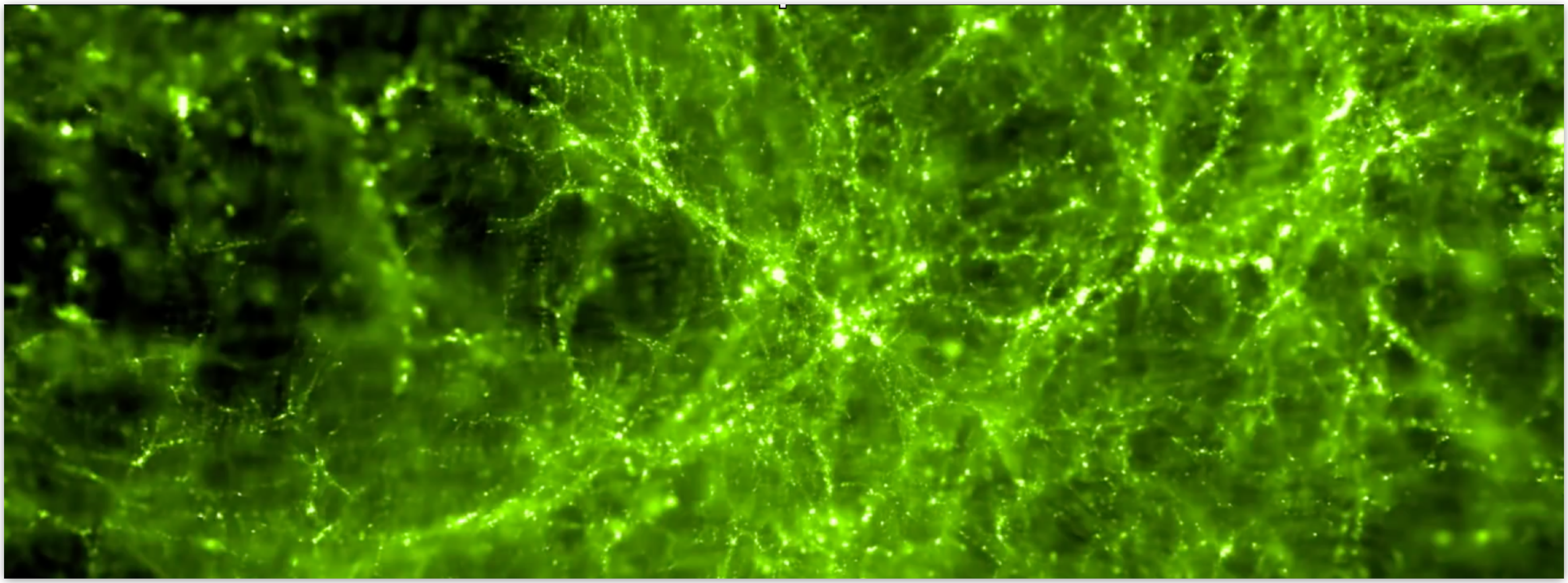
Reconstructing linear information from nonlinear galaxy surveys

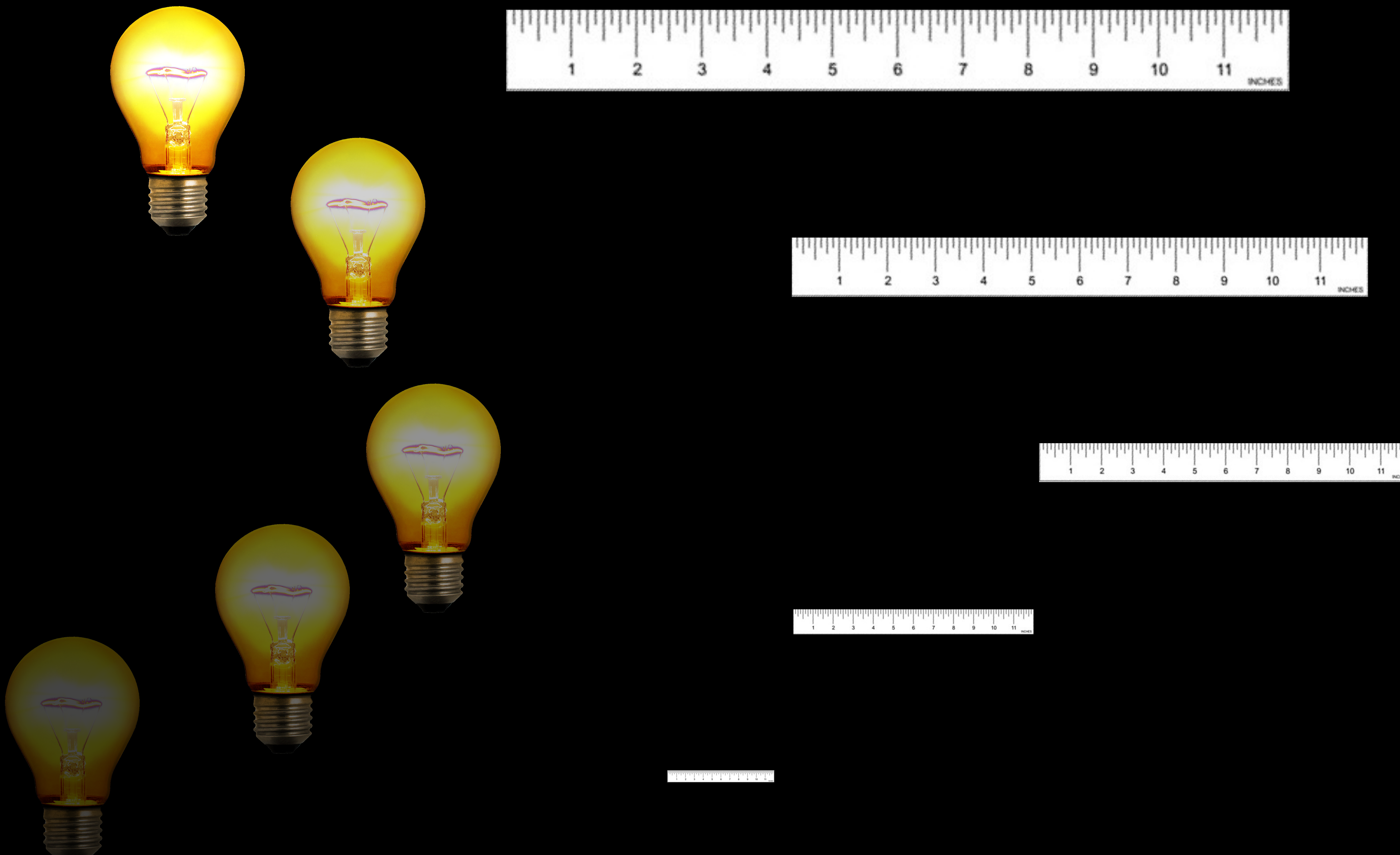


Marcel Schmittfull
Institute for Advanced Study

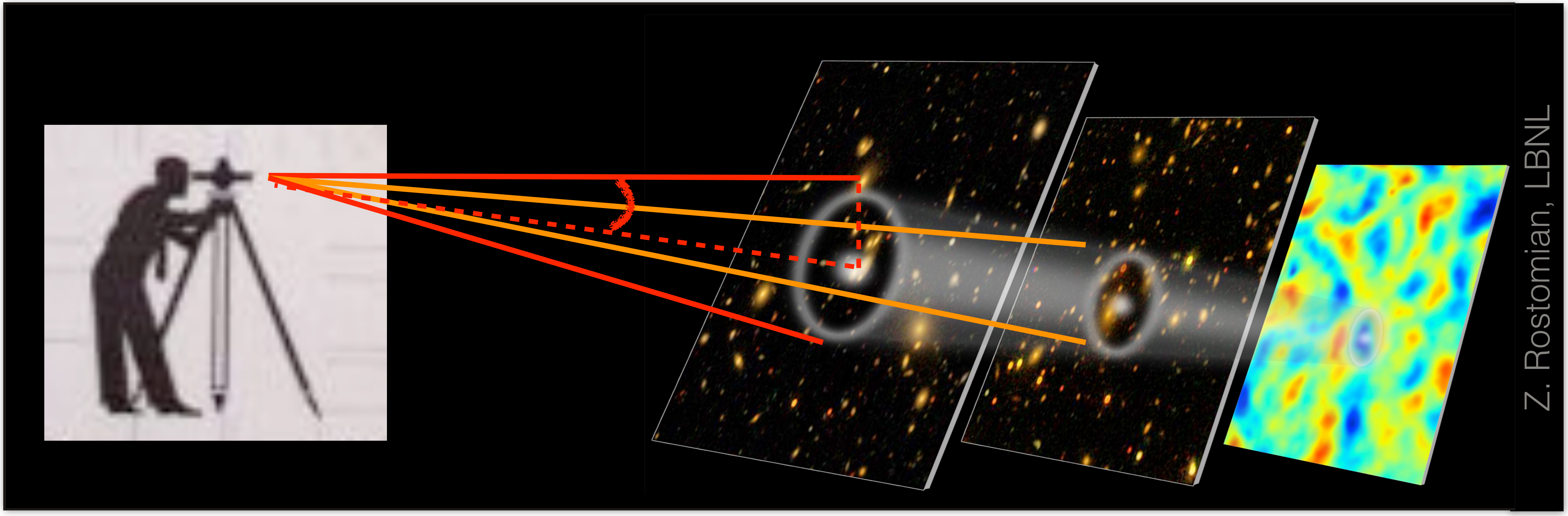
Nordita Stockholm, July 13th 2017

Collaborators: Tobias Baldauf & Matias Zaldarriaga

How do we measure distances?



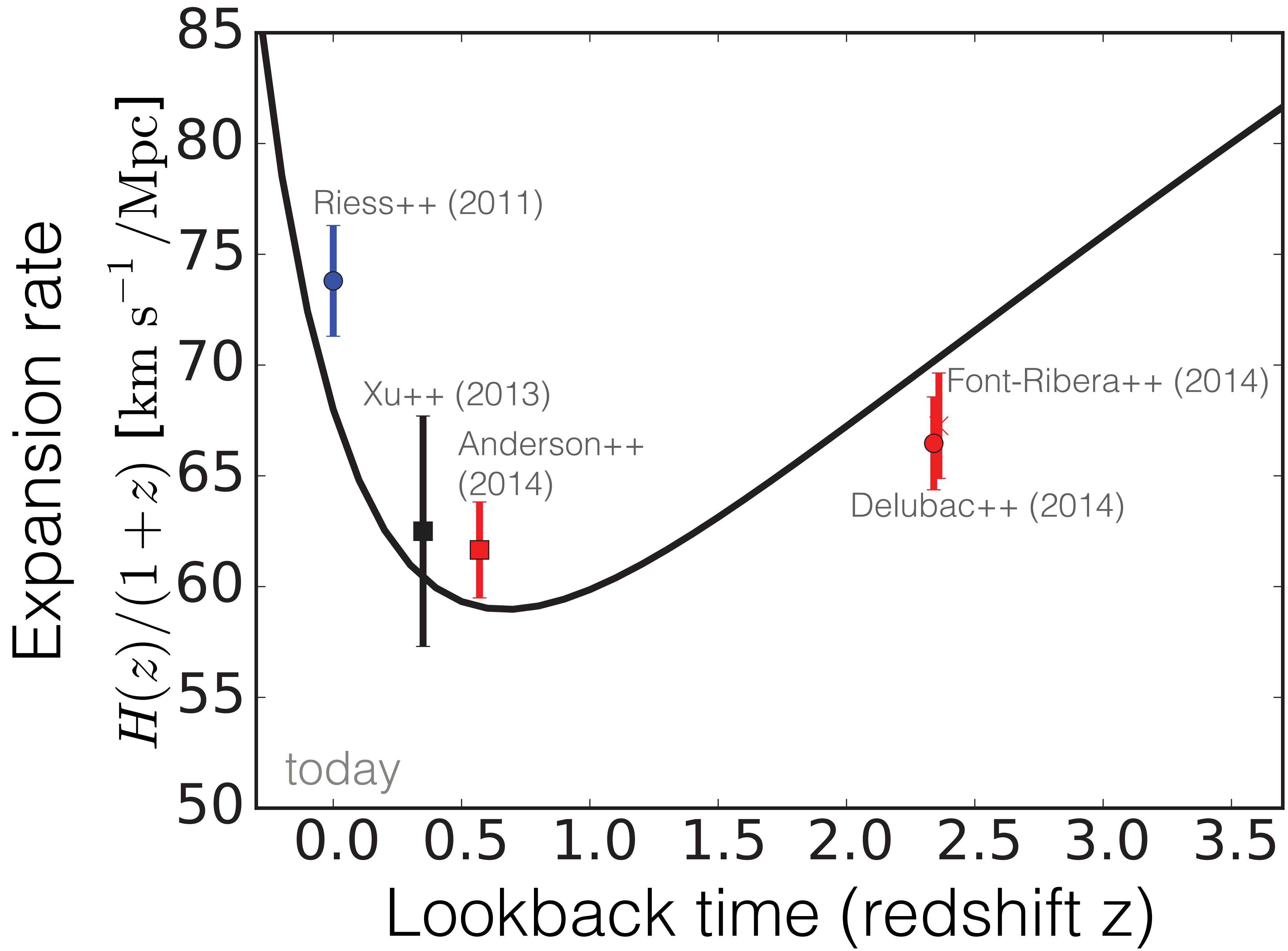
Measure distance as function of time



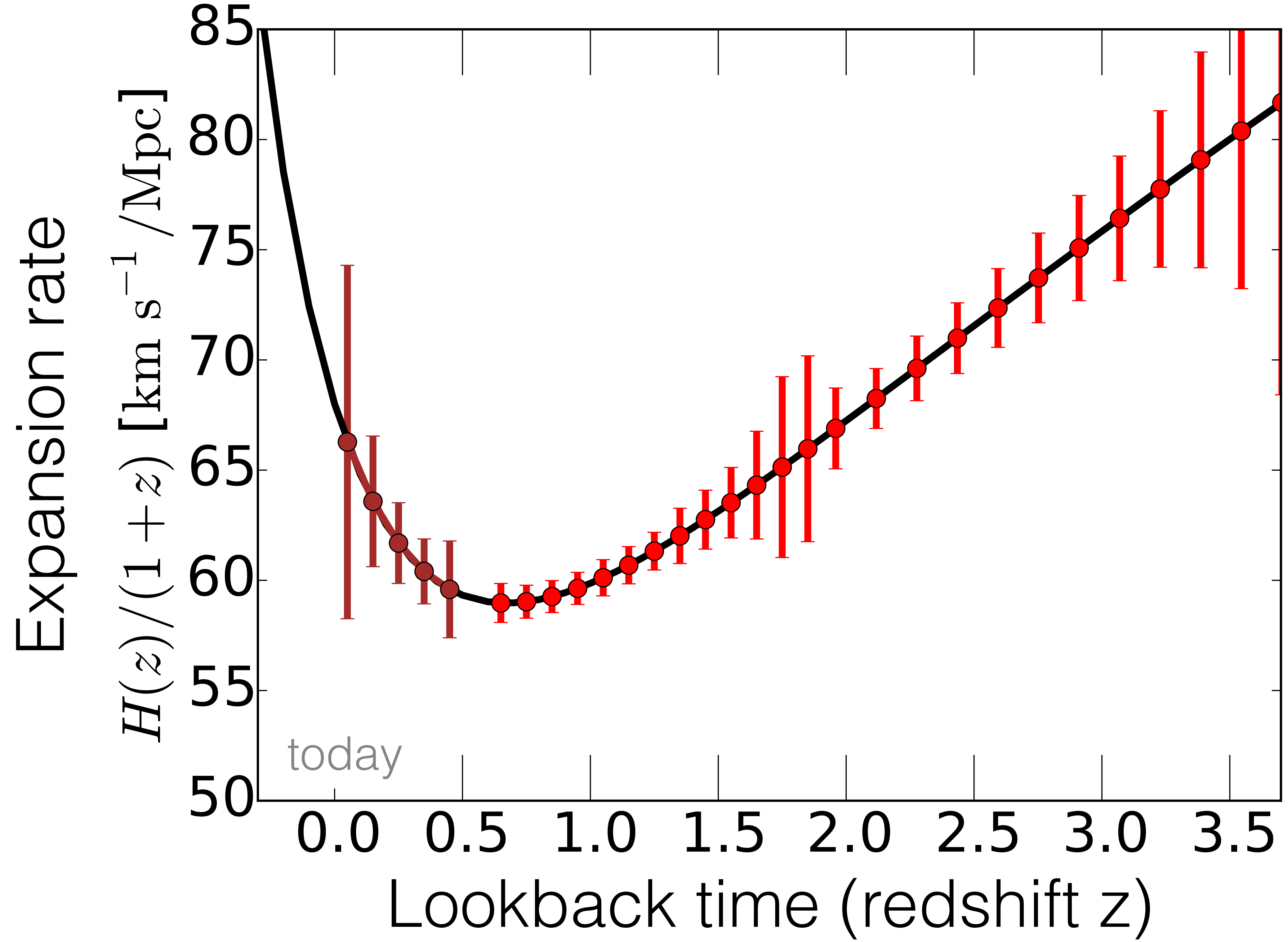
$$\text{Distance} \sim \frac{150\,\text{Mpc}}{\text{angle}} \sim \int_0^z \frac{dz'}{H(z')}$$

Hubble parameter $H(z)$ = expansion rate
Redshift z = stretching factor of wavelength = stretching factor of space

Current state

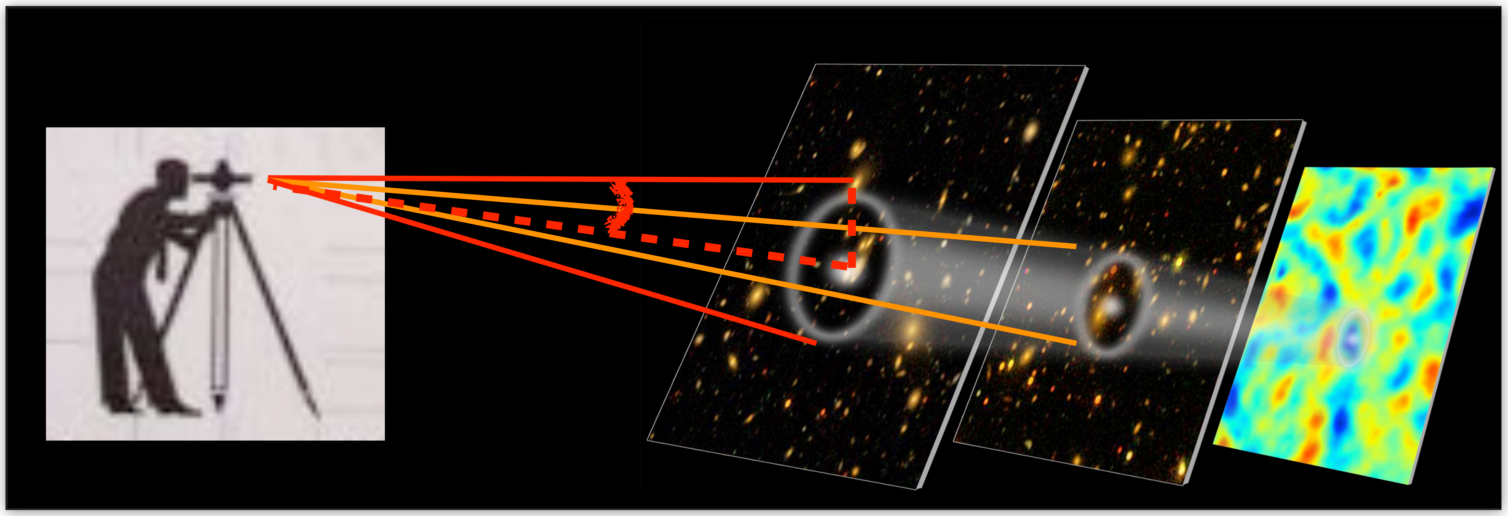


DESI forecast



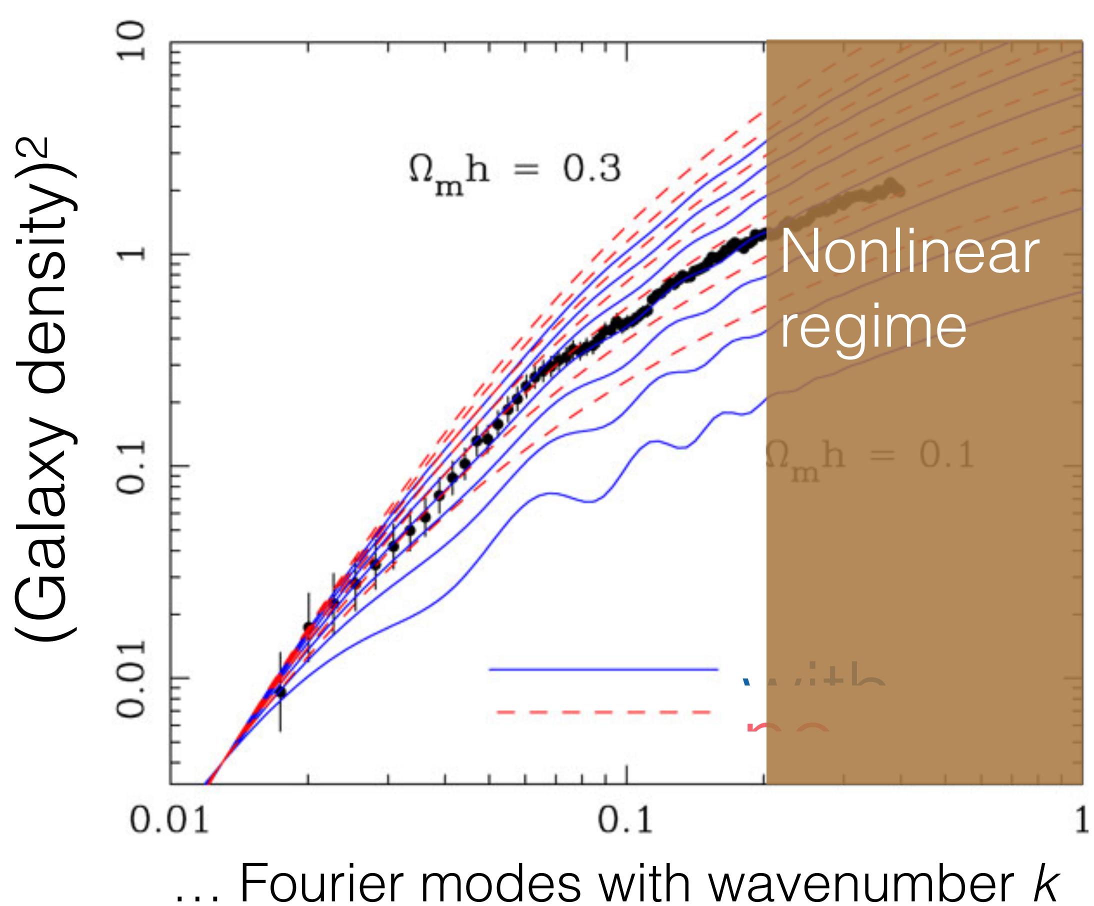
DESI Design Report 2016

Nonlinear structures: A limiting factor



BAO distance measurements

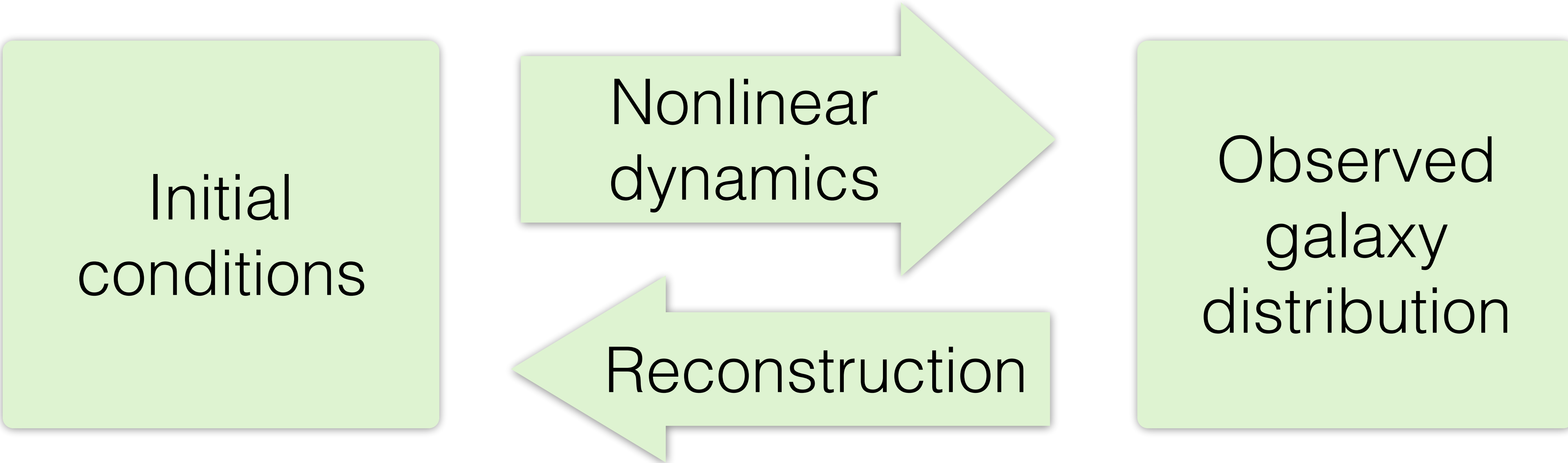
Nonlinear motions wash out primordial BAO scale



Broadband power spectrum

Nonlinear dynamics affects nearby galaxies, so their data is thrown away

Reconstruct linear density to suppress nonlinearities



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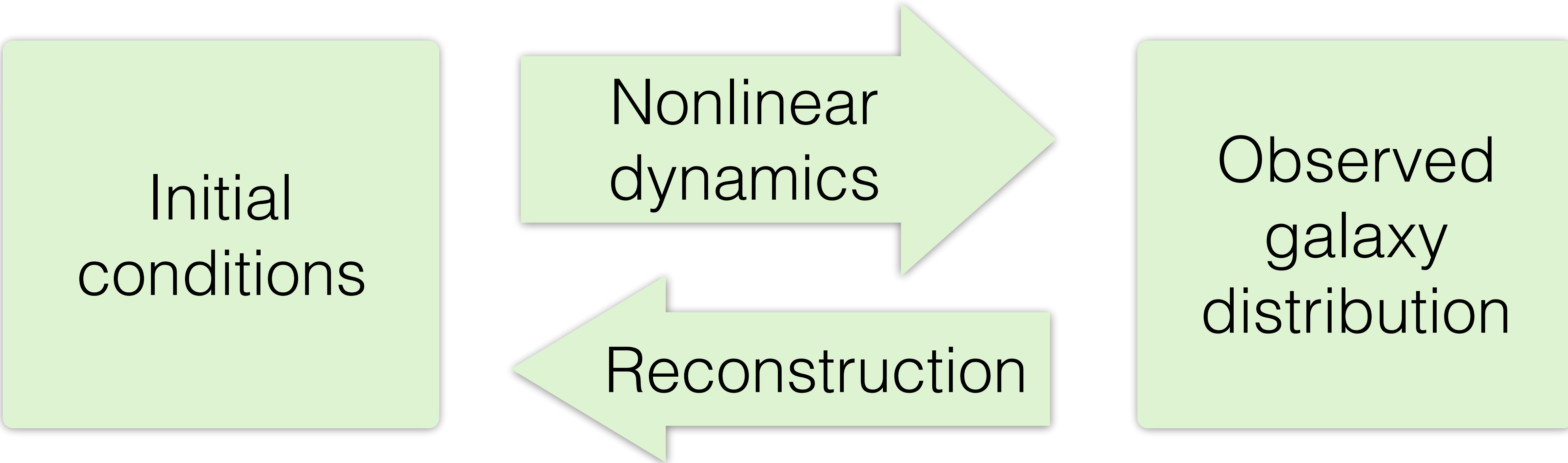

Approach 1: Backward reconstruction

Estimate velocities, move galaxies back

Eisenstein, Padmanabhan, Pen, Tassev, Zaldarriaga, MS, …

Reconstruct linear density to suppress nonlinearities

Initial conditions → Nonlinear dynamics → Observed galaxy distribution

Observed galaxy distribution → Reconstruction → Initial conditions

Approach 1: Backward reconstruction

Estimate velocities, move galaxies back

Eisenstein, Padmanabhan, Pen, Tassev, Zaldarriaga, MS, …

Approach 2: Forward modeling

Sample ICs, evolve forward, compare vs observations, iterate

Jasche, Wandelt, Leclercq, Kitaura, …

Reconstruct linear density to suppress nonlinearities

Initial conditions

Nonlinear dynamics

Observed galaxy distribution

Reconstruction

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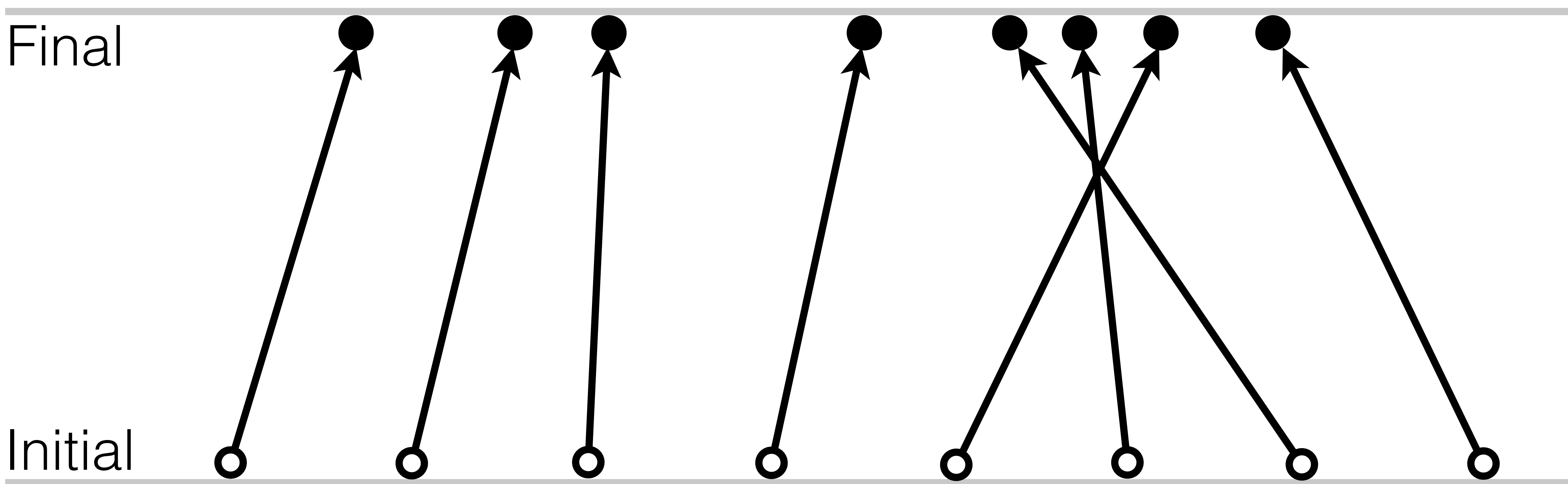
Approach 3: Optimization problem

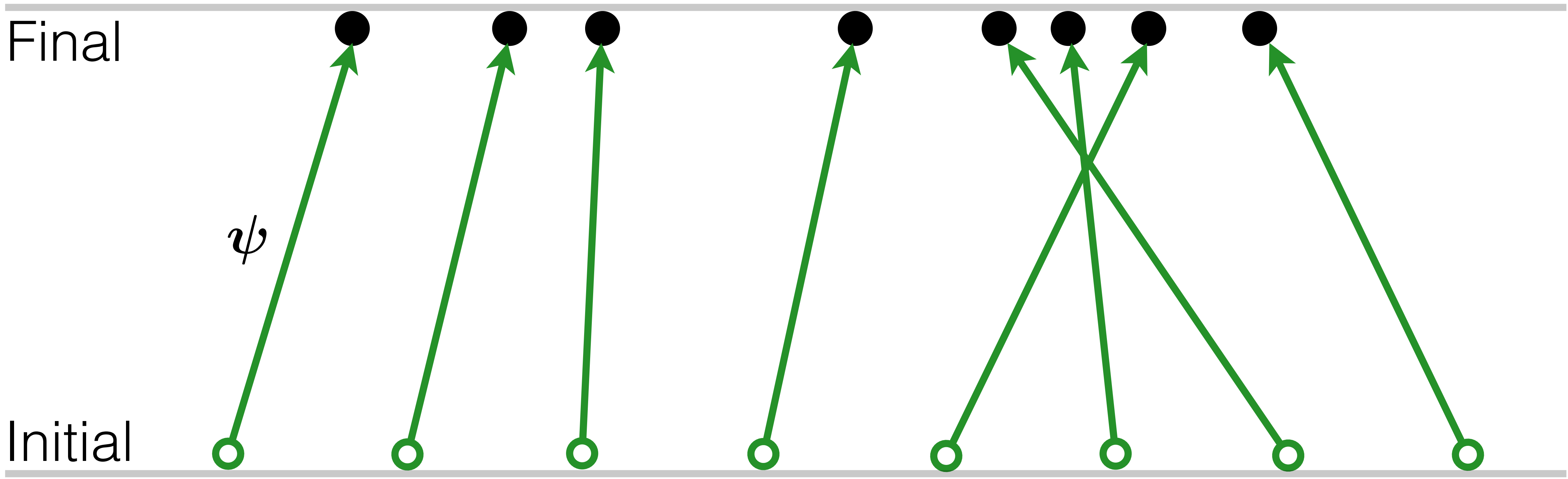
Maximum-likelihood solution by solving optimization problem

Seljak, Aslanyan, Feng, Modi

What nonlinearities are we fighting?

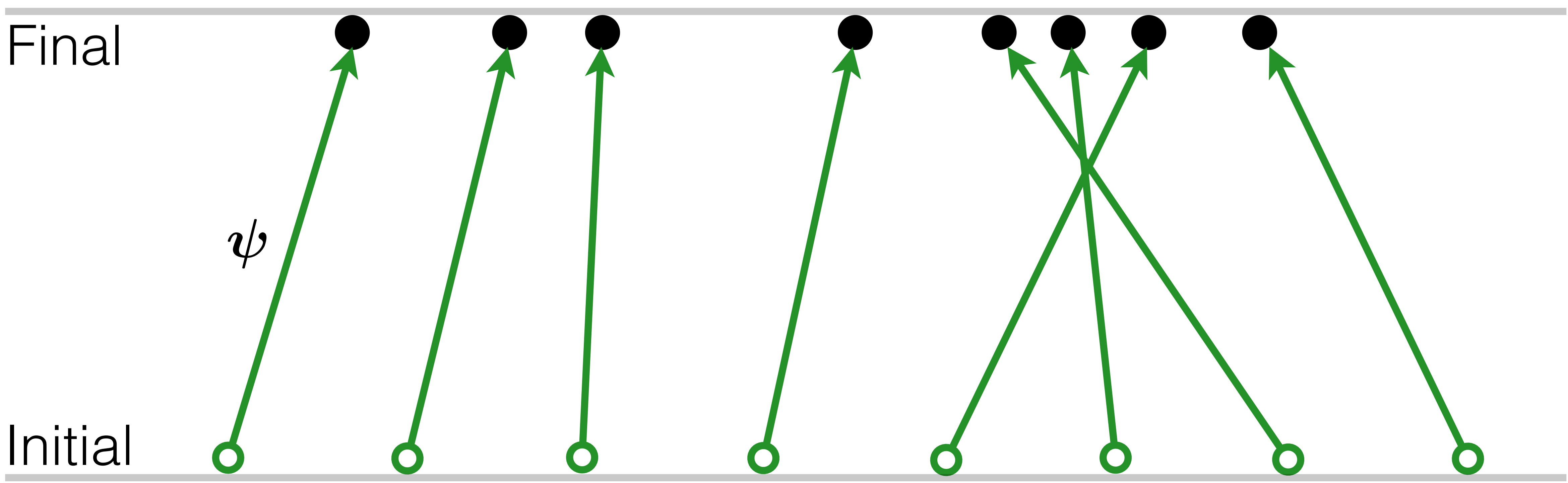


(1) Displacement field is a nonlinear functional of the linear initial density



$$\boldsymbol{\psi}(\mathbf{k}) = \frac{\mathbf{k}}{k^2}\delta_0(\mathbf{k})$$
$$+ \int_{\mathbf{k}_1} \mathbf{L}^{(2)}(\mathbf{k}_1, \mathbf{k} - \mathbf{k}_1)\delta_0(\mathbf{k}_1)\delta_0(\mathbf{k} - \mathbf{k}_1)$$
$$+ \cdots$$

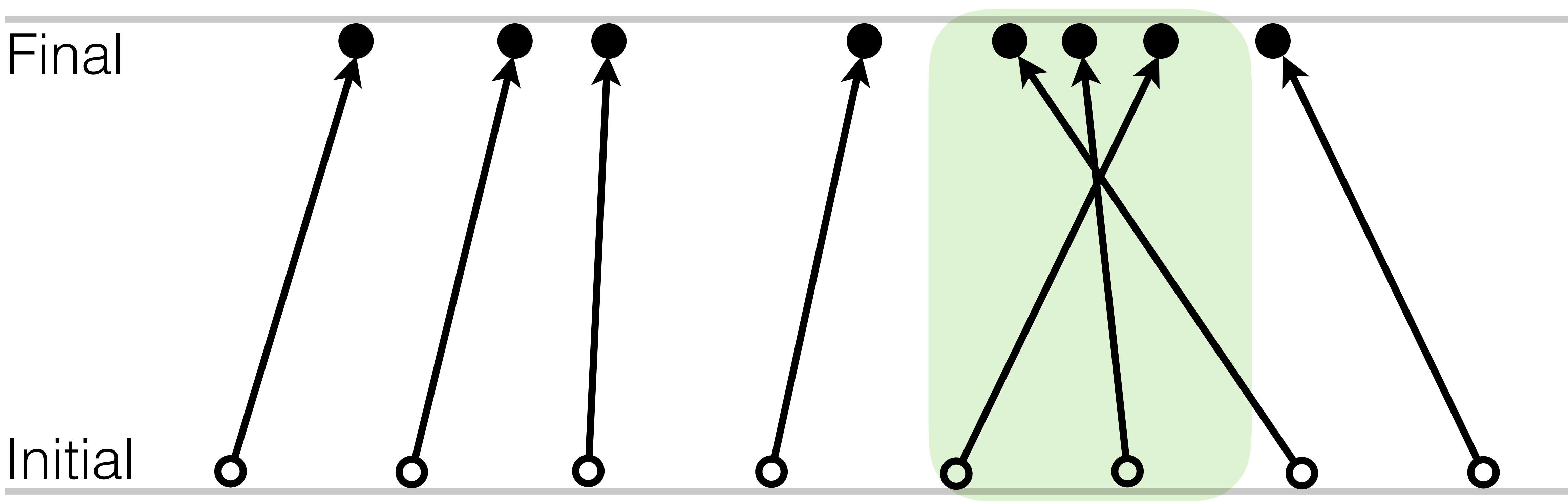
(1) Displacement field is a nonlinear functional of the linear initial density



- Nonlinear terms are small, so displacement is quite linear
- Perturbative modeling works well

e.g. Baldauf+ (2016)

(2) Shell crossing: Trajectories cross each other



- Strongly nonlinear & difficult to model

- Seems like we cannot tell initial from final position
  (How many crossings happened?)

- Expect to loose memory of initial conditions

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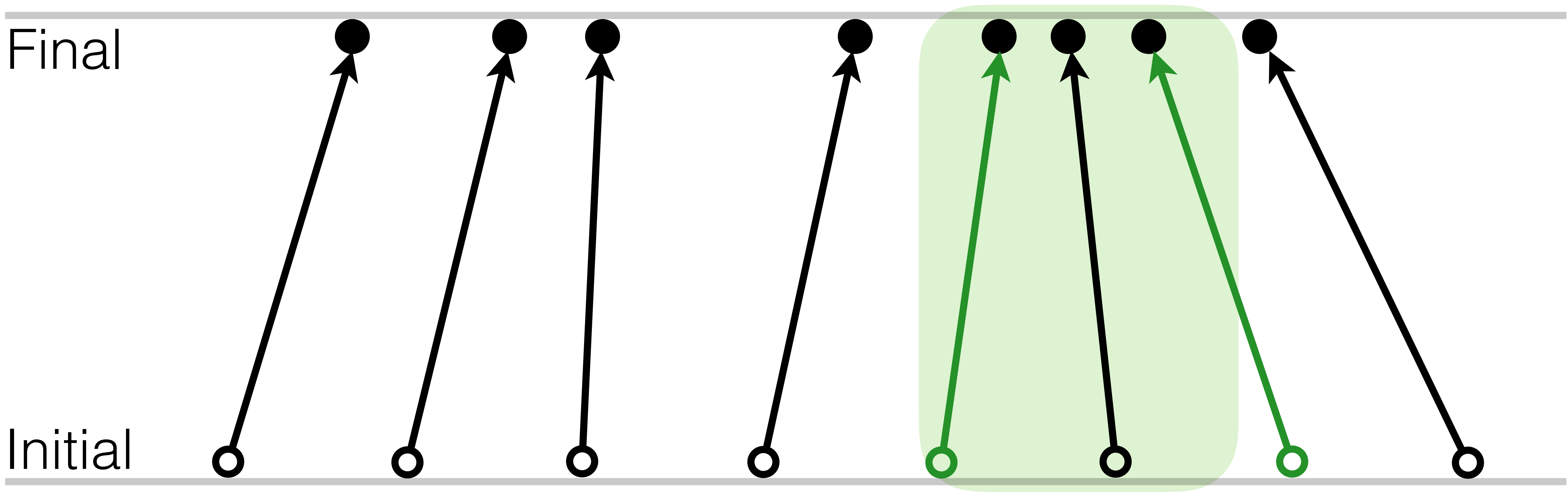

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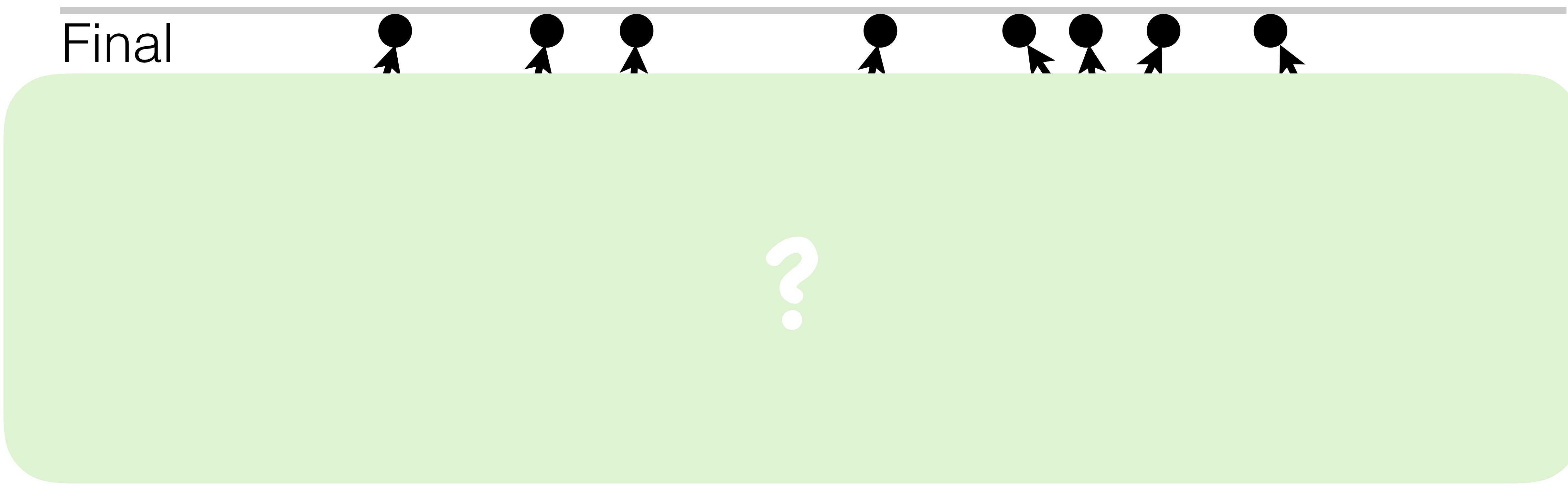
Reconstruction

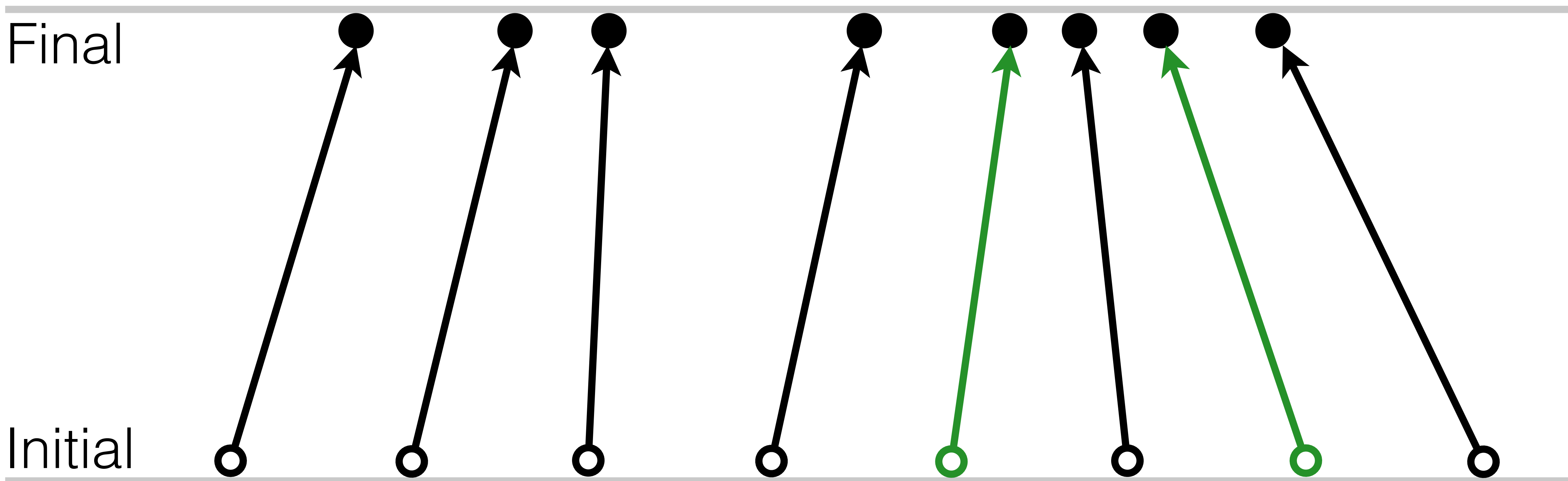


Goal: Estimate linear density from final particle locations

Standard method: Undo Zeldovich displacement

Eisenstein, Seo, Sirko & Spergel (2007)

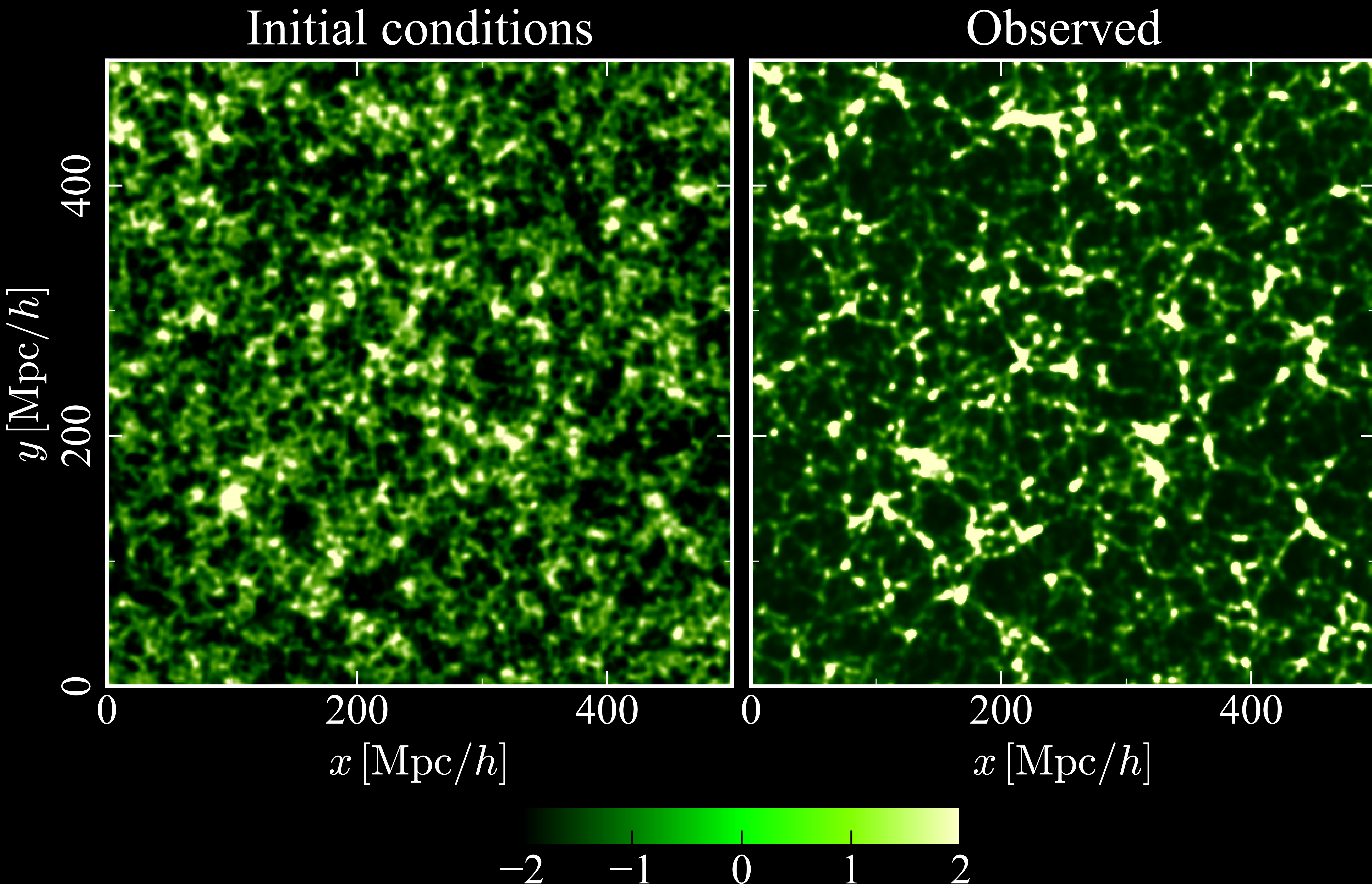
Reconstruction



New strategy:

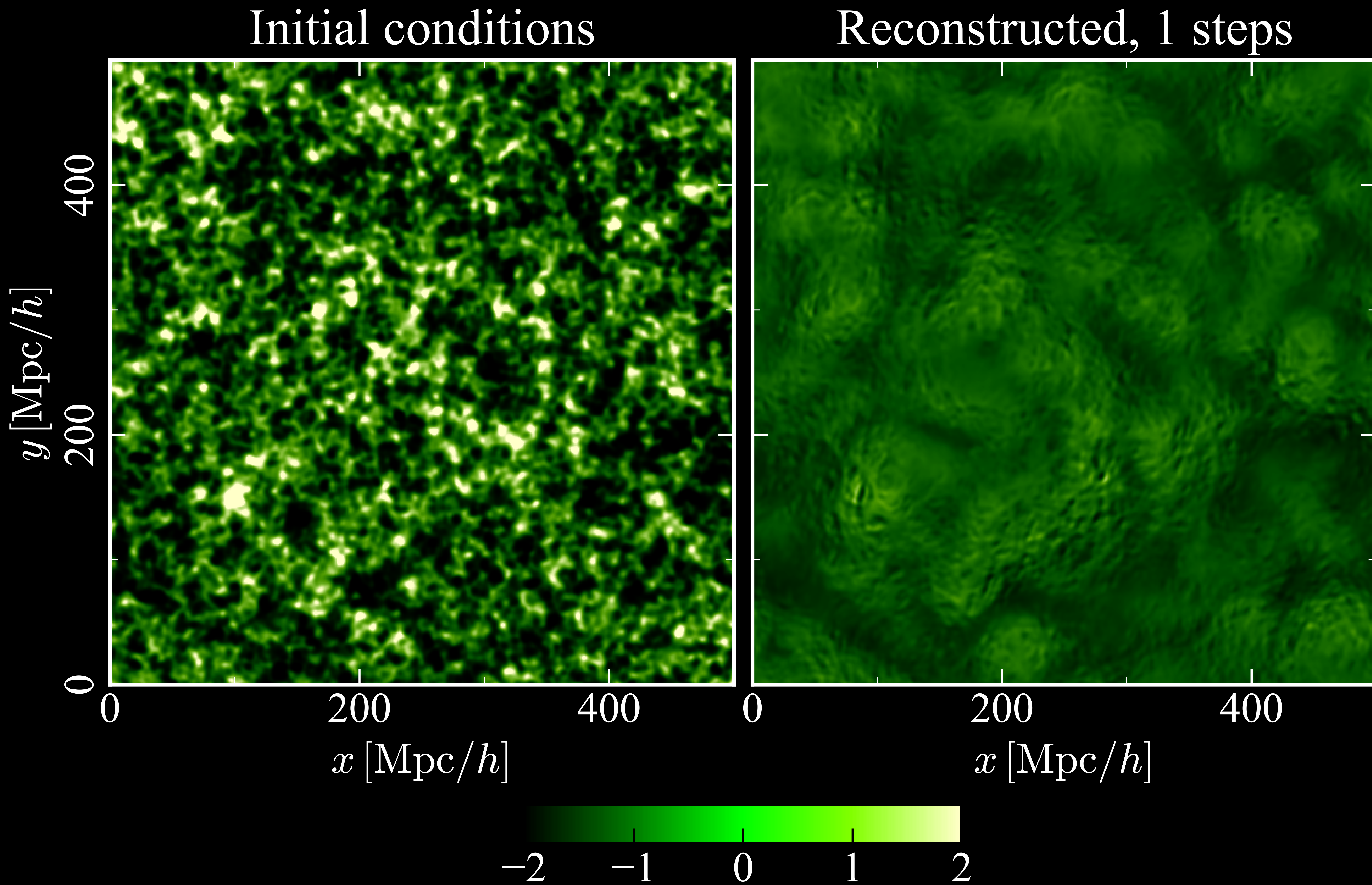
- Estimate displacement assuming no shell crossing
- Then estimate linear density from that displacement (pretty linear!)

Tassev & Zaldarriaga (2012); Zhu, Yu, Pen+ (2017); MS, Baldauf, Zaldarriaga (2017)



MS, Baldauf & Zaldarriaga (2017)

2D slices of 3D density smoothed with R=2 Mpc/h Gaussian
1% subsample of 2048^3 DM particles in 500 Mpc/h per-side box



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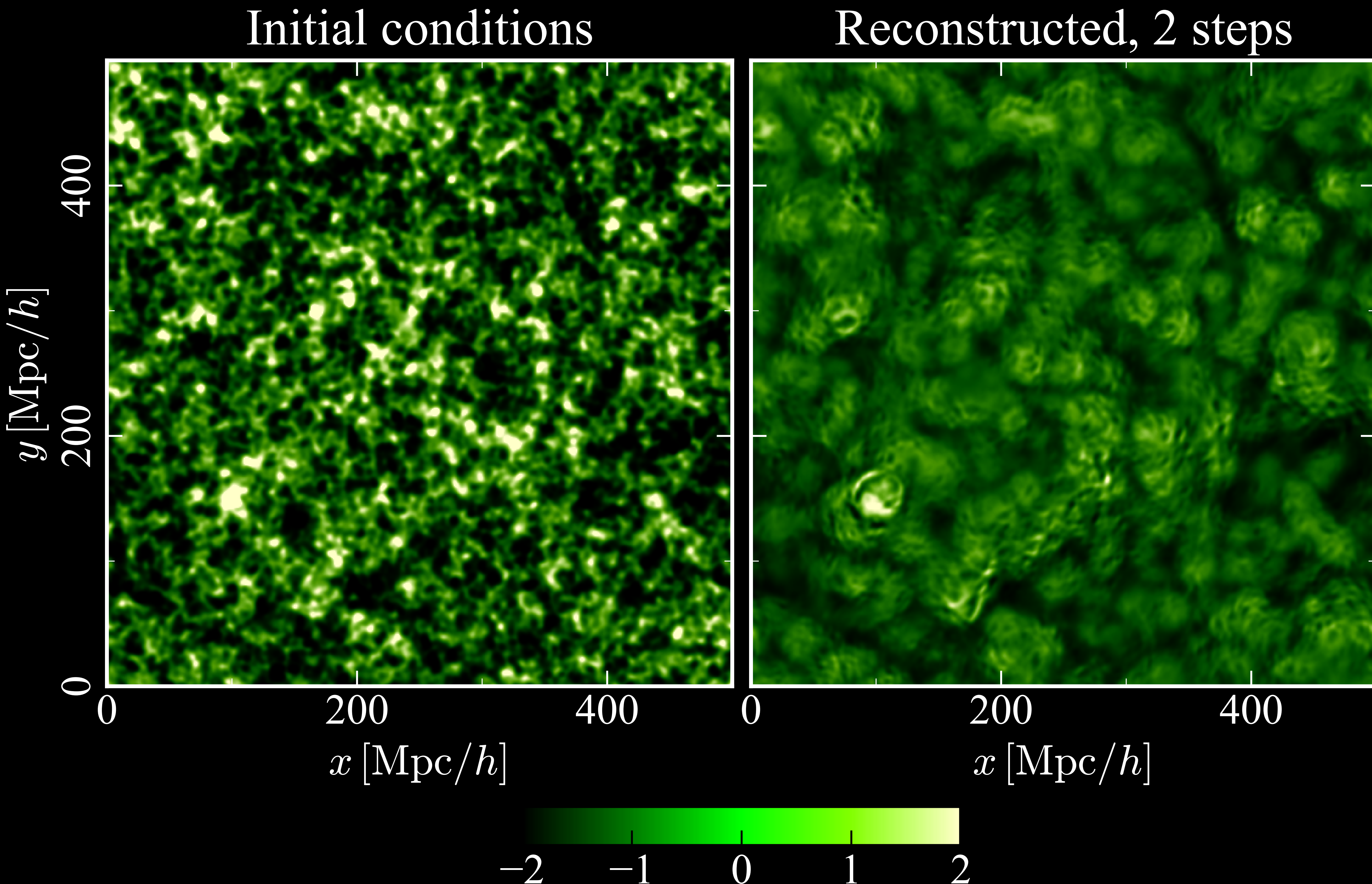

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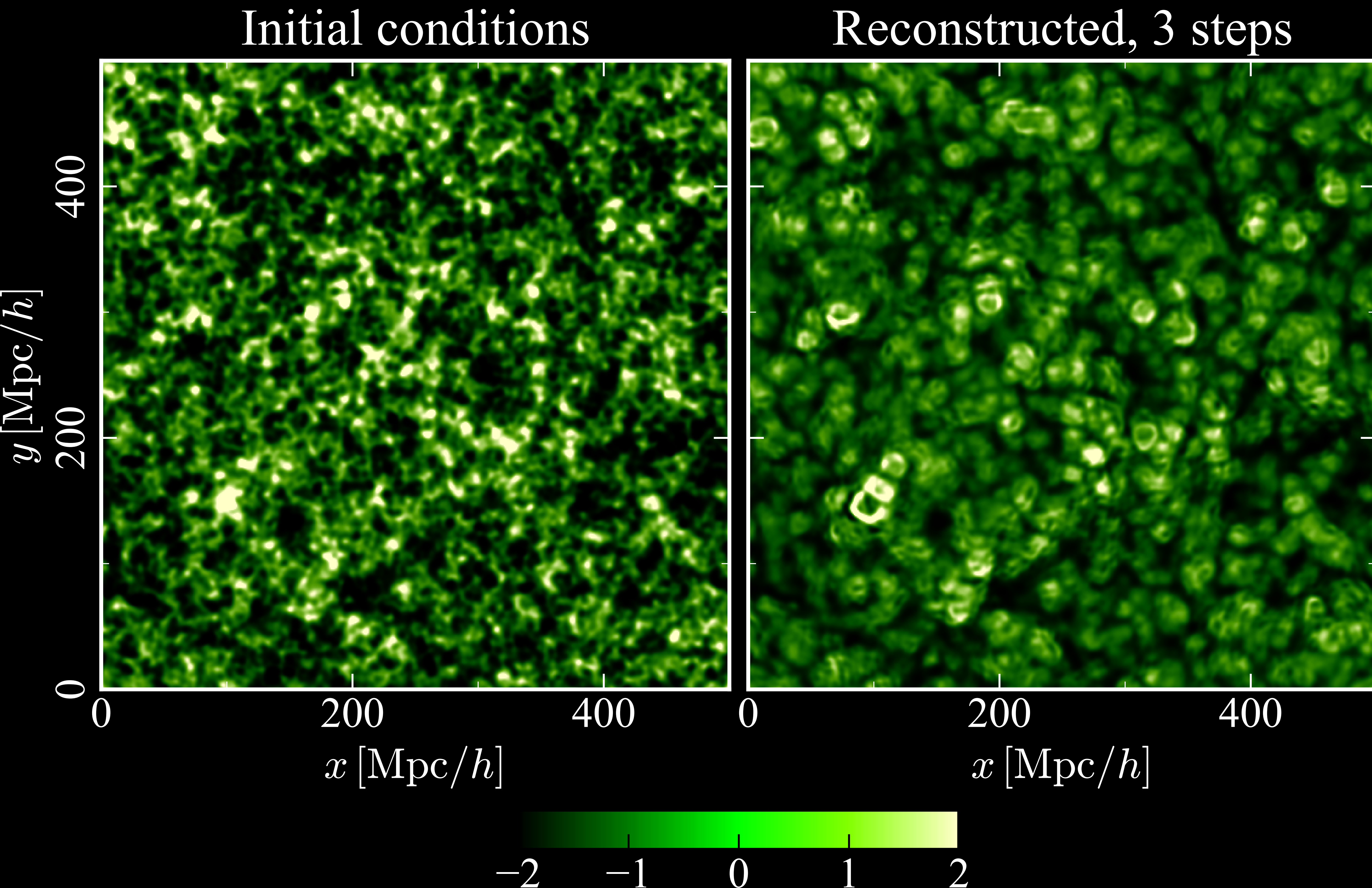

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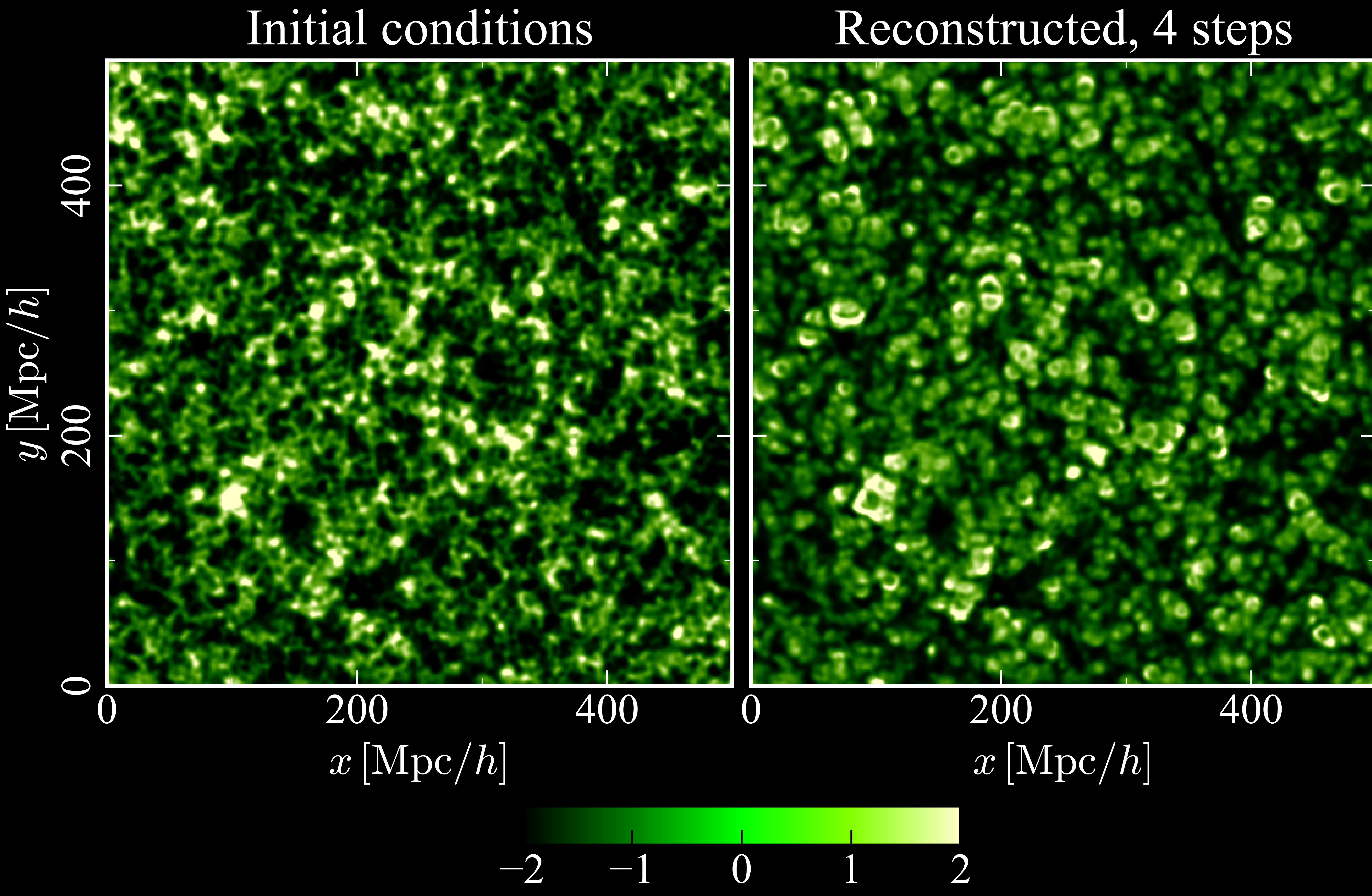

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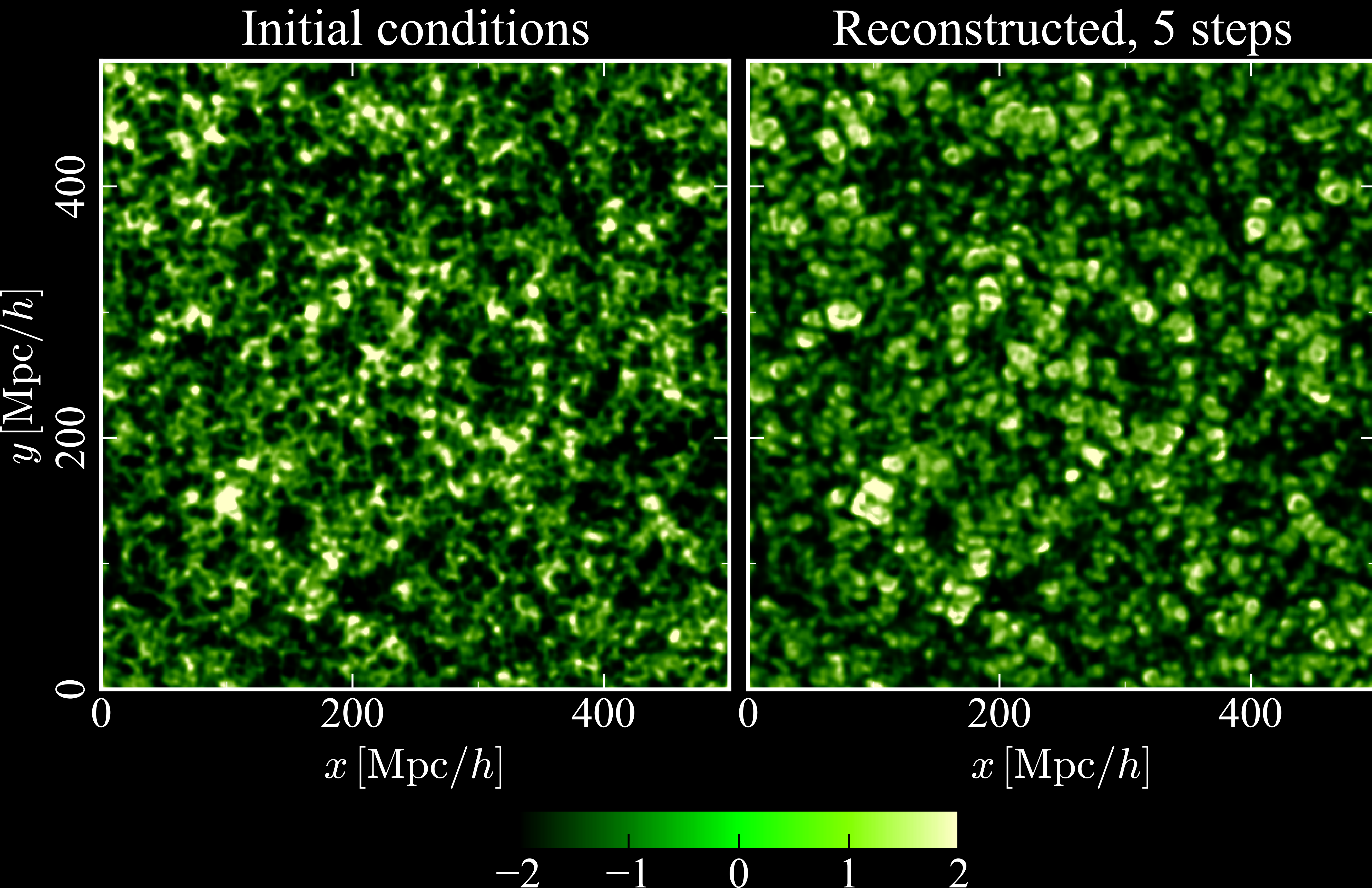

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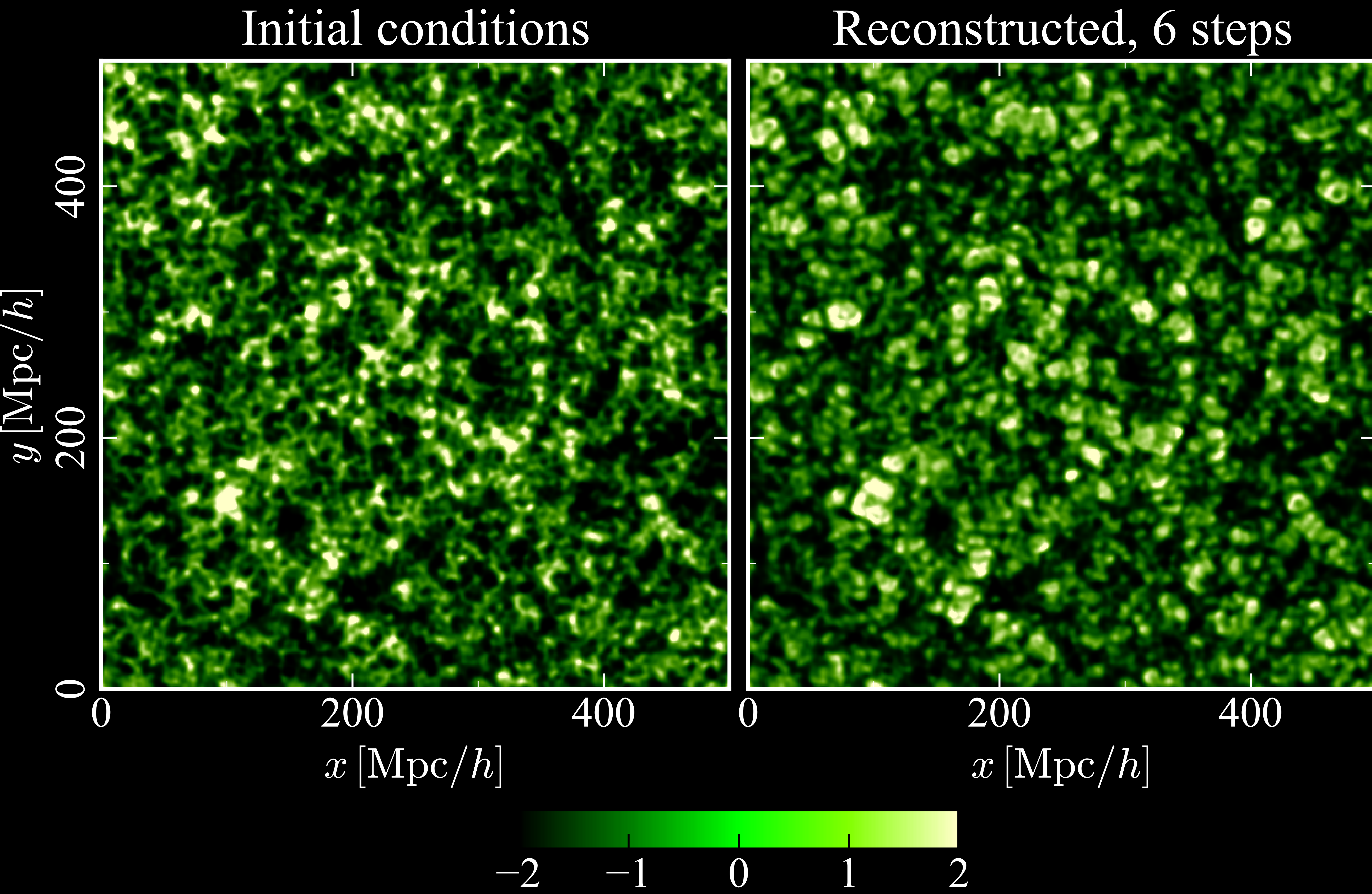

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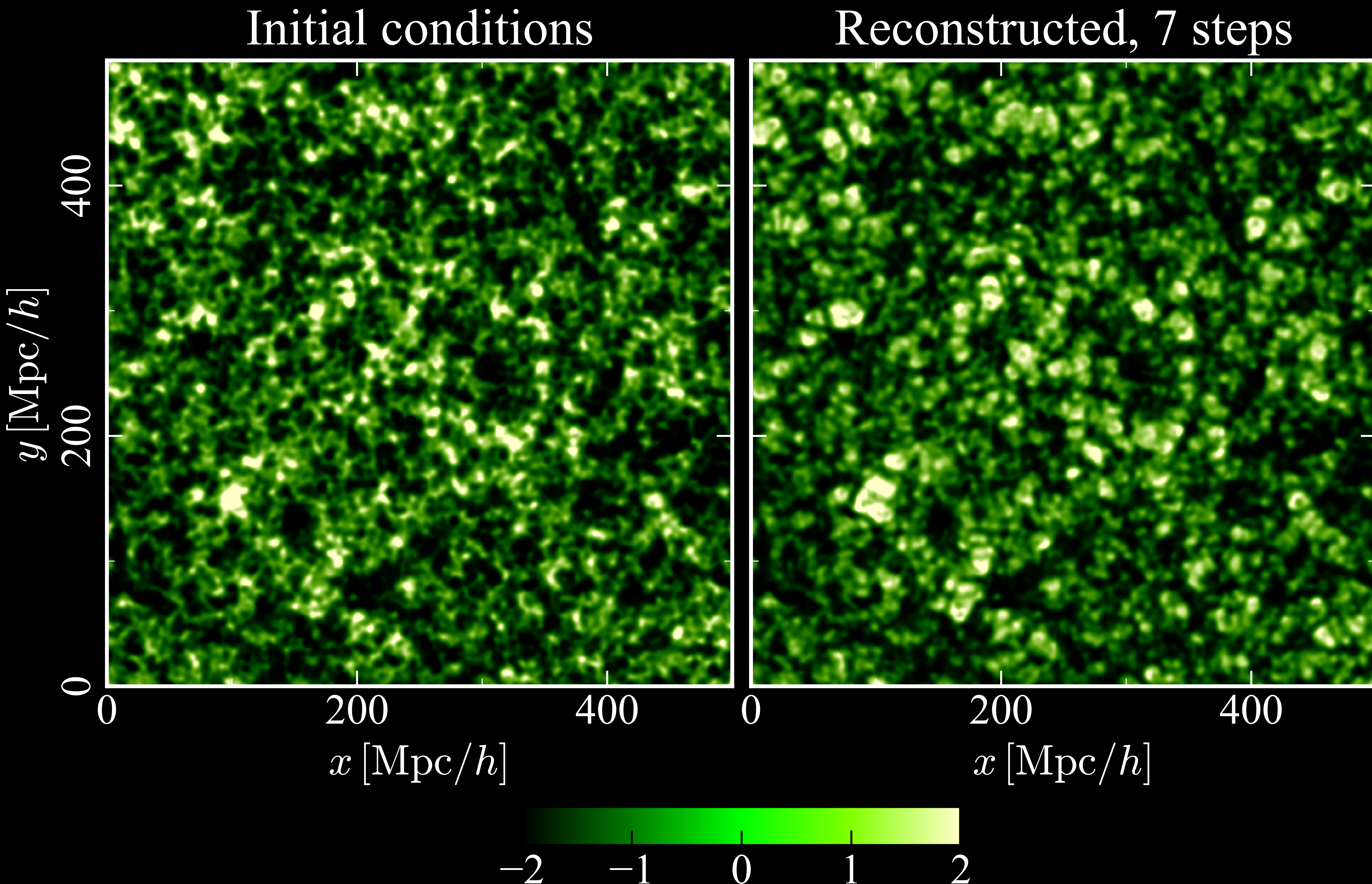

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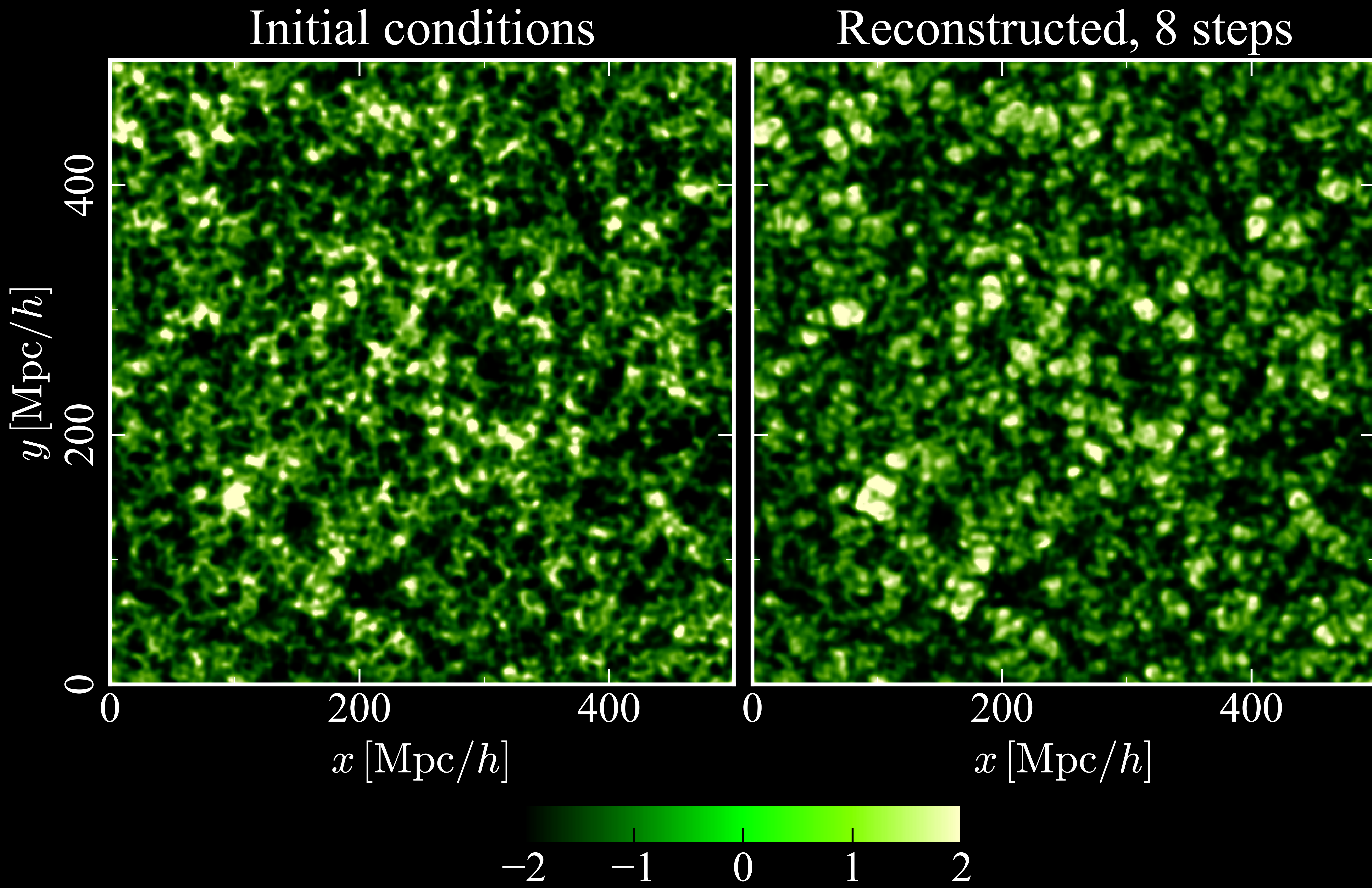

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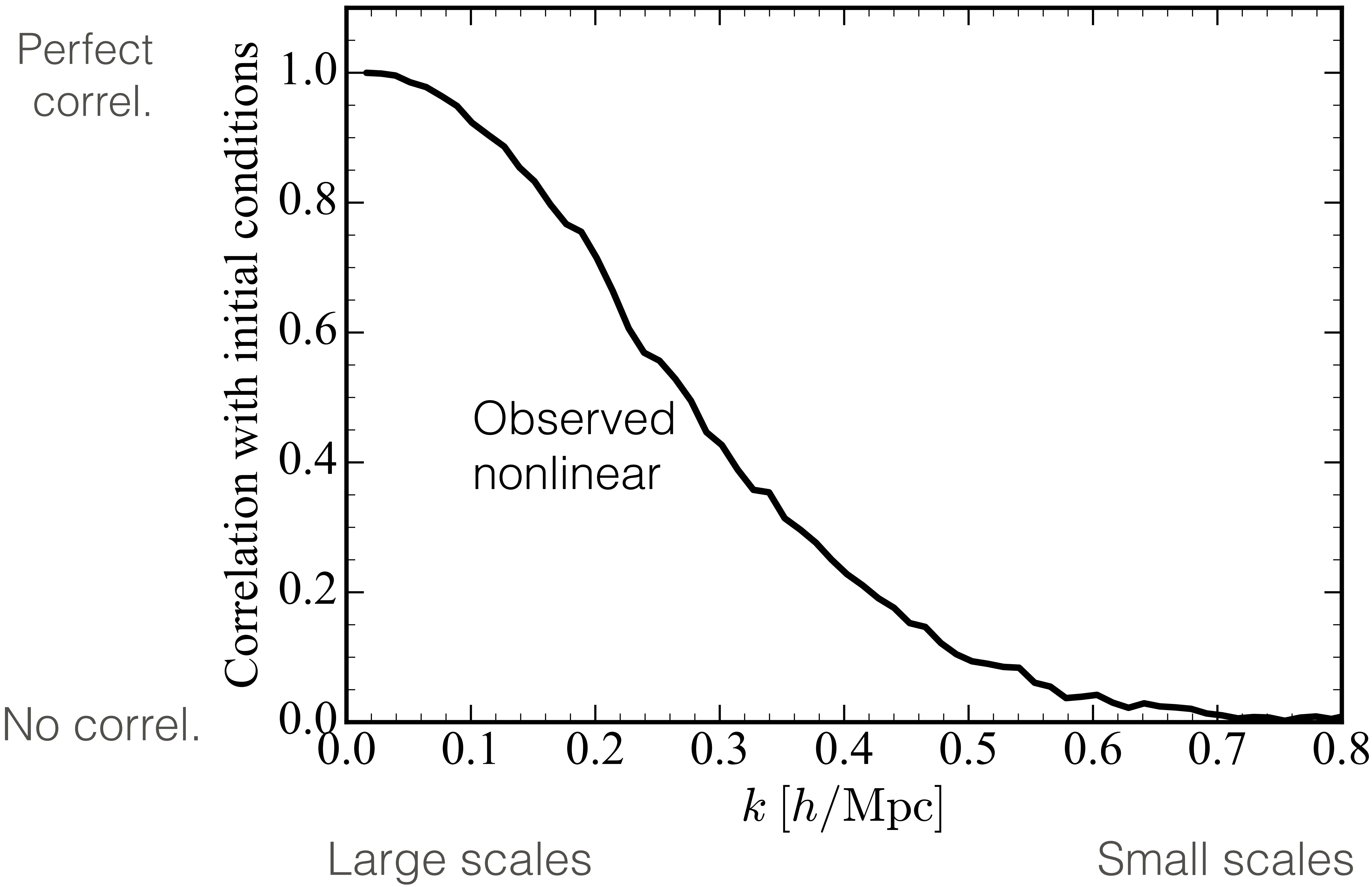
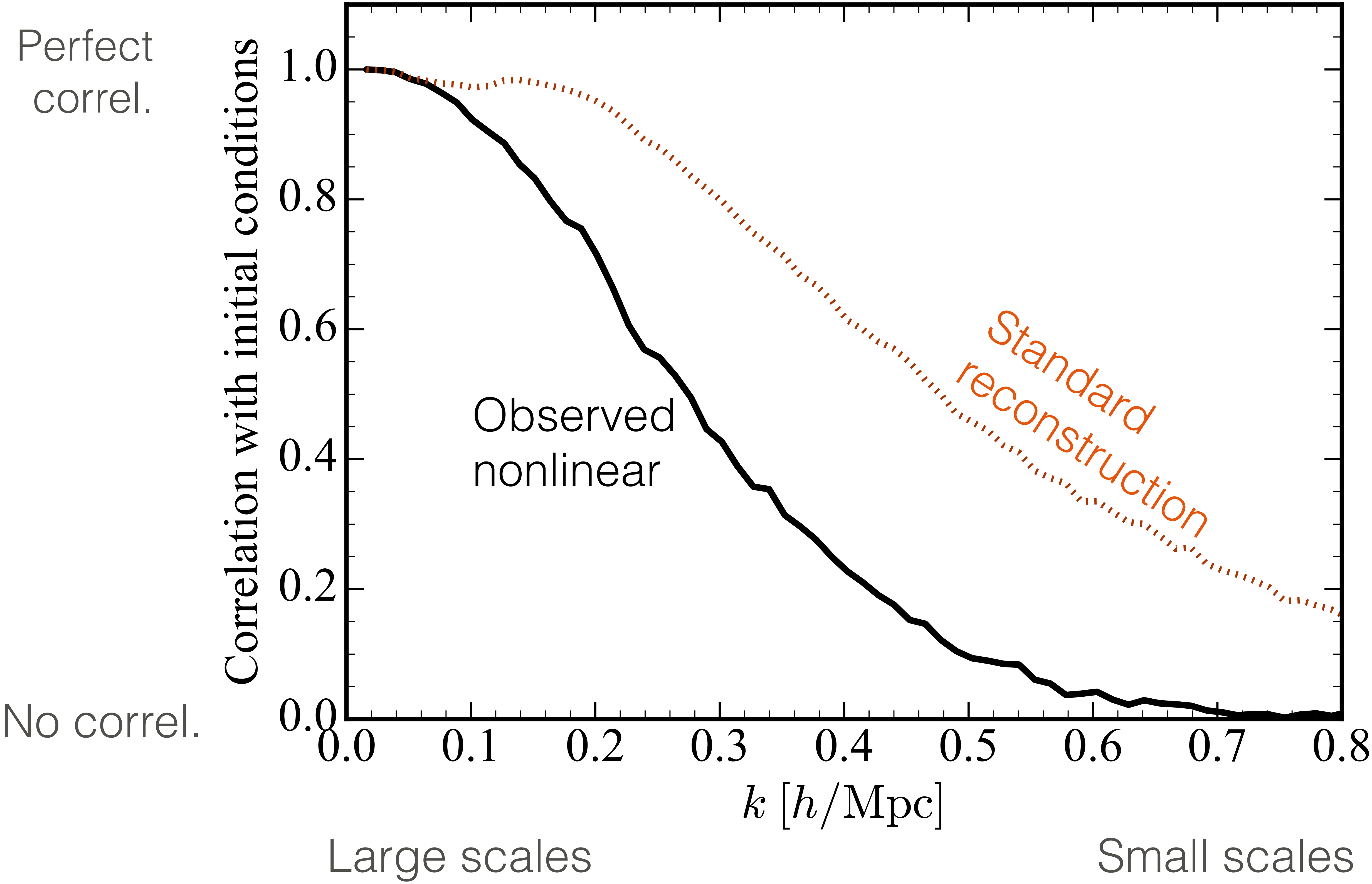
Correlation coefficient with initial conditions



MS, Baldauf, Zaldarriaga (2017); noise-free 4096^3 DM simulations at z=0.6

Correlation coefficient with initial conditions

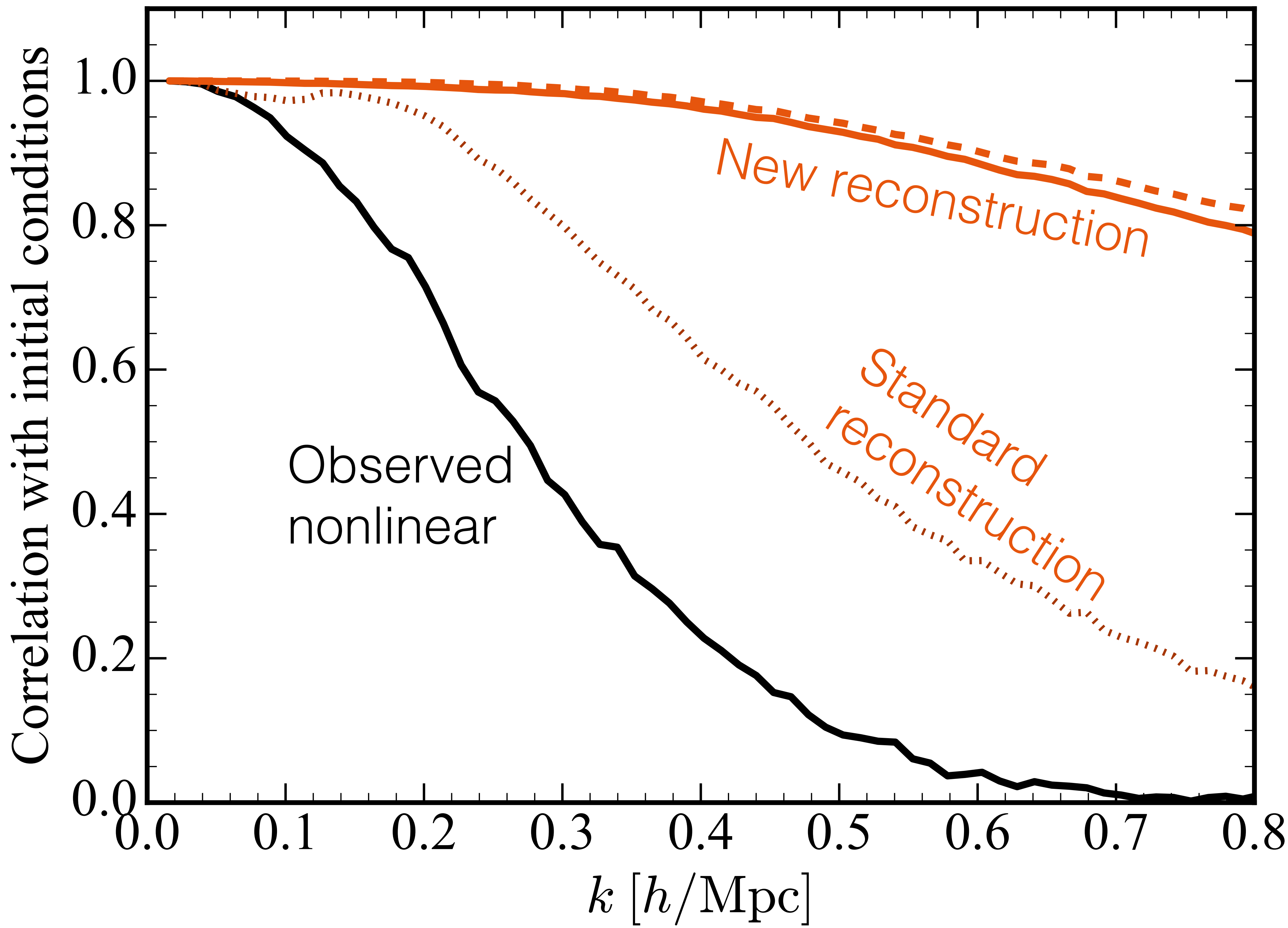


MS, Baldauf, Zaldarriaga (2017); noise-free 4096^3 DM simulations at z=0.6

Correlation coefficient with initial conditions

Perfect correl.

No correl.

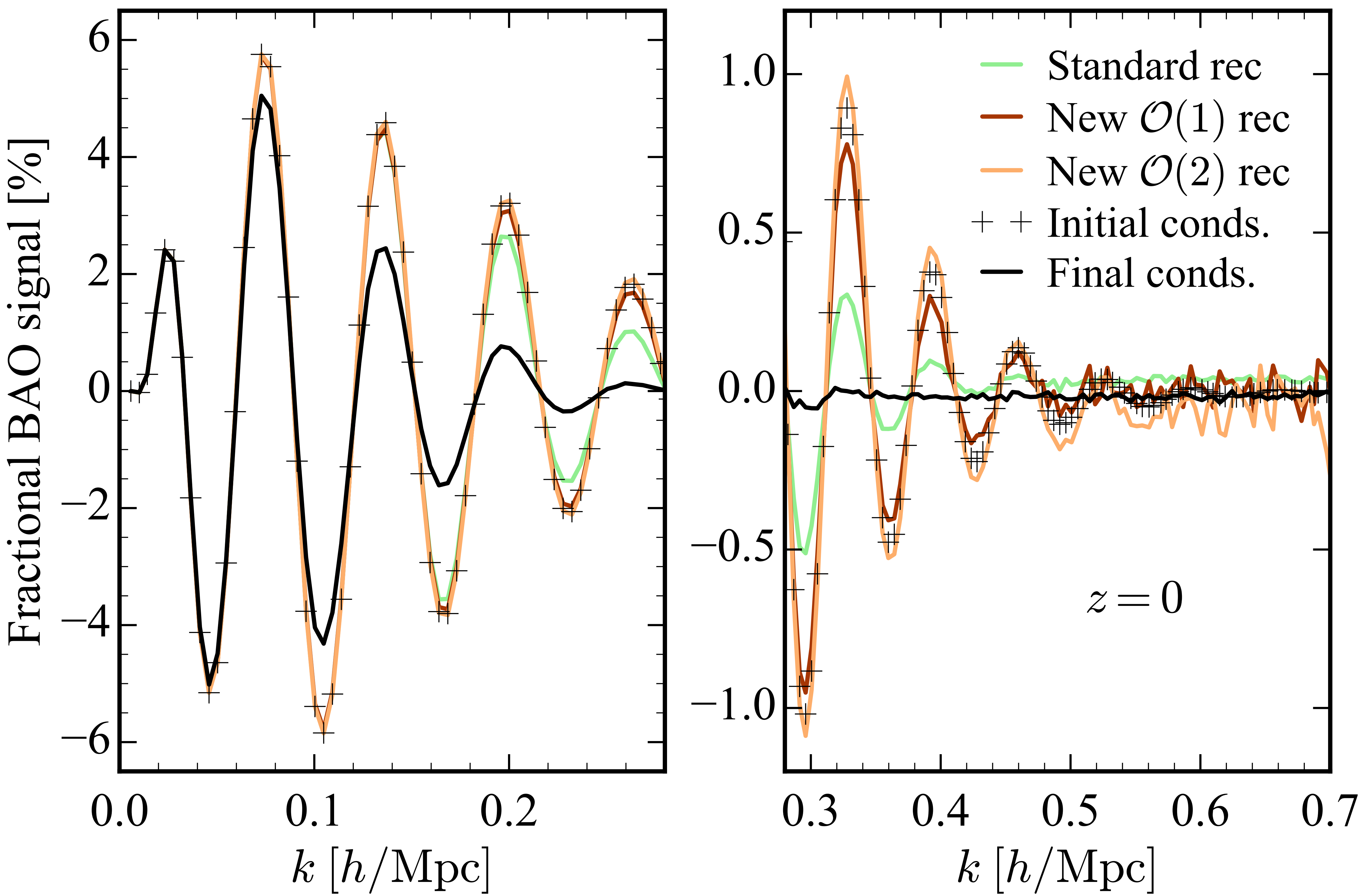


Large scales

Small scales

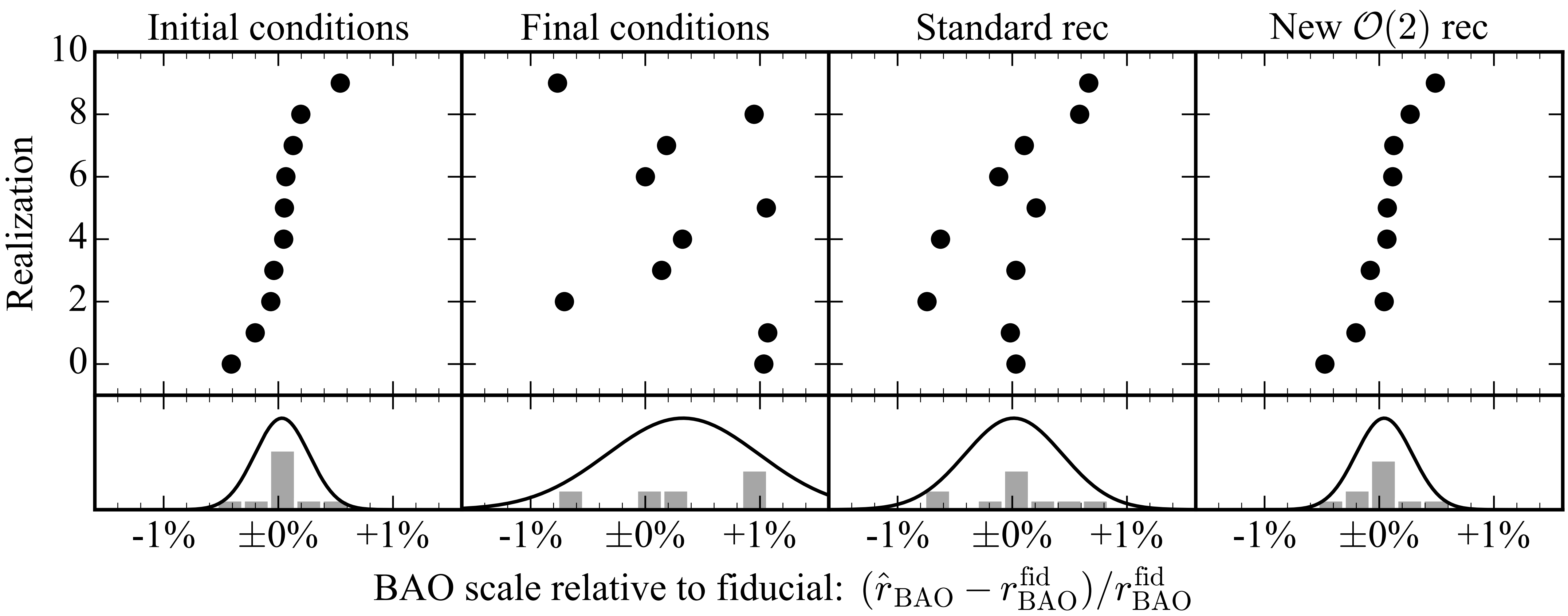
MS, Baldauf, Zaldarriaga (2017); noise-free 4096^3 DM simulations at z=0.6

BAO signal



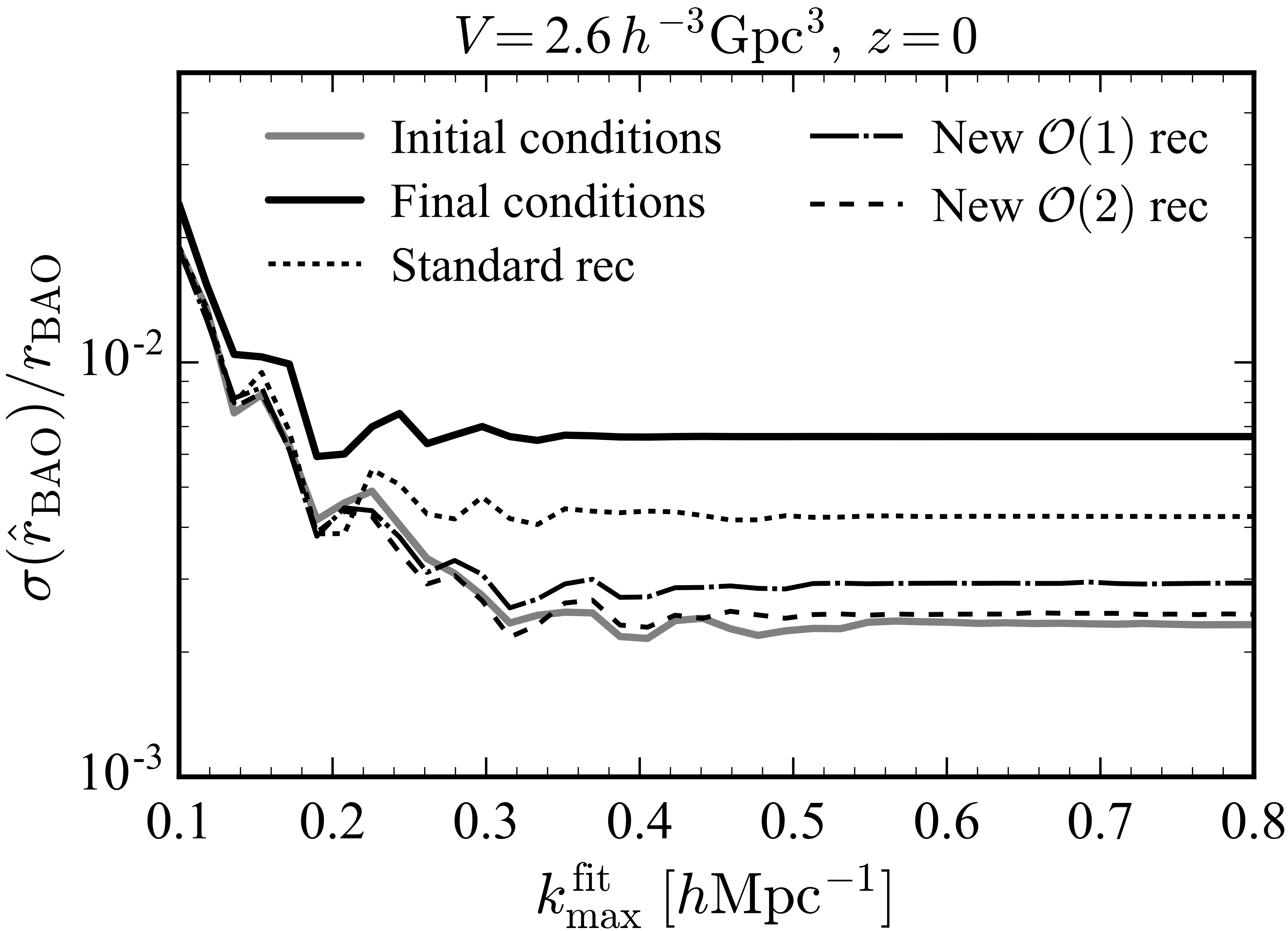
MS, Baldauf, Zaldarriaga (2017)

Best-fit BAO scale in 10 simulations



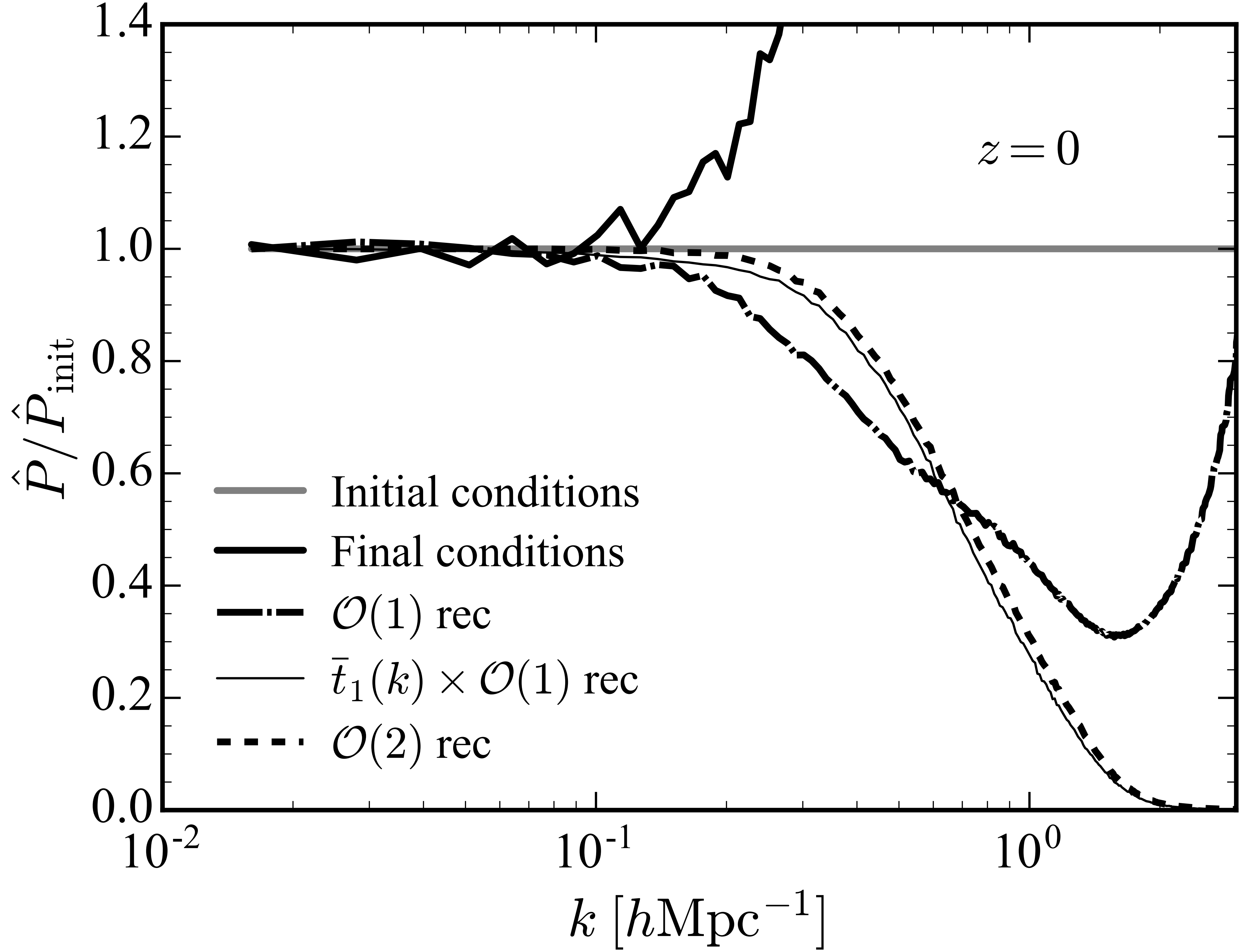
MS, Baldauf, Zaldarriaga (2017)

Fractional error bar of BAO scale



MS, Baldauf, Zaldarriaga (2017)

Broadband power spectrum



MS, Baldauf, Zaldarriaga (2017)

Challenges

Add realism:

- Noise (looks ok)
- Halos & galaxies
- Redshift space distortions
- Survey mask
- …

More complications when applying to real data?

Conclusions

Nonlinear physics limits science return of galaxy surveys

Reconstruction can reduce nonlinear terms

At z=0, reconstruction achieves >95% correlation with linear density at k<0.35 $h\mathrm{Mpc}^{-1}$

Improve BAO signal-to-noise by factor 2.7 (z=0) to 2.5 (z=0.6)

70%-30% improvement over standard BAO reconstruction

Can improve LSS survey science (mostly dark energy, maybe also early universe physics)

Happy to chat about CMB-lensing X clustering forecasts for f_{NL}, bias, σ_8, and neutrino mass; ask me later