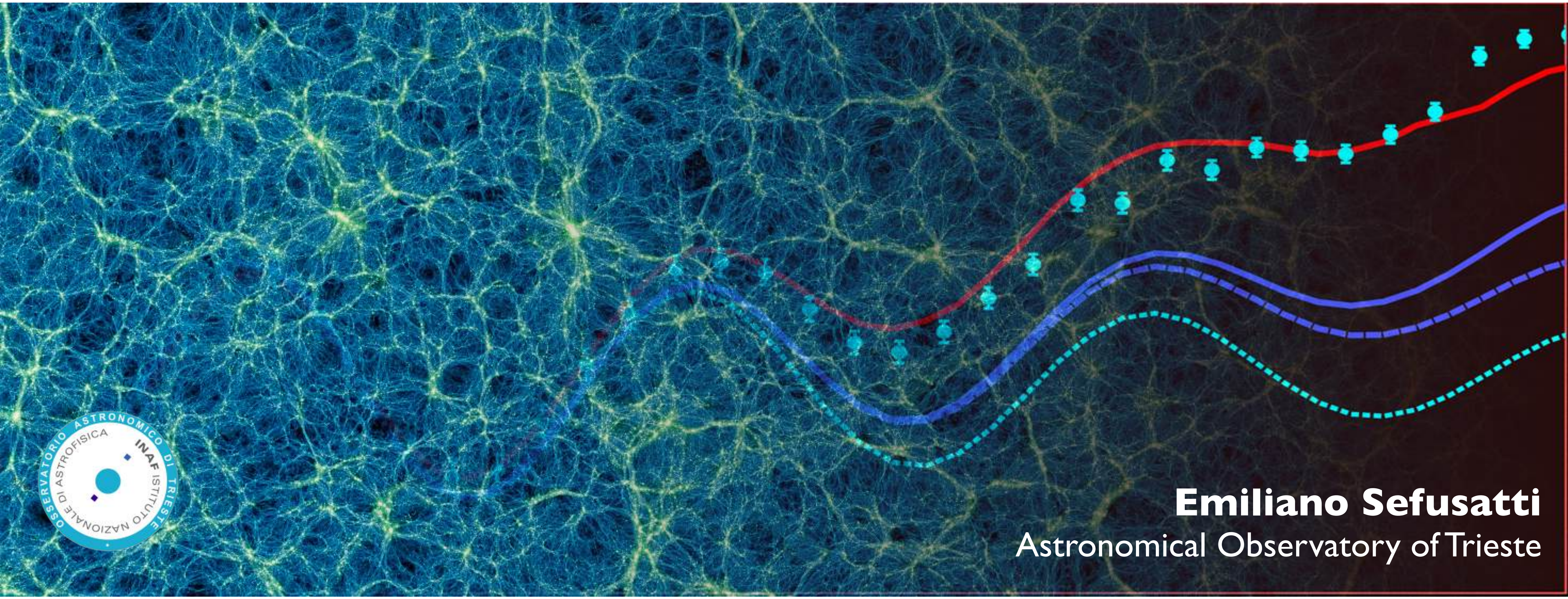
Galaxies, cosmological perturbation theory & neutrinos masses



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Astronomical Observatory of Trieste

November 27th, 2024 - Università di Genova

The Dark Universe

We do not know what constitutes much of energy content

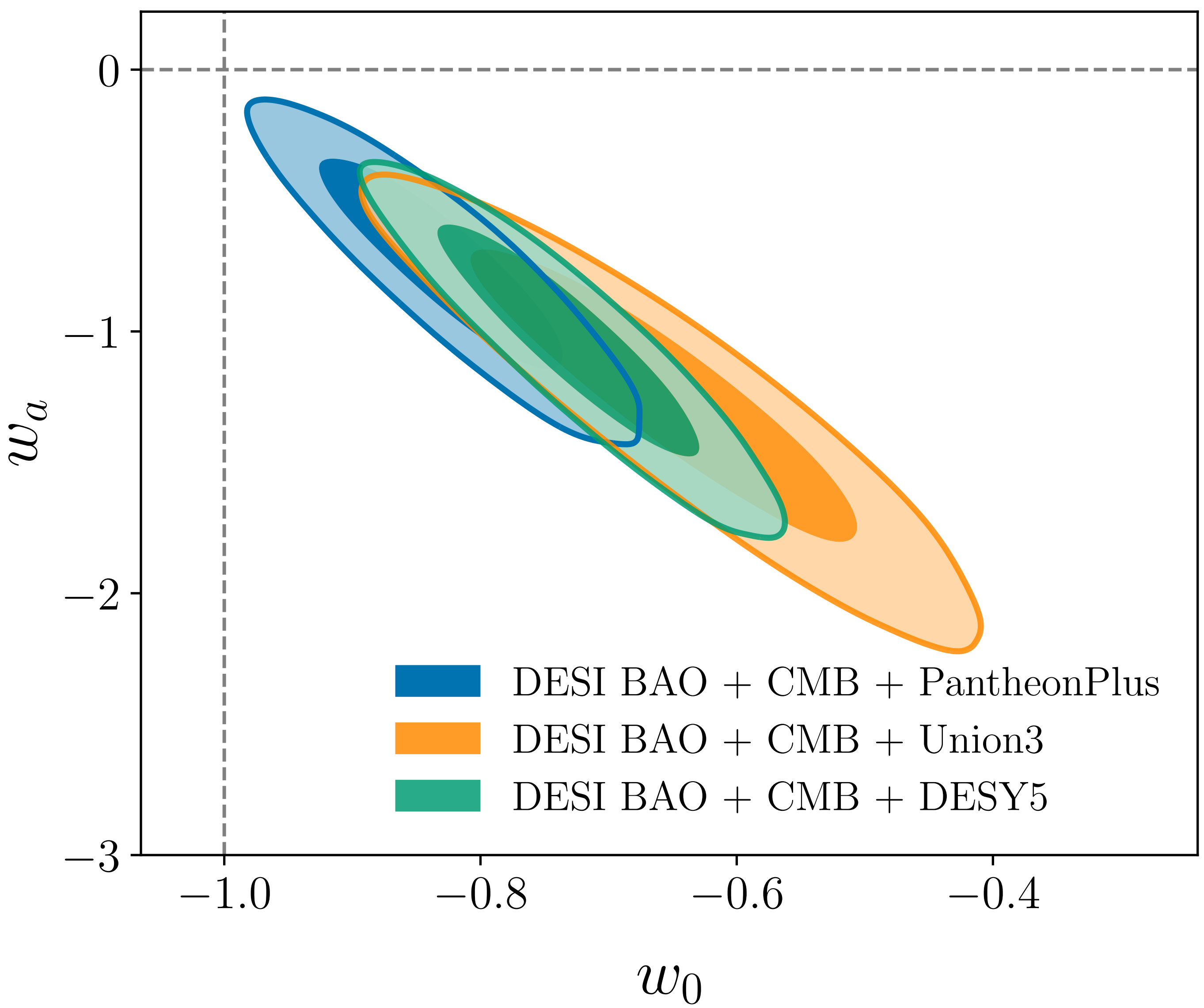
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_m + \rho_{DE}\right)$$

We look for clues on the nature of Dark Energy, its equation of state:

$$p_{DE} = w\rho_{DE}\,, \quad w = w_0 + (1-a)w_a$$

Where $w = -1$ is the standard ΛCDM cosmology

Hints of something beyond might be coming from combinations of cosmological observations …



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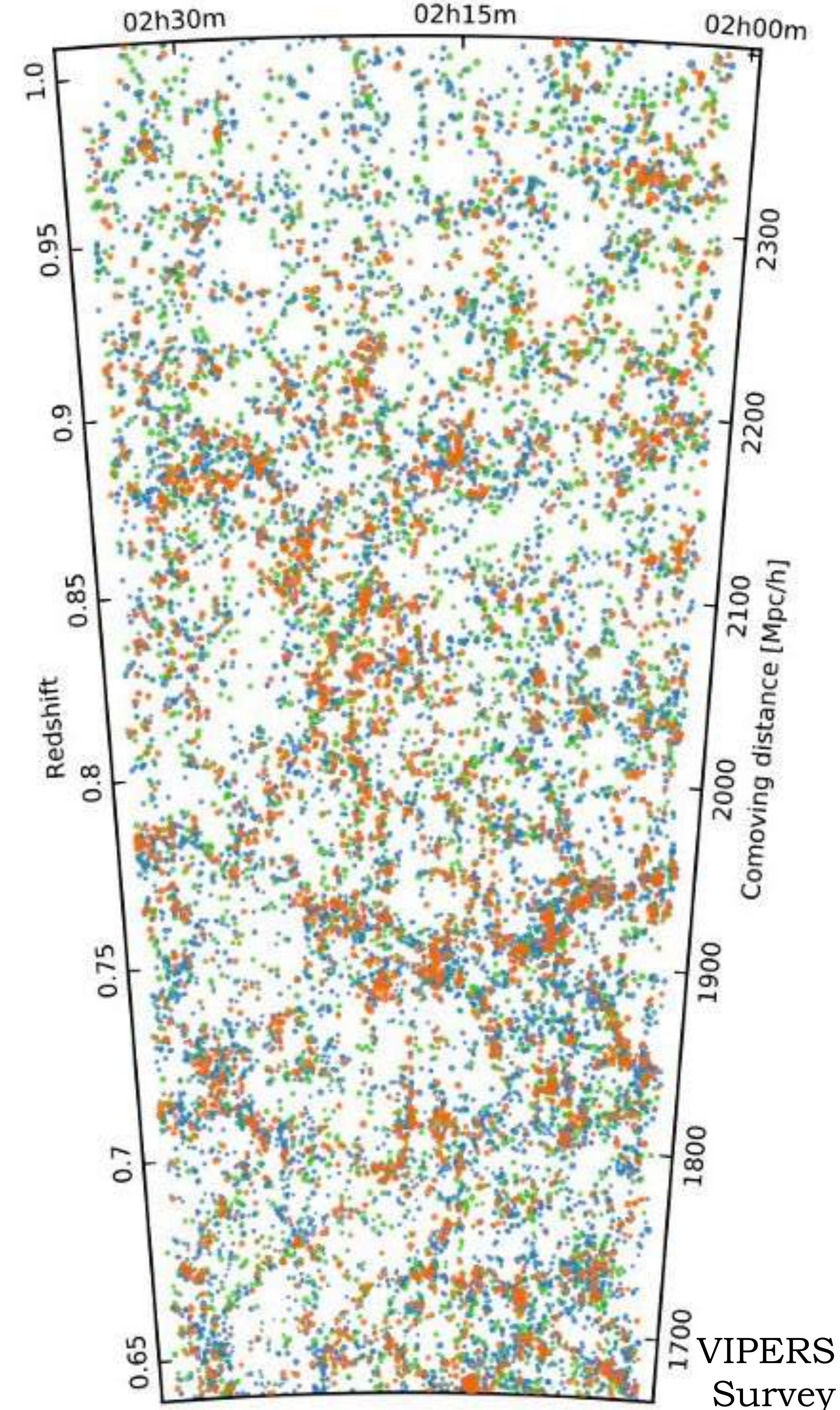
Galaxy surveys



VIPERS Survey

The galaxy 2-point correlation function

We look at perturbations in the galaxy number density

$$n_g(\vec{x}) \equiv \bar{n}_g \left[1 + \delta_g(\vec{x})\right]$$

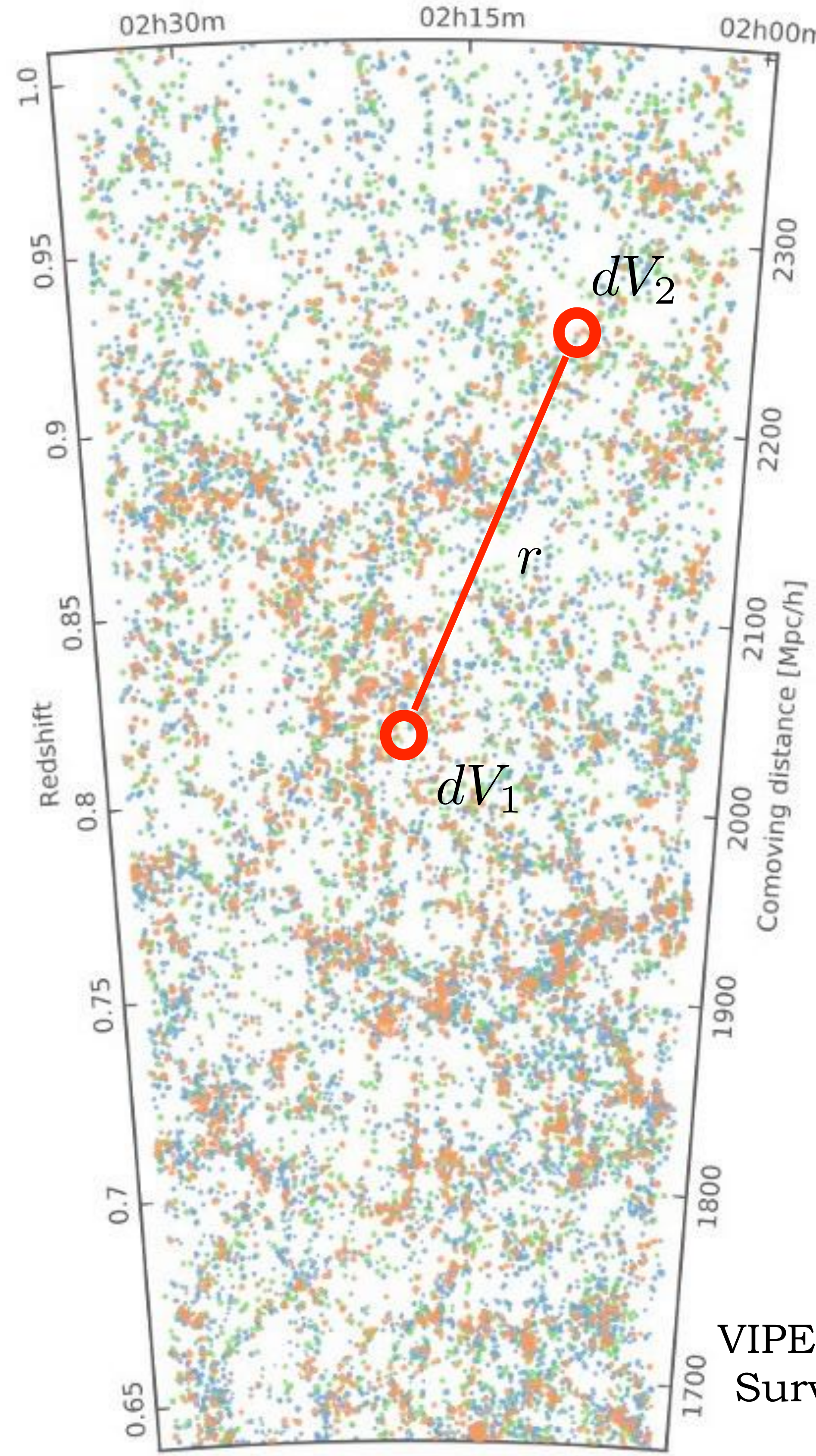
... and we measure the probability of finding two galaxies at a given separation

$$dP = dV_1 \, dV_2 \, \langle \, n_g(\vec{x}_1) \, n_g(\vec{x}_2) \, \rangle$$

$$= dV_1 \, dV_2 \, \bar{n}_g^2 \left[1 + \langle \, \delta_g(\vec{x}_1) \, \delta_g(\vec{x}_2) \, \rangle\right]$$

In fact, its *excess* probability, w.r.t. a random, uncorrelated Poisson distribution

$$\xi(|\vec{x}_1 - \vec{x}_2|) \equiv \langle \, \delta_g(\vec{x}_1) \, \delta_g(\vec{x}_2) \, \rangle$$



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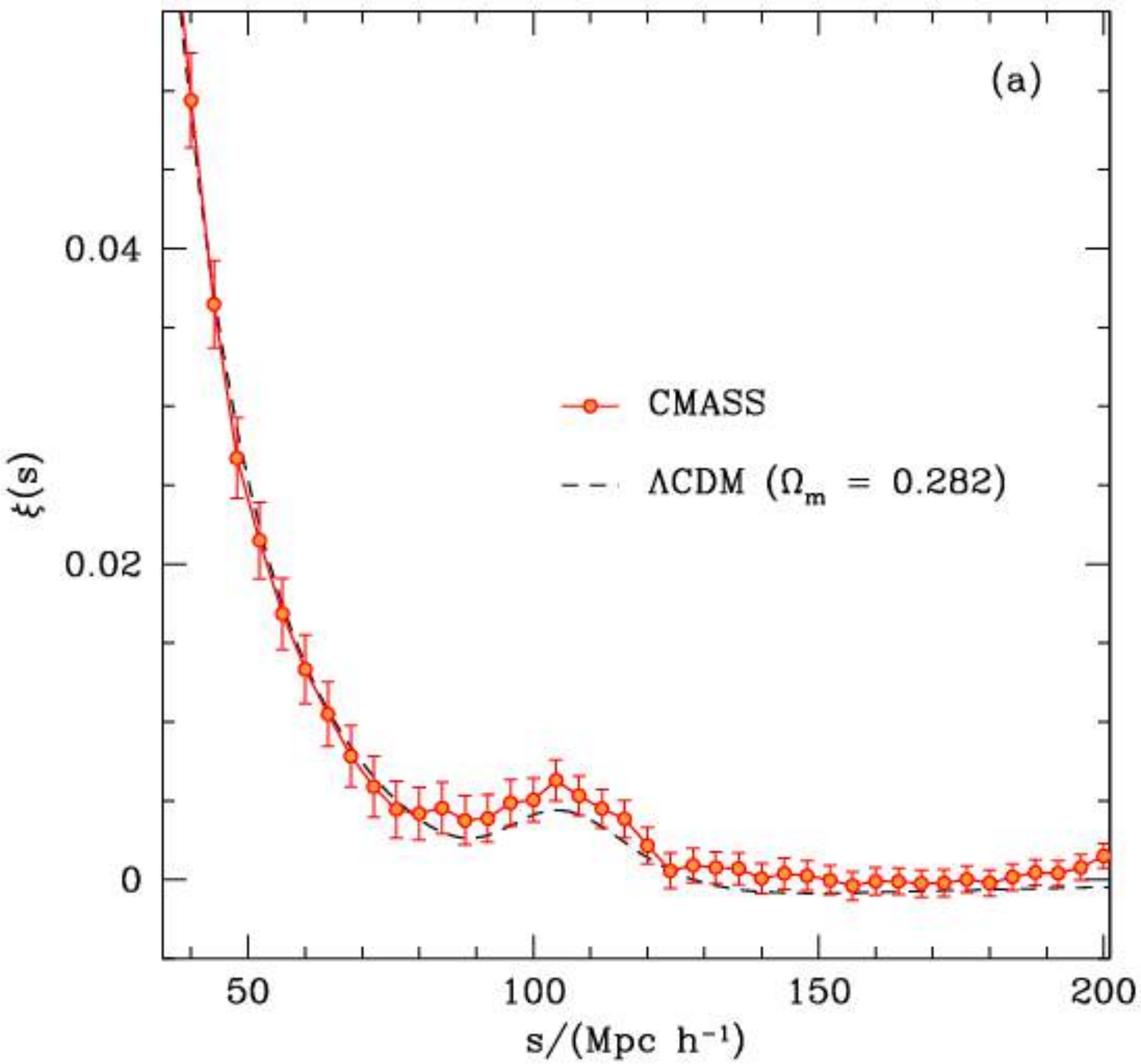
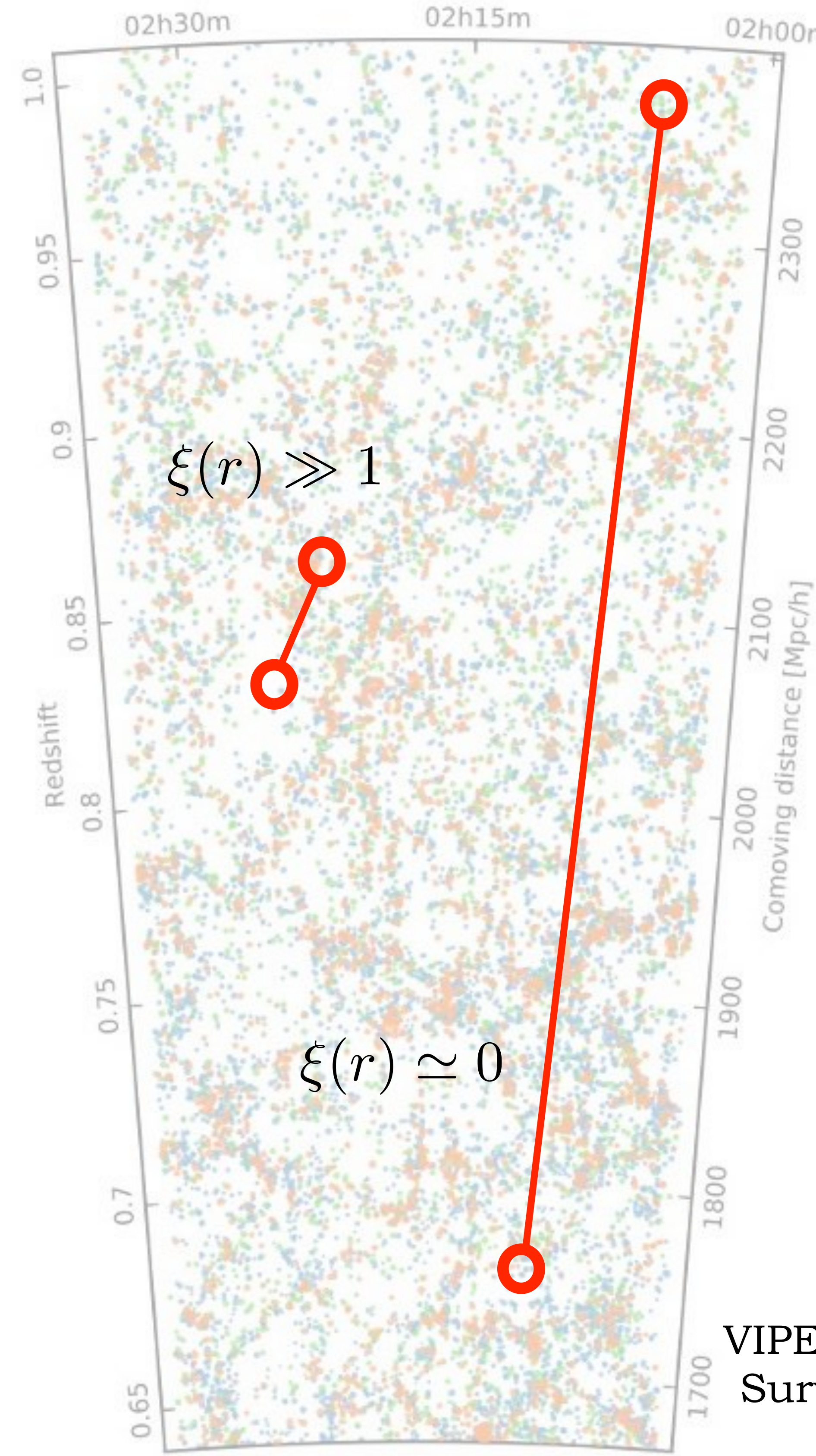




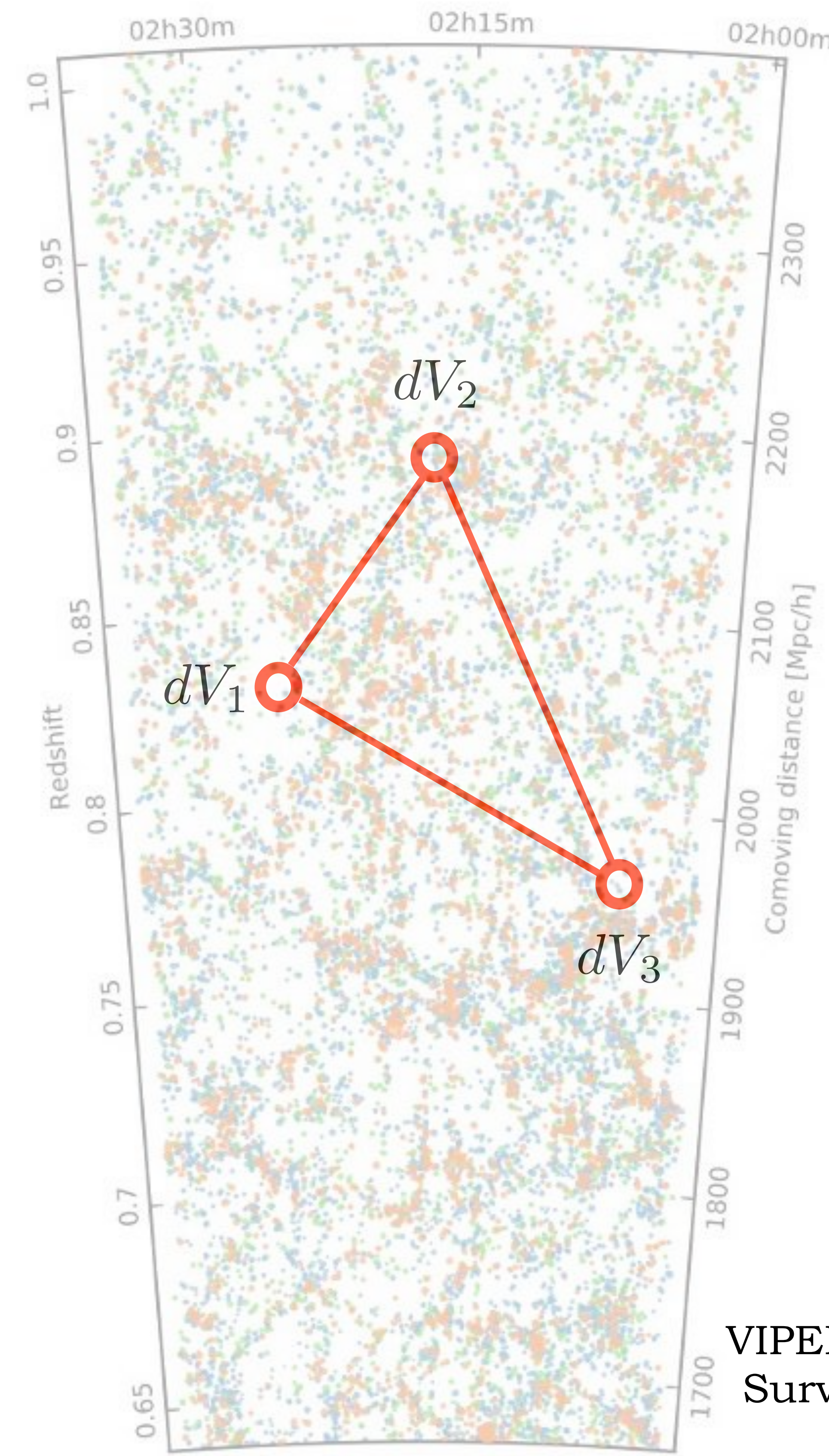
VIPERS Survey

The galaxy 3-point correlation function

Similarly I can ask the probability of finding three galaxies in the volume elements dV_1, dV_2 and dV_3

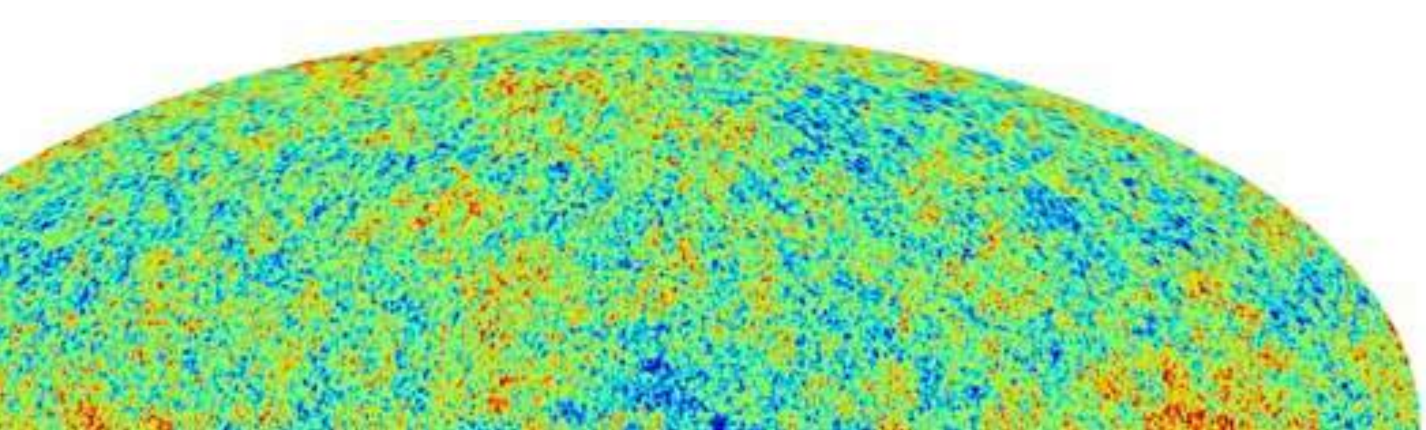
$$dP = dV_1 dV_2 dV_3 \langle n_g(\vec{x}_1) n_g(\vec{x}_2) n_g(\vec{x}_3) \rangle$$
$$= dV_1\, dV_2\, dV_3\, \bar{n}_g^3\, [1 +$$
$$+ \xi(r_{12}) + \xi(r_{13}) + \xi(r_{23}) + \zeta(r_{12}, r_{13}, r_{23})]$$

$$\zeta(r_{12}, r_{13}, r_{23}) \equiv \langle \delta_g(\vec{x}_1) \delta_g(\vec{x}_2) \delta_g(\vec{x}_3) \rangle$$



VIPERS Survey

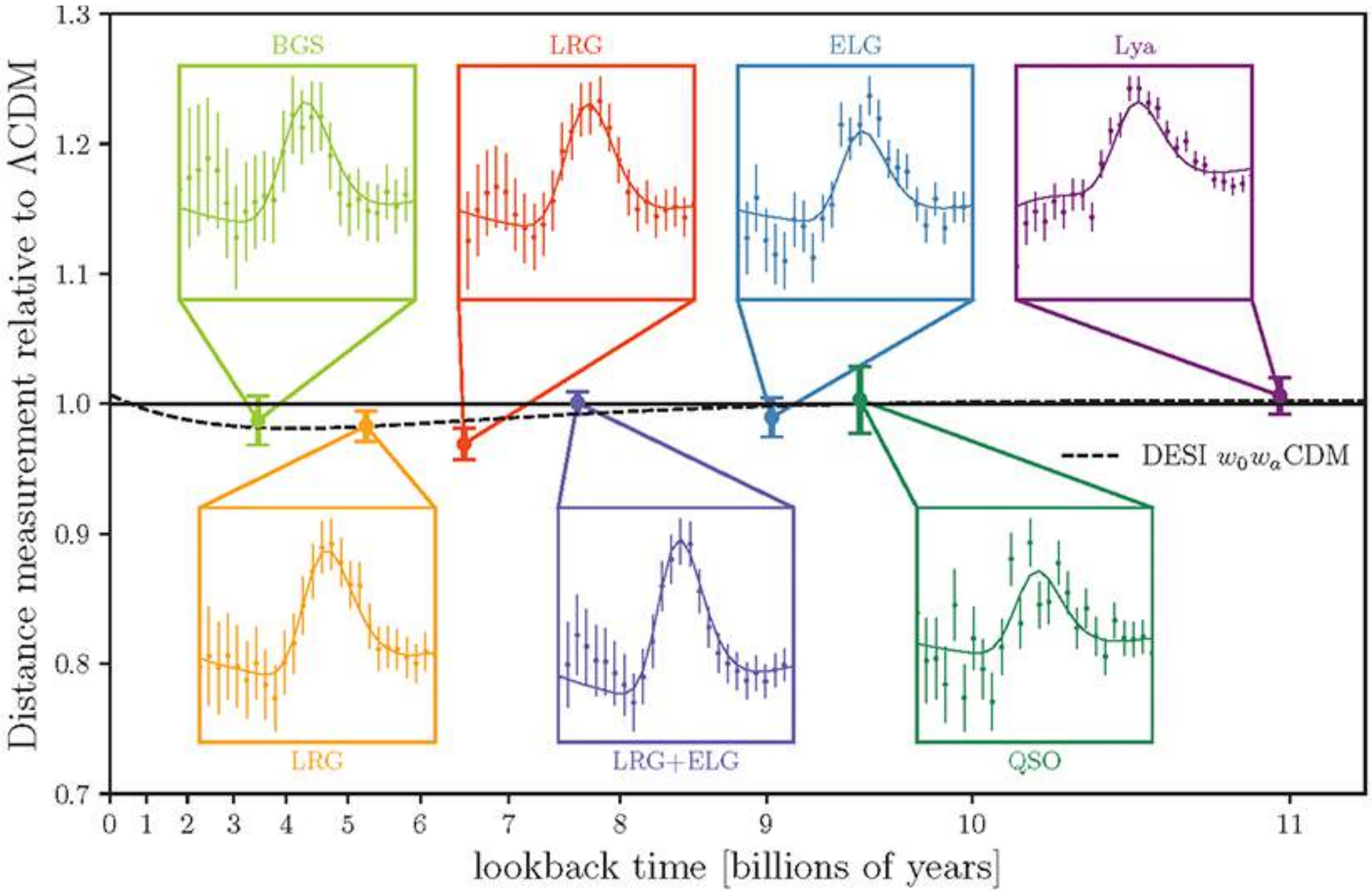
Indeed, the galaxy distribution is a *non-Gaussian random field* even if the initial conditions are very close to Gaussian



The galaxy 2-point correlation function

What do we do with these measurements?

1. Fit the **Baryonic Acoustic Oscillations (BAO)** feature and use it as a ***standard ruler*** to constrain the background expansion



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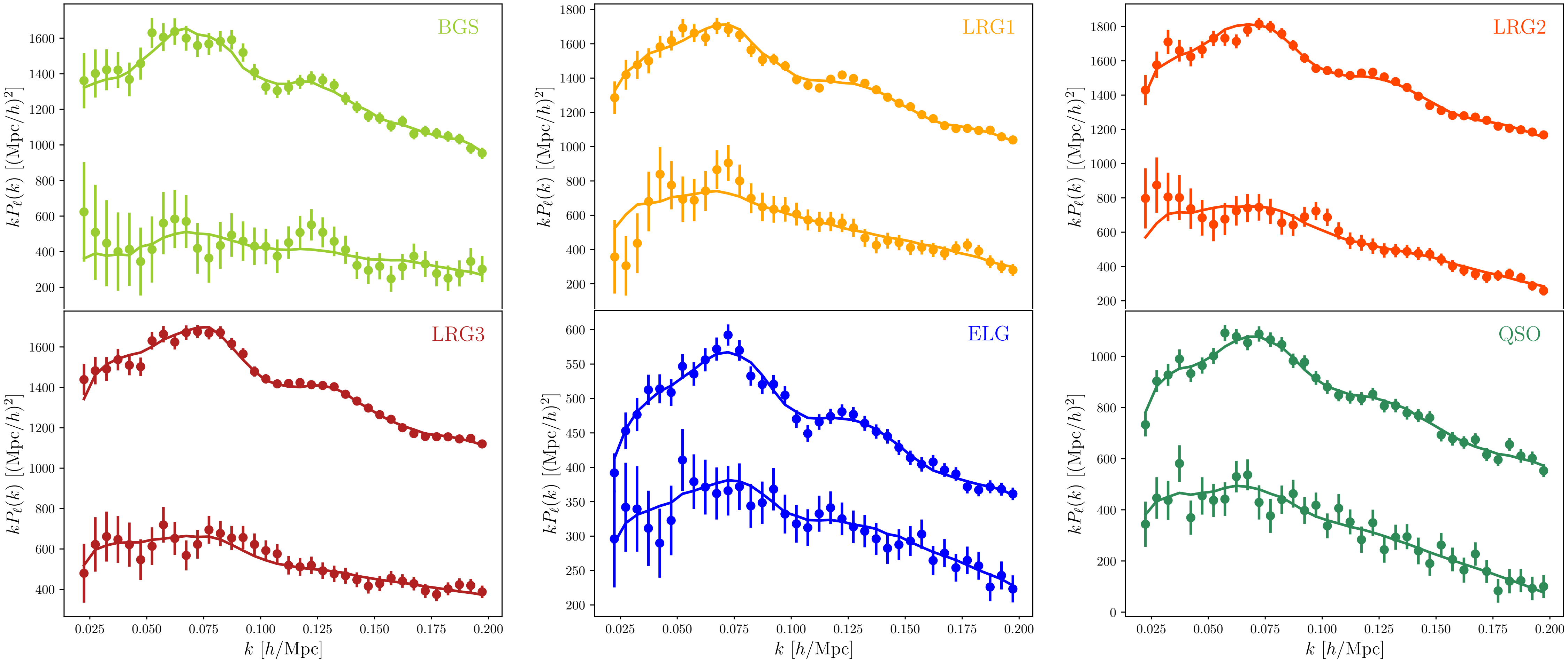
The galaxy 2-point correlation function

What do we do with these measurements?

2. Use the **full information on the shape** of the 2PCF, or its Fourier Transform, the **power spectrum**



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The galaxy 2-point correlation function

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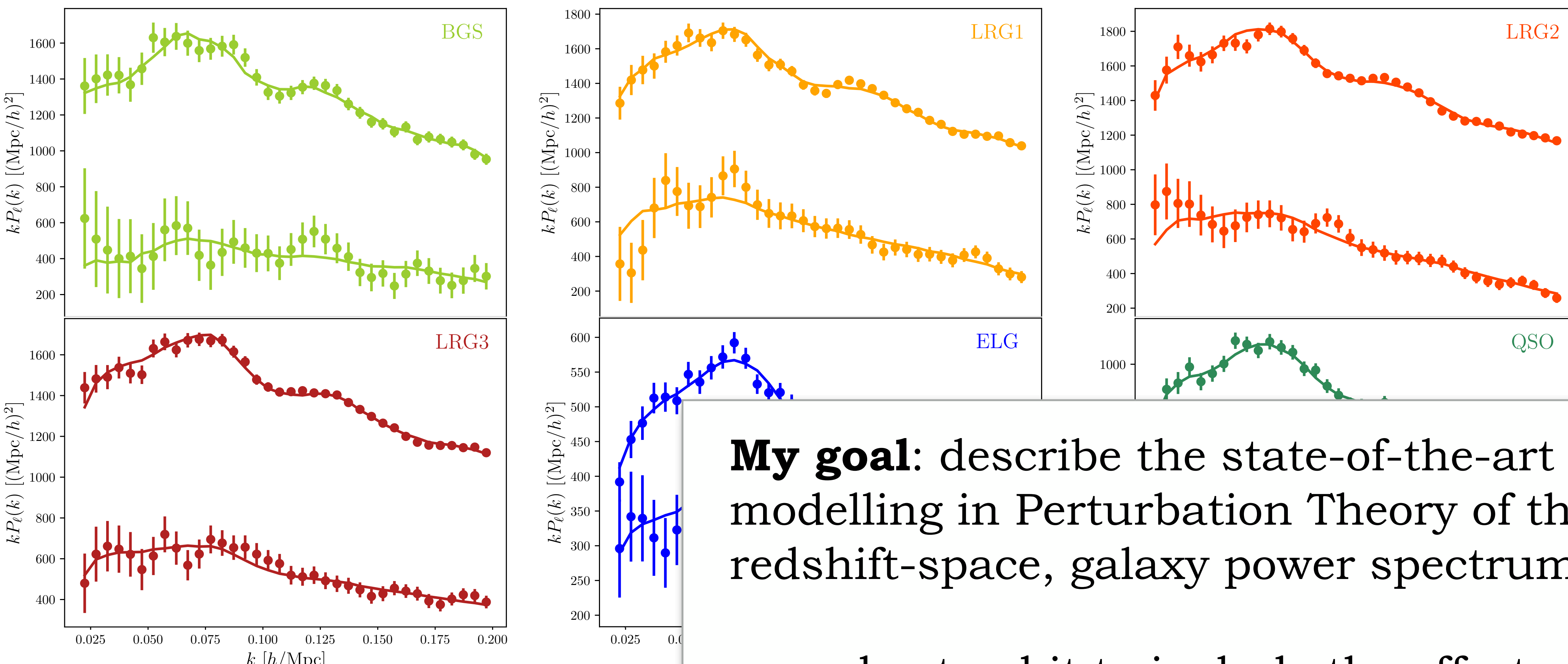
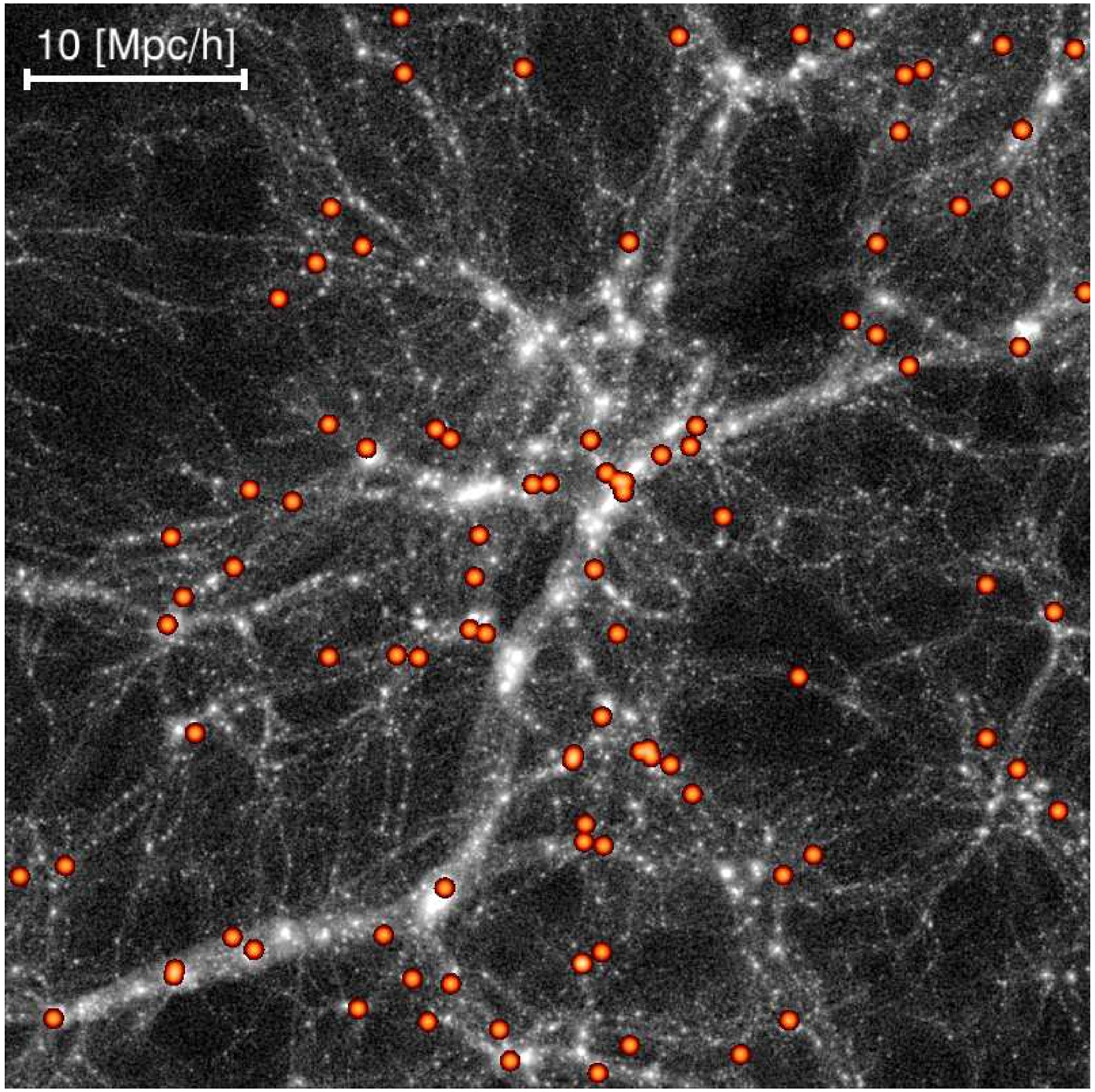


My goal: describe the state-of-the-art modelling in Perturbation Theory of the redshift-space, galaxy power spectrum

… and extend it to include the effects of neutrino masses

The galaxy power spectrum



Orsi *et al.* (2009)

We need:

1. A model for the ***matter* power spectrum**

2. A model for the relation between dark matter and galaxy perturbations, the so-called **galaxy bias**

3. Include the effect of **redshift-space distortions**
   (because we observe galaxies in *redshift-space*)

The matter power spectrum

Enter the **matter perturbations,** $\delta(\vec{x}, \tau)$:

$$\rho(\vec{x}, \tau) = \bar{\rho}(\tau)[1 + \delta(\vec{x}, \tau)]$$

The **matter power spectrum** is the 2-point function in Fourier space

$$\delta_{\vec{k}} = \int \frac{d^3x}{(2\pi)^3} e^{-i\vec{k}\cdot\vec{x}} \delta(\vec{x})$$

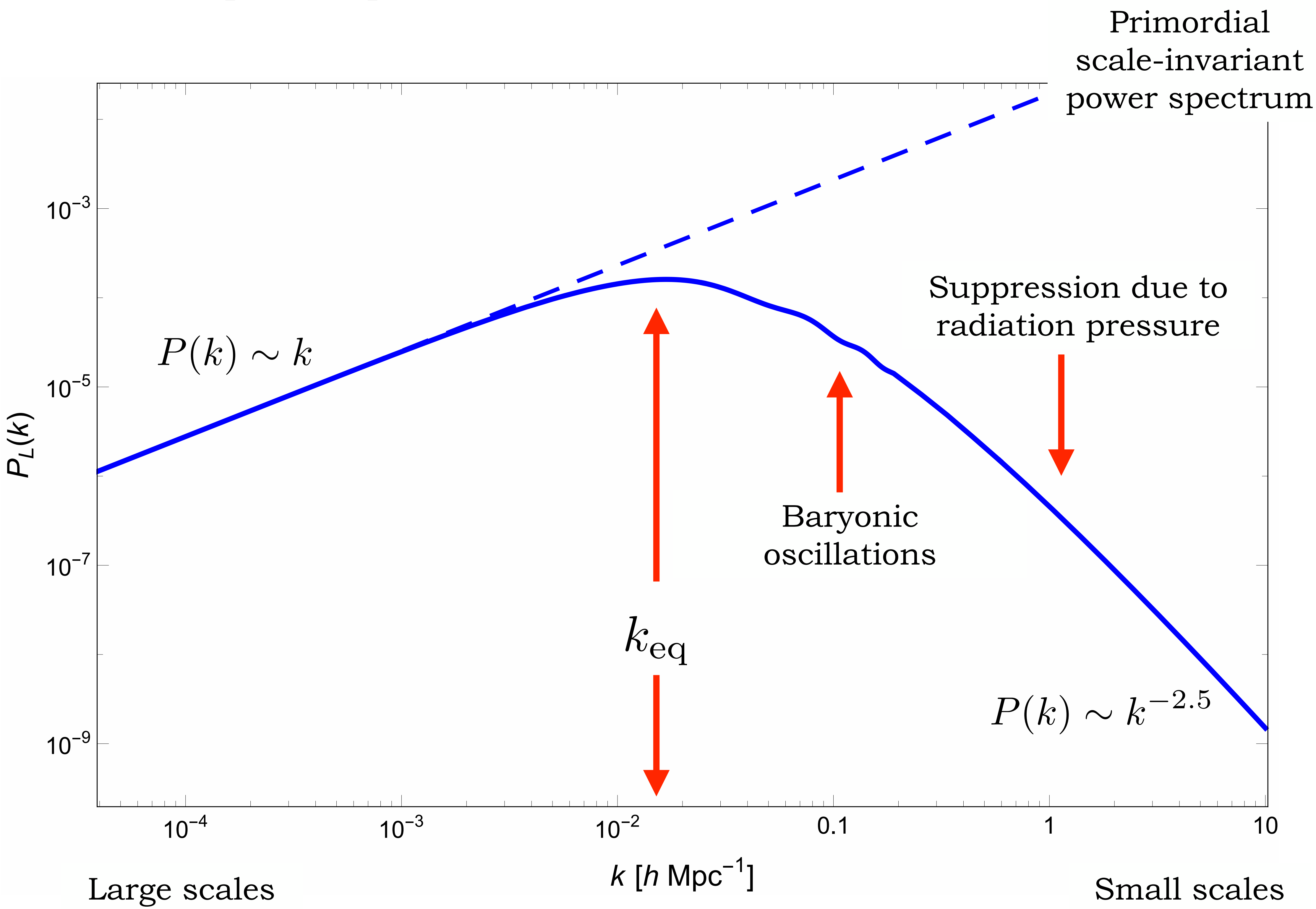
$$\langle\, \delta_{\vec{k}_1}\, \delta_{\vec{k}_2} \rangle = \delta_D(\vec{k}_1 + \vec{k}_2)\, P(k_1)$$

and it is the Fourier Transform of the 2-point correlation function

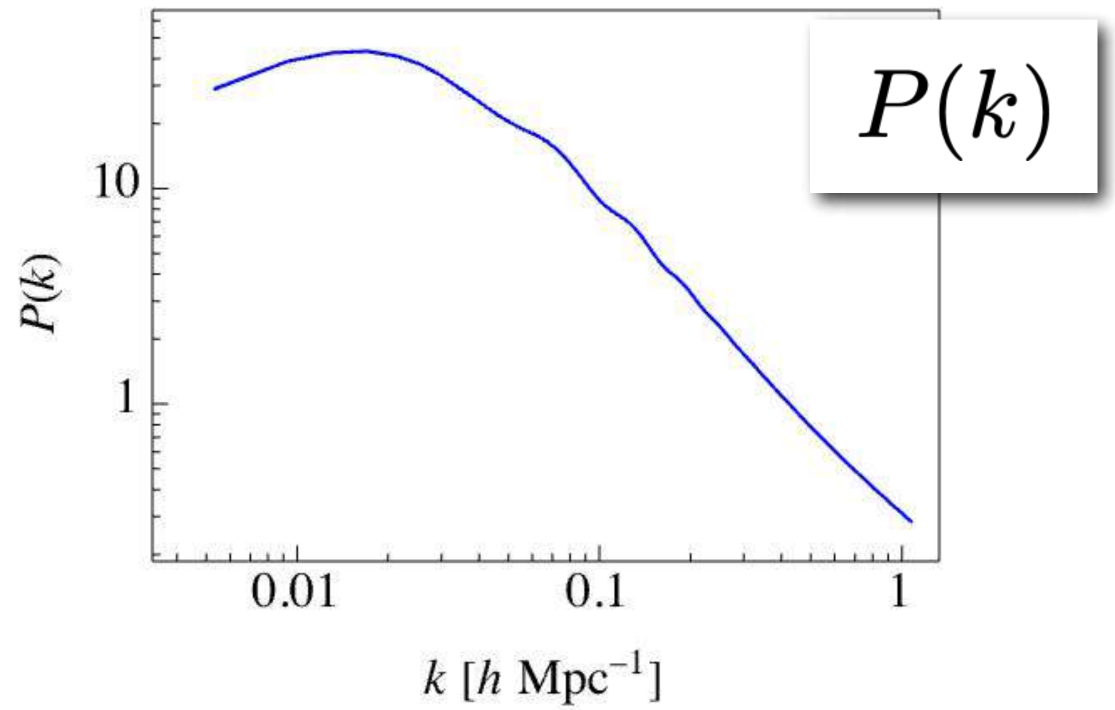
$$P(k) = \int \frac{d^3x}{(2\pi)^3}\, e^{i\,\vec{k}\cdot\vec{x}} \xi(x)$$

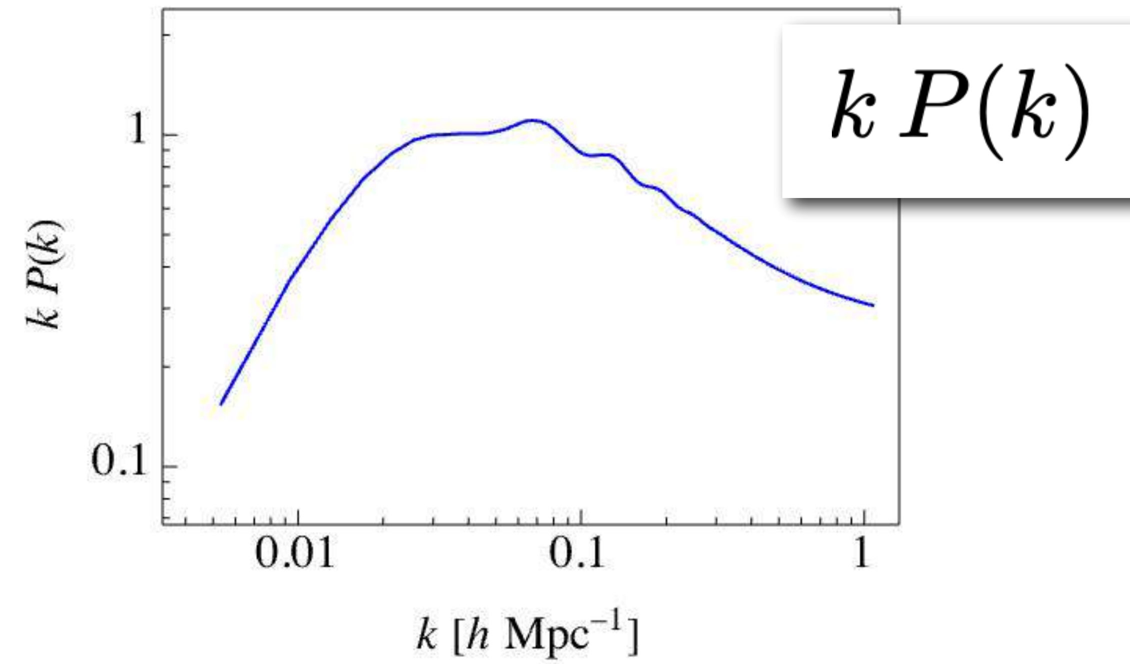
The “initial” matter power spectrum

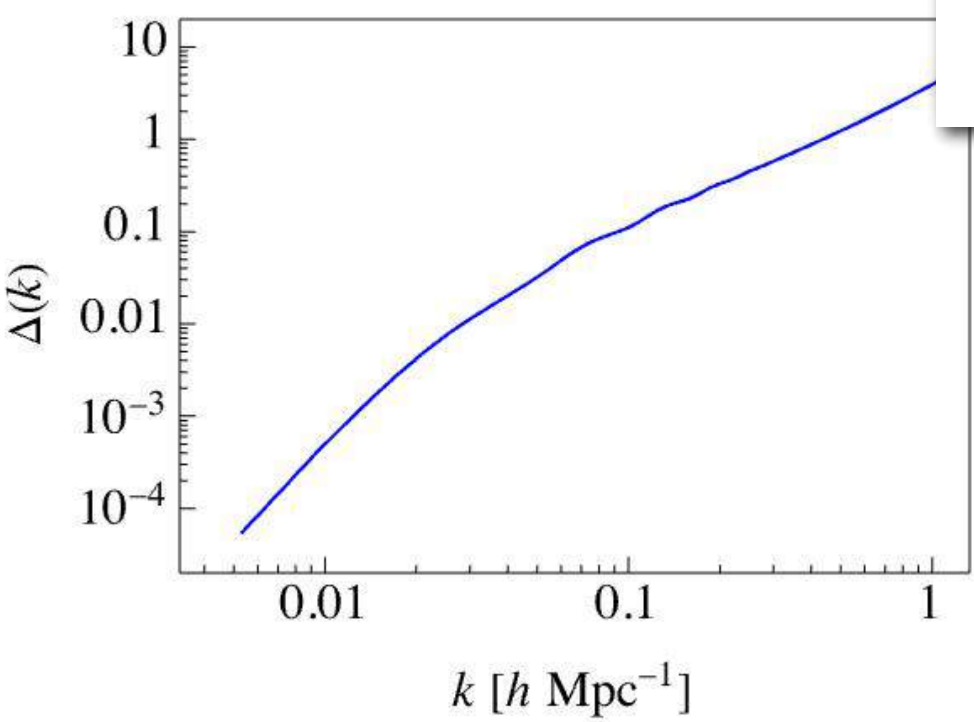
The linear matter power spectrum at recombination, $z \sim 1100$



An extra, pedagogical slide







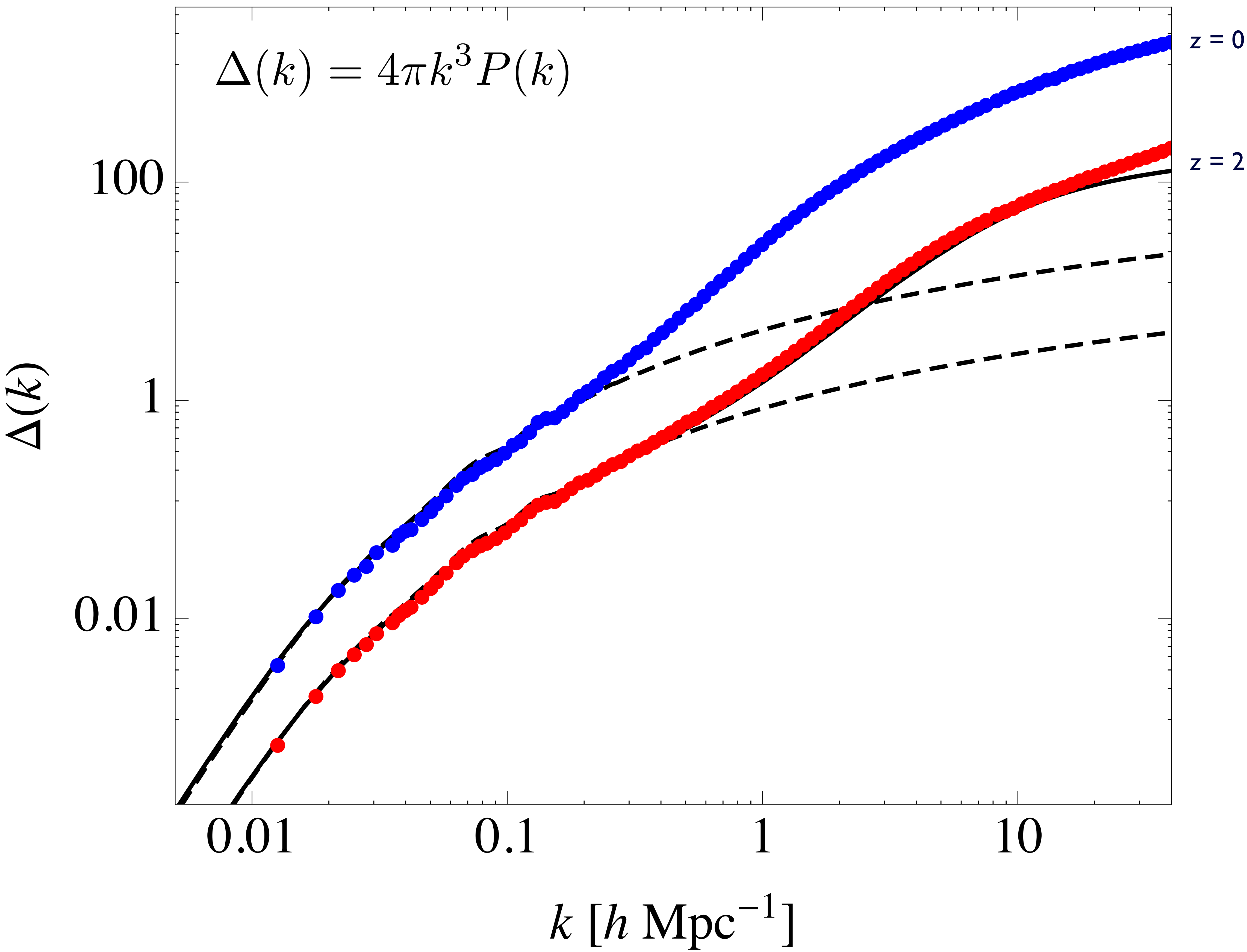
$$\Delta(k) \equiv 4\pi\, k^3\, P(k)$$

adimensional power spectrum

$$\sigma_\delta^2 \equiv \langle \delta^2(\vec{x}) \rangle = 4\pi \int dk\, k^2\, P(k) = \int \frac{dk}{k}\, \Delta(k)$$

The power spectrum is a measure of the amplitude of perturbations as a function of scale

Nonlinear growth of matter perturbations



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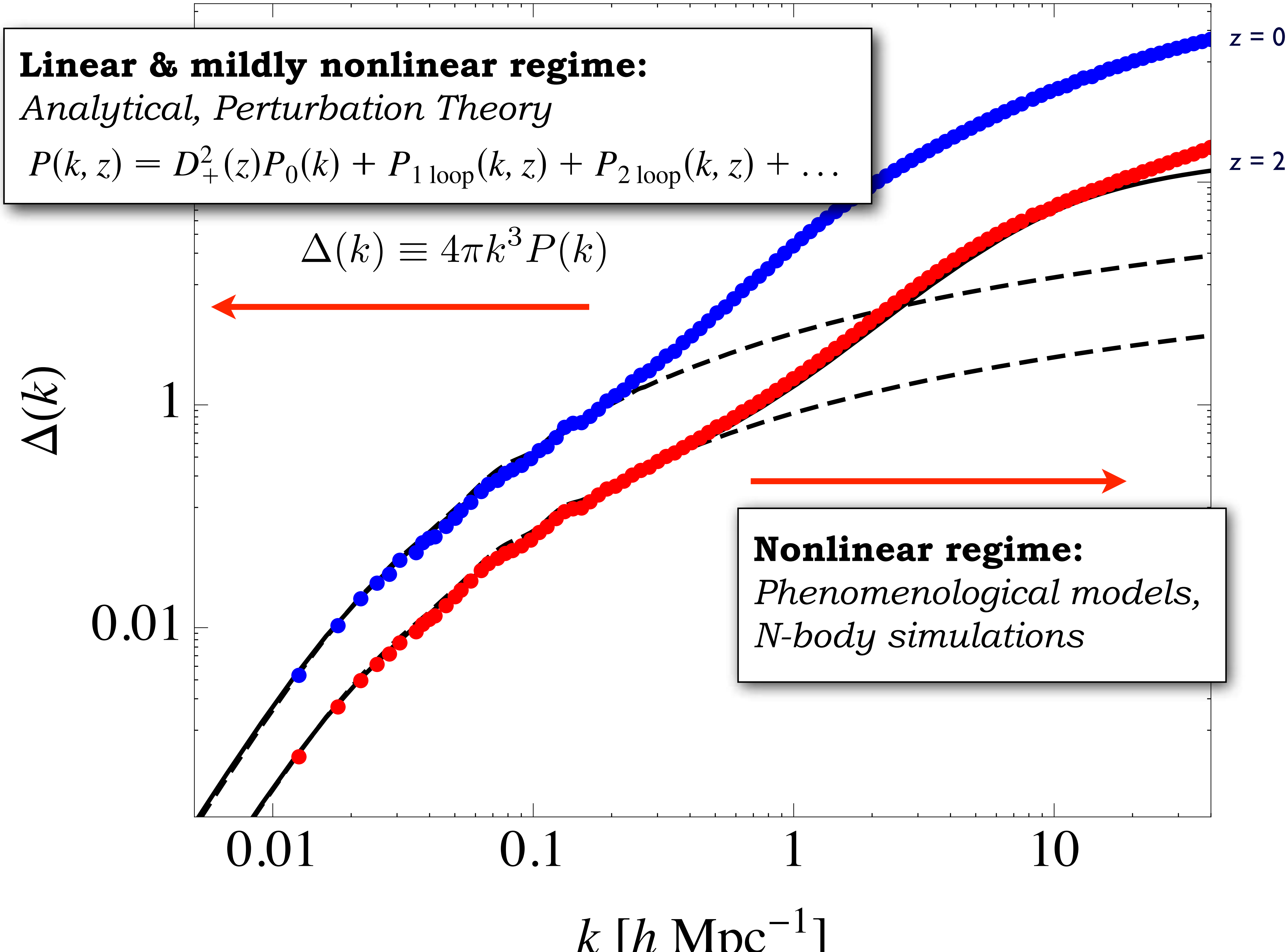


Density & velocity perturbations

We will describe the nonlinear evolution of the matter density field.
We need the equations of motions for *perturbations*

$$\rho(\vec{x},\tau) = \bar{\rho}(\tau)[1+\delta(\vec{x},\tau)] \qquad \delta(\vec{x},\tau)$$

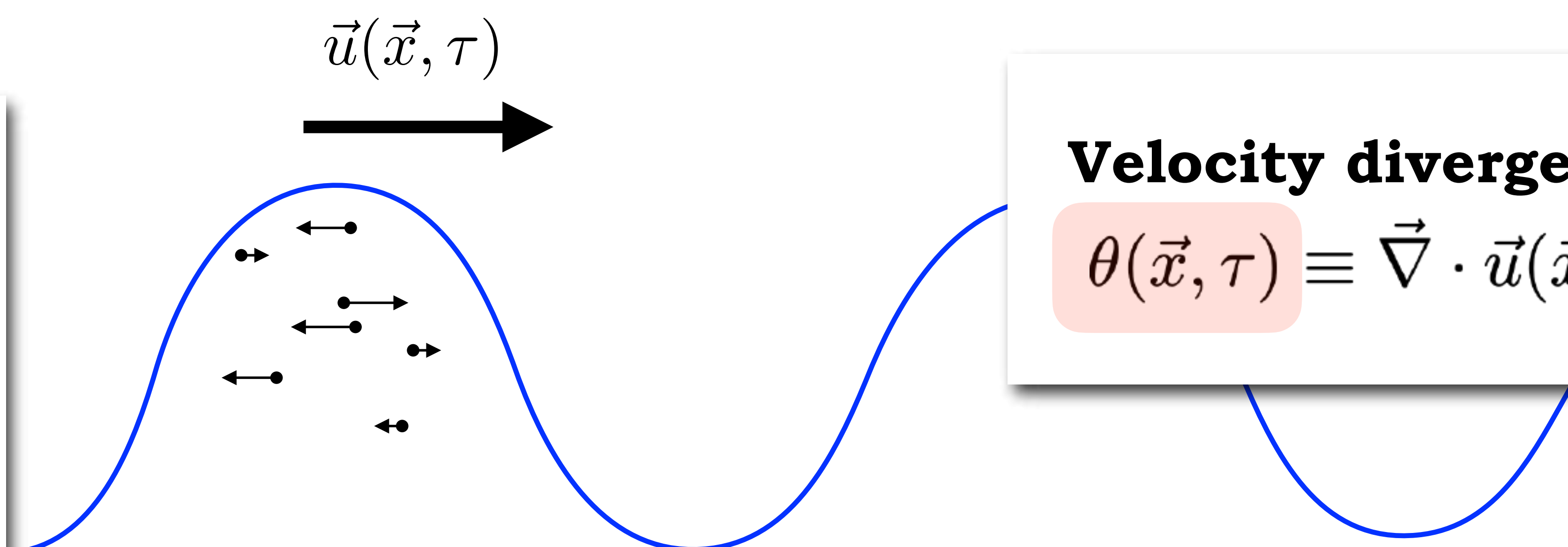
matter perturbations

Velocities have a competent due to the Hubble expansion and one due to peculiar motion

$$\vec{v}(\vec{x},\tau) = \mathcal{H}(\tau)\,\vec{x}(\tau) + \vec{u}(\vec{x},\tau) \qquad \vec{u}(\vec{x},\tau)$$

peculiar velocities

for **Cold** Dark Matter we can ignore the thermal motion of individual particles, and study the evolution of **perturbations**



Velocity divergence

$$\theta(\vec{x},\tau) \equiv \vec{\nabla}\cdot\vec{u}(\vec{x},\tau)$$

Fluid equations

In the Newtonian approximation, $k_{phys} \gg H(a)$

$$\frac{df}{d\tau} \equiv \frac{\partial f}{\partial \tau} + \frac{\vec{p}}{am} \cdot \vec{\nabla} f - a\, m\, \vec{\nabla}\Phi \cdot \vec{\nabla}_p f = 0$$

Phase-space conservation for $f(\tau, \vec{x}, \vec{p})$

$$\int d^3p\, \frac{df}{d\tau} = 0 \quad \rightarrow \quad \frac{\partial \delta}{\partial \tau} + \vec{\nabla} \cdot [(1+\delta)\, \vec{u}] = 0$$

continuity equation

$$\int d^3p\, \frac{p_i}{am}\frac{df}{d\tau} = 0 \quad \rightarrow \quad \frac{\partial \vec{u}}{\partial \tau} + \mathcal{H}\vec{u} + (\vec{u} \cdot \vec{\nabla})\vec{u} = -\vec{\nabla}\Phi$$

Euler equation

We assume the *single-stream approximation*, $\sigma_{ij} = 0$, to get a closed set of equations

$$\int d^3p\, \frac{p_i p_j}{a^2 m^2} f(\tau, \vec{x}, \vec{p}) = \rho(\tau, \vec{x})\, u_i(\tau, \vec{x})\, u_j(\tau, \vec{x}) + \sigma_{ij}(\tau, \vec{x})$$

...

This is accounted for in the **EFTofLSS** (*back to this if we have some time at the end ...!*)

Fluid equations

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Euler equation

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

Poisson equation

We end up with 3 equations & 3 unknowns: $\rho, \vec{u}, \Phi$

Linear solutions in Standard PT

We can look for perturbative solutions of the form

$$\delta_{\vec{k}} = \delta^{(1)}_{\vec{k}} + \delta^{(2)}_{\vec{k}} + \ldots$$

$$\delta^{(1)}_{\vec{k}} \equiv \delta_L(\vec{k}) = D(a)\, \delta^{in}_{\vec{k}}$$

linear solution

$$D(a) = \frac{5}{2} H_0^2\, \Omega_{m,0}\, H(a) \int_0^a \frac{da'}{[a' H(a')]^3}$$

growth factor
(exact solution for a ΛCDM cosmology)

$$P_L(k) = D^2(a)\, P_{in}(k)$$

linear power spectrum:
in linear theory all scales grow at the same rate

PT review: Bernardeau *et al.* (2002)

Nonlinear solutions in Standard PT

We can look for perturbative solutions of the form

$$\delta_{\vec{k}} = \delta_{\vec{k}}^{(1)} + \delta_{\vec{k}}^{(2)} + \ldots$$

$$\delta_{\vec{k}}^{(1)} \equiv \delta_L(\vec{k}) = D(a)\,\delta_{\vec{k}}^{in}$$ linear solution

$$\delta_{\vec{k}}^{(2)} = \int d^3q\, F_2(\vec{k}-\vec{q},\vec{q})\,\delta_{\vec{k}-\vec{q}}^{(1)}\delta_{\vec{q}}^{(1)} \sim D^2(a)$$ quadratic correction

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

PT review: Bernardeau *et al.* (2002)

The nonlinear Power Spectrum

From the density solution we can find
a perturbative solution for the power spectrum

$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \langle \delta^{(1)}_{\vec{k}_1} \delta^{(1)}_{\vec{k}_2} \rangle + \cancel{\langle \delta^{(1)}_{\vec{k}_1} \delta^{(2)}_{\vec{k}_2} \rangle + \text{perm.}} + \langle \delta^{(2)}_{\vec{k}_1} \delta^{(2)}_{\vec{k}_2} \rangle + \langle \delta^{(1)}_{\vec{k}_1} \delta^{(3)}_{\vec{k}_2} \rangle + \text{perm.} + \mathcal{O}(\delta_L^5)$$

Linear power spectrum $P_L(k)$

$\sim \langle \delta^{(1)} \delta^{(1)} \delta^{(1)} \rangle = 0$ for Gaussian initial conditions

$$P(k) = P_L(k) + P_{22}(k) + P_{13}(k) + P_{ctr}(k) + \mathcal{O}(\delta_L^5)$$

$$P_{22}(k) = 2 \int d^3q \, F_2(\vec{q}, \vec{k} - \vec{q}) \, P_L(q) \, P_L(|\vec{k} - \vec{q}|)$$

$$P_{13}(k) = 6 \, P_L(k) \int d^3q \, F_3(\vec{k}, \vec{q}, \vec{k} - \vec{q}) \, P_L(q)$$

one-loop corrections

$$P_{ctr}(k) = c_0 \, k^2 \, P_L(k)$$

EFT counterterm
(*Maybe later!*)

The nonlinear Power Spectrum

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$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \langle \delta^{(1)}_{\vec{k}_1} \delta^{(1)}_{\vec{k}_2} \rangle + \langle \delta^{(1)}_{\vec{k}_1} \delta^{(2)}_{\vec{k}_2} \rangle + \text{perm.} + \langle \delta^{(2)}_{\vec{k}_1} \delta^{(2)}_{\vec{k}_2} \rangle + \langle \delta^{(1)}_{\vec{k}_1} \delta^{(3)}_{\vec{k}_2} \rangle + \text{perm.} + \mathcal{O}(\delta_L^5)$$

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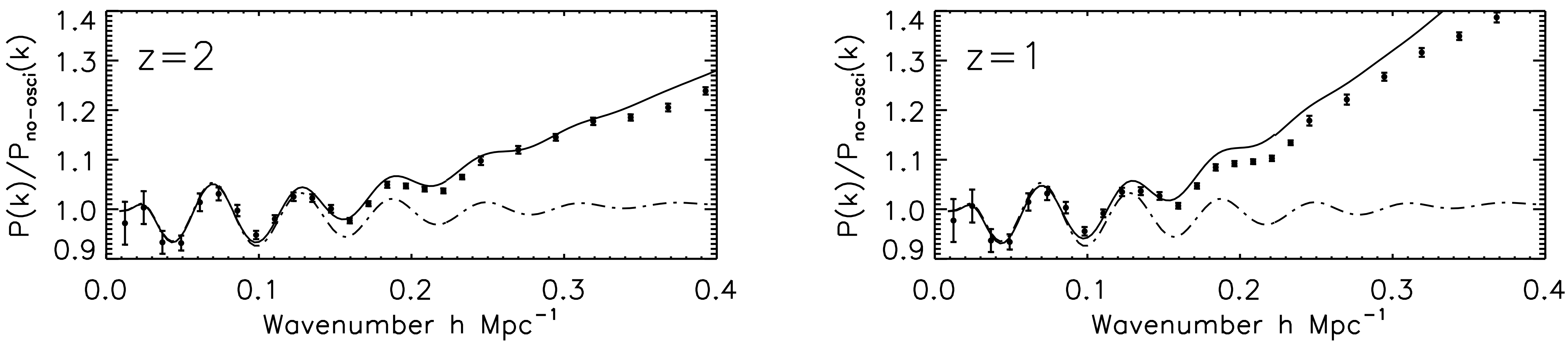
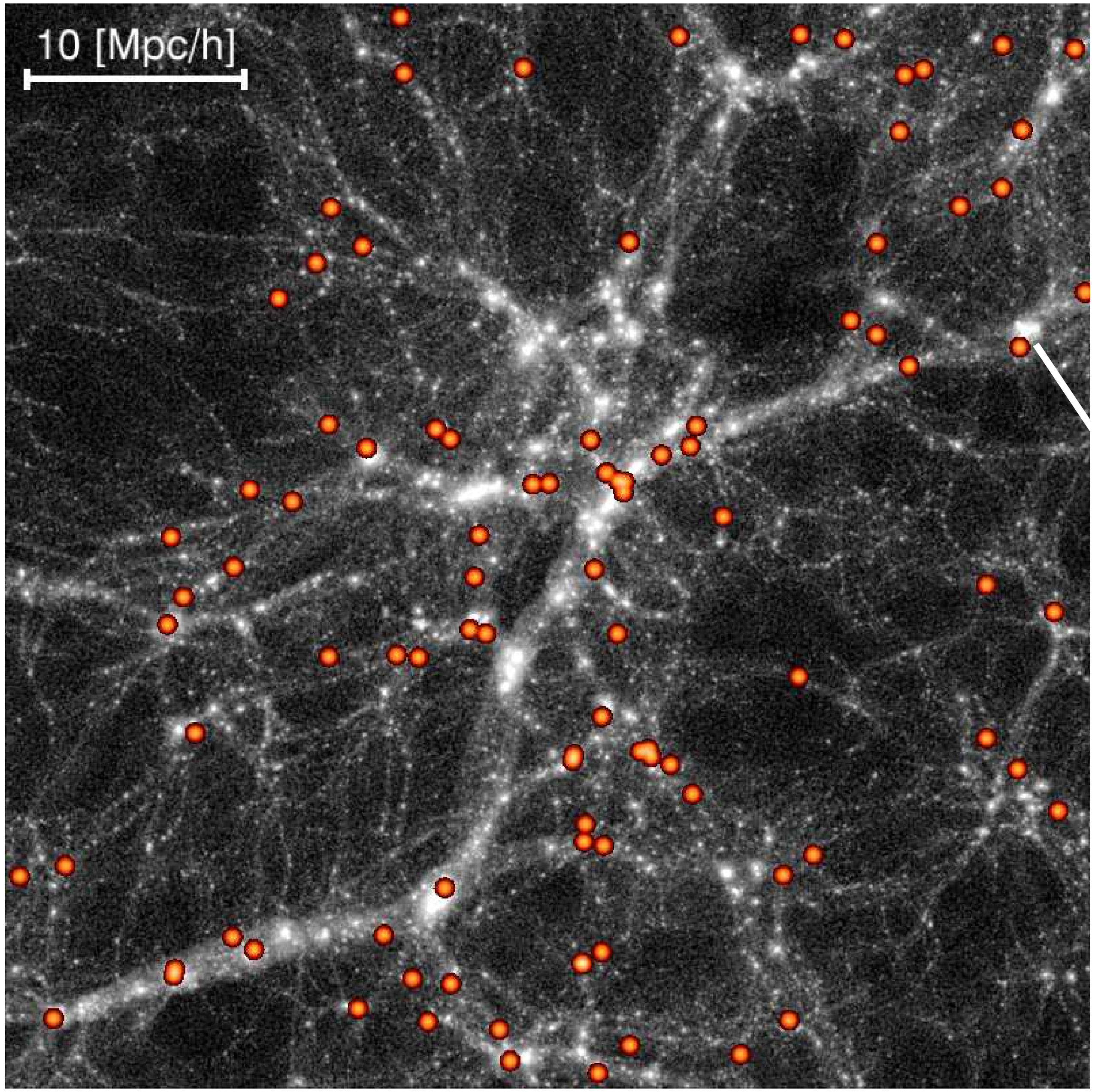


Jeong & Komatsu (2006)

Galaxies



A fair assumption:

galaxy density perturbations trace the underlying matter density perturbations

$$\delta_g(x) \equiv \frac{n_g(x) - \bar{n}_g}{\bar{n}_g} = f\left[\delta(x)\right]$$
$$= b_1\, \delta(x) + \frac{1}{2}\, b_2\, \delta^2(x)$$

Nonlinear & non-local galaxy bias

$$\delta_g(\vec{x}) = f[\nabla_i \nabla_j \Phi(\vec{x}),\, \nabla_i \nabla_j \Phi_v(\vec{x})]$$

Chan, Scoccimarro & Sheth (2012)
Baldauf *et al.* (2012)

We just write down all operators invariant under Galilean transformations:

$$\mathcal{G}_1(\Phi) = \nabla^2 \Phi = \delta$$ local bias

$$\mathcal{G}_2(\Phi) = (\nabla_i \nabla_j \Phi)^2 - (\nabla^2 \Phi)^2$$ tidal bias

And so on … plus the same for the velocity potential $\mathcal{G}_n(\Phi_v)$ …
… then we have their powers, as $\mathcal{G}_1^2(\Phi) = \delta^2$, etc …

At second order the bias expansion is now

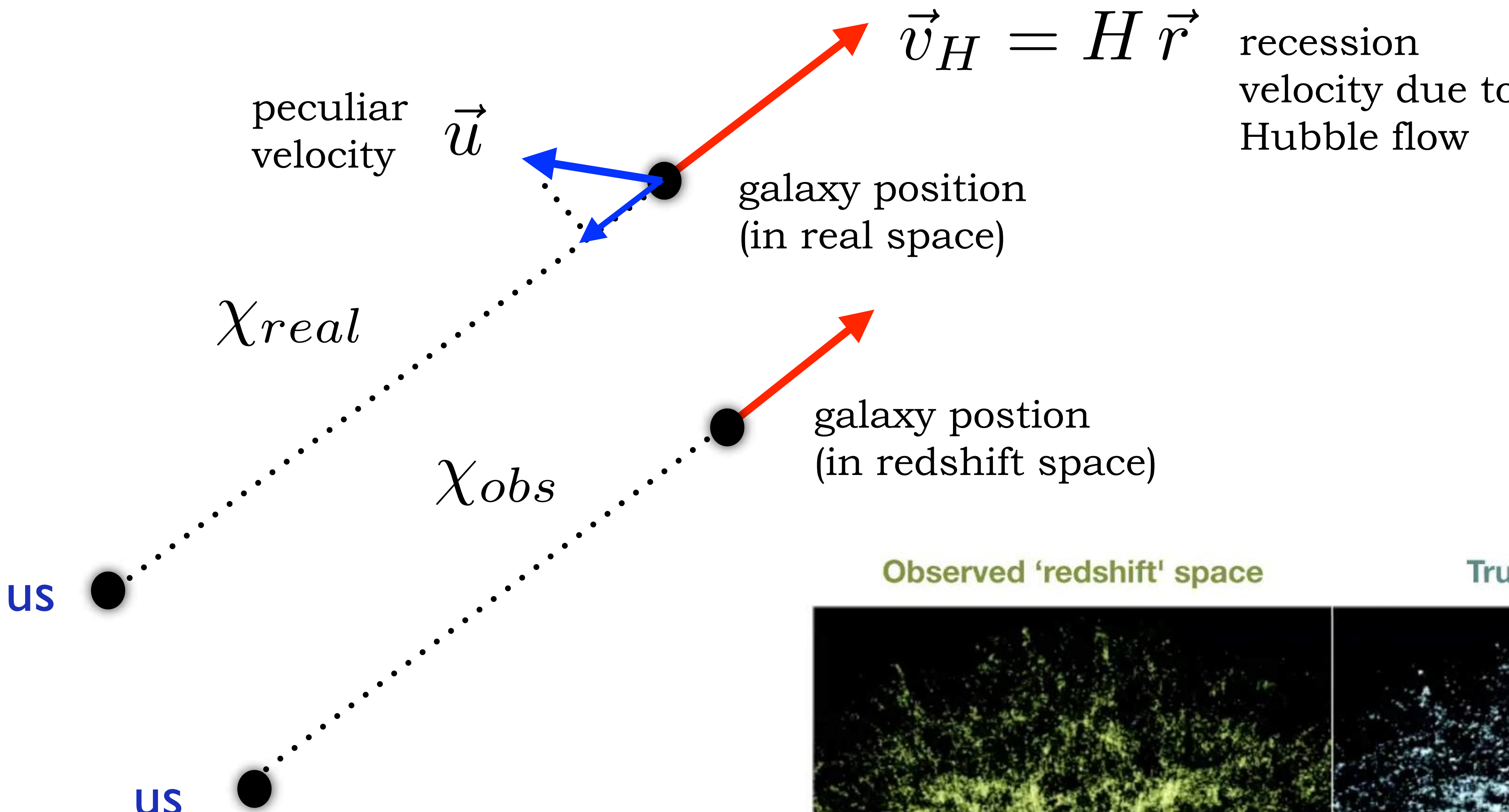
$$\delta_g = b_1\, \delta + \frac{b_2}{2}\, \delta^2 + \gamma_2\, \mathcal{G}_2[\Phi] + \mathcal{O}(\Phi_L^3)$$

a lot of new terms,
free parameters,
additional loop corrections
from bias nonlinearities!

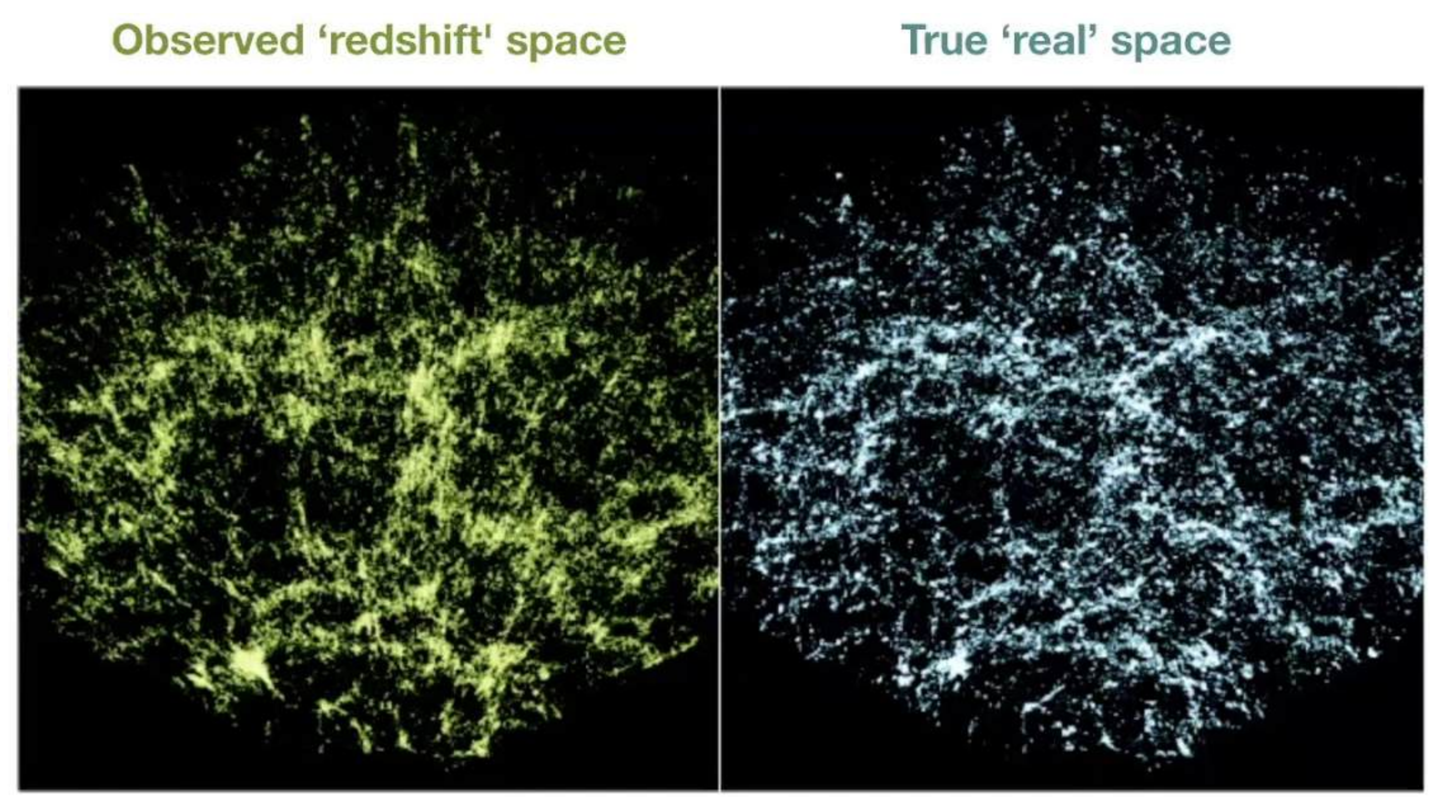
The story is in fact much longer (higher derivative bias, bias renormalisation, shot noise …)
but all told in a recent review, see Desjacques, Jeong & Schmidt (2018)

Redshift-space

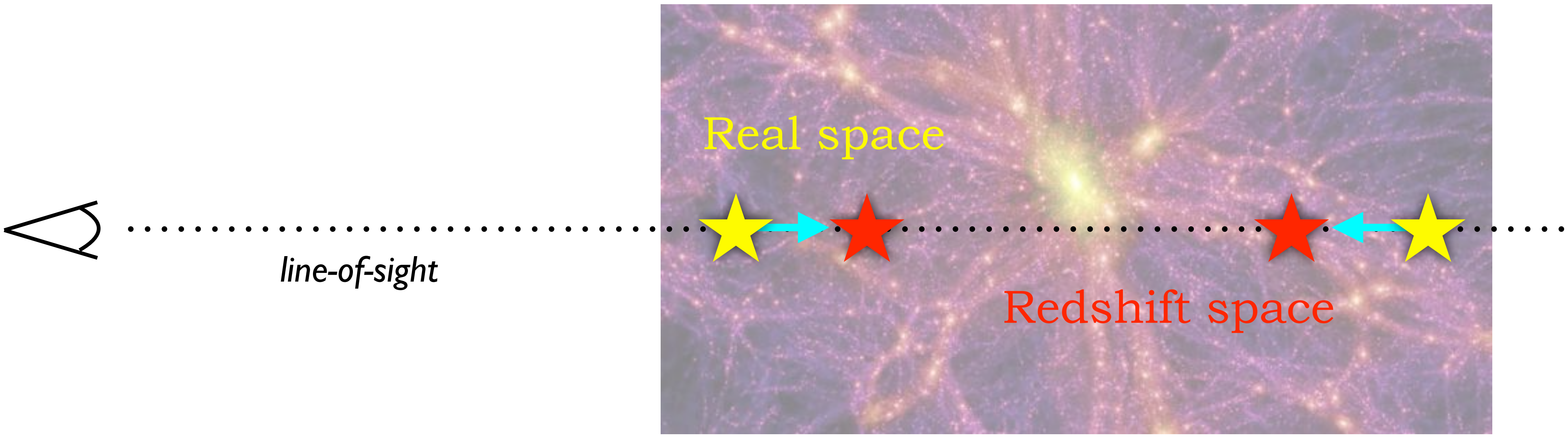
Galaxies are observed in **redshift space** *not* in real space



$$\vec{s} = \vec{x} + \frac{u_z(\vec{x})}{\mathcal{H}}\hat{z}$$



Kaiser effect



For the linear perturbations, this boils down to

$$\delta_{s,L}(\vec{k}) = \delta_L(\vec{k}) - \mu^2 \frac{\theta_L(\vec{k})}{\mathcal{H}} = (1 + f\,\mu^2)\,\delta_L(\vec{k})$$

$$f \equiv \frac{d\ln D(a)}{d\ln a} = \Omega_m^\gamma(z)$$

growth rate

For galaxies

$$\delta_{s,L}(\vec{k}) = (b_1 + f\,\mu^2)\,\delta_L(\vec{k}) \equiv Z_1(\vec{k})\delta_L(\vec{k})$$

Kaiser (1987)

The linear power spectrum in redshift-space

The linear power spectrum is now

$$P_s(\vec{k}) = P_s(k,\mu) = (b_1 + f\,\mu^2)^2\, P_L(k)$$

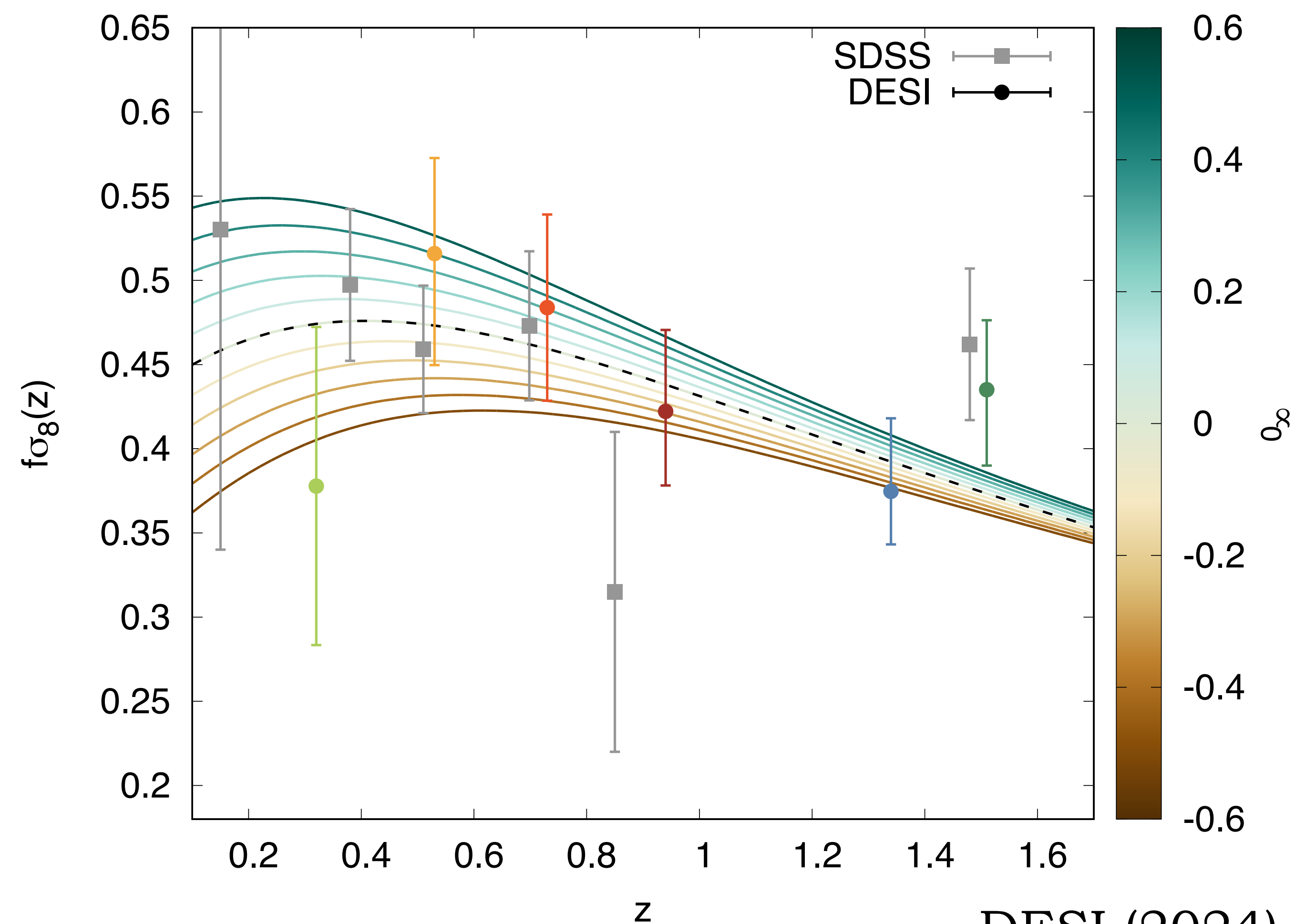
Enhancement along the line-of-sight proportional to the growth rate f

The **redshift-space power spectrum is anisotropic**
we expand it in Legendre polynomials

$$P_s(\vec{k}) = \sum_\ell P_\ell(k)\mathcal{L}_\ell(\mu)$$

Measurements of the distinct multipoles $P_\ell(k)$ provide a *dynamical probe* of structure formation

$$f \equiv \frac{d\ln D(a)}{d\ln a} = \Omega_m^\gamma(z)$$



DESI (2024)

The full model for the power spectrum

Standard **PT** results can be rewritten in terms of **kernels** accounting for **matter evolution**, **bias** and **redshift-space distortions**

$$\delta_s(\vec{k}) = Z_1(\vec{k})\delta_L(\vec{k}) + \int d^3q\, Z_2(\vec{q}, \vec{k}-\vec{q})\delta_L(\vec{q})\delta_L(\vec{k}-\vec{q}) + \dots$$

$$Z_2(\vec{k}_1,\vec{k}_2) = b_1\, F_2(\vec{k}_1,\vec{k}_2) + \frac{b_2}{2} + \gamma\,\Sigma(\vec{k}_1,\vec{k}_2) + f\,\mu_{12}\, G_2(\vec{k}_1,\vec{k}_2) + \frac{f\mu_{12}k_{12}}{2}\left[\frac{\mu_1}{k_1}Z_1(\vec{k}_2) + \frac{\mu_2}{k_2}Z_1(\vec{k}_1)\right]$$

$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k)$$ linear Kaiser effect

$$+2\int \frac{d^3q}{(2\pi)^3} Z_2(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q},\mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|)P_{11}(q)$$

$$+6Z_1(\mu)P_{11}(k)\int \frac{d^3q}{(2\pi)^3} Z_3(\boldsymbol{q},-\boldsymbol{q},\boldsymbol{k},\mu)P_{11}(q)$$

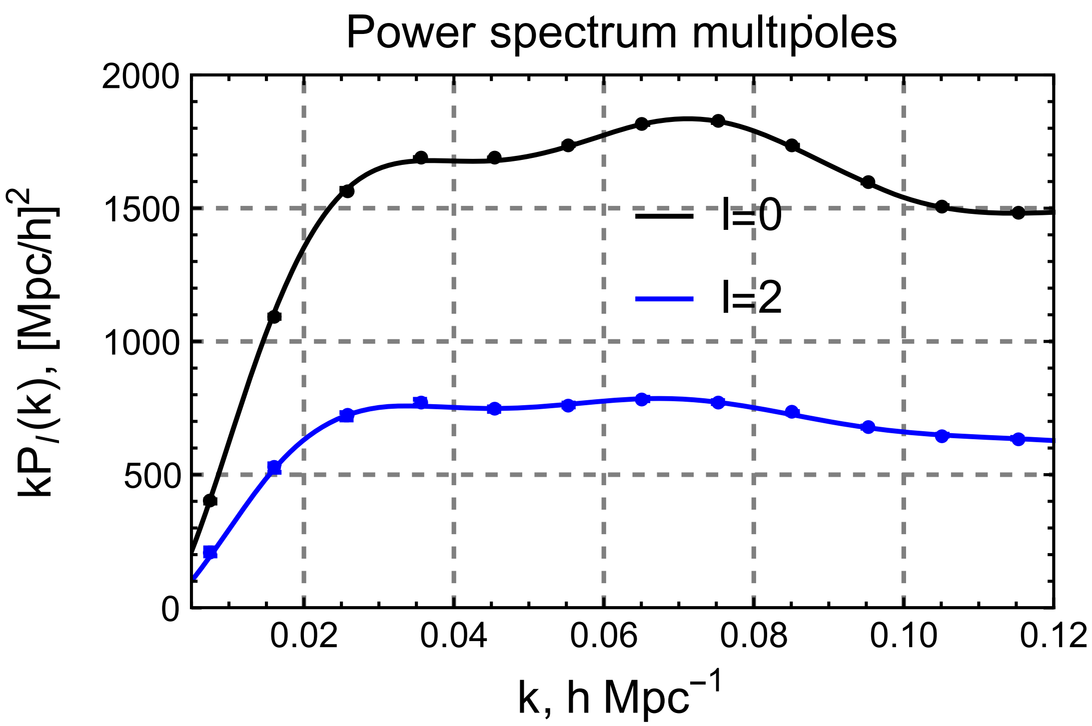
one-loop corrections (matter, bias, RSDs)

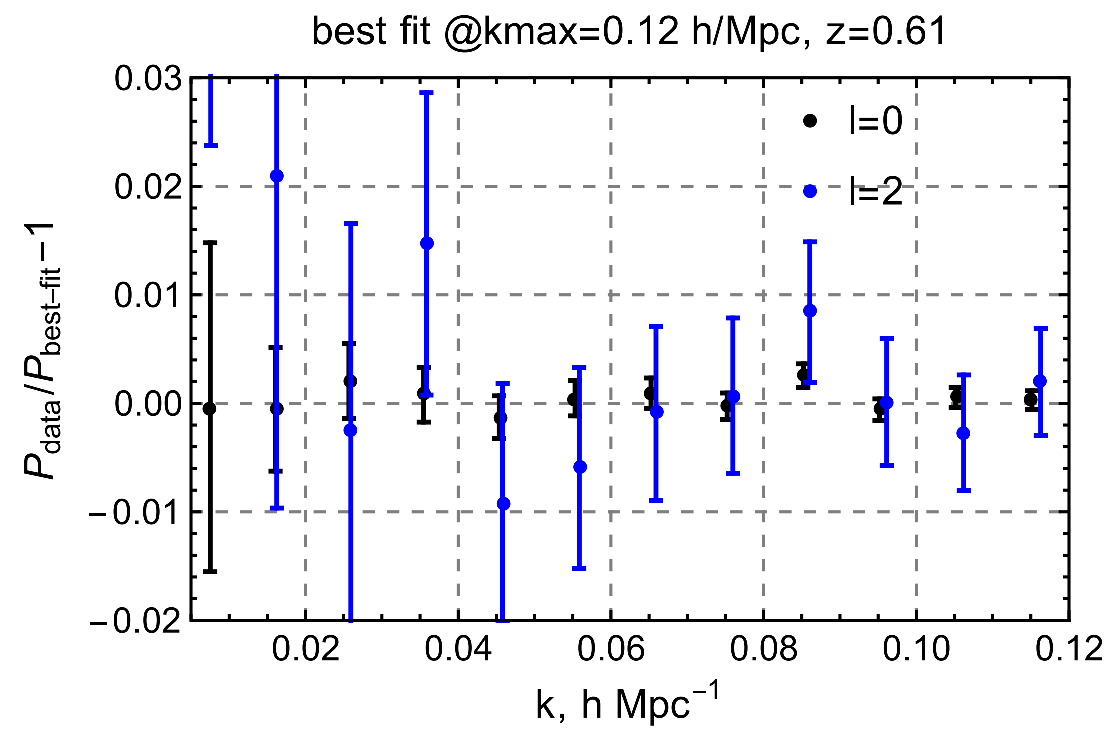
$$+2Z_1(\mu)P_{11}(k)\left(c_{\rm ct}\frac{k^2}{k_{\rm M}^2} + c_{r,1}\mu^2\frac{k^2}{k_{\rm M}^2} + c_{r,2}\mu^4\frac{k^2}{k_{\rm M}^2}\right)$$ counterterms (matter, bias, RSDs)

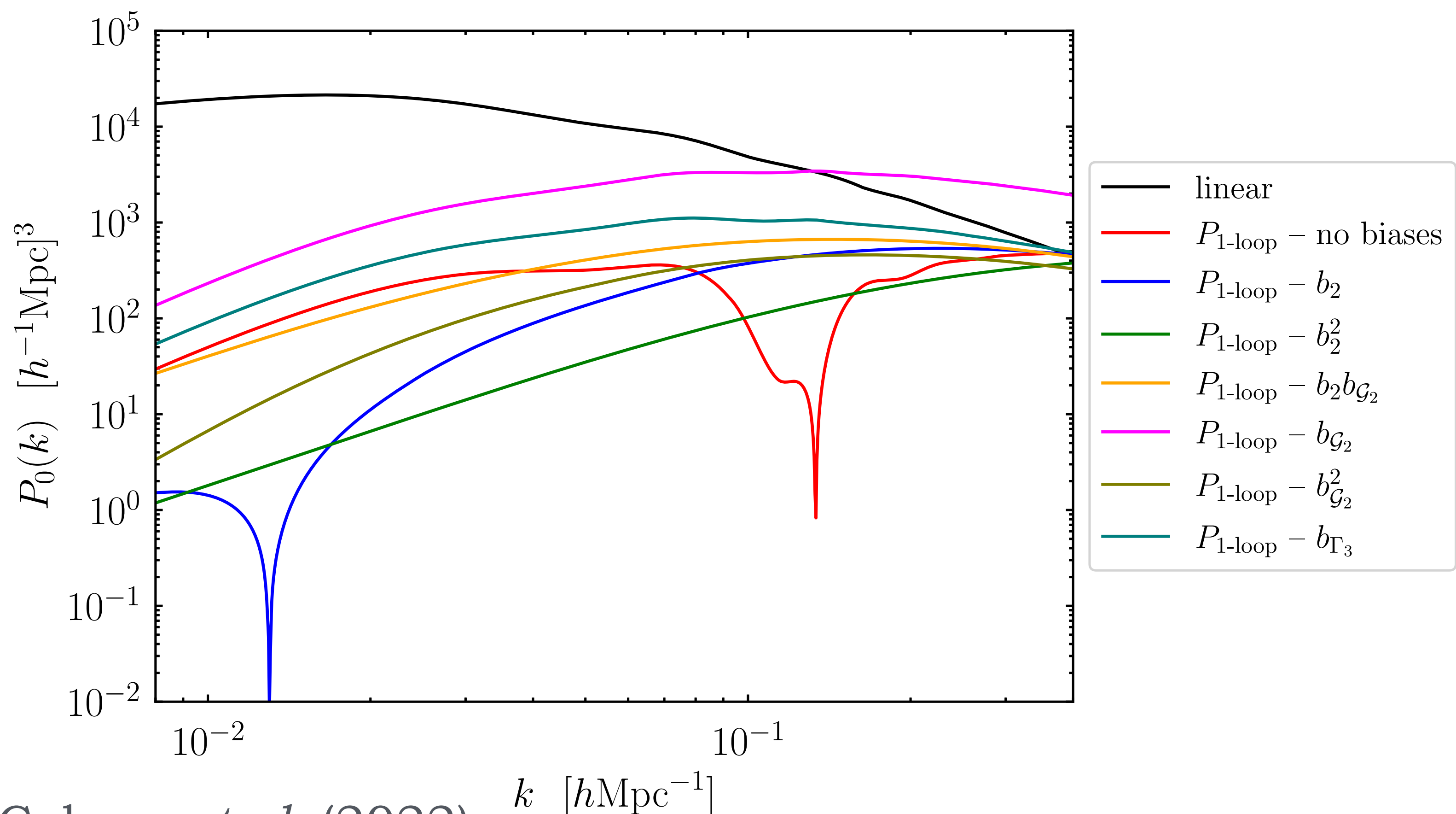
$$+\frac{1}{\bar{n}_g}\left(c_{\epsilon,1} + c_{\epsilon,2}\frac{k^2}{k_{\rm M}^2} + c_{\epsilon,3}f\mu^2\frac{k^2}{k_{\rm M}^2}\right)$$ shot-noise

EFTofLSS Blind Challenge

Nishimichi *et al* (2020)







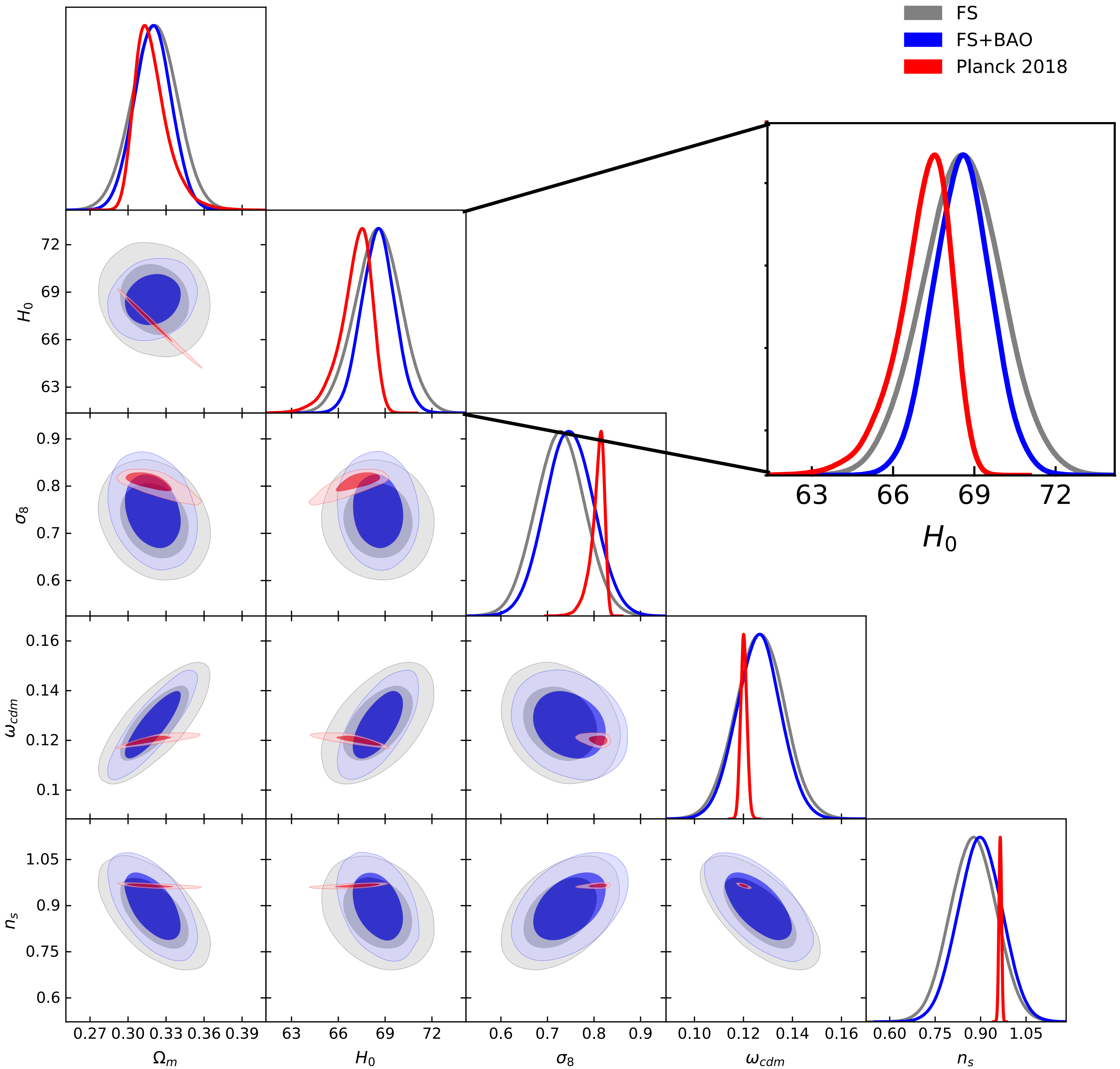
Cabass *et al.* (2022)

Test on very large simulation volume (600 h^{-3}Gpc^3)
(i.e. very small error bars)

The model includes 6 to 8 nuisance parameters
(depending on choices)

All describing the amplitude of very similar corrections

The success of the EFTofLSS



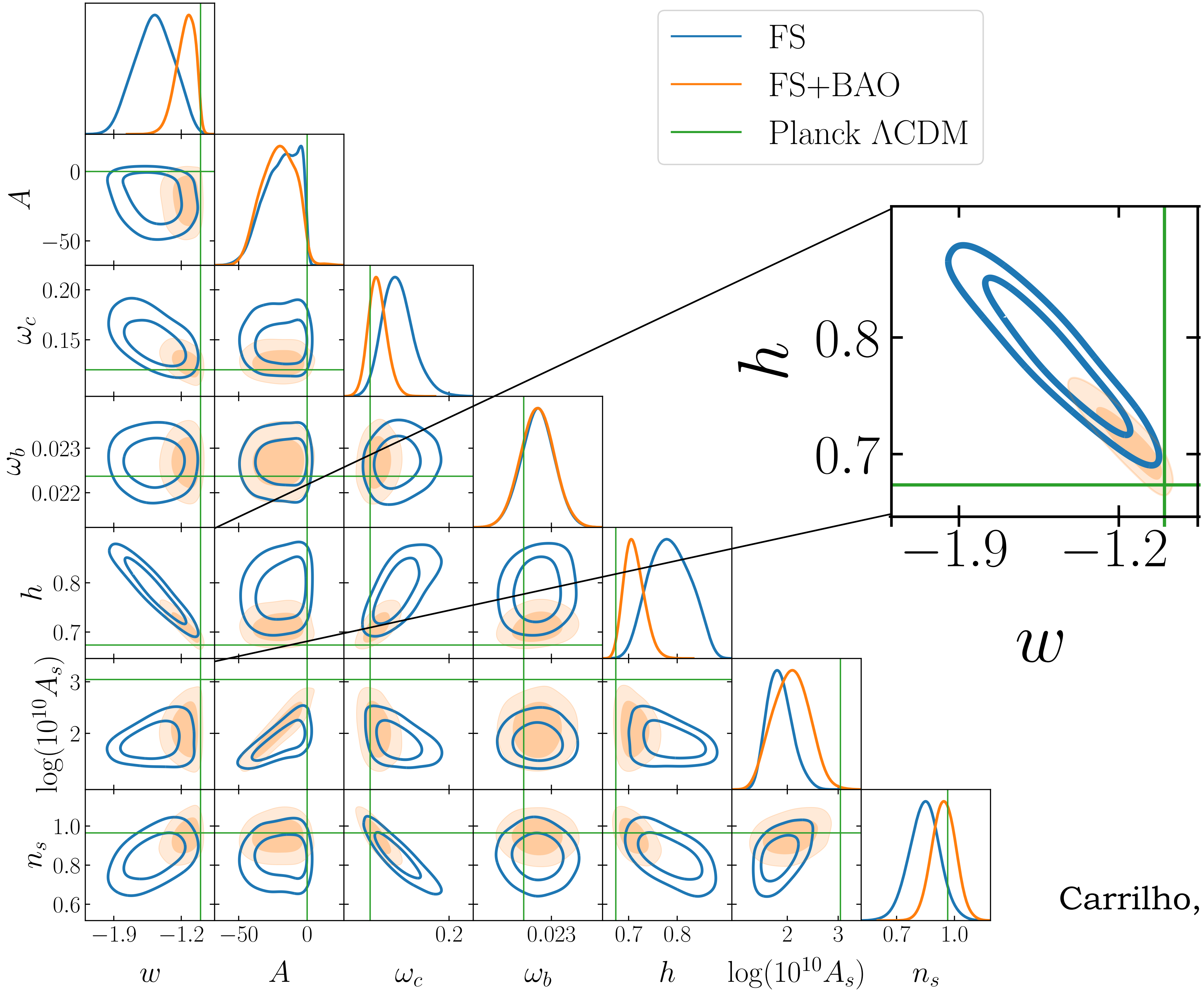
A 1.6% determination of H_0 comparable to the CMB result is obtained from Galaxy Clustering alone (BOSS)

(Although there was no need for any EFT for that …)

Philcox *et al.* (2020)

Similar results from D'Amico *et al.* (2020)

But beyond ΛCDM it gets tough ...



Severe projection effects due to parameter degeneracies prevent constraints on DE parameters

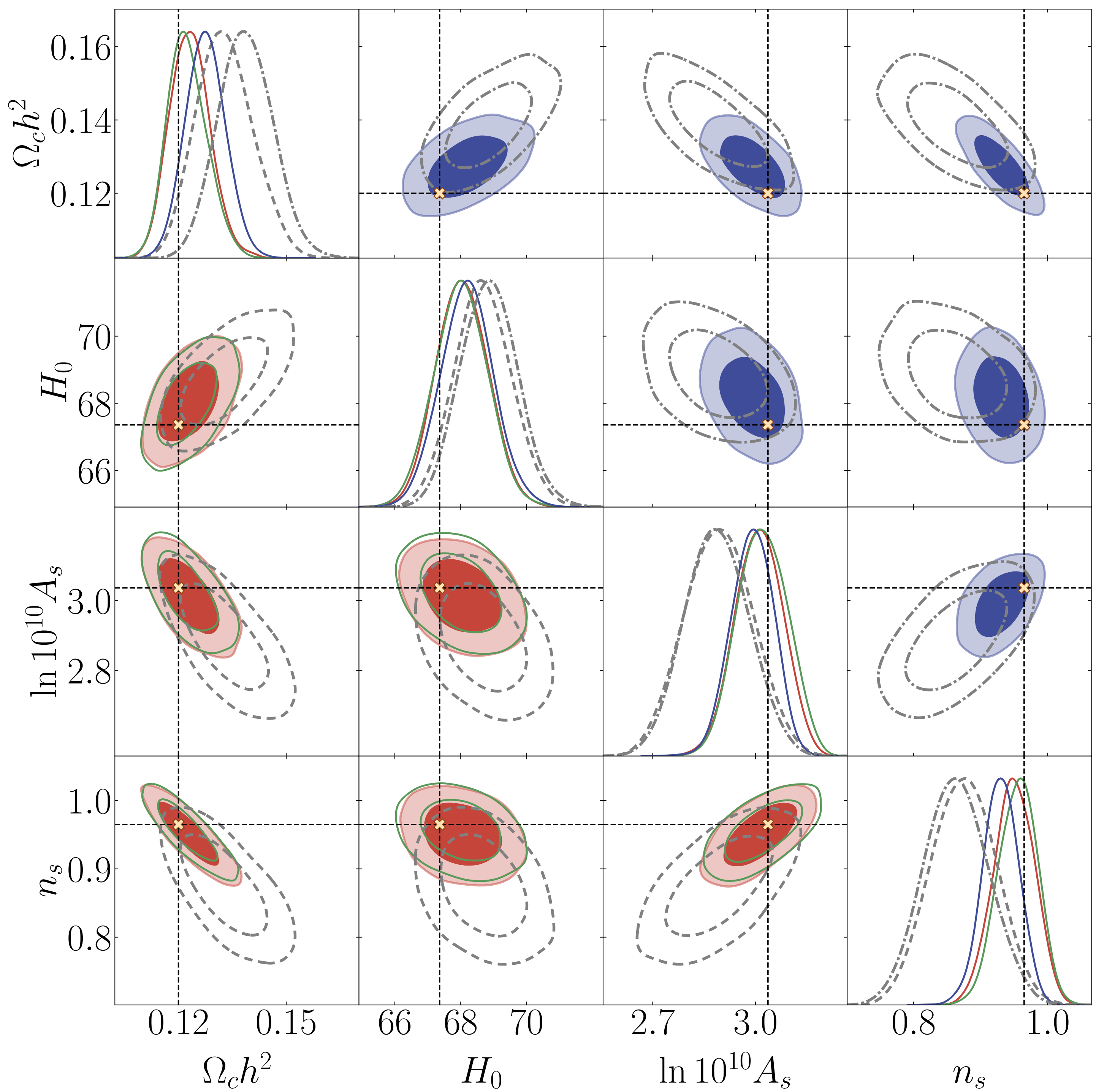
Carrilho, Moretti, Portsidou (2023)

Informative priors?

Do we need informative priors on bias and nuisance parameters from simulations?

Quick simulations are inaccurate ...

“Safe” simulations do not exist



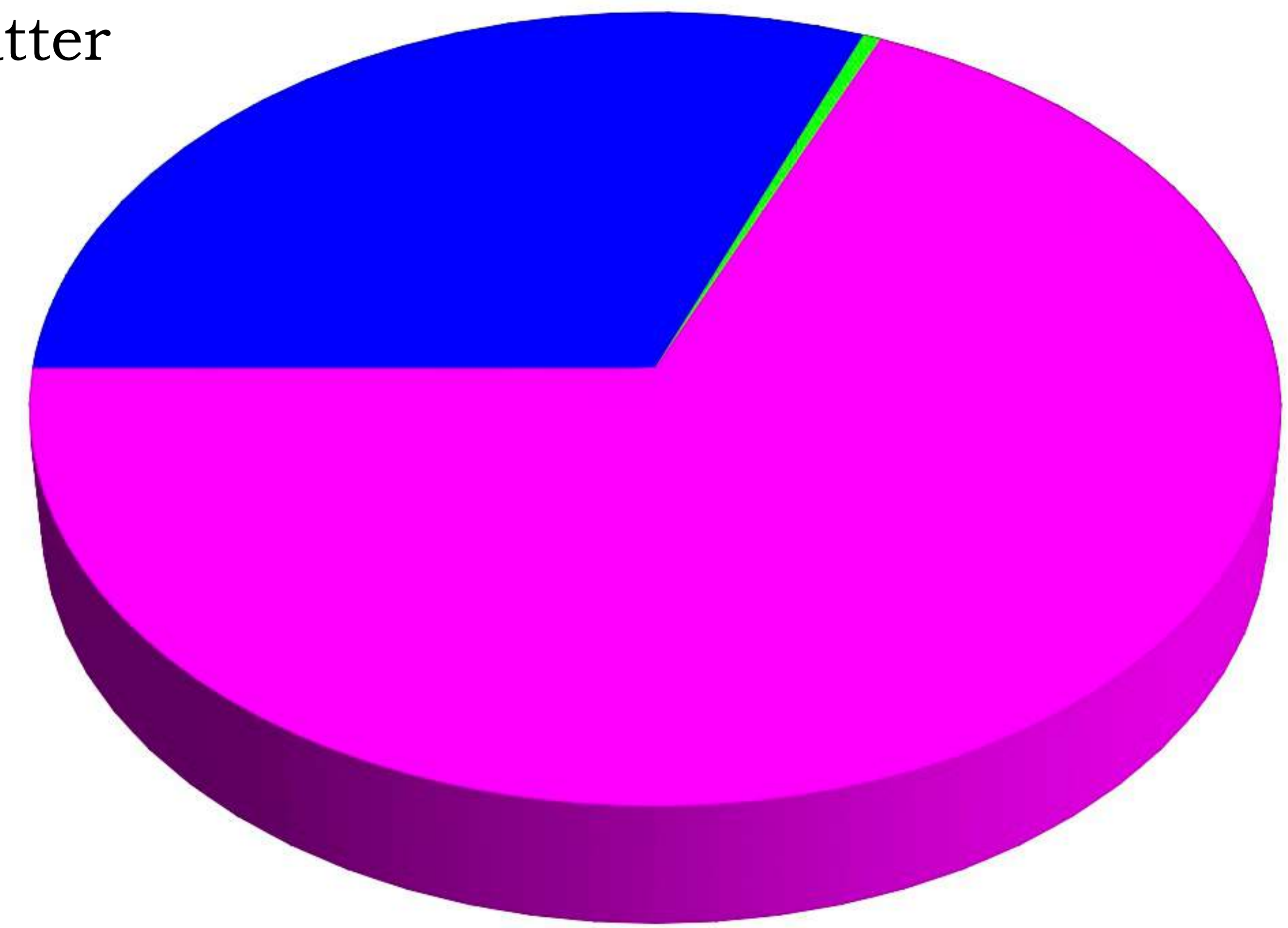
Zhang *et al.* (2024)
See also Chudaykin *et al.* (2024)

A slightly less simple Universe: *Neutrinos*

Neutrinos

$$\Omega_{\nu,0}h^2 = \frac{M_\nu}{93.14\,\mathrm{eV}}.$$

Dark Matter



Dark Energy

Neutrinos

Neutrinos in the early Universe (at high temperature) are kept in equilibrium with other species by weak interactions

$$f_{\rm eq}(p) = \left[\exp\left(\frac{p}{T}\right) + 1\right]^{-1}$$

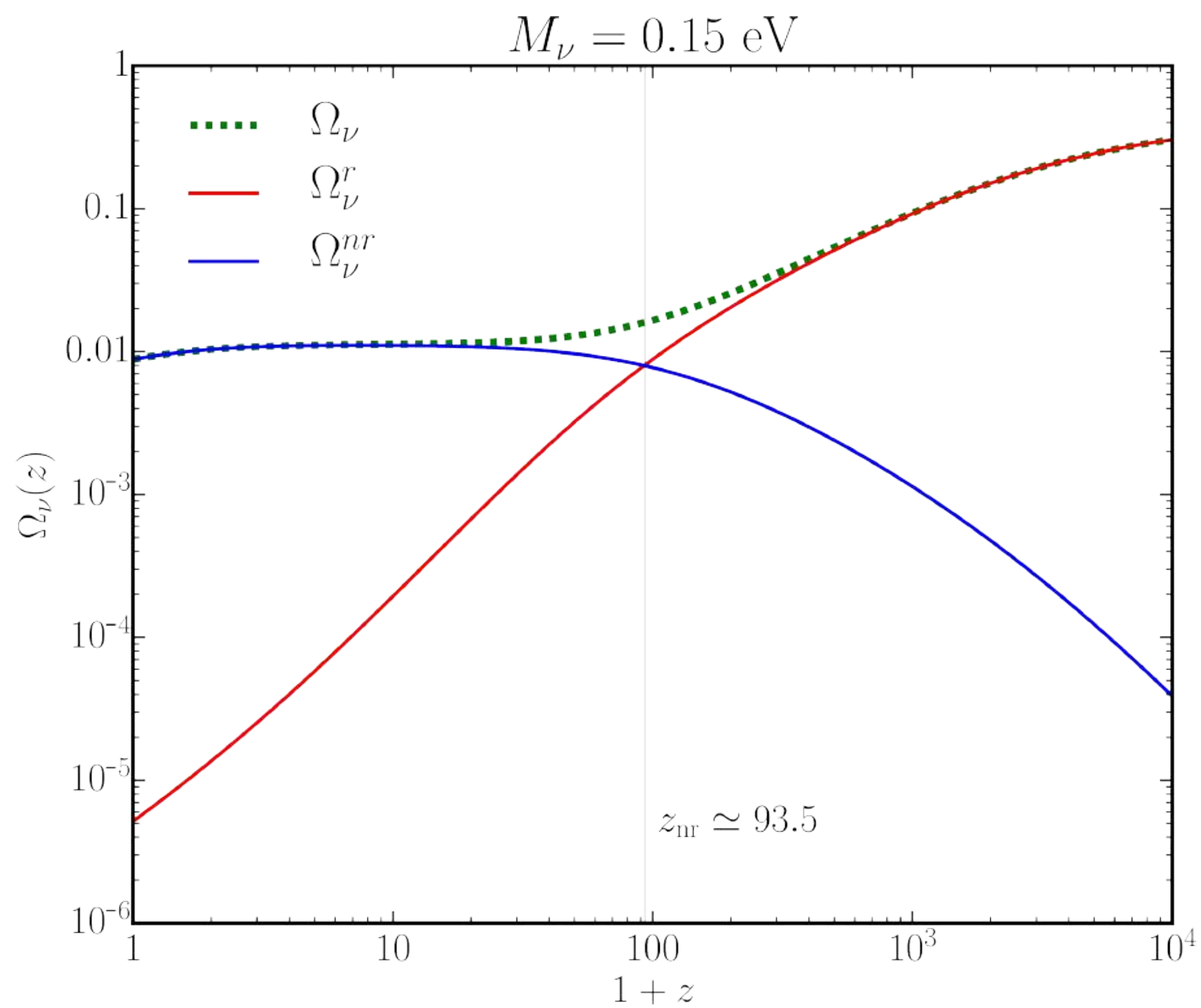
Fermi-Dirac distribution

They decouple when the temperature drops below $T \sim 1\,\mathrm{MeV}$ when they are still ultra relativistic

Two regimes:

- At **high redshift** they (mostly) contribute to the **radiation** energy density
- At **low redshift** they (mostly) contribute to the **matter** energy density

$$1 + z_{nr} \simeq 1890 \frac{m_{\nu,i}}{1\ \mathrm{eV}}$$



Cold and Total matter

A fraction of dark matter is not cold:

$$\Omega_m = \Omega_c + \Omega_\nu \qquad f_\nu \equiv \Omega_\nu / \Omega_m.$$

total matter — *cold* dark matter & baryons — neutrinos

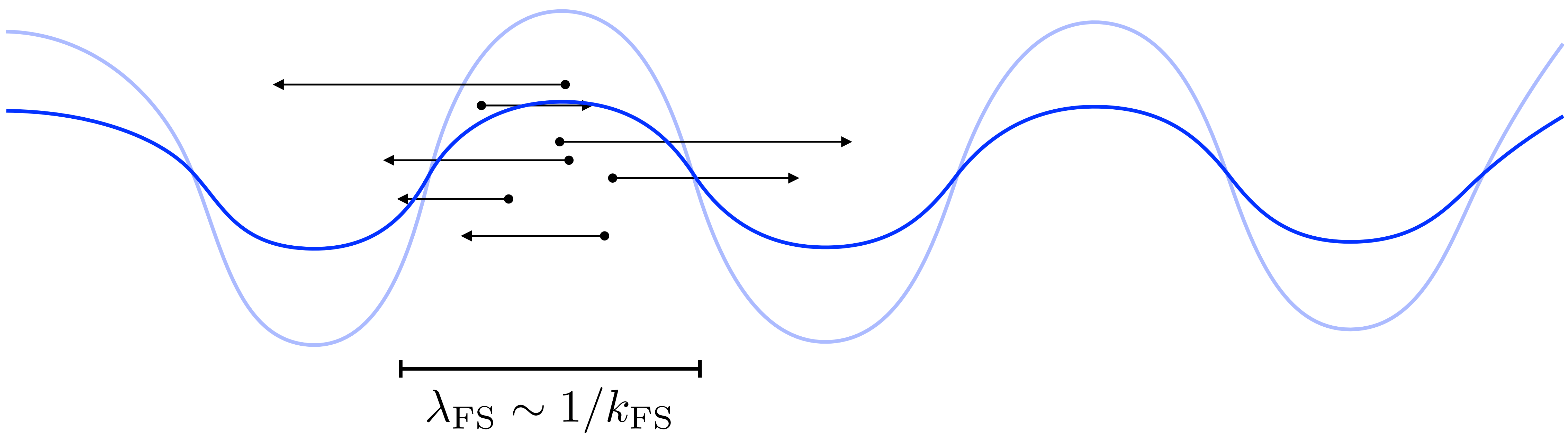
Total matter perturbations have two components …

$$\delta_m = (1 - f_\nu)\, \delta_c + f_\nu\, \delta_\nu$$

…. and *total* matter correlation functions more

$$P_{mm} = (1 - f_\nu)^2 P_{cc} + 2\, f_\nu\, (1 - f_\nu)\, P_{c\nu} + f_\nu^2 P_{\nu\nu}$$

The neutrino free-streaming scale



The free-streaming scale is fairly large (almost linear scales!) for viable values of the neutrino mass, $k_{\rm FS} \lesssim 0.1h\,{\rm Mpc}^{-1}$

$$k_{\rm FS,i} \simeq \frac{0.677}{(1+z)^2}\left(\frac{m_{\nu,\rm i}}{1\ \rm eV}\right)\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{\frac{1}{2}}\ h\ {\rm Mpc}^{-1}.$$

and it is time-dependent! This means that the growth factor and growth rate are now, in turn, scale-dependent

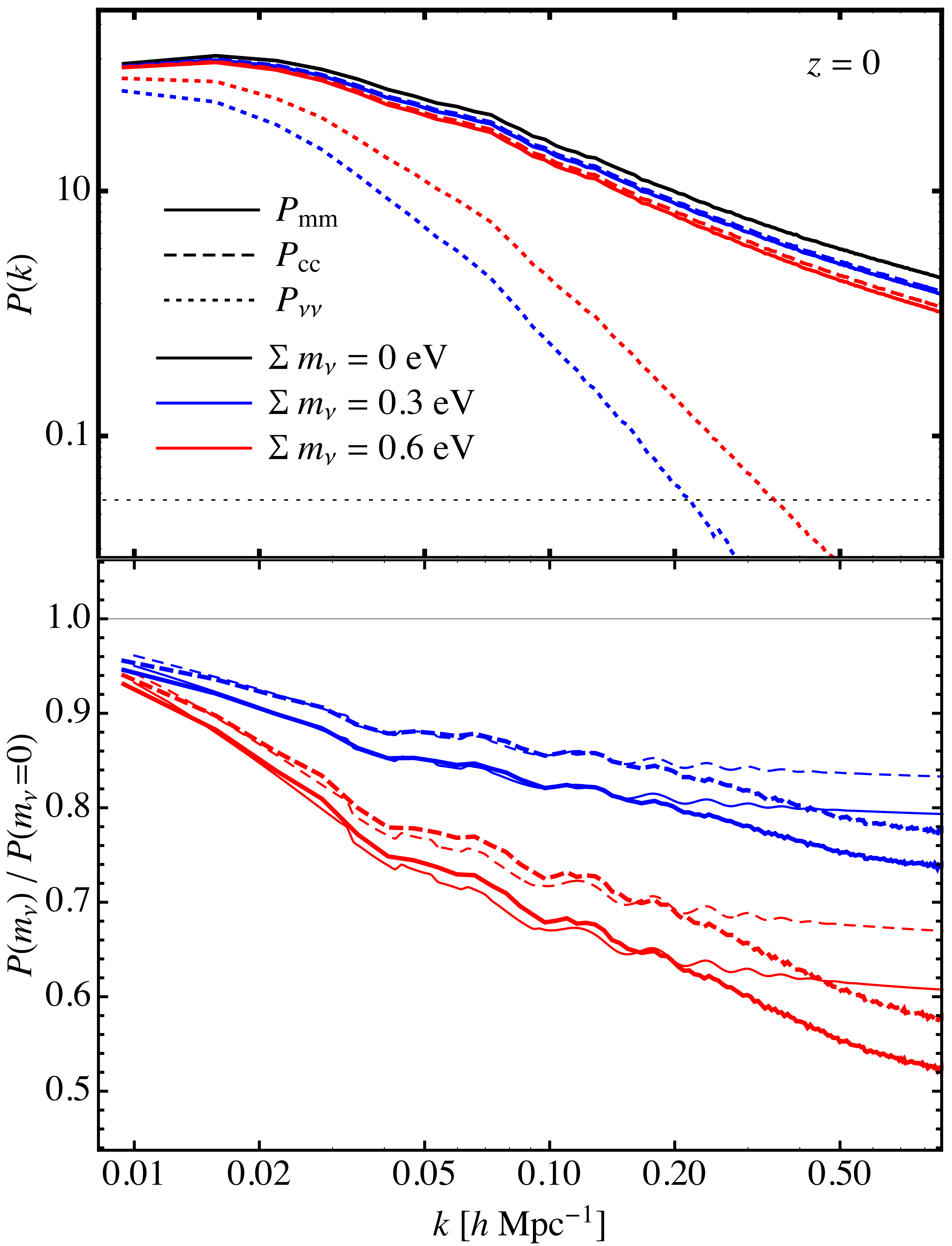
$$D(a), f(a) \quad \rightarrow \quad D(a,k), f(a,k)$$

Matter power spectra

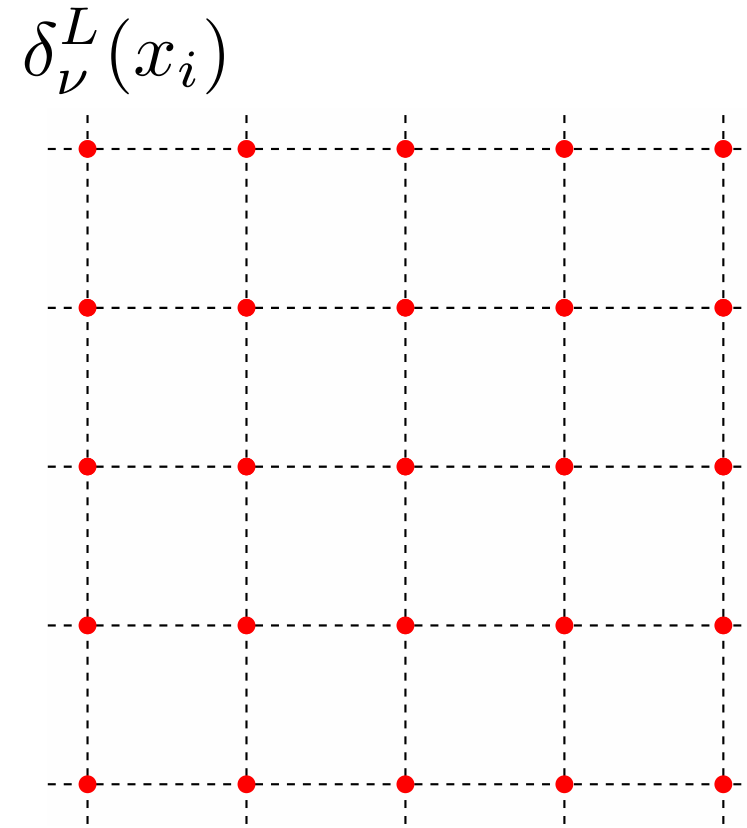
$$P_{mm} = (1 - f_\nu)^2\, P_{cc} + \\ + 2 f_\nu\, (1 - f_\nu)\, P_{c\nu} + f_\nu^2\, P_{\nu\nu}$$

$$\frac{P_{mm}(k; f_\nu)}{P_{mm}(k; f_\nu = 0)} \simeq 1 - 8 f_\nu$$

the suppression of the power spectrum due to neutrinos is proportional to the (total) neutrino mass



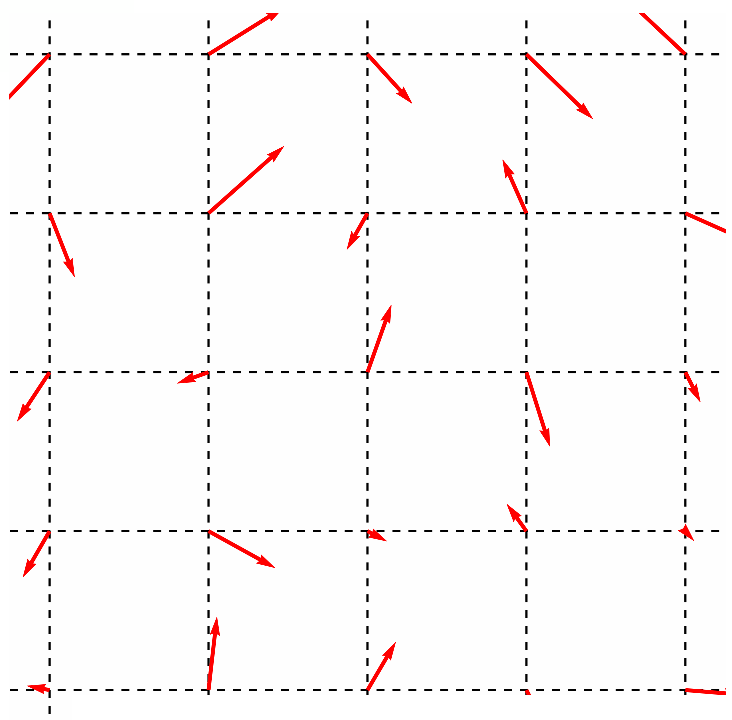
Numerical Simulations with neutrinos



Grid-based

Brandbyge *et al.* (2008), Viel *et al.* (2010)
Ali-Haïmoud & Bird (2013)

neutrino perturbations
are linear by constructions



Particle-based ...

Brandbyge *et al.* (2008), Viel *et al.* (2010)
Ali-Haïmoud & Bird (2013)

shot-noise ?

... and mixed ...

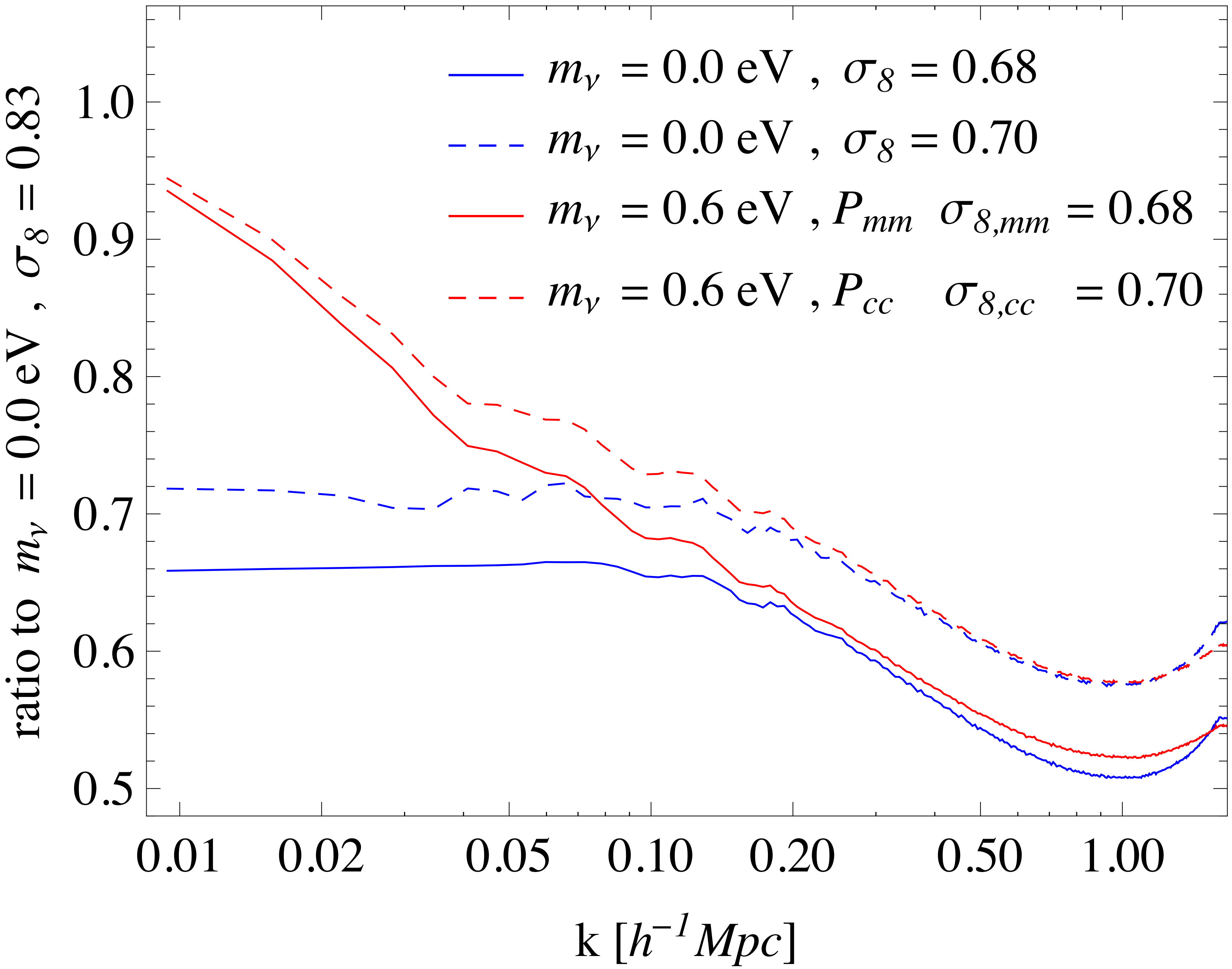
Brandbyge *et al.* (2009), Banerjee & Dalal (2016)

... and relativistic

Adamek *et al.* (2017)

Massive neutrinos simulations are not simple ...

Nonlinear neutrinos effect



Castorina *et al.* (2015)

Galaxy bias with neutrinos

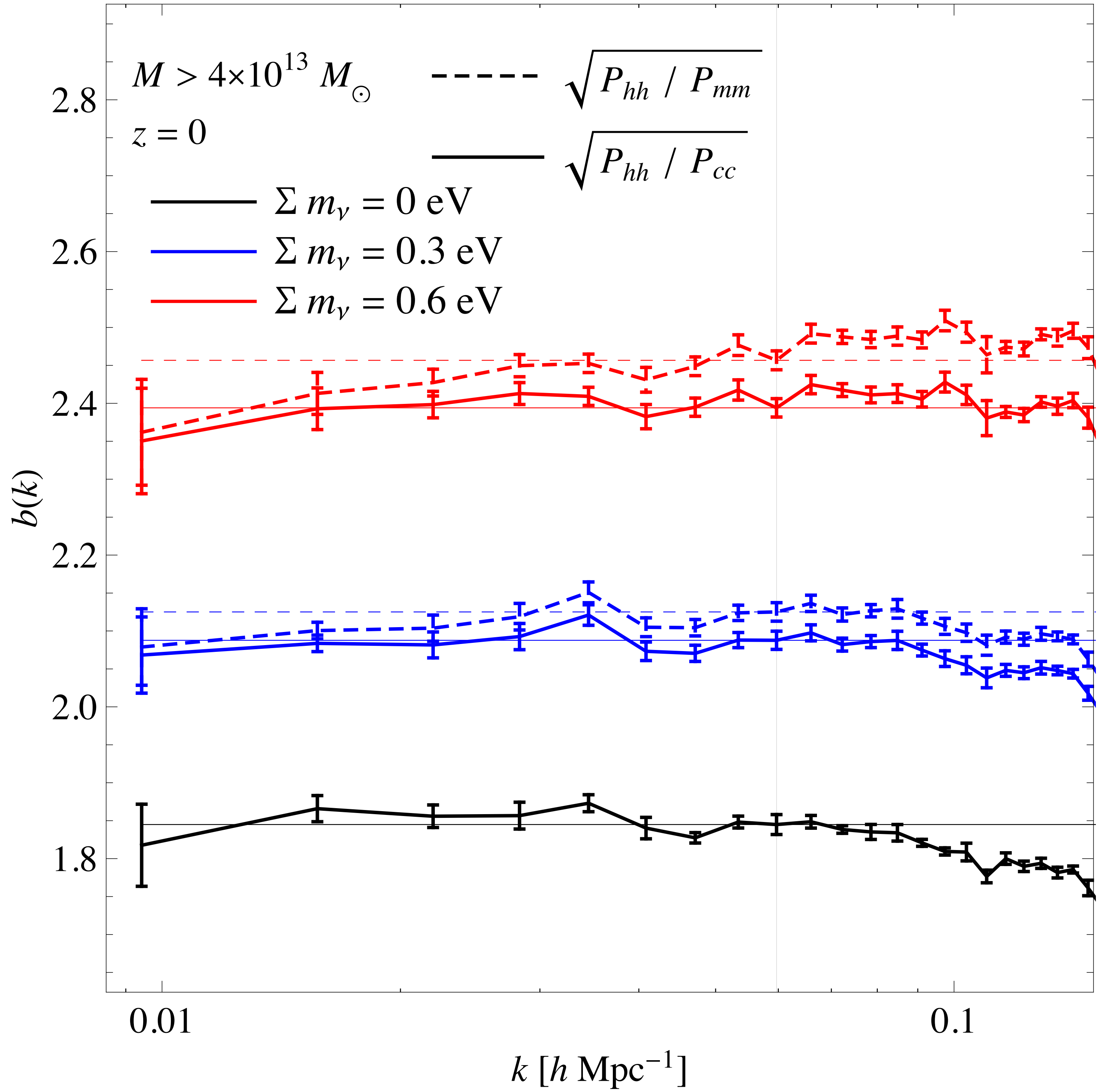
$$\delta_g = b\,\delta_m + \ldots$$

or

$$\delta_g = b\,\delta_c + \ldots$$

?

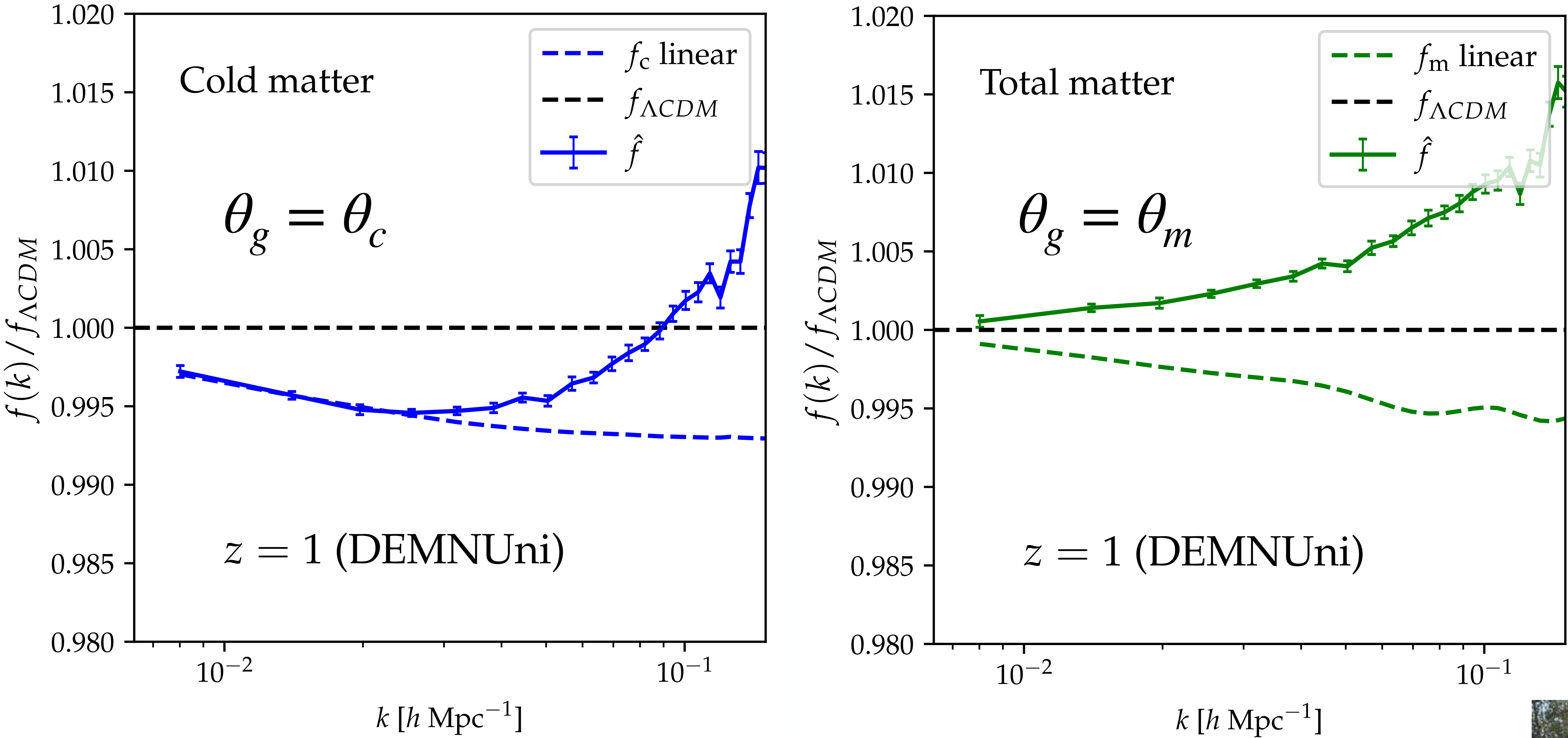
Defining bias w.r.t. the total matter power spectrum introduces a (spurious) scale-dependence



Castorina *et al.* (2014)

Kaiser effect with neutrinos

$$\delta_g = b\,\delta_c - \mu^2 \frac{\theta_m}{\mathscr{H}} \quad \text{or} \quad \delta_g = b\,\delta_c - \mu^2 \frac{\theta_c}{\mathscr{H}} \quad ?$$



$$P_s(k\,\mu) = [b_1 + f(k)\,\mu^2]^2\, P_L(k)$$

Verdiani *et al.* (in prep.)

Model validation against numerical simulations

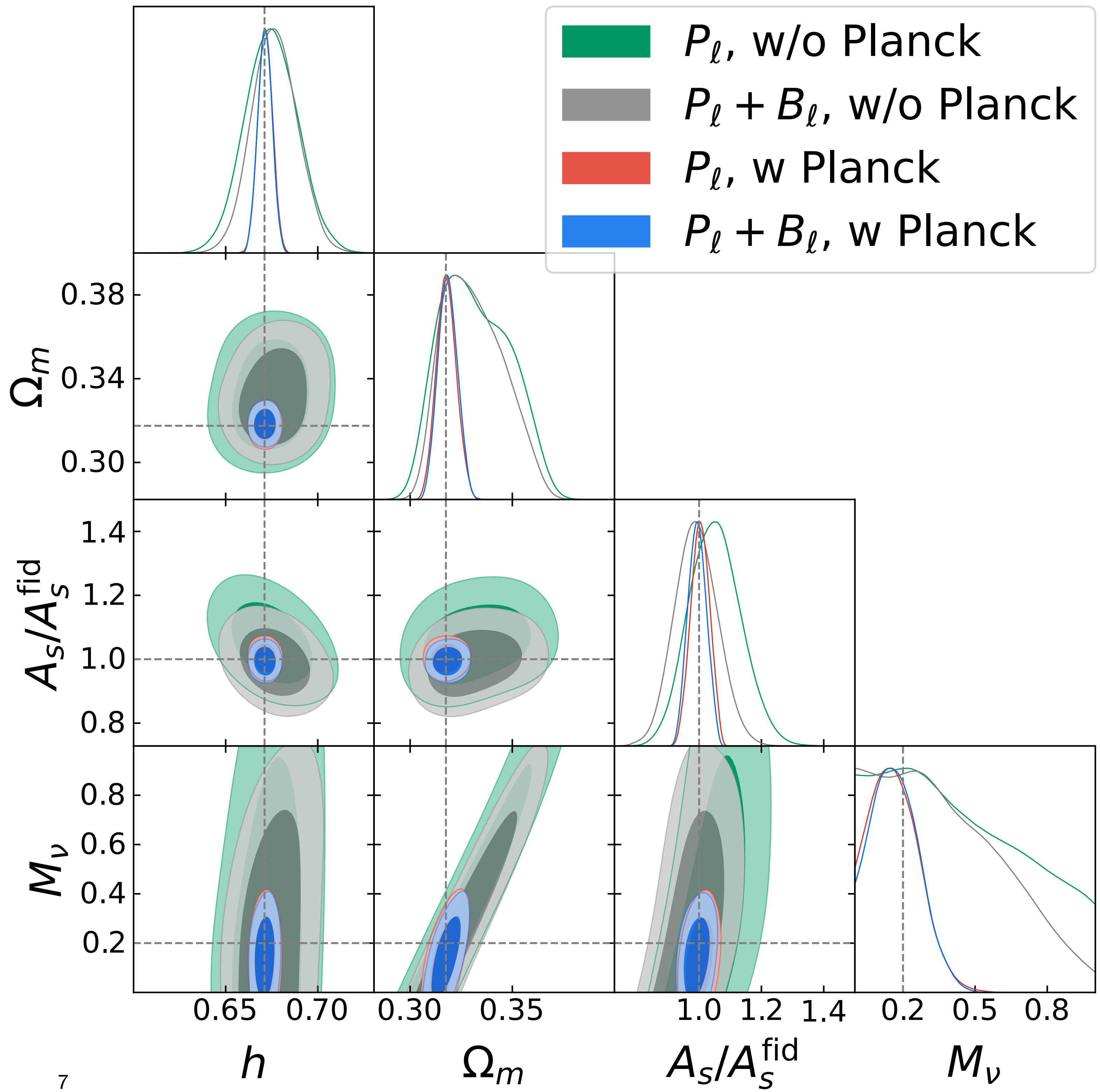
Few works, so far, in the literature:

- Noriega et al. (2020) no galaxies, only halos, only power spectrum
- Noriega et al. (2024), Maus et al. (2024), DESI mock galaxies, only power spectrum

We use two large sets of simulations: Quijote & DEMNUni

and include the bispectrum (and the real-space power spectrum *Q*) … still, Planck priors are necessary

Bellini, Verdiani, Moretti *et al.* (in prep.)

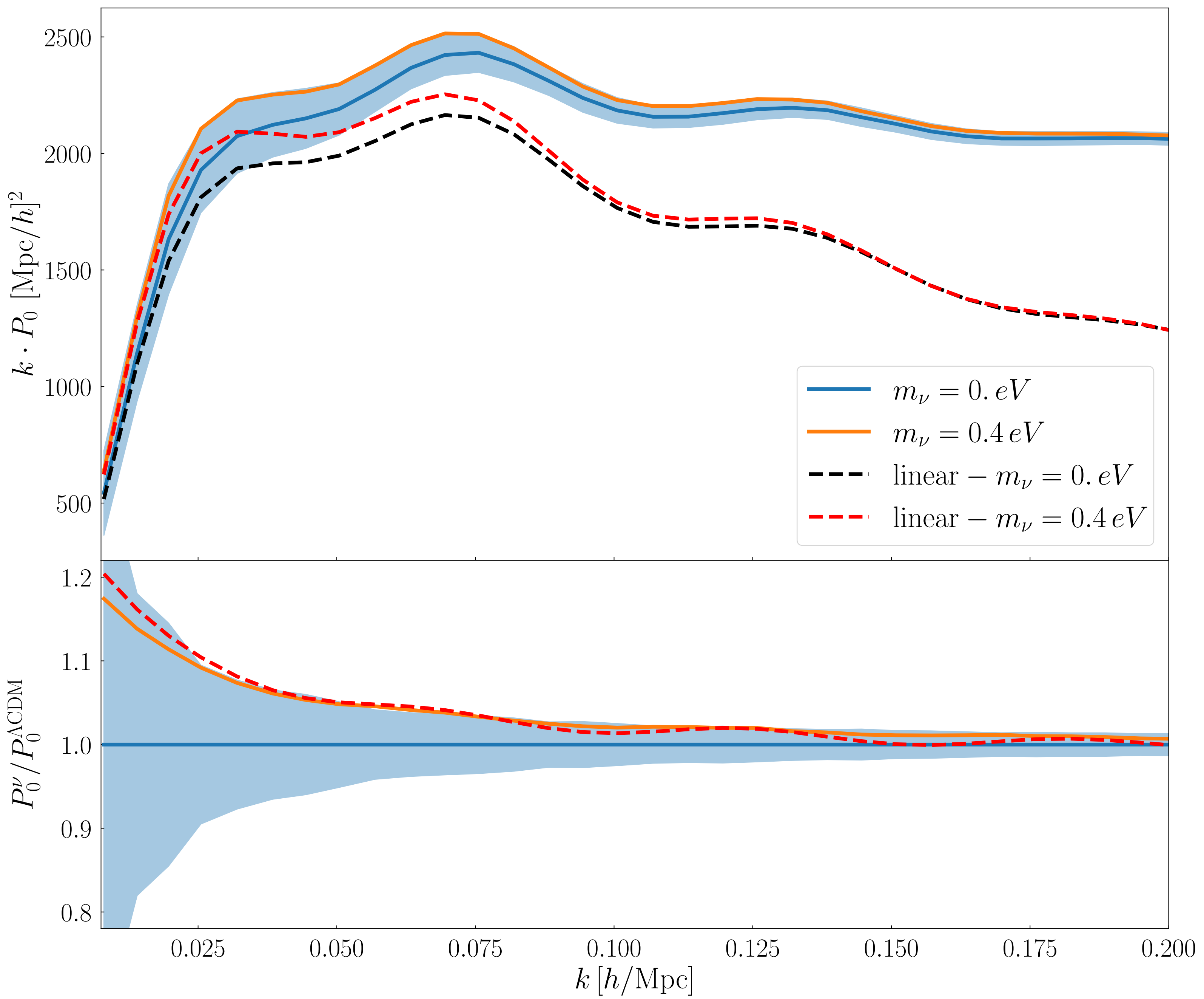


Model validation against numerical simulations

Nonlinear galaxy power spectra and corresponding linear power spectrum (from the full fit)

No clear feature of the free-streaming scale

The same modelling can be extended to *composite dark matter* (coming up!)



Bellini *et al.* (in prep.)

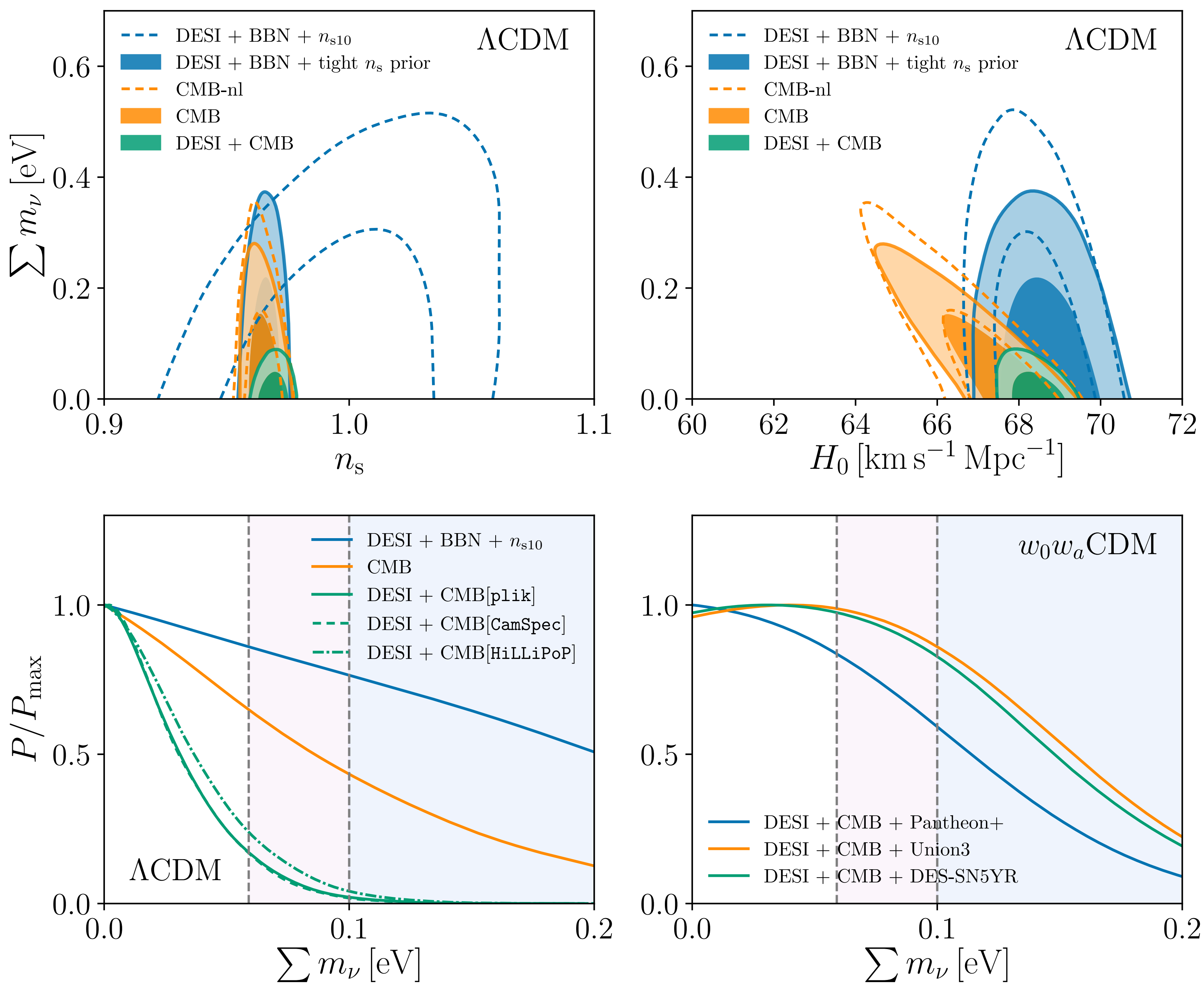
Conclusions

We know have a model that allows us to marginalise over all (?) nonlinear effects

More should be done, maybe in terms of informative priors and probe combinations

The role of N-body simulations will be crucial in the future (*in fact it goes both ways …*)

DESI neutrino results



DESI DR1 Full-Shape Analysis (2024)

Problems with Standard PT

- No small parameters (unlike QED)
- The expansion is ill-defined
- The convergence of the loop integrals is accidental …

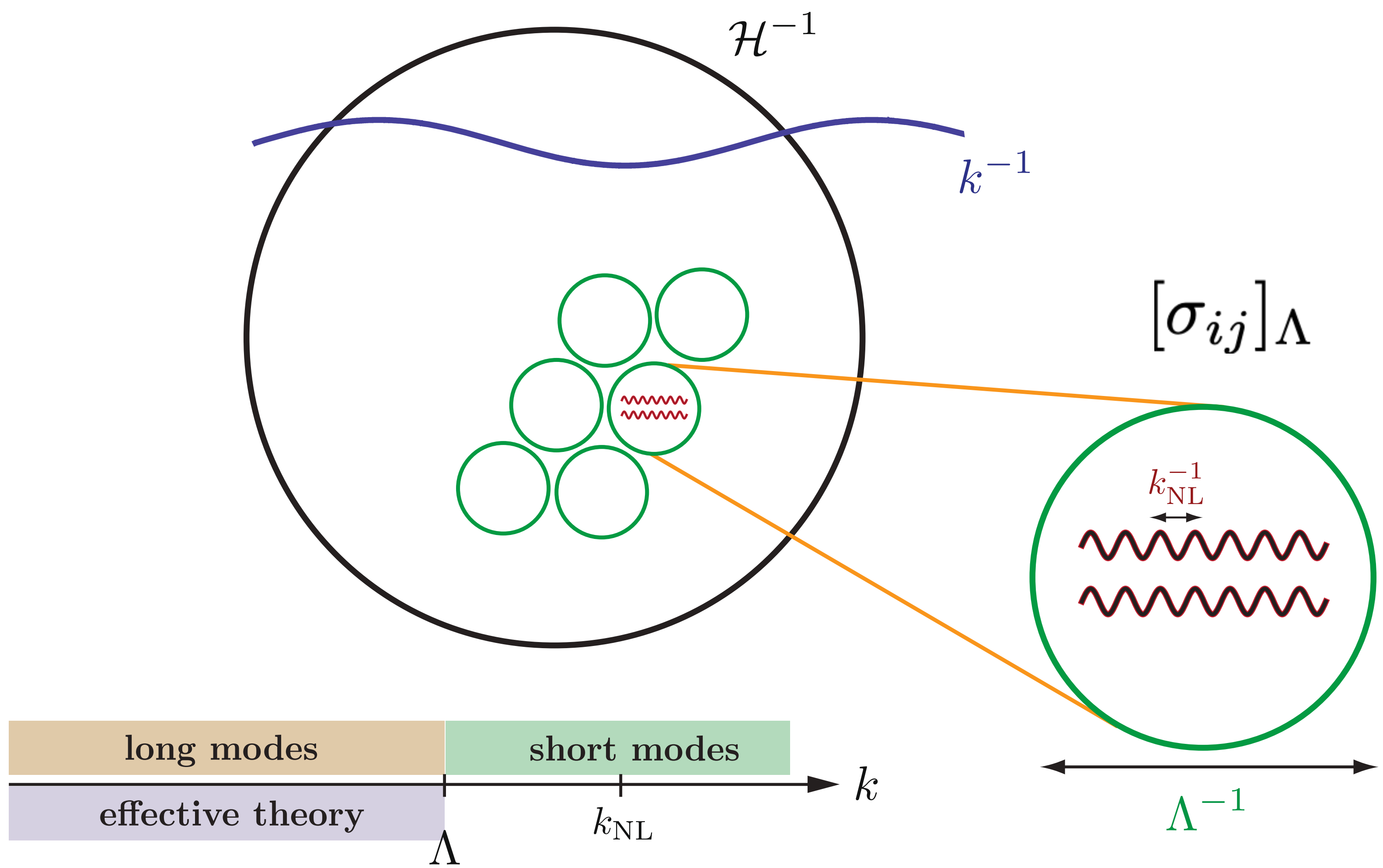
$$P_{22}(k) = 2\int d^3q\, F_2(\vec{q}, \vec{k}-\vec{q})\, P_L(q)\, P_L(|\vec{k}-\vec{q}|)$$

$$P_{13}(k) = 6\, P_L(k)\int d^3q\, F_3(\vec{k}, \vec{q}, \vec{k}-\vec{q})\, P_L(q)$$

Effective Field Theory of Large-Scale Structure

We still have the problem of how to deal with the small scale dynamics, or, more precisely, the *effect of small scales on large-scale perturbations*

$$\delta = \delta_l + \delta_s \qquad \delta_l(\vec{x}) = \int d^3y\, W_\Lambda(|\vec{x}-\vec{y}|)\, \delta(\vec{y})$$



Even assuming a vanishing stress-tensor, $\sigma_{ij} = 0$ (as we did in the single-stream approximation), small-scale dynamics induces an ***effective stress tensor***, affecting the large-scale perturbations

Baumann, Nicolas, Senatore & Zaldarriaga (2010)
Carrasco, Hertzberg & Senatore (2012)

Effective Field Theory of Large-Scale Structure

We can expect an additional term in Euler equation

$$\frac{\partial\theta}{\partial\tau} + \mathcal{H}\theta + \vec{\nabla}\cdot[(\vec{u}\cdot\vec{\nabla})\vec{u}] = -\frac{3}{2}\mathcal{H}^2\delta - \frac{1}{\bar{\rho}}\nabla_i\nabla_j\langle[\sigma_{ij}]_\Lambda\rangle$$

with the effective stress-tensor depending on large-scale fluctuations

$$\langle[\sigma_{ij}]_\Lambda\rangle = \langle[\sigma_{ij}]_\Lambda\rangle_0 + \left.\frac{\partial\langle[\sigma_{ij}]_\Lambda\rangle}{\partial\delta_l}\right|_{\delta_l=0}\delta_l + \mathcal{O}(\delta_l^2)$$

FT →

$$-\frac{1}{\bar{\rho}}k_ik_j\langle[\sigma_{ij}]_\Lambda\rangle \supset k^2\left(c_s^2\delta_l + c_v^2\frac{\theta_l}{f\mathcal{H}}\right) = k^2\,c_0\,\delta_l^{(1)}$$

our nonlinear solution for the matter density becomes

$$\delta_l = \delta_l^{(1)} + \delta_l^{(2)} + \delta_l^{(3)} + c_0\,k^2\,\delta_l^{(1)} + \ldots$$

with c_0 a free parameter ...

The one-loop power spectrum in the EFTofLSS

The 2-point correlator gains a new contribution

$$\langle \delta_l \delta_l \rangle \supset \langle \delta_l^{(1)} \, c_0 \, k^2 \, \delta_l^{(1)} \rangle \sim c_0 \, k^2 \, P_L(k)$$

A counterterm regularising the one-loop integrals

$$P(k) = P_L(k) + P_{22}(k) + P_{13}(k) + c_0 \, k^2 \, P_L(k) + \mathcal{O}(\delta_l^6)$$

$$\int_0^\infty = \int_0^k + \int_k^\infty \quad \longrightarrow \quad P_{22}^{\mathrm{UV}} + P_{13}^{\mathrm{UV}} \simeq P_{13}^{\mathrm{UV}} \simeq \frac{16}{23} P_L(k) k^2 \int_k^\infty \frac{q}{2\pi^2} P_L(q)$$

The value of c_0 ensures the convergence of the integrals. In practice this is a nuisance parameters to be fixed in the comparison with data or simulations