

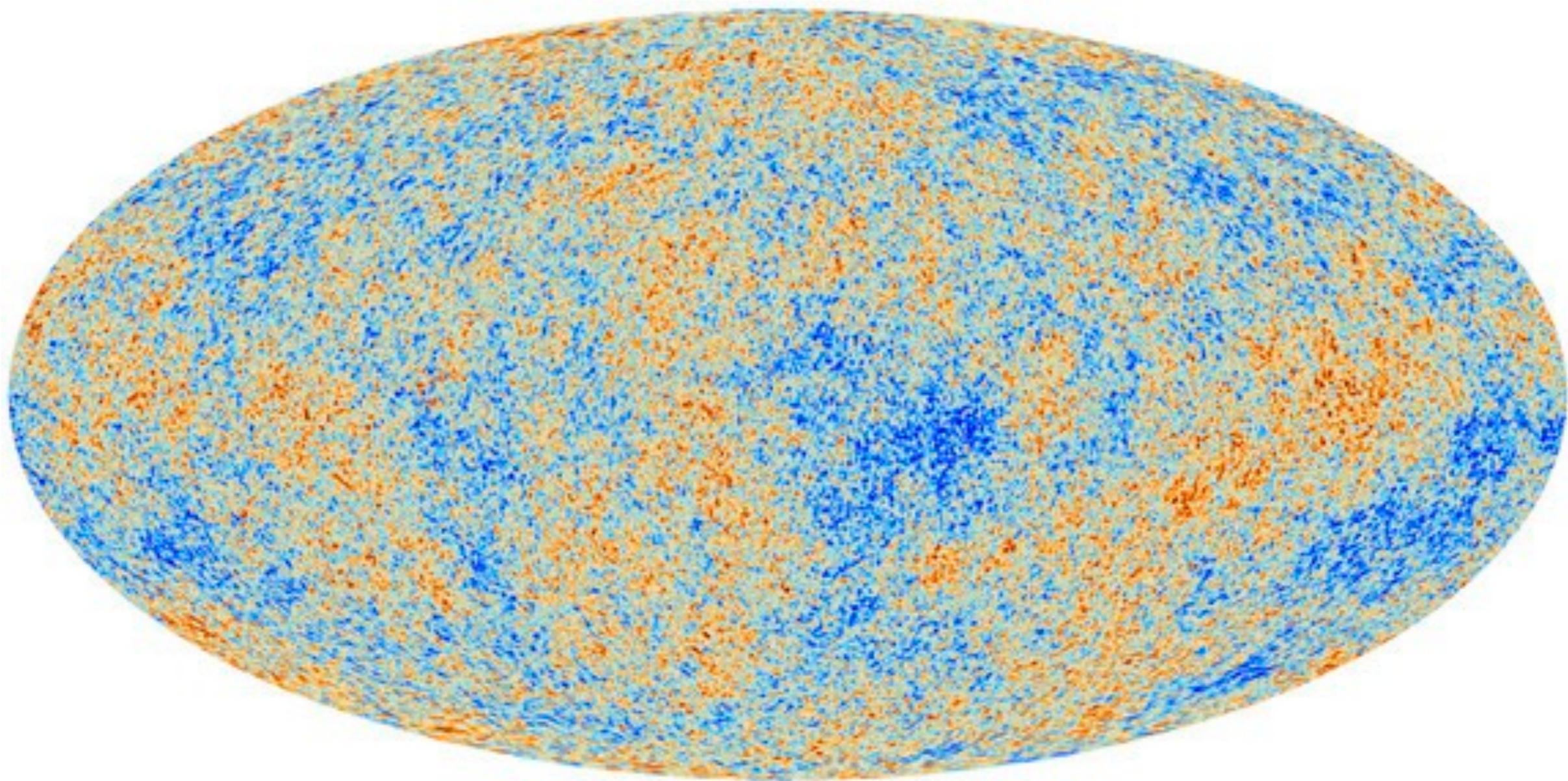
Gravity from Cosmology

Pedro G. Ferreira
University of Oxford

The state of General Relativity in 1957

“There exists... one serious difficulty, and that is the lack of experiments. Furthermore, we are not going to get any experiments, so we have to take the viewpoint of how to deal with the problems where no experiments are available. ... the best viewpoint is to pretend that there are experiments and calculate. In this field we are not pushed by experiments but pulled by imagination.”

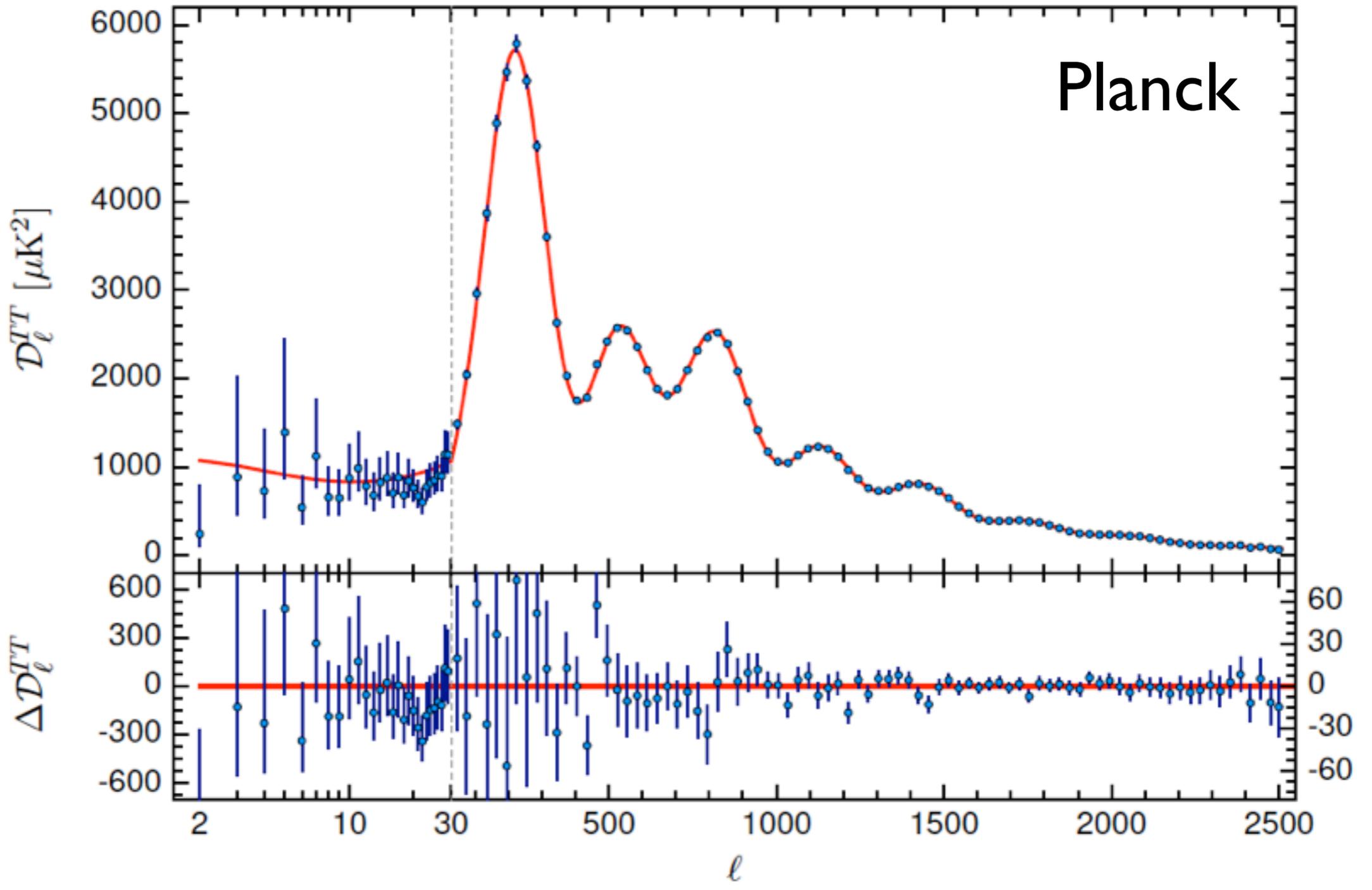
R. Feynman, Chapel Hill workshop on gravitation (1957)

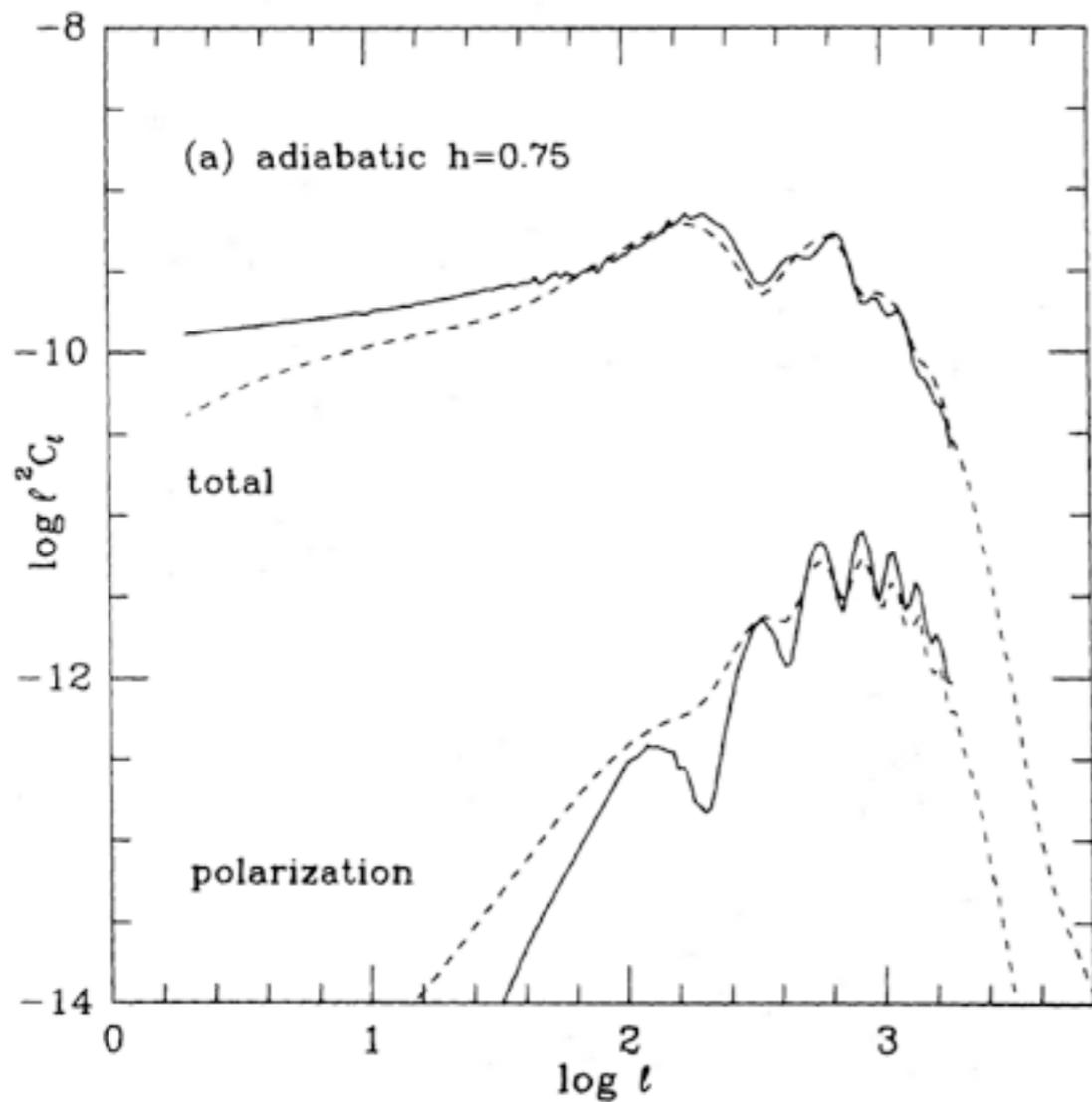


Planck 2015

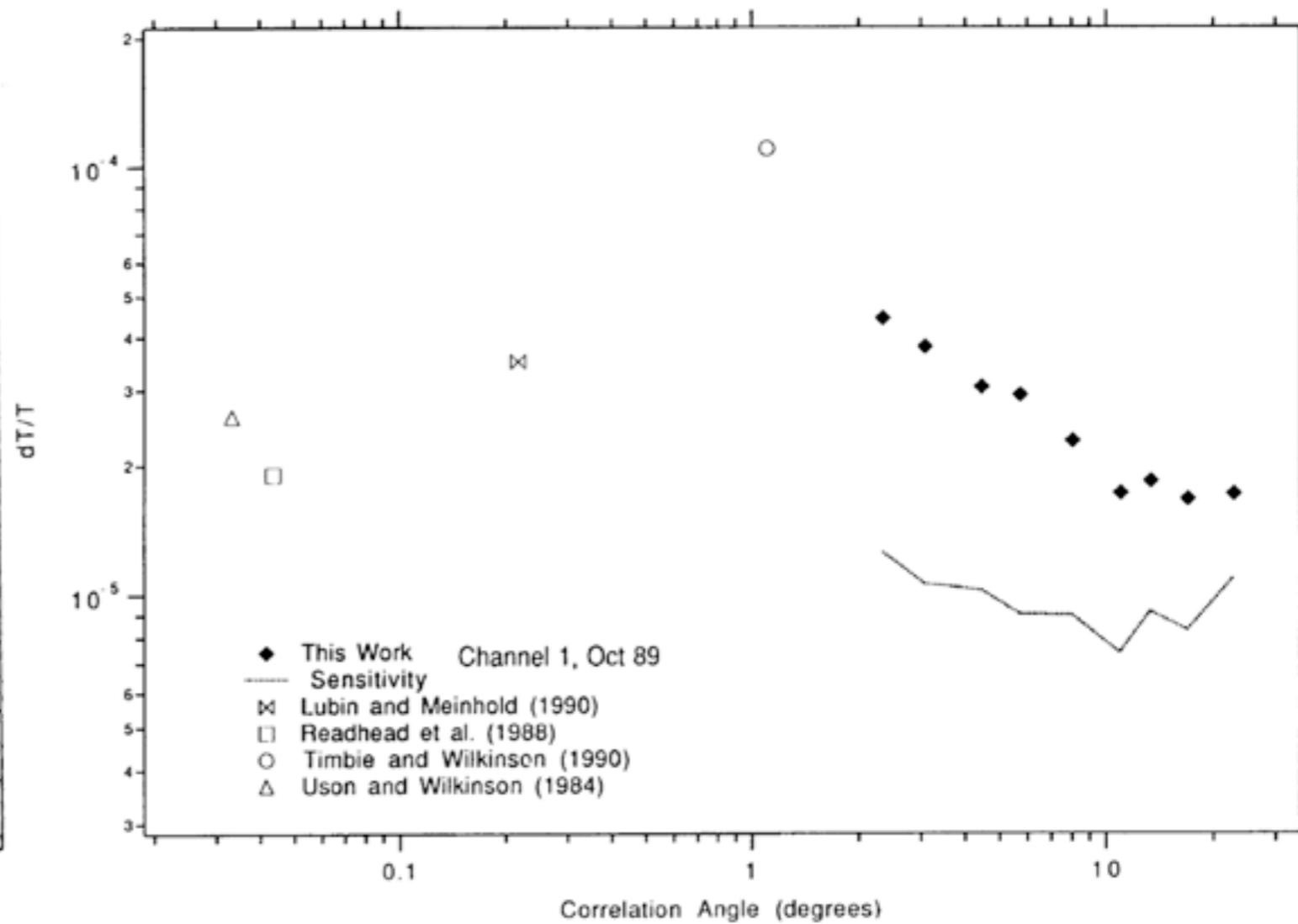
variance of fluctuations

← large scales small scales →

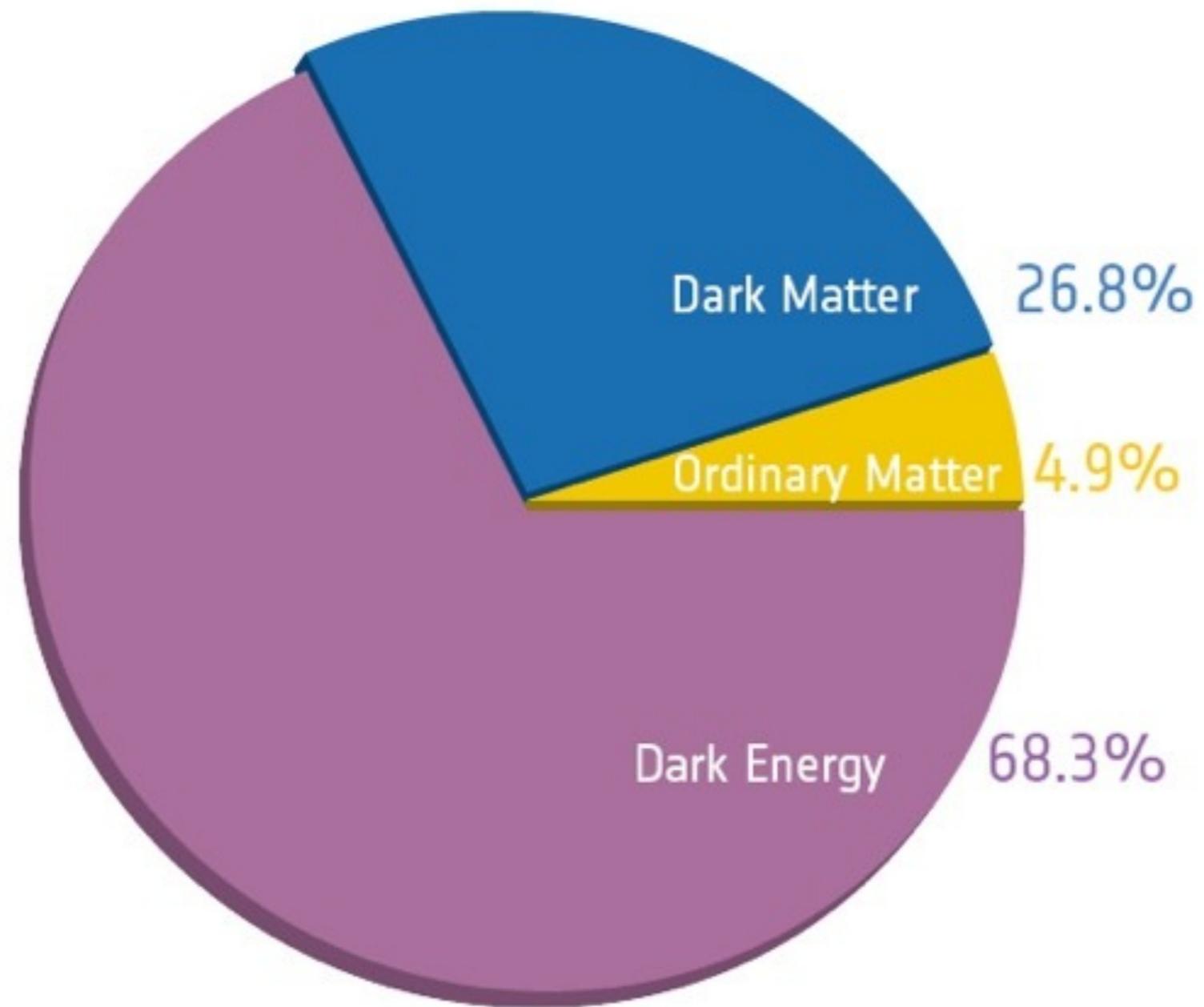




Bond & Efstathiou 1987

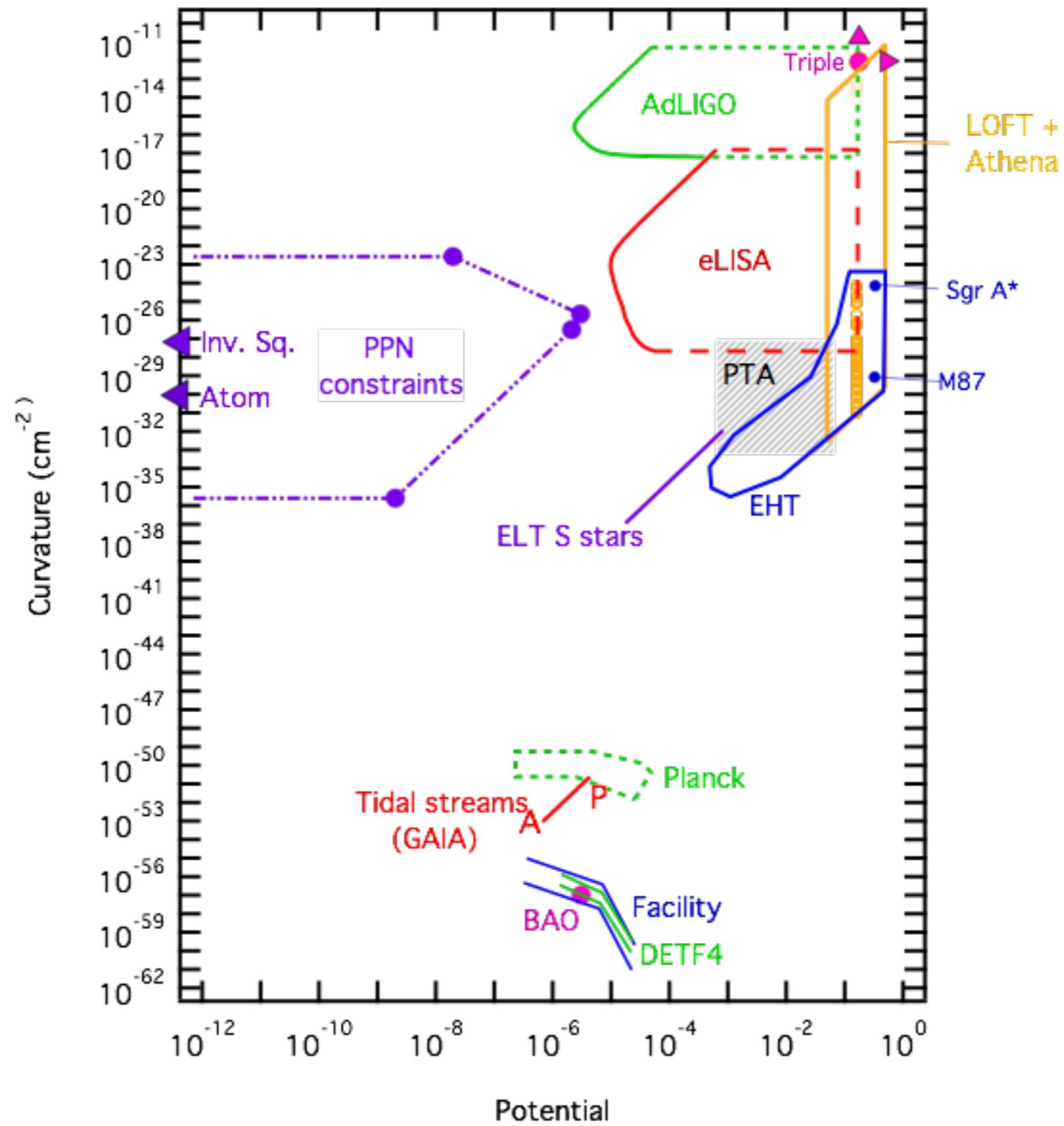


Meyer, Cheng and Page 1991



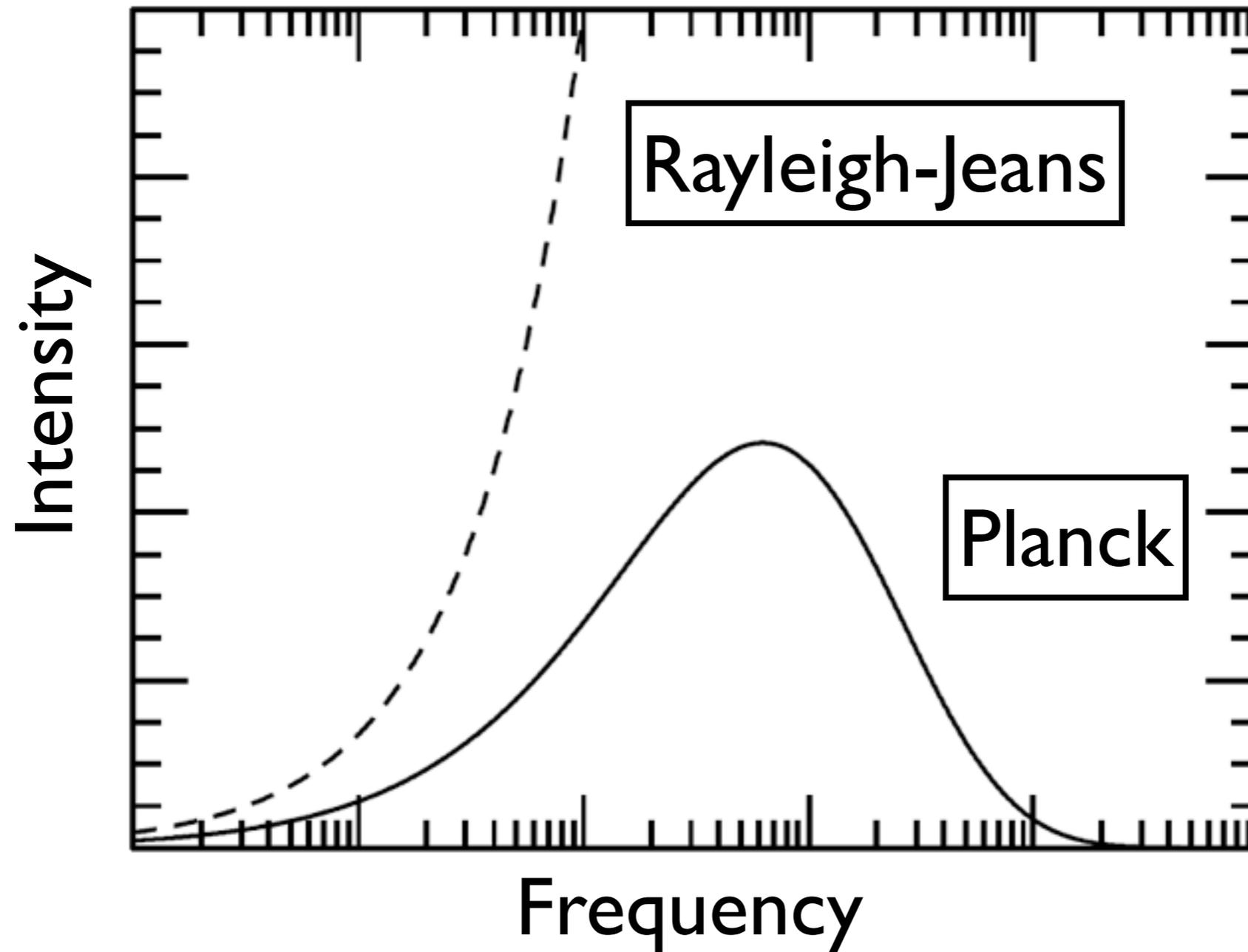
“The elegant logic of general relativity theory, and its precision tests, recommend GR as the first choice for a working model for cosmology. But the Hubble length is fifteen orders of magnitude larger than the length scale of the precision tests, at the astronomical unit and smaller, a spectacular extrapolation.”

Jim Peebles, IAU 2000



(Baker, Psaltis & Skordis 2014)

Big puzzles ...



... small inconsistencies.

- Lamb shift
- Wu parity violation experiment
- Fitch-Cronin CP violation
- Precession of perihelion of Mercury

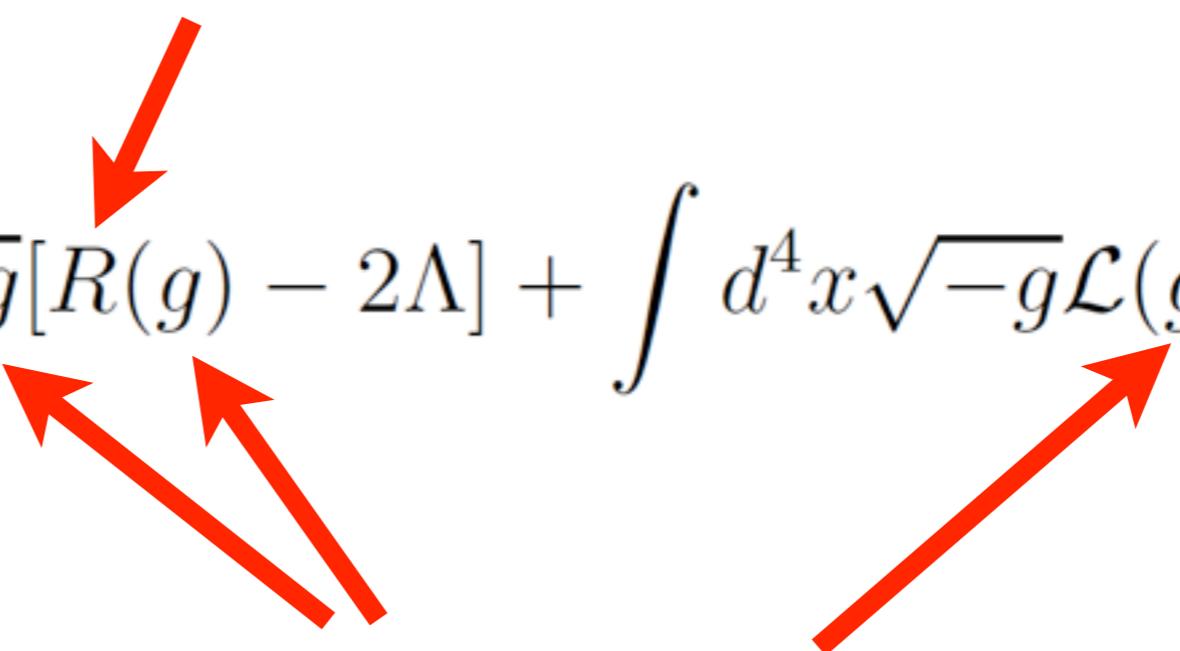
The Theory

Einstein Gravity

Curvature

$$\frac{1}{16\pi G} \int d^4x \sqrt{-g} [R(g) - 2\Lambda] + \int d^4x \sqrt{-g} \mathcal{L}(g, \text{matter})$$

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.”*

See also Hojman, Kuchar & Teitelboim (1976)

The view from field theory

Feynman/Weinberg
Theorem

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$$
$$\square h_{\mu\nu} = 16\pi G(T_{\mu\nu}^M + T_{\mu\nu}^G)$$

Spin-2 field

Feynman (1963)
Weinberg (1965)
Deser (1970)

Unique non-linear completion is GR...

Effective Field Theory

$$\frac{M_p^2}{2}R + a_2R^2 \sim \frac{M_p^2}{2}R \left(1 + 2a_2\frac{R}{M_p}\right) \quad \text{but} \quad \frac{R}{M_p} \ll 1$$

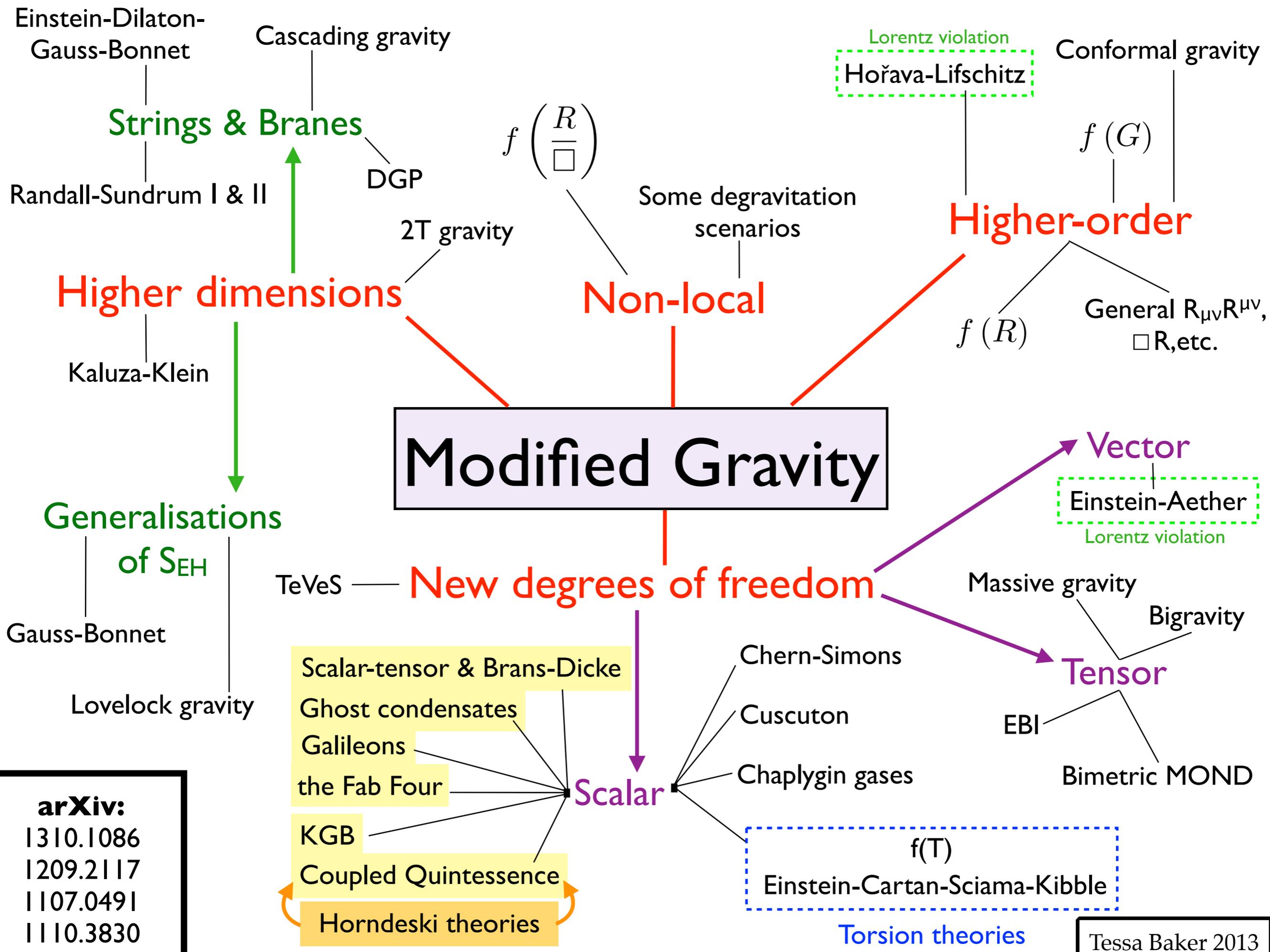
Deviations from GR unlikely in low R and late times ...

Jordan-Brans-Dicke Theory

One free parameter

$$S = \int d^4x \sqrt{-g} \left[\phi R - \frac{\omega_{\text{BD}}}{\phi} \nabla_\mu \phi \nabla^\mu \phi + V + \mathcal{L}_M[g_{\mu\nu}, \varphi] \right]$$


Cassini (Bertotti et al 2003) $\omega_{\text{BD}} > 40,000$



arXiv:
 1310.1086
 1209.2117
 1107.0491
 1110.3830

Tessa Baker 2013

Extra degrees of freedom

metric \longrightarrow add ϕ , A^μ , $f_{\alpha\beta}$ etc.

4D \longrightarrow e.g. in 5 dimensions:

$$g_{AB} = \begin{pmatrix} g_{\alpha\beta} & A_\alpha \\ A_\beta & \phi \end{pmatrix}$$

2nd order \longrightarrow e.g. if $\int d^4x \sqrt{-g} f(R)$ define $\phi = \frac{df}{dR}$.

Local \longrightarrow e.g. $\phi = \frac{R}{\square}$.

All transform differently under diffeomorphisms

Background

$$ds^2 = g_{\mu\nu}^{(0)} dx^\mu dx^\nu = -dt^2 + a^2(t)(d\vec{x})^2$$

$$G_{\alpha\beta} = 8\pi G T_{\alpha\beta} + \underline{U}_{\alpha\beta}$$

where $U_{\alpha\beta}(a, \dot{a}, \rho_M, P_M, \phi, \dots)$ $P_X = \underline{w}\rho_X$

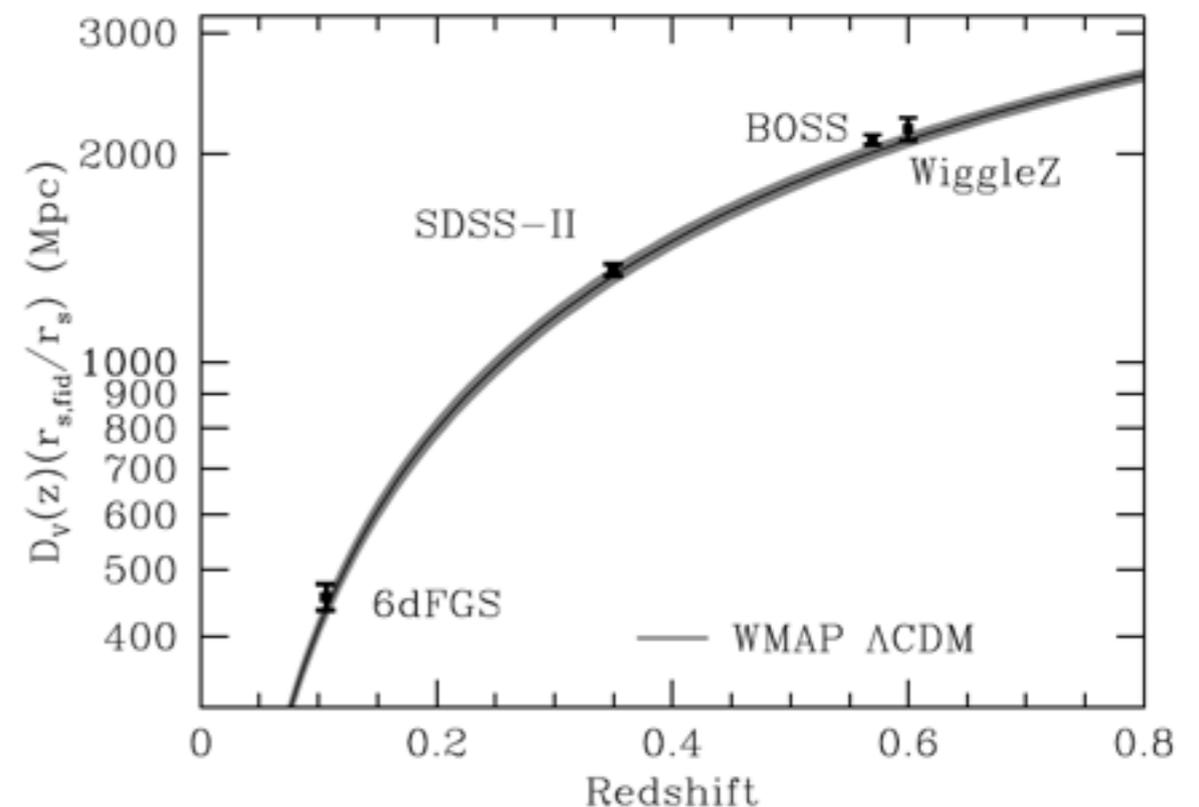
Homogeneity and isotropy

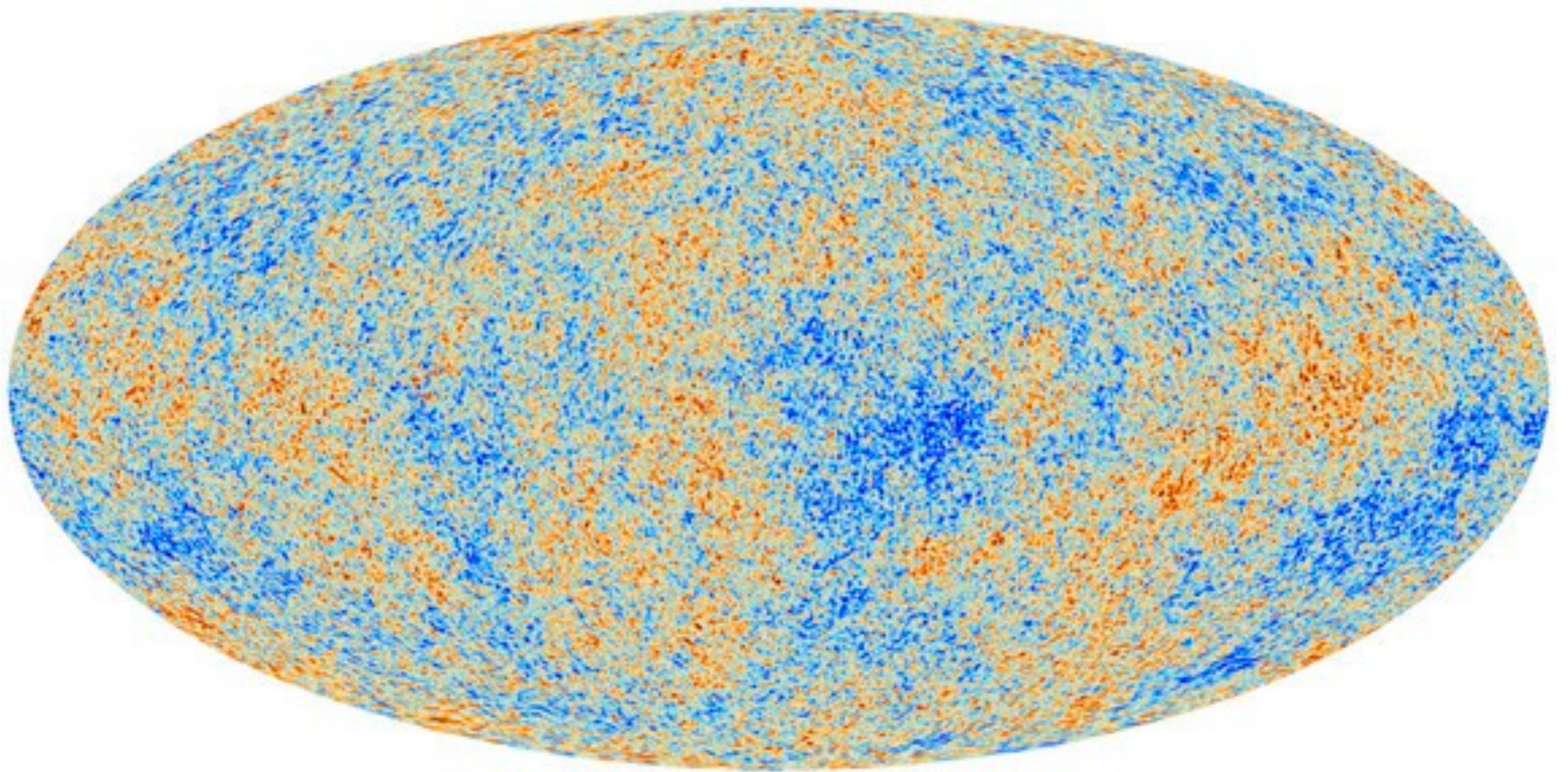
$$U_{\alpha\beta} = 8\pi G \begin{pmatrix} \rho_X & 0 \\ 0 & a^2 P_X \delta_{ij} \end{pmatrix}$$

Bianchi identities

$$\nabla^\alpha [8\pi G T_{\alpha\beta} + U_{\alpha\beta}] = 0$$

BOSS, Anderson et al 2013.





$$\frac{\delta T}{T} \sim 10^{-5}$$



linear perturbation theory

Linear Perturbations

$$g_{\alpha\beta} = g_{\alpha\beta}^{(0)} + h_{\alpha\beta}$$

$$\rho_M = \bar{\rho}_M (1 + \delta_M)$$

$$\phi = \phi_0 + \delta\phi$$

Construct most general quadratic action which has:

- upto 2nd order in time derivatives
- $h_{\alpha\beta} \rightarrow h_{\alpha\beta} + \nabla_\alpha \xi_\beta + \nabla_\beta \xi_\alpha$ where $x^\alpha \rightarrow x^\alpha + \xi^\alpha$
- inherits symmetries of the background

Linear Perturbations

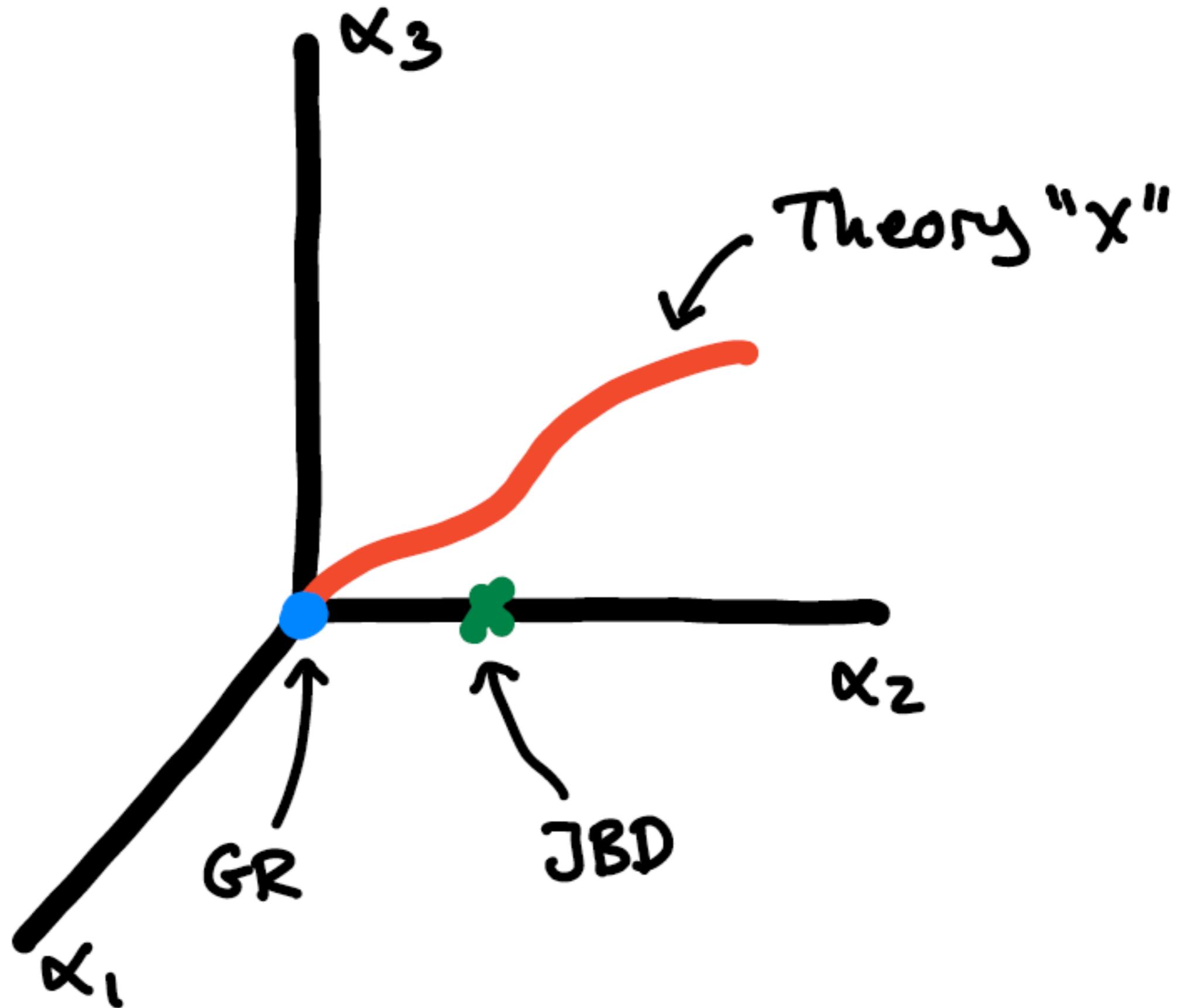
$$S = \int d^4x \sqrt{-g^{(0)}} \left[\alpha_1 \nabla^\mu h^{\alpha\beta} \nabla_\mu h_{\alpha\beta} + \alpha_2 \nabla^\mu h^{\alpha\beta} \nabla_\alpha h_{\mu\beta} \right. \\ \left. + \alpha_3 \nabla^\mu h \nabla^\alpha h_{\mu\alpha} + \alpha_4 \nabla^\mu h \nabla_\mu h + \alpha_5 \nabla^\mu h_{\mu\alpha} \nabla^\alpha \delta\phi + \dots \right]$$

Properties:

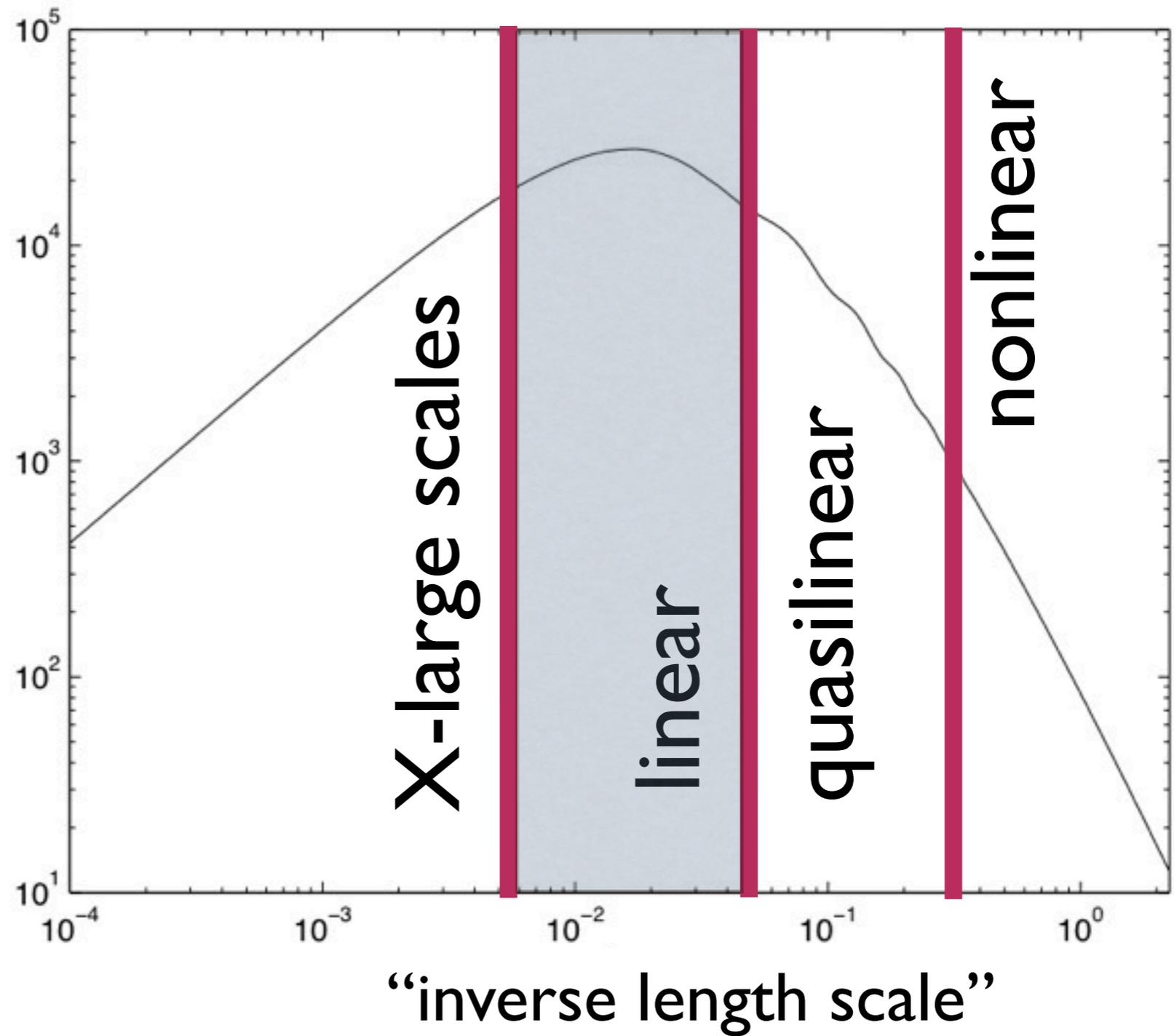
- $(\alpha_1, \alpha_2, \dots)$ are functions of t
- $\alpha_X(t)$ depend on transf. props of extra fields
- clear mapping theory $\longleftrightarrow \alpha_X(t)$
- clear physical interpretation of each $\alpha_X(t)$

Examples:

- Scalar-tensor (Horndeski): five $\alpha_X(t)$
- Vector-tensor (Einstein-Aether, Proca): nine $\alpha_X(t)$
- Tensor-tensor (Bigravity, massive gravity): three $\alpha_X(t)$



“amplitude of clustering”



$$N(k) \propto k^3$$

More statistical power 

The Data

A preferred length scale- the horizon

$$\mathcal{H}^{-1} \equiv \left(\frac{\dot{a}}{a} \right)^{-1} \propto \tau \simeq 3000 h^{-1} \text{Mpc}$$

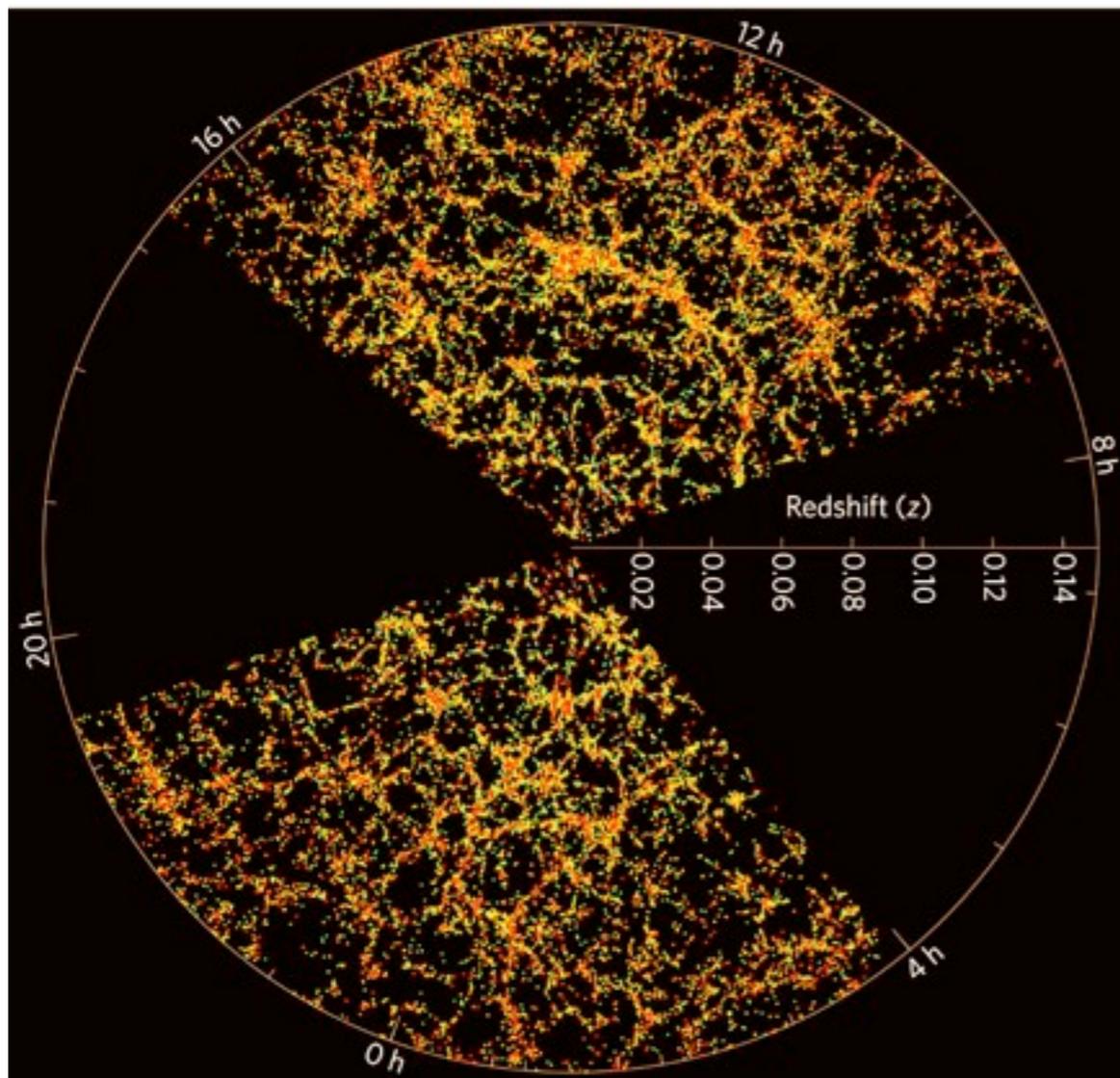
Most surveys $\ll \tau$ so that $k\tau \gg 1$

Newtonian potentials: $h_{\alpha\beta} = 2 \begin{pmatrix} \Phi & 0 \\ 0 & a^2 \Psi \delta_{ij} \end{pmatrix}$

Einstein equations: $-k^2 \Phi = 4\pi G \underline{\mu} a^2 \rho \Delta$
 $\underline{\gamma} \Psi = \Phi$

(μ, γ) are rational functions of $a_X(t)$ and k^2

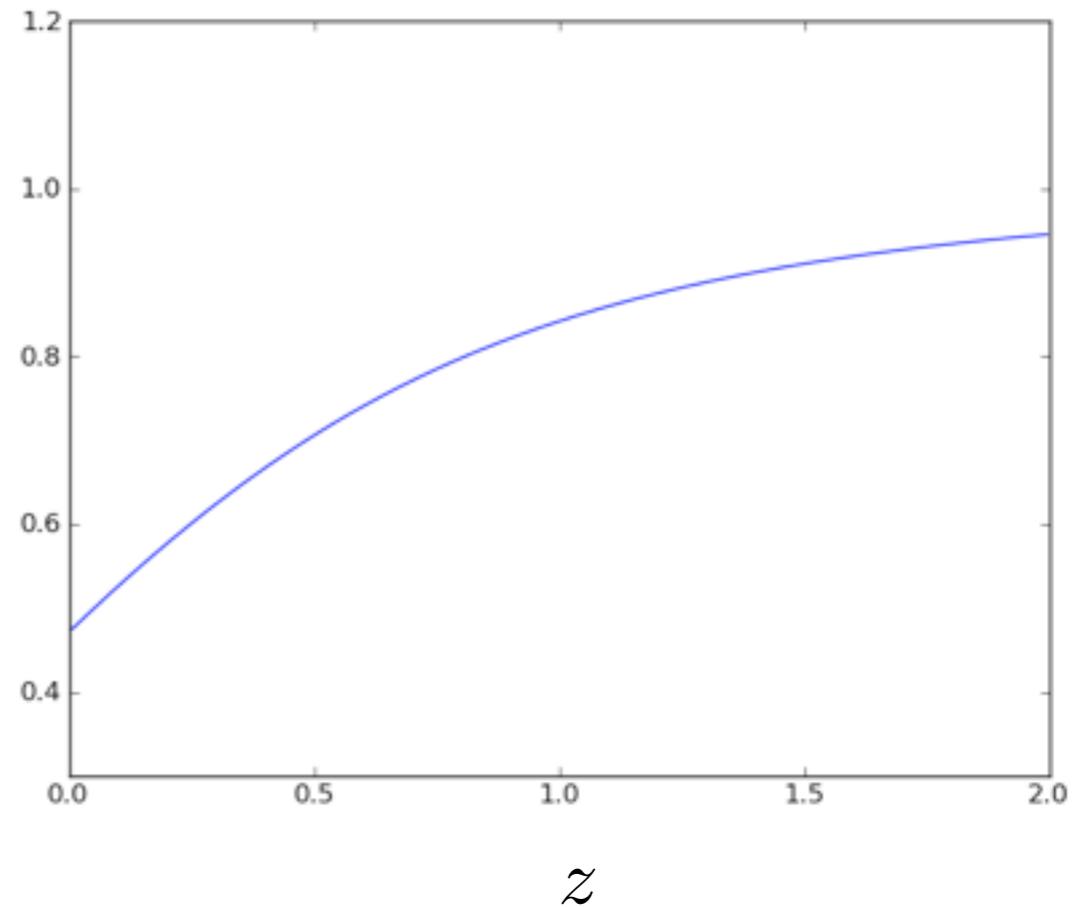
We measure matter and light.



Growth rate

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

f

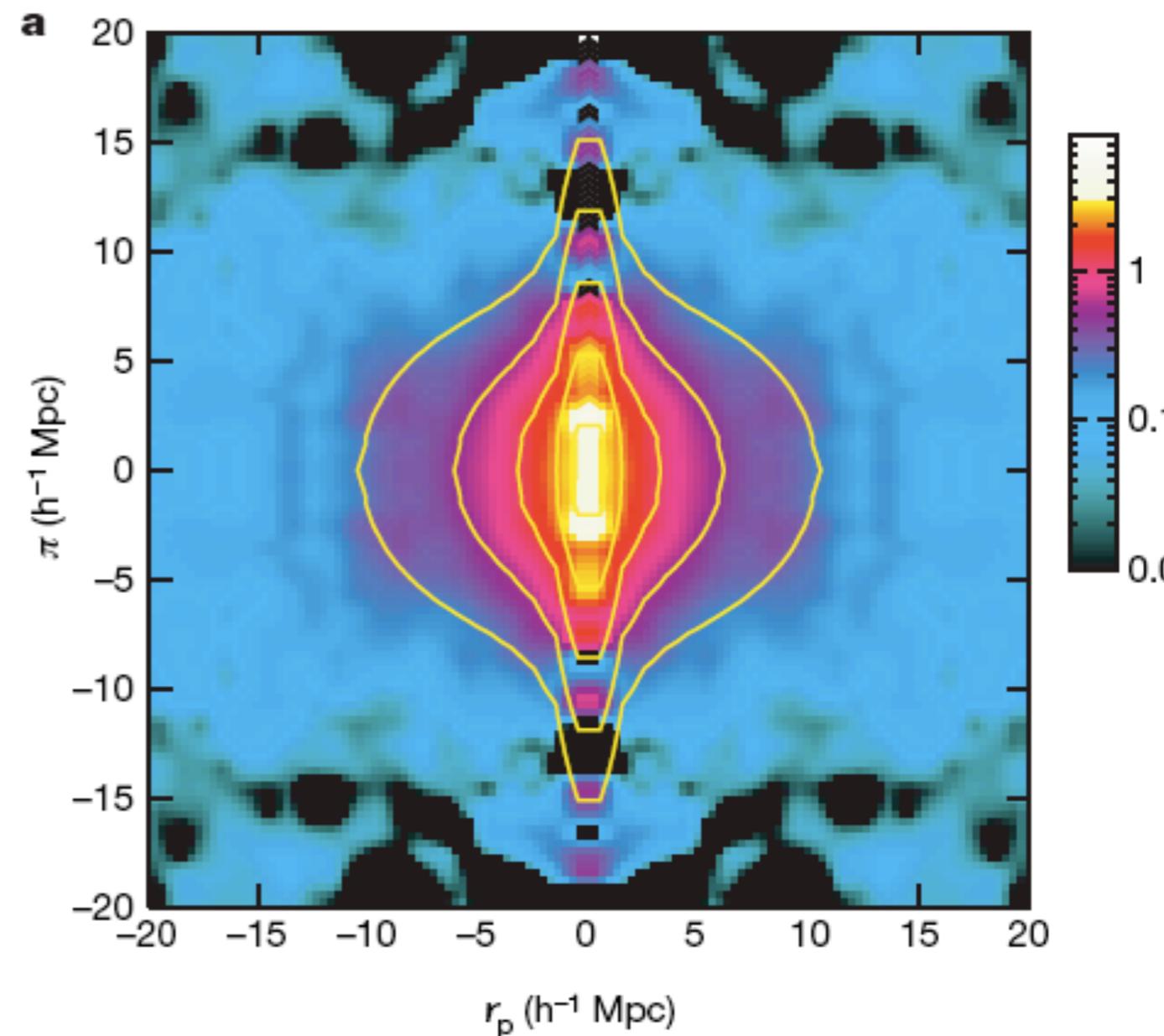
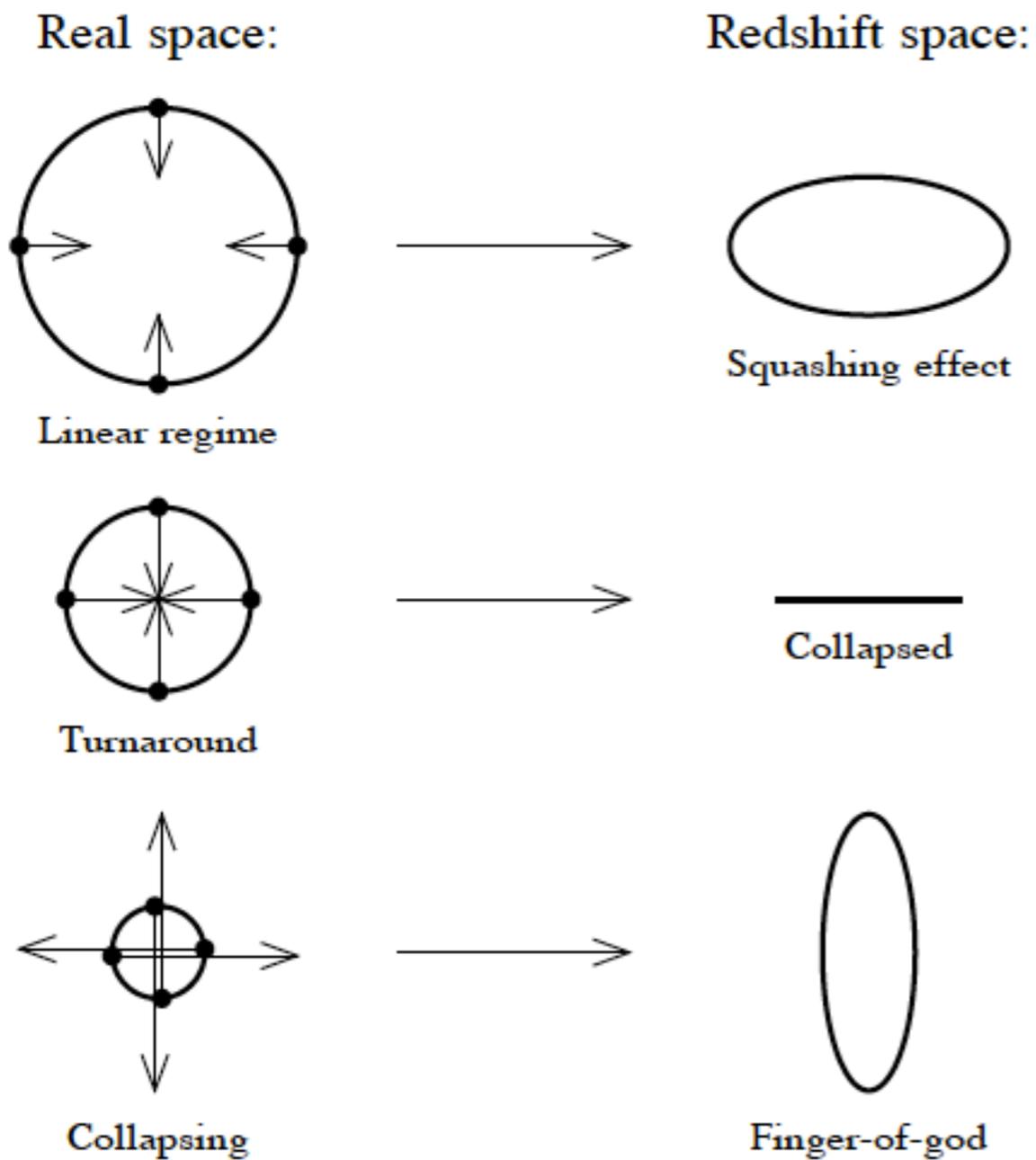


f satisfies a simple ODE

$$\frac{df}{d \ln a} + qf + f^2 = \frac{3}{2} \Omega_M \xi$$

with $q = \frac{1}{2} [1 - 3w(1 - \Omega_M)]$ and $\xi = \frac{\mu}{\gamma}$

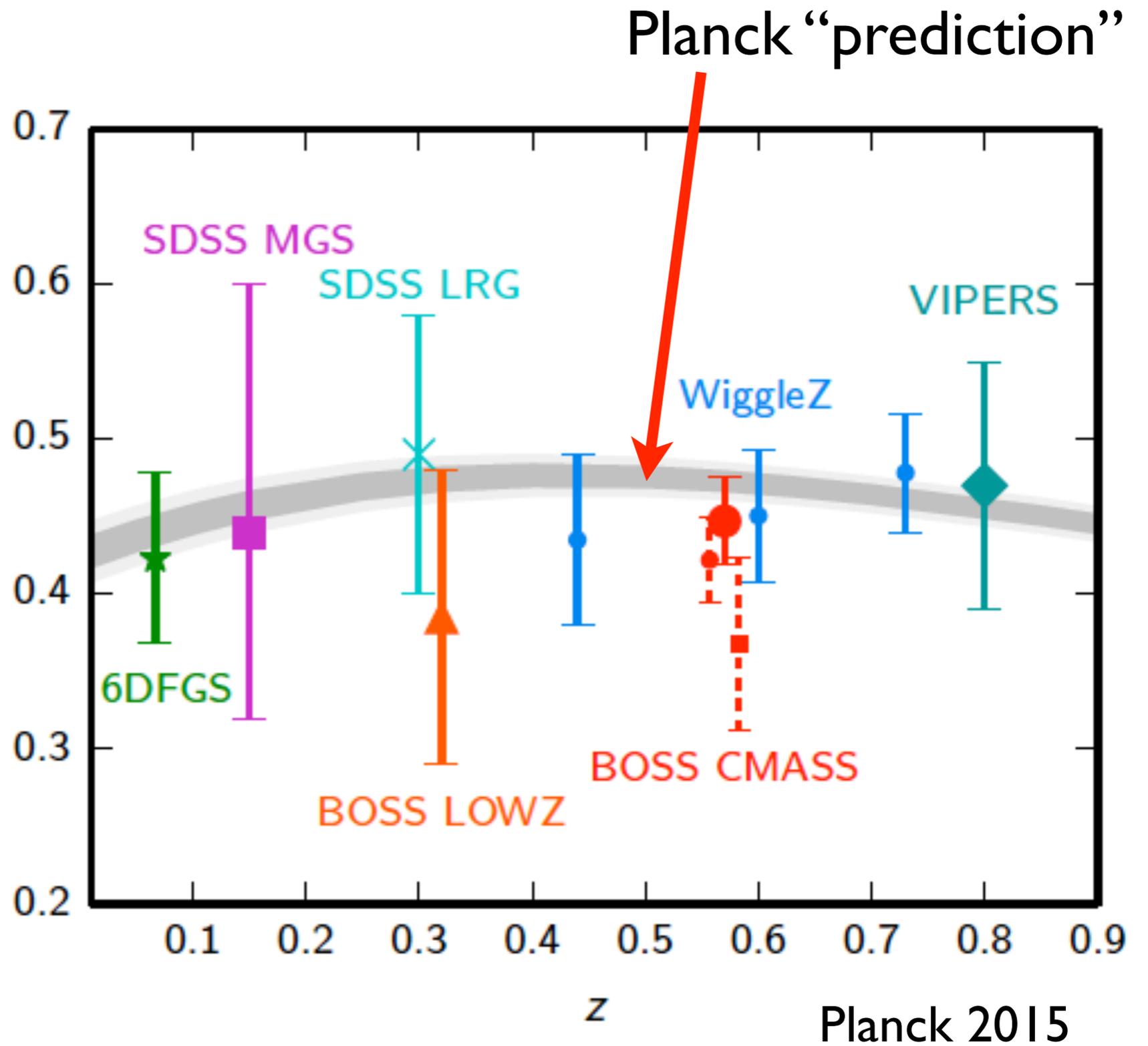
Redshift Space Distortions



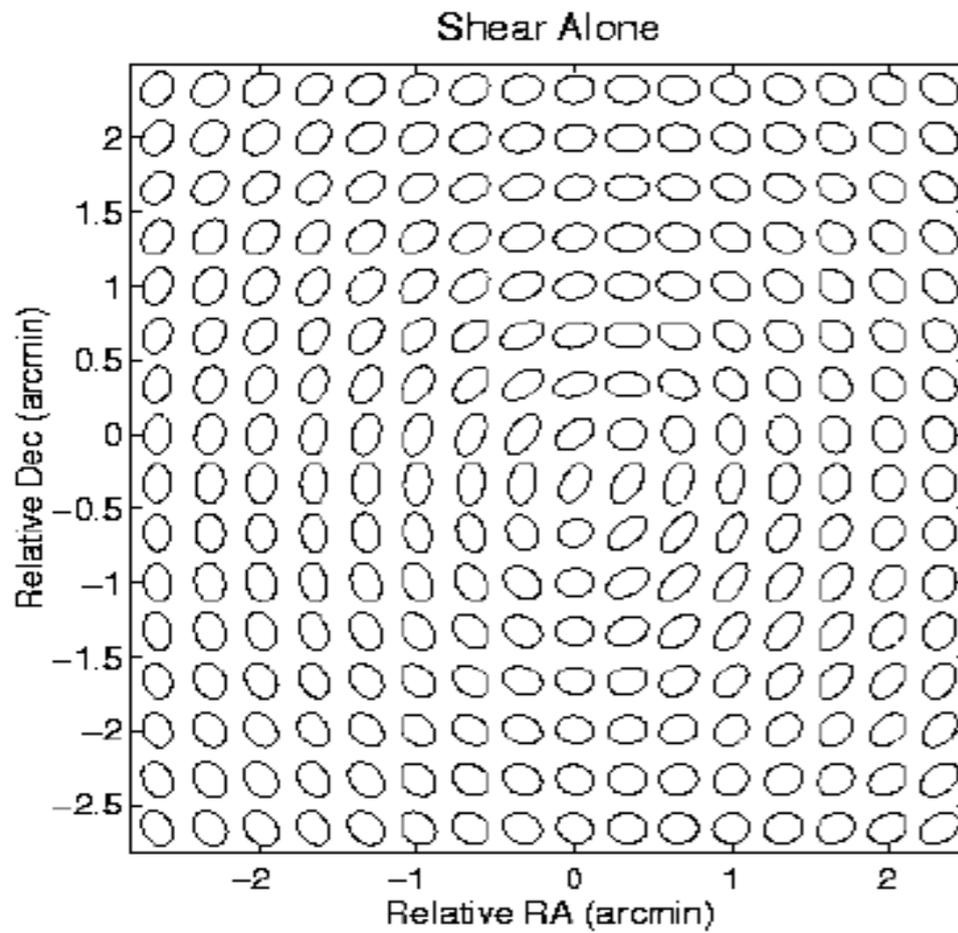
Guzzo et al 2008

“growth rate of structure”

$$f\sigma_8 \propto \frac{d\delta}{d \ln a}$$



Weak Lensing

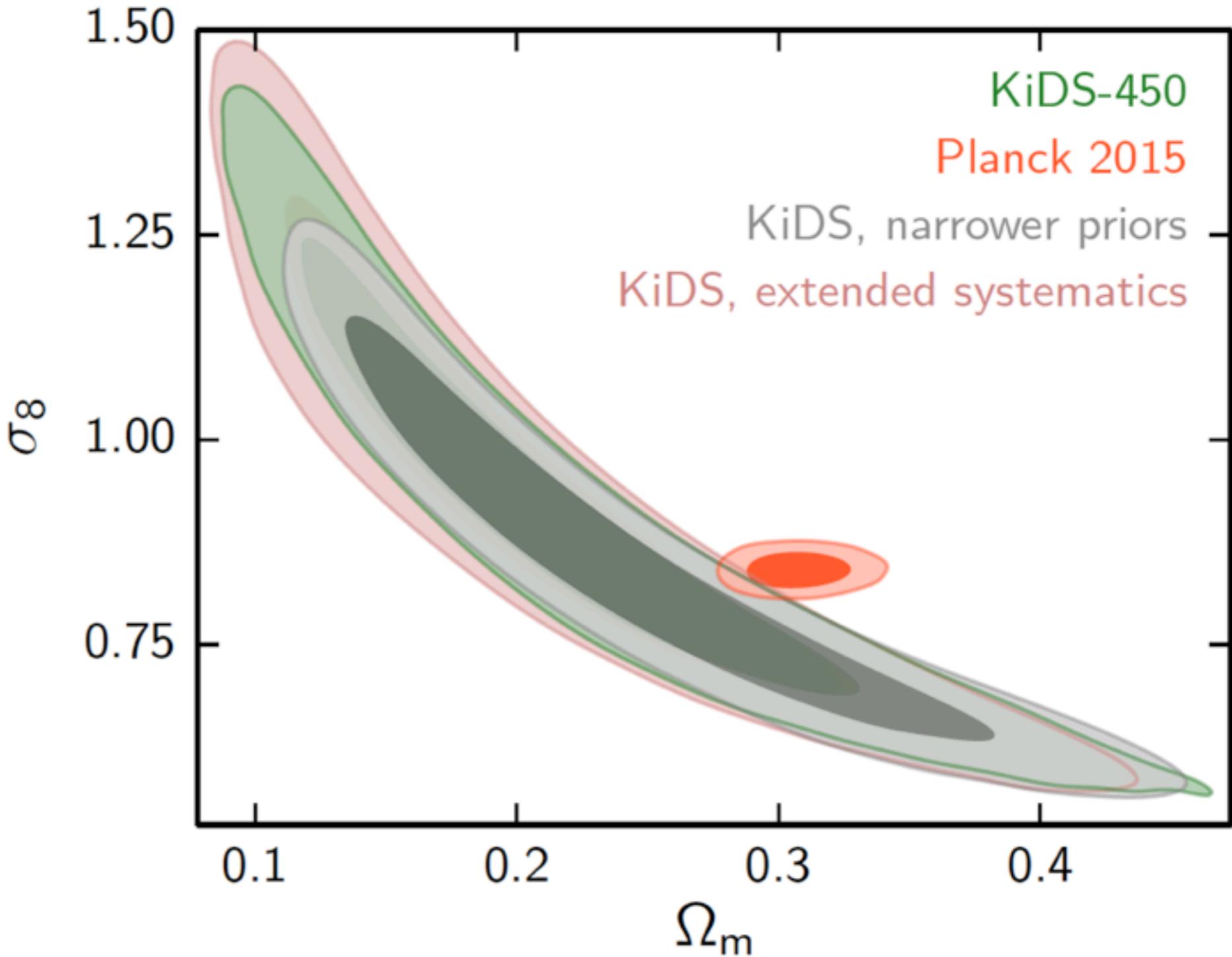


$$\text{shear} \simeq \int_0^{\chi} \nabla_{\perp}^2 [\Phi + \Psi](\chi') \left[\chi' \left(1 - \frac{\chi'}{\chi} \right) \right] d\chi'$$

$$\text{shear} \sim \Sigma \equiv \mu \left(1 + \frac{1}{\gamma} \right)$$

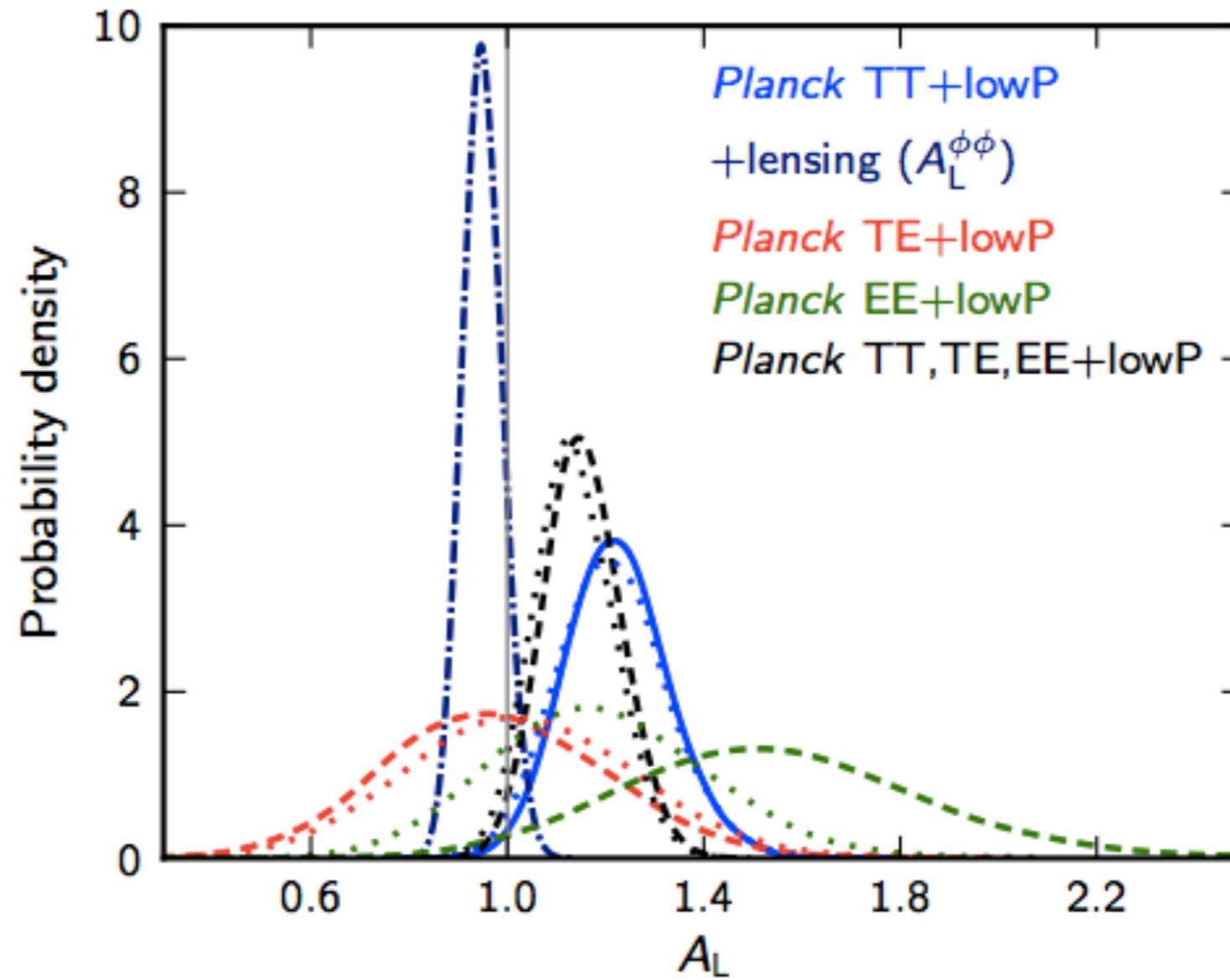
Sarah Bridle lectures (2003)

“amplitude of clustering at 8 h⁻¹ Mpc”

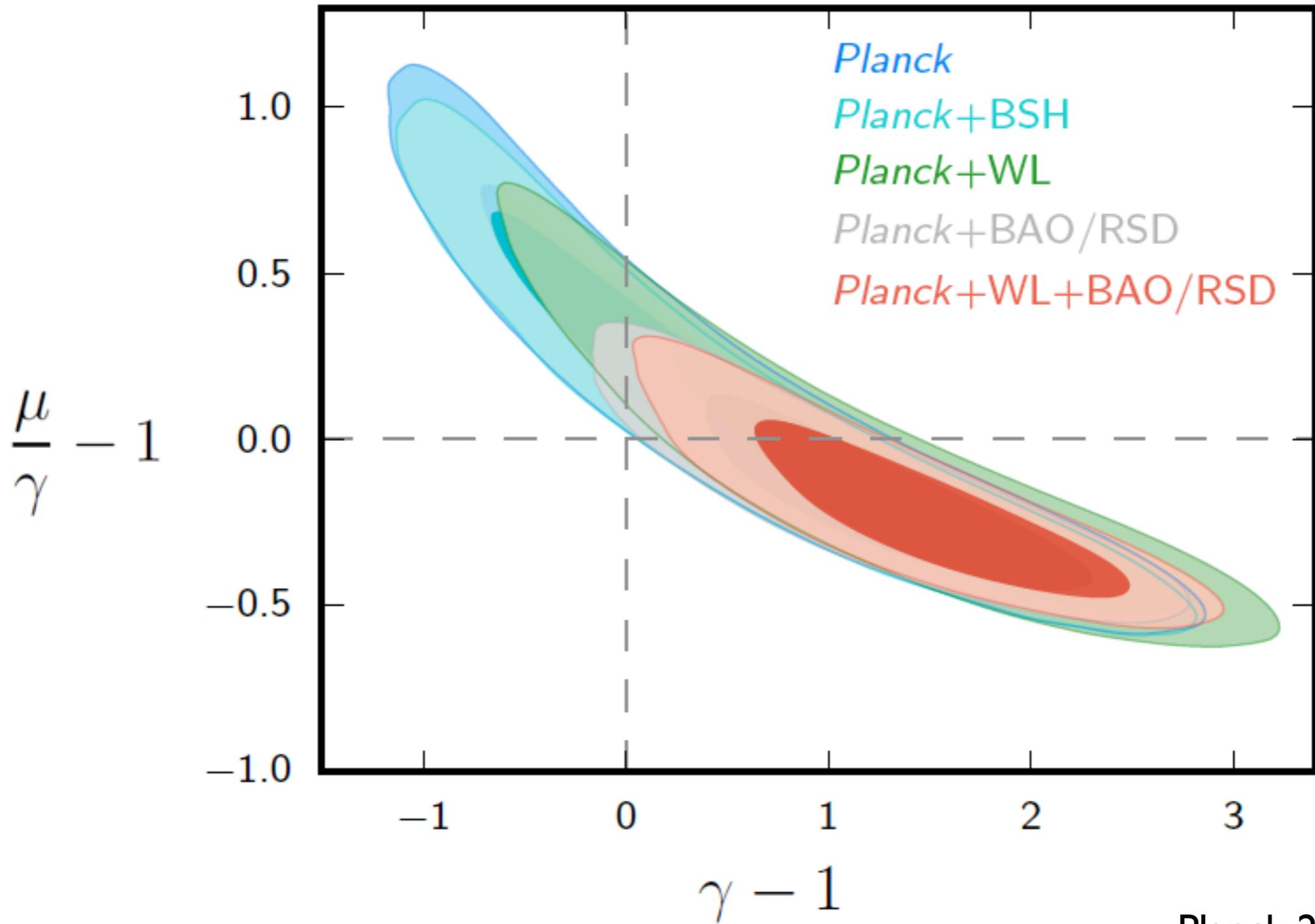


“matter density”

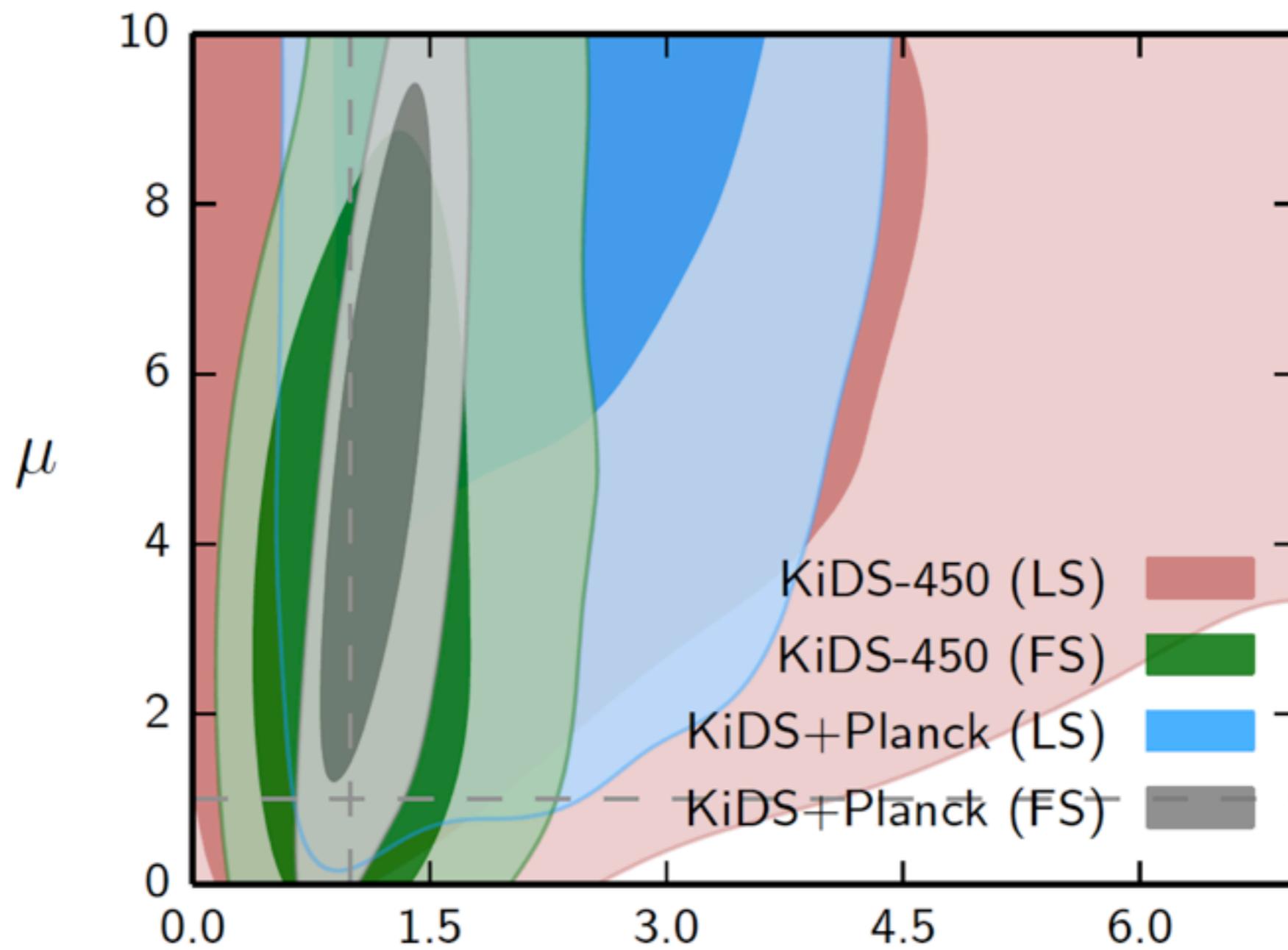
Lensing of CMB



Planck 2015



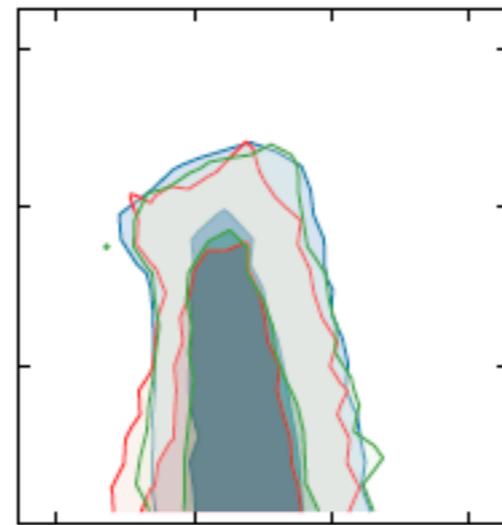
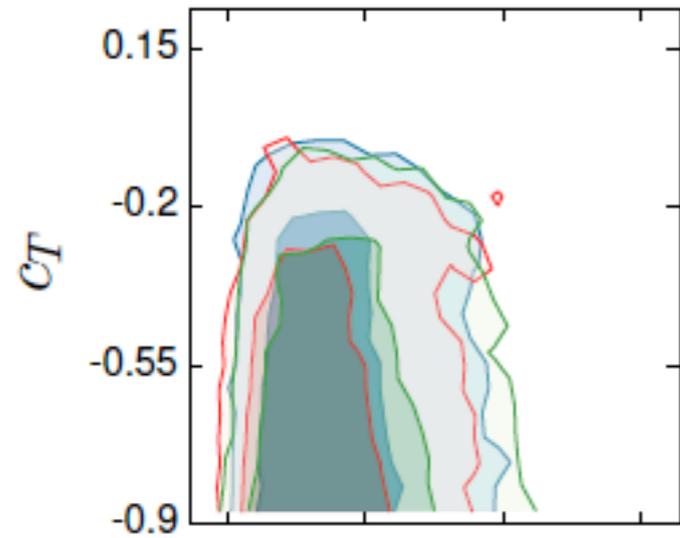
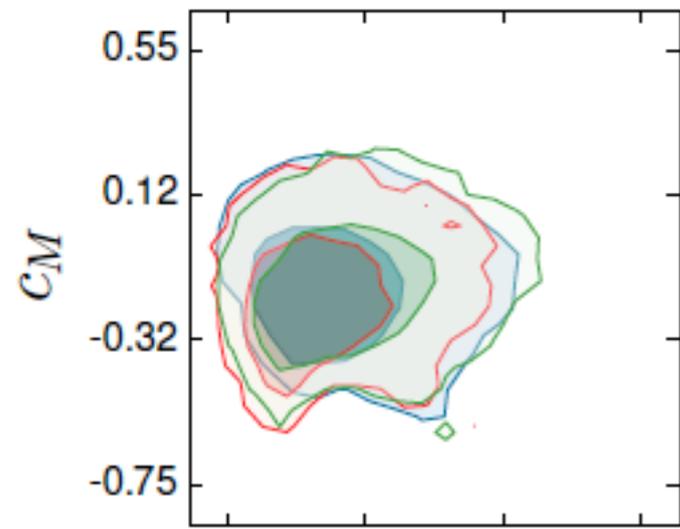
Planck 2015



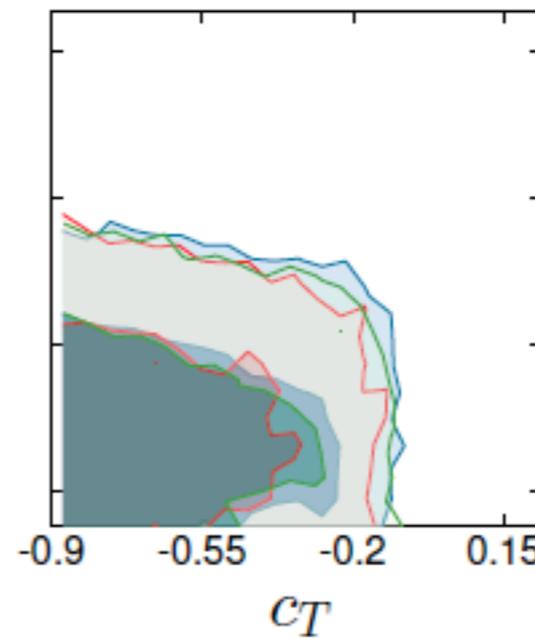
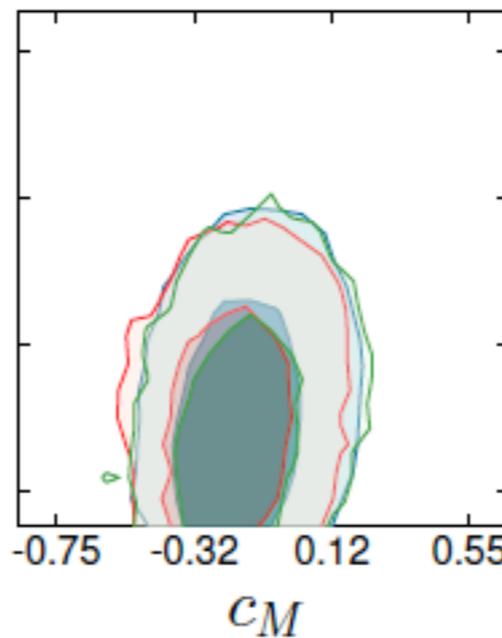
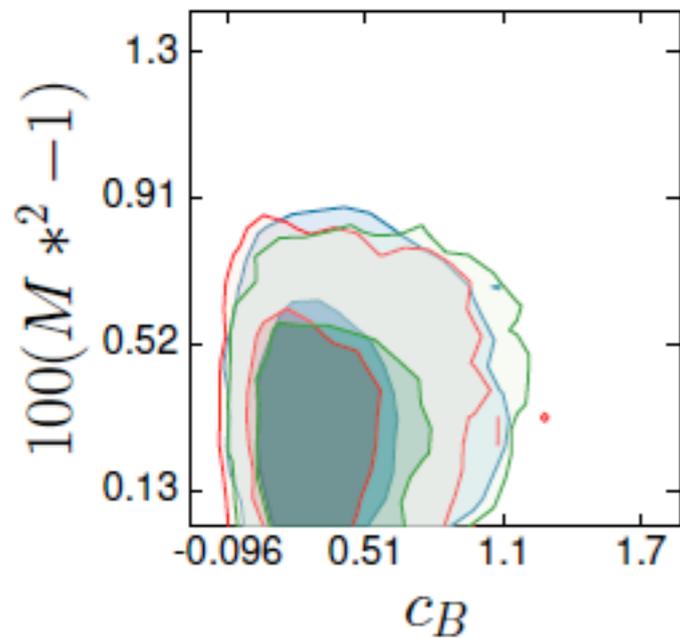
$$\Sigma \equiv \mu \left(1 + \frac{1}{\gamma} \right)$$

Constrain $\alpha_X(t)$ in scalar-tensor theories

Parametrize: $\alpha_X = b_X + c_X \frac{\Omega_{\text{DE}}(z)}{\Omega_{\text{DE}}(z=0)}$



$\sigma(\alpha_X) \sim 0.5$



Bellini et al 2016

Jordan-Brans-Dicke Theory

One free parameter

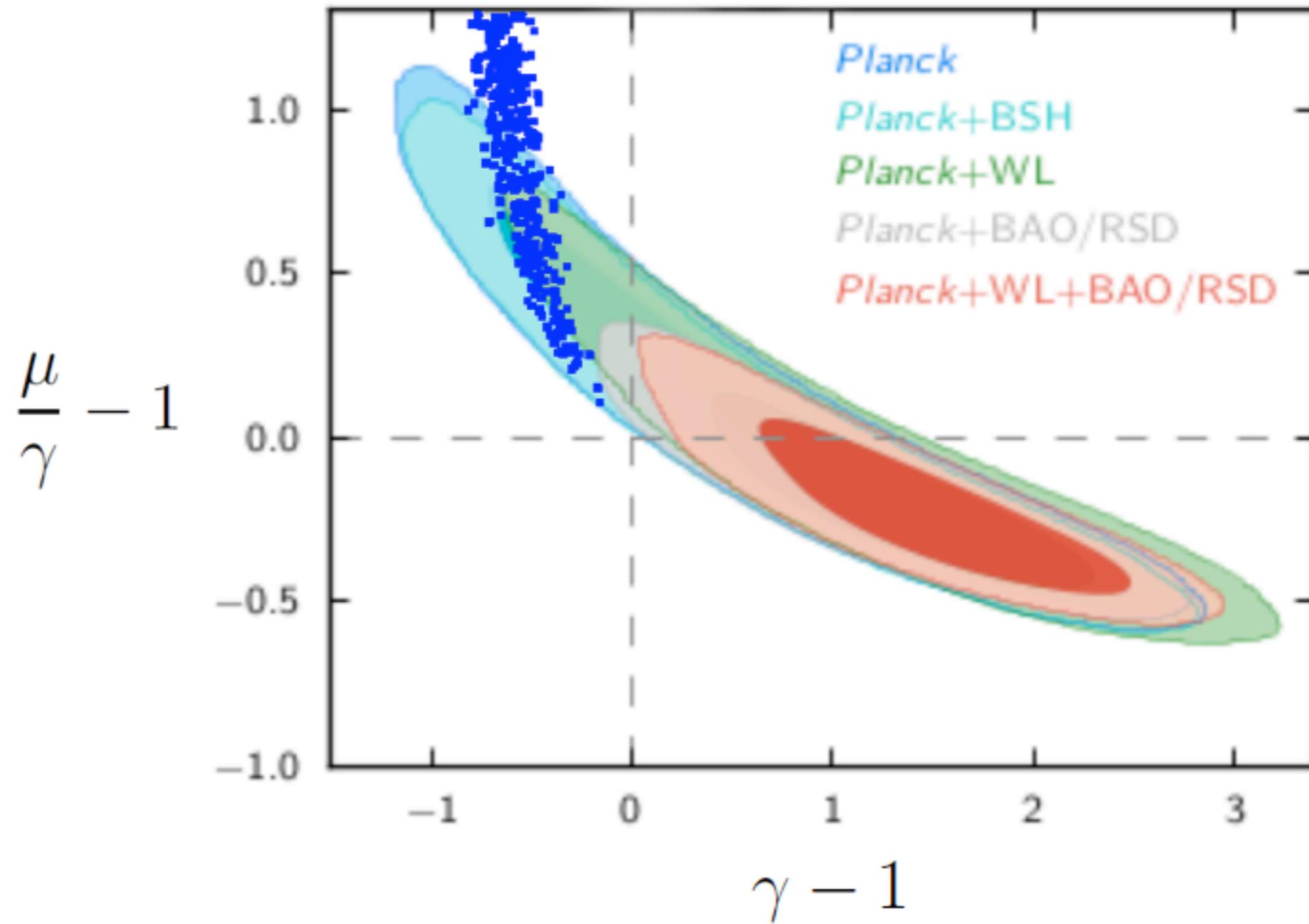
$$S = \int d^4x \sqrt{-g} \left[\phi R - \frac{\omega_{\text{BD}}}{\phi} \nabla_\mu \phi \nabla^\mu \phi + V + \mathcal{L}_M[g_{\mu\nu}, \varphi] \right]$$


Cassini (Bertotti et al 2003) $\omega_{\text{BD}} > 40,000$

Planck (Avilez & Skordis 2015) $\omega_{\text{BD}} > 1,000$

The Challenge

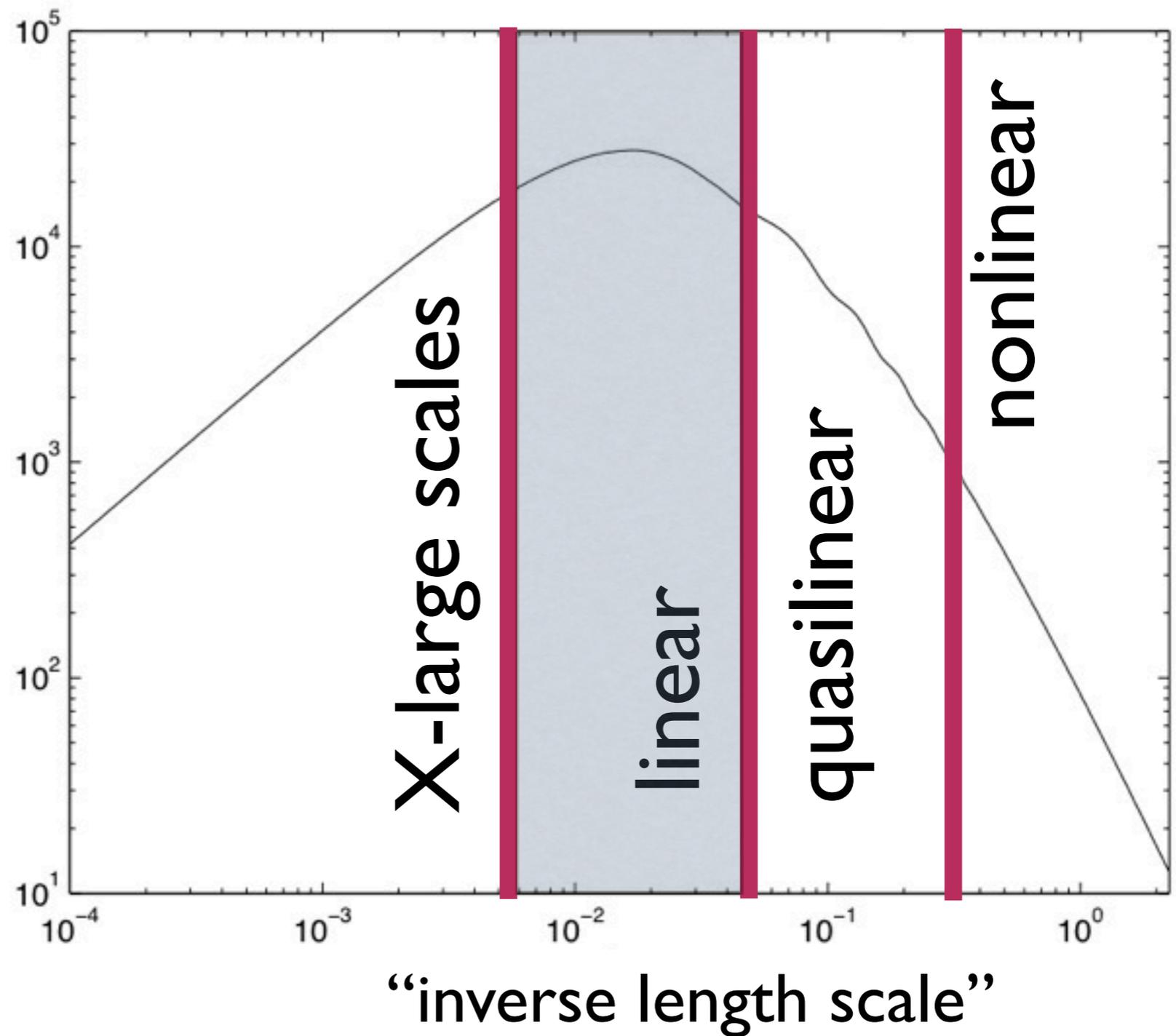
Systematics: priors



Perenon et al 2015

Systematics: non-linear physics

“amplitude of clustering”

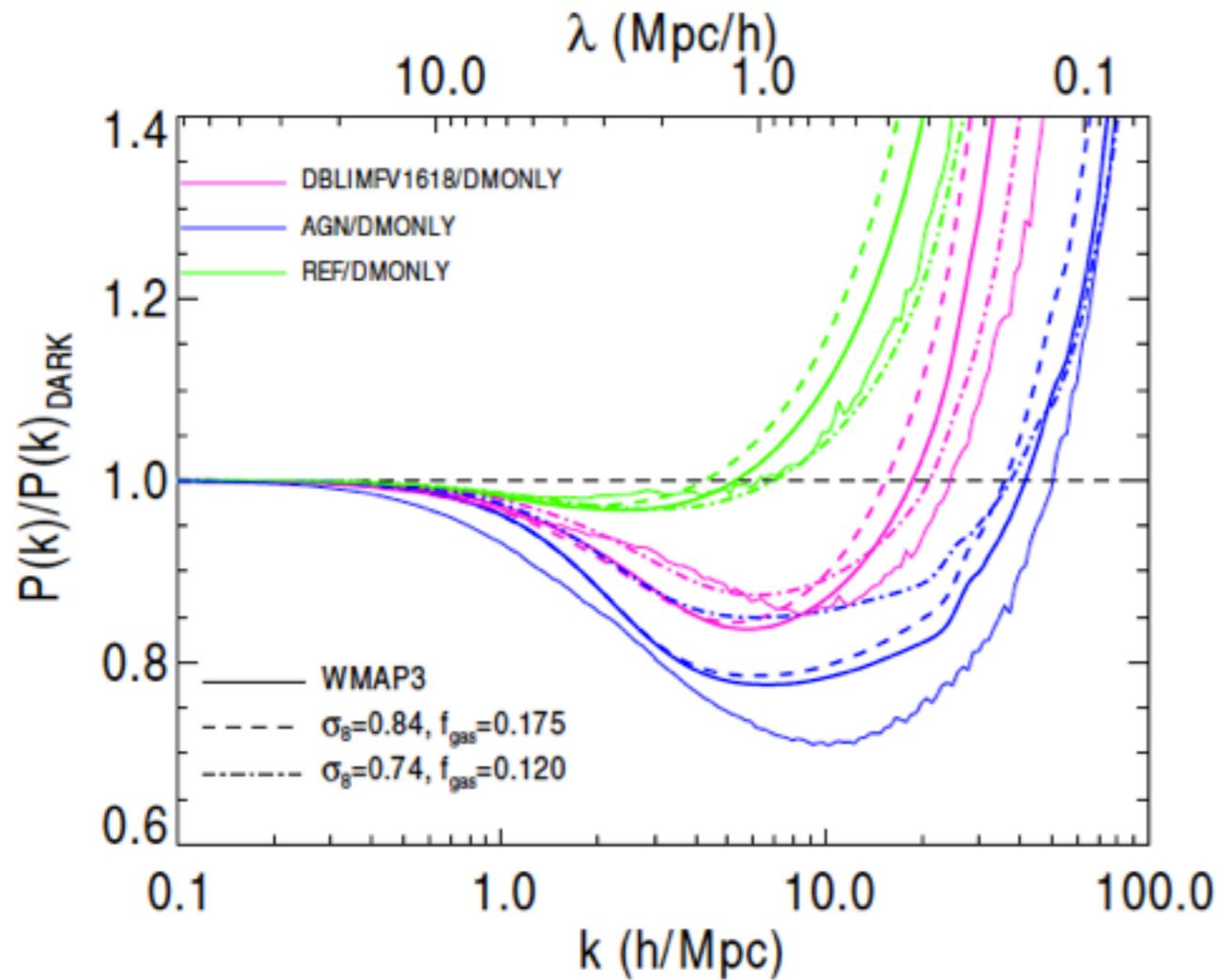


$$N(k) \propto k^3$$

More statistical power 

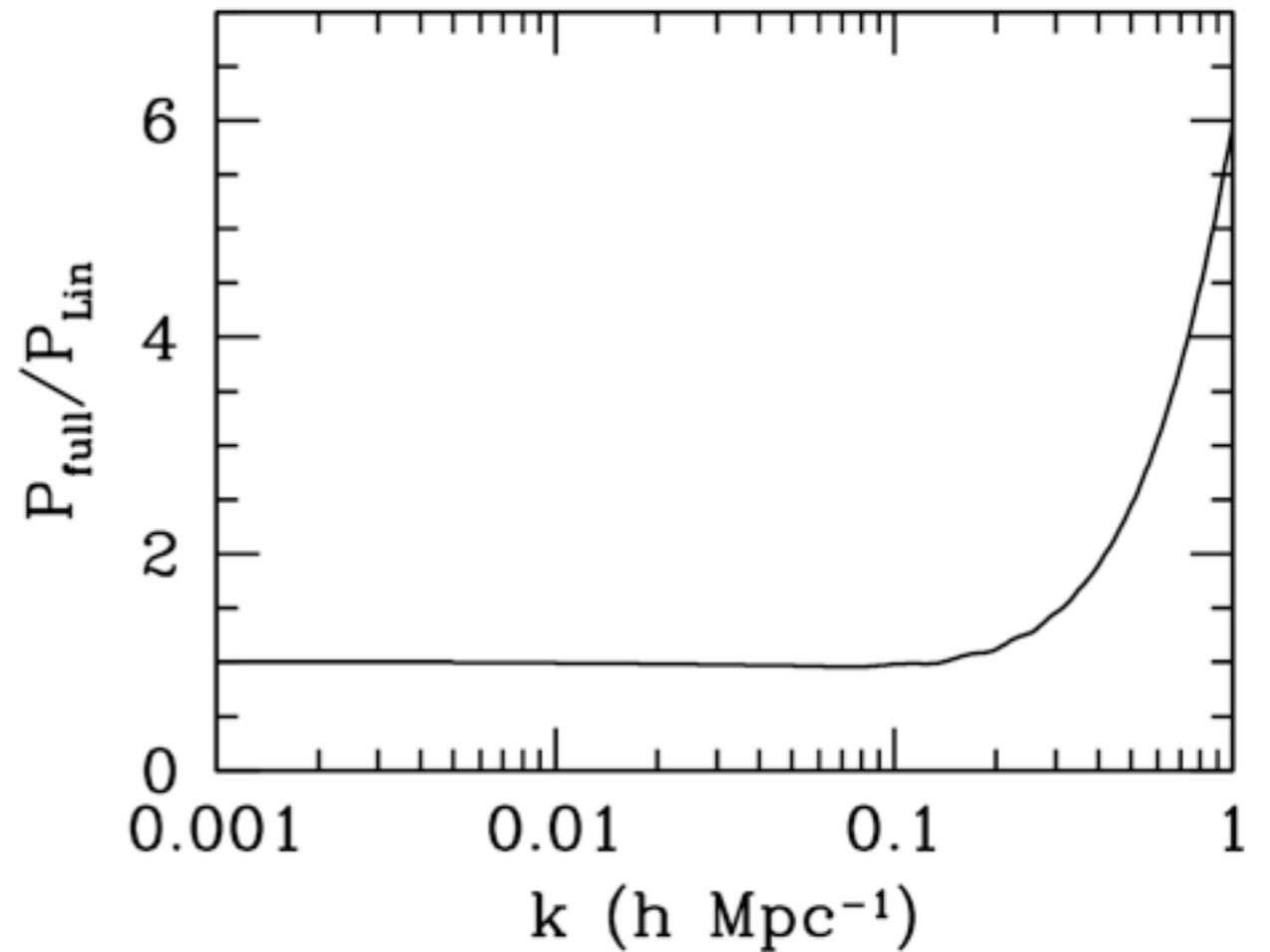
Systematics: non-linear physics

baryonic feedback

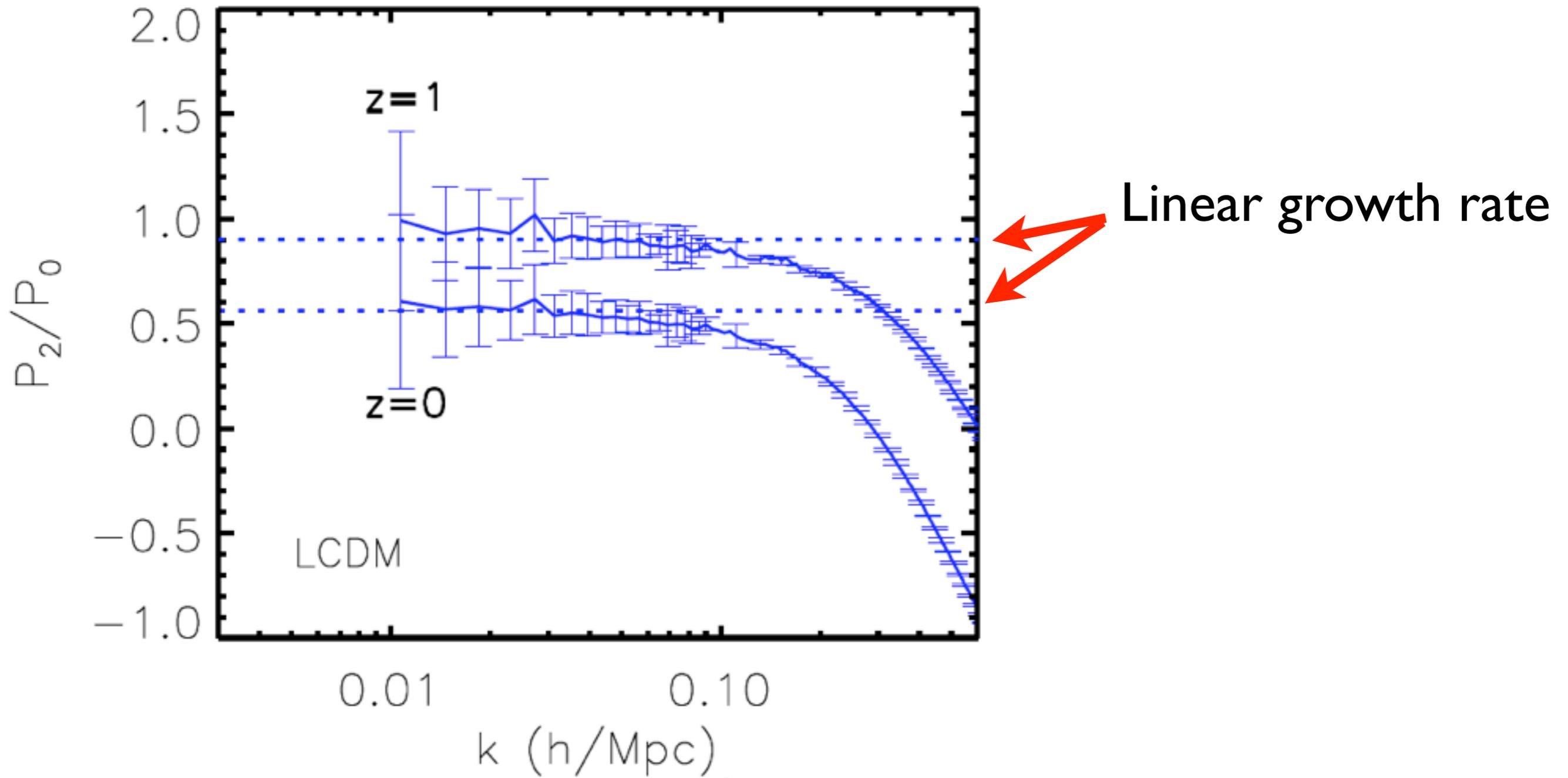


Sembloni et al 2012

non-linear growth



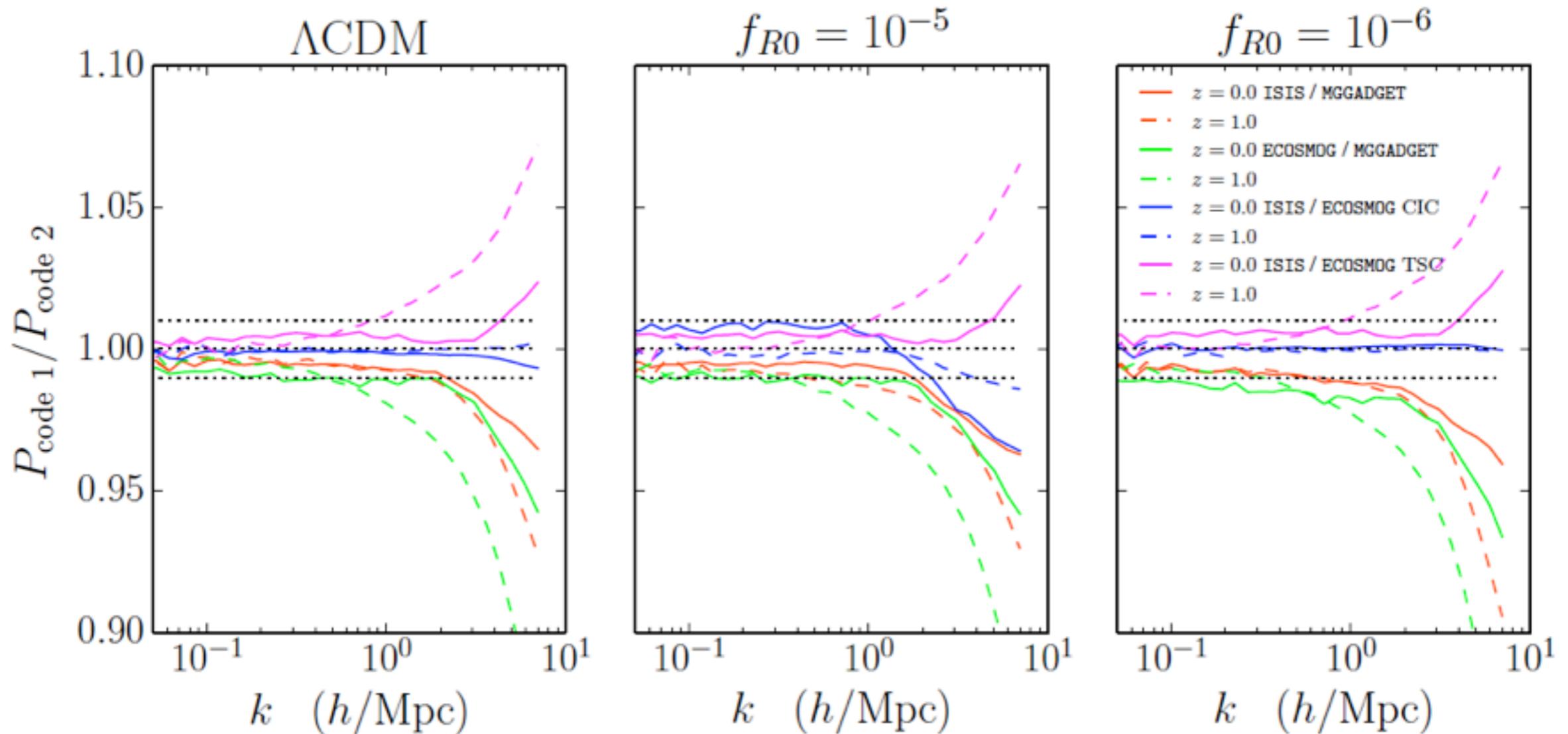
Systematics: non-linear physics



Jennings, Baugh & Pascoli 2015

Systematics: non-linear physics

Comparison of N-body codes: 1% out to $k \sim 1$



Winther et al 2015

Systematics: screening

Newtonian potential

$$\Phi = -\frac{GM}{r}$$

$$\ddot{\vec{r}} = -\nabla[\Phi + \phi]$$

Fifth force

$$\phi = -\frac{\tilde{G}M}{r}e^{-mr}$$

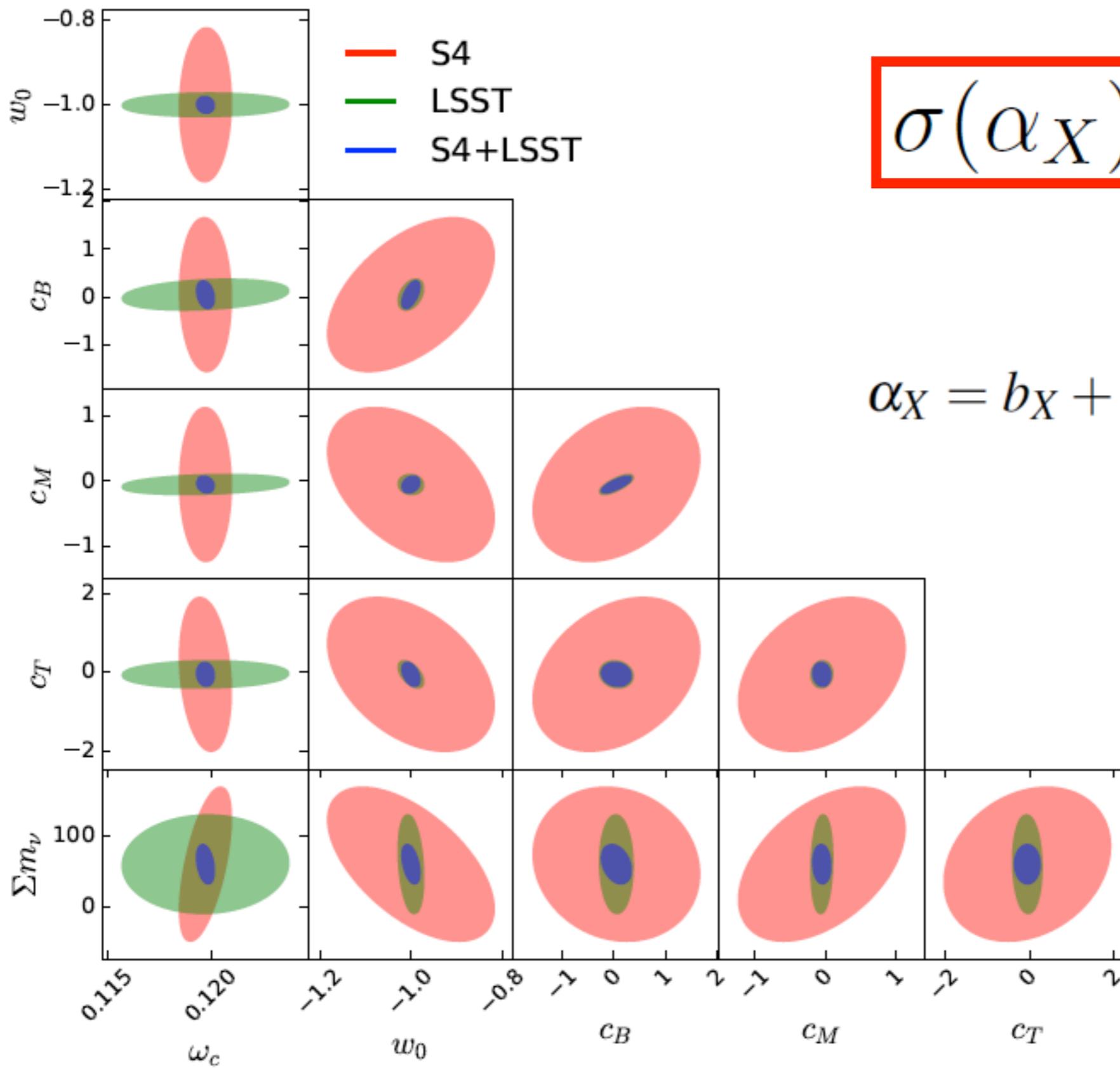
Chameleon: $m = m(\rho)$ $m \rightarrow \infty$ when $\rho \gg \rho_S$

Vainshtein: $\tilde{G} \rightarrow 0$ when $r \ll r_V$

The Future

The Future is now

Data Type	Now	Soon	Future
Photo-z:LSS (weak lensing)	DES, RCS, KIDS	HSC	LSST, Euclid, SKA, WFIRST
Spectro-z (BAO, RSD, ...)	BOSS	DESI,PFS,HETDEX, Weave	Euclid, SKA
SN Ia	HST, Pan-STARRS, SCP, SDSS, SNLS	DES, J-PAS	JWST,LSST
CMB/ISW	WMAP, Planck	AdvACT	Simons Array, Stage IV, LiteBird
sub-mm, small scale lensing, SZ	ACT, SPT,Planck, ACTPol,SPTPol,	PolarBear,Spider, Vista	CCAT, SKA
X-Ray clusters	ROSAT, XMM, Chandra	XMM, XCS, eRosita	
HI Tomography	GBT	Meerkat, Baobab, Chime, Kat 7	SKA



$$\sigma(\alpha_X) \sim 0.1$$

$$\alpha_X = b_X + c_X \frac{\Omega_{\text{DE}}(z)}{\Omega_{\text{DE}}(z=0)}$$

Alonso et al 2016

Jordan-Brans-Dicke Theory

One free parameter

$$S = \int d^4x \sqrt{-g} \left[\phi R - \frac{\omega_{\text{BD}}}{\phi} \nabla_{\mu} \phi \nabla^{\mu} \phi + V + \mathcal{L}_M[g_{\mu\nu}, \varphi] \right]$$


Cassini (Bertotti et al 2003)

$$\omega_{\text{BD}} > 40,000$$

Planck (Avilez & Skordis 2015)

$$\omega_{\text{BD}} > 1,000$$

LSST+SKA+S4 (Alonso et al 2016)

$$\omega_{\text{BD}} > 20,000$$

“An important contribution of the general theory of relativity to cosmology has been to keep out theologians by a straightforward application of tensor analysis.”

E. Schucking

D. Alonso, L. Amendola, M. Amin, T. Baker, R. Bean, E. Bellini, C. Blake, P. Bull, P. Brax, S. Daniels, A. Davies, D. Leonard, G. Gubitosi, P. G. Ferreira, J. Gleyzes, W. Hu, L. Hui, C. Heymans, S. Joudaki, K. Koyama, M. Kunz, M. Lagos, D. Langlois, E. Linder, L. Lombriser, D. Mota, A. Narimani, J. Noller, J. Peacock, F. Piazza, D. Pogosian, D. Sapone, D. Scott, I. Sawicki, A. Silvestri, F. Simpson, A. Taylor, F. Vernizzi, H. Winther, J. Zuntz, ...