MEASURING NEUTRINO PROPERTIES WITH COSMOLOGY

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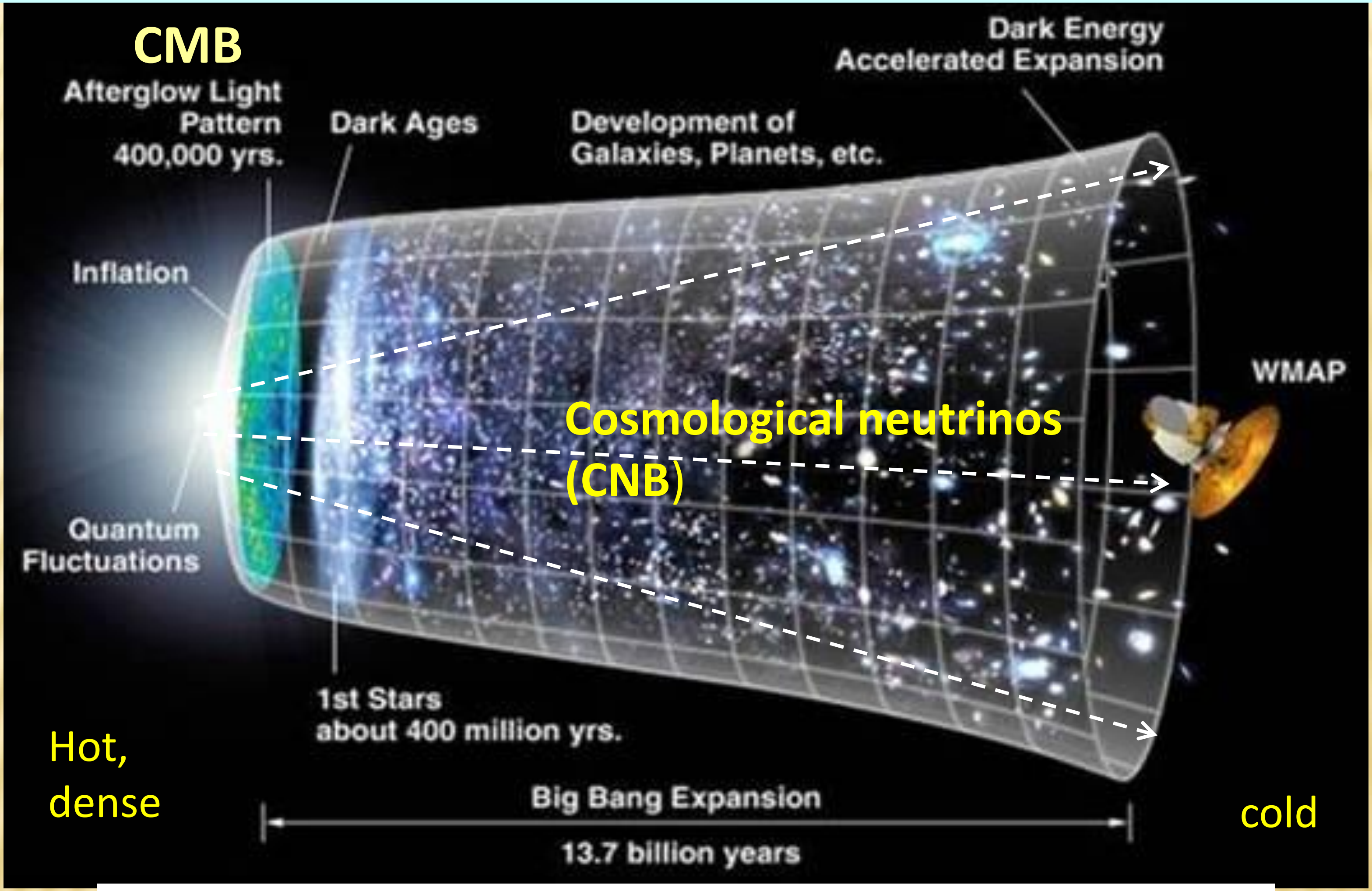
OUTLINE

- Cosmological neutrinos: finite mass, degeneracy
- Effects on expansion history (H)
- Alleviating the H_o problem
- Measuring neutrino mass with matter distribution

HISTORY OF THE UNIVERSE



CNB: most abundant fermions in the universe, 300/cc everywhere produced in the first 1s of the Big Bang.

Figure courtesy NASA/WMAP

NEUTRINOS SHAPE THE UNIVERSE

COSMOLOGICAL NEUTRINOS

Neutrino oscillation expt.s: $m_\nu > 9\text{x}10^{-3}$ eV >> $T_{\nu,0} \approx 2\text{K} \approx 1.6\text{x}10^{-4}$ eV

$\therefore$ Cosmological neutrinos are non-relativistic today.

$v \approx 1{,}500$ km/s today for $m_\nu \sim 0.1$ eV

Neutrino energy density $\rho_\nu = \Sigma_i\, n_{\nu i}\, m_{\nu i}$, $i = 1, 2, 3$ for 3 types of ν

$\Rightarrow \Omega_\nu \equiv 8\pi G\rho_\nu/3H_o \;\; = (\Sigma_i\, m_{\nu i})/47$ eV

CMB, BAO $\Rightarrow \Omega_\nu < 0.02$

$\Rightarrow \Sigma_i\, m_{\nu i} < 1$ eV   even tighter than lab expt.s (6 eV)

- Today: $p_\nu \sim T_{\nu,0} \approx 0.00016$ eV $\Rightarrow \lambda_\nu \approx 0.8$ cm
- Number density $n_\nu \approx 0.18\, T_{\nu,0}^{\;3} \approx 112$ cm^{-3} for each flavor
- $\therefore$ average separation $d = n_\nu^{-1/3} \approx 0.2$ cm $\approx \lambda_\nu/4$
- Expect at least partial degeneracy

Should consider finite m_ν , $\xi_\nu \equiv \mu/T_\nu$; μ = neutrino chemical potential

NEUTRINO COSMOLOGY

- Neutrino energy density

$$\rho_\nu(T) = \int_0^\infty \frac{E}{e^{\frac{p}{T}-\xi}+1} p^2 dp + \int_0^\infty \frac{E}{e^{\frac{p}{T}+\xi}+1} p^2 dp, \qquad \xi \equiv \frac{\mu}{T} \qquad E = (m_i^2 + p^2)^{1/2}$$

$$\frac{\dot{a}}{a} = H(t) = \sqrt{\frac{8\pi G}{3}\left[\rho_m + \rho_\gamma + \rho_\nu\right]}$$

Neutrino mass and degeneracy affect the Hubble expansion

- Cosmological parameters are extracted assuming $\xi = 0$. Should re-fit data with $\{m_i, \xi_i\}$ as parameters as well.

- Neutrino asymmetry important for Leptosynthesis

$$L \equiv \frac{n - \bar{n}}{n_\gamma} = \frac{1}{12\zeta(3)} y_\nu^3 [\xi^3 + \pi^2 \xi]$$

- Majorana fermions: $\xi = 0$
  If cosmological data $\Rightarrow \xi \neq 0$ then neutrinos are Dirac!

EFFECTS OF M_ν AND ξ_ν ON HUBBLE PARAMETER $H(Z)$

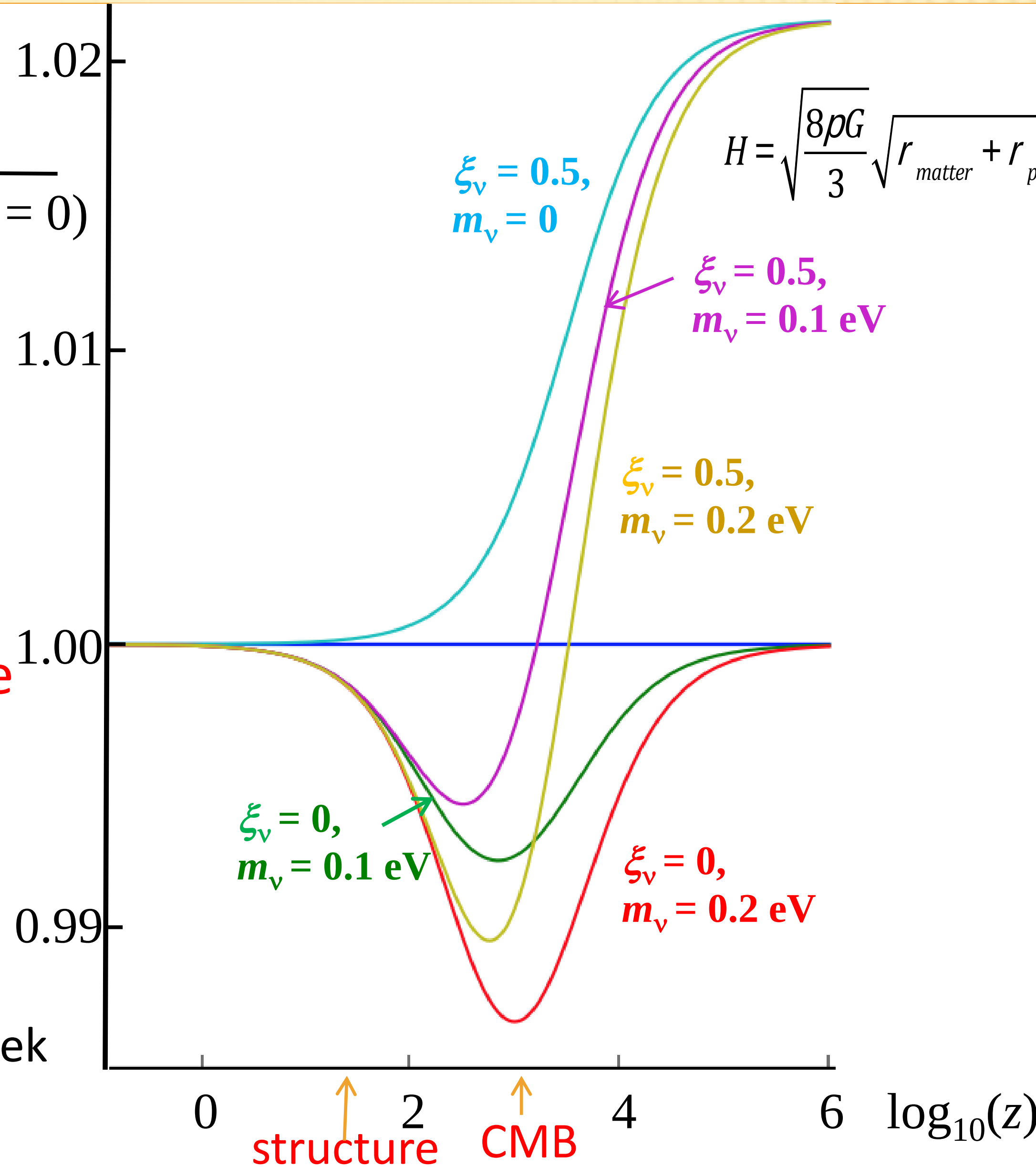
$$\frac{H(\xi_\nu, m_\nu)}{H(\xi_\nu = 0, m_\nu = 0)}$$

ξ_ν : larger H

m_ν : smaller H

Larger expansion rate at CMB, smaller at structure formation!

$$H = \sqrt{\frac{8\pi G}{3}}\sqrt{\rho_{matter} + \rho_{photon} + \ldots + \rho_{neutrino}}$$



Calculations done by Shek Yeung, Carton Zeng

CONSTRAINTS ON ξ_ν

- ξ_ν directly affects the neutron-to-proton ratio and hence the primordial ^{4}He abundance
- BBN $\rightarrow$ $-0.021 \leq \xi_\nu \leq 0.005$ F. Iocco et al., Phys. Rep. **472**, 1 (2009).

- But: BBN constrains only ξ_e
- Large ν_μ-ν_τ mixing $\Rightarrow \xi_\mu = \xi_\tau$; small mixing with $\nu_e \Rightarrow \xi_\mu \neq \xi_e$

- Should use mass basis after decoupling $\{\xi_{e,\,\mu,\,\tau}\} \rightarrow \{\xi_{1,\,2,\,3}\}$
- 1 free parameter: choose $\eta \equiv (\Sigma_i\ \xi_i^{\,2})^{1/2}$

$\eta \sim 1$ still allowed!

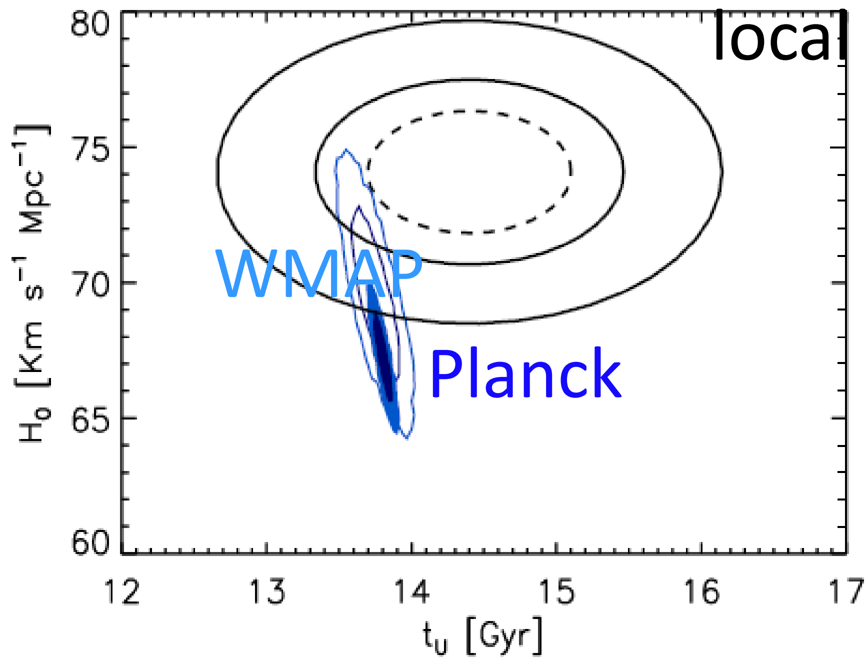
I. ALLEVIATING THE H_O PROBLEM

H_O PROBLEM

$H \equiv \dot{a}/a$, $H_o \equiv H(z = 0)$ today

Astronomers using NASA's Hubble Space Telescope have discovered that the universe is expanding 5 percent to 9 percent faster than expected.

‘It may mean that dark energy is shovin
even greater — or growing — strength.
new type of subatomic particle referred
possibility is that "dark matter," an invis
the bulk of our universe, possesses som
Finally, Einstein's theory of gravity may
These unnerving scenarios are based or
Laureate Adam Riess, who began a que
expansion rate to unprecedented accur
techniques. The new measurement red
uncertainty of only 2.4 percent. That's t
does not agree with expansion measure
fireball relic radiation from the big bang. So it seems like something's amiss — possibly sending cosmologists back to the drawing board.



L. Verde et al., http://arxiv.org/pdf/1306.6766.pdf

http://hubblesite.org/newscenter/archive/releases/2016/17/

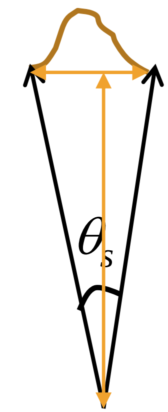
H_O CORRELATES WITH ξ_ν

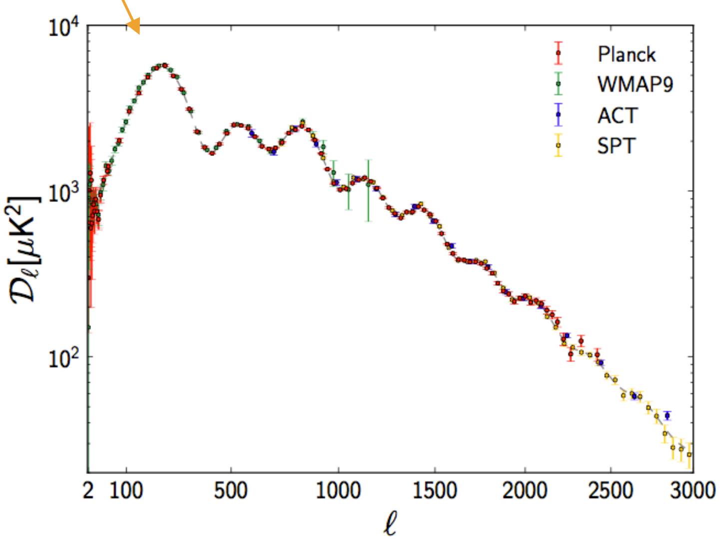
- ΛCDM + $\xi_\nu(=\mu/T)$ + m_ν fitting @ *Planck* C_l^{TT}

Angular scale of first peak

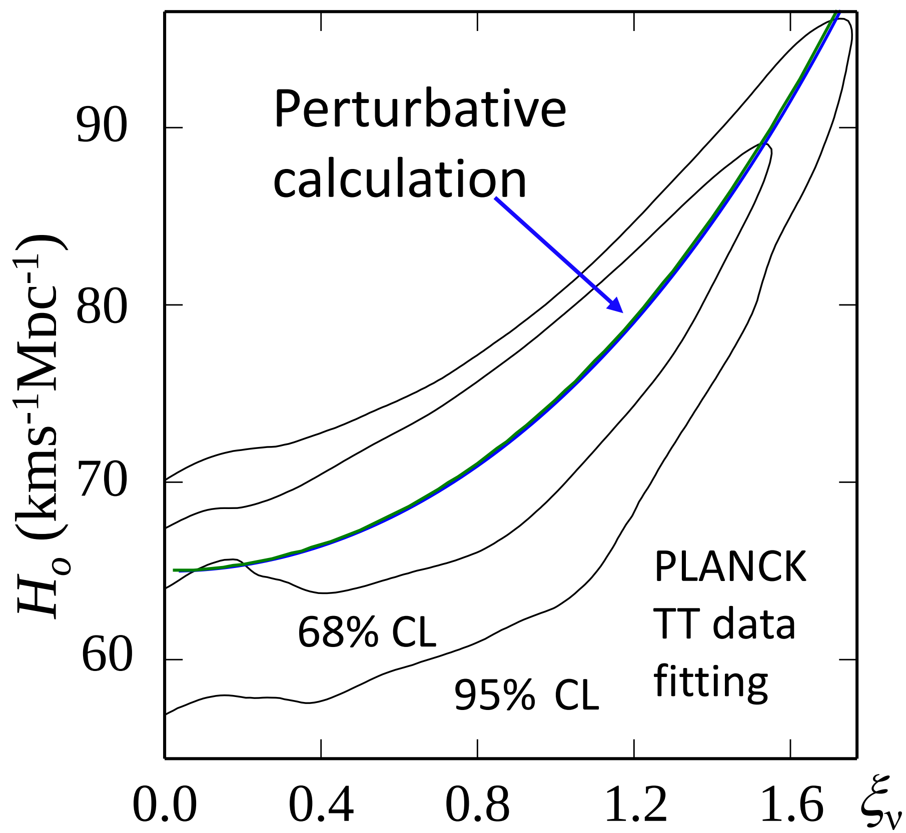
$$\theta_s = \int_0^{a_*} \frac{da}{\sqrt{3(1+R)}\,H(a)a^2} \Big/ \int_{a_*}^{1} \frac{da}{H(a)a^2},$$

= Sound horizon at decoupling/ distance from decoupling to now





$\xi_\nu \sim 0.5 \rightarrow H_o \sim 70$



Calculated by King Lau, Shek Yeung

CMB FITTING WITH FINITE ξ_ν, M_ν

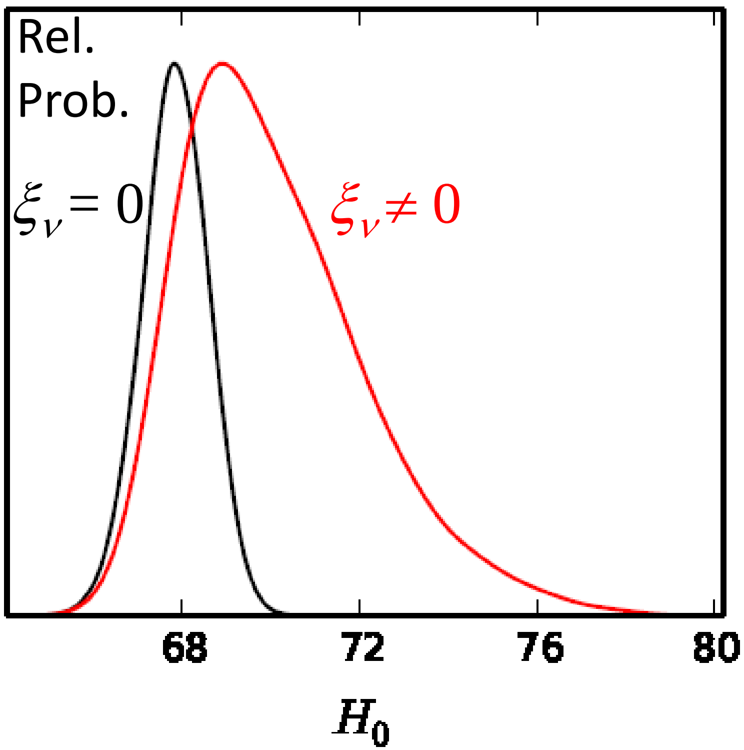
PLANCK C_l^{TT} + BAO fitting

Preliminary results

with $\xi_\nu = 0$:

$H_o = 67.84 \pm 0.73$

$\Sigma m_\nu = 0.12 \pm 0.09$ eV

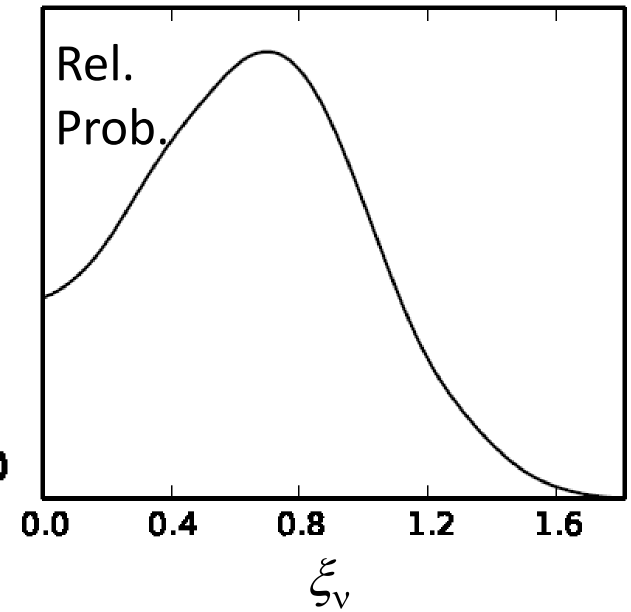


with $\xi_e = 0$, $\xi_\mu = \xi_\tau = \xi_\nu \neq 0$:

$H_o = 70.1 \pm 2.0$

$\Sigma m_\nu = 0.25 \pm 0.18$ eV

$\xi_\nu = 0.65 \pm 0.34$



Calculations done by King Lau, Shek Yeung

TENSION IN HUBBLE CONSTANT

- 1 σ tension in H_0 between cosmological and local measurements
- CMB: 70.1 ± 2.0 kms^{-1}Mpc^{-1} $\xi_\nu \neq 0$

  Local: 73.02 ± 1.79 kms^{-1}Mpc^{-1}

ξ_ν is a forgotten systematics of CMB

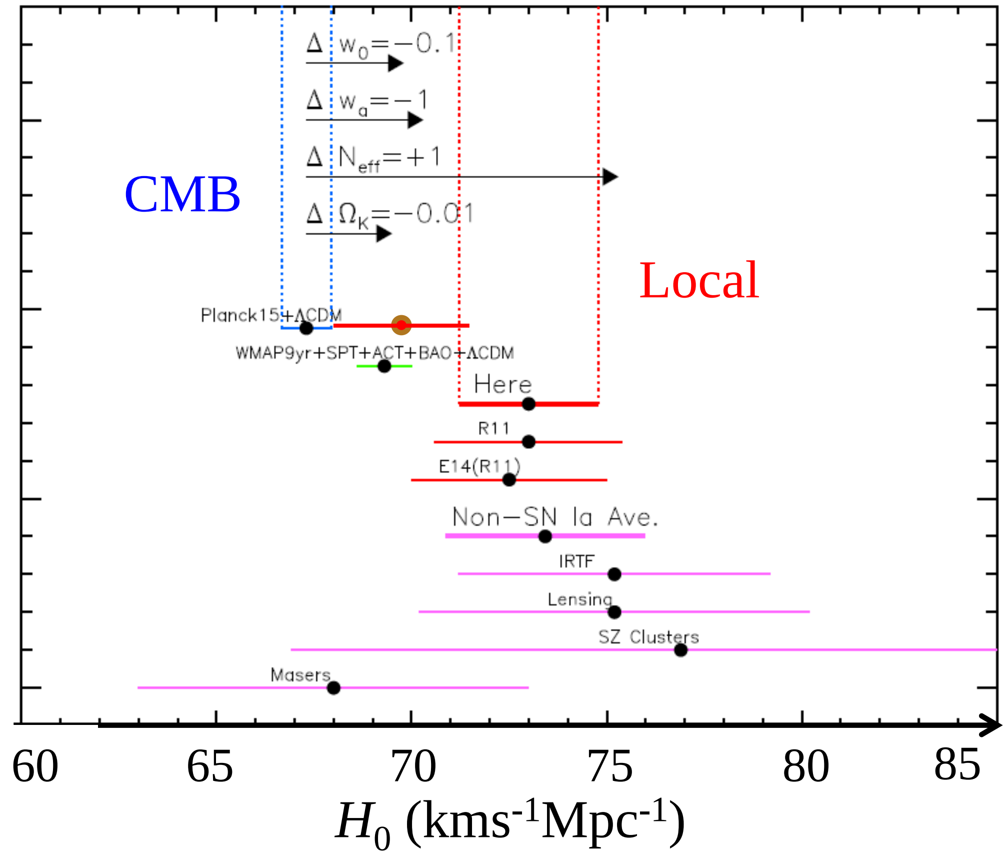


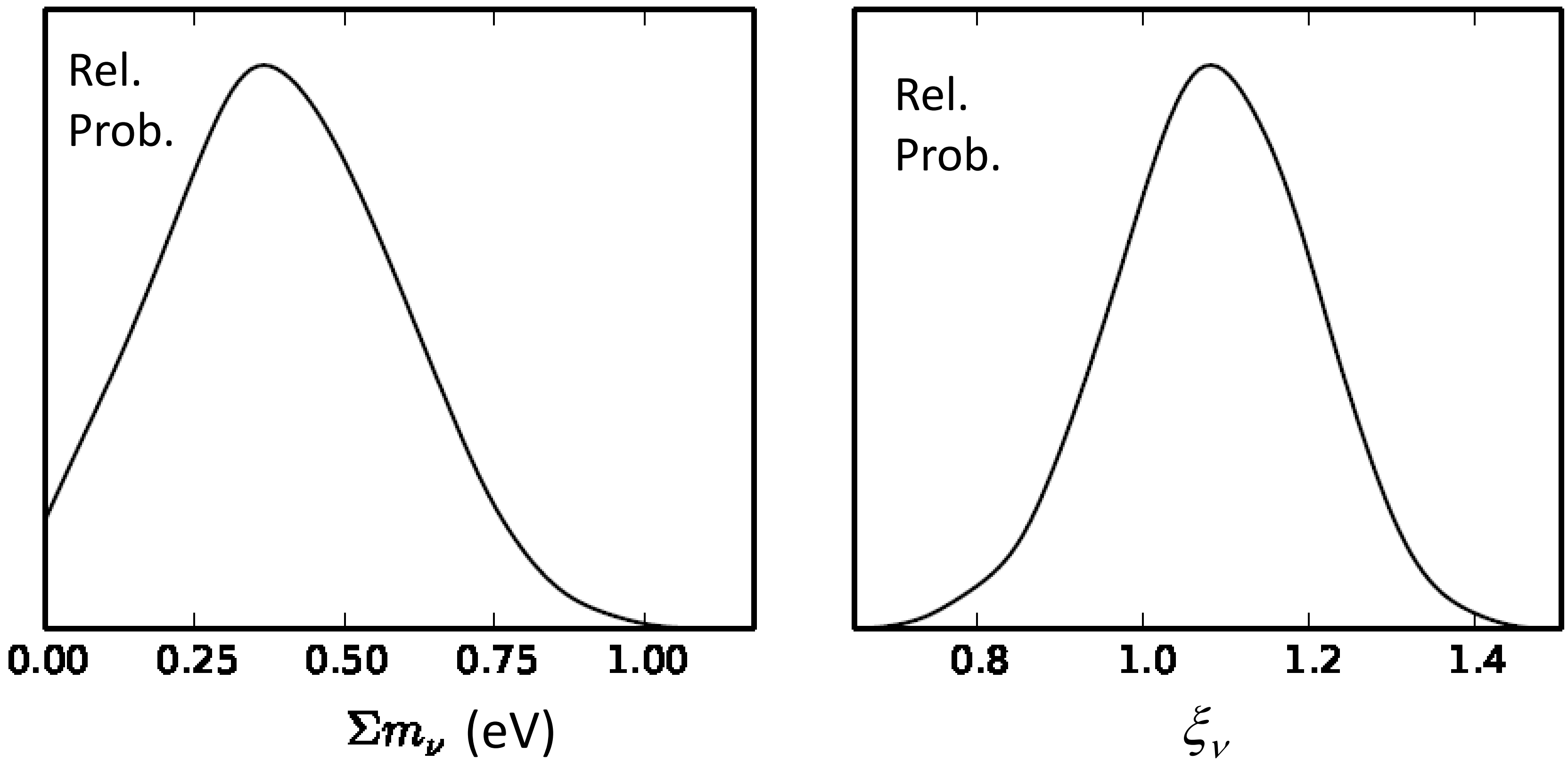
Fig. 12.— Local measurements of H_0 compared to values predicted by CMB data in conjunction with ΛCDM. We show 4 SN Ia-independent values selected for comparison by Planck Collaboration et al. (2014) and their average, the primary fit from R11, its reanalysis by Efstathiou (2014) and the results presented here. The 3.0σ difference between *Planck*+ΛCDM and our result motivates the exploration of extensions to ΛCDM.

A. G. Riess et al., http://arxiv.org/abs/1604.01424 , 2016.

CMB FITTING WITH FIXED H_O

Calculations done by Shek Yeung

PLANCK C_l^{TT} + BAO fitting, H_o = 73 kms^{-1}Mpc^{-1}



Best-fit: $\Sigma m_\nu = 0.39 \pm 0.19$ eV, $\xi_\nu = 1.08 \pm 0.12$

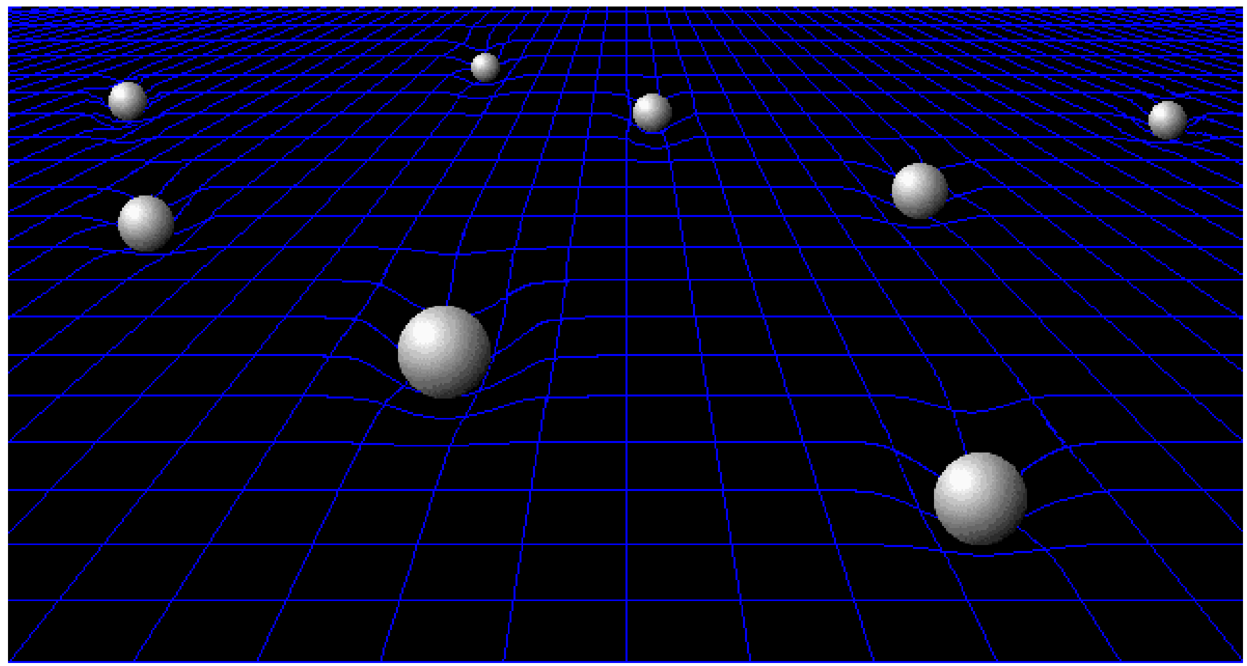
$\rightarrow$ Cosmological neutrinos are rather degenerate!

$\rightarrow$ CMB may give measurement of neutrino mass!

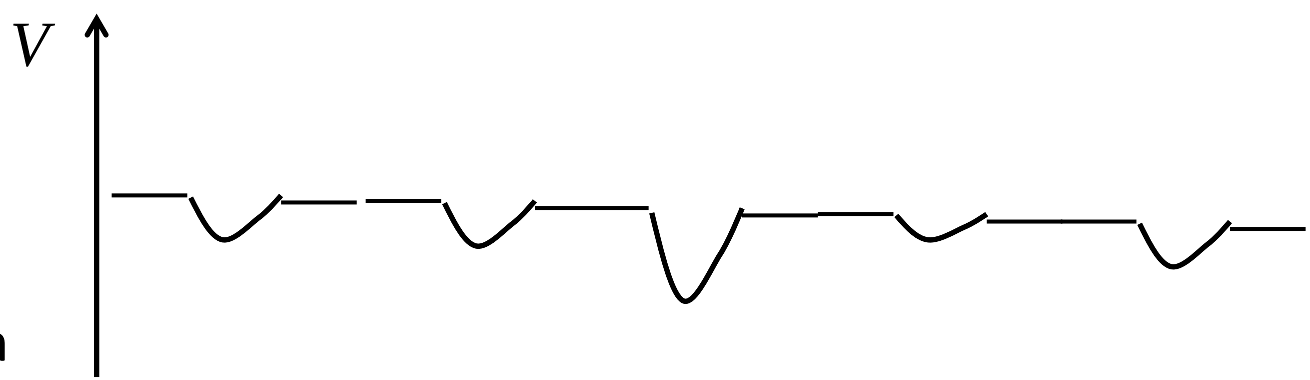
II. MEASURING NEUTRINO MASS WITH MATTER DISTRIBUTION

STRUCTURE FORMATION

Initial: almost uniform density, with small perturbations



Gravitational potential deepens when matter cluster, becomes shallower when space expands.



FREE-STREAMING LENGTH

Given the median speed v of a type of particles, there is a characteristic length of structure R formed by them:

gravity vs. kinetic energy $GM/R = v^2/2 \Rightarrow 8\pi G\rho R^2/3 = v^2$

$$\Rightarrow R \sim (3v^2/8\pi G\rho)^{1/2}$$

Decoupled at relativistic regime: $E_{\text{dec}} \sim p_{\text{dec}} \sim kT_{\text{dec}}$ at decoupling

In expanding space: $\Delta x(t) = a(t)\Delta x(t = 0)$;

$$\rho = \rho_{\text{dec}} a^{-3},\ T = T_{\text{dec}}/a,\ p(a) = p_{\text{dec}}/a$$

eg. neutrino median speed $v_\nu = 150\ \text{eV}/m_\nu a$ km/s

$\approx 1{,}500$ km/s today for $m_\nu \sim 0.1$ eV

$$\therefore R \sim [kT_{\text{dec}}/(G\rho_{\text{dec}})^{1/2}](a^{1/2}/m) \Rightarrow R \propto m^{-1}$$

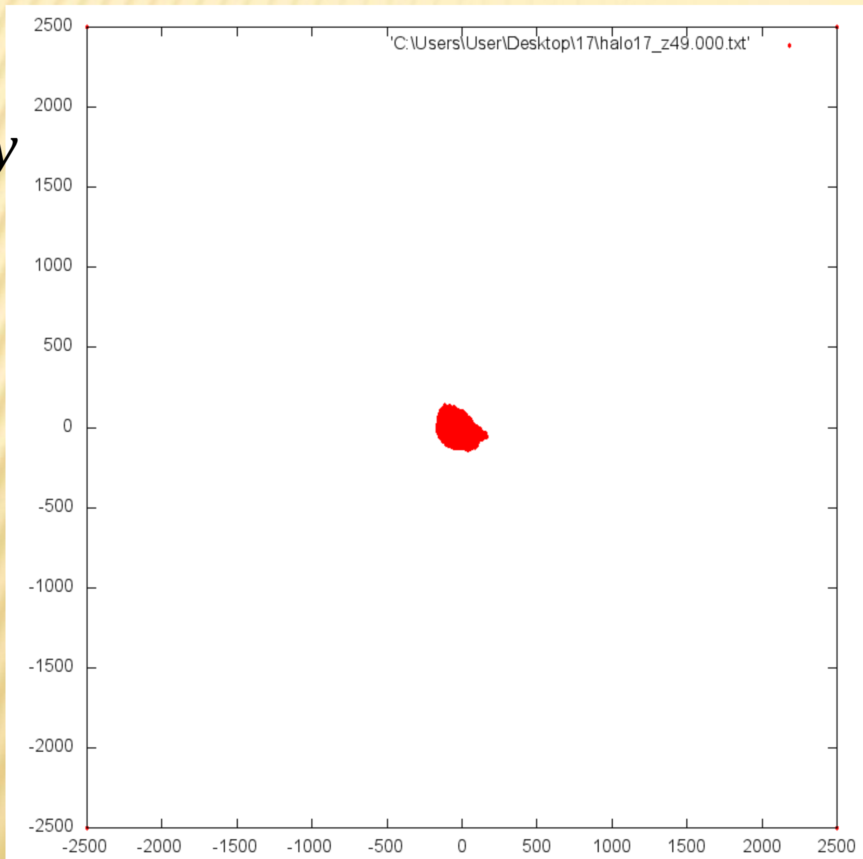
$\Rightarrow$ Light neutrinos have much longer free-streaming length (super-cluster scale) than massive cold dark matter

$\Rightarrow$ Light neutrinos smear out gravitational wells provided by cold dark matter $\Rightarrow$ more diffuse structures

MATTER HALO EVOLUTION

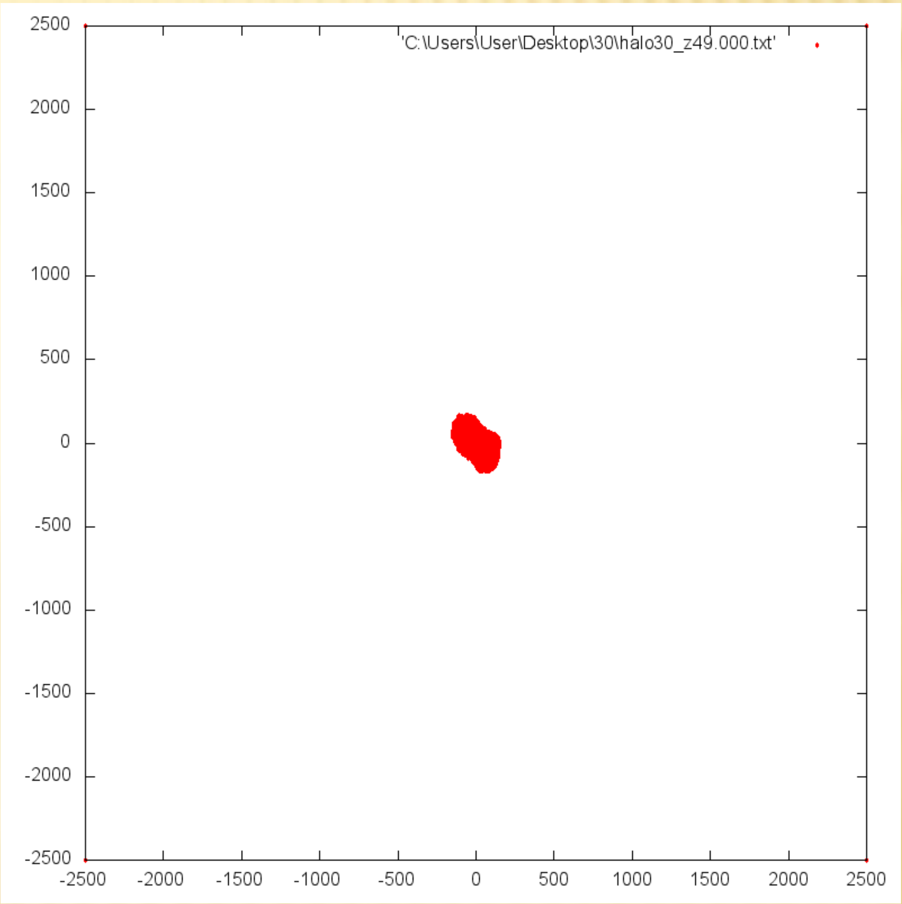
Expansion of universe (space), kinetic energy vs. gravity

y



x

y

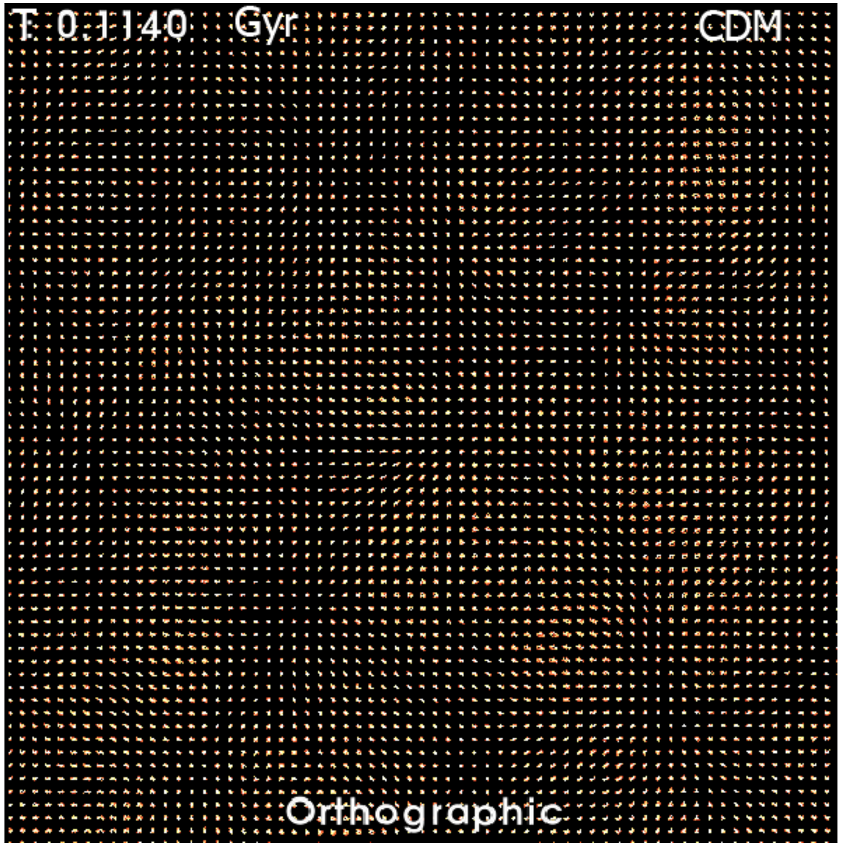


x

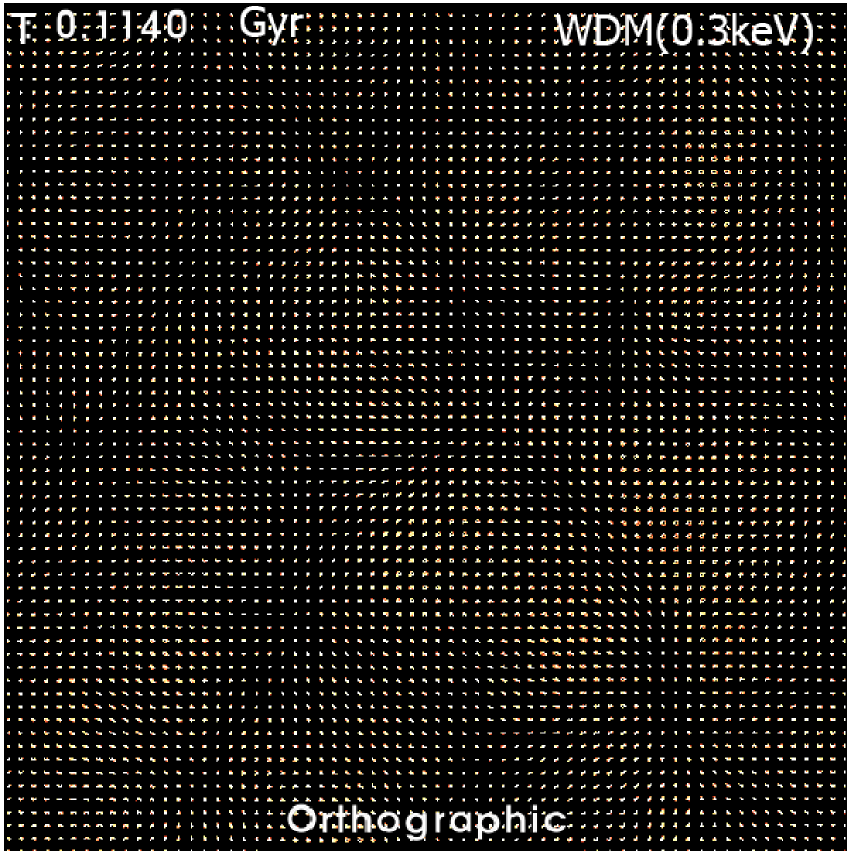
2 dark matter haloes

Simulated by Shihong Liao 廖世鴻

PARTICLE MASS AND EVOLUTION OF THE UNIVERSE



Standard cosmological model (most matter are non-relativistic, cold dark matter)

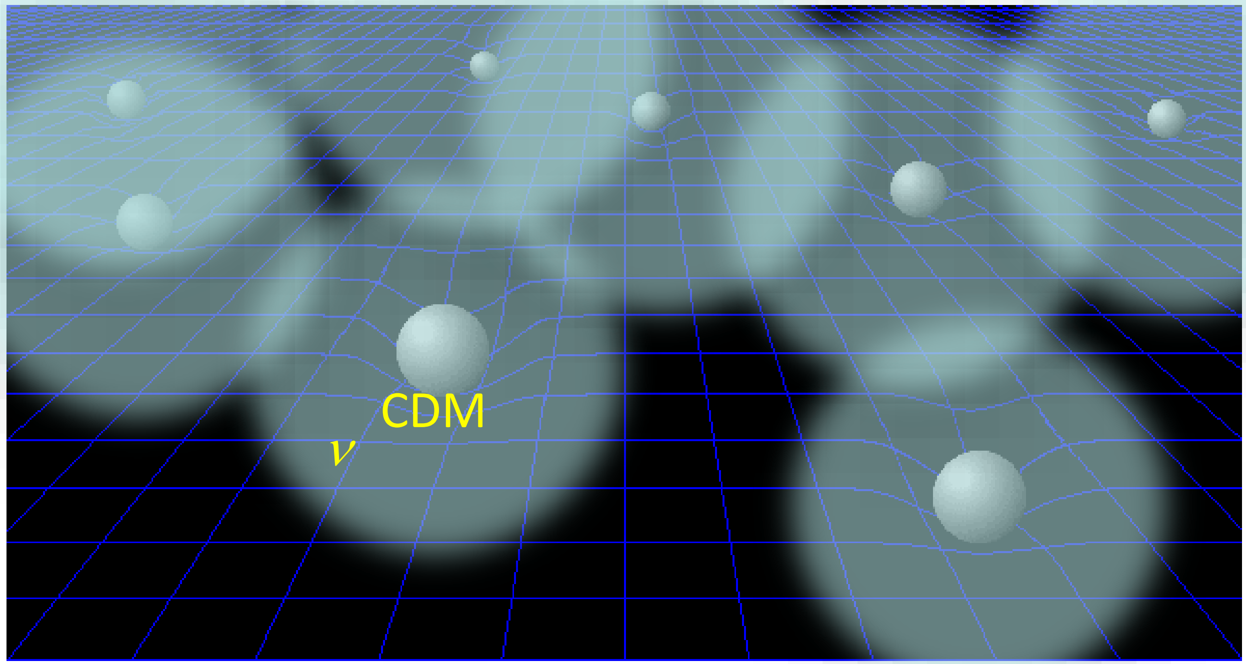


Warm dark matter: all particles have mass smaller than that of electron

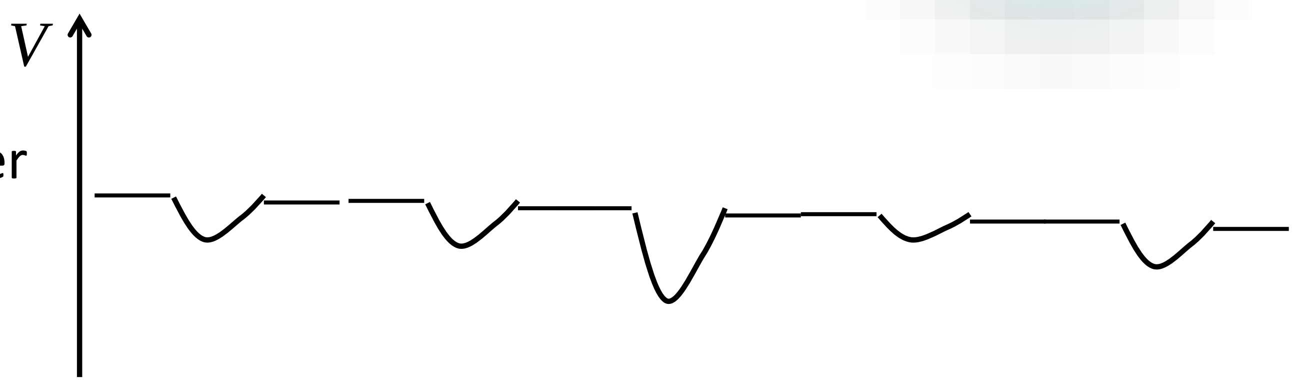
Particle simulation done by Shihong Liao

STRUCTURE FORMATION

Light neutrinos: much longer free-streaming lengths than cold dark matter



Gravitational potential



becomes shallower
$\Rightarrow$ suppresses structures

LINEAR EVOLUTION OF NEUTRINO DENSITY

$$\frac{dF_\nu}{dt} = \frac{\partial F_\nu}{\partial t} + \frac{\partial F_\nu}{\partial r_i}\dot{r}_i + \frac{\partial F_\nu}{\partial p_i}\dot{p}_i = 0$$

$$\dot{\mathbf{p}} = m\nabla\phi = -mG\int \rho_t \frac{\mathbf{r}\text{-}\mathbf{r}'}{|\mathbf{r}\text{-}\mathbf{r}'|^3} d^3r'$$

Collisionless Boltzmann Eq. for neutrino distribution function F_ν
Gravity sourced by all matter ρ_t

$$F_\nu = f_\nu^0(v) + f_\nu'(\mathbf{r}, \mathbf{v})$$

$$\frac{\partial f_\nu'}{\partial s} + \mathbf{u}\cdot\frac{\partial f_\nu'}{\partial \mathbf{x}} - Ga^4 \cdot \frac{\partial f_\nu^0}{\partial \mathbf{u}} \int \bar{\rho}_t \delta_t(s, \mathbf{x}') \frac{\mathbf{x}\text{-}\mathbf{x}'}{|\mathbf{x}\text{-}\mathbf{x}'|^3} d^3x' = 0$$

Assume $f_\nu' \ll f_\nu^0$, linearize Boltzmann Eq. in f_ν'

$$\bar{\rho}_t \delta_t \equiv \rho_t - \bar{\rho}_t = \bar{\rho}_{c+b}\delta_{c+b} + \bar{\rho}_\nu \delta_\nu.$$

$(s, \mathbf{x})$ = co-moving coordinates

$$\widetilde{\delta_\nu}(s, \mathbf{k}) = 4\pi G \int_0^s a^4(s')(s-s')\Phi[\mathbf{k}(s-s')][\bar{\rho}_{c+b}(s')\widetilde{\delta}_{c+b}(s', \mathbf{k}) + \bar{\rho}_\nu(s')\widetilde{\delta_\nu}(s', \mathbf{k})]ds'$$

$$+\Phi(\mathbf{k}s)\widetilde{\delta_\nu}(0, \mathbf{k}) \qquad (1)$$

$$\Phi(\mathbf{q}) = \frac{\int f_\nu^0 e^{-i\mathbf{q}\cdot\mathbf{u}} d^3u}{\int f_\nu^0 d^3u}$$

Solve by Green's function method $\rightarrow$Volterra Eq.: solve by iteration

$\mathbf{x} \rightarrow \mathbf{k}$ Fourier space

NEUTRINO-INVOLVED N-BODY SIMULATION

Initial conditions generated by 2LPT at high z: δ_{c+b}, δ_ν

$\delta_{c+b}\,(t_{n\text{-}1}) \rightarrow \delta_{c+b}\,(t_n)$ using Gadget2 (N-body, fully non-linear)

calculate $\delta_\nu(t_n)$ using Eq. 1 (Volterra Eq.) from $\delta_\nu(t_{n\text{-}1})$, $\delta_{c+b}\,(t_n)$

calculate gravitational potential using $\delta_t\,(t_n) = r_\nu \delta_\nu(t_n) + (1\text{-}r_\nu)\,\delta_{c+b}\,(t_n)$

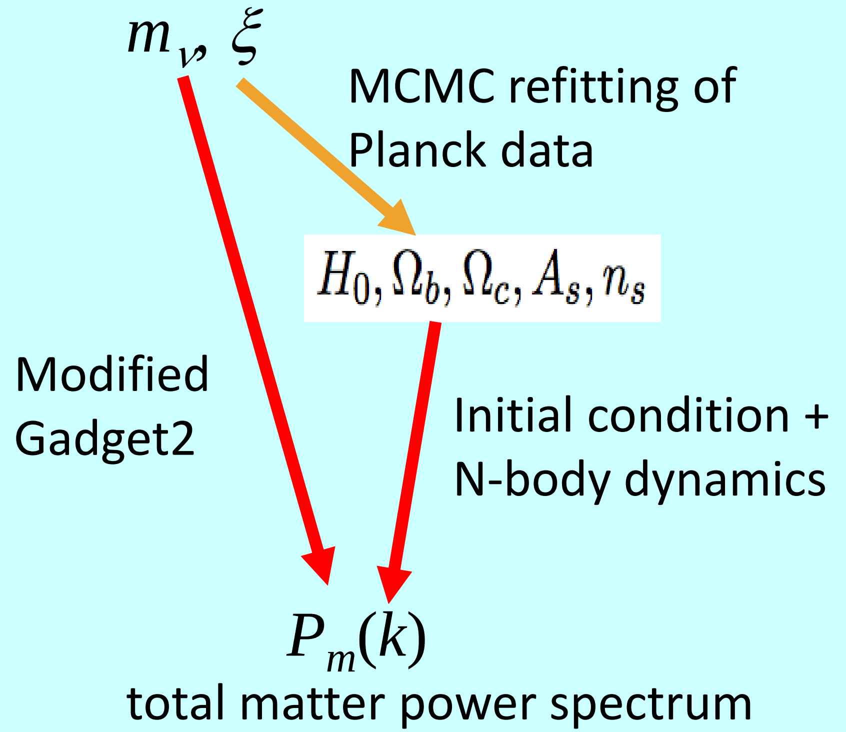
$r_\nu \equiv \Omega_\nu/\Omega_m$

Linear evolution of δ_ν
(using non-linear evolution of δ_{c+b})

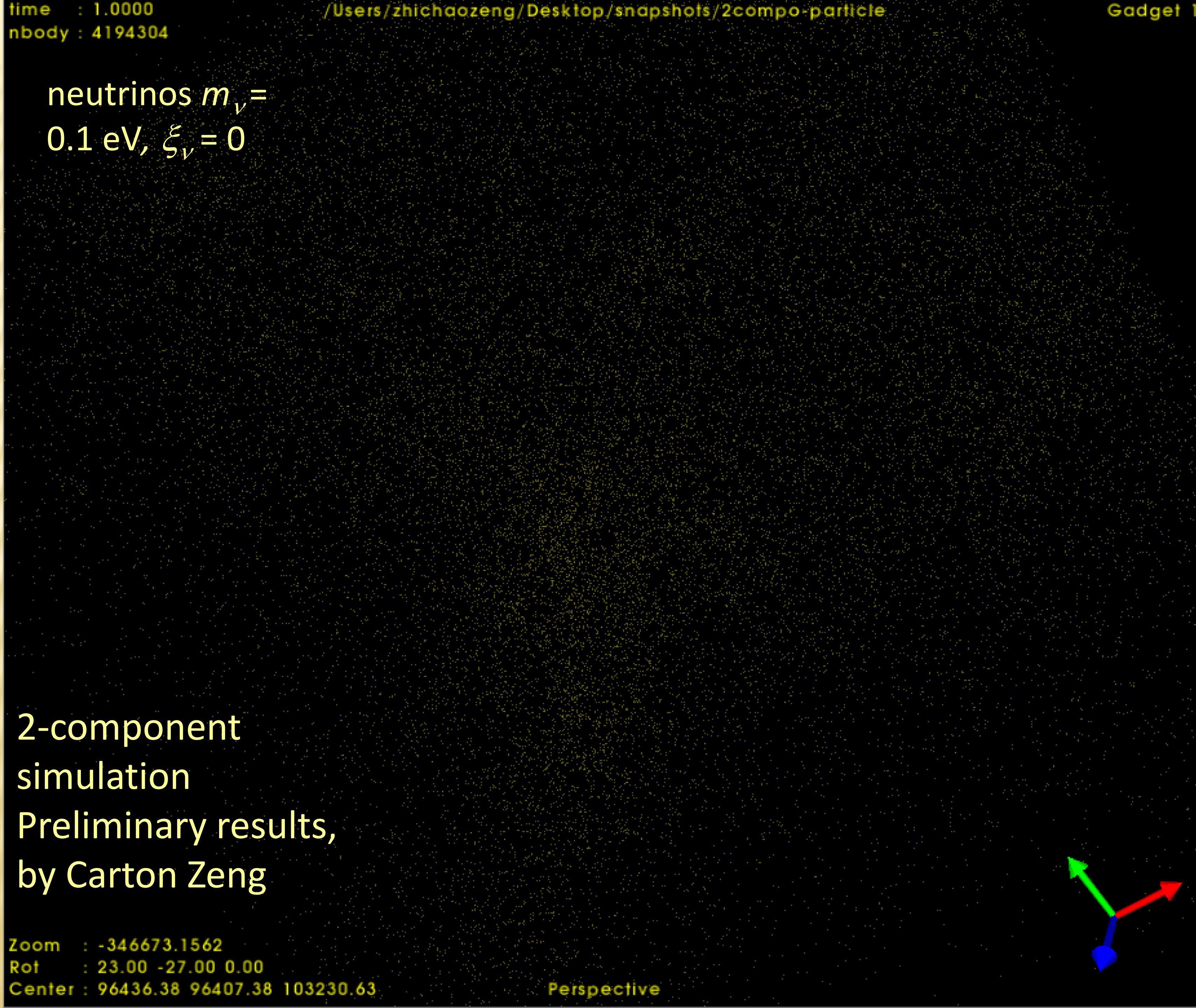
Correction of gravitational potential using δ_ν

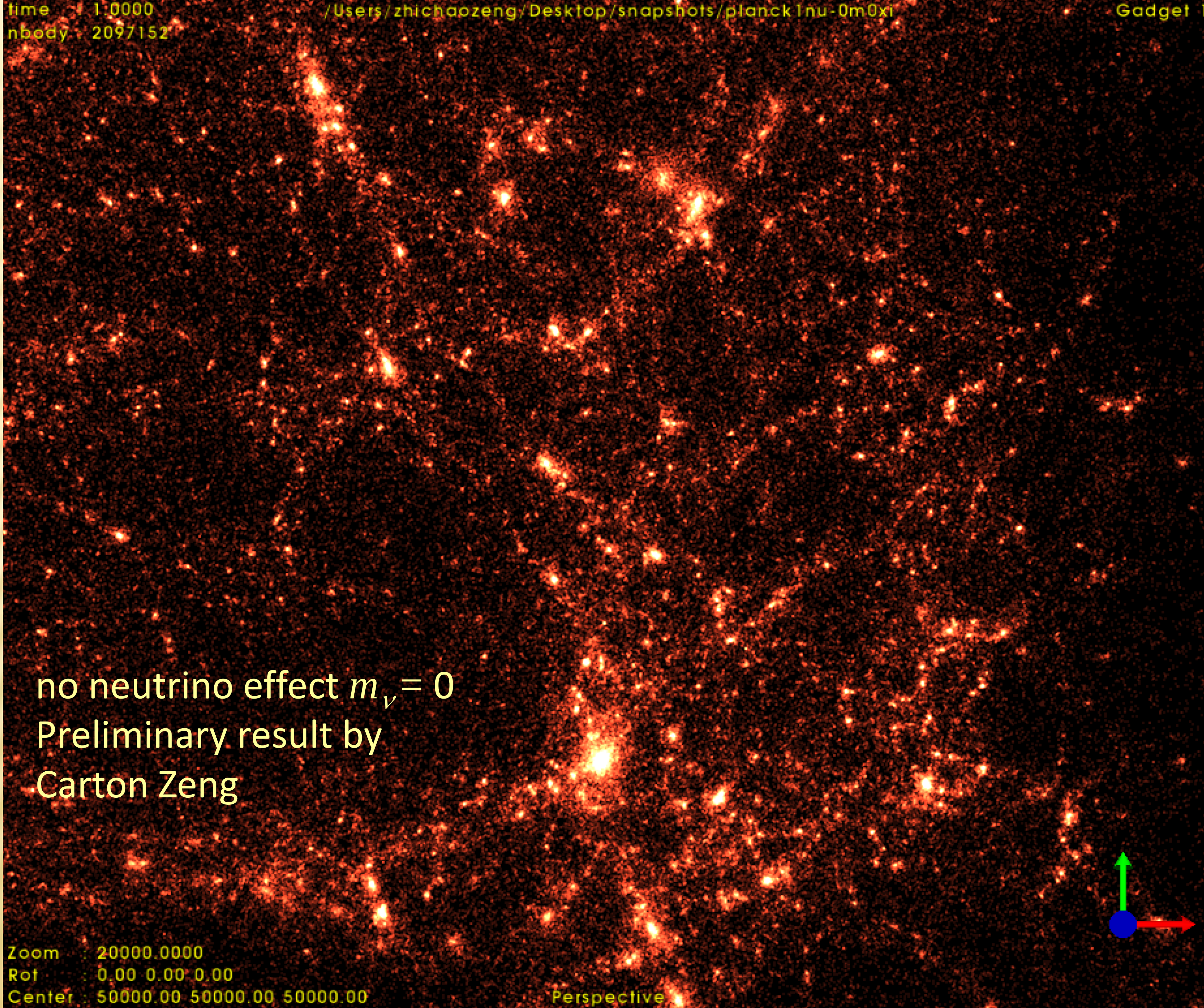
METHODOLOGY

- MCMC code
  - Refit the Planck data with (m_ν, ξ)
- N-body simulation
  - Modified Gadget2
  - Grid-based method: linearly evolve the neutrino density field; correct for the long-range PM force (Ali-Haimoud & Bird 2013)
  - Why grid-based?
    - Efficient
    - Degeneracy pressure: not easy to be interpreted as particle-particle interaction

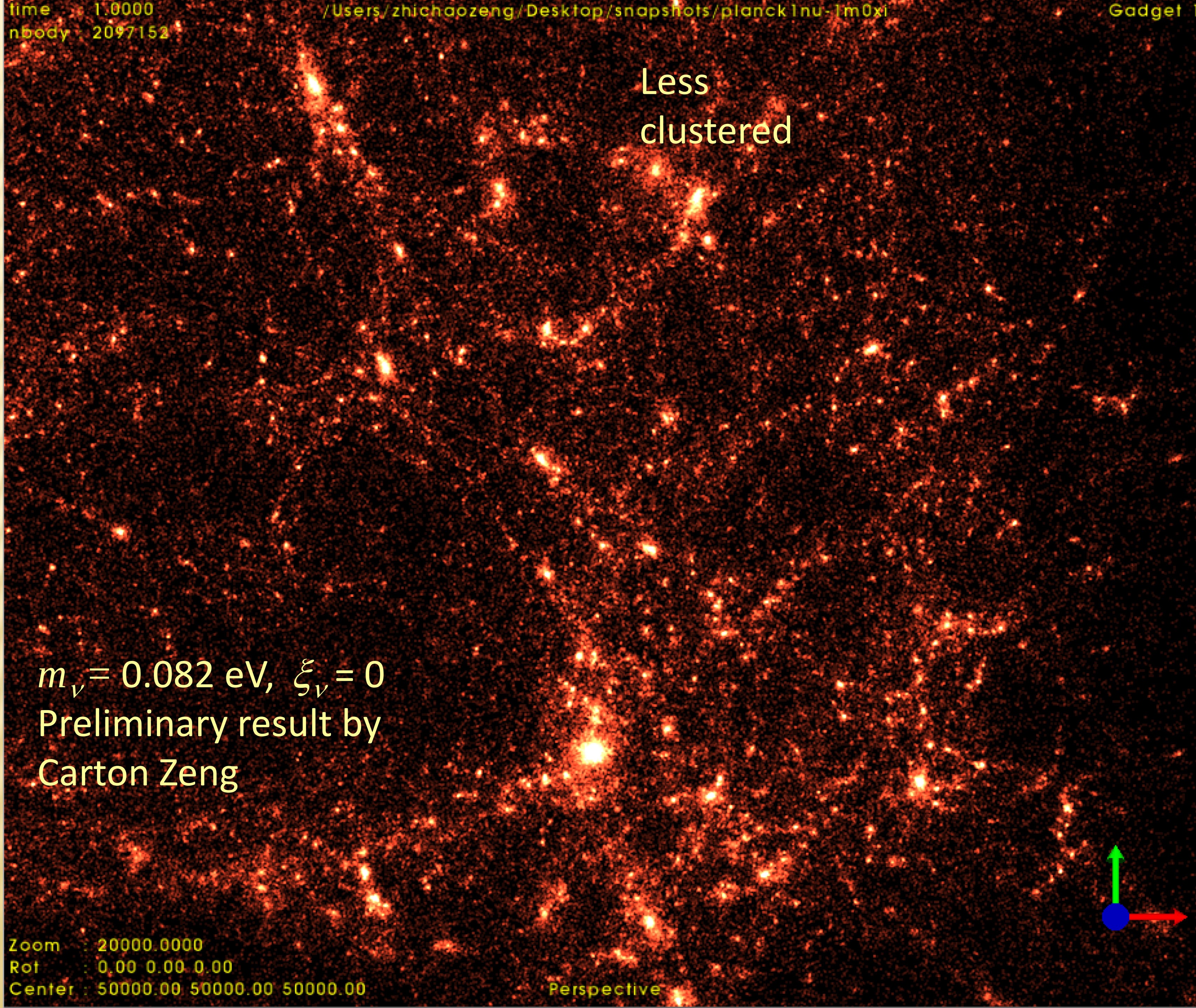


$$m_\nu \equiv (\Sigma_i m_{\nu i})/3, \ \xi \equiv \mu/T$$

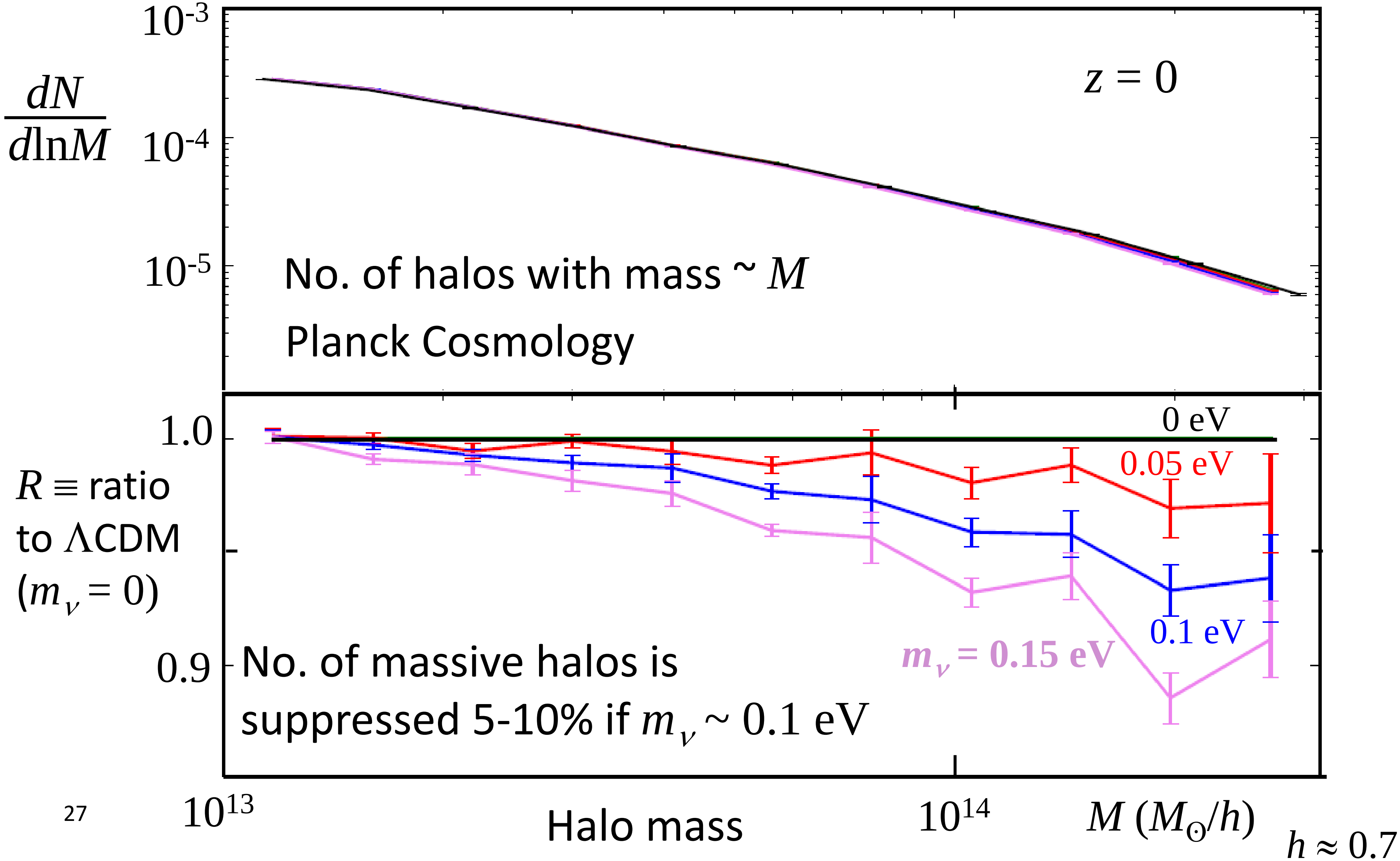

time : 1.0000
nbody : 4194304
/Users/zhichaozeng/Desktop/snapshots/2compo-particle
Gadget 1
neutrinos m_ν = 0.1 eV, ξ_ν = 0
2-component simulation
Preliminary results,
by Carton Zeng
Zoom : -346673.1562
Rot : 23.00 -27.00 0.00
Center : 96436.38 96407.38 103230.63
Perspective



no neutrino effect $m_\nu = 0$
Preliminary result by
Carton Zeng

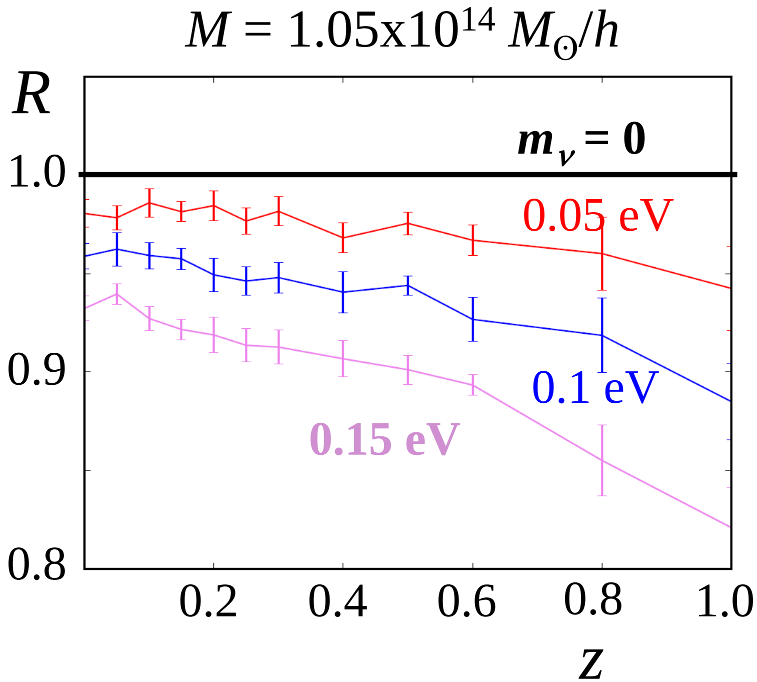

time : 1.0000
nbody : 2097152
/Users/zhichaozeng/Desktop/snapshots/planck1nu-1m0xi
Gadget 1
Less clustered
m_ν = 0.082 eV, ξ_ν = 0
Preliminary result by Carton Zeng
Zoom : 20000.0000
Rot : 0.00 0.00 0.00
Center : 50000.00 50000.00 50000.00
Perspective

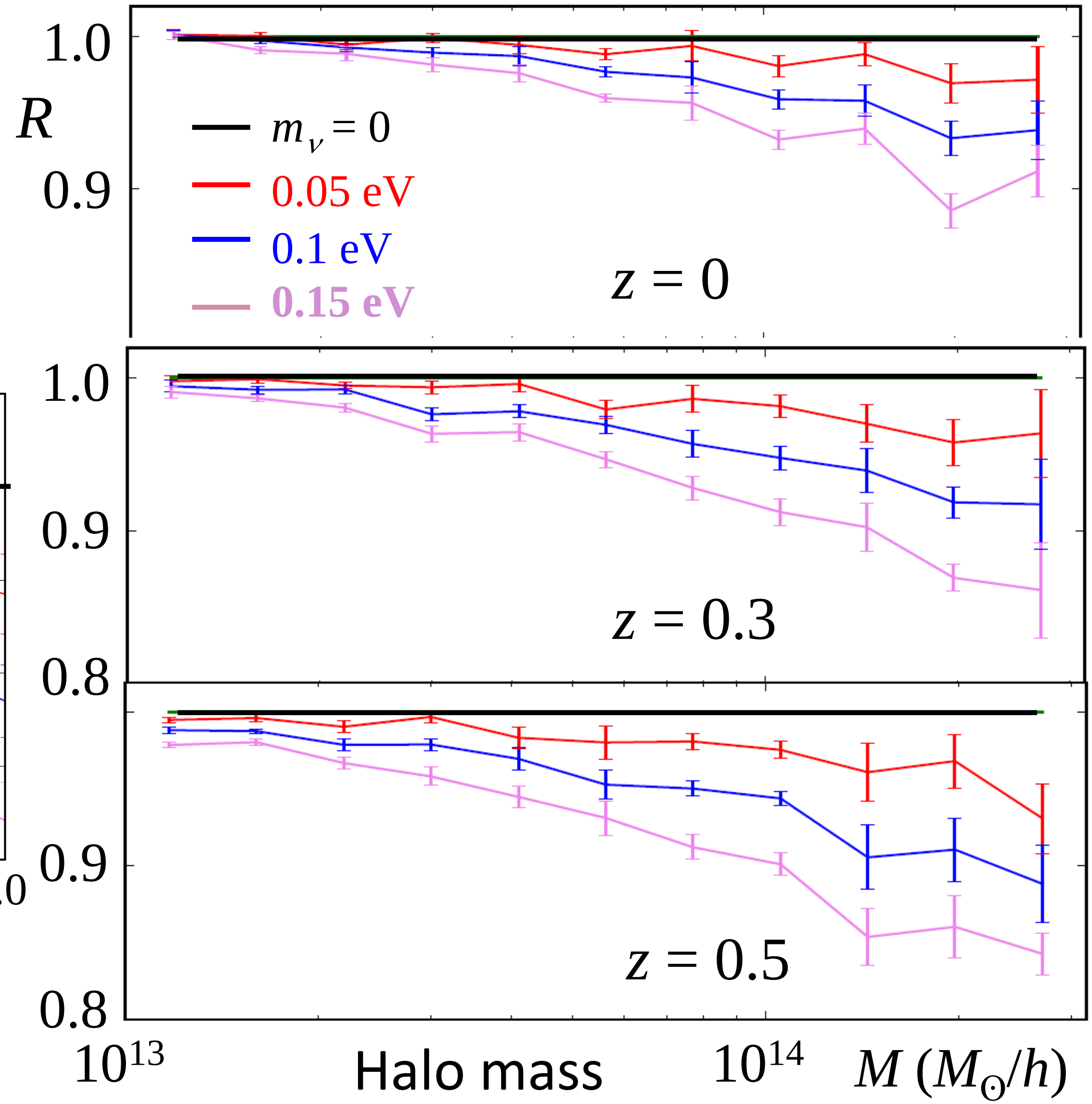
MASS FUNCTION



MASS FUNCTION

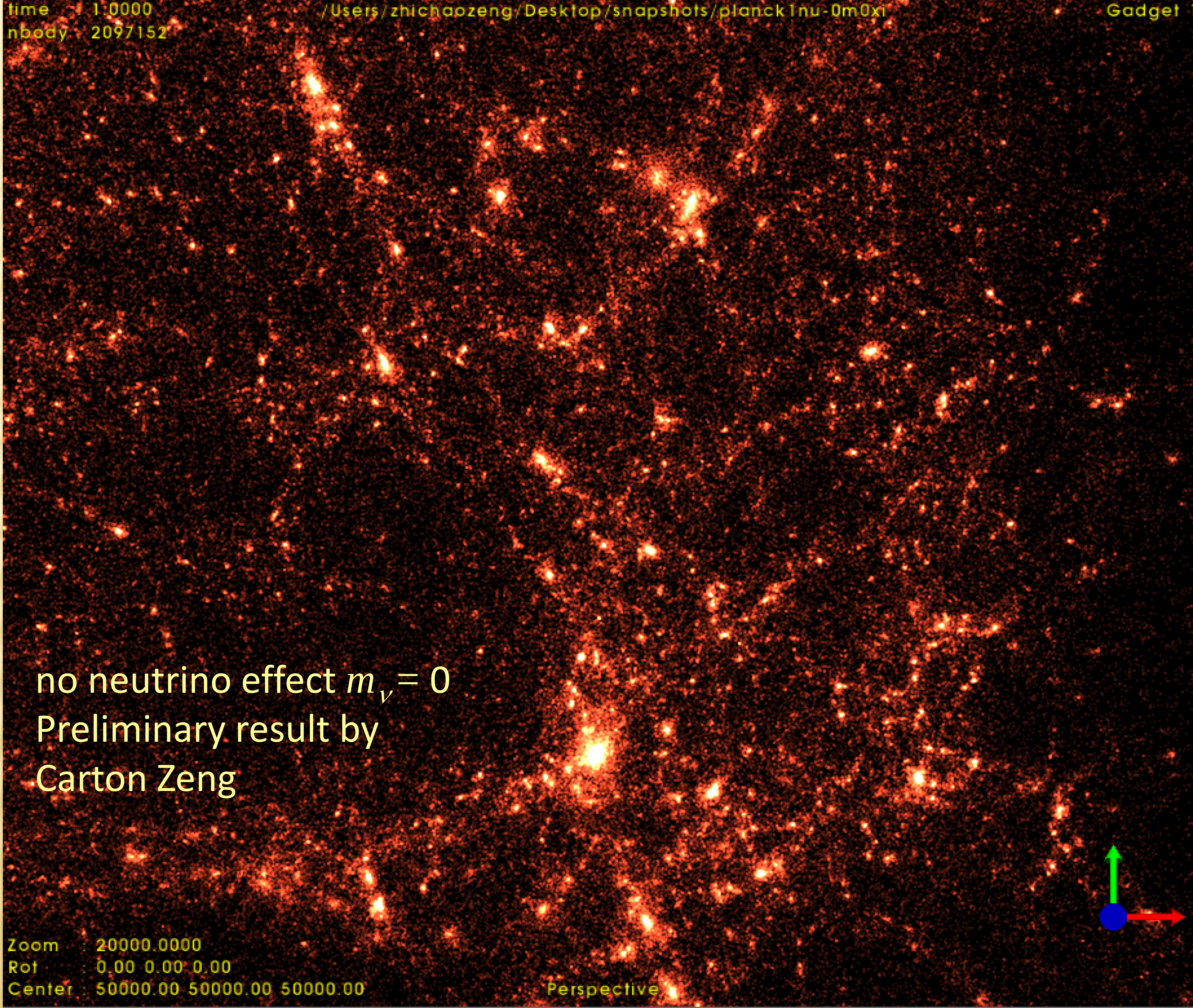
The suppression relative to ΛCDM is sensitive to redshift z (more for larger z).





J-PAS COSMOLOGICAL SURVEY

http://www.j-pas.org/ We plan to join the J-PAS survey!



no neutrino effect $m_\nu = 0$
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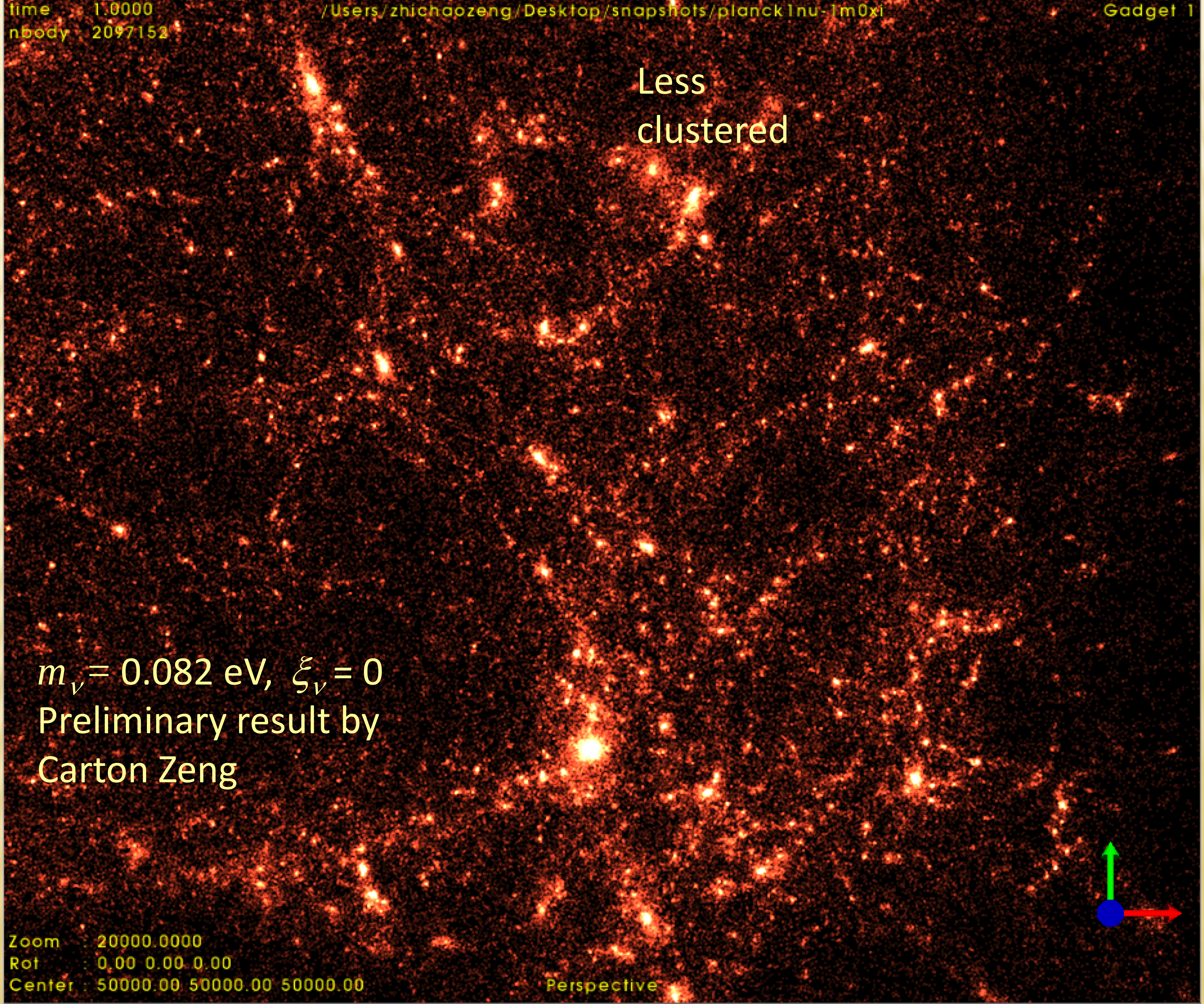
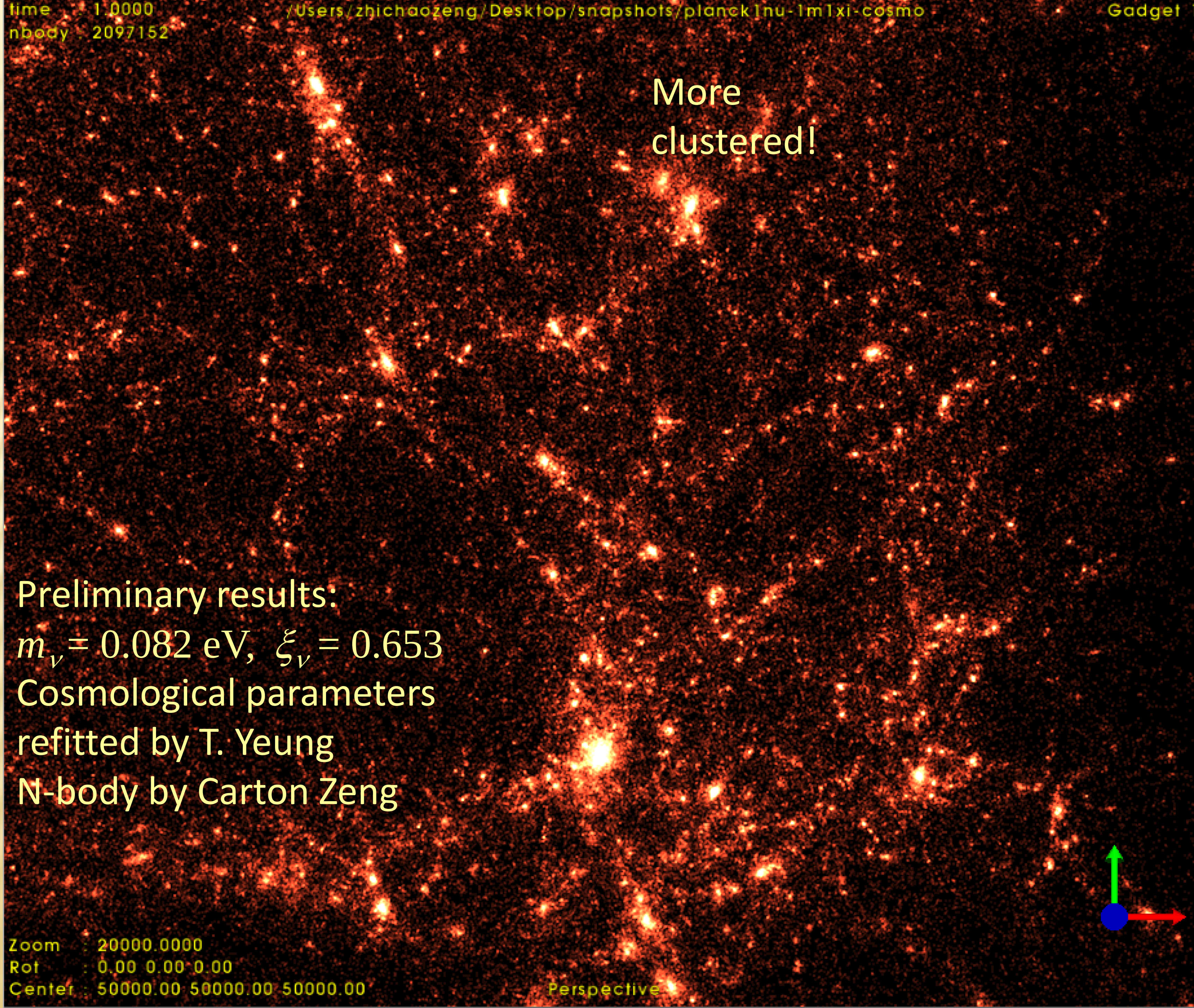

time : 1.0000
nbody : 2097152
/Users/zhichaozeng/Desktop/snapshots/planck1nu-1m0xi
Gadget 1
Less
clustered
m_ν = 0.082 eV, ξ_ν = 0
Preliminary result by
Carton Zeng
Zoom : 20000.0000
Rot : 0.00 0.00 0.00
Center : 50000.00 50000.00 50000.00
Perspective



More clustered!

Preliminary results:

$m_\nu = 0.082$ eV, $\xi_\nu = 0.653$

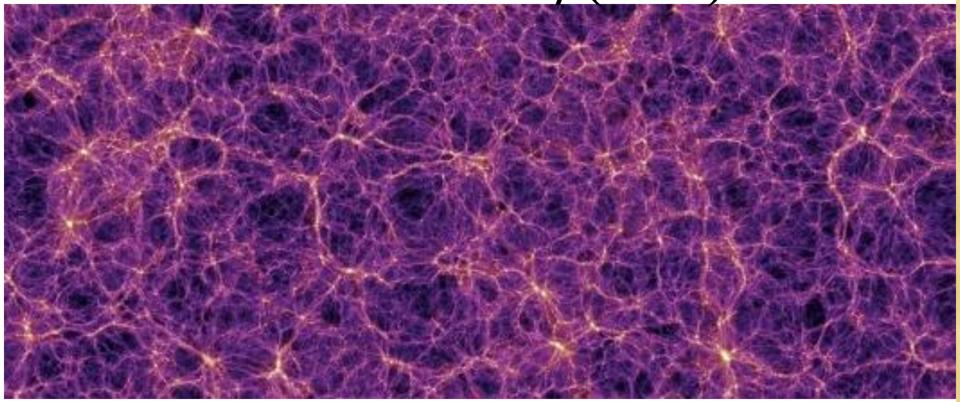
Cosmological parameters refitted by T. Yeung

N-body by Carton Zeng

Matter power spectrum

- Matter distribution: non-linear evolution
- Power spectrum: describes power of fluctuations in wavelengths k

Matter distribution today ($z = 0$)



http://www.dailygalaxy.com/my_weblog/2015/12/new-observations-of-the-cosmic-web-of-the-universe.html0

$$\delta(\mathbf{x}, z) = \frac{\rho(\mathbf{x}, z) - \bar{\rho}(z)}{\bar{\rho}(z)}$$

fluctuations of density field

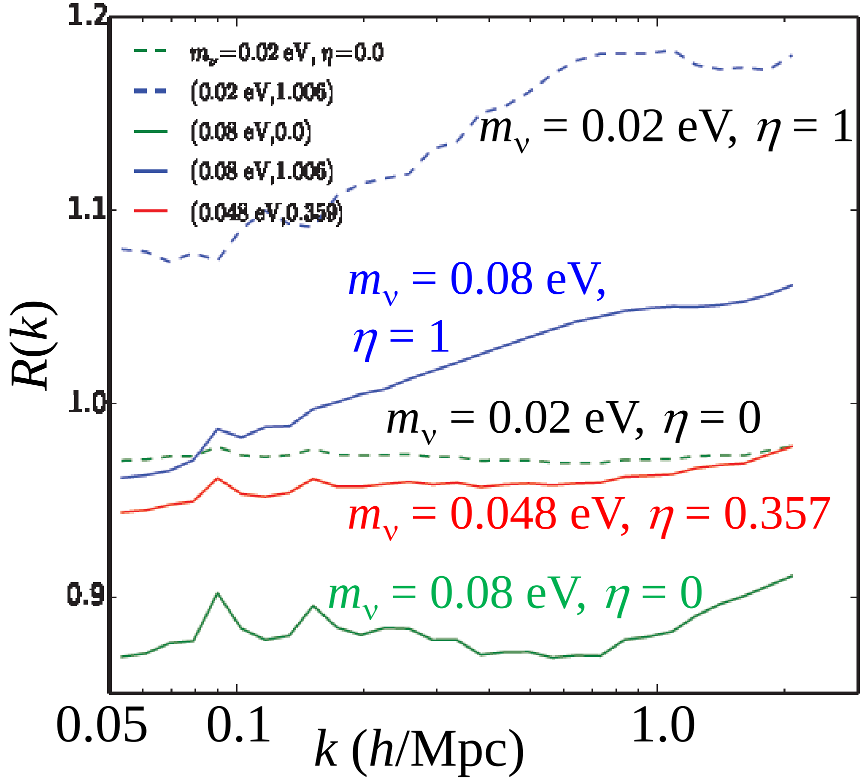
$$\tilde{\delta}(\mathbf{k}, z) = \int \delta(\mathbf{x}, z) e^{-i\mathbf{k}\mathbf{x}} d^3x$$

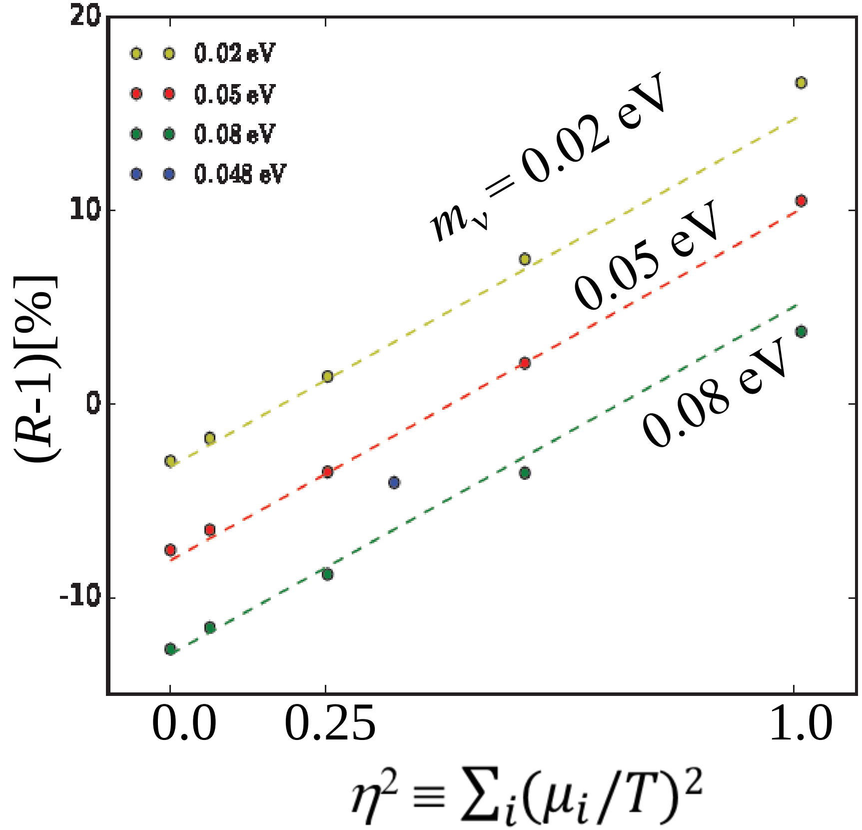
3D Fourier transform

$$P_k = |\delta(\mathbf{k}, z)|^2$$

$$\Delta R \equiv \int_{0.3h}^{1h} dk[P_k(\nu\mathrm{DM})/P_k(\Lambda\mathrm{CDM}) - 1]$$

MATTER POWER SPECTRUM





$R(k) \equiv P_m(m_\nu,\ \eta^2,\ k)/P_m(0,\ 0,\ k)$

$(m_\nu,\ \eta^2)$ = (0.048 eV, 0.357) = mean values from CMB fitting

Suppression of (0.048 eV, 0.357) + refitting = Suppression of (0.022 eV, 0)

~100% error in neutrino mass!

Neutrinos' influence on structure formation

- Neutrino mass m_ν: slows down Hubble expansion, suppresses matter power spectrum in $k = (0.3, 1)\ h\mathrm{Mpc}^{-1}$

- Neutrino chemical potential μ_i : opposite effect to m_ν

$$\frac{\Delta H_0}{H_{0[\Lambda\mathrm{cdm}]}}[\%] = -4.40\frac{m_\nu}{0.1\ \mathrm{eV}} + 4.50\eta^2[\%] \qquad \eta^2 \equiv \Sigma_i(\mu_i/T)^2$$

$$\Delta R(z=0)[\%] = -16.17\frac{m_\nu}{0.1\ \mathrm{eV}} + 17.97\eta^2[\%]$$

- Neutrino mass ~ 0.1 eV produces ~ 10% effect in P_k
- Breaking degeneracy between m_ν and η^2: redshift dependence, other cosmological observables

Zichao Zeng, Shek Yeung, and M.-C. Chu, CUHK preprint 2018.
Calculations done by Carton Zeng (modified Gadget2).

SUMMARY

1. Cosmological neutrinos important:

- Possibly degenerate: alleviate the H_o problem if $\xi \sim 0.6$
- Cosmological parameters should be extracted with $\{m_\nu, \xi\}$
- Majorana, Leptogenesis

2. Measuring neutrino mass with matter distribution:

- Matter distribution sensitive to m_ν
- But ξ has opposite effect!
- m_ν < 0.1 eV measurable with precision cosmological surveys
- Redshift dependence will help

3. Much more high precision high quality cosmological data in the coming decade!

MEASURING NEUTRINO PROPERTIES WITH COSMOLOGY

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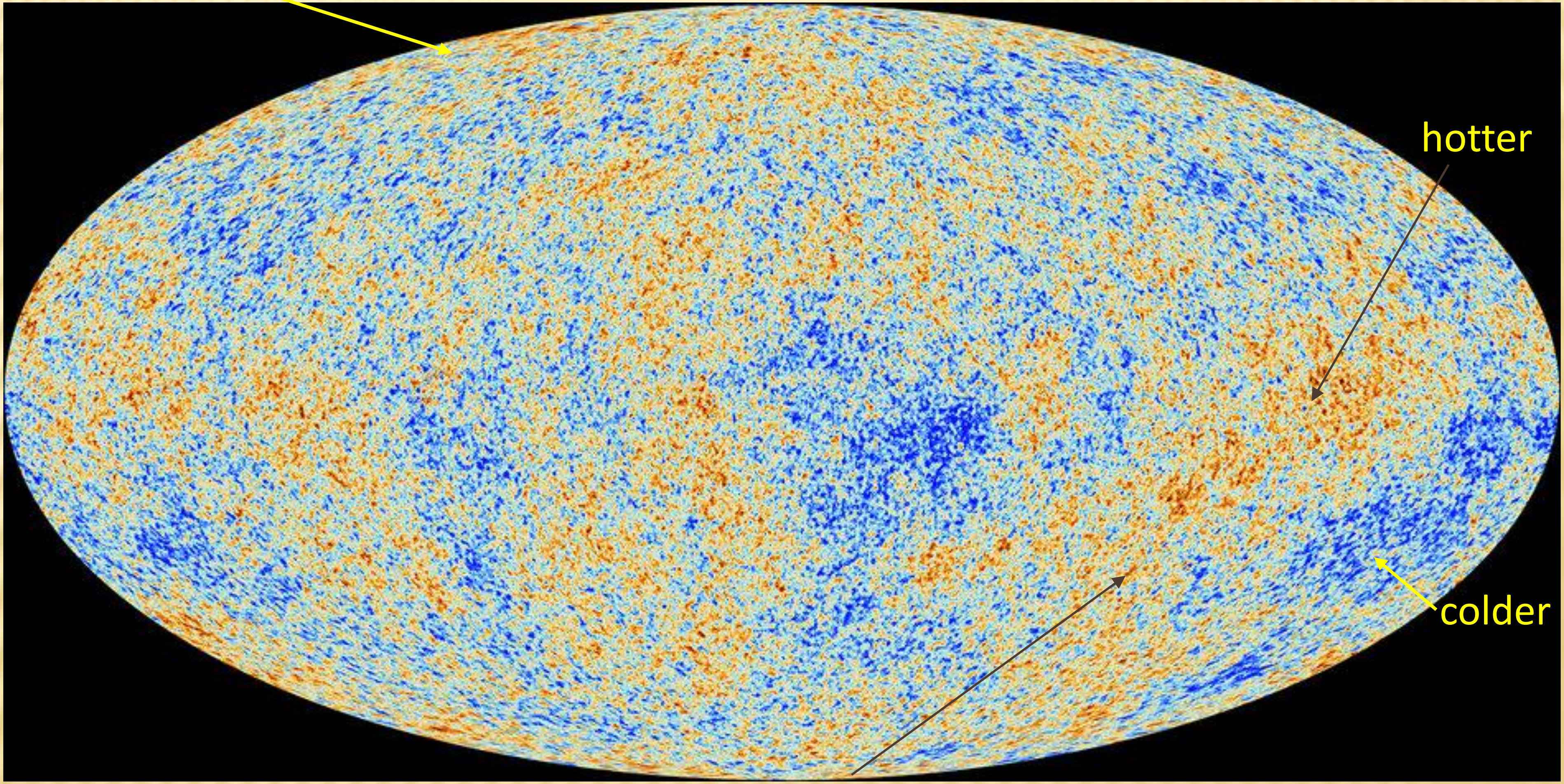
NCTS lunch seminar 20/06/2018

CMB Anisotropies

All-sky projection

$<T_\gamma> = 2.725 \pm 10^{-5}$ K

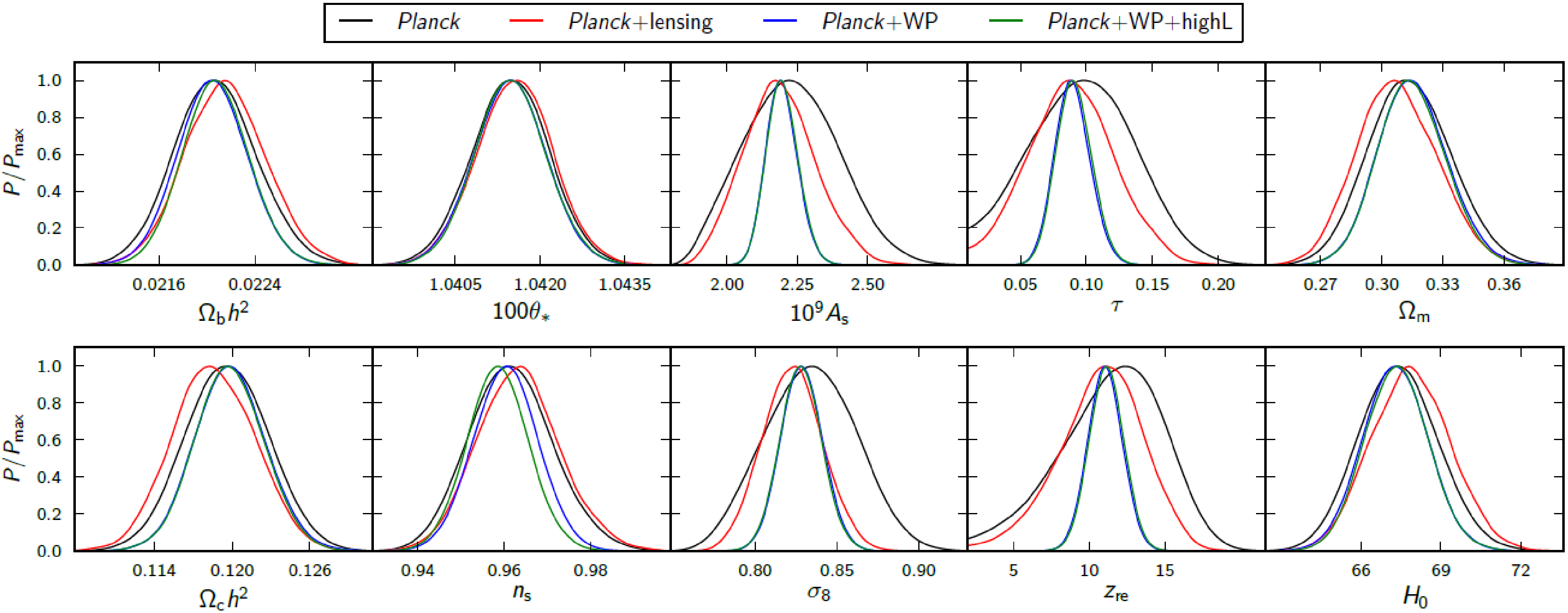


Temperature fluctuations ~ 10^{-5} K

http://www.esa.int/Our_Activities/Space_Science/Highlights/Planck_s_Universe

Figure courtesy PLANCK Telescope

CMB FITTING OF COSMOLOGICAL PARAMETERS



(Planck Collaboration, arXiv:1303.5076)

- ΛCDM 6-parameters fitting: $\{\Omega_b h^2, \Omega_c h^2, \theta_*, A_s, n_s, \tau\}$; $h \equiv H_o/100\ \mathrm{kms^{-1}Mpc^{-1}}$
- Assumptions: Isotropy, Gaussianity, model of reionization, lensing, ΛCDM, $N_{\mathrm{eff}} = 3.046$, $\Sigma m_\nu = 0.06$ eV, $\xi_\nu = 0$, …
- Gives Hubble 'constant': $H \equiv \dot{a}/a$, $H_o \equiv H(z = 0)$ today
- $\rightarrow$ age of universe t_U = 13.82 billion years

STRUCTURE EVOLUTION

N-body simulation using GADGET2 Calculation done by Dalong Cheng

Standard ΛCDM model assumed