Developing a Cosmological Hydrodynamic Code
(Progress Report)

Juhan Kim (CAC@KIAS)
Jihye Shin (KHU)

OUTLINE

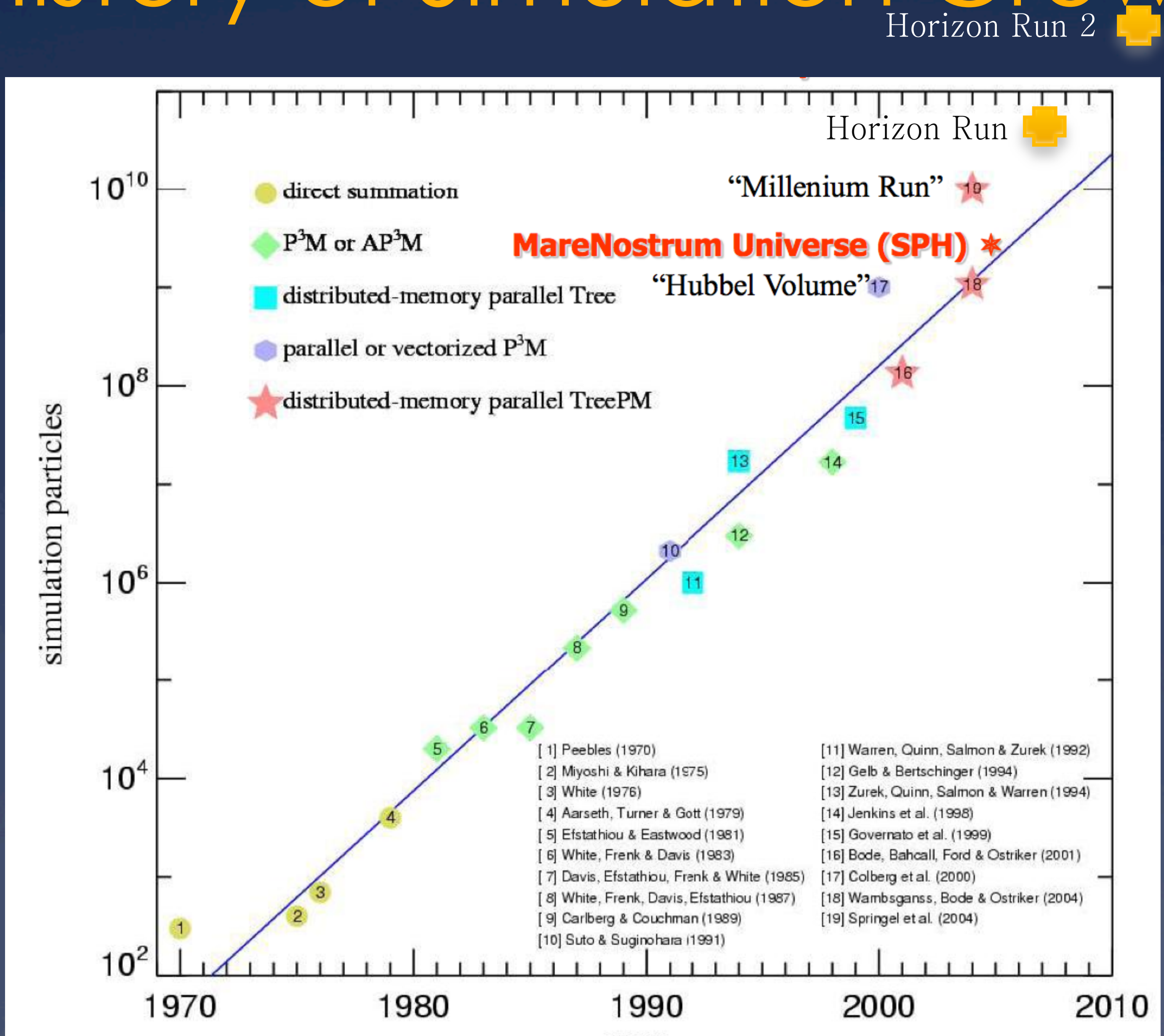
- Cosmological N-body solver: GOTPM
- Cosmological hydrodynamic code
  - Based on the smoothed particle hydrodynamics (SPH)

Popular Cosmological Codes (N>20)

Type	Package Name (builder)
PM	PM(Klypin, Holtzman), PMFAST(Merz & Pen)
Tree	FLY (Becciani), HOT(Warren & Salmon), PKDGRAV(Quinn)
SPH	Athena (Gardiner, et al.; Godunov scheme)
Tree+SPH	AmonSPH(Schwarzmeier), GADGET, GCD+(Kawata), Treecode(Barnes), DRAGON(Goodwin)
AMR (hydro)	CORAL(Iliev), FLASH(Fryxell), Nirvana (Ziegler)
PM+AMR	Enzo (Bryan), WENO(Feng, Shu, Zhang; PM+WENO), Zeus (Norman; PM+FD+MHD)
Tree+PM+SPH	GADGET-2 (Spingel)
APM	Grommet(Magorrian), MLAPM(Knebe), SUPPERBOX(Fellhauer)
AP3M+SPH	Hydra (Couchman)
PM+HPM	MC2 (Habib)
Tree+PM	TPM(Xu &Bode), GOTPM(Dubinski, Kim, Park), TreePM(Bagla)

http://wiki.hmet.net/index.php/Cosmological_Simulation_Codes

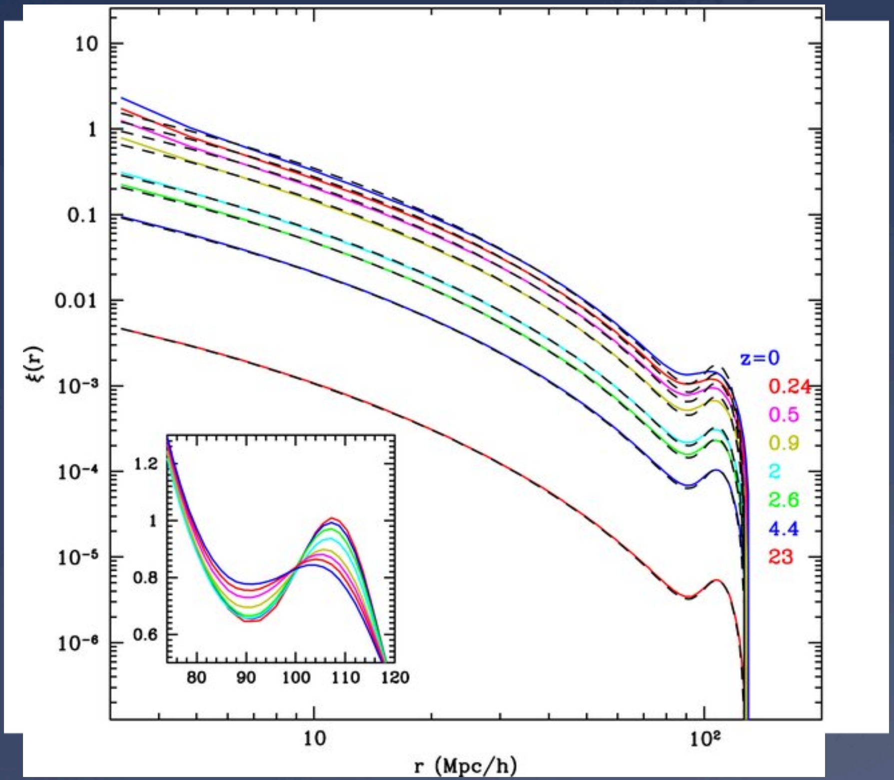
History of Simulation Growth



GOTPM: cosmological n-body solver

- A hybrid method: Particle Mesh + Oct sibling Tree
  - MPI + OpenMP/CUDA
- One of the fastest and most memory efficient codes
  - 4bytes * [3(position)+3(velocity)+2(index)+2(pointer/FFT mesh)+1(workspace)) *N_p =44N_p (bytes) (cf. Gadgt2 needs 80 bytes)
  - One-step-evolution speed=0.03-0.1 ms per particle on a cpu core (cf. Gadget2 speed=0.1 ~ 1 ms)
- Used for the Horizon Run simulation with 4120^3 particles and 1600 cpu cores for 20 days in 2008 (@KISTI)
  - 8 all-sky mock surveys for simulating BOSS
  - 4 snapshot particle data , etc..
- Used for 6000^3 & 7210^3 particle simulations with L_{box}= 7,200 &10,815 h^{-1} Mpc (cf. particle horizon d=10,500h^{-1} Mpc) @ KISTI
  - completed in this month
  - Using 8,000 cores, 17 Tbytes memory, 300 Tbytes disk space
  - 8/27 all-sky mock surveys for simulating BOSS (z_max=0.6/0.7)
  - FoF +sub halos at 40 time steps for SAM analysis

Horizon Run (HR) Simulation



- HR simulation (2008)
  - Based on WMAP 5 year cosmology
  - 4120^3 particles
  - Lbox=6592h^{-1} Mpc
  - The biggest simulation until 2009
  - To simulate the BOSS of SDSS III
  - Used for study of Power spectrum, correlations, and Genus statistics of matter/ LRG galaxies in comoving space & past lightcone space (Kim, et al. 2009)

Why need gas dynamics for Cosmological Simulations?

- N-body simulation
  - Gravitation: dominating force on the formation and evolution of LSS (L_{scale}>a few kpc)
  - Target:
    - Spatial distribution of matter/biased objects,
    - Merging history ,
    - Density evolution,
    - Cosmological parameters
- Gas dynamic simulation
  - Gasdynamics: significant on the small scales (l_{scale} < a few kpc)
  - Target:
    - Star formation (cooling/heating),
    - SuperNovae feedback,
    - environmental effect on the galaxy morphology
    - Dwarf/first star formation

One of motives: Can we achieve the same speed and memory efficiency as we have done in the N-body code?

SPH Basics

- The usual SPH basic equations are adopted.

$$\rho_i = \sum_{j=1}^{N} m_j W(|r_{ij}|, h_i)$$

- The equation of entropy conservation is applied like Gadget-II.

$$\frac{dv_i}{dt} = -\sum_{j=1}^{N} mj \left[\frac{P_i}{\rho_i^2} \nabla_i W_{ij}(h_i) + \frac{P_j}{\rho_j^2} \nabla_i W_{ij}(h_j) \right]$$

- N-nearest neighbors are exactly found using the tree walking on the oct-sibling tree.
- Artificial viscosity term is added to capture shock front.

$$\left.\frac{dv_i}{dt}\right|_{visc} = -\sum_{j=1}^{N} m_j \Pi_{ij} \nabla_i W_{ij}$$

- Individual time step is adopted following the Kick-Drift-Kick scheme.

Cooling/Heating

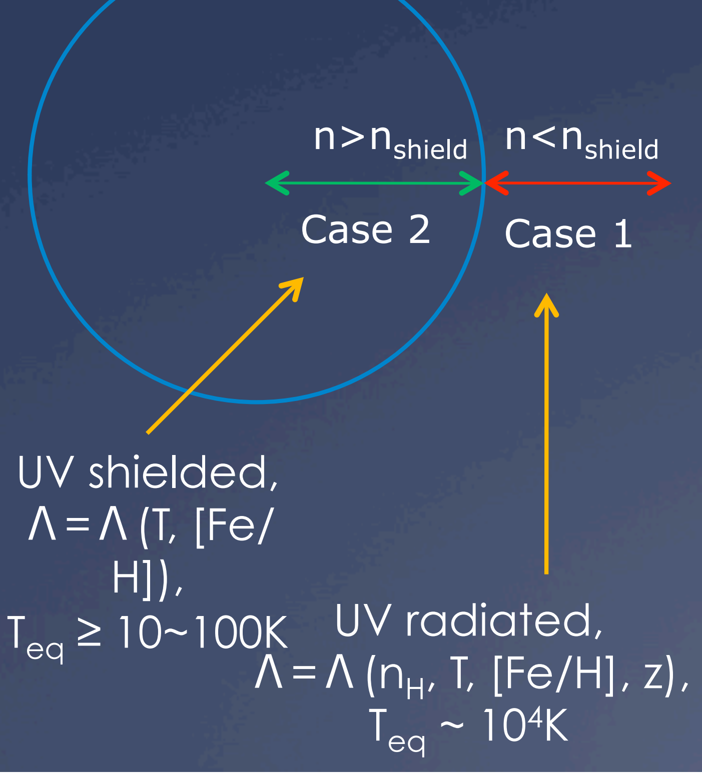
(made but not yet implemented into the main program)

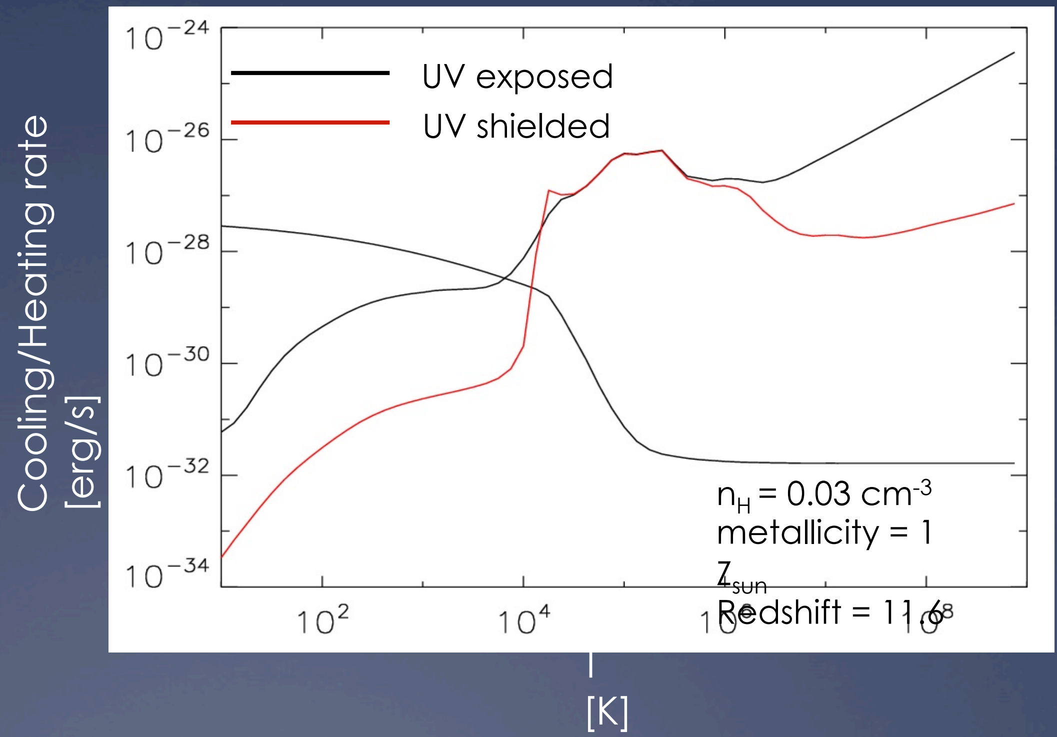
non-adiabatic processes on the evolution of the baryons

Using the publicly available photoionization package CLOUDY90 (Ferland et al. 1998)

Tabulating two kinds of cooling/heating rate

- under existence of the uniform UV/X-ray background (Haardt & Madau 2001)
- case 1: UV radiated medium (Photoionization + collisional ionization + H_2 dissociation)
- case 2: UV shielded medium (collisional ionization)





Star Formation

(made but not yet implemented into the main program)

Converting gas particles into star particles

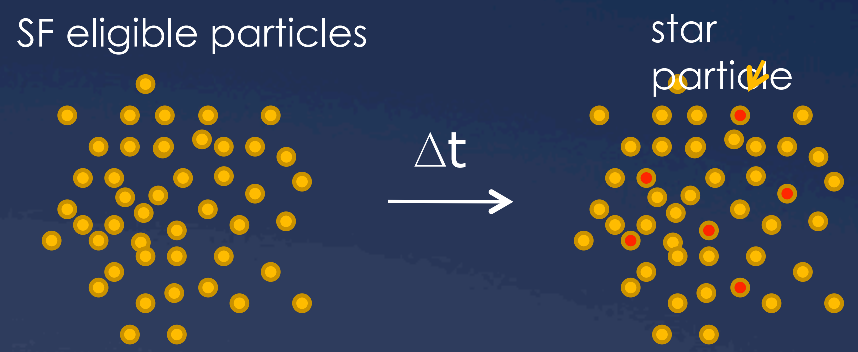
Star formation criteria : (Katz et al. 1996)

$T < 10^4$ K (or <100K)

$n_H > 0.1$ cm^{-3}

$\nabla \cdot v < 0$

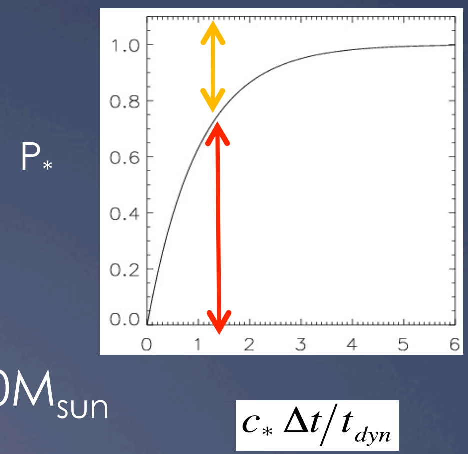
$\rho > 57.7 \rho_{mean}(z)$



$$\frac{d\rho_*}{dt} = c_* \frac{\rho_{gas}}{t_{dyn}}$$

Star formation coefficient (c_*) : calibrated by the Schmidt-Kennicutt relation (global star-formation properties, Kennicutt 1998)

Star formation probability : $$p_* = \frac{m_{gas}}{m_*}\left[1 - \exp\left(-c_* \frac{\Delta t}{t_{dyn}}\right)\right]$$



Containing a single stellar population

metallicity - inherited from the parent gas particles

mass function - Kroupa (2001) with range of $0.08M_{sun}$~$100M_{sun}$

Super Nova Feedback (built but not yet implemented into the main program)

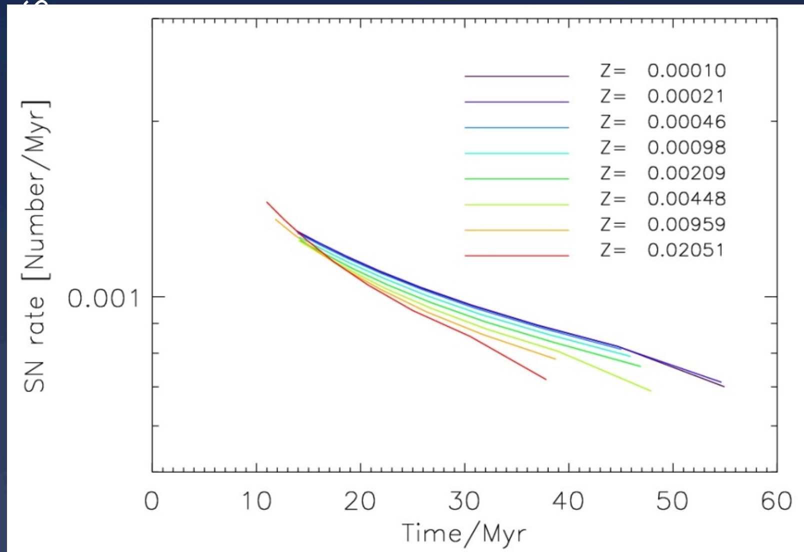
Implementing feedback

in a probabilistic manner

(Okamoto, Nemmen, and Bower 2008)

$$P_{SN} = \int_{t_{SSP,i}}^{t_{SSP,i}+dt} r_{SNII}(t')dt' \Big/ \int_{t_{SSP,i}}^{t_8} r_{SNII}(t')dt'$$

Scaled to $1M_{sun}$ SSP with Kroupa MF



1. energy feedback
 - ΔE of star particle : $\sim 10^{51}$erg/1SN_{II}
 - delicate Δt for surroundings : to prevent overcooling problem (Durier & Vecchia 2011)
 - leading to a self-regulated cycle for star formation activity

2. metal feedback
 - released metal : $$\Delta Z = \int \Psi(m) m_{ej,metal}(m,Z) dm / \Delta M_{SN}$$

$m_{ej,metal}(m,Z)$ from Woosley & Weaver (1995)

 - proportional to solid angles of neighbors : $\Omega_i \propto h_i^2 / r_i^2 \propto n_i^{-2/3} / r_i^2$

$$\Delta Z_{SN,i} = m_i n_i^{-2/3} r_i^{-2} \Delta Z_{SN} \Big/ \sum_{j=1}^{N} m_j n_j^{-2/3} r_j^{-2}$$

 - metal enrichment, and metallicity-dependent heating/cooling

Summary

* What have been done
  * Basic SPH equation
  * Individual time step
  * Subroutines of star formation, SN explosion, heating/cooling process
* What should be done
  * To put the subroutines together
  * To trim off the redundant memory use & to enhance the speed
  * To check the SPH routines
    * 1D shock tube test (by Shin, passed)
    * Test for collapse of spherical gas cloud
    * External/internal shock on the spherical gas cloud

The code will be publicly available late in this year like Gadget2.