Insights from

Galaxies at long distances

Pierre Zhang (ETH Zürich) | 6 Nov 2023 Trieste | New Physics from Galaxy Clustering II

Questions...

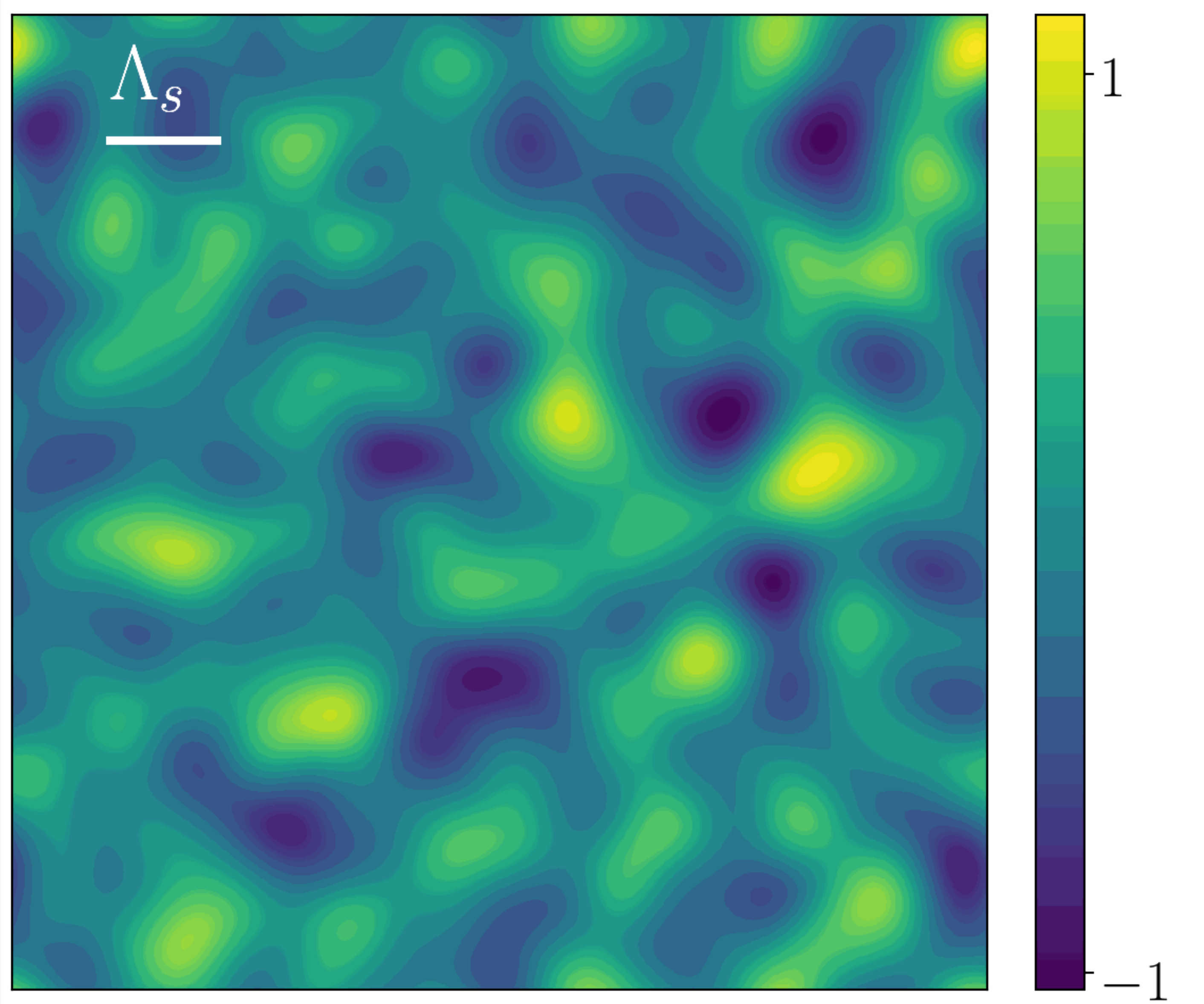
$$\mathcal{P}\left(* \middle| \text{map} \right) = ?$$

$*$: "(new) physics"

$$\mathcal{P}\left(* \middle| \delta \right) = ?$$

$$\delta(\mathbf{x}) \equiv \frac{\rho(\mathbf{x})}{\bar{\rho}} - 1$$

Cosmic maps have the answer?



Coarse-graining

$$\delta(\mathbf{k}) = \delta_\ell(\mathbf{k}) + \delta_s(\mathbf{k})$$
$$\delta_\ell(\mathbf{k}) = \delta(|\mathbf{k}| < \Lambda_s^{-1})$$

$$\delta_\ell(\mathbf{k}) \lesssim \mathcal{O}(1) \text{ for } k \lesssim k_{\rm nl}$$

$$(k < \Lambda_s^{-1} < k_{\rm nl})$$

In this talk

$$\mathcal{P}(\,*\,|\delta) \to \mathcal{P}(\,*\,|\delta_\ell) = ?$$

What can we learn

looking at galaxies from afar?

Plan

1. *Galaxies from afar*: an effective description at long distances
2. Cosmology with galaxies from afar: a *tour d'horizon*
3. *The higher, the better*: roads ahead

Looking at galaxies from afar

An effective description at long wavelength

Effective Field Theory of Large-Scale Structure

Baumann, Carrasco, Hertzberg, Nicolis, Pajer, Senatore, Zaldarriaga, ... 10-13

Looking from afar, we want to know fields describing matter, baryons, galaxies, etc., e.g. $\delta, \delta_b, \delta_g, v, \ldots$

Ingredients

- Dark matter: *Continuity* and *Euler equations* (coarse-grained)
- Gravity: *Poisson equation* $\partial^2\Phi \sim \delta$
- Symmetries: *Galilean invariance* $\mathbf{x} \to \mathbf{x} + \mathbf{n},\ \mathbf{v} \to \mathbf{v} + \partial_t \mathbf{n}$

Weinberg 03, Kehagias, Riotto, Peloso, Pietroni, Creminelli, Gleyzes, Noreña, Simonović, Vernizzi 13

Receipe

- Solve dark matter equations perturbatively
  - $\delta = \delta_1 + \delta_2 + \ldots$
- For unknowns, write down all terms allowed by the symmetries with free Wilson coefficients
  - $\delta_g = b_1\delta_1 + b_2\delta_2 + \ldots$
  - *Euler* $\sim \partial_i\partial_j\tau^{ij}/k_{\rm nl}^2,\ \tau^{ij} = \delta^{ij}c_1\delta_1 + \ldots$
- For UV-sensitive operators, add counterterms

Galaxies fluid expansion

McDonald 06-09, Angulo, Assassi, Baumann, Fasiello, Fujita, Green, Mirbabayi, Schmidt, Senatore, Vlah, Zaldarriaga, ... 14-16

$$\delta_g(\mathbf{x},t) = \int^t dt' \; f\Big(\partial_i\partial_j\Phi(\mathbf{x},t'), \partial_i v_j(\mathbf{x},t'), \partial_i/k_{\rm M}, \epsilon_{ij}(\mathbf{x},t'), \kappa_\star(t,t')\Big)$$

- fluctuations (equivalence principle) $\partial_i\partial_j\Phi, \partial_i v_j$
- gradients (spatial extension) $\partial_i/k_{\rm M}$
- stochasticity ϵ , . . .

- fluid expansion $\mathbf{x} \to \mathbf{x}_{\mathbf{fl}}(\mathbf{x},t,t')$
- time responses $\int^t dt' \; \kappa_\star(t,t')D(t')$, . . .

D'Amico, Donath, Lewandowski, Senatore, Zhang (DDLSZ) 22

Up to 4^{th} order, equivalent to *local-in-time* expansion

$$\delta_g(\mathbf{x},t) = \quad f\Big(\partial_i\partial_j\Phi(\mathbf{x},t), \partial_i v_j(\mathbf{x},t), \partial_i/k_{\rm M}, \epsilon_{ij}(\mathbf{x},t), \kappa_\star(t)\Big)$$

End of the day: $\delta_g(\mathbf{x},t) = \sum_\alpha b_\alpha(t)\mathcal{O}^\alpha[\delta_1(\mathbf{x},t)]$

Summary, part 1

EFTofLSS

- organizes the fields expansion into fluctuations, gradients, etc.
- captures unknowns into free coefficients
- includes redshift-space distortions, IR displacements, baryons, massive neutrinos

Pros

- robust (parametric control)
- flexible (analytic)

Cons

- mildly nonlinear scales only
- many parameters

Tour d'horizon

Cosmology with galaxies at long distances

ΛCDM

Given an observation $\hat{\delta}_g$, what cosmology Ω can we learn, i.e. $\mathcal{P}(\Omega|\hat{\delta}_g)$?

$$\delta_g \sim b_1(t)\delta_1(\mathbf{x},t) + b_{\rm nl}(t)\delta_{\rm nl}(\mathbf{x},t) + f(t)b_{\rm rs}(t)\delta_{\rm rs}(\mathbf{x},t) + \ldots$$

- linear perturbations $\delta_1(\Omega)$ + nonlinear perturbations $\delta_{\rm nl}[\delta_1(\Omega)]$
- redshift-space distortions $f(\Omega)$, $\delta_{\rm rs}[\delta_1(\Omega)]$

In practice

PyBird, CLASS-PT, Velocileptor, FAST-PT, ...

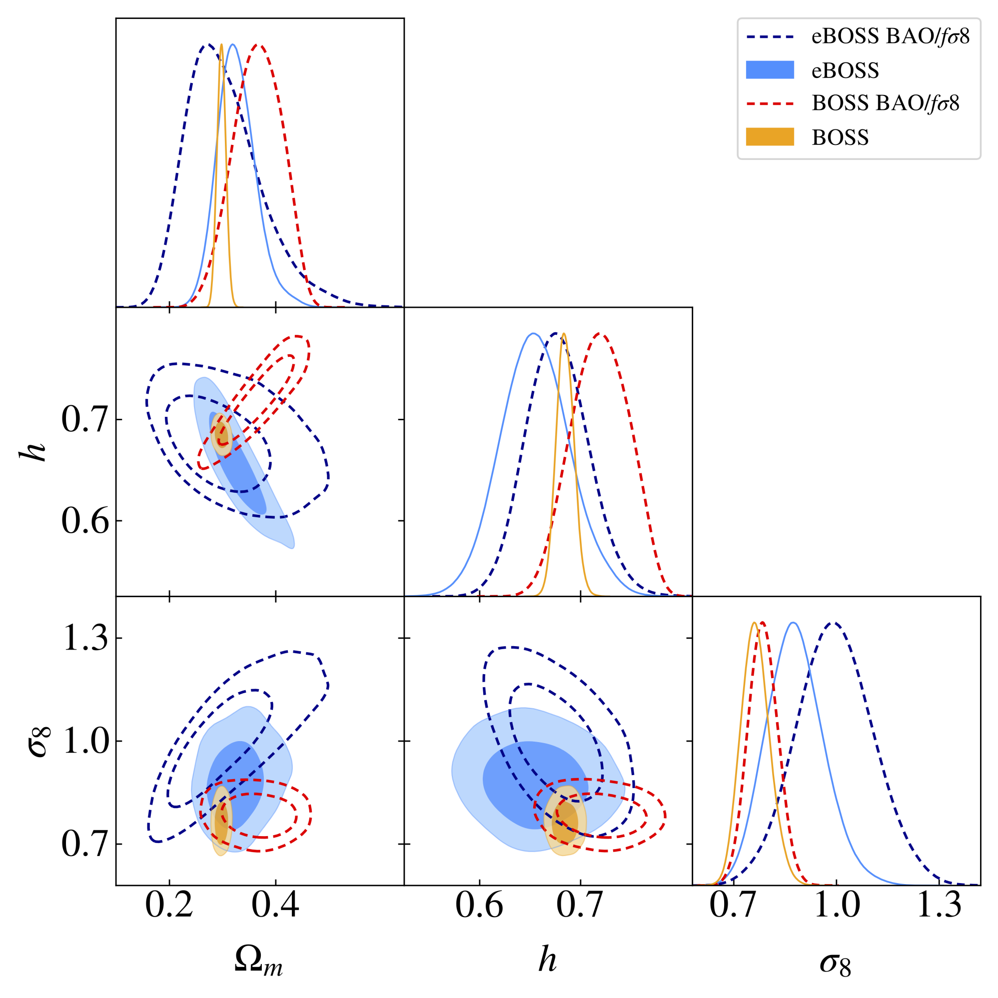
- Compute N-point functions, e.g. $\langle \delta_g(\mathbf{x_1})\delta_g(\mathbf{x_2})\rangle$, $\langle \delta_g(\mathbf{x_1})\delta_g(\mathbf{x_2})\delta_g(\mathbf{x_3})\rangle$ ...
- Explore likelihood $\mathcal{L}(\langle\hat{\delta}_g\hat{\delta}_g\rangle, \langle\hat{\delta}_g\hat{\delta}_g\hat{\delta}_g\rangle|\Omega)$

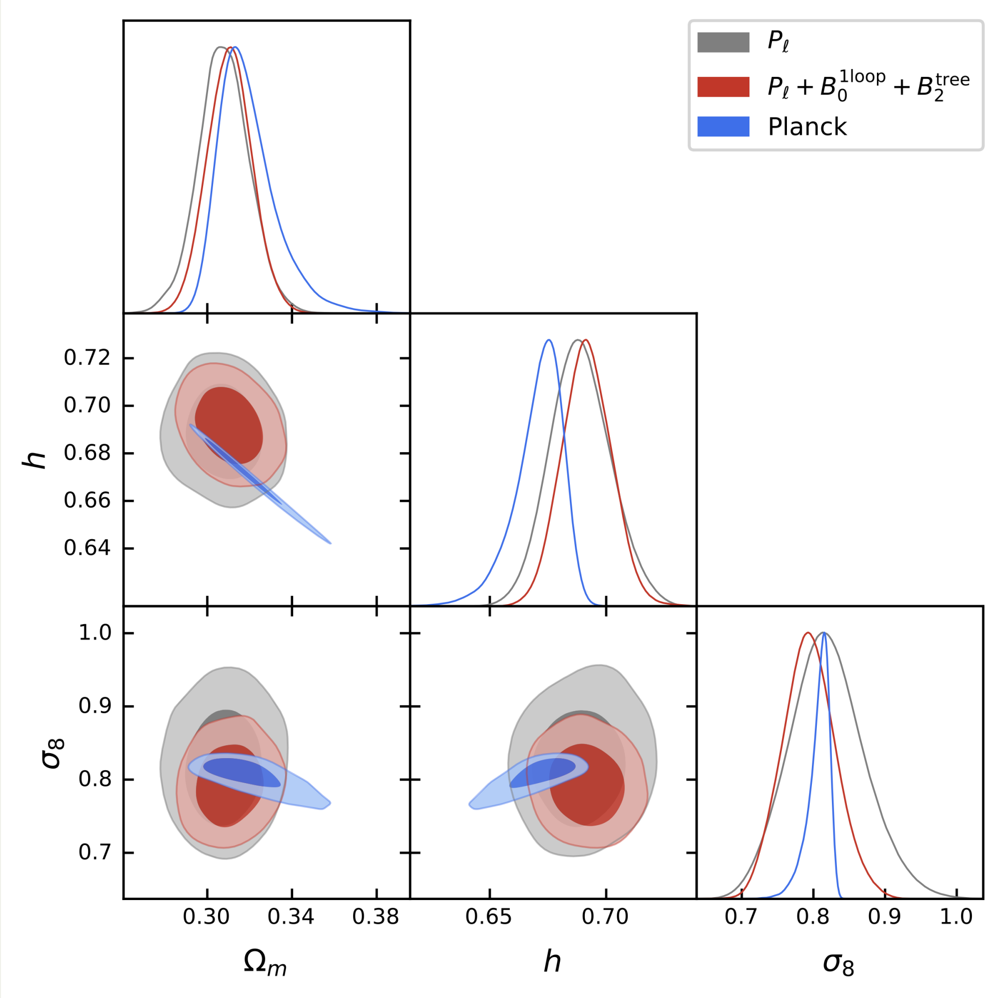
c.f. talks Ivana Babic & Beatriz Tucci?

- Alternative: field-level inference $\mathcal{L}(\hat{\delta}_g|\Omega)$

ΛCDM from (e)BOSS galaxies

Chen, Chudaykin, D'Amico, Ivanov, Kokron, Philcox, Senatore, Simonovic, Vlah, White, Zaldarriaga, Zhang, ... 19-23





$\mathcal{L}(\langle\hat{\delta}_g\hat{\delta}_g\rangle\,|\Omega)$, δ_g up to 3rd order

Simon, Zhang, Poulin 22

$\mathcal{L}(\langle\hat{\delta}_g\hat{\delta}_g\rangle\,,\langle\hat{\delta}_g\hat{\delta}_g\hat{\delta}_g\rangle\,|\Omega)$, δ_g up to 4th order

D'Amico, Donath, Lewandowski, Senatore, Zhang 22

Dark energy and modified gravity

Given an observation $\hat{\delta}_g$, what cosmology Ω can we learn, i.e. $\mathcal{P}(\Omega|\hat{\delta}_g)$?

$$\delta_g \sim b_1 D(t)\delta_1 + b_{\rm nl} g_{\rm nl}(t)\delta_{\rm nl} + f(t) b_{\rm rs} g_{\rm rs}(t)\delta_{\rm rs} + \ldots$$

D'Amico, Donath, Fujita, Lewandowski, Marinucci, Pietroni, Piga, Senatore, Vernizzi, Vlah, Zhang, ... 15-23

c.f. talk Marco Marinucci?

- Generalized nonlinear time evolution $g_{\rm nl}(\Omega)$, $g_{\rm rs}(\Omega)$
- (EFTofDE) $\partial^2\Phi \sim \mu_1\delta + \mu_2\delta^2 + \ldots$

New physics (long range)

Given an observation $\hat{\delta}_g$, what cosmology Ω can we learn, i.e. $\mathcal{P}(\Omega|\hat{\delta}_g)$?

$$\delta_g \sim b_1\delta_1 + b_{\rm nl}\delta_{\rm nl} + f b_{\rm rs}\delta_{\rm rs} + b_*\delta_*$$

- Primordial non-Gaussianity
  - (single-field Inflation) $f_{\rm NL}\phi^2$
  - (multi-field Inflation) Scale-dependent bias $b_\phi f_{\rm NL}\partial^{-2}\delta_1$

Lewandowski 19, Bottaro, Castorina, Costa, Redigolo, Salvioni 23

c.f. talks Salvatore Bottaro & Marco Costa

- Dark long-range force, beyond Horndeski ...
  - Galilean invariance breaking terms $\delta_*[\delta_1, *]$

Dark matter

Given an observation $\hat{\delta}_g$, what cosmology Ω can we learn, i.e. $\mathcal{P}(\Omega|\hat{\delta}_g)$?

$$\delta_g \sim b_1\delta_1 + b_{\rm nl}\delta_{\rm nl} + f b_{\rm rs}\delta_{\rm rs}$$

Kousha, Hooshangi, Abolhasani 23

- Speed-of-sound $c_s^2(t)$: $\delta \supset c_s^2\, \partial^2\delta_1/k_{\rm nl}^2$
  - cold or not cold? comparison with simulations
  - *Issue*: degenerate with $\partial^2\delta_1/k_{\rm M}^2$, $\partial^2\delta_1/k_{\rm rs}^2$, . . .

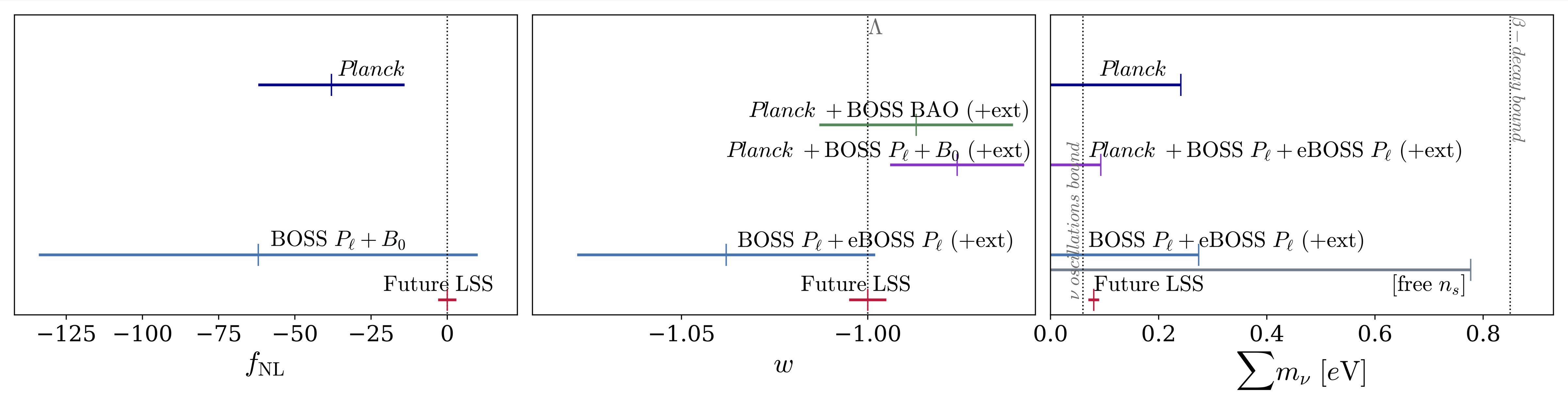
DDLSZ 22, Donath, Lewandowski, Senatore 23

Non-locality-in-time (NLT)

- Clear window onto dark matter from galaxies *in redshift space*
  - via NLT (non degenerate) counterterms *at* 2^{nd} *order* (4^{th} *order* in fluctuations)
- Age of the Universe from signature of galaxies formation time
  - via NLT operators *at* 5^{th} *order* in fluctuations *in real space*

One-loop cosmology: today and tomorrow

D'Amico, Lewandowski, Senatore, Zhang 22
Simon, Zhang, Poulin 22
Bragança, Donath, Senatore, Zheng 23
Spaar, Zhang (to appear)



	$\sigma(f_{\rm NL}^{\rm or})$	$\sigma(f_{\rm NL}^{\rm eq})$
Planck	24	47
BOSS $P_\ell + B_0$	72	293
Future $P_\ell + B_0$	4	16

[ext: eBOSS Ly-α BAO + Pantheon SN]

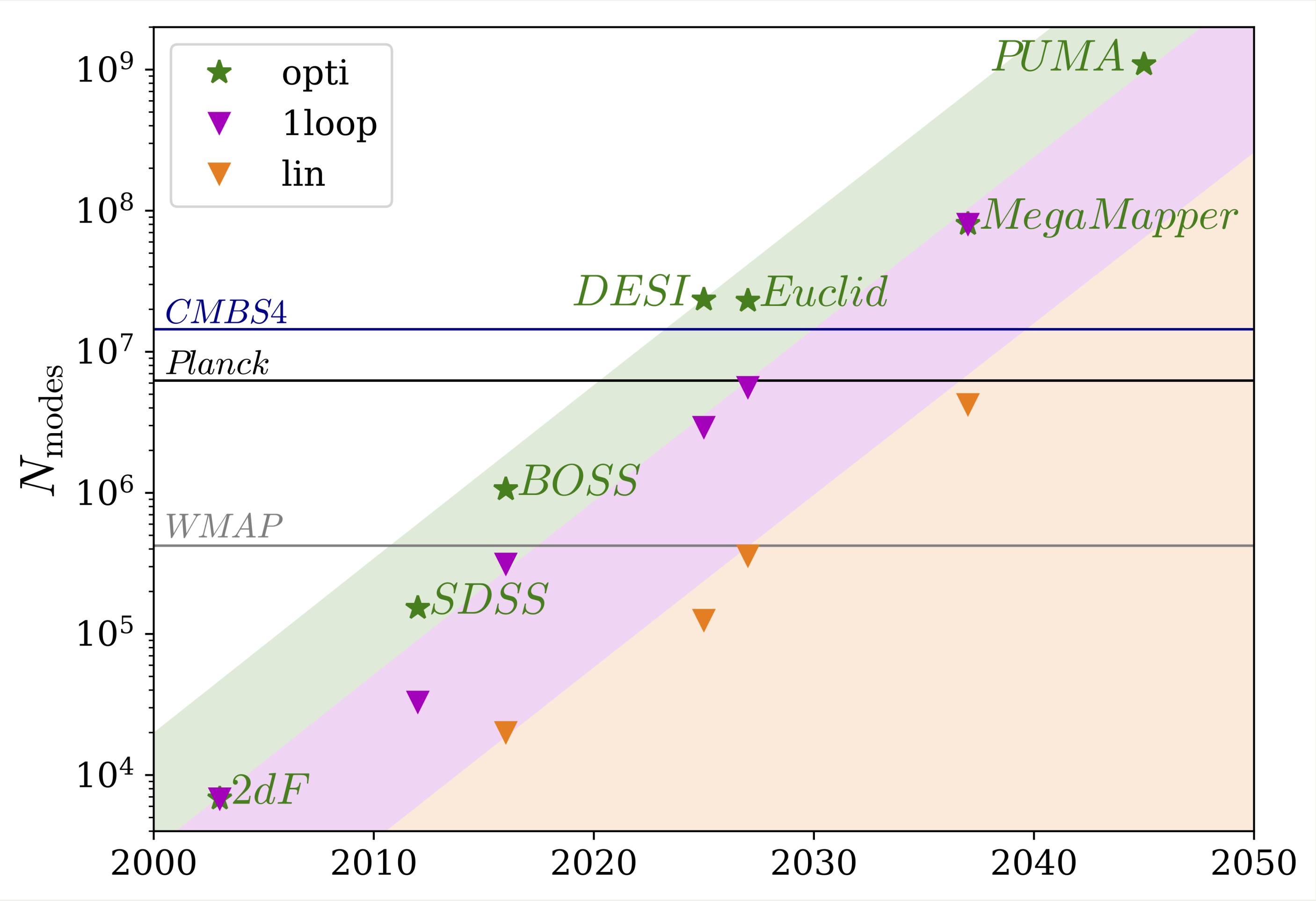
	$\sigma(w)$ [%]
Planck + BOSS BAO + ext	2.6
Planck + BOSS $P_\ell + B_0$ + ext	1.9
BOSS P_ℓ + eBOSS P_ℓ + ext	4.1
Future $P_\ell + B_0$	0.5

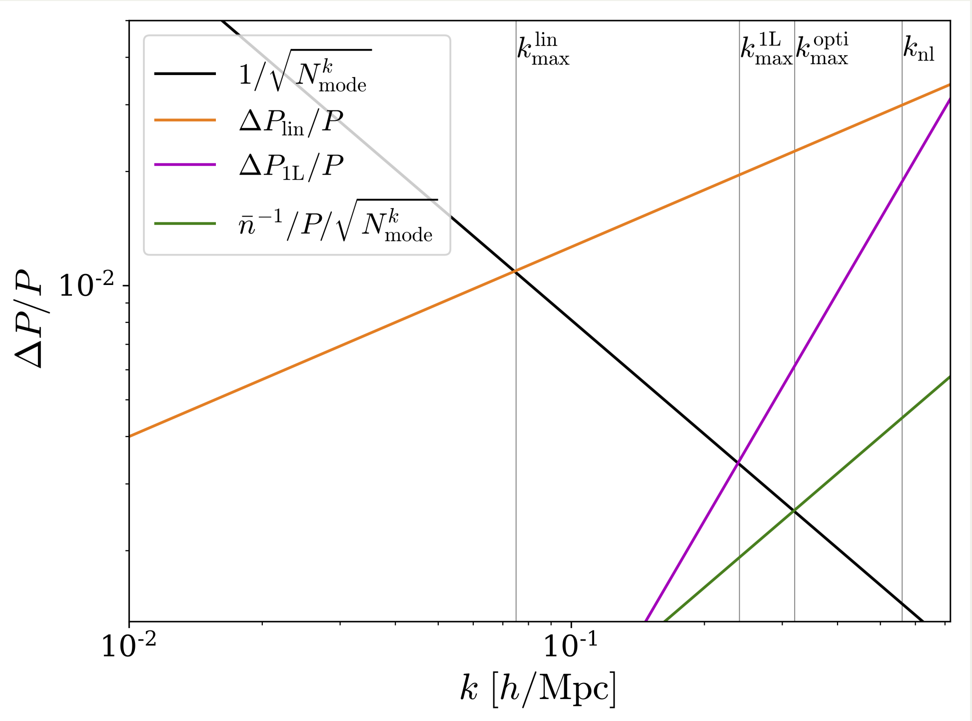
	$\sigma(\sum m_\nu)$
Planck	0.24 ($< 2\sigma$)
Planck BOSS P_ℓ + eBOSS P_ℓ + ext	0.09 ($< 2\sigma$)
BOSS P_ℓ + eBOSS P_ℓ + ext	0.26 ($< 2\sigma$)
Future $P_\ell + B_0$	0.01

The higher, the better

Roads ahead

The higher, the better (1)





$$N_{\rm modes}({\rm CMB}) \sim (\ell_{\rm max})^2$$
$$N^{\diamond}_{\rm modes}({\rm LSS}) \sim V_{\rm survey}(k^{\diamond}_{\rm max})^3/(6\pi^2)$$
$$\diamond = \text{optimal, 1loop, linear}$$

One loop: not yet optimal!

Final words

- **EFTofLSS**
  - *Robust*: galaxies meet precision cosmology
  - *Flexible*: great to include new physics !
  - *Caveat*: mainly long range
- **Cosmology**: a large menu
  - Next-decade BIG targets: $\sum m_\nu$ detection, $\sigma(w) < 1\%$, $\sigma(f_{\rm NL}) \sim \mathcal{O}(1-10)$.
  - Modified gravity, Inflation, dark matter, ...
    - Systematic inclusion (on going)
    - EFT $\leftrightarrow$ UV dictionary?
- **Roads ahead**
  - No *loops*, no chocolate: push theory, we are not yet here
  - No *measures*, no chocolate: new ways to look at data (forward model, estimators)?

Thank you!

Supplements

Redshift space

Lewandowski, Perko, Senatore, Zaldarriaga, ... 14-16, DDLSZ22

Change of coordinates $\mathbf{x} \to \mathbf{x} + (\mathbf{v}_{\mathcal{H}} \cdot \hat{z})\hat{z} \qquad (\mathbf{v}_{\mathcal{H}} \equiv \mathbf{v}/\mathcal{H})$

$$\delta \to \delta + \hat{z}^i \hat{z}^j \partial_i((1+\delta)v^j_{\mathcal{H}}) + \frac{1}{2}\hat{z}^i \hat{z}^j \hat{z}^k \hat{z}^l \partial_i \partial_j ((1+\delta)v^k_{\mathcal{H}} v^l_{\mathcal{H}}) + \ldots$$

Contact term renormalization, e.g. $\delta v^i_{\mathcal{H}} \supset c_{\rm rs}\ \partial_i \delta_1 / k^2_{\rm rs}$

Large IR displacements

Matsubara 07-08, Aviles, Baldauf, Blah, Garny, Ivanov, Lewandowski, Mirbabayi, Porto, Senatore, Seljak, Sibiryakov, Simonovic, Vlah, White, Zaldarriaga, ... 13-16

Lagrangian picture $\mathbf{x}_L(t) = \mathbf{x}(t) + \psi(\mathbf{x}, t)\,, \quad \psi = \psi_1 + \psi_2 + \ldots$

$$\psi_{\ell_{\rm BAO}} \equiv \psi\left(|\mathbf{k}| < 2\pi/\ell_{\rm BAO}\right) \sim \mathcal{O}(1)! \quad (\ell_{\rm BAO} \sim 100\ \mathrm{Mpc}/h)$$

$\psi_{\ell_{\rm BAO}} \simeq \psi_1$: keep **large** displacements ψ_1 , expand in ψ_2 , . . .

$$\delta_g(\mathbf{x}_L) = b_1\delta_1(\mathbf{x}_L) + b_2\delta_2(\mathbf{x}_L) + \ldots$$

$$= b_1\delta_1(\mathbf{x} + \psi_1) + b_1\psi_2^i\,\partial_i\delta_1(\mathbf{x}) + b_2\delta_2(\mathbf{x} + \psi_1) + \ldots$$

$$= b_1\delta_1(\mathbf{x} + \psi_1) + b_2'\delta_2(\mathbf{x} + \psi_1) + \ldots$$

- $\psi_1^i = \frac{\partial_i}{\partial^2}\delta_1\,, \psi_2^i = \frac{\partial_i}{\partial^2}\delta_2\,, \ldots$

$$\delta_g(\mathbf{x}) \to \delta_g(\mathbf{x} + \psi_1)$$

f_{NL} from BOSS 2pt+3pt

[One-loop] D'Amico, Lewandowski, Senatore, Zhang 22 | *[Tree-level] Cabass, Ivanov, Philcox, Simonovic, Zaldarriaga 22

	$\sigma(f_{\mathrm{NL}}^{\mathrm{or}})$	$\sigma(f_{\mathrm{NL}}^{\mathrm{eq}})$
Tree-level	136	437
*Tree-level, b_2 fixed	120	300
One-loop	72	293
One-loop, b_2 fixed	53	209

The higher, the better (2)

- The deeper we dive, the more nonlinear the Universe appears, i.e.
  - As we approach the nonlinear scale $k \to k_{\rm nl}$,
    - higher-order corrections δ_n becomes $\sim \mathcal{O}(1)$ of linear δ_1
  - **… So does the importance of higher-order N-point functions with respect to the two-point!**
    - e.g. $\langle \delta\delta\delta \rangle \sim \langle \delta\delta \rangle$, etc.

$$r \equiv \frac{\mathrm{SNR}(3pt)}{\mathrm{SNR}(2pt)} \sim \frac{8\pi}{3}\left(\frac{k_{\rm max}}{k_{\rm nl}}\right)^3$$

$$r \sim \frac{8\pi}{3}\frac{1}{(2\pi)^3}\left(\frac{k_{\rm max}}{k_{\rm nl}}\right)^2 k_{\rm max}^3\, P(k_{\rm max}) \;, \qquad P(k) \sim (2\pi)^3\left(\frac{1}{k_{\rm nl}}\right)^3\left(\frac{k}{k_{\rm nl}}\right)^n$$

- Tree-level: $k_{\rm max}/k_{\rm nl} \sim 0.2$, $\quad r \sim 0.1 \quad \to \quad \sigma_{2pt+3pt}/\sigma_{2pt} \sim 95\%$
- 1-loop: $k_{\rm max}/k_{\rm nl} \sim 0.5$, $\quad r \sim 1.0 \quad \to \quad \sigma_{2pt+3pt}/\sigma_{2pt} \sim 70\%$

If shot noise, could be that [1-loop 4pt] > [2-loop 2pt] !