

The large-scale structure of the Universe

Matthew Lewandowski
ETH Zurich

Third EuCPT Symposium, CERN
01/06/23

outline

- outstanding questions
- galaxy surveys
- EFT of LSS
- recent results
- looking forward

in collaboration with
G. D'Amico, Y. Donath,
L. Senatore, P. Zhang, ...

ETH zürich

A photograph of a person standing on a sand dune at night, looking up at a starry sky. A bright light source from a flashlight illuminates the person's path on the sand. The sky is filled with stars and a visible galaxy.

Inflation
(initial conditions)

light
relics

baryogenesis

Nature of
dark matter

COSMIC
acceleration

Neutrino
masses

tensions

A photograph of a person standing on a sand dune, looking up at a dark, star-filled sky. The foreground is a sandy slope, and the background is a vast, dark expanse of space.

Inflation
(initial conditions)

light
relics

So, what is
the path?

Nature of
dark matter

COSMIC
acceleration

baryogenesis

Neutrino
masses

tensions

large-scale structure



galaxy maps

SDSS DR9

galaxy maps

we are lucky

SDSS DR9

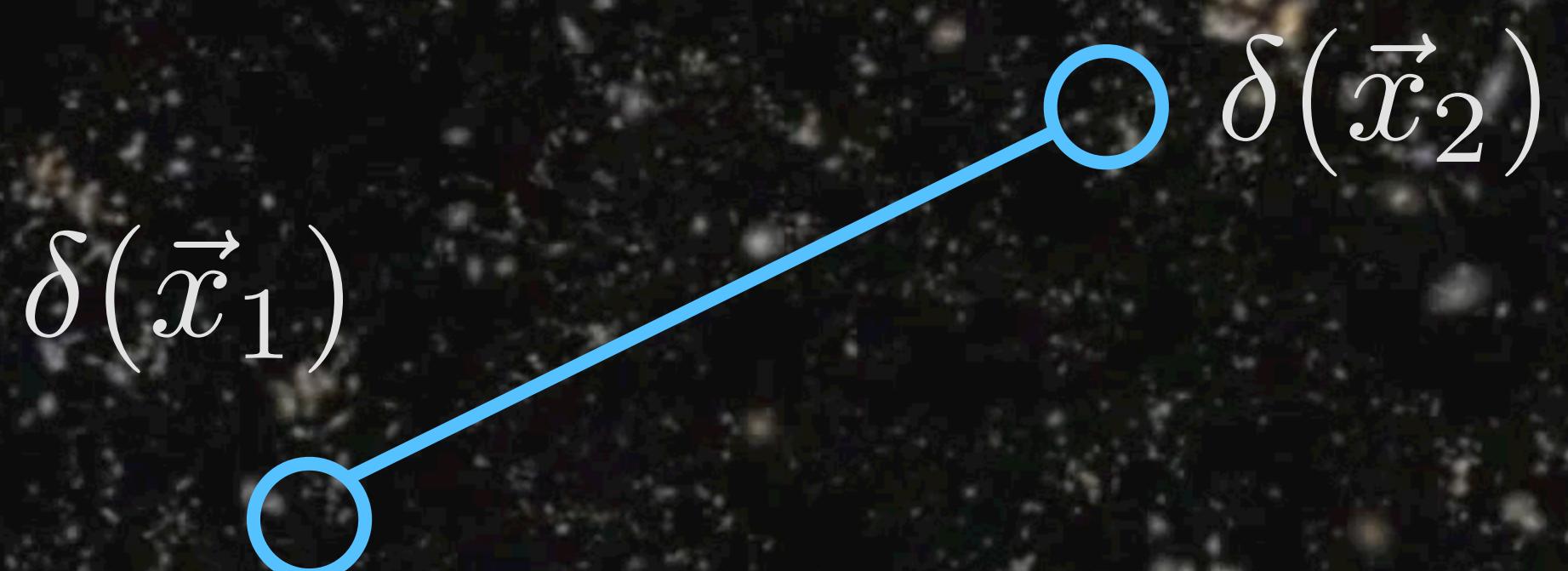
the promise

- this map is sensitive to the Universe's contents, initial conditions, and interactions
- standard evolution - Λ CDM parameters like Ω_m , H_0 , and σ_8
- but also everything else mentioned earlier

the method

summary statistics

two point/power spectrum



$$\langle \delta(\vec{x}_1) \delta(\vec{x}_2) \rangle$$

$$P(k)$$

overdensity: $\delta(\vec{x})$

three point/bispectrum

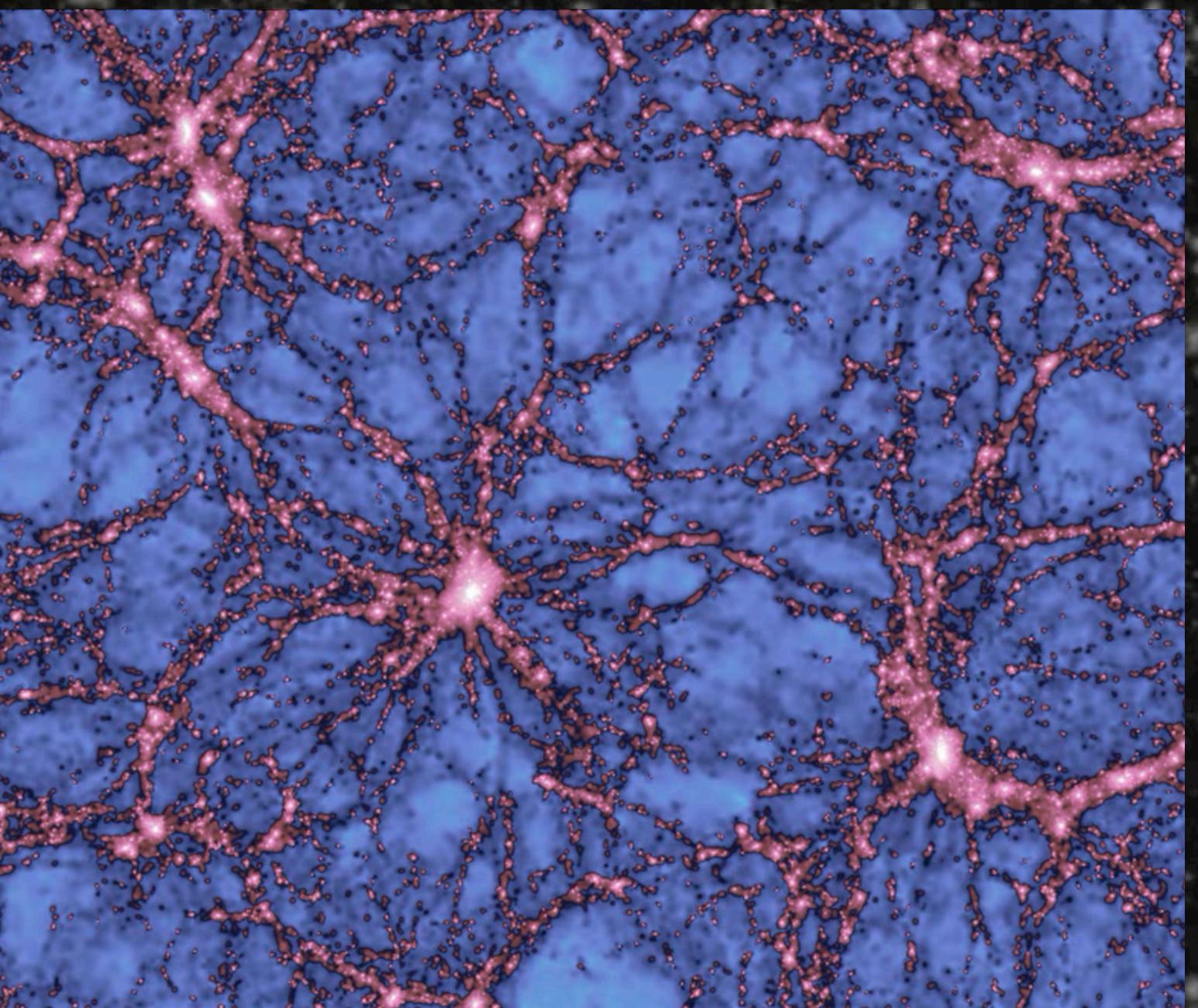
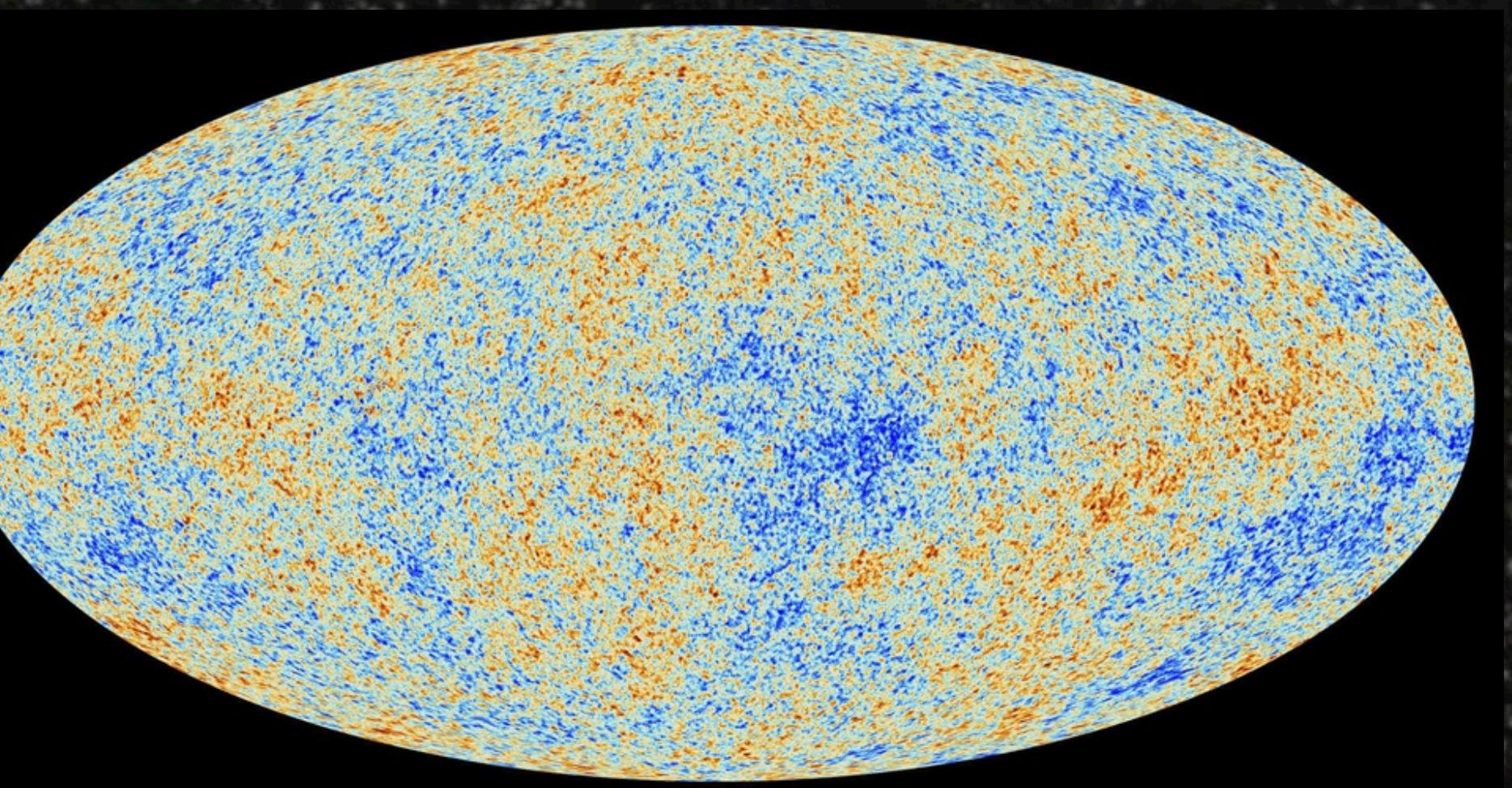
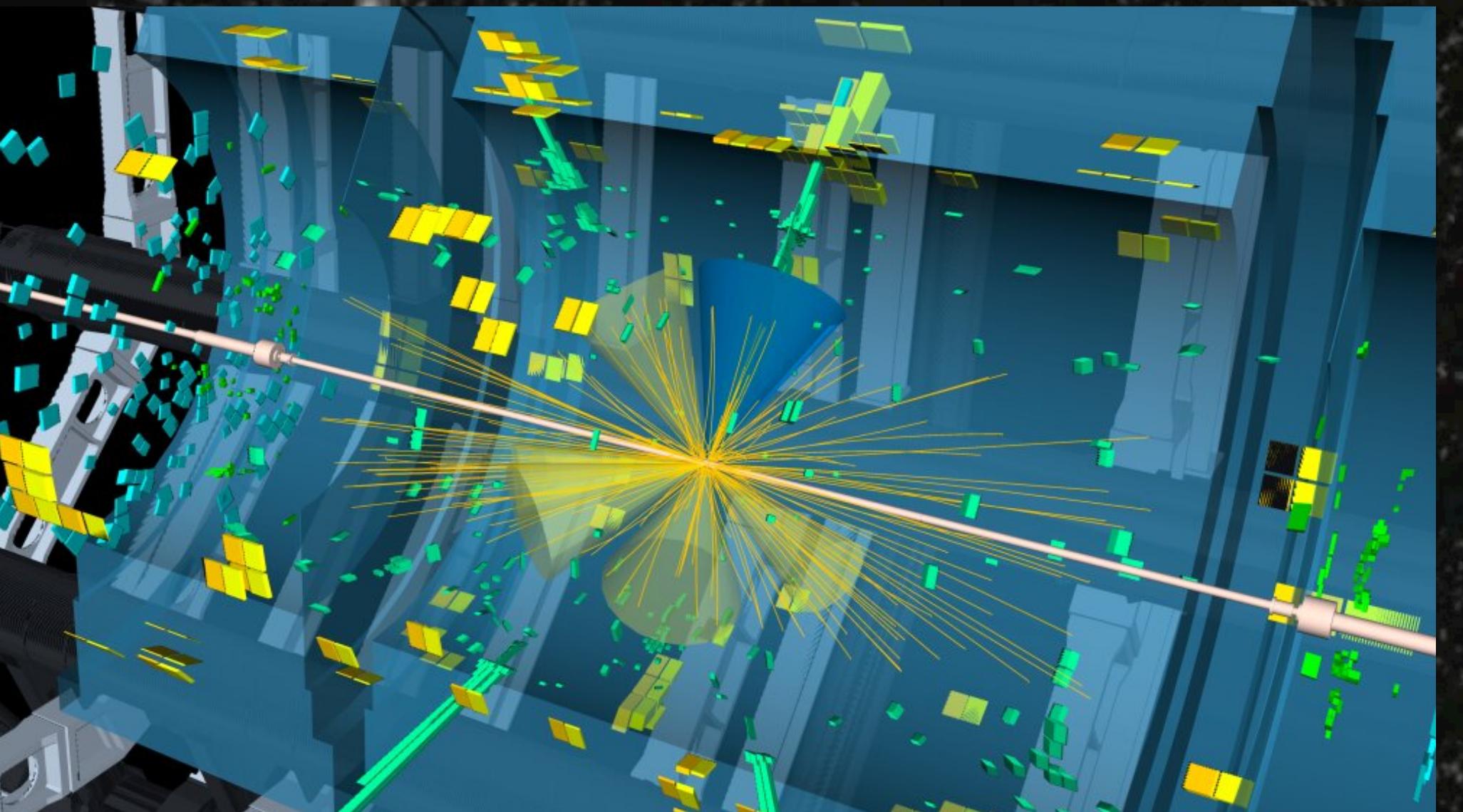


$$\langle \delta(\vec{x}_1) \delta(\vec{x}_2) \delta(\vec{x}_3) \rangle$$

$$B(k_1, k_2, k_3)$$

the challenge

- CMB is linear - lucky again
- think how lucky we are that standard model is weakly coupled
- LSS is highly nonlinear on small scales



the payoff

- but LSS is three-dimensional
- many more available modes

$$\text{error bars} \sim \frac{1}{\sqrt{N_{\text{modes}}}} \sim \frac{1}{\sqrt{V_{\text{survey}} k_{\text{max}}^3}}$$

- interesting point from McDonald and Roy 2009:
 - we pay about \$1,000 per mode for the $\sim 10^6$ modes we have
 - so increasing k_{max} by a factor of 1.3 is essentially worth a billion dollars

the payoff

largest k , smallest
length at which we
trust the theory

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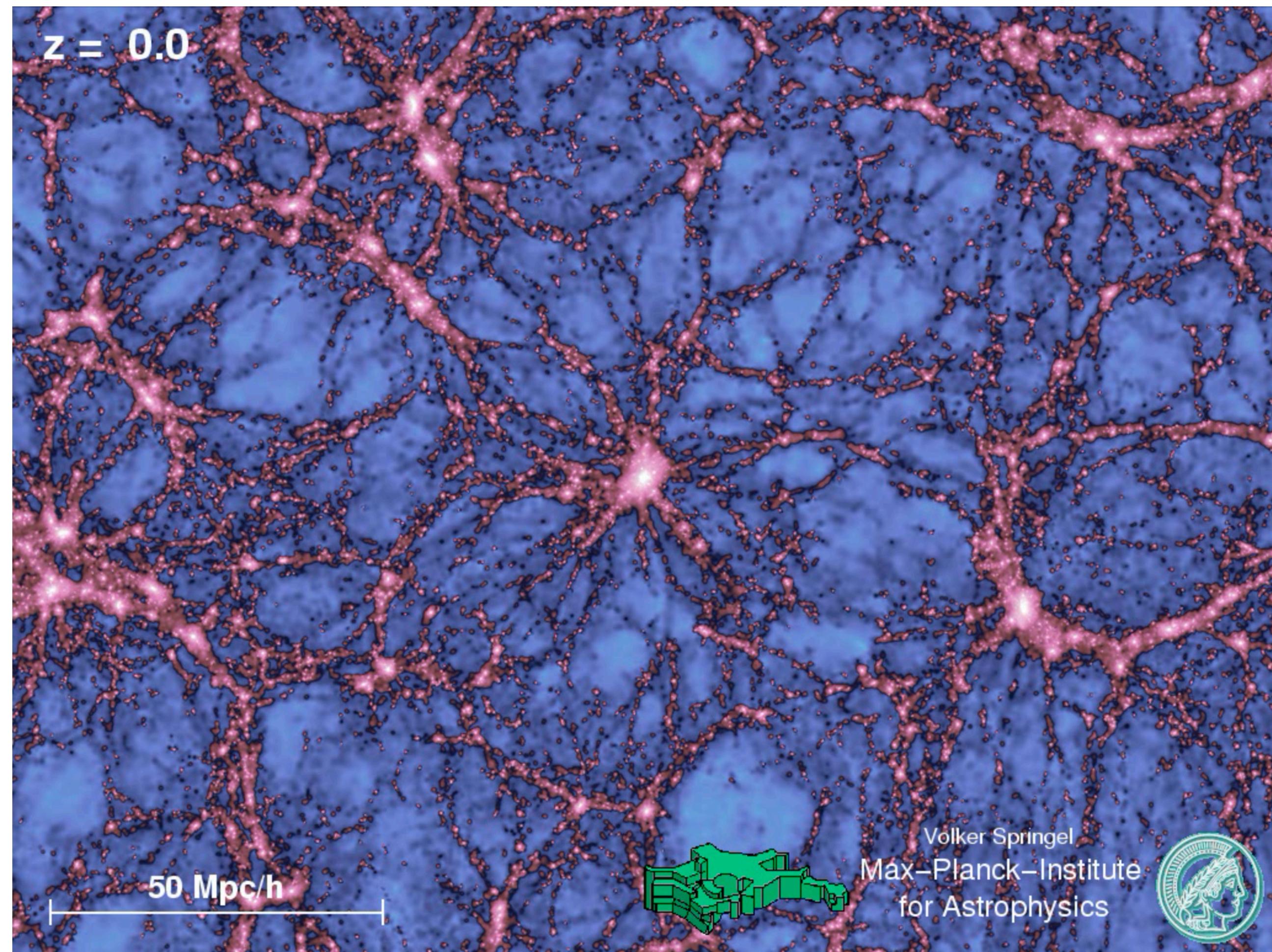
**next-generation surveys
(DESI, Euclid, MegaMapper,
PUMA, etc.) delivering data
in the next 2-10 years**

EFT of LSS

effective field theory (EFT)

- controlled, analytic, perturbative expansion
- how can small scales affect large scales?

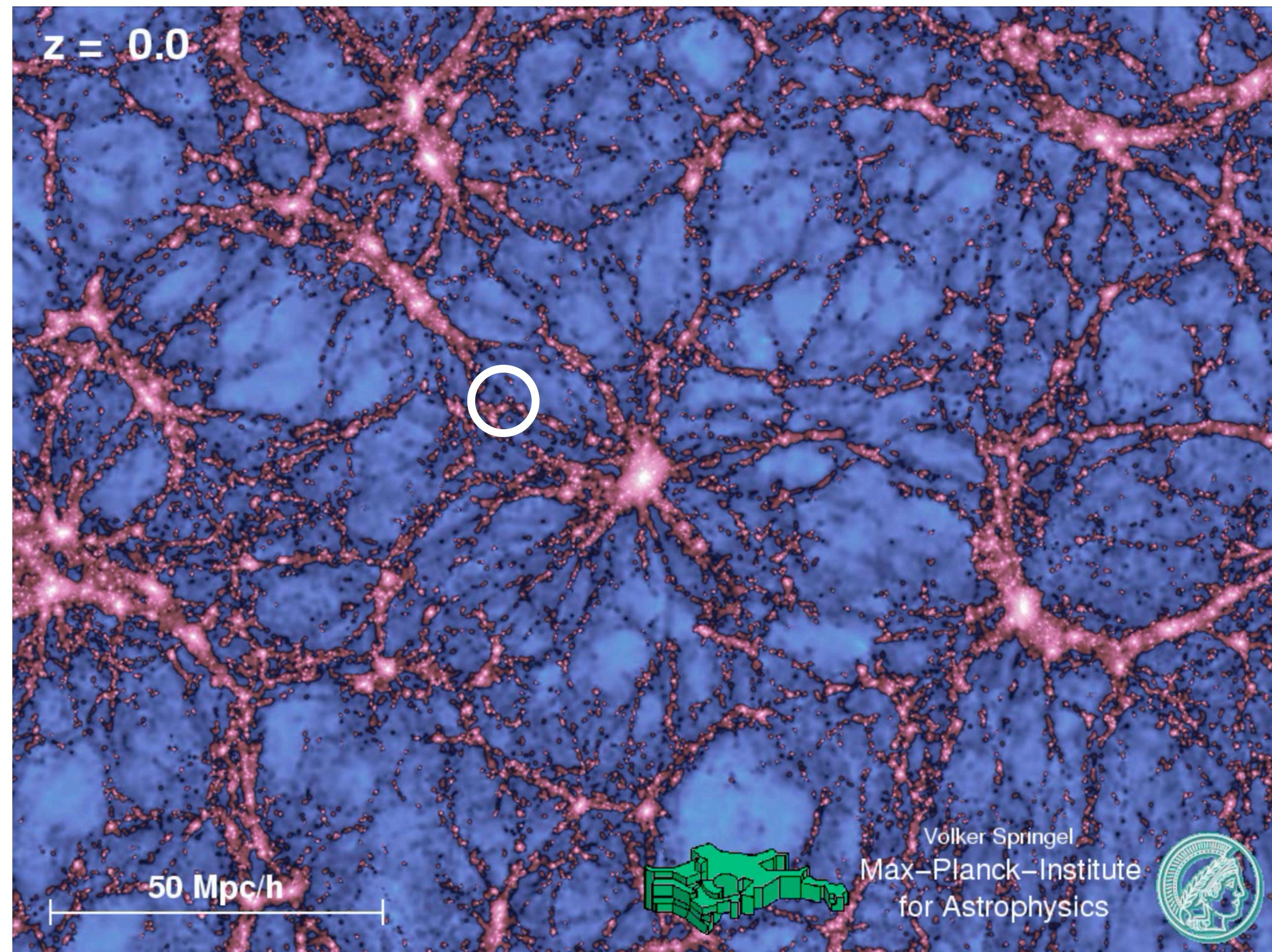
Max-Planck-Institute for Astrophysics,
Volker Springel



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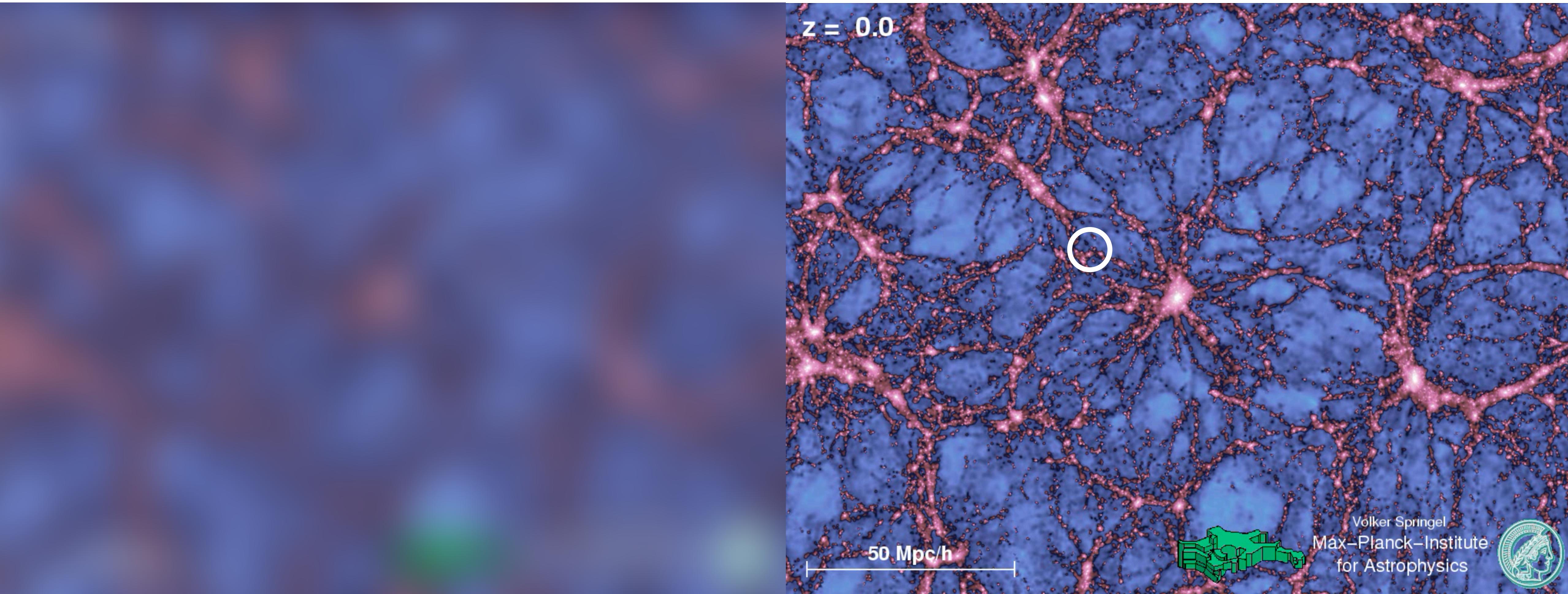
Max-Planck-Institute for Astrophysics,
Volker Springel



effective field theory (EFT)

- controlled, analytic, perturbative expansion
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Max-Planck-Institute for Astrophysics,
Volker Springel



effective field theory of LSS

equations of motion

Baumann, Nicolis,
Senatore, Zaldarriaga 12
Carrasco, Hertzberg,
Senatore 12

what do we actually solve?

continuity

$$= 0$$

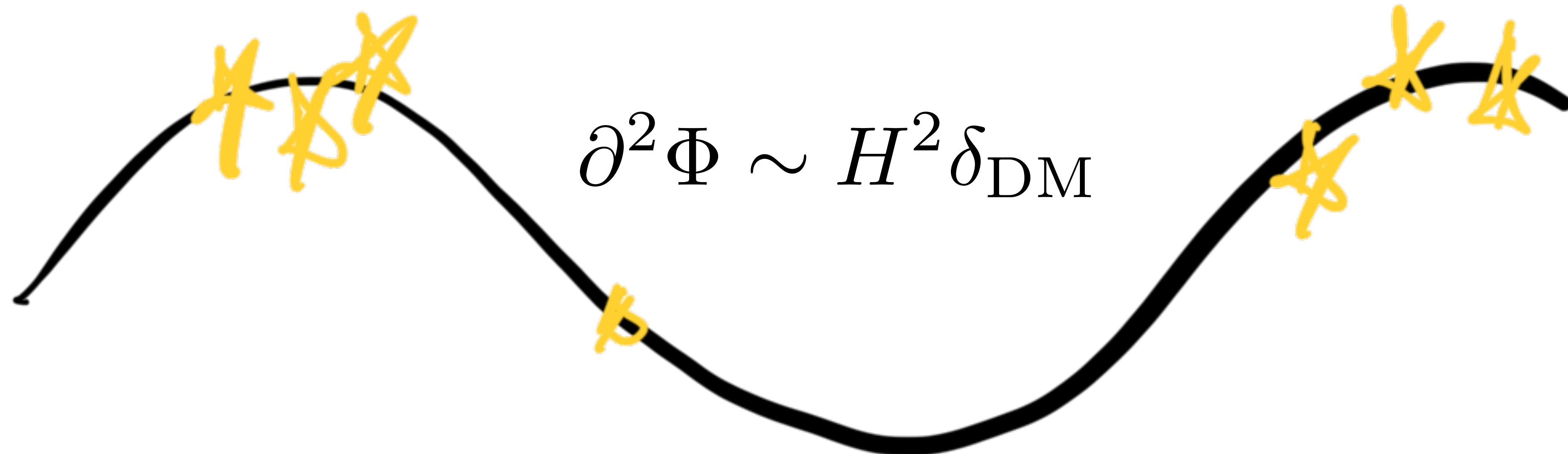
Euler

$$= \frac{\partial_i \partial_j}{k_{\text{NL}}^2} \left(c_s^2 \delta^{ij} \delta + c_2 \partial_i v^j + \frac{c_3}{k_{\text{NL}}^2} \partial_i \delta \partial_j \delta + \frac{c_4}{k_{\text{NL}}^2} \partial_i \partial_j \delta + \dots \right)$$

perfect fluid

EFT counterterms

biased tracers



McDonald 06

McDonald, Roy 10

Senatore 15

Mirbabayi, Schmidt,
Zaldarriaga 14

Desjacques, Jeong,
Schmidt 16

Fujita, Vlah 20

D'Amico, **ML**,
Senatore, Zhang 22

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (2)

D'Amico, Marinucci,
Pietroni, Vernizzi 21

Philcox, Ivanov, Cabass,
Simonović, Zaldarriaga,
Nishimichi 22

many, many more ...



one-loop bispectrum of galaxies

one-loop bispectrum of galaxies

new theoretical progress

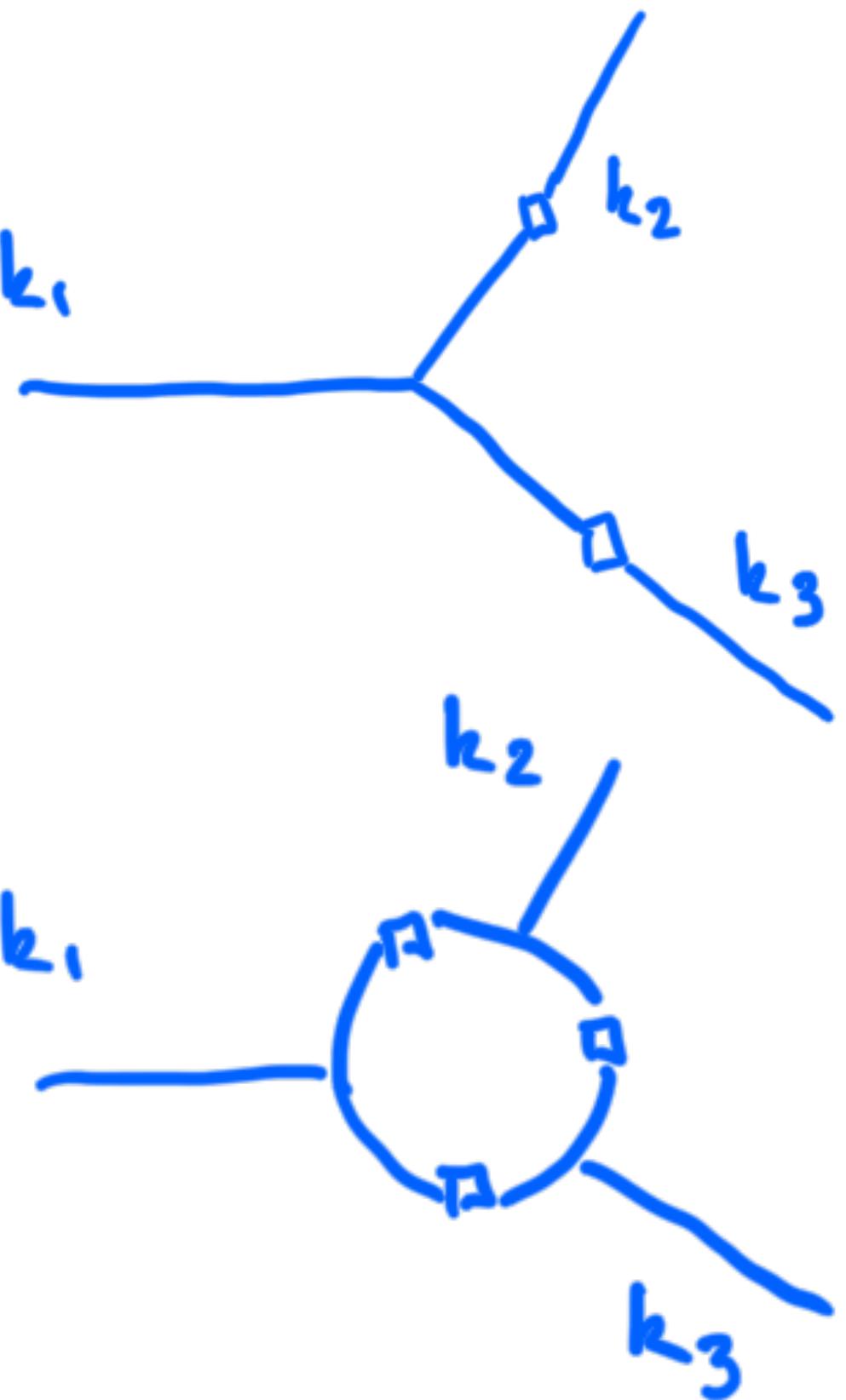
**state-of-the-art
perturbation
theory**

**fully renormalized
in RSS**

**up to 4th order in
perturbations**

linear,
tree level

first correction,
one loop



D'Amico, **ML**,
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Philcox, Ivanov, Cabass,
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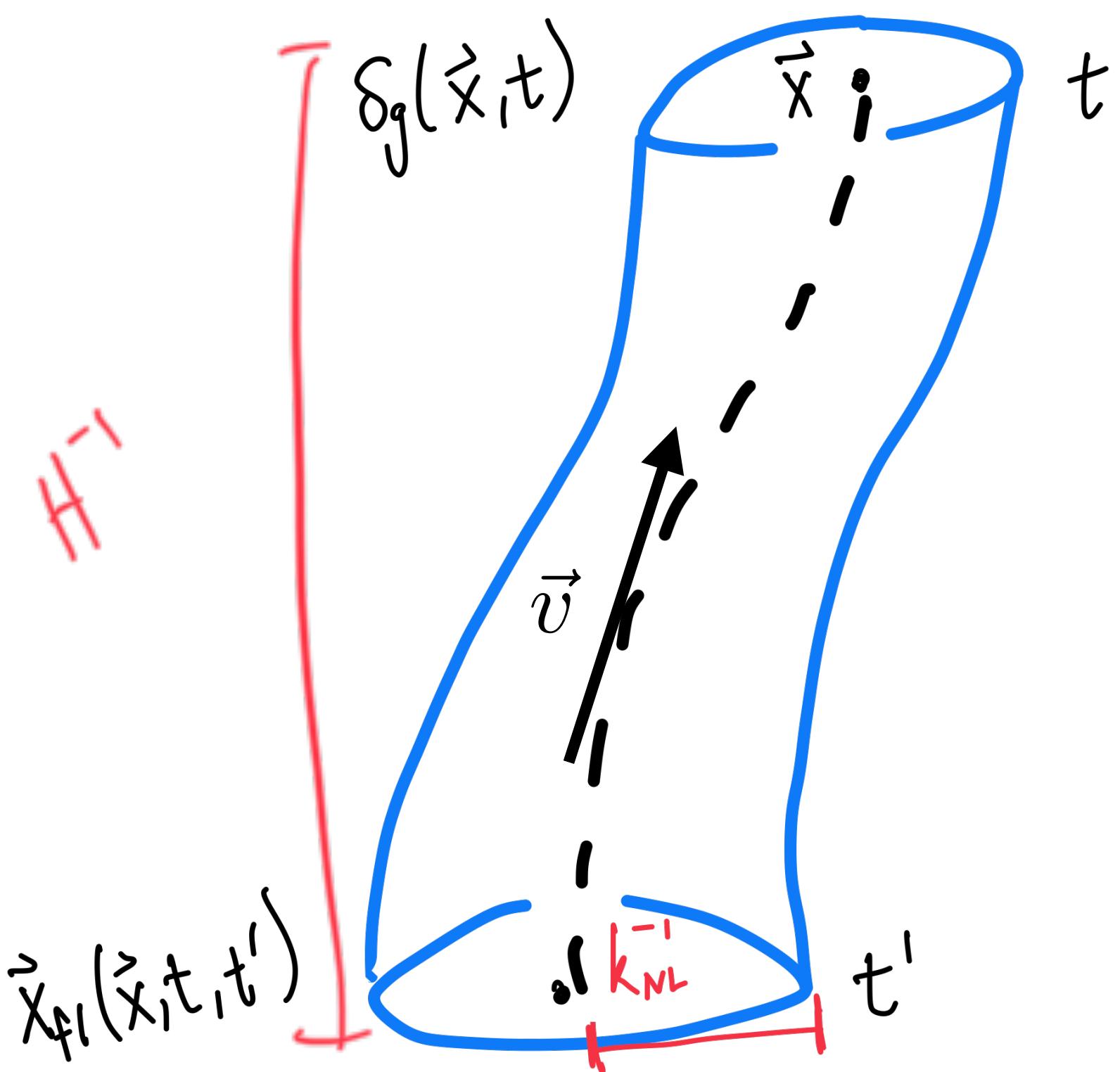
one-loop bispectrum of galaxies

new theoretical progress

D'Amico, **ML**,
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D'Amico, Donath, **ML**,
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Senatore, Zhang 22 (2)



one-loop bispectrum of galaxies

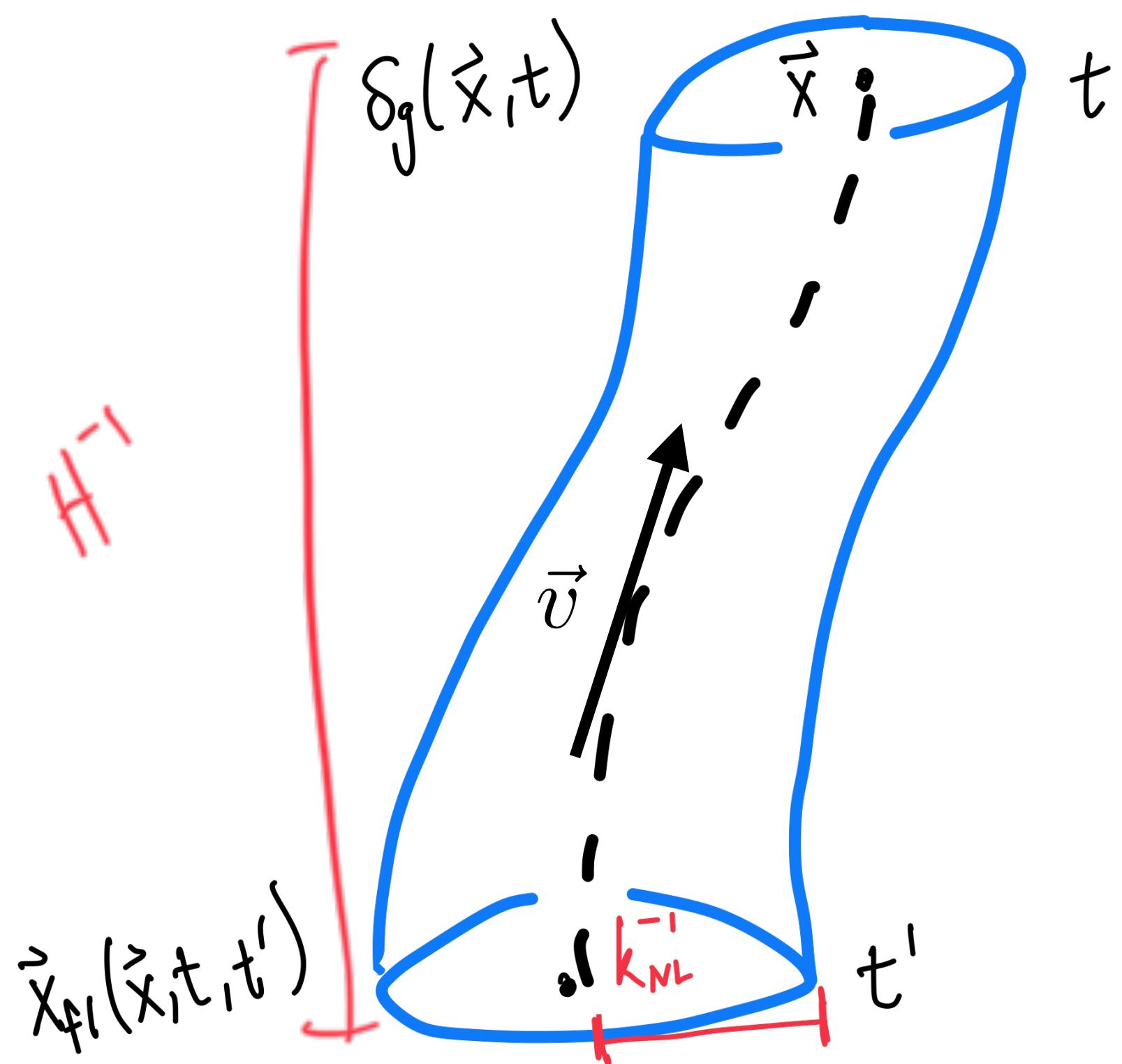
new theoretical progress

$$\delta_g(\vec{x}, t) = \sum_{\mathcal{O}_{\text{DM}}} \int_{t'}^t dt' H(t') c_{\mathcal{O}_{\text{DM}}}(t, t') \mathcal{O}_{\text{DM}}(\vec{x}_{\text{fl}}(\vec{x}, t, t'), t')$$

D'Amico, **ML**,
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D'Amico, Donath, **ML**,
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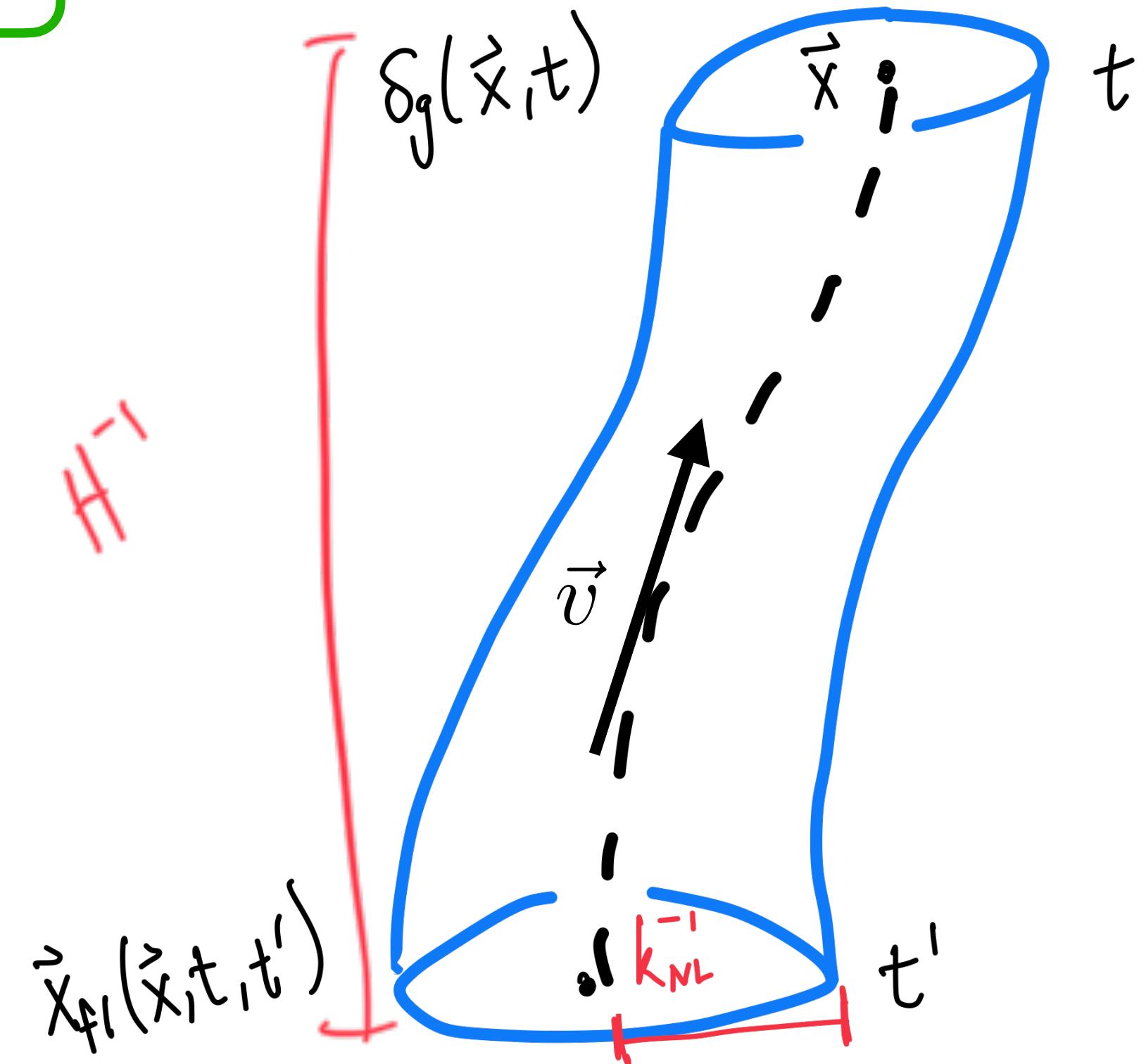


one-loop bispectrum of galaxies

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$$\delta_g(\vec{x}, t) = \sum_{\tilde{\mathcal{O}}_{\text{DM}}} c_{\tilde{\mathcal{O}}_{\text{DM}}}(t) \tilde{\mathcal{O}}_{\text{DM}}(\vec{x}, t)$$



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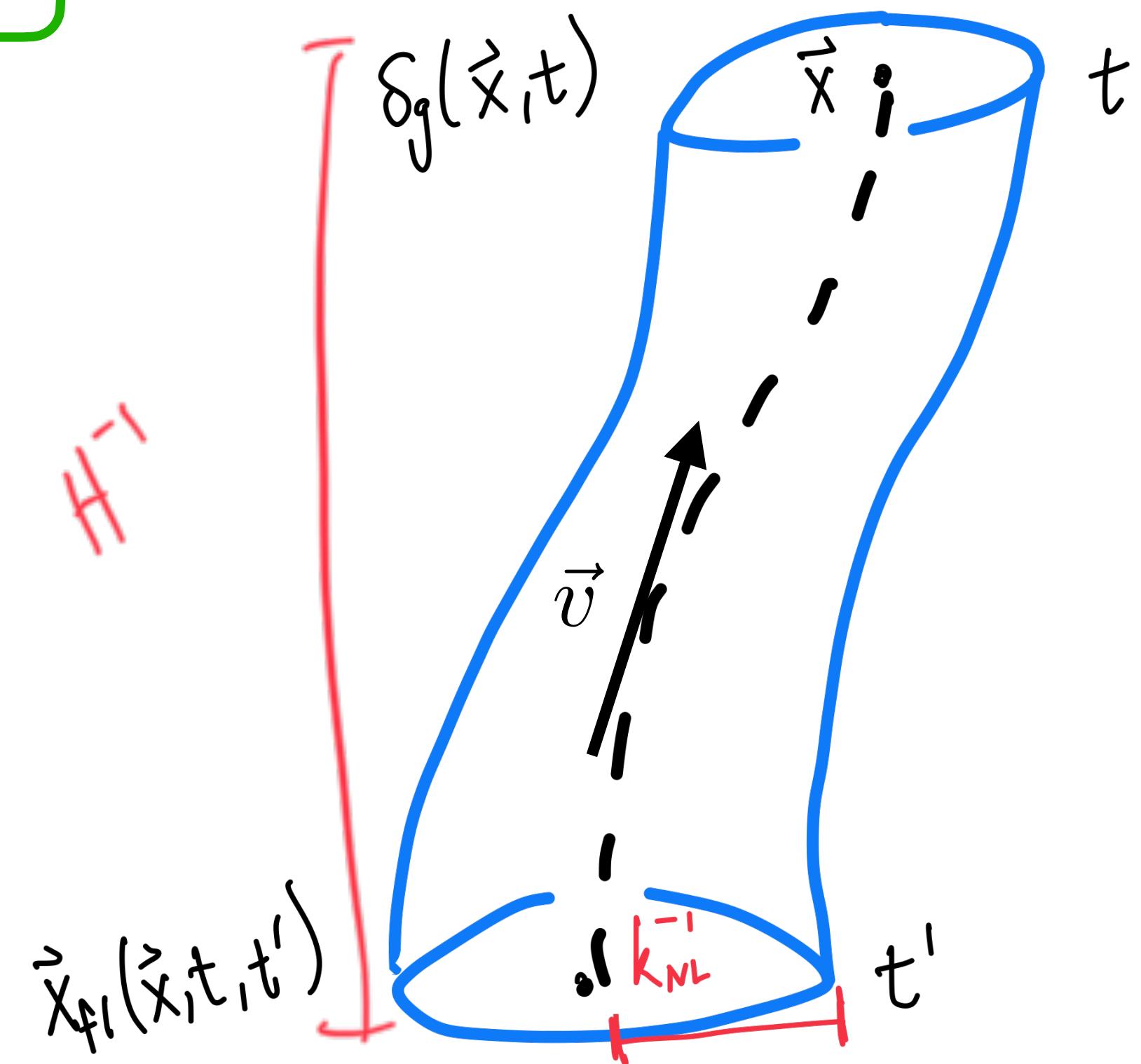
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D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (2)

Donath, **ML**, Senatore
[in prog.]



one-loop bispectrum of galaxies

new theoretical progress

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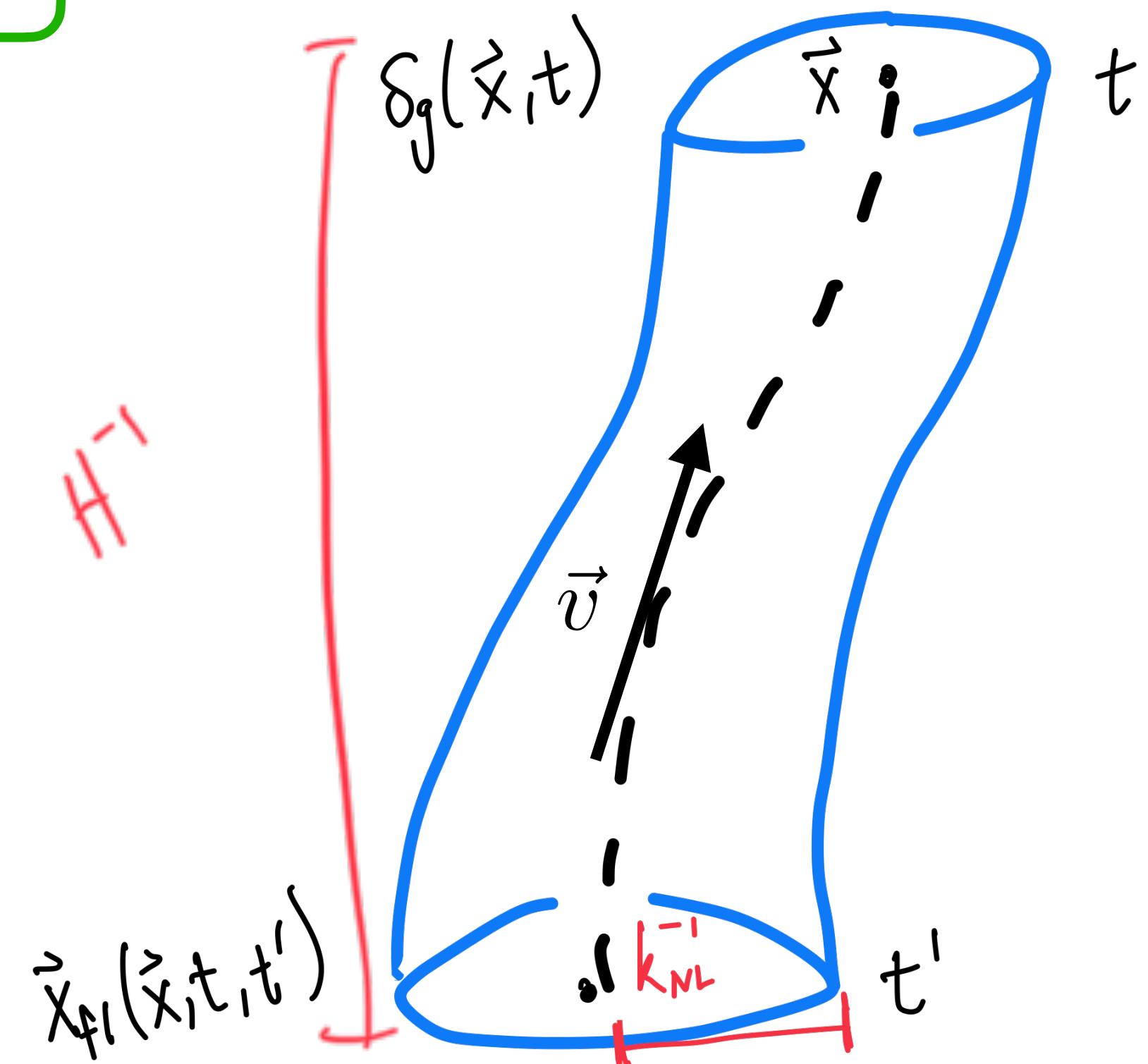
local-in-time limit: $c_{\mathcal{O}_{\text{DM}}}(t, t') \rightarrow c_{\mathcal{O}_{\text{DM}}}(t) \delta_D(t - t')$

D'Amico, **ML**,
Senatore, Zhang 22

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

D'Amico, Donath, **ML**,
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Donath, **ML**, Senatore
[in prog.]



one-loop bispectrum of galaxies

new theoretical progress

$$\delta_g(\vec{x}, t) = \sum_{\mathcal{O}_{\text{DM}}} \int^t dt' H(t') c_{\mathcal{O}_{\text{DM}}}(t, t') \mathcal{O}_{\text{DM}}(\vec{x}_{\text{fl}}(\vec{x}, t, t'), t')$$

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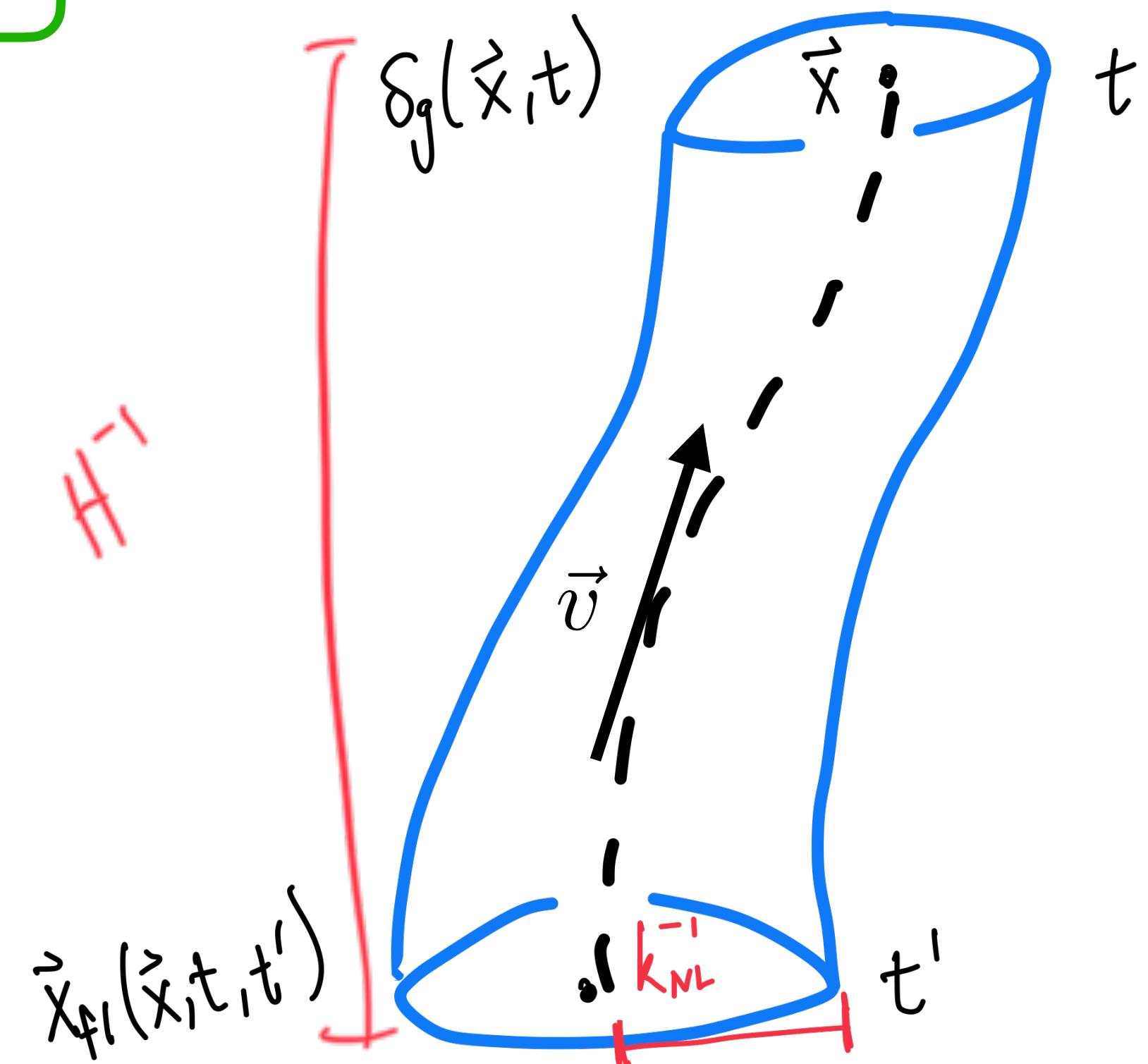
- can compare perturbative expansion of local and non-local expressions
- at 4th order, they are equivalent
- at 5th order (e.g., 2-loop PS), they are not

D'Amico, **ML**,
Senatore, Zhang 22

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (2)

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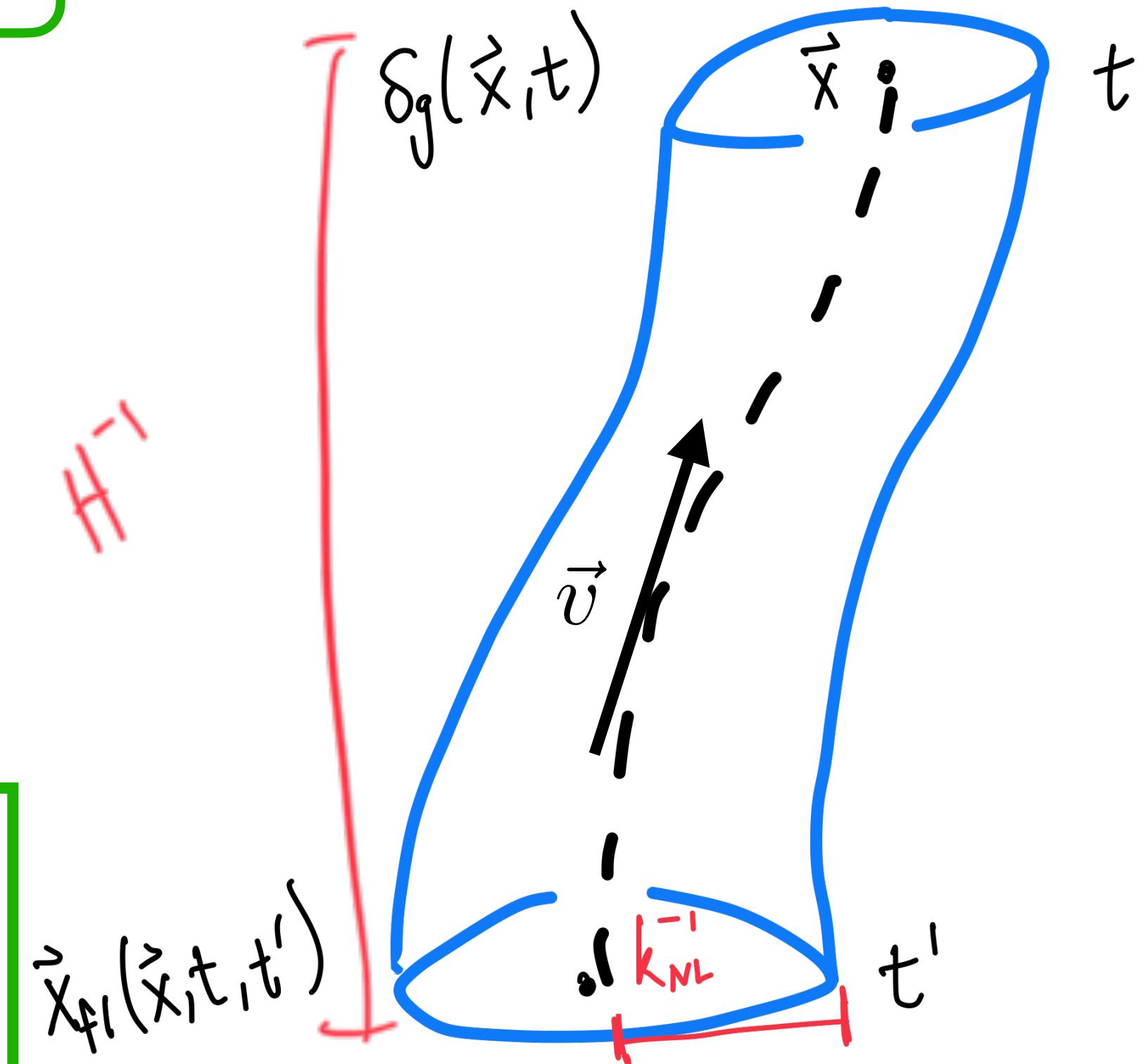
we can measure galaxy formation time using field theory. this has never been done before.

D'Amico, **ML**,
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D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (2)

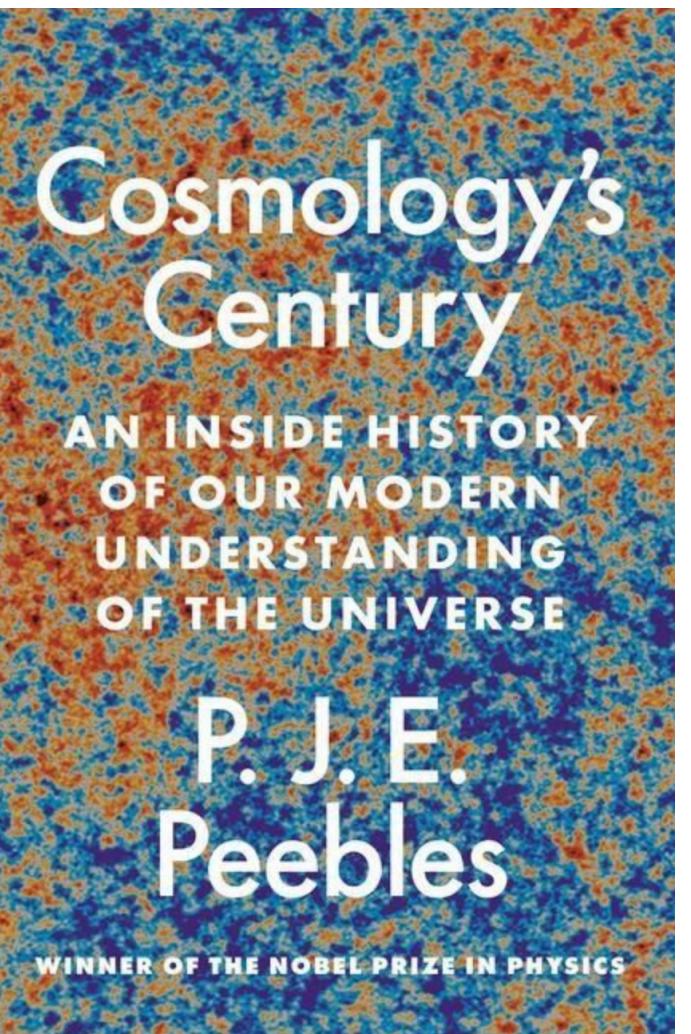
Donath, **ML**, Senatore
[in prog.]



one-loop bispectrum of galaxies

new theoretical progress

“By this time [1980], the 1948 steady-state cosmology was seriously challenged from other directions: ...; the observations that the properties of galaxies differ at high and low redshift...; and most direct and convincing, the [CMB].”



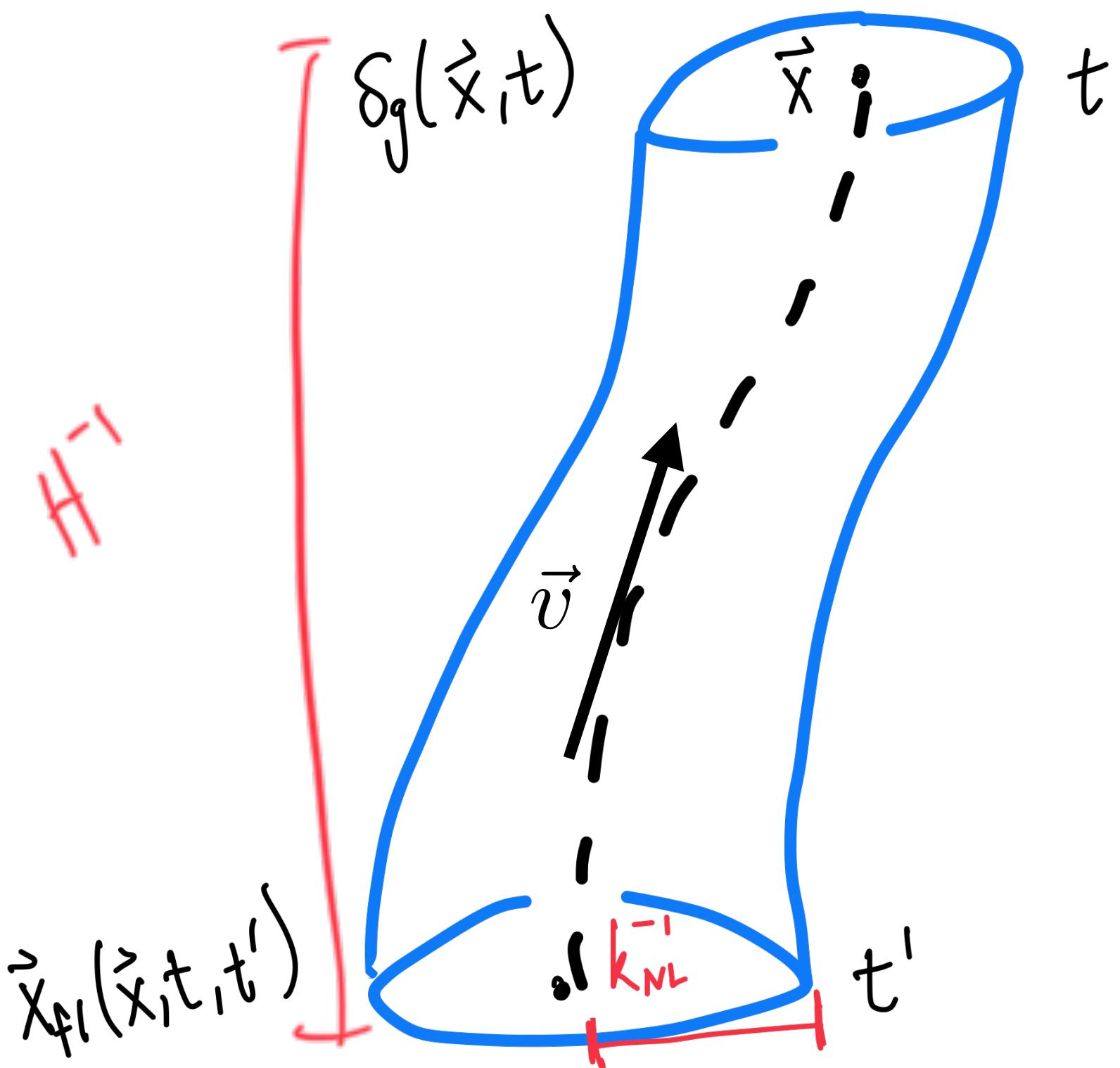
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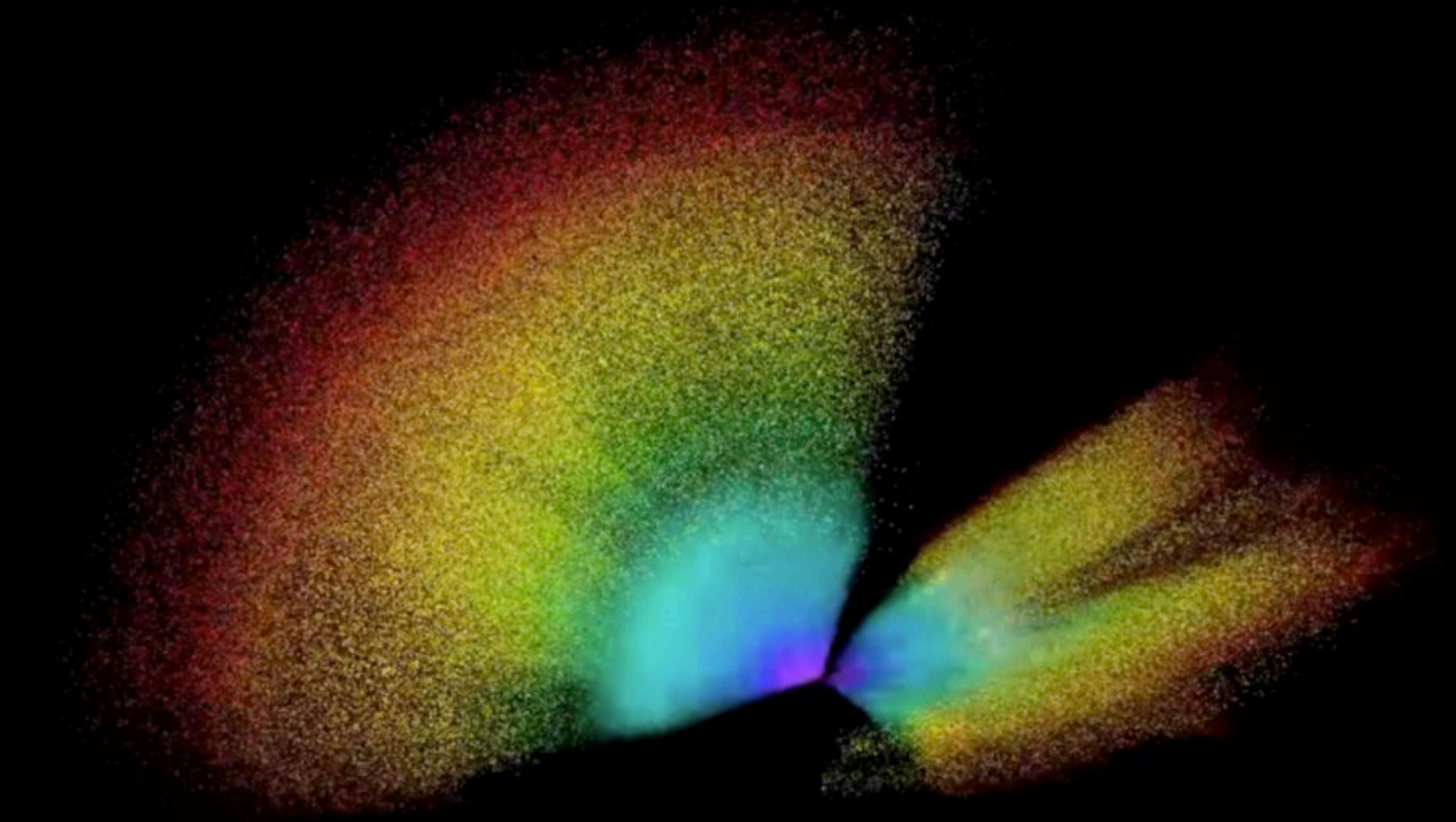
D'Amico, ML,
Senatore, Zhang 22

D'Amico, Donath, ML,
Senatore, Zhang 22 (1)

D'Amico, Donath, ML,
Senatore, Zhang 22 (2)

Donath, ML, Senatore
[in prog.]





the BOSS analysis

the BOSS analysis

D'Amico, **ML**,
Senatore, Zhang 22
D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

- theoretically consistent analysis with the one-loop bispectrum
- opens up ability to analyze much more of the data, giving powerful constraints

k_{\max} determined with the EFT

$$k_{\max} = 0.23 h \text{ Mpc}^{-1} \quad \text{one-loop terms}$$
$$k_{\max} = 0.08 h \text{ Mpc}^{-1} \quad \text{tree-level terms}$$

the BOSS analysis

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Senatore, Zhang 22
D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

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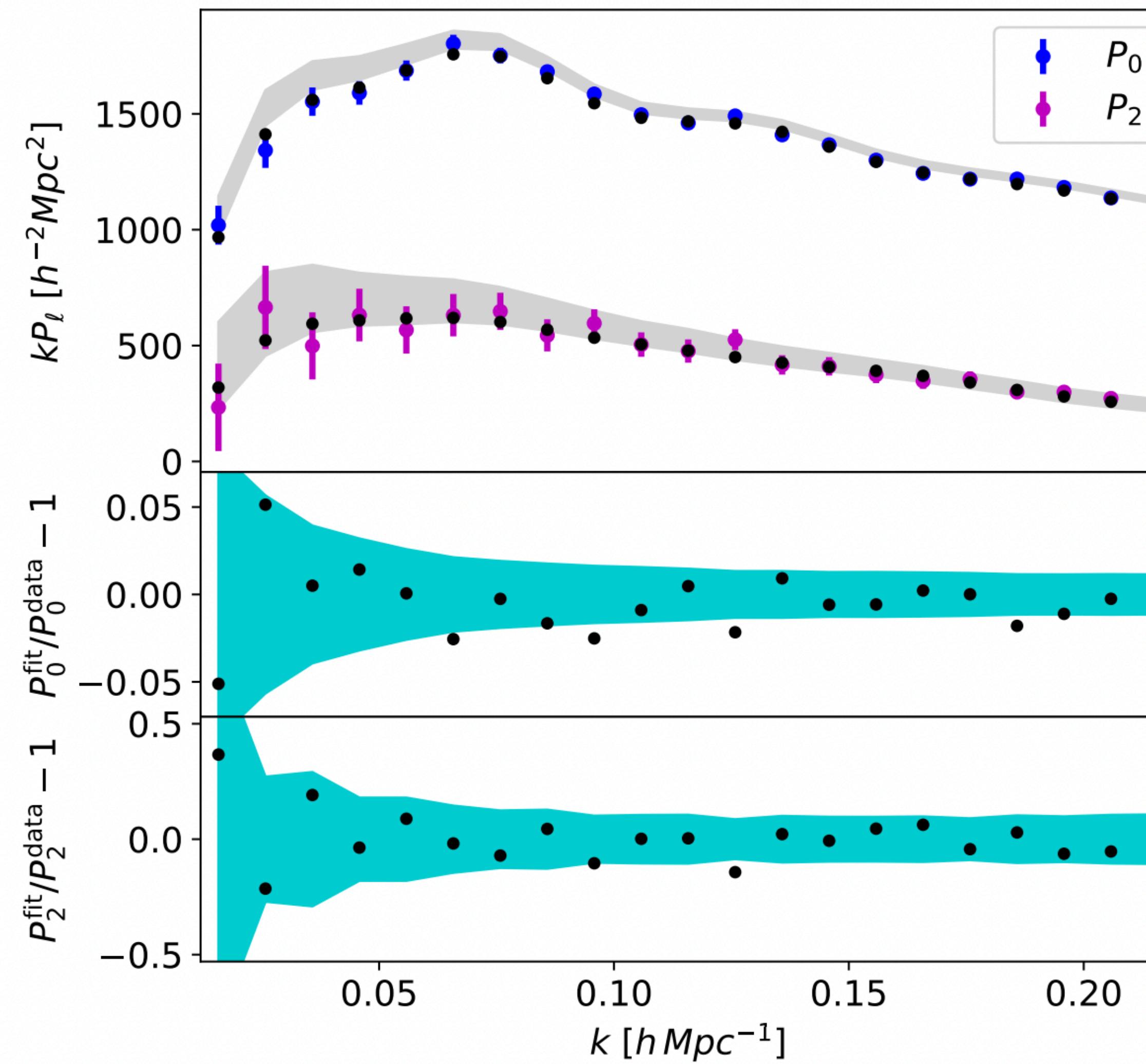
\$2.5B

the BOSS analysis

data - power spectrum

BOSS DR12 LRG sample

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)



BOSS data



Patchy mocks



best fit

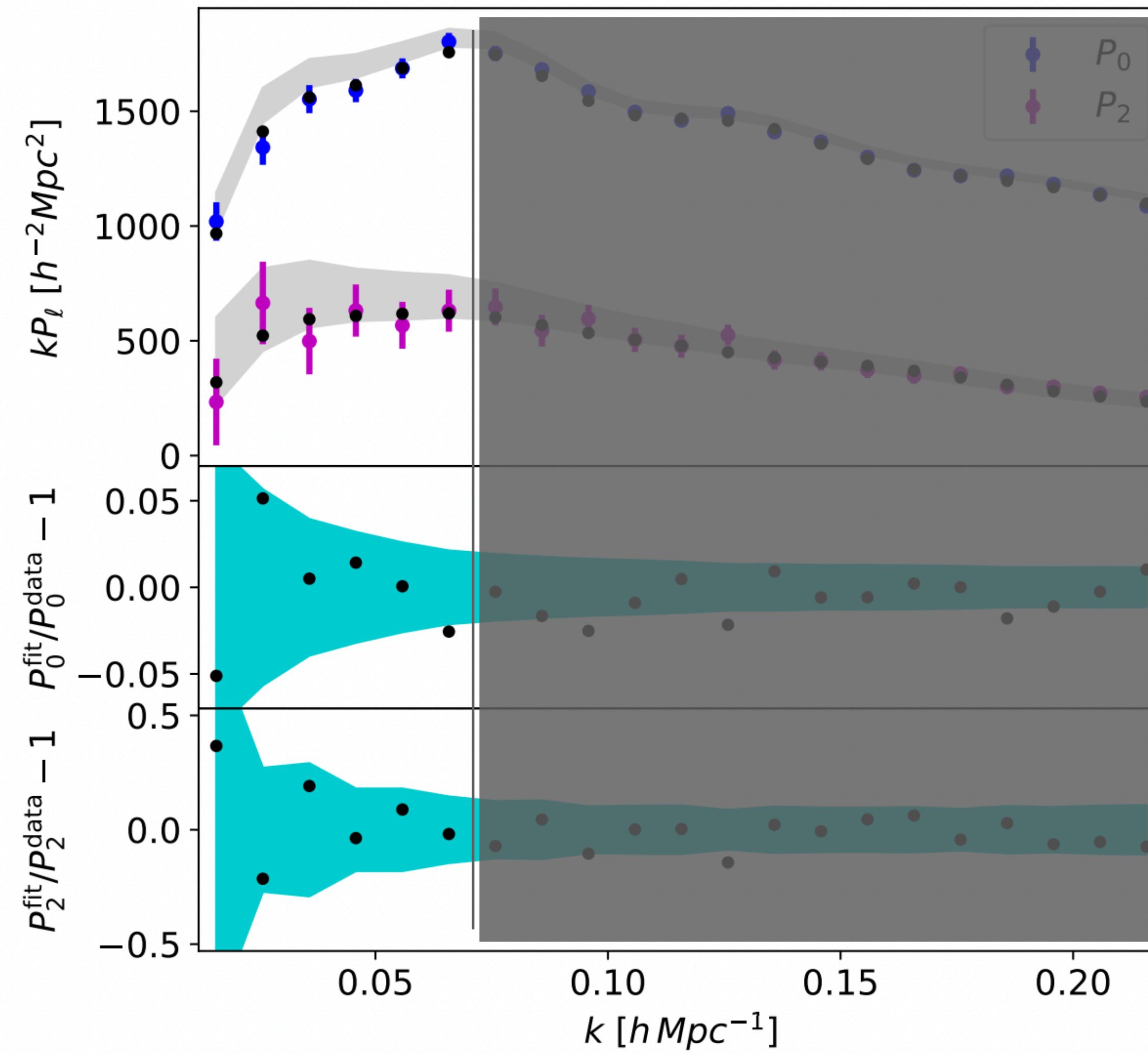
the BOSS analysis

data - power spectrum

BOSS DR12 LRG sample

D'Amico, Donath, **ML**,
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tree level



BOSS data

Patchy mocks

best fit

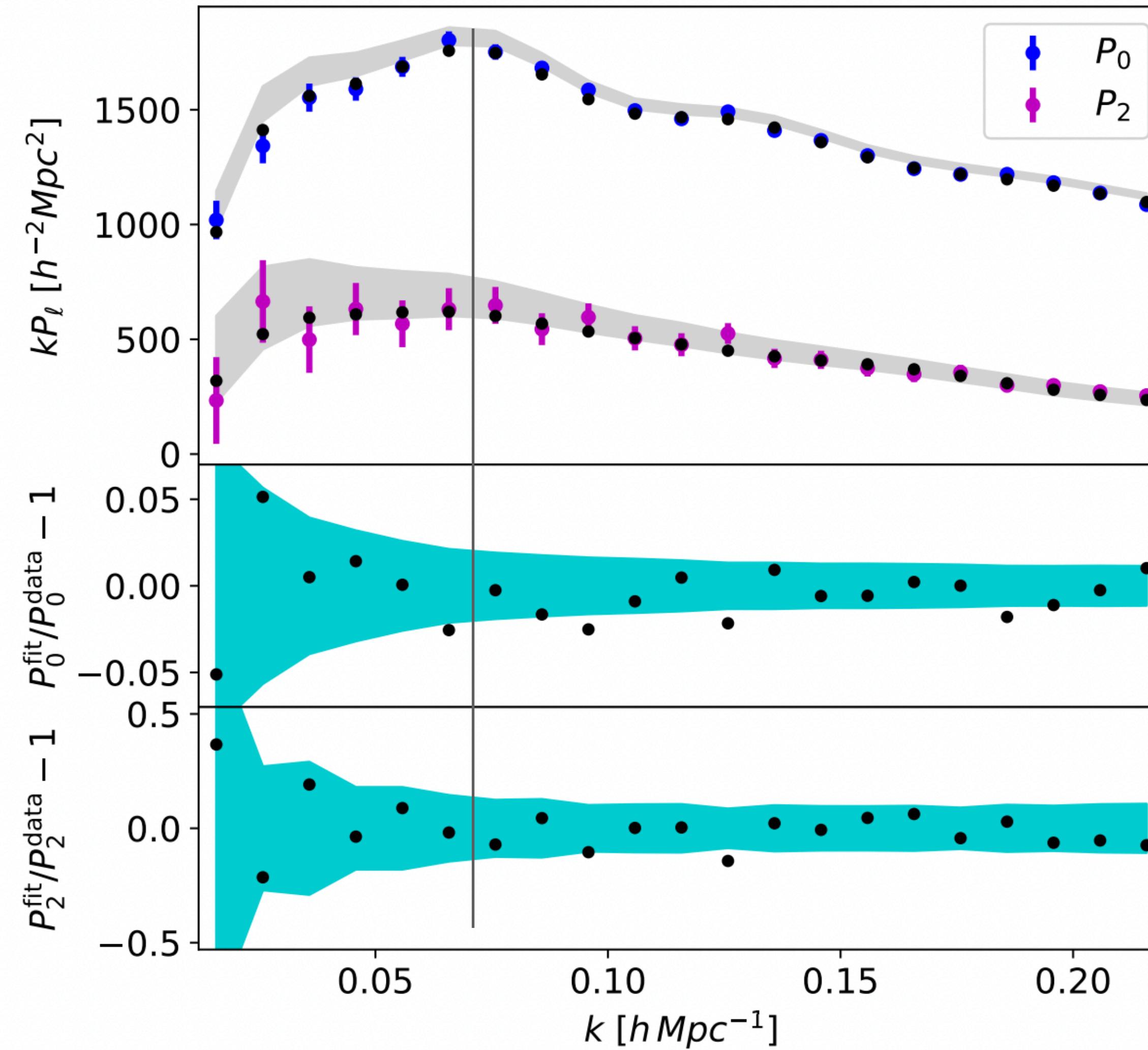
the BOSS analysis

data - power spectrum

BOSS DR12 LRG sample

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

one loop



BOSS data

Patchy mocks



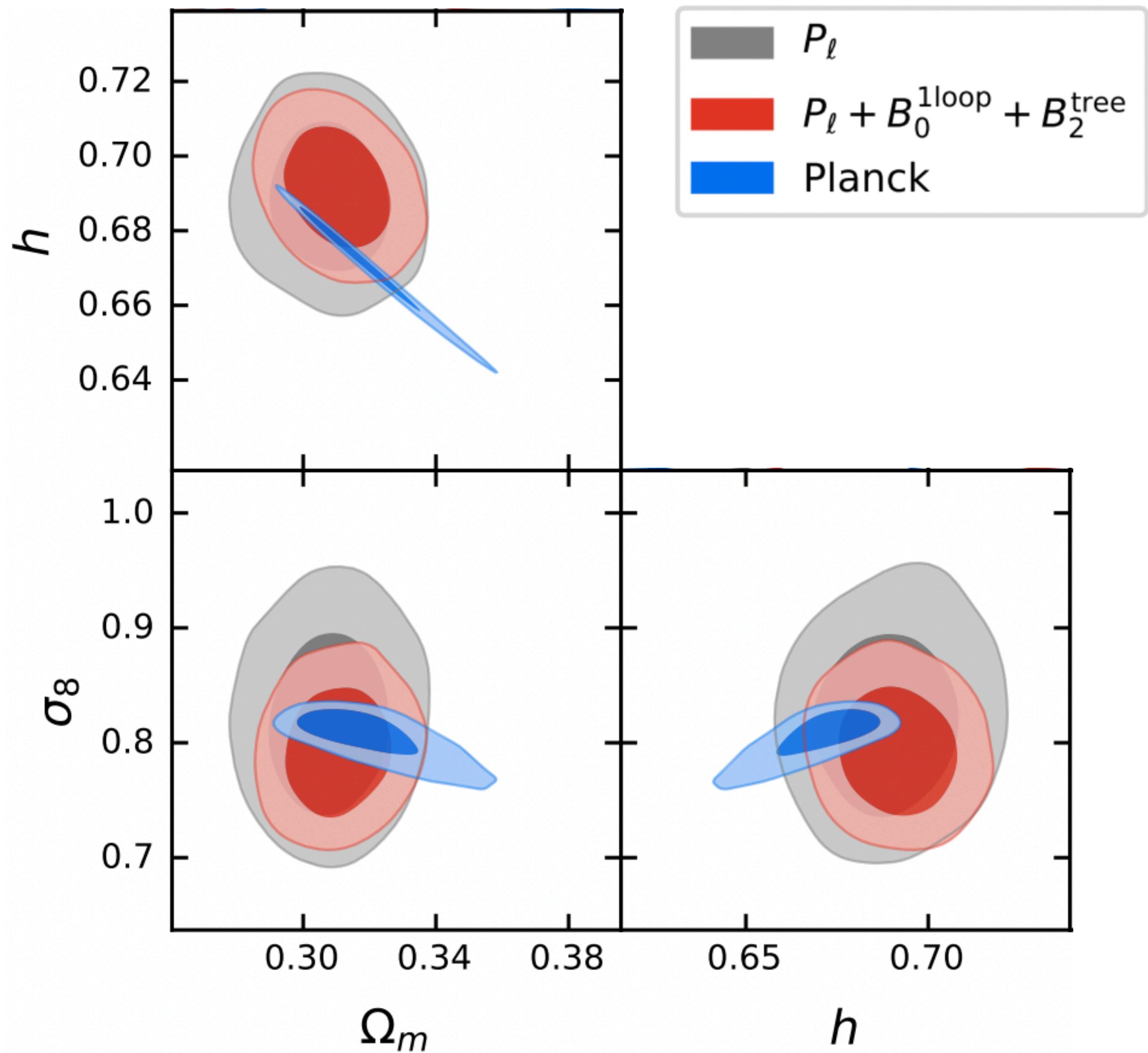
best fit

**even better
for the
bispectrum**

tree: 9 bins
1-loop: 150 bins

the BOSS analysis results

D'Amico, Donath, **ML**,
Senatore, Zhang 22 (1)

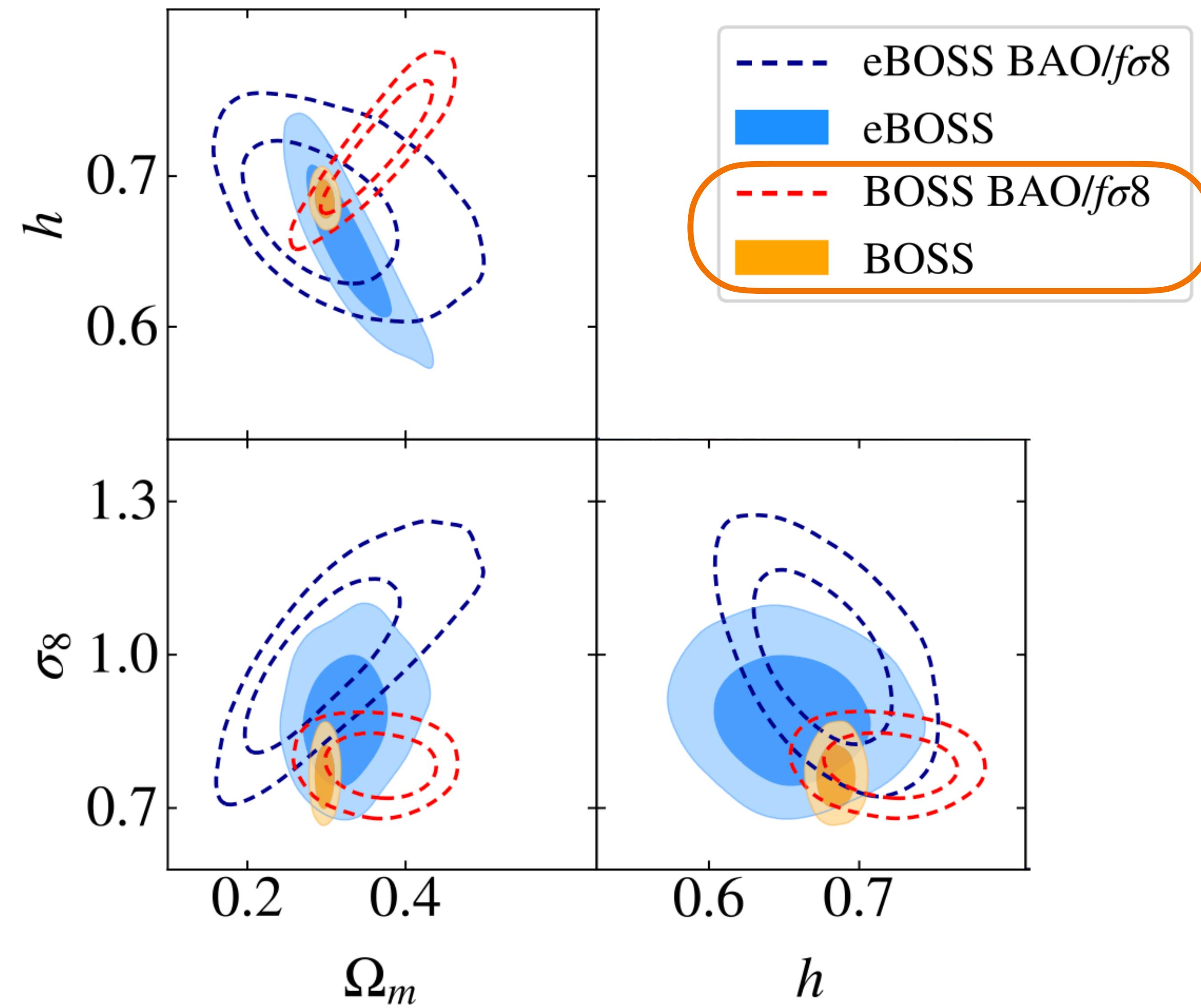


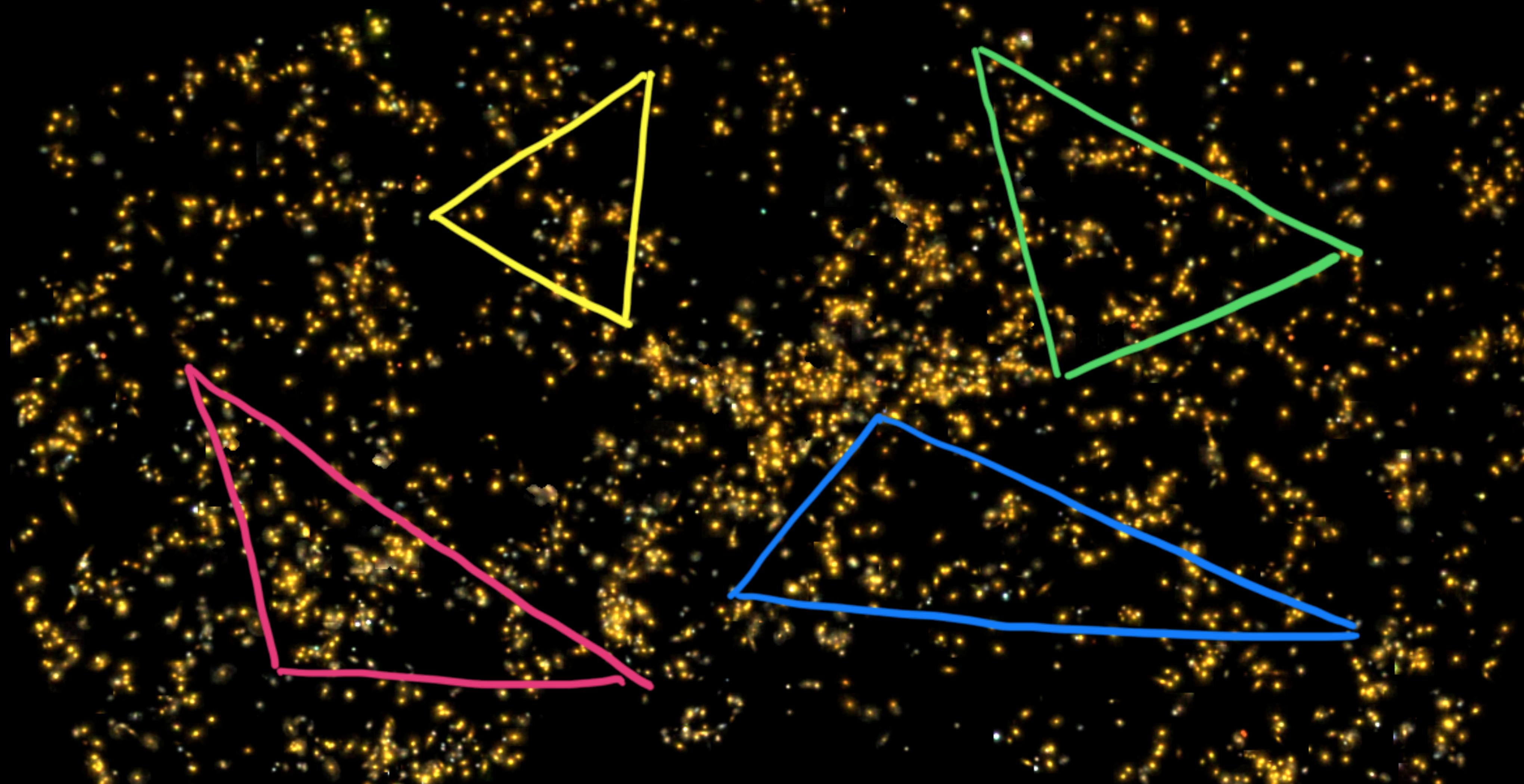
- expected to get much better with new data
- LSS is a much less “clean” system than CMB

- consistency between power spectrum and bispectrum
- no tension with Planck

the BOSS analysis

final takeaway





primordial non-Gaussianity

non-Gaussianity

constraints on primordial non-Gaussianity from LSS

changes initial conditions for δ , induces a bispectrum

$$P_{\text{Gaussian}} \rightarrow P_{\text{Gaussian}} + f_{\text{NL}} P_{\text{NG}}$$

$$B_{\text{Gaussian}} \rightarrow B_{\text{Gaussian}} + f_{\text{NL}} B_{\text{NG}}$$

experiment

date:

2012

2016

2019

	WMAP	BOSS	Planck
$f_{\text{NL}}^{\text{equil.}}$	136	247	47
$f_{\text{NL}}^{\text{forth.}}$	100	68	24
$f_{\text{NL}}^{\text{loc.}}$	19.9	38	5.1
$f_{\text{NL}}^{\text{loc. PS only}}$	60		

D'Amico, **ML**,
Senatore, Zhang 22

- approx. 2 x error reduction from previous LSS constraints on $f_{\text{NL}}^{\text{loc.}}$
- bispectrum gains you a factor of 1.6 for $f_{\text{NL}}^{\text{loc.}}$
- original BOSS did not measure $f_{\text{NL}}^{\text{forth.}}$
- could have beaten WMAP with $f_{\text{NL}}^{\text{forth.}}$ before Planck

an upswell of new analyses

• Λ CDM

Ivanov, Philcox, Cabass,
Nishimichi, Simonović,
Zaldarriagga 23

Simon, Zhang,
Poulin 22 (1)
Simon, Zhang,
Poulin, Smith 22

Simon, Zhang,
Poulin 22 (2)
Chudaykin, Ivanov 22

• f_{NL}

Cabass, Ivanov, Philcox,
Simonović 22 (1)

Cabass, Ivanov, Philcox,
Simonović 22 (2)

Cabass, Ivanov, Philcox 22
DESI 23

• dark energy

D'Amico, Senatore, Zhang 20
D'Amico, Donath,
Senatore, Zhang 20

Sugiyama et. al. 23 (1)
Piga, Marinucci, D'Amico,
Pietroni, Vernizz, Wright 23

some theory:

Cusin, **ML**, Vernizzi 17 (1)
Cusin, **ML**, Vernizzi 17 (2)

• LSS consistency relations

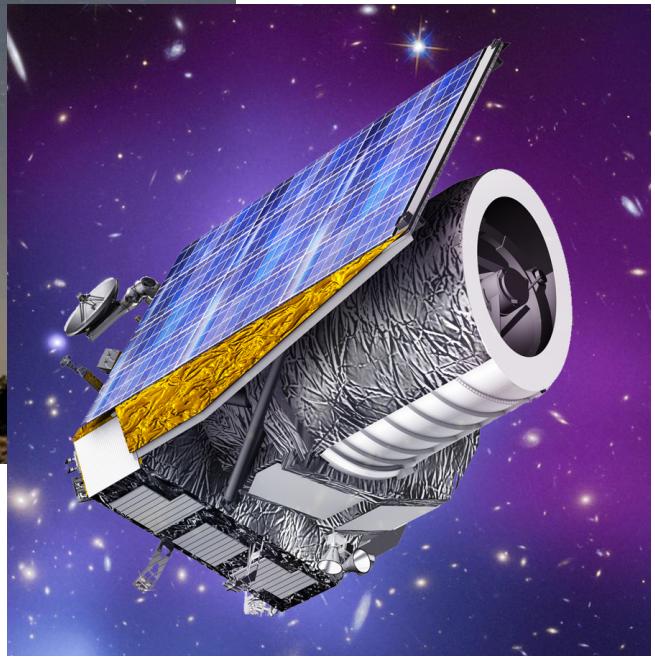
Sugiyama et. al. 23 (2)

Creminelli, Noreña,
Simonović, Vernizzi,
Gleyzes, Hui, 13/14

Crisostomi, **ML**,
Vernizzi 20
ML 20

looking forward bright future for LSS

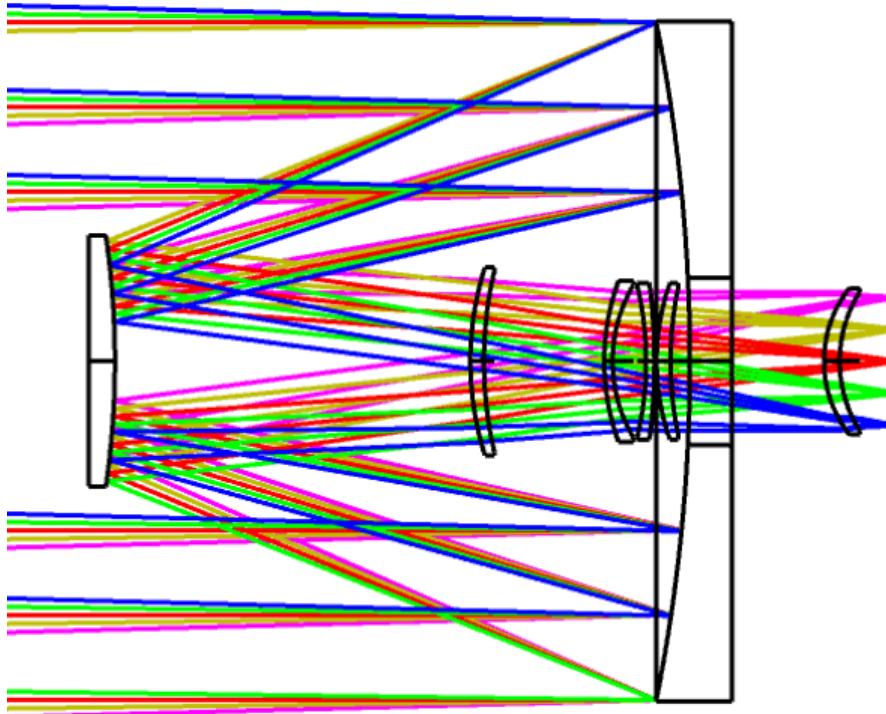
2209.03585
1907.11171
1907.12559



DESI/Euclid

~ 3 yrs.

galaxies
 $z \sim 1.2$



MegaMapper

~ 10-20 yrs.

galaxies
 $2 < z < 5$



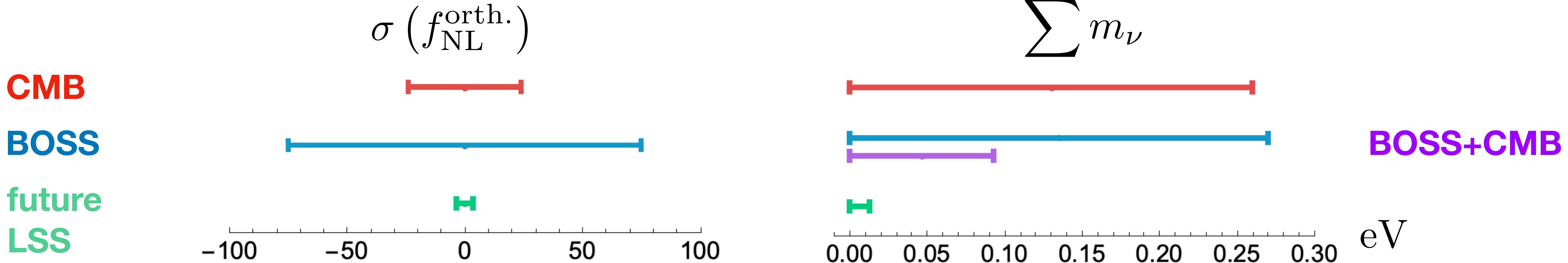
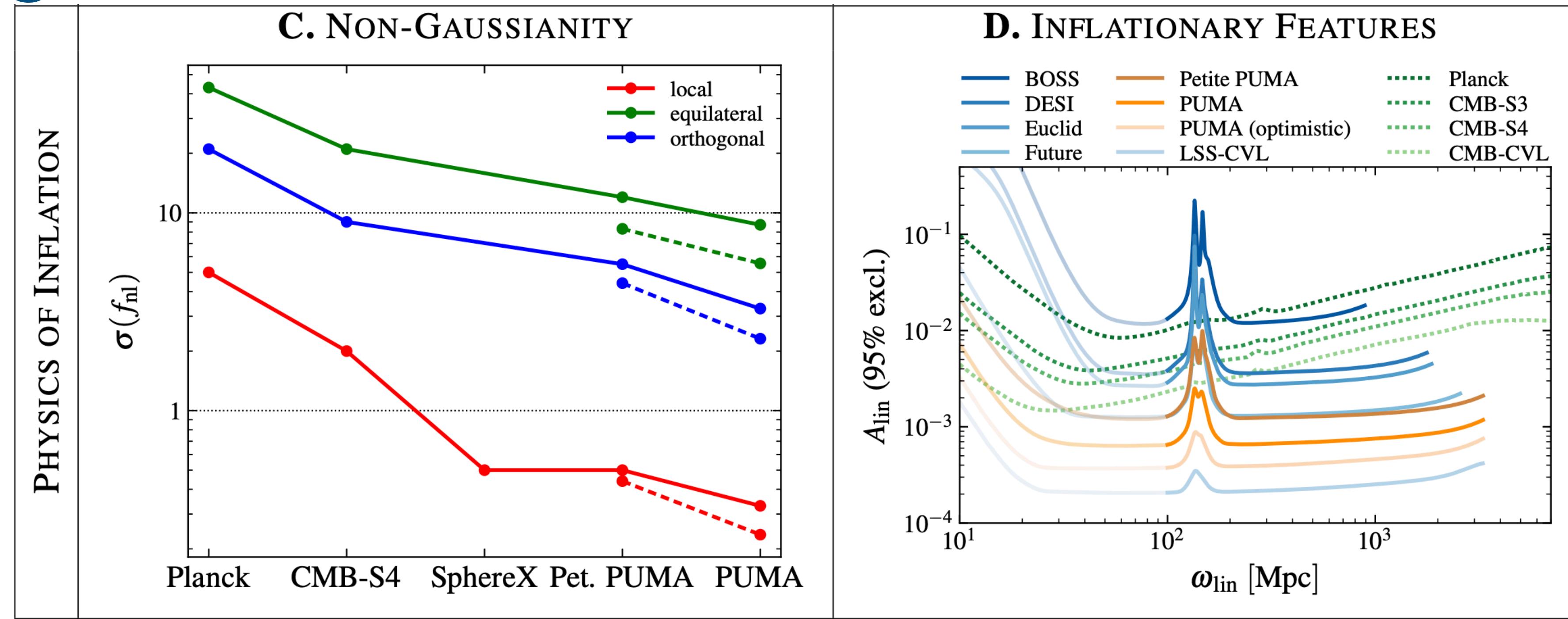
PUMA

~ 15-25 yrs.

21cm (neutral
hydrogen)
 $0.3 < z < 6$

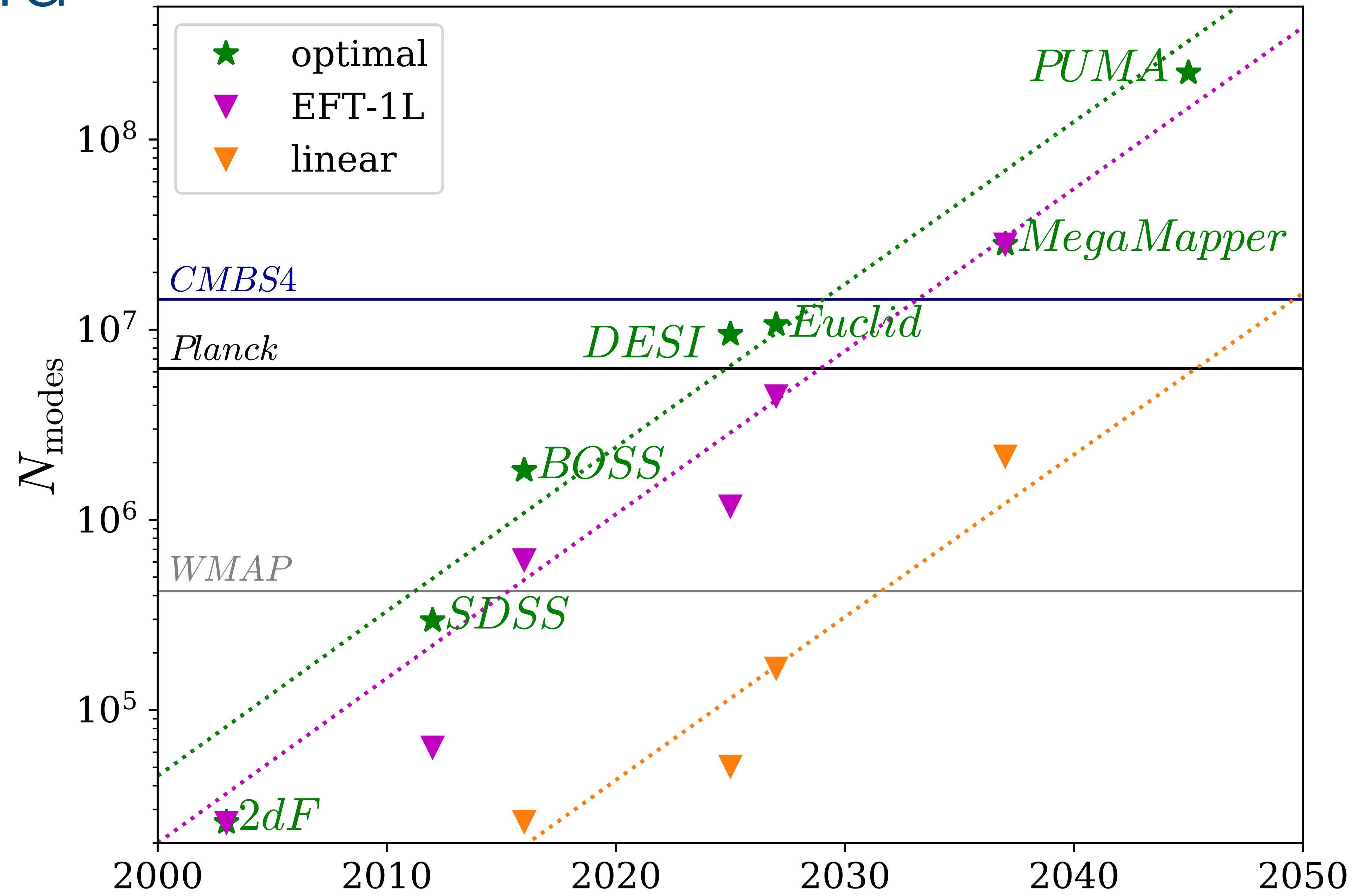
looking forward bright future for LSS

PUMA



looking forward

bright future for LSS



looking forward

bright future for LSS

preliminary forecasts
very very rough

work in progress

Y. Donath, L. Senatore, H. Zheng

$\sim \sigma$	PUMA	current
H_0	0.001	0.01
Ω_m	0.0005	0.02
$\sum m_\nu$	0.01	0.1
$f_{\text{NL}}^{\text{equil.}}$	20	47
$f_{\text{NL}}^{\text{orth.}}$	5	24
$f_{\text{NL}}^{\text{loc.}}$	0.5	5

long road of development

data
analysis

- precision
 - higher N-point,
 - higher loop,
 - integration
- positivity, EFT params
- theory models
- analysis, prior volume
- bias relations, physical priors

QCD
amplitudes
GW
particle physics
pheno

DESI
Euclid
simulations
machine learning

theory
data-forward

long road of development

Thank
You!

data analysis

- precision
 - higher N-point,
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QCD
amplitudes
GW
particle physics
pheno

DESI
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machine learning

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