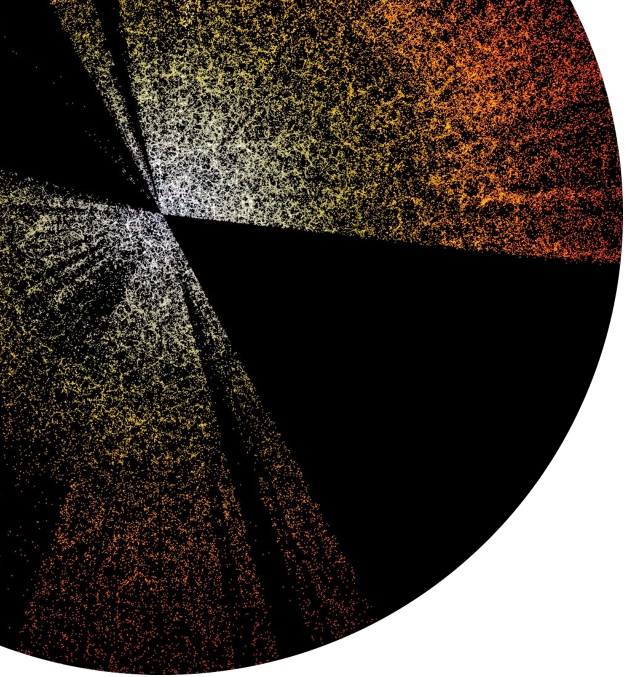
Cosmology from galaxies at long distances

The "pen & paper" approach

Pierre Zhang (ETH Zürich)

3 July 2024

New Strategies for Extracting Cosmology from Galaxy Surveys - 2nd edition | Sesto Center for Astrophysics Riccardo Giacconi



— DESI 2024 —

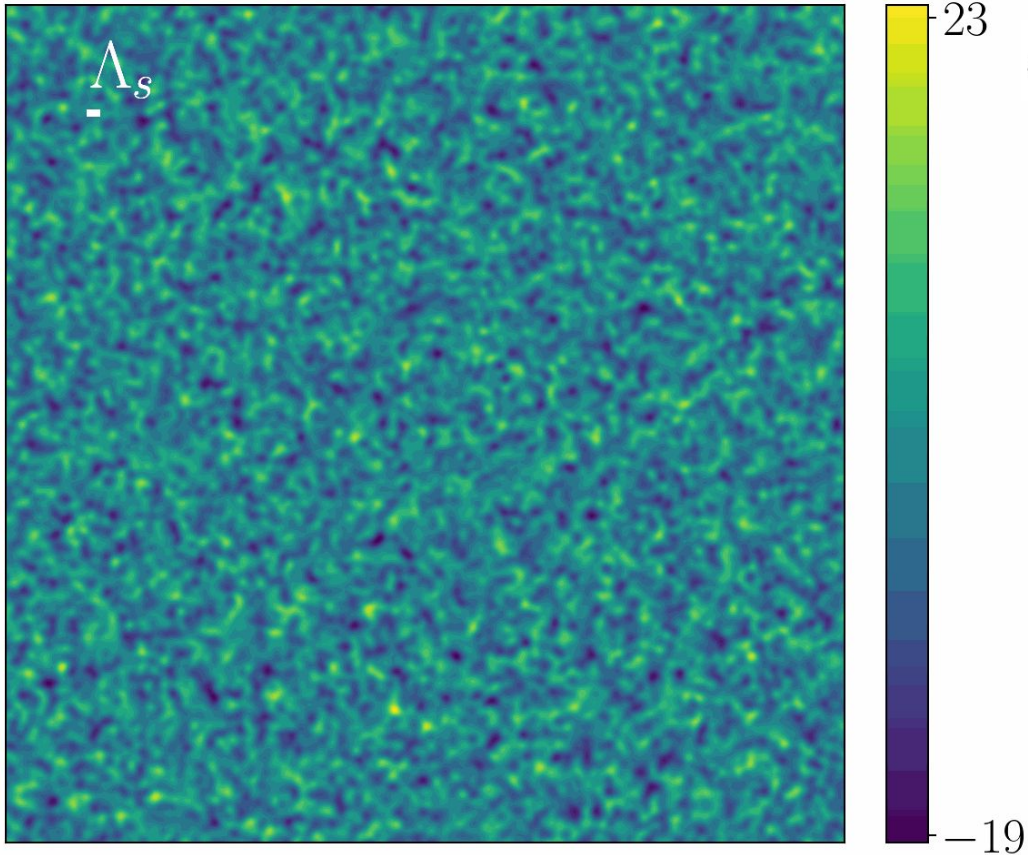
$$\mathcal{P}\left(\Omega \middle| \mathrm{map}\right) = ?$$

Ω : (new) physics

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

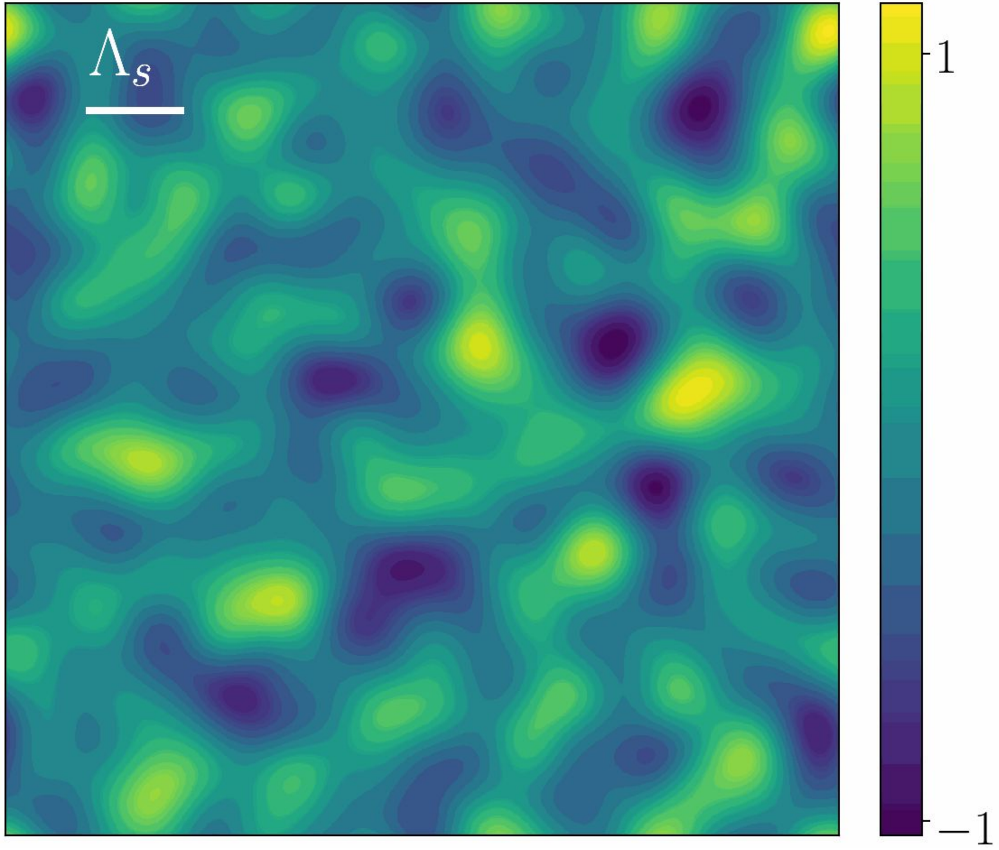
$$\delta(\boldsymbol{x}) = \frac{\rho(\boldsymbol{x})}{\bar{\rho}} - 1$$

$$\delta_\ell(\boldsymbol{x}) = \mathrm{FT}\left[\delta_\ell(\boldsymbol{k}) = \delta(|\boldsymbol{k}| < \Lambda_s^{-1})\right]$$



$$\delta_\ell(\boldsymbol{k}) \lesssim \mathcal{O}(1) \text{ for } k \lesssim \Lambda_s^{-1} \lesssim k_{\rm nl}$$

$$\delta_\ell(\boldsymbol{x}) = \mathrm{FT}\left[\delta_\ell(\boldsymbol{k}) = \delta(|\boldsymbol{k}| < \Lambda_s^{-1})\right]$$



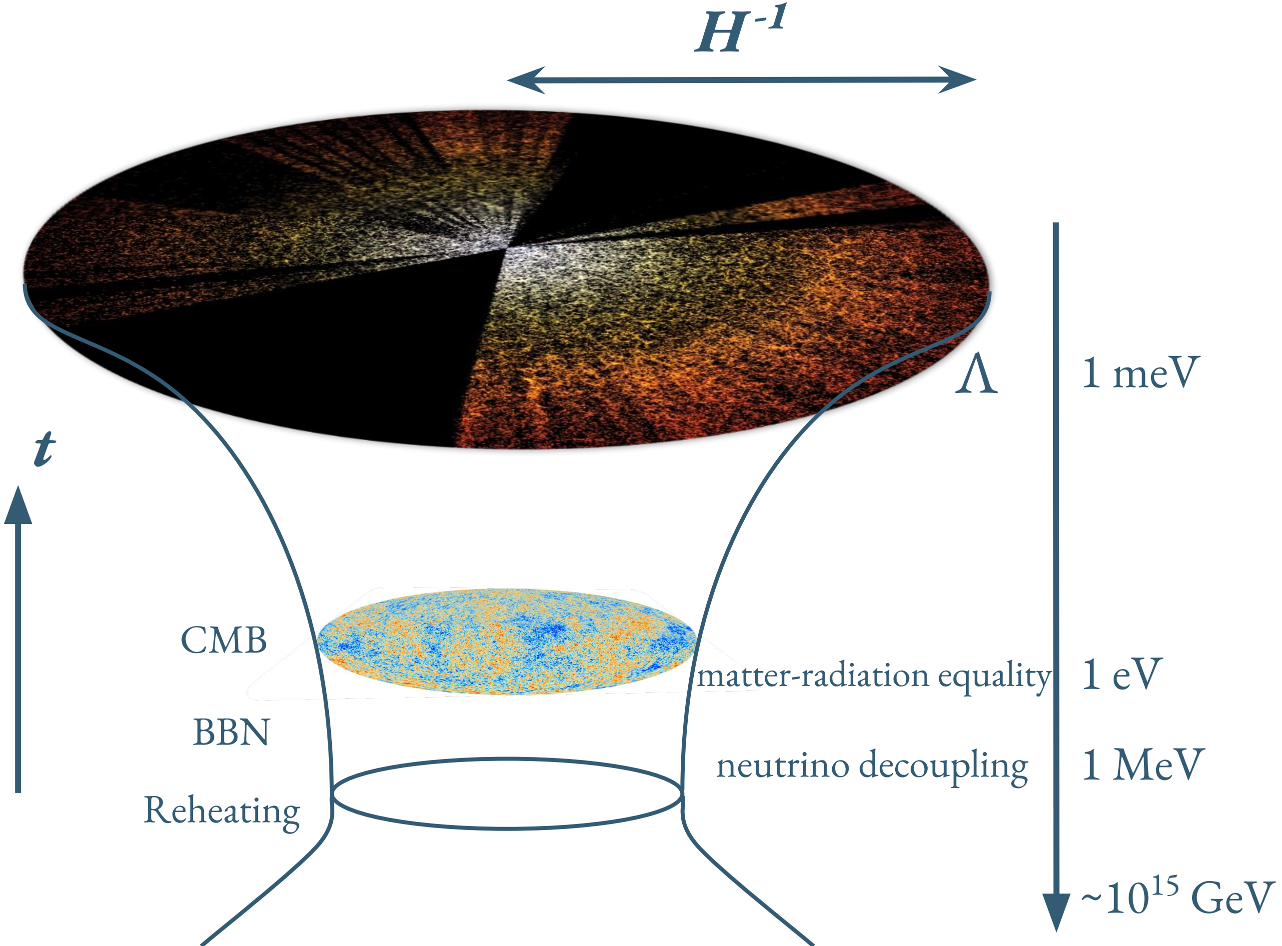
$$\delta_\ell(\boldsymbol{k}) \lesssim \mathcal{O}(1) \text{ for } k \lesssim \Lambda_s^{-1} \lesssim k_{\mathrm{nl}}$$

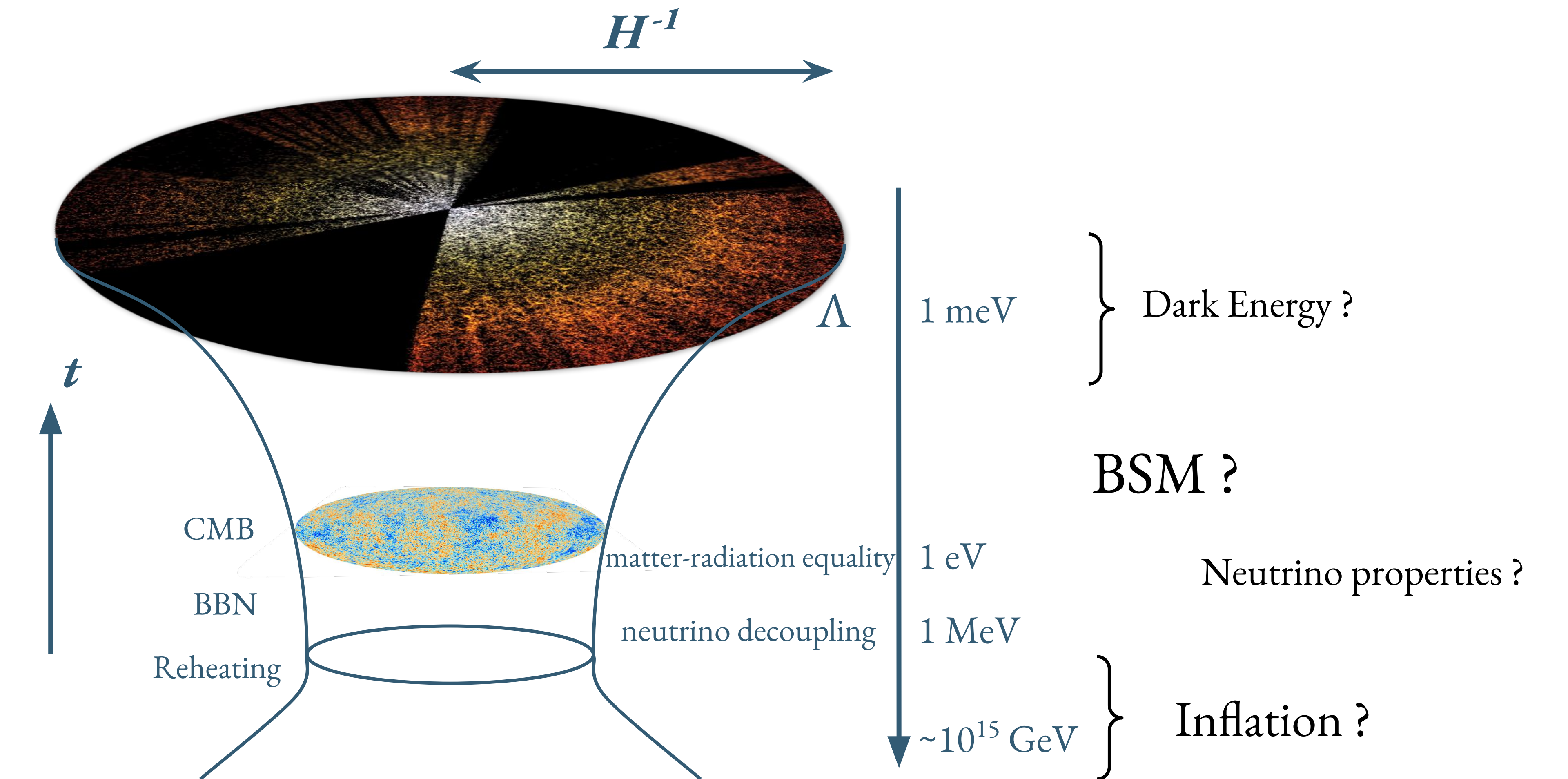
— In this talk —

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

What galaxies at long distances can tell us?

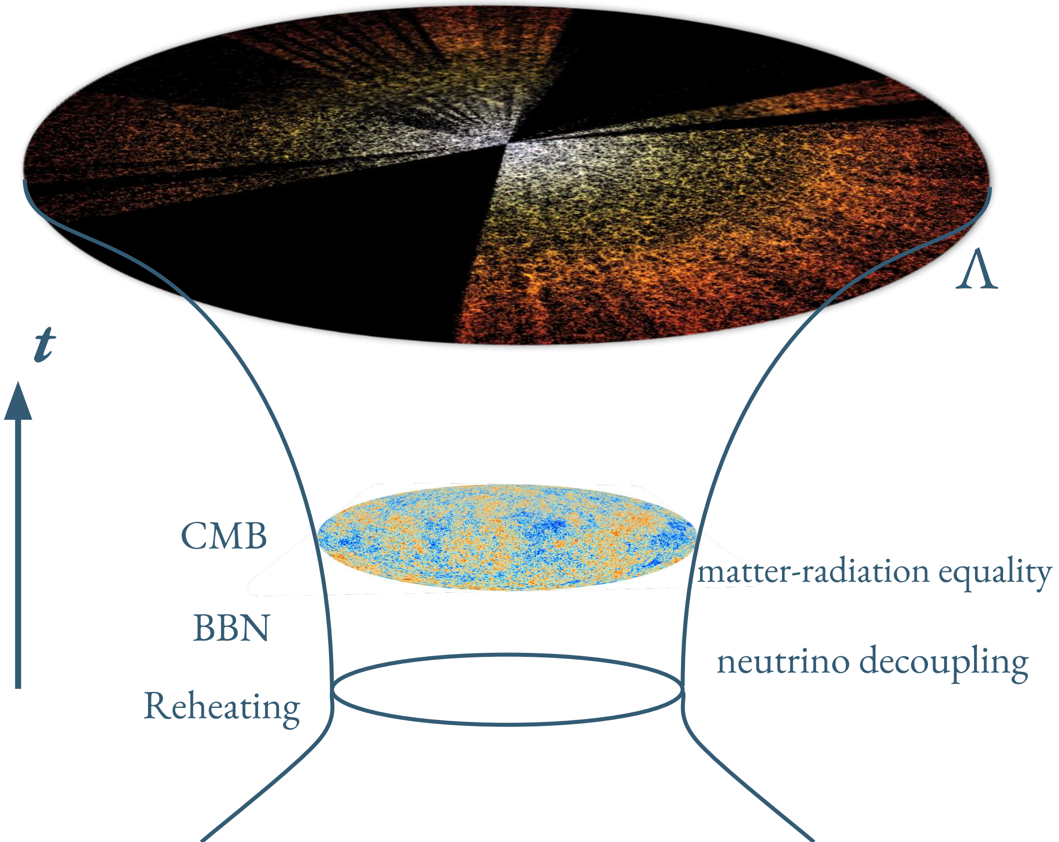
The Universe as a Microscope





H^{-1}
Λ
t
CMB
BBN
Reheating
matter-radiation equality
neutrino decoupling
1 meV
1 eV
1 MeV
~10^{15} GeV
Dark Energy ?
BSM ?
Neutrino properties ?
Inflation ?

EFT: a natural language to decipher the Universe



Galaxies formation:

- ✔ On large scales: Equivalence principle
- ✔ Coarse-grained fluid-like description

Hot Big-Bang:

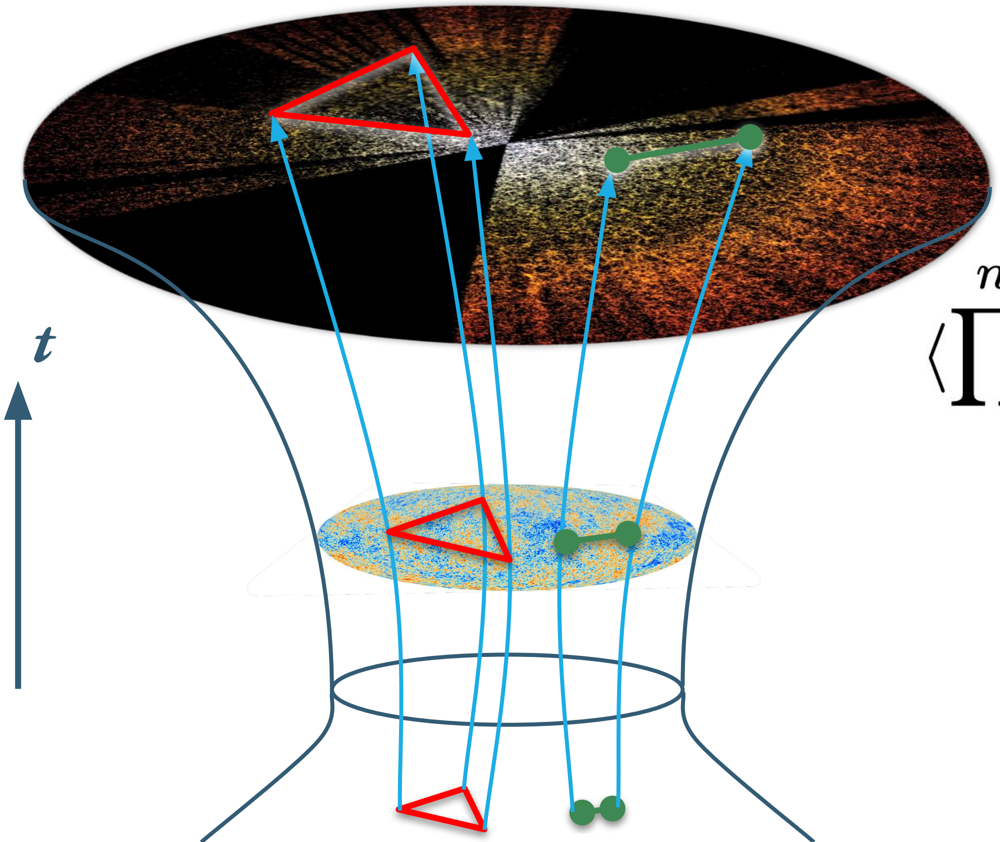
- ✔ Weakly-perturbed plasma
- ✔ Linear theory

Inflation:

- ✔ Near-de Sitter phase
- ✔ Spontaneously-broken time translation

— In this talk —

map = {correlators}



$$\langle \prod^{n} \delta_a^{\rm gal} \rangle \sim \sum^{d} \prod^{n} \mathcal{K}_a \; \langle \prod^{m} \delta_{a'}^{\rm lin} \rangle$$

$$\langle \prod^{n} \delta_a^{\rm lin} \rangle \sim \prod^{n} \Delta_a \; \langle \prod^{n} \zeta_a \rangle$$

— Plan —

Part 1 - The LSS as a *coarse-grained, effective* field

Part 2 - The *"Pen & Paper"* approach in action

Part 3 - Insights from galaxies at long distances *beyond 2pt*

— 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.*, δ, δ_b, δ_g, v, ...

Ingredients

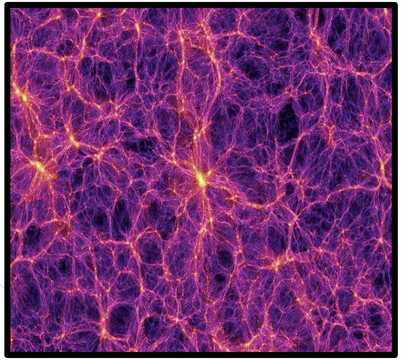
- Dark matter: *Continuity* and *Euler equations* (coarse-grained)
- Gravity: *Poisson equation* $\partial^2\Phi \sim \delta$
- Symmetries: *Galilean invariance* $x \to x + n,\ v \to v + \partial_t n$

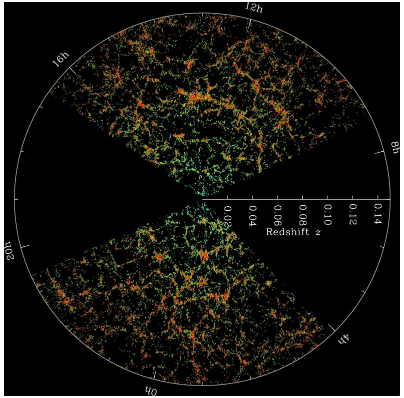
Weinberg 03, Kehagias, Riotto, Peloso, Pietroni, Creminelli, Gleyzes, Noreña, Simonović, Vernizzi 13

Receipe

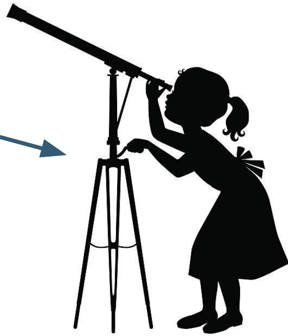
- Solve dark matter equations perturbatively
  - $\delta = \delta_1 + \delta_2 + \dots$
- For unknowns, write down all terms allowed by the symmetries with free Wilson coefficients
  - $\delta_g = b_1 \delta_1 + b_2 \delta_2 + \dots$
- For UV-sensitive operation, add counterterms

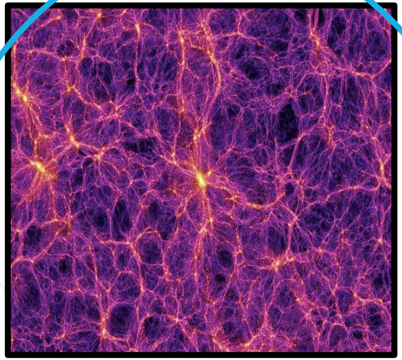
— Roadmap —

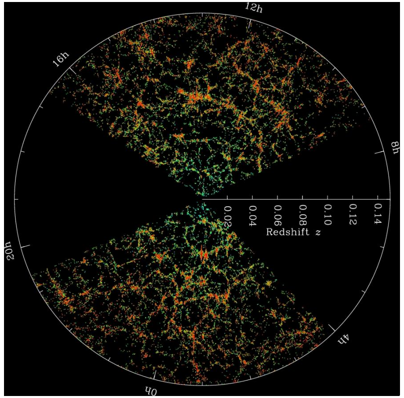




$\zeta(\mathbf{x})$ → Perturbation theory → $\delta(\mathbf{x})$ → Bias expansion → $\delta_g(\mathbf{x})$ → Redshift space distortions → $\delta_g(z)$







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Perturbation theory

$\delta(\mathbf{x})$

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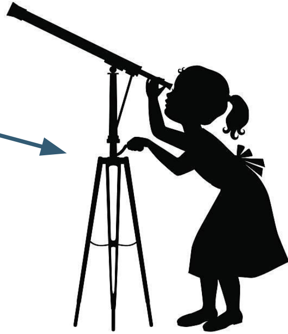

— Dark matter —

review: 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

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

Momentum conservation

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

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

— Dark matter —

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

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

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

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

— Dark matter —

review: Bernardeau, Colombi, Gaztanaga, Scoccimarro 01

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

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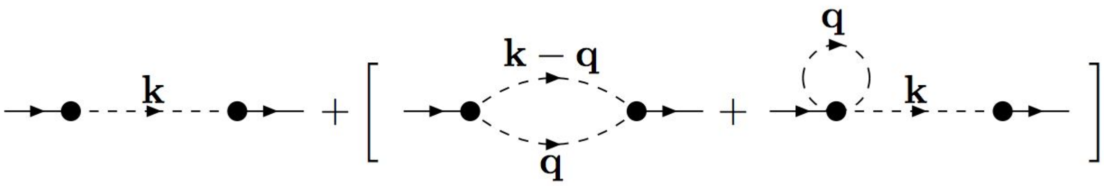

(P_{11}) (P_{22}) (P_{13})

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

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

PT contributions

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

— Dark matter —

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

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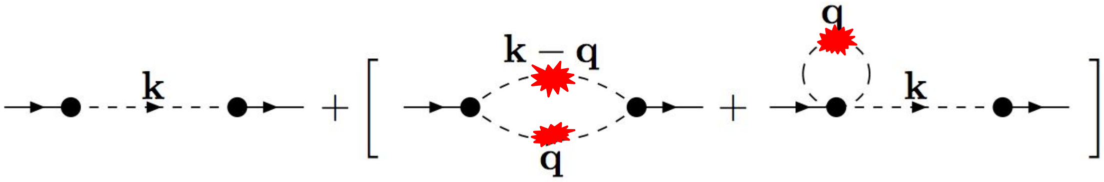

(P_{11}) (P_{22}) (P_{13})

But divergent integrals !

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

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PT contributions

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

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

— Dark matter —

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

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

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

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

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

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

— Dark matter —

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

Coarse-graining

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

leads to a

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

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

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

Stress tensor
enclosing short-distance physics

for the long-distance fluid

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

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

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

EFT expansion

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

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

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

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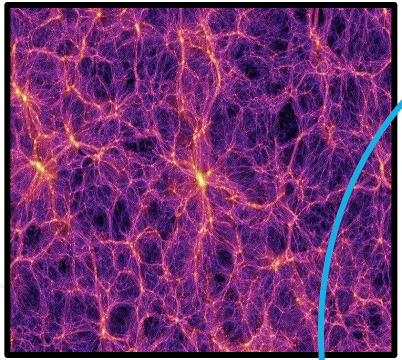
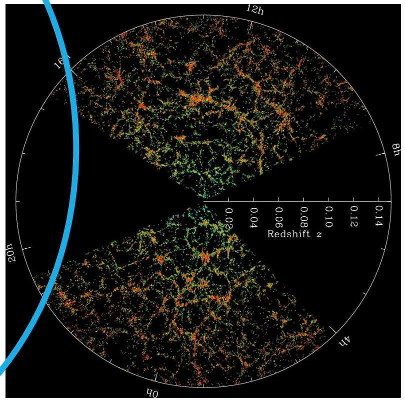
$$\dot{v}^i_\ell + H v^i_\ell + \frac{1}{a} v^j \partial_j v^i_\ell + \frac{1}{a}\partial_i \Phi_\ell = -\frac{1}{a}\partial_i \left(\frac{1}{\rho_\ell}\partial_j \tau^{ij}\right)_s \quad \sim c_s^2(a)\frac{\partial^2}{k^2_{\rm NL}}\delta_\ell + \ldots$$

Renormalization

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

Pajer, Zaldarriaga 13





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Perturbation theory

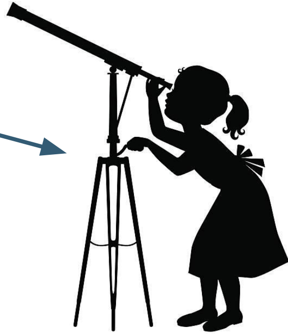
$\delta(\mathbf{x})$

Bias expansion

$\delta_g(\mathbf{x})$

Redshift space distortions

$\delta_g(z)$



— Galaxy bias expansion —

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

$$\delta_g(\boldsymbol{x},t) = \int^t dt'\, f\Big(\overbrace{\partial_i\partial_j\Phi(\boldsymbol{x},t'), \partial_i v_j(\boldsymbol{x},t')}^{\text{(Galilean inv.) fluctuations}}, \underbrace{\partial_i/k_{\rm M}}_{\text{(spatial) gradients}}, \overbrace{\epsilon_{ij}(\boldsymbol{x},t')}^{\text{stochasticity}}, \underbrace{\kappa_\star(t,t')}_{\text{time responses}}\Big)$$

— Galaxy bias expansion —

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Remarks

- Fluid expansion $\boldsymbol{x} \to \boldsymbol{x}_{\mathrm{fl}} = \boldsymbol{x} + \int_t^{t'} \frac{dt''}{a(t'')}\boldsymbol{v}(\boldsymbol{x}_{\mathrm{fl}}(\boldsymbol{x},t,t'),t'')$
- Equivalent to *local-in-time* basis up to 4th order, w/ D'Amico, Donath, Lewandowski, Senatore 22a

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

  - ... but not at 5th order! Donath, Lewandowski, Senatore 23
- An equivalent formulation (up to renormalisation) is,

  Consider *local-in-time* expansion & advect with LPT displacements Schmidt 21

— Galaxy bias expansion —

At the end of the day,

$$\delta_g(\boldsymbol{x}, t) = \sum_{n=1} b_\alpha(t)\ \mathcal{O}_\alpha^{(n)}(\boldsymbol{x}, t)$$

"Galaxy" overdensity

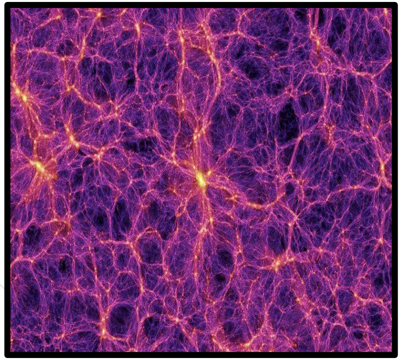
⇔ Map coarse-grained 3D "pixel"

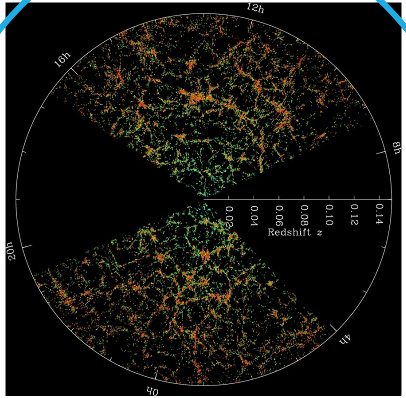
Wilson coefficients

Parametrize our ignorance of short-scale "astro"-physics

Operator Expansion governed by Equivalence Principle

$$\mathcal{O}_\alpha^{(n)} \equiv \mathcal{O}_\alpha^{(n)}[\partial_i\partial_j\Phi, \partial_i]$$





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— Redshift space —

Matsubara 08, Lewandowski, Senatore, Zaldarriaga, ... 14-16
w/ D'Amico, Donath, Lewandowski, Senatore 22a

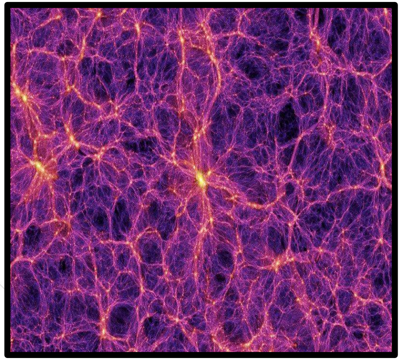
- Comoving coordinates relation real space to redshift space: $\boldsymbol{x} \to \boldsymbol{x} + (\boldsymbol{v}_{\mathcal{H}} \cdot \hat{z})\hat{z}$ $\quad (\boldsymbol{v}_{\mathcal{H}} \equiv \boldsymbol{v}/\mathcal{H})$

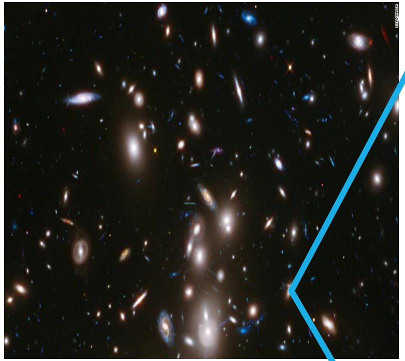
$$\delta \to \delta + \sum_{n=1} \frac{(-1)^n}{n!} \prod_{a=1}^{n} \partial_{i_a} \left((1+ \boxed{\delta) \prod_{b=1}^{n} v_{\mathcal{H}}^{i_b}} \right) \hat{z}^{i_a} \hat{z}^{i_b}$$

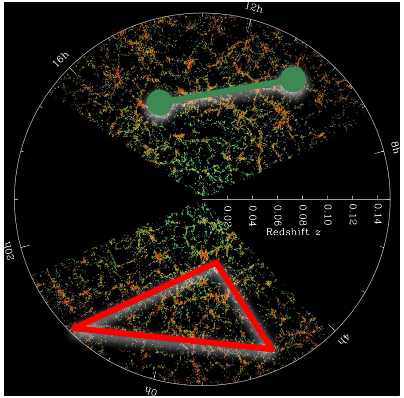
- Counterterms are added such that products of local operators have the correct properties under Galilean transformations ...

- *e.g.*, $\delta v_{\mathcal{H}}^i \supset c_{\rm rs}\, \partial_i \delta_1 / k_{\rm rs}^2$

$$[v^i]_R \to [v^i]_R + \chi^i \;,$$
$$[v^i v^j]_R \to [v^i v^j]_R + [v^i]_R \chi^j + [v^j]_R \chi^i + \chi^i \chi^j$$
$$[\delta_h v^i]_R \to [\delta_h v^i]_R + [\delta_h]_R \chi^i$$







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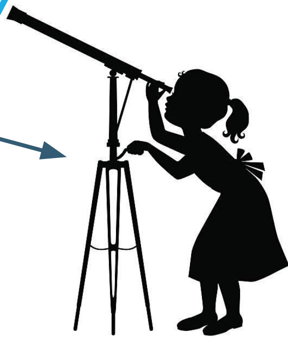


— Correlation function —

- A pedestrian's example

$$\delta_g(\boldsymbol{x},\tau) = F\Big(\partial_i\partial_j\phi(\boldsymbol{x},\tau), \partial_i v_j(\boldsymbol{x},\tau), \partial_i\partial_j/k_{\rm M}^2, \epsilon_{ij}(\boldsymbol{x},\tau), c_n(\tau)\Big)$$

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

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

— Correlation function —

- A pedestrian's example

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

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

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

— Correlation function —

- A pedestrian's example

$$\delta_g(\boldsymbol{x},\tau) = F\Big(\partial_i\partial_j\phi(\boldsymbol{x},\tau), \partial_i v_j(\boldsymbol{x},\tau), \partial_i\partial_j/k_{\rm M}^2, \epsilon_{ij}(\boldsymbol{x},\tau), c_n(\tau)\Big)$$

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

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

— Correlation function —

- A pedestrian's example

$$\delta_g(\boldsymbol{x},\tau) = F\Big(\partial_i\partial_j\phi(\boldsymbol{x},\tau), \partial_i v_j(\boldsymbol{x},\tau), \partial_i\partial_j/k_{\rm M}^2, \epsilon_{ij}(\boldsymbol{x},\tau), c_n(\tau)\Big)$$

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

$$\langle\delta_g\delta_g\rangle \supset b_1^2\left(P_{11}(k) + \langle\delta^{(2)}\delta^{(2)}\rangle + 2\langle\delta^{(1)}\delta^{(3)}\rangle\right) + 2b_1c_s^2\frac{k^2}{k_{\rm NL}^2}P_{11}(k)$$

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

— Correlation function —

- A pedestrian's example

$$\delta_g(\boldsymbol{x},\tau) = F\Big(\partial_i\partial_j\phi(\boldsymbol{x},\tau), \partial_i v_j(\boldsymbol{x},\tau), \partial_i\partial_j/k_{\rm M}^2, \epsilon_{ij}(\boldsymbol{x},\tau), c_n(\tau)\Big)$$

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

$$\langle\delta_g\delta_g\rangle \supset b_1^2\left(P_{11}(k) + \langle\delta^{(2)}\delta^{(2)}\rangle + 2\langle\delta^{(1)}\delta^{(3)}\rangle\right) + 2b_1c_s^2\frac{k^2}{k_{\rm NL}^2}P_{11}(k)$$

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

— Correlation function —

- A pedestrian's example

$$\delta_g(\boldsymbol{x},\tau) = F\Big(\partial_i\partial_j\phi(\boldsymbol{x},\tau), \partial_i v_j(\boldsymbol{x},\tau), \partial_i\partial_j/k_{\rm M}^2, \epsilon_{ij}(\boldsymbol{x},\tau), c_n(\tau)\Big)$$

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

$$\langle\delta_g\delta_g\rangle \supset b_1^2\left(P_{11}(k) + \langle\delta^{(2)}\delta^{(2)}\rangle + 2\langle\delta^{(1)}\delta^{(3)}\rangle\right) + 2b_1c_s^2\frac{k^2}{k_{\rm NL}^2}P_{11}(k)$$

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

$$\langle\delta_g\delta_g\rangle \supset 2b_1b_2\langle\delta^{(2)}\delta^2\rangle + b_2^2\langle\delta^2\delta^2\rangle$$

Part 1 - The LSS as a *coarse-grained, effective* field

Part 2 - The *"Pen & Paper"* approach in action

One comment.

One technical point.

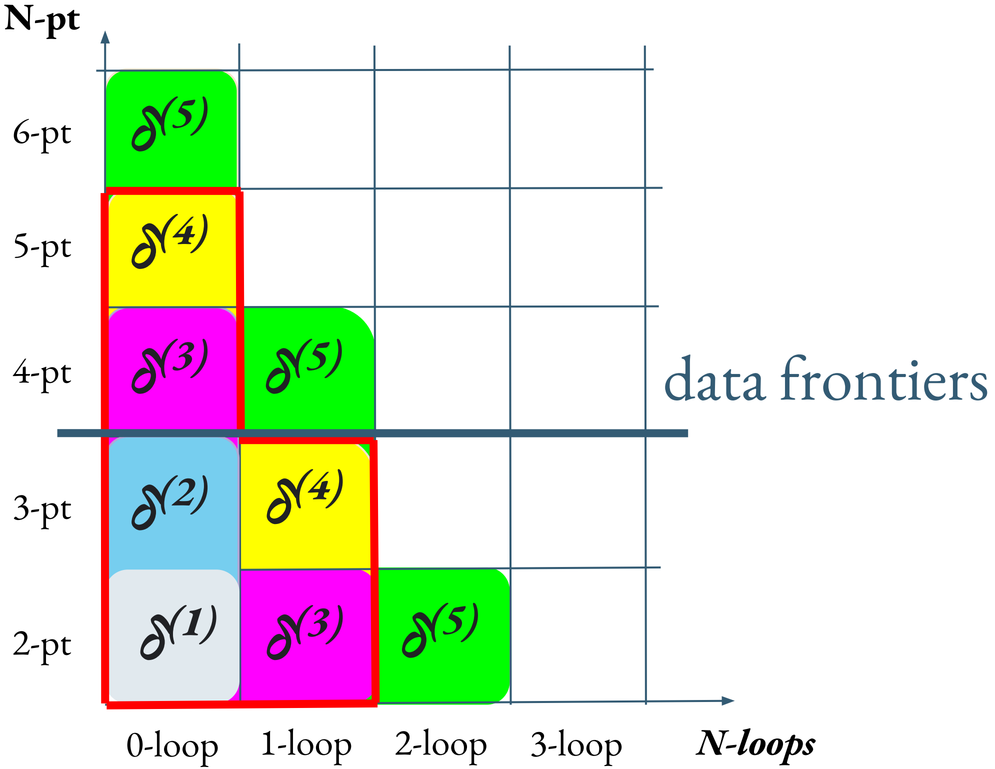
Some validations.

One example.

Part 3 - Insights from galaxies at long distances *beyond 2pt*

— EFT & Galaxy Survey —

- Where are we?



	DM	*Gal*	*RSD*
$\delta^{(3)}$	✓	✓	✓
$\delta^{(4)}$	✓	✓	✓
$\delta^{(5)}$	✓	✓	✗

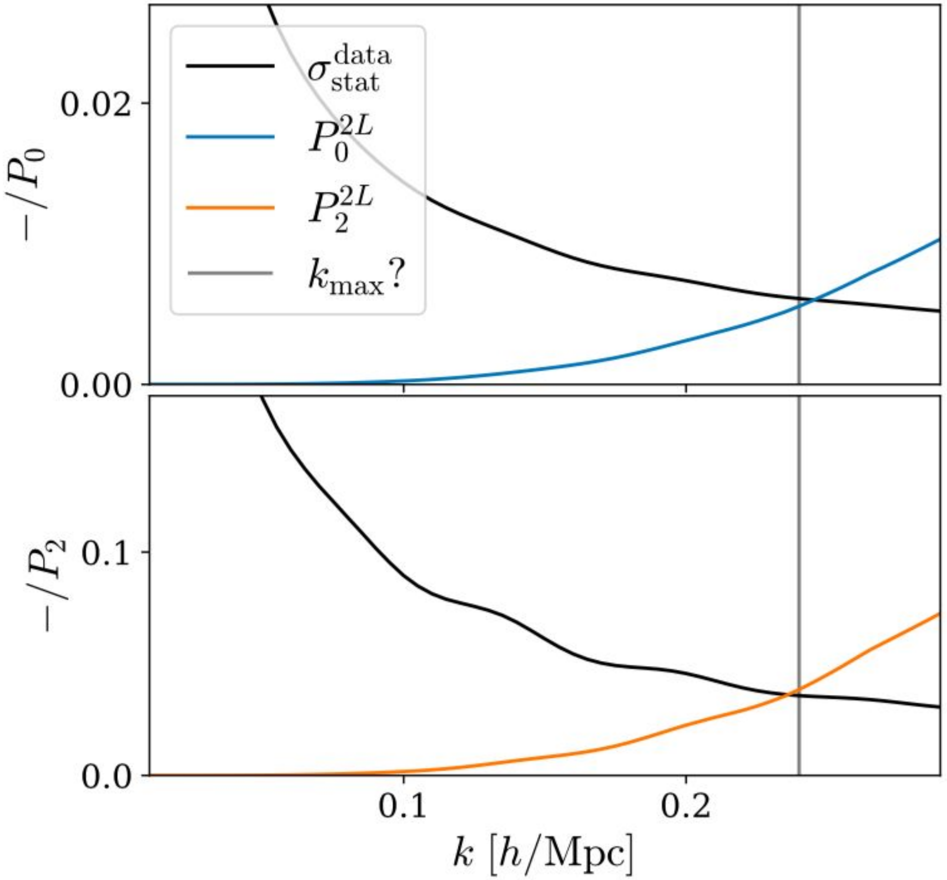
One aspect of EFT analyses

The Scale cut

— EFT scale cut —

w/ D'Amico, Senatore, Nishimichi 21
w/ D'Amico Senatore, Zhao, Cai 21
w/ Simon & Poulin 22

- What error we make when truncating the EFT expansion?



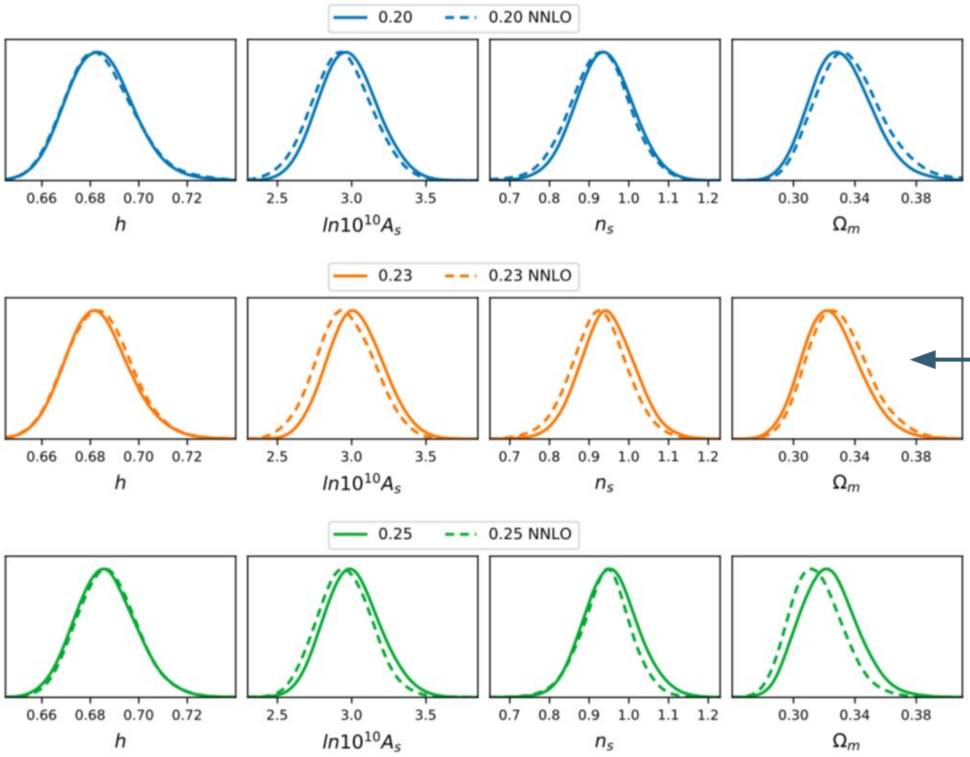
Theory error at 1-loop (NLO) = 2-loop (NNLO)

$$P_{2L}^{\mu=0}(k) \sim c_e \frac{k^2}{k_{\rm M}^2} P_{1L}^{\mu=0}(k)$$

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

— EFT scale cut —

w/ D'Amico, Senatore, Nishimichi 21
w/ D'Amico Senatore, Zhao, Cai 21
w/ Simon & Poulin 22



1. Self-determination of scale cut

from measuring shift upon adding NNLO

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

2. Automatic calibration of governing scales

such that $|c_{NLO}| \sim |c_{NNLO}| \sim O(1)$

$$k_{\rm M}^{\rm BOSS} = 0.7h\,{\rm Mpc}^{-1}, \qquad k_{\rm R}^{\rm BOSS} = 0.35h\,{\rm Mpc}^{-1},$$
$$k_{\rm M}^{\rm eBOSS} = 0.7h\,{\rm Mpc}^{-1}, \qquad k_{\rm R}^{\rm eBOSS} = 0.25h\,{\rm Mpc}^{-1}.$$

Disclaimer: Most analyses in this talk are setting w_b to BBN preferred value

EFT pipelines

Some validations

- PyBird: *https://github.com/pierrexyz/pybird*
  w/ D'Amico & Senatore 20

Also: Velocileptors, CLASS-PT, PBJ, FOLPS, CLASS-OneLoop, …

— Tests against simulations —

For BOSS 2pt @1-loop

— Lettered challenge —

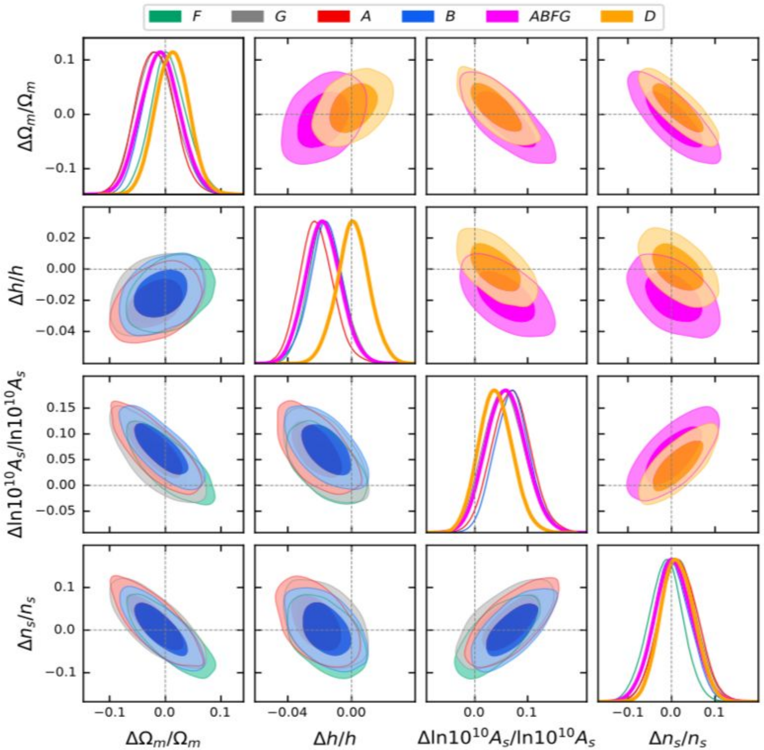
$L_{box} \sim (2.5\ Gpc/h)^3$

$V_{tot} \sim 6\ V_{BOSS}$

w/ D'Amico, Gleyzes, Kokron, Markovic, Senatore, Beutler, Gil-Marin 19

w/ Colas, D'Amico, Senatore, Beutler 19

In real space w/ D'Amico, Senatore, Zhao, Cai 21



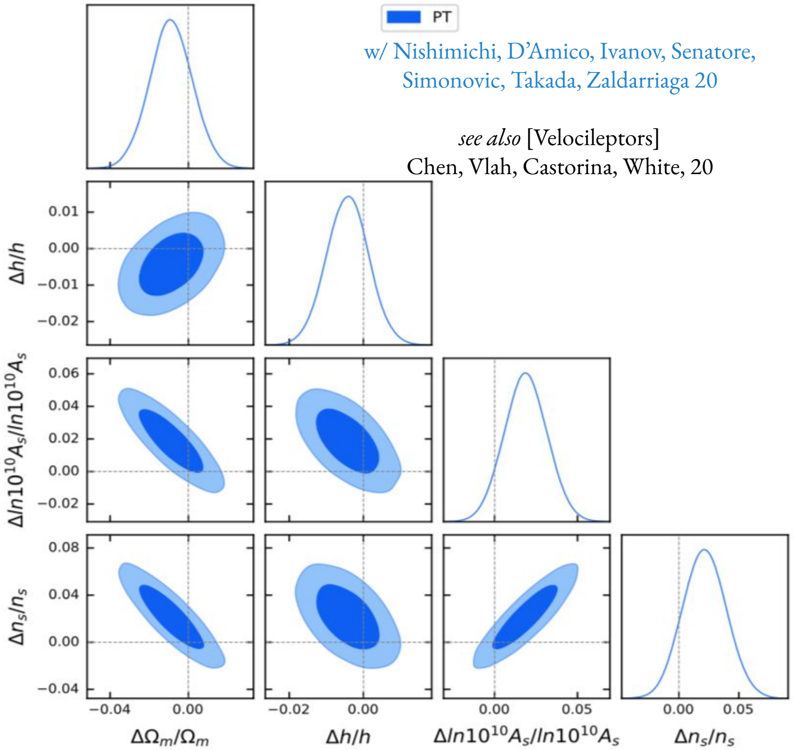
— [blind] PT challenge —

$V_{box} \sim 566\ (Gpc/h)^3$

$V_{tot} \sim 100\ V_{BOSS}$

w/ Nishimichi, D'Amico, Ivanov, Senatore, Simonovic, Takada, Zaldarriaga 20

see also [Velocileptors] Chen, Vlah, Castorina, White, 20

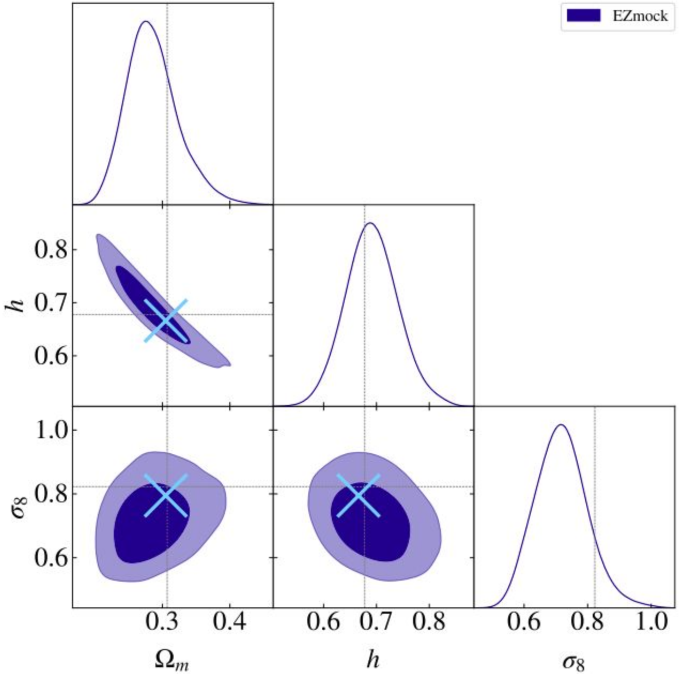


— Tests against simulations —

For eBOSS 2pt @1-loop

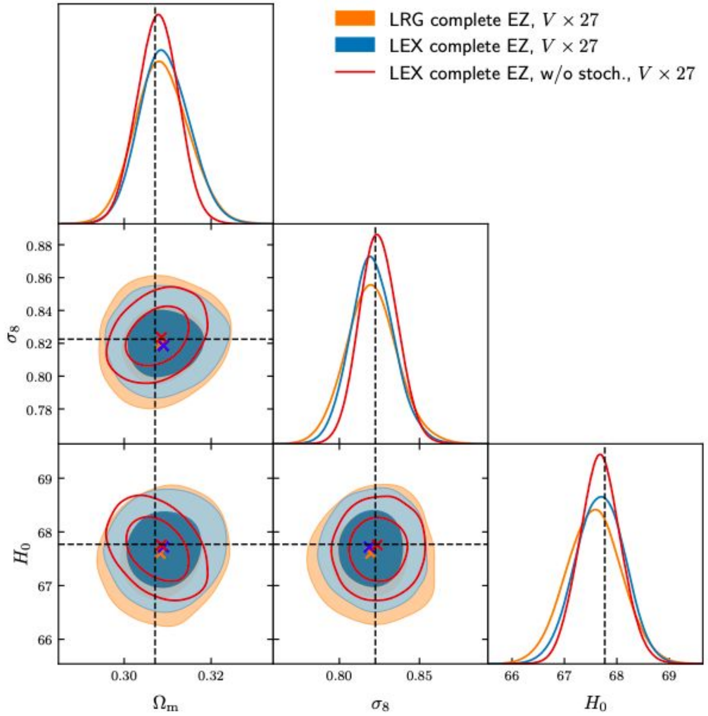
— QSO —

w/ Simon & Poulin 22
Ivanov & Chudaykin 22



— LRG + ELG —

[multi-tracers] Zhao *et al.* 23
Ivanov 21

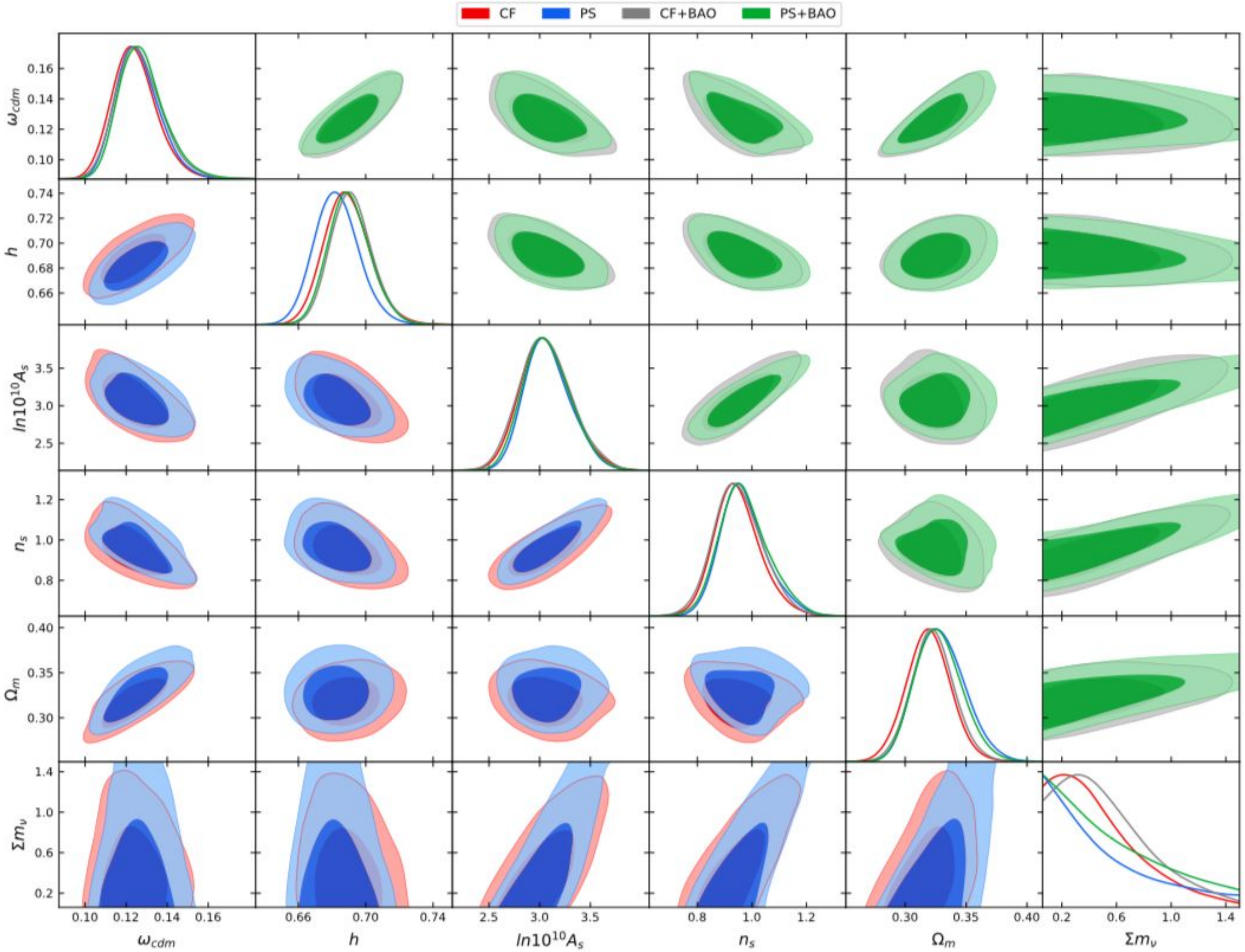


— Pipeline comparison —

For BOSS 2pt @1-loop

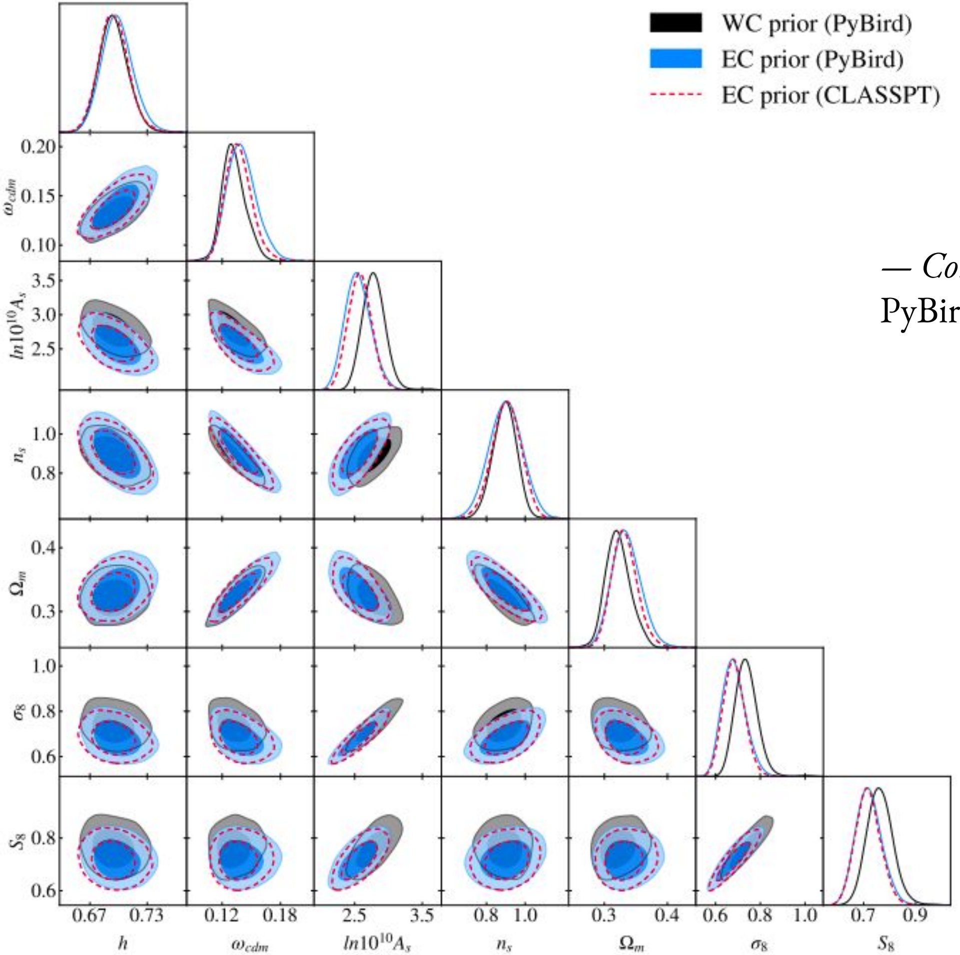
— Consistency PS vs. CF —

w/ D'Amico, Senatore, Cheng, Cai 21



— Pipeline comparison —

For BOSS 2pt @1-loop



— Consistency of BOSS EFT analyses —

PyBird vs. CLASS-PT

w/ Simon, Poulin, Smith 22

For other comparisons, see also

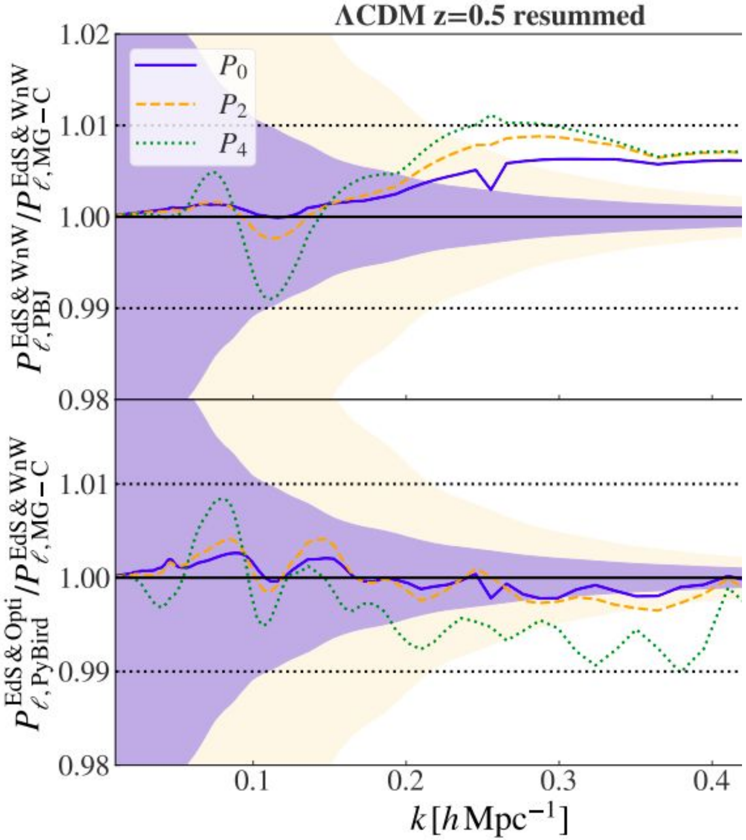
[PBJ] Carrilho, Morettia, Pourtsidou 22

[CLASS-OneLoop] Linde, Moradinezhad Dizgah, Radermacher, Casas, Lesgourgues 24

— Pipeline comparison — *For LSS-S4 2pt @1-loop*

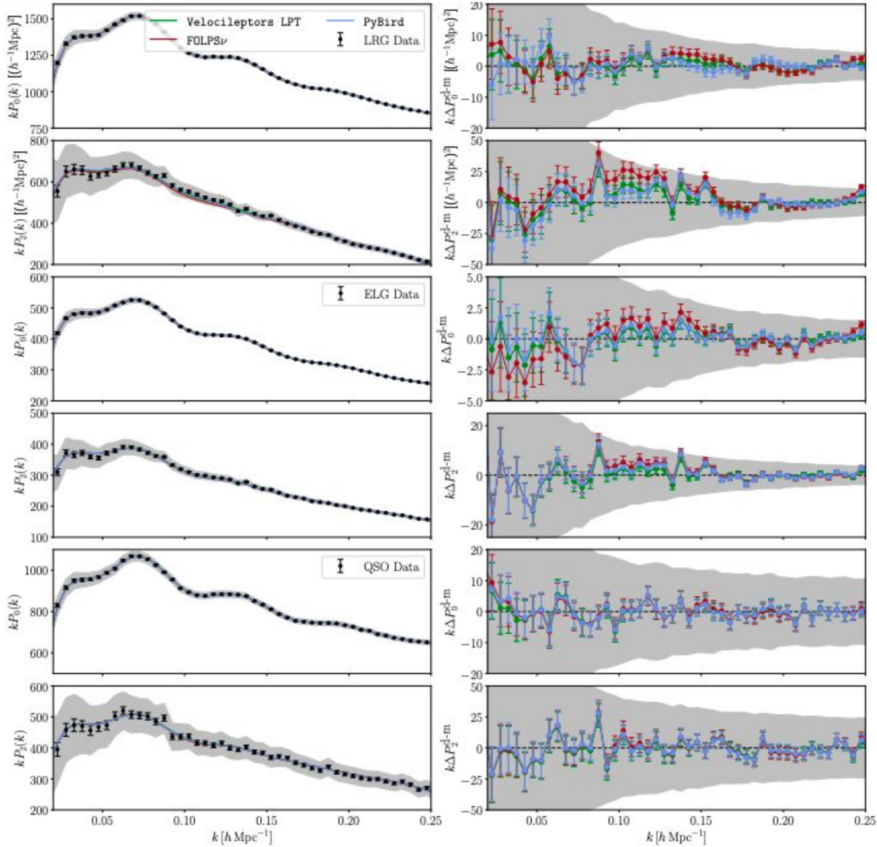
— Euclid collaboration — Bose *et al.* 24

PyBird vs. PBJ vs. MG-Copter (vs. simulations)



— DESI collaboration — Maus *et al.* 24

PyBird vs. Velocileptors vs. FOLPS (vs. Abacus simulations.)



Part 1 - The LSS as a *coarse-grained, effective* field

Part 2 - The *"Pen & Paper"* approach in action

Part 3 - Insights from galaxies at long distances *beyond 2pt*

BOSS 2+3pt @ 1-loop

[theory] w/ D'Amico, Donath, Lewandowski, Senatore 22a
[code] Anastasiou, Bragança, Senatore, Zheng 22
[analysis] w/ D'Amico, Donath, Lewandowski, Senatore 22b

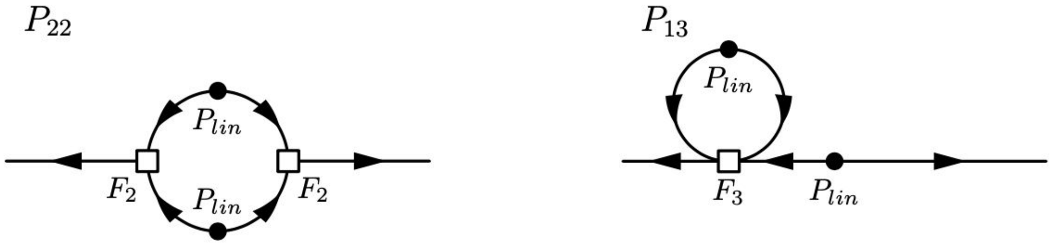
— Galaxies in redshift space —

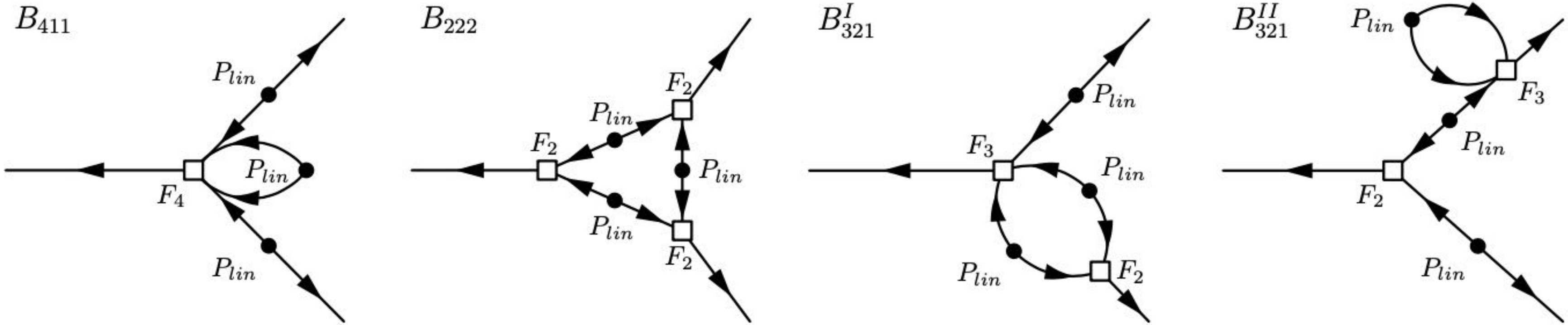
2+3pt @1-loop

w/ D'Amico, Donath, Lewandowski, Senatore 22a

$$P^{r,h}_{\text{1-loop tot.}} = P^{r,h}_{11} + (P^{r,h}_{13} + P^{r,h,ct}_{13}) + (P^{r,h}_{22} + P^{r,h,\epsilon}_{22})$$

$$B^{r,h}_{\text{1-loop tot.}} = B^{r,h}_{211} + (B^{r,h,(II)}_{321} + B^{r,h,(II),ct}_{321}) + (B^{r,h}_{411} + B^{r,h,ct}_{411})$$
$$+ (B^{r,h}_{222} + B^{r,h,\epsilon}_{222}) + (B^{r,h,(I)}_{321} + B^{r,h,(I),\epsilon}_{321})$$





— Galaxies in redshift space —

2+3pt @1-loop

w/ D'Amico, Donath, Lewandowski, Senatore 22a

$$P^{r,h}_{\text{1-loop tot.}} = P^{r,h}_{11} + (P^{r,h}_{13} + P^{r,h,ct}_{13}) + (P^{r,h}_{22} + P^{r,h,\epsilon}_{22})$$

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➢ PT contributions

$$P^{r,h}_{11}[b_1]\ , \quad P^{r,h}_{13}[b_1, b_3, b_8]\ , \quad P^{r,h}_{22}[b_1, b_2, b_5]\ ,$$

$$B^{r,h}_{211}[b_1, b_2, b_5]\ , \quad B^{r,h,(II)}_{321}[b_1, b_2, b_3, b_5, b_8]\ , \quad B^{r,h}_{411}[b_1, \dots, b_{11}]\ ,$$

$$B^{r,h}_{222}[b_1, b_2, b_5]\ , \quad B^{r,h,(I)}_{321}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}]\ ,$$

— Galaxies in redshift space —

2+3pt @1-loop

w/ D'Amico, Donath, Lewandowski, Senatore 22a

$$P^{r,h}_{\text{1-loop tot.}} = P^{r,h}_{11} + \left(P^{r,h}_{13} + P^{r,h,ct}_{13}\right) + \left(P^{r,h}_{22} + P^{r,h,\epsilon}_{22}\right)$$

$$B^{r,h}_{\text{1-loop tot.}} = B^{r,h}_{211} + \left(B^{r,h,(II)}_{321} + B^{r,h,(II),ct}_{321}\right) + \left(B^{r,h}_{411} + B^{r,h,ct}_{411}\right) + \left(B^{r,h}_{222} + B^{r,h,\epsilon}_{222}\right) + \left(B^{r,h,(I)}_{321} + B^{r,h,(I),\epsilon}_{321}\right)$$

➢ PT contributions

$$P^{r,h}_{11}[b_1] \,, \quad P^{r,h}_{13}[b_1, b_3, b_8] \,, \quad P^{r,h}_{22}[b_1, b_2, b_5] \,,$$
$$B^{r,h}_{211}[b_1, b_2, b_5] \,, \quad B^{r,h,(II)}_{321}[b_1, b_2, b_3, b_5, b_8] \,, \quad B^{r,h}_{411}[b_1, \ldots, b_{11}] \,,$$
$$B^{r,h}_{222}[b_1, b_2, b_5] \,, \quad B^{r,h,(I)}_{321}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}] \,,$$

➢ Counterterm contributions

$$P^{r,h,ct}_{13}[b_1, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}] \,, \quad P^{r,h,\epsilon}_{22}[c^{\text{St}}_1, c^{\text{St}}_2, c^{\text{St}}_3] \,,$$
$$B^{r,h,(II),ct}_{321}[b_1, b_2, b_5, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}] \,, \quad B^{r,h,\epsilon,(I)}_{321}[b_1, c^{\text{St}}_1, c^{\text{St}}_2, \{c^{\text{St}}_i\}_{i=4,\ldots,13}] \,,$$
$$B^{r,h,ct}_{411}[b_1, \{c_{h,i}\}_{i=1,\ldots,5}, c_{\pi,1}, c_{\pi,5}, \{c_{\pi v,j}\}_{j=1,\ldots,7}] \,, \quad B^{r,h,\epsilon}_{222}[c^{(222)}_1, c^{(222)}_2, c^{(222)}_5] \,.$$

with insertions of *order in fields*

1st response
2nd response
1st stochastic
1st & 2nd stochastic

— Galaxies in redshift space — *2+3pt @1-loop*

w/ D'Amico, Donath, Lewandowski, Senatore 22a

- 11 bias / 14 response / 16 stochastic parameters
- All counterterms neccessary & sufficient for 2+3pt renormalisation @1loop

$$P^{r,h}_{\text{1-loop tot.}} = P^{r,h}_{11} + \left(P^{r,h}_{13} + P^{r,h,ct}_{13}\right) + \left(P^{r,h}_{22} + P^{r,h,\epsilon}_{22}\right)$$

$$B^{r,h}_{\text{1-loop tot.}} = B^{r,h}_{211} + \left(B^{r,h,(II)}_{321} + B^{r,h,(II),ct}_{321}\right) + \left(B^{r,h}_{411} + B^{r,h,ct}_{411}\right) + \left(B^{r,h}_{222} + B^{r,h,\epsilon}_{222}\right) + \left(B^{r,h,(I)}_{321} + B^{r,h,(I),\epsilon}_{321}\right)$$

➢ PT contributions

$$P^{r,h}_{11}[b_1]\,, \quad P^{r,h}_{13}[b_1, b_3, b_8]\,, \quad P^{r,h}_{22}[b_1, b_2, b_5]\,,$$
$$B^{r,h}_{211}[b_1, b_2, b_5]\,, \quad B^{r,h,(II)}_{321}[b_1, b_2, b_3, b_5, b_8]\,, \quad B^{r,h}_{411}[b_1, \ldots, b_{11}]\,,$$
$$B^{r,h}_{222}[b_1, b_2, b_5]\,, \quad B^{r,h,(I)}_{321}[b_1, b_2, b_3, b_5, b_6, b_8, b_{10}]\,,$$

➢ Counterterm contributions

$$P^{r,h,ct}_{13}[b_1, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}]\,, \quad P^{r,h,\epsilon}_{22}[c^{\rm St}_1, c^{\rm St}_2, c^{\rm St}_3]\,,$$
$$B^{r,h,(II),ct}_{321}[b_1, b_2, b_5, c_{h,1}, c_{\pi,1}, c_{\pi v,1}, c_{\pi v,3}]\,, \quad B^{r,h,\epsilon,(I)}_{321}[b_1, c^{\rm St}_1, c^{\rm St}_2, \{c^{\rm St}_i\}_{i=4,\ldots,13}]\,,$$
$$B^{r,h,ct}_{411}[b_1, \{c_{h,i}\}_{i=1,\ldots,5}, c_{\pi,1}, c_{\pi,5}, \{c_{\pi v,j}\}_{j=1,\ldots,7}]\,, \quad B^{r,h,\epsilon}_{222}[c^{(222)}_1, c^{(222)}_2, c^{(222)}_5]\,.$$

with insertions of *order in fields*

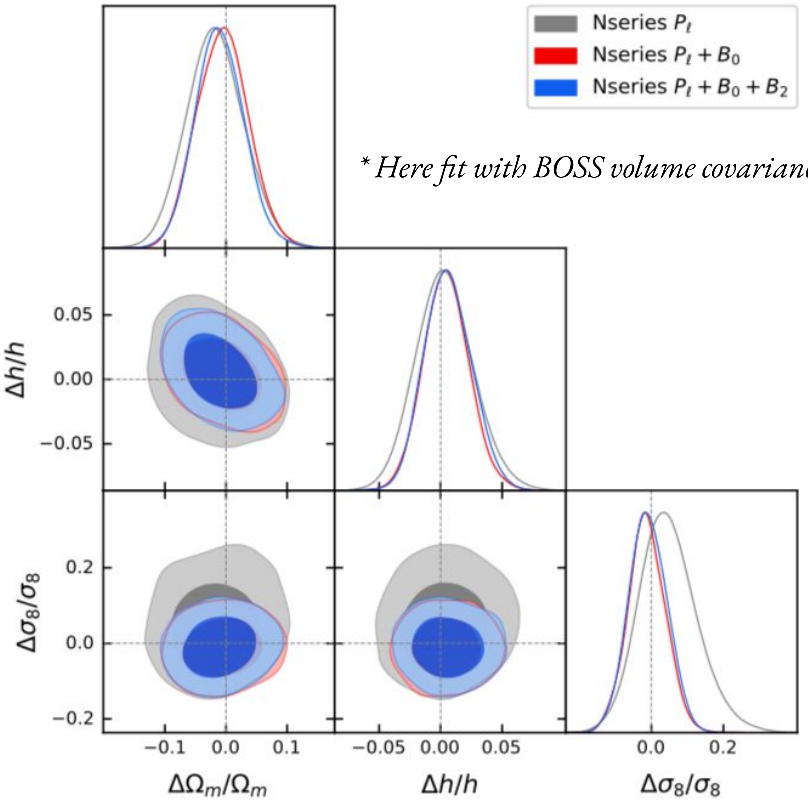
1st response
2nd response
1st stochastic
1st & 2nd stochastic

— Tests against simulations —

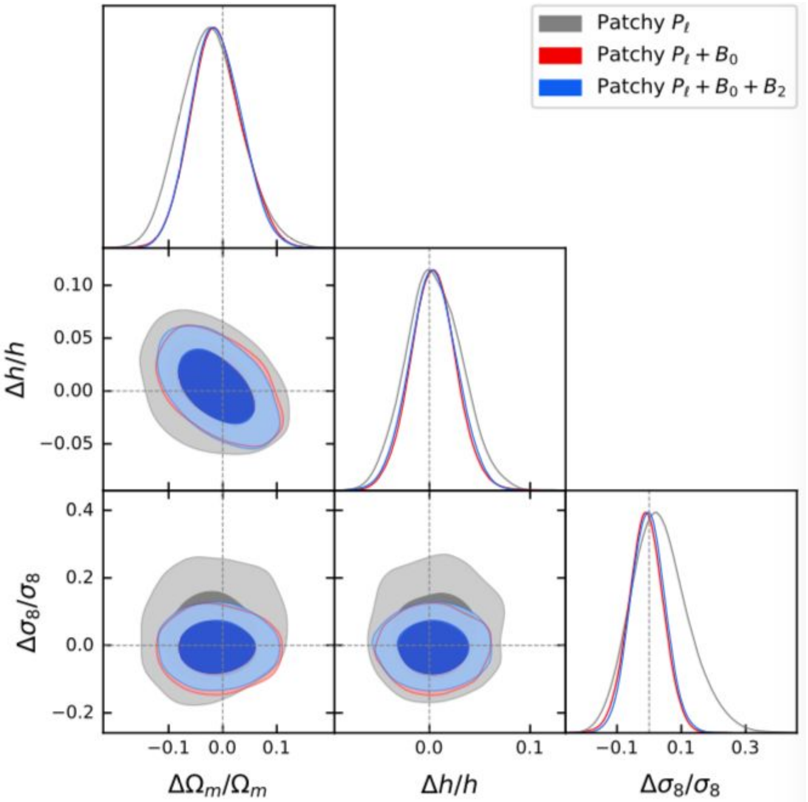
BOSS 2+3pt @1-loop

w/ D'Amico, Donath, Lewandowski, Senatore 22b

see also Philcox, Ivanov, Cabass, Simonovic, Zaldarriaga, Nishimichi 22



* *Here fit with BOSS volume covariance*



— Best-fit —

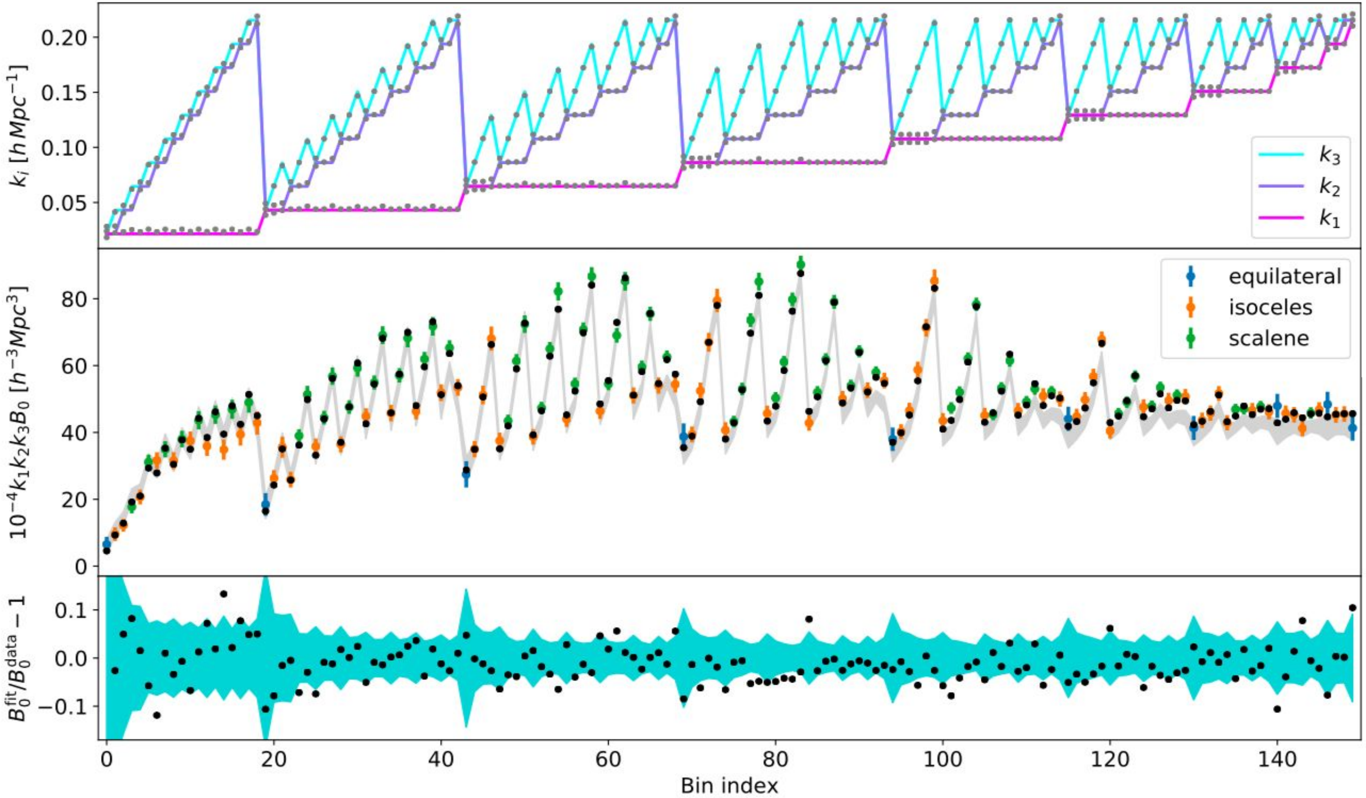
BOSS 2+3pt @1-loop

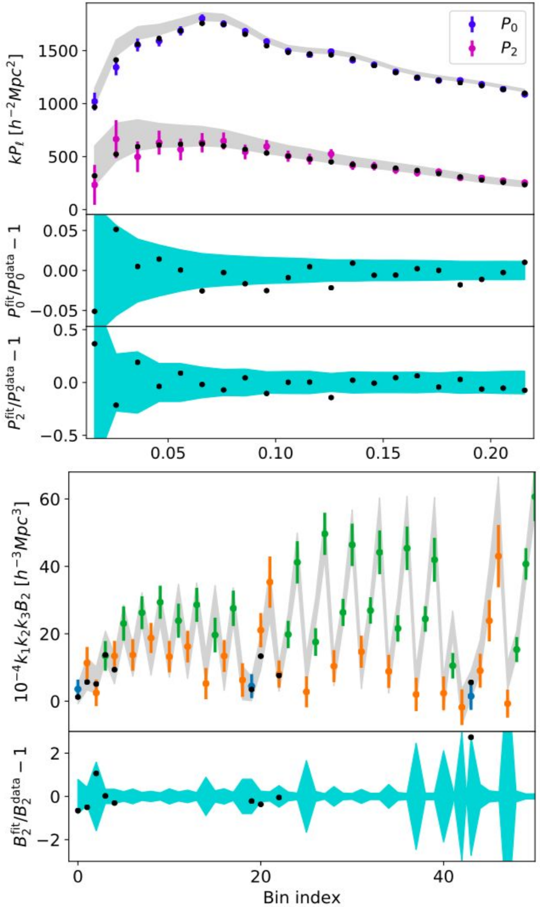
w/ D'Amico, Donath, Lewandowski, Senatore 22b

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

$$B_0(k) \mid k \in [0.01, 0.23]$$

$$B_2(k) \mid k \in [0.01, 0.08]$$

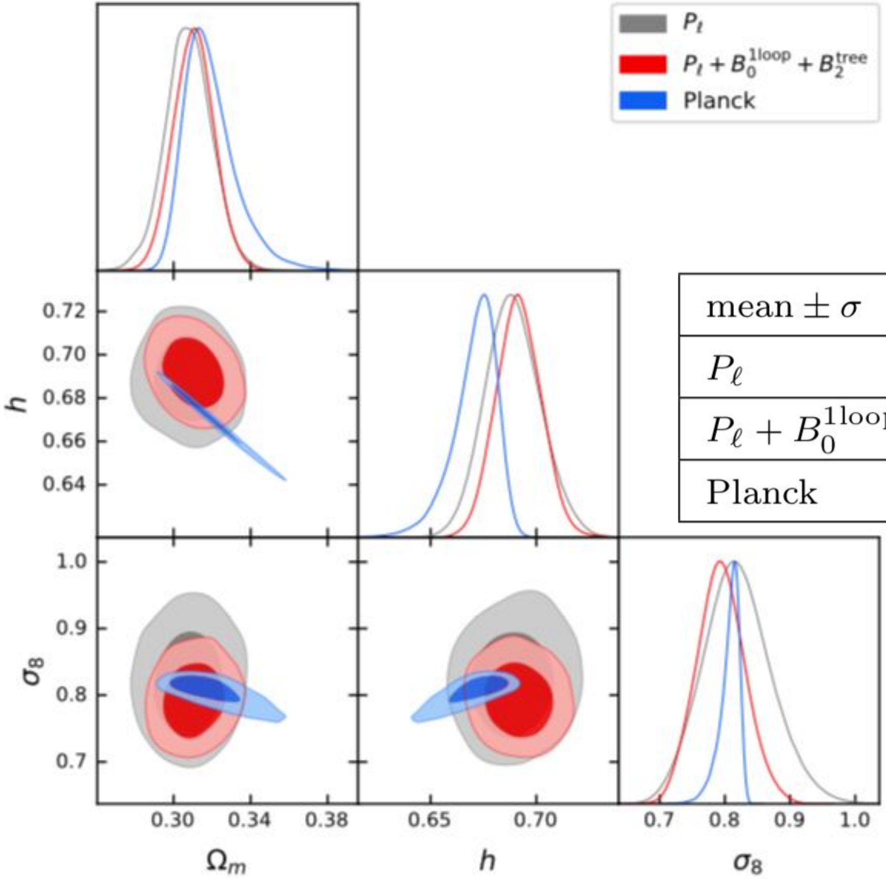




— ΛCDM —

BOSS 2+3pt @1-loop

w/ D'Amico, Donath, Lewandowski, Senatore 22b



➢ *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	$0.689^{+0.012}_{-0.014}$	$0.819^{+0.049}_{-0.055}$
$P_\ell + B_0^{1\text{loop}} + B_2^{\text{tree}}$	0.311 ± 0.010	0.692 ± 0.011	0.794 ± 0.037
Planck	$0.3191^{+0.0085}_{-0.016}$	$0.671^{+0.012}_{-0.0067}$	$0.807^{+0.018}_{-0.0079}$

See also [tree-level 3pt] Ivanov, Philcox, Cabass, Nishimichi, Simonovic,Zaldarriaga 23

— wCDM —

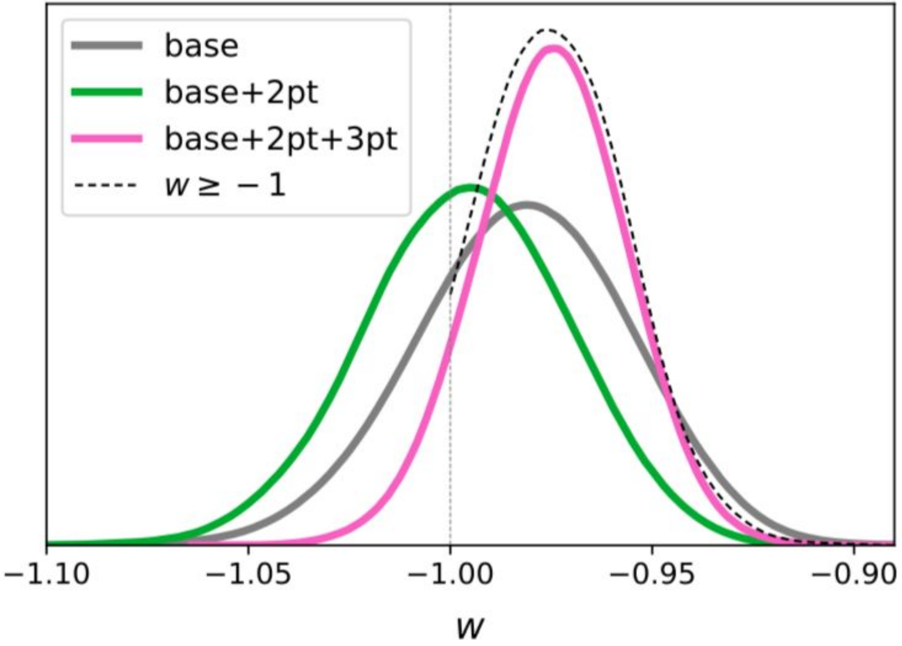
BOSS 2+3pt @1-loop

w/ Spaar 23

base = Planck + ext-BAO + PanPlus

wCDM					
	base	base+BAO	base+2pt	base+2pt+3pt (tree)	base+2pt+3pt (1loop)
w	-0.982 ± 0.027	-0.987 ± 0.026	-0.996 ± 0.026	-1.010 ± 0.025	-0.975 ± 0.019

~ 30% improvement



- ➢ First combined analysis w/ BOSS 2+3pt @1-loop
- ➢ … with actual improvements over Planck + BAO!

— A (not so) new strategy for extracting cosmology from galaxy surveys —
— *The "Pen & Paper" approach* —

- *"Cheap"*
  - *Well-defined, principle-based* framework for predicting galaxy correlators at large scales
  - *Flexible* exploration: for modification at background / linear level only, it is *Plug & Play*

- *"Little margin for mistakes"*
  - *Parametric control* over theory error
  - Assumptions are as *general* as possible: We work only with Equivalence Principle!

- *"Green"*
  - Likelihood is *analytic* (vs. simulation / ML based inference)
  - Iterations (over codes, models, etc.) are cheap

- *"Historical"*
  - Observational systematics, at least at the 2pt level, are well studied

- *"Benchmark"*
  - *NO reason to NOT do it*
  - Indeed now *standard* in DESI / Euclid

— Open questions —

There are limitations…

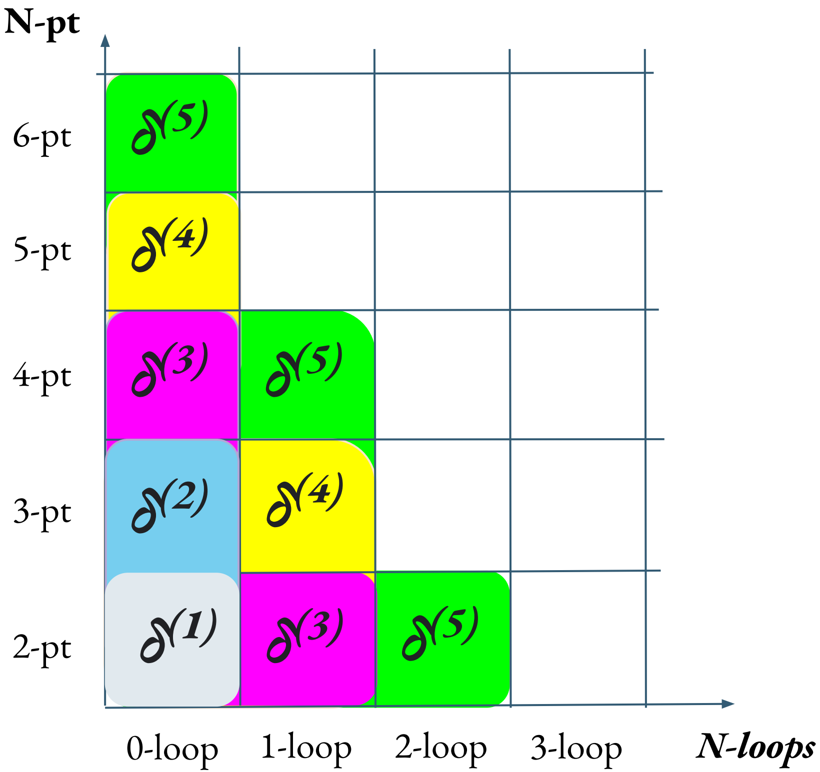
- Mildly nonlinear scales only. What to do with the small scales? SBI? Talks Chang?
- Many parameters to marginalise over our ignorance. Prior-informed analysis?

Beyond 2pt, *mainly a data analysis frontier*

- Need better estimation of covariance for 3pt
- No estimators beyond 3pt
- Systematics are not well understood
- Forward-model-based Inference is promising Talks Beatriz & Ivana?

— Last comment —

- I have the computer. Why not do full *Field-Level Inference*?



— Short answer —

Scale cuts

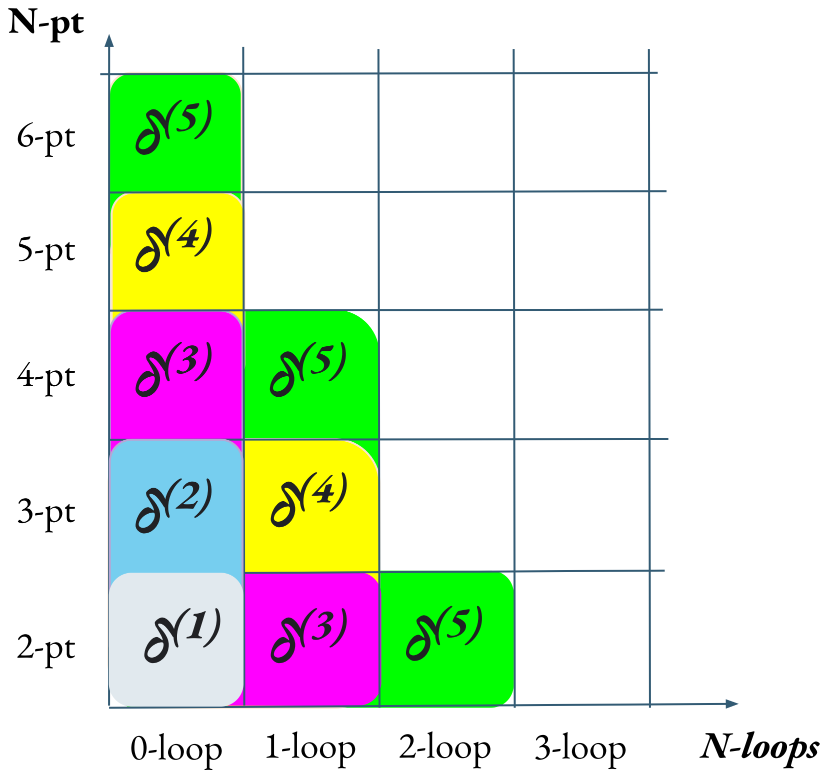
at Field Level

& on Correlators

are not *One-to-One*

— Last comment —

- I have the computer. Why not do full *Field-Level Inference*?



— Short answer —

Scale cuts

at Field Level

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are not *One-to-One*

Thank you!