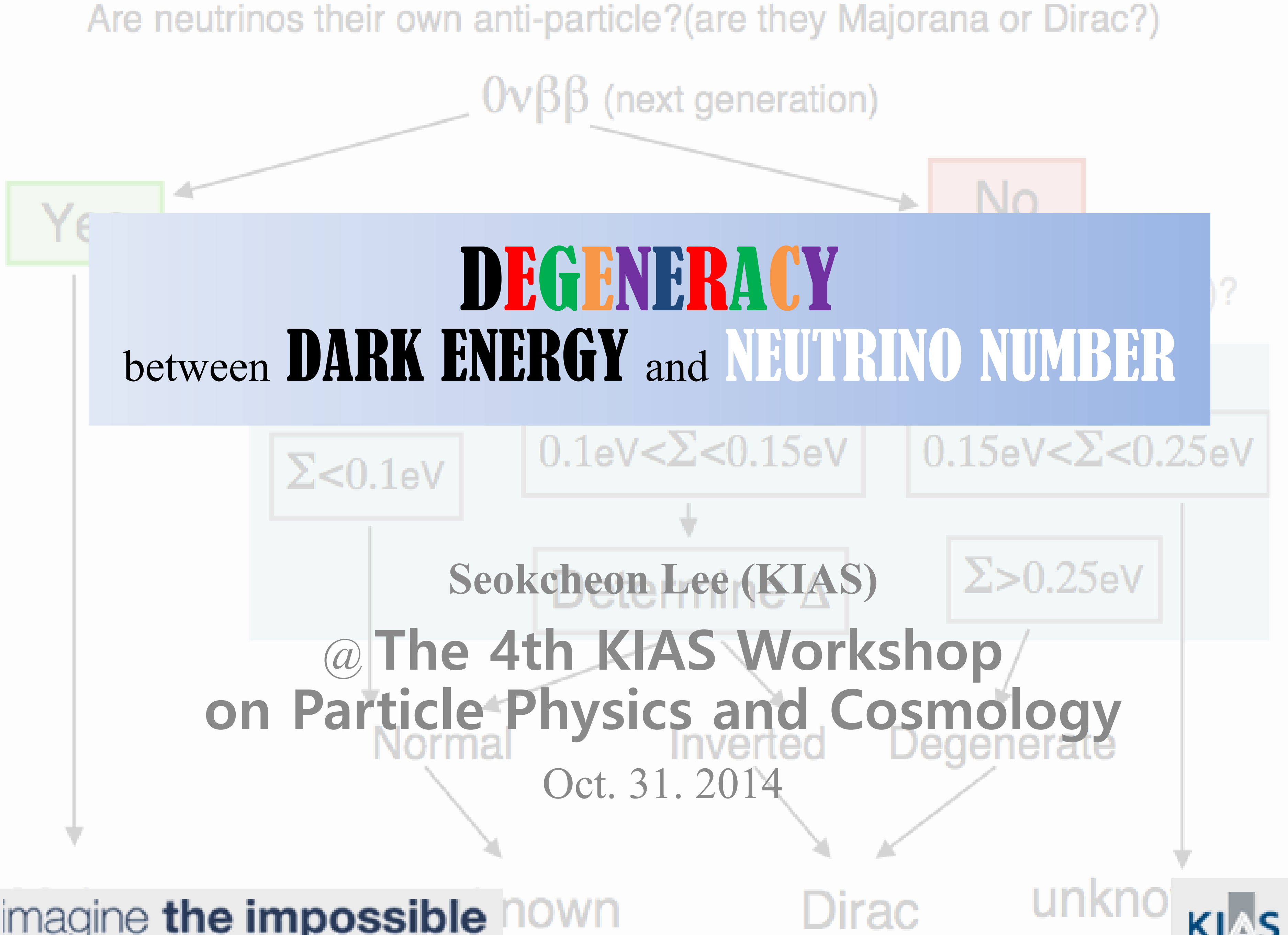


DEGENERACY

between DARK ENERGY and NEUTRINO NUMBER

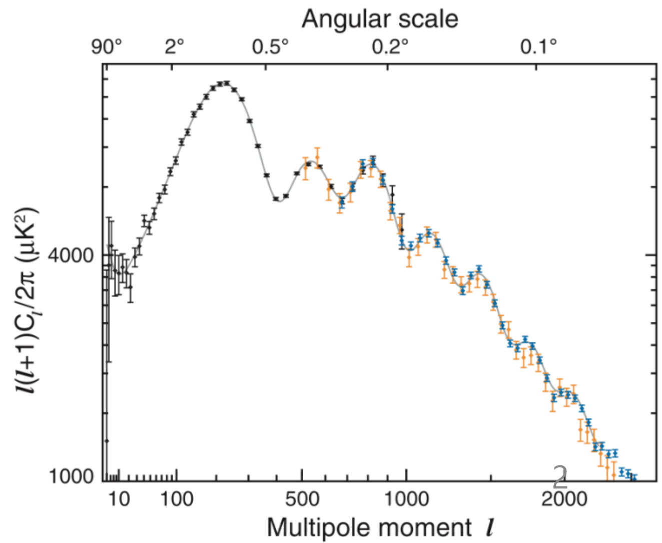
Seokcheon Lee (KIAS)

@ The 4th KIAS Workshop on Particle Physics and Cosmology

Oct. 31. 2014

OUTLINE

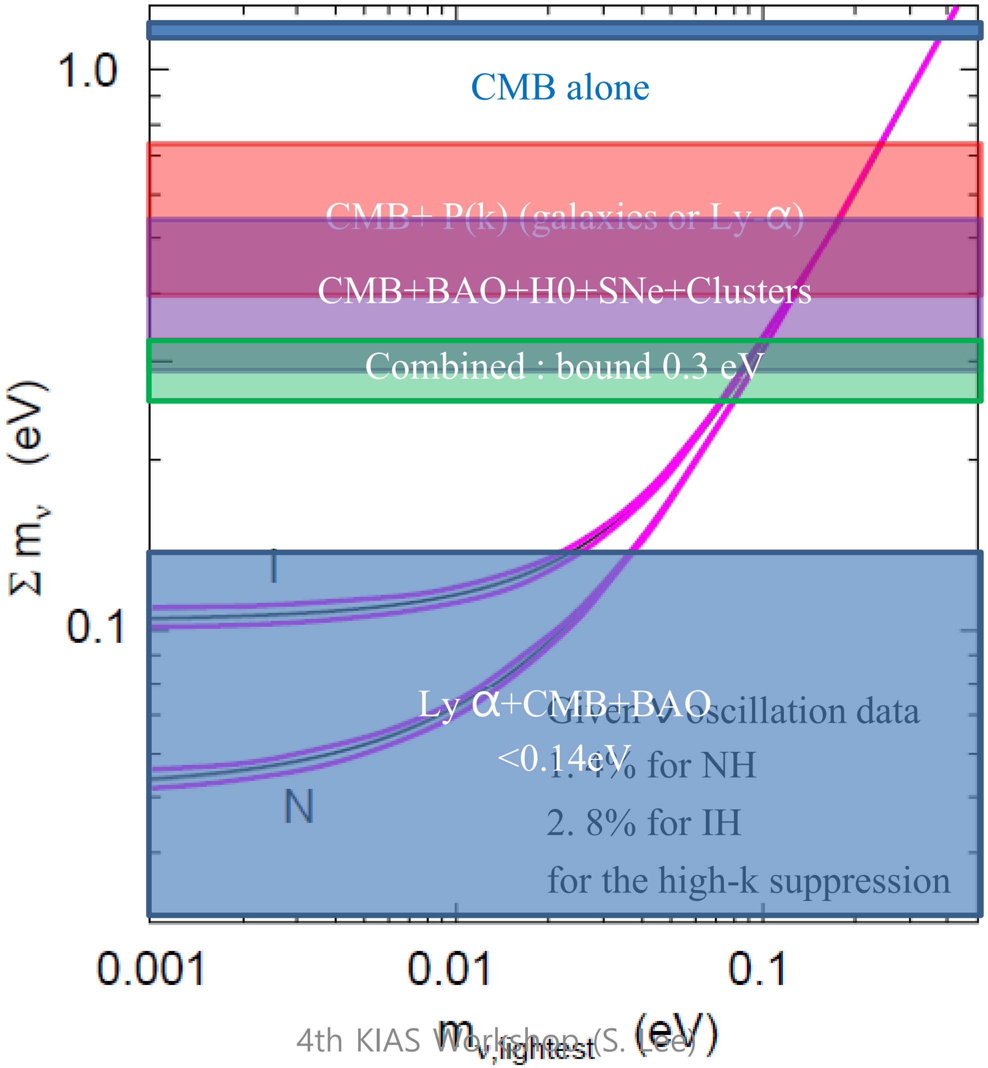
- Motivation
- Current bounds on Neutrino mass and bound
- Cosmological observable
- Consistency of observable
- Degeneracy of CMB angular power spectrum between N_{eff} and w
- Breaking CMB degeneracy with LSS
- CMB degeneracy between w and h
- CMB degeneracy between N_{eff} and h



MOTIVATION

- **particle physics (oscillation) < Σm_ν < cosmology (CMB+BAO+LSS)** Distance Perturbation
- **$\Sigma m_\nu > 0.06$ eV (active)** : solar, atmospheric, reactor, and accelerator neutrino data **with $N_\nu = 3$** (Battye et al. 13), not much room to change
- **$\Sigma m_\nu < 0.248$ eV (active) with $N_\nu = 3$ or $m_{\nu,sterile} < 0.42$ eV with $N_{eff} < 3.80$** : Planck + WMAP Pol + BAO (Ade et al. 13) , **keep decreasing (good news?)**

NEUTRINO MASSES
(CURRENT LIMITS 2-σ, ΛCDM+m_ν)



Larson et al. 10

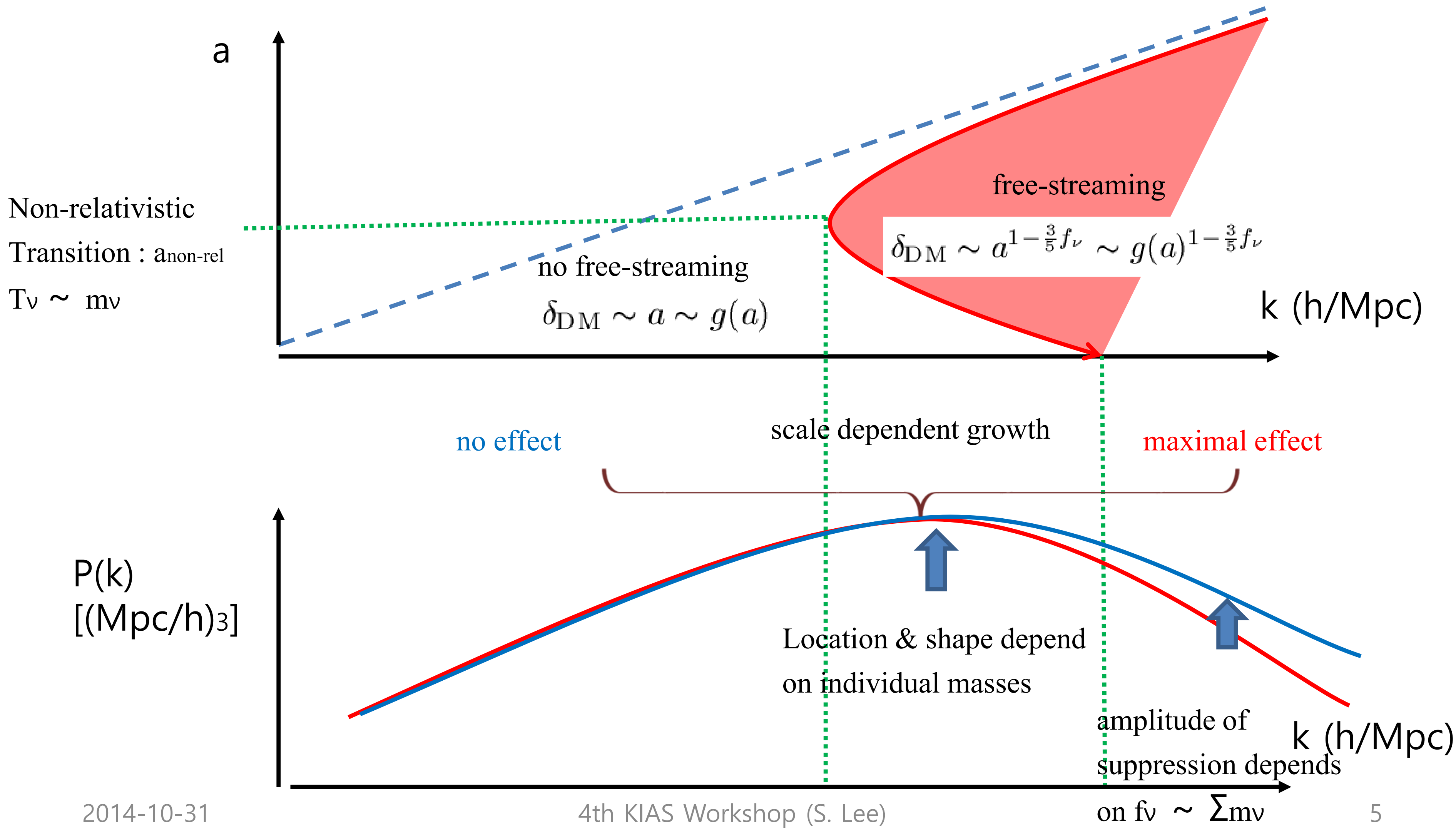
Hamann et al. 10
Swanson et al. 10
Thomas et al. 10
Viel et al. 10

Komatsu et al. 10
Hannestad et al. 10
Reid et al. 10
Jose et al. 11
Ade et al. 13

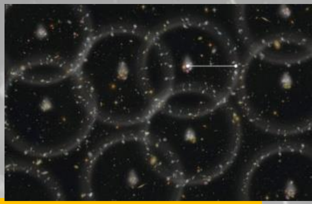
1410.7244
Palanque-Delabrouille et al (**Rossi**)

MASSIVE NEUTRINO (STRUCTURE FORMATION)

Refer Talks by Jeong, Boehm, Rott, Rossi



COSMOLOGICAL OBSERVATIONS (PROBE FOR m_ν)



- Indirect probe of HDM fraction
- ν : radiation (at z_{eq}) & matter (at $z \sim 0$)
- ω_{DM} (z_{eq}) change
- Degeneracy with other parameters

CMB

P(k) / BAO

SNe / H0

Lyman-α

Clusters

Lensing (CMB/Galaxy)

Direct probe of free-streaming (i.e. scale-dependent g(a,k))

Not probing m_ν but removing degeneracy with other parameters

ACCURACY of OBSERVATION

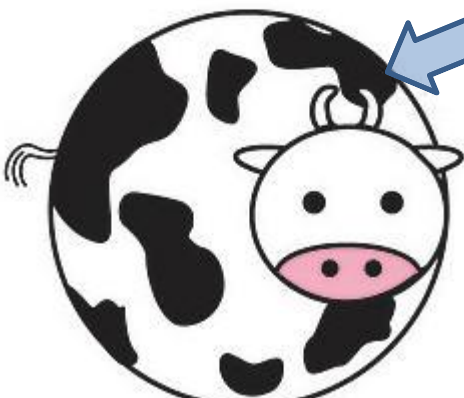
(When z, Where k,l, Who Earth, What γ,ν,δ, How **Ground, Satellite**)

Real Universe

Observed Universe

Refer : Boehm

Theories can never be proved, only disproved.
NOT FAIR?



extra neutrino from CMB & LSS

Modified Gravity from SNe

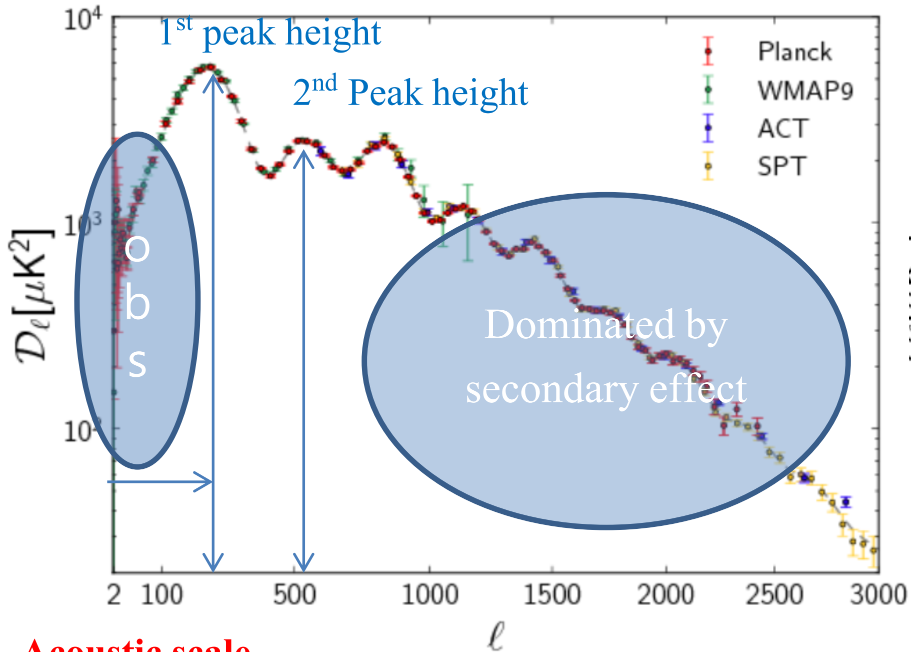
TeVeS from Rot Curve

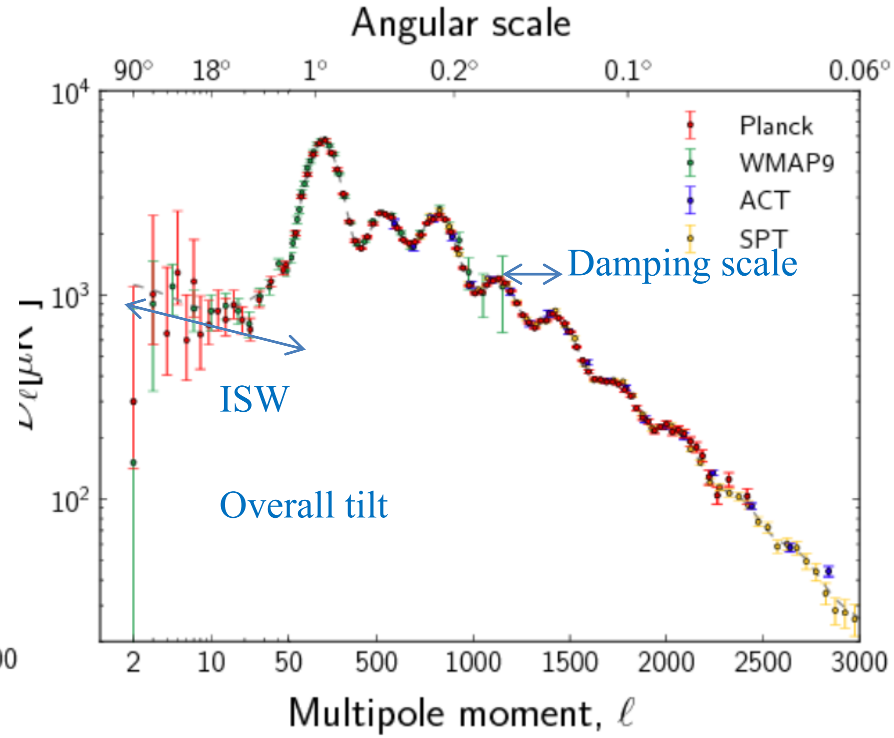
DGP from LSS

Obtained Universes

CMB angular power spectrum

- Measuring Temperature fluctuation anisotropies (at least 11parameters)



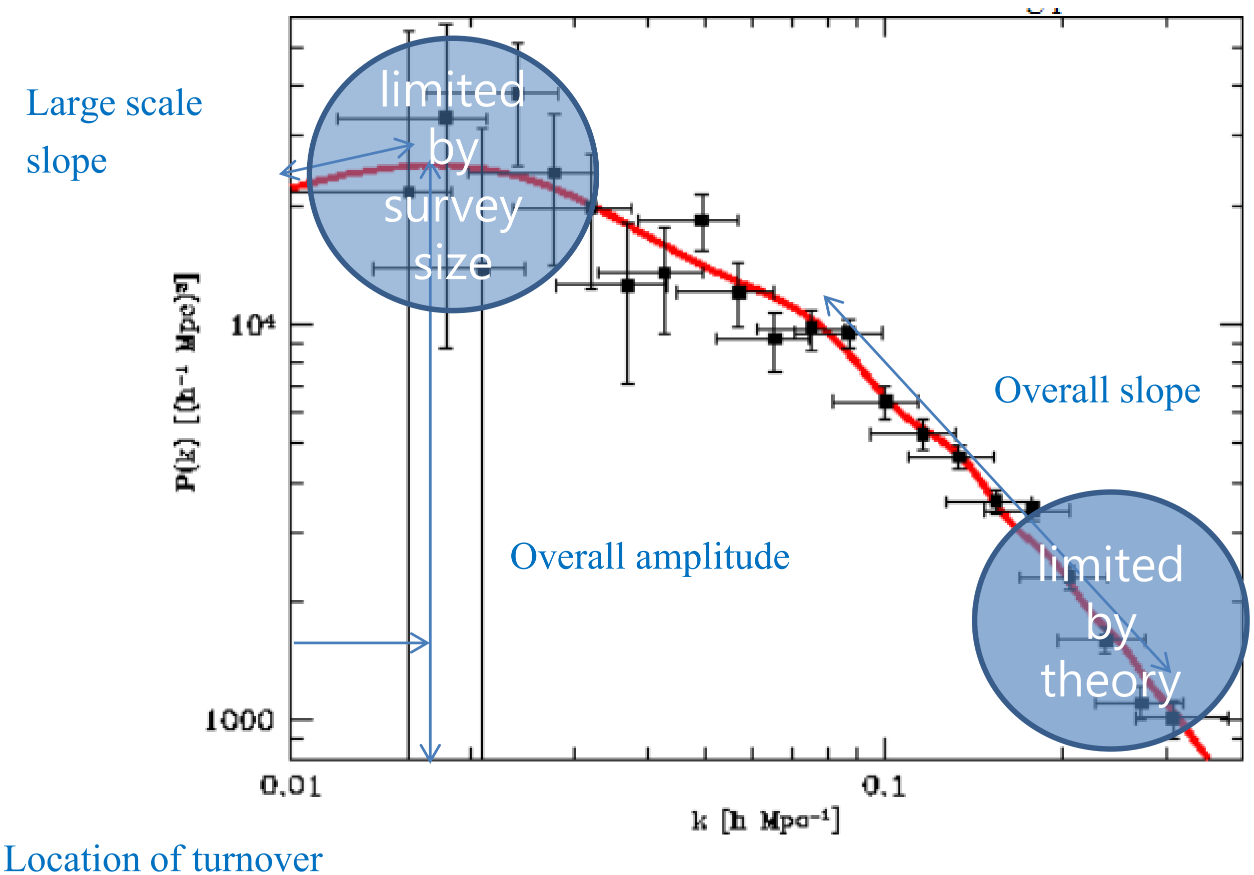


Acoustic scale
:best measurement

Angular scale

Breaking CMB Degeneracy by LSS

- Linear matter power spectrum (**Still about 20% error**)



Peak Location : k_{eq}

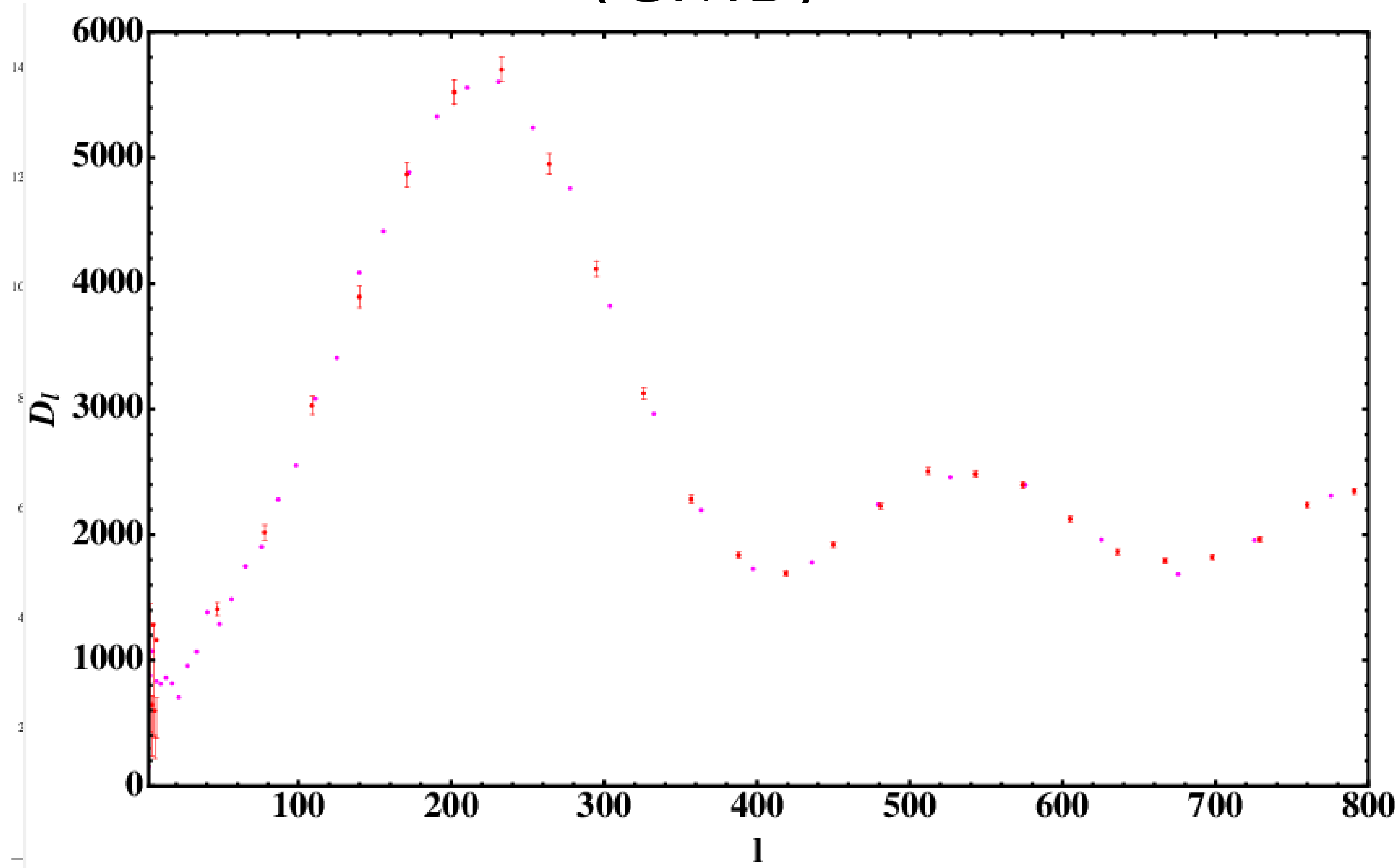
Overall amplitude : A_s, ω_m, b

Large Scale Slope : ns

Small scale slope : ω_b/ω_c

Bias factor b : unknown

CONSISTENCY OF OBSERVABLE (CMB)



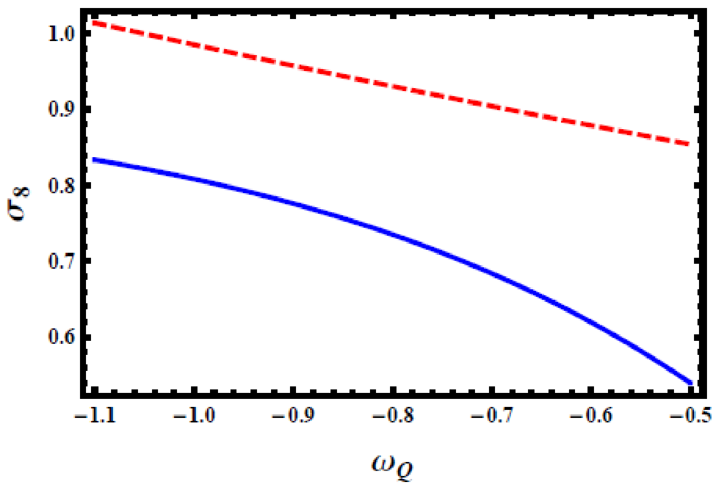
CONSISTENCY OF OBSERVABLE (LSS)

- Matter power spectrum suffers from bias factor b(z,k) : we don't understand
- **Transfer function** embedded in the P(k) compensated by b(z,k) : baryon trace matter
- Cluster number analysis : over simplified (SL, Ng 10)

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.78 \pm 0.01$$

- Growth function : over simplified

(SL, 11)



CMB Degeneracy between N_{eff} and w

- Based on arXiv : 1409.1355, 1410.1260 (SL 14)
- Situation : reactor experiments and cosmology claimed the existence of extra light particles
- Motivations : How much cosmology can tell about this?
- Cosmic microwave background (CMB) : thermal radiation from big bang. Acoustic waves (coupling btw γ & b under gravitational potential well created by DM)
- CMB mean Temperature : T=2.725 K
- Fluctuation of CMB T : ΔT = 10-100 μK
- Gaussian distributed if fluctuation is generated from inflation : average of $\Delta T = 0$ (variance = power spectrum is not 0)

DECOMPOSE COSMOLOGICAL PARAMETERS I

Can guess about
Early DE model
Deviation

- Peak location (acoustic scale) : most accurately measured quantities → depends on geometry and energy densities

$$\theta_s[z_*, N_{eff}, w, h] \equiv \frac{r_s[z_*, N_{eff}, w, h]}{d_A^{(c)}[z_*, N_{eff}, w, h]}$$

$$r_s(z_*) = \frac{c}{\sqrt{3}H_0}\int_{z_*}^{\infty}\frac{dz}{\sqrt{1+R[z]}E[z]},$$ → No DE

$$d_A^{(c)}(z_*) = \frac{c}{H_0}\int_0^{z_*}\frac{dz}{E[z]},$$ → DE dependence

$$E[z, N_{eff}, w, h] = \frac{H}{H_0} = \frac{1}{h}\sqrt{\omega_m(1+z)^3 + \omega_r(1+z)^4 + (h^2 - \omega_m - \omega_r)(1+z)^{3(1+w)}}$$

Degeneracy
btw N_{eff} & w

- Height of the 1st peak : matter/radiation density ratio
- Height of the 2nd peak : baryon/radiation density ratio
- Ratio of odd to even peaks : baryon/photon
- Time of m-r equality : amplitude of all peaks (fix z_{eq})

$$\omega_c[N_{eff}] = \omega_\gamma(1 + 0.22711 N_{eff})(1 + z_{eq}) - \omega_b$$

DECOMPOSE COSMOLOGICAL PARAMETERS II

- High-l peaks (damping scale) : affected by number of neutrino and helium abundance (can be cross checked

$$\frac{\theta_{\rm s}[z, N_{\rm eff}, {\rm w}, {\rm h}]}{\theta_{\rm d}(z_*)[z, N_{\rm eff}, {\rm w}, {\rm h}, {\rm Y_P}]} = \frac{r_{\rm s}(z_*)[z, N_{\rm eff}, {\rm w}, {\rm h}]}{r_{\rm d}(z_*)[z, N_{\rm eff}, {\rm w}, {\rm h}, {\rm Y_P}]}$$

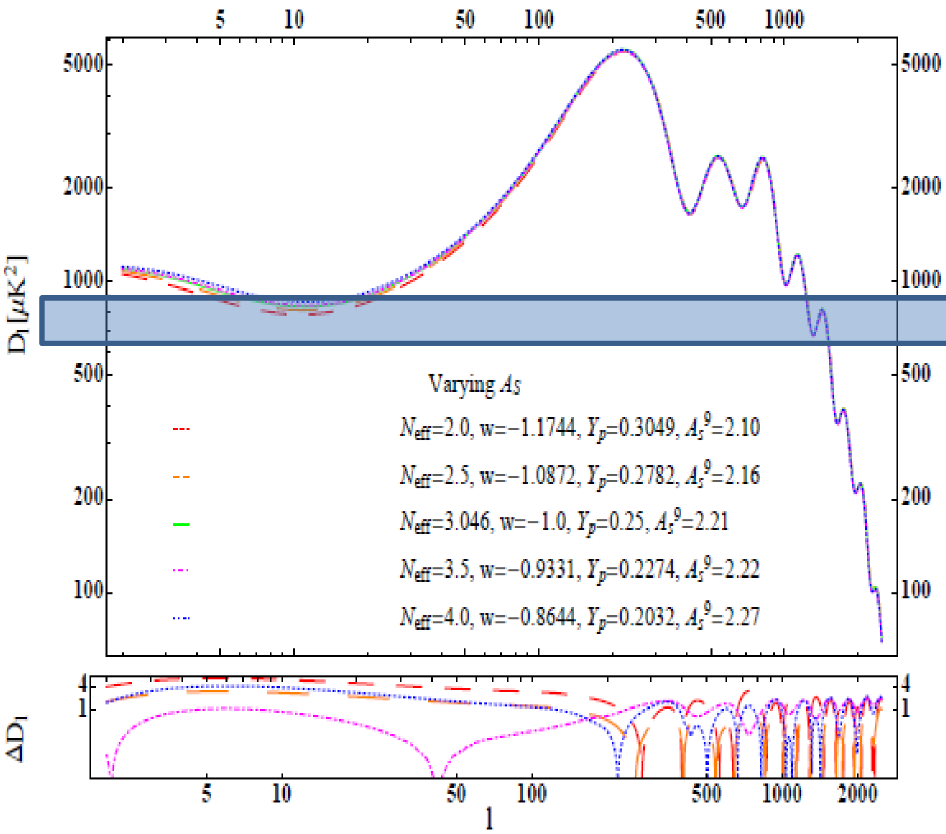
$$\begin{aligned} r_d(z_*) &= \sqrt{\frac{c\pi^2}{H_0}\int_{z_*}^{\infty}\frac{(1+z)dz}{\sigma_T X_e n_b (1-Y_P)E[z]}\left[\frac{R^2+\frac{16}{15}(1+R)}{6(1+R^2)}\right]} \\ &= \sqrt{\frac{c\pi^2}{H_0}\frac{1}{\sigma_T X_e \omega_{\rm b}}\frac{1-0.007119 Y_P}{(1.12284\cdot 10^{-5})(1-Y_P)}\int_{z_*}^{\infty}\frac{dz}{(1+z)^2 E[z]}\left[\frac{R^2+\frac{16}{15}(1+R)}{6(1+R^2)}\right]} \end{aligned}$$

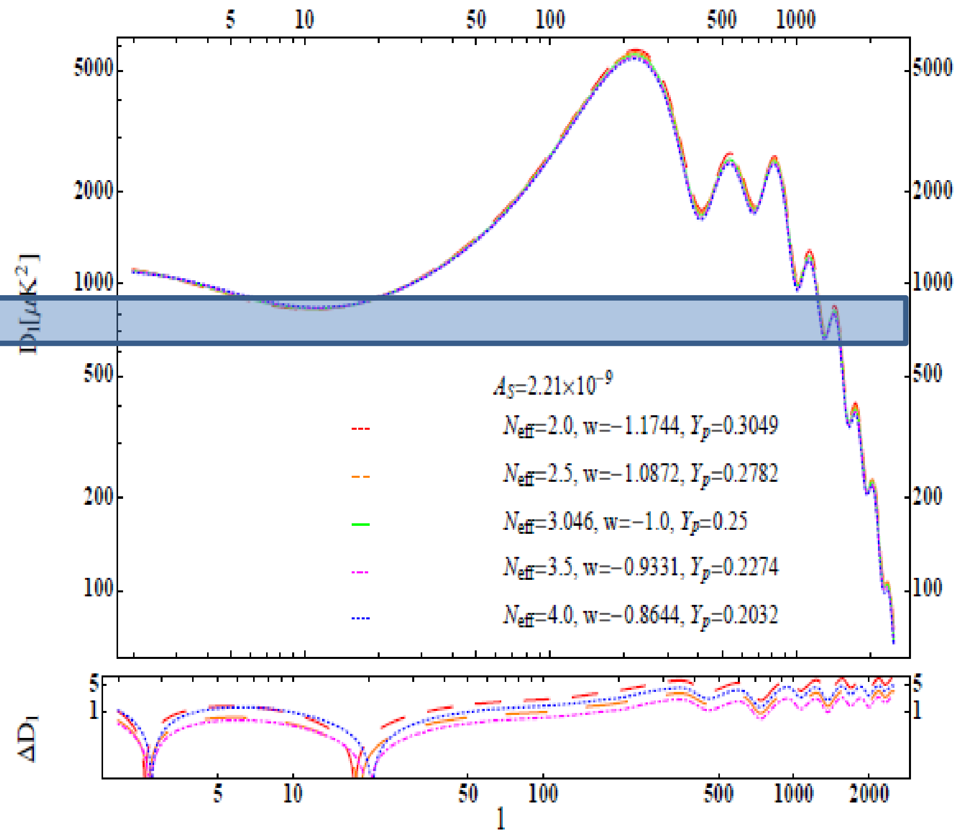
- Global amplitudes : A_s
- Global Tilt : n_s

Check sensitivities of cosmological
Parameters using MC or Fisher Matrix

DEGENERATED CMB (N_{eff}, w)

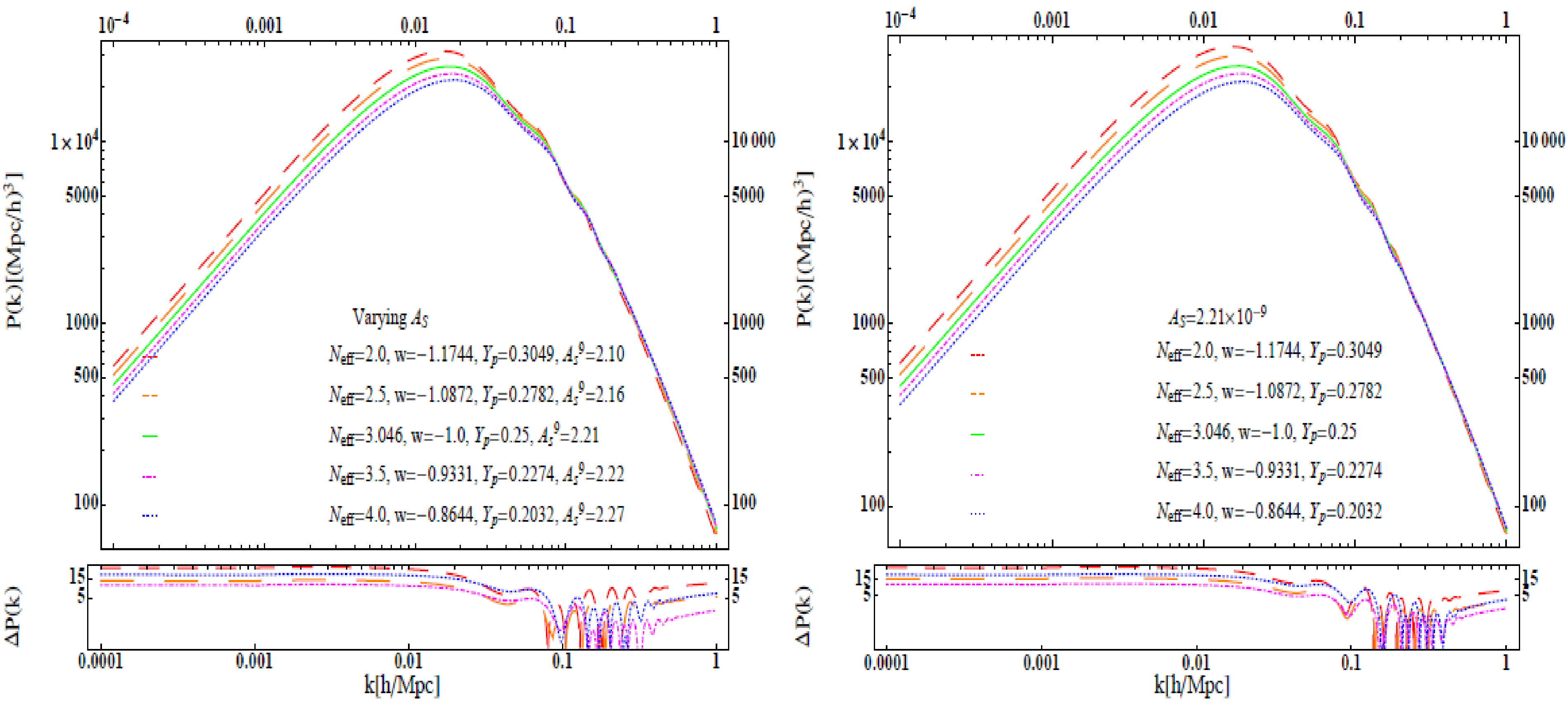
- We need to keep all other cosmological parameters except





LINEAR MATTER POWER SPECTRUM

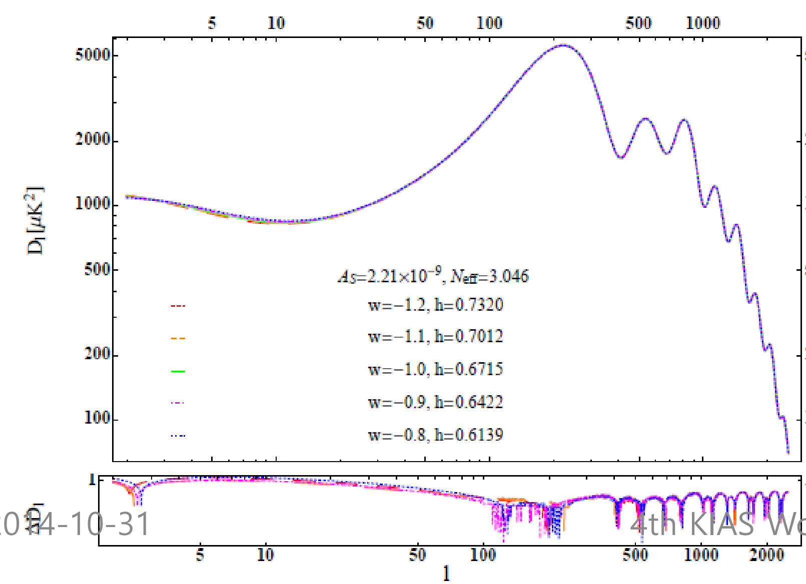
- $k_{eq}=a_{eq}H_{eq}/c$ (effect will be clearer in massive neutrino case : paper)

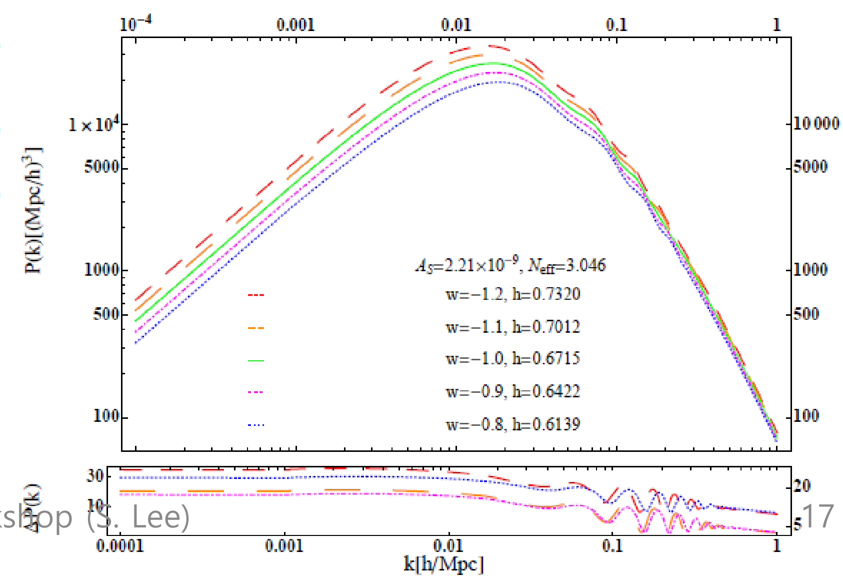


CMB DEGENERACY (w,h)

- Fixed Neff = 3.046 & A_s (direct comparison in MPS less powerful : b)

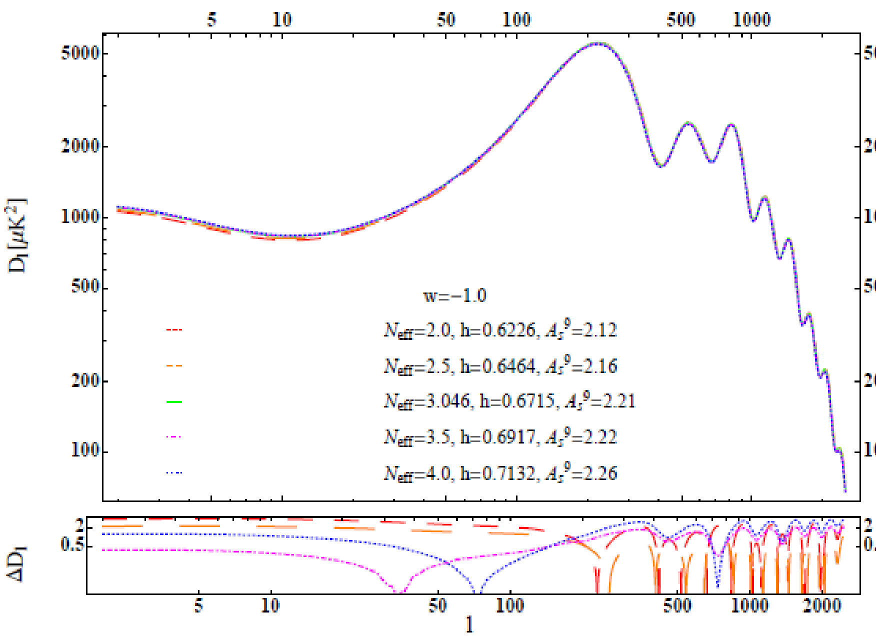
$N_{\rm eff} = 3.046$					$w = -1.0$							
w	h	σ_8	$f\sigma_8$	$\Delta f\sigma_8$	$N_{\rm eff}$	h	Y_P	$A_S(10^9)$	σ_8	$f\sigma_8$	$\Delta f\sigma_8$	
-0.8	0.6139	0.785	0.455	2.1	2.0	0.6226	0.3049	2.12	0.7909	0.418	-6.4	
-0.9	0.6422	0.815	0.451	1.1	2.5	0.6464	0.2782	2.16	0.8174	0.431	-3.3	
-1.0	0.6715	0.840	0.446	0	3.046	0.6715	0.25	2.21	0.8452	0.446	0	
-1.1	0.7012	0.875	0.442	-1.1	3.5	0.6917	0.2274	2.22	0.8607	0.454	1.8	
-1.2	0.7320	0.905	0.437	-2.1	4.0	0.7132	0.2032	2.26	0.8819	0.466	4.3	

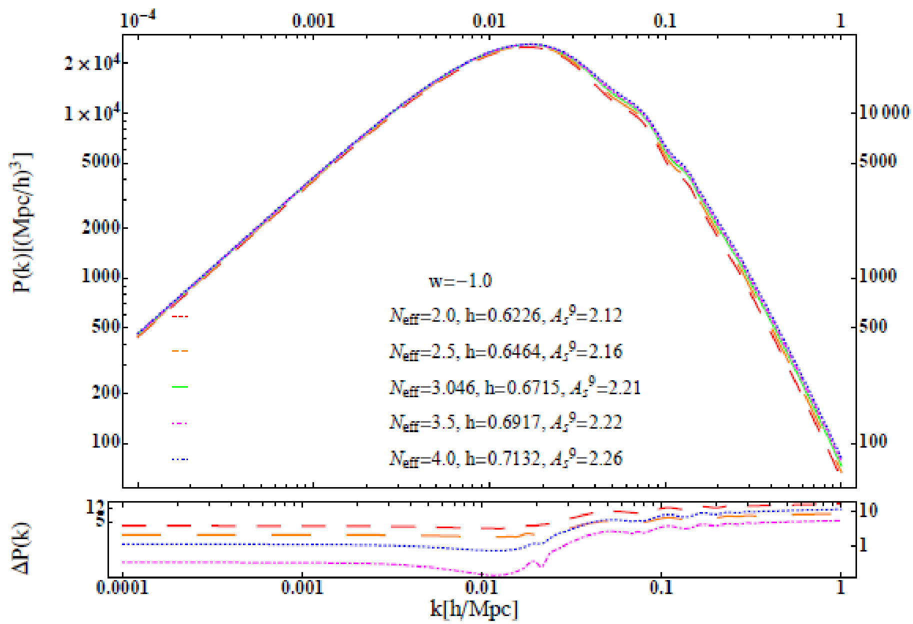




CMB DEGENERACY (N_{eff}, h)

- Fix w=-1.0 (ΛCDM)





SUMMARY

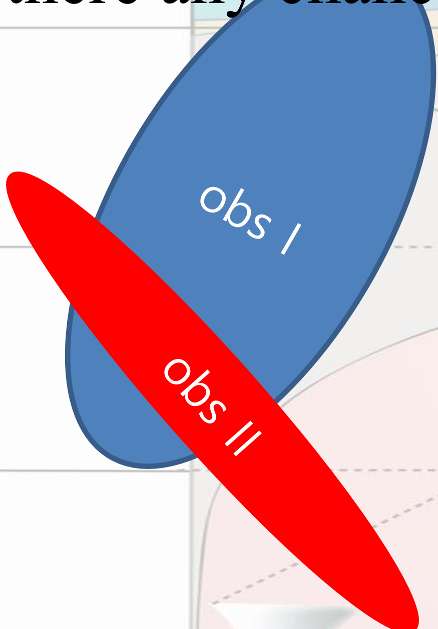
	BBN	CMB			LSS	BAO	SNe	Ly-α
Epoch (z, t)	(10^{10}, 1min)	(1089, 379,000 yrs)				0.06~0.57	0.3 ~ 3	2.2~4.4
Scales (l, k)		$l \leq 800$	$l \leq 2500$	$l > 2500$	$k < 0.15h/\mathrm{Mpc}$	150 Mpc		0.15 h/Mpc
massive ν massless ν	Ω_m Ω_r	height height	both both	length length	height z_{eq}	both length	sensitive insensitive	sensitive insensitive
error sources	systematic in H-II regions	different mask	beam uncertainties	secondary effect	modeling data analysis	statistics modeling	K-correction Standard Candle	hydro simulation
observational accuracy		location of 1st peak						
number of parameters	$\Omega_b h^2, \eta$ Y_P, N_{eff}	$A_s, n_s, \tau, H_0, \omega_m, \omega_b$ w,$\omega_\gamma, N_{eff}, Y_P, m_\nu$			A_s, n_s Ω_m, b, N_{eff}	Ω_m, H_0 N_{eff}	ω_m w	Ω_m, σ_8 H_0, N_{eff}
Flat Universe Prior								

Small scales observable is not determined by gravity only

BREAKING DEGENERACIES ?

- Does Joint analysis (Complimentary Observable) really break the degeneracy? (**Which parts of cow we looking at?)**
- Is there any chance to be biased from one to another observation?

(data analysis is based on model)



A theory probes observations?

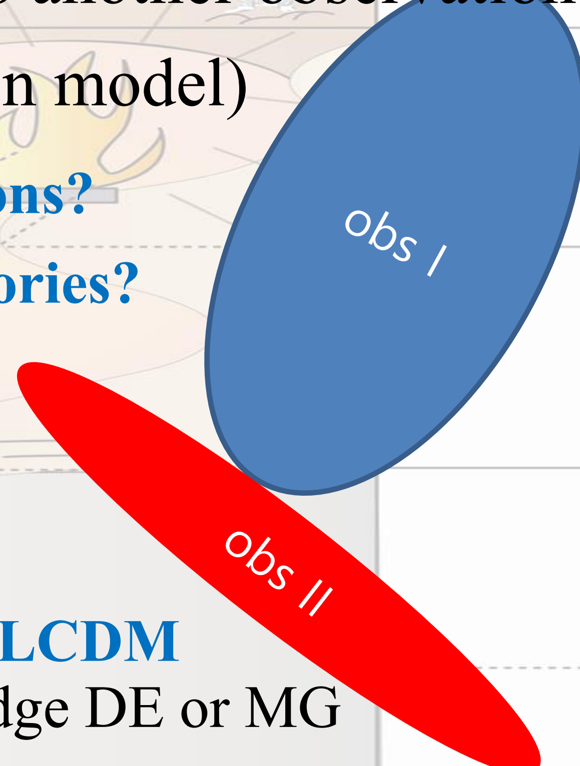
An observation probes theories?

Ruiz, Huterer 1410.5832

w=-1 (Geometry),w=-0.8(δ)

SL 12 (**Bad Conclusion**)

LSS shows deviation from LCDM



Current LSS data is not accurate enough to judge DE or MG

Better conclusion

CONCLUSION

- CMB provides strong constraints on cosmological parameters (compliment with LSS)
- However, many parameters are degenerated.
- Previous works, focus on effect of N_{eff} degeneracy with h on CMB (hard to break with LSS)
- Dark energy also affects to N_{eff} and it might be too early to say about the existence of extra neutrino (dark radiation)
- LSS might help to break CMB degeneracy on parameters
- Need to investigate **more robust observable** to distinguish models