Title: Testing gravity at cosmological scales: from linear to nonlinear regimes

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Abstract: Observations are opening new windows to test general relativity at cosmological scales. In this talk, I will discuss how gravity determines the expansion and structure formation of the universe, what smoking guns of gravity in the cosmos we are expecting, what difficulties we are facing to perform unambiguous tests of gravity and what are possible ways to overcome these difficulties.

Testing general relativity at cosmological scales: from linear to nonlinear regimes

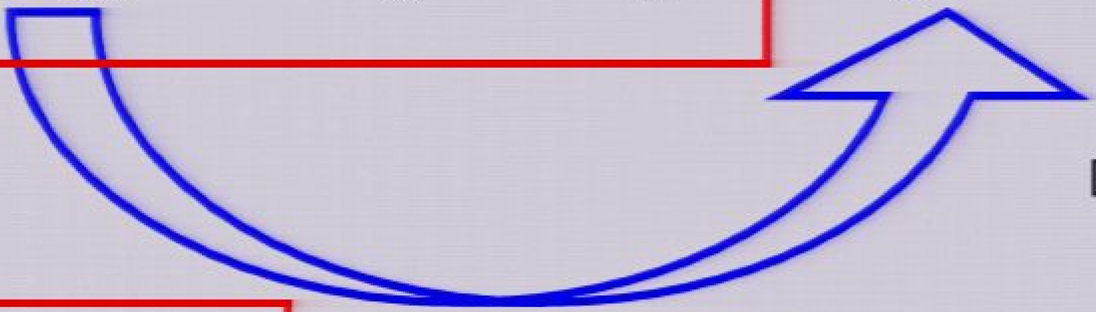
张鹏杰（**Zhang, Pengjie)**

中国科学院上海天文台
Shanghai Astronomical Observatory
Chinese Academy of Science

Perimeter institute 2010

Modified gravity vs. DM/DE

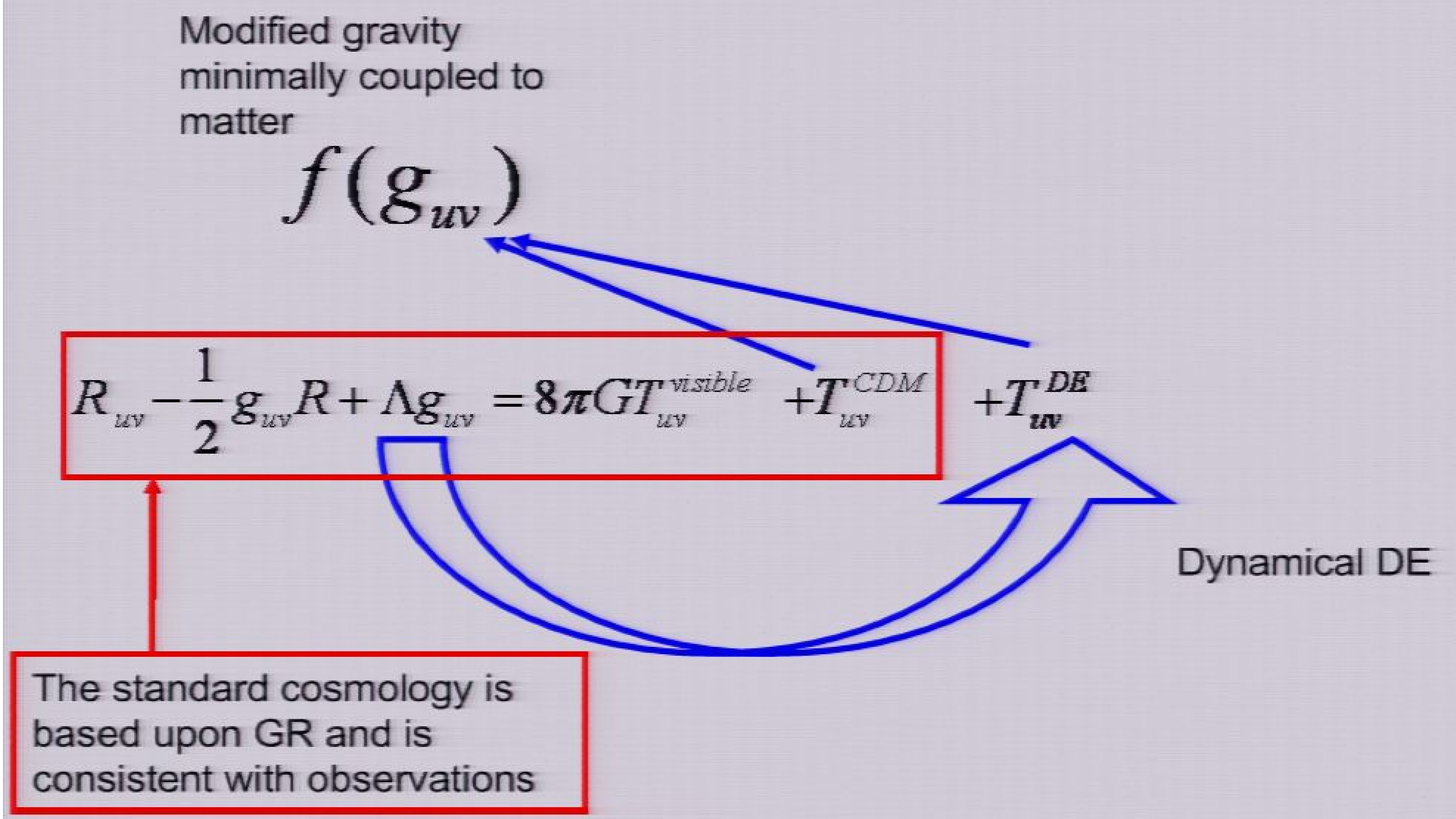
$$\boxed{R_{uv} - \frac{1}{2} g_{uv} R + \Lambda g_{uv} = 8\pi G T_{uv}^{visible} \quad + T_{uv}^{CDM}} \quad + T_{\boldsymbol{uv}}^{\boldsymbol{DE}}$$



Dynamical DE

The standard cosmology is based upon GR and is consistent with observations

Modified gravity vs. DM/DE



Modified gravity minimally coupled to matter

$$f(g_{uv})$$

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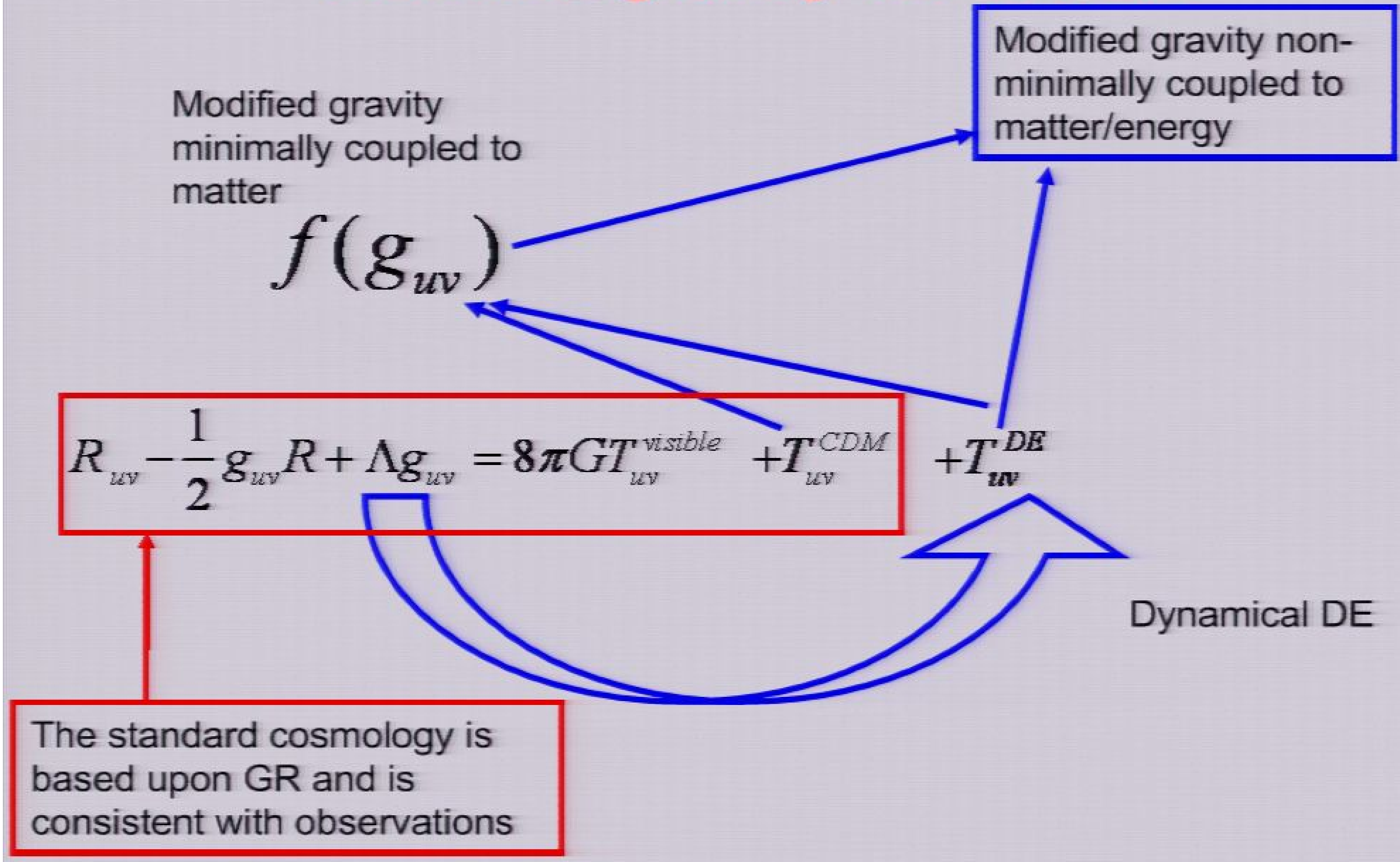

Modified gravity non-minimally coupled to matter/energy

Modified gravity minimally coupled to matter

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Testing GR in the cosmos

- **Zero order (The overall expansion and geometry)**

$$H(z), D_L, D_A, .. \leftrightarrow \rho_m, \rho_{DE}, w_{DE}, M^{(5)}_{Planck}(DGP)....$$

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example: H in
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$$H^2 = \frac{8\pi G}{3}\rho$$

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for
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Modified gravity

$$\nabla^2\phi = 4\pi G\rho$$

$$\nabla^2\phi = 4\pi G_{eff}\rho$$

Probes of the expansion

- **Type Ia supernovae** ***(standard candles)***
- **Baryon acoustic oscillation in LSS and CMB** ***(standard ruler)***

- **Fundamental plane, Faber-Jackson & Tully-Fisher of galaxies**
- **Age (globular clusters, galaxy age-z..)**
- **Gravitational lensing time delay**
- **SZ-X ray cluster fluxes**
- **Cluster gas fraction**
- **Gamma ray bursts**
- **Alcock-Paczynski (AP) test**

- **Standard sirens**
- **Walter maser**
- **Sandage-Loeb test .....**

Probes of the large scale structure

- gravitational potentials
  - Gravitational lensing
  - Galaxy/cluster peculiar velocities
  - The integrated Sachs-Wolfe effect
  - redshift distortion
- density
  - galaxy clustering
  - cluster abundance
- fluid velocity
  - The kinetic Sunyaev Zel'dovich effect?
- Thermal content
  - The thermal SZ effect

Testing specific models: expansion and DGP

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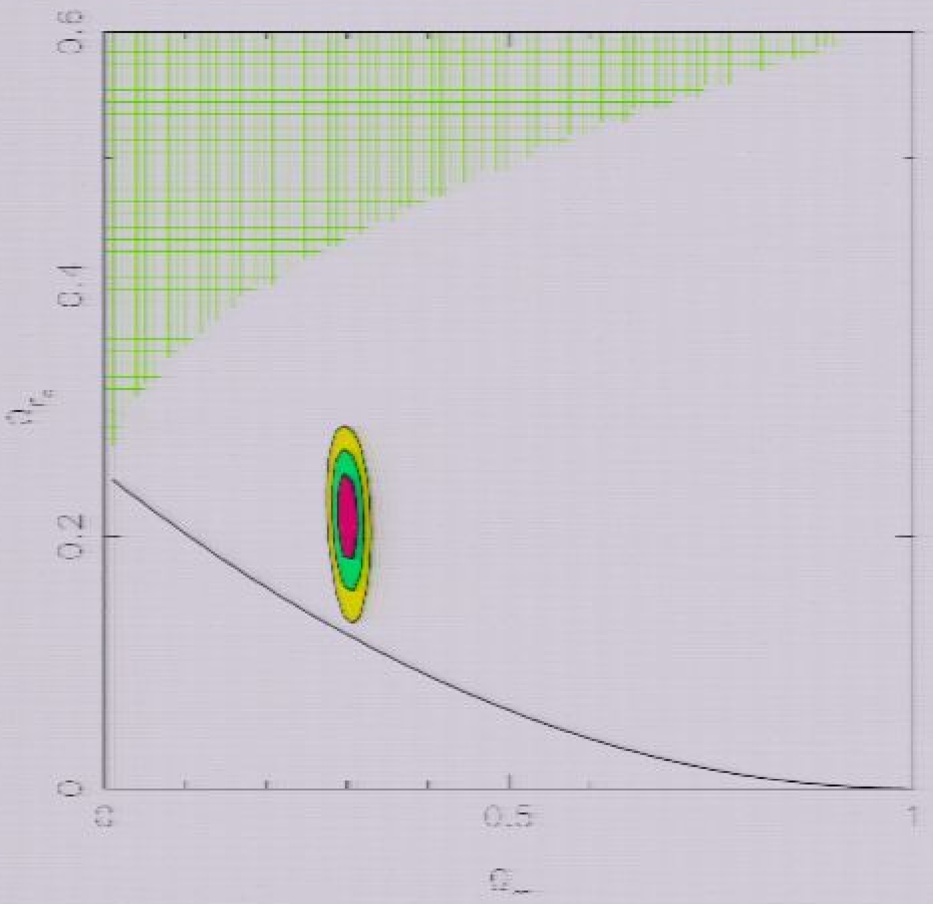


Fig. 3. Probability contours over Ω_{r_c} and Ω_m for the combination of the 172 SNeIa taken from Tonry et al. (2003) and the 9 X-ray clusters from Allen et al. (2002, 2003). The 68%, 95% and 99% confidence levels in the Ω_{r_c} - Ω_m plane are shown in red, green, and yellow shaded areas, respectively. The cross-hatched region at the upper left represents the "no-big-bang" region, while the thick solid line corresponds to the flat universe. The best fit happens at $\Omega_m = 0.29$ and $\Omega_{r_c} = 0.21$, hence giving a closed universe with $\Omega_k = -0.36$. However, the results depends on the X-ray gas mass fraction data from Allen et al. (2002, 2003), in which the errorbars might be on the optimistic side.

Zhu & Alcaniz 2004

DGP is disfavored comparing to LCDM

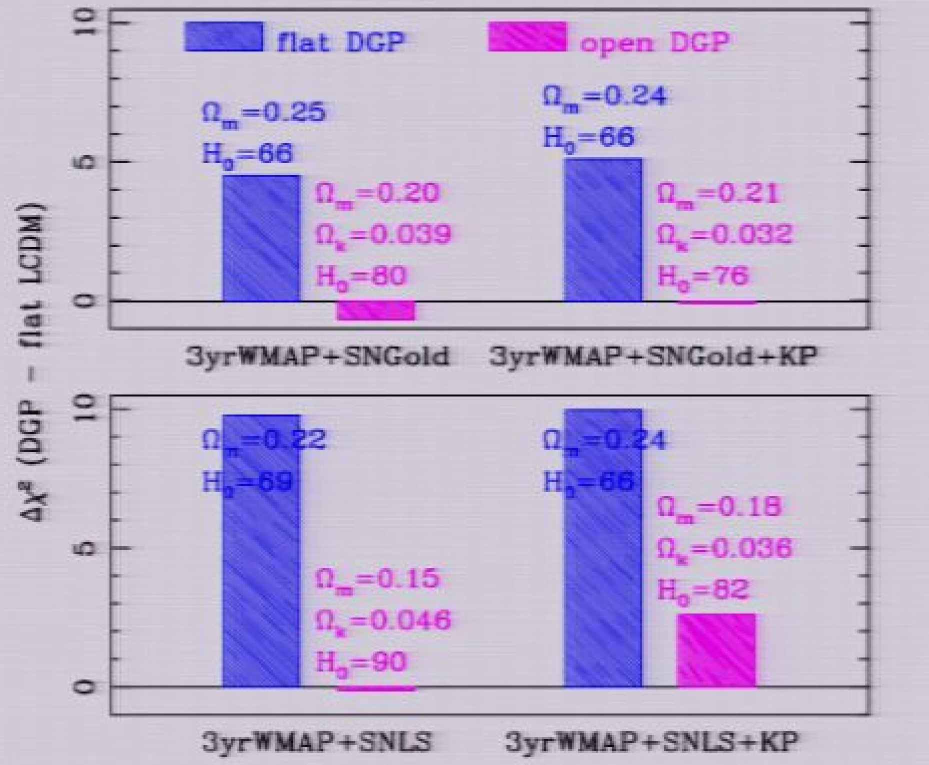


FIG. 1: The $\Delta\chi^2$ between the best fit flat and open DGP versus that of flat ΛCDM model. SNGold supernova (SN) data set is used in the top panel and SNLS SN data set is used in the bottom panel. The DGP model requires curvature and a high Hubble constant. With the addition of Key Project (KP) direct Hubble constant measurements open DGP is a marginally poorer fit to the data than flat ΛCDM.

Song et al. 2006

To test gravity, we need to break the *dark degeneracy I*: MG and DE can mimic each other exactly in H(z)

produced by any model

$$H^2 = H_0^2(\Omega_0 a^{-3} + \Omega_{DE} e^{3\int_a^1 (1+w_{DE}) da/a} + \Omega_k a^{-2})$$

There are always dark energy models with degenerate H!

$$w_{DE} = -\frac{a}{3}[\ln(E^2 - \Omega_0 a^{-3} - \Omega_k a^{-2})]'$$

$$E \equiv H / H_0$$

To distinguish between DE and MG, one must have LSS, besides the overall expansion of the universe!

CMB and DGP

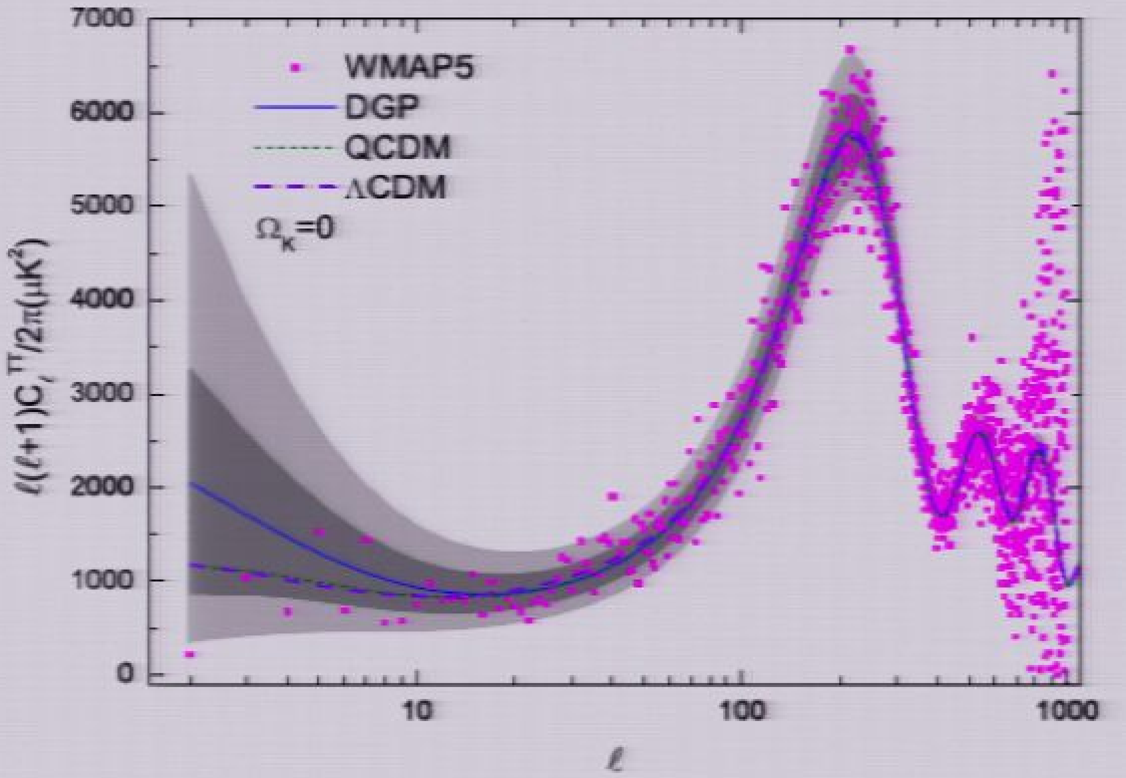


FIG. 2: Predictions for the power spectra of the CMB temperature anisotropies $C_\ell^{\rm TT}$ of the best-fit DGP (solid), QCDM with the same expansion history as DGP (short-dashed), and ΛCDM (dashed, coincident with QCDM at low ℓ) models obtained by fitting to SNLS + WMAP5 (both temperature and polarization) + HST, *assuming a flat universe*. Bands repre-

Fang et al. 200

Weak lensing/galaxy clustering and Yukawa-like gravity

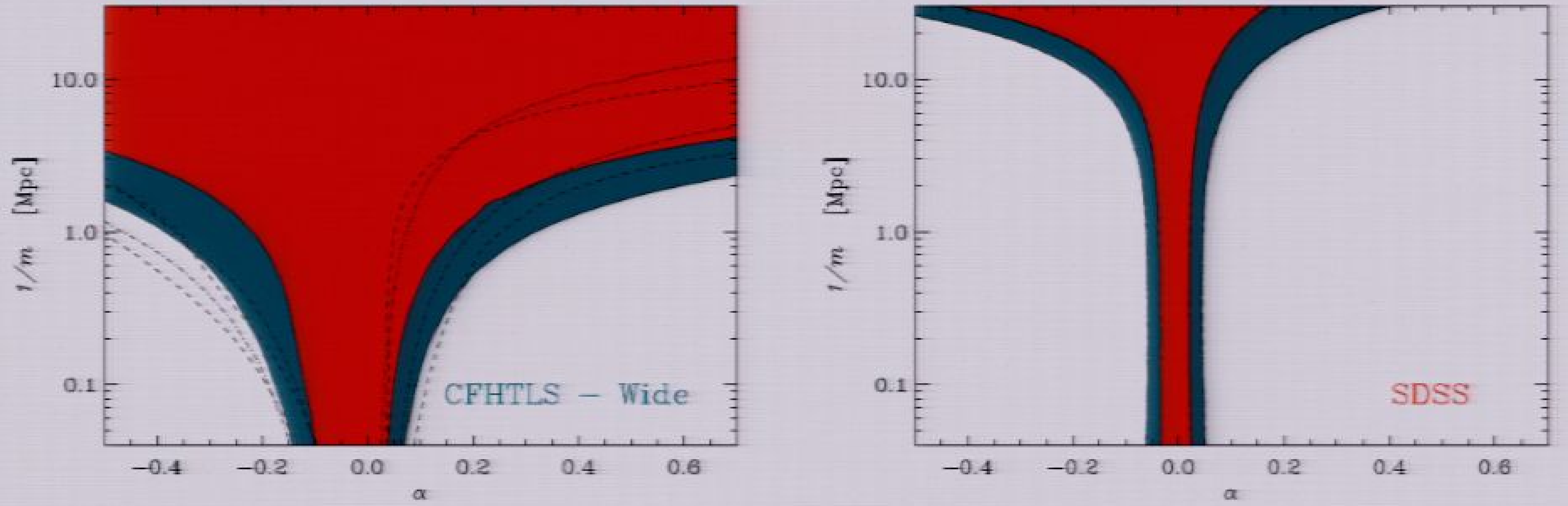


FIG. 2: Likelihood contours at 68% and 95% confidence levels for the $1/m$ and α parameters of the Yukawa type modification to gravity. The left panel corresponds to the CFHTLS-Wide constrains while the right panel corresponds to SDSS LRGs. Colored contours correspond for CFTHSL-Wide to the use of the M_{ap}^2 statistic with the halofit non-linear prescription. The dashed lines were obtained using the M_{ap}^2 statistic with the Peacock and Dodds [76] prescription whereas the dot-dashed lines were obtained with the halofit non-linear prescription but using the ξ_E statistic. The agreement between these various prescriptions and statistics is a satisfying of robustness of our measurement. As expected given the wider area covered by SDSS (42 times bigger than the current status of CFHTLS-Wide), the SDSS constraints are much narrower despite the bias uncertainty.

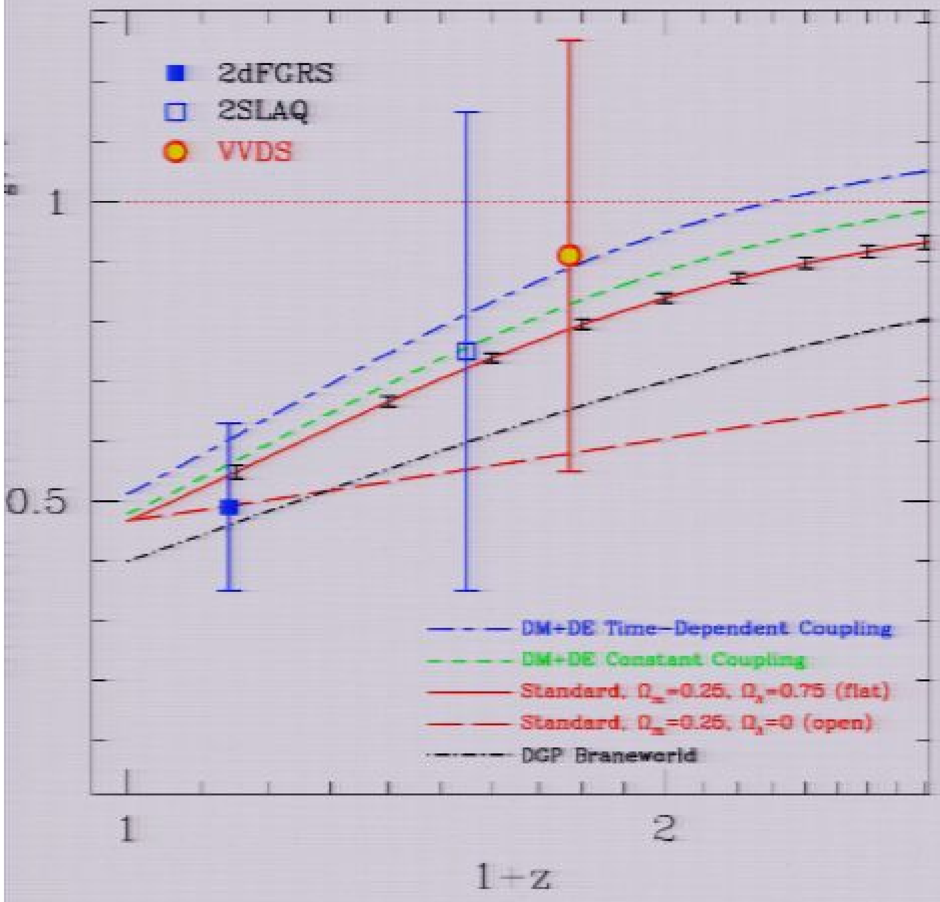
$$\Phi(\mathbf{r}) = (1-\alpha)\Phi(\mathbf{r},0) + \alpha\Phi(\mathbf{r},m)$$

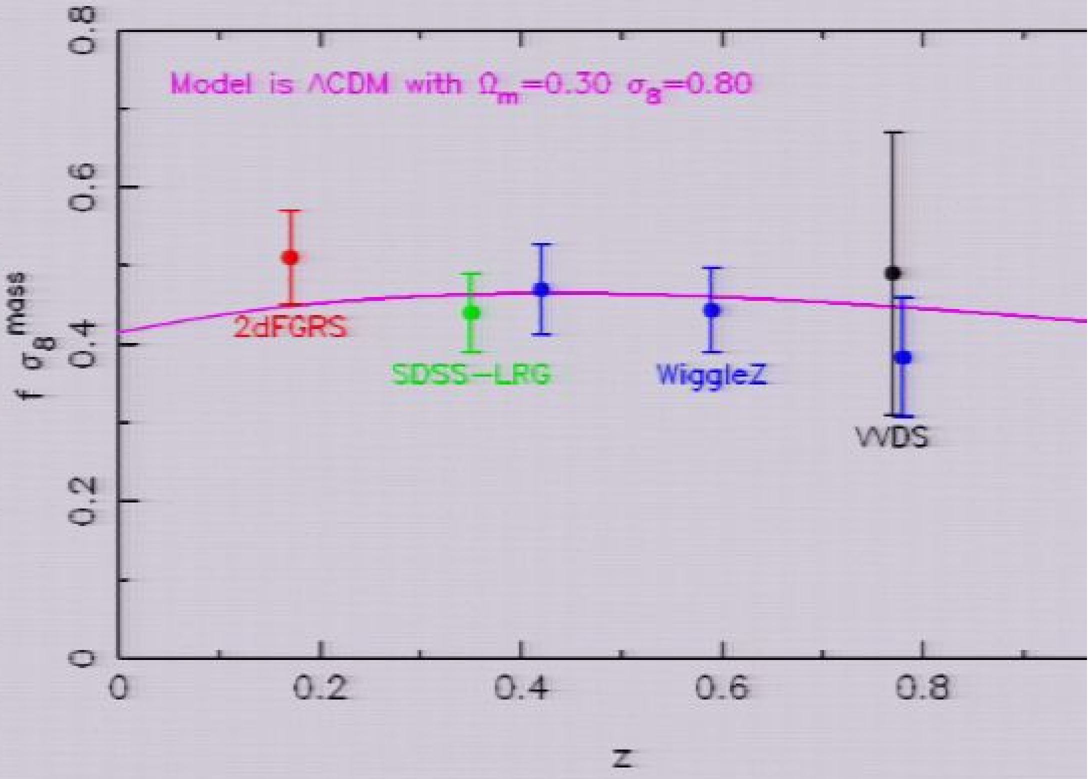
$$\Phi(\mathbf{r},m) = G\int \frac{\rho(\mathbf{r}')d^3\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}e^{-m|\mathbf{r}-\mathbf{r}'|}.$$

Dore et al. 2007

Redshift distortion and DGP

f=dlnD/dlna

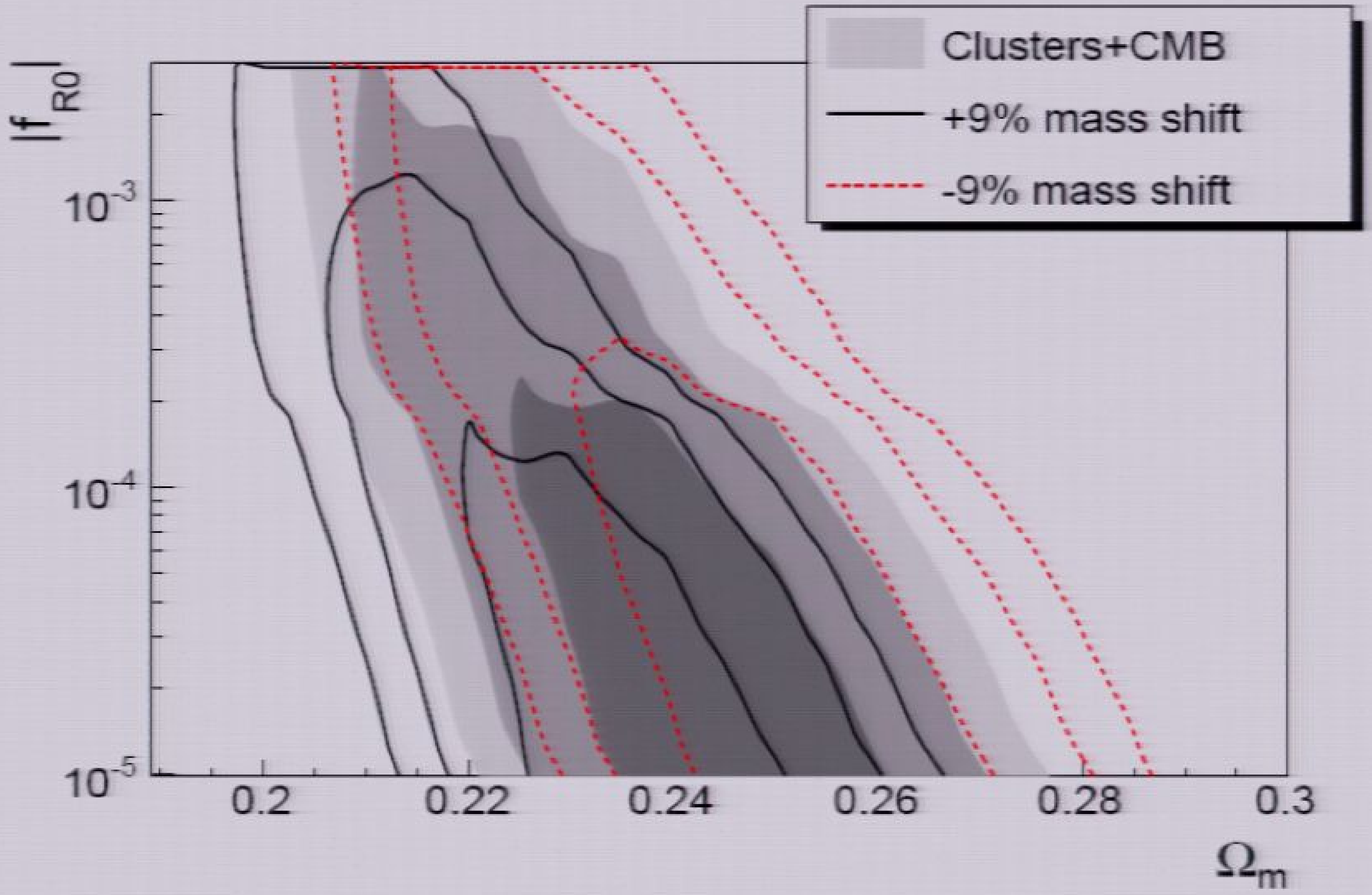




Blake et al. 2010

Guzzo et al. 2008

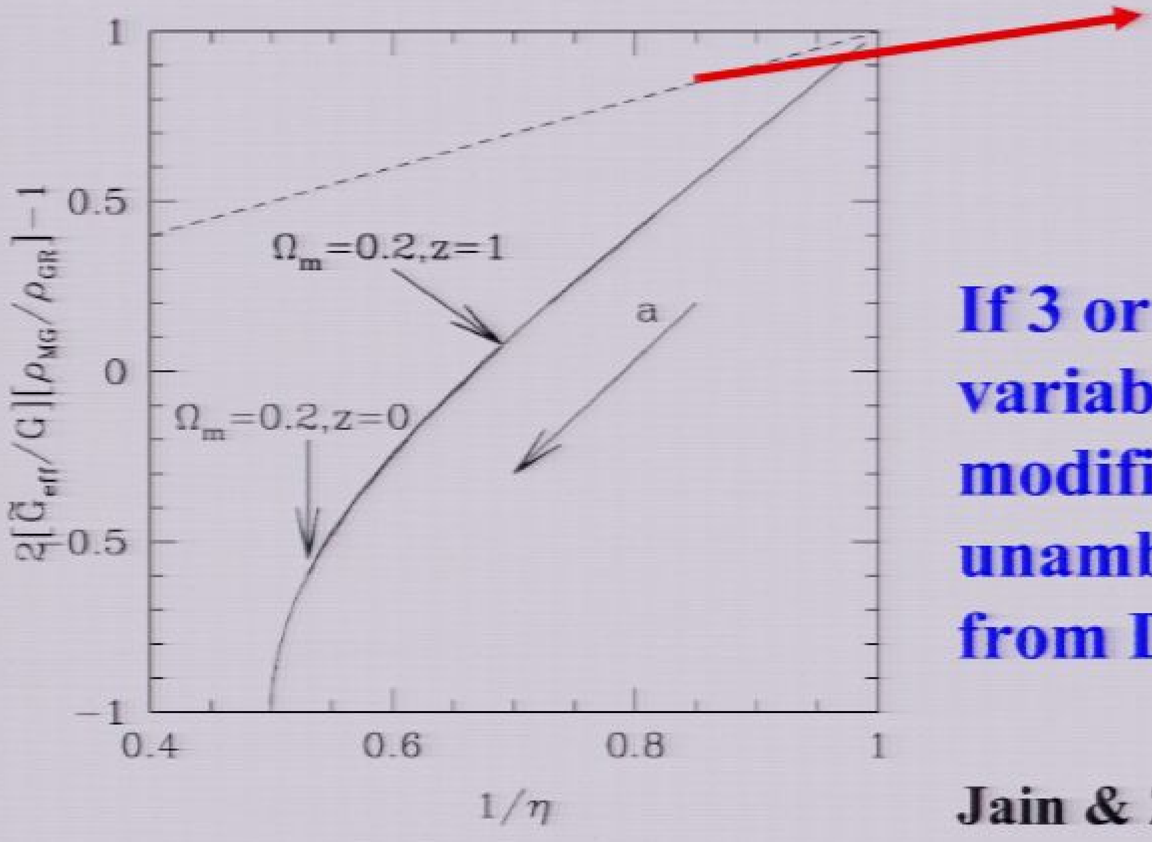
Cluster abundance and f(R)



Schmidt,Vikhlinlin & Hu 2009

Break the dark degeneracy II:

MG and DE can mimic each other in LSS!



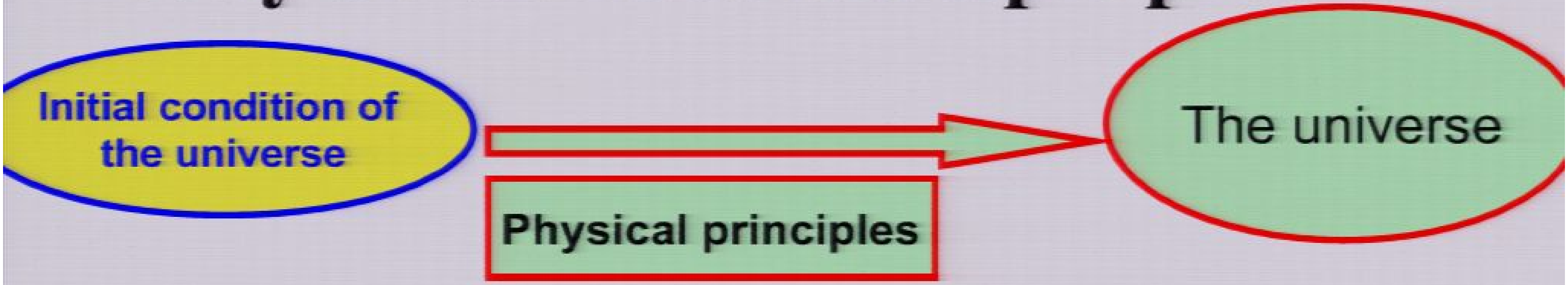
One necessary condition for DE to mimic MG

If 3 or more independent LSS variables can be measured, modified gravity models can be unambiguously discriminated from DE/DM

Jain & ZPJ, 2008

FIG. 2: First consistency condition for at least one DE model to mimic ϕ, ψ and δ in a flat DGP model. The dashed line given by Eqn. 41 represents the required condition, while the solid curve is the actual relation in flat DGP. When $a \to 0$, $\eta \to 1$ and for $a \to \infty$, $\eta \to 1/2$. The points on the curve with $a = 0.5$ and $a = 1$ are indicated. (For flat DGP lines with different Ω_m lie on top of each other.) The disagreement between the two curves shows that DGP is a modified gravity model that can not be mimicked by any dark energy model.

Why do we need multiple probes?



Initial condition of the universe

Physical principles

The universe

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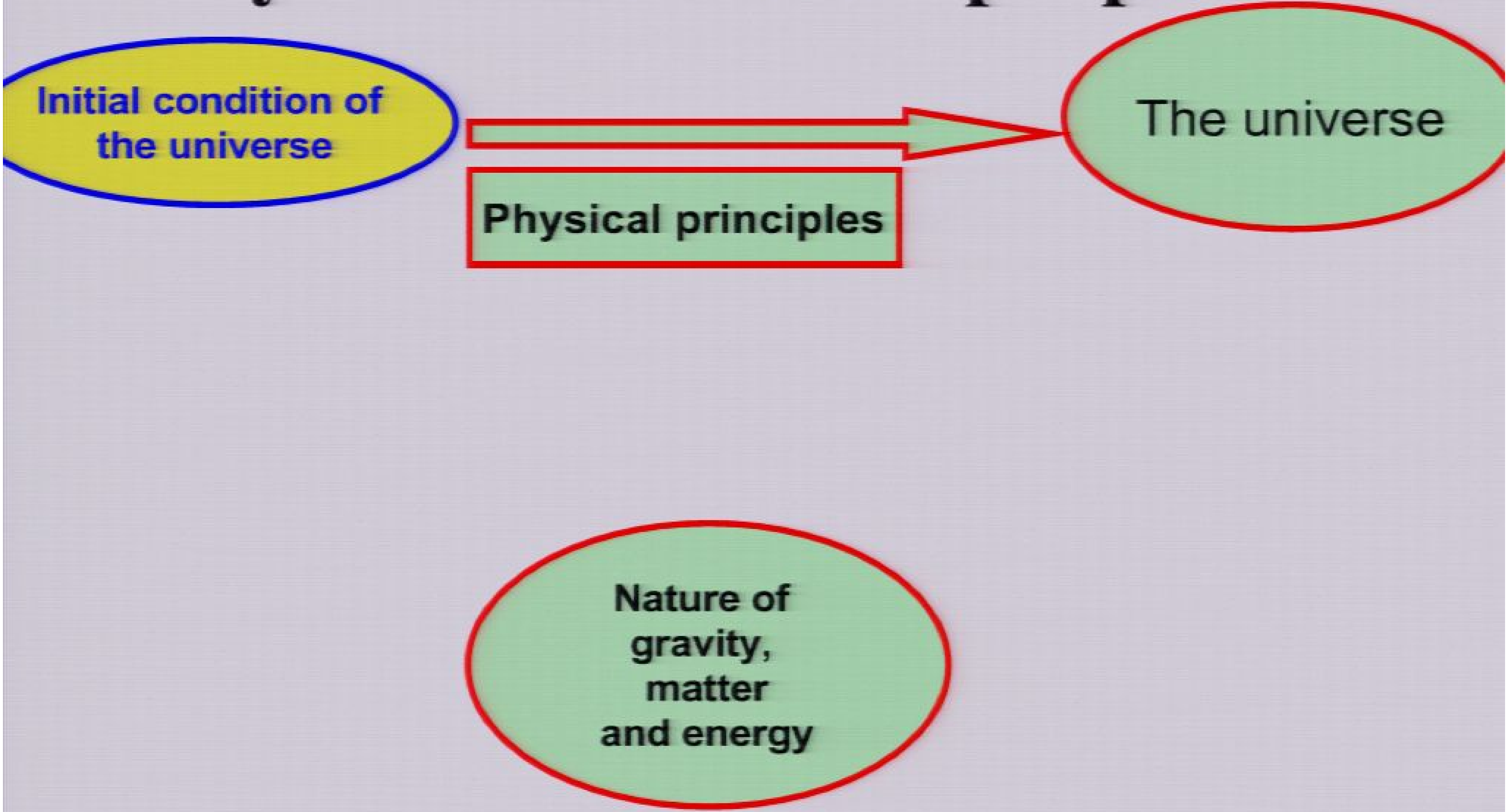

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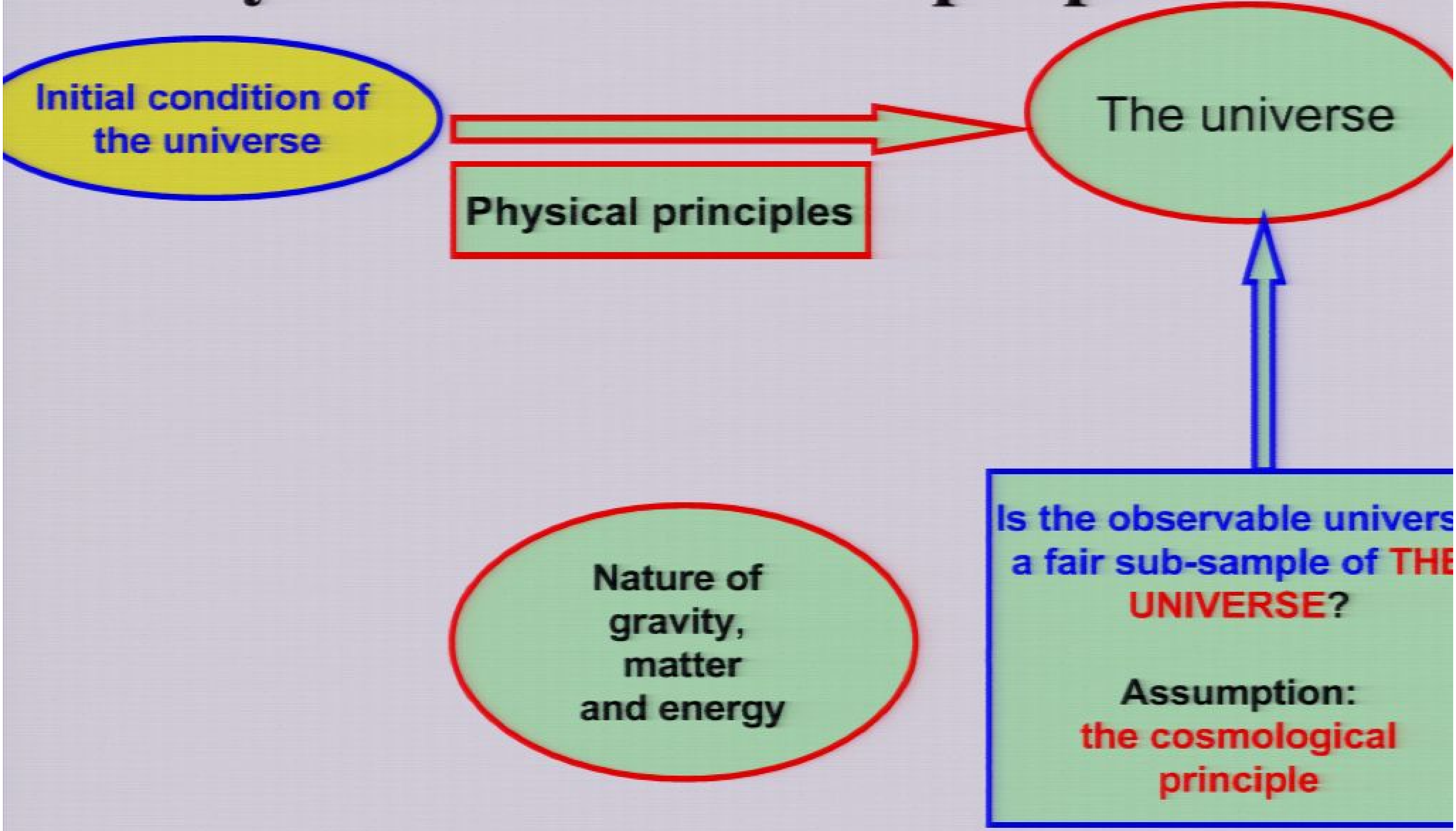

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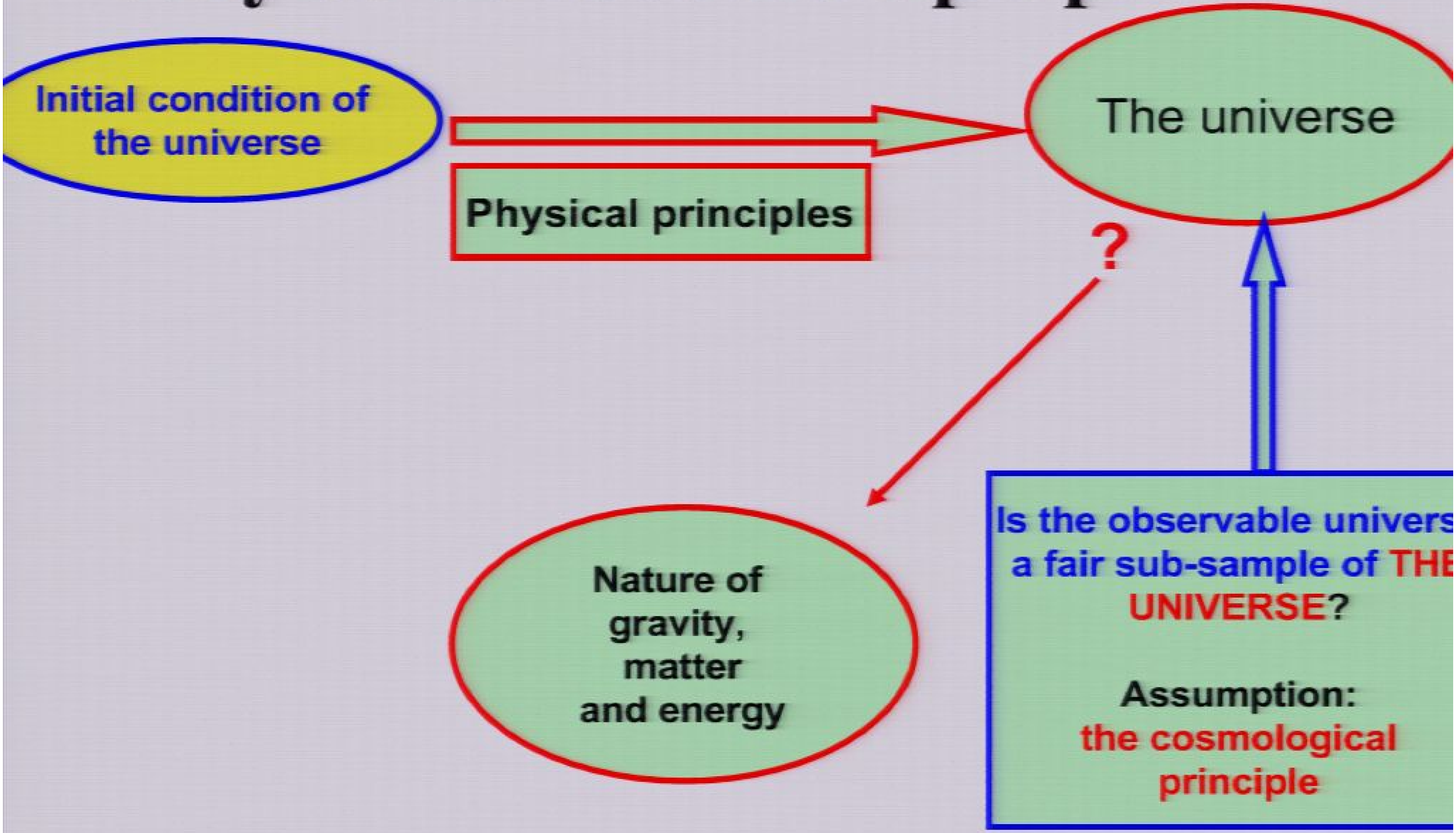

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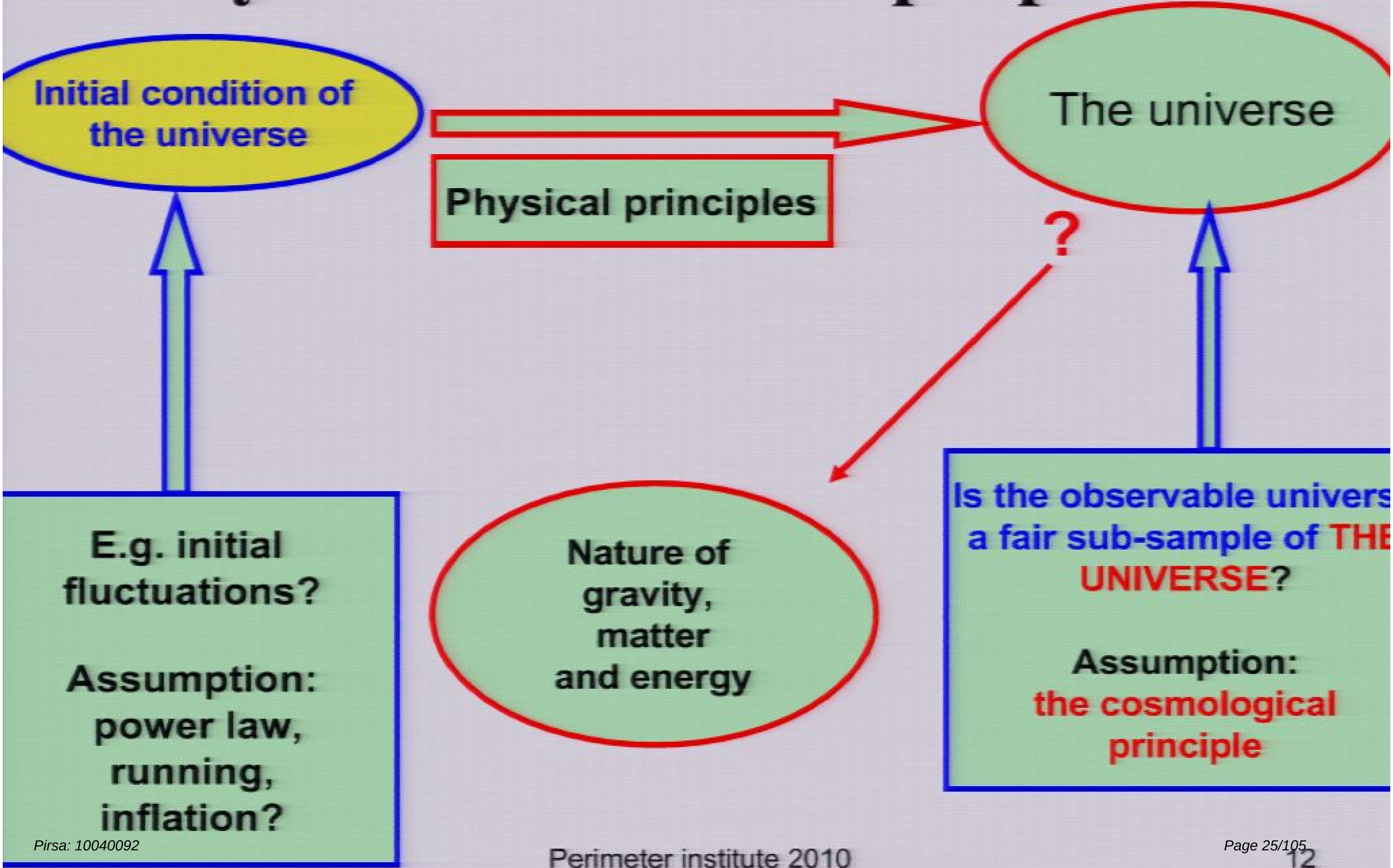

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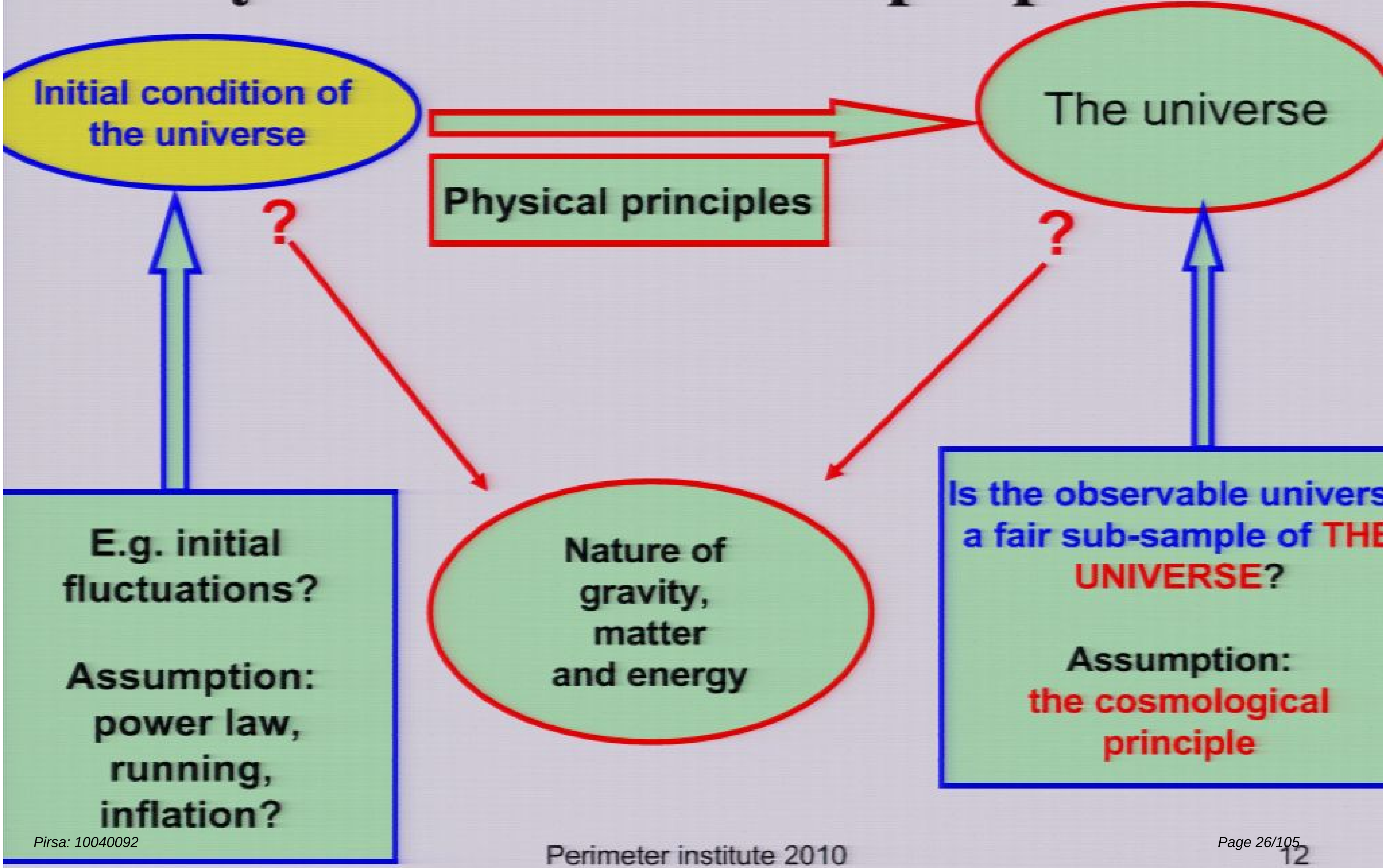

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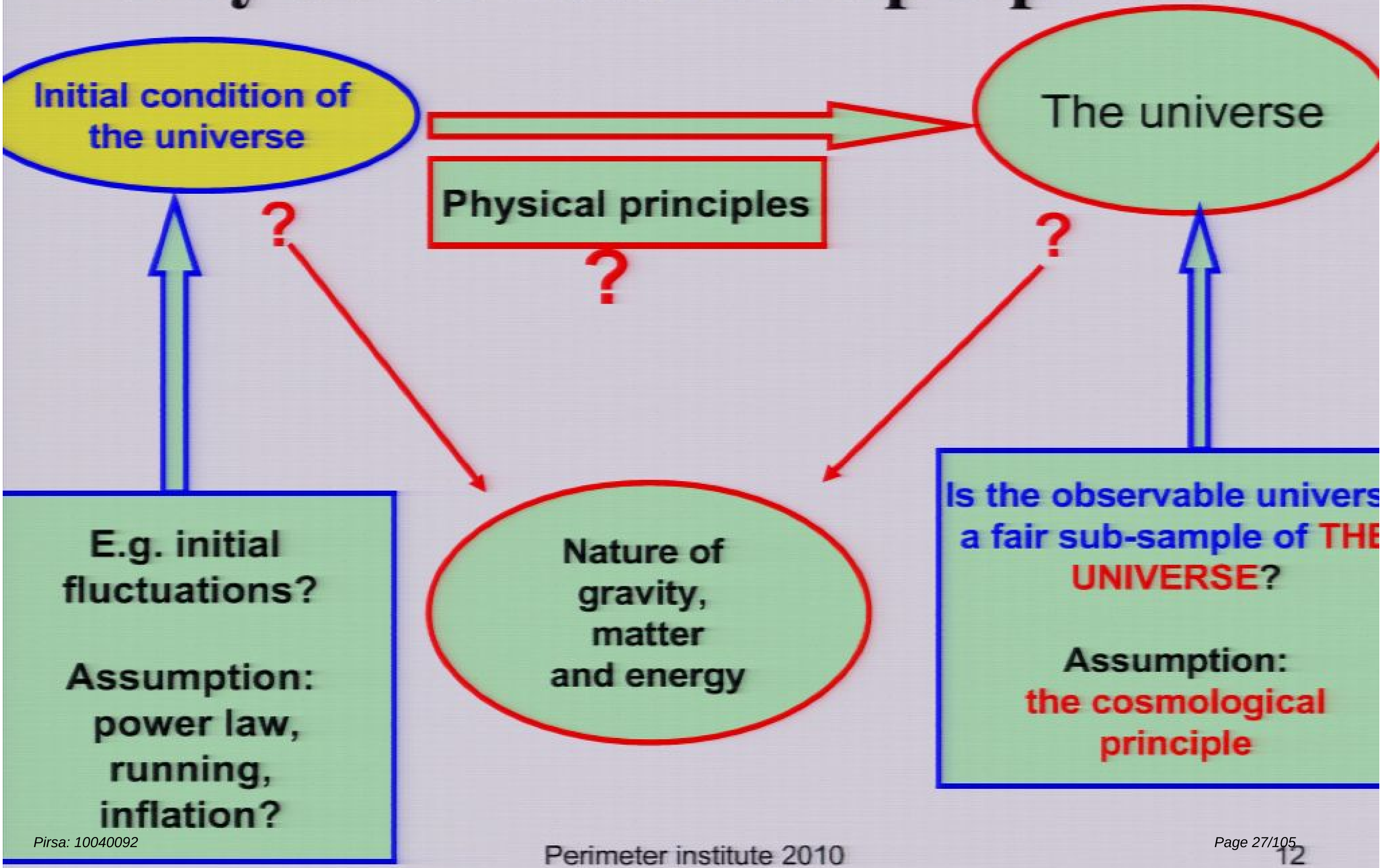

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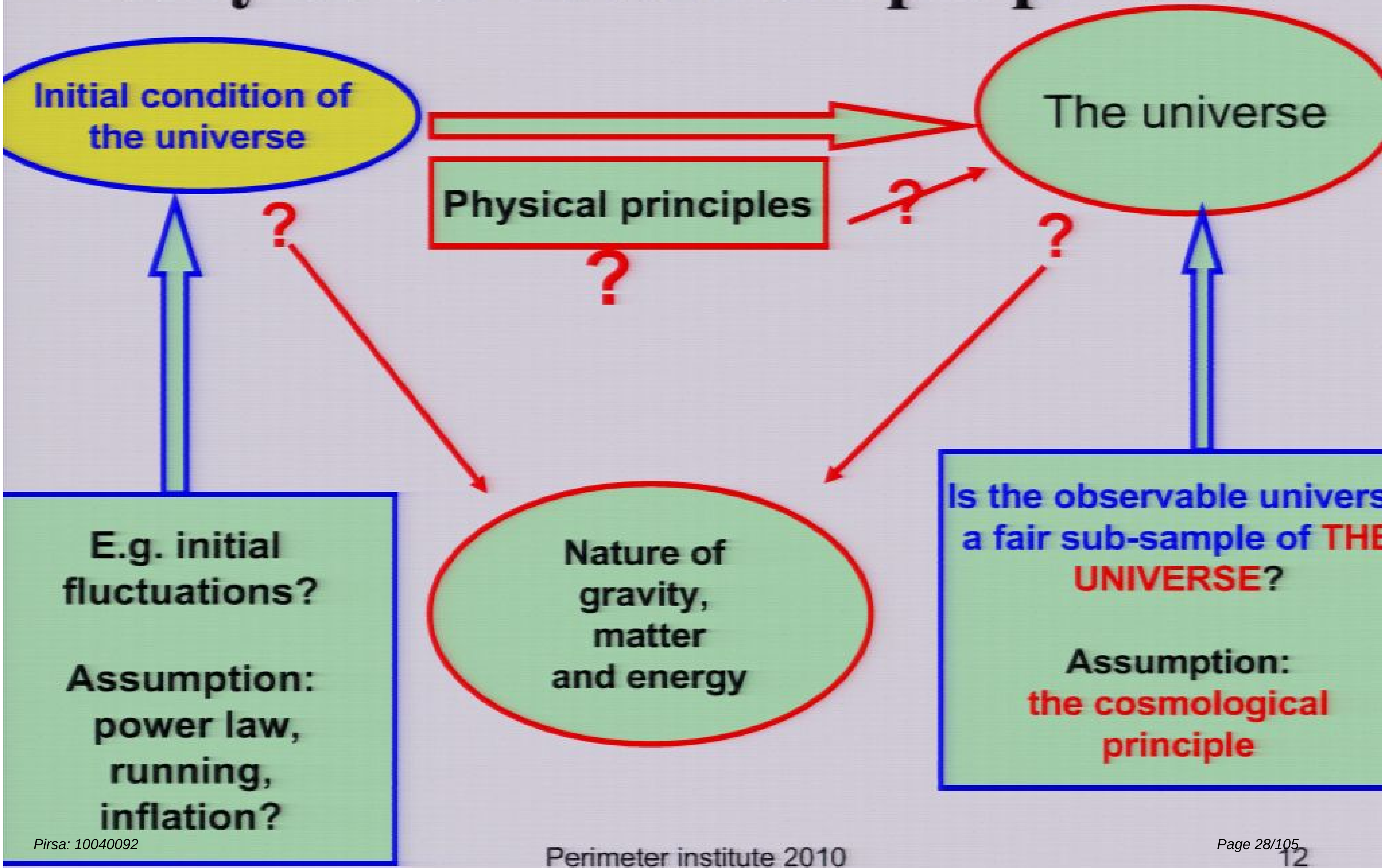

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Consistency relation of GR at cosmological scales

The expansion rate

The rate of structure growth

Consistency relation of GR at cosmological scales

$$\frac{d^2\delta}{da^2}+\frac{d\delta}{da}\left(\frac{dH/da}{H}+\frac{3}{a}\right)-\frac{3}{2}\frac{\delta}{a^2}\frac{\Omega_0 H_0^2}{H^2a^3}=$$

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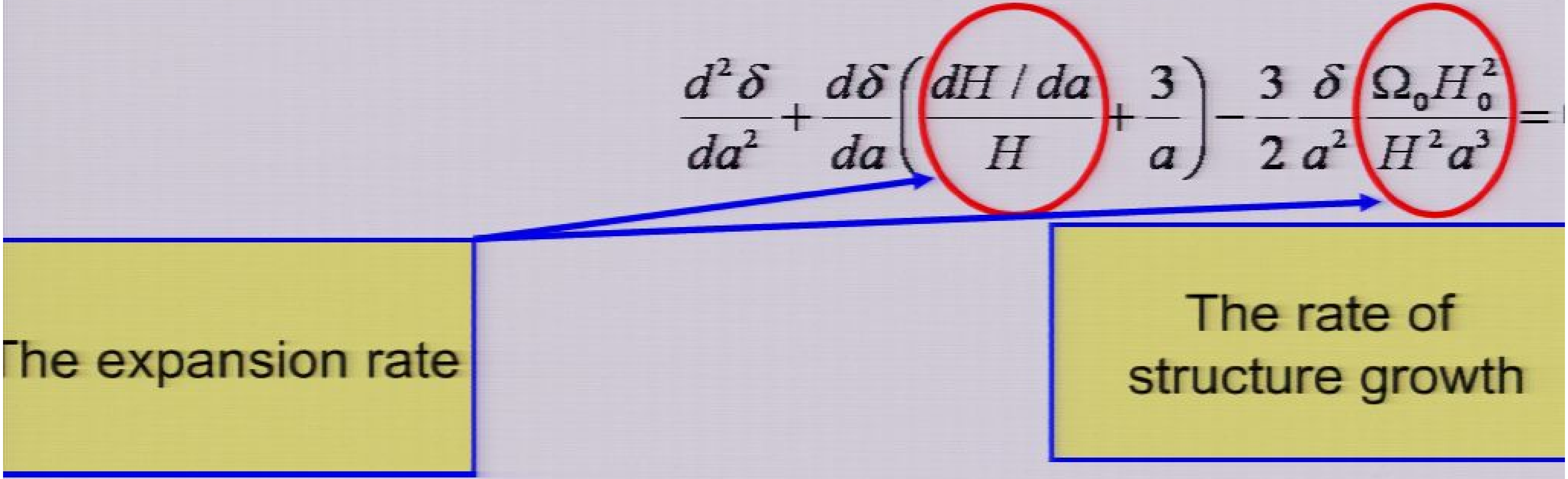
Consistency relation of GR
at cosmological scales



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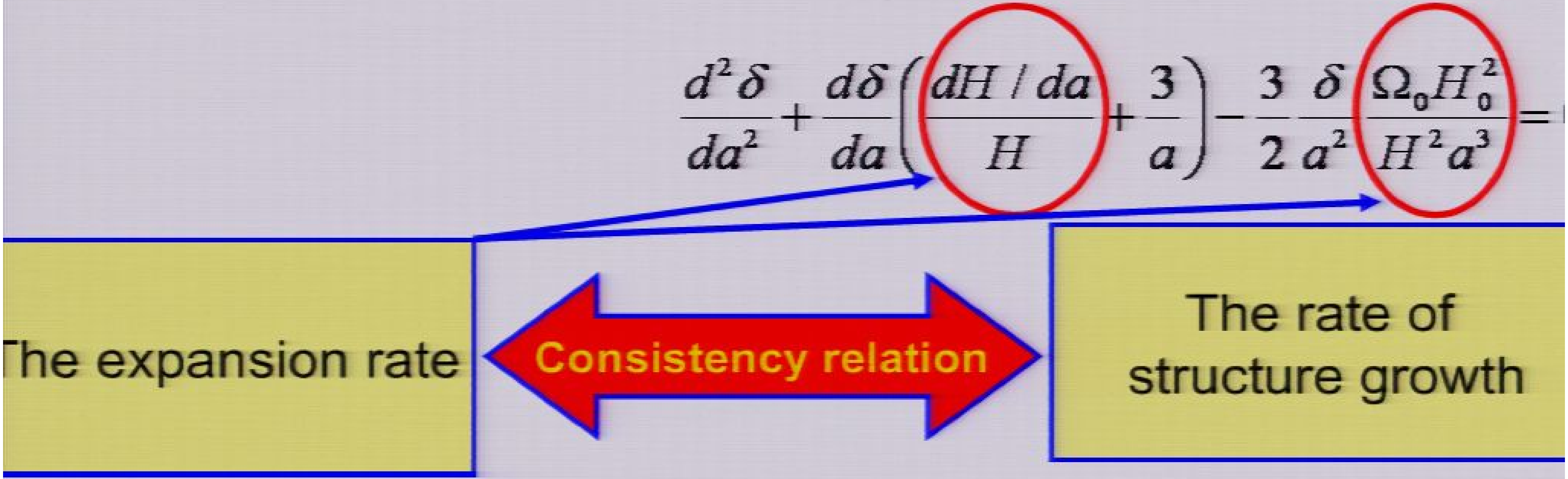

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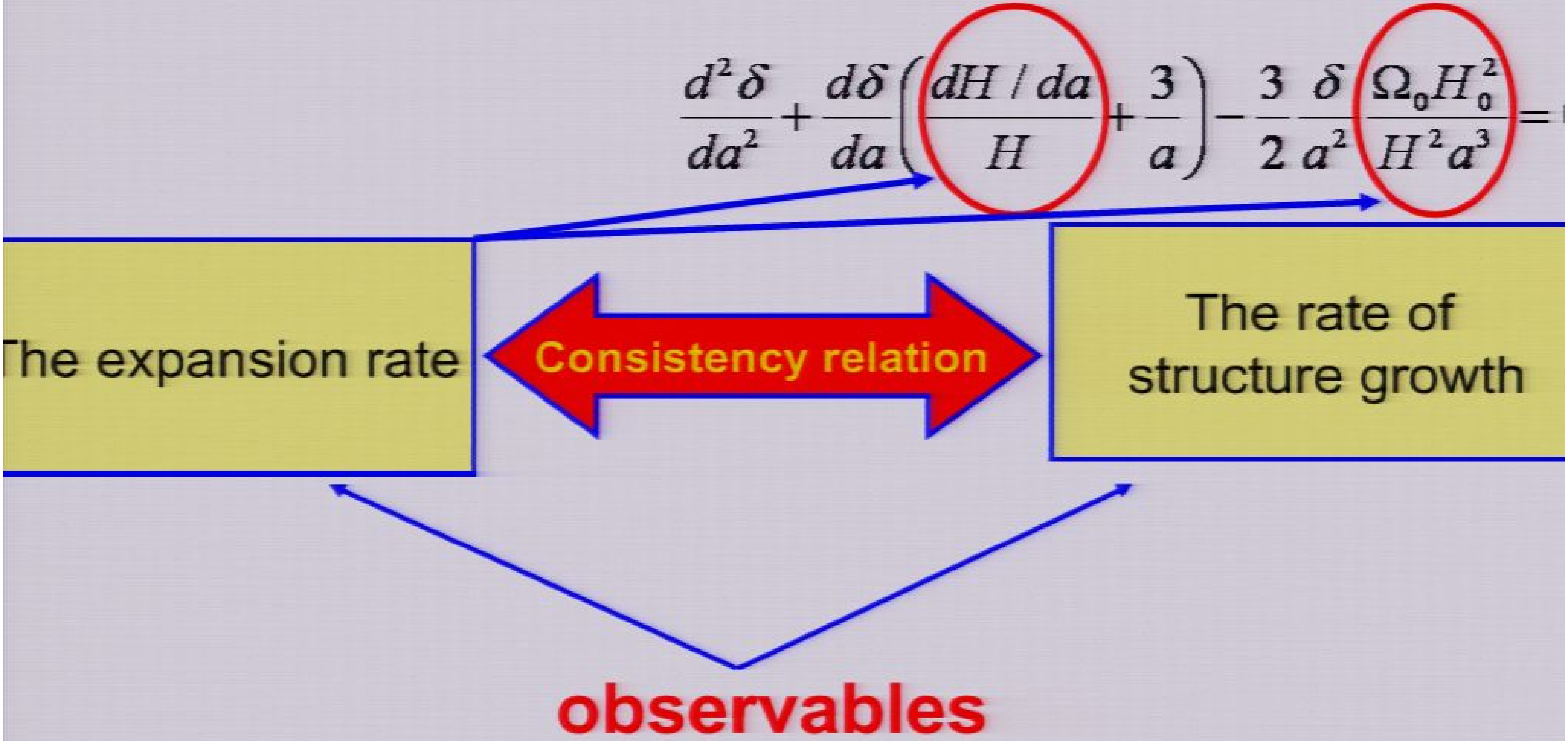


The expansion rate

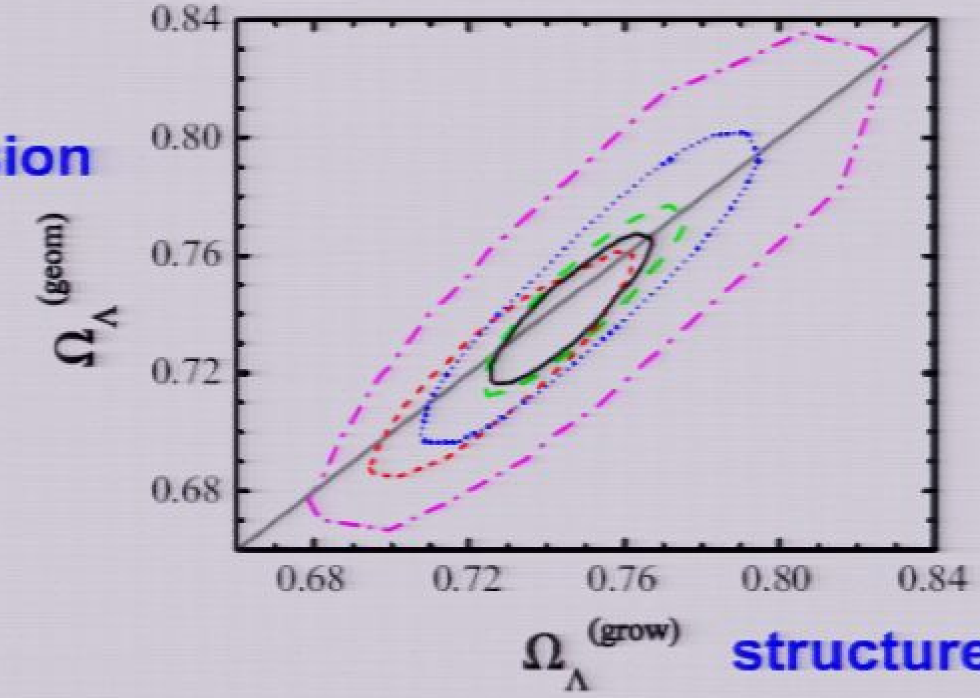
Consistency relation

The rate of structure growth

observables

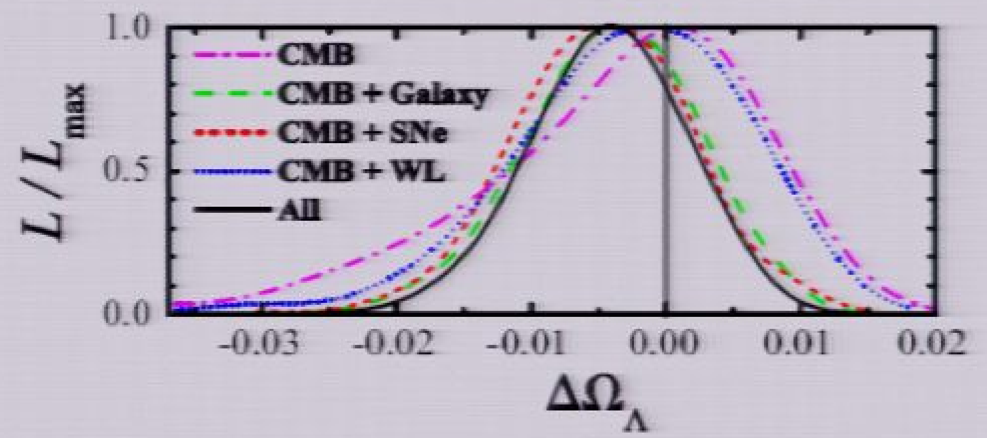
Consistency check of GR: **Real data!!**

Expansion



structure growth

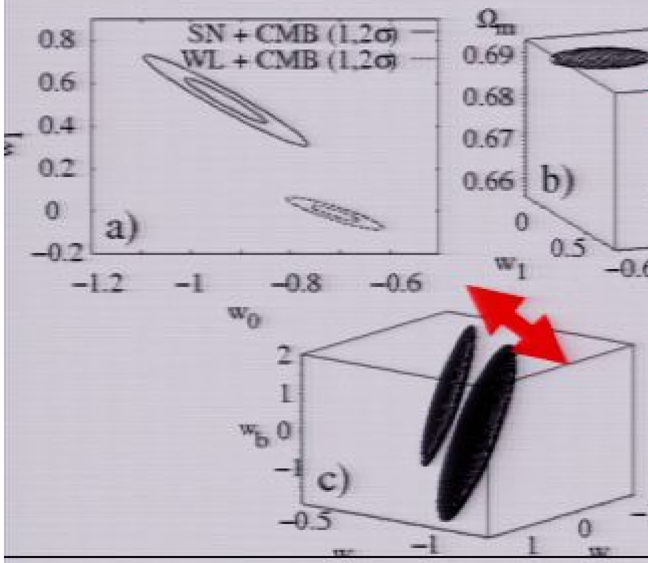
Consistent with GR



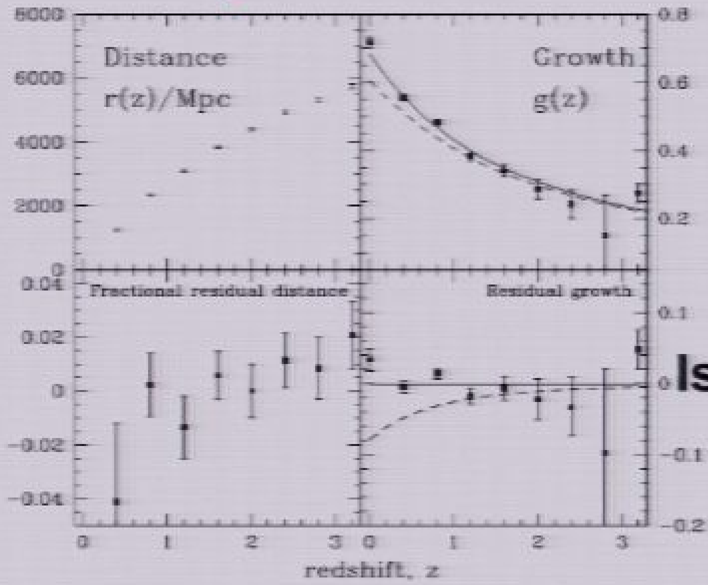
Wang et al. 2007
arXiv:0705.0165

Perimeter institute 2010

Future surveys can do much better to test the consistency relation



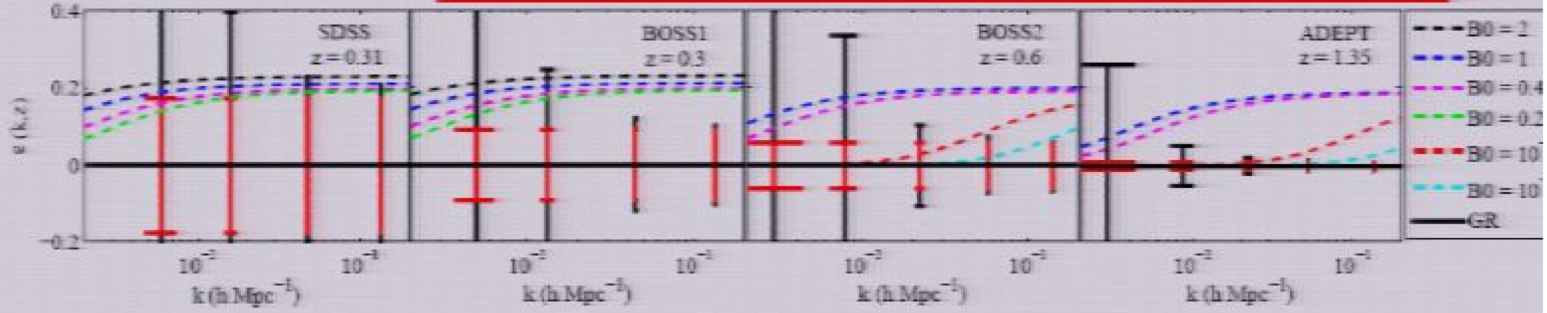
Underlying gravity: DGP.
Fit with GR
Knox et al. 2005



LCDM vs
DGP

Ishak et al. 20

$$\epsilon(k,a) = \Omega_m^{-\gamma(a)}\frac{d\ln D}{d\ln a} - 1 = \frac{a^{3\gamma}H(a)^{2\gamma}}{(\Omega_{m,0}H_0^2)^{\gamma}}\frac{d\ln D}{d\ln a} - 1$$



Acquaviva et al. 2008

Physics behind the consistency relation

or smooth DE

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$$ds^2 = -(1 + 2\psi)dt^2 + a^2(1 + 2\phi)dx^i$$

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$$\frac{d^2\delta}{da^2} + \frac{d\delta}{da}\left(\frac{dH/da}{H} + \frac{3}{a}\right) - \frac{3}{2}\frac{\delta}{a^2}\frac{\Omega_0 H_0^2}{H^2 a^3} = 0$$

Imprints of gravity in the LSS

Amendola et al. 2007
Bertschinger& Zukin. 2008
Caldwell et al. 2007
Hu & Sawicki 2007
Jain & ZPJ 2008
Uzan 2006
ZPJ et al. 2007

See also Constantinos Skordis, arXiv:0806.1238

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$$\begin{tikzcd}
\rho \arrow[r, "G_{Newton}"] & \phi \arrow[r, "\text{equivalent}"] & \psi \arrow[r] & \dot{V} \arrow[lll, bend left]
\end{tikzcd}$$

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\rho \arrow[r, "\cancel{G_{Newton}}", "G_{eff}"'] & \phi \arrow[r, "\cancel{\text{equivalent}}", "\eta"'] & \psi \arrow[r] & \dot{V} \arrow[lll, bend left]
\end{tikzcd}$$

Imprints of gravity in the LSS

Amendola et al. 2007
Bertschinger& Zukin. 2008
Caldwell et al. 2007
Hu & Sawicki 2007
Jain & ZPJ 2008
Uzan 2006
ZPJ et al. 2007

the Newtonian gauge

$$ds^2 = -(1+2\psi)dt^2 + a^2(1+2\phi)dx^{i,2}$$

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$f(R)$ gravity: $\tilde{G}_{eff} = \frac{G}{1+f_R}$

DGP gravity: $\tilde{G}_{eff} = 1$

TeVeS: $\tilde{G}_{eff} = \tilde{G}_{eff}(g_{uv}, \text{other fields})$

DE: $k^2(\phi+\psi) = 12\pi G\rho(1+w)$

DGP: $\eta = \eta(z) \neq 1$

Testing the (generalized) Poisson Equation

e Newtonian gauge

$$ds^2 = -(1+2\psi)dt^2 + a^2(1+2\phi)dx^{i,2}$$

$$\nabla^2(\phi - \psi) \overset{?}{=} -8\pi G\bar{\rho}\delta$$

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Layers of assumptions/approximations

$$\boxed{P_g^s(k,u)=(P_g+2u^2P_{gv}+u^4P_v+..)F(ku\sigma_{12})}$$

e.g. Matsubara 2007

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Perimeter institute 2010

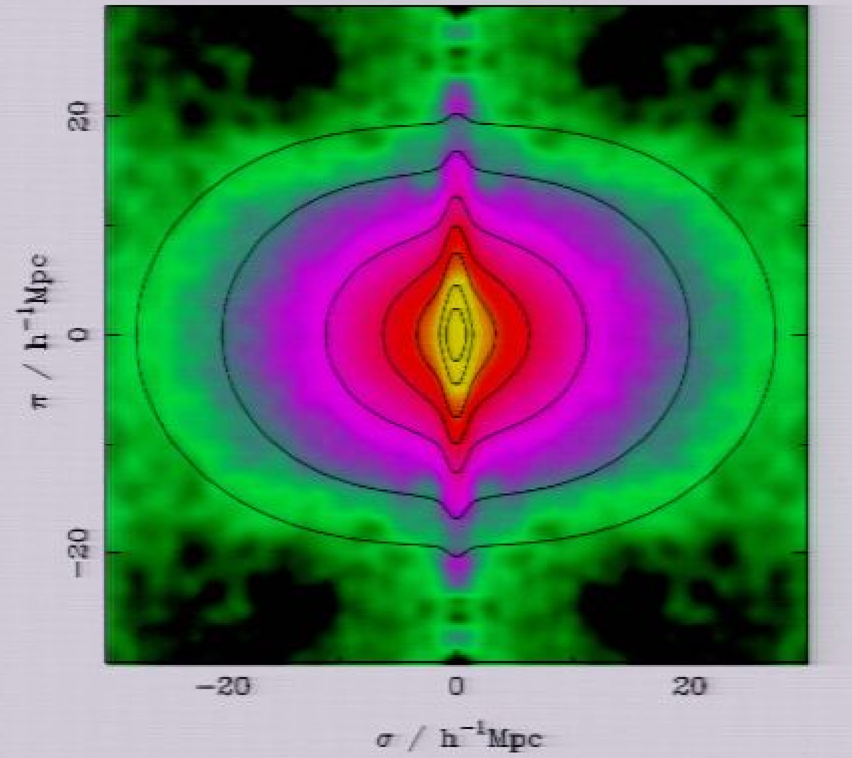

Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma, \pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The function was estimated by counting pairs in boxes of side $0.2\,h^{-1}$ Mpc (assuming an $\Omega = 1$ geometry), and then smoothing with a Gaussian of rms width $0.5\,h^{-1}$ Mpc.

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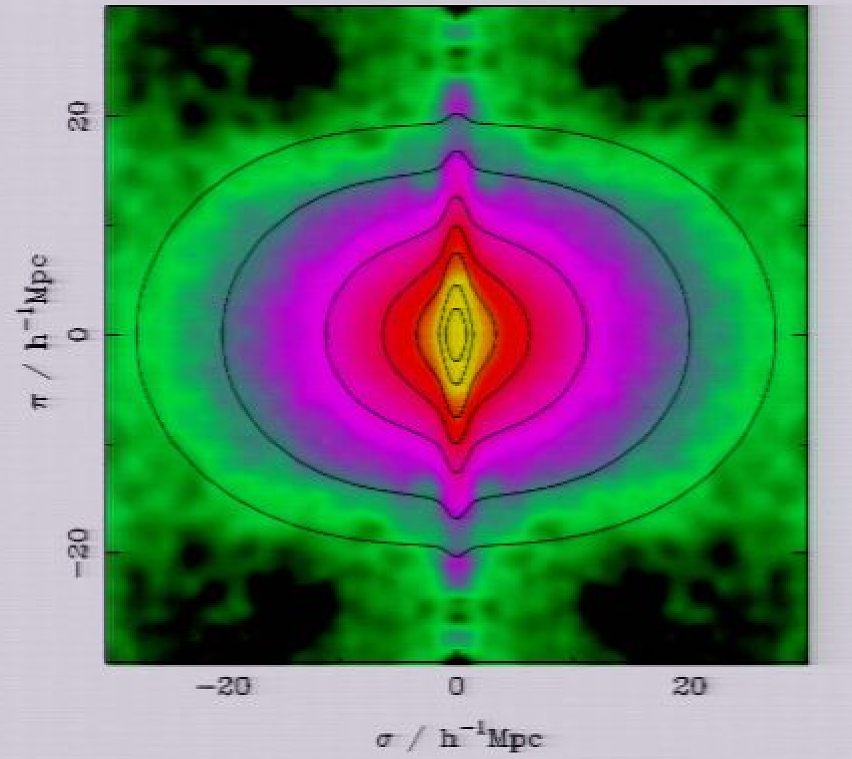

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$$E_G \propto \frac{P_{\nabla^2(\phi-\psi)g}}{P_{g\theta}} \propto \frac{\nabla^2(\phi-\psi)}{\delta}\frac{1}{f}$$

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galaxy-galaxy lensing

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redshift distortion

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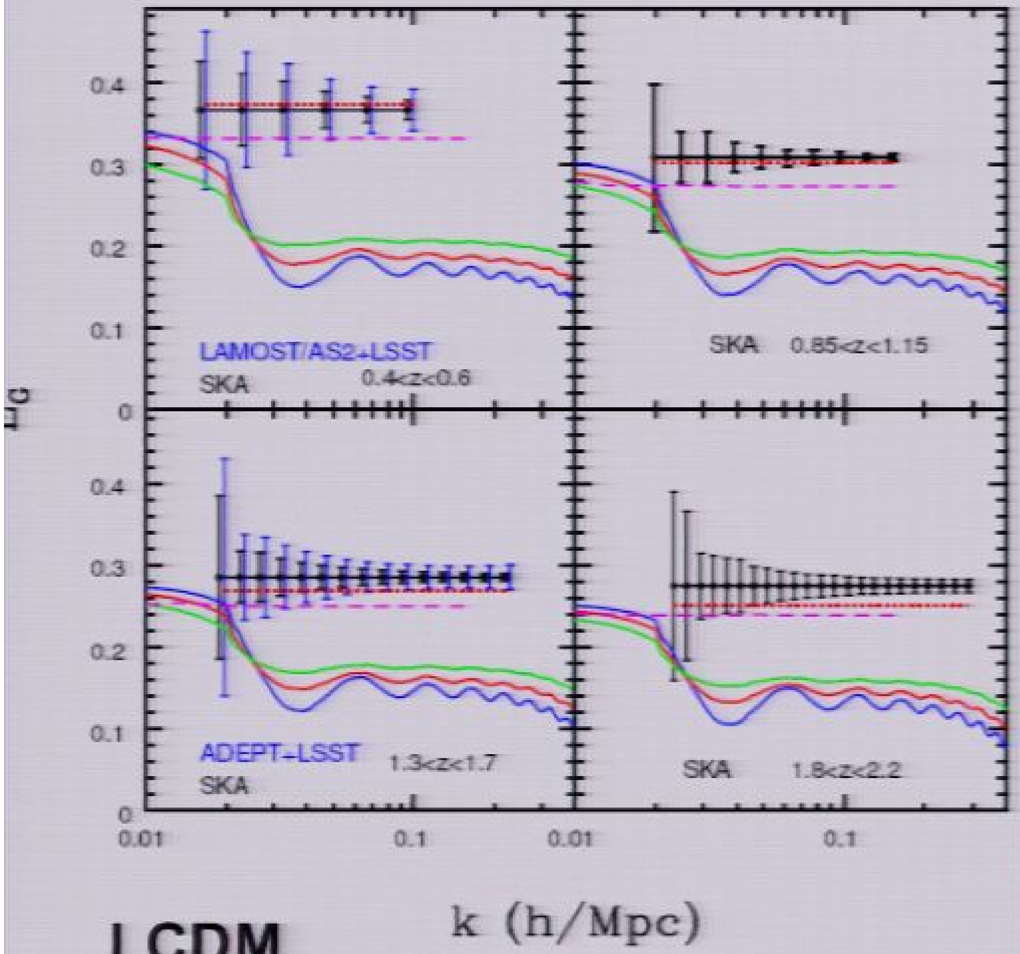
- **Contains smoking guns of modifications in gravity and particle physics**
    - **Changes in the amplitude**
    - **Violation of the scale independence**



LCDM
f(R)
DGP
MOND/TeVeS

ZPJ et al. 2007

- **E_G will be measured to 1% level accuracy within two decades**
- **Promising to detect one percent level deviation from general relativity+canonical dark energy model (if systematics can be controlled)!**

TABLE I: Summary of target surveys. For quantitative evaluation, we adopt the listed survey configurations and capabilities of these ongoing/proposed surveys, which may be uncertain.

	redshift	deg^2	$N_{\rm gal}$	band	operation
LAMOST[a]	$z< 0.8$	10,000	$\sim 10^6$	optical	2008
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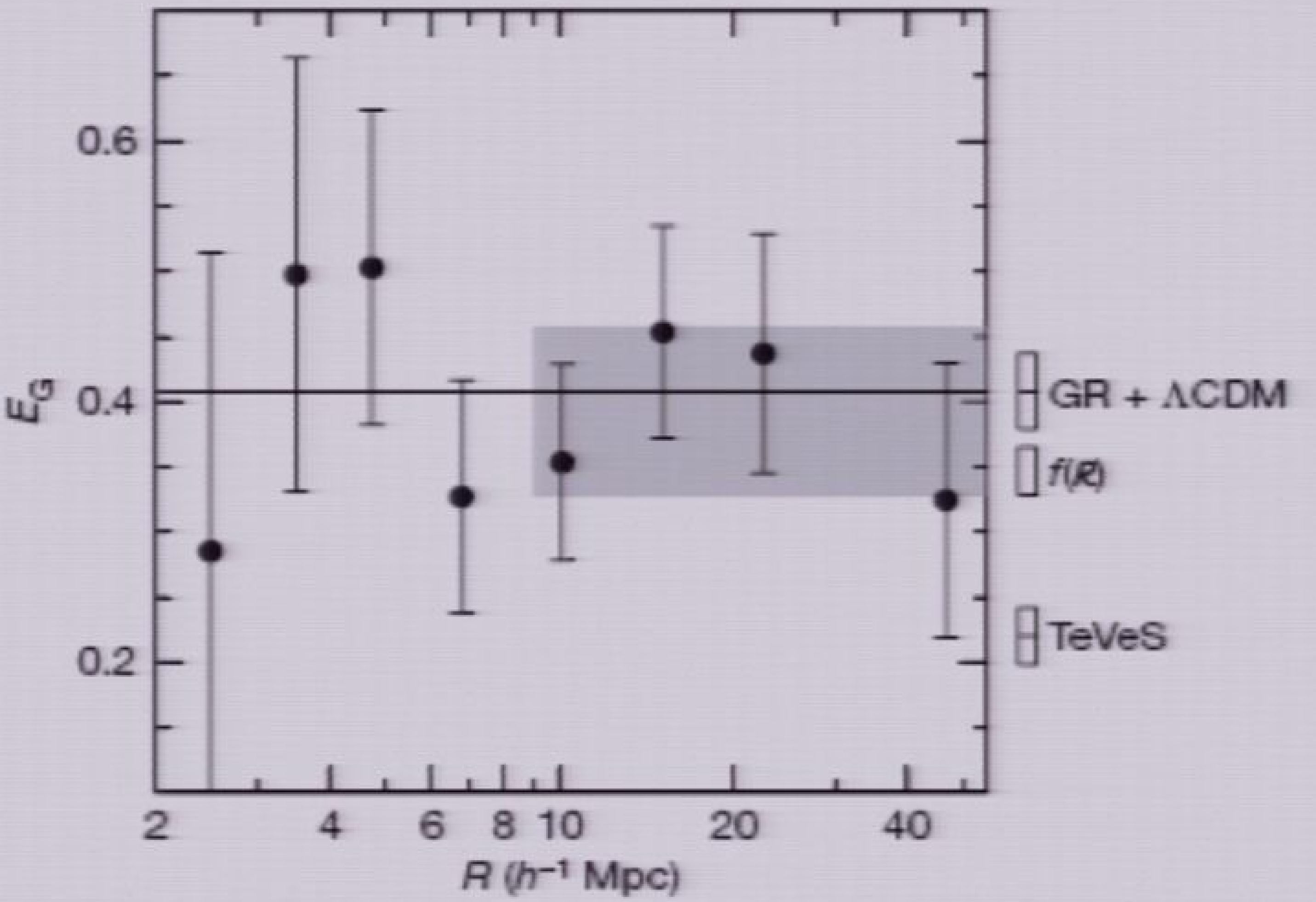
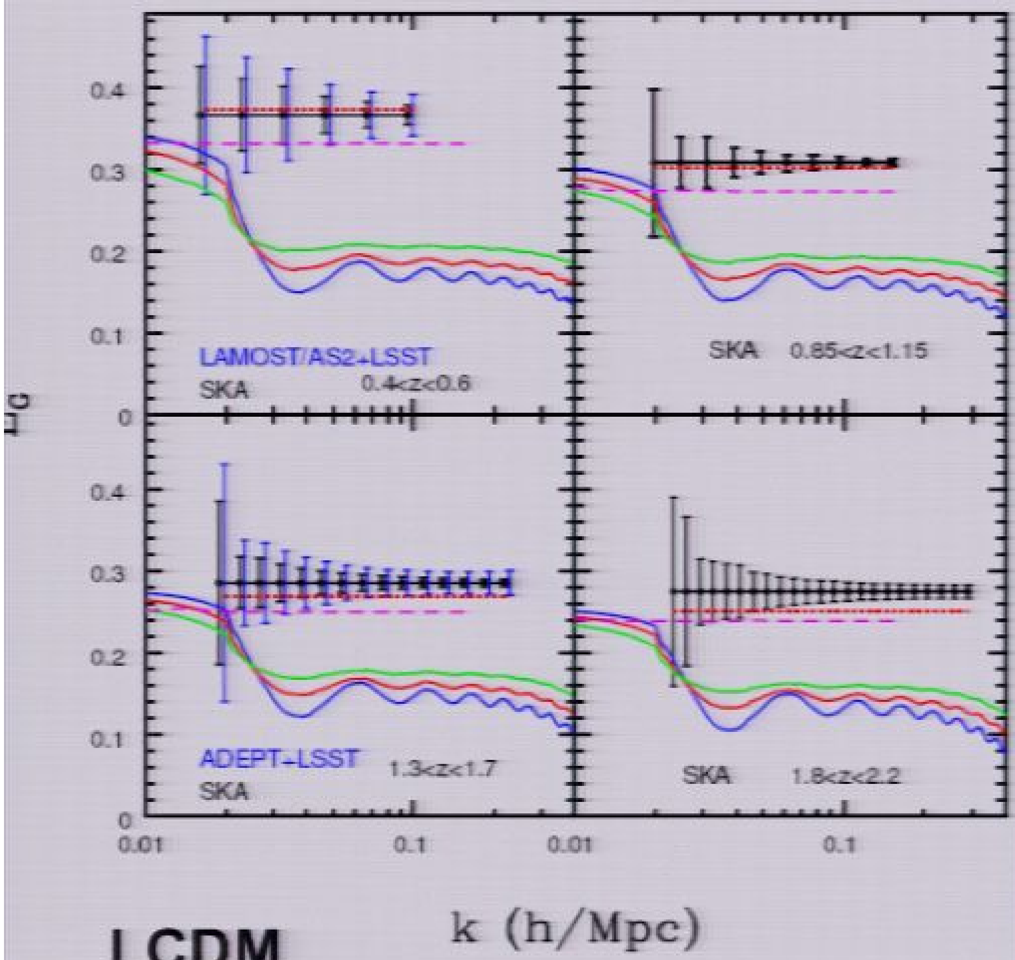
The first E_G measurement

Confirmation of GR at ~10-40 Mpc/h scales



Reyes et al. 2010



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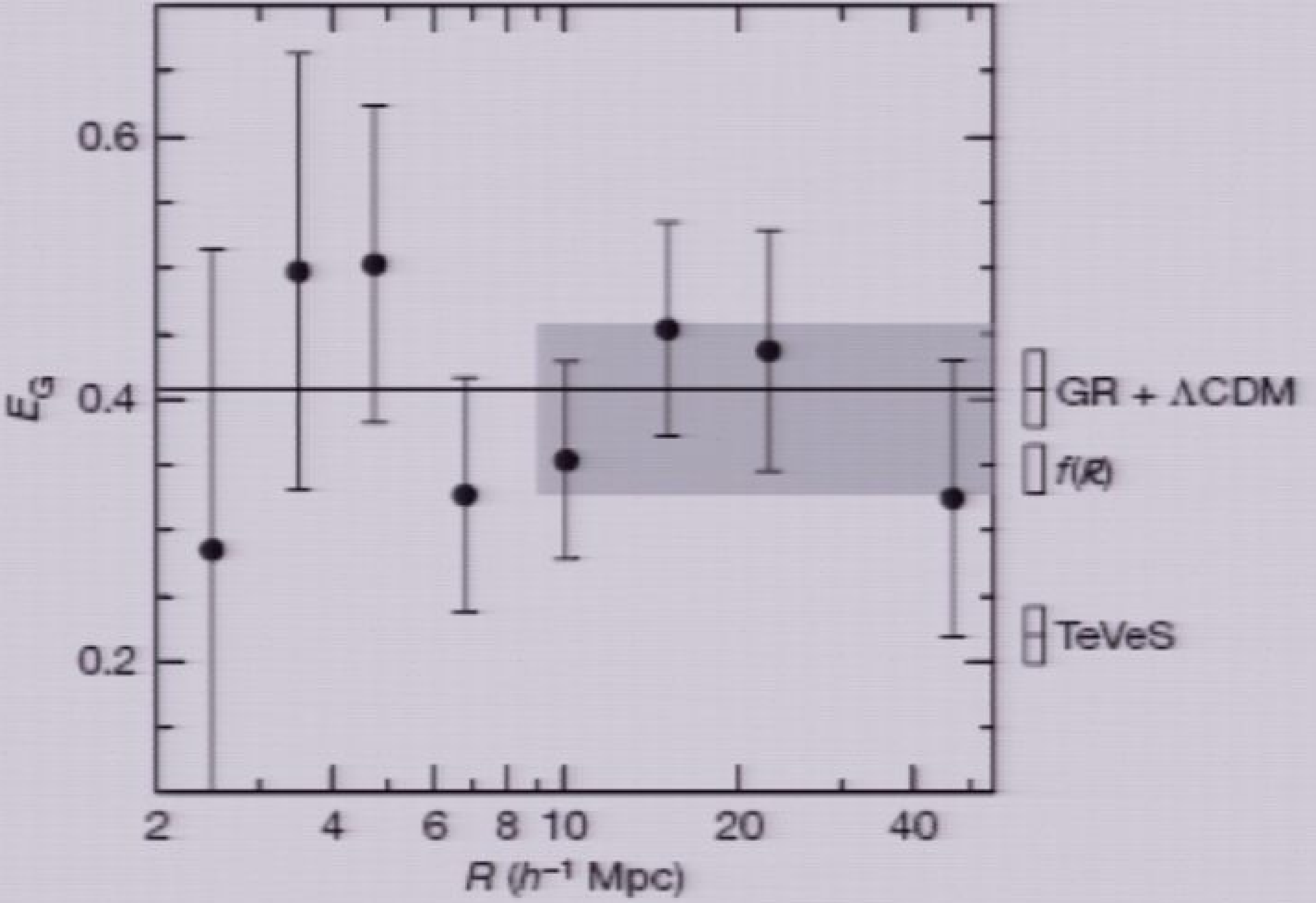

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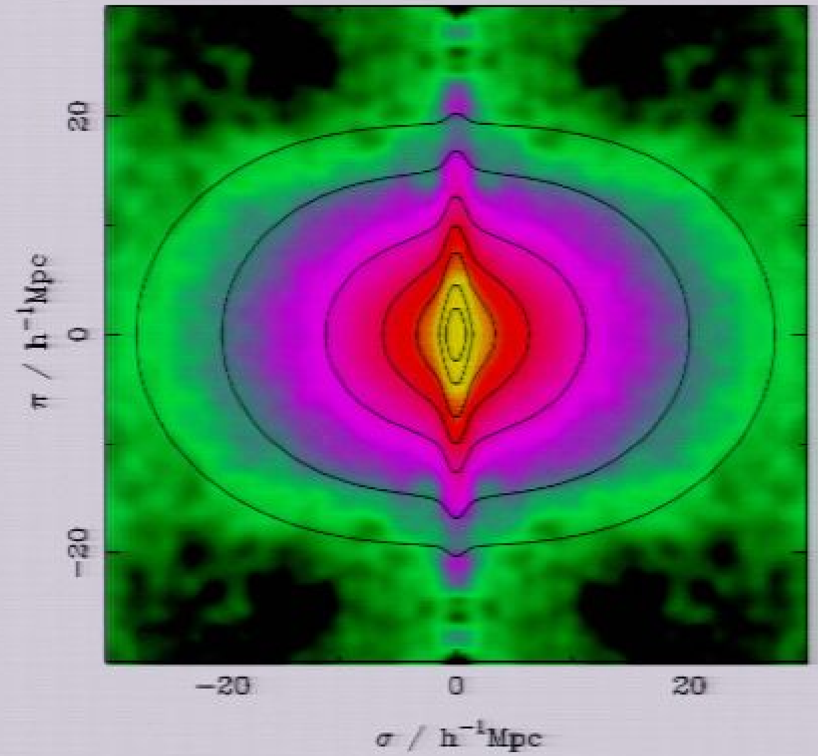

Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma,\pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The function was estimated by counting pairs in boxes of side $0.2\,h^{-1}$ Mpc (assuming an $\Omega = 1$ geometry), and then smoothing with a Gaussian of rms width $0.5\,h^{-1}$ Mpc.

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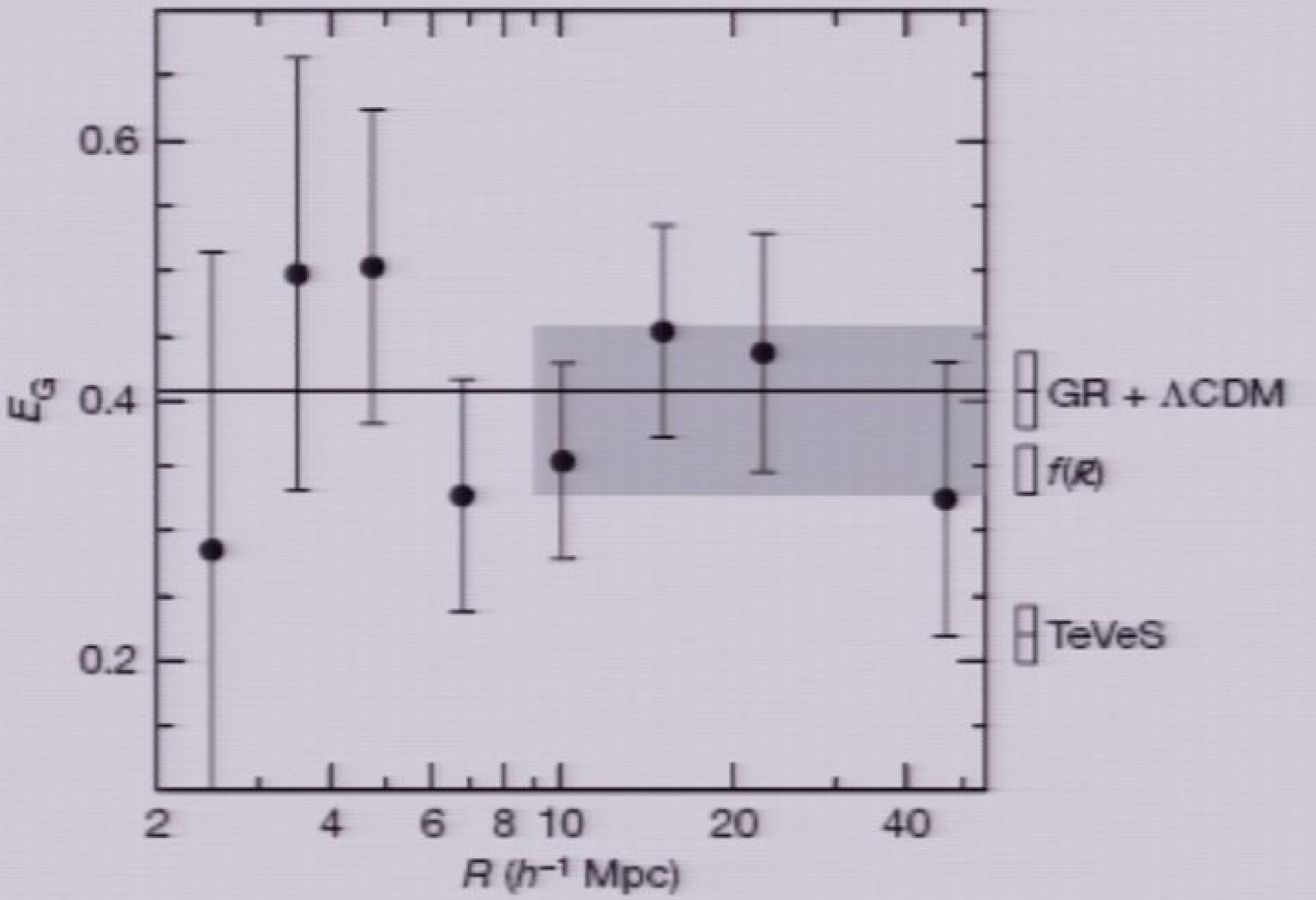

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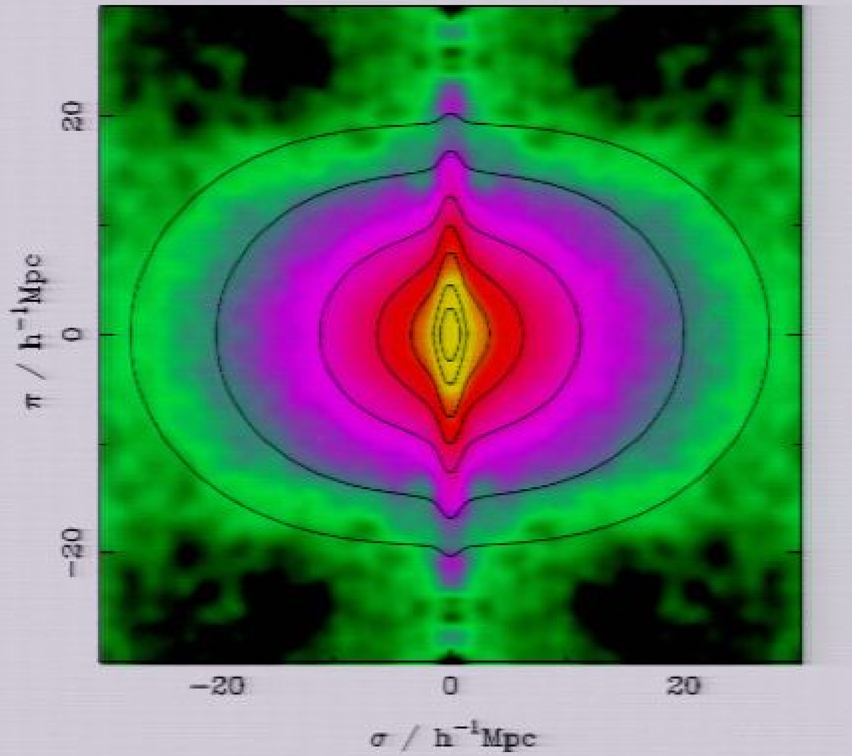

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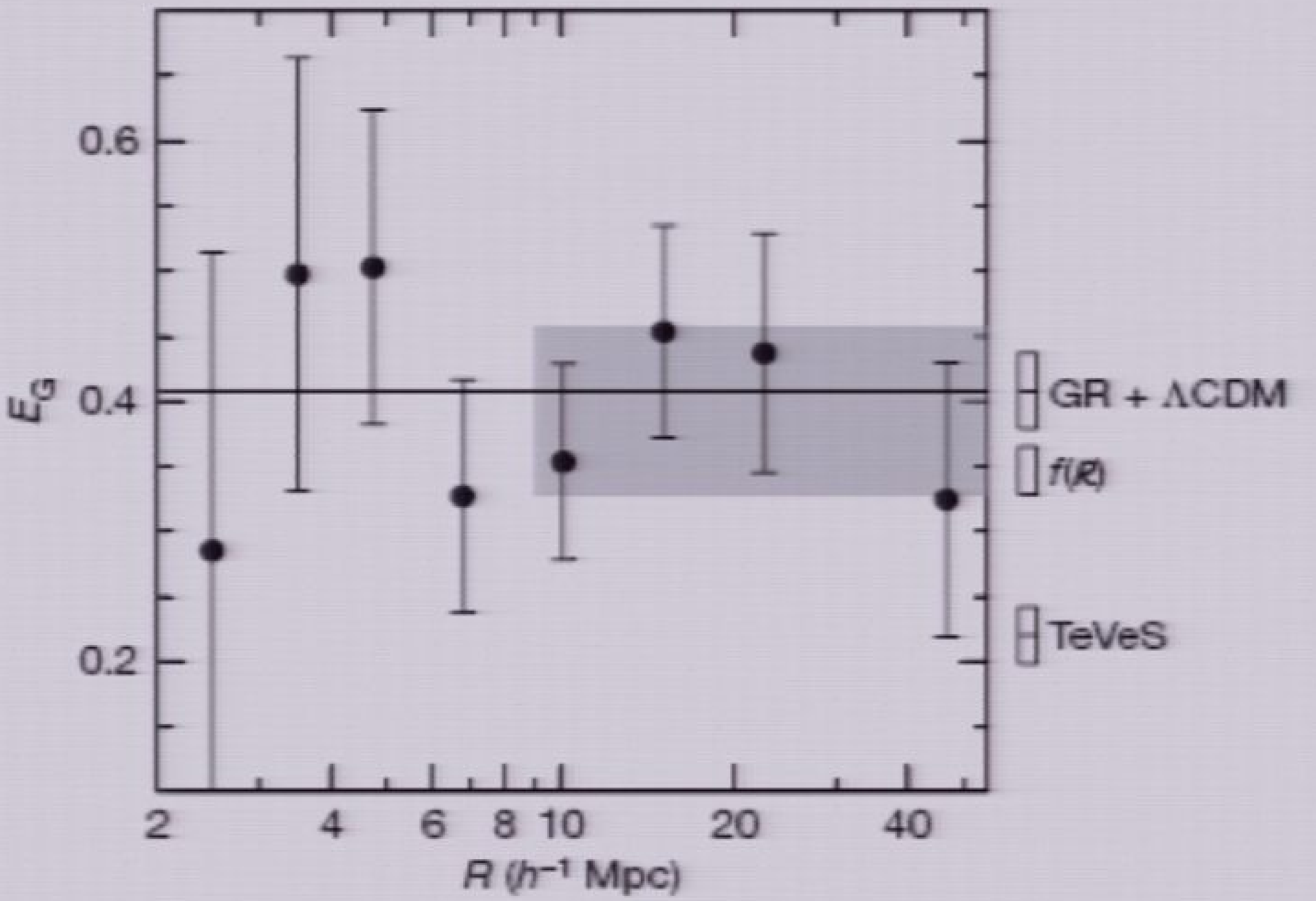

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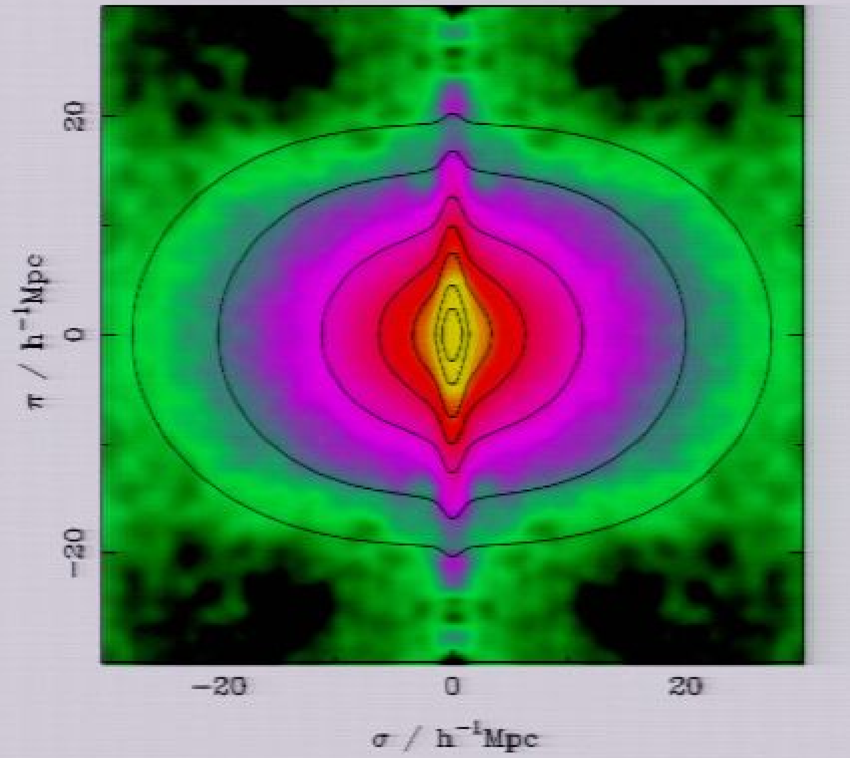

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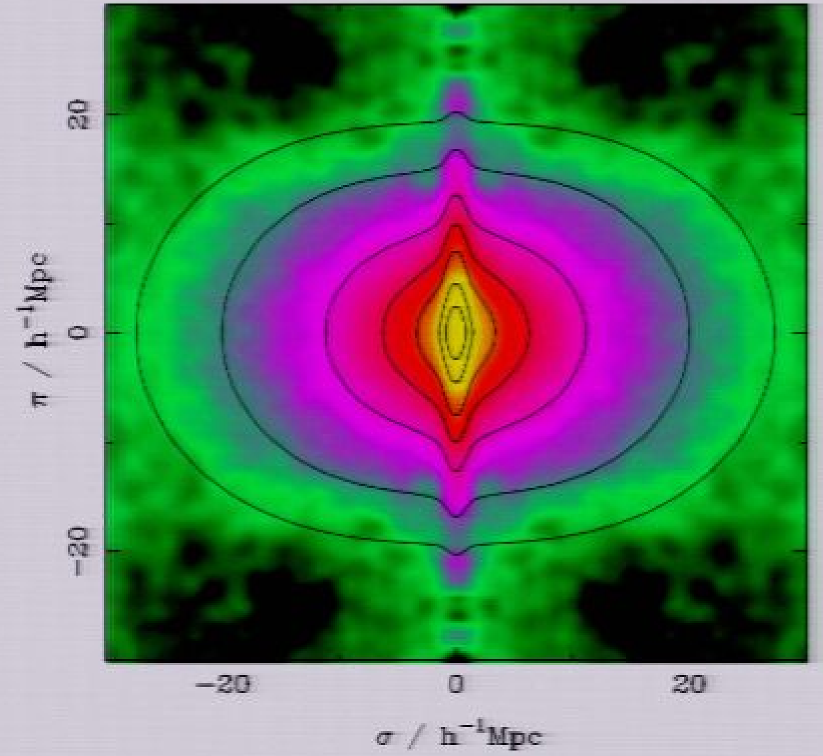

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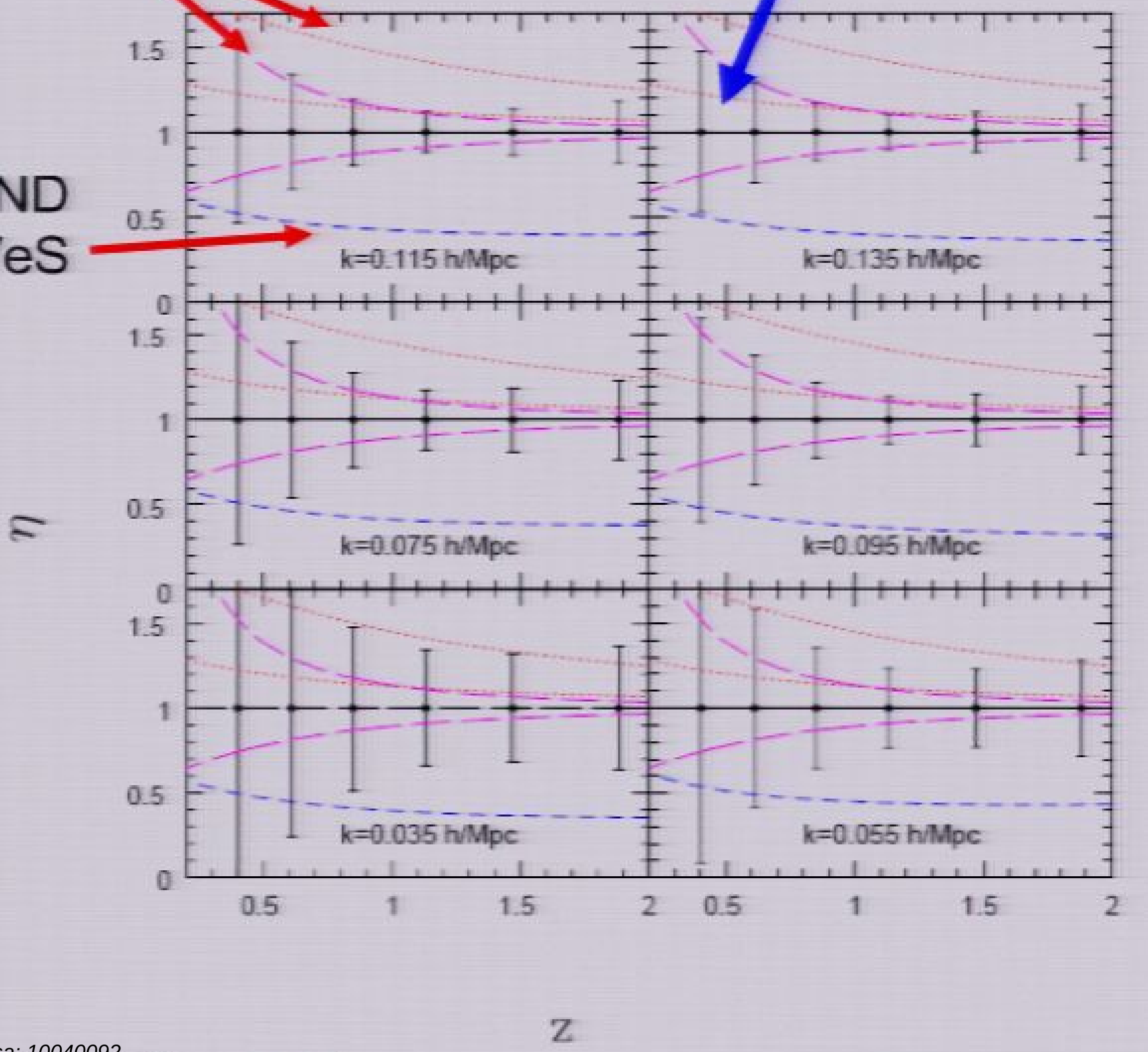
One can further construct an estimator of $\eta \equiv \frac{-\phi}{\psi}$

Lensing: Φ-Ψ; Peculiar velocity: Ψ



DGP

dark energy with anisotropic stress

MOND

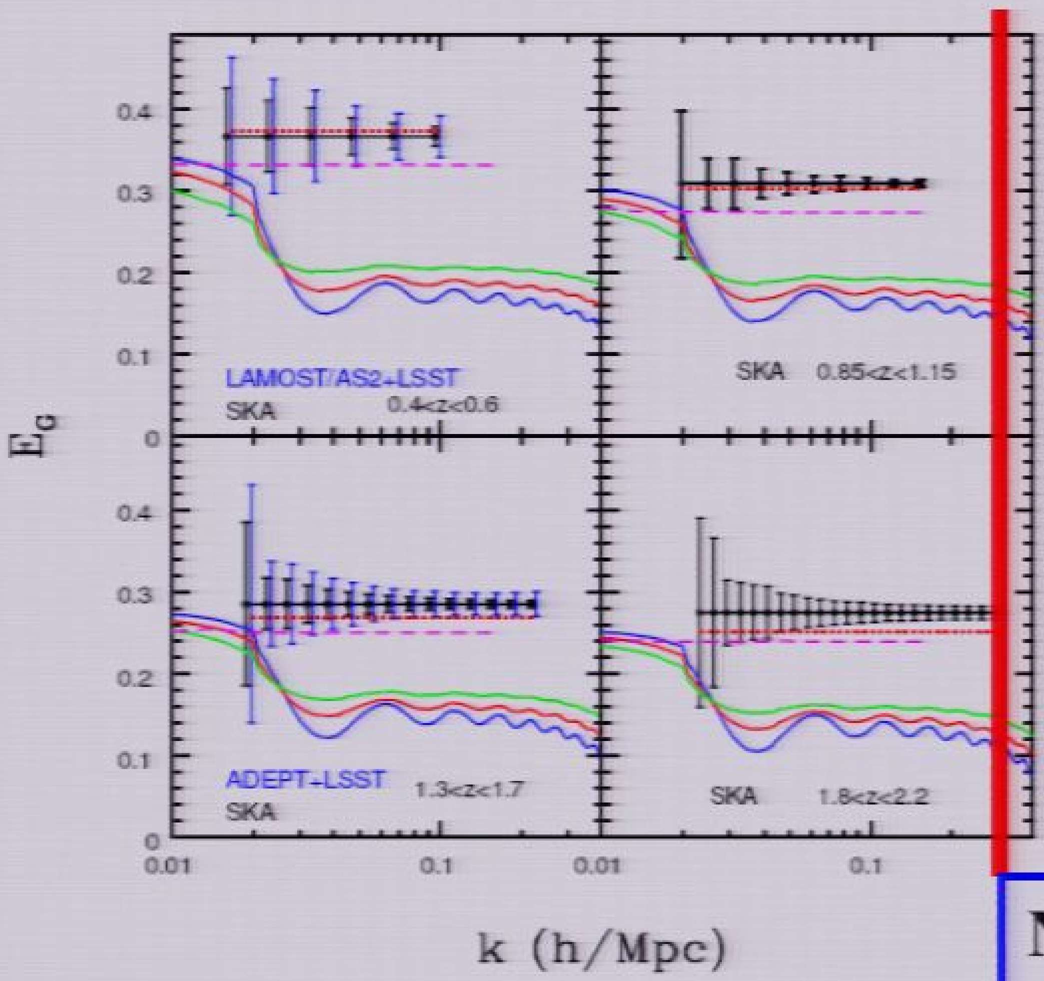
TeVeS

- eta can be measured to 10% accuracy.

- Errors in eta is larger than errors in E_G
- Even so, eta can have stronger discriminating power, in some cases.
  - η of DGP differs significantly from that of LCDM. (E_G of DGP is very close to that of LCDM.)
- eta and E_G are complementary
  - DGP with high Omega_m

SKA forecast

ZPJ et al. 2008



Nonlinear scales:
measurements: (much) higher S/N
Theory: (much) more difficult to calculate

One can further construct an estimator of $\eta \equiv \frac{-\phi}{\psi}$

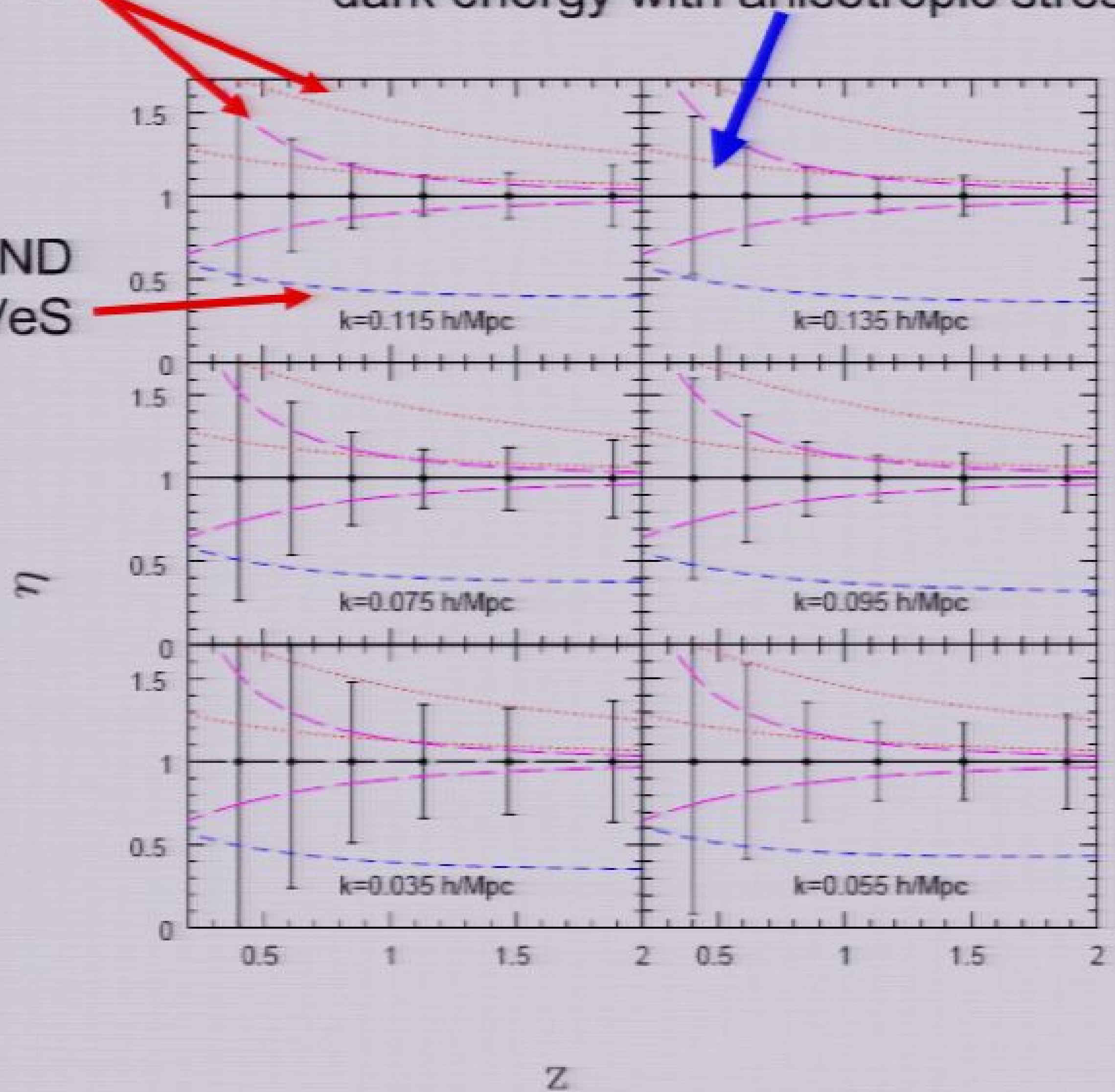
Lensing: $\Phi - \Psi$; Peculiar velocity: Ψ

DGP

dark energy with anisotropic stress

MOND

TeVeS



- •eta can be measured to 10% accuracy.

- •Errors in eta is larger than errors in E_G
- •Even so, eta can have stronger discriminating power, in some cases.
  - •η of DGP differs significantly from that of LCDM. (E_G of DGP is very close to that of LCDM.)
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SKA forecast

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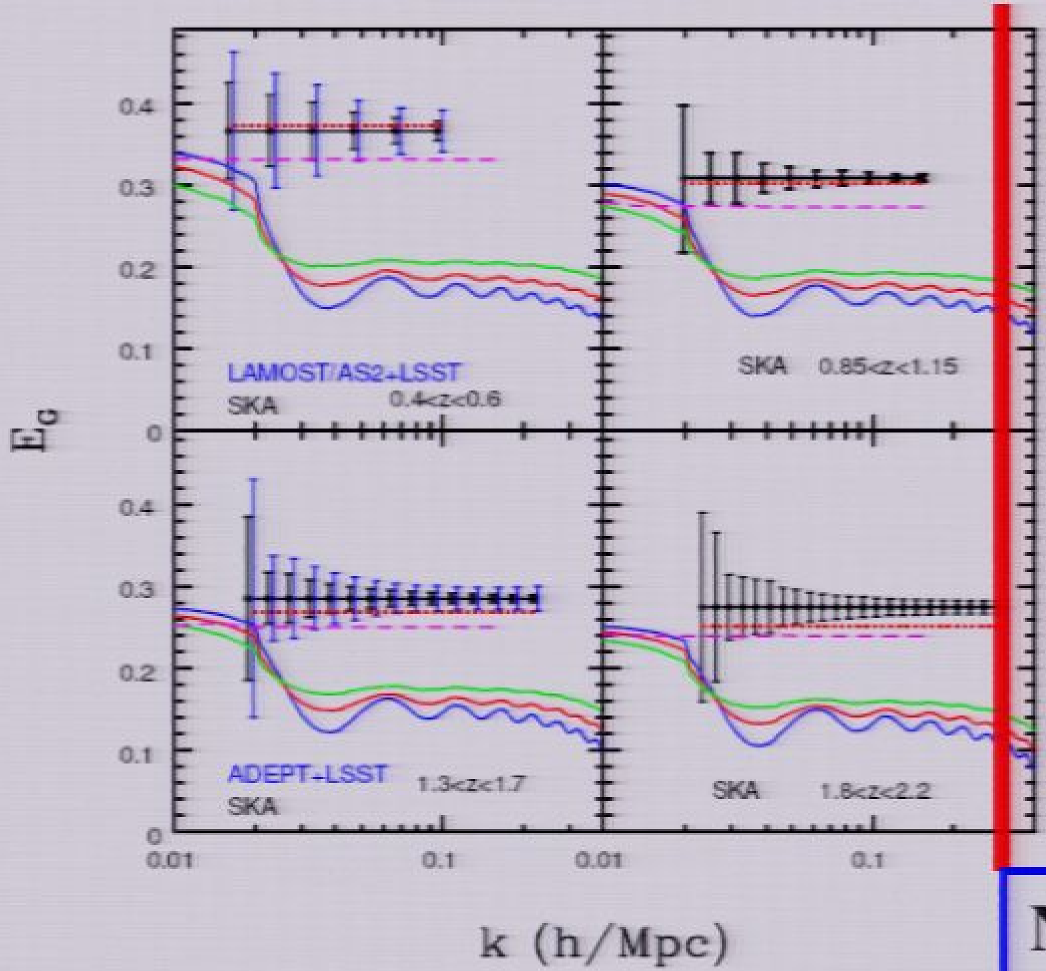

Nonlinear scales: measurements: (much) higher S/N
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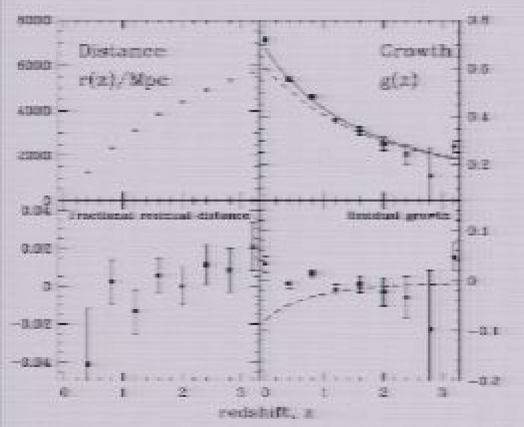
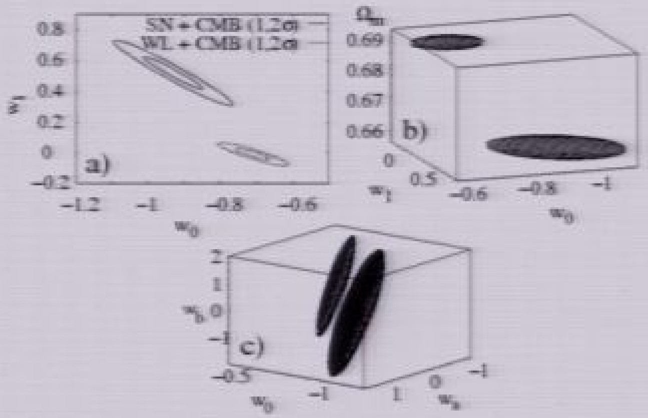
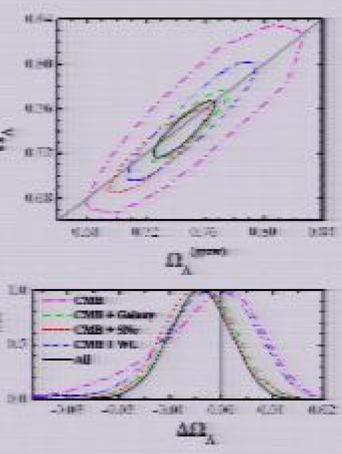


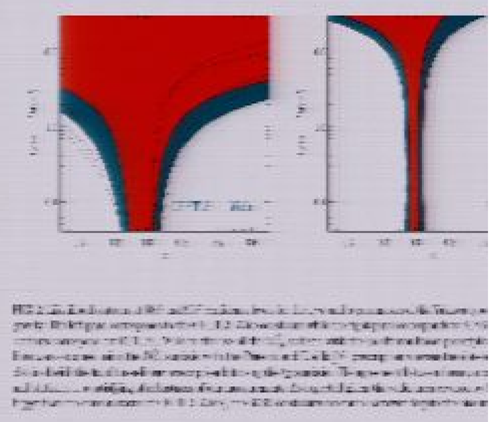
nox et al. 2005



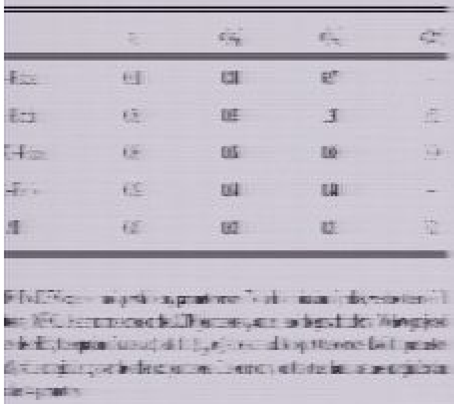
Ishak et al. 2005



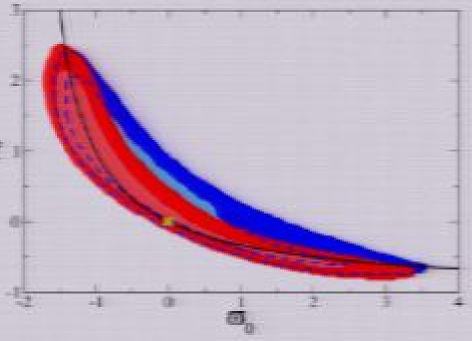
Wang et al. 2007



Dore et al. 200



lbrecht et al. 2009



Daniel et al. 2010

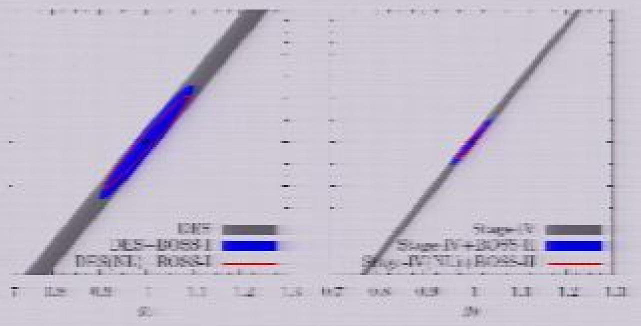
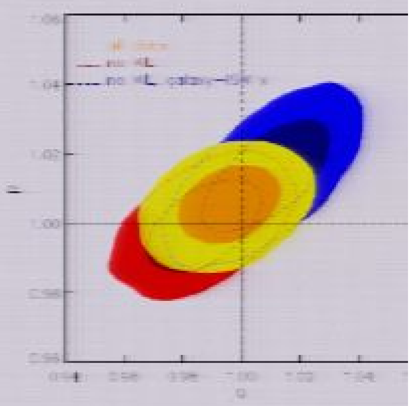


FIG. 7: Correlation between modified gravity parameters for the DES and BOSS-I surveys (left panel) and for Stage IV surveys (right panel). The error contours are as in Fig. 5.

Guzik et al. 2009



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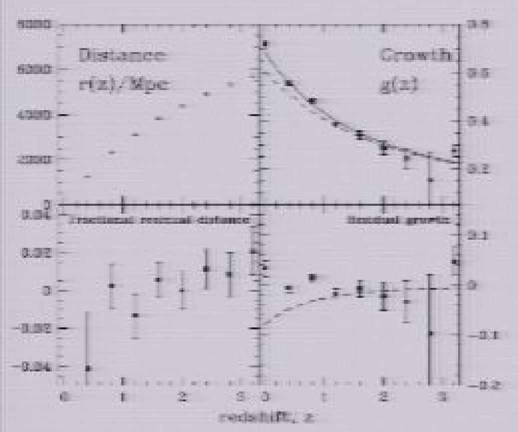
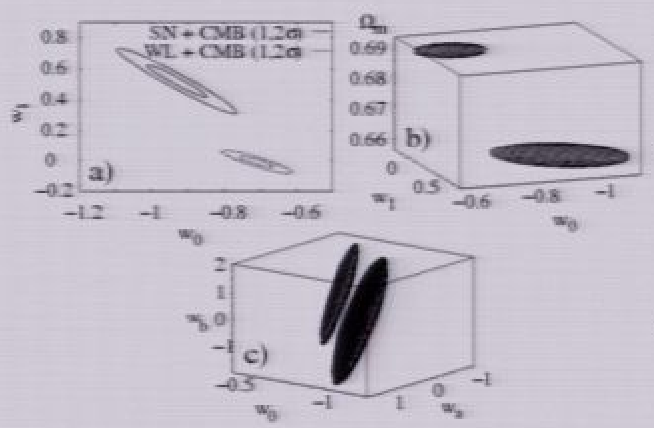
Tangmatitham 20

esting GR relies much on information in the nonlinear regim



nox et al. 2005



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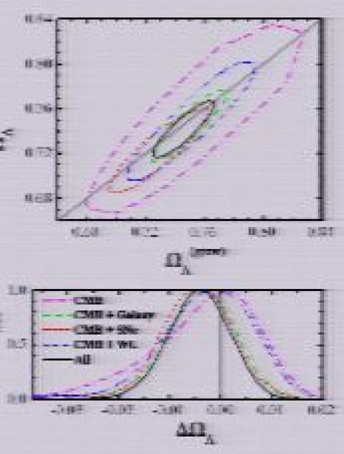
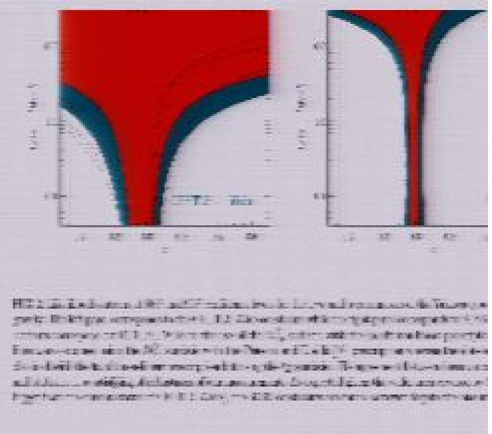
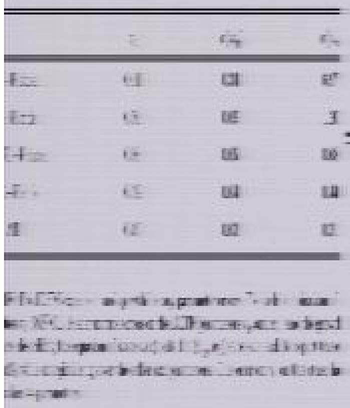


Wang et al. 2007



Dore et al. 200



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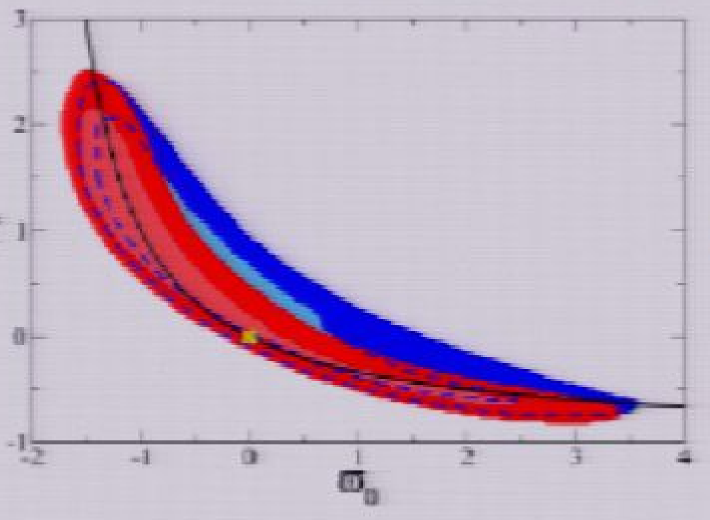

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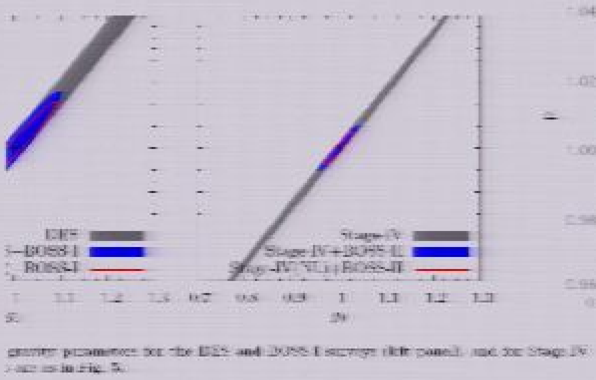
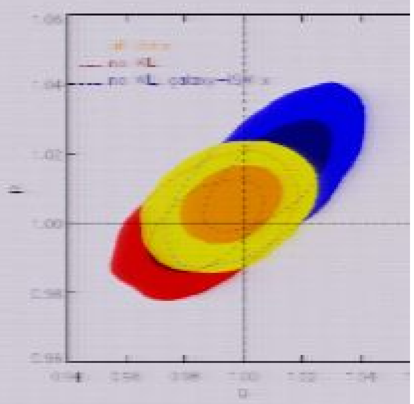


Guzik et al. 2009



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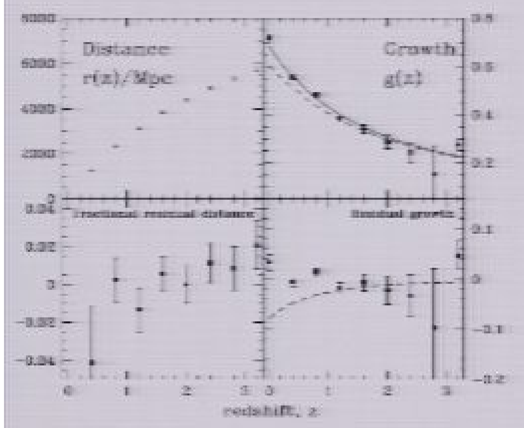

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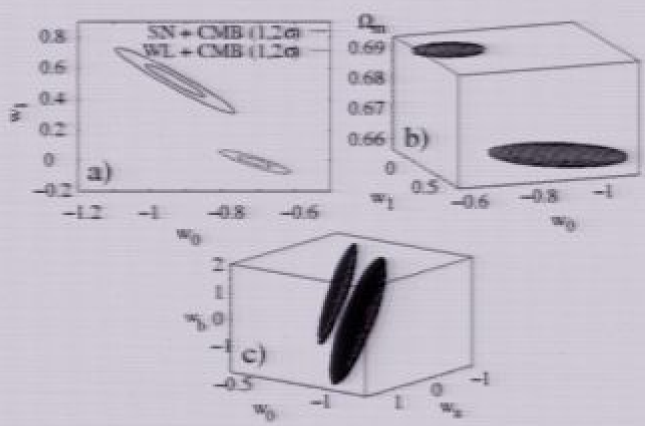

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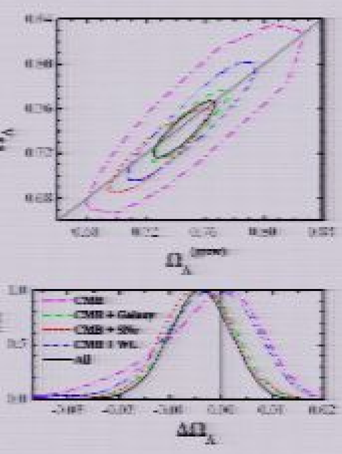

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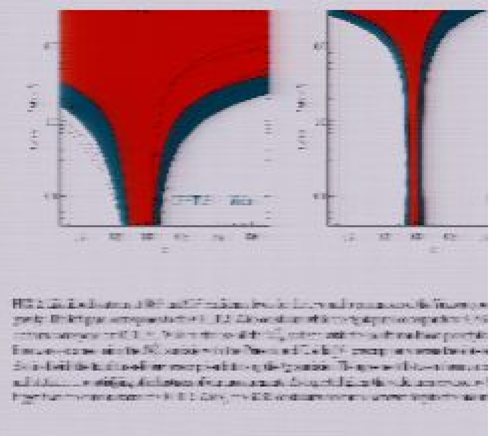

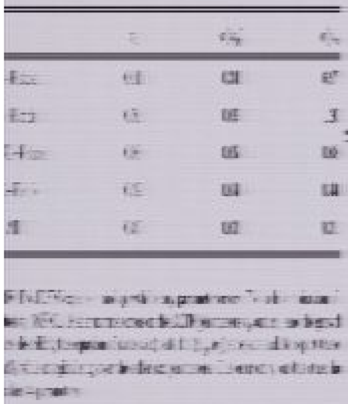

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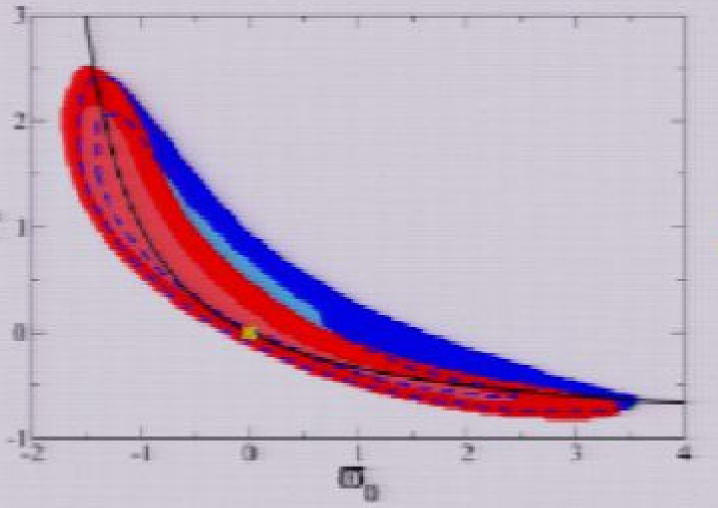

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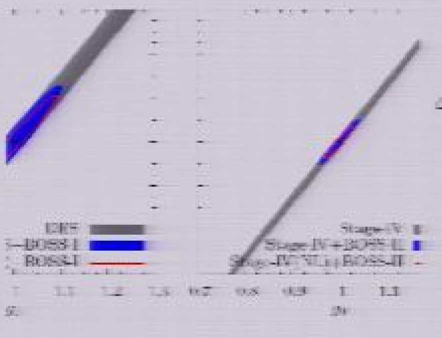

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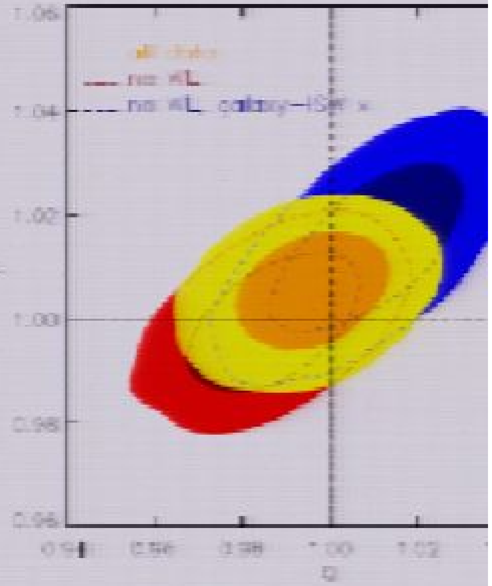
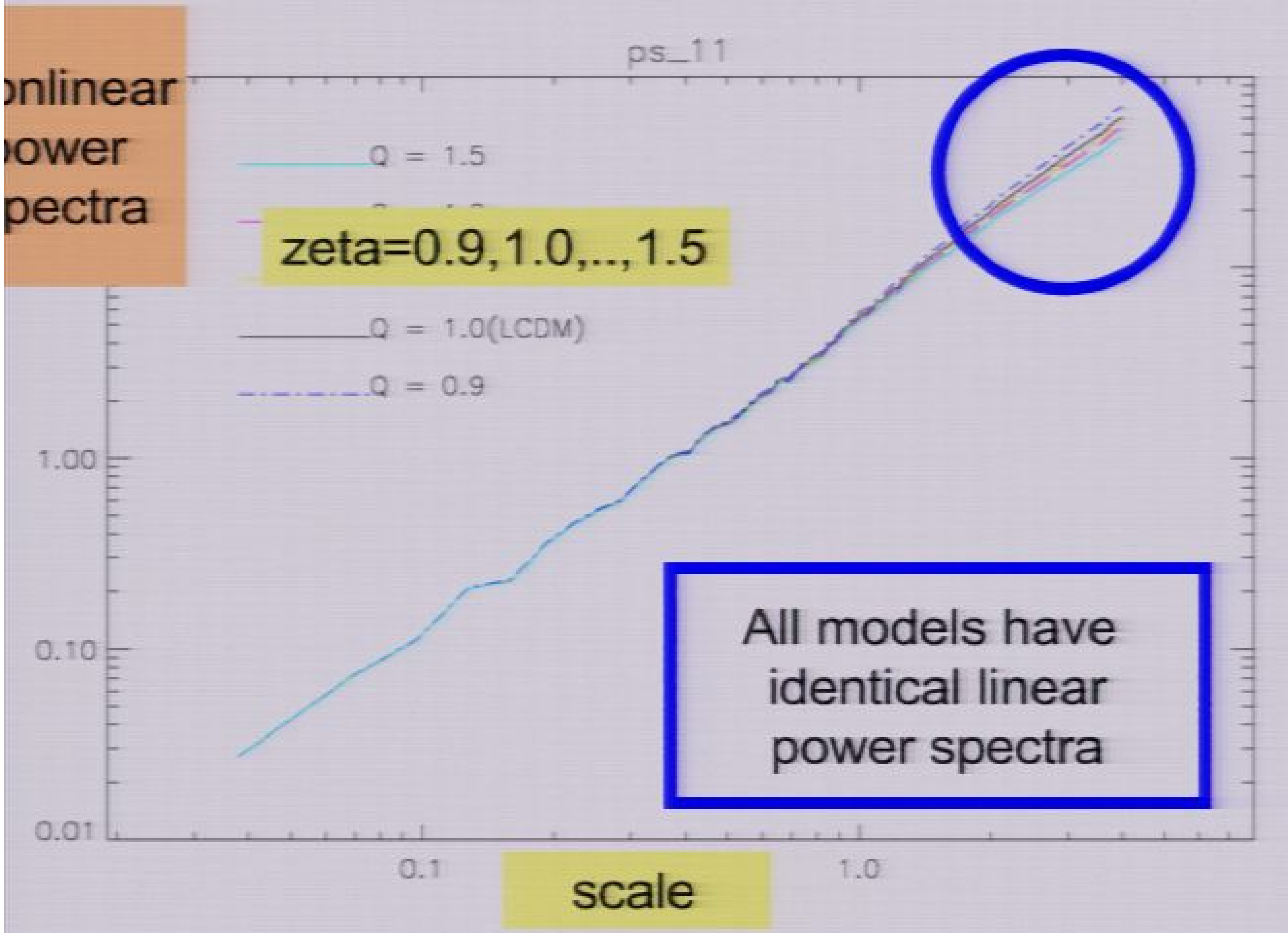


Bean &
Tangmatitham 20

Are the existing fitting formulae sufficiently accurate?

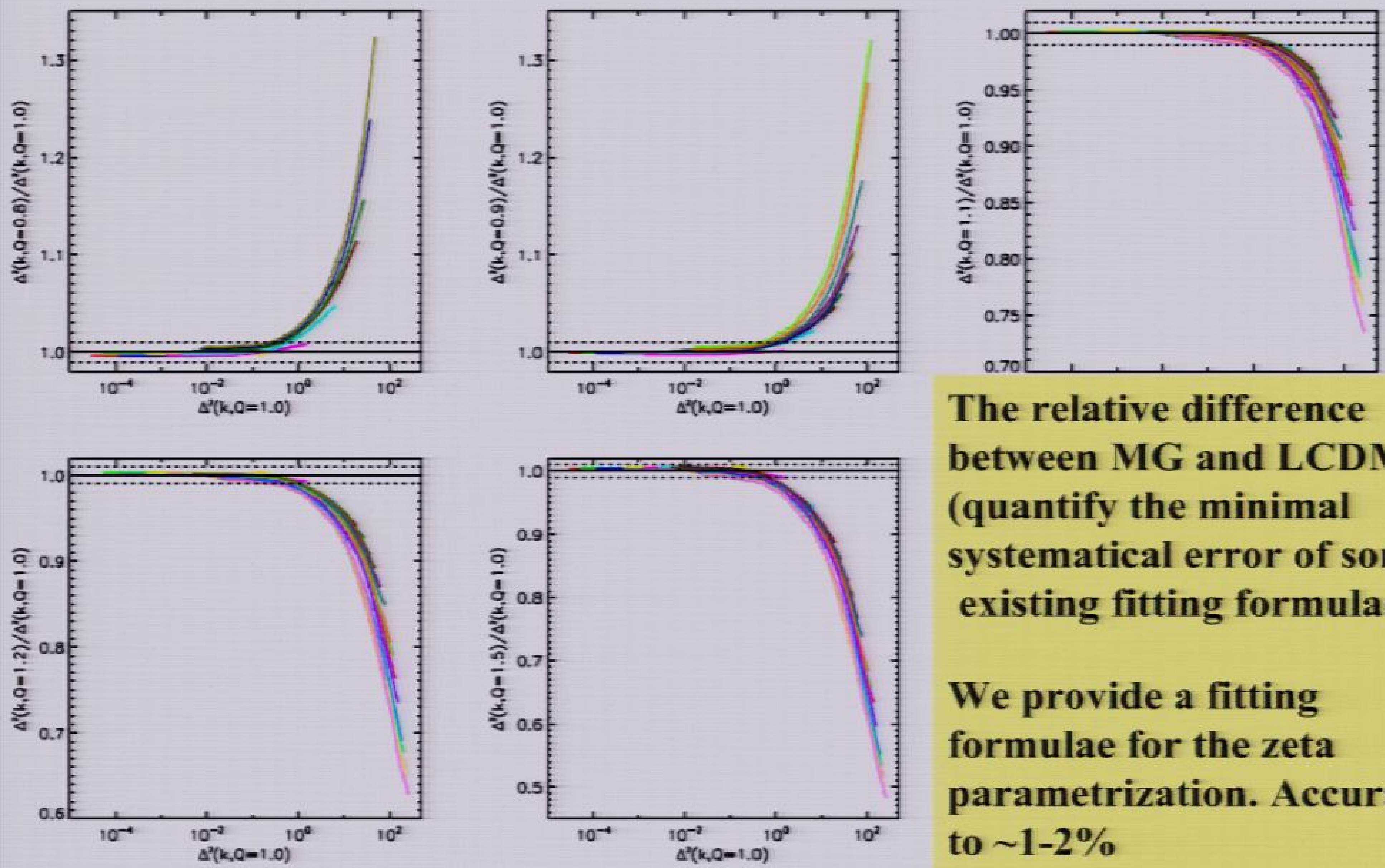


All models have identical linear power spectra

- zeta=Geff/eta determines the structure growth
- The nonlinear PS depends on not only the linear PS at the same epoch.
- Apply existing fitting formulae (e.g. Smith et al. halofit) to MG can lead to ~10% systematical error in nonlinear PS

512^3 N-body simulations
Cui, ZPJ, Yang, 2010

See also
Stabenau & Jain 2006
Martino, Stabenau & Sheth 20



The relative difference between MG and LCDM (quantify the minimal systematical error of some existing fitting formulae)

We provide a fitting formulae for the zeta parametrization. Accurate to ~1-2%

Will run more simulations with more models.

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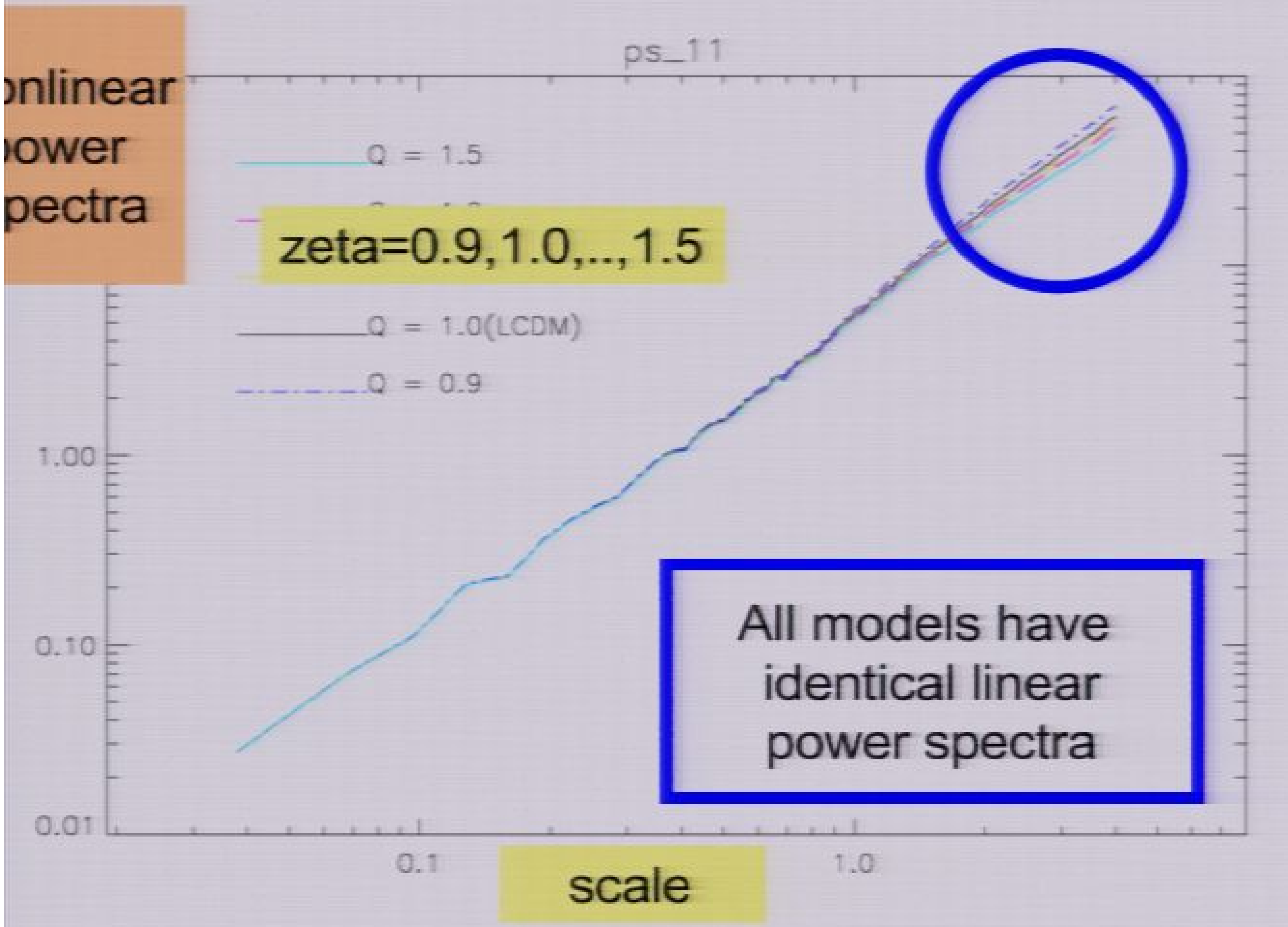

zeta=0.9,1.0,..,1.5

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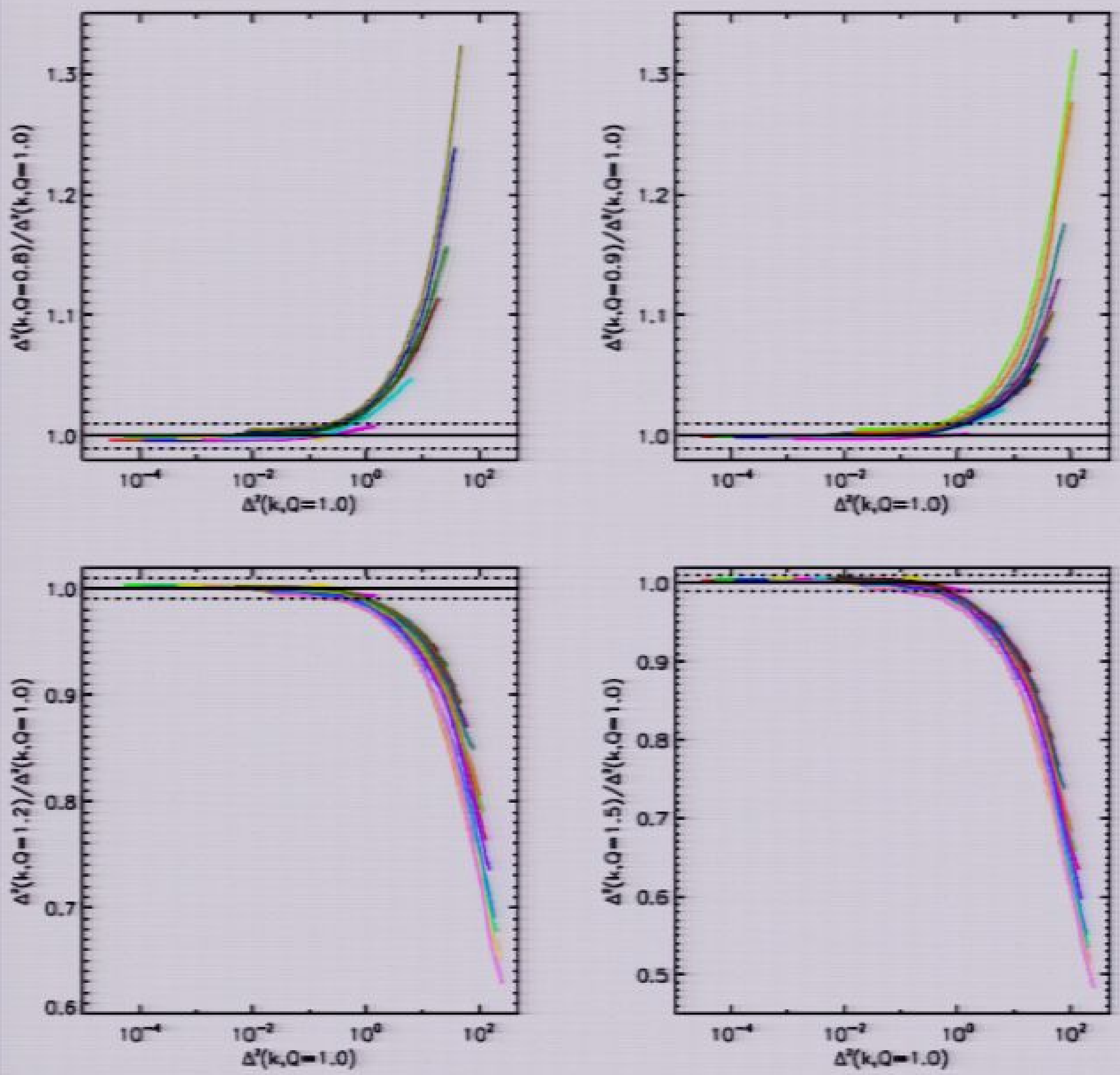

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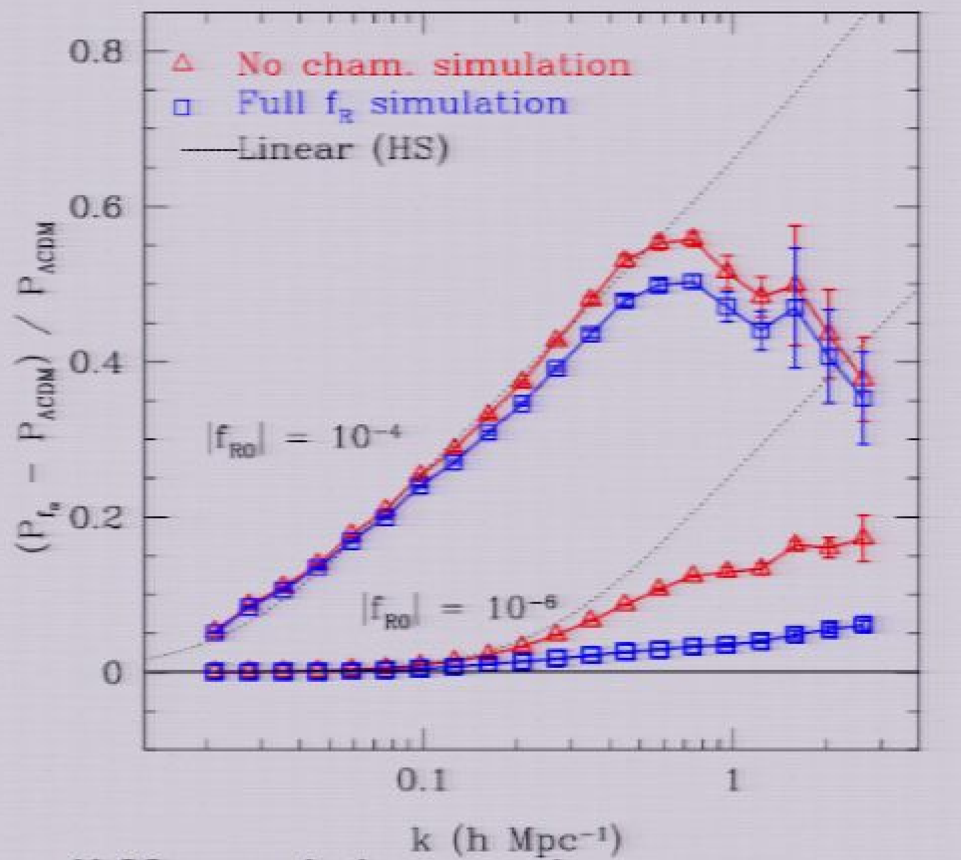
beyond the environmental-independent parametrizations



Solving nonlinear differential equations:

f(R): Oyaizu 2008, Oyaizu et al. 2008, Fabian et al. 2008

DGP: Fabian et al. 2009, Chan & Scoccimarro 2009

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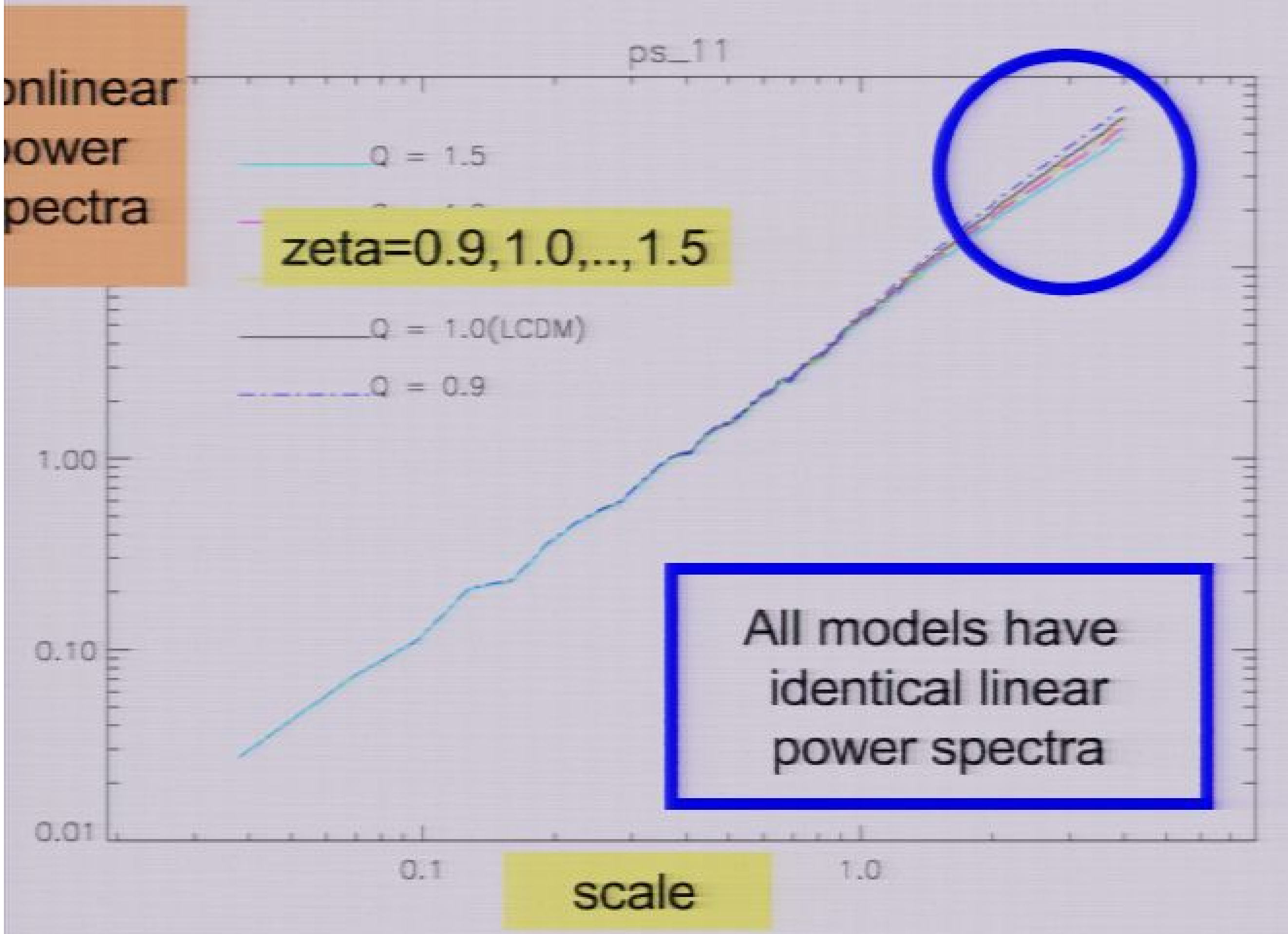

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$$f = \frac{d\ln D}{d\ln a} = \Omega_m^{\gamma}$$

Are the existing fitting formulae sufficiently accurate?

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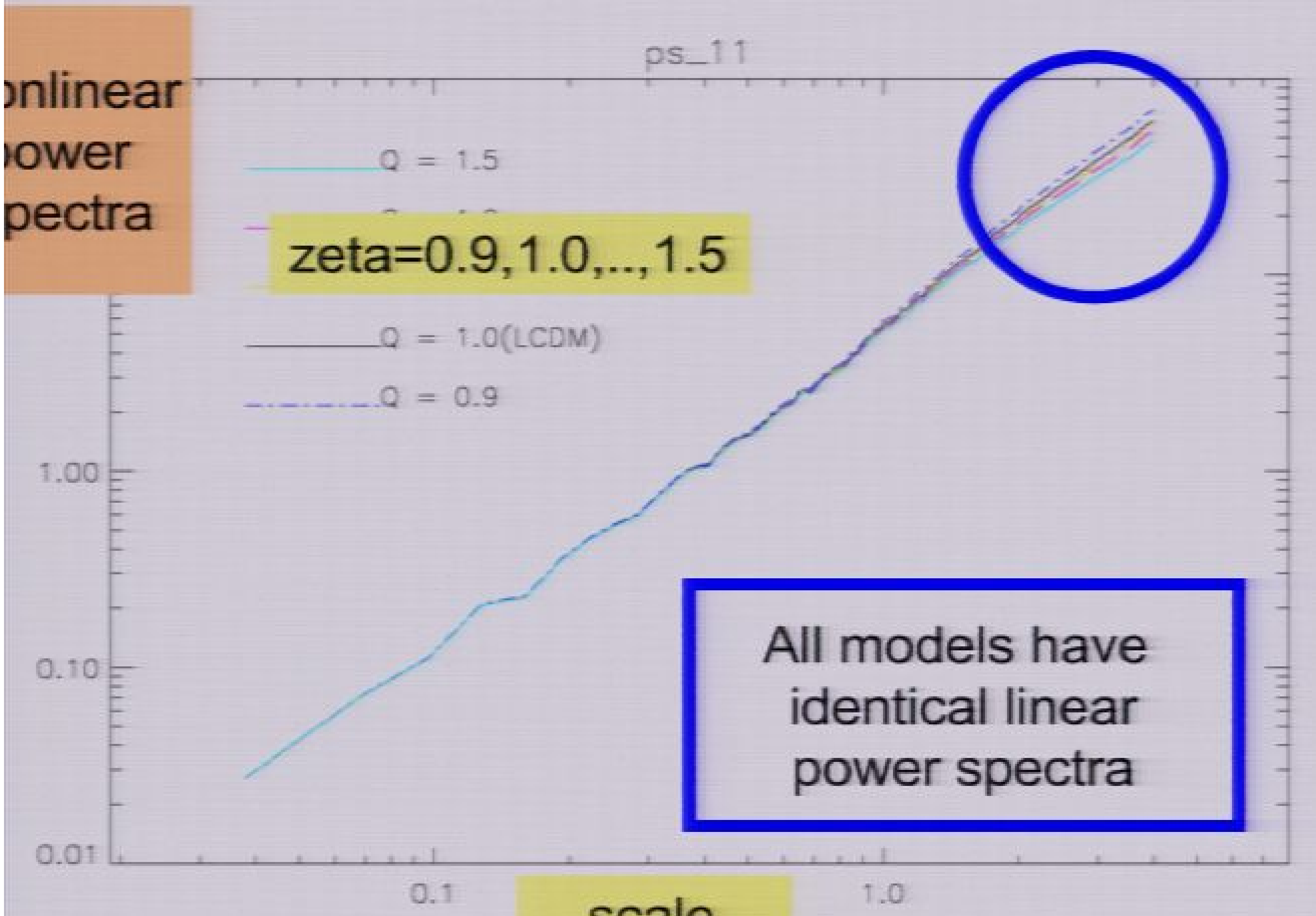

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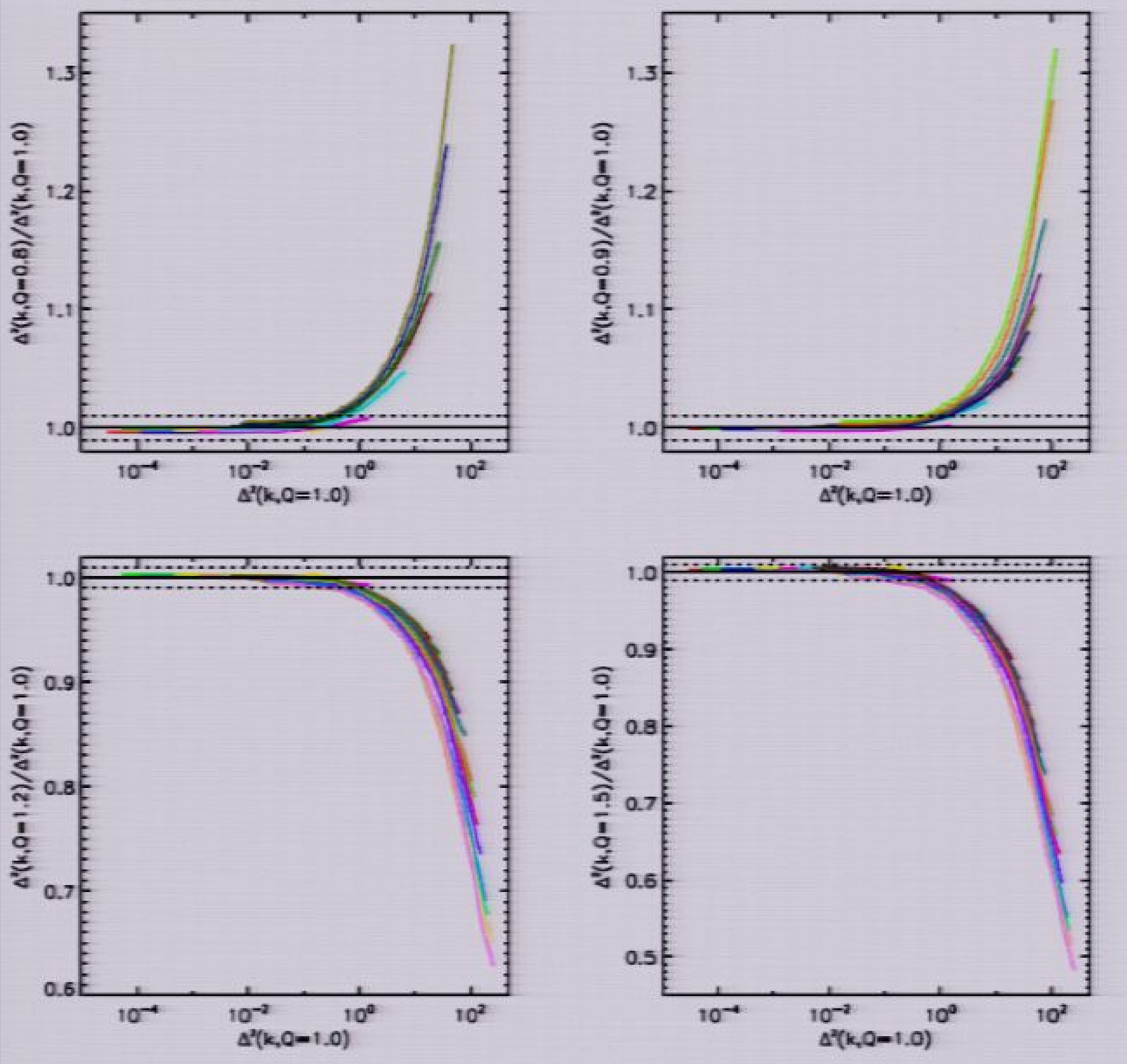

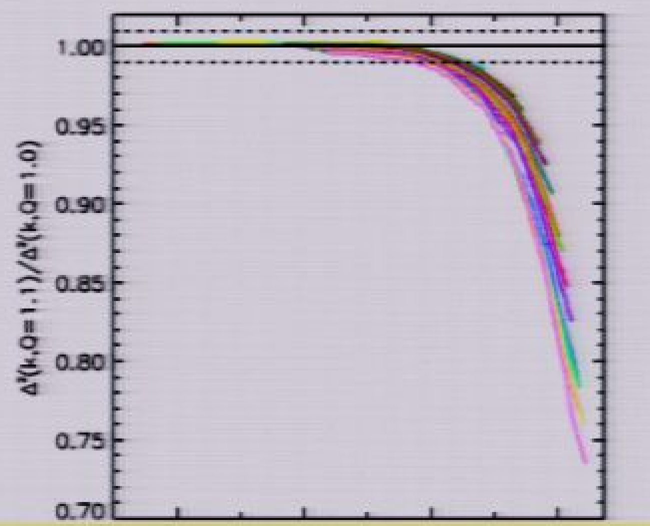

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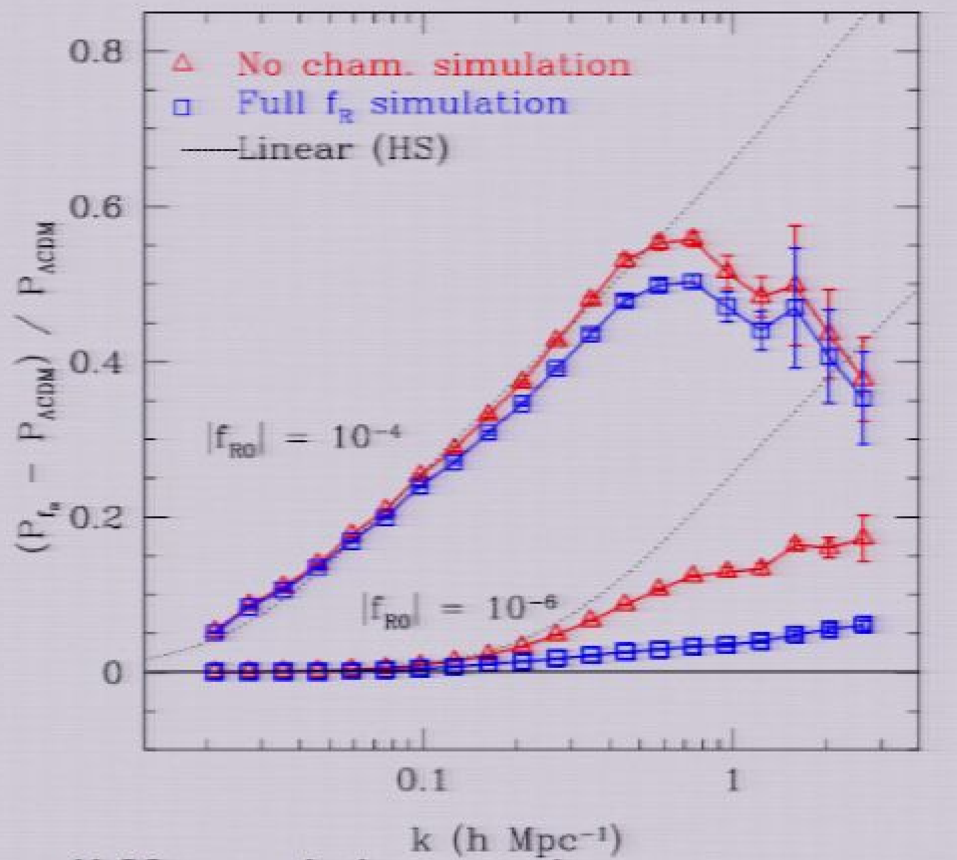

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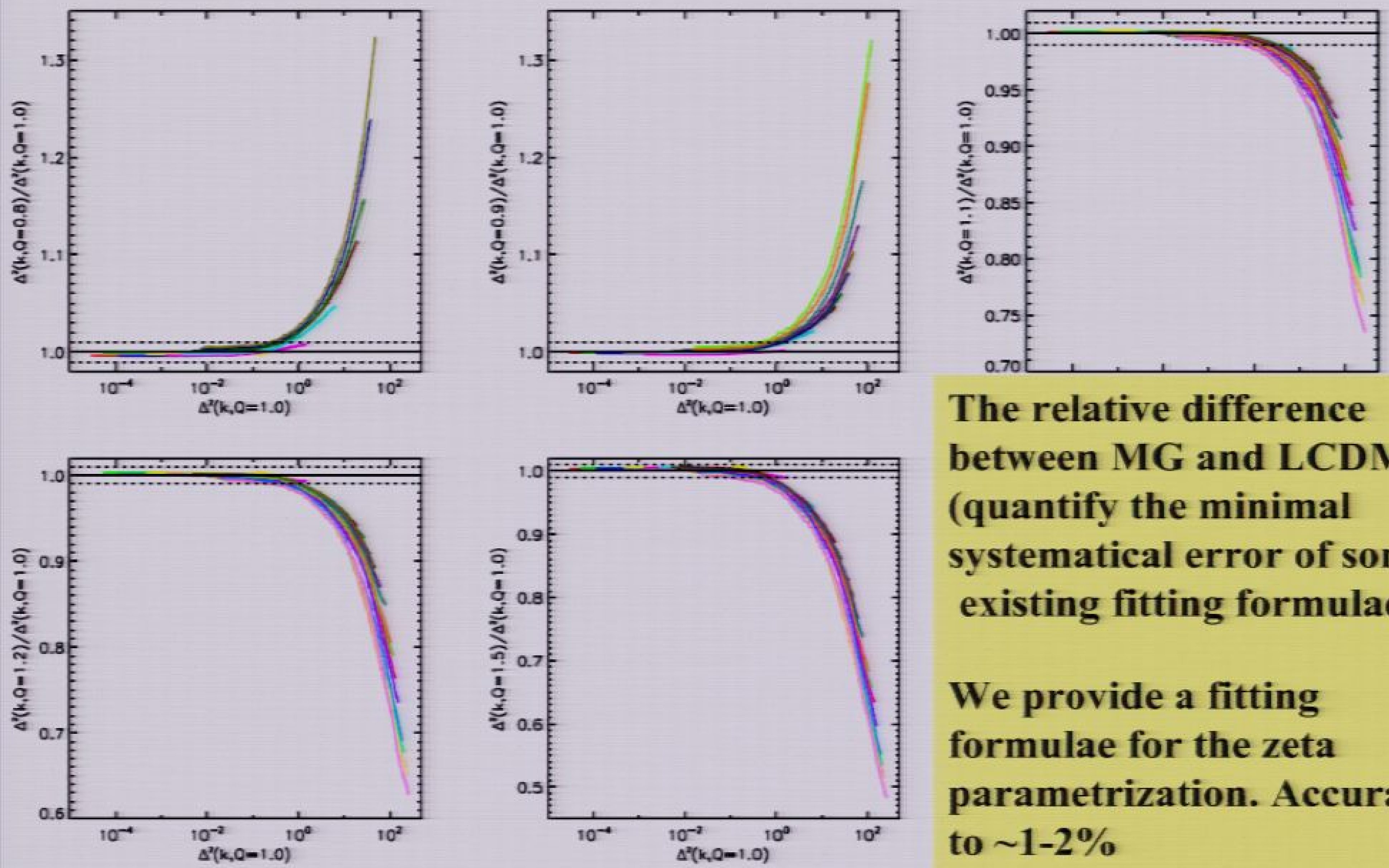

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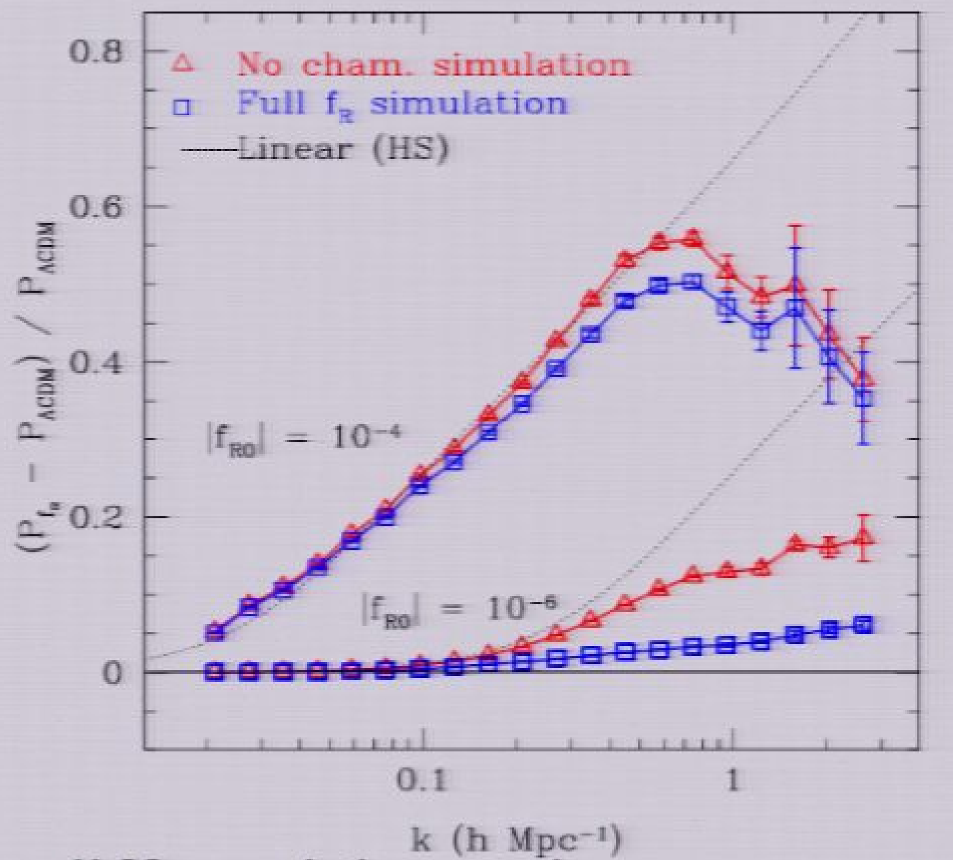

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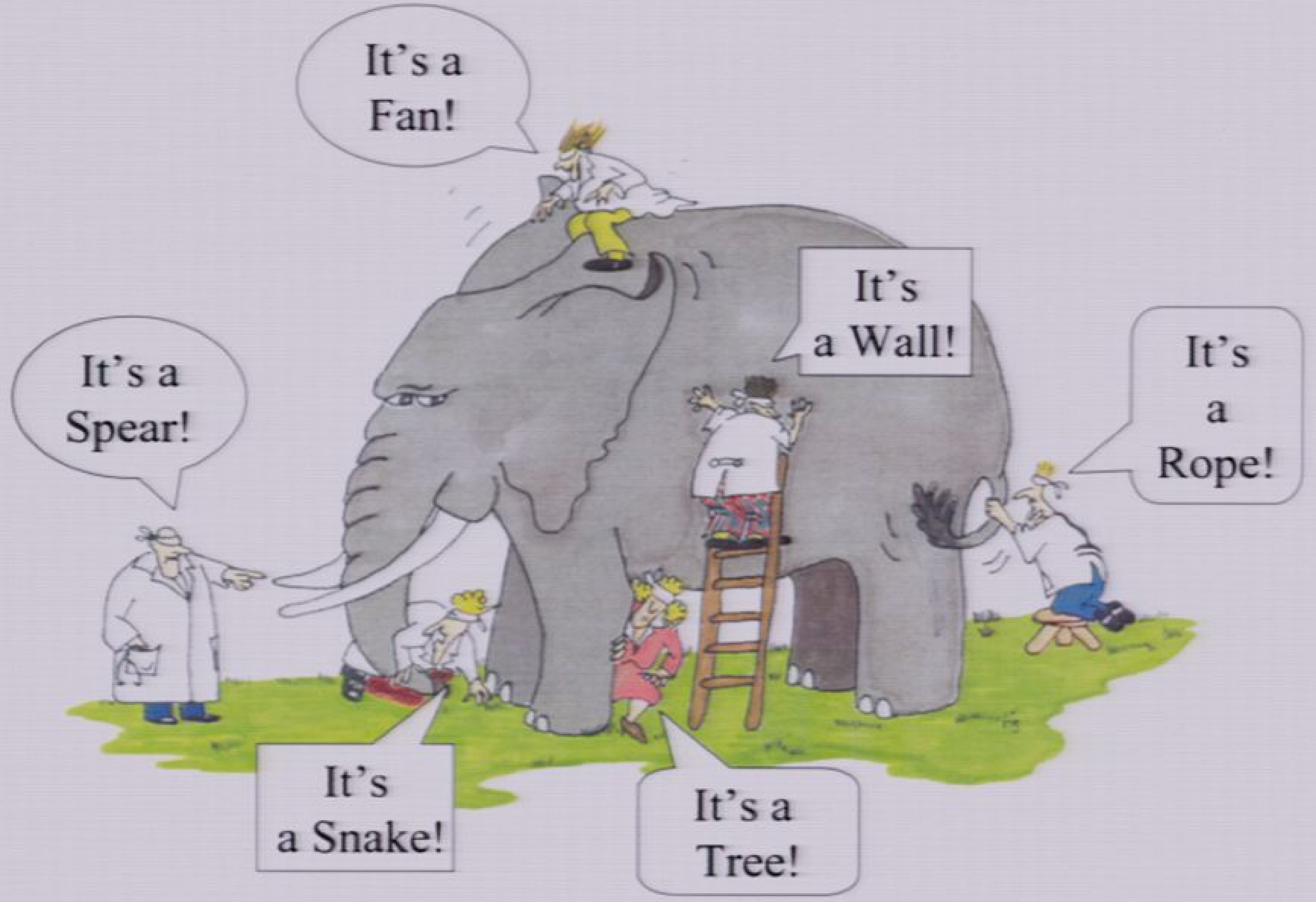
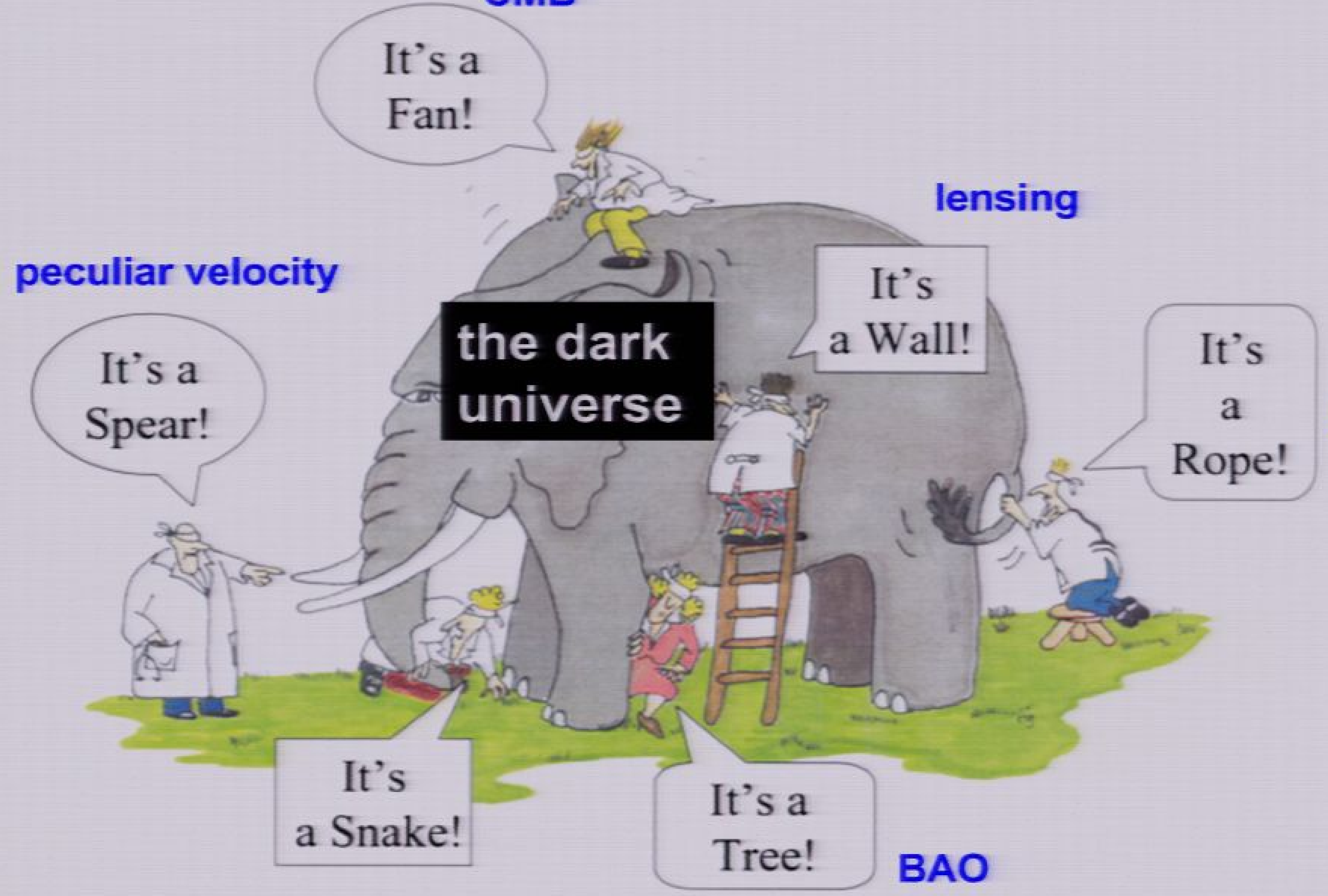

It's a Fan!
It's a Wall!
It's a Spear!
It's a Rope!
It's a Snake!
It's a Tree!

CMB



the dark universe

lensing

peculiar velocity

SNe Ia

BAO

cluster abundance

In O(20) years, hopefully we able to put everything together to reconstruct the elephant.

the dark universe

CMB

lensing

peculiar velocity

SNe Ia

BAO

cluster abundance