Guido D'Amico

UNIVERSITÀ DI PARMA

INFN Istituto Nazionale di Fisica Nucleare

The EFTofLSS: an overview, latest developments, and going forward

Based on several works with L. Senatore, P. Zhang, Y. Donath, M. Lewandowski, et al.

https://github.com/pierrexyz/pybird

Theoretical Modelling of LSS, Edinburgh, 2024/6/3

What is this for?

- We are just starting to get a wealth of data. What's the end goal?

- Understanding the universe, which means measuring known and detecting unknown physics across a wide range of energy scales (neutrino masses, PNG, dynamical DE, light mediators, relics)

- As with any experimental information, we struggle for
  - Precision: more volume, more galaxies, more time
  - Accuracy: less and less systematics, and a reliable interpretation of the data

- EFTofLSS gives us just that – analytical understanding / parametrization of the system based on good old effective theory

The EFTofLSS: a humble approach

- Basic dofs and symmetries: CDM smoothed density and momentum, translations, rotations, diffs
- Physical cutoff of the theory: $k_{\rm NL}, k_{\rm R}$
- Expansion parameter: basically $k/k_{\rm NL}$, k/k_R
- Do perturbation theory, where possible.
  Resum non-perturbative effects
- Add biasing scheme to get to observable. Add eventual known systematics
- Apply to data. Analysis issues (priors, anyone?) will hopefully subside

Start from dark matter

Equations of motion for dark matter

$$\dot{\delta} + \frac{1}{a\bar{\rho}}\partial_i \pi^i = 0$$

$$\dot{\pi}^i + 4H\pi^i + \frac{\bar{\rho}}{a}\,\partial_i\Phi = -\frac{\partial_j}{a}\left(\frac{2M_{\rm Pl}^2}{a^2}\left(\partial_i\Phi\partial_j\Phi - \frac{1}{2}\delta_{ij}(\partial\Phi)^2\right) + \frac{\pi^i\pi^j}{\rho} + \tau^{ij}\right)$$

EFT stress-tensor $\tau^{ij} = \tau^{ij}_{\rm ct} + \tau^{ij}_{\epsilon}$

$$\tau^{ij}_{\rm ct} = c_1\left(\frac{\partial^i\partial^j\delta^{(1)}}{\partial^2} + \frac{\partial_k\partial^i\partial^j\delta^{(1)}}{\partial^2}\frac{\partial_k\delta^{(1)}}{\partial^2}\right) + c_3\delta^{ij}\left(\delta^{(1)} + \partial_k\delta^{(1)}\frac{\partial_k\delta^{(1)}}{\partial^2}\right)$$
$$+ c_2\left(\frac{\partial^i\partial^j\delta^{(2)}}{\partial^2} - \frac{\partial_k\partial^i\partial^j\delta^{(1)}}{\partial^2}\frac{\partial_k\delta^{(1)}}{\partial^2}\right) + \ldots$$

$$\tau^{ij}_{\epsilon} = \epsilon^{ij}_1 + \partial_k\epsilon^{ij}_1\frac{\partial_k\delta^{(1)}}{\partial^2} + \epsilon^{ijkl}_3\frac{\partial_k\partial_l\delta^{(1)}}{\partial^2} + \ldots$$

$$\left\langle \epsilon^{ij}_a(\vec{k})\epsilon^{kl}_b(\vec{k}')\right\rangle' = c^{(1)}_{a,b}\delta^{ij}_K\delta^{kl}_K + c^{(1)}_{a,b}\delta^{i(k}_K\delta^{l)j}_K + \mathcal{O}(k^2/k^2_{\rm NL})$$

Bias expansion

Write all contractions of $r_{ij} = \frac{2}{3\Omega_{\rm m}\mathcal{H}^2}\partial_i\partial_j\Phi \qquad p_{ij} = -\frac{1}{f\mathcal{H}}\partial_i v_j$

$$\begin{aligned}\delta_h(\vec{x},t) = \int^t dt' H(t')\big[&c_\delta(t,t')\delta(x_{\rm fl},t') + c_\theta(t,t')\theta(x_{\rm fl},t')\\
&+ c_{\delta^2}(t,t')\delta^2(x_{\rm fl},t') + c_{\delta\theta}(t,t')\delta\theta(x_{\rm fl},t') + c_{\theta^2}(t,t')\theta^2(x_{\rm fl},t')\\
&+ c_{r^2}(t,t')r^2(x_{\rm fl},t') + c_{rp}(t,t')rp(x_{\rm fl},t') + c_{p^2}(t,t')p^2(x_{\rm fl},t')\\
&+ c_{\delta^3}(t,t')\delta^3(x_{\rm fl},t') + c_{\delta^2\theta}(t,t')\delta^2\theta(x_{\rm fl},t') + c_{\delta\theta^2}(t,t')\delta\theta^2(x_{\rm fl},t') + c_{\theta^3}(t,t')\theta^3(x_{\rm fl},t')\\
&+ c_{r^3}(t,t')r^3(x_{\rm fl},t') + c_{r^2p}(t,t')r^2p(x_{\rm fl},t') + c_{rp^2}(t,t')rp^2(x_{\rm fl},t') + c_{p^3}(t,t')p^3(x_{\rm fl},t')\\
&+ c_{r^2\delta}(t,t')r^2\delta(x_{\rm fl},t') + c_{rp\delta}(t,t')rp\delta(x_{\rm fl},t') + c_{p^2\delta}(t,t')p^2\delta(x_{\rm fl},t')\\
&+ c_{r^2\theta}(t,t')r^2\theta(x_{\rm fl},t') + c_{rp\theta}(t,t')rp\theta(x_{\rm fl},t') + c_{p^2\theta}(t,t')p^2\theta(x_{\rm fl},t')\\
&+ c_{\delta^4}(t,t')\delta^4(x_{\rm fl},t') + c_{\delta r^3}(t,t')\delta r^3(x_{\rm fl},t') + c_{\delta^2 r^2}(t,t')\delta^2 r^2(x_{\rm fl},t')\\
&+ c_{(r^2)^2}(t,t')\left(r^2\right)^2(x_{\rm fl},t') + c_{r^4}(t,t')r^4(x_{\rm fl},t')\big]\Big|\end{aligned}$$

$$\vec{x}_{\rm fl} = \vec{x} + \int_t^{t'} \frac{{\rm d}t''}{a(t'')}\vec{v}\,(\vec{x}_{\rm fl}(\vec{x},t,t''),t'')$$

Then, expand in v

$$\begin{aligned}\mathcal{O}(x_{\rm fl}(\vec{x},t,t'),t') \approx\ & \mathcal{O}(\vec{x},t') + \partial_i\mathcal{O}(\vec{x},t')\int_t^{t'}\frac{dt_1}{a(t_1)}\,v^i(\vec{x},t_1)\\
&+ \frac{1}{2}\partial_i\partial_j\mathcal{O}(\vec{x},t')\int_t^{t'}\frac{dt_1}{a(t_1)}\,v^i(\vec{x},t_1)\int_t^{t'}\frac{dt_2}{a(t_2)}\,v^j(\vec{x},t_2)\\
&+ \partial_i\mathcal{O}(\vec{x},t')\int_t^{t'}\frac{dt_1}{a(t_1)}\,\partial_j v^i(\vec{x},t_1)\int_t^{t_1}\frac{dt_2}{a(t_2)}\,v^j(\vec{x},t_2)\end{aligned}$$

MacDonald , Roy (2010)
Senatore (2014)
Desjaques, Jeong, Schmidt (2014)
Many others

Bias expansion

Finally, do the time integrals, getting

$$\mathcal{O}_m^{(n)}(\vec{x}_{\rm fl}(\vec{x},t,t'),t') = \sum_{\alpha=1}^{n-m+1} \left(\frac{D(t')}{D(t)}\right)^{\alpha+m-1} \mathbb{C}^{(n)}_{\mathcal{O}_m,\alpha}(\vec{x},t)$$

And remove degeneracies. At 4th order, we have

$$\begin{aligned}
\delta_h(\vec{x},t) =& b_1 \left(\mathbb{C}^{(1)}_{\delta,1}(\vec{x},t) + \mathbb{C}^{(2)}_{\delta,1}(\vec{x},t) + \mathbb{C}^{(3)}_{\delta,1}(\vec{x},t) + \mathbb{C}^{(4)}_{\delta,1}(\vec{x},t)\right) \\
&+ b_2 \left(\mathbb{C}^{(2)}_{\delta,2}(\vec{x},t) + \mathbb{C}^{(3)}_{\delta,2}(\vec{x},t) + \mathbb{C}^{(4)}_{\delta,2}(\vec{x},t)\right) + b_3 \left(\mathbb{C}^{(3)}_{\delta,3}(\vec{x},t) + \mathbb{C}^{(4)}_{\delta,3}(\vec{x},t)\right) \\
&+ b_4\, \mathbb{C}^{(4)}_{\delta,4}(\vec{x},t) + b_5 \left(\mathbb{C}^{(2)}_{\delta^2,1}(\vec{x},t) + \mathbb{C}^{(3)}_{\delta^2,1}(\vec{x},t) + \mathbb{C}^{(4)}_{\delta^2,1}(\vec{x},t)\right) \\
&+ b_6 \left(\mathbb{C}^{(3)}_{\delta^2,2}(\vec{x},t) + \mathbb{C}^{(4)}_{\delta^2,2}(\vec{x},t)\right) + b_7\, \mathbb{C}^{(4)}_{\delta^2,3}(\vec{x},t) + b_8 \left(\mathbb{C}^{(3)}_{r^2,2}(\vec{x},t) + \mathbb{C}^{(4)}_{r^2,2}(\vec{x},t)\right) \\
&+ b_9\, \mathbb{C}^{(4)}_{r^2,3}(\vec{x},t) + b_{10} \left(\mathbb{C}^{(3)}_{\delta^3,1}(\vec{x},t) + \mathbb{C}^{(4)}_{\delta^3,1}(\vec{x},t)\right) + b_{11}\, \mathbb{C}^{(4)}_{r^3,2}(\vec{x},t) \\
&+ b_{12}\, \mathbb{C}^{(4)}_{\delta^3,2}(\vec{x},t) + b_{13}\, \mathbb{C}^{(4)}_{r^2\delta,2}(\vec{x},t) + b_{14}\, \mathbb{C}^{(4)}_{\delta^4,1}(\vec{x},t) + b_{15}\, \mathbb{C}^{(4)}_{\delta r^3,1}(\vec{x},t)
\end{aligned}$$

Redshift space

Finally, redshift space

$$\delta_{r,h}(\vec{k},\hat{z}) = \delta_h(\vec{k}) + \int d^3x\, e^{-i\vec{k}\cdot\vec{x}} \left(\exp\left[-i \frac{(\hat{z}\cdot\vec{k})}{aH} (\hat{z}\cdot\vec{v}(\vec{x})) \right] - 1 \right) (1+\delta_h(\vec{x}))$$

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

Scoccimarro (2004)
Lewandowski, Senatore, Prada, Zhao, Chuang (2015)
Perko, Senatore, Jennings, Wechsler (2016)

Renormalising products

Important to respect extended Galilean invariance

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

...

$$[\delta_h]_R = \delta_h + \mathcal{O}_{\delta_h} \ ,$$
$$[\pi_h^i]_R = \rho_h v^i + v^i \mathcal{O}_{\rho_h} + \mathcal{O}^i_{\pi_h} \ ,$$
$$[\pi_h^i v^j]_R = \rho_h v^i v^j + v^i v^j \mathcal{O}_{\rho_h} + v^i \mathcal{O}^j_{\pi_h} + v^j \mathcal{O}^i_{\pi_h} + \mathcal{O}^{ij}_{\pi_h v} \ ,$$
$$[\pi_h^i v^j v^k]_R = \rho_h v^i v^j v^k + v^i v^j v^k \mathcal{O}_{\rho_h} + (v^i v^j \mathcal{O}^k_{\pi_h} + 2 \text{ perms.}) + (v^i \mathcal{O}^{jk}_{\pi_h v} + 2 \text{ perms.}) + \mathcal{O}^{ijk}_{\pi_h v^2} \ ,$$
$$[\pi_h^i v^j v^k v^l]_R = \rho_h v^i v^j v^k v^l + v^i v^j v^k v^l \mathcal{O}_{\rho_h} + (v^i v^j v^k \mathcal{O}^l_{\pi_h} + 3 \text{ perms.}) + (v^i v^j \mathcal{O}^{kl}_{\pi_h v} + 5 \text{ perms.}) + (v^i \mathcal{O}^{jkl}_{\pi_h v^2} + 3 \text{ perms.}) + \mathcal{O}^{ijkl}_{\pi_h v^3}$$

Scoccimarro (2004)
Lewandowski, Senatore, Prada, Zhao, Chuang (2015)
Perko, Senatore, Jennings, Wechsler (2016)
GDA, Donath, Lewandowski, Senatore (2022)

New momentum counterterm

At 4th order in redshift space, must have

$$\delta_r(\vec{x}) \supset \frac{1}{H\bar{\rho}} \hat{z}^i \hat{z}^j \partial_i \pi^j(\vec{x}) \sim \hat{z}^i \hat{z}^j \frac{\partial_i \partial_j \partial_k \partial_m}{k_{\rm NL}^2 \partial^2} \left(\frac{\partial_k \partial_l}{H^2} \Phi(\vec{x}) \frac{\partial_l \partial_m}{H^2} \Phi(\vec{x}) \right)$$

It absorbs the following B_{411} piece

$$B_{411}^r \big|_{\rm UV} \supset \frac{2(c_5 - c_3)}{99} \frac{f(k_1^2 - k_2^2)^2 (k_1^2 + k_2^2)(k_1 \mu_1 + k_2 \mu_2)^2}{k_{\rm NL}^2 k_1^2 k_2^2 k_3^2} P_{11}(k_1) P_{11}(k_2) + 2 \text{ perms.}$$

Questions of scale

$$P^{r,h}_{\text{1-loop tot.}}(k,\hat{k}\cdot\hat{z},a) = D(a)^2 P^{r,h}_{11}(k,\hat{k}\cdot\hat{z}) + D(a)^4 (P^{r,h}_{22}(k,\hat{k}\cdot\hat{z}) + P^{r,h}_{13}(k,\hat{k}\cdot\hat{z}))$$

It depends on 4 biases, and the following UV

$$P^{r,h\text{ct}}_{13}(k,\hat{k}\cdot\hat{z}) = 2K^{h,r}_1(\vec{k};\hat{z})P_{11}(k)\frac{k^2}{k^2_{\rm NL}}\left(c_{\rm ct} + c_{r,1}(\hat{k}\cdot\hat{z})^2 + c_{r,2}(\hat{k}\cdot\hat{z})^4\right)$$

$$P^{r,h,\epsilon}_{22}(k,\hat{k}\cdot\hat{z}) = \frac{1}{\bar{n}}\left(c^{\rm St}_1 + c^{\rm St}_2\frac{k^2}{k^2_{\rm NL}} + c^{\rm St}_3\frac{k^2}{k^2_{\rm NL}}f(\hat{k}\cdot\hat{z})^2\right)$$

Questions of scale

- We kept one scale $k_{\rm M} \simeq k_{\rm NL}$ as the physical cutoff of the theory
  But: we measured $c_{r,2}$ to be larger than others, why?

- In fact it is consistent to assume there are 2 cutoff scales for different UV operators $k_{\rm NL} \simeq 0.7\, h/{\rm Mpc}$, $k_{\rm R} \simeq 0.25\, h/{\rm Mpc}$

$$\langle \tau_{ij}(\vec{x},t)\rangle = \left(\frac{aH}{k_{\rm NL}^2}\right)\left(c_0\delta_{ij} + c_s^2(t)\delta(\vec{x},t) + c_4(t)\frac{\partial^2}{k_{\rm NL}^2}\delta(\vec{x},t) + \dots\right)$$

$$\delta_g(\vec{x},t) = b_1(t)\delta^{(1)}(\vec{x},t) + c_{ct,2}(t)\frac{\partial^2}{k_{\rm M}^2}\delta(\vec{x},t) + \dots$$

$$\langle v_i(\vec{x},t)v_j(\vec{x},t)\rangle = \left(\frac{aH}{k_{\rm R}}\right)^2\left[c_1(t)\delta_{ij} + \left(c_2(t)\delta_{ij} + c_3(t)\frac{\partial_i\partial_j}{\nabla^2}\right)\delta(\vec{x},t) + \tilde{c}_r(t)\frac{\partial_i\partial_j}{k_{\rm NL}^2}\delta(\vec{x},t) + \dots\right]$$

GDA, Senatore, Zhang, Nishimichi (2021)
Ivanov, Philcox, Simonović, Zaldarriaga, Nishimichi, Takada (2021)

Where do we stop?

- Very important issue: where to stop the fit?
  Usual tradeoff between *accuracy* and *precision*: smaller scales have smaller errors, but perturbative approach starts to fail

- Two avenues: fits on simulations and/or adding NNLO estimate

- On simulations, we measure theoretical error as shift of 1σ region from the truth, after combining: we stop when we reach $\sim 0.3\sigma_{\rm data}$
  Why? If we combine in quadrature, then it means we shift the result by 5%

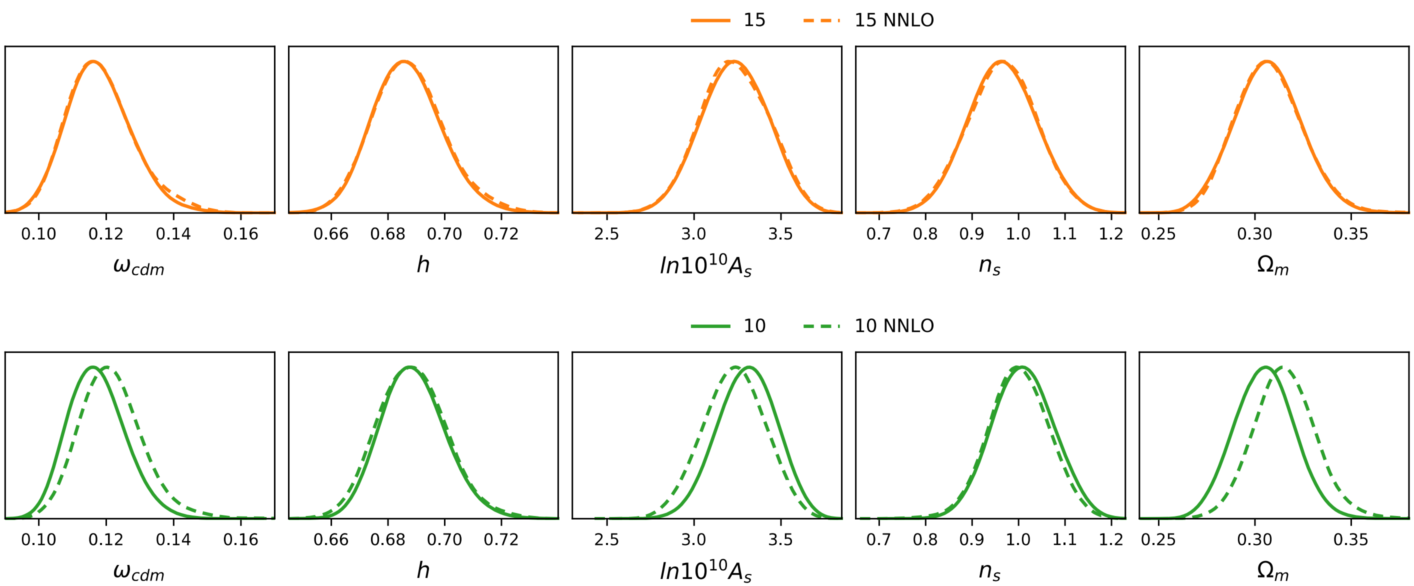
- NNLO estimate is *an estimate of the largest neglected term*: if it is detected, then we are not allowed to use those scales

Scale-cut without simulations

- Because of scale enhancement, the largest terms are the k_R suppressed ones, for which *we actually know the functional dependence*

$$\xi^{\ell}_{\rm NNLO}(s) = i^{\ell} \int \frac{dk}{2\pi^2} k^2 P^{\ell}_{\rm NNLO}(k) j_{\ell}(ks)$$

$$P^{\ell}_{\rm NNLO}(k) = b^{\ell}_{k^2 P_{\rm NLO}} \frac{k^2}{k^2_{\rm M}} P^{\ell}_{\rm NLO}(k) + c_{r,4} b_1^2 \mu^4 \frac{k^4}{k^4_{\rm M,R}} P_{11}(k)\Big|_{\ell} + c_{r,6} b_1 \mu^6 \frac{k^4}{k^4_{\rm M,R}} P_{11}(k)\Big|_{\ell}$$



$$s_{\rm min} \simeq 15\,{\rm Mpc}/h$$

Zhang, GDA, Senatore, Cheng, Cai (2021)

Beyond 2-pt: the 1-loop bispectrum in LSS

- Lots of work to develop the pipeline for 1-loop bispectrum
  - Biased tracers to 4^{th} order in perturbations
  - Redshift distortions up to 4^{th} order
  - Counterterms up to 2^{nd} order
  - Efficient way of computing loop integrals
  - Generalization to non-Gaussian initial conditions

GDA, Lewandowski, Senatore, Zhang (2022a, 2022b)
GDA, Donath, Lewandowski, Senatore, Zhang (2022)
Philcox, Ivanov, Cabass, Simonovic, Zaldarriaga (2022a, 2022b, 2022c)

Theory Model

- Perturbation theory up to 4th order: 11 bias parameters

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

- Stochastic and counterterms up to 2nd order: 30 parameters

$$P_{13}^{r,h,ct}[b_1,c_1^h,c_1^\pi,c_1^{\pi v},c_3^{\pi v}]\ ,\quad P_{22}^{r,h,\epsilon}[c_1^{\rm St},c_2^{\rm St},c_3^{\rm St}]\ ,$$
$$B_{321}^{r,h,(II),ct}[b_1,b_2,b_5,c_1^h,c_1^\pi,c_1^{\pi v},c_3^{\pi v}]\ ,\quad B_{321}^{r,h,(I),\epsilon}[b_1,c_1^{\rm St},c_2^{\rm St},\{c_i^{\rm St}\}_{i=4,\ldots,13}]\ ,$$
$$B_{411}^{r,h,ct}[b_1,\{c_i^h\}_{i=1,\ldots,5},c_1^\pi,c_5^\pi,\{c_j^{\pi v}\}_{j=1,\ldots,7}]\ ,\quad B_{222}^{r,h,\epsilon}[c_1^{(222)},c_2^{(222)},c_5^{(222)}]$$

A numerical workhorse: FFTLog

- Integrals over the PS are challenging and slow, and the PS changes at each cosmology… We FFTLog to separate cosmology dependence

$$P_{11}(k_n) = \sum_{m=-N_{\rm max}/2}^{N_{\rm max}/2} c_m k_n^{\nu+i\eta_m}$$

$$c_m = \frac{1}{N_{\rm max}} \sum_{l=0}^{N_{\rm max}-1} P_{11}(k_l) k_l^{-\nu} k_{\rm min}^{-i\eta_m} e^{-2iml/N} \qquad \eta_m = \frac{2\pi m}{\log(k_{\rm max}/k_{\rm min})}$$

- Then ~everything is a matrix multiplication of the coefficients

$$P_\sigma(k) = k^3 \sum_{m_1,m_2} c_{m_1} k^{-2\nu_1} M_\sigma(\nu_1,\nu_2) k^{-2\nu_2} c_{m_2}$$

Hamilton (1997)
Simonovic, Baldauf, Zaldarriaga, Carrasco, Kollmeier (2017)

Problems with 1-loop bispectrum

- B_{222} is annoying... Number of integrals scales as $N^3_{\rm basis}$!

- Idea: change basis to one with scales
  We only need $N_{\rm basis} = 16$. We have to be careful about matching

$$P_{\rm fit}(k) = \frac{\alpha_0}{1+\frac{k^2}{k^2_{UV,0}}} + \sum_{n=1}^{N-1} \alpha_n f(k^2, k^2_{{\rm peak},n}, k^2_{{\rm UV},n}, i_n, j_n)$$

$$f(k^2, k^2_{\rm peak}, k^2_{\rm UV}, i, j) = \frac{(k^2/k_0^2)^i}{\left(1+\frac{(k^2-k^2_{\rm peak})^2}{k^4_{\rm UV}}\right)^j}$$

Anastasiou, Bragança, Senatore, Zheng (2022)

Theory model

- Window: use approximation (on linear term) from Gil-Marin et al. (2014)

$$B_{211}^{r,h} = 2K_1^{r,h}(\vec{k}_1;\hat{z})K_1^{r,h}(\vec{k}_2;\hat{z})K_2^{r,h}(\vec{k}_1,\vec{k}_2;\hat{z})[W * P_{11}](\vec{k}_1)[W * P_{11}](\vec{k}_2) + \text{ 2 perms. },$$

$$[W * P_{11}](\vec{k}) = \int \frac{\mathrm{d}^3k'}{(2\pi)^3} W(\vec{k}-\vec{k}')P_{11}(\vec{k}')$$

- Binning effect is important: it is performed (together with AP) exactly on the linear part, loop terms are small
- Effect of approximations are small

$\Delta_{\rm shift}/\sigma_{\rm stat}$	Ω_m	h	σ_8
$P_\ell + B_0$: base - w/ NNLO	-0.03	-0.09	-0.03
$P_\ell + B_0$: base - w/o B_0 window	0.11	-0.05	0.01
$P_\ell + B_0 + B_2$: base - w/o B_0, B_2 window	0.51	0.09	0.02

Emulate the theory: Effort.jl

- Pybird, CLASS-PT, Velocileptors, CLASS-OneLoop have been developed by (more or less) millennials, but we are already too old for the cool kids of today

- We managed to compute things in ~O(sec), and built likelihood for efficient sampling, but there can be a better way

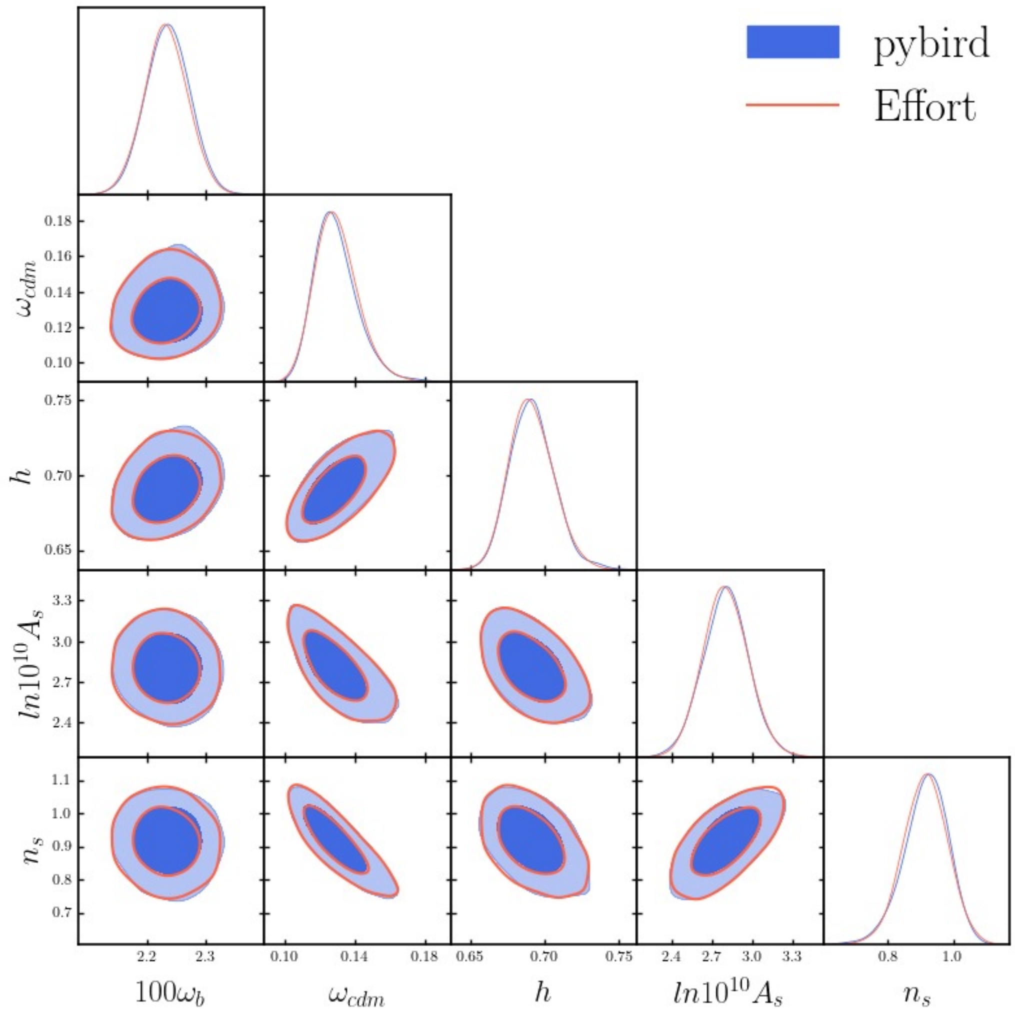
- Emulate the theory! For 2-pt very easy. Moreover, one can afford more precision in the code, since the NN is trained only once.
  Each evaluation takes $\sim O(100\,\mu\text{sec})$

- And, we can differentiate on parameters! So one can easily do minimization, profile likelihoods, and we can use differentiable samplers

Bonici, GDA, *to appear*

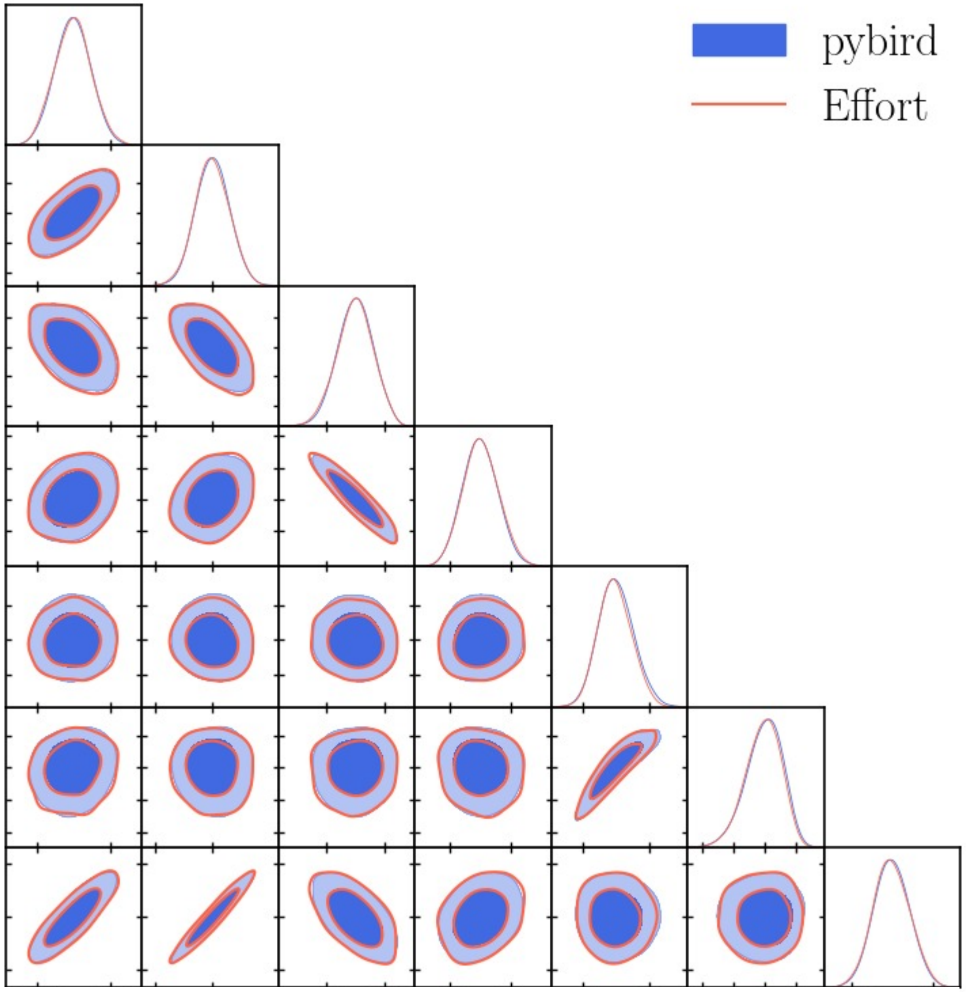
Emulate the theory: Effort.jl

BOSS 4sky



Emulate the theory: Effort.jl

PT Challenge



A note on priors

- In Bayesian analysis, data update our belief on the model and its parameters. Must start from a probability measure on parameters. *There is no "uninformative prior"*.
- And what if data are not precise enough?

The status of LSS EFT analysis: two manifestly equivalent implementations of the manifestly correct theory on manifestly the same data produce manifestly different results. #cosmology

Priors on counterterms? The encarnation of the devil on Earth.

A note on priors

- ''Typically'', data determine well cosmological parameters. We put a large uniform prior on them: akin to frequentist maximum likelihood approach.

- On the EFT parameters?
We know they have to be small, but not much more: except for a few, we center them at 0 with σ=2.

- Other choices are possible, as long as they cover the physically allowed region, but *EFT parametrization stays the same*.
''West Coast'' and ''East Coast'' parameters are a *linear transformation of each other.* Prior choice is, however, different.

- Now, best fits are unchanged, since both priors cover the allowed region. 1d projected posteriors are slightly different, due to different projection effects.

Simon, Zhang, Poulin, Smith (2022)
Carrilho, Moretti, Pourtsidou (2022)

What to do?

- Just wait. Sooner or later data will just not care about the priors

- Perturbativity prior

$$\mathcal{P}_P = \frac{1}{2N^P_{\rm bins}} \sum_{i\in {\rm bins}_P} \left(\frac{P^h_{\text{1-loop}}(k_i)}{\sigma_P^{\rm P.P.}(k_i)} \right)^2 \qquad \mathcal{P}_B = \frac{1}{2N^B_{\rm bins}} \sum_{i\in {\rm bins}_B} \left(\frac{B^h_{\text{1-loop}}(k^i_1, k^i_2, k^i_3)}{\sigma_B^{\rm P.P.}(k^i_1, k^i_2, k^i_3)} \right)^2$$

$$\sigma_P^{\rm P.P.}(k) \sim S^P(k) P^{k_{\rm max}}_{\text{1-loop}} \, , \qquad \sigma_B^{\rm P.P.}(k_1, k_2, k_3) \sim S^B(k_1, k_2, k_3) B^{k_{\rm max}}_{\text{1-loop}}$$

$$S^P_{\text{1-loop}}(k) \sim b_1^2 P_{11}(k) \left(\frac{k}{k_{\rm NL}} \right)^{3+n(k)} \qquad S^B_{\text{1-loop}}(k_1, k_2, k_3) \sim B^h_{211}(k_1, k_2, k_3) \sum_{i=1}^{3} \left(\frac{k_i}{k_{\rm NL}} \right)^{3+n(k_i)}$$

- Get some controlled UV information.
  We used some old fitting formulas from simulations.
  Now, the idea is to do a dedicated search. As a first step, fitting HOD. But have to marginalise over them.

Bragança, Donath, Senatore, Zheng (2023)

Ivanov et al. (2024)

Getting new physics

- As if we didn't have enough parameters…
- We can get new physics *in a model-independent way*: boostrap
- Impose symmetries, and parametrize the kernels with basic building blocks
- Modifications from, e.g., EFT of DE

$$G_2(\vec{k}_1, \vec{k}_2) = 2\beta(\vec{k}_1, \vec{k}_2) + d_1^{(2)}\,\gamma(\vec{k}_1, \vec{k}_2)$$

$$G_3(\vec{k}_1, \vec{k}_2, \vec{k}_3) = 2\,\beta(\vec{k}_1, \vec{k}_2)\beta(\vec{k}_{12}, \vec{k}_3) + d_5^{(3)}\gamma(\vec{k}_1, \vec{k}_2)\gamma(\vec{k}_{12}, \vec{k}_3) - 2\,\left(d_{10}^{(3)} - h\right)\gamma(\vec{k}_1, \vec{k}_2)\beta(\vec{k}_{12}, \vec{k}_3)$$
$$+ 2(d_1^{(2)} + 2\,d_{10}^{(3)} - h)\beta(\vec{k}_1, \vec{k}_2)\gamma(\vec{k}_{12}, \vec{k}_3) + d_{10}^{(3)}\gamma(\vec{k}_1, \vec{k}_2)\alpha_a(\vec{k}_{12}, \vec{k}_3) + \mathrm{cyc.}$$

GDA, Marinucci, Pietroni, Vernizzi (2021)

3x2pt

- Photometric part of surveys will also play a big part in the future of LSS — e.g., for Euclid lensing is as important as clustering

- Why can't we apply the EFTofLSS to 3x2pt analysis?
  Yes we can!

- Some systematics can be dealt with in an EFT-like way: baryonic effects and intrinsic alignments

- Main practical challenges: determine the scale cuts, and keep the number of free parameters under control

GDA, Zhang, Refregier, Senatore, *to appear*

Projection integrals

$$w^i(\theta) = \int \frac{\mathrm{d}l\, l}{2\pi} J_0(l\theta) \frac{2}{\pi} \int \mathrm{d}k\, k^2 \int \mathrm{d}\chi_1 \int \mathrm{d}\chi_2 f^i_{\delta_g}(\chi_1) f^j_{\delta_g}(\chi_2) P_{gg}\left(k, z(\chi_1), z(\chi_2)\right)$$

$$\gamma_{\mathrm{t}}^{ij}(\theta) = \int \frac{\mathrm{d}l\, l}{2\pi} J_2(l\theta) \frac{2}{\pi} \int \mathrm{d}k\, k^2 \int \mathrm{d}\chi_1 \int \mathrm{d}\chi_2 f^i_{\delta_g}(\chi_1) f^j_{\kappa}(\chi_2) P_{gm}\left(k, z(\chi_1), z(\chi_2)\right)$$

$$\xi_+^{ij}(\theta) = \int \frac{\mathrm{d}l\, l}{2\pi} J_0(l\theta) \int \mathrm{d}\chi \frac{f^i_\kappa(\chi) f^j_\kappa(\chi)}{\chi^2} P_{mm}\left(\frac{l}{\chi}; z(\chi)\right)$$

$$\xi_-^{ij}(\theta) = \int \frac{\mathrm{d}l\, l}{2\pi} J_4(l\theta) \int \mathrm{d}\chi \frac{f^i_\kappa(\chi) f^j_\kappa(\chi)}{\chi^2} P_{mm}\left(\frac{l}{\chi}; z(\chi)\right)$$

Power spectra and parameters

- Standard EFTofLSS expressions for the P_{mm} , P_{mg} , P_{gg} .
- However, we are integrating parameters with unknown time dependence!
- Assume parameter is almost constant over the bin, so each redshift bin combination now has its own parameters, e.g.

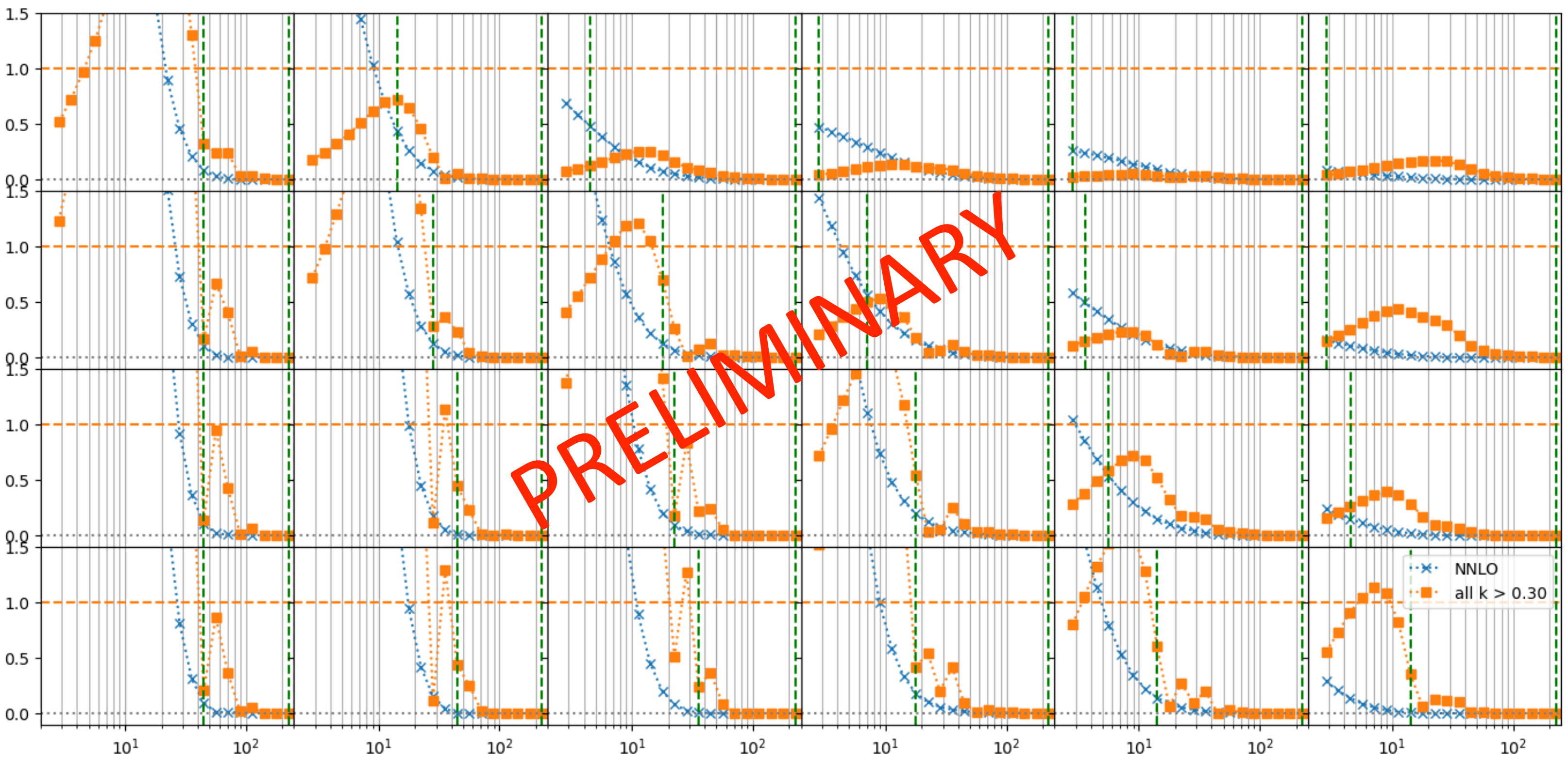
$$\xi^{ij}_{+/-}(\theta) \supset 2\frac{c^{ij}_{+/-}}{k^2_{\rm NL}} \int \frac{{\rm d}l\, l}{2\pi} J_{0/4}(l\theta) \int {\rm d}\chi \frac{f^i_\kappa(\chi) f^j_\kappa(\chi)}{\chi^2} D^2_+(z) P_{11}\left(\frac{l}{\chi}\right) \frac{l^2}{\chi^2} \, .$$

- How to reduce their impact? Simple, we correlate them! After all, their time dependence is smooth and of order Hubble.

Scale cut: NNLO and UV sensitivity

$$\xi_{ab}^{\mathrm{NNLO}}(\theta) = c_{ab}^{\mathrm{NNLO}} \int \frac{\mathrm{d}l\, l}{2\pi} J_\mu(l\theta) \int \mathrm{d}\chi\, \frac{f_a(\chi) f_b(\chi)}{\chi^2} P_{ab}^{\mathrm{NNLO}}\left(\frac{l}{\chi}, z\right)$$

$$P_{ab}^{\mathrm{NNLO}}(k,z) = \frac{k^2}{k_{\mathrm{M}}^2} P_{ab}^{\mathrm{NLO}}(k,z)$$



Where we stand

- Power spectrum at one loop: practically settled.
  - Several codes agreeing
  - Observational effects fairly under control
  - $k_{\max}$ determination solid
  - Analytical covariance available (Wadekar, Scoccimarro 2019)

- Bispectrum at one loop: on its way.
  - Done: one loop expression, efficient implementation, $k_{\max}$ determination
  - Missing: independent confirmation to our analysis (see also Philcox et al. 2022), a practical treatment of the mask, a better understanding of IR-resummation
  - Approximate analytical covariance available (Salvalaggio et al, 2024)

And where do we go?

- Higher loops?
  At least 5th order for 2-loop power spectrum is doable.
  Integrals are complicated. Actual covariance is probably still ok.

- Higher point functions?
  Now we can go up to tree-level 5pt, no difficulty in computing.
  However, no estimators, and which covariance to use?

- Can we gain by doing field level analysis? (Linde, GDA, *in preparation*)

- Focus also on other observables: 21cm, Ly-α, lensing (3x2pt), …

Thank you!