Dark Matter Dynamics

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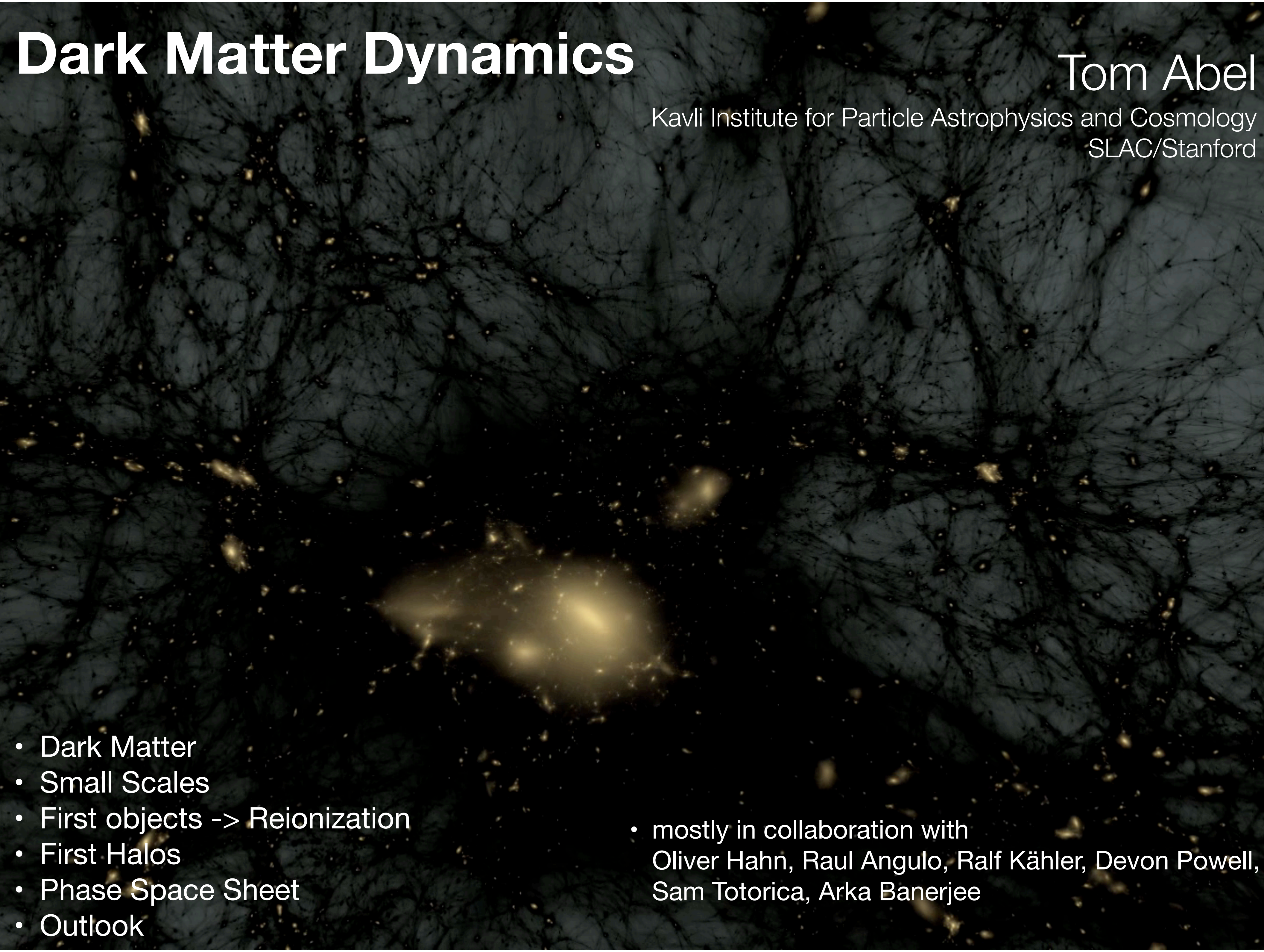


- Dark Matter
- Small Scales
- First objects -> Reionization
- First Halos
- Phase Space Sheet
- Outlook

- mostly in collaboration with
  Oliver Hahn, Raul Angulo, Ralf Kähler, Devon Powell, Sam Totorica, Arka Banerjee

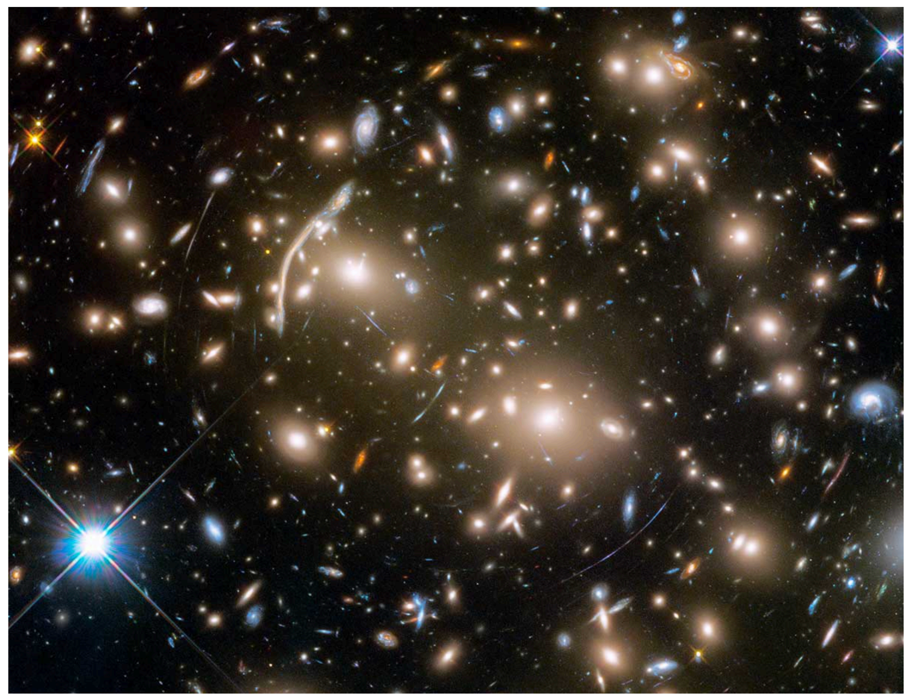
Dark Matter Ubiquitous

- Zwicky 1933: Estimates 400 times more mass in the Coma Cluster to explain the large velocity dispersion of “nebulae” than estimated mass from the light alone.
- Vera Rubin: Rotation Curves of Andromeda and many other spiral nebulae are flat. Dark matter must dominate.
- Gravitational Lenses (Walsh, Carswell, Weymann 1979, Lynds, Petrosian, Soucail 86) Strongly constrains mass in Clusters of Galaxies. Confirms Zwicky’s estimates.

Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Zwicky 1933



Galaxy cluster Abell 370, located about 4 billion light-years away, contains an astounding assortment of several hundred galaxies tied together by the mutual pull of gravity. Entangled among the galaxies are mysterious-looking arcs of blue light. These are actually distorted images of remote galaxies behind the cluster. These far-flung galaxies are too faint for Hubble to see directly. Instead, the gravity from the cluster acts as a huge lens in space that magnifies and stretches images of background galaxies like a funhouse mirror. Nearly 100 distant galaxies have multiple images caused by the lensing effect. The most stunning example is "the Dragon," an extended feature that is probably several duplicated images of a single background spiral galaxy stretched along an arc. Astronomers chose Abell 370 as a target for Hubble because its gravitational lensing effects can be used for probing remote galaxies that inhabited the early universe. Credit: NASA, ESA, and J. Lotz and the HFF Team (STScI) NEWS RELEASE: 2017-20 >

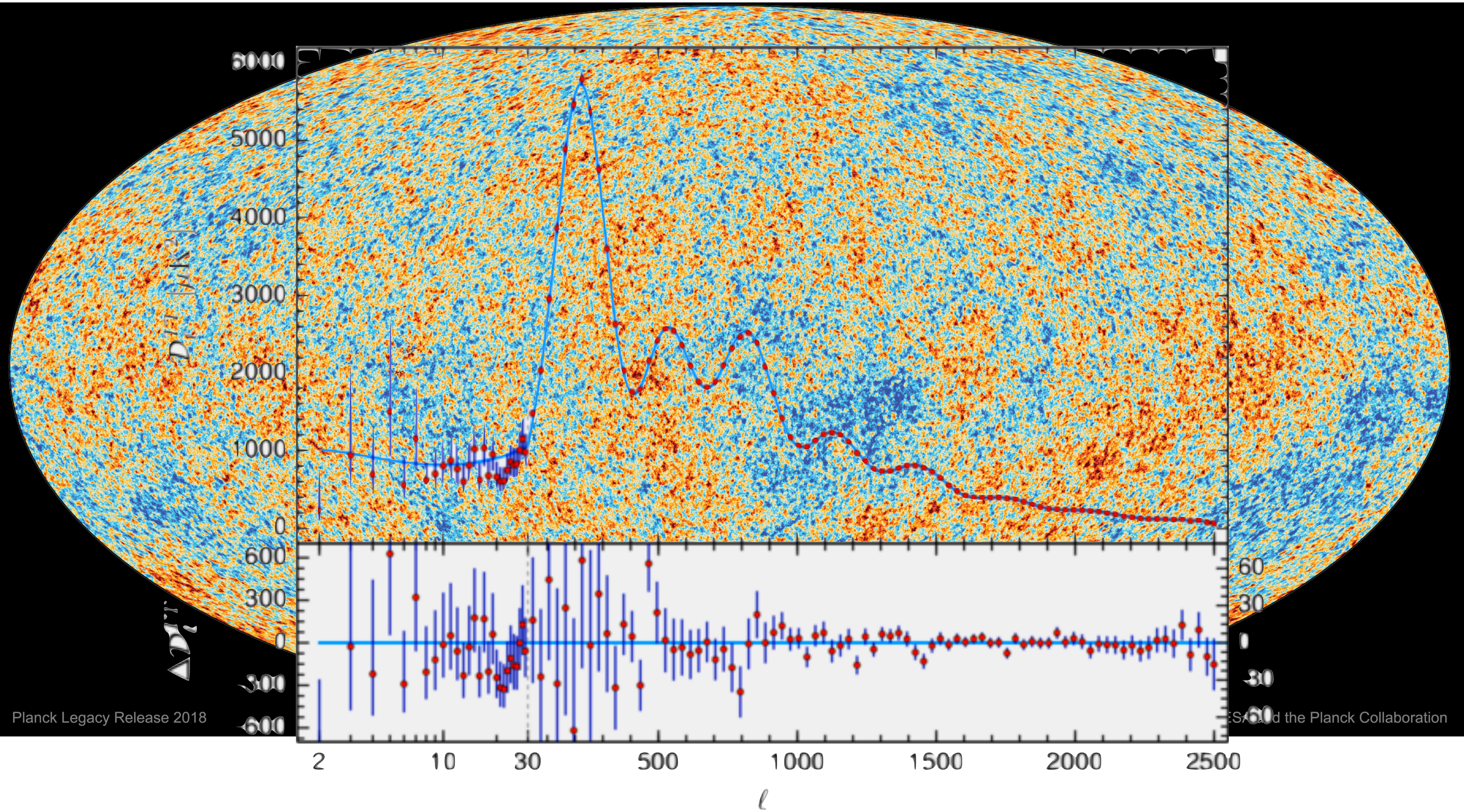
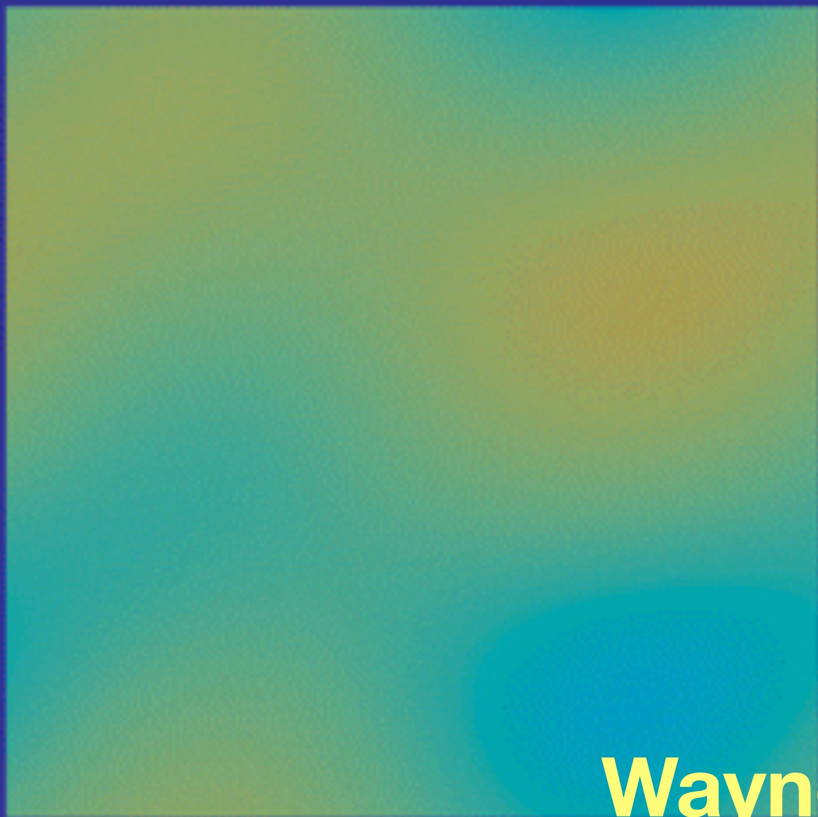
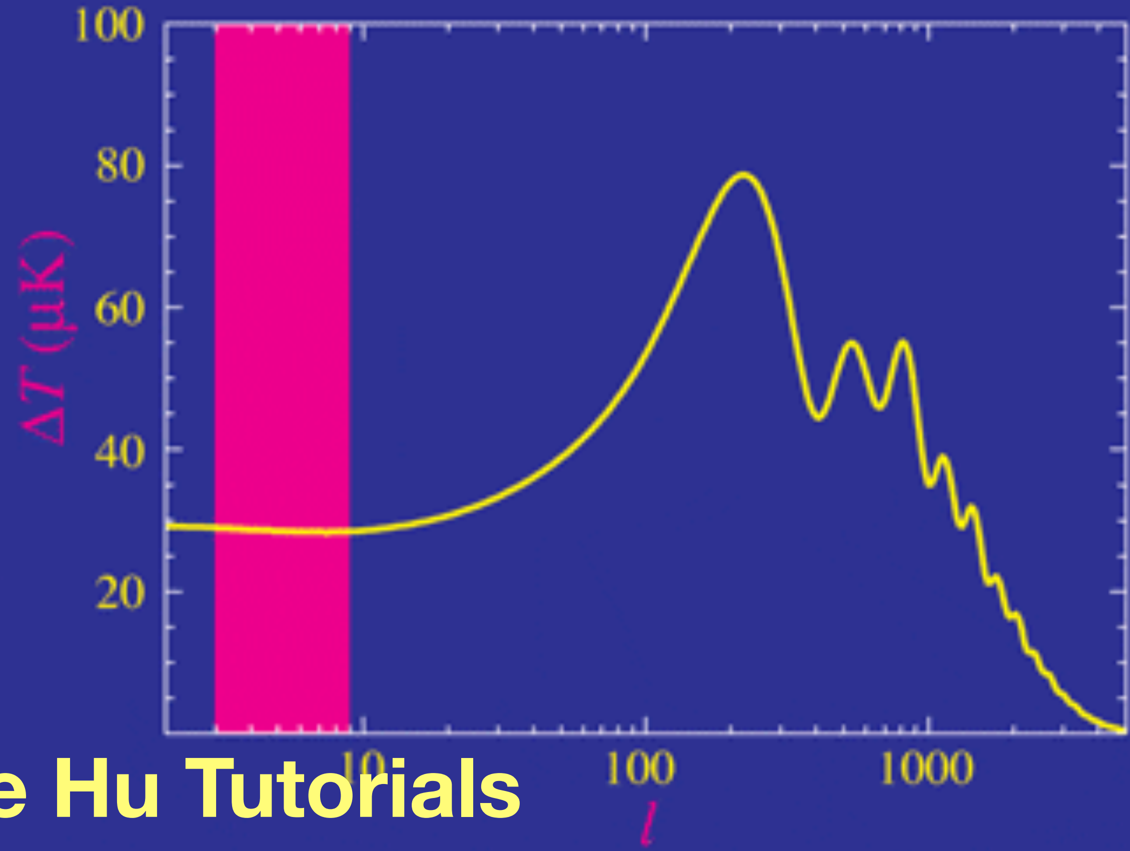
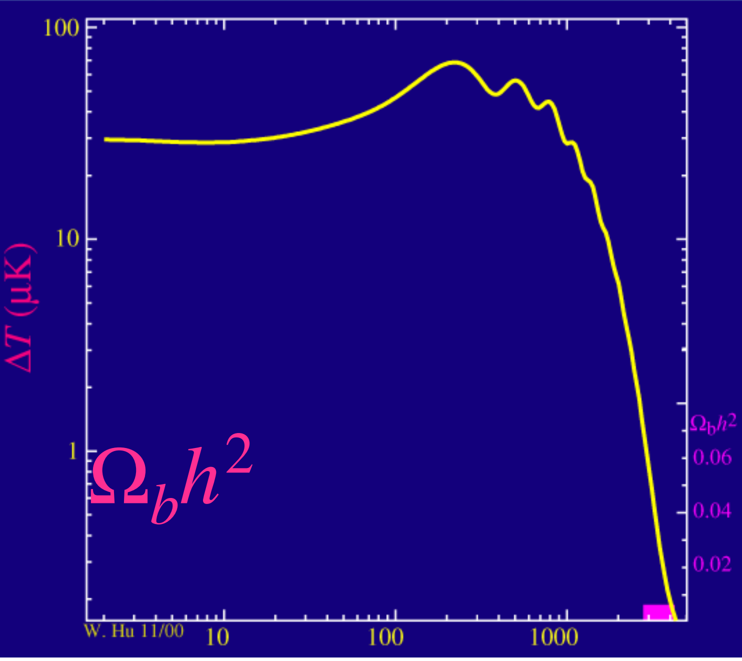


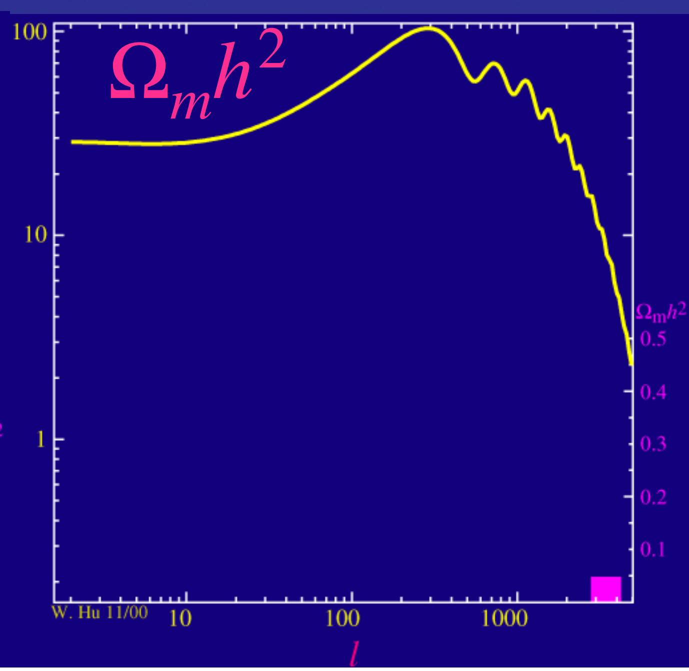
Fig. 1. *Planck* 2018 temperature power spectrum. At multipoles $\ell \geq 30$ we show the frequency-coadded temperature spectrum computed from the `Plik` cross-half-mission likelihood, with foreground and other nuisance parameters fixed to a best fit assuming the base-ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the `Commander` component-separation algorithm, computed over 86 % of the sky. The base-ΛCDM theoretical spectrum best-fit to the *Planck* TT,TE,EE+lowE+lensing likelihoods is plotted in light blue in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ diagonal uncertainties, including cosmic variance (approximated as Gaussian) and not including uncertainties in the foreground model at $\ell \geq 30$.

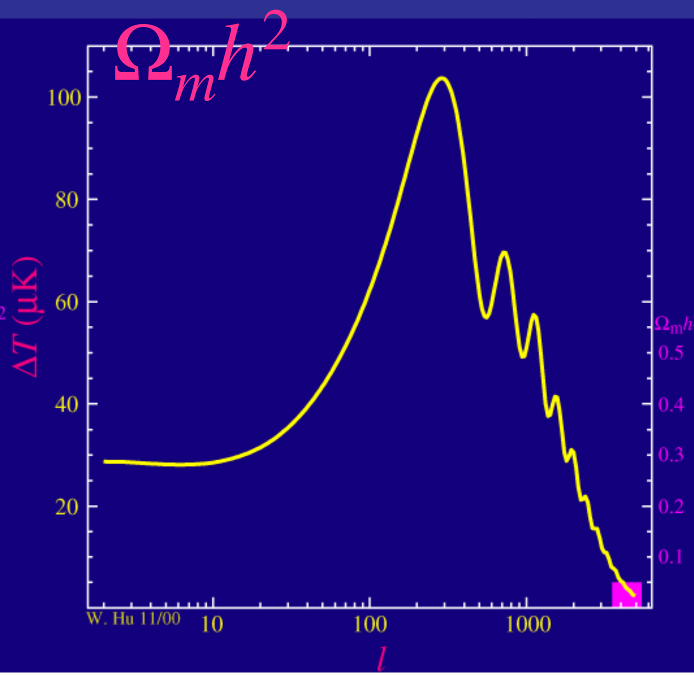
Wayne Hu Tutorials











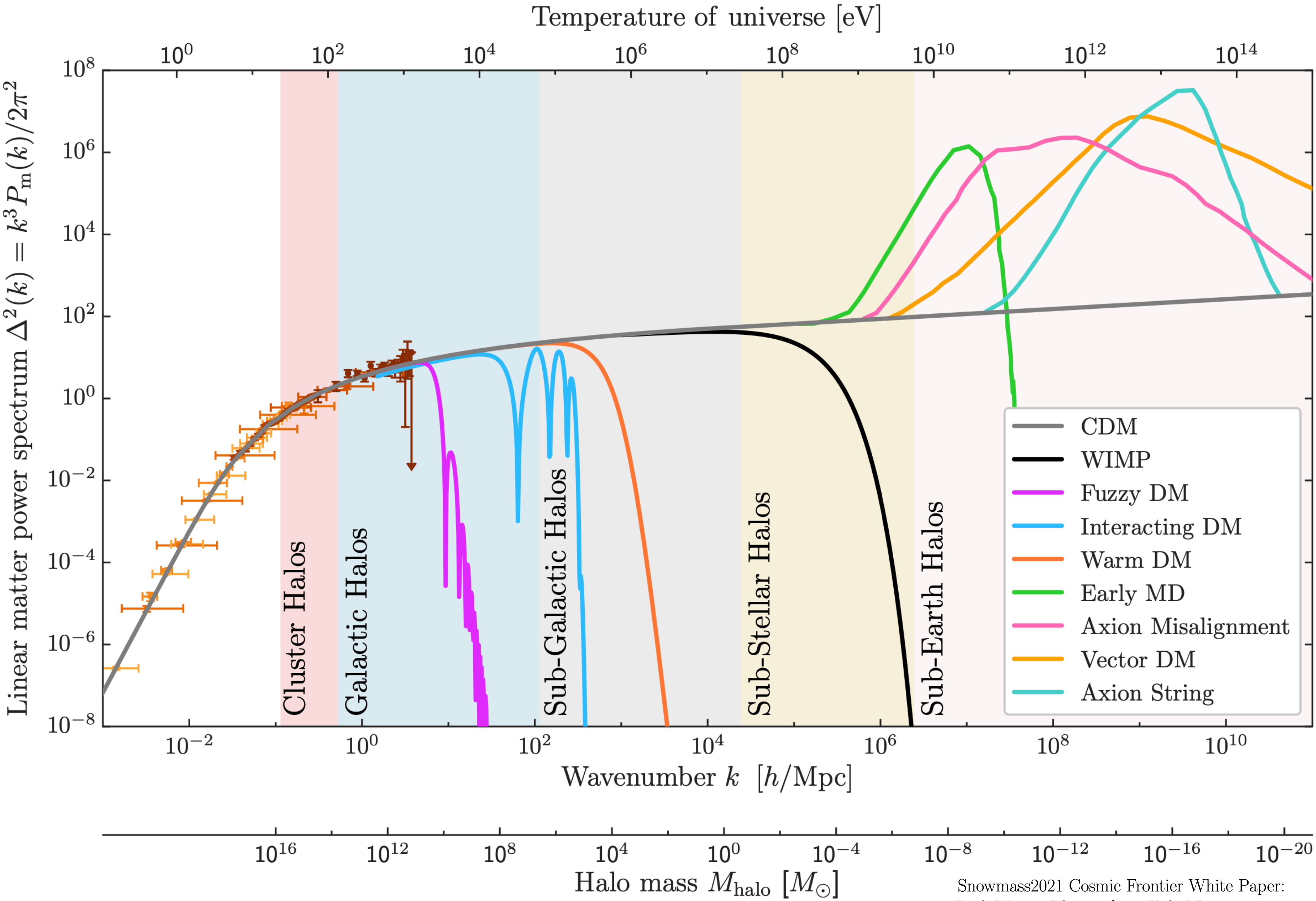
Universe at 400,000 years

- Temperature 3000K, fluctuations 1 part in 100,000
- Density 300 per cm^3, fluctuations 1 part in 1,000
- Hydrogen 76% & Helium 24%.
  Ion fraction: 2 part in 100,000
- Dark Matter about 6 times more than baryons
- **No observations between 400,000 and 800 million years of the universe! So called Dark Ages.**

A New Era in the Quest for Dark Matter

Gianfranco Bertone[1] and Tim M.P. Tait[1,2]

Figure 1. Visualization of possible solutions to the dark matter problem.



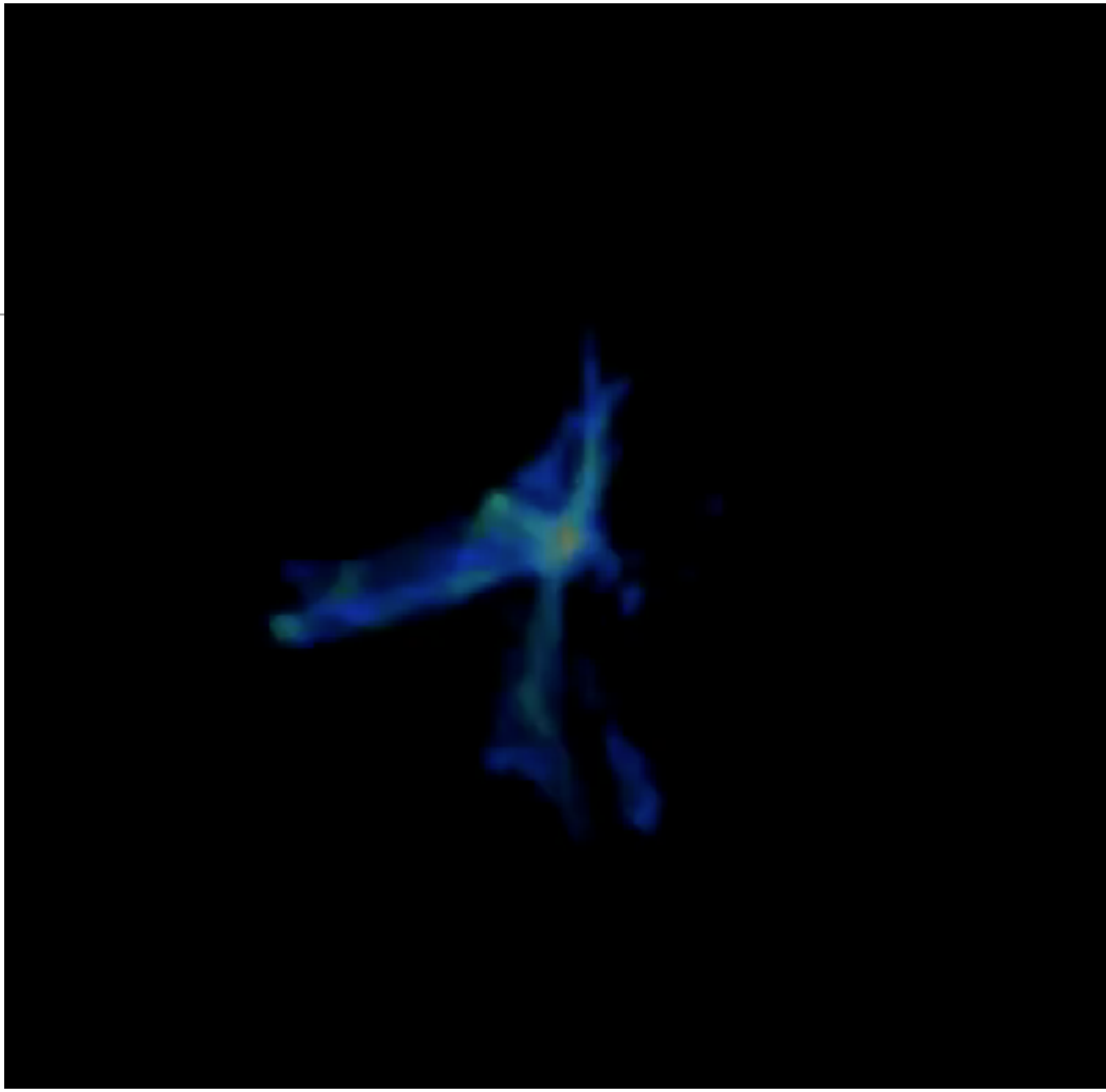
Snowmass2021 Cosmic Frontier White Paper:
Dark Matter Physics from Halo Measurements

Keith Bechtol[1], Simon Birrer[2,3,4], Francis-Yan Cyr-Racine[5], Katelin Schutz[6], Susmita Adhikari[7,8], Arka Banerjee[7,9], Simeon Bird[10], Nikita Blinov[11], Kimberly K. Boddy[12], Celine Boehm[13], Kevin Bundy[14,15], Malte Buschmann[16], Sukanya Chakrabarti[17], David Curtin[18], Liang Dai[19], Alex Drlica-Wagner[8,9,20], Cora Dvorkin[21], Adrienne L. Erickcek[22], Daniel Gilman[23], Saniya Heeba[6], Stacy Kim[24], Vid Iršič[25,26], Alexie Leauthaud[14], Mark Lovell[27], Zarija Lukić[28], Yao-Yuan Mao[29], Sidney Mau[2,3], Andrea Mitridate[30], Philip Mocz[31], Julian B. Muñoz[32], Ethan O. Nadler[33,34], Annika H. G. Peter[35], Adrian Price-Whelan[36], Andrew Robertson[37], Nashwan Sabti[38], Neelima Sehgal[39], Nora Shipp[8,20], Joshua D. Simon[33], Rajeev Singh[42], Ken Van Tilburg[35,40], Risa H. Wechsler[2,3,4], Axel Widmark[41], and Hai-Bo Yu[10]

First Things in the Universe

Physics problem:

- Initial Conditions measured
- Constituents, Density Fluctuations, Thermal History
- Physics: Gravity: DM & Gas, HD, Chemistry, Radiative Cooling, Radiation Transport, Cosmic Rays, Dust drift & cooling, Supernovae, Stellar evolution, etc.
- Transition from Linear to Non-Linear:
  - Using patched based structured adaptive (space & time) mesh refinement
  - Use a computer!
- Assume dark matter is a collisionless fluid made of particles heavier than about 40 keV (constrained from free streaming scale) that interact only gravitationally



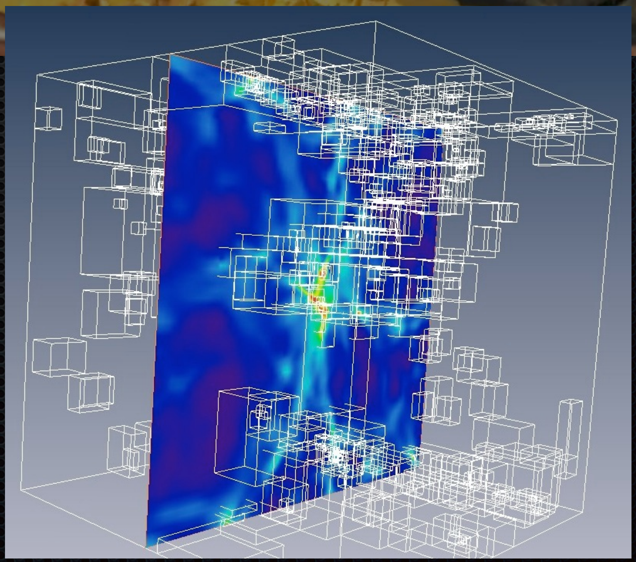
Ralf Kähler & Tom Abel for PBS Origins. Aired Dec 04

$$\frac{\mathrm{R}_\odot}{\mathrm{R}_{\mathrm{Milky\,Way}}} \approx 10^{-12}$$

$$\frac{\mathrm{P}_{\odot,\mathrm{Kepler}}}{\mathrm{t}_{\mathrm{Hubble}}(\mathrm{z}=30)} \approx 10^{-12}$$

Cosmological Adaptive Mesh Refinement

- **Enzo: Bryan and Norman 1997-; Abel et al 97; Anninos et al 97; Bryan, Abel & Norman 2002; O'Shea et al; Abel, Wise & Bryan 2006, Bryan et al. 2014**
- **~300,000 lines of code in C++ and F77, F90**
  - **Cosmological Radiation Hydrodynamics adapting in space and time**
  - **Dynamic range up to 1e15 using quadruple precision coordinates in space and time**
  - **Dynamically load balanced parallel with MPI**
  - **Gravity, DM, Gas, Chemistry, Radiation, star formation & feedback**
  - **Developments @ KIPAC: dimensionally unsplit hydro algorithms, higher order time updates, exact 3D radiation transport, very high density chemistry, HD & fine structure line cooling, relativistic hydro, MHD, new visualization toolkits**



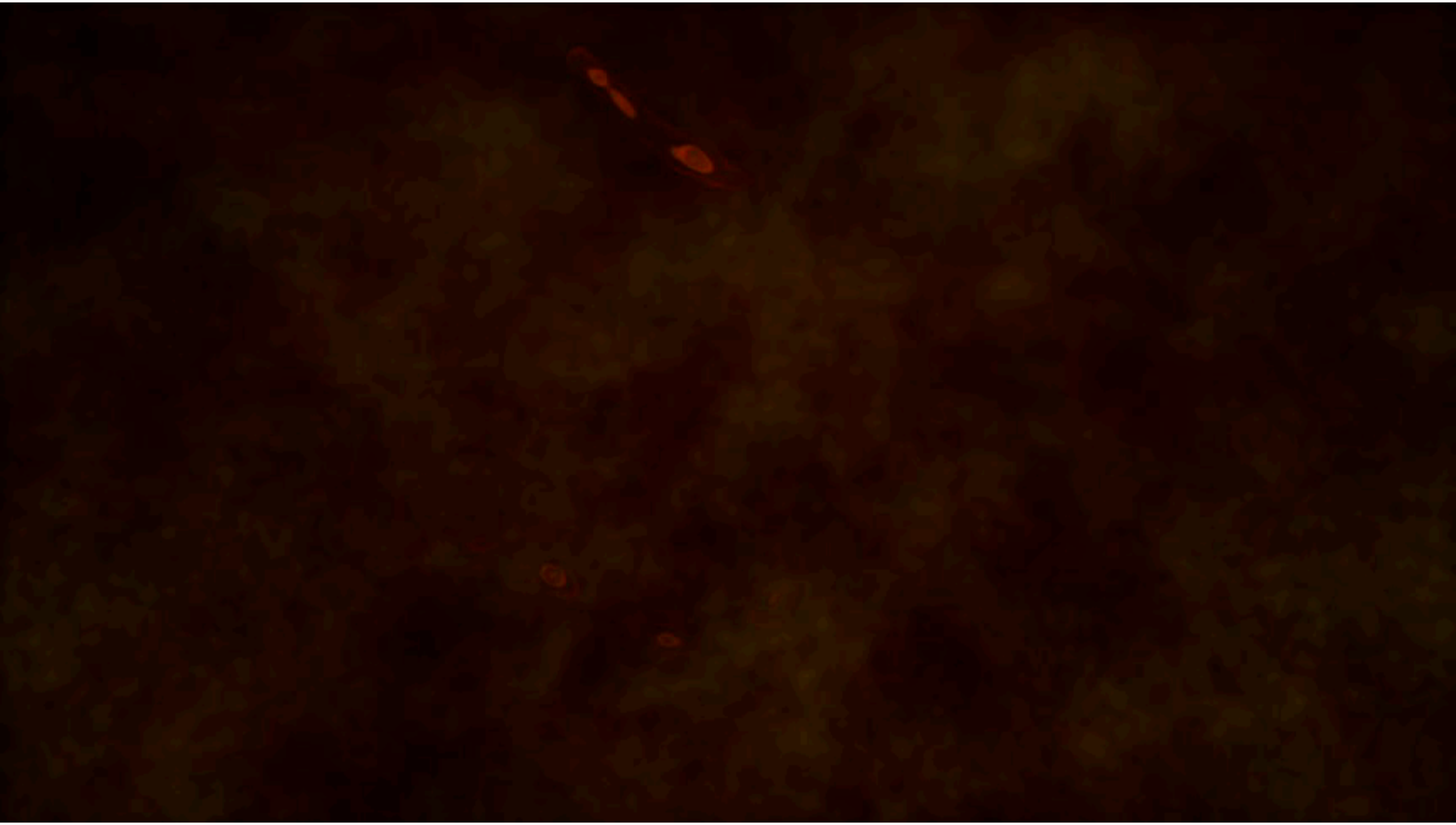
Primordial Gas Chemistry

(1)	$H + e^- \rightarrow H^+ + 2e^-$
(2)	$H^+ + e^- \rightarrow H + h\nu$
(3)	$He + e^- \rightarrow He^+ + 2e^-$
(4)	$He^+ + e^- \rightarrow He + h\nu$
(5)	$He^+ + e^- \rightarrow He^{++} + 2e^-$
(6)	$He^{++} + e^- \rightarrow He^+ + h\nu$
(7)	$H + e^- \rightarrow H^- + h\nu$
(8)	$H + H^- \rightarrow H_2 + e^-$
(9)	$H + H^+ \rightarrow H_2^+ + h\nu$
(10)	$H_2^+ + H \rightarrow H_2 + H^+$
(10)	$H_2^+ + H \rightarrow H_2 + H^+$
(11)	$H_2 + H^+ \rightarrow H_2^+ + H$
(12)	$H_2 + e^- \rightarrow 2\,H + e^-$
(13)	$H_2 + H \rightarrow 3\,H$
(14)	$H^- + e^- \rightarrow H + 2e^-$
(15)	$H^- + H \rightarrow 2\,H + e^-$
(16)	$H^- + H^+ \rightarrow 2\,H$
(17)	$H^- + H^+ \rightarrow H_2^+ + e^-$
(18)	$H_2^+ + e^- \rightarrow 2\,H$
(19)	$H_2^+ + H^- \rightarrow H_2 + H$

- Reaction 8 is much faster than reaction 7.
- I.e. (7) will continue as long as free electrons are available -> H2 formation timescale = recombination timescale
- However, $k_7 \propto T^{0.88}$ hence adiabatic contraction important. Requires sufficiently high virial temperatures and so introduces a temperature (mass) scale based on chemistry

$$T_{vir}^{Chem} \approx 10^3\,\mathrm{K}$$

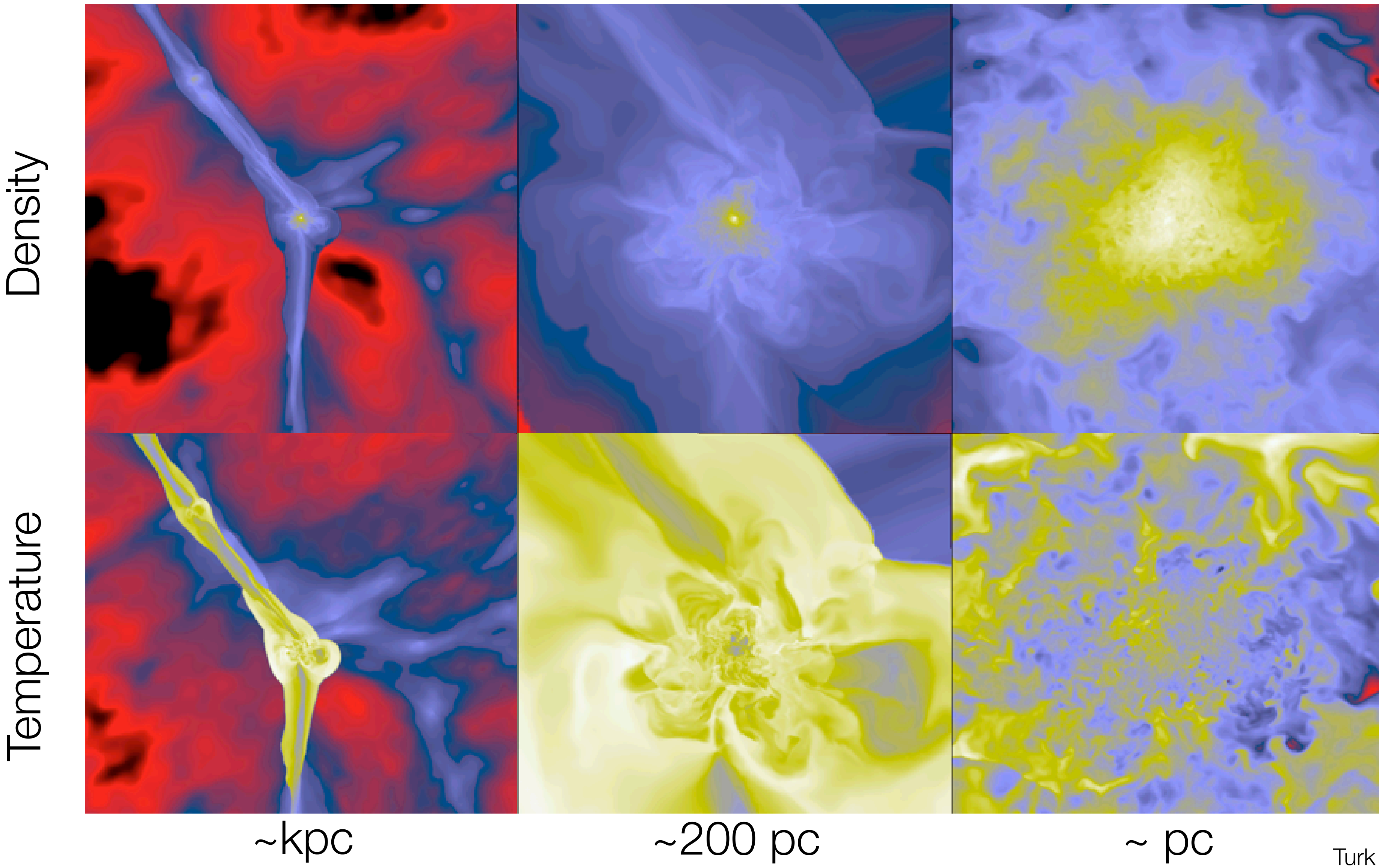
Making a proto-star



Simulation: Tom Abel (KIPAC/Stanford), Greg Bryan (Columbia), Mike Norman (UCSD)
Viz: Ralf Kähler (AEI, ZIB, KIPAC), Bob Patterson, Stuart Levy, Donna Cox (NCSA), Tom Abel

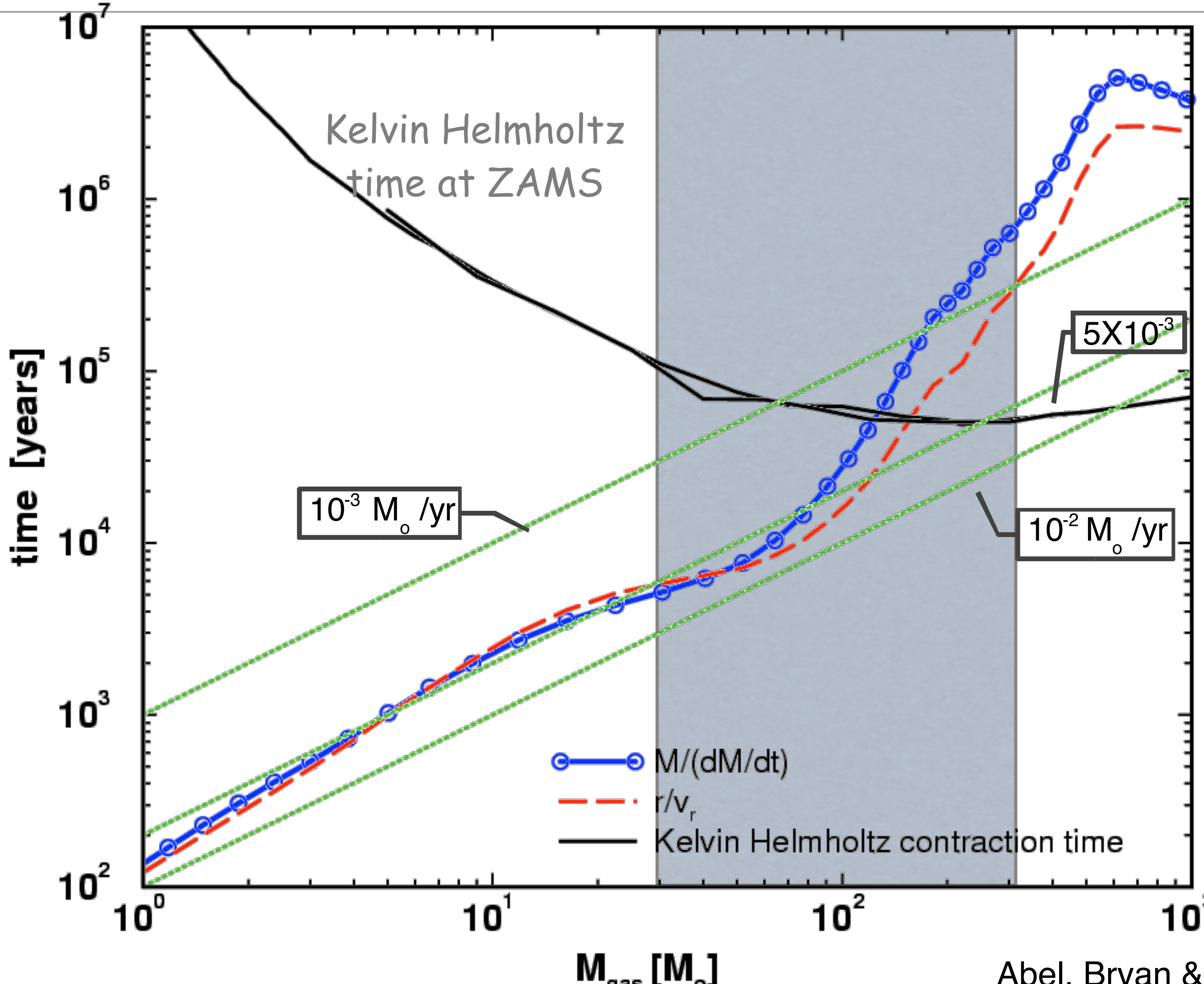
Formation of the very first stars very well suited to ab initio modeling

Can only increase effective Reynolds number with super-computing
Average properties such as mass and temperature profiles converge reasonably well.
Amount of turbulence, vorticity and magnetic field generated less so.



Turk et al, 2009-

Mass Scales?

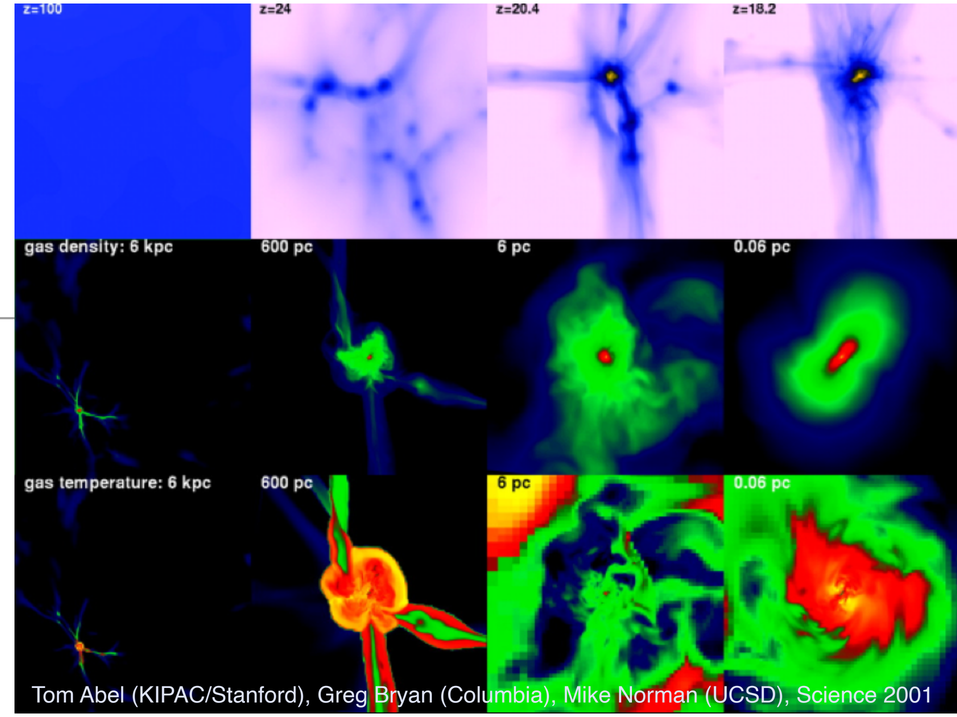


Abel, Bryan & Norman 2002

~30 high res sims of different environments
At least one out of five cases
Binaries and even triple systems are made in first collapse.

Simulation: Matthew Turk, Tom Abel (KIPAC/Stanford), Brian O'Shea (UMich) 2009 Science
Viz: Ralf Kähler, Tom Abel
See in Physics Today April 2011 article

Recap



First Stars are massive and form differently than present day stars

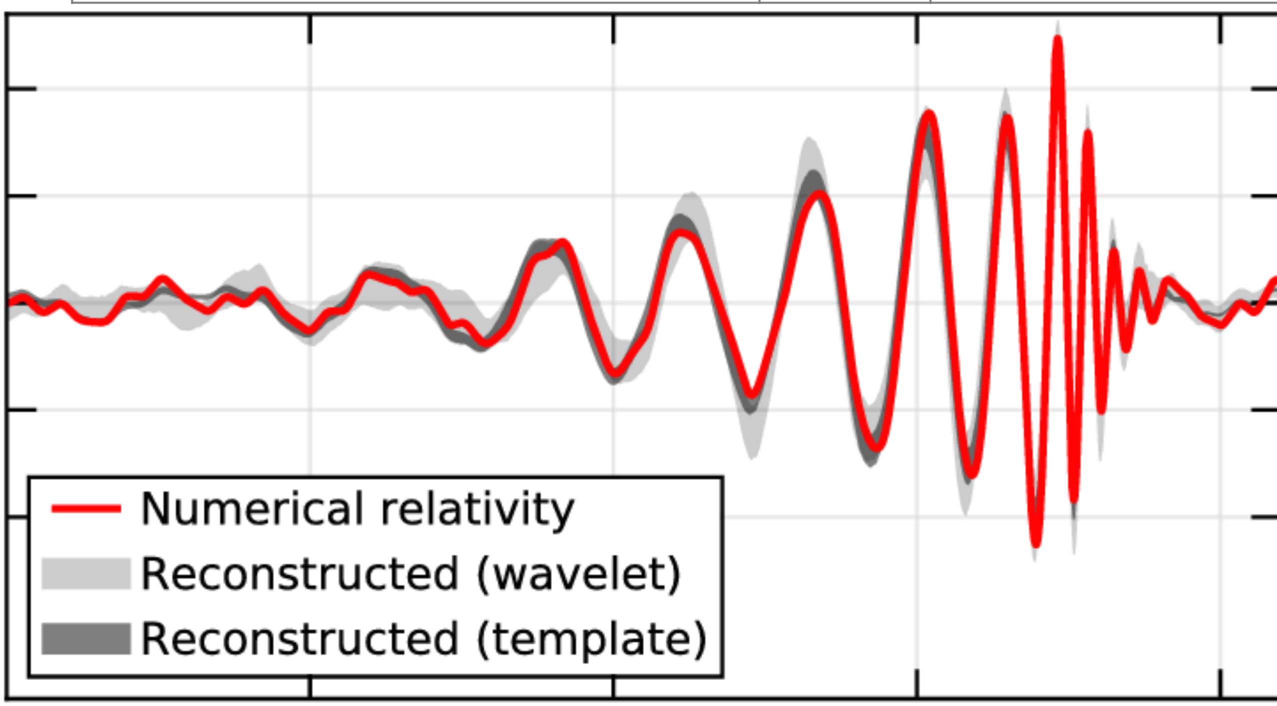
- Theoretical uncertainty: 30 - 300 solar mass
  Many simulations with three different numerical techniques and a large range of numerical resolutions have converged to this result. Some of these calculations capture 20 orders of magnitude in density!
  Non-equilibrium chemistry & cooling, three body H2 formation, chemical heating, H2 line transfer, collision induced emission and its transport, and sufficient resolution to capture chemo-thermal and gravitational instabilities.
  Stable results against variations on all so far test dark matter variations, as well as strong soft UV backgrounds.
- Massive Binaries and multiple systems in at least 1 out of 5 cases
- Work by (Clarke, Klessen, Glover et al 2012-) claim that perhaps a small number of additional lower mass stars and brown dwarfs surround these big ones

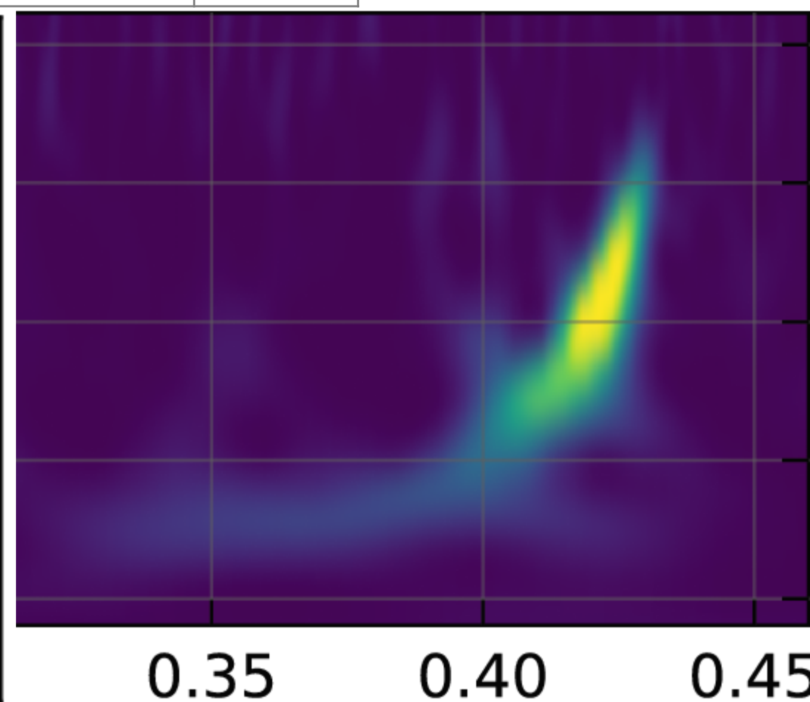
cosmological: Abel et al 1998; Abel, Bryan & Norman 2000, 2002; O'Shea et al 2006; Yoshida et al 2006; Gao et al 2006
idealized spheres: Haiman et al 1997; Nishi & Susa 1998; Bromm et al 1999, 2000, 2002; Ripamonti & Abel 2004

Estimated source parameters

GW170104

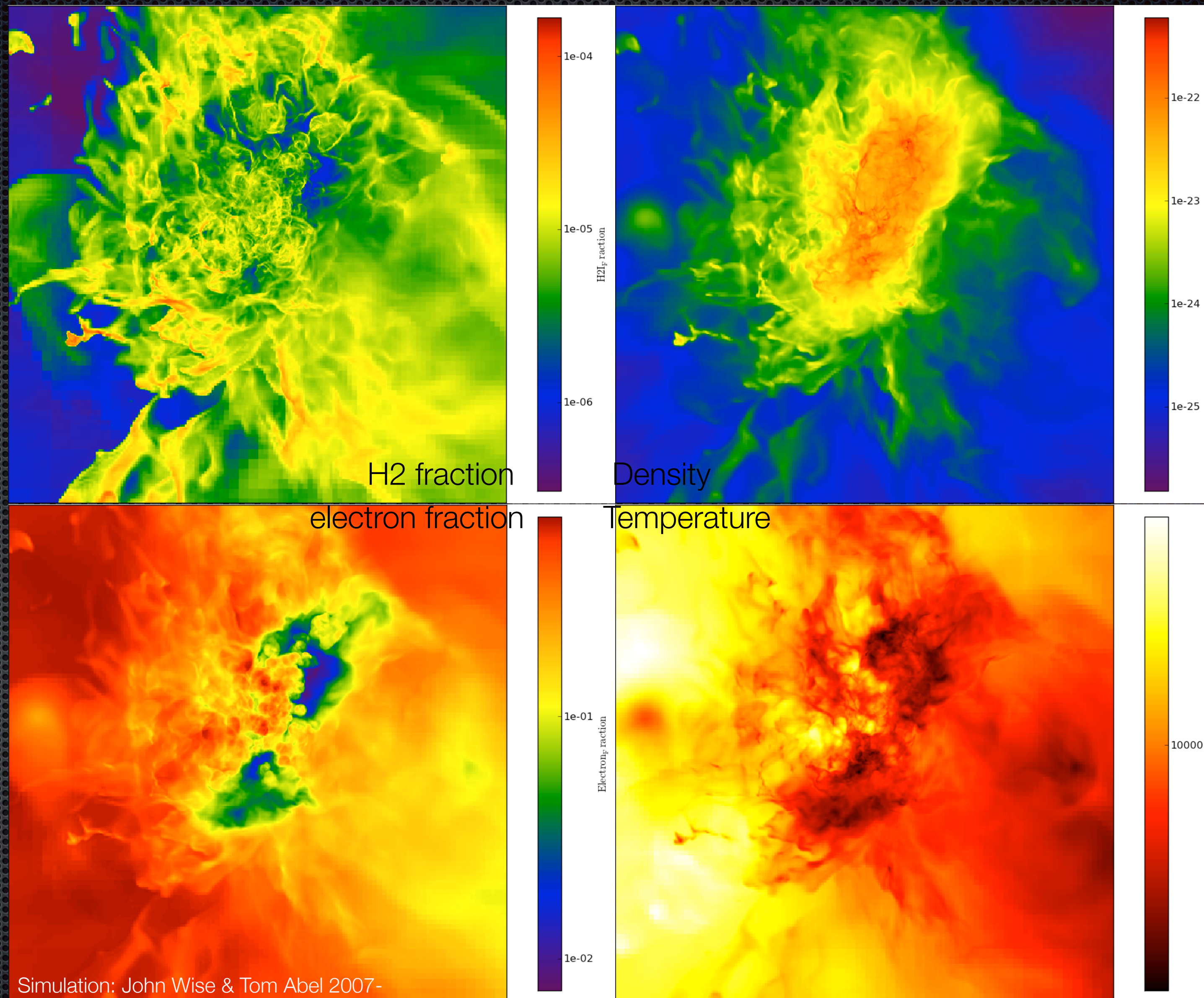
Quantity	Value	Upper/Lower error estimate	Unit
Primary black hole mass	36	+5 -4	M sun
Secondary black hole mass	29	+4 -4	M sun
Final black hole mass	62	+4 -4	M sun
Final black hole spin	0.67	+0.05 -0.07	
Luminosity distance	410	+160 -180	Mpc
Source redshift, z	0.09	+0.03 -0.04	
Energy radiated	3	+0.5 -0.5	M sun

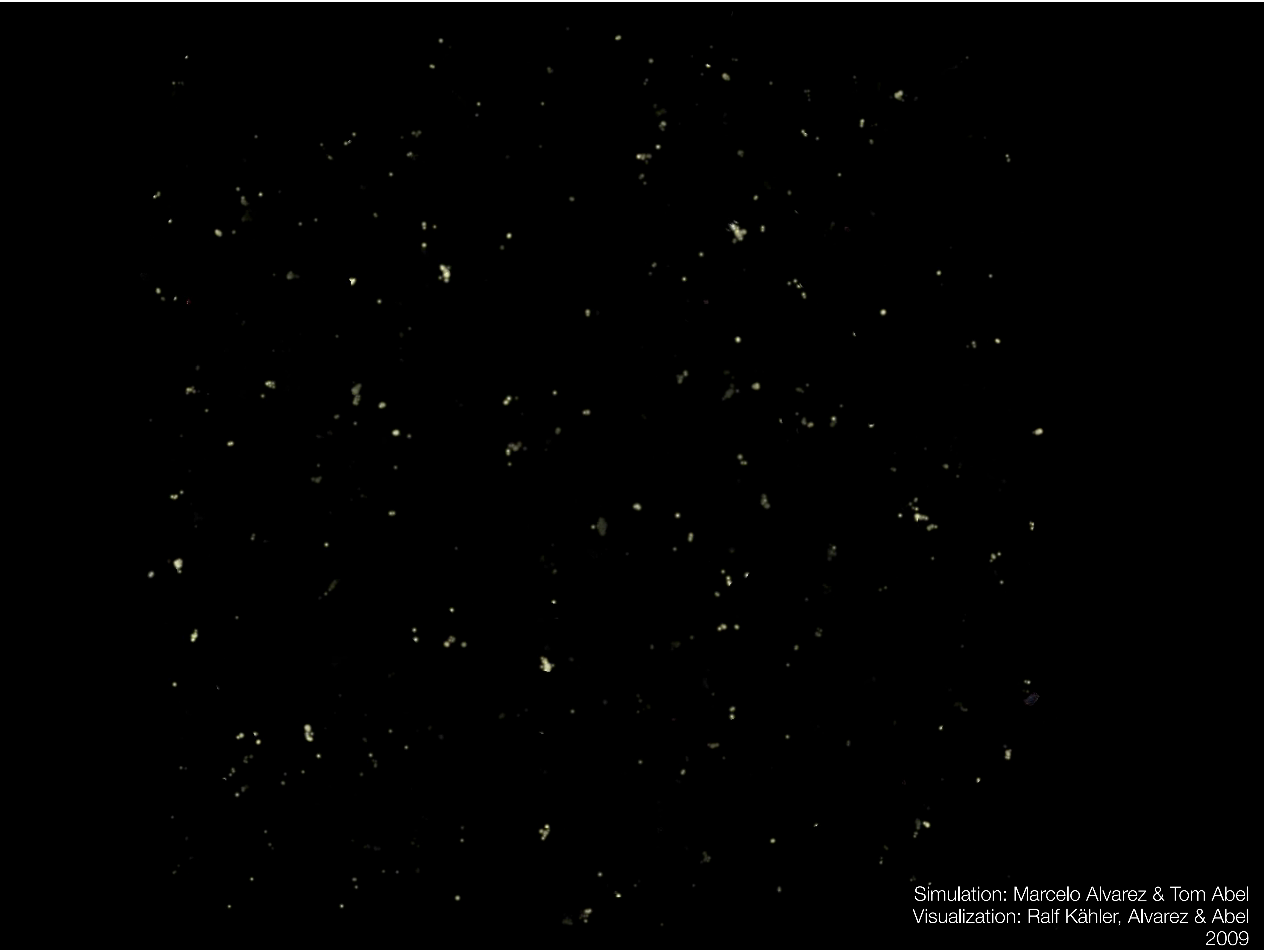




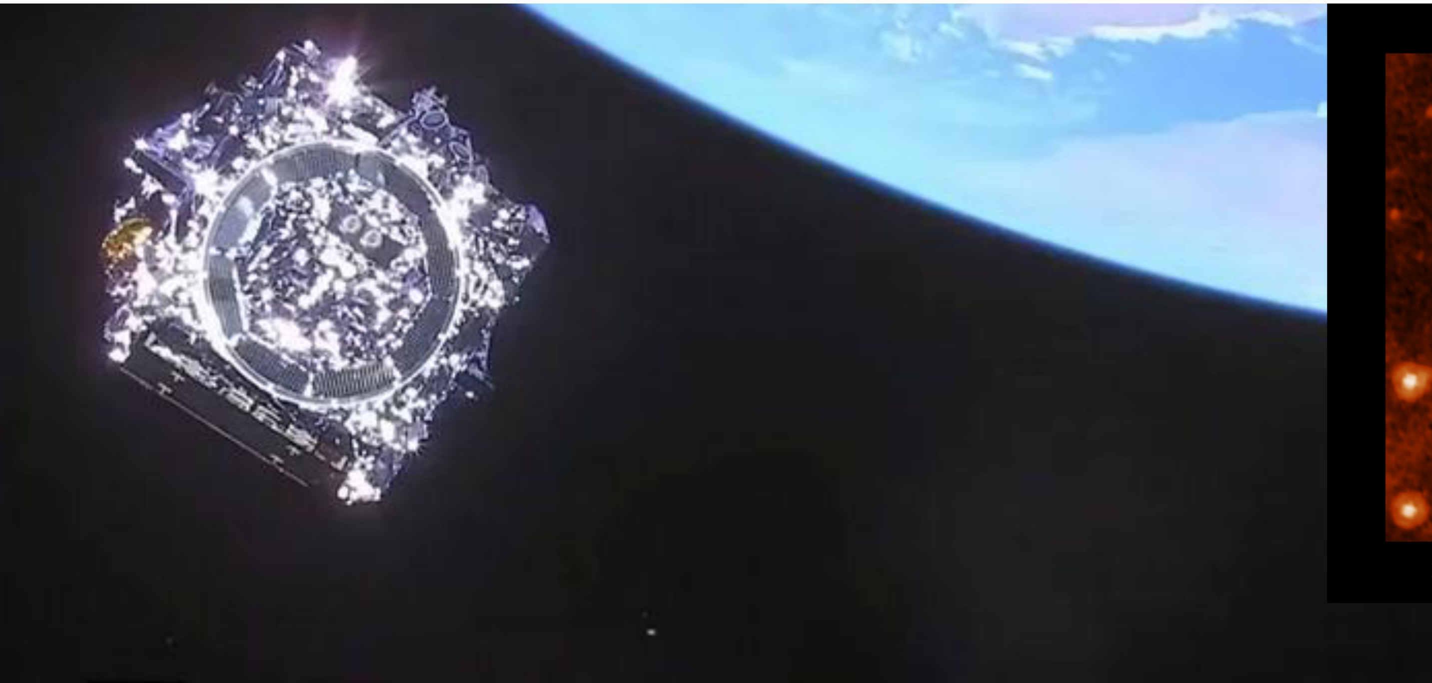
Virtual Galaxies are starting to look reasonable

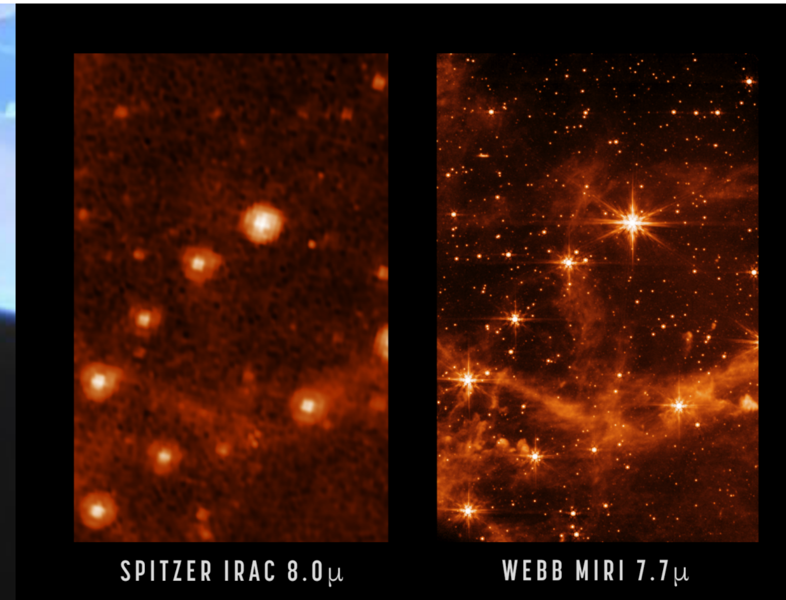
- Modern techniques
- Large super-computers
- Billions of resolution elements
- thousands such early galaxies are now part of the Milky Way
- Still not as good as the real thing of course …



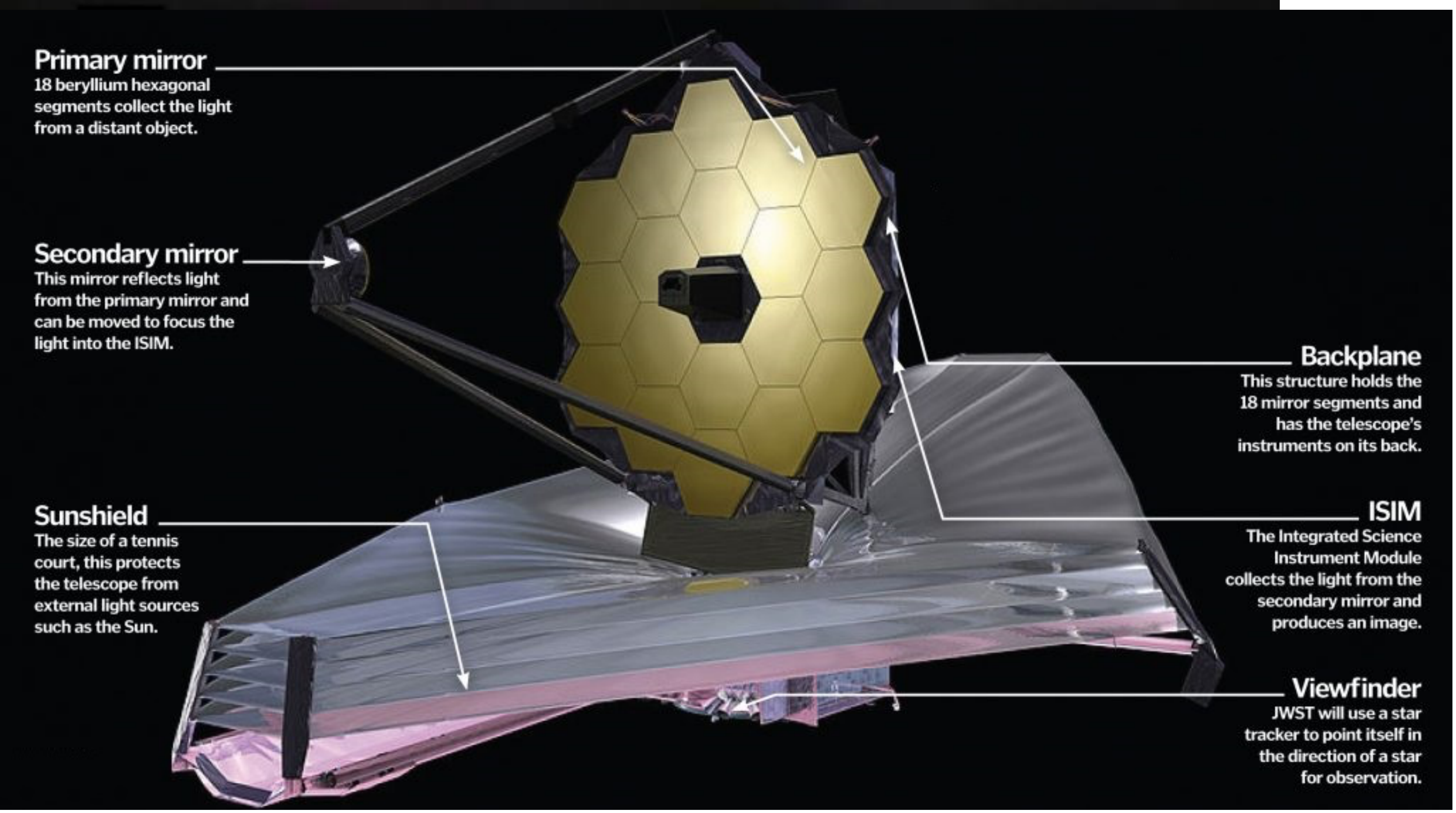


Simulation: Marcelo Alvarez & Tom Abel
Visualization: Ralf Kähler, Alvarez & Abel
2009





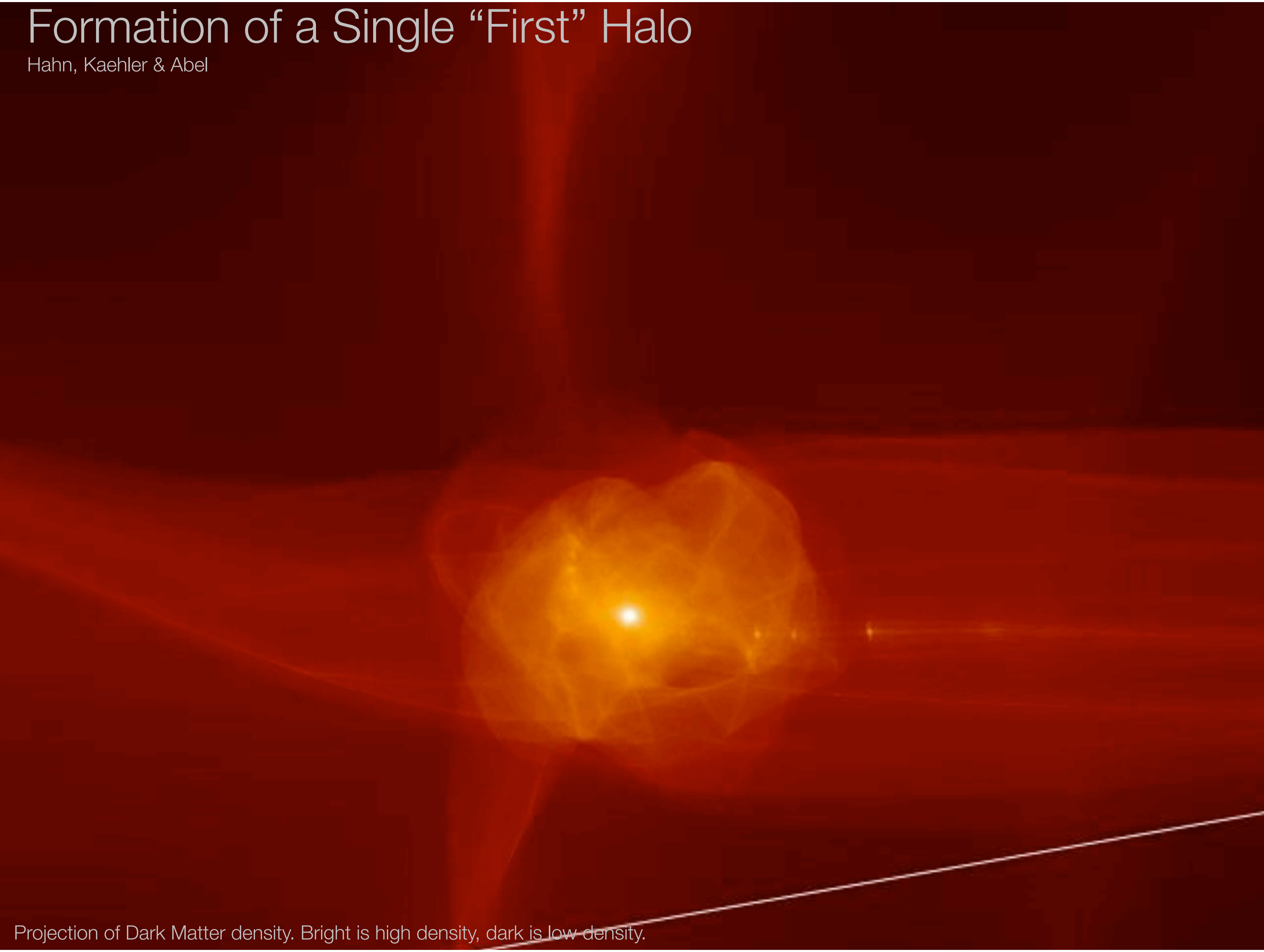
First images in 2 weeks ..



esa
JWST

Formation of a Single “First” Halo

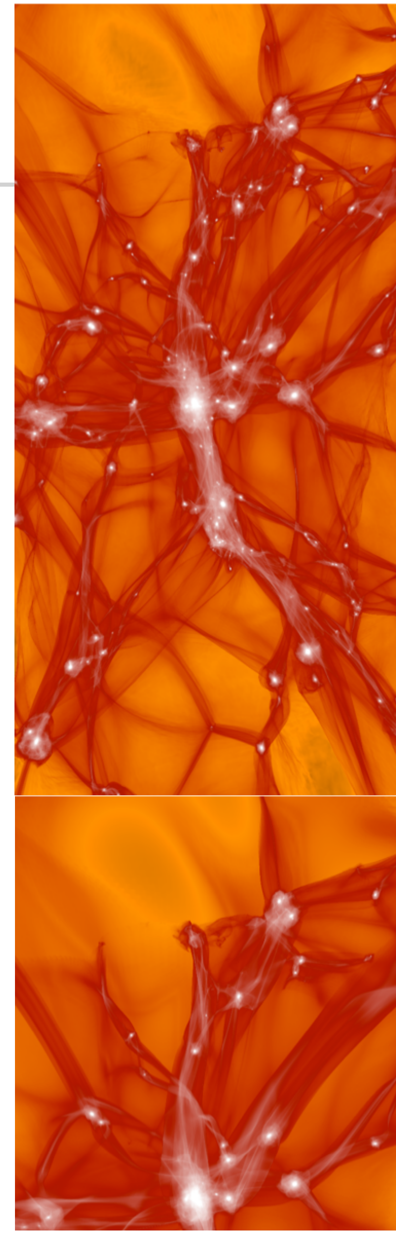
Hahn, Kaehler & Abel



Projection of Dark Matter density. Bright is high density, dark is low density.

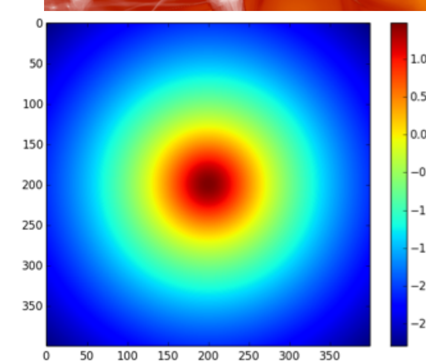
Cosmological N-body simulations

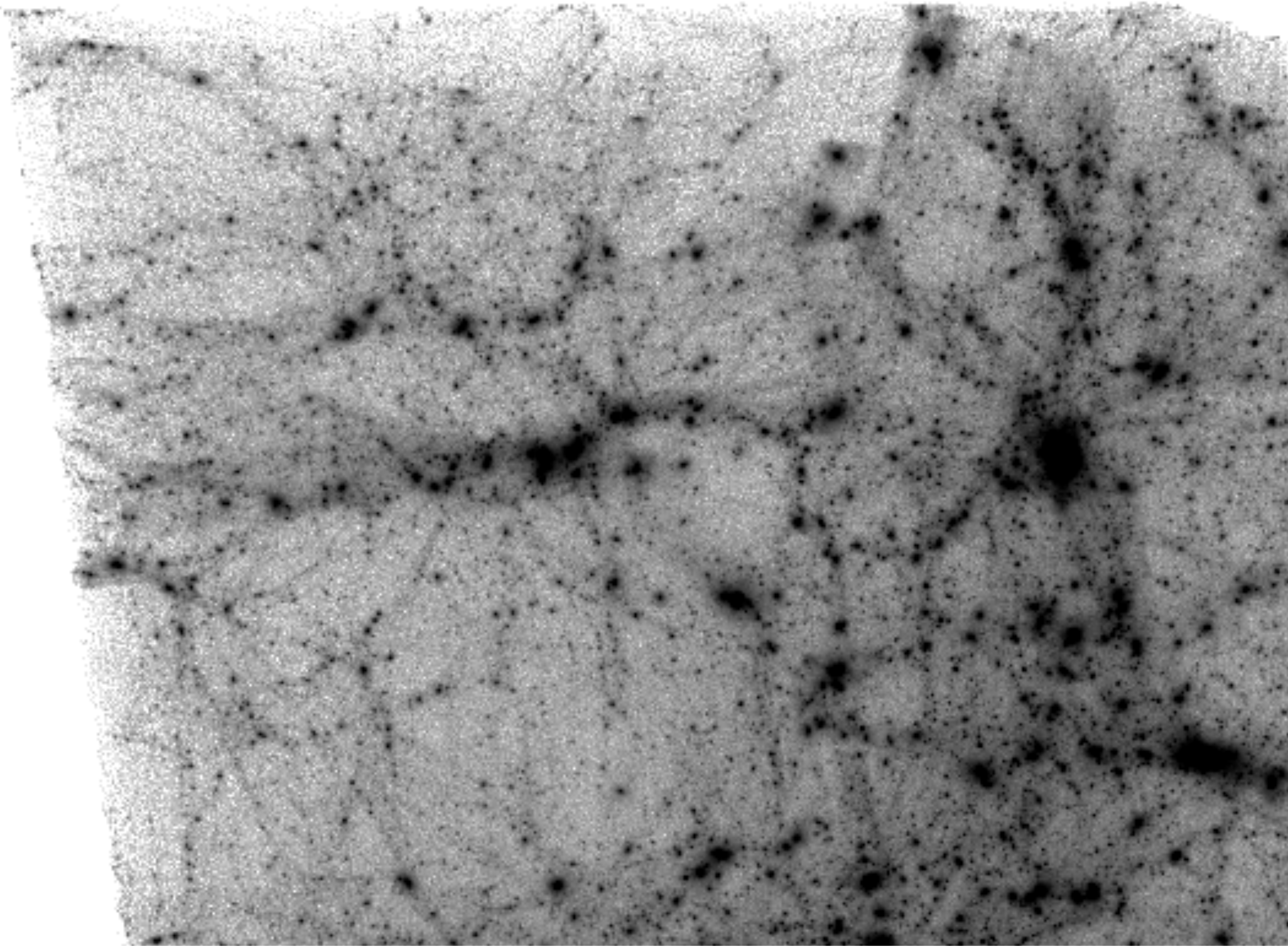
$$\dot{\mathbf{x}} = \mathbf{v}(t) \qquad \dot{\mathbf{v}}_{\mathbf{i}} = -\sum_{i \neq j}^{N} G m_i m_j \frac{(\mathbf{x}_{\mathbf{j}} - \mathbf{x}_{\mathbf{i}})}{|\mathbf{x}_{\mathbf{j}} - \mathbf{x}_{\mathbf{i}}|^3}$$



- All modern cosmological simulation codes only differ in how they accelerate the computation of the sum over all particles to obtain the net force
- End result are simply the positions and velocities of all particles
- Softening of forces (add epsilon^2 in denominator) avoids singularities.
- Limit N goes to infinity must give correct answer, right?
- Plummer softening

$$\dot{\mathbf{v}}_i = -\sum_{i \neq j}^{N} G\, m_i\, m_j \frac{(\mathbf{x}_j - \mathbf{x}_i)}{\left(|\mathbf{x}_j - \mathbf{x}_i|^2 + \epsilon^2\right)^{3/2}}$$





GRAVITY:

TOTAL MASS DENSITY

POISSON EQUATION: $\nabla^2 \phi = 4\pi G \rho$

CONTINUUM DESCRIPTION $\vec{F}/m = -\nabla \phi$

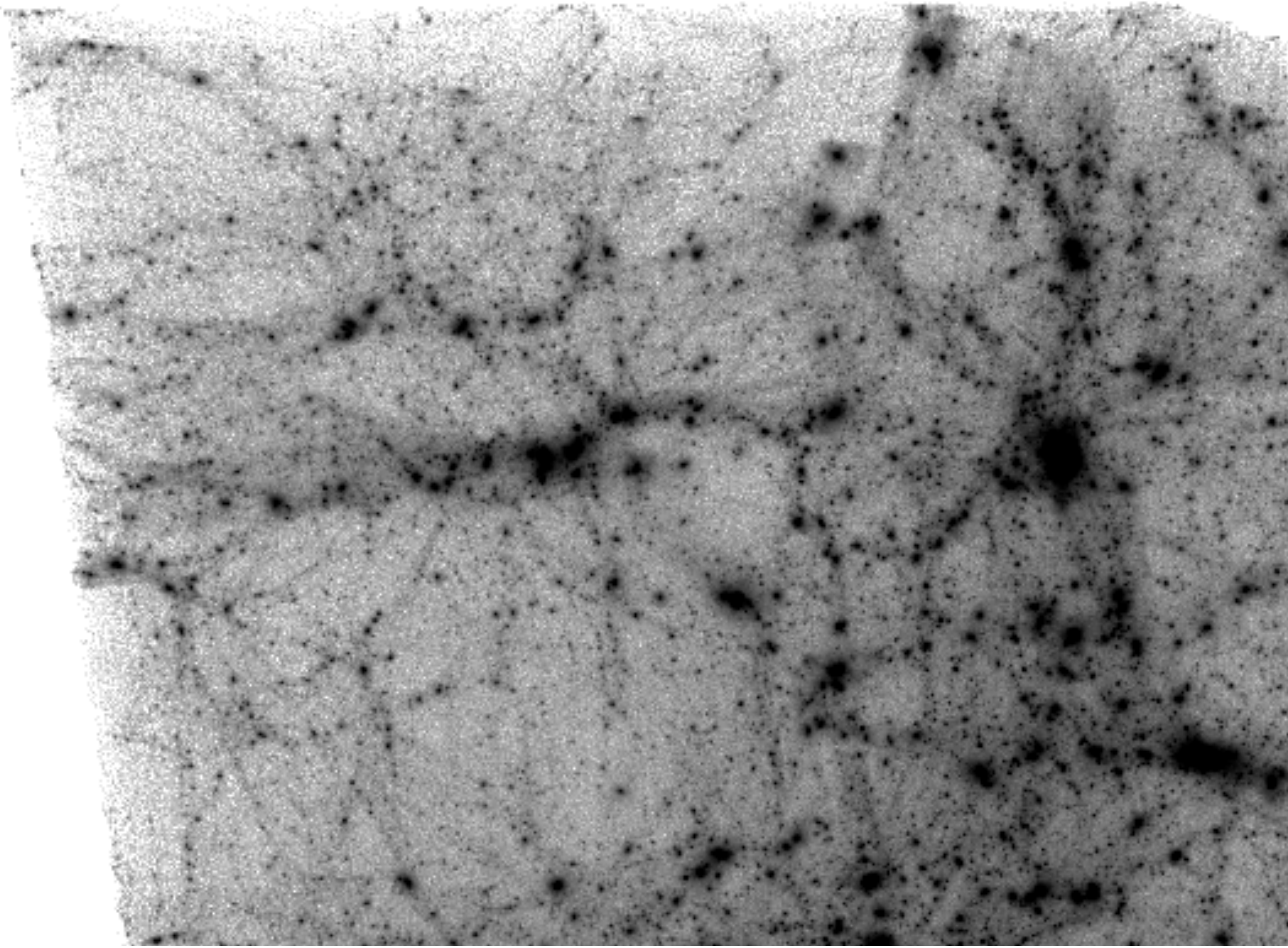
VLASOV EQUATION $\frac{\partial f}{\partial t} + v \nabla_x f - \nabla \phi \nabla_v f = 0$

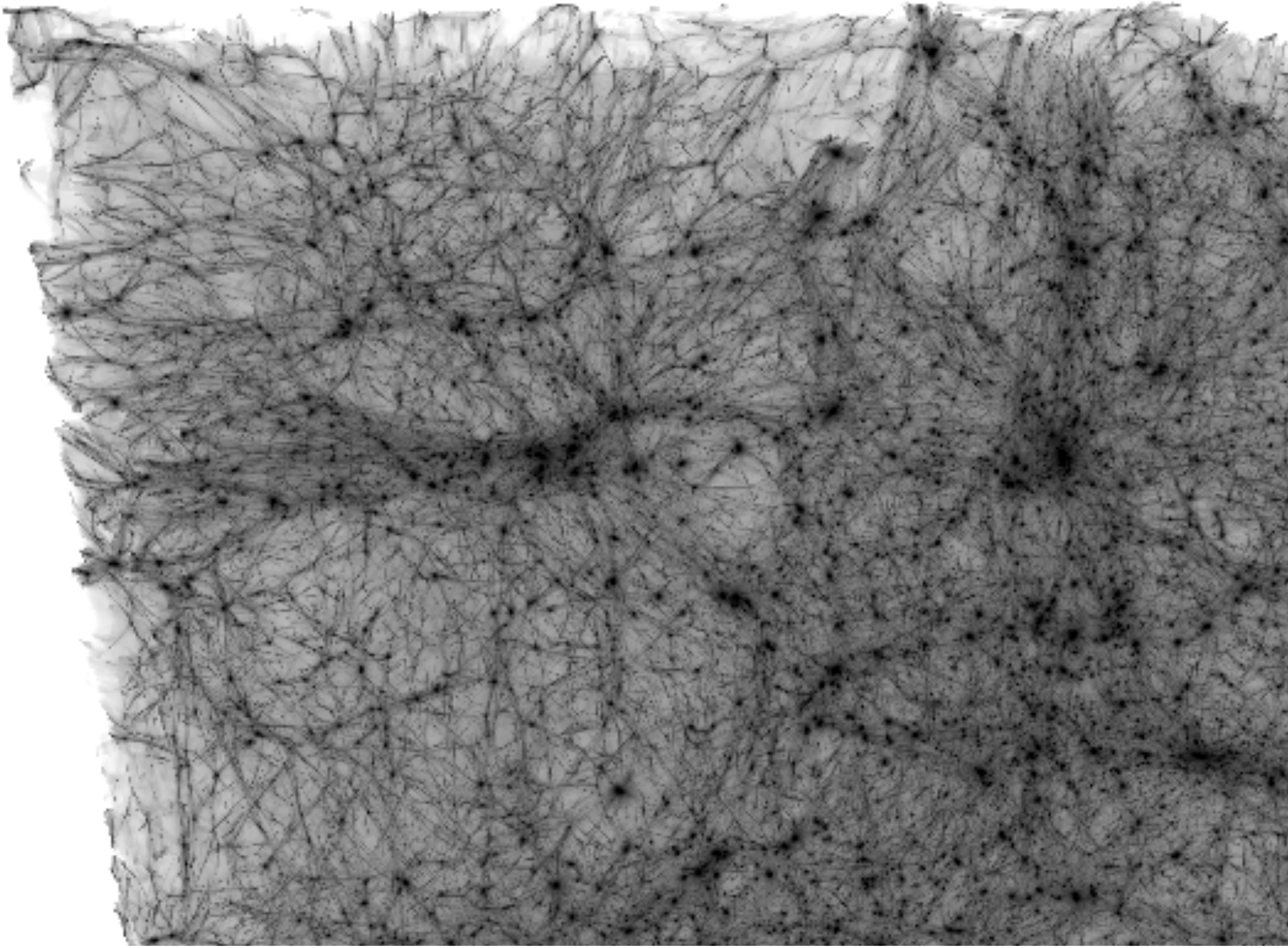
FOR $N \to \infty$ IDENTICAL

N POINT MASSES: $\vec{a}_j = -\sum_{i \neq j} \frac{G m_i}{|\vec{x}_j - \vec{x}_i|^2 + \varepsilon^2} \frac{(\vec{x}_j - \vec{x}_i)}{|\vec{x}_j - \vec{x}_i|}$

PARTICLE PICTURE

Particle "advection": $\frac{\partial \vec{x}_j}{\partial t} = \vec{v}$; $\frac{\partial \vec{v}_j}{\partial t} = \vec{a}_j$





The Dark Matter Sheet?

Fluid

OF DARK MATTER PARTICLES IN THE MILKY WAY :

$$N_{DM} \approx 10^{67}\left(\frac{100\,GeV}{m_{DM}}\right) \gg \text{\# OF STARS IN THE UNIVERSE}$$

$$\gg \text{\# OF PARTICLES THAT FIT ON A COMPUTER}$$

USING ALL THE COMPUTERS IN THE WORLD : $\lesssim 10^{17}$ particles

SOLVE VLASOV-POISSON SYSTEM INSTEAD.

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\nabla_x f + \vec{a}\cdot\vec{\nabla}_v f = 0$$

$$\vec{a} = -\vec{\nabla}\phi$$

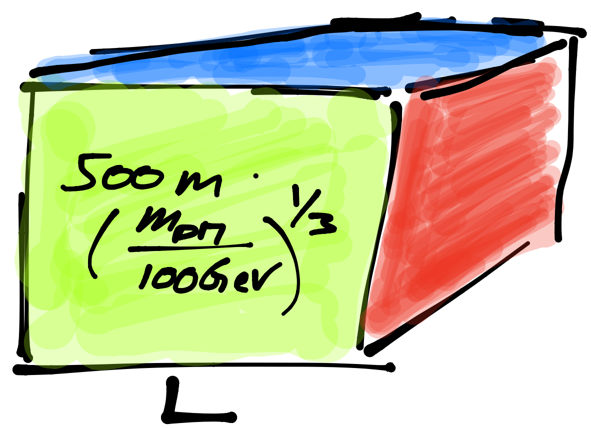
$$\nabla^2\phi = 4\pi G\rho$$

f: distribution function in PHASE SPACE

ϕ: potential

FOR PHASE SPACE ELEMENT TO CONTAIN 10^6 PARTICLES @ MEAN DENSITY IT HAS TO BE LARGER THAN

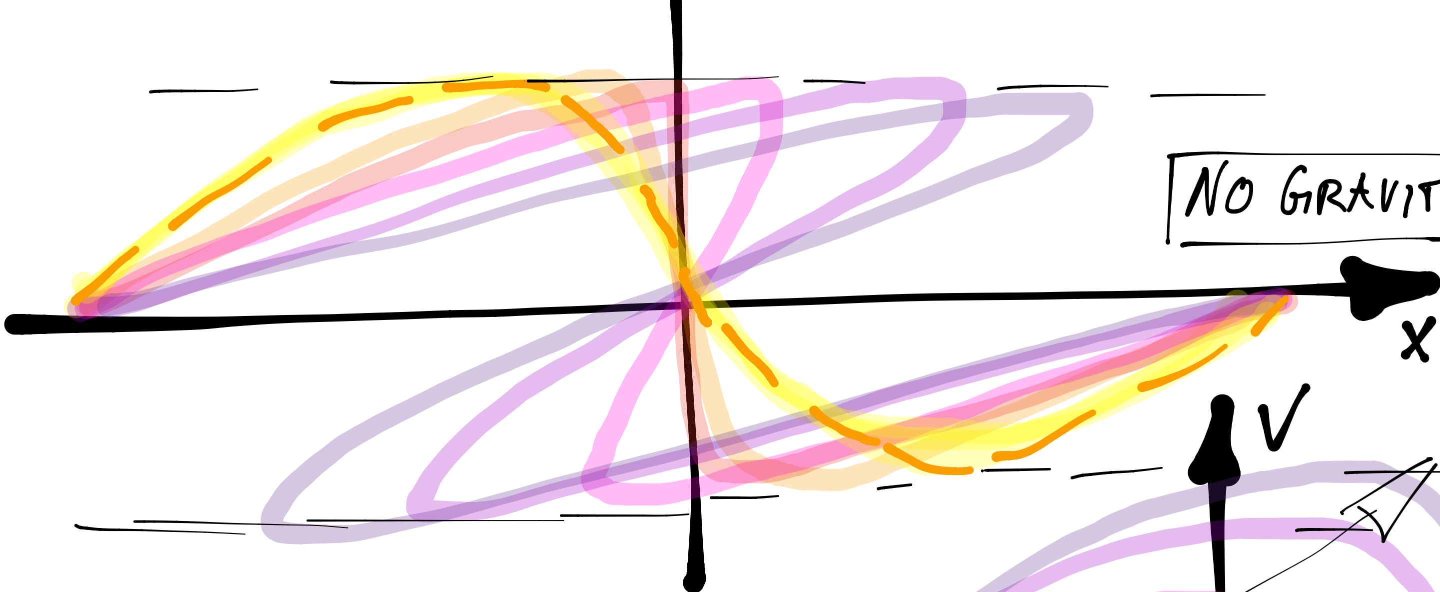
$$L \sim 500\,m\left(\frac{m_{DM}}{100\,GeV}\right)^{1/3}$$



DARK MATTER

m.f.p. >> SYSTEM

PHASE SPACE

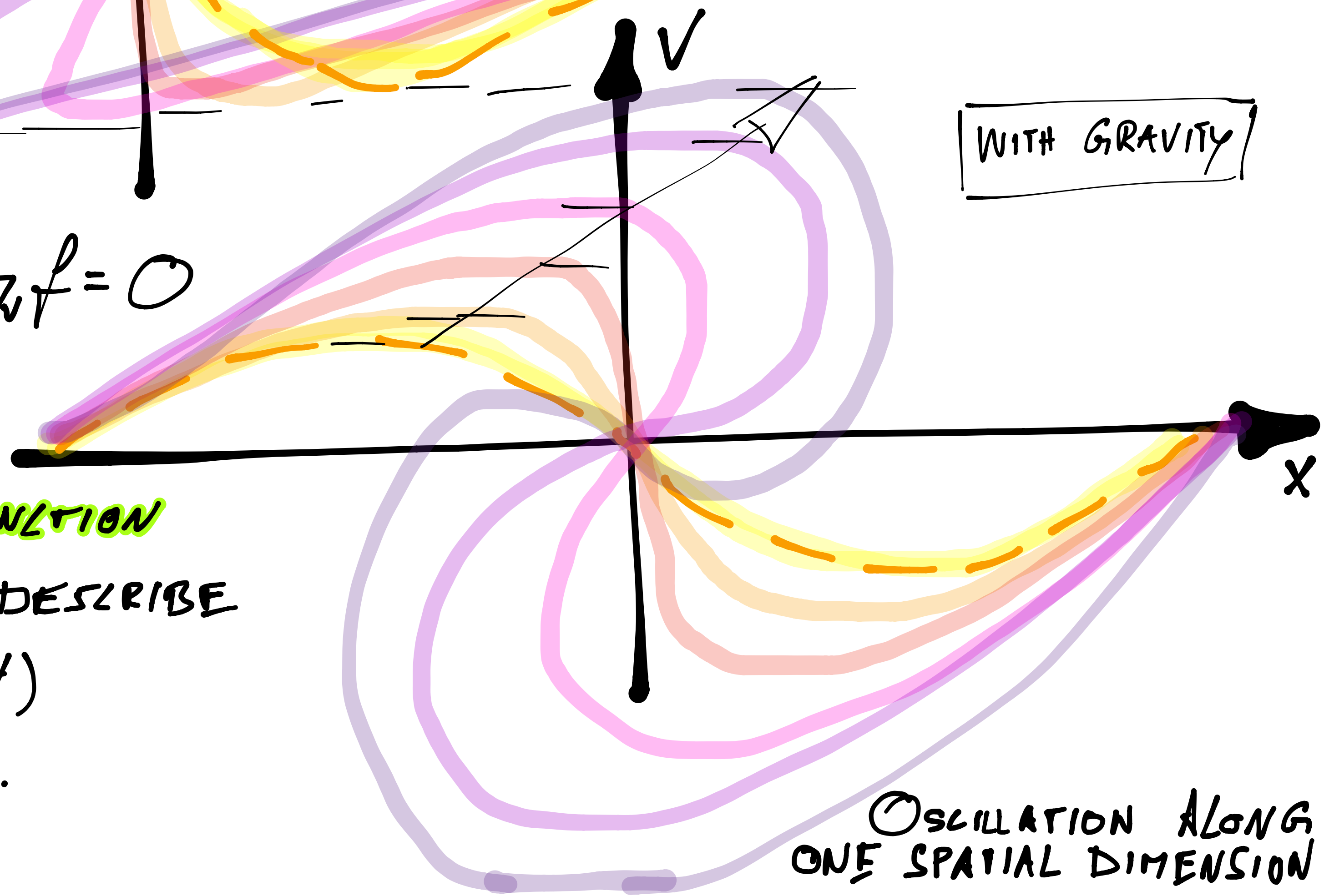


$$\frac{\partial f}{\partial t} + v \nabla_x f - \nabla_x \phi \nabla_v f = 0$$

VLASOV EQU.

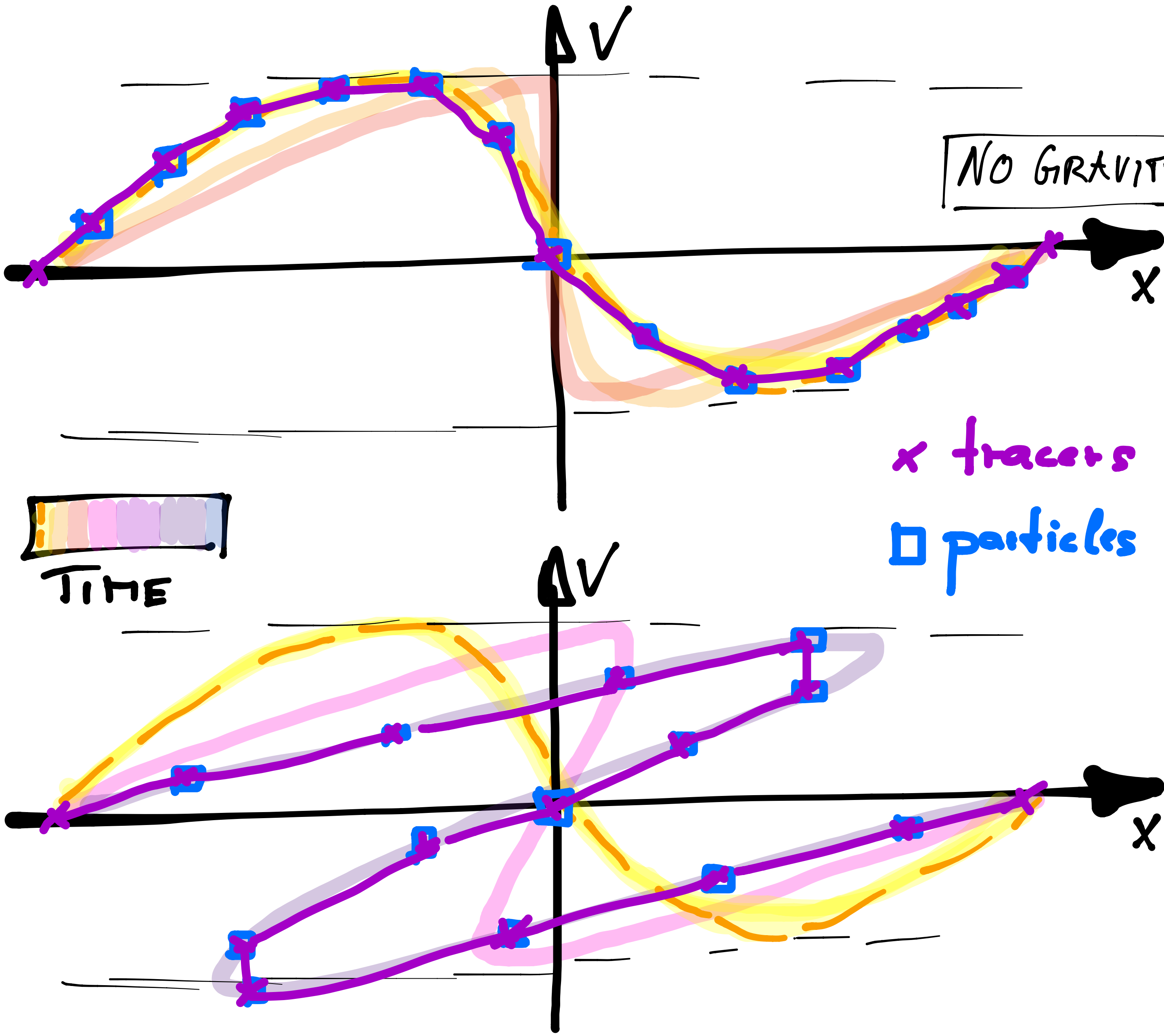
USE **DISTRIBUTION FUNCTION** IN PHASE SPACE TO DESCRIBE EVOLUTION : $f(\vec{x}, \vec{v}, t)$

YES. 7 DIMENSIONS...



OSCILLATION ALONG ONE SPATIAL DIMENSION

DISCRETIZE DARK MATTER DISTRIBUTION: Mass or Volume?

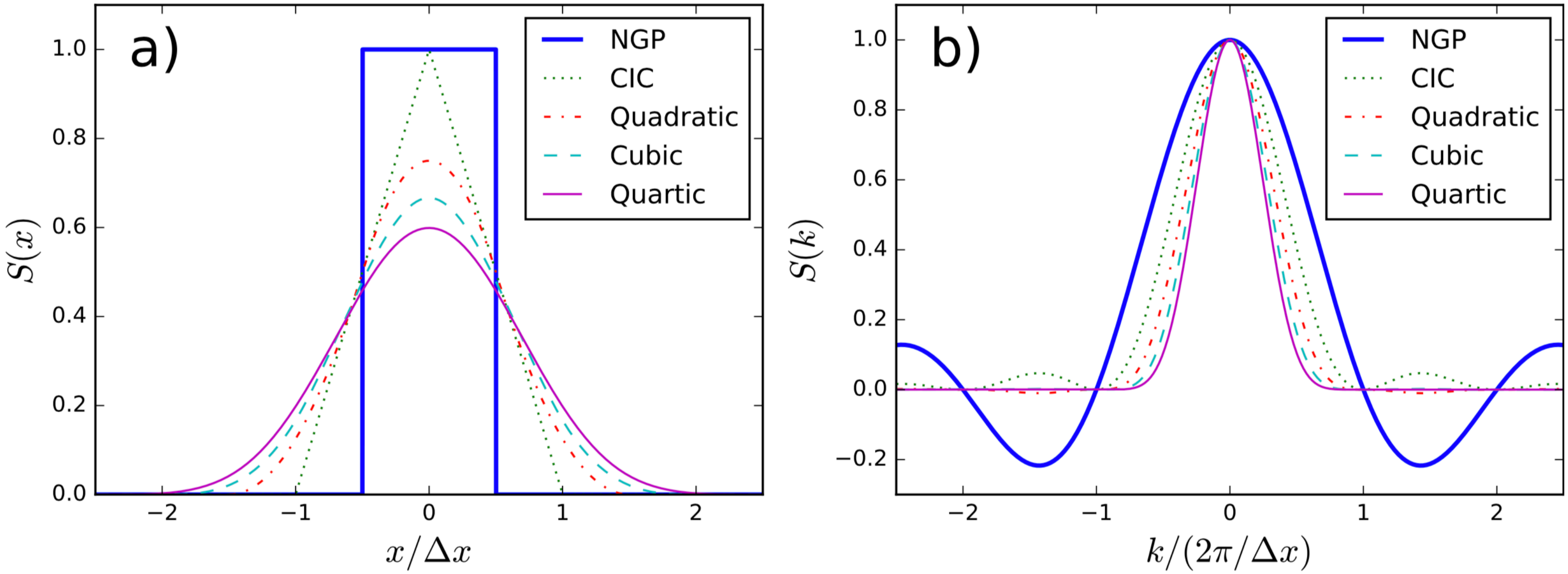


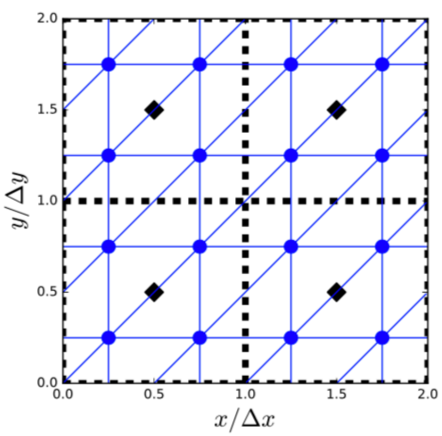
COUNT PARTICLES IN RANDOM VOLUMES GIVES AVERAGE DENSITIES

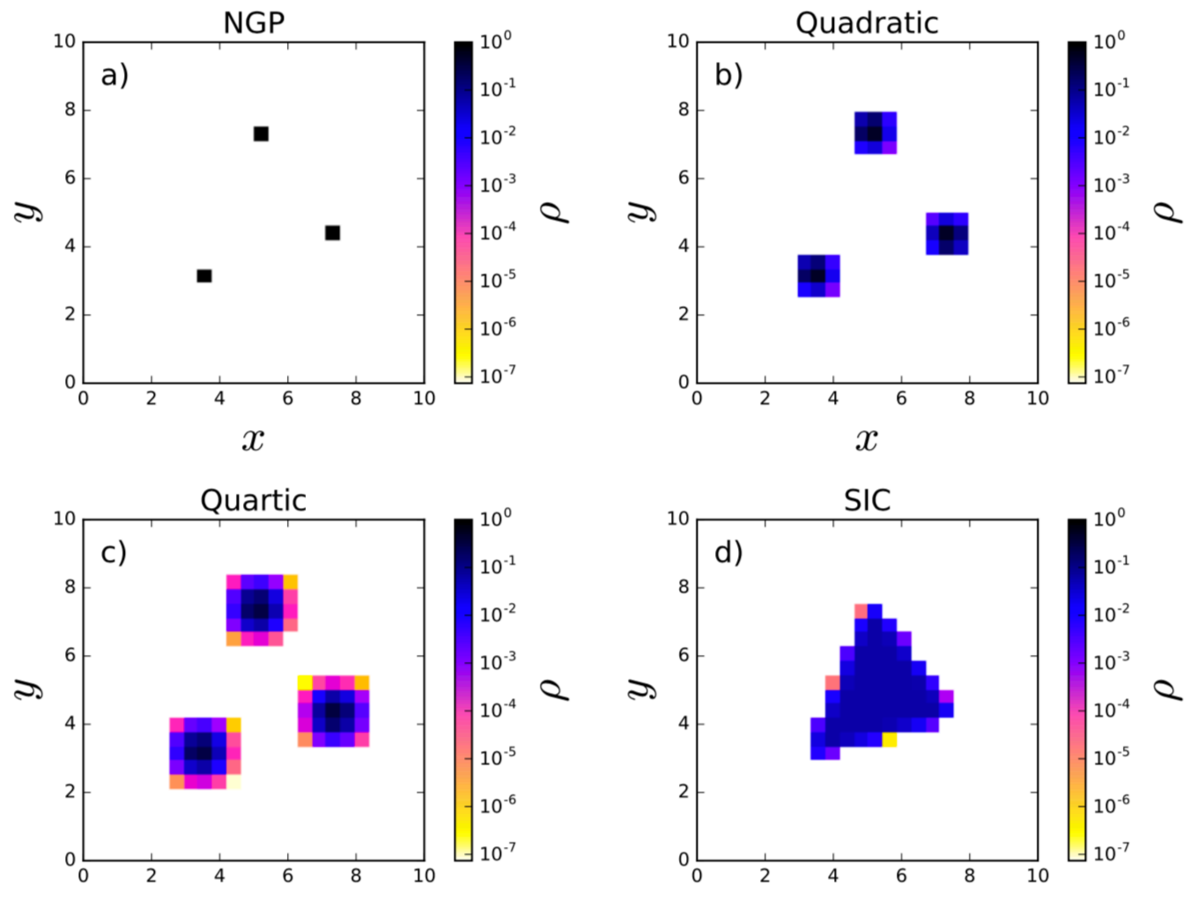
THINK MASS BETWEEN PARTICLES !

⟹ DENSITY KNOWN EVERYWHERE !

Density Estimators

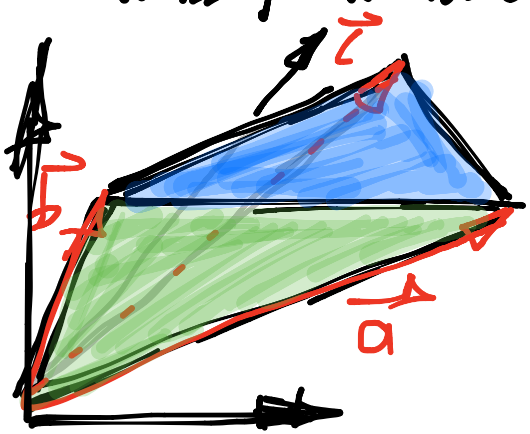




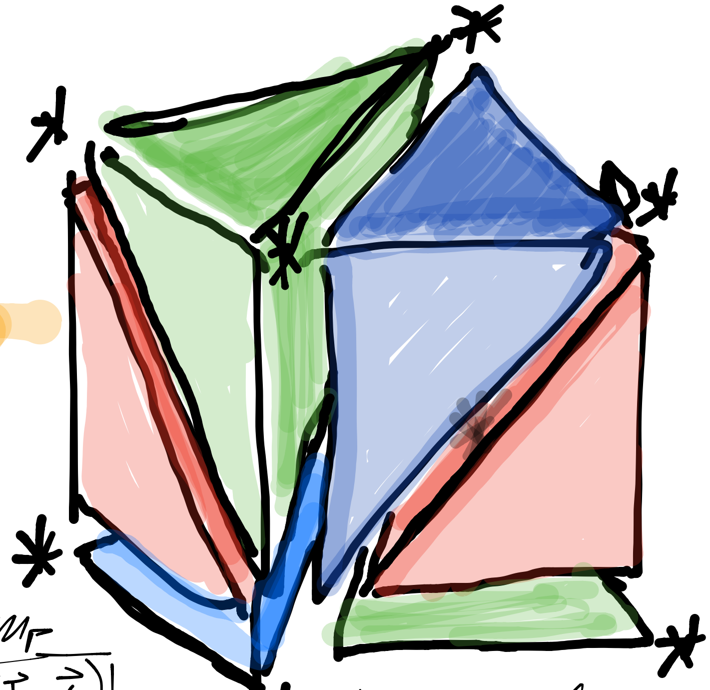


Tesselate 3D Manifold & Track in 6D Phase Space

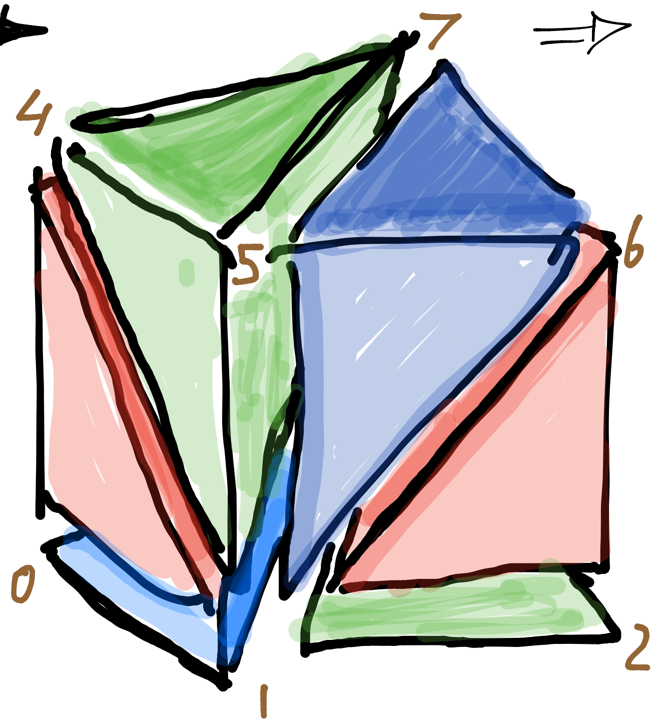
- Natural Tesselation splits cube into 6 equal sized tetrahedra
- mass per tetrahedron = 1/6 of DM particle mass.



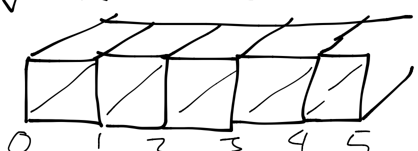
$$V = \frac{|\vec{a}\cdot(\vec{b}\times\vec{c})|}{6}$$



$$\Rightarrow \rho = \frac{m_p}{6V} = \frac{m_p}{|\vec{a}\cdot(\vec{b}\times\vec{c})|}$$

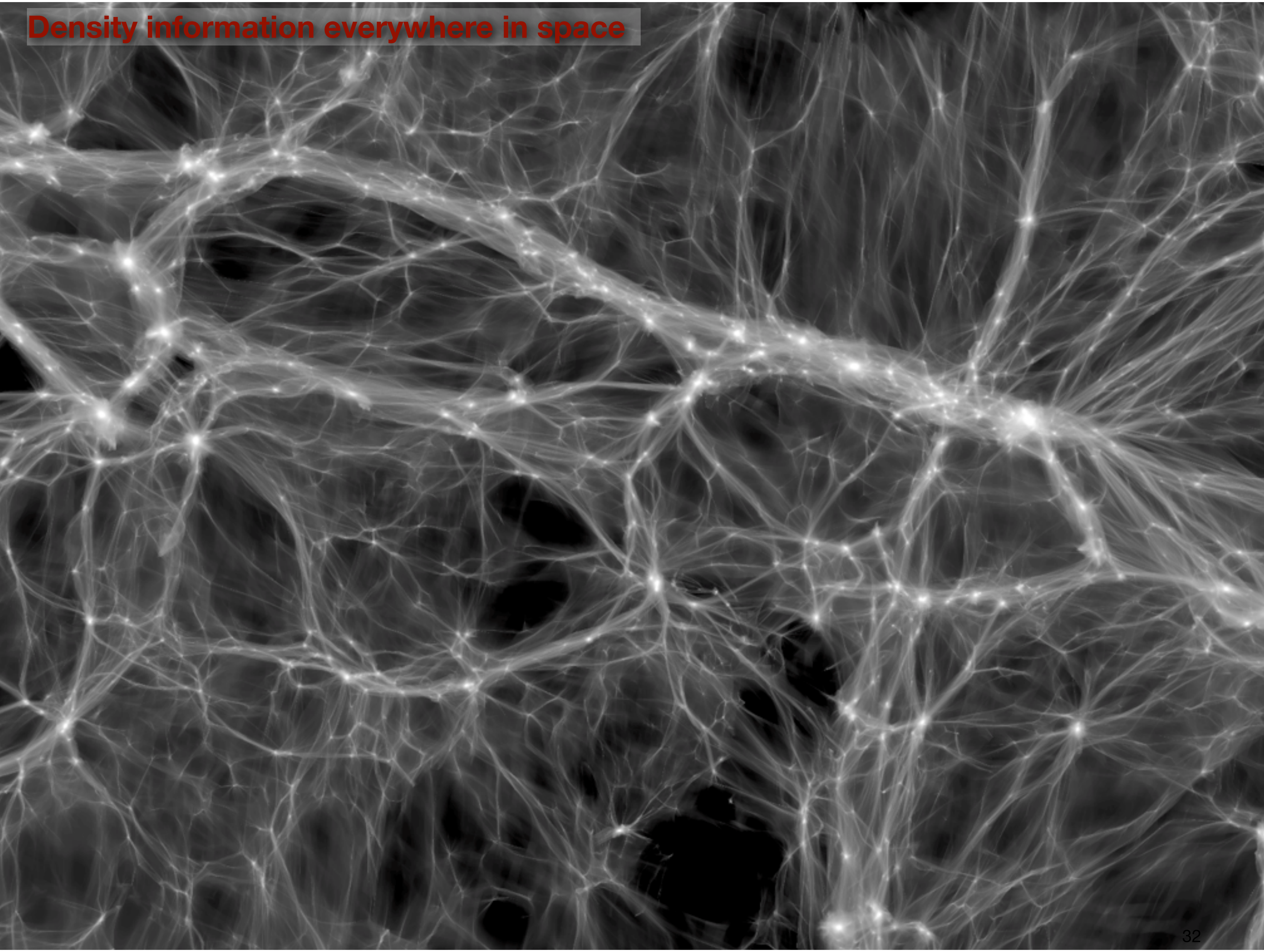


- Number the edges of the cube
- think of lattice
- Looping over



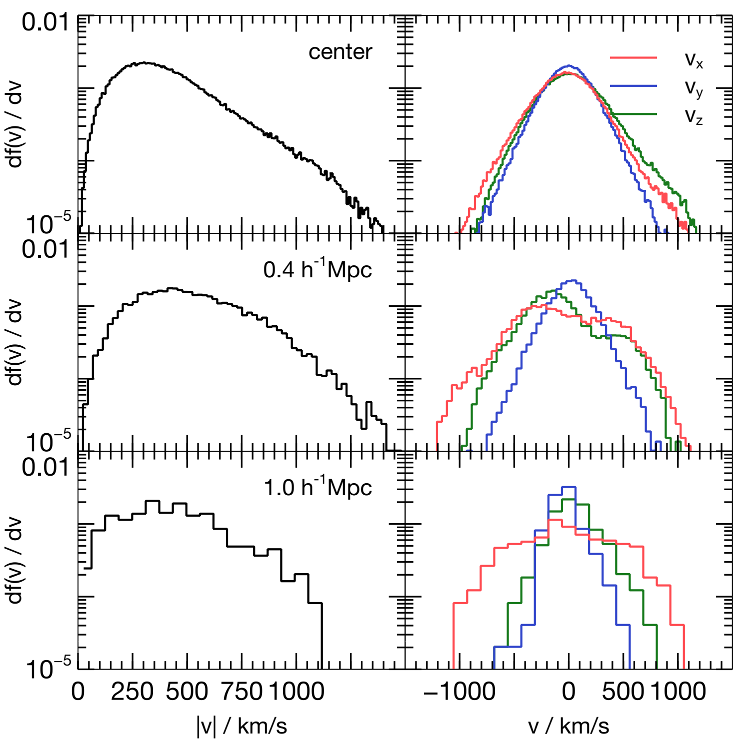
The initial cartesian (LAGRANGIAN lattice generates the 6N tetrahedra.

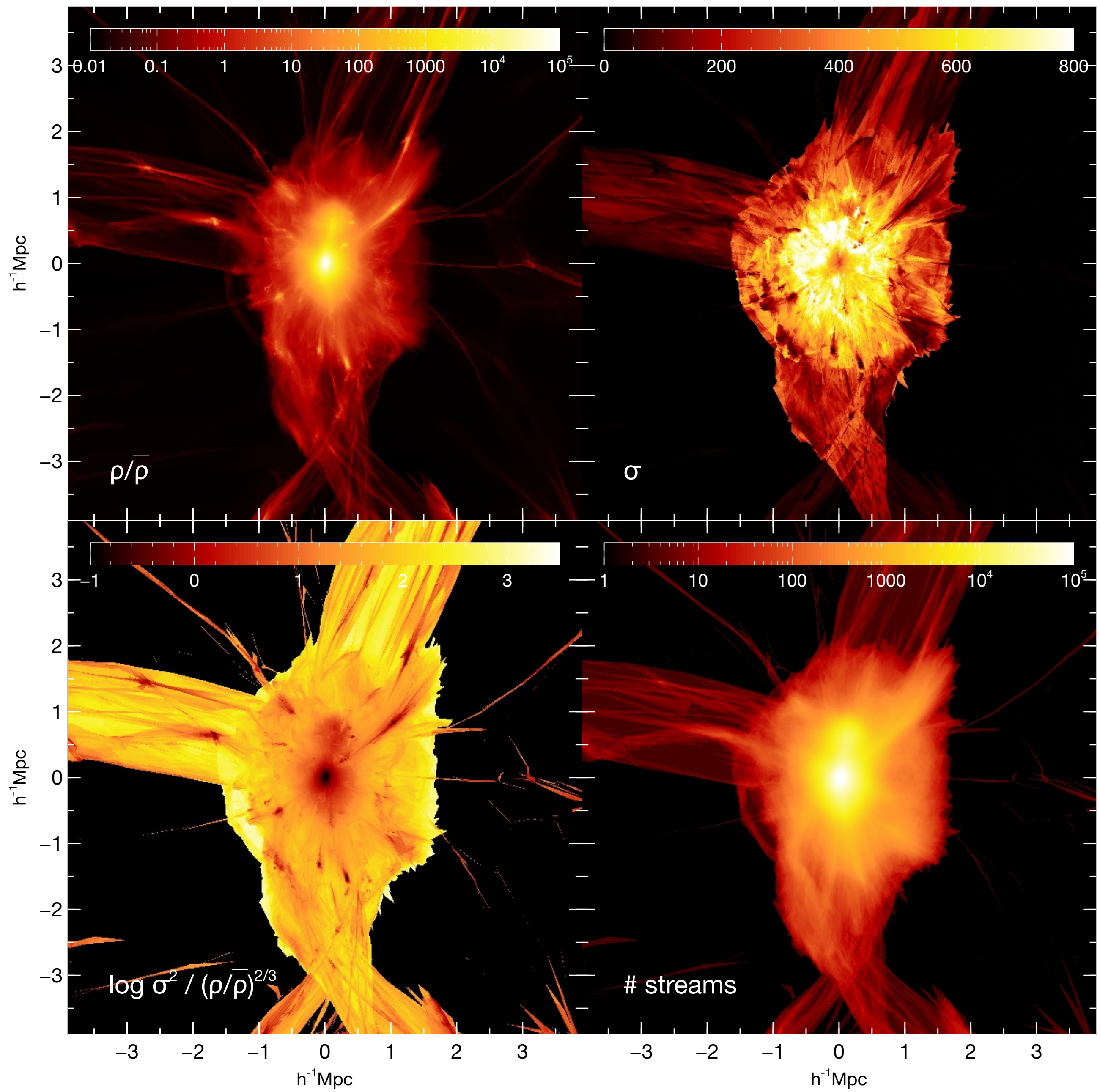
Density information everywhere in space

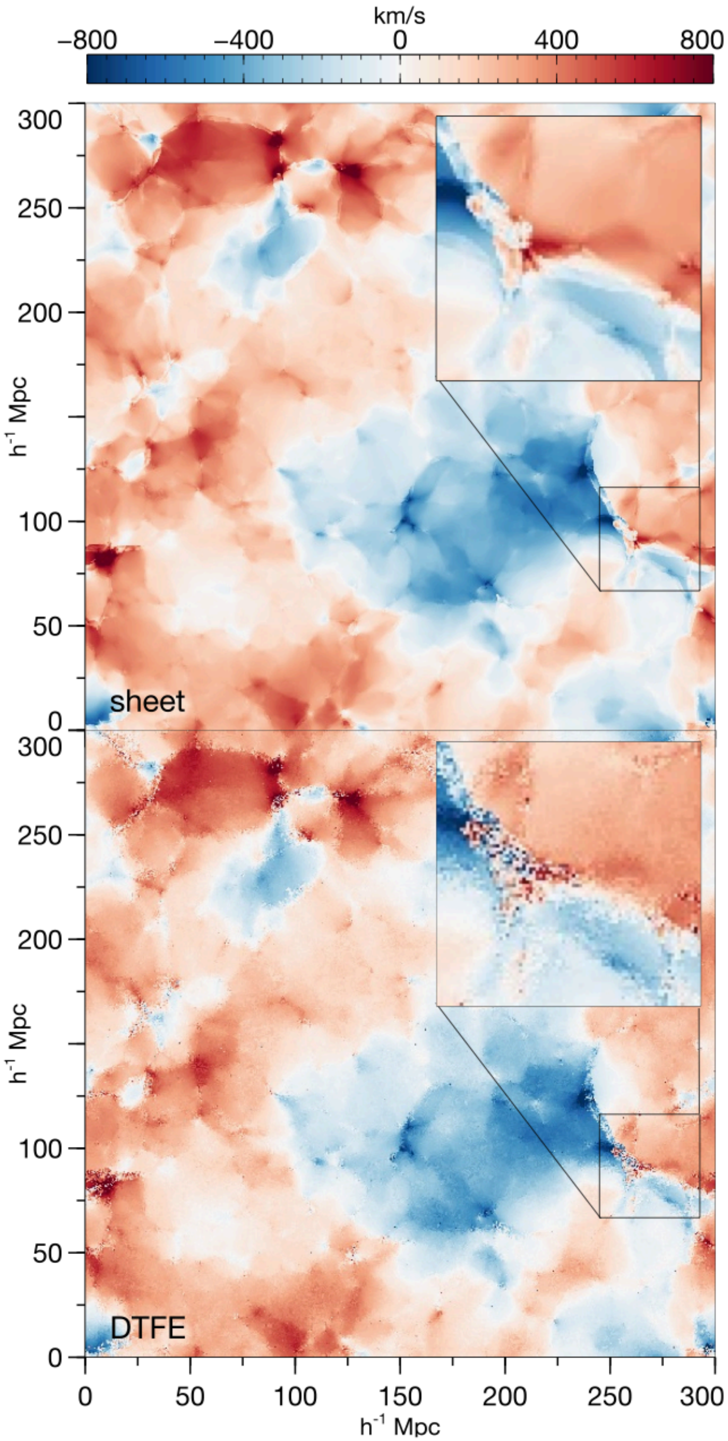


All microphysical phase space information available

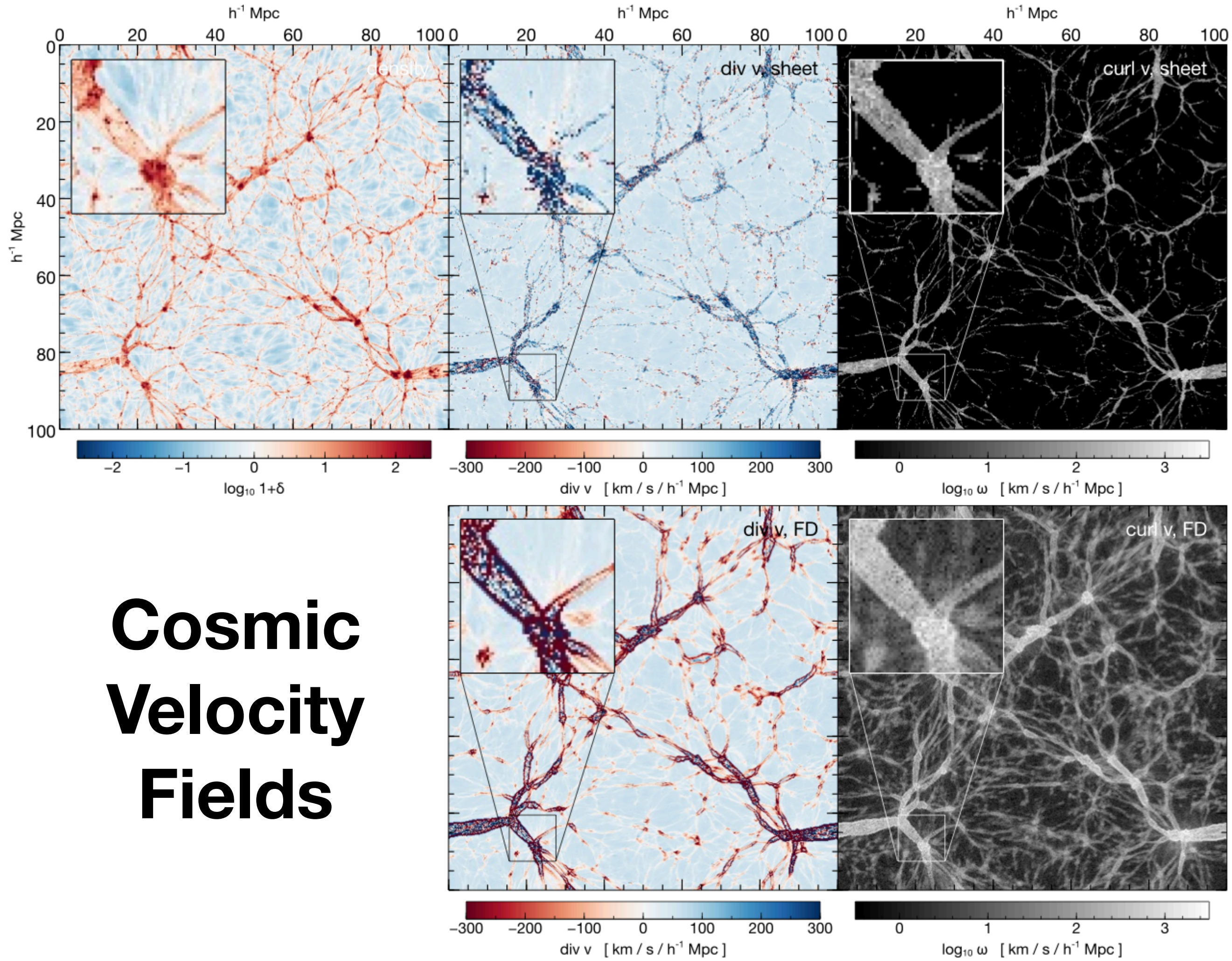
can probe fine-grained phase space structure.

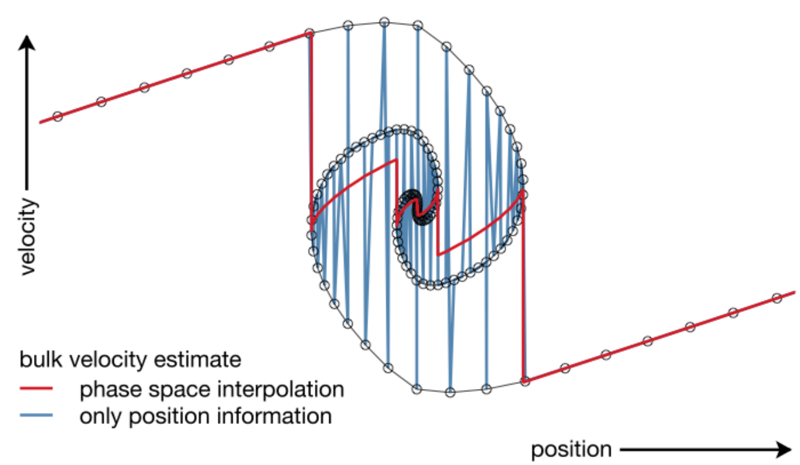






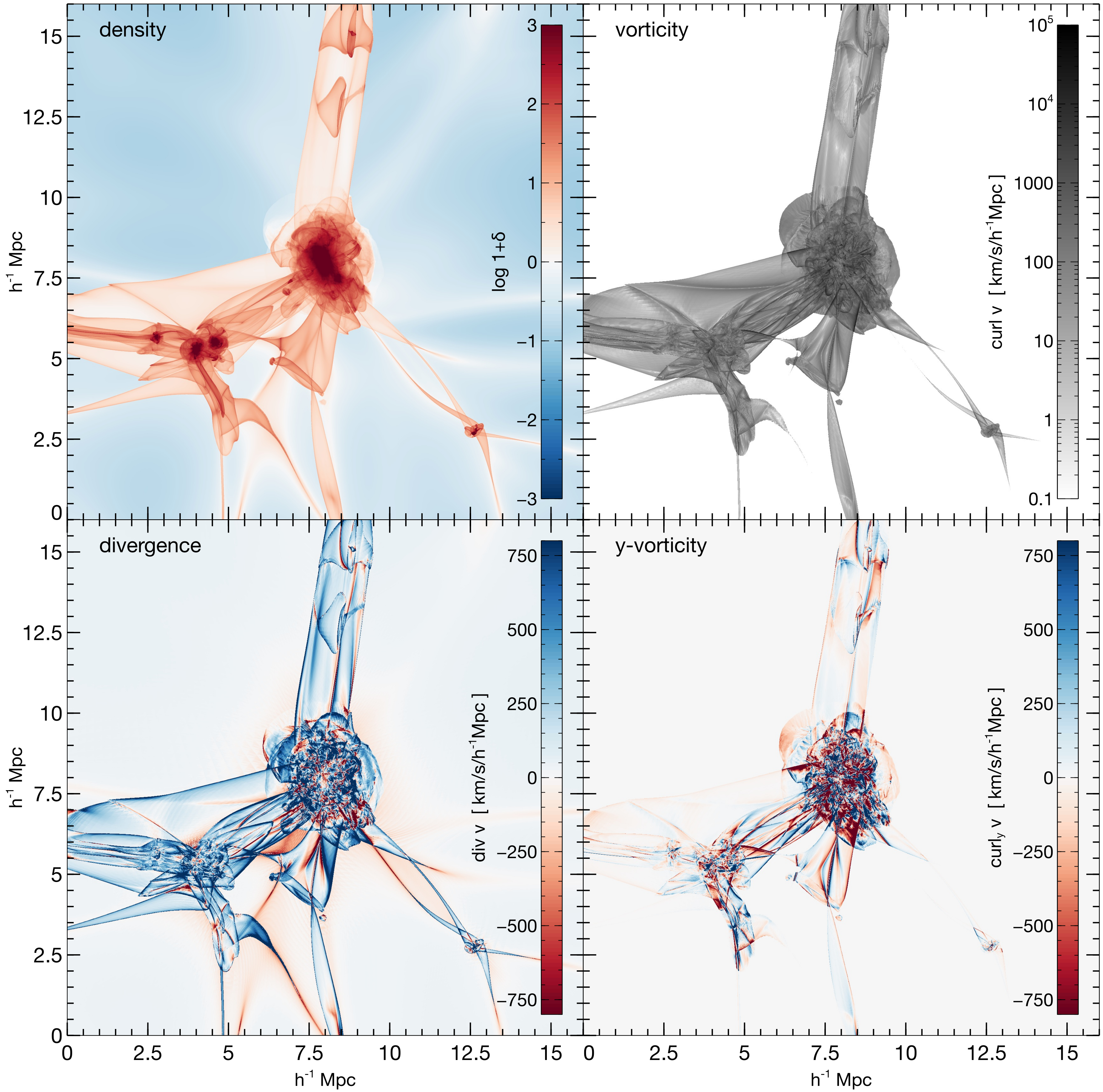
Cosmic Velocity Fields

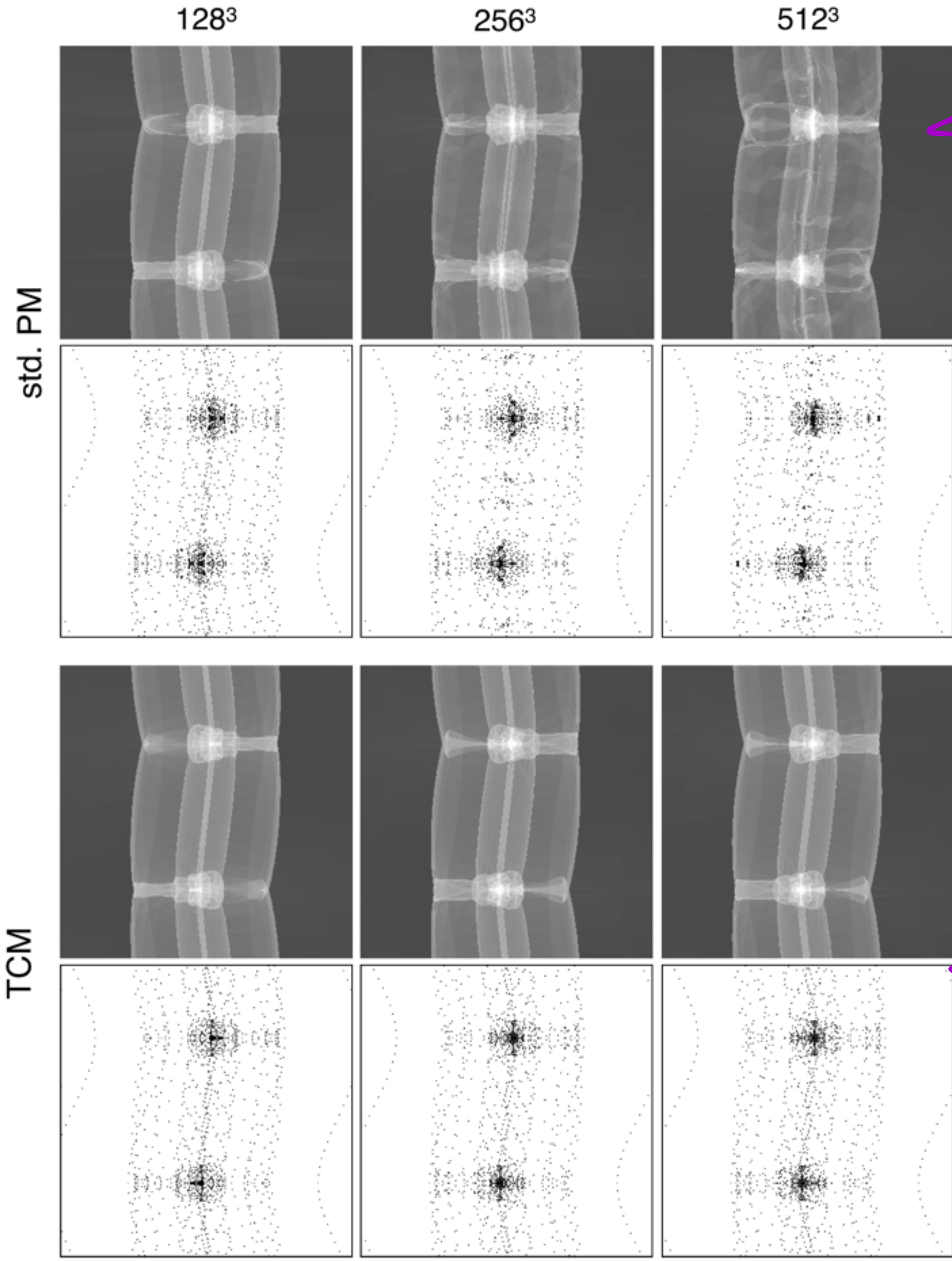




The properties of cosmic velocity fields

Oliver Hahn,[1★] Raul E. Angulo[2] and Tom Abel[3]


density
vorticity
divergence
y-vorticity
log 1+δ
curl v [km/s/h^{-1}Mpc]
div v [km/s/h^{-1}Mpc]
curl$_y$ v [km/s/h^{-1}Mpc]
h^{-1} Mpc
0
2.5
5
7.5
10
12.5
15
3
2
1
0
−1
−2
−3
10^5
10^4
1000
100
10
1
0.1
750
500
250
0
−250
−500
−750



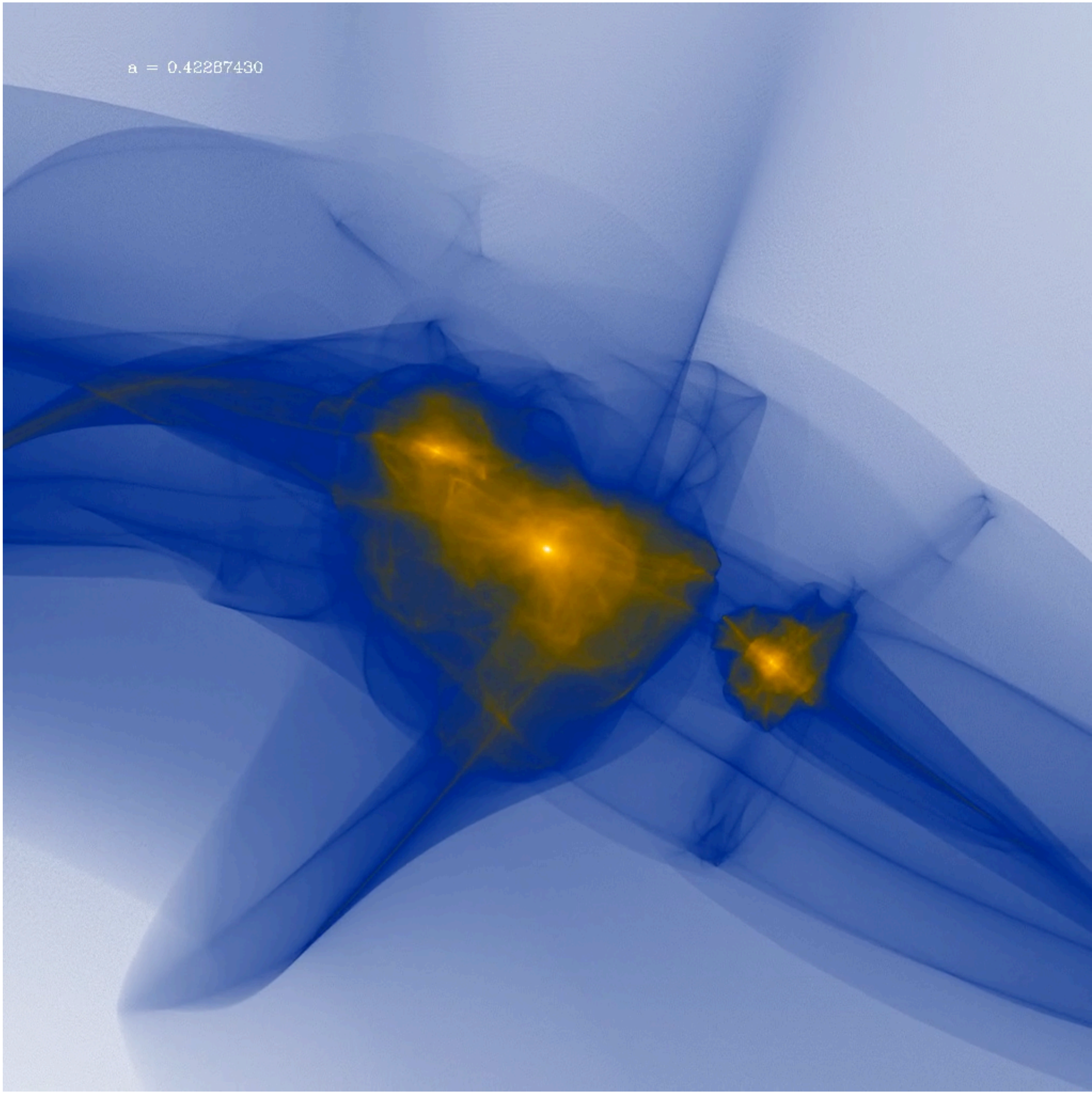
two body scattering
undesirable ...

Note how the new visualization technique helps in spotting errors in the N-body integration

Constant mass resolution
Vary force resolution

excellent convergence behavior of our new method.

Warm dark matter halo with refinement and higher order elements

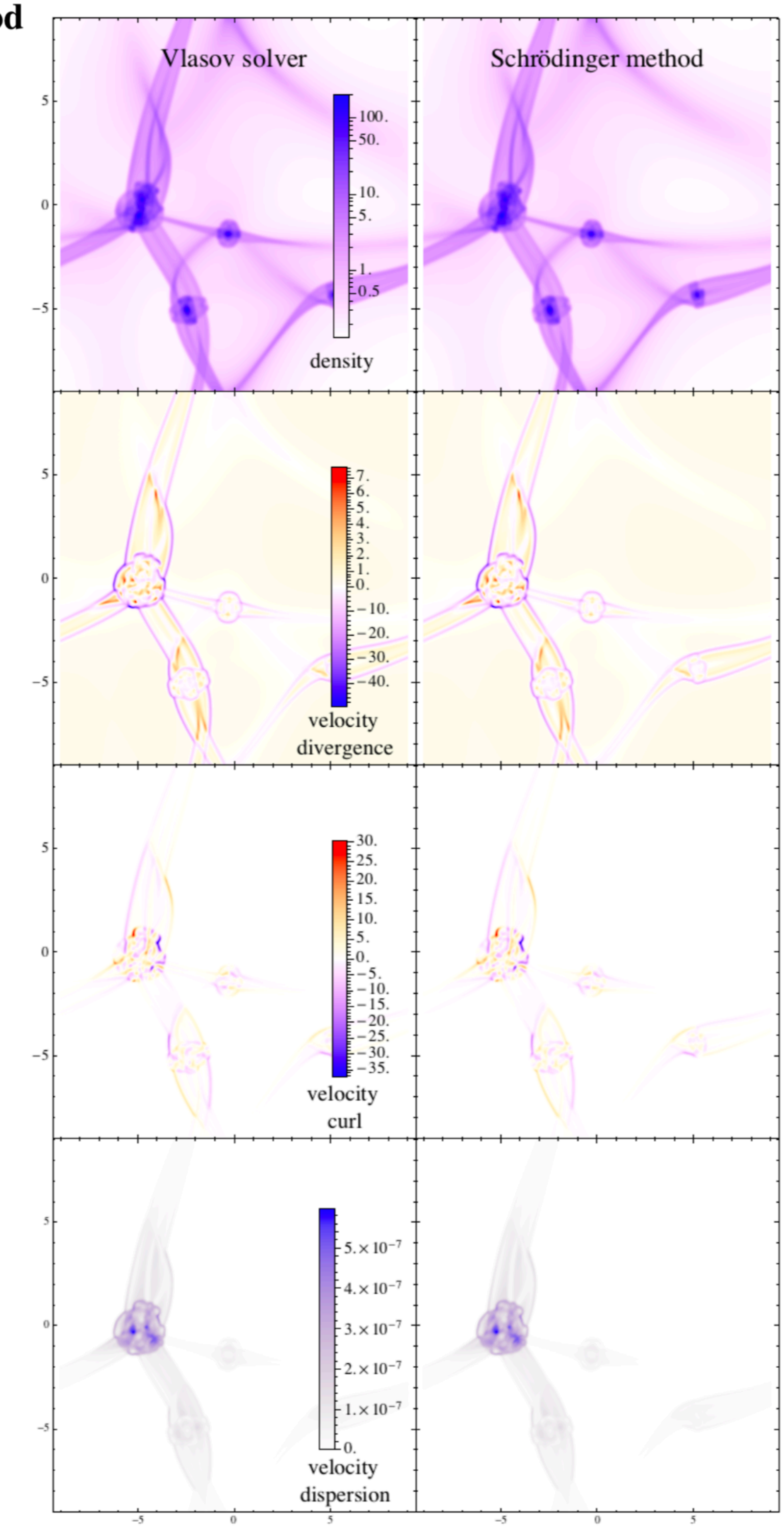


Solving the Vlasov equation in two spatial dimensions with the Schrödinger method

Michael Kopp,[1,2,*] Kyriakos Vattis,[1,3,†] and Constantinos Skordis[1,2,‡]

Physical Review D, Volume 96, December 2017

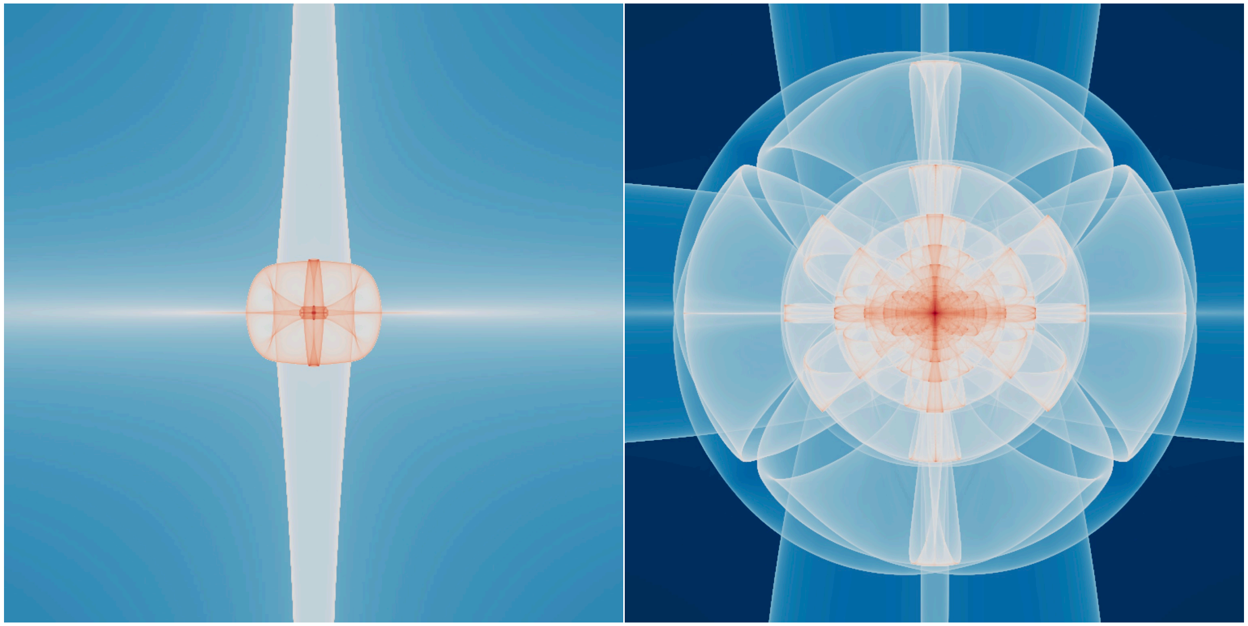
FIG. 1. Time snapshots of a two-dimensional cosmological simulation evolved to the present time $a = 1$. Both codes were started with the same single-stream initial conditions, set up using the Zel'dovich approximation at $a_{\text{ini}} = 1/51$. From top to bottom: density, velocity divergence, velocity curl and trace of the velocity dispersion tensor. The left column shows the smoothed results of the 2D-version of the Vlasov solver `ColDICE` [13]. The result of the Schrödinger method is shown in the right column. The differences are barely visible by eye. A quantitative comparison is presented in Sec. IV.



used:

`ColDICE`: a parallel Vlasov-Poisson solver using moving adaptive simplicial tessellation

Thierry Sousbie[a,b,c,*], Stéphane Colombi[a]



Summary

- Smallest halos/object ever formed may hold information micro-physical properties of dark matter.
- There have been and continue to be many subtle things to learn on the dynamics of the many-body dynamics of the dark matter fluid.
- Self-interactions (attractive, elastic, etc.), baryon-CDM interactions, large Compton wavelengths, complex dark sector, decay, large annihilation rates, etc. all modify the dynamics of the fluid:
    - Algorithmic developments/improvements needed to calculate how microphysical differences manifest in large scale distributions
    - Further develop the comparison of astrophysical observables and numerical predictions
- Simulations are essential for much of this program.