new music, numerical universes, and faster simulations

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University of Vienna, Austria

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

universität wien

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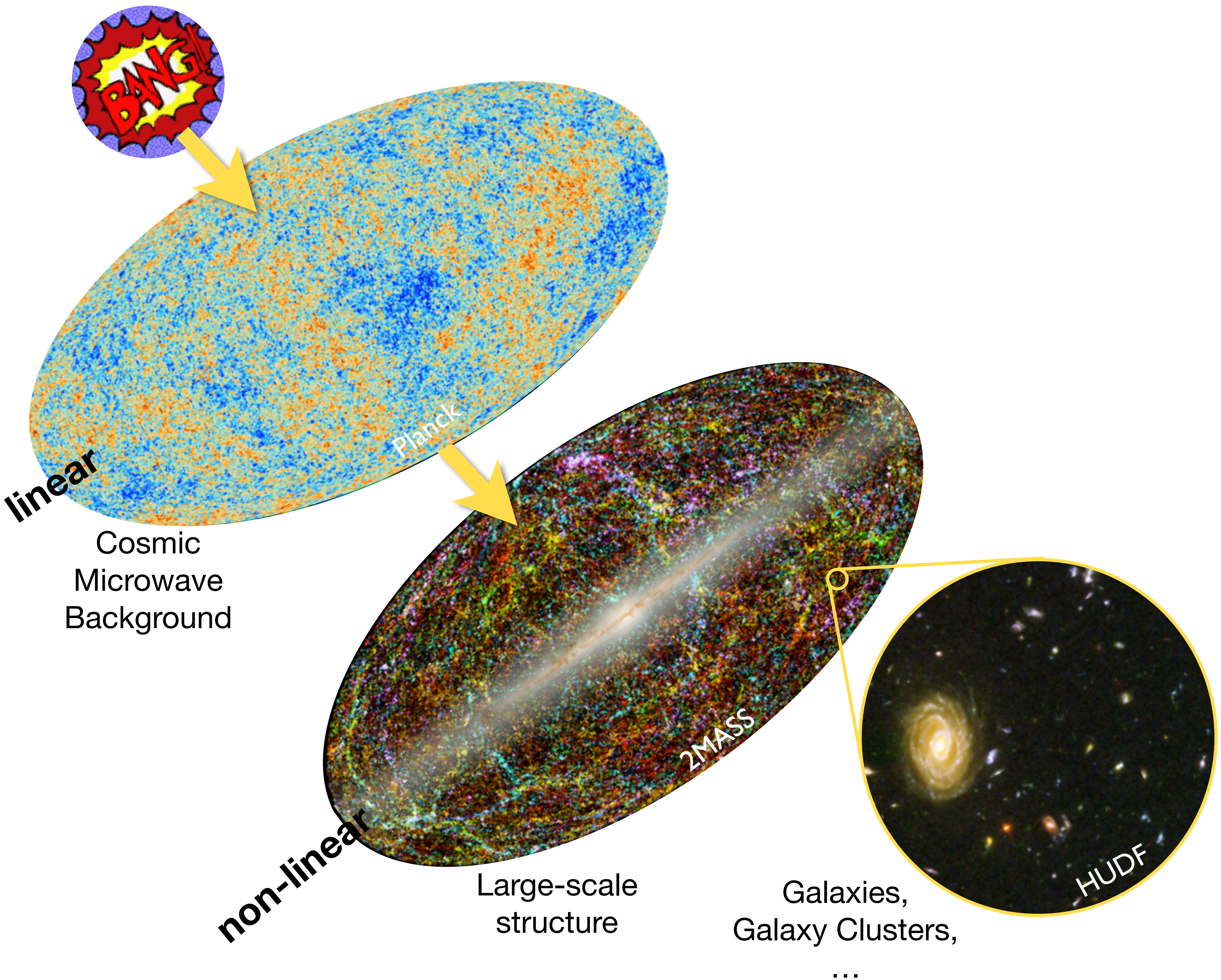
The MUSIC numeriverse: 30 orders of magnitude?



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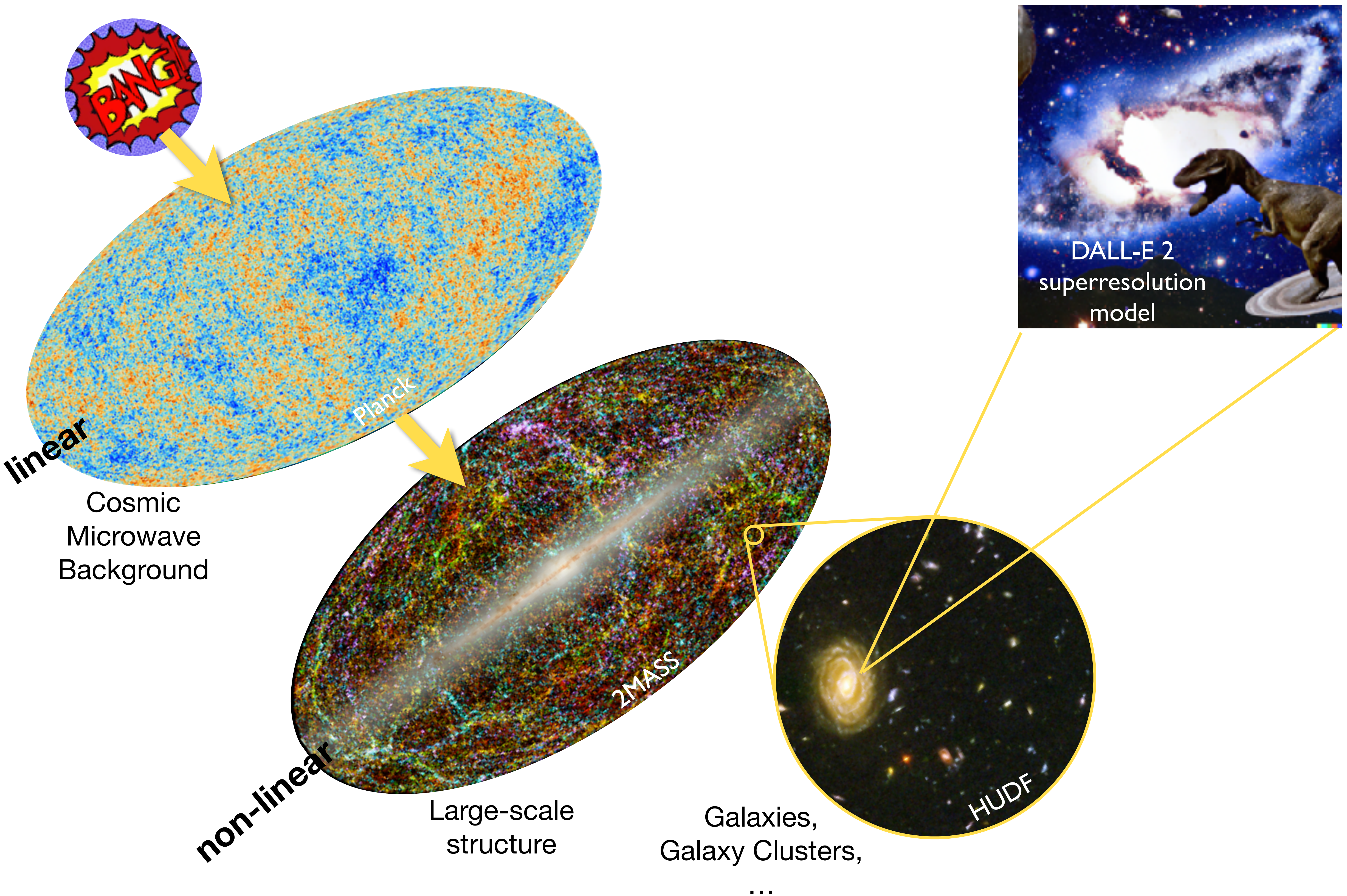
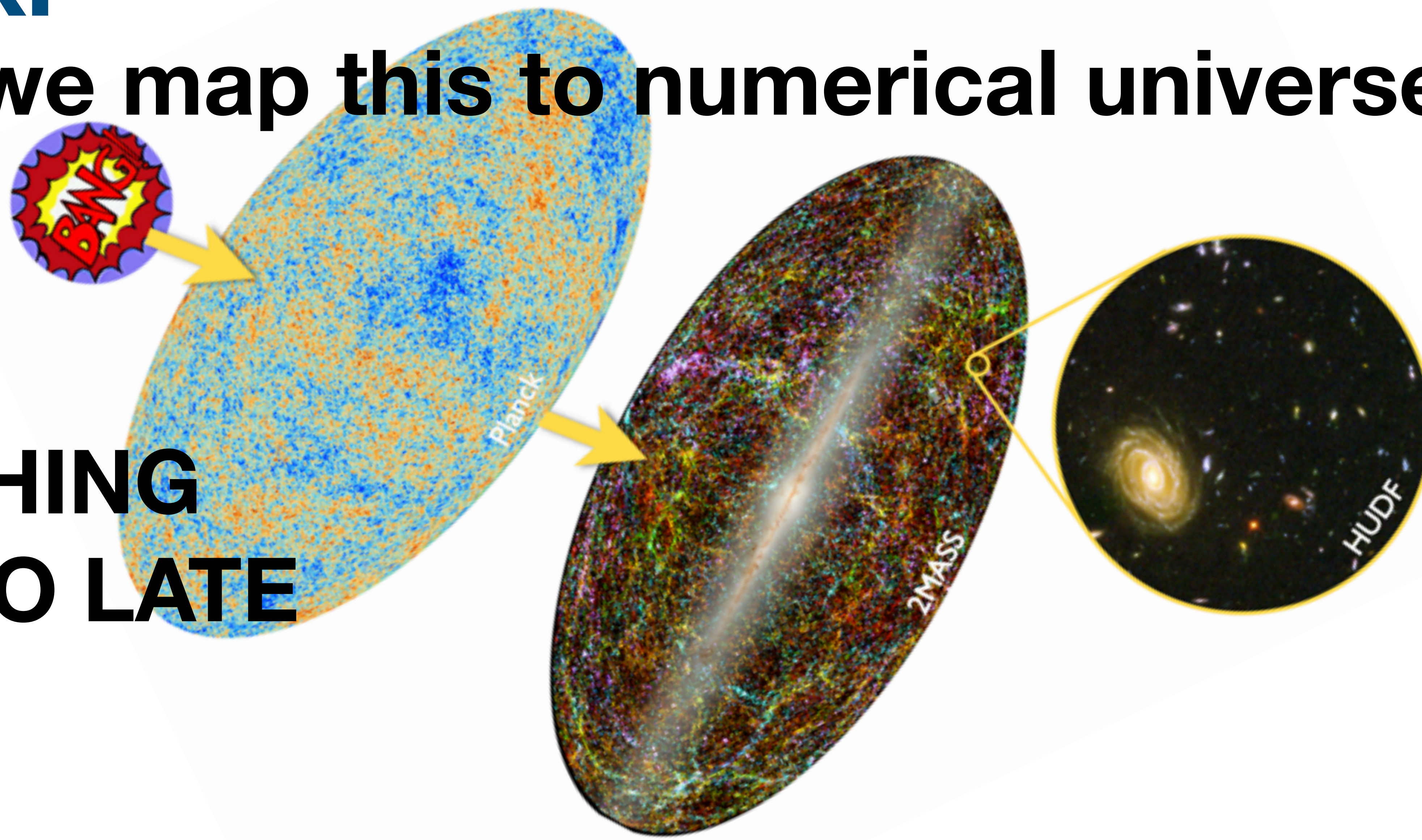


This talk:

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: δ and θ

Matching problem!

Late physics:

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

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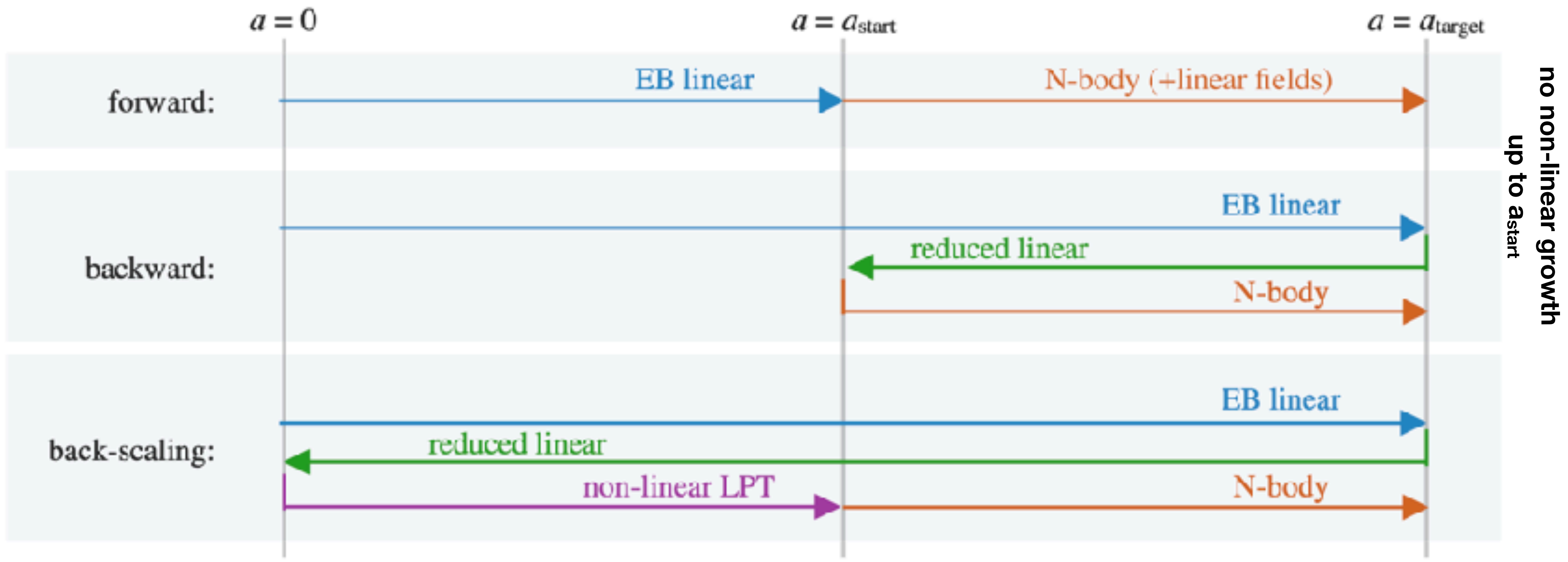


Two-component precision simulations

Cold two-fluid system, coupled by grav.

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

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

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

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?

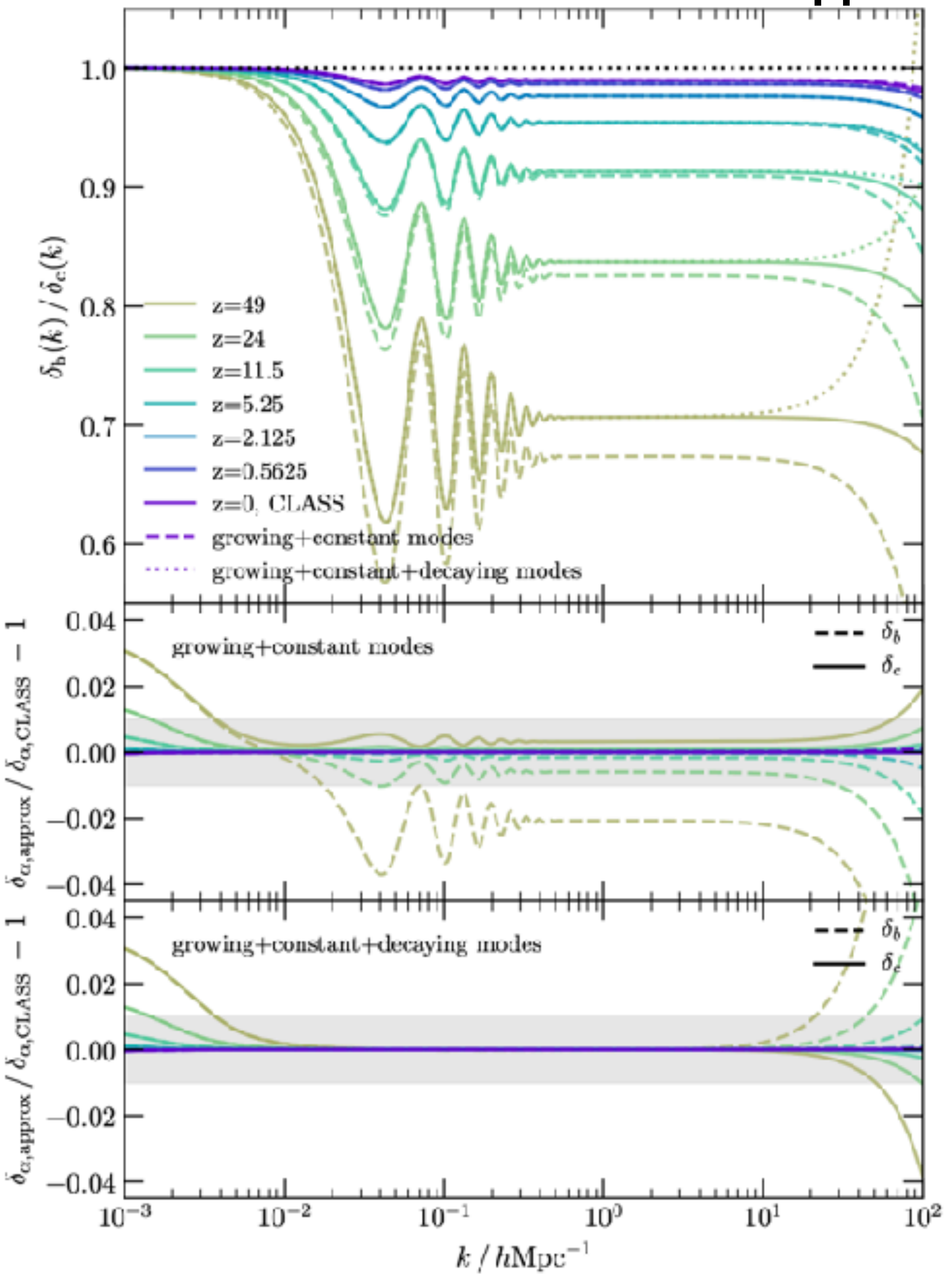
varying baryon-to-cdm fraction

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

Baryons catch up with CDM over time

evolution is captured by lin. Boltzmann-Einstein

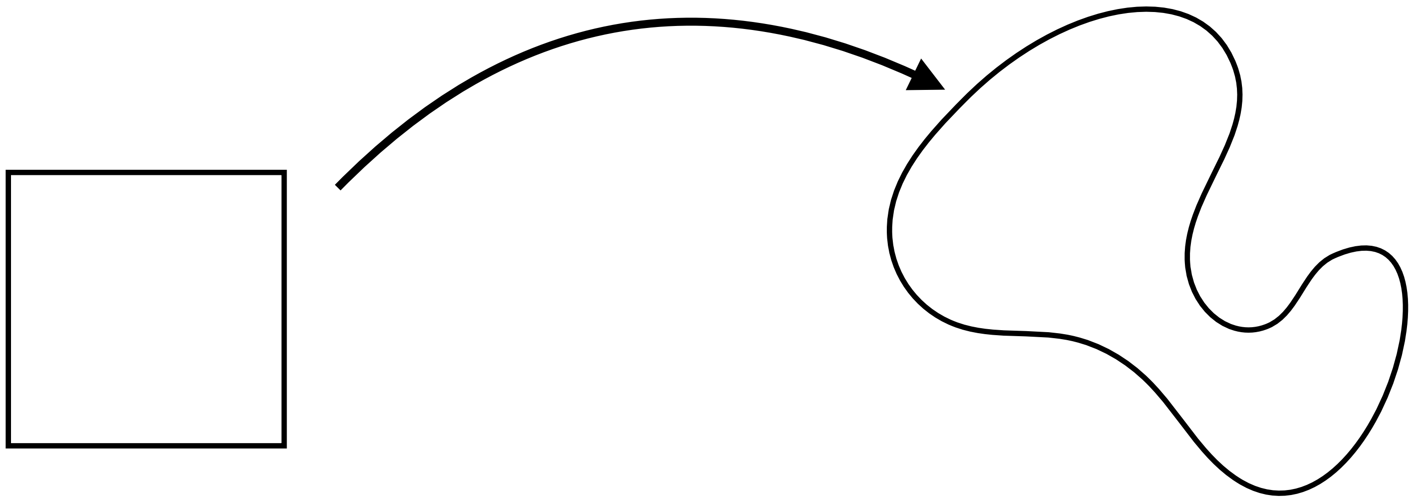
Linear evolution from CLASS + approx.



Discrete evolution vs. fluid evolution

Lagrangian description, evolution of fluid element

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

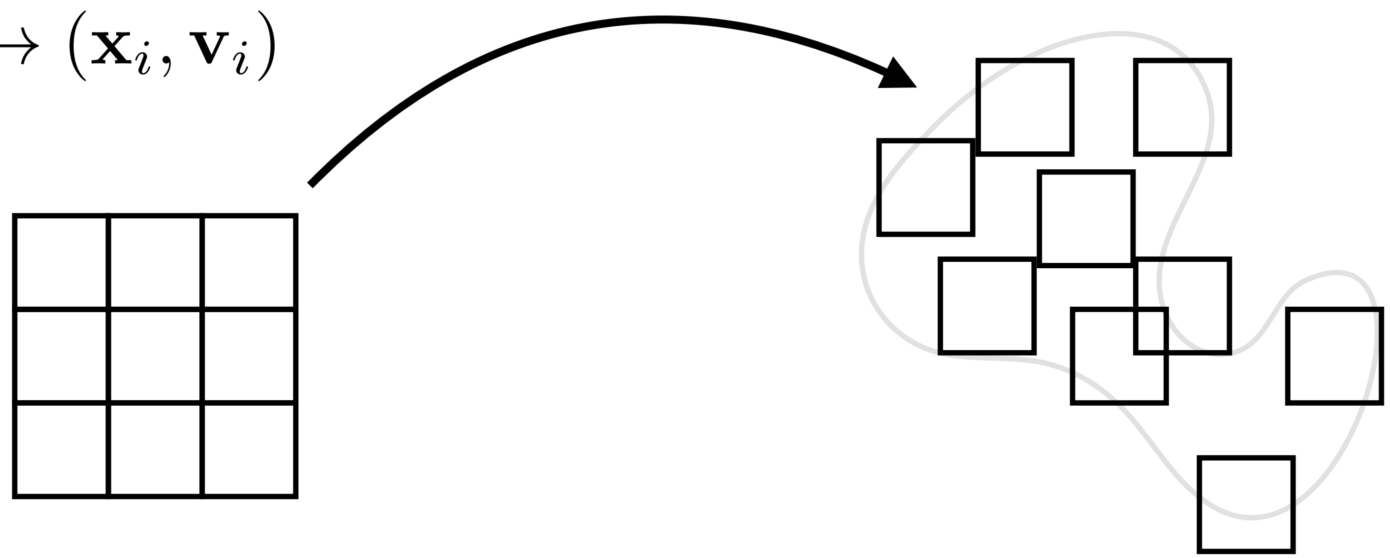


$$\frac{\mathrm{D} f_m}{\mathrm{D}t} = 0$$

The N-body approximation:

cover distribution function with N characteristics, estimate f_m from them

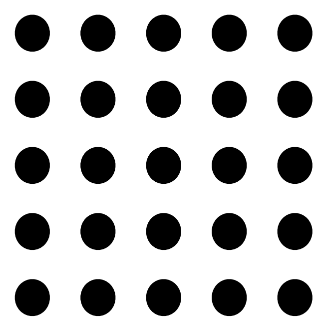
$$i \in \{1 \dots N\} \mapsto (\mathbf{x}_i, \mathbf{v}_i)$$



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 particle scale -> "discreteness"

but global symmetry ok e.g. for:
- Bravais lattices
- glasses
- special tilings

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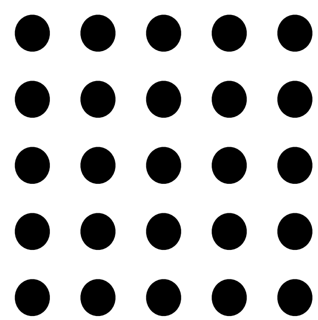

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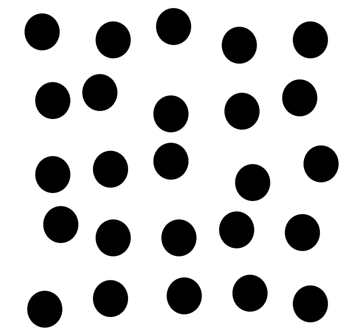
perturbed state



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

variant 1: first order method:

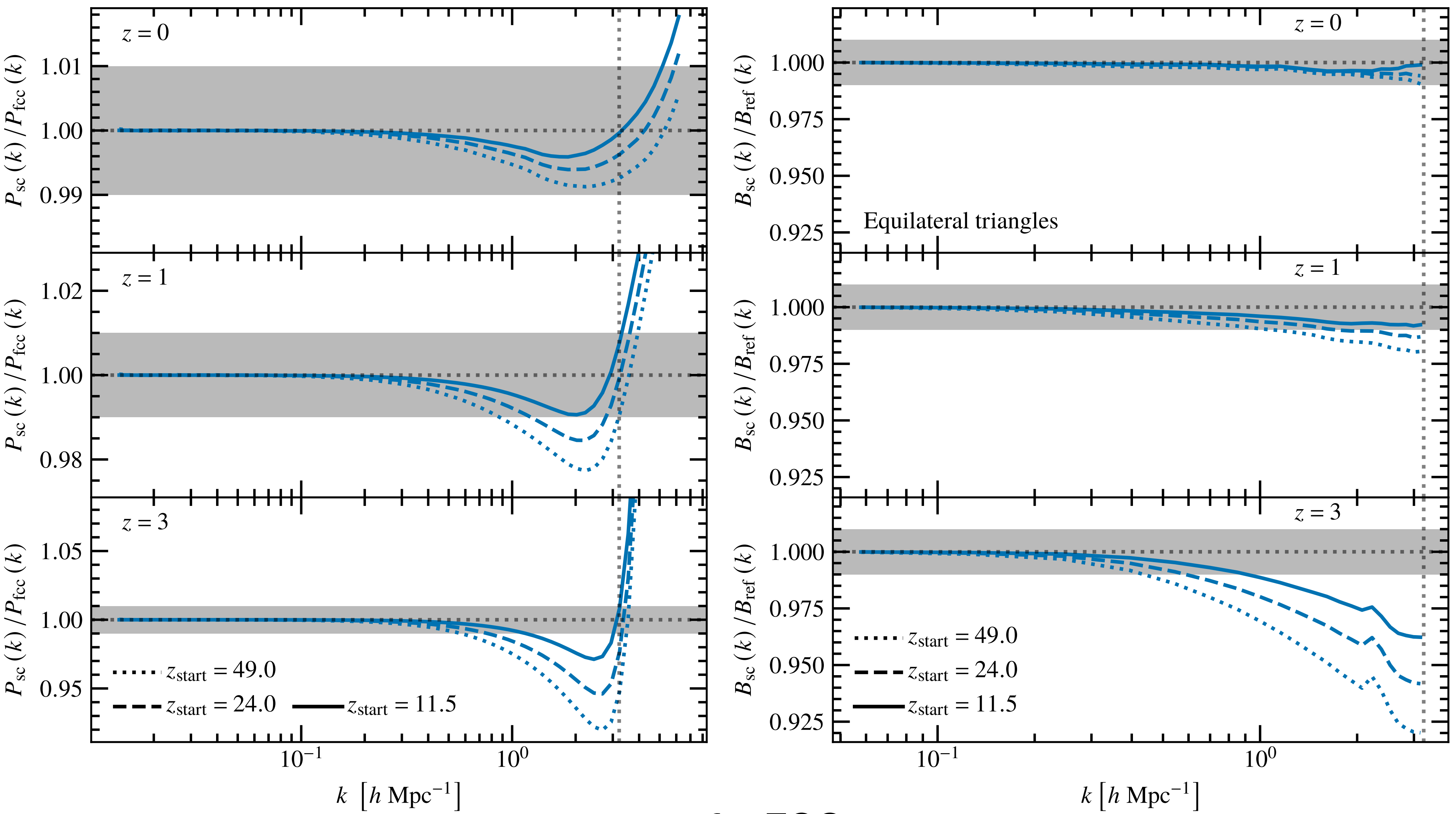
$$\vec{\psi}_{\rm ini} = \vec{\nabla}\,\nabla^{-2}\delta_{\rm ini}$$
$$\dot{\vec{\psi}}_{\rm ini} = \vec{\nabla}\,\nabla^{-2}\theta_{\rm ini}$$

variant 2: LPT (nonlinear)

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

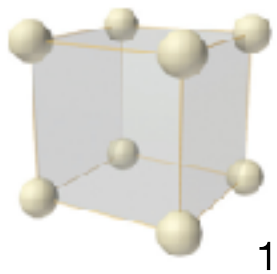
Discreteness — impact on low-z power spectrum

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



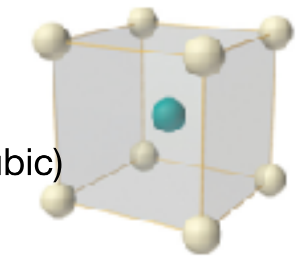
ref = FCC

SC
(simple cubic)



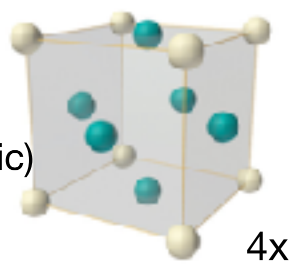
1x

BCC
(body-centred cubic)



2x

FCC
(face-centred cubic)



4x

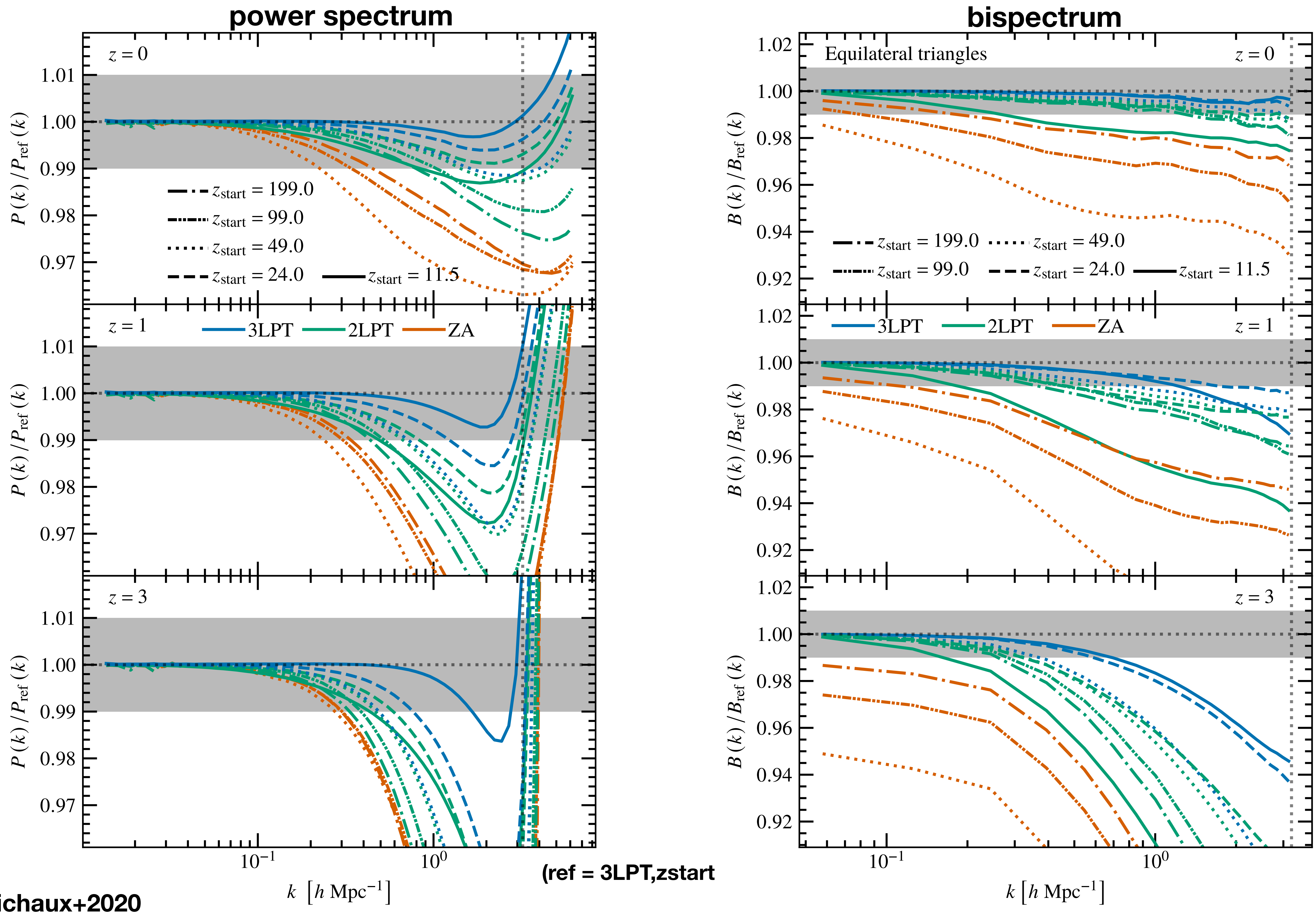
(cf. also Marcos 2008)

Michaux+2020

discreteness effects strongest at high z

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

Impact of nLPT vs. discreteness on low-z spectra



(ref = 3LPT,zstart

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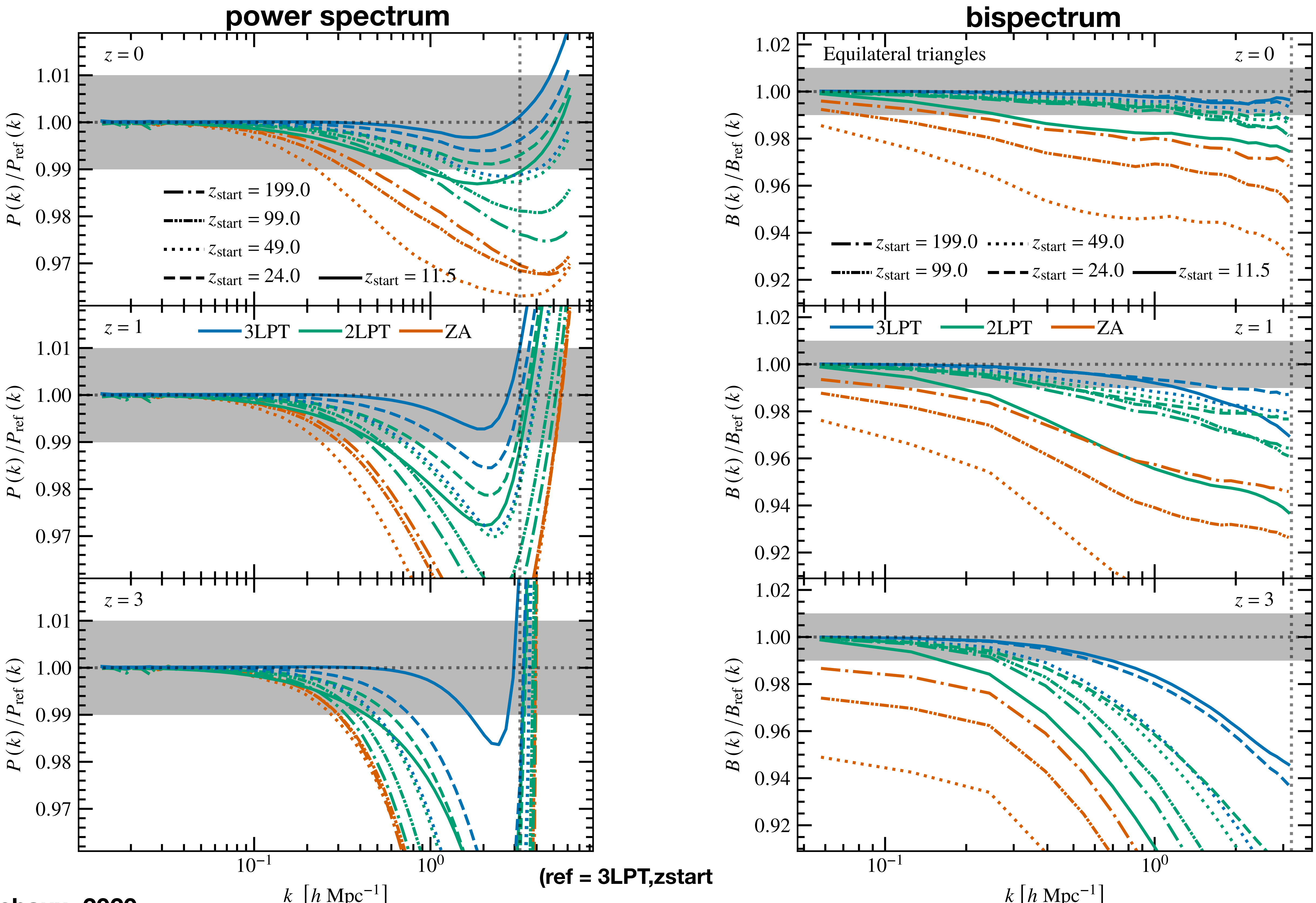


(ref = 3LPT,zstart

Michaux+2020

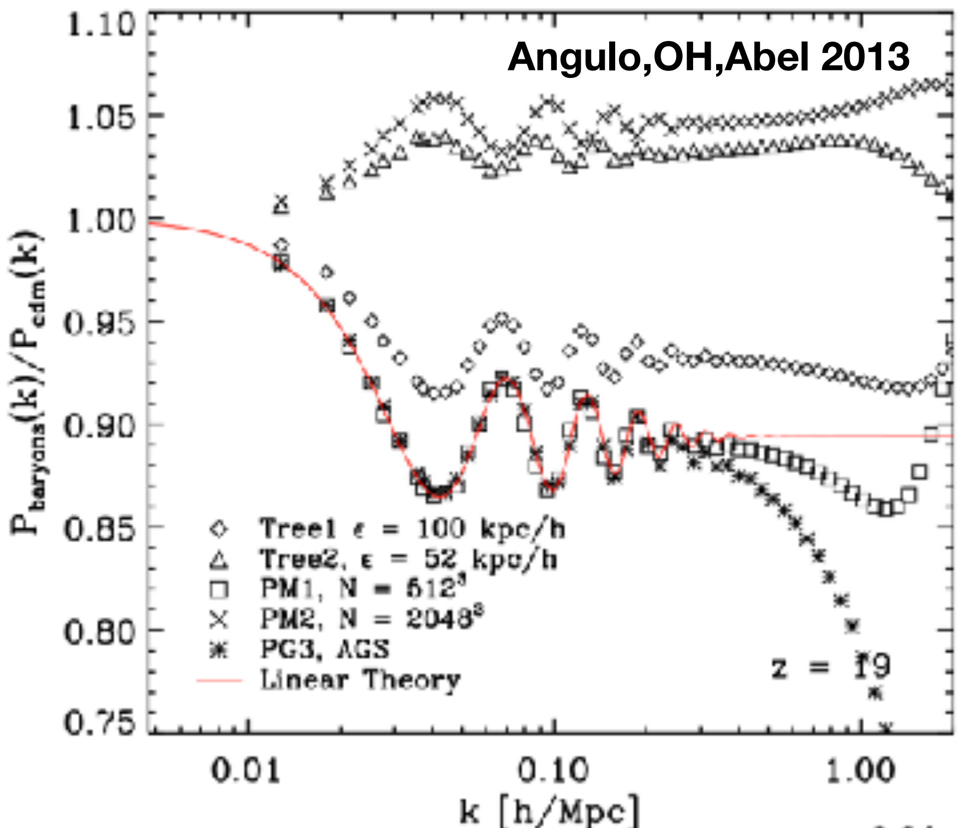
discreteness always dominates when starting@z too high (cf also Garrison+2016)

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

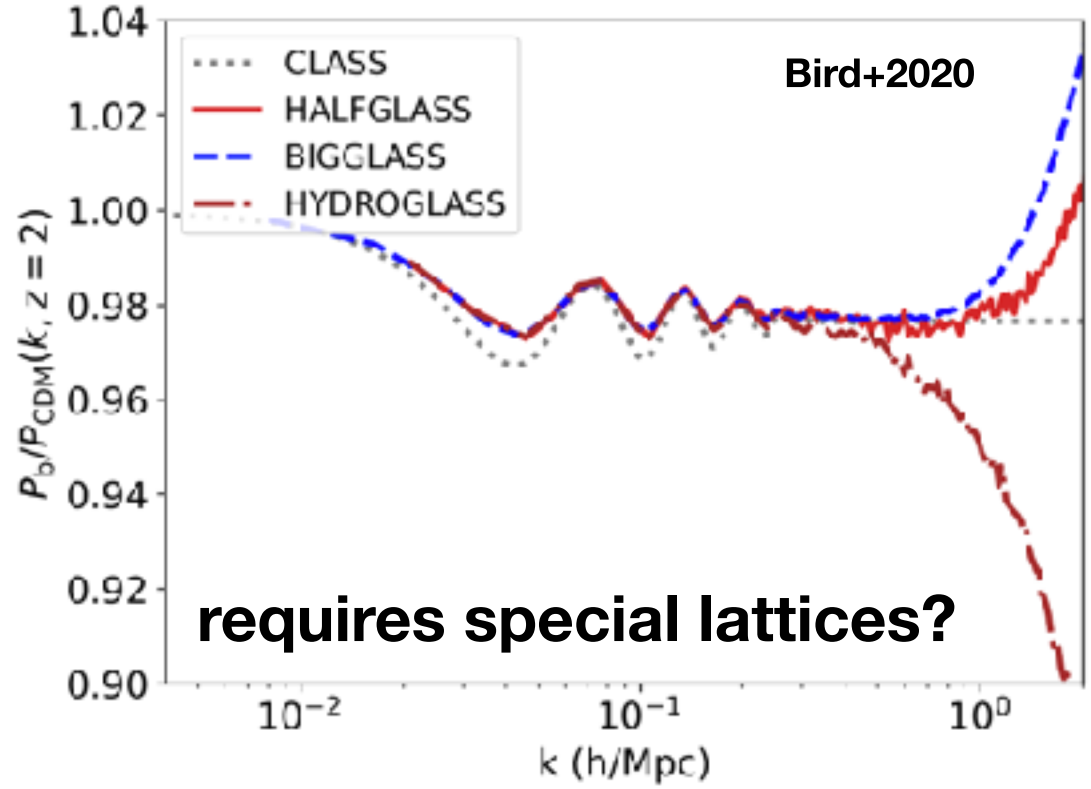
What about 2-species? Baryons+DM….

Precision CDM+baryon two-fluid simulations

N-body two-fluid sims have dominant discreteness errors



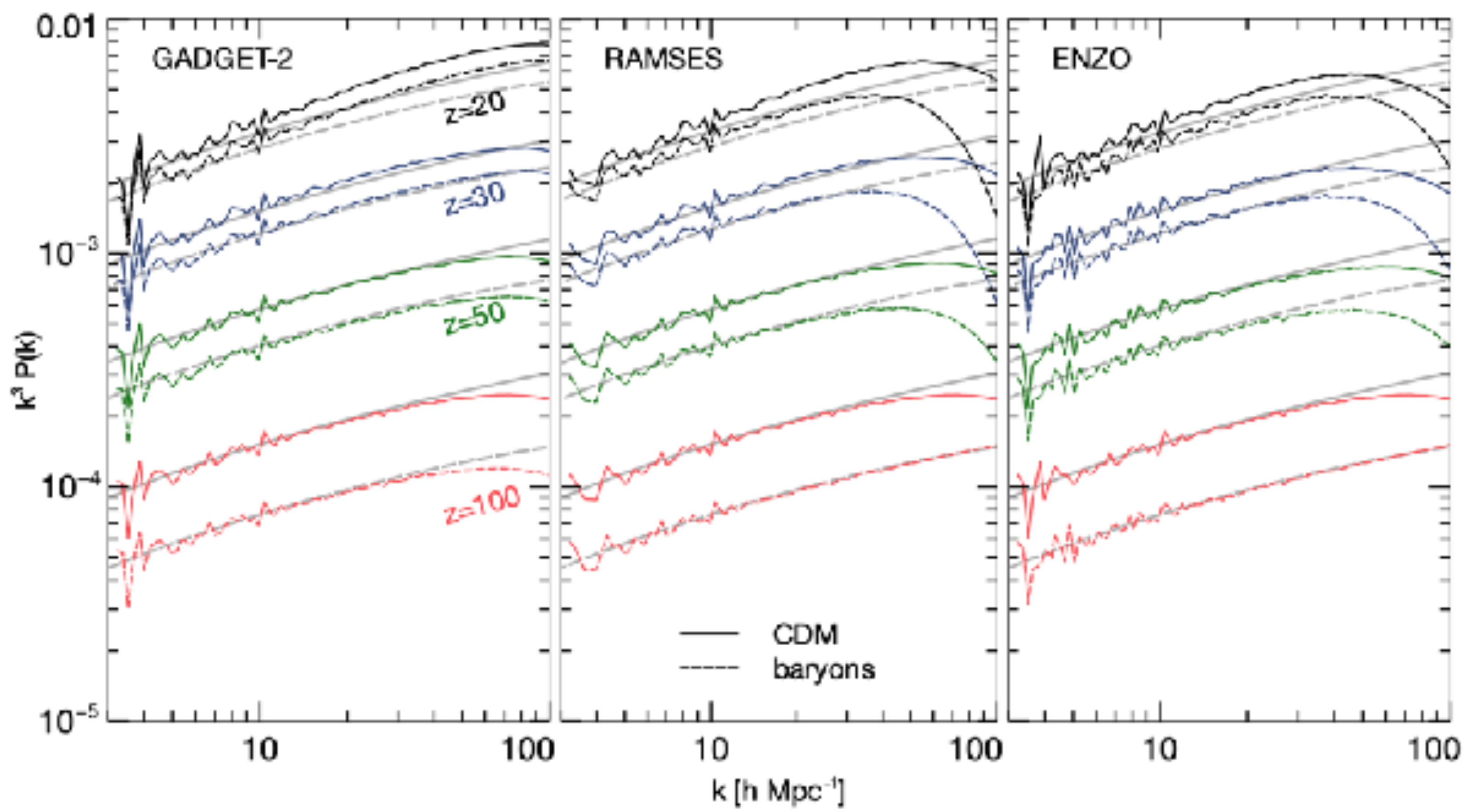
requires large softening?



requires special lattices?

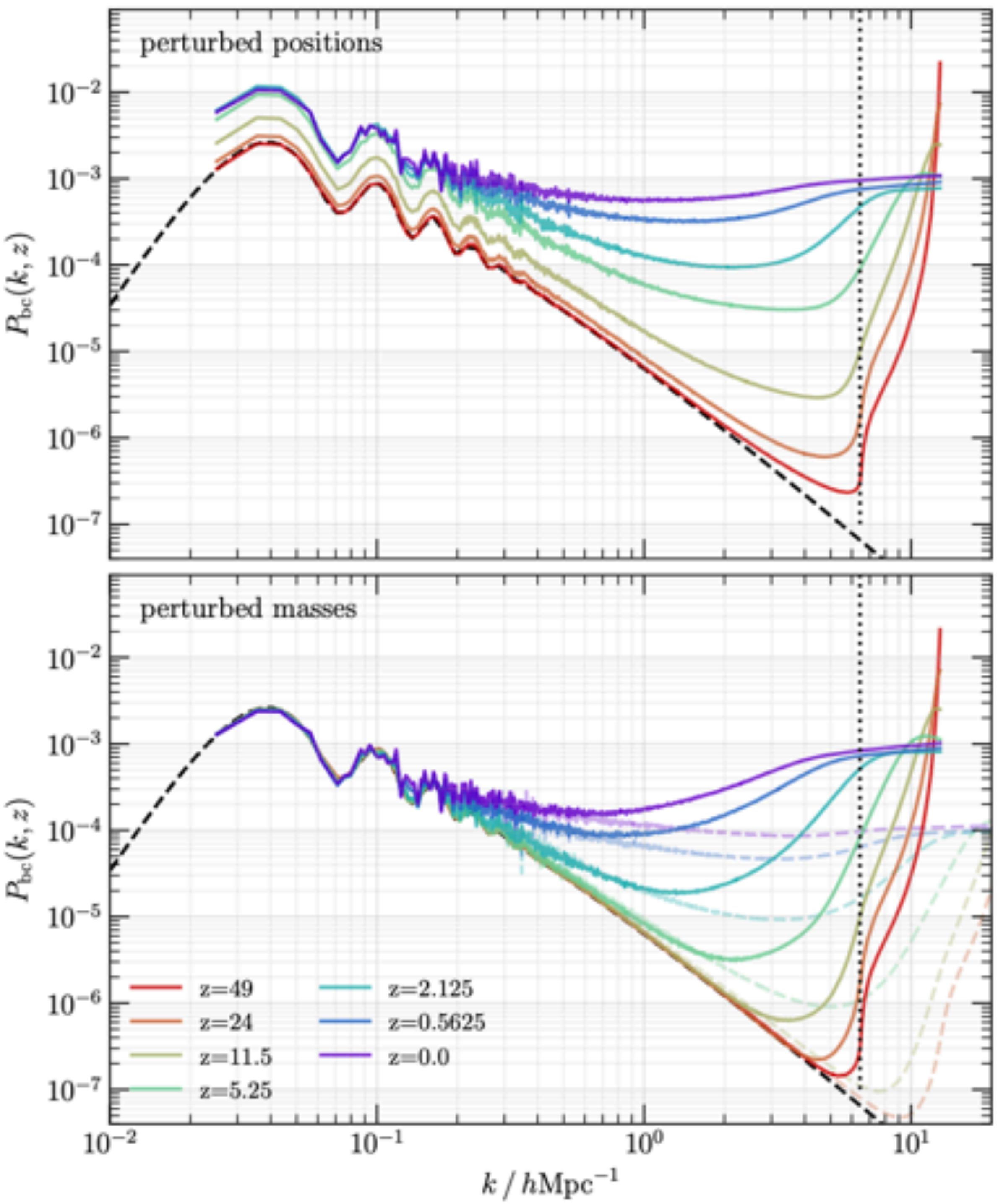
Finite-Volume Eulerian simulations suffer from advection errors:

OH&Abel 2012



Perturbing masses vs. displacements for isocurvature modes

Constant mode not constant when perturbing positions for isocurvature



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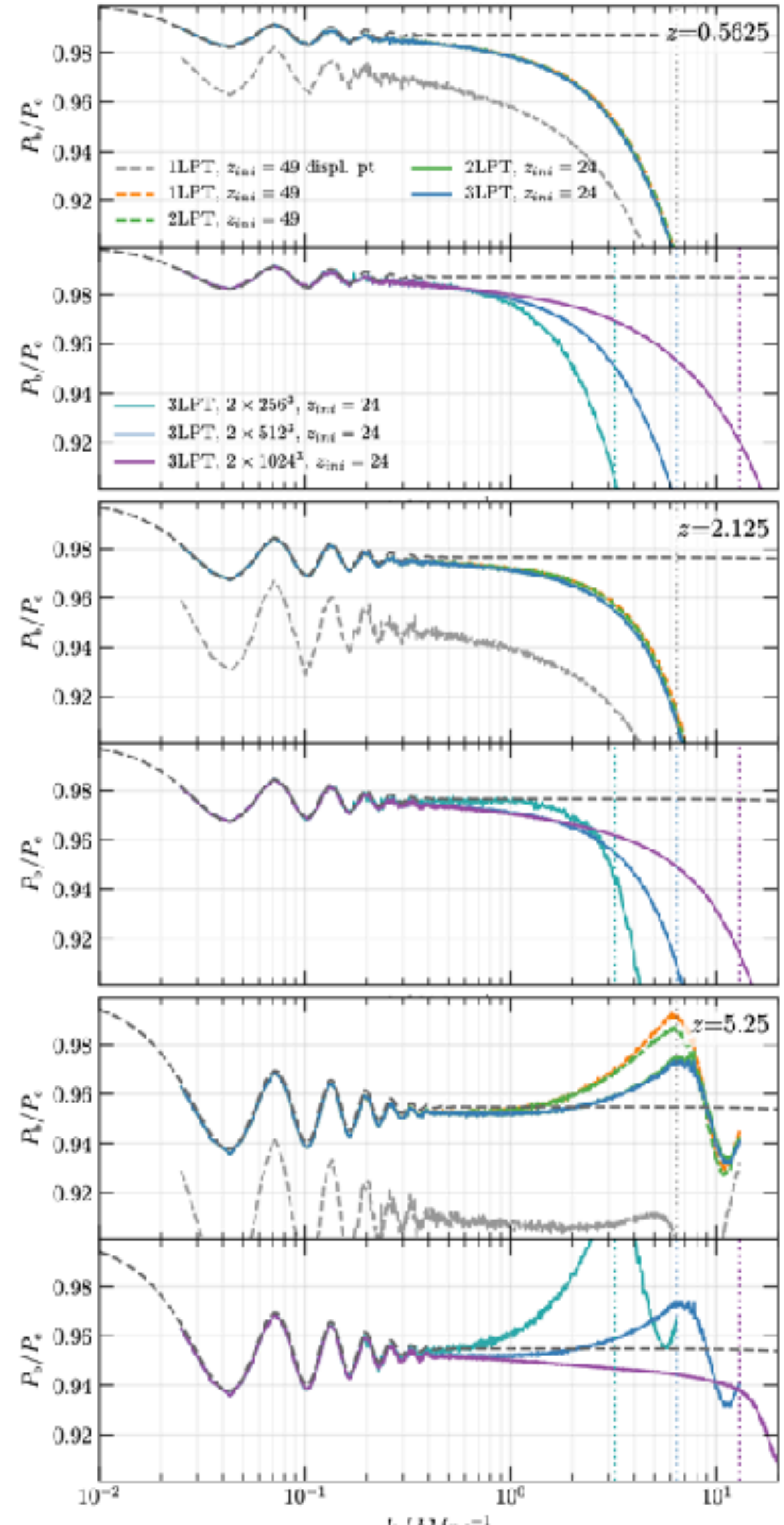


Evolution of baryons vs. CDM completely off in two-fluid N-body sims

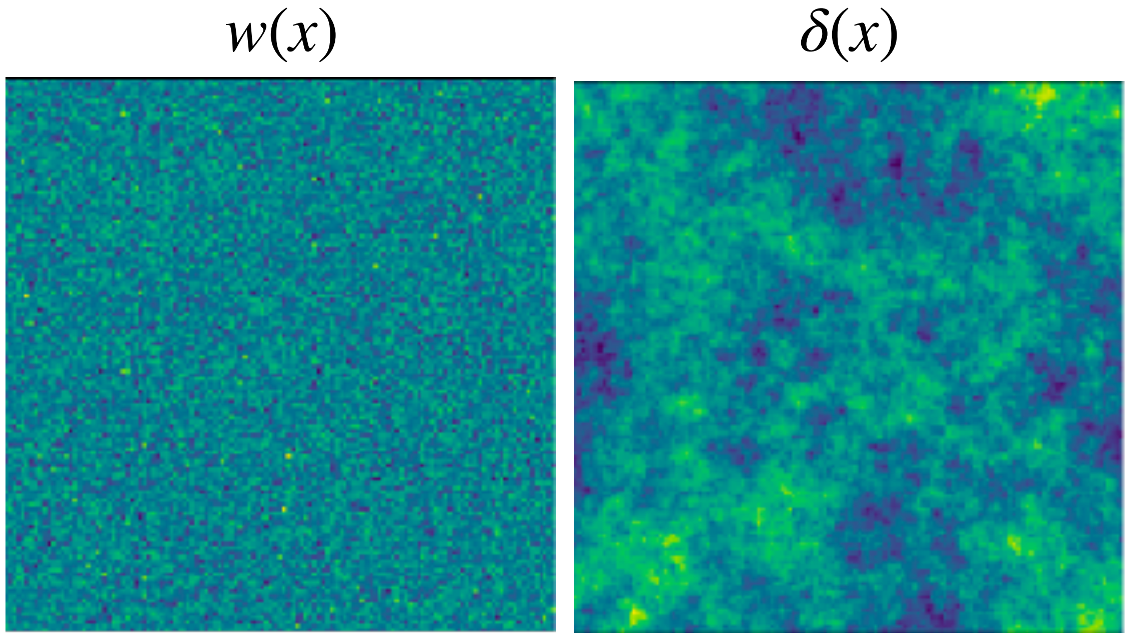
Ok, ok. Boring n-spectra….
This is a cosmic web meeting!
Show us the field!

Numerical Universes

Originate from a Gaussian random process

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

covariance (power spectrum) diagonal in Fourier space



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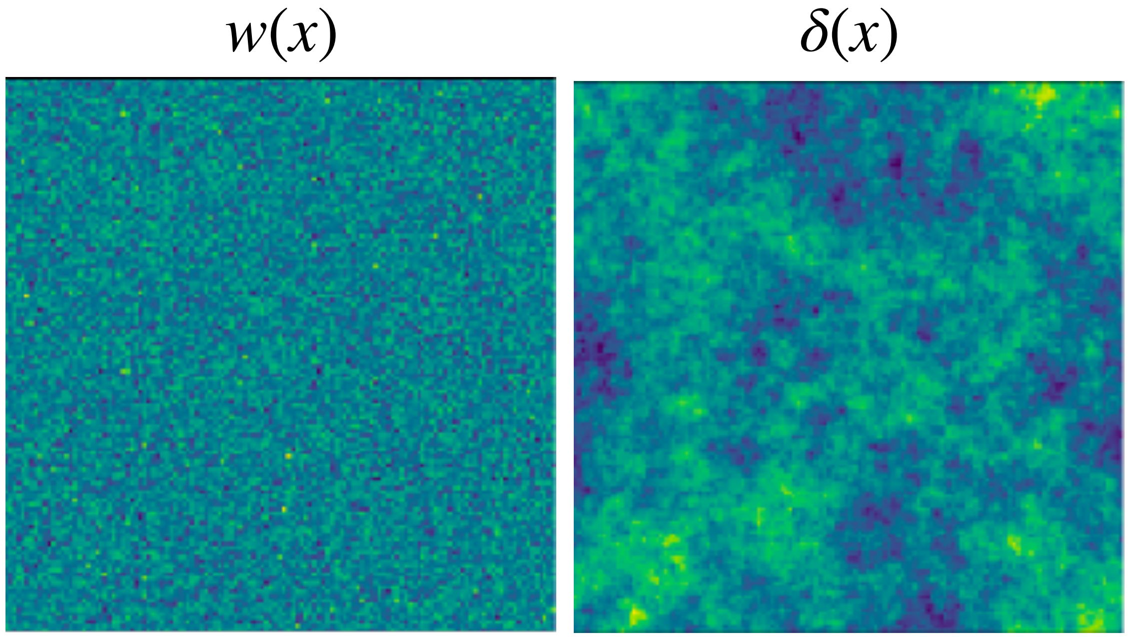

<u>Problem:</u> How do we create a multi-scale Gaussian random process that guarantees that structure is stable?
(i.e. we get the same LSS when we change resolution)

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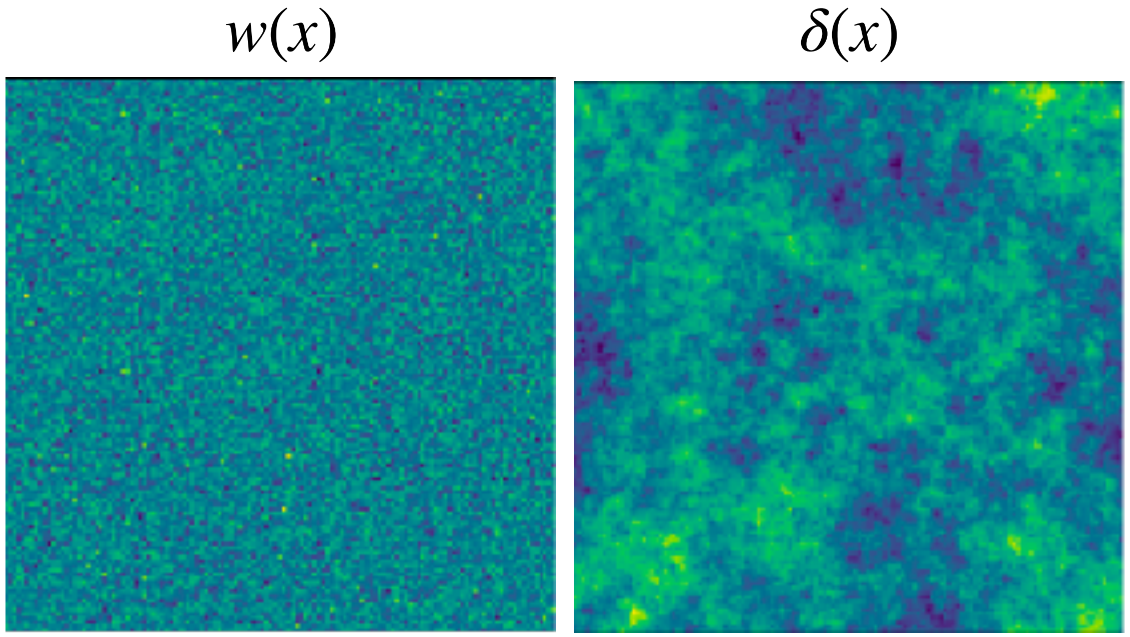

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(implemented e.g. in N-GenIC by Springel)

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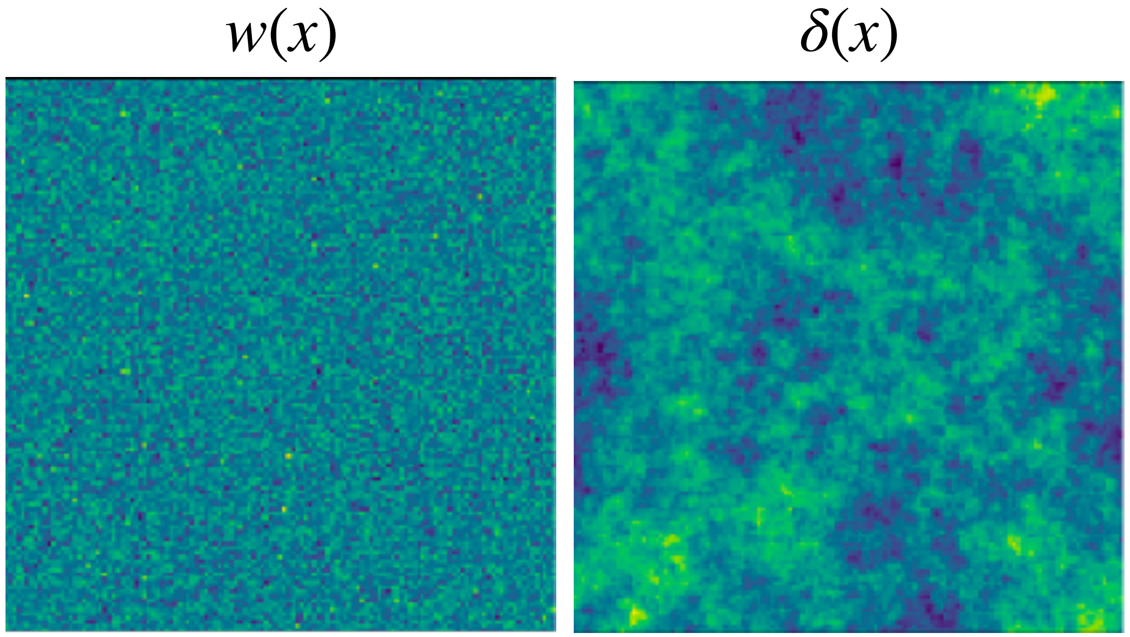

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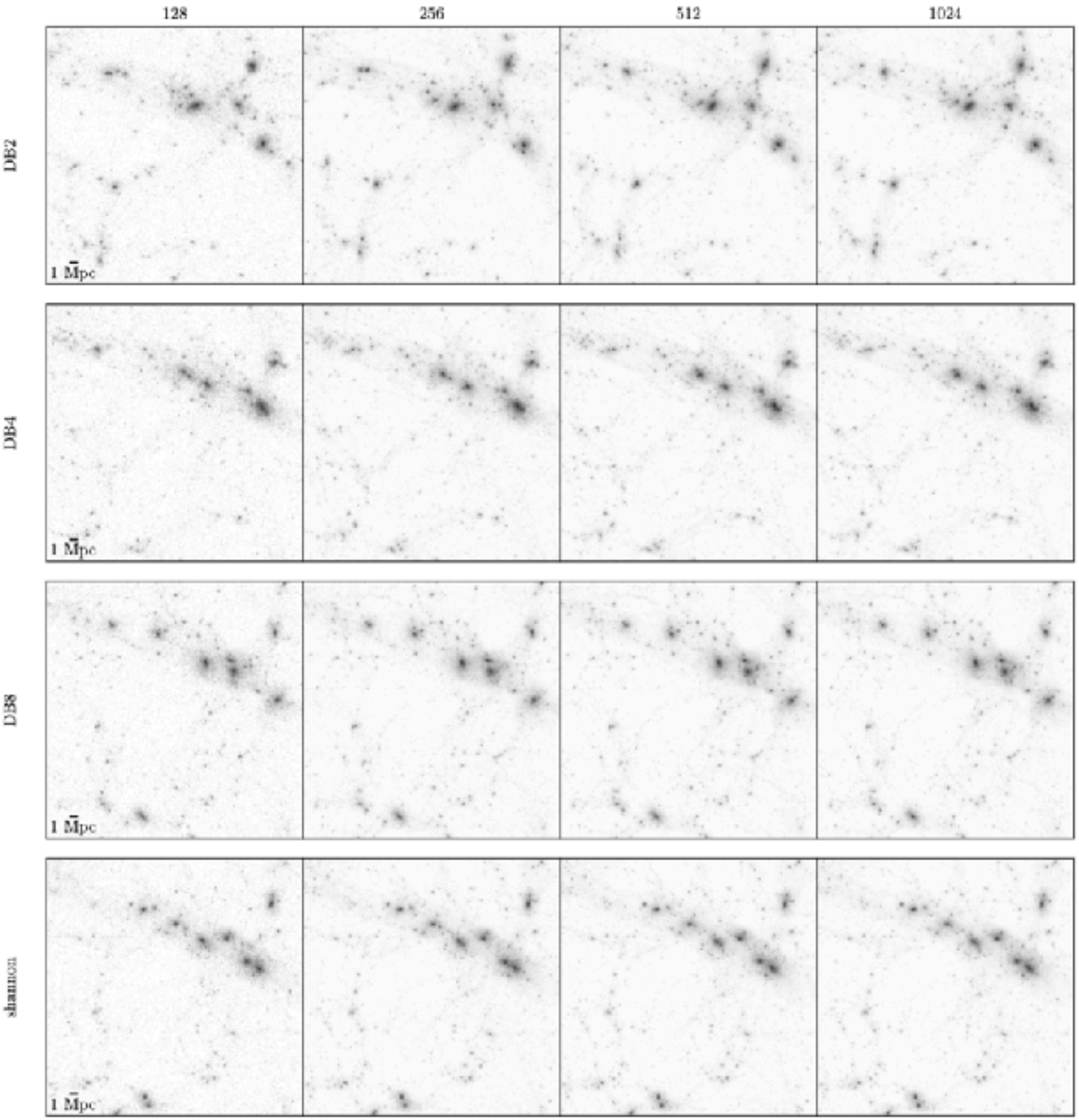
<u>Solution 2:</u> use PANPHASIA (Jenkins 2013)
+ local process
+ allows unique universes with zoom capability
- not particularly stable

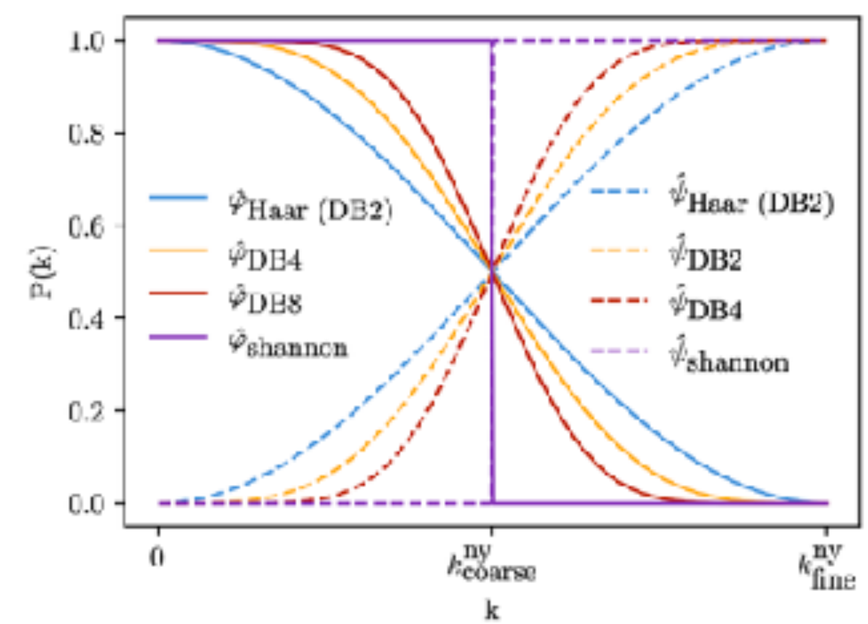
Stable Numerical Universes



OH, Glatter, Winkler 2023 (to be submitted)

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)

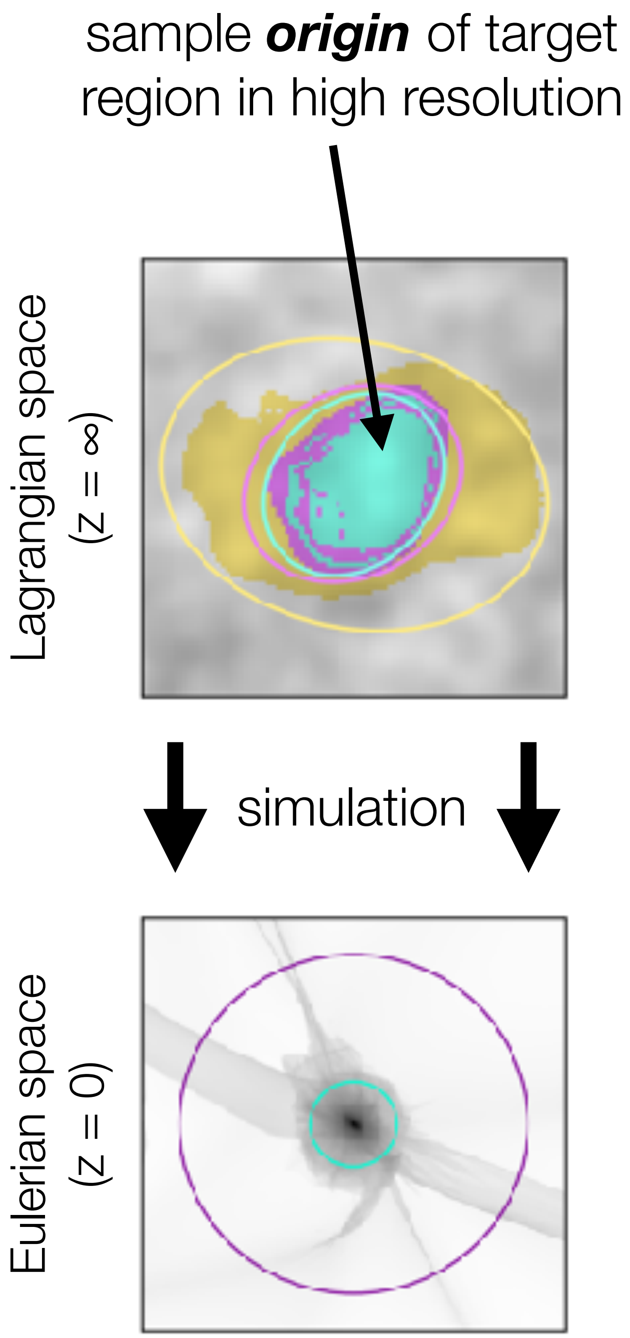
now that we have a ‘stable’ numerical universe, we can zoom into it…

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)



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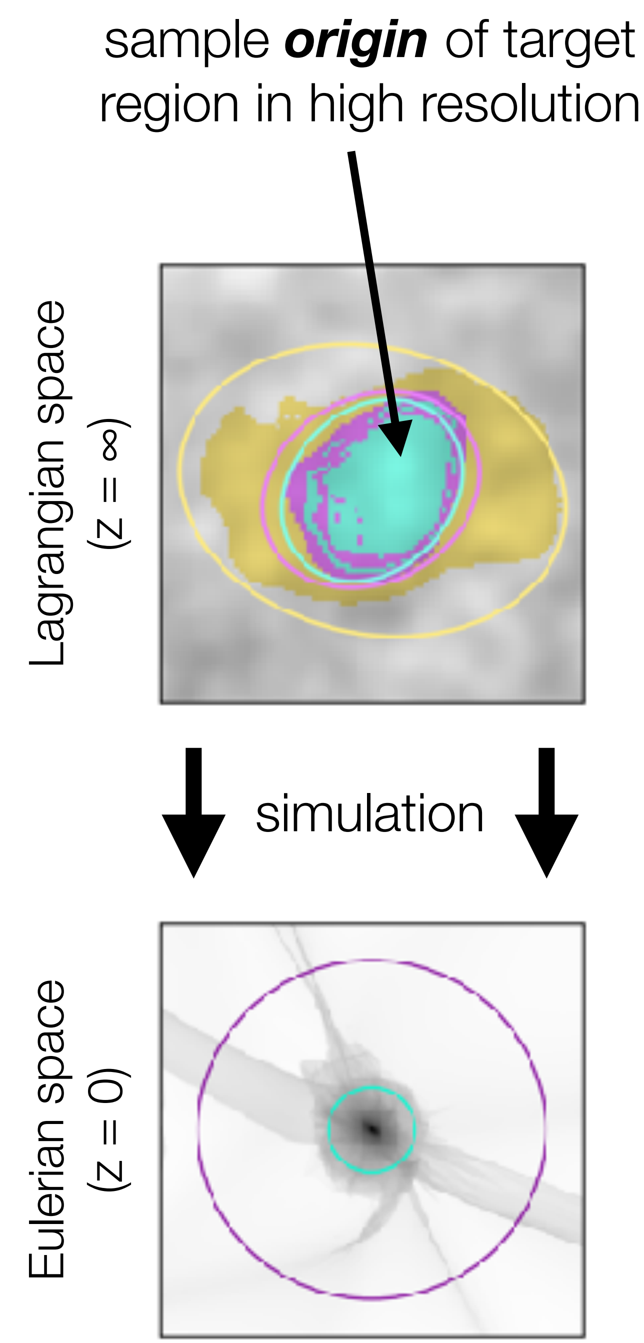

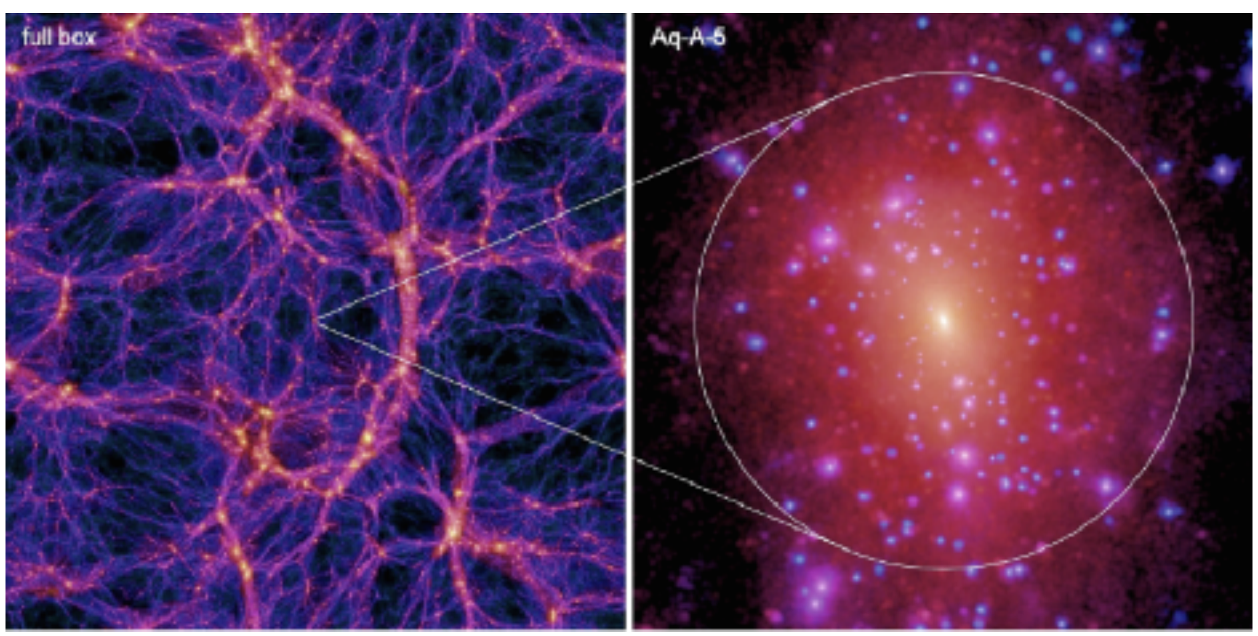

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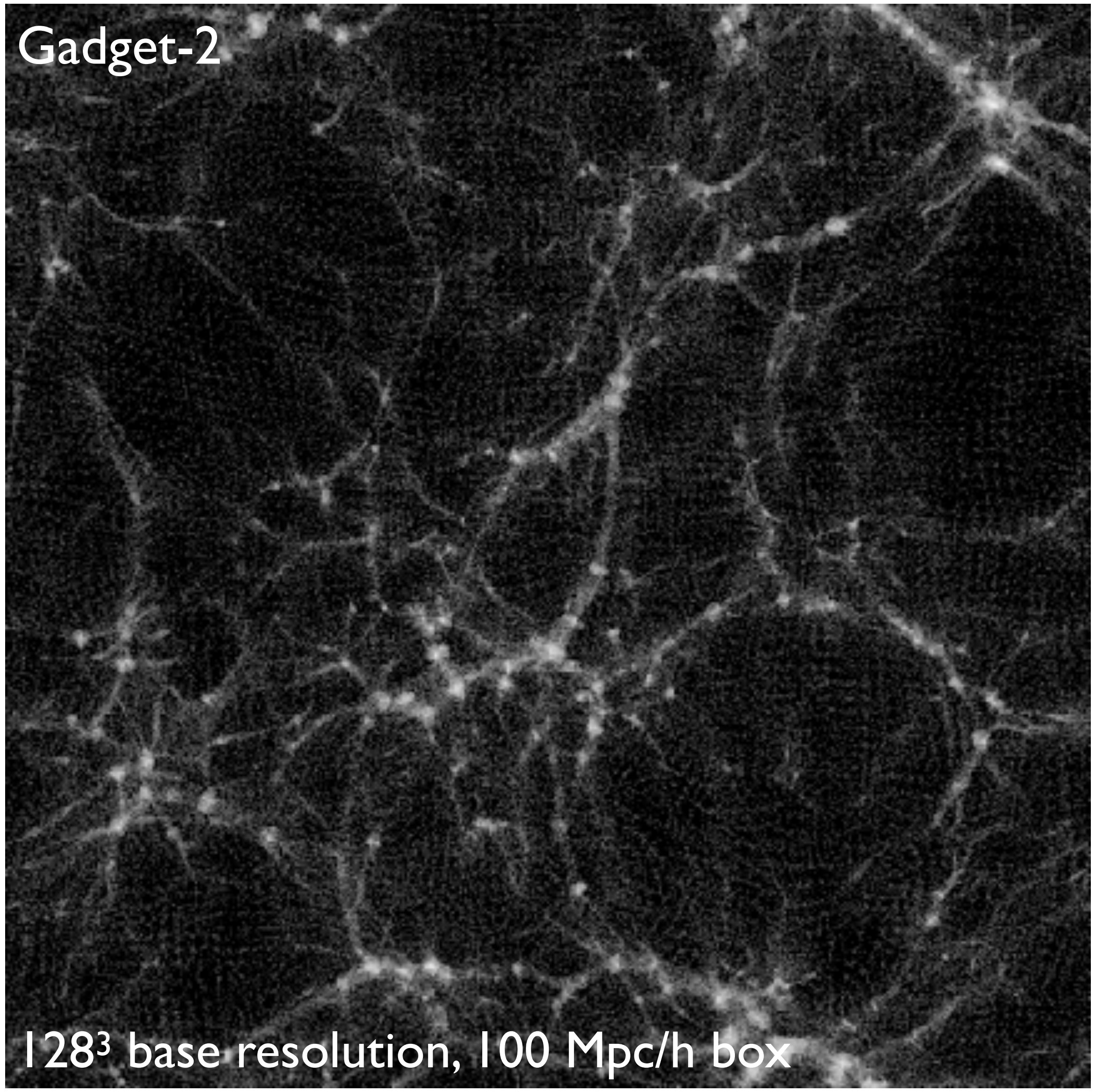
MUSIC 1 — zoomin' since 2011

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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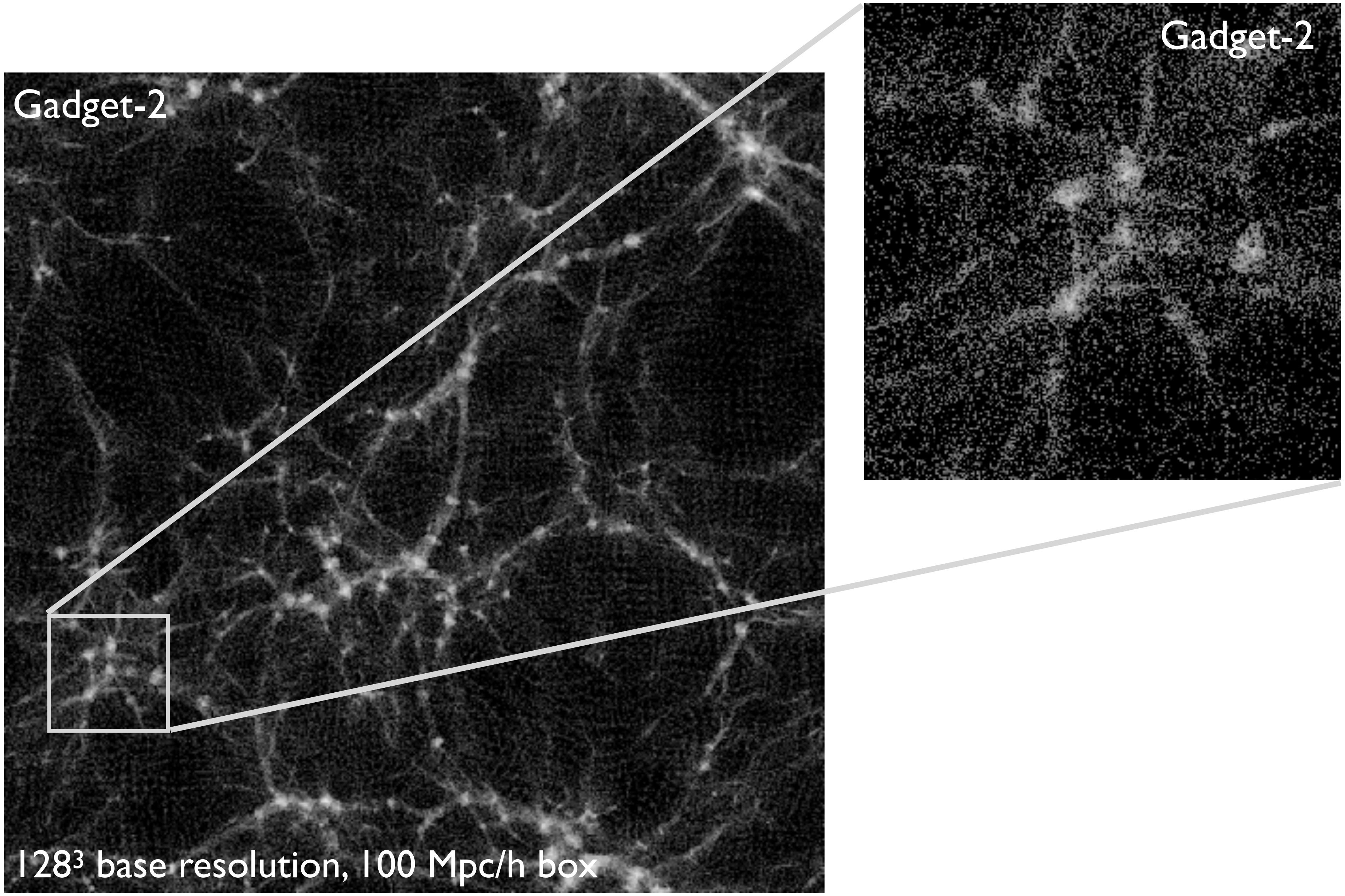

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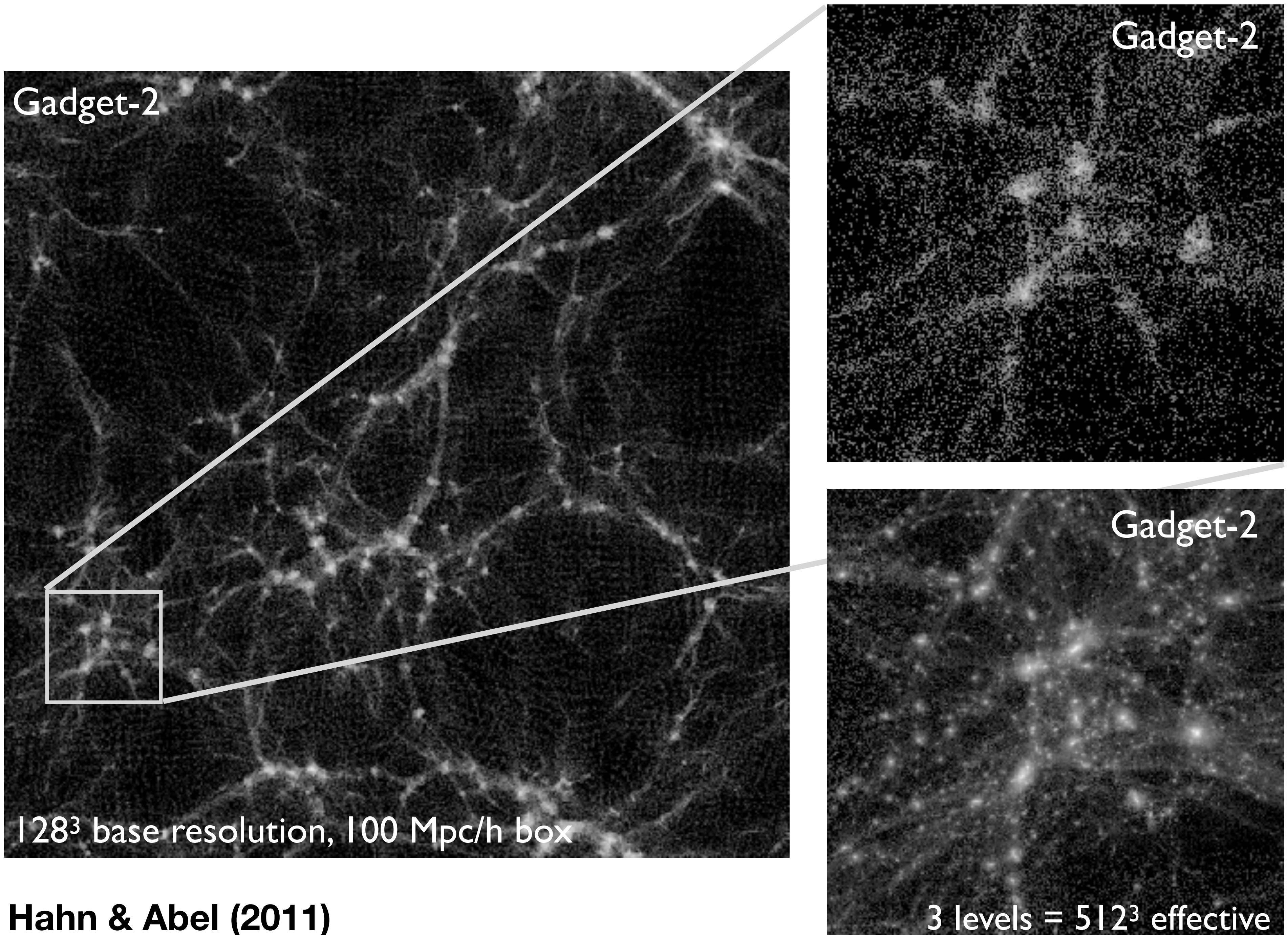

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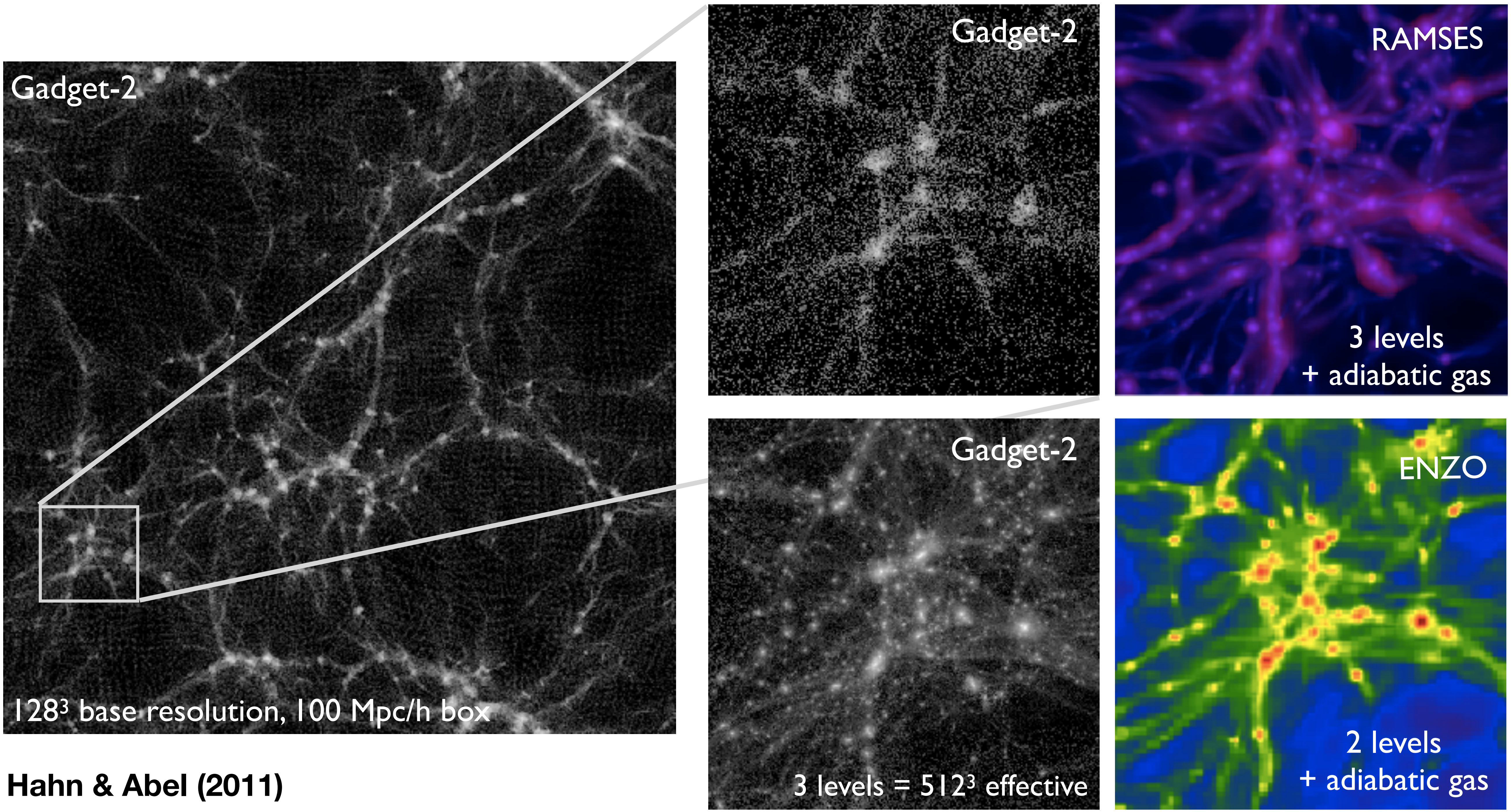
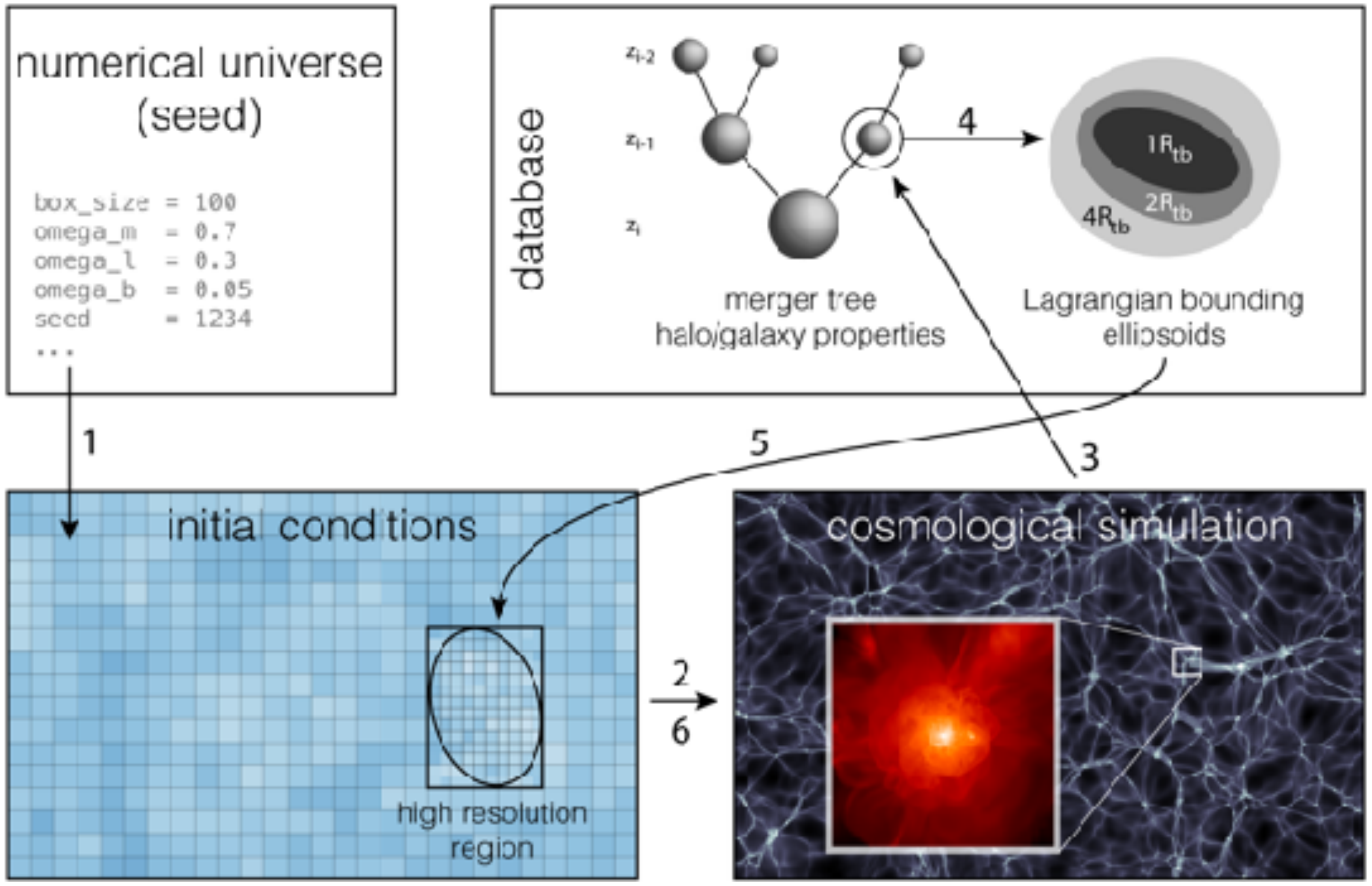


Hahn & Abel (2011)

Motivation for the cosmICweb 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

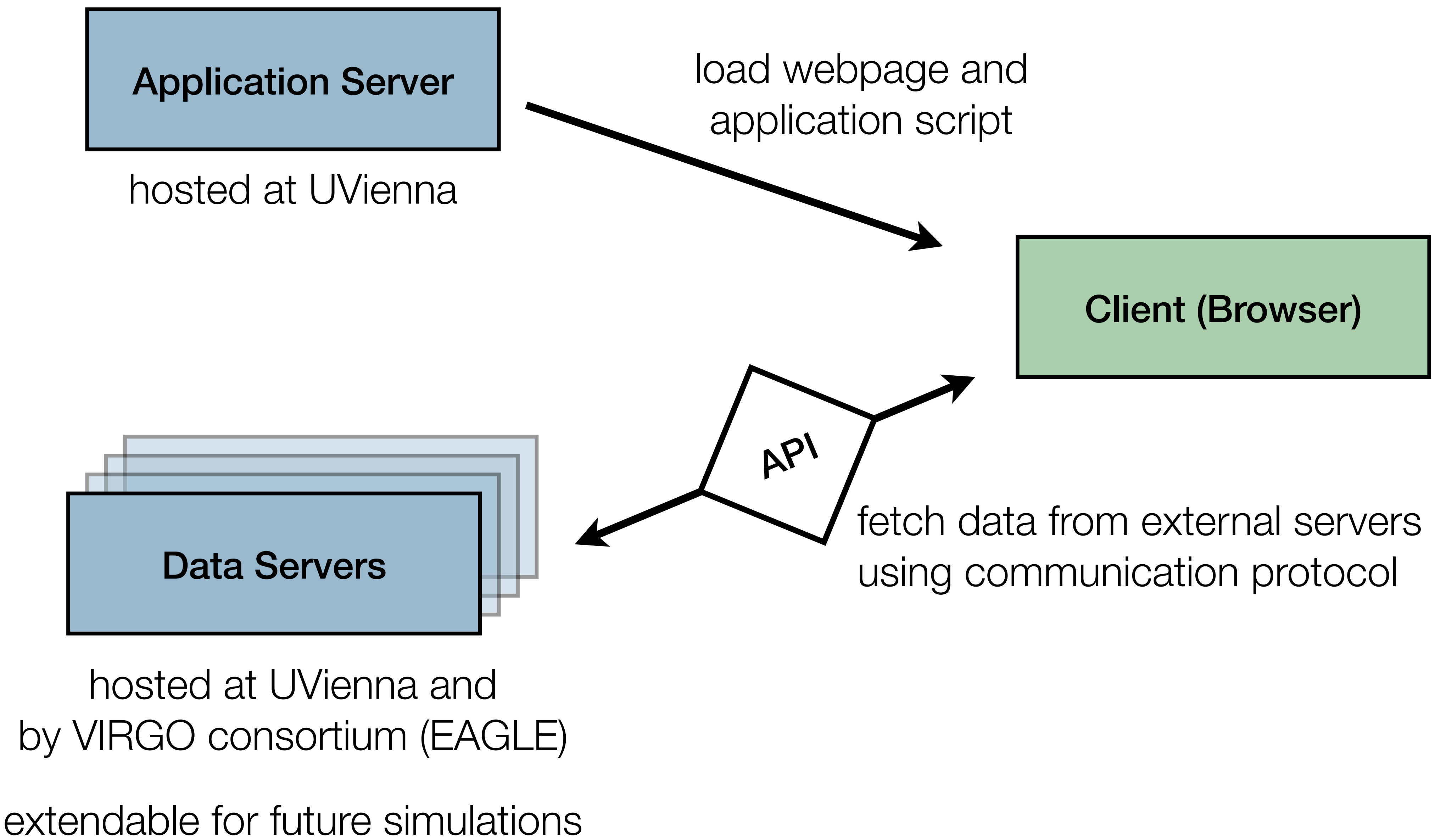
6: run zoom simulation with additional physics, etc.

cosmICweb:
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



Buehlmann+, in prep

Overview of cosmICweb – 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
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Overview of cosmICweb – Workflow

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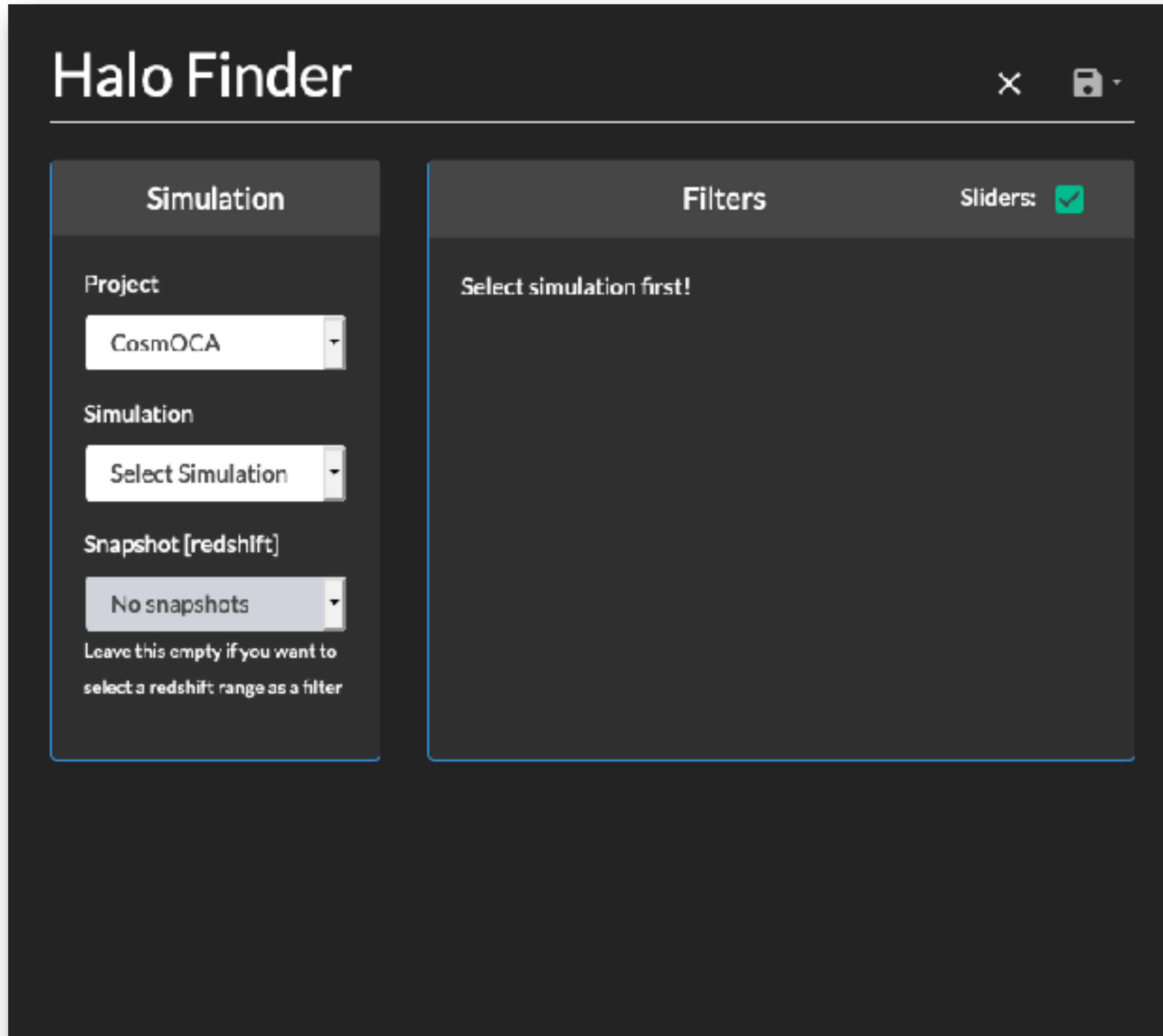

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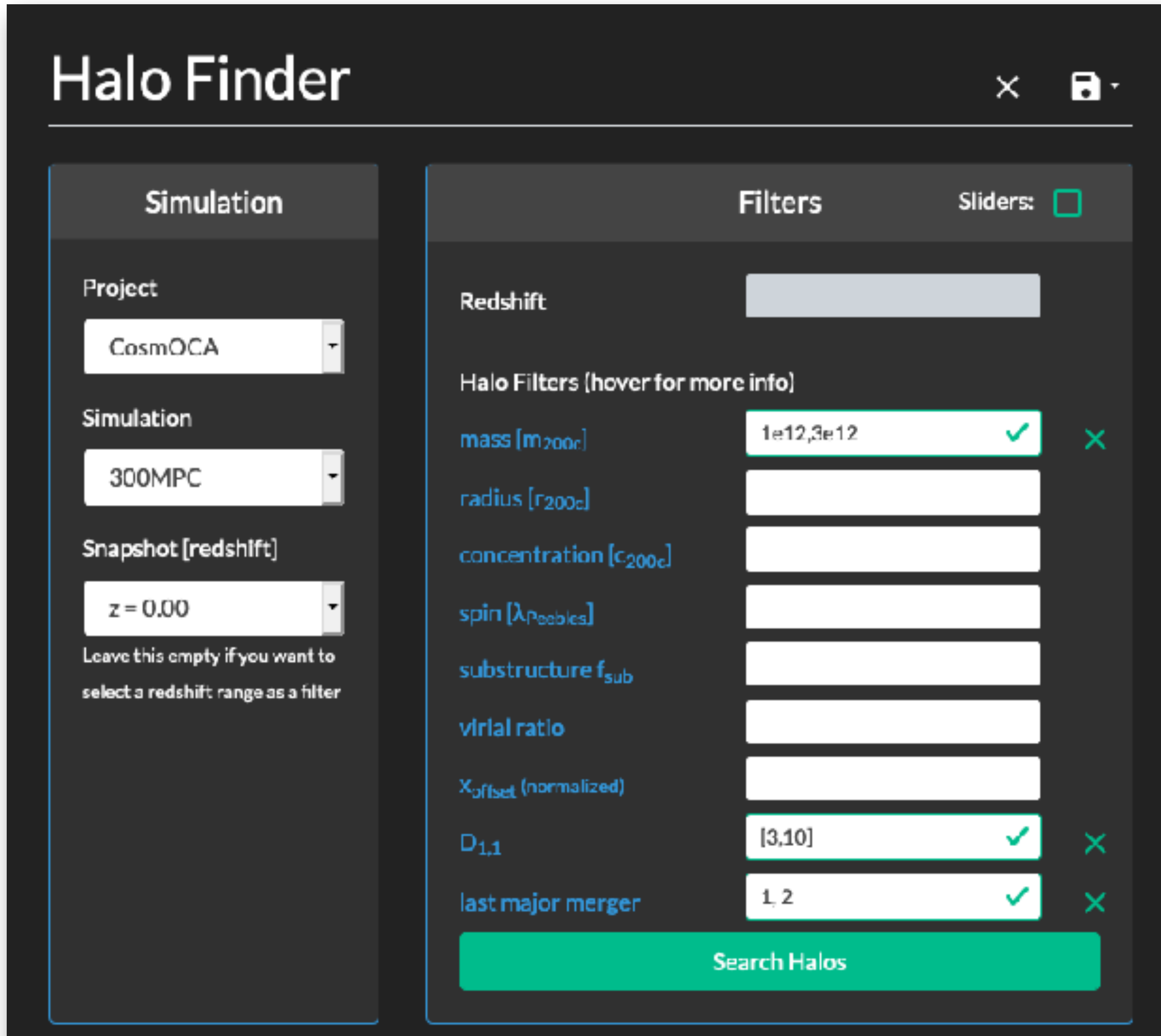

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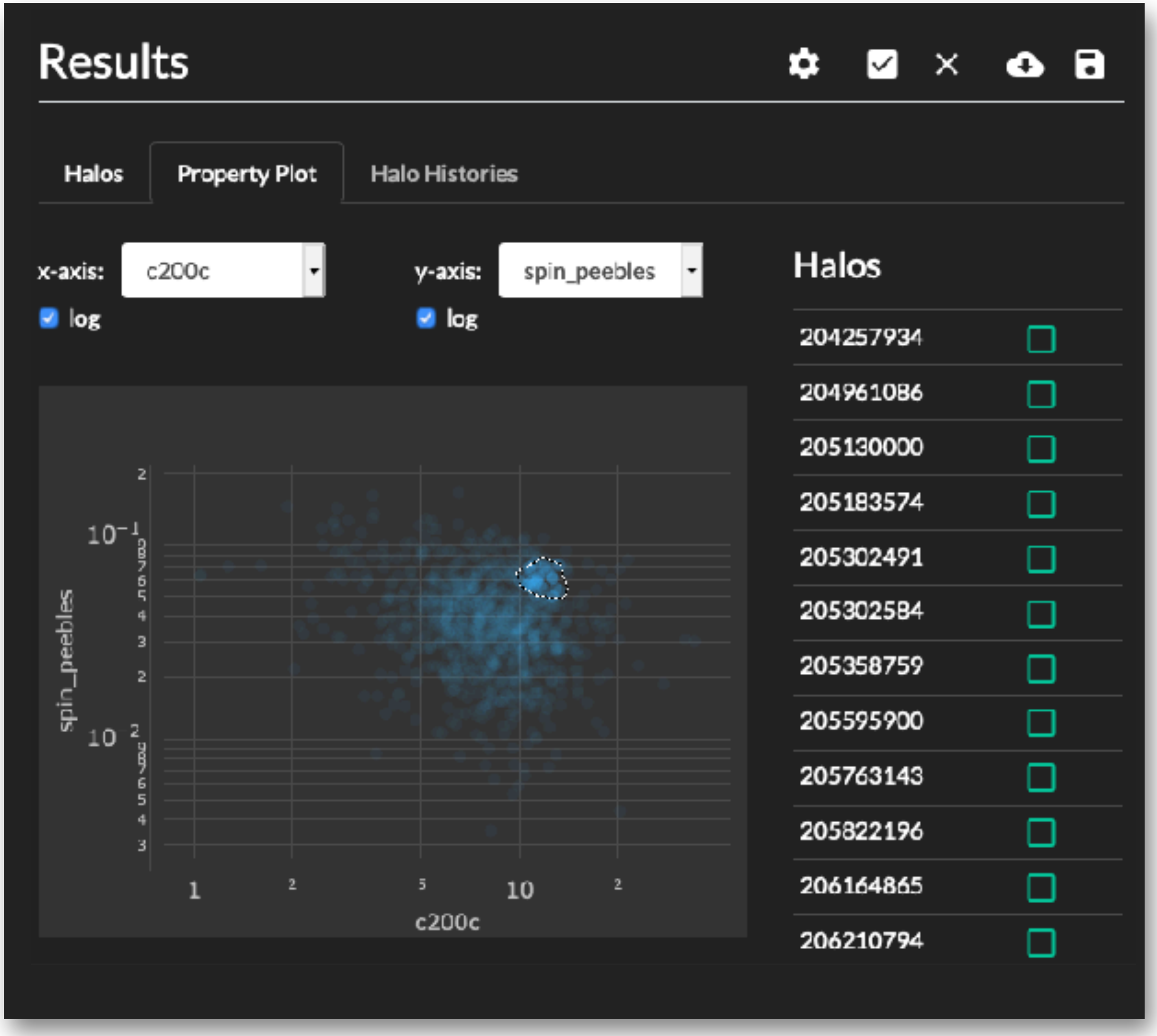

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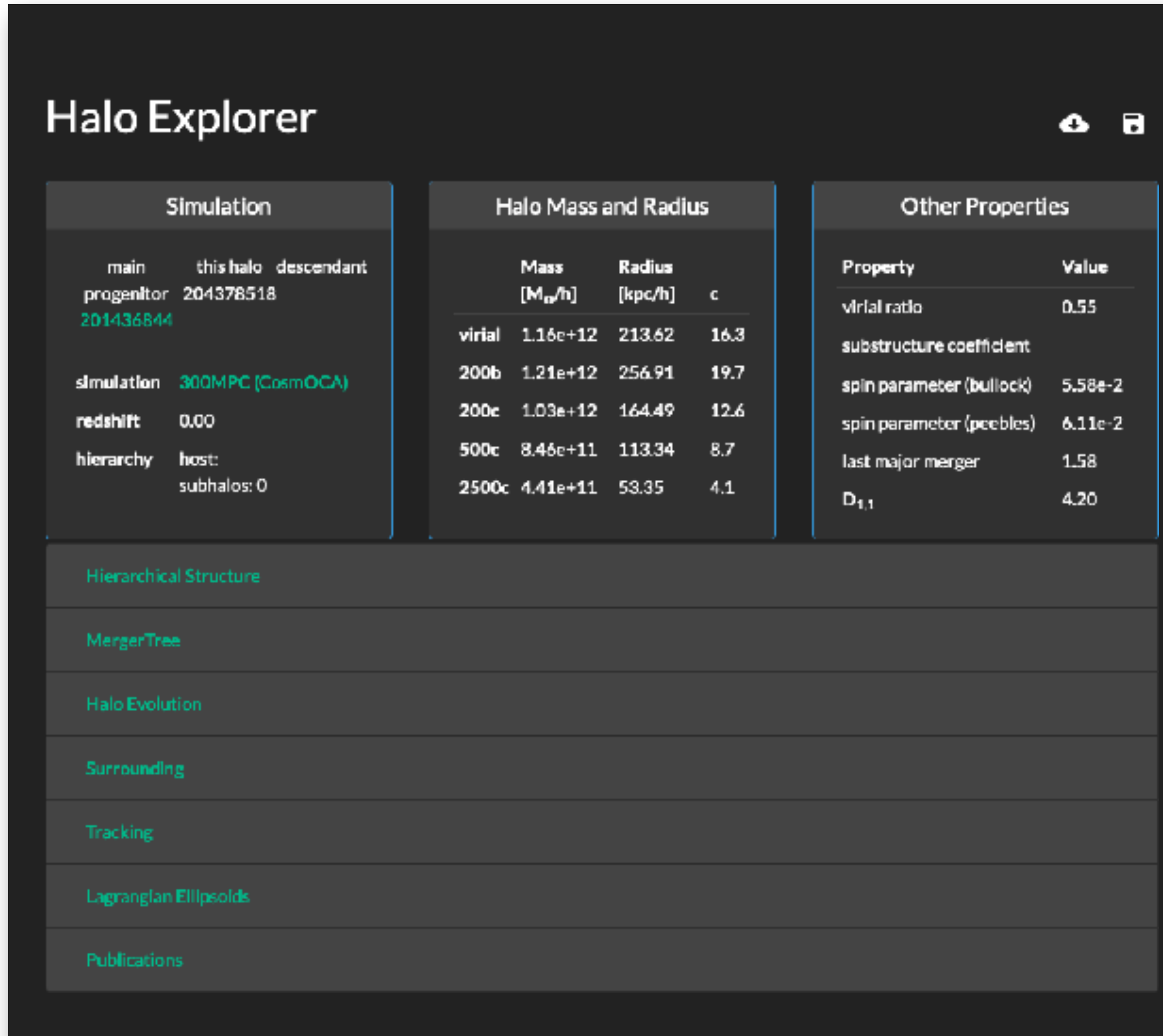

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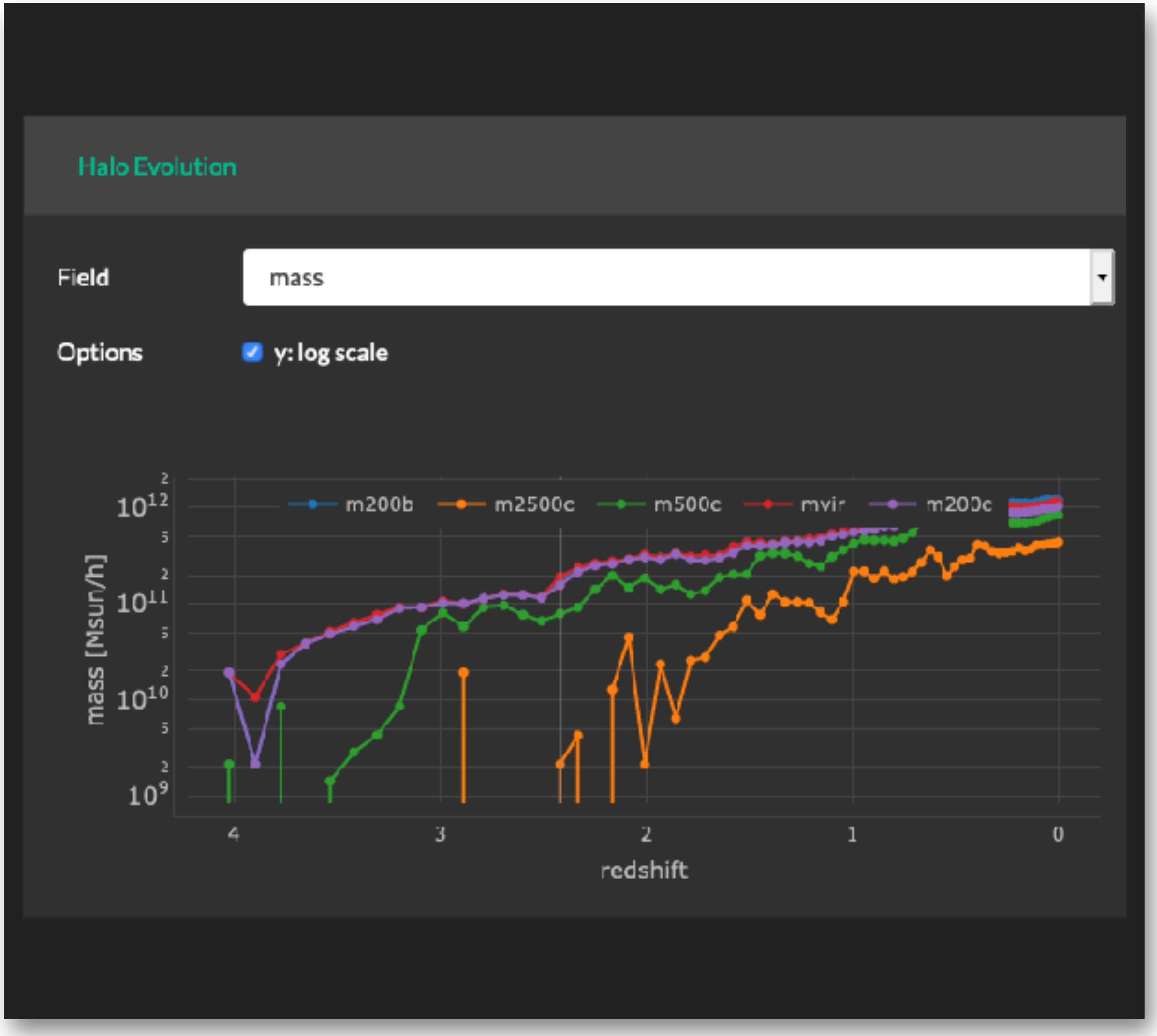

Overview of cosmICweb – Workflow

slide courtesy M. Buehlmann

finding

processing

referencing

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

Download initial conditions

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

Publish initial conditions

9. reference collection
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Research community

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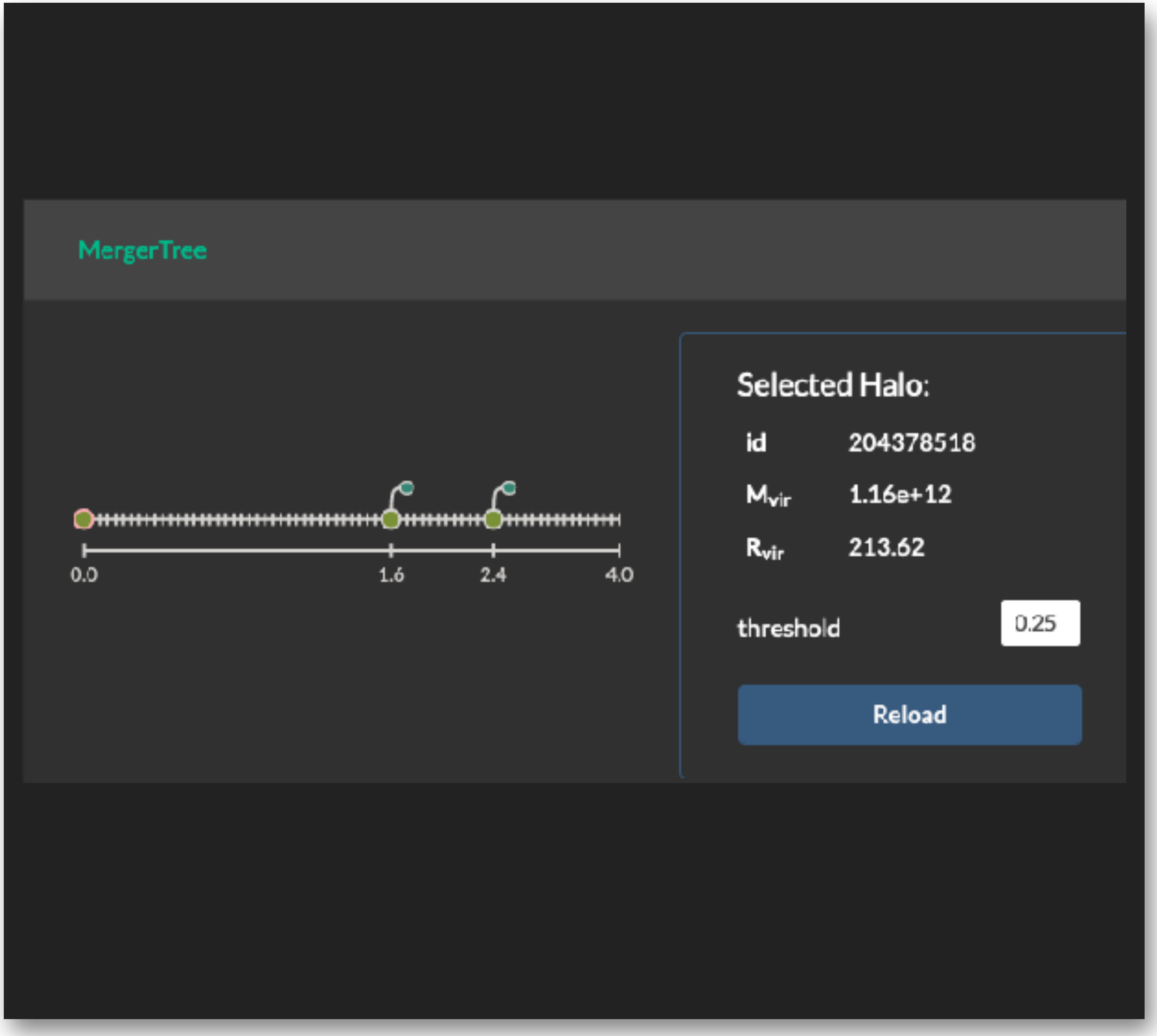

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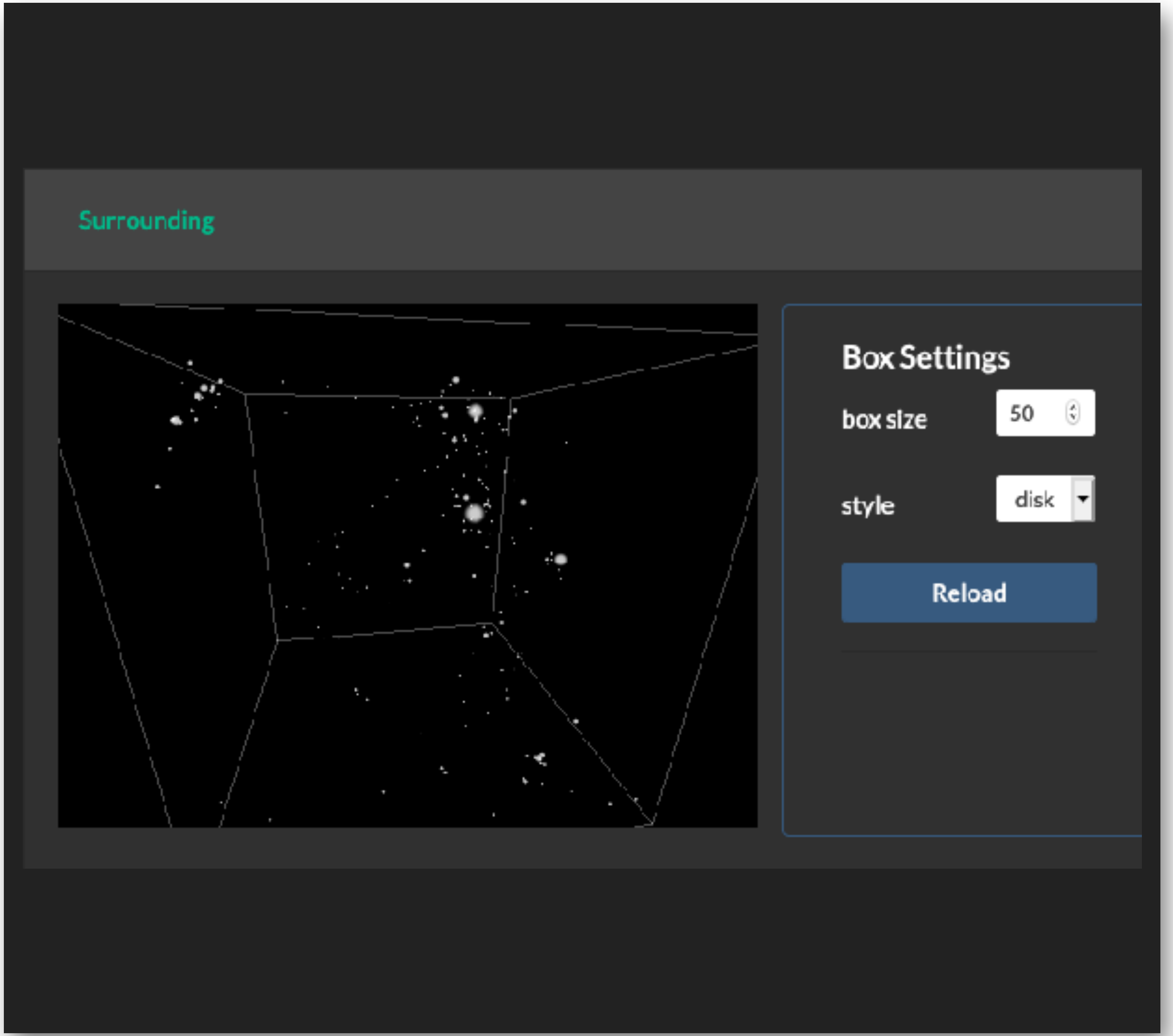

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Lagrangian Ellipsoids

Available Ellipsoids

Traceback radius	Ellipsoid Mass	Efficiency
1.0 Rvir	6.74e+12	0.173
2.0 Rvir	7.84e+12	0.199
4.0 Rvir	1.81e+13	0.143
10.0 Rvir	1.62e+14	0.048

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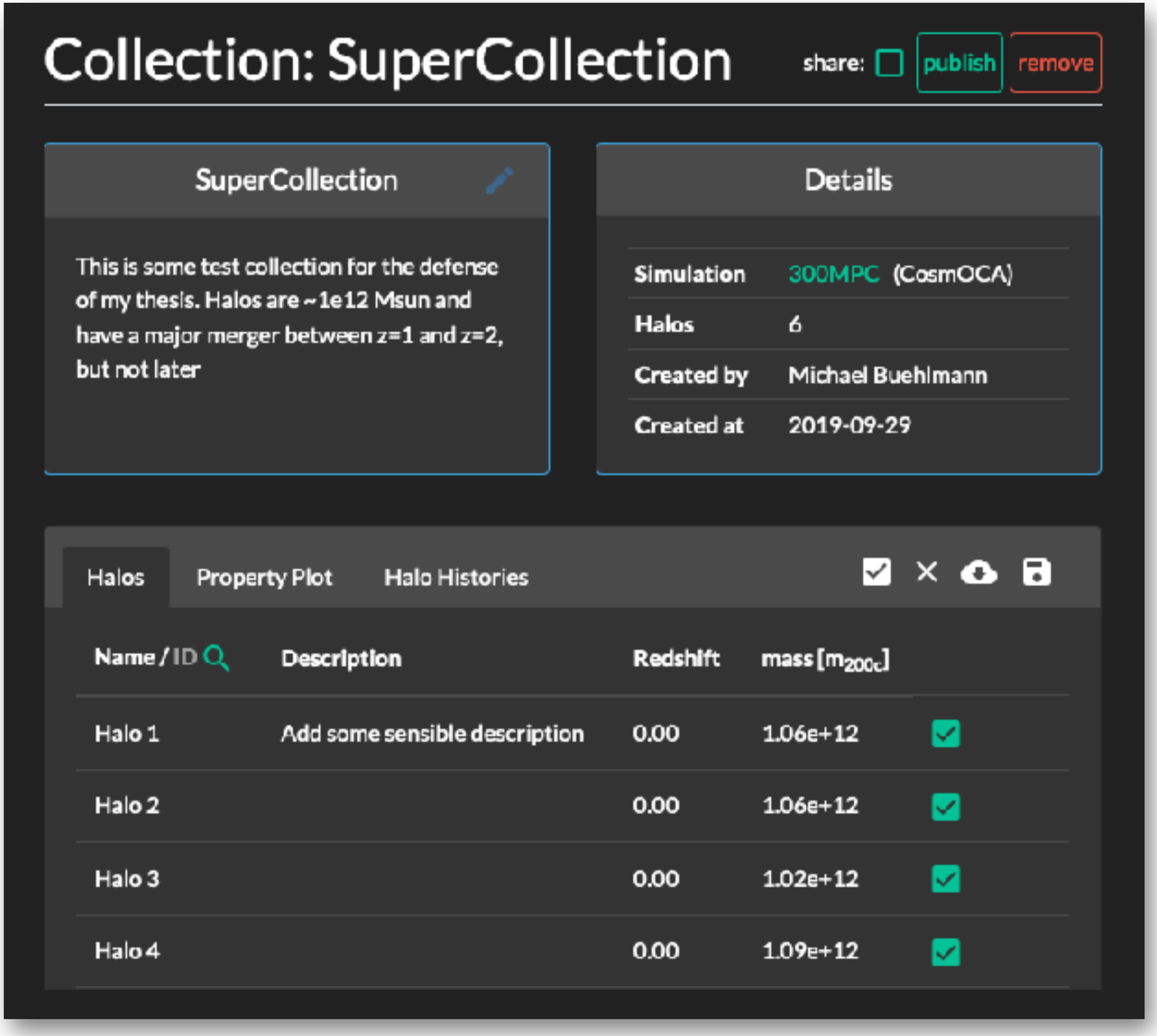

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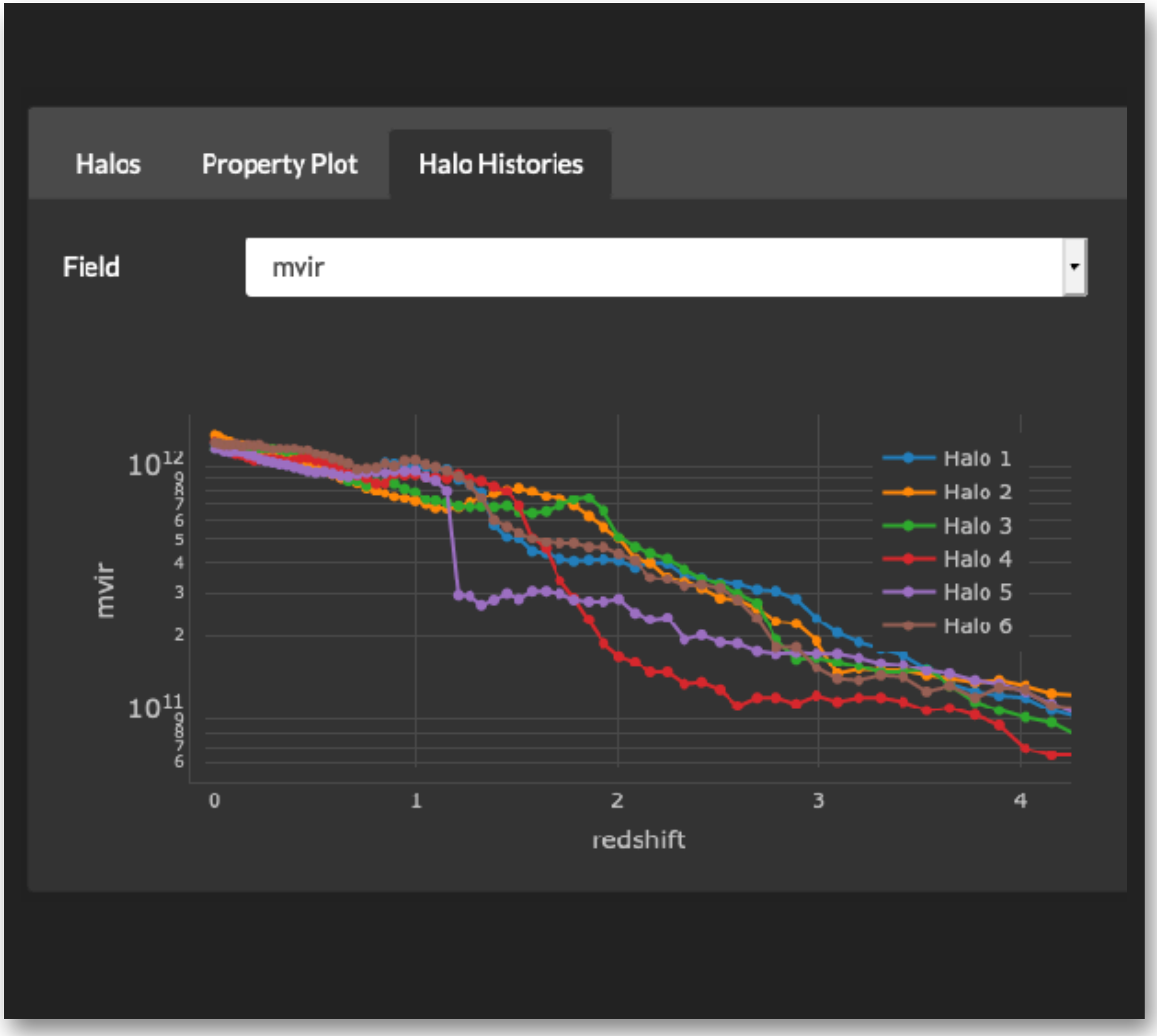

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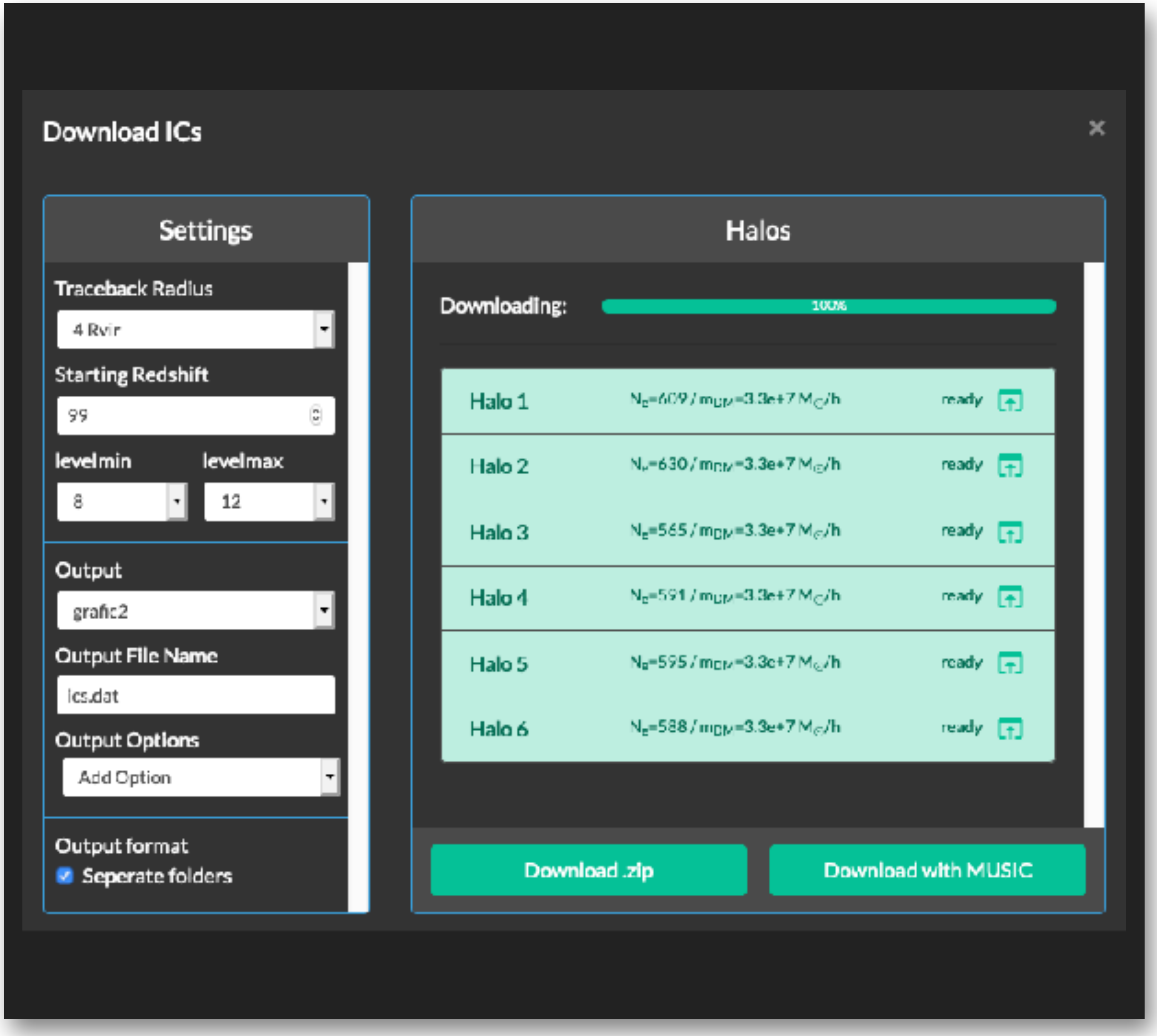

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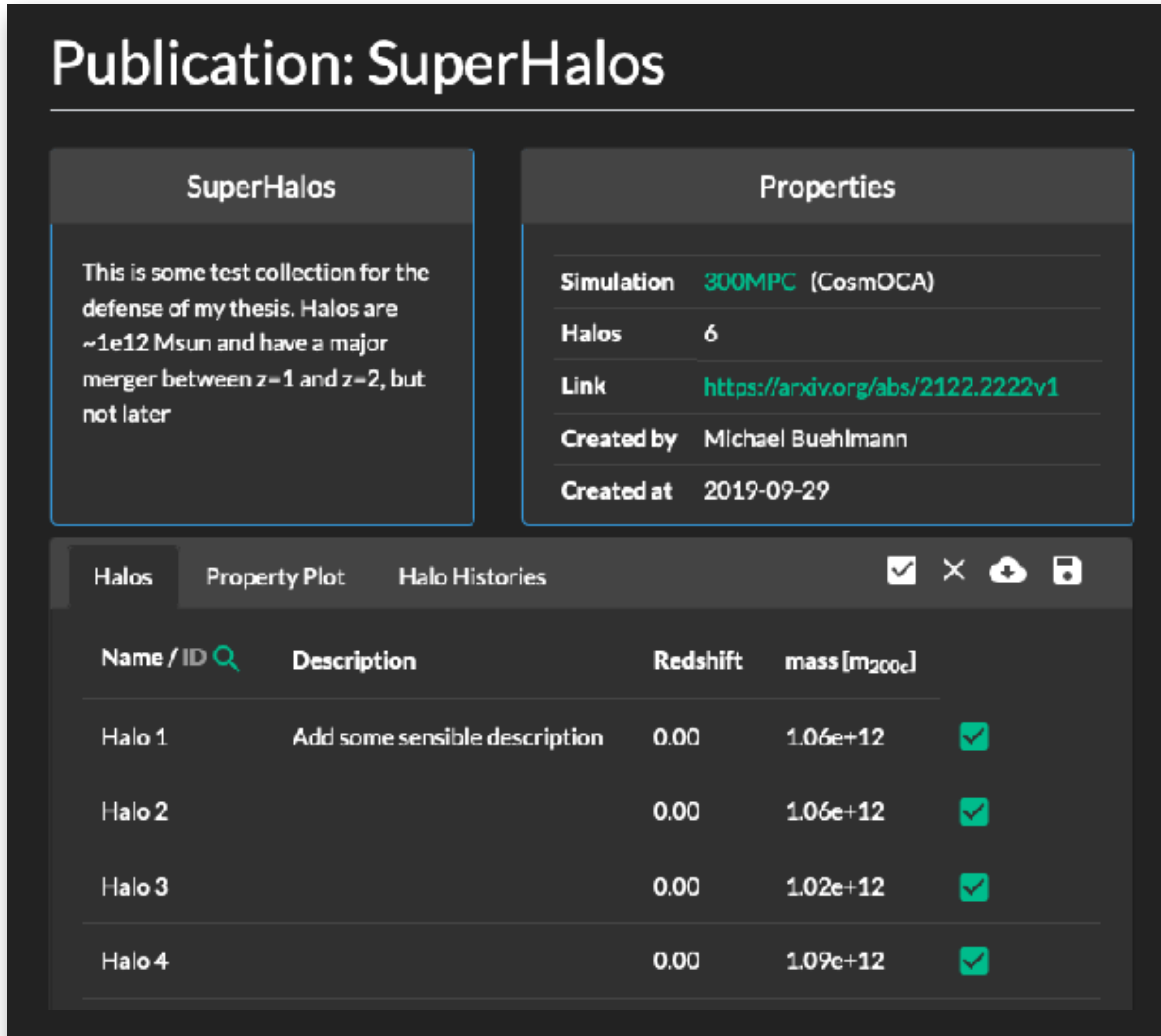


LIVE DEMO

Overview of cosmICweb – Data

Currently:

slide courtesy M. Buehlmann

locally hosted simulations:

- set of DM-only simulations ranging from 60 to 1000 Mpc^3
- 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!

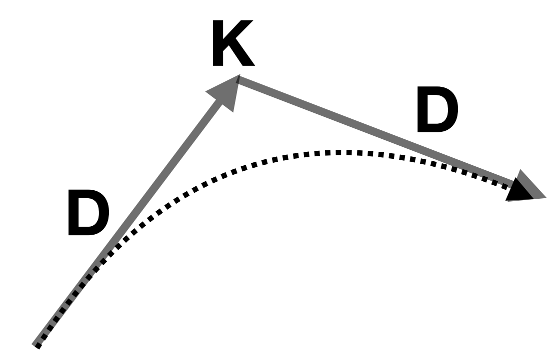
		size $[h^{-1}\mathrm{Mpc}]$	cosmo.	DM resolution $[h^{-1}M_\odot]$	[b]	snapshots $[z_{\max} - z_{\min}]$	structure finder	$N^e_{\min}$
local	150MPC	150	[P1]	2.70×10^8		101 [12 – 0]	ROCKSTAR	100
	150MPC_lowres	150	[P1]	2.16×10^9		101 [12 – 0]	ROCKSTAR	500
	300MPC	300	[P1]	2.14×10^9		101 [12 – 0]	ROCKSTAR	100
	300MPC_lowres	300	[P1]	1.71×10^{10}		101 [12 – 0]	ROCKSTAR	500
	AGORA	60	[W1]	1.21×10^8		101 [12 – 0]	ROCKSTAR	1000
	RHAPSODY	1000	[W2]	6.46×10^{10}		101 [12 – 0]	ROCKSTAR	1000
	RHAPSODY_NewCosmo	1000	[P1]	7.99×10^{10}		101 [12 – 0]	ROCKSTAR	1000
EAGLE	Ref-L0025N0376	16.94	[P2]	6.57×10^6	✓	29 [20.3 – 0]	FoF & SUBFIND	1000
	L0025N0376	16.94	[P2]	7.63×10^6		29 [20.3 – 0]	FoF & SUBFIND	1000
	Ref-L0100N1504	67.77	[P2]	6.57×10^6	✓	29 [20.3 – 0]	FoF & SUBFIND	1000
	L0100N1504	67.77	[P2]	7.63×10^6		29 [20.3 – 0]	FoF & SUBFIND	1000

[b]: run with baryonic physics

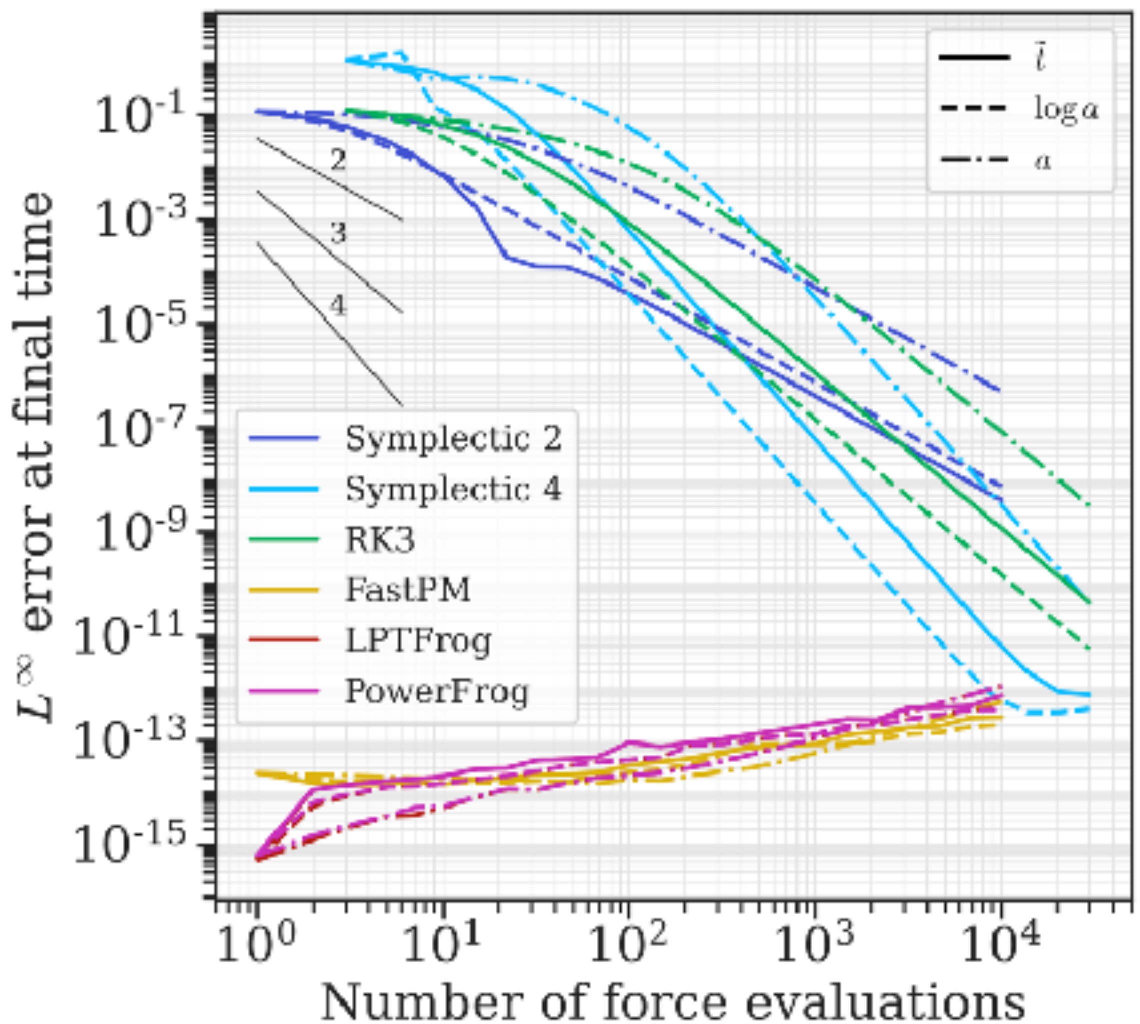
Get in touch if you'd like to add yours!

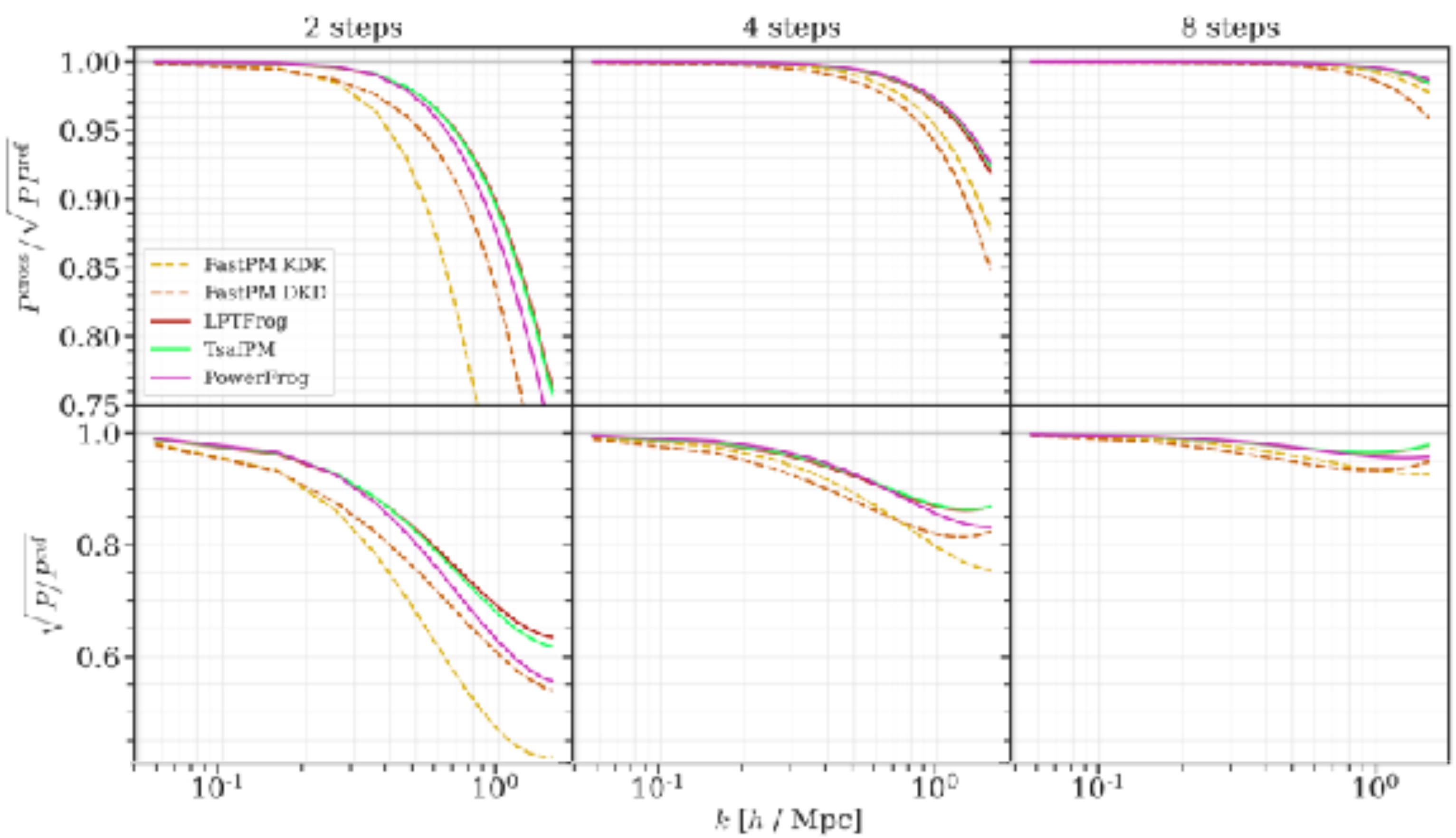
Perturbation-theory informed integrators

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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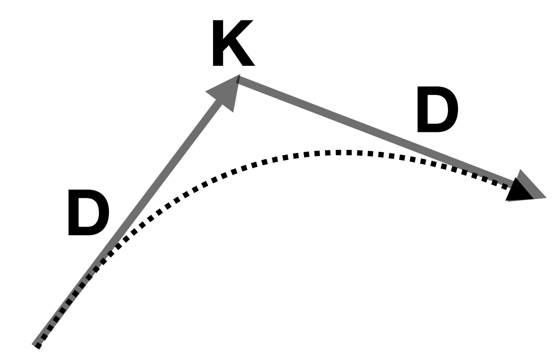

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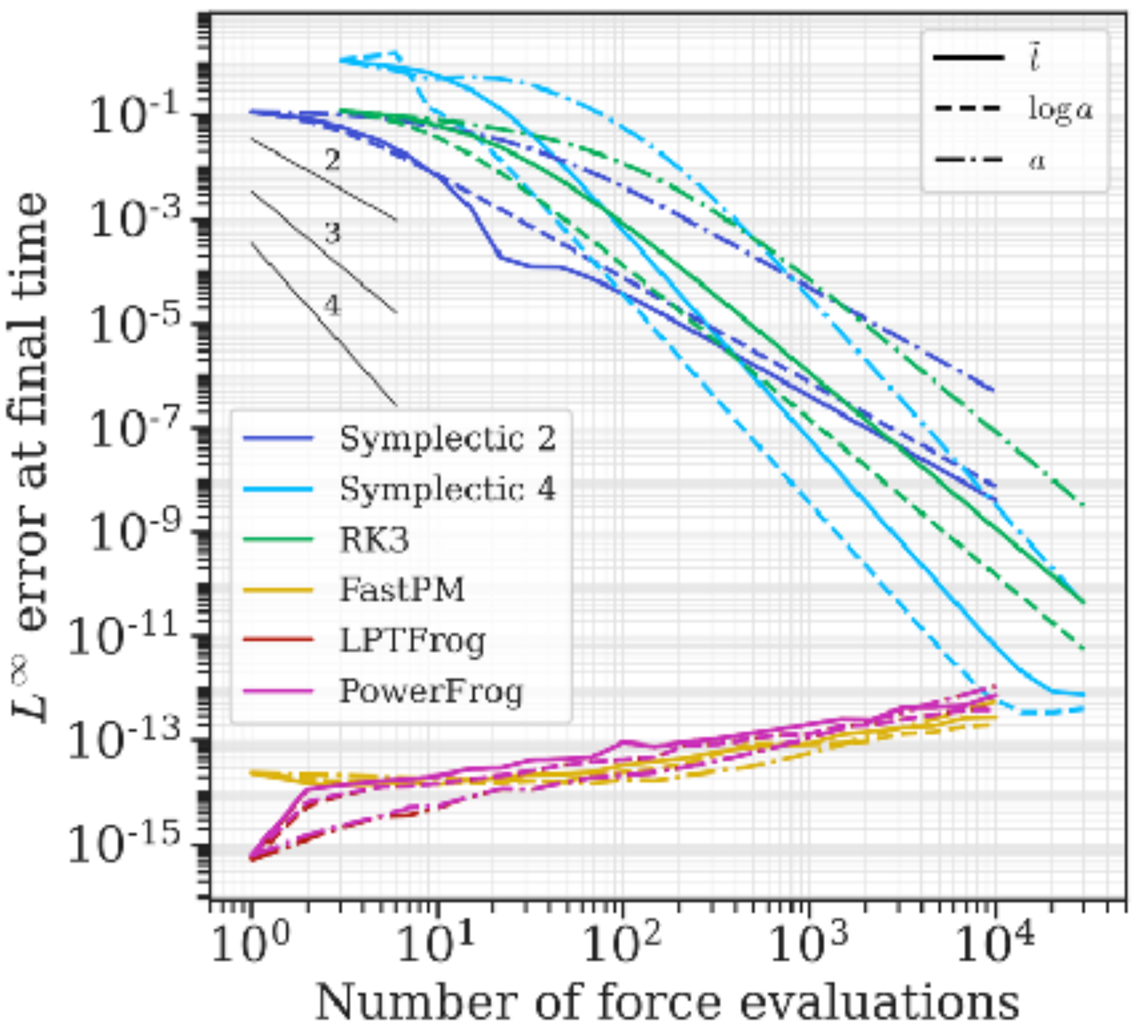
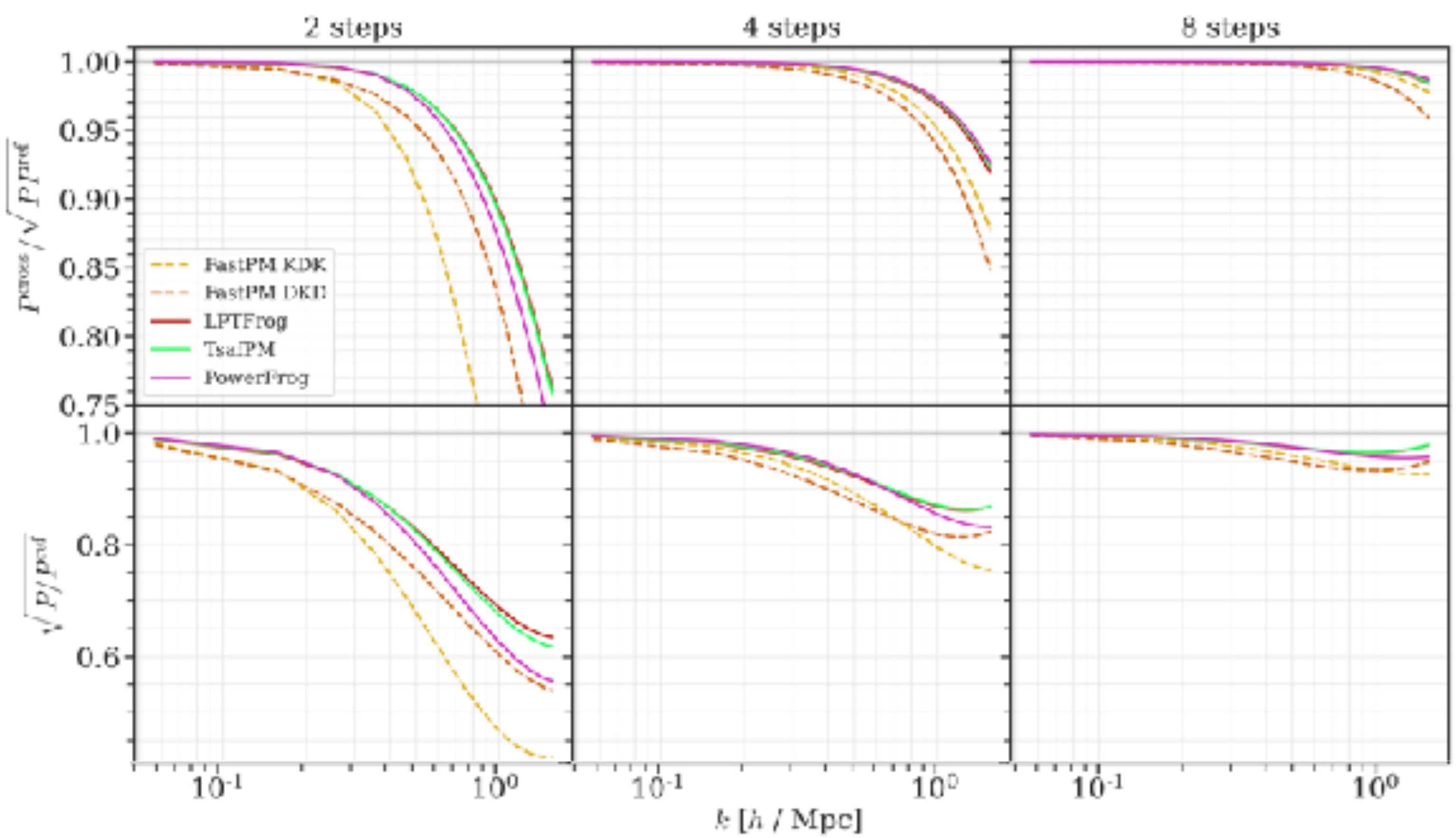


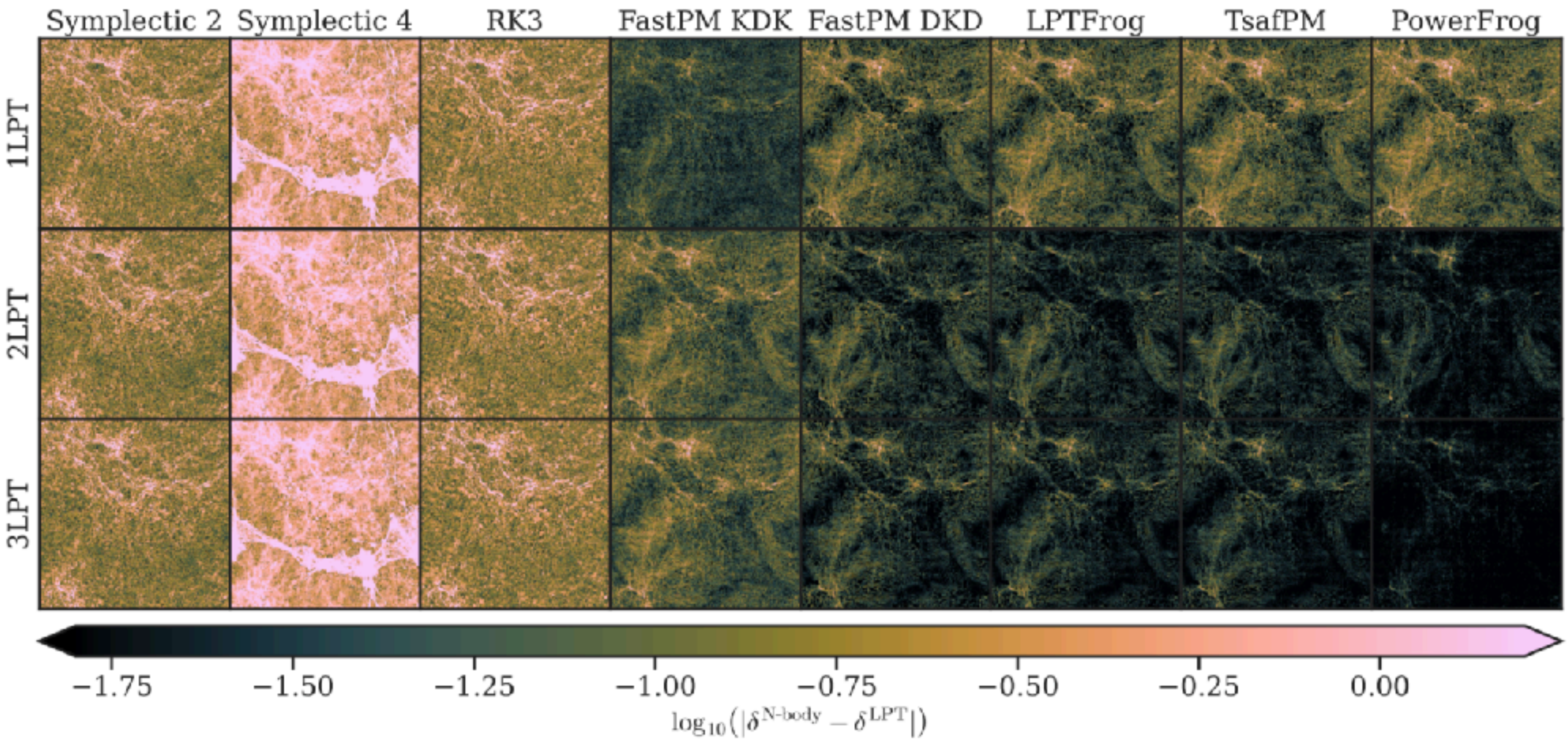


List&Hahn 23

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

Perturbation-theory informed integrators

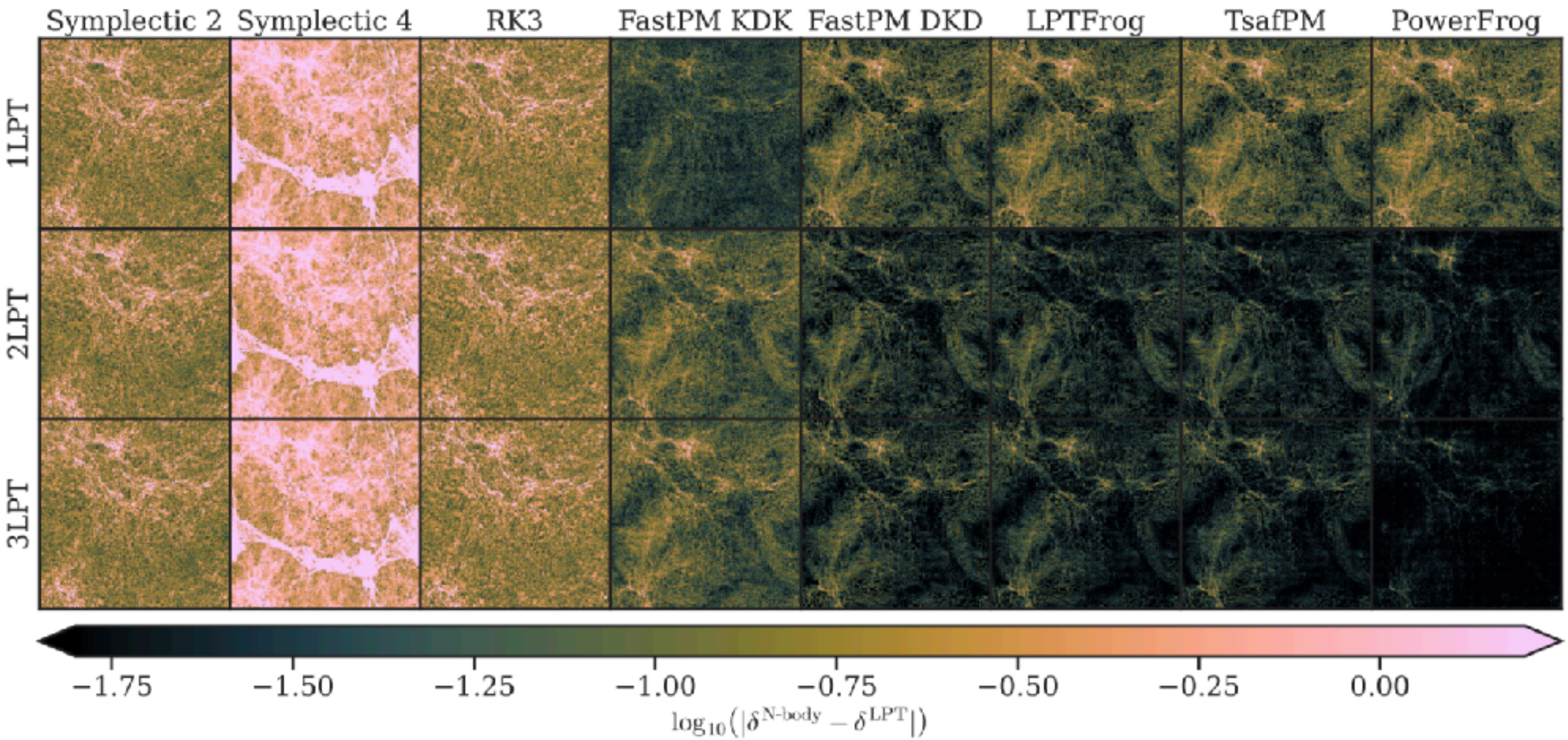
Residual between PTinformed and LPT:



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