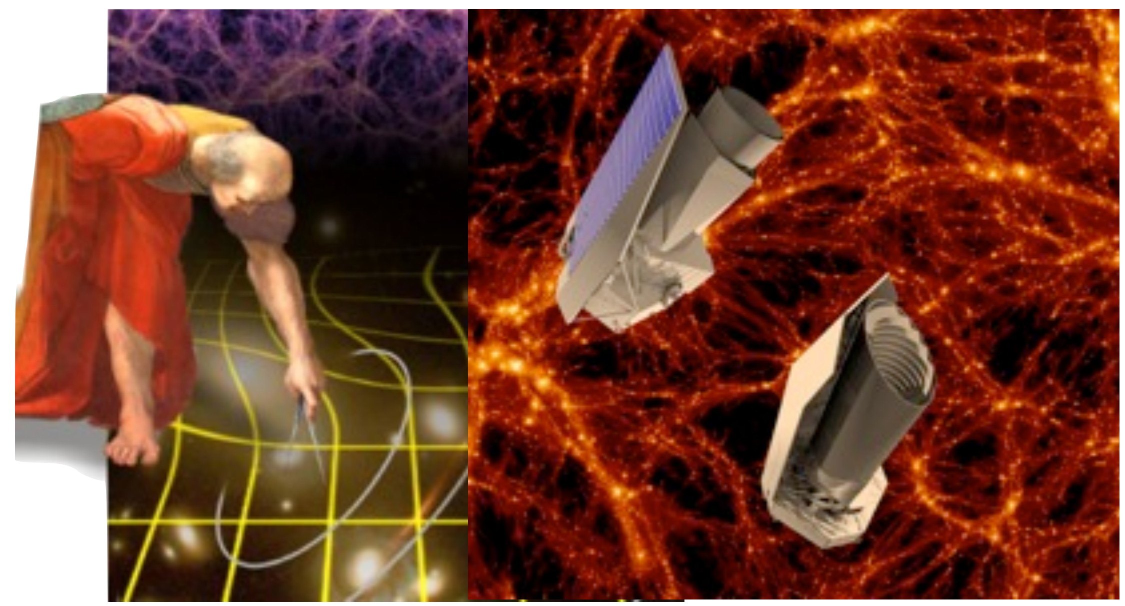
Zuntz et al 2011

The Future

Soon: ground-based galaxy weak lensing.

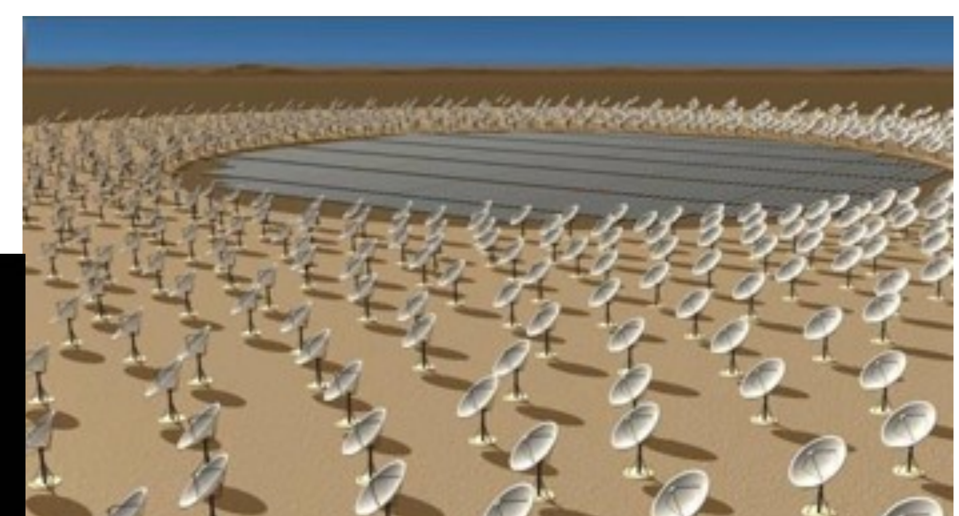


Soon-ish (2020): Euclid mission. Space-based weak lensing and redshift-space distortions.

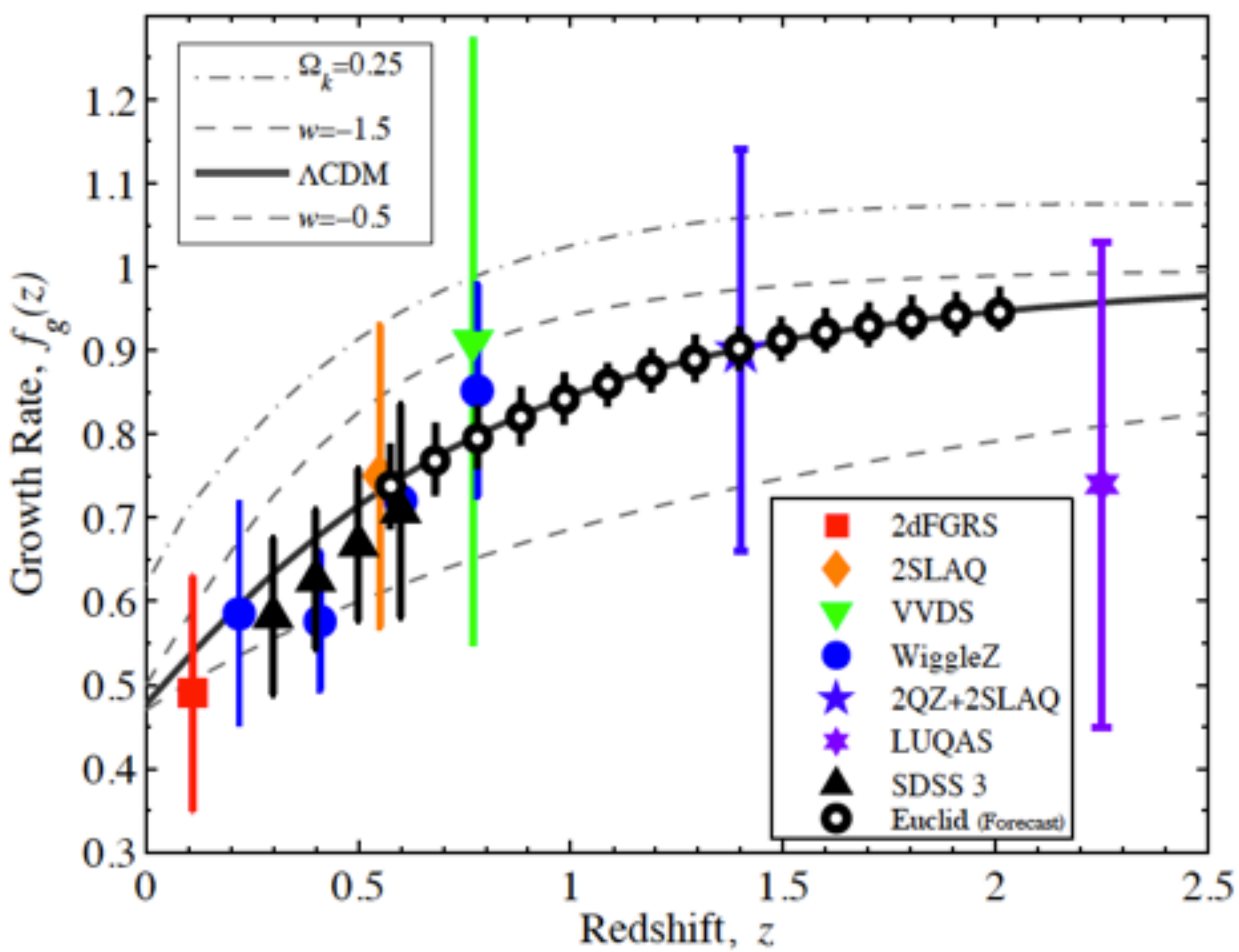


The future? The Square Kilometer Array (2020 onwards). An almighty survey of radio galaxies to high z ⇒ RSDs,

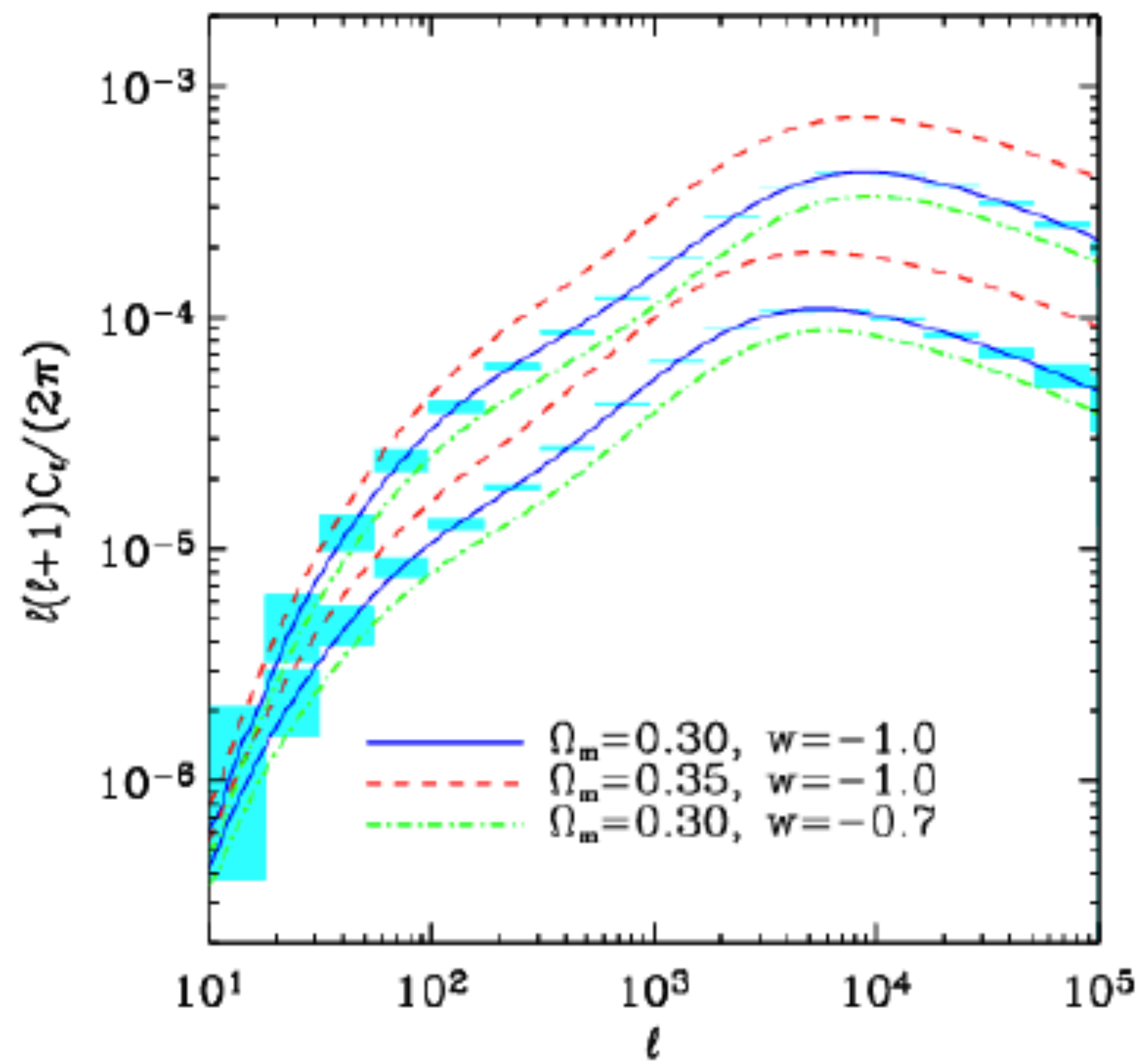
peculiar velocities, BAO; also continuum mapping.



The Future



Ω_k=0.25
w=-1.5
ΛCDM
w=-0.5
2dFGRS
2SLAQ
VVDS
WiggleZ
2QZ+2SLAQ
LUQAS
SDSS 3
Euclid (Forecast)
Growth Rate, $f_g(z)$
Redshift, z



Ω_m=0.30, w=−1.0
Ω_m=0.35, w=−1.0
Ω_m=0.30, w=−0.7
$\ell(\ell+1)C_\ell/(2\pi)$
ℓ

Summary

- The large scale structure of the Universe can be used to test gravity.
- There is a immense landscape of gravitational theories.
- We need a unified framework- “PPF”- for constraining such theories.
- We need to focus on linear scales (for now) although non-linear scales can be incredibly powerful.
- Signatures on large scales and growth rate.
- There are a plethora of new experiments to look forward to.

Collaborators

- Tessa Baker (Oxford)
- Tim Clifton (QMW)
- Tony Padilla (Nottingham)
- Constantinos Skordis (Nottingham)
- Mario Santos (IST/Lisbon)
- Joseph Zuntz (Oxford/UCL)