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# new music, numerical universes, and faster simulations

**Oliver Hahn**

Institute for Astrophysics & Institute for Mathematics  
University of Vienna, Austria

**with Michael Bühlmann, Cornelius Rampf, Florian List, Michaël Michaux, Cora Uhlemann,  
Lukas Winkler, Fridolin Glatter**



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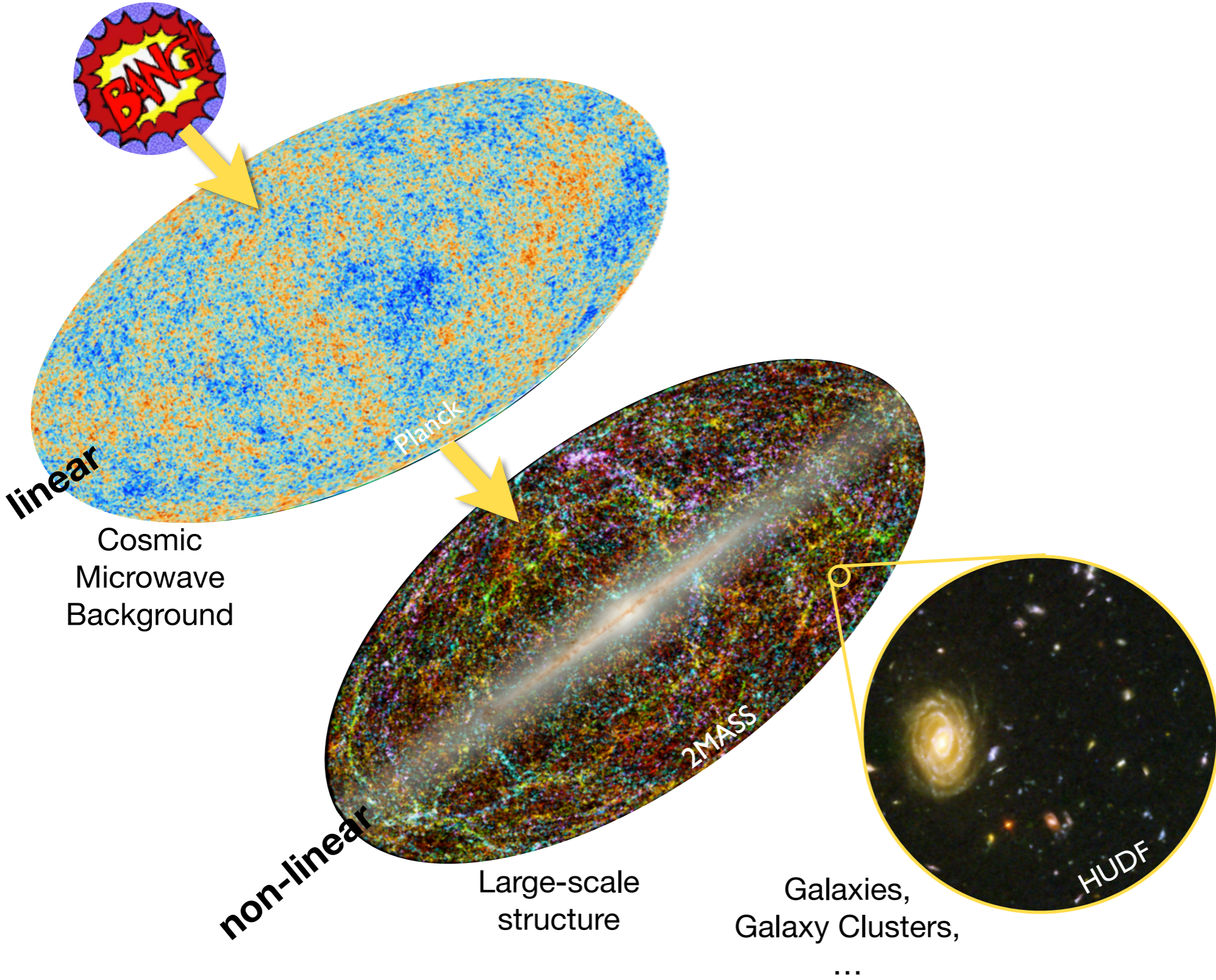
# new music, numerical universes, and faster simulations

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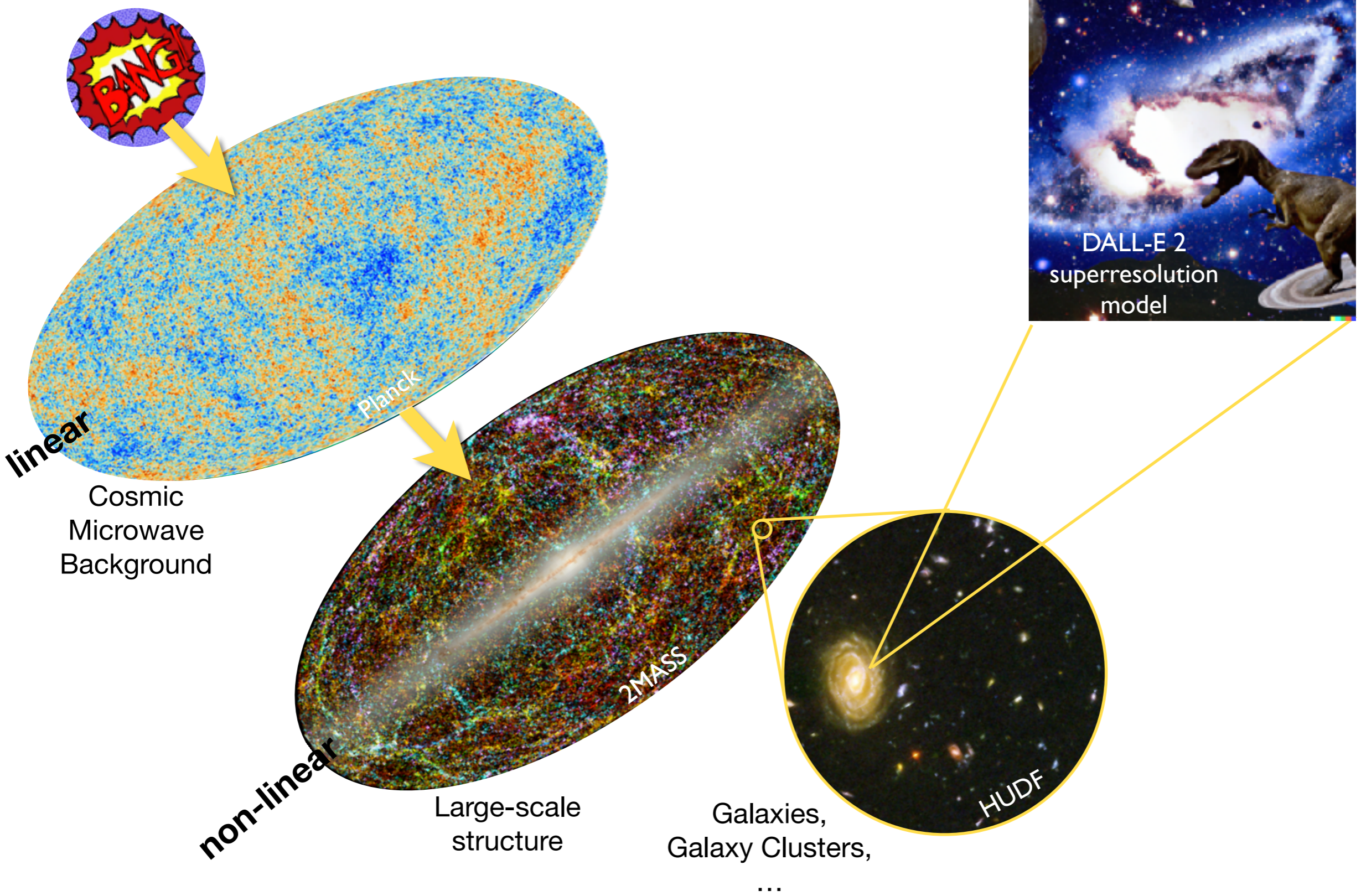
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# The MUSIC numeriverse: 30 orders of magnitude?

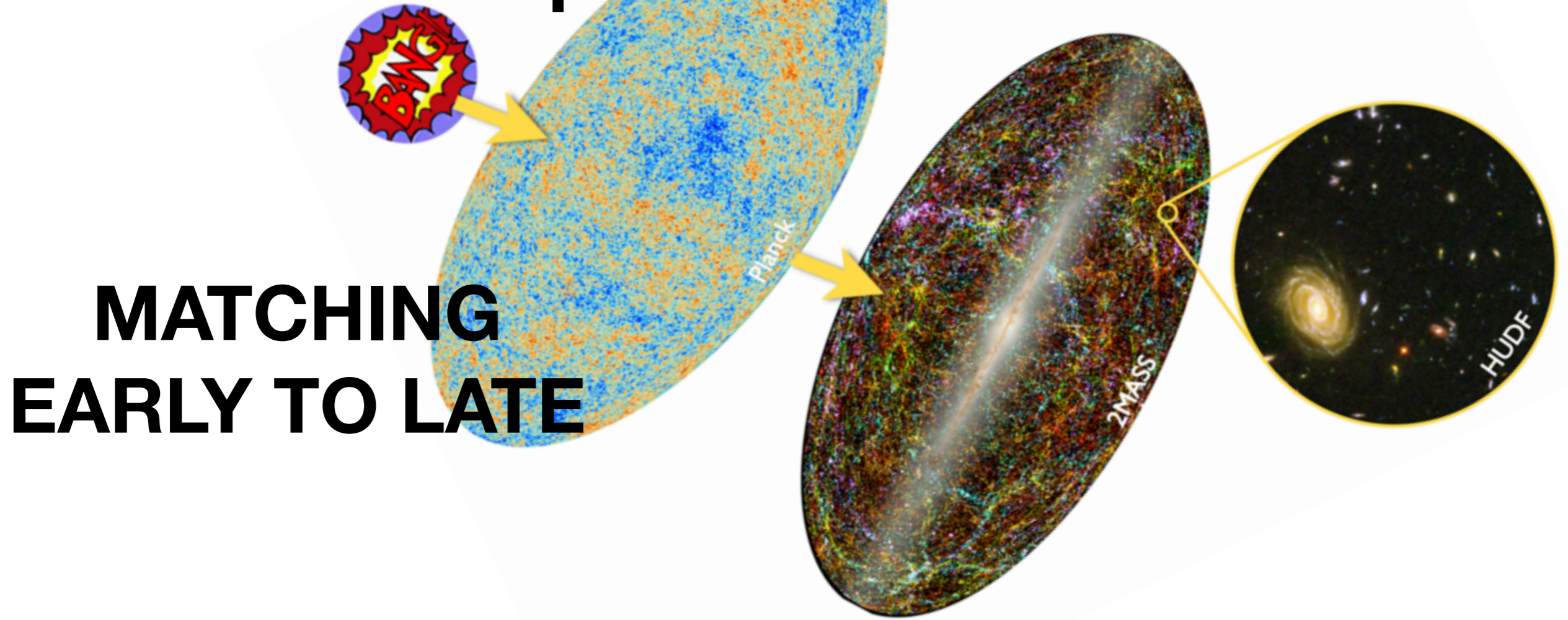


# The MUSIC numeriverse: 30 orders of magnitude?



# This talk:

## How do we map this to numerical universes?



**MATCHING  
EARLY TO LATE**

**HOW TO NUMERICALLY  
OBSERVE **ONE** UNIVERSE?**

**PRECISION & ACCURACY** (because 'qualitative' is so 2000s!)  
**& EFFICIENCY** (do more with less!)

# Matching early linear to late non-linear

## Early physics:

- GR effects (horizon+rel. species+aniso-stress)
- multi-species (CDM+baryon+photons+neutrinos)
- photon-baryon coupling + recombination
- perturbative quantity:  $\delta$  and  $\theta$

## Late physics:

- Newtonian gravity + small corrections
- mostly interested in mass distribution, CDM+baryons
- non-linear growth
- perturbative quantity:  $\psi$  (displacement)

**Matching problem!**

# Matching early linear to late non-linear

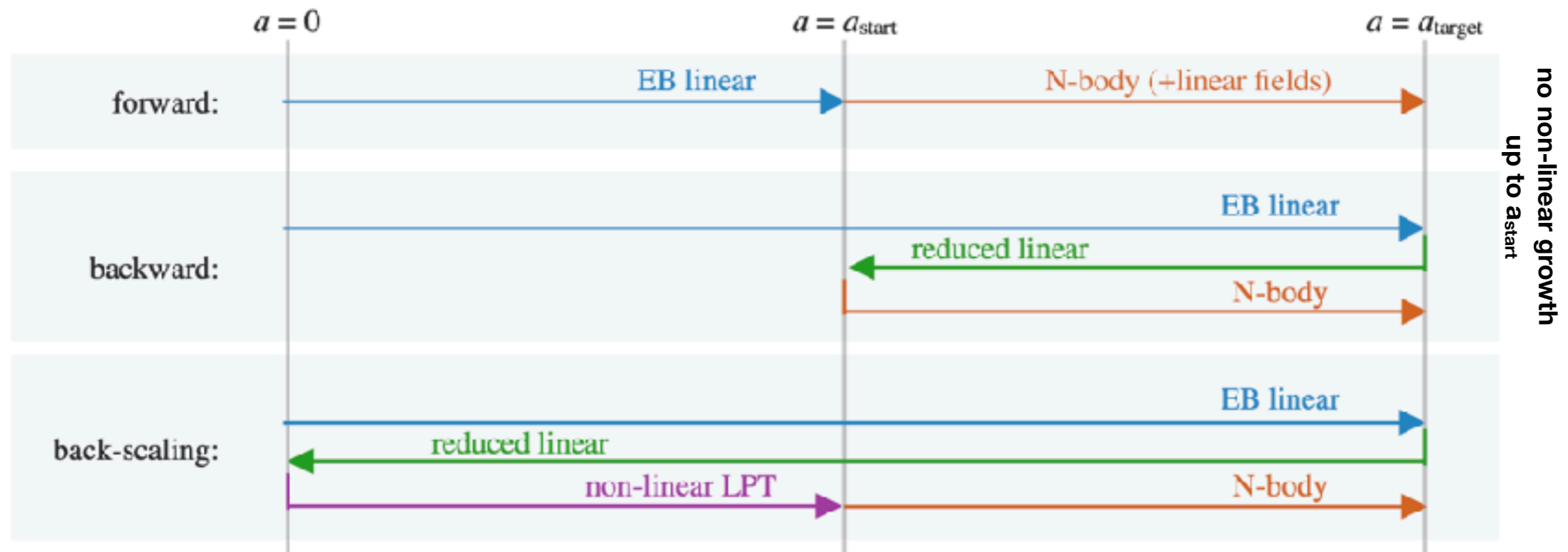
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## Matching problem!



# Two-component precision simulations

Cold two-fluid system, coupled by grav.

$$\partial_D \mathbf{v}_\alpha + \mathbf{v}_\alpha \cdot \nabla \mathbf{v}_\alpha = -\frac{3g}{2D} (\mathbf{v}_\alpha + \nabla \varphi),$$

$$\partial_D \delta_\alpha + \nabla \cdot [(1 + \delta_\alpha) \mathbf{v}_\alpha] = 0,$$

$$\nabla^2 \varphi = \frac{1}{D} (f_b \delta_b + f_c \delta_c),$$

Main modes in linear baryon-CDM system:

- 1 growing mode:  $D_+$
- 2 decaying modes: global+BC-relative velocity
- 1 constant mode: compensated isocurvature

What is isocurvature?

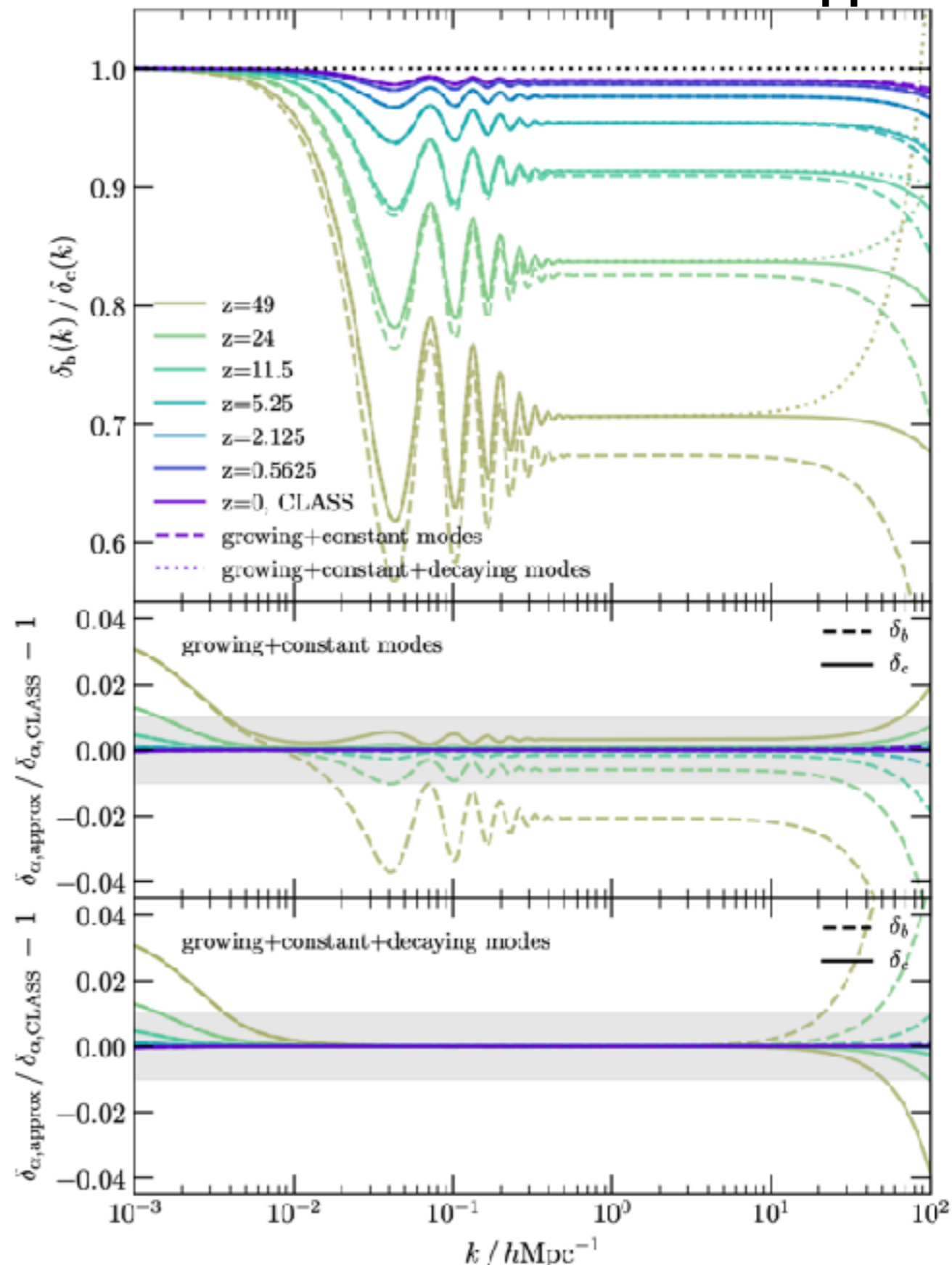
varying baryon-to-cdm fraction

$$\frac{\rho_b}{\rho_c} \neq \frac{\Omega_b}{\Omega_c} \quad \text{while} \quad \rho_b + \rho_c = \rho_m$$

Baryons catch up with CDM over time

evolution is captured by lin. Boltzmann-Einstein

Linear evolution from CLASS + approx.

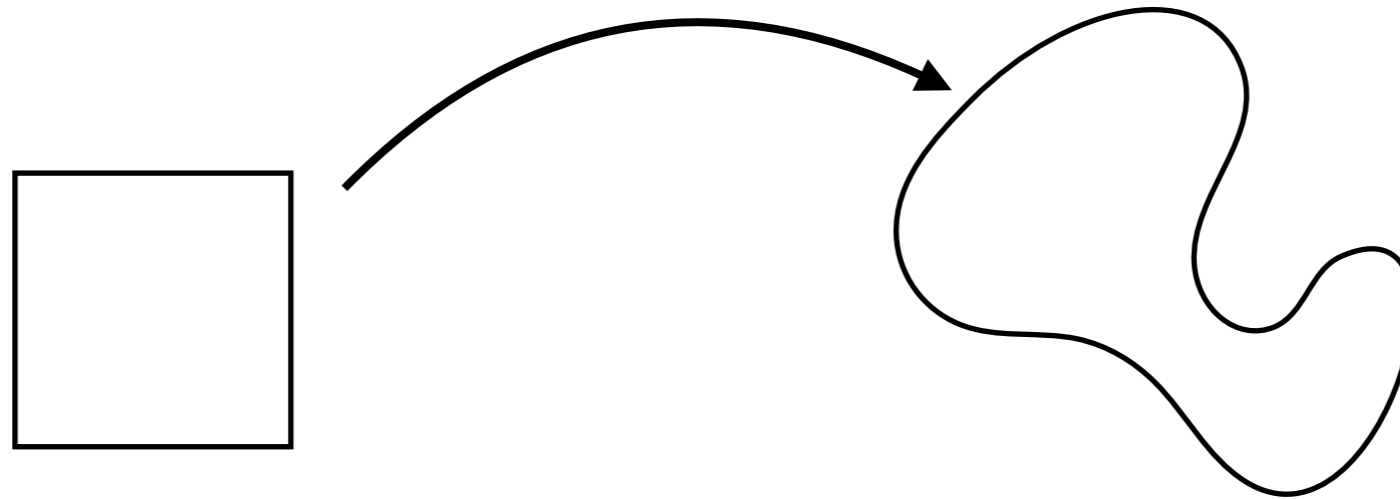




# Discrete evolution vs. fluid evolution

Lagrangian description, evolution of fluid element

$$\mathcal{Q} \subset \mathbb{R}^3 \rightarrow \mathbb{R}^6 : \mathbf{q} \mapsto (\mathbf{x}_{\mathbf{q}}(t), \mathbf{v}_{\mathbf{q}}(t))$$

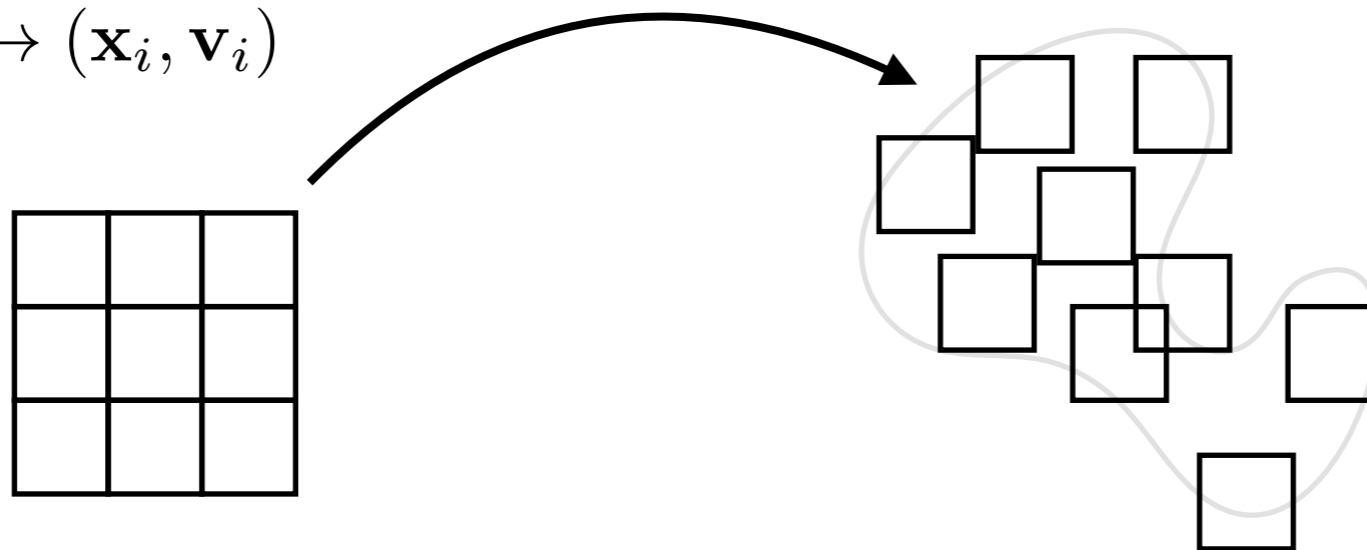


$$\frac{Df_m}{Dt} = 0$$

## The N-body approximation:

cover distribution function with N characteristics, estimate  $f_m$  from them

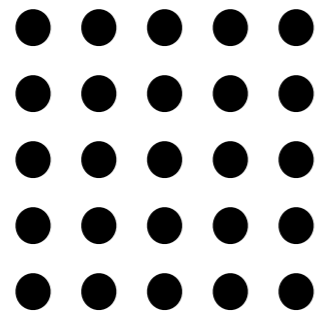
$$i \in \{1 \dots N\} \mapsto (\mathbf{x}_i, \mathbf{v}_i)$$



**This can re-introduce short-range interactions -> softening...**

# Setting up initial conditions for N-body simulations

**(globally) isotropic  
and homogeneous state**



system in (unstable) equilibrium,  
velocities zero

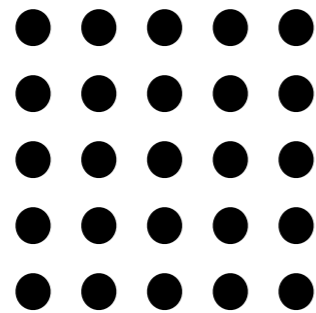
*symmetry always broken at  
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but global symmetry ok e.g. for:

- Bravais lattices
- glasses
- special tilings

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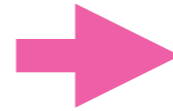


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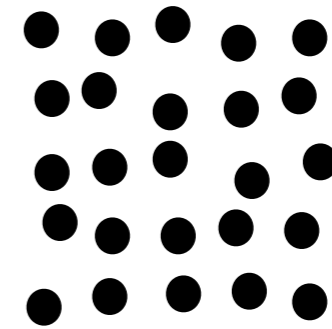
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perturbed state



system out of equilibrium,  
positions and velocities set to  
reproduce linear/non-linear modes

variant 1: first order method:

$$\vec{\psi}_{\text{ini}} = \vec{\nabla} \nabla^{-2} \delta_{\text{ini}}$$

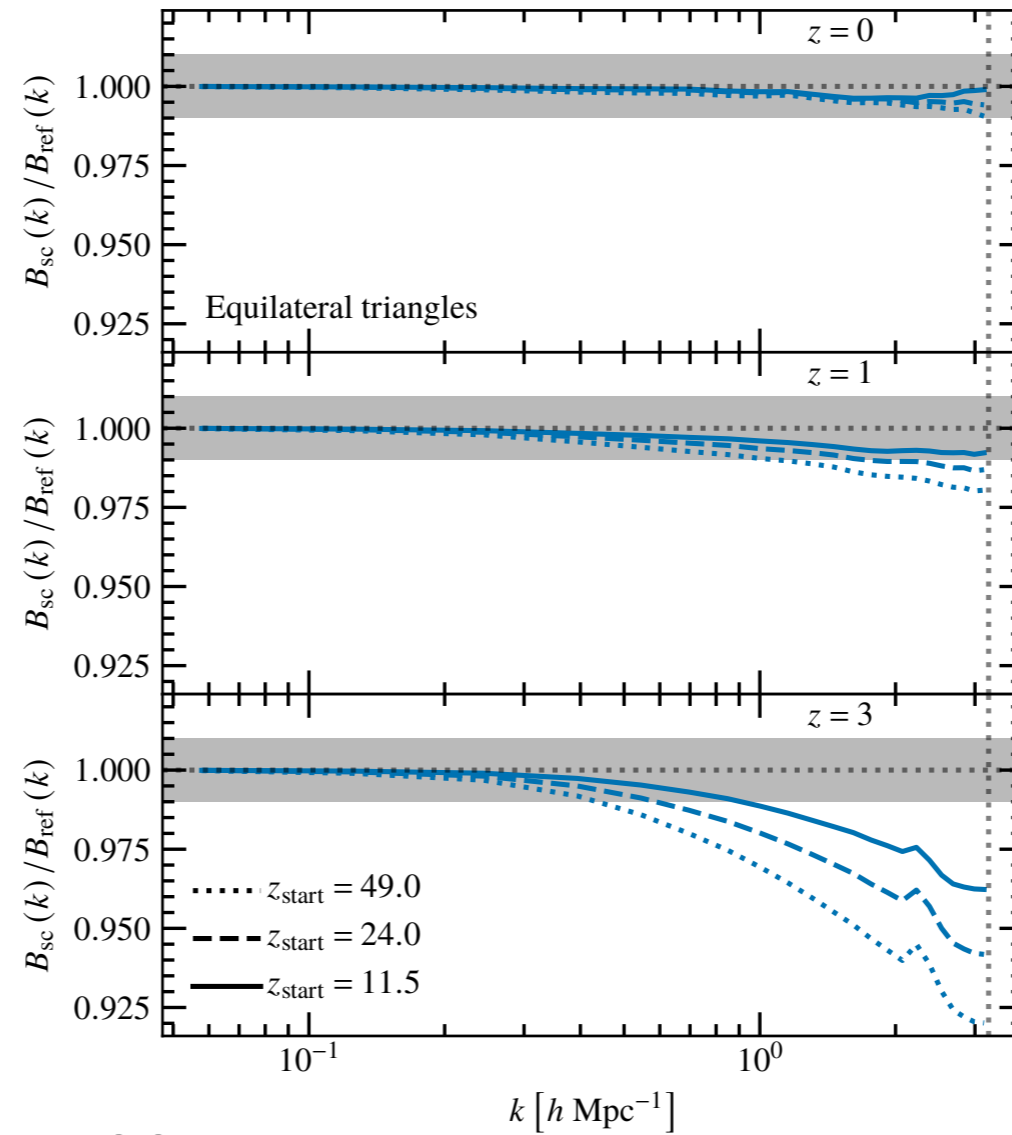
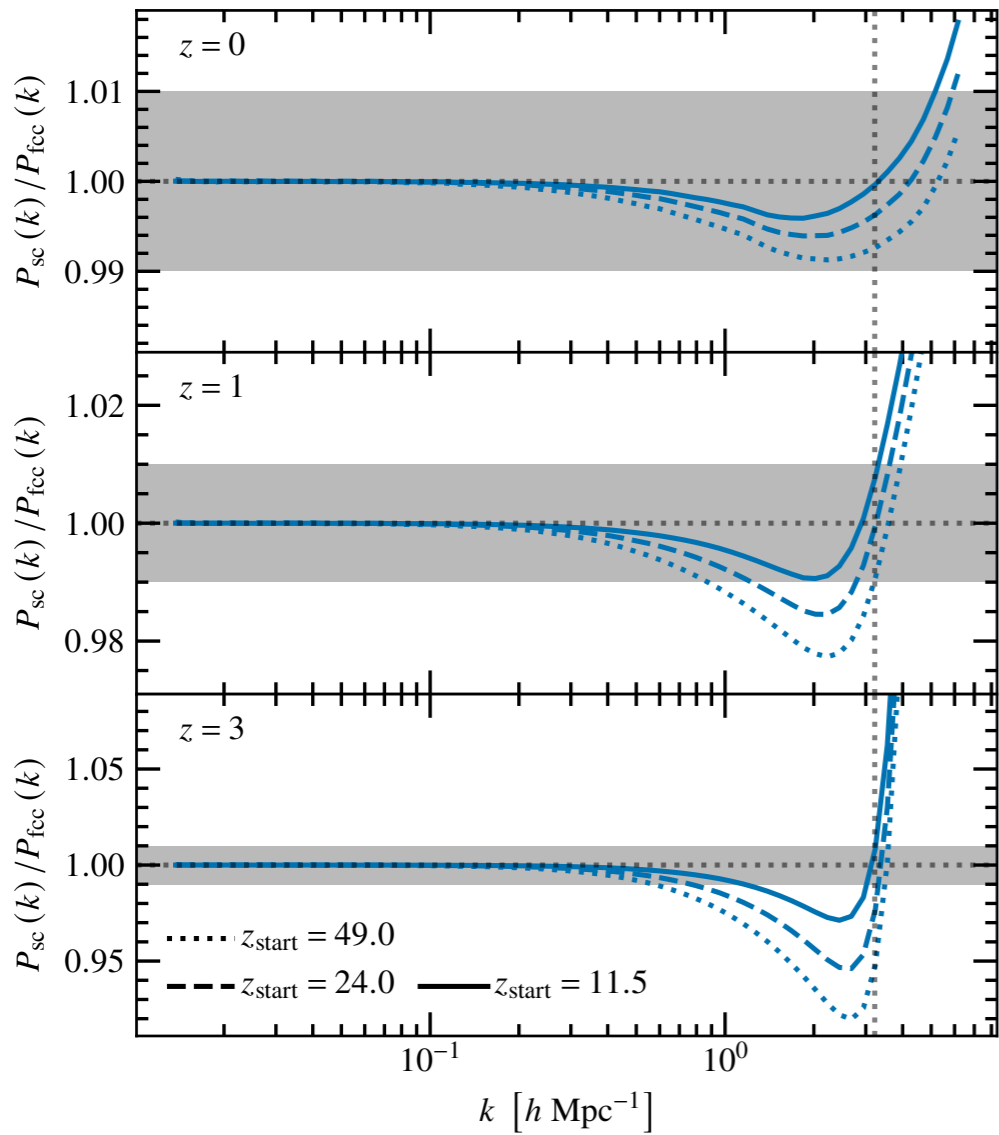
$$\dot{\vec{\psi}}_{\text{ini}} = \vec{\nabla} \nabla^{-2} \theta_{\text{ini}}$$

variant 2: LPT (nonlinear)

$$\vec{\psi}_{\text{ini}} = \sum_{i=1}^n D_+^{(n)} \vec{\psi}^{(n)}$$

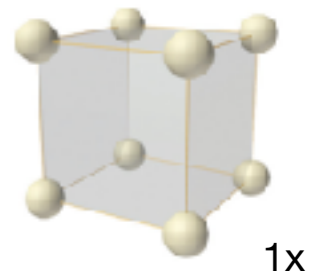
# Discreteness – impact on low-z power spectrum

effect on PS at  $z=0$  wiped out by non-linearity (scale-mixing), not at higher  $z$

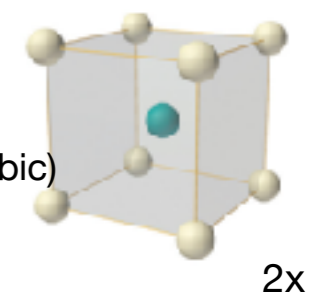


ref = FCC

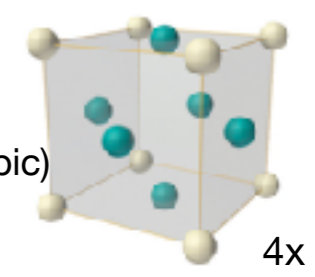
SC  
(simple cubic)



BCC  
(body-centred cubic)



FCC  
(face-centred cubic)



(cf. also Marcos 2008)

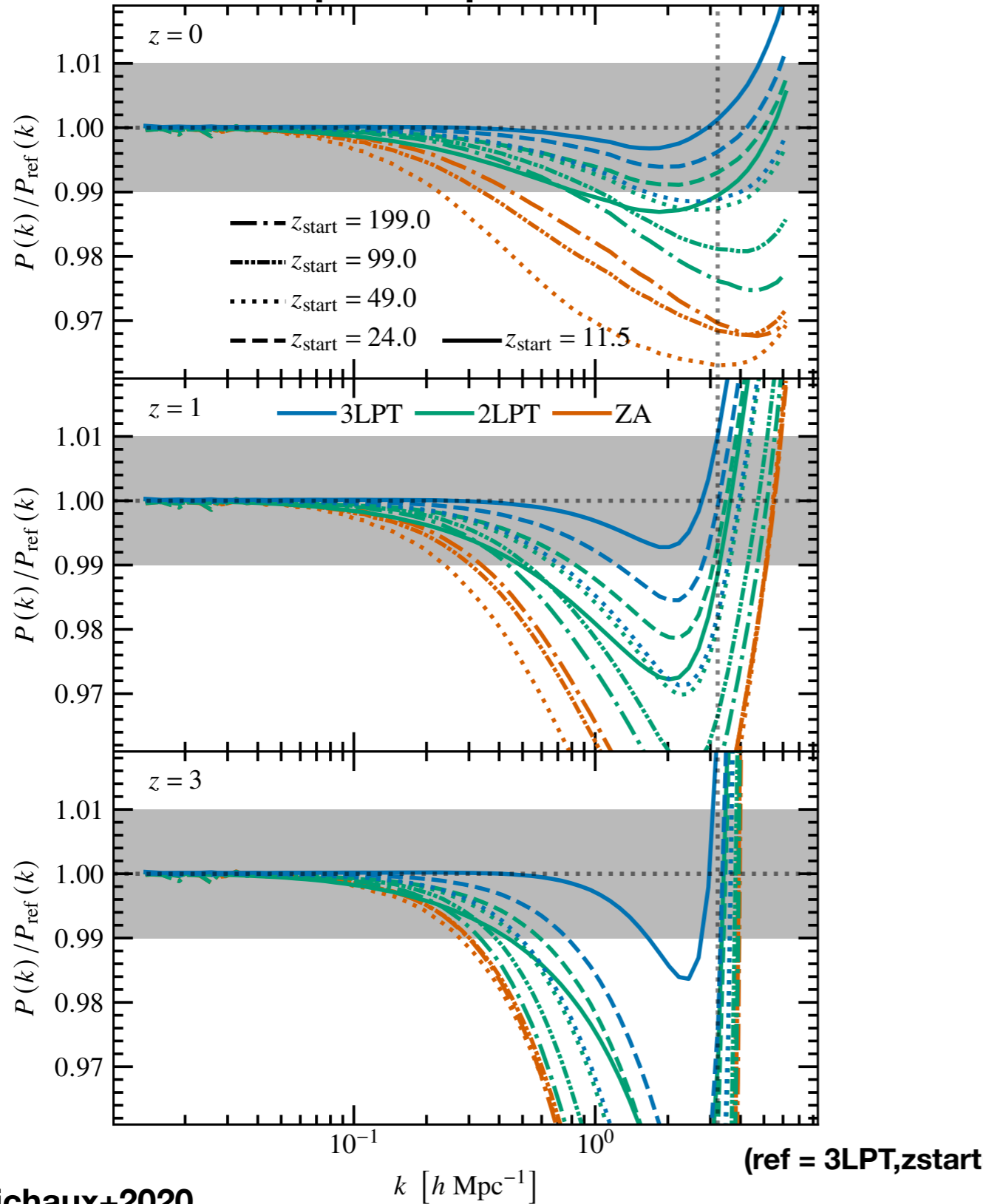
Michaux+2020

discreteness effects strongest at high  $z$

very slow convergence with particle number ( $\propto k_{Ny}^3$ )

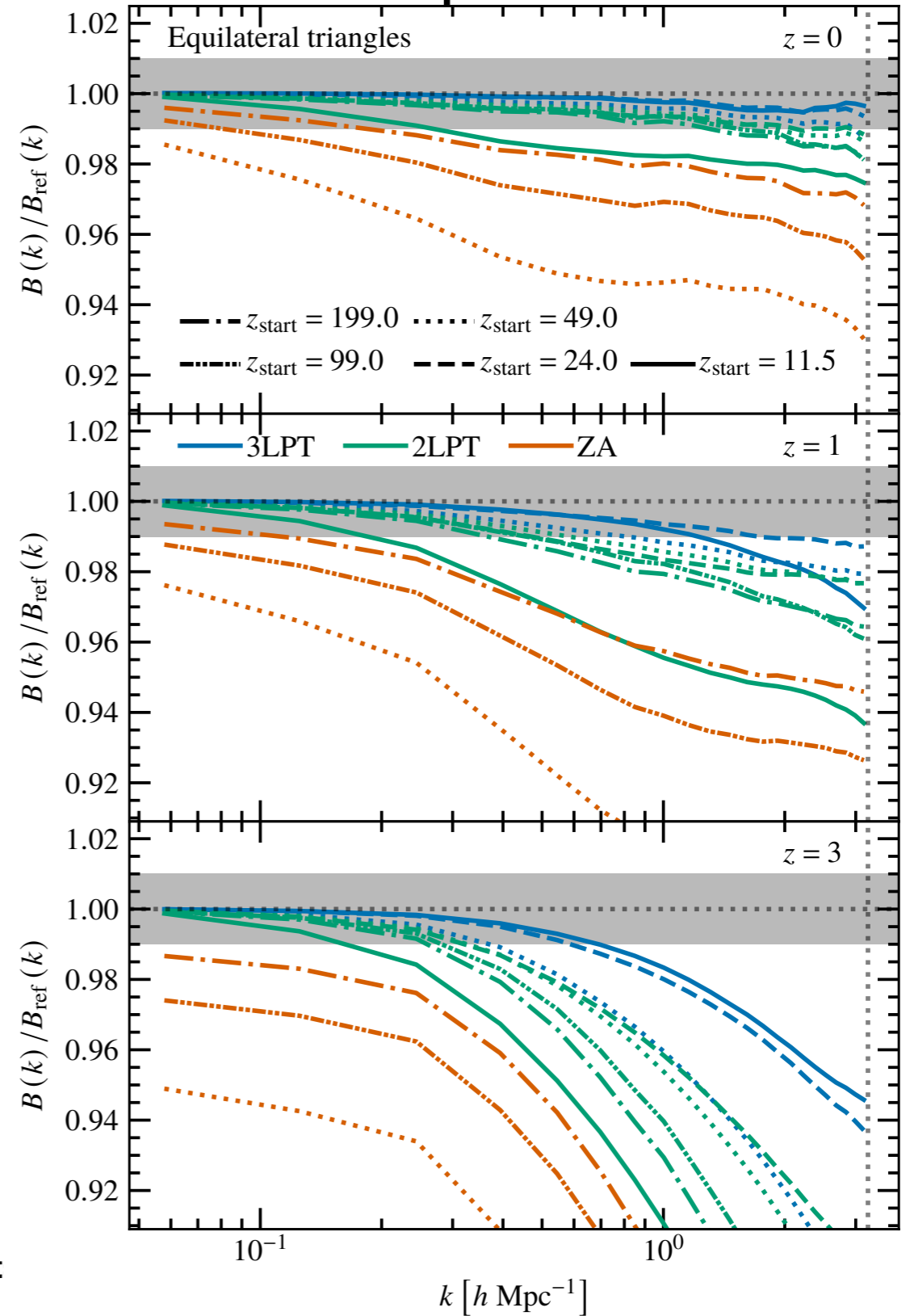
# Impact of nLPT vs. discreteness on low- $z$ spectra

power spectrum

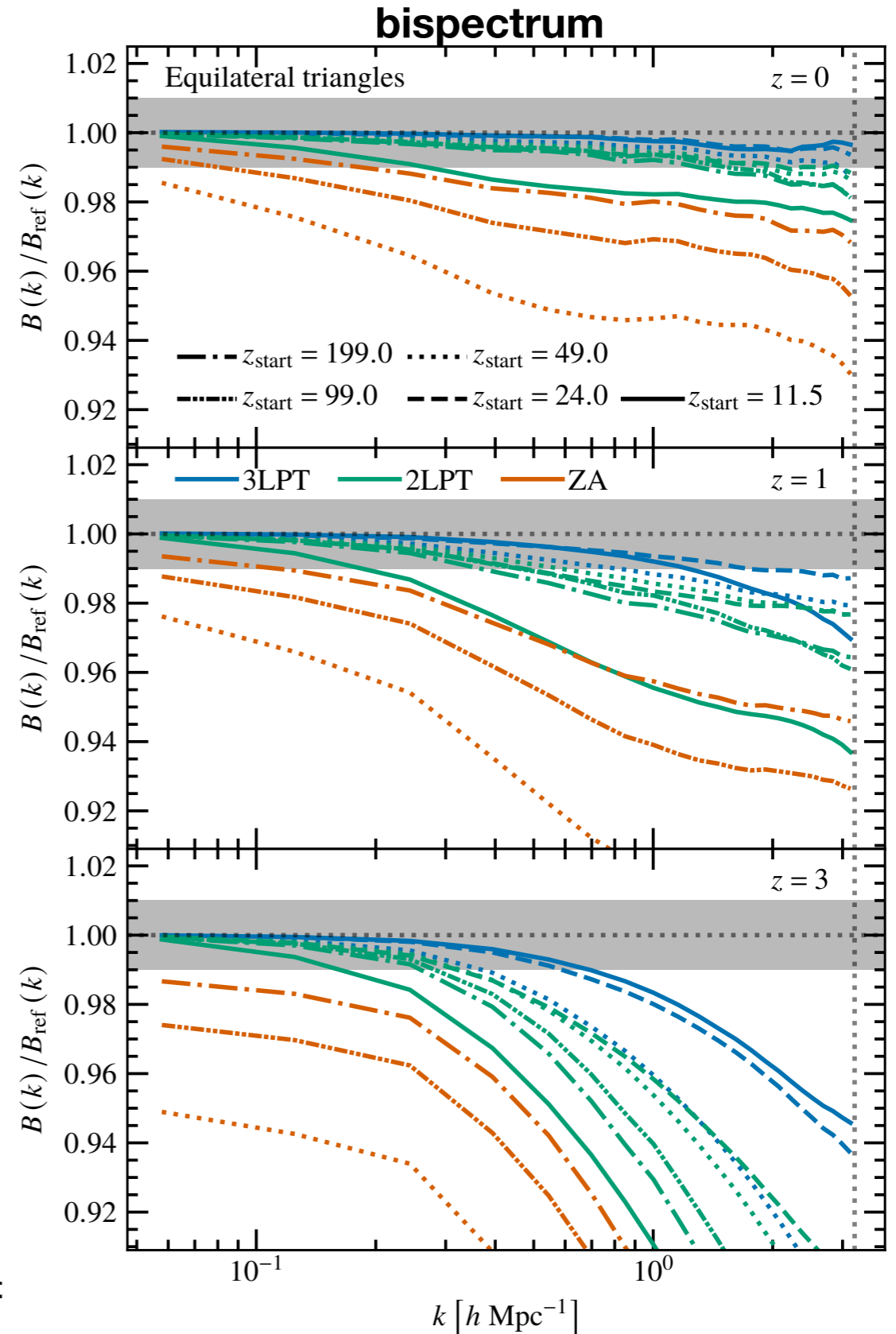
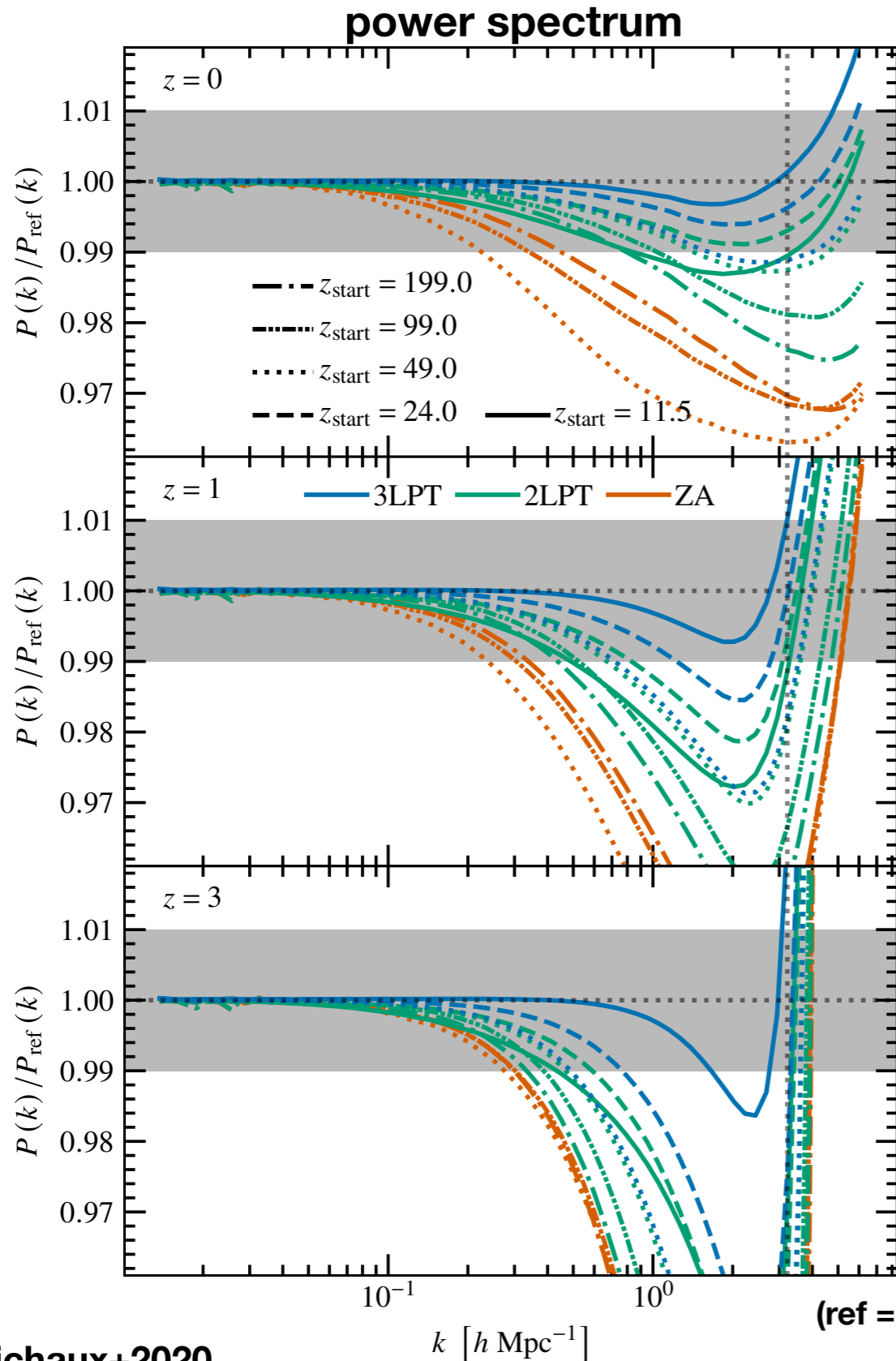


Michaux+2020

bispectrum



# Impact of nLPT vs. discreteness on low- $z$ spectra



Michaux+2020

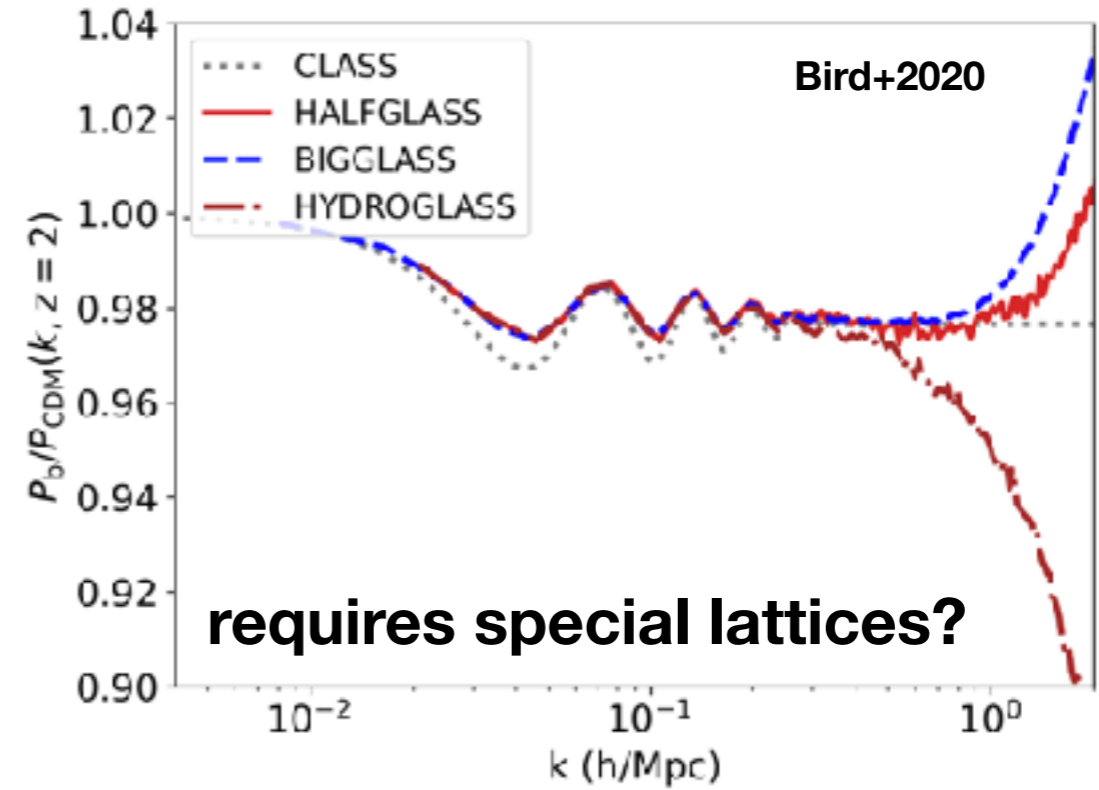
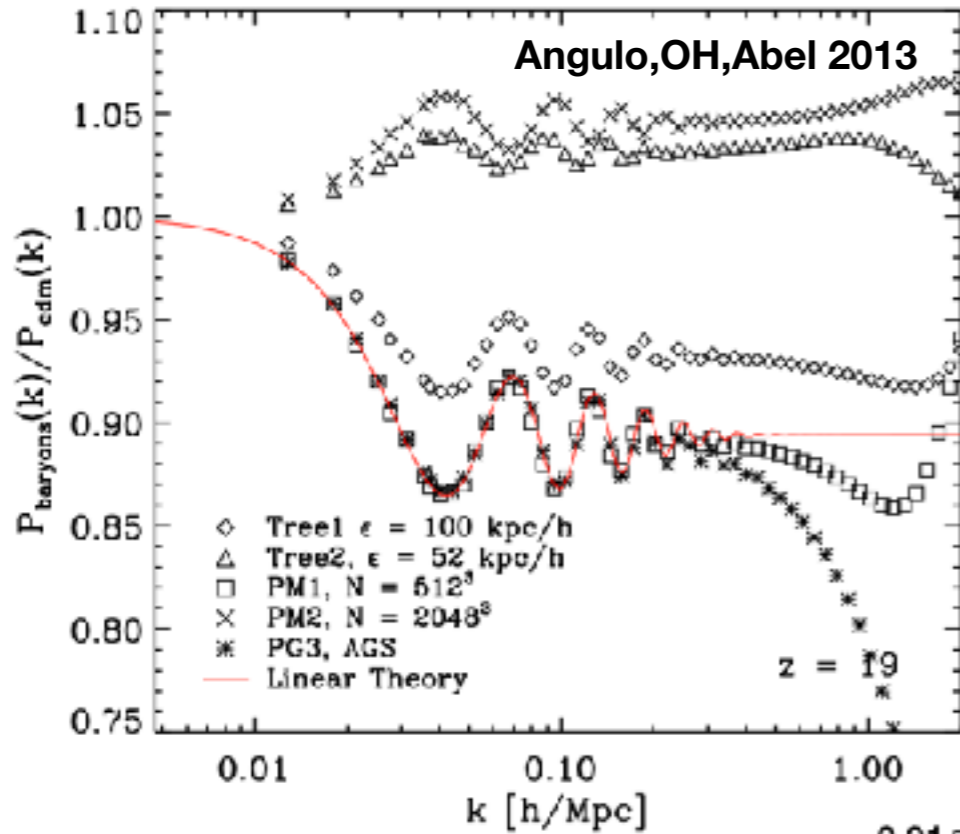
discreteness always dominates when starting@ $z$  too high (cf also Garrison+2016)

best results with high order LPT and low starting redshift (counter to common lore!)

# What about 2-species? Baryons+DM....

# Precision CDM+baryon two-fluid simulations

N-body two-fluid sims have dominant discreteness errors

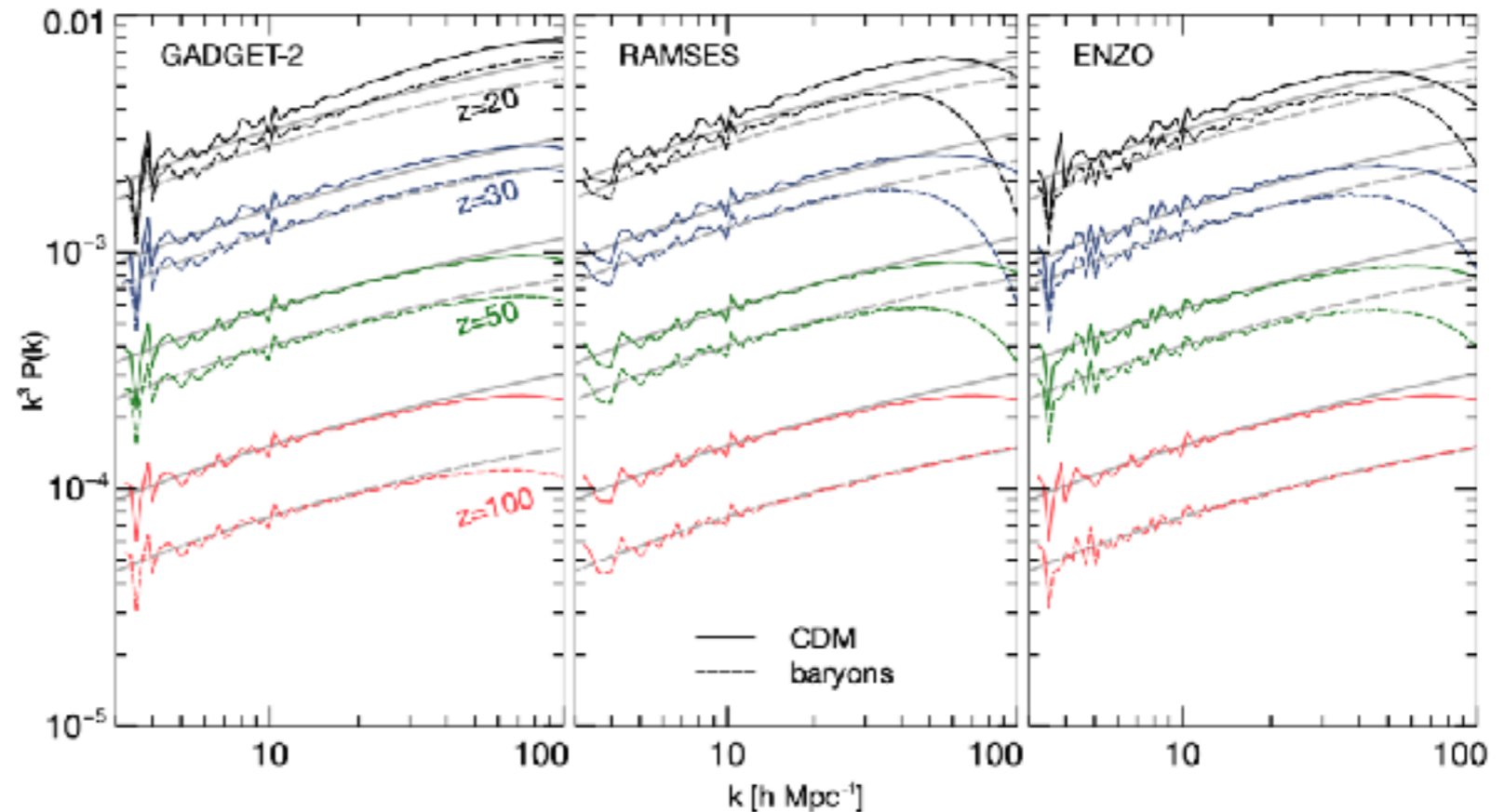


requires special lattices?

requires large softening?

Finite-Volume Eulerian simulations suffer from advection errors:

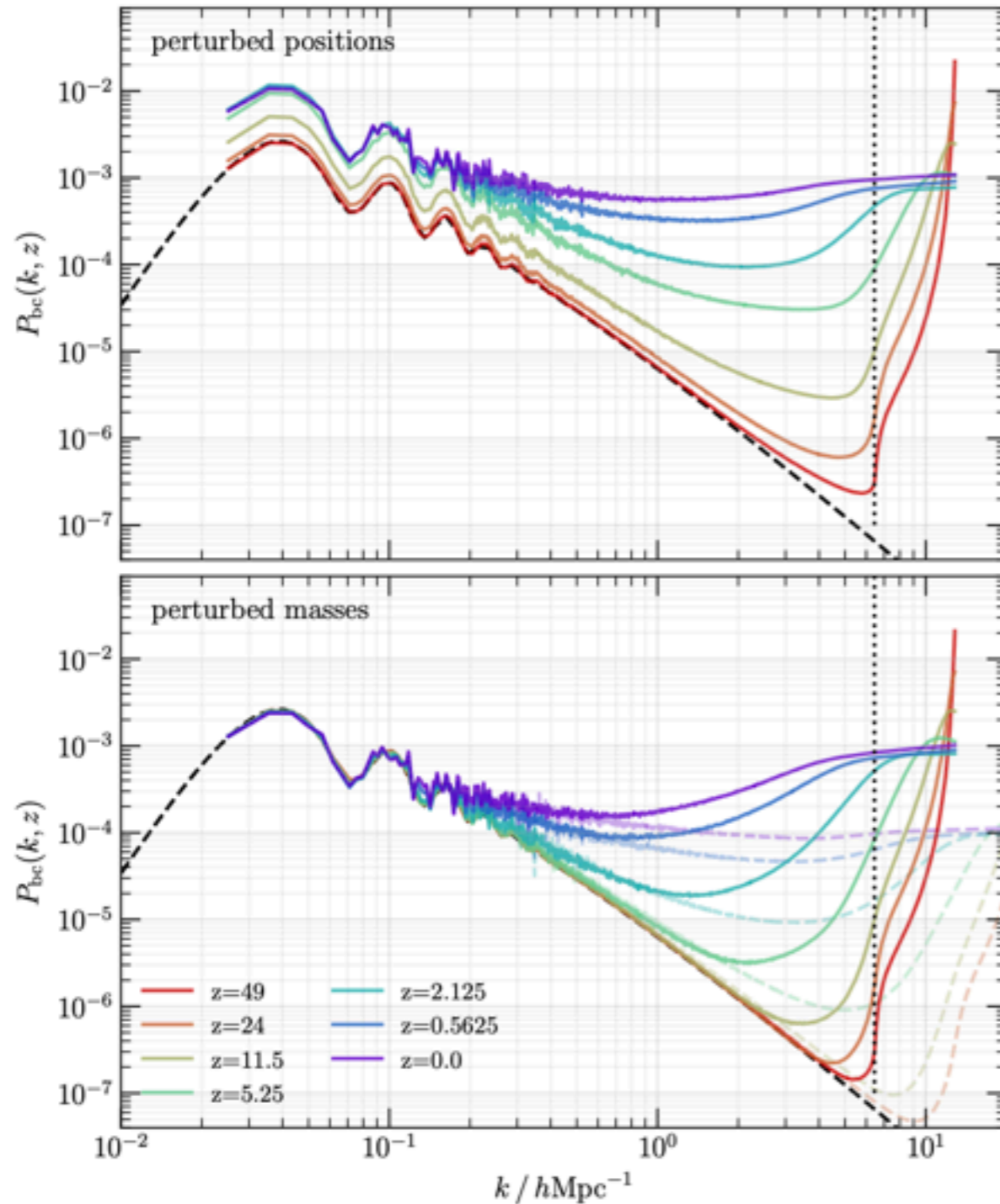
OH&Abel 2012





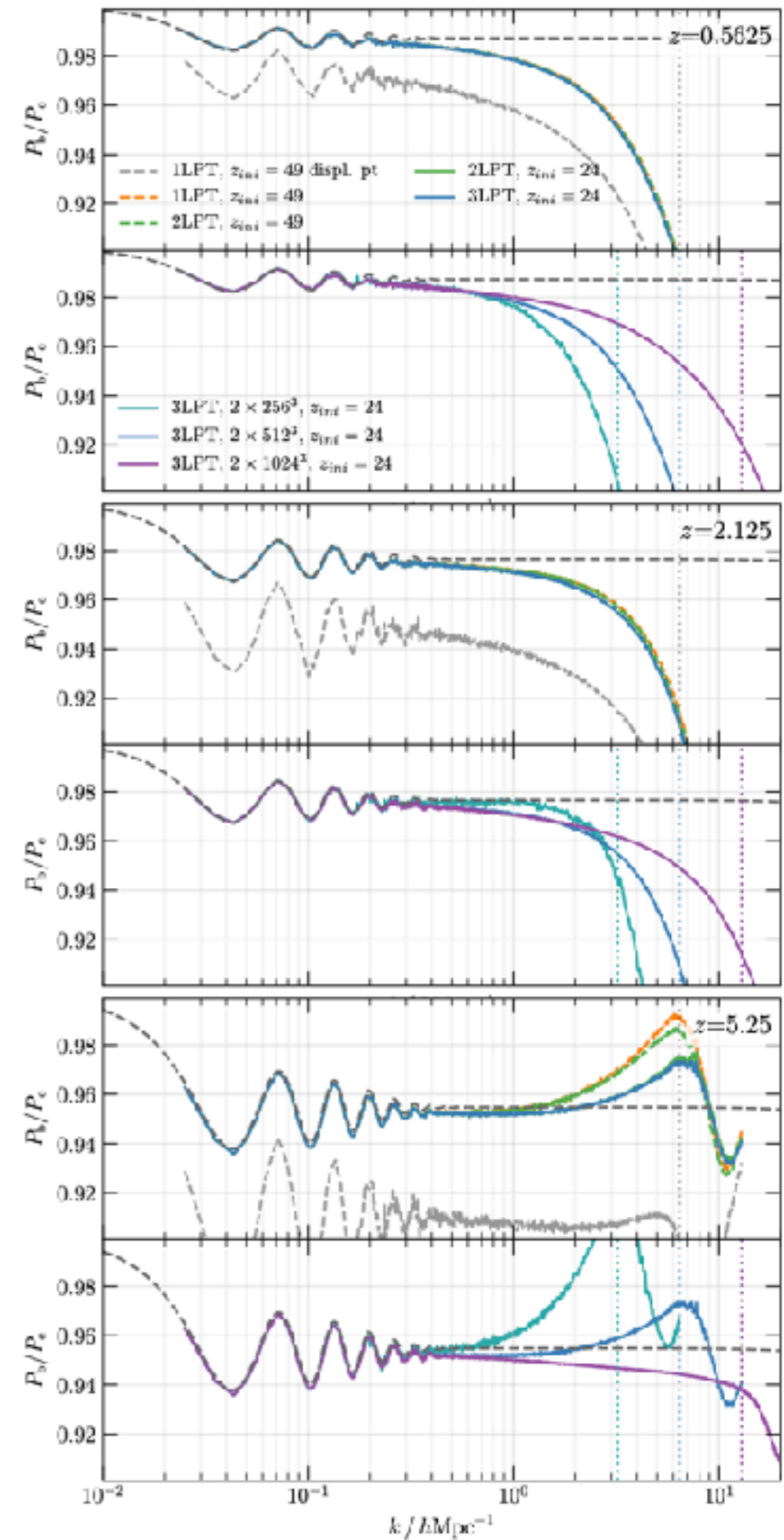
# Perturbing masses vs. displacements for isocurvature modes

Constant mode not constant when perturbing positions for isocurvature



Michaux+2020

Evolution of baryons vs. CDM completely off in two-fluid N-body sims



**Ok, ok. Boring n-spectra....**  
**This is a cosmic web meeting!**  
**Show us the field!**

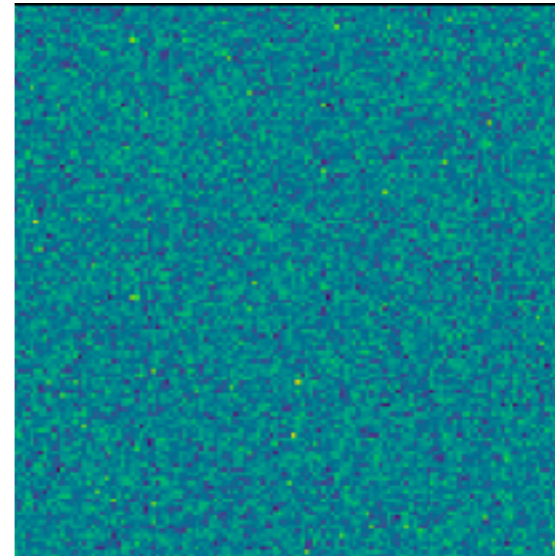
# Numerical Universes

Originate from a Gaussian random process

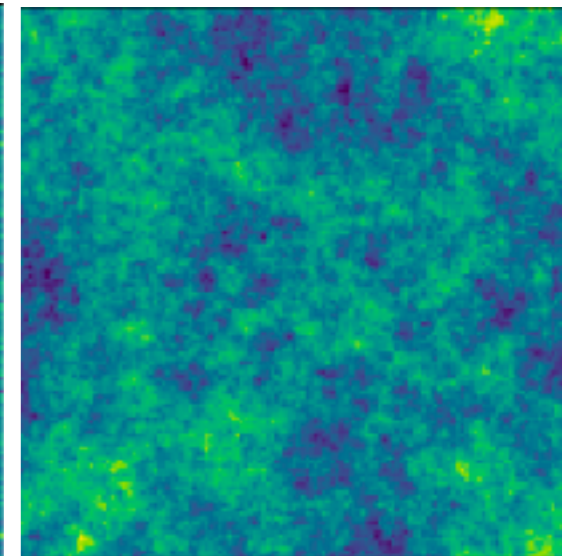
$$\tilde{\delta}(k) = \tilde{w}(k) \sqrt{P(\|k\|)} \quad \text{with} \quad w \sim \mathcal{N}(0,1)$$

covariance (power spectrum) diagonal in Fourier space

$w(x)$



$\delta(x)$

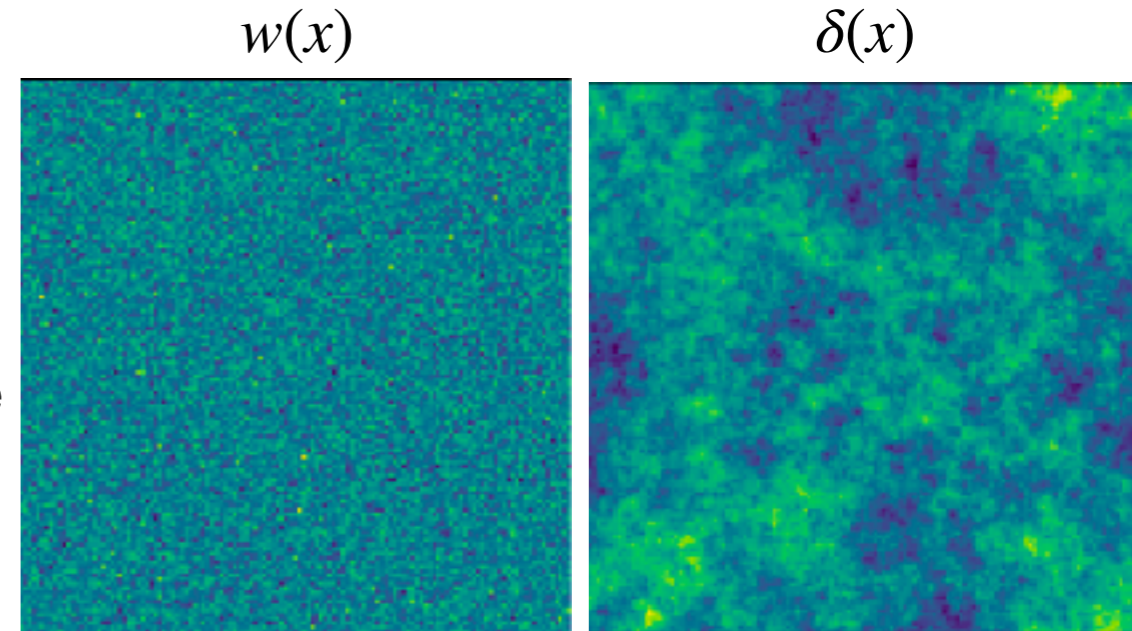


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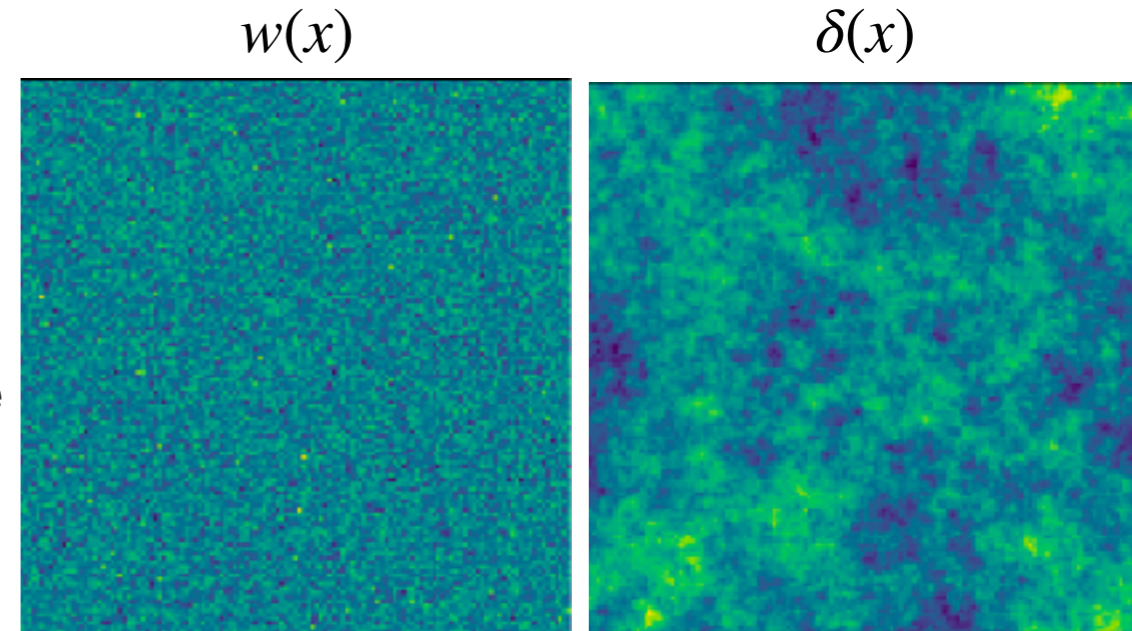
**Problem:** How do we create a multi-scale Gaussian random process that guarantees that structure is stable?  
(i.e. we get the same LSS when we change resolution)

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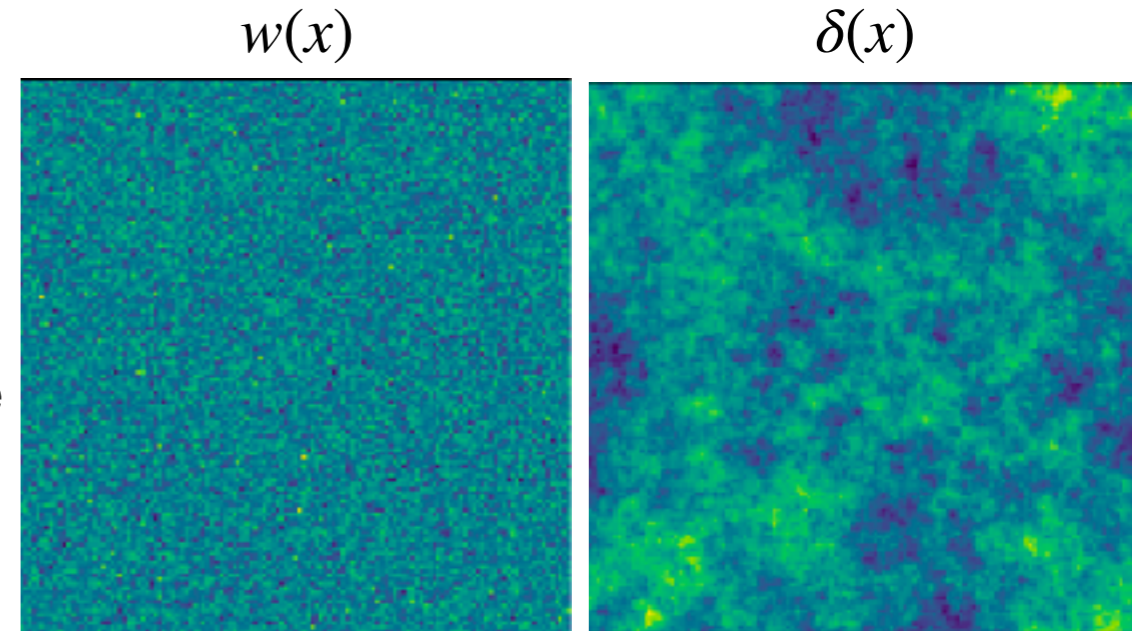
**Solution 1:** add new modes in Fourier space (problem: non-local process) (implemented e.g. in N-GenIC by Springel)

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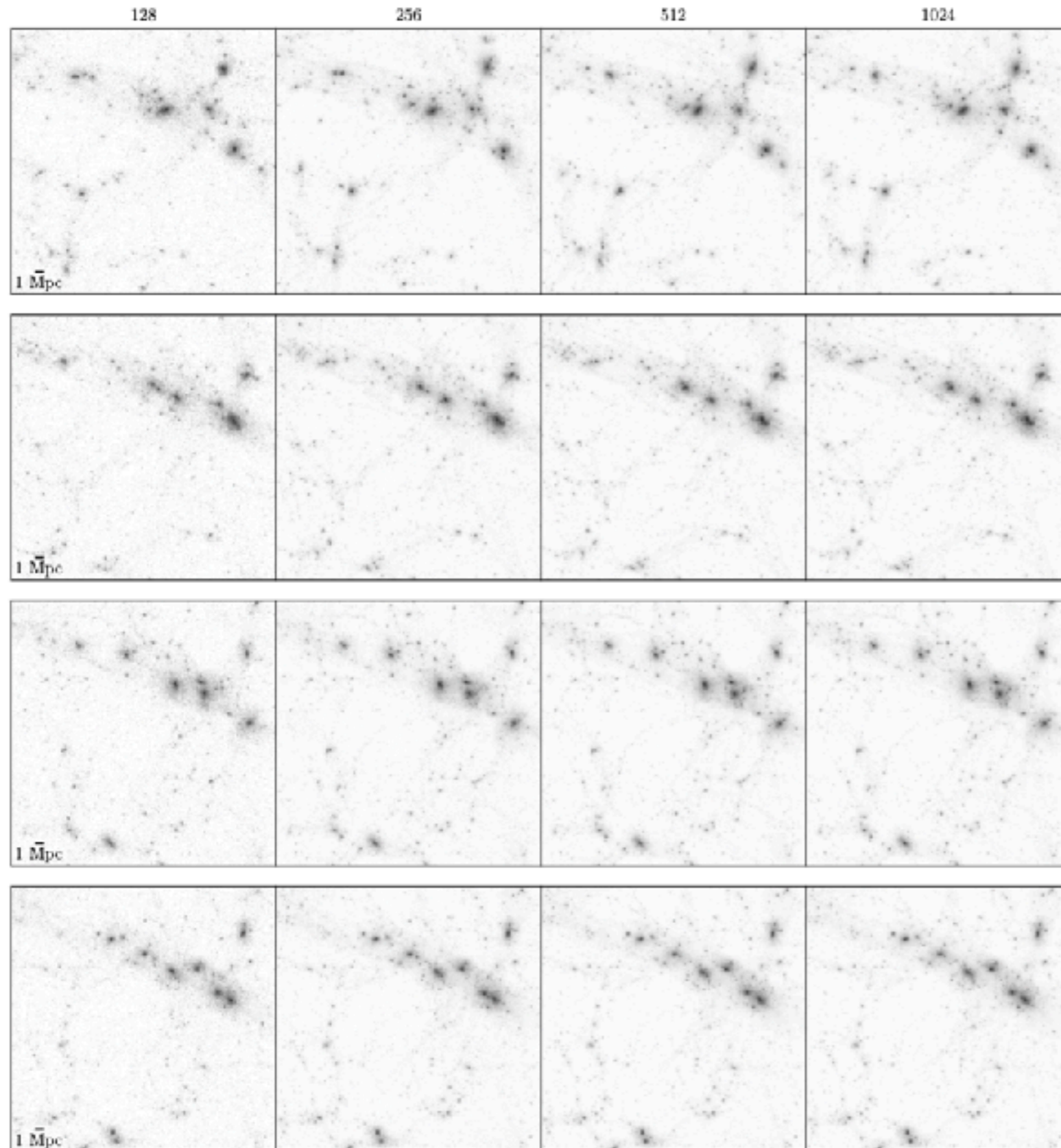


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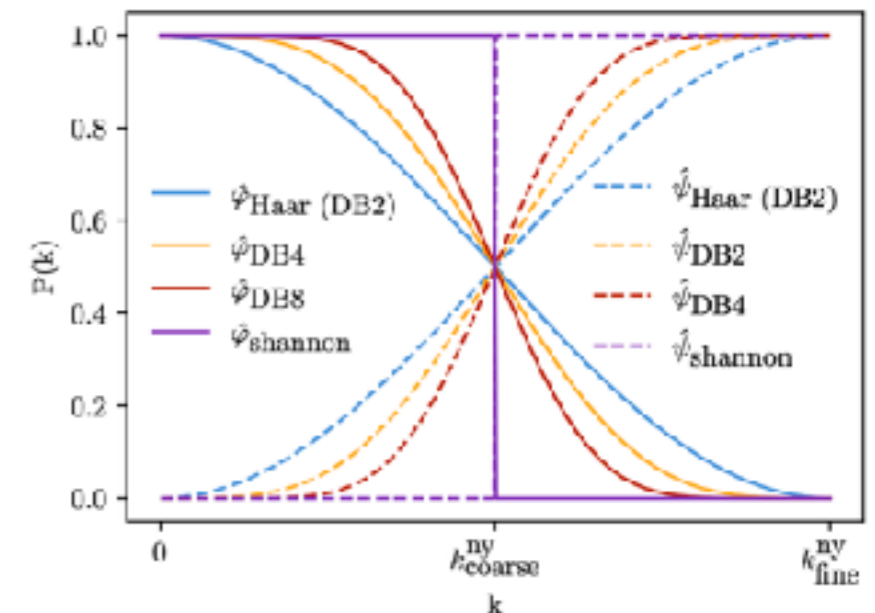
**Solution 2:** use PANPHASIA (Jenkins 2013)  
+ local process  
+ allows unique universes with zoom capability  
- not particularly stable

# Stable Numerical Universes



To increase stability of LSS  
to adding small modes  
need to improve scale-separation

Can do with discrete wavelets  
which have compact support  
and guarantee good  
scale-separation  
(in next version of MUSIC  
— OH, Glatter, Winkler 23)



or with PANPHASIA-HO  
(Jenkins in prep.)  
using high-order octree  
basis functions  
(already in monofonIC)

OH, Glatter, Winkler 2023 (to be submitted)

**now that we have a 'stable' numerical universe, we can zoom into it...**

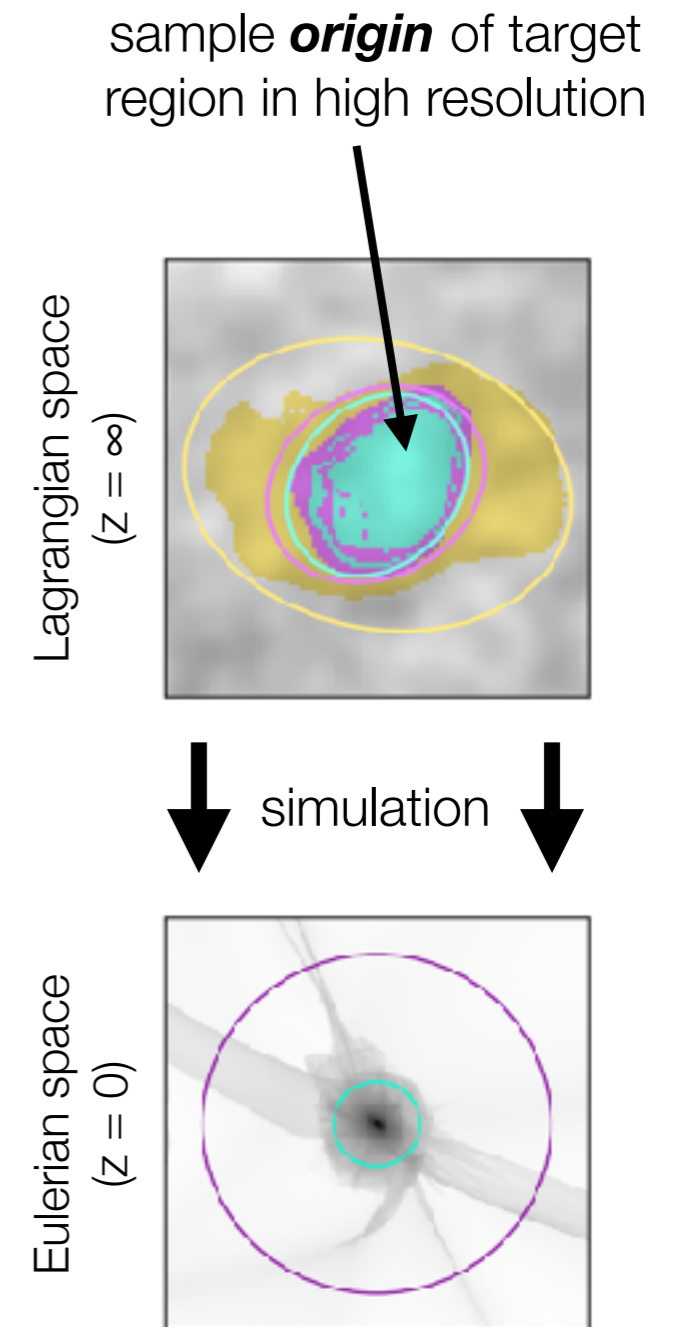


# Cosmological Zoom Simulations

Focus computational resources on object of interest

- "what happens inside a galaxy far far away will not influence our galaxy"
- use coarser resolution for distant regions
- high resolution, complex and computationally expensive physics for individual object

see **Buehlmann et al. 2022, in prep. for details (also eff. of zooms)**



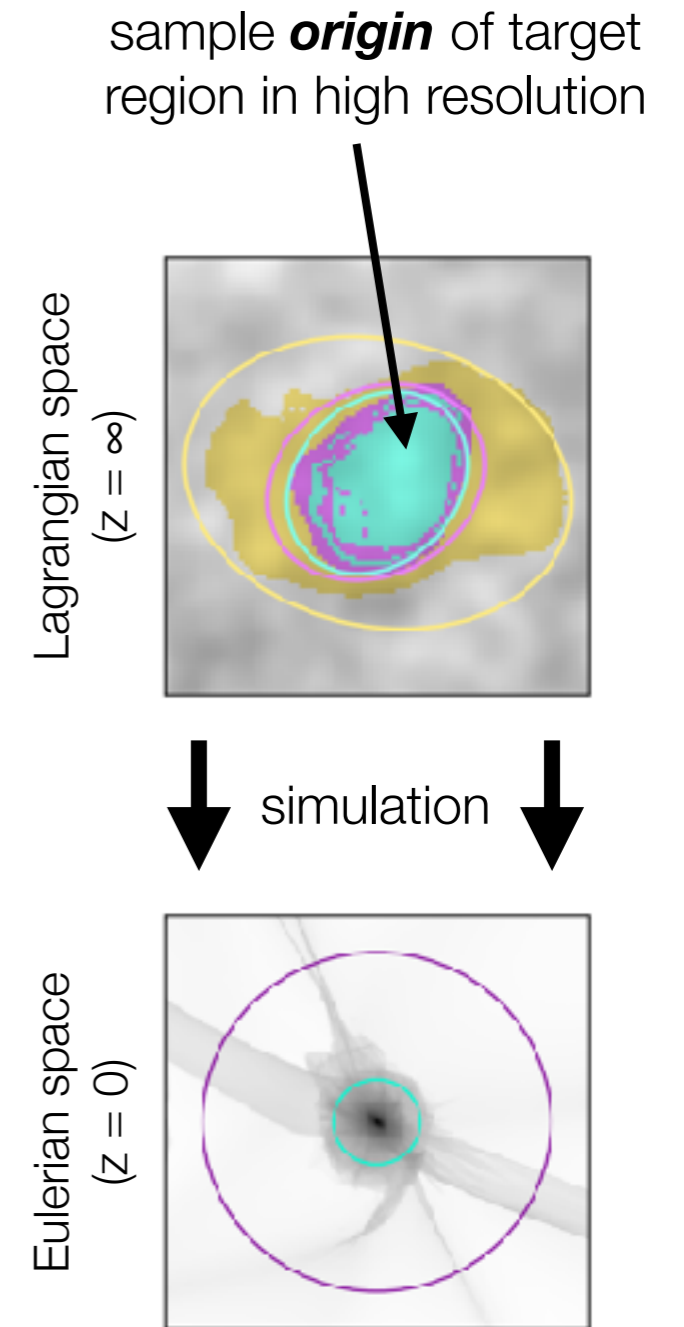
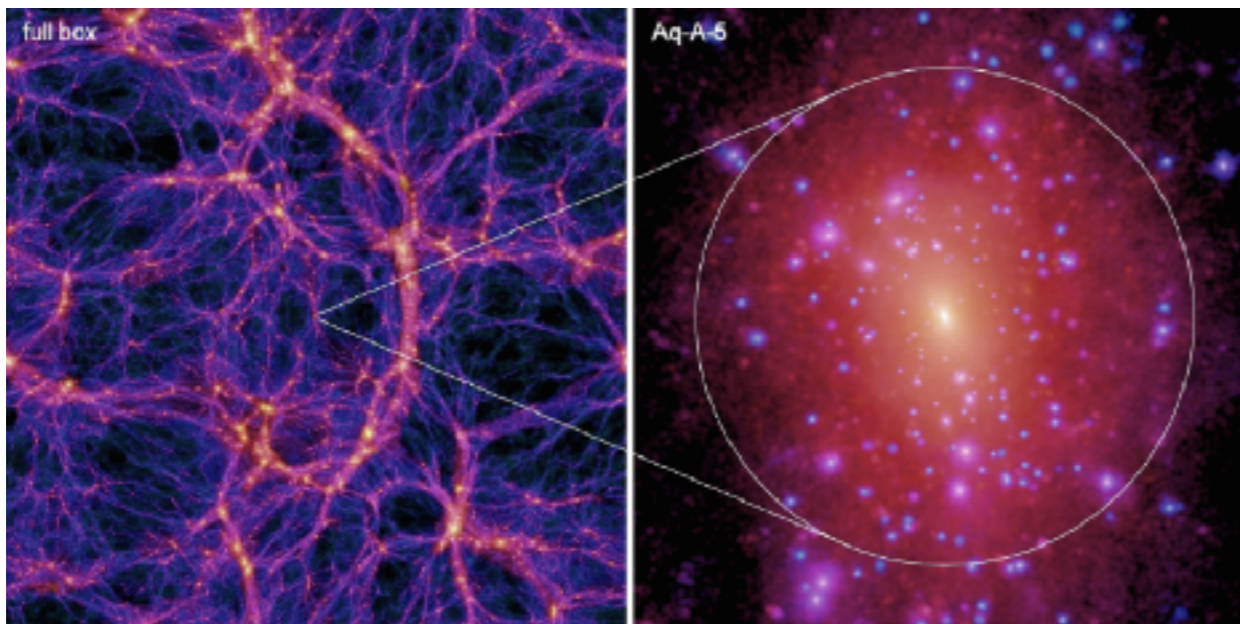
slide courtesy M. Buehlmann

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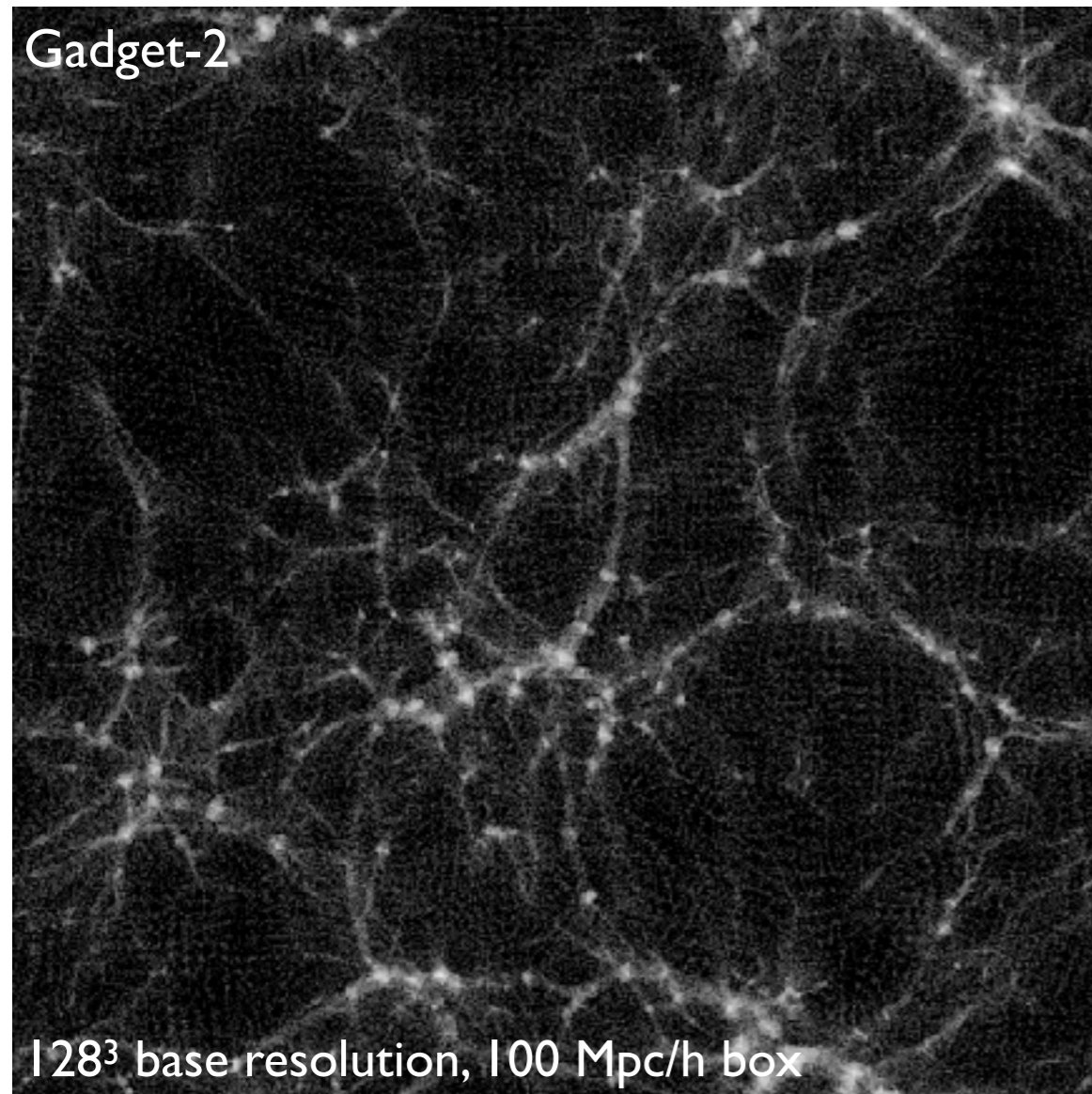
# MUSIC 1 – zoomin' since 2011

ORIGINAL SLIDE CA. 2012

very widely used in community for zoom simulations

supports all major codes (Gadget, RAMSES, Arepo, ENZO, ART, GIZMO, Nyx,...)

<https://bitbucket.com/ohahn/music>



Hahn & Abel (2011)

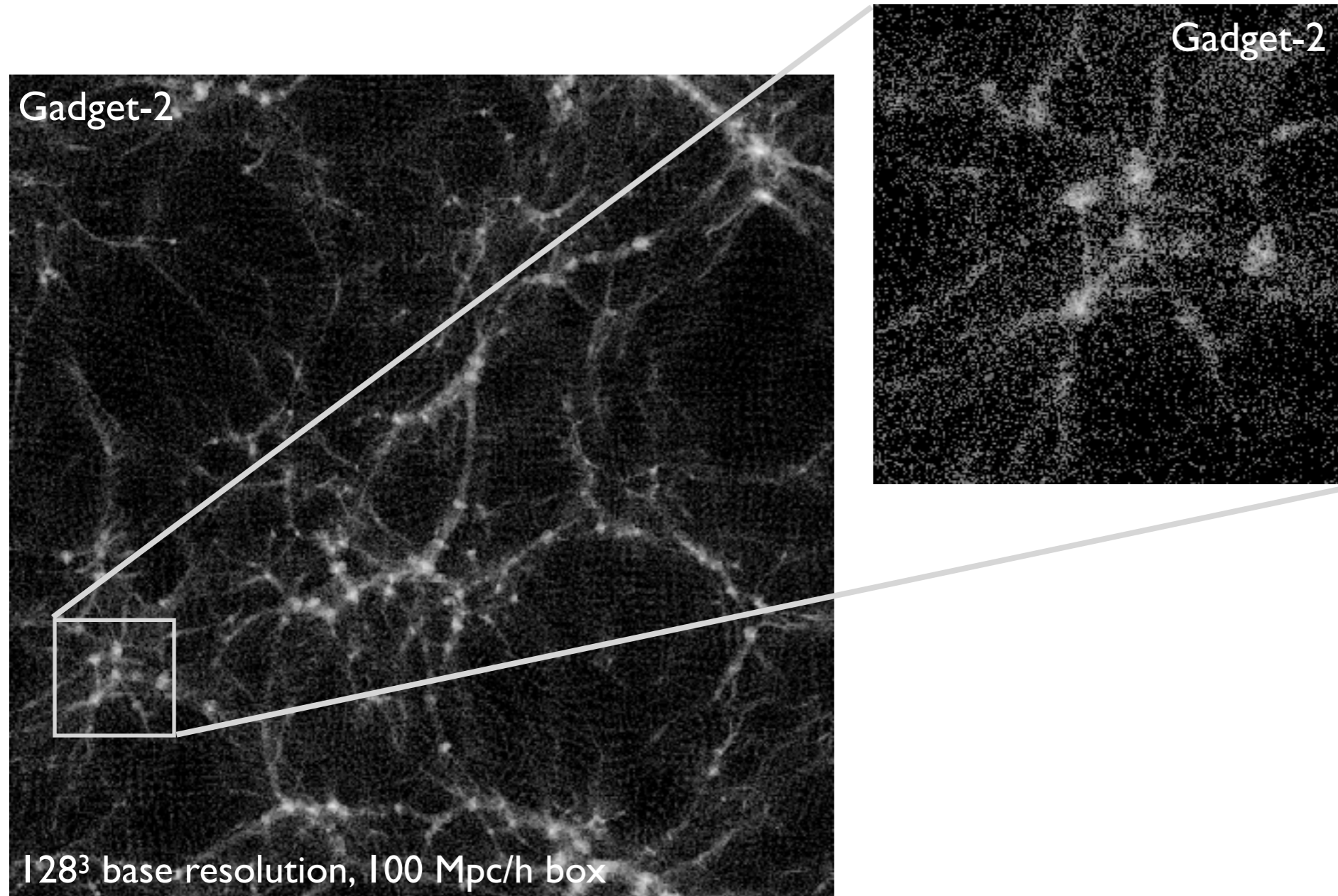
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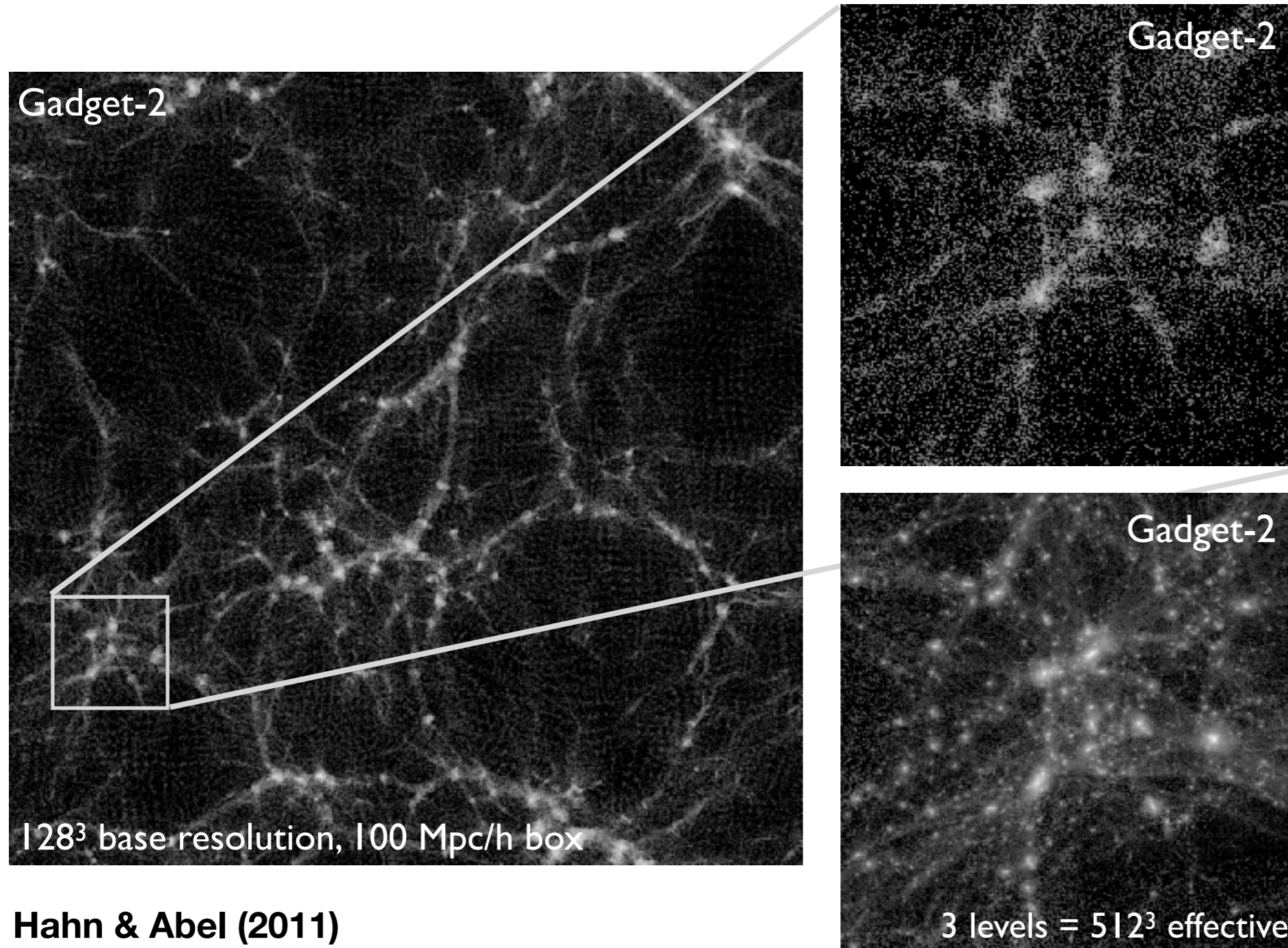
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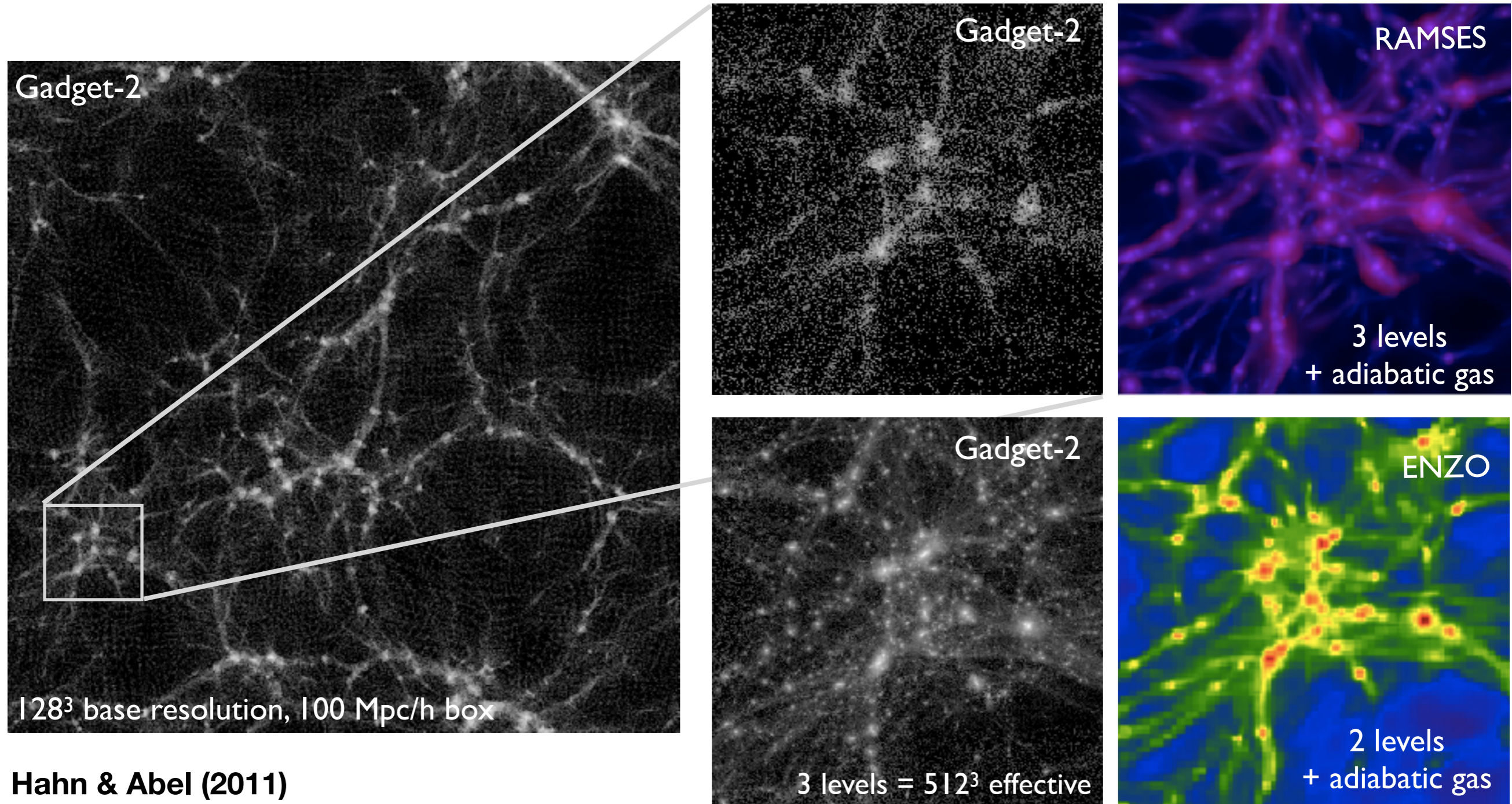
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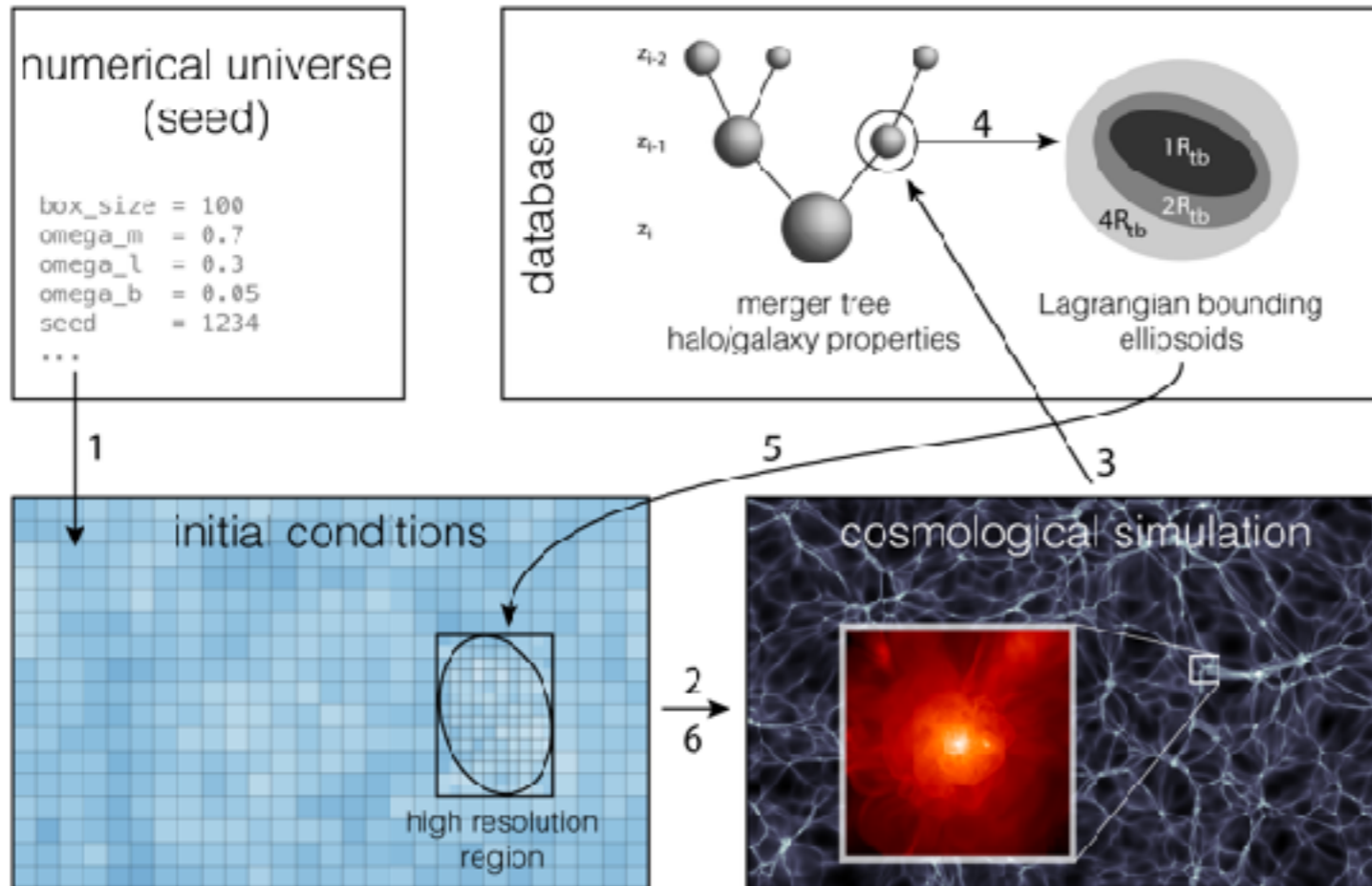
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# Motivation for the cosmlCweb platform

## Where to go from MUSIC1 towards MUSIC2 ecosystem



1: create ICs from cosmo parameters and random seed

2: running simulation, storing snapshots

3: structure finding and linking across time: merger trees

4: for each halo, find Lagrangian patch (origin)

5: for chosen halo, refine that patch in ICs

6: run zoom simulation with additional physics, etc.

### cosmlCweb:

A database and web interface for

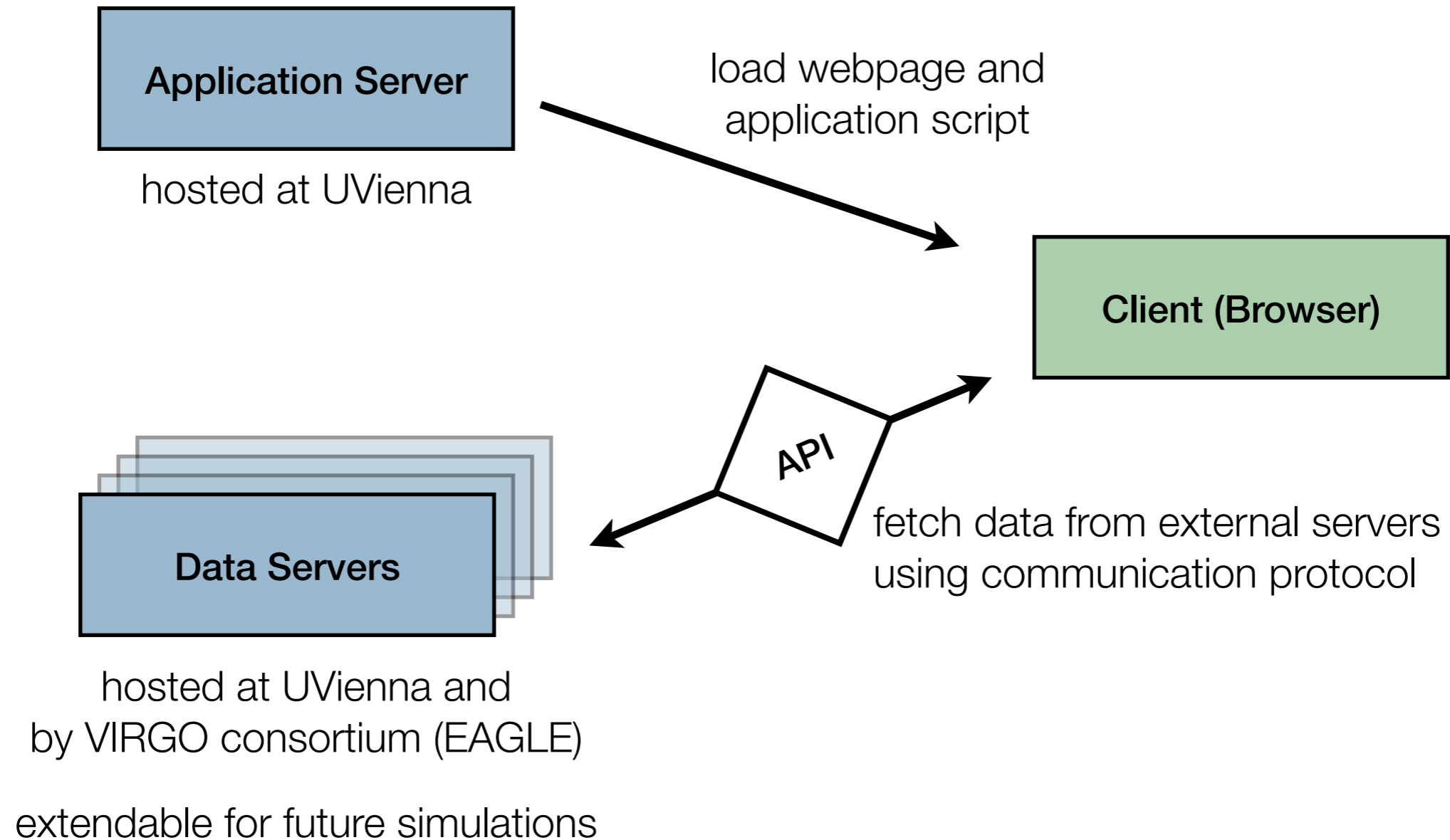
1. **Finding** the right objects to re-simulate

2. **Obtaining** initial conditions for these objects

3. **Referencing** objects in articles / papers

slide courtesy M. Buehlmann

# Overview of cosmICweb – modular architecture





# Overview of cosmlCweb – Workflow

slide courtesy M. Buehlmann

finding

## Find simulation targets

1. chose base simulation
2. set filters for simulation targets
3. select some halos  
create collection
4. verify individual halos
5. refine collection

processing

## Download initial conditions

6. configure and download initial conditions refined on targets
7. run zoom simulations
8. write awesome paper

referencing

## Publish initial conditions

9. reference collection  
link collection to paper

## Research community

- A. download initial conditions from published results
- B. reproduce, compare, and improve results



# Overview of cosmlCweb – Workflow

slide courtesy M. Buehlmann

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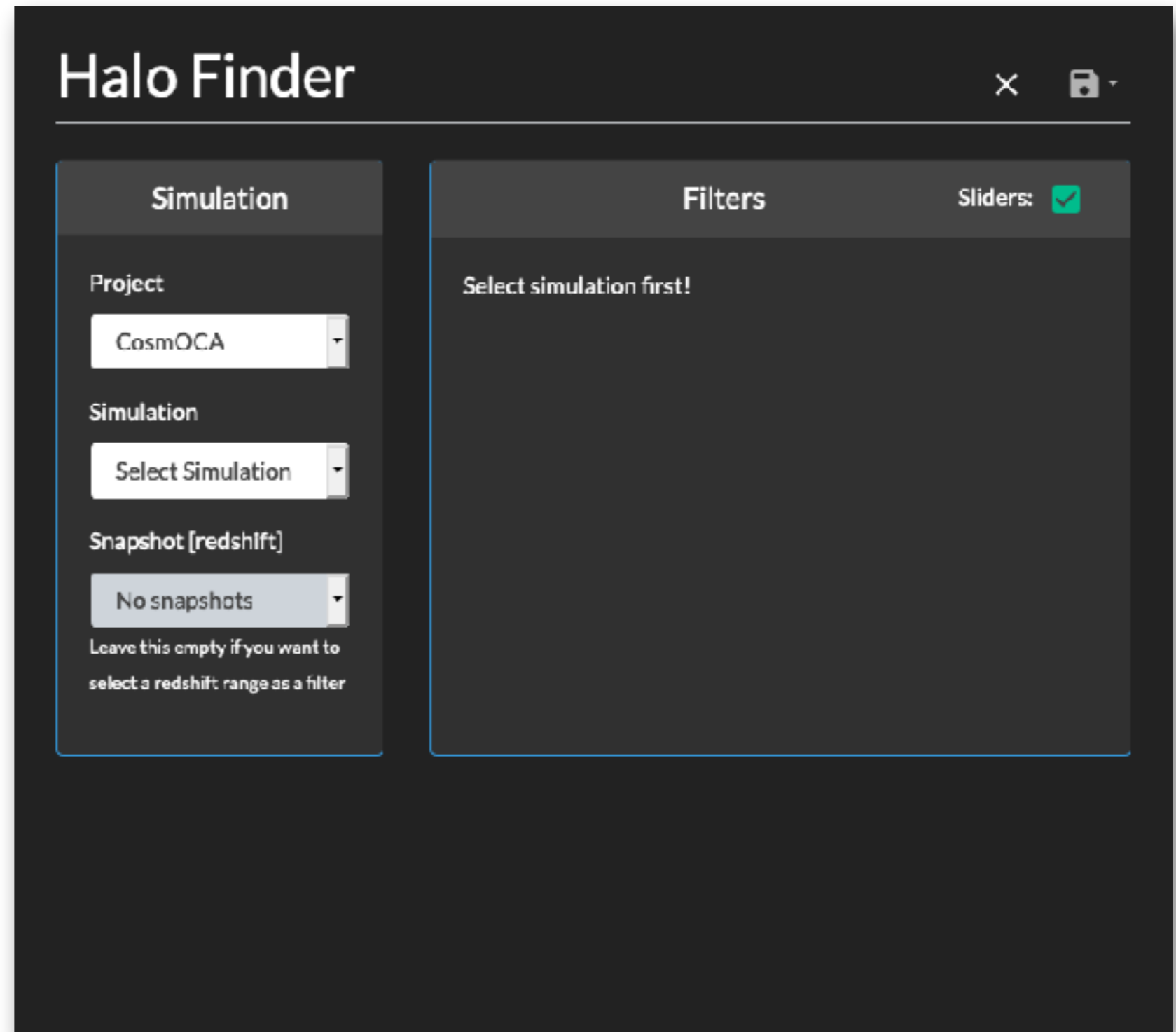
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## Halo Finder

Simulation

Project  
CosmOCA

Simulation  
300MPC

Snapshot [redshift]  
z = 0.00

Leave this empty if you want to select a redshift range as a filter

Filters

Sliders:

Redshift

Halo Filters (hover for more info)

mass [ $m_{200c}$ ] 1e12,3e12 ✓ ✕

radius [ $r_{200c}$ ]

concentration [ $c_{200c}$ ]

spin [ $\lambda_{\text{pebbles}}$ ]

substructure  $f_{\text{sub}}$

virial ratio

$X_{\text{offset}}$  (normalized)

$D_{1,1}$  [3,10] ✓ ✕

last major merger 1,2 ✓ ✕

Search Halos

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slide courtesy M. Buehlmann

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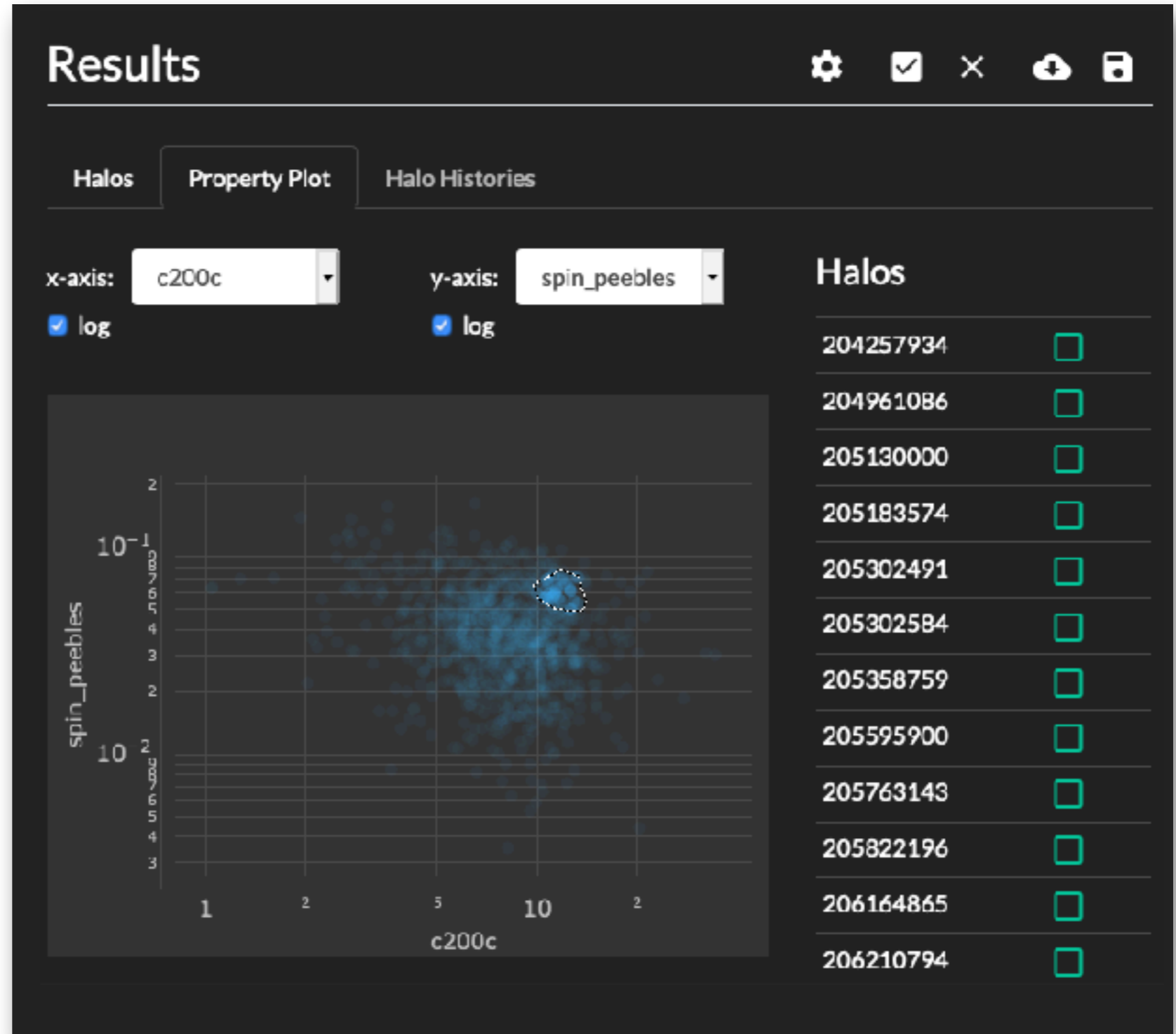
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**Halo Explorer**

Simulation			Halo Mass and Radius			Other Properties		
main	this halo	descendant	Mass	Radius		Property	Value	
progenitor	204378518		[ $M_{vir}/h$ ]	[kpc/h]	c	virial ratio	0.55	
201436844			virial	1.16e+12	213.62	16.3	substructure coefficient	
simulation	300MPC (CosmOCA)		200b	1.21e+12	256.91	19.7	spin parameter (bullock)	5.58e-2
redshift	0.00		200c	1.03e+12	164.49	12.6	spin parameter (peebles)	6.11e-2
hierarchy	host:		500c	8.46e+11	113.34	8.7	last major merger	1.58
	subhalos: 0		2500c	4.41e+11	53.35	4.1	$D_{1,1}$	4.20

Hierarchical Structure

MergerTree

Halo Evolution

Surrounding

Tracking

Lagrangian Ellipsoids

Publications

# Overview of cosmlCweb – Workflow

slide courtesy M. Buehlmann

finding

## Find simulation targets

1. chose base simulation
2. set filters for simulation targets
3. select some halos  
create collection
4. **verify individual halos**
5. refine collection

processing

## Download initial conditions

6. configure and download initial conditions refined on targets
7. run zoom simulations
8. write awesome paper

referencing

## Publish initial conditions

9. reference collection  
link collection to paper

## Research community

- A. download initial conditions from published results
- B. reproduce, compare, and improve results



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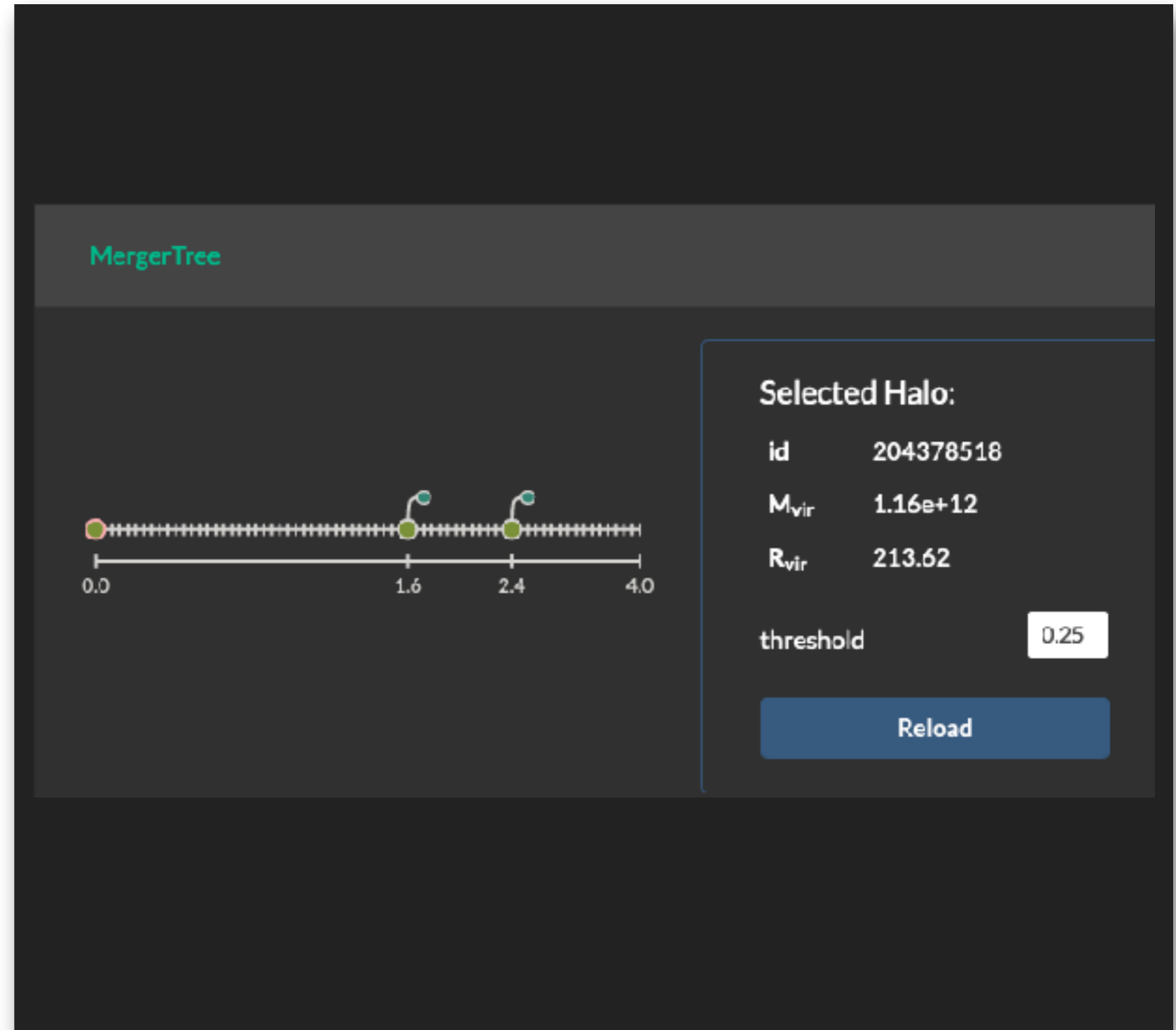
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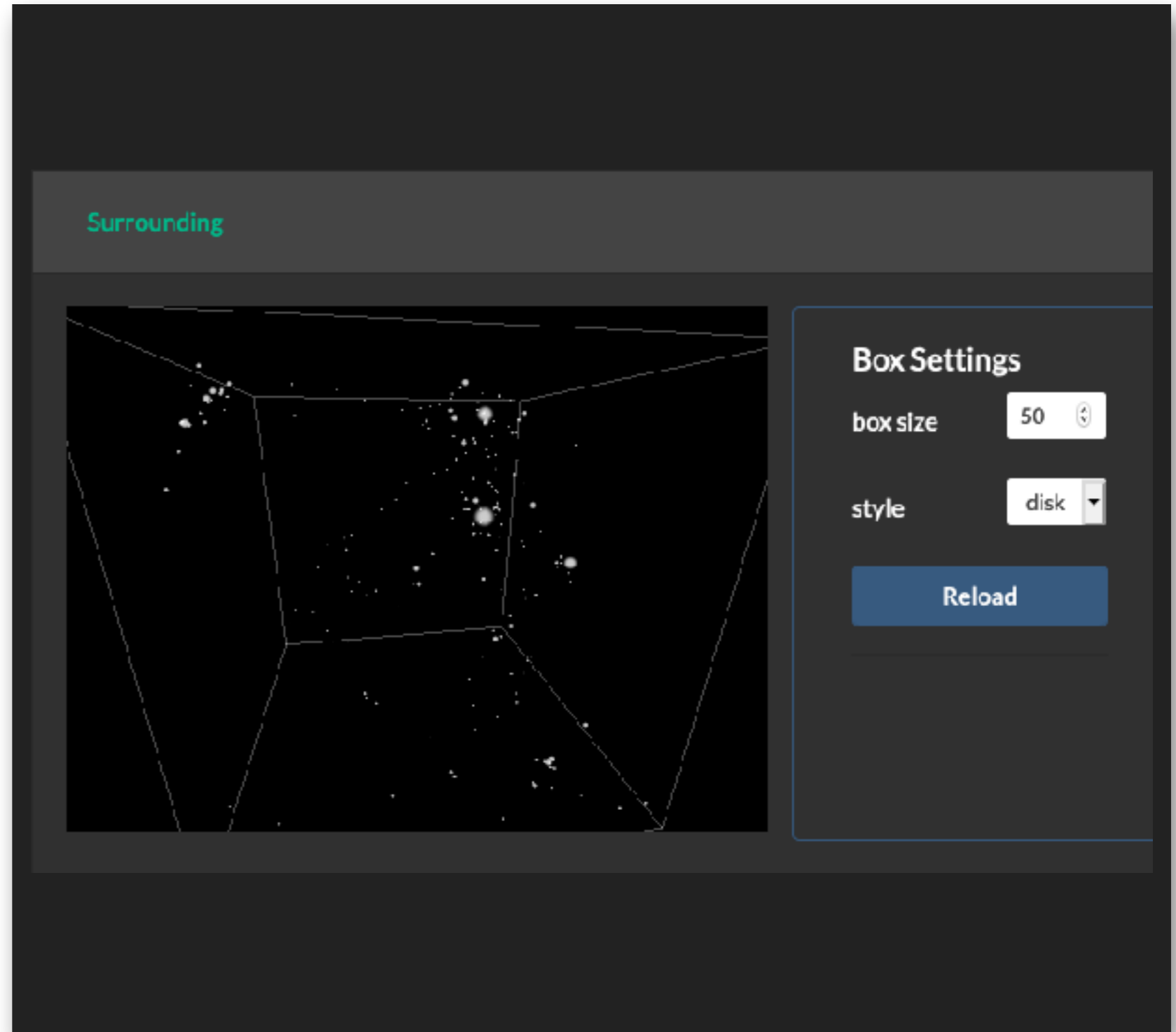
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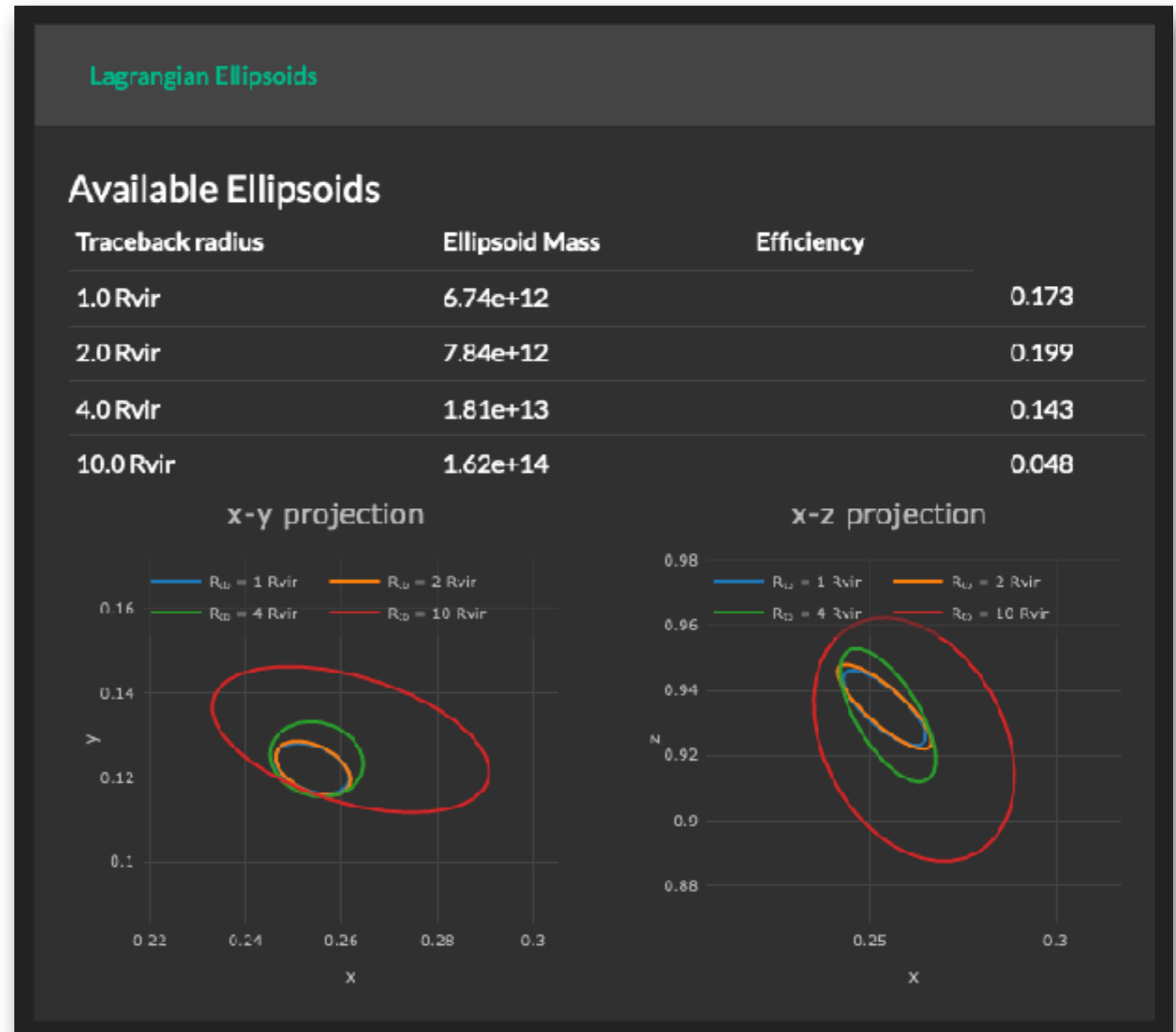
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The screenshot displays the 'Collection: SuperCollection' interface. At the top right, there are 'share', 'publish', and 'remove' buttons. The main content is divided into two panels: 'SuperCollection' and 'Details'. The 'SuperCollection' panel contains a description: 'This is some test collection for the defense of my thesis. Halos are ~1e12 Msun and have a major merger between z=1 and z=2, but not later'. The 'Details' panel shows: Simulation: 300MPC (CosmOCA), Halos: 6, Created by: Michael Buehlmann, Created at: 2019-09-29. Below these panels is a table with tabs for 'Halos', 'Property Plot', and 'Halo Histories'. The 'Halos' tab is active, showing a table with columns: Name / ID, Description, Redshift, mass [m<sub>200c</sub>], and a checkmark column.

Name / ID	Description	Redshift	mass [m <sub>200c</sub> ]	
Halo 1	Add some sensible description	0.00	1.06e+12	✓
Halo 2		0.00	1.06e+12	✓
Halo 3		0.00	1.02e+12	✓
Halo 4		0.00	1.09e+12	✓

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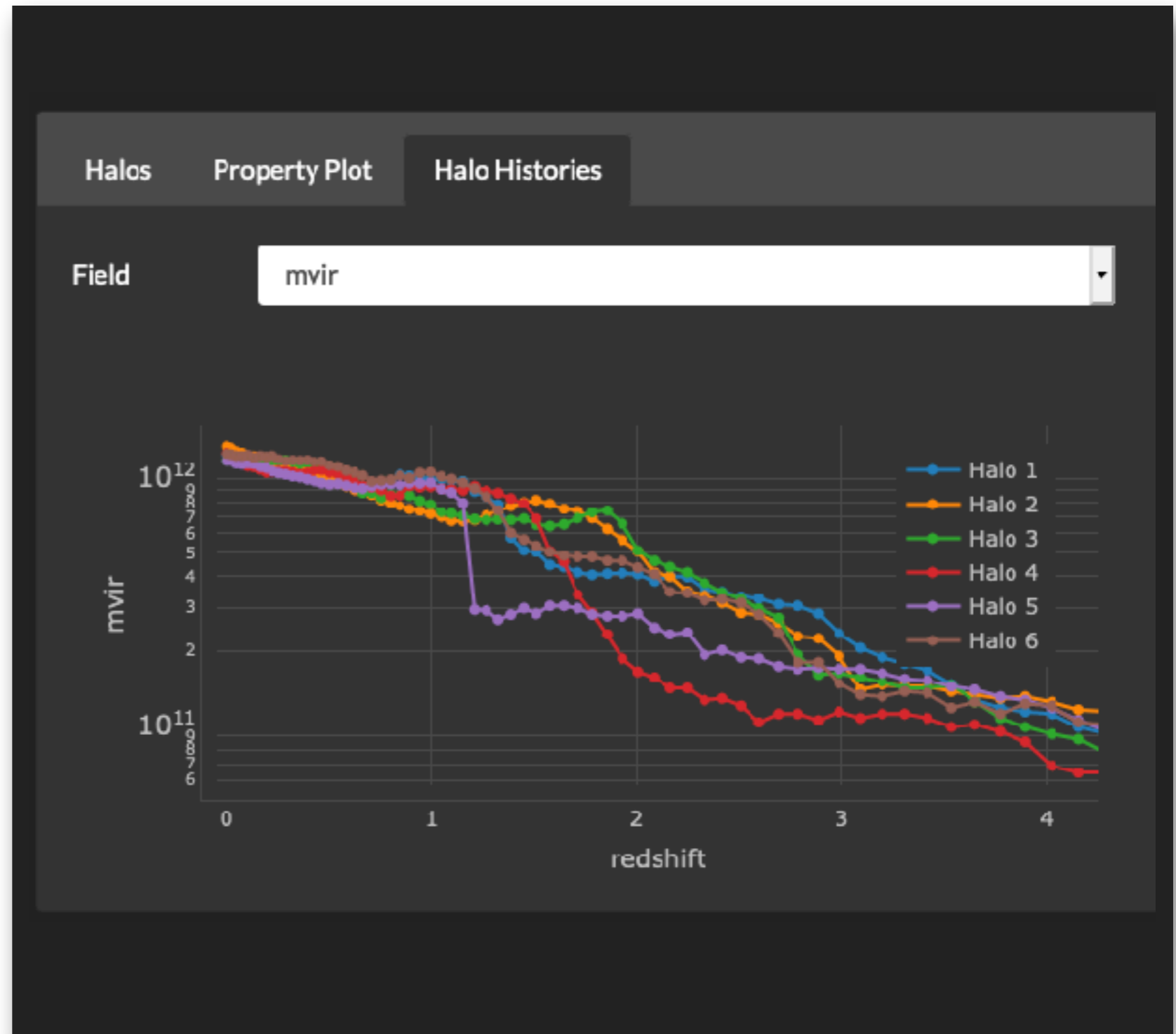
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**Download ICs**

**Settings**

Traceback Radius  
4 Rvir

Starting Redshift  
99

levelmin 8 levelmax 12

Output  
grafic2

Output File Name  
ics.dat

Output Options  
Add Option

Output format  
 Seperate folders

**Halos**

Downloading: 100%

Halo 1	$N_c=609 / m_{\text{GP}}=3.3e+7 M_{\odot}/h$	ready
Halo 2	$N_c=630 / m_{\text{GP}}=3.3e+7 M_{\odot}/h$	ready
Halo 3	$N_c=565 / m_{\text{GP}}=3.3e+7 M_{\odot}/h$	ready
Halo 4	$N_c=591 / m_{\text{GP}}=3.3e+7 M_{\odot}/h$	ready
Halo 5	$N_c=595 / m_{\text{GP}}=3.3e+7 M_{\odot}/h$	ready
Halo 6	$N_c=588 / m_{\text{GP}}=3.3e+7 M_{\odot}/h$	ready

Download .zip Download with MUSIC

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## Publication: SuperHalos

### SuperHalos

This is some test collection for the defense of my thesis. Halos are  $\sim 1e12$  Msun and have a major merger between  $z=1$  and  $z=2$ , but not later

### Properties

Simulation	300MPC (CosmOCA)
Halos	6
Link	<a href="https://arxiv.org/abs/2122.2222v1">https://arxiv.org/abs/2122.2222v1</a>
Created by	Michael Buehlmann
Created at	2019-09-29

### Halos

Property Plot Halo Histories

Name / ID	Description	Redshift	mass [ $m_{200c}$ ]	
Halo 1	Add some sensible description	0.00	1.06e+12	✓
Halo 2		0.00	1.06e+12	✓
Halo 3		0.00	1.02e+12	✓
Halo 4		0.00	1.09e+12	✓

**LIVE DEMO**



# Overview of cosmlCweb – Data

## Currently:

slide courtesy M. Buehlmann

### locally hosted simulations:

- set of DM-only simulations ranging from 60 to 1000 Mpc<sup>3</sup>
- AGORA and RHAPSODY from existing zoom-projects
- data hosted at UVienna

### EAGLE simulations: *Evolution and Assembly of GaLaxies and their Environments*

- baryonic physics & DM-only simulations from the EAGLE project
- data hosted by VIRGO consortium (externally)

Why EAGLE? : PANPHASIA field decomposition!

	size [ $h^{-1}$ Mpc]	cosmo.	DM resolution [ $h^{-1} M_{\odot}$ ]	[b]	snapshots [ $z_{\max} - z_{\min}$ ]	structure finder	$N_{\min}^e$
local	150MPC	[P1]	$2.70 \times 10^8$		101 [12 – 0]	ROCKSTAR	100
	150MPC_lowres	[P1]	$2.16 \times 10^9$		101 [12 – 0]	ROCKSTAR	500
	300MPC	[P1]	$2.14 \times 10^9$		101 [12 – 0]	ROCKSTAR	100
	300MPC_lowres	[P1]	$1.71 \times 10^{10}$		101 [12 – 0]	ROCKSTAR	500
	AGORA	[W1]	$1.21 \times 10^8$		101 [12 – 0]	ROCKSTAR	1000
	RHAPSODY	[W2]	$6.46 \times 10^{10}$		101 [12 – 0]	ROCKSTAR	1000
	RHAPSODY_NewCosmo	[P1]	$7.99 \times 10^{10}$		101 [12 – 0]	ROCKSTAR	1000
EAGLE	Ref-L0025N0376	[P2]	$6.57 \times 10^6$	✓	29 [20.3 – 0]	FoF & SUBFIND	1000
	L0025N0376	[P2]	$7.63 \times 10^6$		29 [20.3 – 0]	FoF & SUBFIND	1000
	Ref-L0100N1504	[P2]	$6.57 \times 10^6$	✓	29 [20.3 – 0]	FoF & SUBFIND	1000
	L0100N1504	[P2]	$7.63 \times 10^6$		29 [20.3 – 0]	FoF & SUBFIND	1000

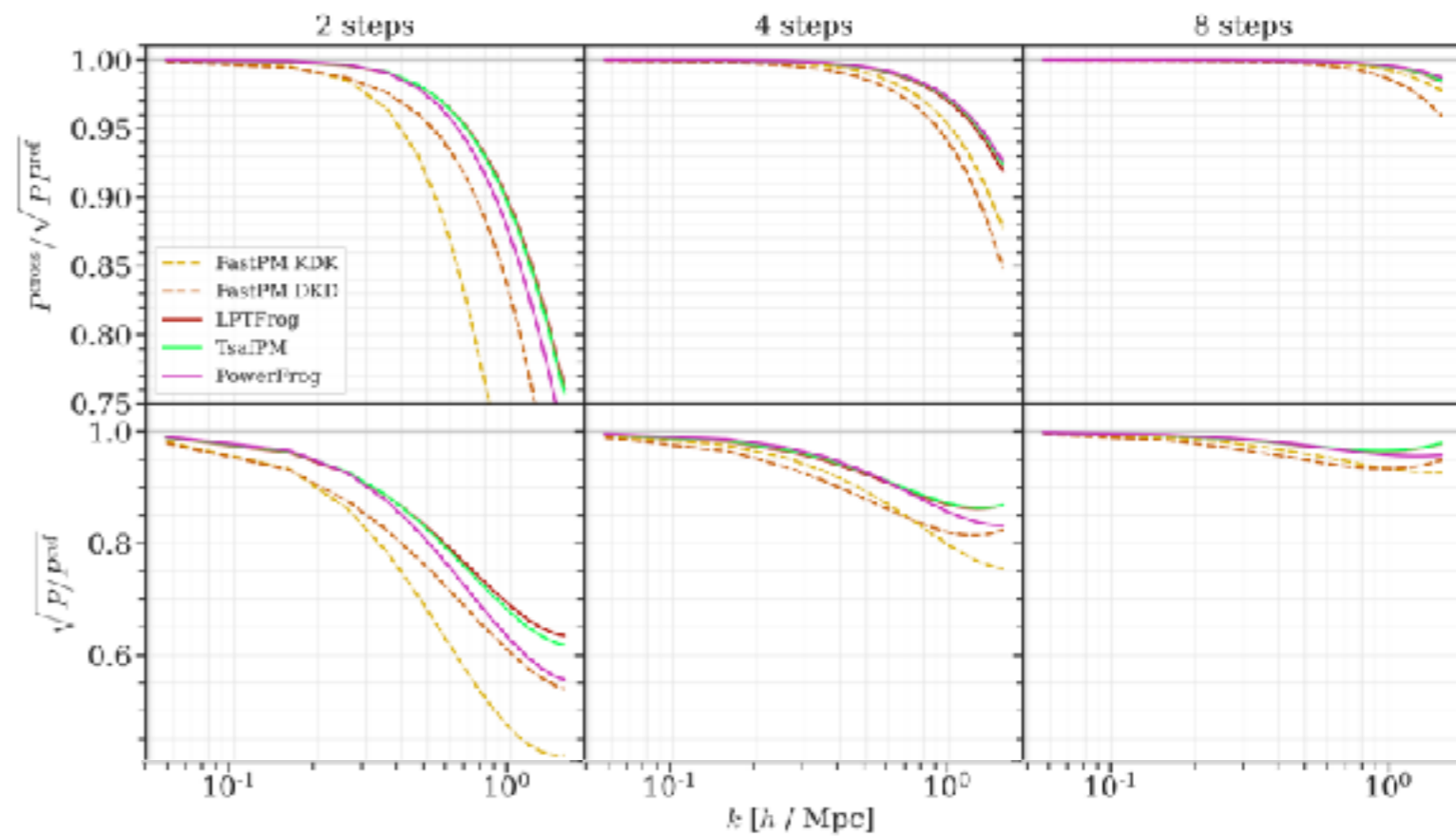
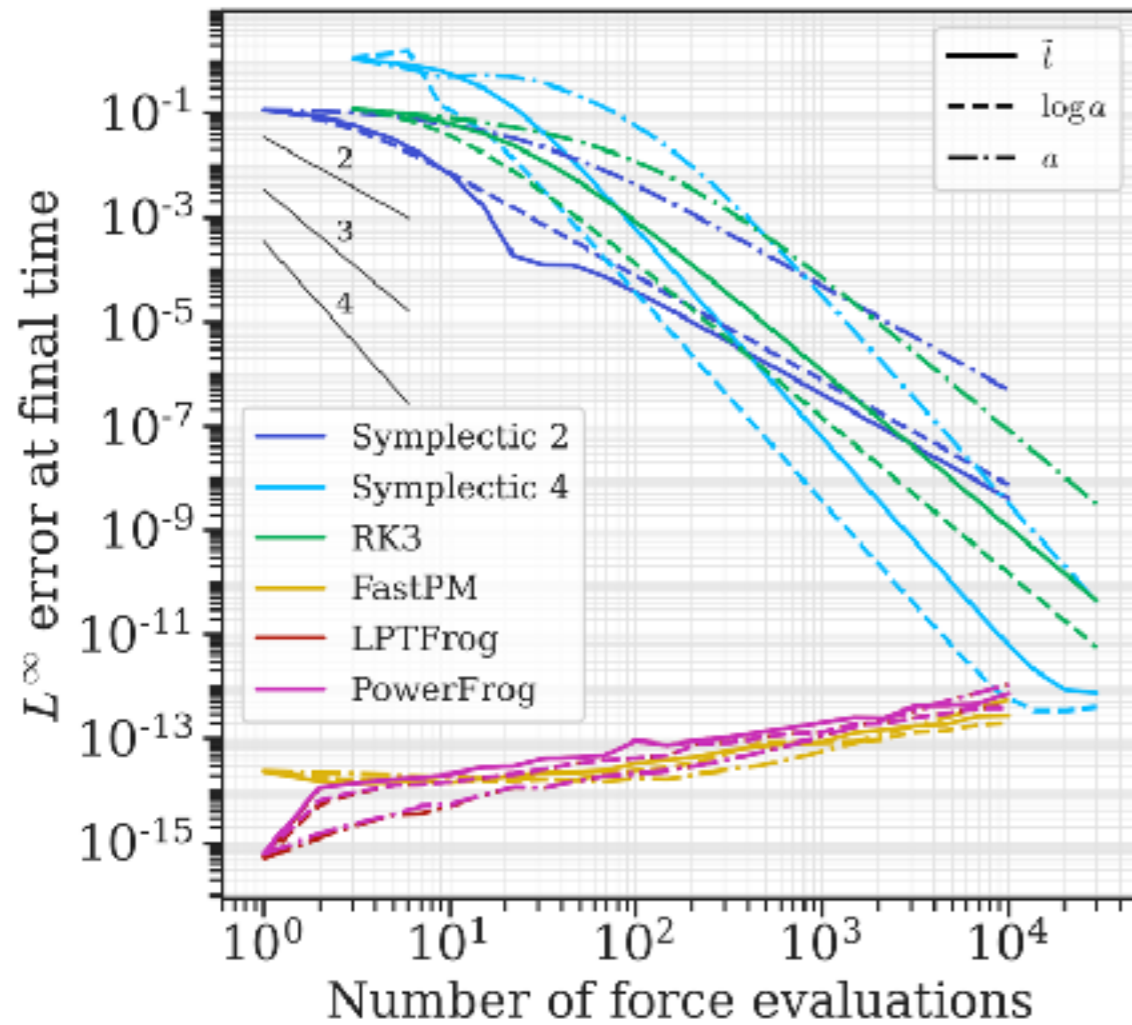
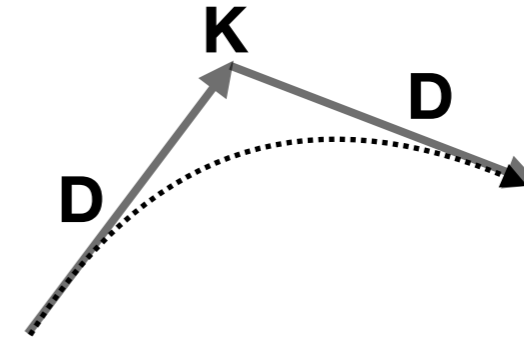
[b]: run with baryonic physics

**Get in touch if you'd like to add yours!**

# Perturbation-theory informed integrators

Integrators for N-body simulations are agnostic about perturbation theory (derived naively from Hamiltonian)

Exception: FastPM (Feng+16 - match Zel'dovich)  
 BUT: Can make them agree to 2nd order!

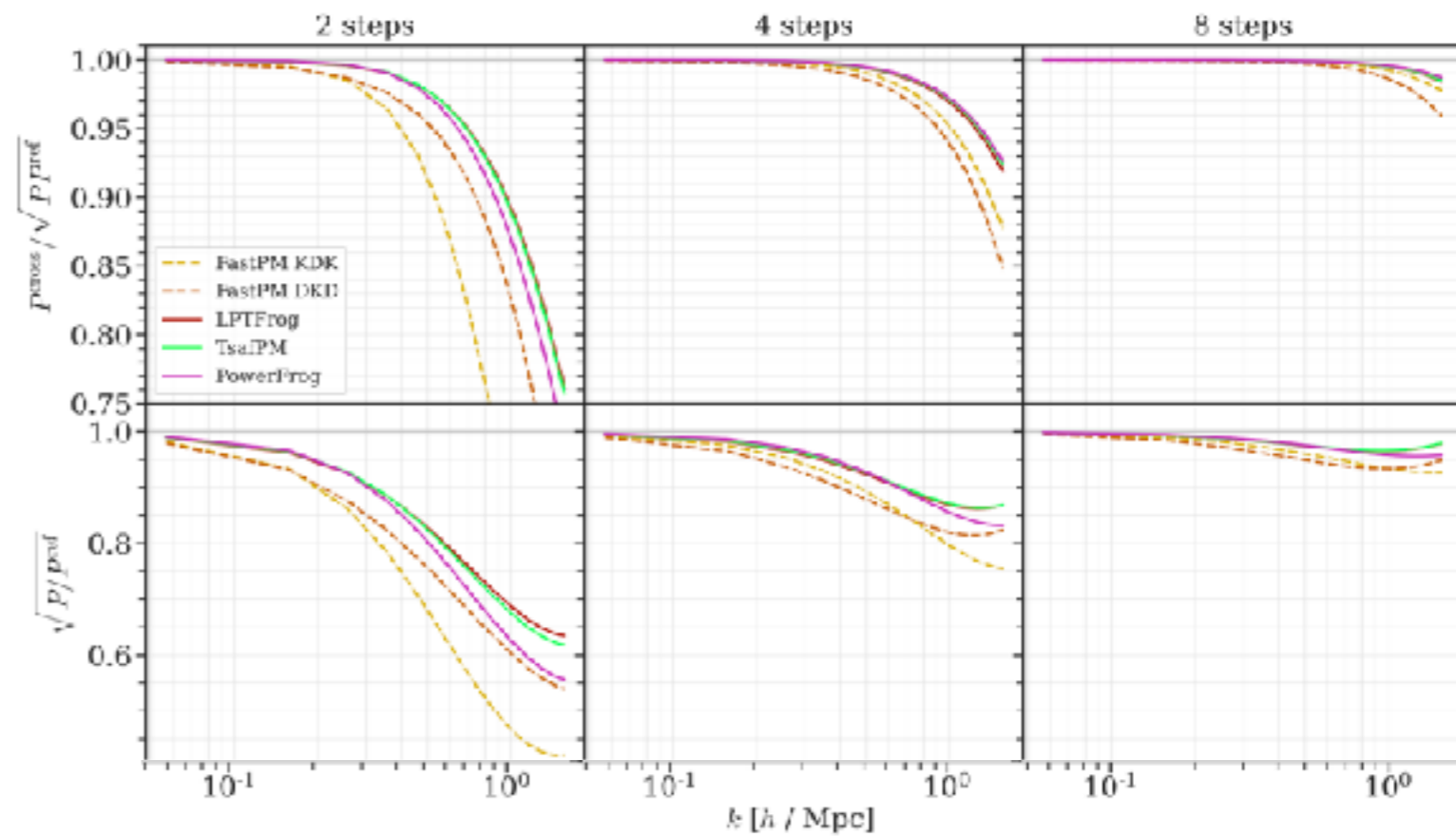
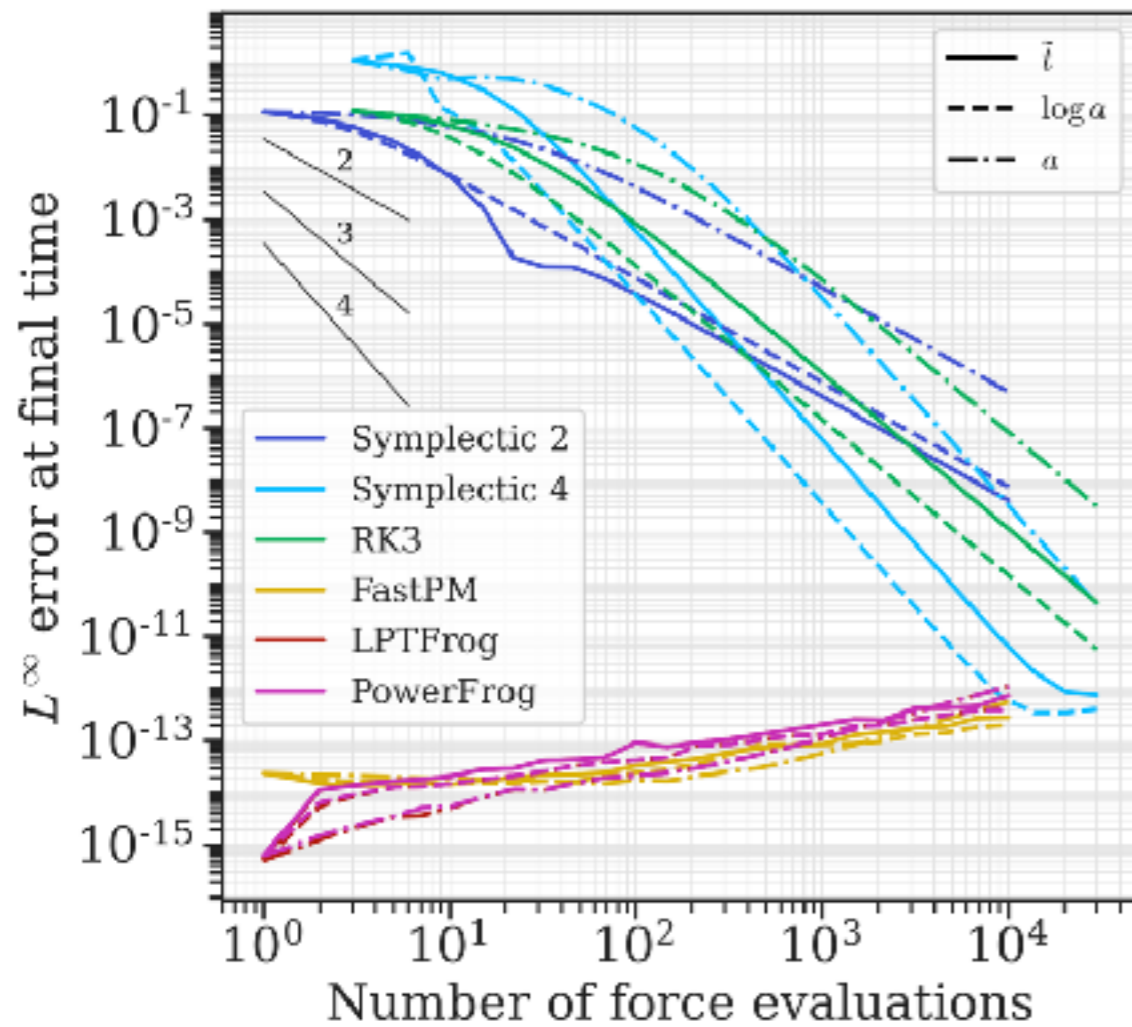
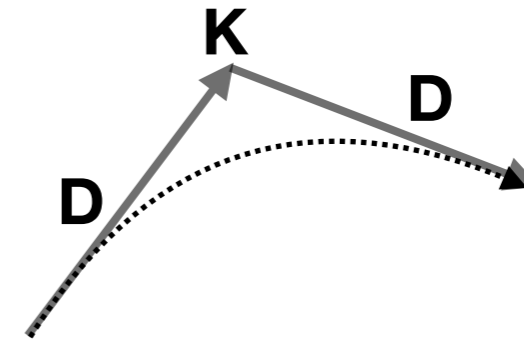


List&Hahn 23

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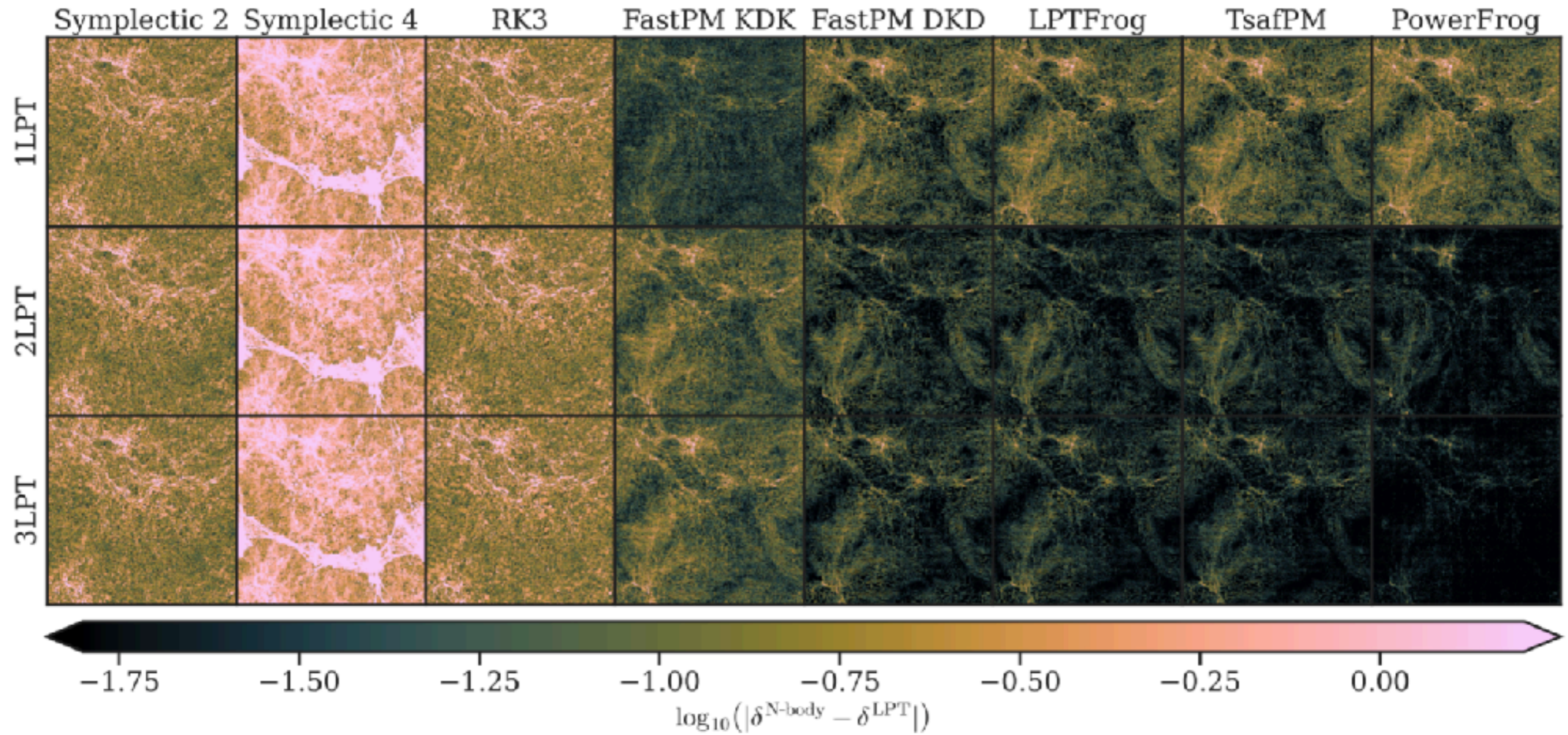


List&Hahn 23

This opens the door to bypass high-order ICs completely! (List&Hahn 23 in prep.)  
**STAY TUNED!**

# Perturbation-theory informed integrators

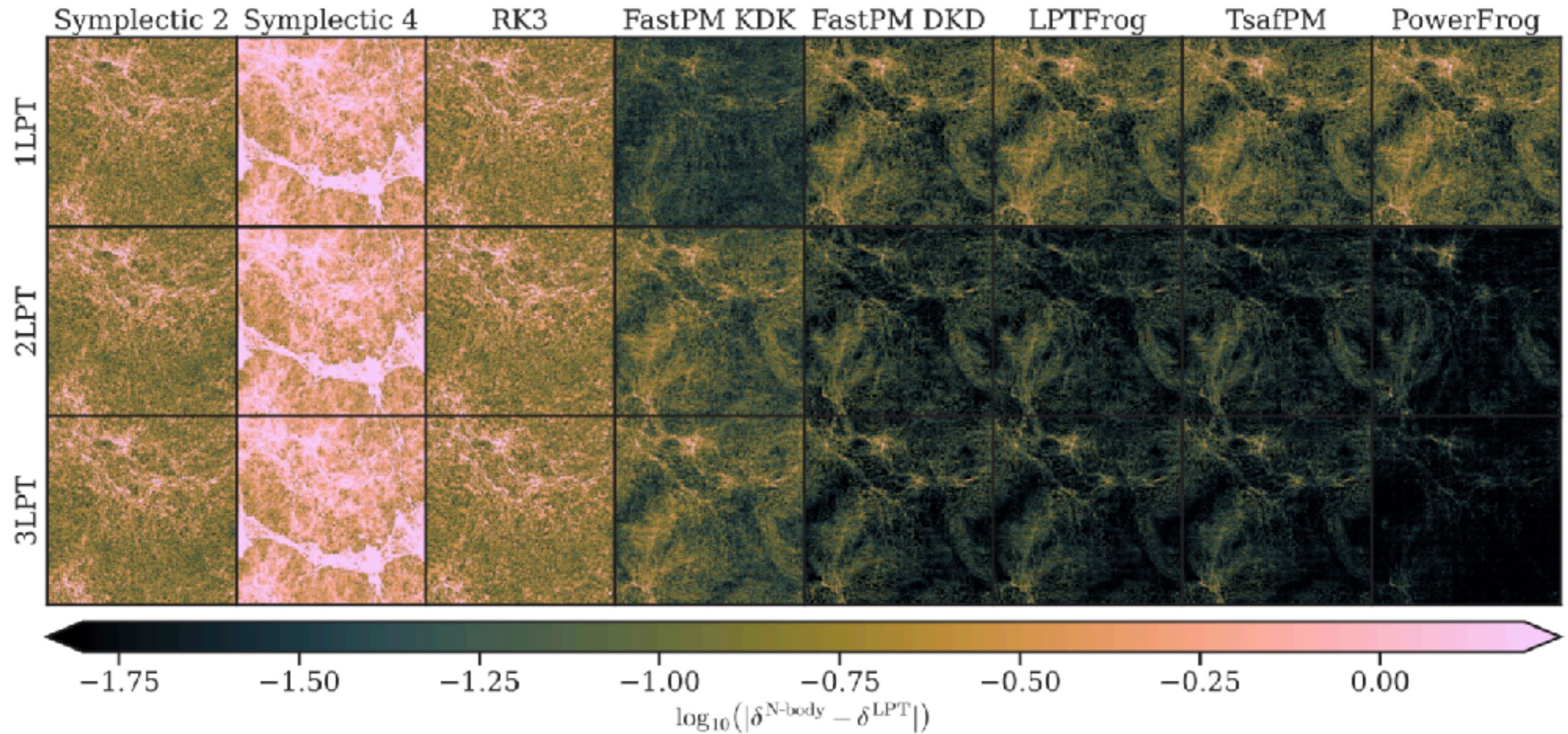
Residual between PTinformed and LPT:



List&Hahn 23

# Perturbation-theory informed integrators

Residual between PTinformed and LPT:



List&Hahn 23

**This opens the door to bypass high-order ICs completely! (List&Hahn 23 p2 in prep.)  
STAY TUNED!**

# MUSIC2 – monofonIC

All freely available for your enjoyment!

<https://bitbucket.org/ohahn/monofonic>

Modular high-precision IC generator for cosmological simulations. MUSIC2-monofonIC is for non-zoom full box ICs (use [MUSIC](#) for zooms, MUSIC2 for zooms is in the works).

Note that this program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY.

BEWARE: This software package is currently in a beta testing phase! Proceed with caution before using it for large-scale simulations.

The full manual is available [here as a wiki](#). Quick instructions can be found below.

Currently supported features (the list is growing, so check back):

- Support for up to 3rd order Lagrangian perturbation theory (i.e. 1,2, and 3LPT)
- Support for PPT (Semiclassical PT for Eulerian grids) up to 2nd order
- Support for mixed CDM+baryon sims
- Multiple Einstein-Boltzmann modules: direct interface with [CLASS](#), file input from CAMB, and fitting formulae (Eisenstein&Hu).
- Multiple output modules for RAMSES, Arepo, Gadget-2/3, SWIFT, and HACC (courtesy M.Buehlmann) via plugins (Nyx is next).
- Multiple random number modules (MUSIC1, NGenIC, Panphasia,...) (A new MUSIC2 module is in development)
- Multiple pre-IC modules (various Bravais lattices, glass)
- Hybrid parallelization with MPI+OpenMP/threads.
- Requires FFTW v3, GSL (and HDF5 for output for some codes), as well as a CMake build system and a reasonably new C++14 compliant compiler.

New modules/plugins can be easily added (see how to contribute in CONTRIBUTING.md file)

# MUSIC2 – polyfonIC

Currently in the works!

<https://bitbucket.org/ohahn/music> : branch 'music20'

## All the goodies of MUSIC 1:

MUSIC is a computer program to generate nested grid initial conditions for high-resolution "zoom" cosmological simulations. A detailed description of the algorithms can be found in [Hahn & Abel \(2011\)](#). You can download the user's guide [here](#), or [read the Wiki](#) instead. Please consider joining the [user mailing list](#).

Current MUSIC key features are:

- Supports output for RAMSES, ENZO, Arepo, Gadget-2/3, ART, Pkdgrav/Gasoline and NyX via plugins. New codes can be added.
- Support for first (1LPT) and second order (2LPT) Lagrangian perturbation theory, local Lagrangian approximation (LLA) for baryons with grid codes.
- Pluggable transfer functions, currently CAMB, Eisenstein&Hu, BBKS, Warm Dark Matter variants. Distinct baryon+CDM fields.
- Minimum bounding ellipsoid and convex hull shaped high-res regions supported with most codes, supports refinement mask generation for RAMSES.
- Parallelized with OpenMP
- Requires FFTW (v2 or v3), GSL (and HDF5 for output for some codes)

## But NOW (some points only thanks to this workshop):

- **significantly reduced memory usage (almost 8x)**
- **precision cosmology modules from monofonIC (full CLASS integration)**
- **full integration of PANPHASIA**
- **higher accuracy**

# MUSIC2 – cosmICweb – the cloud!

BETA testing open, please register and give us feedback

<https://cosmicweb.astro.univie.ac.at>



The screenshot shows the homepage of the cosmICweb website. At the top, there is a navigation bar with links for 'cosmICweb', 'Simulations', 'Publications', 'Halo-Finder', and 'About'. A 'Log In' button is located in the top right corner. The main header features the 'cosmICweb' logo in large white text, with the subtitle 'A Database for Cosmological Initial Conditions for Zoom Simulations' below it. The page is divided into three main functional areas, each in a dark grey box with white text:

- Select Dark Matter Halos:** Search in a large collection of state of the art cosmological dark matter simulations and filter halo catalogs according to your needs.
- Generate Zoom-In Initial Conditions:** Create initial conditions for a large number of cosmological simulation codes with refined particle resolution around your selected halos.
- Reference Halos in Publications:** Create references for halos that you used in your studies so that research colleagues can easily reproduce and test your results using their own simulation codes.

Below these boxes is a section titled 'Cosmological Zoom-In Simulations'. It contains two paragraphs of text and a small image of a zoomed-in simulation. The first paragraph explains that numerical simulations play an important role in modern cosmology, extending from hundreds of Megaparsecs to the order of kiloparsecs. The second paragraph discusses the computational cost of simulating the full dynamic range and how the zoom technique circumvents this by simulating the immediate region around the object of interest with higher resolution.

Numerical simulations play an important role in modern cosmology. They extend over an enormous range of scales: from hundreds of Megaparsecs, studying the growth of the largest structures in our universe, to the order of kiloparsecs, modeling the evolution of molecular clouds, galaxies and feedback processes, down to the scales of stellar systems and individual stars.

The computational cost of computing and storing the full dynamic range in the entire simulated volume sets a limit on the upper and lower scales that can be simulated in a single run. A popular approach to circumvent this limitation is the zoom technique, in which the immediate region around the object of interest is simulated with a highly increased resolution compared to its surrounding large scale environment. This allows to capture both

