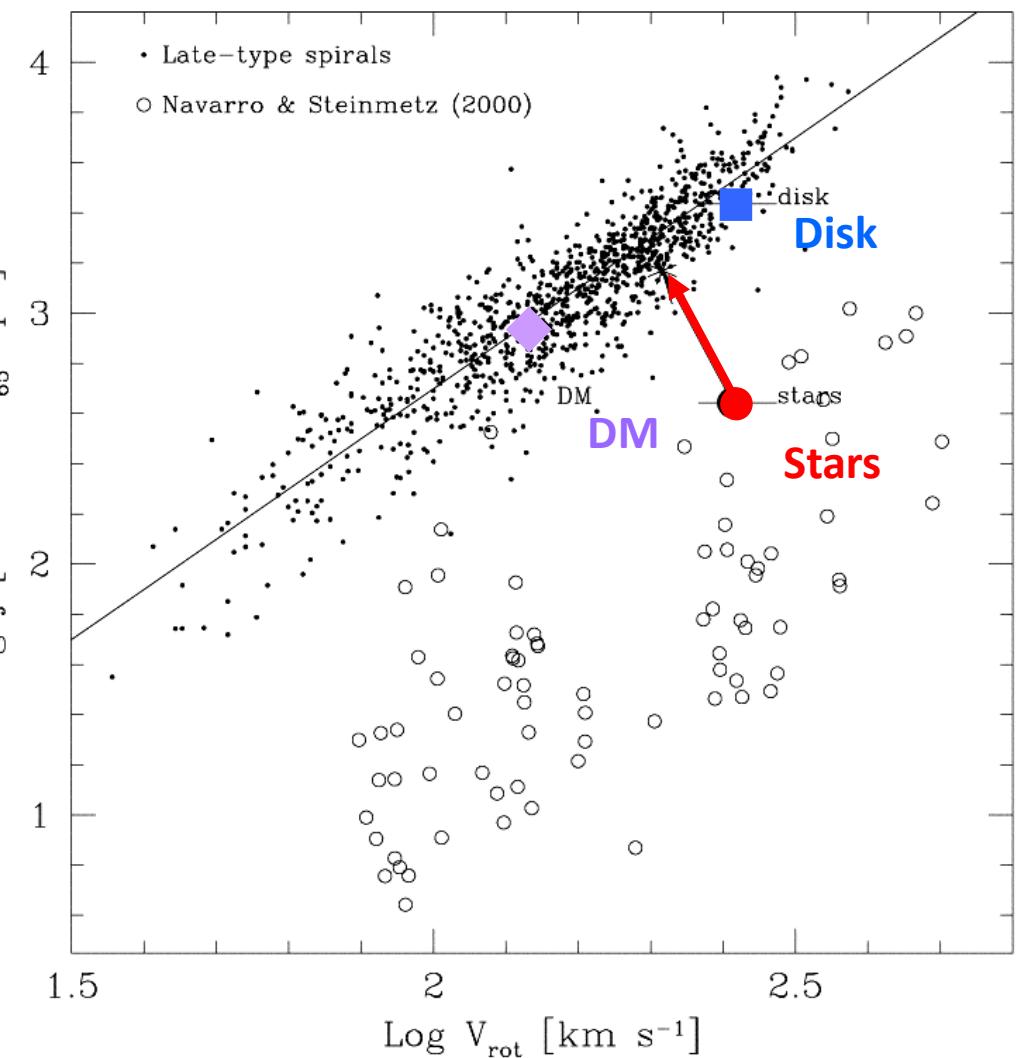


# DISPH 法による 銀河形成シミュレーション

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# 銀河形成シミュレーション



Abadi et al. 2003

- 宇宙初期の密度揺らぎ・質量分布からの時間進化を解く
- 立派な星の円盤が出来ないという角運動量問題があった
  - 最初の3Dシミュレーションの頃から指摘されていた(see Katz & Gunn 1991, Navarro & Benz 1991)
- Feedback が鍵とされている
- が今回は流体解法の問題について

# Contents



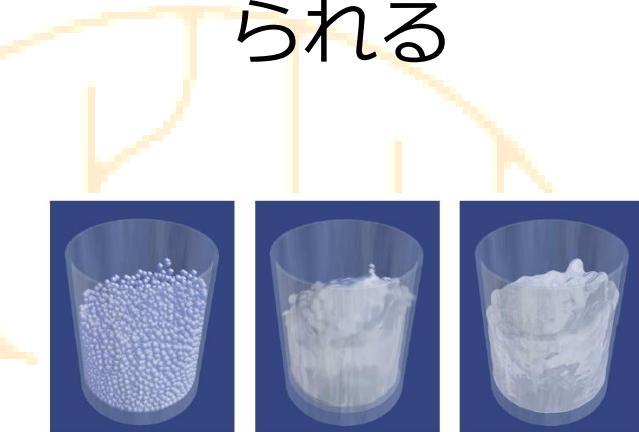
- Standard Smoothed Particle Hydrodynamics 法から Density independent Smoothed Particle Hydrodynamics 法へ
- サンタバーバラクラスター テスト
- DISPH 銀河形成シミュレーション

# Smoothed Particle



# Hydrodynamics (SPH) とは

- SPH 法は、Lucy (1977)、Gingold & Monaghan (1977) により開発された圧縮性流体の解放
  - ラグランジュ法の一種
  - 流体物理量は粒子からの寄与の畳み込みで与えられる

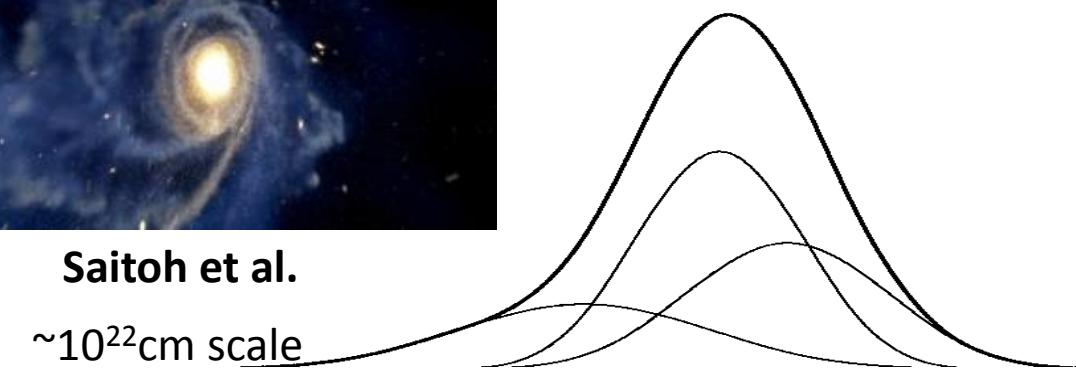


Saitoh et al.

Muller+’03 SIGGRAPH

~cm scale

~ $10^{22}$ cm scale



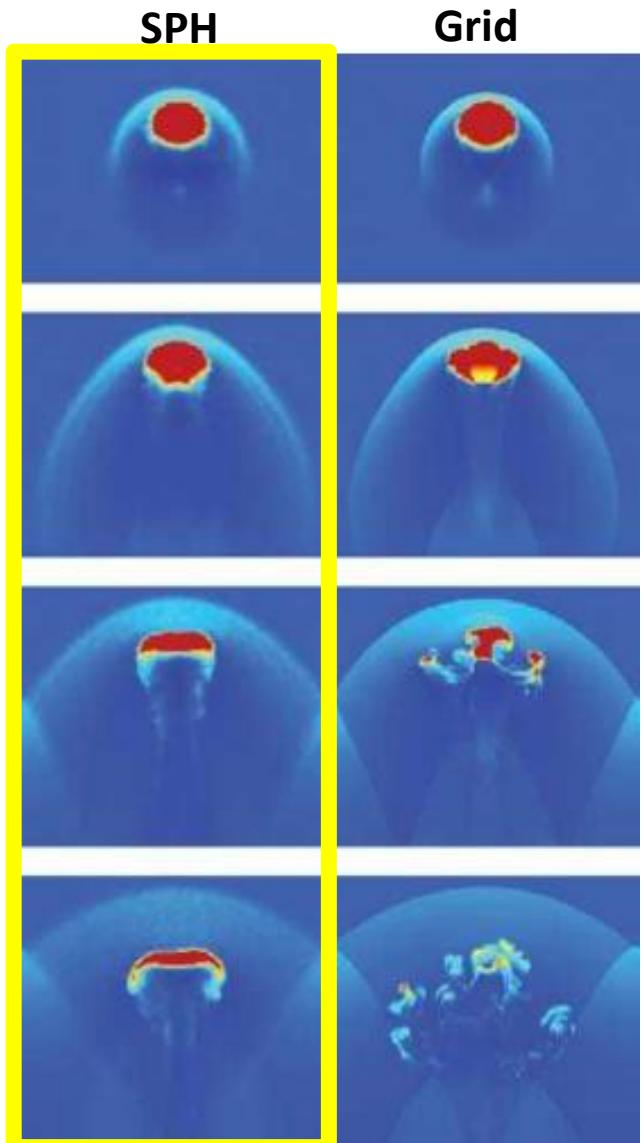
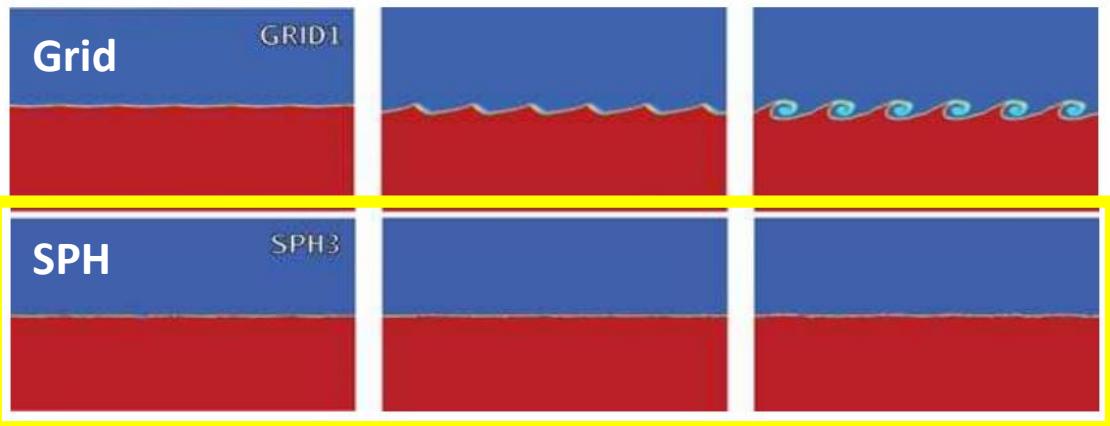
# SPH 法の利点/欠点



- 利点
  - ガリレイ不変
  - ダイナミックレンジの大きな天文学の問題に適している
  - 高密度領域で高分解能
- 欠点
  - 場の量を表現するのが苦手
  - ショックの分解能が低い

# SPH 法の問題点

- Agertz+2007
  - SPH 法と Euler 法の比較
  - SPH は接触不連続面の扱いが苦手
    - 不安定性成長の抑制
    - fundamental difference
  - 原因はSPHの定式化に密度の微分可能性を用いているから



# Density Independent SPH



- カーネル近似をした物理量の推定：

$$f(\mathbf{r}) = \int f(\mathbf{r}') W(|\mathbf{r} - \mathbf{r}'|, h) d\mathbf{r}'$$

- 通常の離散化

$$\rho_i = \sum_j m_j W(r_{ij}, h)$$

- 我々の採用した離散化(圧力を評価)

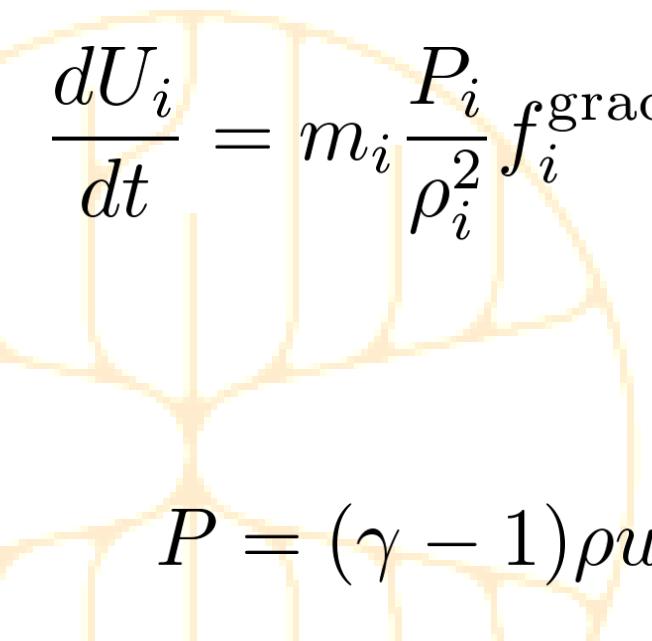
$$q_i = \sum_j U_j W(r_{ij}, h_i) \quad U_j = m_j u_j$$
$$q_j = \rho_j u_j$$

– 運動方程式などは機械的に求まる (Saitoh&Makino 2013)

# SPH 方程式

$$\rho_i = \sum_j m_j W(r_{ij}, h)$$

$$m_i \frac{d\mathbf{v}_i}{dt} = - \sum_j m_i m_j \left( \frac{P_i}{\rho_i^2} f_i^{\text{grad}} \nabla_i W_{ij}(h_i) + \frac{P_j}{\rho_j^2} f_j^{\text{grad}} \nabla_i W_{ij}(h_j) \right)$$


$$\frac{dU_i}{dt} = m_i \frac{P_i}{\rho_i^2} f_i^{\text{grad}} \sum_j m_j \mathbf{v}_{ij} \cdot \nabla_i W_{ij}(h_i)$$

$$f_i^{\text{grad}} = \left( 1 + \frac{h_i}{3\rho_i} \frac{\partial \rho_i}{\partial h_i} \right)^{-1}$$

$$P = (\gamma - 1) \rho u$$

# DISPH 方程式



$$q_i = \sum_j U_j W(r_{ij}, h_i)$$

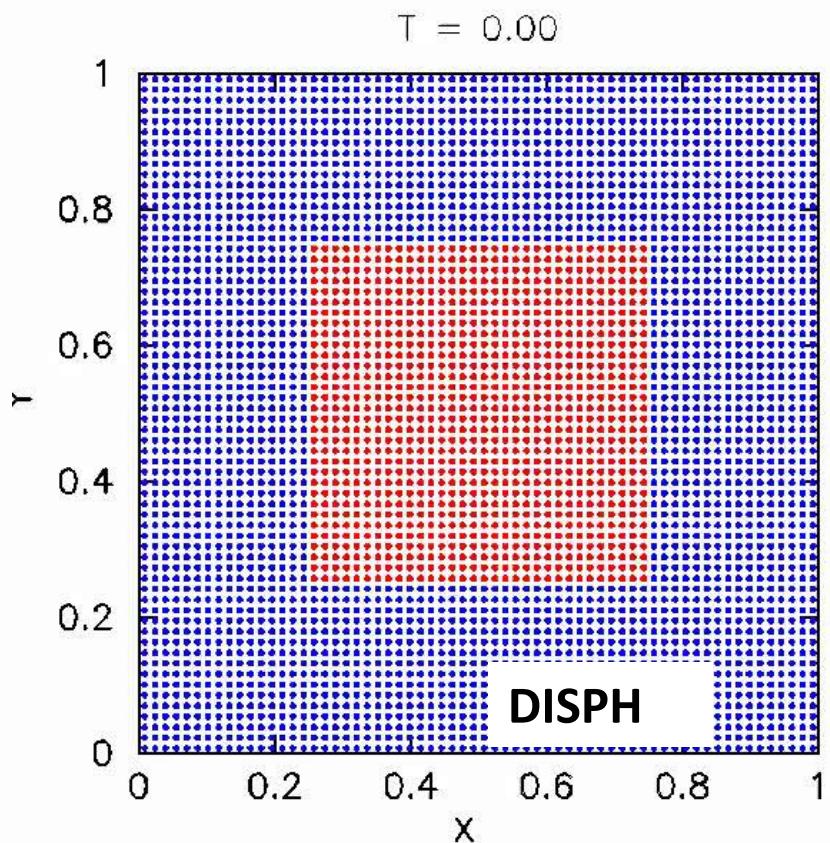
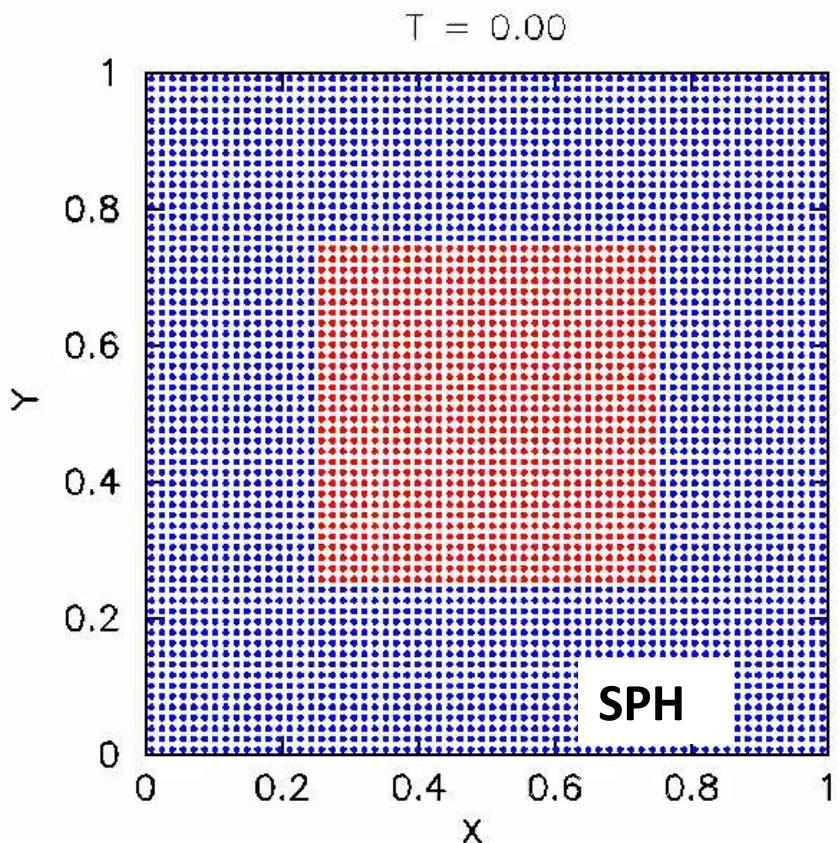
$$m_i \frac{dv_i}{dt} = -(\gamma - 1) \sum_j U_i U_j \left( \frac{f_i^{\text{grad}}}{q_i} \nabla_i W_{ij}(h_i) + \frac{f_j^{\text{grad}}}{q_j} \nabla_i W_{ij}(h_j) \right)$$

$$\frac{dU_i}{dt} = (\gamma - 1) \sum_j \frac{U_i U_j}{q_i} f_i^{\text{grad}} \mathbf{v}_{ij} \cdot \nabla_i W_{ij}(h_i)$$

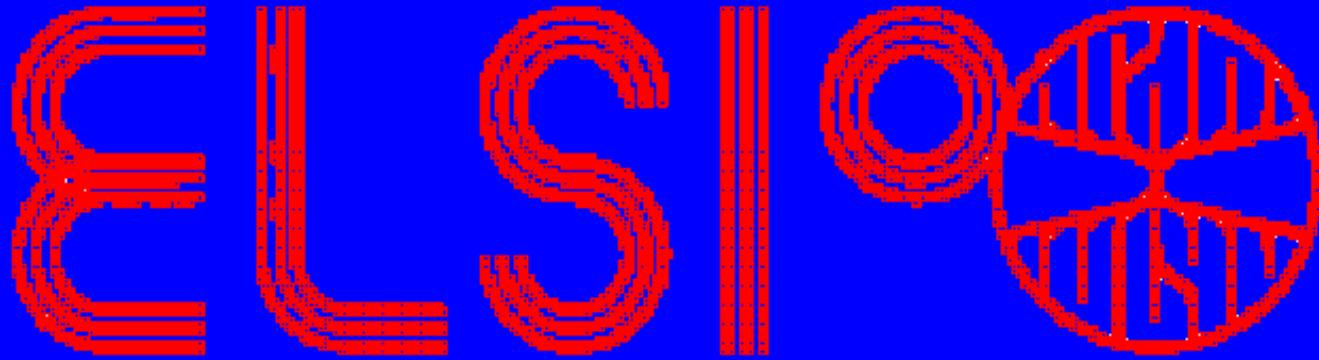
$$P = (\gamma - 1) \rho u$$

$$f_i^{\text{grad}} = \left( 1 + \frac{h_i}{3q_i} \frac{\partial q_i}{\partial h_i} \right)^{-1}$$

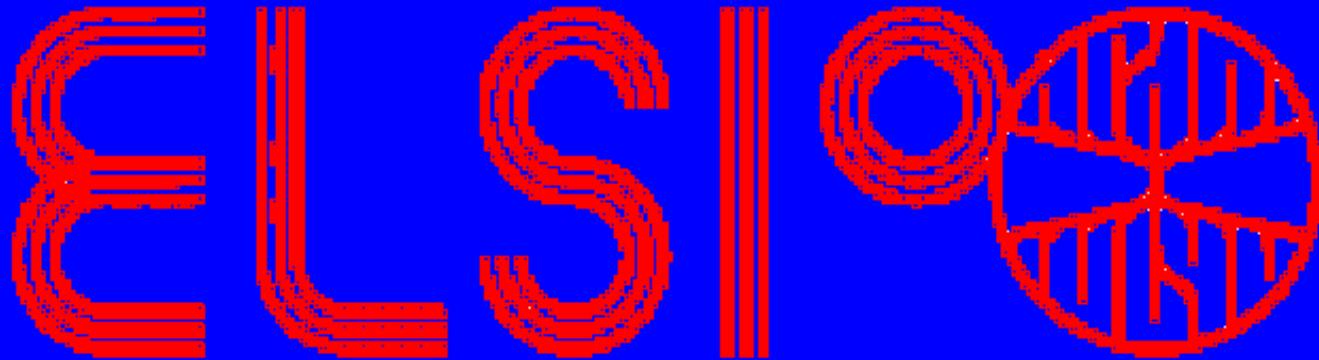
# Hydrostatic Equilibrium test



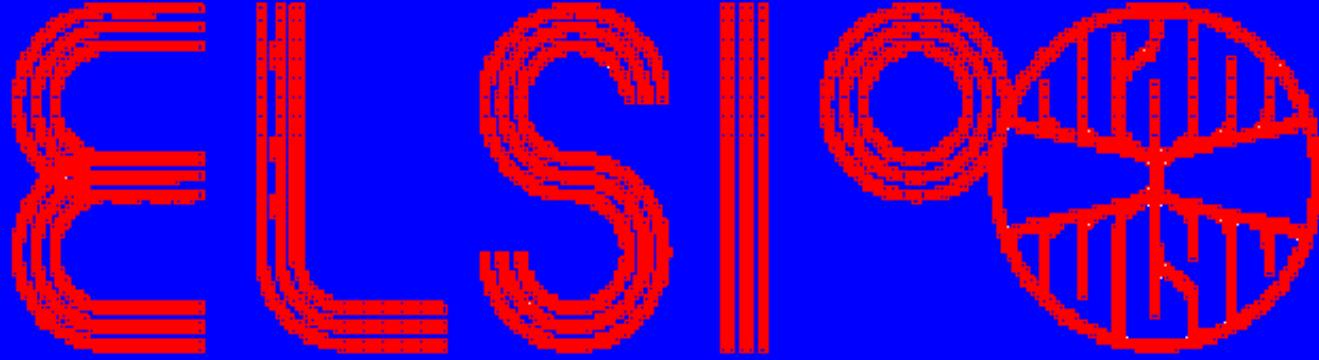
Initial condition

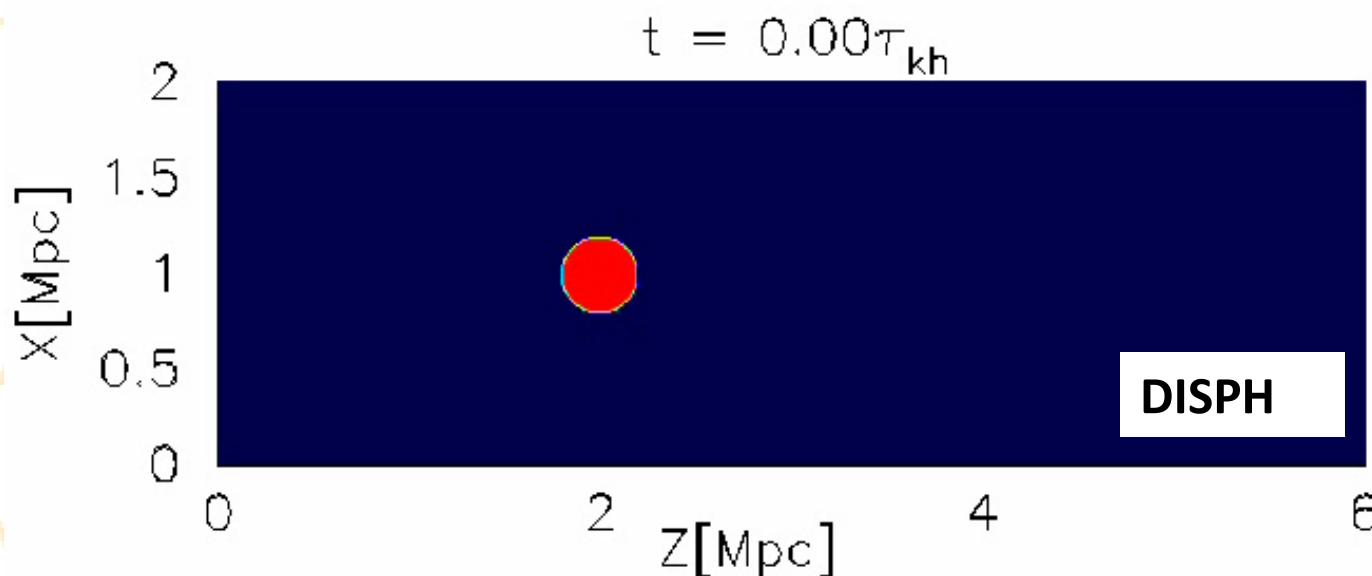
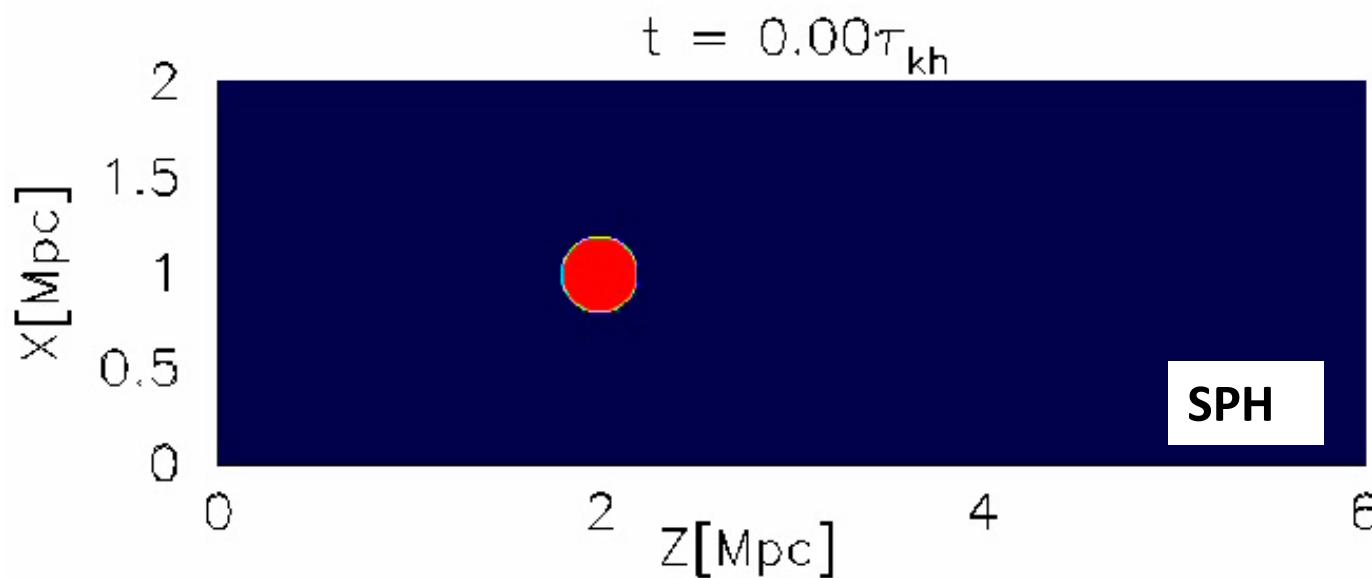


Our SPH



Standard SPH





# Contents



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# Santa Barbara Cluster Comparison Test



Frenk+1999

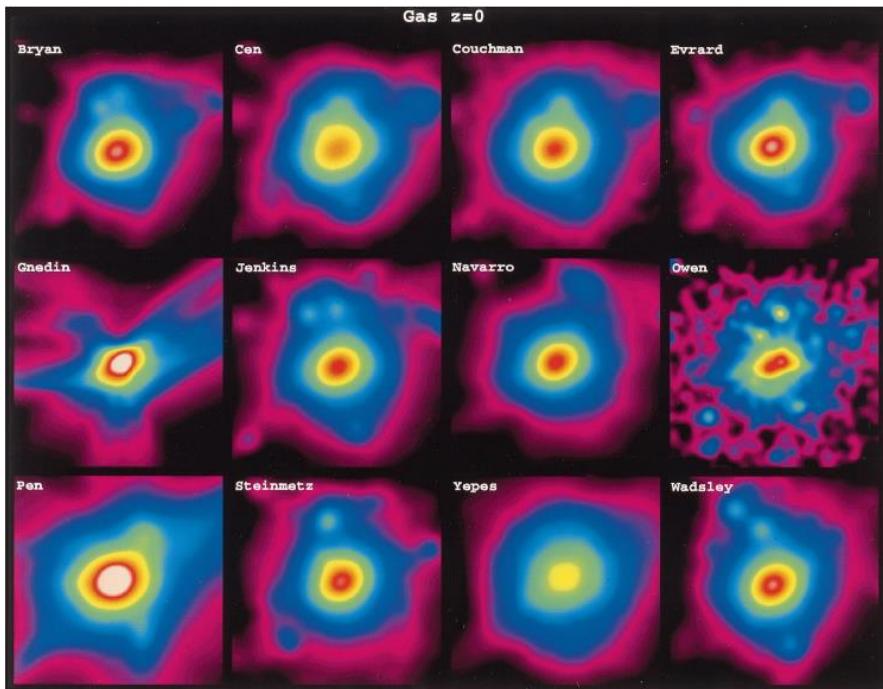


FIG. 3.—Projected gas density at  $z = 0$ . The images, covering the inner 8 Mpc of each simulation cube, have been smoothed using the standard Gaussian filter of 250 kpc half-width described in the text.

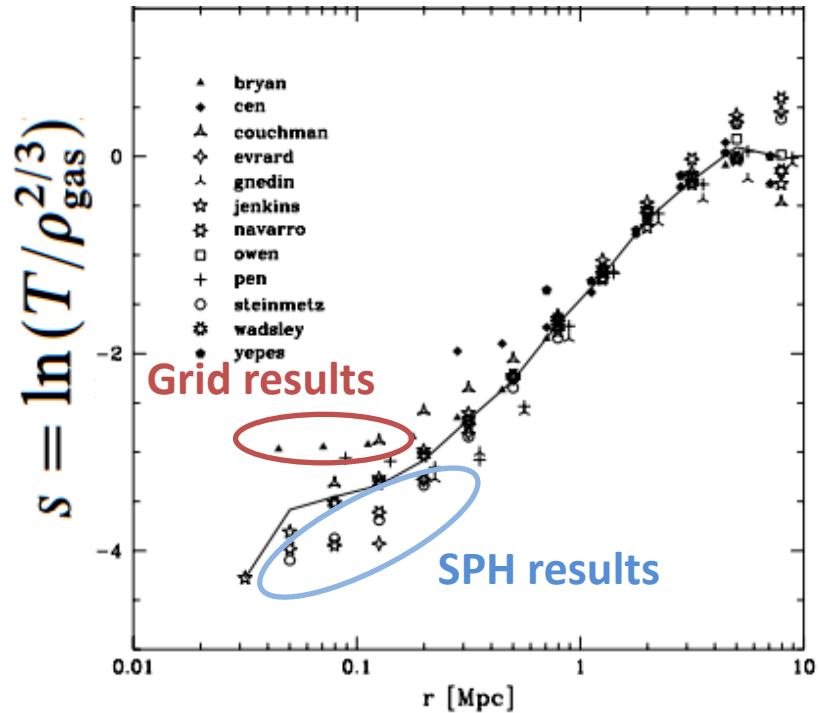


FIG. 18.—Radial variation of the gas entropy. The entropy is defined as  $s = \ln(T / \rho_{\text{gas}}^{2/3})$ . See legend to Fig. 10 for further details.

- エントロピープロファイルに系統的な違い
  - Grid results: **Core at the center**
  - SPH results: **No entropy core**

# エントロピープロファイルの 違いの起源は？

- Frenk+1999 の解釈

the entropy remains approximately constant within  $\sim 200$  kpc. This difference might reflect differences in the way in which shocks are treated in the SPH and grid codes; however, the effect is small and occurs at the resolution

- 従来の SPH 法は接触不連続面に非物理的表面張力が発生(e.g., Agertz+2007)
  - クランプ落下時にラム圧・流体不安定性による破壊を免れて低エントロピー成分を中心に供給する可能性
  - Blob test (Agertz+2007) の結果が示唆的
  - See also Power+2014

# メッシュの問題： !=ガリレイ不变 数値拡散

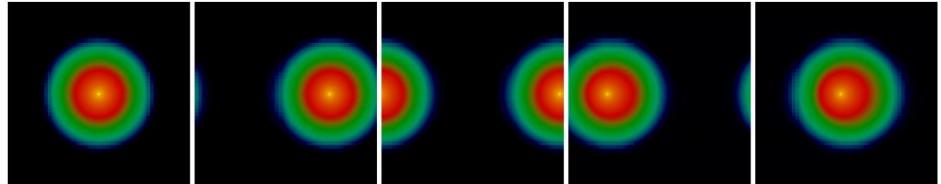


Figure 12. Density projections of the cluster over the course of 1 Gyr in which it moves once around the simulation box. Images taken at 0, 250, 500, 750, 1000 Myr with projected density range  $[10^{8.4}, 10^{16.5}] M_{\odot} \text{Mpc}^{-3}$ . Yellow and red shows higher density regions than green, while black is very low density. [Images produced with ENZO (ZEUS).]

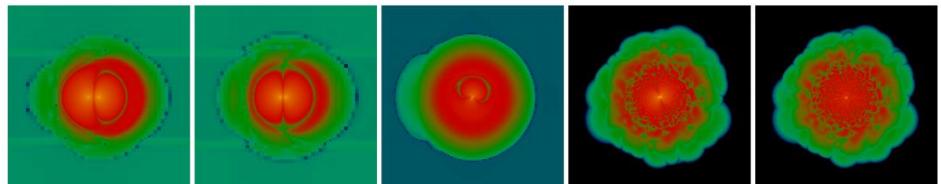
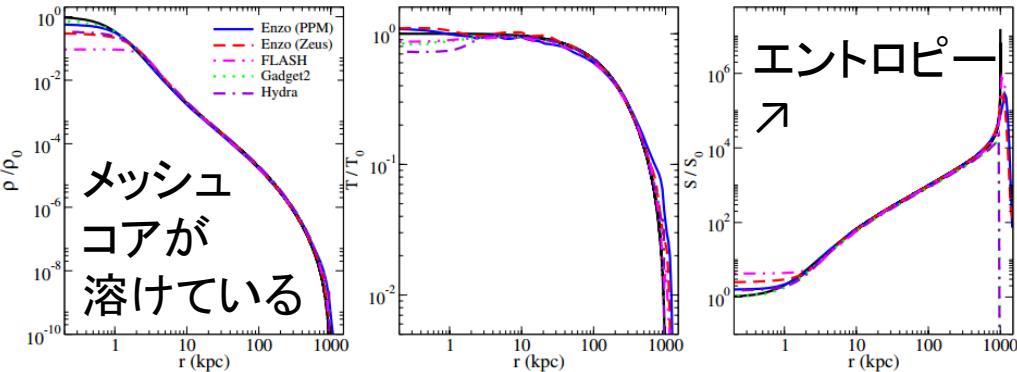


Figure 13. Image subtractions of the density projections at the start and end of the translating cluster test. From left- to right-hand side shows ENZO (PPM), ENZO (ZEUS), FLASH, GADGET2 and HYDRA. The projected density range is  $[10^4, 10^{18.6}] M_{\odot} \text{Mpc}^{-3}$ .



Tasker+2008

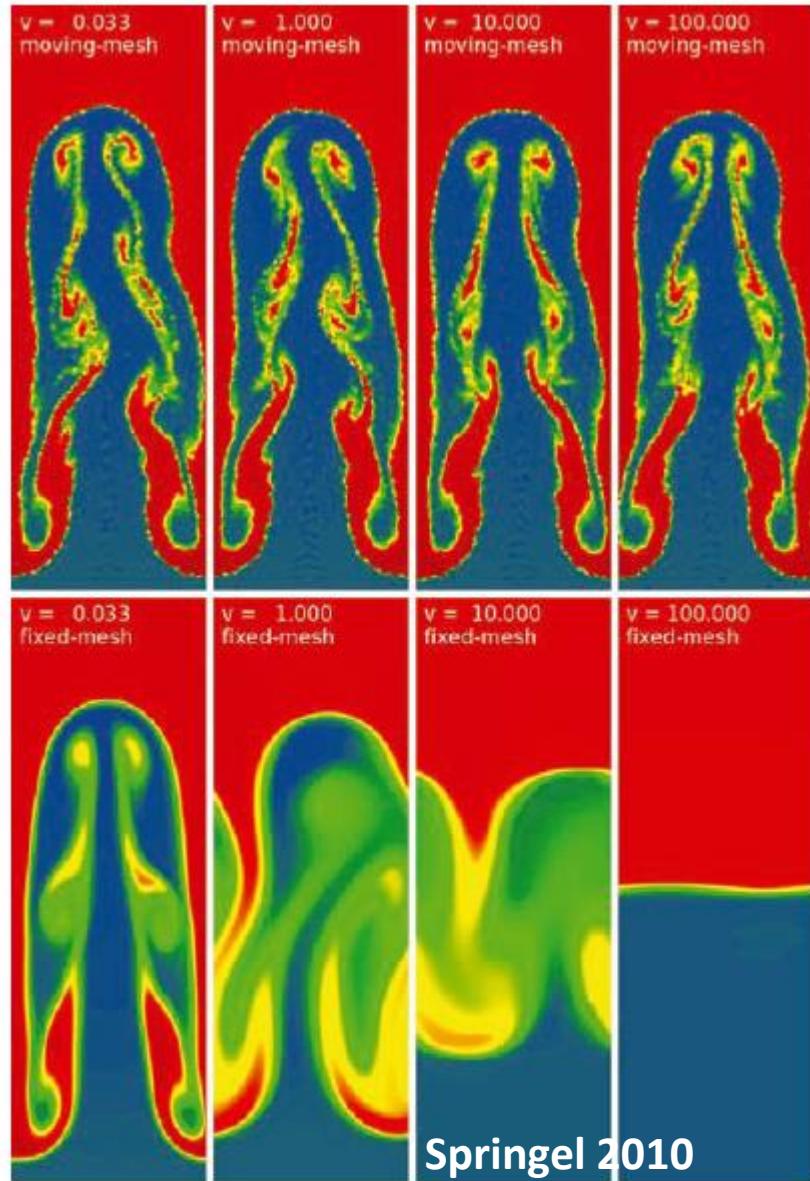
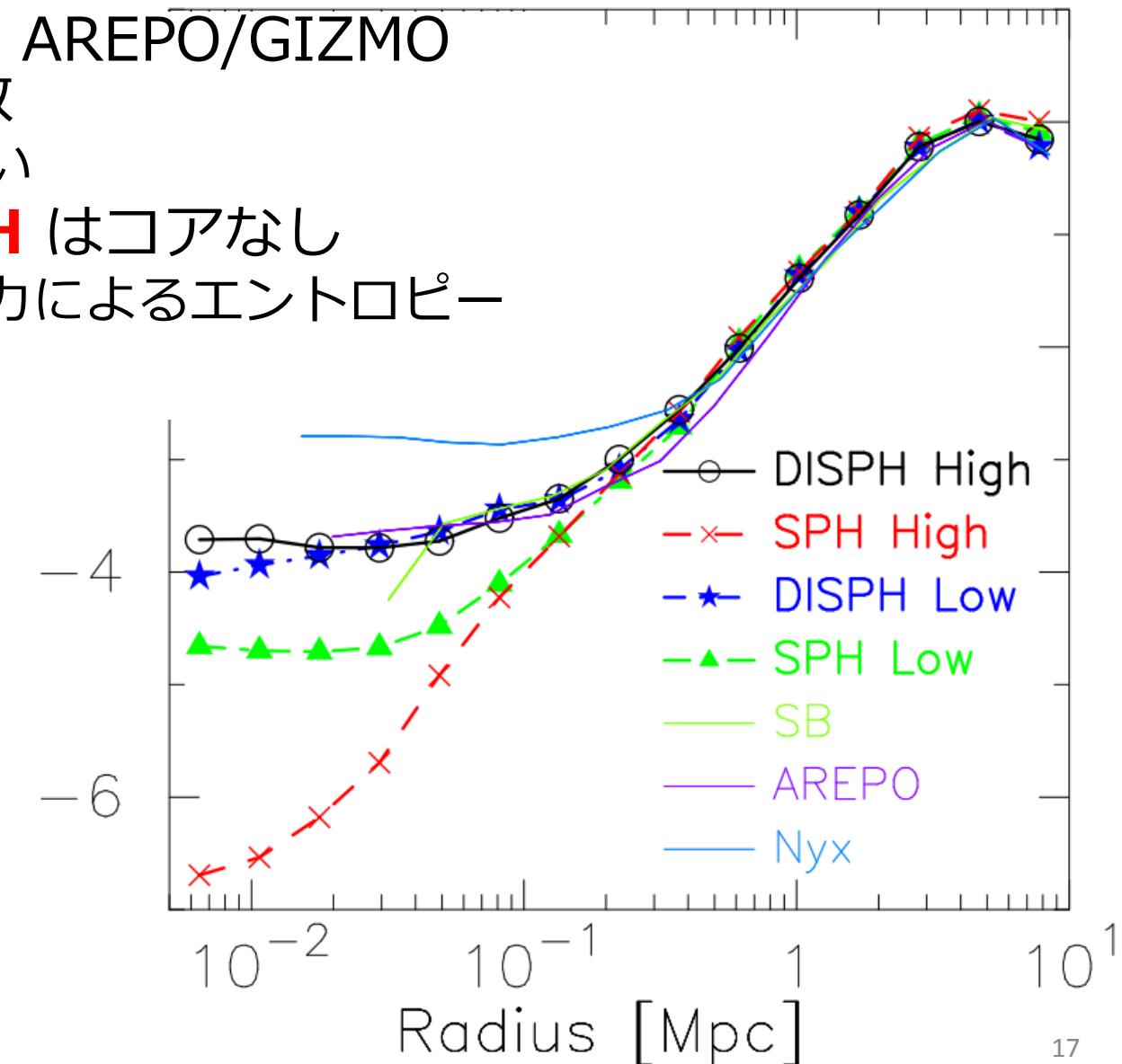
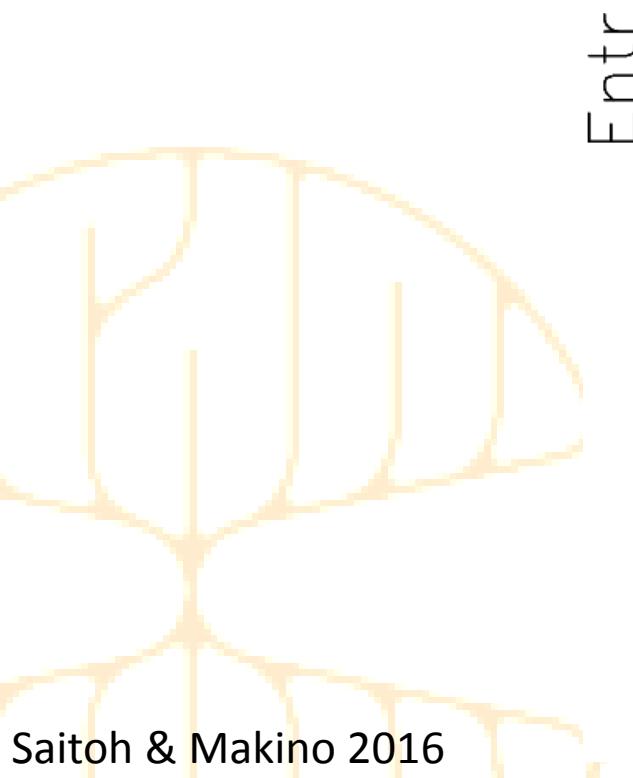


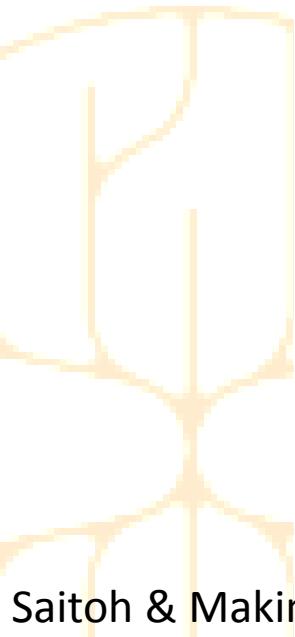
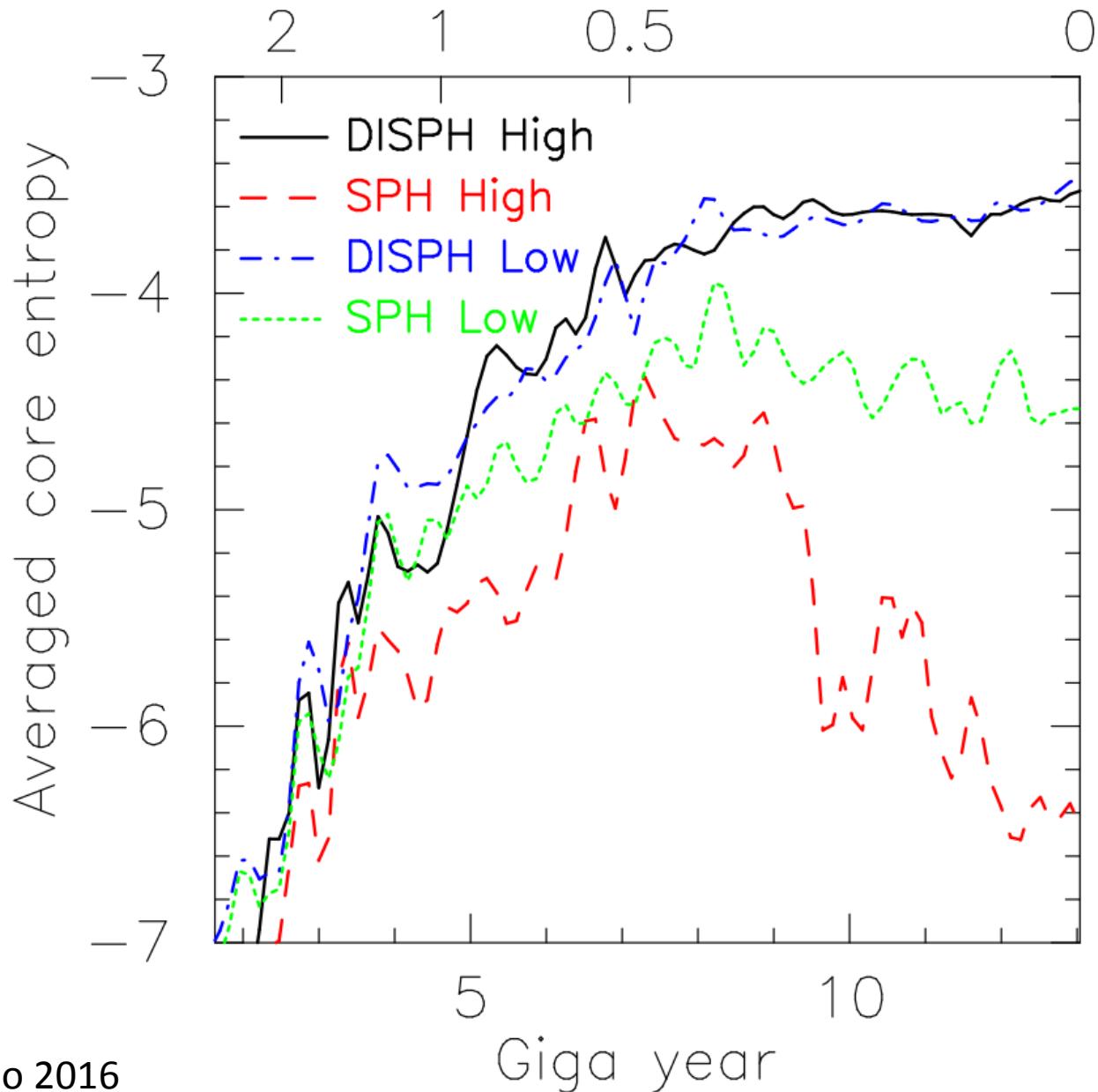
Figure 36. RT instability calculated with different Galilean boosts  $v_x$  in the horizontal direction (the simulation domain is periodic in the  $x$ -direction). The correct result should in principle be independent of  $v$ . The top row shows the result at time  $t = 15.0$  computed with our moving-mesh approach, while the bottom row of panels gives the corresponding results for a fixed-mesh calculation with AREPO.

# Entropy Profile

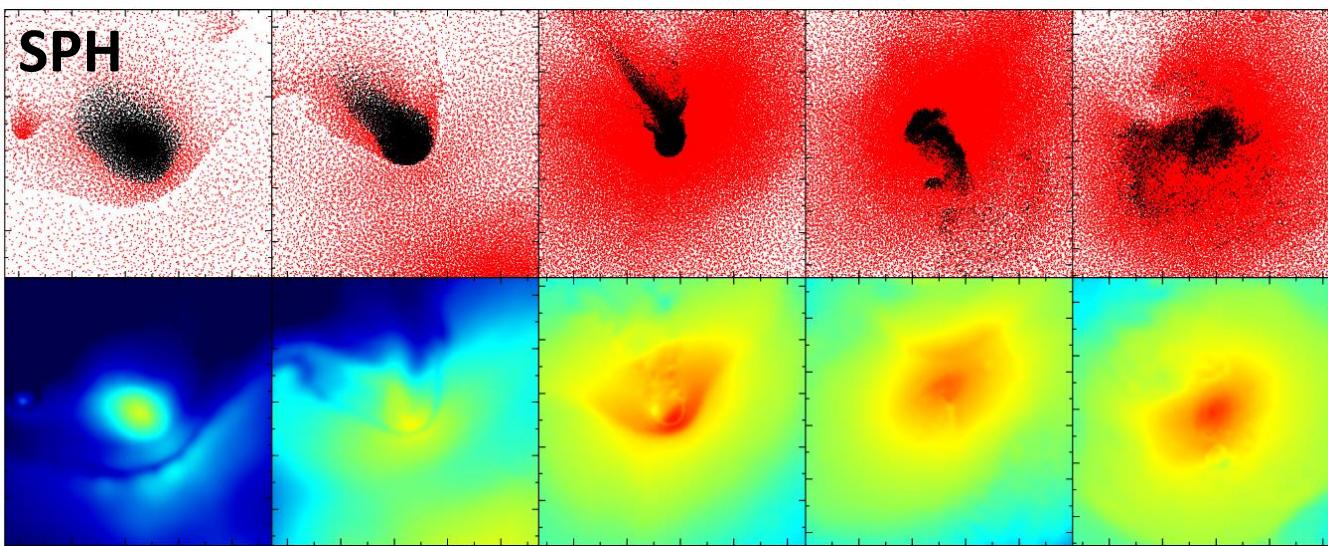
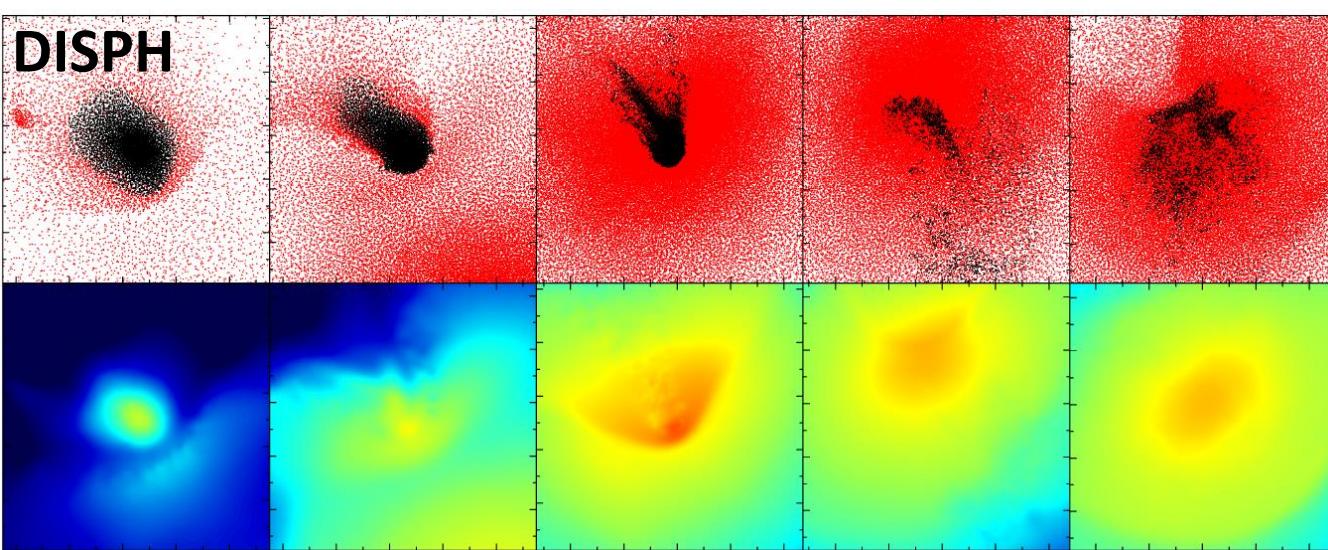
- DISPH の結果は AREPO/GIZMO の結果と良く一致
  - 分解能によらない
- 高分解能版 SSPH はコアなし
  - 非物理的表面張力によるエントロピー生成の阻害



# Averaged Core Entropy



# 低エントロピークラシファイア の非物理的表面張力



- SSPH の計算ではクランプとハローの間にギャップが発生 → ギャップがクランプをラム圧から守る
- DISPH の計算ではギャップはない

# Contents



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- C (C99) + MPI
- Domain decomposition: ORB
- Gravity: Parallel Tree+GRAPE
  - Phantom-GRAPE (Tanikawa+ 2012)
  - Symmetrized softening for tree (Saitoh & Makino 2012)
- Hydro : Smoothed Particle Hydrodynamics
  - DISPH (Saitoh & Makino 2013)
- Time integrator: Leap-frog
  - + Individual time steps
  - + Time-step limiter (Saitoh & Makino 2009)
  - + FAST (Saitoh & Makino 2010)

# Models

- **Cooling/Heating functions:** Cloudy c13.03 + Haardt & Madau (2012) UVB + Rahmati et al (2013)'s self-shielding model (extended to  $z \sim 15$ )
- **Star formation:** High density/low temperature threshold model (Saitoh et al. 2008)
- **Feedback & Chemical evolution:** Type II/Ia/AGB (CELib, Saitoh 2016, in prep.)
  - The Chabrier IMF (Chabrier 2003)
  - The Susa (Pop III) IMF for extremely low-metal stars (Susa et al. 2013)

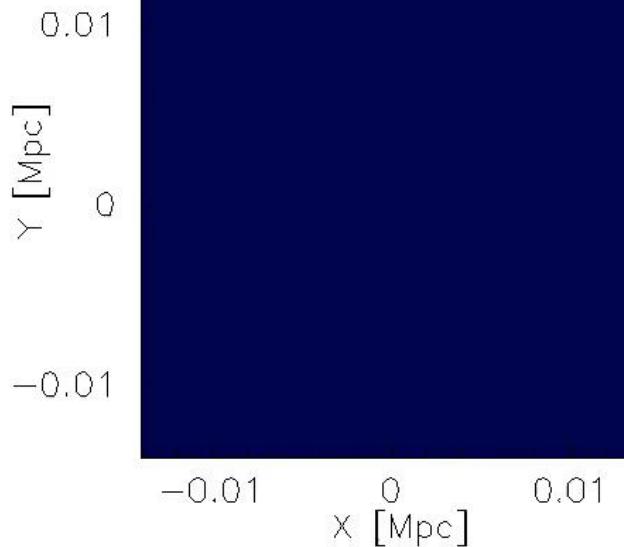
# Init condition / Runs/resolutions

- Initial condition
  - Zoom-in 初期条件(Planck cosmology params)
    - 半径~18Mpc/h、解放境界
    - $M_h \sim 10^{12} M_\odot @ z=0$
- Two runs
  - DISPH
  - SSPH
- Some parameters
  - Mass:  $\sim 10^6 M_\odot$  for gas
  - Softening: 50 pc for gas, 100 pc for DM

# DISPH

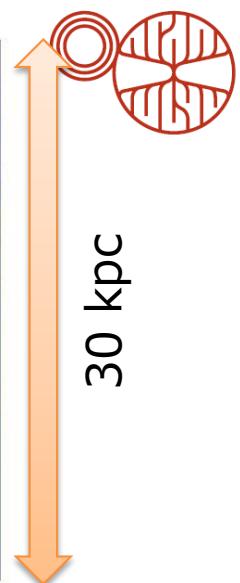
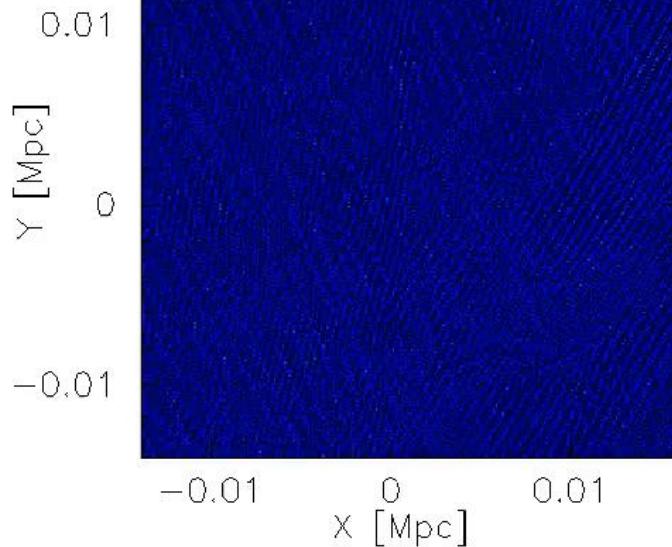
星

ガス

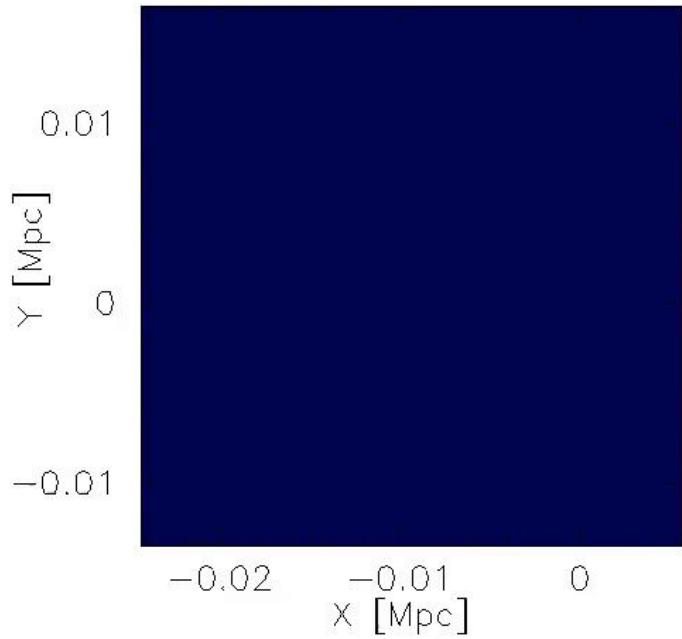


星

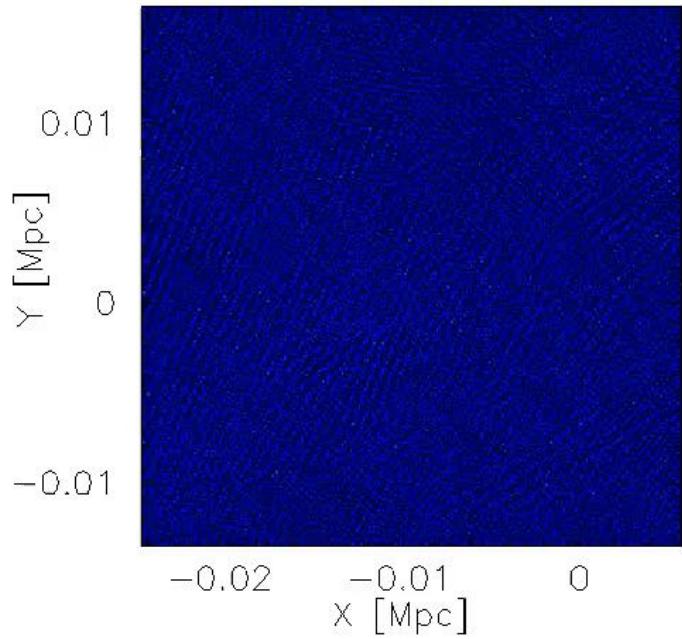
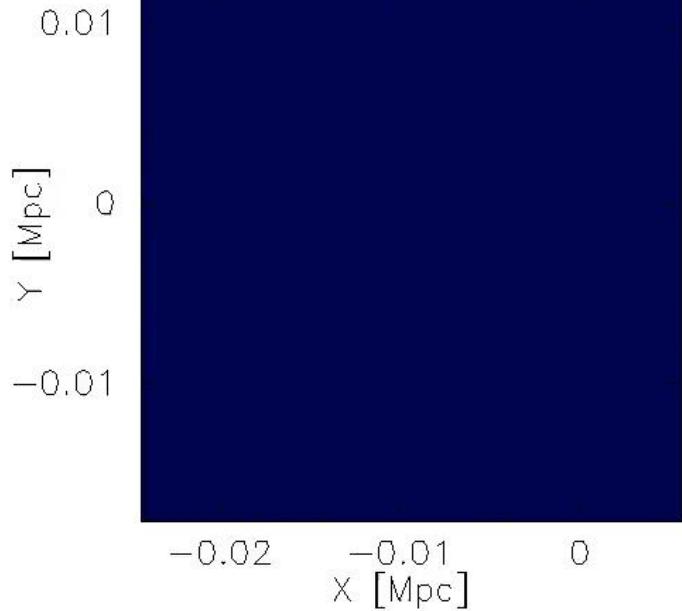
ガス



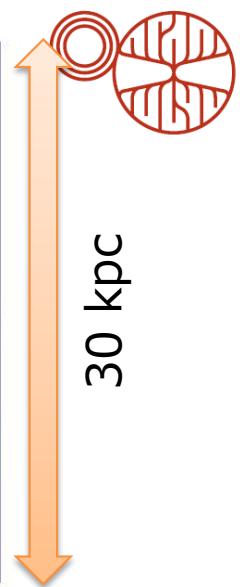
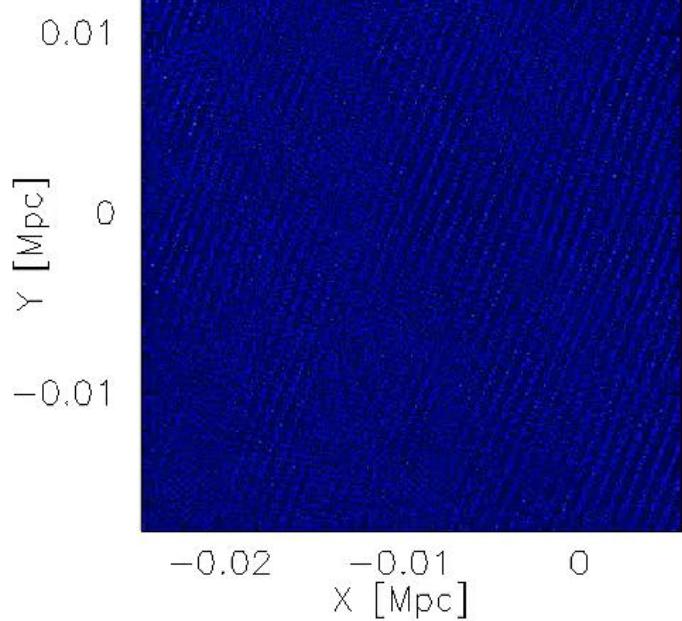
# SSPH



星



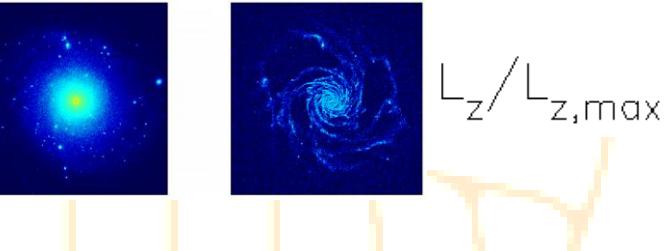
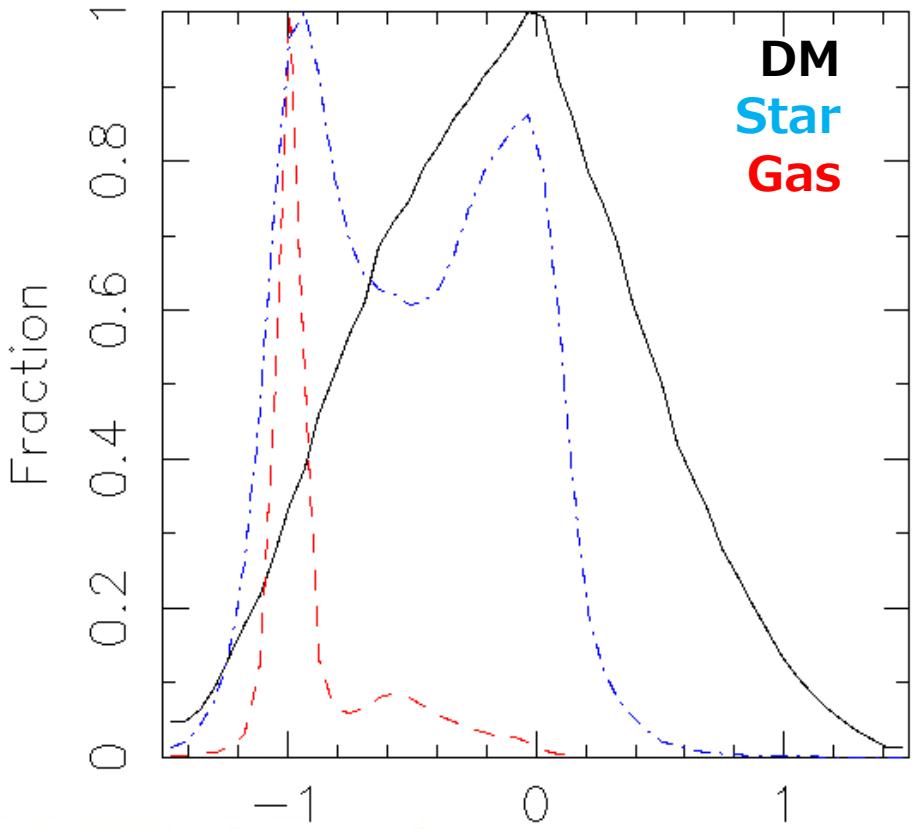
ガス



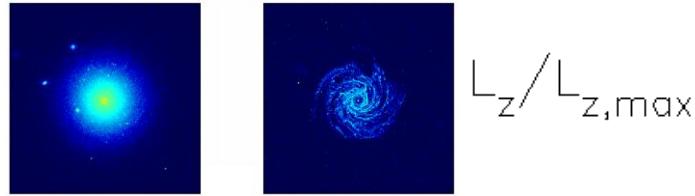
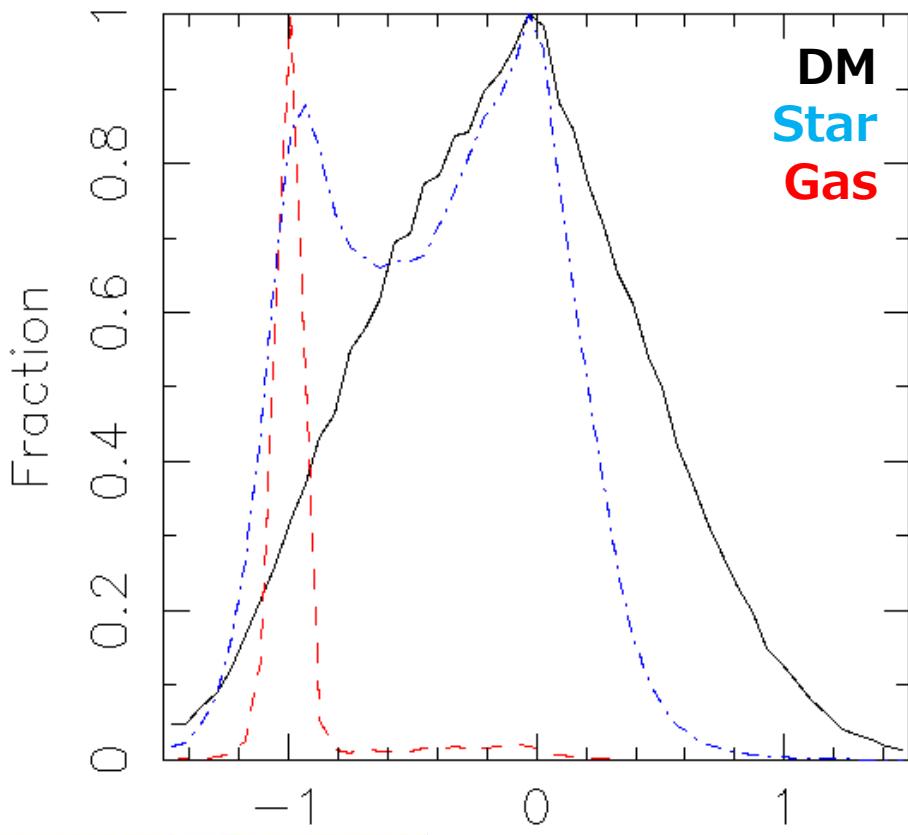
30 kpc

# A.M. distributions

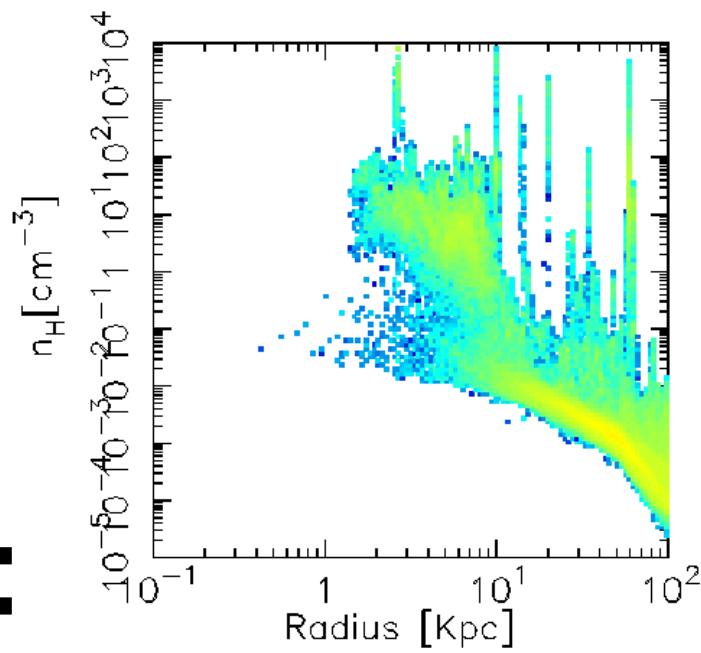
**DISPH**



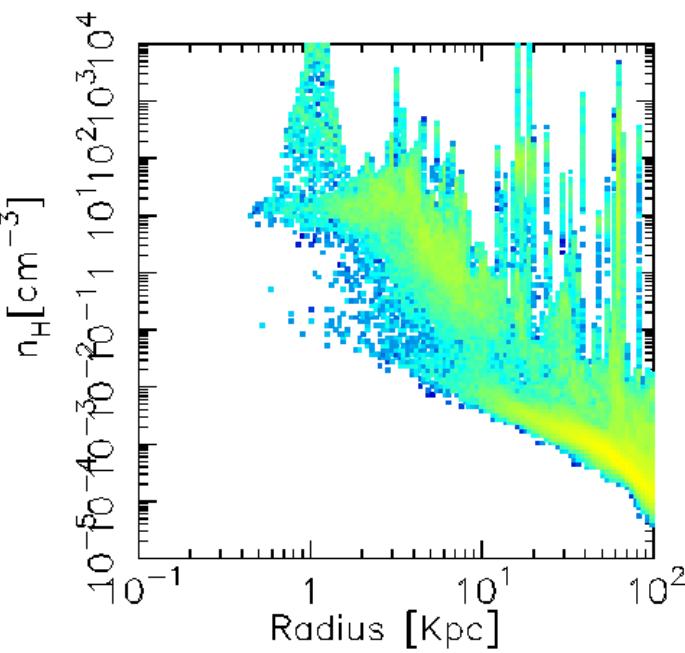
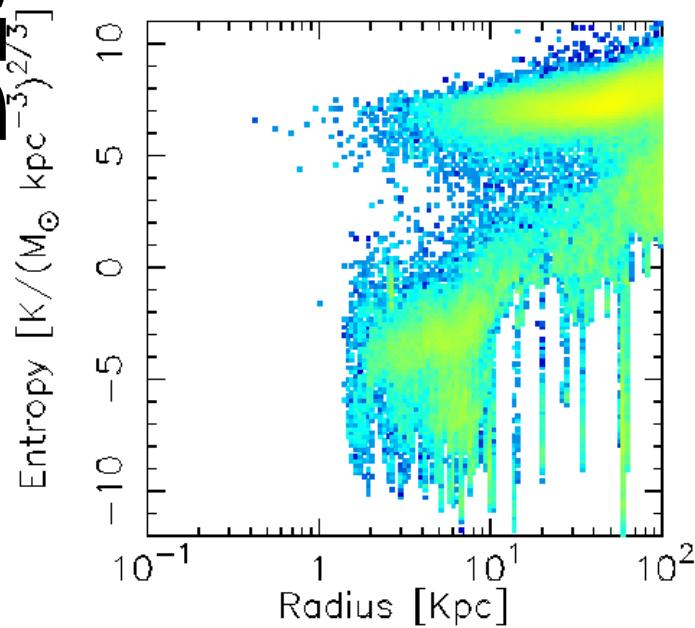
**SSPH**



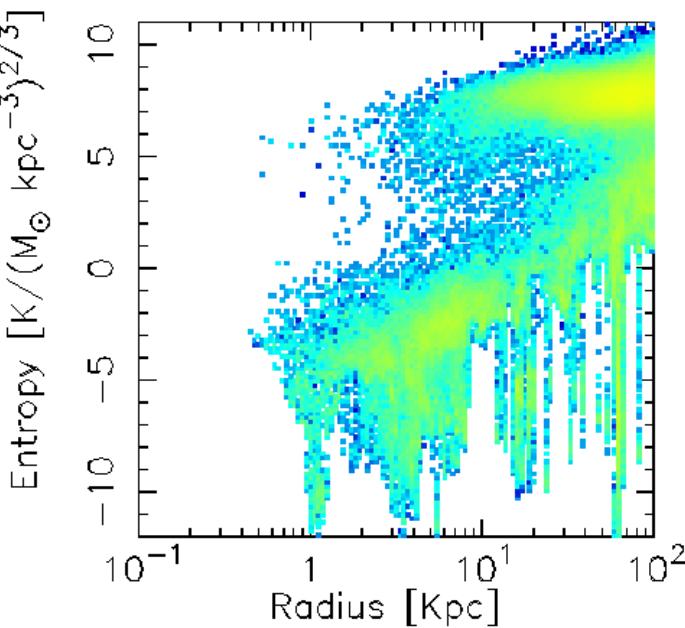
# DISPH



$z=4.3$

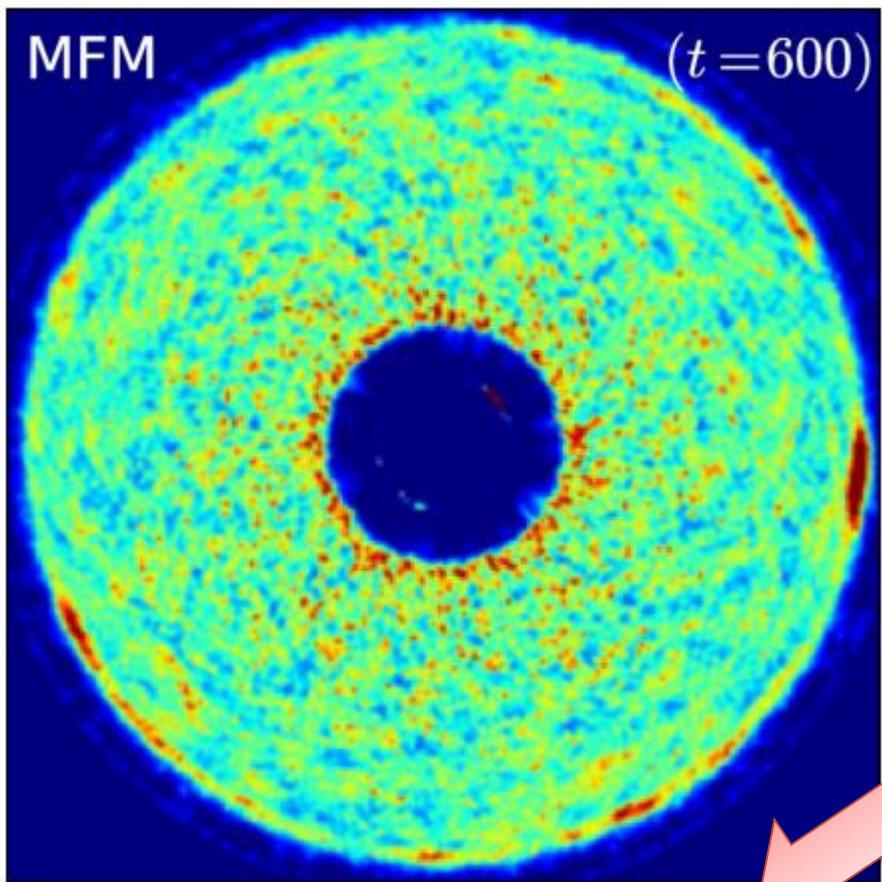


**HdSS**



# Gizmo?

- Hopkins (2015) のメッシュフリー法
  - Higher special order
  - Riemann solver for shock



, at time  $t = 600$  (not a typo)!

~100回転ぐらい保つ

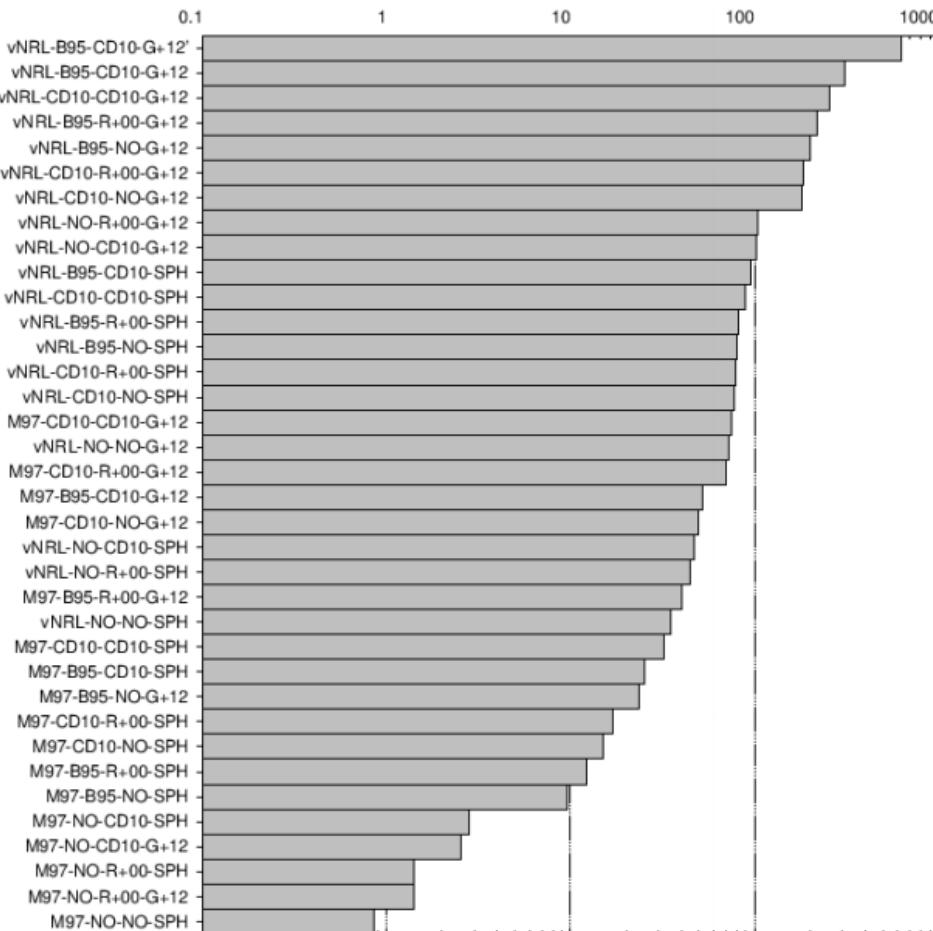
Figure 7. Keplerian disc as Fig. 6, at time  $t = 600$  (not a typo)! The inner ( $r \sim 0.5$ ) disc has executed  $>250$  orbits, at this time, without decaying or disrupting.

# Artificial Viscosity tests

- AV の組み合わせからベストを探す

Type	Abbreviation	Equations	Reference
Form of AV	vNRL	(1)	von Neumann & Richtmyer (1950); Landshoff (1955)
	M97	(6)	Monaghan (1997)
Shock indicator	No	No	Do not use
	R+00	(16)	Rosswog et al. (2000)
Shear switch	CD10	(18)-(21)	Cullen & Dehnen (2010)
	No	No	Do not use
	B95	(22)	Balsara (1995)
	CD10	(25)-(27)	Cullen & Dehnen (2010)
$\nabla \cdot v$	SPH	(3)	Lucy (1977)
	G+12	(4)	García-Senz et al. (2012)

- 最も良いもので100回転以上
- SSPH/DISPH どちらでも有効



# まとめ

- 圧力を使った定式化をした SPH 法(DISPH)は、接触不連続面をより正しく扱える
- サンタバーバラクラスターテストに DISPH を適用すると、エントロピーコアが出来る
  - コアのサイズはメッシュ法より小さく、AREPO/GIZMO とよく一致
- Cooling/heating, SF, FB を考慮した銀河形成シミュレーションでも、DISPH/SSPH で構造に大きな違い
  - SSPH の非物理的表面張力はここでも大きな問題
  - 今後もDISPHで