2015年9月20〜21日
新学術領域「宇宙はなぜ加速するのか？」
発足シンポジウム@ カブリIPMU

A02

Large-scale structure formation : ΛCDM model and beyond

Atsushi Taruya
(Yukawa Institute for Theoretical Physics)

Outline

Theory of large-scale structure formation to confront with precision observations

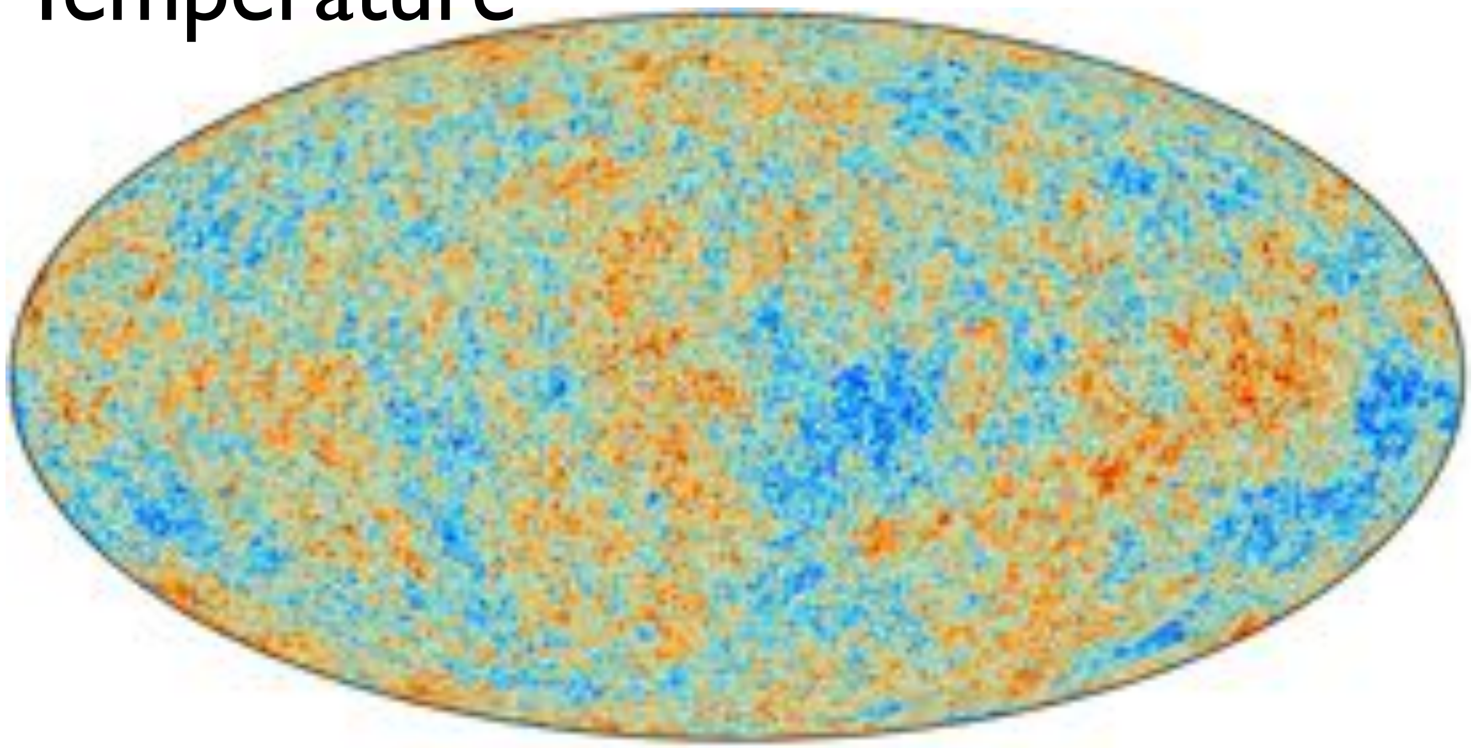
- ΛCDM model: our current view of the Universe
- Key observations beyond ΛCDM model
- Theoretical issues : improving/renovating theoretical tools

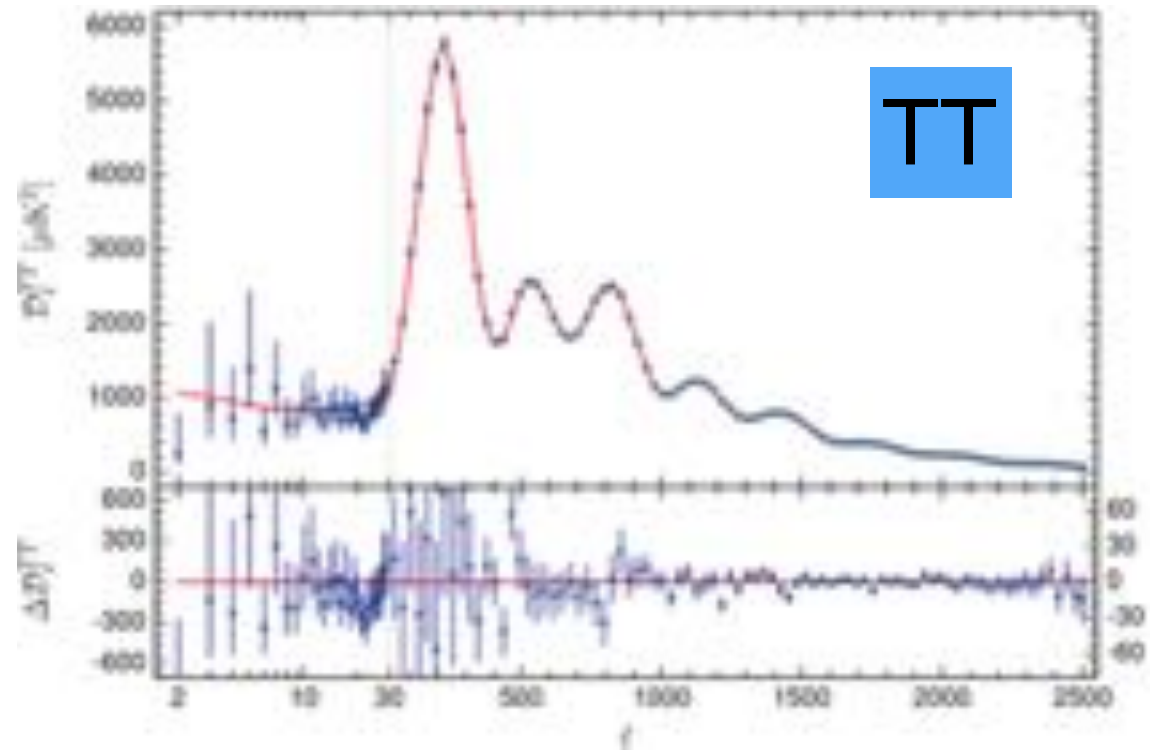
Perturbation theory (PT) calculations:
limitation and beyond

Hard core

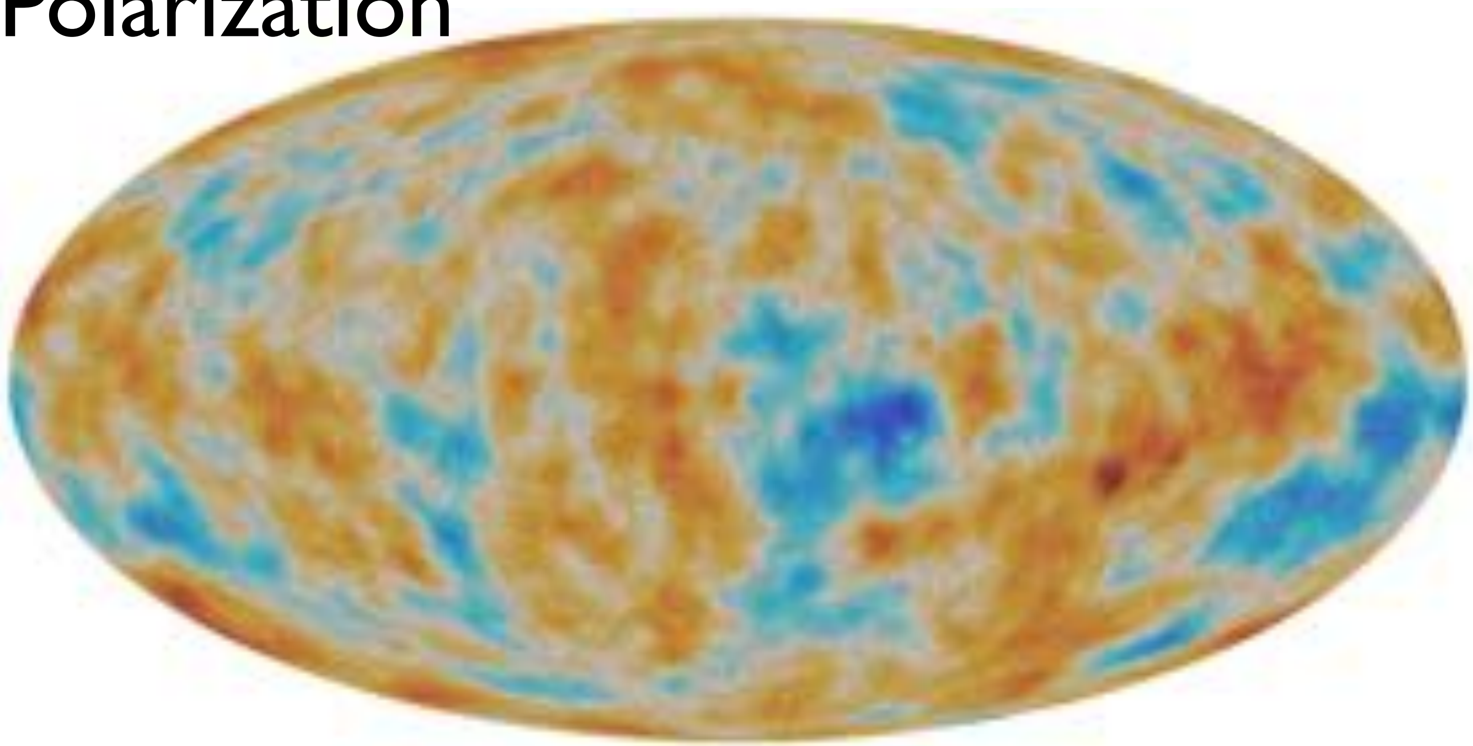
Planck 2015

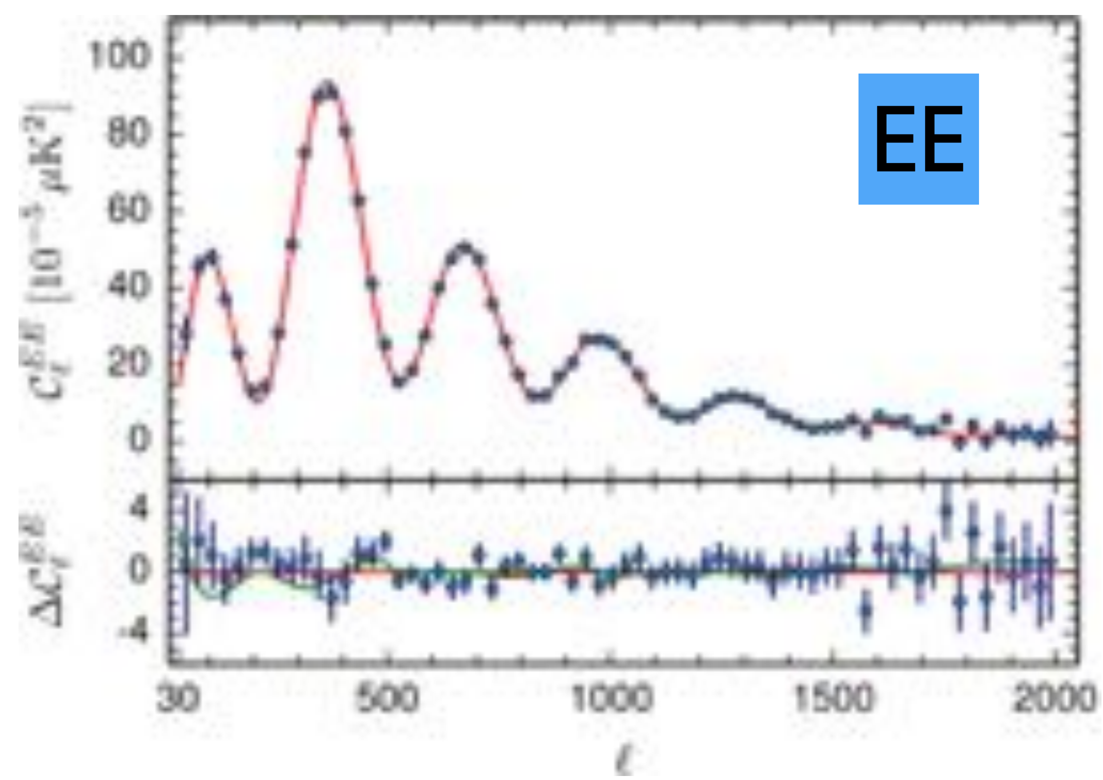
Temperature





Polarization





http://www.cosmos.esa.int/web/planck/

Base ΛCDM model

flat universe with cosmological constant
& adiabatic power-law initial fluctuations

- Minimal model characterized by only **6** parameters:

$\Omega_{\mathrm{b}} h^2$: baryon density

$\Omega_{\mathrm{c}} h^2$: CDM density

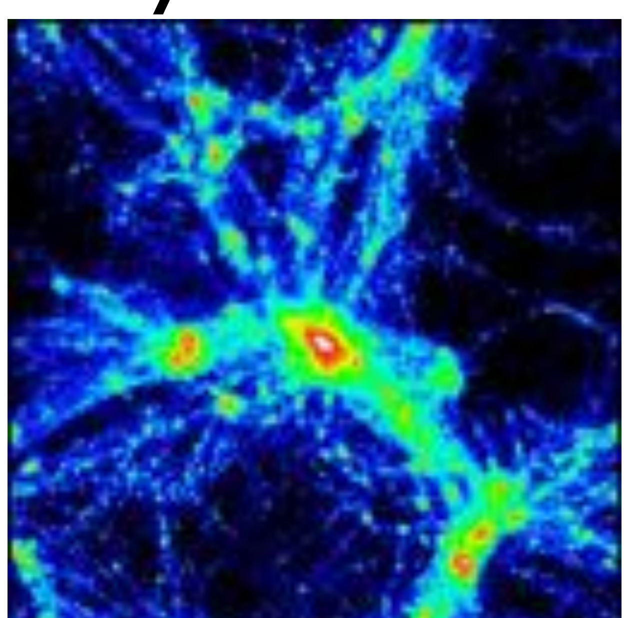
θ_{MC} : distance ratio to last scattering surface

n_{s} : scalar spectral index

A_{s} : amplitude of curvature fluctuation

τ : reionization optical depth

- Model consistently describes both cosmic expansion & structure formation



“Beyond ΛCDM” model

No evidence for significant deviation from ΛCDM model

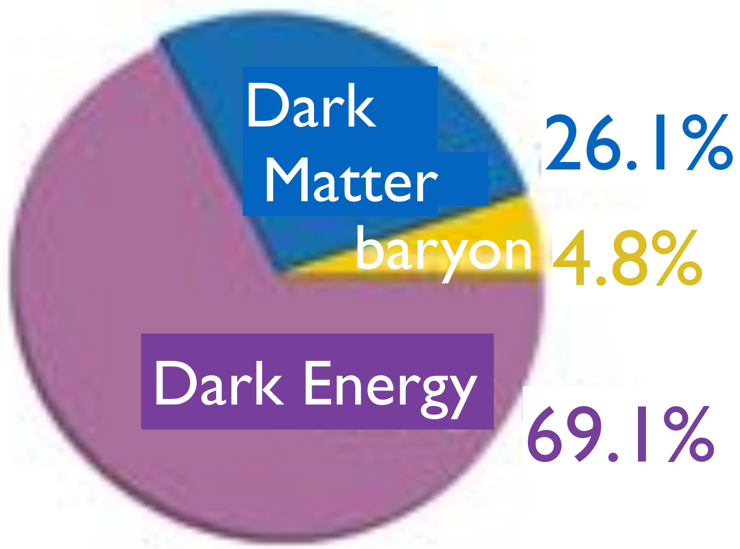
------- Success of Occam’s razor

However,

Success of minimal model does not imply model is convincing :

✓ **Untested hypothesis :** General relativity on cosmological scales, Gaussianity of fluctuations, Copernican principle, …

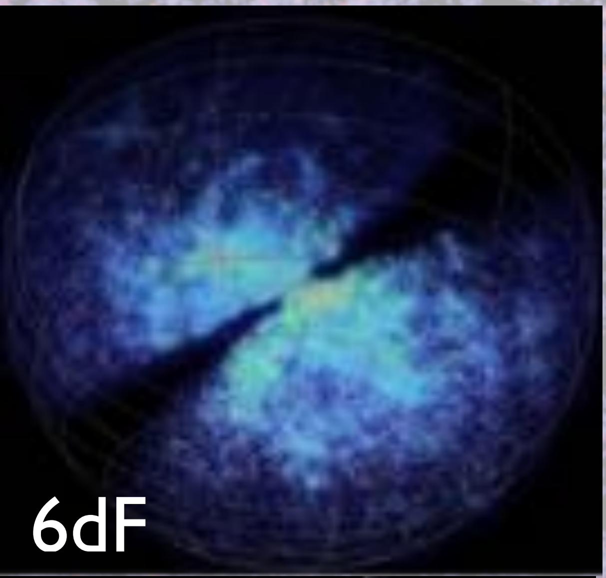
✓ **Invisible components:** Dark matter, Dark energy

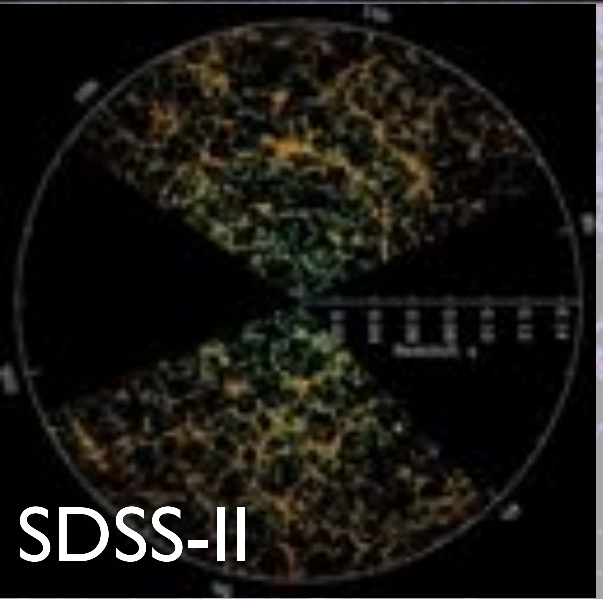


Need a sensitive probe to test/clarify these issues

Large-scale structure (LSS)

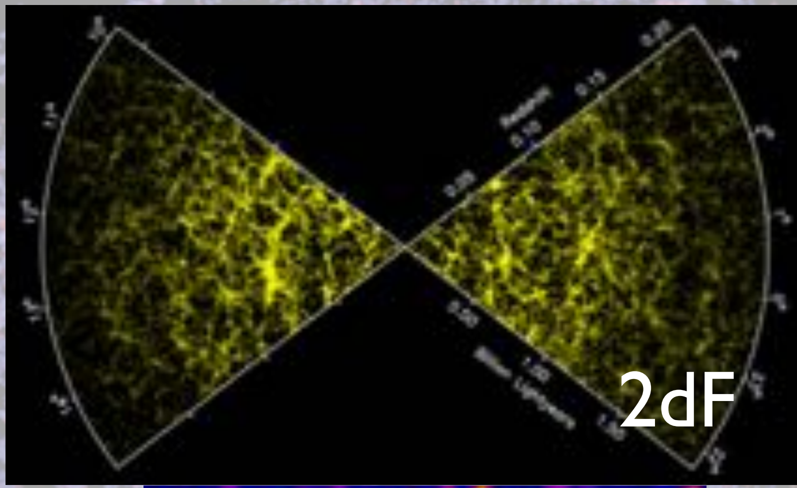
- Spatial matter inhomogeneity over ~ Gpc
- has evolved under the influence of gravity & cosmic expansion

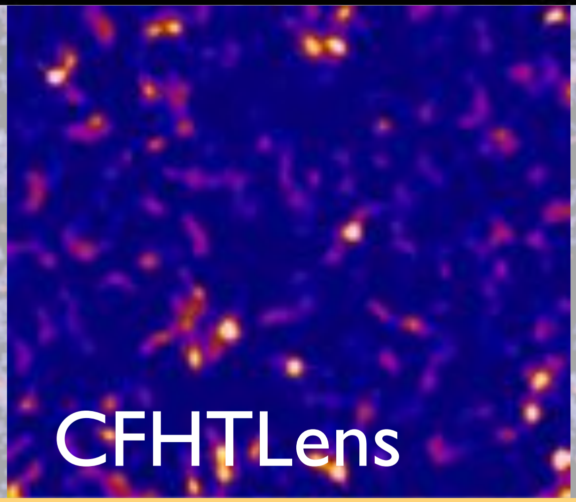




Rich cosmological info on:

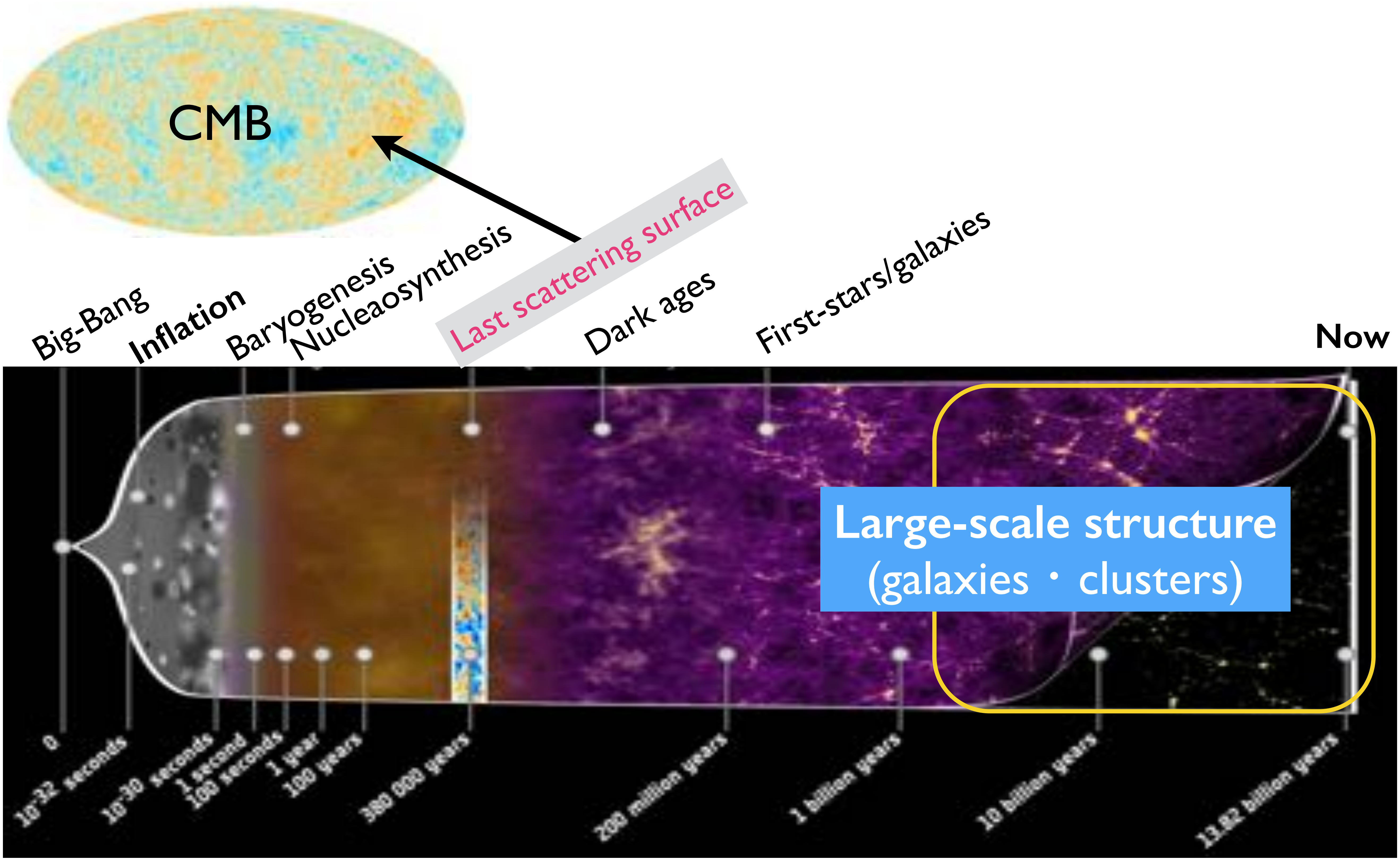
✓primordial fluctuations
✓structure formation
✓dynamics of cosmic expansion





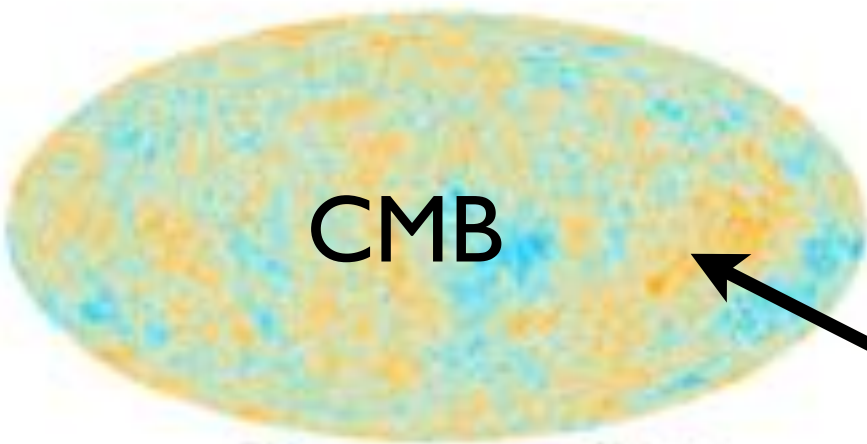
LSS offers testing grounds of ΛCDM model,
and can provide a clue to 'beyond ΛCDM' model

Timeline of Universe

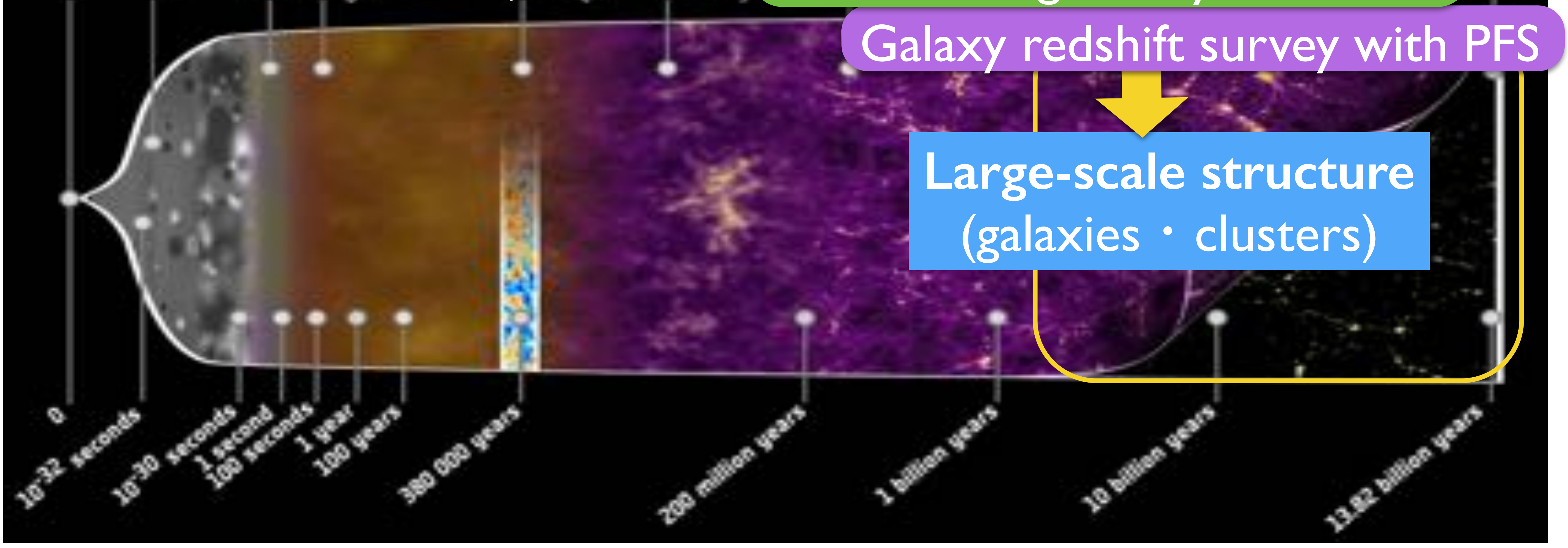


380,000 yrs **13.8G yrs**

Timeline of Universe



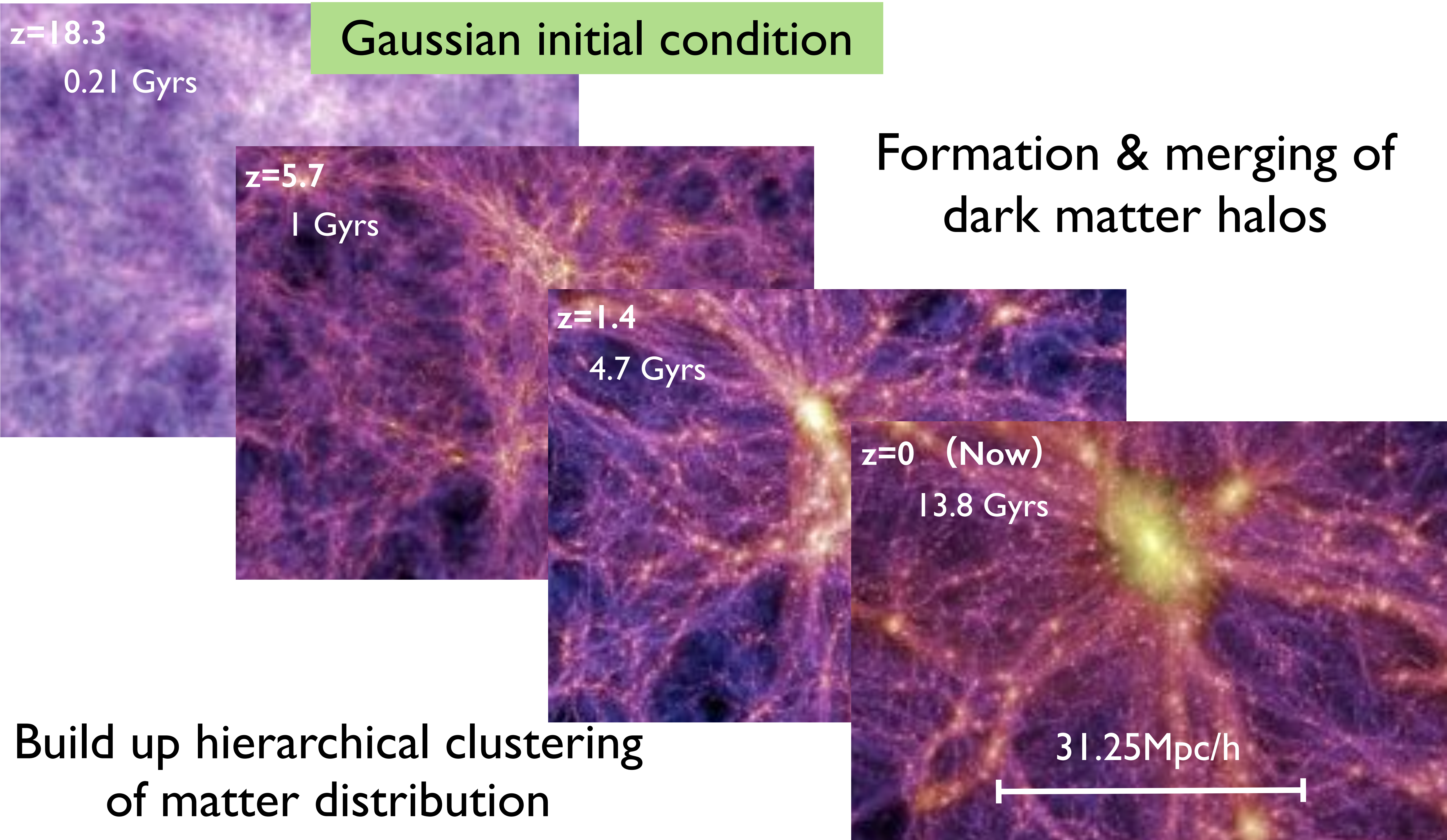
SuMIRe is powerful to pin down late-time universe (z~1)



380,000 yrs

13.8G yrs

LSS formation in ΛCDM model



Formation & merging of dark matter halos

Build up hierarchical clustering of matter distribution

http://www.mpa-garching.mpg.de/galform/millennium/

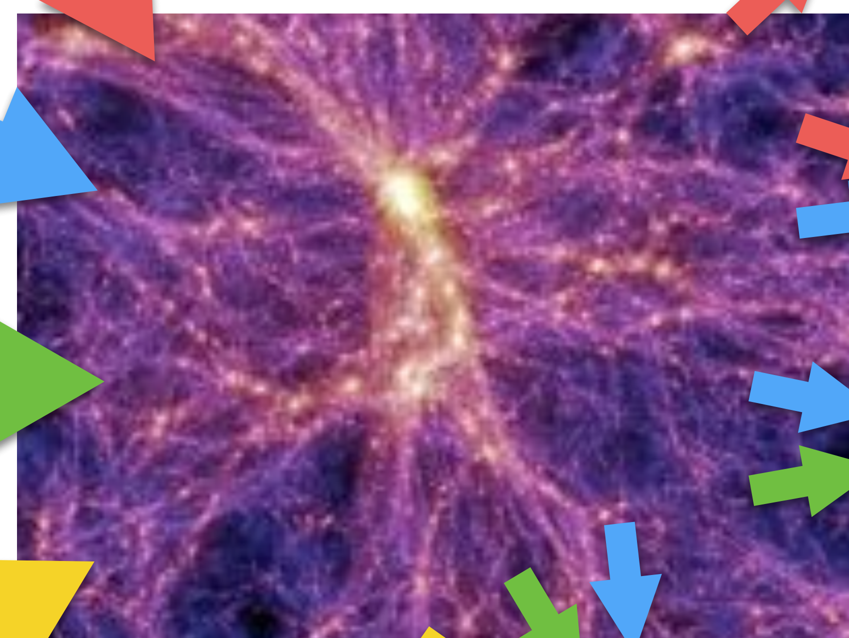
Signature of “beyond ΛCDM”

Cosmic acceleration (dark energy)

Modification of gravity

Hot/warm components of dark matter

Primordial non-Gaussianity



Geometric distance to LSS (galaxies)

Growth of structure

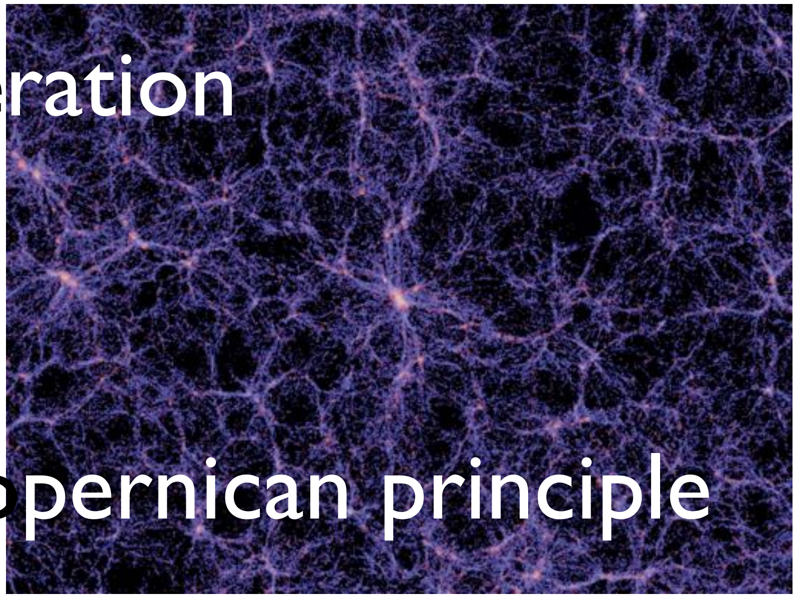
Structure of halos

Formation & clustering of halos/galaxies

All the tiny deviations from ΛCDM are imprinted on statistical properties of LSS $\rightarrow$ precision statistical measurement is a key

Key LSS observations: summary

Clustering properties of galaxies/halos ($\gtrsim 10\,h^{-1}\,\mathrm{Mpc}$)

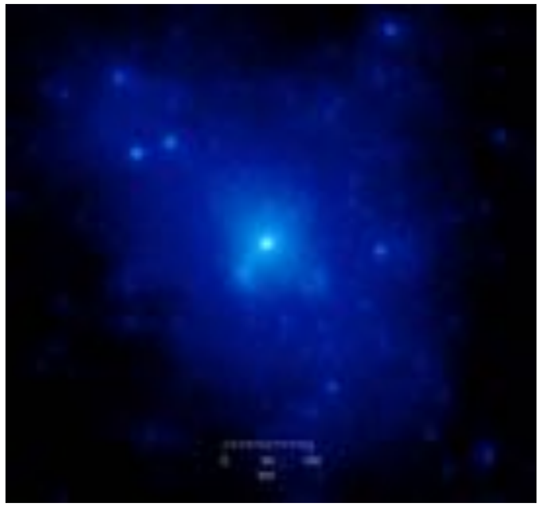


- **Baryon Acoustic Oscillation** : cosmic acceleration
- **Redshift-space distortion** : test of gravity
- **Free-streaming damping** : mass of neutrinos
- **Ultra-large scale clustering**: Gaussianity /Copernican principle

Further

Shape of WL & galaxy power spectra → cosmological parameters

Structure of dark matter halo ($\lesssim 10\,h^{-1}\,\mathrm{Mpc}$)



- **Profiles of halo**
- **Abundance of substructure (subhalo)**

: diagnosis of CDM paradigm & nature of gravity

Theoretical issues

Confronting with the era of *data-driven cosmology,*

Need improvement on <u>theory of large-scale structure formation</u>

(theoretical template)

- Improving **accuracy** of theoretical predictions
- Controlling/reducing **systematics** (e.g., galaxy bias)
- Incorporating **new physical effects** beyond ΛCDM model

  (how/warm dark matter, relativistic effect, modification to gravity, …)

Further,

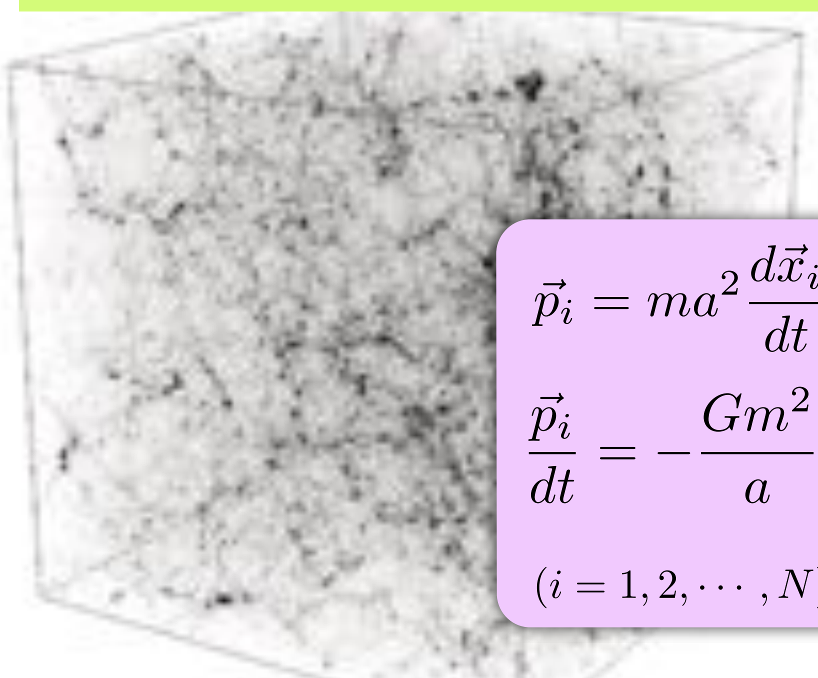
Standard theoretical tools have to be renovated

Tools for theory of LSS formation

Beyond linear theory, theory of *dark-matter dominated* structure formation build up with several analytical & numerical tools

(e.g., simulation, halo model, perturbation theory, …)

Cosmological N-body simulation



$$\vec{p}_i = m a^2 \frac{d\vec{x}_i}{dt}$$

$$\frac{\vec{p}_i}{dt} = -\frac{Gm^2}{a}\sum_{j\neq i}^{N}\frac{\vec{x}_i-\vec{x}_j}{|\vec{x}_i-\vec{x}_j|^3}$$

$(i = 1, 2, \cdots, N)$

http://www.projet-horizon.fr/

Discreteness

Making/locating galaxies

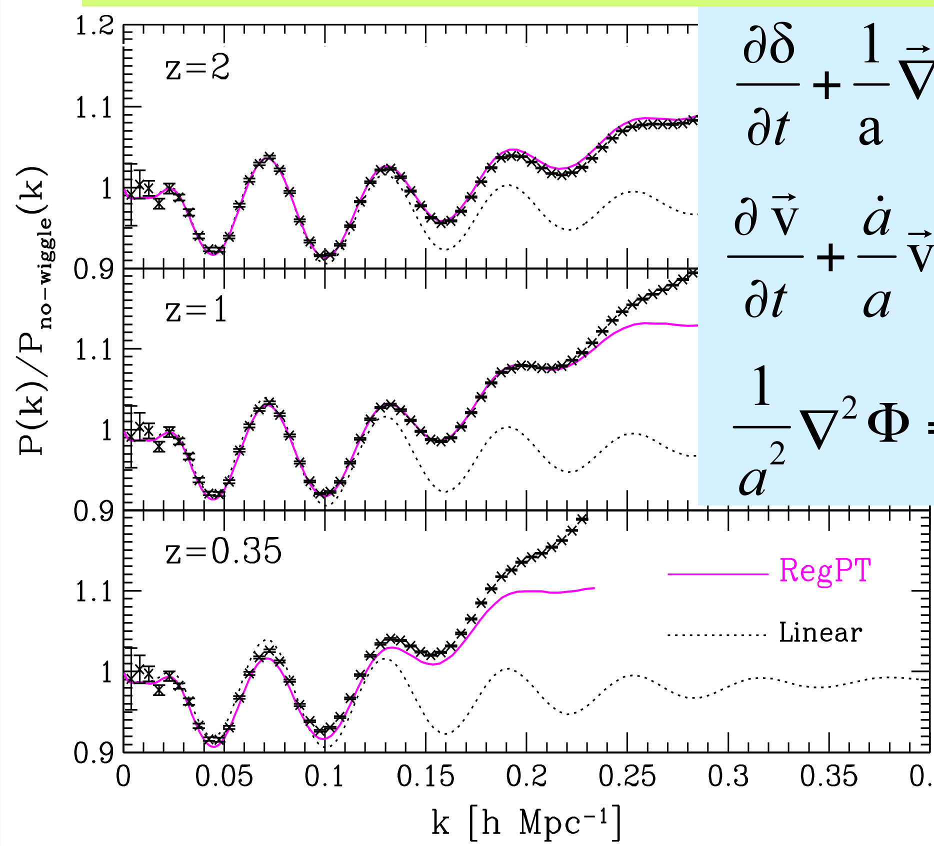
Perturbation theory (PT)

(based on fluid approx.)

$$\frac{\partial\delta}{\partial t}+\frac{1}{a}\vec{\nabla}\cdot\left[(1+\delta)\vec{v}\right]=0$$

$$\frac{\partial\vec{v}}{\partial t}+\frac{\dot{a}}{a}\vec{v}+\frac{1}{a}(\vec{v}\cdot\vec{\nabla})\vec{v}=-\frac{1}{a}\vec{\nabla}\Phi$$

$$\frac{1}{a^2}\nabla^2\Phi=4\pi G\,\bar{\rho}_m\,\delta$$

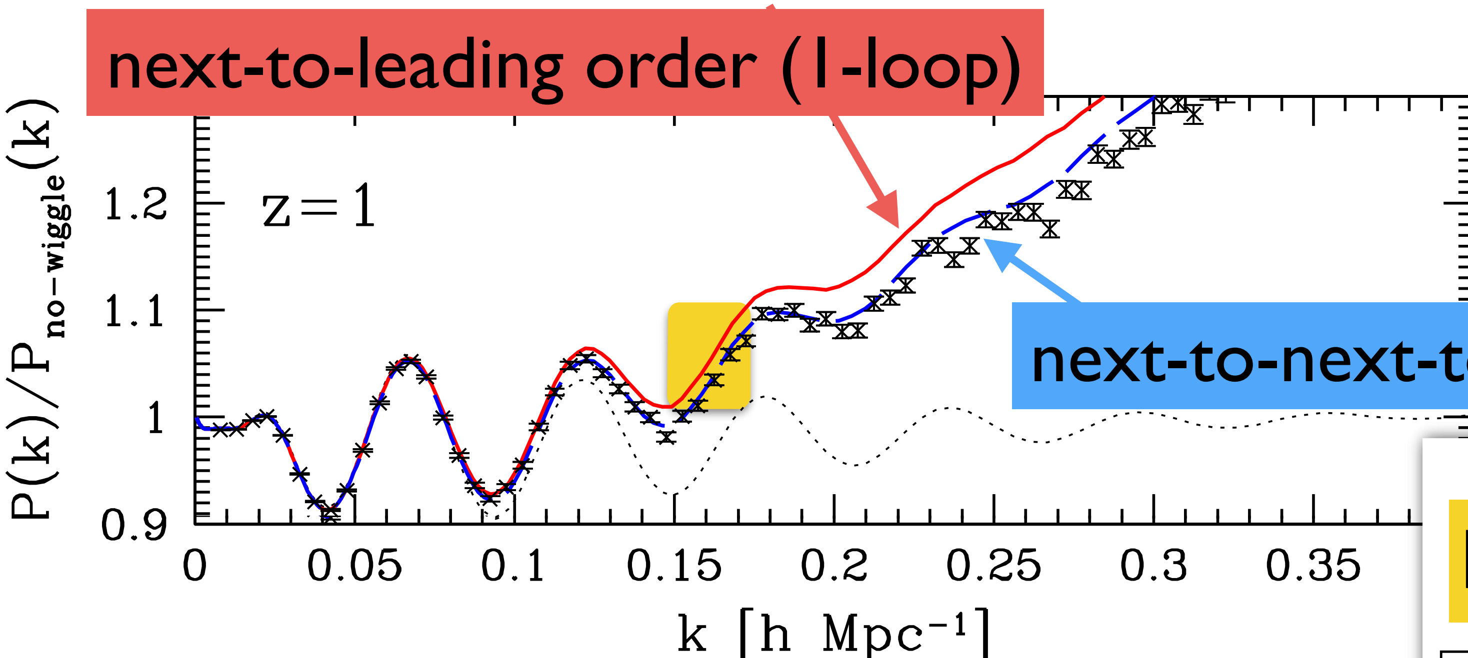


AT et al. ('12)

UV-sensitivity at higher order

UV problem in perturbation theory

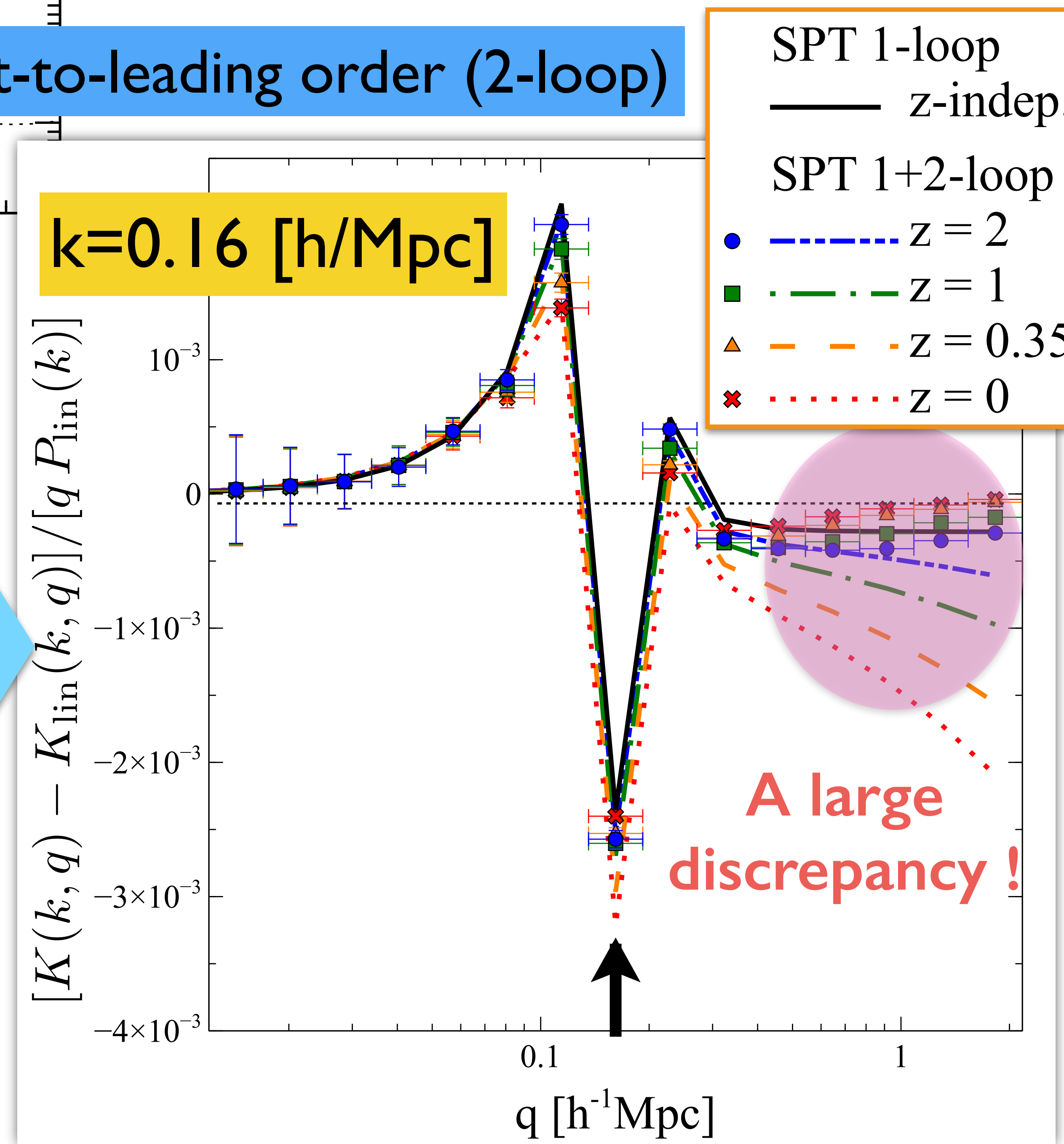
Nishimichi, Bernardeau & AT
(arXiv:1411.2970)



Nonlinear response to a small initial variation in P(k):

$$\delta P_{\rm nl}(k) = \int d\ln q\, K(k,q)\, \delta P_0(q)$$

nonlinear *linear (initial)*



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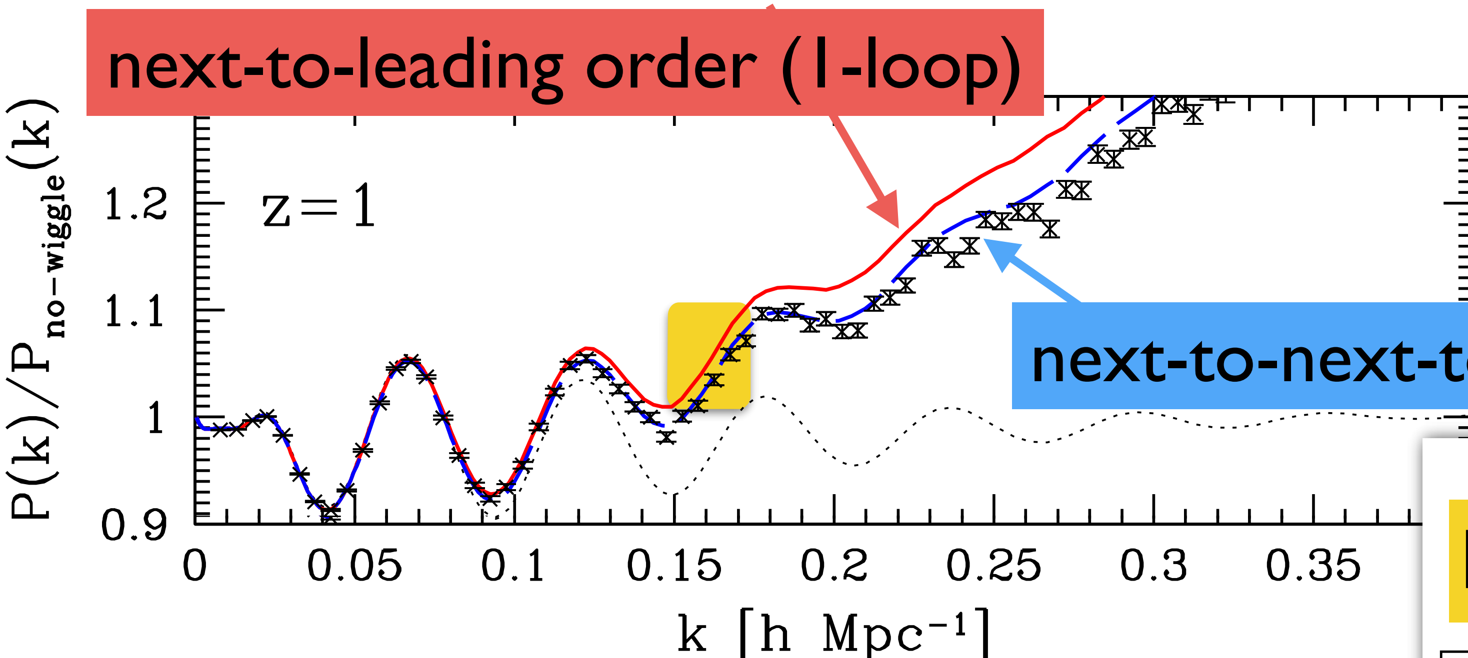

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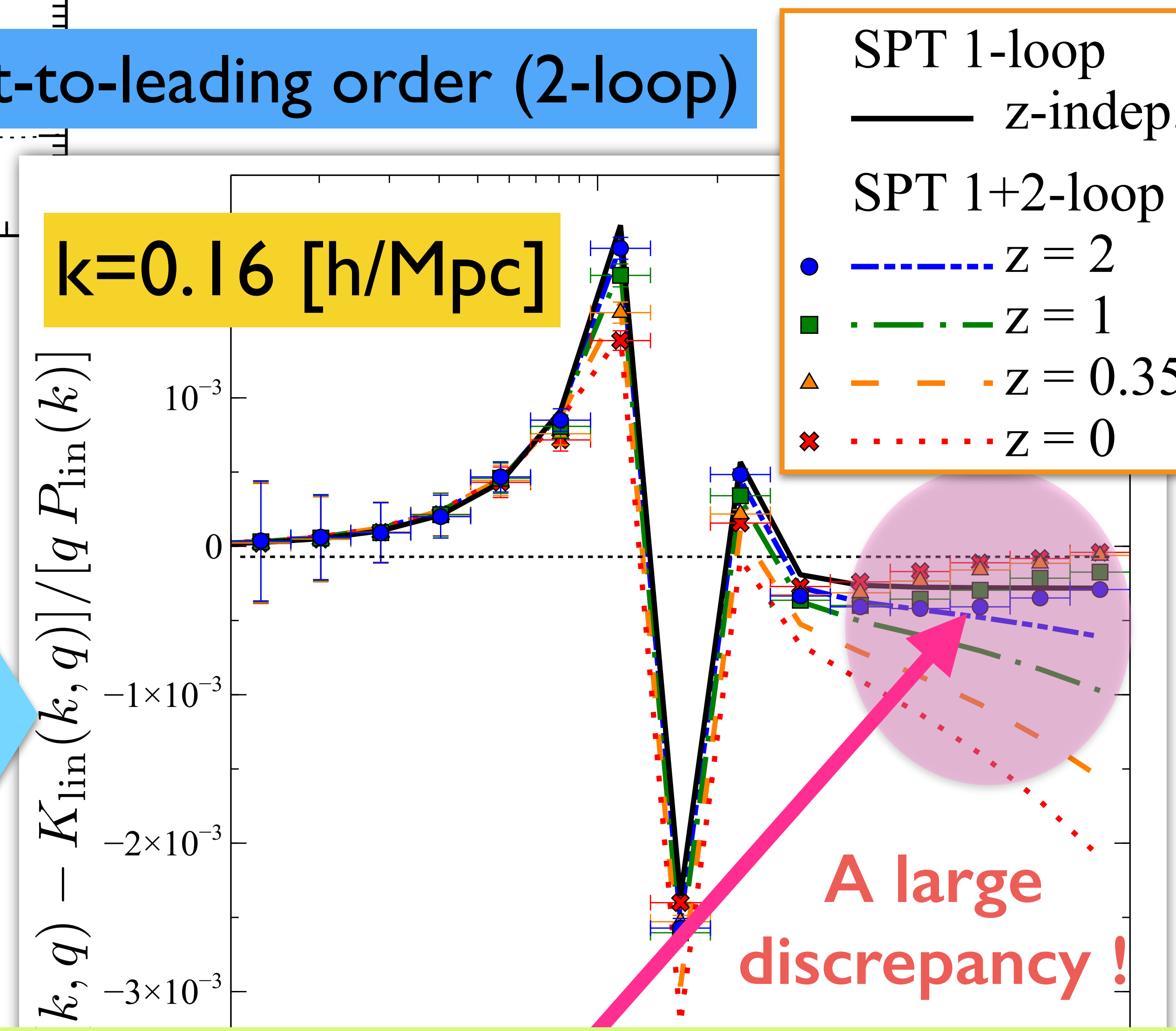
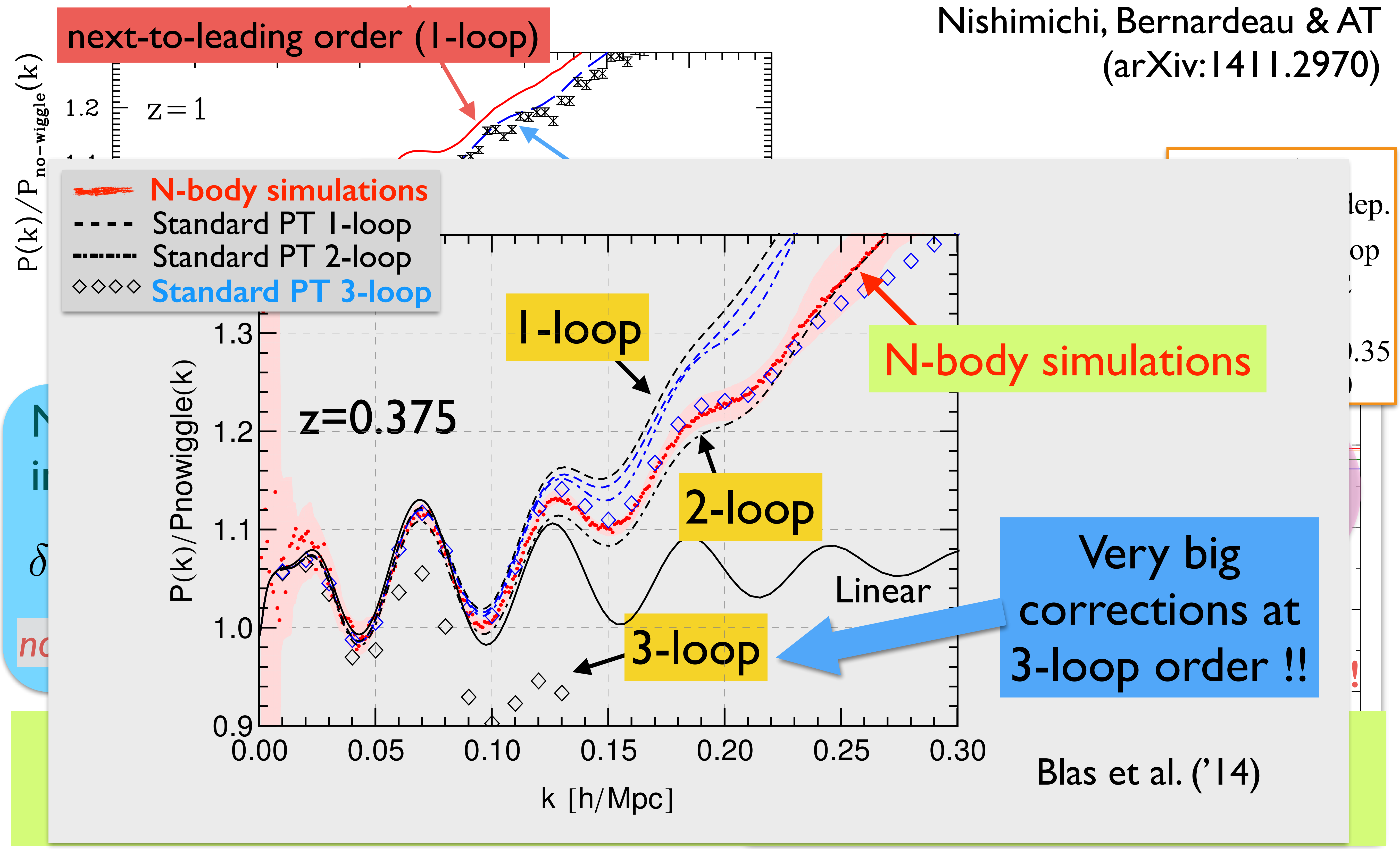


Actual mode-coupling is UV-*insensitive* at high-q (i.e., coupling btw small & large scales is suppressed) → *breakdown* of PT

UV problem in perturbation theory

Nishimichi, Bernardeau & AT
(arXiv:1411.2970)



Blas et al. ('14)

Effective field theory ?

"*UV-insensitive*" behavior in simulations would be attributed to small-scale physics that cannot be dealt with fluid approx.

(e.g., formation/merging of halos)

"Effective field theory (EFT)" of large-scale structure

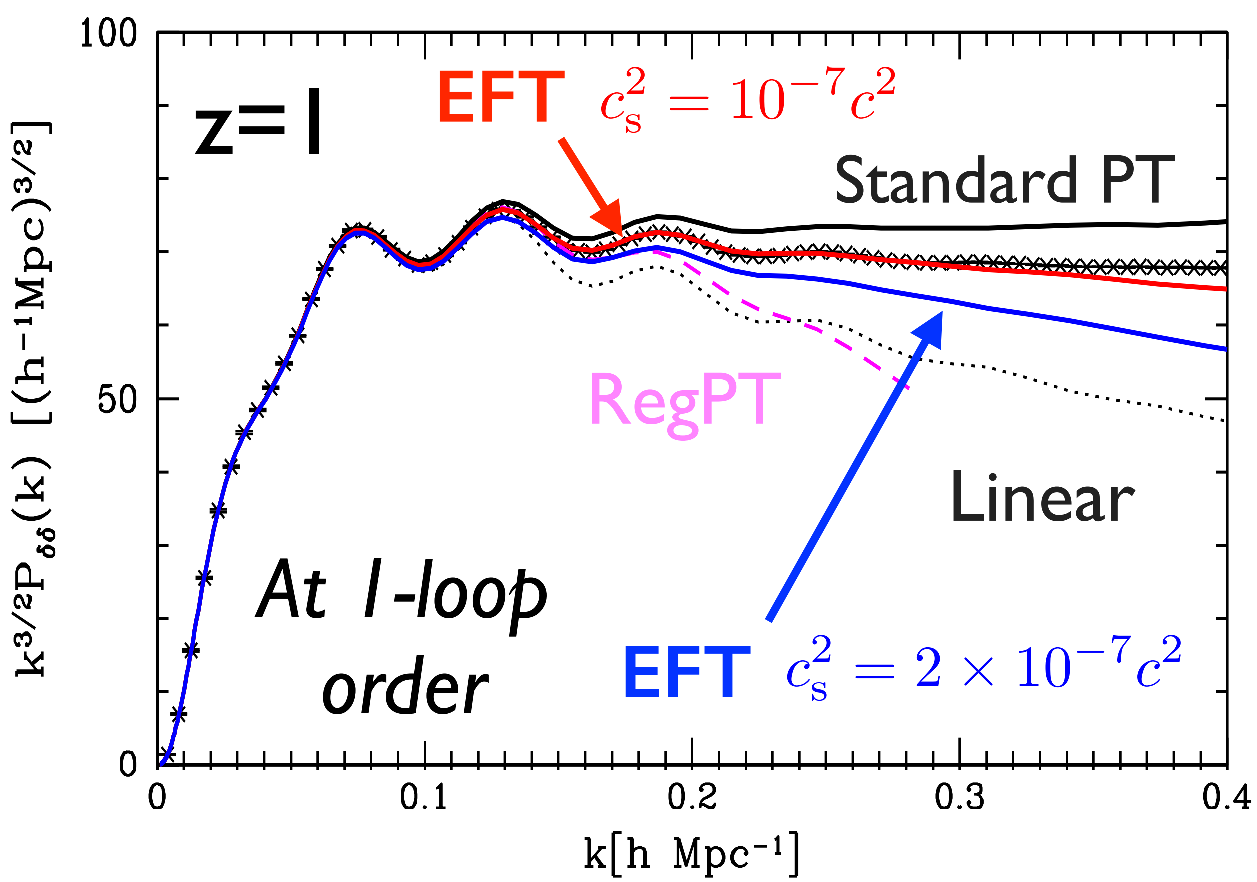
Introducing effective stress tensor to counteract with UV-sensitive terms in PT calculation

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla\cdot[(1+\delta)\boldsymbol{v}] = 0,$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + H\,\boldsymbol{v} + \frac{1}{a}(\boldsymbol{v}\cdot\nabla)\cdot\boldsymbol{v} = -\frac{1}{a}\nabla\psi - \boxed{\frac{1}{\rho_{\rm m}}\frac{1}{a}\nabla\tau_{ij}}$$

$$\frac{1}{a^2}\nabla^2\psi = \frac{\kappa^2}{2}\,\rho_{\rm m}\,\delta$$

Pressure, viscosity, …



Baumann et al. ('12), Carrasco, Herzberg & Senatore ('12), Carrasco et al. ('13ab), …

Effective field theory ?

"*UV-insensitive*" behavior in simulations would be attributed to small-scale physics that cannot be dealt with fluid approx.

(e.g., formation/merging of halos)

*"Effective field theory (**EFT**)" of large-scale structure*

Introducing effective stress tensor to counteract with UV-sensitive terms in PT calculation

Remarks EFT *superficially* looks better, *but*

- Free parameters need to be calibrated with simulations

  → lose predictability

- It does not imply EFT properly describes nonlinear mode-coupling structure of gravitational dynamics

⟶ **Need a more fundamental treatment**

Vlasov-Poisson: back to the source

A more fundamental description :

Vlasov-Poisson system

(collisionless Boltzmann)

$$\left[a\frac{\partial}{\partial t}+\frac{\boldsymbol{v}}{a}\cdot\frac{\partial}{\partial \boldsymbol{x}}-a\frac{\partial \phi}{\partial \boldsymbol{x}}\cdot\frac{\partial}{\partial \boldsymbol{v}}\right]f(\boldsymbol{x},\,\boldsymbol{v};\,t)=0$$

$$\nabla^2\phi(x;\,t)=4\pi\,G\,a^2\!\int d^3\boldsymbol{v}\,f(\boldsymbol{x},\,\boldsymbol{v};\,t)$$

- N→∞ limit of self-gravitating N-body system
- Reduced to a (pressureless) fluid system for *single-stream flow*:

$$f(\boldsymbol{x},\,\boldsymbol{v};\,t)\to\overline{\rho}(t)\,\{1+\delta(\boldsymbol{x};\,t)\}\,\delta_{\rm D}\left(\boldsymbol{v}-\boldsymbol{v}(\boldsymbol{x};\,t)\right)$$

Single-stream flow is initially correct, but will be later violated

(at small scales)

Vlasov-Poisson: back to the source

A more fundamental description :

Vlasov-Poisson system

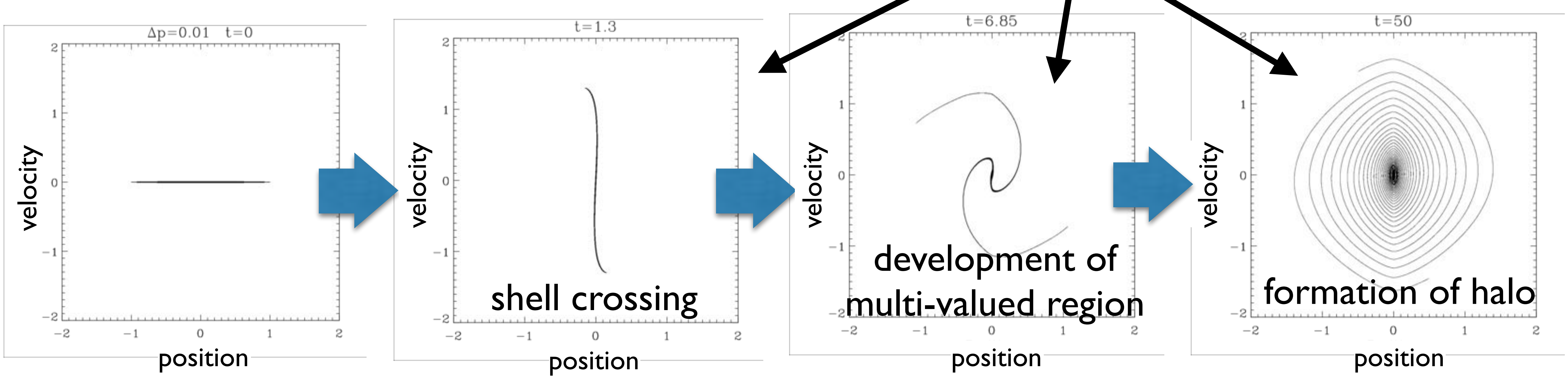
(collisionless Boltzmann)

$$\left[a\,\frac{\partial}{\partial t}+\frac{\boldsymbol{v}}{a}\cdot\frac{\partial}{\partial \boldsymbol{x}}-a\,\frac{\partial\phi}{\partial \boldsymbol{x}}\cdot\frac{\partial}{\partial \boldsymbol{v}}\right]f(\boldsymbol{x},\,\boldsymbol{v};\,t)=0$$

$$\nabla^2\phi(x;\,t)=4\pi\,G\,a^2\!\int\! d^3\boldsymbol{v}\,f(\boldsymbol{x},\,\boldsymbol{v};\,t)$$

cannot be described by fluid-based PT treatment

<u>Cold collapse in 1D gravity (simulation)</u>



Post-collapse perturbation theory

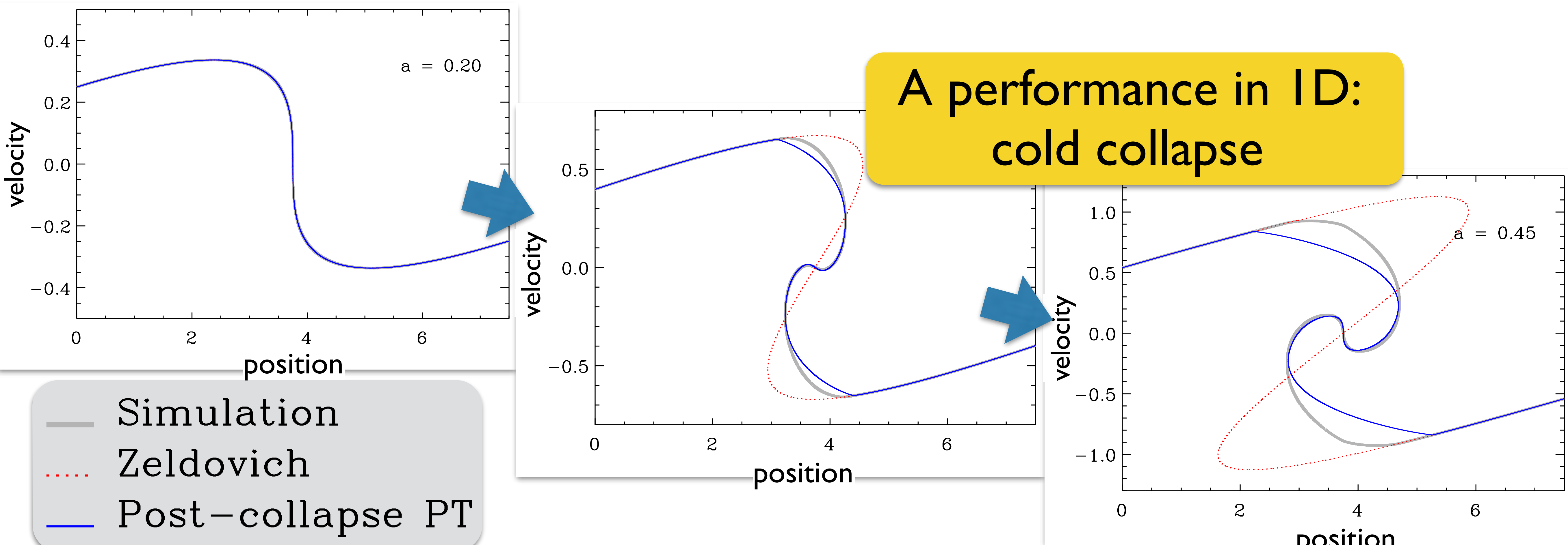
Going beyond shell-crossing, a new analytical framework needs to be developed

Post-collapse PT

Colombi ('15), AT & Colombi (in progress)

Lagrangian-based PT that can follow post-collapse dynamics

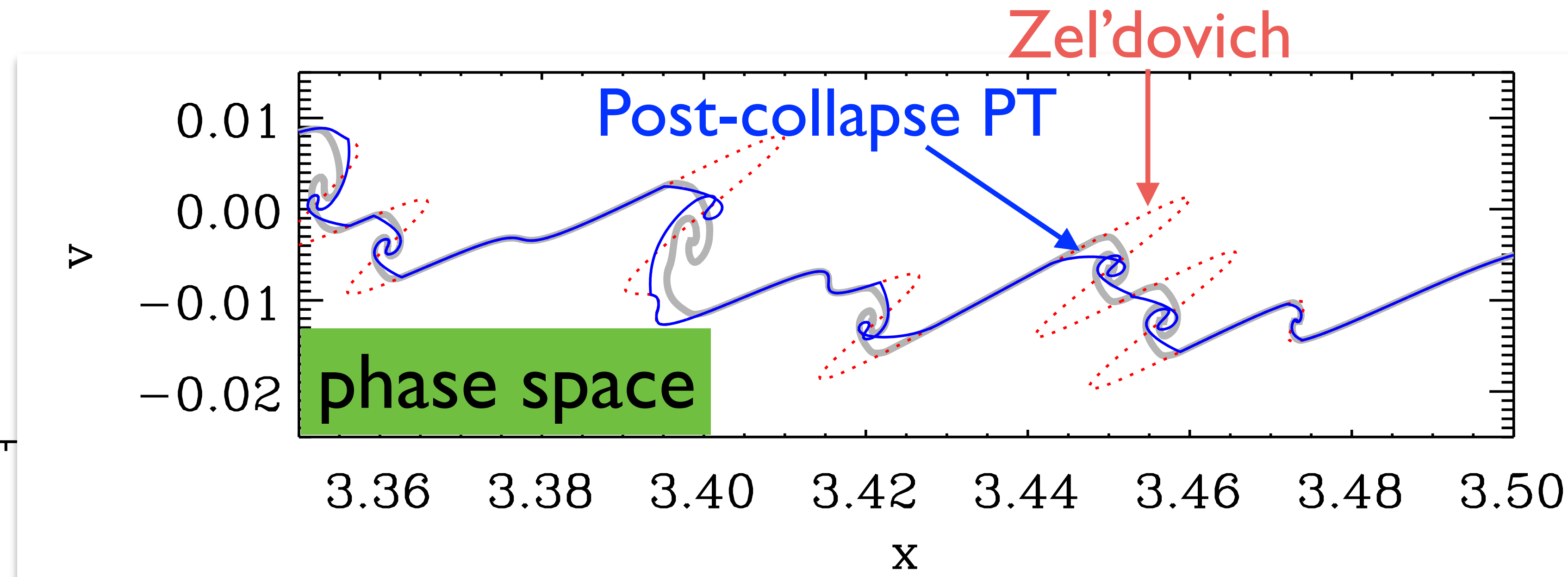
A performance in 1D: cold collapse

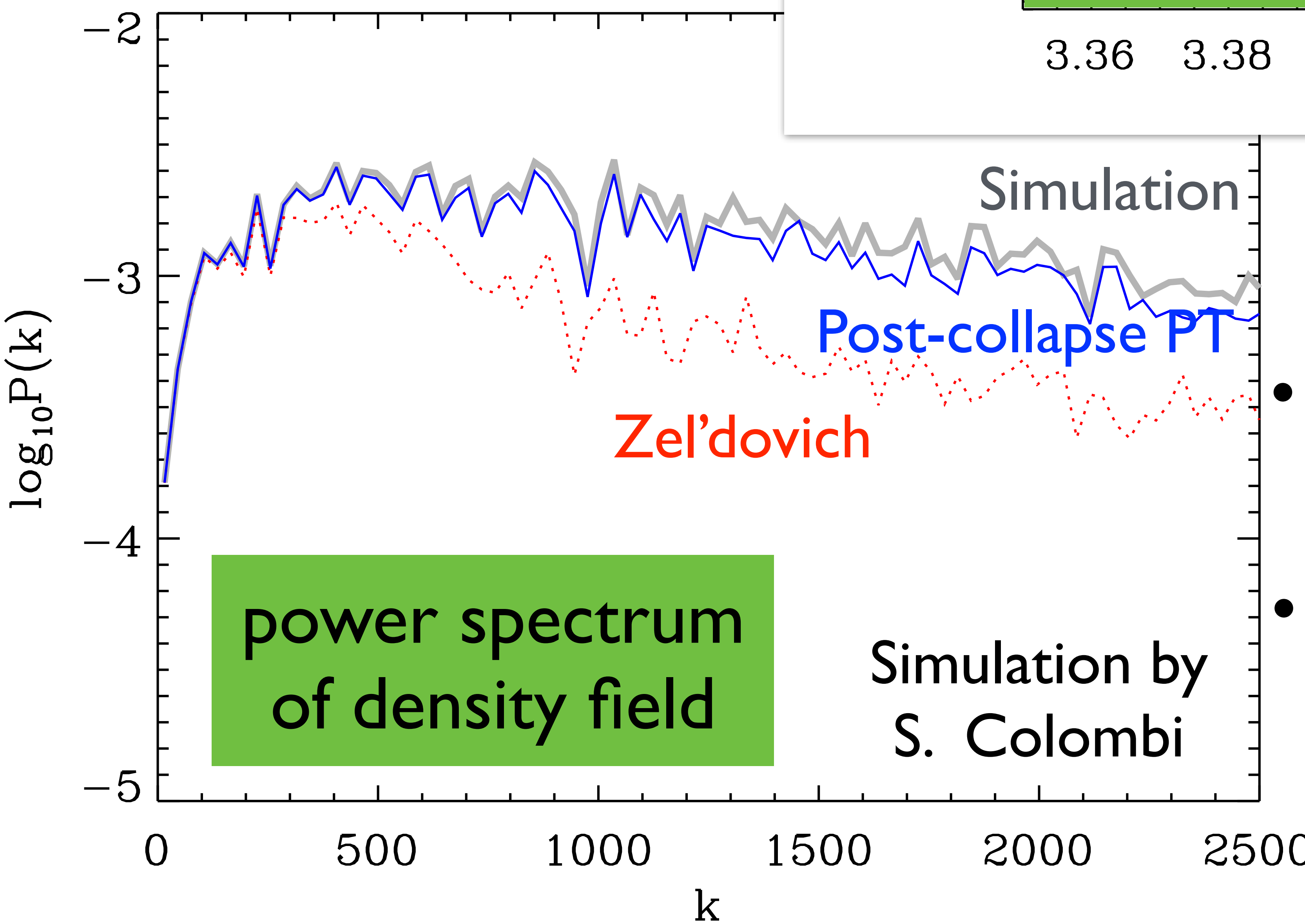


Note—. Zel'dovich solution is exact in 1D before shell crossing

Post-collapse perturbation theory

Random initial condition (in 1D)





- Post-collapse PT surpasses fluid-based PT methods
- Extension from 1D to 3D is straightforward

AT & Colombi (in progress)

State-of-the-art 6D Vlasov code

2013

DIRECT INTEGRATION OF THE COLLISIONLESS BOLTZMANN EQUATION IN SIX-DIMENSIONAL PHASE SPACE: SELF-GRAVITATING SYSTEMS

Kohji Yoshikawa[1], Naoki Yoshida[2,3], and Masayuki Umemura[1]
[1] Center for Computational Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305–8577, Japan;
[2] Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
[3] Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Kashiwa, Chiba 277-8583, Ja
Received 2012 June 18; accepted 2012 November 23; published 2012 December 20

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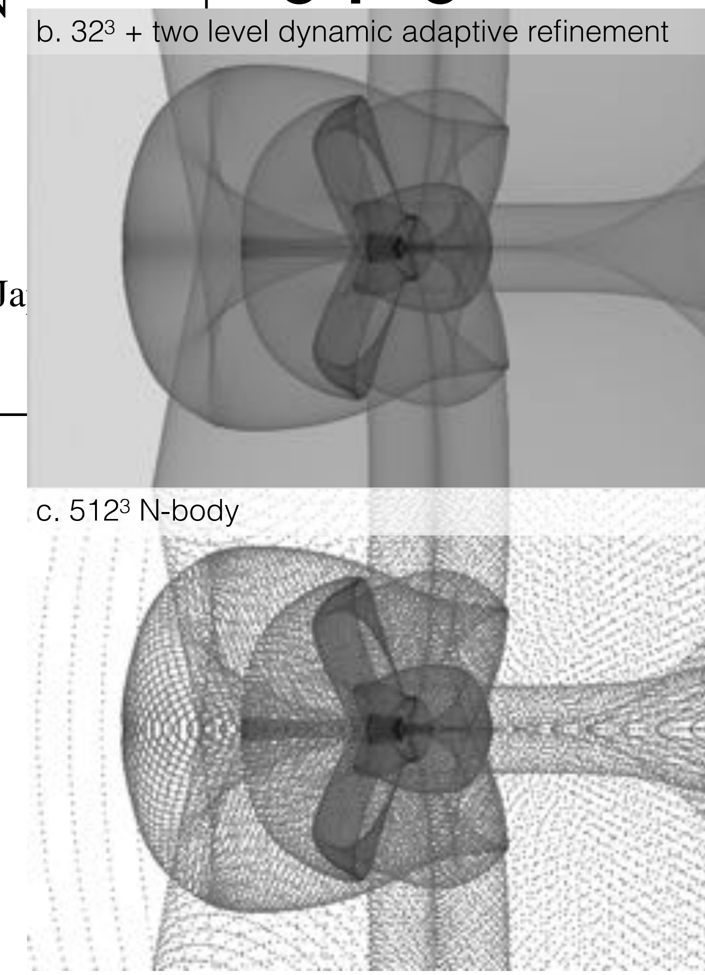
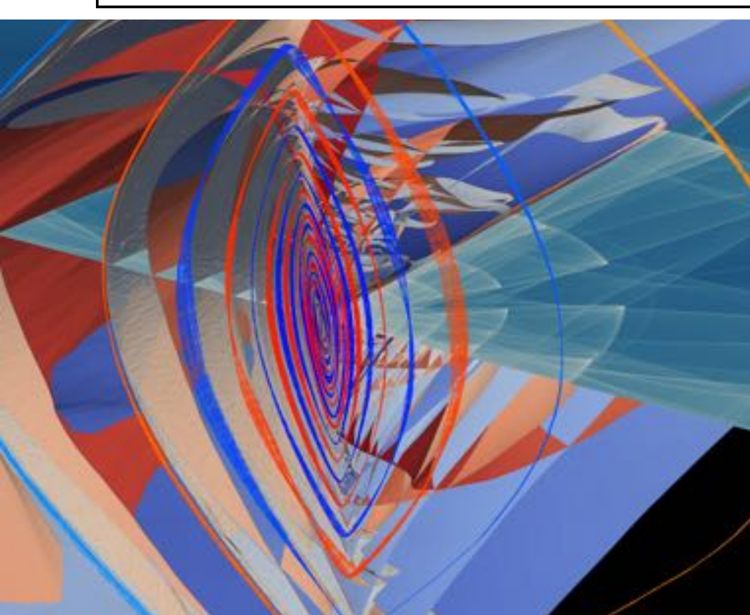


An adaptively refined phase-space element method for cosmological simulations and collisionless dynamics

Oliver Hahn⋆[1] and Raul E. Angulo†[2]
[1] *Department of Physics, ETH Zurich, CH-8093 Zürich, Switzerland*
[2] *Centro de Estudios de Física del Cosmos de Aragón, Plaza San Juan 1, Planta-2, 44001, Teruel, Spain.*

2015

submitted to MNRAS Jan. 8, 2015



A phase-space Vlasov-Poisson solver for cold dark matter

Thierry Sousbie and Stephane Colombi

2015 (in prep.)

Institut D'Astrophysique de Paris, CNRS UMR 7095 and UPMC, 98bis, bd. Arago, F-75014, Paris, France

New analytic framework will also help to develop cosmological Vlasov code

Summary

Precision observations of large-scale structure will provide an important clue to go beyond ΛCDM model

To confront with precision observations,

Theoretical tool (template) needs to be improved:

accuracy, systematics, new physical effects, …

Renovating perturbation theory (PT) tool:

- Limitation of current PT framework based on single-stream approx
- "*post-collapse PT*": new PT treatment based on Vlasov-Poisson

$\rightarrow$ performance in 1D cosmology

Should help to clarify/understand nature of dark matter/dark energy