Warm-Hot Intergalactic Medium

SIMD Acceleration in Astrophysical Simulations

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Warm-Hot Intergalactic Medium

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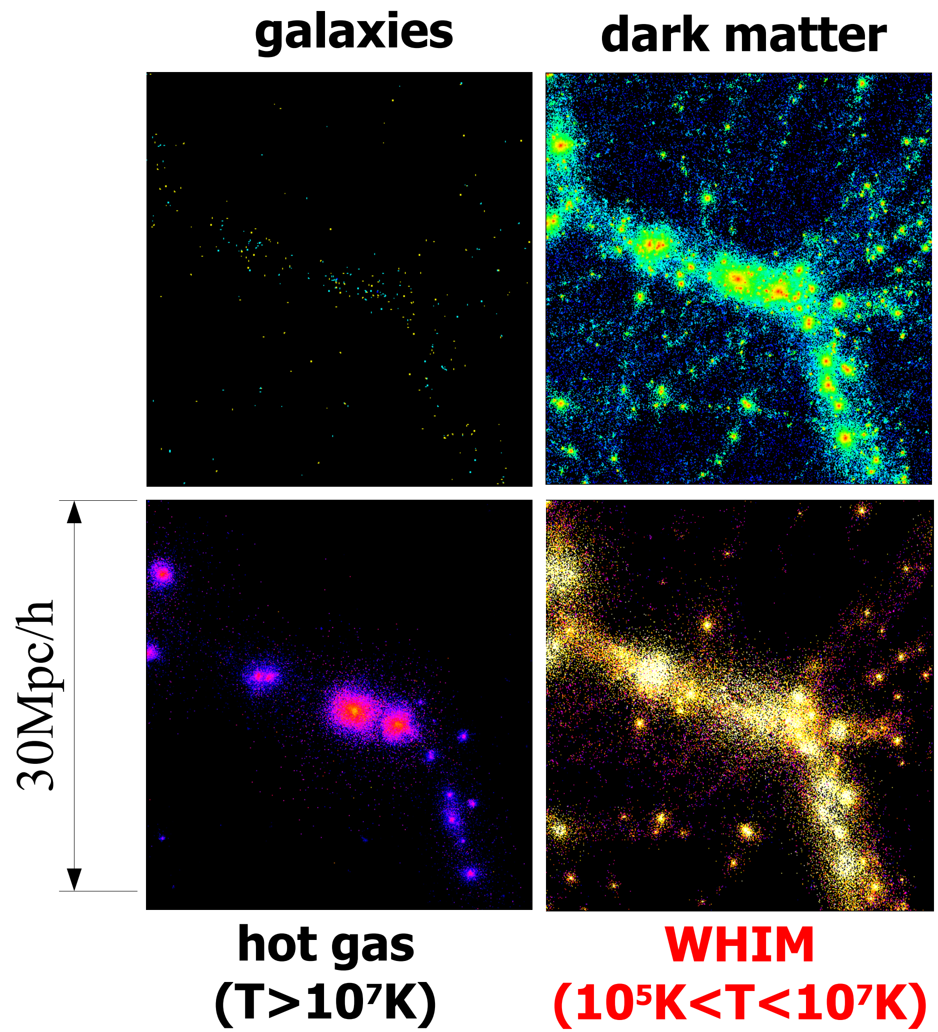
WHIM as Cosmic Missing Baryons

Warm-Hot Intergalactic Medium

- temperature : 10^5K < T <10^7K
- density : 10^{-6} cm^{-3} < n_H < 10^{-4} cm^{-3}
- heated by cosmological shocks during the structure formation
- distributed along filaments and around groups and clusters of galaxies



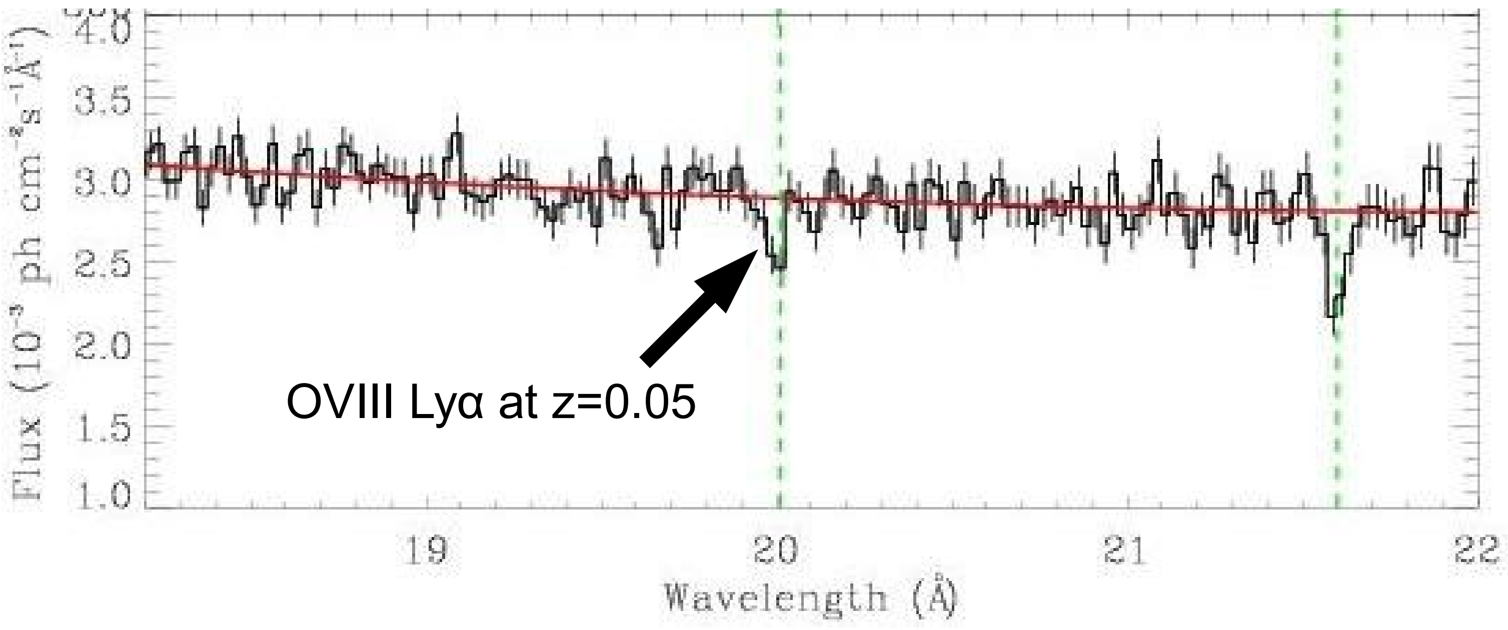
▶ Many difficulties in detecting the WHIM

very low emission measure due to its low density

so many contaminations such as Galactic emission and CXB.

Detection of WHIM through Absorption Lines

Chandra LETG spectrum toward PKS 2155-304 Fang et al. (2007)



Detection through Emission Lines

Yoshikawa et al. (2003) PASJ, 55, 879

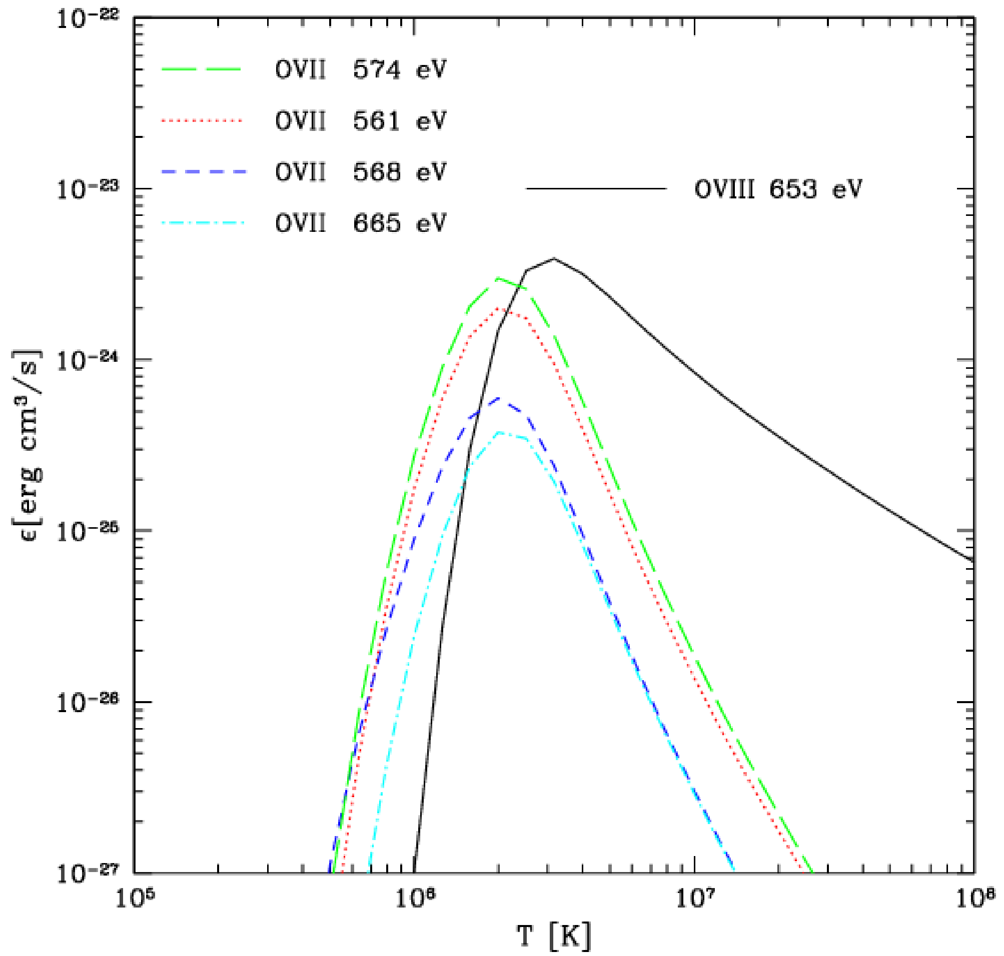
We explored the possibility to detect WHIM through its emission.

OVII (561eV, 568eV, 574eV / 665eV)
OVIII (653eV)

WHIM can be detected through its metal emission lines by next generation X-ray missions.

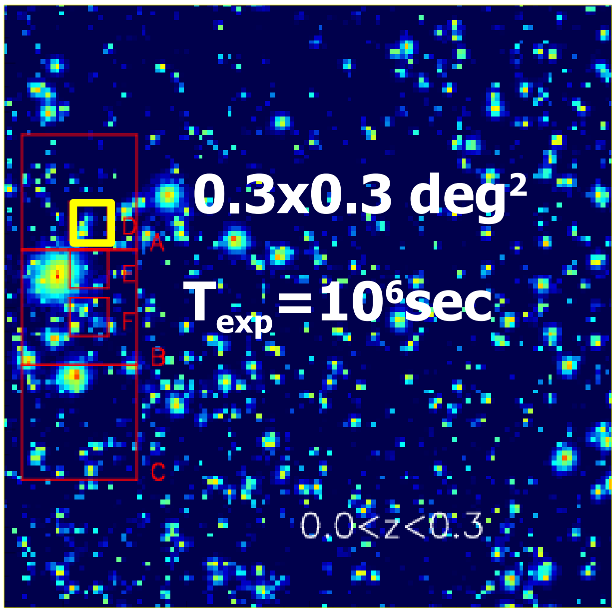
Requirements for instruments

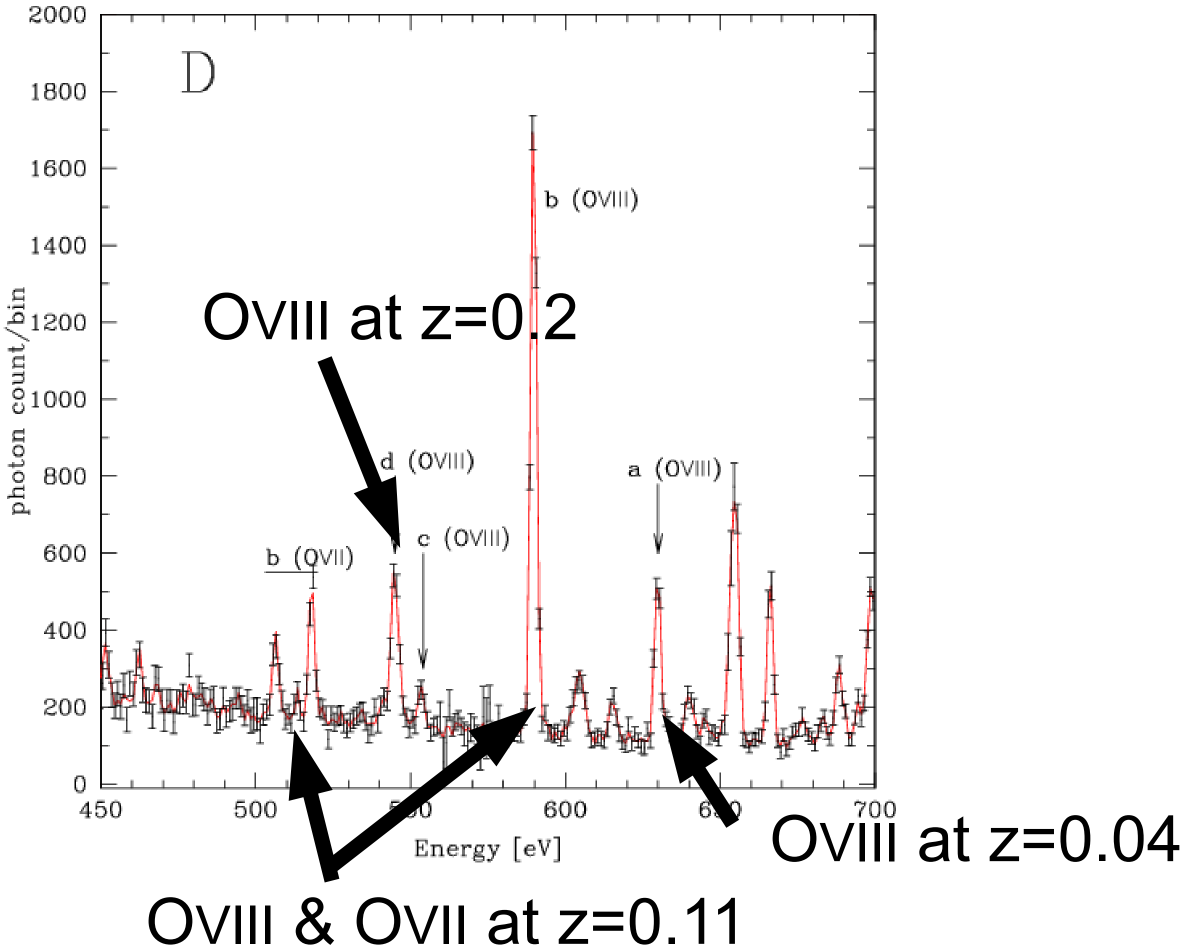
- large effective area and FOV
- high spectral resolution in soft X-ray bands



Example of Simulated Spectra

mock observations based on cosmological hydrodynamic simulations



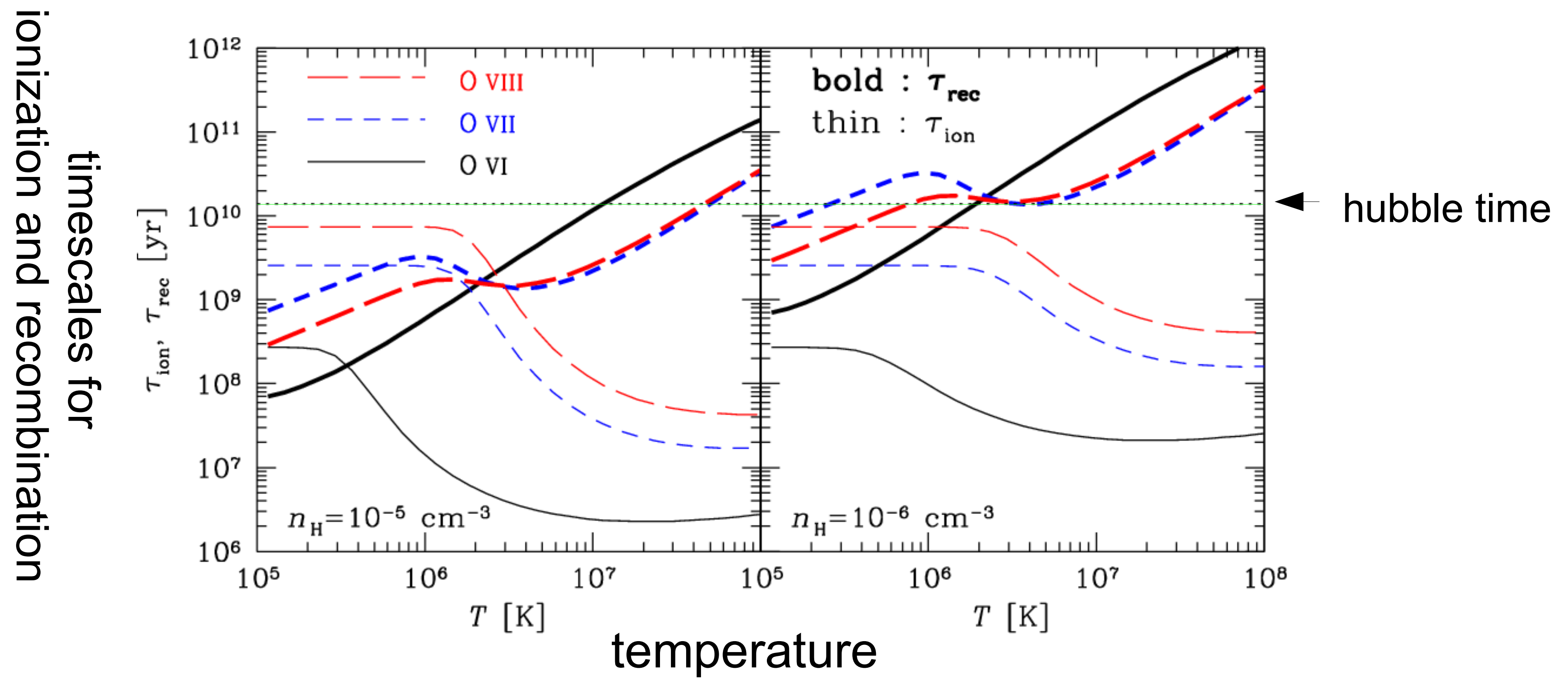


WHIM at the outskirts of clusters and groups of galaxies can be detected with next generation X-ray missions.

Detection of WHIM

- **Yoshikawa et al. (2004) , PASJ, 56, 939**
  - Detectability of WHIM in the local universe (r<100Mpc) based on the constrained simulation of the local universe
  - We found several sweet spots for the detection of WHIM through emission lines.
- **Kawahara, KY, et al. (2006), PASJ, 58, 657**
  - Detectability of WHIM through absorption lines using GRB afterglows.
  - Combined analysis of WHIMobs. using both of emission and absorption lines.

Non-equilibrium Ionization States in WHIM

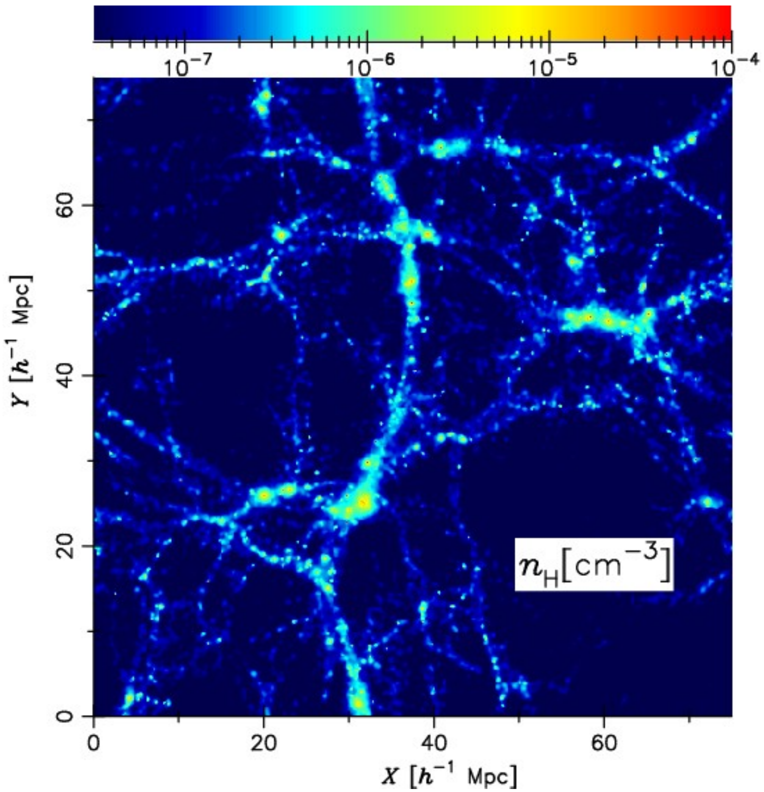


Timescales for Ionizations and recombinations are not short enough

→ Ionization equilibrium is not achieved

Time evolution of ionization states is investigated in cosmological hydrodynamic simulations

cosmological N-body + Hydro(SPH) simulation

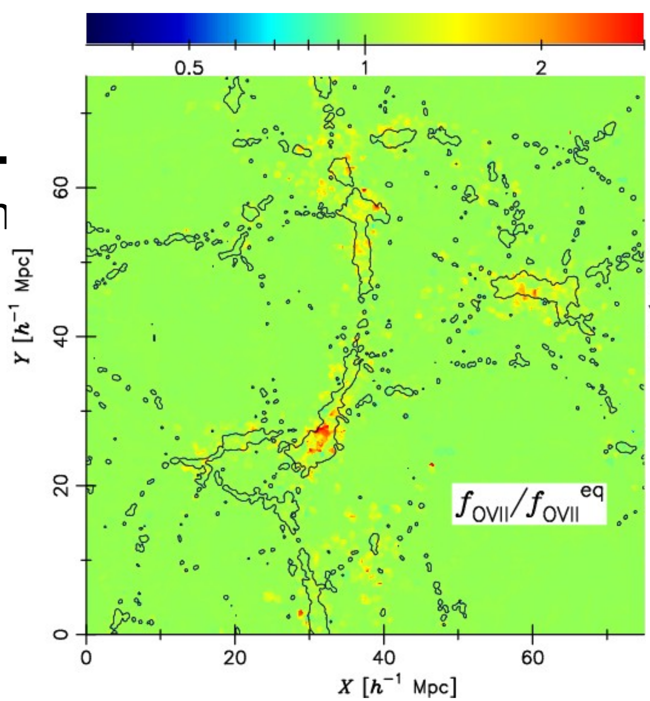


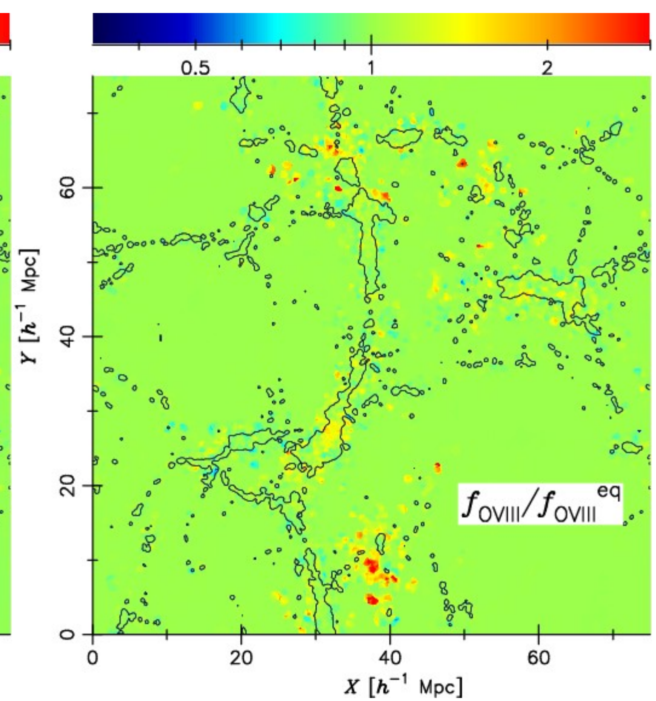
- ΛCDM $\left(\Omega_m=0.3, \Omega_\Lambda=0.7, h=0.7, \sigma_8=1.0\right)$
- UV/X-ray background radiation
- radiative cooling
- non-equilibrium ionization : H, He, C, N, O, Ne, Mg, Si, Fe

$$\frac{df_j}{dt}=\sum_{k=1}^{j-1} S_{j-k,k} f_k - \sum_{i=j+1}^{Z+1} S_{i-j,j} f_j - \alpha_j f_j + \alpha_{j+1} f_{j+1}$$

color: $\dfrac{\text{f(OVII), f(OVIII)}}{\text{f(OVII), f(OVIII) in equilibrium}}$

contour: gas density





SIMD Acceleration in Astrophysical Simulations

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SIMD Instructions on Modern CPUs

SIMD = Single Instruction Multiple Data

Simultaneous execution of the same operations on multiple data

SIMD units are usually equipped on modern commodity CPUs

Intel / x86, x86-64 : Streaming SIMD Extension (SSE/SSE2/SSE3/SSSE3)

AMD / x86, x86-64: 3DNow! (Enhanced 3DNow!, 3DNow! Professional), SSE

IBM / PowerPC G4/G5: AltiVec/VMX

Originally developed for 3D graphics and media streaming

We explore the possibility to accelerate computations in astrophysical simulations with the aid of SIMD units / instructions

In this work, Streaming SIMD Extension is adopted

Streaming SIMD Extension (SSE)

4 single precision (32bit) data

2 double precision (64bit) data

can be stored in a dedicated 128bit-length register

single precision	f0	f1	f2	f3

double precision	d0	d1

f0	f1	f2	f3
+			
g0	g1	g2	g3
=			
f0+g0	f1+g1	f2+g2	f3+g3

f0	f1	f2	f3
×			
g0	g1	g2	g3
=			
f0×g0	f1×g1	f2×g2	f3×g3

available operations

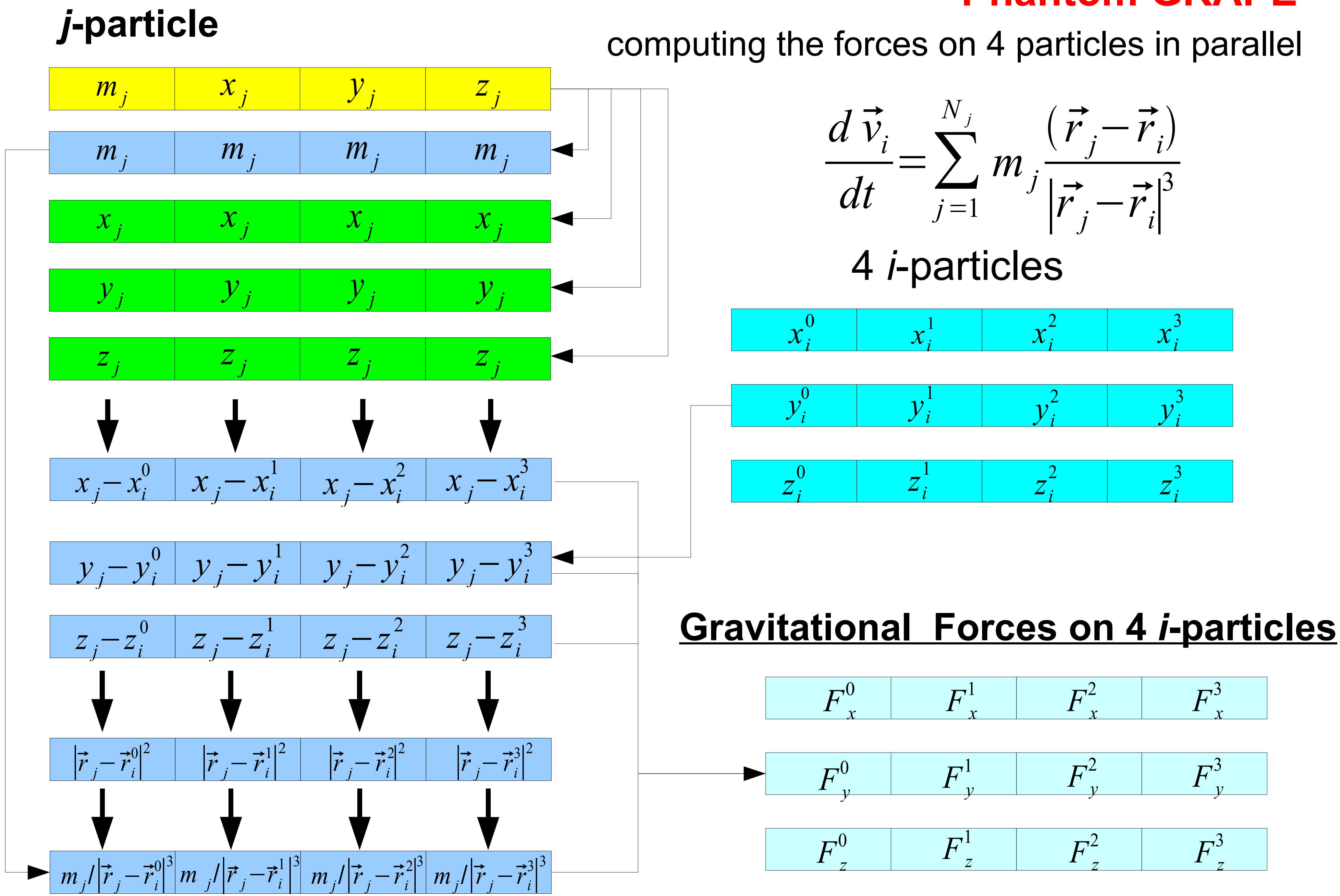
add, sub, mul, div, sqrt , inverse sqrt, cast, shuffle, comp, logical ops, horizontal operations

Computing Gravitational Forces using SSE

Phantom GRAPE

computing the forces on 4 particles in parallel

$$\frac{d\vec{v}_i}{dt} = \sum_{j=1}^{N_j} m_j \frac{(\vec{r}_j - \vec{r}_i)}{|\vec{r}_j - \vec{r}_i|^3}$$



Phantom GRAPE

- Acceleration of gravitational force calculation using SSE.

  emulation of a GRAPE chip with 4 pipelines on commodity CPUs

  significant speed up achieved with the aid of SSE

- 480M interaction/sec (18.3Gflops) on a single core of Core 2 Duo (2.4GHz)

  30M interaction/sec (1.1Gflops) without SSE

- Force shapes of newton's law with cutoff are also supported.

  260M interaction/sec on a single core of Core 2 Duo (2.4GHz)

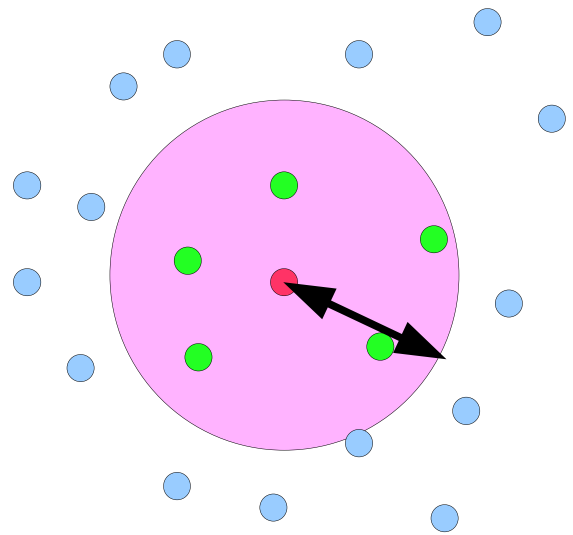
  50M interaction/sec without SSE

- APIs are compatible with those of GRAPE-5, 6 libraries

SPH Calculations using SSE

$$\rho_i = \sum_{j=0}^{N-1} m_j W(r_{ij}, h_i)$$

$$\rho_i (\nabla \cdot \vec{v}_i) = \sum_{j=0}^{N-1} m_j \vec{v}_{ij} \cdot \nabla W(r_{ij}, h_i)$$



4 interactions are simultaneously computed using SSE.

cycle counts per interaction

	with SSE	w/o SSE	gain
1st loop	54.9	166	3.03
2nd loop	81.3	327	4.02