

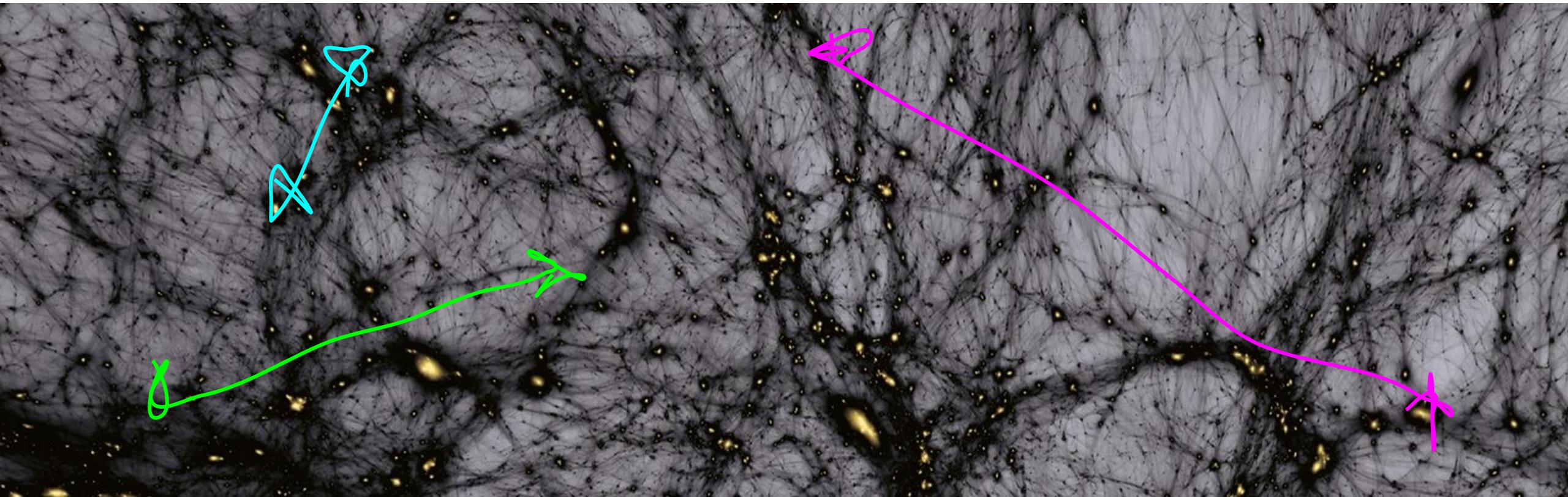
Cosmological inference from the **Effective Field Theory of Large-Scale Structure**

Pierre Zhang - ETH Zurich

January the 17th, 2023 | GDR CoPhy

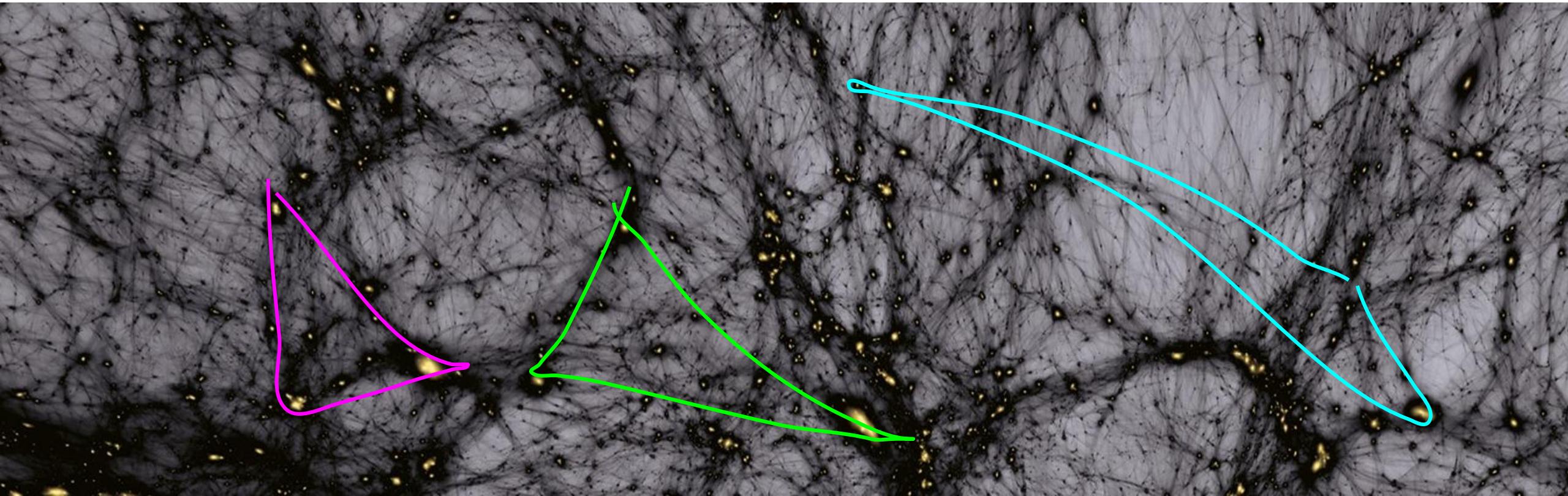
Game I

2pt function / power spectrum

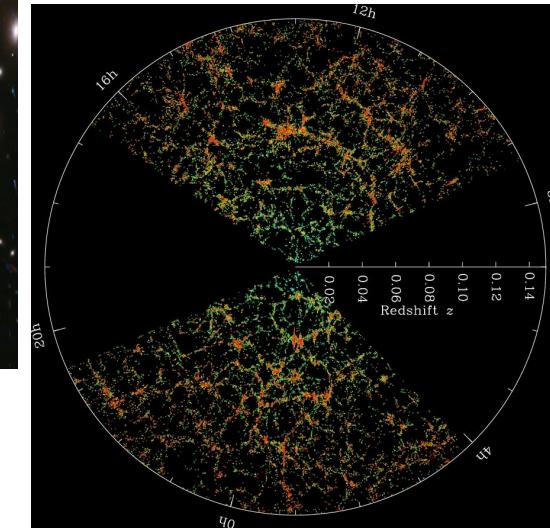
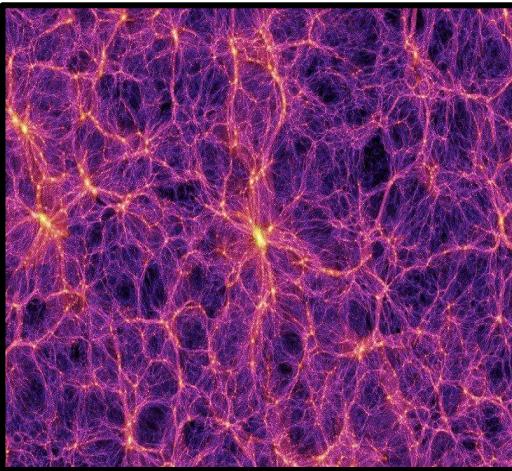


Game II

3pt function / bispectrum



The Playbook



$$\zeta(\mathbf{x})$$

Perturbation theory
N-body simulations

$$\delta(\mathbf{x})$$

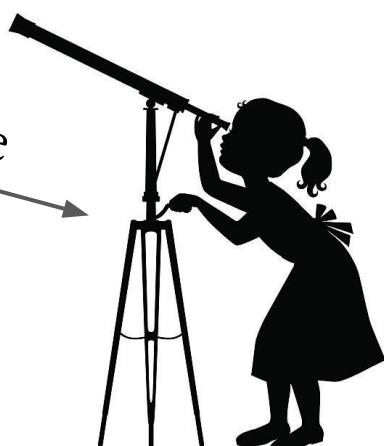
Tracers biases

$$\delta_g(\mathbf{x})$$

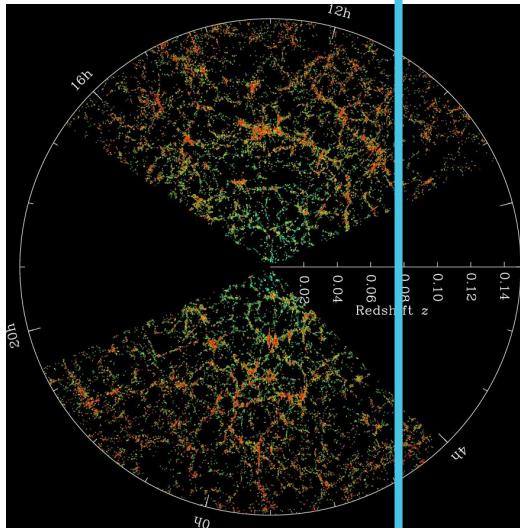
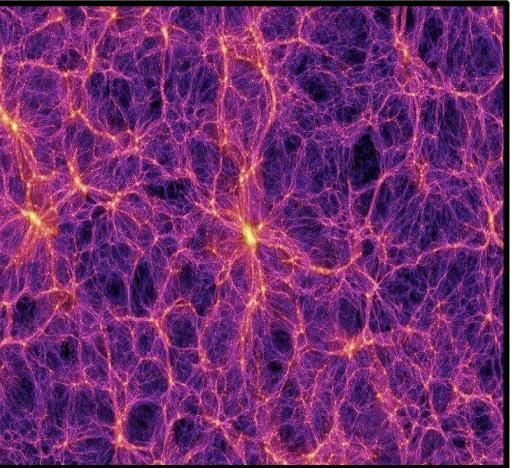
Redshift space
distortions

$$\delta_g(z)$$

Time



I. Effective Field Theory of Large-Scale Structure



$$\zeta(\mathbf{x})$$

Perturbation theory $\delta(\mathbf{x})$

Tracers biases $\delta_g(\mathbf{x})$

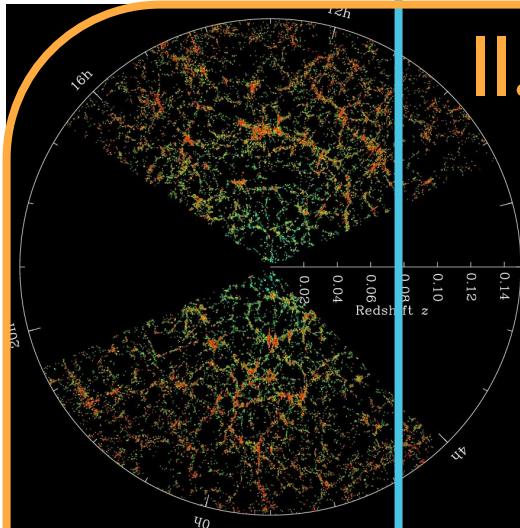
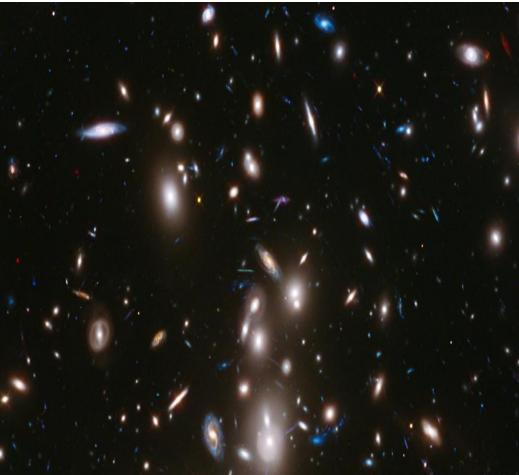
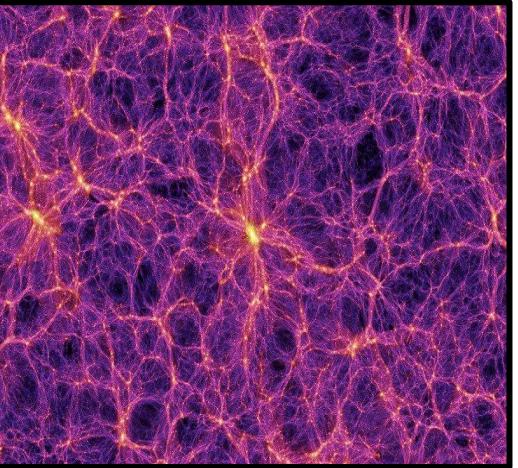
Redshift space
distortions $\delta_g(z)$

Time





I. Effective Field Theory of Large-Scale Structure



$$\zeta(\mathbf{x})$$

Perturbation theory

$$\delta(\mathbf{x})$$

Tracers biases

$$\delta_g(\mathbf{x})$$

Redshift space
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$$\delta_g(z)$$

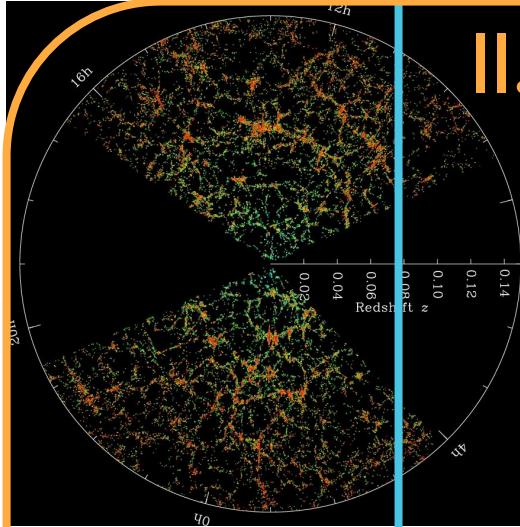
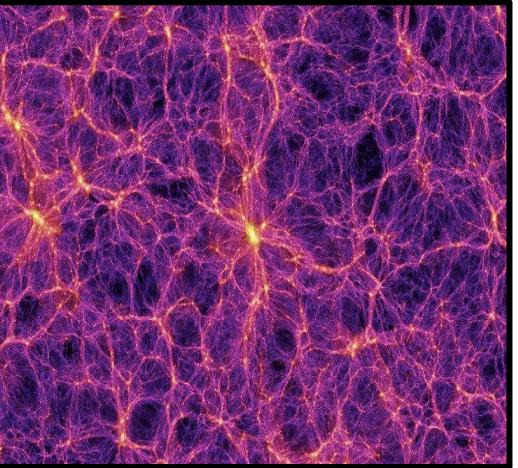
Time



II. Analysis Pipeline



I. Effective Field Theory of Large-Scale Structure



$$\zeta(\mathbf{x})$$

Perturbation theory

$$\delta(\mathbf{x})$$

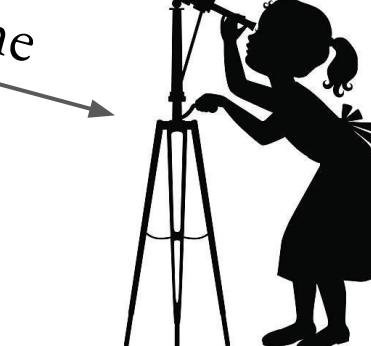
Tracers biases

$$\delta_g(\mathbf{x})$$

Redshift space
distortions

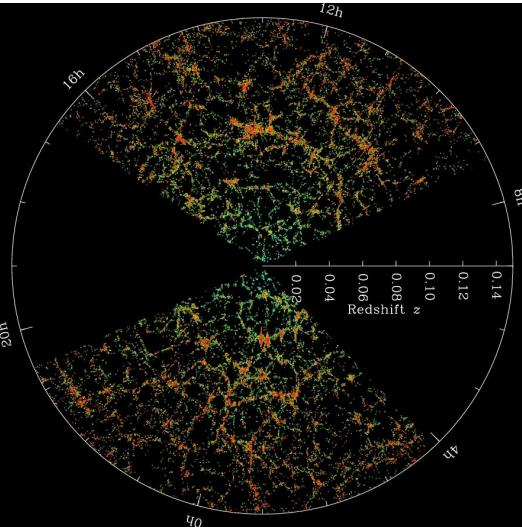
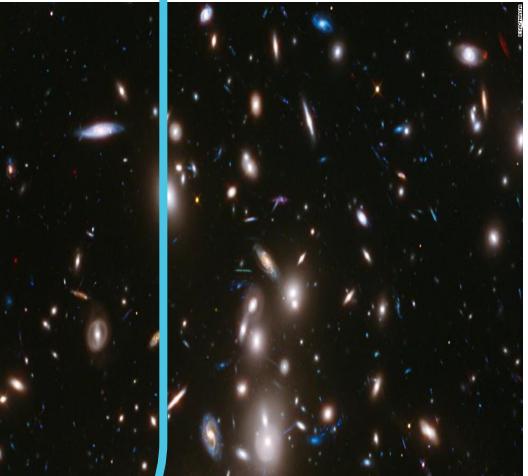
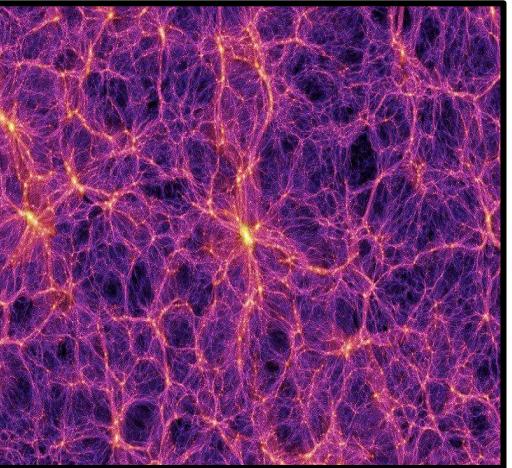
$$\delta_g(z)$$

II. Analysis Pipeline



III. Cosmological results

I. Effective Field Theory of Large-Scale Structure



$$\zeta(\mathbf{x})$$

Perturbation theory

$$\delta(\mathbf{x})$$

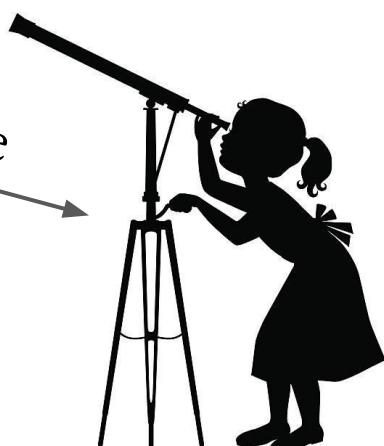
Tracers biases

$$\delta_g(\mathbf{x})$$

Redshift space
distortions

$$\delta_g(z)$$

Time



Perturbation Theory of Large-Scale Structure

Dark matter: equations of motions

See review by Bernardeau, Colombi, Gaztanaga, Scoccimarro 01

Variables

Density

$$\rho(\boldsymbol{x}, a) = \bar{\rho}(a)(1 + \delta(\boldsymbol{x}, a))$$

Velocity

$$v^i(\boldsymbol{x}, a)$$

Perturbation Theory of Large-Scale Structure

Dark matter: equations of motions

See review by Bernardeau, Colombi, Gaztanaga, Scoccimarro 01

$$\partial^2 \Phi = \frac{3}{2} \mathcal{H}^2 \Omega_m \delta$$

Poisson equation

$$\dot{\delta} + \frac{1}{a} \partial_i ((1 + \delta) v^i) = 0$$

Energy conservation

$$\dot{v}^i + H v^i + \frac{1}{a} v^j \partial_j v^i + \frac{1}{a} \partial_i \Phi = 0$$

Momentum conservation

$$\rho(\mathbf{x}, a) = \bar{\rho}(a)(1 + \delta(\mathbf{x}, a))$$

$$v^i(\mathbf{x}, a)$$

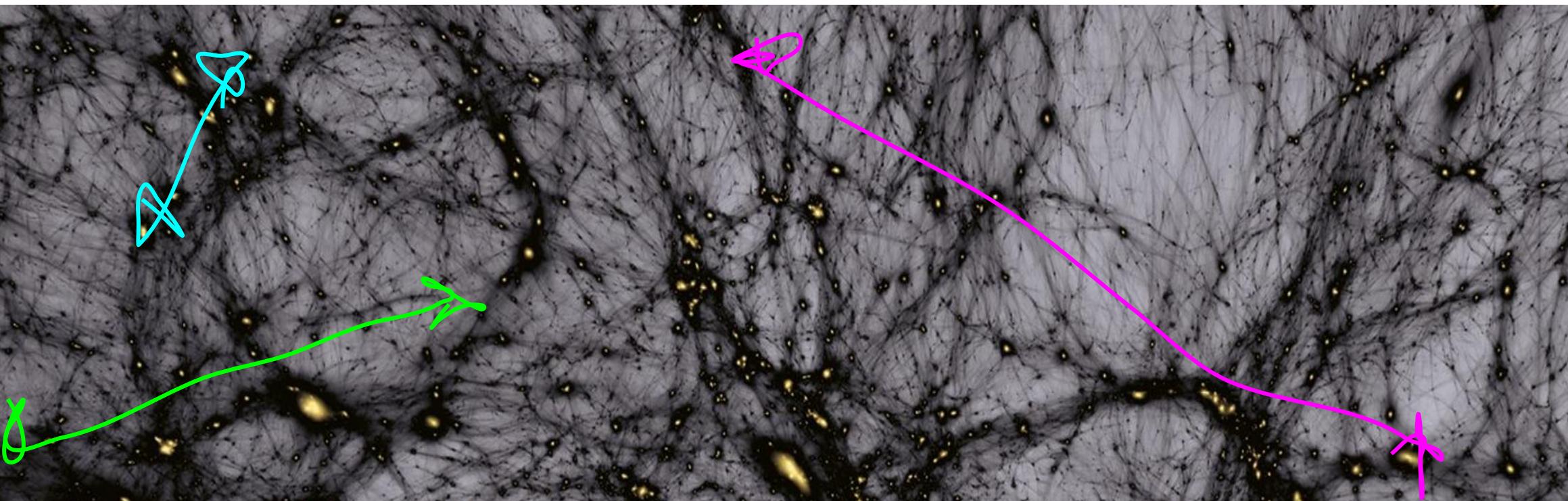
Perturbation Theory of Large-Scale Structure

Dark matter: Power Spectrum

See review by Bernardeau, Colombi, Gaztanaga, Scoccimarro 01

$$\partial^2 \Phi = \frac{3}{2} \mathcal{H}^2 \Omega_m \delta$$

$$\langle \delta(\mathbf{k}, a) \delta(\mathbf{k}', a) \rangle = (2\pi)^3 \delta_D(\mathbf{k} + \mathbf{k}') P_{mm}(k, a)$$



Perturbation Theory of Large-Scale Structure

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$$\dot{\delta} + \frac{1}{a} \partial_i ((1 + \delta) v^i) = 0$$

$$\dot{v}^i + H v^i + \frac{1}{a} v^j \partial_j v^i + \frac{1}{a} \partial_i \Phi = 0$$

$$P_{mm}(k, a) = a^2 P_{11}(k)$$

Perturbation Theory of Large-Scale Structure

Dark matter: One-loop Power Spectrum

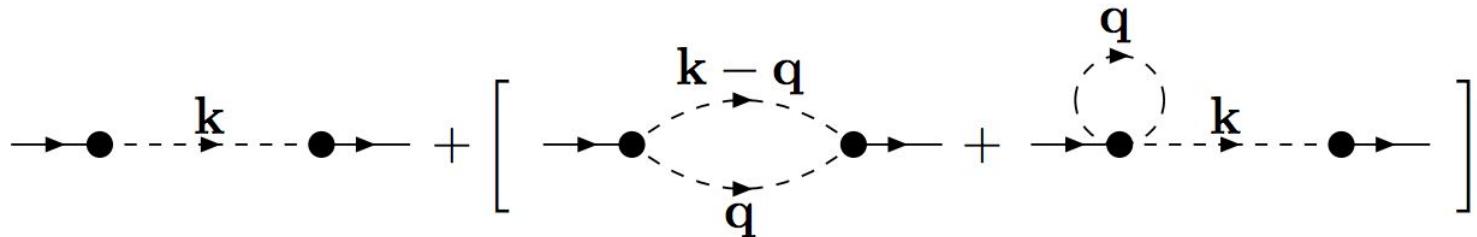
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$$P_{mm}(k, a) = a^2 P_{11}(k) + a^4 P_{22-13}(k)$$



(P_{11})

(P_{22})

(P_{13})

Perturbation
Theory
treatment

$$P_{22} = 2 \int d^3 q [F_2(\mathbf{k} - \mathbf{q}, q)]^2 P_{11}(|\mathbf{k} - \mathbf{q}|) P_{11}(q)$$

$$P_{13} = 6 \int d^3 q F_3(\mathbf{k}, \mathbf{q}, -\mathbf{q}) P_{11}(k) P_{11}(q),$$

Perturbation Theory of Large-Scale Structure

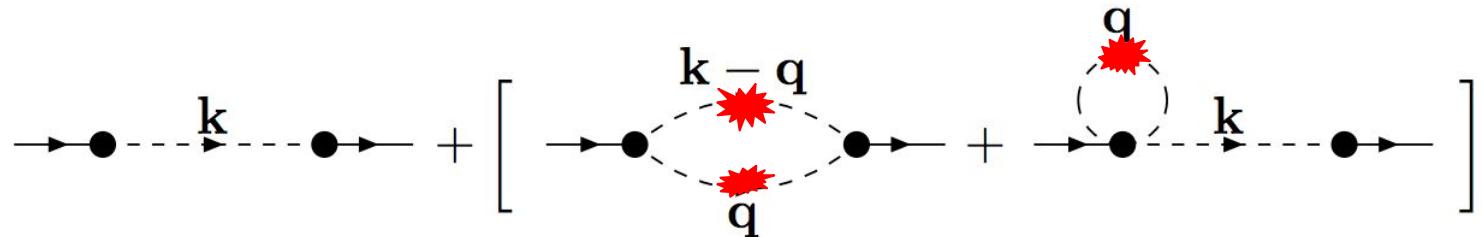
Dark matter: One-loop Power Spectrum

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(P_{11})

(P_{22})

(P_{13})

But divergent integrals !

Perturbation
Theory
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Early regularisation:

Scoccimarro & Friedman, Jain & Bertschinger 96
Bernardeau, Crocce, Scoccimarro, Pietroni, Valageas 06-08

Perturbation Theory of Large-Scale Structure

Dark matter: equations of motions

$$\partial^2 \Phi = \frac{3}{2} \mathcal{H}^2 \Omega_m \delta$$

$$\delta(\mathbf{k}) \equiv \delta_\ell(\mathbf{k}) + \delta_s(\mathbf{k})$$

$$\dot{\delta} + \frac{1}{a} \partial_i ((1 + \delta) v^i) = 0$$

$$\dot{v}^i + H v^i + \frac{1}{a} v^j \partial_j v^i + \frac{1}{a} \partial_i \Phi = 0$$

$$P_{mm}(k, a) = a^2 P_{11}(k) + a^4 P_{22-13}(k)$$

$$\delta_\ell(\mathbf{k}) = \begin{cases} \delta(\mathbf{k}) & \text{if } k < \Lambda^{-1} \sim k_{\text{NL}} \\ 0 & \text{otherwise} \end{cases}$$

Effective Field Theory of Large-Scale Structure

Dark matter: equations of motions

Baumann, Nicolis, Senatore, Zaldarriaga 10
Carrasco, Hertzberg, Senatore 12

$$\partial^2 \Phi_\ell = \frac{3}{2} \mathcal{H}^2 \Omega_m \delta_\ell$$

$$\dot{\delta}_\ell + \frac{1}{a} \partial_i ((1 + \delta_\ell) v_\ell^i) = 0$$

$$\dot{v}_\ell^i + H v_\ell^i + \frac{1}{a} v^j \partial_j v_\ell^i + \frac{1}{a} \partial_i \Phi_\ell = -\frac{1}{a} \partial_i \left(\frac{1}{\rho_\ell} \partial_j \tau^{ij} \right)_s$$

Coarse-graining

$$\delta(\mathbf{k}) \equiv \delta_\ell(\mathbf{k}) + \delta_s(\mathbf{k})$$

$$P_{mm}(k, a) = a^2 P_{11}(k) + a^4 P_{22-13}(k)$$

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Coarse-graining

$$\delta(\mathbf{k}) \equiv \delta_\ell(\mathbf{k}) + \delta_s(\mathbf{k})$$

leads to a

Stress tensor
enclosing short-distance physics

for the long-distance fluid

$$P_{mm}(k, a) = a^2 P_{11}(k) + a^4 P_{22-13}(k)$$

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Coarse-graining

$$\delta(\mathbf{k}) \equiv \delta_\ell(\mathbf{k}) + \delta_s(\mathbf{k})$$

EFT expansion = Gradient expansion

$$P_{mm}(k, a) = a^2 P_{11}(k) + a^4 P_{22-13}(k)$$

Effective Field Theory of Large-Scale Structure

Dark matter: one-loop power spectrum

Baumann, Nicolis, Senatore, Zaldarriaga 10
Carrasco, Hertzberg, Senatore 12

$$\partial^2 \Phi_\ell = \frac{3}{2} \mathcal{H}^2 \Omega_m \delta_\ell$$

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Coarse-graining

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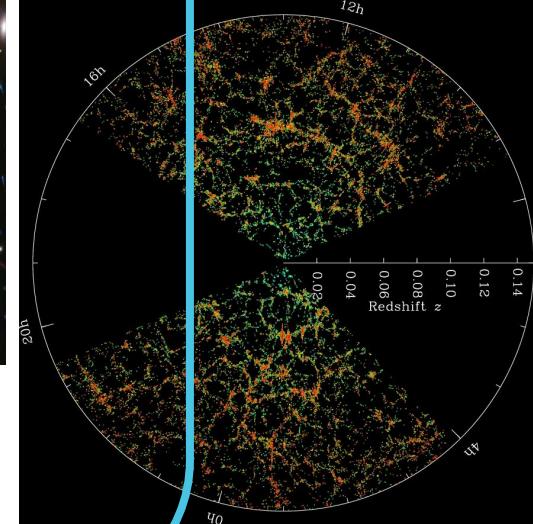
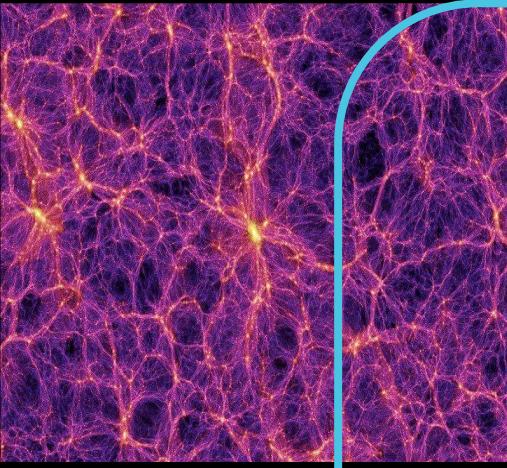
EFT expansion = Gradient expansion

Renormalization

$$P_{mm}(k, a) = a^2 P_{11}(k) + a^4 P_{22-13}(k) + c_s^2(a) \frac{k^2}{k_{\text{NL}}^2} P_{11}(k)$$



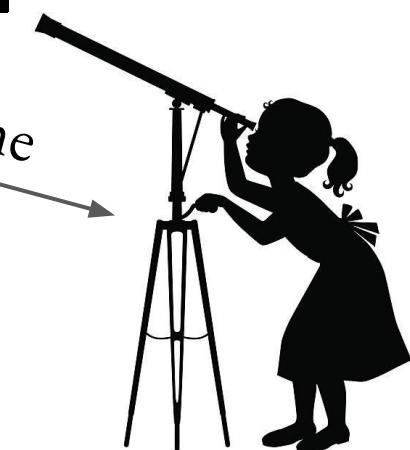
I. Effective Field Theory of Large-Scale Structure



$$\zeta(\mathbf{x}) \xrightarrow{\text{Perturbation theory}} \delta(\mathbf{x})$$

$$\xrightarrow{\text{Tracers biases}} \delta_g(\mathbf{x})$$

$$\xrightarrow{\text{Redshift space distortions}} \delta_g(z)$$



Effective Field Theory of Large-Scale Structure

Galaxy: expansions in *fluctuations* ...

McDonald, & Roy, 06, 10

Senatore 14

Mirbabayi, Schmidt, Zaldarriaga 14

- EFT expansion of galaxy overdensity:

$$\delta_g(\mathbf{x}, \tau) = F\left(\partial_i \partial_j \phi(\mathbf{x}, \tau), \partial_i v_j(\mathbf{x}, \tau), \partial_i \partial_j / k_M^2, \epsilon_{ij}(\mathbf{x}, \tau), c_n(\tau)\right)$$

Effective Field Theory of Large-Scale Structure

Galaxy: expansions in *fluctuations* ...

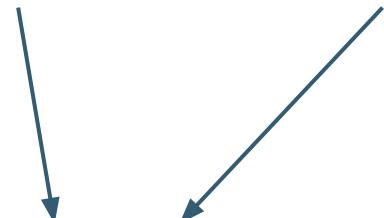
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- Invariant under *Galilean transformations*

$$x \rightarrow x' = x + n(\tau)$$

$$v^i \rightarrow v^i + \chi^i$$

Weinberg adiabatic mode 03

Kehagias & Riotto, Peloso & Pietroni 13

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

Effective Field Theory of Large-Scale Structure

Galaxy: *expansions in fluctuations & derivatives ...*

McDonald, & Roy, 06, 10

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Effective Field Theory of Large-Scale Structure

Galaxy: expansions in *fluctuations*
& derivatives + *stoch* ...

McDonald, & Roy, 06, 10

Senatore 14

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- EFT expansion of galaxy overdensity:

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Effective Field Theory of Large-Scale Structure

*Galaxy: expansions in fluctuations
& derivatives + stoch + time...*

McDonald, & Roy, 06, 10

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Effective Field Theory of Large-Scale Structure

Galaxy: expansions in fluctuations

& derivatives + stoch + *time non-locality?*

- EFT expansion of galaxy overdensity:

$$\delta_g(\mathbf{x}, \tau) = F\left(\partial_i \partial_j \phi(\mathbf{x}, \tau), \partial_i v_j(\mathbf{x}, \tau), \partial_i \partial_j / k_M^2, \epsilon_{ij}(\mathbf{x}, \tau), c_n(\tau)\right)$$

- Up to 4th order, can be written as a sum of *products of local-in-time operators*:

D'Amico, Donath, Lewandowski, Senatore, **PZ** 22b

see also:

$$\delta_g(\mathbf{x}, \tau) = \sum_i b_i(\tau) O_i(\mathbf{x}, \tau)$$

EFT parameters

Desjacques, Jeong, Schmidt 16
Eggemeier, Scoccimarro, Smith 19

Effective Field Theory of Large-Scale Structure

Galaxy: *expansions*

& *one-loop power spectrum*

- (local-in-time) EFT expansion of galaxy overdensity:

$$\delta_g(\mathbf{x}, \tau) = F\left(\partial_i \partial_j \phi(\mathbf{x}, \tau), \partial_i v_j(\mathbf{x}, \tau), \partial_i \partial_j / k_M^2, \epsilon_{ij}(\mathbf{x}, \tau), c_n(\tau)\right)$$

$$\delta_g \supset c_1 \partial^2 \phi$$

$$\delta_g \supset c_2 \partial^2 \phi \partial^2 \phi$$

Effective Field Theory of Large-Scale Structure

Galaxy: expansions

& one-loop power spectrum

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$$\delta_g \supset c_1 \partial^2 \phi \equiv b_1 \delta$$

$$\delta_g \supset c_2 \partial^2 \phi \partial^2 \phi \equiv b_2 \delta^2$$

Effective Field Theory of Large-Scale Structure

Galaxy: expansions

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$$\delta_g \supset c_1 \partial^2 \phi \equiv b_1 \delta \supset b_1 (\delta^{(1)} + \delta^{(2)} + \delta^{(3)}) + c_s^2 \frac{\partial^2}{k_{NL}^2} \delta^{(1)}$$

$$\delta_g \supset c_2 \partial^2 \phi \partial^2 \phi \equiv b_2 \delta^2$$

Effective Field Theory of Large-Scale Structure

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$$\langle \delta_g \delta_g \rangle \supset b_1^2 (P_{11}(k) + \langle \delta^{(2)} \delta^{(2)} \rangle + 2 \langle \delta^{(1)} \delta^{(3)} \rangle) + 2b_1 c_s^2 \frac{k^2}{k_{\text{NL}}^2} P_{11}(k)$$

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Effective Field Theory of Large-Scale Structure

Galaxy: *expansions*

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$$\delta_g \supset c_2 \partial^2 \phi \partial^2 \phi \equiv b_2 \delta^2 \supset b_2 (\delta^2)^{(2)}$$

Effective Field Theory of Large-Scale Structure

Galaxy: *expansions*

& *one-loop power spectrum*

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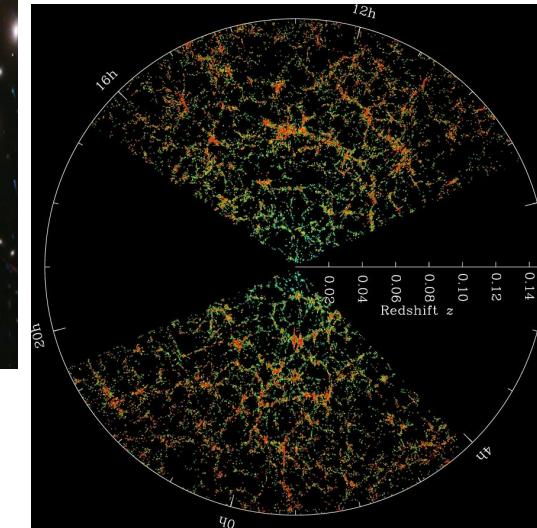
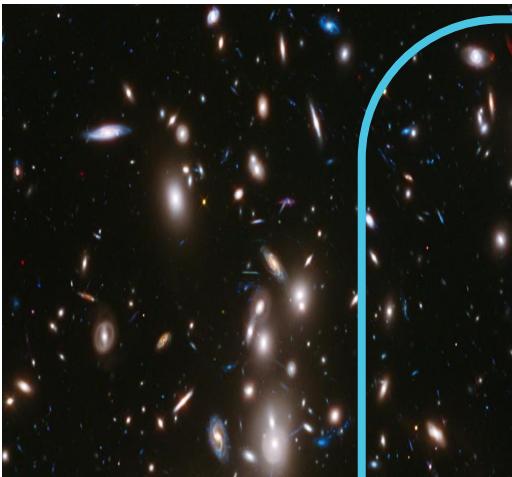
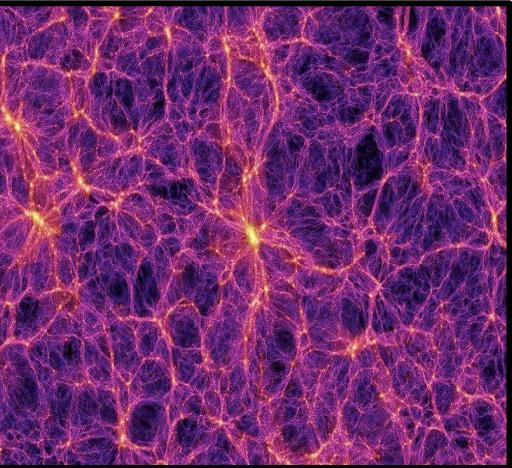
$$\delta_g \supset c_1 \partial^2 \phi \equiv b_1 \delta \supset b_1 (\delta^{(1)} + \delta^{(2)} + \delta^{(3)}) + c_s^2 \frac{\partial^2}{k_{\text{NL}}^2} \delta^{(1)}$$

$$\langle \delta_g \delta_g \rangle \supset b_1^2 (P_{11}(k) + \langle \delta^{(2)} \delta^{(2)} \rangle + 2 \langle \delta^{(1)} \delta^{(3)} \rangle) + 2b_1 c_s^2 \frac{k^2}{k_{\text{NL}}^2} P_{11}(k)$$

$$\delta_g \supset c_2 \partial^2 \phi \partial^2 \phi \equiv b_2 \delta^2 \supset b_2 (\delta^2)^{(2)}$$

$$\langle \delta_g \delta_g \rangle \supset 2b_1 b_2 \langle \delta^{(2)} \delta^2 \rangle + b_2^2 \langle \delta^2 \delta^2 \rangle$$

I. Effective Field Theory of Large-Scale Structure



$$\zeta(\mathbf{x}) \xrightarrow{\text{Perturbation theory}} \delta(\mathbf{x})$$

$$\xrightarrow{\text{Tracers biases}} \delta_g(\mathbf{x})$$

$$\xrightarrow{\text{Redshift space distortions}} \delta_g(z)$$



Effective Field Theory of Large-Scale Structure

Redshift-space distortions

Matsubara 07

Senatore, Zaldarriaga 14

Lewandowski, Senatore, et al. 16

- Comoving coordinates relation real space to redshift space: $s = x + \left(\frac{\mathbf{v}}{\mathcal{H}} \cdot \hat{z} \right) \hat{z}$
- Density relation real space to redshift space:

$$\delta_{h,r}(\mathbf{k}) = \delta_h(\mathbf{k}) + \sum_{n=1}^{\infty} \frac{1}{n!} \int d^3x e^{-i\mathbf{k}\cdot\mathbf{x}} \left(-ik_z \frac{v_z}{\mathcal{H}}\right)^n (1 + \delta_h)$$

- Expansion up to products of 4 fields:

$$\begin{aligned} \delta_{r,h} &= \delta_h - \frac{\hat{z}^i \hat{z}^j}{aH} \partial_i ((1 + \delta_h) v^j) + \frac{\hat{z}^i \hat{z}^j \hat{z}^k \hat{z}^l}{2(aH)^2} \partial_i \partial_j ((1 + \delta_h) v^k v^l) \\ &\quad - \frac{\prod_{a=1}^6 \hat{z}^{i_a}}{3!(aH)^3} \partial_{i_1} \partial_{i_2} \partial_{i_3} ((1 + \delta_h) v^{i_4} v^{i_5} v^{i_6}) + \frac{\prod_{a=1}^8 \hat{z}^{i_a}}{4!(aH)^4} \partial_{i_1} \partial_{i_2} \partial_{i_3} \partial_{i_4} (v^{i_5} v^{i_6} v^{i_7} v^{i_8}) + \dots \end{aligned}$$

Effective Field Theory of Large-Scale Structure

Redshift-space distortions: more renormalization

Matsubara 07

Senatore, Zaldarriaga 14

Lewandowski, Senatore, et al. 16

- Counterterms are added such that products of local operators have the correct properties under Galilean transformations ...

$$[v^i]_R \rightarrow [v^i]_R + \chi^i ,$$

$$[v^i v^j]_R \rightarrow [v^i v^j]_R + [v^i]_R \chi^j + [v^j]_R \chi^i + \chi^i \chi^j$$

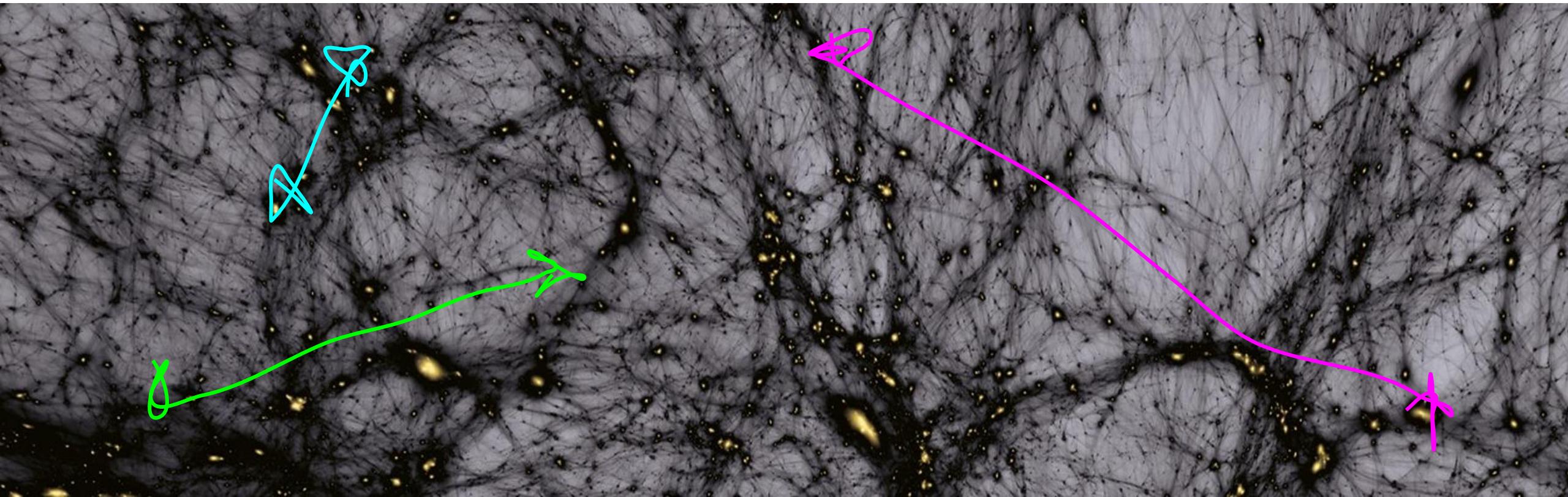
$$[\delta_h v^i]_R \rightarrow [\delta_h v^i]_R + [\delta_h]_R \chi^i$$

$$\begin{aligned} \delta_{r,h} = & \delta_h - \frac{\hat{z}^i \hat{z}^j}{aH} \partial_i ((1 + \boxed{\delta_h}) v^j) + \frac{\hat{z}^i \hat{z}^j \hat{z}^k \hat{z}^l}{2(aH)^2} \partial_i \partial_j ((1 + \delta_h) \boxed{v^k v^l}) \\ & - \frac{\prod_{a=1}^6 \hat{z}^{i_a}}{3!(aH)^3} \partial_{i_1} \partial_{i_2} \partial_{i_3} ((1 + \delta_h) \boxed{v^{i_4} v^{i_5} v^{i_6}}) + \frac{\prod_{a=1}^8 \hat{z}^{i_a}}{4!(aH)^4} \partial_{i_1} \partial_{i_2} \partial_{i_3} \partial_{i_4} (\boxed{v^{i_5} v^{i_6} v^{i_7} v^{i_8}}) + \dots \end{aligned}$$

Game I

Power spectrum of galaxies in redshift at one-loop

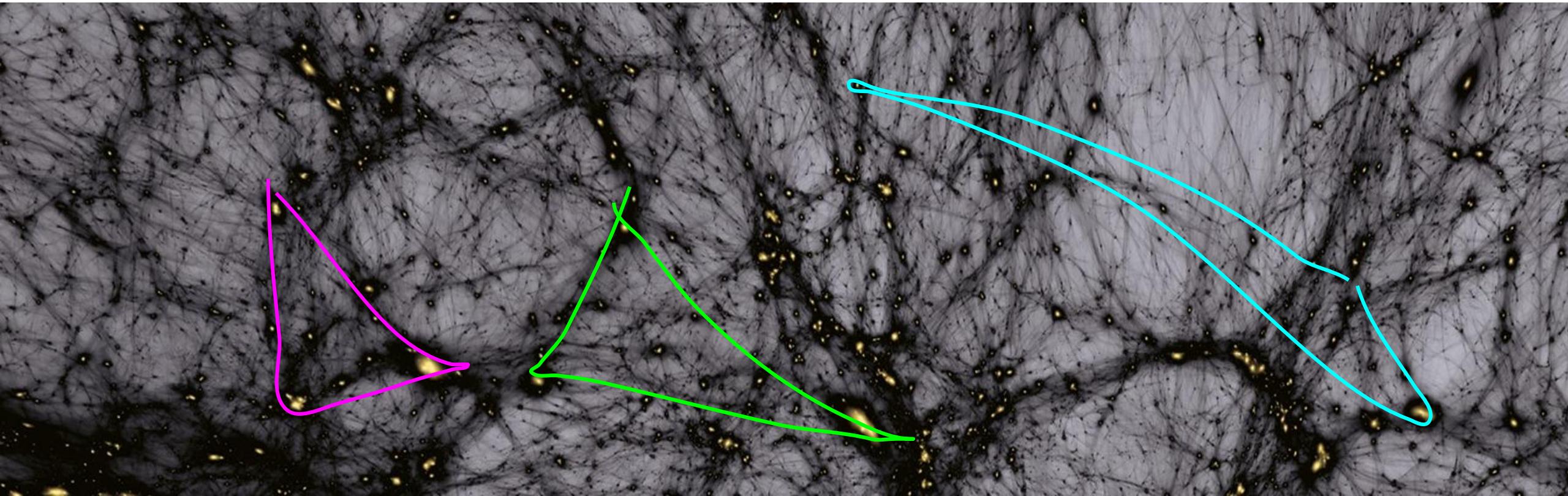
Perko, Senatore, Jennings, Wechsler 16

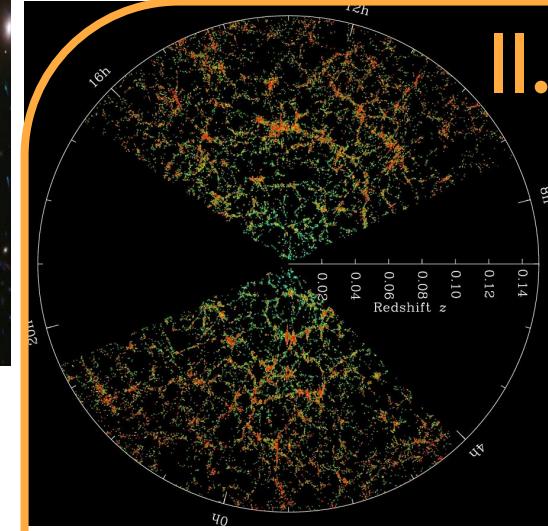
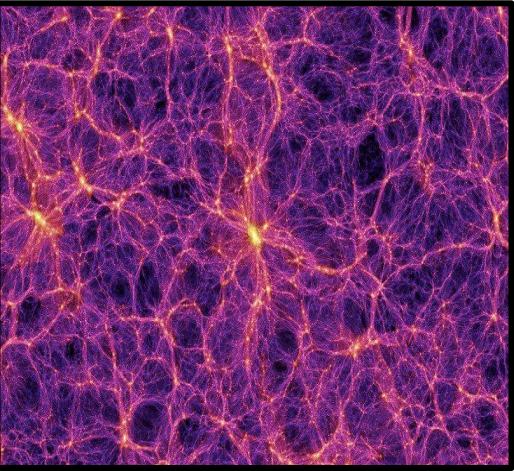


Game II

Bispectrum of galaxies in redshift at one-loop

D'Amico, Donath, Lewandowski, Senatore, **PZ** 22b





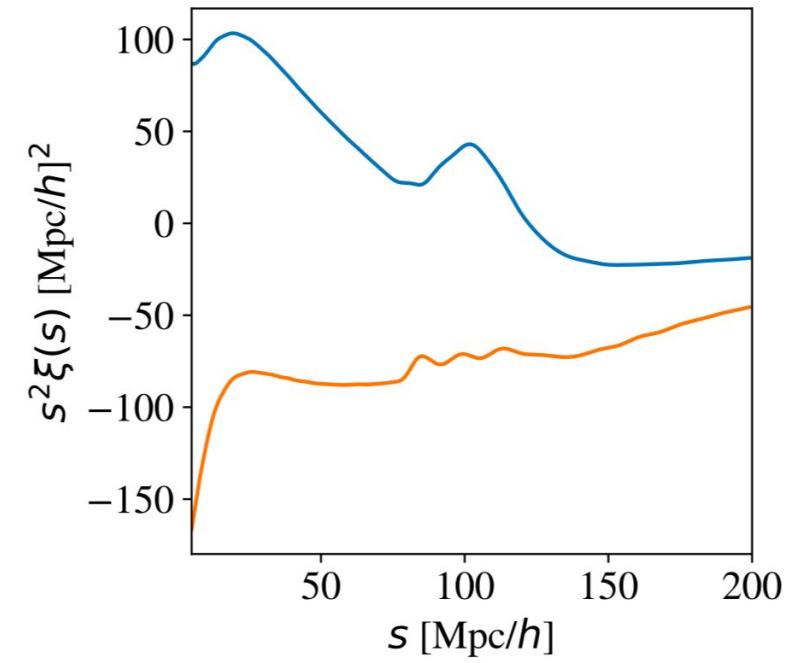
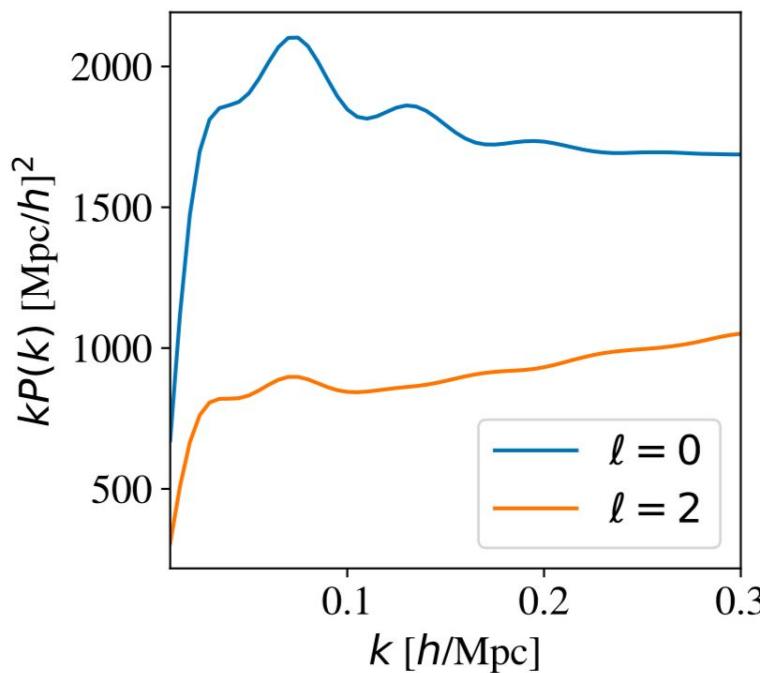
II. Analysis Pipeline



Analysis pipeline

PyBiRd: Python code for Biased tracers in Redshift space

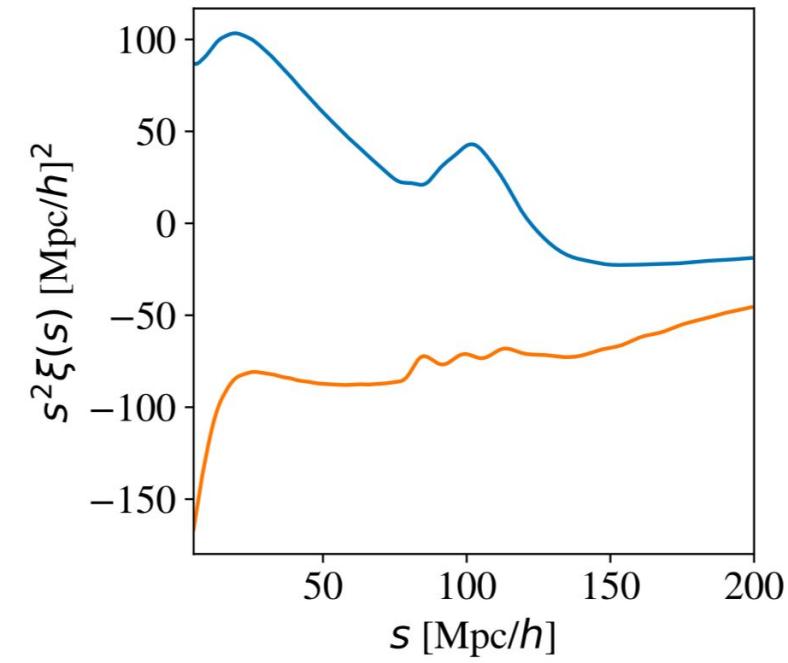
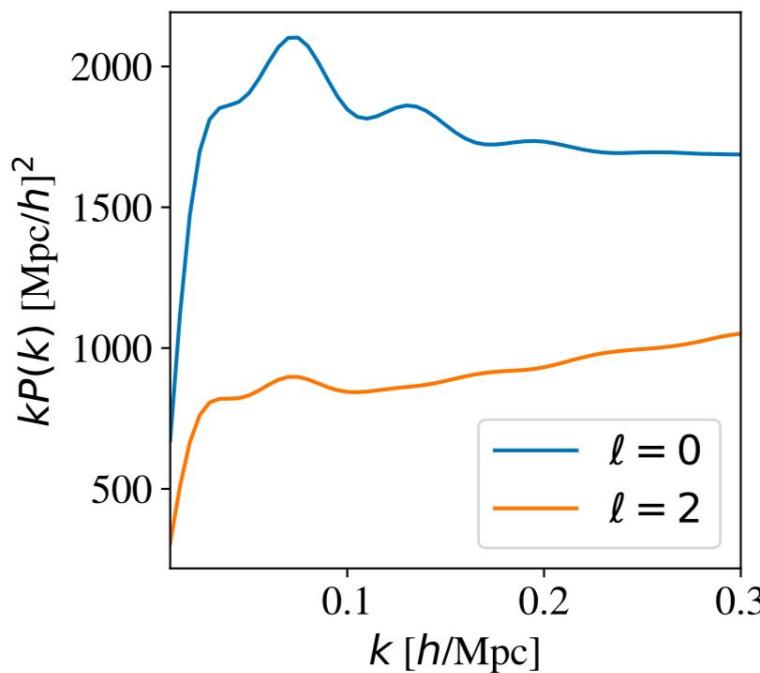
- Evaluates EFT correlators in cosmological inference setup
- Includes all relevant observational effects for a all-in-one analysis
- Stand-alone tool: can be plugged to any Boltzmann code
- Publicly available at: <https://github.com/pierrexyz/pybird>



Analysis pipeline

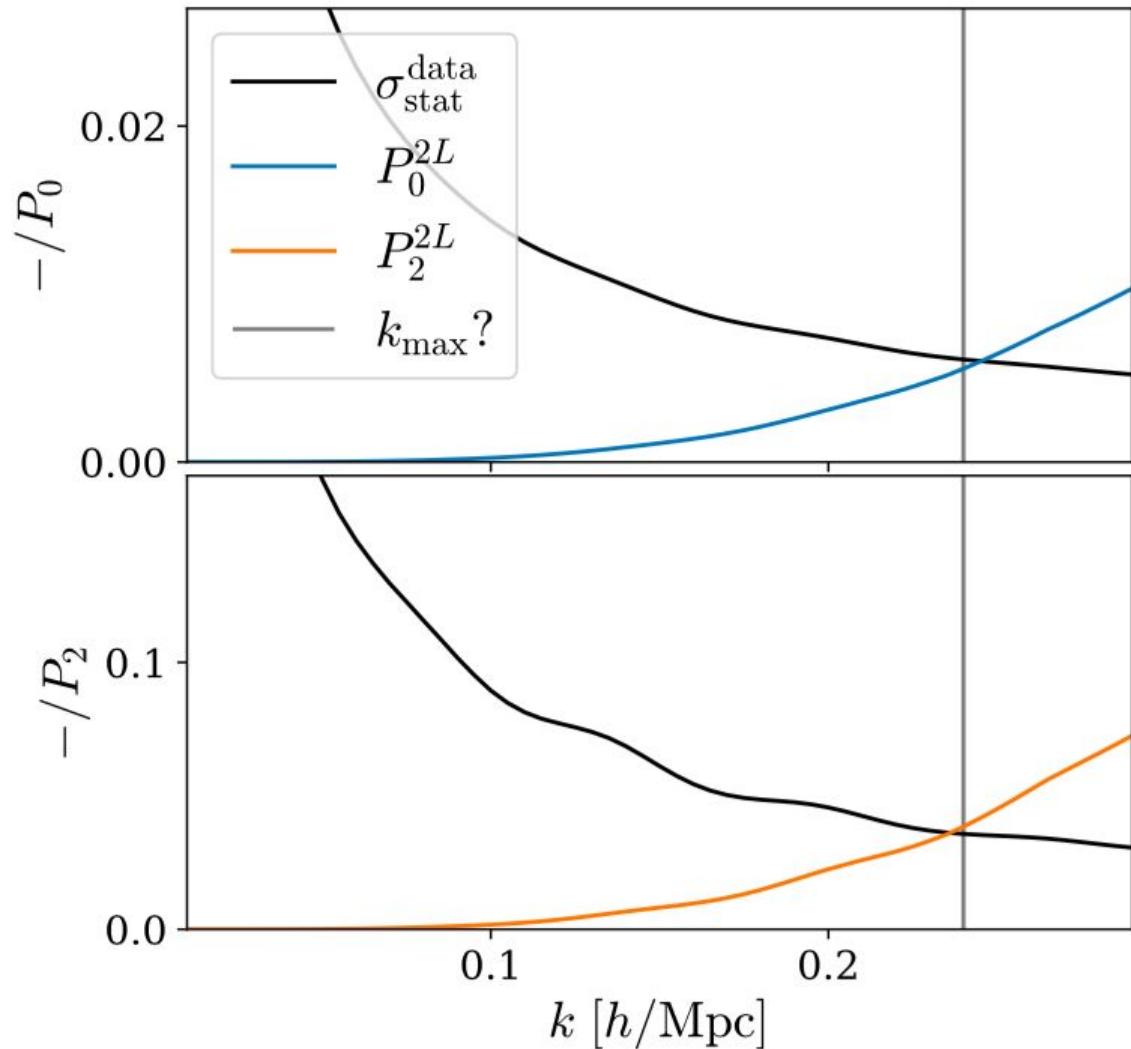
PyBiRd: Python code for Biased tracers in Redshift space

- Evaluates EFT correlators in cosmological inference setup
- Includes all relevant observational effects for a all-in-one analysis
- Stand-alone tool: can be plugged to any Boltzmann code
- Publicly available at: <https://github.com/pierrexyz/pybird>
- !!! Send me an email to get the latest version !!!



Pipeline validation

Scale cut from governing scales

D'Amico, Senatore, **PZ** 21**PZ**, D'Amico, Senatore, Zhao, Cai 21

$$k_M^{\text{BOSS}} = 0.7h \text{ Mpc}^{-1}, \quad k_R^{\text{BOSS}} = 0.35h \text{ Mpc}^{-1},$$

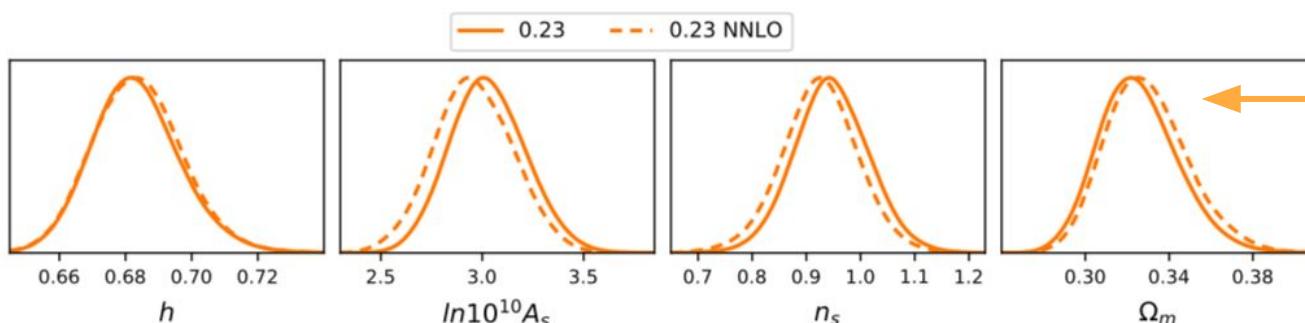
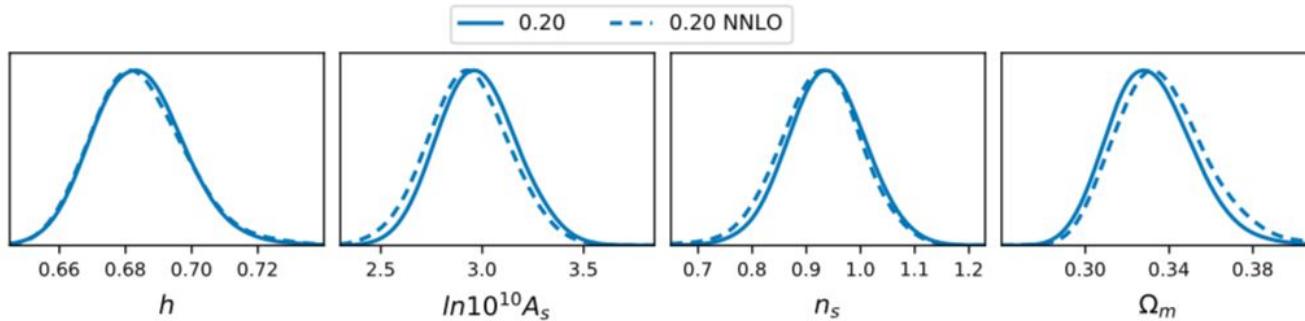
$$k_M^{\text{eBOSS}} = 0.7h \text{ Mpc}^{-1}, \quad k_R^{\text{eBOSS}} = 0.25h \text{ Mpc}^{-1}.$$

$$|P_{2L}| \sim \frac{1}{4} b_1 (c_{r,4} b_1 + c_{r,6} \mu^2) \mu^4 \frac{k^4}{k_R^4} P_{11}(k)$$

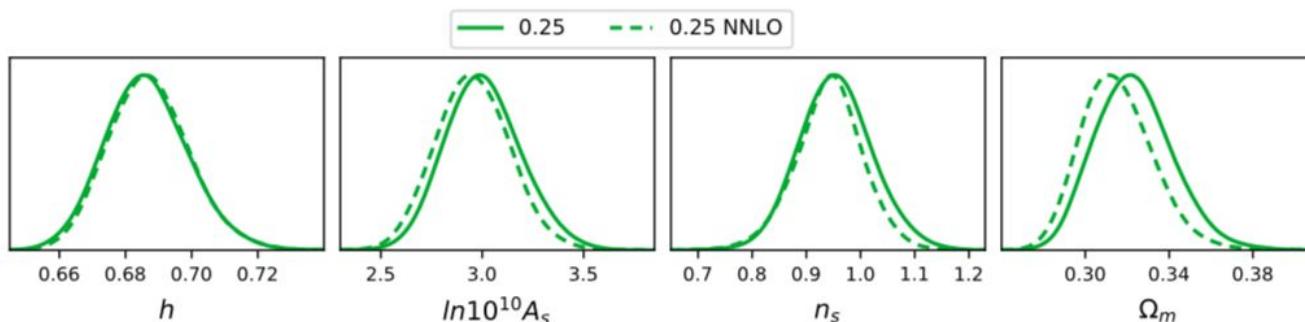
Pipeline validation

Scale cut from governing scales

D'Amico, Senatore, **PZ** 21
PZ, D'Amico, Senatore, Zhao, Cai 21



$$\sigma_{\text{sys}} < \frac{1}{3} \sigma_{\text{stat}}^{\text{data}}$$

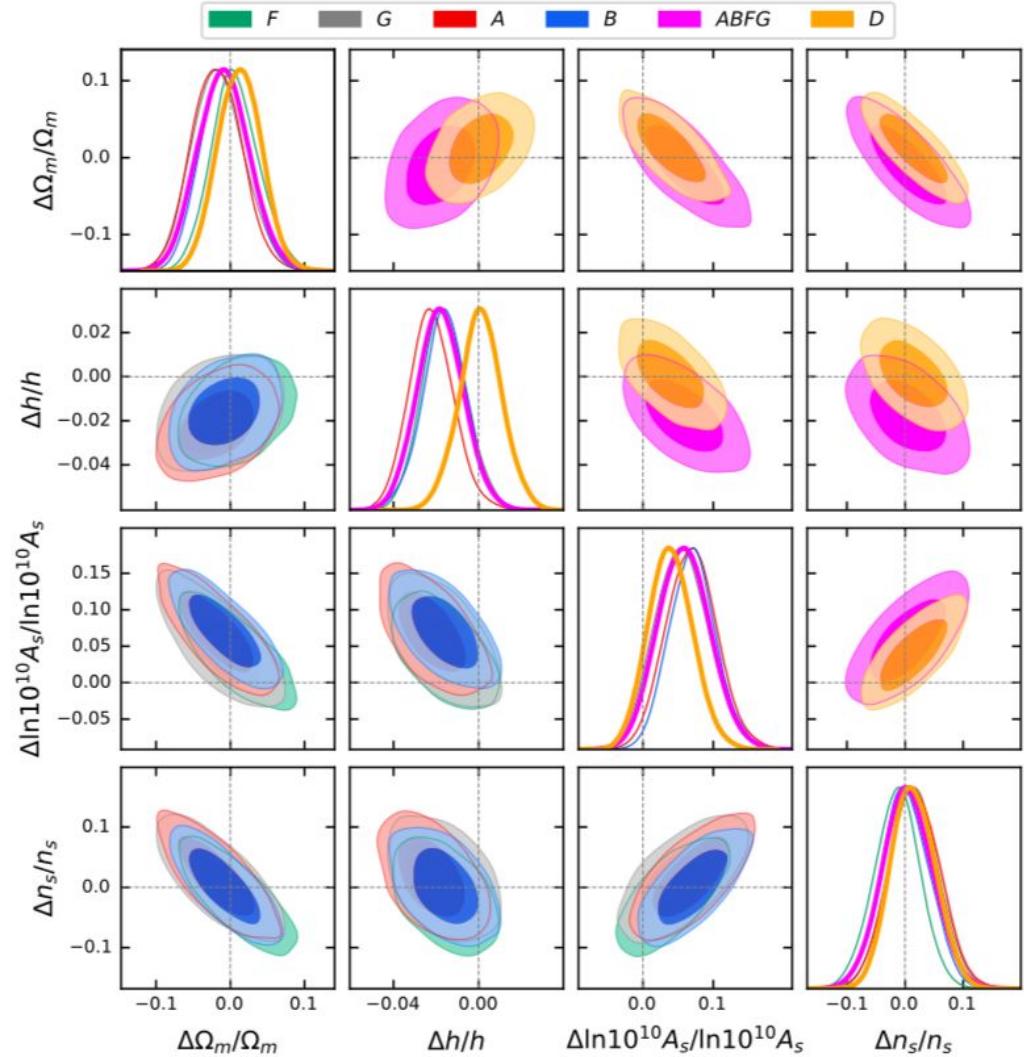


$$|P_{2L}| \sim \frac{1}{4} b_1 (c_{r,4} b_1 + c_{r,6} \mu^2) \mu^4 \frac{k^4}{k_R^4} P_{11}(k)$$

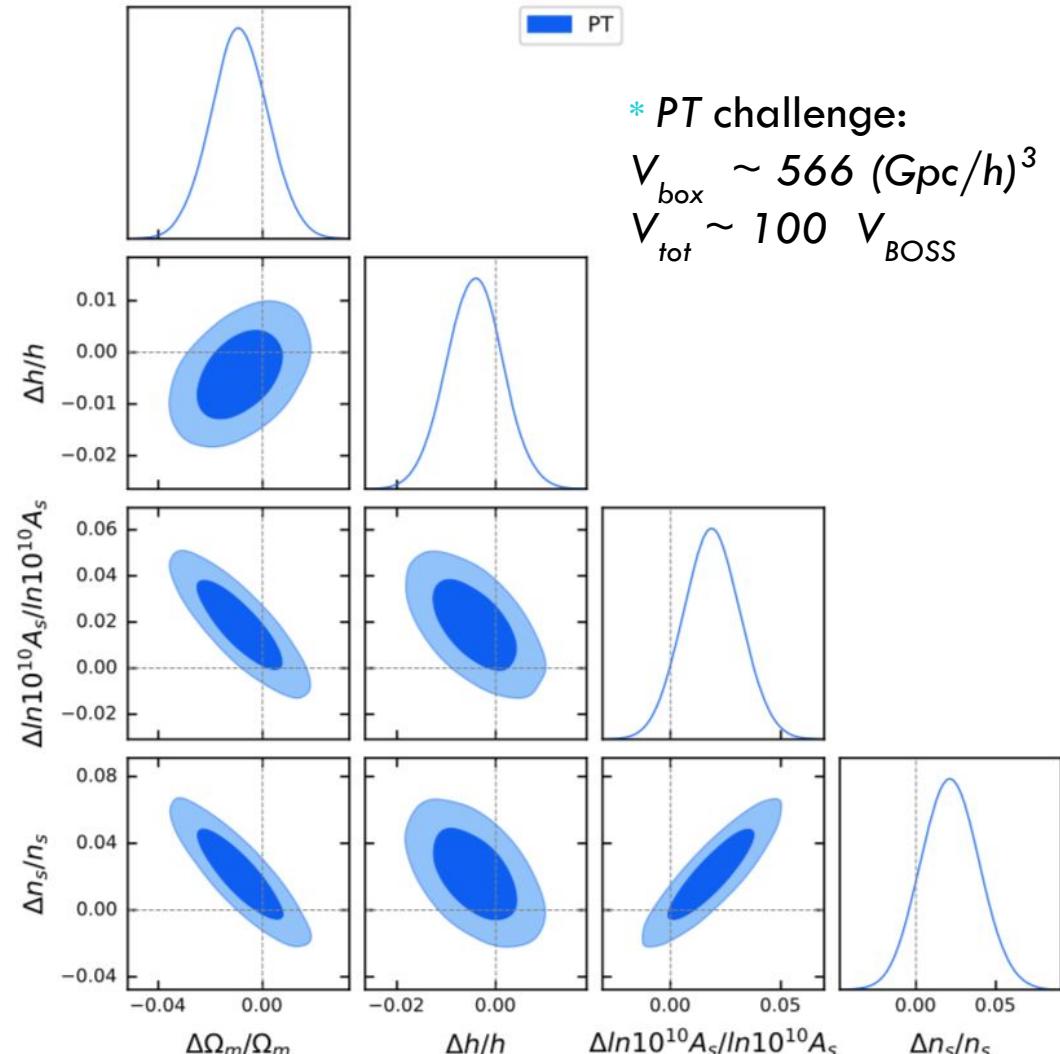
Pipeline validation

Tests against simulations

+ D'Amico, Gleyzes, Kokron, Markovic, Senatore, **PZ**, Beutler, Gil-Marin 19
+ Colas, D'Amico, Senatore, **PZ**, Beutler 19
* Nishimichi, D'Amico, Ivanov, Senatore, Simonovic, Takada, Zaldarriaga, **PZ** 20
+ **PZ**, D'Amico, Senatore, Zhao, Cai 21

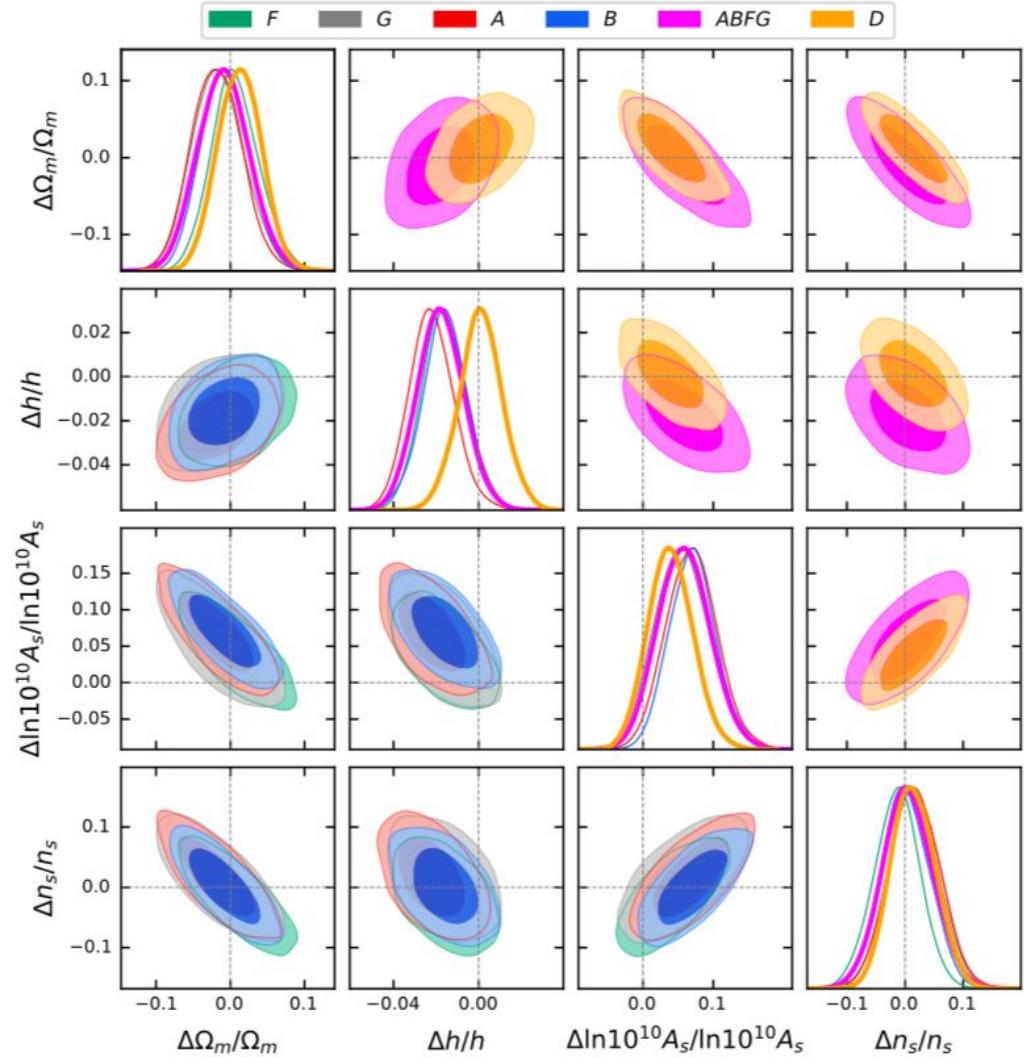


+ Lettered challenge:
A, B, F, G + D
 $L_{\text{box}} \sim (2.5 \text{ Gpc}/h)^3$
 $V_{\text{tot}} \sim 5.5 V_{\text{BOSS}}$



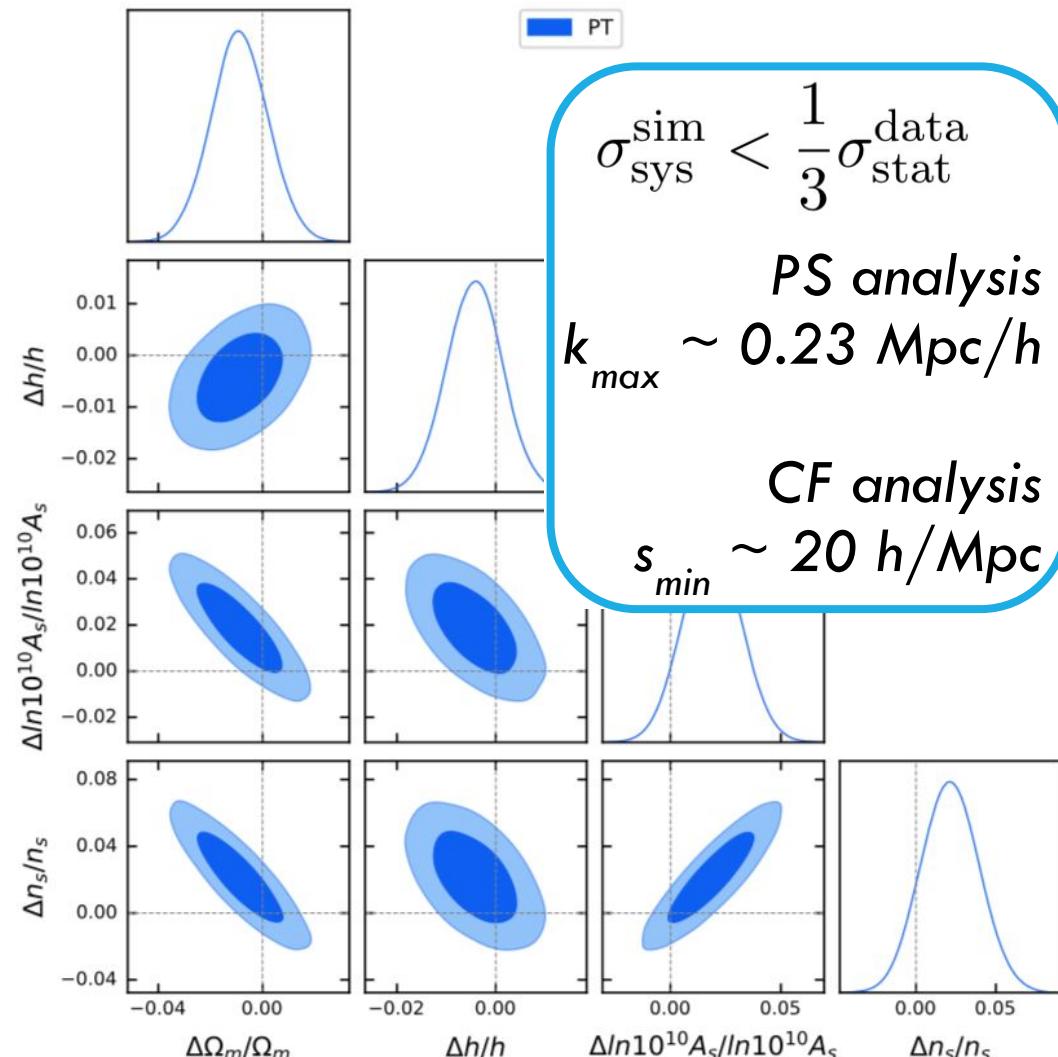
Pipeline validation

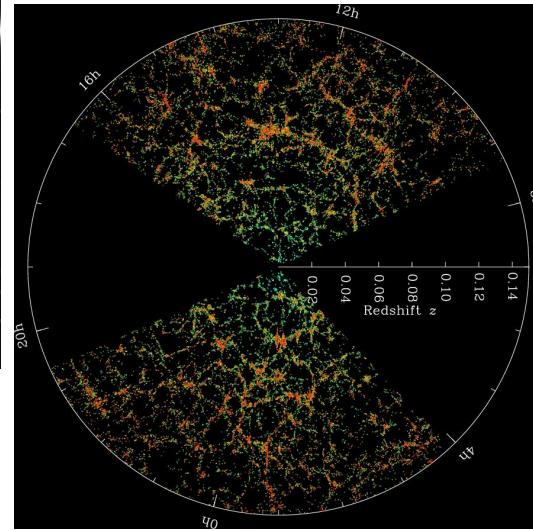
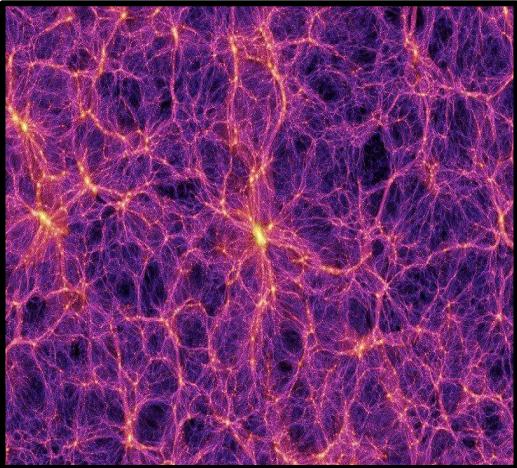
Tests against simulations



+ Lettered challenge:
 $A, B, F, G + D$
 $L_{\text{box}} \sim (2.5 \text{ Gpc}/h)^3$
 $V_{\text{tot}} \sim 5.5 V_{\text{BOSS}}$

$$\sigma_{\text{sys}}^{\text{sim}} \equiv \max(|\text{mean-truth}| - \sigma_{\text{stat}}^{\text{sim}}, 0)$$





III. Cosmological results

Λ CDM from BOSS 2pt

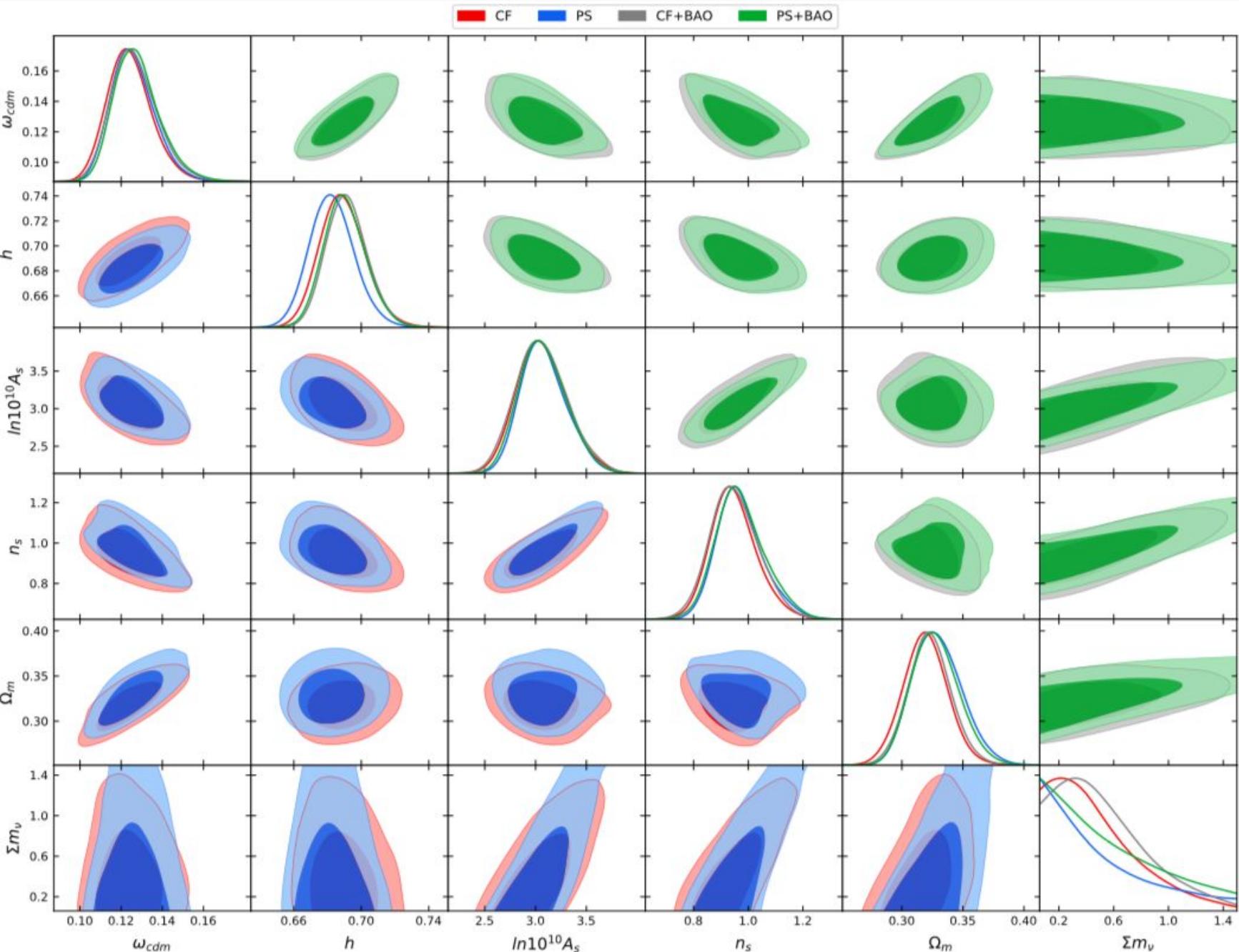
Consistency PS/CF

Colas, D'Amico, Senatore, **PZ**, Beutler 19
PZ, D'Amico, Senatore, Zhao, Cai 21

See also:

Ivanov, Simonovic, Zaldarriaga 19
Philcox, Ivanov, Simonovic, Zaldarriaga 20
Chen, Vlah, White 21

GDR CoPhy

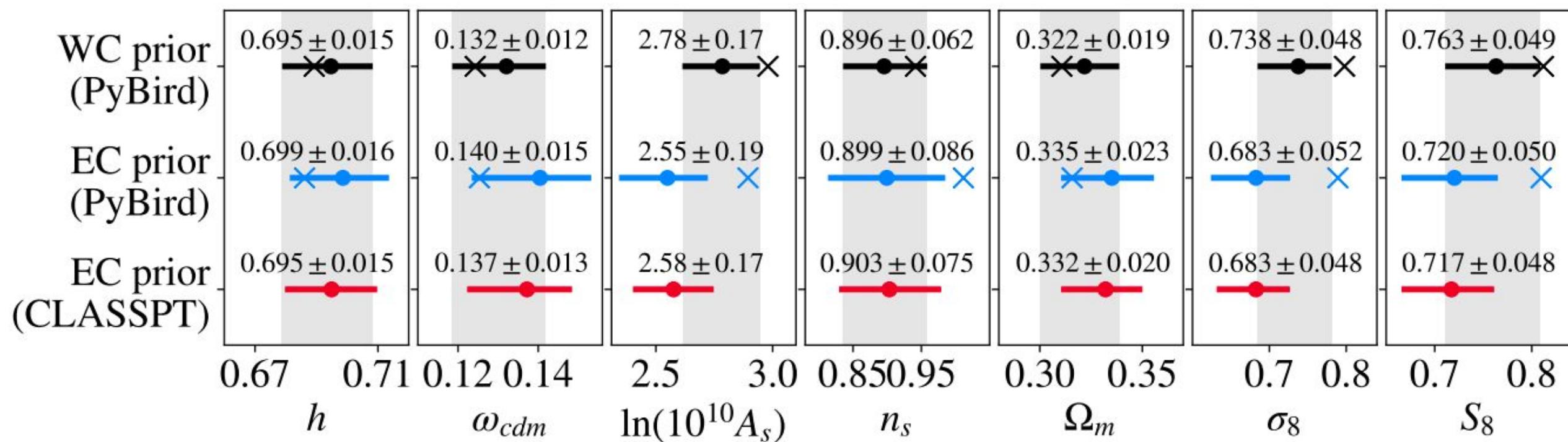


Λ CDM

from BOSS 2pt: a comment on the EFT prior

Simon, PZ, Poulin, Smith 22

Consistency between independent analyses

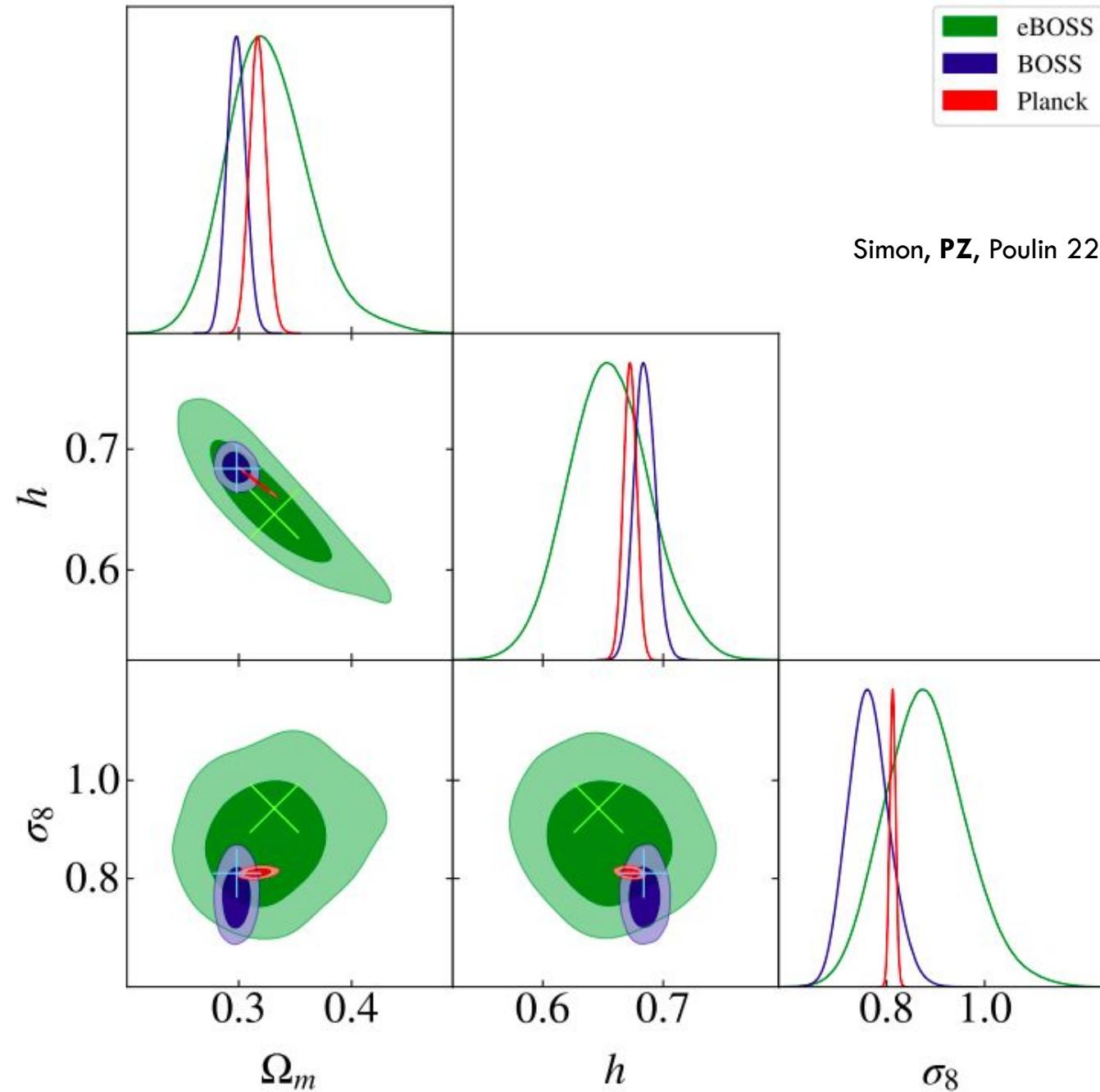


Λ CDM

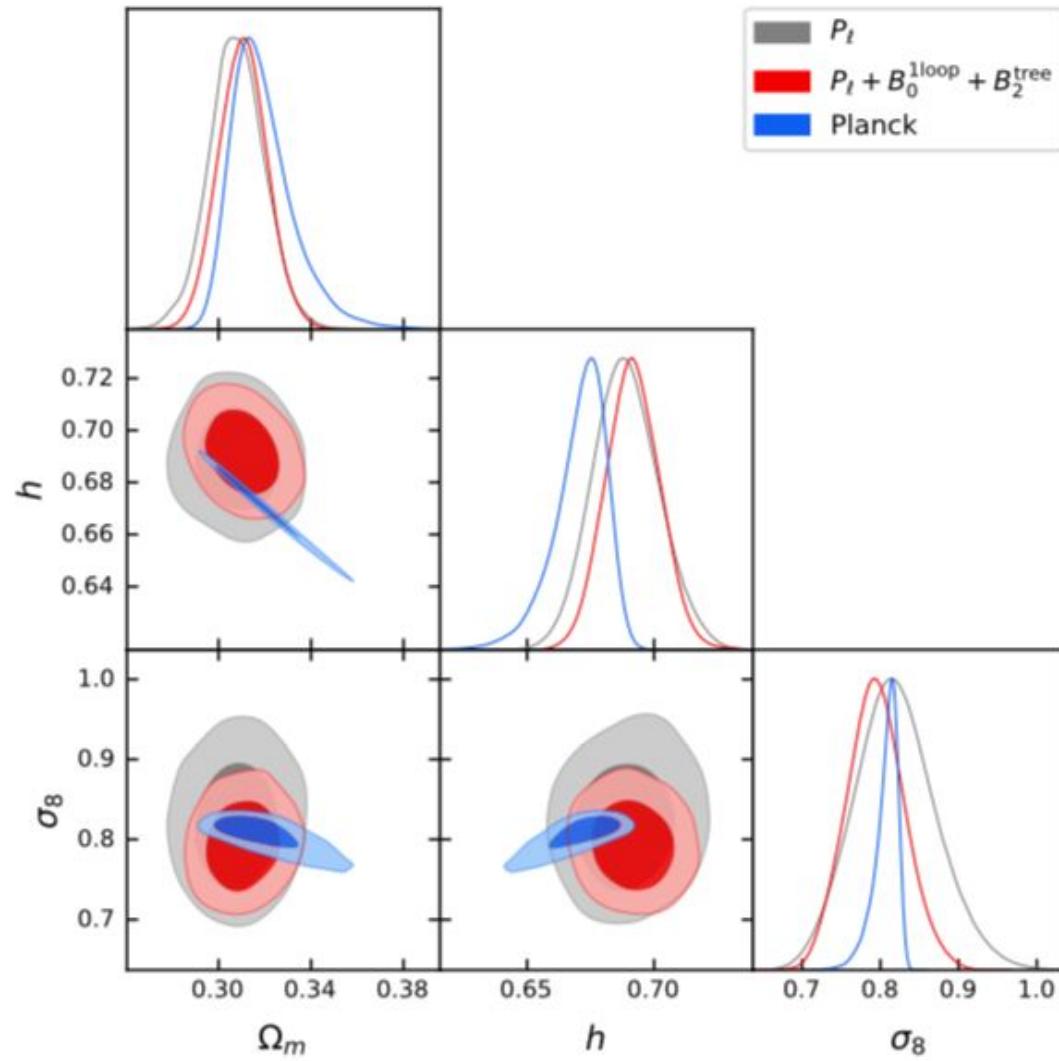
from BOSS / eBOSS 2pt

Consistency across tracers & redshifts

BOSS	LRG	$z \sim 0.5$
eBOSS	QSO	$z \sim 1.5$



Λ CDM from BOSS 2+3pt ($P+B$)



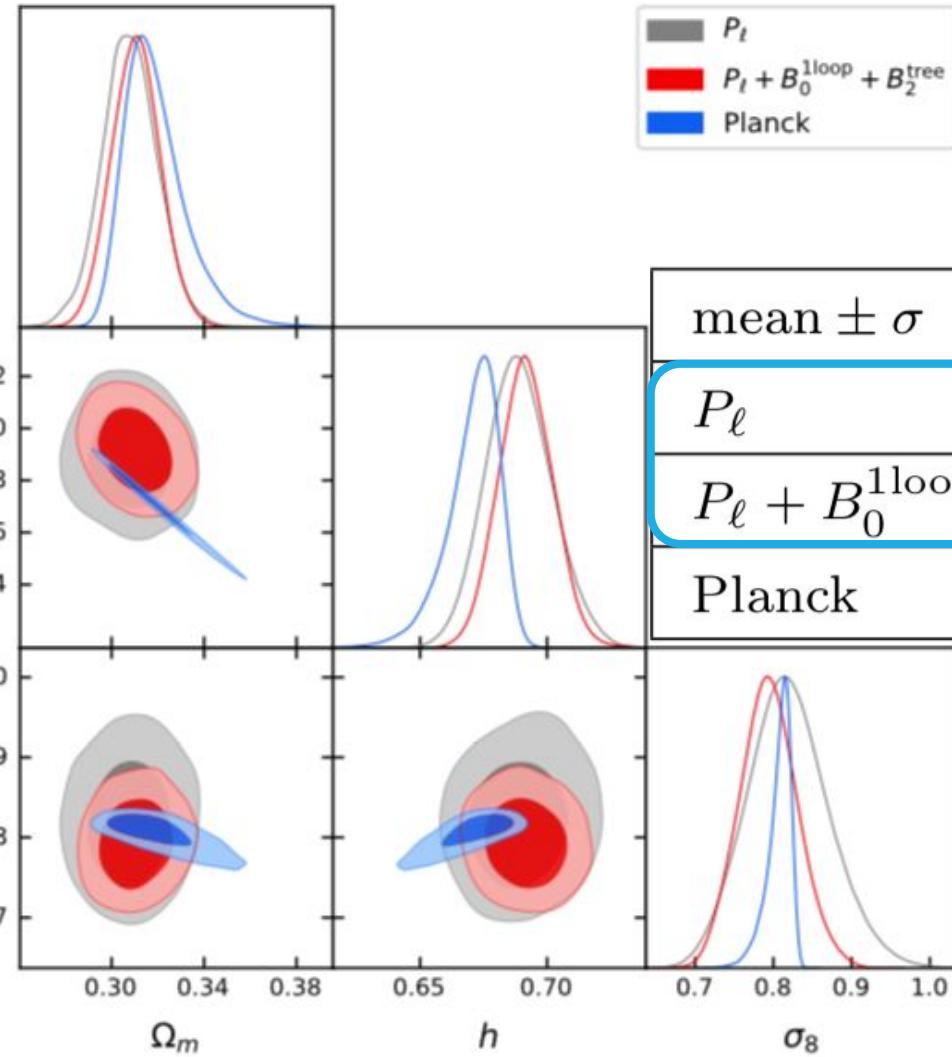
D'Amico, Donath, Lewandowski, Senatore, **PZ 22a**

Consistency across multiple observables

Λ CDM

from BOSS 2+3pt ($P+B$)

D'Amico, Donath, Lewandowski, Senatore, **PZ 22a**



error reduction from P to $P+B$:

13% on Ω_m

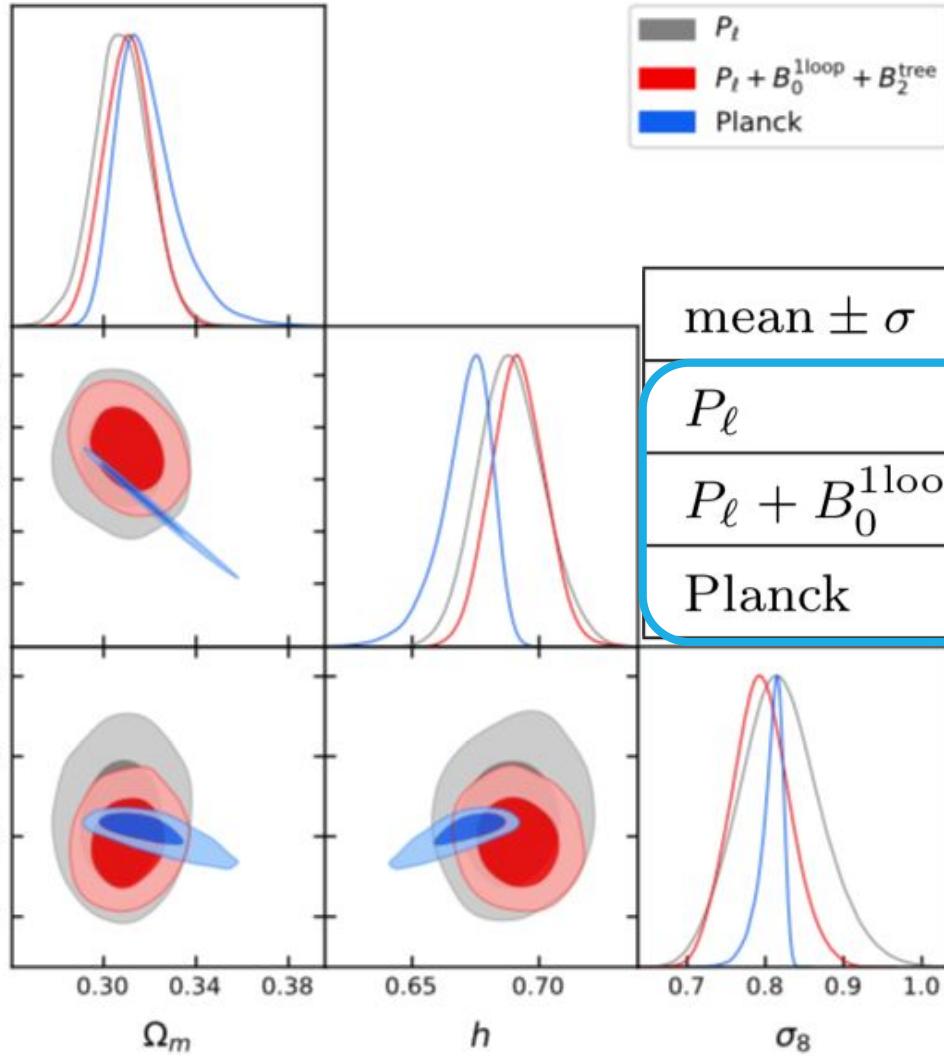
18% on h

30% on σ_8

mean $\pm \sigma$	Ω_m	h	σ_8
P_l	0.308 ± 0.012	$0.689^{+0.012}_{-0.014}$	$0.819^{+0.049}_{-0.055}$
$P_l + B_0^{\text{loop}} + B_2^{\text{tree}}$	0.311 ± 0.010	0.692 ± 0.011	0.794 ± 0.037
Planck	$0.3191^{+0.0085}_{-0.016}$	$0.671^{+0.012}_{-0.0067}$	$0.807^{+0.018}_{-0.0079}$

Λ CDM

from BOSS 2+3pt ($P+B$)

D'Amico, Donath, Lewandowski, Senatore, **PZ 22a**

➤ **error reduction from P to $P+B$:**

13% on Ω_m

18% on h

30% on σ_8

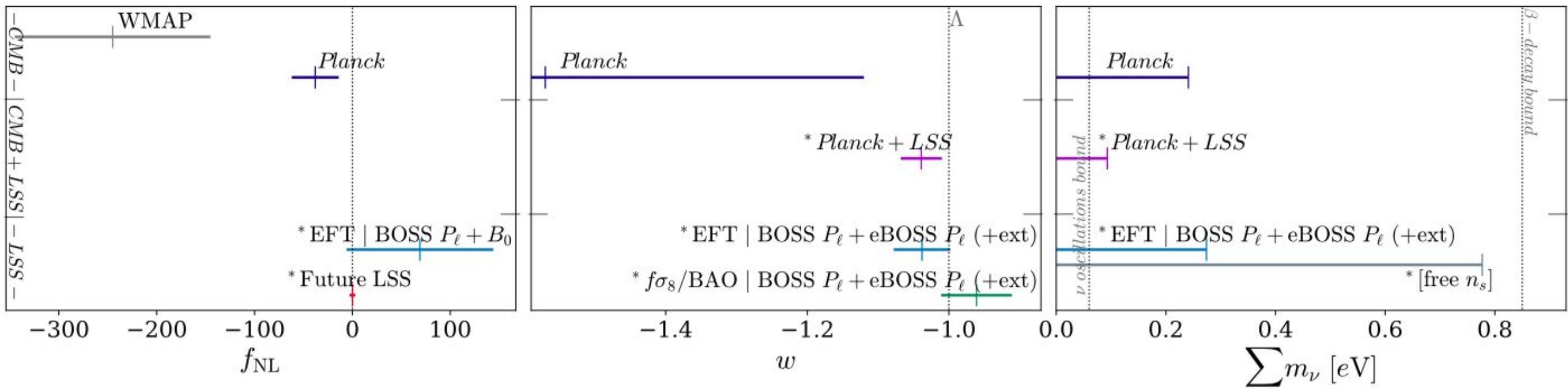
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Planck	$0.3191^{+0.0085}_{-0.016}$	$0.671^{+0.012}_{-0.0067}$	$0.807^{+0.018}_{-0.0079}$

➤ **Consistent results with Planck**

Le mot de la fin

- The LSS observational program is underway
- The EFT approach is now matured and bearing fruit
- Let's jam!

D'Amico, Lewandowski, Senatore, **PZ** 22
 Simon, **PZ**, Poulin 22



* <https://github.com/cheng-zhao/powspec>, <https://github.com/bccp/nbodykit>, <https://github.com/pierrexyz/fkpwin>

** <https://github.com/cheng-zhao/FCFC>

*+ <https://github.com/gilmarin/rusticoX>

*** publicly available at <https://github.com/pierrexyz/pybird>

**** https://github.com/brinckmann/montepython_public ; <http://class-code.net>

Likelihood

& posterior sampling

➤ Data, covariances, simulations, from BOSS/eBOSS:

- Data: BOSS LRG DR12 16 / eBOSS QSO DR16 22
- Catalogues: Reid et al. 16 / Ross et al. 20
- Covariance built from patchy/EZ mocks: Kitaura et al. 16 / Chuang et al. 15

➤ Measurements:

- Power spectrum and window functions from Yamamoto (FKP) estimator *
- Bispectrum from Scoccimarro (FKP) estimator +
- Correlation function from Landy & Szalay estimator **

BOSS 2pt: **PZ**, D'Amico, Senatore, Zhao, Cai 21

BOSS 3pt: D'Amico, Donath, Lewandowski, Senatore, **PZ** 22a

eBOSS 2pt: Beutler, McDonald 22

➤ Likelihood:

D'Amico, Gleyzes, Kokron, Markovic, Senatore, **PZ**, et al. 19, D'Amico, Senatore, **PZ** 20

- Using properties from Gaussian integrals, analytic marginalization over parameters appearing only *linearly* in the predictions (so at most quadratically in the likelihood)
- Likelihood function of cosmo + 3 ‘non-Gaussian’ EFT parameters (per skycut) ***

➤ Prior:

- BBN prior on baryon abundance $\omega_b \sim N(0.02233, 0.00036)$: Mossa et al. (2020)
- Large flat prior on other cosmological parameters: $\omega_{cdm}, H_0, A_s, n_s, \dots$
- Gaussian prior $\sim N(0, 2)$ on EFT parameters

➤ Sampling:

- MontePython with CLASS linear power spectrum ****

Effective Field Theory of Large-Scale Structure

Power spectrum and bispectrum at one loop

D'Amico, Donath, Lewandowski, Senatore, **PZ 22**

$$\begin{aligned} P_{\text{1-loop tot.}}^{r,h} &= P_{11}^{r,h} + (P_{13}^{r,h} + P_{13}^{r,h,ct}) + (P_{22}^{r,h} + P_{22}^{r,h,\epsilon}) \\ B_{\text{1-loop tot.}}^{r,h} &= B_{211}^{r,h} + (B_{321}^{r,h,(II)} + B_{321}^{r,h,(II),ct}) + (B_{411}^{r,h} + B_{411}^{r,h,ct}) \\ &\quad + (B_{222}^{r,h} + B_{222}^{r,h,\epsilon}) + (B_{321}^{r,h,(I)} + B_{321}^{r,h,(I),\epsilon}) \end{aligned}$$

Perturbation theory contributions

$$\begin{aligned} P_{11}^{r,h}[b_1] , \quad P_{13}^{r,h}[b_1, b_3, b_8] , \quad P_{22}^{r,h}[b_1, b_2, b_5] , \\ B_{211}^{r,h}[b_1, b_2, b_5] , \quad B_{321}^{r,h,(II)}[b_1, b_2, b_3, b_5, b_8] , \quad B_{411}^{r,h}[b_1, \dots, b_{11}] , \\ B_{222}^{r,h}[b_1, b_2, b_5] , \quad B_{321}^{r,h,(I)}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}] , \end{aligned}$$

with insertions of

- 1st-order-in-fields response
- 2nd order-in-fields response
- 1st-order-in-fields stochastic
- 1st and 2nd order-in-fields stochastic

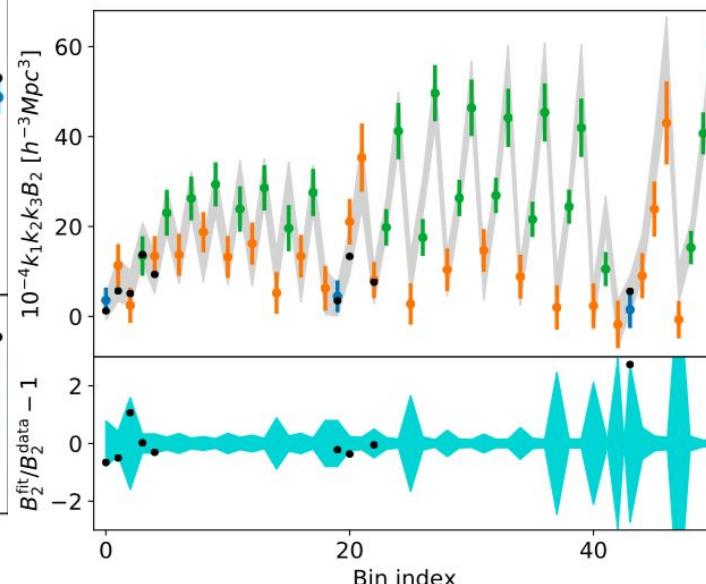
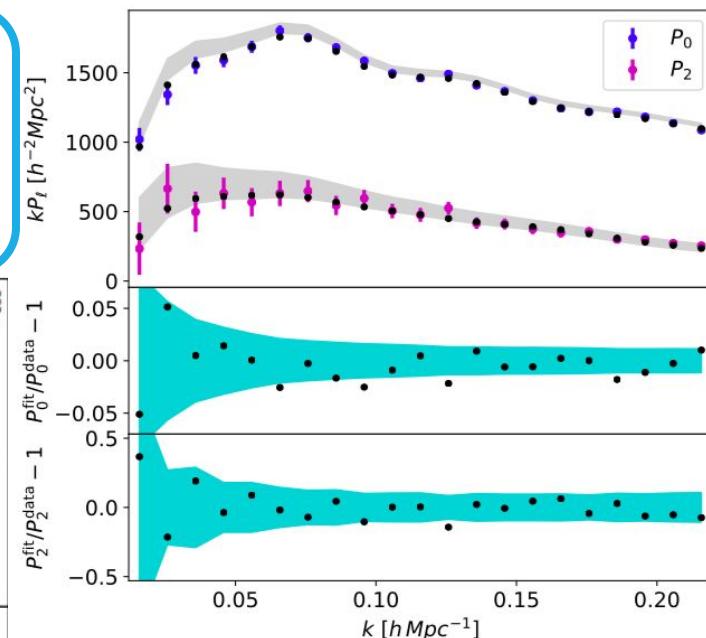
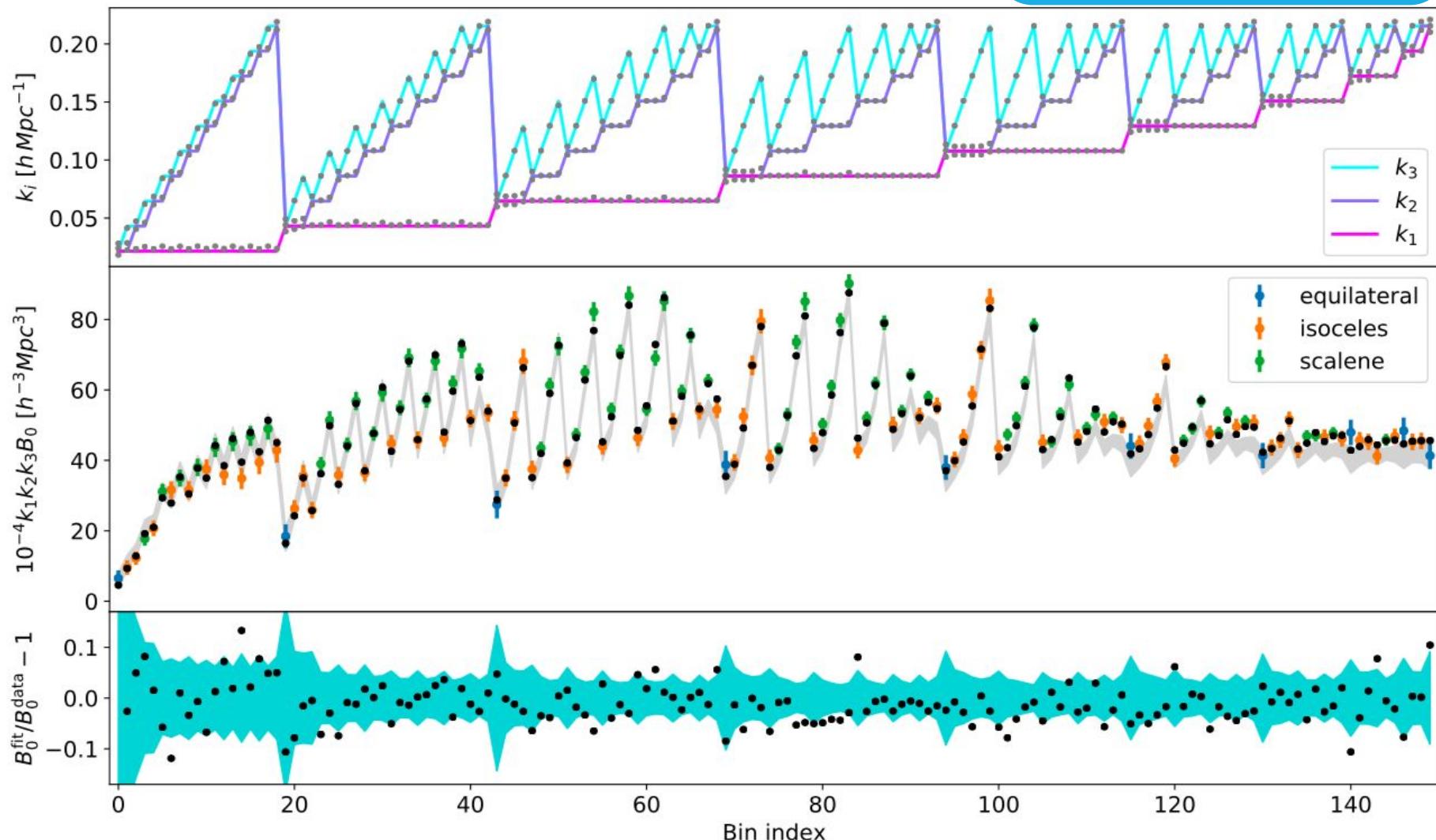
Counterterm contributions

$$\begin{aligned} P_{13}^{r,h,ct}[b_1, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}] , \quad P_{22}^{r,h,\epsilon}[c_1^{\text{St}}, c_2^{\text{St}}, c_3^{\text{St}}] , \\ B_{321}^{r,h,(II),ct}[b_1, b_2, b_5, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}] , \quad B_{321}^{r,h,\epsilon,(I)}[b_1, c_1^{\text{St}}, c_2^{\text{St}}, \{c_i^{\text{St}}\}_{i=4,\dots,13}] , \\ B_{411}^{r,h,ct}[b_1, \{c_{h,i}\}_{i=1,\dots,5}, c_{\pi,1}, c_{\pi,5}, \{c_{\pi v,j}\}_{j=1,\dots,7}] , \quad B_{222}^{r,h,\epsilon}[c_1^{(222)}, c_2^{(222)}, c_5^{(222)}] . \end{aligned}$$

Λ CDM

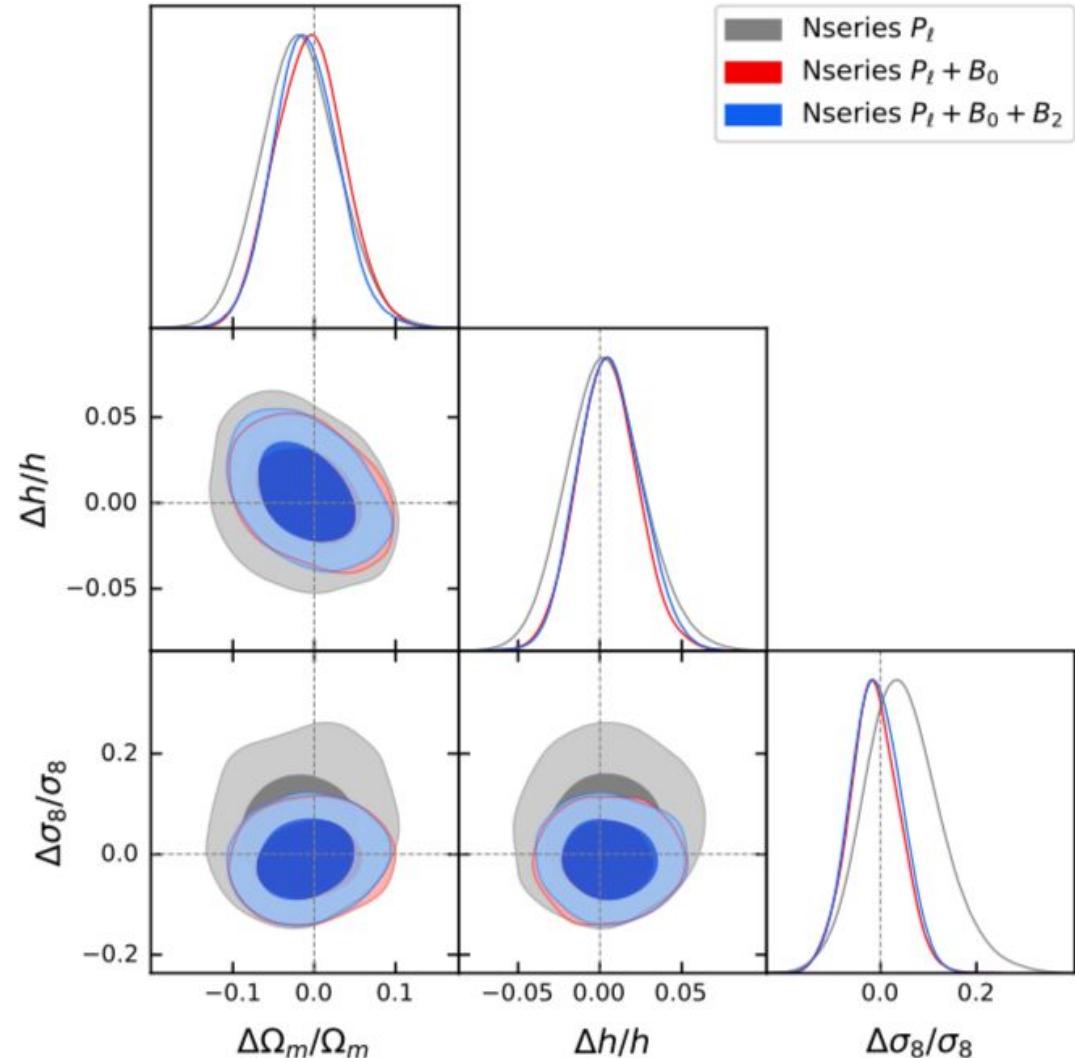
from BOSS 2+3pt ($P+B$): best fit

$P_\ell(k) \mid k \in [0.01, 0.23]$
 $B_0(k) \mid k \in [0.01, 0.23]$
 $B_2(k) \mid k \in [0.01, 0.08]$



Λ CDM

from BOSS 2+3pt ($P+B$): tests against simulations



$$\sigma_{\text{sys}}^{\text{sim}} \equiv \max(|\text{mean}-\text{truth}| - \sigma_{\text{stat}}^{\text{sim}} / \sqrt{N_{\text{sim}}}, 0)$$



$\sigma_{\text{sys}}^{\text{sim}} / \sigma_{\text{stat}}^{\text{data}}$	Ω_m	h	σ_8
Nseries $P_\ell + B_0$	0.02	0.17	0.15
Nseries $P_\ell + B_0 + B_2$	0.16	0.25	0.08
Patchy $P_\ell + B_0$	0.27	0.21	0.23
Patchy $P_\ell + B_0 + B_2$	0.31	0.2	0.07

