Theoretical Cosmology

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“Modern Physical Cosmology”

“오직 큰 규모의 구조만 고려한다면, 우리는 물질들이 거대한 공간에 걸쳐서 고르게 분포하고 있다고 표현할 수 있을 것이다,…”

“If we are concerned with the structure only on a large scale, we may represent matter to ourselves as being uniformly distributed over enormous spaces, …”

A. Einstein (1917)

Cosmological Principle

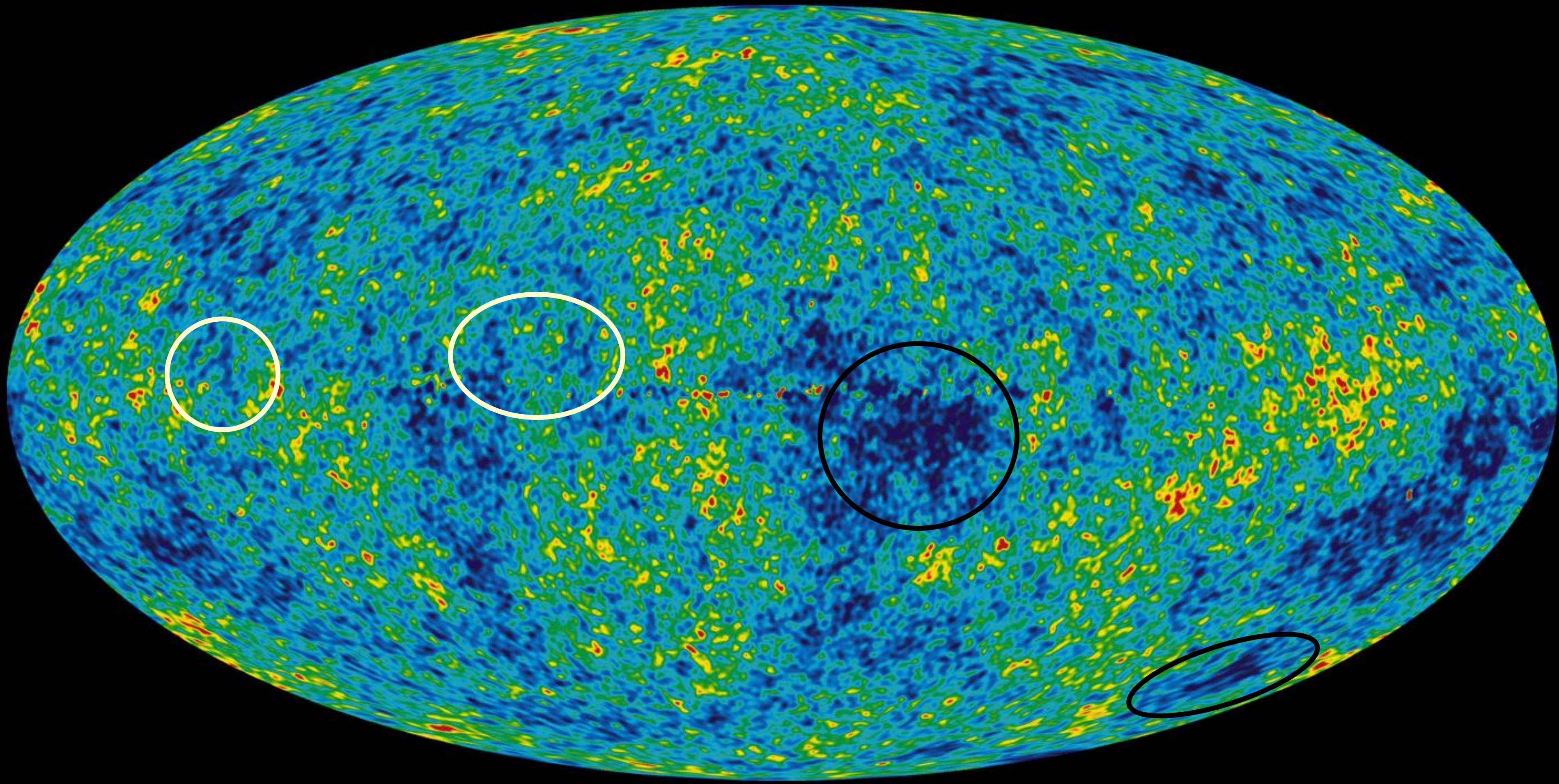
“우주론에서 원리란 증거에 의해 지지되지 않는 가정과 같은 뜻으로 종종 쓰이는데, 그것 없이는 분야가 진행 될 수 없다.”

“Principles in cosmology have often connoted assumptions unsupported by evidence, but without which the subject can make no progress.”

Martin Rees (2000)

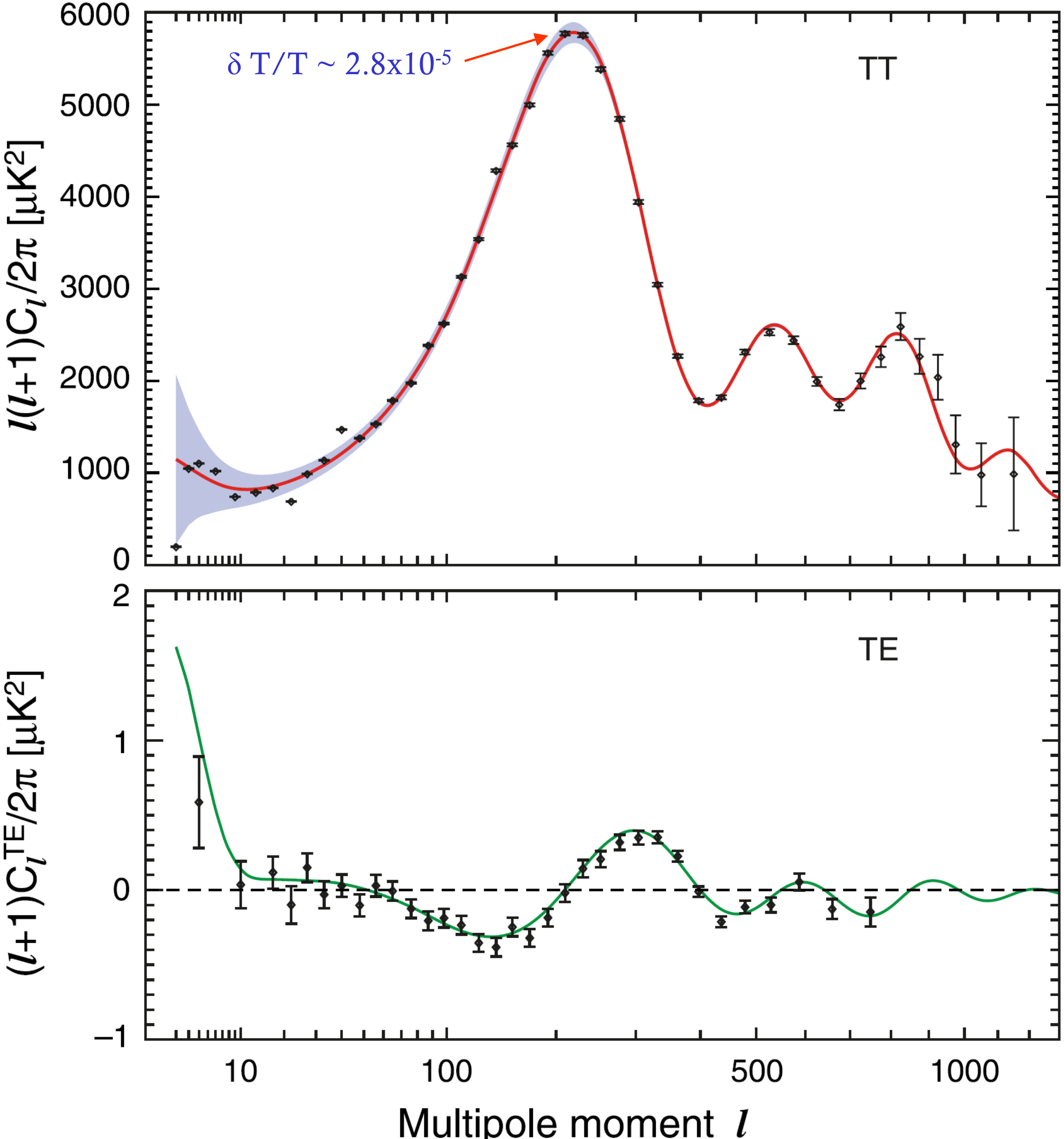
Observations

CMB: linear structure $\delta T/T \sim 0.001\%$



WMAP 5-year, http://map.gsfc.nasa.gov/m_or.html

WMAP 7-year



Jarosik et al, arXiv:1001.4744

WMAP 7-year

Table 8. *WMAP* Seven-year Cosmological Parameter Summary

Description	Symbol	*WMAP* -only	*WMAP* +BAO+H_0
Parameters for Standard ΛCDM Model [a]			
Age of universe	t_0	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr
Hubble constant	H_0	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
Baryon density	Ω_b	0.0449 ± 0.0028	0.0456 ± 0.0016
Physical baryon density	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02260 ± 0.00053
Dark matter density	Ω_c	0.222 ± 0.026	0.227 ± 0.014
Physical dark matter density	$\Omega_c h^2$	0.1109 ± 0.0056	0.1123 ± 0.0035
Dark energy density	Ω_Λ	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_\mathcal{R}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.801 ± 0.030	0.809 ± 0.024
Scalar spectral index	n_s	0.963 ± 0.014	0.963 ± 0.012
Redshift of matter-radiation equality	$z_{\rm eq}$	3196^{+134}_{-133}	3232 ± 87
Angular diameter distance to matter-radiation eq. [c]	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc	14238^{+128}_{-129} Mpc
Redshift of decoupling	z_*	$1090.79^{+0.94}_{-0.92}$	$1090.89^{+0.68}_{-0.69}$
Age at decoupling	t_*	379164^{+5187}_{-5243} yr	377730^{+3205}_{-3200} yr
Angular diameter distance to decoupling [c,d]	$d_A(z_*)$	14116^{+160}_{-163} Mpc	14073^{+129}_{-130} Mpc
Sound horizon at decoupling [d]	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc	146.2 ± 1.1 Mpc
Acoustic scale at decoupling [d]	$l_A(z_*)$	302.44 ± 0.80	302.40 ± 0.73
Reionization optical depth	τ	0.088 ± 0.015	0.087 ± 0.014
Redshift of reionization	$z_{\rm reion}$	10.5 ± 1.2	10.4 ± 1.2
Parameters for Extended Models [e]			
Total density [f]	$\Omega_{\rm tot}$	$1.080^{+0.093}_{-0.071}$	$1.0023^{+0.0056}_{-0.0054}$
Equation of state [g]	w	$-1.12^{+0.42}_{-0.43}$	-0.980 ± 0.053
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	< 0.36 (95% CL)	< 0.24 (95% CL)
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	-0.034 ± 0.026	-0.022 ± 0.020
Neutrino density [j]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0062 (95% CL)
Neutrino mass [j]	$\sum m_\nu$	< 1.3 eV (95% CL)	< 0.58 eV (95% CL)
Number of light neutrino families [k]	$N_{\rm eff}$	> 2.7 (95% CL)	$4.34^{+0.86}_{-0.88}$

precision cosmology

Golden age?

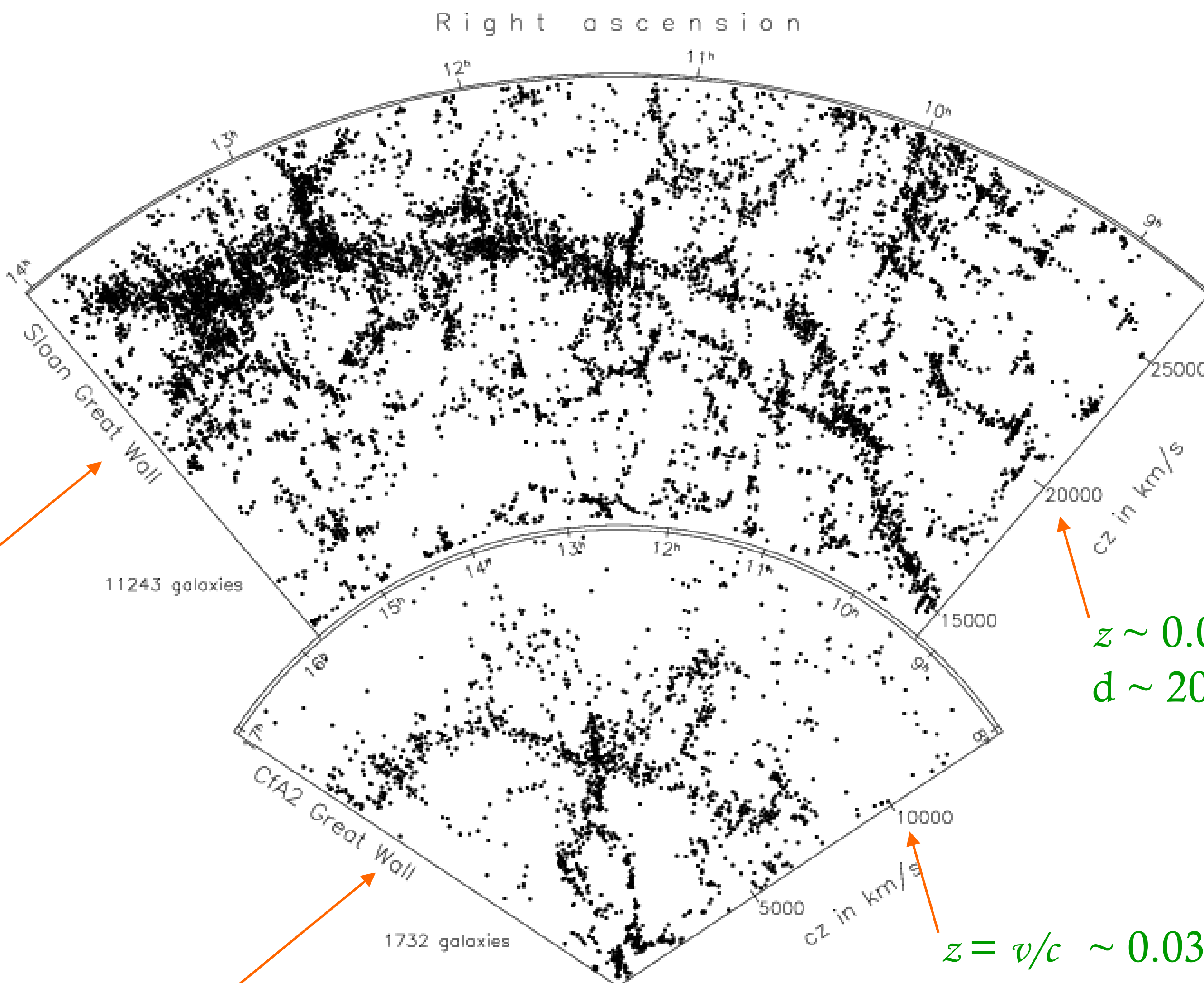
[a]The parameters reported in the first section assume the 6 parameter flat ΛCDM model, first using *WMAP* data only (Larson et al. 2010), then using *WMAP* +BAO+H_0 data (Komatsu et al. 2010). The H_0 data consists of a Gaussian prior on the present-day value of the Hubble constant, $H_0 = 74.2 \pm 3.6$ km s^{-1} Mpc^{-1}(Riess et al. 2009), while the BAO priors on the distance ratio $r_s(z_d)/D_V(z)$ at $z = 0.2,\ 0.3$ are obtained from the Sloan Digital Sky Survey Data Release 7 (Percival et al. 2009). Uncertainties are 68% CL unless otherwise noted.

[b]$k = 0.002$ Mpc^{-1} $\longleftrightarrow$ $l_{\rm eff} \approx 30$.

$\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, n_s, \Delta_R^2, \tau$

Jarosik et al, arXiv:1001.4744

LSS: non-linear structure



SDSS

$z \sim 0.06$

d ~ 200h^{-1}Mpc

$z = v/c \sim 0.03$

d = v/H ~ 100h^{-1}Mpc

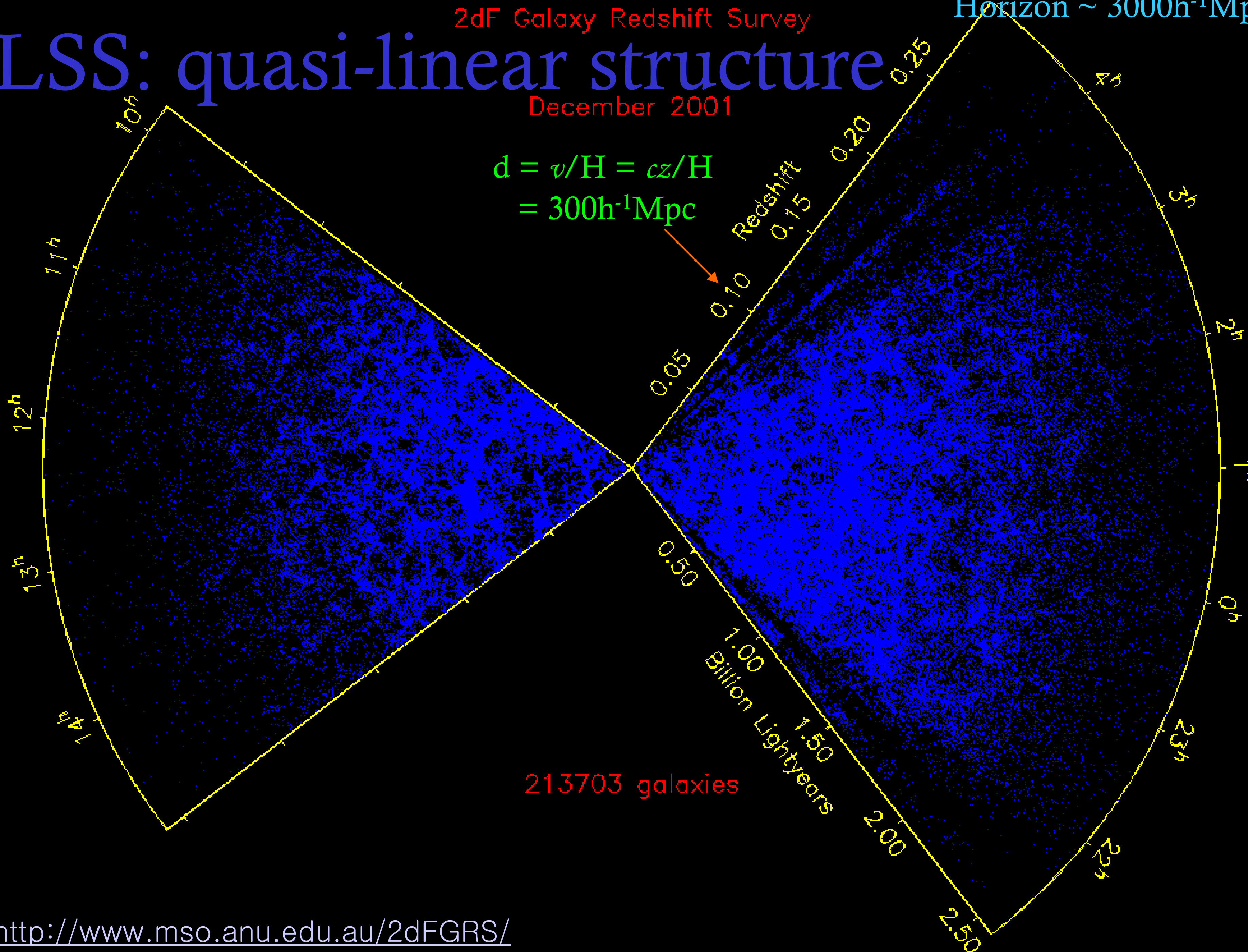
de Lapparent *etal.* (1986)

http://www.sdss.org/

Horizon ~ $3000h^{-1}$Mpc

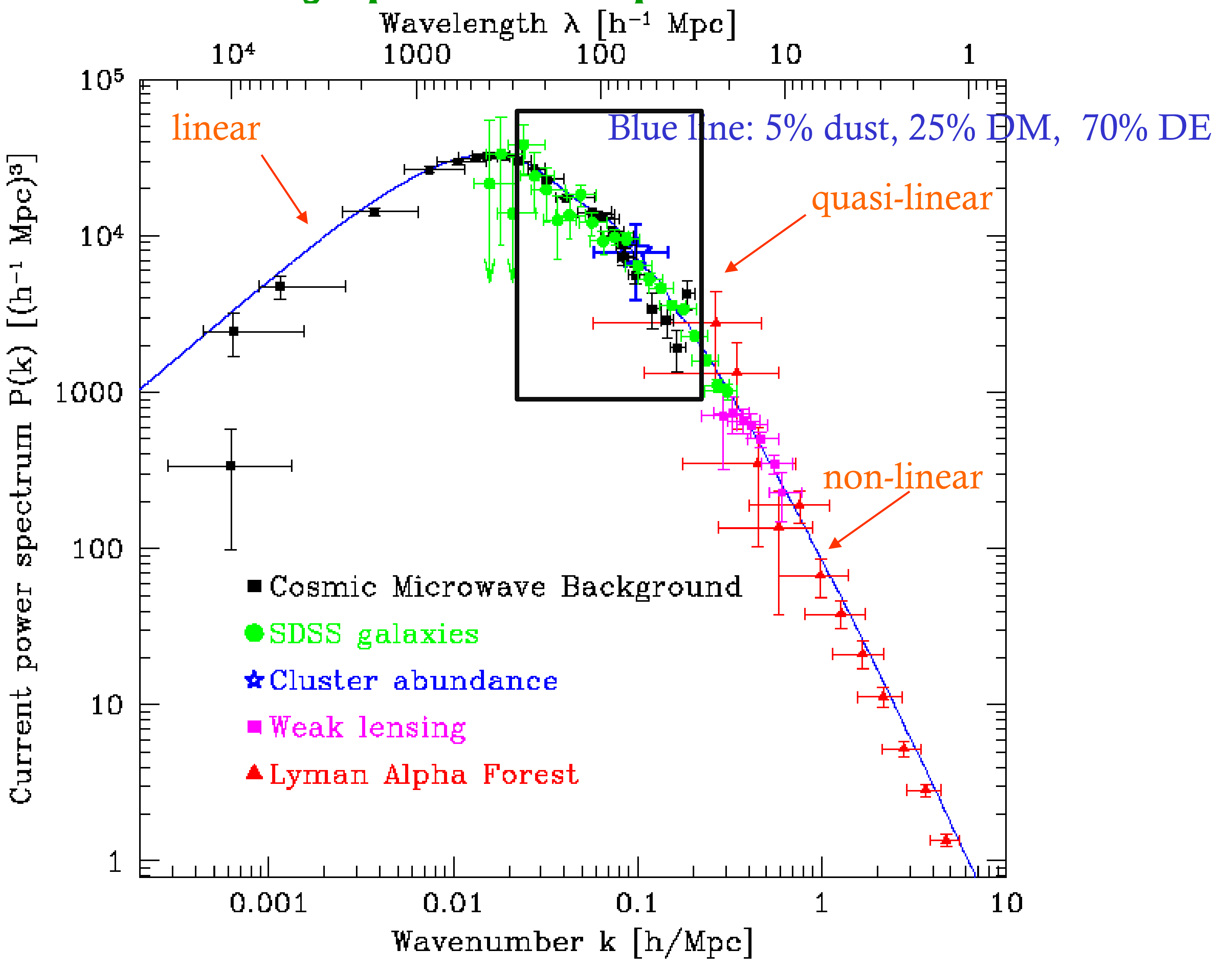
LSS: quasi-linear structure

$$d = v/H = cz/H$$
$$= 300h^{-1}\mathrm{Mpc}$$



http://www.mso.anu.edu.au/2dFGRS/

Density power spectrum



Tegmark, M., et al, http://xxx.lanl.gov/pdf/astro-ph/0207047

SDSS DR7 LRG

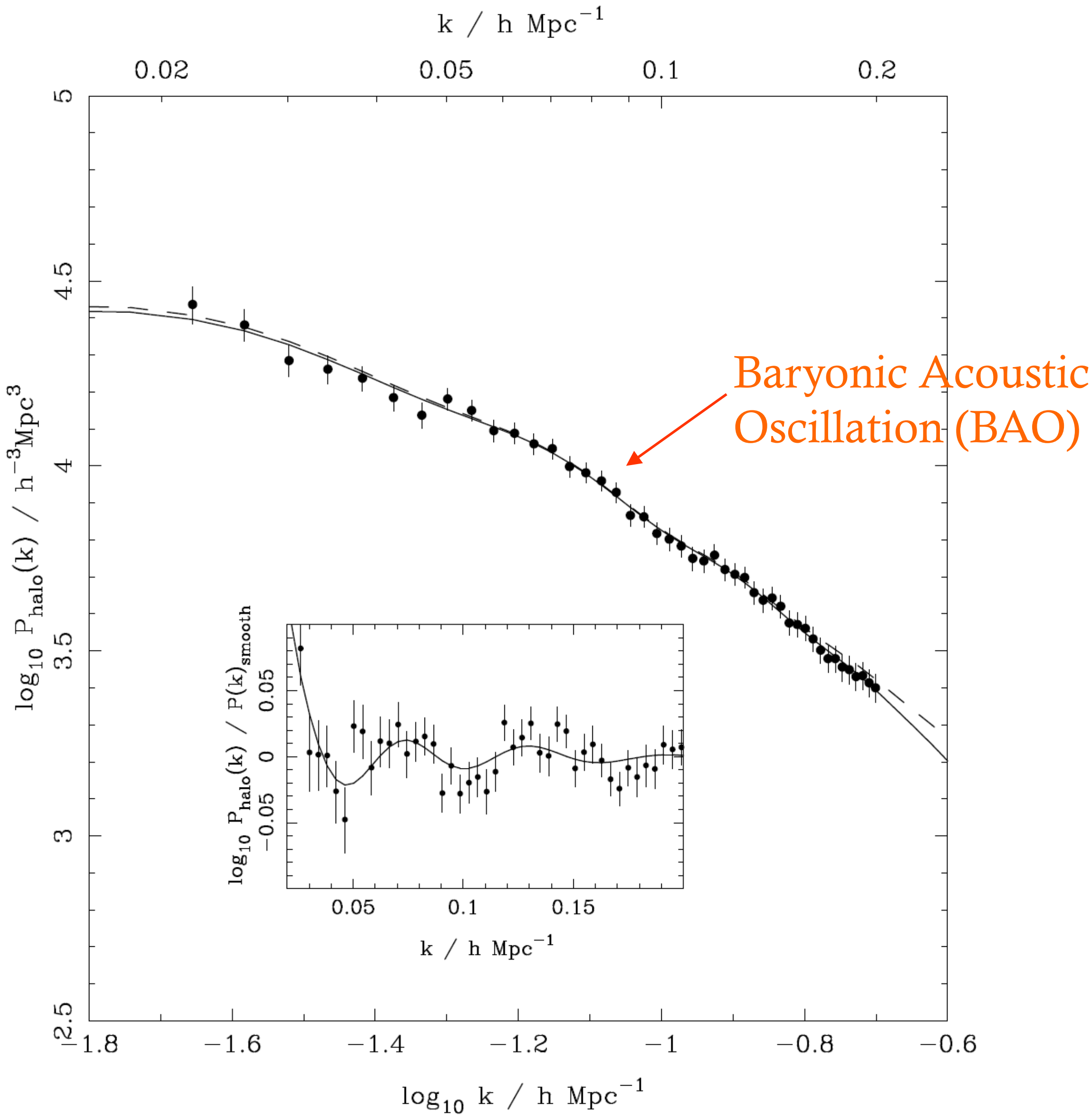


Figure 8. Points with errors show our measurement of $\hat{P}_{halo}(k)$. We show $\sqrt{C_{ii}}$ as error bars; recall that the points are positively correlated. We plot the best-fitting WMAP5+LRG ΛCDM model $(\Omega_m, \Omega_b, \Omega_\Lambda, n_s, \sigma_8, h)$ = (0.291, 0.0474, 0.709, 0.960, 0.820, 0.690) with best-fitting nuisance parameters $a_1 = 0.172$ and $a_2 = -0.198$ (solid curve), for which $\chi^2 = 40.0$; the dashed line shows the same model but with $a_1 = a_2 = 0$, for which $\chi^2 = 43.3$. The BAO inset shows the same data and model divided by a spline fit to the smooth component, P_{smooth}, as in Fig. 4 of P09. In Section 5.1 we find the significance of the BAO detection in the $\hat{P}_{halo}(k)$ measurement is $\Delta\chi^2 = 8.9$.

Reid et al, arXiv:0907.1659v2

Observations

- CMB: spectrum, temperature and polarization anisotropies, non-Gaussianity
- Large-scale structures: density and velocity power spectra, baryon acoustic oscillation (BAO), X-ray, IR
- Expansion rate: Hubble constant, isotropic?
- Acceleration: SNIa
- Ages
- Light elements abundances
- Weak lensing
- Perturbation growth rate

The field is currently observation (technology) driven.

Theory

Theoretical World Models

Four ingredients (assumptions):

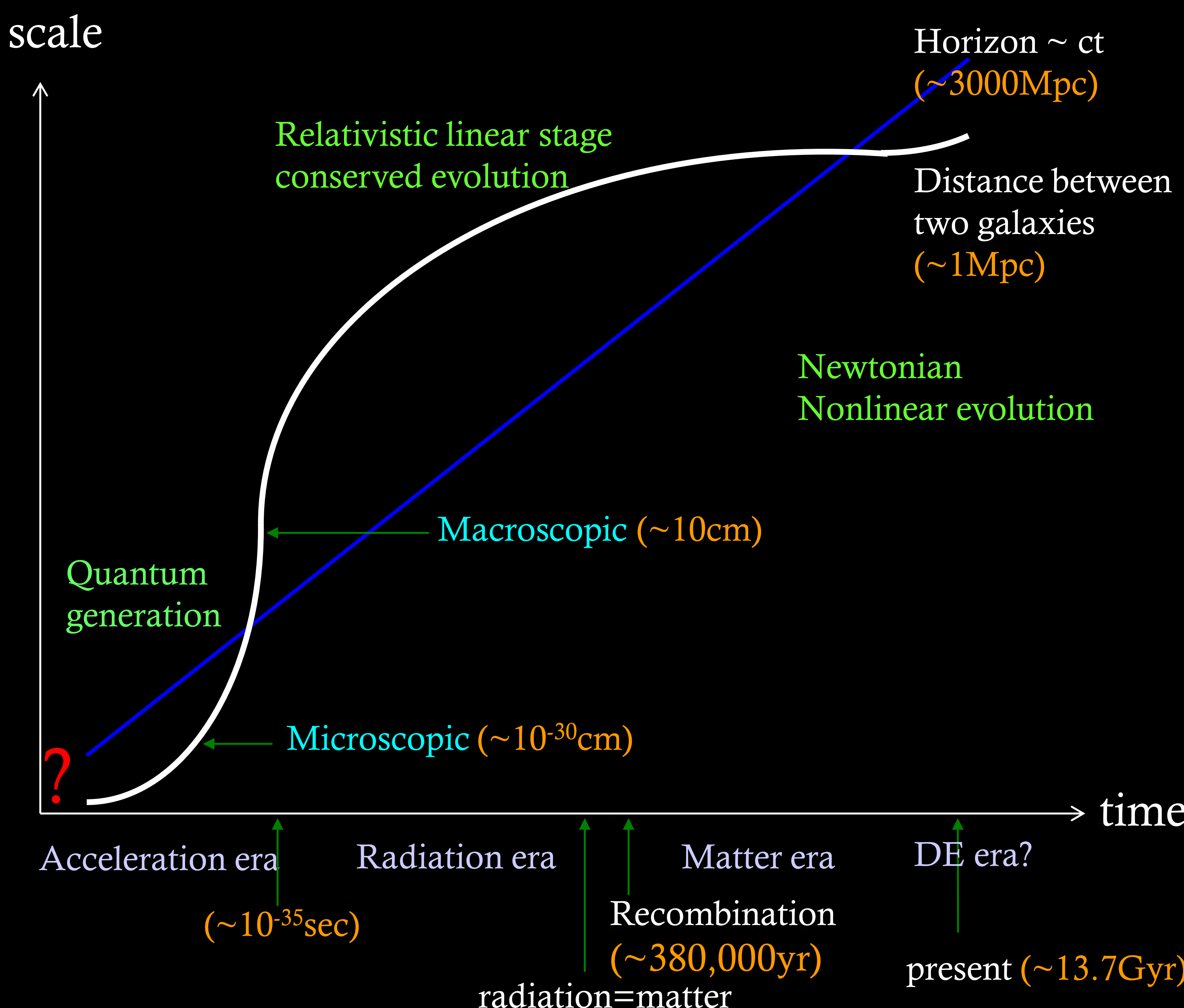
❖ Gravity: Einstein gravity or generalized gravity

❖ Spatial geometry: homogeneous and isotropic, or more complicated geometries.

❖ Matter contents: dust, radiation, fields, and others.

❖ Topology (global geometry): small universe? undetermined in the gravity level.

Scenario



scale
Horizon ~ ct
(~3000Mpc)
Relativistic linear stage
conserved evolution
Distance between
two galaxies
(~1Mpc)
Newtonian
Nonlinear evolution
Macroscopic (~10cm)
Quantum
generation
?
Microscopic (~10^{-30}cm)
time
Acceleration era
Radiation era
Matter era
DE era?
(~10^{-35}sec)
Recombination
(~380,000yr)
present (~13.7Gyr)
radiation=matter

Origin and evolution of LSS

- Quantum origin
  - Space-time quantum fluctuations from uncertainty pr.
  - Become macroscopic due to inflation.
- Linear evolution (Relativistic)
  - Linear evolution of the macroscopic seeds.
  - Structures are described by conserved amplitudes.
- Nonlinear evolution (Newtonian)
  - Nonlinear evolution inside the horizon.
  - Newtonian numerical computer simulation.

Consensus Model

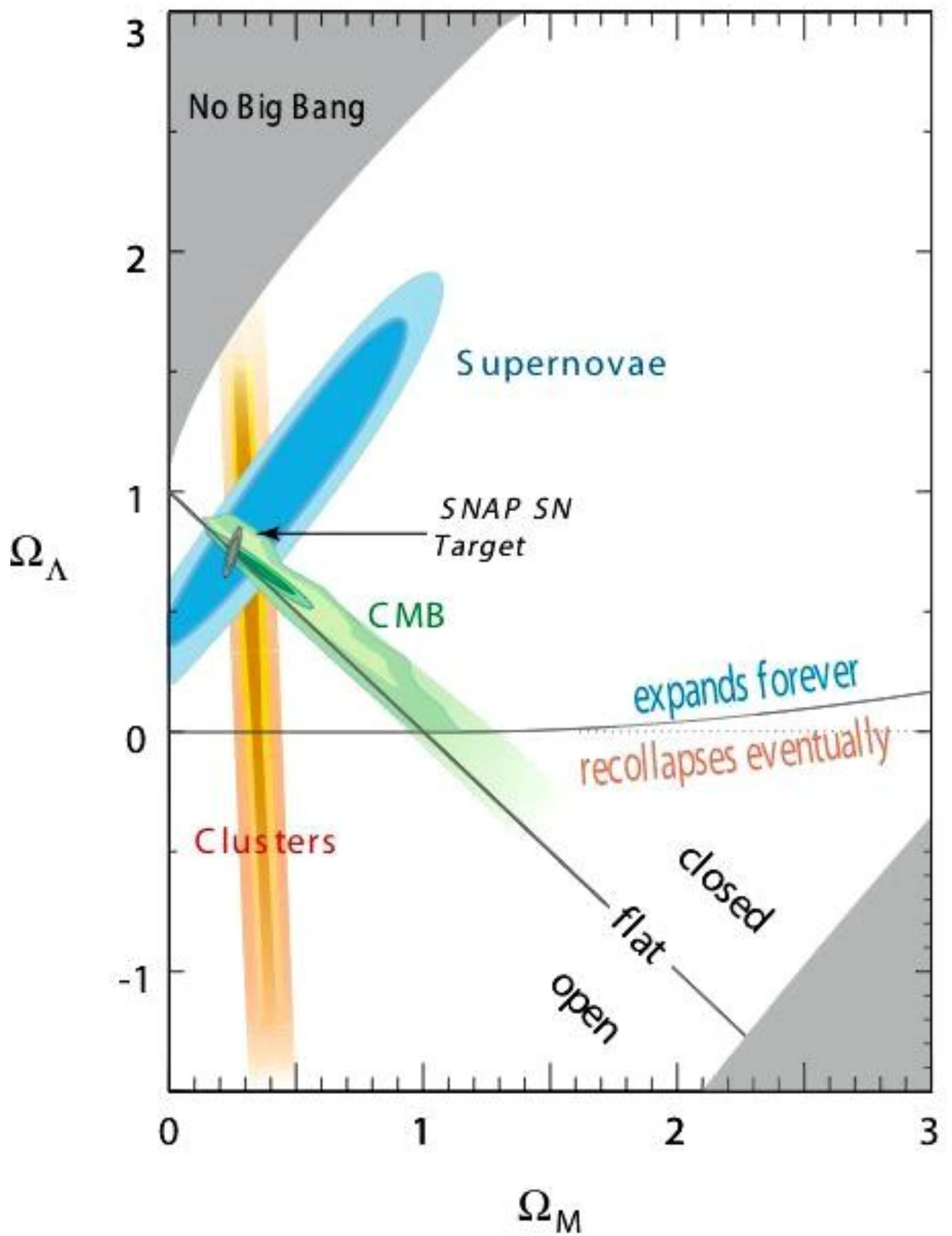
Observable Universe

- **Baryons:** Radiation emitted and absorbed
  Major part of observational cosmology/astronomy
- **Dark matter (DM):** No radiation emitted or absorbed. Indirectly observed: major part of what is
- **Dark energy (DE):** No radiation emitted and absorbed. Existence inferred: dominant energy form

- **Concordance (consensus) model:**
  Baryon(4%), DM(23%), DE(73%)
  Based on Robertson-Walker geometry, general relativity with cosmological constant, and inflation generated seed fluctuations.
- **ΛCDM scenario:** (inflation) + CDM + Λ

G.F.R. Ellis "Unity of the Universe" meeting, Portsmouth (2009)

Concordance model



http://snap.lbl.gov/

Issues

- Dark Matter: nature? exotic matter? new gravity theory? Experimental lab search,
- Dark Energy: nature? cosmological constant? other equation of state? scalar field? modified gravity? vacuum state? string theory? other dimensions?
- Origin of structures: quantum fluctuations?
- Evolution of large-scale structures (LSS)
- Parameter search: precision cosmology, Bayesian era, MCMC
- Observations as probes of the early universe
- LSS and Galaxy formation: nonlinear-non-equilibrium nature?

Under a certain cosmological paradigm!

Dark Energy

- Redshift-distance measurement of SNIa
- Indicated by observations, not predicted.
- Consistent with cosmological constant.
- Theoretical disaster:

  observation/theory $\sim 10^{-121}$
- Experimental search not feasible.
- Burst of exotic alternative field and gravity.
- Serious alternative: change geometry!

  challenging, though

“그것의 본질은 (상수이건, 변수이건) 이론물리학에서 가장 중요한 문제 중 하나이다.”

“암흑에너지가 있다는 추정은 우주가 큰 규모에서 공간이 균일하고 등방한 로버트슨-워커 기하학으로 기술된다는 가정에 달려있다.”

“Its nature (whether constant, or varying) is a major problem for theoretical physics”

“The deduction of the existence of dark energy is based on the assumption that the universe has a Robertson-Walker geometry - spatially homogeneous and isotropic on a large scale. ”

G.F.R. Ellis (2009)

Test the foundations

We need to test the foundations of standard cosmology in all possible ways –
Don’t just take them for granted!

- Expansion
- CMB temperature at high z
- Ages of objects at high z
- Helium and metal abundances with z
- Homogeneity
- Isotropy

Early Universe

Early Universe

- Singularity?
- Inflation: origin of cosmic structures and gravitational waves.
- Baryogenesis: baryon asymmetry $\eta \equiv n_b / n_\gamma \sim 10^{-9}$
- Nucleoynthesis: H, D, He^3, He^4, Li^7
- Cosmic neutrinos: $n_\nu \sim n_\gamma$ detection?
- Recombination
- First star?
- Reionization
- Metal enrichment?

Inflation Scenario

- Early acceleration phase.
- Origin of seed inhomogeneities from quantum fluctuations: Naturally gives nearly Harrison-Zel'dovich spectrum: $n_s \sim 1$. Currently, the only viable scenario.
- Density and gravitational waves: n_s, Δ_R^2, $r \equiv T/S$
- Demand flat background.
- Too many viable models proposed.
- GWs and Non-Gaussianity detections in CMB are crucial for test.
- Not a single scalar field has yet been physically detected!

Inflation

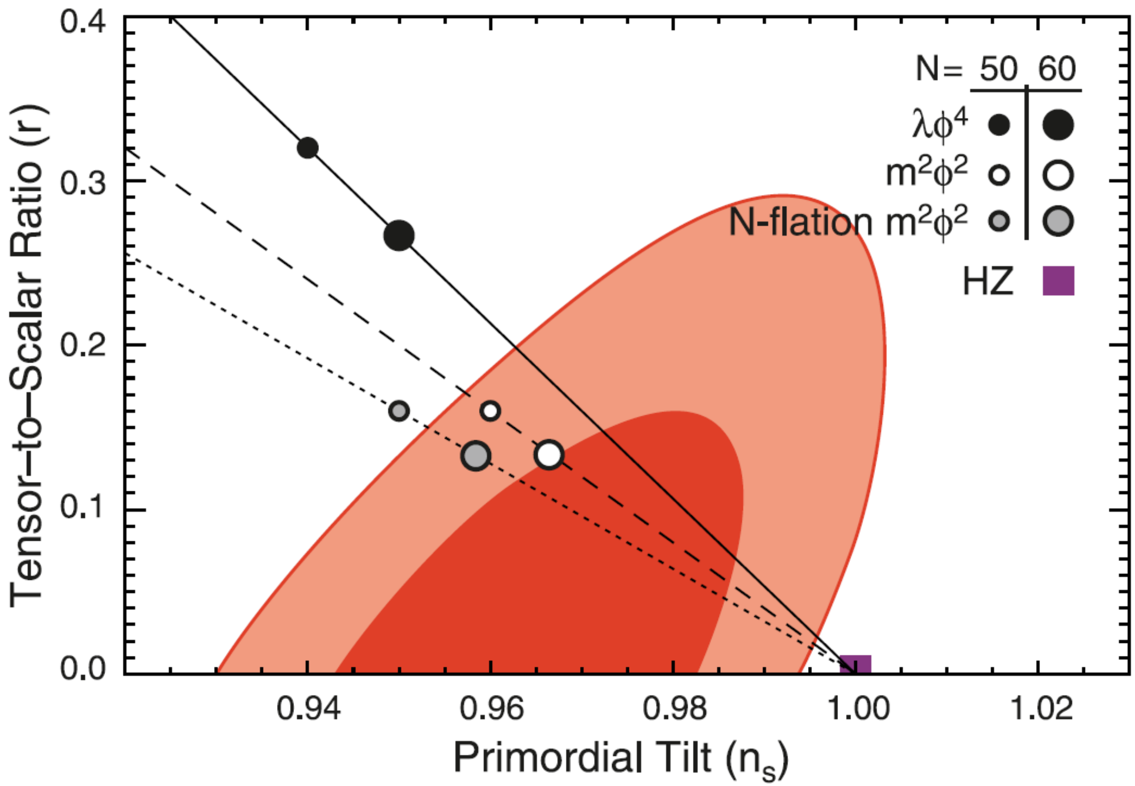


FIG. 19.— Two-dimensional joint marginalized constraint (68% and 95% CL) on the primordial tilt, n_s, and the tensor-to-scalar ratio, r, derived from the data combination of *WMAP*+BAO+H_0. The symbols show the predictions from "chaotic" inflation models whose potential is given by $V(\phi) \propto \phi^\alpha$ (Linde 1983), with $\alpha = 4$ (solid) and $\alpha = 2$ (dashed) for single-field models, and $\alpha = 2$ for multi-axion field models with $\beta = 1/2$ (dotted; Easther & McAllister 2006).

Komatsu et al, arXiv:1001.4538

Metaphysical Cosmology

Cosmological Metaphysics

Ironic (speculative, untestable) cosmology:

- **Before inflation:** creation out of nothing, no boundary proposal, cyclic, …
- **Outside the horizon:** cosmological principle, multiverse, chaotic inflation, eternal inflation, many worlds, megaverse, string landscape, …
- **Other dimensions:** string theory, M-theory, braneworld, Kaluza-Klein, parallel universes, …
- **Far future:** big crunch, big chill, big rip, cyclic, …

Without observationally testable consequences

"… 관측으로 확인되지 않은 생각을 굳게 믿는 것, …
이러한 확인이 없다면 우리는 과학을 형이상학과 구별할 유일한 방법을 잃는다."

"… danger of strongly believing in ideas not confirmed by observation, … without this confirmation we lose the only way we can distinguish science from metaphysics."

"어떤 모델에서 나온 현상이 실험이나 관측에 의한 검증이 아닌 주장에 의해서만 확인된다면, 단지 개인적 선택에만 기초한 것이므로 과학적이지 않다. 다시 말하면, 그런 식으로 얻은 확신이라면 도그마 [의심 없이 받아들여야만 하는 믿음]에 불과하다."

"When a feature of a model is ascertained through imposition rather than by experimental or observational check it is unscientific because it is *only* based on personal choices. In other words, a certainty achieved that way becomes a dogma."

M. R. Ribeiro, etal (1998)

"우주론자들은 실수는 자주하면서도 의심할 줄 모른다."

"Cosmologists are often in error, but never in doubt."

L. D. Landau (1908-1968)

Status of Untestable models

Multiverse claims:

Unobservable universe domains,
Untested claimed physics (hypothetical)
What tests are possible of the claims?
No observational data whatever are available!
Theory takes precedence over observations
Reasonable philosophical proposal.
Not provable science.
Scientifically irresponsible!

Which is more important in cosmology:

theory (explanation) or
observations (tests against reality) ?

G.F.R. Ellis “Unity of the Universe” meeting Portsmouth (2009)

“우리의 [우주]모형이 [호라이즌] 보다 더 큰 규모에서 우주의 상황에 대하여 예측하는 경우, 그것이 아무리 그럴듯해도 전적으로 검증이 불가능하다”

“When our models give predictions of the nature of the Universe on a larger scale than the Hubble radius, these are strictly unverifiable, however appealing they may be.”

G. F. R. Ellis (1993)

“[호라이즌 너머에 대한 논의는] 우리가 영향을 주거나 실험할 수 없는 지역에 대한 것이므로, 우리의 이론은 전적으로 우리가 하는 가정에 맡겨져 있다.”

“Because we wish to talk about regions we cannot directly influence or experiment on, our theory is at the mercy of the assumptions we make.”

G. F. R. Ellis (1975)

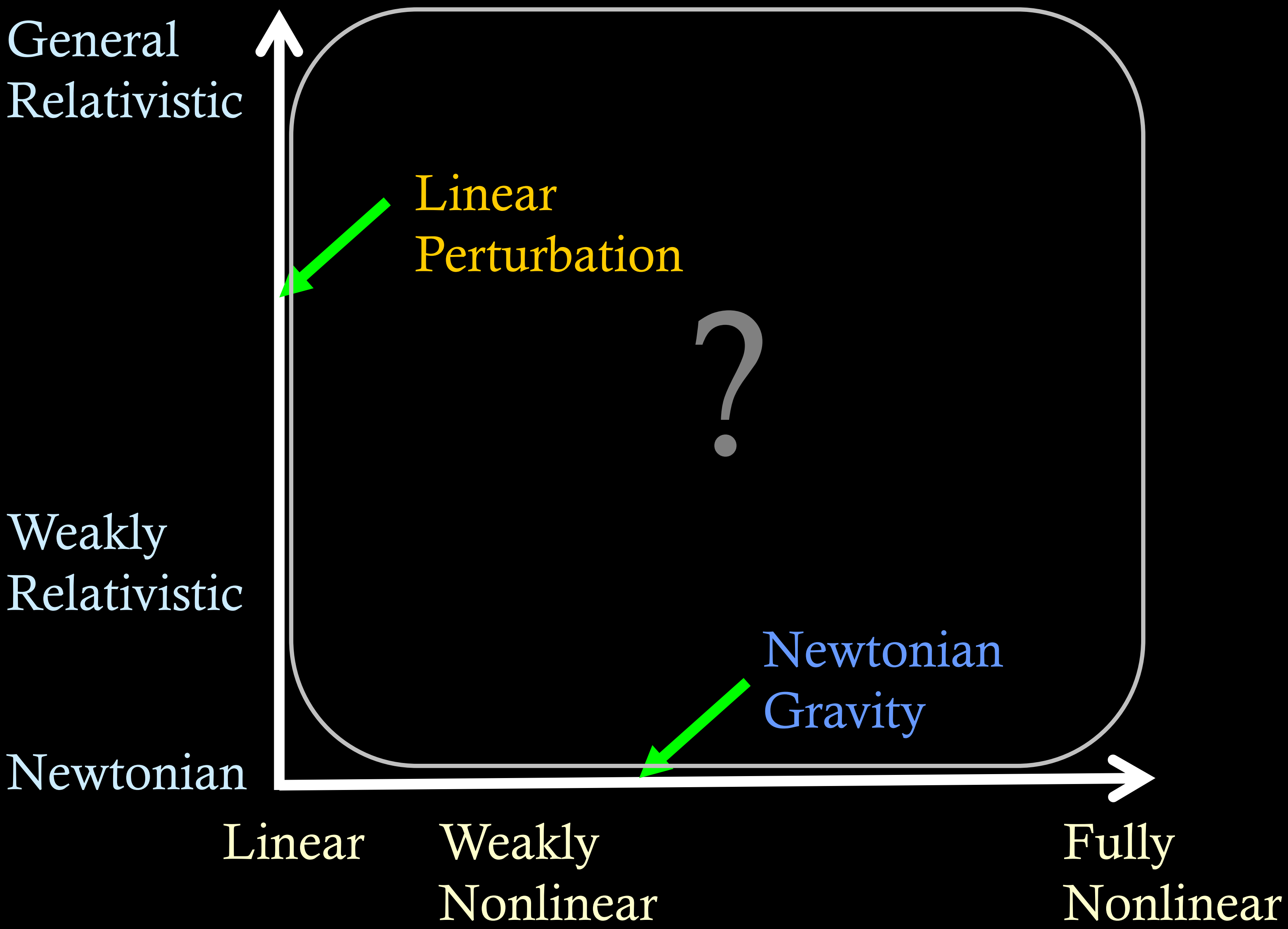
“천상에 대한 논의가 매혹적이고 중요한 것은 그에 대한 우리의 지식이 불완전하다는 것으로 유지된다.”

“The charm and importance of a study of the heavens was matched only by the uncertainty of the knowledge produced.”

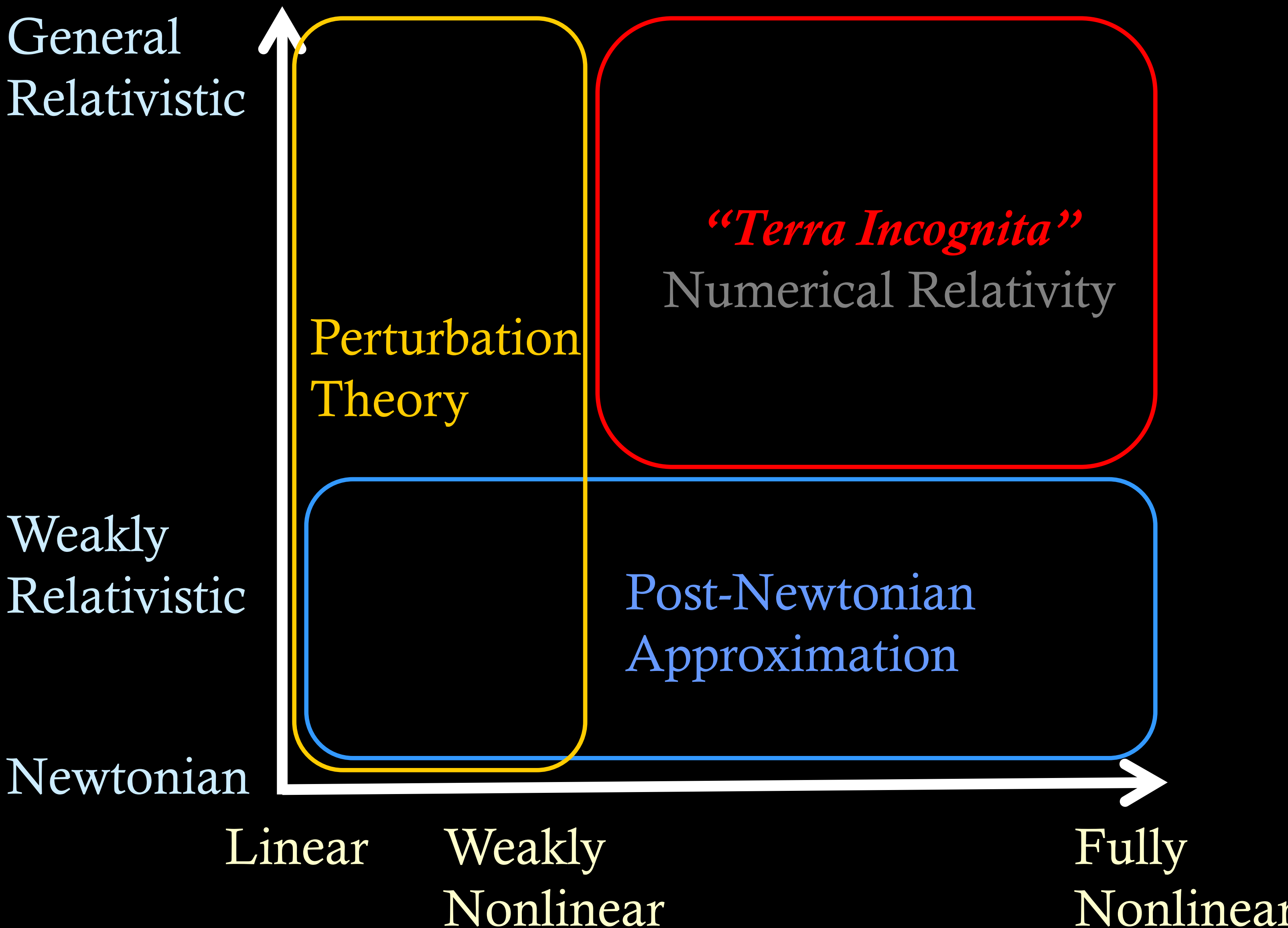
Aristotle (384-322 B.C.)

Nonlinear stages

Studies of Large-scale Structure



Perturbation Theory *vs.* Post-Newtonian



Cosmology and Large-Scale Structure