Status of numerical implementations of PT – What's "done"? What are their strengths? What's missing?

- Many emulators available (for PT/EFT based and hybrid models) but not much available for beyond LCDM

- Information gains from small scales impressive (30-40% for some parameters) but… enough? (shot noise limitations, smallest scales described by models)

- For emulators: what cosmological parameter range do we need?

- How to correctly introduce theoretical errors? (for all models, but in particular emulator based models; cosmology dependence of theory errors?)

Matteo Zennaro

PT-codes– What's "done"? What are their strengths? What's missing?

INSTITUTO DE CIENCIAS FÍSICAS

- 3-dimensional (spectroscopic) power spectrum PT codes in LCDM **are complete** now. Extending to 2-loops is unlikely to provide additional benefits.

- **Speed:** Using emulators can significantly accelerate computations, although they can sometimes be less reliable. Other options available, e.g., SFT (Class-one loop talk)

- **Add complementary statistics**, such as the bispectrum and BAO post-reconstruction. It's common to calculate them outside the pk-codes

- **Cross-correlations** with other probes. Better if we have them under theoretical control, within comprehensive EFT frameworks.

- Models **beyond LCDM,** where EdS kernels are not accurate

Evaluating loop integrals

Pierre Zhang

1-loop 2pt, 2-loop 2pt, 1-loop 3pt

$$P_{\rm 1loop}(k) \supset \int d^3q \; F(k^2, q^2, |k-q|^2) \; P_{\rm lin}(q) P_{\rm lin}(|k-q|) \tag{1}$$

$$P_{\rm 2loop}(k) \supset \int d^3q d^3p \; G(k^2, q^2, |k-q|^2, |k-p|^2, |q-p|^2) \; P_{\rm lin}(q) P_{\rm lin}(p) P_{\rm lin}(|k-q-p|) \tag{2}$$

$$B_{\rm 1loop}(k_1, k_2, k_3) \supset \int d^3q \; H(k_1^2, k_2^2, q^2, |k_1-q|^2, |k_2+q|^2) \; P_{\rm lin}(q) P_{\rm lin}(|k_1-q|) P_{\rm lin}(|k_2+q|) \tag{3}$$

The game

- Find a good decomposition onto basis functions $f_n(k)$:

$$P_{\rm lin}(k) \simeq \sum_n^N \; c_n f_n(k) \; , \tag{4}$$

- such that $A_{mn}(k) = P_{\rm 1loop}[f_n(k), f_m(k)]$ well-behaved and precomputable
- so that loops $\sim$ simple, fast, matrix multiplications:

$$P_{\rm 1loop}[P_{\rm lin}(k)] \simeq c_n c_m A_{nm}(k) \tag{5}$$

The limitation: memory (more than speed)

$$B_{\rm 1loop} \simeq c_n c_m c_l A'_{nml} \; , \qquad P_{\rm 2loop} \simeq c_n c_m c_l A''_{nml} \tag{6}$$

- Naively *one* A'_{nml} takes $2 * 64\text{b} \times N^3 \sim 0.013\text{Gb}$ for $N \sim 100$
- so for $N_k \sim 100$ and $N_{222} \sim 50$, *all* A'_{nml} take $\sim 50\text{Gb}$!

***Code Developers**: Ivanov, Simonovic, Philcox, Cabass*

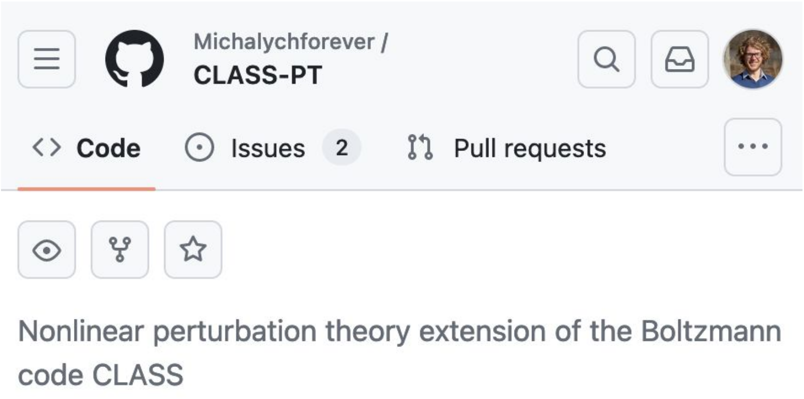
CLASS-PT

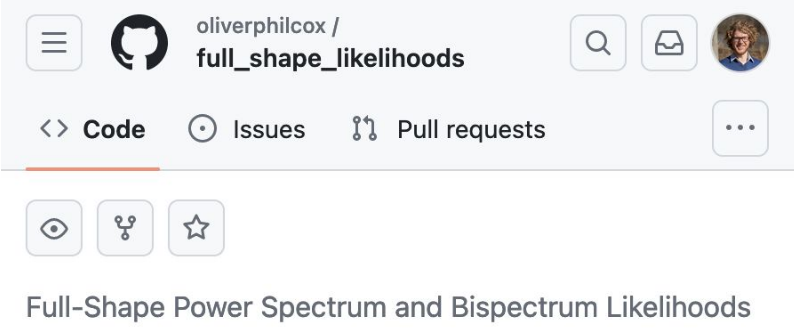
Currently in public code:

- Full C++/Python implementation
- Features:
  - Power Spectrum Multipoles: 1-loop
  - Real-space power spectra
  - BAO wiggles
  - Bispectrum Multipoles: Tree-level (+ beyond)
- Full nuisance-marginalized likelihoods in ~ seconds.
- Includes **primordial non-Gaussianity** and collider physics
- Jupyter tutorials & montepython likelihoods

What could / should we add?

- Baryon effects (e.g. relative velocity?)
- Line-of-sight biases (e.g. Lyman-alpha?)
- Late-time physics?
- Primordial physics
- Higher-loops?





\+ *processed data (with PolyBin3D)*

Status of numerical implementations of PT

- When do we stop to write new codes?
- Comparison of codes at spectrum level?
- Emulators?
- Extended cosmologies (beyond $M_\nu, f_{\rm NL}, \Omega_k$):
  - Check consensus for using current implementation for "easy extensions of LCDM":
    - inflation -> running, features, isocurvature ...
    - $N_{\rm eff}$
    - Dark Matter -> C+WDM, C+DDM, DM with feeble interaction at large z ...
  - Check what to do for "more difficult cases":
    - Light relics, DM with feeble interaction at small z, modified gravity ...
- Extended observables:
  - Several simultaneous tracers with all cross terms
  - Line-intensity mapping
  - Continue on Lyman-alpha (Ivanov et al.)
  - ...