Gravity from Cosmology

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Erice 2015

GR1: Chapel Hill 1957

"It is unfortunate to note that the situation with respect to the experimental checks of GR is not much better than it was a few years after the theory was discovered- say in the 1920s. It is a great challenge to ... try to improve this situation"

R. Dicke

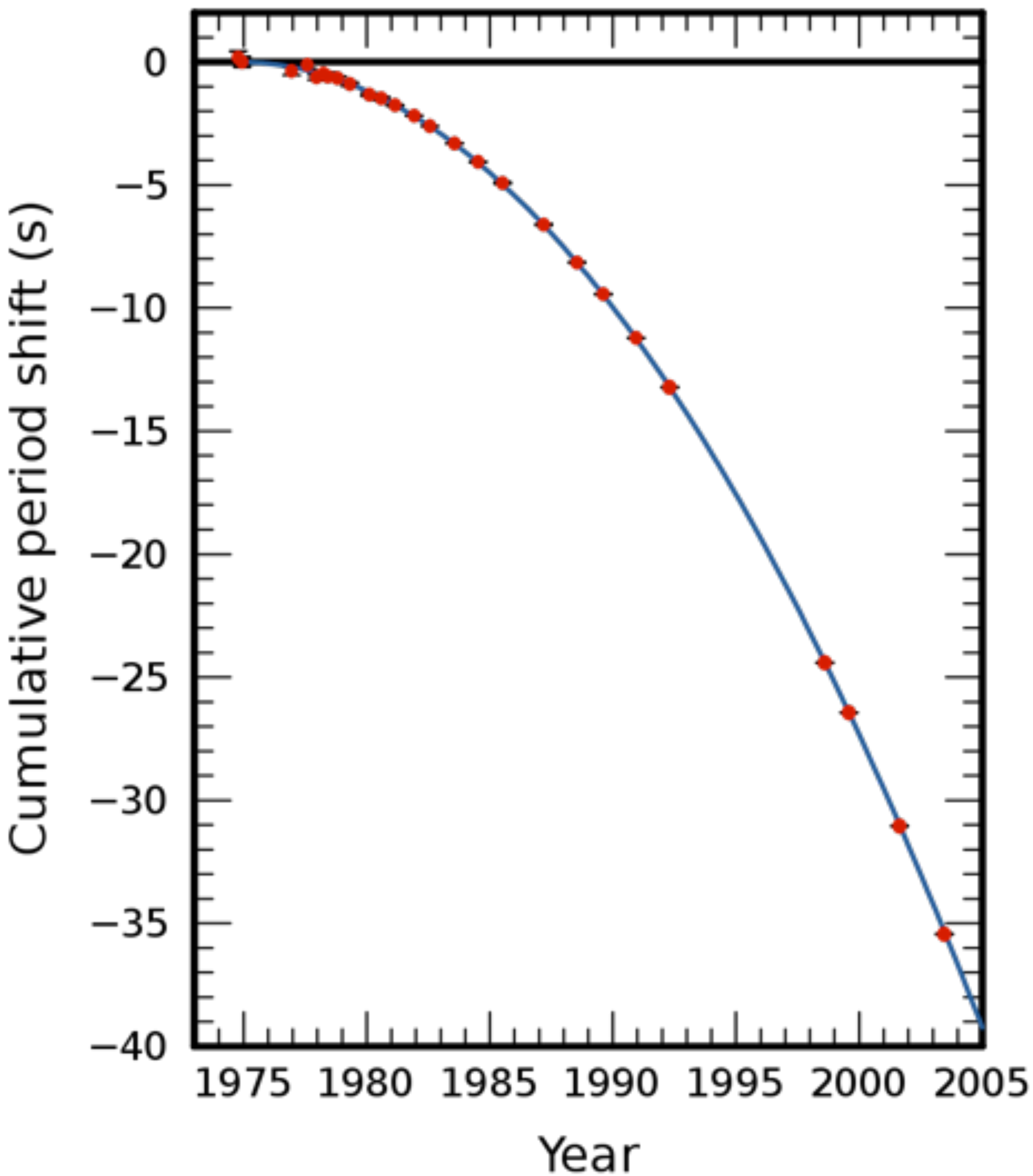
“Here we have a case that allowed one to suggest that the relativists with their sophisticated work were not only magnificent cultural ornaments but might actually be useful to science!

“Everyone is pleased: the relativists who feel they are ... suddenly experts in a field they hardly knew existed; the astrophysicists for having enlarged ... their empire by the annexation of another subject: general relativity!

“What a shame it would be if we had to go and dismiss all the relativists again!”

Thomas Gold, Texas Symposium, (1963)

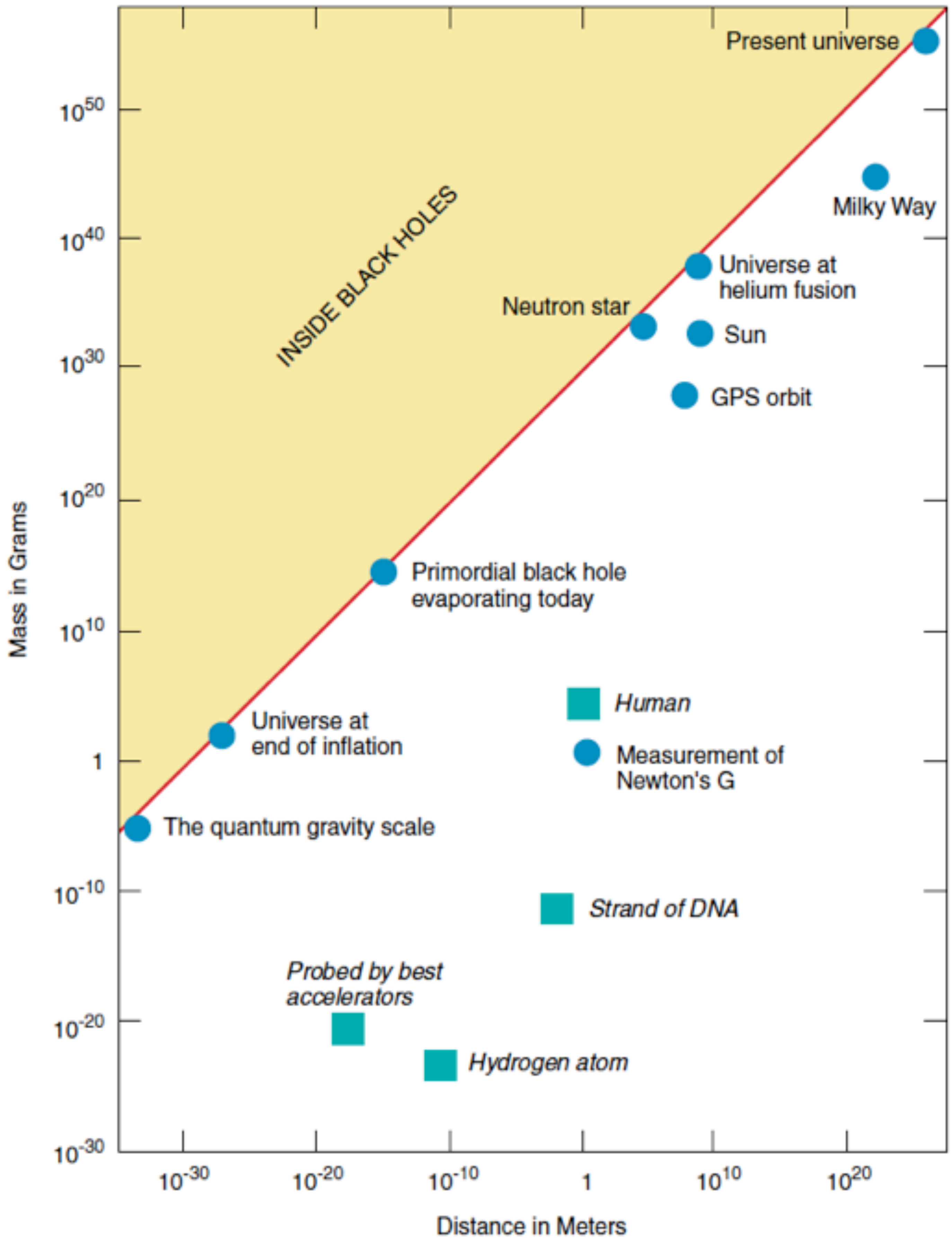
Now: Solar System and Pulsars



Hulse-Taylor 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	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
α_3	4×10^{-20}	Self-acceleration	Pulsar spin-down
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

PPN parameters

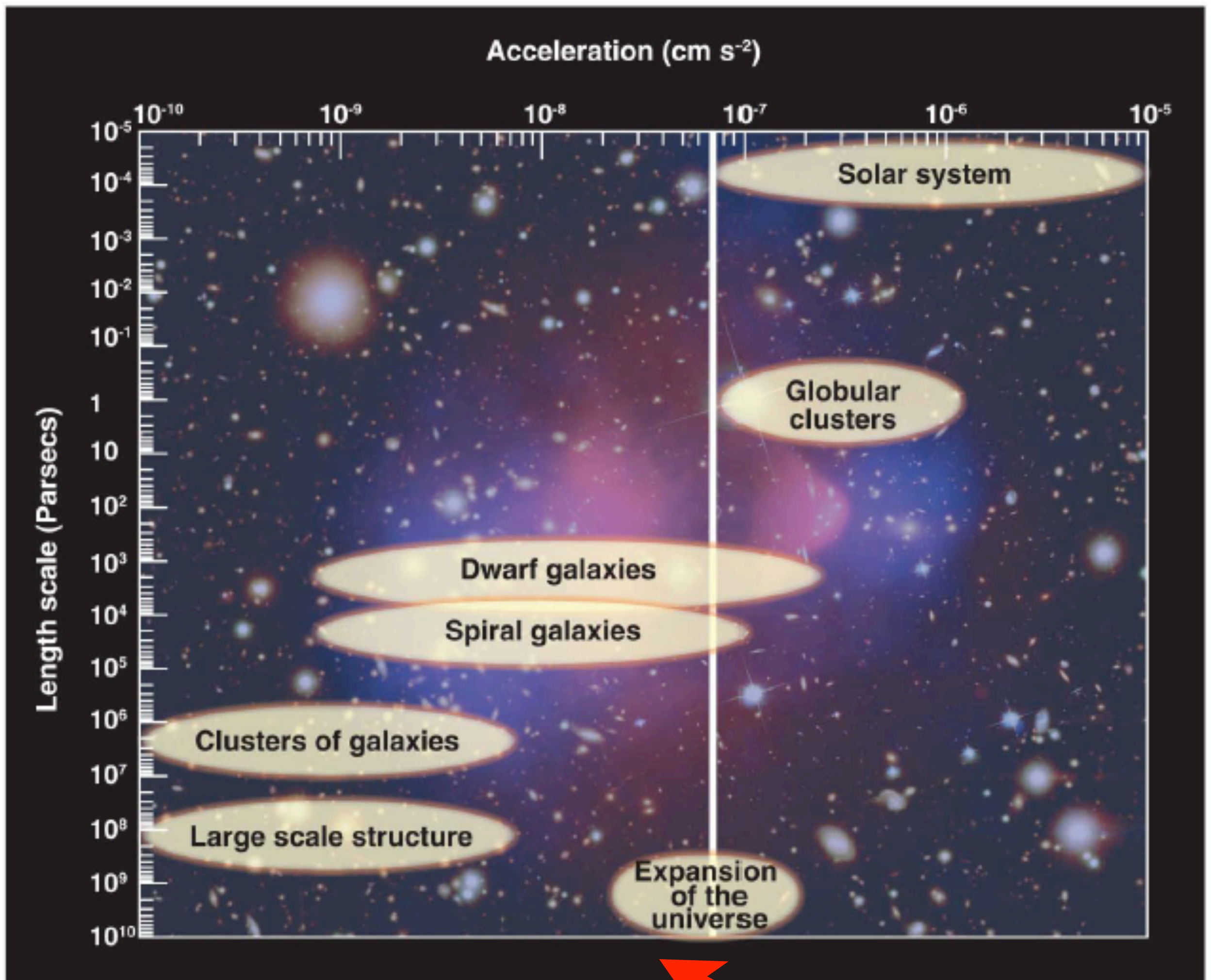


"... by pushing a theory to its extremes, we also find out where the cracks in its structure might be hiding."

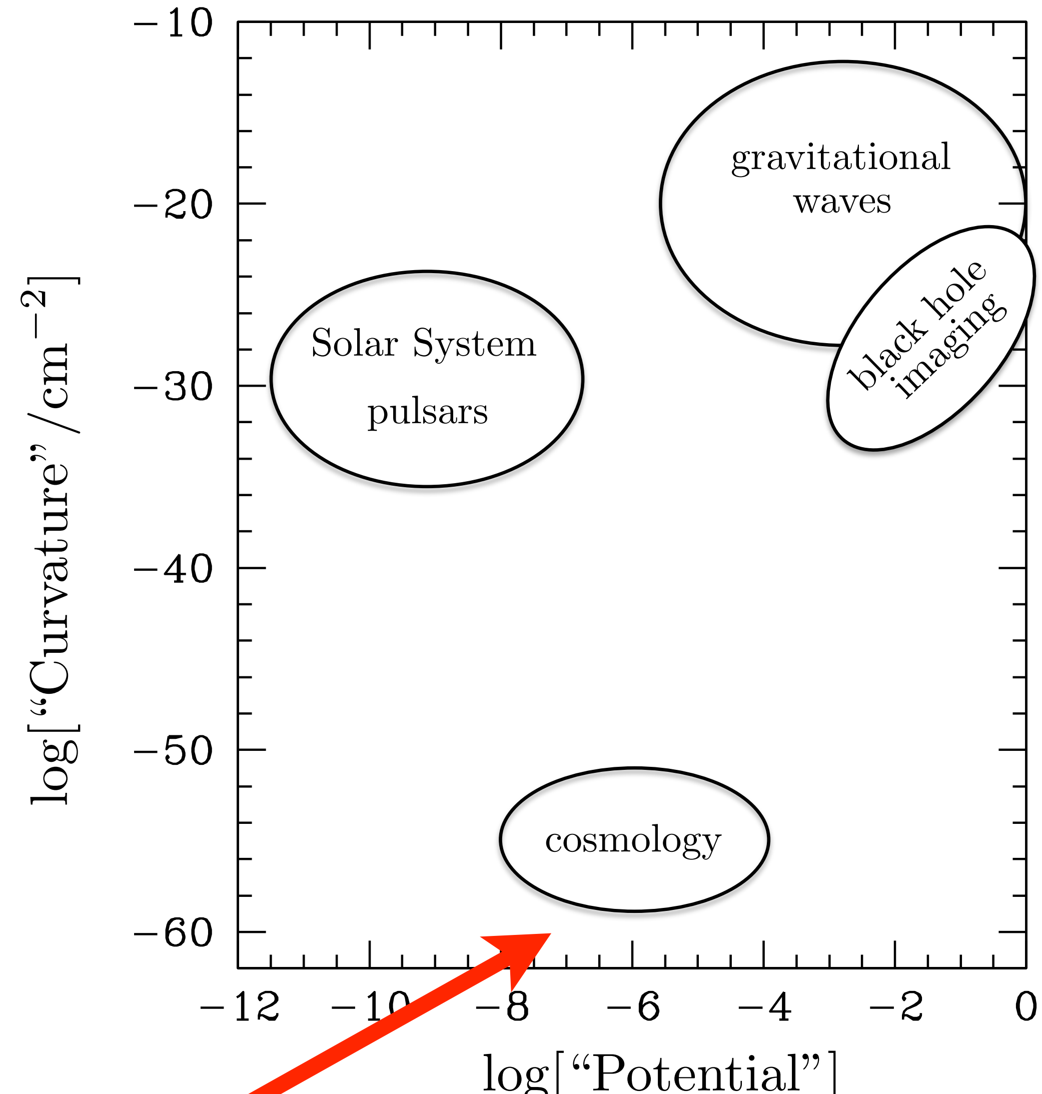
John Wheeler

Decadal Survey 2000

Regimes



Ferreira & Starkman, 2009

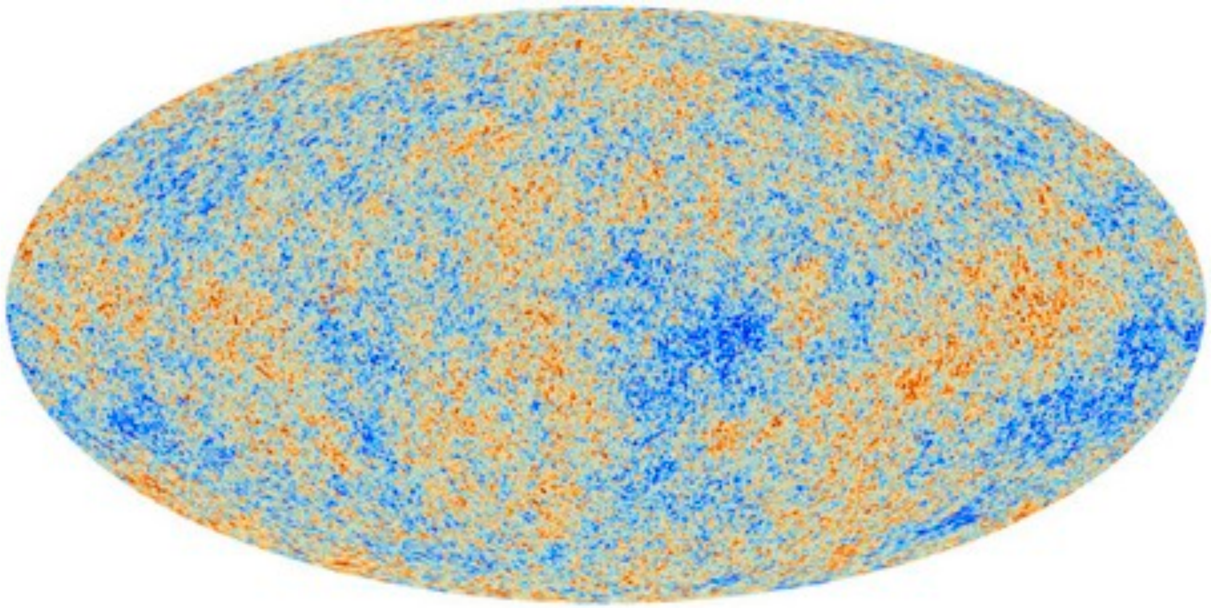


Adapted from Baker, Psaltis, Skordis 2009

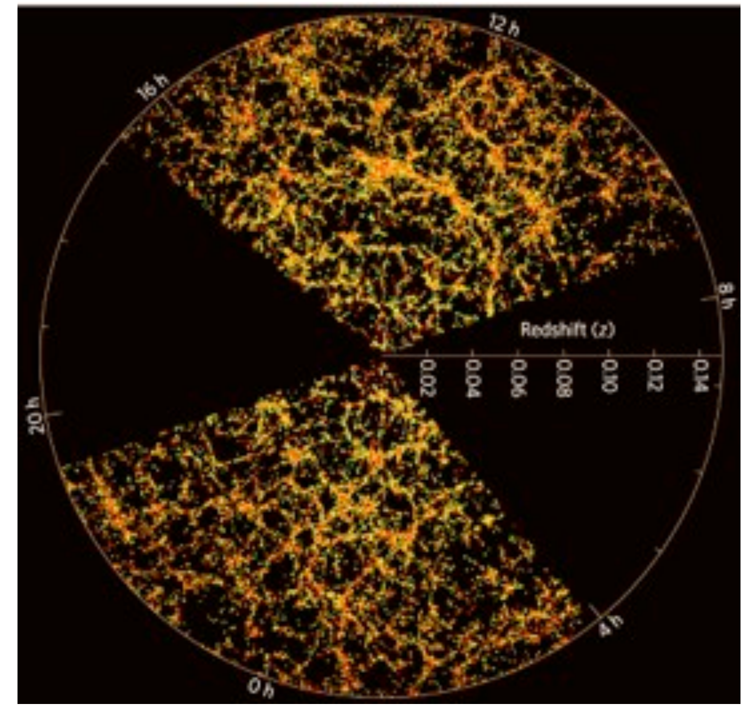
Cosmological scales

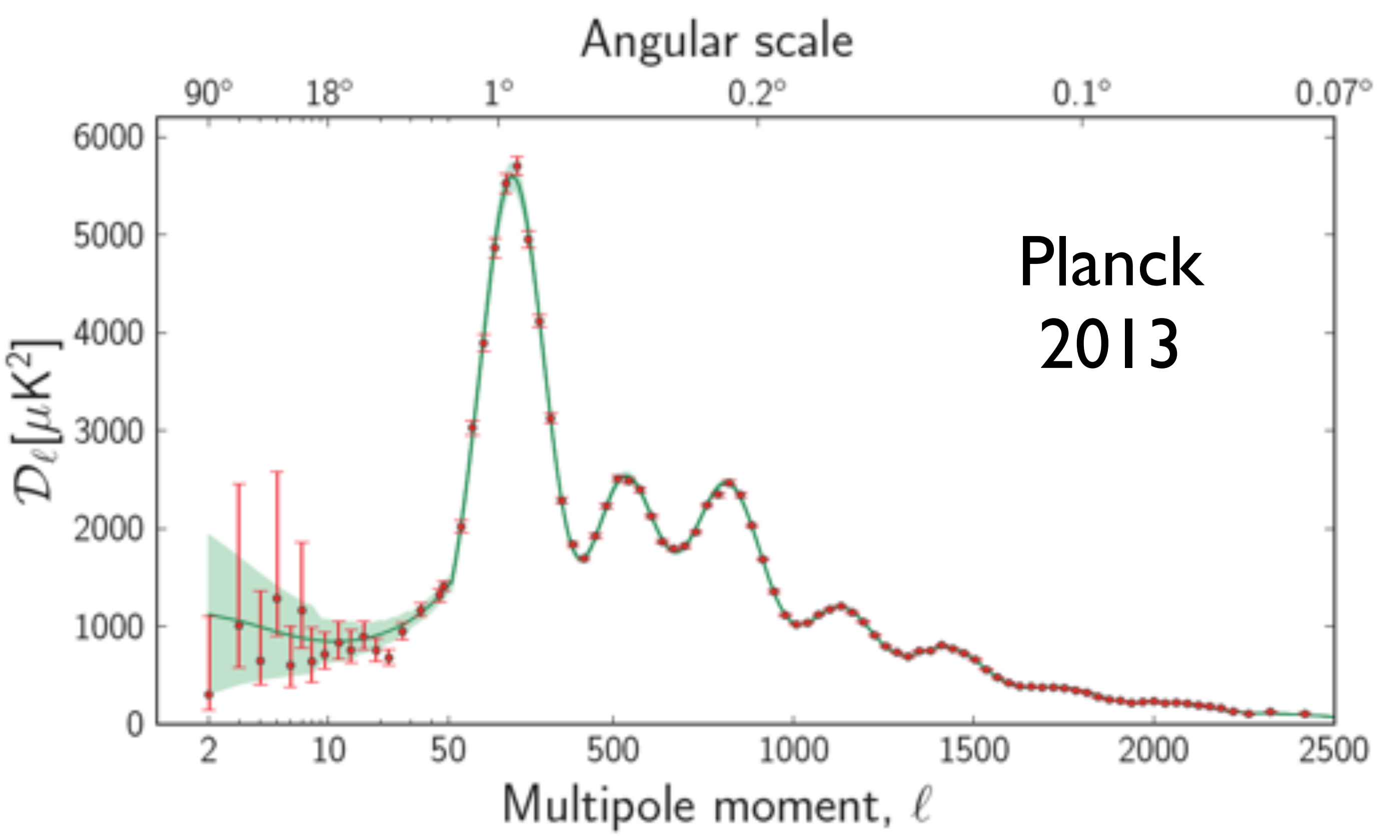
The Large Scale Structure of the Universe

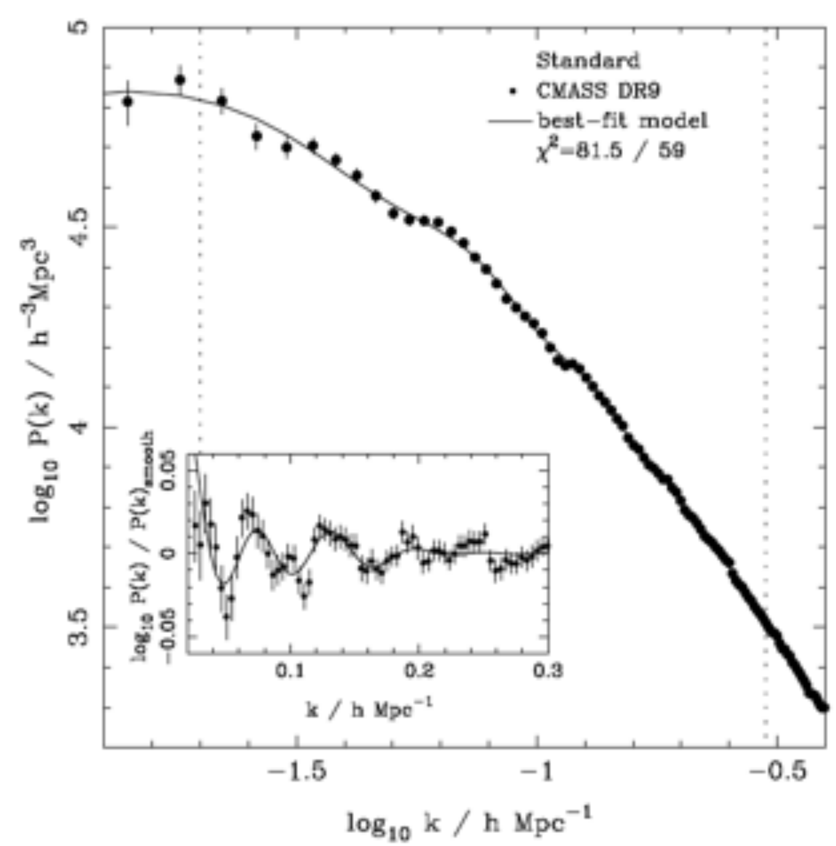
Planck



SDSS







"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

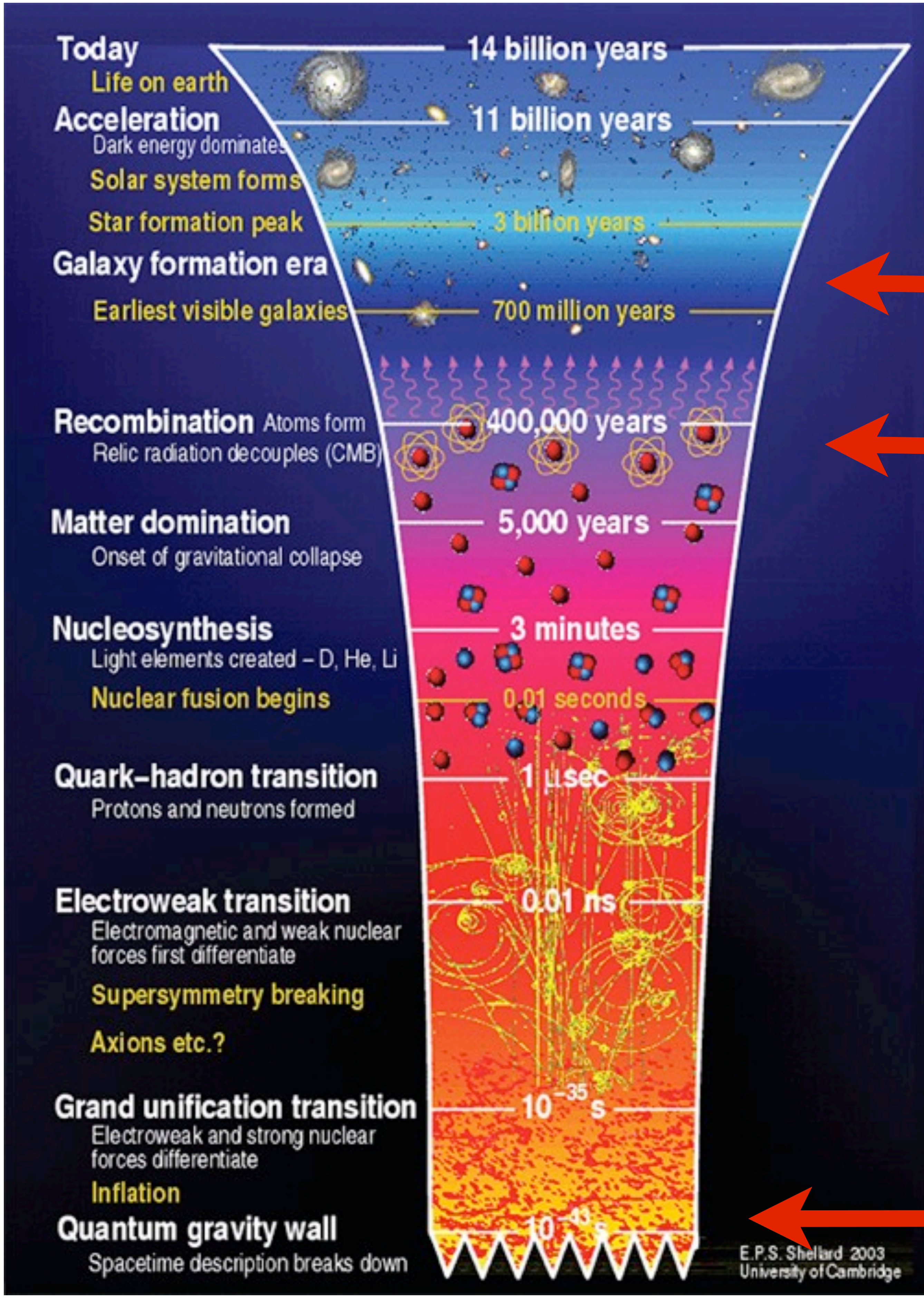
Einstein Gravity

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."*



Reionization ("EoR")
Dark ages

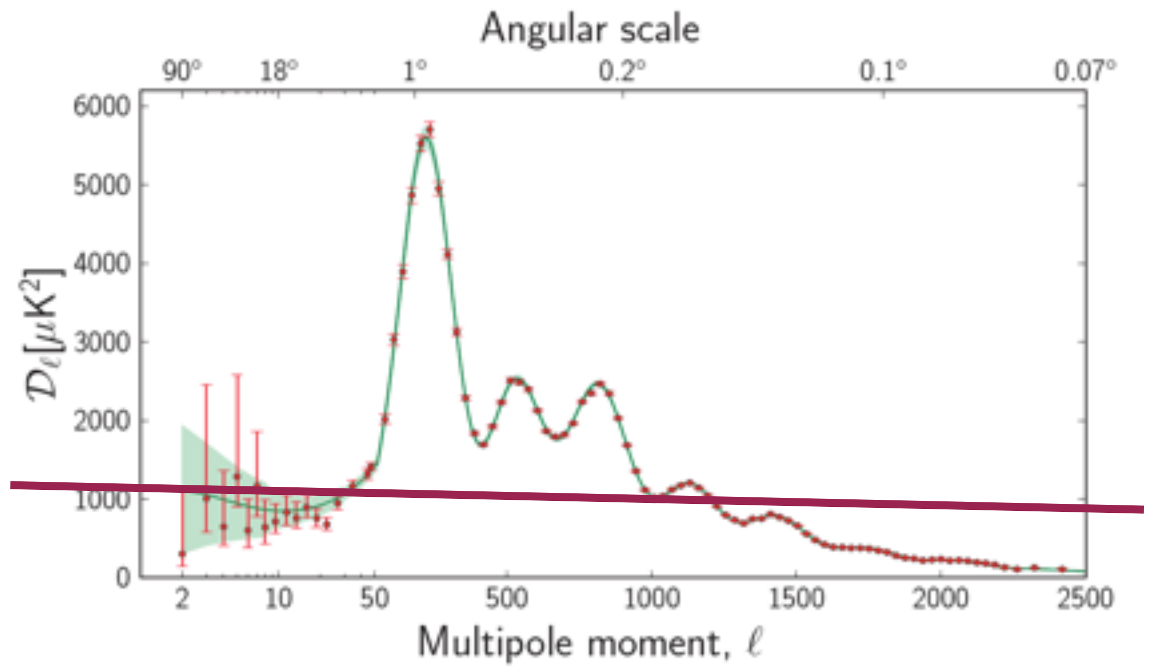
Recombination

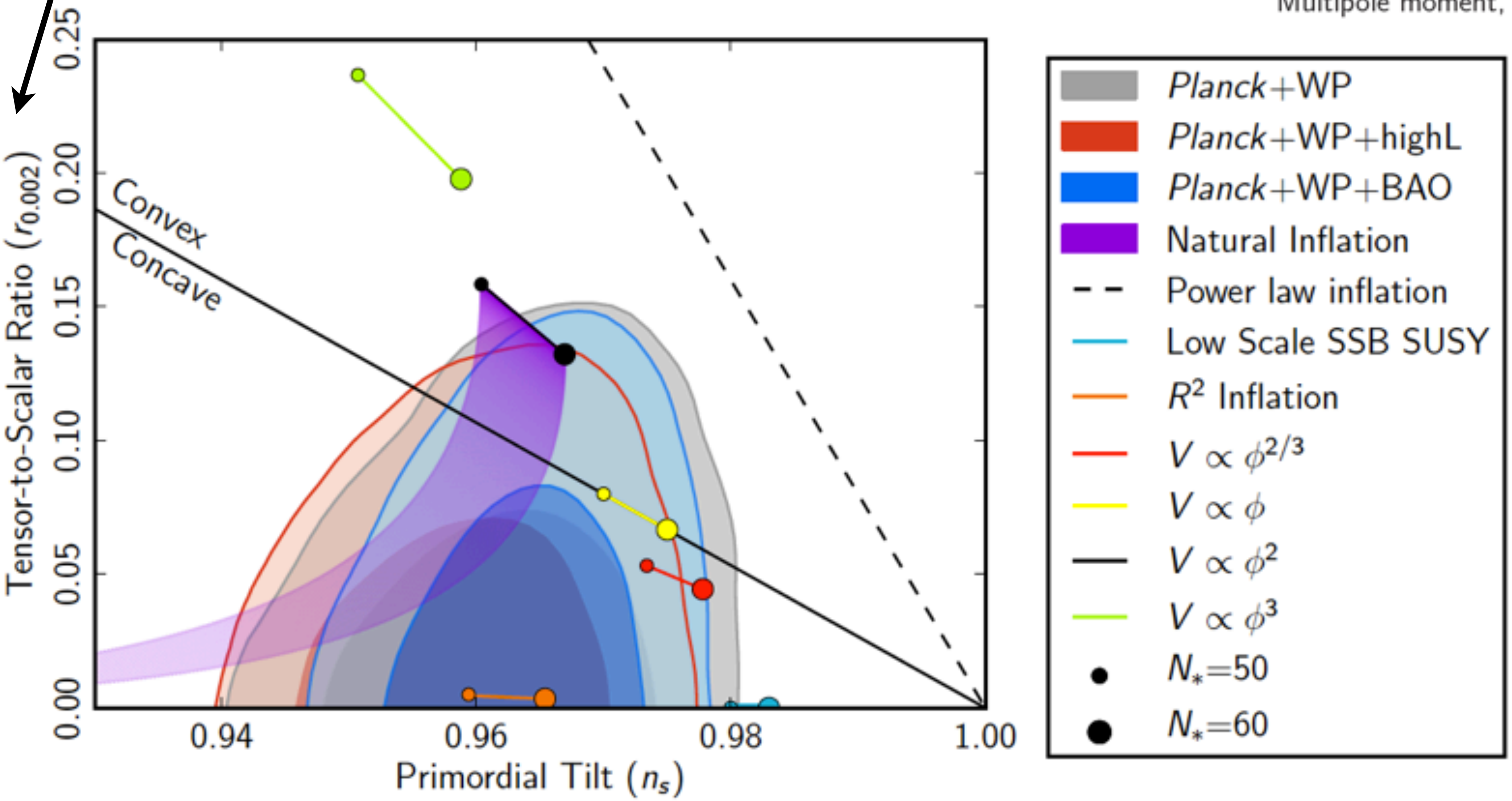
Initial Conditions

Initial Conditions

Primordial Gravitational Waves

Primordial Tilt



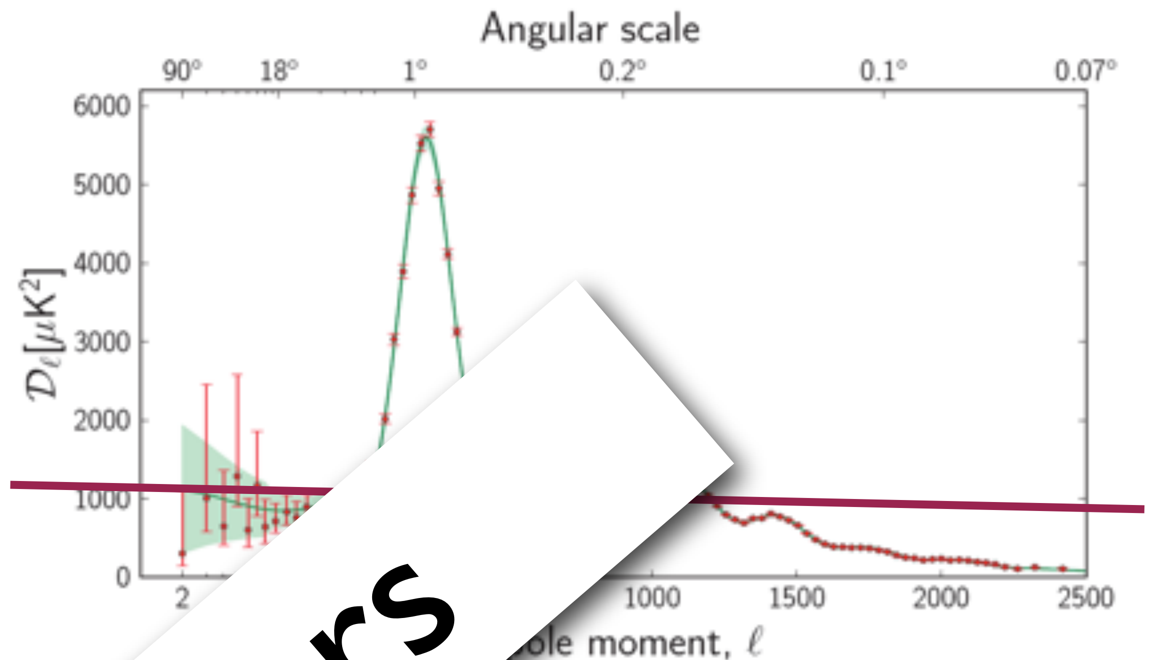


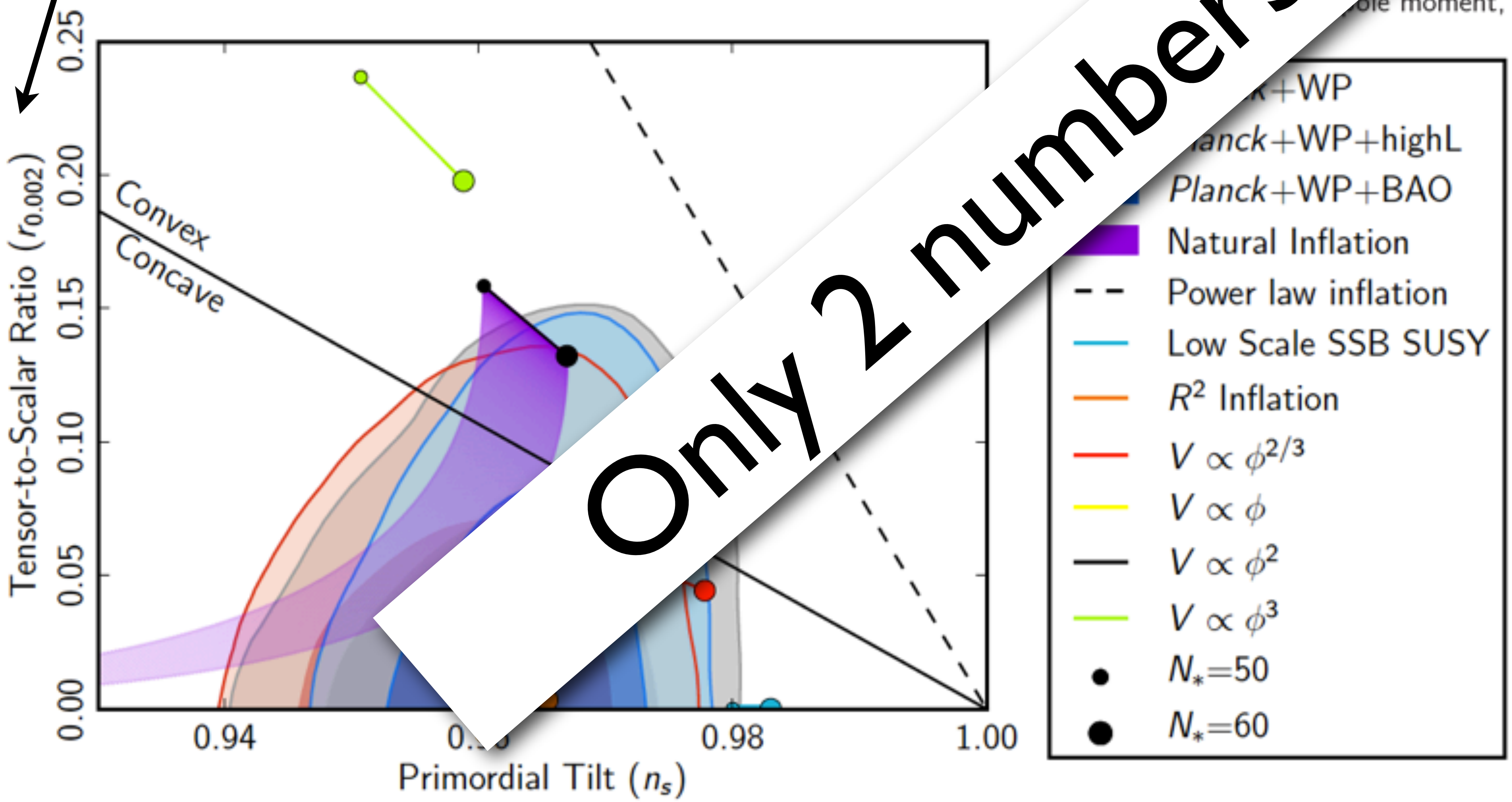
Planck XXII

Initial Conditions

Primordial Gravitational Waves

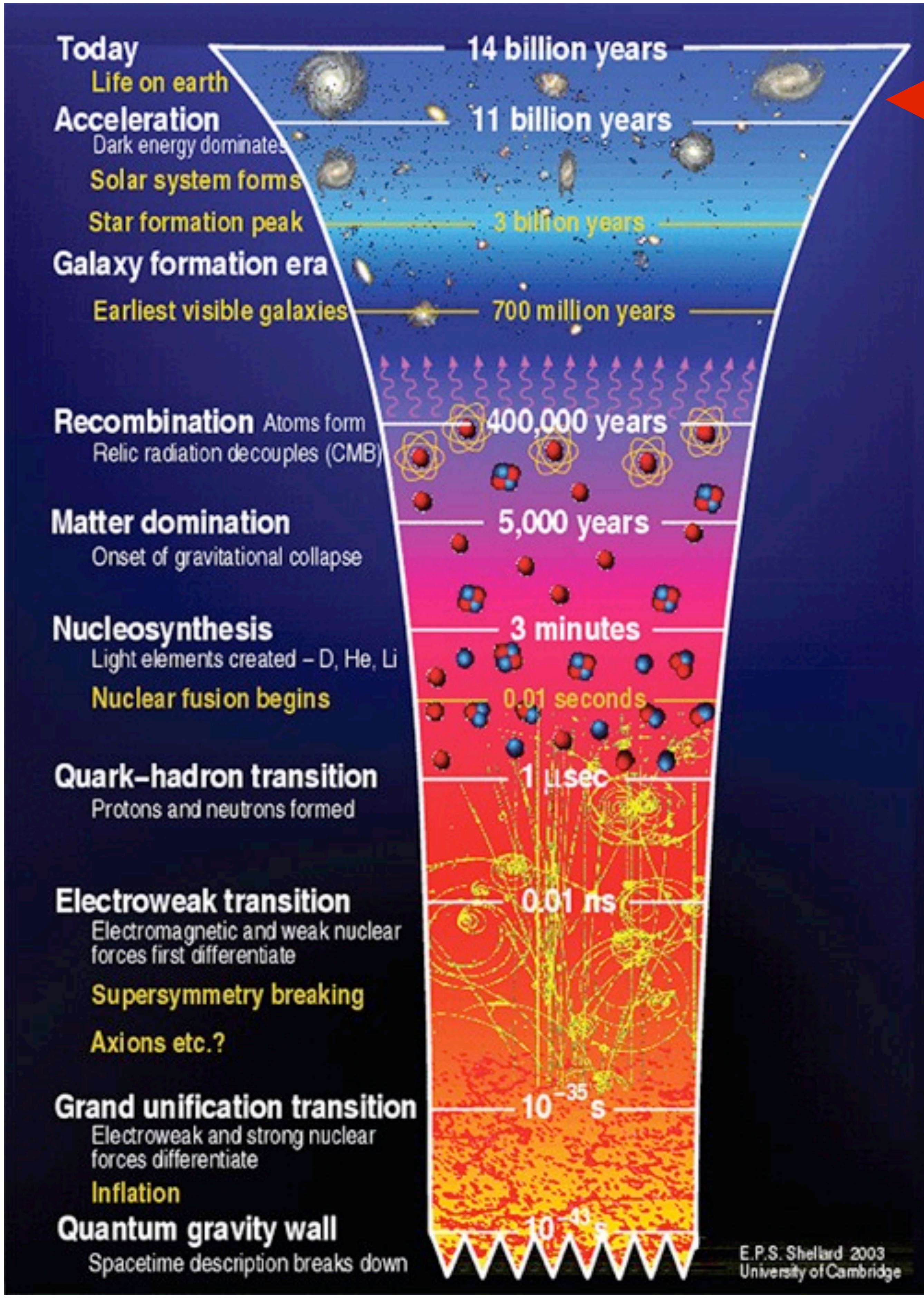
Primordial Tilt





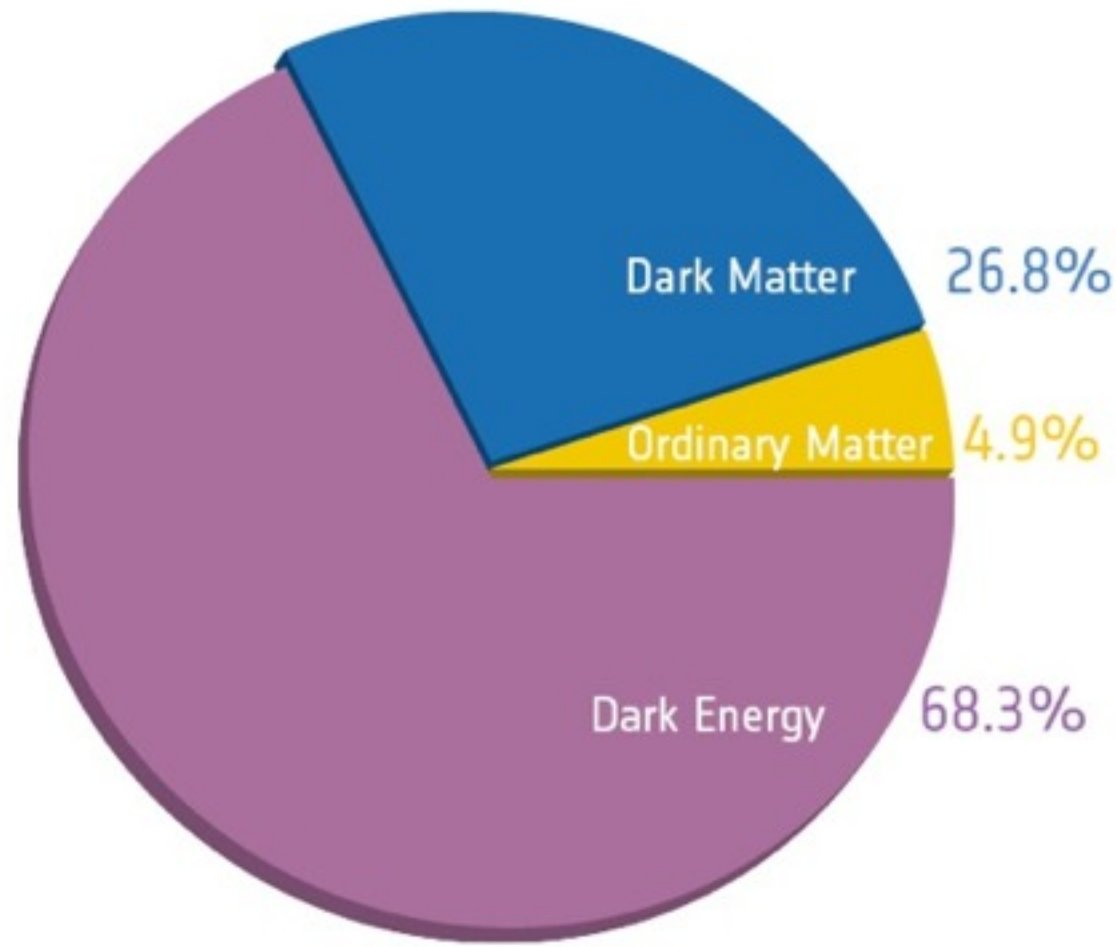
Only 2 numbers

Planck XXII



Acceleration

Where strange things *do* happen...



Planck XVIII

Effective Field Theory

"Cutoff": m $\quad a_i \sim \mathcal{O}(1)$

$$
\begin{aligned}
-\frac{\mathcal{L}_{\rm eff}}{\sqrt{-g}} &= \lambda + \frac{M_p^2}{2} R + a_1 R_{\mu\nu} R^{\mu\nu} \\
&\quad + a_2 R^2 + a_3 R_{\mu\nu\lambda\rho} R^{\mu\nu\lambda\rho} + a_4 \Box R \\
&\quad + \frac{b_1}{m^2} R^3 + \frac{b_2}{m^2} R R_{\mu\nu} R^{\mu\nu} + \frac{b_3}{m^2} R_{\mu\nu} R^{\nu\lambda} R_\lambda{}^\mu
\end{aligned}
$$

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

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

The Feynman/Weinberg "Theorem"

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

$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}$ Spin-2 field

$$S = \frac{1}{16\pi G} \int d^4x \left[-\frac{1}{2}\partial_\lambda h_{\mu\nu}\partial^\lambda h^{\mu\nu} + \partial_\mu h_{\nu\lambda}\partial^\nu h^{\mu\lambda} - \partial_\mu h^{\mu\nu}\partial_\nu h + \partial_\lambda h \partial^\lambda h \right]$$

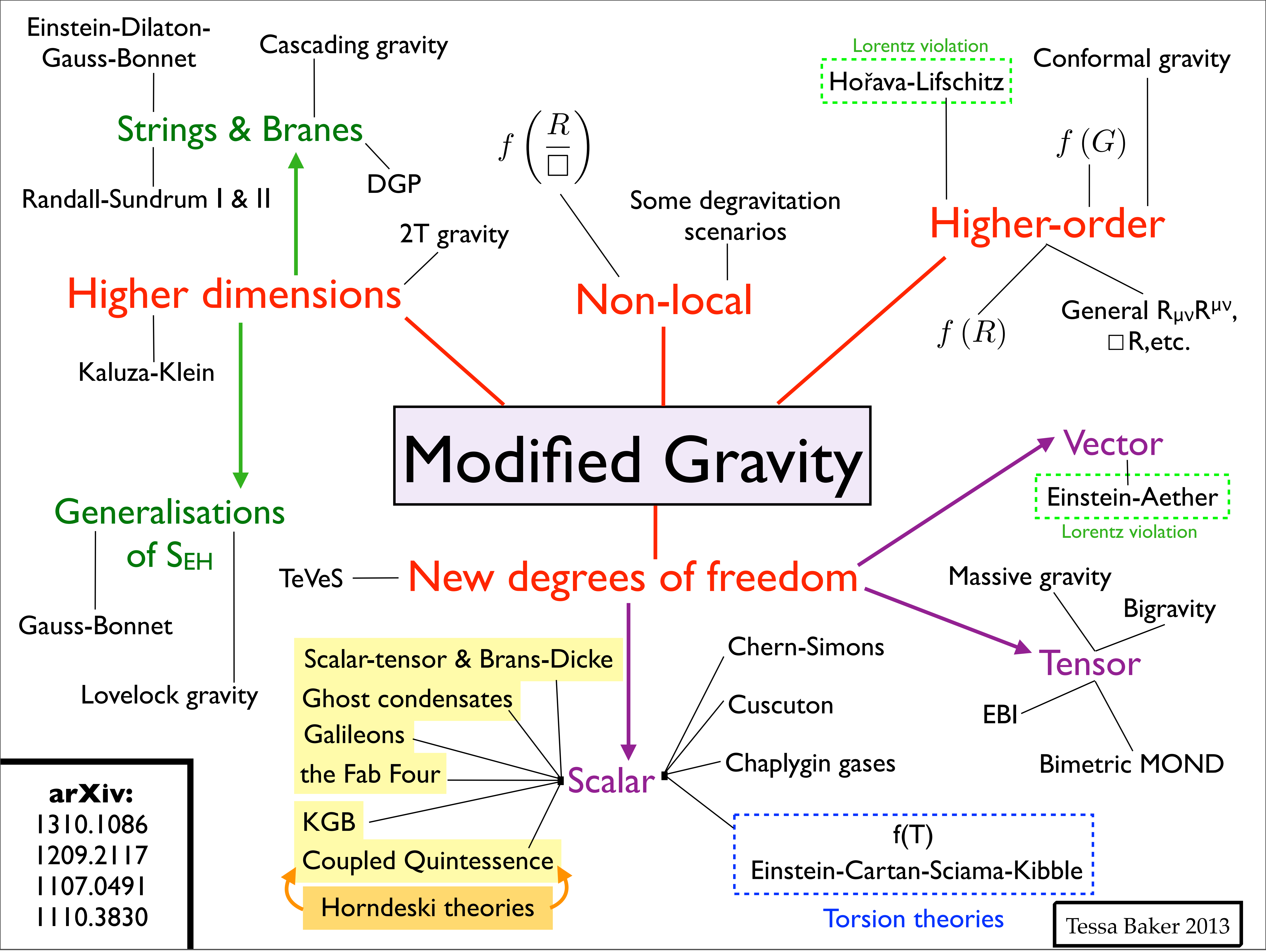
$$g_{\mu\nu}(y) = \frac{\partial x^\alpha}{\partial y^\mu}\frac{\partial x^\beta}{\partial y^\nu} g_{\alpha\beta}(x) \longrightarrow h_{\alpha\beta} \to h_{\alpha\beta} + \partial_\alpha \xi_\beta + \partial_\beta \xi_\alpha$$

Couple to matter: $S_M = \int d^4x h_{\alpha\beta} T_M^{\alpha\beta}$

Self energy of the graviton: $T^G_{\mu\nu} \sim (\partial h)(\partial h)$

$$\Box h_{\mu\nu} = 16\pi G (T^M_{\mu\nu} + T^G_{\mu\nu})$$

Unique non-linear completion is GR...


Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
DGP
Randall-Sundrum I & II
2T gravity
Higher dimensions
Kaluza-Klein
$f\left(\frac{R}{\Box}\right)$
Non-local
Some degravitation scenarios
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f\left(G\right)$
Higher-order
$f\left(R\right)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Modified Gravity
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
TeVeS
New degrees of freedom
Vector
Einstein-Aether
Lorentz violation
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Scalar
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
arXiv:
1310.1086
1209.2117
1107.0491
1110.3830
Tessa Baker 2013

Example: Jordan-Brans-Dicke

$$S = \int \sqrt{-g} d^4x \left[\phi R - \frac{\omega}{\phi} (\nabla\phi)^2 \right]$$

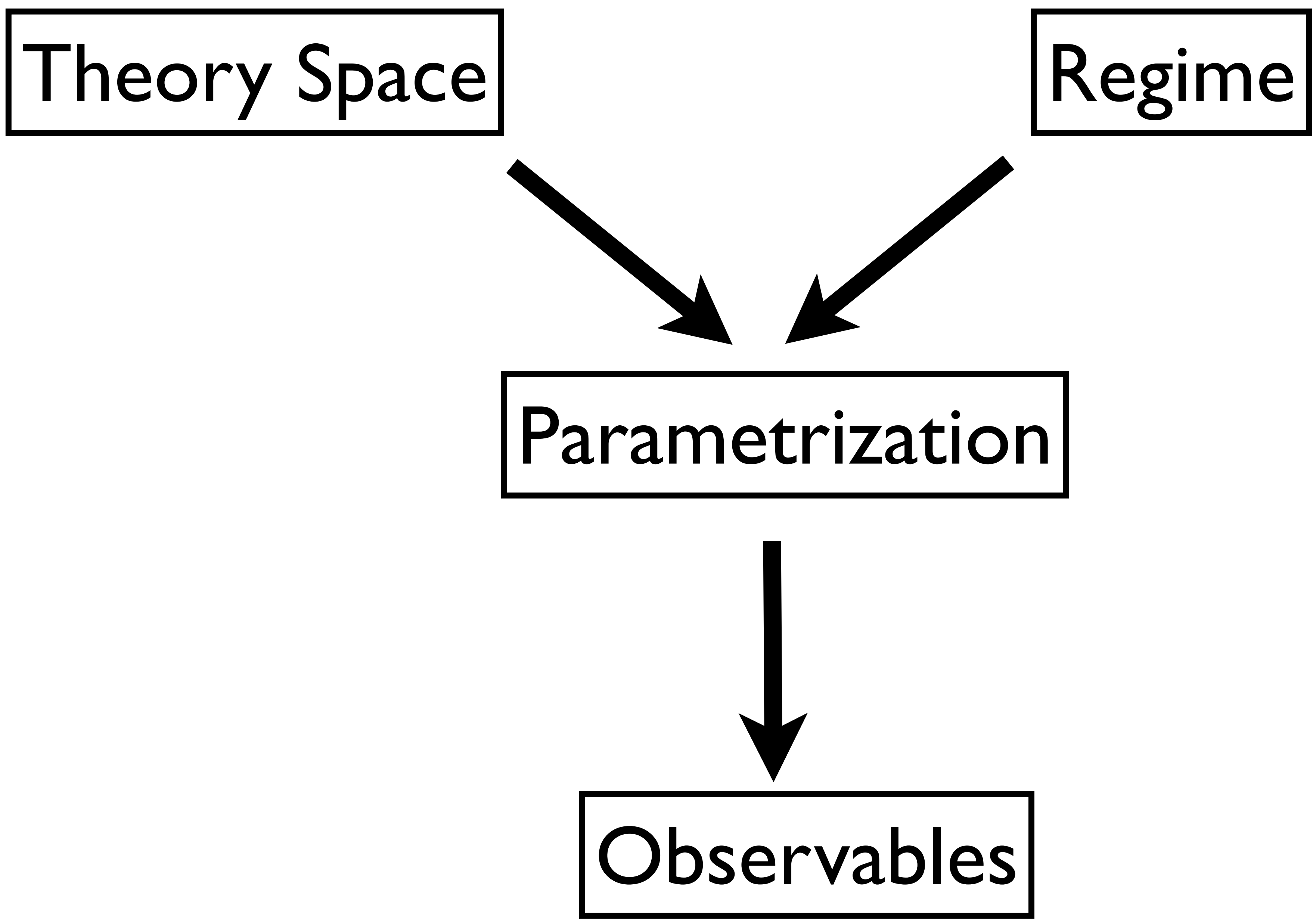
$$\Box\phi = \frac{1}{(2\omega + 3)} T_{matt}$$

$$G = \frac{4 + 2\omega}{3 + 2\omega} \frac{1}{\phi_0}$$

Recall Dirac: $"\Box" \frac{1}{G} \propto \rho$

GR: $\omega \rightarrow \infty$

The Process



The Universe: background cosmology

$$ds^2 = a^2\gamma_{\mu\nu}dx^\mu dx^\nu$$

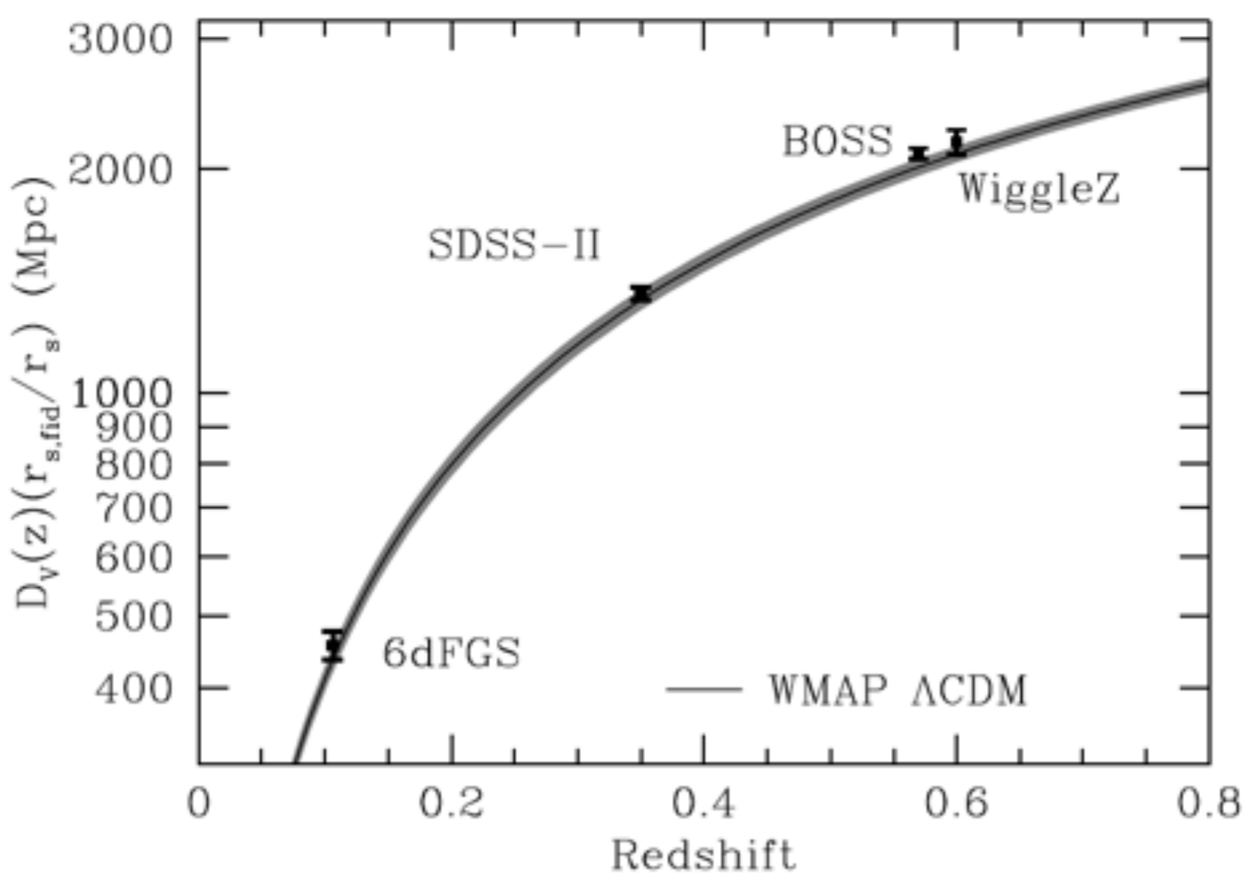
FRW equations

$$G_{\alpha\beta} = 8\pi G T_{\alpha\beta} \longrightarrow \mathcal{H}^2 = \frac{8\pi G}{3}a^2\rho$$

<u>Any</u> theory (modified gravity or otherwise)

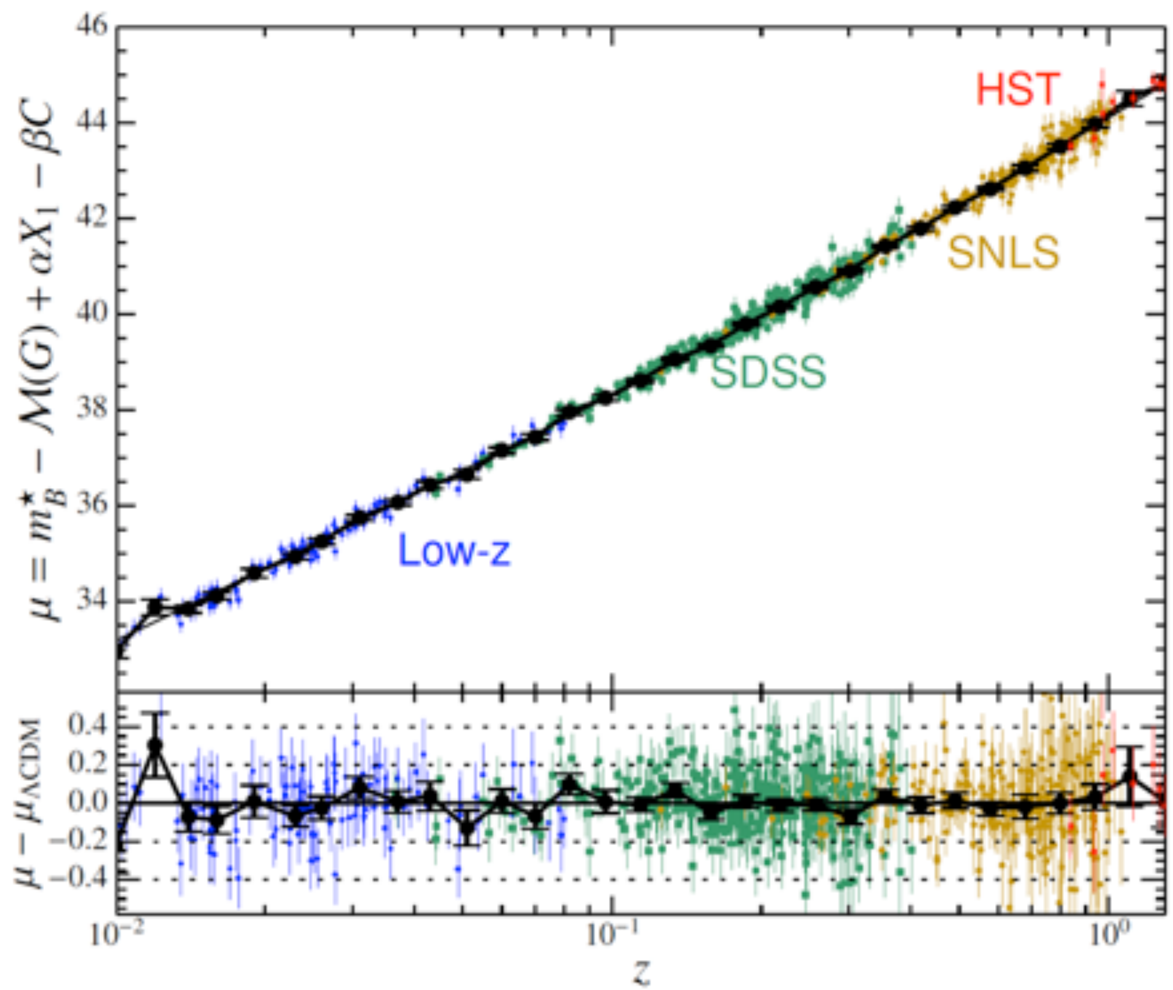
$$G_{\alpha\beta} = 8\pi G T_{\alpha\beta} + U_{\alpha\beta} \longrightarrow \rho_X(\tau), P_X(\tau)$$

The Universe: background cosmology



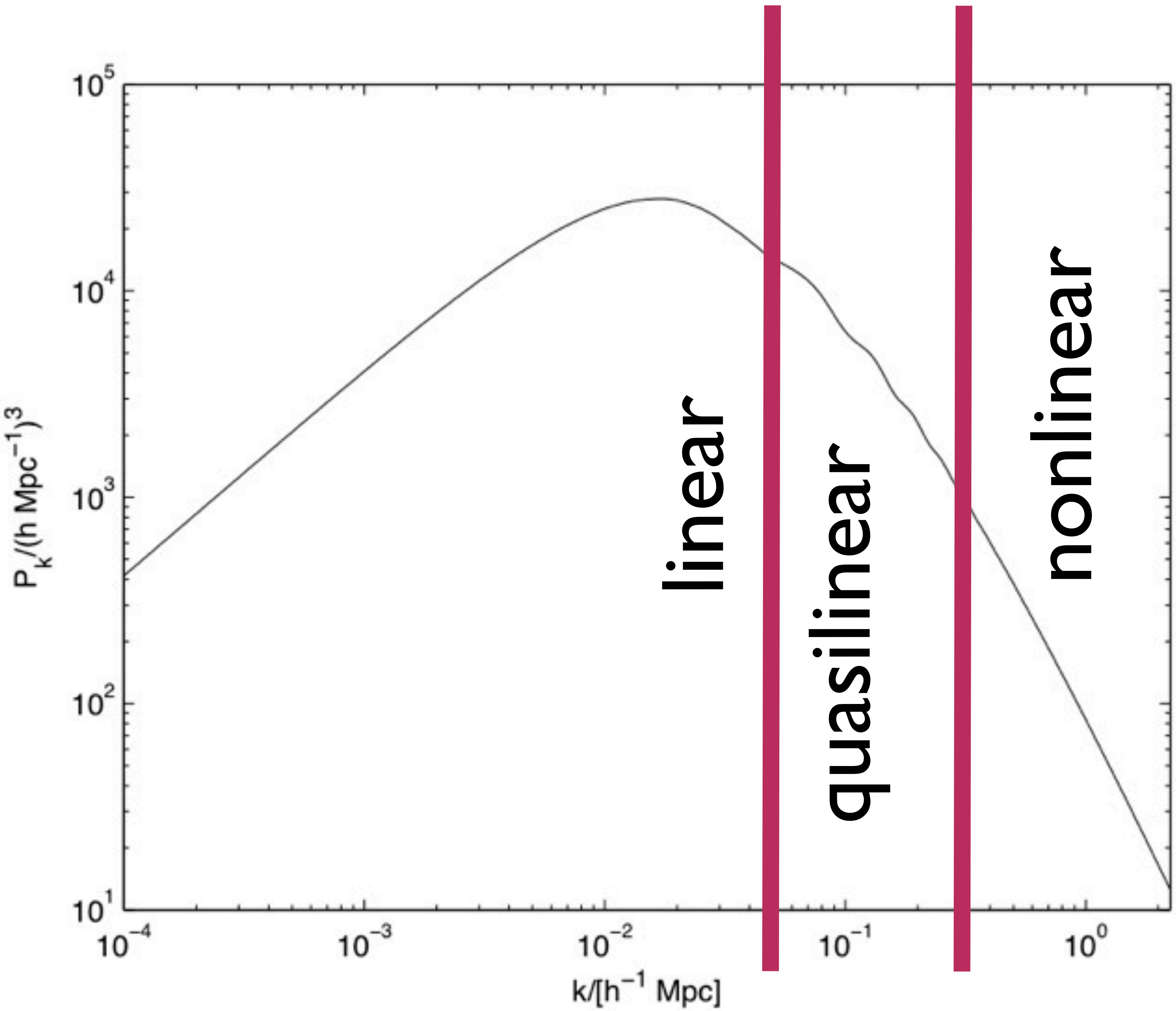
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}.$$

BOSS, Anderson et al 2013.



Betoule et al (2014)

The Universe: large scale structure



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

$$ds^2 = a^2(\gamma_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu$$

Diffeomorphism invariance ⟶ Gauge invariant Newtonian potentials

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

$$\rho \to \rho(\tau)[1 + \delta(\tau, \mathbf{r})]$$

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

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

$$\delta G_{00}^{(gi)} : \; 2\vec{\nabla}^2\hat{\Phi} - 6\mathcal{H}k\hat{\Gamma} = 8\pi G a^2 \rho \delta^{(gi)}$$

$$\delta G_{0i}^{(gi)} : \; 2k\hat{\Gamma} = 8\pi G(\rho + P)\theta^{(gi)}$$

$$\delta G_{ij}^{(gi)} : \; \hat{\Phi} - \hat{\Psi} = 8\pi G a^2 (\rho + P)\Sigma^{(gi)}$$

← fluid momentum and anisotropic stress

(+ $\delta G_{ii}^{(gi)}$ equation)

Extending Einstein's equations

$$\delta G_{\mu\nu} = 8\pi G \delta T^{M}_{\mu\nu} + \delta U_{\mu\nu}$$

↓

Linear in $\hat{\Phi}, \hat{\Gamma}, \hat{\chi}, \dot{\hat{\chi}}$

Baker, Ferreira, Skordis 2012

ArXiv:1209.2117

Extending Einstein's equations

Key: Matter + Metric + New degree of freedom

$$-a^2\delta G^{0\,(gi)}_{0} = \kappa a^2 G\,\rho_M \delta_M^{(gi)} + \alpha_0 k^2 \hat{\chi} + \alpha_1 k \dot{\hat{\chi}} + A_0 k^2 \hat{\Phi} + F_0 k^2 \hat{\Gamma}$$

ArXiv:1209.2117

Extending Einstein's equations

Key: Matter + Metric + New degree of freedom

$$-a^2\delta G^{0\,(gi)}_{0} = \kappa a^2 G\,\rho_M\delta_M^{(gi)} + \alpha_0 k^2\hat{\chi} + \alpha_1 k\dot{\hat{\chi}} + A_0 k^2\hat{\Phi} + F_0 k^2\hat{\Gamma}$$

Functions of time (and scale).

$$-a^2\delta G^{0\,(gi)}_{i} = \nabla_i\left[\kappa a^2 G\,\rho_M(1+\omega_M)\theta_M^{(gi)} + \beta_0 k\hat{\chi} + \beta_1\dot{\hat{\chi}} + B_0 k\hat{\Phi} + I_0 k\hat{\Gamma}\right]$$

$$a^2\delta G^{i\,(gi)}_{i} = 3\,\kappa a^2 G\,\rho_M\Pi_M^{(gi)} + \gamma_0 k^2\hat{\chi} + \gamma_1 k\dot{\hat{\chi}} + \gamma_2\ddot{\hat{\chi}} + C_0 k^2\hat{\Phi} + C_1 k\dot{\hat{\Phi}} + J_0 k^2\hat{\Gamma} + J_1 k\dot{\hat{\Gamma}}$$

$$a^2\delta G^{i}_{j} = D^i_j\left[\kappa a^2 G\,\rho_M(1+\omega_M)\Sigma_M + \epsilon_0\hat{\chi} + \frac{\epsilon_1}{k}\dot{\hat{\chi}} + \frac{\epsilon_2}{k^2}\ddot{\hat{\chi}} + D_0\hat{\Phi} + \frac{D_1}{k}\dot{\hat{\Phi}} + K_0\hat{\Gamma} + \frac{K_1}{k}\dot{\hat{\Gamma}}\right]$$

ArXiv:1209.2117

... but "Integrability condition" can help

$$U_{\alpha\beta} = \frac{2}{\sqrt{-g}} \frac{\delta S_U}{\delta g^{\alpha\beta}}$$

Use general principles to restrict S_U

$$S_U = \int d^4x \sqrt{-g} L(N, N^i, h_{ij}, {}^{(3)} R_{ij}, K_{ij})$$

with general time dependent coefficients.

Gleyzes, Langlois, Vernizzi 1411.3712

… but “Integrability conditi n” can help

$$U_{\alpha\beta} = \ldots$$

Use general pri

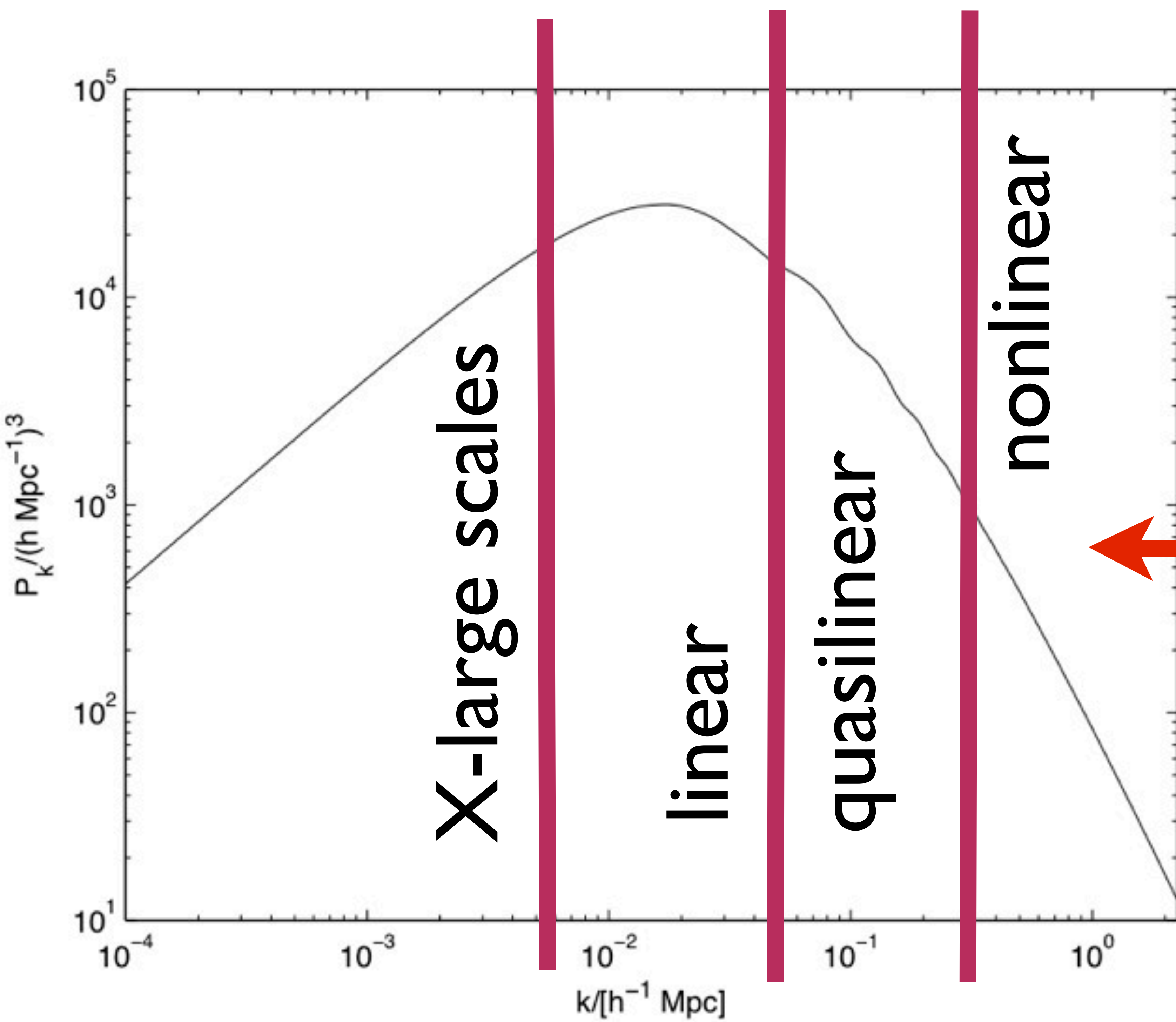
$$S \ldots , N^i, h_{ij}, {}^{(3)}R_{ij}, K_{ij})$$

with general ti ndent coefficients.

Gleyzes, Langlois, Vernizzi 1411.3712

Integrability

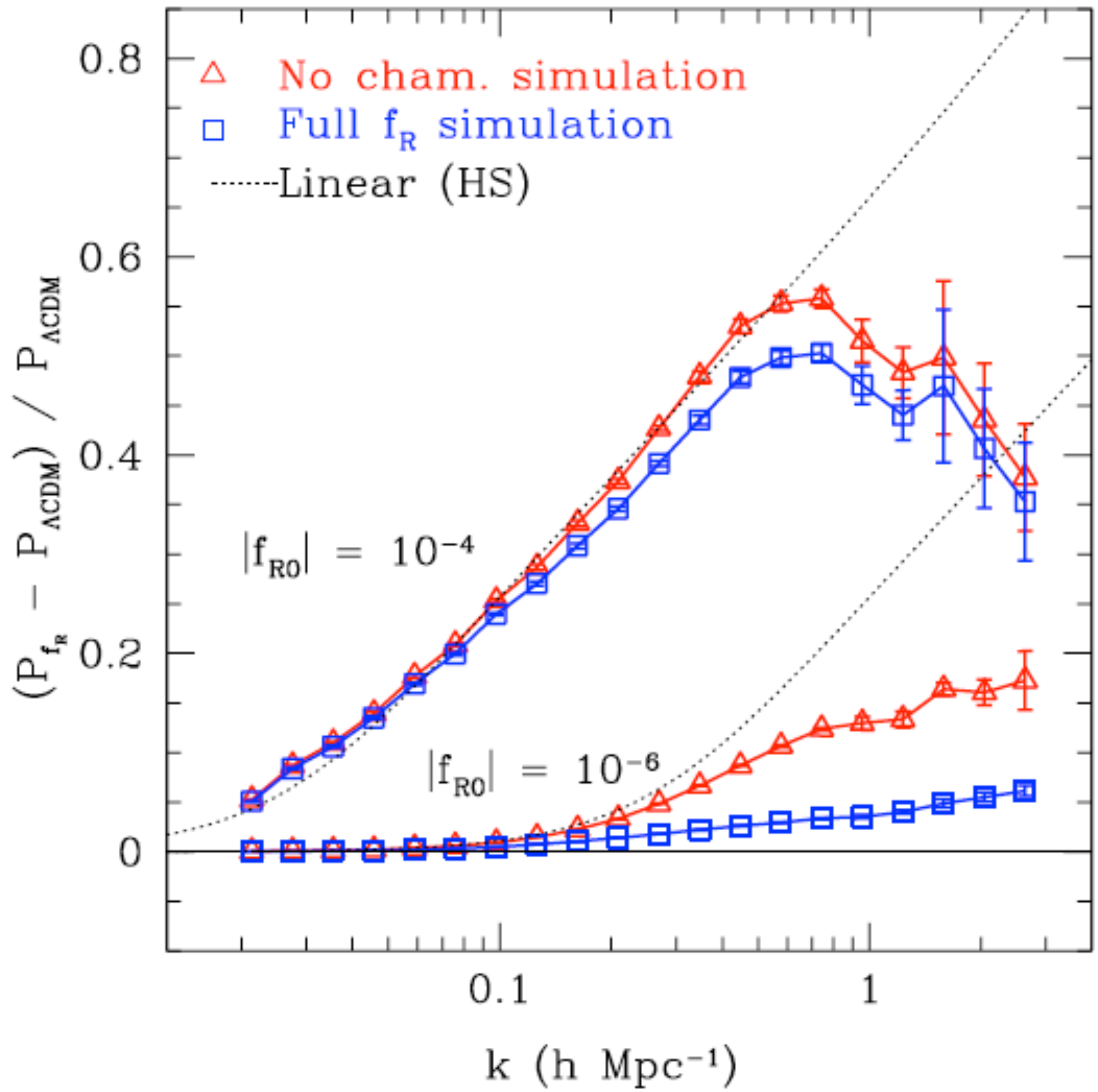
7 free functions of time



More statistical power ...

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

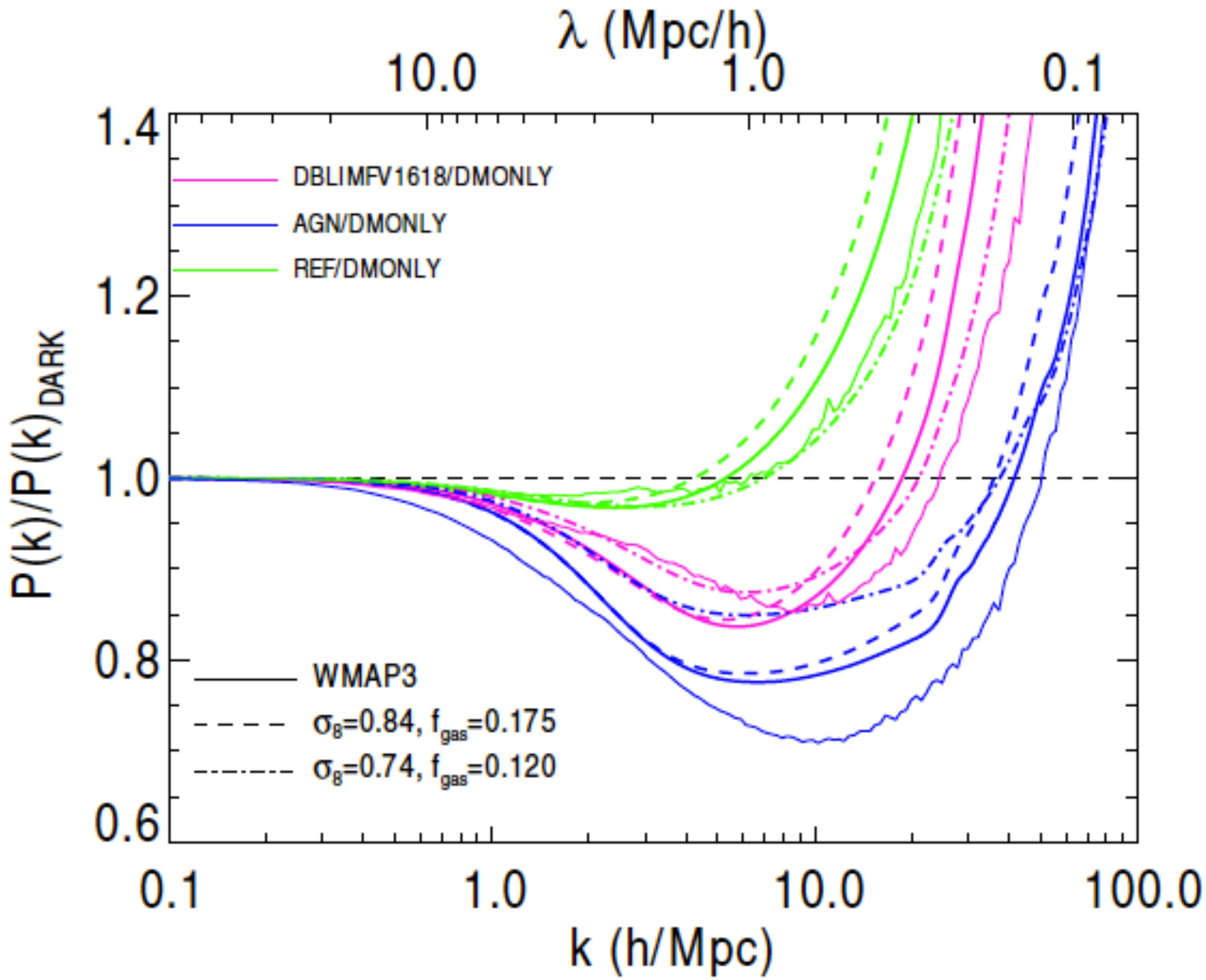
The non-linear regime



Courtesy of Hans Winther

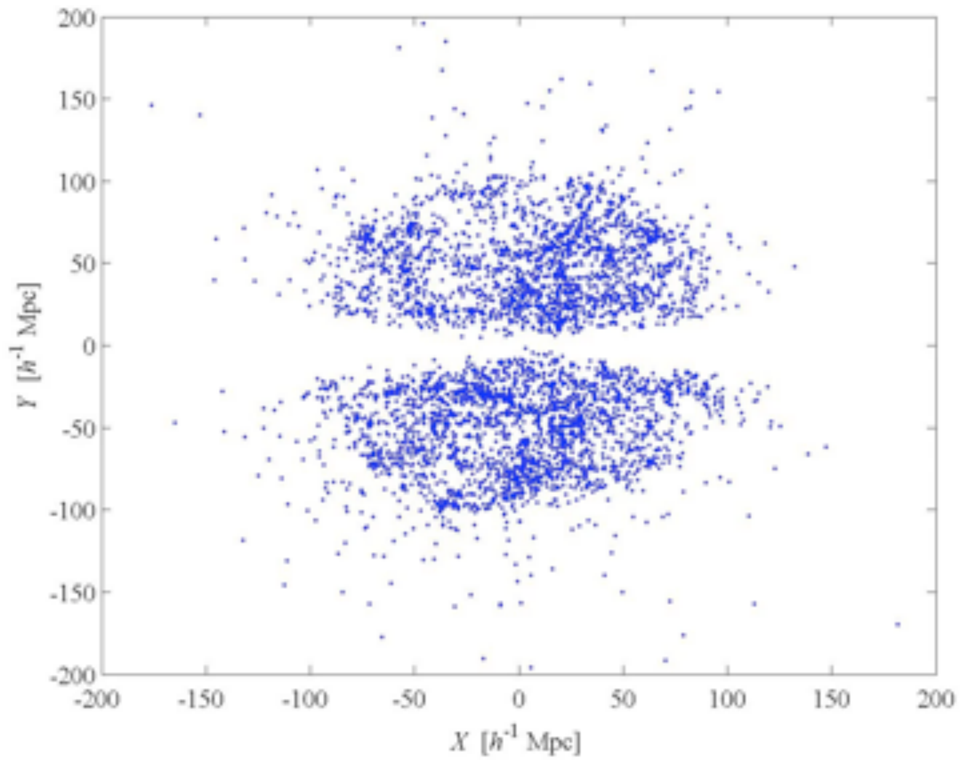
What about the non-linear regime?

Baryon, feedback and bias



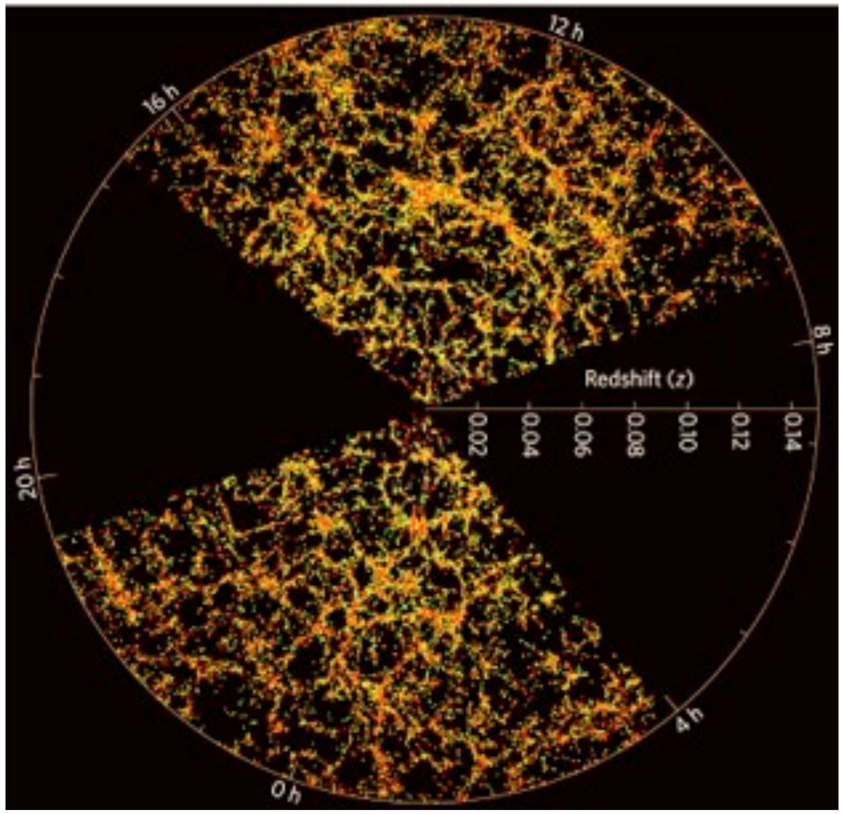
Semboloni et al 2012

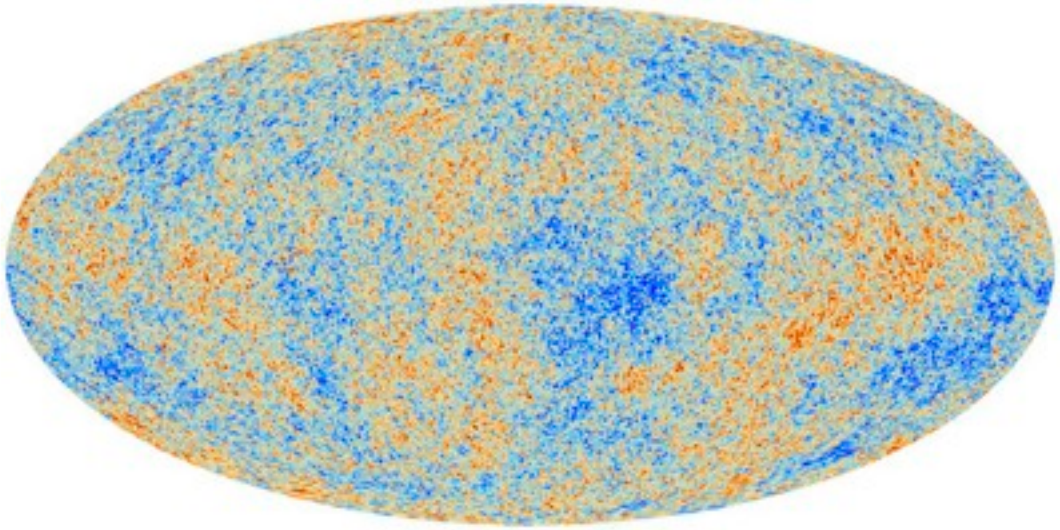
What we observe.



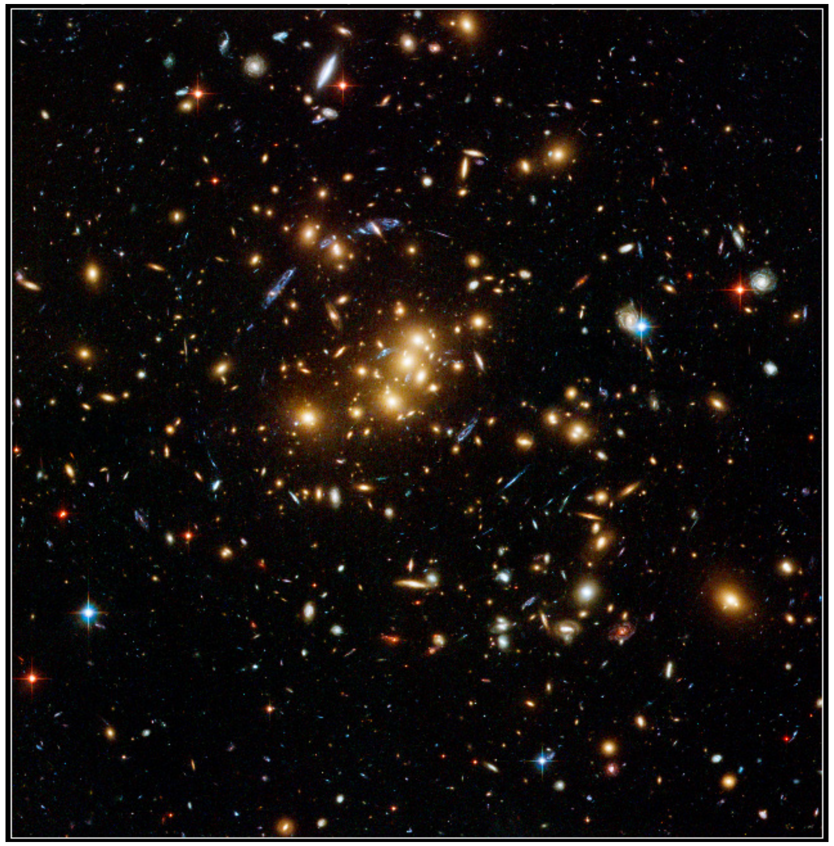
$\vec{v}$

$\delta, \vec{v}$

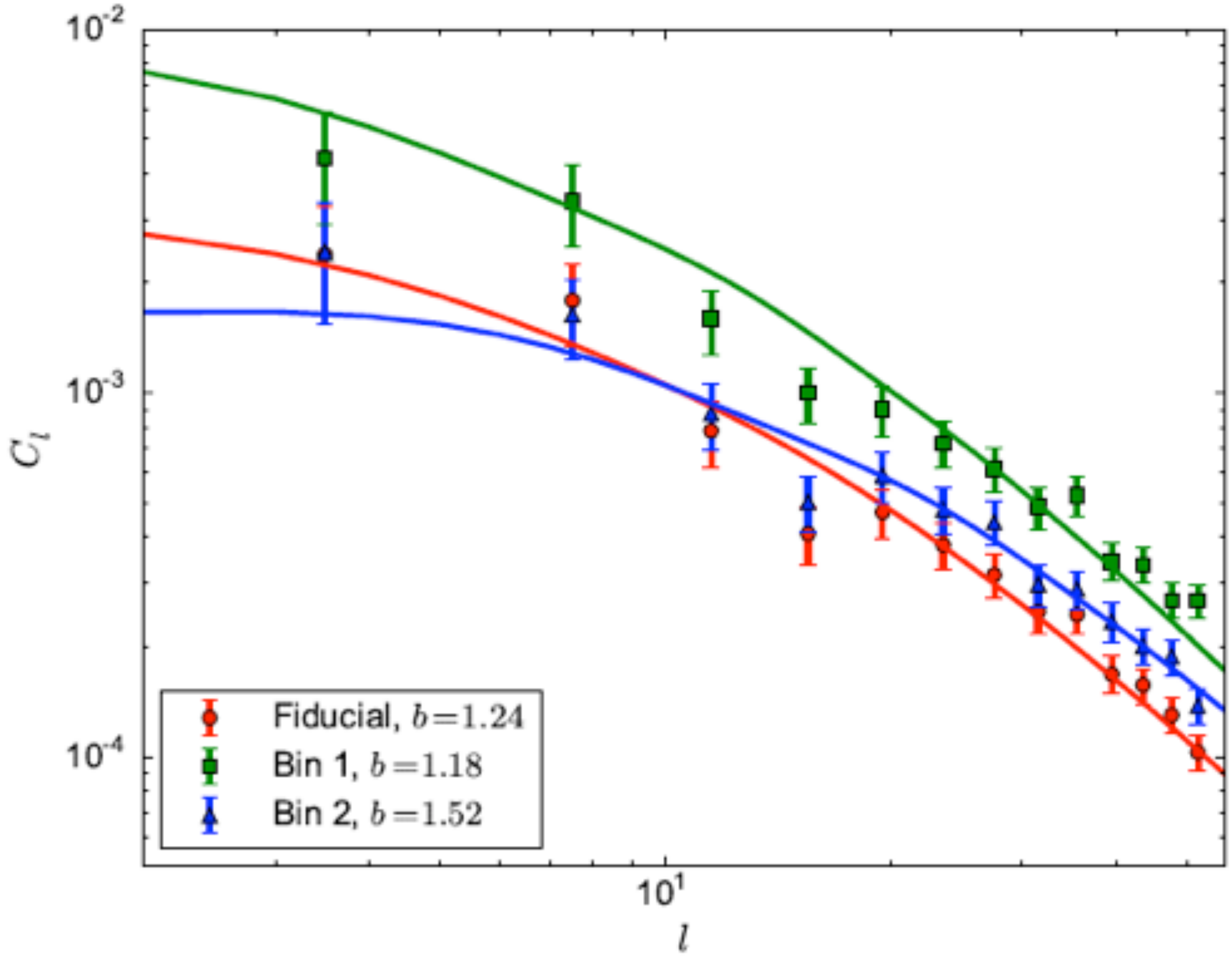




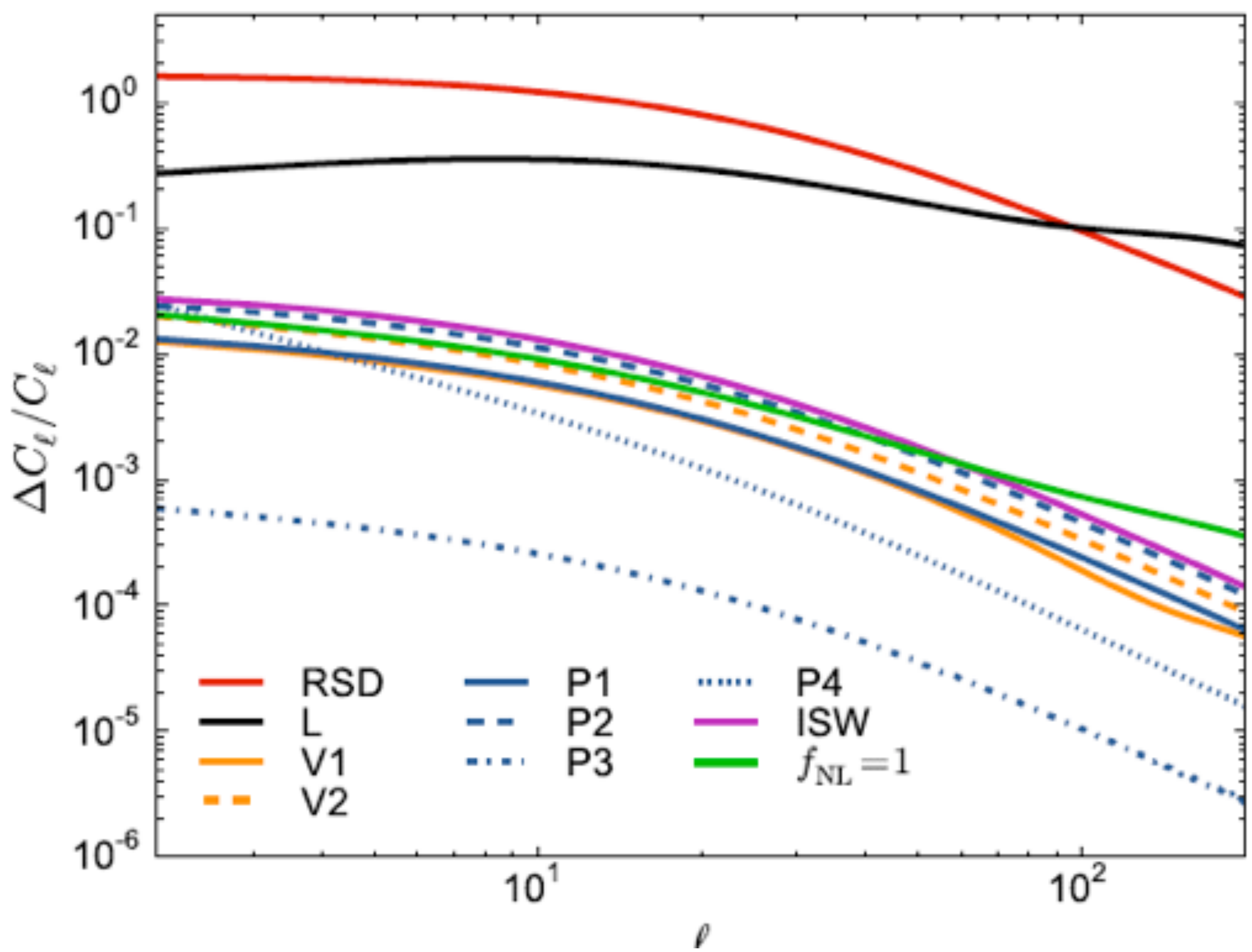
Φ, Ψ



Large Scales: horizon scale effects

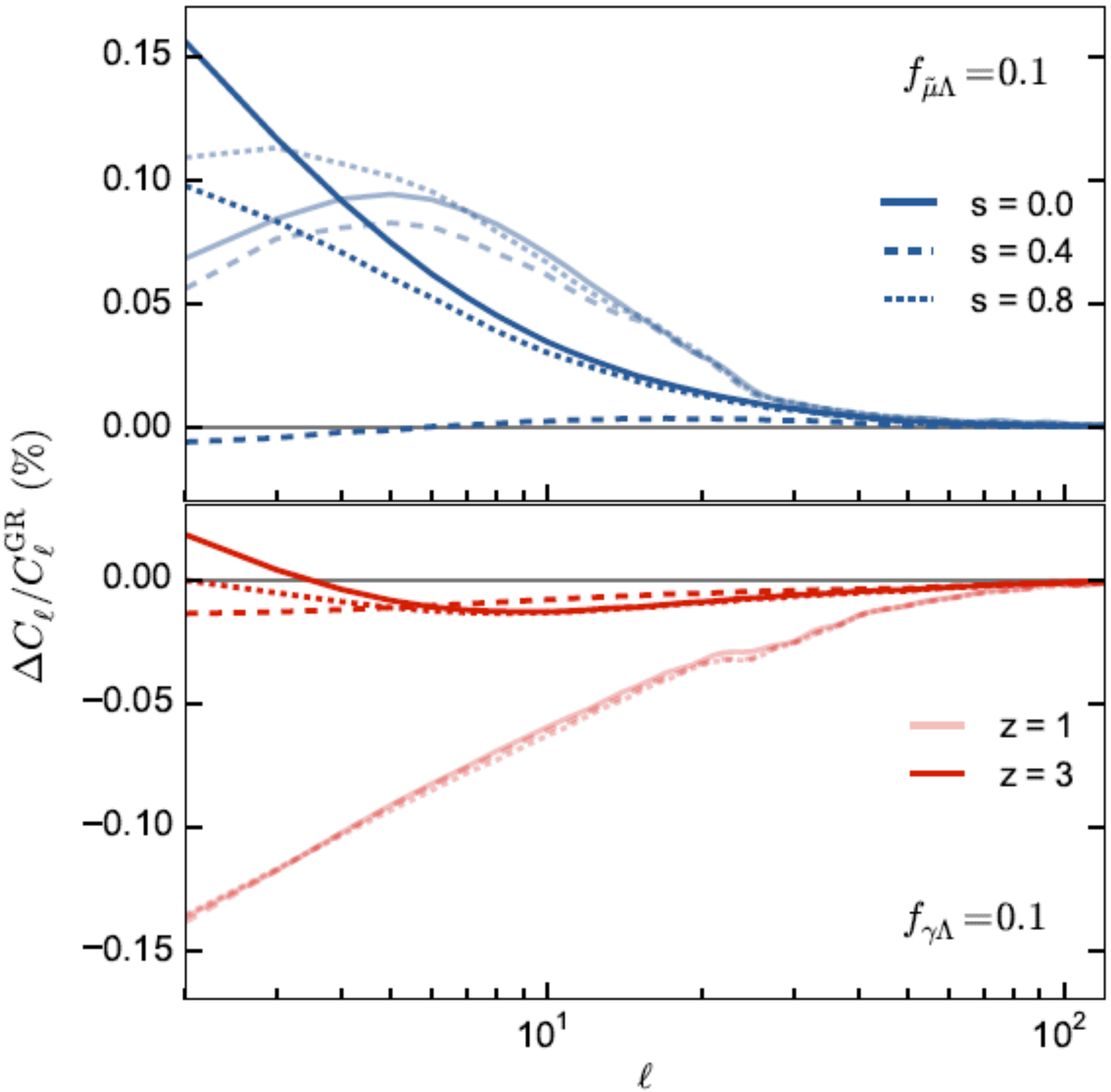


Alonso et al 2014 (2MASS)



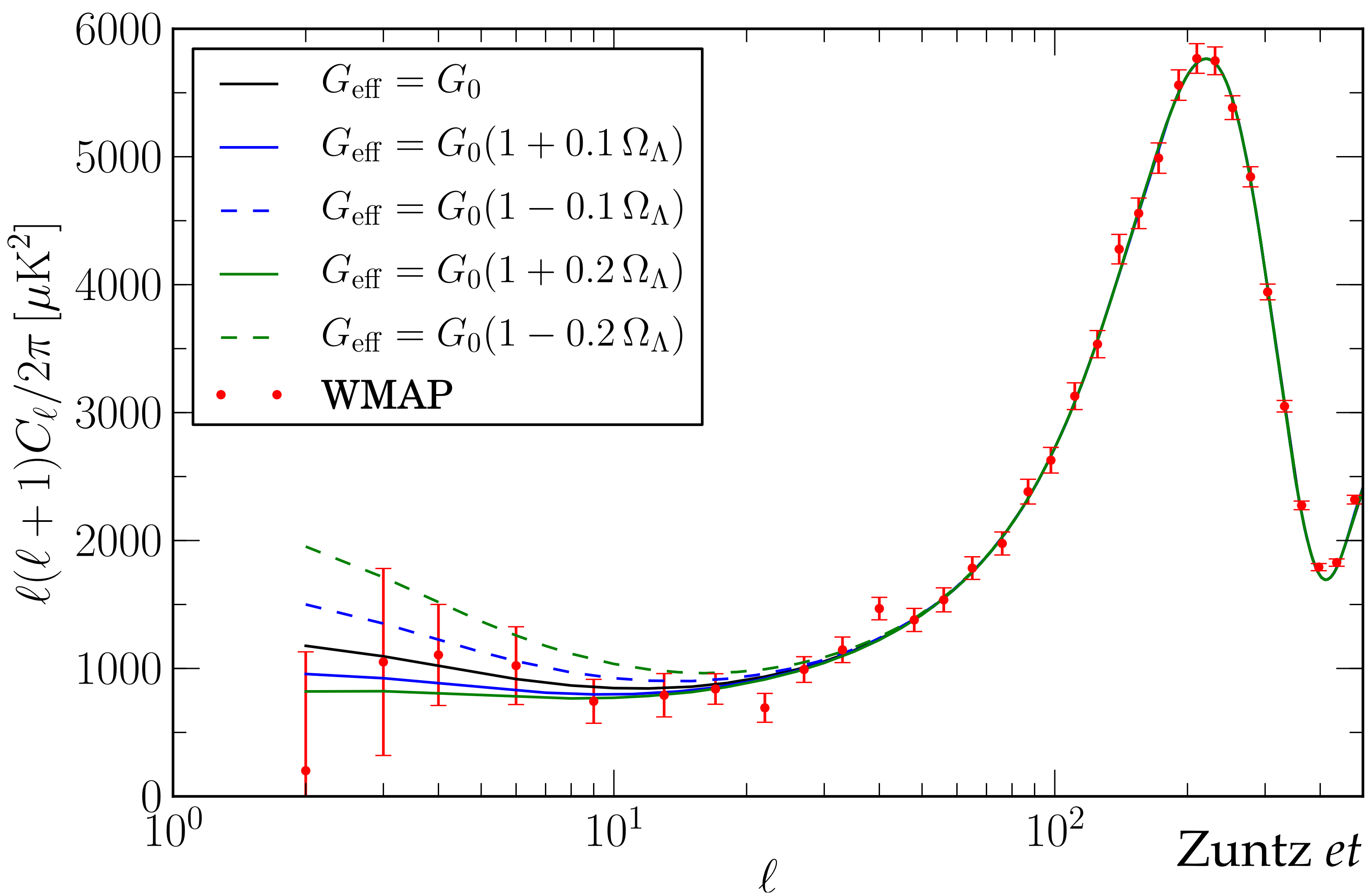
Alonso et al 2015

Large Scales: horizon scale effects



Baker & Bull 2015

Large Scales: the problem with cosmic variance

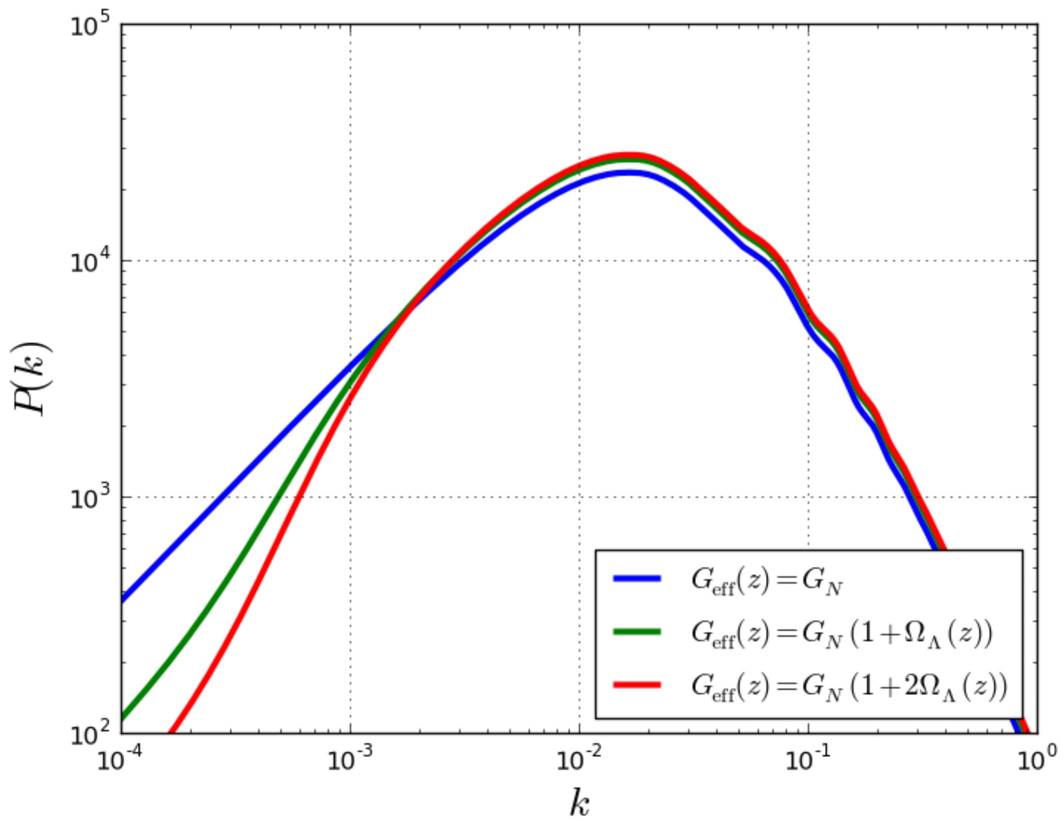


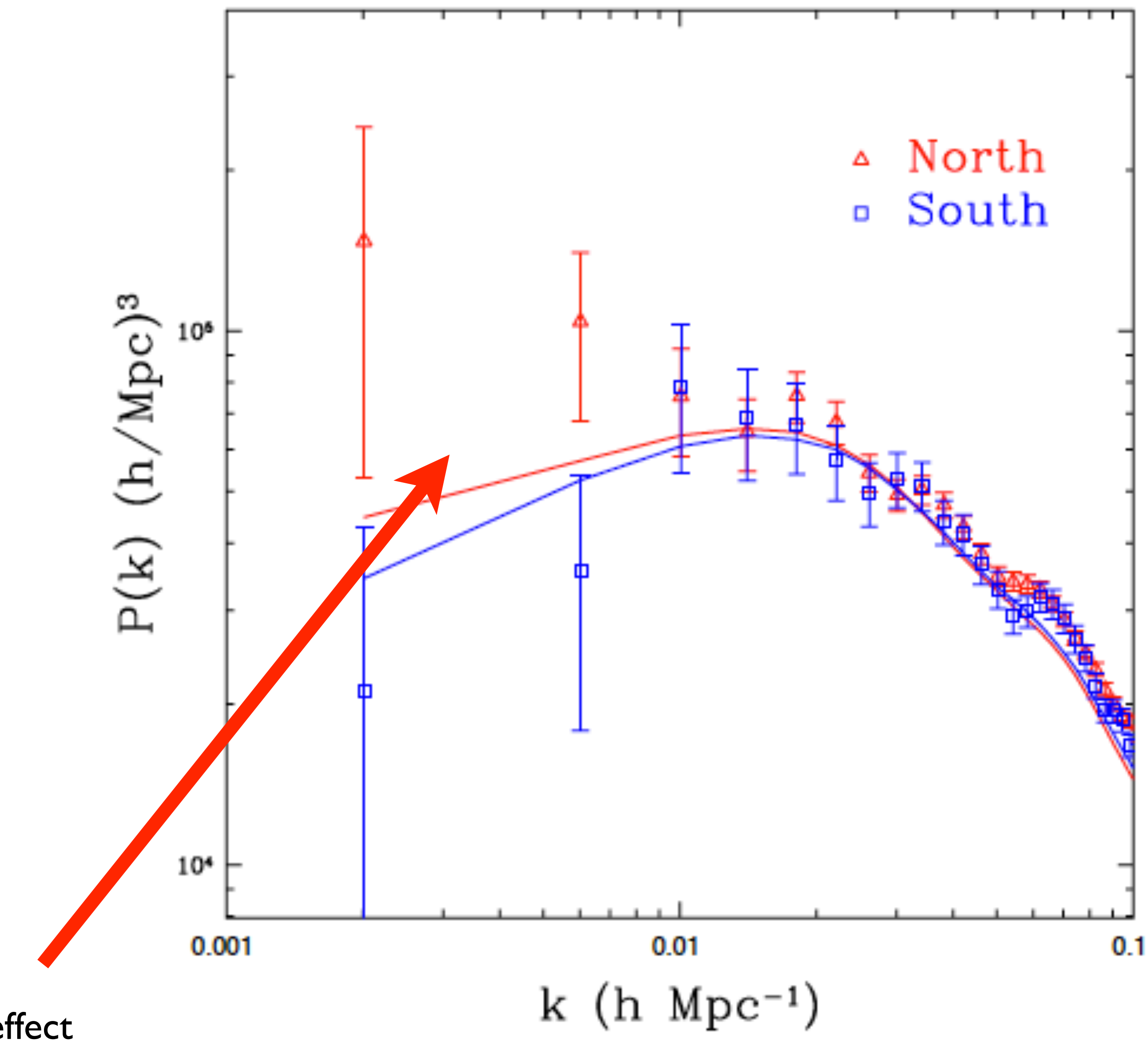
Zuntz *et al.* 2011

ISW- late time effects on large scales

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

Large Scales: the problem with cosmic variance





Systematic effect
due to stellar
densities

Ross et al (BOSS) 2012

Not so large scale: "quasi-static" regime

A preferred length scale- the horizon

↓

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

Focus on scales such that $k\tau \gg 1$

Most surveys $\leq 300h^{-1}\mathrm{Mpc}$

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

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

$$\gamma\Psi = \Phi$$

Note: not applicable to CMB!

Not so large scale: "quasi-static" regime

The "quasi-static" functions reduce to a simple form

$$\mu = \mu_0(a)\left[1+\left(\frac{M_1(a)}{k}\right)^2\right]$$
$$\gamma = \gamma_0(a)\left[1+\left(\frac{M_2(a)}{k}\right)^2\right]$$

DeFelice et al 2011
Baker et al 2012
Silvestri et al 2013

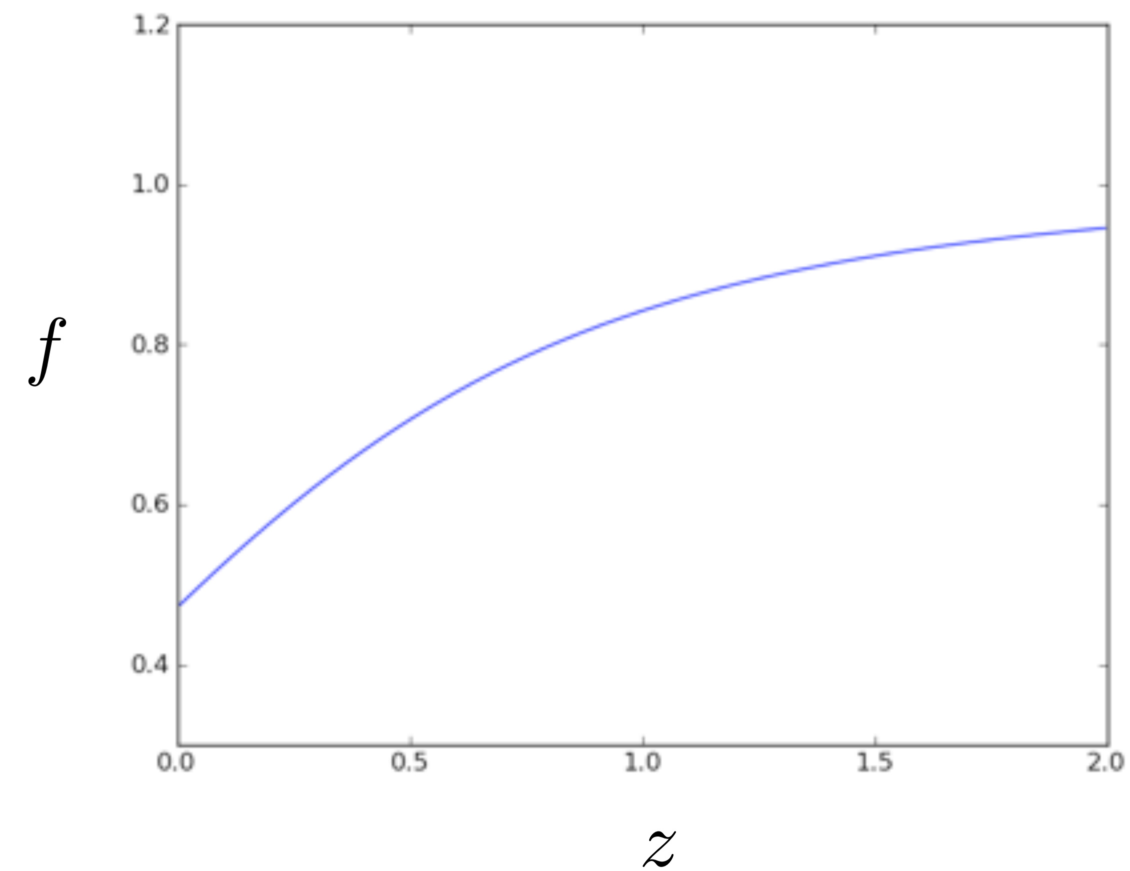
which depends on locality, Lorentz invariance, extra degrees of freedom, screening, etc.

Goal: to use k and z dependent measurements of (γ, μ) to constrain PPF functions

Growth of Structure

Growth rate

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

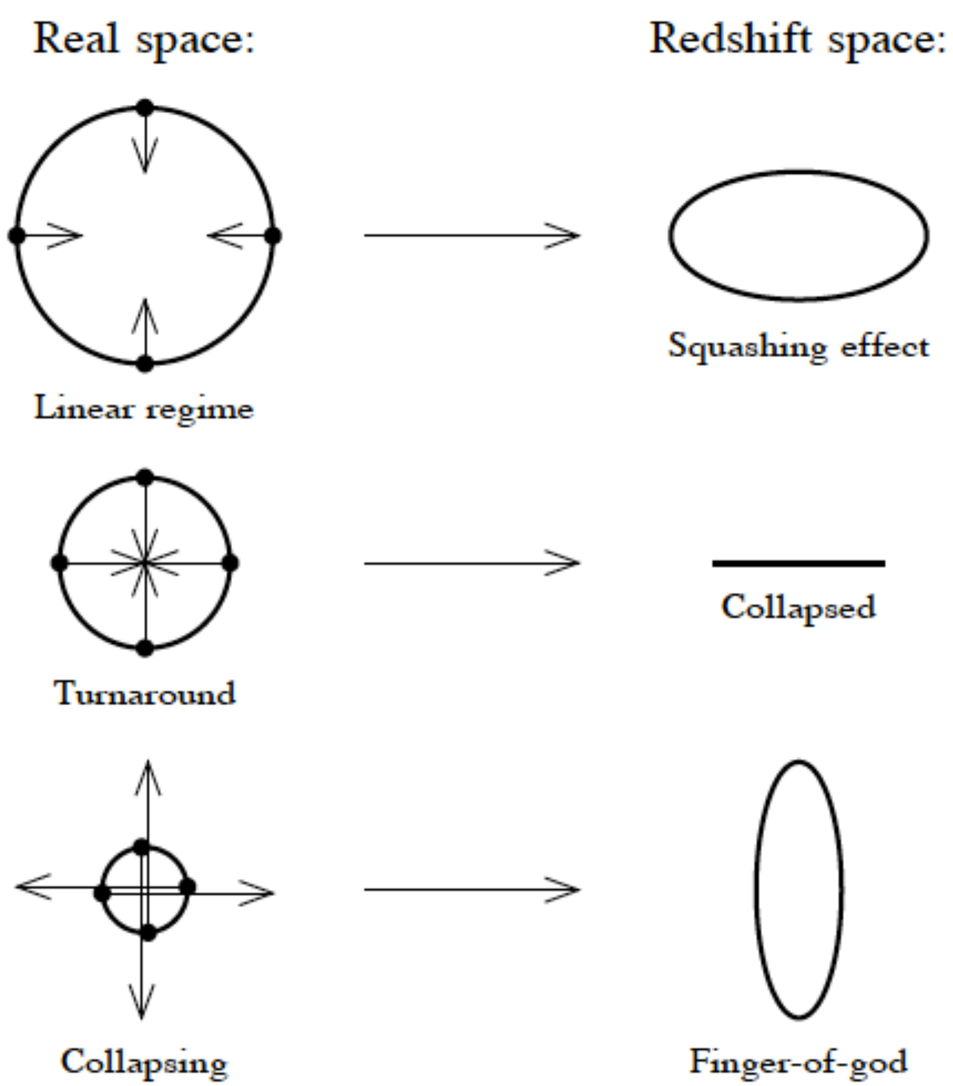


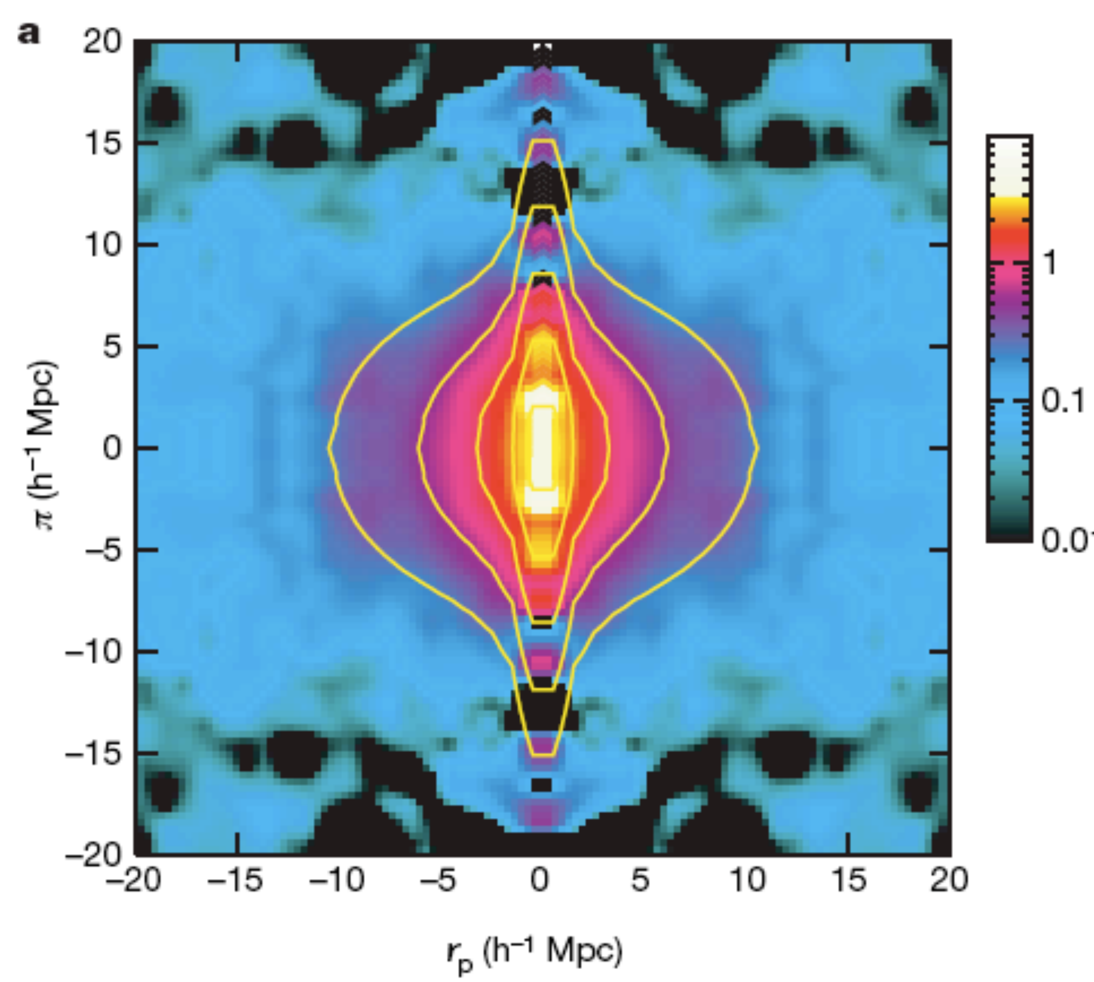
f satisfies a simple ODE

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

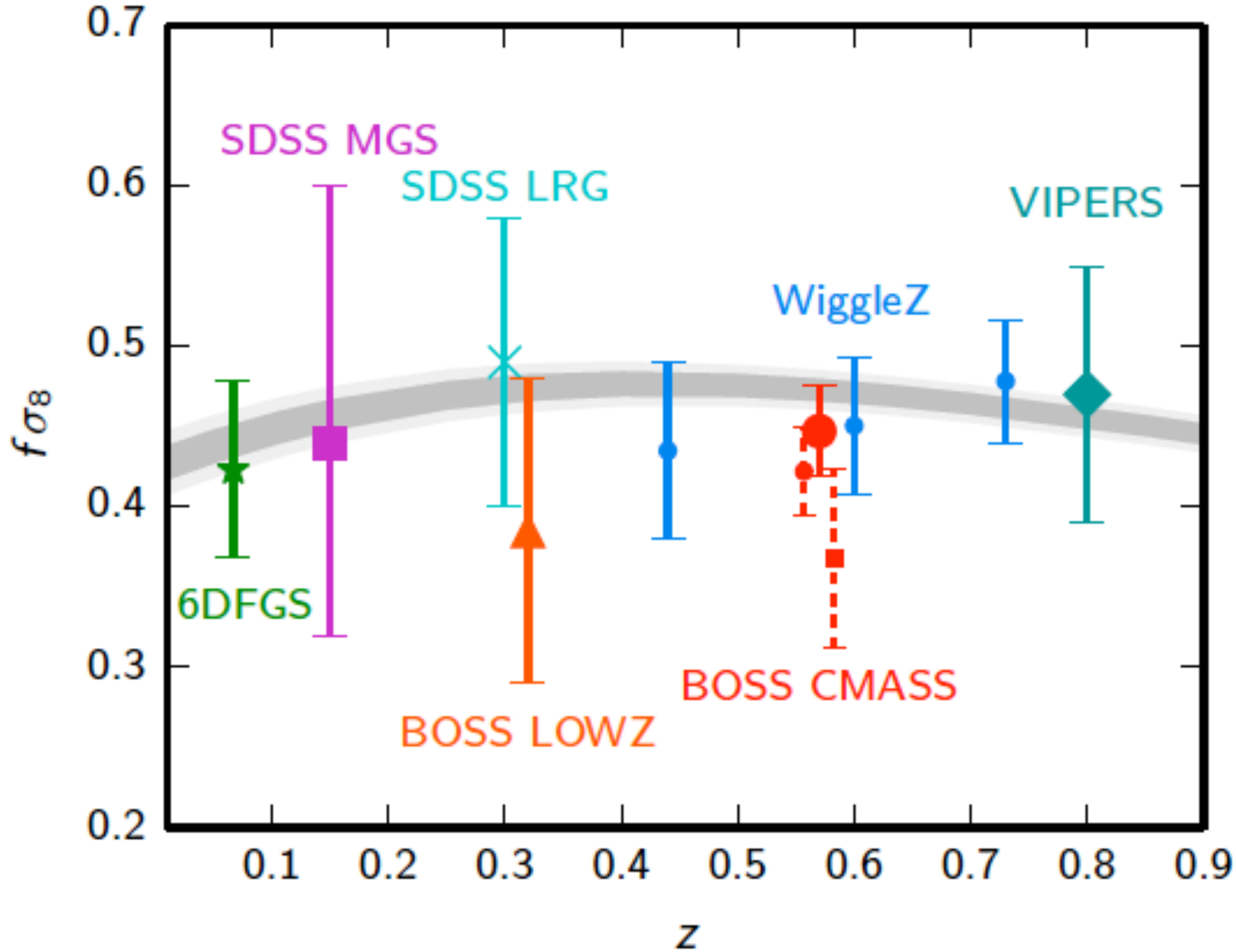
with $q = \frac{1}{2}[1 - 3w(1-\Omega_M)]$ and $\xi = \frac{\mu}{\gamma}$

Growth of structure: Redshift Space Distortions





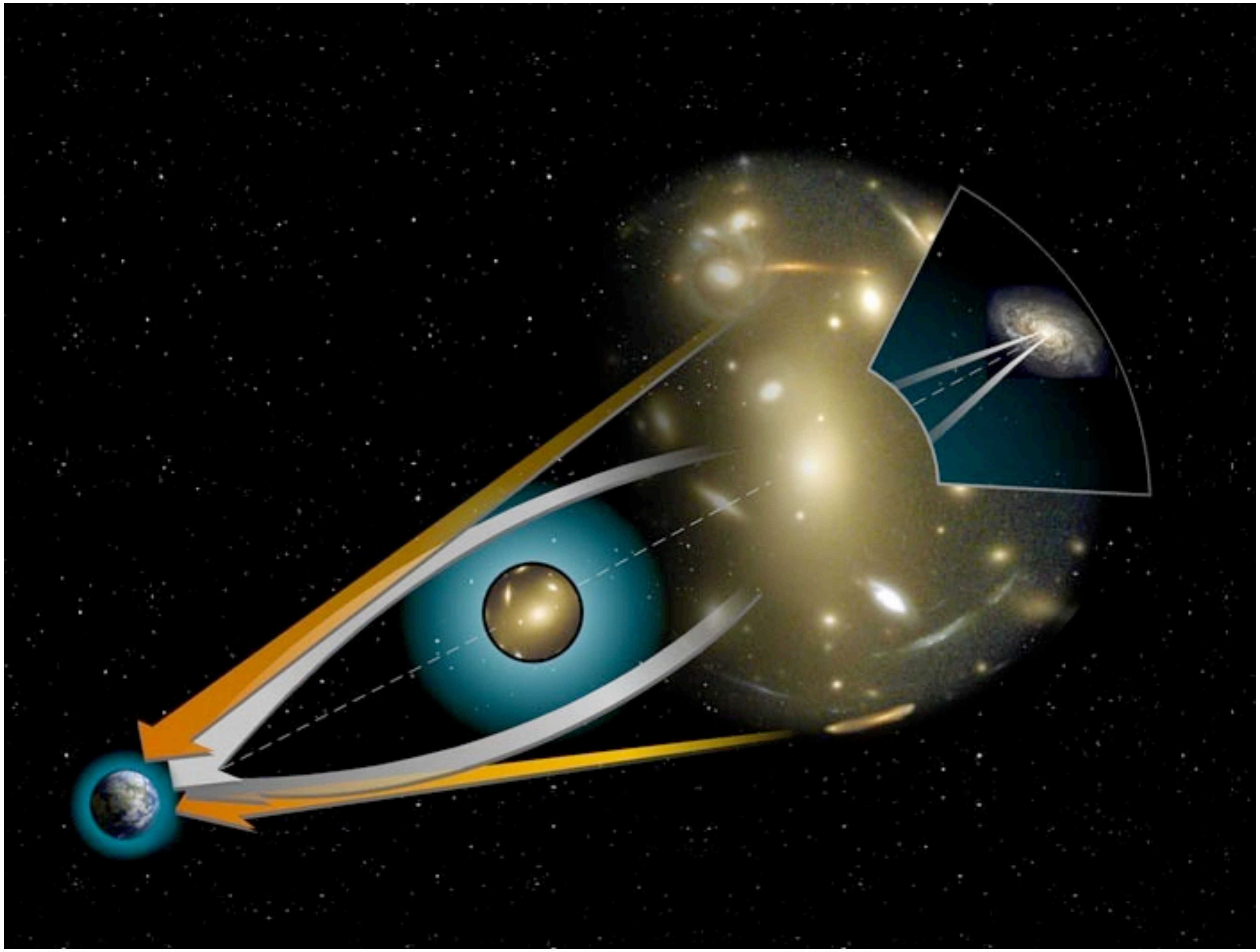
Guzzo et al 2008



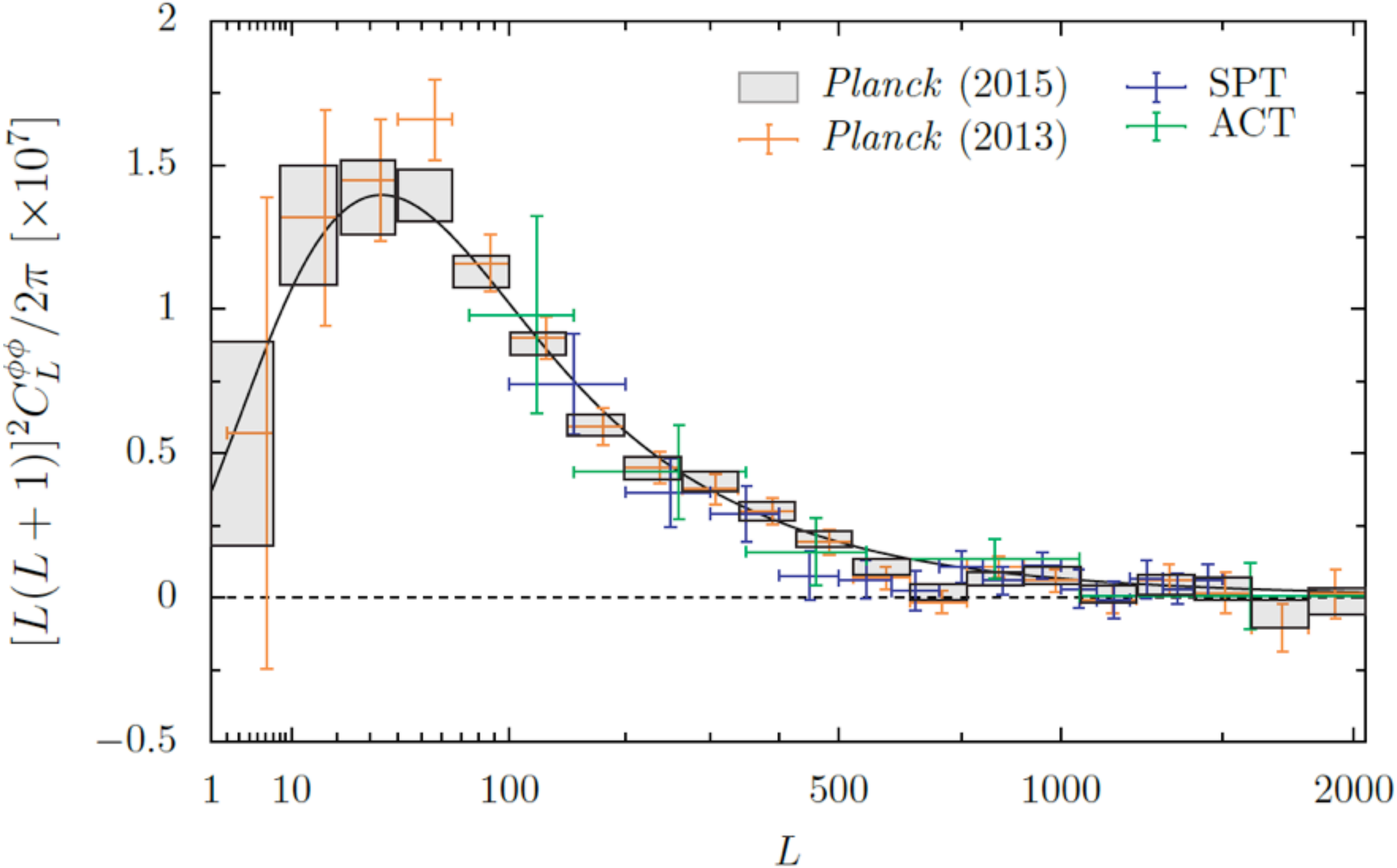
Planck 2015

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

Weak Lensing

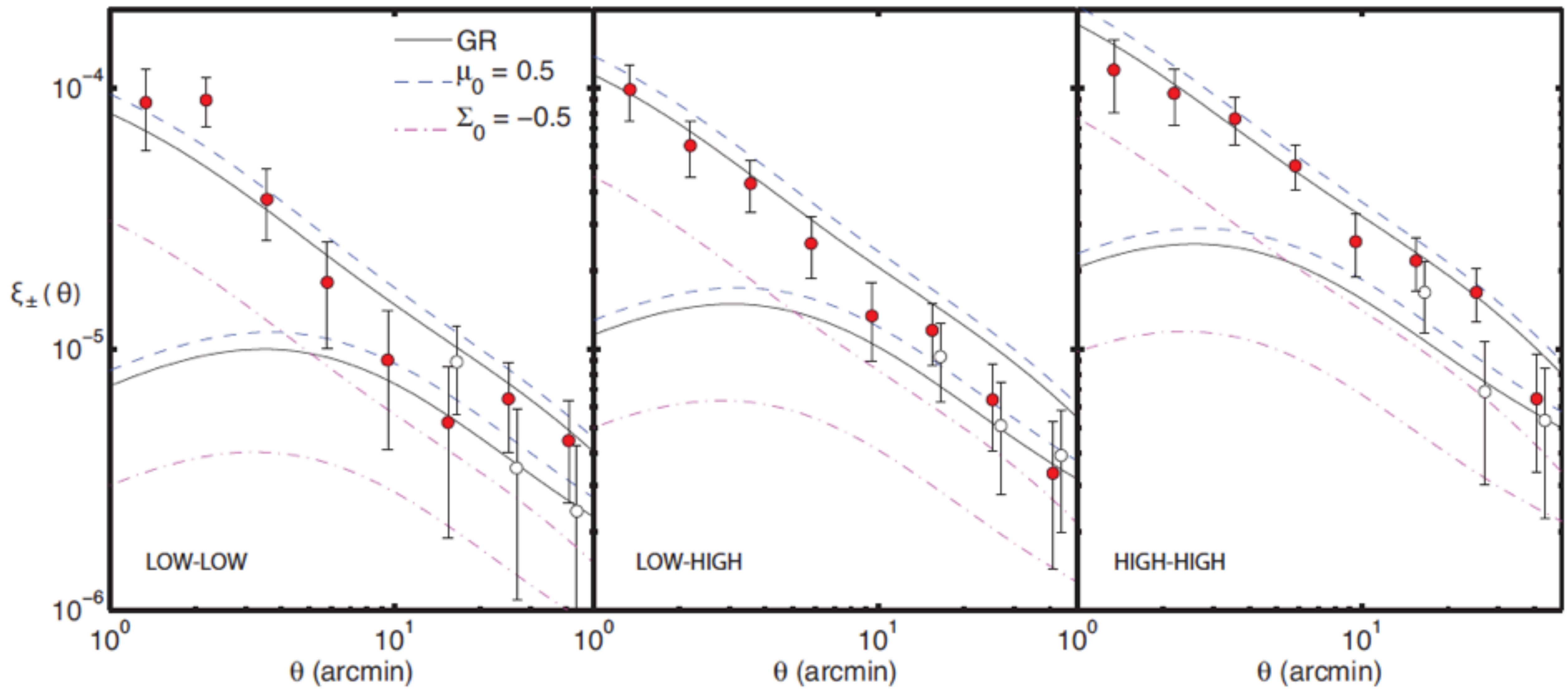


Weak Lensing of the CMB



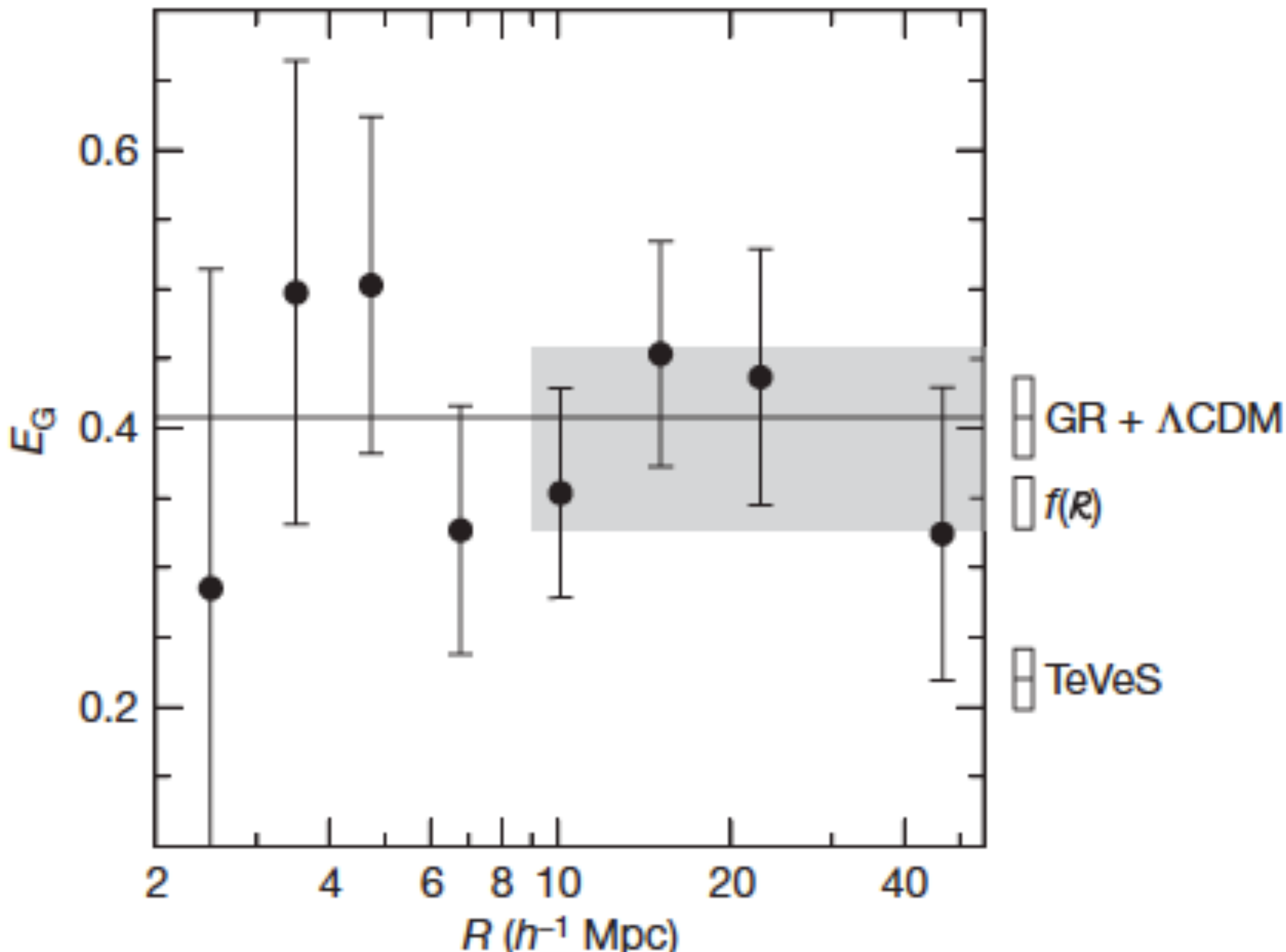
Planck 2015

Galaxy Weak Lensing



Simpson et al 2012
(CFHTLens)

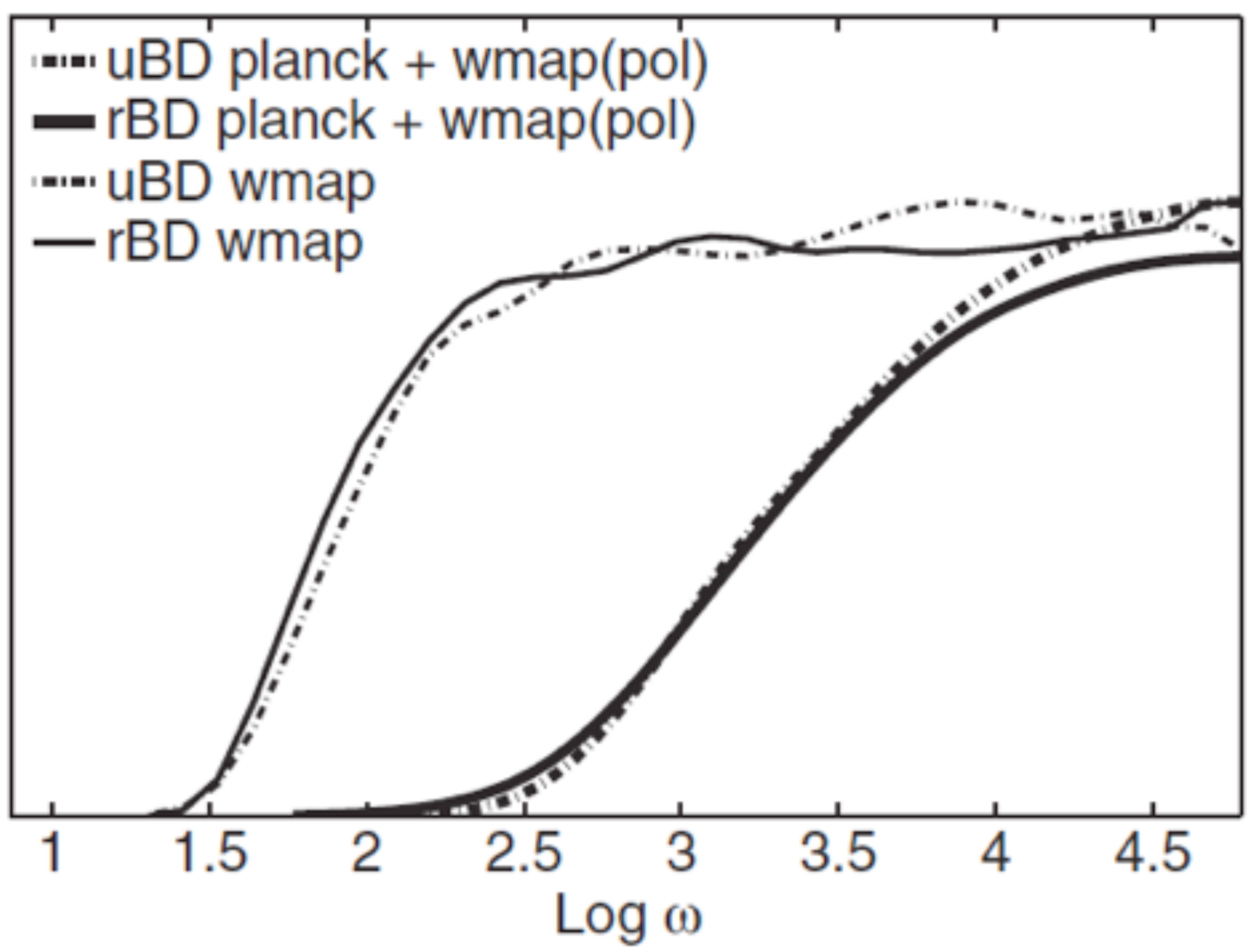
Cross correlating data sets



Reyes et al 2010

Example: Jordan-Brans-Dicke

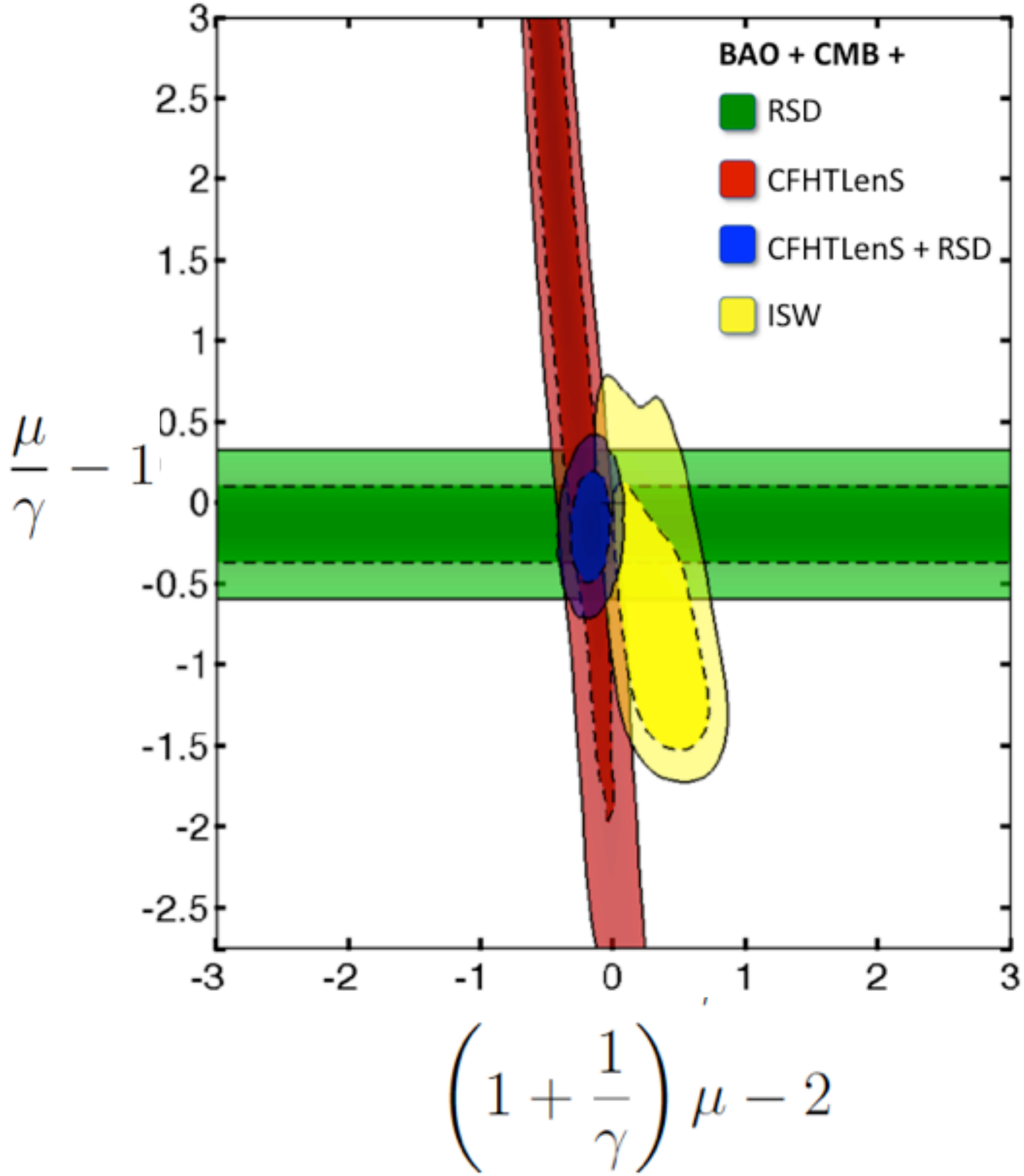
$$S = \int \sqrt{-g} d^4x \left[\phi R - \frac{\omega}{\phi} (\nabla \phi)^2 \right]$$



$$\omega > 692$$

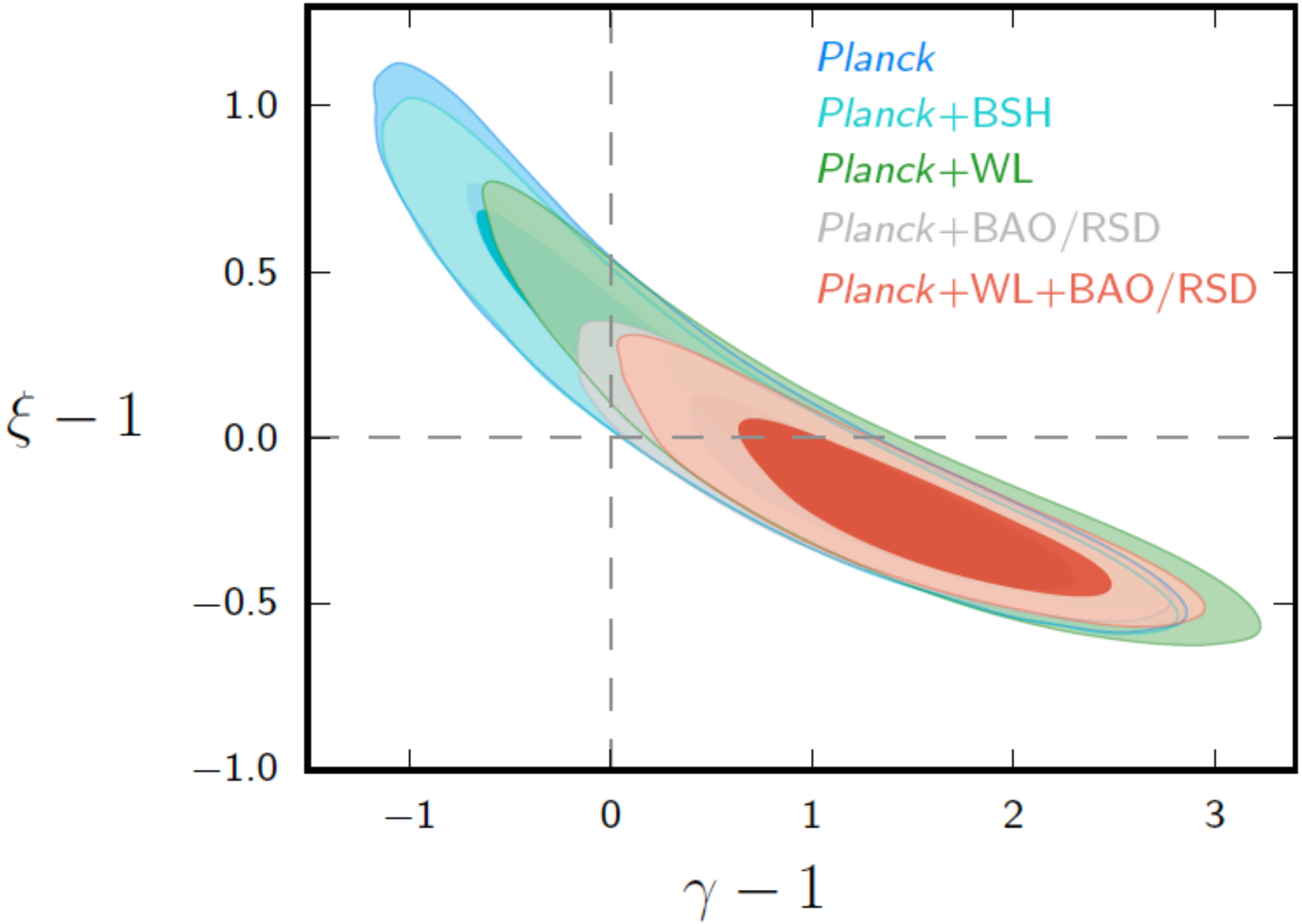
Avillez & Skordis 2014

Galaxy Weak Lensing



Simpson et al 2012
(CFHTLens)

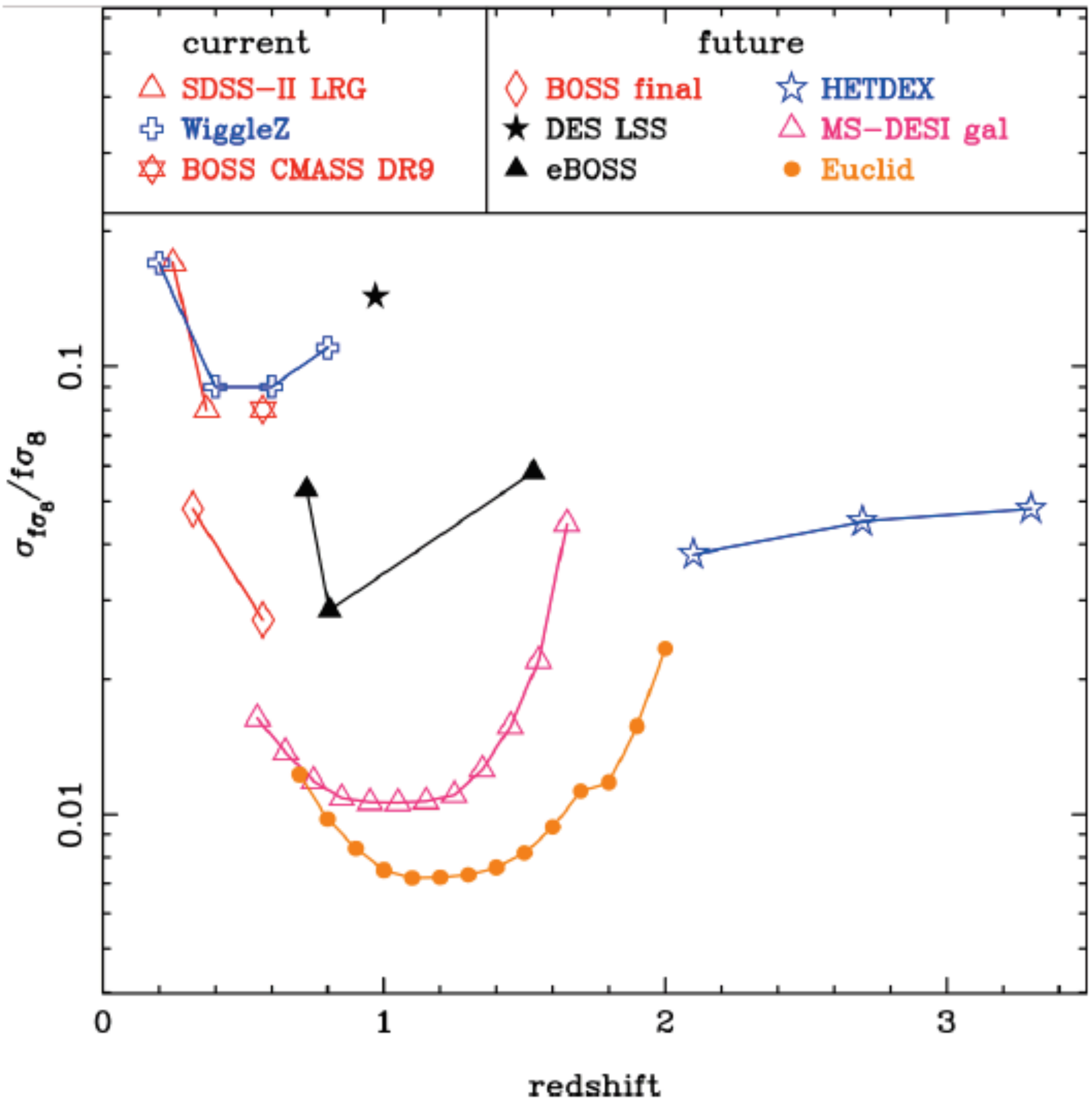
State of the art: Planck 2015



The Future is now

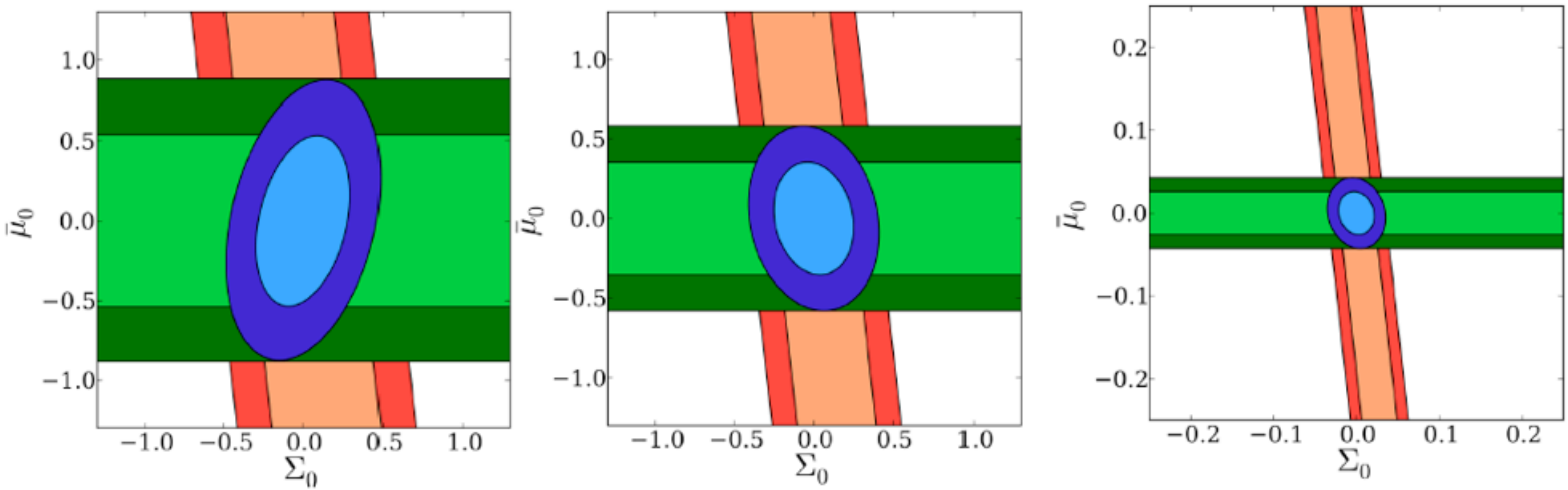
Data Type	Now	Soon	Future
Photo-z:LSS (weak lensing)	DES, RCS, KIDS	HSC	LSST, Euclid, SKA
Spectro-z (BAO, RSD, ...)	BOSS	MS-DESI,PFS,HETDEX, Weave	Euclid, SKA
SN Ia	HST, Pan-STARRS, SCP, SDSS, SNLS	DES, J-PAS	JWST,LSST
CMB/ISW	WMAP	Planck	
sub-mm, small scale lensing, SZ	ACT, SPT	ACTPol,SPTPol, Planck,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

The Future: Redshift Space Distortions



Percival 2013

DETF-IV (scale indep.) constraints



Growth (e.g. RSDs)

$$\bar{\mu}_0 = \frac{\mu}{\gamma}$$

Lensing

$$\Sigma_0 = (1+\gamma)\frac{\mu}{\gamma}$$

Leonard et al 2015

Example: Jordan-Brans-Dicke

$$S = \int \sqrt{-g} d^4x \left[\phi R - \frac{\omega}{\phi} (\nabla \phi)^2 \right]$$

Cosmology

Now: $\frac{1}{\omega} < 6 \times 10^{-3}$ Avillez & Skordis 2014

Euclid: $\frac{1}{\omega} < 3 \times 10^{-4}$ (RSDs only) Baker, Ferreira & Skordis, 2013

Solar System

Now: $\frac{1}{\omega} < 1 \times 10^{-4}$ Cassini

Summary

- The large scale structure of the Universe can be used to test gravity (different eras probe different scales).
- There is an immense landscape of gravitational theories (how credible or natural is open for debate).
- We need a unified framework to test gravity
- Focus on linear scales at late times (for now).
- Non-linear scales can be incredibly powerful but much more complicated
- Need new methods and observations to access the really large scales (is HI tomography the future?).
- There are a plethora of new experiments to look forward to.