Bologna University - INAF
Ph.D. in **Computational Cosmology**

AX-Gadget:

a N-Body hydrodynamical code for axion cosmology simulations

MATTEO NORI

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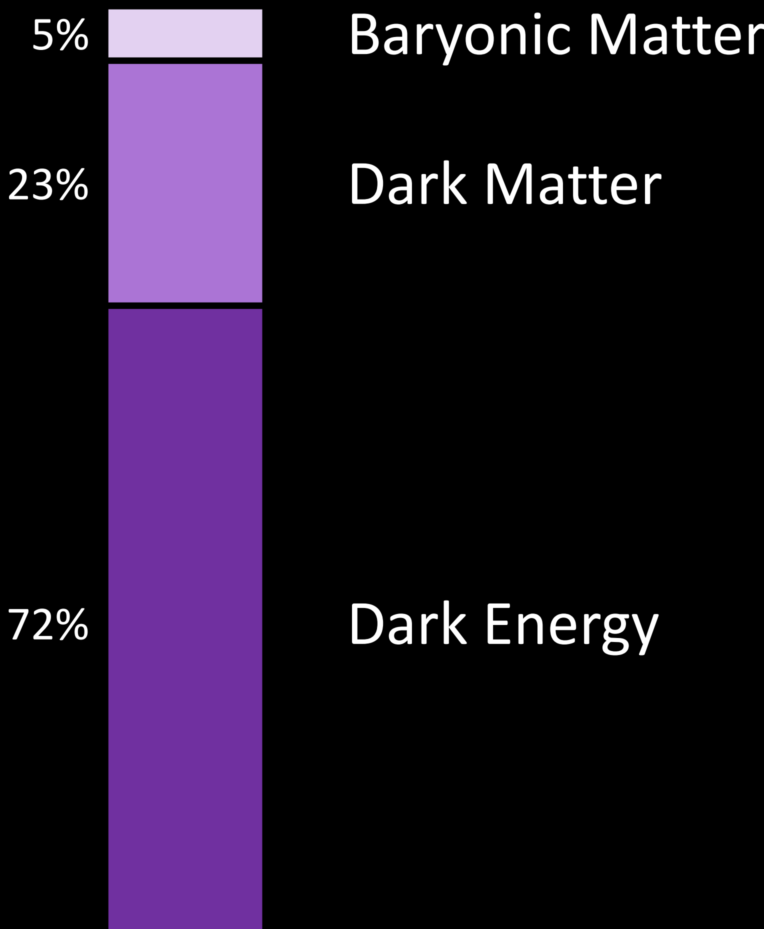
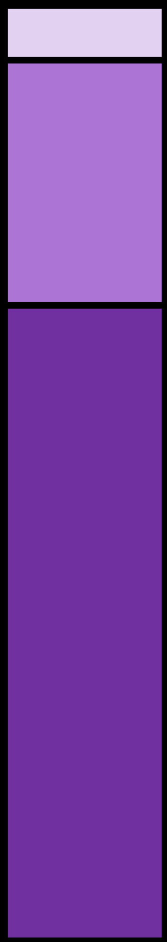
Supervisor
Dr. Marco BALDI

ΛCDM cosmology



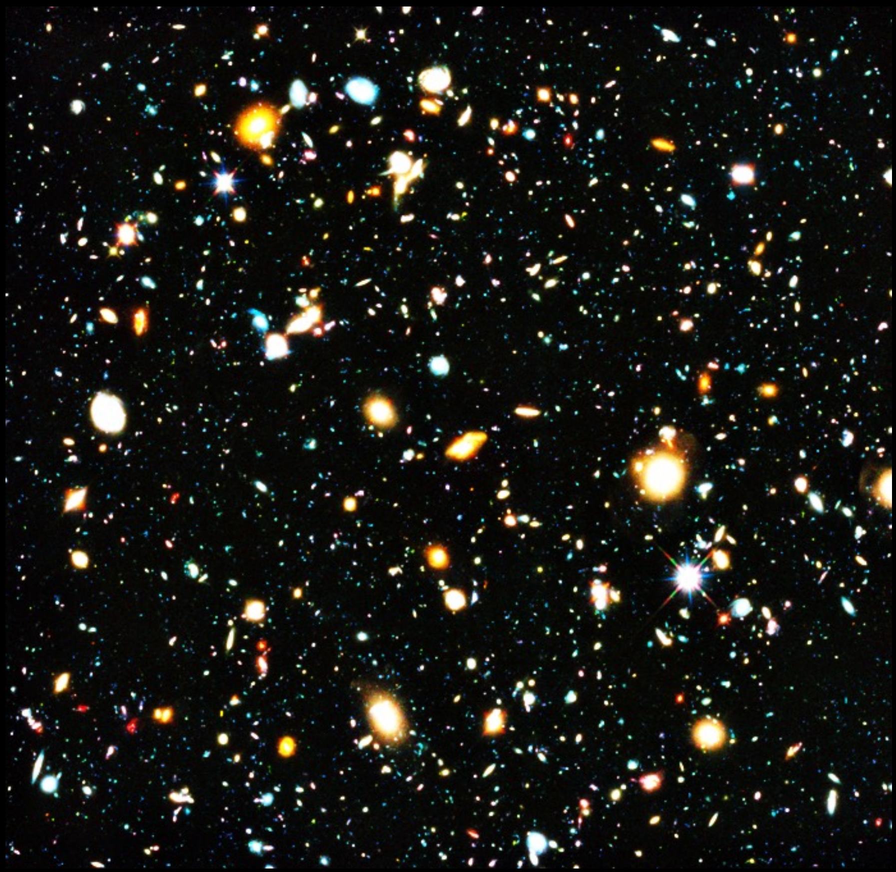
ΛCDM cosmology



5% Baryonic Matter

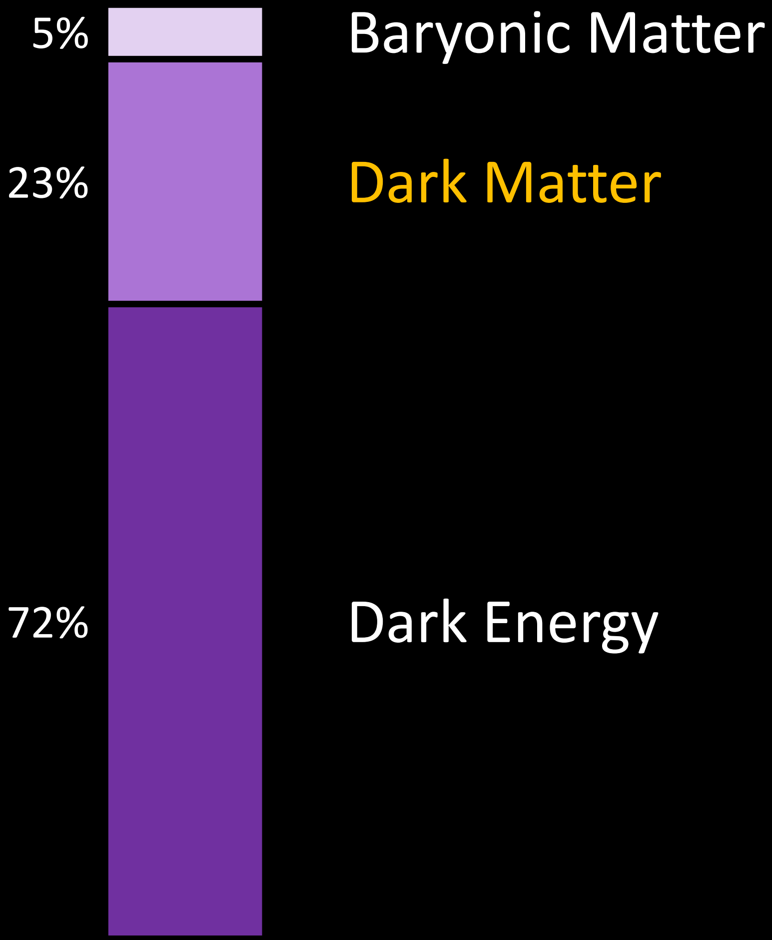
23% Dark Matter

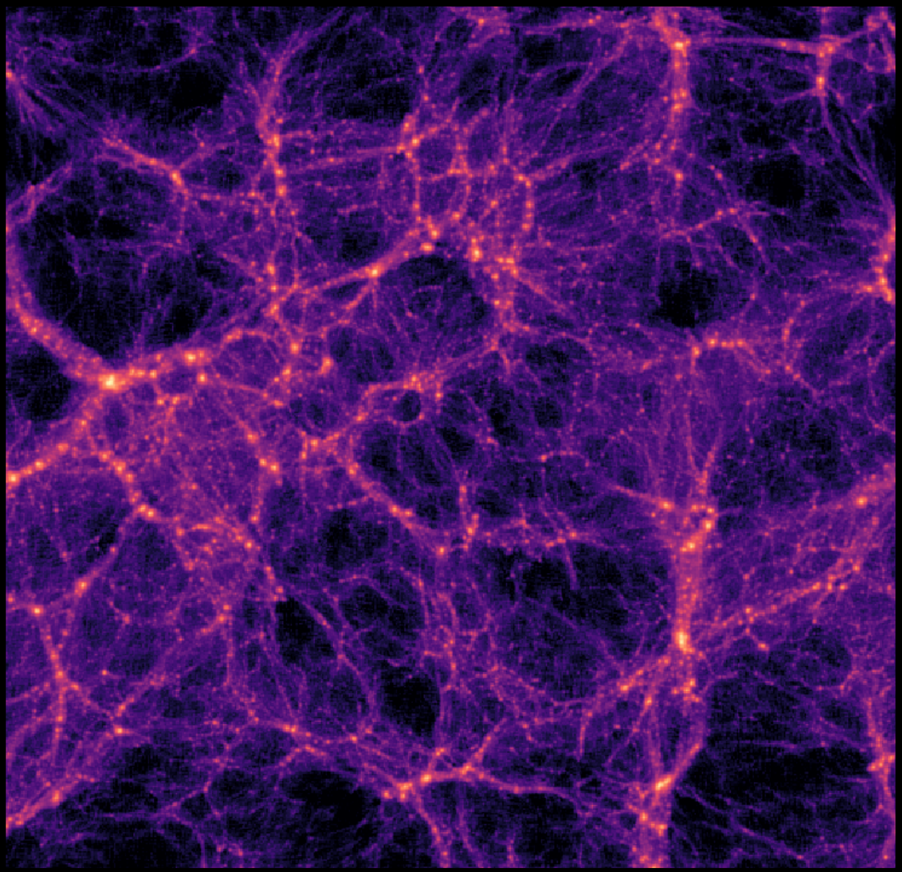
72% Dark Energy



Hubble Ultra-Deep field (NASA)

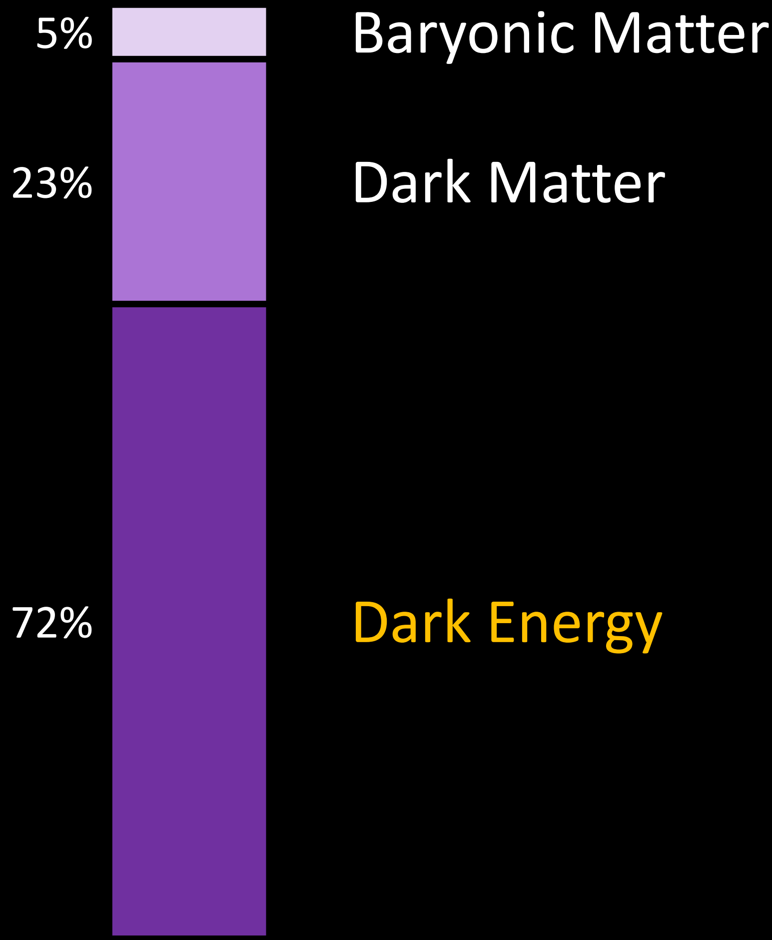
ΛCDM cosmology

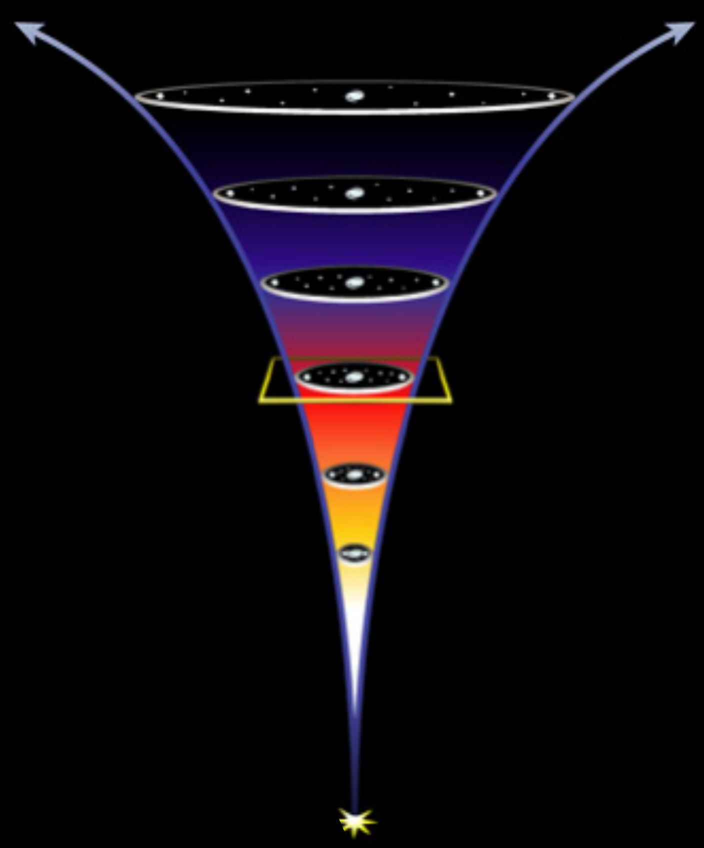




ΛCDM simulation

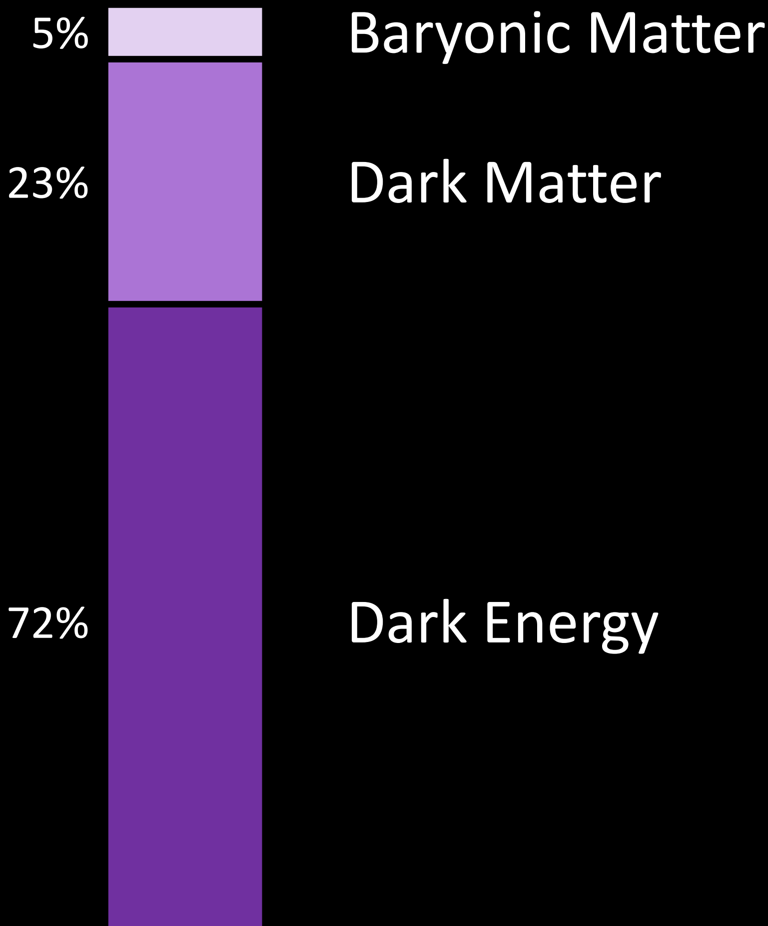
ΛCDM cosmology



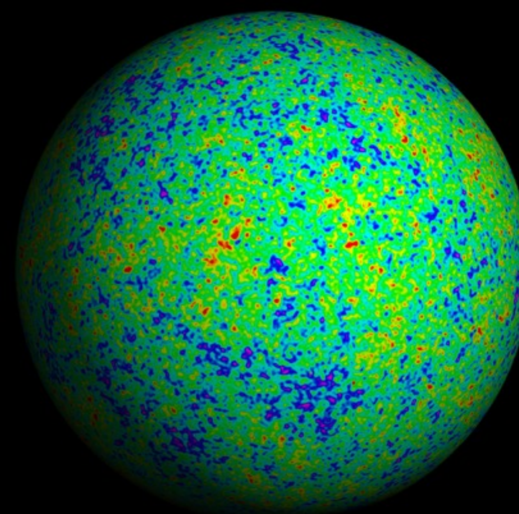


Accelerating expansion

ΛCDM cosmology

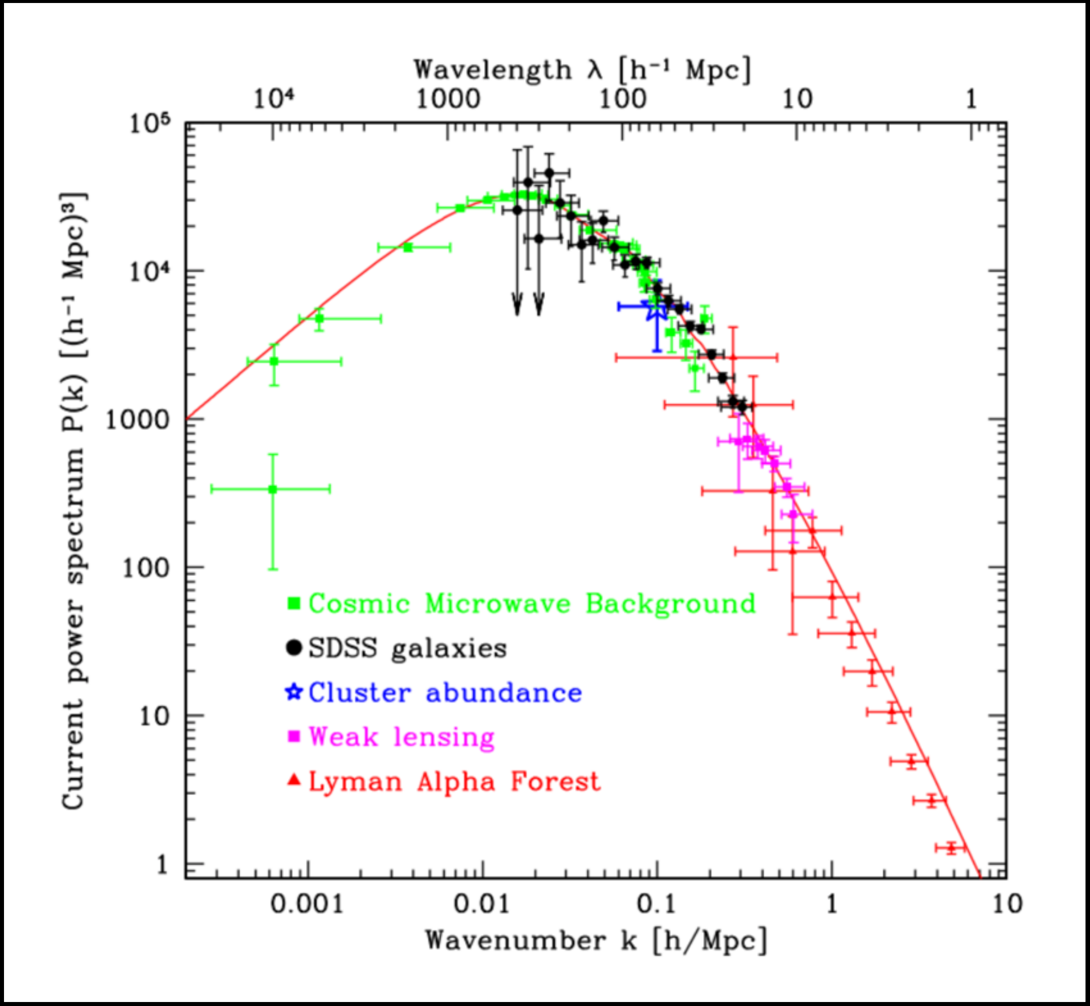


(Nearly) Scale invariant primordial density fluctuations



Cosmic Microwave Background

ΛCDM cosmology



Tegmark +04

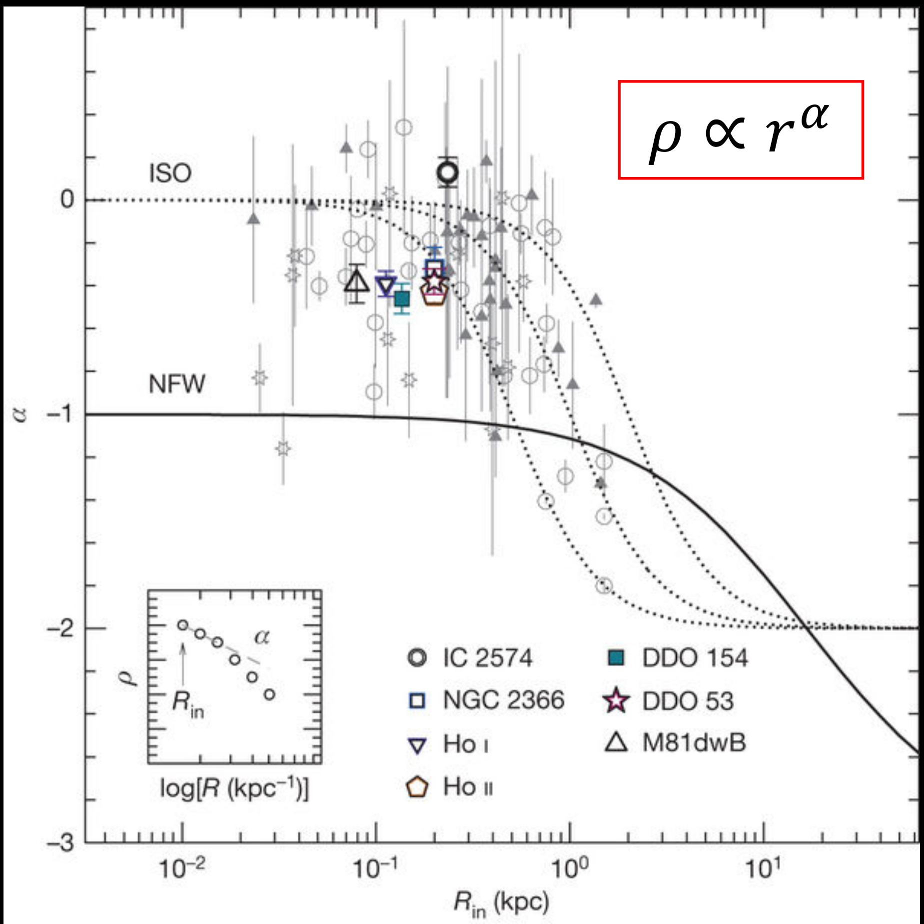
Problems on small scales

- Cusp Core

Observations: “CORE”

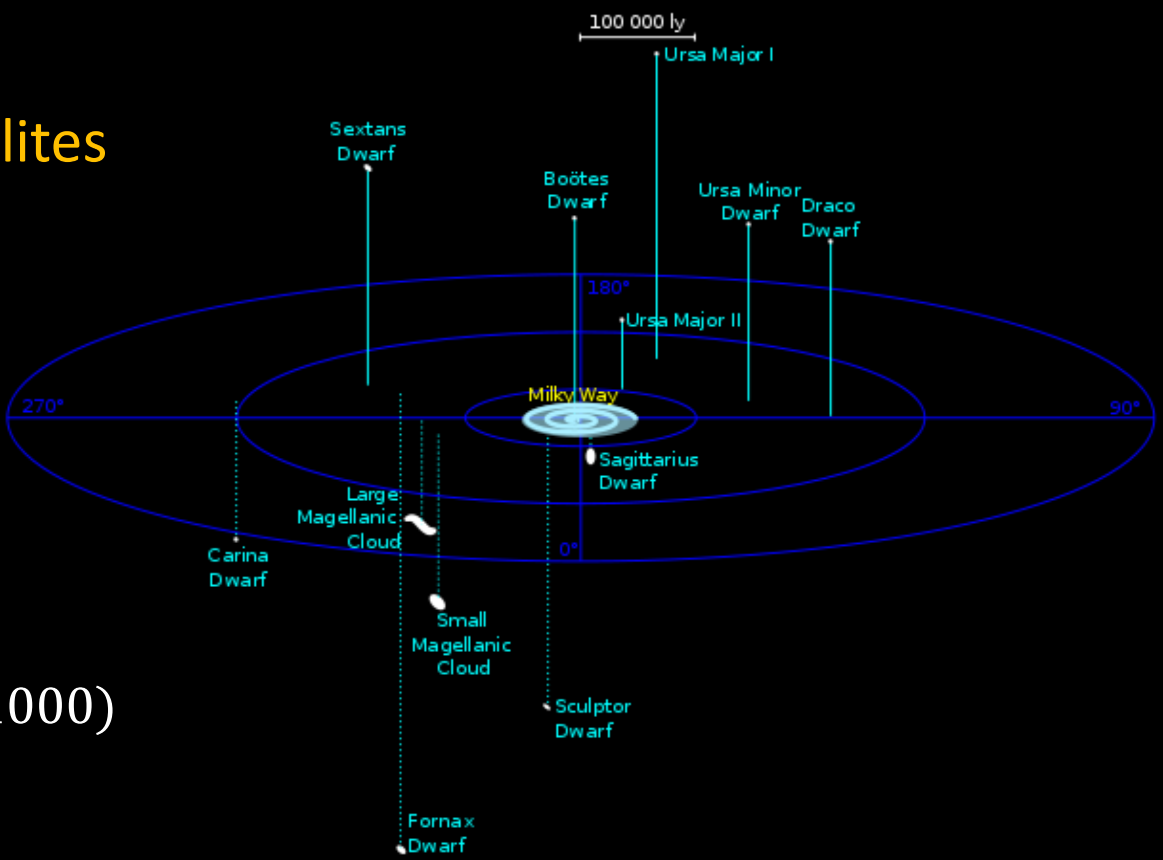
Simulations: “CUSP”

Oh +11



Problems on small scales

- Cusp Core
- Missing Satellites



Simulations:

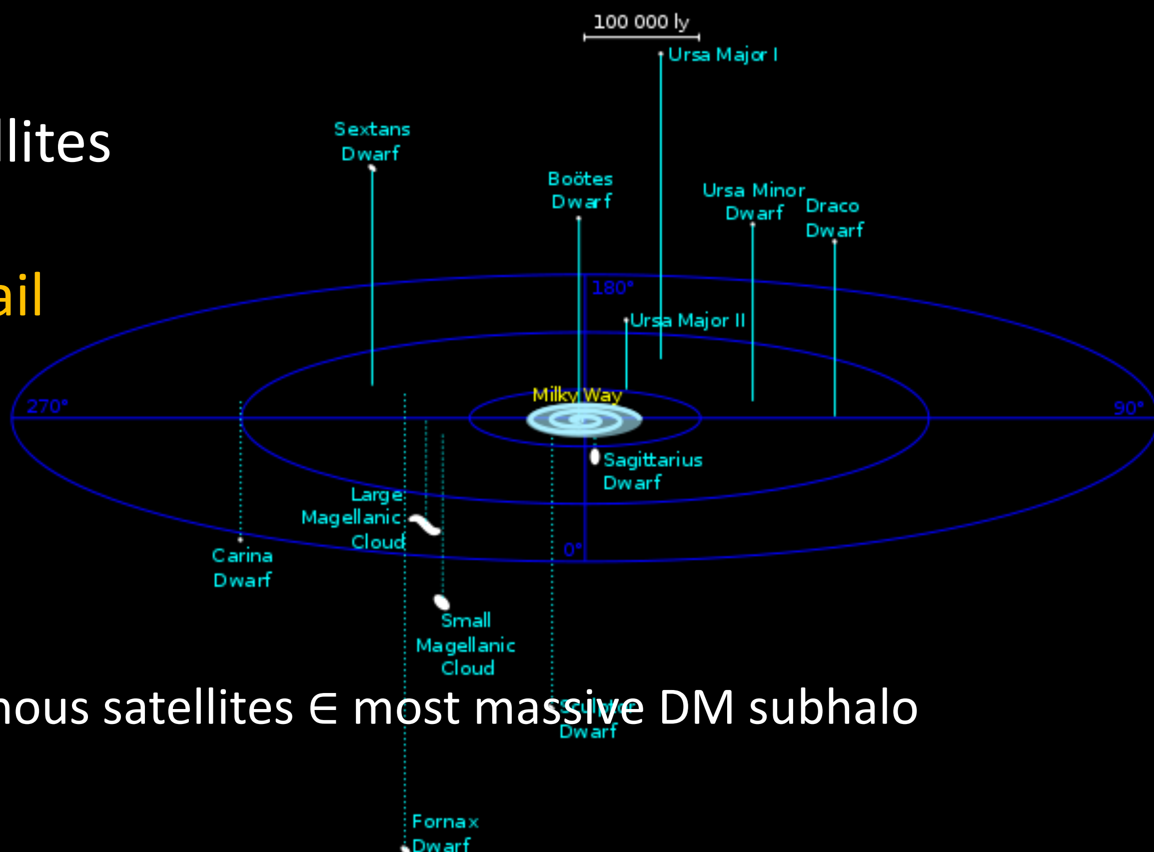
$$O(100-1000)$$

Observed:

$$O(10)$$

Problems on small scales

- Cusp Core
- Missing Satellites
- Too-Big-To-Fail



Simulations:

most luminous satellites ∈ most massive DM subhalo

Observed:

stellar dynamics inconsistent with dense subhalos

Problems on small scales

- Cusp Core
- Missing Satellites
- Too-Big-To-Fail

Excess of structures at small scales

Problems on small scales

- Cusp Core
- Missing Satellites
- Too-Big-To-Fail

Excess of structures at small scales

Possible solutions

Baryonic Physics

Modify Dark Matter

Modify Gravity

Problems on small scales

- Cusp Core
- Missing Satellites
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Excess of structures at small scales

Possible solutions

Baryonic Physics | Modify Dark Matter | Modify Gravity

Why Ultra-light Axions?

On the hypothesis that cosmological dark matter is composed of ultra-light bosons

Lam Hui*
Department of Physics, Columbia University, New York, NY 10027

Jeremiah P. Ostriker†
Department of Astronomy, Columbia University, New York, NY 10027 and
Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544

Solve CP violation

Suppress Matter PS

Quantum effects

Non thermal species

Very light
$m \sim 10^{-22} eV$

From Schrödinger to Navier-Stokes

$$i\hbar\,\partial_t\hat{\psi} = -\frac{\hbar^2}{2m}\nabla^2\hat{\psi}$$

From Schrödinger to Navier-Stokes

$$i\hbar\,\partial_t\hat{\psi} = -\frac{\hbar^2}{2m}\nabla^2\hat{\psi}$$

$$\hat{\psi}(\vec{r},t) = \sqrt{Nm\boldsymbol{\rho}(\vec{r},t)}\,e^{i\theta(\vec{r},t)}$$

$$\vec{\mathbf{v}} = \frac{\hbar}{m}\vec{\nabla}\,\theta$$

From Schrödinger to Navier-Stokes

$$i\hbar\, \partial_t \hat{\psi} = -\frac{\hbar^2}{2m} \nabla^2 \hat{\psi}$$

$$\partial_t \vec{\mathrm{v}} + \left(\vec{\mathrm{v}} \cdot \vec{\nabla}\right)\vec{\mathrm{v}} = \frac{\hbar^2}{2m^2} \vec{\nabla} \left(\frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}} \right)$$

From Schrödinger to Navier-Stokes

$$i\hbar\,\partial_t\hat{\psi} = -\frac{\hbar^2}{2m}\nabla^2\hat{\psi}$$

KINETIC

$$\partial_t\vec{\mathrm{v}} + (\vec{\mathrm{v}}\cdot\vec{\nabla})\vec{\mathrm{v}} = \frac{\hbar^2}{2m^2}\vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

From Schrödinger to Navier-Stokes

$$i\hbar\,\partial_t\hat{\psi} = -\frac{\hbar^2}{2m}\nabla^2\hat{\psi} + m\Phi\hat{\psi}$$

KINETIC **GRAVITY**

$$\partial_t\vec{\mathrm{v}} + (\vec{\mathrm{v}}\cdot\vec{\nabla})\vec{\mathrm{v}} = \frac{\hbar^2}{2m^2}\vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right) - \vec{\nabla}\Phi$$

From Schrödinger to Navier-Stokes

$$i\hbar\,\partial_t\hat{\psi} = -\frac{\hbar^2}{2m}\nabla^2\hat{\psi} + m\Phi\hat{\psi} + gNm\left|\hat{\psi}\right|^2\hat{\psi}$$

KINETIC GRAVITY SELF-INTERACTION

$$\partial_t\vec{\mathrm{v}} + \left(\vec{\mathrm{v}}\cdot\vec{\nabla}\right)\vec{\mathrm{v}} = \frac{\hbar^2}{2m^2}\vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right) - \vec{\nabla}\Phi + g\vec{\nabla}\rho$$

Simulating an Ultra-light boson field

Cold and Fuzzy Dark Matter

Wayne Hu, Rennan Barkana & Andrei Gruzinov
Institute for Advanced Study, Princeton, NJ 08540
Revised February 1, 2008

Cold dark matter (CDM) models predict small-scale structure in excess of observations of the cores and abundance of dwarf galaxies. These problems might be solved, and the virtues of CDM models retained, even without postulating *ad hoc* dark matter particle or field interactions, if the dark matter is composed of ultra-light scalar particles ($m \sim 10^{-22}$eV), initially in a (cold) Bose-Einstein condensate, similar to axion dark matter models. The wave properties of the dark matter stabilize gravitational collapse providing halo cores and sharply suppressing small-scale linear power.

Linear and z independent theory

1D simulations

Simulating an Ultra-light boson field

Cold and Fuzzy Dark Matter

Wayne Hu, Rennan
Institute for Advance
Revised

Cold dark matter (CDM) models predict sma
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Ultra-Light Scalar Fields and the Growth of Structure in the Universe

David J. E. Marsh
Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, Oxford, OX1 3NP, UK

Pedro G. Ferreira
Astrophysics, University of Oxford, DWB, Keble Road, Oxford, OX1 3RH, UK

Ultra-light scalar fields, with masses of between $m = 10^{-33}$ eV and $m = 10^{-22}$ eV, can affect the growth of structure in the Universe. We identify the different regimes in the evolution of ultra-light scalar fields, how they affect the expansion rate of the universe and how they affect the growth rate of cosmological perturbations. We find a number of interesting effects, discuss how they might arise in realistic scenarios of the early universe and comment on how they might be observed.

Linear simulations
Definition on mass range

Simulating an Ultra-light boson field

Cold and Fuzzy Dark Matter

Wayne Hu, Rennan
Institute for Advance
Revised

Cold dark matter (CDM) models predict sm

Ultra-Light Scalar Fields and the Growth of Structure in the Universe

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CONTRASTING GALAXY FORMATION FROM QUANTUM WAVE DARK MATTER, ψDM, WITH ΛCDM, USING PLANCK AND HUBBLE DATA

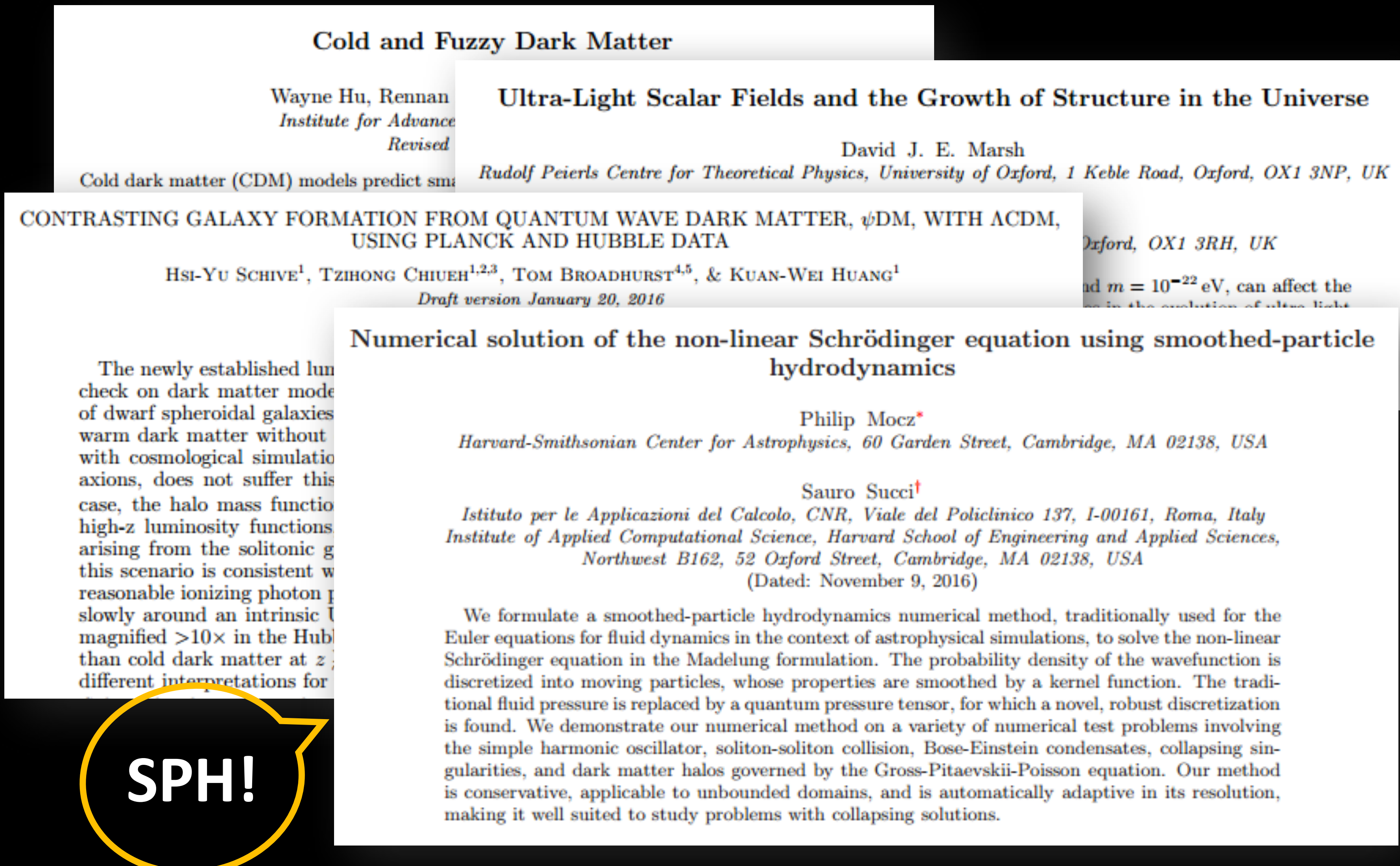
Hsi-Yu Schive[1], Tzihong Chiueh[1,2,3], Tom Broadhurst[4,5], & Kuan-Wei Huang[1]
Draft version January 20, 2016

ABSTRACT

The newly established luminosity functions of high-z galaxies at $4 \lesssim z \lesssim 10$ can provide a stringent check on dark matter models that aim to explain the core properties of dwarf galaxies. The cores of dwarf spheroidal galaxies are understood to be too large to be accounted for by free streaming of warm dark matter without overly suppressing the formation of such galaxies. Here we demonstrate with cosmological simulations that wave dark matter, ψDM, appropriate for light bosons such as axions, does not suffer this problem, given a boson mass of $m_\psi \geq 1.2 \times 10^{-22}$ eV (2σ). In this case, the halo mass function is suppressed below $\sim 10^{10}\,M_\odot$ at a level that is consistent with the high-z luminosity functions, while simultaneously generating the kpc-scale cores in dwarf galaxies arising from the solitonic ground state in ψDM. We demonstrate that the reionization history in this scenario is consistent with the Thomson optical depth recently reported by Planck, assuming a reasonable ionizing photon production rate. We predict that the luminosity function should turn over slowly around an intrinsic UV luminosity of $M_{\rm UV} \gtrsim -16$ at $z \gtrsim 4$. We also show that for galaxies magnified >10× in the Hubble Frontier Fields, ψDM predicts an order of magnitude fewer detections than cold dark matter at $z \gtrsim 10$ down to $M_{\rm UV} \sim -15$, allowing us to distinguish between these very different interpretations for the observed coldness of dark matter.

Non linear simulations
Full wave solvers

Simulating an Ultra-light boson field



Cold and Fuzzy Dark Matter

Wayne Hu, Rennan
Institute for Advance
Revised

Cold dark matter (CDM) models predict sma

Ultra-Light Scalar Fields and the Growth of Structure in the Universe

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CONTRASTING GALAXY FORMATION FROM QUANTUM WAVE DARK MATTER, ψDM, WITH ΛCDM, USING PLANCK AND HUBBLE DATA

Hsi-Yu Schive[1], Tzihong Chiueh[1,2,3], Tom Broadhurst[4,5], & Kuan-Wei Huang[1]
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than cold dark matter at z
different interpretations for

Numerical solution of the non-linear Schrödinger equation using smoothed-particle hydrodynamics

Philip Mocz*
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Sauro Succi†
Istituto per le Applicazioni del Calcolo, CNR, Viale del Policlinico 137, I-00161, Roma, Italy
Institute of Applied Computational Science, Harvard School of Engineering and Applied Sciences, Northwest B162, 52 Oxford Street, Cambridge, MA 02138, USA
(Dated: November 9, 2016)

We formulate a smoothed-particle hydrodynamics numerical method, traditionally used for the Euler equations for fluid dynamics in the context of astrophysical simulations, to solve the non-linear Schrödinger equation in the Madelung formulation. The probability density of the wavefunction is discretized into moving particles, whose properties are smoothed by a kernel function. The traditional fluid pressure is replaced by a quantum pressure tensor, for which a novel, robust discretization is found. We demonstrate our numerical method on a variety of numerical test problems involving the simple harmonic oscillator, soliton-soliton collision, Bose-Einstein condensates, collapsing singularities, and dark matter halos governed by the Gross-Pitaevskii-Poisson equation. Our method is conservative, applicable to unbounded domains, and is automatically adaptive in its resolution, making it well suited to study problems with collapsing solutions.

AX-Gadget

Nori M., Baldi M., in prep

- **Faster** wrt full-wave solvers (SPH)

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- Whatever self-interaction possible through $P(\rho)$

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- **Faster** wrt full-wave solvers (SPH)
- Whatever self-interaction possible through $P(\rho)$
- **Multiple DM and mixed DM** species allowed

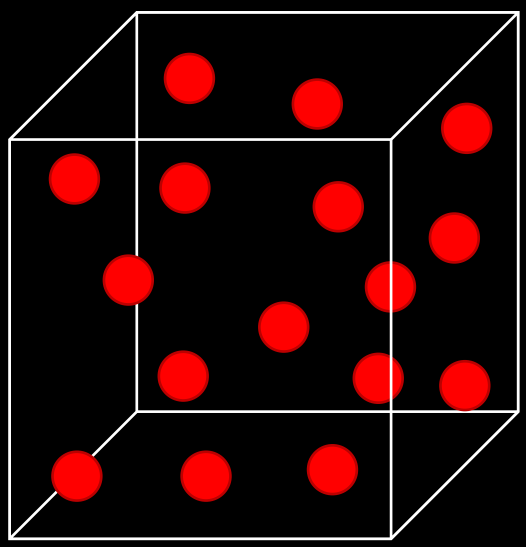
AX-Gadget

Nori M., Baldi M., in prep

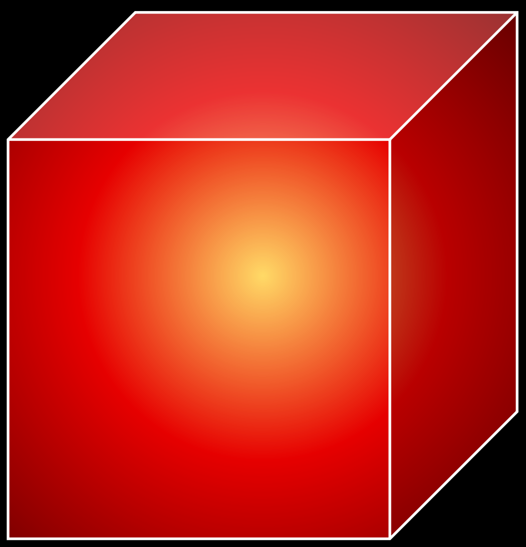
- **Faster** wrt full-wave solvers (SPH)
- Whatever self-interaction possible through $P(\rho)$
- **Multiple DM and mixed DM** species allowed
- All the cool stuff **Gadget3** can do are inherited (Modified Gravity, Dark Energy, Baryonic Physics)

SPH implementation

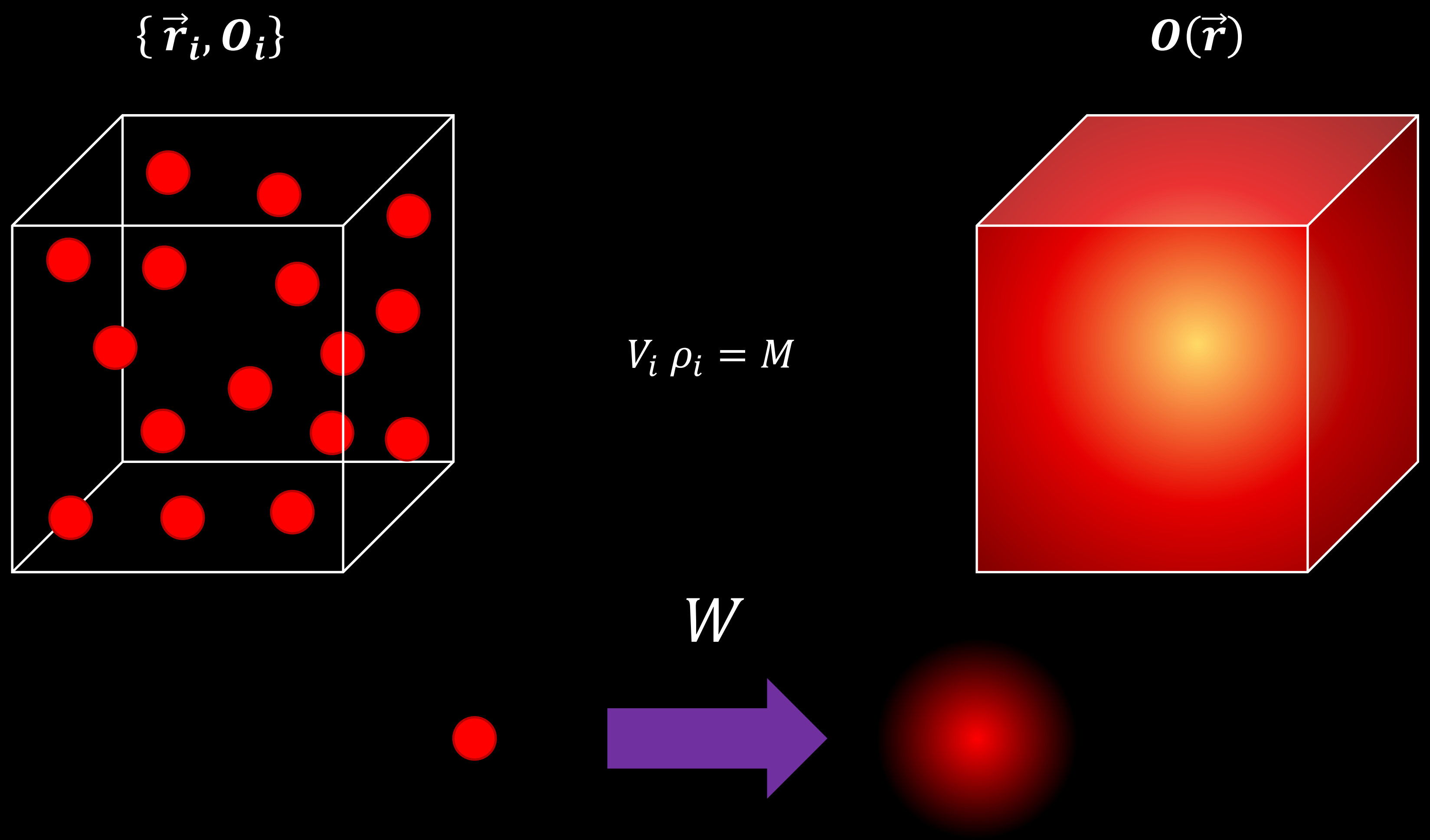
$\{\vec{r}_i, O_i\}$



$O(\vec{r})$

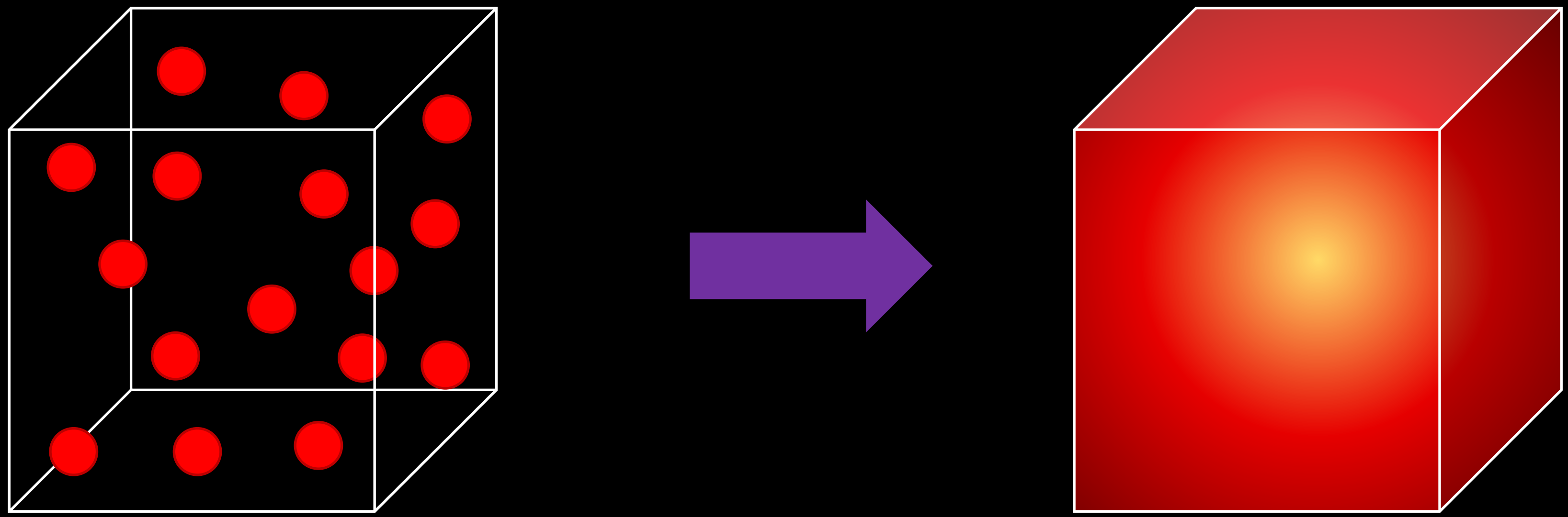


SPH implementation



SPH implementation

$\{\vec{r}_i, O_i\}$ $\quad$ $O(\vec{r})$

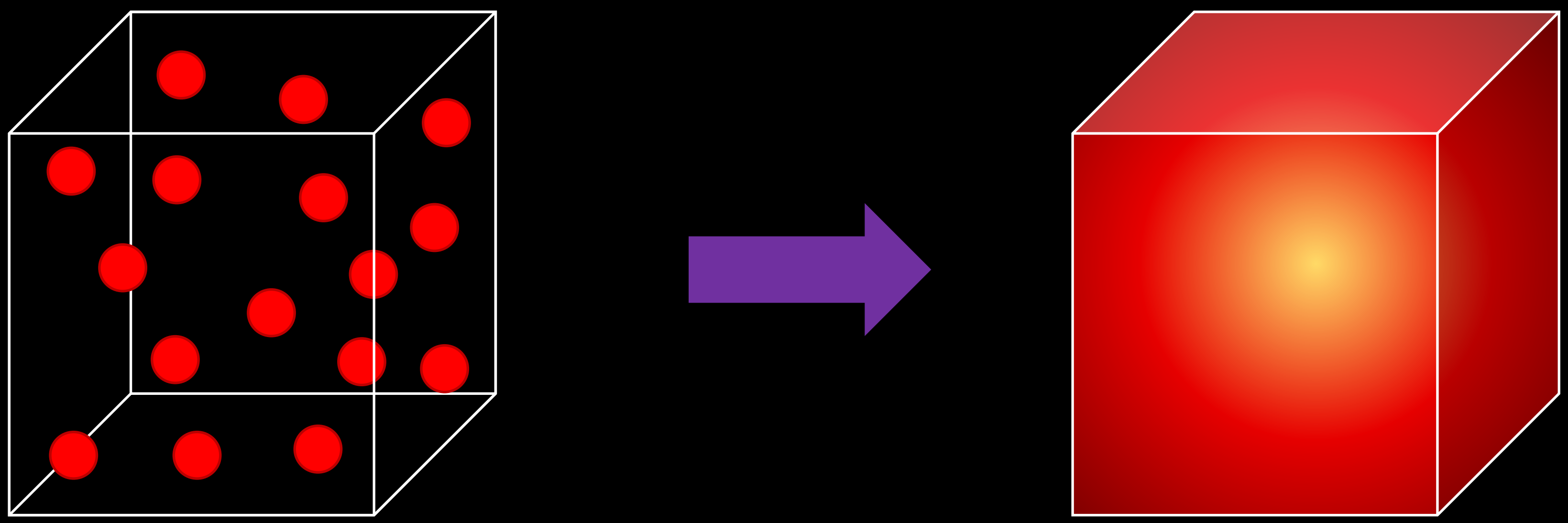


$$O_i = \sum_j m_j W_{ij} \frac{O_j}{\rho_j}$$

$$\vec{\nabla} O_i = \sum_j m_j \vec{\nabla} W_{ij} \frac{O_j}{\rho_j}$$

SPH implementation

$\{\vec{r}_i, O_i\}$ $O(\vec{r})$



$$\vec{\nabla} Q = \vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

$$O_i = \sum_j m_j W_{ij} \frac{O_j}{\rho_j}$$

$$\vec{\nabla} O_i = \sum_j m_j \vec{\nabla} W_{ij} \frac{O_j}{\rho_j}$$

3° derivatives

=

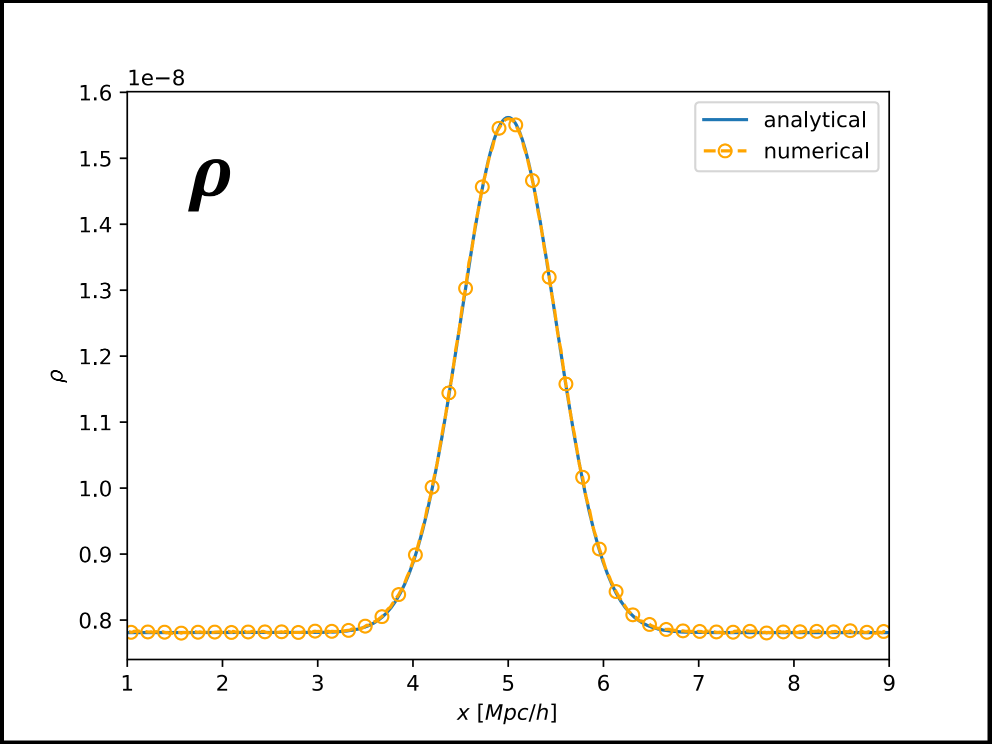
$3 \cdot N \cdot N_{nn}$

SPH implementation

$$\vec{\nabla}\rho_i = \sum_j m_j \vec{\nabla} W_{ij}$$

$$\nabla^2\rho_i = \sum_j m_j \nabla^2 W_{ij}$$

$$\vec{\nabla}Q = \vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$



Gaussian overdensity $\rho \propto c + \exp(-x^2/2\sigma^2)$

SPH implementation

$$\vec{\nabla}\rho_i = \sum_j m_j \vec{\nabla} W_{ij}$$

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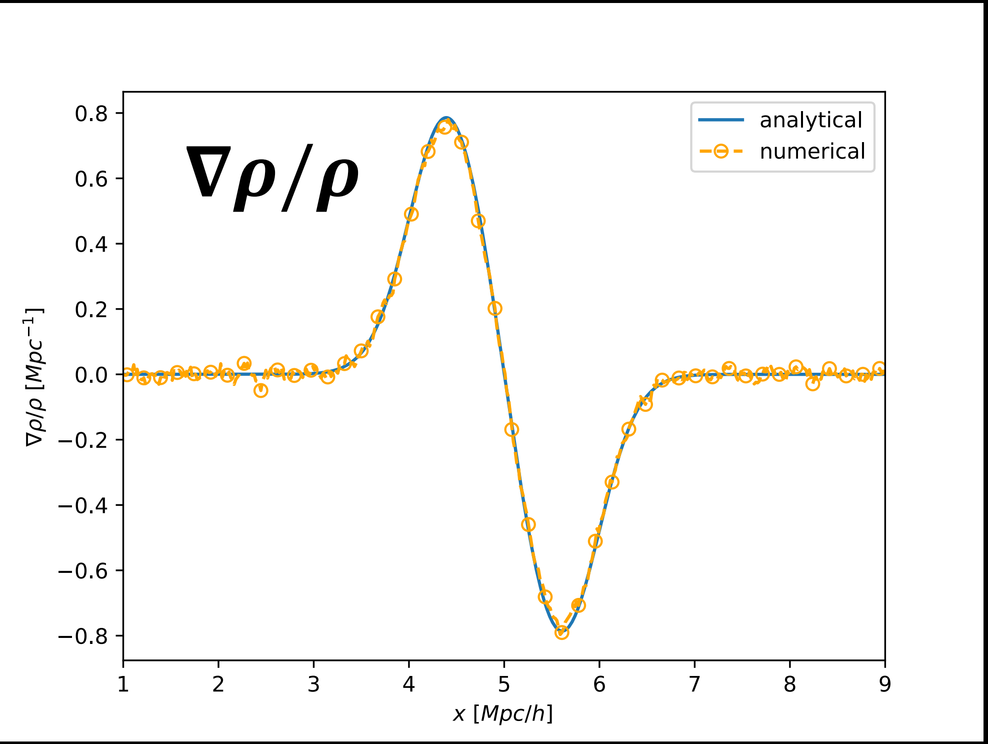

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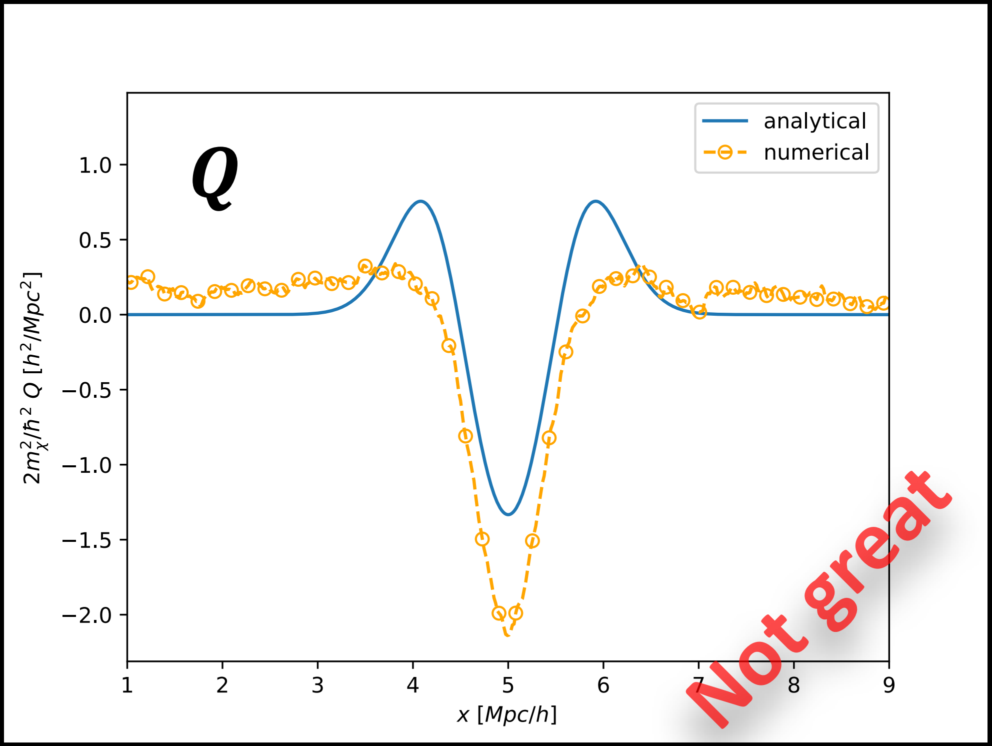

Gaussian overdensity $\rho \propto c + \exp(-x^2/2\sigma^2)$

SPH implementation

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$$\vec{\nabla}\mathrm{Q} = \vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

Analytical equivalence

$\neq$

Numerical equivalence

SPH implementation

$$\vec{\nabla}\rho_i = \sum_{\mathrm{j}} m_j \vec{\nabla} W_{ij}$$

$$\vec{\nabla}\rho = \frac{1}{\phi}\left[\vec{\nabla}(\phi\rho) - \rho\vec{\nabla}\phi\right]$$

$$\nabla^2\rho_i = \sum_{\mathrm{j}} m_j \nabla^2 W_{ij}$$

$$\nabla^2\rho = \frac{1}{\phi}\left[\nabla^2(\phi\rho) - \rho\nabla^2\phi - 2\,\vec{\nabla}\rho\cdot\vec{\nabla}\phi\right]$$

$$\vec{\nabla}\mathrm{Q} = \vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

SPH implementation

$$\vec{\nabla}\rho_i = \sum_{\mathrm{j}} m_j \vec{\nabla} W_{ij} \frac{\rho_j - \rho_i}{\rho_j \phi_i / \phi_j}$$

$$\nabla^2 \rho_i = \sum_{\mathrm{j}} m_j \nabla^2 W_{ij} \frac{\rho_j - \rho_i}{\rho_j \phi_i / \phi_j} - \frac{2}{\phi_i} \vec{\nabla}\rho_i \cdot \vec{\nabla}\phi_i$$

$$\vec{\nabla}\mathrm{Q} = \vec{\nabla}\left(\frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}\right)$$

In literature

$$\phi = \begin{cases} 1 \\ \sqrt{\rho} \\ \rho \end{cases}$$

SPH implementation

$$\vec{\nabla}\rho_i = \sum_{\mathrm{j}} m_j \vec{\nabla} W_{ij} \frac{\rho_j - \rho_i}{\sqrt{\rho_i \rho_j}}$$

$$\nabla^2 \rho_i = \sum_{\mathrm{j}} m_j \nabla^2 W_{ij} \frac{\rho_j - \rho_i}{\sqrt{\rho_i \rho_j}} - \frac{1}{\rho_i} \left|\vec{\nabla}\rho_i\right|^2$$

$$\vec{\nabla}\mathrm{Q} = \vec{\nabla}\left(\frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}\right)$$

SPH implementation

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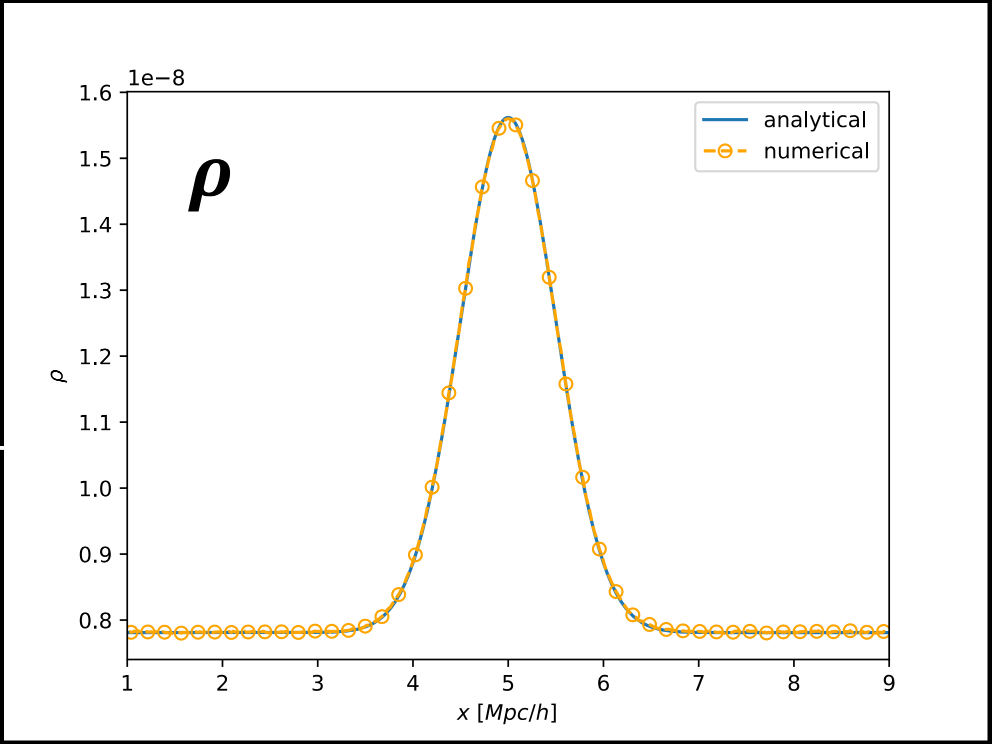

Gaussian overdensity $\rho \propto c + \exp(-x^2/2\sigma^2)$

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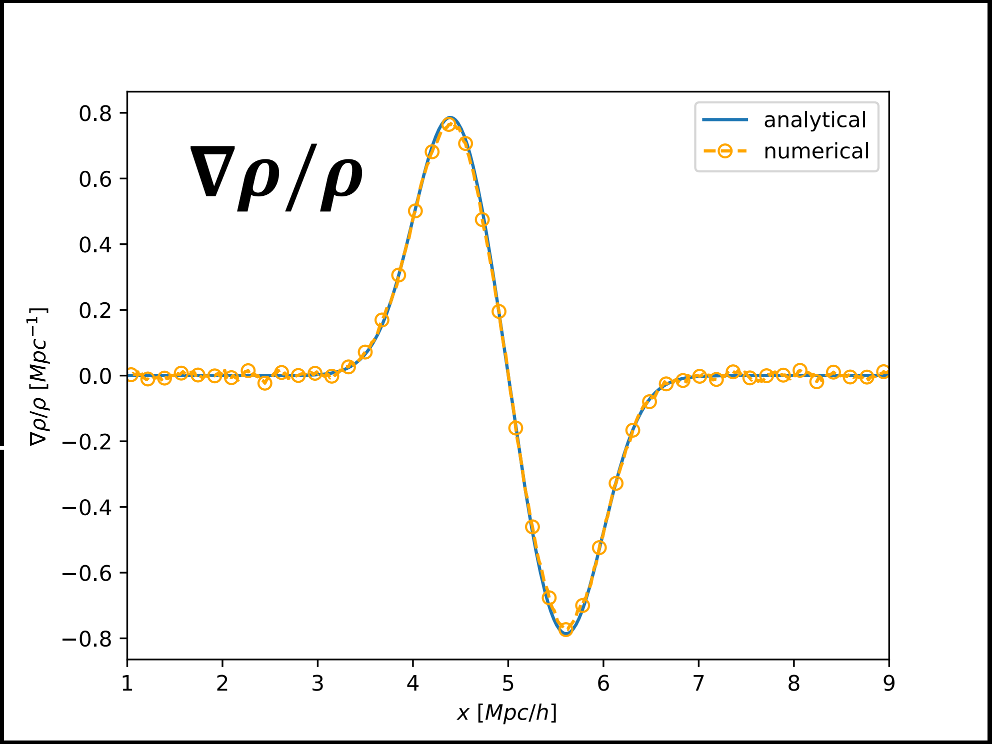

$$\vec{\nabla} Q = \vec{\nabla}\left(\frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}\right)$$

Gaussian overdensity $\rho \propto c + \exp(-x^2/2\sigma^2)$

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$$\vec{\nabla}\rho_i = \sum_j m_j \vec{\nabla} W_{ij} \frac{\rho_j - \rho_i}{\sqrt{\rho_i \rho_j}}$$

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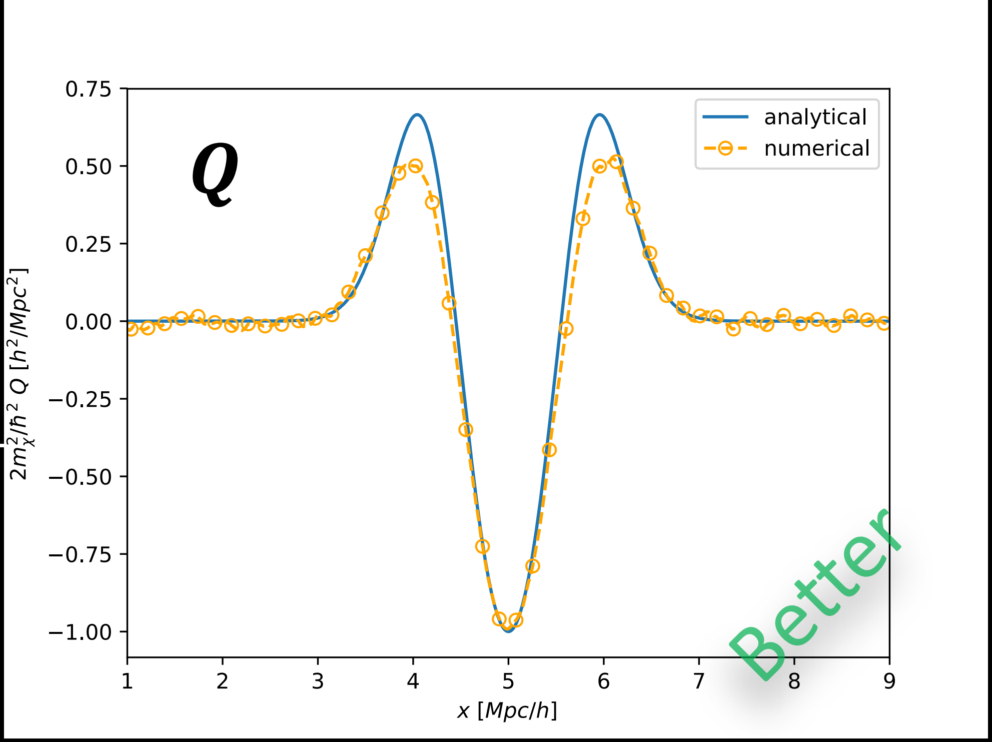


Gaussian overdensity $\rho \propto c + \exp(-x^2/2\sigma^2)$

Zhang et al, arXiv:1611.00892

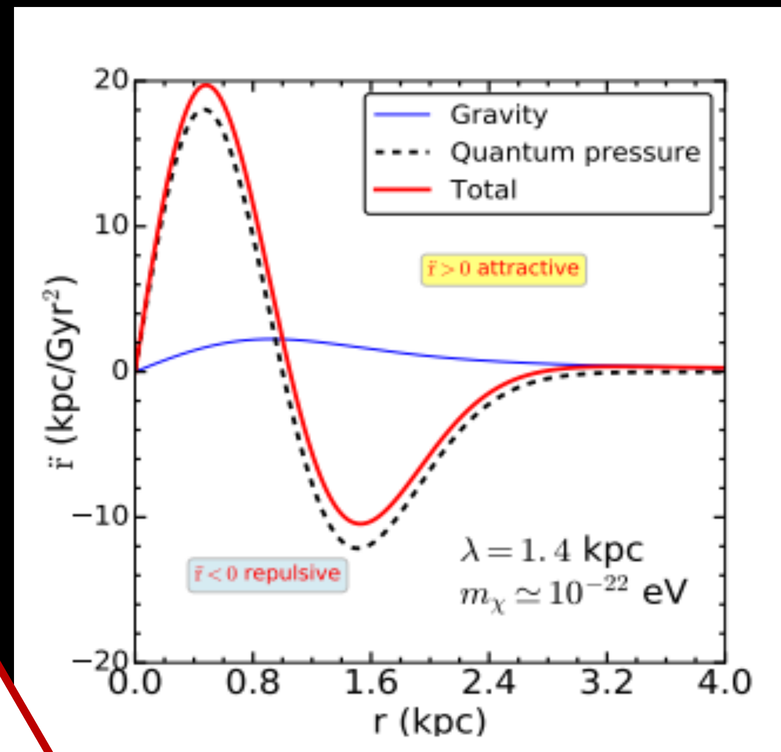
$$\int f(q)\,\mathbf{d^3x} \;\rightarrow\; \sum_j f(q_j)\,\mathbf{V_j}$$

$V_j = M/\rho_j$ is not constant!

In SPH what is constant is:

$$M = \rho_j V_j$$

$$\vec{\nabla} Q = \vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\cancel{\sqrt{\rho}}}\right)$$



!

Quantum Jeans length

$$\lambda_Q = 2\pi \left(\frac{\lambda_H^2 \, \lambda_m^2}{6 \, \Omega_0} \right)^{1/4} (z+1)^{1/4}$$

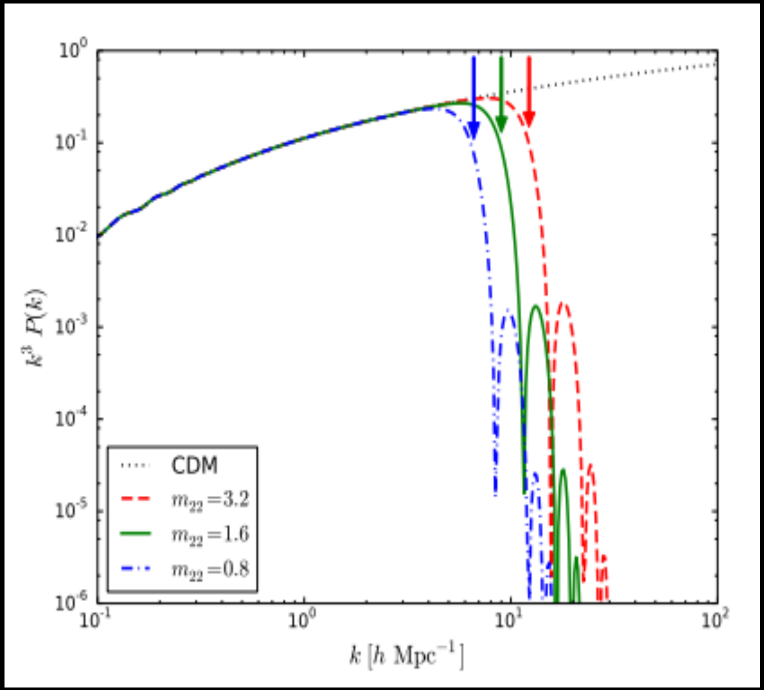
Quantum Jeans length

$$\lambda_Q \sim\ 88\ \mathrm{Kpc}\ (\mathrm{z}+1)^{1/4}/\sqrt{\mathrm{m}_{22}}$$

Quantum Jeans length

$$\lambda_Q \sim 88\ \mathrm{Kpc}\ (z+1)^{1/4}/\sqrt{m_{22}}$$

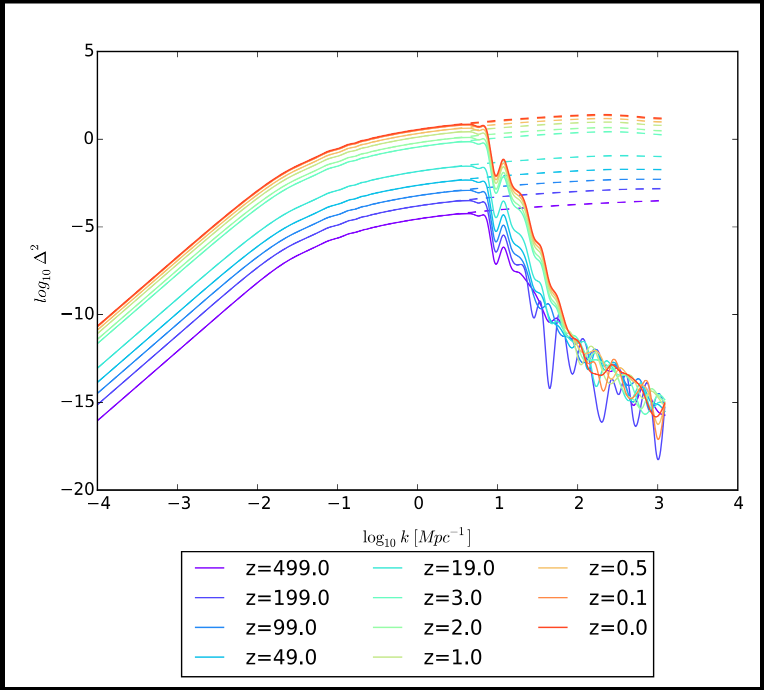
Schive +16



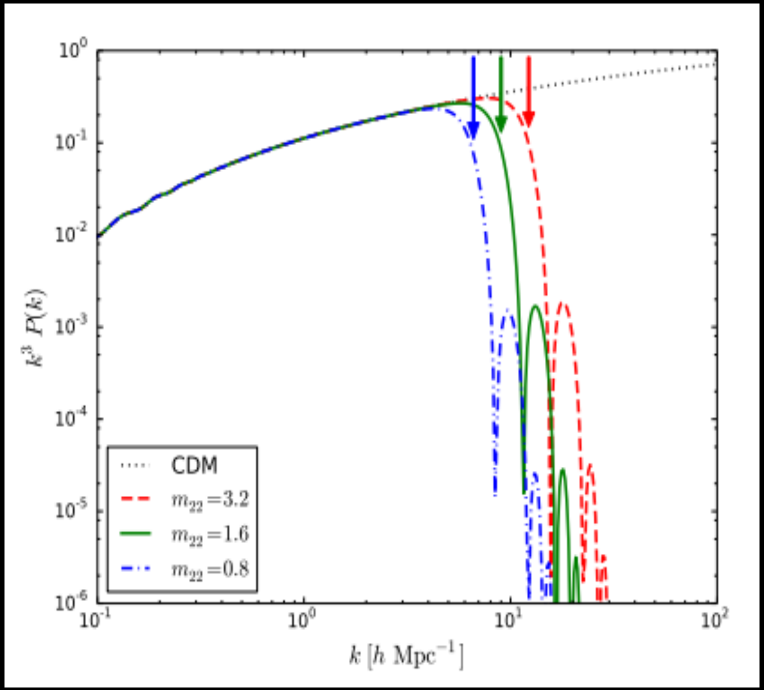
Quantum Jeans length

$$\lambda_Q \sim 88\ \mathrm{Kpc}\ (z+1)^{1/4}/\sqrt{m_{22}}$$

axionCAMB – Hlozek +15



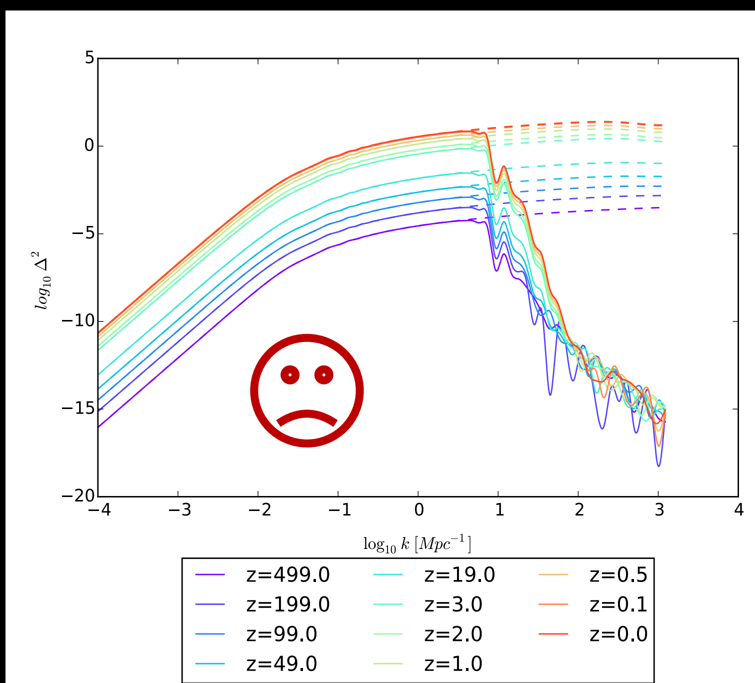
Schive +16



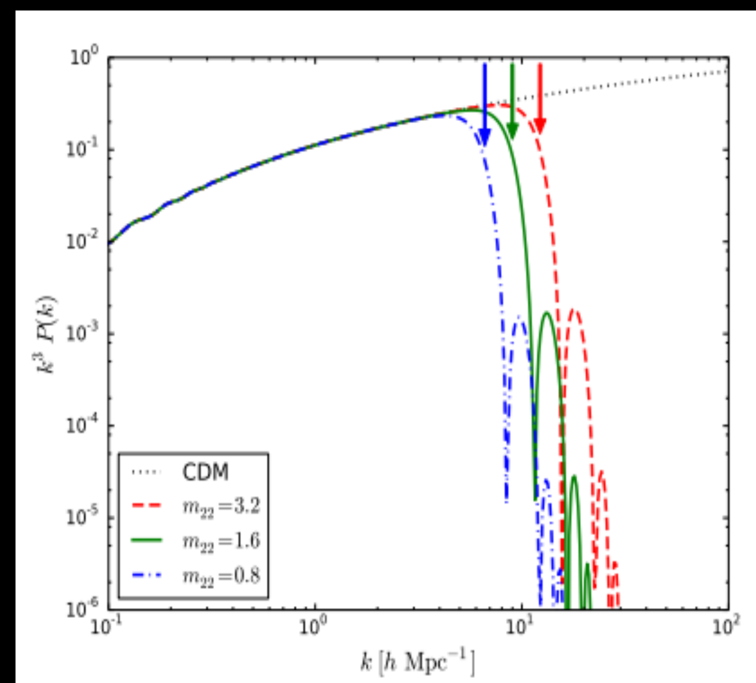
Quantum Jeans length

$$\lambda_Q \sim 88\ \mathrm{Kpc}\,(z+1)^{1/4}/\sqrt{m_{22}}$$

axionCAMB – Hlozek +15



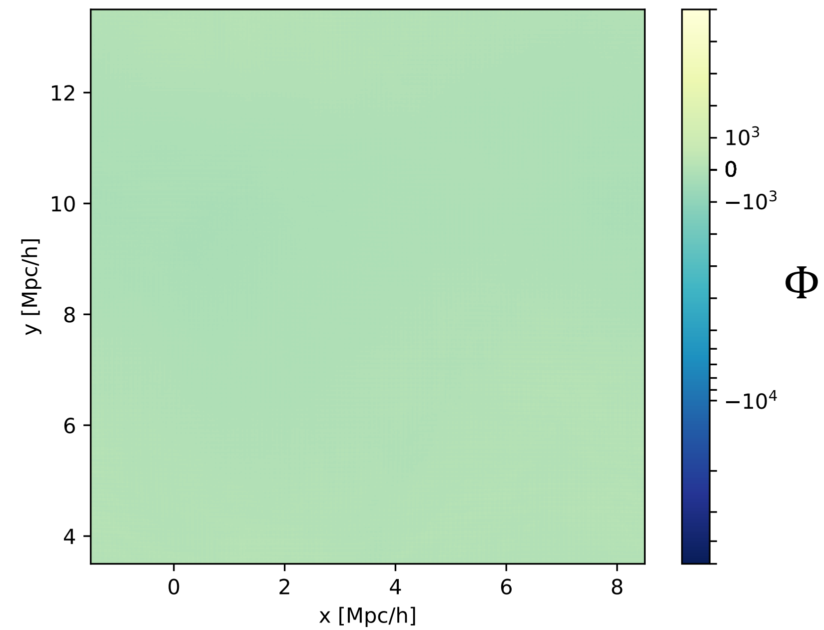
Schive +16

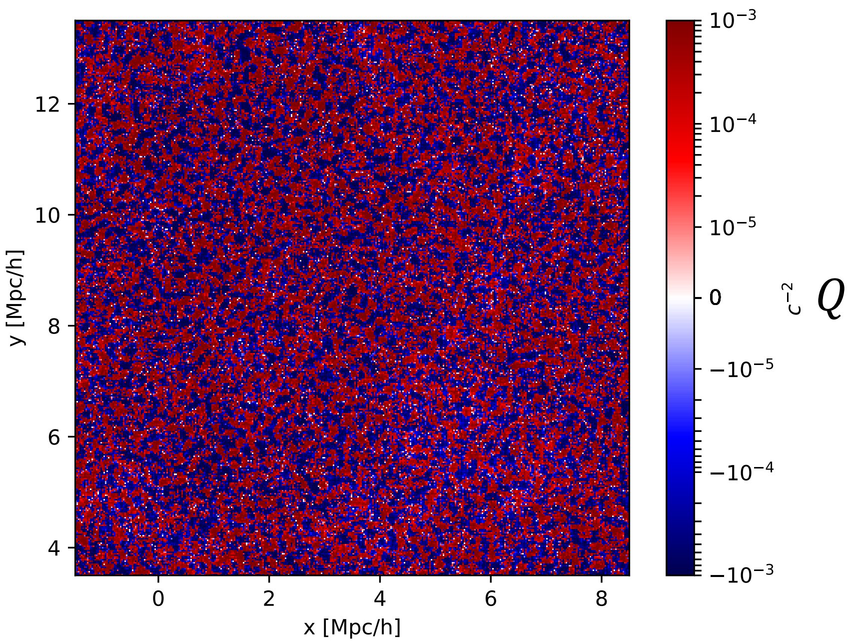


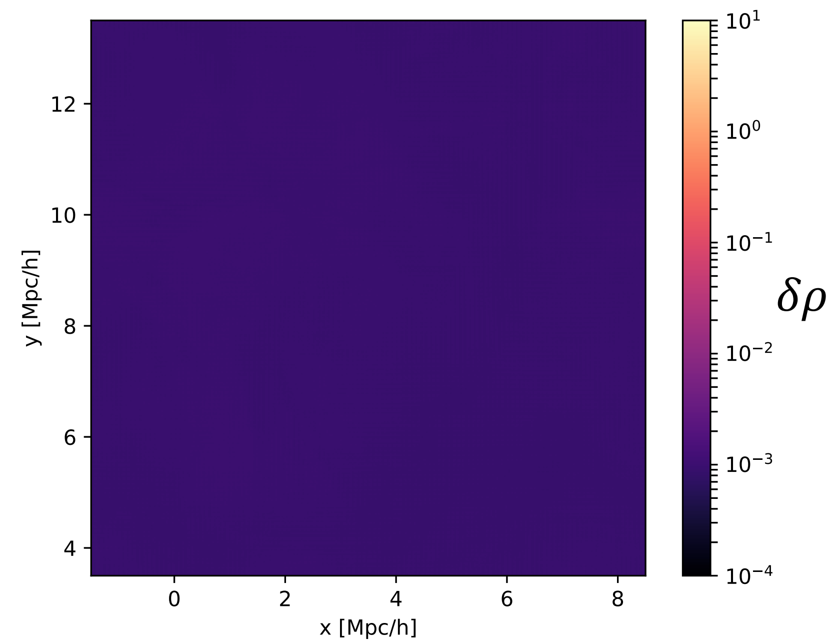
Simulation

$10\ Mpc$ side box
256^3 particles

$z = 99$



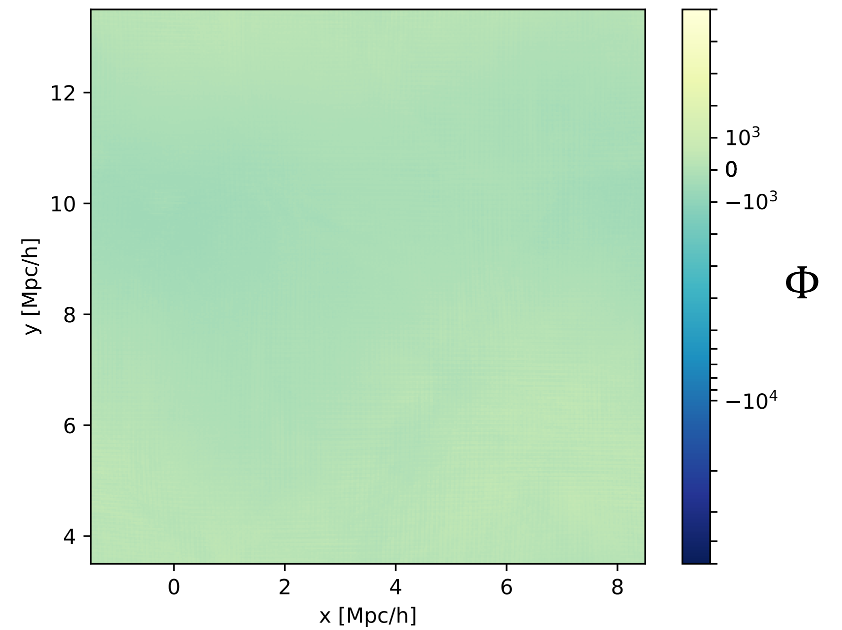


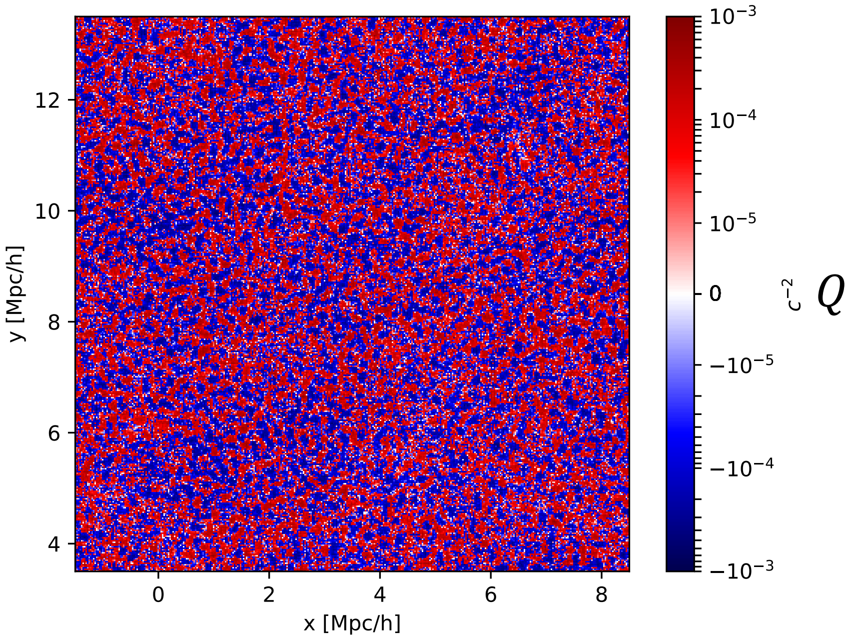


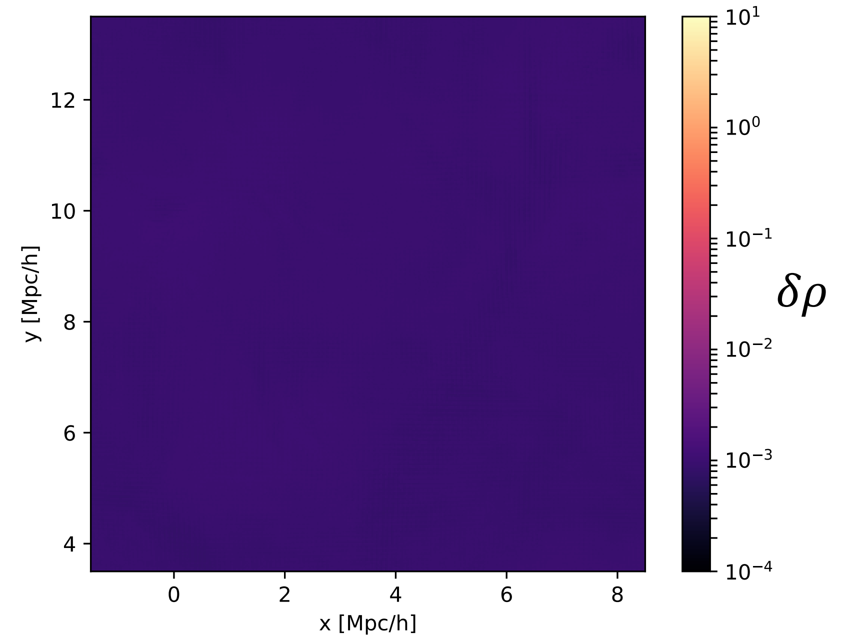
Simulation

10 Mpc side box
256^3 particles

$z = 49$



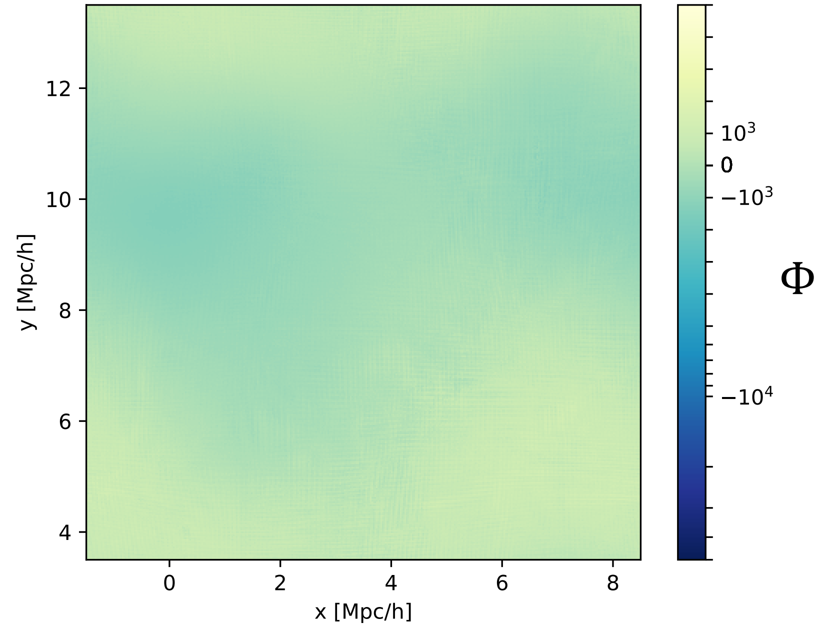


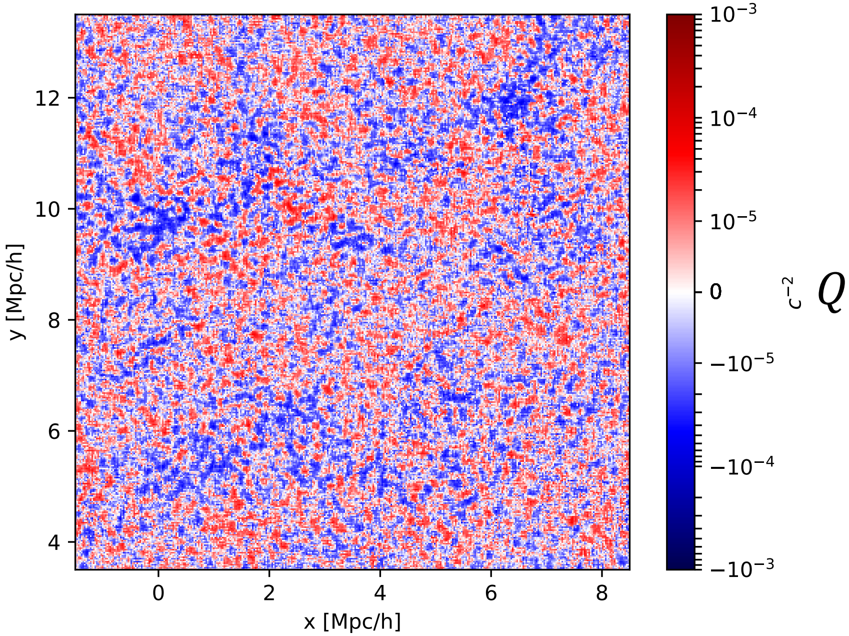


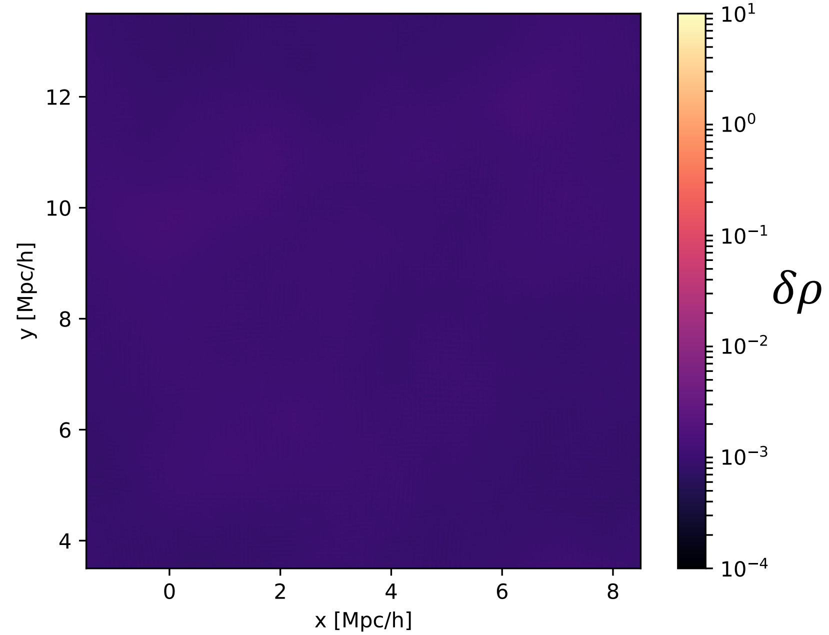
Simulation

$10\ Mpc$ side box
256^3 particles

$z = 19$



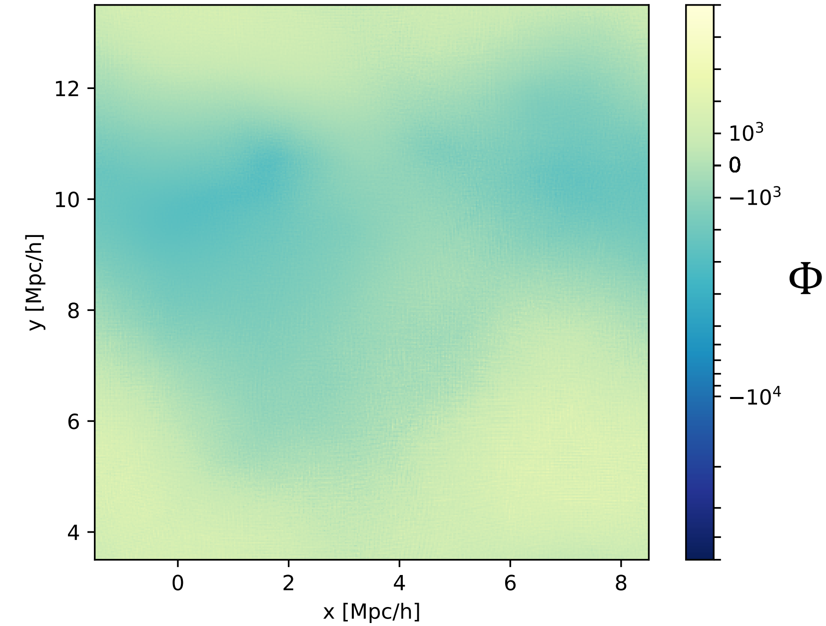


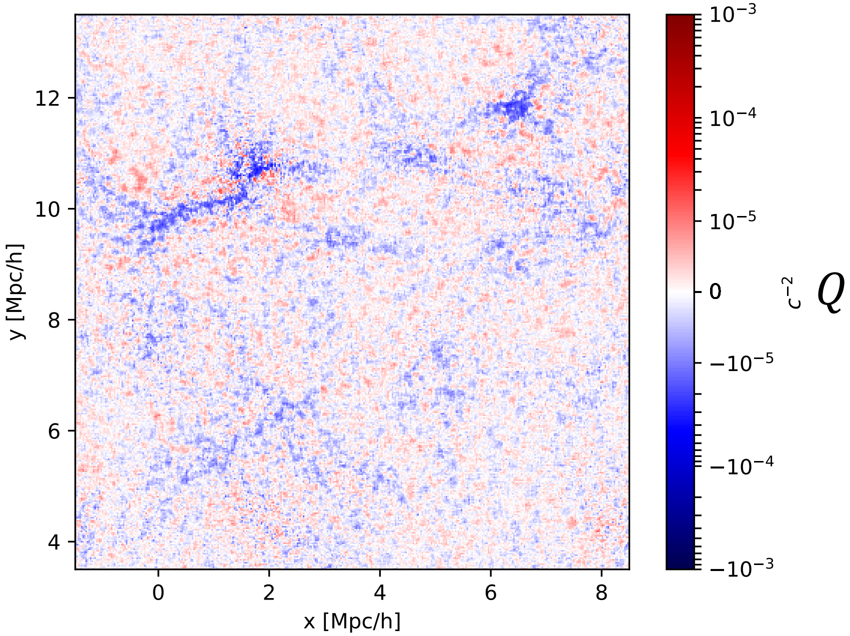


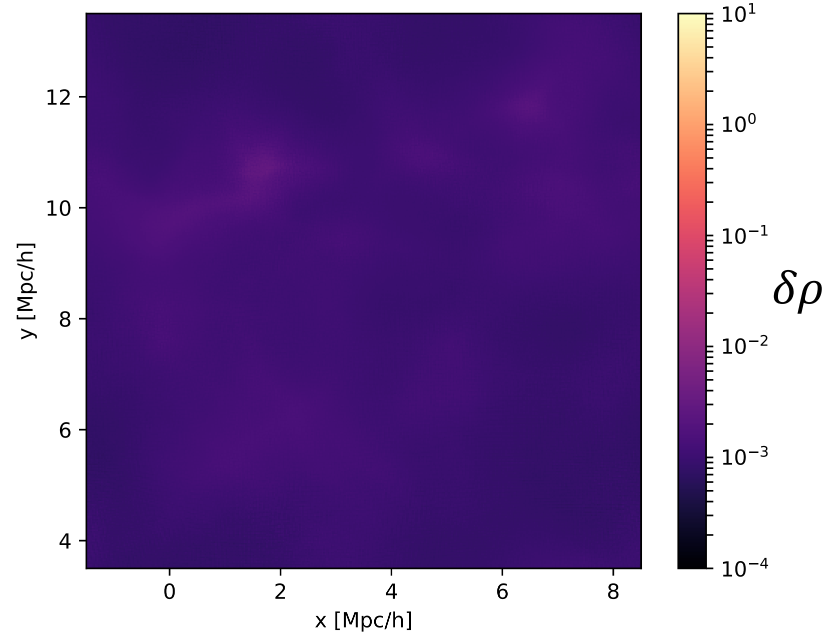
Simulation

10 Mpc side box
256^3 particles

$z = 9$



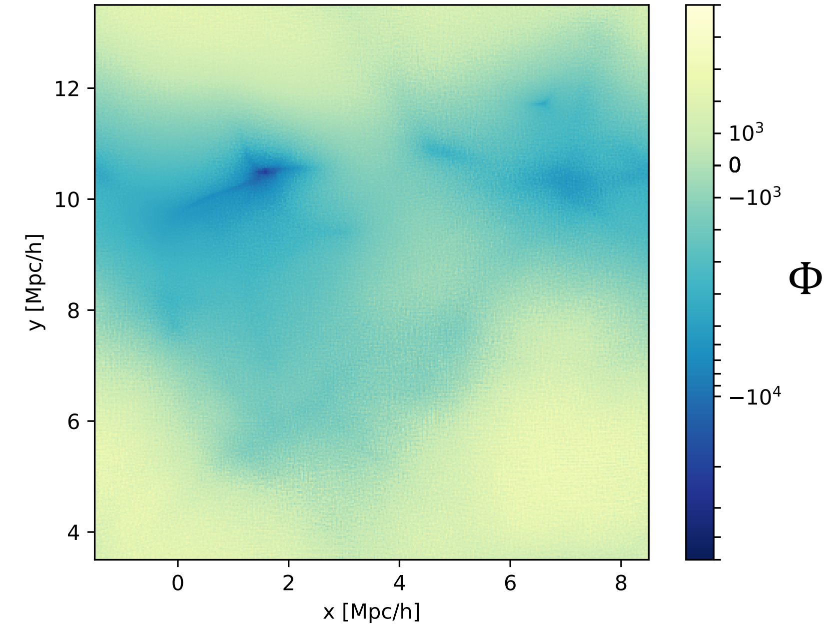


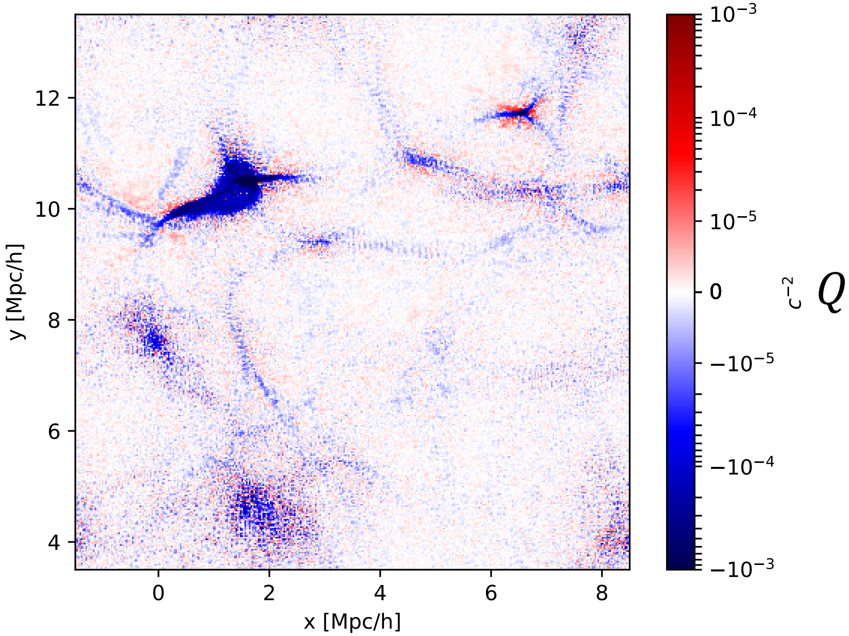


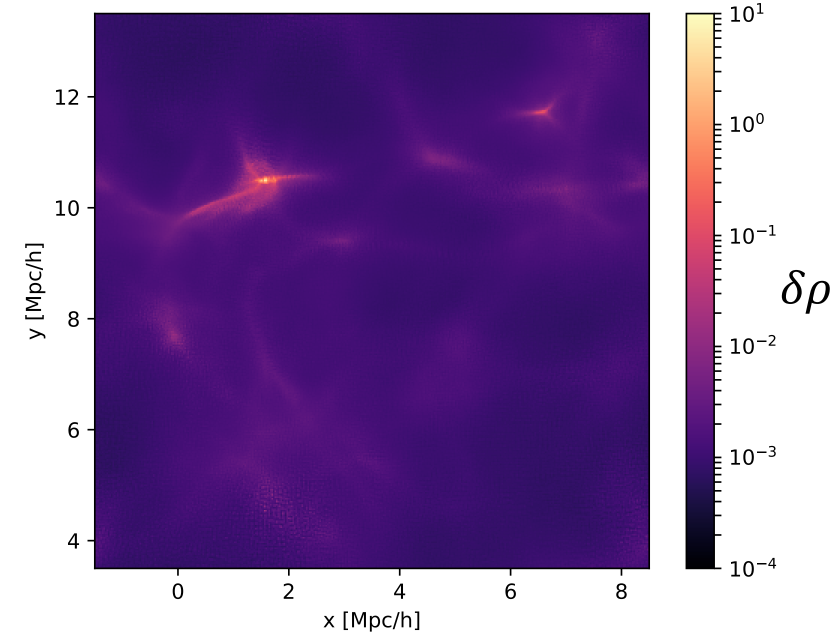
Simulation

10 Mpc side box
256^3 particles

$z = 5$



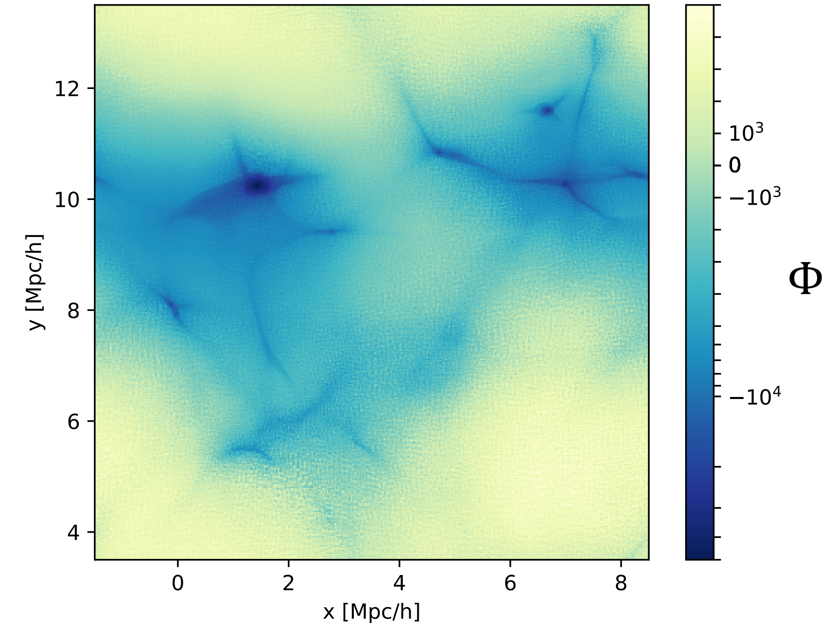


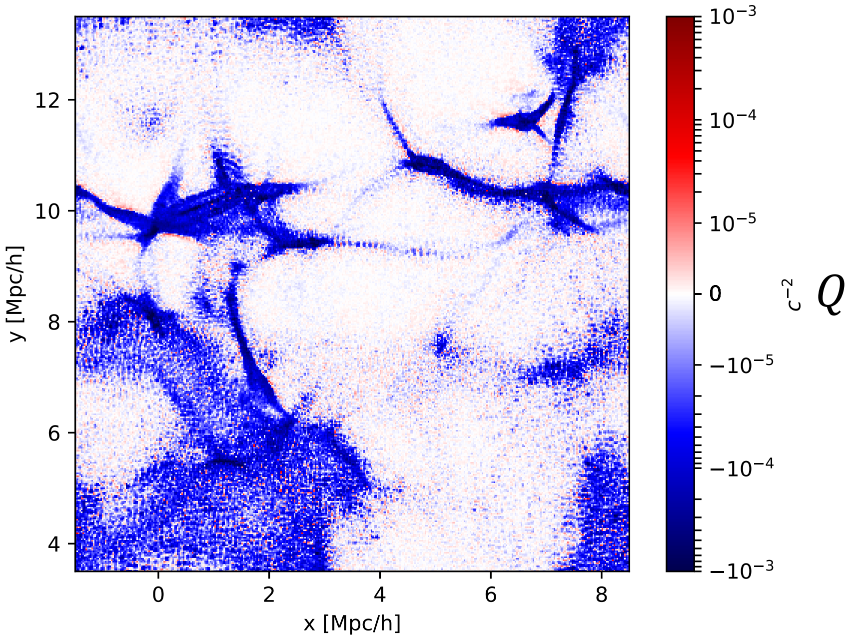


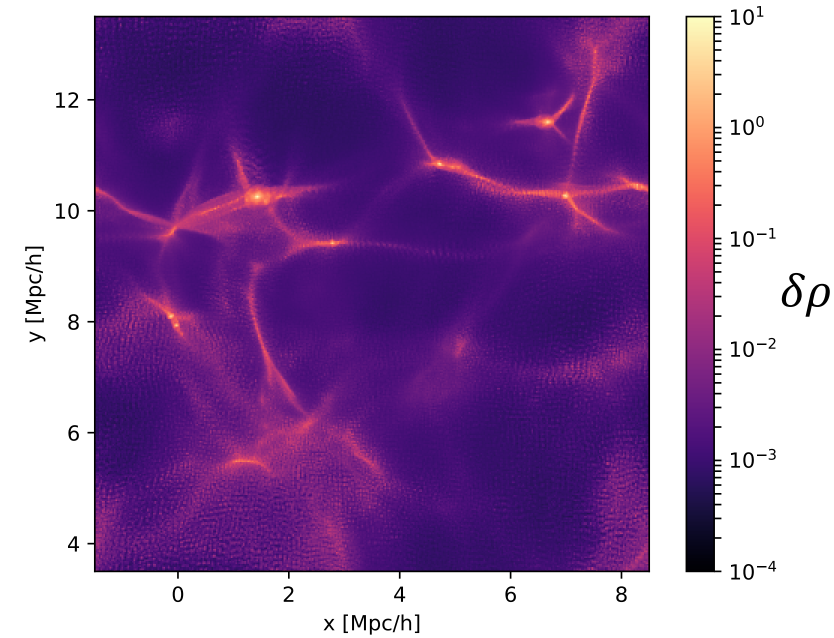
Simulation

$10\ Mpc$ side box
256^3 particles

$z = 3$



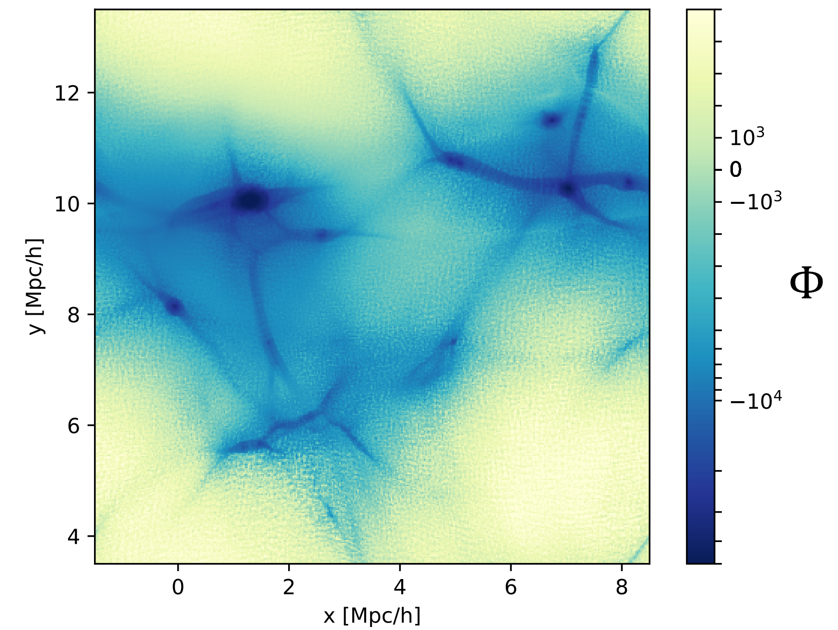


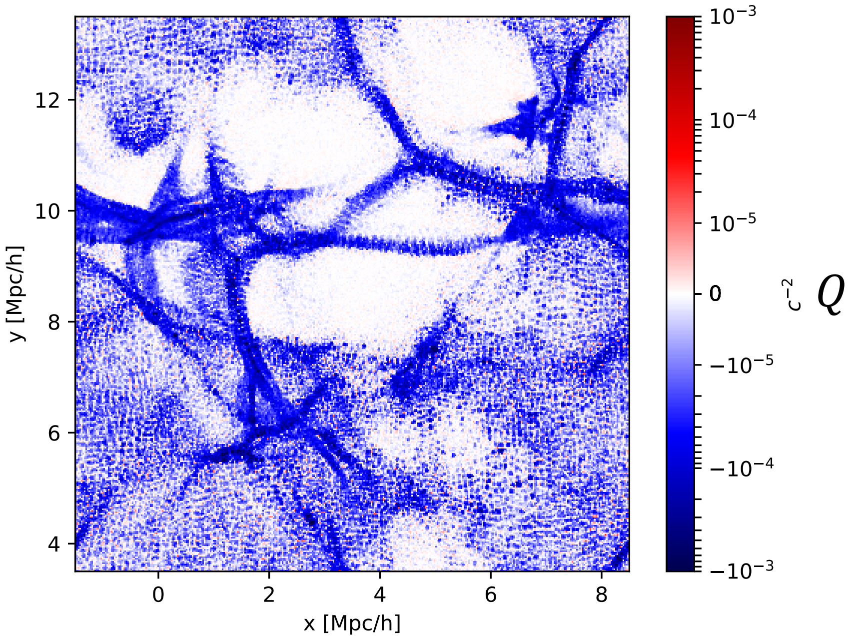


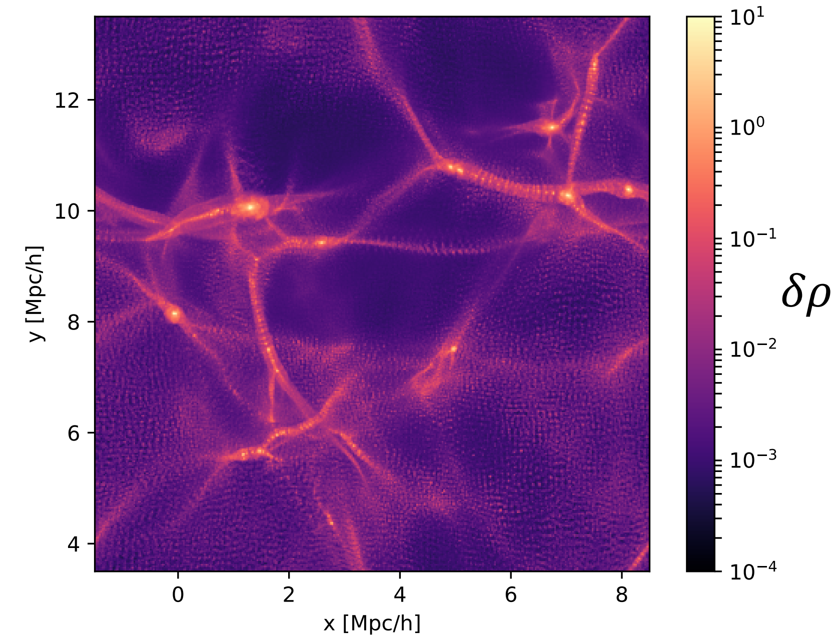
Simulation

10 Mpc side box
256^3 particles

$z = 2$



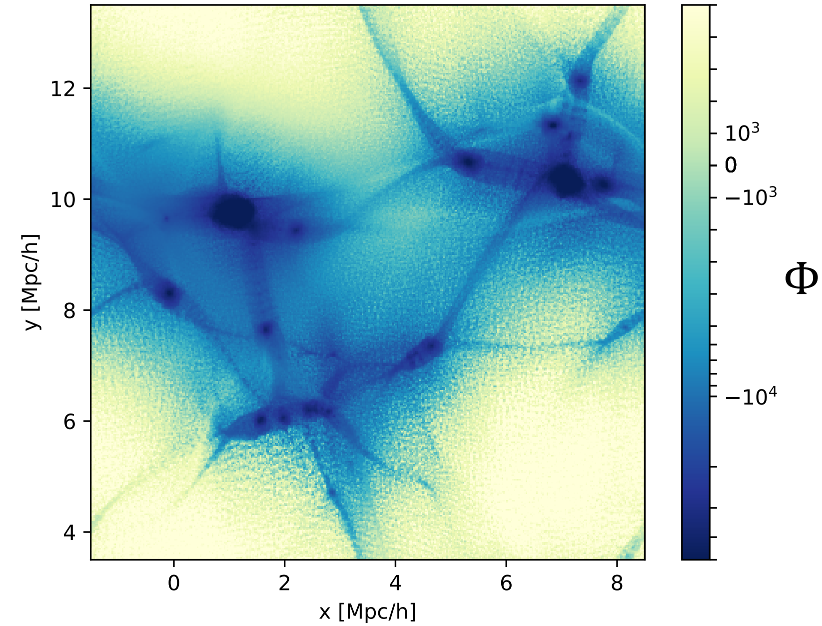


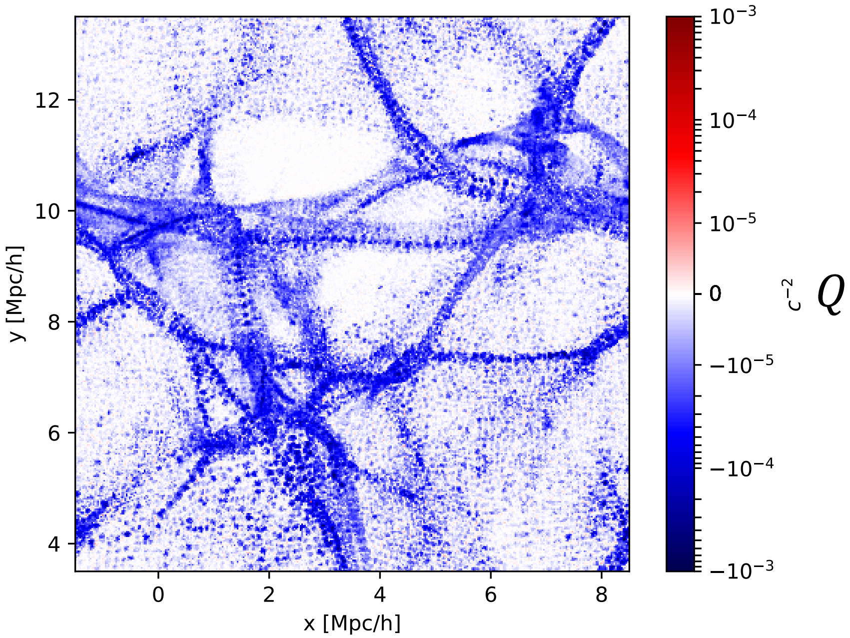


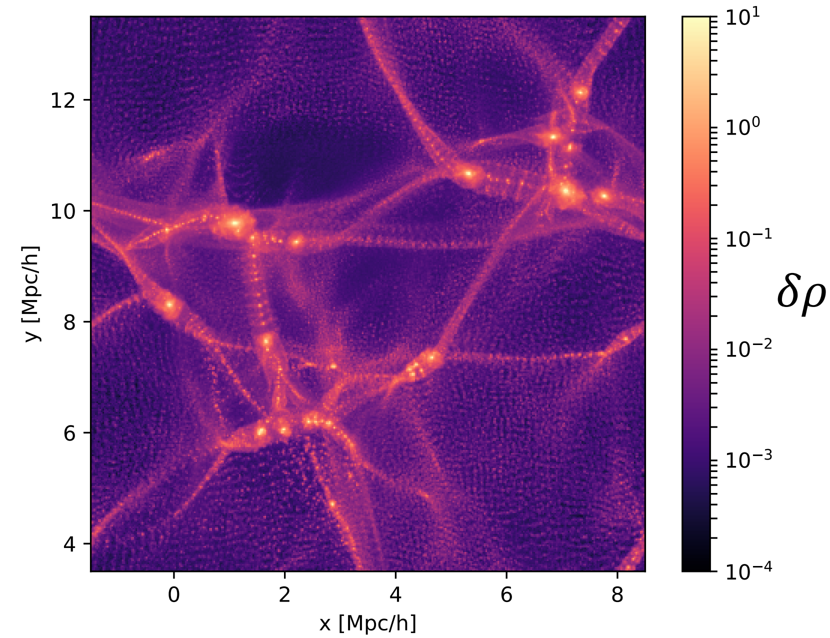
Simulation

10 Mpc side box
256^3 particles

$z = 1$



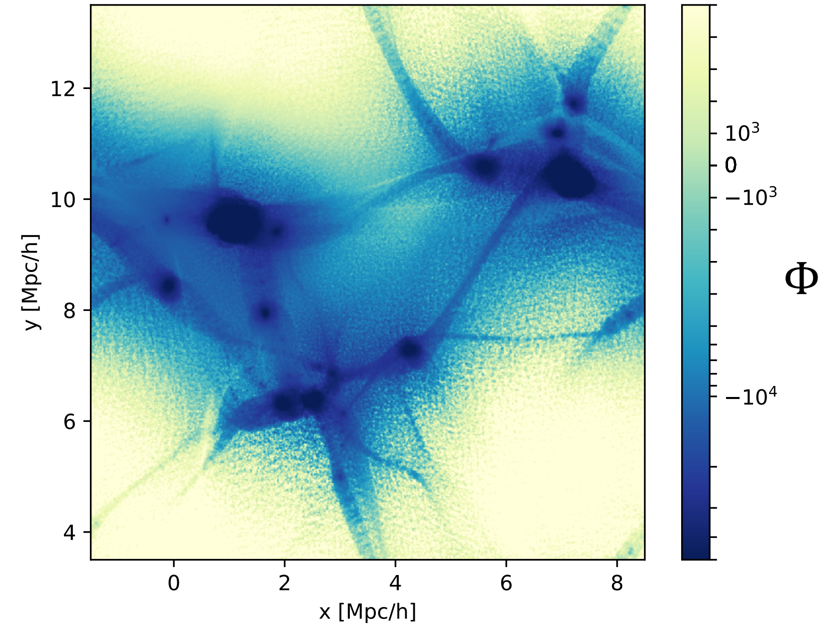


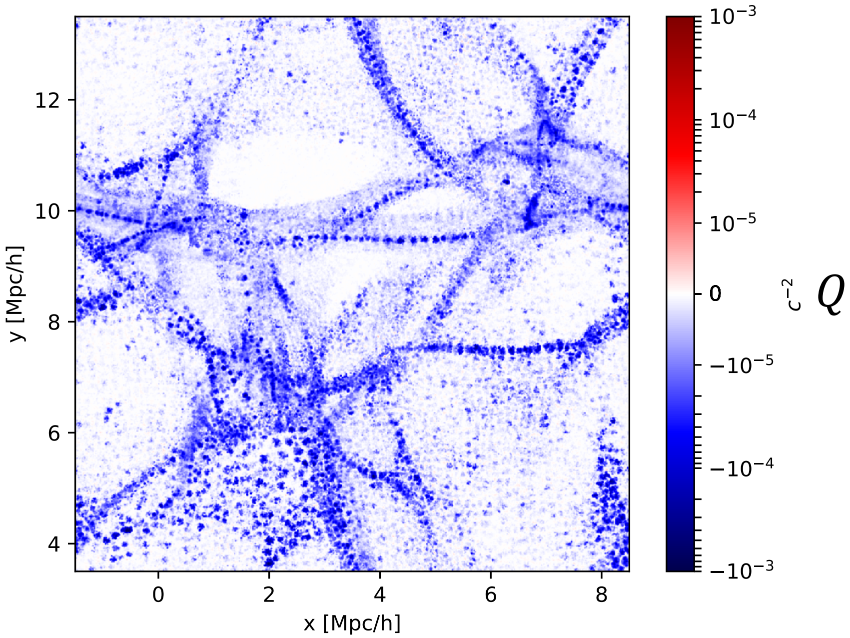


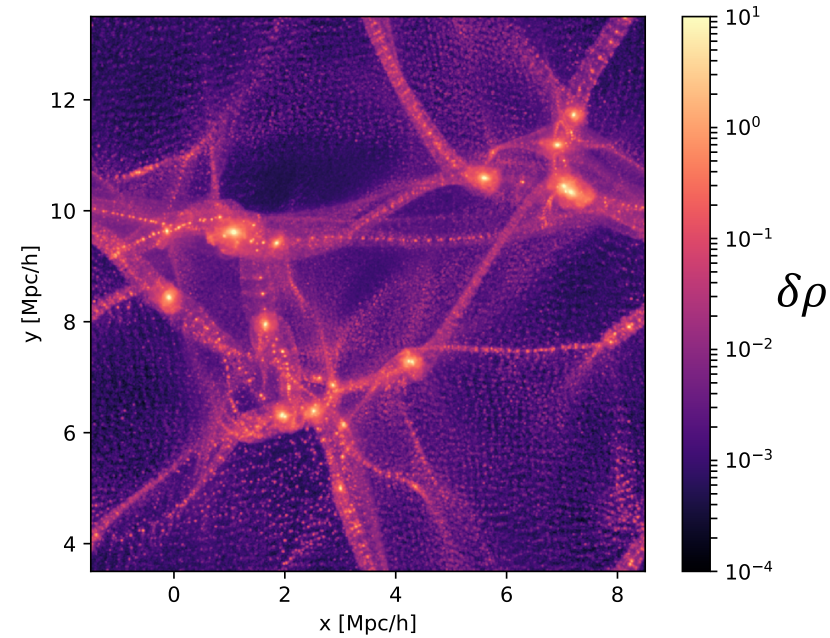
Simulation

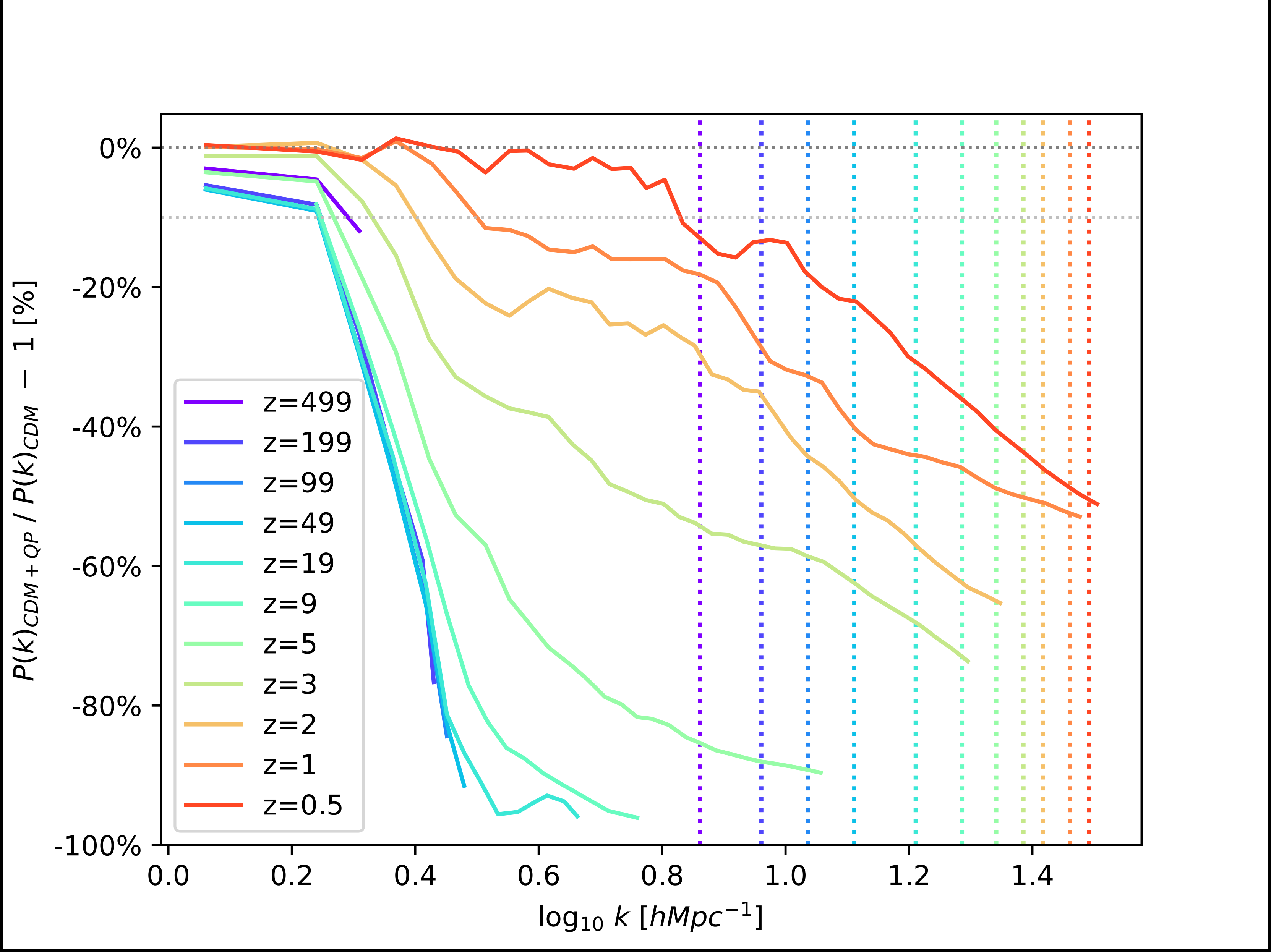
$10\ Mpc$ side box
256^3 particles

$z = 0.5$

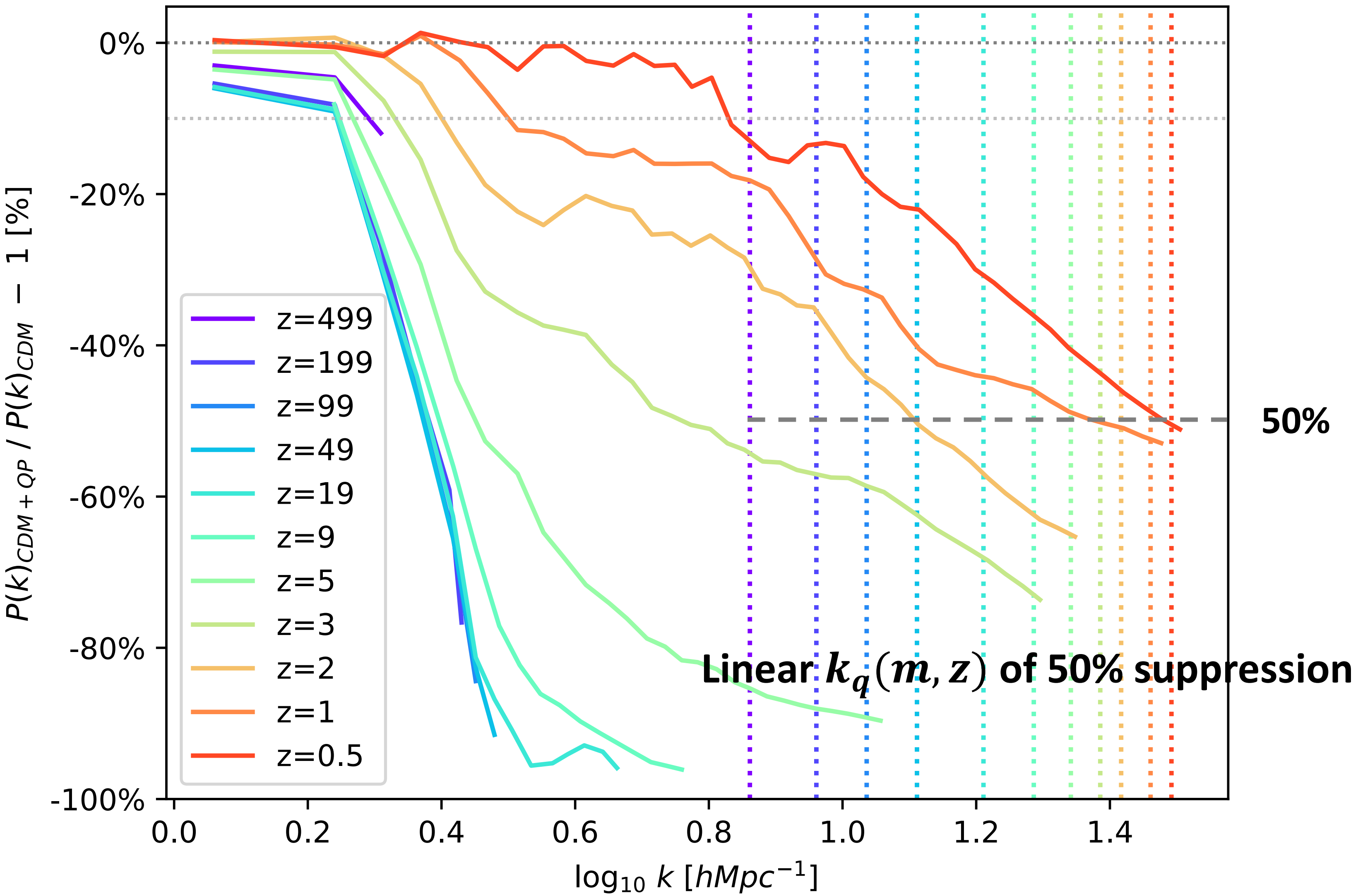








0%
-20%
-40%
-60%
-80%
-100%
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$\log_{10} k$ [$hMpc^{-1}$]
$P(k)_{CDM+QP}$ / $P(k)_{CDM}$ − 1 [%]
z=499
z=199
z=99
z=49
z=19
z=9
z=5
z=3
z=2
z=1
z=0.5



0%
-20%
-40%
-60%
-80%
-100%
$P(k)_{CDM+QP}$ / $P(k)_{CDM}$ − 1 [%]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$\log_{10} k$ [$hMpc^{-1}$]
z=499
z=199
z=99
z=49
z=19
z=9
z=5
z=3
z=2
z=1
z=0.5
50%
Linear $k_q(m, z)$ of 50% suppression

Initial Conditions

Schive+16

"It is appropriate to use simulations of collisionless particles with FDM initial power spectra to approximate real FDM simulations"

Initial Conditions

Schive+16

"It is appropriate to use simulations of collisionless particles with FDM initial power spectra to approximate real FDM simulations"

Cosmological particle-in-cell simulations with ultralight axion dark matter

Jan Veltmaat and Jens C. Niemeyer
Institut für Astrophysik
Universität Göttingen

(Dated: January 3, 2017)

We study cosmological structure formation with ultralight axion dark matter, or "fuzzy dark matter" (FDM), using a particle-mesh scheme to account for the quantum pressure arising in the Madelung formulation of the Schrödinger-Poisson equations. Subpercent-level energy conservation and correct linear behavior are demonstrated. Whereas the code gives rise to the same core-halo profiles as direct simulations of the Schrödinger equation, it does not reproduce the detailed interference patterns. In cosmological simulations with FDM initial conditions, we find a maximum relative difference of O(10%) in the power spectrum near the quantum Jeans length compared to using a standard N-body code with identical initial conditions. This shows that the effect of quantum pressure during nonlinear structure formation cannot be neglected for precision constraints on a dark matter component consisting of ultralight axions.

Veltmaat +16
Particle – Mesh scheme code

Initial Conditions

Schive+16

"It is appropriate to use simu
with FDM initial power spectra to
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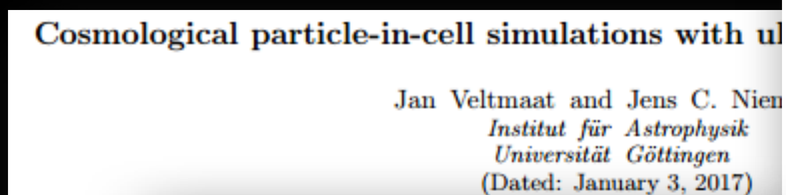
Cosmological particle-in-cell simulations with ul

Jan Veltmaat and Jens C. Nien
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(Dated: January 3, 2017)

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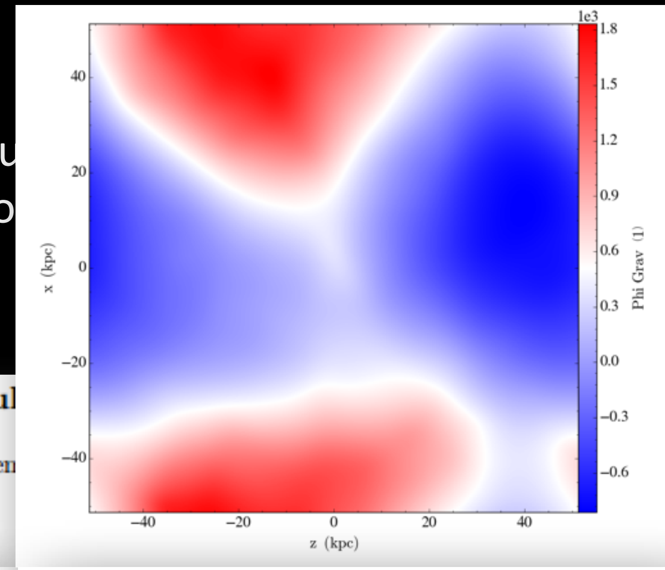
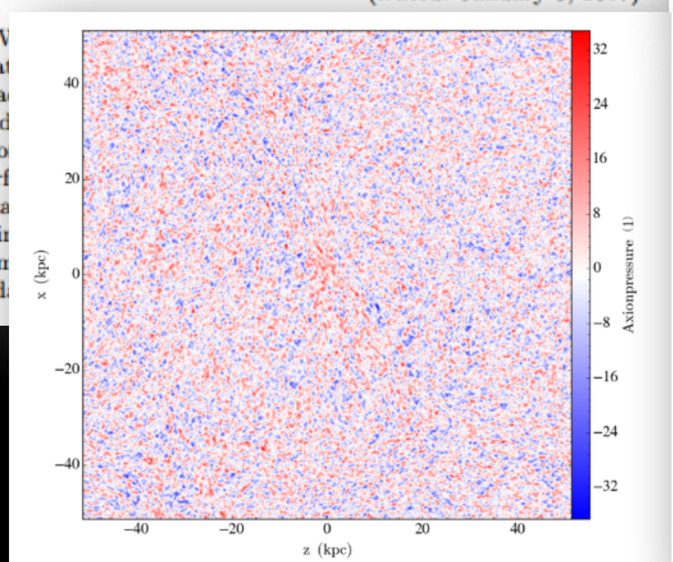
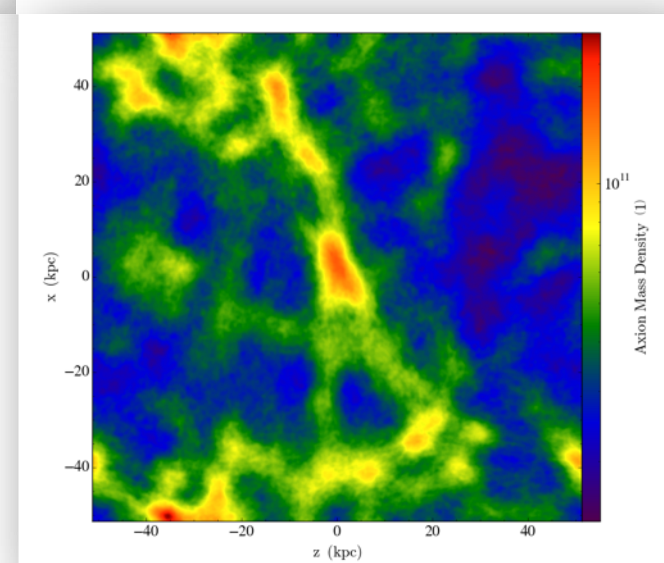




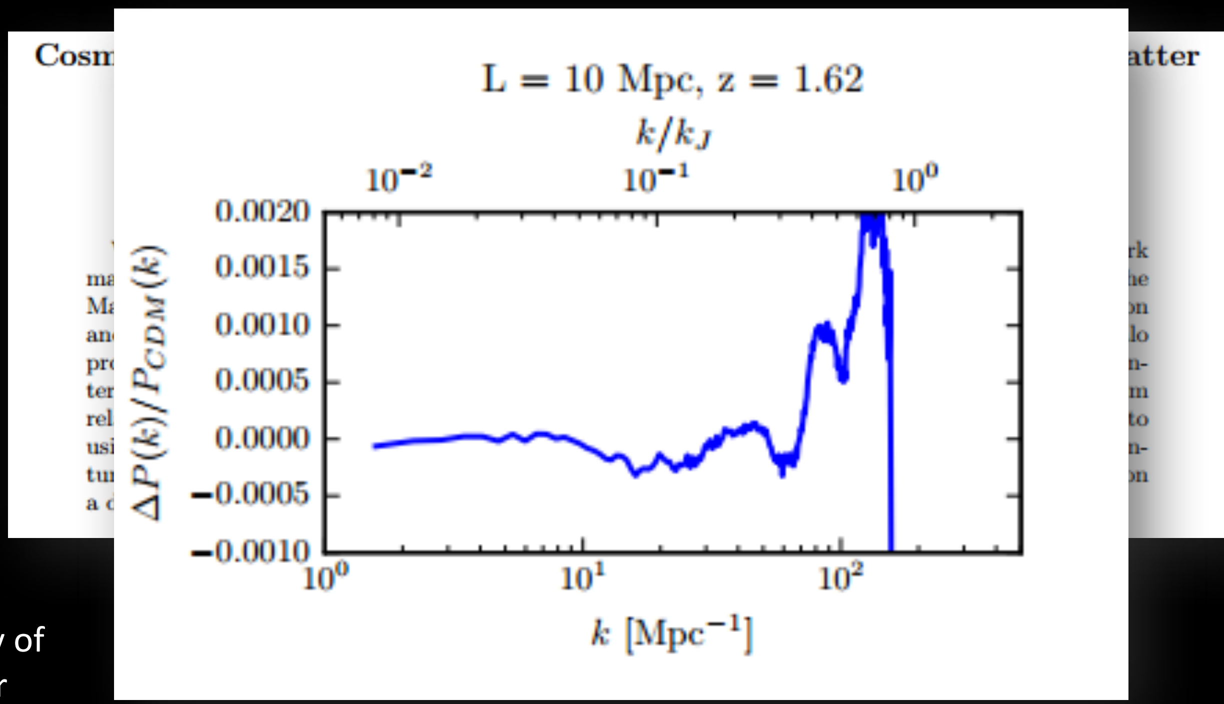


Images: courtesy of
Jens Niemeyer

Initial Conditions

Schive+16

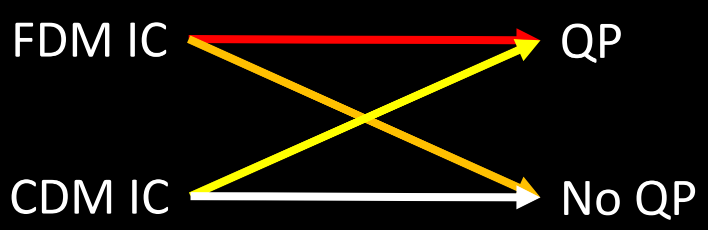
"It is appropriate to use simulations of collisionless particles with FDM initial power spectra to approximate real FDM simulations"

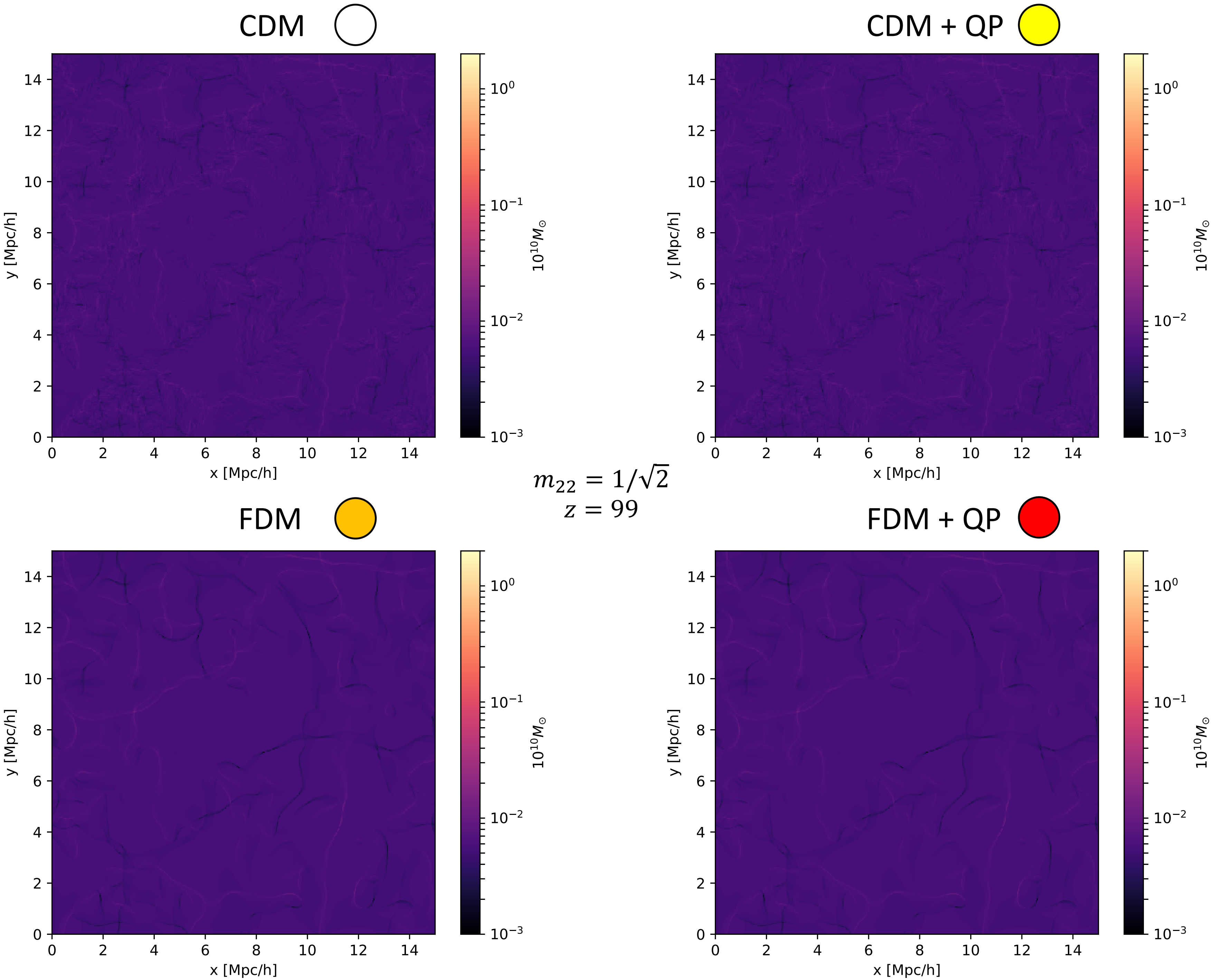


Images: courtesy of Jens Niemeyer

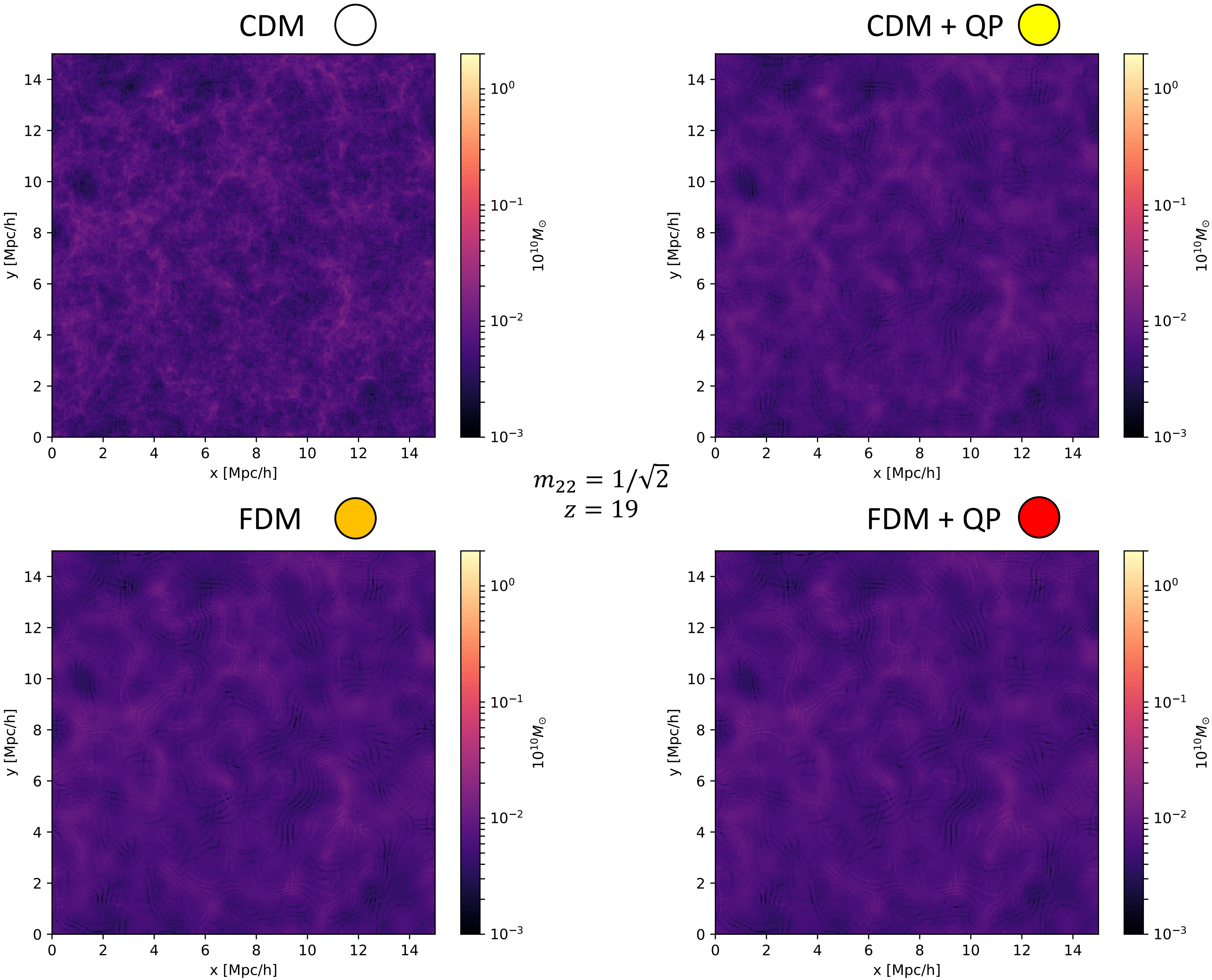
Initial Conditions

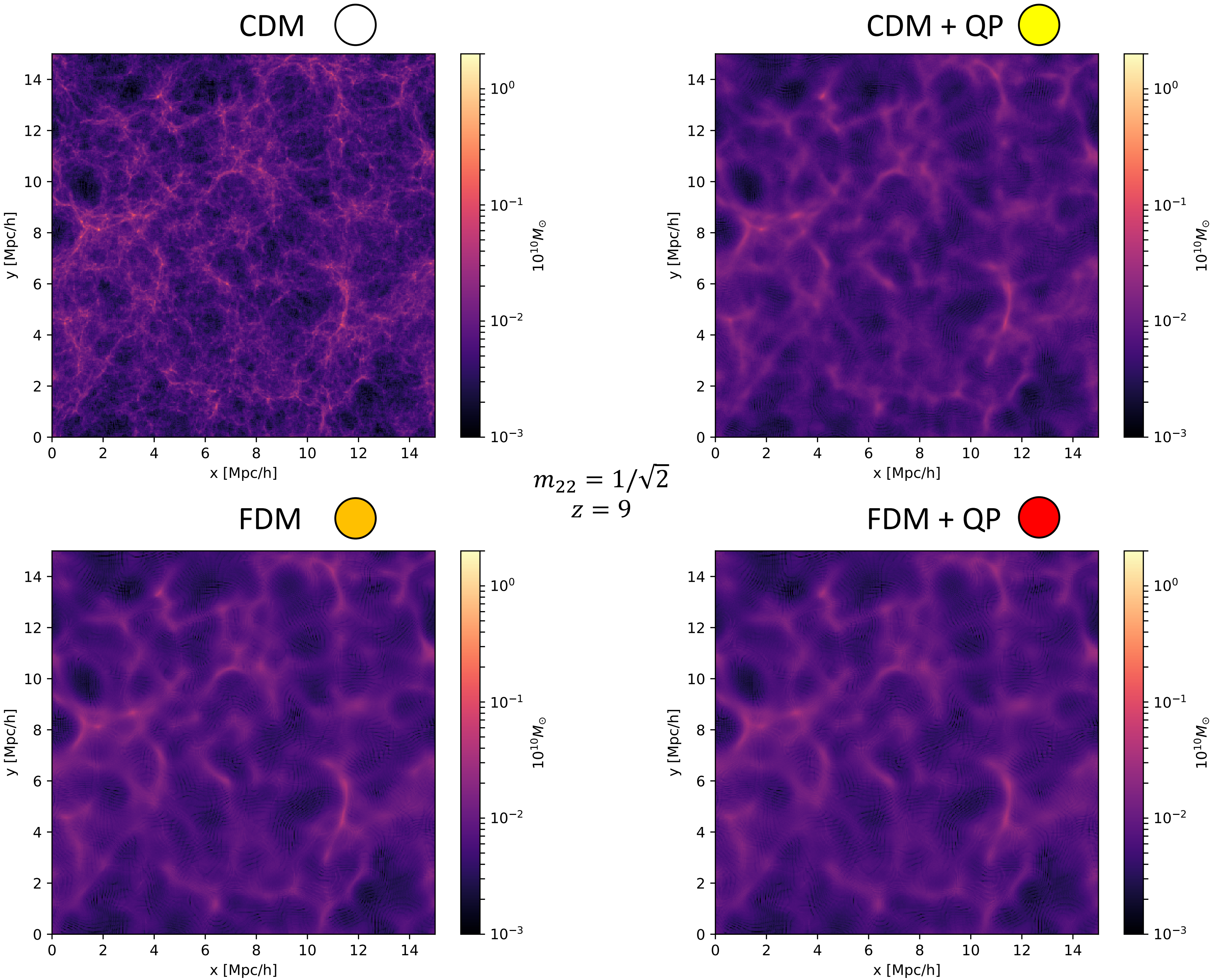
- **Strategy 1:**
  - Dynamics: QP
  - Initial Conditions: CDM
- **Strategy 2:**
  - Dynamics: NO QP
  - Initial Conditions: FDM
- **Strategy 3:**
  - Dynamics: QP
  - Initial Conditions: FDM

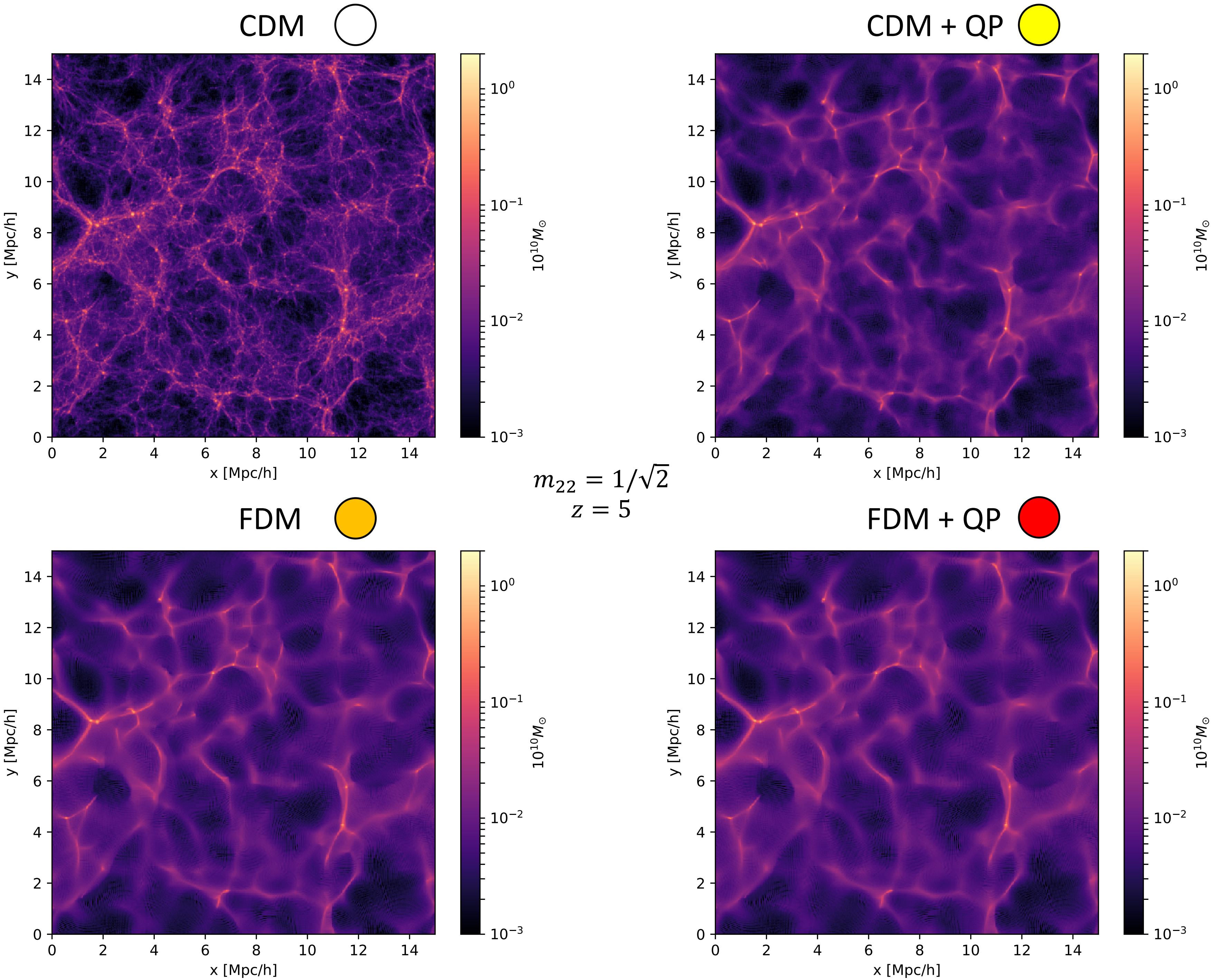


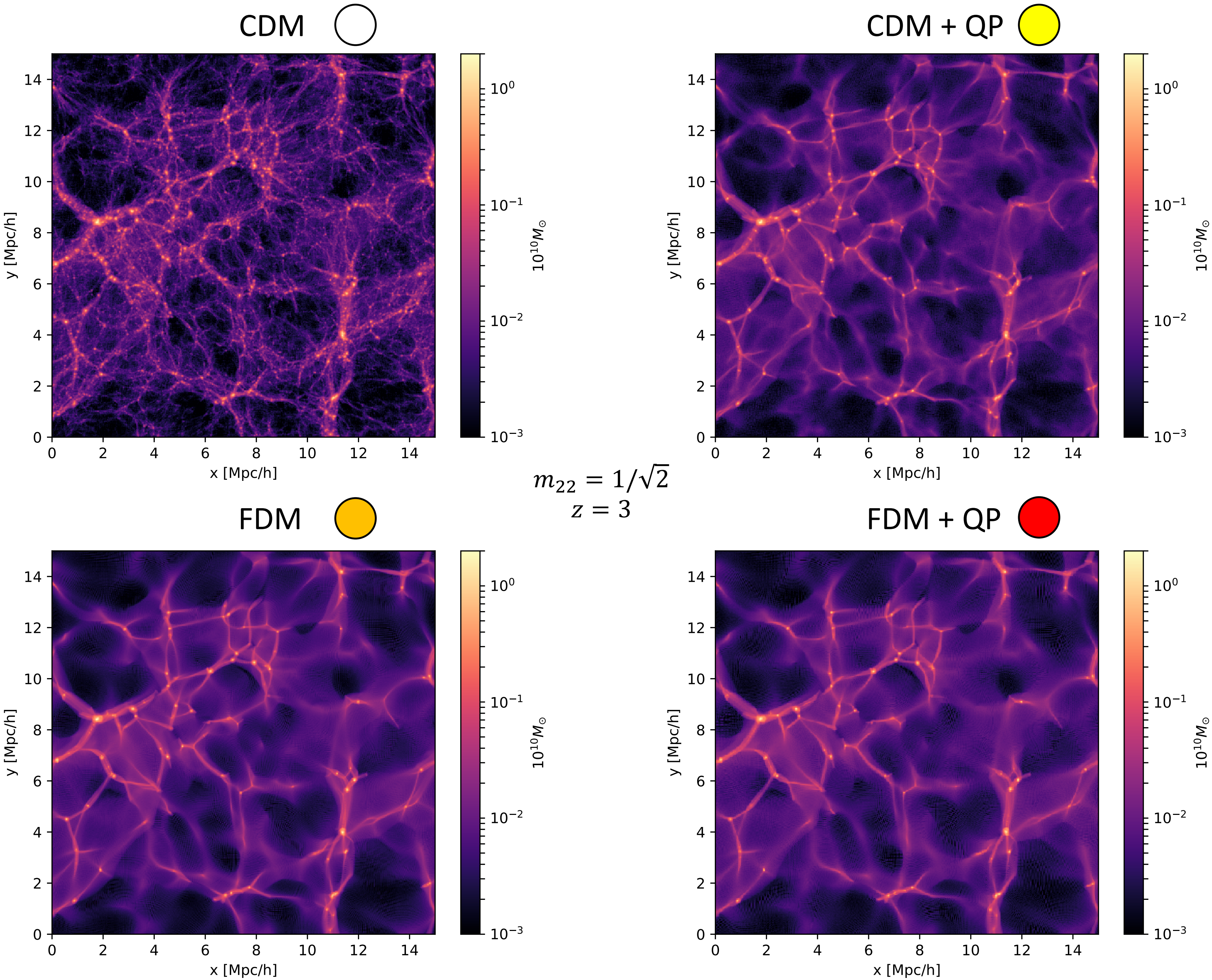


CDM
CDM + QP
FDM
FDM + QP
$m_{22} = 1/\sqrt{2}$
$z = 99$
x [Mpc/h]
y [Mpc/h]
$10^{10} M_\odot$


CDM
CDM + QP
FDM
FDM + QP
$m_{22} = 1/\sqrt{2}$
$z = 19$
x [Mpc/h]
y [Mpc/h]
$10^{10} M_\odot$
10^{0}
10^{-1}
10^{-2}
10^{-3}

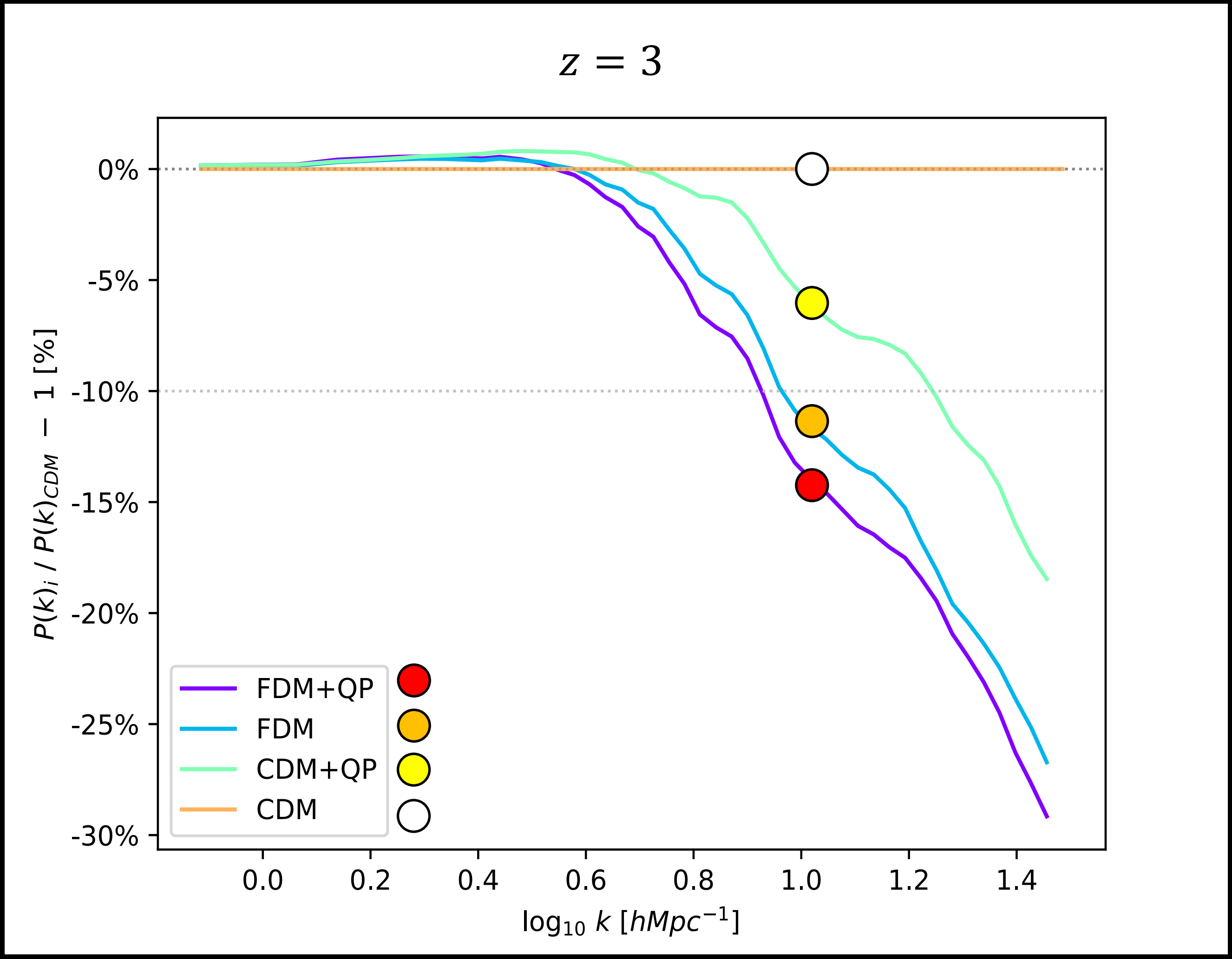

CDM
CDM + QP
FDM
FDM + QP
$m_{22} = 1/\sqrt{2}$
$z = 9$
x [Mpc/h]
y [Mpc/h]
$10^{10} M_{\odot}$
10^{0}
10^{-1}
10^{-2}
10^{-3}


CDM
CDM + QP
FDM
FDM + QP
$m_{22} = 1/\sqrt{2}$
$z = 5$
x [Mpc/h]
y [Mpc/h]
$10^{10}M_\odot$
10^{0}
10^{-1}
10^{-2}
10^{-3}

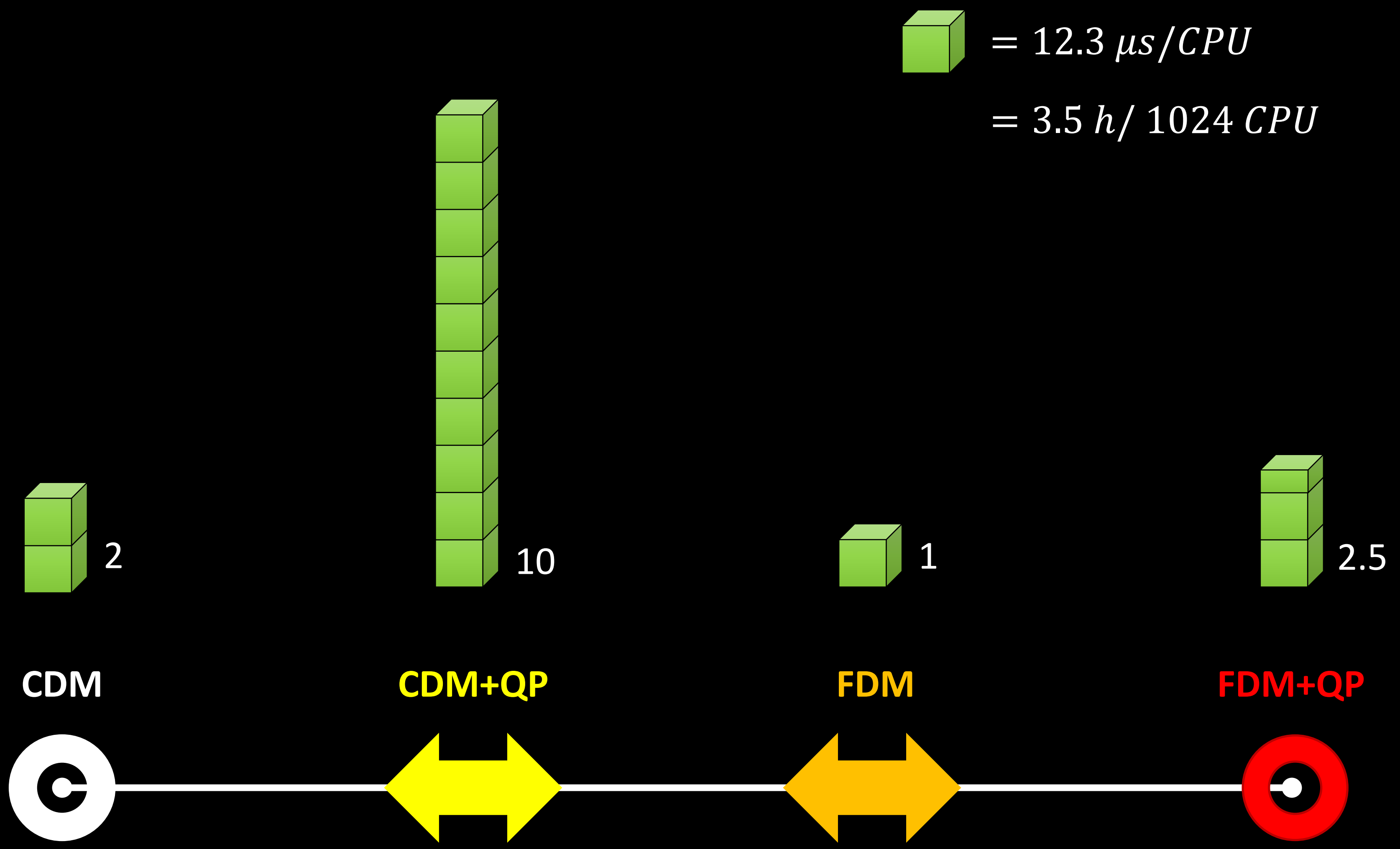


CDM
CDM + QP
FDM
FDM + QP
$m_{22} = 1/\sqrt{2}$
$z = 3$
y [Mpc/h]
x [Mpc/h]
$10^{10} M_\odot$
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10
12
14

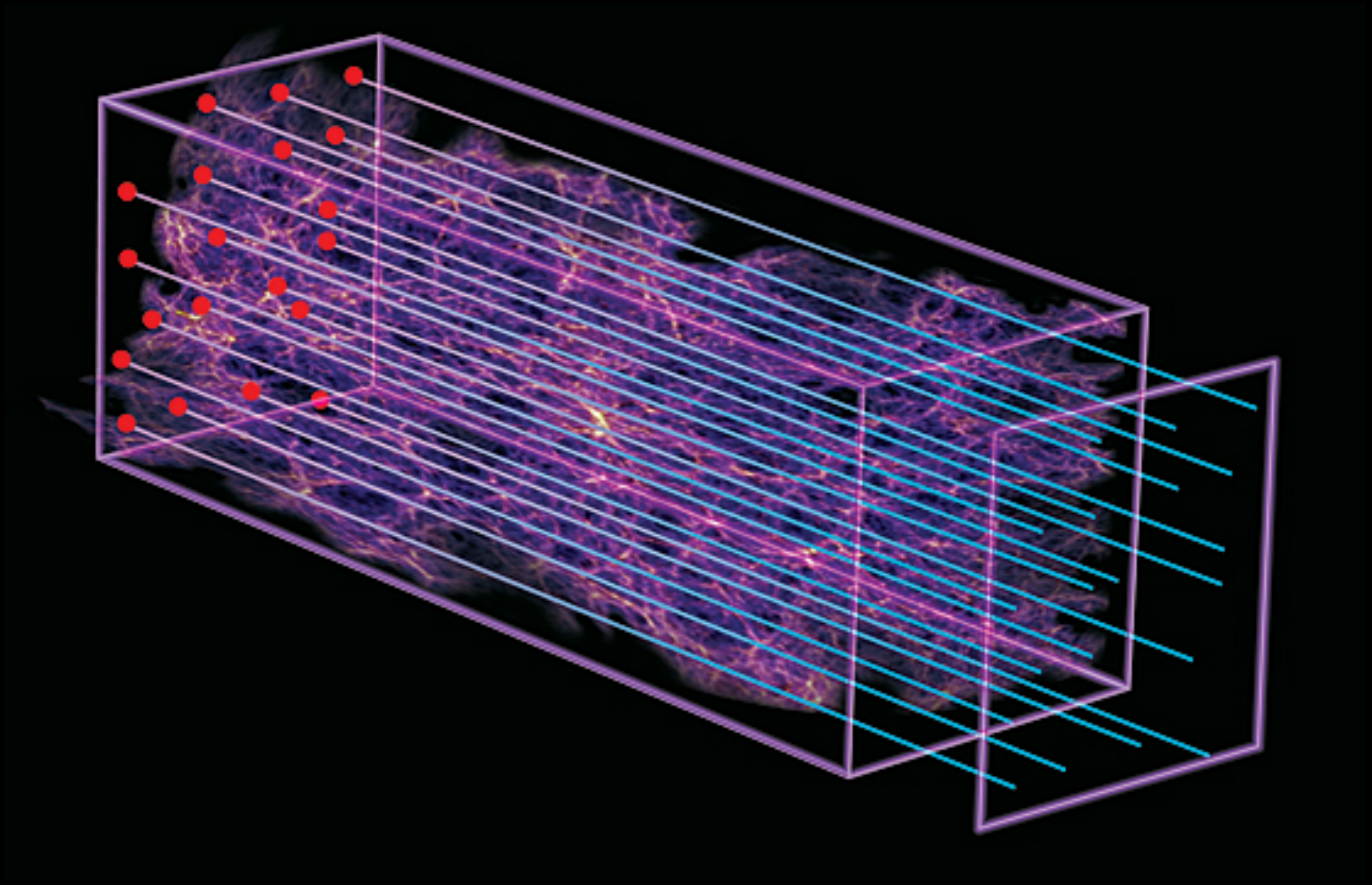
Initial Conditions



Performance



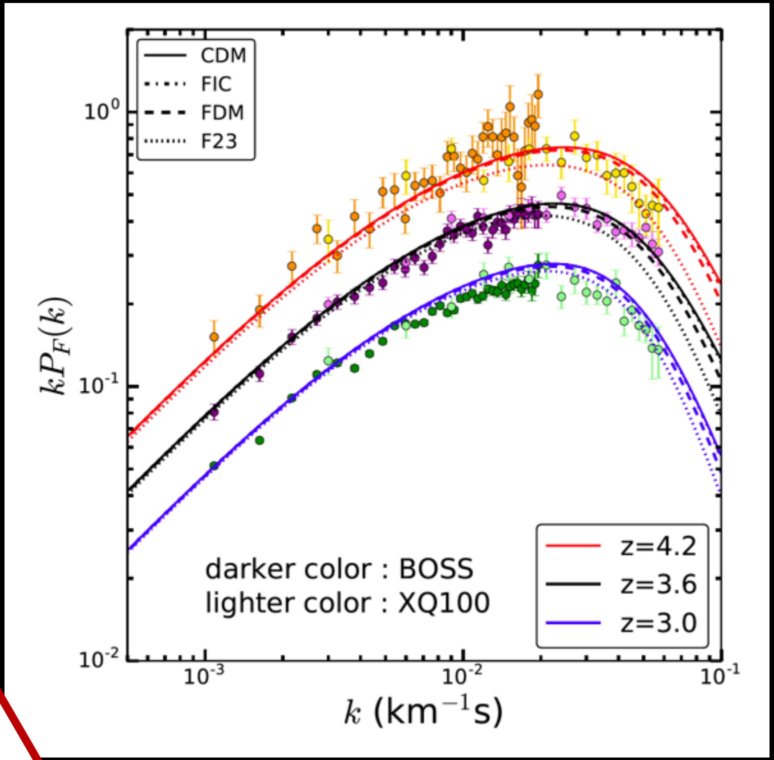
Lyman-Alpha Forest



SDSS III (BOSS) - Lyman-alpha team

Lyman-Alpha Forest

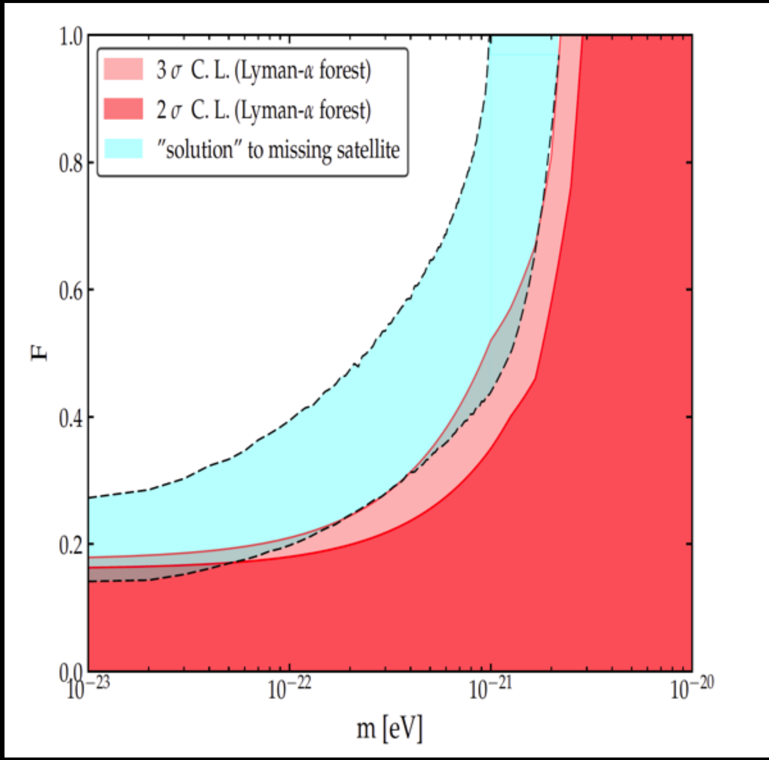
Attempt to constrain on a linear level m_χ with the 1D power spectrum



Zhang +17

Lyman-Alpha Forest

Attempt to constrain on a linear level m_χ with the 1D power spectrum

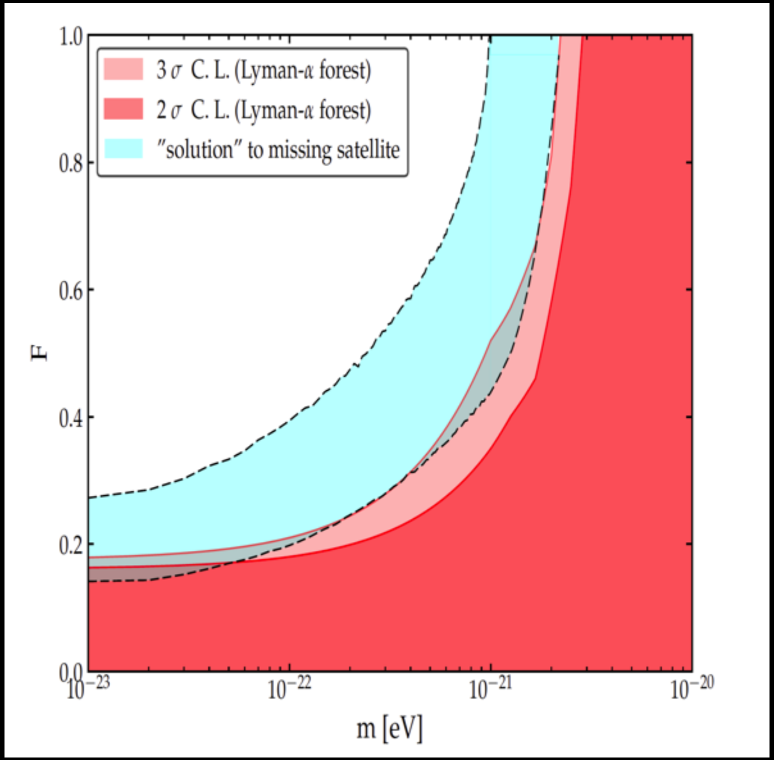


Kobayashi +17

Lyman-Alpha Forest

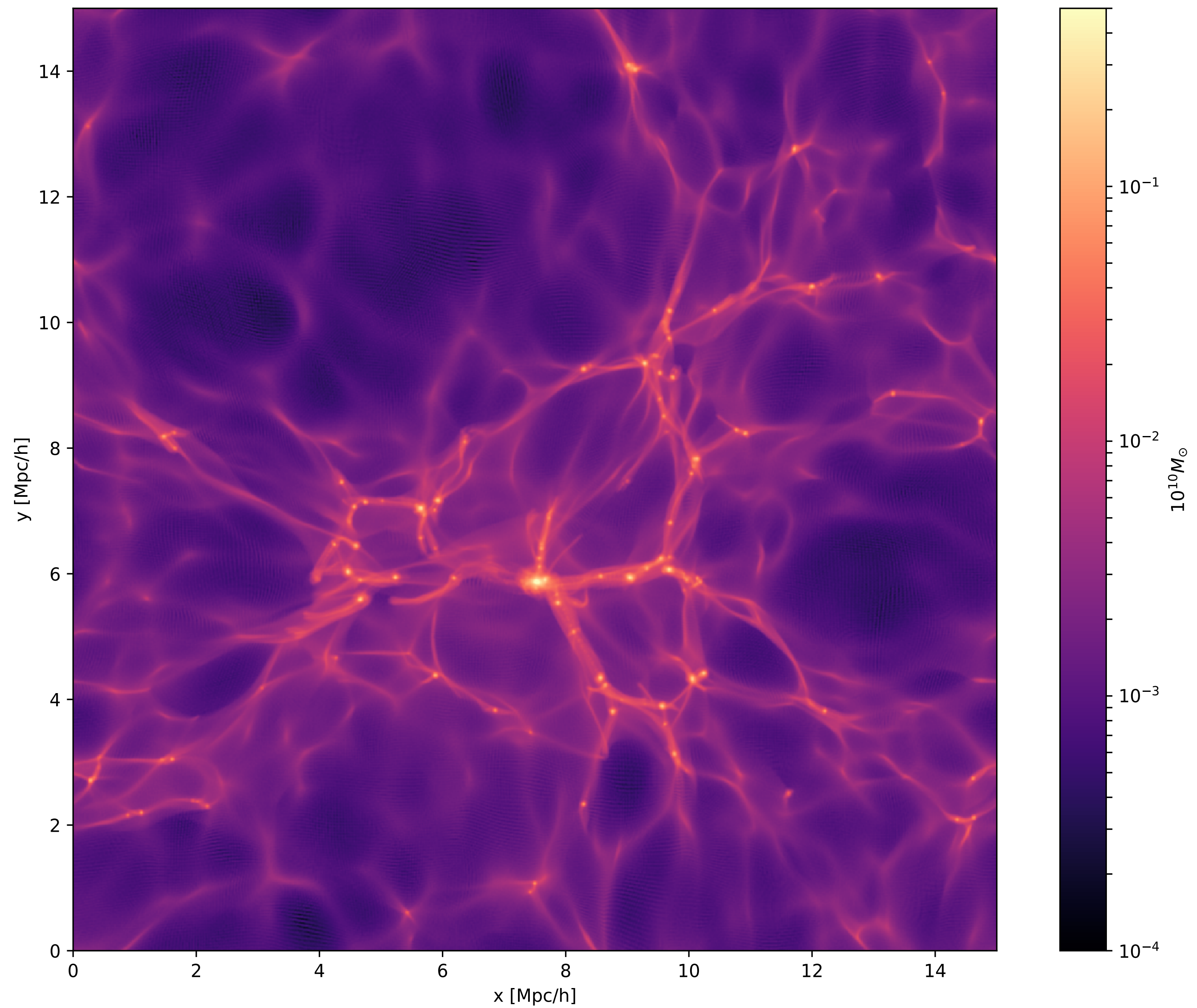
Attempt to constrain on a linear level m_χ with the 1D power spectrum

Full hydrodynamic simulation with Cooling and Star Formation mechanisms (Nori M., Murgia R., Baldi M., Viel M. in prep)

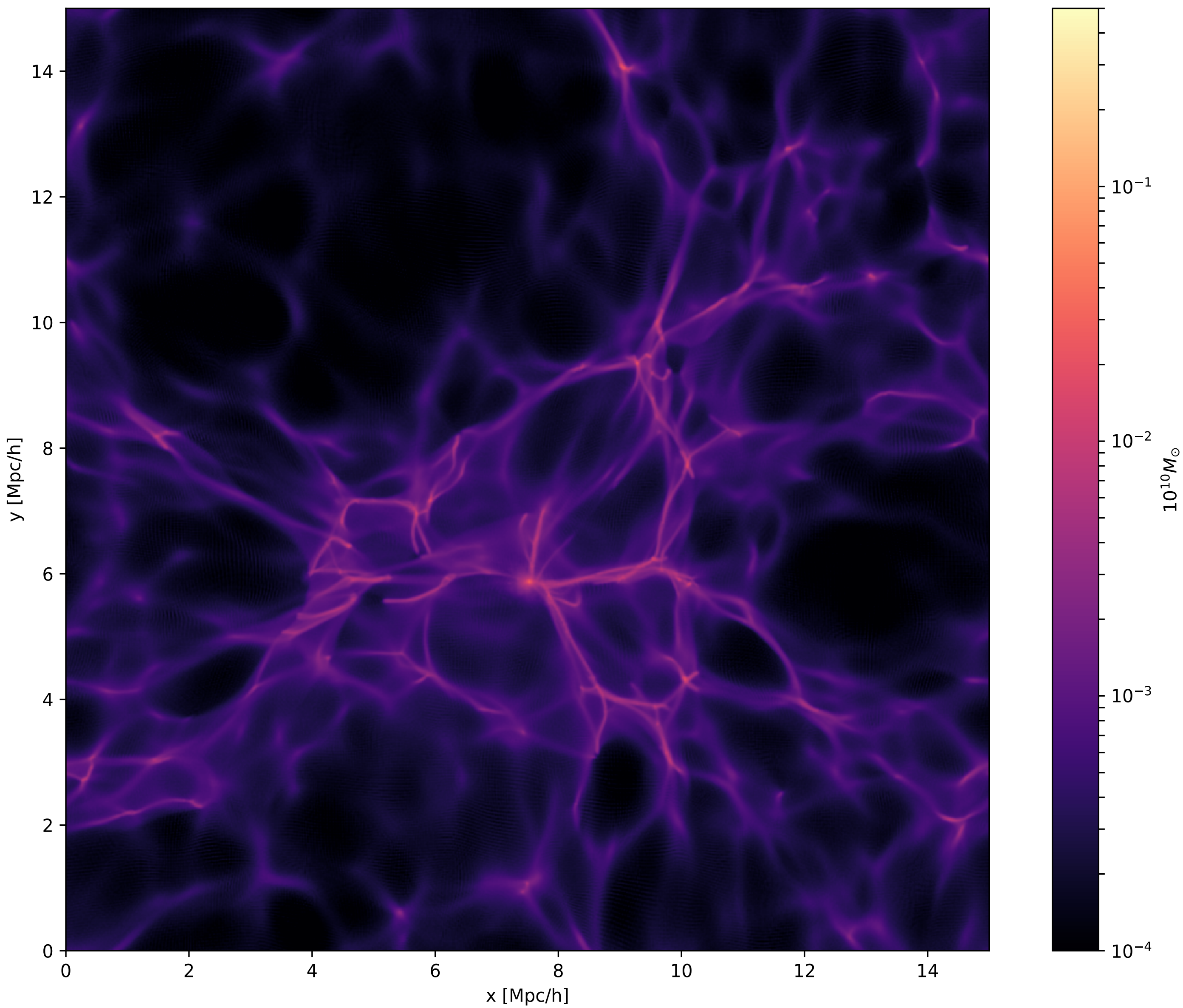


Kobayashi +17

Dark Matter

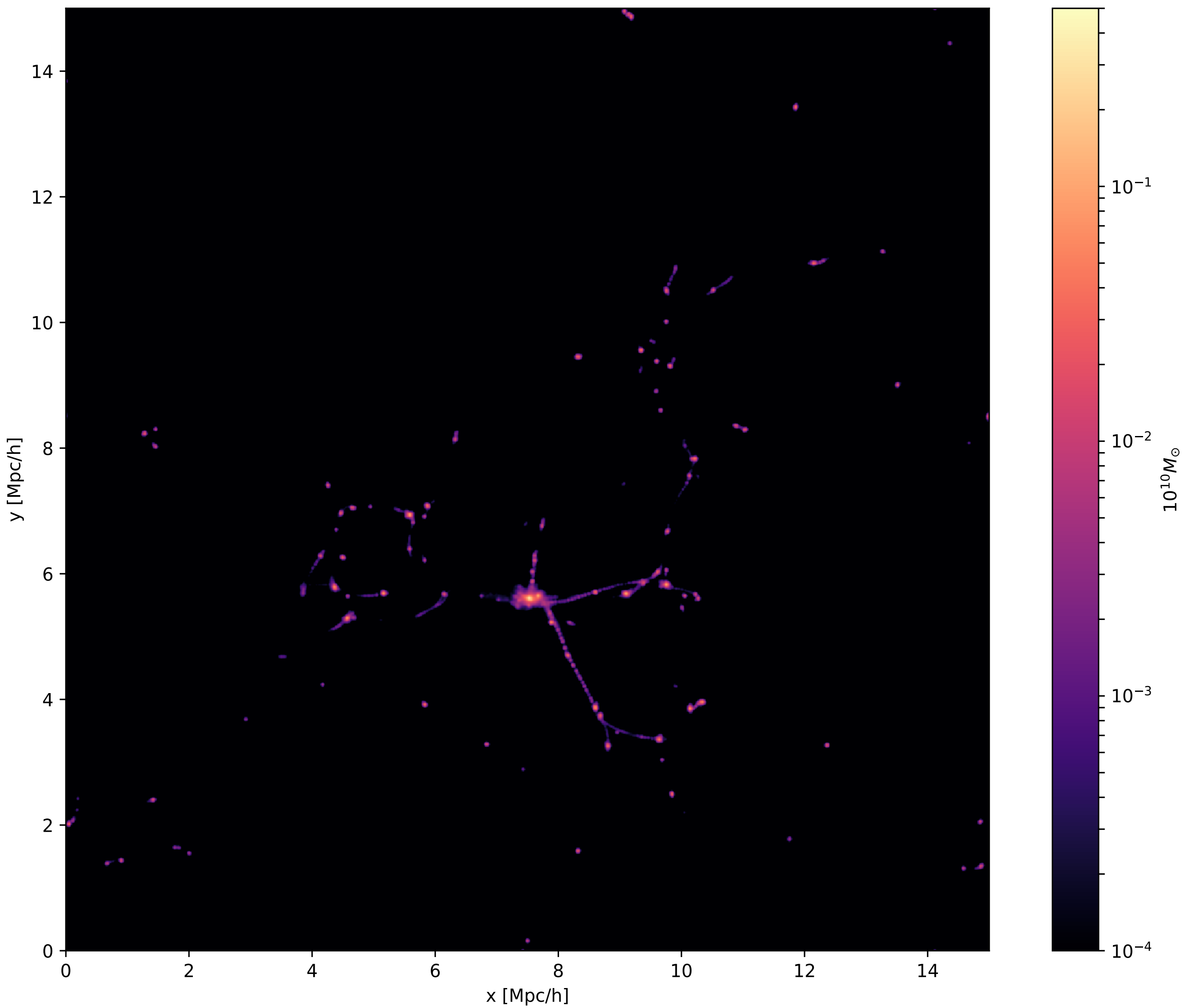


Gas



14
12
10
8
6
4
2
0
y [Mpc/h]
0
2
4
6
8
10
12
14
x [Mpc/h]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$10^{10} M_\odot$

Stars



Conclusions

AX-Gadget (Nori M., Baldi M., in prep.) module

implemented through **SPH** for FDM models

QP is **relevant** in FDM models,

at least for scales under $\sim 1\ Mpc$

Good agreement with predictions from full wave-solvers

in **suppressing small scales**, Lyman-Alpha constraint soon!

(Nori M., Murgia R., Baldi M., Viel M., in prep.)

Better performances!

One loop over N more wrt hydro-simulations with Gadget3

Thank you

References

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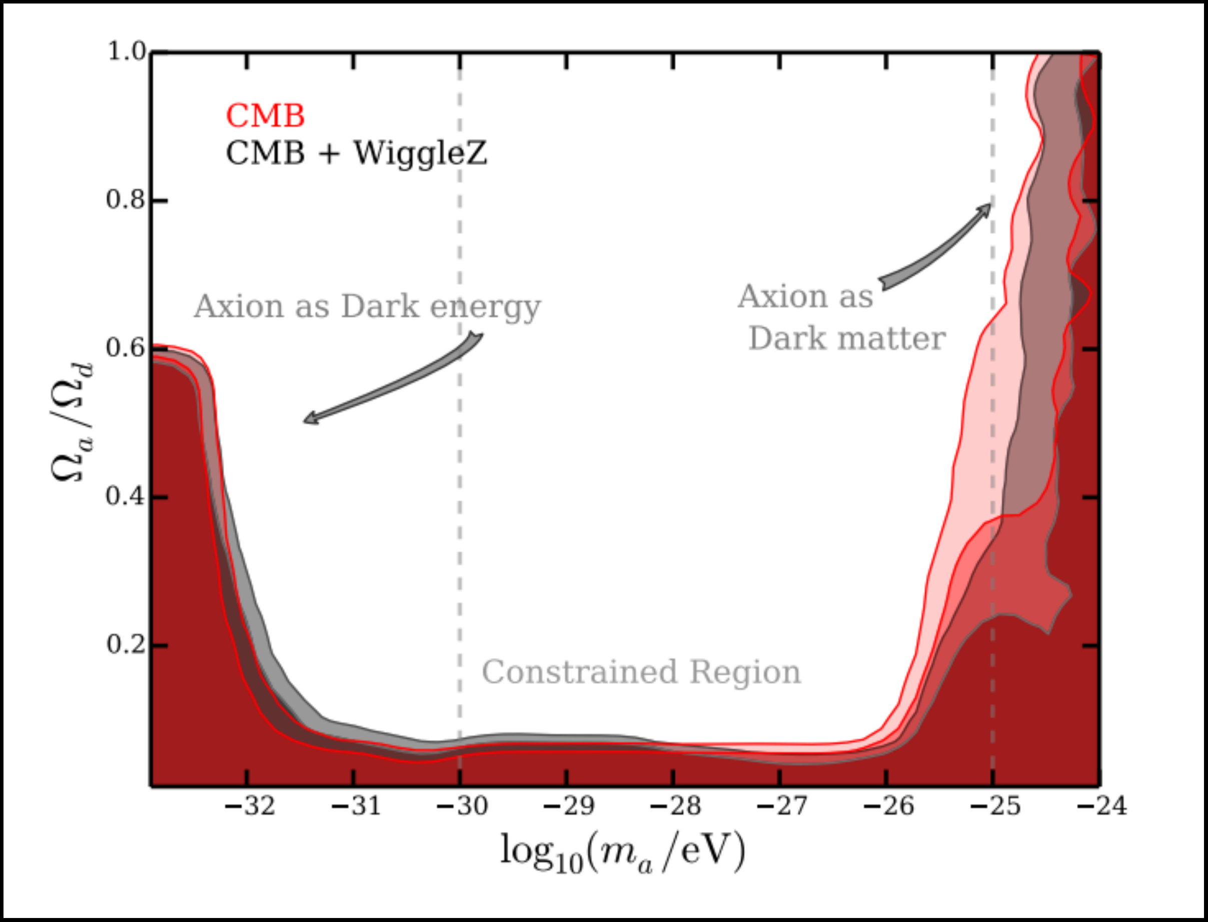
m_{ax}

Hlozek et al. Phys.Rev. D91 (2015) no.10, 103512 arXiv:1410.2896



m_{ax}

Hlozek et al. arXiv:1607.08208