Leonardo Senatore (ETH)

QCD methods for the Large-Scale Structure of the Universe

Where do we stand in Cosmology for fundamental physics?

The Effective Field Theory of Inflation

- Inflation: beyond the standard model

- Could be simple, but always simple.

- Symmetries allow general parametrization: mapping from data to theory.

$$S_\pi = \int d^4\sqrt{-g}\ \left[\frac{\dot{H}M_{\rm Pl}^2}{c_s^2}\left(\dot{\pi}^2 - c_s^2(\partial_i\pi)^2\right) + \frac{\dot{H}M_{\rm Pl}^2}{c_s^2}\left[\dot{\pi}(\partial_i\pi)^2 + \tilde{c}_3\,\dot{\pi}^3\right]\right]$$

with Cheung *et al*. **2008**

- We know very little of the parameters of this Lagrangian

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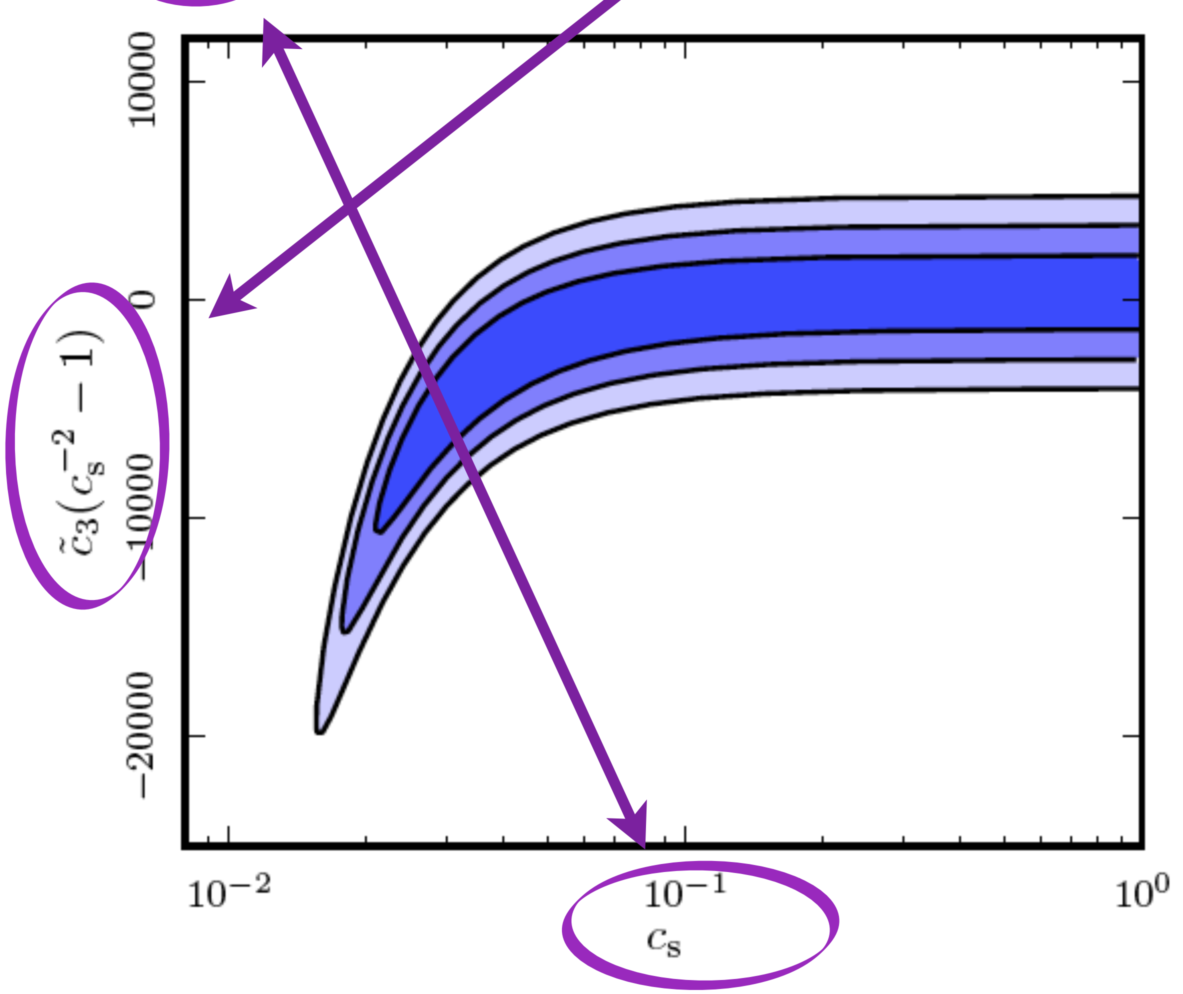


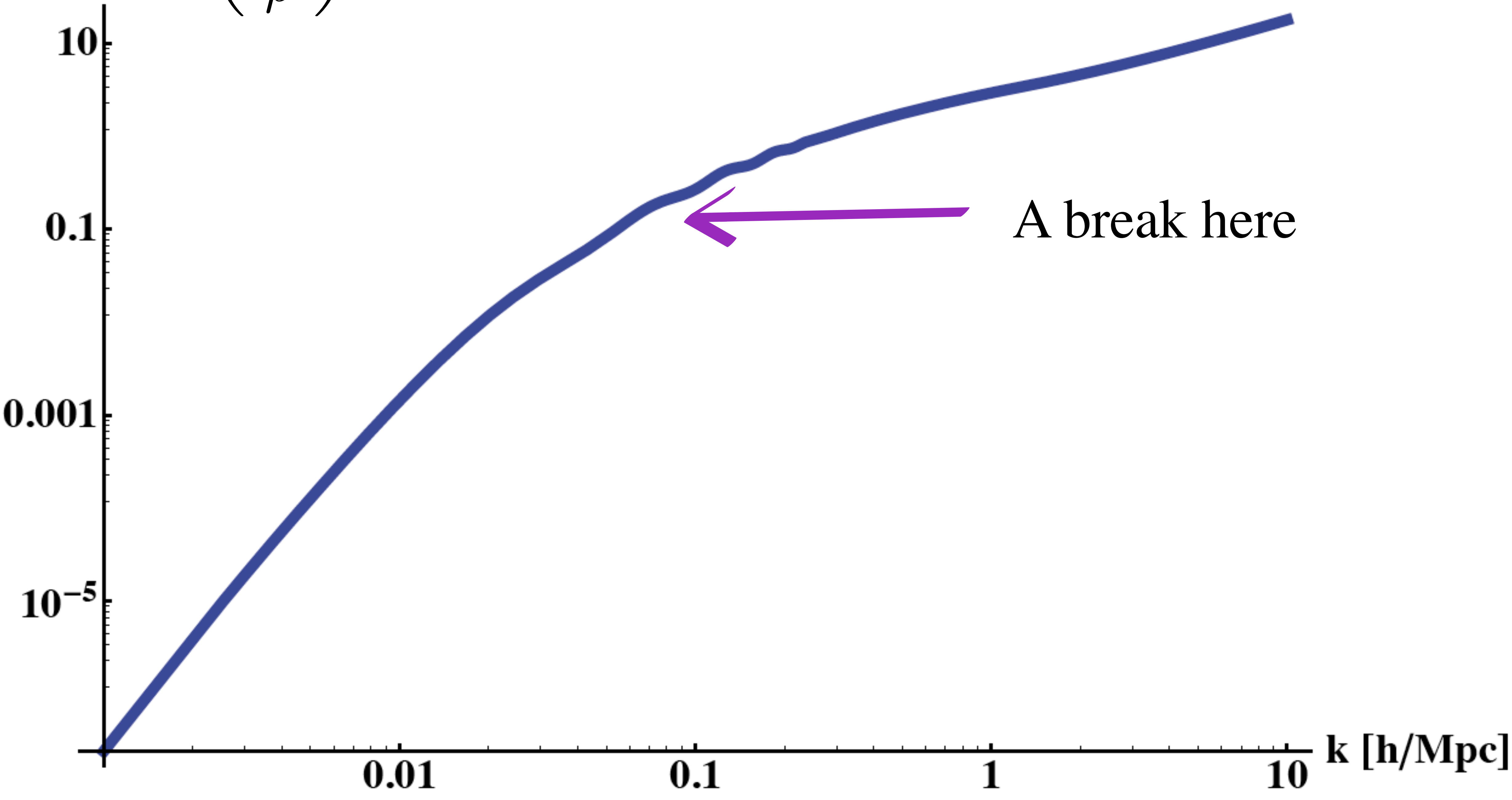
with Smith and Zaldarriaga, **2010**
WMAP final **2012**
Planck Collaboration **2013, 2015, 2018**

- We know very little of the parameters of this Lagrangian

Neutrino Masses

- Close to detect Neutrino Masses. Current bound $\lesssim 0.14\,\mathrm{eV}$, Minimal mass: $0.05\,\mathrm{eV}$

$$k^3 P(k) \sim \left(\frac{\delta\rho}{\rho}\right)^2$$

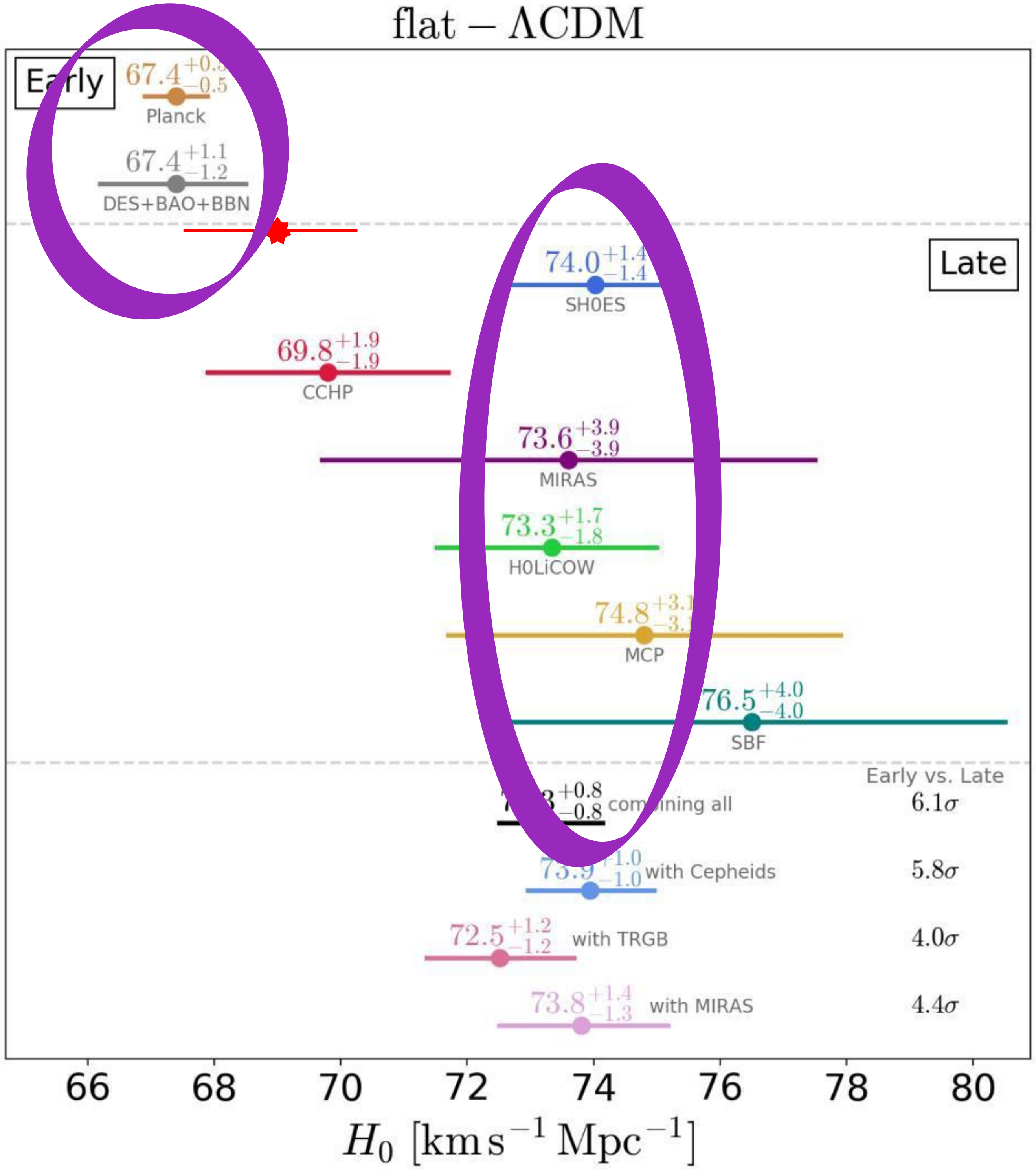


A break here

$$k\ [h\,\mathrm{Mpc}^{-1}]$$

Hubble Tension

- Qualitatively different methods disagree



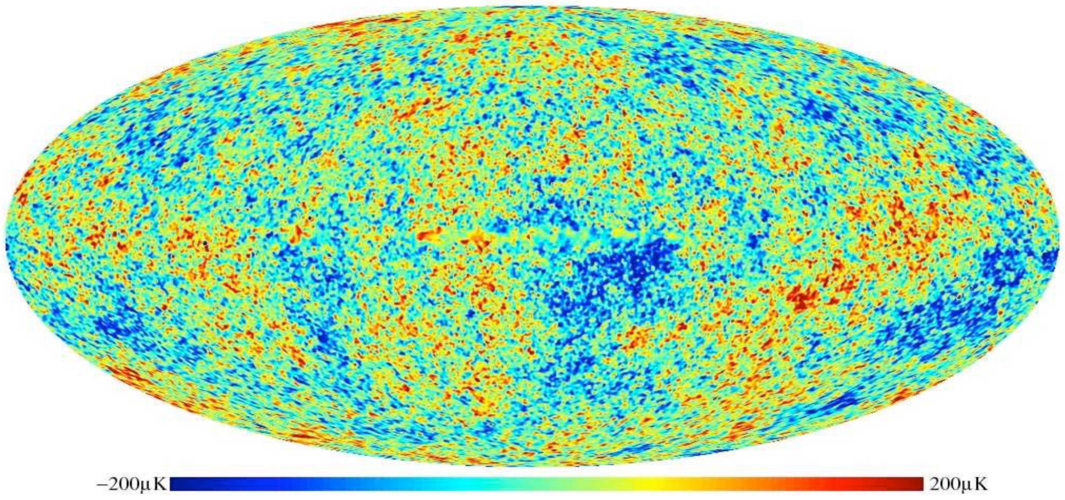
Summary plot by
Verde, Treu, and Riess
2019

The way ahead

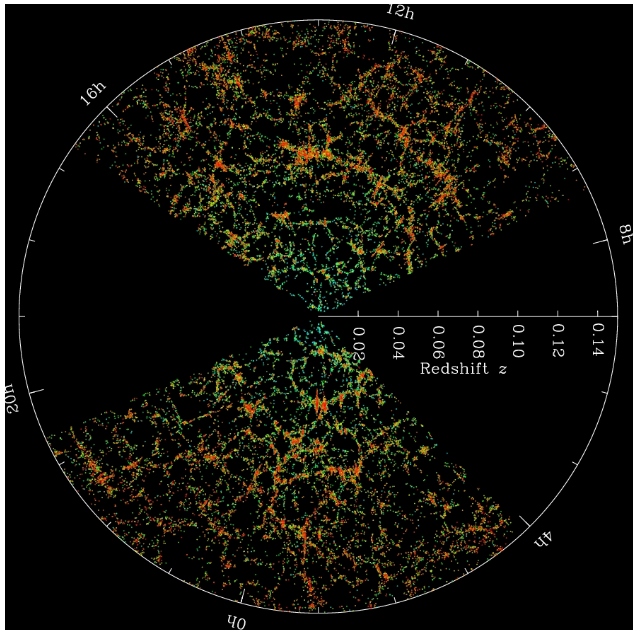
Cosmology is a luminosity experiment

- Progress through observation of the primordial fluctuations
- They are statically distributed:
  - To increase knowledge: more modes:

$$\Delta(\text{everything}) \propto \frac{1}{\sqrt{N_{\text{pixel}}}}$$



credit: WMAP



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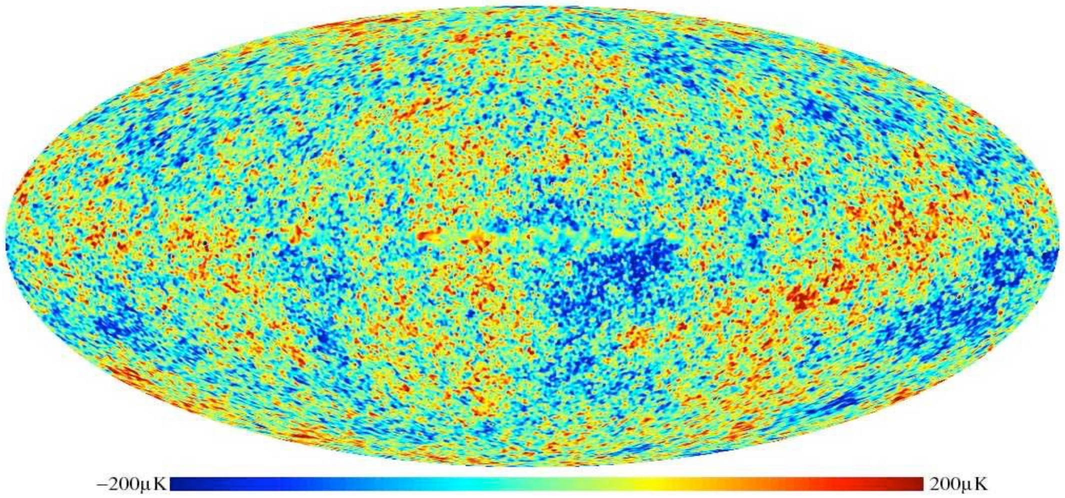
Planck has observed
almost all the modes in CMB



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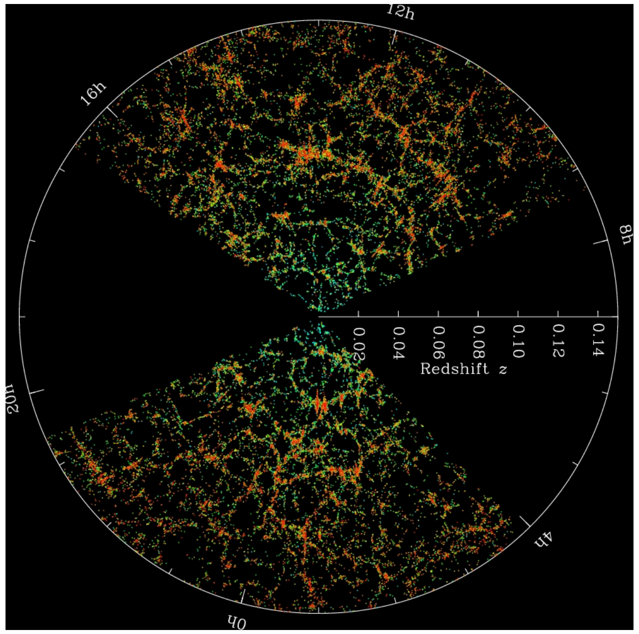

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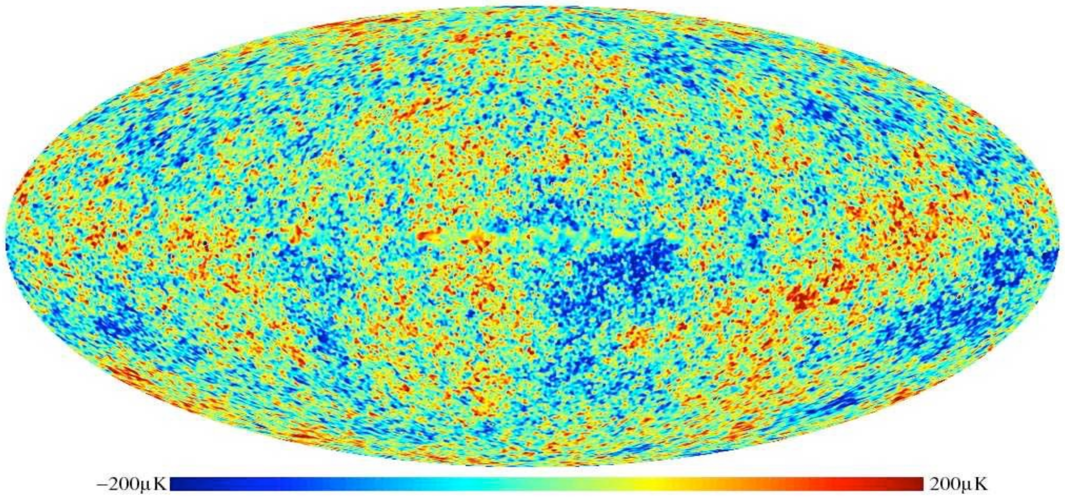
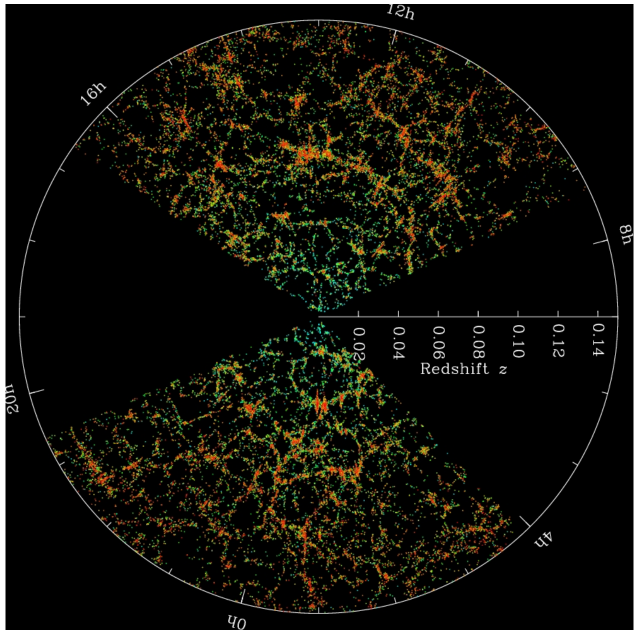


credit: WMAP

Large-Scale Structure (LSS)
offer the only medium-term opportunity



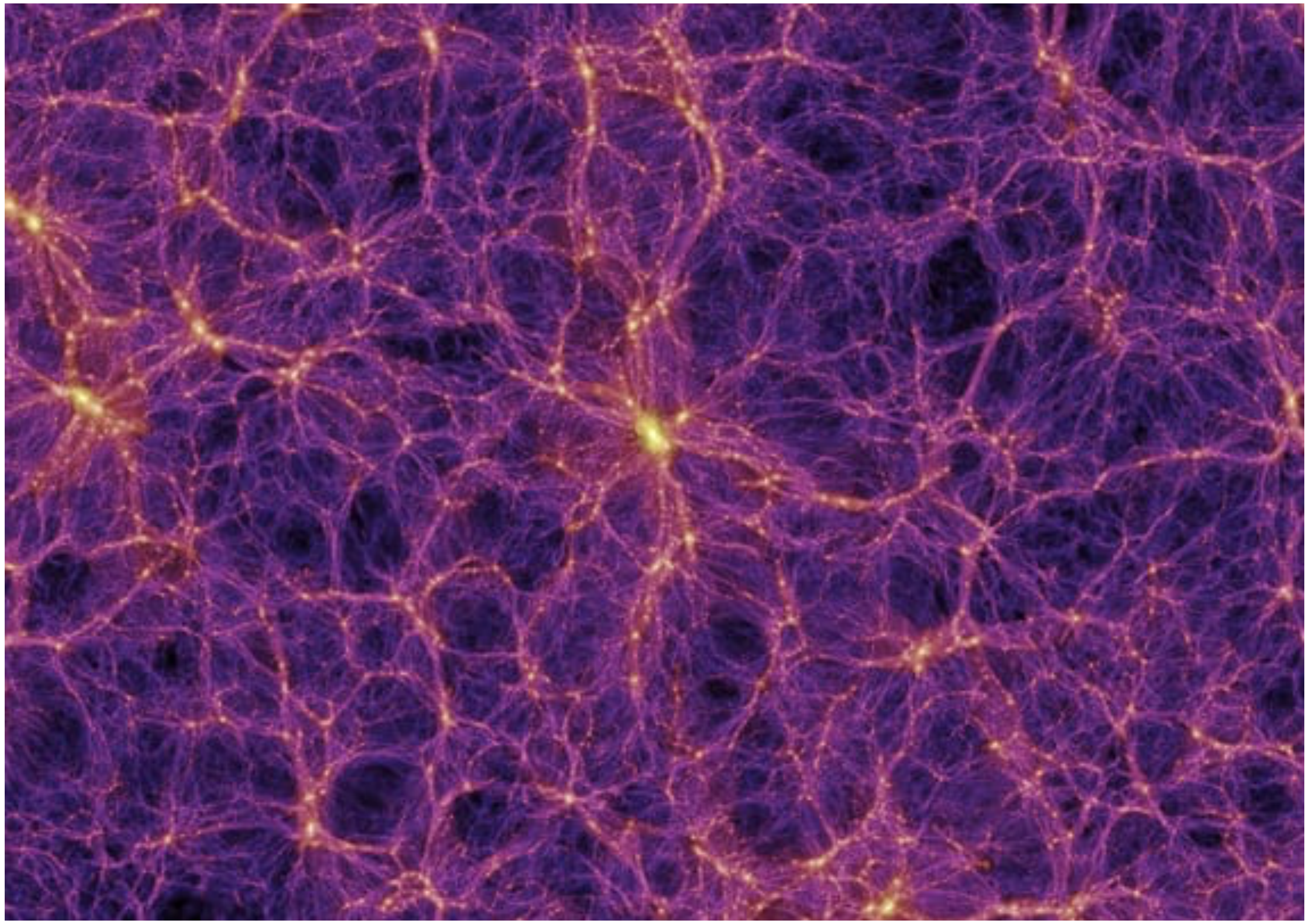
credit: SDSS/BOSS

What is the challenge?

- As many modes as possible:

$$N_{\rm modes} \sim \int^{k_{\rm max}} d^3k \sim k^3_{\rm max}$$

- Need to understand short distances



credit: Millenium Simulation, Springel *et al*. (2005)

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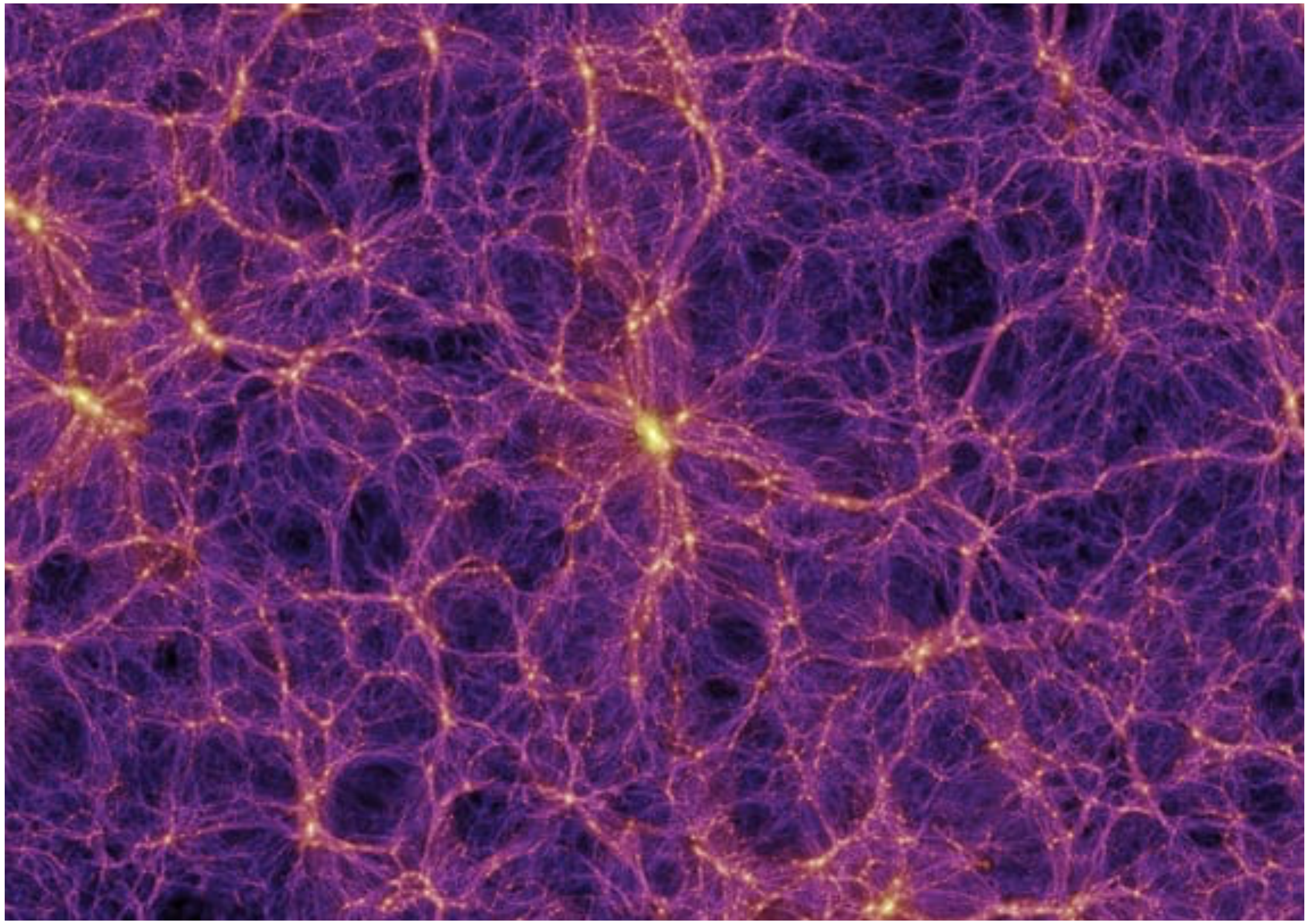
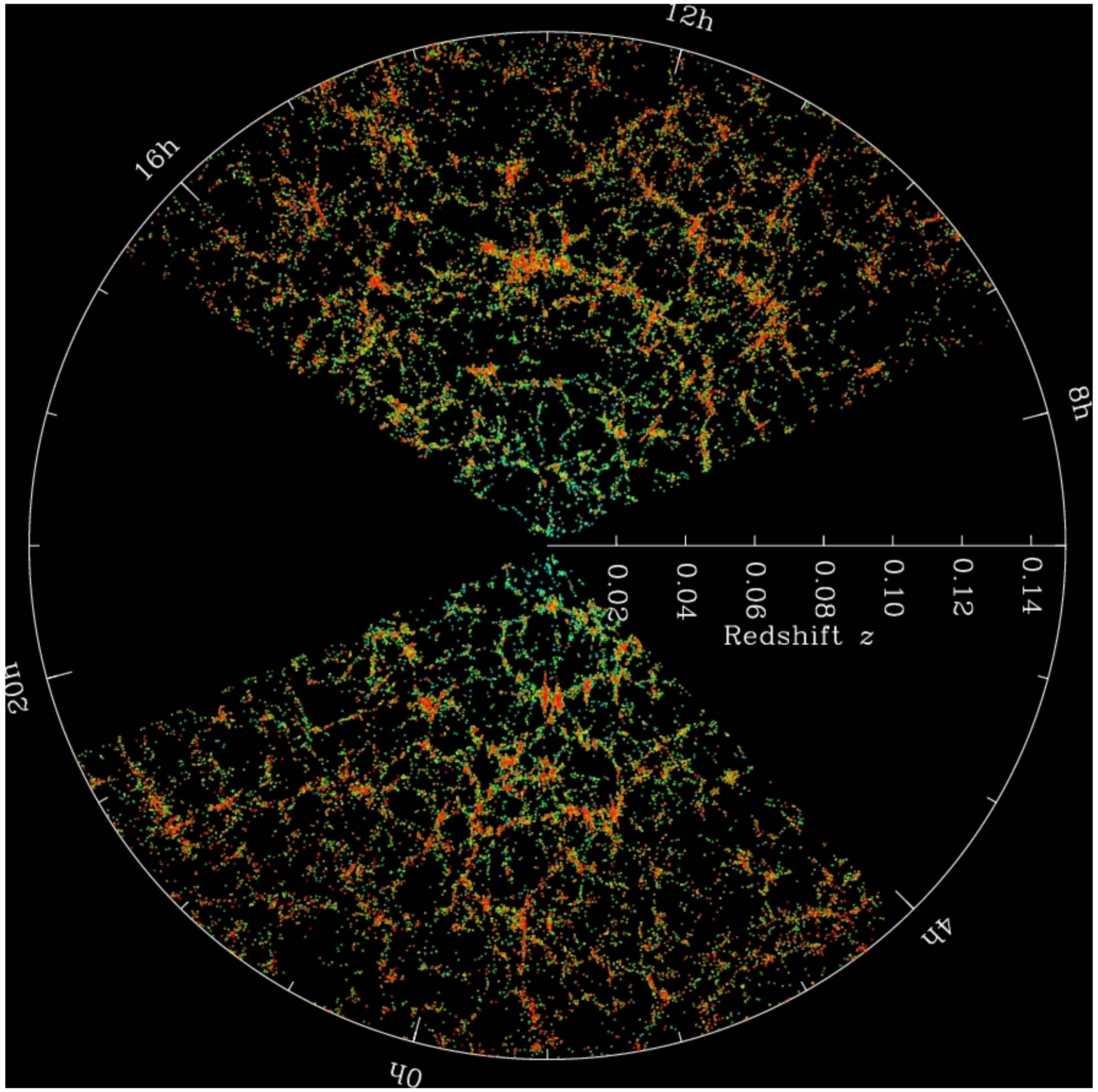
- Need to understand short distances
  - Like having LHC but not having QCD



credit: Millenium Simulation, Springel *et al*. (2005)

The Observables

$$\langle n_{\rm gal}(\vec{x})\, n_{\rm gal}(\vec{y})\rangle \quad \Leftrightarrow \quad \langle n_{\rm gal}(\vec{k})\, n_{\rm gal}(\vec{k}')\rangle \equiv P(\vec{k})\,\delta^{(3)}\left(\vec{k}+\vec{k}'\right)$$



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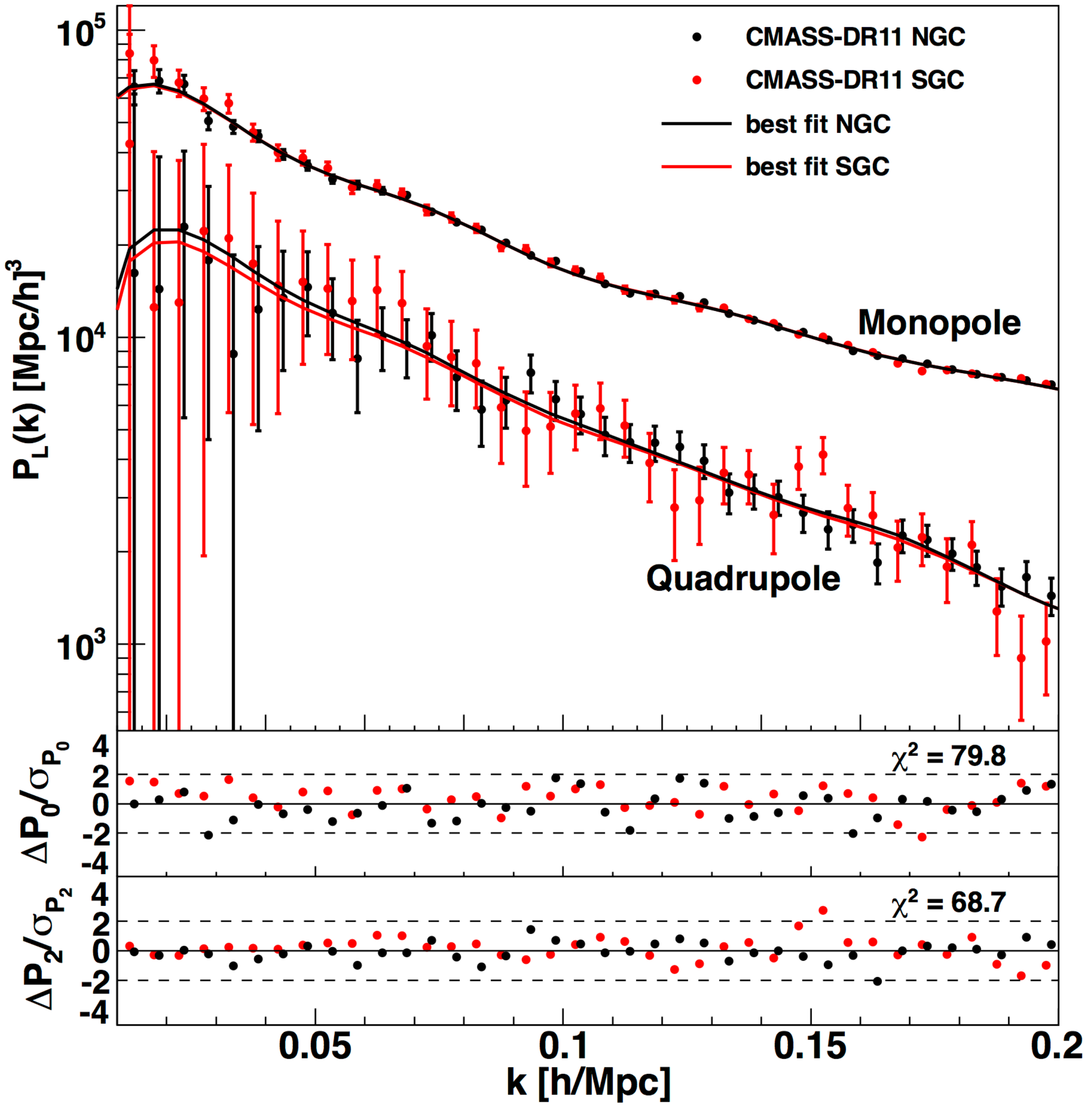

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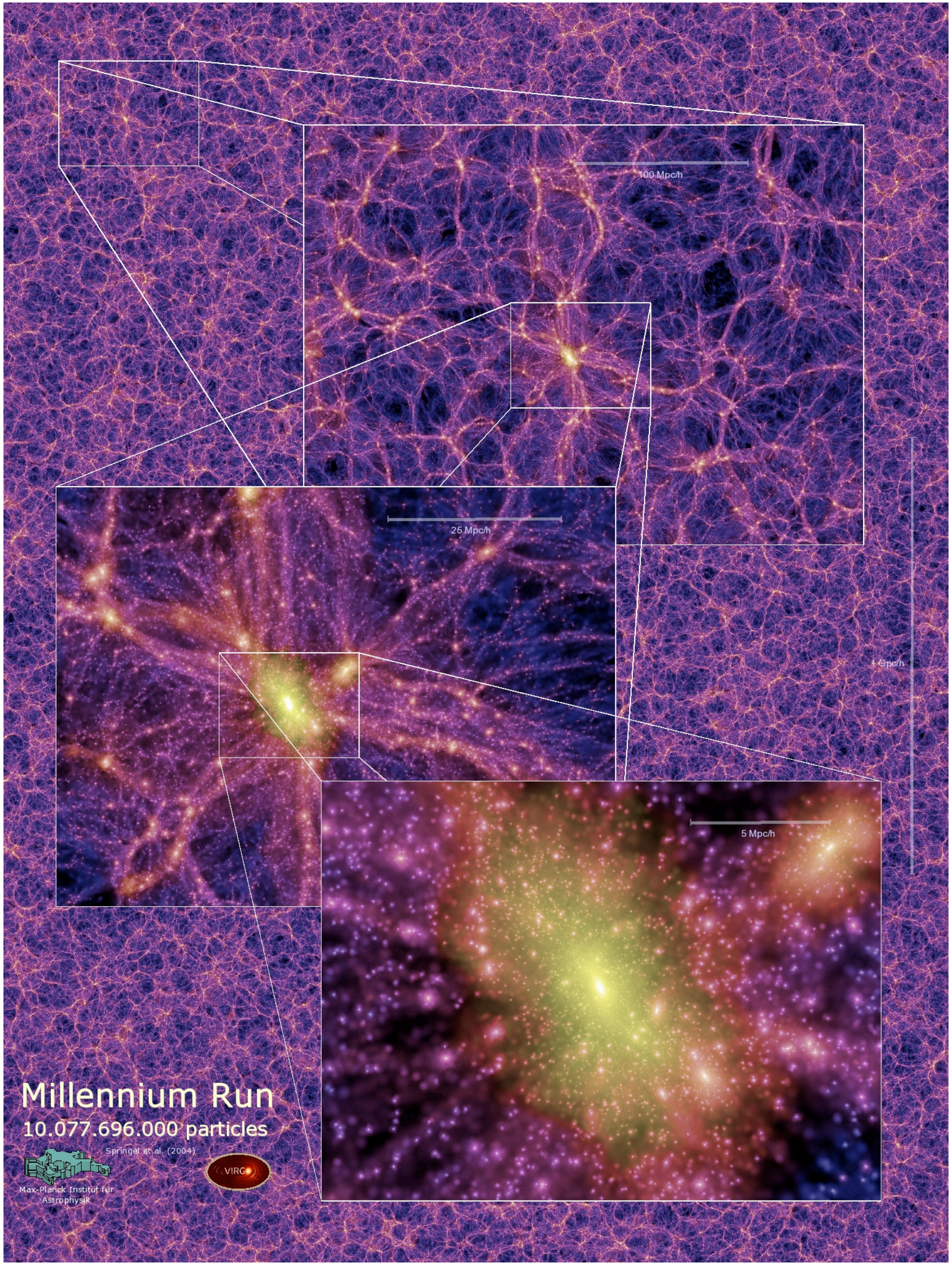
Normal Approach: numerics



Large-Scale Structure

credit NASA/ESA

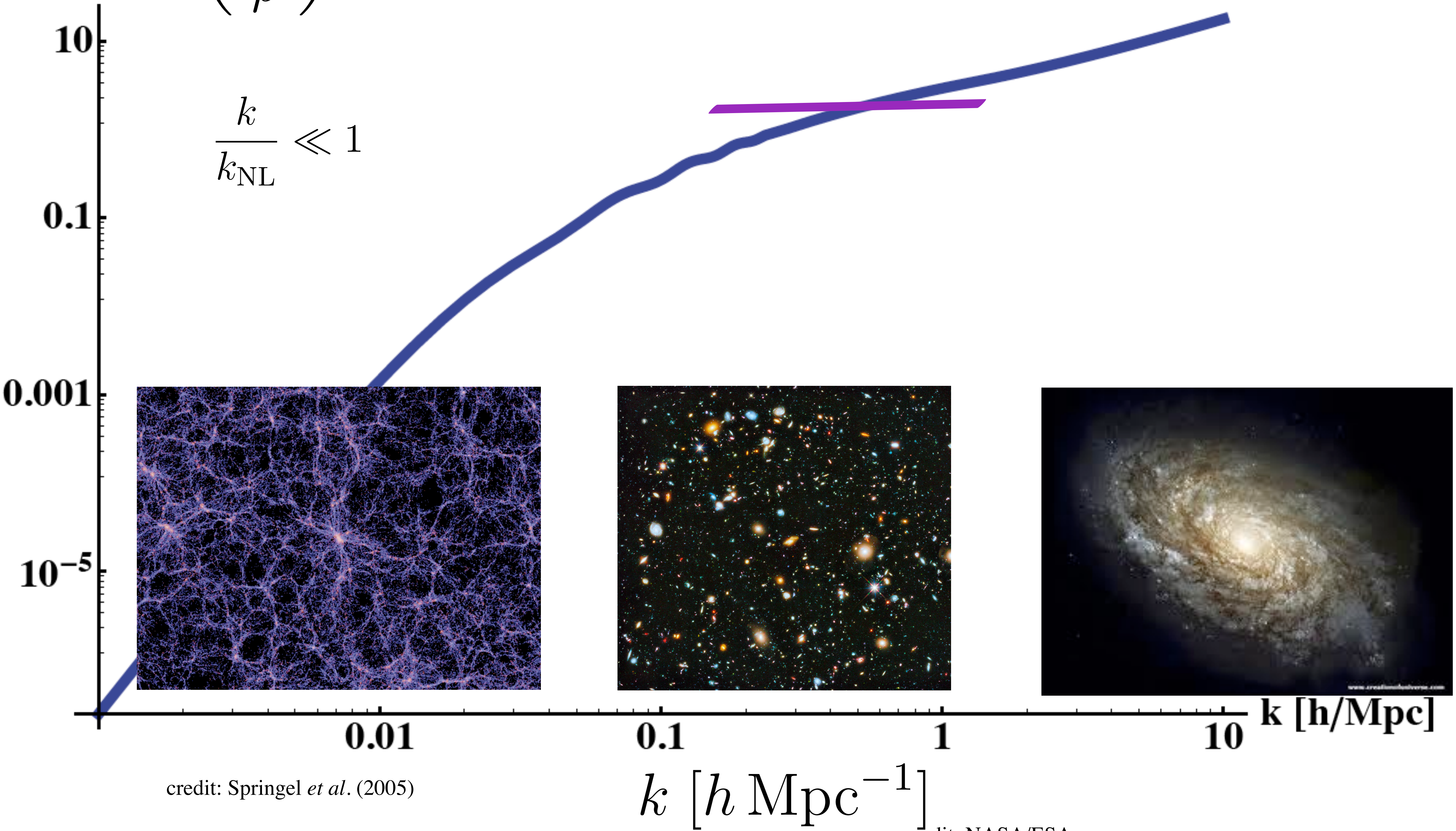
– DESI, Euclid, Vera Rubin, Megamapper…

– Can we use them to make a lot of fundamental physics?

Mini theory review

The EFTofLSS:
A well defined perturbation theory

$$k^3 P(k) \sim \left(\frac{\delta\rho}{\rho}\right)^2$$



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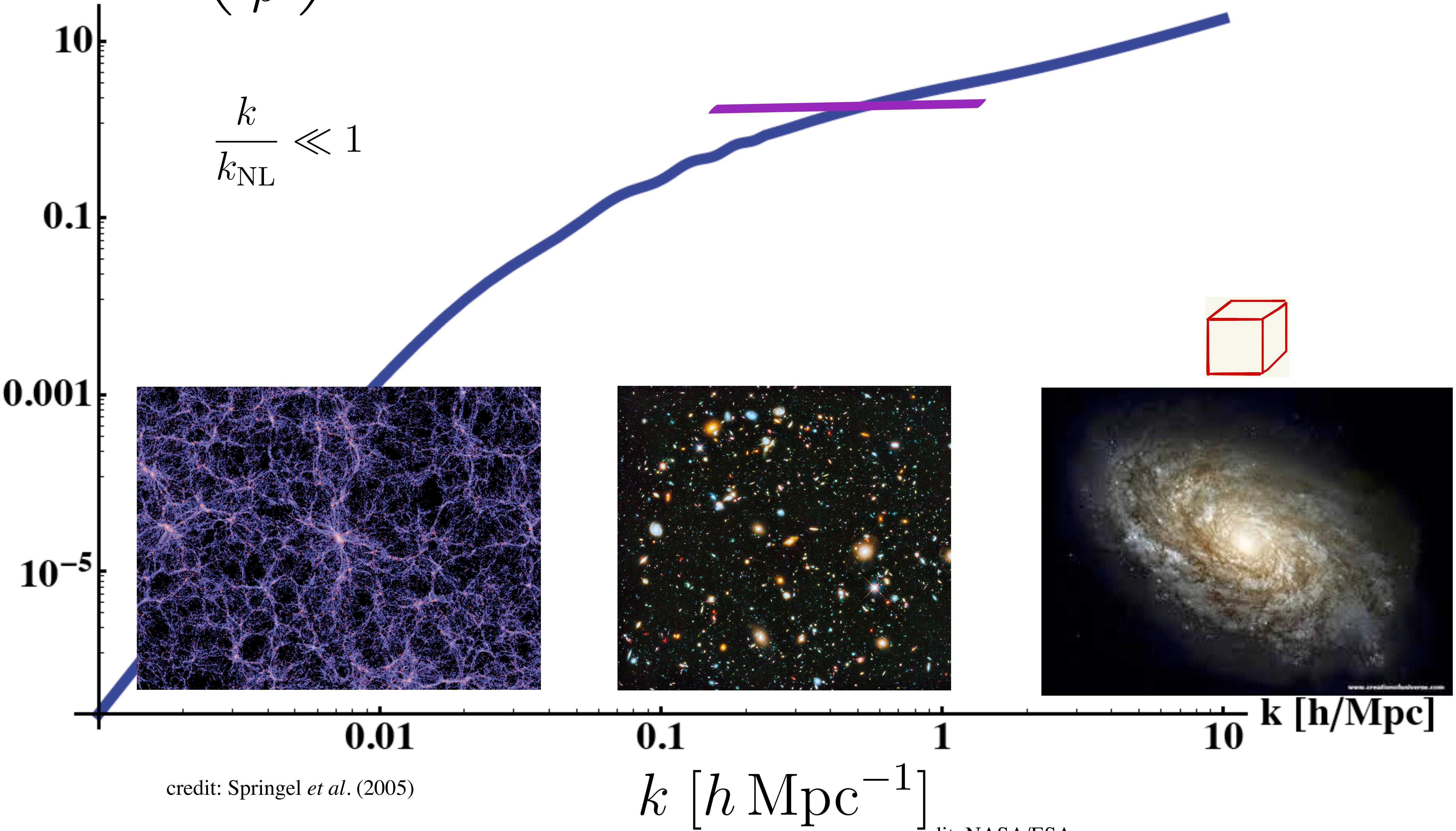

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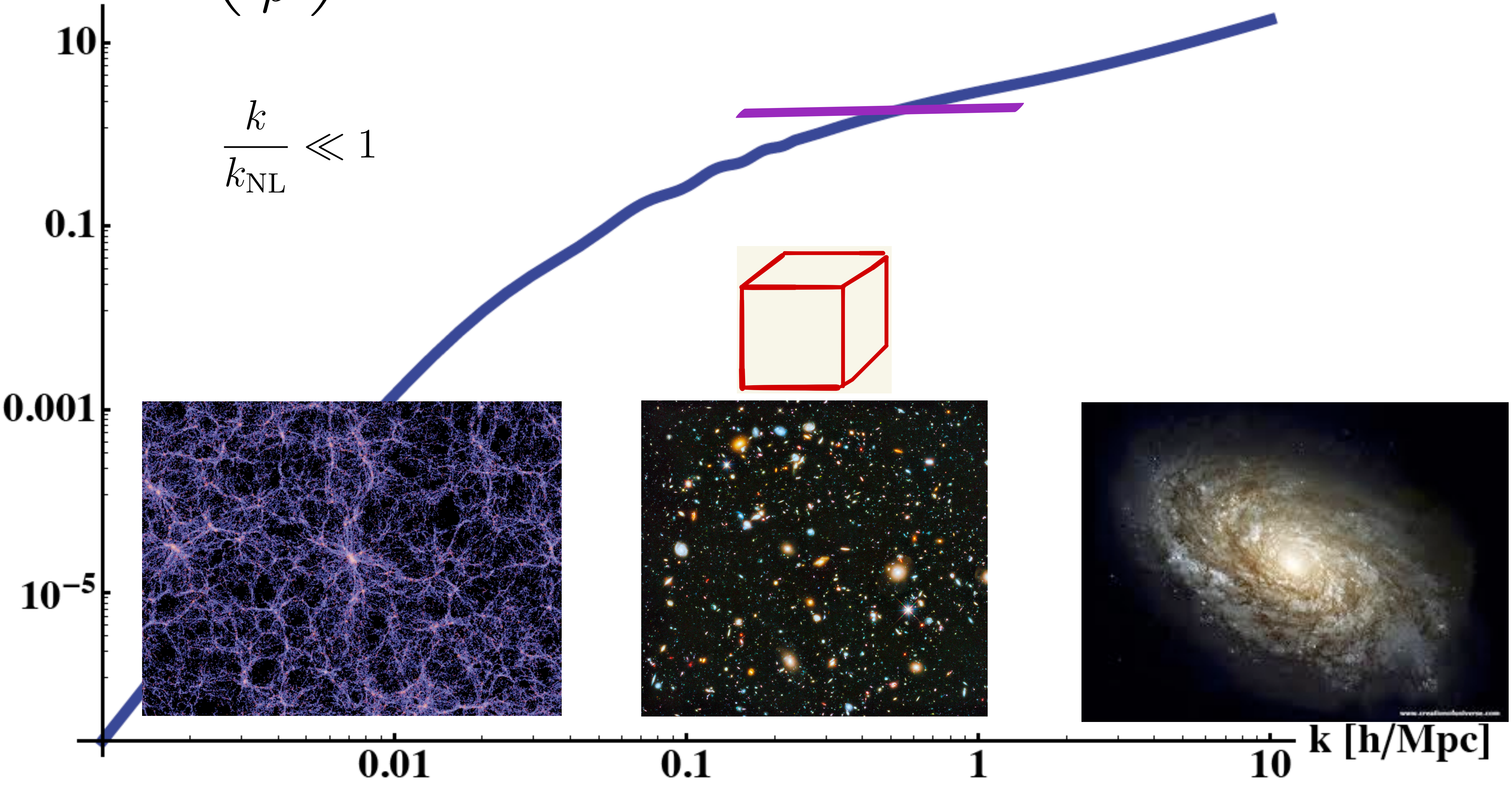

$k \ [h\,{\rm Mpc}^{-1}]$

credit: Springel *et al*. (2005)

credit: NASA/ESA

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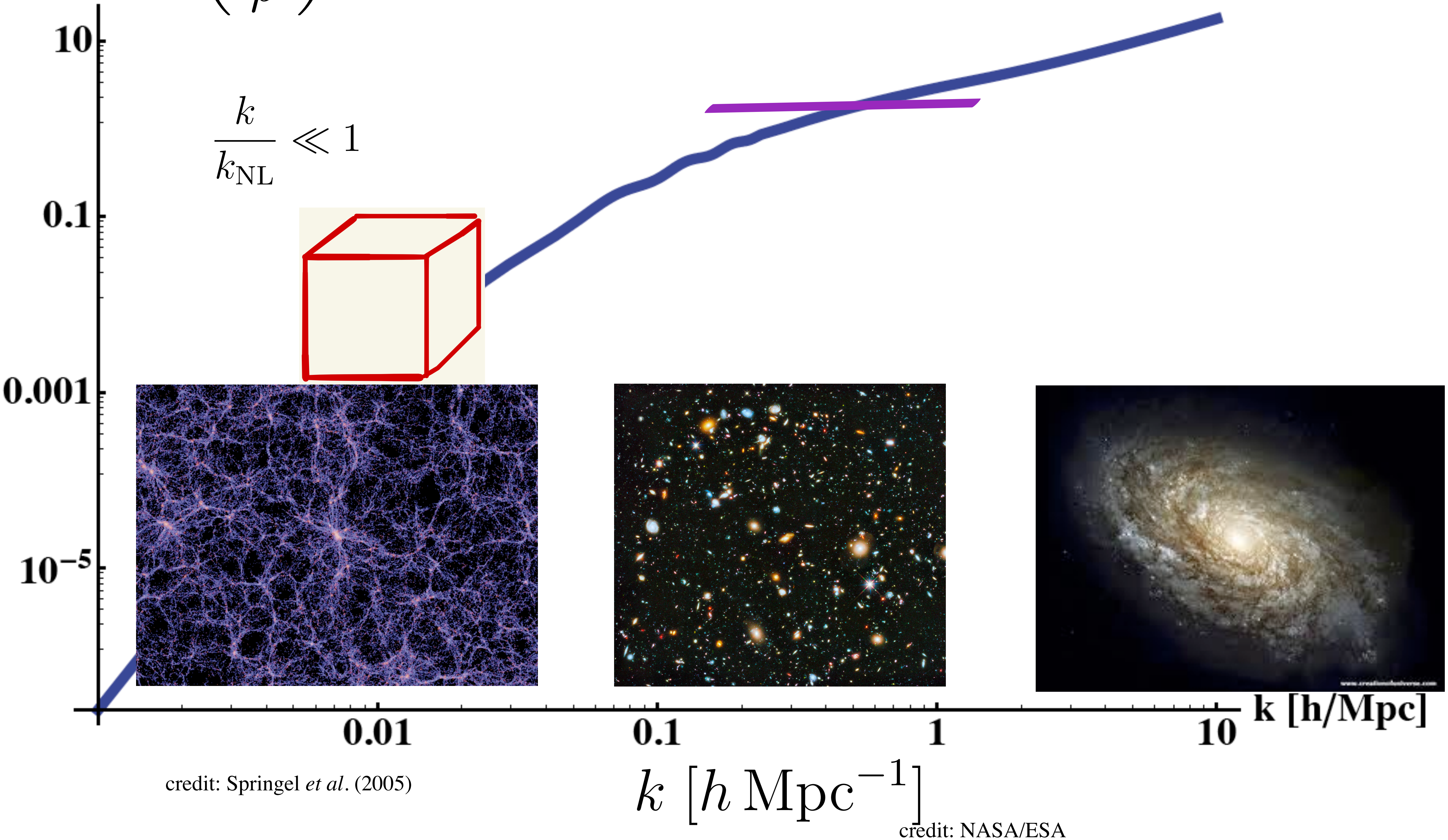
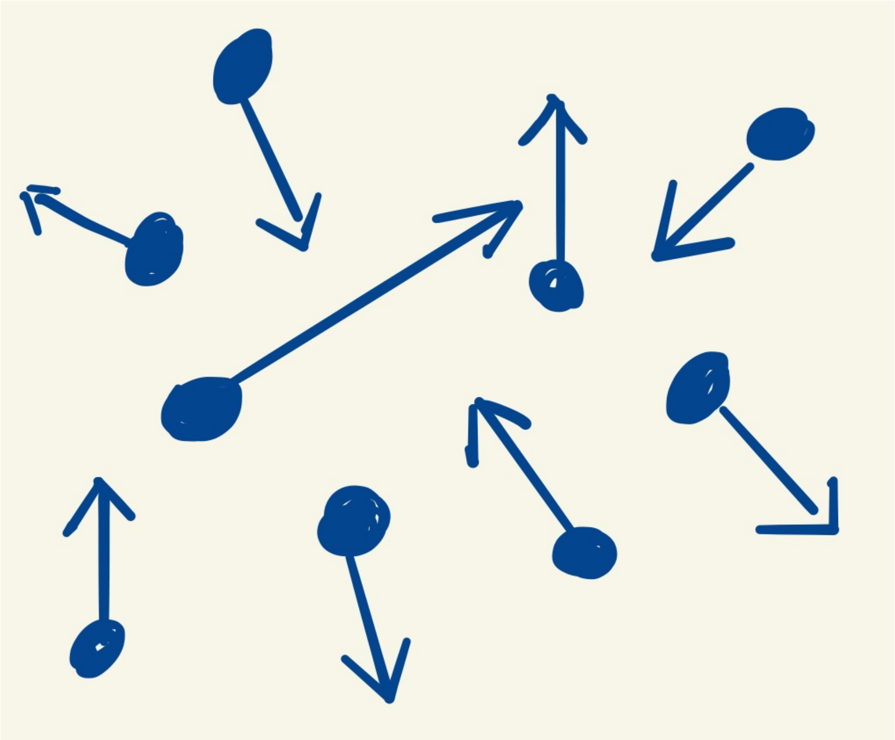


credit: Springel *et al*. (2005)

credit: NASA/ESA

What is a fluid?



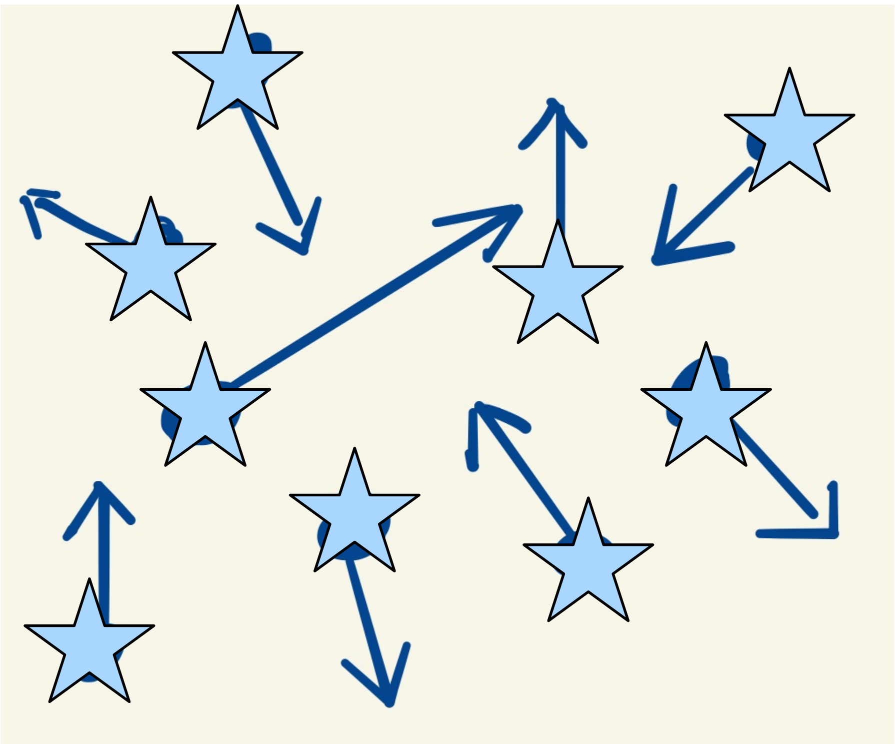
wikipedia: credit
National Oceanic and Atmospheric
Administration/
Department of Commerce

$$\partial_t \rho_\ell + \partial_i \left(\rho_\ell v^i_\ell \right) = 0$$

$$\partial_t v^i_\ell + v^j_\ell \partial_j v^i_\ell + \frac{1}{\rho_\ell} \partial_i p_\ell = \text{viscous terms}$$

- From short to long
- The resulting equations are simpler.
- Description arbitrarily accurate
  - construction can be made without knowing the nature of the particles.
- short distance physics appears as a non trivial stress tensor for the long-distance fluid

Do the same for matter in our Universe



credit NASA/ESA

with Baumann, Nicolis and Zaldarriaga **JCAP 2012**
with Carrasco and Hertzberg **JHEP 2012**

$$\nabla^2\Phi_\ell = H^2\left(\delta\rho_\ell/\rho\right)$$

$$\partial_t\rho_\ell + H\rho_\ell + \partial_i\left(\rho_\ell v_\ell^i\right) = 0$$

$$\partial_t v_\ell^i + v_\ell^j\partial_j v_\ell^i + \partial_i\Phi_\ell = \partial_j\tau^{ij}$$

– From short to long

– The resulting equations are simpler.

– Description arbitrarily accurate

  – construction can be made without knowing the nature of the particles.

– short distance physics appears as a non trivial stress tensor for the long-distance fluid

$$\tau_{ij} \sim \delta_{ij}\,\rho_{\text{short}}\,\left(v_{\text{short}}^2 + \Phi_{\text{short}}\right)$$

Dealing with the Effective Stress Tensor

- For long distances: expectation value over short modes (integrate them out)

$$\langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} = f_{\text{very complicated}}\left(\{H,\Omega_m,\dots,m_{\text{dm}},\dots,\rho_\ell(x)\}_{\text{past light cone}}\right)$$

At *long* wavelengths $\Downarrow$ Taylor Expansion

$$\langle \tau_{ij}(\vec{x},t)\rangle_{\text{long fixed}} = \int^t dt' \left[c(t,t')\,\frac{\delta\rho_\ell}{\rho}(\vec{x}_{\text{fl}},t') + \mathcal{O}\left((\delta\rho_\ell/\rho)^2\right)\right]$$

- Equations with only long-modes

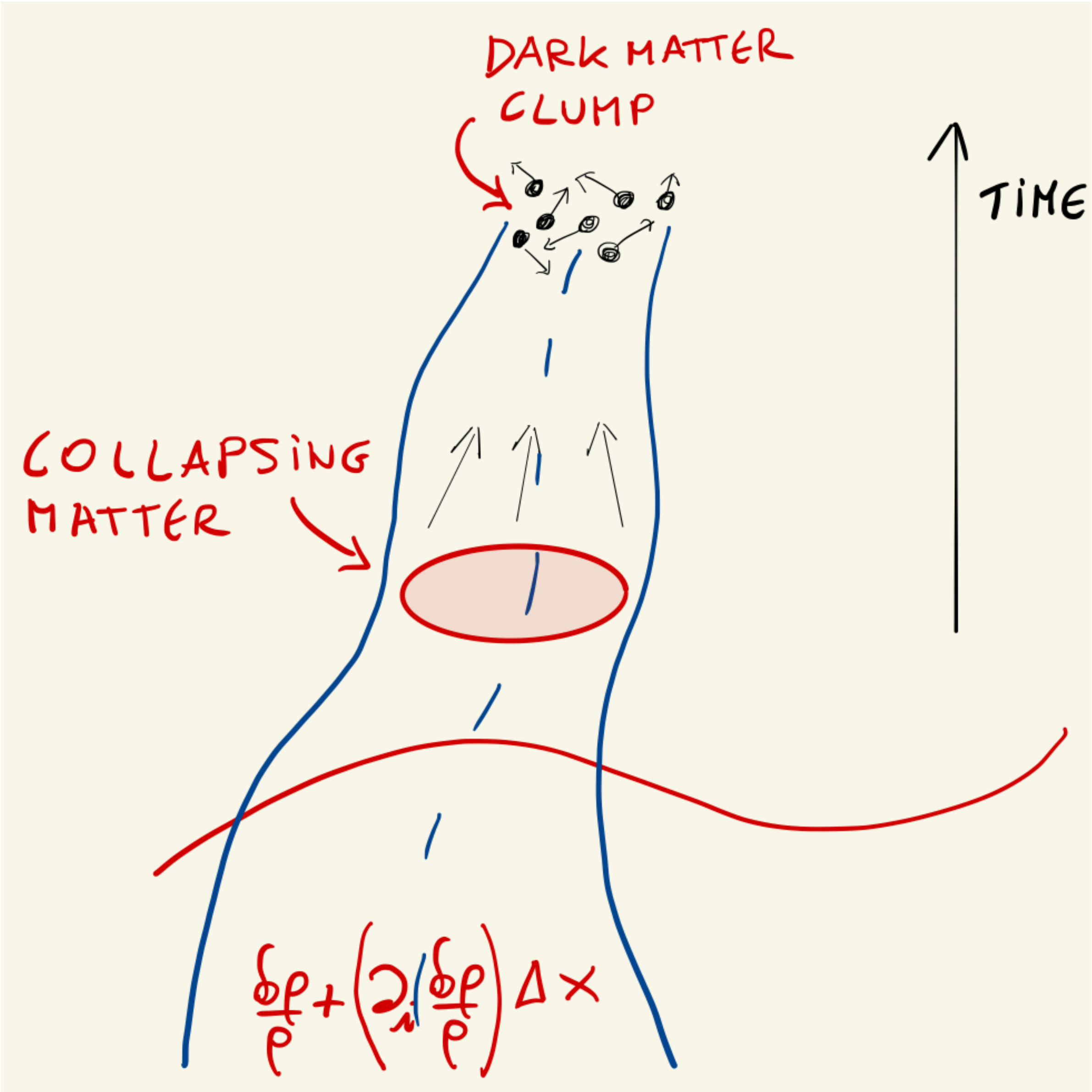
$$\partial_t v^i_\ell + v^j_\ell \partial_j v^i_\ell + \partial_i \Phi_\ell = \partial_j \tau^{ij}$$

$$\tau_{ij} \sim \delta\rho_\ell/\rho + \dots$$

every term allowed by symmetries

- each term contributes as factor of

$$\frac{\delta\rho_l}{\rho} \sim \frac{k}{k_{\text{NL}}} \ll 1$$



Perturbation Theory within the EFT

- In the EFT we can solve iteratively $\delta_\ell, v_\ell, \Phi_\ell \ll 1$, where $\delta_\ell = \dfrac{\delta\rho_\ell}{\rho}$

$$
\begin{aligned}
&\nabla^2\Phi_\ell = H^2\left(\delta\rho_\ell/\rho\right)\\
&\partial_t\rho_\ell + H\rho_\ell + \partial_i\left(\rho_\ell v_\ell^i\right) = 0\\
&\partial_t v_\ell^i + \enclose{circle}{v_\ell^j\partial_j v_\ell^i} + \partial_i\Phi_\ell = \partial_j\tau^{ij}
\end{aligned}
$$

$$\tau_{ij} \sim \delta\rho_\ell/\rho + \ldots$$

- Two scales:

$$k\left[\text{Mean Free Path Scale}\right] \sim k\left[\left(\frac{\delta\rho}{\rho}\right) \sim 1\right] \sim k_{\rm NL}$$

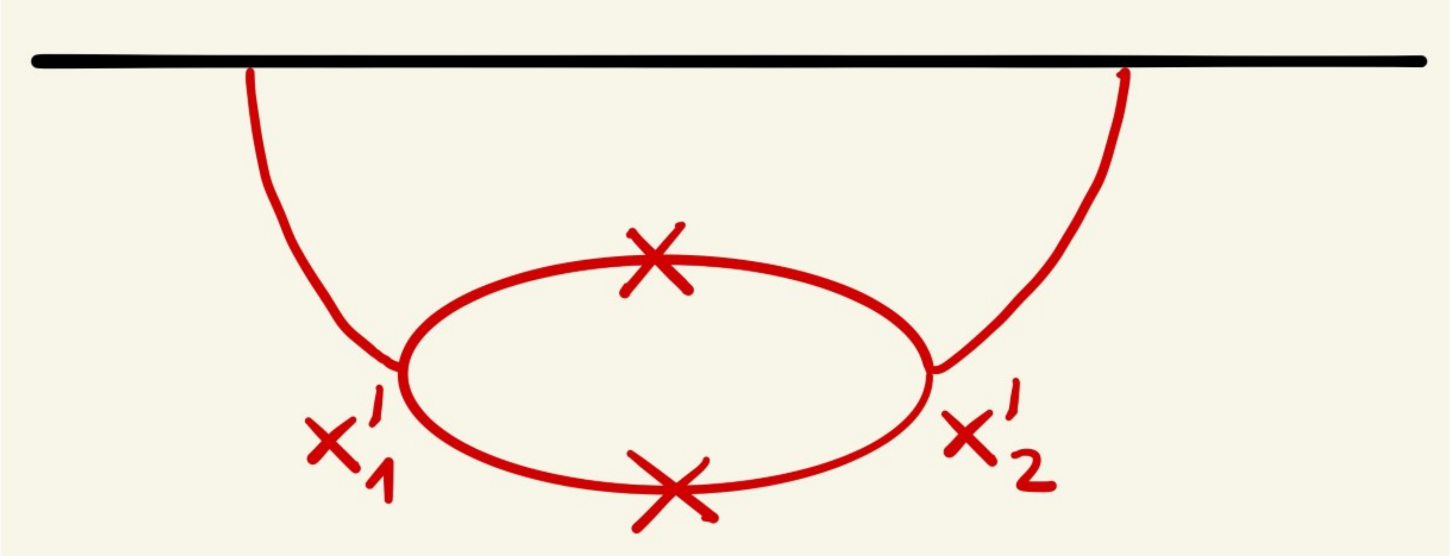
Perturbation Theory within the EFT

- Solve iteratively some non-linear eq. $\delta_\ell = \delta_\ell^{(1)} + \delta_\ell^{(2)} + \ldots \ll 1$
- Second order:

$$\partial^2 \delta_\ell^{(2)} = \left(\delta_\ell^{(1)}\right)^2 \quad \Rightarrow \quad \delta_\ell^{(2)}(x) = \int d^4x' \; \mathrm{Greens}(x, x') \; \left(\delta_\ell^{(1)}(x')\right)^2$$

- Compute observable:

$$\langle \delta_\ell(x_1)\delta_\ell(x_2)\rangle \supset \langle \delta_\ell^{(2)}(x_1)\delta_\ell^{(2)}(x_2)\rangle \sim \int d^4x_1' d^4x_2' \; (\mathrm{Green's})^2 \; \langle \delta_\ell^{(1)}(x_1')^2 \delta_\ell^{(1)}(x_2')^2\rangle$$



- We obtain Feynman diagrams
- Sensitive to short distance

$$x_2' \to x_1'$$

  - Need to add counterterms from $\tau_{ij} \supset c_s^2 \delta_\ell$ to correct
- Loops and renormalization applied to galaxies

Perturbation Theory within the EFT

Pajer and Zaldarriaga **2013**

- Regularization and renormalization of loops (no-scale universe) $P_{11}(k) = \frac{1}{{k_{\rm NL}}^3}\left(\frac{k}{k_{\rm NL}}\right)^n$

    –evaluate with cutoff:

$$P_{1-{\rm loop}} = c_1^\Lambda \left(\frac{\Lambda}{k_{\rm NL}}\right)\left(\frac{k}{k_{\rm NL}}\right)^2 P_{11} + c_1^{\rm finite}\left(\frac{k}{k_{\rm NL}}\right)^3 P_{11} + \text{subleading in } \frac{k}{k_{\rm NL}}$$

$$\langle \left(\frac{\delta\rho}{\rho}\right)^2_k \rangle$$

– divergence (we extrapolated the equations where they were not valid anymore)

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–we just re-derived renormalization

–after renormalization, result is finite and small for $\frac{k}{k_{\rm NL}}\ll 1$

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  –after renormalization, result is finite and small for $\frac{k}{k_{\rm NL}} \ll 1$

…. lots of work ….

Galaxy Statistics

Senatore **1406**
with Lewandowsky *et al* **1512**
with Perko *et al*. **1610**

Galaxies in the EFTofLSS

Senatore **1406**

- On galaxies, a long history before us, summarized by McDonald, Roy **2010** .
  - Senatore **1406** provided first complete parametrization.

- Nature of Galaxies is very complicated

$$n_{\rm gal}(x) = f_{\rm very\ complicated}\left(\{H, \Omega_m, \ldots, m_e, g_{ew}, \ldots, \rho(x)\}_{\rm past\ light\ cone}\right)$$

Galaxies in the EFTofLSS

Senatore **1406**

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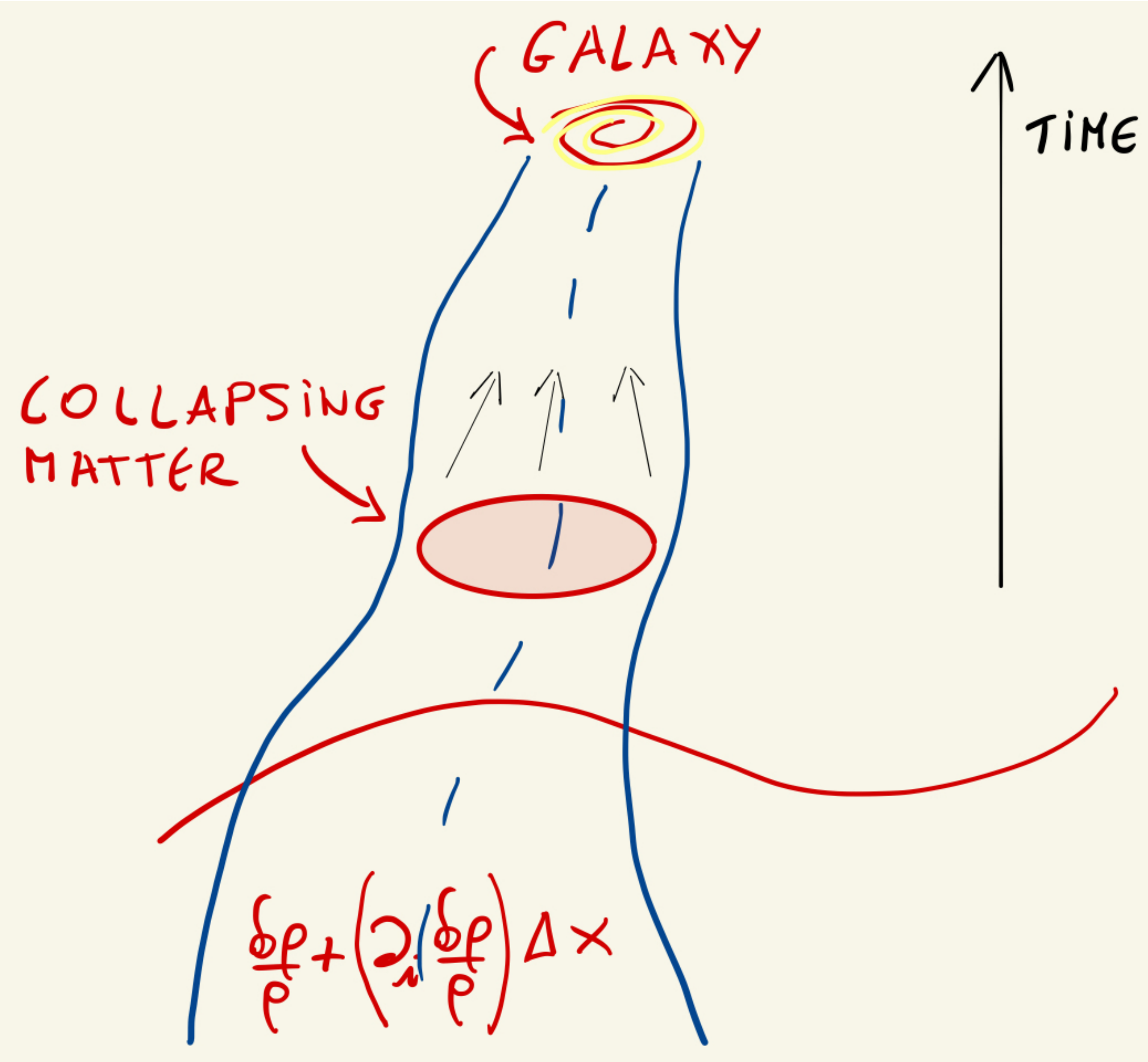
At *long* wavelengths $\Downarrow$ Taylor Expansion

$$\left(\frac{\delta n}{n}\right)_{{\rm gal},\ell}(x) \sim \int^t dt' \,\left[c(t,t')\,\left(\frac{\delta\rho}{\rho}\right)(\vec x_{\rm fl}, t') + \ldots\right]$$

- all terms allowed by symmetries
- all physical effects included
  - –e.g. assembly bias
- .

$$\left\langle \left(\frac{\delta n}{n}\right)_{{\rm gal},\ell}(x)\left(\frac{\delta n}{n}\right)_{{\rm gal},\ell}(y)\right\rangle =$$

$$= \sum_n {\rm Coeff}_n \cdot \langle \text{matter correlation function}\rangle_n$$



It is familiar in dielectric E&M

- Polarizability:

$$\vec{P}(\omega) = \chi(\omega)\vec{E}(\omega) \quad \Rightarrow \quad \vec{P}(t) = \int dt'\chi(t-t')\vec{E}(t')$$

- and in fact, also the EFT of Non-Relativistic binaries Goldberger and Rothstein **2004**

  is non-local in time.

Consequences of non-locality in time

with Carrasco, Foreman, Green **1310**
Senatore **1406**

- The EFT is non-local in time $\Longrightarrow$ $\langle \tau_{ij}(\vec{x},t)\rangle_{\rm long\ fixed} \sim \int^{t} dt'\ K(t,t')\ \delta\rho(\vec{x}_{\rm fl},t') + \dots$
- Perturbative Structure has a decoupled structure

$$\delta\rho(x,t') = D(t')\delta\rho(\vec{x})^{(1)} + D(t')^2\delta\rho(\vec{x})^{(2)} + \dots$$

- A few coefficients for each counterterm:

$$\Rightarrow \quad \langle \tau_{ij}(\vec{x},t)\rangle_{\rm long\ fixed} \sim \int^{t} dt'\ K(t,t')\ \left[D(t')\delta\rho(\vec{x})^{(1)} + D(t')^2\delta\rho(\vec{x})^{(2)} + \dots\right] \simeq$$

$$\simeq c_1(t)\ \delta\rho(\vec{x})^{(1)} + c_2(t)\ \delta\rho(\vec{x})^{(2)} + \dots$$

- where $c_i(t) = \int dt'\ K(t,t')\ D(t')^i$

- Difference:

$$\text{Time-Local QFT:} \quad c_1(t)\left[\delta\rho(\vec{x})^{(1)} + \delta\rho(\vec{x})^{(2)} + \dots\right]$$

$$\text{Non-Time-Local QFT:} \quad c_1(t)\ \delta\rho(\vec{x})^{(1)} + c_2(t)\delta\rho(\vec{x})^{(2)} + \dots$$

  - More terms, but not a disaster

Consequences of non-locality in time

with Carrasco, Foreman, Green **1310**
Senatore **1406**

- This means that one *does not* get the same terms as in the local-in-time expansion
  - it just happens that at lowest orders in PT, these terms are degenerate, and so, with the first few orders, it is impossible to distinguish. But not in principle.

- If we could measure one of these terms, we could *measure* that Galaxies take an Hubble time to form. We have never measured this: we take pictures of different galaxies at different stages of their evolution. But we have never *seen* a galaxy form in an Hubble time.

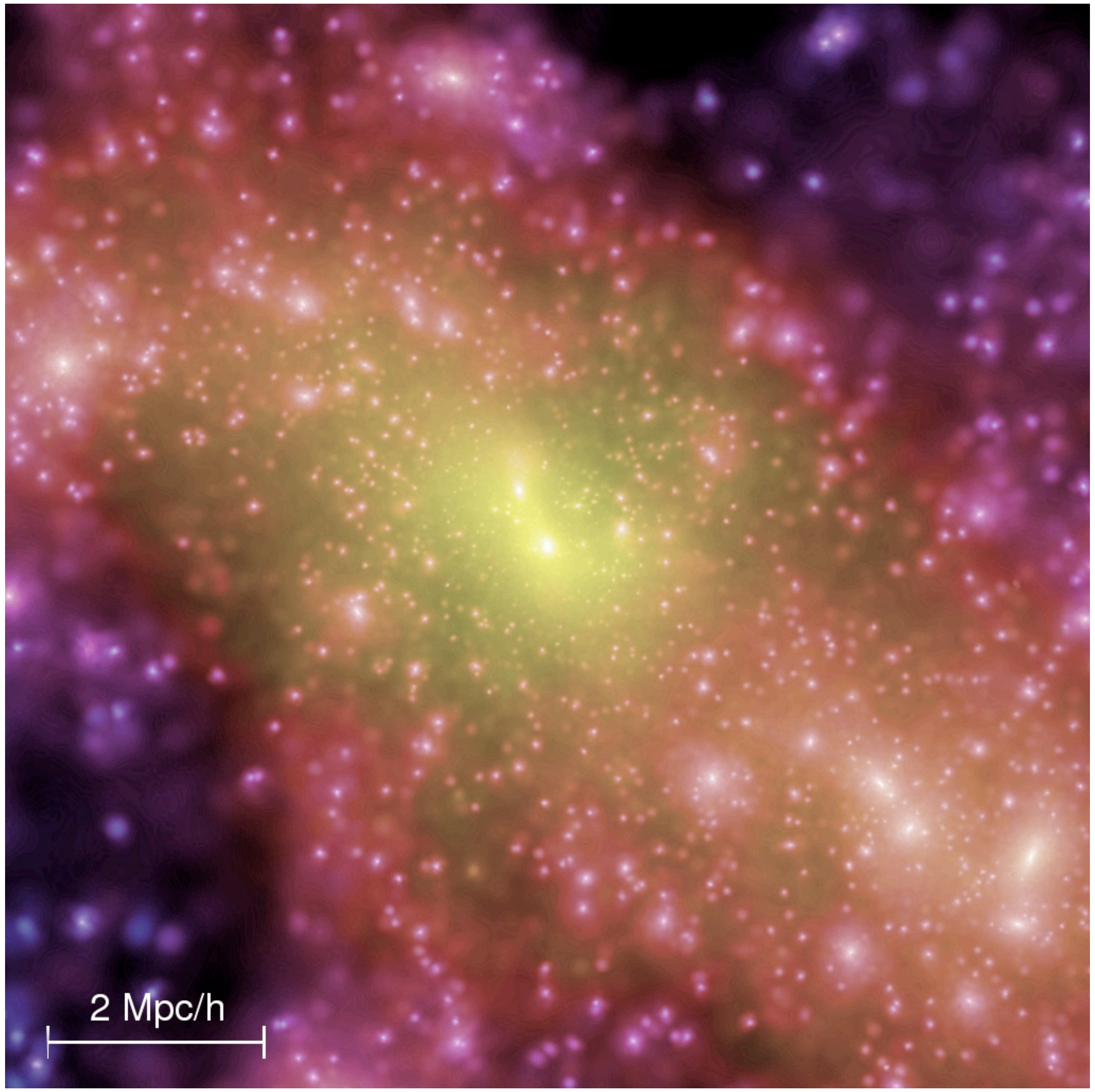
- So, detecting a non-local-in-time bias would allow us to measure that, and from the size, the formation time. Unfortunately, so far, not yet.

The EFTofLSS with Baryonic Effects

with Lewandowski and Perko **JCAP 2015**
with Braganca, Lewandowski and Sgier **JCAP 2021**

Baryonic effects

- When stars explode, baryons behave differently than dark matter



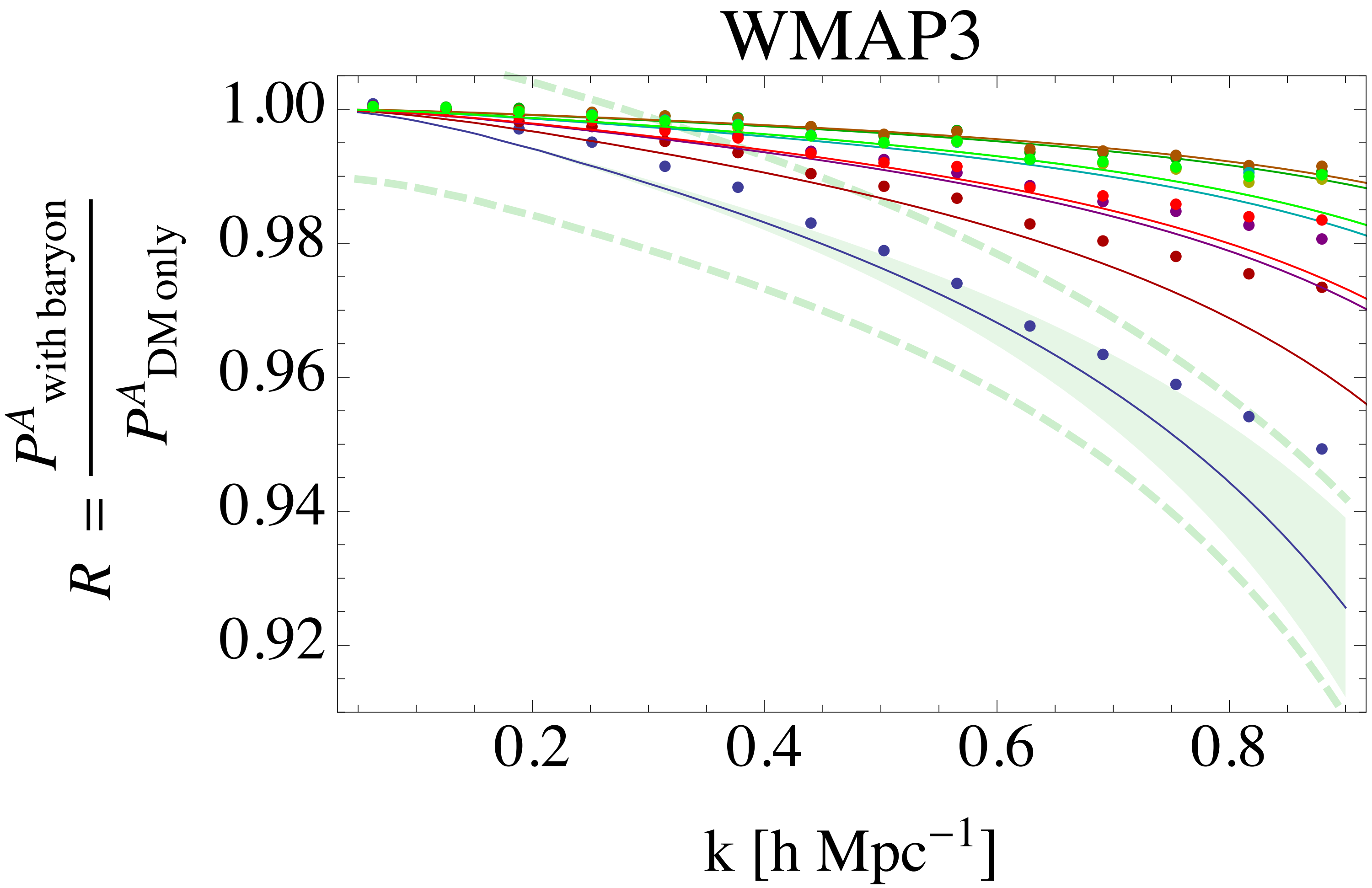
credit: Millenium Simulation,
Springel *et al*. (2005)

- They cannot be reliably simulated due to large range of scales

Baryons

- Idea for EFT for dark matter:
  - Dark Matter moves $1/k_{\rm NL} \sim 10\,{\rm Mpc}$
    - $\Longrightarrow$ an effective fluid-like system with mean free path ~ $1/k_{\rm NL}$
- Baryons heat due to star formation, but move the same:
  - Universe with CDM+Baryons $\Longrightarrow$ EFTofLSS with 2 specie

$$\Delta P_b(k) \simeq c_\star^2 \left(\frac{k}{k_{\rm NL}}\right)^2 P_{11}^A(k)$$



Baryons

- EFT Equations:

$$\text{Continuity:} \quad \dot{\rho}_\sigma + 3H\rho_\sigma + a^{-1}\partial_i \pi^i_\sigma = 0 \ ,$$

$$\text{Momentum:} \quad \dot{\pi}^i_c + 4H\pi^i_c + a^{-1}\partial_j\left(\frac{\pi^i_c\pi^j_c}{\rho_c}\right) + a^{-1}\rho_c\partial_i\Phi = +a^{-1}\gamma^i - a^{-1}\partial_j\tau^{ij}_c \ ,$$

$$\dot{\pi}^i_b + 4H\pi^i_b + a^{-1}\partial_j\left(\frac{\pi^i_b\pi^j_b}{\rho_b}\right) + a^{-1}\rho_b\partial_i\Phi = -a^{-1}\gamma^i - a^{-1}\partial_j\tau^{ij}_b \ .$$

Baryons

- EFT Equations:

$$\text{Continuity:} \quad \dot{\rho}_\sigma + 3H\rho_\sigma + a^{-1}\partial_i \pi^i_\sigma = 0 \ ,$$

$$\text{Momentum:} \quad \dot{\pi}^i_c + 4H\pi^i_c + a^{-1}\partial_j \left(\frac{\pi^i_c \pi^j_c}{\rho_c} \right) + a^{-1}\rho_c \partial_i \Phi = \boxed{+a^{-1}\gamma^i} - a^{-1}\boxed{\partial_j \tau^{ij}_c} ,$$

$$\dot{\pi}^i_b + 4H\pi^i_b + a^{-1}\partial_j \left(\frac{\pi^i_b \pi^j_b}{\rho_b} \right) + a^{-1}\rho_b \partial_i \Phi = \boxed{-a^{-1}\gamma^i} - a^{-1}\partial_j \tau^{ij}_b \ .$$

dynamical friction

effective force

- Counterterms:

$$\partial_i(\partial\tau_\rho)^i_c - \partial_i(\gamma)^i_c = -g\, w_b \boxed{aH\, \partial_i v^i_I} + 9(2\pi)H^2 \Big\{ \frac{c^2_{c,g}}{k^2_{\rm NL}} \left(w_c \partial^2\delta_c + w_b \partial^2 \delta_b \right) + \frac{c^2_{c,v}}{k^2_{\rm NL}} \partial^2 \delta_c$$

$$+ \frac{1}{k^2_{\rm NL}} \left(c^{cc}_{1c} \partial^2 \delta^2_c + c^{cb}_{1c} \partial^2 \left(\delta_c \delta_b \right) + c^{bb}_{1c} \partial^2 \delta^2_b \right)$$

$$+ \frac{c^2_{4c,g}}{a^2 k^4_{\rm NL}} \left(w_c \partial^4 \delta_c + w_b \partial^4 \delta_b \right) + \frac{c^2_{4c,v}}{a^2 k^4_{\rm NL}} \partial^4 \delta_c \Big\} + \dots$$

A relevant operator

- Dynamical friction term is indeed needed for renormalization of the theory, i.e. it is generated.

- Dynamical friction is a relevant operator: i.e. it cannot be treated perturbatively: it is an essential part of the linear *equations:*

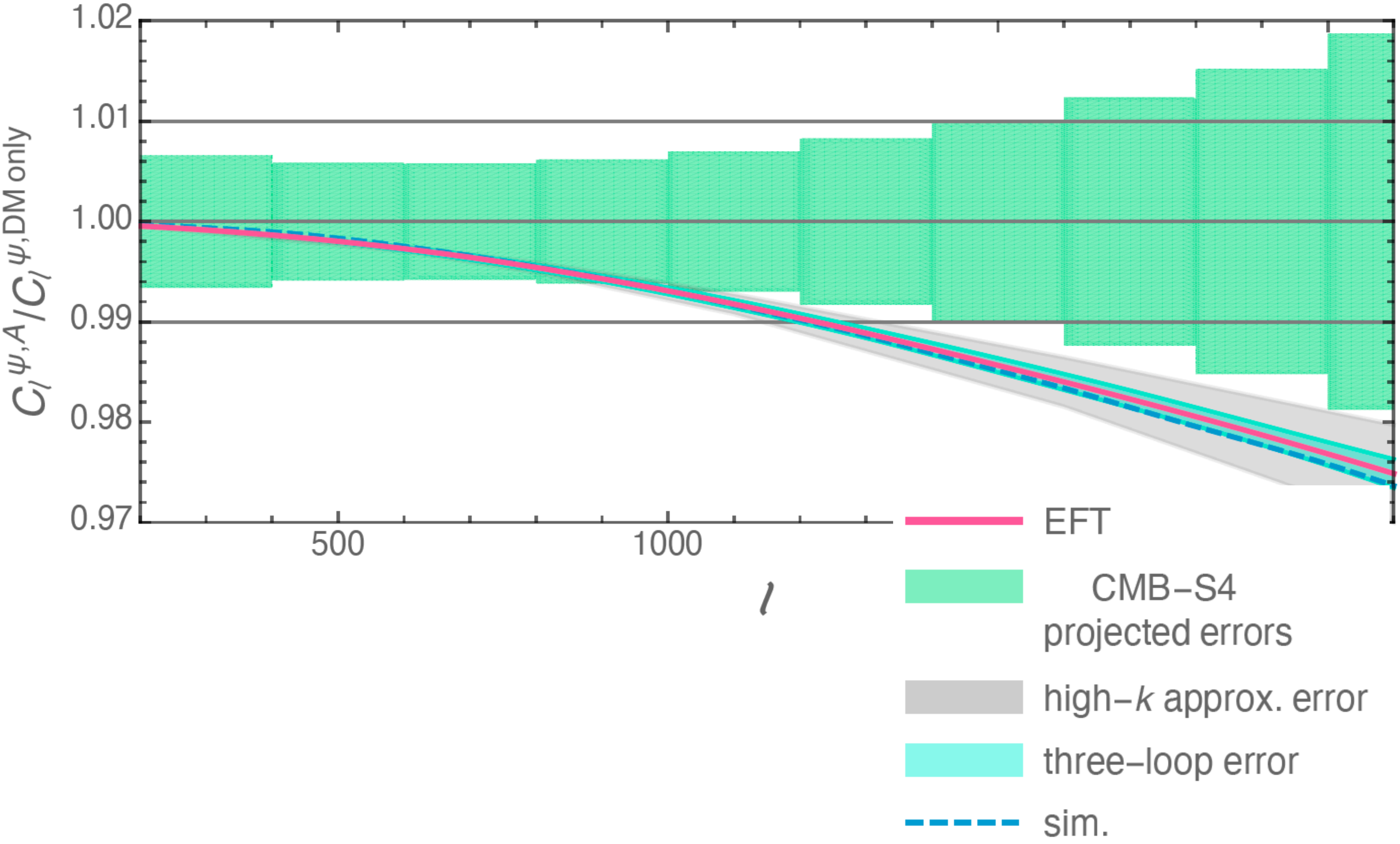
$$a^2\delta_I^{(1)\prime\prime}(a,\vec{k})+\left(2+\frac{a\mathcal{H}'(a)}{\mathcal{H}(a)}\right)a\delta_I^{(1)\prime}(a,\vec{k})=\int^a da_1 g(a,a_1)\, a_1\delta_I^{(1)\prime}(a_1,\vec{k})\ .$$

  - due to the time-translation breaking and actually even non-locality, very very very very very very hard to handle consistently.
    - we can make some guesses

- Luckily: it only affect the decaying mode of the isocurvature, which is very very very very very small.

Predictions for CMB Lensing

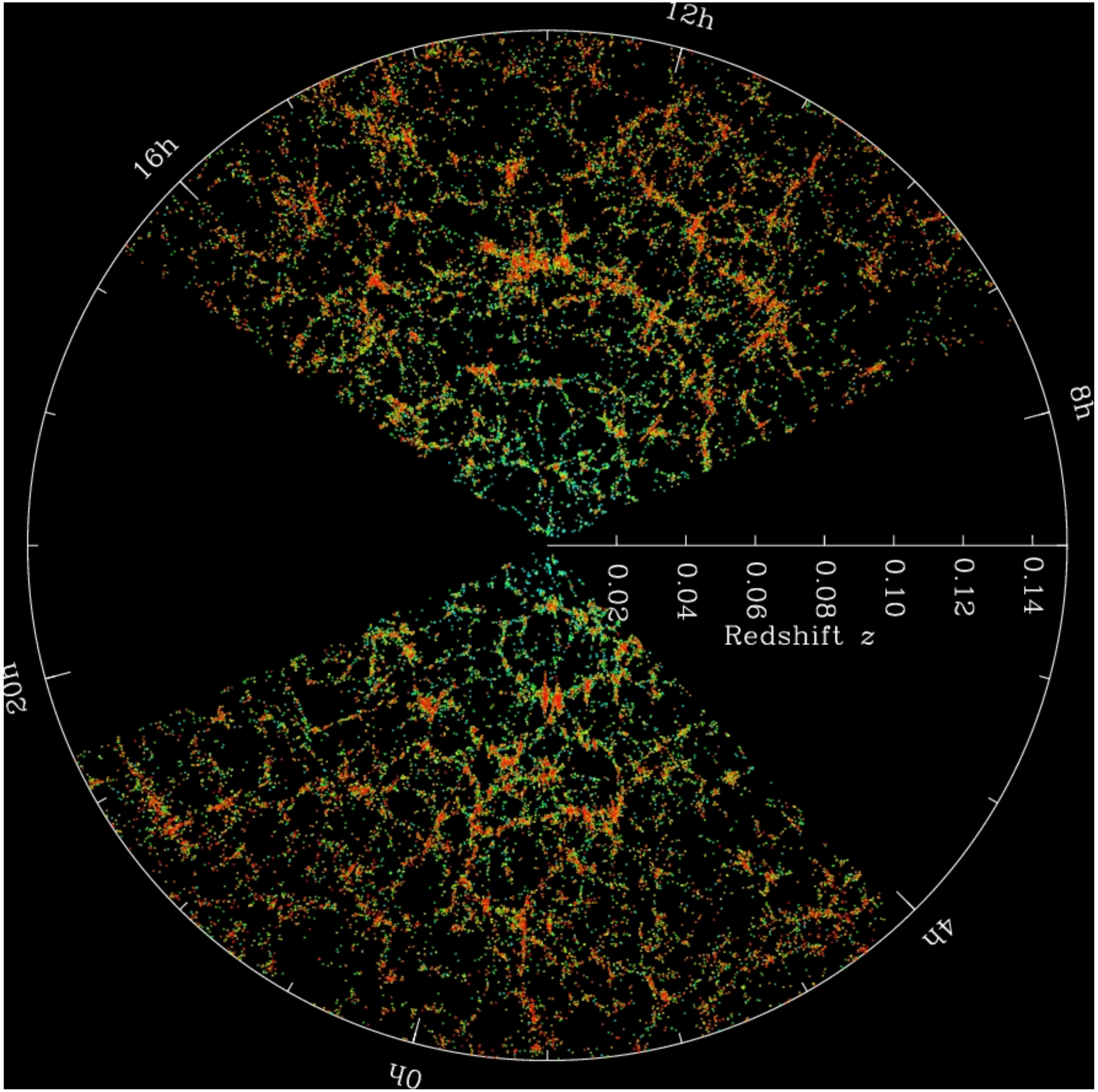
- Baryon corrections are detectable in next CMB S-4 experiments. But we can predict it:



Redshift space

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

Redshift Space



credit:
SDSS/BOSS

- Need to compute also momentum of galaxies.

Counterterms

with Zaldarriaga **1409**
with Lewandowsky *et al* **1512**

- Redshift space is a field-dependent local change of coordinates:

$$\rho_r(\vec{x}_r)\ d^3x_r = \rho(\vec{x})\ d^3x \ , \quad \Rightarrow \quad \delta_r(\vec{x}_r) = [1+\delta\left(\vec{x}(\vec{x}_r)\right)] \left| \frac{\partial \vec{x}_r}{\partial \vec{x}} \right|^{-1}_{\vec{x}(\vec{x}_r)} - 1 \ .$$

- Need for counterterms (expectation value on short modes)

$$\delta_{\ell,g,r}(\vec{k},t) = \delta_{\ell,g}(\vec{k},t) - i\frac{k_z}{aH} v^z_{\ell,g}(\vec{k},t) + \frac{i^2}{2}\left(\frac{k_z}{aH}\right)^2 [v^z_{\ell,g}(\vec{x},t)^2]_{\vec{k}} \quad + \ldots$$

fields at same location: add counterterms

$$[v_z^2]_{R,\vec{k}} = [v_z^2]_{\vec{k}} + \left(\frac{aH}{k^r_{\rm NL}}\right)^2 \left[c_{11}\delta^{(3)}_D(\vec{k}) + \left(c_{12}+c_{13}\mu^2\right)\delta(\vec{k})\right]$$

expectation value

response

- Now, all pieces ingredients are prepared.

IR-resummation

with Zaldarriaga **JCAP2015**

IR-resummation and the BAO peak

with Zaldarriaga **JCAP2015**

- Perturbation theory slow to converge for the BAO due to effect of IR-displacements.

- Consistent way to resum the effect obtained in

with Zaldarriaga **2014**

$$P_{\mathrm{IR-resummed}}(k) \sim \int dq\; M(k,q) \cdot P_{\mathrm{non-resummed}}(q)$$

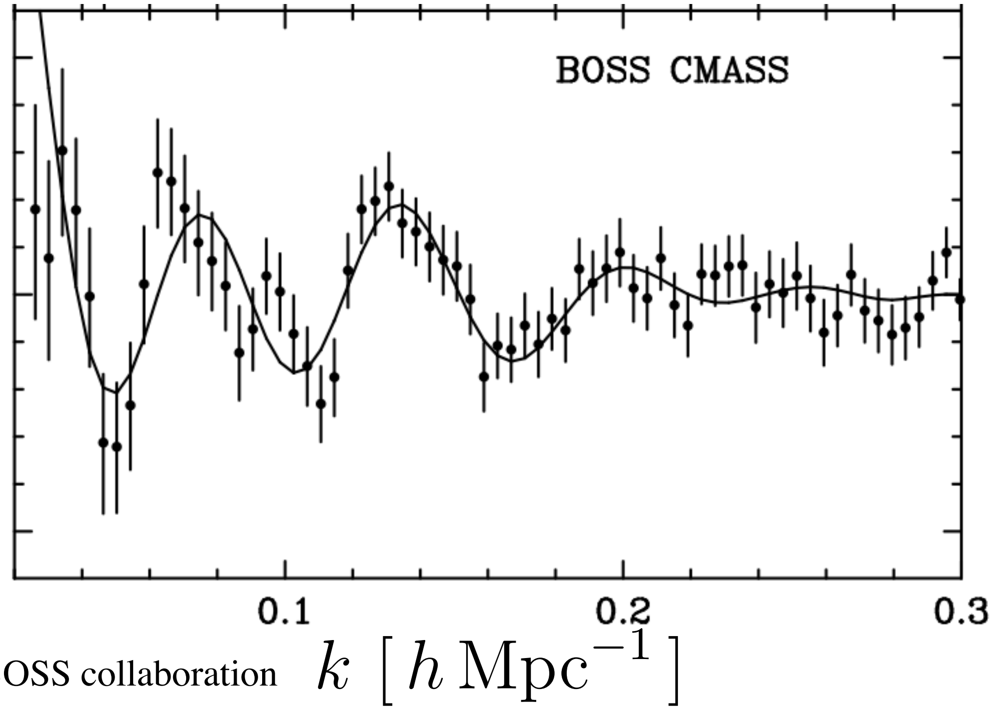
  - with subsequent simplifications/approximation

Baldauf, Mirbabayi, Simonovic, Zaldarriaga **2015**
Ivanov, Sybiriakov, **2016** Vlah, Seljak *et al* **2015**
...

  - To see an explicit derivation of these from original
  - formulation, with explicit uncontrolled errors

with Lewandowski **1810**

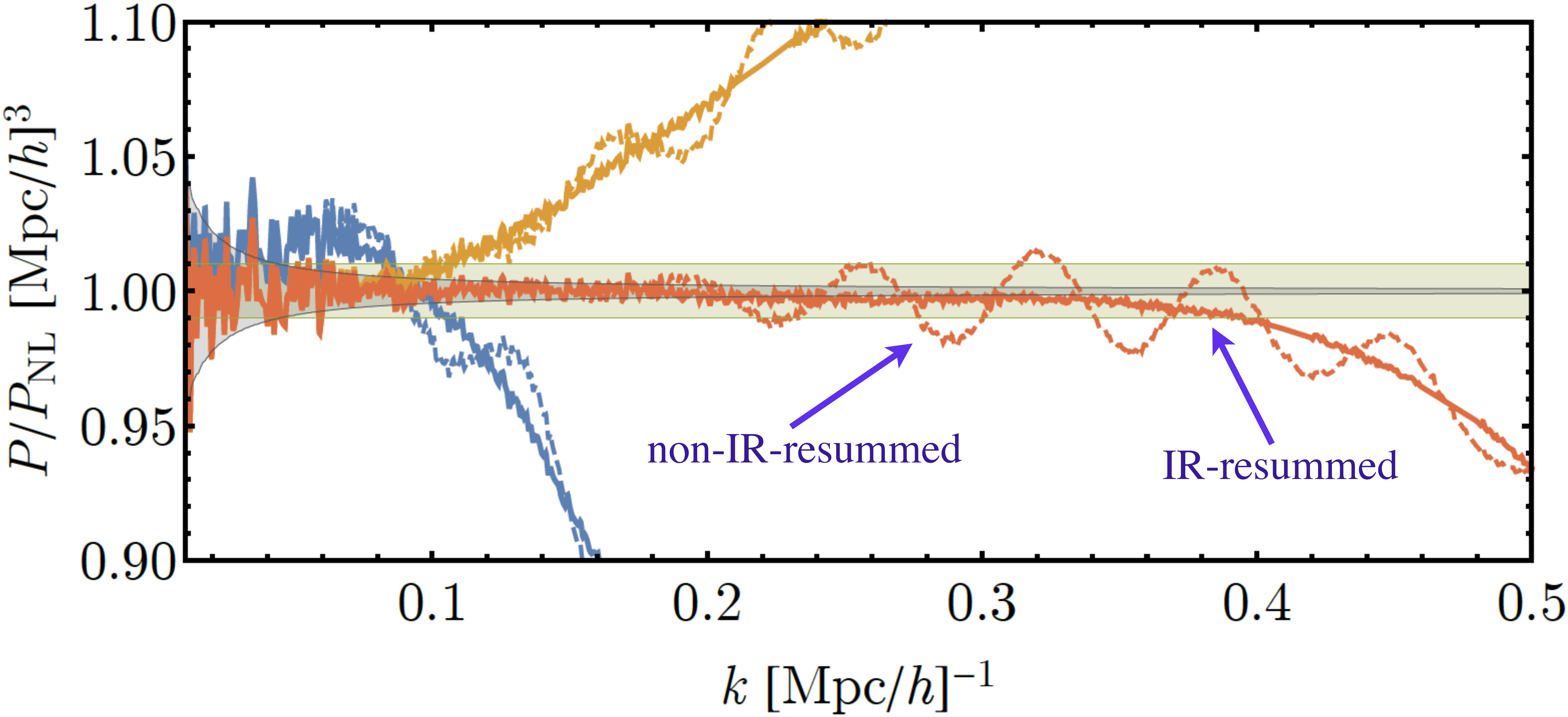
$\sim P(k)$



credit: BOSS collaboration

IR-resummation and the BAO peak

with Zaldarriaga **JCAP2015**
with Trevisan **JCAP2018**
with Lewandowski *et al* **PRD2018**



- It works very well

The power spectrum model for data

- All this work, lead to an EFTofLSS power-spectrum model applicable to data, published in

with Perko, Jennings and Wechsler **1610**

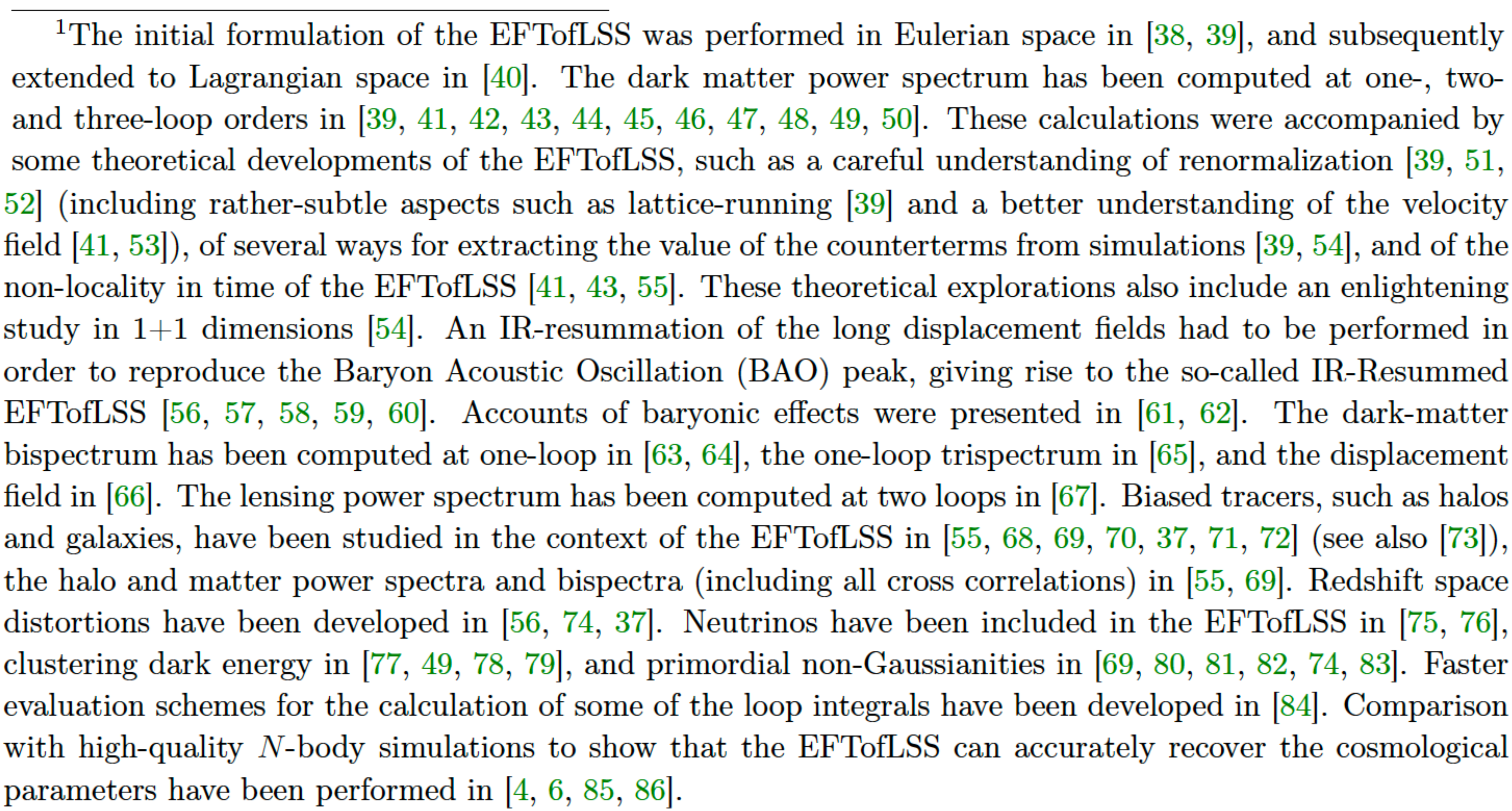
- Some authors acknowledge the data-analysis papers when using these models.
  - –It like citing ATLAS and CMS for the QCD

Why the footnote:

- With completion of with Perko, Jennings, Wechsler **1610** , observables the EFTofLSS predicted
- but widespread skepticism of the usefulness of the EFTofLSS
- Handful of people working on this subject

The Footnote:

- We put this footnote in our data-analysis papers



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[1] The initial formulation of the EFTofLSS was performed in Eulerian space in [38, 39], and subsequently extended to Lagrangian space in [40]. The dark matter power spectrum has been computed at one-, two- and three-loop orders in [39, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50]. These calculations were accompanied by some theoretical developments of the EFTofLSS, such as a careful understanding of renormalization [39, 51, 52] (including rather-subtle aspects such as lattice-running [39] and a better understanding of the velocity field [41, 53]), of several ways for extracting the value of the counterterms from simulations [39, 54], and of the non-locality in time of the EFTofLSS [41, 43, 55]. These theoretical explorations also include an enlightening study in 1+1 dimensions [54]. An IR-resummation of the long displacement fields had to be performed in order to reproduce the Baryon Acoustic Oscillation (BAO) peak, giving rise to the so-called IR-Resummed EFTofLSS [56, 57, 58, 59, 60]. Accounts of baryonic effects were presented in [61, 62]. The dark-matter bispectrum has been computed at one-loop in [63, 64], the one-loop trispectrum in [65], and the displacement field in [66]. The lensing power spectrum has been computed at two loops in [67]. Biased tracers, such as halos and galaxies, have been studied in the context of the EFTofLSS in [55, 68, 69, 70, 37, 71, 72] (see also [73]), the halo and matter power spectra and bispectra (including all cross correlations) in [55, 69]. Redshift space distortions have been developed in [56, 74, 37]. Neutrinos have been included in the EFTofLSS in [75, 76], clustering dark energy in [77, 49, 78, 79], and primordial non-Gaussianities in [69, 80, 81, 82, 74, 83]. Faster evaluation schemes for the calculation of some of the loop integrals have been developed in [84]. Comparison with high-quality N-body simulations to show that the EFTofLSS can accurately recover the cosmological parameters have been performed in [4, 6, 85, 86].

- A review of the papers *before* the application to data: to acknowledge the contribution

EFTofLSS is not PT

- The EFTofLSS represent the equations that govern LSS at long distances.
  - One can solve them using perturbatively (PT)
  - non perturbatively (on a computer, like fluids)
  - mixed
    - we do mix:
      - long-displacements effects are solved non-perturbatively
        - IR-resummation or Lagrangian PT
      - tidal effects are solved perturbatively

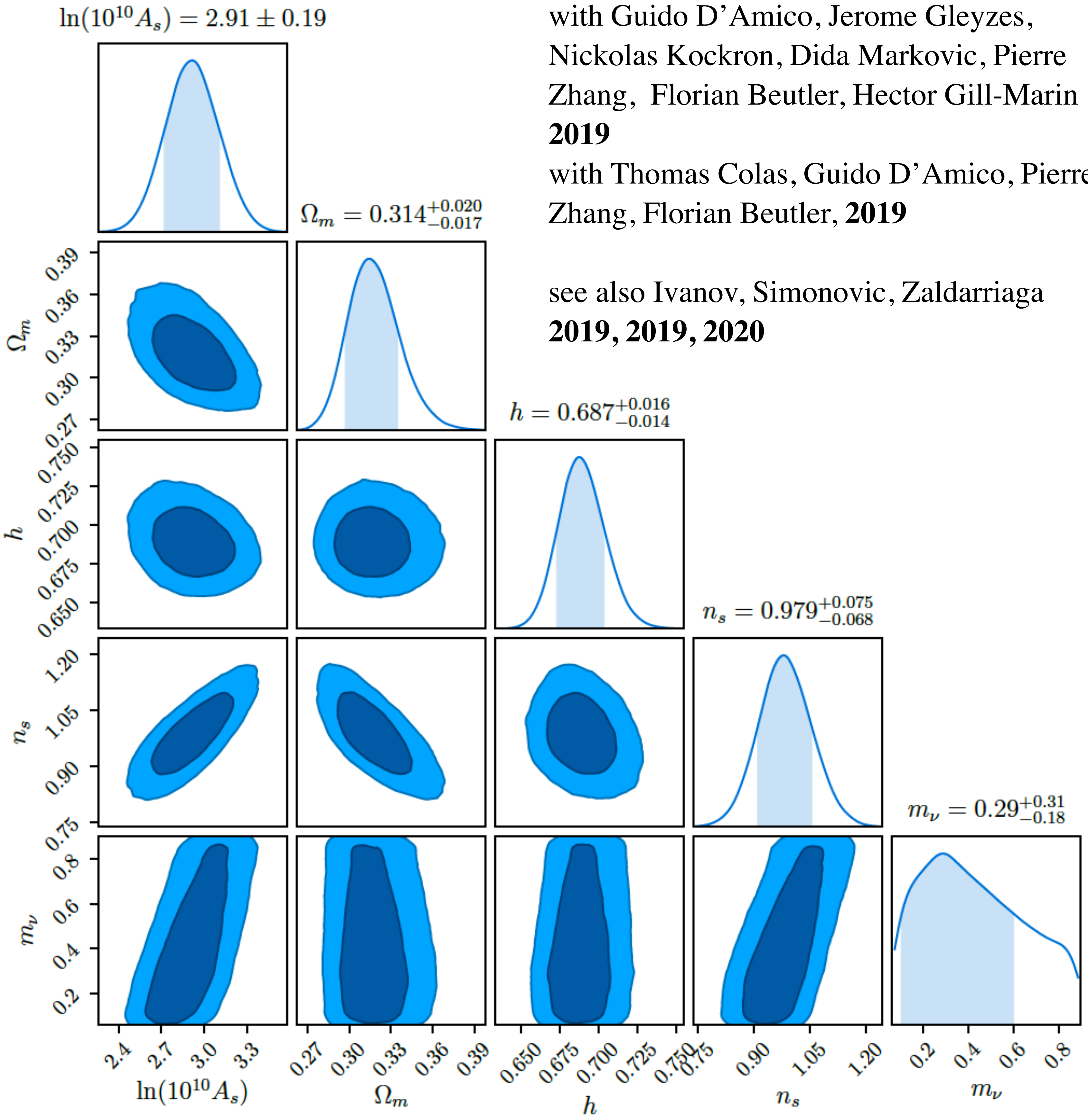
- So, it is technically not correct to call the EFTofLSS as Perturbation Theory

Data

Analysis of the SDSS/BOSS Power Spectrum

– Results of the power spectrum analysis of the BOSS data

- just BBN prior
- measure all parameters
- *major qualitative and quantitate* improvement
- changing the whole *legacy* of SDSS.
  - – Ω_m similar to Planck2018
  - – H_0 similar to Plank and Cosmic ladder


$\ln(10^{10}A_s) = 2.91 \pm 0.19$

$\Omega_m = 0.314^{+0.020}_{-0.017}$

$h = 0.687^{+0.016}_{-0.014}$

$n_s = 0.979^{+0.075}_{-0.068}$

$m_\nu = 0.29^{+0.31}_{-0.18}$

with Guido D'Amico, Jerome Gleyzes, Nickolas Kockron, Dida Markovic, Pierre Zhang, Florian Beutler, Hector Gill-Marin **2019**

with Thomas Colas, Guido D'Amico, Pierre Zhang, Florian Beutler, **2019**

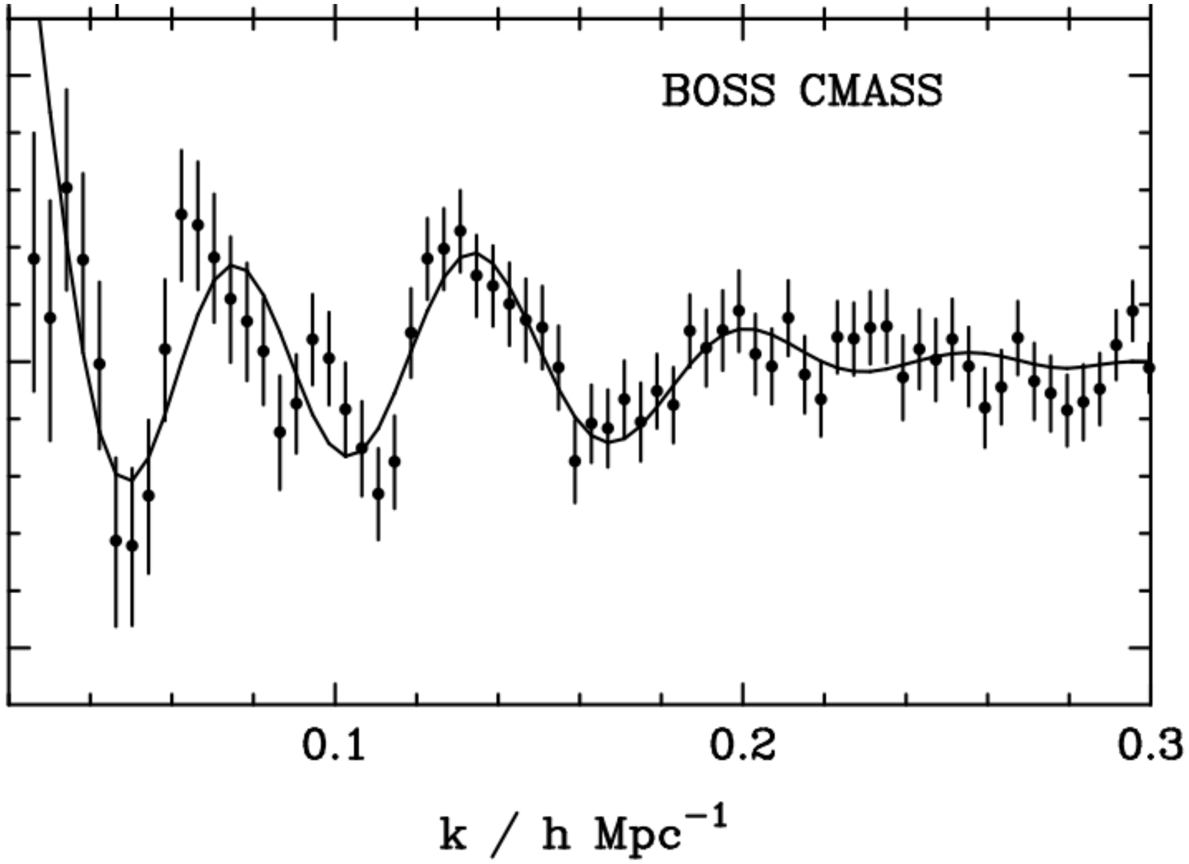
see also Ivanov, Simonovic, Zaldarriaga **2019, 2019, 2020**

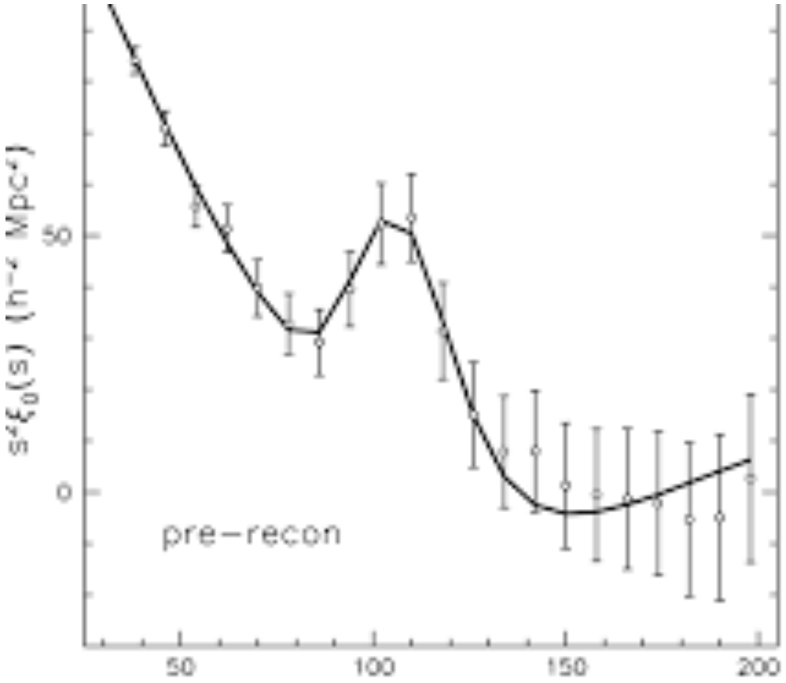
Correlation Function

with Pierre Zhang, Guido D’Amico, Cheng Zhao, Yifu Can **2110.07539**

Main Idea

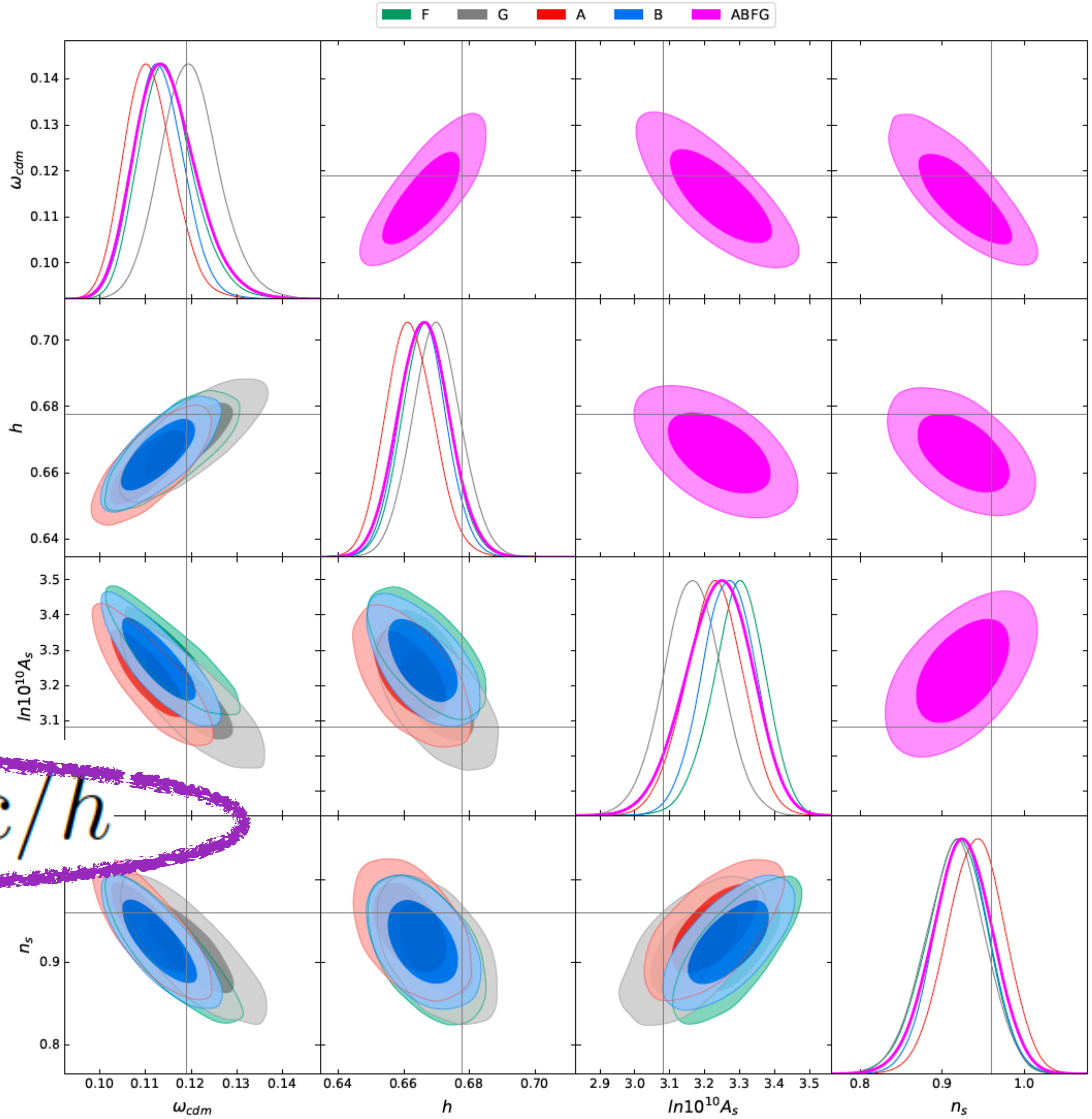
- Two fold:
    - In the Correlation Function (CF) analysis, easier to include all BAO information available in the BAO
    - Useful to check for systematics (either theory or data)





credit: BOSS collaboration

Scale-cut with Simulations



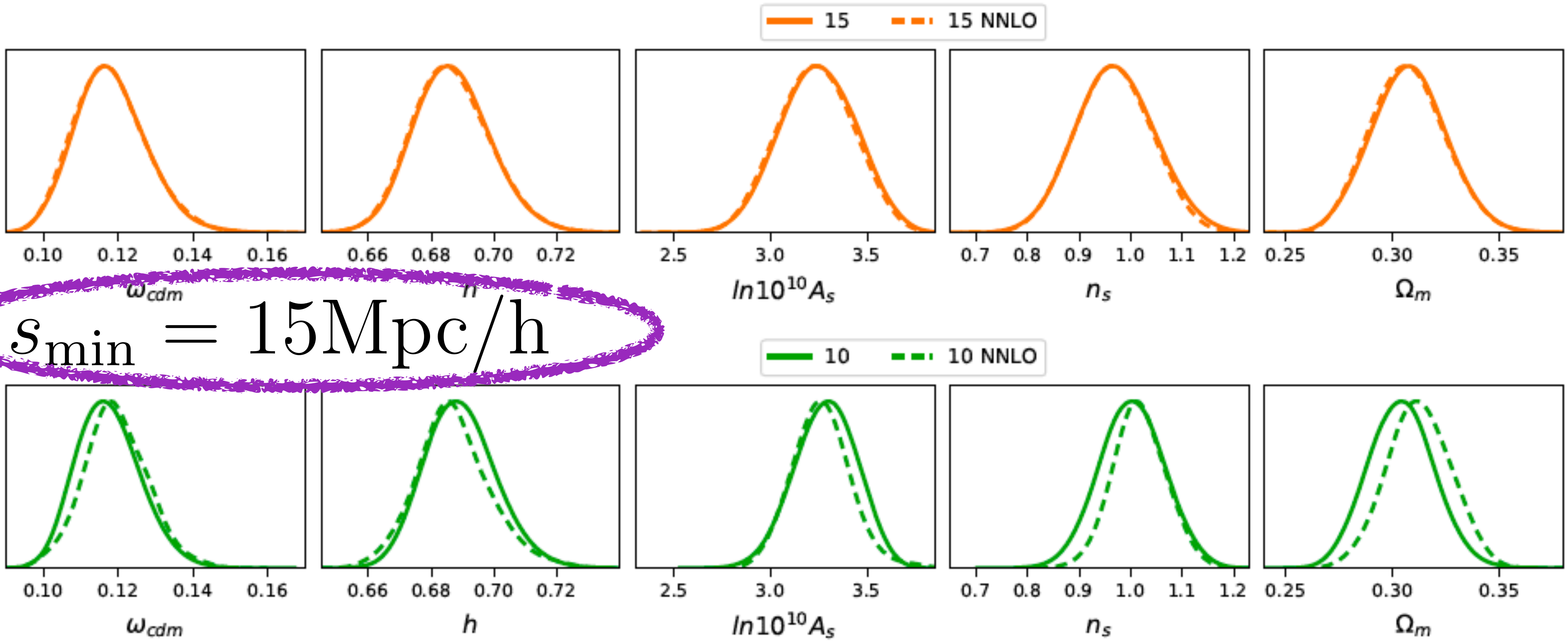
$$s_{\rm min} = 20{\rm Mpc}/h$$

Scale-cut *without* Simulations

- In the EFTofLSS, we can estimate the contribution of next-order effects, and we can estimate when they make a difference:

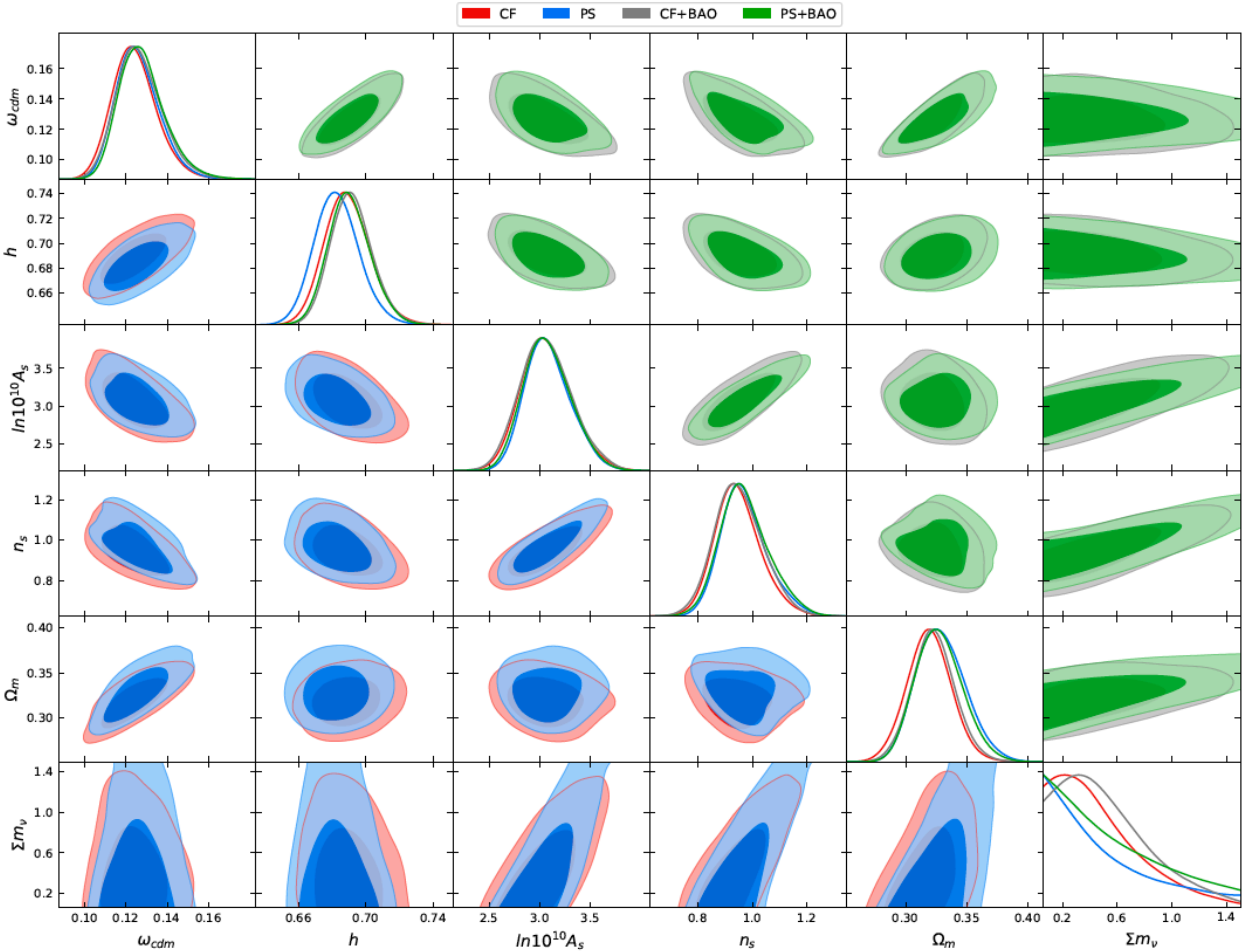
$$\xi^{\ell}_{\rm NNLO}(s) = i^{\ell} \int \frac{dk}{2\pi^2} k^2 P^{\ell}_{\rm NNLO}(k) j_{\ell}(ks) \, ,$$

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



$s_{\rm min} = 15{\rm Mpc/h}$

PS vs CF



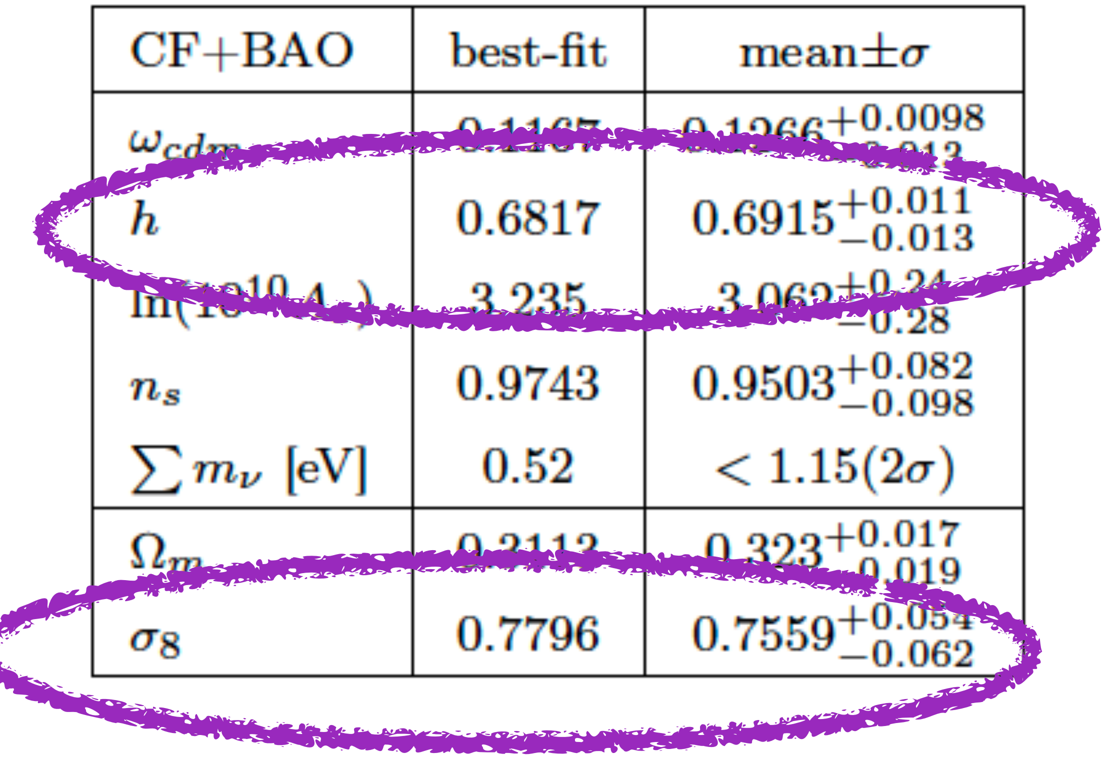
- Disagreement is statistically compatible

No σ_8 Tension!

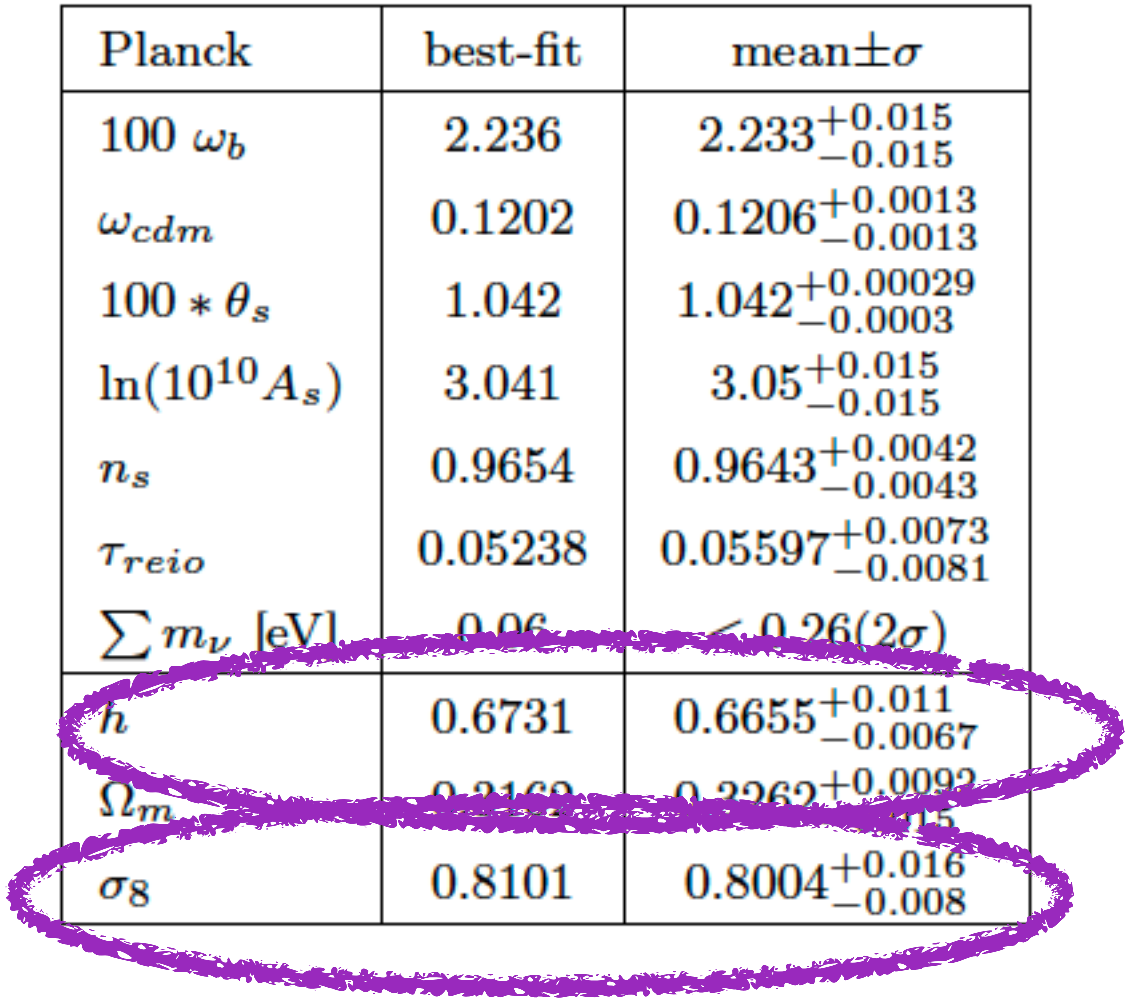
No H_0 Tension!

No Tensions!!

- We find no tension in H_0 and in σ_8



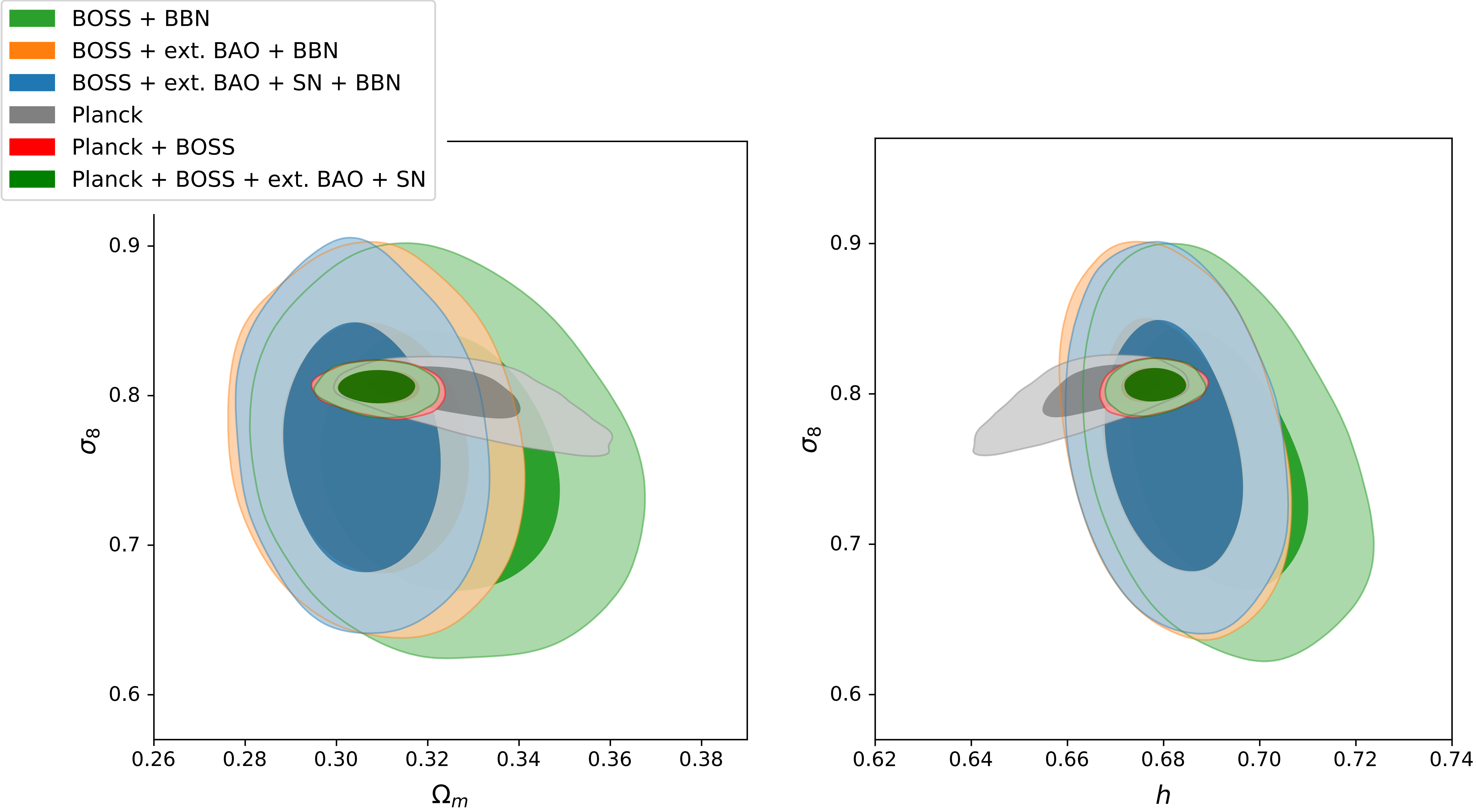
CF+BAO	best-fit	mean±σ
ω_{cdm}	0.1167	$0.1266^{+0.0098}_{-0.013}$
h	0.6817	$0.6915^{+0.011}_{-0.013}$
$\ln(10^{10}A_s)$	3.235	$3.062^{+0.24}_{-0.28}$
n_s	0.9743	$0.9503^{+0.082}_{-0.098}$
$\sum m_\nu$ [eV]	0.52	$< 1.15(2\sigma)$
Ω_m	0.3113	$0.323^{+0.017}_{-0.019}$
σ_8	0.7796	$0.7559^{+0.054}_{-0.062}$



Planck	best-fit	mean±σ
$100\ \omega_b$	2.236	$2.233^{+0.015}_{-0.015}$
ω_{cdm}	0.1202	$0.1206^{+0.0013}_{-0.0013}$
$100 * \theta_s$	1.042	$1.042^{+0.00029}_{-0.0003}$
$\ln(10^{10}A_s)$	3.041	$3.05^{+0.015}_{-0.015}$
n_s	0.9654	$0.9643^{+0.0042}_{-0.0043}$
τ_{reio}	0.05238	$0.05597^{+0.0073}_{-0.0081}$
$\sum m_\nu$ [eV]	0.06	$< 0.26(2\sigma)$
h	0.6731	$0.6655^{+0.011}_{-0.0067}$
Ω_m	0.3162	$0.3262^{+0.0092}_{-0.015}$
σ_8	0.8101	$0.8004^{+0.016}_{-0.008}$

- Former tension in σ_8 was due to bug in power spectrum estimator of BOSS collaboration
  - we found this by using new catalogues, found explicitly by Chen, Vlah, White **2110**

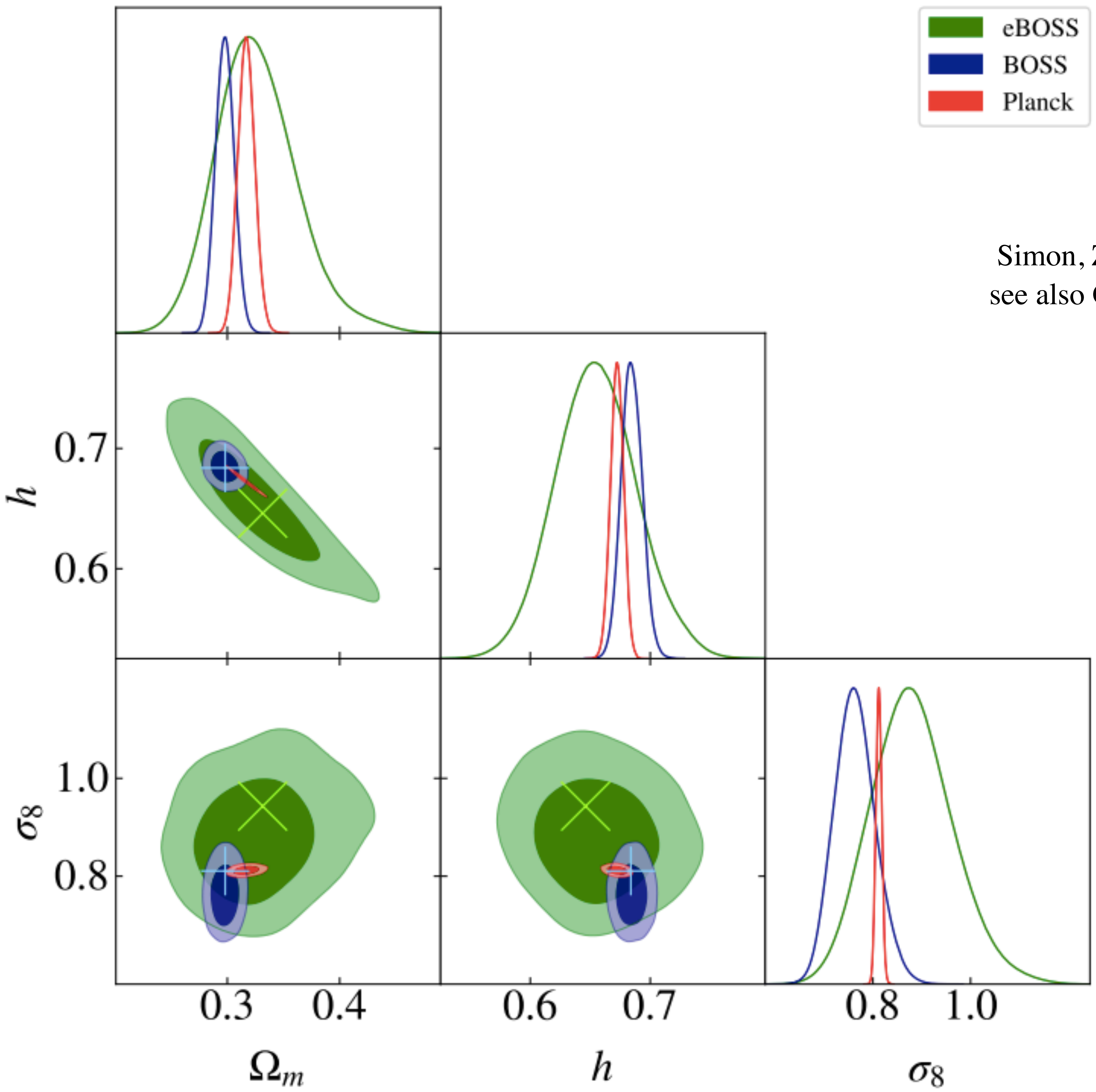
No Tensions!!


BOSS + BBN
BOSS + ext. BAO + BBN
BOSS + ext. BAO + SN + BBN
Planck
Planck + BOSS
Planck + BOSS + ext. BAO + SN
σ_8
0.9
0.8
0.7
0.6
0.26
0.28
0.30
0.32
0.34
0.36
0.38
Ω_m
σ_8
0.9
0.8
0.7
0.6
0.62
0.64
0.66
0.68
0.70
0.72
0.74
h

BOSS + eBOSS power spectrum

Simon, Zhang, Poulin **2211**
see also Chudaykin, Ivanov **2011**

Very nice, consistent, and strong



Simon, Zhang, Poulin **2211**
see also Chudaykin, Ivanov **2011**

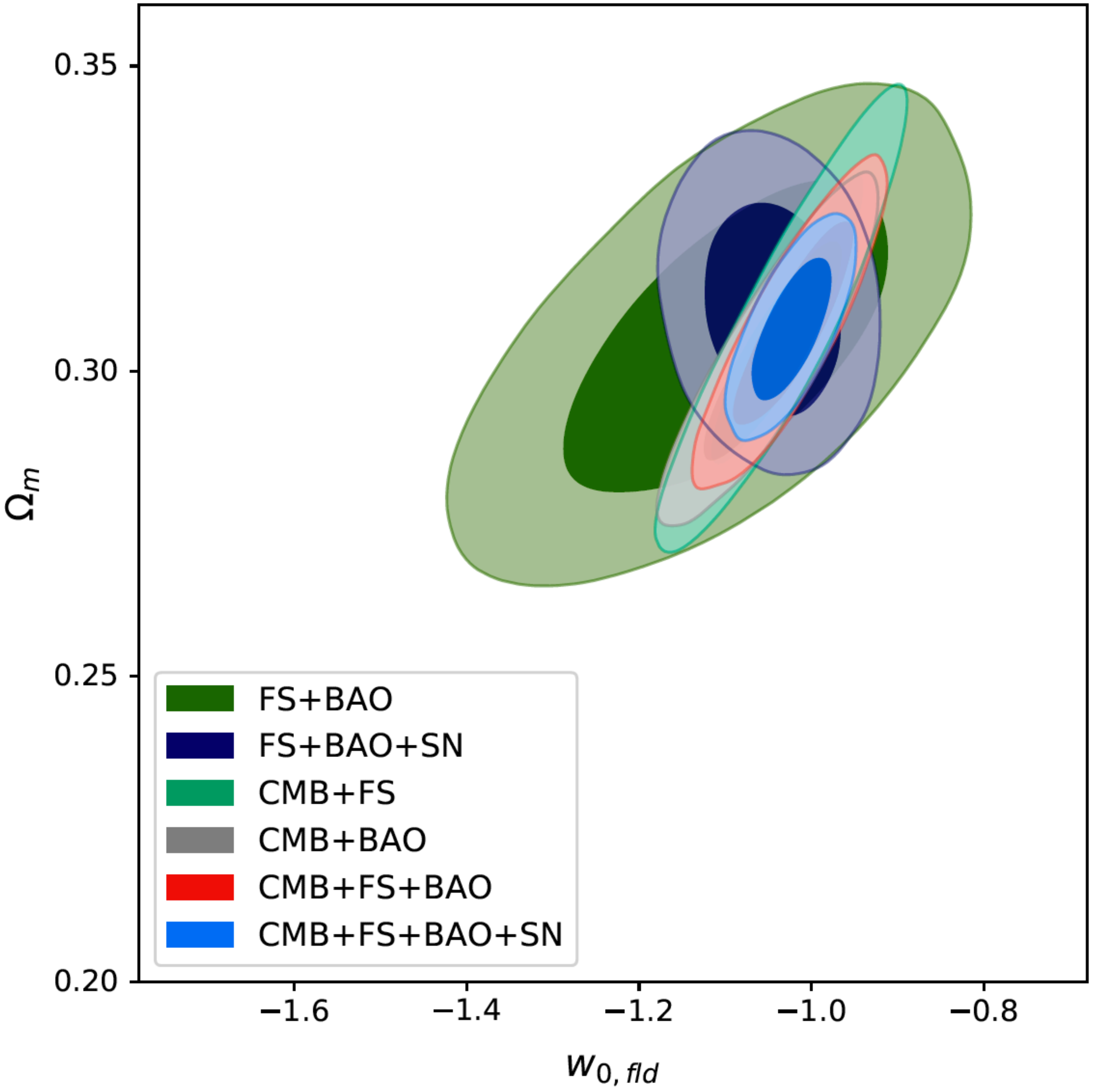
wCDM

with Guido D'Amico, Pierre Zhang, **2003**

wCDM Analysis, BBN prior

- Checked on simulations

- 5% measurement from late time only (without DES)
- world record is 3% using CMB

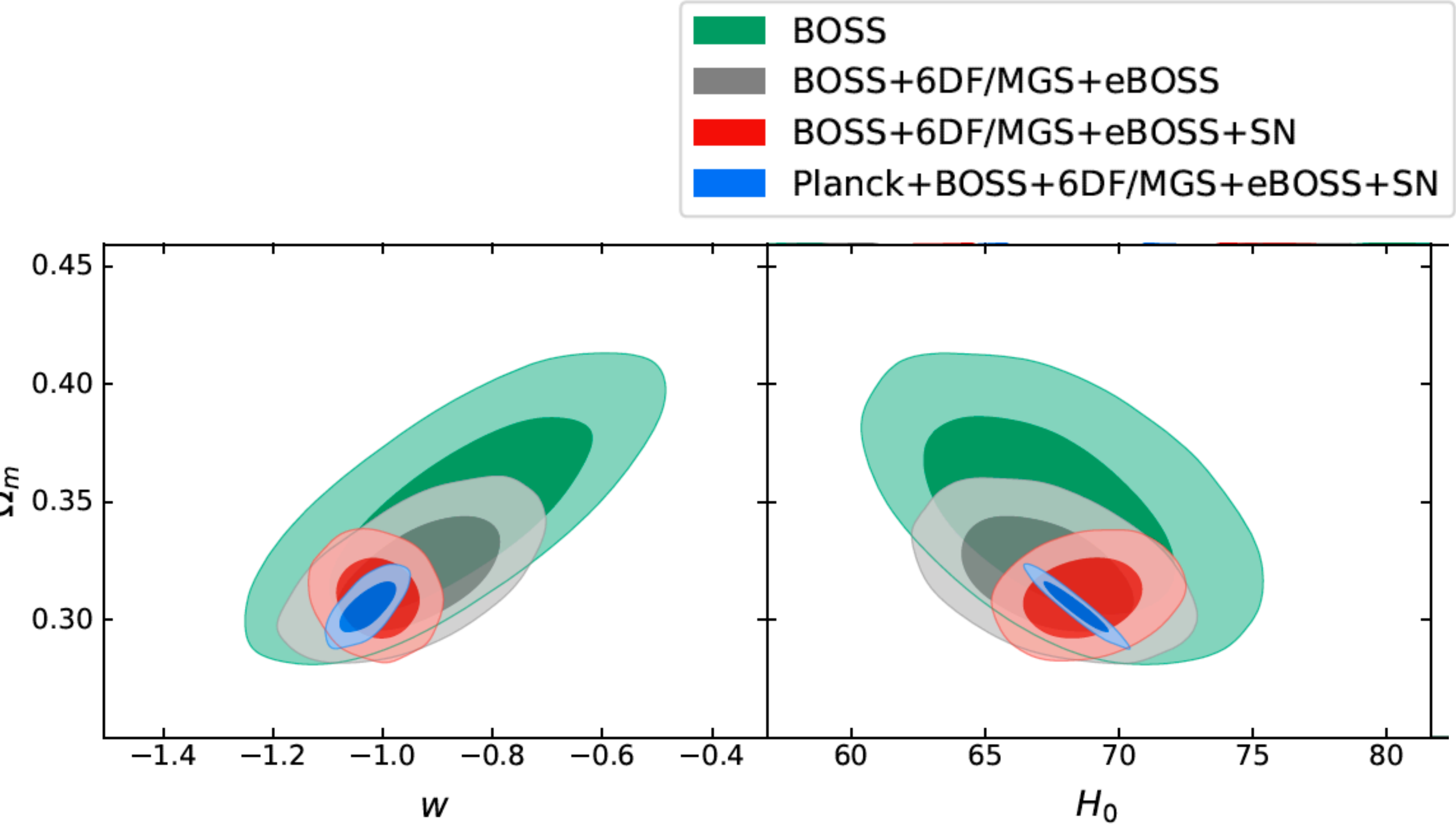


Clustering Quintessence

with Guido D'Amico, Yaniv Donath. Pierre Zhang, **2012**

Clustering Quintessence

- The only quintessence model that can consistently predict w<-1 is Clustering Quintessence: stability requires $c_s^2 \rightarrow 0,$



Bispectrum at one loop

with D’Amico, Donath, Lewandowski, Zhang **2206**

Bispectrum

- The tree level bispectrum had been already used for cosmological parameter analysis in

  with Guido D'Amico, Jerome Gleyzes,
  Nickolas Kockron, Dida Markovic, Pierre Zhang, Florian Beutler, Hector Gill-Marin **1909.05271**

  Philcox, Ivanov **2112**

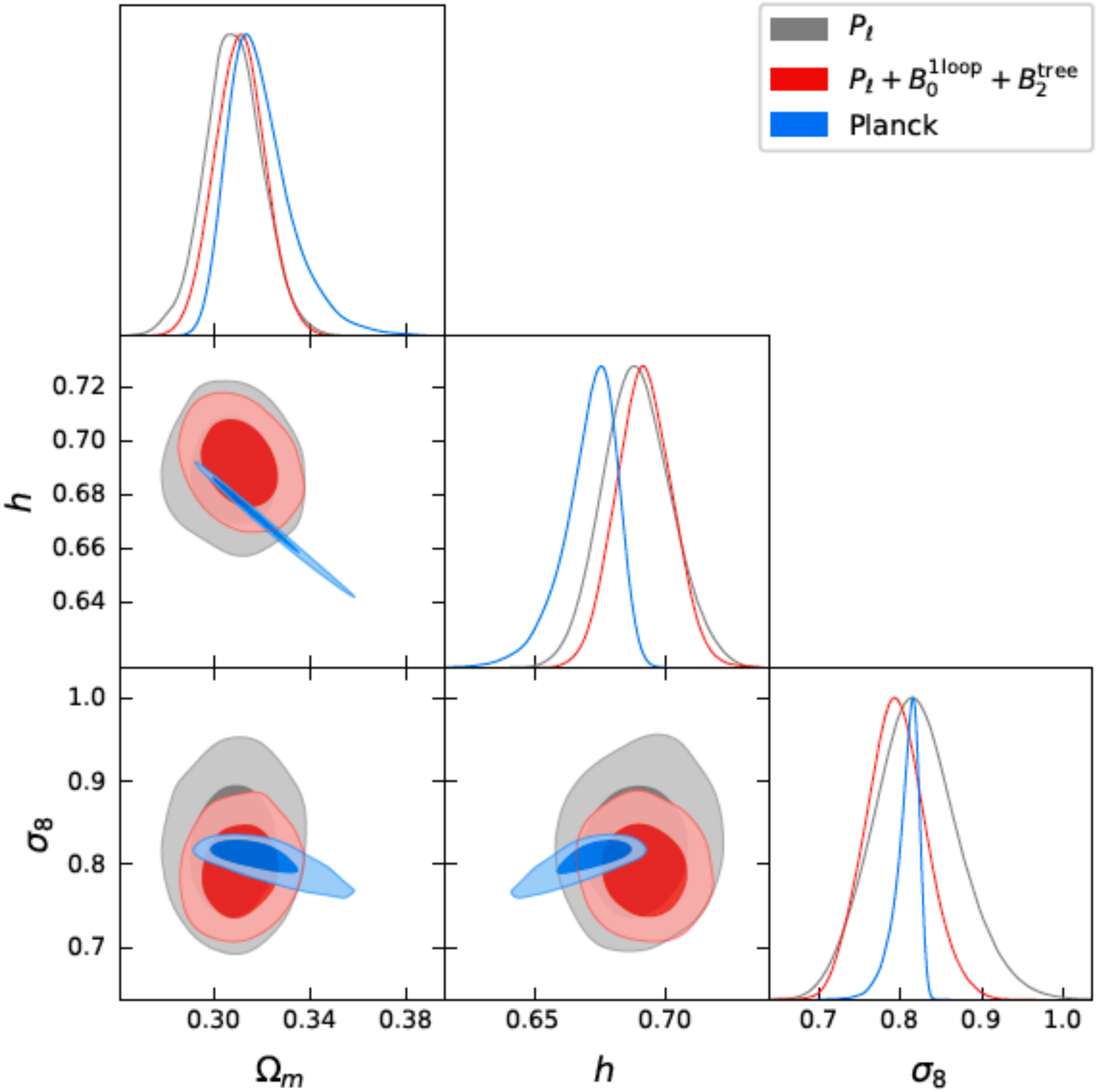
  - ~10% improvement on A_s

- Time to move to one-loop:
  - Large effort:
    - data analysis with D'Amico, Donath, Lewandowski, Zhang **2206**
    - theory model with D'Amico, Donath, Lewandowski, Zhang **2211**
    - theory integration with Anastasiou, Braganca, Zheng **2212**

Data Analysis

with D'Amico, Donath, Lewandowski, Zhang **2206**

- Main result:
    - Improvements:
    - 30% on σ_8
    - 18% on h
    - 13% on Ω_m
- Compatible with Planck
    - –no tensions



Theory Model

with D'Amico, Donath, Lewandowski, Zhang **2206**

- We add all the relevant biases (4th order) and counterterms (2nd order):

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

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

- IR-resummation:
  - For the power spectrum, we use the correct and controlled IR-resummation.
  - For the bispectrum, we use the wiggle/no-wiggle approximation Ivanov and Sibiryakov **2018**

$$
B_{211}^{r,h} = 2K_1^{r,h}(\vec{k}_1;\hat{z})K_1^{r,h}(\vec{k}_2;\hat{z})K_2^{r,h}(\vec{k}_1,\vec{k}_2;\hat{z})P_{\rm LO}(k_1)P_{\rm LO}(k_2) + \ 2 \text{ perms.}\ ,
$$

$$
P_{\rm LO}(k) = P_{\rm nw}(k) + (1+k^2\Sigma_{\rm tot}^2)e^{-\Sigma_{\rm tot}^2}P_{\rm w}(k)
$$

    - For the loop, we just use $P_{\rm NLO}(k) = P_{\rm nw}(k) + e^{-\Sigma_{\rm tot}^2}P_{\rm w}(k)\ ,$ in the non-integrated power spectra

Derivation of theory model

with D'Amico, Donath, Lewandowski, Zhang

2211

Derivation of theory model

with D'Amico, Donath, Lewandowski, Zhang
2211

- Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects.
- Renormalization of velocity
  - In the EFTofLSS, the velocity is a composite operator $v^i(x) = \dfrac{\pi^i(x)}{\rho(x)}$, so, it needs to be renormalized:

$$[v^i]_R = v^i + \mathcal{O}^i_v \ ,$$

  - Under a diffeomorphisms:

$$v^i \to v^i + \chi^i \quad \Rightarrow \quad \mathcal{O}^i_v \text{ is a scalar}$$

  - In redshift space, we have local product of velocities, which need to be renormalized but have non-trivial transformations under diff.s:

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

  - To achieve this, one can do: (so must include products $v^i \cdot \mathcal{O}^i_v$)

$$[v^i v^j]_R = [v^i]_R [v^j]_R + \mathcal{O}^{ij}_{v^2} \ , \quad \text{where } \ \mathcal{O}^{ij}_{v^2} \ \text{ is a scalar}$$

Derivation of theory model

with D'Amico, Donath, Lewandowski, Zhang
2211

- Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects.
- Non-local-contributing counterterm.
    - This is a normal effect, just strange-looking in the EFTofLSS context.
    - Normally, counterterms are local, but, contributing through non-local Green's functions, they contribute non-locally.

Derivation of theory model

with D'Amico, Donath, Lewandowski, Zhang
2211

- Counterterms: major algebraic effort for 4th order and some theoretical subtle aspects.
- Non-local-contributing counterterm.
  - In the EFTofLSS, the Green's function is simple: $\dfrac{1}{\partial^2}$
  - Counterterms typically come with $\partial^2 \mathcal{O}_{\rm local} \quad \Rightarrow \quad \delta_{\rm counter} \sim \dfrac{1}{\partial^2}\partial^2 \mathcal{O}_{\rm local} \sim \mathcal{O}_{\rm local}$
    - result almost trivial
  - But at second order, and for velocity fields, contracted along the line of sight, the derivative do not cancel, so we get

$$\delta_{\rm counter}(\vec{x}) \sim \hat{z}^i \hat{z}^j \partial_i \pi^j_{(2)}(\vec{x}) \quad \sim \quad \hat{z}^i \hat{z}^j \frac{\partial_i \partial_j \partial_k \partial_m}{\partial^2} \mathcal{O}_{\rm local}$$

$$\sim \quad \hat{z}^i \hat{z}^j \frac{\partial_i \partial_j \partial_k \partial_m}{\partial^2} \left(\frac{\partial_k \partial_l}{H^2} \Phi(\vec{x}) \frac{\partial_l \partial_m}{H^2} \Phi(\vec{x}) \right)$$

  - This is truly non-locally contributing, truly non-trivial.

  - We check that all these terms are *needed and sufficient* for renormalization

Evaluational/Computational Challenge

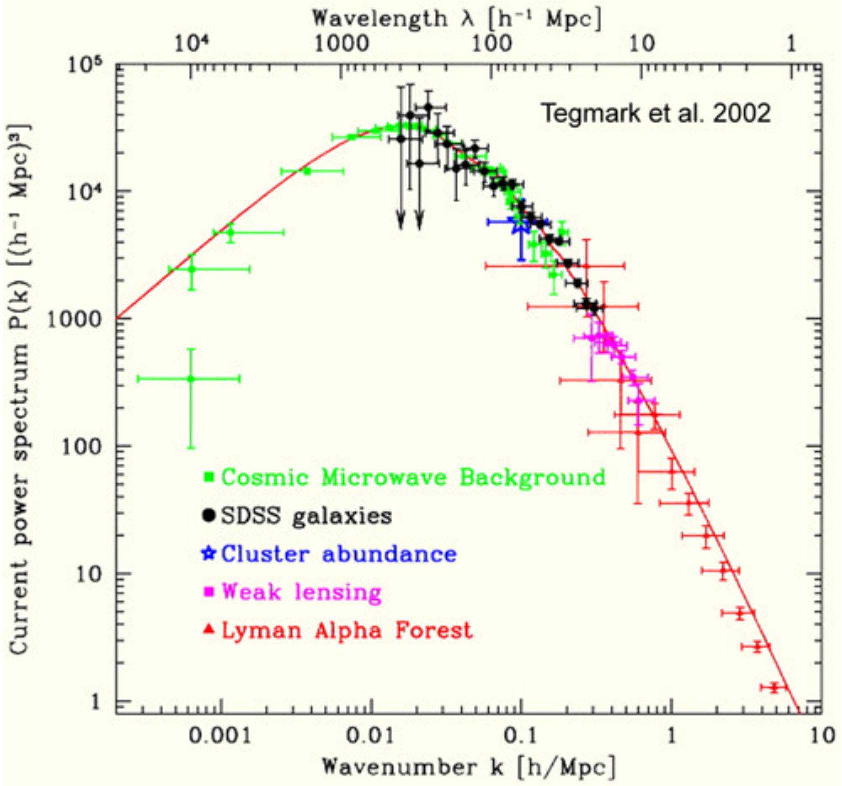
with Anastasiou, Braganca, Zheng **2212**

see Braganca talk next

The best approach so far

Simonovic, Baldauf, Zaldarriaga,
Carrasco, Kollmeier **2018**

- Nice trick for fast evaluation of the loops integrals
- The power spectrum is a numerically computed function



- Decompose linear power spectrum

$$P_{11}(k) = \sum_n c_n\, k^{\mu+i\alpha\, n}$$

- Loop can be evaluated analytically

$$P_{1-\text{loop}}(k) = \int_{\vec{q}} K(\vec{q},\vec{k})\; P_{11}(k-q)\, P_{11}(q) =$$

$$= \sum_{n_1,n_2} c_{n_1} c_{n_2} \left(\int_{\vec{q}} K(\vec{q},\vec{k})\; k^{\mu+i\alpha n_1}\; k^{\mu+i\alpha n_2} \right) = \sum_{n_1,n_2} c_{n_1} c_{n_2} M_{n_1,n_2}(k)$$

–using quantum field theory techniques

– $M_{n_1 n_2}$ is cosmology independent $\Rightarrow$ so computed once

Computational Challenge

Philcox, Ivanov, Cabass,
Simonovic, Zaldarriaga **2022**

- Two difficulties:

$$P_{1-\mathrm{loop}}(k) = \int_{\vec{q}} K(\vec{q},\vec{k})\; P_{11}(k-q)\, P_{11}(q) =$$

$$= \sum_{n_1,n_2} c_{n_1} c_{n_2} \left(\int_{\vec{q}} K(\vec{q},\vec{k})\; k^{\mu+i\alpha n_1}\; k^{\mu+i\alpha n_2} \right) = \sum_{n_1,n_2} c_{n_1} c_{n_2} M_{n_1,n_2}(k)$$

  - integrals are complicated due to fractional, complex exponents
  - many functions needed, the matrix $M_{n_1 n_2 n_3}$ for bispectrum is about 50Gb, so, ~impossible to load on CPT for data analysis

- In order to ameliorate (solve) these issues, we use a different basis of functions.

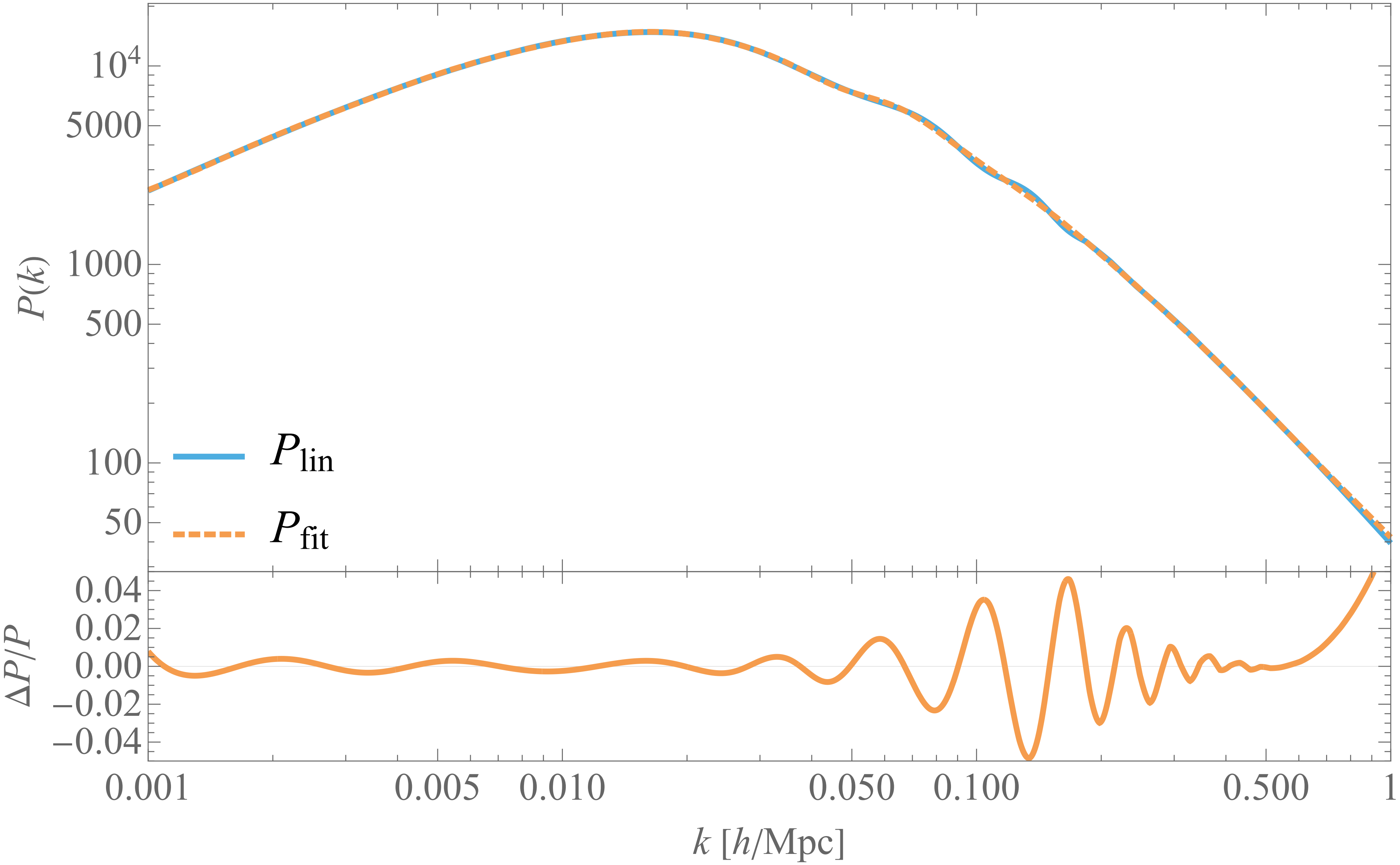
Complex-Masses Propagators

with Anastasiou, Braganca, Zheng
2212

- Use as basis:

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

- With just 16 functions:



Complex-Masses Propagators

with Anastasiou, Braganca, Zheng
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- This basis is equivalent to massive propagators to integer powers

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

$$\frac{k_{\rm UV}^2}{\left(k^2-k_{\rm peak}^2-i\,k_{\rm UV}^2\right)\left(k^2-k_{\rm peak}^2+i\,k_{\rm UV}^2\right)} = -\frac{i/2}{k^2-k_{\rm peak}^2-i\,k_{\rm UV}^2}+\frac{i/2}{k^2-k_{\rm peak}^2+i\,k_{\rm UV}^2}$$

- So, each basis function:

$$f(k^2,k_{\rm peak}^2,k_{\rm UV}^2,i,j) = \sum_{n=1}^{j} k_{\rm UV}^{2(n-i)}\,k^{2i}\left(\frac{\kappa_n}{(k^2+M)^n}+\frac{\kappa_n^*}{(k^2+M^*)^n}\right)$$

Complex-Masses Propagators

with Anastasiou, Braganca, Zheng
2212

- This basis is equivalent to massive propagators to integer powers

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

$$\frac{k_{\rm UV}^2}{\left(k^2-k_{\rm peak}^2-i\,k_{\rm UV}^2\right)\left(k^2-k_{\rm peak}^2+i\,k_{\rm UV}^2\right)} = \boxed{-\frac{i/2}{k^2-k_{\rm peak}^2-i\,k_{\rm UV}^2}} + \frac{i/2}{k^2-k_{\rm peak}^2+i\,k_{\rm UV}^2}$$

Complex-Mass propagator

- So, each basis function:

$$f(k^2,k_{\rm peak}^2,k_{\rm UV}^2,i,j) = \sum_{n=1}^{j} k_{\rm UV}^{2(n-i)}\,k^{2i}\left(\frac{\kappa_n}{(k^2+M)^n}+\frac{\kappa_n^*}{(k^2+M^*)^n}\right)$$

Complex-Masses Propagators

with Anastasiou, Braganca, Zheng
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- We end up with integral like this:

$$L(n_1,d_1,n_2,d_2,n_3,d_3) = \int_q \frac{(\boldsymbol{k}_1-\boldsymbol{q})^{2n_1}\boldsymbol{q}^{2n_2}(\boldsymbol{k}_2+\boldsymbol{q})^{2n_3}}{((\boldsymbol{k}_1-\boldsymbol{q})^2+M_1)^{d_1}(\boldsymbol{q}^2+M_2)^{d_2}((\boldsymbol{k}_2+\boldsymbol{q})^2+M_3)^{d_3}}$$

- with integer exponents.

- First we manipulate the numerator to reduce to:

$$T(d_1,d_2,d_3) = \int_q \frac{1}{((\boldsymbol{k}_1-\boldsymbol{q})^2+M_1)^{d_1}(\boldsymbol{q}^2+M_2)^{d_2}((\boldsymbol{k}_2+\boldsymbol{q})^2+M_3)^{d_3}},$$

- Then, by integration by parts, we find (i.e. Babis teach us how to) recursion relations

$$\int_q \frac{\partial}{\partial q_\mu}\cdot\left(q_\mu t(d_1,d_2,d_3)\right)=0$$

$$\Rightarrow \quad (3-d_{1223})\hat{0}+d_1 k_{1s}\widehat{1^+}+d_3(k_{2s})\widehat{3^+}+2M_2 d_2\widehat{2^+}-d_1\widehat{1^+}\widehat{2^-}-d_3\widehat{2^-}\widehat{3^+}=0$$

- relating same integrals with raised or lowered the exponents (easy terminate due to integer exponents).

Complex-Masses Propagators

with Anastasiou, Braganca, Zheng
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- We end up to three master integrals:
- Tadpole:

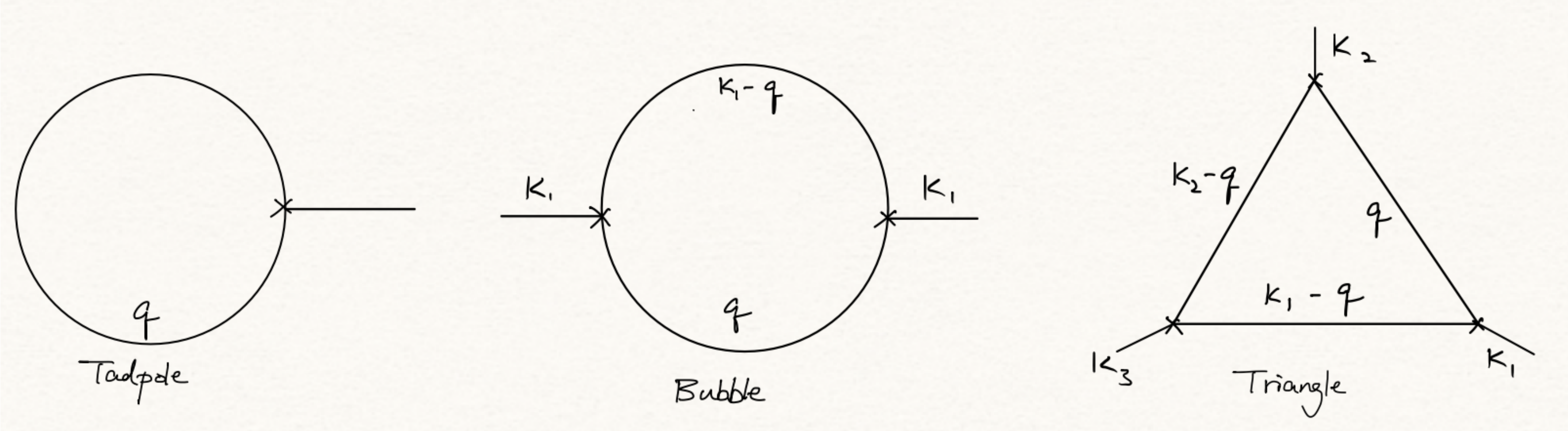
$$\text{Tad}(M_j, n, d) = \int \frac{d^3\boldsymbol{q}}{\pi^{3/2}} \frac{(\boldsymbol{p}_i^2)^n}{(\boldsymbol{p}_i^2 + M_j)^d}$$

- Bubble:

$$B_{\text{master}}(k^2, M_1, M_2) = \int \frac{d^3\boldsymbol{q}}{\pi^{3/2}} \frac{1}{(q^2 + M_1)(|\boldsymbol{k} - \boldsymbol{q}|^2 + M_2)}$$

- Triangle:

$$T_{\text{master}}(k_1^2, k_2^2, k_3^2, M_1, M_2, M_3) = \int \frac{d^3\boldsymbol{q}}{\pi^{3/2}} \frac{1}{(q^2 + M_1)(|\boldsymbol{k}_1 - \boldsymbol{q}|^2 + M_2)(|\boldsymbol{k}_2 + \boldsymbol{q}|^2 + M_3)},$$



Complex-Masses Propagators

with Anastasiou, Braganca, Zheng

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- The master integrals are evaluated with Feynman parameters, but with great care of branch cut crossing, which happens because of complex masses.

- Bubble Master:

$$B_{\text{master}}(k^2, M_1, M_2) = \frac{\sqrt{\pi}}{k} i[\log\left(A(1, m_1, m_2)\right) - \log\left(A(0, m_1, m_2)\right) \\ - 2\pi i H(\operatorname{Im} A(1, m_1, m_2)) H(-\operatorname{Im} A(0, m_1, m_2))] \,,$$

$$A(0, m_1, m_2) = 2\sqrt{m_2} + i(m_1 - m_2 + 1) \,,$$

$$A(1, m_1, m_2) = 2\sqrt{m_1} + i(m_1 - m_2 - 1) \,,$$

$$m_1 \;=\; M_1/k^2 \;\text{ and }\; m_2 \;=\; M_2/k^2$$

- Triangle Master:

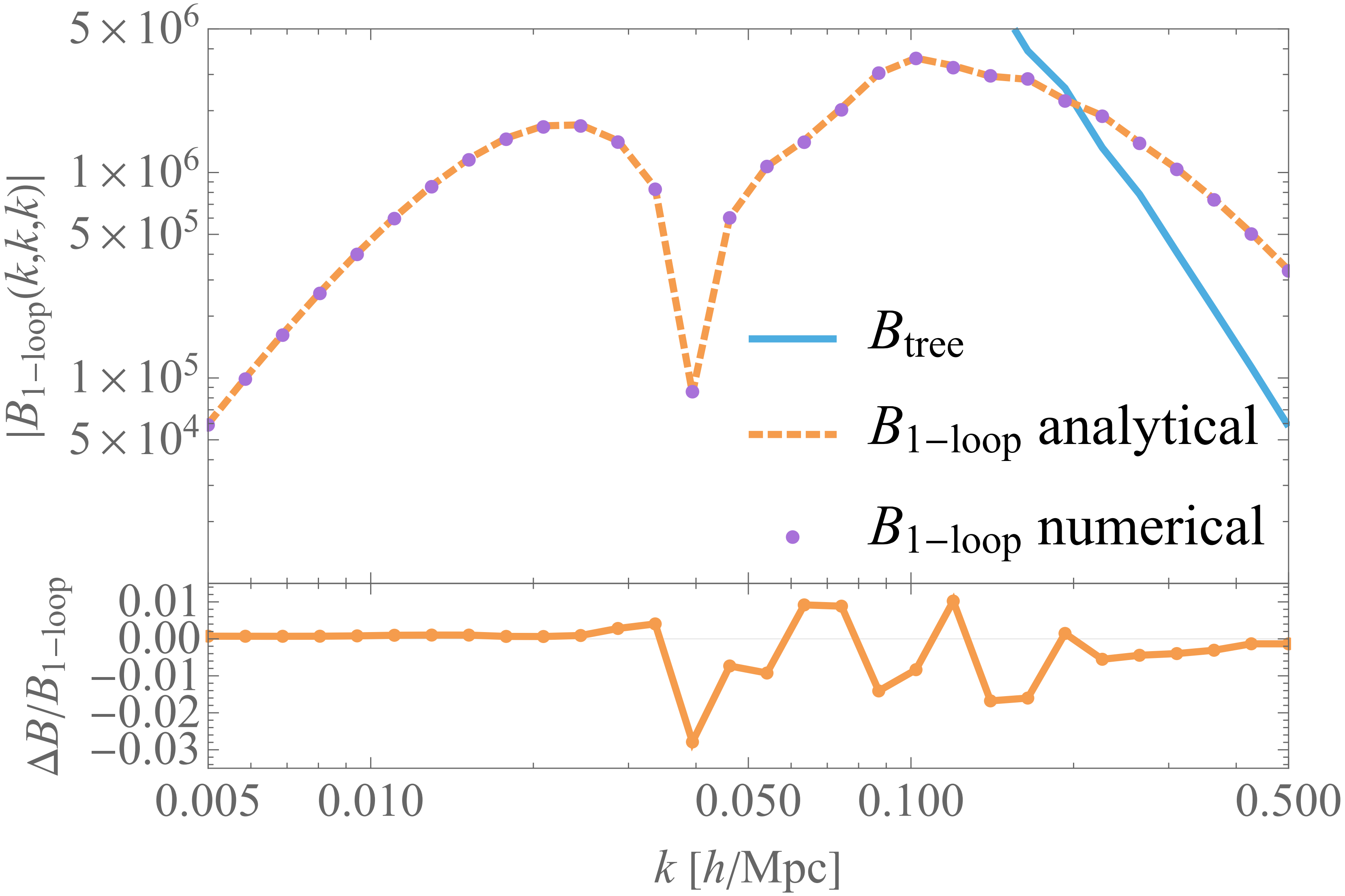
$$F_{\text{int}}(R_2, z_+, z_-, x_0) = s(z_+, -z_-) \frac{\sqrt{\pi}}{\sqrt{|R_2|}} \left. \frac{\arctan\left(\frac{\sqrt{z_+ - x}\sqrt{x_0 - z_-}}{\sqrt{x_0 - z_+}\sqrt{x - z_-}}\right)}{\sqrt{x_0 - z_+}\sqrt{x_0 - z_-}} \right|_{x=0}^{x=1} .$$

- Very simple expressions with simple rule for branch cut crossing.

Result of Evaluation

with Anastasiou, Braganca, Zheng
2212

- All automatically coded up.
- For BOSS analysis, evaluation of matrix is 2.5CPU hours and 800 Mb storage, very fast matrix contractions.
- Accuracy with 16 functions:

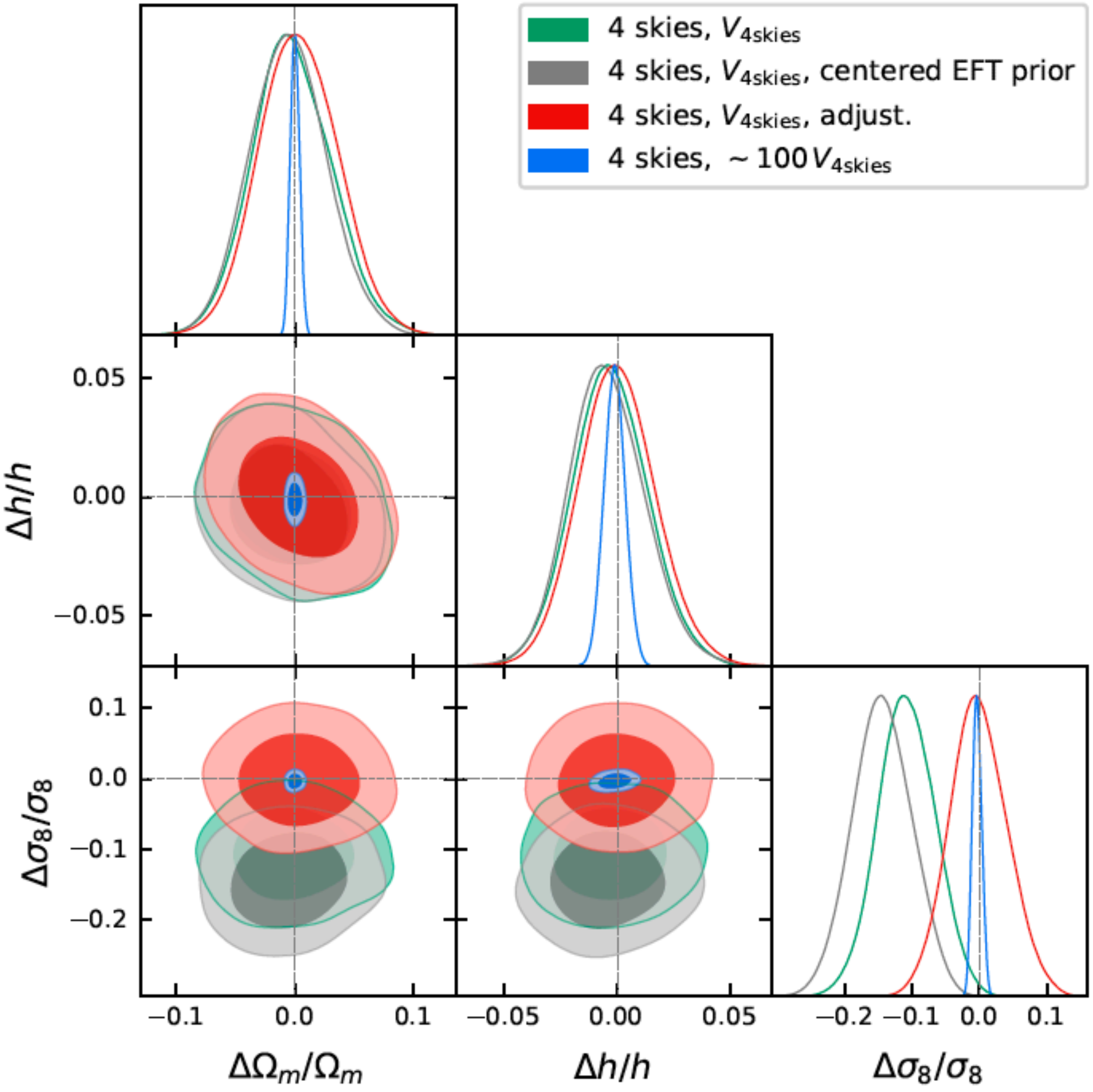


Back to data-analysis:
Pipeline Validation

with D’Amico, Donath, Lewandowski, Zhang **2206**

Measuring and fixing phase space

- We consider synthetic data, i.e. data made out of the model, and analyze them:
  - Green: biased.
- Why?
  - Priors centered on zero?
    - Grey: biased
  - Bug in pipeline?
    - Test by reducing covar.
    - Red: non-biased
- It must be phase space projection
- But the grey line offers
  - an honest measurement of it.
-



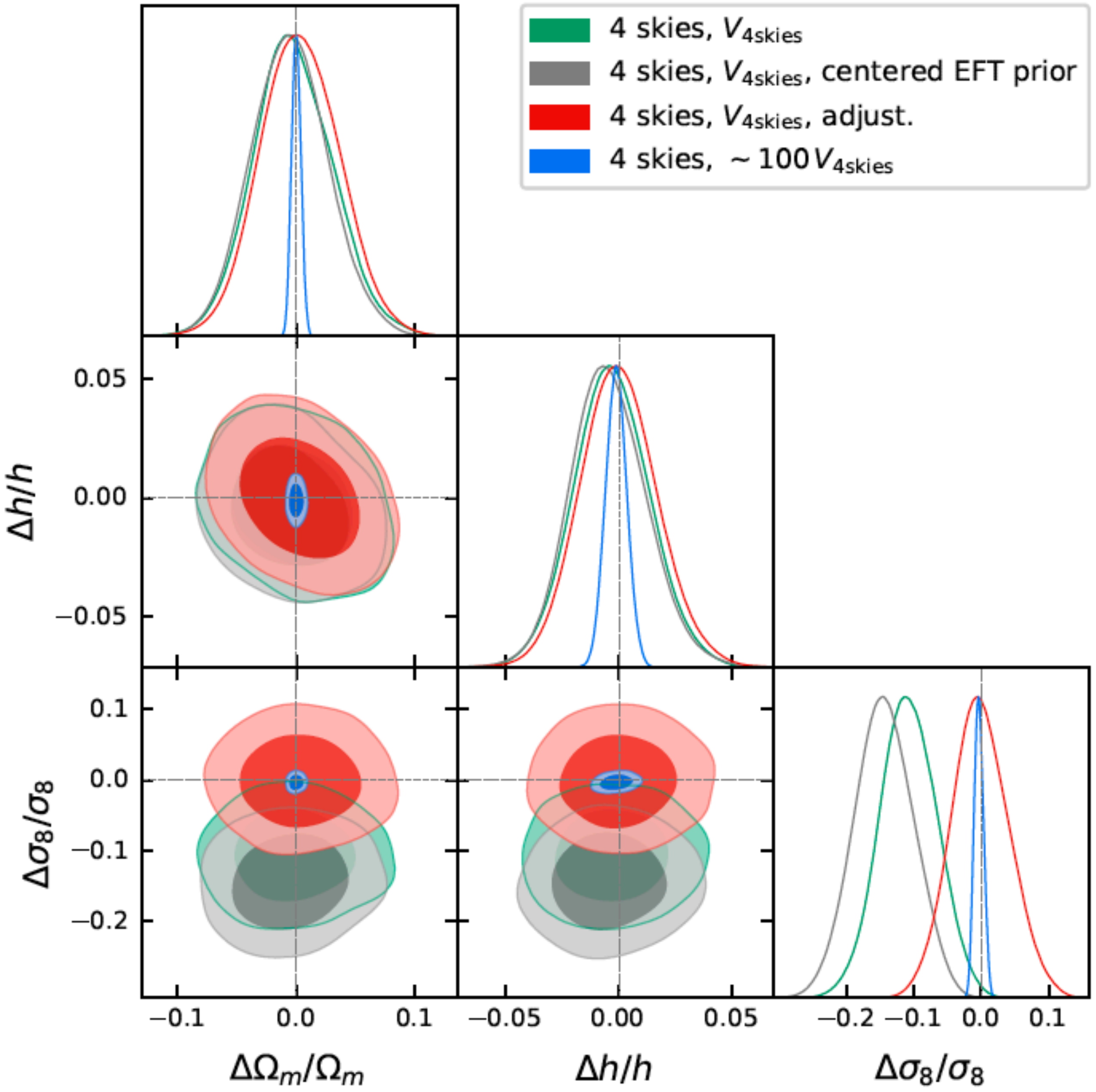
with D’Amico, Donath, Lewandowski, Zhang **2206**

Measuring and fixing phase space

- We add:

$$\ln \mathcal{P}_{\rm pr}^{\rm ph.\ sp.\ 4sky} = -48\left(\frac{b_1}{2}\right) + 32\left(\frac{\Omega_m}{0.31}\right) + 48\left(\frac{h}{0.68}\right) \ ,$$

$\sigma_{\rm proj}/\sigma_{\rm stat}$	Ω_m	h	σ_8	ω_{cdm}
1 sky, $\sim 100\, V_{\rm 1sky}$	-0.1	-0.14	-0.21	-0.2
1 sky, $V_{\rm 1sky}$, adjust.	0.13	0.06	0.04	0.15
4 skies, $V_{\rm 4skies}$, adjust.	0.1	0.	-0.05	0.07



- no more proj. effect.

Scale cut from NNLO

with D'Amico, Donath, Lewandowski, Zhang **2206**

- We can estimate the $k_{\rm max}$ without the use of simulations, by adding NNLO terms, and seeing when they make a difference on the posteriors.

$$P_{\rm NNLO}(k,\mu) = \frac{1}{4} c_{r,4} b_1^2 \mu^4 \frac{k^4}{k^4_{\rm NL,R}} P_{11}(k) + \frac{1}{4} c_{r,6} b_1 \mu^6 \frac{k^4}{k^4_{\rm NL,R}} P_{11}(k)\,,$$

$$\begin{aligned} B_{\rm NNLO}(k_1,k_2,k_3,\mu,\phi) &= 2 c_{\rm NNLO,1} K_2^{r,h}(\vec{k}_1,\vec{k}_2;\hat{z}) K_1^{r,h}(\vec{k}_2;\hat{z}) f \mu_1^2 \frac{k_1^4}{k^4_{\rm NL,R}} P_{11}(k_1) P_{11}(k_2) \\ &+ c_{\rm NNLO,2} K_1^{r,h}(\vec{k}_1;\hat{z}) K_1^{r,h}(\vec{k}_2;\hat{z}) P_{11}(k_1) P_{11}(k_2) f \mu_3 k_3 \frac{(k_1^2+k_2^2)}{4 k_1^2 k_2^2 k^4_{\rm NL,R}} \Big[-2\vec{k}_1\cdot\vec{k}_2 (k_1^3\mu_1 + k_2^3\mu_2) \\ &+ 2 f \mu_1\mu_2\mu_3 k_1 k_2 k_3 (k_1^2+k_2^2) \Big] + \text{perm.}\,, \end{aligned}$$

- For our $k_{\rm max}$, we find the following shifts, which are ok:

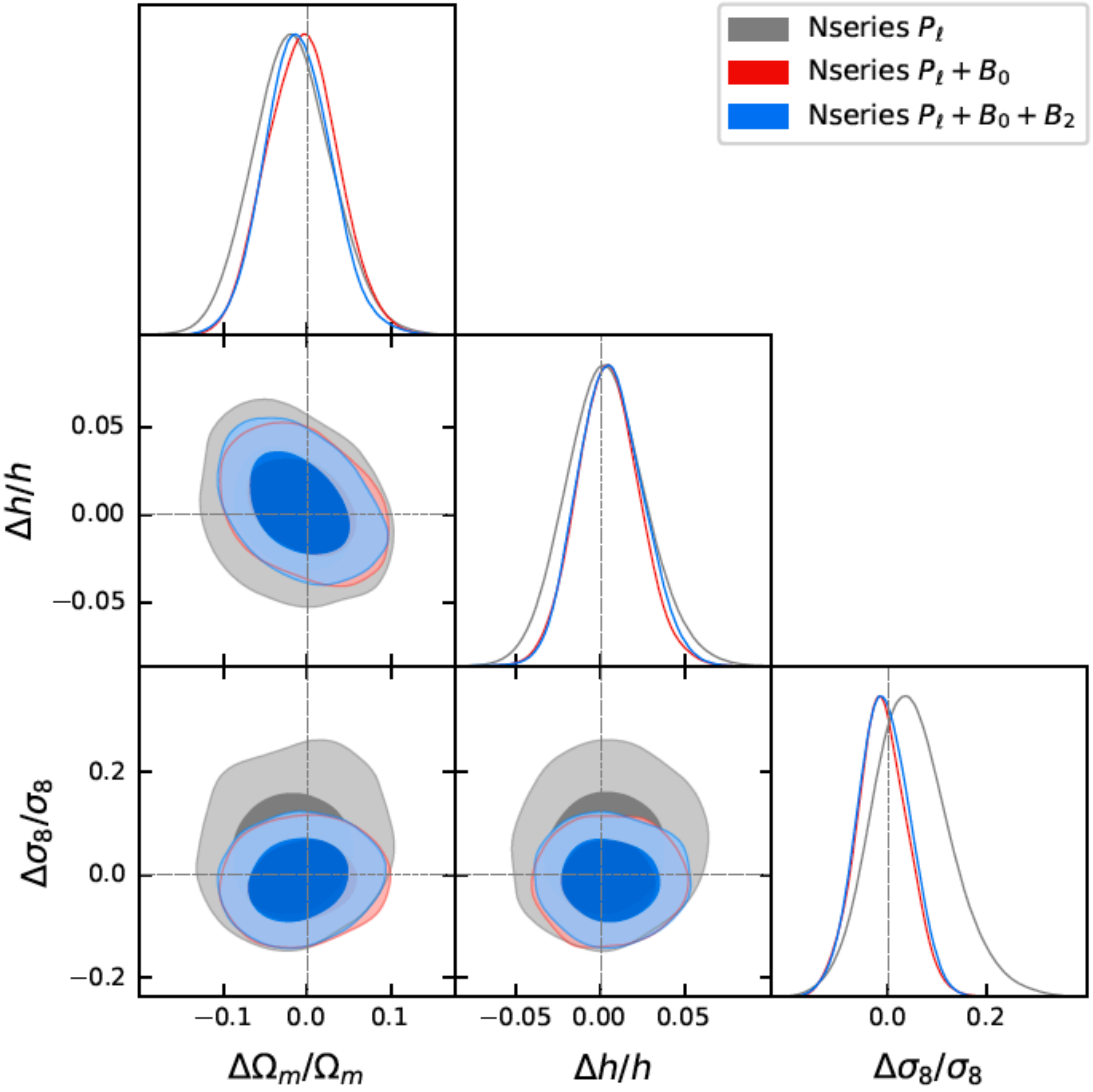
$\Delta_{\rm shift}/\sigma_{\rm stat}$	Ω_m	h	σ_8	ω_{cdm}	$\ln(10^{10}A_s)$	S_8
$P_\ell + B_0$: base - w/ NNLO	-0.03	-0.09	-0.03	-0.1	0.05	-0.04

Scale-cut from simulations

with D'Amico, Donath, Lewandowski, Zhang **2206**

- N-series
  - Volume ~80 BOSS
  - safely within $\sigma_{\rm data}/3$

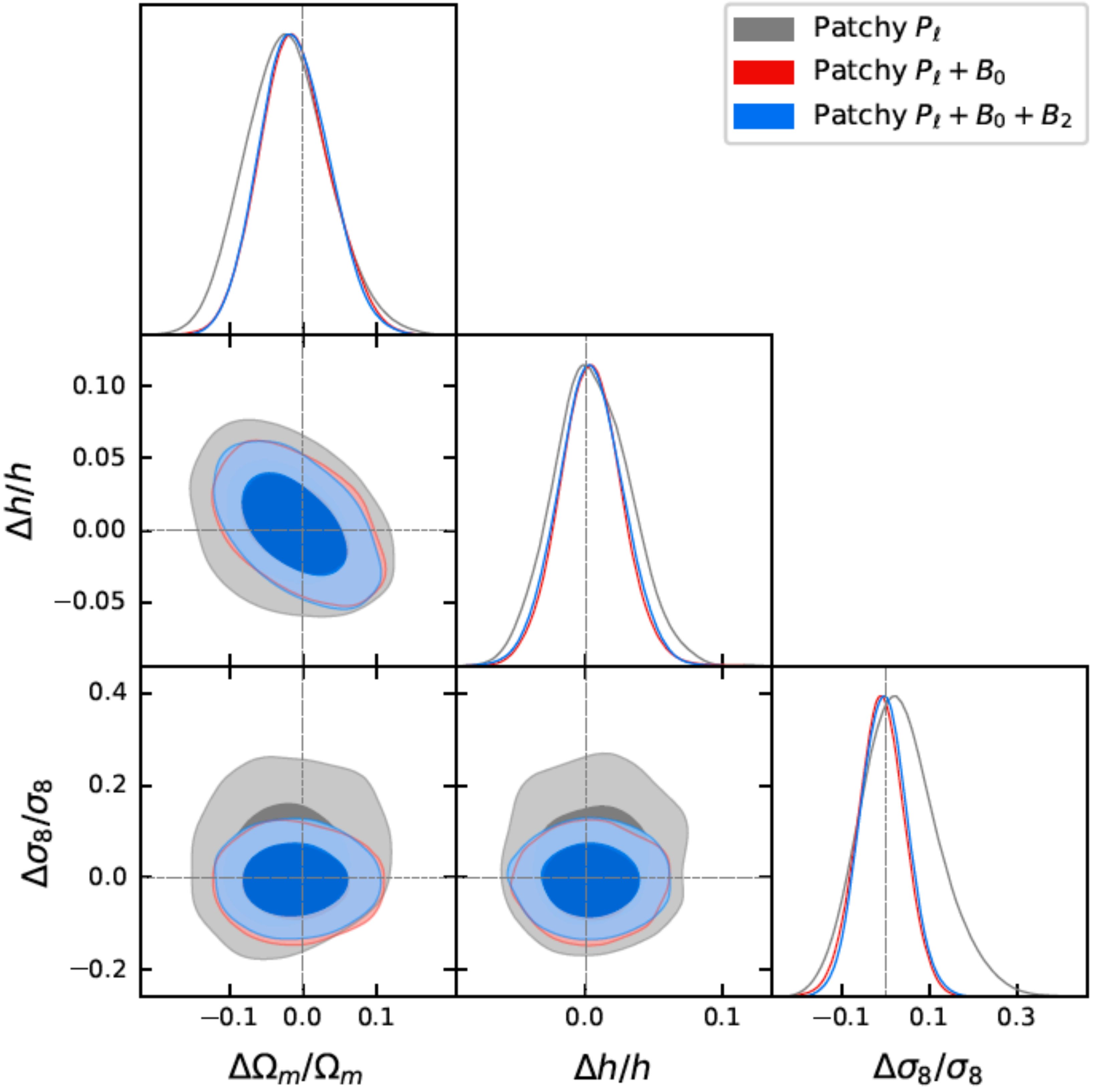
- After phase-space correction



Scale-cut from simulations

with D'Amico, Donath, Lewandowski, Zhang **2206**

- Patchy:
  - Volume ~2000 BOSS
  - safely within $\sigma_{\rm data}/3$
- After phase-space correction

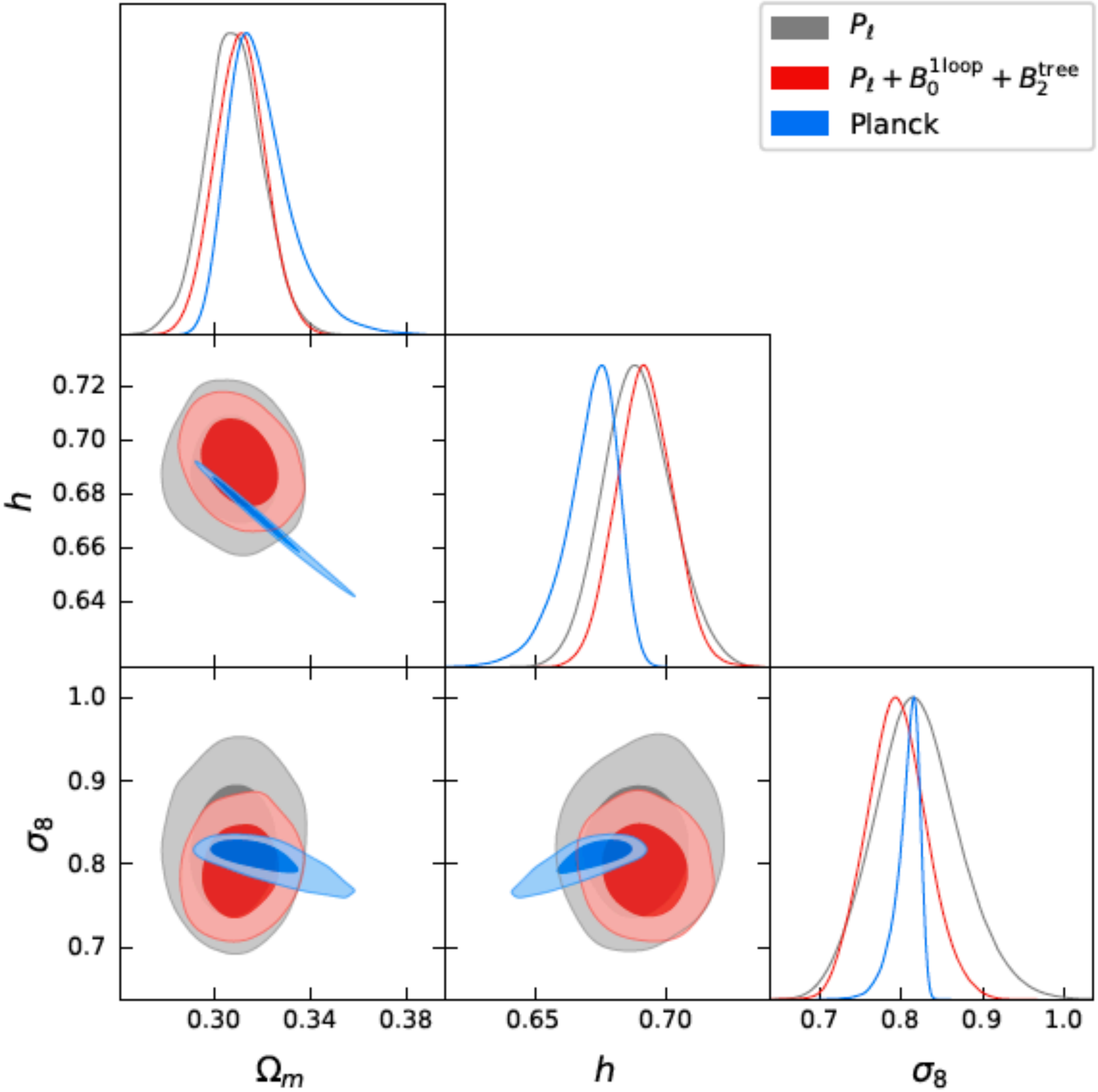


BOSS data

Data Analysis

with D'Amico, Donath, Lewandowski, Zhang **2206**

- Main result:
  - Improvements:
  - 30% on σ_8
  - 18% on h
  - 13% on Ω_m



- Compatible with Planck
  - –no tensions
- Remarkable consistency
  - –of observables

Summary

- After a long, painful developments, the EFTofLSS has been applied to data
    - we understand Large-Scale Structure

- So far, it has shown that already-completed surveys have the power to measure all cosmological parameters with just a BBN prior.
    - and for some, competitive with world record measurement
    - a trustable environment to look for new physics
- Lots of analyses and projects are going on

- Hopefully, this will enable upcoming surveys to deliver spectacular results.

- Now, level of needed competences goes beyond for example, my competences. So that, perhaps, stronger people than I are now needed.

Pipeline

with D’Amico, Donath, Lewandowski, Zhang **2206**

- We analyze one-loop quantities to $k_{\max} = 0.23h\,\mathrm{Mpc}^{-1}$ and tree level ones to $k_{\max} = 0.08h\,\mathrm{Mpc}^{-1}$

- Best fits are good: