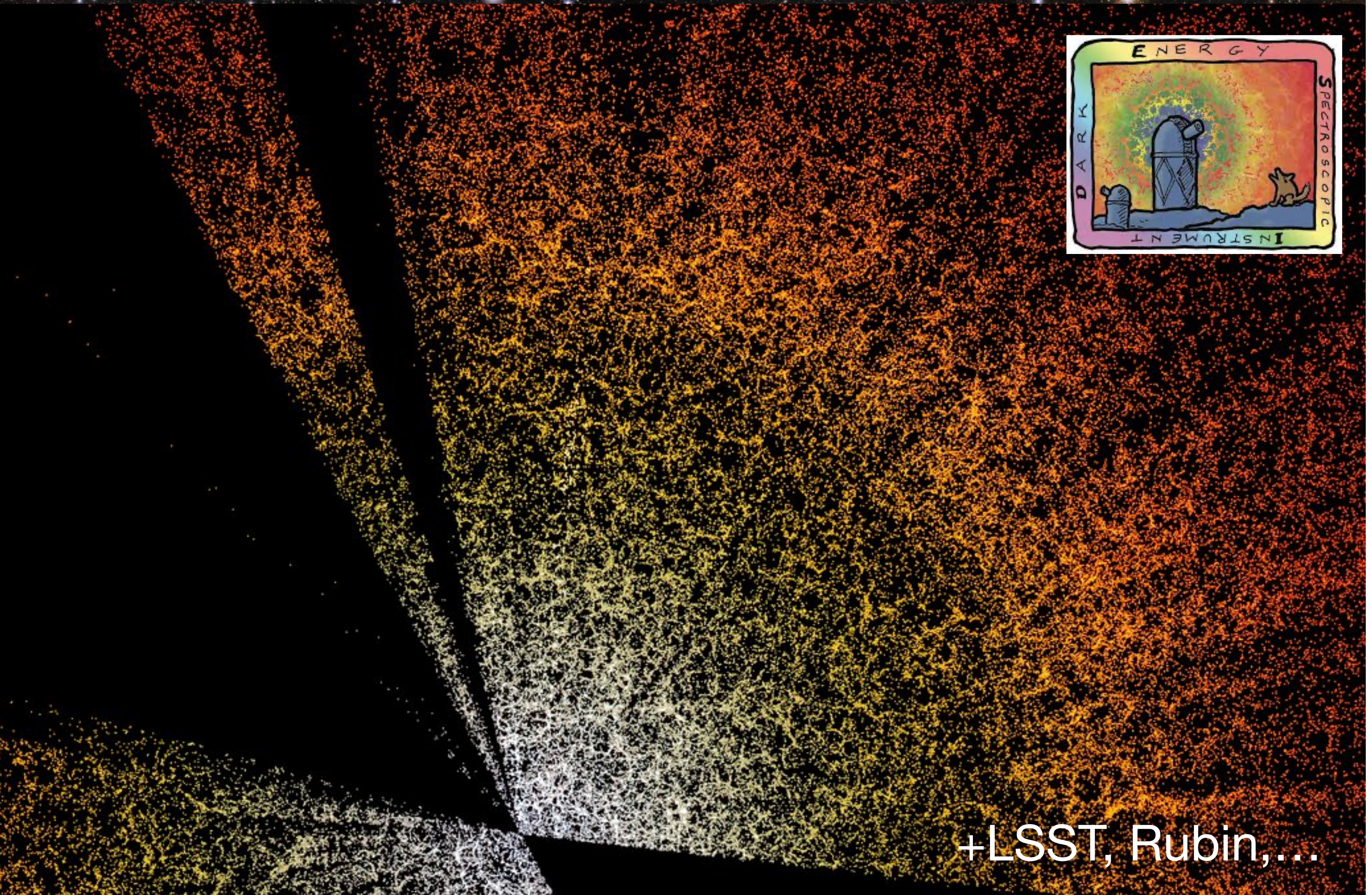
Differentiable Modelling for Cosmology

Oliver Hahn
Dept. of Mathematics & Inst. f. Astrophysics
University of Vienna

Work mostly with Florian List, Cornelius Rampf, Natalia Porqueres, Lukas Winkler

02 Apr 2024, ALPS24, Obergurgl, Austria



Precision Cosmology Post-CMB

era of large-scale structure has begun

key questions remain

- law of gravity? any deviations from GR?
- any hints beyond cosmological constant? w(z)?
- initial conditions? what inflation?
- dark matter nature?
- neutrino masses?

huge model space (DM,DE,MG,inf)

multi-probe era

significantly more accurate modelling will be needed than so far…

Classical approach

Model

Cosmological parameters
$\theta = \{\Omega_m, \Omega_b, H_0, \sigma_8, \ldots\}$

H_0 $\Omega_m, \Omega_\Lambda, \Omega_b,$ σ_8 $n_s, A_s,$ $\sum m_\nu,$ w_0, w_a

Energy content | Primordial/ Inflation | massive Neutrinos | dark energy EOS

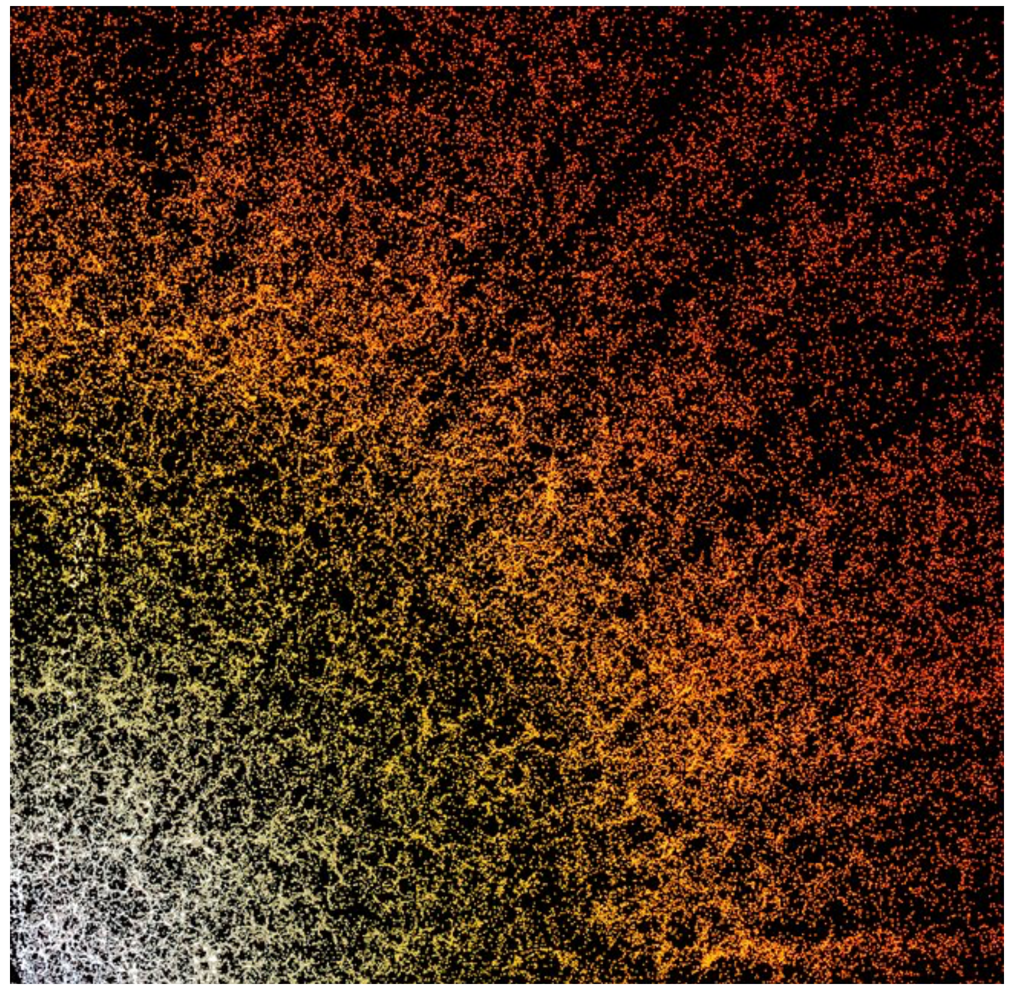
General relativity
Inflation
Nature of Dark Matter
Astrophysics

model PS

fit

estimate PS

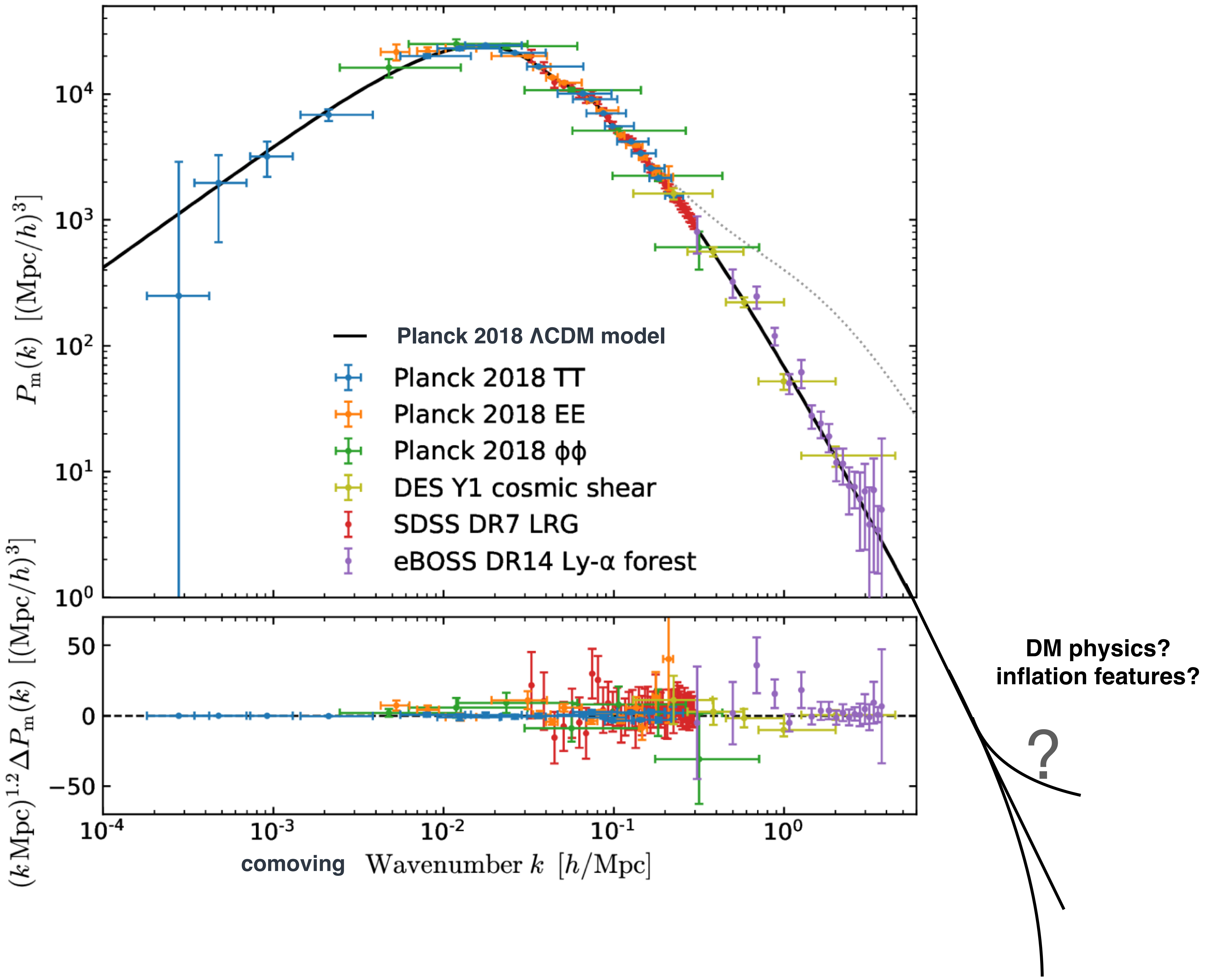
Data



DESI collaboration

Summary Statistic (2pt, 3pt, ...)

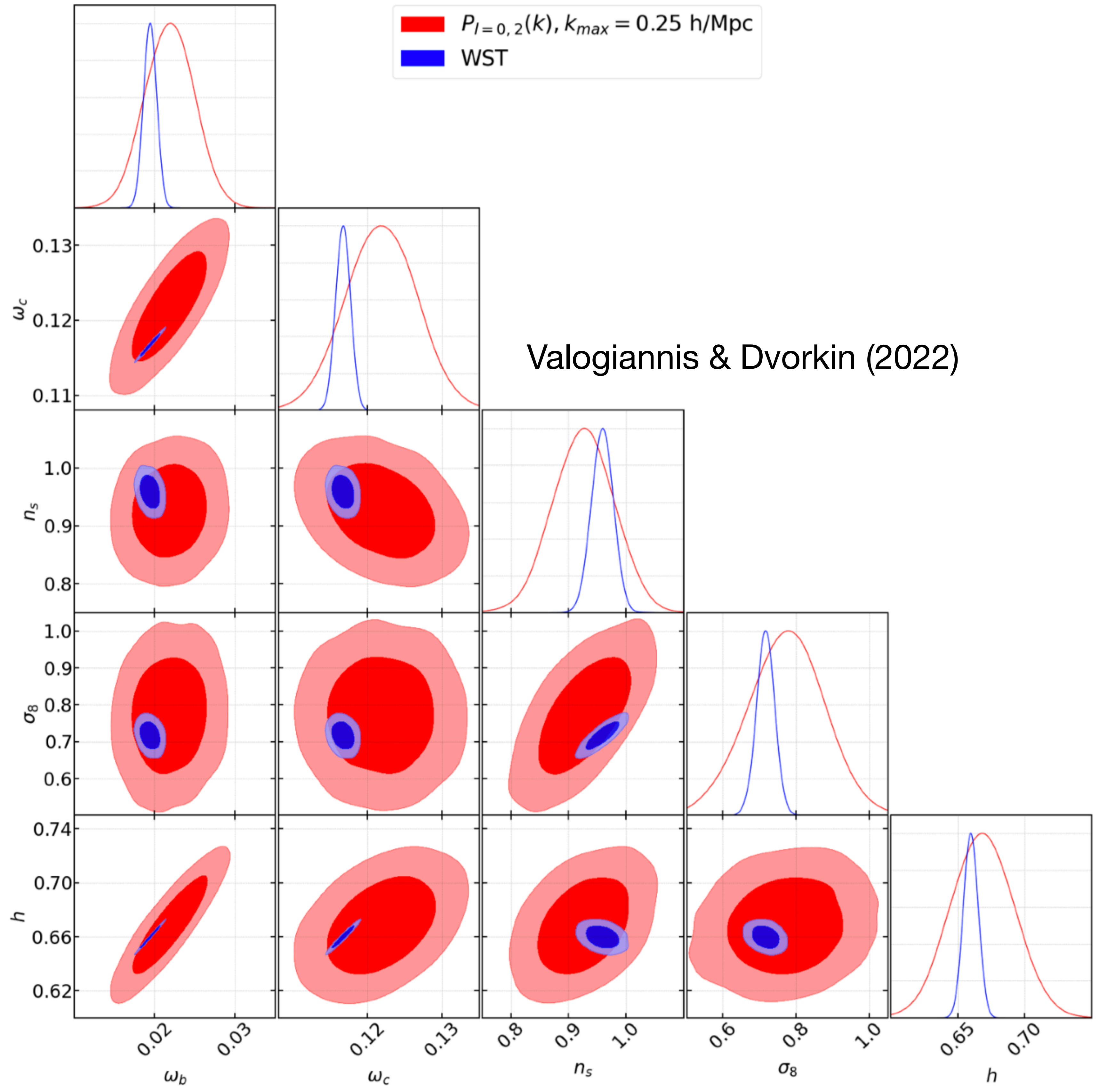
Chabanier et al. 2019



Move beyond simple statistics

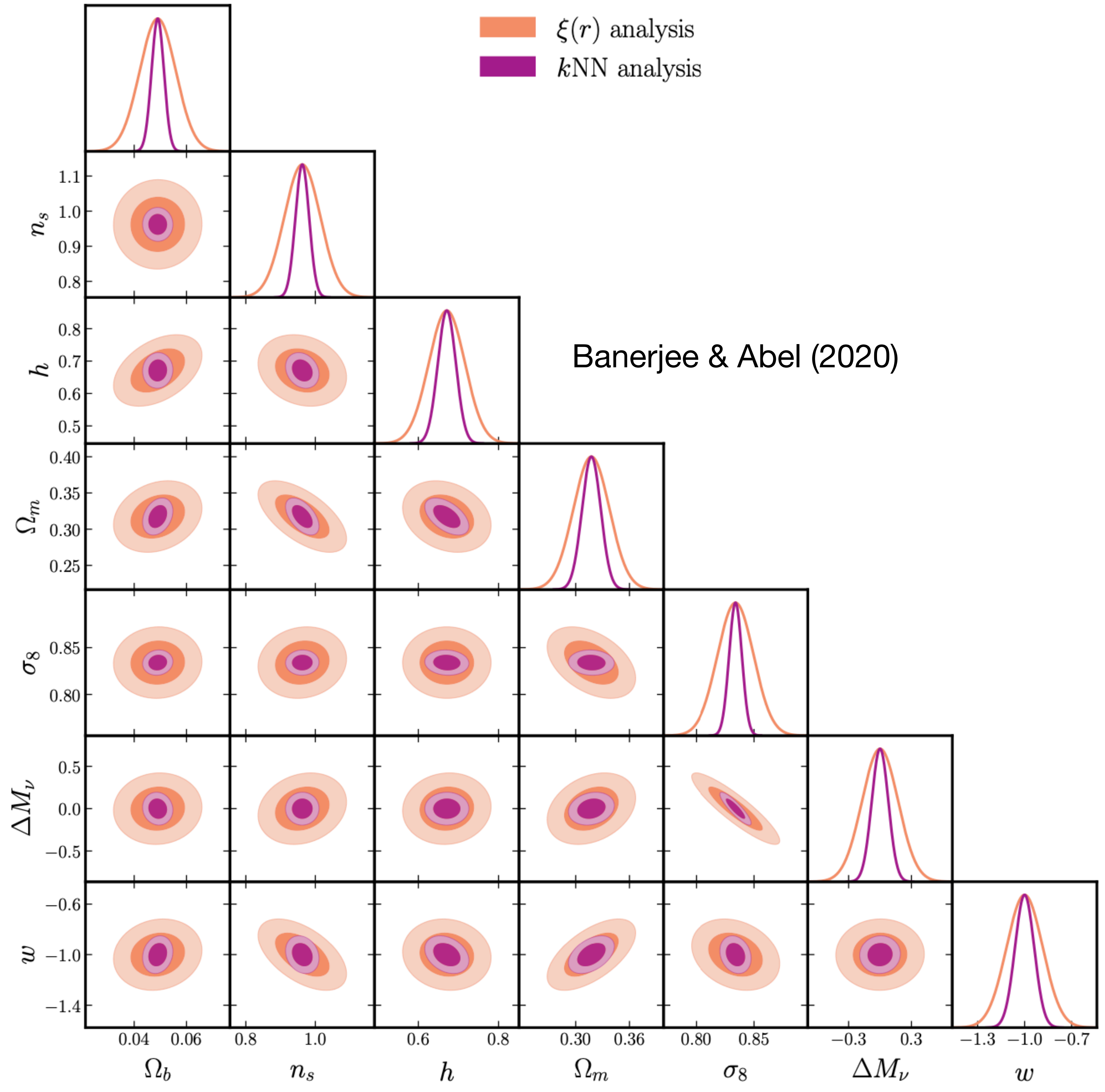
- two-point statistics is complete description only for Gaussian fields
- n-point functions are useful in weakly non-Gaussian case, others exist:

Wavelet Scattering Transform Mallat 2012, Cheng+2020



Valogiannis & Dvorkin (2022)

kNN statistics Banerjee & Abel (2020)



Banerjee & Abel (2020)

- alternative: ‘field-level modelling’: use all data without a priori compression, model observables

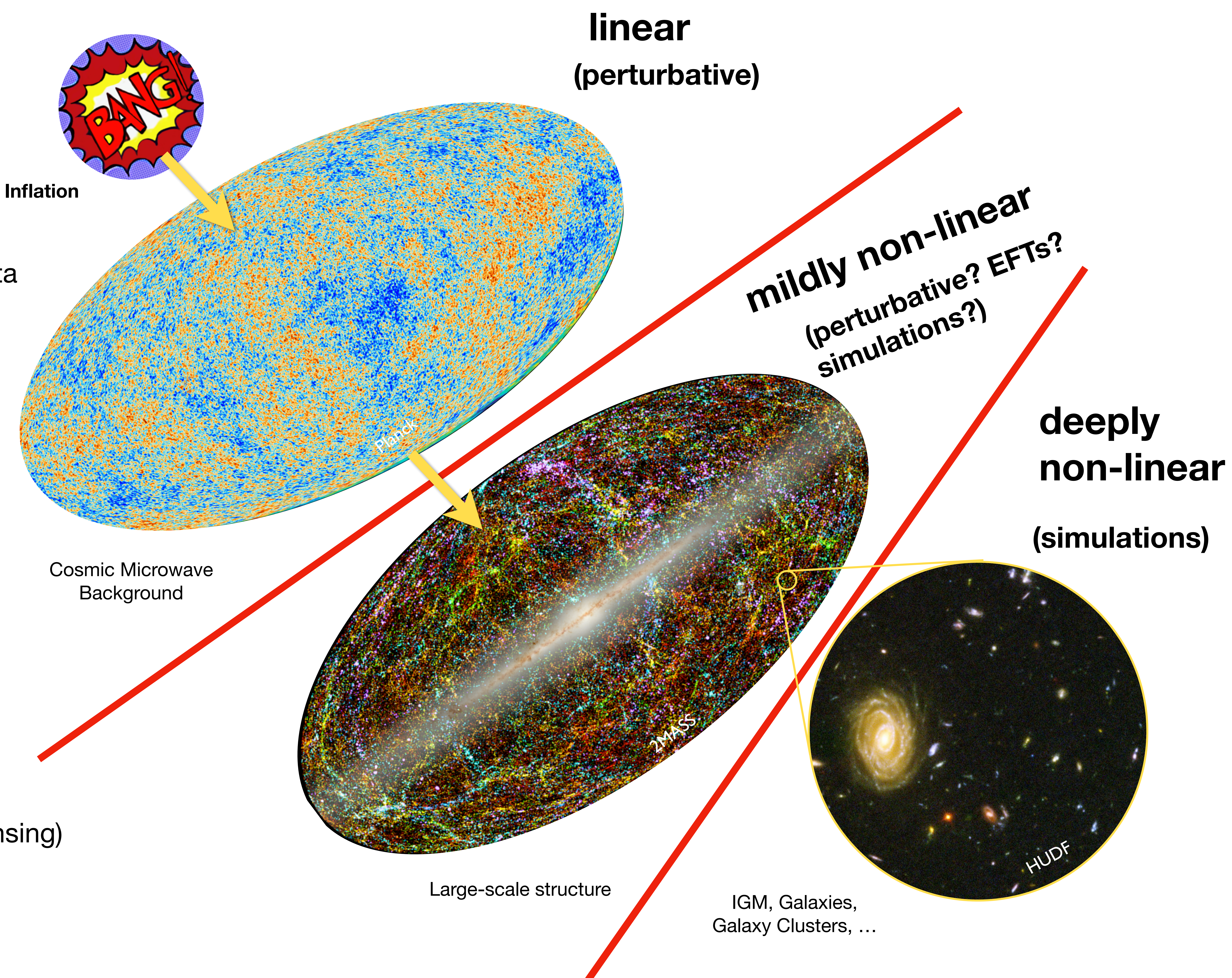
The forward model

Modelling challenge:

predict mapping between physical model and all observables

taking into account uncertainties, and all cross correlations

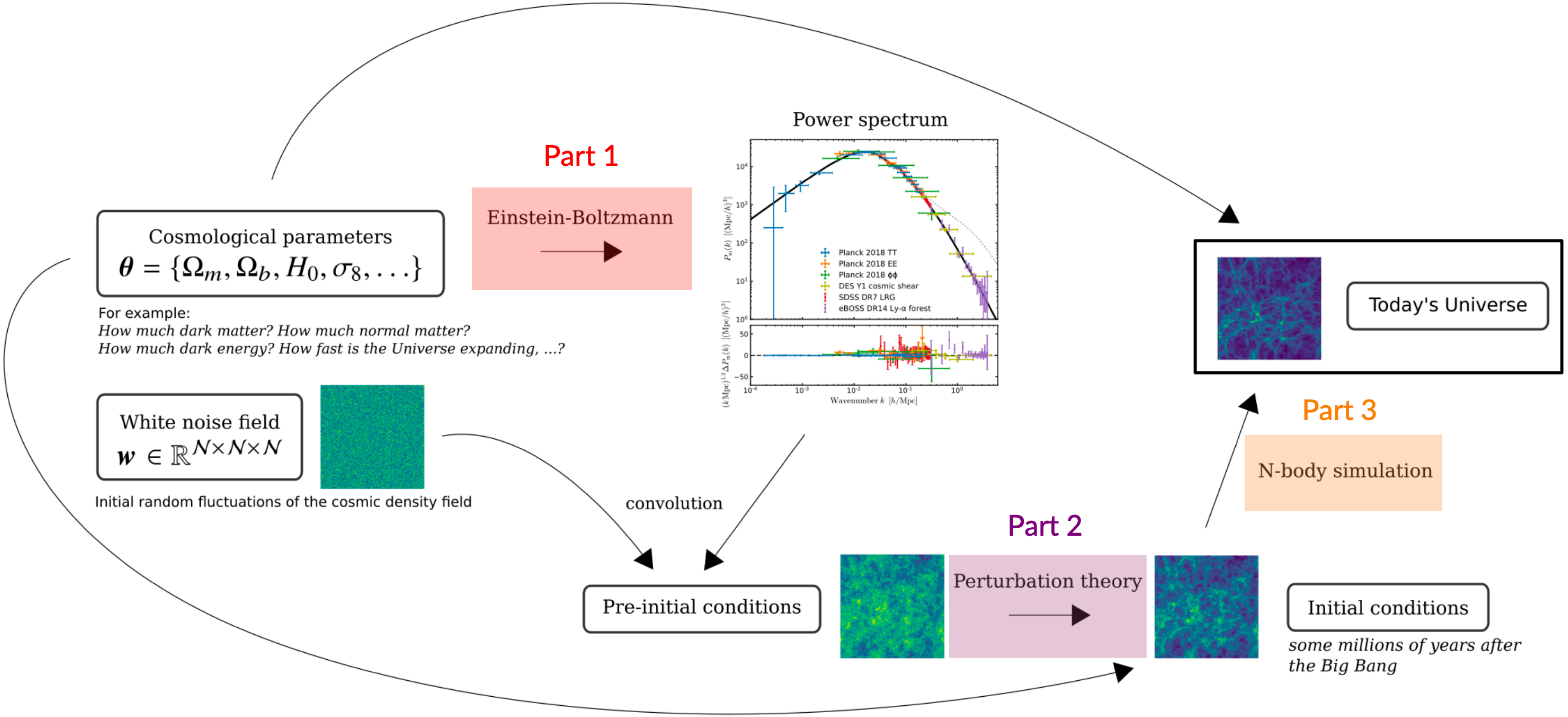
inference limitation is from modelling, not data already with current surveys!



Astronomical Survey Observables

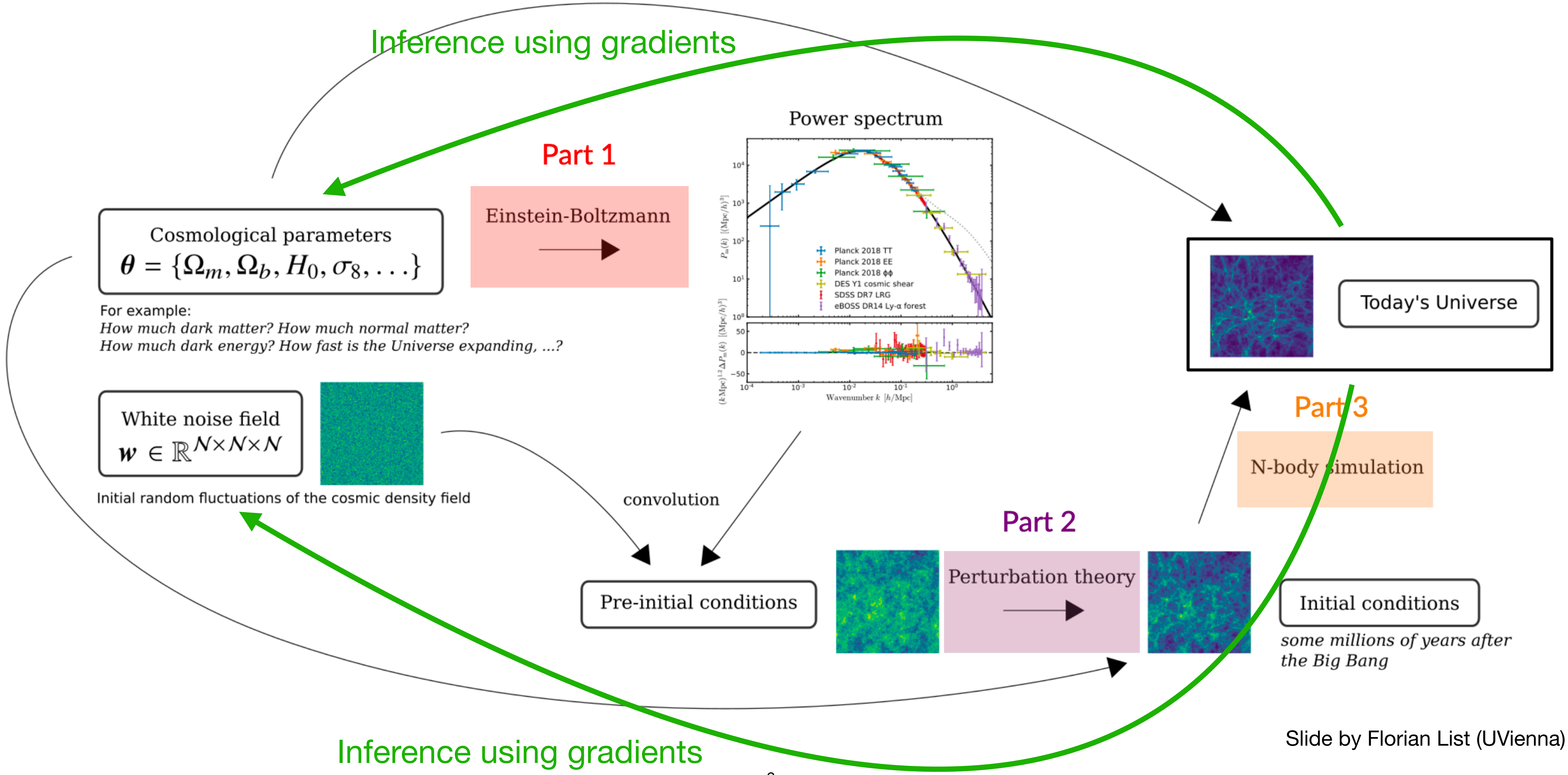
Galaxy distribution (clustering, n-point, etc.)
Gravitational Lensing (weak, strong, CMB lensing)
Galaxy Clusters (optical, X-ray, tSZ)
Ly-a, HI mapping

Field-level modelling



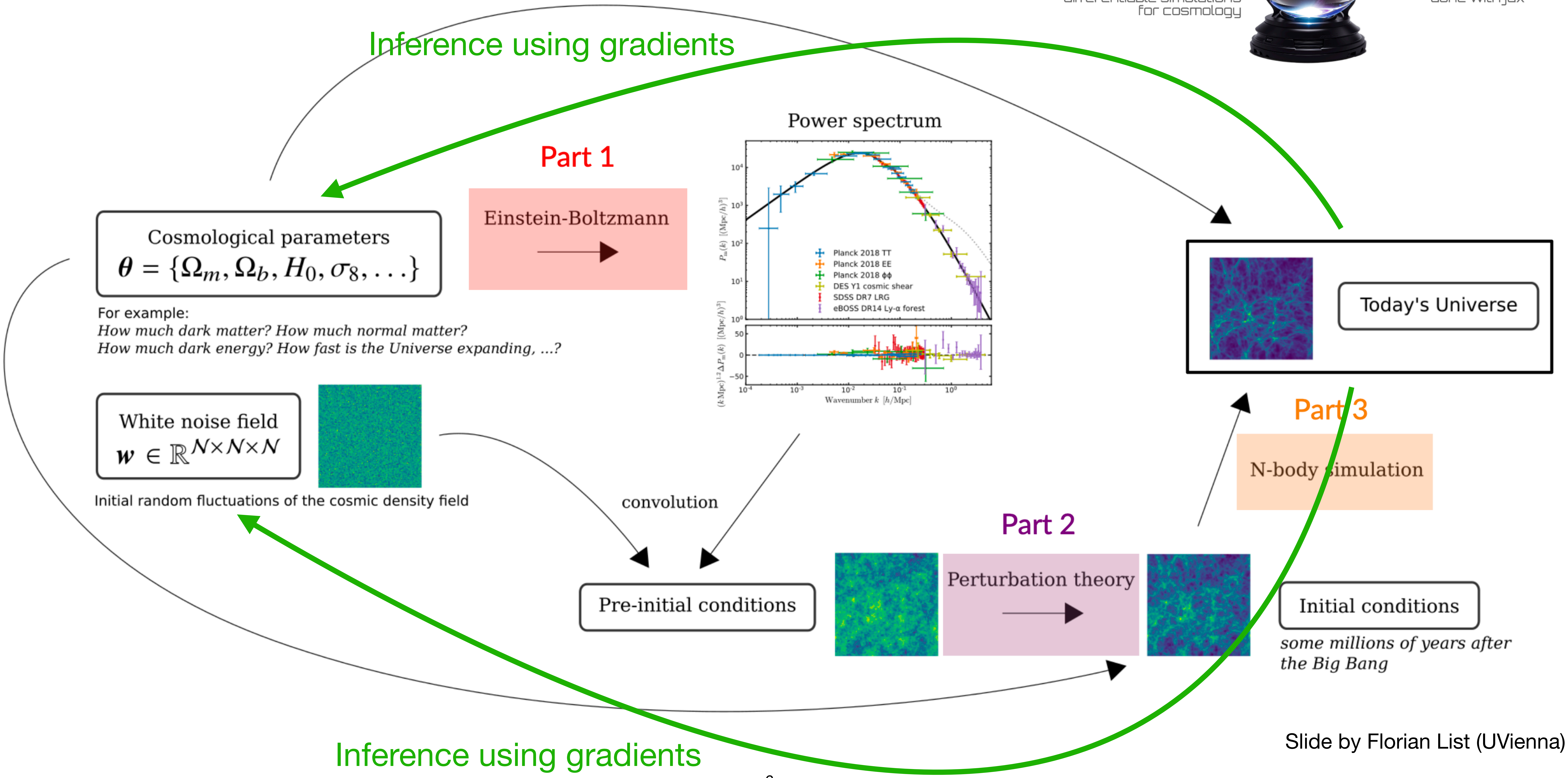
Slide by Florian List (UVienna)

Field-level modelling



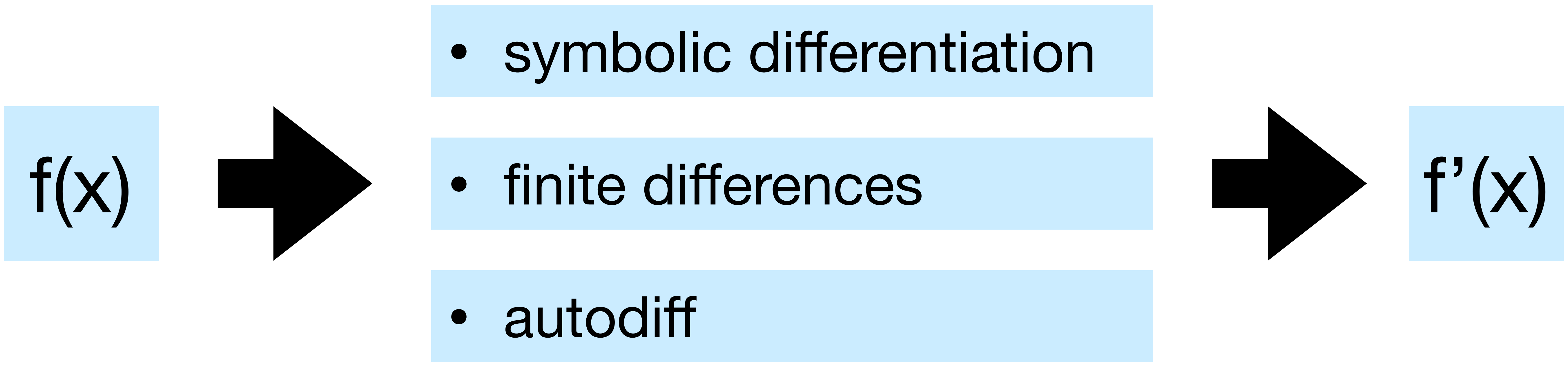
Slide by Florian List (UVienna)

Field-level modelling



Slide by Florian List (UVienna)

Automatic differentiation/differentiable programming



- Computing gradients through long numerical expressions is a standard operation in machine learning (e.g. propagate gradient through NN)
- Two fundamental approaches: recursive application of chain rule
  - forward accumulation (tangent mode)
  - reverse accumulation (adjoint mode)
- Many high performance implementations exist through ML frameworks: pytorch, tensorflow, JAX, but also Julia has support
- Advantage: automatic, non-approximate, fast

Matching epochs in cosmological modelling

Early physics:

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

Eulerian

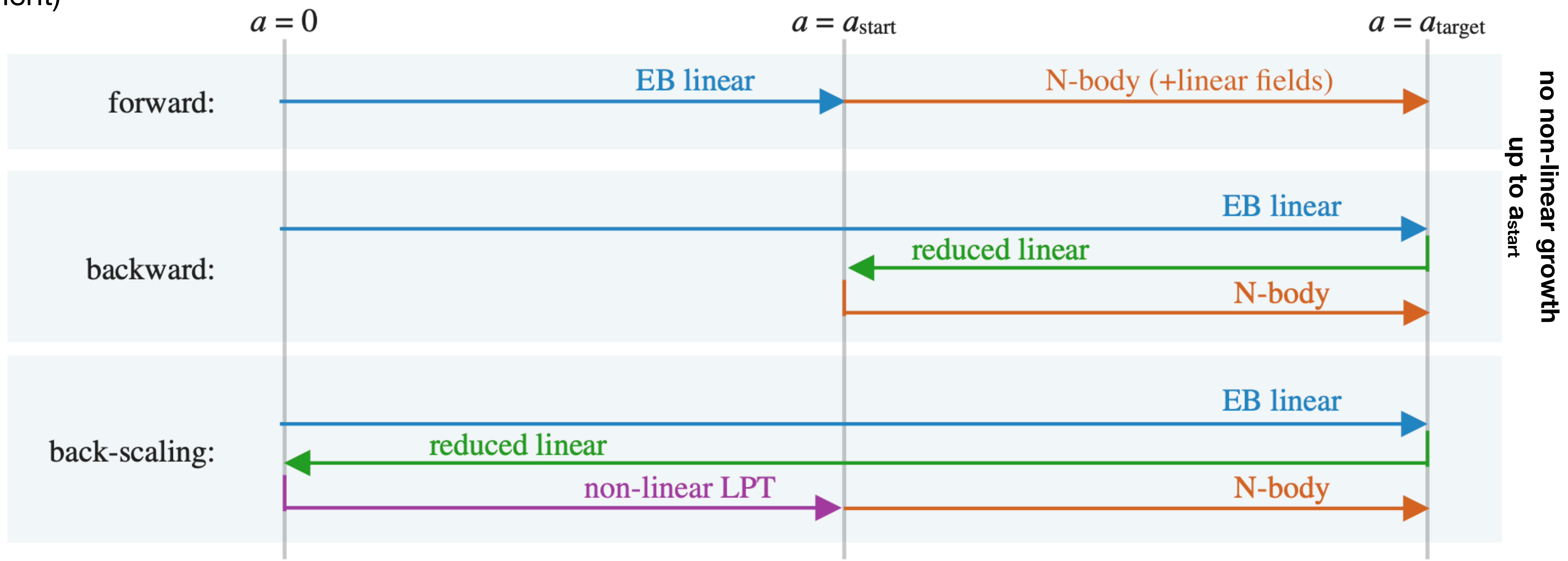
Matching problem!

Late physics:

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

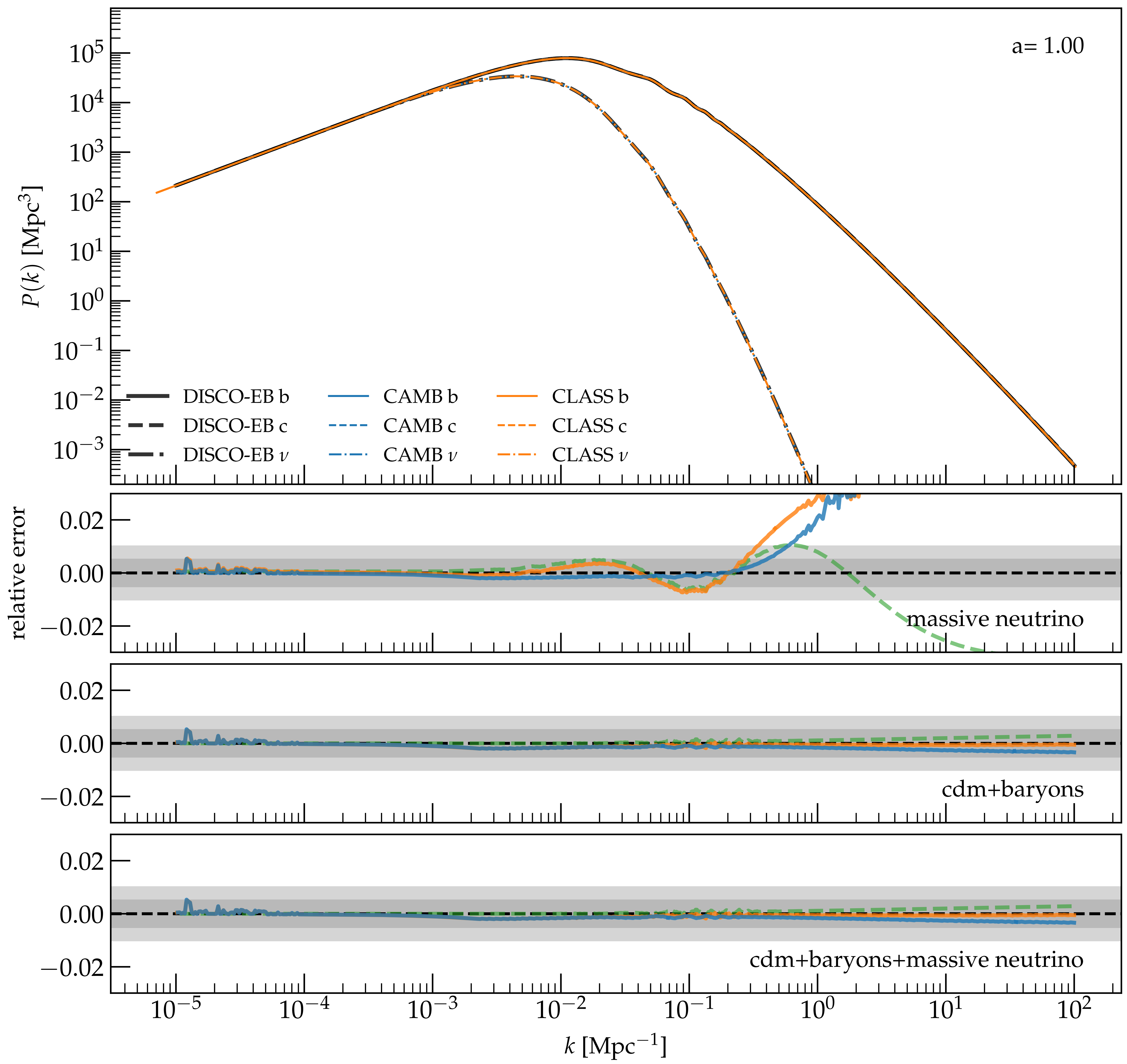
Lagrangian

choices in the literature:



Angulo & Hahn 2022 review

Differentiable Einstein-Boltzmann Solver (DISCO-EB)



OH, List & Porqueres (2023, subm. to JCAP)

Multi-species fluid of DM+baryon+photon+(massive)neutrino+DE
→**linear** Einstein-Boltzmann solver
(e.g. Ma & Bertschinger 1995, CLASS, CAMB)

~100 coupled ODEs (some stiff)

clean easily readable and extendable Python/JAX code

We use high order implicit solver from Diffrax library (Kidger 2022), supports forward and reverse mode differentiation

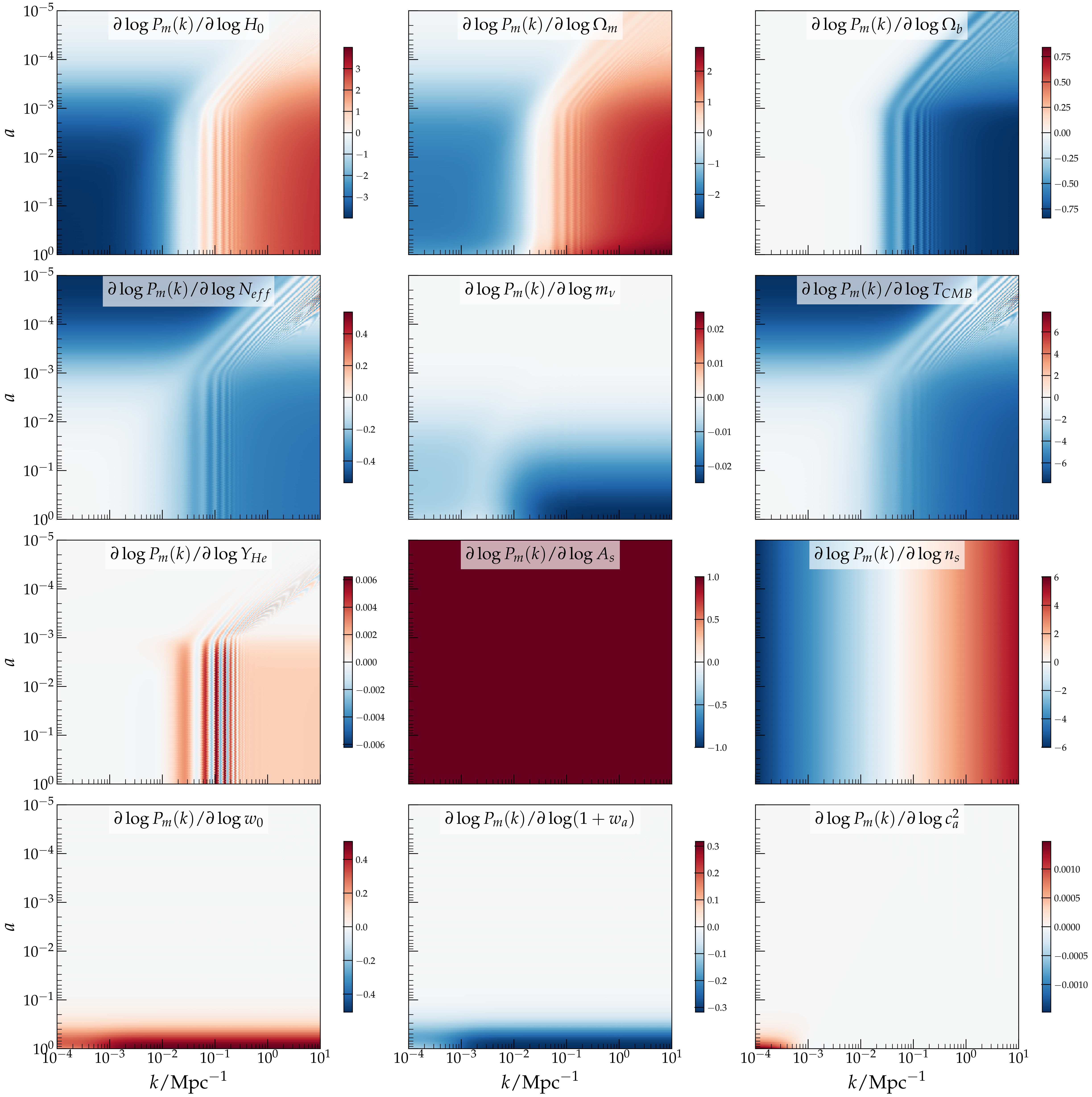
no need to specify Jacobian, due to autodiff

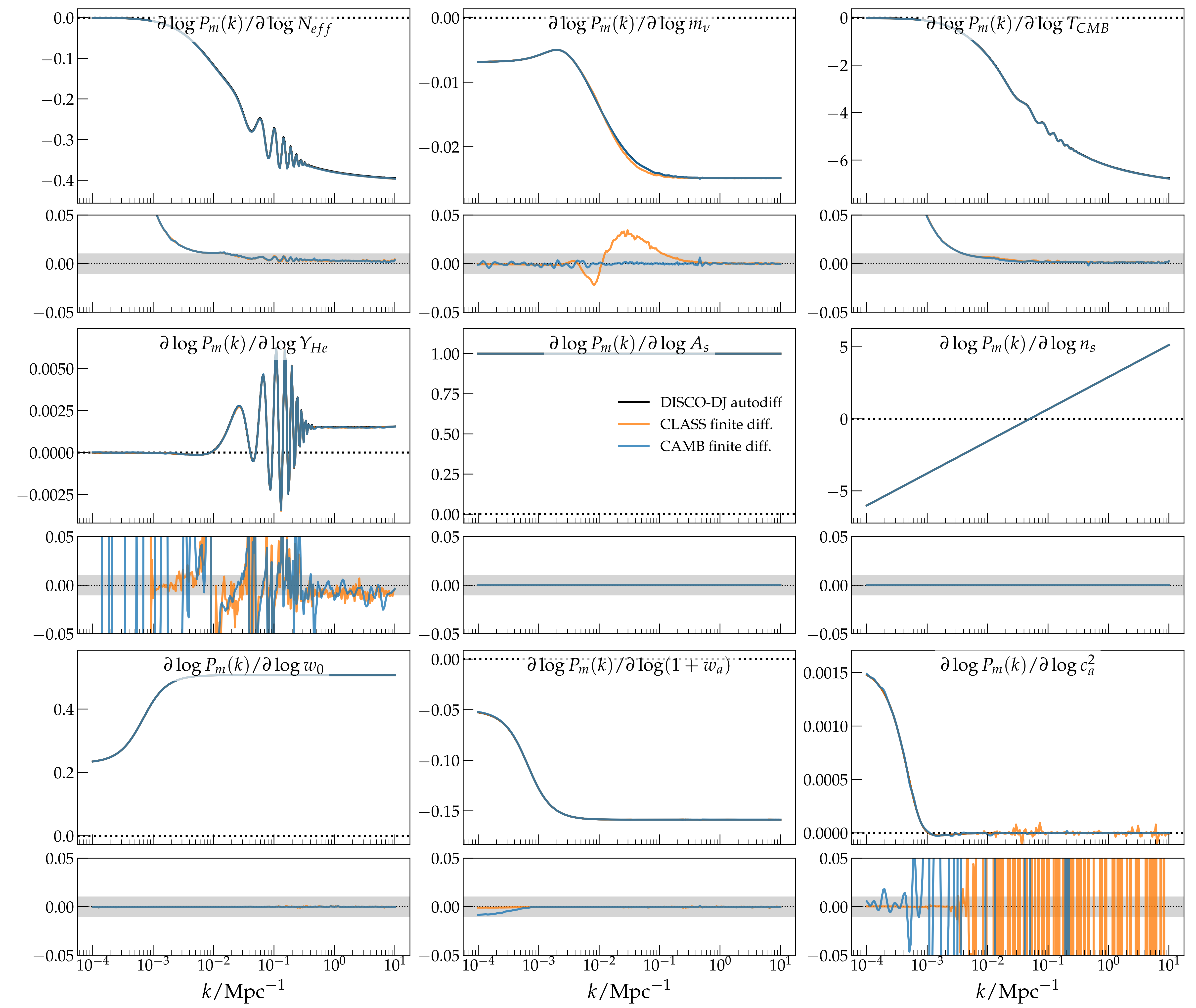
Current limitation: JAX does not support sparse matrices well

code publicly available in few weeks time, or on request:
oliver.hahn@univiea.ac.at

DISCO-DJ
differentiable simulations for cosmology
done with jax

Differentiable Einstein-Boltzmann Solver (DISCO-EB)





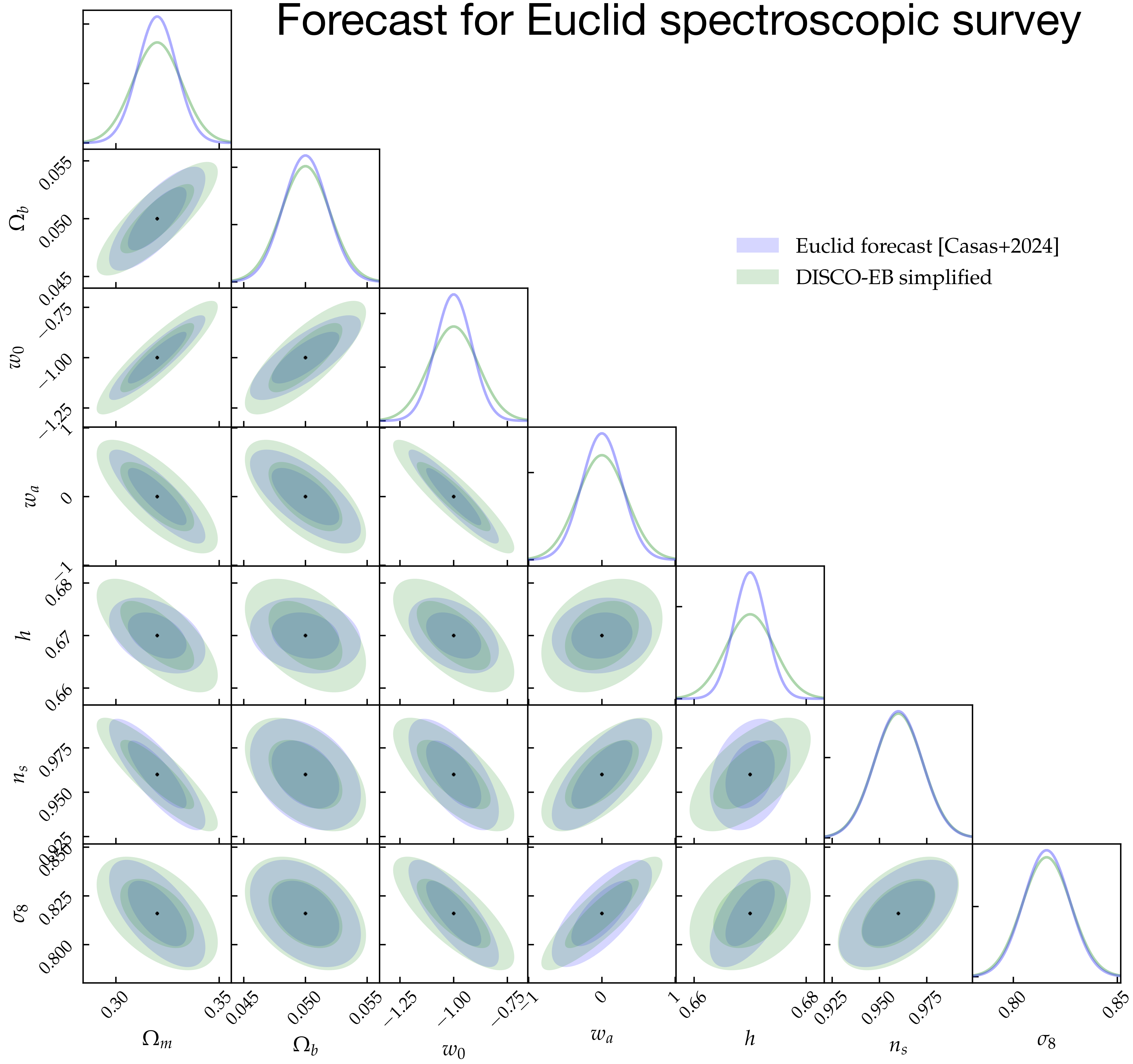
OH, List & Porqueres (2023, subm. to JCAP)

code publicly available in few weeks time, or on request:
oliver.hahn@univiea.ac.at

DISCO-DJ
differentiable simulations for cosmology
done with jax

Differentiable Einstein-Boltzmann Solver (DISCO-EB)

Forecast for Euclid spectroscopic survey



OH, List & Porqueres (2023, subm. to JCAP)

Fisher matrices are just calls to autodiff:

$$F_{ij} = \sum_{\ell} \frac{\partial y(\ell)^\top}{\partial \theta_i} \Sigma^{-1}(\ell) \frac{\partial y(\ell)}{\partial \theta_j}$$

Known/modelled *precision matrix* of the observables

Change of the *observable* w.r.t. the i-th *parameter*
→ **compute with autodiff**

code publicly available in few weeks time, or on request:
oliver.hahn@univiea.ac.at

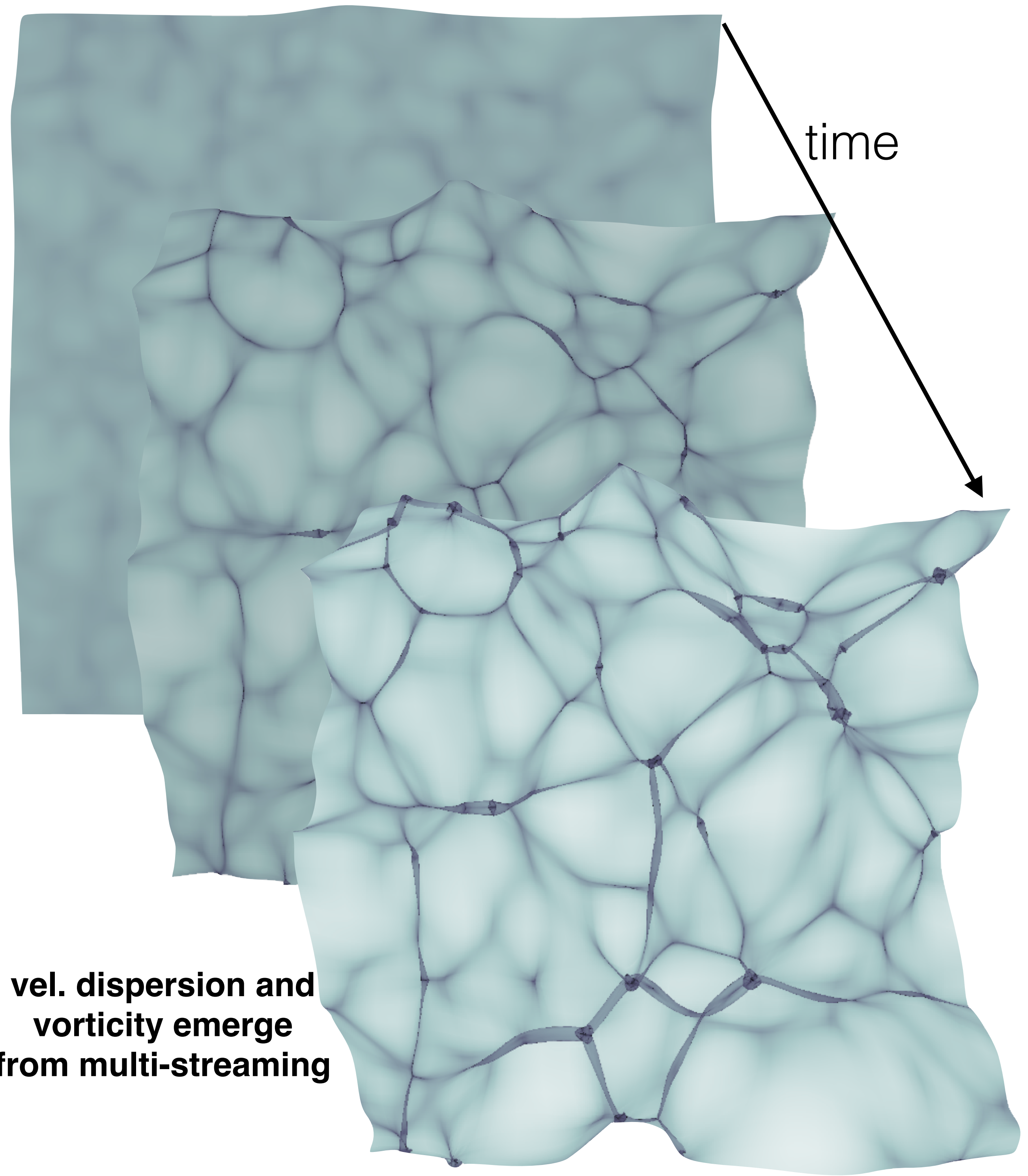
DISCO-DJ
differentiable simulations for cosmology
done with jax

Non-Linear Evolution of Fluctuations

Cold Dark Matter lives on Lagrangian submanifold

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{v}}{a^2} \cdot \boldsymbol{\nabla}_x f - \boldsymbol{\nabla}_x \phi \cdot \boldsymbol{\nabla}_v f = 0 \quad \Leftrightarrow \quad \mathbf{x}'' + \mathcal{H}\mathbf{x}' = -\nabla\phi$$



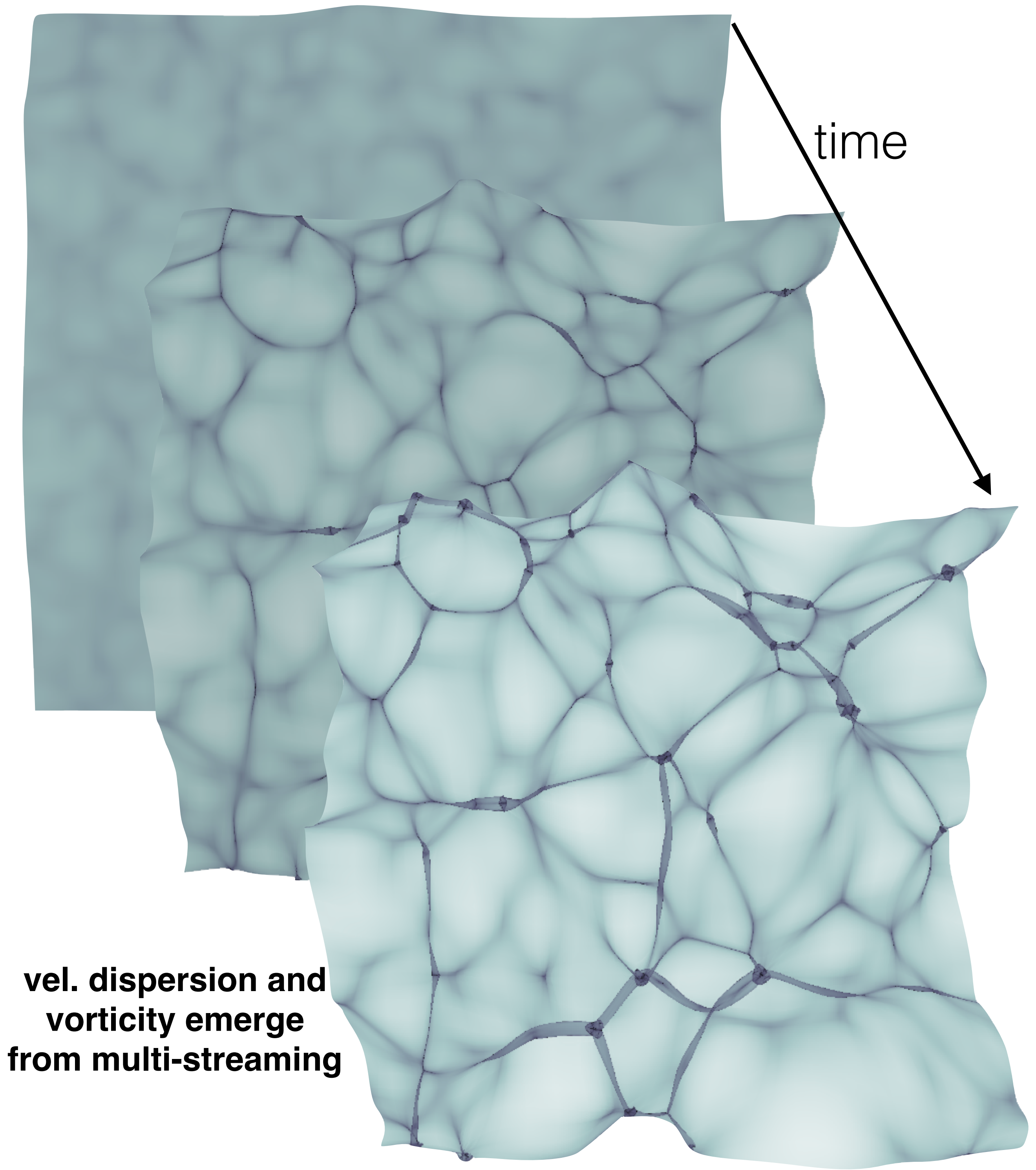
vel. dispersion and vorticity emerge from multi-streaming

Non-Linear Evolution of Fluctuations

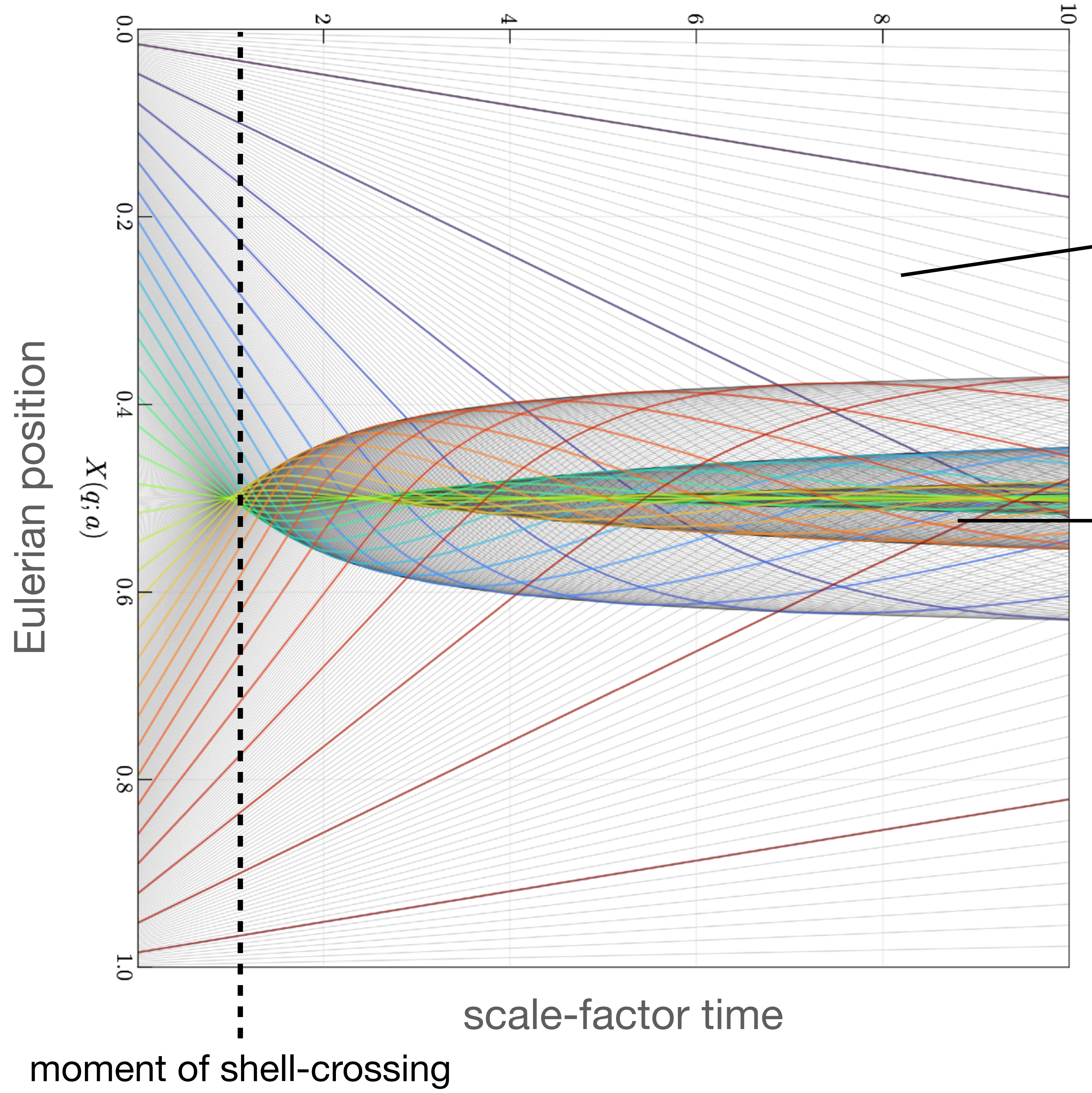
Cold Dark Matter lives on Lagrangian submanifold

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{v}}{a^2} \cdot \boldsymbol{\nabla}_x f - \boldsymbol{\nabla}_x \phi \cdot \boldsymbol{\nabla}_v f = 0 \qquad \Leftrightarrow \qquad \mathbf{x}'' + \mathcal{H}\mathbf{x}' = -\nabla\phi$$



density + acceleration singularities



monokinetic, single-valued
(analytic treatment possible)

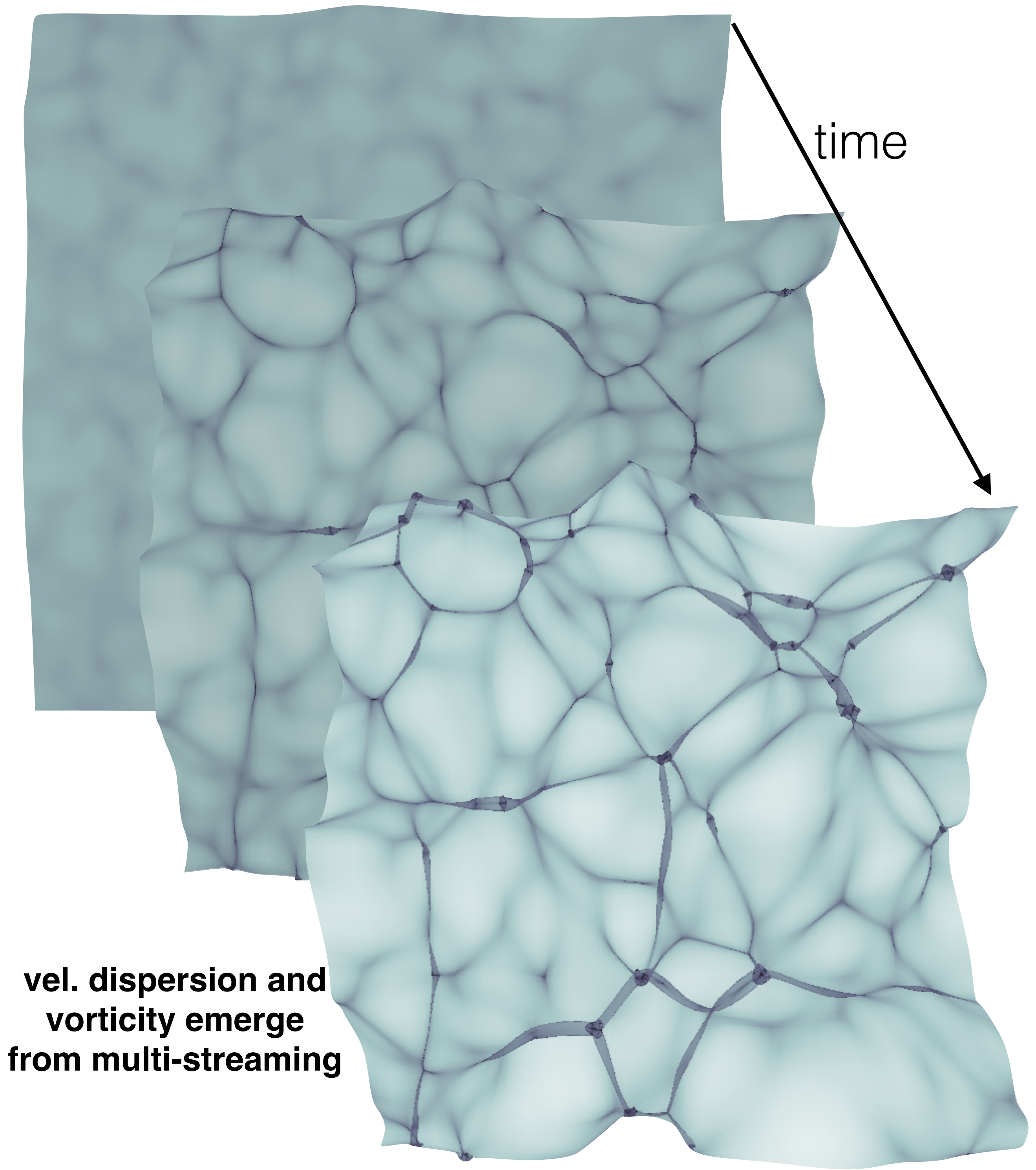
multikinetic, multi-valued
(simulations, EFTs [by integrating out])

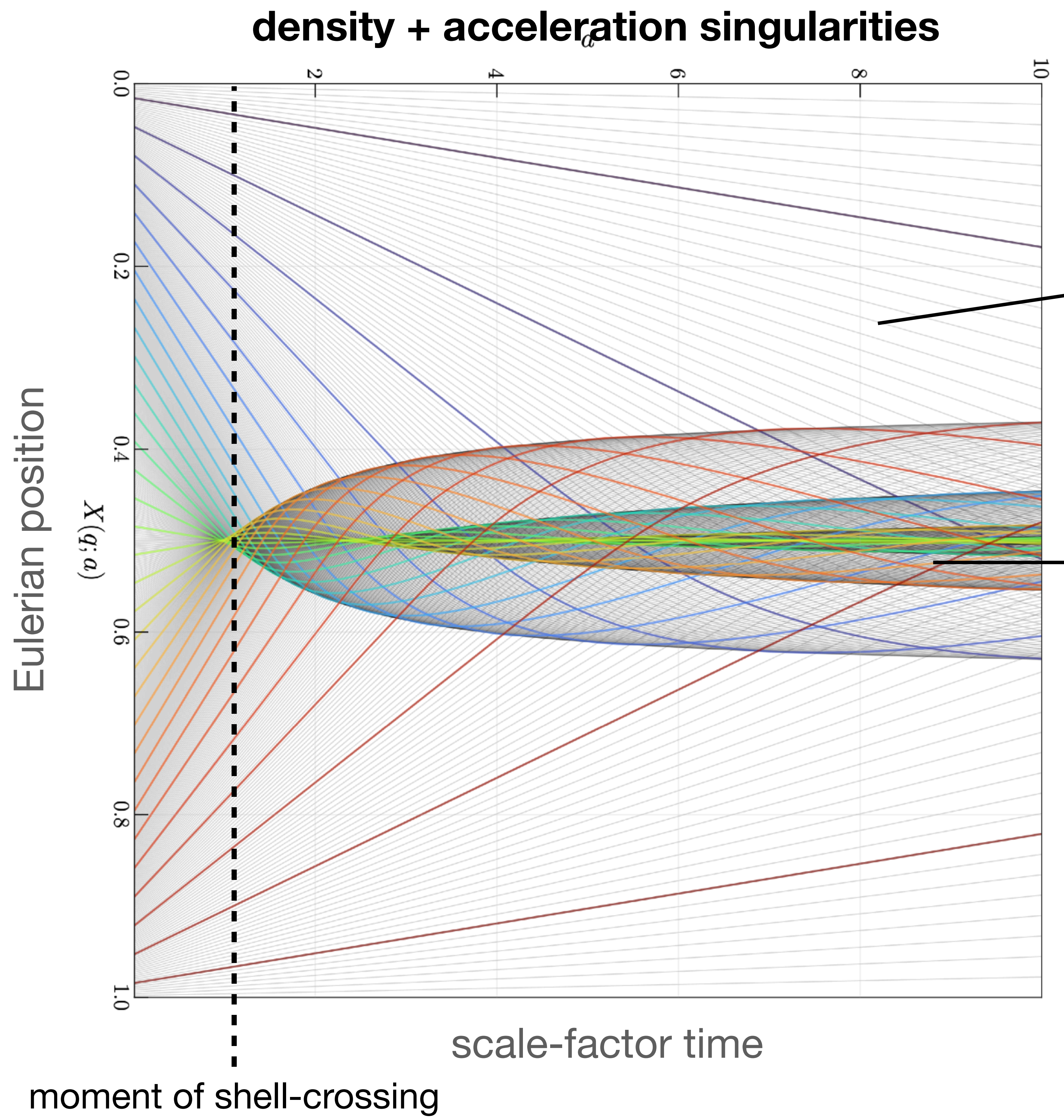
Non-Linear Evolution of Fluctuations

Cold Dark Matter lives on Lagrangian submanifold

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{v}}{a^2} \cdot \boldsymbol{\nabla}_x f - \boldsymbol{\nabla}_x \phi \cdot \boldsymbol{\nabla}_v f = 0 \quad \Leftrightarrow \quad \mathbf{x}'' + \mathcal{H}\mathbf{x}' = -\nabla\phi$$





monokinetic, single-valued
(analytic treatment possible)

multikinetic, multi-valued
(simulations, EFTs [by integrating out])

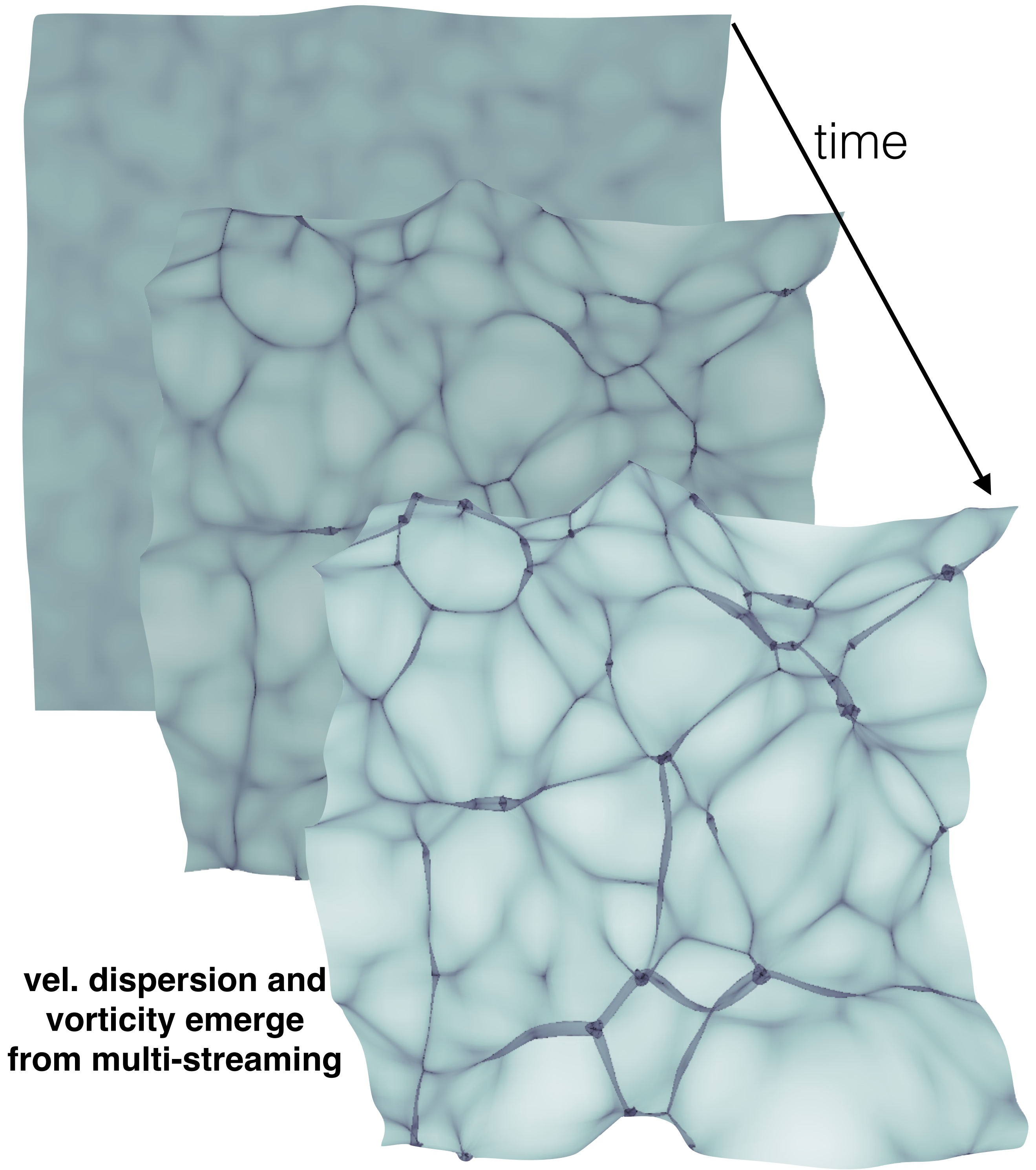
Zeldovich (1970) solution (straight lines) is exact prior to shell-crossing and outside shell-crossed regions

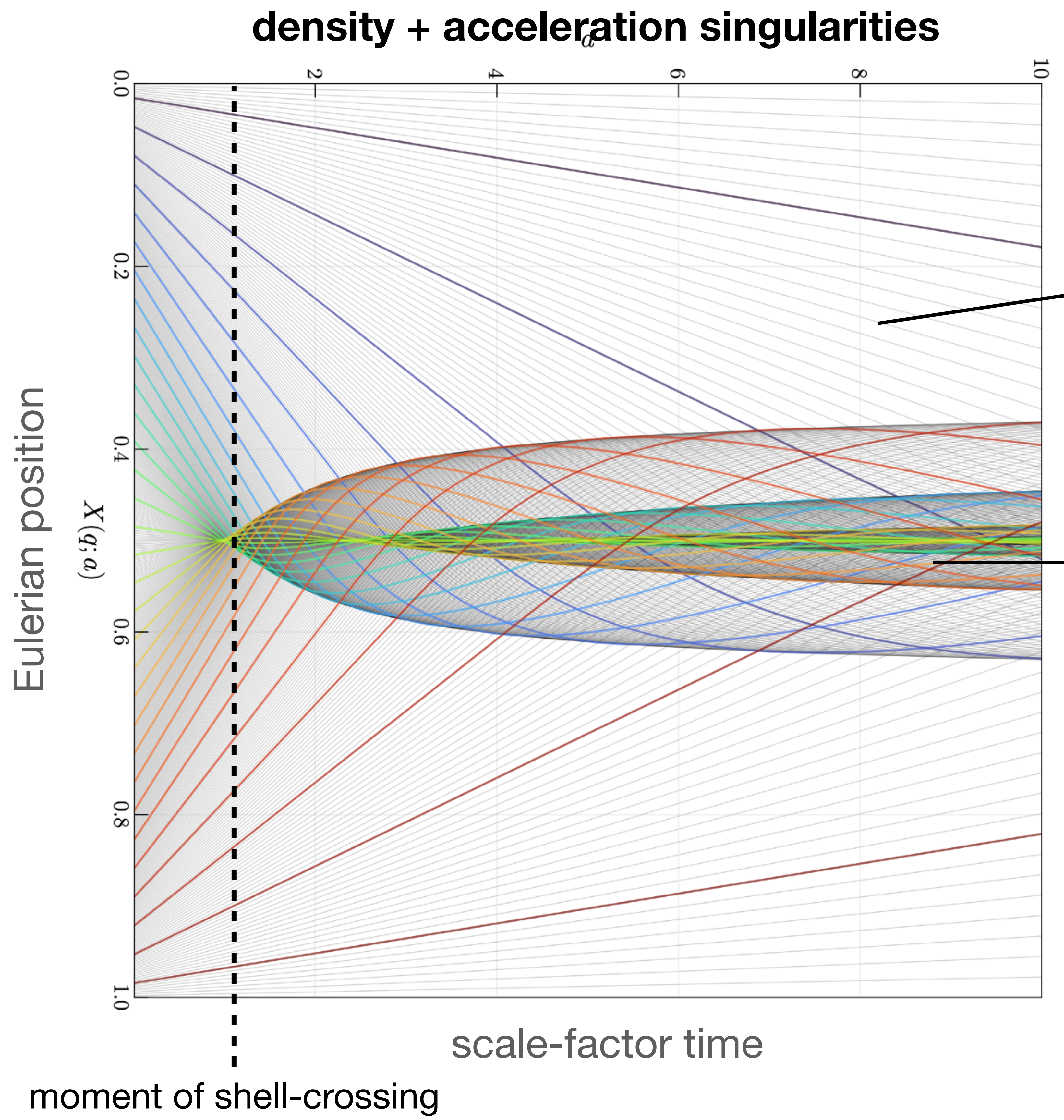
Non-Linear Evolution of Fluctuations

Cold Dark Matter lives on Lagrangian submanifold

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{v}}{a^2} \cdot \boldsymbol{\nabla}_x f - \boldsymbol{\nabla}_x \phi \cdot \boldsymbol{\nabla}_v f = 0 \quad \Leftrightarrow \quad \mathbf{x}'' + \mathcal{H}\mathbf{x}' = -\nabla\phi$$





entering the multi-stream region is non-analytic (only finitely many bounded derivatives)

monokinetic, single-valued
(analytic treatment possible)

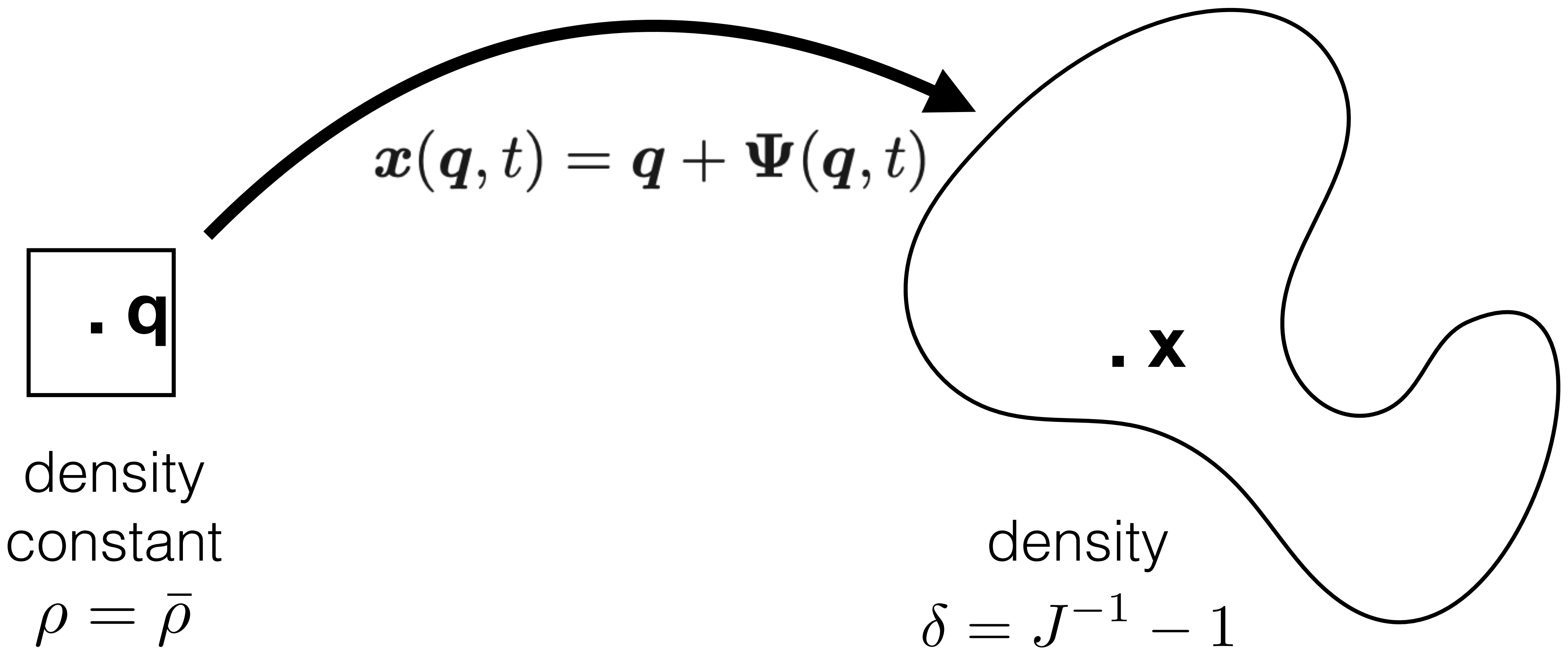
multikinetic, multi-valued
(simulations, EFTs [by integrating out])

Zeldovich (1970) solution (straight lines) is exact prior to shell-crossing and outside shell-crossed regions

Modelling LSS — Lagrangian perturbation theory

Non-linear evolution of perturbations

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$

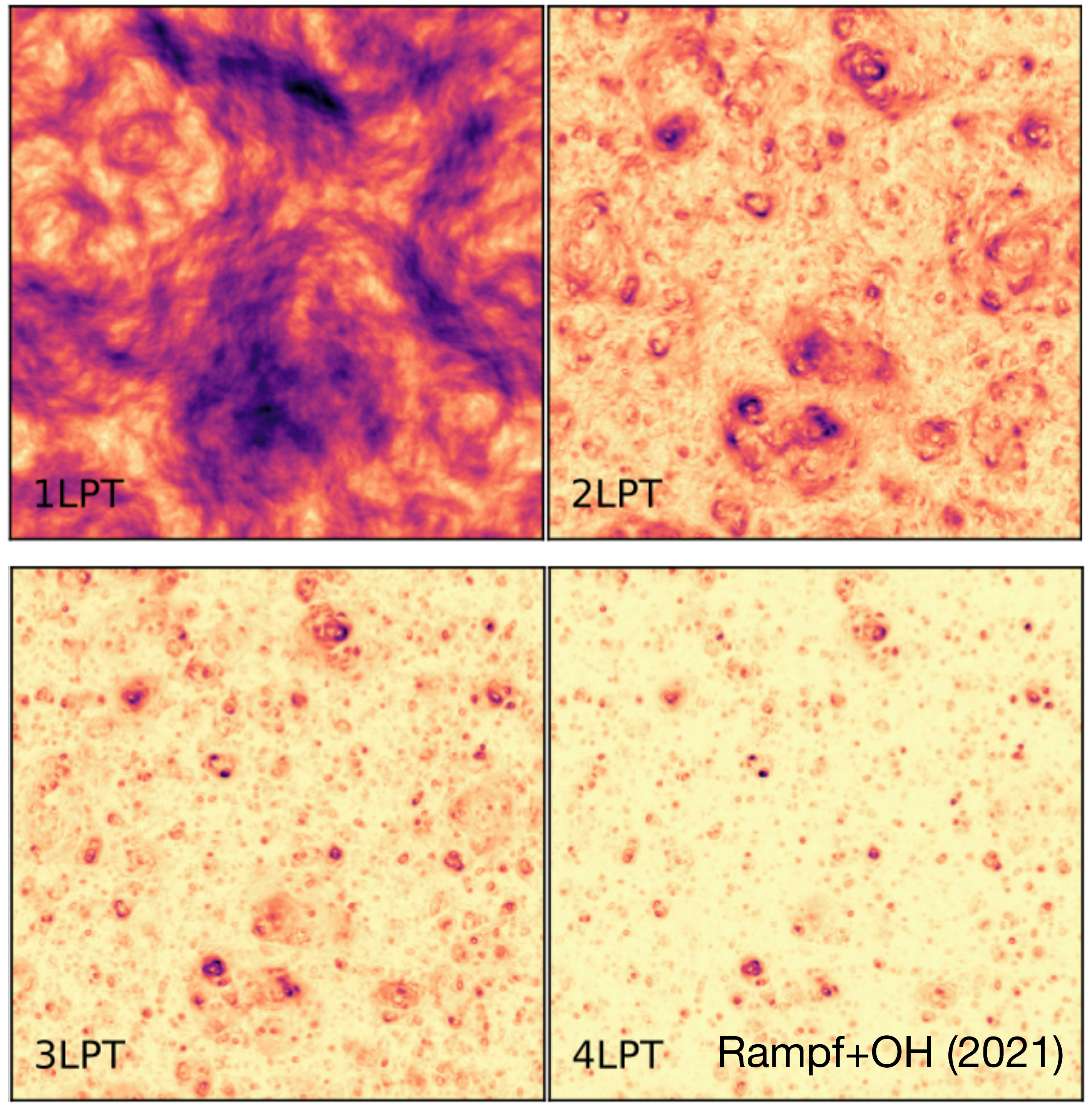


density constant
$\rho = \bar{\rho}$

density
$\delta = J^{-1} - 1$

all-order recursion relations first implemented in code

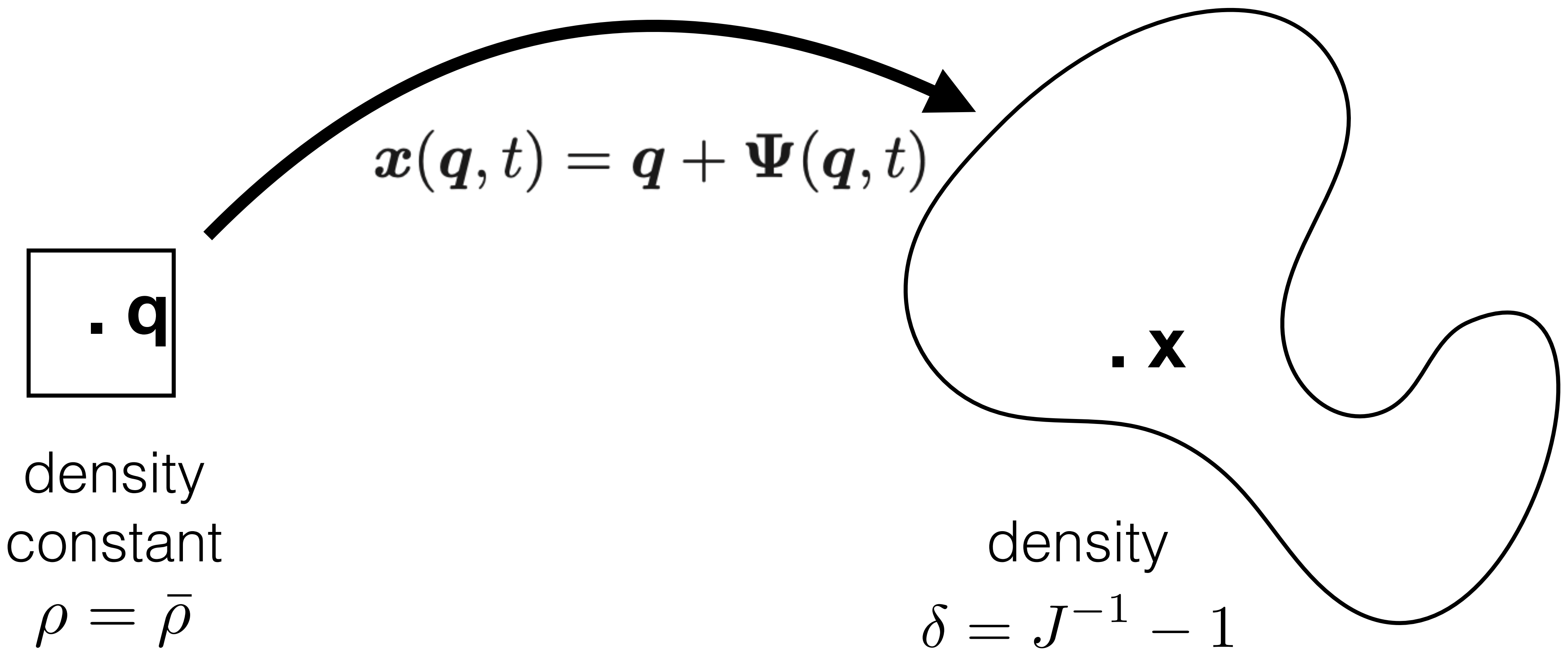
Rampf+OH (2021)
Schmidt (2021)



Modelling LSS — Lagrangian perturbation theory

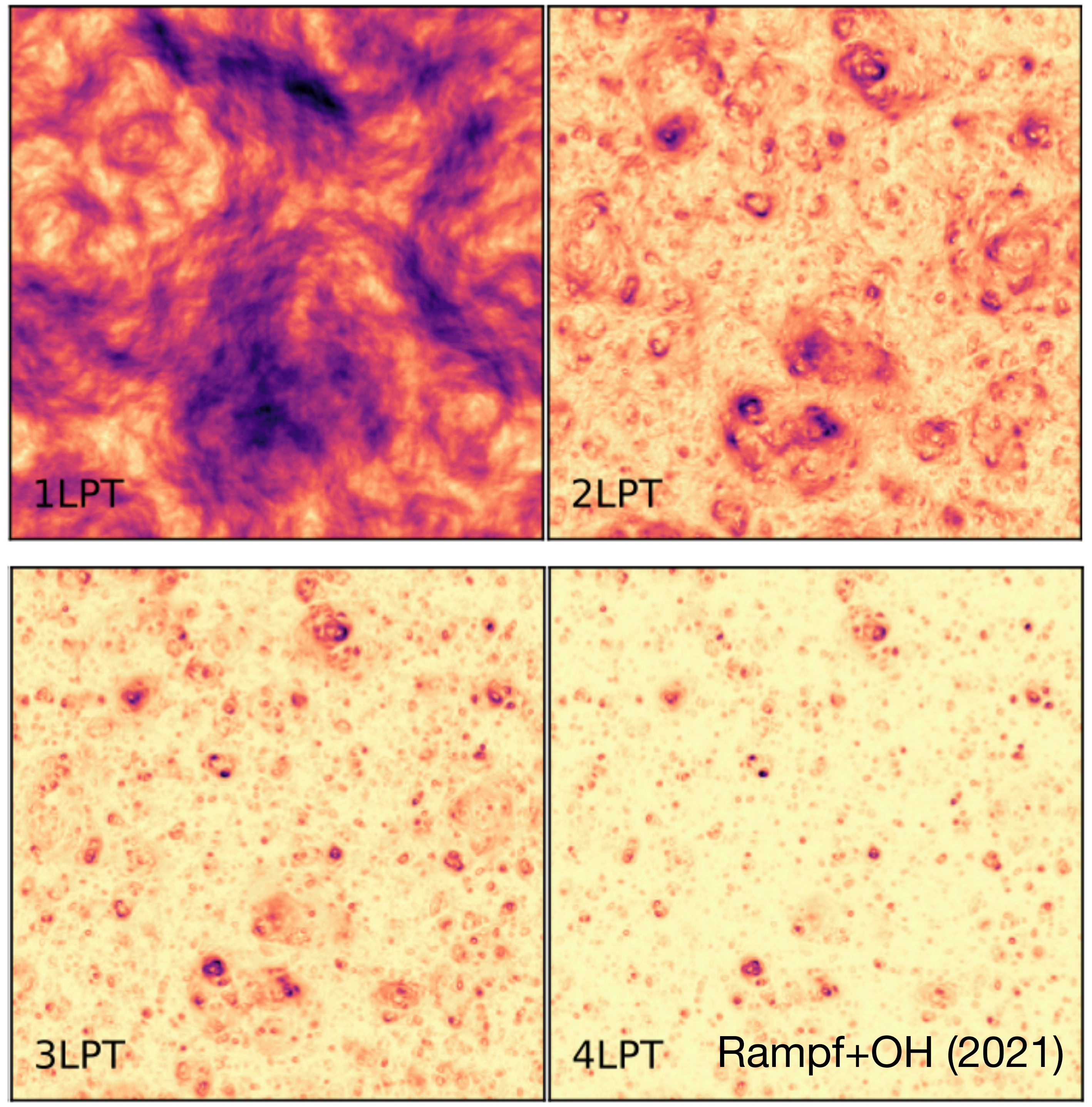
Non-linear evolution of perturbations

Solve Vlasov-Poisson on submanifold characteristics $(\boldsymbol{q}, t) \mapsto (\boldsymbol{x}(\boldsymbol{q}, t), \boldsymbol{p}(\boldsymbol{q}, t))$



all-order recursion relations first implemented in code

Rampf+OH (2021)
Schmidt (2021)



We want to solve this as a perturbative series (D is small parameter)

$$\boldsymbol{\Psi}(\mathbf{q}, \tau) = \sum_{n=1}^{\infty} D(\tau)^n \, \boldsymbol{\Psi}^{(n)}(\mathbf{q})$$

Buchert (1994), Catelan (1995), Bouchet+(1995), n=3
Rampf (2012), Zheligovsky&Frisch (2014), Matsubara (2015), all order

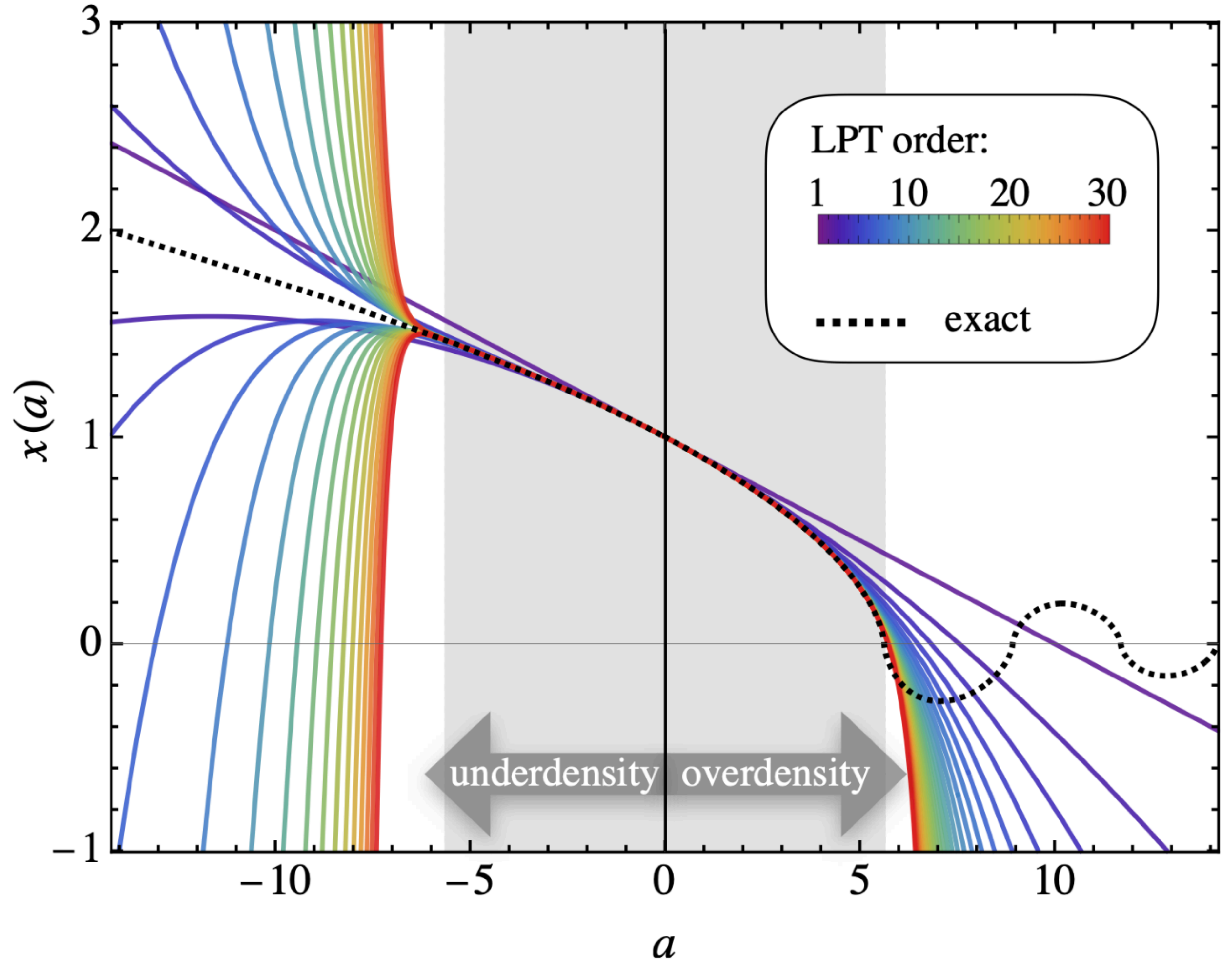
Modelling LSS — Lagrangian perturbation theory

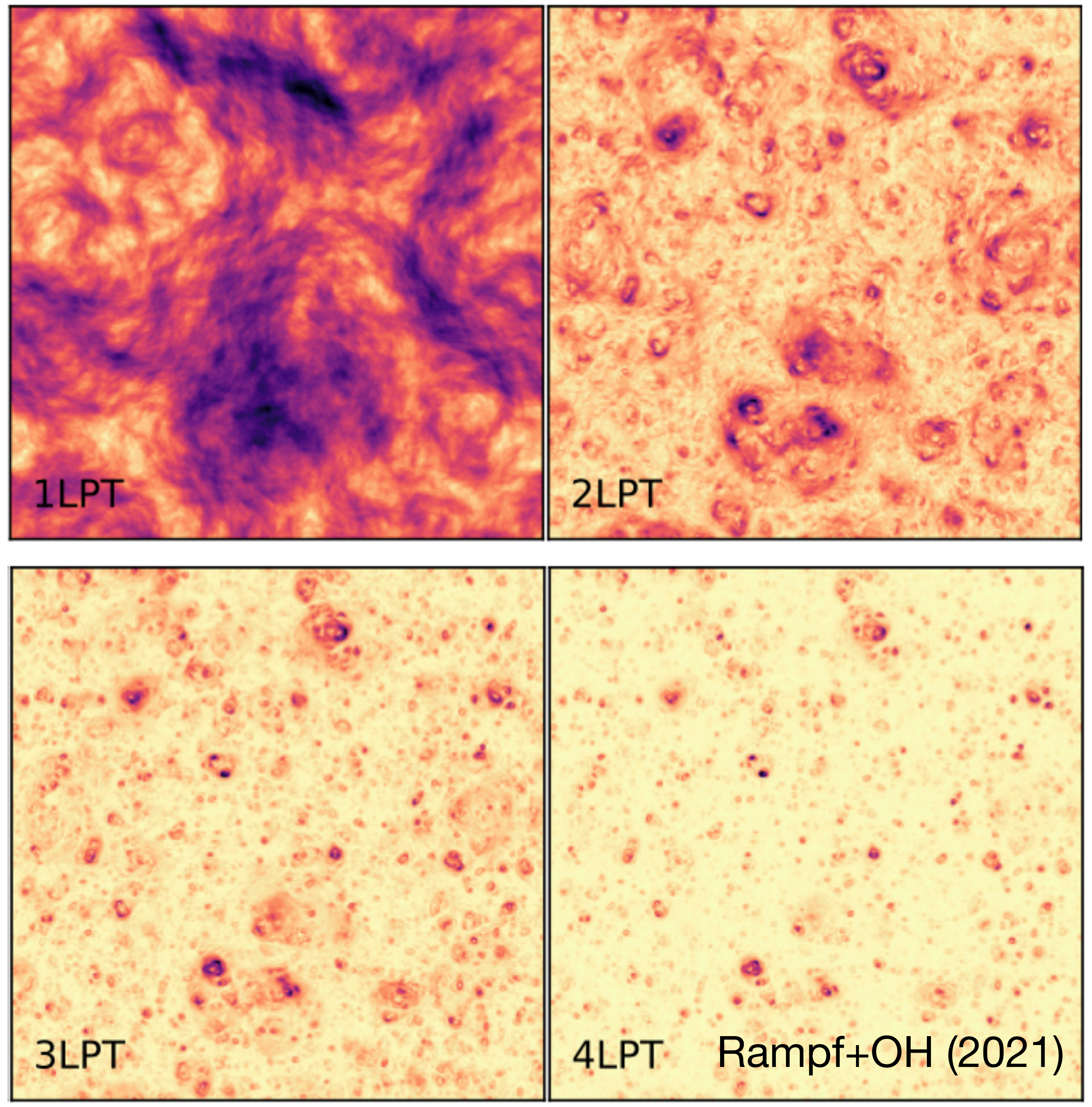
Non-linear evolution of perturbations

Solve Vlasov … $, t), \boldsymbol{p}(\boldsymbol{q}, t))$

. q

density
constant
$\rho = \bar{\rho}$





all-order recursion relations first implemented in code

Rampf+OH (2021)
Schmidt (2021)

We want to solve this as a perturbative series (D is small parameter)

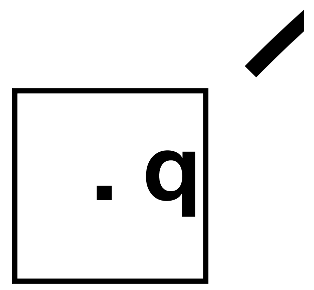
$$\boldsymbol{\Psi}(\mathbf{q},\tau) = \sum_{n=1}^{\infty} D(\tau)^n\, \boldsymbol{\Psi}^{(n)}(\mathbf{q})$$

Buchert (1994), Catelan (1995), Bouchet+(1995), n=3
Rampf (2012), Zheligovsky&Frisch (2014), Matsubara (2015), all order

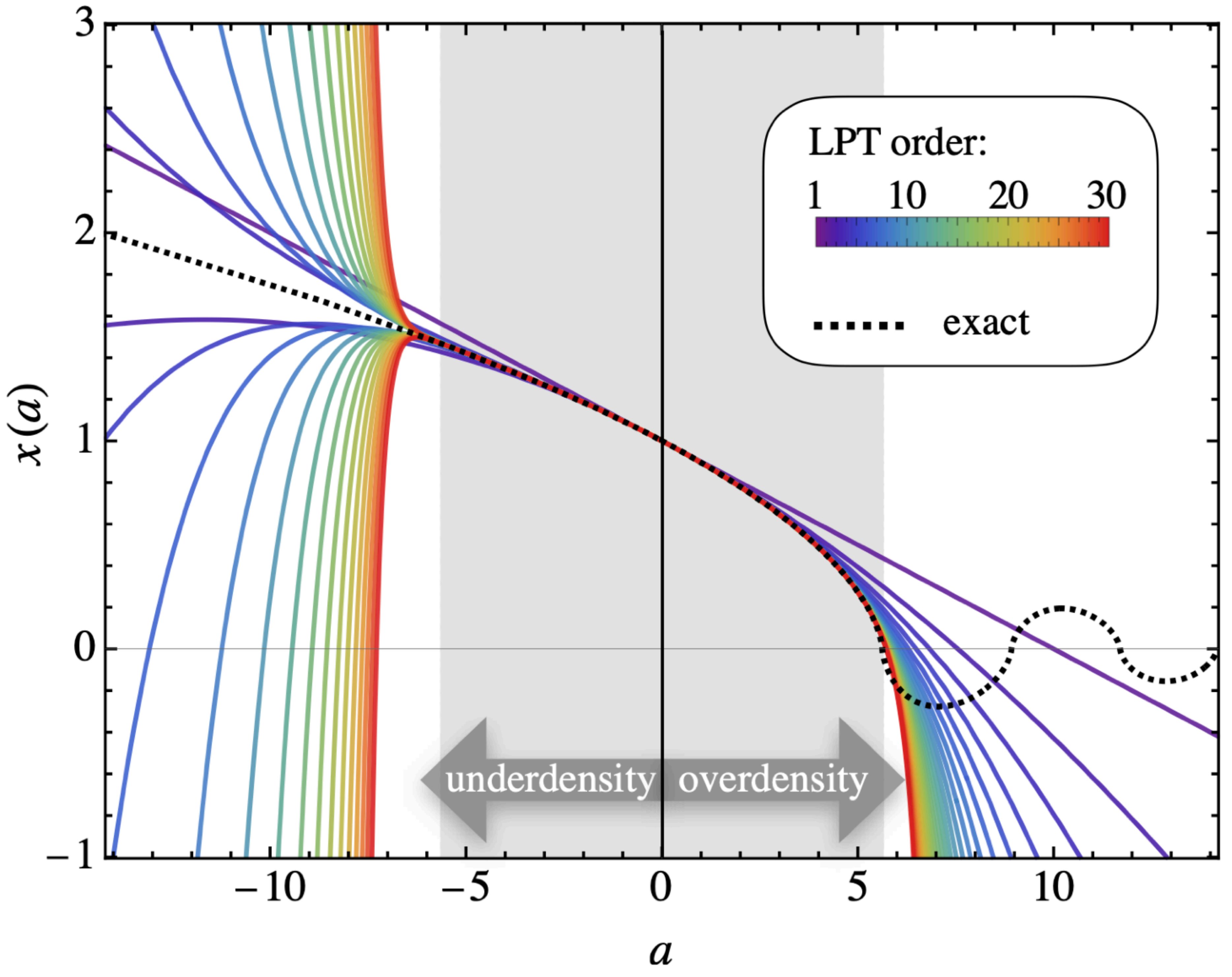
Modelling LSS — Lagrangian perturbation theory

Non-linear evolution of perturbations

Solve Vlasov … $, t), \boldsymbol{p}(\boldsymbol{q}, t))$

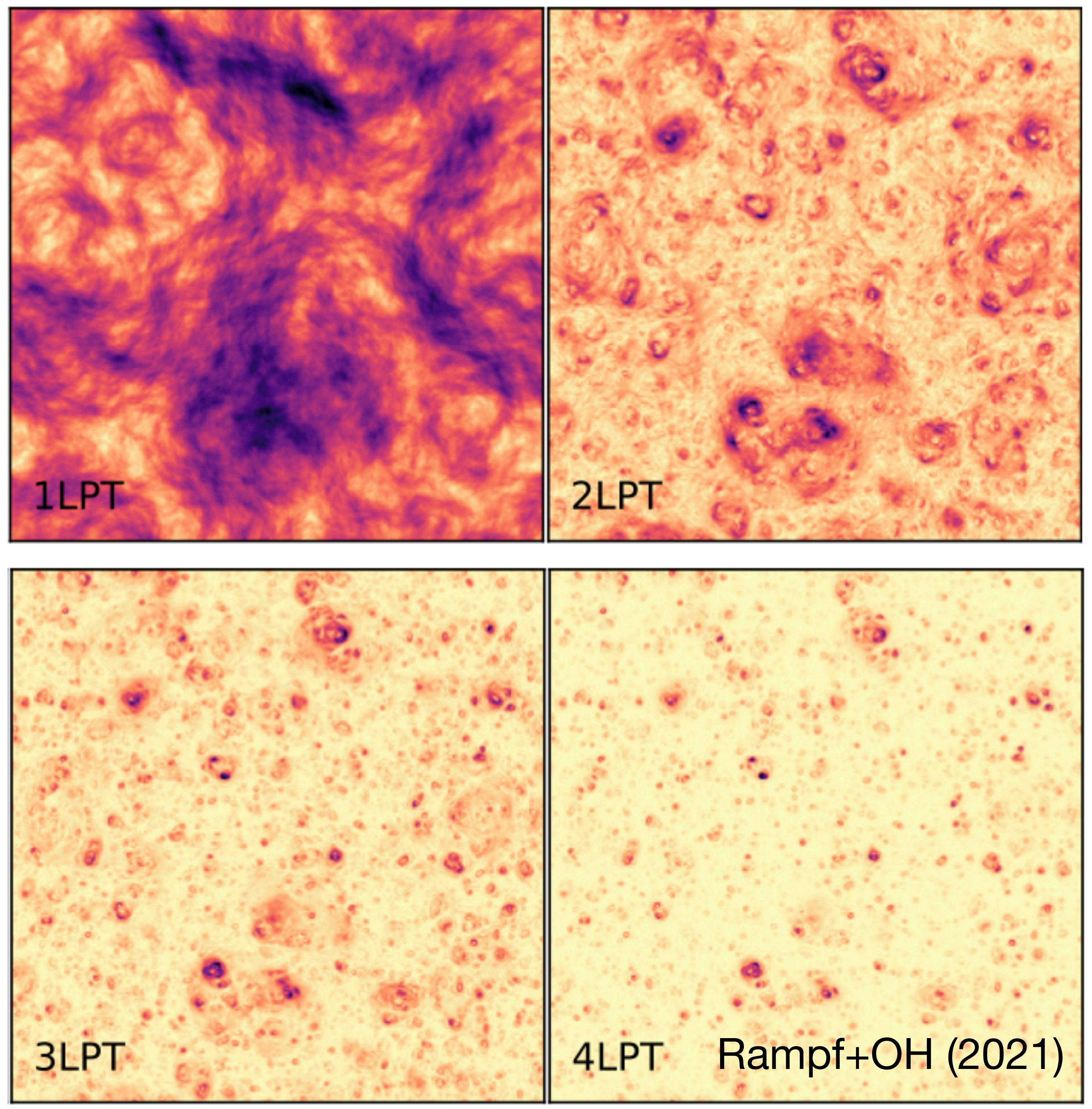


density
constant
$\rho = \bar{\rho}$



all-order recursion relations first implemented in code

Rampf+OH (2021)
Schmidt (2021)



We want to solve this as a perturbative series (D is small parameter)

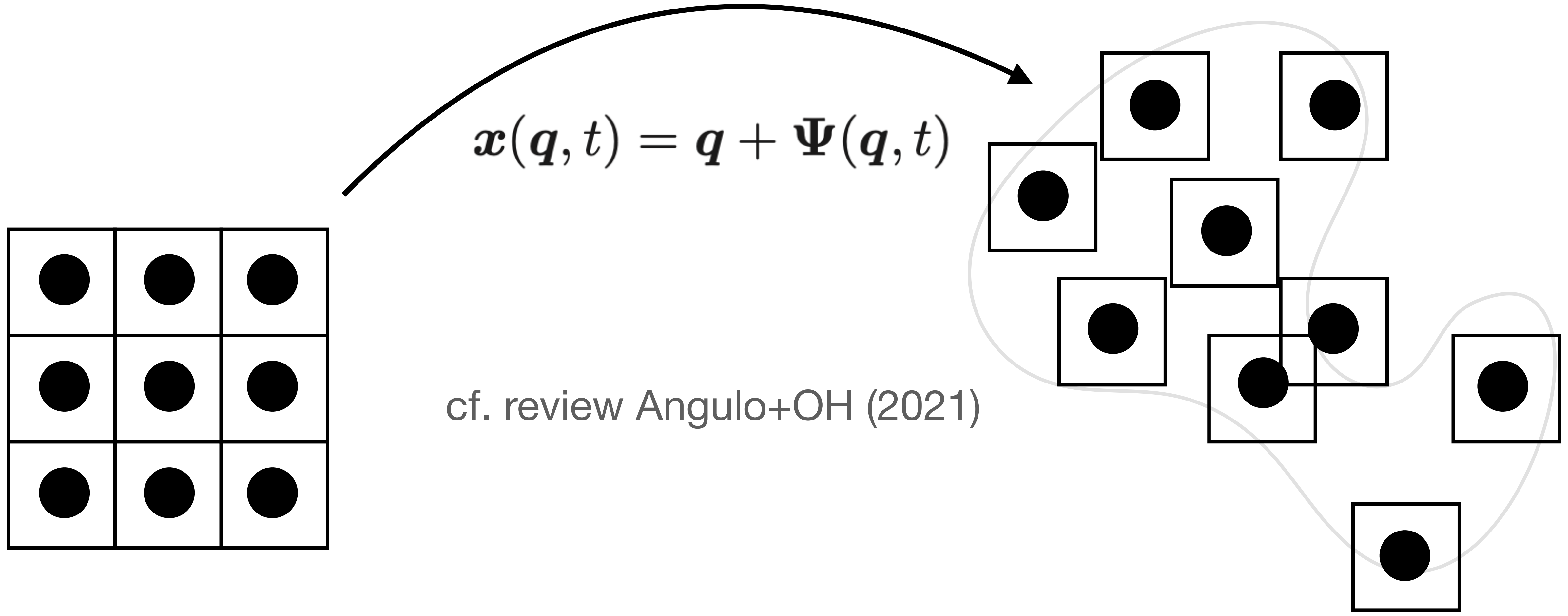
$$\boldsymbol{\Psi}(\mathbf{q}, \tau) = \sum_{n=1}^{\infty} D(\tau)^n \, \boldsymbol{\Psi}^{(n)}(\mathbf{q})$$

Buchert (1994), Catelan (1995), Bouchet+(1995), n=3
Rampf (2012), Zheligovsky&Frisch (2014), Matsubara (2015), all order

All order recursion fully implemented in upcoming DISCO-DJ module (stay tuned!
List, OH et al (2024, in prep)

Modelling LSS: Numerical N-body simulations

simulation maps discrete fluid elements from Lagrangian space to Eulerian space



cf. review Angulo+OH (2021)

the 10^{12} particle frontier:

(from Angulo+OH review)

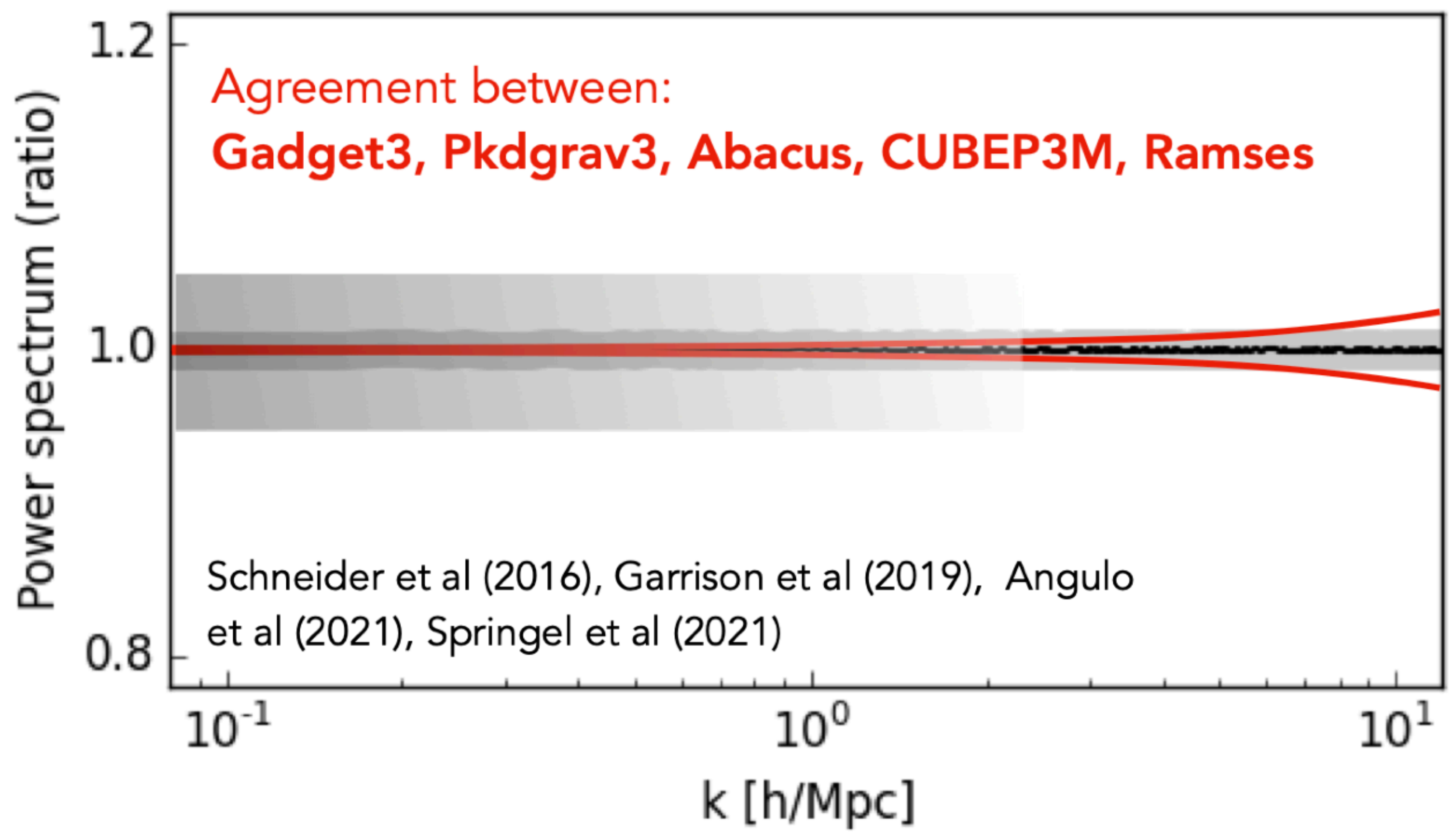
Year	Simulation	Code	Supercomputer	Cores [10^3]	N_p [10^{12}]	Box [h^{-1}Gpc]	Algorithm	ϵ [h^{-1}kpc]
2014	Dark Sky [916]	2HOT	Titan, USA	20	1.1	8	FMM	36.8
2017	TianNu [469]	CUBEP^{3}M	Tianhe-2, China	331	2.97	1.2	PM-PM-PP	13
2017	Euclid Flagship [201]	PKDGRAV3	PizDaint, Switzerland	4	2.0	3.	Tree-FMM	4.8
2019	Outer Rim [917]	HACC	Mira, USA	524	1.07	3.0	Tree-PM	2.84
2019	Cosmo-π [613]	CUBE	π 2.0, China	20	4.39	3.2	PM-PM	195
2020	Ushuu [918]	GREEM	ATERUI-II, Japan	<40	2.0	2.0	Tree-PM	4.3
2020	Last Journey [919]	HACC	Mira, USA	524	1.24	3.4	Tree-PM	3.14

+ Farpoint (2021)

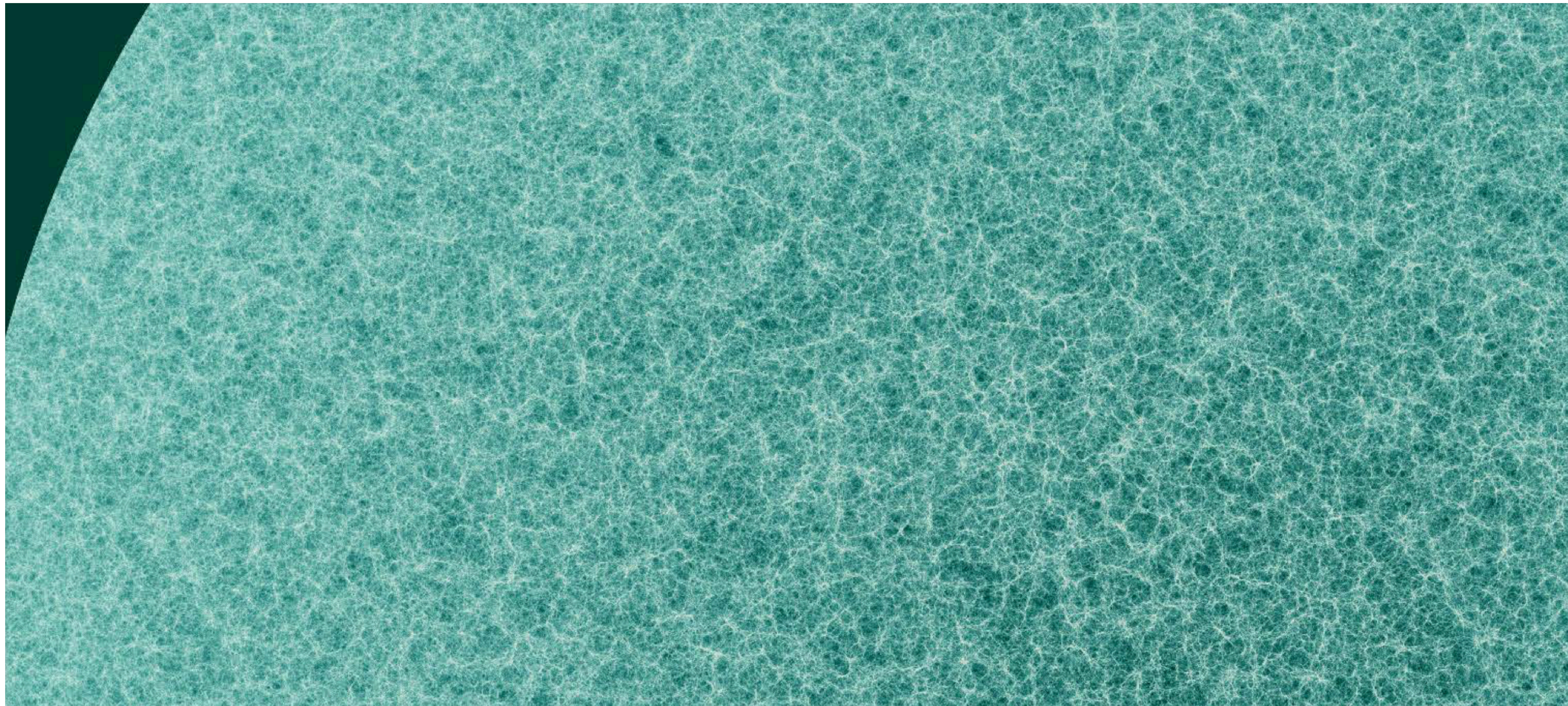
N-body simulations still the main work horse of LSS!

Theory error in non-linear simulations under control (without including astrophysics effects)

Gravity only LCDM predictions for matter distribution in the Universe have essentially no theory error any more



4π Lightcone from the Euclid Flagship simulation (Potter et al. 2017)



Standard N-body simulations have difficulty reproducing nLPT

Feng+2016: FastPM idea: modify time integrator to get 1LPT agreement

Can do better: second order LPT (2LPT) can be written

$$\boldsymbol{X}_i(D) = \boldsymbol{X}_i^n + [D - D_n]\boldsymbol{\psi}_i^{n,(1)} + [D - D_n]^2\boldsymbol{\psi}_i^{n,(2)}$$

$$\mathrm{d}_D \boldsymbol{X}_i(D) = \boldsymbol{\psi}_i^{n,(1)} + 2[D - D_n]\boldsymbol{\psi}_i^{n,(2)},$$

$$\mathrm{d}_D^2 \boldsymbol{X}_i(D) = 2\boldsymbol{\psi}_i^{n,(2)} = \text{const.}$$

i.e. acceleration can be made constant

Standard N-body simulations have difficulty reproducing nLPT

Feng+2016: FastPM idea: modify time integrator to get 1LPT agreement

Can do better: second order LPT (2LPT) can be written

$$\boldsymbol{X}_i(D) = \boldsymbol{X}_i^n + [D - D_n]\boldsymbol{\psi}_i^{n,(1)} + [D - D_n]^2\boldsymbol{\psi}_i^{n,(2)}$$

$$\mathrm{d}_D \boldsymbol{X}_i(D) = \boldsymbol{\psi}_i^{n,(1)} + 2[D - D_n]\boldsymbol{\psi}_i^{n,(2)},$$

$$\mathrm{d}_D^2 \boldsymbol{X}_i(D) = 2\boldsymbol{\psi}_i^{n,(2)} = \text{const.}$$

i.e. acceleration can be made constant

This can be matched in various ways to yield new integrators that can reproduce 2LPT.

Standard N-body simulations have difficulty reproducing nLPT

Feng+2016: FastPM idea: modify time integrator to get 1LPT agreement

Can do better: second order LPT (2LPT) can be written

$$\boldsymbol{X}_i(D) = \boldsymbol{X}_i^n + [D - D_n]\boldsymbol{\psi}_i^{n,(1)} + [D - D_n]^2\boldsymbol{\psi}_i^{n,(2)}$$

$$\mathrm{d}_D \boldsymbol{X}_i(D) = \boldsymbol{\psi}_i^{n,(1)} + 2[D - D_n]\boldsymbol{\psi}_i^{n,(2)},$$

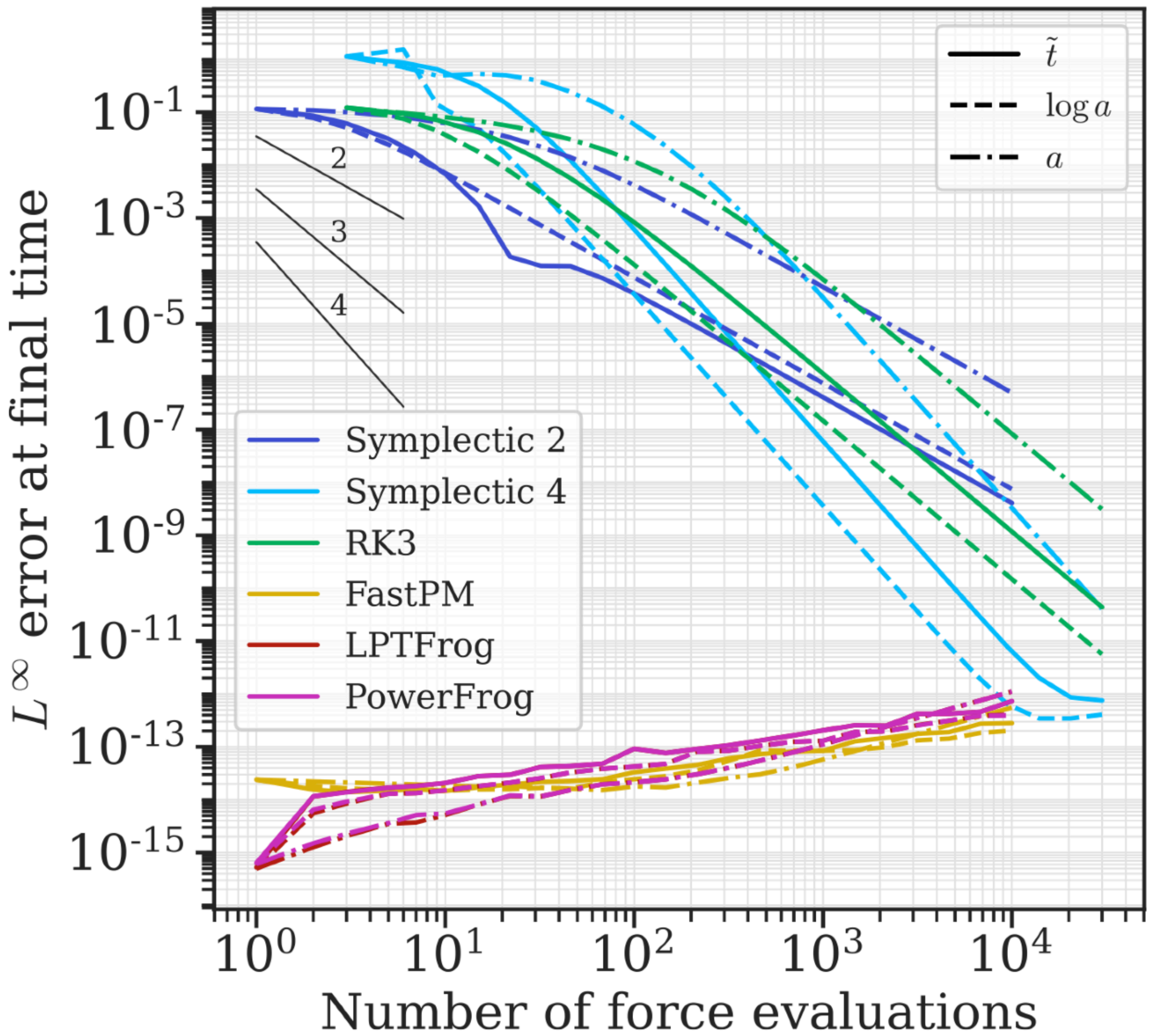
$$\mathrm{d}_D^2 \boldsymbol{X}_i(D) = 2\boldsymbol{\psi}_i^{n,(2)} = \mathrm{const.}$$

i.e. acceleration can be made constant

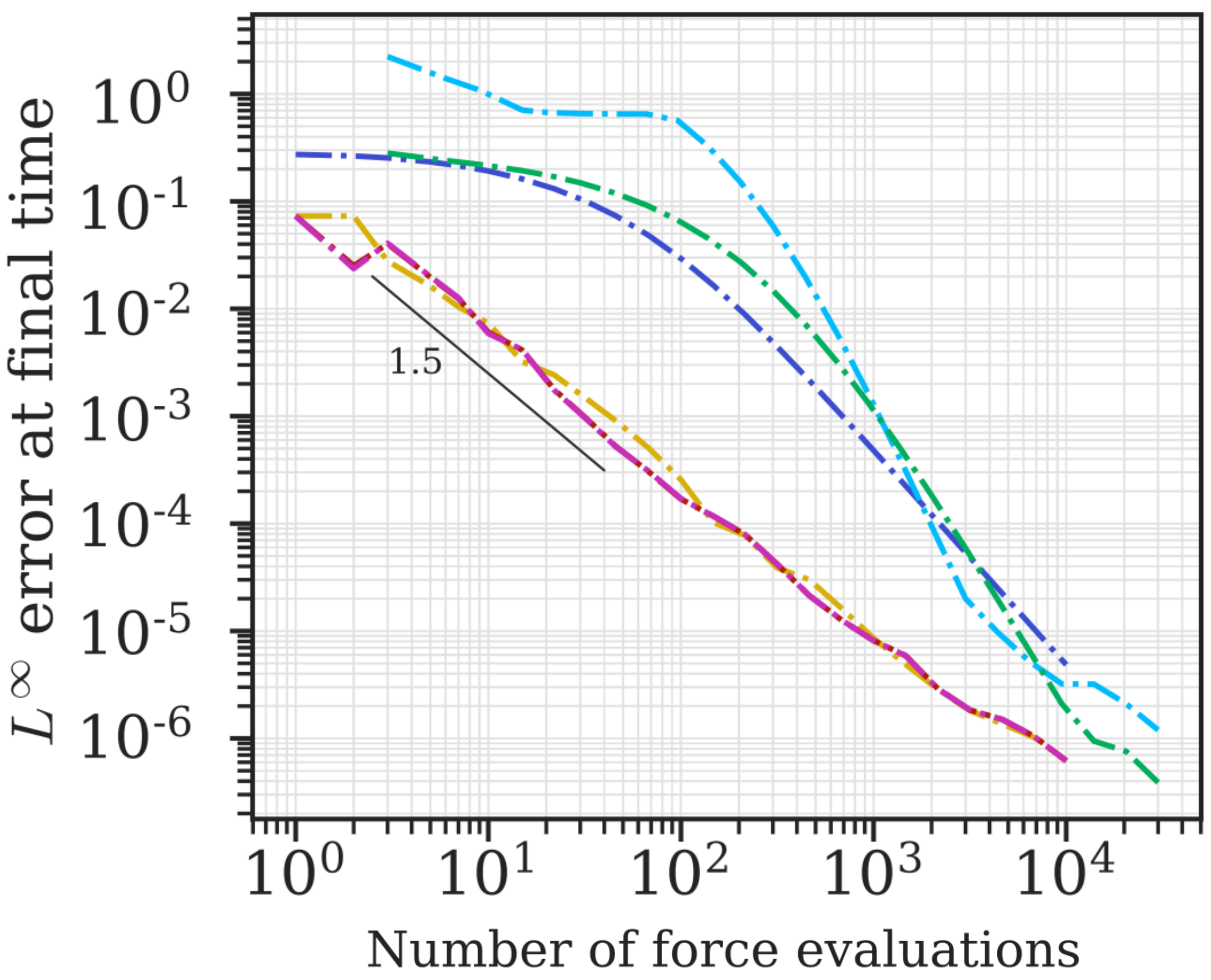
This can be matched in various ways to yield new integrators that can reproduce 2LPT.

Tests for 1D collapse

Growing mode plane wave



post shell-crossing:



Standard N-body simulations have difficulty reproducing nLPT

Feng+2016: FastPM idea: modify time integrator to get 1LPT agreement

Can do better: second order LPT (2LPT) can be written

$$\boldsymbol{X}_i(D) = \boldsymbol{X}_i^n + [D - D_n]\boldsymbol{\psi}_i^{n,(1)} + [D - D_n]^2\boldsymbol{\psi}_i^{n,(2)}$$

$$\mathrm{d}_D \boldsymbol{X}_i(D) = \boldsymbol{\psi}_i^{n,(1)} + 2[D - D_n]\boldsymbol{\psi}_i^{n,(2)},$$

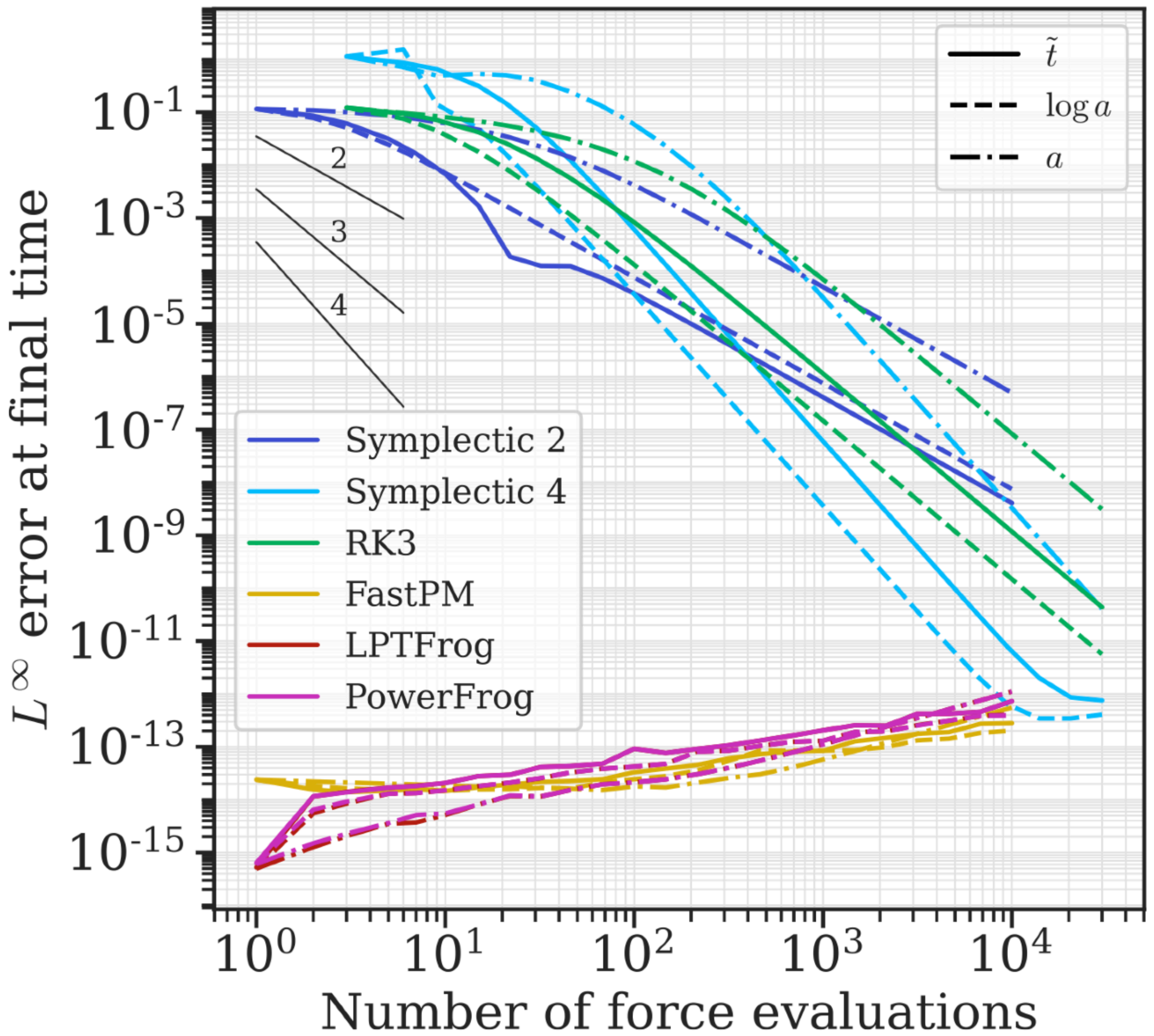
$$\mathrm{d}_D^2 \boldsymbol{X}_i(D) = 2\boldsymbol{\psi}_i^{n,(2)} = \text{const.}$$

i.e. acceleration can be made constant

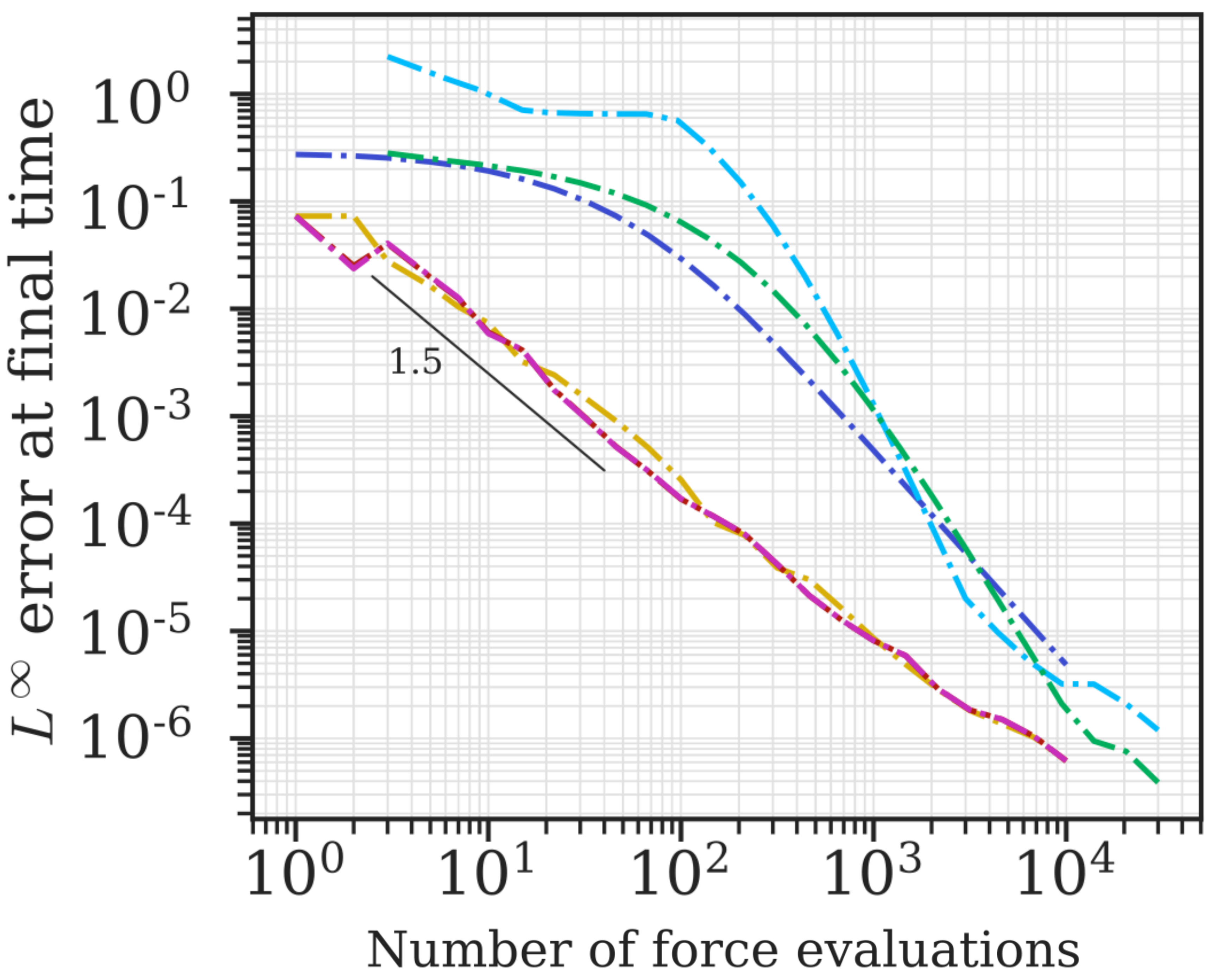
This can be matched in various ways to yield new integrators that can reproduce 2LPT. List & OH 2024, JCP subm.

Tests for 1D collapse

Growing mode plane wave



post shell-crossing:



Standard N-body simulations have difficulty reproducing nLPT

Feng+2016: FastPM idea: modify time integrator to get 1LPT agreement

Can do better: second order LPT (2LPT) can be written

$$\boldsymbol{X}_i(D) = \boldsymbol{X}_i^n + [D - D_n]\boldsymbol{\psi}_i^{n,(1)} + [D - D_n]^2\boldsymbol{\psi}_i^{n,(2)}$$

$$\mathrm{d}_D\boldsymbol{X}_i(D) = \boldsymbol{\psi}_i^{n,(1)} + 2[D - D_n]\boldsymbol{\psi}_i^{n,(2)},$$

$$\mathrm{d}_D^2\boldsymbol{X}_i(D) = 2\boldsymbol{\psi}_i^{n,(2)} = \mathrm{const.}$$

i.e. acceleration can be made constant

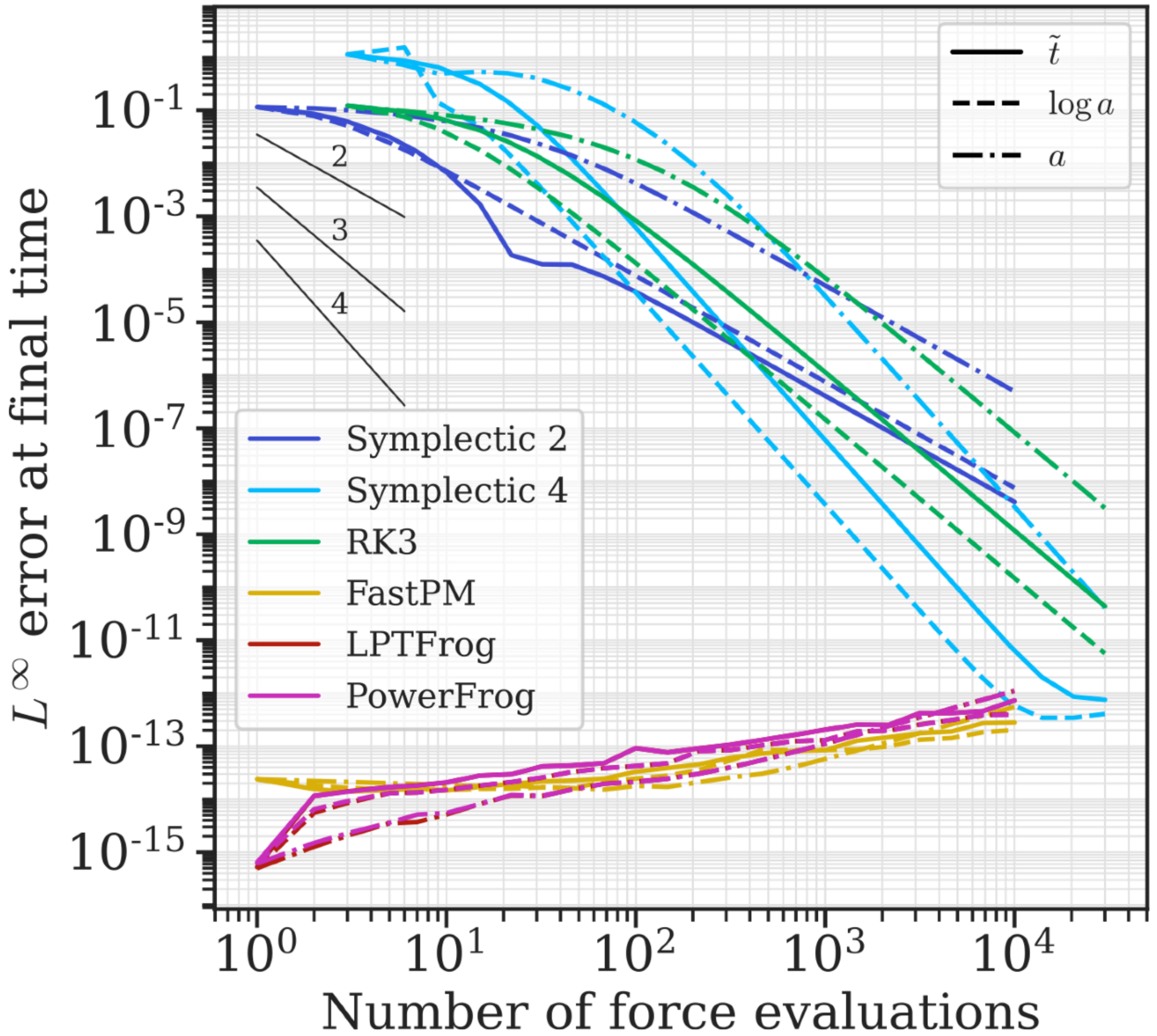
This can be matched in various ways to yield new integrators that can reproduce 2LPT.

List & OH 2024, JCP subm.

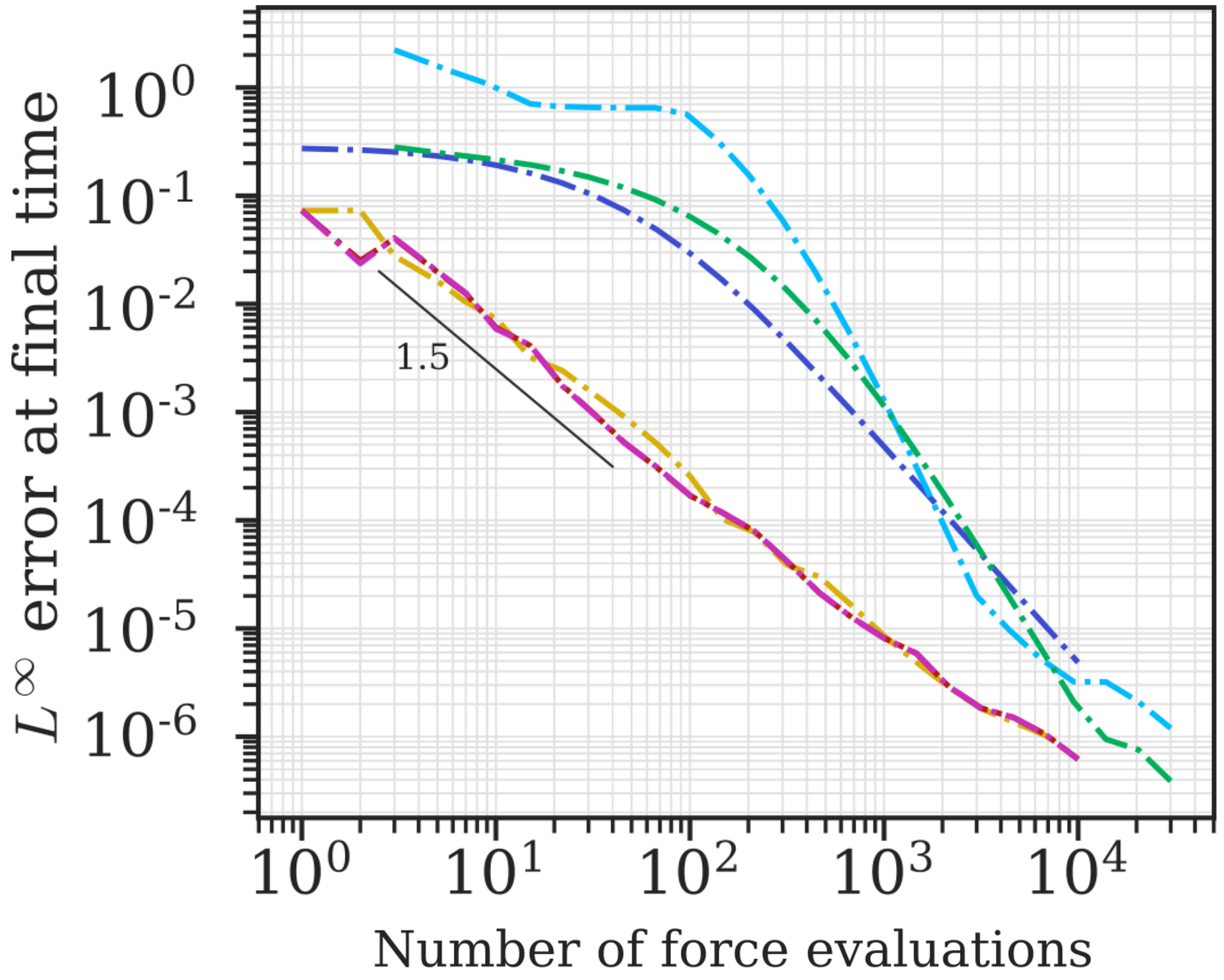
Rampf, List & OH 2024, in prep.

Tests for 1D collapse

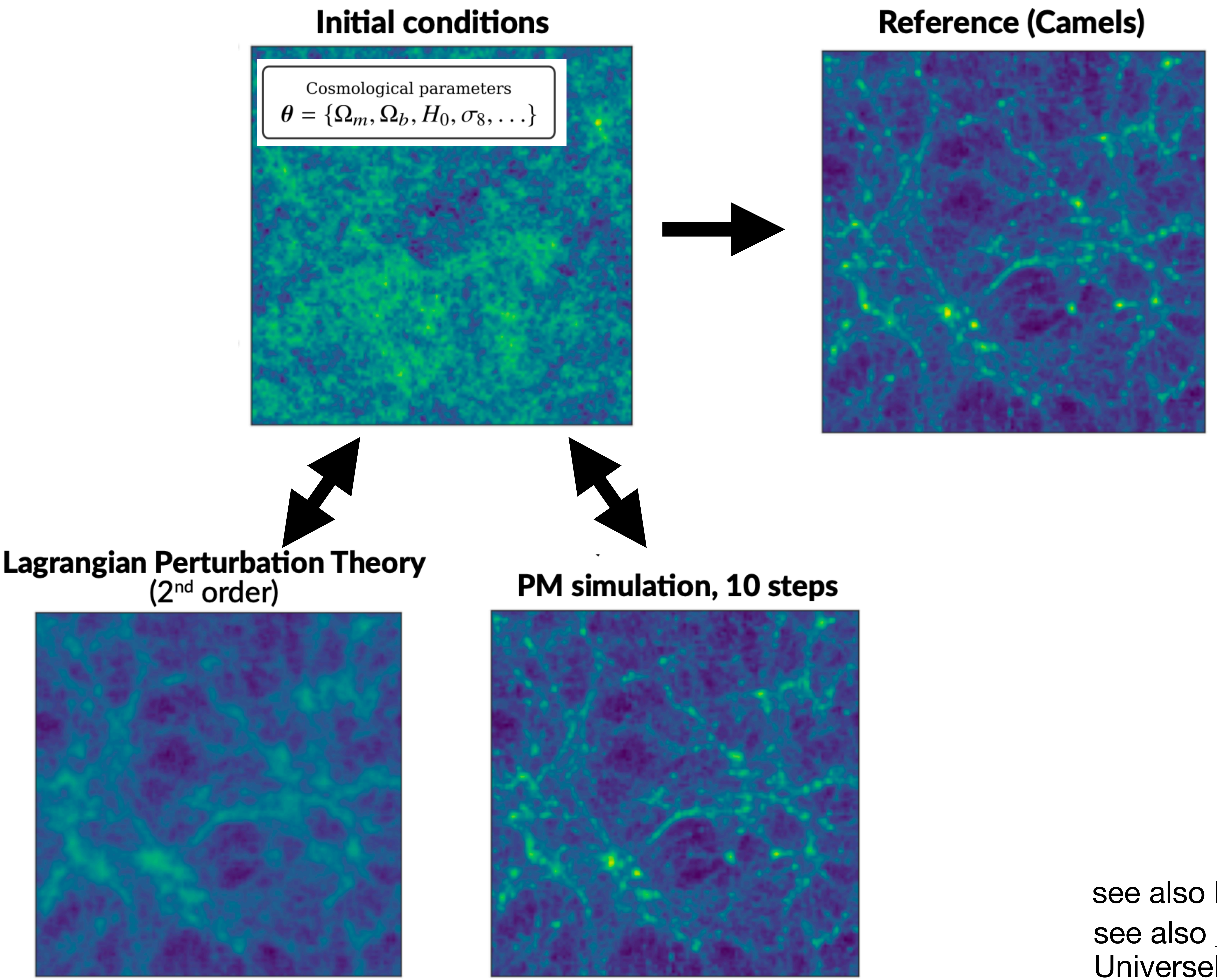
Growing mode plane wave



post shell-crossing:



Comparison of methods



Performed using the Gadget-3 simulation code
[Springel+ 2005]

- accurate TreePM forces
- thousands of timesteps

Density field when universe was 1/3 of the current size in each dimension

DISCO-DJ
differentiable simulations for cosmology
done with jax

see also https://github.com/eelregit/pmwd by Yin Li

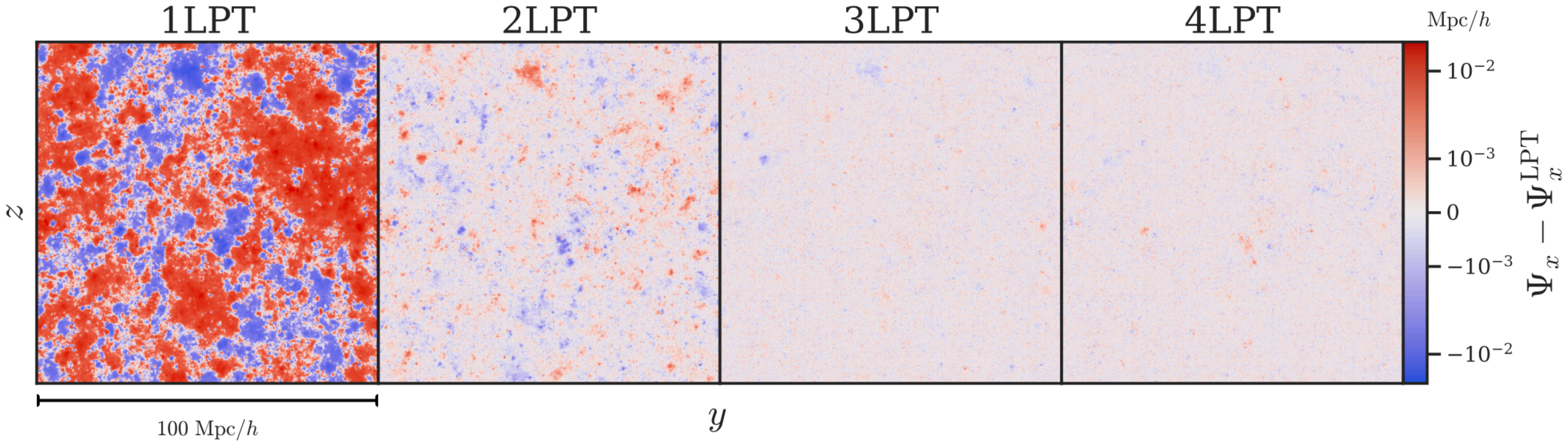
see also https://github.com/DifferentiableUniverseInitiative/JaxPM by François Lanusse et al

see also FlowPM by Seljak & collaborators

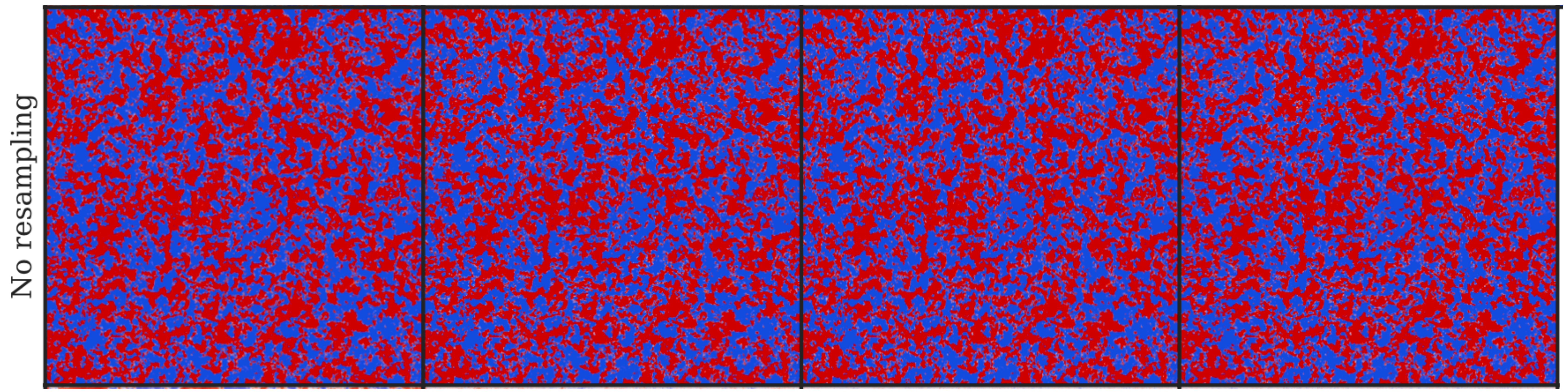
Unifying LPT and N-body…(but UV-complete!)

PowerFrog integrator is asymptotically consistent with 2LPT for a→0, so can start at a=0 as we do in LPT

Residual of single PowerFrog step from a=∞ to a=0.05, wrt. nLPT:



This is only possible after controlling **all** discreteness effects in the N-body simulation, otherwise:



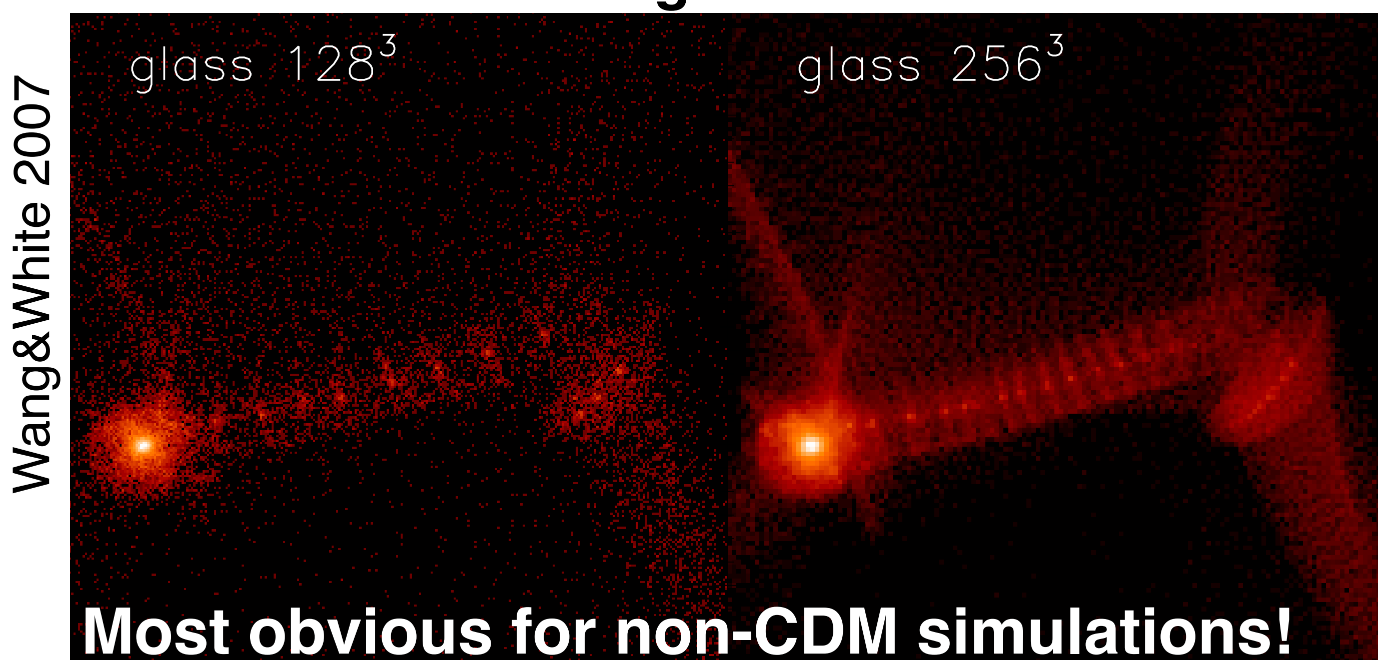
List, OH & Rampf (2024, PRL)

Towards the fluid limit for dark matter modelling

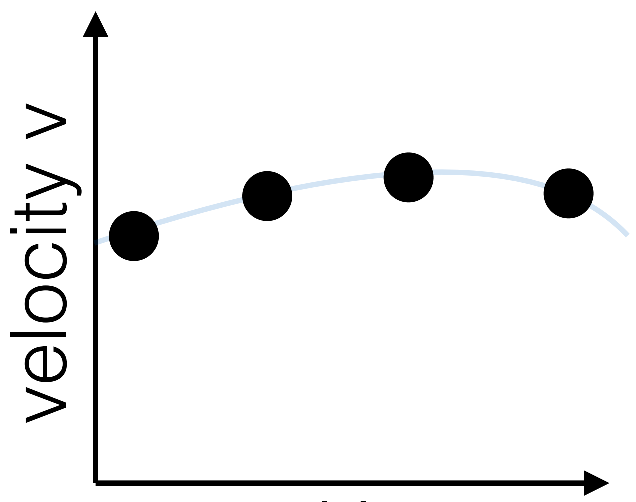
Curing Discreteness Noise in N-body and Fragmentation

spurious fragmentation is well-known phenomenon in N-body sims with cut-off

“Beads-on-a-string” in WDM simulations



N-body just have particles

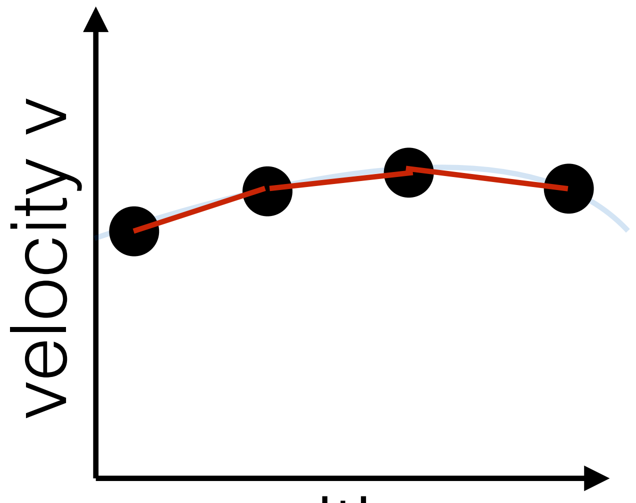


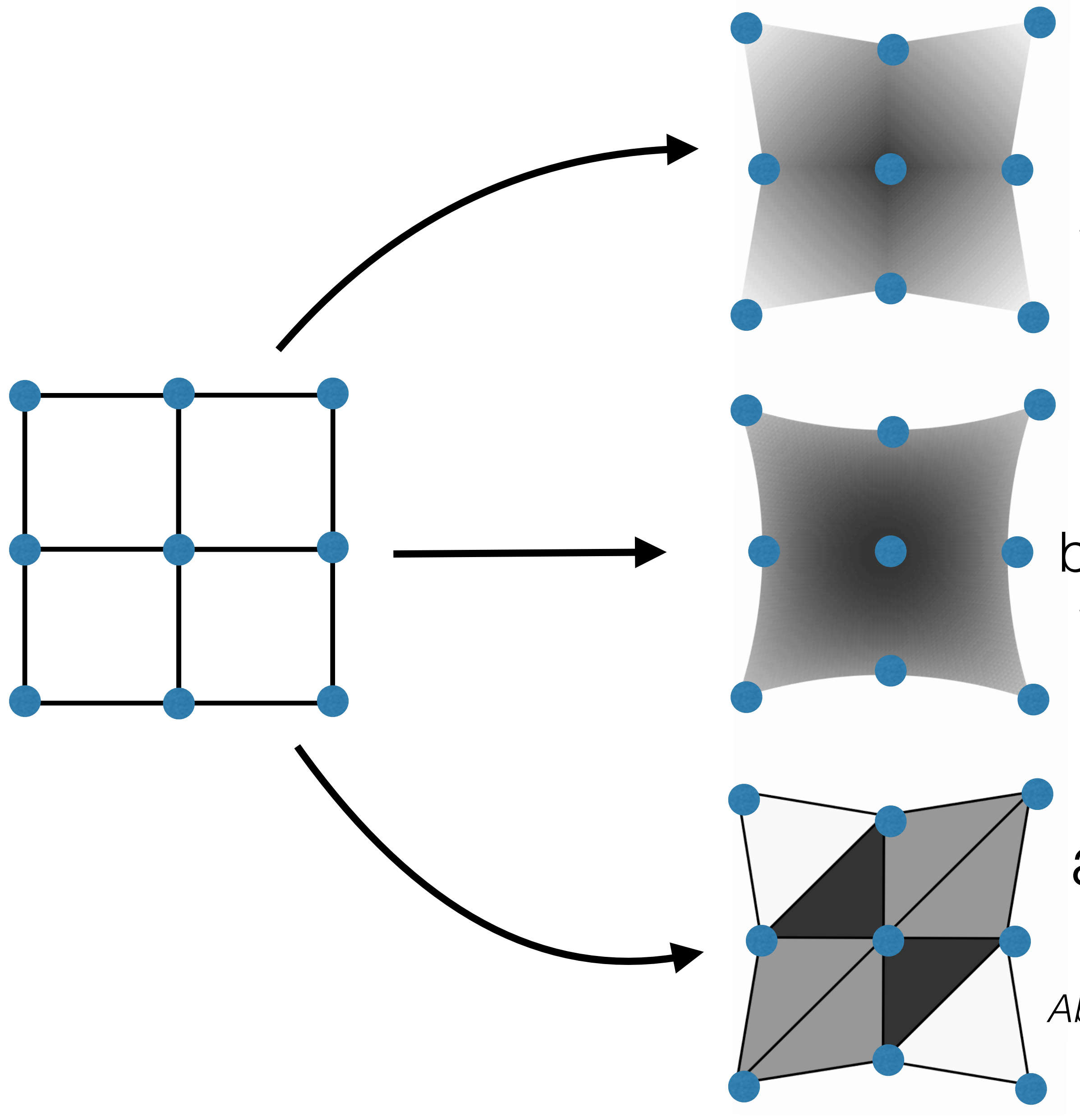
In >1 dim: multivariate maps

Abel, Hahn & Kaehler 2012

Schandarin et al. 2012

now: connect particles by interpolating functions





k=1
bi/tri-linear
Hahn&Angulo 2016

k=2
bi/tri-quadratic
Hahn&Angulo 2016

affine map
tetrahedral
Abel, Hahn & Kaehler 2012
Schandarin et al. 2012

Sousbie&Colombi 2015
(also ***quadratic*** *tetrahedra)*

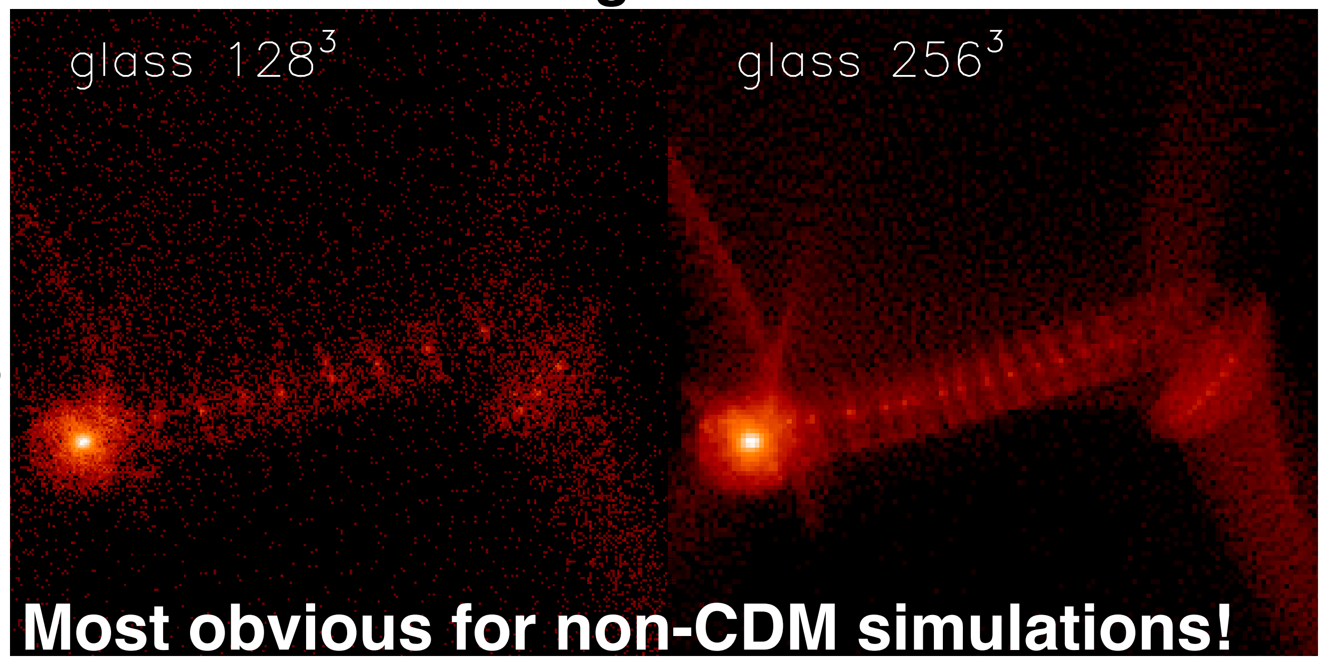
Towards the fluid limit for dark matter modelling

Curing Discreteness Noise in N-body and Fragmentation

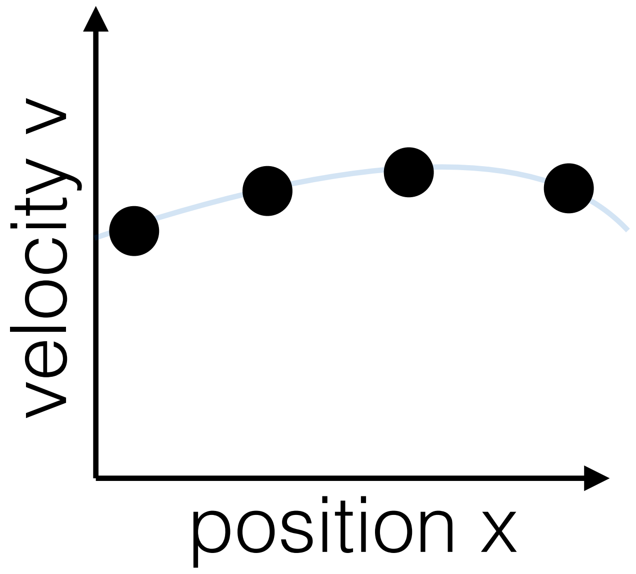
spurious fragmentation is well-known phenomenon in N-body sims with cut-off

“Beads-on-a-string” in WDM simulations

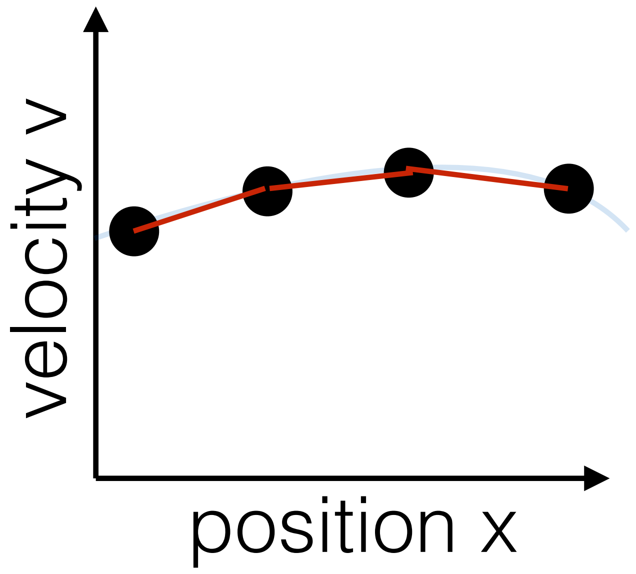
Wang&White 2007



N-body just have particles

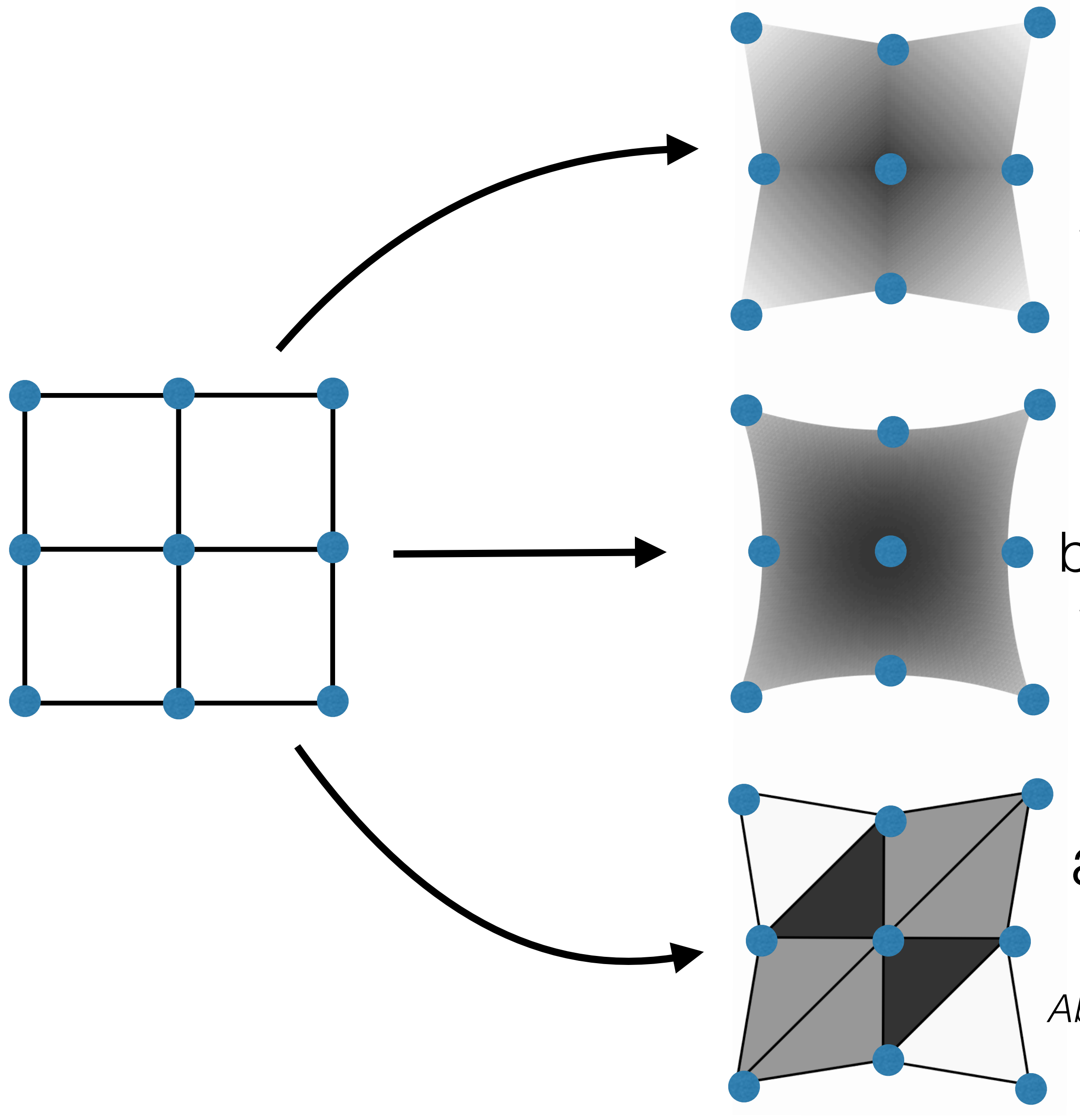


now: connect particles by interpolating functions



In >1 dim: multivariate maps

Abel, Hahn & Kaehler 2012 *Schandarin et al. 2012*



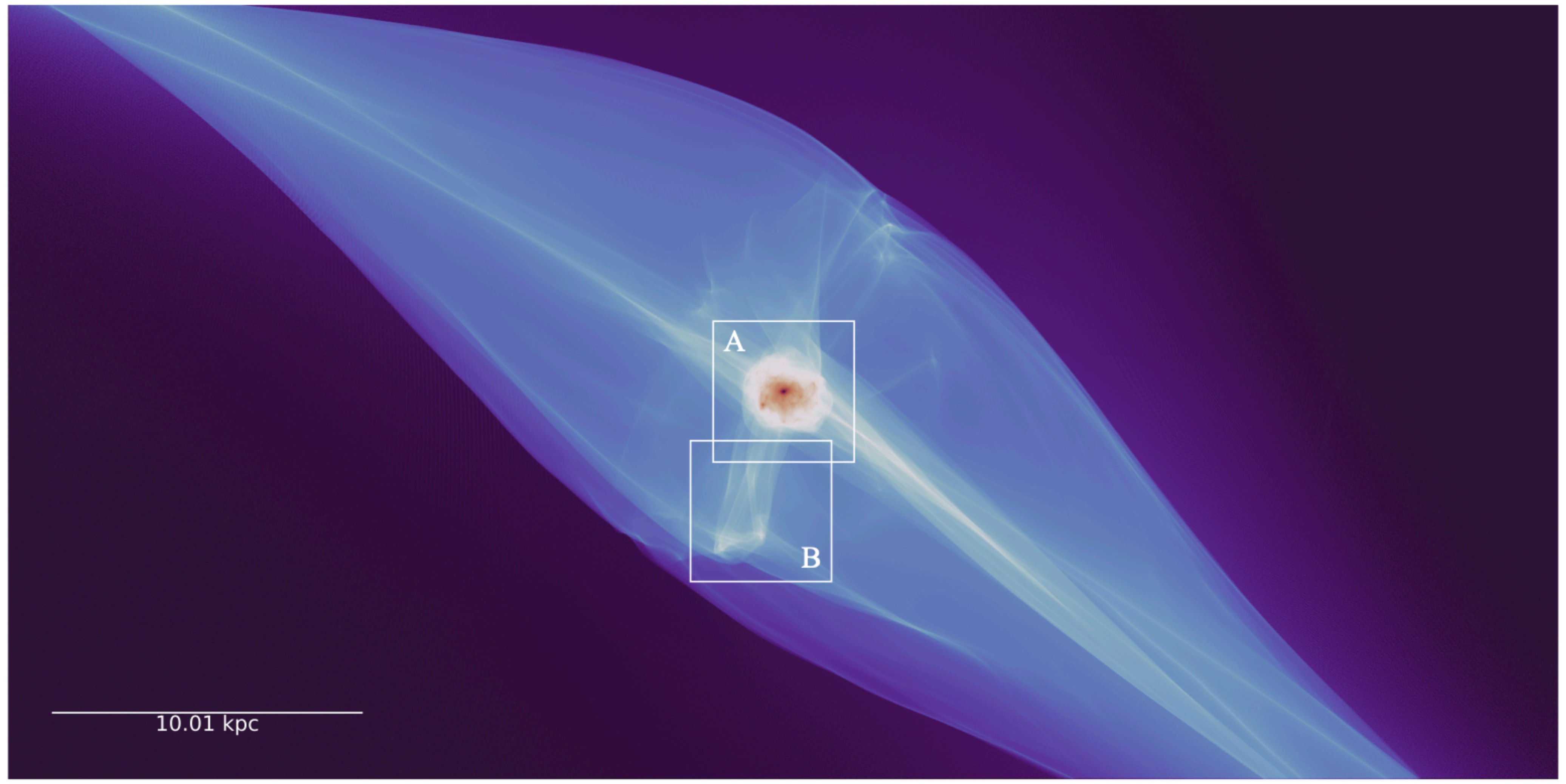
k=1
bi/tri-linear
Hahn&Angulo 2016

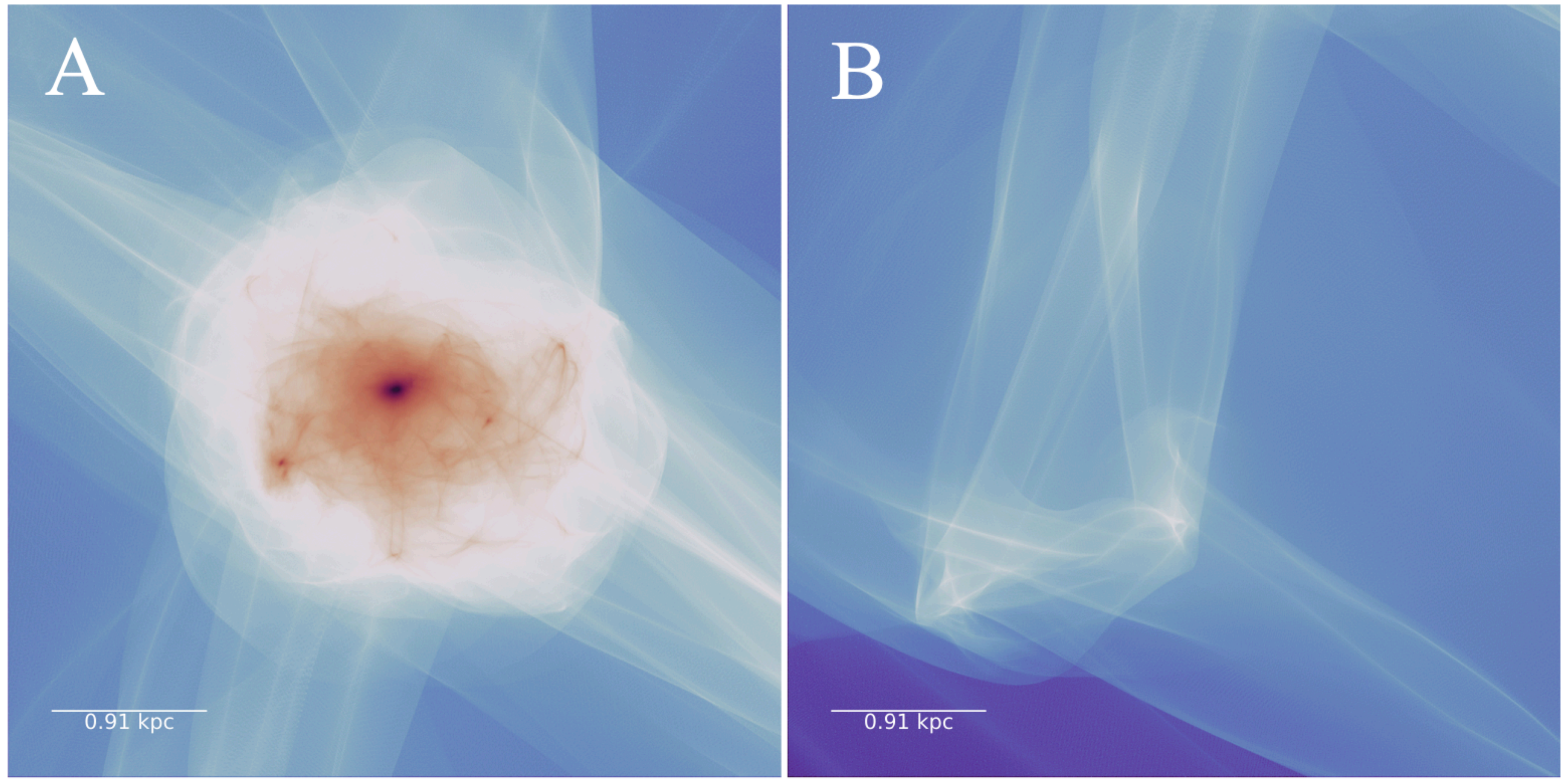
k=2
bi/tri-quadratic
Hahn&Angulo 2016

affine map
tetrahedral
Abel, Hahn & Kaehler 2012
Schandarin et al. 2012

Sousbie&Colombi 2015
*(also **quadratic** tetrahedra)*

Latest incarnation of sheet-based simulations of prompt CDM cusps (deviations from NFW of first gen. haloes)





Ondaro-Mallea et al. 2023

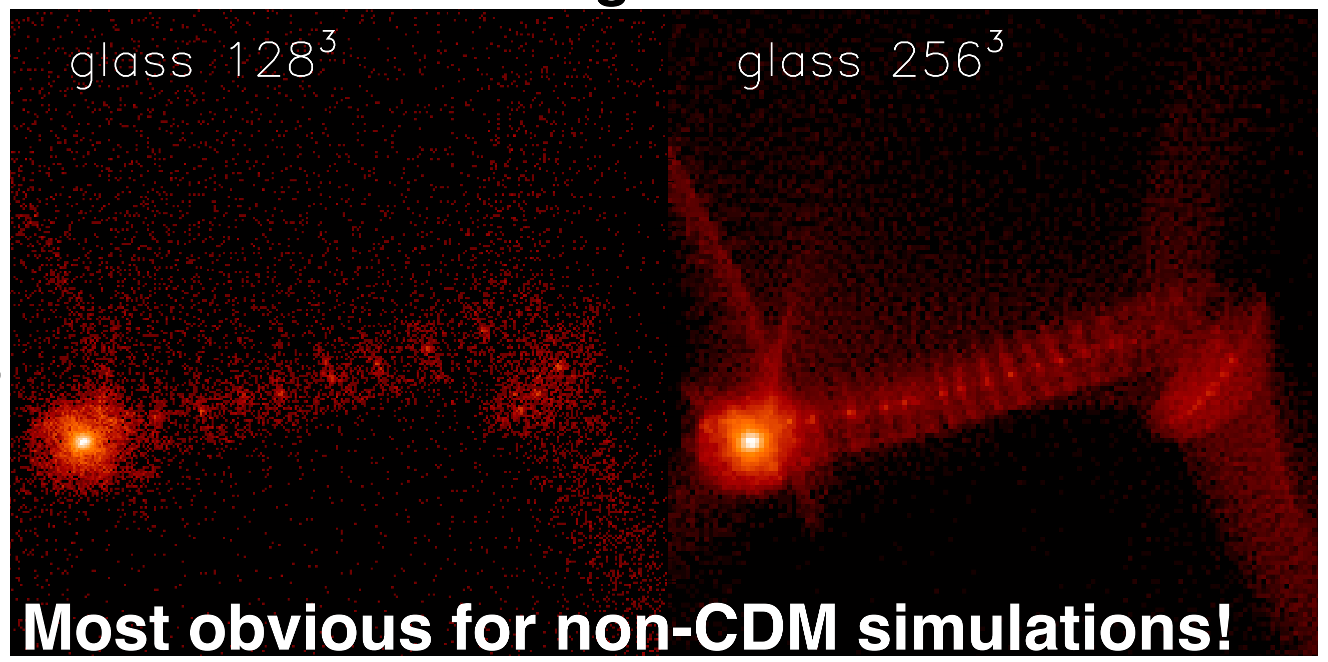
Towards the fluid limit for dark matter modelling

Curing Discreteness Noise in N-body and Fragmentation

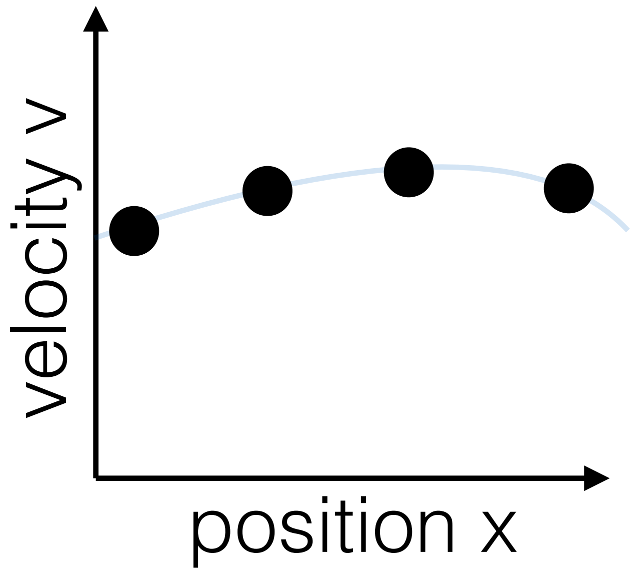
spurious fragmentation is well-known phenomenon in N-body sims with cut-off

"Beads-on-a-string" in WDM simulations

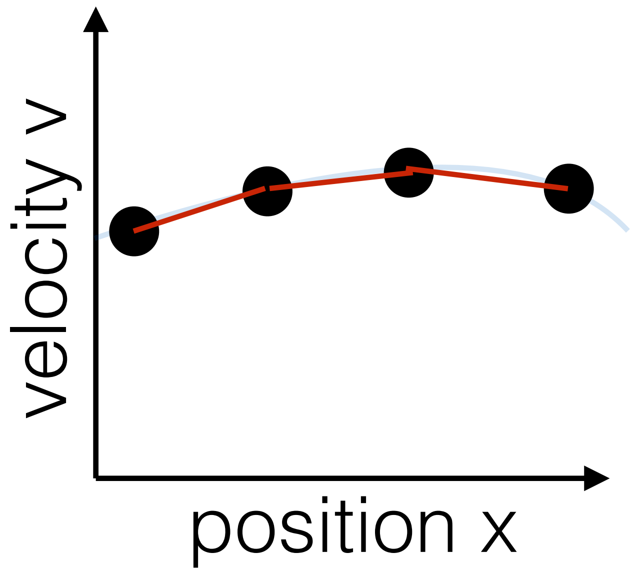
Wang&White 2007



N-body just have particles

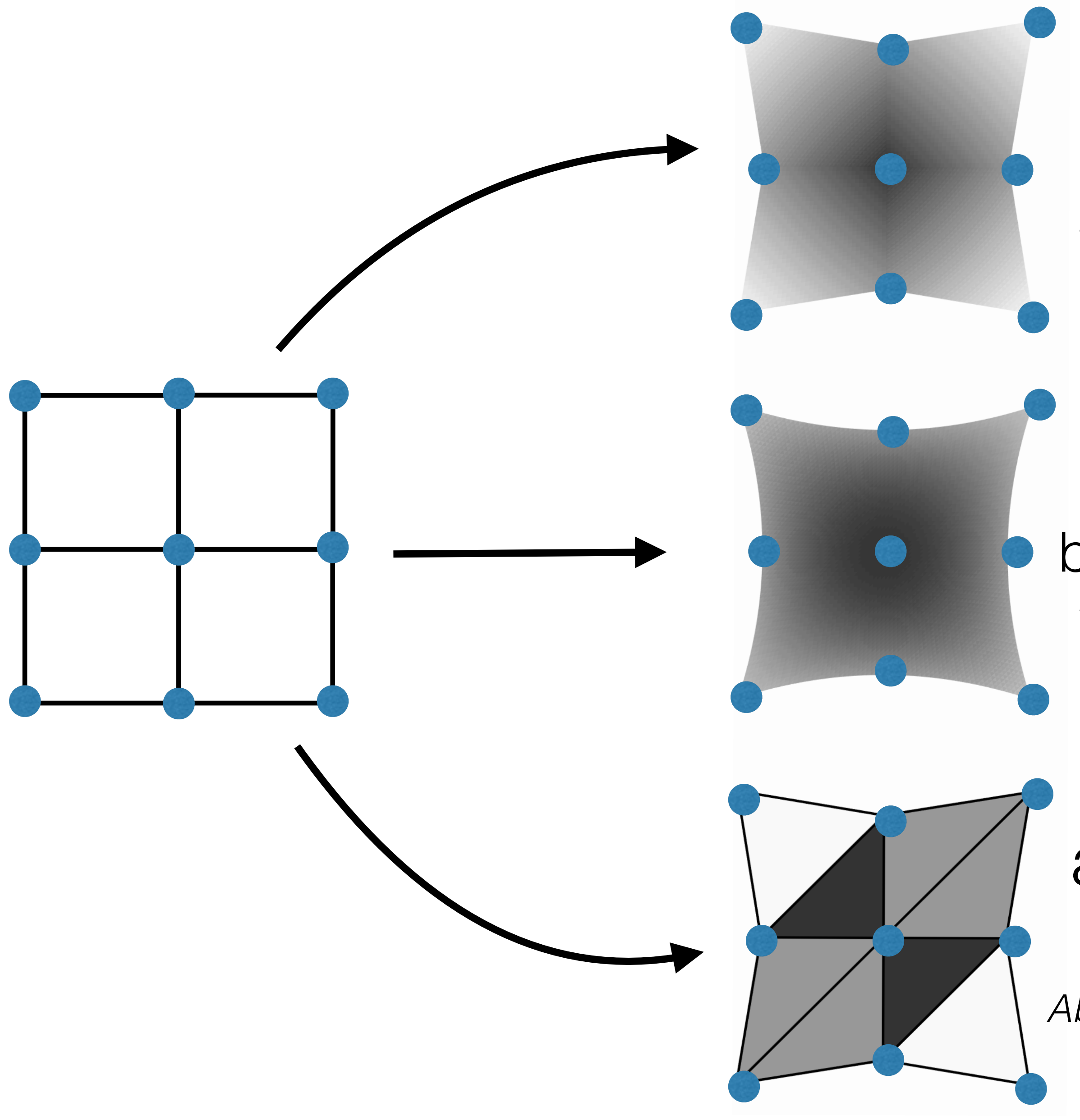


now: connect particles by interpolating functions



In >1 dim: multivariate maps

Abel, Hahn & Kaehler 2012 *Schandarin et al. 2012*



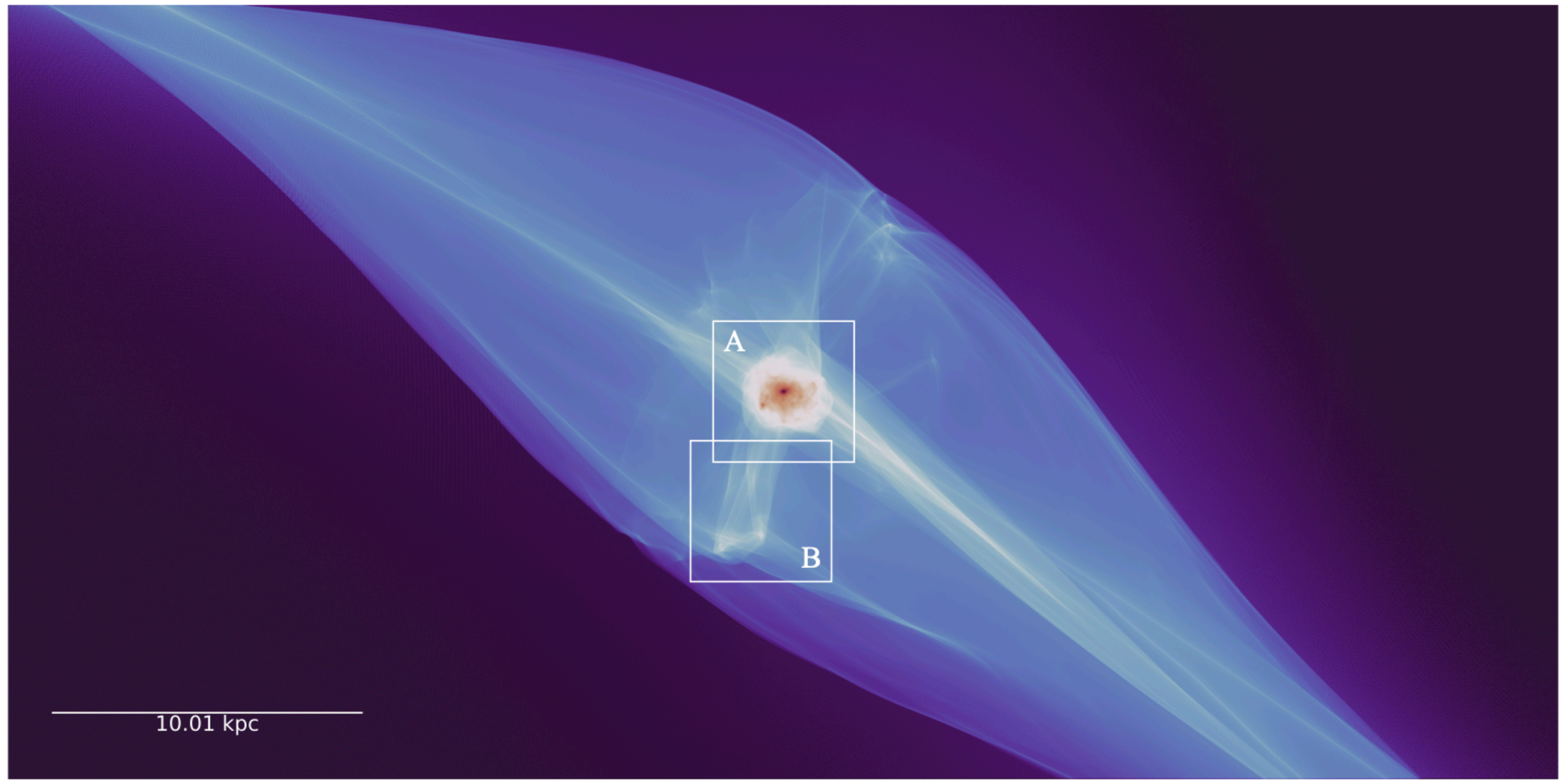
k=1
bi/tri-linear
Hahn&Angulo 2016

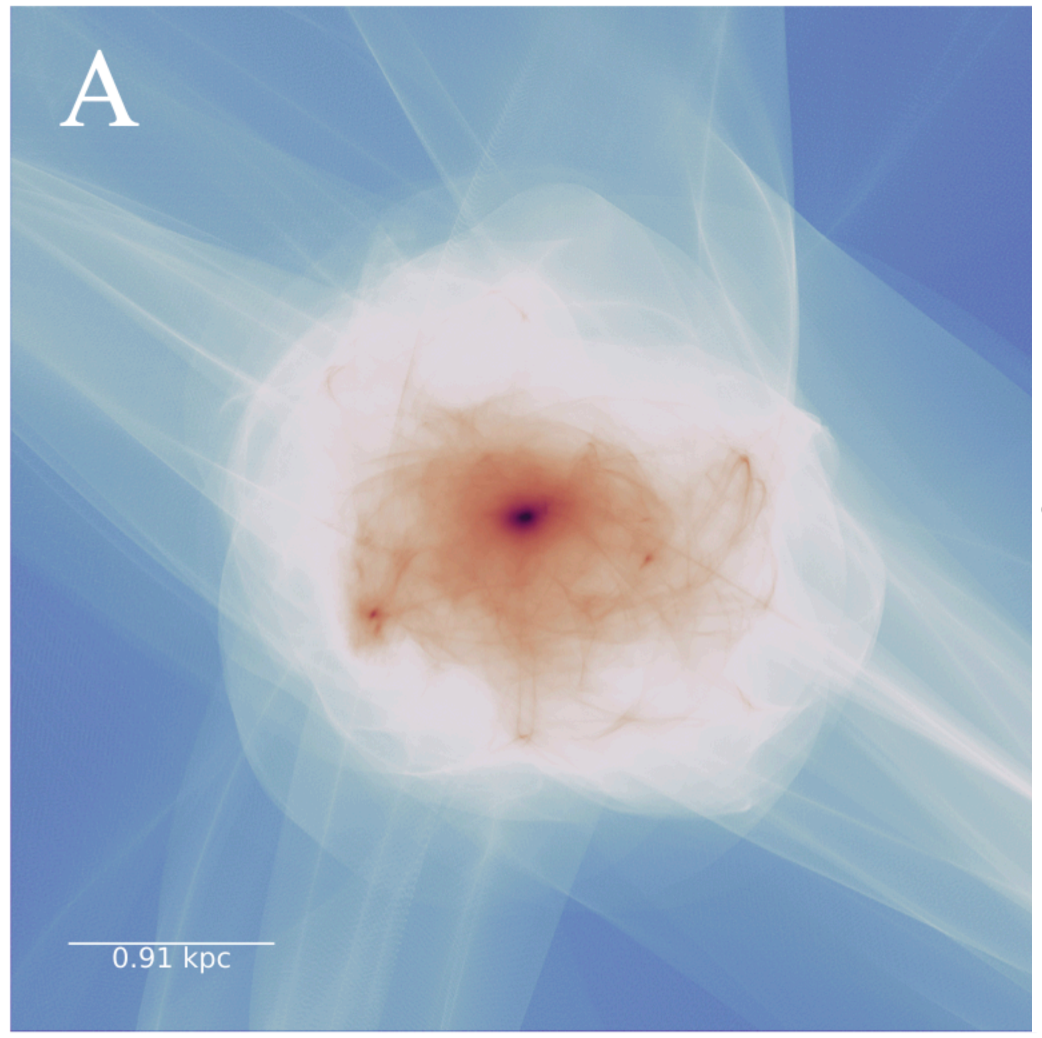
k=2
bi/tri-quadratic
Hahn&Angulo 2016

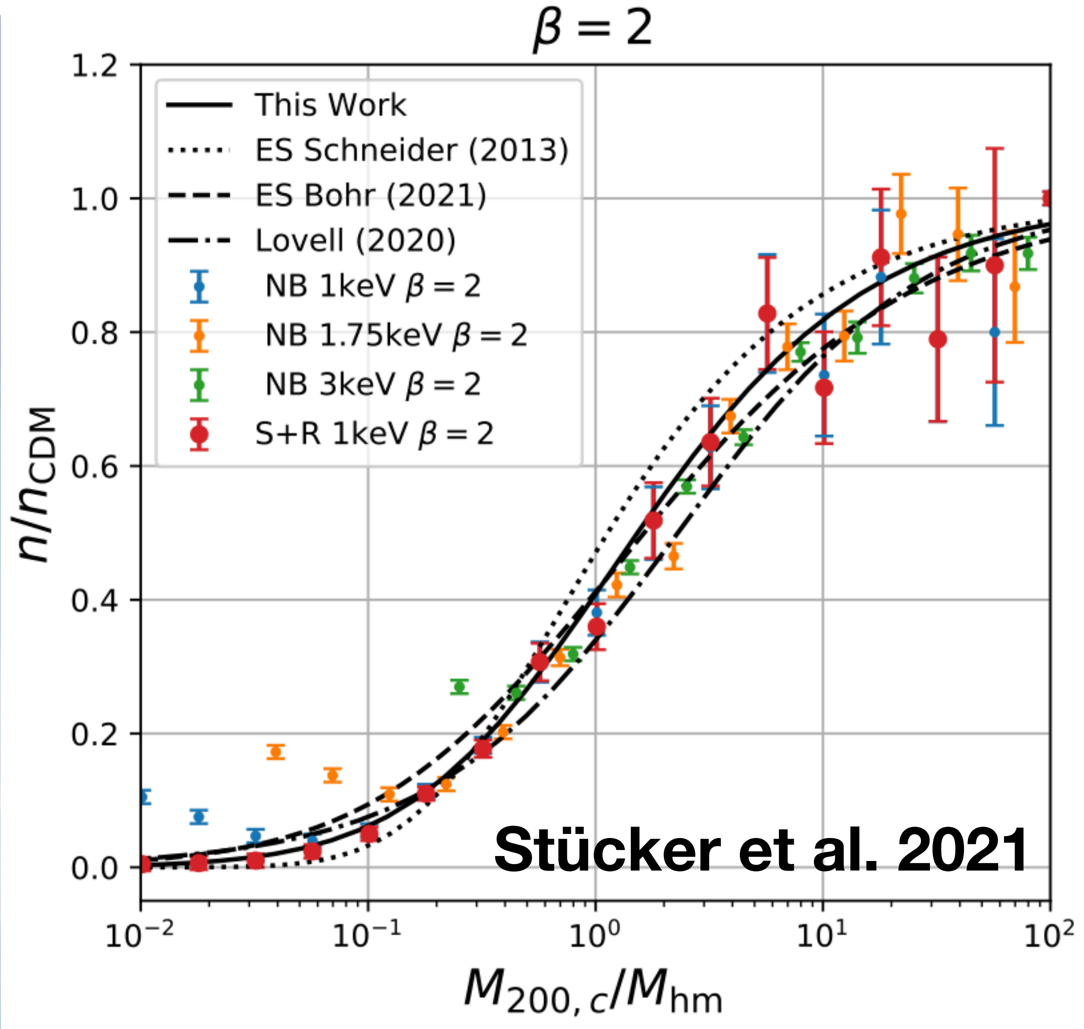
affine map
tetrahedral
Abel, Hahn & Kaehler 2012
Schandarin et al. 2012

Sousbie&Colombi 2015
*(also **quadratic** tetrahedra)*

Latest incarnation of sheet-based simulations of prompt CDM cusps (deviations from NFW of first gen. haloes)







Ondaro-Mallea et al. 2023

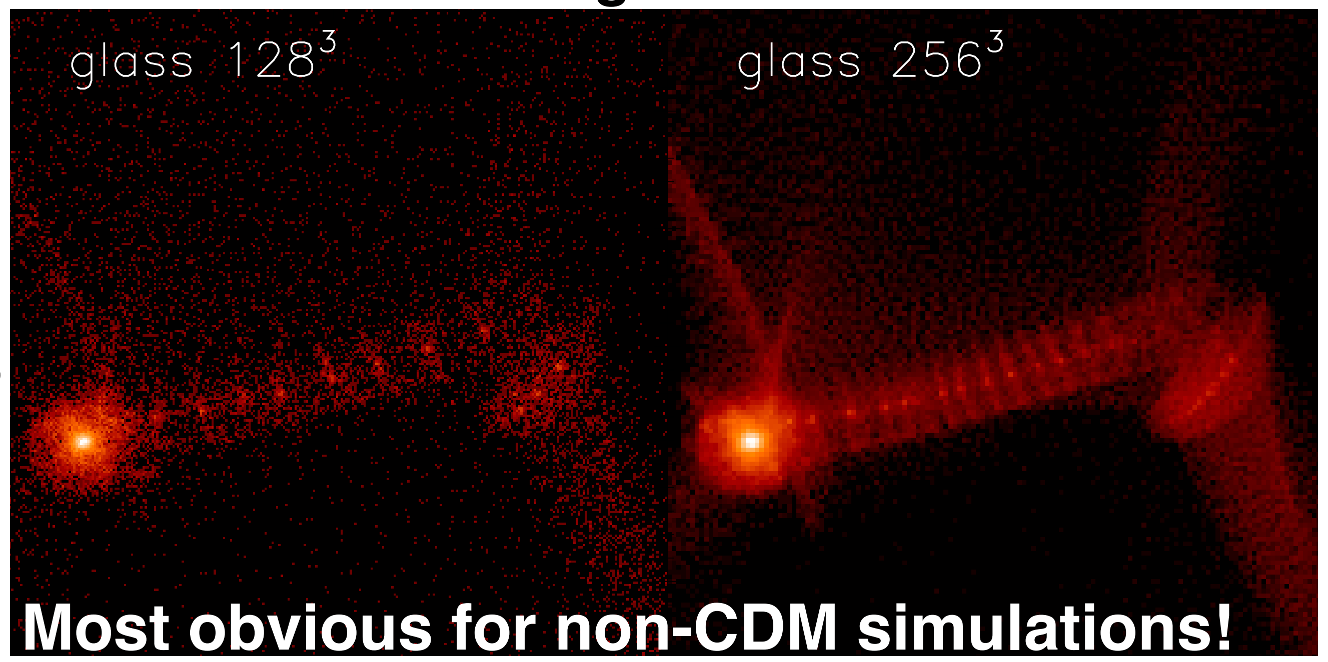
Towards the fluid limit for dark matter modelling

Curing Discreteness Noise in N-body and Fragmentation

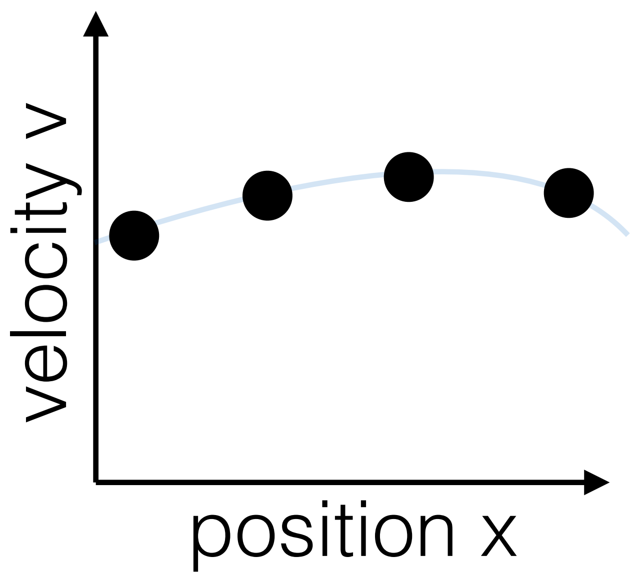
spurious fragmentation is well-known phenomenon in N-body sims with cut-off

“Beads-on-a-string” in WDM simulations

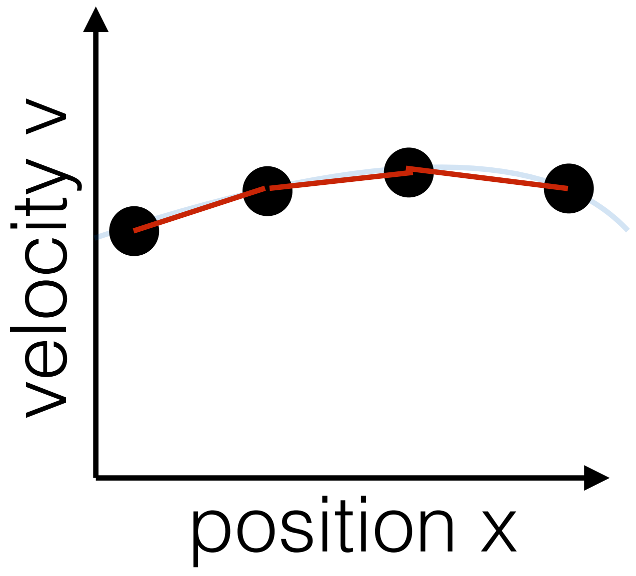
Wang&White 2007



N-body just have particles

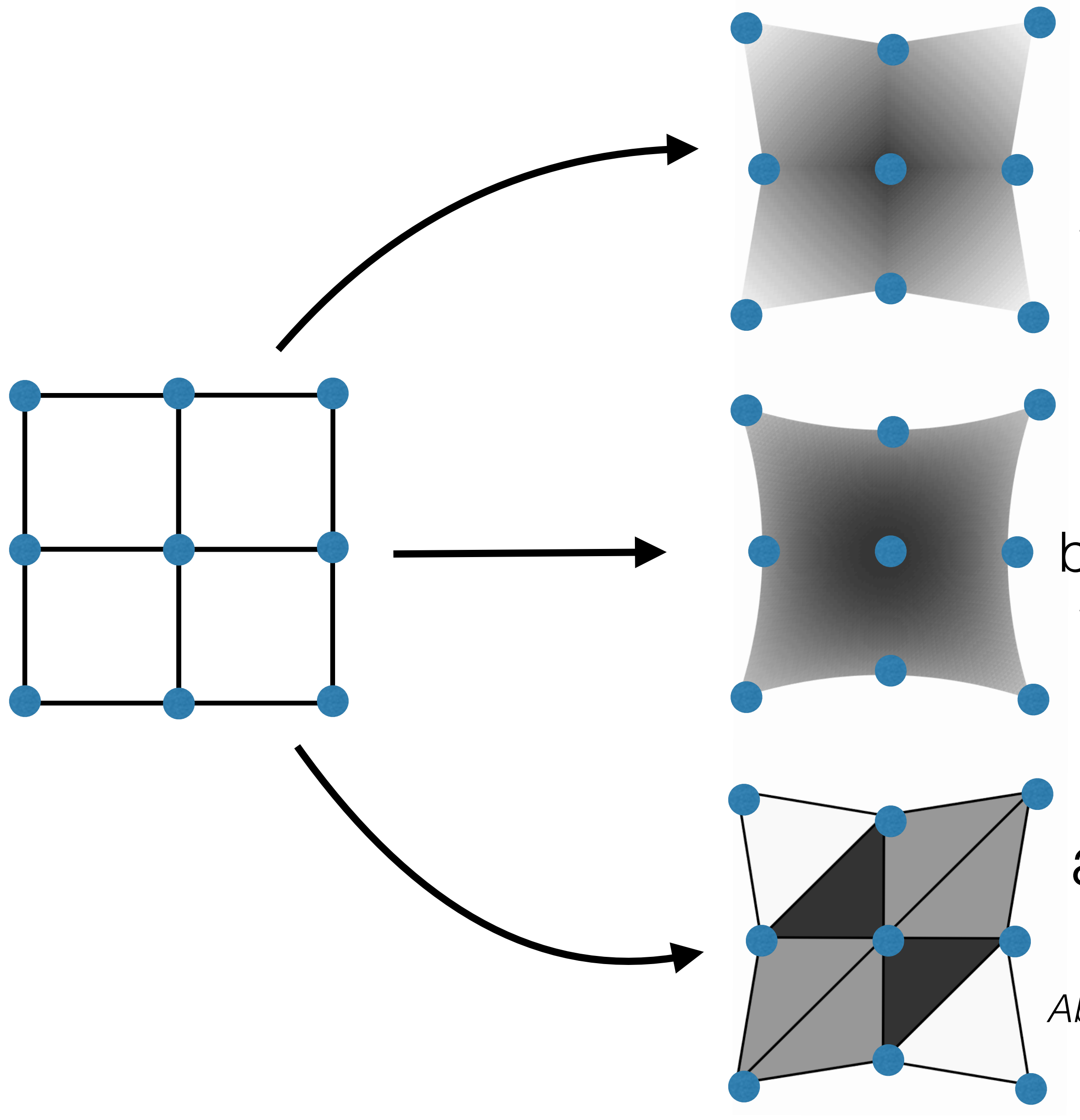


now: connect particles by interpolating functions



In >1 dim: multivariate maps

Abel, Hahn & Kaehler 2012 *Schandarin et al. 2012*



k=1
bi/tri-linear
Hahn&Angulo 2016

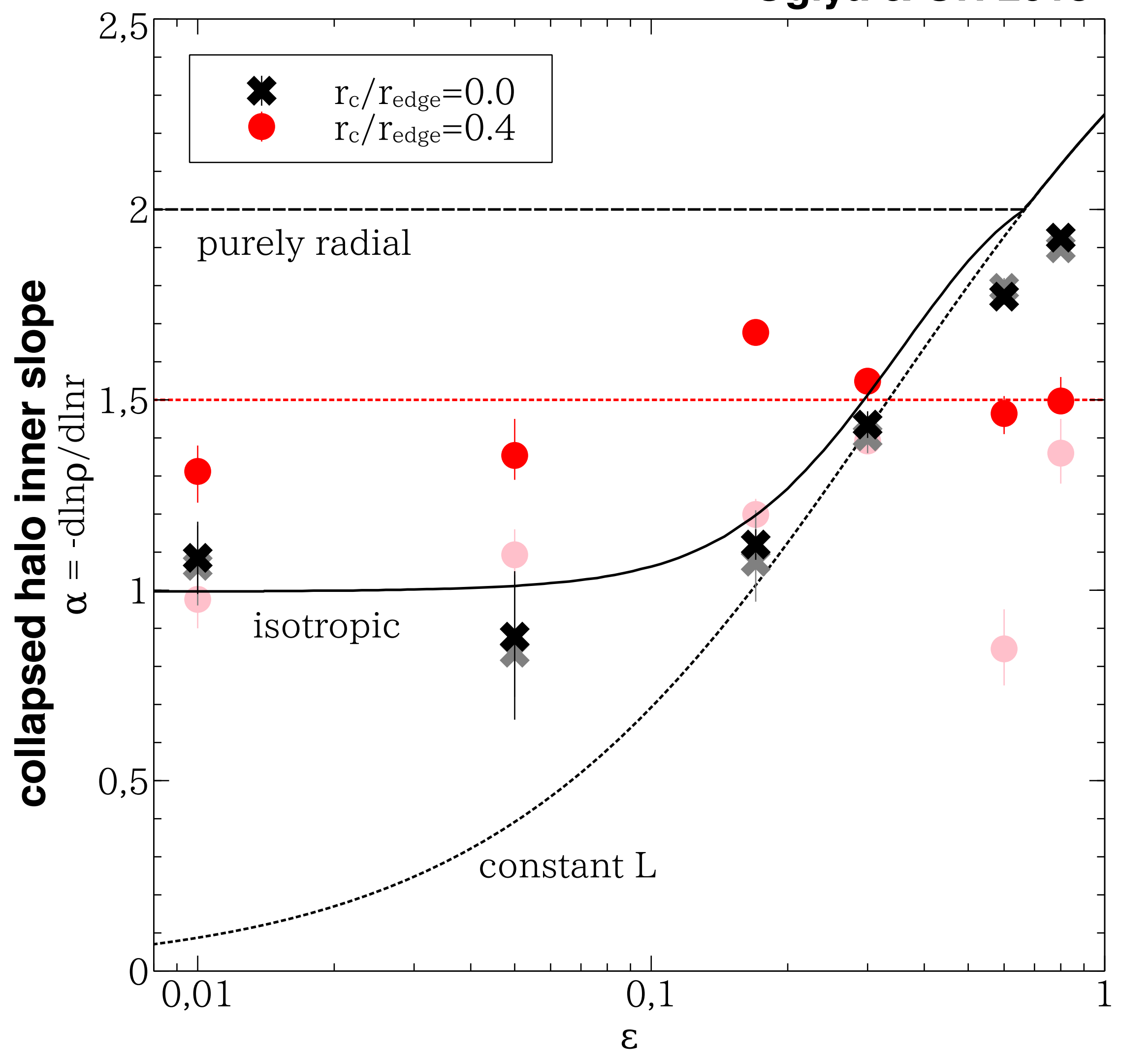
k=2
bi/tri-quadratic
Hahn&Angulo 2016

affine map
tetrahedral
Abel, Hahn & Kaehler 2012
Schandarin et al. 2012

Sousbie&Colombi 2015
*(also **quadratic** tetrahedra)*

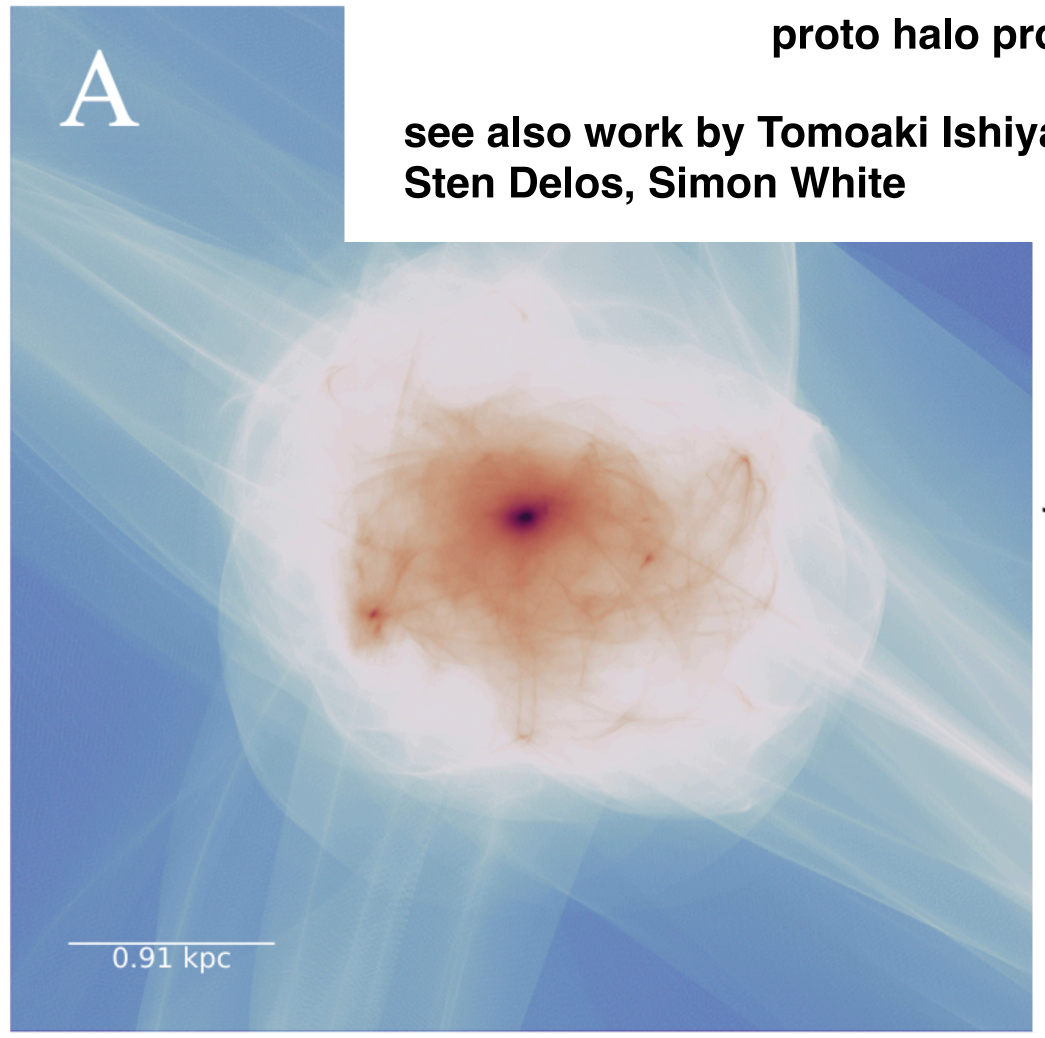
Latest incarnation of sheet-based simulations of prompt CDM cusps (deviations

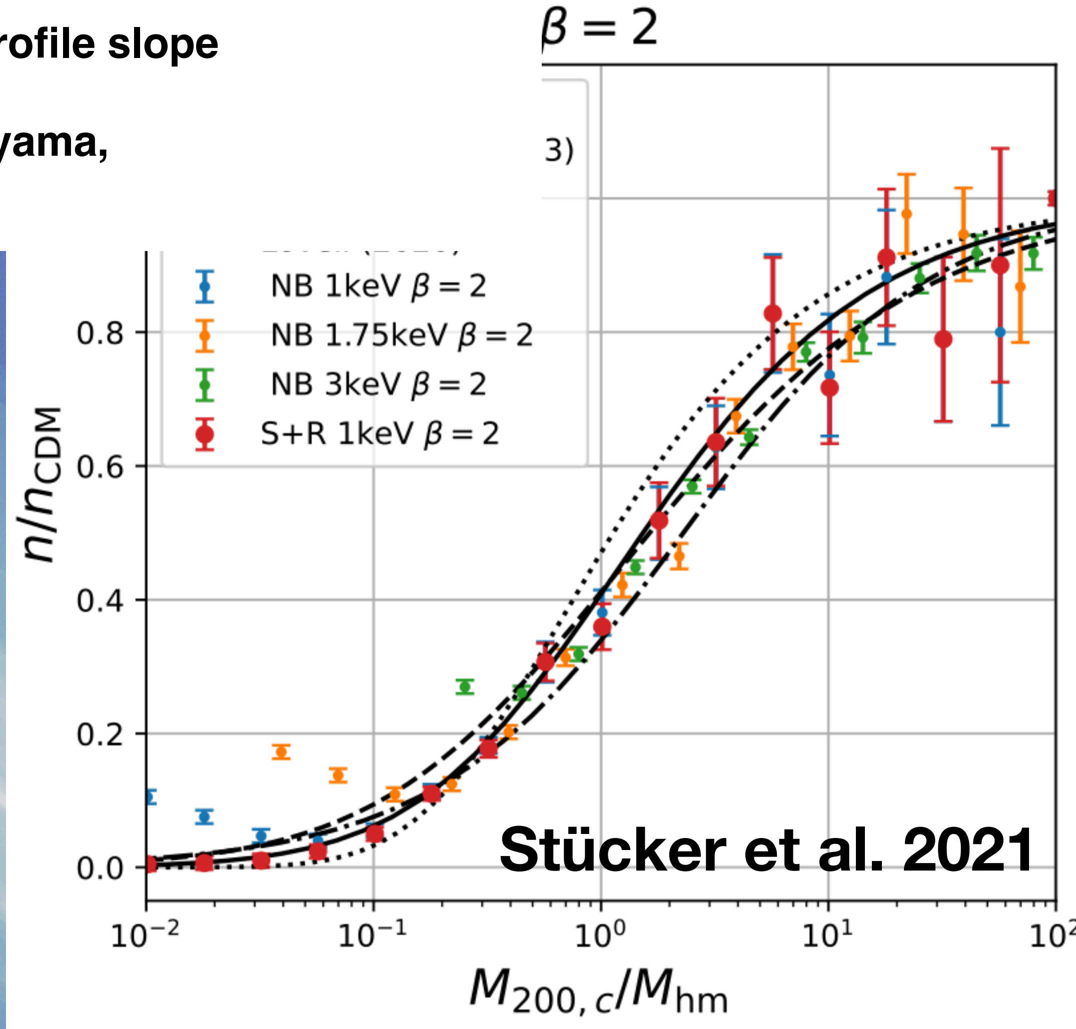
Ogiya & OH 2018



proto halo profile slope

see also work by Tomoaki Ishiyama, Sten Delos, Simon White



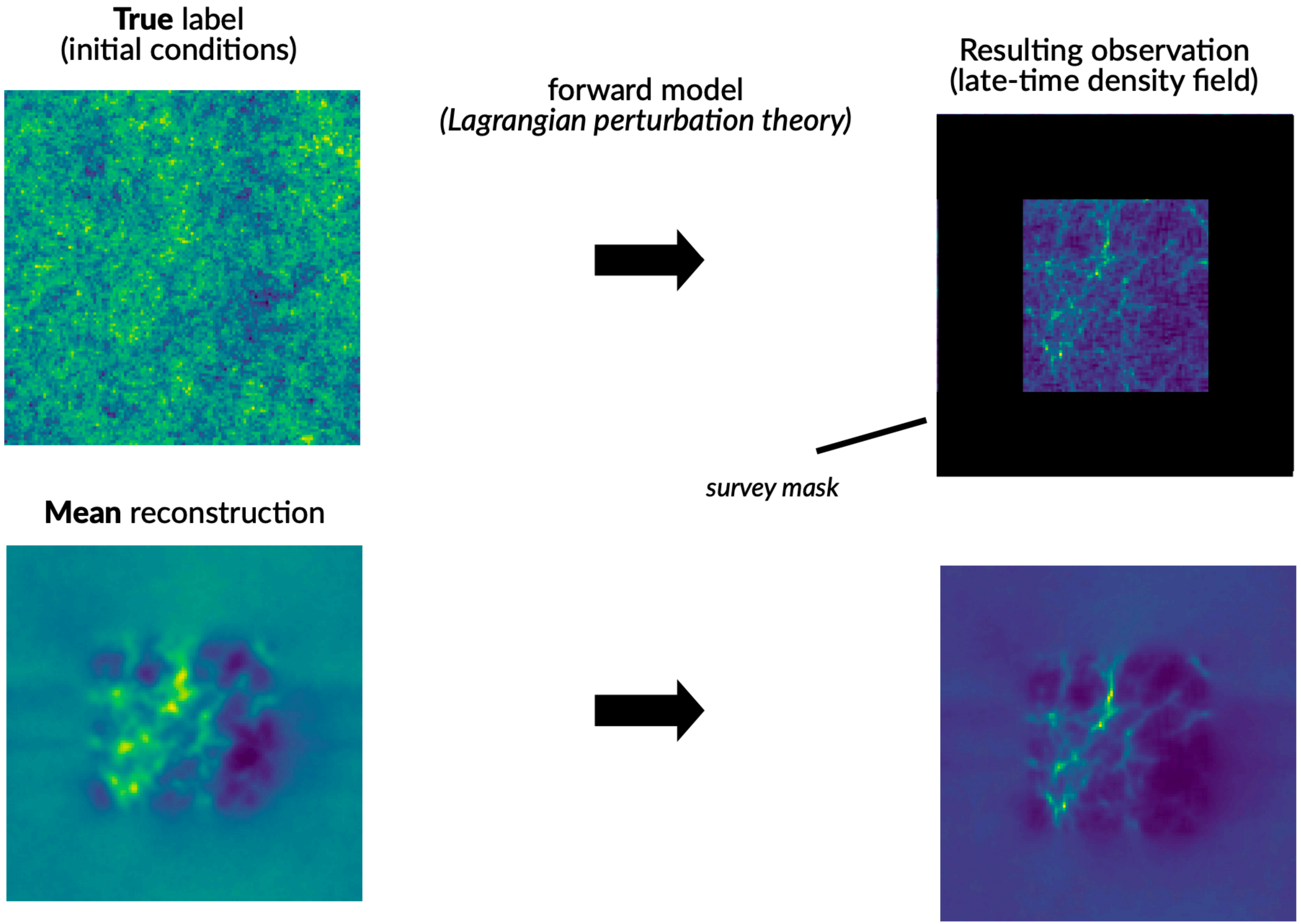


Ondaro-Mallea et al. 2023

Field-level inference: reconstruction

Task: given a (simulated) **late-time density field**, reconstruct **initial conditions**

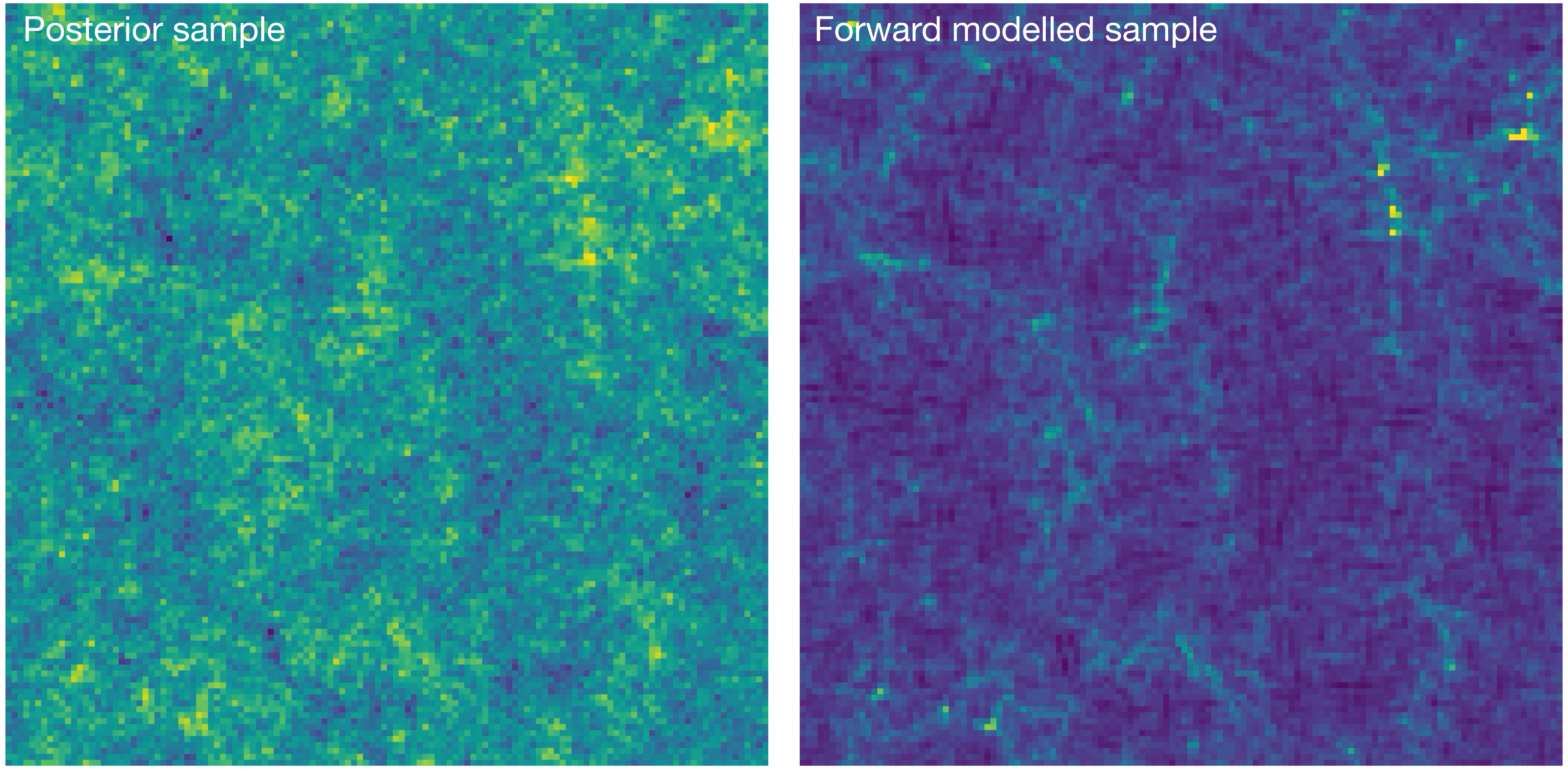
$$\mathbb{P}(\Phi \mid \delta) \propto \mathbb{P}(\delta \mid \Phi)\, \mathbb{P}(\Phi)$$



Field-level inference: reconstruction

$$\mathbb{P}(\Phi \mid \delta) \propto \mathbb{P}(\delta \mid \Phi)\, \mathbb{P}(\Phi)$$

Example: drawing posterior samples (PhD thesis of Lukas Winkler)



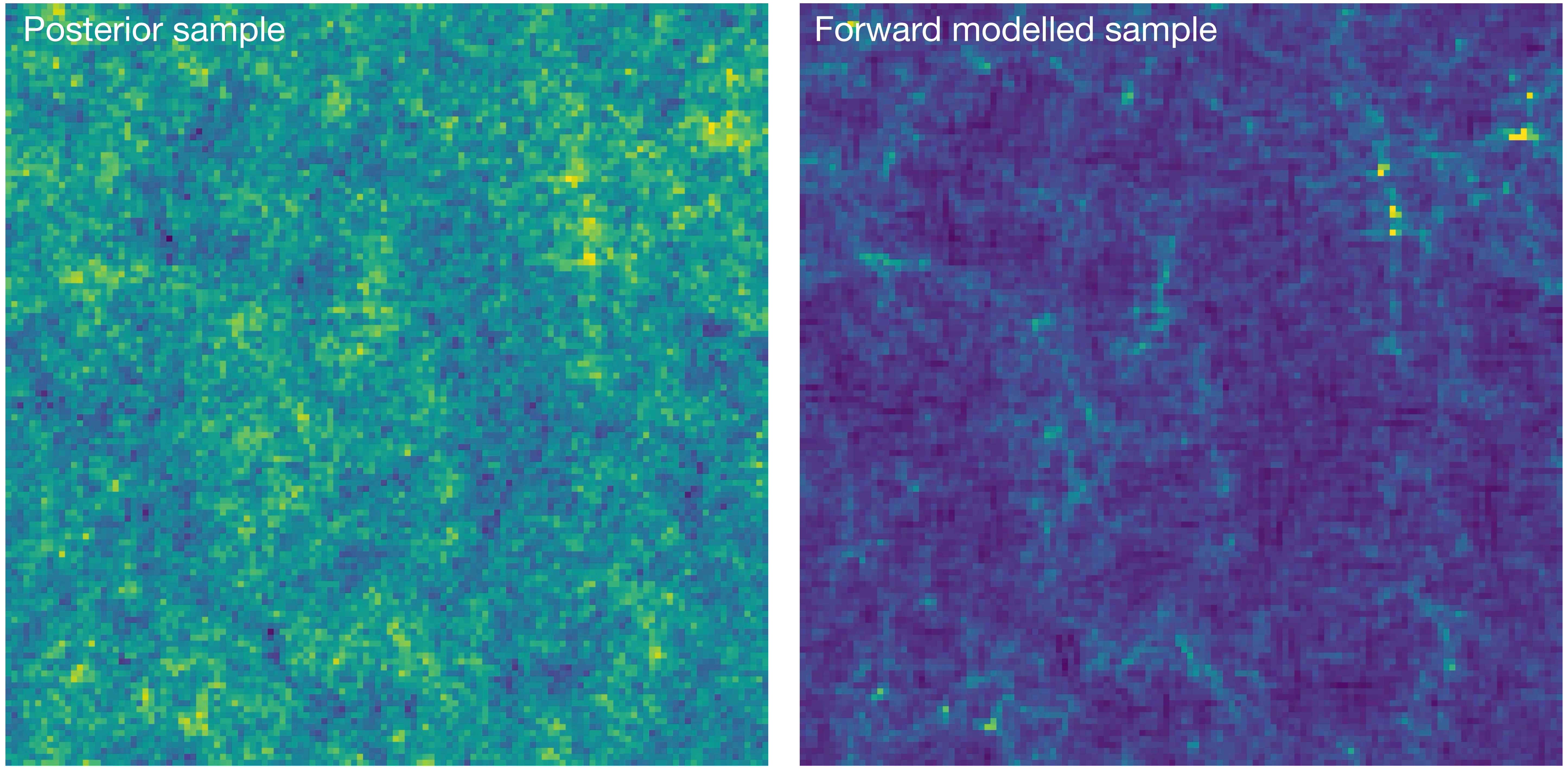
Here, we use a **No U-Turn Sampler (NUTS)** – a variant of Hamiltonian Monte Carlo – provided by the `BlackJax` library https://blackjax-devs.github.io/blackjax/.

see also work by BORG collaboration

Field-level inference: reconstruction

$$\mathbb{P}(\Phi \mid \delta) \propto \mathbb{P}(\delta \mid \Phi)\, \mathbb{P}(\Phi)$$

Example: drawing posterior samples (PhD thesis of Lukas Winkler)



Here, we use a **No U-Turn Sampler (NUTS)** – a variant of Hamiltonian Monte Carlo – provided by the `BlackJax` library https://blackjax-devs.github.io/blackjax/.

see also work by BORG collaboration

Summary

- Diff’able model = prediction + dprediction/d{parameters,ICs,…}
- Differentiable models allow new ways of confronting data -> beyond simple summary statistics
- DISCO-DJ new contender:
  - DISCO-EB Einstein-Boltzmann solver
    - “easy” forecasting, add your models
    - currently still too slow for MCMC analysis (work in progress…)
  - DISCO-DJ LSS model (optimized PM solver, see also JaxPM, pmwd, FlowPM)
    - will directly integrate with EB module (differentiate through both)
    - nLPT recursion
    - new PT-informed time integrators+discreteness suppression
    - currently only single GPU, multi-GPU is WIP

- http://cosmology.univie.ac.at
- oliver.hahn@univie.ac.at