The University of California
High-Performance AstroComputing Center

International Summer School on AStro-Computing: Galaxy Simulations

Introduction

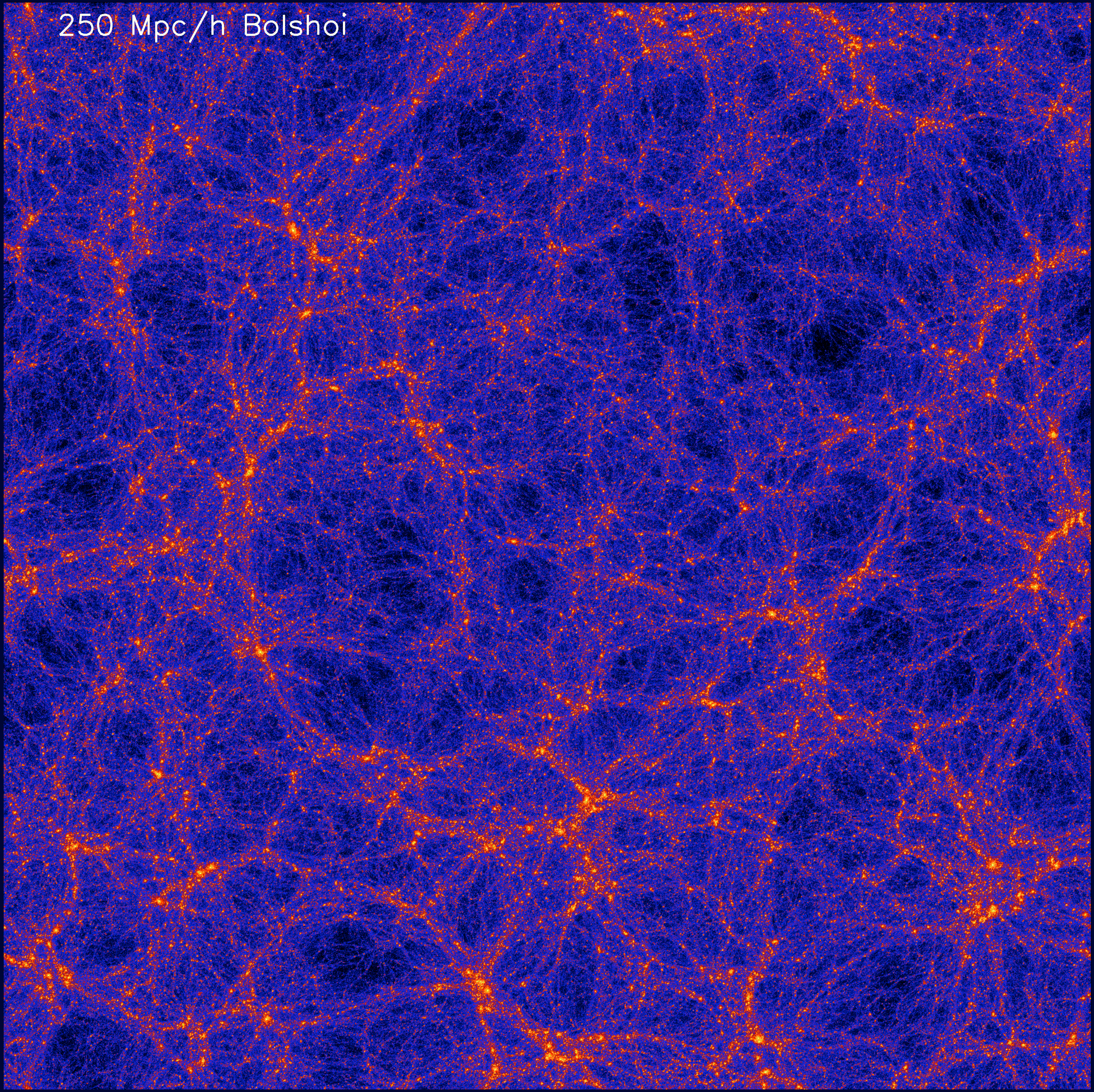
Anatoly Klypin

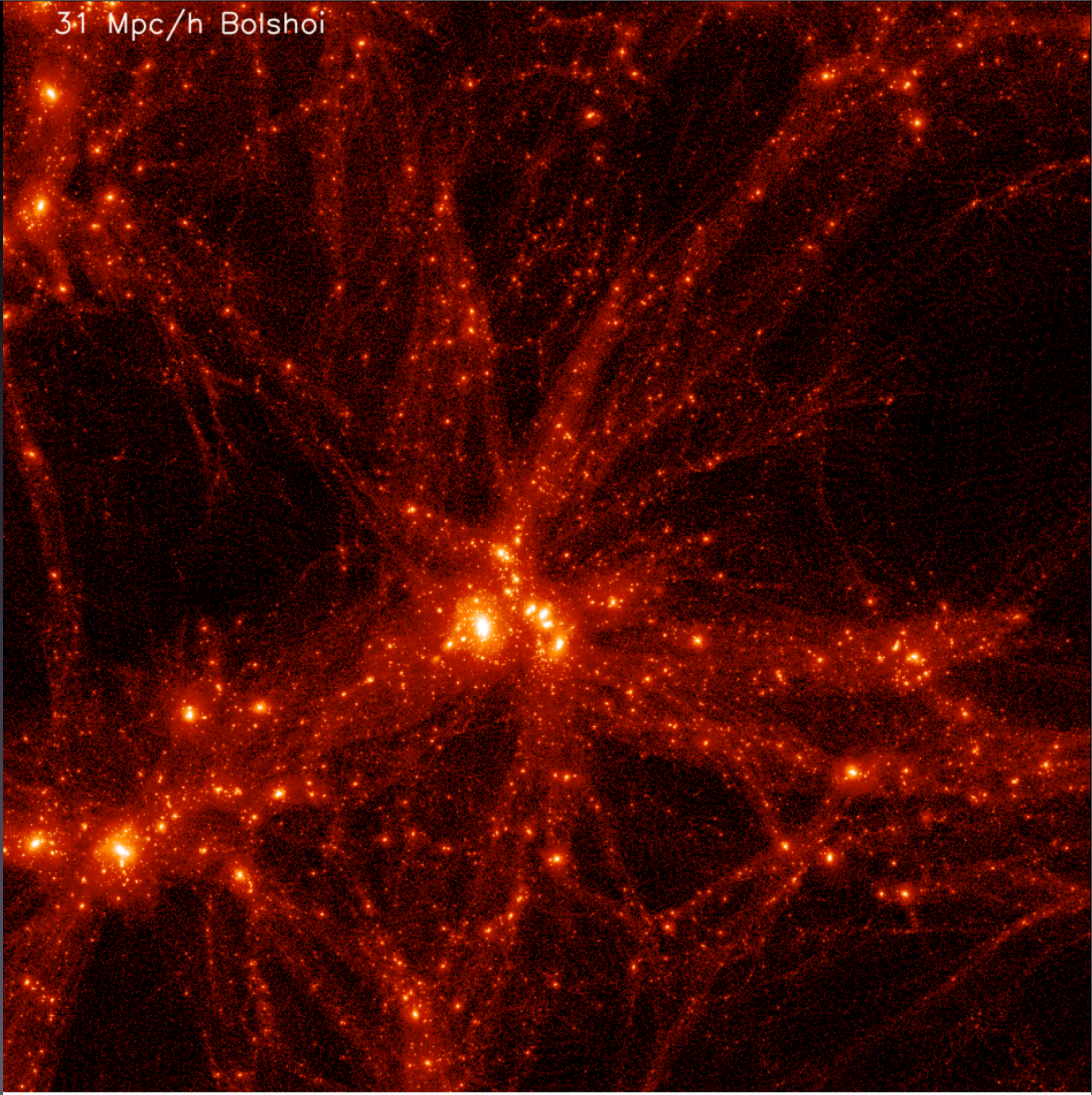
What we will do:

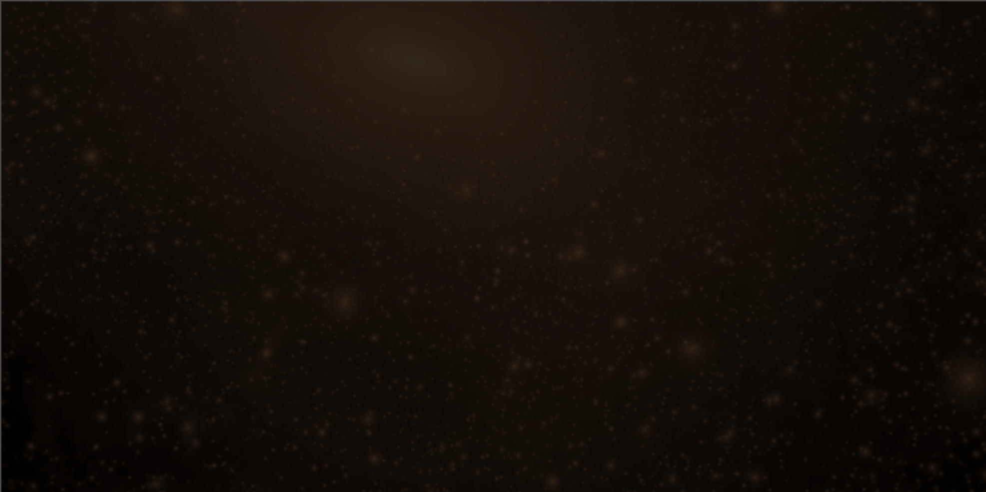
- Lectures on different codes: what they can do, how to use them, how to understand results, algorithms ...
- Physics of galaxy formation: how galaxies form, how star formation affects them, different aspects and physical processes
- Projects:
  - use codes to make small runs
  - analyze results of more realistic simulations

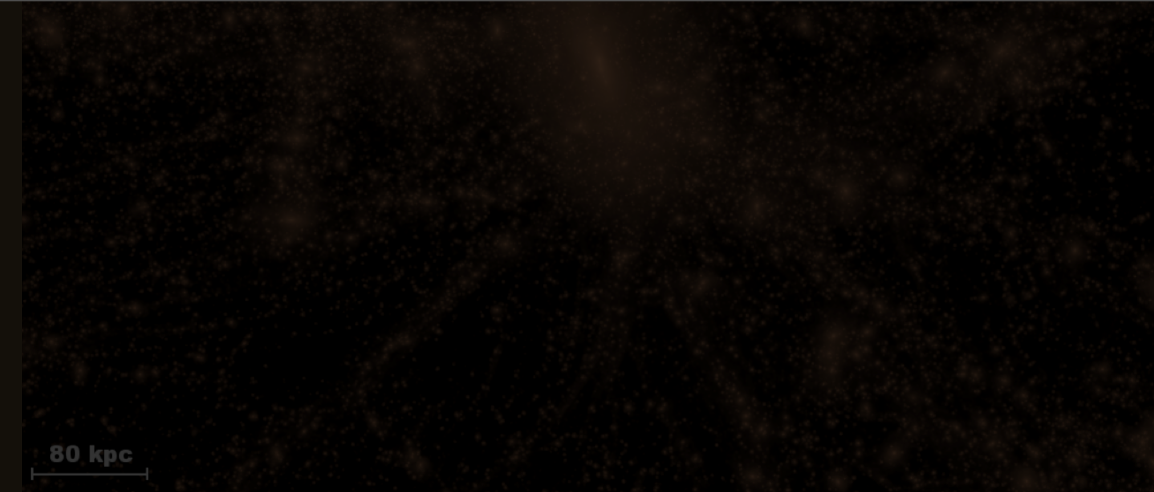
Dark Matter is the backbone for formation of galaxies.

Filamentary distribution of dark matter is mirrored by baryons



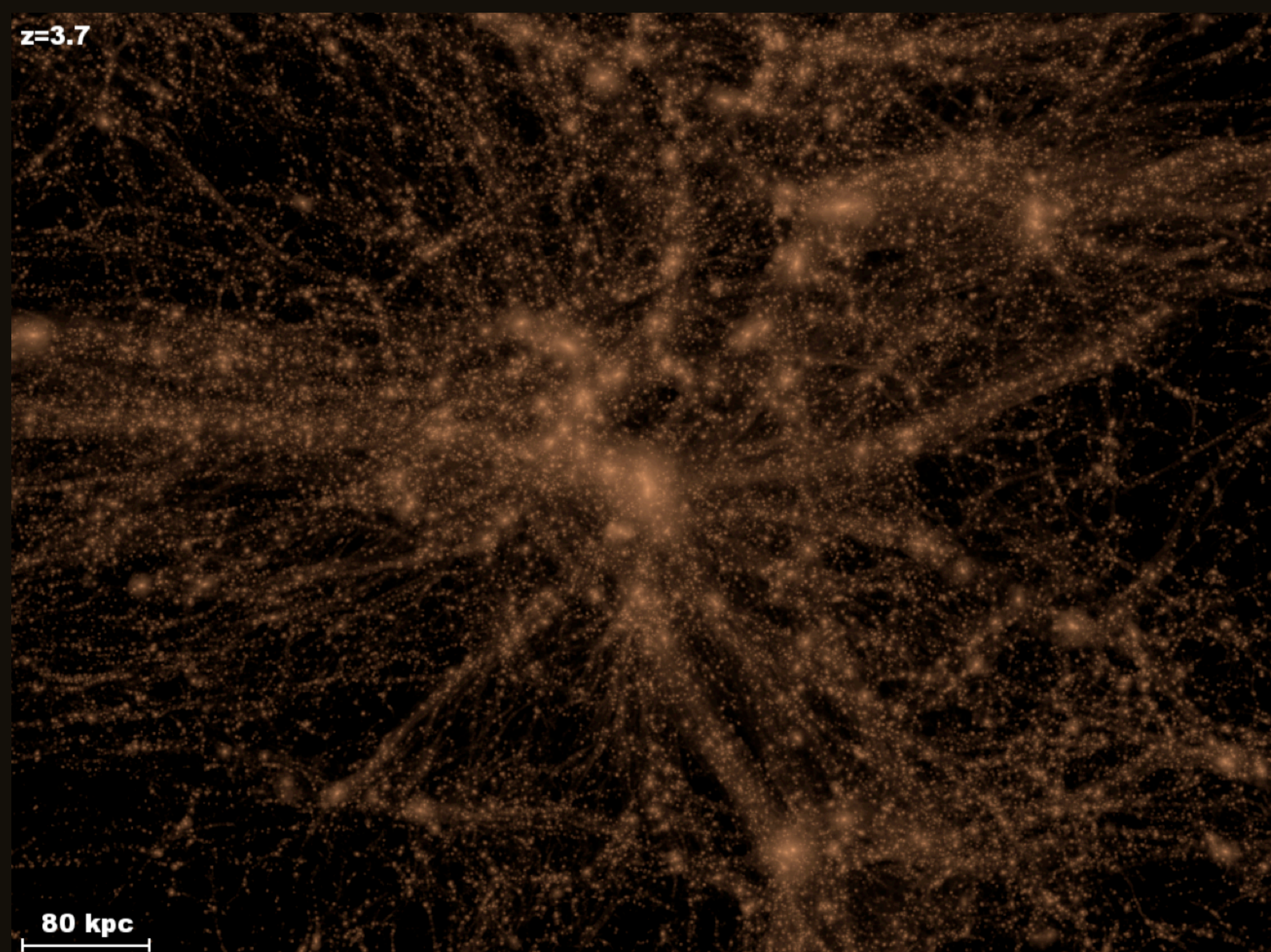

31 Mpc/h Bolshoi



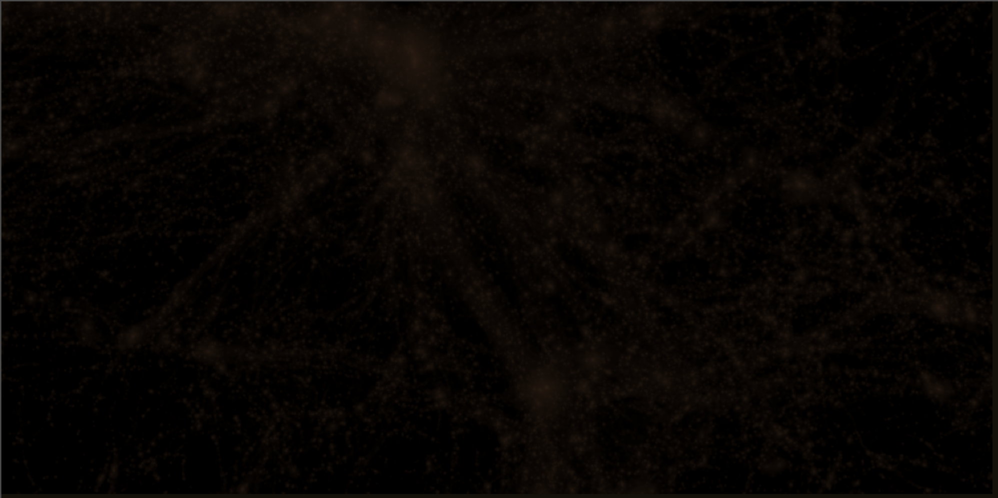


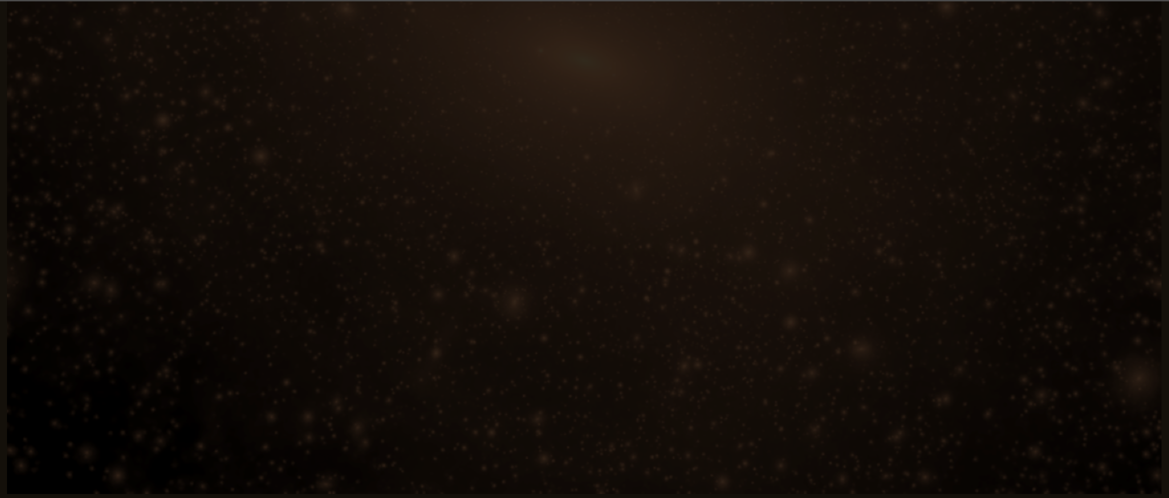
Milky Way formation: DM

600kpc



Madau,
Diemand,
Kuhen





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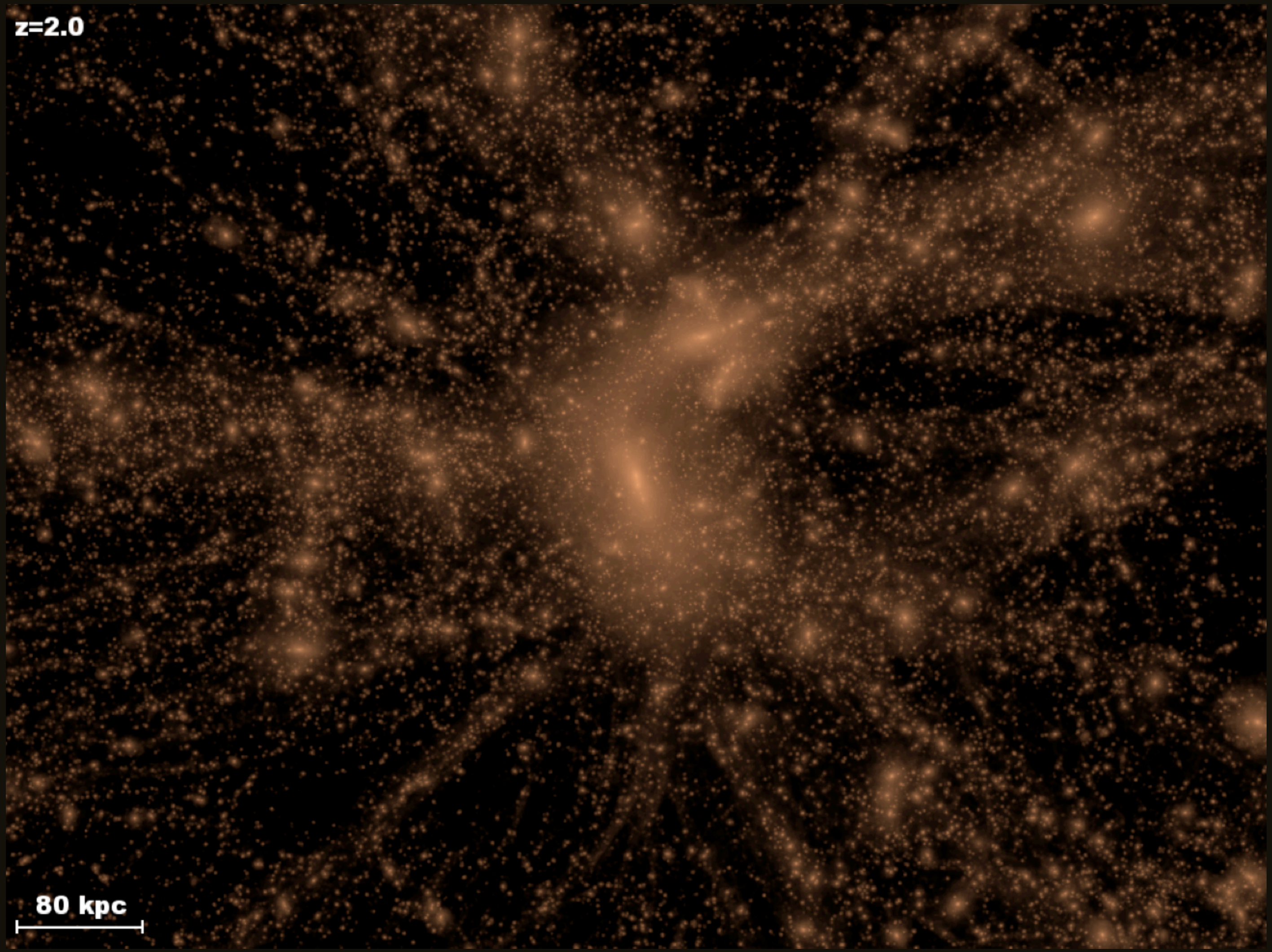
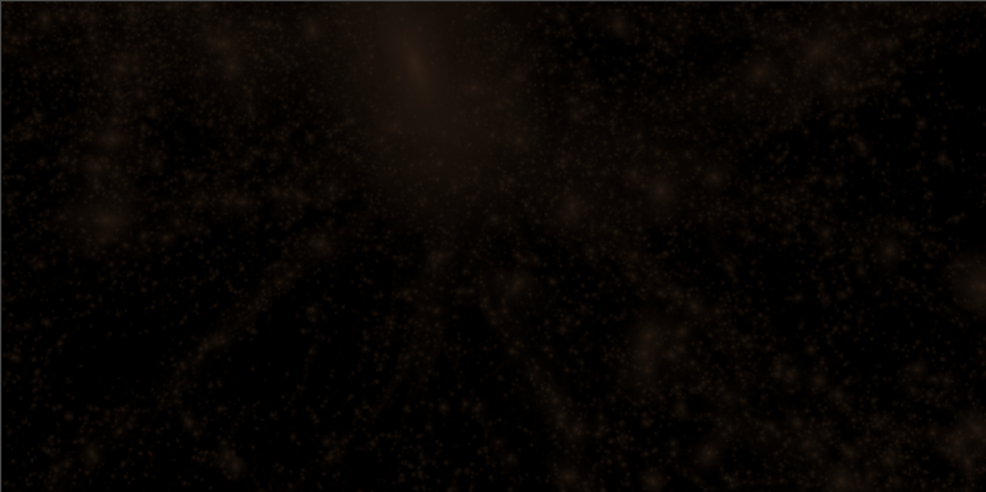
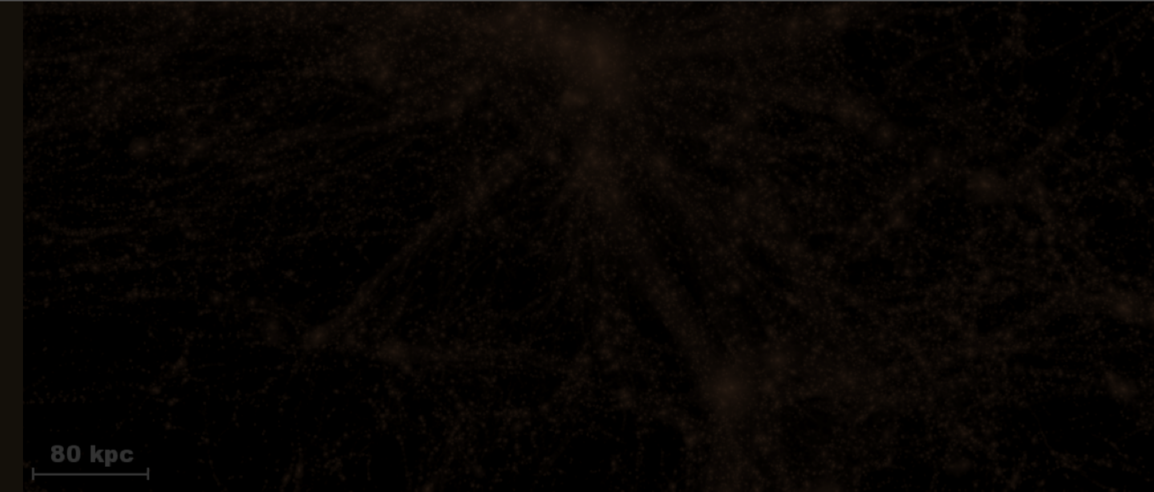


Madau, Diemand, Kuhen





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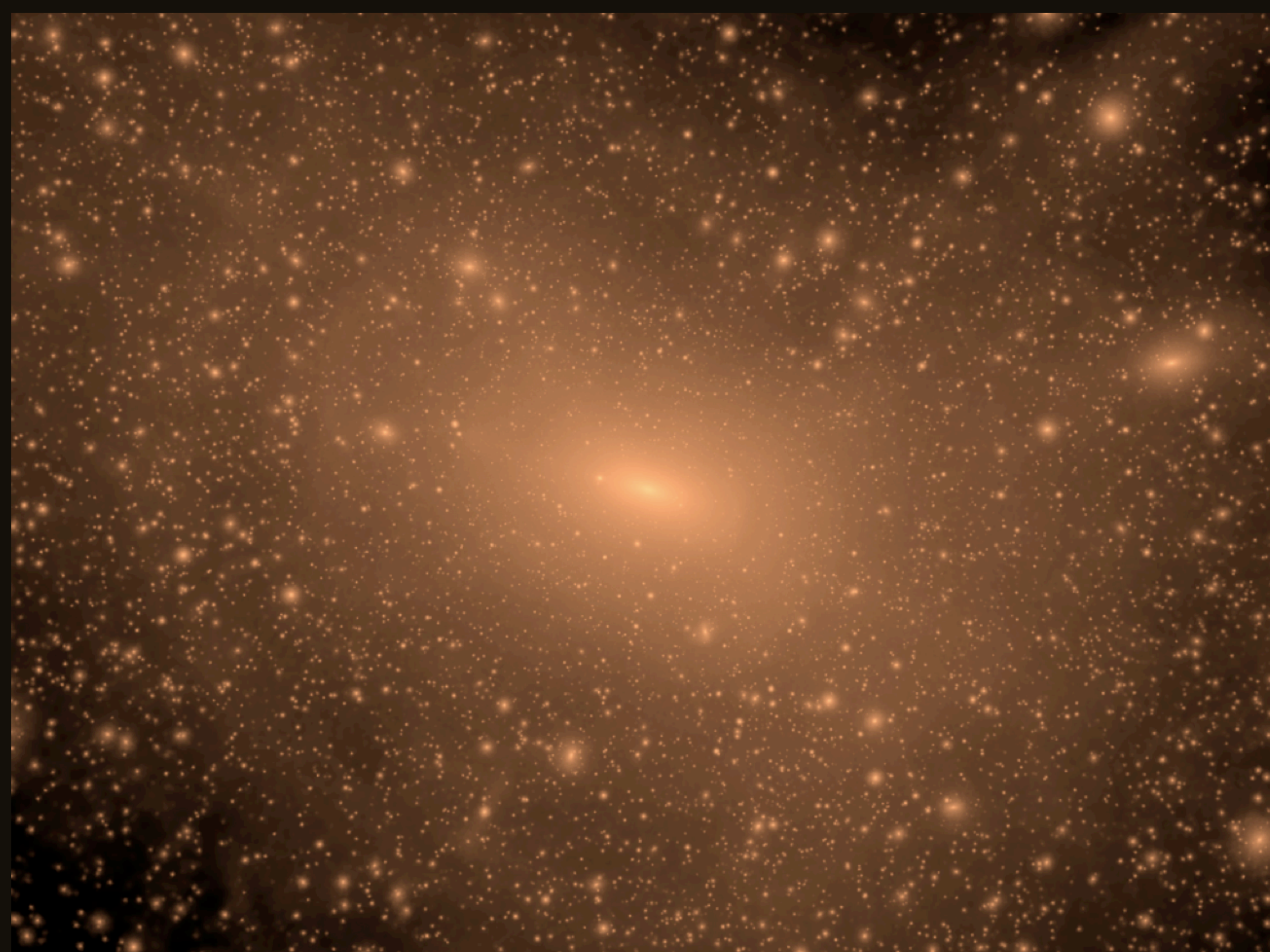


Madau, Diemand, Kuhen

Cosmology: formation of MW galaxy

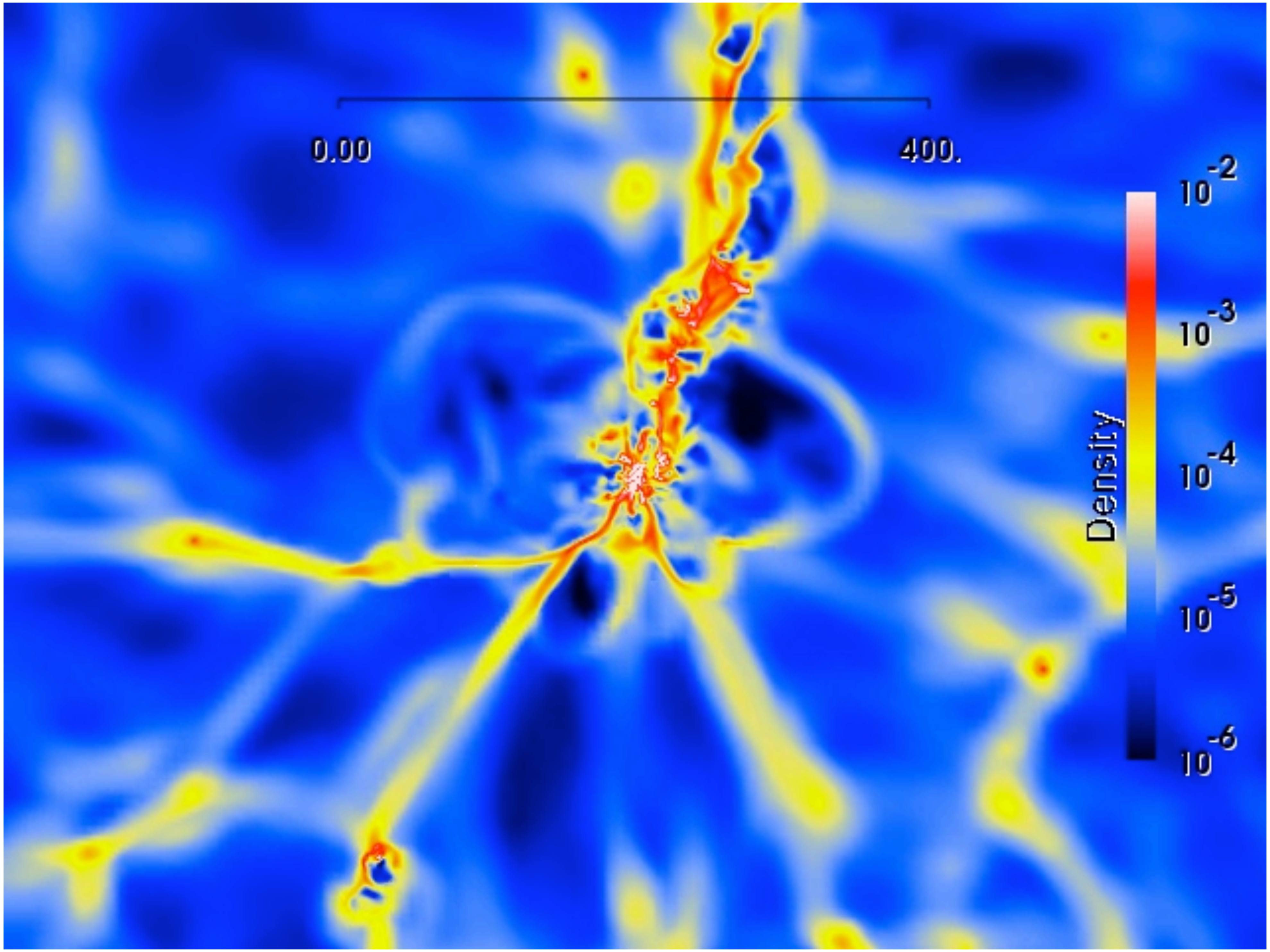
z=3.5 Major progenitor. 45 pc resolution
Face-on view SFR =10Msun/year
Ceverino & Klypin 2007

ART N-body+hydro code (Kravtsov)

400 kpc proper

Cold Flow regime

Slice of gas density



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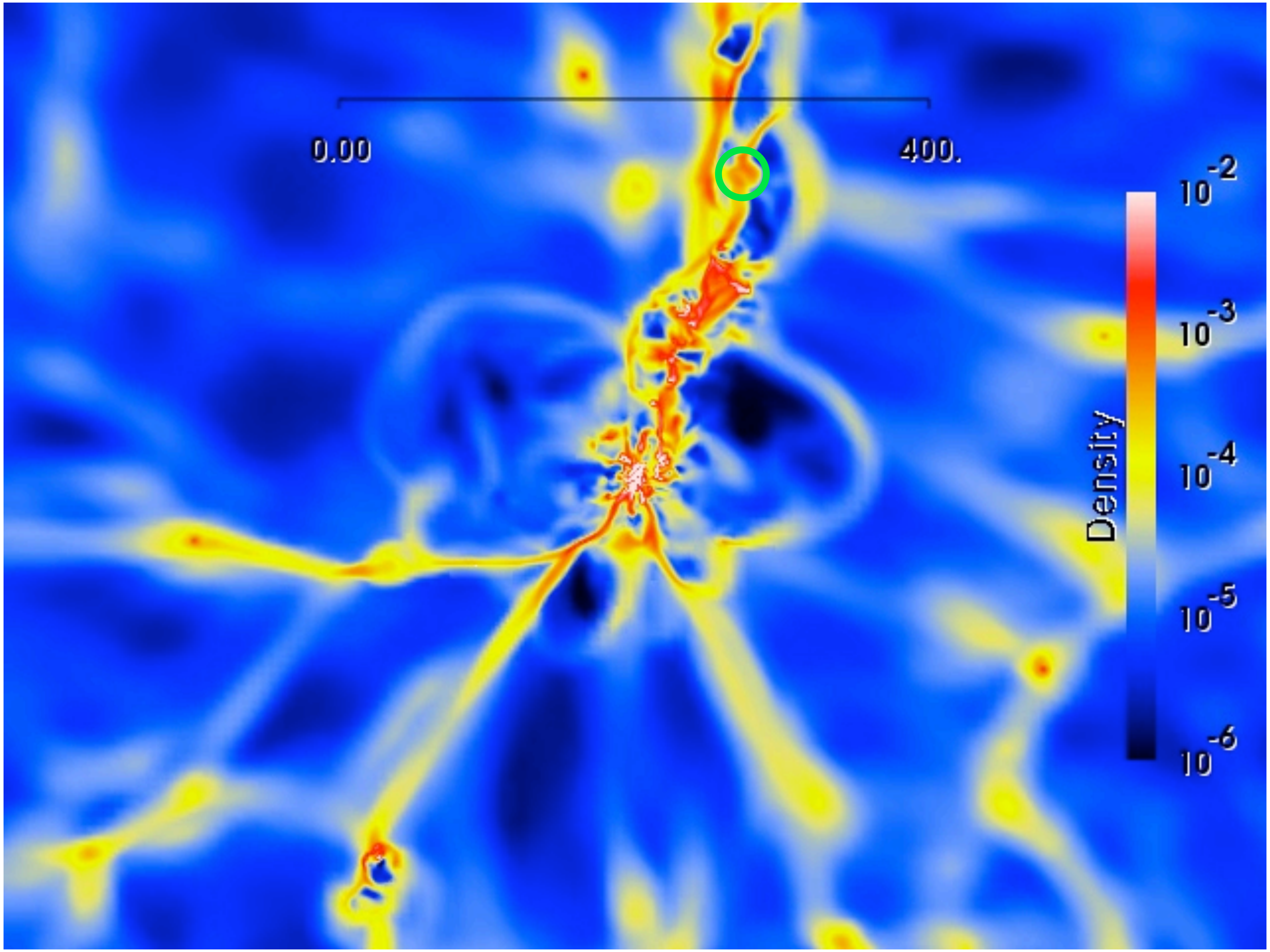

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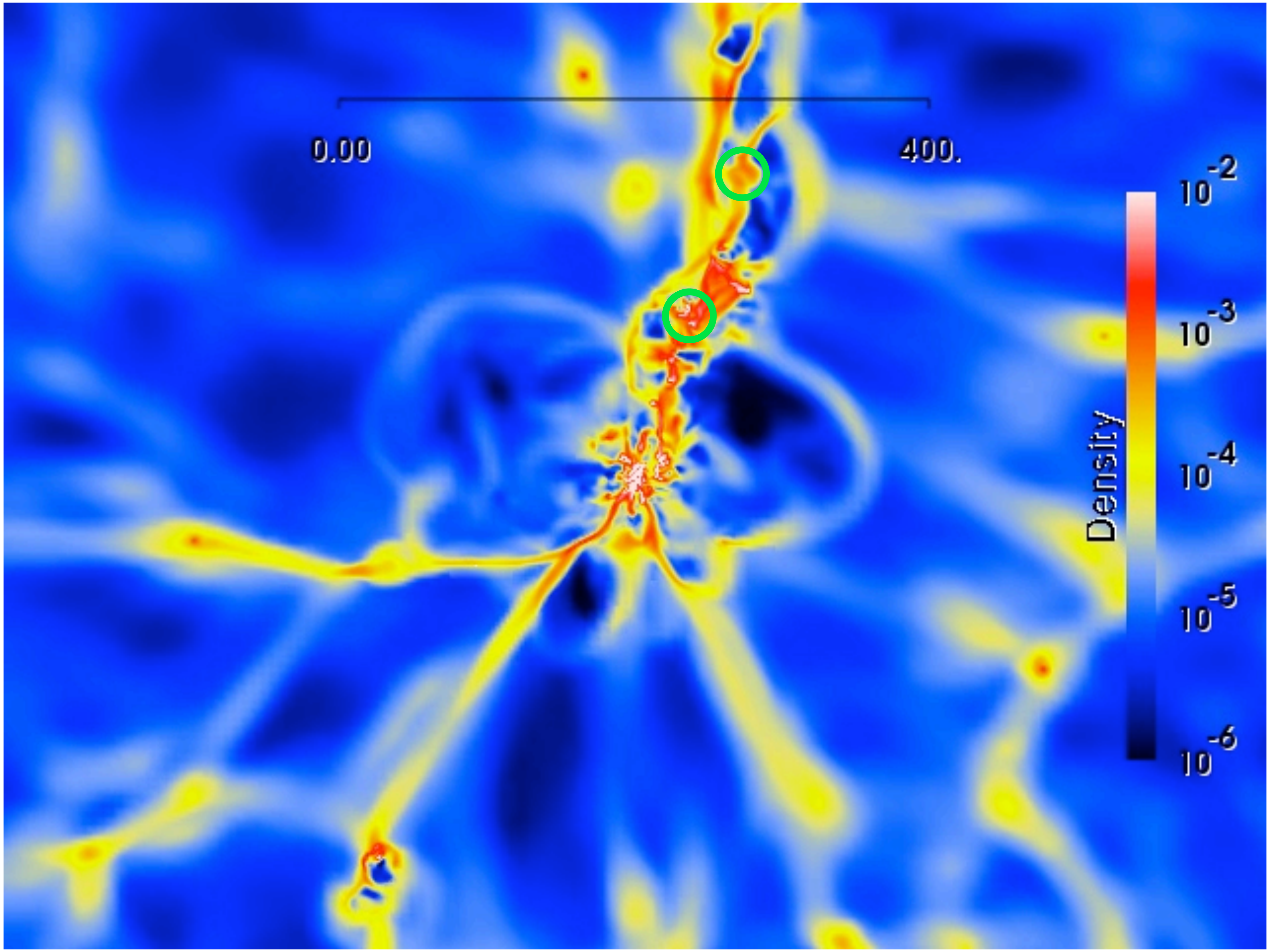

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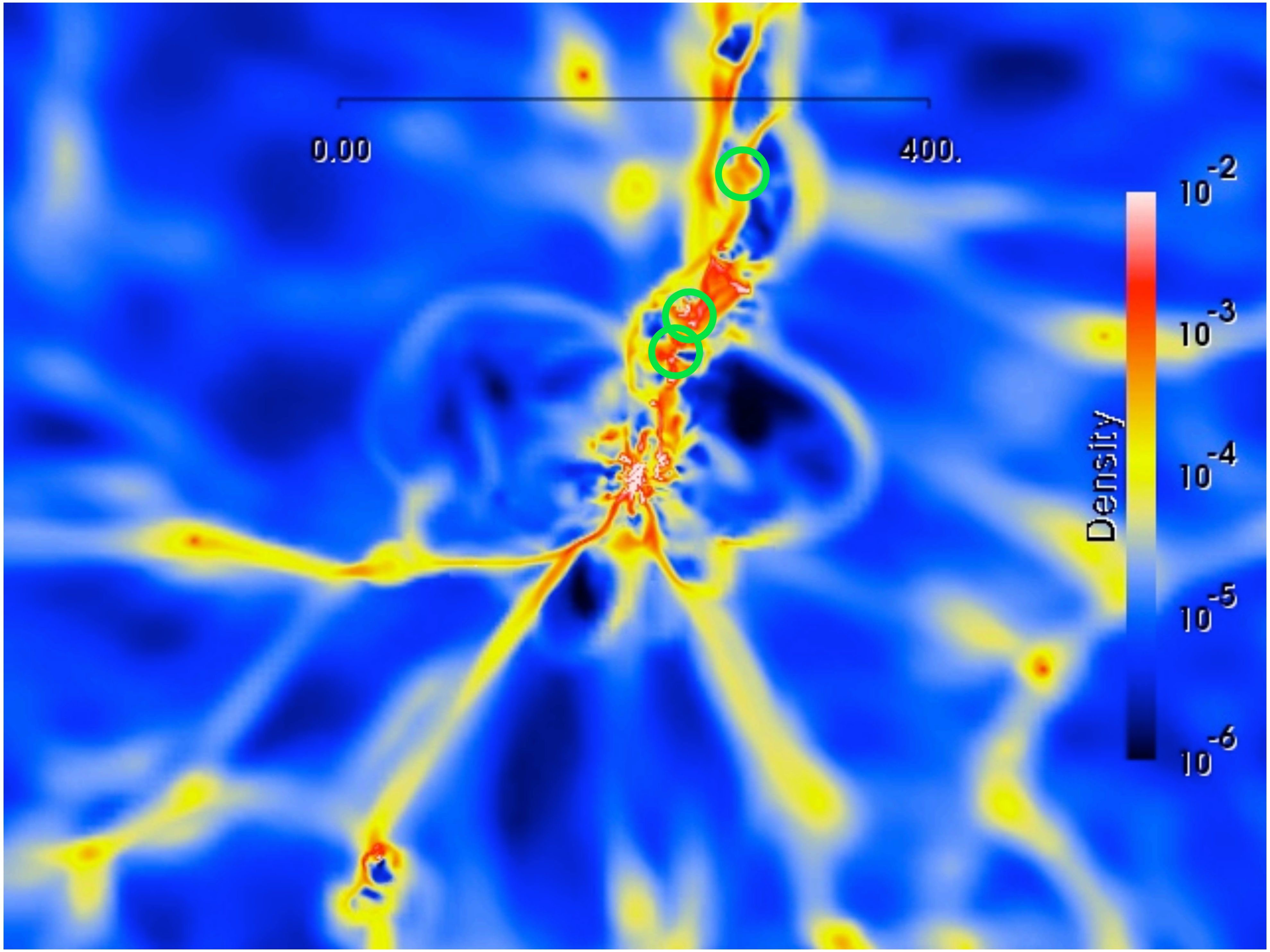

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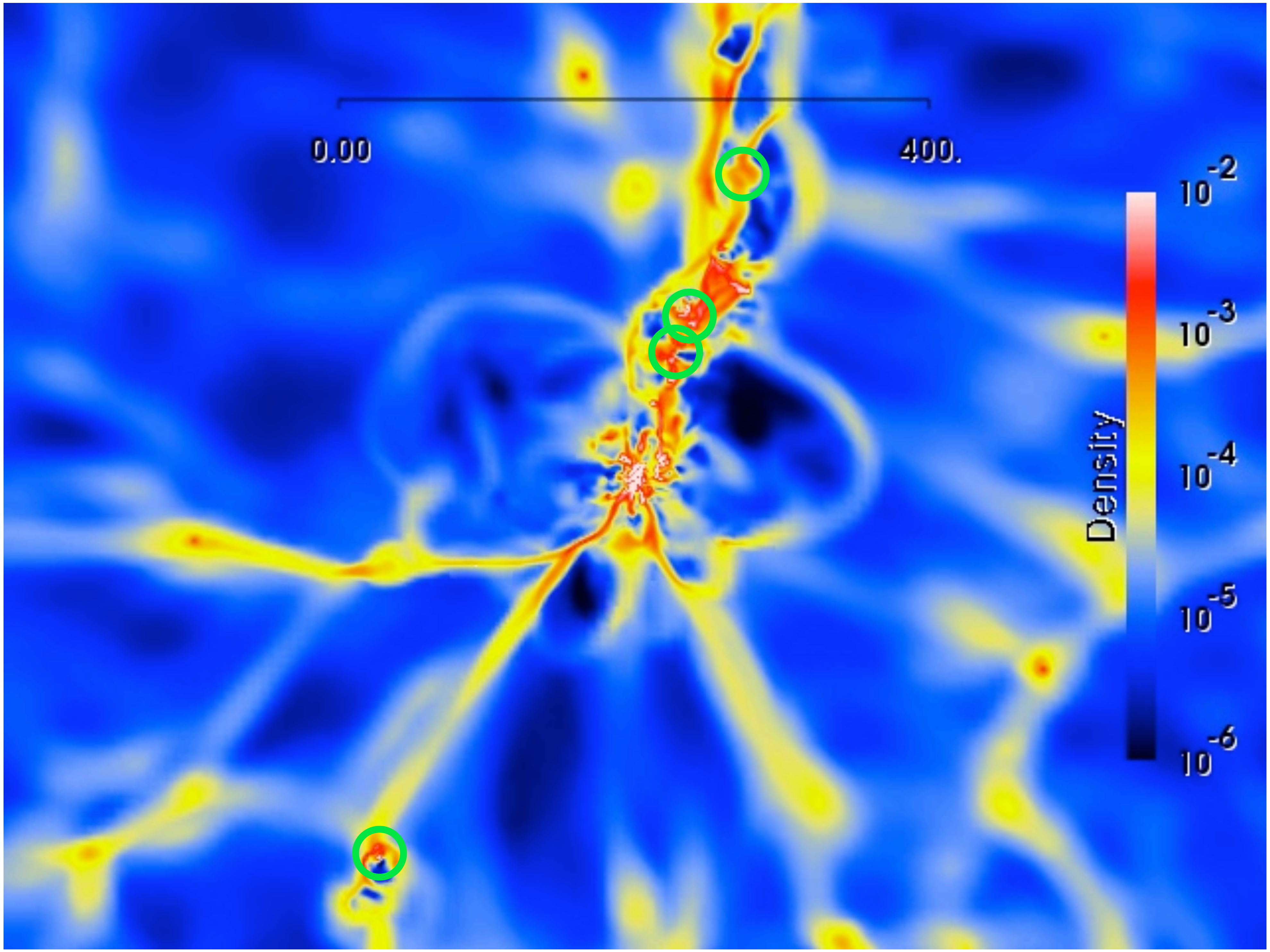

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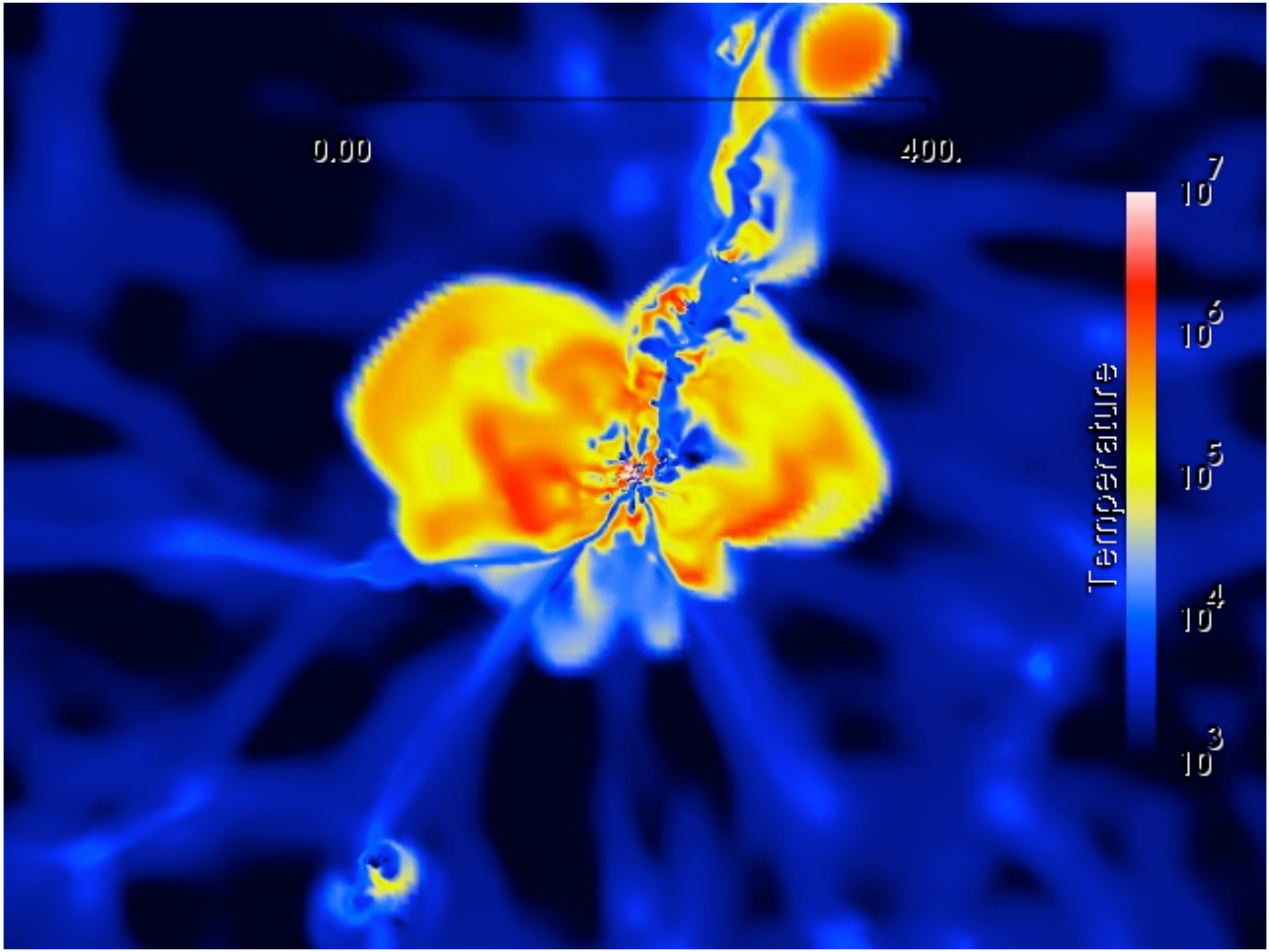


Slice of temperature

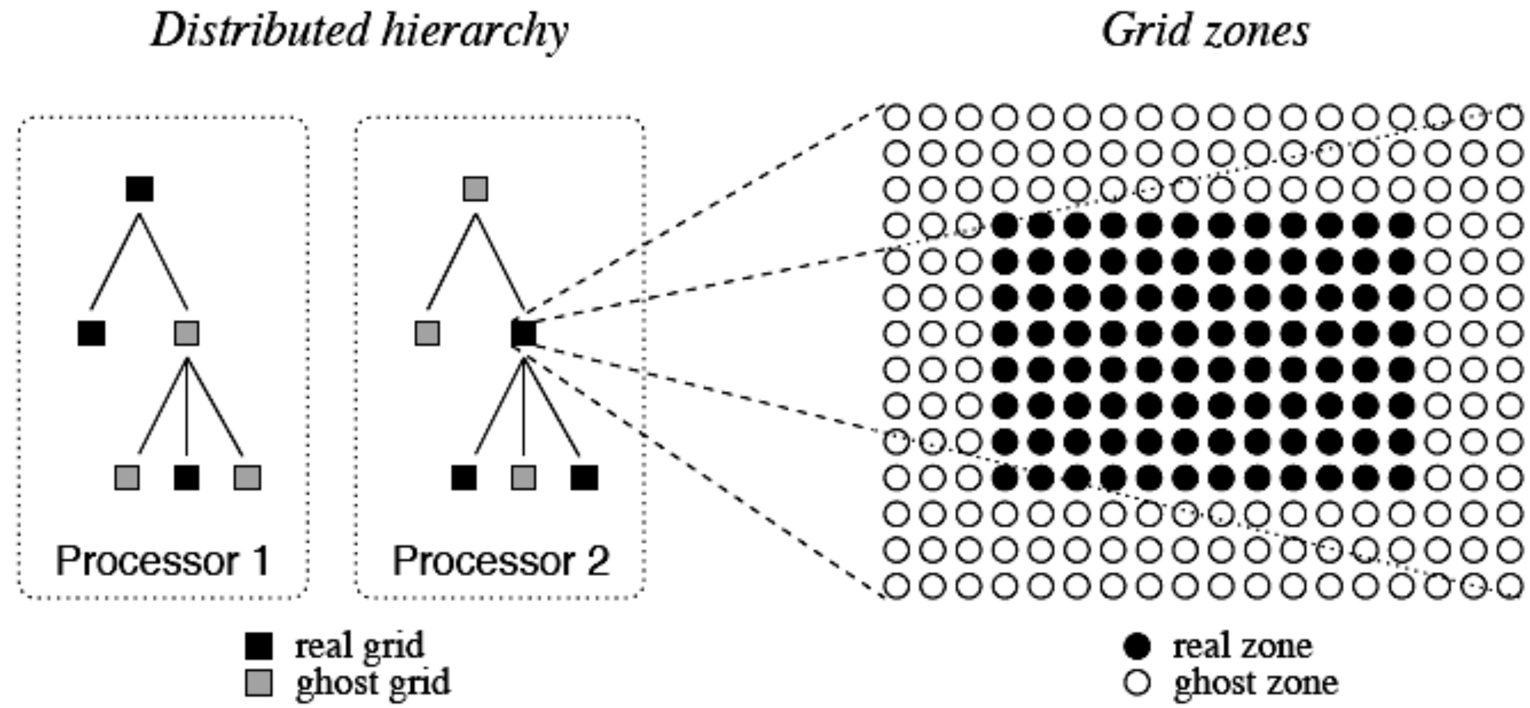
Galaxies in simulations look like real ones

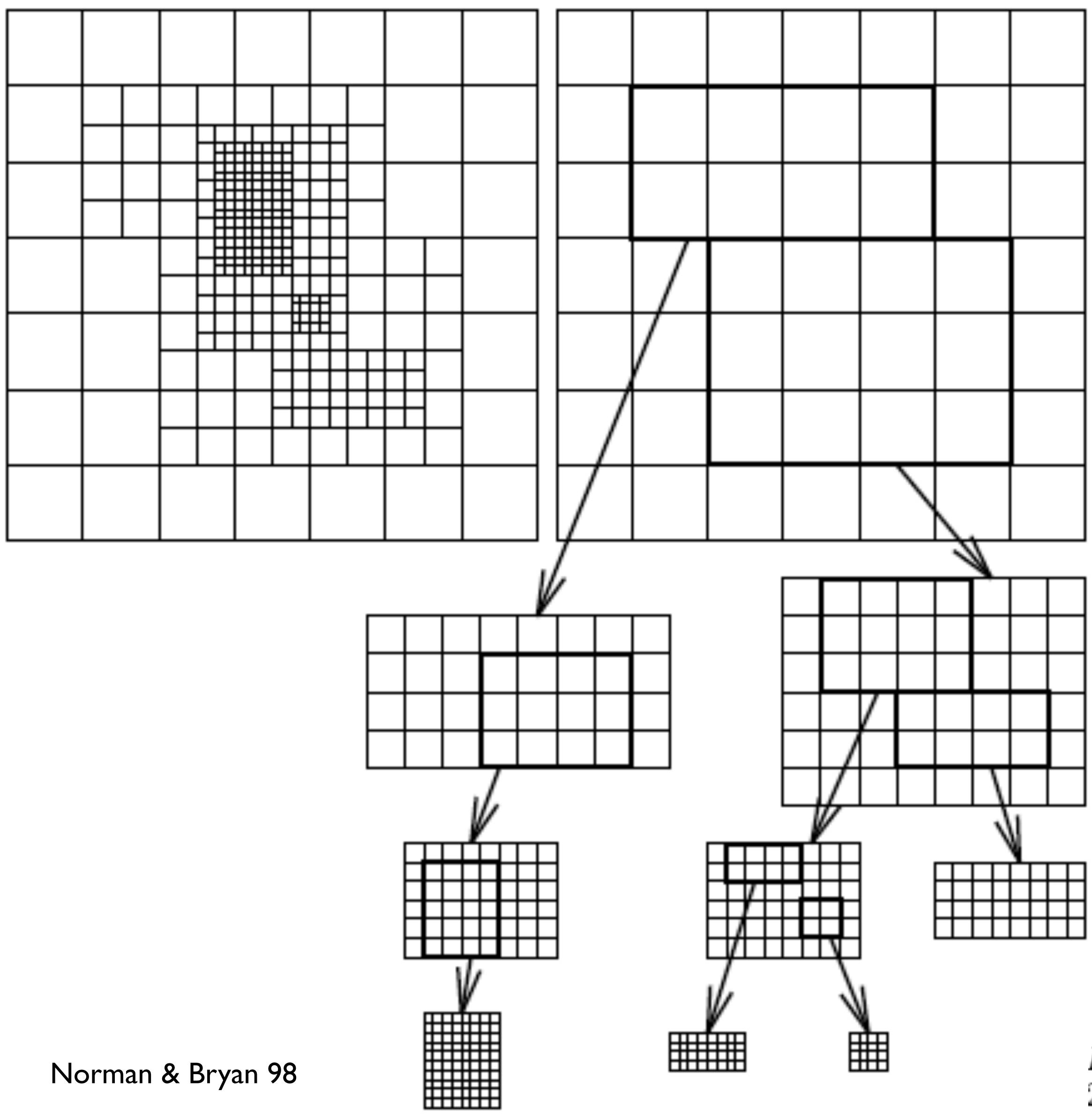
Agertz, Teyssier, Moore 2010

Codes:

Type	Name	Main features	Largest runs
AMR	Enzo	Block splitting, PPM hydro sover MPI parallelization, Shock capturing, C++ and Fortran	64G particles 1000 processors
	ART	Cell splitting, MUSCLE hydro MPI+OpenMP parallelization, Shock capturing all possible combinations of F77/F90/C	N-body: 8G particles,13824 processors Hydro: 10-200pc
	RAMSES	Cell splitting MPI parallelization, Shock capturing F90	64G particles (Horizon run), 20000 processors
TREE	GASOLINE/ PKDGRAV	Tree, MPI, C	1G particles
	GADGET-2	Tree-PM, MPI, C	N-body: 300G particles, 14K cores Hydro: 1G particles, 200-300 pc
analysis	Sunrise	Radiative transfer, AMR	

ENZO: block splitting





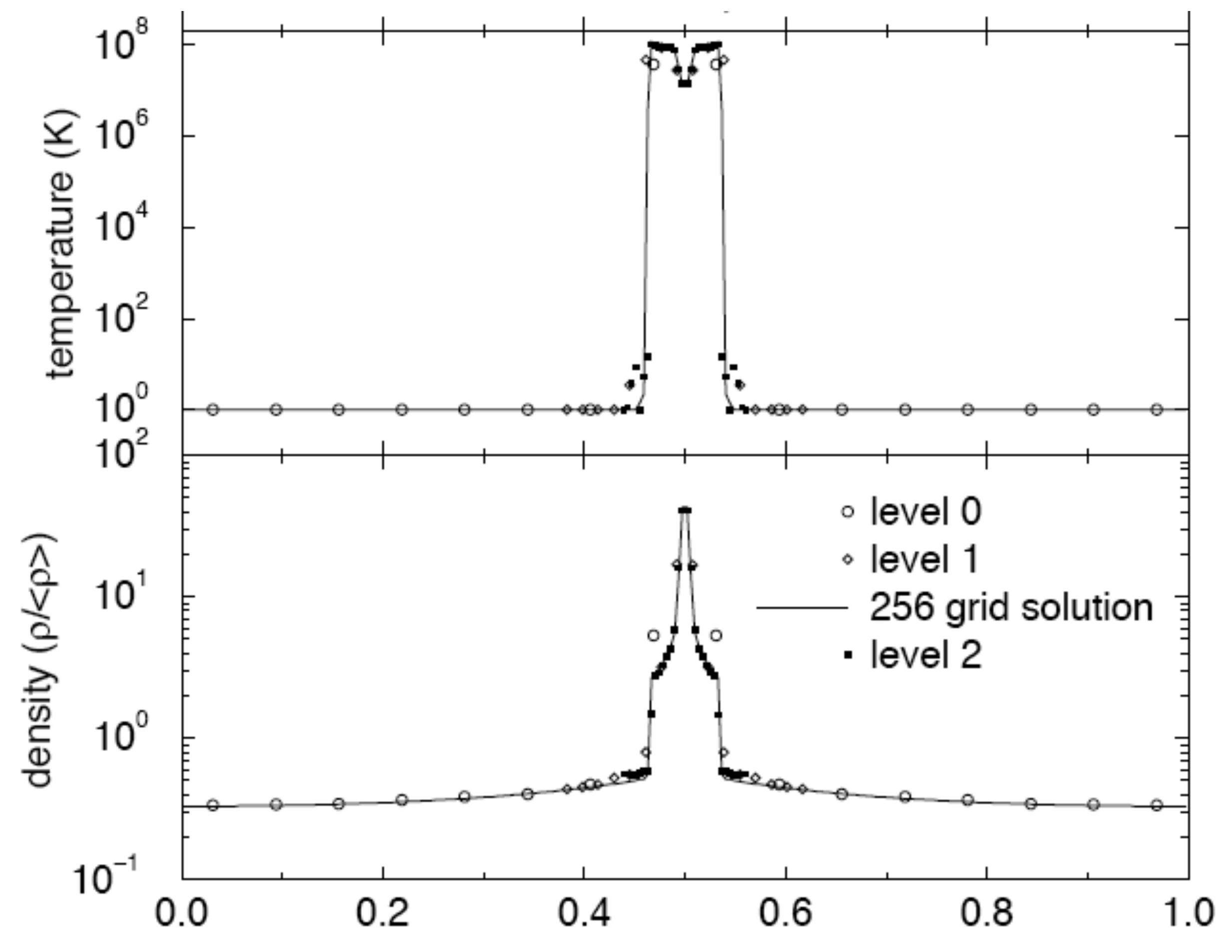
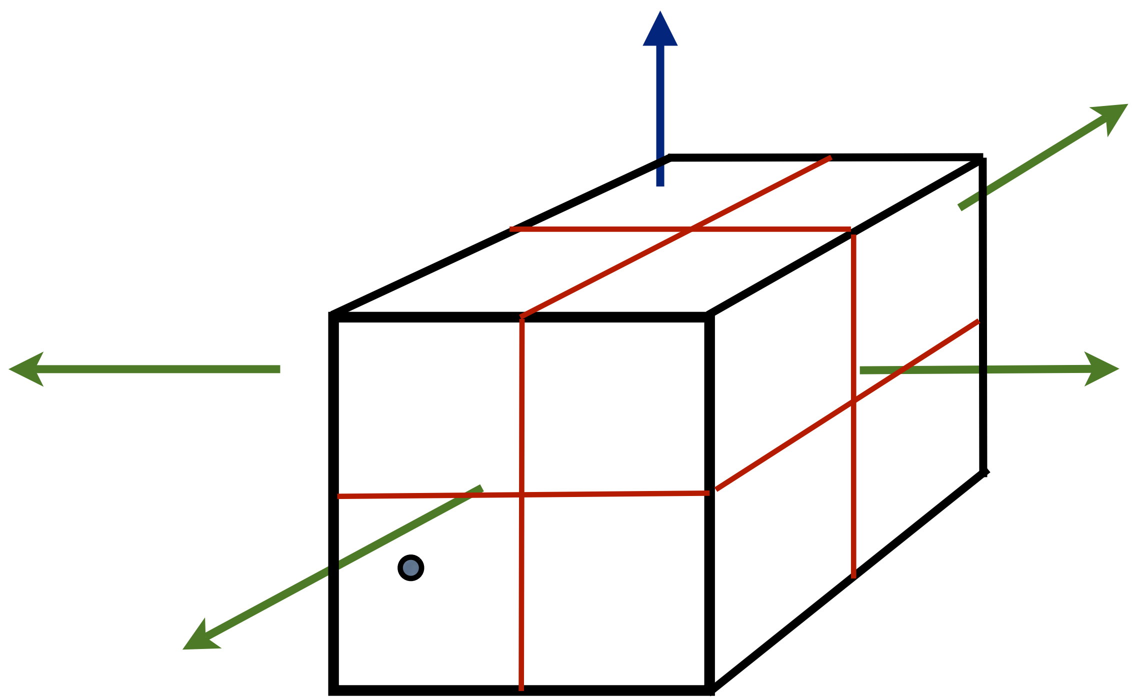


Figure 2. 1D Zeldovich pancake test problem. 3-level solution (symbols) is overlaid on 256 zone uniform grid solution (solid line).

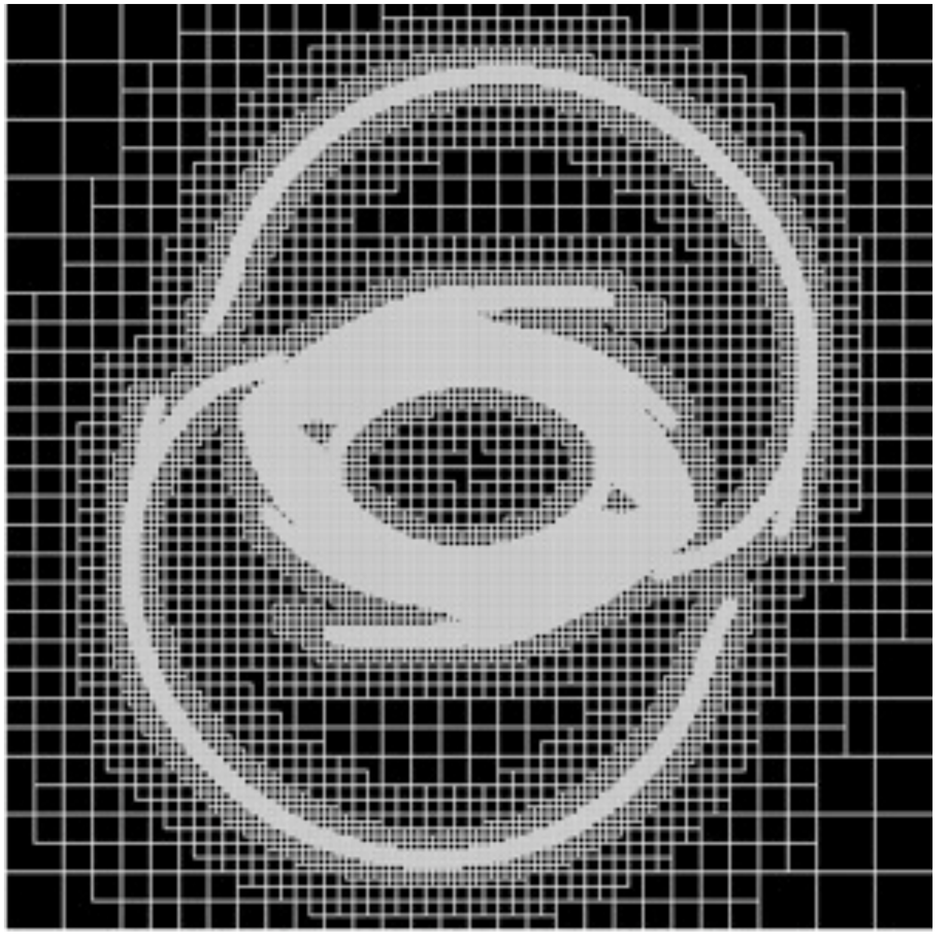
Norman & Bryan 98

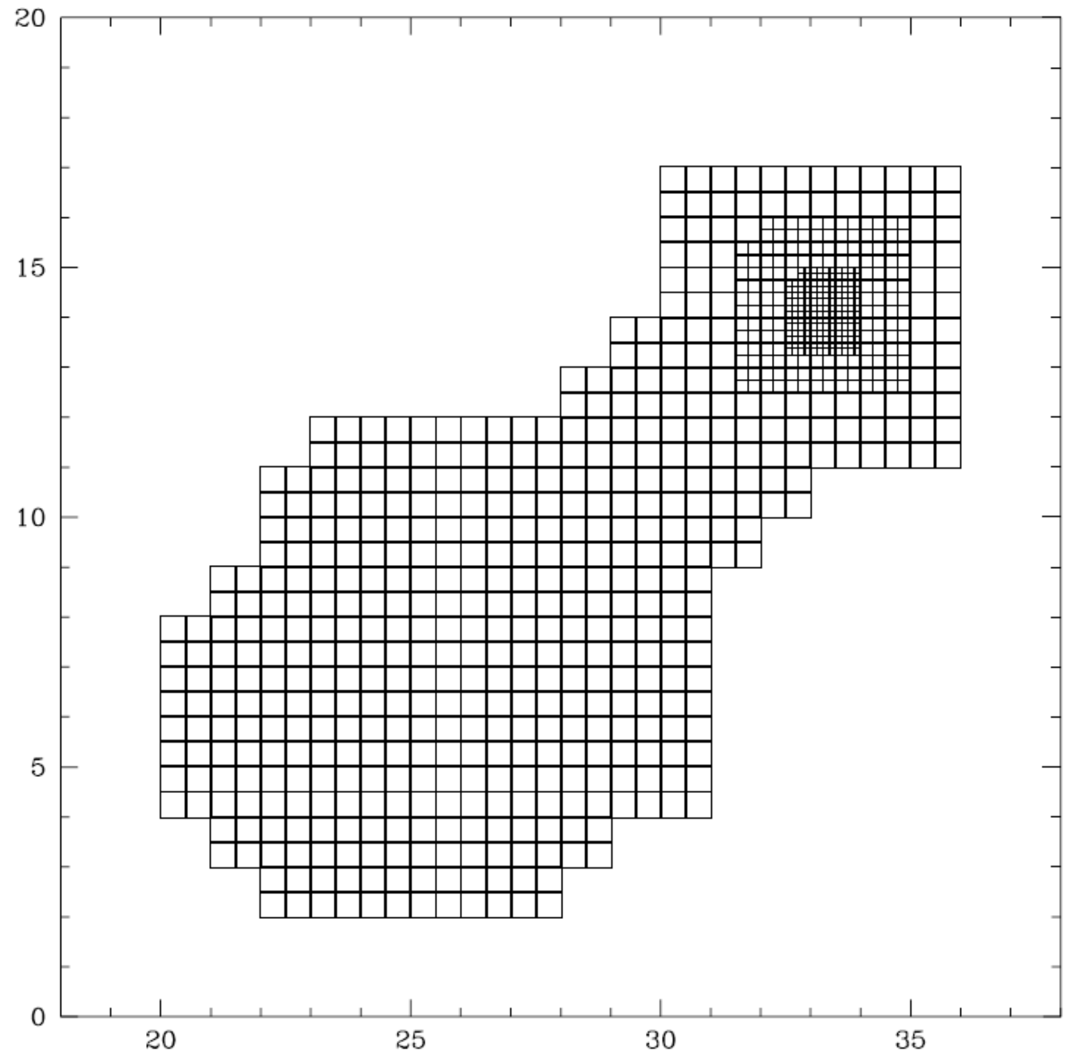
ART/RAMSES: cell splitting



Oct:

- pointers to 6 neighbors
- pointer to parent
-pointer to first child





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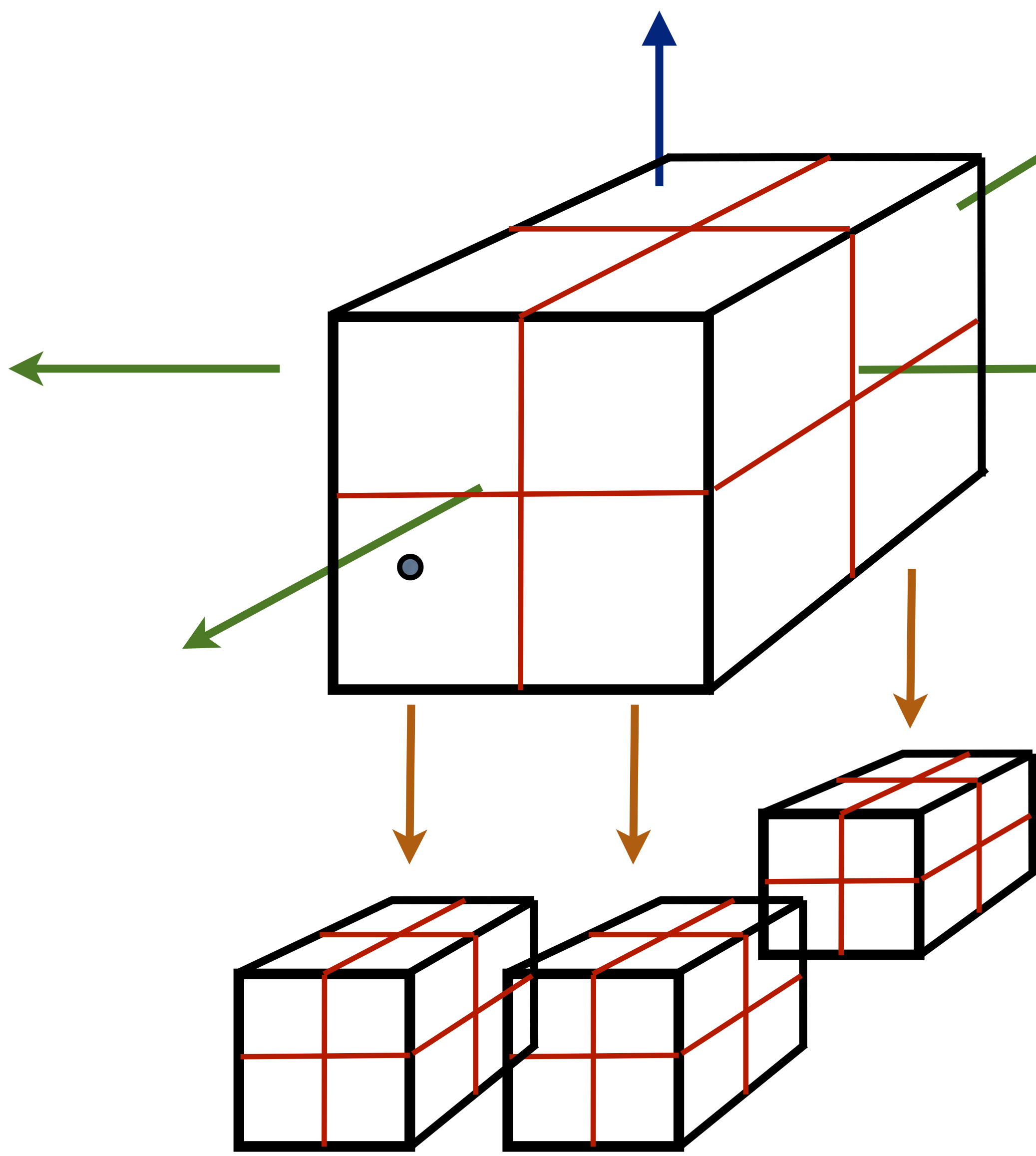

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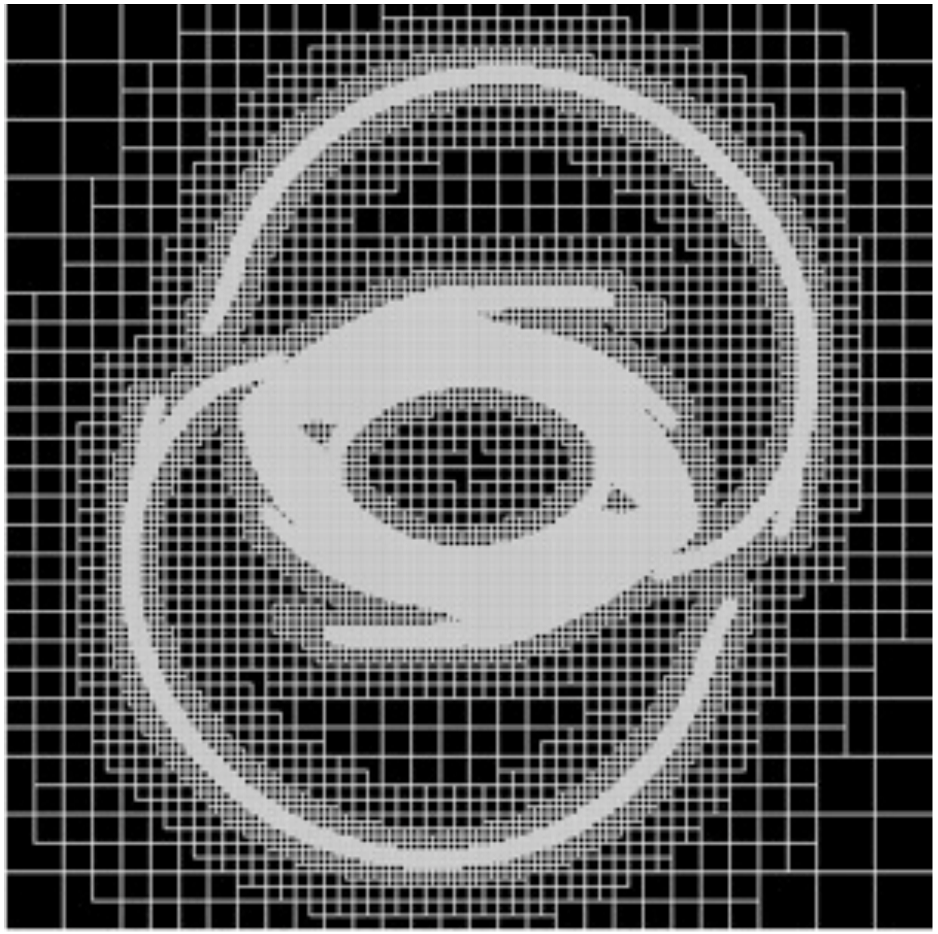

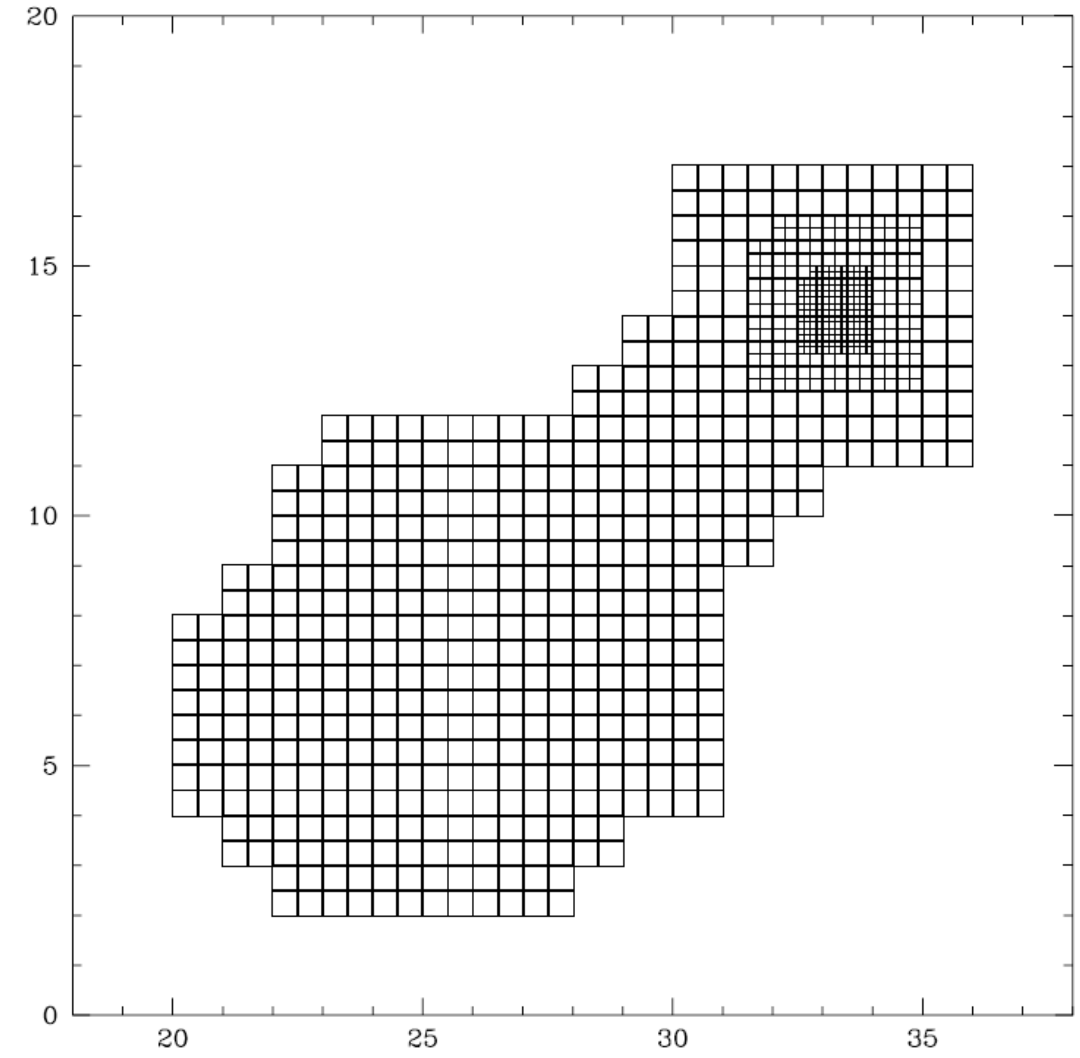

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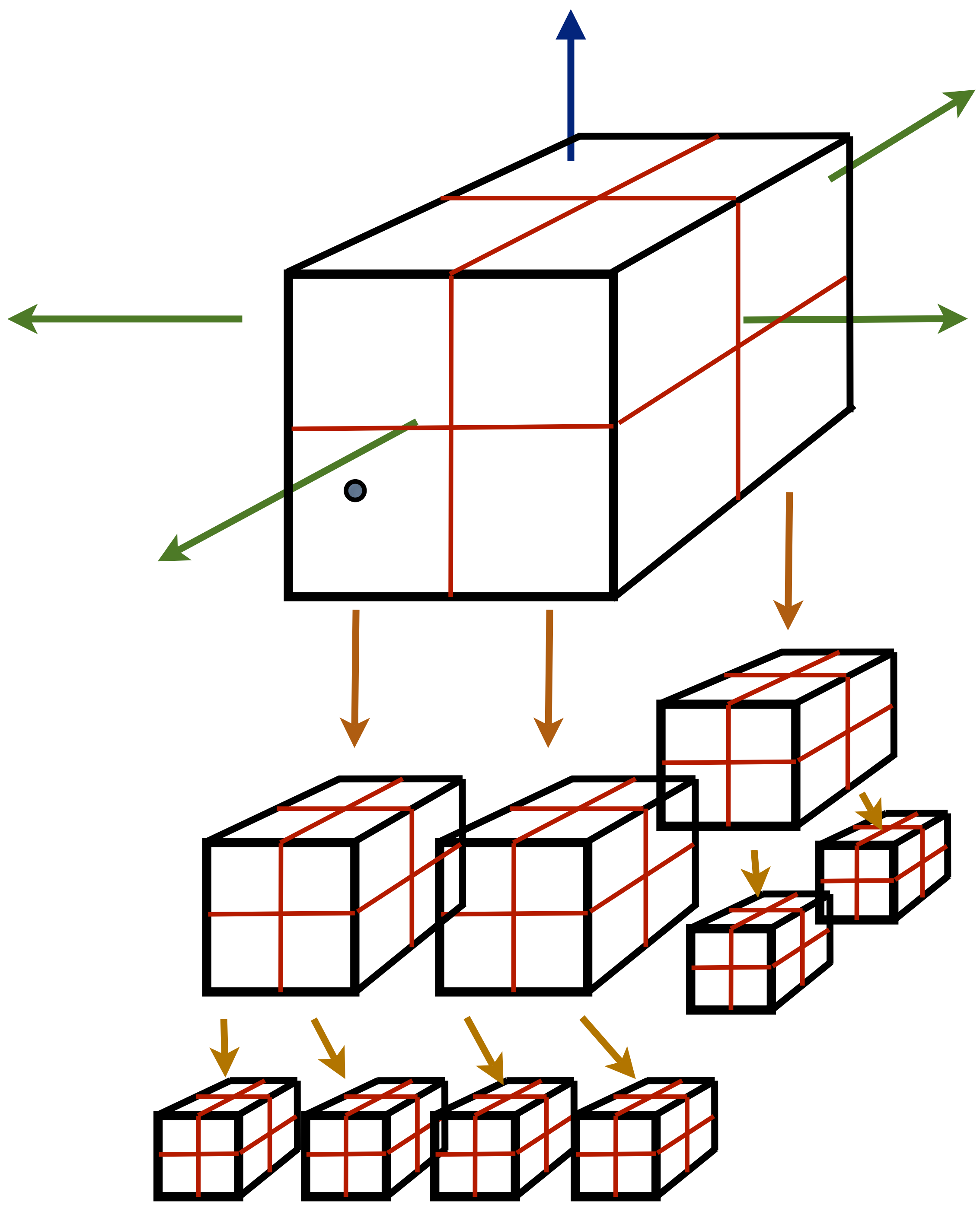

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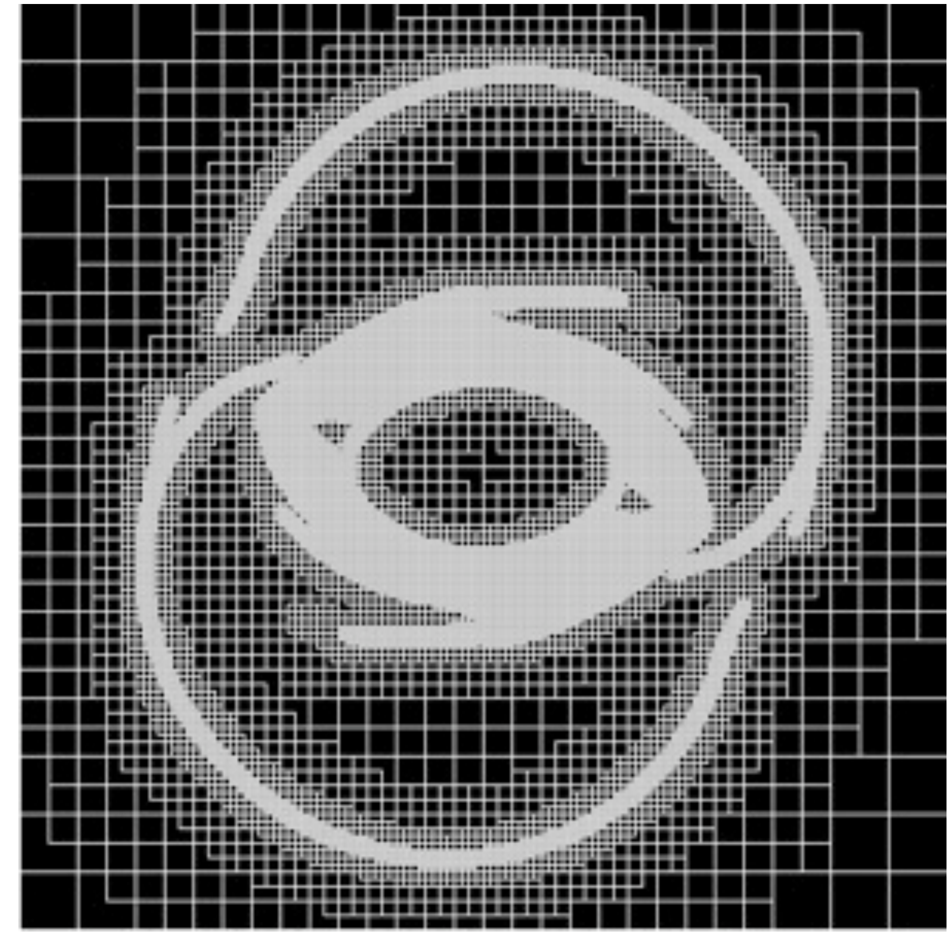
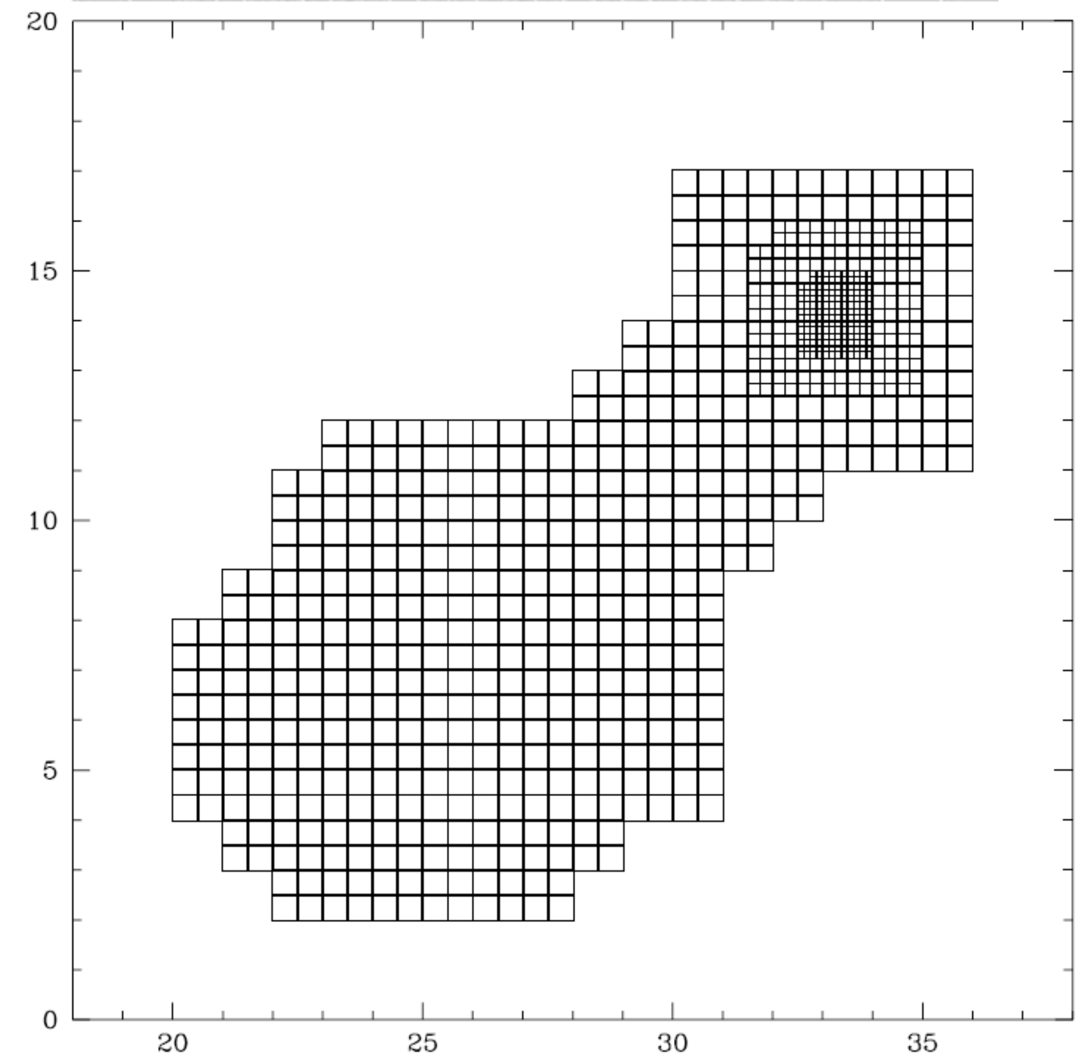




Adaptive Refinement:

Mesh is refined where the density exceeds a given threshold. Other quantity (such as jumps in pressure) can be used as additional condition for refinement. Refinement field defines how refinement is done.

Each cell can be split into 8 new cells, each having twice smaller size. This is ideal for tracing anisotropic structures such as filaments.

Adjacent cells can differ not more than by one level

Time-step decreases by factor two with each level

ARTistic family

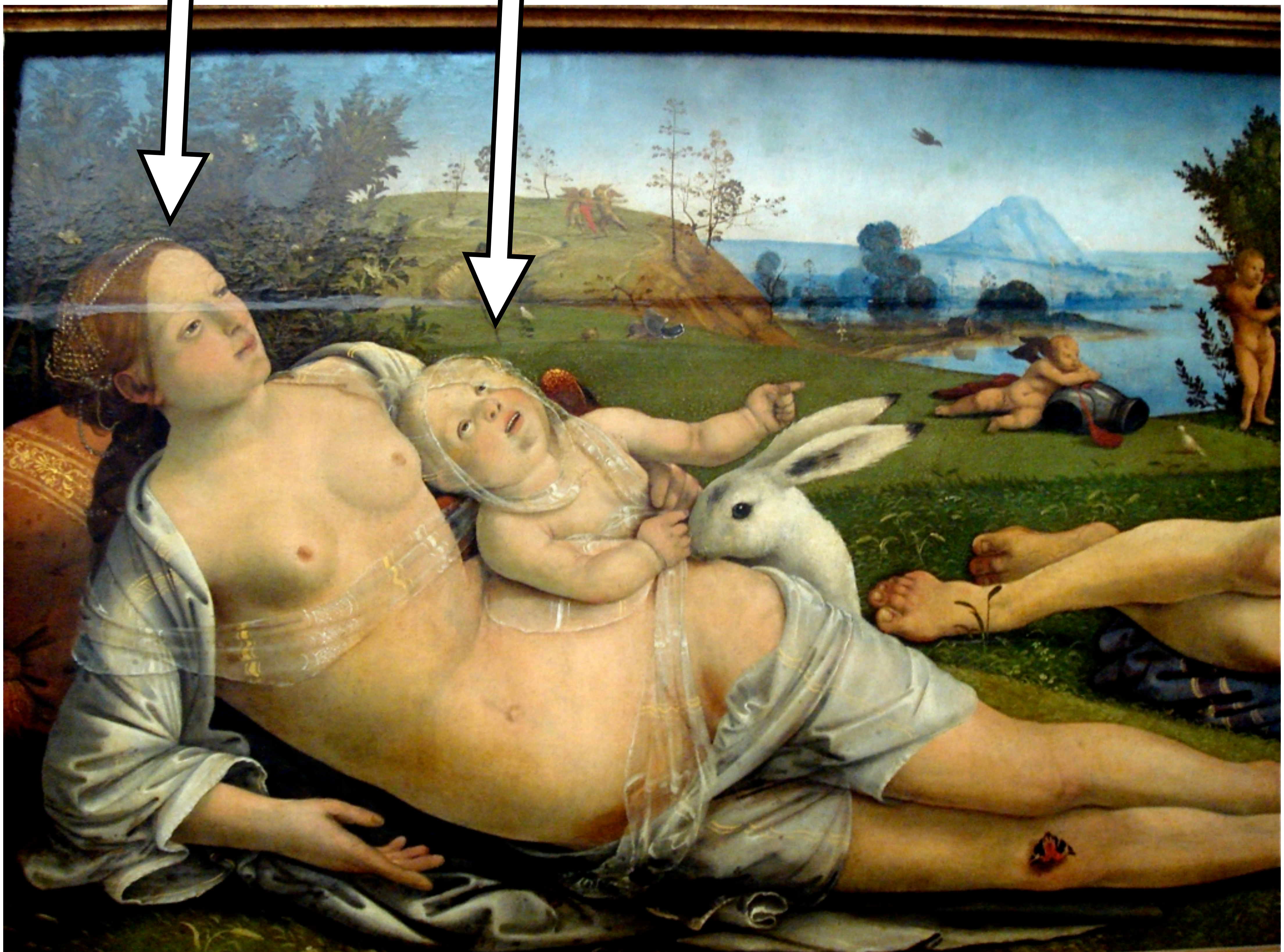
ARTistic family

ART N-body code

ARTistic family

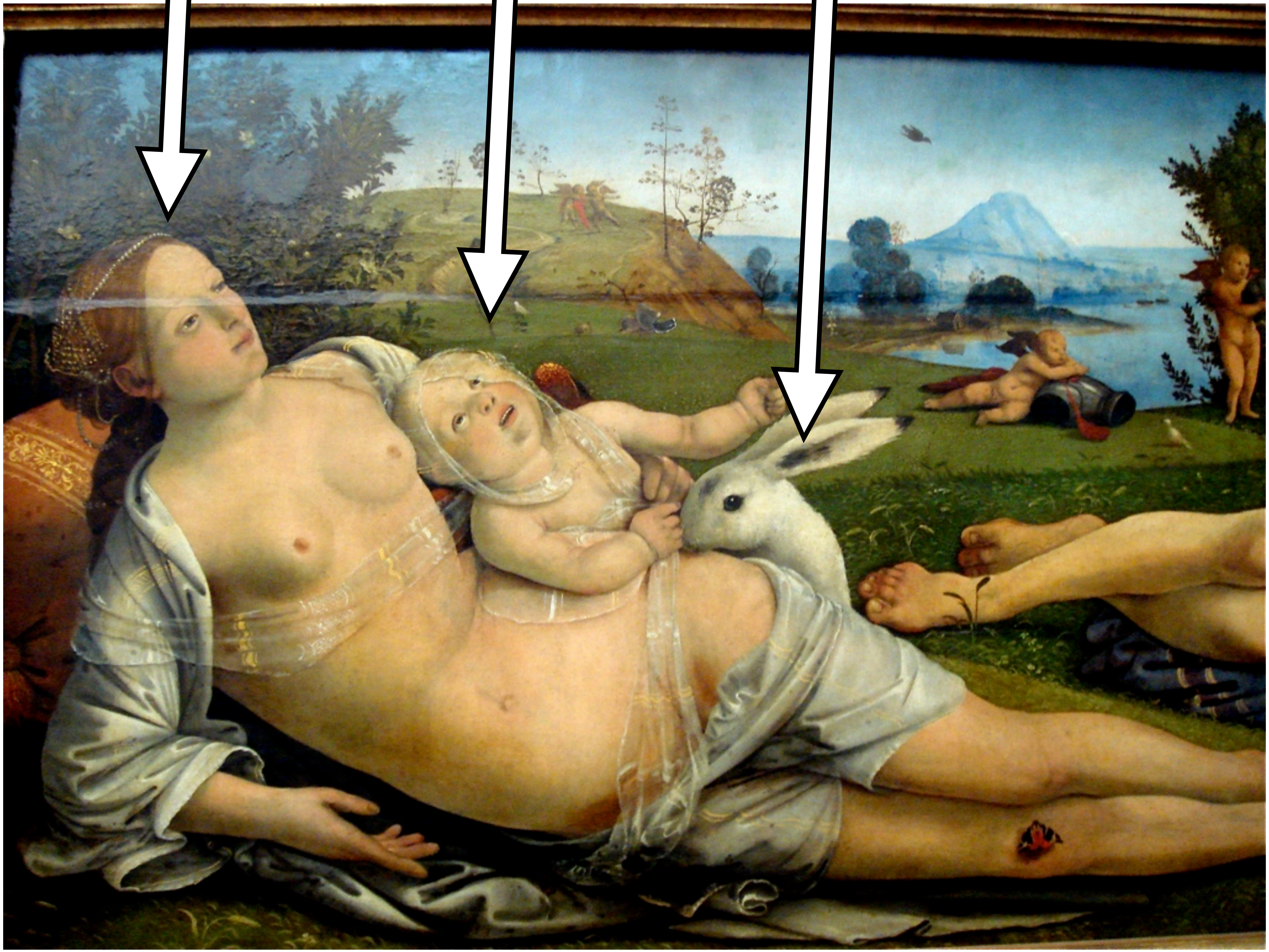
ART N-body code

baby ART hydro



ARTistic family

ART N-body code baby ART hydro rabbit ART hydro



History:

- Particle-Mesh (PM): 1980, Klypin & Shandarin
- Adaptive Mesh Refinement (AMR) with irregular mesh: 1996, Khokhlov
- N-body ART: 1997, Kravtsov, Klypin, Khokhlov
- Hydro OpenMP: 2000 Kravtsov, Khokhlov
- Hydro MPI: 2005 Rudd, Kravtsov
- Radiative Transfer: 2004-5, Gnedin, Kravtsov

ART: gravity

Poisson equation

$$\nabla^2\phi = \rho$$

$$\frac{\partial\phi}{\partial\tau} = \nabla^2\phi - \rho$$

Diffusion equation with fake time: stationary solution is the Poisson equation

$$\phi^{n+1}_{i,j,k} = \phi^{n}_{i,j,k} + \frac{\Delta\tau}{\Delta^2}\left(\sum_{\mathrm{nb}=1}^{6}\phi^{n}_{\mathrm{nb}} - 6\phi^{n}_{i,j,k}\right) - \rho_{i,j,k}\Delta\tau$$

$$\phi^{n+1}_{i,j,k} = \frac{1}{6}\left(\sum_{\mathrm{nb}=1}^{6}\phi^{n}_{\mathrm{nb}} - 6\phi^{n}_{i,j,k}\right) - \frac{\Delta^2}{6}\rho_{i,j,k}$$

$$\phi^{n+1}_{*}\Big| = \omega\phi^{n+1} + (1-\omega)\phi^{n}$$

ART: time-stepping

equations

$$\frac{d\mathbf{p}}{dt} = -\nabla_x \phi \ , \quad \frac{d\mathbf{x}}{dt} = \frac{\mathbf{p}}{a^2}$$

$$\nabla_x^2 \phi = 4\pi G a^2 (\rho - \overline{\rho})$$

$$\frac{d\tilde{\mathbf{p}}}{da} = -f(\Omega_M, \Omega_\Lambda, a)\tilde{\nabla}\tilde{\phi} \ ,$$

$$\frac{d\tilde{\mathbf{x}}}{da} = f(\Omega_M, \Omega_\Lambda, a)\, \frac{\tilde{\mathbf{p}}}{a^2} \ ,$$

$$\tilde{\nabla}^2\tilde{\phi} = \frac{3\Omega_M}{2a}\,(\tilde{\rho} - 1) \ .$$

$$f(\Omega_M, \Omega_\Lambda, a) = \frac{1}{\sqrt{1 + \Omega_M(1/a - 1) + \Omega_\Lambda(a^2 - 1)}} \ .$$

dimensionless variables

$$\mathbf{x} = x_0 \tilde{\mathbf{x}} \ , \quad t = \tilde{t}/H_0 \ , \quad \phi = \tilde{\phi}(x_0 H_0)^2 \ ,$$

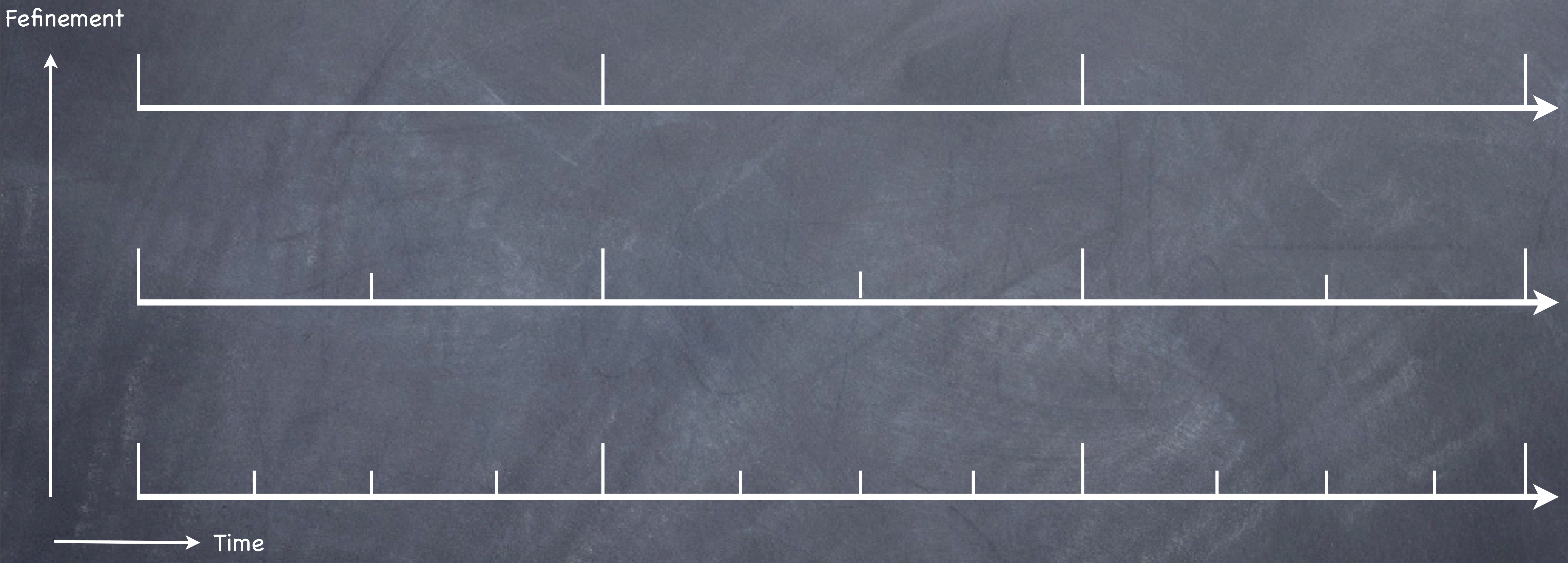
$$p = \tilde{p}(x_0 H_0) \ , \quad \rho = \tilde{\rho}\,\frac{3H_0^2}{8\pi G}\,\frac{\Omega_M}{a^3} \ ,$$

leap-frog scheme

$$\tilde{\mathbf{p}}_{n+1/2} = \tilde{\mathbf{p}}_{n-1/2} - f(\Omega_M, \Omega_\Lambda, a_n)\tilde{\nabla}\tilde{\phi}_n \Delta a \ ,$$

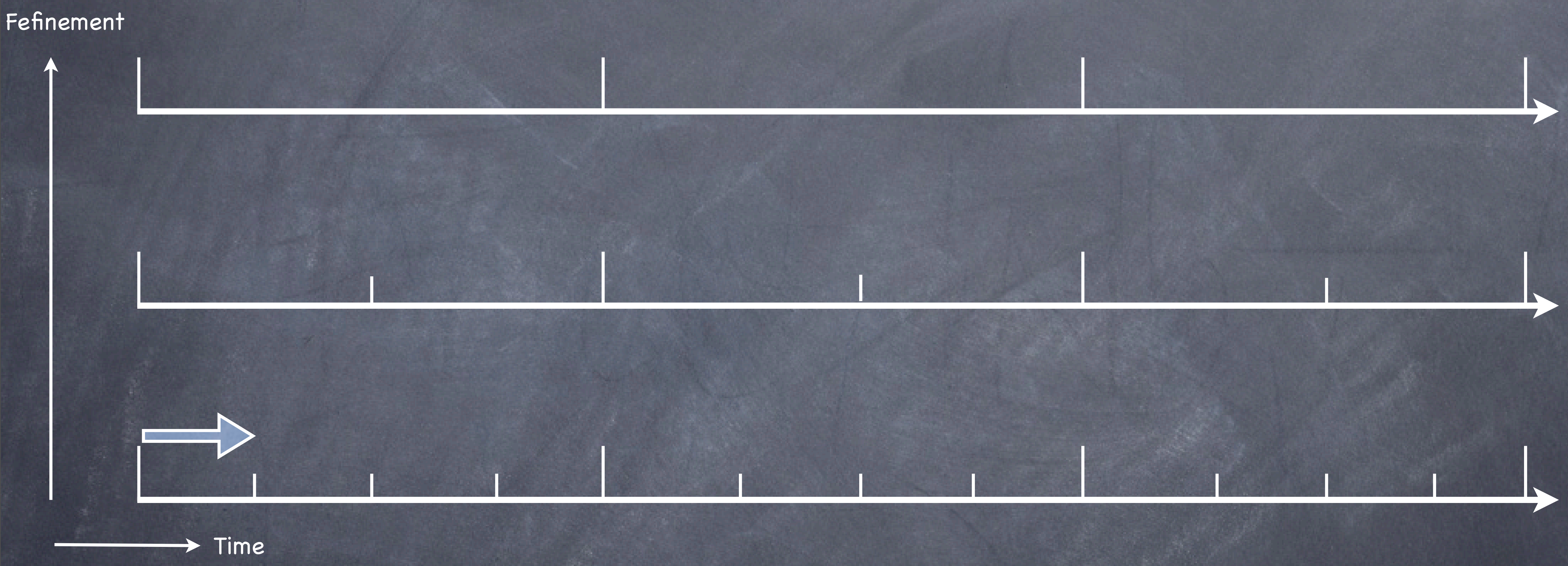
$$\tilde{\mathbf{x}}_{n+1} = \tilde{\mathbf{x}}_n + f(\Omega_M, \Omega_\Lambda, a_{n+1/2})\,\frac{\tilde{\mathbf{v}}_{n+1/2}}{a_{n+1/2}^2}\,\Delta a$$

Time stepping



Refinement structure is rebuild every zero-level time step.

Time stepping



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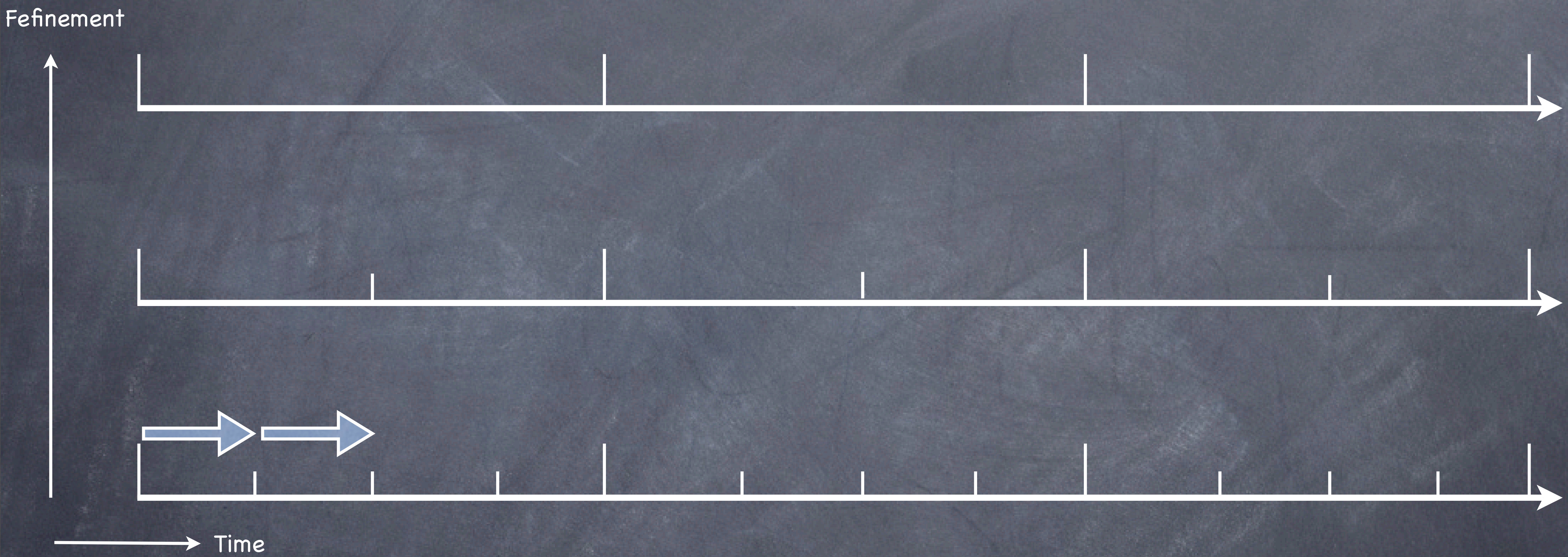

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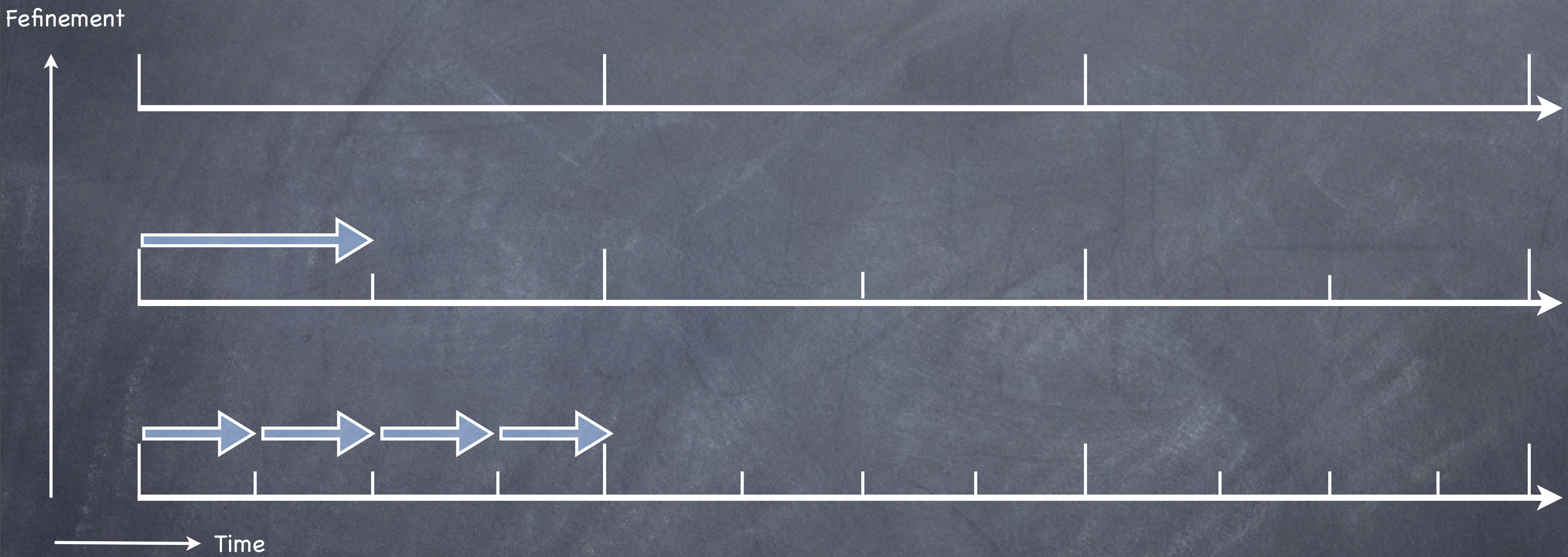

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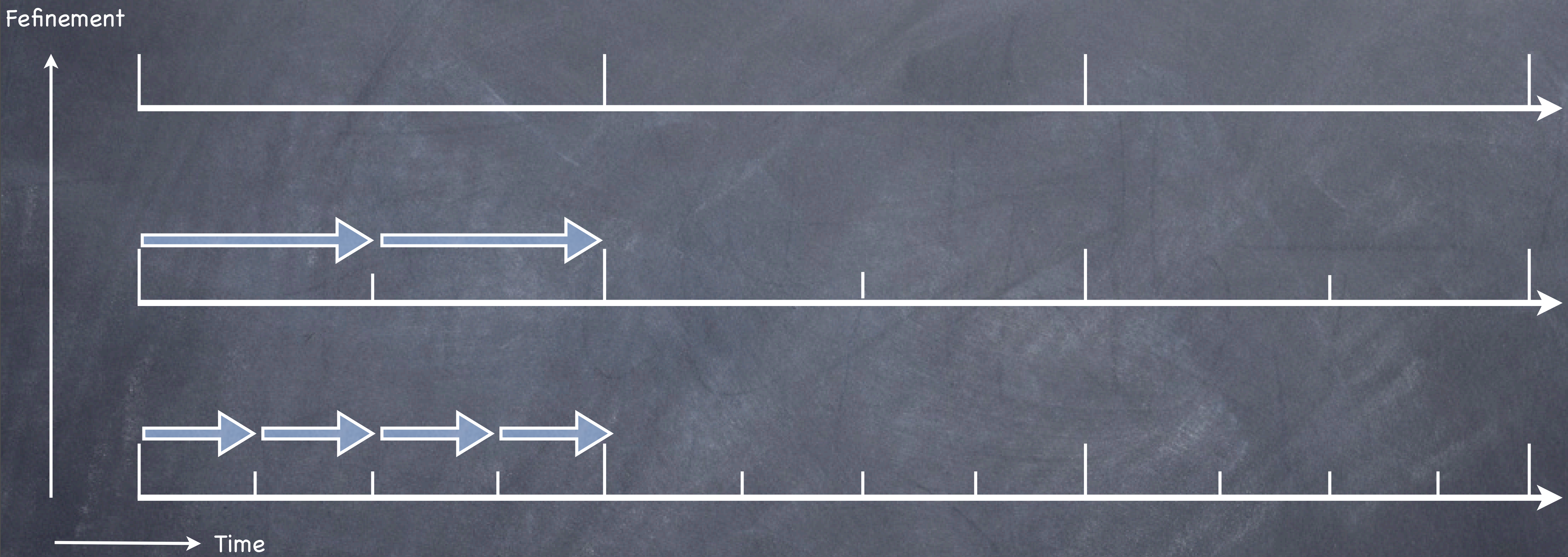

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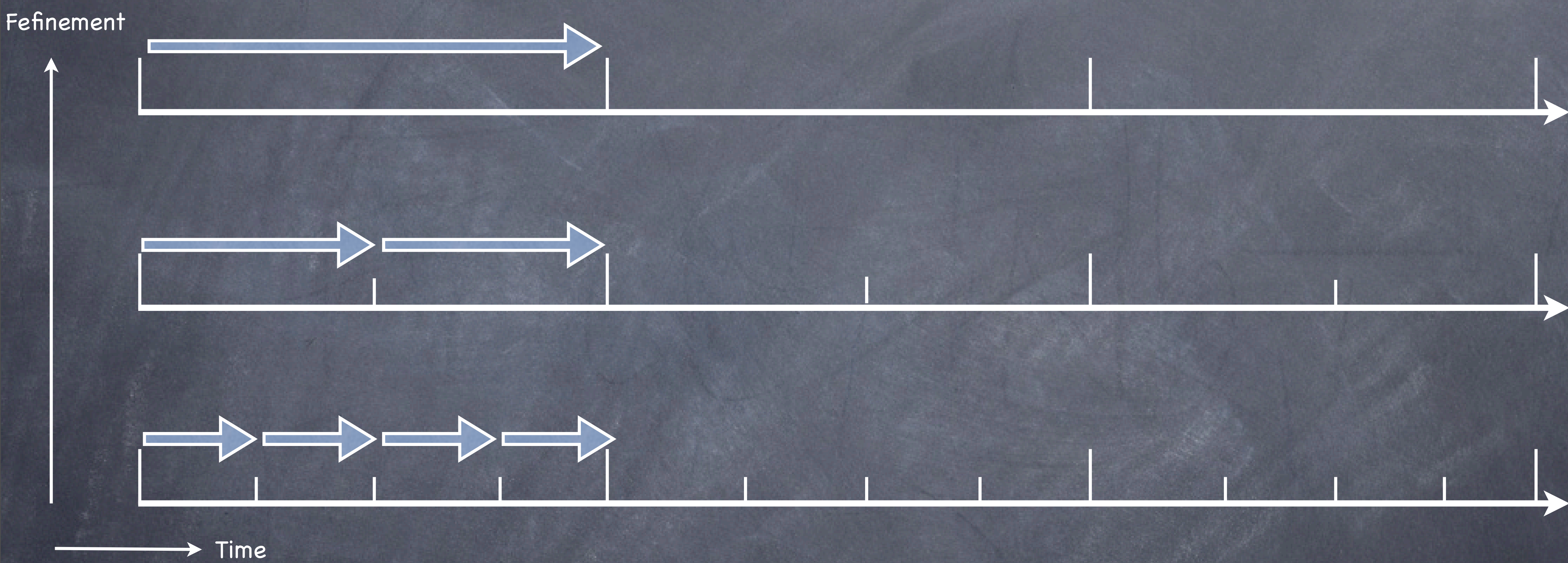

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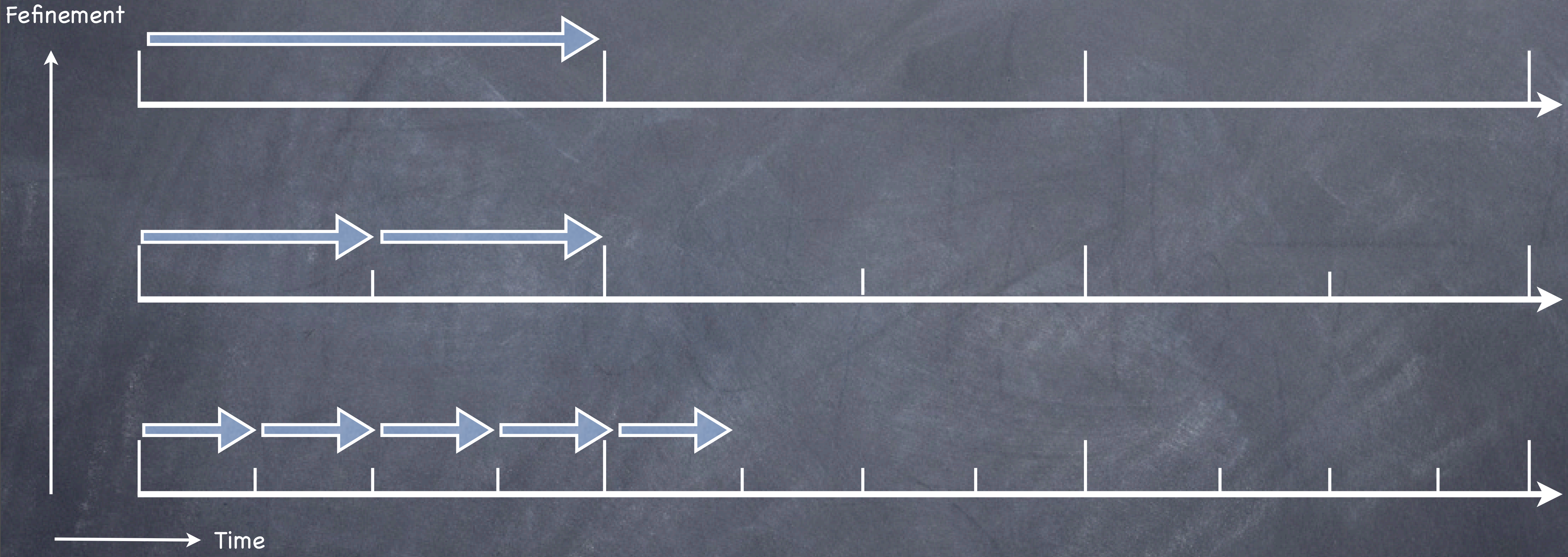

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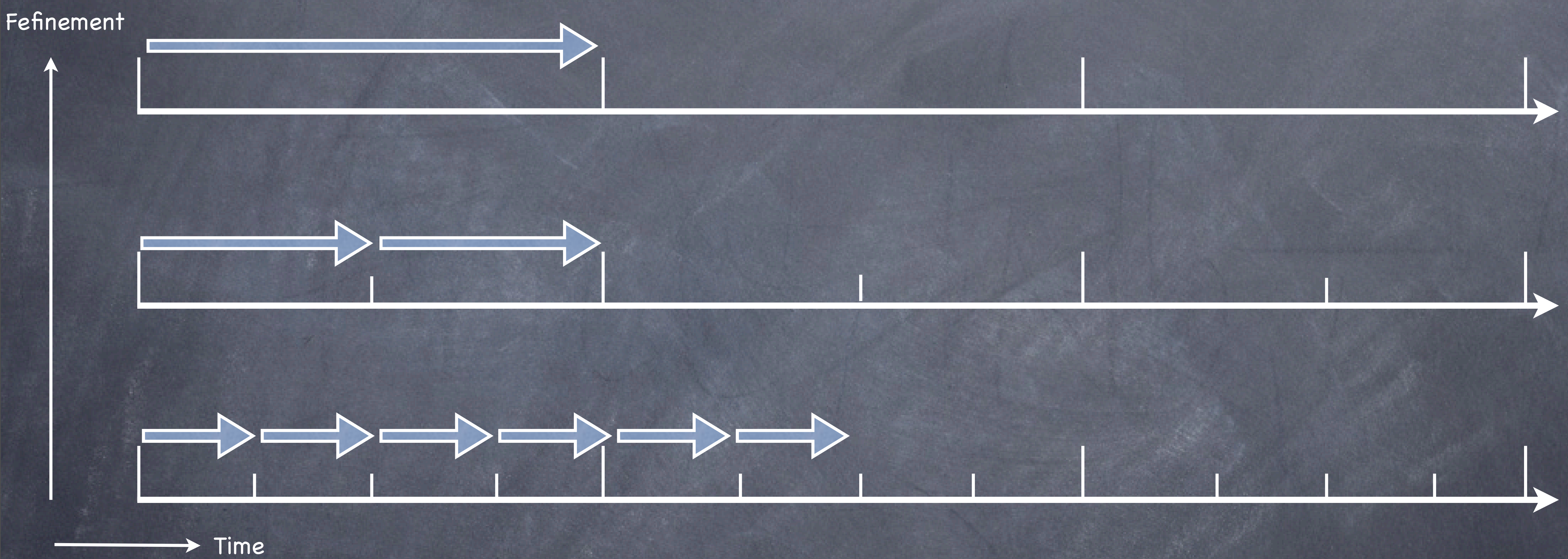

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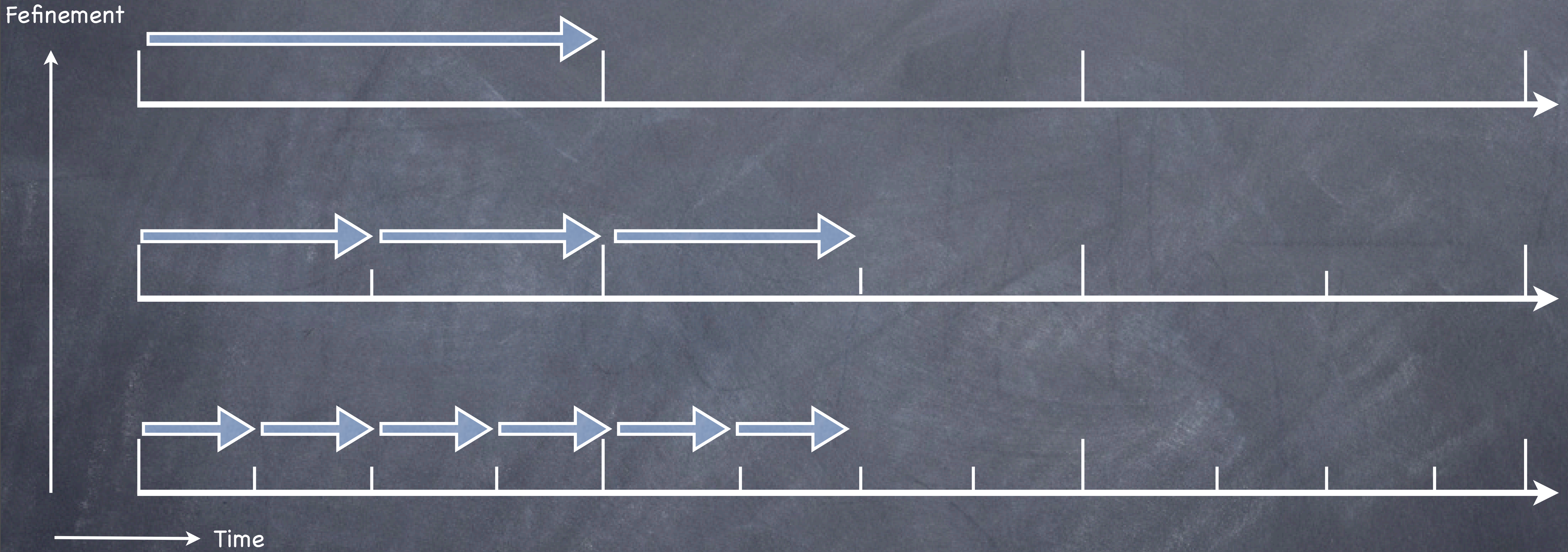

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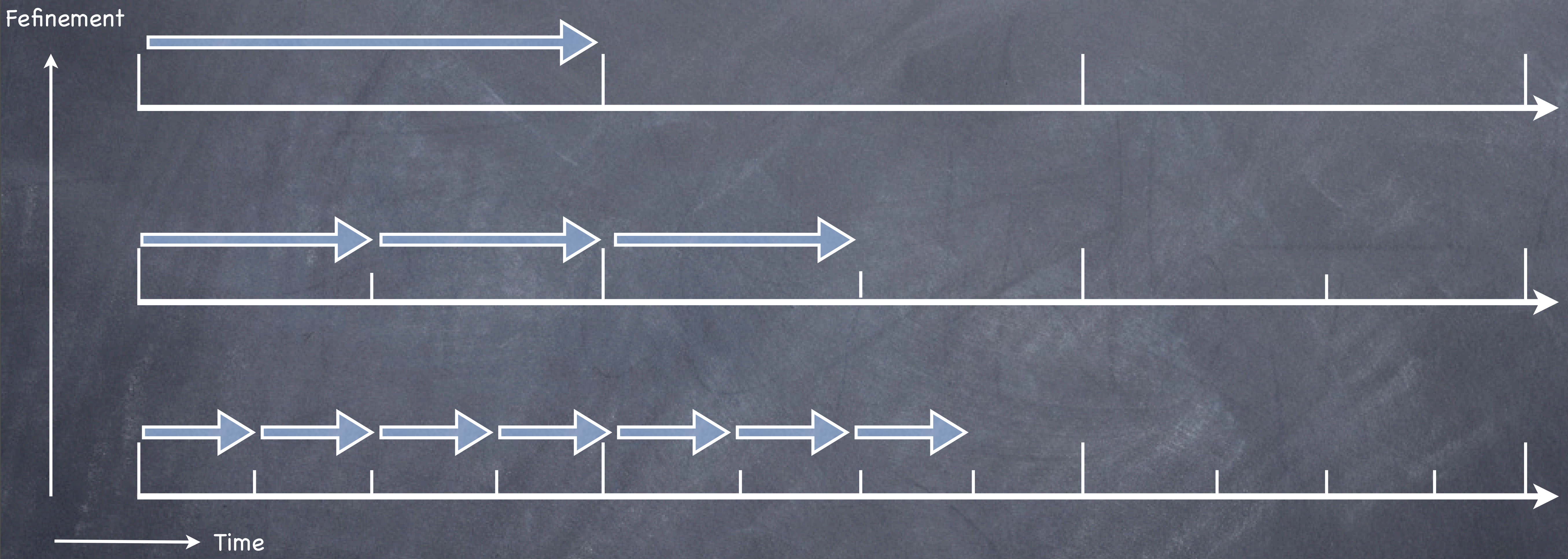

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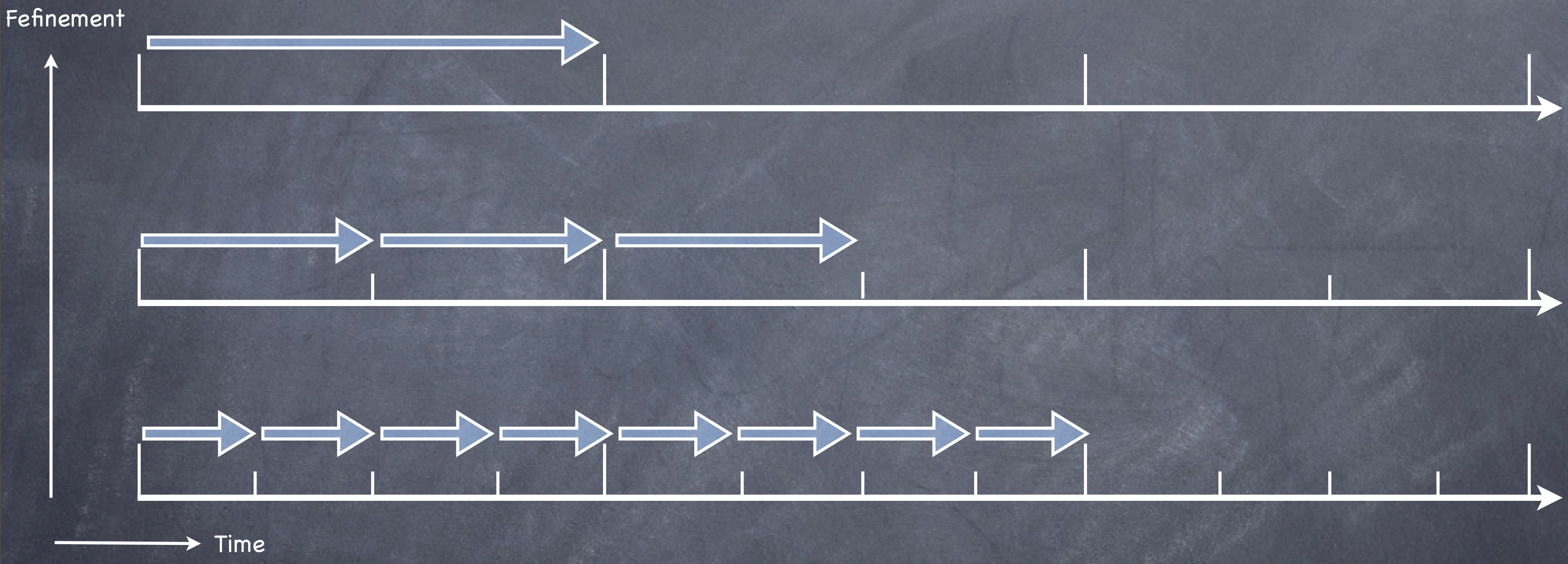

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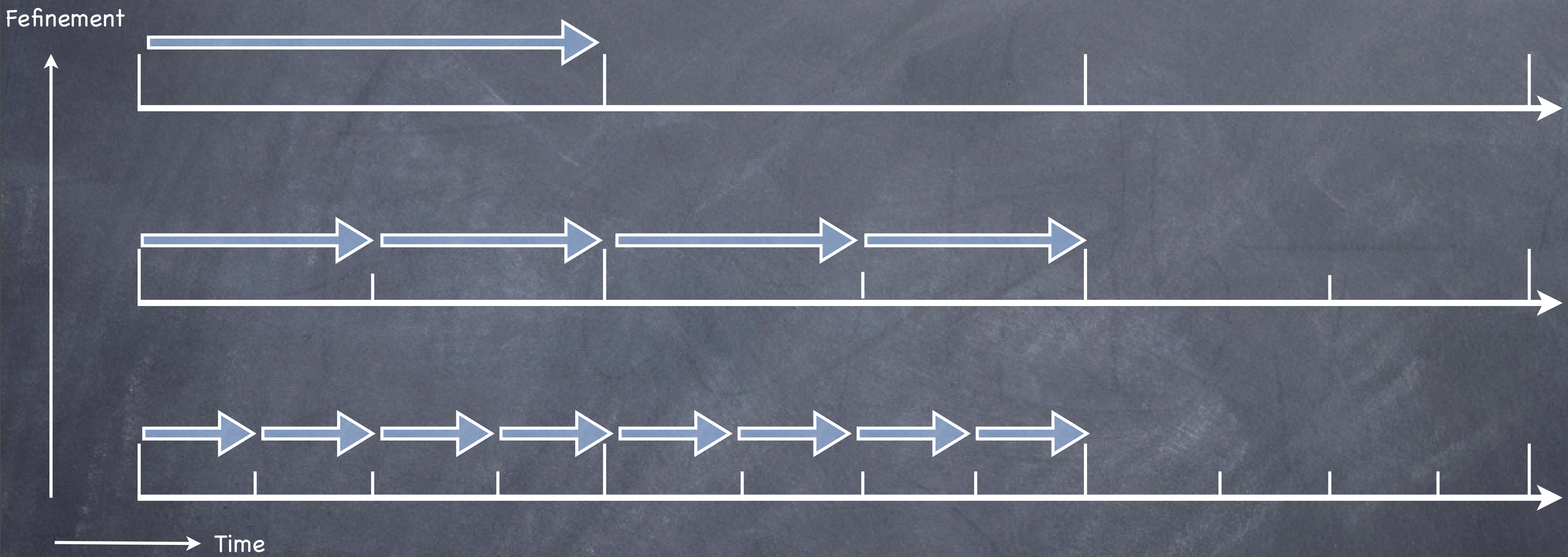

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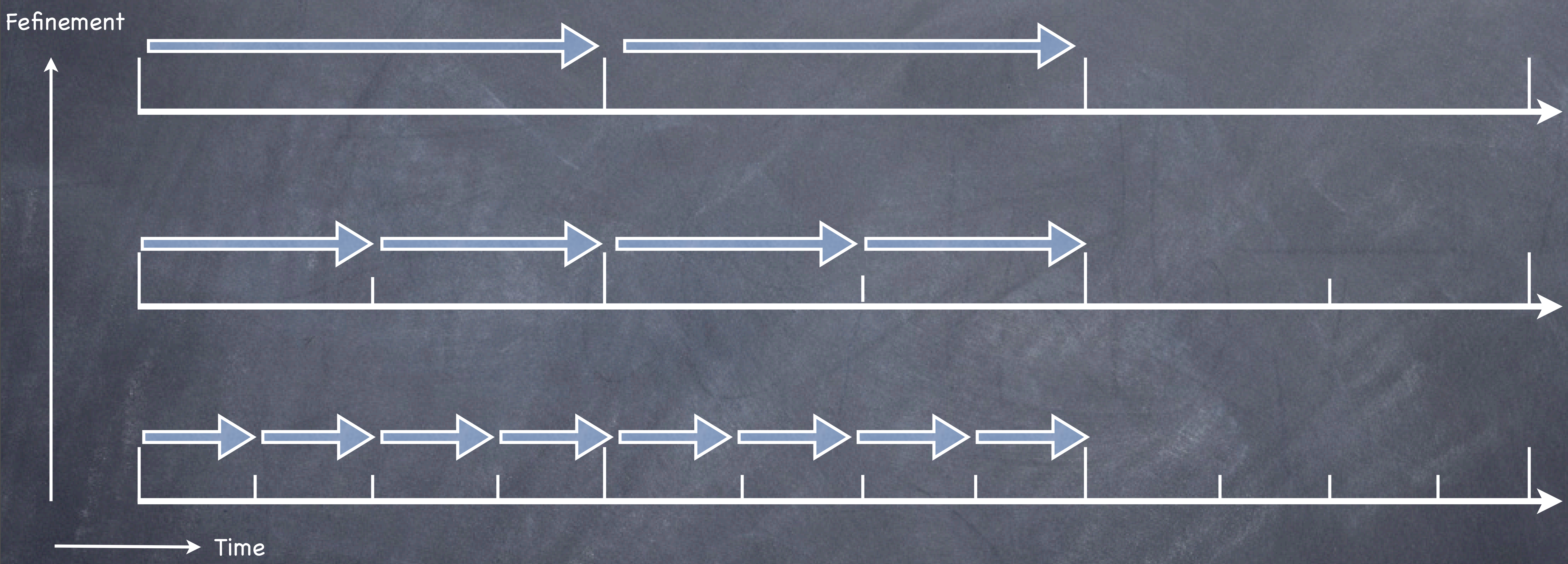

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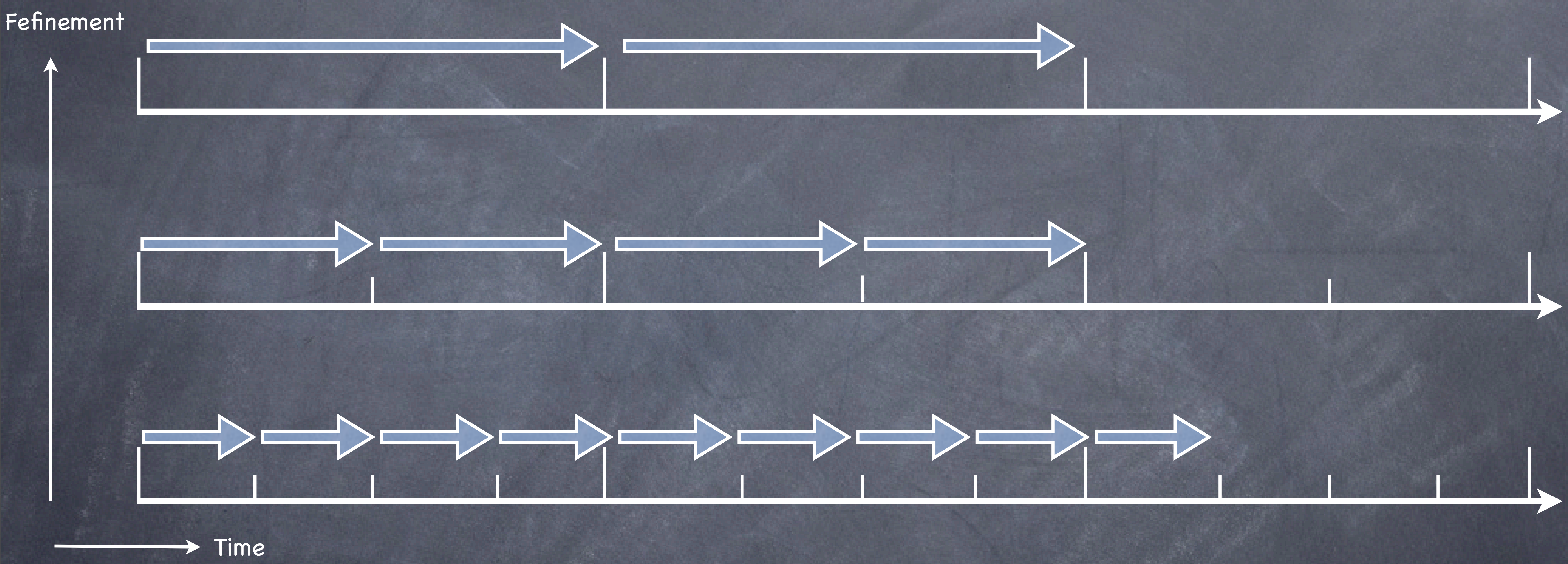

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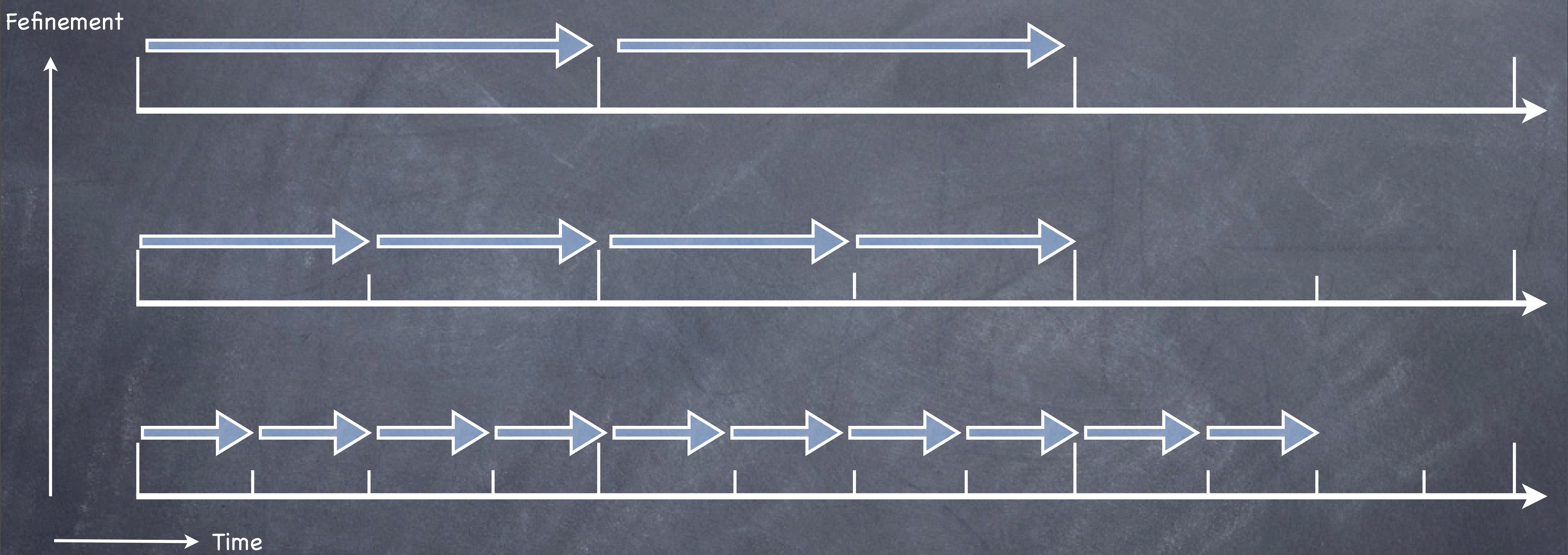

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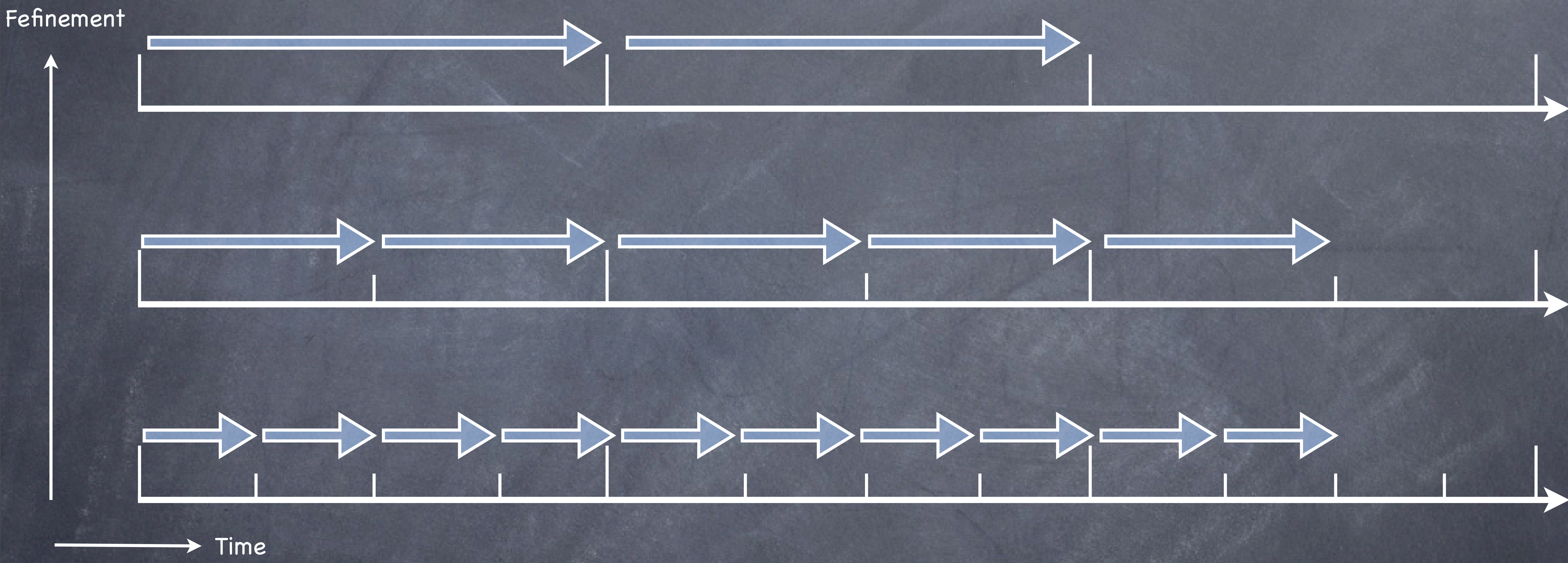

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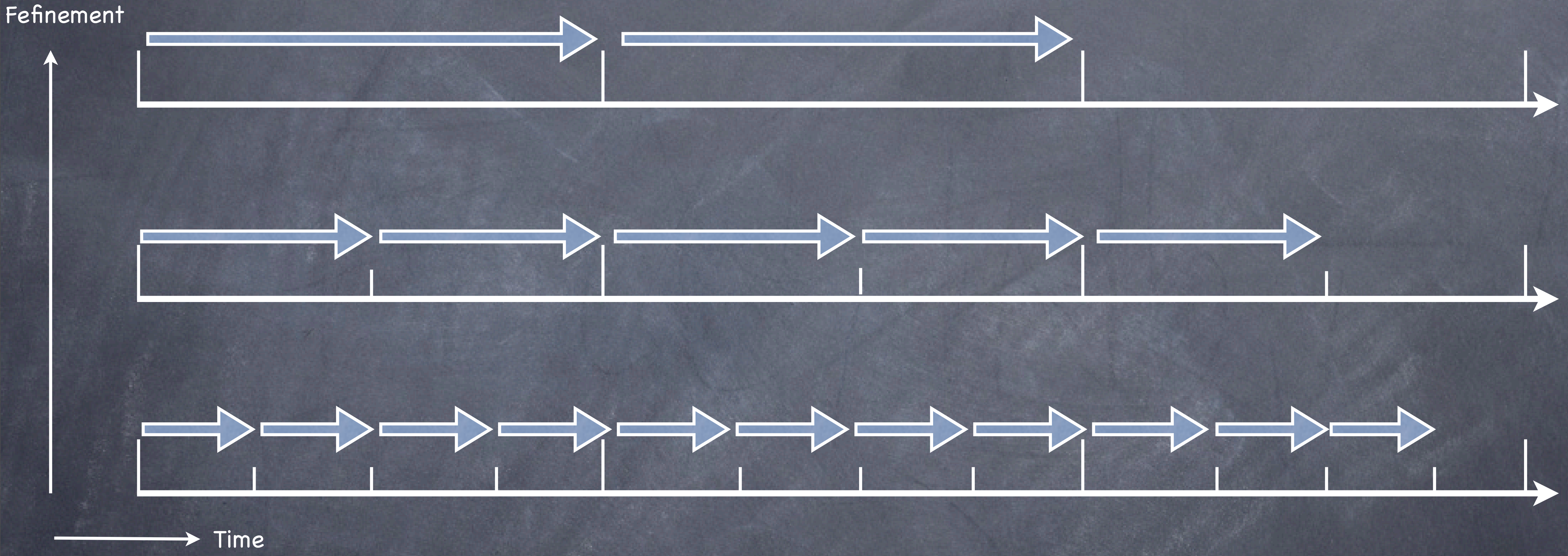

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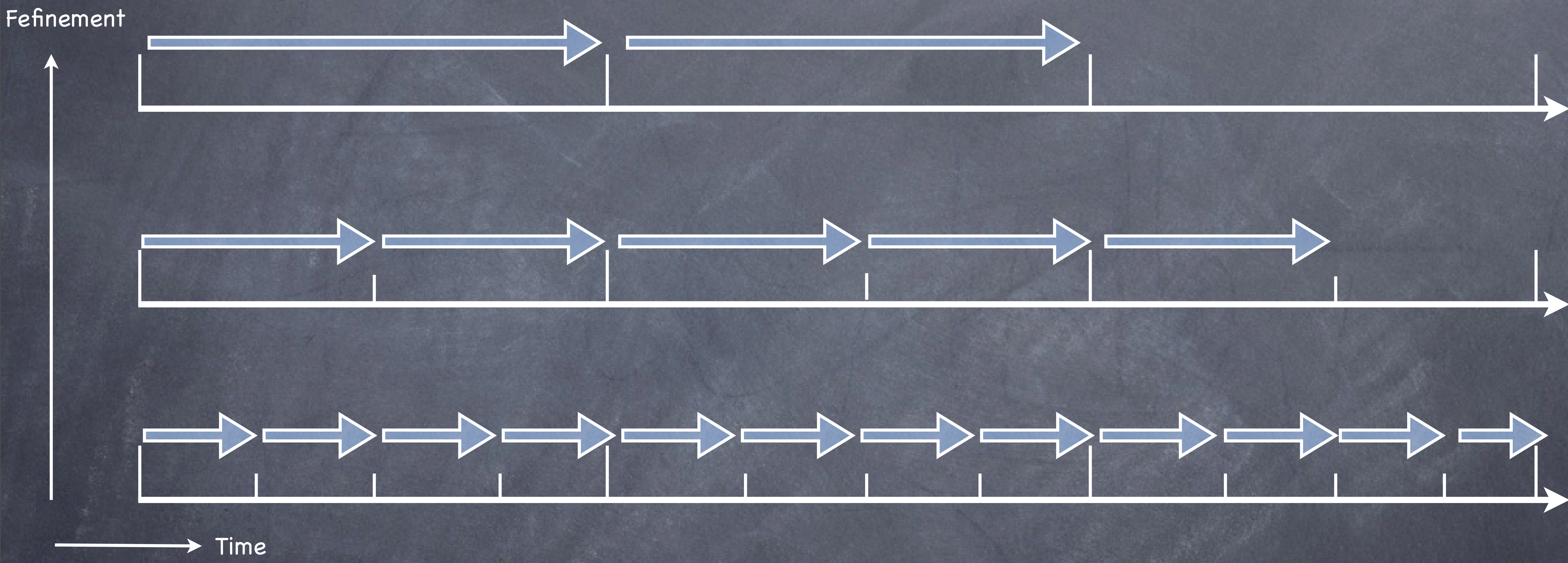

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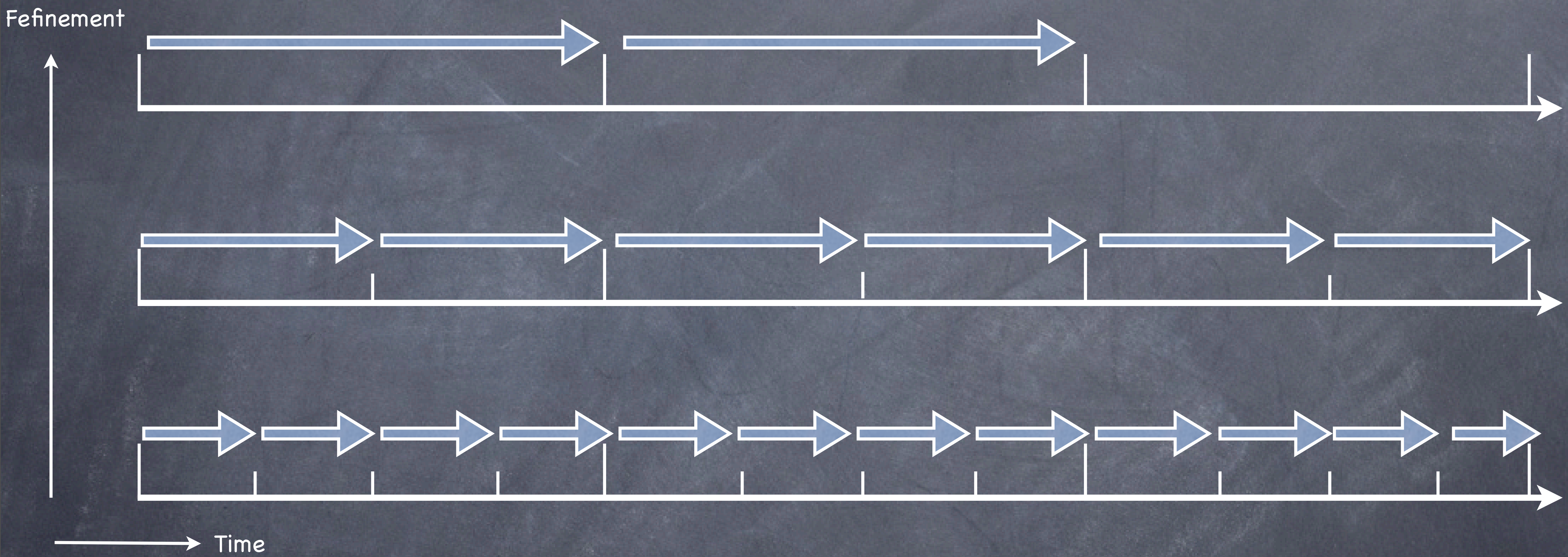

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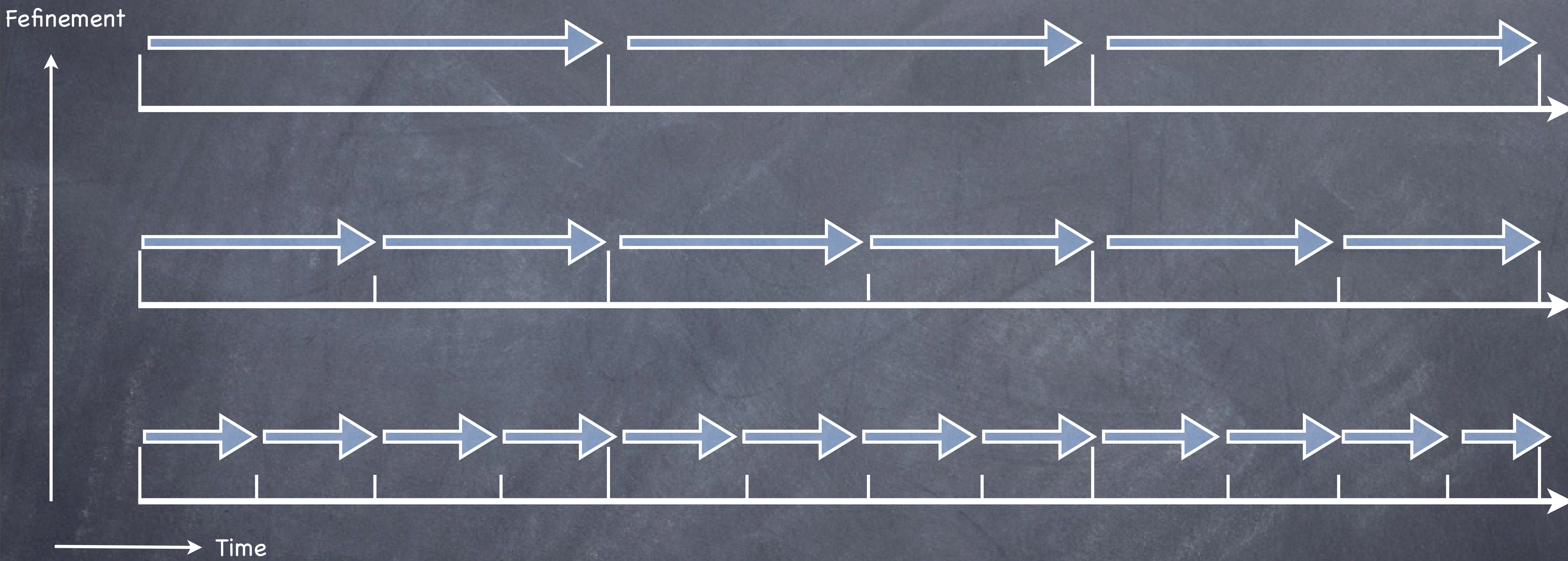


Refinement structure is rebuild every zero-level time step.

Time stepping

- Scale of the time-step is defined by the time-step at the zero-level mesh
- On each subsequent level of refinement the time-time step decreases by factor two.
- For a particle moving with a constant speed the fraction of a cell, which it crosses per one time-step is independent on the level of refinement at which the particle moves.
- “Courant condition”: particles should not move more than a fraction of a cell per step. It is a global (refinement level independent) condition
- In practice, maximum particle displacement is 0.1-0.2 of a cell.

ART: hydro equations

Equations

$$\frac{\partial\tilde{\rho}}{\partial\tilde{t}} + \tilde{\nabla}\tilde{\rho}\tilde{\mathbf{v}} = 0,$$

$$\frac{\partial\tilde{\mathbf{v}}}{\partial\tilde{t}} + (\tilde{\mathbf{v}}\cdot\tilde{\nabla})\tilde{\mathbf{v}} = -\frac{\tilde{\nabla}\tilde{P}}{\tilde{\rho}} - \tilde{\nabla}\tilde{\phi},$$

$$\frac{\partial\tilde{E}}{\partial\tilde{t}} + \tilde{\nabla}\cdot[(\tilde{E}+\tilde{P})\tilde{\mathbf{v}}] = -\tilde{\rho}\tilde{\mathbf{v}}\cdot\tilde{\nabla}\tilde{\phi} + \tilde{\rho}\tilde{H}(2\tilde{\varepsilon} - 3\tilde{P}/\tilde{\rho}) + (\tilde{\Gamma} - \tilde{\mathrm{L}}),$$

$$\tilde{\nabla}^2\tilde{\phi} = 6a\tilde{\delta},$$

$$\tilde{\varepsilon} = \frac{1}{\gamma-1}\frac{\tilde{P}}{\tilde{\rho}},$$

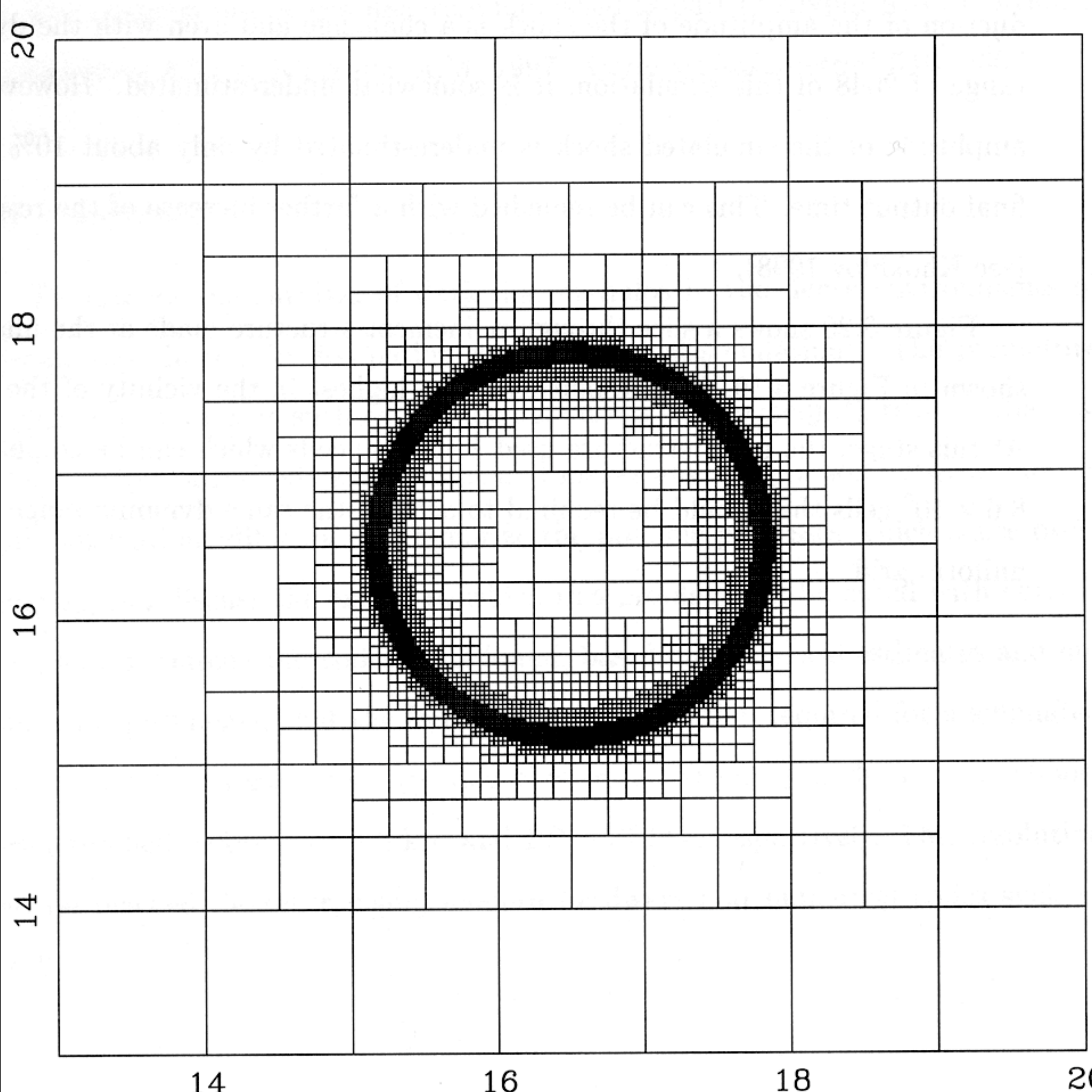
dimensionless variables

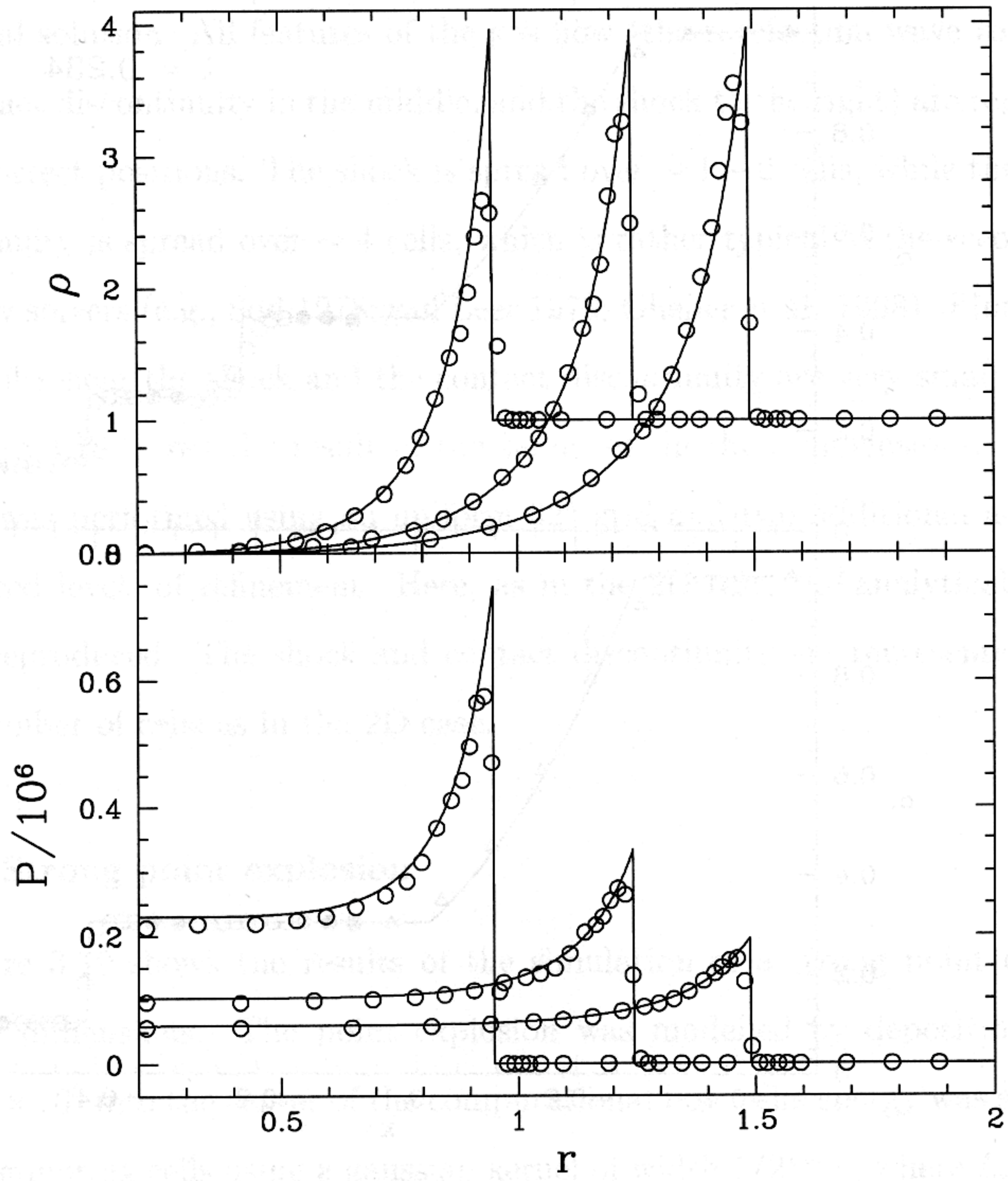
$$\begin{aligned}
\tilde{\mathbf{r}} &\equiv a^{-1}\frac{\mathbf{r}}{r_0}, \\
d\tilde{t} &\equiv a^{-2}\frac{dt}{t_0}, \\
\tilde{\rho} &\equiv a^3\,\frac{\rho}{\rho_0}, \\
\tilde{\mathbf{v}} &\equiv a\,\frac{\mathbf{v}}{v_0}, \\
\tilde{\phi} &\equiv a^2\,\frac{\phi}{\phi_0}, \\
\tilde{P} &\equiv a^5\,\frac{P}{P_0}, \\
\tilde{\varepsilon} &\equiv a^2\,\frac{\varepsilon}{\varepsilon_0},
\end{aligned}$$

$$\begin{aligned}
t_0 &\equiv \frac{2}{H_0}\frac{1}{\sqrt{\Omega_0}}, \\
v_0 &\equiv \frac{r_0}{t_0}, \\
\rho_0 &\equiv \frac{3H_0^2}{8\pi G}\Omega_0, \\
\phi_0 &\equiv \frac{r_0^2}{t_0^2} = v_0^2, \\
P_0 &\equiv \rho_0 v_0^2, \\
\varepsilon_0 &\equiv \frac{P_0}{\rho_0} = v_0^2,
\end{aligned}$$

Units: r_0= cell size at zero level

ART: test of strong shock solution

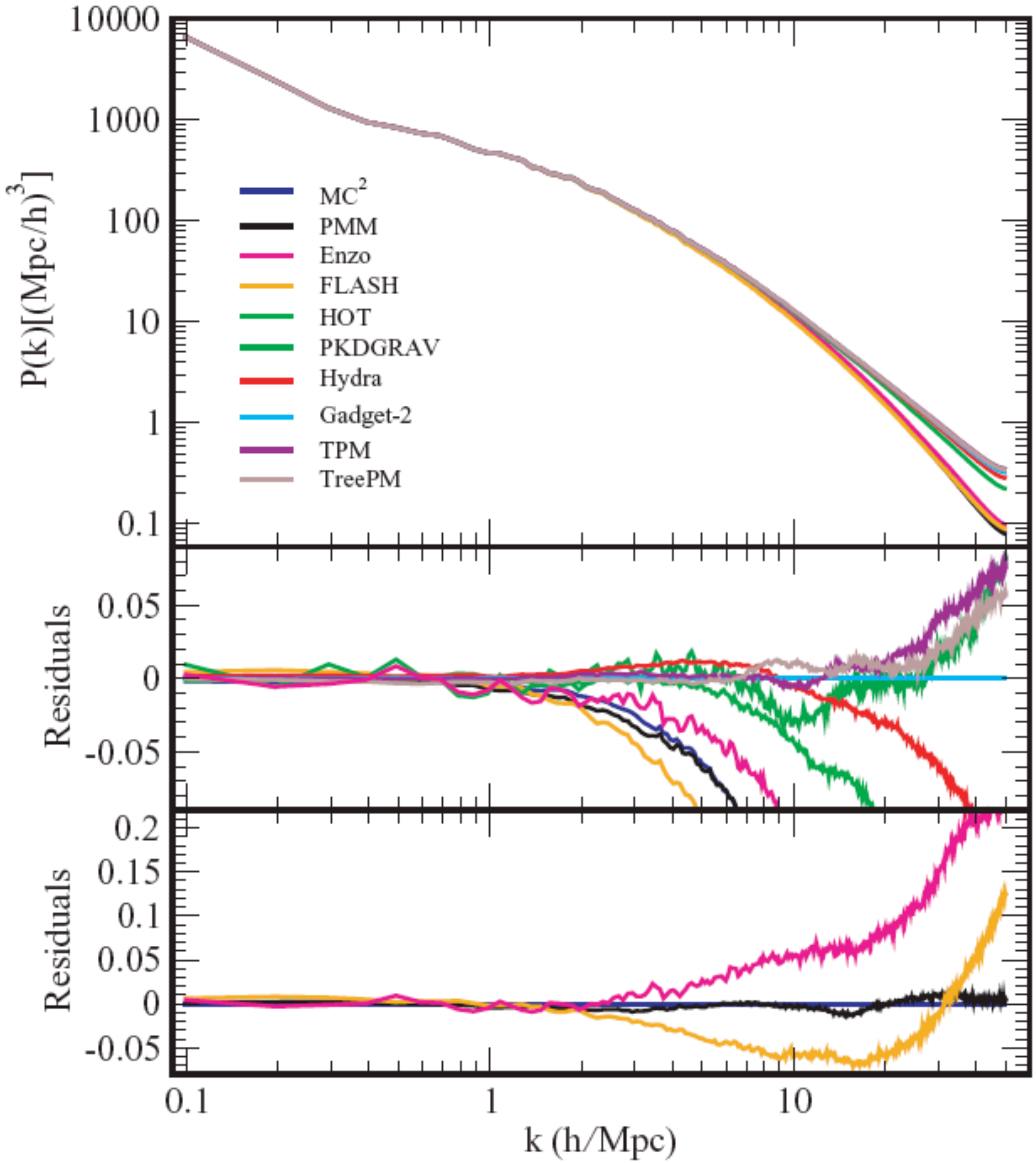


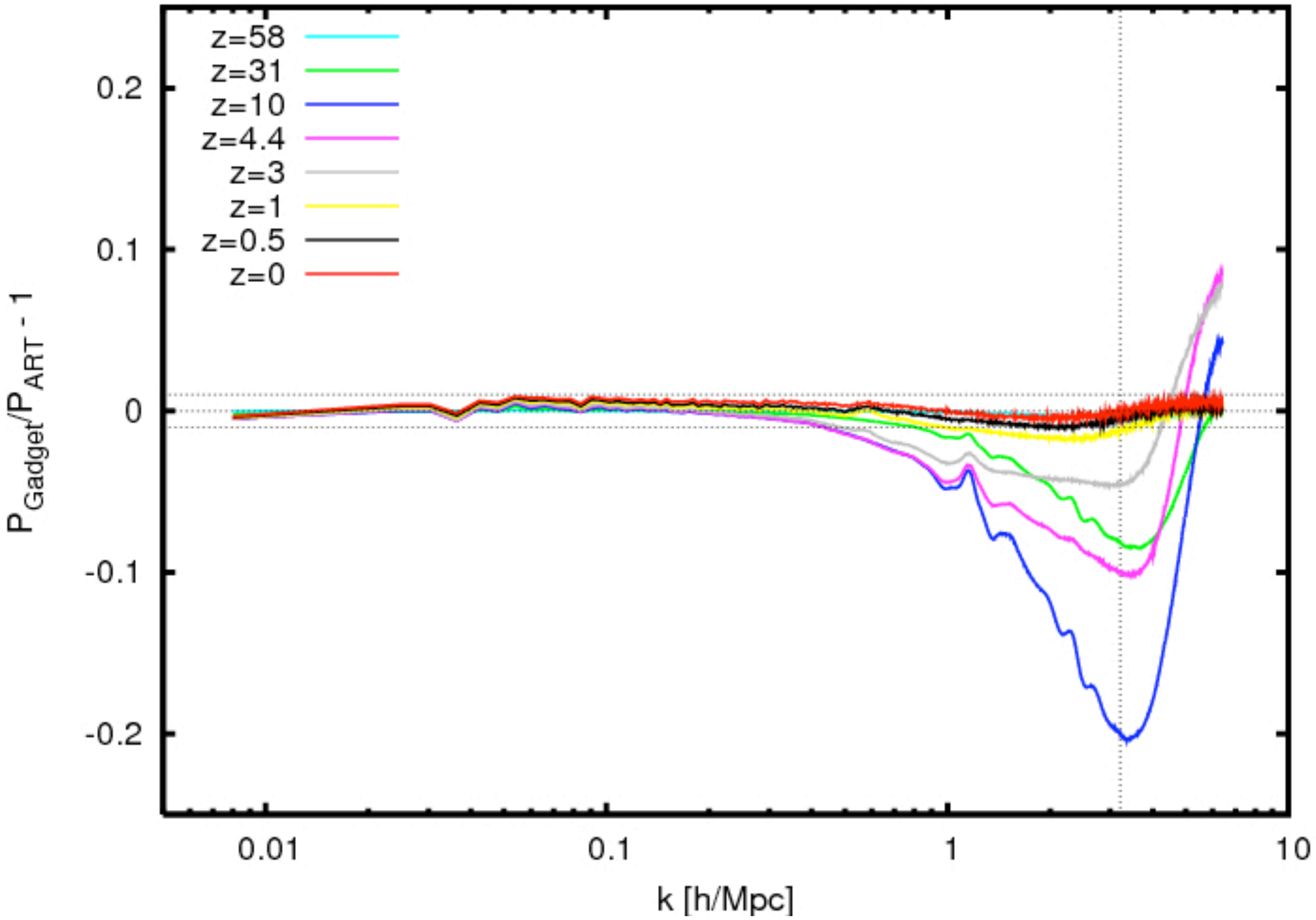


Heitmann et al 2008

Code comparison: evolution of perturbations

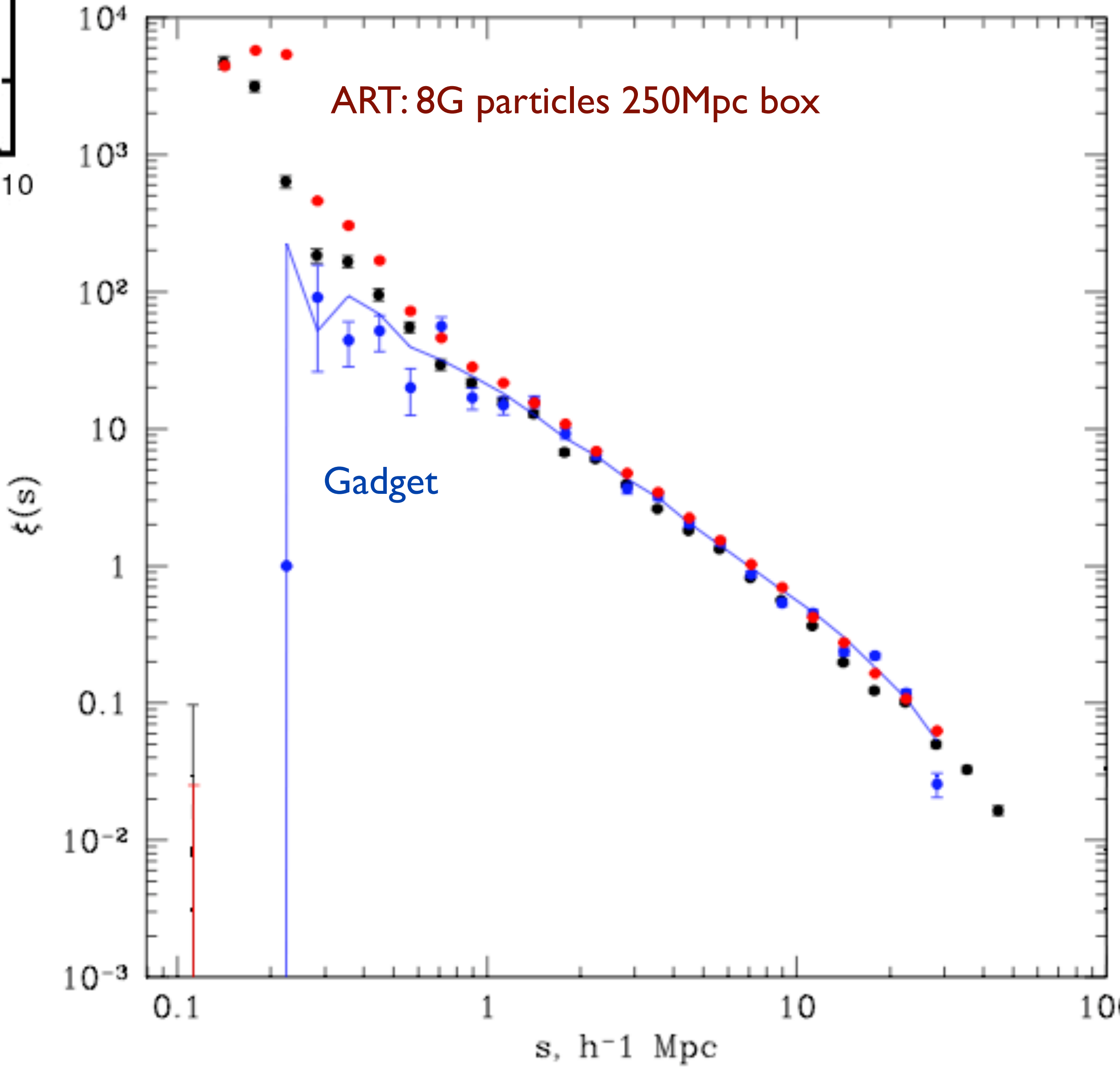
64Mpc/h box 256**3 particles





Comparison of P(k) evolution in ART and Gadget-2 codes. This is for ***1Gpc/h*** box with ***1G particles***. The same initial conditions were used for the runs. The Gadget run and the plot was produced by Ch.Wagner. The vertical line is the Nyquist frequency of particles. Gadget suppresses the growth of fluctuations at high frequencies by 5-20%. The difference gets smaller at low redshifts and practically undetected at z<1.

ART vs Gadget on cosmological simulations



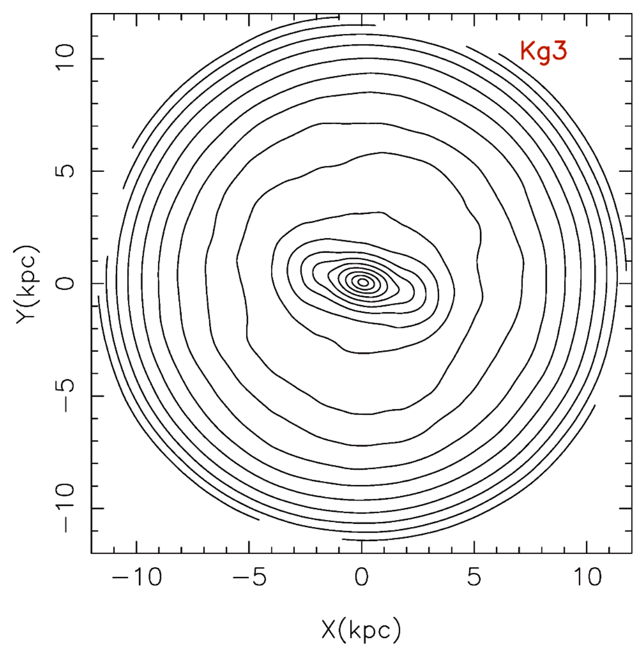
z=2 correlation function of halos with Vcirc > 270km/s

overmerging in Millennium runs (blue)

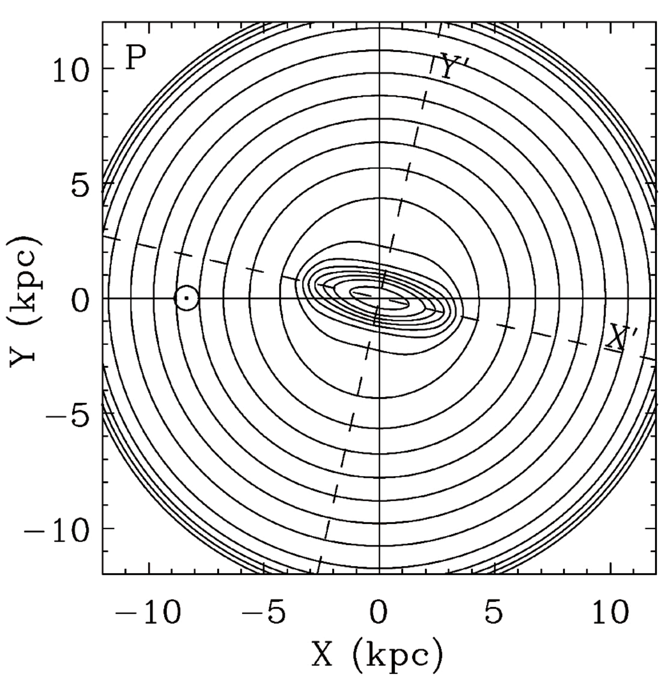
Stellar-dynamics: formation of a barred isolated (not cosmological) galaxy:

Code comparison: pretty good

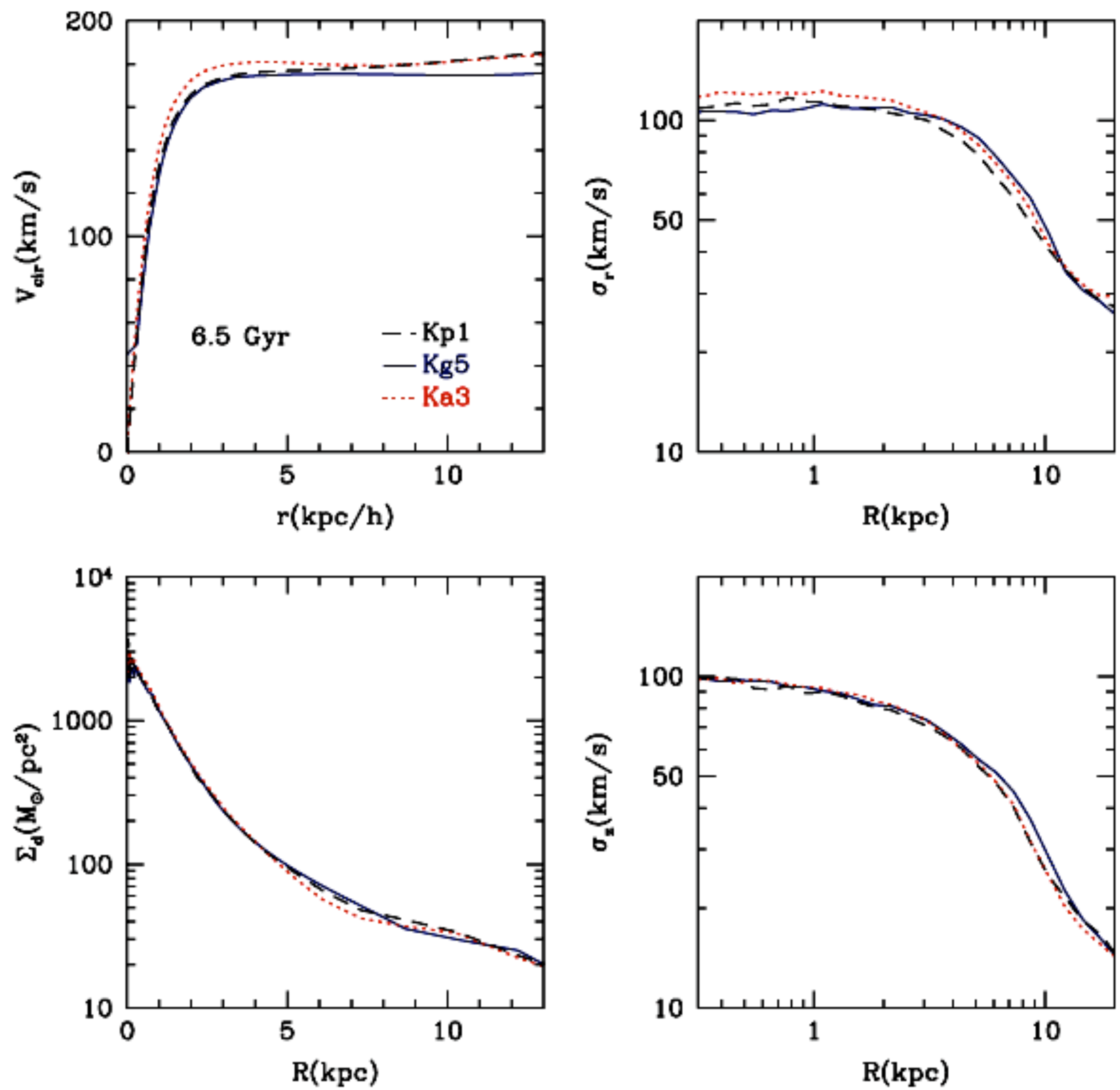
5M particles, 20pc resolution
Kp1 = PKDGRAV
Kg5 = Gadget-2
Ka3 = ART



Model



Milky Way



Star formation and stellar feedback: basic ideas

"It is a very complicated situation. Lots of things are poorly understood. But we do our best."

Star formation and stellar feedback: basic ideas

"*It is a very complicated situation. Lots of things are poorly understood. But we do our best.*"

Donkey

Star formation and stellar feedback: basic ideas

$$\frac{d\rho_{*,\mathrm{young}}}{dt} = \frac{\rho_{\mathrm{gas}}}{\tau}$$

ρ_{gas} is the gas density

τ star formation timescale.

τ should be in the range 2-20 Myr.

$$\frac{du}{dt} + p\nabla \cdot \mathbf{v} = \Gamma - \Lambda$$

where u is the internal energy per unit volume

Γ is the heating rate due to stellar feedback, $\Gamma = \rho_{*,\mathrm{young}}\Gamma'$

The cooling rate $\Lambda = n_H^2 \Lambda'$,

Conditions for star formation (Cen & Ostriker 92):
(1) contracting flow
(2) cooling time less than dynamic time
(3) Jeans unstable
(4) spread energy over 27 cells

Resolution: 200 pc.

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GALAXY SIZE PROBLEM AT $z = 3$: SIMULATED GALAXIES ARE TOO SMALL
M. Ryan Joung[1], Renyue Cen[1], and Greg L. Bryan[2] 2009

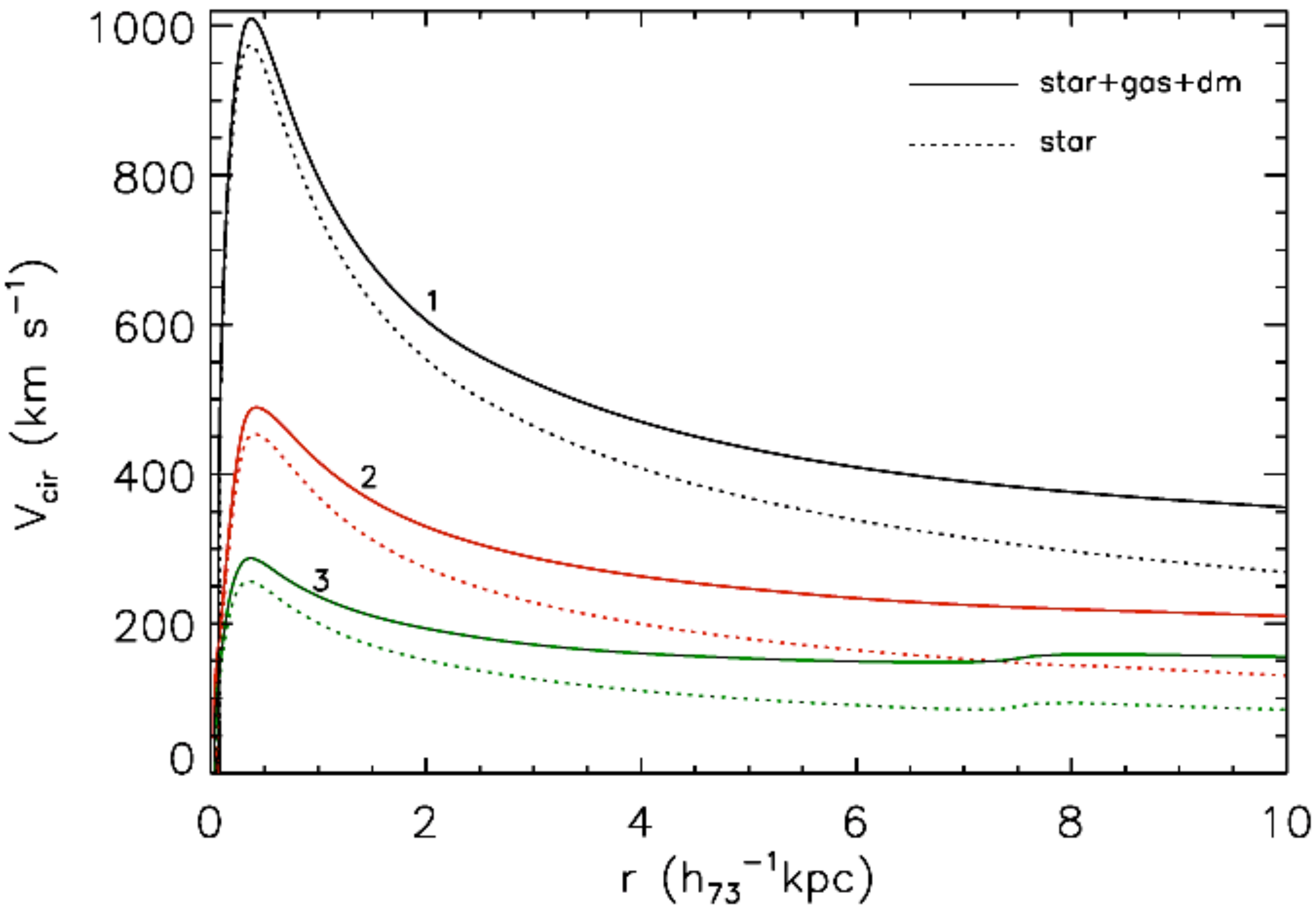

Figure 3. Rotation velocity curves for the three galaxies labeled "1," "2," and "3" in Figure 1. The solid curves represent rotation velocities due to all the matter within a given galactocentric radius, while the dotted curves show those due to stellar mass only. The virial masses of the three galaxies are 8×10^{11}, 4×10^{11}, and 1×10^{11} $M_{\odot}$, respectively.

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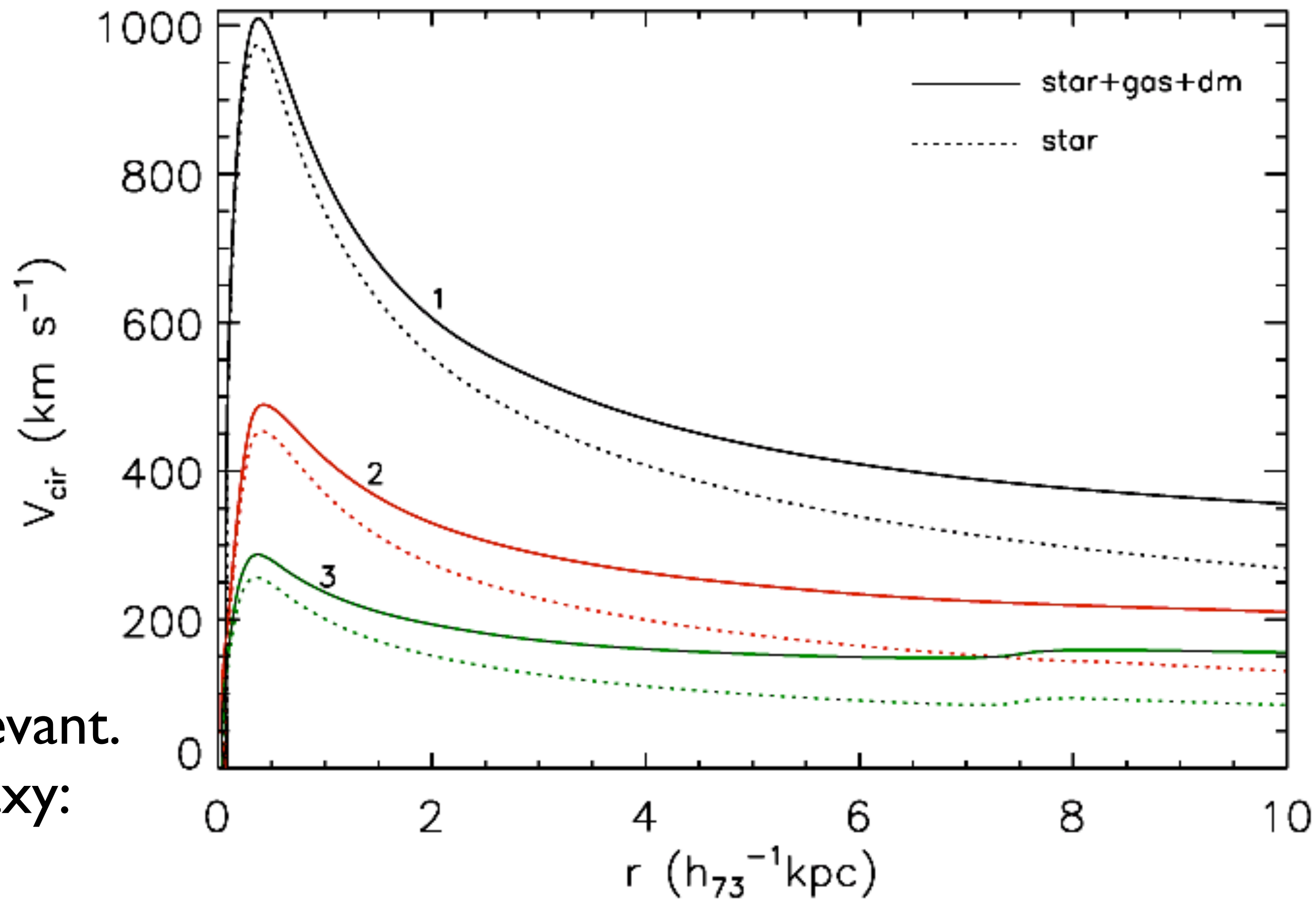

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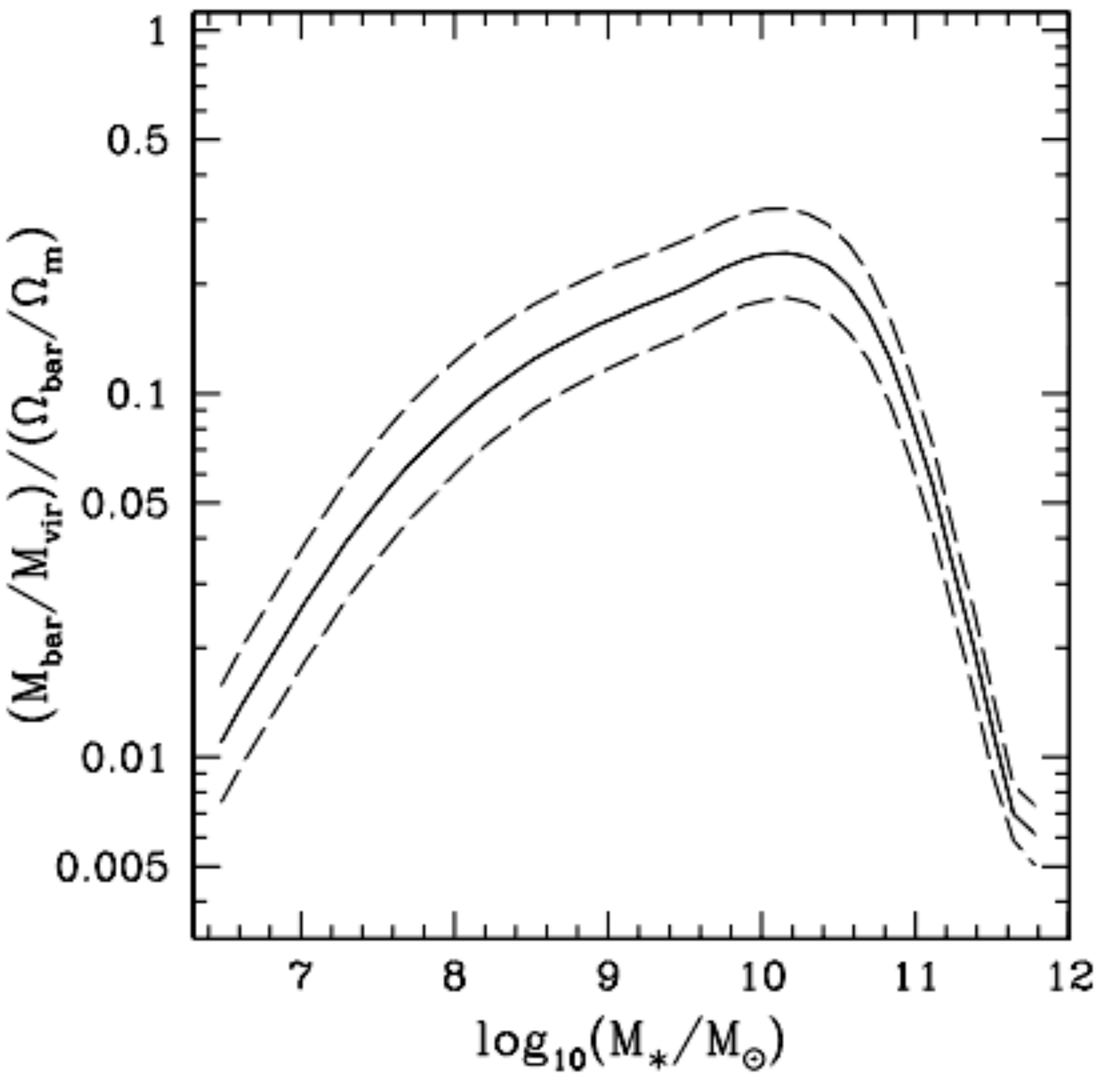
With this resolution none of the conditions are justified or even relevant. Apply those conditions to our Galaxy: they would not work.
This is an example of misplaced physical arguments: good arguments applied on wrong scales. They are fine for sub-pc scales of individual stars, not for a large chunk of a galaxy.

<u>As the result of unrealistic feedback conditions modeled "galaxies" are totally unrealistic.</u>

What are the observational constraints?

- Fraction of baryons: much lower than previously estimated
- Flat rotation curves
- Disk size appropriate for galaxies
- Reasonable Bulge/Disk ratios
- Star formation prescriptions

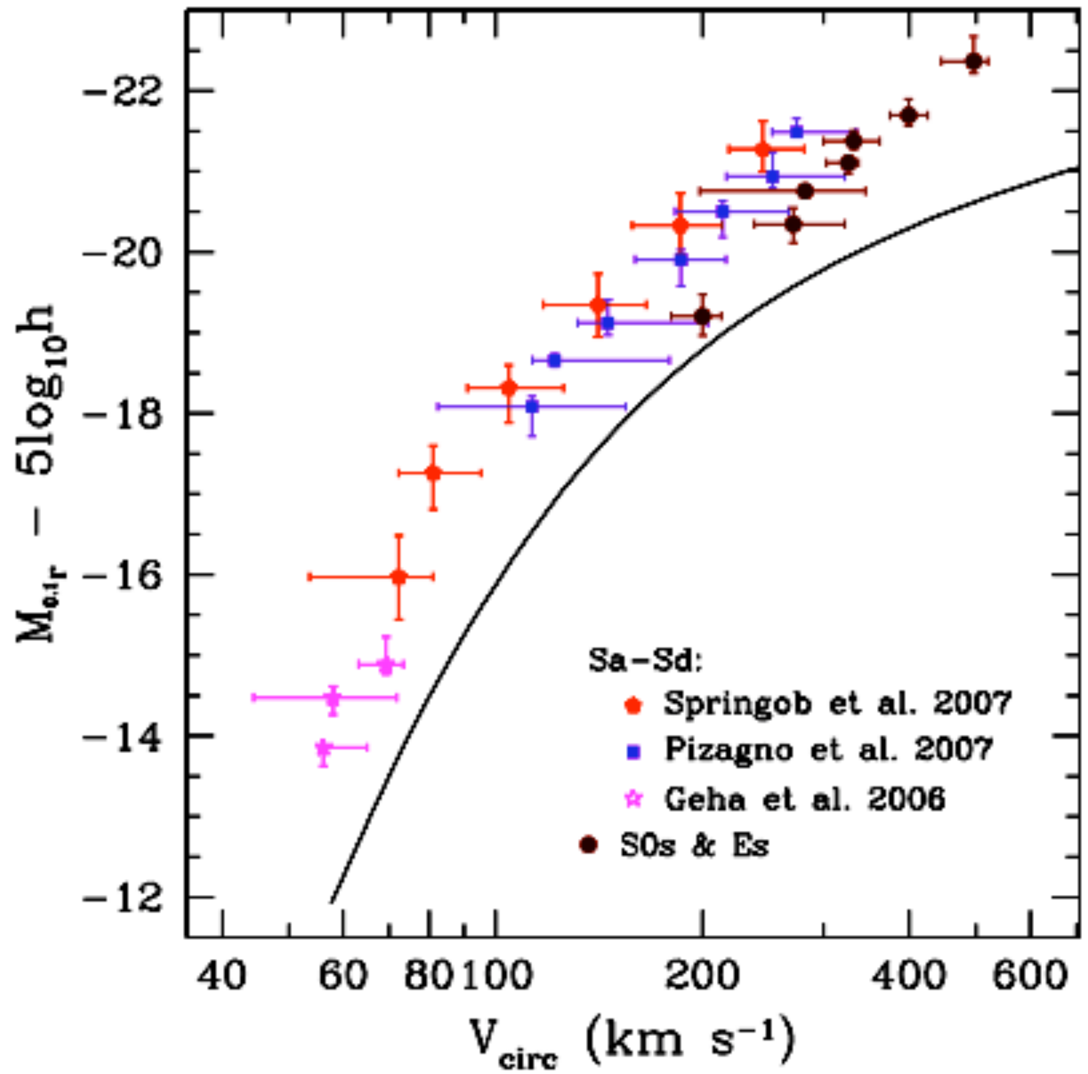
Baryon Fractions and outflows



Abundance-matching: mass in stars and cold gas inside virial radius of dark matter halos required in order to produce observer Luminosity Function in r-band   Trujillo et al 2010

Fraction of 'cold' baryons is very small: at best 1/5 of cosmological baryons inside virial radius.

This is what happens when 1/2 of baryons are in galaxies: no way to fit observations



Conclusions: most of baryons must be expelled from galaxies. This argues for a strong feedback. Metallicites of QSO absorption lines point in the same direction

Disk length and angular momentum

Here is the usual argument why LCDM should predict acceptable (in general terms) disk lengths:

- typical spin parameter (measure of rotation) of dark matter halos is $\lambda = 0.03$
- assume that baryons and dark matter rotate in the same way
- Virial radius of a Milky-Way-size galaxy is 300 kpc
- In order to get to $\lambda = 1$ (rotationally supported), baryons need to shrink
    - by a factor of 30
- This gives a disk of 10 kpc as observed.

Disk length and angular momentum

This heuristic argument works as long as most of baryons end up in the central galaxy.

It badly fails if - as required by observations - only a small fraction of baryons fall to the central galaxy.

In this case one expects that only the baryons, which collapsed at high redshifts turn into stars. Indeed, disk of our MW galaxy is very old and was in place more than 10 Gyrs ago.

The angular momentum of the gas, which came into MW at high z was small and cannot produce an extended observed disk.

Conclusions: significant gas outflow or mixing must have happened.

Every research group has its own pet *feedback mechanism* *Physics*

It is easy to get lost in the forest of feedback schemes unless we pay attention to physics: how the prescription affects motion of gas in a forming galaxy.

It is also very easy to argue that other's pet prescription does not work.

Star formation and stellar feedback: basic ideas

$$\frac{d\rho_{*,\mathrm{young}}}{dt} = \frac{\rho_{\mathrm{gas}}}{\tau}$$

ρ_{gas} is the gas density
τ star formation timescale.

where u is the internal energy per unit volume
Γ is the heating rate due to stellar feedback,

$$\frac{du}{dt} + p\nabla \cdot \mathbf{v} = \Gamma - \Lambda$$

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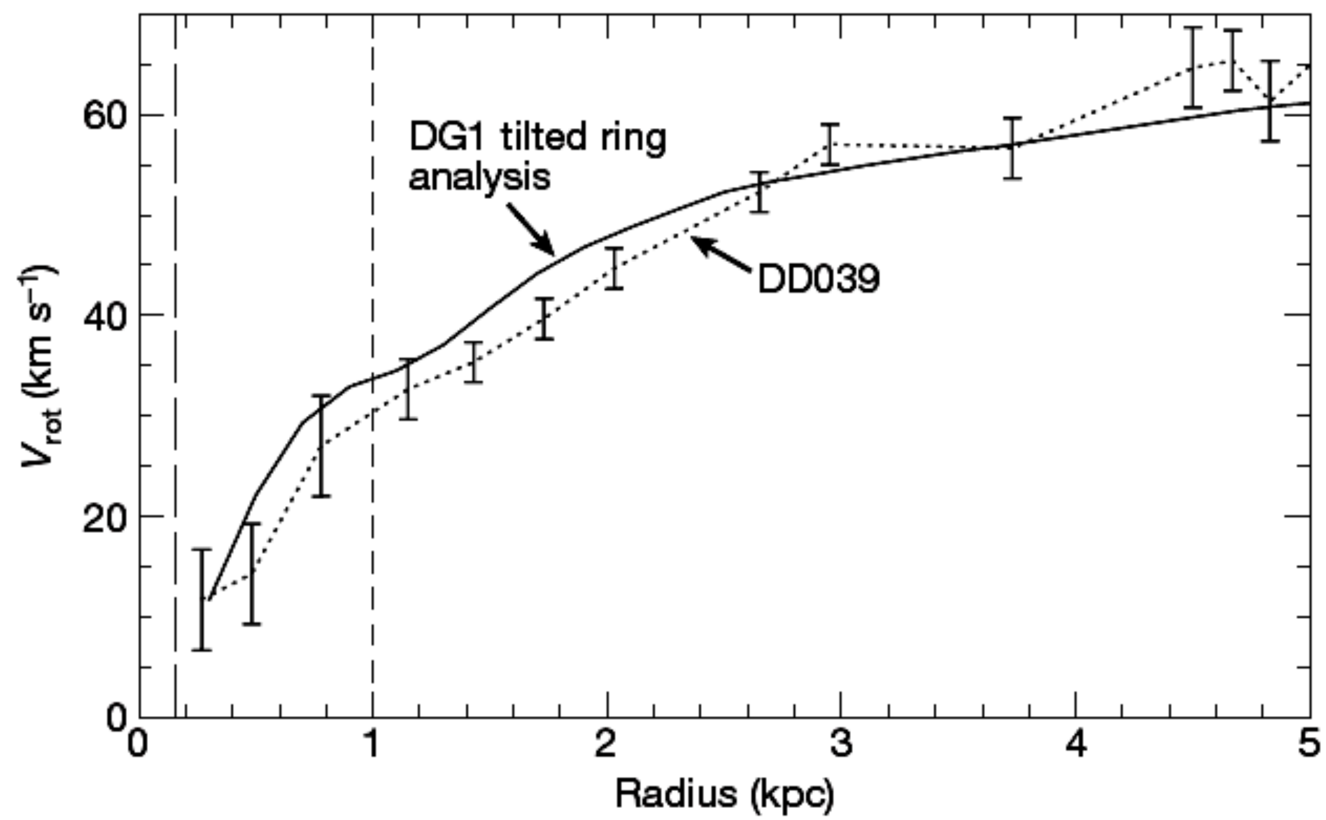
Science english	russian-english	situation
blast-waves	no cooling	Most of energy of SF is lost inside GMC. Archaic model of ISM. GMC are not disrupted by SNs
galactic winds	kicking out particles	It should happen, but this approximation is a bit too rough
semi analytical models	curse	nothing wrong, but needs imagination

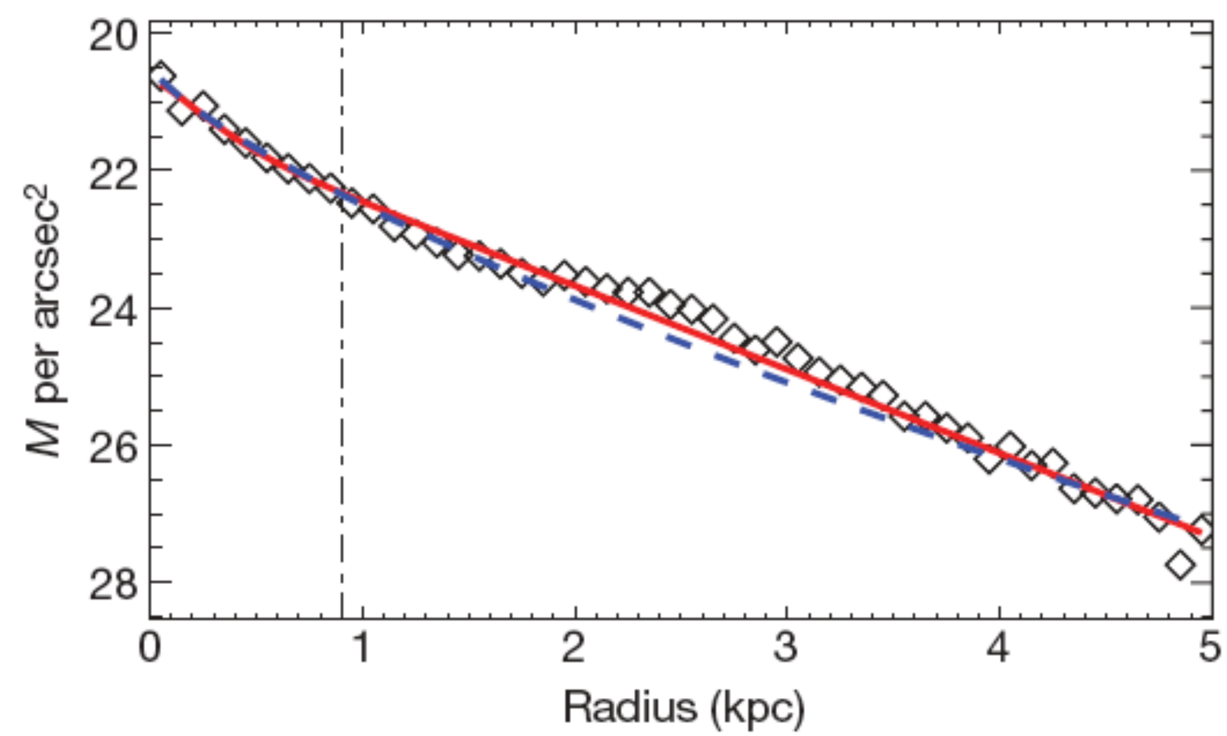
Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]

Strong feedback can produce a realistic model of dwarf galaxy.

Blast-wave = no cooling feedback





The formation of disk galaxies in a ΛCDM universe

Oscar Agertz[1⋆], Romain Teyssier[1,2] and Ben Moore[1]

We argue that previous attempts to form disk galaxies have been unsuccessful because of the universal adoption of strong feedback combined with high star formation efficiencies. Unless extreme amounts of energy are injected

We show that a low efficiency of star-formation more closely models the sub-parsec physical processes, especially at high redshift. We highlight the successful formation of extended disk galaxies with scale lengths $r_\mathrm{d} = 4 - 5\,\mathrm{kpc}$, flat rotation curves and

$$\Delta t = 50\,\mathrm{Myr}.$$

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1977). To allow for this to take place, we turn off cooling $\Delta t = 50\,\mathrm{Myr}.$ in the cells containing young stars to allow for the blast-wave to grow and be resolved by few cells, hence converting

This is actually a very strong feedback coupled with low rate of star formation

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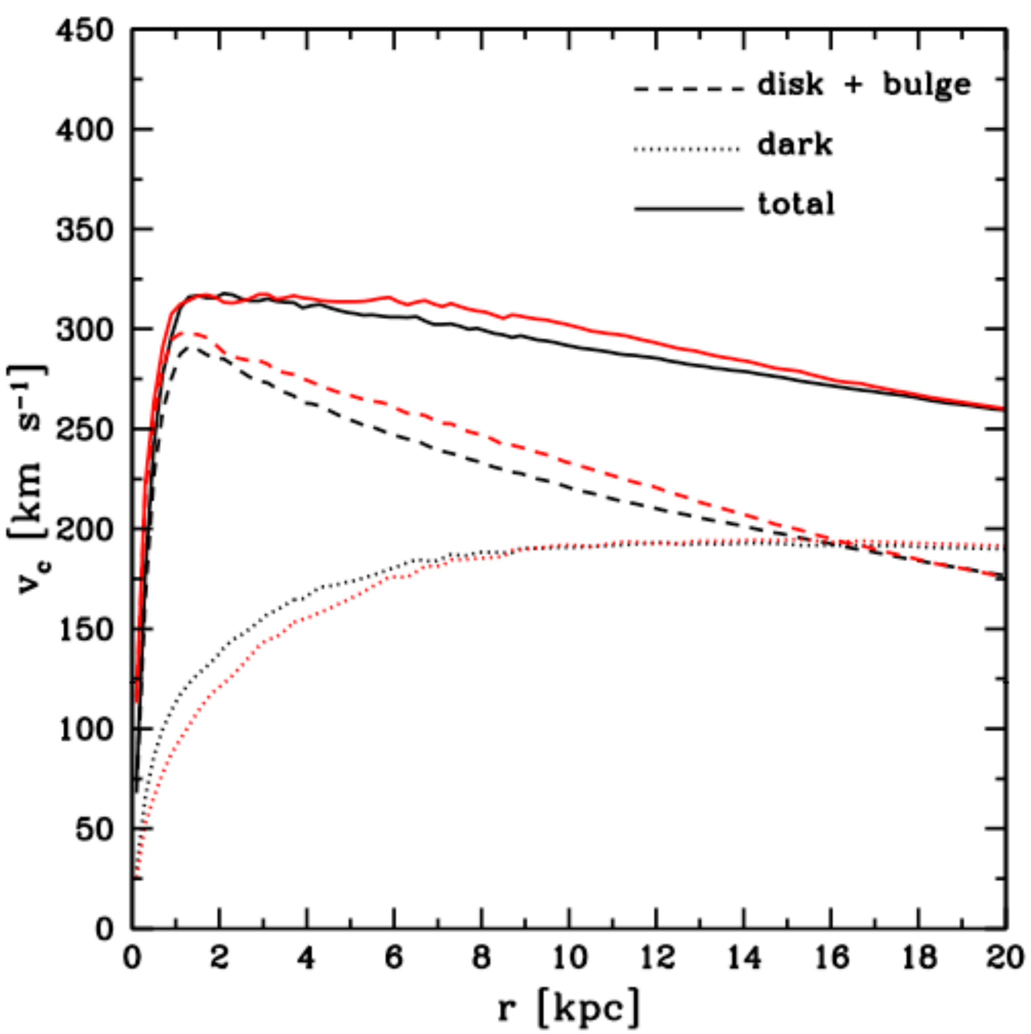
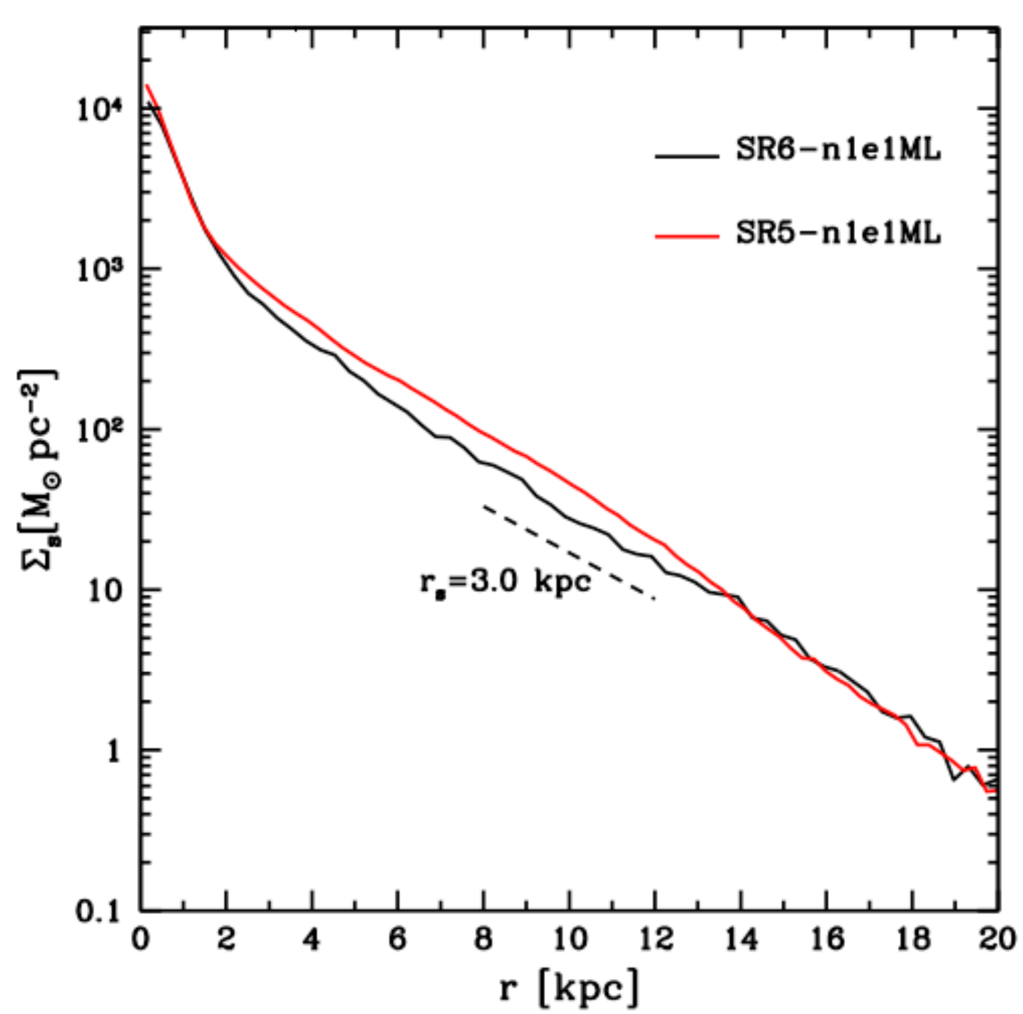




This produces an Sb galaxy with extended disk. Good.

Unfortunately, vast majority of galaxies with Vcirc =325km/s are E or S0. Real Universe does not have Sb's with this rotation velocity

Our implementation

Ceverino & Klypin 2007

Kravtsov ART hydro code: Physical processes included:

- AMR shock capturing hydro
- metallicity-dependent cooling + UV heating (Haardt & Madau). CLOUDY. Compton cooling
- Temperature range for cooling: 10^2K -10^8K
- Jeans length resolved with 4 cells
- Energy release from stellar winds+ SNII +SNI
- Thermal feedback: most * form at T< 1000K n>$10cm^{-3}$
- Runaway stars: massive stars move with exp(-v/17km/s)

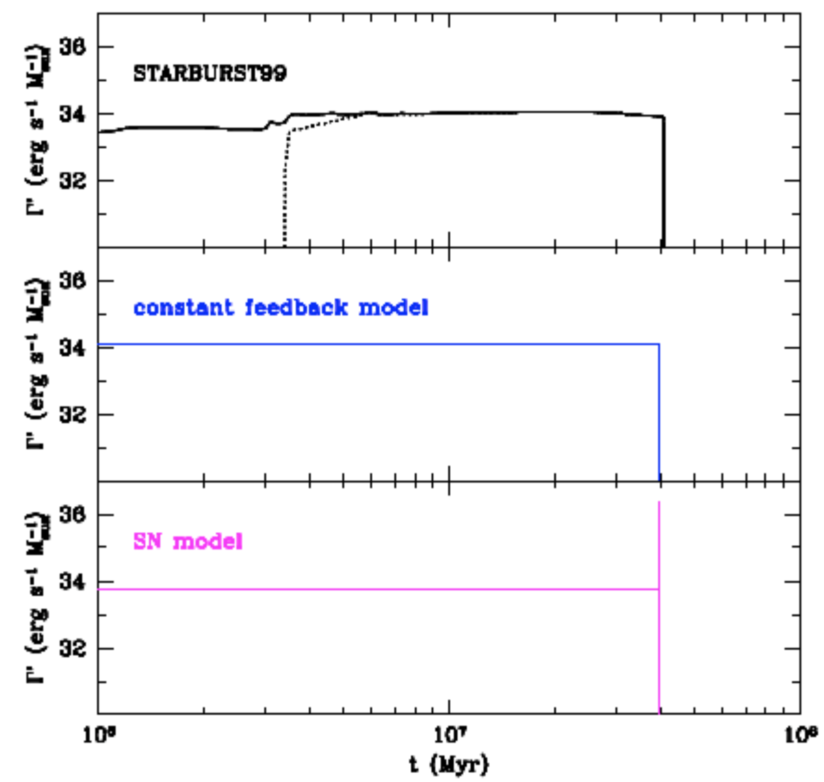


Fig. 1.— Rate of energy losses per unit mass from a single stellar population. Top panel shows the results from the STARBURST99 code, assuming a Miller-Scalo IMF for a mass range (0.1 – 100) $M_\odot$.

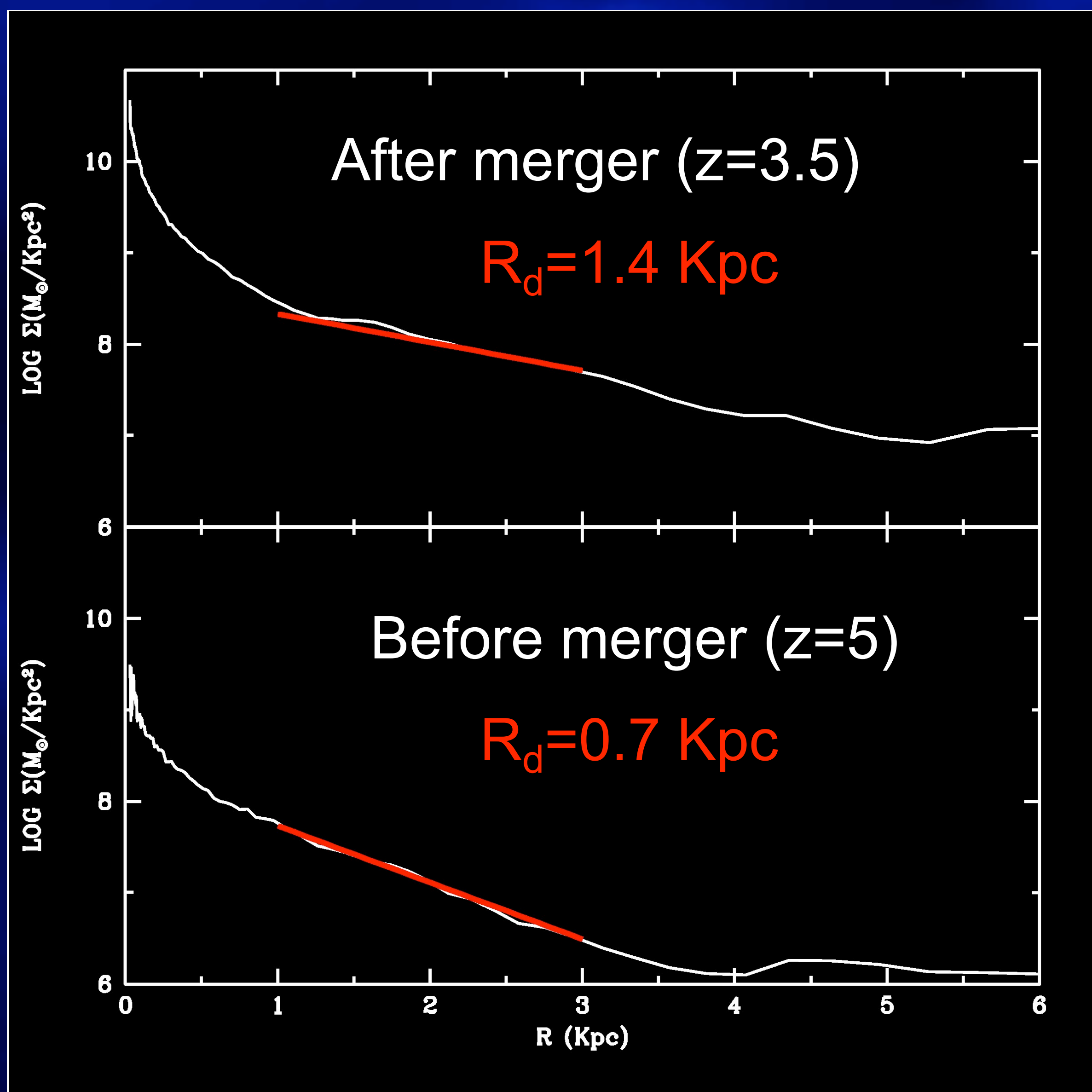
$$\frac{d\rho_{*,\mathrm{young}}}{dt} = \frac{\rho_{\mathrm{gas}}}{\tau}$$

τ =2-20 Myrs

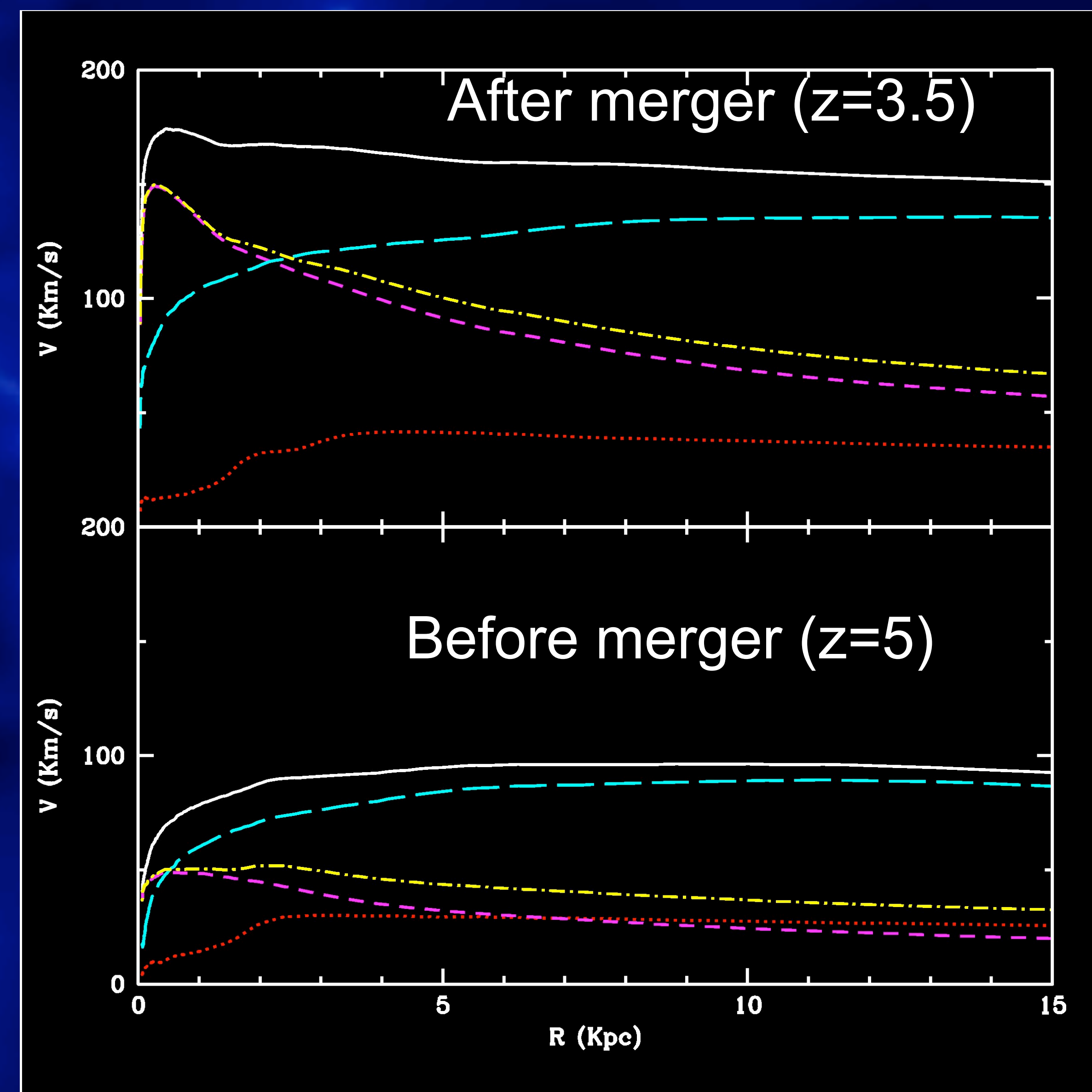
Effective τ =150-1000 Myrs

Mass consumption rate per free-fall time averaged over gas "molecular" gas (n>$30cm^{-3}$) is 0.03

Growth of a disk after a major merger



Surface density of stars



Circular velocity

The disk grows in mass and size after a merger

Conclusions:
You are coming to the galaxy formation in right time: so much is unknown and so much is expected