Reducing Systematics in Cosmology

The 3rd IBS-KIAS Joint Workshop at High 1

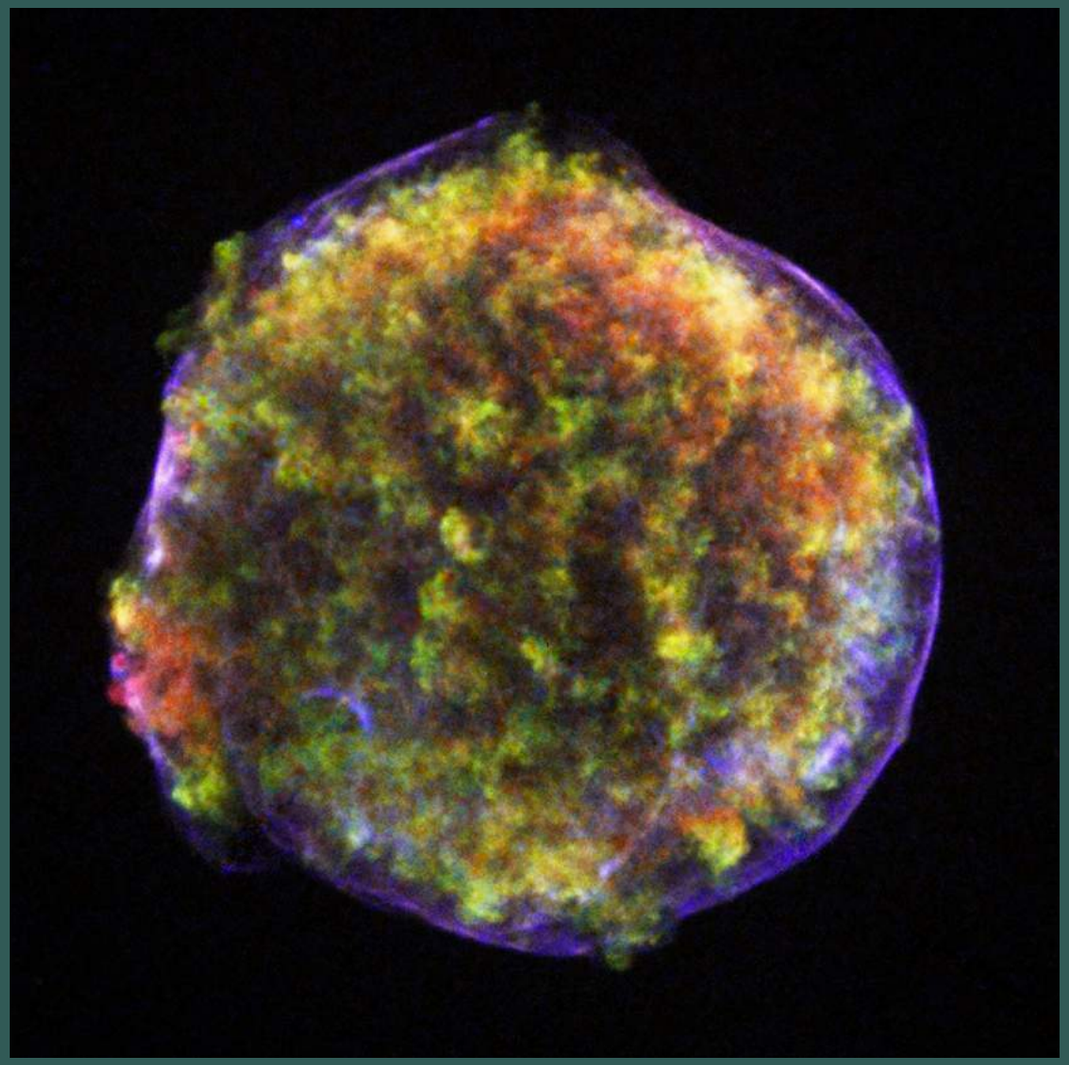
Feb.15th. 2019

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OUTLINE

- Astronomy
- Cosmology
- Systematics in observations
- Systematics in theories
- How much one can improve ?
- Conclusions

ASTRONOMY I



SN1572 A SNR : X-ray

The annals of the Chosun dynasty, Seonjo yr27 (1594), Aug.2nd

- 觀象監啓曰: "去壬辰年十月間, 日官以婁星所屬天倉星內, 有無名一星, 指以爲客星, 至於啓達矣。 厥後其星, 久在其處, 不爲變動, 隨天隱見, 故或啓、或停。 今自七月七日間, 又見於東方, 而形體及宿次, 依舊不動。 近來散處日官之諳鍊天文者, 稍稍來集, 皆以爲: '自古客星行度進退, 異於經星, 無三年不變之理。 必是經星之無名者, 而當初日官, 不謹候察, 誤以客星, 指的啓達, 極爲駭愕。 請令解事日官, 更爲詳細候察, 而姑勿以客星書啓, 何如?" 上從之。

經星 = 恒星 = *stellar* // 客星 = *Comet, SN*

ASTRONOMY II

- Not a first principle science
- Interpret the observations with fitting formulae (too many dynamics are involved)
- Ex) star formation : ISM, GMC, hydrodynamics
- The smaller the observables are, the harder they are predicted
- Same as that Newton's law or Bernoulli equation can explain idealized systems only

COSMOLOGY I

- Based on GR (only gravity)
- Interpret the observations with formulae derived from the first principle (simple dynamics are involved)
- Due to BB and inflation models, cosmology now becomes predictable theories (refer Ryan, Arman, and Benjamin's talks for the risks of this approaches) 액땜 (Aek-Daem) : Consider yourself lucky, it could have been worse.
- Ex) Background evolutions (H, D_L, D_A), LSS, CMB, Clusters
- Border : Lensing, galaxies,
- The smaller the observables are, the harder they are predicted

SYSTEMATICS IN OBSERVATIONS

Dinosaur Fossils



Can we say anything about color, feature, and others of Velociraptor from its fossil ?

Limitation on accuracy.
Need to check DNA and etc.

SYSTEMATICS IN OBSERVATIONS (CONTINUED)

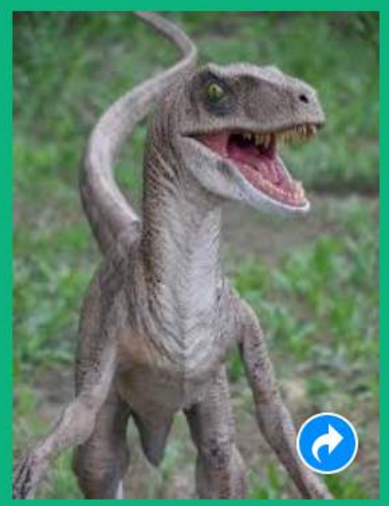
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SYSTEMATICS IN OBSERVATIONS (CONTINUED)



SYSTEMATICS IN OBSERVATIONS (CONTINUED)



Due to

systematics & statistical observational errors



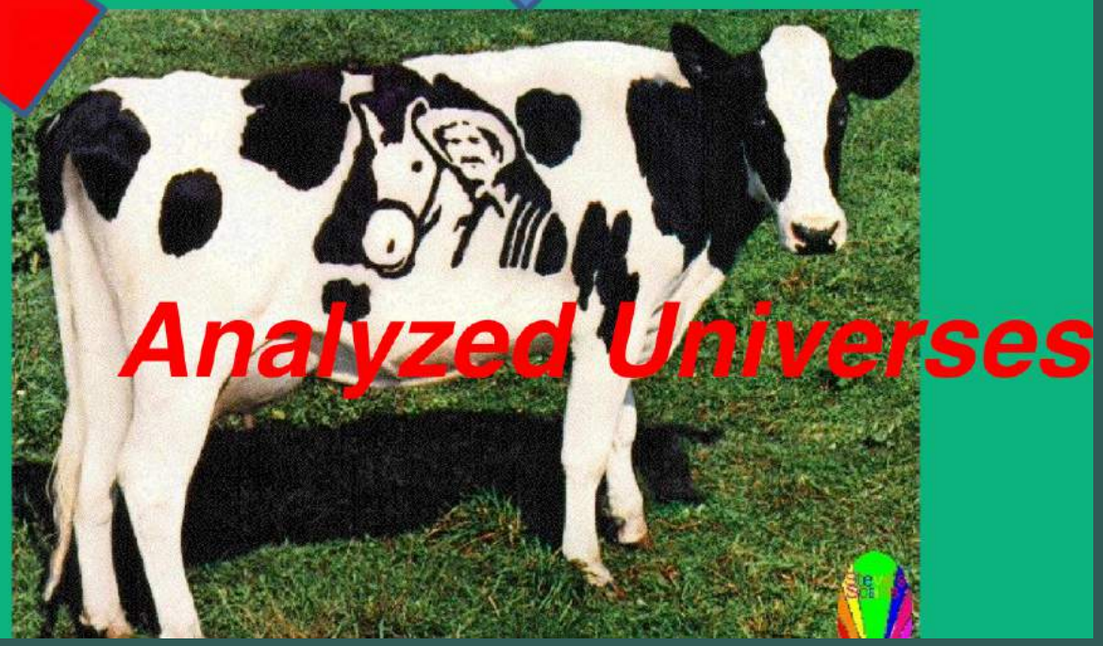
Depend on what (γ, v, δ, v), how (ground, space) to measure. Cosmological observations : not reproducible (limits on both sys and stat) → rely on ergodic hypothesis

SYSTEMATICS IN THEORIES

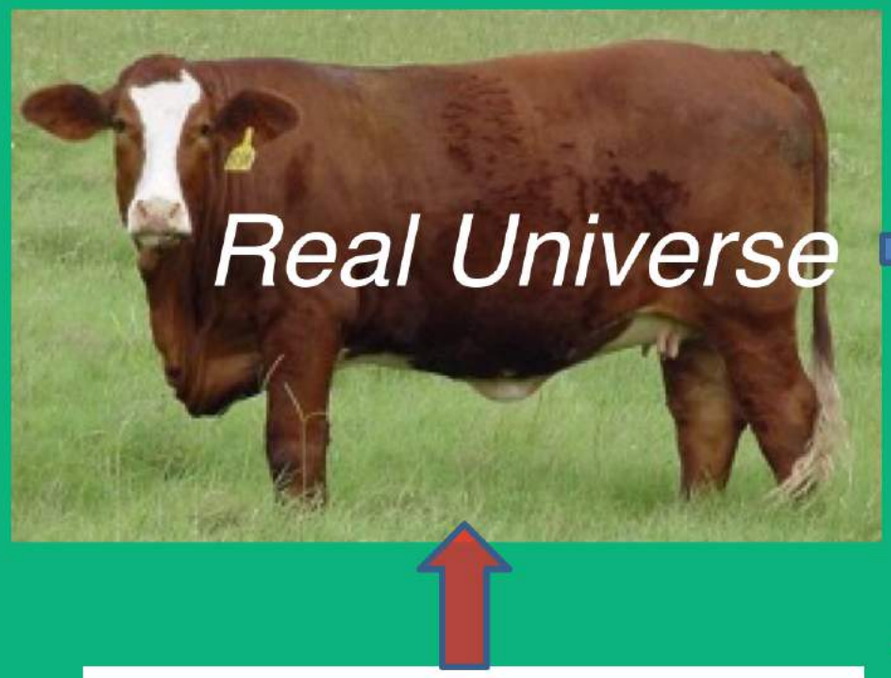


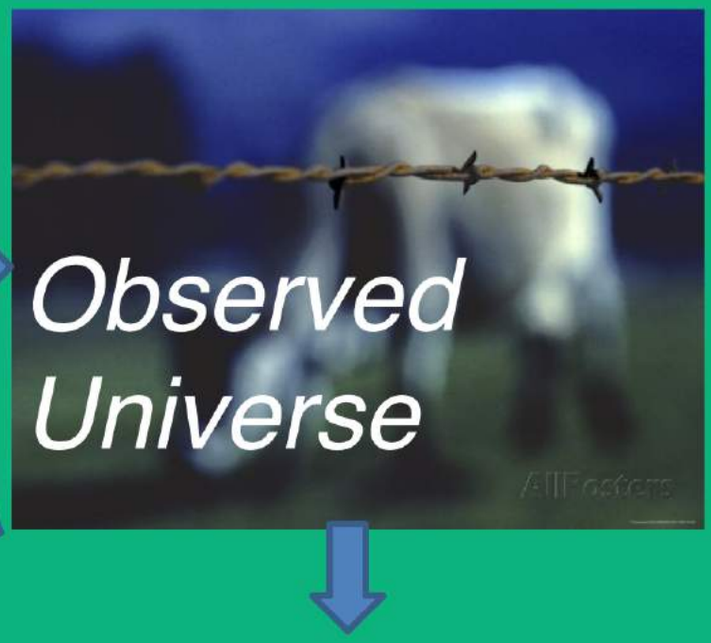


Due to sys & stat in theories
: lucky case



SYSTEMATICS IN THEORIES (CONTINUED)





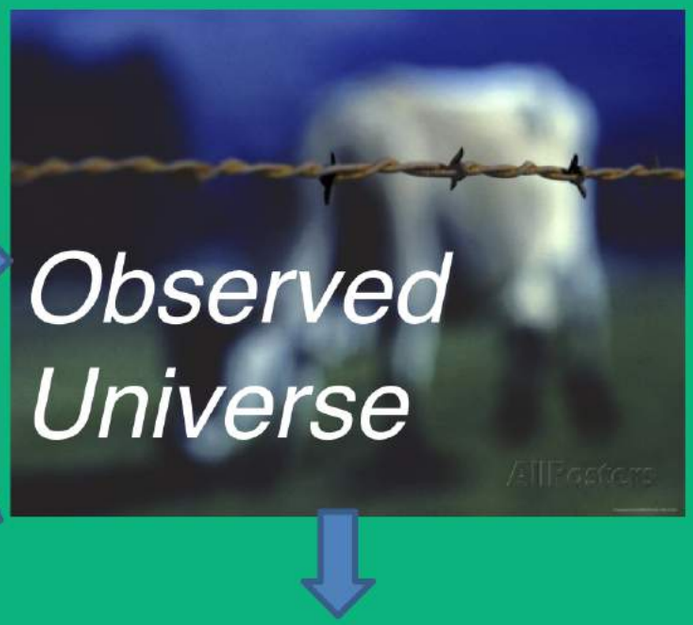


Due to sys & stat in theories
: unlucky case

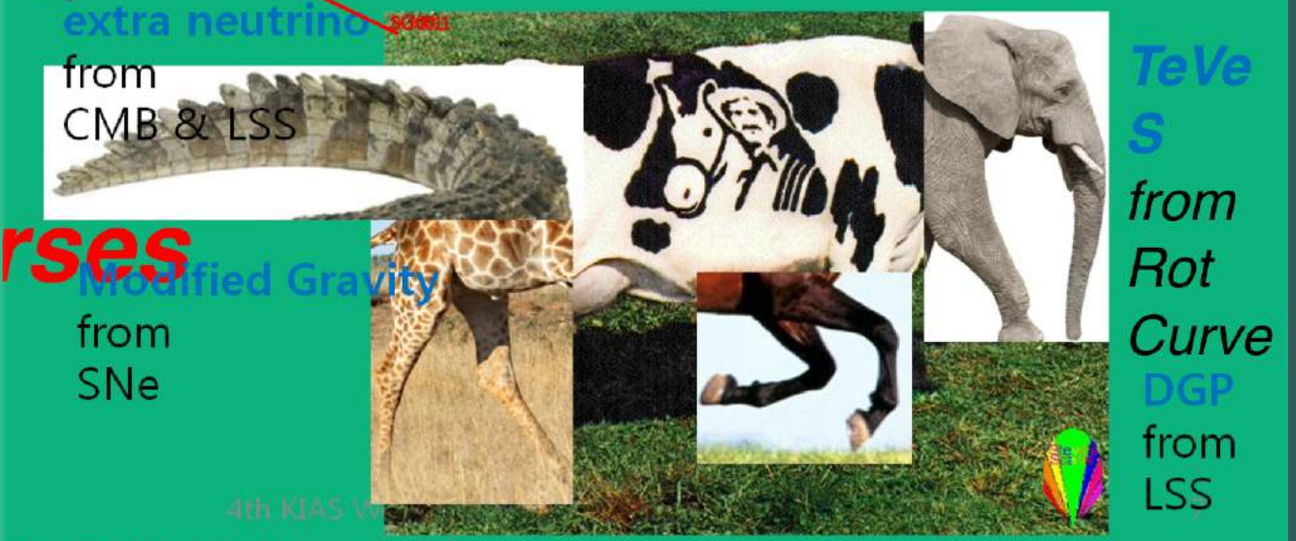
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SYSTEMATICS IN THEORIES (CONTINUED)



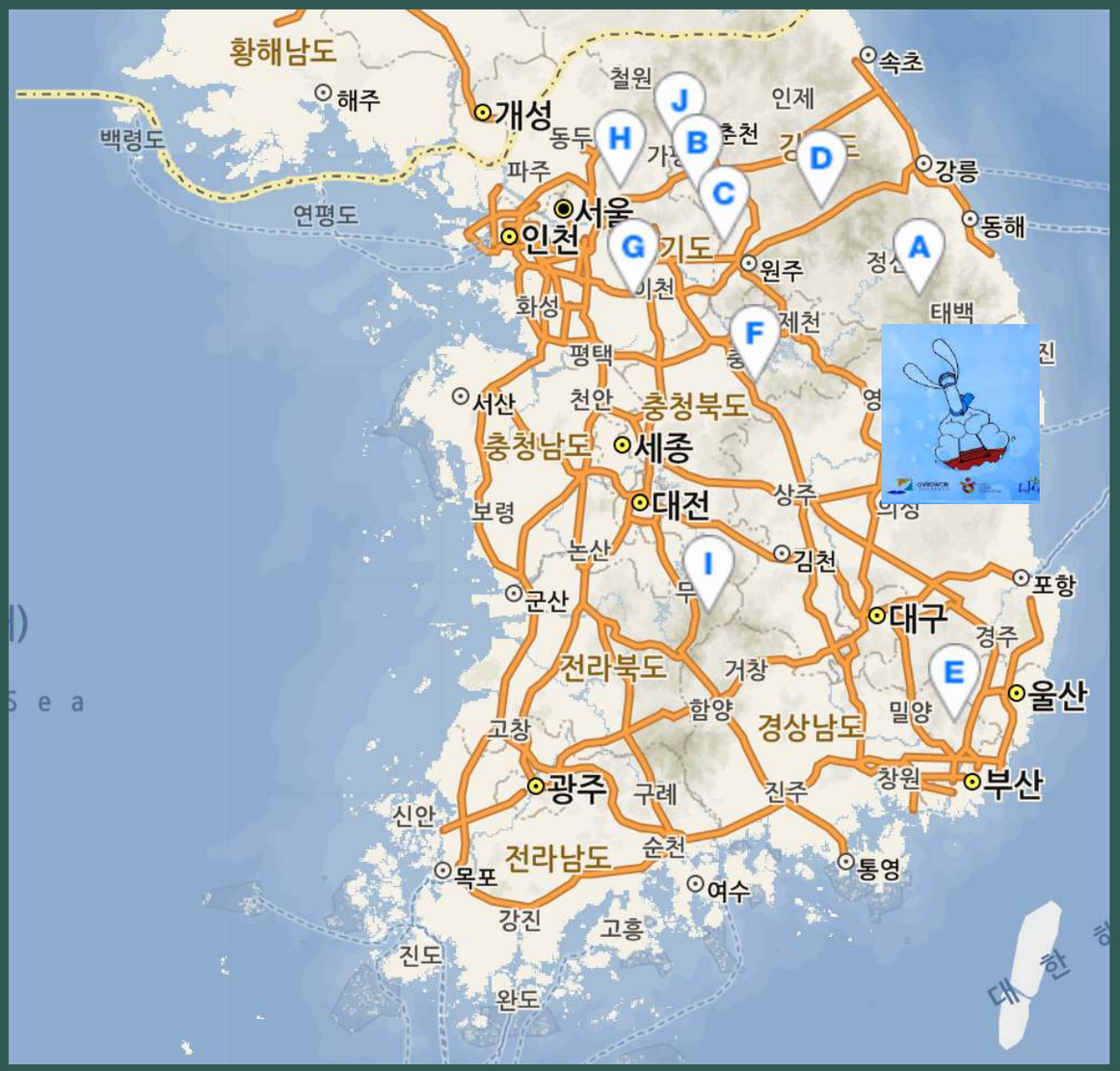


Risks in combining various observations. Some are sensitive for specific scales, epochs, or specific models



ERGODICITY

- What is the most visited ski resort by south Korean?



Two methods

i) Choose a day and count # of Korean who visit each resort

ii) Choose a person and count how open she visits each resort per year.

iii) If i) = ii), then ensemble is called as ergodic :

< >_{ensemble} = < >_{time}

OBSERVATIONS-1

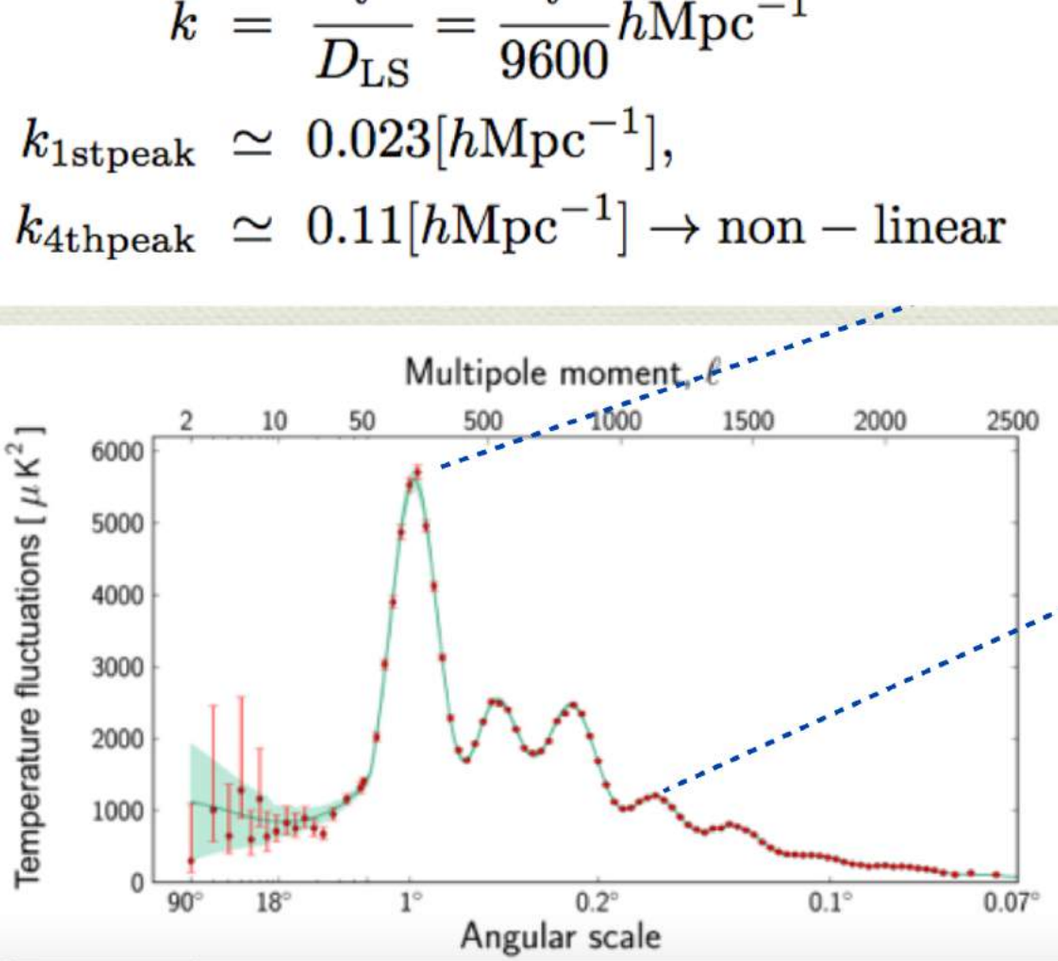
Link LSS with CMB

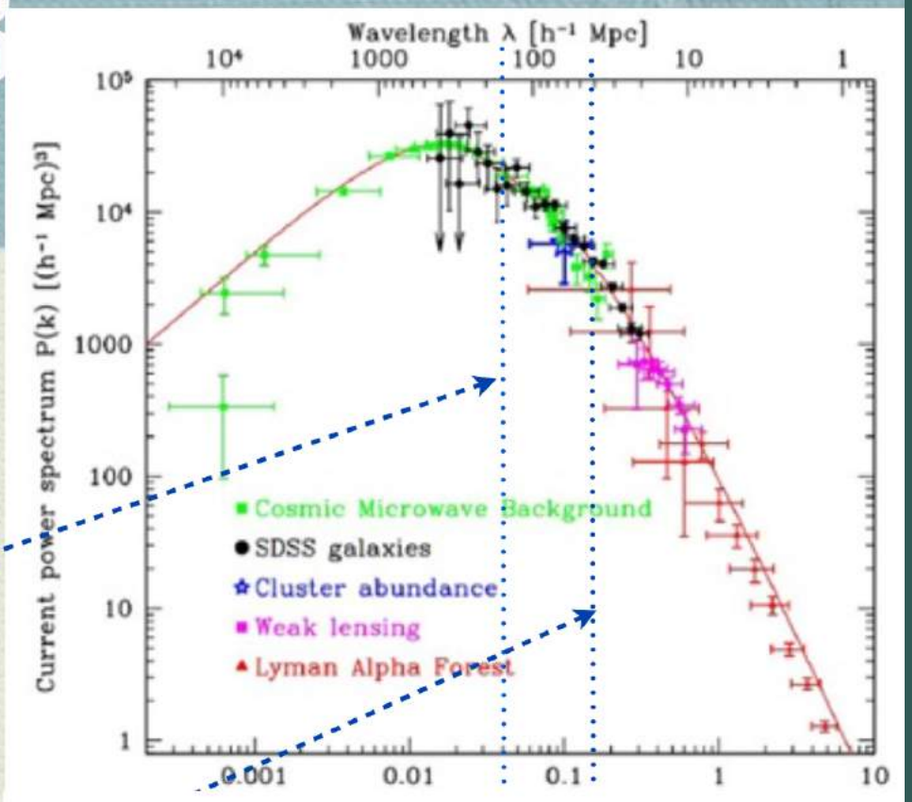
SL 15

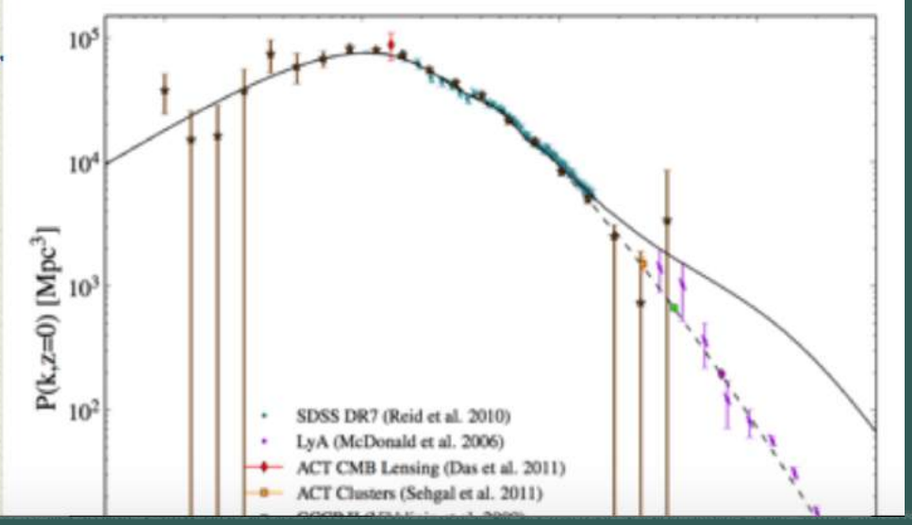
$$k = \frac{l}{D_{\rm LS}} = \frac{l}{9600} h{\rm Mpc}^{-1}$$

$$k_{\rm 1stpeak} \simeq 0.023[h{\rm Mpc}^{-1}],$$

$$k_{\rm 4thpeak} \simeq 0.11[h{\rm Mpc}^{-1}] \rightarrow {\rm non-linear}$$

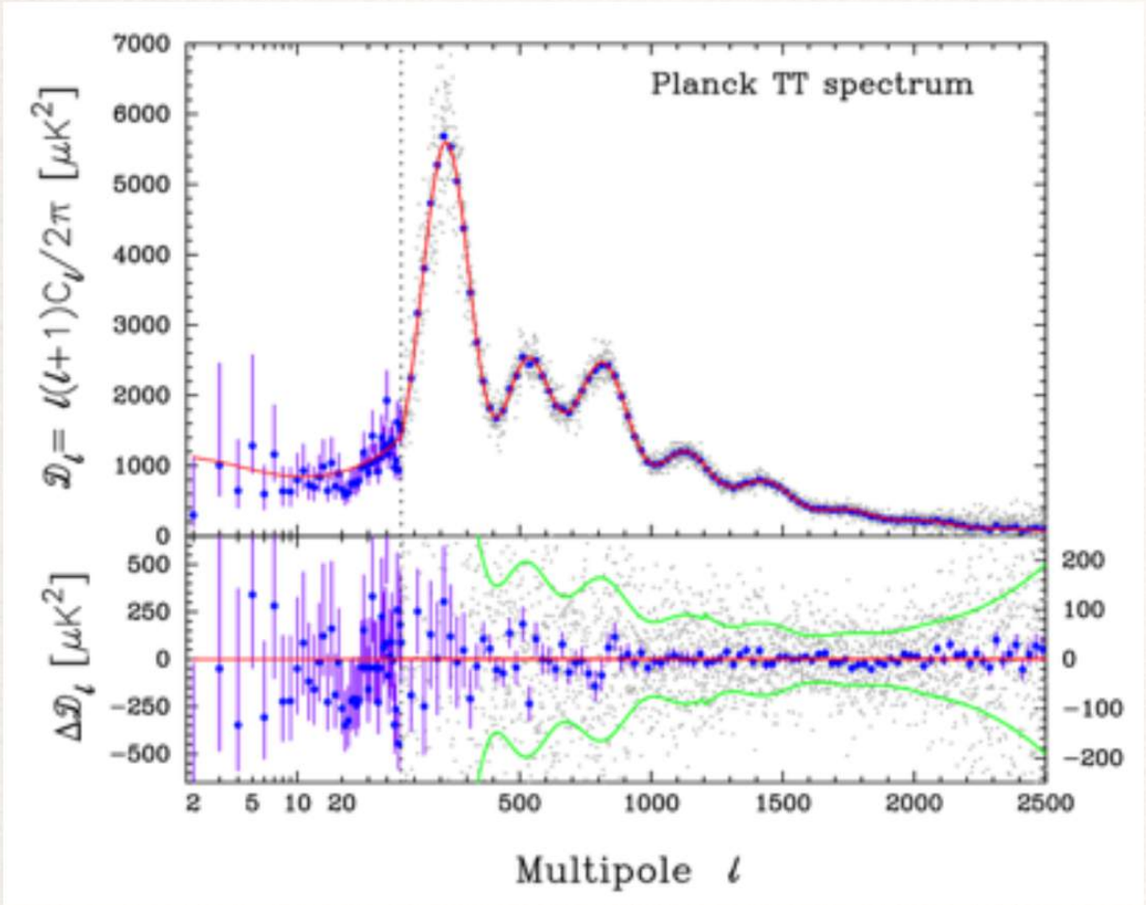


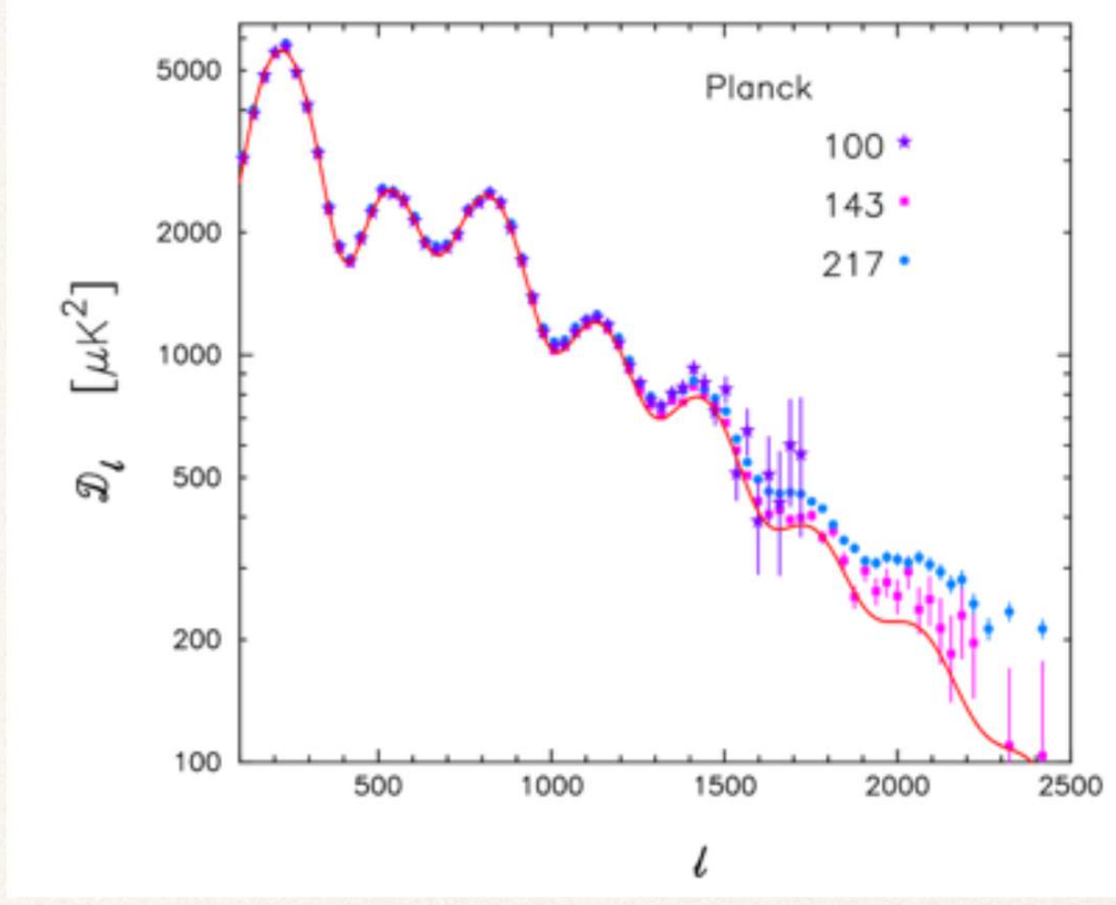




OBSERVATIONS-1-1

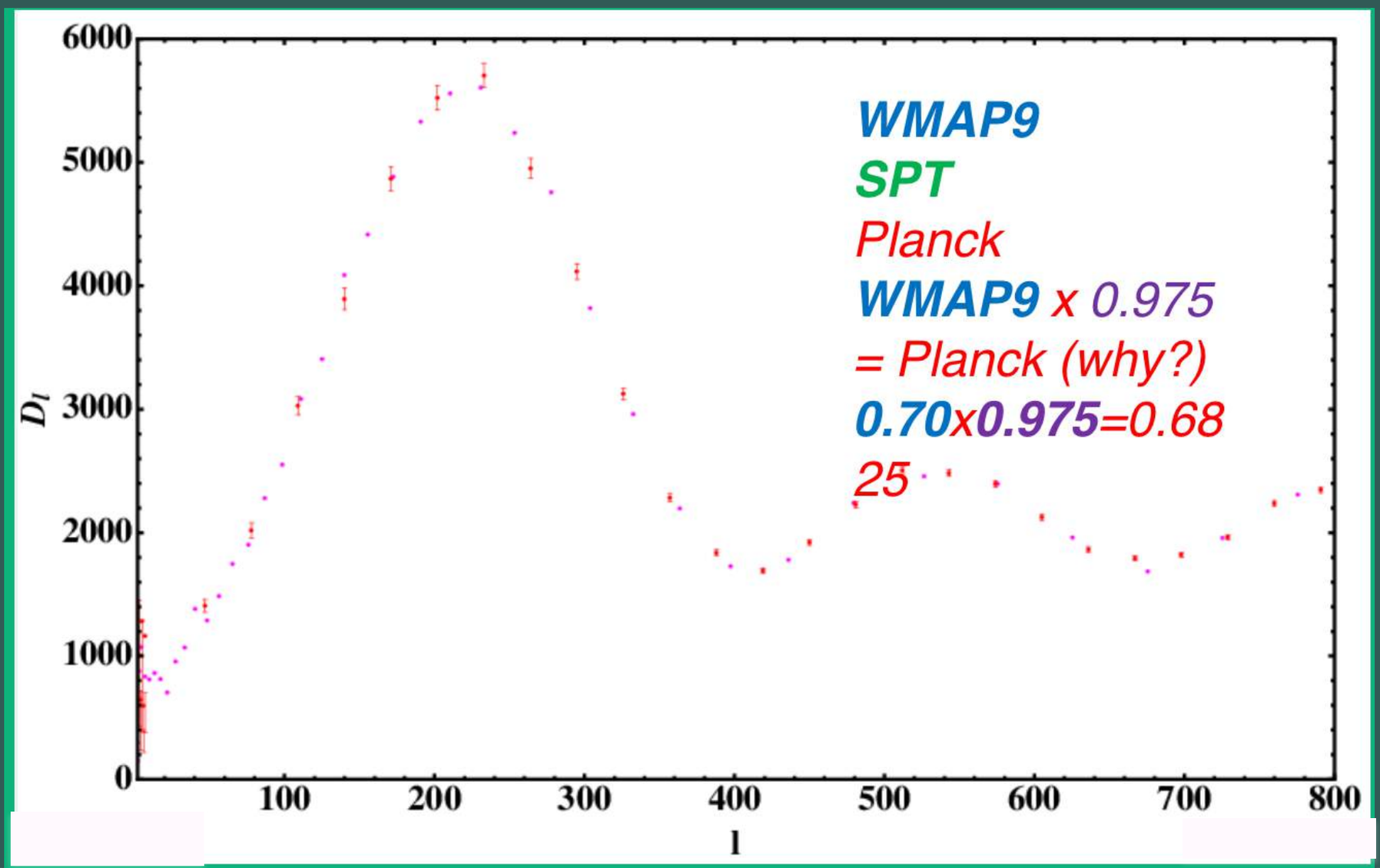
CMB TT PS (2015)





OBSERVATIONS-1-2

SL (in preparation)



OBSERVATIONS-2

Example : constrains on massive and massless neutrinos from various observations (SL, 15)

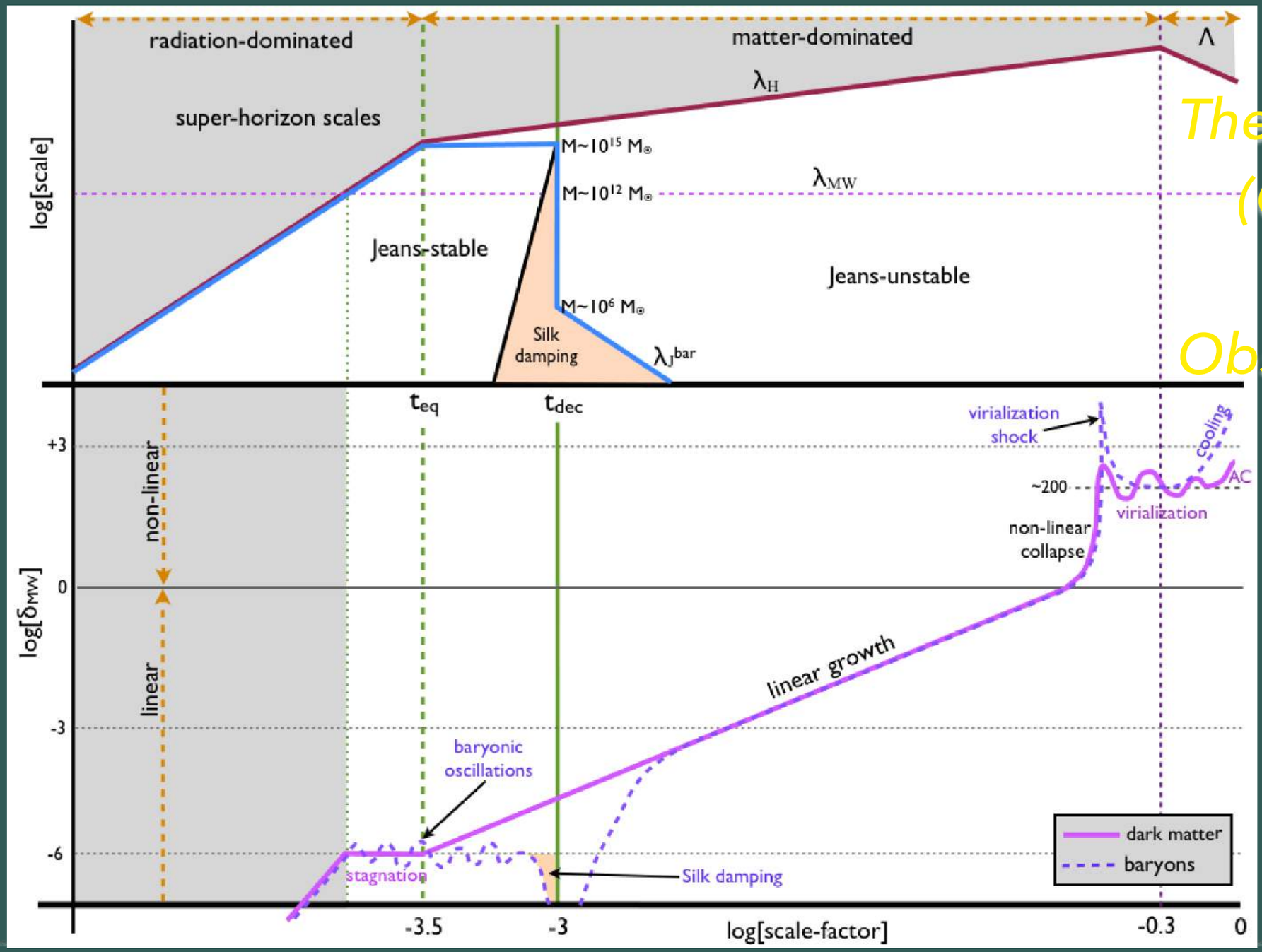
	BBN	CMB			LSS	BAO	SNe	Ly-α
Epoch (z, t)	(10^{10}, 1min)	(1089, 379,000 yrs)				0.06~0.57	0.3 ~ 3	2.2~4.4
Scales (l, k)		$l \leq 800$	$l \leq 2500$	$l > 2500$	$k < 0.15h$/Mpc	150 Mpc		0.15 h/Mpc
massive ν	Ω_m	height	both	length	height	both	sensitive	sensitive
massless ν	Ω_r	height	both	length	z_{eq}	length	insensitive	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								

WHAT WE NEED TO IMPROVE

- GR is just a gravity
- Suitable for large scale only (at least bigger or equal to cluster size, 1Mpc, $10^{15}M_{\odot}$)
- What we calculate (DM δ) vs what we observe (baryon δ) : relation between them by nuisance parameter : b
- Need to reduce the theoretical systematics
- This may reduce the tensions in small scale predictions

DM VS B FLUCTUATIONS

$$\delta_b(k,t) = b(k,t)\delta_{DM}(k,t) = b(k,t)\,T(k)\,D(t)$$



Theory prediction (Gravity only)

$b(k,t) \leq 1$

Obsertional result

$b(k,t) \geq 1$

DM VS B FLUCTUATIONS -2

$$\delta_b(k,t) = b(k,t)\delta_{DM}(k,t) = b(k,t)\,T(k)\,D(t)$$

Theory prediction (Gravity only) b(k,t) ≤ 1

Obsertional result b(k,t) ≥ 1

It might be possible to obtain this nuisance parameter directly from the observation (SL, 15)

$$P'_{\rm gal}(k',z) = \frac{1}{f_\parallel^2 f_\perp^2} b^2 P_{\rm m}(k,z_0)(1+\beta\mu^2)^2 \left(\frac{g(z)}{g(z_0)}\right)^2,$$

$$b(k,z) = \frac{3}{2}\Omega_{\rm m}(z)\sigma_{\rm gal}(z)\left[\left(\frac{1}{2}-\frac{3}{2}w\Omega_{\rm de}(z)\right)f\sigma_8 - (1+z)\frac{d(f\sigma_8)}{dz}\right]^{-1}$$

$$= \frac{3}{2}\Omega_{\rm m}(z)\sigma_{\rm gal}(z)\left[\left(\frac{1}{2}-\frac{3}{2}w\Omega_{\rm de}(z)\right)\beta\sigma_{\rm gal} - (1+z)\frac{d(\beta\sigma_{\rm gal})}{dz}\right]^{-1}$$

I) CLUSTERS-1

- What's a cluster ?
- Composition : 50-1000 galaxies + hot X-ray emitting gas + dark matter (DM)
- Diameter : 2 - 10 Mpc
- Mass : 10^{14} - 10^{15} $M_\odot$

CLUSTERS-2

- Why clusters ?
- Clusters : the largest virialized objects // determined solely by gravitational physics (irrelevant to gas dynamics, star formation, and feedback : systematics)
- Abundance of clusters and their distribution in redshift determined by both geometry of the Univ and (quasi)-linear matter power spectrum

CLUSTER NUMBER

http://w.astro.berkeley.edu/~mwhite/teachdir/mini_ps.pdf

- Comoving number density dn of objects in the range dM :

$$dn = (\rho_m^0/M)|d\ln\sigma/dM|f(M)dM$$

- Press-Schechter (PS) formalism (74) :

Based on linear theory assumption

$$dn(M,z) = \sqrt{\frac{2}{\pi}}\frac{\rho_m^0}{M^2}\left|\frac{d\ln\sigma}{d\ln M}\right|\frac{\delta_c}{\sigma}\exp\left[-\frac{\delta_c^2}{2\sigma^2}\right]dM$$

- $\delta_c = 1.69$: traditional value (1.58 : exact value SL, K-W Ng, 10) : 6.5% errors // Exp[] 24% errors
- PS predicts too many low mass clusters and too few high mass clusters (σ, δ_c)

ANSATZ OF PS THEORY

δ : Gaussian random field, linear gravitational growth, spherical collapse

- Faction of mass (δM) in halos more massive than M is related to the faction of the volume (δV) in which the smoothed initial density field is above some critical density, δ_c : $P(\delta > \delta_c) = \int_{\delta}^{\infty} d\delta_M \frac{1}{\sqrt{2\pi}\,\sigma(M)} \exp\left[-\frac{\delta_M^2}{2\,\sigma^2(M)}\right] = \frac{1}{2}\mathrm{erfc}\left(\frac{\delta}{\sqrt{2}\,\sigma(M)}\right)$
- Various smoothing window but a top-hat window is most common
- δ_c = 1.69 (1.58) :extrapolated linear over-density at which a spherical top-hat perturbation would collapse.

SPHERICAL COLLAPSE MODEL I

SL 09

- Evolutions of whole Universe (scale factor : a) and locally bound system (radius of spherical clusters : R)

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left[\rho_{\rm cluster} + (1+3\omega_{\rm de})\rho_{\rm dec}\right],$$

$$\dot{\rho}_{\rm cluster} + 3\left(\frac{\dot{R}}{R}\right)\rho_{\rm cluster} = 0,$$

$$\dot{\rho}_{\rm dec} + 3(1+\omega_{\rm de})\left(\frac{\dot{R}}{R}\right)\rho_{\rm dec} = \alpha\Gamma,$$

$$\text{where } \Gamma = 3(1+\omega_{\rm de})\left(\frac{\dot{R}}{R} - \frac{\dot{a}}{a}\right)\rho_{\rm dec} \quad \text{with } 0 \le \alpha \le 1$$

a = 0 : clustered DE,
1 : homogeneous DE

$$\rho_{\rm dec}(a,R) = \rho_{\rm dec}^{\rm ta}\left(\frac{a}{a_{\rm ta}}\right)^{-3(1+\omega_{\rm de})\alpha}\left(\frac{R}{R_{\rm ta}}\right)^{-3(1+\omega_{\rm de})(1-\alpha)}$$

$$x = \frac{a}{a_{\rm ta}}, \qquad y = \frac{R}{R_{\rm ta}}$$

$$\frac{dx}{d\tau} = \frac{1}{\sqrt{x\Omega_{\rm m}(x)}} = \sqrt{x^{-1} + \frac{1}{Q_{\rm ta}}x^{-3\omega_{\rm de}-1}},$$

$$\frac{d^2y}{d\tau^2} = -\frac{1}{2}\left[\zeta y^{-2} + (1+3\omega_{\rm de})\frac{1}{Q_{\rm cta}}x^{-3(1+\omega_{\rm de})\alpha}y^{-3(1+\omega_{\rm de})(1-\alpha)+1}\right]$$

$$d\tau \equiv H_{\rm ta}\sqrt{\Omega_{\rm m}(x_{\rm ta})}dt,\ \zeta \equiv \frac{\rho_{\rm cluster}}{\rho_{\rm m}}\Big|_{z_{\rm ta}},\ Q_{\rm ta} \equiv \frac{\rho_{\rm m}}{\rho_{\rm de}}\Big|_{z_{\rm ta}} = \frac{\Omega_{\rm m}^0}{\Omega_{\rm de}^0}(1+z_{\rm ta})^{-3\omega_{\rm de}}$$

SPHERICAL COLLAPSE MODEL II

$$\delta_{\rm lin}(z_{\rm vir}) = \frac{3}{5}(\sqrt{\zeta})^{\frac{2}{3}}\left(\left(\frac{3}{4}+\frac{9\pi}{8}\right)\frac{1}{\sqrt{\zeta}}\right)^{\frac{2}{3}} = \frac{3}{20}(6+9\pi)^{\frac{2}{3}} \simeq 1.58$$

$$\delta_{\rm lin}(z) = \frac{D_g(z)}{D_g(z_{\rm vir})}\delta_{\rm lin}(z_{\rm vir})$$

- Solutions

$$\int_0^x dx'\sqrt{x'\Omega_{\rm m}(x')} = \int_0^\tau d\tau' \;\Rightarrow\; \frac{2}{3}x^{\frac{3}{2}}F\left[\frac{1}{2},-\frac{1}{2\omega_{\rm de}},1-\frac{1}{2\omega_{\rm de}},-\frac{x^{-3\omega_{\rm de}}}{Q_{\rm ta}}\right] = \tau$$

$$\tau_{\rm ta} = \frac{2}{3}F\left[\frac{1}{2},-\frac{1}{2\omega_{\rm de}},1-\frac{1}{2\omega_{\rm de}},-Q_{\rm ta}^{-1}\right]$$

$$\frac{d^2y}{d\tau^2} = -\frac{1}{2}\left[\zeta y^{-2}+(1+3\omega_{\rm de})\frac{1}{Q_{\rm ta}}x^{-3(1+\omega_{\rm de})}y\right]$$

$$\frac{dy^2}{d\tau^2} = -\frac{1}{2}\zeta y^{-2} \equiv f(y) \;\Rightarrow\; \int_0^y \frac{dy'}{\sqrt{-c_1+2\int^{y'} f(y'')dy''}} = c_2 \pm \tau$$

$$\text{ArcSin}[\sqrt{\text{y}}] - \sqrt{\text{y}(1-\text{y})} = \sqrt{\zeta_{13}}\tau \text{ , when } \tau \le \tau_{\rm ta13}\,,$$
$$\sqrt{y(1-y)} - \text{ArcSin}[\sqrt{\text{y}}] + \frac{\pi}{2} = \sqrt{\zeta_{13}}(\tau-\tau_{\rm ta13}) \text{ , when} \tau \ge \tau_{\rm ta13}$$

$$\zeta_{\rm sk} = \left(\frac{3\pi}{4}\right)^2\Omega_{\rm mta}^{-0.724+0.157\Omega_{\rm mta}+\alpha(1+\omega_{\rm de})(1+3\omega_{\rm de})(0.064-0.368\Omega_{\rm mta})}$$

$$\sqrt{y(1-y)} - \text{ArcSin}[\sqrt{\text{y}}] + \frac{\pi}{2} + \left(-\frac{(1+3\omega_{\rm de})}{3}\Omega_{\rm mta}\right)^{2.7+0.1\Omega_{\rm mta}-3.4(1+\omega_{\rm de})-0.02\zeta_{\rm sk}+3(\text{z}_{\rm ta}-0.6)}$$
$$= \sqrt{\zeta_{\rm sk}}(\tau-\tau_{\rm ta}) \qquad (2.24$$
$$= \frac{2}{3}\sqrt{\zeta_{\rm sk}}\left(x^{\frac{3}{2}}F\left[-\frac{1}{2\omega_{\rm de}},\frac{1}{2},1-\frac{1}{2\omega_{\rm de}},-\frac{x^{-3\omega_{\rm de}}}{Q_{\rm ta}}\right] - F\left[-\frac{1}{2\omega_{\rm de}},\frac{1}{2},1-\frac{1}{2\omega_{\rm de}},-\frac{1}{Q_{\rm ta}}\right]\right).$$

NON-LINEAR OVERDENSITY

- Conventional values for over-density adopted at the collapse epoch

$$\Delta_c^{\rm EdS} = \zeta\left(\frac{x_c}{y_{\rm vir}}\right)^3 = \left(\frac{3\pi}{4}\right)^2\left(\frac{2^{\frac{2}{3}}}{2^{-1}}\right)^3 = 18\pi^2 \simeq 178$$

SL, 10

- This value should be obtained from the virialized epoch

$$\Delta_{\rm vir}^{\rm EdS} = \zeta\left(\frac{x_{\rm vir}}{y_{\rm vir}}\right)^3 = \left(\frac{3\pi}{4}\right)^2\left(\frac{\left(\frac{1}{\pi}+\frac{3}{2}\right)^{\frac{2}{3}}}{2^{-1}}\right)^3 = 18\pi^2\left(\frac{1}{2\pi}+\frac{3}{4}\right)^2 \simeq 147$$

17% improvement

- This value also depends on the background universe (with/ without DE)

$$\Delta_{\rm vir} \equiv \Delta(z_{\rm vir}) = \left.\frac{\rho_{\rm cluster}}{\rho_{\rm m}}\right|_{z_{\rm vir}} = \zeta\left(\frac{x_{\rm vir}}{y_{\rm vir}}\right)^3 = 18\pi^2\frac{x_{\rm vir}^3}{4(F\left[\frac{1}{2},\frac{3}{2},\frac{5}{2},-\frac{x_{\rm vir}}{Q_{\rm ta}}\right])^2}$$

Simulation community uses ~ 200 for this

STANDARD PERTURBATION THEORY

$$\frac{\partial\hat{\delta}}{\partial\tau}+\hat{\theta} = -\int d^3k_1\int d^3k_2\delta_{\rm D}(\vec{k}_{12}-\vec{k})\alpha(\vec{k}_1,\vec{k}_2)\hat{\theta}(\tau,\vec{k}_1)\hat{\delta}(\tau,\vec{k}_2)\,,$$

$$\frac{\partial\hat{\theta}}{\partial\tau}+\mathcal{H}\hat{\theta}+\frac{3}{2}\Omega_m\mathcal{H}^2\hat{\delta} = -\frac{1}{2}\int d^3k_1\int d^3k_2\delta_{\rm D}(\vec{k}_{12}-\vec{k})\beta(\vec{k}_1,\vec{k}_2)\hat{\theta}(\tau,\vec{k}_1)\hat{\theta}(\tau,\vec{k}_2)\,,$$

$$\alpha(\vec{k}_1,\vec{k}_2)\equiv\frac{\vec{k}_{12}\cdot\vec{k}_1}{k_1^2},\ \text{and}\ \beta(\vec{k}_1,\vec{k}_2)\equiv\frac{k_{12}^2(\vec{k}_1\cdot\vec{k}_2)}{k_1^2k_2^2}$$

$$\hat{\delta}(\tau,\vec{k}) \equiv \sum_{n=1}^{\infty}\hat{\delta}^{(n)}(\tau,\vec{k})\,,$$

$$\hat{\theta}(\tau,\vec{k}) \equiv \sum_{n=1}^{\infty}\hat{\theta}^{(n)}(\tau,\vec{k})\,,$$

$$\hat{\delta}^{(1)}(a,\vec{k}) \equiv D_1(a)\delta_1(\vec{k})\,,$$

$$\hat{\theta}^{(1)}(a,\vec{k}) \equiv D_{\theta 1}(a)\theta_1(\vec{k}) \equiv -a\mathcal{H}\frac{dD_1}{da}\delta_1(\vec{k})\,,$$

$$\hat{\delta}^{(2)}(a,\vec{k}) \equiv \sum_{i=1}^{2}D_{2i}(a)K_{2i}(\vec{k}) \equiv D_1^2(a)\sum_{i=1}^{2}c_{2i}(a)K_{2i}(\vec{k})\,,$$

$$\hat{\theta}^{(2)}(a,\vec{k}) \equiv \sum_{i=1}^{2}D_{\theta 2i}(a)K_{2i}(\vec{k}) \equiv a\mathcal{H}D_1\frac{dD_1}{da}\sum_{i=1}^{2}c_{\theta 2i}(a)K_{2i}(\vec{k})\,,$$

$$\hat{\delta}^{(3)}(a,\vec{k}) \equiv \sum_{i=1}^{6}D_{3i}(a)K_{3i}(\vec{k}) \equiv D_1^3(a)\sum_{i=1}^{6}c_{3i}(a)K_{3i}(\vec{k})\,,$$

$$\hat{\theta}^{(3)}(a,\vec{k}) \equiv \sum_{i=1}^{6}D_{\theta 3i}(a)K_{3i}(\vec{k}) \equiv a\mathcal{H}D_1^2\frac{dD_1}{da}\sum_{i=1}^{6}c_{\theta 3i}(a)K_{3i}(\vec{k})\,,$$

exact SPT : SL, Park, Biern 14
exact LPT : SL 14
about 4 % improvement

MASS FLUCTUATION

- RMS linear mass fluctuation

$$\sigma_R^2(a) \equiv \left\langle \left| \frac{\delta M}{M(R,a)} \right|^2 \right\rangle = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k,a) \left| W(kR) \right|^2 dk$$

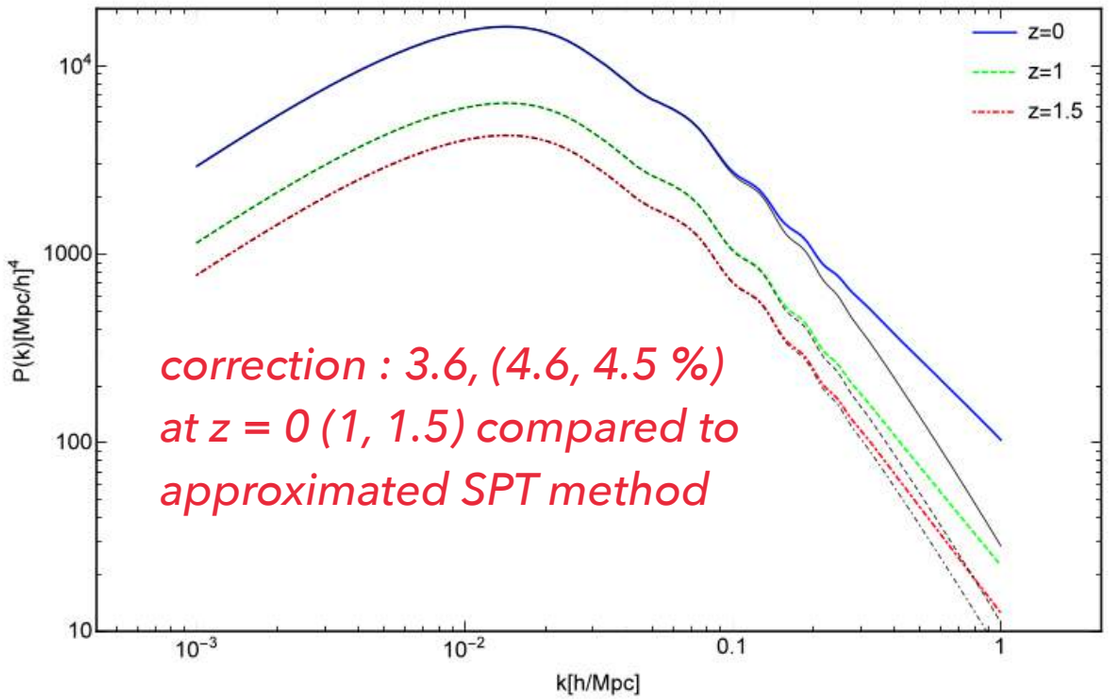
$$\sigma(M,z) \simeq (-\omega_{\rm Q})^{0.72+0.36\omega_{\rm Q}} \left(3.90 - 0.22 \log \left[\frac{M}{h^{-1} M_\odot} \right] \right) \left(\frac{D_g(z)}{D_g(z_0)} \right)$$

- If we include quasi-linear effect, then (SL 17)

$$\sigma_R(z) = D_1(z) \sigma_R^{\rm lin} \sqrt{1 + D_1^2(z) \delta_{\sigma_R}(z)} \simeq D_1(z) \sigma_R^{\rm lin} \sqrt{1 + 32 D_1^2(z) \times R({\rm Mpc/h})^{-1.7}}$$

- Difference btw linear & quasi-linear

MASS FLUCTUATION



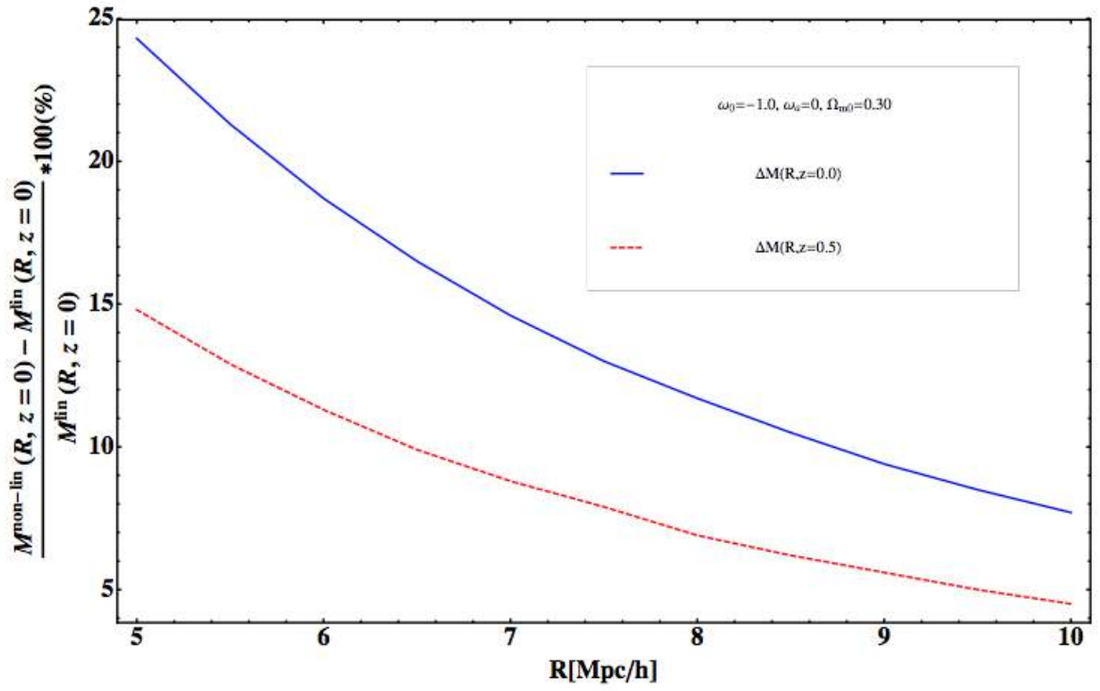
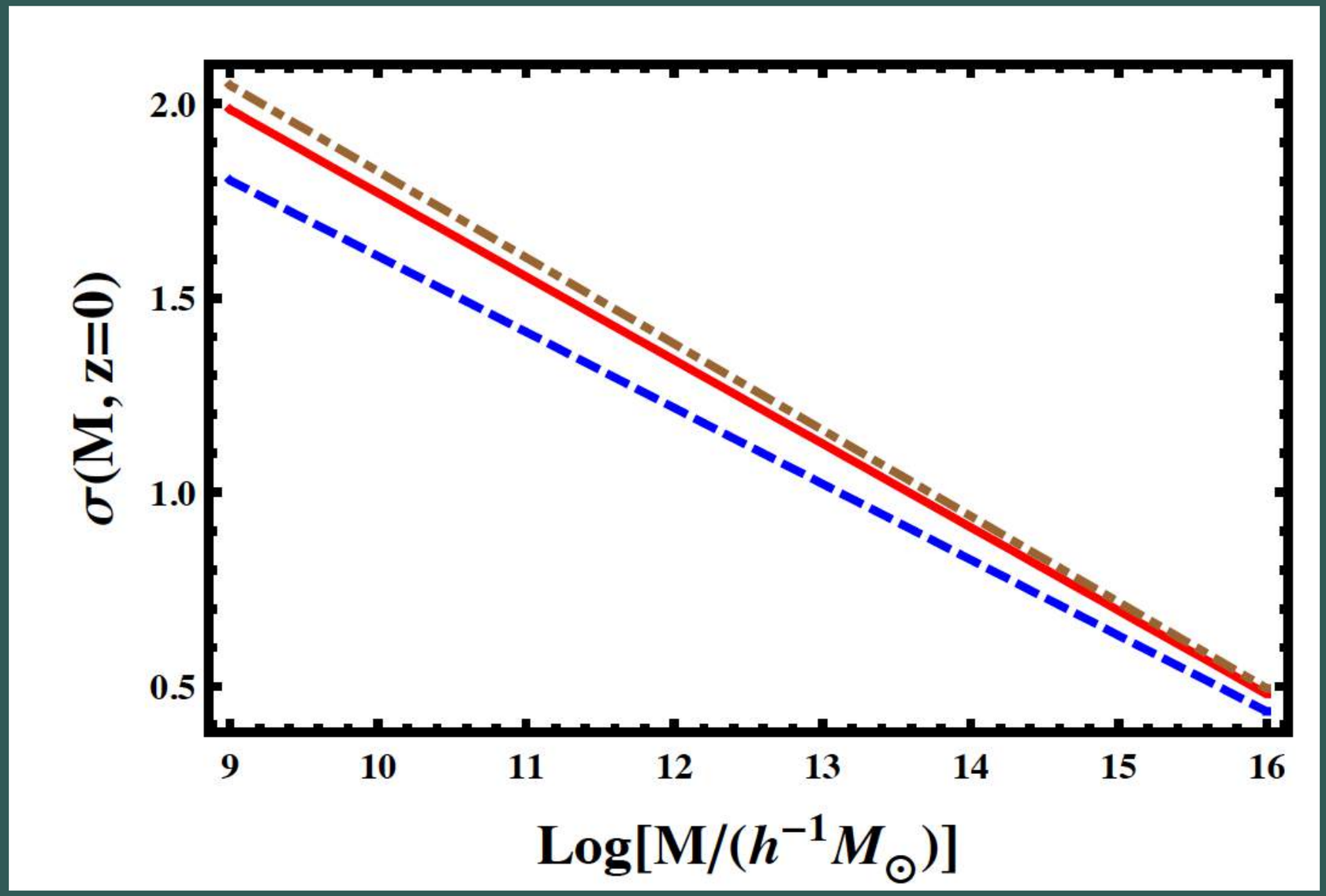


Figure 2: a)The matter power spectrum with one-loop correction at present for $\omega = -1.0$ and $\Omega_{m0} = 0.26$ model. Gray lines are the linear power spectra. b) ΔM for the different smoothing scale R at different redshifts

- Difference btw linear & quasi-linear (SL, Park, Biern 14, SL in preparation)

MASS FLUCTUATION

- As a function of mass



CLUSTER ABUNDANCES

- With correct δ_c and σ (SL 10)

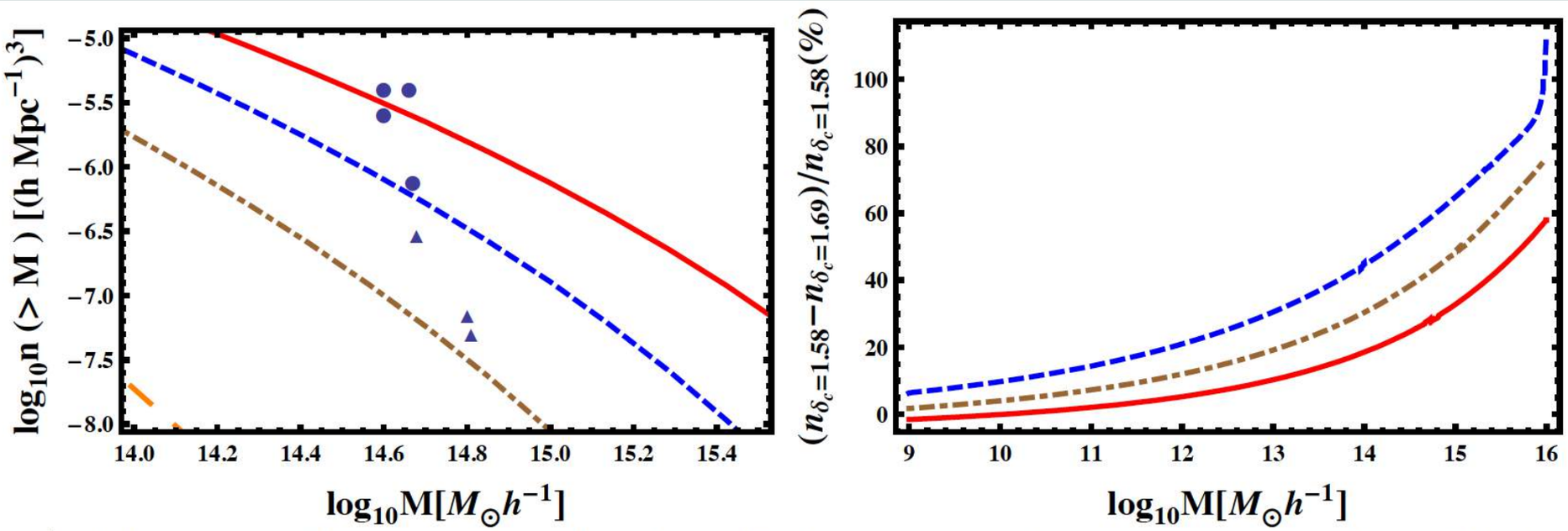


Figure 4: a) The comoving number density of clusters n of mass greater than M for different values of $z = 0$, 0.5, 1.0, and 2.0 (from top to bottom) when $\omega_{\rm Q} = -1$ and $\delta_c = 1.58$. The circular ($z \simeq 0$) and triangular ($0.18 \leq z \leq 0.85$) dots represent the data from Ref. [39]. b) Errors of n when we use the correct threshold density contrast $\delta_c = 1.58$ instead of 1.69 for different values of $z = 0$, 0.5, and 1.0 (from bottom to top).

MASS FUNCTIONS

$$f_{\rm ST}(\sigma) = A\sqrt{\frac{2b}{\pi}}\exp\left[-\frac{b\delta_c^2}{2\sigma^2}\right]\left[1+\left(\frac{\sigma^2}{b\delta_c^2}\right)^p\right]\frac{\delta_c}{\sigma}$$

$$f_{\rm mod}(\sigma,z) = \tilde{A}\sqrt{\frac{2}{\pi}}\exp\left[-\frac{\tilde{b}\delta_c^2}{2\sigma^2}\right]\left[1+\left(\frac{\sigma^2}{\tilde{b}\delta_c^2}\right)^{\tilde{p}}\right]\left(\frac{\delta_c\sqrt{\tilde{b}}}{\sigma}\right)^{\tilde{q}}$$

- In order to match with N-body simulation, there exit various mass functions
- Do we need f(M) or other sources of inconsistency

$$f_{\rm LN}(\sigma,z) = 0.32\sqrt{\frac{2(0.67)}{\pi}}\exp\left[-\frac{0.67\delta_c^2}{2\sigma^2}\right]\left[1+\left(\frac{\sigma^2}{0.67\delta_c^2}\right)^{0.32}\right]\frac{\delta_c}{\sigma}$$

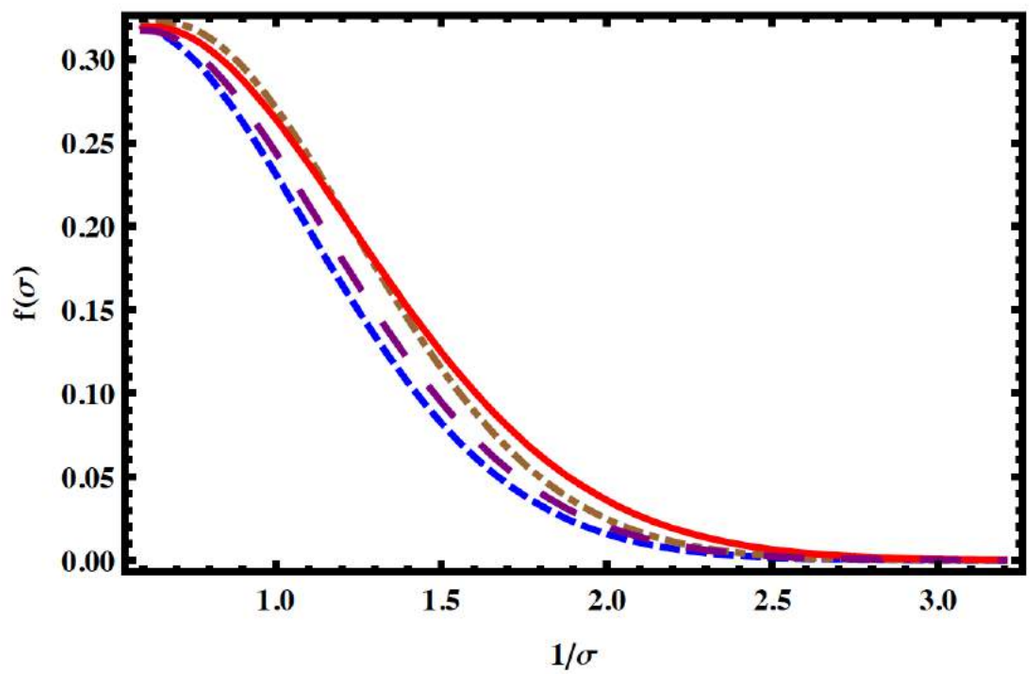
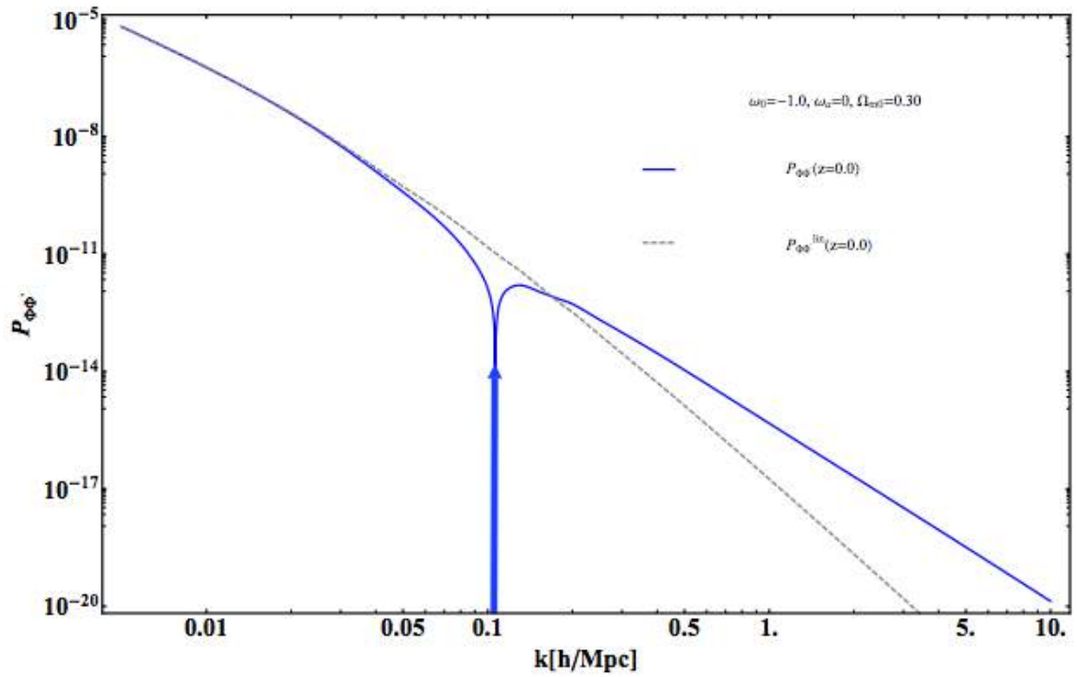


Figure 6: The different mass functions as a function of σ: $f_{\rm ST}$, $f_{\rm Manera}$, $f_{\rm LN}$, and $f_{\rm mod}$ (from bottom to top).

REES-SCIAMA EFFECT

- Non-linear effect on ISW effect (SL 15, 16)



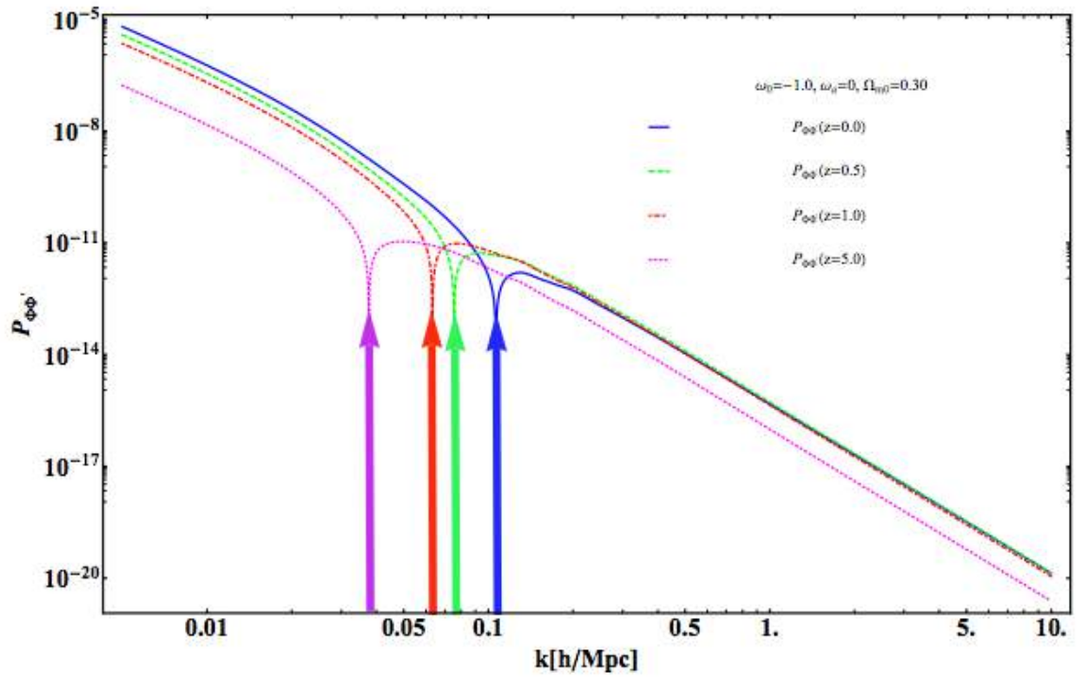


FIG. 1: RS effect for ΛCDM model with $\Omega_{m0} = 0.3$. a) Comparison between ISW effect (dahsed line) and RS effect (solid line) at $z = 0$. b) Different flipping scales from anti-correlated to correlated power spectra at different redshifts. The solid, dashed, dotdashed, and dotted lines correspond to $z = 0$, 0.5, 1, and 5, respectively.

FIG. 1: CMB-WL cross-correlation spectra, $C_l^{\mathrm{RS}-\kappa}$ of different dark energy models for different WL surveys ($n_{1(2)}$). a) $C_l^{\mathrm{RS}-\kappa}$ for n_1 (deep survey). The dotted, the solid, and the dashed lines represent $\omega = -0.7, -1.0$, and -1.3, respectively. b) $C_l^{\mathrm{RS}-\kappa}$ for n_2 (shallow survey) with the same notation as the left panel.

REES-SCIAMA EFFECT-2

- Non-linear effect on ISW effect (SL 15, 16)

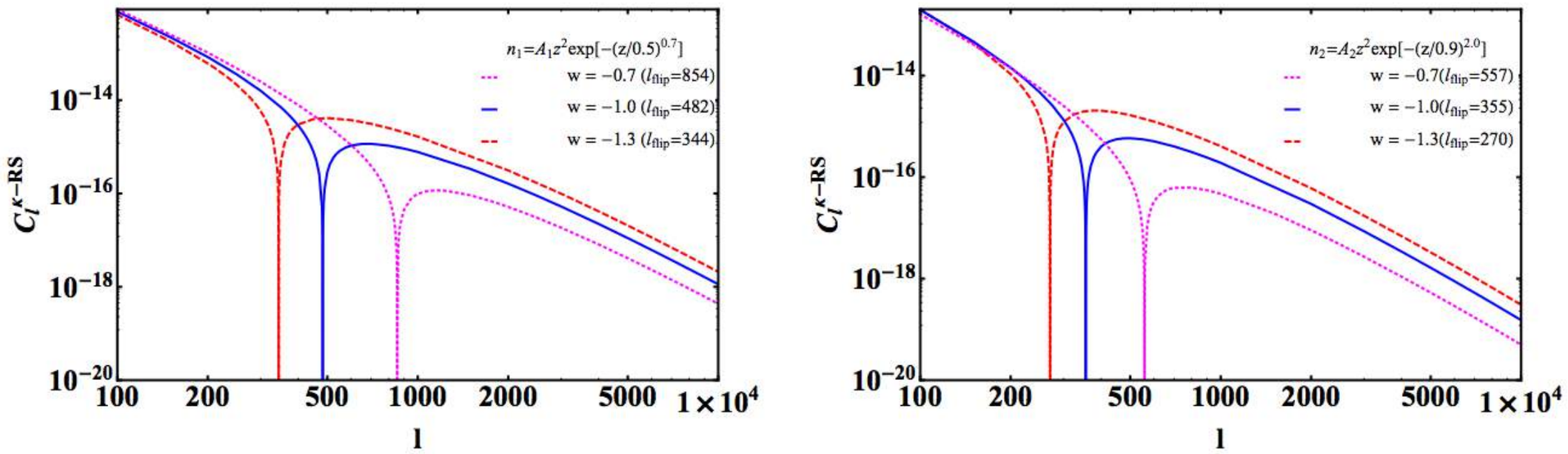
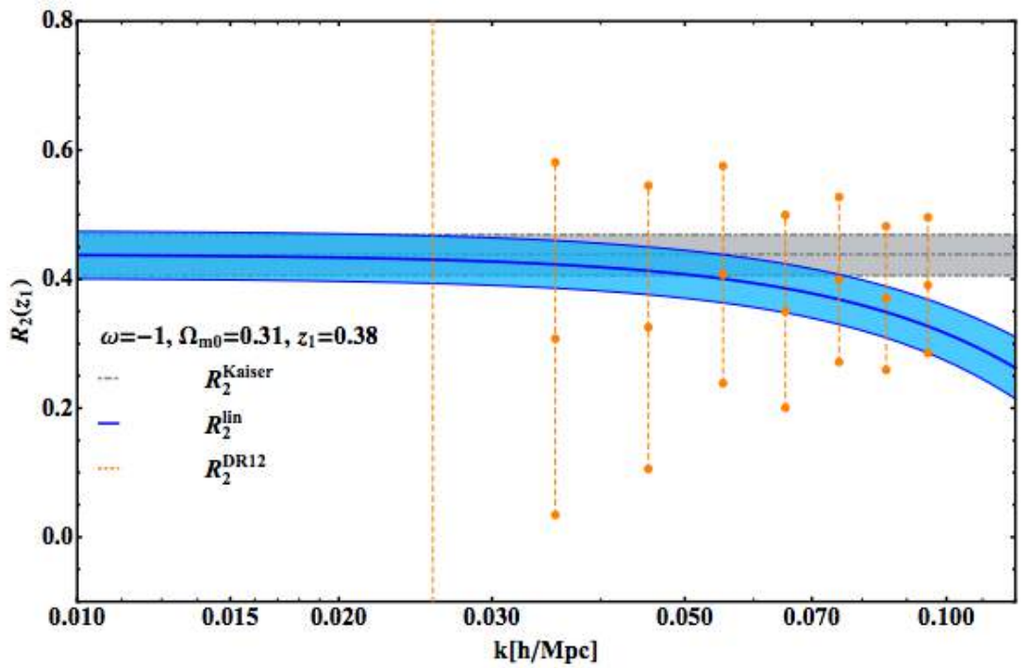


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RECONSTRUCTION PS FROM OBSERVATION

- SL 18 (Using DR12 data, Beutler et.al 17)



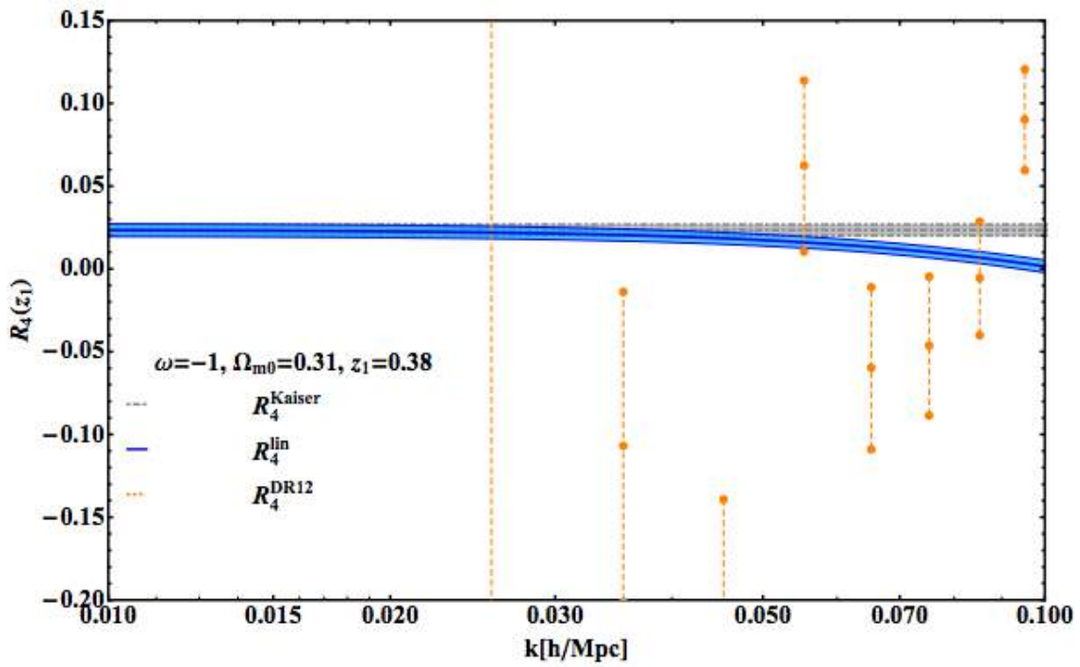


Figure 2. The values of R_2 and R_4 at $z = 0.38$. a) The ratio of quadrupole to monopole, R_2. The dark shaded region is the 1-σ prediction of the Kaiser limit. The bright shaded region is the 1-σ prediction of the linear theory. The vertical dashed lines indicate the 1-σ results of the DR12. b) The ratio of hexadecapole to monopole, R_4 with the same notation as in the left panel.

RECONSTRUCTION PS FROM OBSERVATION

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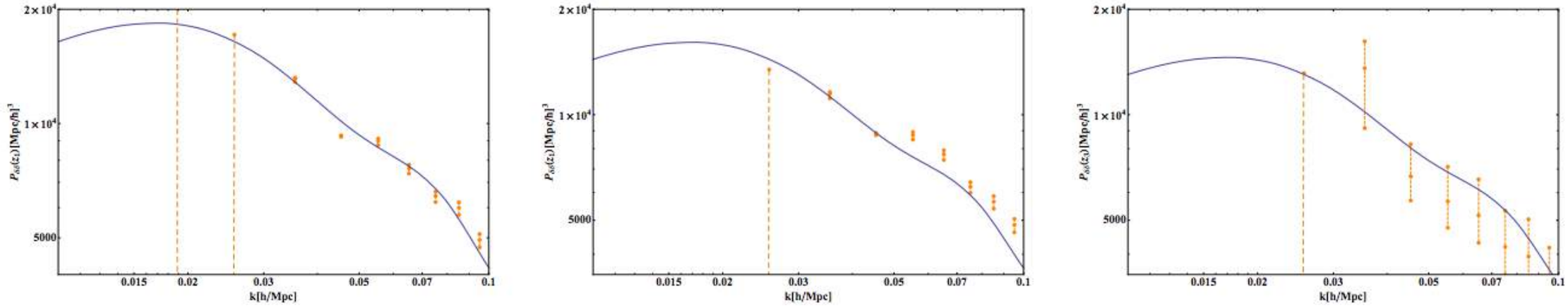


Figure 5. The recovered matter power spectra at z_1, z_2, and z_3. a) The solid line is the linear matter power spectrum of the fiducial model at z_1. The vertical lines are 1-σ measurements of the recovered power spectrum. b) The linear theory matter power spectrum (solid line) and the recovered power spectrum (vertical dashed lines) at z_2. c) The linear matter PS and the recovered PS from measurement at z_3.

POSSIBLE CANDIDATES FOR INCONSISTENCY

- Should we rely on linear prediction?
- If we include quasi-linear effect in mass fluctuation, then the theory is still consistent?
- Using the correct critical density can partly cure the PS problem.
- f(M) ?

MASSIVE GWs 1

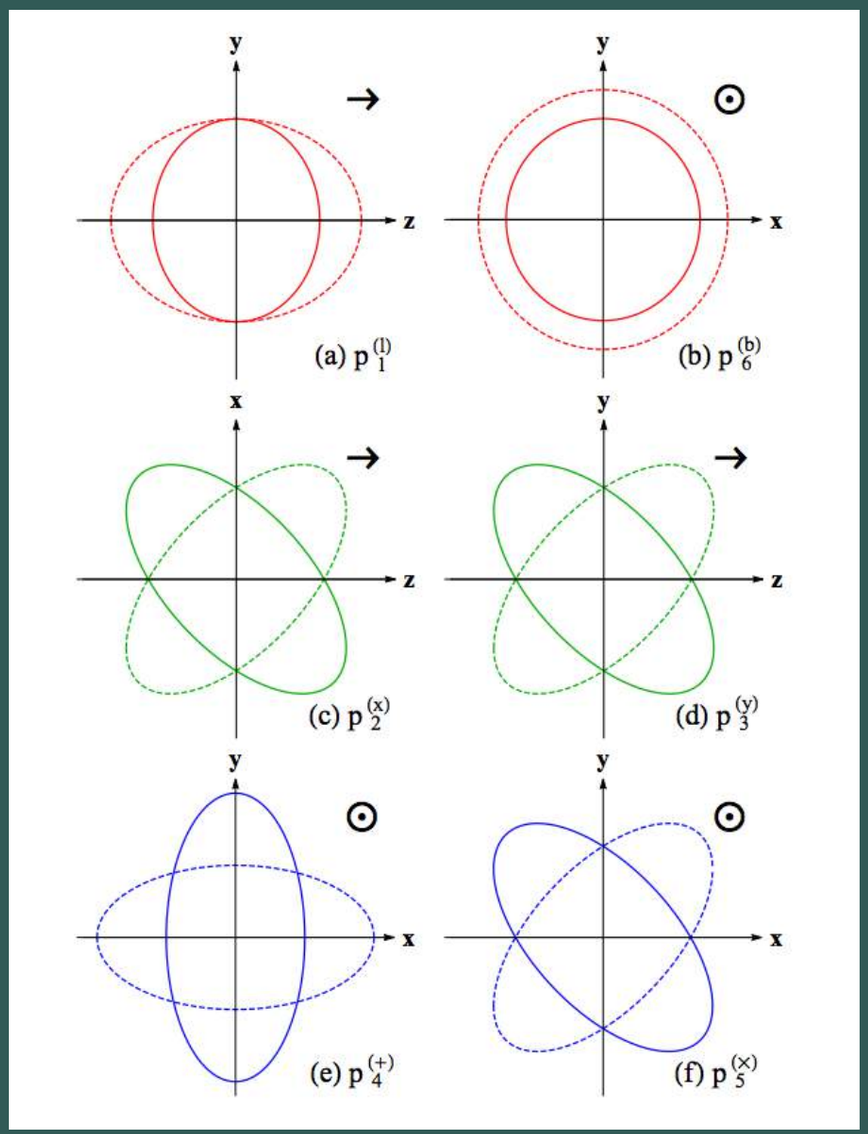
- GW is a nothing but just a source of a deviation of two nearby geodesic (YH Hyun, YB Kim, SL, 18) x^μ and $x^\mu + \xi^\mu$

$$\frac{D^2\xi^\mu}{D\tau^2} = -R^\mu{}_{\nu\rho\sigma}\xi^\rho \frac{dx^\nu}{d\tau}\frac{dx^\sigma}{d\tau} = -R^\mu{}_{\nu\rho\sigma}\xi^\rho u^\nu u^\sigma$$
$$\longrightarrow \ddot{\xi}_i = -R_{0i0j}\xi^j$$

- Thus, the Riemann tensor is all the necessary information for the GW polarization

MASSIVE GWs 2

- Riemann tensor vs GW polarizations



$$S = \begin{pmatrix} R_{txtx} & R_{txty} & R_{txtz} \\ R_{tytx} & R_{tyty} & R_{tytz} \\ R_{tztx} & R_{tzty} & R_{tztz} \end{pmatrix} = \begin{pmatrix} \frac{1}{2}(p_4+p_6) & p_5 & p_2 \\ p_5 & \frac{1}{2}(-p_4+p_6) & p_3 \\ p_2 & p_3 & p_1 \end{pmatrix}$$

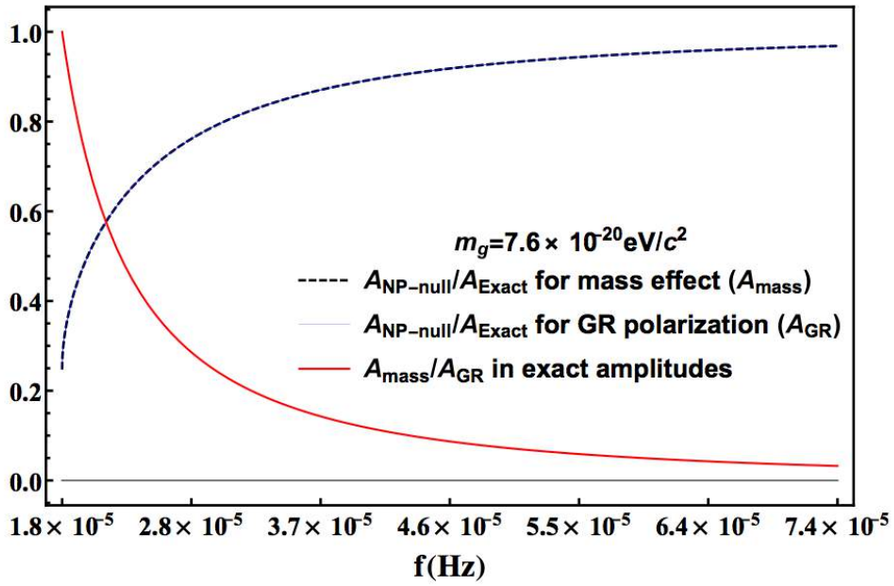
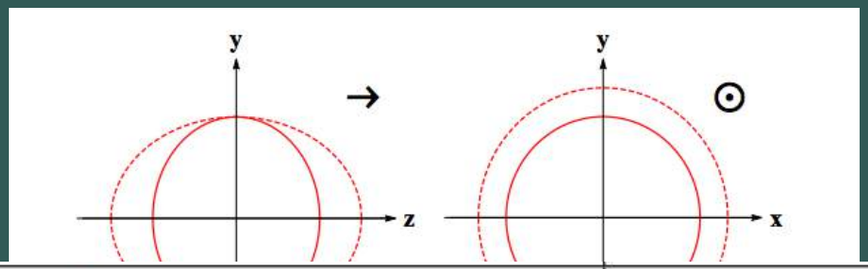


Figure 3. The ratio between the approximate and exact mode amplitudes in the low-frequency region is shown for the weakest model-independent graviton mass bound. The more the mode amplitude appearing for the time-like geodesic is enhanced, the more the deviation of the approximate amplitude from the exact one grows.

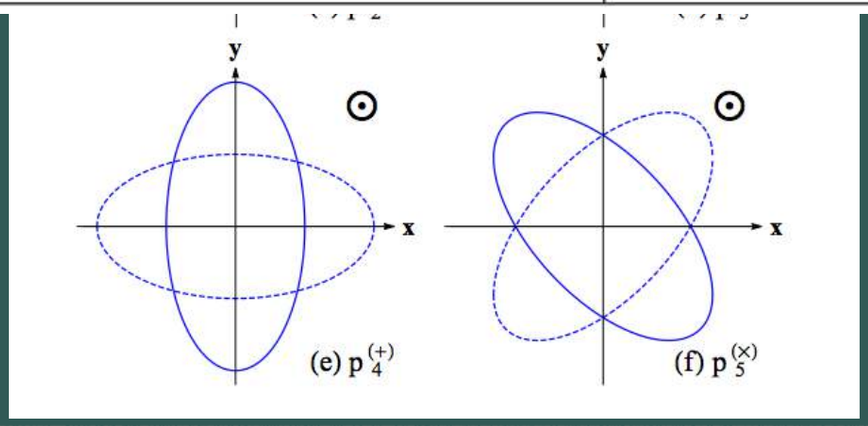
MASSIVE GWs 2

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polarization amplitude	$p^{(l)} \equiv \Psi_2$	$p^{(l)} \equiv R_{tztz} = 6\Psi_2 - [2(\Psi_2 + 2\Lambda)]$
difference of amplitudes between null(N) and non-null(NN) GWs (about correction terms)	$\Delta p^{(l)} \equiv \underbrace{p^{(l)}\vert_{\rm NN}}_{\text{when } \tilde{k}^\mu \not\propto k^\mu} - \underbrace{p^{(l)}\vert_{\rm N}}_{\text{when } \tilde{k}^\mu \propto k^\mu} = \Psi_2\vert_{\rm NN} - \Psi_2\vert_{\rm N} = \mathcal{O}(\epsilon_n R)$	$\Delta p^{(l)} \equiv p^{(l)}\vert_{\rm NN} - p^{(l)}\vert_{\rm N} = 6(\Psi_2\vert_{\rm NN} - \Psi_2\vert_{\rm N}) - \{[2(\Psi_2 + 2\Lambda)]\vert_{\rm NN} - [2(\Psi_2 + 2\Lambda)]\vert_{\rm N}\}$



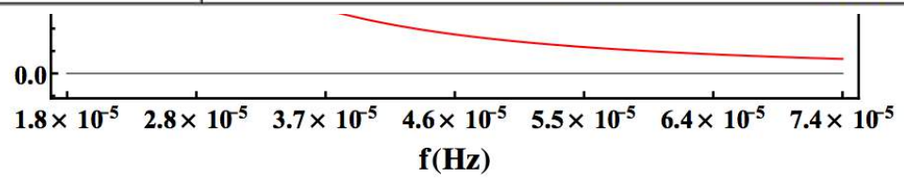


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SUMMARY

- Systematics in cosmological observations is severe than particle physics one because of its lack of reproducibility.
- Systematics in theories are sometimes ignored because of its original starting from astronomy.
- Especially as a first principle theory, the results are safe in large scales but need care in small scales
- We still have many rooms to improve theoretical systematics by performing more careful calculations
- Still its just based on BB + inflation. It's possible that our universe is different from this. Then we need the whole new paradigm.


imagine the impossible!
THANKS!
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