Cosmology and the structure formation in the universe

Zvonimir Vlah

CERN

2018 LHC Days in Split

Overview

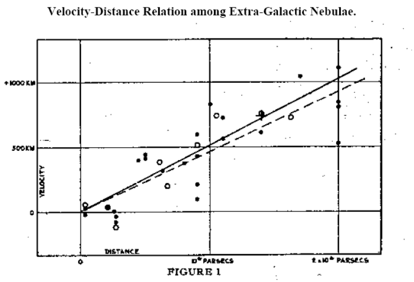
- homogeneous universe and expansion
- linear theory and the story of success
- quick survey of observables after Planck
- diving into nonlinearities of large scale structure (LSS)

Homogeneous universe

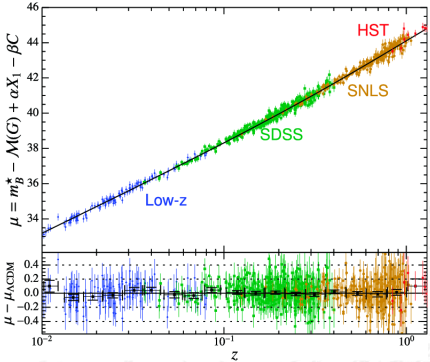
- test of Friedmann equation: redshift-distance relation & standard candles

$$(\dot{a}/a)^2 = H^2 = \rho - k/a^2, \quad \rho = \rho_m/a^3 + \rho_\gamma/a^4 + \rho_{de} + \rho_\nu(a)$$

- Nobel prize for accelerating expansion of the universe (2011)



[Hubble, 1929]



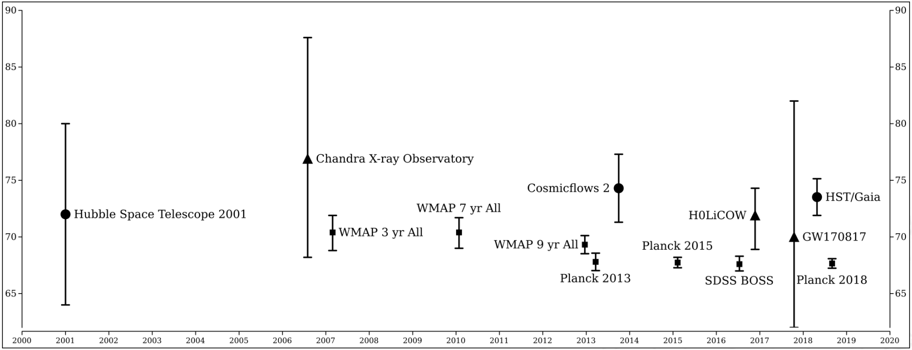
[Betoule et al, 15]

Homogeneous universe

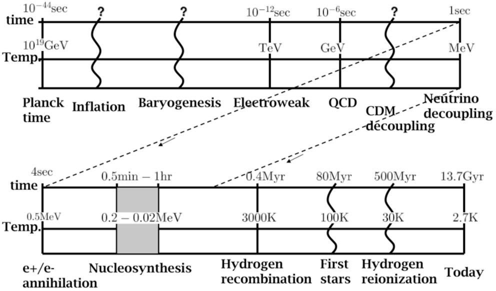
- test of Friedmann equation: redshift-distance relation & standard candles

$$(\dot{a}/a)^2 = H^2 = \rho - k/a^2, \quad \rho = \rho_m/a^3 + \rho_\gamma/a^4 + \rho_{de} + \rho_\nu(a)$$

- Nobel prize for accelerating expansion of the universe (2011)



Cosmic thermal history



[Loeb, '13]

- early universe was a hot and dense plasma of particles in thermal equilibrium
- big bang nucleosynthesis (z$\simeq 3 \times 10^8$) - formation of most of the universe's He
- recombination (z$\simeq$1100): $p^+ + e^- \to H$, universe is transparent for CBM photons that freestream
- reionization of the universe (z$\simeq$15) from first stars and quasars; $\sim$ 7%of the photons re-scatter
- we observe these photons at $T \simeq 2.725K$.

Fluctuations in the universe

CMB: $\Delta\rho/\rho \sim 10^{-6}$

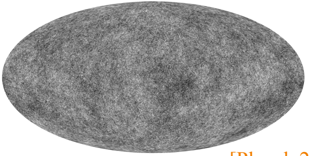
z=1100

LSS: $\Delta\rho/\rho \sim 10^{0}$

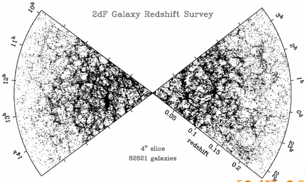
z=2

Galaxies: $\Delta\rho/\rho \sim 10^{6}$

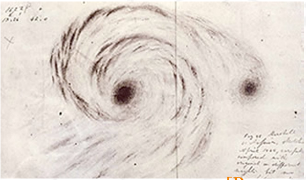
z=0



[Planck,2013]

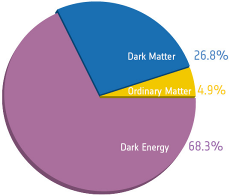


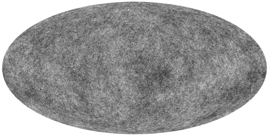
[2dF, 2002]



[Parsons, 1845]

Cosmological Standard Model: ΛCDM





Homogeneous background:

- dark energy $\Omega_{de} \sim 68\%$
- cold dark matter $\Omega_m \sim 27\%$
- baryonic matter $\Omega_b \sim 5\%$

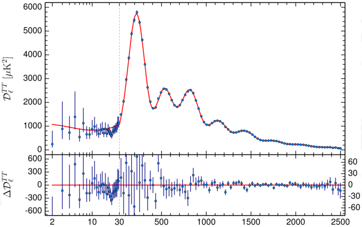
Fluctuations: A_s, n_s

- near-scale invariance
- Gaussian initial conditions

Power spectrum: statistical iso. & hom. $\Delta T \simeq 10^{-4} K$,

$$\Delta T = \sum_{\ell m} a_{\ell m} Y_{\ell m},$$

$$\delta_{\ell\ell'} \delta_{mm'} C_\ell^T = \langle a_{\ell m} a^*_{\ell m} \rangle$$



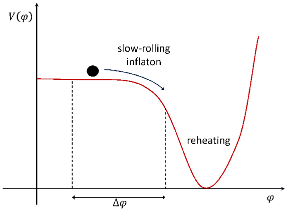
Origin of perturbations: inflationary paradigm

- inflation - an early period of rapid expansion: $\ddot{a} > 0$
- introduced to salve homogeneity, flatness and mag. monopole problems
- turned out to be the main paradigm for seeding the IC of the universe

negative pressure

$$\ddot{a}/a = -(\rho + 3p), \qquad \text{with} \qquad p < -\rho/3$$

simplest cause can be inflaton field



$$(\dot{a}/a)^2 = H^2 = \dot{\phi}^2/2 + V(\phi)$$
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

-shape of the potential? energy scales?
-additional degrees of freedom?

Post Planck era of Cosmology

- optimal experiment crosses some theoretical threshold (LHC - TeV)
- Planck - spectrum tilt ($2.5\sigma \to 6\sigma$)
- Energy scale - H^2/Λ^2: from Wmap to Planck $\sqrt{3}$
- Planck was a chance to detect, but in the absence of detection not much has changed for primordial physics
- with Planck we have used up all the CMB large scale modes
- Large Scale Structures (LSS) offer the only med-term hunting ground - but we are compelled to understand them better

LSS: motivations and observations

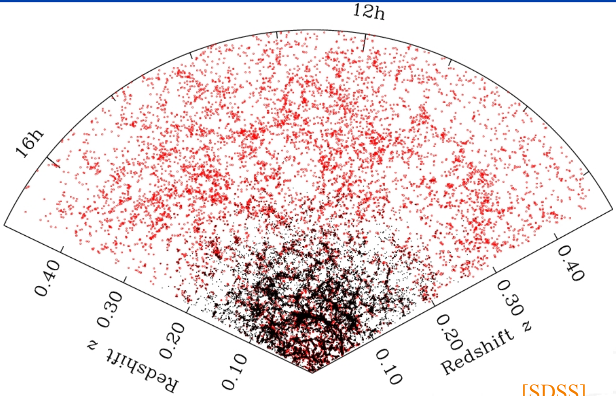
Theoretical motivations:

- Inflation - origin of structures
- Expansion history
- Composition of the universe
- Nature of dark energy and dark matter
- Neutrino mass and number of species
- Test of GR and modifications of gravity

Current and future observations:

- 2dF Galaxy Redshift Survey
- SDSS and SDSS3/4: Sloan Digital Sky Survey
- BOSS: the Baryon Oscillation Spectroscopic Survey
- DES: the Dark Energy Survey
- LSST: the large synoptic survey telescope.
- Euclid: the ESA mission to map the geometry of the dark Universe
- DESI: Dark Energy Spectroscopic Instrument

Galaxy clustering



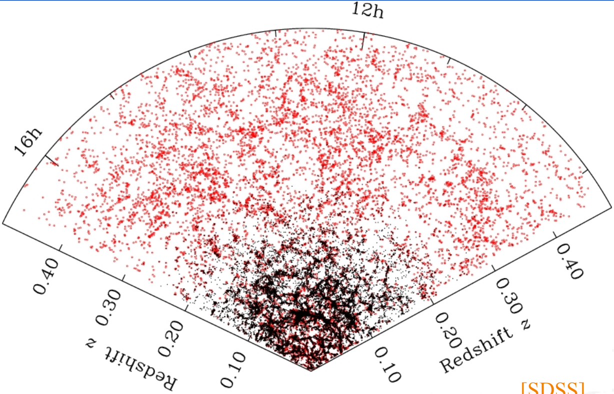
[SDSS]

- Measured 3D distribution $\Rightarrow$ much more modes than projected quantities (CMB, etc.) - *some analogy with LEP to LHC transition*
- Redshift surveys measure: θ, ϕ, redshift z; NofM $= (k_{max}/k_{min})^3$

  overdensity: $\delta = (n - \bar{n})/\bar{n}$,

  power spectrum: $P(k) \sim \langle \delta(\mathbf{k}) | \delta(\mathbf{k}) \rangle$

Galaxy clustering



[SDSS]

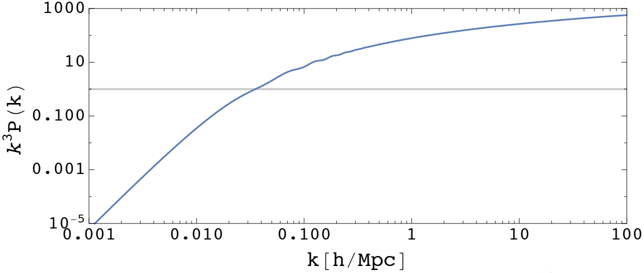
- Measured $3D$ distribution $\Rightarrow$ much more modes than projected quantities (CMB, etc.) - *some analogy with LEP to LHC transition*
- Redshift surveys measure: θ, ϕ, redshift z; NofM $= (k_{max}/k_{min})^3$

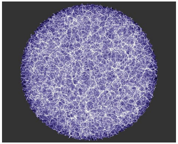
Generalization is the multi-spectra:

$$\langle \delta(\mathbf{k}_1) \ldots \delta(\mathbf{k}_N) \rangle_c \sim P_N(\mathbf{k}_1, \ldots, \mathbf{k}_N)$$

Quasi-linear scales

Separation of physical scales

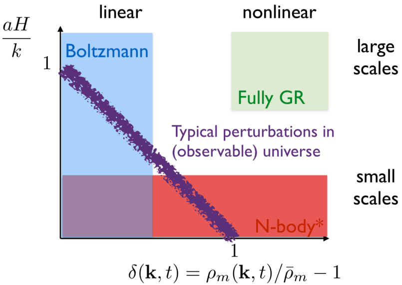




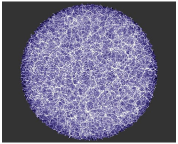
In history of universe dark matter moves about $1/k_{nl} \sim 10\text{Mpc}/h$
- local in space, non-local in time

Quasi-linear scales

Separation of physical scales

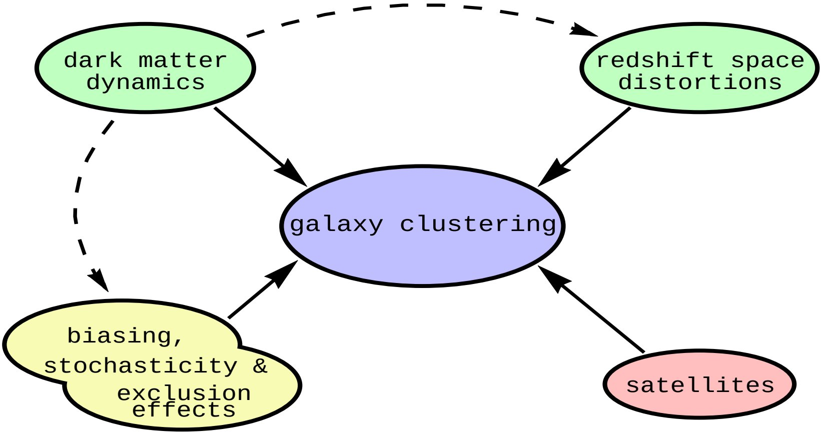


[Schmidt, '17]



In history of universe dark matter moves about $1/k_{nl} \sim 10\mathrm{Mpc}/h$
- local in space, non-local in time

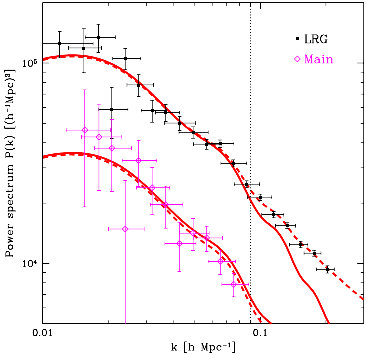
Galaxy clustering scheme



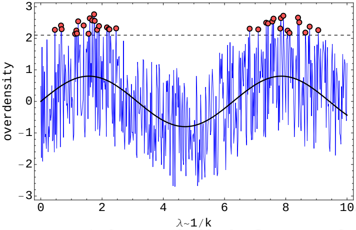
+ others: baryons, assembly bias, neutrinos, (clustering) dark energy, GR effects, multiple d.m. species ...

Galaxies and biasing of dark matter halos

- cosmological theory (sims) give dark matter distribution, but not galaxy distribution.
- what we observe from survey are galaxies, not dark matter.
- Bias: How does galaxy distribution related to the matter?



[Tegmark et al, 2006]



- galaxies form at high peaks: $\Longrightarrow$ exhibit higher clustering
- Tracer detriments the amplitude: $P_g(k) = b^2 P_m(k) + \ldots$

Biasing: effective approach to the clustering of tracers

Local biasing model: tracer field is a smooth function of just d.m. field

$$\delta_{\rm x} = c_\delta \delta + c_{\delta^2}\delta^2 + c_{\delta^3}\delta^3 + \ldots$$ [Fry & Gaztanaga, 1993]

Quasi-local (in space) relation of the halo density field to the dark matter
[McDonald & Roy 2008, Desjacques et al, 2016, ...]

$$\delta_{\rm x} = c_\delta \delta + c_{\delta^2}\delta^2 + c_{\delta^3}\delta^3 + c_{s^2}s^2 + c_{\delta s^2}\delta s^2 + c_\psi \psi + c_{st} st + c_{s^3}s^3 + c_\epsilon \epsilon \ldots,$$

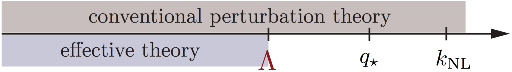
with (effective) coefficients c_x and (”long”) fields:

$$s_{ij} = \partial_i\partial_j\phi - \frac{1}{3}\delta^{\rm K}_{ij}\delta, \qquad t_{ij} = \partial_i v_j - \frac{1}{3}\delta^{\rm K}_{ij}\theta - s_{ij},$$

$$\psi = [\theta - \delta] - \frac{2}{7}s^2 + \frac{4}{21}\delta^2,$$

where ϕ is the gravitational potential, and ϵ noise (stochasticity) field.

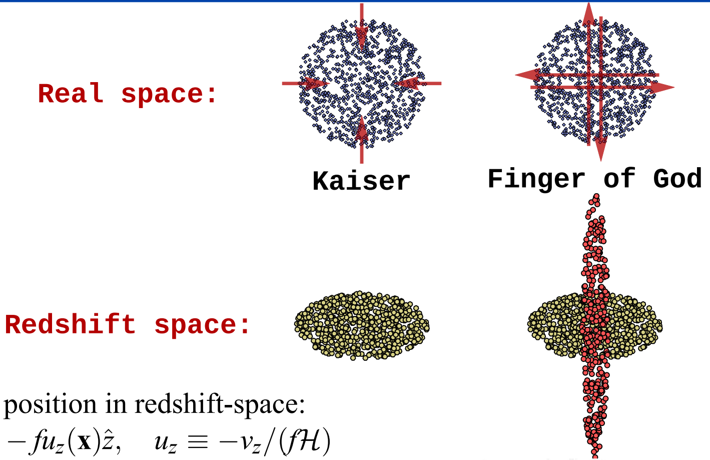
Biasing: effective approach to the clustering of tracers



Bias coefficients incorporate complicated galaxy formation physics in addition to the UV effects:

- dark matter halo formation
- merger history
- chemistry and cooling processes
- background radiation
- feedback (SN, AGN, ...)
- (and more ...)

Redshift space distortions (RSD)



Object position in redshift-space:

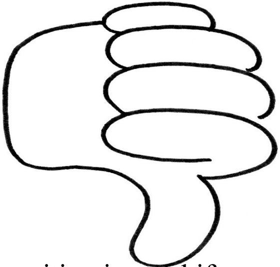
$$\mathbf{s} = \mathbf{x} - f u_z(\mathbf{x})\hat{z}, \quad u_z \equiv -v_z/(f\mathcal{H})$$

Density in redshift-space:

$$\delta_s(\mathbf{s}) = \int_r \delta(\boldsymbol{r})\delta^D(\mathbf{s} - \boldsymbol{x} - f u_z(\mathbf{x})\hat{z}).$$

Redshift space distortions (RSD)

Fingers of God (FoG)



Object position in redshift-space:

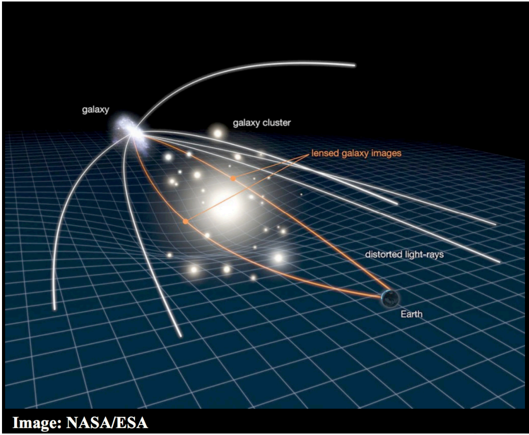
$$\mathbf{s} = \mathbf{x} - f u_z(\mathbf{x})\hat{z}, \quad u_z \equiv -v_z/(f\mathcal{H})$$

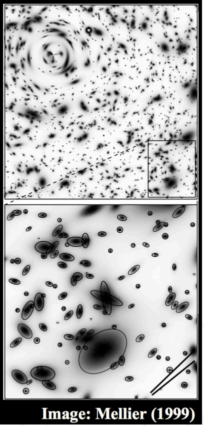
Density in redshift-space:

$$\delta_s(\mathbf{k}) = \int_x e^{i\boldsymbol{k}\cdot\boldsymbol{x}} e^{-ifk_z u_z(\mathbf{x})} \Big(\delta(\boldsymbol{x}) + f\nabla_z u_z(\mathbf{x})\Big), \quad f\nabla_z u_z(\mathbf{x}) < 1.$$

Weak lensing

- weak lensing: small preferential distortions of background galaxy shapes
- small effects, can be studied statistically, averaging over many objects





Convergence (κ): isotropic focusing of light, size & brightness change

Shear (γ): anisotropic focusing of light, shapes get distorted

Intrinsic alignments (IA)

Shift in the angle in lensing can be described by

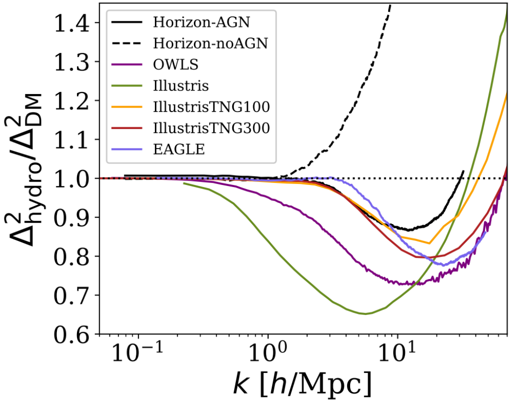
$$\boldsymbol{\gamma} = \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix} = \kappa\delta^K + \gamma_1\sigma_3 + \gamma_2\sigma_1,$$

- intrinsic alignment of galaxies - shape and orientation before lensing
- intrinsic shape or ellipticity is larger contributor to single galaxy shapes than the effects of gravitational shear
- IA: random component + component correlated with LSS
- primary physical systematic in weak gravitational lensing
- isolating the effect of IA from weak lensing is not trivial.
- very interesting for galaxy surveys (SDSS, LSST, Euclid, DES, ...)
- baryonic component - big systematic effects, window to small scale physics

Total observed shear : $\boldsymbol{\gamma}_{\mathrm{obs}} = \boldsymbol{\gamma}_{\mathrm{G}} + \boldsymbol{\gamma}_{\mathrm{I}}$

The impact of baryons on the total matter power

- baryonic component - big systematic effects, window to small scale physics
- opportunity to constrain small scale physics and constrain astro-models



[Chisari et all, '18]

Why perturbative approach?

- Goal is the high precision at large scales (in scope of next gen. surveys), as well as to push to small scales.
- This problem is also amenable to direct simulation.
  - Though the combination of volume, mass and force resolution and numerical accuracy is very demanding - in scope of next gen. surveys.
  - PT is a viable alternative as well as a guide what range of k, M_h, scales are necessary and what statistics are needed.
  - N-body can be used to test PT for 'fiducial' models.
- However PT can be used to search a large parameter space efficiently, and find what kinds of effects are most important.
  - Can be much more flexible/inclusive, especially for biasing schemes.
  - It is much easier to add new physics, especially if the effects are small (e.g. neutrinos, clustering dark energy, non-Gaussianity)
- Gaining insights!
- Complementarity reason; if we can, we should.

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p} \cdot \nabla f - am\nabla\phi \cdot \nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

Integral moments of the distribution function:

mass density field & mean streaming velocity field

$$\rho(\mathbf{x}) = ma^{-3}\int d^3p\, f(\boldsymbol{x},\boldsymbol{p}), \qquad v_i(\mathbf{x}) = \frac{\int d^3p\, \frac{p_i}{am} f(\boldsymbol{x},\boldsymbol{p})}{\int d^3p\, f(\boldsymbol{x},\boldsymbol{p})},$$

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p} \cdot \nabla f - am\nabla\phi \cdot \nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

Eulerian framework - fluid approximation:

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$
$$\frac{\partial v_i}{\partial \tau} + \mathcal{H}v_i + \mathbf{v} \cdot \nabla v_i = -\nabla_i\phi - \frac{1}{\rho}\nabla_i(\rho\sigma_{ij}),$$

where σ_{ij} is the velocity dispersion.

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p} \cdot \nabla f - am\nabla\phi \cdot \nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

Eulerian framework - **pressureless perfect fluid** approximation:

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$

$$\frac{\partial v_i}{\partial \tau} + \mathcal{H} v_i + \mathbf{v} \cdot \nabla v_i = -\nabla_i \phi.$$

Irrotational fluid: $\theta = \nabla \cdot \mathbf{v}$.

Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p}\cdot\nabla f - am\nabla\phi\cdot\nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

EFT approach introduces a tress tensor for the long-distance fluid:

$$\frac{\partial \delta}{\partial \tau} + \nabla\cdot[(1+\delta)\mathbf{v}] = 0$$
$$\frac{\partial v_i}{\partial \tau} + \mathcal{H}v_i + \mathbf{v}\cdot\nabla v_i = -\nabla_i\phi - \frac{1}{\rho}\nabla_j(\tau_{ij}),$$

with given as $\tau_{ij} = p_0\delta_{ij} + c_s^2\delta\rho\delta_{ij} + O(\partial^2\delta,\ldots)$
-derived by smoothing the short scales in the fluid with
the smoothing filter $W(\Lambda)$, where $\Lambda \propto 1/k_{\rm NL}$.

[Baumann et al 2010, Carrasco et al 2012]

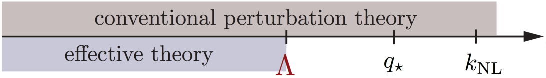
Gravitational clustering of dark matter

Evolution of collisionless particles - Vlasov equation:

$$\frac{df}{d\tau} = \frac{\partial f}{\partial \tau} + \frac{1}{m}\mathbf{p} \cdot \nabla f - am\nabla\phi \cdot \nabla_p f = 0,$$

and $\nabla^2\phi = 3/2\mathcal{H}\Omega_m\delta$.

EFT approach introduces a tress tensor for the long-distance fluid:



with given as $\tau_{ij} = p_0\delta_{ij} + c_s^2\delta\rho\delta_{ij} + O(\partial^2\delta, \ldots)$

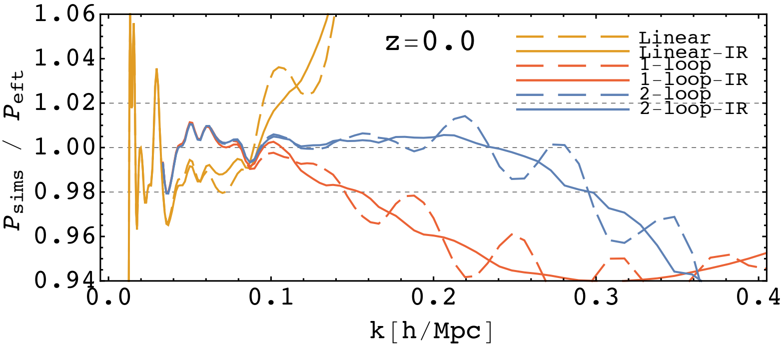
-derived by smoothing the short scales in the fluid with
 the smoothing filter $W(\Lambda)$, where $\Lambda \propto 1/k_{\rm NL}$.

[Baumann et al 2010, Carrasco et al 2012]

Power spectrum, correlation function & BAO

$$P_{\text{EFT-1-loop}} = P_{11} + P_{\text{1-loop}} - 2(2\pi)c^2_{s(1)}\frac{k^2}{k^2_{\text{NL}}}P_{11}$$

$$P_{\text{EFT-2-loop}} = P_{11} + P_{\text{1-loop}} + P_{\text{2-loop}} - 2(2\pi)c^2_{s(1)}\frac{k^2}{k^2_{\text{NL}}}(P_{11} + P_{\text{1-loop}}) + \text{c.t.}$$



[Carrasco et al, '12/'13, Senatore et al '14, Baldauf et al '15, Foreman et al '15, Vlah et al '15]

- Well defined/convergent expansion in k/k_{NL} (one parameter).
- Six c. t. for two-loop - approximate degeneracy! [Zaldarriaga et al, '15]

Lagrangian vs Eulerian framework

Eulerian:

Lagrangian:

Coordinate of a (t)racer particle at a given moment in time $\mathbf{r}$

$$\mathbf{r}(\mathbf{q},\tau) = \mathbf{q} + \psi(\mathbf{q},\tau),$$

is given in terms of Lagrangian displacement.

Continuity equation:

$$(1+\delta(\mathbf{r}))\, d^3r = d^3q \quad \text{vs.} \quad 1+\delta(\mathbf{r}) = \int_q \delta^D\left(\mathbf{r}-\mathbf{q}-\psi(\mathbf{q})\right),$$

Shell crossing

$$(1+\delta(\mathbf{r}))\, d^3r = \sum_{shells} d^3q \quad \text{vs.} \quad 1+\delta(\mathbf{r}) = \int_q \delta^D\left(\mathbf{r}-\mathbf{q}-\psi(\mathbf{q})\right),$$

Lagrangian vs Eulerian framework

Eulerian:

Lagrangian:

Coordinate of a (t)racer particle at a given moment in time $\mathbf{r}$

$$\mathbf{r}(\mathbf{q}, \tau) = \mathbf{q} + \psi(\mathbf{q}, \tau),$$

is given in terms of Lagrangian displacement.
Continuity equation:

$$(1 + \delta(\mathbf{r}))\, d^3 r = d^3 q \quad \text{vs.} \quad 1 + \delta(\mathbf{r}) = \int_q \delta^D \left(\mathbf{r} - \mathbf{q} - \psi(\mathbf{q})\right),$$

Fourier space

$$(2\pi)^3 \delta^D(\mathbf{k}) + \delta(\mathbf{k}) = \int_q e^{i\mathbf{k}\cdot\mathbf{q}} \exp\left(i\mathbf{k} \cdot \psi\right),$$

Lagrangian dynamics and EFT

Fluid element at position $\boldsymbol{q}$ at time t_0, moves due to gravity:

The evolution of ψ is governed by

$$\ddot{\psi} + \mathcal{H}\dot{\psi} = -\nabla\Phi(\boldsymbol{q} + \psi(\boldsymbol{q})).$$

Integrating out short modes (using filter $W_R(\boldsymbol{q}, \boldsymbol{q}'))$ system is splitting tnto $L-$long and $S-$short wavelength modes, e.g.

$$\psi_L(\boldsymbol{q}) = \int_q W_R(\boldsymbol{q}, \boldsymbol{q}')\psi(\boldsymbol{q}'), \quad \psi_S(\boldsymbol{q}, \boldsymbol{q}') = \psi(\boldsymbol{q}') - \psi_L(\boldsymbol{q}).$$

This defines δ_L as the long-scale component of the density perturbation corresponding to ψ_L and also Φ_L as the gravitational potential $\nabla^2\Phi_L \sim \delta_L$.
E.o.m. for long displacement: [Vlah et al, '15]

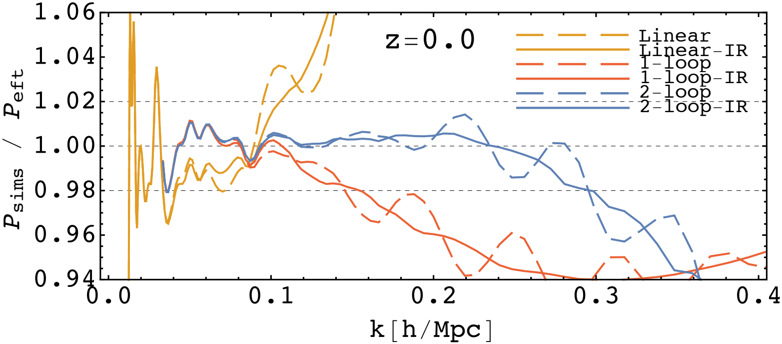
$$\ddot{\psi}_L + \mathcal{H}\dot{\psi}_L = -\nabla\Phi_L(\boldsymbol{q} + \psi_L(\boldsymbol{q})) + \boldsymbol{a}_S\big(\boldsymbol{q}, \psi_L(\boldsymbol{q})\big),$$

and $\boldsymbol{a}_S(\boldsymbol{q}) = -\nabla\Phi_S(\boldsymbol{q} + \psi_L(\boldsymbol{q})) - \frac{1}{2}Q_L^{ij}(\boldsymbol{q})\nabla\nabla_i\nabla_j\Phi_L(\boldsymbol{q} + \psi_L(\boldsymbol{q})) + \ldots,$
Similar formalism was also derived in [Porto et al, '14].

Linear power spectrum, correlation function & BAO

$$P_{\text{EFT-1-loop}} = P_{11} + P_{\text{1-loop}} - 2(2\pi)c_{s(1)}^2 \frac{k^2}{k_{\text{NL}}^2} P_{11}$$

$$P_{\text{EFT-2-loop}} = P_{11} + P_{\text{1-loop}} + P_{\text{2-loop}} - 2(2\pi)c_{s(1)}^2 \frac{k^2}{k_{\text{NL}}^2}(P_{11} + P_{\text{1-loop}}) + \text{c.t.}$$

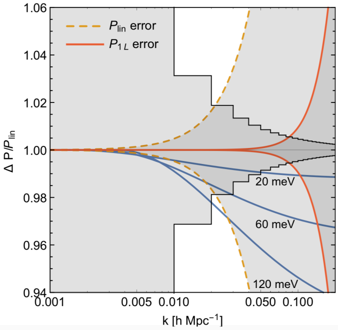


[Carrasco et al, '12/'13, Senatore et al '14, Baldauf et al '15, Foreman et al '15, Vlah et al '15]

- Well defined/convergent expansion in k/k_{NL} (one parameter).
- IR resummation (Lagrangian approach) - BAO peak! [Vlah et al '15]
- Six c. t. for two-loop - approximate degeneracy! [Zaldarriaga et al, '15]

Neutrinos

- free streaming neutrinos inhibit structure formation on small scales
- massive neutrinos contribute to total matter, but given that they don't clump small scales power is suppressed
- min. signal at $0.06eV$ gives 4% suppression at $k < 0.2\text{Mpc}/h$ (SDSS - σ & DESI $2-3\sigma$)
- Planck $\sum m_\nu < 0.23eV$



[Simonovic et all, '17]

Path integrals and going beyond shell crossing

- as we saw the Lagrangian framework includes shell crossing
- Lagrangian dynamics can be compactly written using

$$\boldsymbol{L}_0\phi + \boldsymbol{\Delta}_0(\phi) = \boldsymbol{\epsilon},$$

where:

$$\phi \equiv (\psi, \upsilon)\,, \quad [\boldsymbol{L}_0]_{i_2 i_1} = \begin{pmatrix} \frac{\partial}{\partial\eta_2} & -1 \\ -\frac{3}{2} & \frac{\partial}{\partial\eta_2} + \frac{1}{2} \end{pmatrix}, \quad \boldsymbol{\Delta}_0(\phi) = \frac{3}{2}\left(0, \partial_{\boldsymbol{x}}\partial_{\boldsymbol{x}}^{-2}\delta + \psi\right).$$

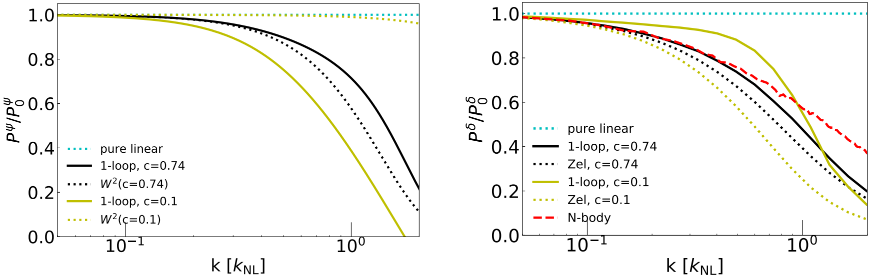
Statistics of interest given by generating function

$$Z(\boldsymbol{j}) \equiv \int d\boldsymbol{\epsilon}\; e^{-\frac{1}{2}\boldsymbol{\epsilon}\boldsymbol{N}^{-1}\boldsymbol{\epsilon}+\boldsymbol{j}\phi[\boldsymbol{\epsilon}]} \quad \text{and} \quad \langle\phi_{i_1}\phi_{i_2}\rangle = \frac{\partial^2}{\partial j_{i_1}\partial j_{i_2}} Z(\boldsymbol{j})\Big|_{\boldsymbol{j}=0},$$

which after the variable change becomes

$$Z(\boldsymbol{j}) \equiv \int d\phi\; e^{-S(\phi)+\boldsymbol{j}\phi},$$

with $S(\phi) = 1/2\left[\boldsymbol{L}_0\phi + \boldsymbol{\Delta}_0(\phi)\right]\boldsymbol{N}^{-1}\left[\boldsymbol{L}_0\phi + \boldsymbol{\Delta}_0(\phi)\right].$ [McDonald&Vlah, ’17]

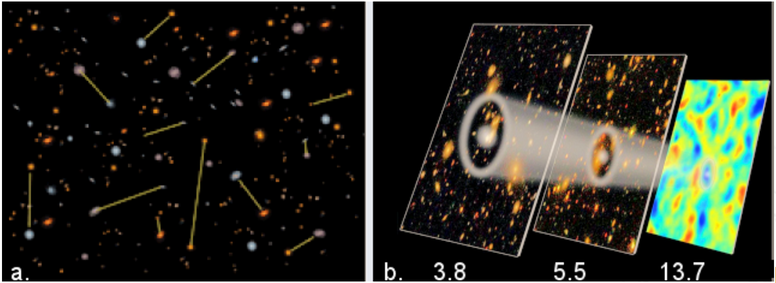


Significance and connection EFT formalism:

- no need of EFT free parameters, i.e. counter terms are predicted
- CMB lensing: direct information on baryonic and neutrinos physics
- reduction of degeneracy in galaxy bias coefficients
- possible connection to the EFT formalism by matching the $k \to 0$ limit

Baryon acoustic oscillation

- before recombination, photon-baryon interactions create pressure contracting gravitational collapse (1/2c)
- after recombination there is a residual baryonic overdensity left that evolves only gravitationally



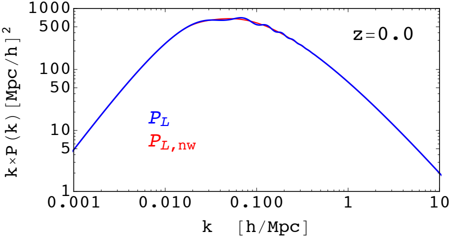
[BOSS, '12]

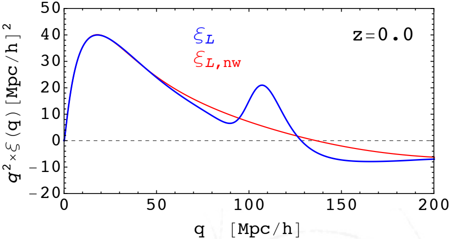
- residual wall stalls, velocity plummets, at scale $\sim 147 Mpc$

Linear power spectrum, correlation function & BAO

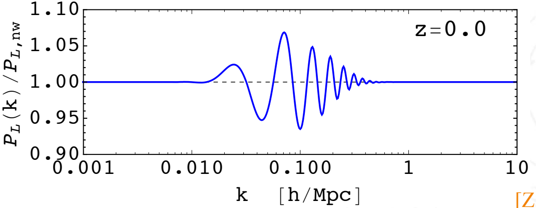
Linear power spectrum $P_{\rm L}$: obtained form Boltzmann codes (CAMB, Class). Formally we can divide it into smooth part $P_{\rm L,nw}$ and wiggle part $P_{\rm L,w}$ so that:

$$P_{\rm L} = P_{\rm L,nw} + P_{\rm L,w}$$





Wiggle power spectrum: $P_{\rm L,w} \quad \rightarrow \quad \sigma_n = \int_q q^{-n} P_{\rm L,w}(q) = 0$ for $n = \{0, 2\}$.

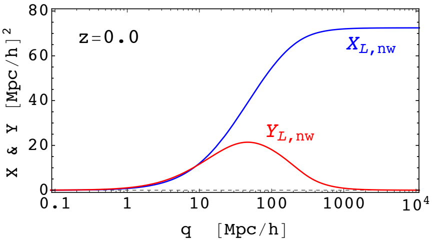


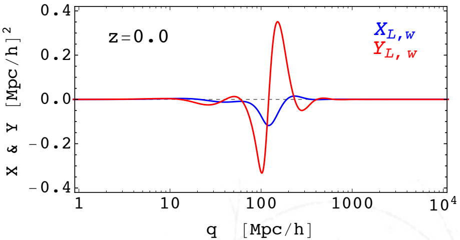
[Z.V. et al, '14 & '15]

Resummation of IR modes

Separating the wiggle and non-wiggle part $A^{ij}_{\mathrm{L}}(\boldsymbol{q}) = A^{ij}_{\mathrm{L,nw}}(\boldsymbol{q}) + A^{ij}_{\mathrm{L,w}}(\boldsymbol{q})$;

$$P = P_{\mathrm{nw}} + \int_q e^{i\boldsymbol{k}\cdot\boldsymbol{q} - (1/2)k_i k_j A^{ij}_{\mathrm{L,nw}}} \left[-\frac{k_i k_j}{2} A^{ij}_{\mathrm{L,w}} + \cdots \right] \simeq P_{\mathrm{nw}} + e^{-k^2\Sigma^2} P_{\mathrm{L,w}} + \ldots$$



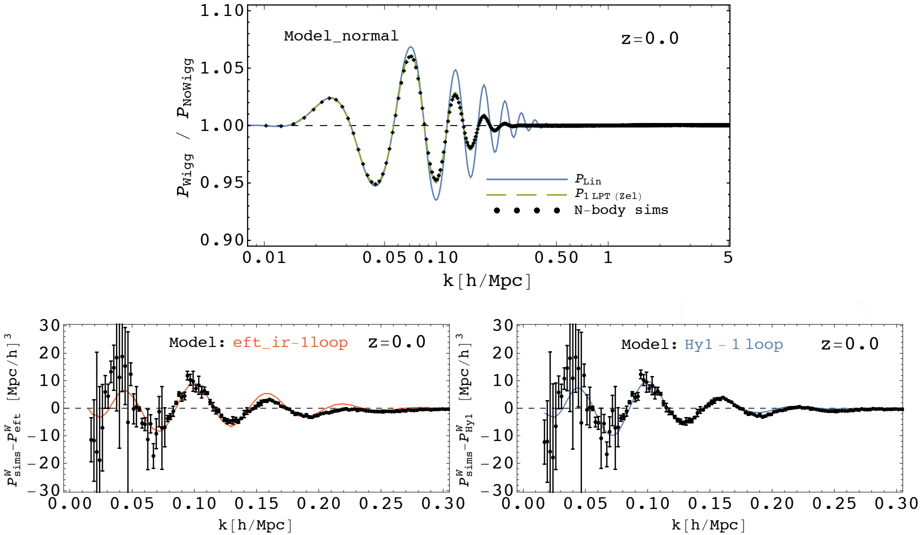


IR-SPT resummation model with $\Sigma^2 = \int \frac{dp}{3\pi^2}(1 - j_0(q_{\mathrm{max}}k))P_L(p)$:

$$P_{\mathrm{dm}}(k) = P_{\mathrm{nw,L}}(k) + P_{\mathrm{nw,SPT,1-loop}}(k) + \alpha_{\mathrm{SPT,1-loop,IR}}(k)k^2 P_{\mathrm{nw,L}}(k)$$
$$+ e^{-k^2\Sigma^2}\Big(\Delta P_{\mathrm{w,SPT,1-loop}}(k) + \left(1 + (\alpha_{\mathrm{SPT,1-loop,IR}} + \Sigma^2)k^2\right) \Delta P_{\mathrm{w,L}}(k) \Big).$$

Alternative derivation in: [Baldauf et al, 2015]

Wiggle residuals in our schemes: BAO



Wiggles for halos in redshift rpace

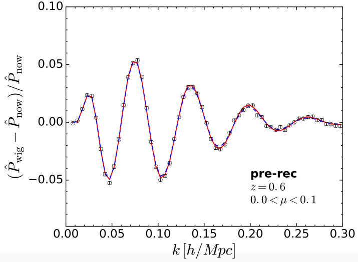
$$P(\boldsymbol{k}) = \int_q e^{-i\boldsymbol{q}\cdot\boldsymbol{k}}\Big(1 - \text{bias}\Big)\exp\left(-\frac{1}{2}A^s(\boldsymbol{k},\boldsymbol{q})\right)\Bigg|_{\lambda_1=\lambda_2=0} + \text{h.o.} + \text{“stochastic”},$$

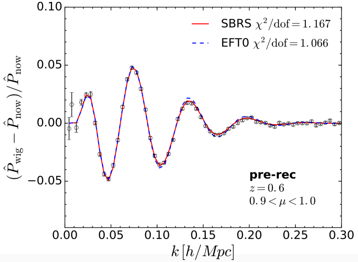
where we e.g. $A^s(\boldsymbol{k},\boldsymbol{q}) = \left\langle \Big(\lambda_1\delta_L(\boldsymbol{q}_1) + \lambda_2\delta_L(\boldsymbol{q}_2) + \boldsymbol{k}\cdot\Delta^s(\boldsymbol{q})\Big)^2 \right\rangle_c$, gives [Ding, Seo, et. al., '17]

$$\delta P(k,\nu) = e^{-k^2(1+f(2+f)\nu^2)\Sigma^2(q_{\max})}\left(b_1^2 + 2fb_1\nu^2 + f^2\nu^4 + b_\partial\left(b_1 + f\nu^2\right)\frac{k^2}{k_L^2}\right)\delta P_L(k,\tau) + \text{h.o.}$$

where $q_{\max}$ implicitly given by $\frac{\partial}{\partial q}\left[\Big(1 - i\hat{c}_q(\partial_{\lambda_1} + \partial_{\lambda_2}) - \hat{c}_q^2\partial_{\lambda_1}\partial_{\lambda_2}\Big)\delta\mathcal{A}^s(\boldsymbol{k},\boldsymbol{q})\right]_{\substack{\lambda_1=\lambda_2=0\\ q=q_{\max}}} = 0.$

depends on k,ν as well as bias parameters $c_\delta, c_{\partial^2\delta}, \ldots$ simplest $\Sigma^2 = \int \frac{dp}{3\pi^2}(1 - j_0(qk))P_L(p)$.

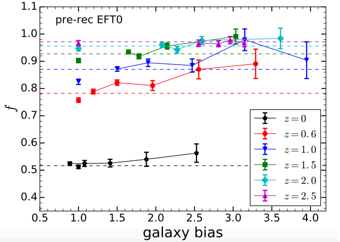


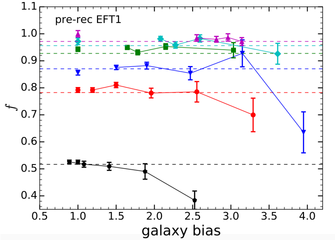


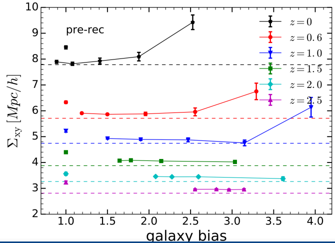
Wiggles for halos in redshift rpace

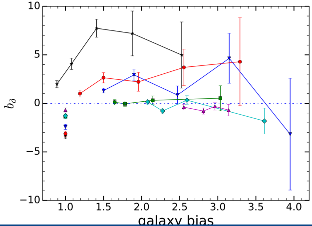
	Pre-reconstruction
EFT0 model	Free: $\alpha_{\perp}, \alpha_{\parallel}, f, b_1, b_{\partial}$ Fixed: $\Sigma_{xy}, \Sigma_z (= (1+f_{\rm fid})\Sigma_{xy})$. For matter, $b_1 = 1$.
EFT1 model	Free: $\alpha_{\perp}, \alpha_{\parallel}, \Sigma_{xy}, f, b_1, b_{\partial}$. Note* $\Sigma_z = (1+f_{\rm fid})\Sigma_{xy}$ Fixed: for matter, $b_1 = 1$.

Preliminary results:









Beyond the EdS-like approximations

standard Eularian fluid solution: [Fasiello& Z.V. 2016]

$$\delta(\boldsymbol{k}, a) = \sum_n F_n(\boldsymbol{q}_1..\boldsymbol{q}_n, a)\delta_L(\boldsymbol{q}_1, a)\dots\delta_L(\boldsymbol{q}_n, a)$$

$$\theta(\boldsymbol{k}, a) = \sum_n G_n(\boldsymbol{q}_1..\boldsymbol{q}_n, a)\delta_L(\boldsymbol{q}_1, a)\dots\delta_L(\boldsymbol{q}_n, a)$$

where:

$$F_n(\eta) = \int_{-\infty}^{\eta} d\tilde{\eta} \left\{ e^{(n-1)(\tilde{\eta}-\eta)} \frac{\tilde{f}_+}{\tilde{f}_+ - \tilde{f}_-} \left[\left(\tilde{h}_\beta^{(n)} - \frac{\tilde{f}_-}{\tilde{f}_+} \tilde{h}_\alpha^{(n)} \right) + e^{\tilde{\eta}-\eta} \frac{D_-(\eta)}{\tilde{D}_-(\eta)} \left(\tilde{h}_\alpha^{(n)} - \tilde{h}_\beta^{(n)} \right) \right] \right\}$$

similar for G_n, D_+ is linear growth rate and f_+ logarithmic growth rate.

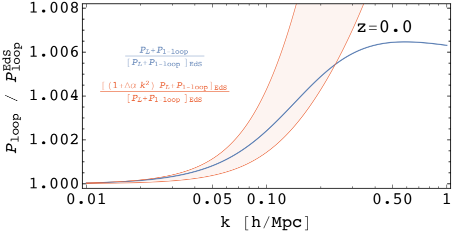
- integral and differential formulation: [Bernardeau, 1994]

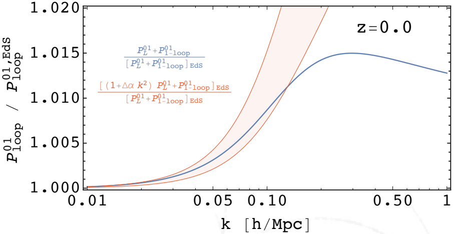
$$F_n(\boldsymbol{q}_1..\boldsymbol{q}_n, a) = \sum_i I_i(a)\mathcal{F}_i(\boldsymbol{q}_1..\boldsymbol{q}_n).$$

[Schmittfull, Z.V., McDonald 2016]

Beyond the EdS-like approximations

$$P_{1-\text{loop}} = P_{\text{lin}} + P_{22} + 2P_{13} + P_{\text{c.t.}} \qquad \text{and} \qquad P_{01} = \frac{dP_{00}}{d\ln a}$$





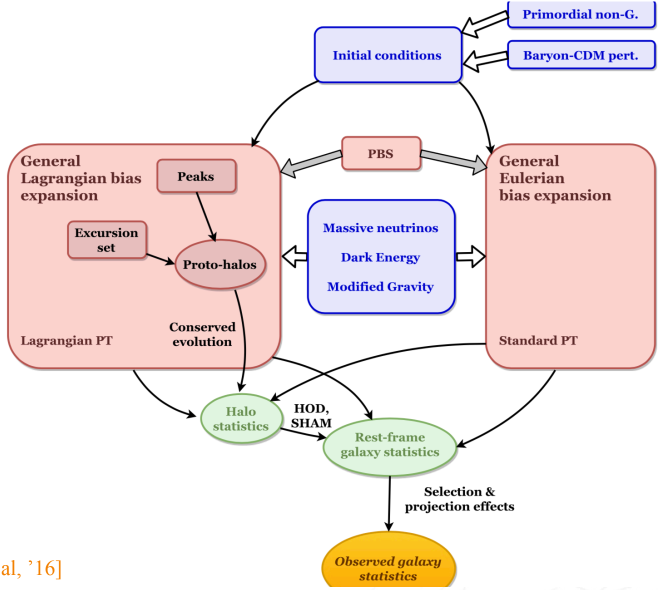
- important for RSD! [Fasiello&Z.V. 2016, de la Bella et al 2017]
- biasing models of galaxy clustering (brake some of the degeneracies?)
- sensitive to different dark energy models - quintessence!

Summary

Key points:

- After Planck, Large Scale Structure offers a new powerful window into new physics of our universe.
- New approaches to describe Large Scale Structures are being developed: also many applications for astrophysics.
- Many analytical techniques come from particle physics.
- Nonlinear scales are crucial - many more modes.
- Impact on understanding of primordial cosmology, neutrinos, dark energy.

Summary of LSS



[Desjacques et al, ’16]