Neutrino masses from cosmological perturbation theory

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Outline

1. Large scale structure of the Universe
   - Power spectrum
   - Redshift space distortions
   - Alcock-Paczynski effect
   - Bispectrum
2. Theoretical model
   - Cosmological perturbation theory
   - IR-resummation
   - Non-linear galaxy bias
   - Effective field theory approach
3. Euclid specification and methodology
4. Results

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Current status of neutrino mass constraints

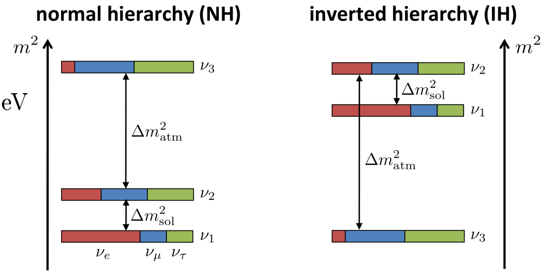
Direct searches

$m_{\nu_e} < 2\,\text{eV}$ Troitsk nu-mass

Cosmological constraints

$\sum m_\nu < 0.24\,\text{eV}$ Planck
$\sum m_\nu < 0.12\,\text{eV}$ Planck+BAO
$\sum m_\nu < 0.12\,\text{eV}$ Planck+Lyα

$\sum m_\nu > 0.06\,\text{eV}$



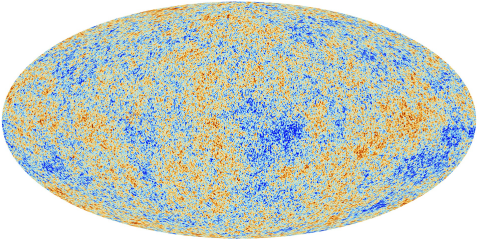
$\sum m_\nu > 0.1\,\text{eV}$

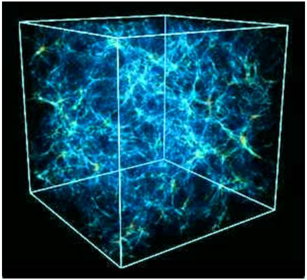
CMB vs LSS

$$\sigma \sim \frac{1}{\sqrt{N}}$$

$$N_{\mathrm{CMB}} \sim l_{\mathrm{max}}^2 \sim 10^7$$

$$N_{\mathrm{LSS}} \sim \left(\frac{\lambda_{\mathrm{max}}}{\lambda_{\mathrm{min}}}\right)^3 \sim 10^9$$



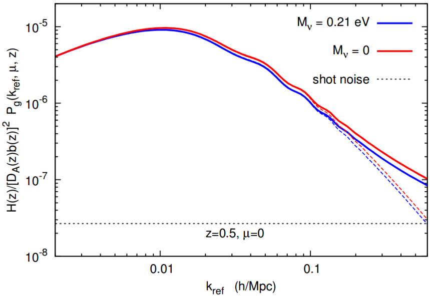


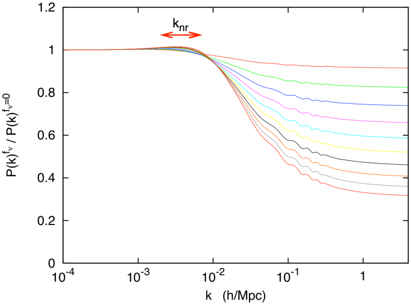
$$\delta_{cb} \equiv \frac{\Omega_c \delta_c + \Omega_b \delta_b}{\Omega_c + \Omega_b}$$

$$\Downarrow$$

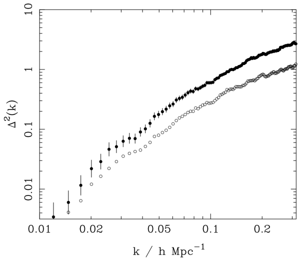
$$\langle \delta_{cb}(\mathbf{k_1}) \delta_{cb}(\mathbf{k_2}) \rangle = (2\pi)^3 \, \delta(\mathbf{k}_1 + \mathbf{k}_2) P_{cb}(k)$$

$$\frac{P_{cb}^{\rm lin}(k, z=0)^{m_\nu \neq 0}}{P_{cb}^{\rm lin}(k, z=0)^{m_\nu = 0}} \approx 1 - 6 \frac{\Omega_\nu}{\Omega_m} \, .$$





$$\delta_g(\vec{x},t) = \sum_O b_O(t) O(\vec{x},t)$$



Shape dependencies of $O(\vec{x},t)$ are driven by

- Equivalence principle
- Rotation symmetry

$$\delta_g = b_1\delta_c + \frac{b_2}{2}\delta_c^2 + \frac{b_{\mathcal{G}_2}}{2}((\partial_i\partial_j\Phi)^2 - (\Delta\Phi)^2) + ...$$

Redshift space

$\mathcal{H} = aH \qquad f = \ln D_+ / \ln a \qquad \delta_L = D_+ \delta_0 \qquad \mu \equiv k_z / k$

$\vec{v}$

line-of-sight

$z = \mathcal{H} r + v_z$

$$\mathbf{r} \to \mathbf{s} + \hat{\mathbf{z}} \frac{v_z}{\mathcal{H}}$$

$$\delta_{\mathbf{k}} \to \delta_{\mathbf{k}}^{(s)} (1 + f\mu^2)$$

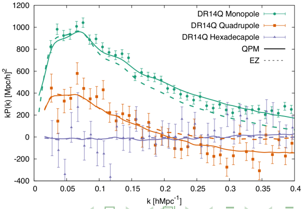
Kaiser effect

$$P_g(k) \to P_g^{(s)}(k) = P_g(k) \left(1 + \frac{f}{b_1}\mu^2\right)^2 = \sum_{\ell=0}^{\infty} P_\ell(k) L_\ell(\mu)$$

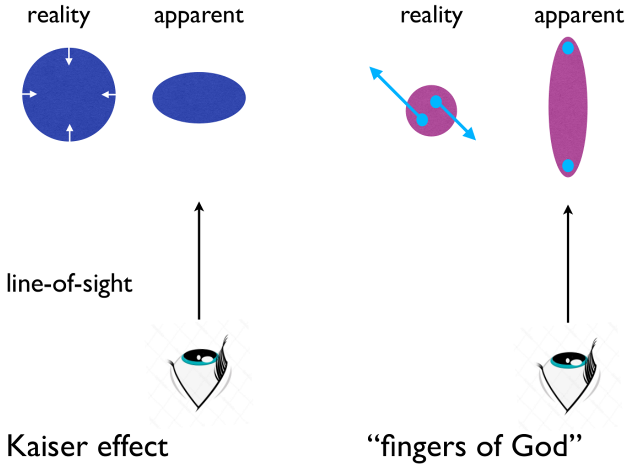
$$P_{0,g}(k) = \left[1 + \frac{2}{3}\frac{f}{b_1} + \frac{1}{5}\left(\frac{f}{b_1}\right)^2\right] P_g(k)$$

$$P_{2,g}(k) = \left[\frac{4}{3}\frac{f}{b_1} + \frac{4}{7}\left(\frac{f}{b_1}\right)^2\right] P_g(k)$$

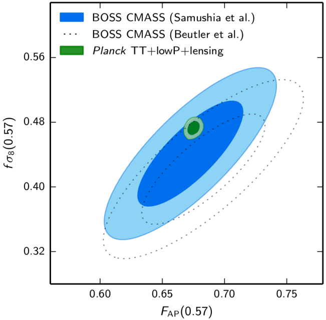
$$P_{4,g}(k) = \left[\frac{8}{35}\left(\frac{f}{b_1}\right)^2\right] P_g(k)$$



Redshift space distortions



$$P_{obs}(k_{obs},\mu_{obs}) = P_g(k_{true},\mu_{true}) \cdot \frac{D^2_{A,\mathrm{obs}} H_{\mathrm{true}}}{D^2_{A,\mathrm{true}} H_{\mathrm{obs}}}$$



$$k^2_{\mathrm{true}} = k^2_{\mathrm{obs}} \left[\left(\frac{H_{\mathrm{true}}}{H_{\mathrm{obs}}} \right)^2 \mu^2_{\mathrm{obs}} + \left(\frac{D_{A,\mathrm{obs}}}{D_{A,\mathrm{true}}} \right)^2 (1-\mu^2_{\mathrm{obs}}) \right]$$

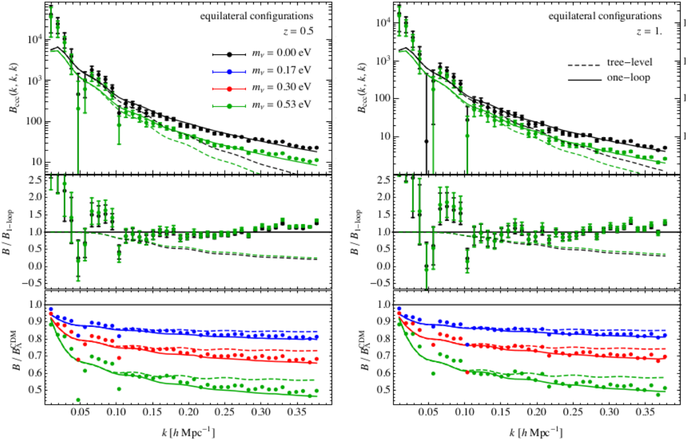
$$\mu^2_{\mathrm{true}} = \left(\frac{H_{\mathrm{true}}}{H_{\mathrm{obs}}} \right)^2 \mu^2_{\mathrm{obs}} \left[\left(\frac{H_{\mathrm{true}}}{H_{\mathrm{obs}}} \right)^2 \mu^2_{\mathrm{obs}} + \left(\frac{D_{A,\mathrm{obs}}}{D_{A,\mathrm{true}}} \right)^2 (1-\mu^2_{\mathrm{obs}}) \right]^{-1}$$

$$\Downarrow$$

$$P_{\ell,\mathrm{AP}}(k) = \frac{2\ell+1}{2} \int_{-1}^{1} d\mu_{obs}\, P_{obs}(k_{obs},\mu_{obs}) \cdot L_\ell(\mu_{obs})$$

$$\langle \delta_{cb}(\mathbf{k}_1)\delta_{cb}(\mathbf{k}_2)\delta_{cb}(\mathbf{k}_3)\rangle = (2\pi)^3\, \delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) B_{cb}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

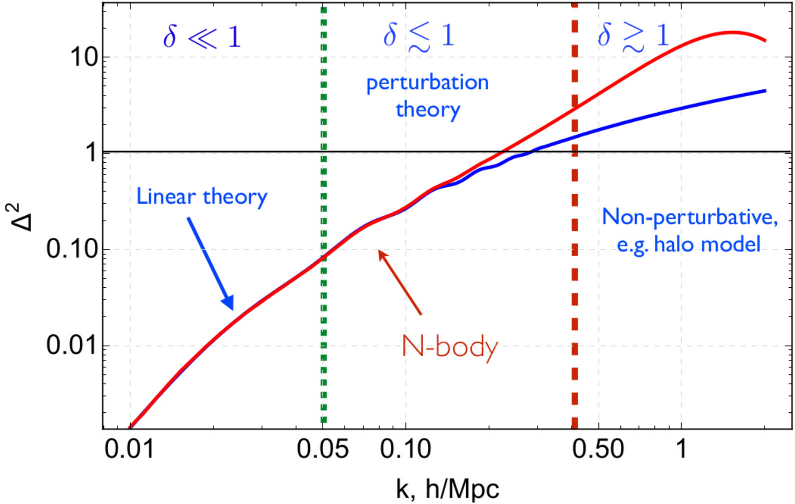
$$\frac{B^{\rm lin}_{cb}(k,k,k)^{m_\nu\neq 0}}{B^{\rm lin}_{cb}(k,k,k)^{m_\nu=0}} \approx 1 - 12\frac{\Omega_\nu}{\Omega_m}\,.$$



Outline

Non-linearities

$$\Delta^2 = \frac{k^3}{2\pi^2} P(k)$$



Eulerian standard cosmological perturbation theory

$$\theta \equiv -\nabla \mathbf{v}/(f\mathcal{H})$$

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

$$\nabla^2\Phi = 4\pi G a^2 \bar{\rho}\delta$$

ЛО: $\theta = -f\delta$

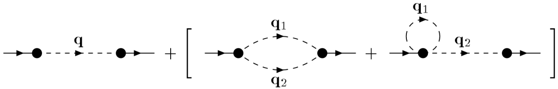
Standard perturbation theory

$$\delta(\mathbf{q}) = \sum_n \int F_n(\mathbf{q}_1, ..., \mathbf{q}_n)\delta_L(\mathbf{q}_1)...\delta_L(\mathbf{q}_n), \quad \theta(\mathbf{q}) = \sum_n \int G_n(\mathbf{q}_1, ..., \mathbf{q}_n)\delta_L(\mathbf{q}_1)...\delta_L(\mathbf{q}_n)$$

$$Z[J] = \mathcal{N}^{-1} \int \mathcal{D}\delta_0 \exp\left\{-\frac{\delta_0^2}{2P_0} + J\cdot\delta_t\right\}$$

$\delta_0 \to \delta_{NL}, \mathbf{v}_{NL}$

$$P_{1-\text{loop}} = P_{\text{lin}}(k) + \int_0^\infty d^3q_1 P_{\text{lin}}(q_1,t) \int_0^\infty d^3q_2 P_{\text{lin}}(q_2,t) \left[2F_2^2(\mathbf{q}_1,\mathbf{q}_2) + 6F_3(\mathbf{q}_1,-\mathbf{q}_1,\mathbf{q}_2)\right] =$$



Time-sliced perturbation theory

$$\partial_t \mathcal{P} + \frac{\partial}{\partial \delta}\left(\dot{\delta}\mathcal{P}\right) = 0$$

$$\mathcal{P}[\delta]|_{t=0} = \mathcal{N}^{-1} \exp\left[-\frac{1}{2}\int \frac{\delta_0(k)\delta_0(-k)}{P(k,t_0)}\right]$$

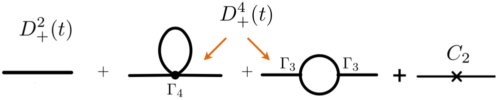
Probability distribution function

$$\mathcal{P}(\delta, t) = \mathcal{N}^{-1} \exp\left\{-\sum_{n=1} \frac{1}{n!}\int [dq]^n \Gamma_n(t, \{q_j\})\delta^n\right\}$$

$$Z[J] = \mathcal{N}^{-1}\int \mathcal{D}\delta_t \mathcal{P}[\delta_t] \exp\{J\cdot\delta_t\}$$

$$\mathcal{P}[\delta_0] \to \mathcal{P}[\delta_{NL}, \mathbf{v}_{NL}, \ldots]$$

$P_{1-\text{loop}} =$



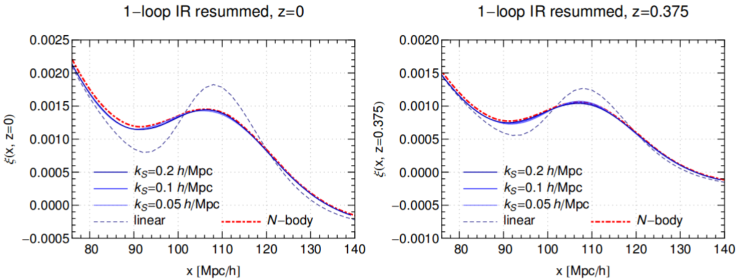
IR-resummation: real space

$$P_{\text{lin}} = P_{nw}(k) + P_w(k)$$

$$P_{\text{lin}}(k) \to P_{\text{nw}}(k) + e^{-k^2\Sigma^2} P_{\text{w}}(k)$$

$$\Sigma^2 \equiv \frac{4\pi}{3}\int_0^{k_S} dq P_{\text{nw}}(q)\left[1 - j_0\left(\frac{q}{k_{osc}}\right) + 2j_2\left(\frac{q}{k_{osc}}\right)\right]$$

$$\boxed{P_g(k) \to P_{\text{nw}}(k) + e^{-k^2\Sigma^2} P_{\text{w}}(k)(1 + k^2\Sigma^2) + P_{\text{1-loop}}[P_{\text{nw}} + e^{-k^2\Sigma^2} P_{\text{w}}]}$$

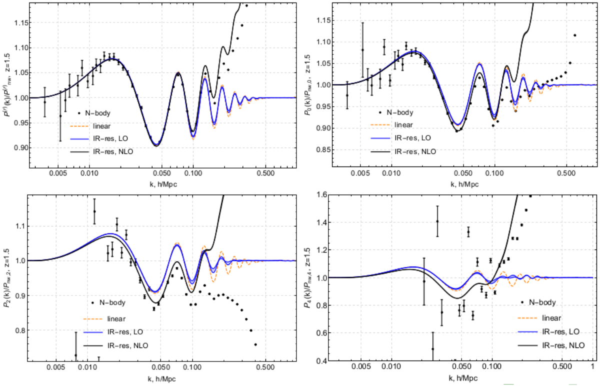


IR-resummation: redshift space

$$P_{\text{lin}}(k,\mu) \to P_{\text{nw}}(k) + e^{-k^2\Sigma^2_{\text{tot}}(\mu)} P_{\text{w}}(k)$$

$$\Sigma^2_{\text{tot}}(\mu) = (1 + f\mu^2(2+f))\Sigma^2 + f^2\mu^2(\mu^2-1)4\pi \int_0^{k_S} dq P_{\text{nw}}(q) j_2\left(\frac{q}{k_{osc}}\right)$$

$$P_g \to P_{\text{nw}}(k,\mu) + P_{\text{nw, 1-loop}}(k,\mu) + e^{-k^2\Sigma^2_{\text{tot}}} P_{\text{w}}(k,\mu)(1 + k^2\Sigma^2_{\text{tot}}(\mu)) + e^{-k^2\Sigma^2_{\text{tot}}(\mu)} P_{\text{w, 1-loop}}(k,\mu)$$



Non-linear galaxy bias

$$\delta_g = b_1\delta_{\rm cb} + \frac{b_2}{2}\delta_{\rm cb}^2 + b_{\mathcal{G}_2}\mathcal{G}_2 + b_{\Gamma_3}\Gamma_3 - R_*^2 k^2 \delta_{\rm cb} + \varepsilon$$

$$\mathcal{G}_2(\Phi) \equiv (\partial_i\partial_j\Phi)^2 - (\partial^2\Phi)^2$$
$$\Gamma_3(\Phi,\Phi_v) \equiv \mathcal{G}_2(\Phi) - \mathcal{G}_2(\Phi_v)$$

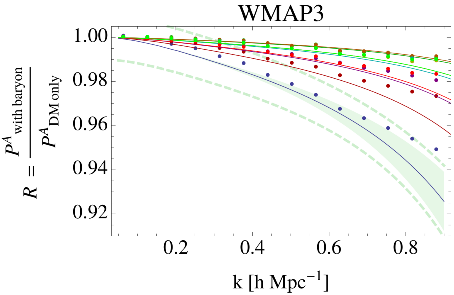
$$\begin{aligned}
P_{0,g}(k) =& P^{\rm tree}_{0,\theta\theta}(k) + P^{\rm 1\text{-}loop}_{0,\theta\theta}(k) + b_1(P^{\rm tree}_{0,\theta\delta}(k) + P^{\rm 1\text{-}loop}_{0,\theta\delta}(k)) + b_1^2(P^{\rm tree}_{0,\delta\delta}(k) + P^{\rm 1\text{-}loop}_{0,\delta\delta}(k)) \\
&+ 0.25 b_2^2 \mathcal{I}_{\delta^2\delta^2}(k) + b_1 b_2 \mathcal{I}_{0,\delta\delta^2}(k) + b_2 \mathcal{I}_{0,\theta\delta^2}(k) + b_1 b_{\mathcal{G}_2}\mathcal{I}_{0,\delta\mathcal{G}_2}(k) + b_{\mathcal{G}_2}\mathcal{I}_{0,\theta\mathcal{G}_2}(k) \\
&+ b_2 b_{\mathcal{G}_2}\mathcal{I}_{\delta^2\mathcal{G}_2}(k) + b_{\mathcal{G}_2}^2\mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(k) + (2b_{\mathcal{G}_2} + 0.8 b_{\Gamma_3})(b_1\mathcal{F}_{0,\delta\mathcal{G}_2}(k) + \mathcal{F}_{0,\theta\mathcal{G}_2}(k)) \\
&+ c_0 P_{0,\nabla^2\delta}(k) + P_{\rm shot}\,, \\
P_{2,g}(k) =& P^{\rm tree}_{2,\theta\theta}(k) + P^{\rm 1\text{-}loop}_{2,\theta\theta}(k) + b_1(P^{\rm tree}_{2,\theta\delta}(k) + P^{\rm 1\text{-}loop}_{2,\theta\delta}(k)) + b_1^2 P^{\rm 1\text{-}loop}_{2,\delta\delta}(k) \\
&+ b_1 b_2 \mathcal{I}_{2,\delta\delta^2}(k) + b_2\mathcal{I}_{2,\theta\delta^2}(k) + b_1 b_{\mathcal{G}_2}\mathcal{I}_{2,\delta\mathcal{G}_2}(k) + b_{\mathcal{G}_2}\mathcal{I}_{2,\theta\mathcal{G}_2}(k) \\
&+ (2b_{\mathcal{G}_2} + 0.8 b_{\Gamma_3})\mathcal{F}_{2,\theta\mathcal{G}_2}(k) + c_2 P_{2,\nabla^2\delta}(k) \\
P_{4,g}(k) =& P^{\rm tree}_{4,\theta\theta}(k) + P^{\rm 1\text{-}loop}_{4,\theta\theta}(k) + b_1 P^{\rm 1\text{-}loop}_{4,\theta\delta}(k) + b_1^2 P^{\rm 1\text{-}loop}_{4,\delta\delta}(k) \\
&+ b_2\mathcal{I}_{4,\theta\delta^2}(k) + b_{\mathcal{G}_2}\mathcal{I}_{4,\theta\mathcal{G}_2}(k) + c_4 P_{4,\nabla^2\delta}(k)\,,
\end{aligned}$$

Effective field theory approach

$$\boxed{P_{\ell,g} \to P_{\ell,g} + c_\ell P_{\ell,\nabla^2\delta}}$$

$$P_{\ell,\nabla^2\delta} = -2k^2 \cdot \int_{-1}^{1} d\mu L_\ell(\mu) P_{\rm lin}(k,\mu)\,, \qquad \ell = 0,2,4$$

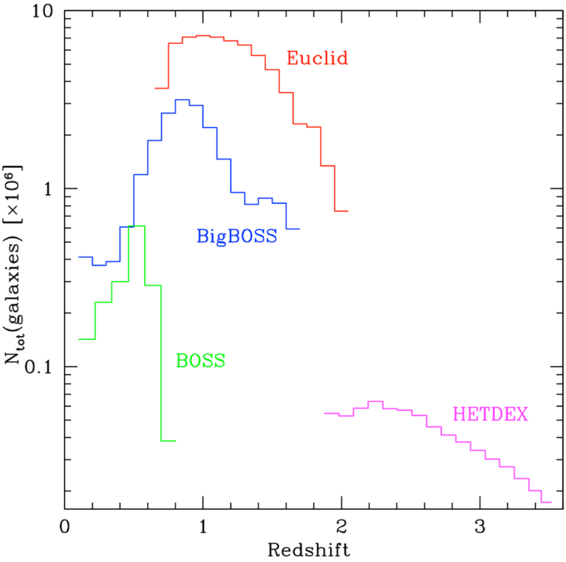
- Inaccuracy of integration over infinite momentum in perturbation theory loop integrals
- Beyond the perfect-fluid approximation: shell-crossing and virialization
- Fingers of the God effect
- Velocity bias
- Baryonic feedback



- Non-linearity in the neutrino fluid

Outline

Laureijs et al., 2011



Statistical error $k \in [0.01, 1] \cdot h\,\mathrm{Mpc}^{-1}$ $N_k = 40$

Pozzetti et al., 2016

$\bar{z}$	$V(\bar{z})$	$n_g(\bar{z})$	$V_{\rm eff}(\bar{z})$
0.6	4.58	3.83	4
0.8	6.44	2.08	4.98
1.0	8.01	1.18	5.09
1.2	9.23	0.7	4.37
1.4	10.15	0.39	2.98
1.6	10.81	0.21	1.55
1.8	11.25	0.12	0.68
2.0	11.53	0.07	0.28

$$C_{kk'}^{(\ell\ell')} = \frac{(2\pi)^3}{V(z)} \frac{(2\ell+1)(2\ell'+1)}{2\pi k^3 d\ln k} \int_{-1}^{1} d\mu\, L_\ell(\mu) L_{\ell'}(\mu) P_{\ell,g}(k,z) P_{\ell',g}(k',z) \delta_{kk'} \,.$$

$$V_{\rm eff}(\bar{z}) \approx V(\bar{z}) \left[\frac{\bar{n}_g(\bar{z}) b_1^2(\bar{z}) P_{\rm lin}(k,\bar{z})}{1 + \bar{n}_g(\bar{z}) b_1^2(\bar{z}) P_{\rm lin}(k,\bar{z})} \right]^2 \Bigg|_{k=0.1\,h\,\mathrm{Mpc}^{-1}} .$$

Theoretical error: power spectrum $k \in [0.01, 1] \cdot h\,\mathrm{Mpc}^{-1}$ $N_k = 40$

Baldauf, Mirbabayi, Simonović, Zaldarriaga, 2016

$$(C_e)^{(\ell\ell')}_{kk'} = E_{\ell,p}(k,z) E_{\ell',p}(k',z) \exp\left\{ -\frac{(k-k')^2}{2\Delta k^2} \right\}$$

$\Delta k = 0.1 \cdot h\,\mathrm{Mpc}^{-1}$

$k_{\mathrm{bin}} \ll \Delta k$

$$E_{\ell,p}(k,z) = D_+^4(z) P^{\mathrm{tree}}_{\ell,g}(k,z) \left(\frac{k}{0.45\, h\mathrm{Mpc}^{-1}} \right)^{3.3} \qquad \ell = 0, 2$$

$$E_{4,p}(k,z) = D_+^4(z) P^{\text{1-loop}}_{4,g}(k,z) \left(\frac{k}{0.45\, h\mathrm{Mpc}^{-1}} \right)^{3.3}$$

$$E_{\ell,p}(k,z) = (k f D_+(z) \sigma_v)^4 \left(\ell + \frac{1}{2} \right) \int_{-1}^{1} d\mu\, \mu^4\, P_g^{\mathrm{tree}}(k,\mu,z) L_\ell(\mu)$$

$$-2 \ln \mathcal{L}_P = \sum_{a=1}^{N_z} \sum_{\ell,\ell'=0,2,4} \sum_{i,j=1}^{N_k} (P_\ell^{\mathrm{theory}}(k_j,z_a) - P_\ell^{\mathrm{data}}(k_j,z_a))$$
$$\times (C^{(\ell\ell')}_{k_i k_j}(z_a) + (C_e)^{(\ell\ell')}_{k_i k_j}(z_a))^{-1} (P_{\ell'}^{\mathrm{theory}}(k_i,z_a) - P_{\ell'}^{\mathrm{data}}(k_i,z_a))\,.$$

$$B_g(k_1,k_2,k_3) = [F_2^{(b)}(\mathbf{k}_1,\mathbf{k}_2) b_1^2 P_{\rm lin}(k_1) P_{\rm lin}(k_2) + \text{cycl.}] + P_{\rm shot} \sum_{a=1}^{3} b_1^2 P_{\rm lin}(k_a) + B_{\rm shot}$$

$$F_2^{(b)}(\mathbf{k}_1,\mathbf{k}_2) = \frac{b_2}{2} + b_{\mathcal{G}_2}\left(\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2 k_2^2} - 1\right) + b_1 F_2(\mathbf{k}_1,\mathbf{k}_2)\,,$$

$$F_2(\mathbf{k}_1,\mathbf{k}_2) = \frac{5}{7} + \frac{1}{2}\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)}{k_1 k_2}\left(\frac{k_1}{k_2} + \frac{k_2}{k_1}\right) + \frac{2}{7}\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{k_1^2 k_2^2}$$

$$C_{TT'} = \frac{(2\pi)^3}{V(z)}\frac{\pi s_{123}}{dk_1 dk_2 dk_3}\frac{\delta_{TT'}}{k_1 k_2 k_3}\prod_{a=1}^{3}\left(b_1^2(z) P_{\rm lin}(k_a,z) + \frac{1}{\bar{n}_g(z)}\right)$$

$$C_{TT'}^{\ell=0} = \frac{(2\pi)^3}{V(z)}\frac{\pi s_{123}}{dk_1 dk_2 dk_3}\frac{\delta_{TT'}}{k_1 k_2 k_3}\frac{1}{4\pi}\int_0^{2\pi} d\phi \int_0^{\pi} d\omega\,\sin\omega \prod_{a=1}^{3}\left[P_g(k_a,\mu_a) + \frac{1}{\bar{n}_g}\right]$$

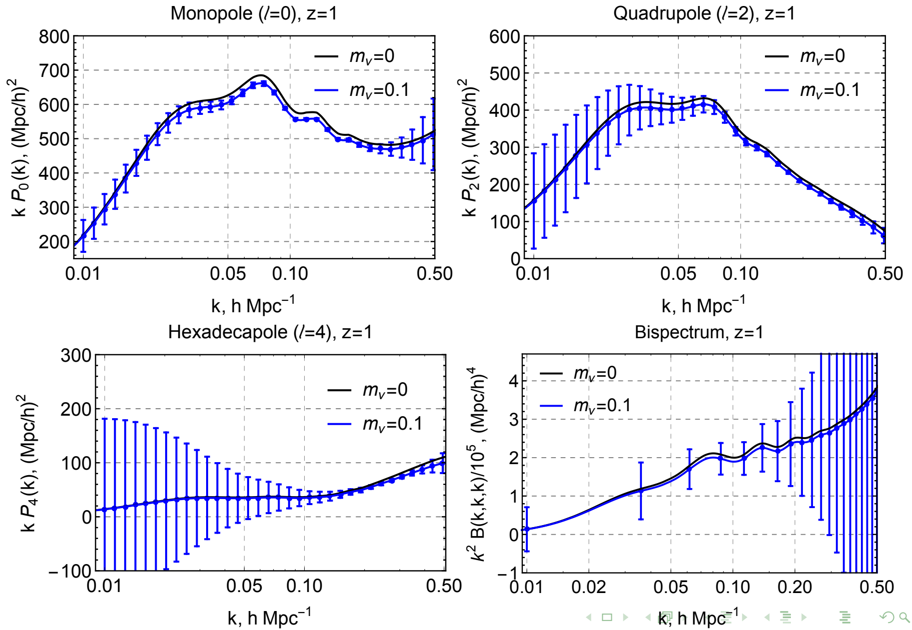
$$(C_e)_{TT'} = E_b(k_1, k_2, k_3, z) E_b(k_1', k_2', k_3', z) \prod_{a=1}^{3} \exp\left\{ -\frac{(k_a - k_a')^2}{2\Delta k^2} \right\}$$

$$E_b(k_1, k_2, k_3, z) = 3B_g^{\mathrm{tree}}(k_1, k_2, k_3, z) D_+^{2l}(z) \begin{cases} \left(\dfrac{k_t/3}{0.31\,h\mathrm{Mpc}^{-1}}\right)^{1.8} & l = 1\,, \\ \left(\dfrac{k_t/3}{0.45\,h\mathrm{Mpc}^{-1}}\right)^{3.3} & l = 2\,, \end{cases}$$

$$k_1 \le k_2 \le k_3 \qquad \sum_T \equiv \sum_{k_1=k_{\min}}^{k_{\max}} \sum_{k_2=k_{\min}}^{k_1} \sum_{k_3=k_*}^{k_2} \qquad k_* = \max(k_{\min}, k_1 - k_2)$$

$$-2\ln\mathcal{L}_B = \sum_{a=1}^{N_z} \sum_{\mathrm{triangles}\ T,T'} \left(B_T^{\mathrm{theory}}(z_a) - B_T^{\mathrm{data}}(z_a)\right) \times \left(C_{TT'}(z_a) + (C_e)_{TT'}(z_a)\right)^{-1} \left(B_{T'}^{\mathrm{theory}}(z_a) - B_{T'}^{\mathrm{data}}(z_a)\right).$$

One-loop power spectrum and tree-level monopole bispectrum



Outline

Fiducial cosmology $A_{s,\text{fid}} = 2.1 \times 10^{-9}$

Parameter	Definition	Fiducial value
h	Hubble parameter $H_0/100\,\text{km/s/Mpc}$	0.6736
ω_{cdm}	Cold dark matter density $\Omega_{cdm}h^2$	0.12
ω_b	Baryon density $\Omega_b h^2$	0.02237
$A \equiv A_s/A_{s,\text{fid}}$	Amplitude of the primordial power spectrum	1
n_s	Spectral index of the primordial power spectrum	0.9649
m_ν	Total neutrino mass	0.1 eV

$$b_1(z) = 0.9 + 0.4z \qquad b_2(z) = -0.704 - 0.208z + 0.183z^2 - 0.00771z^3$$

$$b_{\mathcal{G}_2}(z) = -\frac{2}{7}(b_1(z) - 1) \qquad b_{\Gamma_3}(z) = \frac{23}{42}(b_1(z) - 1)$$

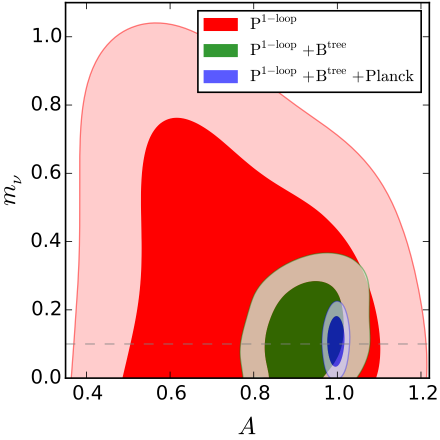
$$c_0 = c_2 = 25D_+^2(z)\,[\text{Mpc}/h]^2 \qquad c_4 = R_*^2 = 1 \times D_+^2(z)\,[\text{Mpc}/h]^2$$

$$P_{\text{shot}} = \bar{n}_g^{-1} \qquad B_{\text{shot}} = \bar{n}_g^{-2}$$

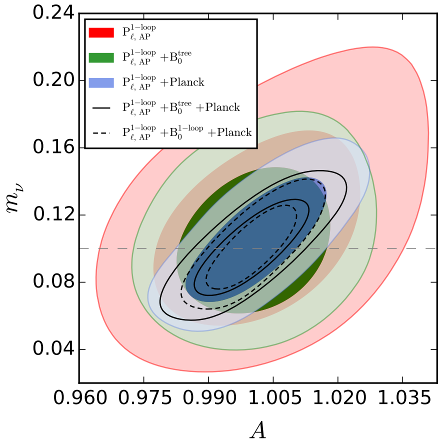
$\bar{z}$	$b_1(\bar{z})$	$b_2(\bar{z})$	$b_{\mathcal{G}_2}(\bar{z})$	$b_{\Gamma_3}(\bar{z})$	$R_*^2(\bar{z})$	$c_0(\bar{z})$	$c_2(\bar{z})$	$c_4(\bar{z})$
0.6	1.14	-0.765	-0.04	0.077	0.536	13.398	13.398	0.536
0.8	1.22	-0.757	-0.063	0.121	0.442	11.060	11.06	0.442
1.0	1.30	-0.737	-0.086	0.164	0.369	9.236	9.236	0.369
1.2	1.38	-0.703	-0.109	0.208	0.312	7.799	7.799	0.312
1.4	1.46	-0.658	-0.131	0.252	0.266	6.658	6.658	0.266
1.6	1.54	-0.600	-0.154	0.296	0.230	5.740	5.740	0.230
1.8	1.62	-0.531	-0.177	0.340	0.200	4.993	4.993	0.200
2.0	1.70	-0.450	-0.200	0.383	0.175	4.380	4.380	0.175

Markov Chain Monte Carlo: 6 cosmological and 40 nuisance parameters

$$(\omega_b, \omega_{cdm}, n_s, h, A, m_\nu) \times \prod_{i=1}^{N_z=8} (b_1^{(i)}, b_2^{(i)}, b_{\mathcal{G}_2}^{(i)}, R_*^{2(i)}, P_{\rm shot}^{(i)})$$



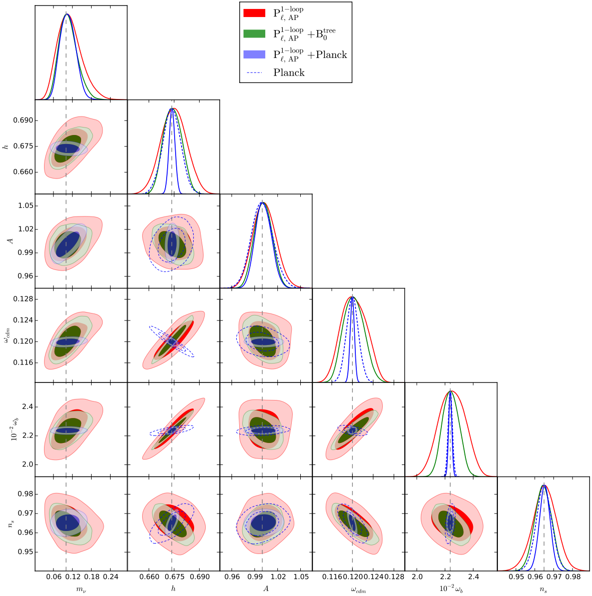
$$(\omega_b, \omega_{cdm}, n_s, h, A, m_\nu) \times \prod_{i=1}^{N_z=8} (b_1^{(i)}, b_2^{(i)}, b_{\mathcal{G}_2}^{(i)}, c_0^{(i)}, c_2^{(i)}, c_4^{(i)}, P_{\rm shot}^{(i)}, B_{\rm shot}^{(i)})$$



Final constraints

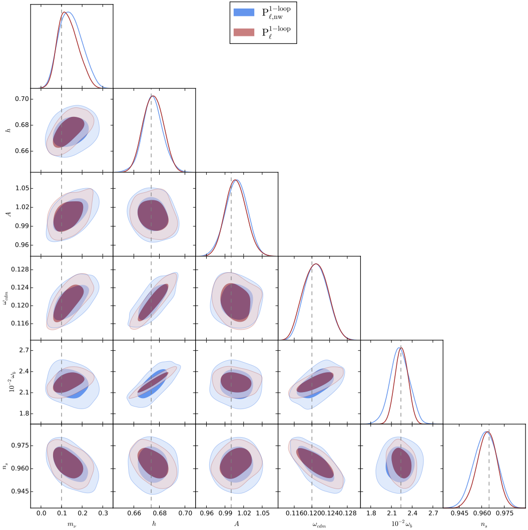
Set	$10^3\, h$	$10^2\, A$	$10^3\, \omega_{cdm}$	$10^4\, \omega_b$	$10^3\, n_s$	m_ν, meV
Planck	5.4	1.4	1.2	1.5	4.2	–
$\mathrm{P}^{\text{1-loop}}$	37.4	18.9	13.8	38.1	62.2	406
$\mathrm{P}^{\text{1-loop}}+\mathrm{B}^{\text{tree}}$	17.3	7	6.6	17.8	22	121
$\mathrm{P}^{\text{1-loop}}+\mathrm{B}^{\text{tree}}+$Planck	0.8	1.3	0.2	1.1	3	48
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{nw}}$	7.9	1.8	2.7	13.8	7.6	55
$\mathrm{P}^{\text{1-loop}}_{\ell}$	7.7	1.7	2.7	9.3	6.5	48
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{ AP}}$	7.6	1.6	2.4	9.1	6.2	38
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{ AP}}+\mathrm{B}^{\text{tree}}_0$	5.5	1.1	2	6	4.6	28
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{ AP}}+$Planck	1.8	1	0.4	1.1	2.9	24
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{ AP}}+\mathrm{B}^{\text{tree}}_0+$Planck	0.8	0.9	0.2	1.1	1.9	19
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{ AP}}+\mathrm{B}^{\text{1-loop}}_0$	4.8	0.9	1.8	5.2	3.8	23
$\mathrm{P}^{\text{1-loop}}_{\ell,\text{ AP}}+\mathrm{B}^{\text{1-loop}}_0+$Planck	0.8	0.7	0.2	1	1.7	17

Synergy of CMB and LSS



Information content of baryon acoustic oscillations

Set	$10^3\,h$	$10^2\,A$	$10^3\,\omega_c$	$10^4\,\omega_b$	$10^3\,n_s$	m_ν, meV
$P^{\text{1-loop}}_{\ell,\text{nw}}$	7.9	1.8	2.7	13.8	7.6	55
$P^{\text{1-loop}}_{\ell}$	7.7	1.7	2.7	9.3	6.5	48



Conclusions

- Complete analytical model which does not rely on any semi-analytical and phenomenological prescriptions allows to robustly and systematically address galaxy clustering on mildy non-linear scales.
- Accuracy of perturbative calculations controlled by the correlated theoretical error allows to accumulate the whole wavenumber range thus providing with additional cosmological information.
- Even under the most agnostic assumptions about the short-scale physics and galaxy bias the Euclid data alone are able to constrain the total neutrino mass with an errorbar of 28 meV. When combined with the most recent Planck likelihood this uncertainty decreases to 19 meV. Reducing the theoretical error on the bispectrum down to the two-loop level marginally tightens the bound to 17 meV.

New pipeline predicts the detection of the minimal total neutrino mass with 3.2σ (5.3σ) significance in the case of the direct (inverted) hierarchy.

Counterterm convention

$$P_{0,\nabla^2\delta}(k) = -k^2 \cdot \left(\frac{b_1^2 f^2}{3} + \frac{2b_1 f^3}{5} + \frac{f^4}{7} \right) P_{\text{lin}}(k)\,,$$

$$P_{2,\nabla^2\delta}(k) = -k^2 \cdot \left(\frac{2b_1^2 f^2}{3} + \frac{8b_1 f^3}{7} + \frac{10 f^4}{21} \right) P_{\text{lin}}(k)\,,$$

$$P_{4,\nabla^2\delta}(k) = -k^2 \cdot \frac{8f^2}{35} P_{\text{lin}}(k)\,,$$

Nuisance parameters