Perturbation Theory of Large Scale Structure Numerical Code: CLASS-PT

Pierros Ntelis
POSTDOC in CPPM

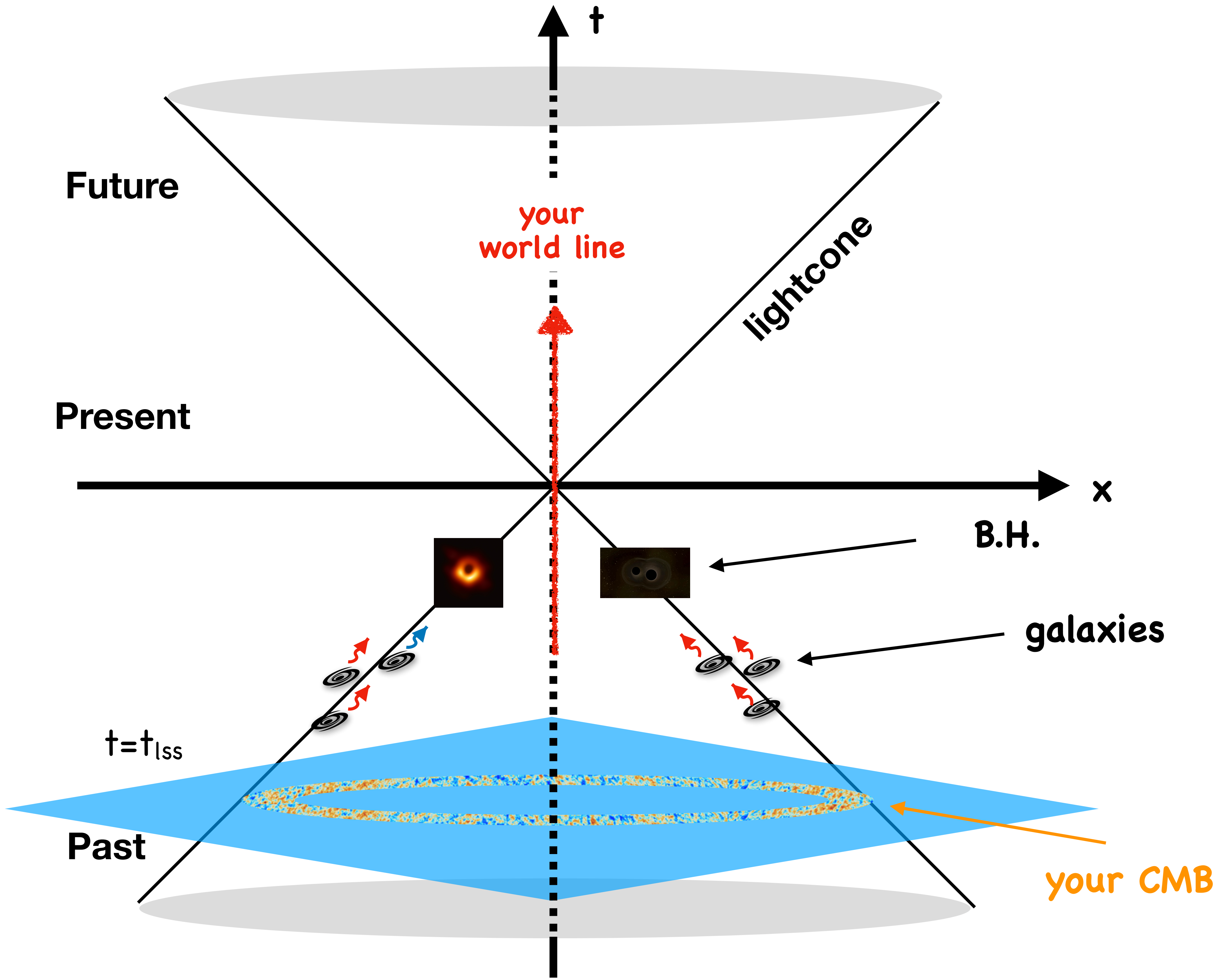
“ on behalf of the
Anton Chudaykin, Mikhail M. Ivanov, Marko Simonović “
https://arxiv.org/pdf/2004.10607.pdf
code git forked

PTofLSS CLASS-PT

Clustering

of

Large
Scale
Structures



Currently the non-linear and mildly non-linear regime of large scale structure is subjective !!!

Subjective to what ?

To the way we interpret the Large Scale Structures in these regimes !!!

Fortunately,

theoreticians provide their predictions in num-codes

to integrated them and compare those models systematically using LSS surveys, such as Euclid and DESI, … !

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Outline:

- **Basics of PTofLSS**
- **Presentation of the code**
- **IR-Resummation scheme**
- **CLASS-PT Comparison**
- **Installation guidelines**
- **Conclusion and outlook**

loops

PTofLSS CLASS-PT

Perturbation Theory of Large Scale Structures

PT of LSS
PTofLSS

Standard PT (SPTofLSS)

Effective Field Theory (EFTofLSS)

Motivations from (EFTofLSS) suggest the inclusion on SPTofLSS:
counterterms
and
IR-resummation

E.Sefusatti ++

$$P_{\rm Full}(z,k) \equiv P_{\rm lin}(z,k) + P_{\rm 1-loop,SPT}(z,k) + P_{ctr}(z,k)$$

effective sound speed
normally nuisance
under many authors

but it can be modelled IMO

2.3 Power Spectrum of Biased Tracers

In order to calculate the one-loop power spectrum of biased tracers, we have to include all possible operators up to third order in the bias expansion:

$$\delta_g = b_1\delta + \epsilon + \frac{b_2}{2}\delta^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + \frac{b_3}{6}\delta^3 + b_{\delta\mathcal{G}_2}\delta\mathcal{G}_2 + b_{\mathcal{G}_3}\mathcal{G}_3 + b_{\Gamma_3}\Gamma_3 + R_*^2\partial^2\delta \,. \tag{2.7}$$

Here we have defined

$$\mathcal{G}_2(\Phi_g) \equiv (\partial_i\partial_j\Phi_g)^2 - (\partial_i^2\Phi_g)^2 \,, \tag{2.8}$$

where Φ_g is gravitational potential. The only cubic operator that gives nontrivial contribution to the one-loop power spectrum can be written as

$$\Gamma_3 \equiv \mathcal{G}_2(\Phi_g) - \mathcal{G}_2(\Phi_v) \,, \tag{2.9}$$

where Φ_v is velocity potential.[7] For the definition of $\mathcal{G}_3$ and relations of our operators to other equivalent choices of basis, see [58]. The term ϵ denotes the stochastic contribution which is uncorrelated with the large-scale density field. Poisson noise,

-> Result to more terms such as:

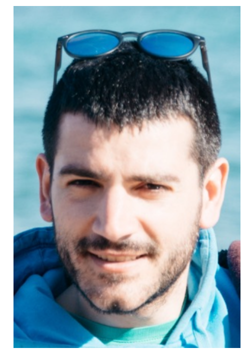
$$P_{gg}(z,k) = b_1^2(z)(P_{\rm lin}(z,k) + P_{\text{1-loop, SPT}}(z,k)) + b_1(z)b_2(z)\mathcal{I}_{\delta^2}(z,k)$$
$$+ 2b_1(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\mathcal{G}_2}(z,k) + (2b_1(z)b_{\mathcal{G}_2}(z) + \frac{4}{5}b_1(z)b_{\Gamma_3}(z))\mathcal{F}_{\mathcal{G}_2}(z,k)$$
$$+ \frac{1}{4}b_2^2(z)\mathcal{I}_{\delta^2\delta^2}(z,k) + b_{\mathcal{G}_2}^2(z)\mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\delta^2\mathcal{G}_2}(z,k)$$
$$+ P_{\nabla^2\delta}(z,k)$$
$$+ P_{\epsilon\epsilon}(z,k) \longrightarrow$$ **stochastic component**

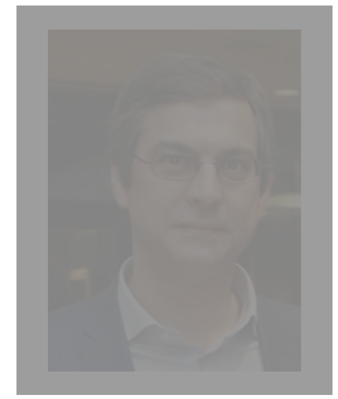
Gravitational Instabilities

taken from https://arxiv.org/pdf/2004.10607.pdf

What does CLASS-PT do ?

E. Sefusatti



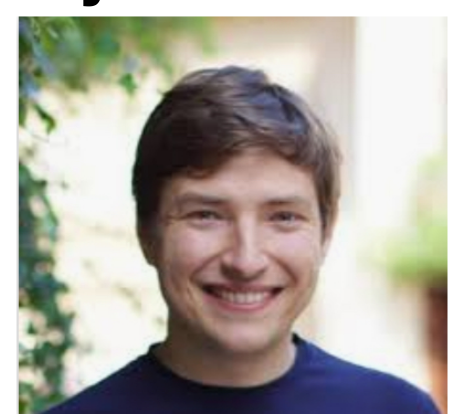


A. Eggemeier

All the aforementioned +++

Anton Chudaykin

Marko Simonović



Mikhail M. Ivanov

IR-Resummation

is imperative to properly describe the spread of the BAO peak, which was not implemented in the previous formulas

Simply put it, in Real Space:

$$P_{\rm lin}(k) = P_{\rm nw}(k) + P_{\rm w}(k)$$

Wiggle-Non-Wiggle Splitting

$$\Sigma^2(z) \equiv \frac{1}{6\pi^2}\int_0^{k_S} dq\, P_{\rm nw}(z,q)\left[1 - j_0\left(\frac{q}{k_{osc}}\right) + 2j_2\left(\frac{q}{k_{osc}}\right)\right]$$

Sophisticated damping factor

$$P_{\rm mm,\,LO}(z,k) = P_{\rm nw}(z,k) + {\rm e}^{-k^2\Sigma^2(z)} P_{\rm w}(z,k)$$

Using the Leading Order

$$P_{\rm XY} = P_{\rm tree,\,XY}[P_{\rm mm,\,LO}] + P_{\rm 1-loop,\,XY}[P_{\rm mm,\,LO}]\,,$$

We map it on

$P_{\rm tree,\,XY}$ are given by

$$P_{\rm tree,\,mm} = P_{\rm nw}(z,k) + {\rm e}^{-k^2\Sigma^2(z)} P_{\rm w}(z,k)(1 + k^2\Sigma^2(z))\,,$$

$$P_{\rm tree,\,gm} = b_1 P_{\rm tree,\,mm}\,, \quad P_{\rm tree,\,gg} = b_1^2 P_{\rm tree,\,mm}\,.$$

Matter Spectra

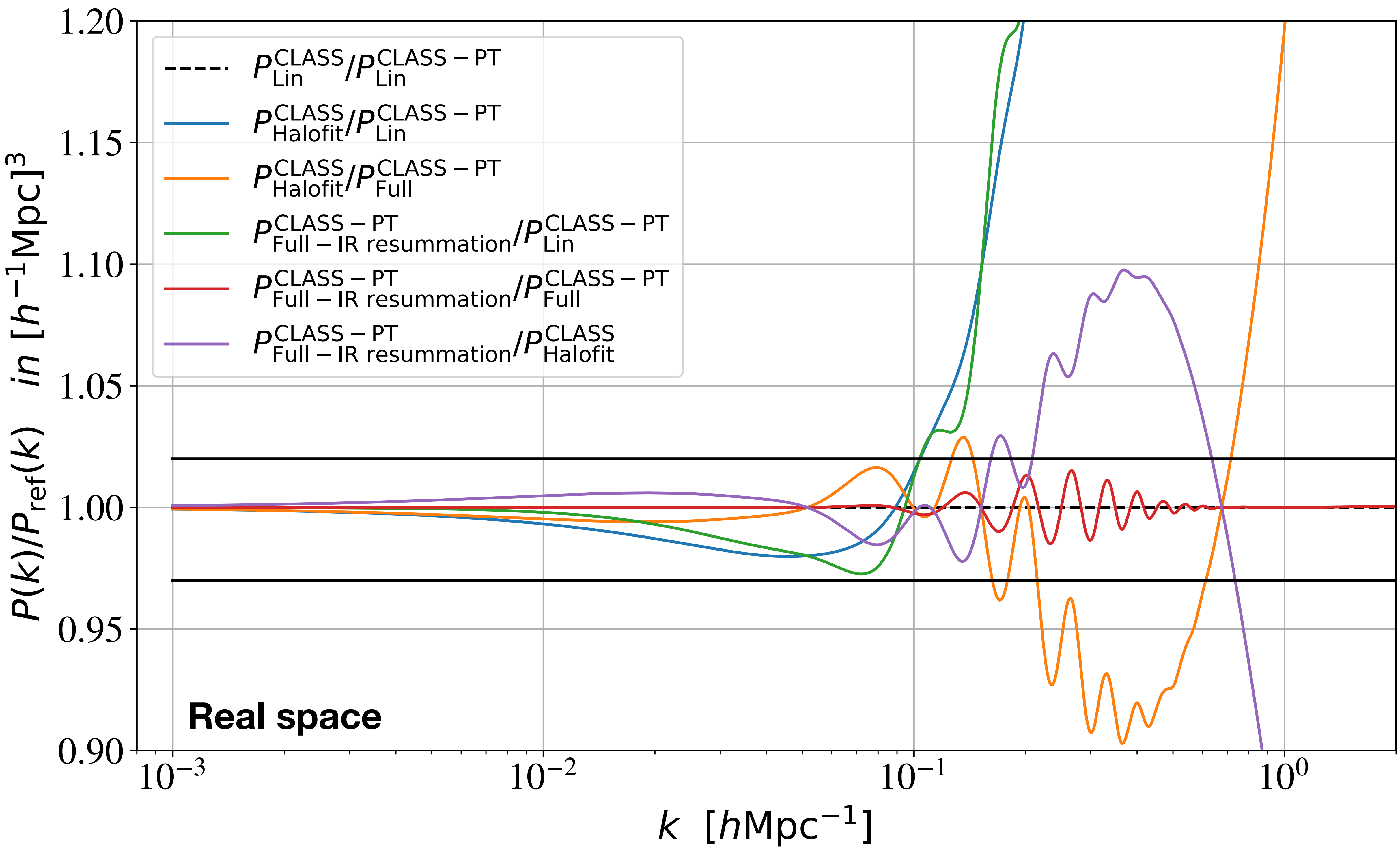
Galaxy Spectra

Based on FFTlog

taken from https://arxiv.org/pdf/2004.10607.pdf

=> For k < 0.1 h/Mpc : LSS NL models agree at < 5 %

=> For k > 0.1 h/Mpc : LSS NL models models are subjective



CAVEATS:

1) Note that all those complex concepts are collapsed to simple numerical functions of one argument

2) The observables that we use are also collapsed information

3) EFTofLSS does the same but with more complex models

Systematic treatment:

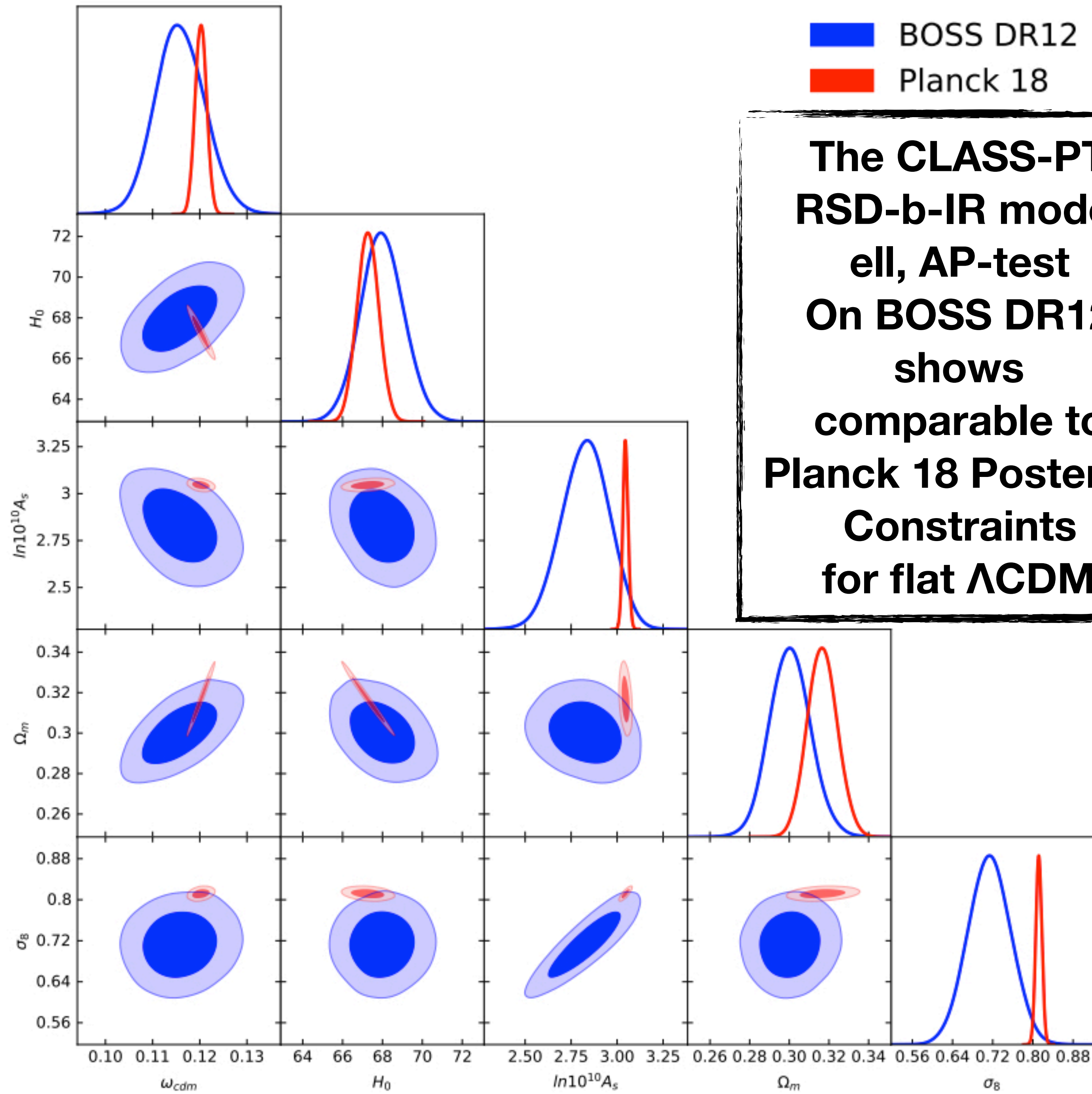
To understand better these models:

We should be model the observables in >= 1 argument functionals

Such as { AP-Test = [$P_{ell}(k)$, $P(k_{||},k_{perp})$] , or … }

taken from https://arxiv.org/pdf/2004.10607.pdf

PTofLSS CLASS-PT - CLASS-PT Comparison



The CLASS-PT RSD-b-IR model ell, AP-test On BOSS DR12 shows comparable to Planck 18 Posterior Constraints for flat ΛCDM

But any NL modelling interprets the LSS under some assumptions

A joint analysis of BOSS-DR12 PLANCK18 With this NL-model to come ! (You) (DESI or Euclid)

taken from https://arxiv.org/pdf/2004.10607.pdf

To enjoy multiple CLASS implementations which do not conflict

Do as the authors suggest
except since the CLASS-PT wrapper changes the structure of CLASS wrapper

Then

In the
python/setup.py
change

the line 33

```
    name='classy',
=>
    name=‘classy_pt',
```

And line 38

```
    ext_modules=[Extension("classy", [“classy.pyx"],
=>
    ext_modules=[Extension("classy_pt", [“classy.pyx"],
```

And then in their jupyter notebook in line 7 Import it as
from classy_pt import Class

taken from https://arxiv.org/pdf/2004.10607.pdf

Conclusions and Outlook:

- **LSS prediction tools are important since they allow to interpret the LSS with the latest understanding of Perturbation Theories**

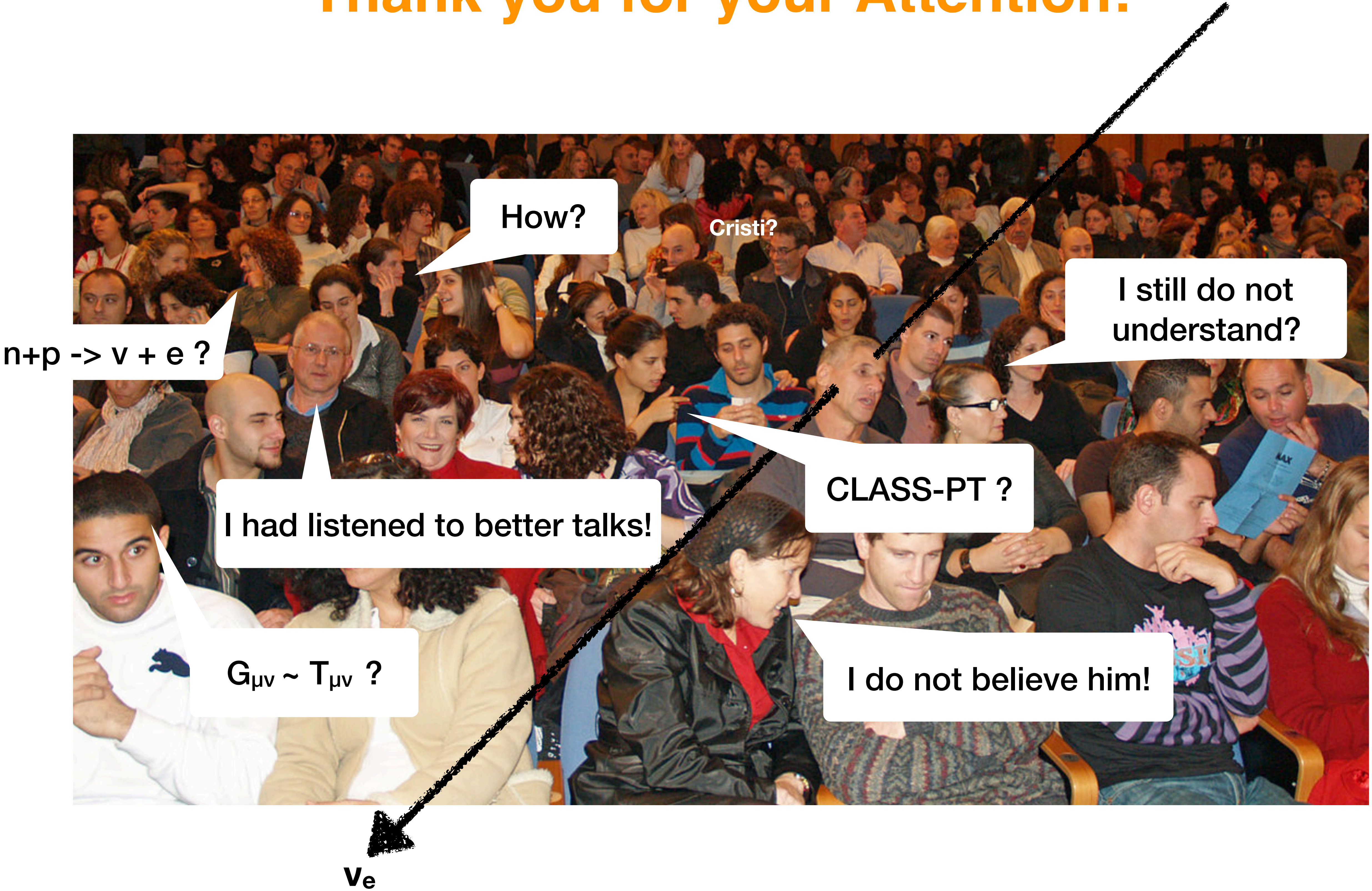
- **CLASS-PT is already undertaken in Euclid Consortium GC-SWG-modelling challenge**

- **CLASS-PT FULL-IR Resummation agrees with Halofit < 5 % C.L. (at k<0.1h/Mpc)**

- **The model selection is under development**
  - **New models**
  - **New simulations to validate them**
  - **New likelihood (Gaussian, Non-Gaussian, …)**
  - **New free-likelihood analysis (F.Leclercq)**

- **We should compare these codes/interpretations of LSS systematically with current and future survey**

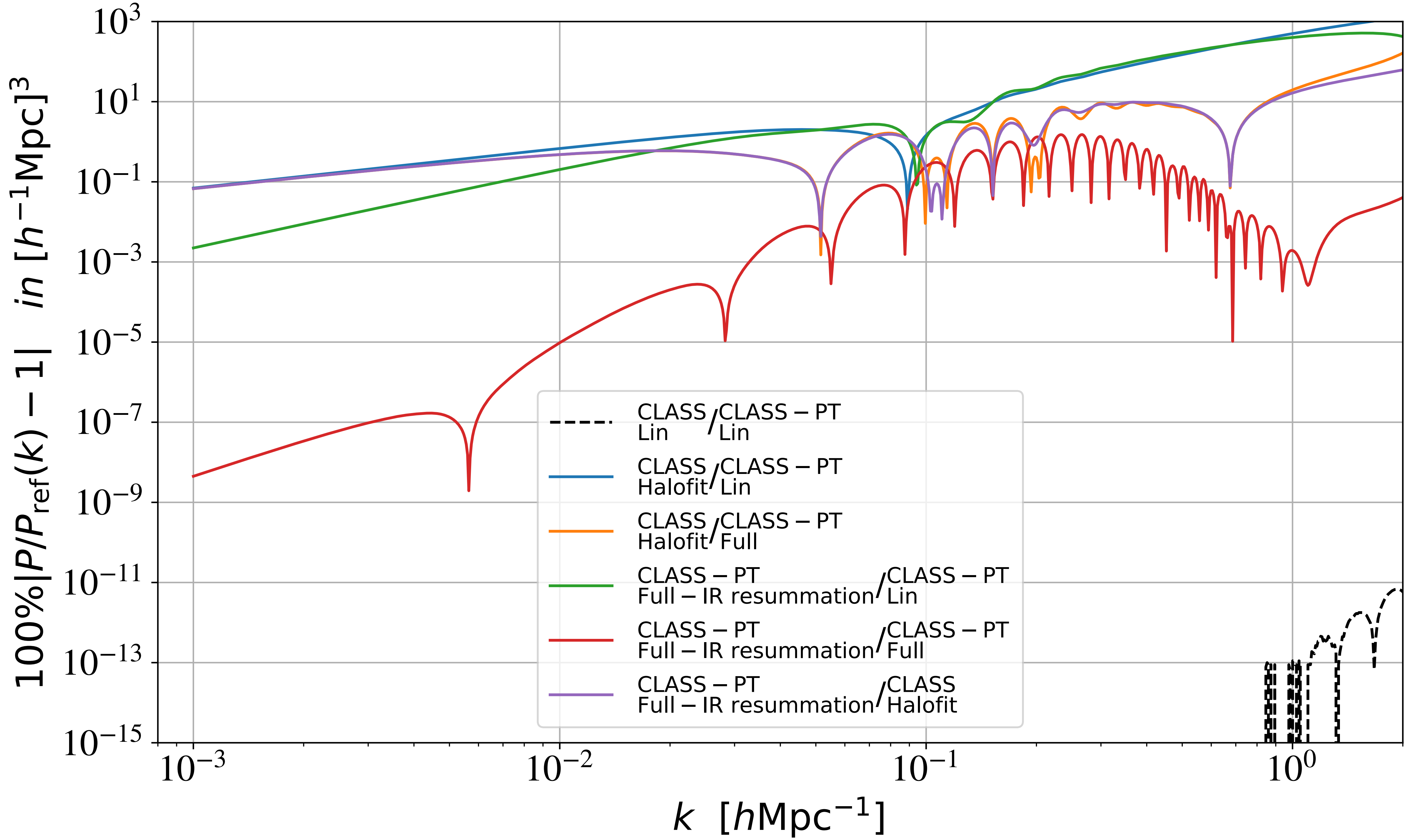
Thank you for your Attention!



PTofLSS CLASS-PT

Back ↑

=> For k < 0.1 h/Mpc : LSS NL models agree at less than 10% Rel. E.
=> For k > 0.1 h/Mpc : LSS NL models models are subjective



Caveats of CLASS-PT code

It is important to stress that our implementation of IR resummation at one loop order contains four potential sources of error:

- Imperfectness of wiggly-non-wiggly decomposition,
- Dependence of the damping factor on the separation cutoff,
- Inaccuracy of the factorization prescription,
- One-loop corrections $\mathcal{O}(P_{\rm w}^2)$ from two insertions of $P_{\rm w}$.
- **Bispectra are not implemented here, but easily retrievable**

taken from https://arxiv.org/pdf/2004.10607.pdf

EXTRA SLIDES

The FFTLog method is based on the representation of the linear matter power spectrum as a sum of complex power-laws in k. This is naturally achieved using the discrete Fourier transform with equal spacing in $\log k$, hence the name FFTLog [83]. The discrete approximation to the linear power spectrum in a finite momentum interval $[k_{\min}, k_{\max}]$, denoted as $\bar{P}(0,k)$, can be written as

$$\bar{P}_{\rm lin}(0,k) = \sum_{m=-N/2}^{m=N/2} c_m k^{\nu+i\eta_m}\,, \qquad (4.1)$$

where the Fourier coefficients c_m and exponents η_m are given by

$$c_m = \frac{1}{N}\sum_{j=0}^{N-1} P_{\rm lin}(0,k_j) k_j^{-\nu} k_{\min}^{-i\eta_m} e^{-2\pi i m j/N}\,, \quad \eta_m = \frac{2\pi m}{\ln(k_{\max}/k_{\min})}\,. \qquad (4.2)$$

ν=-0.3 (matter) and ν=-1.6 (biased tracers)

taken from https://arxiv.org/pdf/2004.10607.pdf

Adding some Redshift Space Distortions:

$$\begin{aligned}P_{\mathrm{gg,RSD}}(z,k,\mu) =& Z_1^2(\mathbf{k})P_{\mathrm{lin}}(z,k) + 2\int_{\mathbf{q}} Z_2^2(\mathbf{q},\mathbf{k}-\mathbf{q})P_{\mathrm{lin}}(z,|\mathbf{k}-\mathbf{q}|)P_{\mathrm{lin}}(z,q)\\ &+ 6Z_1(\mathbf{k})P_{\mathrm{lin}}(z,k)\int_{\mathbf{q}} Z_3(\mathbf{q},-\mathbf{q},\mathbf{k})P_{\mathrm{lin}}(z,q)\\ &+ P_{\mathrm{ctr,RSD}}(z,k,\mu) + P_{\epsilon\epsilon,\mathrm{RSD}}(z,k,\mu)\,.\end{aligned} \tag{2.13}$$

Kernels become more complicated
but smartly solvable by the authors !!!

taken from https://arxiv.org/pdf/2004.10607.pdf

$$P_{\text{Full}}(z,k) \equiv P_{\text{lin}}(z,k) + P_{1-\text{loop,SPT}}(z,k) + P_{ctr}(z,k)$$

$$P_{1-\text{loop,SPT}}(z,k) \equiv D^4(z)|P_{13}(k) + P_{22}(k)|$$

$$P_{ctr}(z,k) \equiv -2c_s^2(z)k^2 P_{\text{lin}}$$

effective sound speed normally nuisance under many authors

but it can be modelled IMO

Counter term Needed for the Consistency of 1-loop result

$$P_{22}(k) = 2\int_{\mathbf{q}} F_2^2(\mathbf{q},\mathbf{k}-\mathbf{q})P_{\text{lin}}(q)P_{\text{lin}}(|\mathbf{k}-\mathbf{q}|)\,,$$

$$P_{13}(k) = 6P_{\text{lin}}(k)\int_{\mathbf{q}} F_3(\mathbf{k},-\mathbf{q},\mathbf{q})P_{\text{lin}}(q)\,.$$

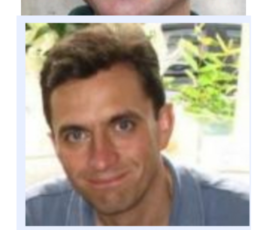
$F_{i=2,3}$**(k,k,k) :** Standard Perturbation Theory Kernels of 2nd,3rd order

see Bernardeau, Gaztañaga, Scoccimaro, ++

Perturbed Einstein-Boltzmann Equation Solvers

(CLASS)

Cosmological
Linear
Anisotropy
Solving
System



(CAMB)

Code for the
Anisotropies
in the cosmic
Microwave
Background

Despite their names, they actually solve numerically the 8 coupled Perturbed Einstein-Boltzmann equations described in their references.
for a short description **see**
Which result to $P_{Lin}(z,k) = D^2(z)\, P_{mm}(k,z=0)$

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Here we have defined

$$\mathcal{G}_2(\Phi_g) \equiv (\partial_i\partial_j\Phi_g)^2 - (\partial_i^2\Phi_g)^2\,, \quad (2.8)$$

where Φ_g is gravitational potential. The only cubic operator that gives nontrivial contribution to the one-loop power spectrum can be written as

$$\Gamma_3 \equiv \mathcal{G}_2(\Phi_g) - \mathcal{G}_2(\Phi_v)\,, \quad (2.9)$$

where Φ_v is velocity potential.[7] For the definition of $\mathcal{G}_3$ and relations of our operators to other equivalent choices of basis, see [58]. The term ϵ denotes the stochastic contribution which is uncorrelated with the large-scale density field. Poisson noise,

Free Parameters:

$$b_1 \equiv \text{linear bias}$$
$$b_2 \equiv \text{Quadratic bias}$$
$$b_{\mathcal{G}_2} \equiv \text{Tidal bias}$$
$$b_{\delta\mathcal{G}_2} \equiv \text{Perturbations of Tidal bias}$$
$$b_{\Gamma_3} \equiv \text{non}-\text{trivial cubic } 1-\text{loop bias}$$
$$R_\star \equiv \text{Parameter of the 2nd order perturbations of the field}\,\delta$$

-> Result to more terms such as:

$$P_{gg}(z,k) = b_1^2(z)(P_{\rm lin}(z,k) + P_{\text{1-loop, SPT}}(z,k)) + b_1(z)b_2(z)\mathcal{I}_{\delta^2}(z,k)$$
$$+ 2b_1(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\mathcal{G}_2}(z,k) + (2b_1(z)b_{\mathcal{G}_2}(z) + \frac{4}{5}b_1(z)b_{\Gamma_3}(z))\mathcal{F}_{\mathcal{G}_2}(z,k)$$
$$+ \frac{1}{4}b_2^2(z)\mathcal{I}_{\delta^2\delta^2}(z,k) + b_{\mathcal{G}_2}^2(z)\mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2(z)b_{\mathcal{G}_2}(z)\mathcal{I}_{\delta^2\mathcal{G}_2}(z,k)$$
$$+ P_{\nabla^2\delta}(z,k)$$

Gravitational Instabilities

$$+ P_{\epsilon\epsilon}(z,k)$$ ⟶ **stochastic component**

taken from https://arxiv.org/pdf/2004.10607.pdf

EXTRA SLIDES

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