Horizon Run Cosmological N-Body Simulations

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Computers for the Horizon Run Simulations

	HR1	HR2 & HR3
Year performed	2007-2008	2010-2011
System used	Tachyon SUN Blade (KISTI)	Tachyon-II SUN Blade (KISTI)
# of nodes	188	3176
Rpeak	24 Tflops	300 Tflops
Processor	AMD Opteron 2GHz (quad)	Intel Xeon 2.93 GHz (quad)
# of CPUs	3,008 cores (16 /node)	25,408 cores (8/node)
Total Memory	6 TB (32GB/node)	76.8 TB (24GB/node)
Total Storage	207 TB (SUN Lustre)	1.1 PB (SUN Lustre)
Network	Infiniband 4x DDR	Infiniband 40G 4x QDR
Occupation of System resources	50%	33%

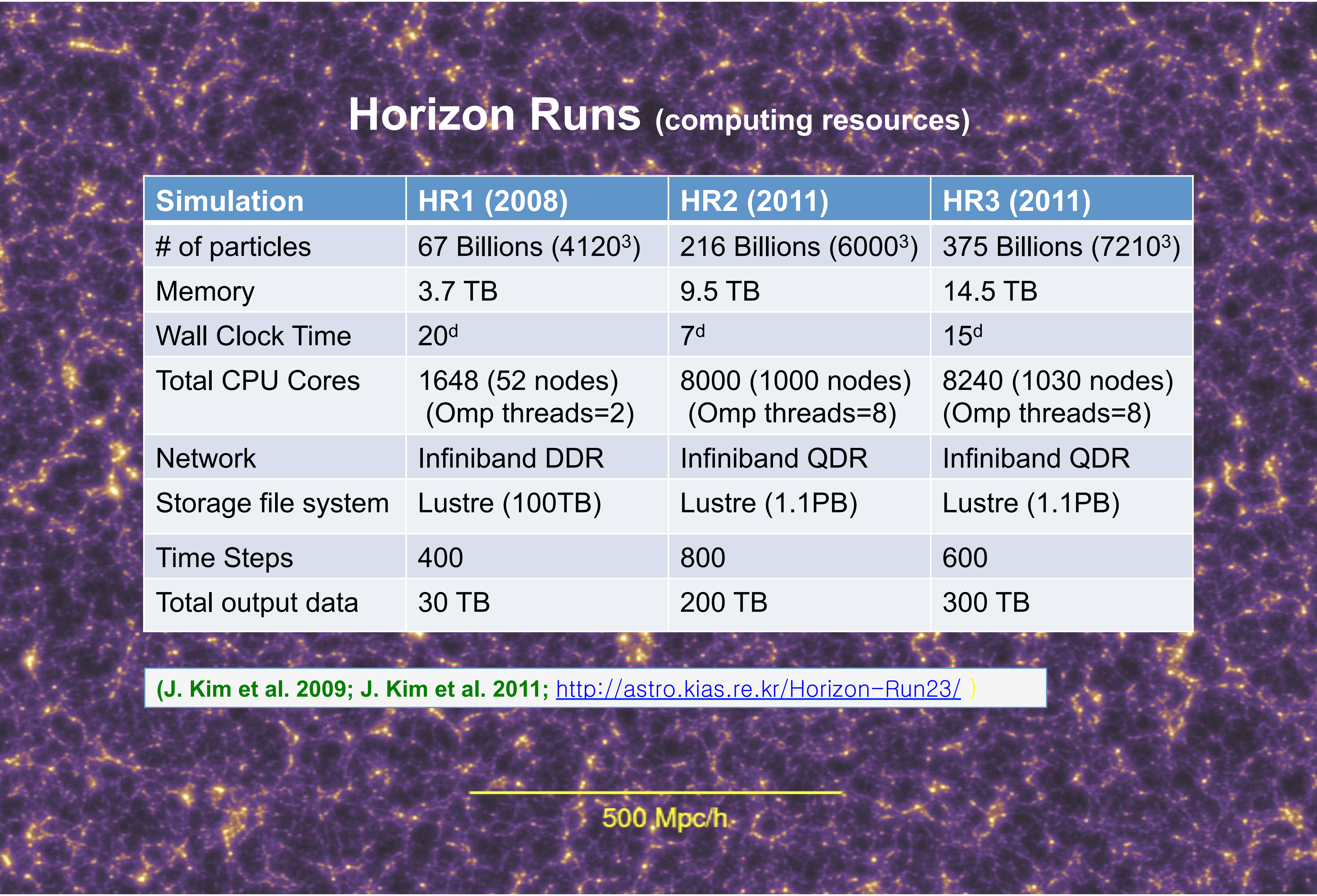
500 Mpc/h

KISTI @ http://www.ksc.re.kr

Horizon Runs (computing resources)

Simulation	HR1 (2008)	HR2 (2011)	HR3 (2011)
# of particles	67 Billions (4120^3)	216 Billions (6000^3)	375 Billions (7210^3)
Memory	3.7 TB	9.5 TB	14.5 TB
Wall Clock Time	20^d	7^d	15^d
Total CPU Cores	1648 (52 nodes) (Omp threads=2)	8000 (1000 nodes) (Omp threads=8)	8240 (1030 nodes) (Omp threads=8)
Network	Infiniband DDR	Infiniband QDR	Infiniband QDR
Storage file system	Lustre (100TB)	Lustre (1.1PB)	Lustre (1.1PB)
Time Steps	400	800	600
Total output data	30 TB	200 TB	300 TB

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



Horizon Runs (physics)

Simulation	HR1 (2008)	HR2 (2011)	HR3 (2011)
# of particles	4120^3	6000^3	7210^3
Ω_m , Ω_b , Ω_Λ	0.26, 0.044, 0.74	0.26, 0.044, 0.74	0.26, 0.044, 0.74
n_s, h, σ_8	0.96, 72, 0.794	0.96, 72, 0.794	0.96, 72, 0.794
Box size (h^{-1}Mpc)	6592	7200	10815
Starting redshift	23	32	27
particle d (h^{-1}Mpc)	1.6	1.2	1.5
# of halos at z=0	140 Millions	500 Millions	700 Millions
Minimum halo mass ($M_\odot$/h)	8.87×10^{12}	3.74×10^{12}	7.31×10^{12}
halo d (h^{-1}Mpc)	13.08	9.01	11.97
Initial Linear Power Spectrum	Eisenstein & Hu	CAMB Source	CAMB Source

THE HORIZON RUN 1, 2 & 3 (Kim et al. 2009; Kim et al. 2011) http://astro.kias.re.kr/Horizon-Run23/

Simulations

Generation of initial conditions → Evolution of matter particles → Data outputs (snapshots & past light cone) → Dark halo identification & merger tree → Numerical answers, Mock surveys & Stat. tests

Initial conditions

Particle displacements and comoving velocities in accordance with the WMAP 5 yr cosmological parameters.

Equations to solve

$$(da/dt)^2 = 8\pi G\rho_0(\Omega_i^{-1} - 1 + a(t)^{-1})/3$$

$$\dot{v}_i + 2\frac{\dot{a}}{a}v_i = -a^{-3}\sum_{i\neq j}\frac{Gm_j x_{ij}}{\left|x_{ij}\right|^3} = a^{-3}F_i/m_i, v(t) = dx/dt$$

$$\frac{du_i}{da} + 2A(a)u_i = B(a)F_i/m_i$$

First order expansion of the symplectic form

$$u = \frac{dx}{da}, A(a) = \frac{(2 + \ddot{a}a/\dot{a}^2)}{2a}, B(a) = \frac{1}{\dot{a}^2 a^3}$$

N-body (GOTPM) code: A PMTree code (Park 1990; Dubinski, Kim, Park et al. 2004)

1. Long range (r>4 pixels, PM) + Short range(Tree) g-forces

   Tree generation in each slab & in each cube of $(4+4+4)^3$ pixels

   (***grid-based oct-sibling tree***)

   Min. # of particles for tree generation – Direct P^2 if #(in local cubes) < N_{tree}

2. Memory : ~[11] x words per particle

   * 11 per particle: index^2, position^3, velocity^3, work^1, pointer^2 (or mesh for PM & FFT)
     - structure switching technique: PM particle ←→ Tree particle
   * pmparticletype {float4 x,y,z,vx,vy,vz;long8 index} + float4 2*den(fft stuffs)
   * treeparticletype (floa4t x,y,z,vx,vy,vz; long8 index;pointer *next} + float4 work(tree)
   * 4120^3 particles = 3.3 TB (2.7 TB if not using the index)

3. Simple method to enhance position accuracy using single precision

   * Typical Method: float4 positions (x,y,z) : ex) r=(0.344543, 6453.33,4567.21)
   * Advanced Method: float4 shifts (dx,dy,dz) from Lagrangian position (index; x0,y0,z0)

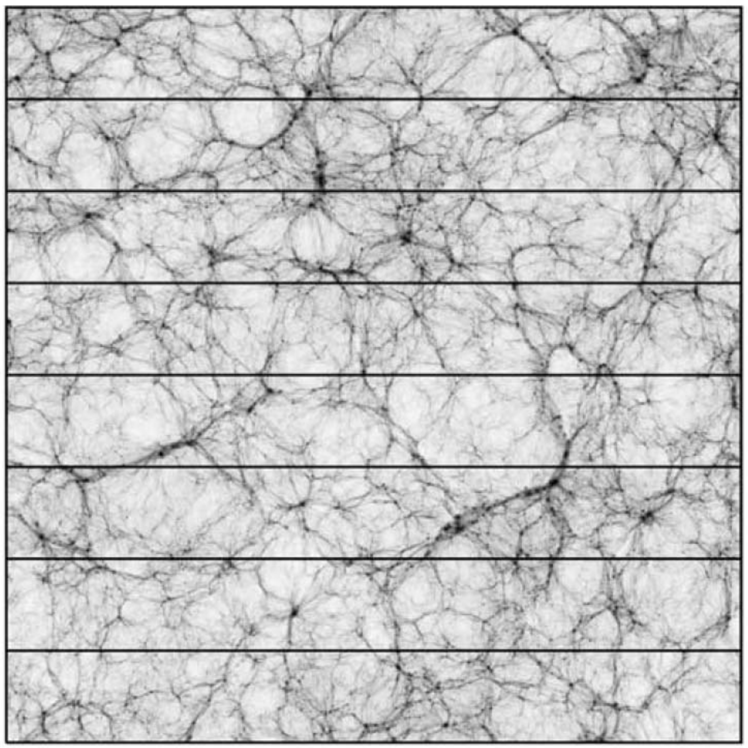
     → more accurate position (x0+dx,y0+dy,z0+dz)

     ex) r=(0.344543,6453.33457,4567.214356)

Parallelization

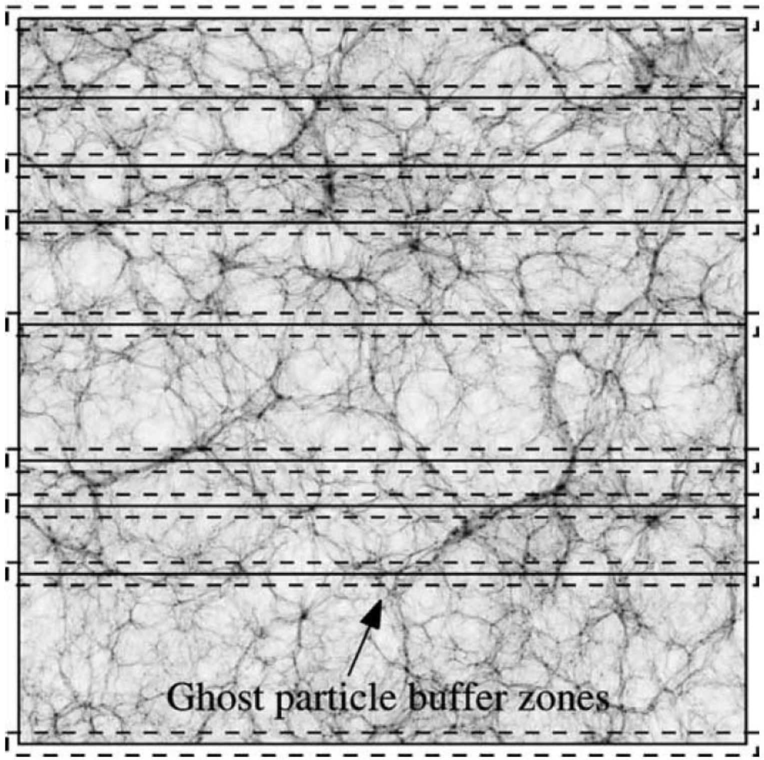
1. FFT part (FFTW)

: Domain slabs of equal(?) thickness

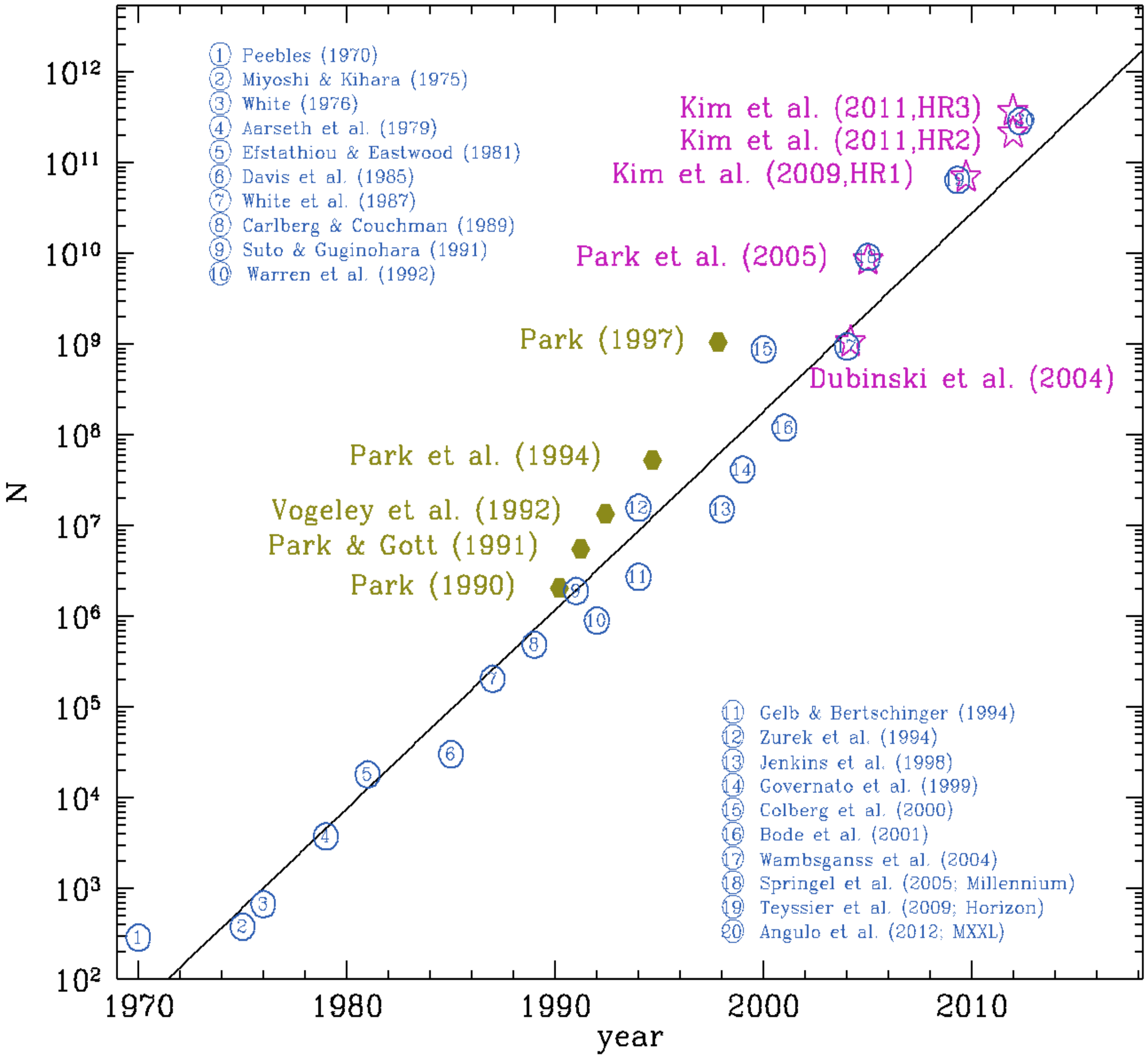


2. PM & Tree part

: Domain slabs of equal # of tree force interactions & buffer zone particles

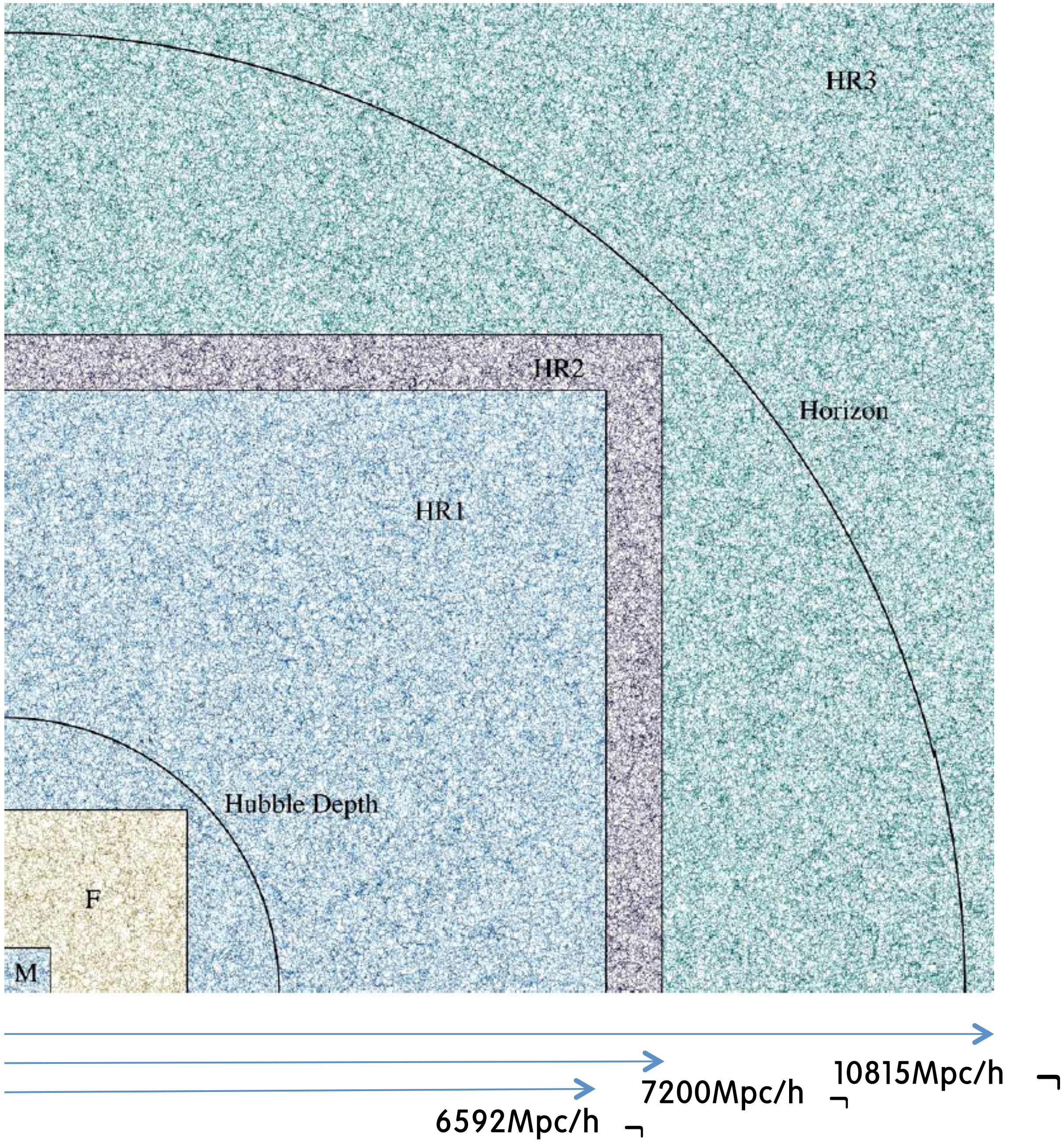


Increase in the size of Cosmological N-body Simulations



The Horizon Run
N-Body Simulations

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



Needs for Large Cosmological N-body Simulations

1) Study of rare objects like the SGW can be only addressed realistically through mock surveys in very large simulations.

cf: Park et al. (2012) using HR3.

[Y. Suto 2010, private communication]

2) The validity of linear theory, in particular the max wavenumber that linear theory can be used for statistics, can be confirmed only by large N-body simulations.

cf: Takahashi et al. Simulations of baryon acoustic oscillations - I. Growth of large-scale density fluctuations, MNRAS 389(2008)1675 Nishimichi et al. Modeling Nonlinear Evolution of Baryon Acoustic Oscillations: Convergence Regime of N-body Simulations and Analytic Models PASJ 61(2009)321

3) The covariance between different modes of power spectrum can be only estimated by a large number of N-body simulations

c.f.: Takahashi et al. Simulations of Baryon Acoustic Oscillations. II. Covariance Matrix of the Matter Power Spectrum, ApJ 700(2009)479

4) There is no good model for redshift-space distortion that can be reliably used for the future dark energy surveys.

c.f., Taruya et al. Nonlinear evolution of baryon acoustic oscillations from improved perturbation theory in real and redshift spaces PRD (2009) 80.123503

ias cannot be really modeled without simulations (N-body simula

erful in this respect. Halo bias is one approach even though not quite

tried to remove the biasing effect only by empirical modeling.

Dark halo identification [Kim & Park 2006]

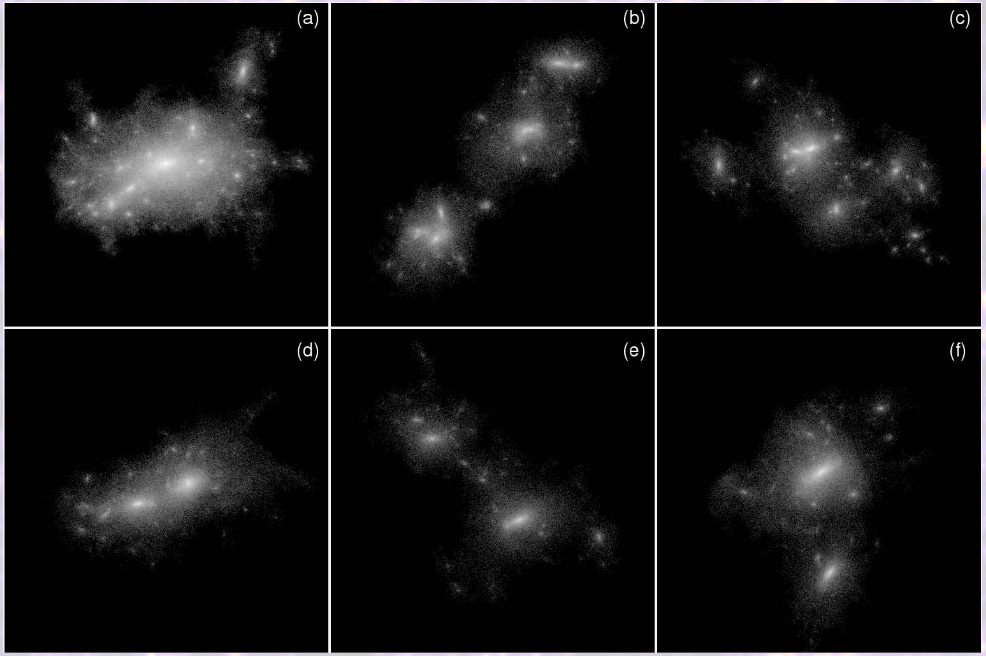
Physically Self-Bound halos/subhalos (isolated, central & satellite halos)

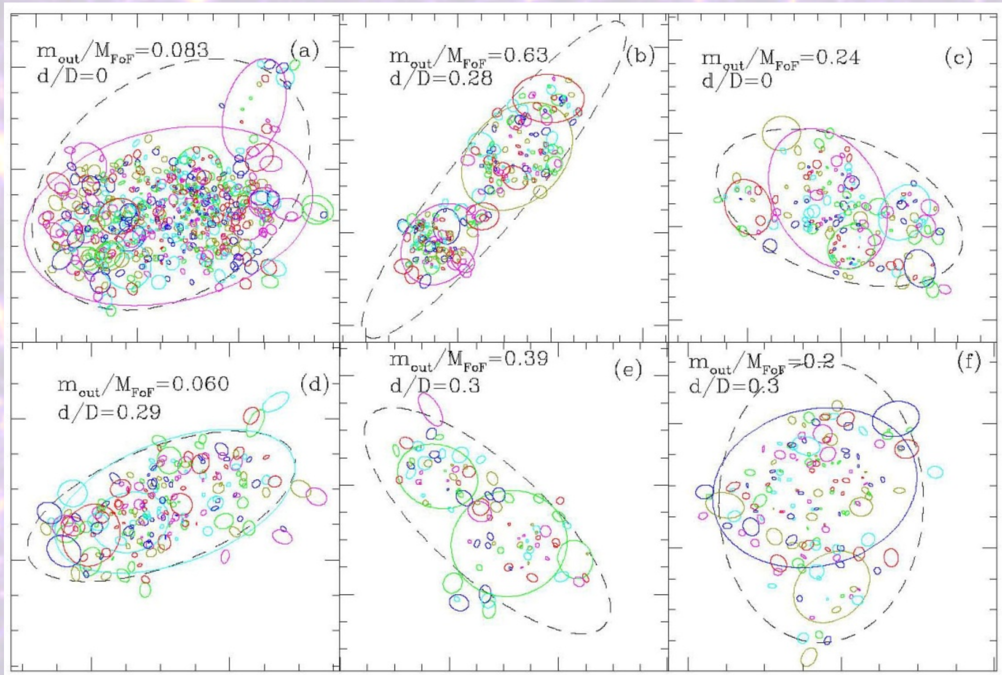
Halo centers - local density peaks

Gravitationally-bound, tidally-stable halos with >30 particles.

matter – dark halos – galaxies

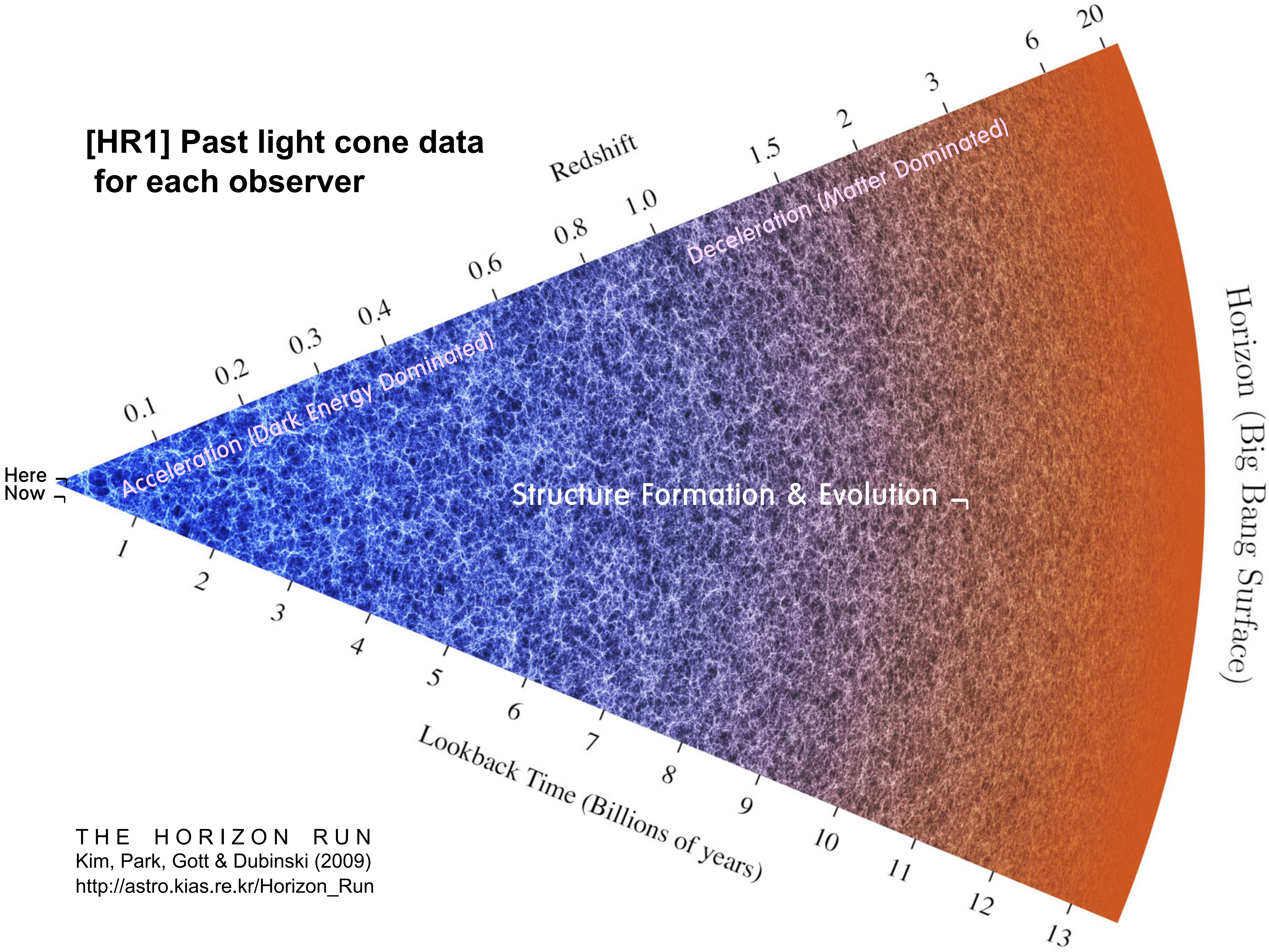
subHalo-galaxy 1-1 correspondence model



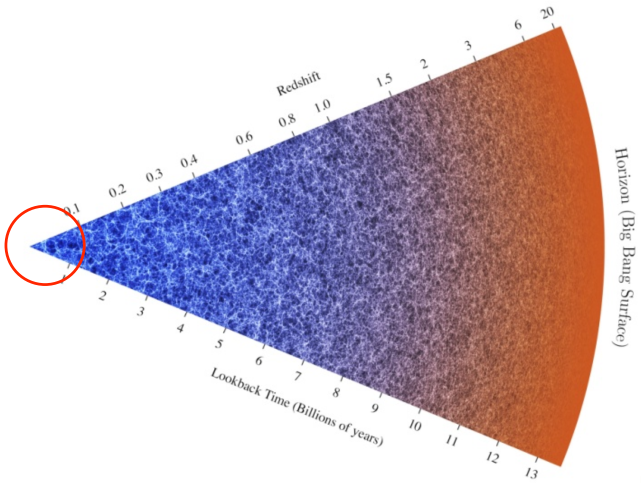


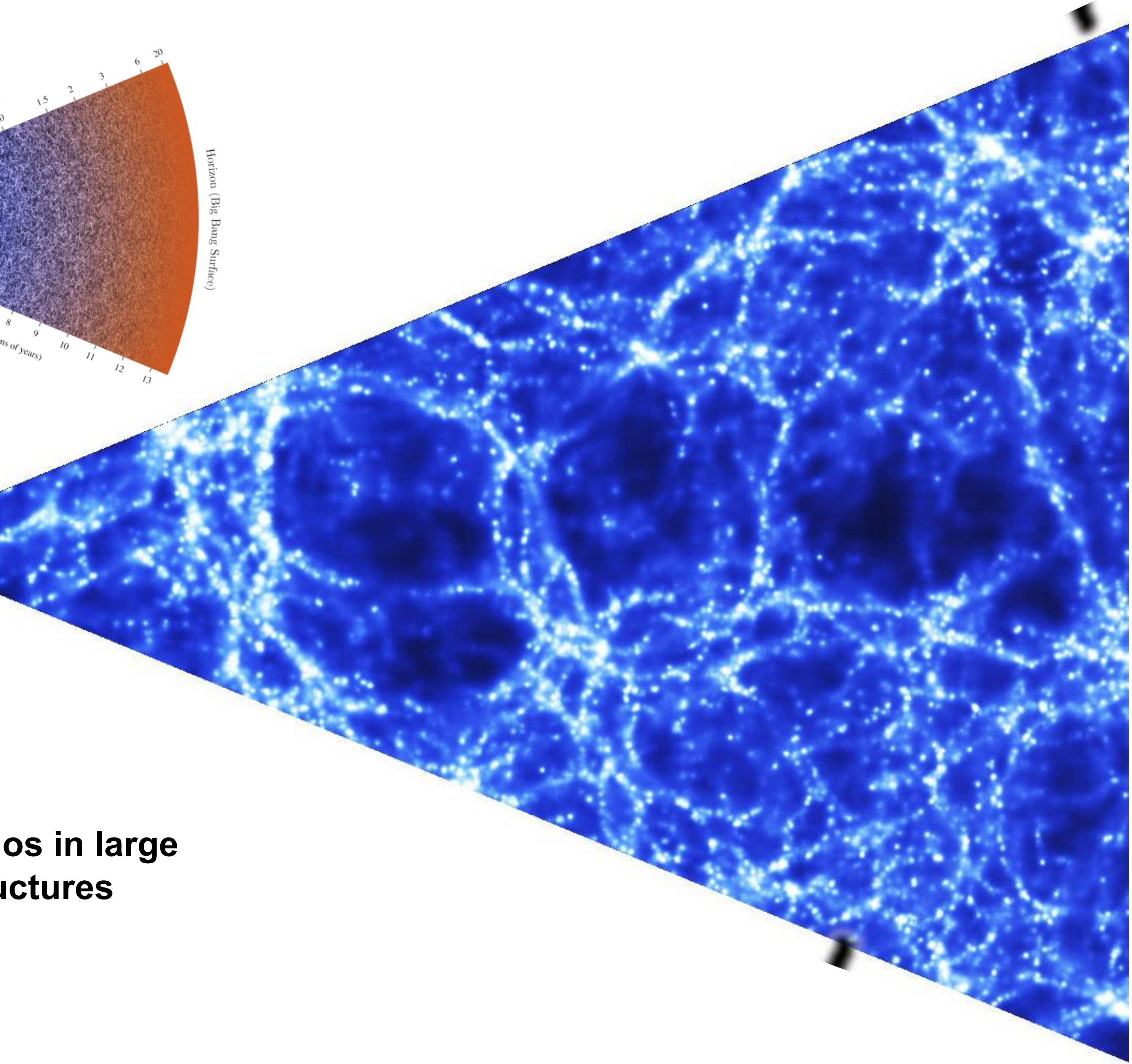
(FoF with l=0.2)

[HR1] Past light cone data for each observer



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





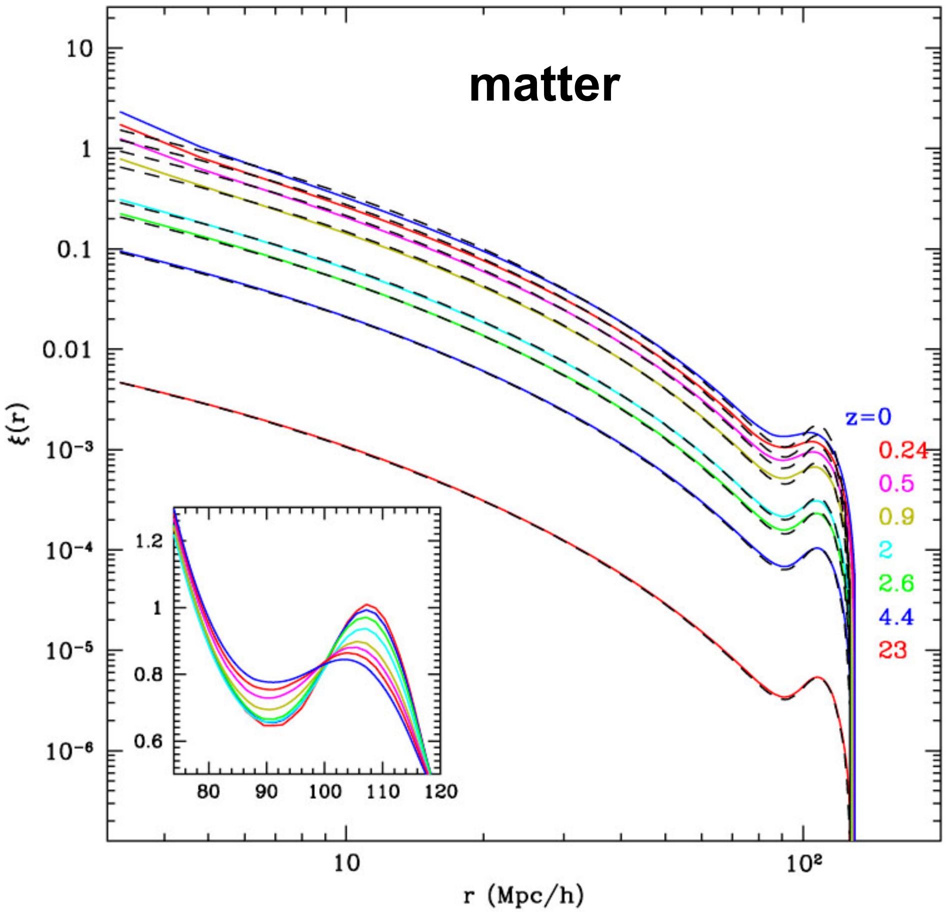
[HR1] Halos in large scale structures

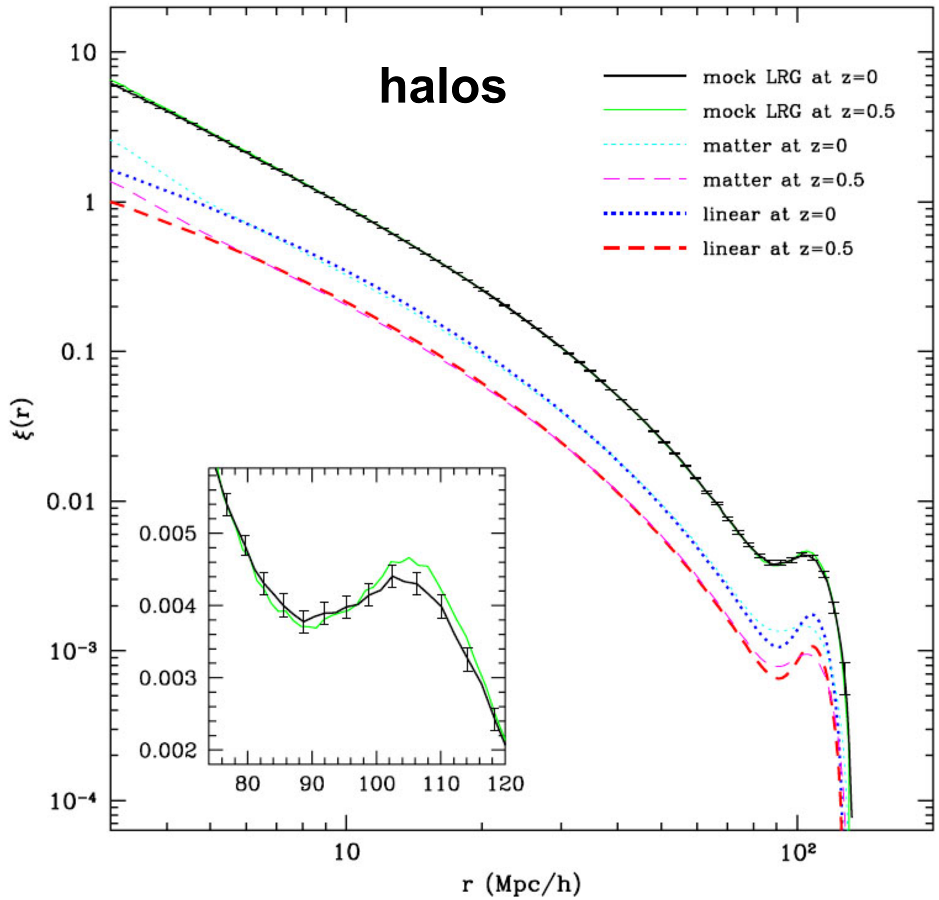
Simulation Outputs

- Mass resolution ($M_\odot$/h):
  - 8.87×10^{12} (HR1), 3.74×10^{12} (HR2), 7.31×10^{12}(HR3)
- For study of redshift evolution
  - Snapshot particle/halo data at z=0,0.5, 1, & 2 (HR2/3)
  - Snapshot particle/halo data at z=0,0.1,0.3,0.5,0.7, & 1 (HR1)
- To simulate BOSS Survey
  - 8/8/27 (HR1/2/3) shallow all-sky past lightcone space data to z=0.6 (HR1), 0.7(HR2/3)
- To simulate BigBOSS Survey
  - Deep all-sky past lightcone space data to z=1.85 (HR2), 4 (HR3)

Scientific Results [J. Kim et al. 2009]

Correlation functions : Effects of gravitational evolution, halo biasing, z-space distortion





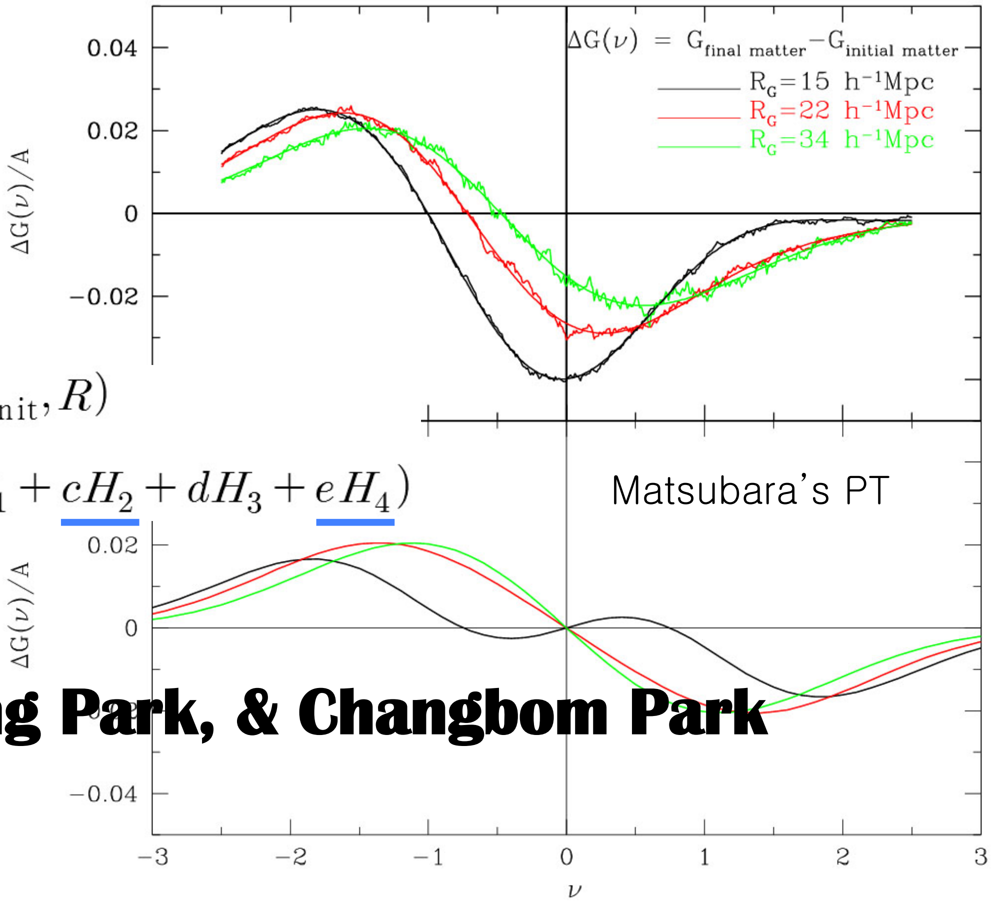
Biases in amplitude & shape : linear, matter, halos

Study of Redshift Evolution

Non-linear gravitational effects on the genus

HR2 (6000^3, $7200 h^{-1}$Mpc)
Matter density at z=0 & ∞

$$\Delta G_{grav}(\nu; z, R) = G(\nu; z, R) - G(\nu; z_{init}, R)$$
$$= Ae^{-\nu^2/2}(aH_0 + bH_1 + cH_2 + dH_3 + eH_4)$$



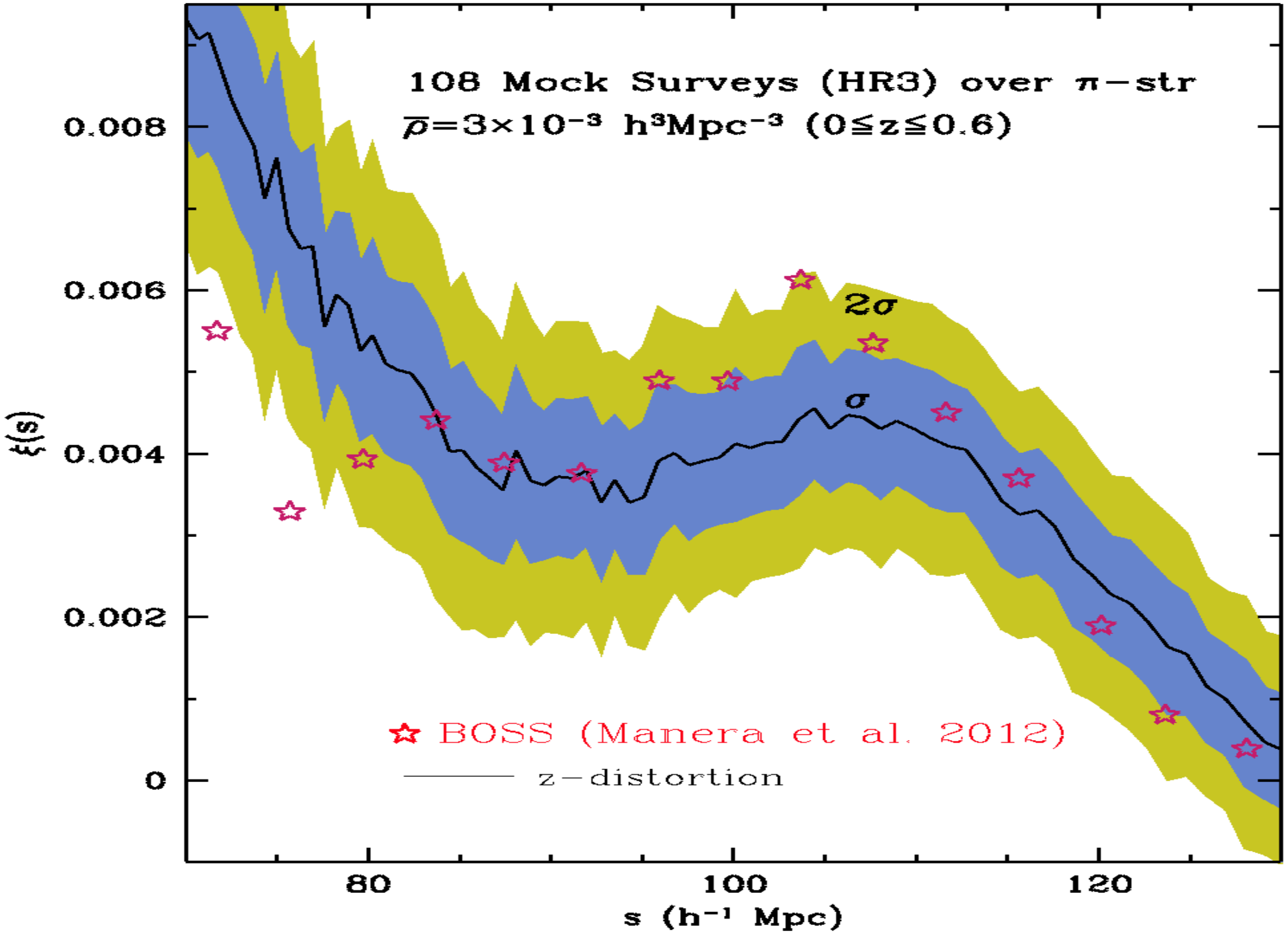
Young-Rae Kim, Yun-Young Park, & Changbom Park (in preparation 2012)

$$G_3(\nu_f) = \frac{1}{(2\pi)^2}\left(\frac{\sigma_1}{\sqrt{3}\sigma_0}\right)^3 e^{-\nu_f^2/2} \times (1 - \nu_f^2 + [(S^{(1)} - S^{(0)})(\nu_f^3 - 3\nu_f) + (S^{(2)} - S^{(0)})\nu_f]\sigma_0)$$

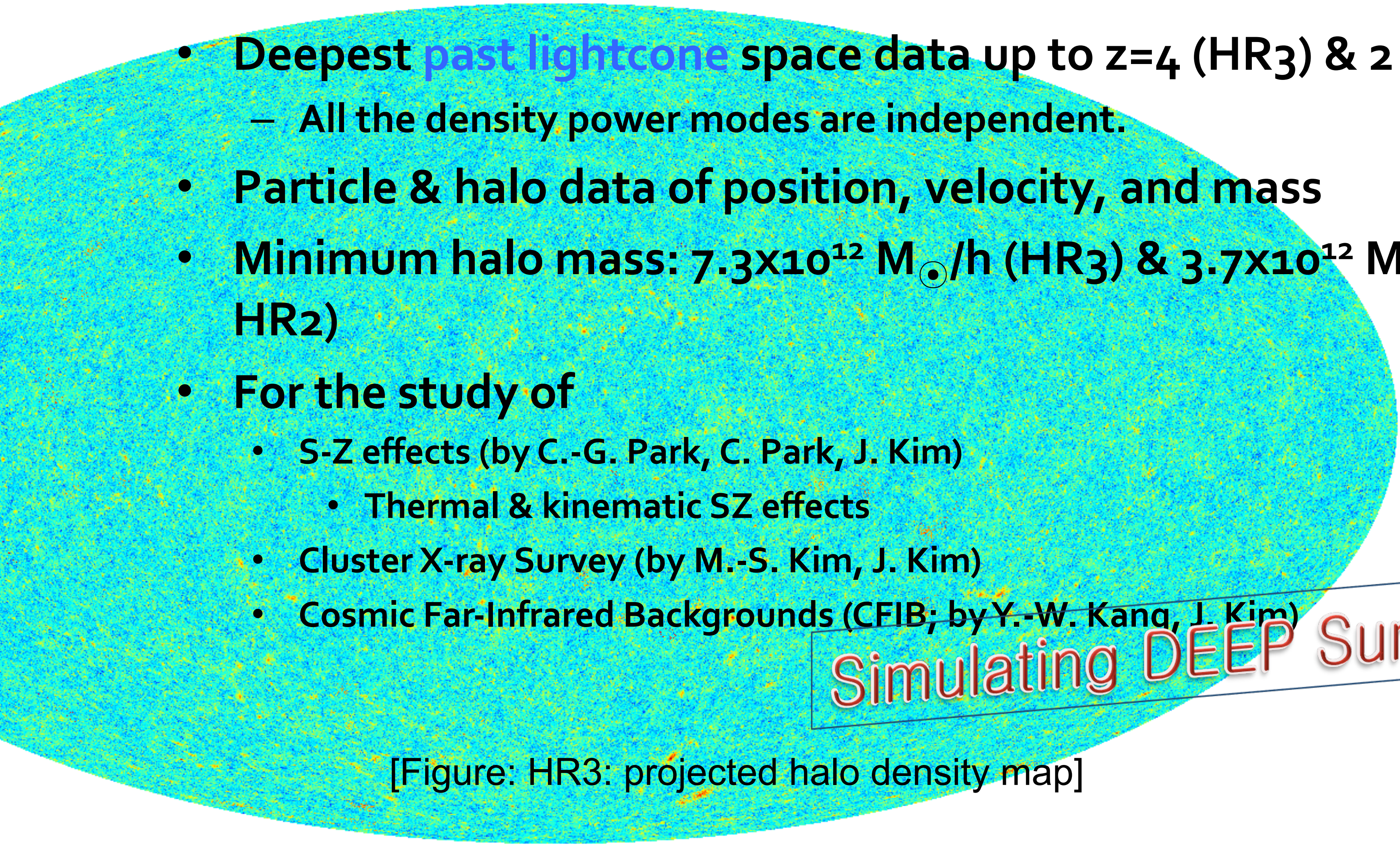
(Matsubara 2003)

LRG Correlations in BOSS

[Rossi, Park, & Kim 2012]



Deep All-Sky Data

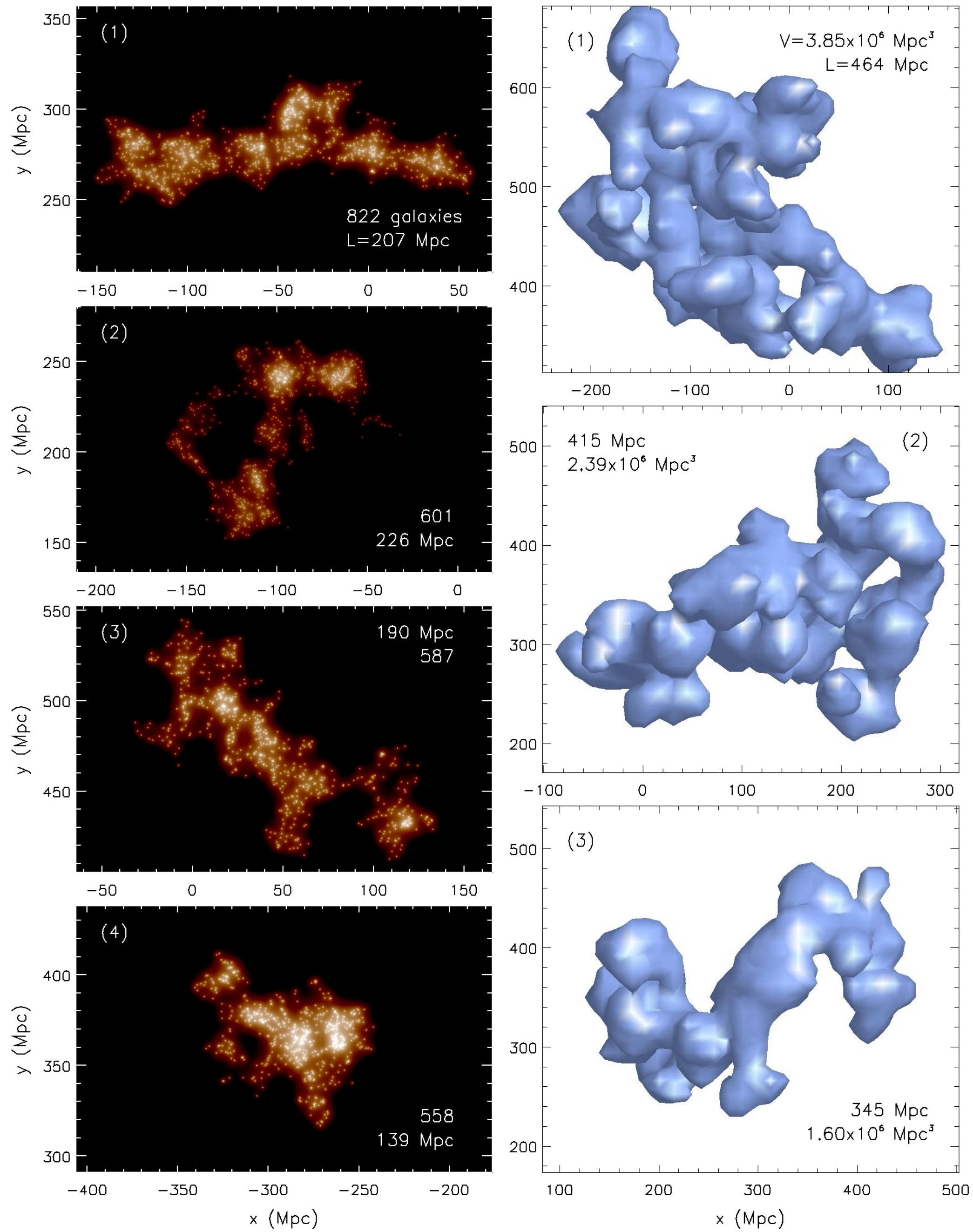


- Deepest past lightcone space data up to z=4 (HR3) & 2 (HR2)
  - All the density power modes are independent.
- Particle & halo data of position, velocity, and mass
- Minimum halo mass: $7.3 \times 10^{12}\ M_{\odot}/h$ (HR3) & $3.7 \times 10^{12}\ M_{\odot}/h$ (HR2)
- For the study of
  - S-Z effects (by C.-G. Park, C. Park, J. Kim)
    - Thermal & kinematic SZ effects
  - Cluster X-ray Survey (by M.-S. Kim, J. Kim)
  - Cosmic Far-Infrared Backgrounds (CFIB; by Y.-W. Kang, J. Kim)

Simulating DEEP Surveys

[Figure: HR3: projected halo density map]

The Largest Structure



- Park, Choi, Kim et al. (2012, ApJL)

Summary

1.Three large Horizon Run cosmological N-body simulations of the WMAP 5yr cosmological model presented. HR2 and HR3 evolved $6000^3 = 2.16 \times 10^{11}$ and $7210^3 = 3.74 \times 10^{11}$ particles, and span a volume of $(7.200\ h^{-1}\ \mathrm{Gpc})^3$ and $(10.815\ h^{-1}\mathrm{Gpc})^3$, respectively.

2. Made 35 all-sky mock BOSS surveys along the past light cone out to z = 0.7 (HR 2/3)
8 all-sky mock BOSS surveys out to z=0.6 (HR1)
One mock BOSS survey out to z=1.85 (HR2) and 4 (HR3), respectively.

3. Applications of our unprecedented large-volume N-body simulations for a variety of studies in cosmology and astrophysics, ranging from
*physics of NL gravitational evolution, halo biasing, redshift-space distortion,
*test of the concordance model through large-scale rare objects,
*large-scale structure topology,
*baryon acoustic oscillations,
*dark energy and the characterization of the expansion history of the universe,
*galaxy formation science in connection with the SDSS-III BOSS survey.

Thanks!