7th SSG:17/01/2018

Non-Standard Cosmological Simulations

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KIAS & KASI

Cosmology in Problem

- <u>The Concordance LCDM: The Dark Age of Cosmology</u>!
  - Plenty of cosmological data: LSS, G-lensing, CMB, SN Ia, etc.
  - Friedman Universe (DM+DE+GR+…)
  - Some argue that nothing left but to *narrow down the parameter values below sub-% level accuracy.* → **precision cosmology**
- <u>But Mostly Unknown to **Us**!</u>
  - Unknown Matter & Energy contents
    - About 96% of the Energy (DM+DE) are not known.
    - Dark Matter: no positive evidence among the current probable models (WIMP, Axion, etc…)
    - Dark Energy: cosmological constant or not?
  - Gravitational force
    - General Relativity has only proved within the solar system.
    - Could it be verified on the cosmological scales?
    - Variant models include DGP, f(R), etc

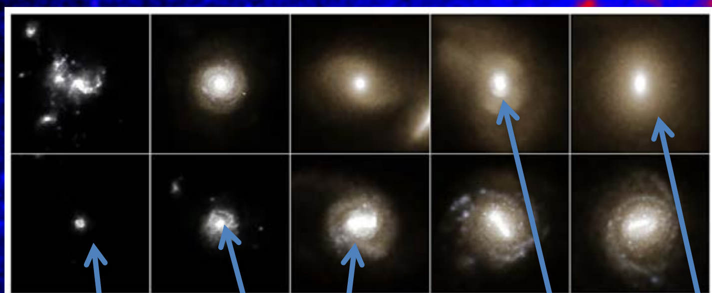
The Role of Cosmological Simulation

between extragalaxies and Cosmology

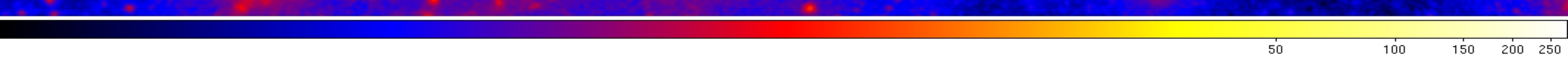
- **Why Simulation is needed?**
  - To understand the physical processes in formation of galaxies and the Large-Scale Structures of the universe
  - To test cosmological models with extragalactic observations
    - To measure systematic effects (Shot noises, Survey area effects) and cosmic variance.
  - To perform the feasibility study for redshift surveys of galaxies.
    - To study target selection, # of sources, survey area, # of tiles, fiber density, exposure time, etc..

How To Build Mock Galaxies from Simulation

- Methods
  - Halo Occupation Distribution (HOD)
  - Abundance Matching (AM)
  - Semi-Analytic Model (SAM)
  - Hydrodynamic Simulation (HSIM)
  - Complexity: HOD<AM<SAM<HSIM



- Abundance matching (Kim+08, Hong+16)
  - Relate the subhalos and real galaxies by a rule that the heavier the brighter.
  - Primary tools: subHalo mass function and galaxy luminosity function (or stellar mass function)
  - Sometimes called one-to-one correspondence



A New AM Method (Hong, Park, & Kim, 2016)

- Extracts Most Bound Particles (MBP) of just forming halos from N-body simulation and trace them until now.
  - **Merger tree of MBP**
- Assumes MBP's as mock galaxies.
- Uses tidal disruption timescale (Jiang+08).
  - If survives, then it is satellite galaxy
  - If not, then it is merged to the central galaxy
- Is highly flexible.
  - Being extended to a hybrid (HOD+ simple SAM) method

$$\frac{t_{\rm merge}}{t_{\rm dyn}} = \frac{f(\epsilon)}{\ln\{1 + M_{\rm host}/M_{\rm sat}\}} \left(\frac{M_{\rm host}}{M_{\rm sat}}\right)^{1.5}$$

The Astrophysical Journal, 823:103 (10pp), 2016 June 1

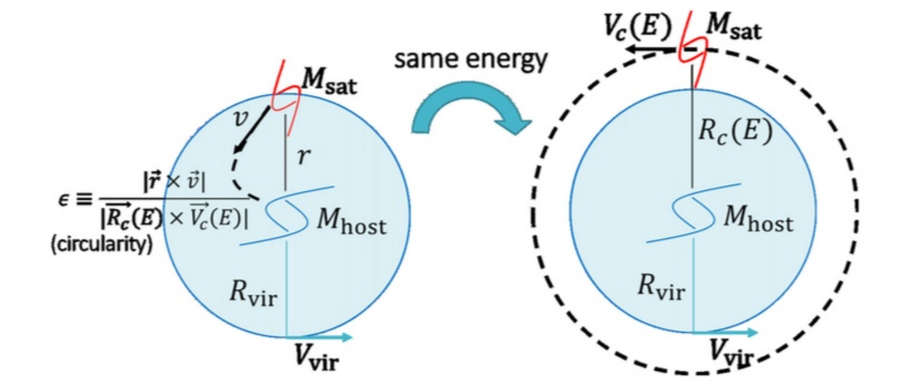
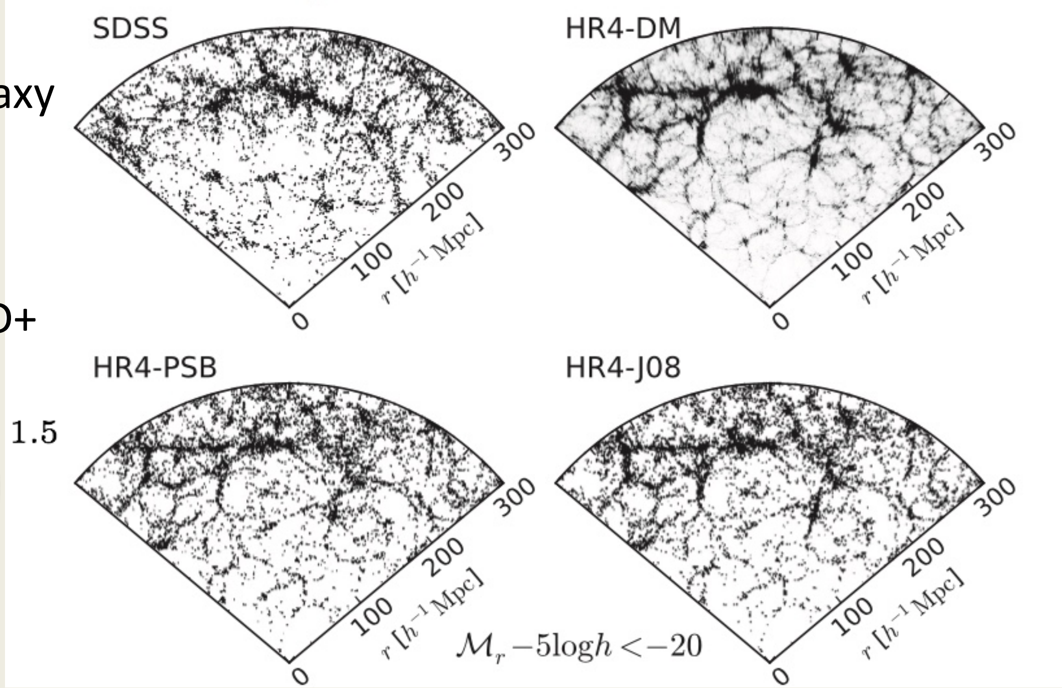
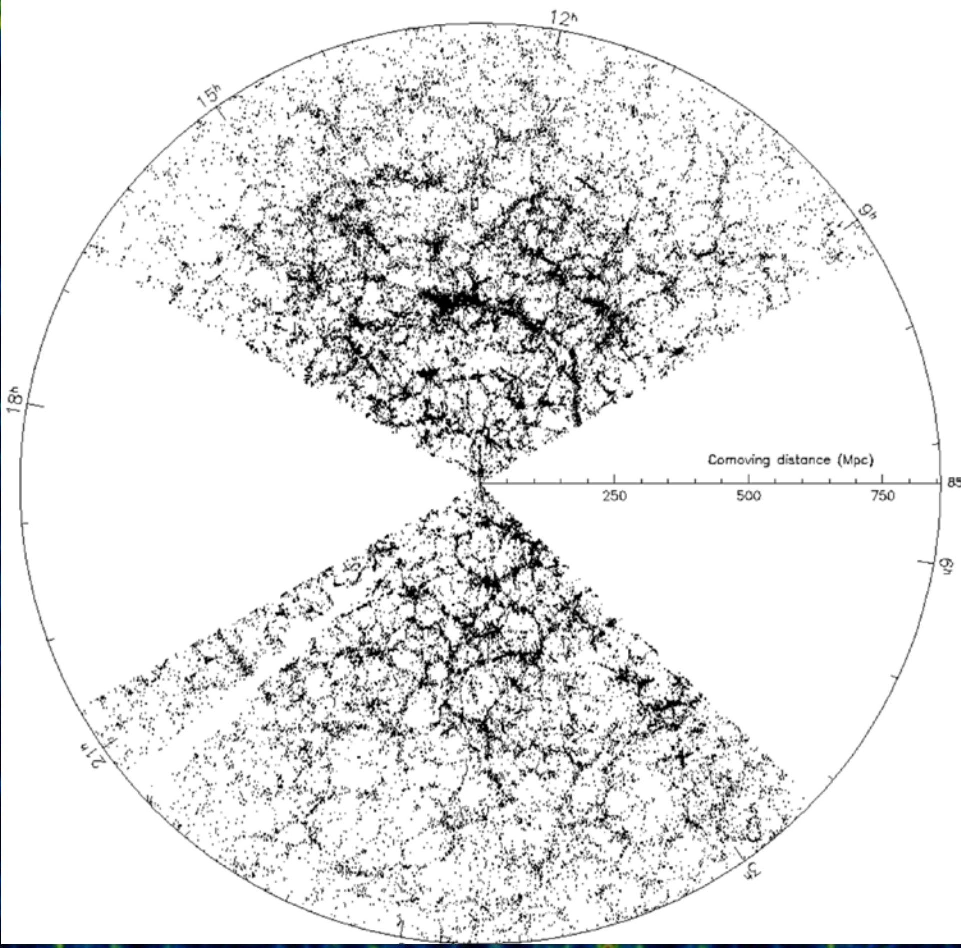


Figure 3. Cartoon depicting the parameters used to estimate the merger timescale of a satellite. $\boldsymbol{r}$, $\boldsymbol{v}$: relative position and velocity of the satellite from its host. $R_{\rm vir}$, $V_{\rm vir}$: virial radius and the circular velocity at the virial radius of the host halo. $M_{\rm sat}$, $M_{\rm host}$: masses of the satellite and its host. $R_c(E)$, $V_c(E)$: radius and velocity of an imaginary circular orbit of the satellite having an identical total energy. ϵ: circularity of the satellite orbit.

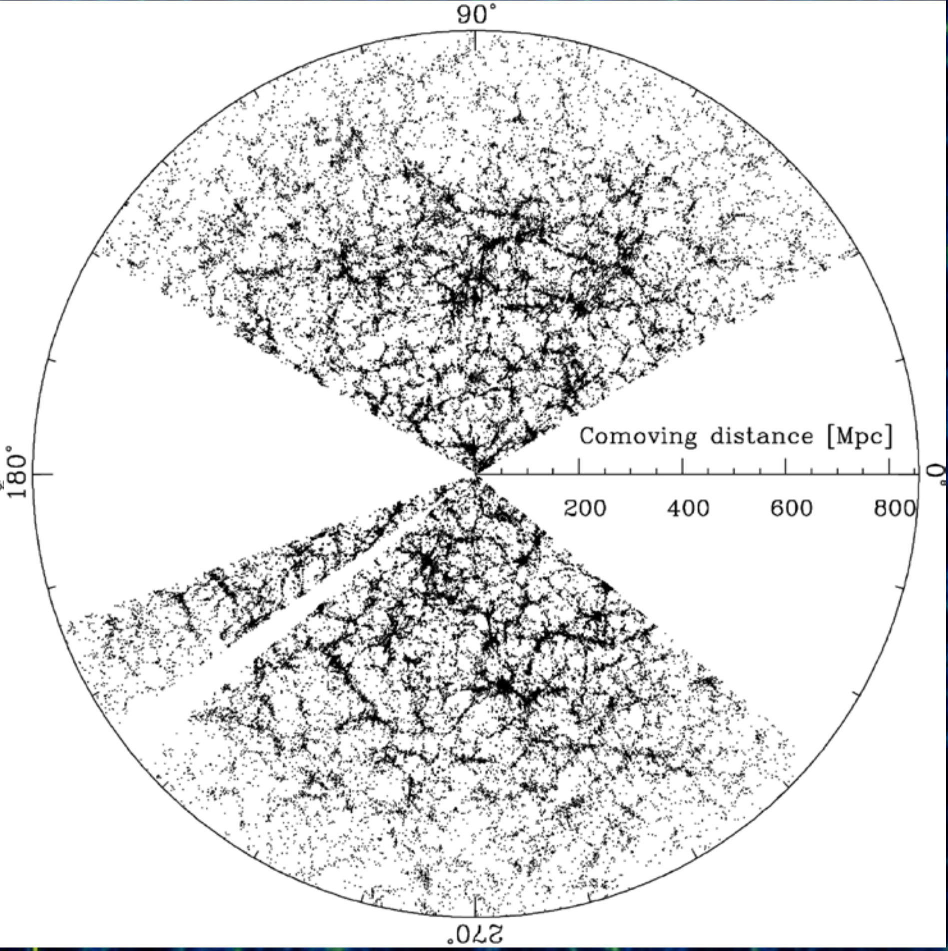


Galaxy Distributions

SDSS Main Galaxies



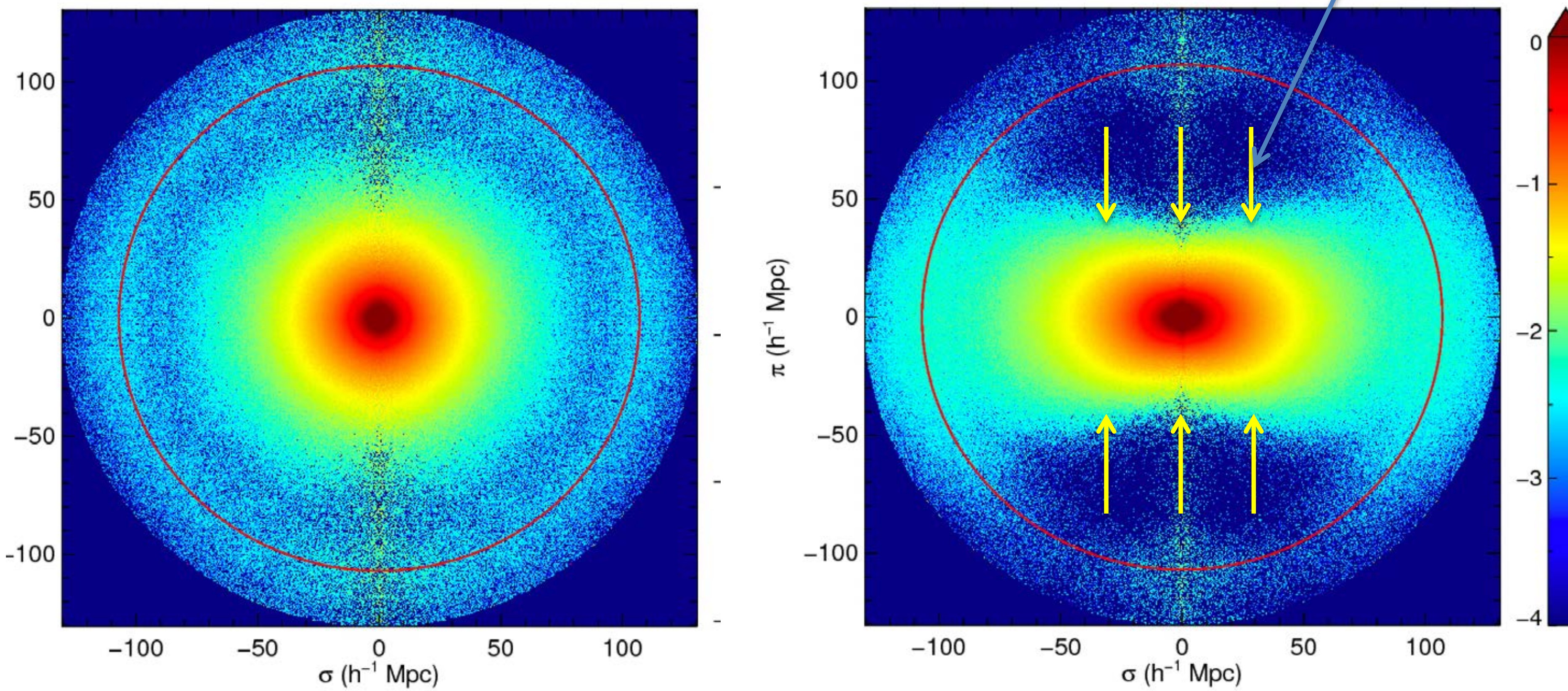
Horizon Run 4 Mock Galaxies



Correlations of Galaxies (Kim+16)

RSD (Kaiser) effect depending on cosmology

No peculiar motion **Peculiar motion effect**

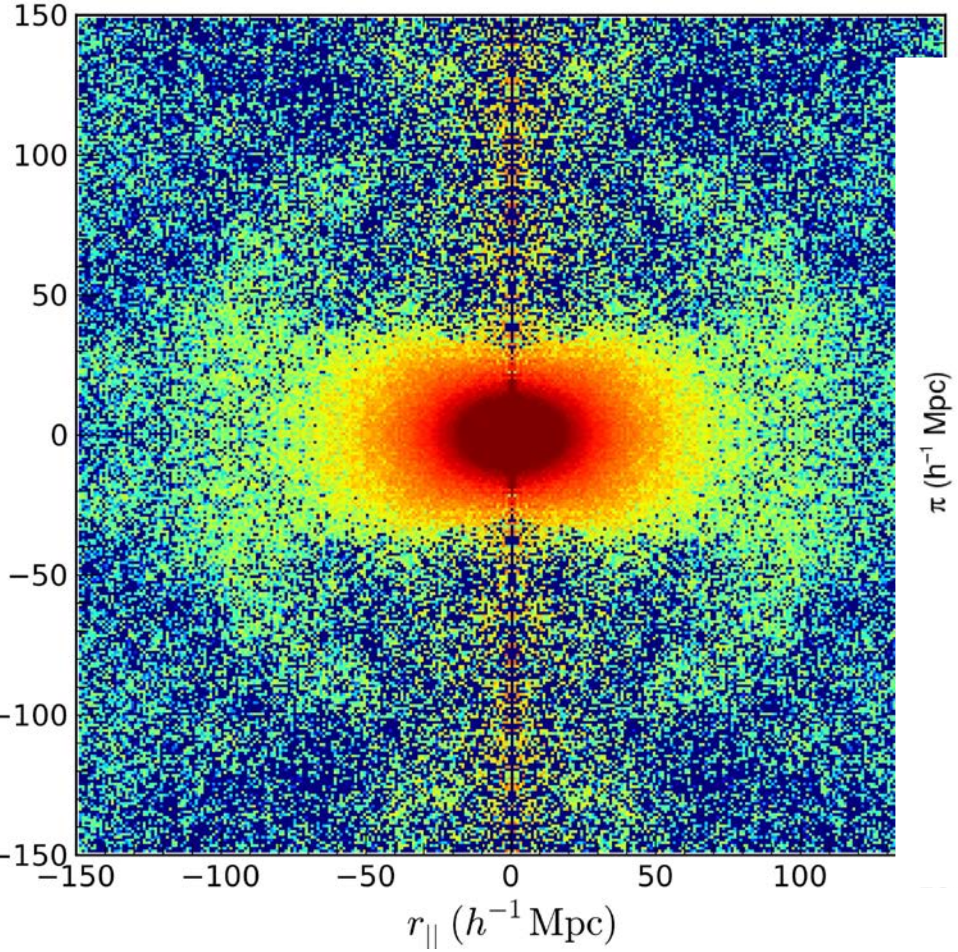


$$\delta(k,s) = (b + f\mu^2)\delta(k,r) = b(1 + \beta\mu^2)\delta(k,r)$$

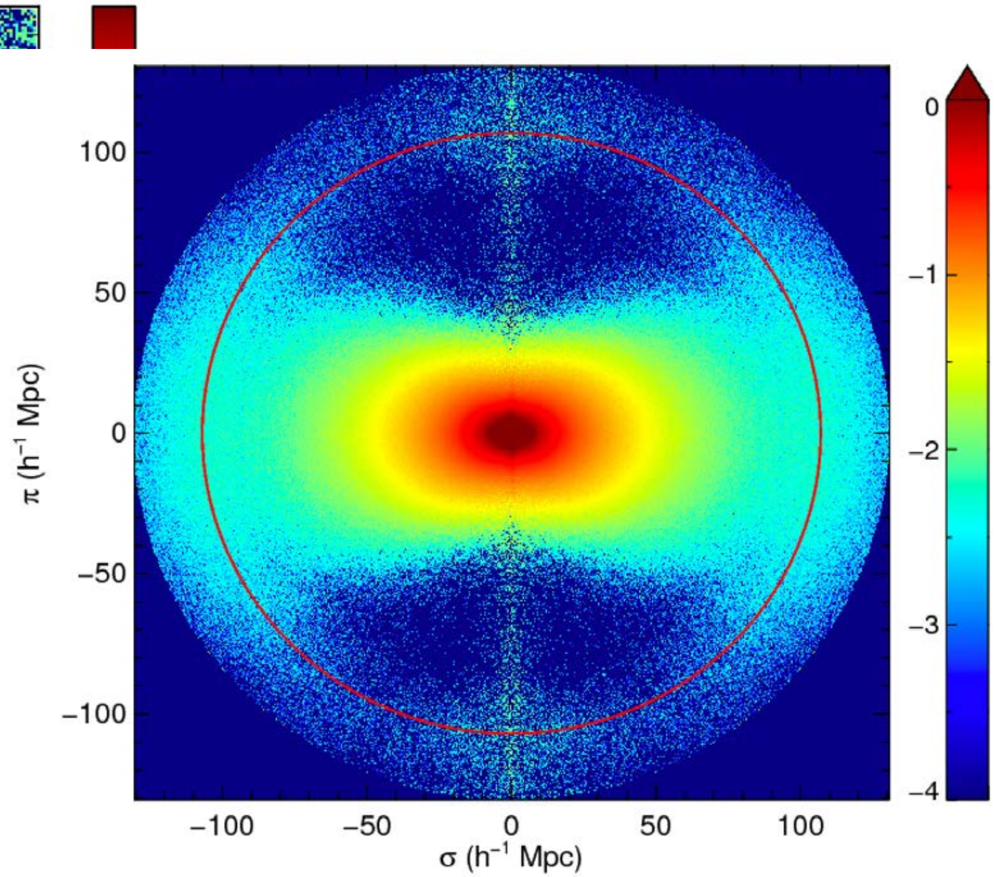
where f is growth rate, b is bias, μ is the angle between the line of sight and separation line, $f \equiv d\ln D^+/d\ln a$, and D^+ is growth factor

Correlation of LRG Galaxies (Kim+16)

SDSS LRG



HR4 Mock LRG



Non-Standard Cosmology

- We are **right on time** for study of non-standard models because of …
  - ***Big*** *extragalactic* ***Data*** being accumulated in the near future
    - Data Size (eBOSS, DESI, DES, LSST, Euclid, etc.)= 100TB ~ 100PB
    - Help us not only narrow down parameters but also probe the non-standard cosmological models.
  - ***Big*** *simulation* ***Data*** for non-standard cosmologies
    - **MultiVerse Simulation Set** (Kim+18 *in prep*.) with seven 2048^3 simulations with L_B=1024 Mpc/h, 112 TB data
      - LCDM(3) + QDE(2) + CPL(2)
    - Extracting model-dependent physical quantities.
      - Two-dimensional correlations (Li, Park, Hong, Kim +) & P(k;s)→ $f\sigma_8$
      - Genus statistics (Appleby, Chingangbam, Hong, Kim, Park +) → nonlinear gravity evolution → model parameters & $f\sigma_8$
      - Merger tree (Lee, Kim, Hong, Park +) → star formation history in Multiverse

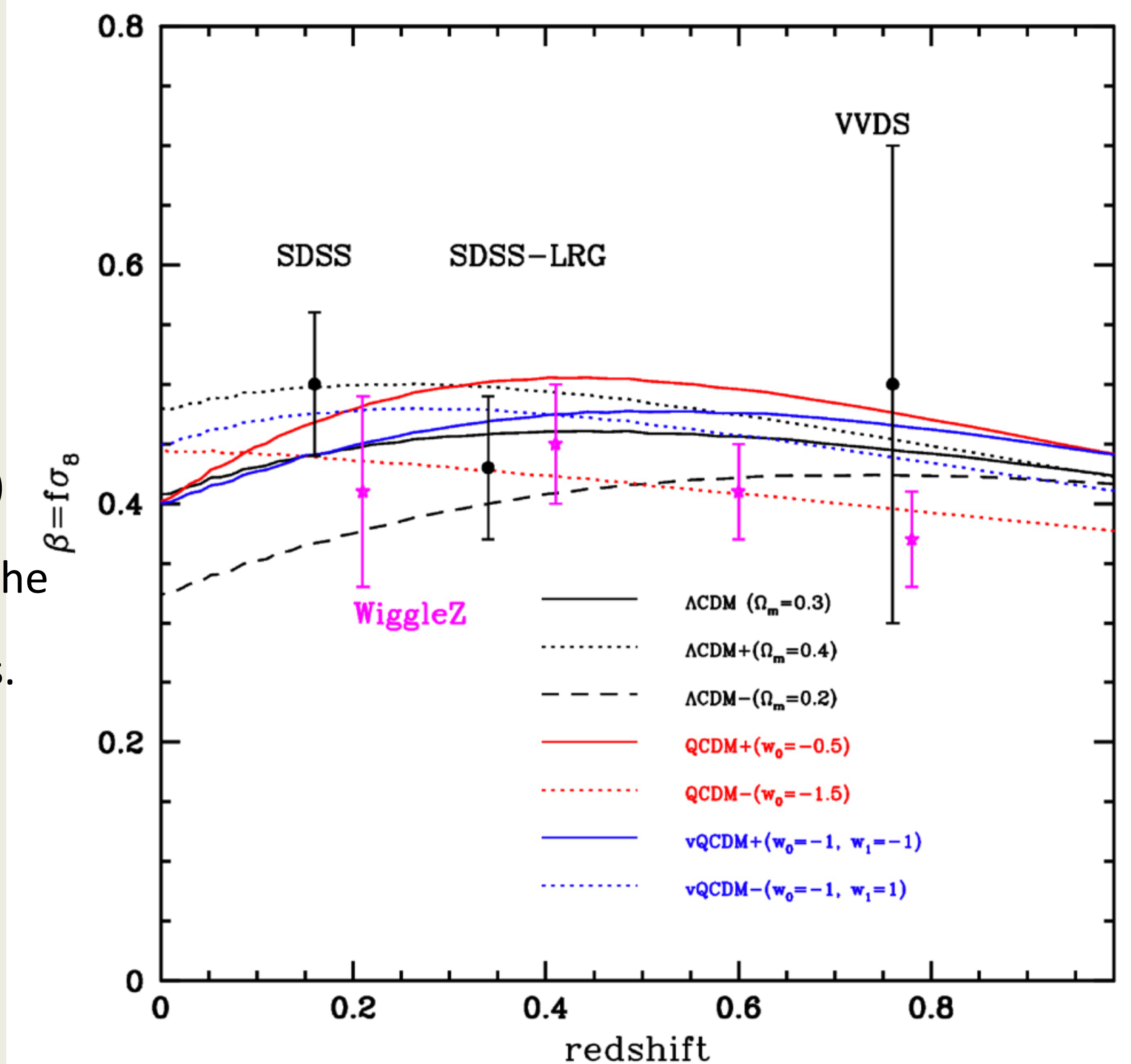
Extension of GOTPM

- Implementation of the non-standard models into our simulation code, **GOTPM**
  - Non Gaussian initial conditions $(f_{\rm NL}, g_{\rm NL} \neq 0)$
    - $\Phi = \Phi_L + f_{\rm NL}(\Phi_L^2 - <\Phi_L^2>) + g_{\rm NL}(\Phi_L^3 - <\Phi_L^3>) + \cdots$
    - $\Phi_{\rm L}$: Gaussian potential & WMAP: $f_{\rm NL} <$ a few
  - Quintessence Dark Energy (DE) Model
    - Spatial-clustering DE & $w \neq -1$ where $w \equiv P/\rho$
  - CPL DE Model
    - Time-varying DE & $w = w_0 + w_1 z/(1+z)$
  - Non-General Relativity Model, f(R) (in this Spring)
    - $S = \int d^4x\sqrt{-g}\left\{\frac{R+f(R)}{16\pi G}\right\} + S_m$, where S is action and R is Ricci scalar
  - DGP, etc…

MultiVerse Simulations

- Three LCDM models:
  $(\Omega_m, \Omega_\Lambda)$ = (0.3, 0.7), (0.2, 0.8), and (0.4, 0.6)
  for each we set (w_0, w_1) = (-1,0)
- Quintessence Dark Energy (DE) Model
  (w_0, w_1) = (-1.5,0) and (-0.5,0) where $w \equiv P/\rho$
  for each we set $(\Omega_m, \Omega_\Lambda)$ = (0.3, 0.7)
- CPL DE Model
  (w_0, w_1) = (-1,-1) and (-1,1) where $w \equiv P/\rho$
  for each we set $(\Omega_m, \Omega_\Lambda)$ = (0.3, 0.7)
- Non-General Relativity Model
  - f(R) will be included in this Spring

Observations .vs. Models



- Observed **β** (0.35—0.5) measured from RSD effect are well within the expected range of **MultiVerse** simulations.
- We will need **bigger** observational data to discriminate non-standard models.

Quintessence & CPL models

$P_w(a)$: Dark energy correction factor to gravitational force
Then, the Poission equation takes a form of

$$\nabla^2\phi = \frac{3}{2}\mathcal{H}^2\Omega_m(a)P_w(a) \tag{1}$$

where

Correction term applied to matter (mass/density)

$$\boxed{P_w(a) \quad = \quad 1 + (1+w)\frac{F_Q(a)}{F_m(a)}} \tag{2}$$

$$F_X(a) \quad \equiv \quad \int_0^a \left[\frac{5}{2} - \frac{3}{2}\frac{D_+(a')}{a'}\right]\Omega_X(a')da' \tag{3}$$

$$D_+(a) \quad \equiv \quad \frac{5}{2}H_0^2\Omega_{m,0}H(a)\int_0^a \frac{C_w(a')}{[a'H(a')]^3}da' \tag{4}$$

$$C_w(a) \quad \equiv \quad 1 + (1+w)\Omega_Q(a)/\Omega_m(a) \tag{5}$$

In a flat universe,

$$\left(\frac{H(a)}{H_0}\right)^2 = \Omega_{m,0}(1+z)^3 + (1-\Omega_{m,0})e^{3\int_0^z d\ln(1+z')(1+w(z'))} \tag{6}$$

CPL: Chevallier-Polarski-Linder

Previous Method on Simulating f(R)-gravity

- Modified Gravity-Gadget (Puchwein+13)
  - The Poisson equation by the modified gravity:

$$\nabla^2\phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R.$$

And the relation between the Ricci tensor R and matter density is

$$\boxed{\nabla^2 f_R = \frac{1}{3c^2}(\delta R - 8\pi G\Delta_\rho)} \quad (1)$$

where c is the speed of light, $f_R \equiv \partial f(R)/\partial R$, and $\Delta_\rho \equiv \rho - \bar{\rho}$. The background curvature field of $f_R \equiv df(R)/dR$ is defined as

$$\bar{f}_R(a) = \bar{f}_{R0}\left(\frac{\bar{R}_0}{\bar{R}(a)}\right)^2 \quad (2)$$

and $\delta R \equiv \bar{R}(a)(\sqrt{\bar{f}_R(a)/f_R} - 1)$.

  - Iterative Solver with Multigrid Method
    - Newton-Gauss-Seidel method: Update by relaxation method

$$\boxed{u^{i+1} = u^i - \left(\frac{\mathcal{L}^i - \mathcal{F}}{d\mathcal{L}^i/du^i}\right)} \quad (3)$$

where $\mathcal{L} \equiv \nabla^2 e^u + \bar{R}(a)(1 - e^{-u/2})/3c^2\bar{f}_R(a)$ and $u \equiv \ln(f_R/\bar{f}_R)$.

    - On a static uniform grid it is well known that the error can not be lowered below 10%.
    - But On a standard multi-grid, the error can be lowered significantly.
    - Starting from a top coarse grid, solve equation (2). And, then, move to one step deeper grid and solve equation (2) for the finer grid.

Solve the second derivative in real space and **apply Newton-Gauss-Seidel relaxation** method in real space

Adaptive Mesh Refinement is used to solve the equation hierarchically and to lower error measurement below %.

In order to solve this equation for u on a grid, we need to discretize $\nabla^2 e^u$. We do this in the same way as in Oyaizu (2008), i.e.

$$\begin{aligned}(\nabla^2 e^u)_{i,j,k} = \frac{1}{h^2}\Big[&b_{i-\frac{1}{2},j,k}u_{i-1,j,k} + b_{i+\frac{1}{2},j,k}u_{i+1,j,k} \\ &- \left(b_{i-\frac{1}{2},j,k} + b_{i+\frac{1}{2},j,k}\right)u_{i,j,k}\Big] \\ + \frac{1}{h^2}\Big[&b_{i,j-\frac{1}{2},k}u_{i,j-1,k} + b_{i,j+\frac{1}{2},k}u_{i,j+1,k} \\ &- \left(b_{i,j-\frac{1}{2},k} + b_{i,j+\frac{1}{2},k}\right)u_{i,j,k}\Big] \\ + \frac{1}{h^2}\Big[&b_{i,j,k-\frac{1}{2}}u_{i,j,k-1} + b_{i,j,k+\frac{1}{2}}u_{i,j,k+1} \\ &- \left(b_{i,j,k-\frac{1}{2}} + b_{i,j,k+\frac{1}{2}}\right)u_{i,j,k}\Big],\end{aligned} \quad (17)$$

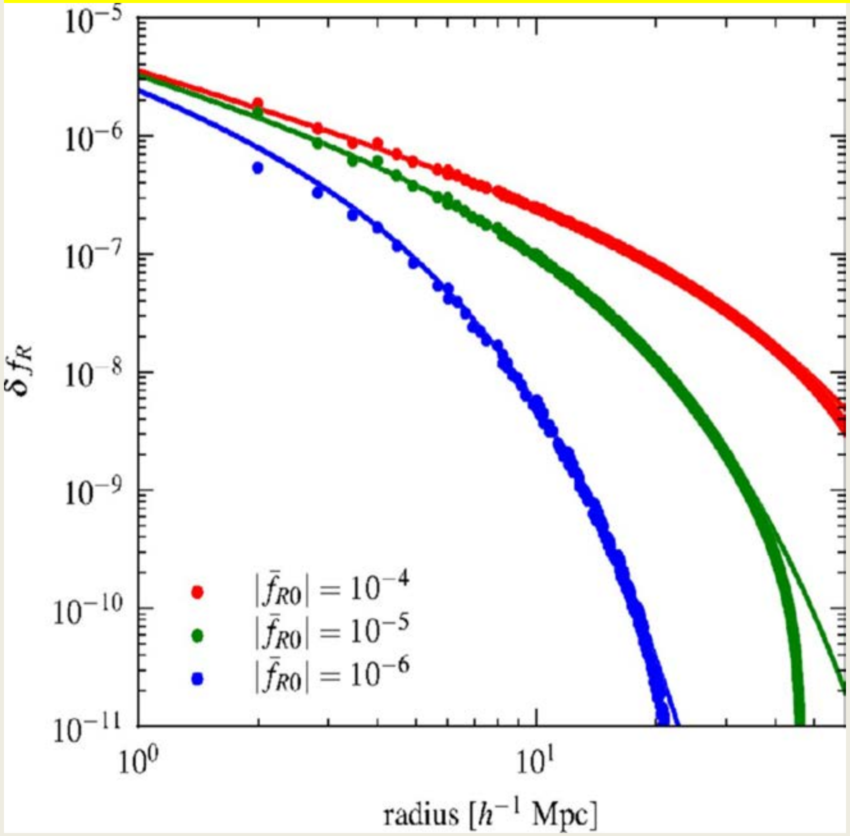
where i, j, k are the cell indices in the x, y and z directions, respectively. h is the physical side length of a cell and

$$b_{i-\frac{1}{2},j,k} \equiv \frac{1}{2}(e^{u_{i-1,j,k}} + e^{u_{i,j,k}}), \quad (18)$$

$$b_{i+\frac{1}{2},j,k} \equiv \frac{1}{2}(e^{u_{i,j,k}} + e^{u_{i+1,j,k}}). \quad (19)$$

Puchwein+13

f_R Test of Point-Mass Case



Yukawa potential

Point mass satisfying equation (2) has a solution of Yukawa potential of

$$\Delta f_R = f_R - \bar{f}_R = \frac{2Gm}{3c^2 r} e^{-r/\lambda_e} \tag{1}$$

where $\lambda_e \equiv (3c^2 f_{RR})^{1/2}$. Therefore, given $\bar{f}_R$ we may obtain the analytic solution of the nonlinear equation.

A New f(R)-gravity Solver

According to $f(R)$ model, one should modify the Poisson equation as

$$\nabla^2\phi = 4\pi G\Delta_\rho - \frac{c^2}{2}\nabla^2 f_R \quad (1)$$

where $f_R \equiv df(R)/dR$, and f_R could be obtained from

$$\boxed{\bar{f}_R(a)\nabla^2 C + \frac{\bar{R}(a)}{3c^2}\left(1 - 1/\sqrt{C}\right) + \left(\frac{H_0}{c}\right)^2\left(\frac{\Omega_{m,0}}{a^3}\right)\delta_\rho = 0} \quad (2)$$

where

$$C \equiv \left(\frac{f_R}{\bar{f}_R(a)}\right) \quad (3)$$

$$f(R) \equiv -\mathcal{M}^2\frac{c_1(R/\mathcal{M}^2)^n}{c_2(R/\mathcal{M}^2)^n + 1} \quad (4)$$

$$\mathcal{M}^2 \equiv H_0^2\Omega_{m,0} \quad (5)$$

To solve the nonlinear equation (2), we are using the Fourier-space Relaxation method.

Another type of relaxation method different from the Newton-Gauss-Seidel

FOURIER RELAXATION METHOD

In the Fourier space, equation (2) can be expressed as

$$\boxed{L_k(C_k) \equiv I(a,\lambda_k)C_k - J(a)v_k - K(a)\delta_k = 0} \quad (6)$$

where

$$I(a,\lambda_k) \equiv \bar{f}_R(a)\left(\frac{1}{a^2}\right)\left(\frac{2\pi}{\lambda_k}\right)^2 \quad (7)$$

$$= \bar{f}_R(a)\left(\frac{2\pi}{a}\right)^2\left(\frac{u_k}{L_B}\right)^2 < 0, \quad (8)$$

and λ_k is the comoving wave length of the k mode. Also, v_k, and δ_k are the Fourier-space counterparts of $(1-1/\sqrt{C})$, and δ_ρ, respectively.

During the simulation run, we utilize the distribtuion of C obtained in the previous step, which can be used as an initial guess to the current step. Let us adopt the iterative relaxation scheme based on the FFT . We may transform equation (2) in Fourier space as

$$C_k = \left[\frac{J(a)v_k + K(a)\delta_k}{I(a,\lambda_k)}\right]. \quad (9)$$

We utilize an iterative relaxation scheme similar to what is adopted by Chan & Scoccimarro (2007) as

$$C_k^{\rm new} = \frac{w}{1+w}C_k^{\rm old} + \frac{1}{1+w}\left[\frac{J(a)v_k + K(a)\delta_k}{I(a,\lambda_k)}\right], \quad (10)$$

where w is a weighting having a range of $w \geq 0$. This update can be further simplified to

$$C_k^{\rm new} = C_k^{\rm old} - \frac{1}{1+w}\mathcal{L}_k(C_k^{\rm old}), \quad (11)$$

where $\mathcal{L}_k \equiv L_k/I(a,\lambda_k)$ (see Eq. 6 for defintion of L_k). In this equation, the meaning of w is clearly seen. The term of $1/(1+w)$ is multiplied to damp the numerical oscillation around the solution. Or in real space

$$\boxed{C^{\rm new} = C^{\rm old} - \frac{1}{1+w}\mathcal{L}(C^{\rm old}).} \quad (12)$$

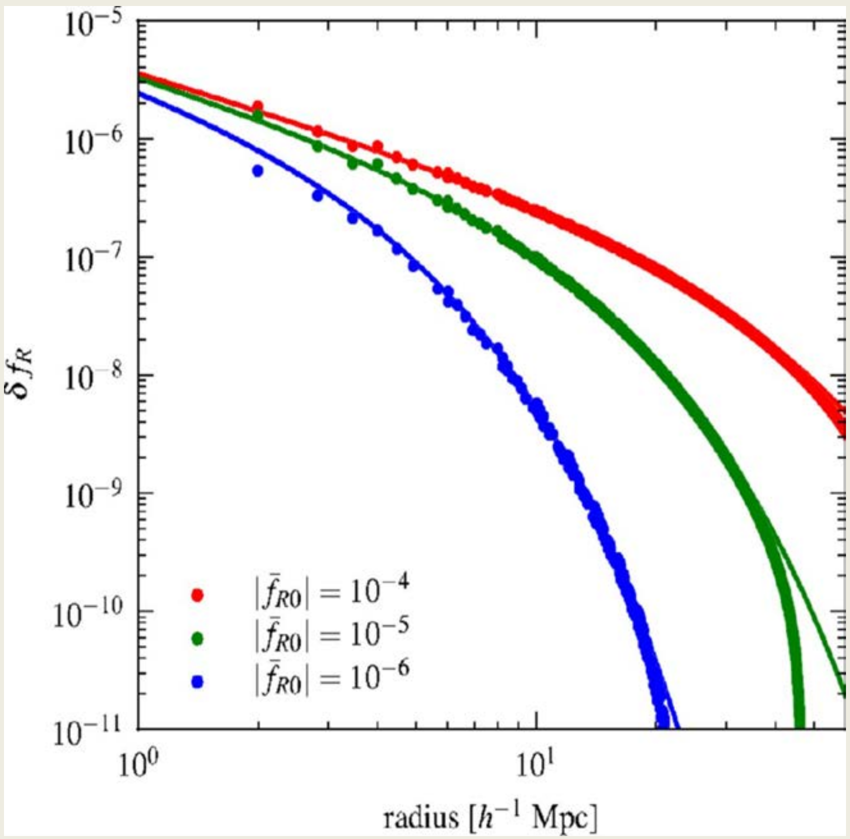
Likewise,

$$\boxed{v^{\rm new} = v^{\rm old} + \frac{1}{1+w}\frac{L(C^{\rm old})}{J(a)},} \quad (13)$$

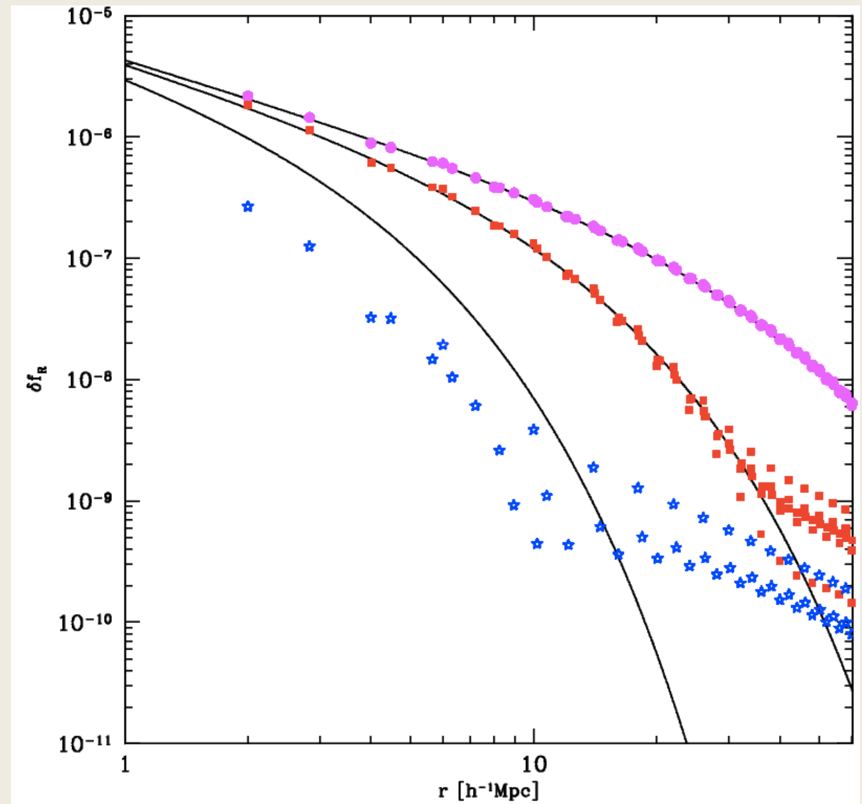
which should be calculated at each pixel. In the linear mode where $I(a) \ll J(a)$ and $K(a)$ or $\mathcal{L}_k(C_k^{\rm lin}) \to 0$, this update is stable around the linear solution.

f_R Test of Point-Mass Case

Puchwein+13



Our method (temporary)

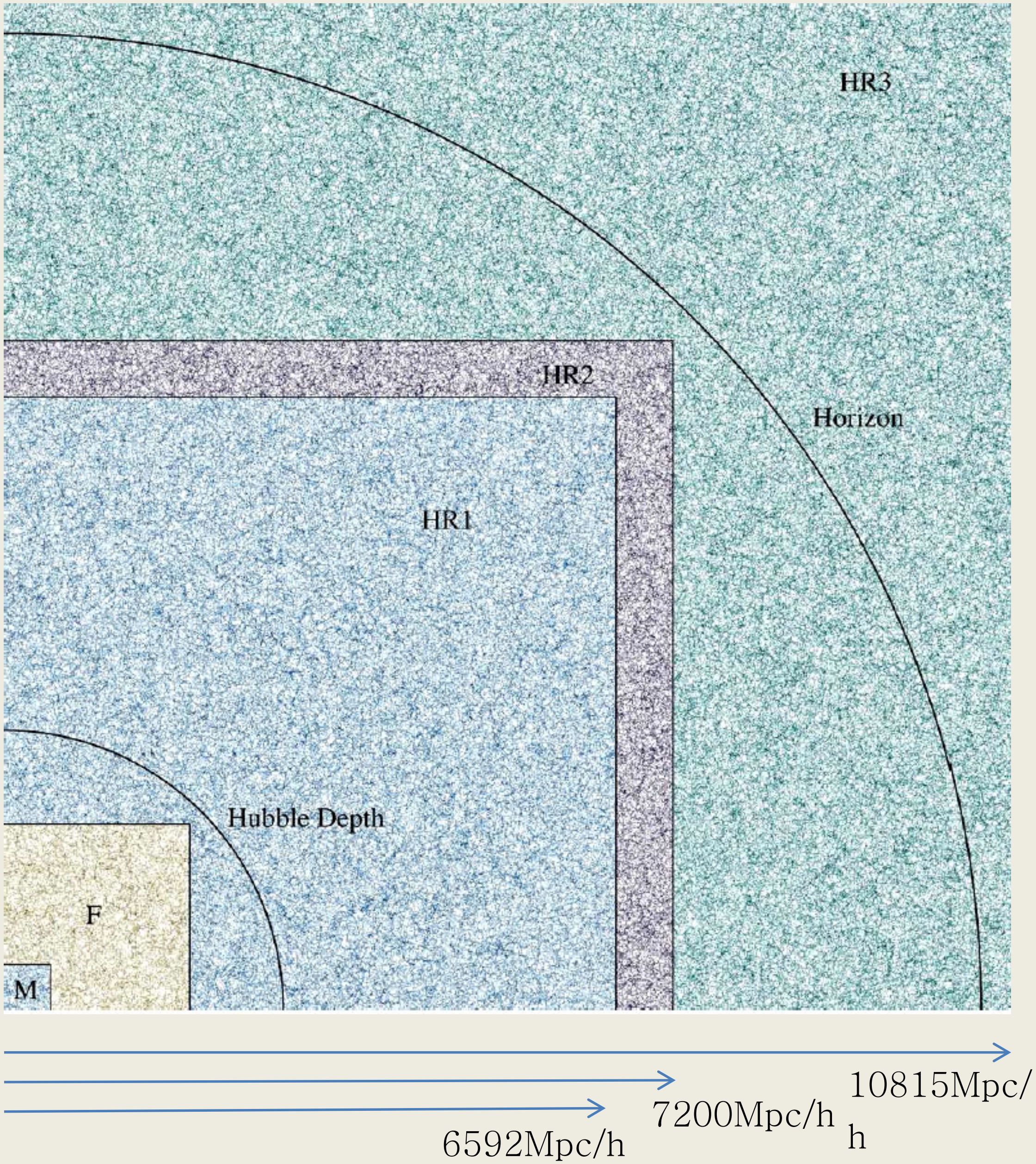


Conclusion

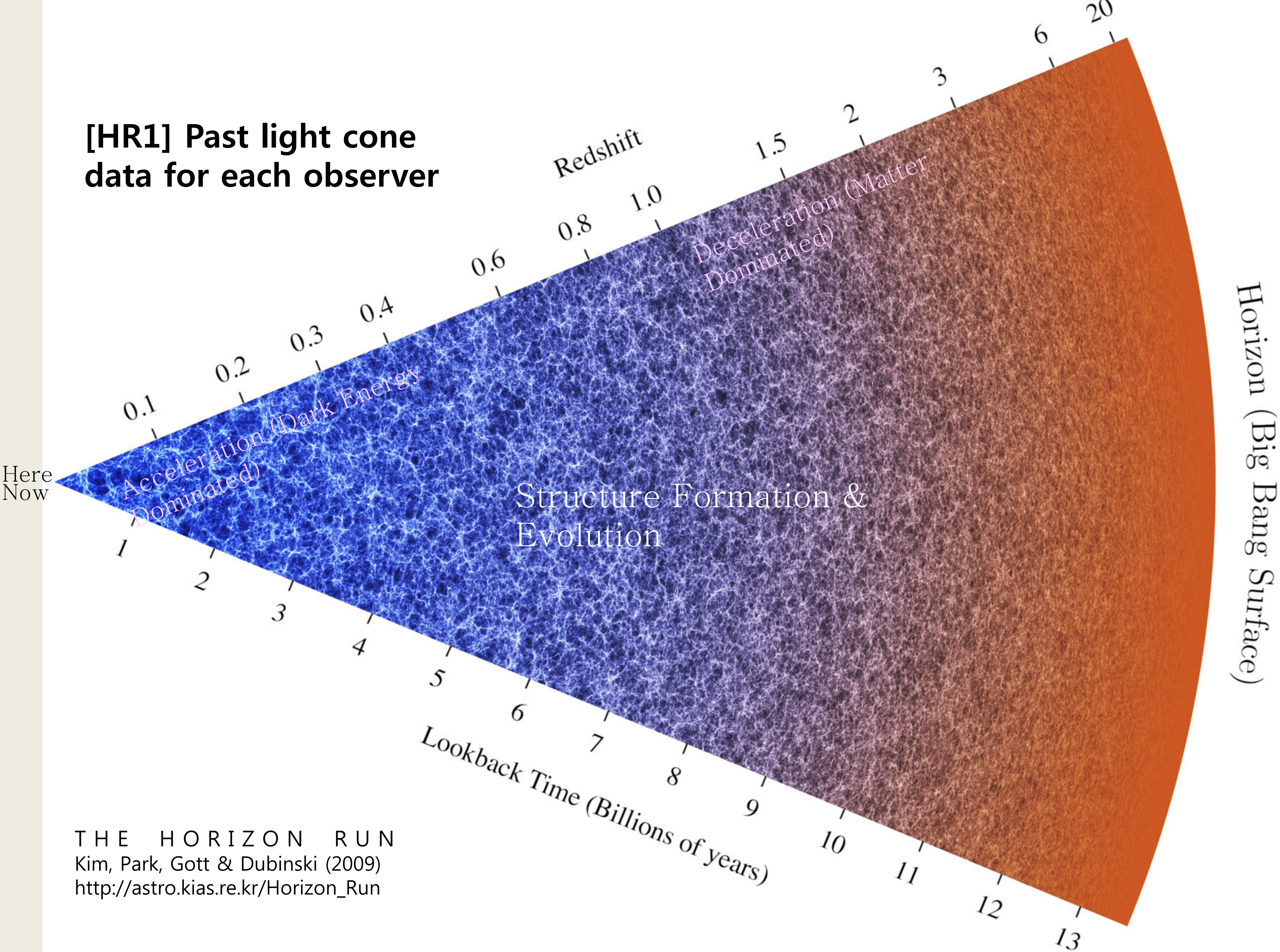
- Extension of GOTPM (Cosmological N-body Simulation Code) to include simulations of various non-standard cosmological models
  - Currently we are working on f(R), and visit DGP model in this spring.
- MultVerse Simulation Set
  - To include various and probable models to be falsifiable by the near-future extragalactic observations
- Any collaboration would be welcome.
  - New non-standard model
  - New method to split model degeneration

The Horizon Run
N-Body Simulations

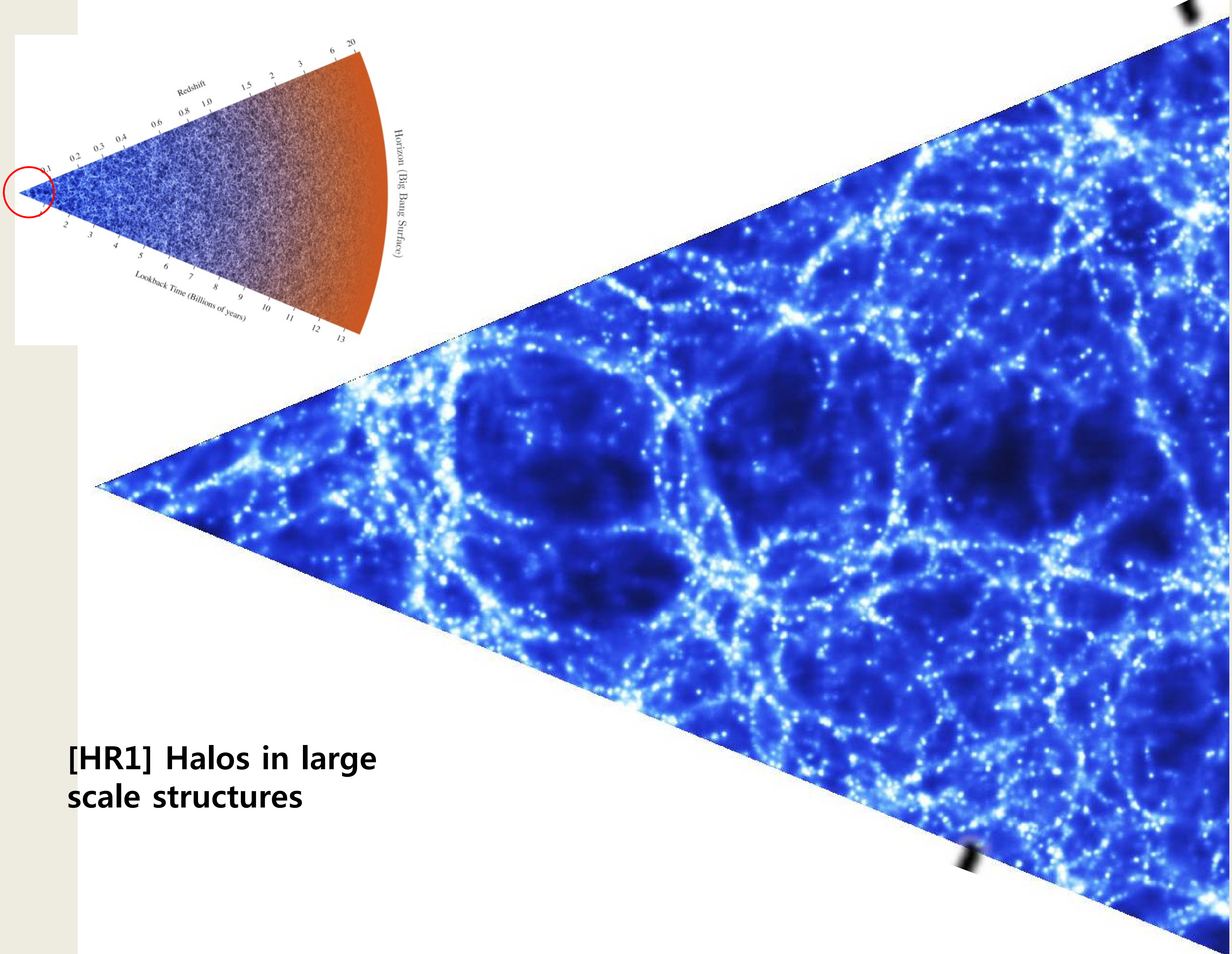
(J. Kim et al. 2009; J. Kim et al. 2011; http://astro.kias.re.kr/Horizon-Run23/)



[HR1] Past light cone data for each observer



THE HORIZON RUN
Kim, Park, Gott & Dubinski (2009)
http://astro.kias.re.kr/Horizon_Run



[HR1] Halos in large scale structures