Model independent searches of New Physics from the Large Scale Structure

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Planck 2025@Padova 29/05/2025

In collaboration with:

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Outline

1) Beyond **Λ**CDM, model independently
2) The “LSS bootstrap”
3) From field correlators to the field itself

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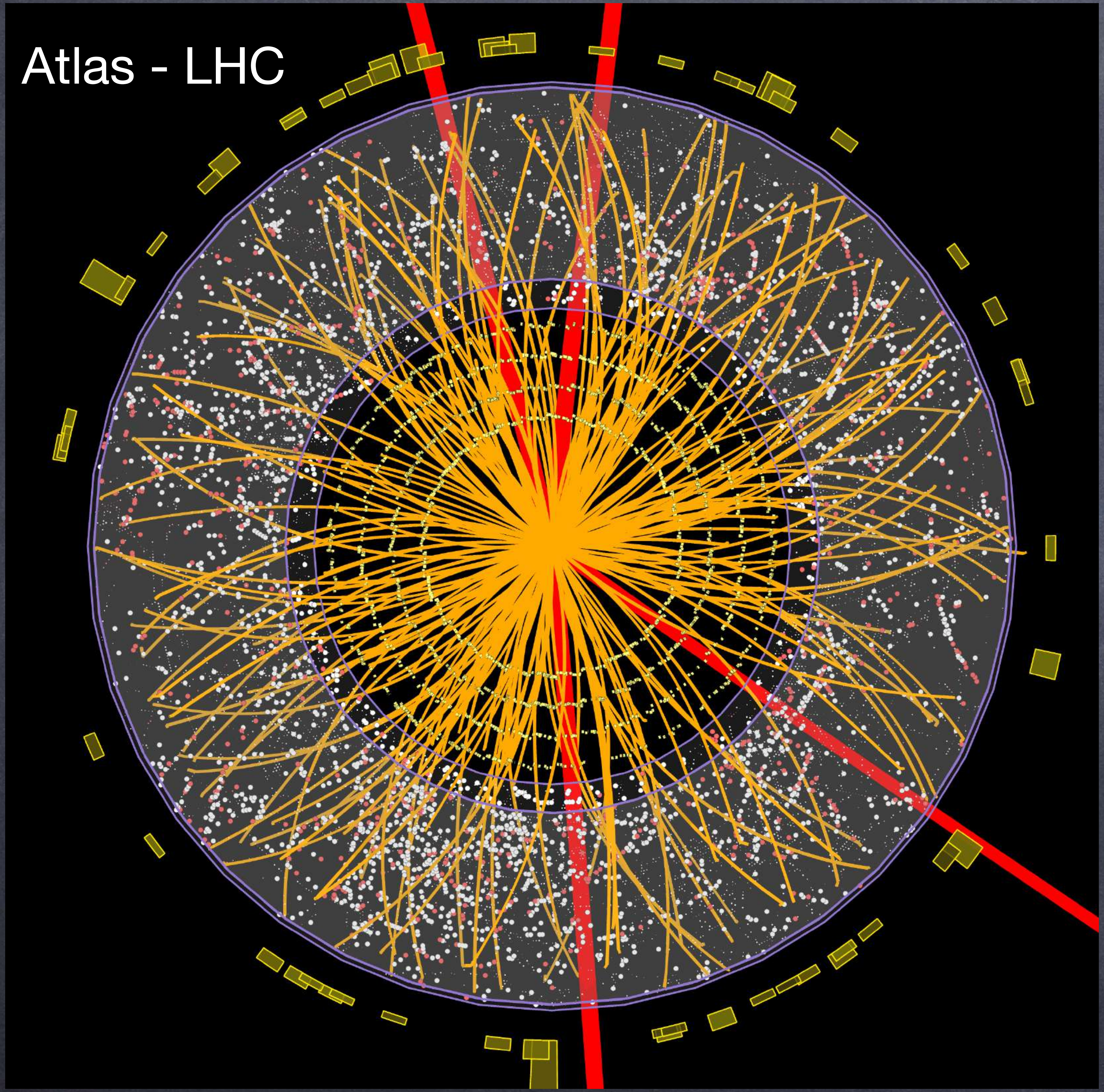
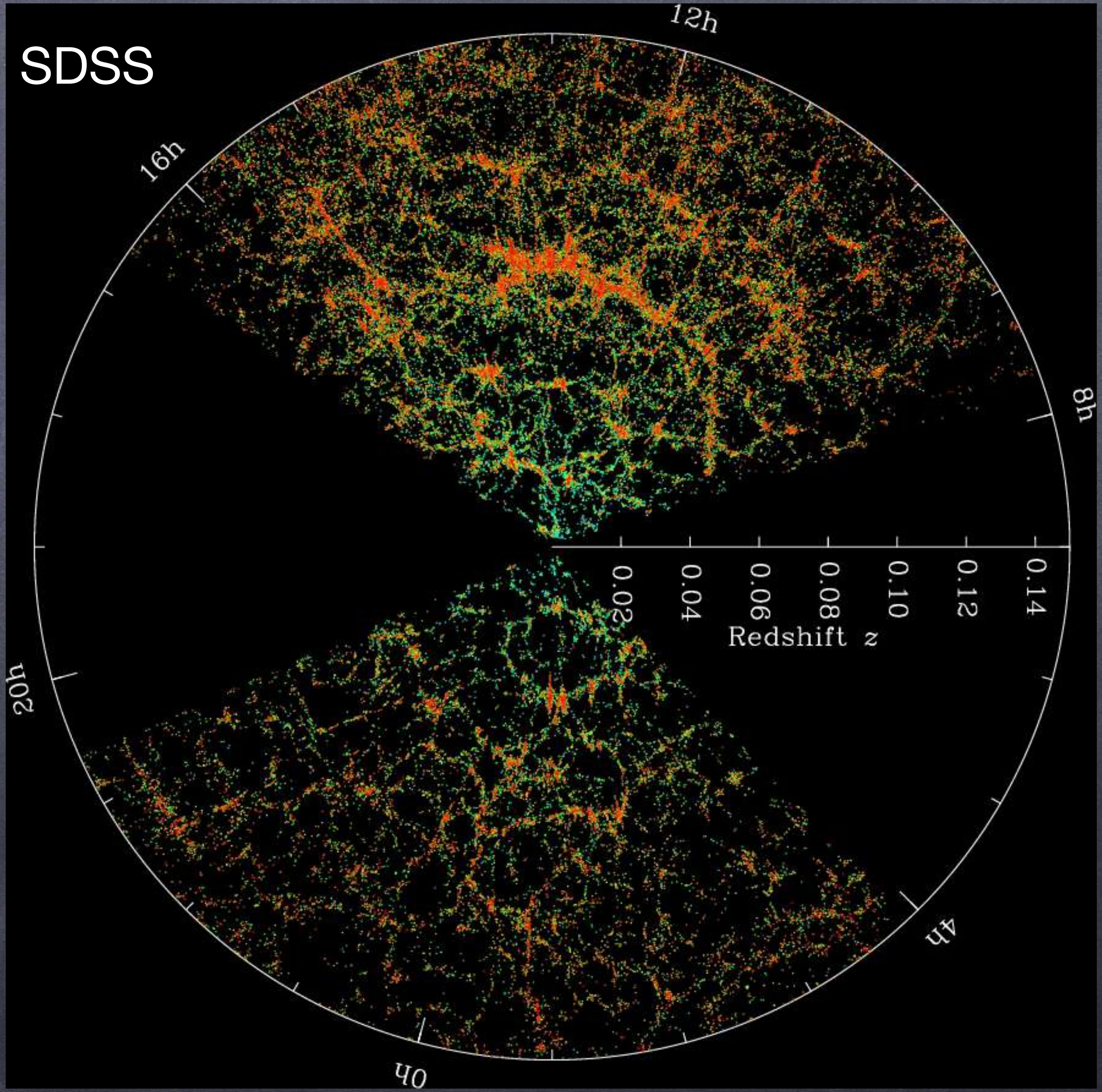
1) Beyond **Λ**CDM, model independently
2) The "LSS bootstrap"
3) From field correlators to the field itself
4) Antonio's magic powers!

Standard Model(s) established now, search for New Physics!





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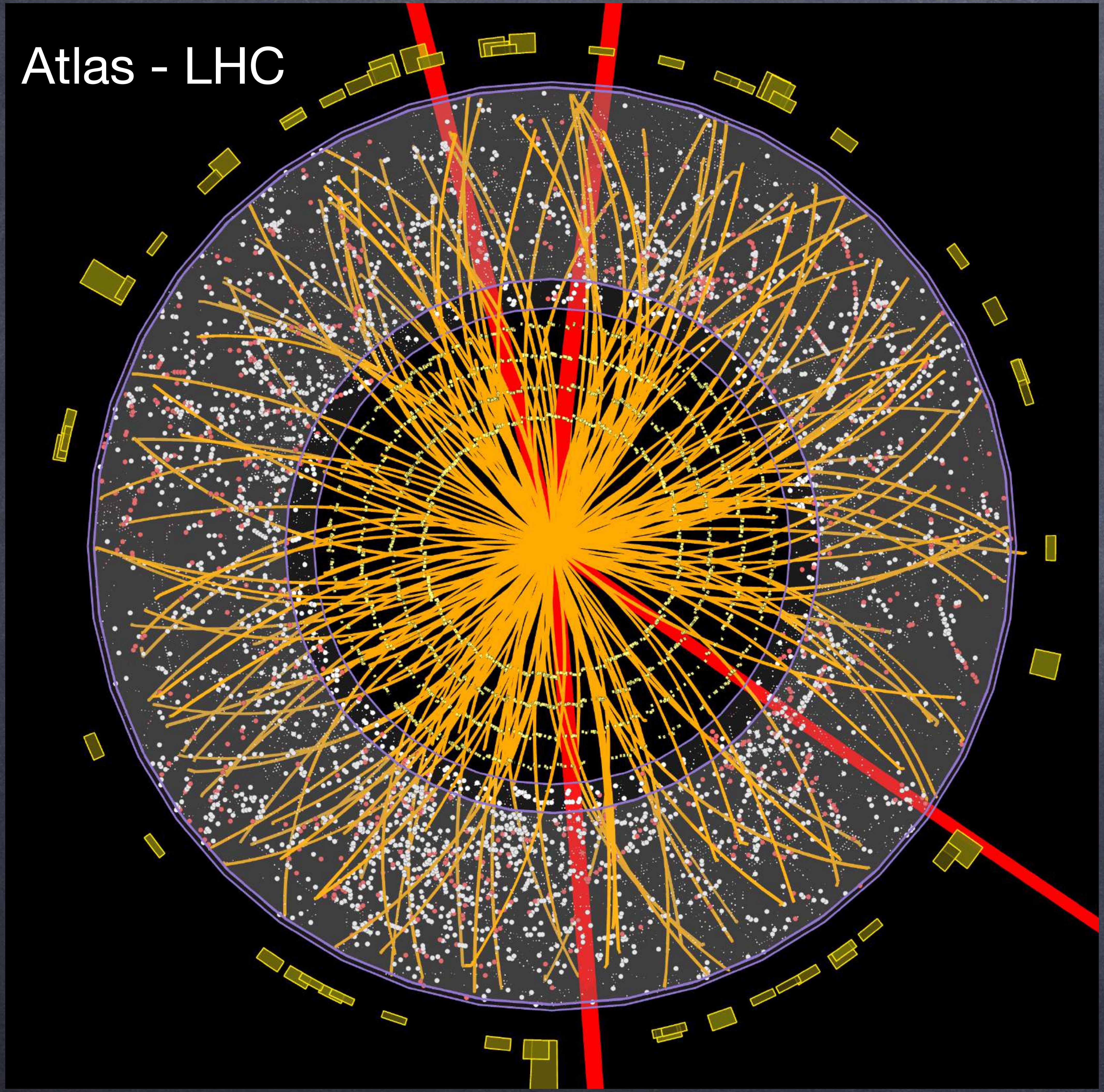
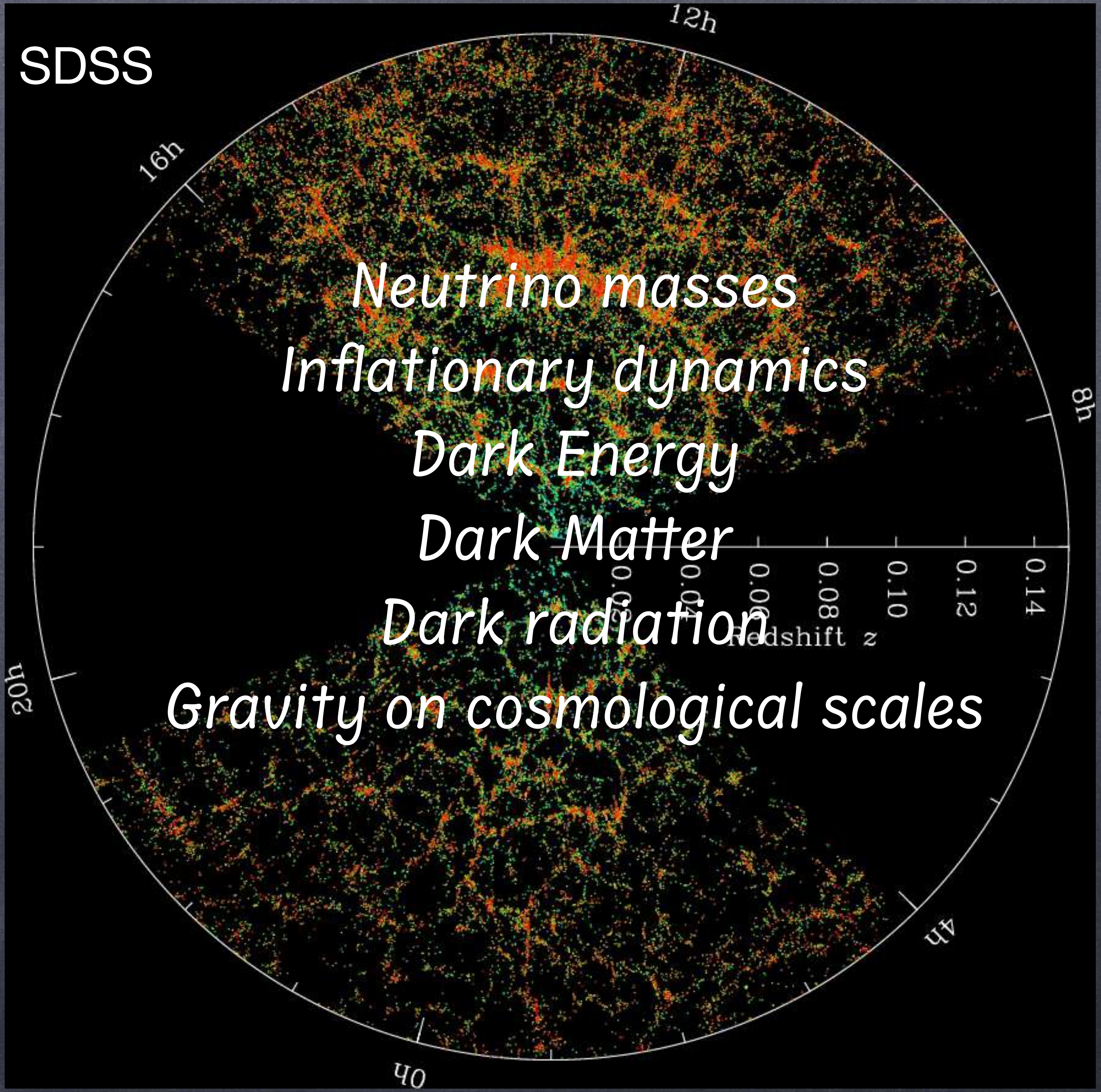
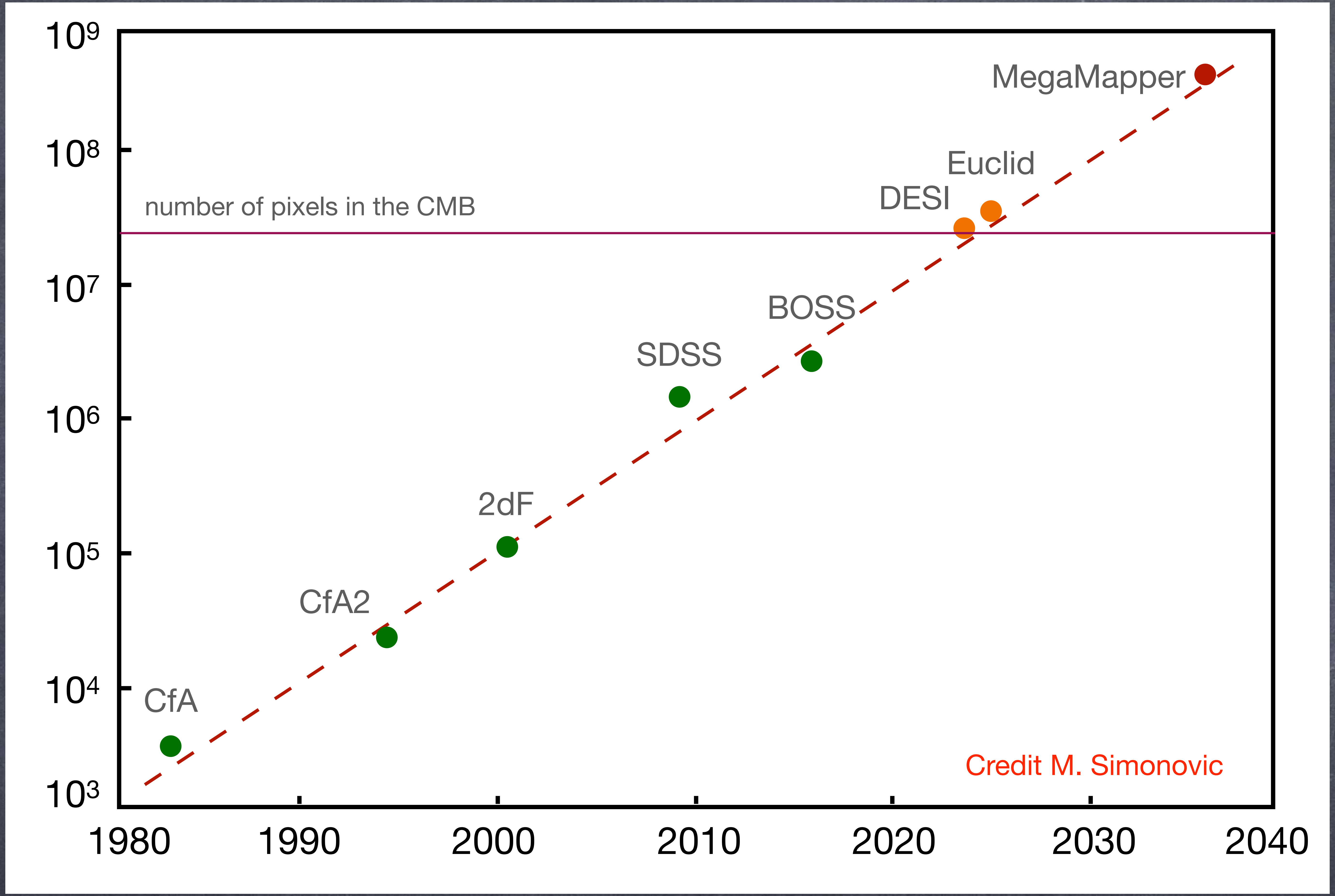


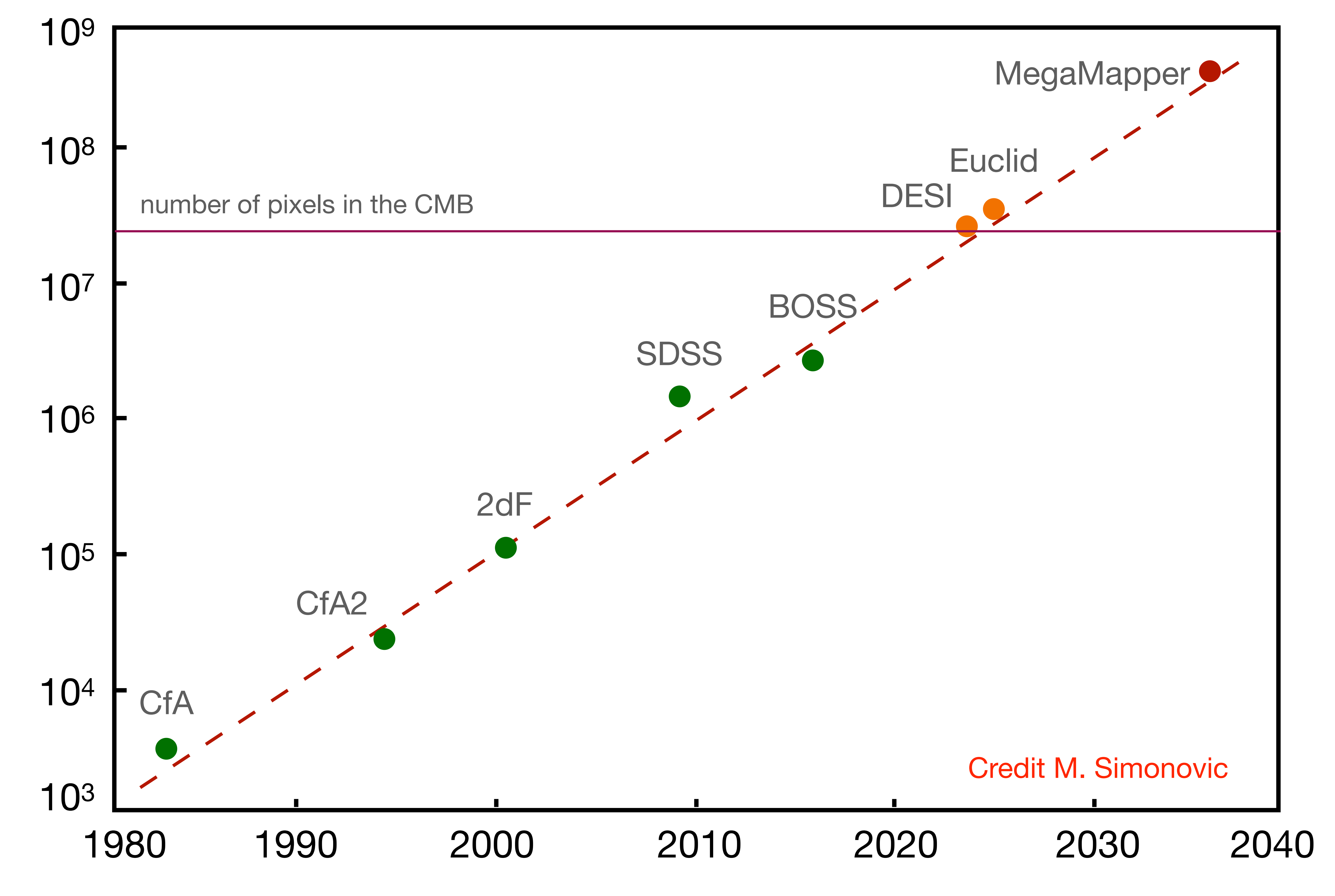


The CMB–LSS relay race



Info in CMB ≃ Info in LSS

The CMB-LSS relay race



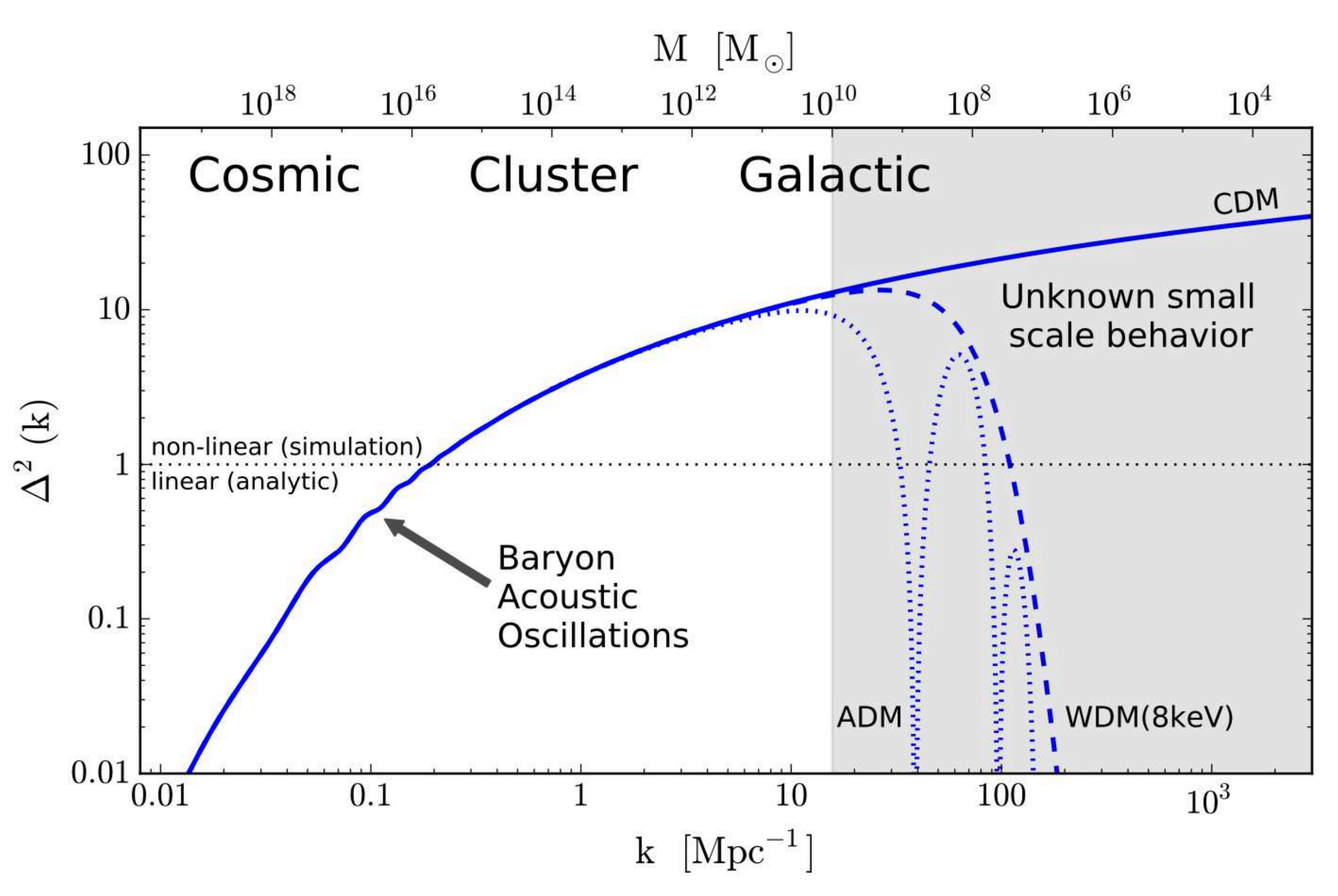
Info in CMB ≃ Info in LSS

CMB is (mostly) linear – LSS is (mostly) nonlinear

New Physics in LSS: "Energy" vs "Intensity"

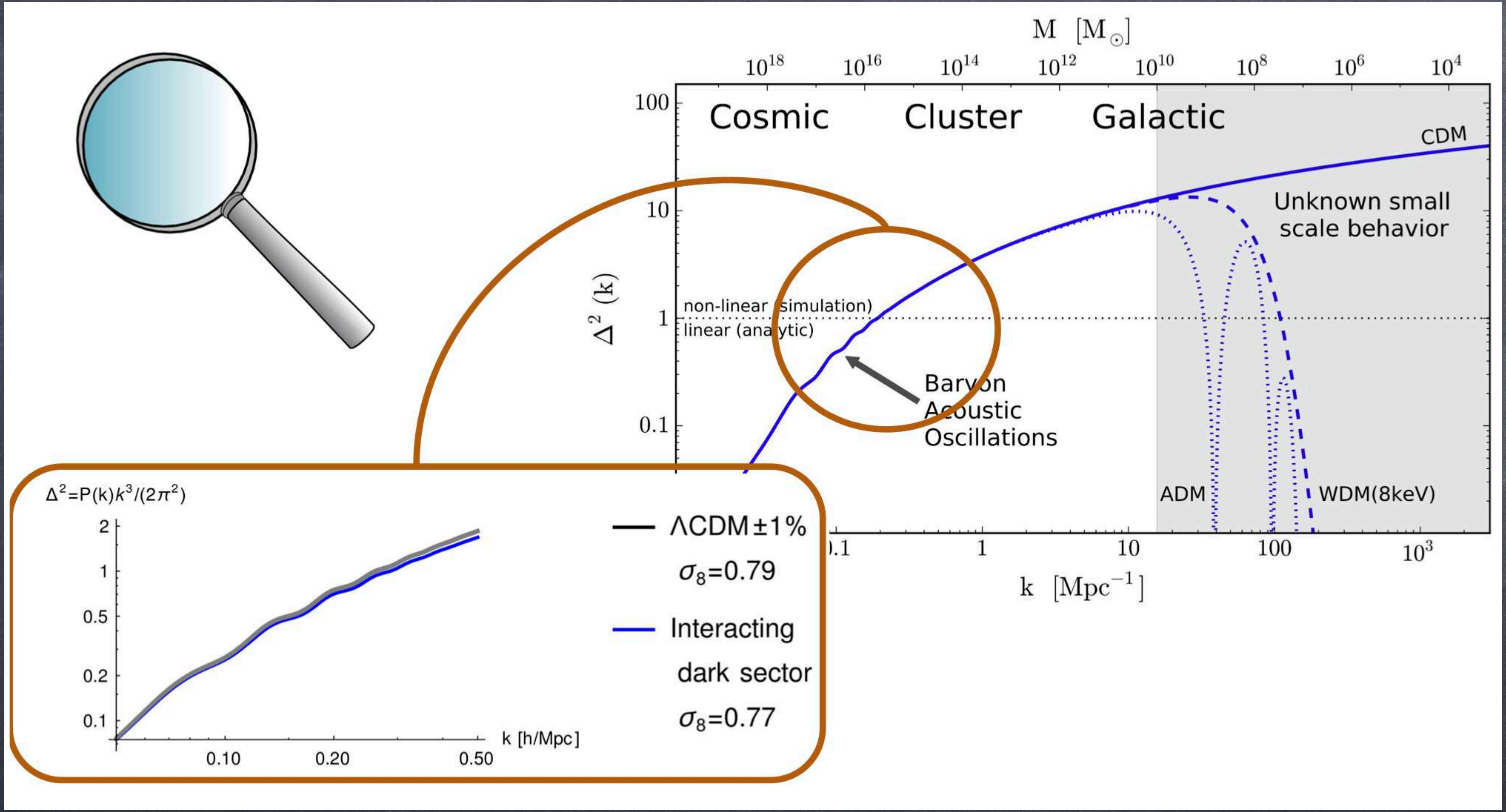
New Physics in LSS: “Energy” vs “Intensity”

example: Non Cold Dark Matter



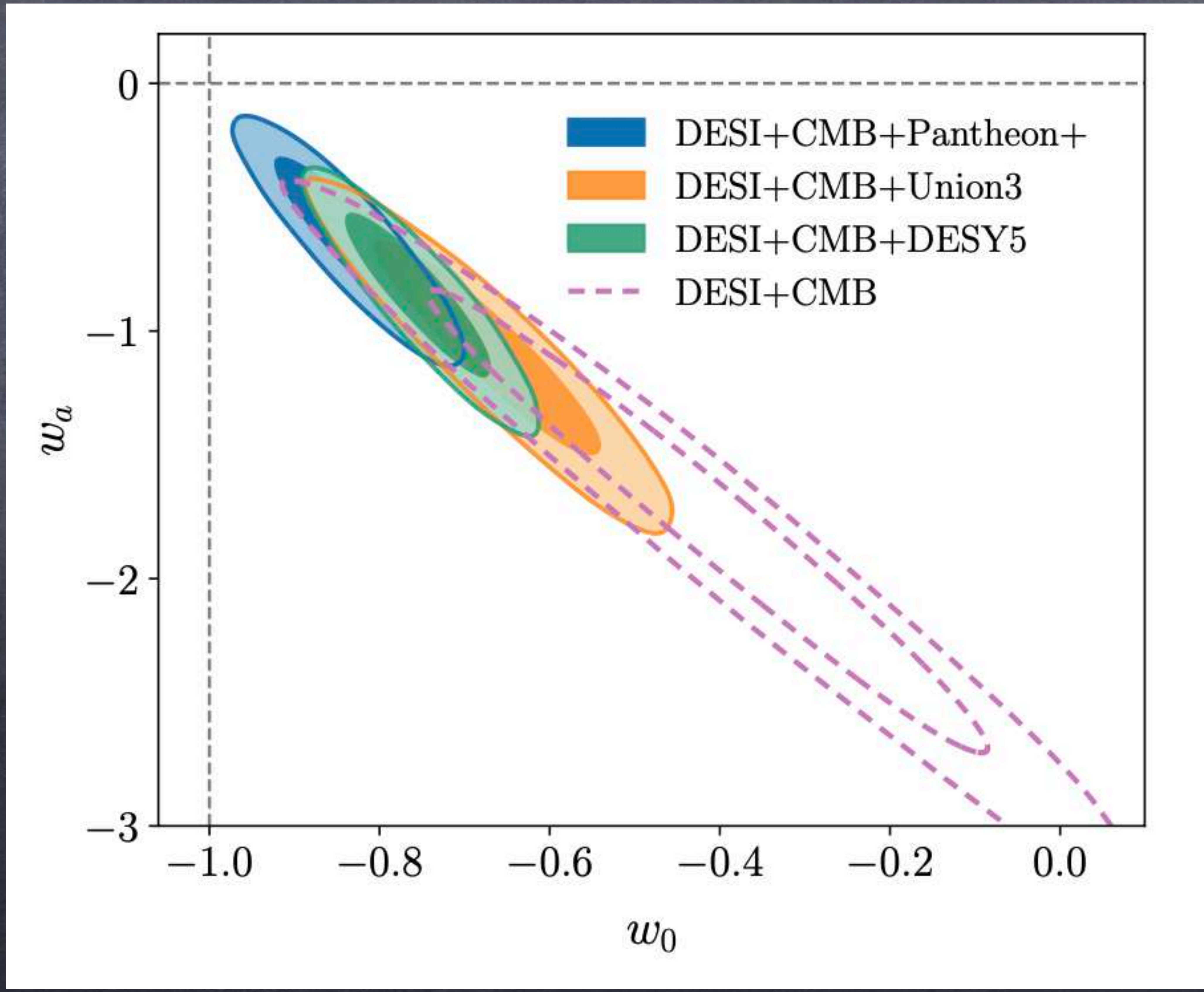
Kuhlen, Vogelsberger, Angulo 1209.5745

Precision frontier vs *small-scale* frontier



Slide by M. Garny (see also Castorina, Redigolo, Salvioni+)

IF DESI results are correct,
is it “just” Dark Energy (= background)
or (e.g.) Modified GR (= background + perturbations)?



DESI DR2: 2503.14738

The state of the art: EFToLSS + bias expansion

Baumann, Nicolis, Senatore, Zaldarriaga 2010
MP, Mangano, Saviano, Viel, 2011
Carrasco, Hertzberg, Senatore, 2012
… see Desjacques, Jeong, Schmidt, Phys Rep. 733 (2018)

convolution of IR fields

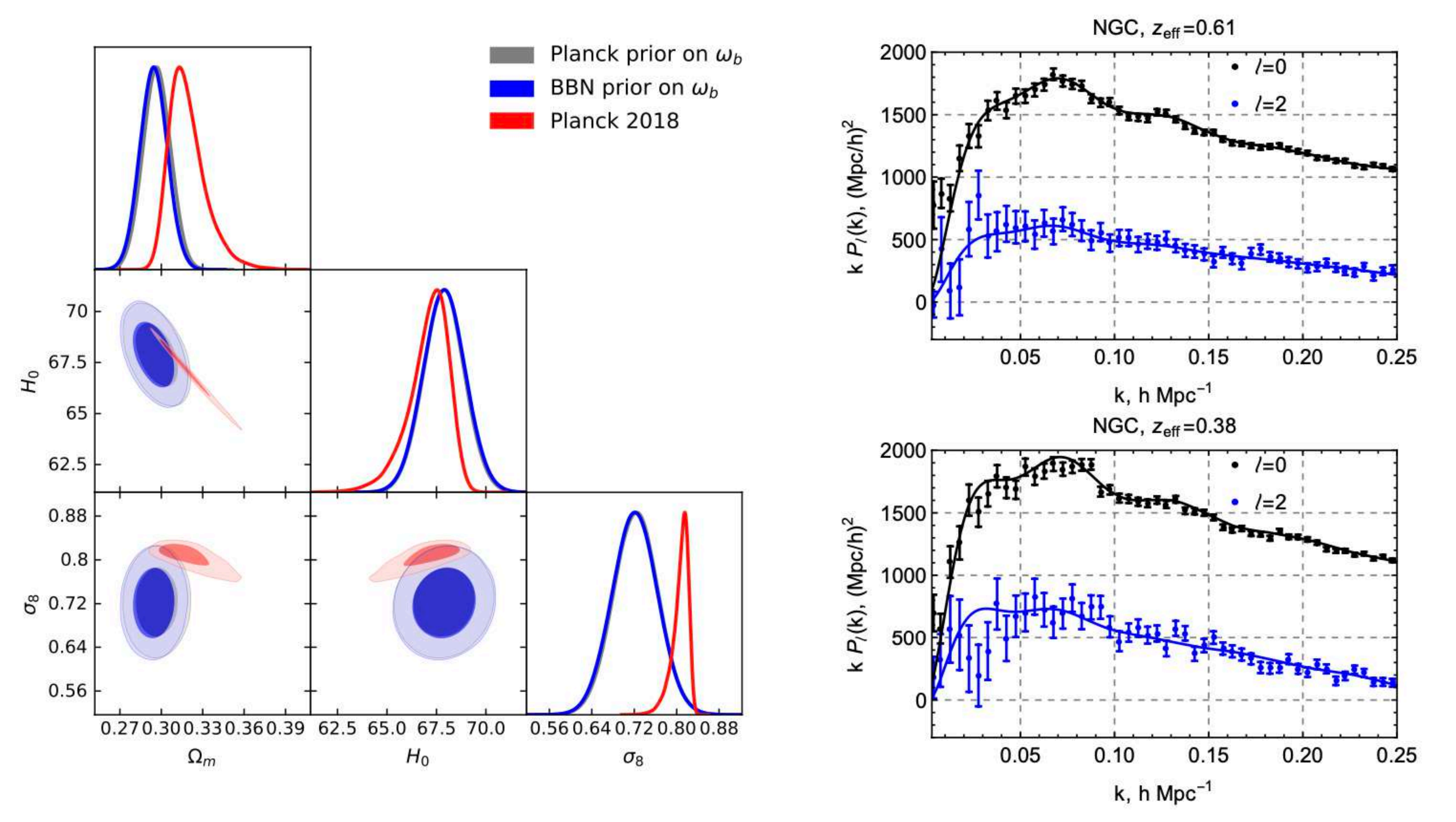
$$\delta(\mathbf{k}) = \sum_{n=1} \left[\delta^{(n)}_{\rm PT}(\mathbf{k}) + \sum_{p=0} c_{n,p} \left(\frac{k^2}{k^2_{\rm NL}} \right)^p O_{n,p}(\mathbf{k}) \right]$$

UV physics

PT + symmetry-based OPE for nonperturbative effects:

- beyond fluid approximation;
- (gastro)physics of galaxy formation;
- stocasticity.

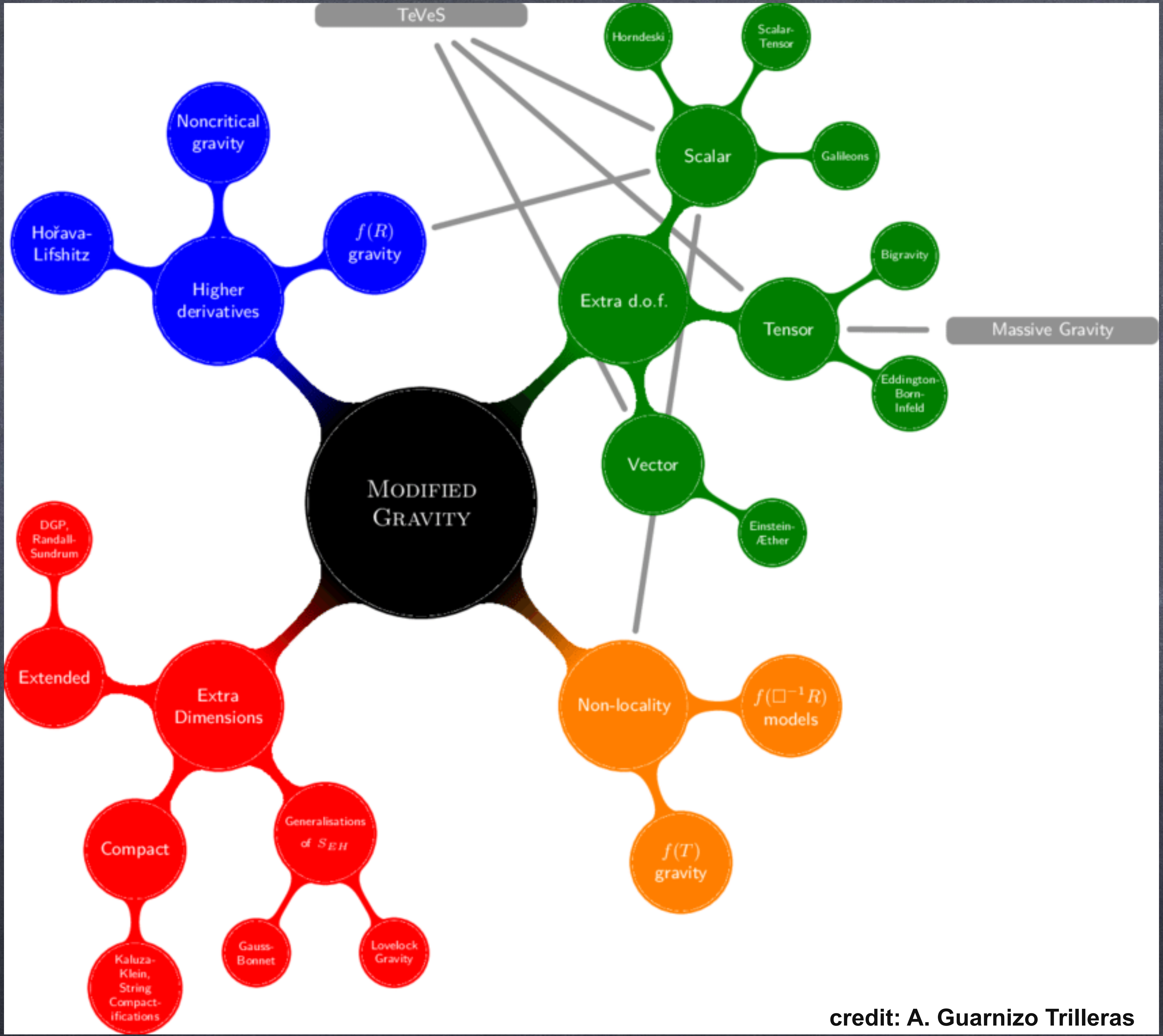
ΛCDM vs. BOSS data



Boss Power Spectrum (+ BBN prior) competitive with CMB-Planck!

D'Amico et al. 1909.05271
Ivanov et al. 1909.05277

beyond ΛCDM: what is it?



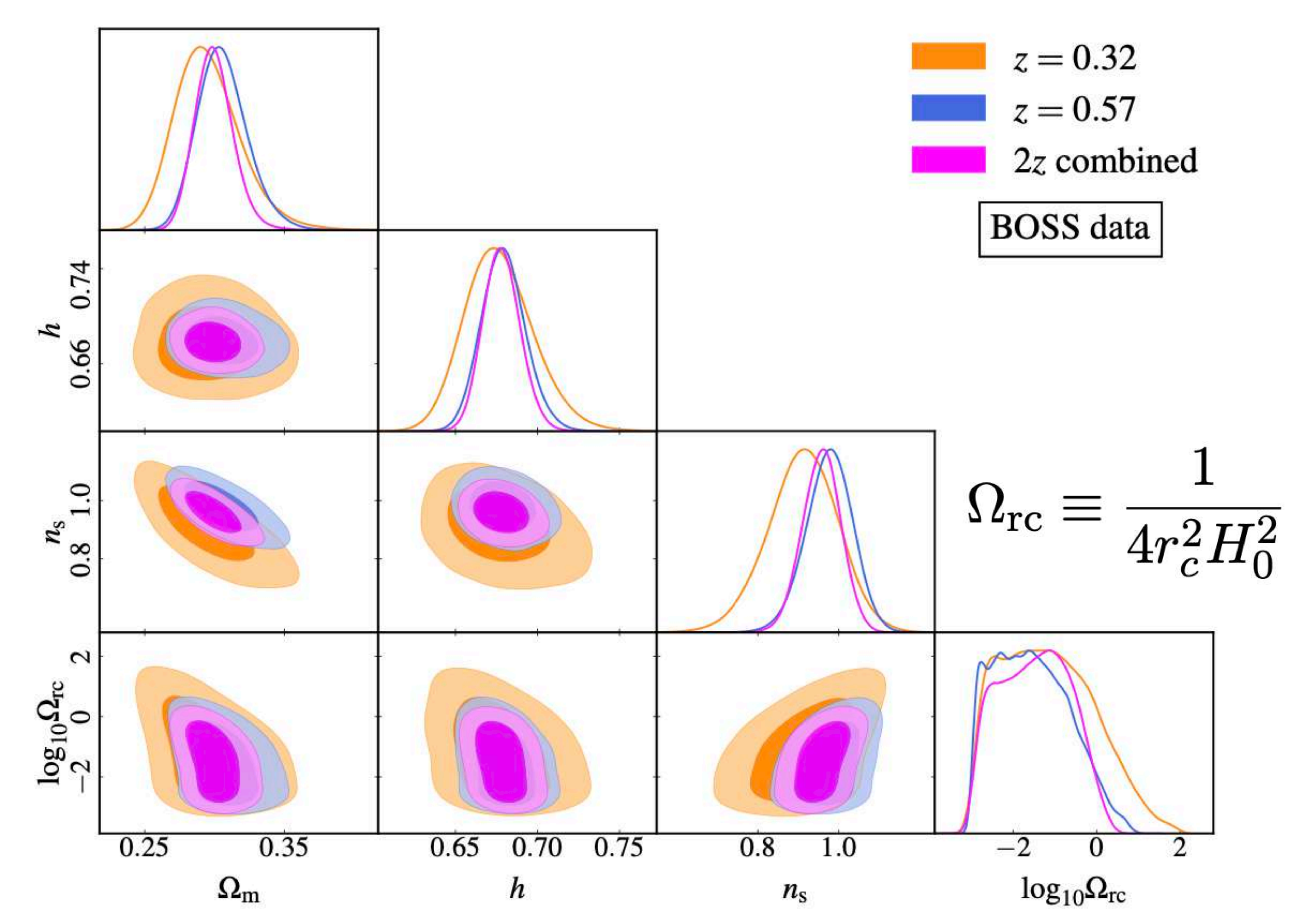
credit: A. Guarnizo Trilleras

Strategy #1

Model by model, or lagrangian by lagrangian

nDGP meets BOSS data

r_c : cross-over scale between 4d and 5d cosmology



Piga, Marinucci, D'Amico, MP, Vernizzi, Wright, 2211.12523

Imposing a Planck prior on A_s

$r_c > 1.12\ H_0^{-1}$ @ 95% C.L.

Strategy #2

one lagrangian: Effective field theory of DE

(most generic lagrangian compatibile with symmetries)

EFToDE

$$S = \int d^4x \sqrt{-g} \Big[\frac{M_\star^2 f(t)}{2}\, {}^{(4)}R - \Lambda(t) - c(t) g^{00} + \frac{m_2^4(t)}{2} \left(\delta g^{00}\right)^2 - \frac{M_3^3(t)}{2} \delta K \delta g^{00} - m_4^2(t) \left(\delta K^2 - \delta K^\nu_\mu \delta K^\mu_\nu - \frac{1}{2} \delta g^{00\,(3)}R \right) \Big]$$

Gleyzes, Langlois, Piazza, Vernizzi, '13

arbitrary time-dependence of the coefficients

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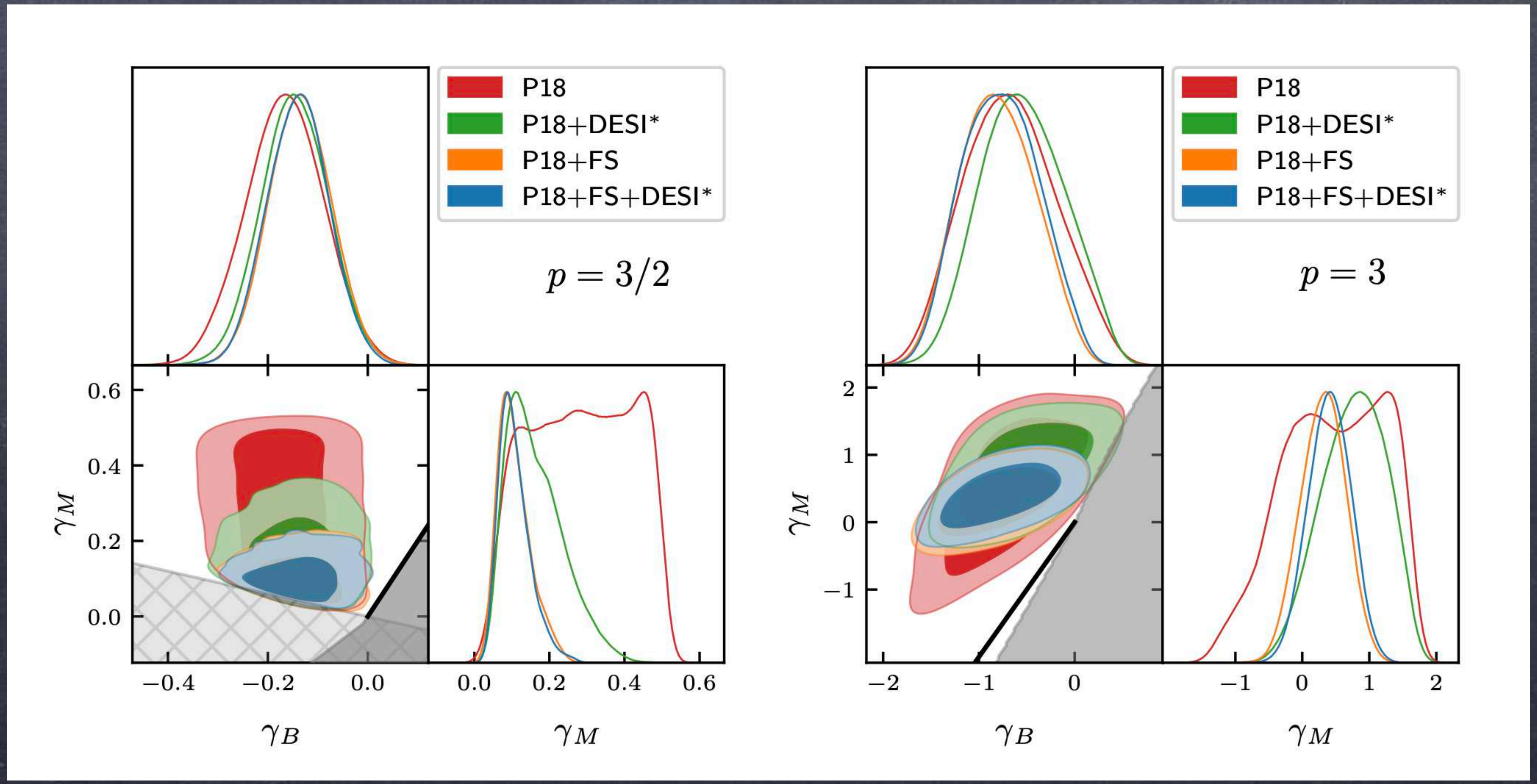
Gleyzes, Langlois, Piazza, Vernizzi, '13

arbitrary time-dependence of the coefficients

$$\alpha_{\rm B}(a) = \gamma_{\rm B}\left(\frac{a}{a_0}\right)^p, \qquad \alpha_{\rm M}(a) = \gamma_{\rm M}\left(\frac{a}{a_0}\right)^p,$$



Taule, Marinucci, Biselli, MP, Vernizzi, 2409.08971

Strategy #3

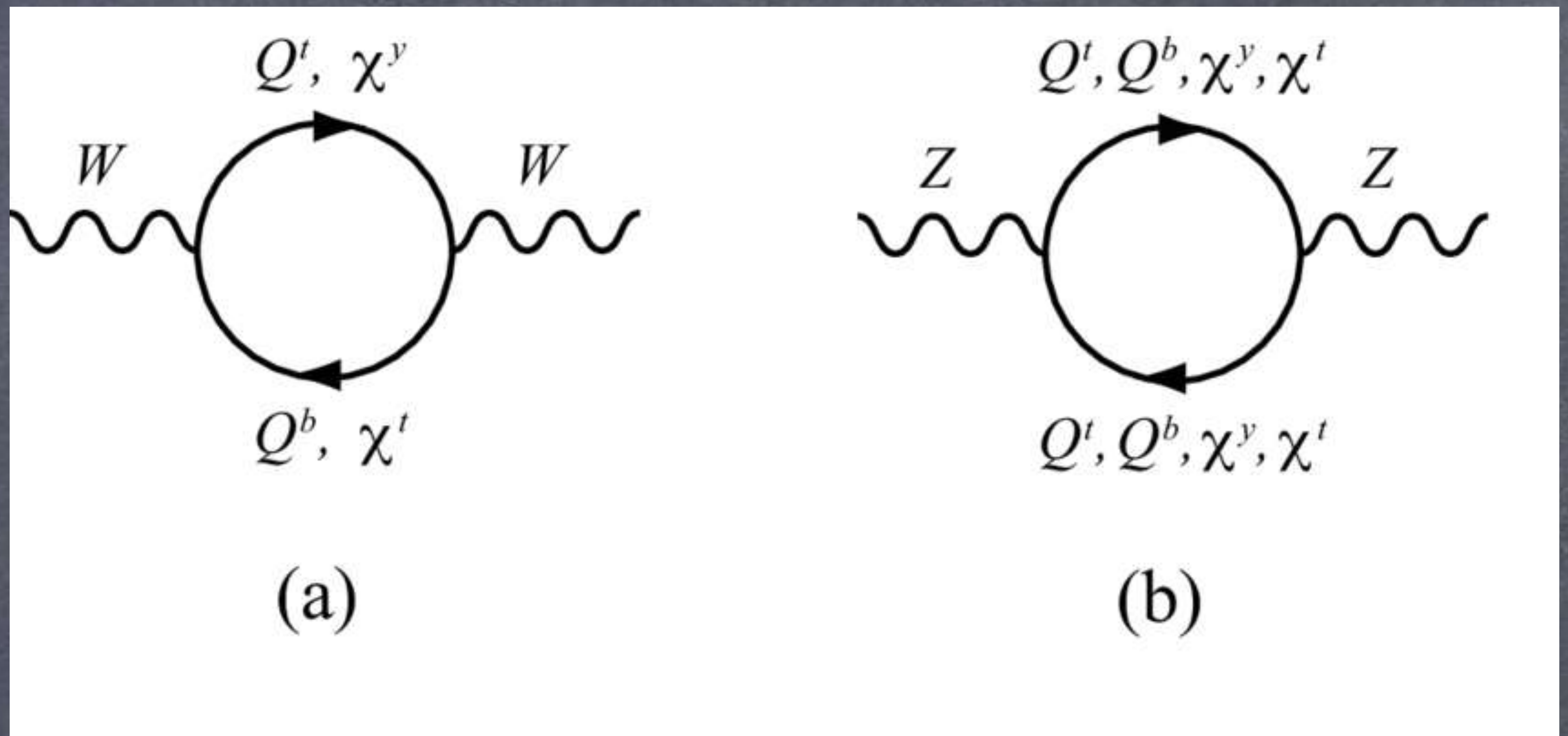
No lagrangian: symmetries!

(most generic observables compatibile with symmetries)

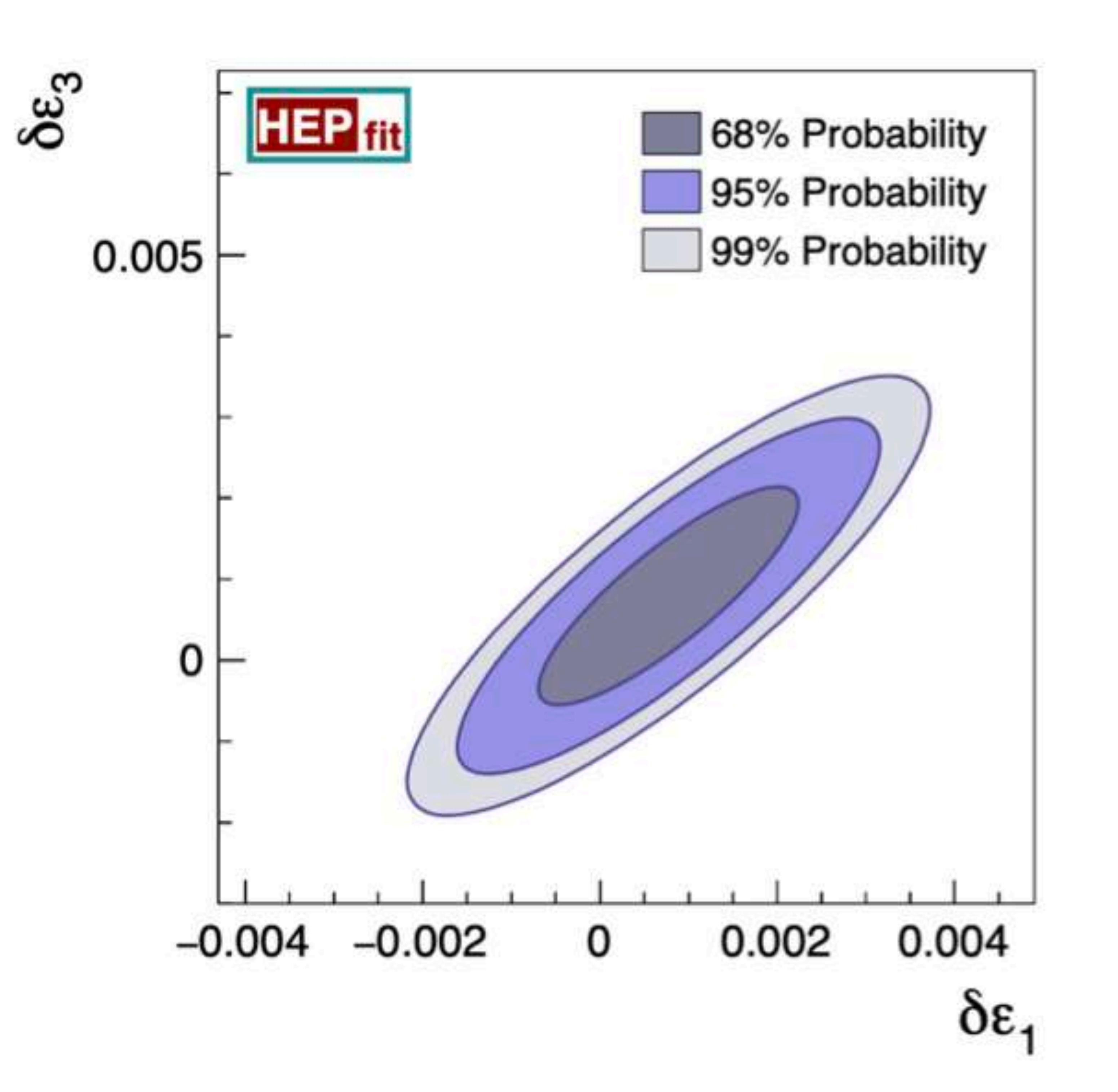
Model independent tests of the Standard Model of Particle Physics

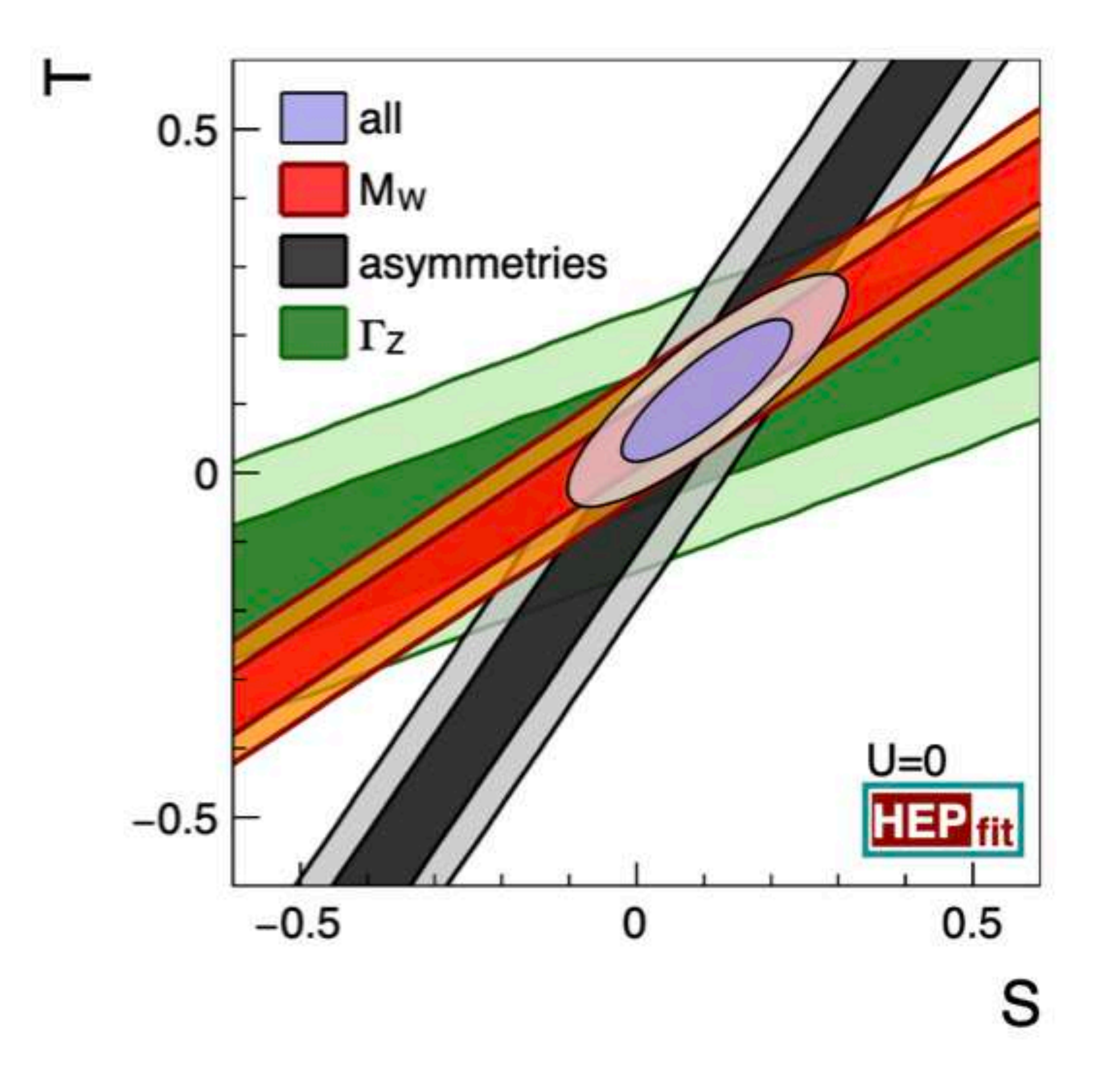
Ex: "custodial" SU(2) breaking by new physics in the loops:

$$\delta\epsilon_1 = \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2}$$



Altarelli, Barbieri, '92
Peskin, Takeuchi, '92





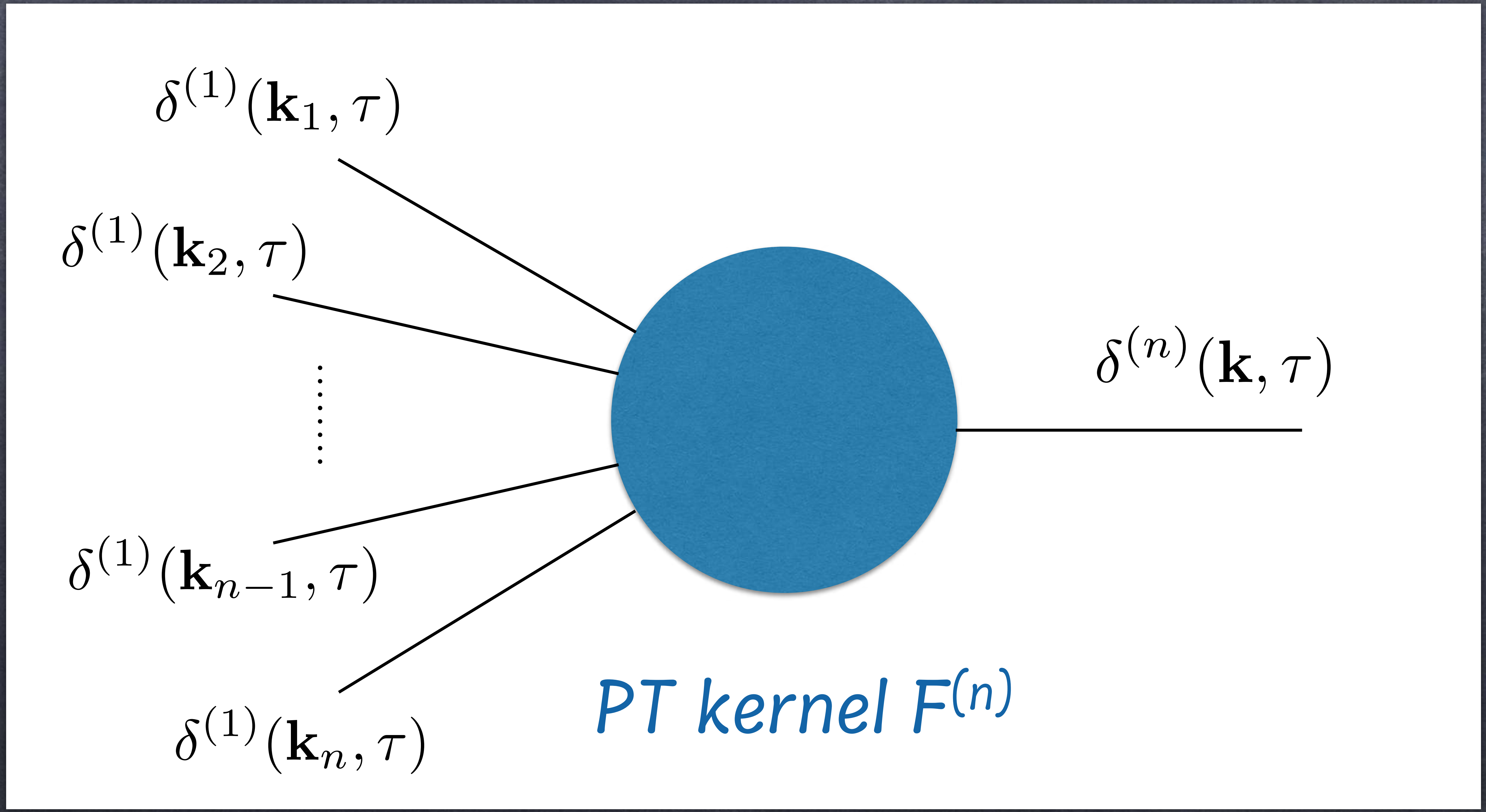
de Blas et al, 1608.01509

Model independent PT: the LSS bootstrap

Perturbation theory (PT) without assuming equations of motion

Enforcing symmetry constraints on the observables

$$\delta(\mathbf{k},\tau) = \sum_{n=1} \delta^{(n)}(\mathbf{k},\tau)\ , \quad \theta(\mathbf{k},\tau) = \sum_{n=1} \theta^{(n)}(\mathbf{k},\tau)$$



Extended "Galilean" invariance
(a.k.a. the Equivalence Principle)

Non perturbative level:
Soft limits of nonlinearities, Consistency Relations

Peloso, MP, '13; Kehagias, Riotto, '13;
Creminelli, Norena, Simonovic, Vernizzi, '13

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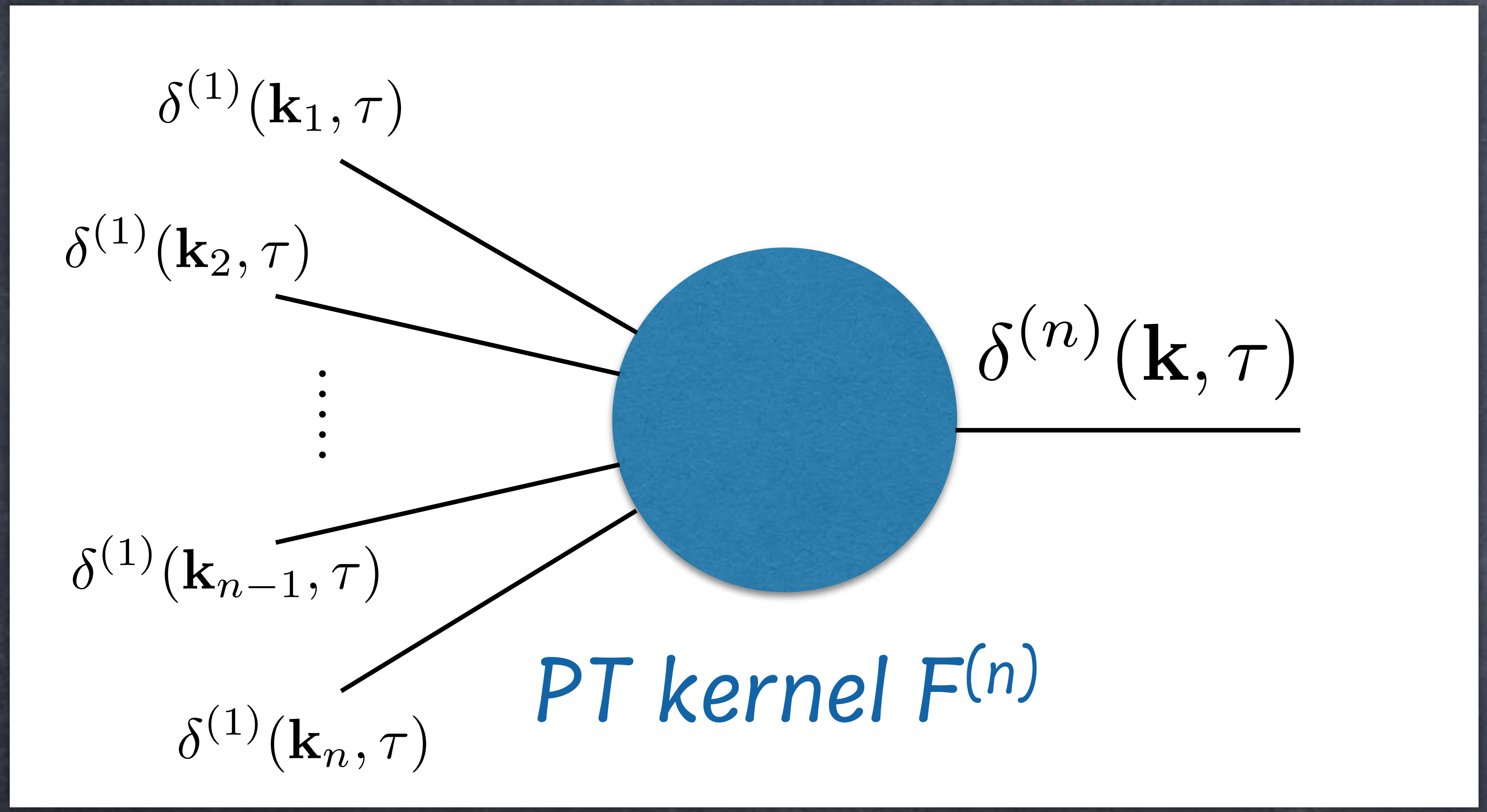
Perturbation theory: the LSS bootstrap

G. D'Amico, M. Marinucci, MP, F. Vernizzi 2109.09573
see also T. Fujita, Z. Vlah, 2003.10114
M. Marinucci, K. Pardede, MP, 2405.08413
A. Ansari, A. Banerjee, S. Jain, S. Lalsodagar 2504.01078

Extended "Galilean" invariance constraints on the PT kernels

$$\mathbf{x} + \mathbf{d}(\tau) \qquad \delta(\mathbf{k},\tau) \rightarrow \mathbf{e}^{\mathbf{ik}\cdot\mathbf{d}(\tau)}\delta(\mathbf{k},\tau)$$

linear displacement: $$\delta^{(n)}(\mathbf{k},\tau) \rightarrow \mathbf{ik}\cdot\mathbf{d}^{(1)}(\tau)\delta^{(\mathbf{n-1})}(\mathbf{k},\tau) + \cdots$$



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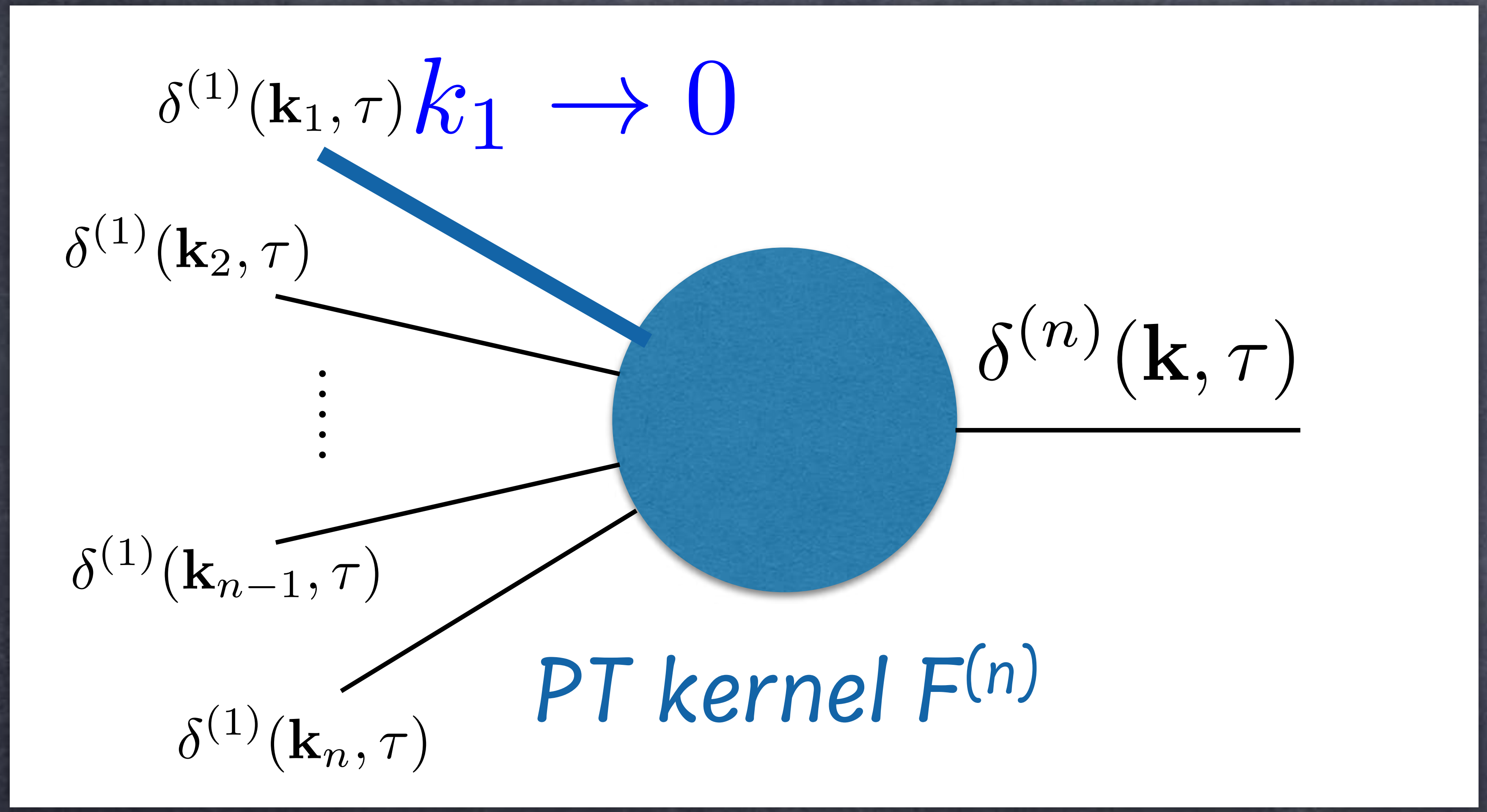

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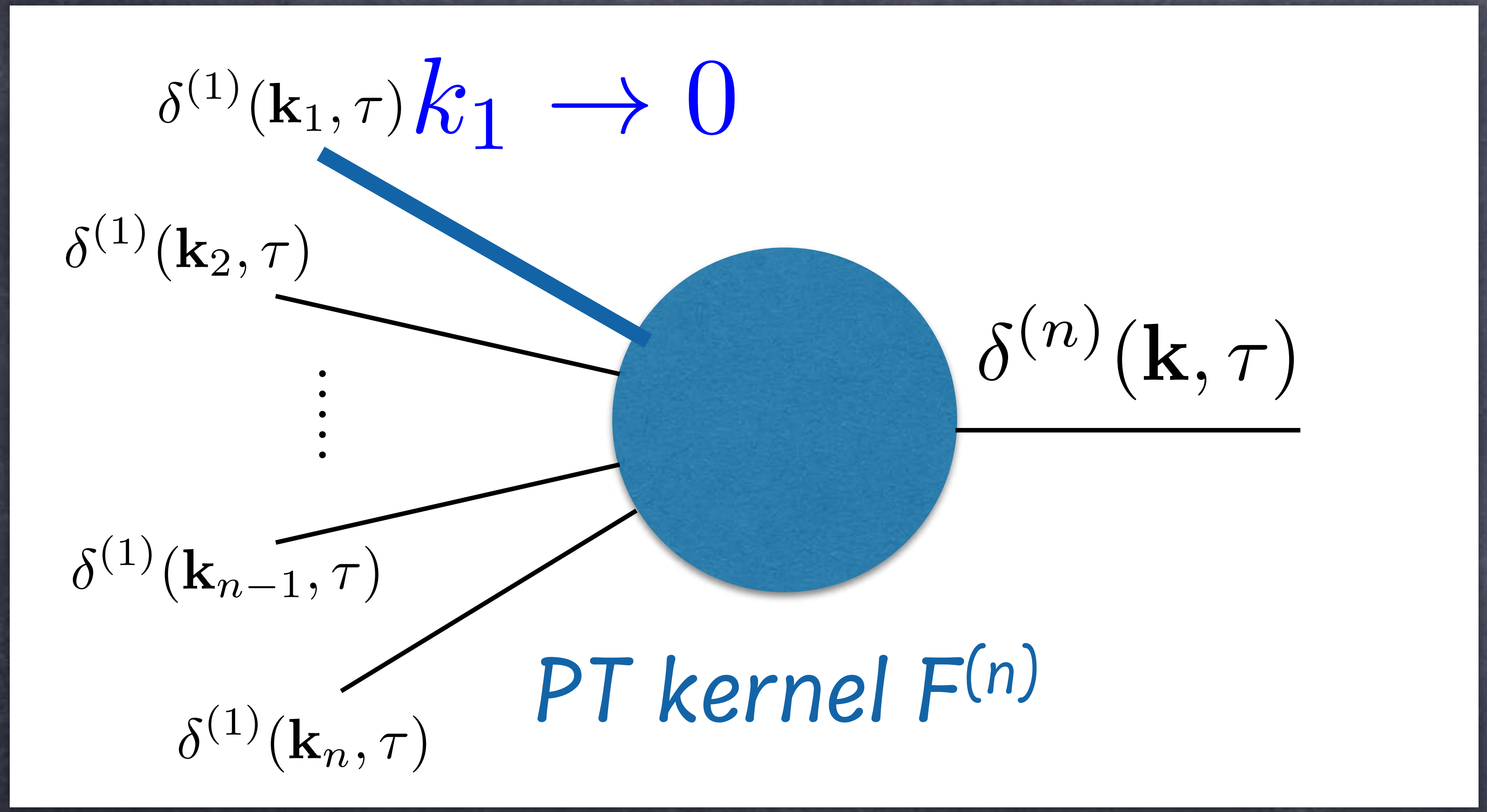

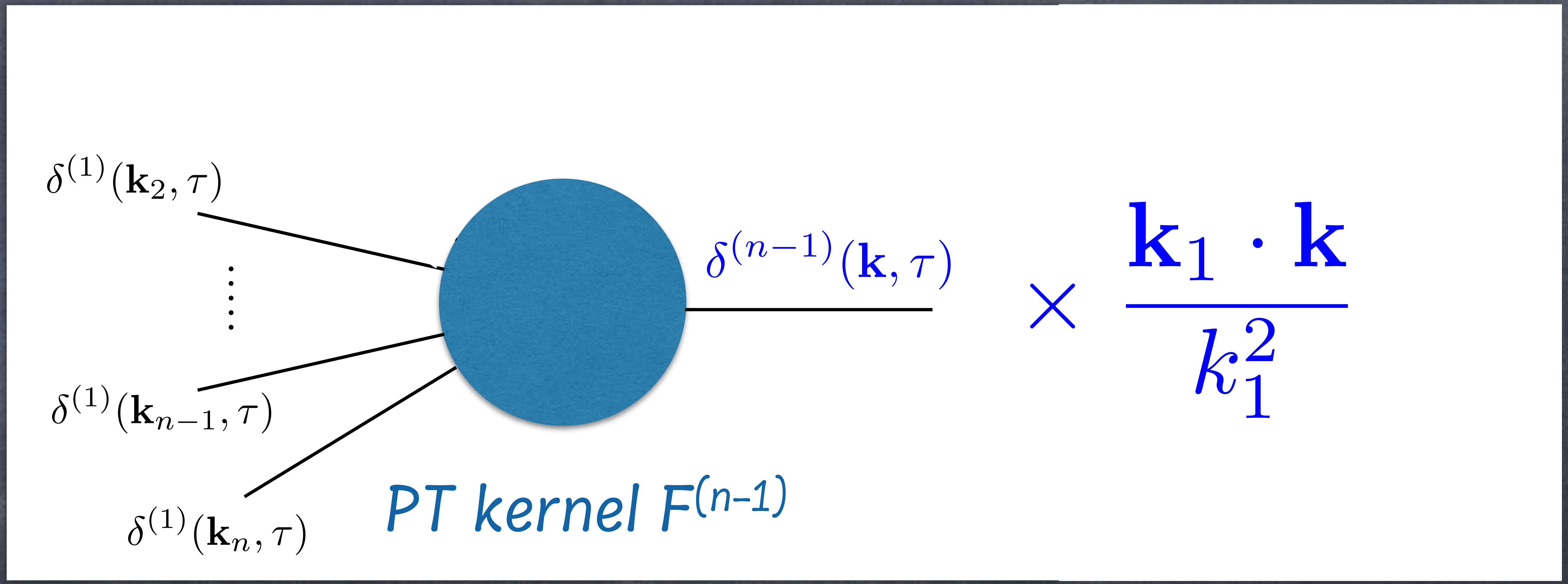

Extended "Galilean" invariance constraints on the PT kernels

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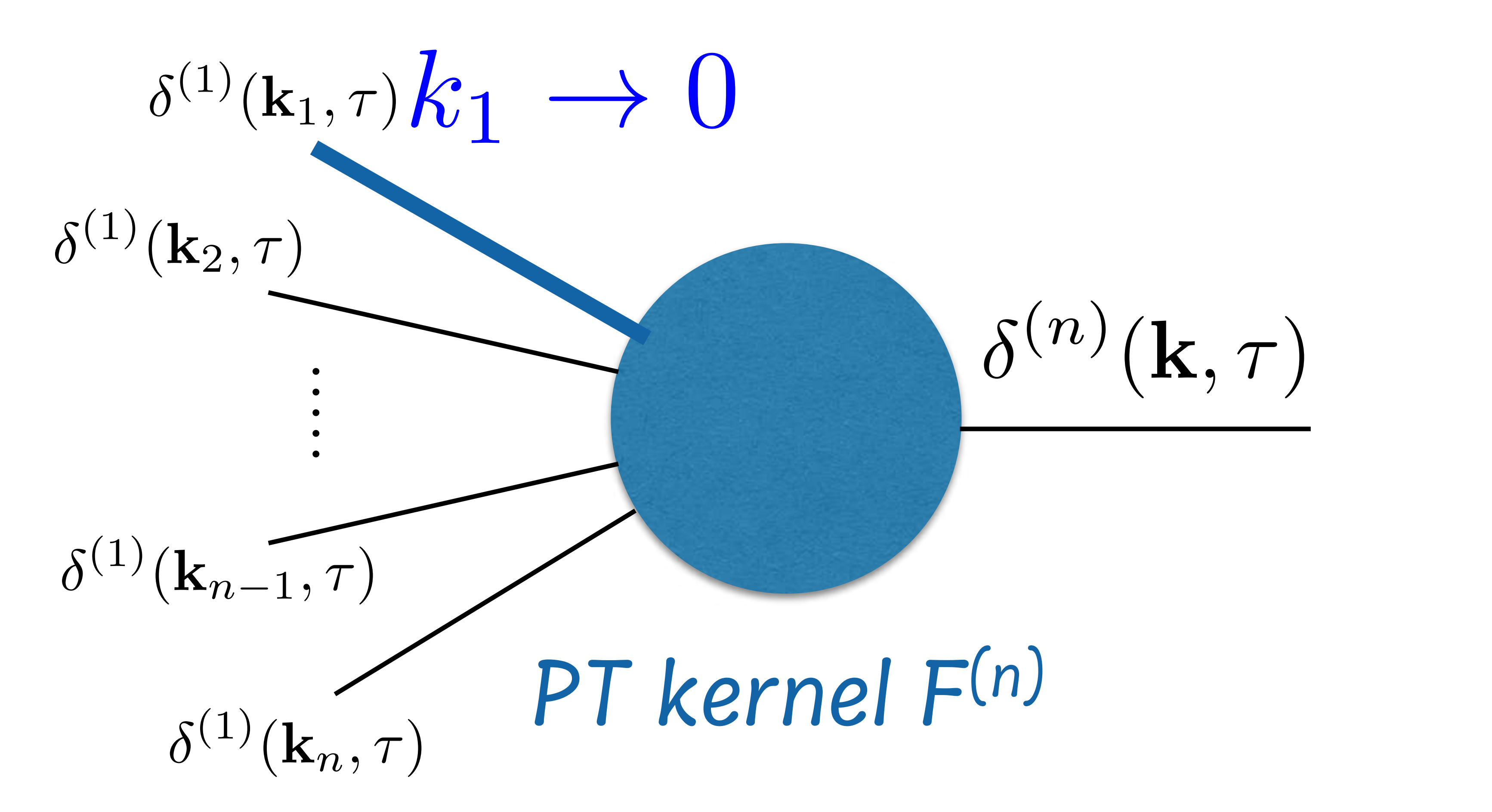

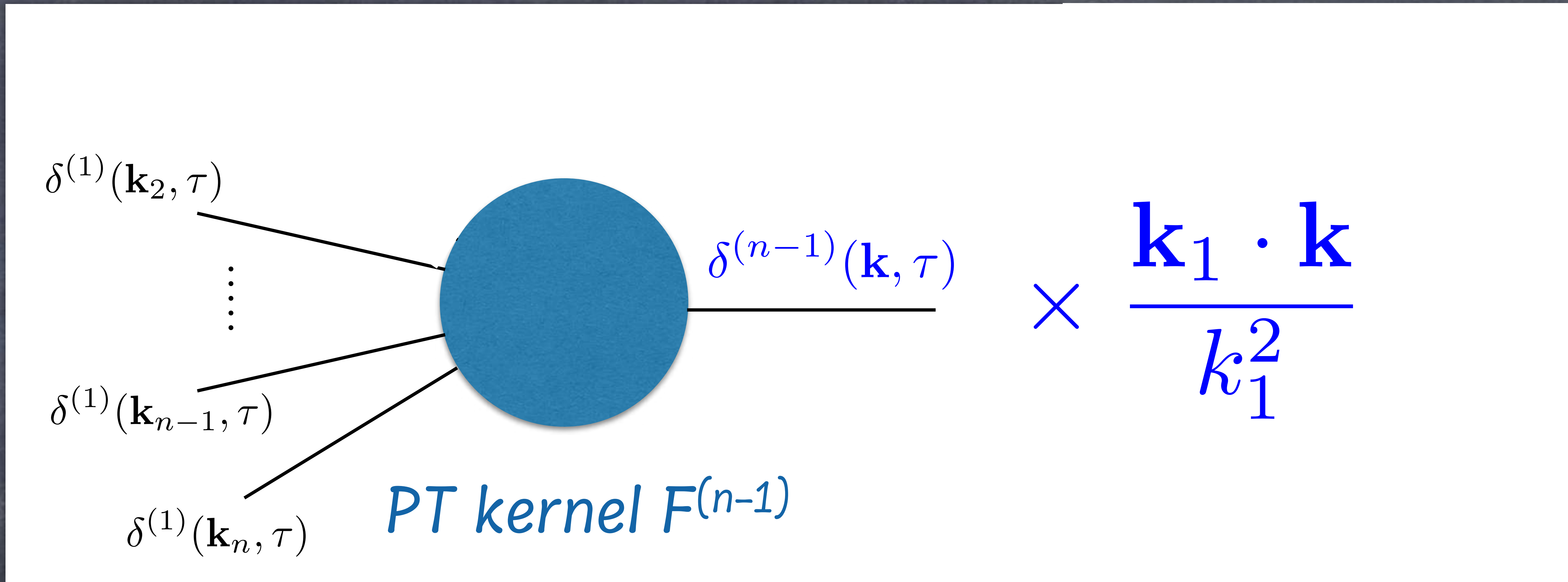

$$\lim_{k_1 \to 0} F^{(n)}(\mathbf{k}_1, \cdots, \mathbf{k}_n) = \frac{\mathbf{k}_1 \cdot \mathbf{k}}{k_1^2} F^{(n-1)}(\mathbf{k}_2, \cdots, \mathbf{k}_n) + O(1)$$

Extended "Galilean" invariance constraints at NLO

quadratic displacement: $\delta^{(n)}(\mathbf{k},\tau) \to \mathbf{ik}\cdot\mathbf{d}^{(\mathbf{2})}(\tau)\delta^{(\mathbf{n-2})}(\mathbf{k},\tau) + \cdots$

$$\lim_{\mathbf{k}_1+\mathbf{k}_2\to 0} F^{(n)}(\mathbf{k}_1,\cdots,\mathbf{k}_n;\tau) = \frac{(\mathbf{k}_1+\mathbf{k}_2)\cdot\mathbf{k}}{|\mathbf{k}_1+\mathbf{k}_2|^2} F^{(n-2)}(\mathbf{k}_3,\cdots,\mathbf{k}_n;\tau)\int^{\tau} d\tau'\, f(\tau')\mathcal{H}(\tau')\frac{D^2(\tau')}{D^2(\tau)}\, G^{(2)}(\mathbf{k}_1,\mathbf{k}_2;\tau')$$

soft sum limit

velocity kernel

+ iterations + NNLO…

Mass and momentum conservation (Peebles '80)

$$\int d^3x\, \delta(\mathbf{x}, \eta) = 0 \qquad \int d^3x x^i\, \delta(\mathbf{x}, \eta) = 0$$

↓

$$\lim_{\mathbf{k}\to 0} F^{(n)}(\mathbf{k}_1, \cdots, \mathbf{k}_n; \tau) = 0$$

$$\lim_{\mathbf{k}\to 0} \frac{\partial}{\partial k_1^i} F^{(n)}(\mathbf{k}_1, \cdots, \mathbf{k}_n; \tau) = 0 \qquad \mathbf{k} = \sum \mathbf{k}_i$$

Holds for Dark Matter, but not, in general, for biased tracers (more free coefficients)

Bootstrap at n=2

rotational invariants with at most $O(1/q_i)$ poles (velocity is grad. potential at large scales):

$$1\,, \qquad \frac{\mathbf{q}_1\cdot\mathbf{q}_2}{q_1^2}, \qquad \frac{\mathbf{q}_1\cdot\mathbf{q}_2}{q_2^2}, \qquad \frac{(\mathbf{q}_1\cdot\mathbf{q}_2)^2}{q_1^2 q_2^2}\,.$$

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change basis:

$$1, \qquad \gamma(\mathbf{q},\mathbf{p}) = 1 - \frac{(\mathbf{q}\cdot\mathbf{p})^2}{q^2 p^2}\,, \qquad \beta(\mathbf{q},\mathbf{p}) \equiv \frac{|\mathbf{q}+\mathbf{p}|^2\, \mathbf{q}\cdot\mathbf{p}}{2 q^2 p^2}\,, \qquad \alpha_a(\mathbf{q},\mathbf{p}) = \frac{\mathbf{q}\cdot\mathbf{p}}{q^2} - \frac{\mathbf{p}\cdot\mathbf{q}}{p^2}\,,$$

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"Bose symmetry"

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"Bose symmetry"

most general kernel:

$$F_2(\mathbf{q}_1,\mathbf{q}_2;\eta) = a_0^{(2)}(\eta) + a_1^{(2)}(\eta)\,\gamma(\mathbf{q}_1,\mathbf{q}_2) + a_2^{(2)}(\eta)\,\beta(\mathbf{q}_1,\mathbf{q}_2)$$

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Extended Galileian Invariance: $a_2^{(2)}(\eta) = 2$

Mass conservation: $a_0^{(2)}(\eta) = 0$

Bootstrap at n=2

matter:

$$F_2(\mathbf{q}_1, \mathbf{q}_2; \eta) = 2\beta(\mathbf{q}_1, \mathbf{q}_2) + a_1^{(2)}(\eta)\,\gamma(\mathbf{q}_1, \mathbf{q}_2)$$

velocity:

$$G_2(\mathbf{q}_1, \mathbf{q}_2) = 2\beta(\mathbf{q}_1, \mathbf{q}_2) + d_1^{(2)}\,\gamma(\mathbf{q}_1, \mathbf{q}_2)$$

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cosmology dependent

$$a^{(2)}_{1,\mathrm{EdS}} = \frac{10}{7}$$
$$d^{(2)}_{1,\mathrm{EdS}} = \frac{6}{7}$$

(Lifshitz simmetry)

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biased tracer:
(no mass and momentum conservation)

$$K_1(\mathbf{q}_1) = c_0^{(1)}\,,$$
$$K_2(\mathbf{q}_1, \mathbf{q}_2) = c_0^{(2)} + 2\,c_0^{(1)}\,\beta(\mathbf{q}_1, \mathbf{q}_2) + c_1^{(2)}\,\gamma(\mathbf{q}_1, \mathbf{q}_2)$$

3 tracer-dependent parameters
(b_1, b_2, b_{G2})

Bootstrap at n=2

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3 tracer-dependent parameters
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Bootstrap at n=3

matter and velocity: 2 more cosmology-dependent parameters
biased tracer: 4 more tracer-dependent parameters

Bootstrap at n=2

matter: $$F_2(\mathbf{q}_1,\mathbf{q}_2;\eta) = 2\beta(\mathbf{q}_1,\mathbf{q}_2) + a_1^{(2)}(\eta)\,\gamma(\mathbf{q}_1,\mathbf{q}_2)$$

velocity: $$G_2(\mathbf{q}_1,\mathbf{q}_2) = 2\beta(\mathbf{q}_1,\mathbf{q}_2) + d_1^{(2)}\,\gamma(\mathbf{q}_1,\mathbf{q}_2)$$

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Bootstrap at n=3

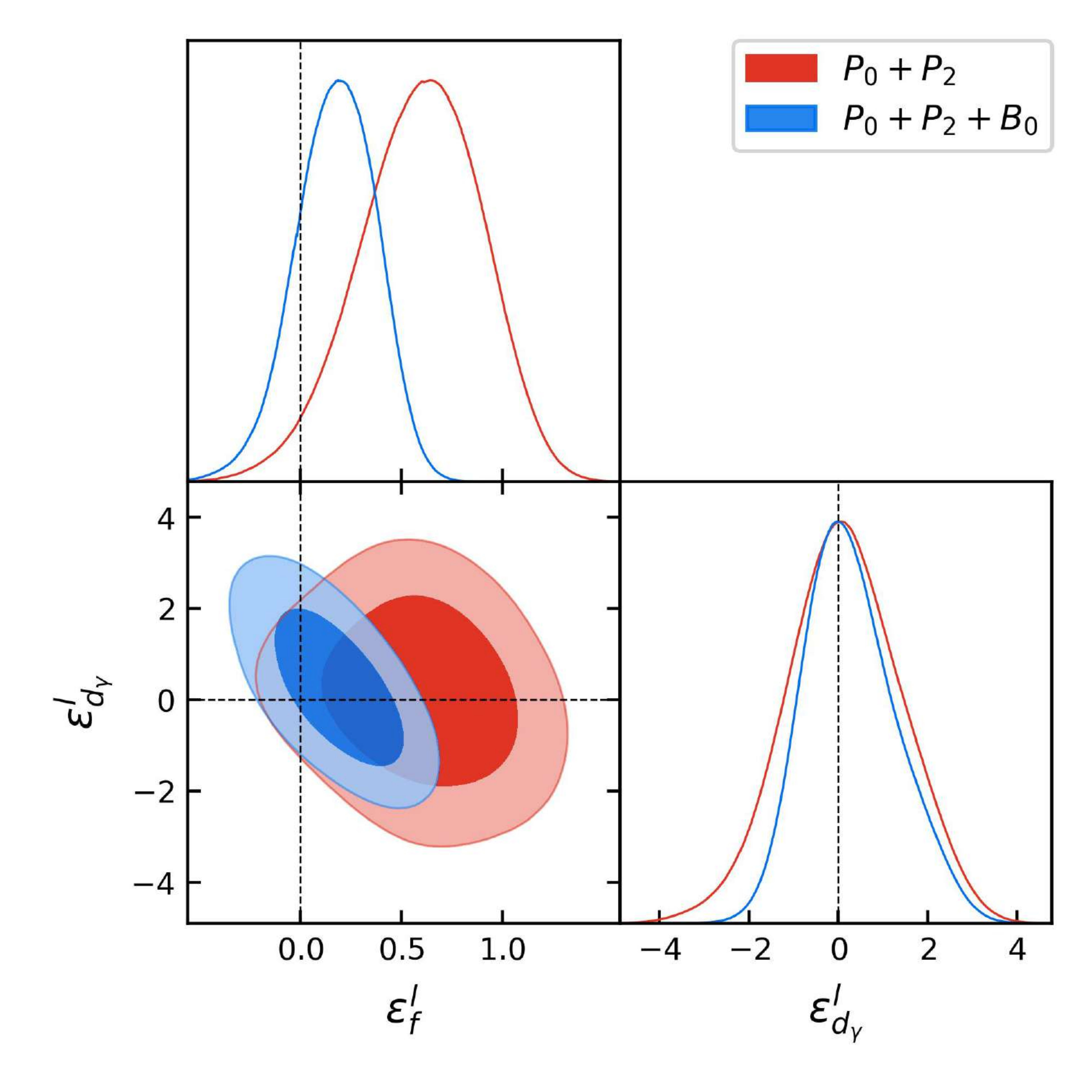
matter and velocity: 2 more cosmology-dependent parameters

biased tracer: 4 more tracer-dependent parameters

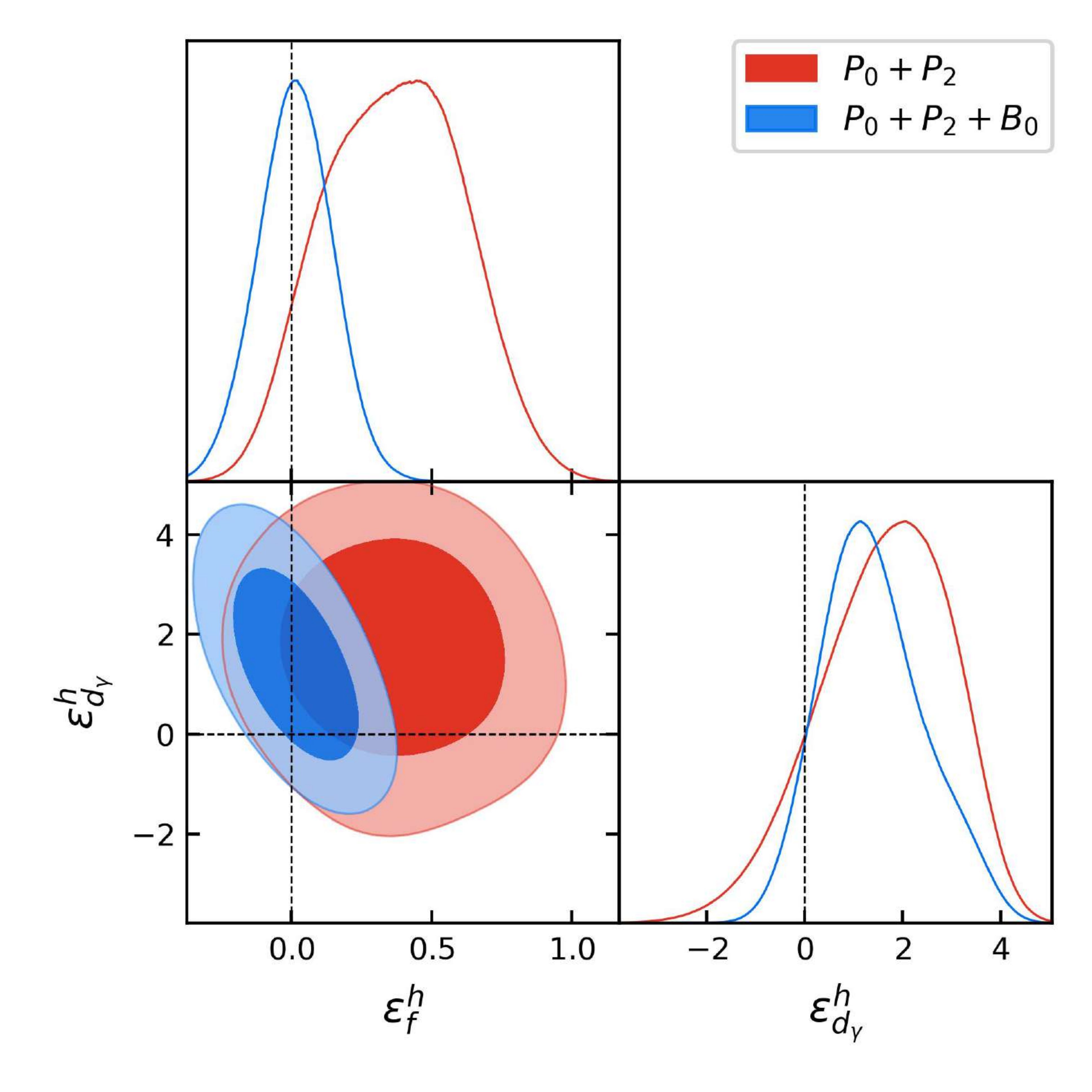
Can we constrain the cosmology-dependent parameters?

Today: BOSS data

"low-z" z=0.32

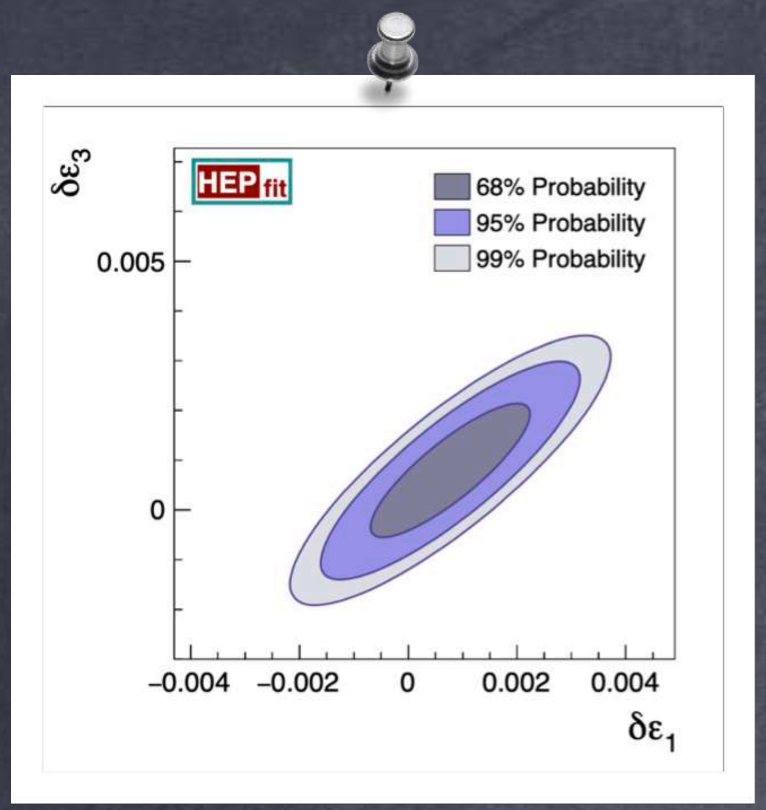


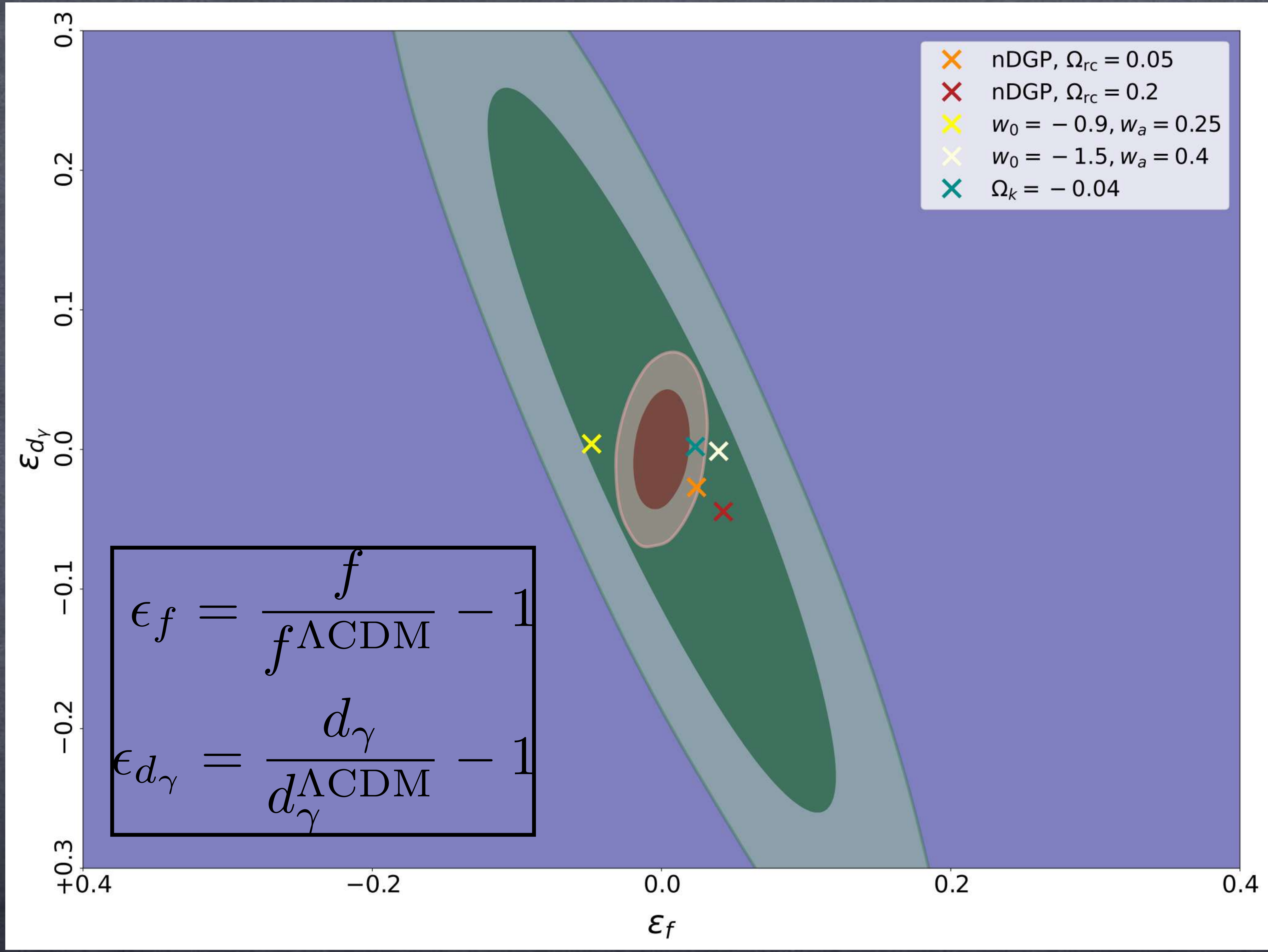
"CMASS" z=0.57



Preliminary : G. Biselli, M. Marinucci, T. Nishimichi, M. Peron, MP

Future tests of ΛCDM at the linear(f) + nonlinear (d_γ) levels





courtesy of M. Marinucci

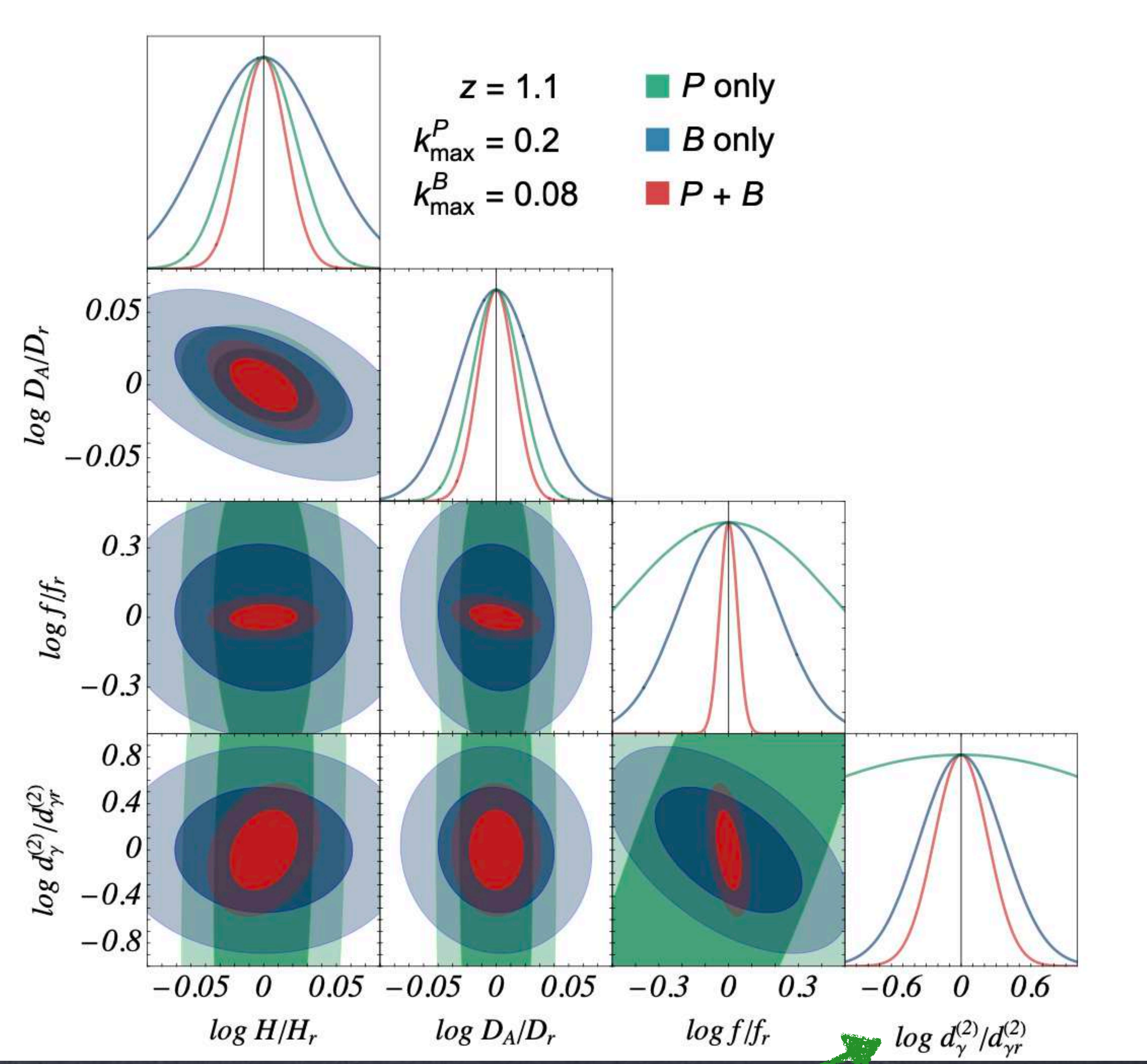
P+B, Euclid-like volume, z=1

(k^P_{max}=0.25 h/Mpc k^B_{max}=0.1 h/Mpc)

Free-Power!

- *Marginalize over linear P(k)*
- *Bootstrap PT kernels*
- *EFToLSS + cosmo-dep params*
- *wedges*

O(5-10%) constraints on $H(z)/H_0$
O(10%) constraints on f
O(50%) constraints on d_γ



analogous to $b_{\mathcal{G}_2}$ but tracer-independent!

L. Amendola, M. Marinucci, MP, M. Quartin, 2205.00569, 2307.02117 (see also Shape-Fit, Gil Marin, Verde...)

Can we do better than P+B?

$$P(k) = \langle \delta(\mathbf{k}) \delta(-\mathbf{k}) \rangle \qquad B(k_1, k_2, k_3) = \langle \delta(\mathbf{k}_1) \delta(\mathbf{k}_2) \delta(\mathbf{k}_3) \rangle$$

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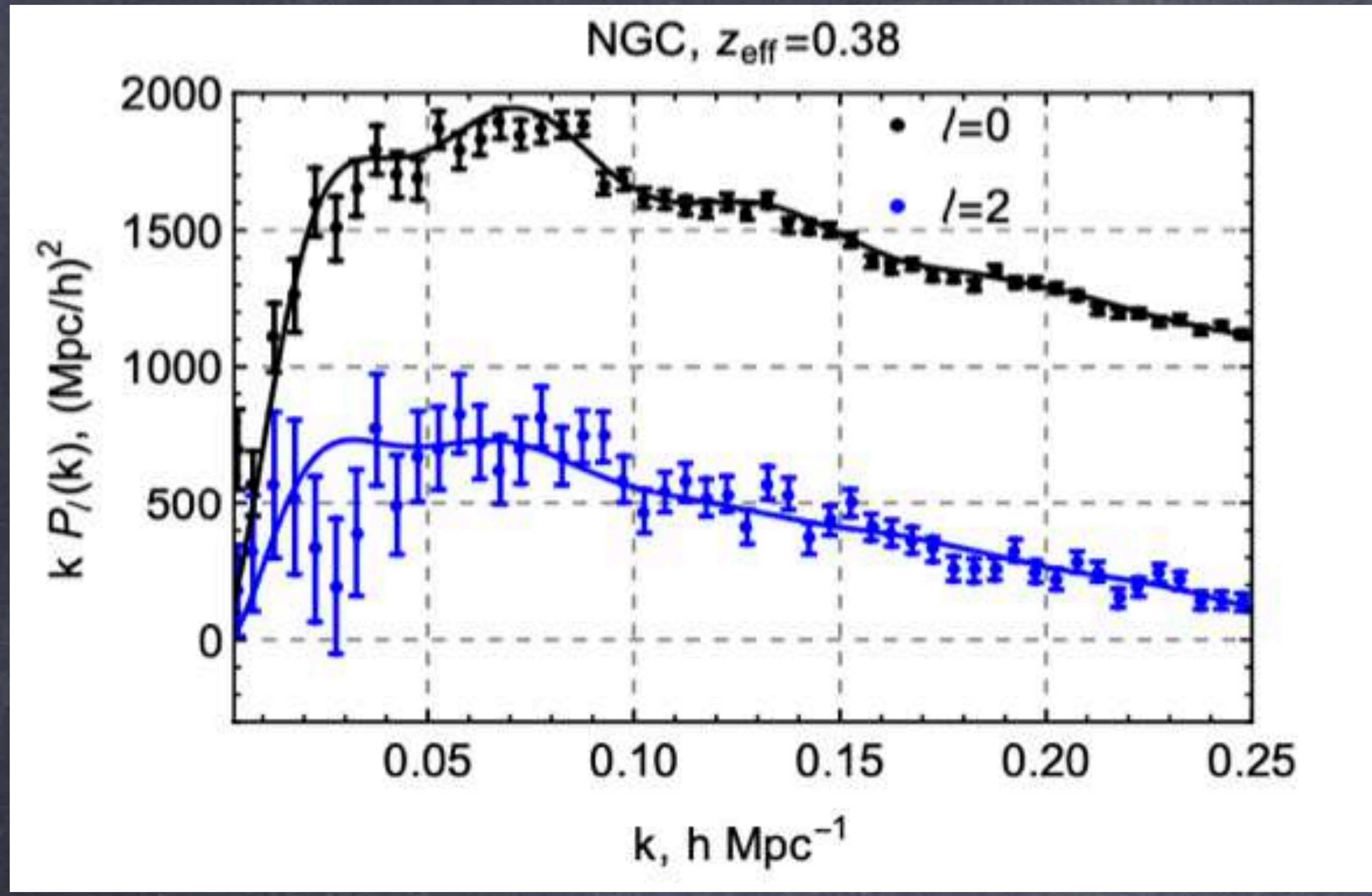
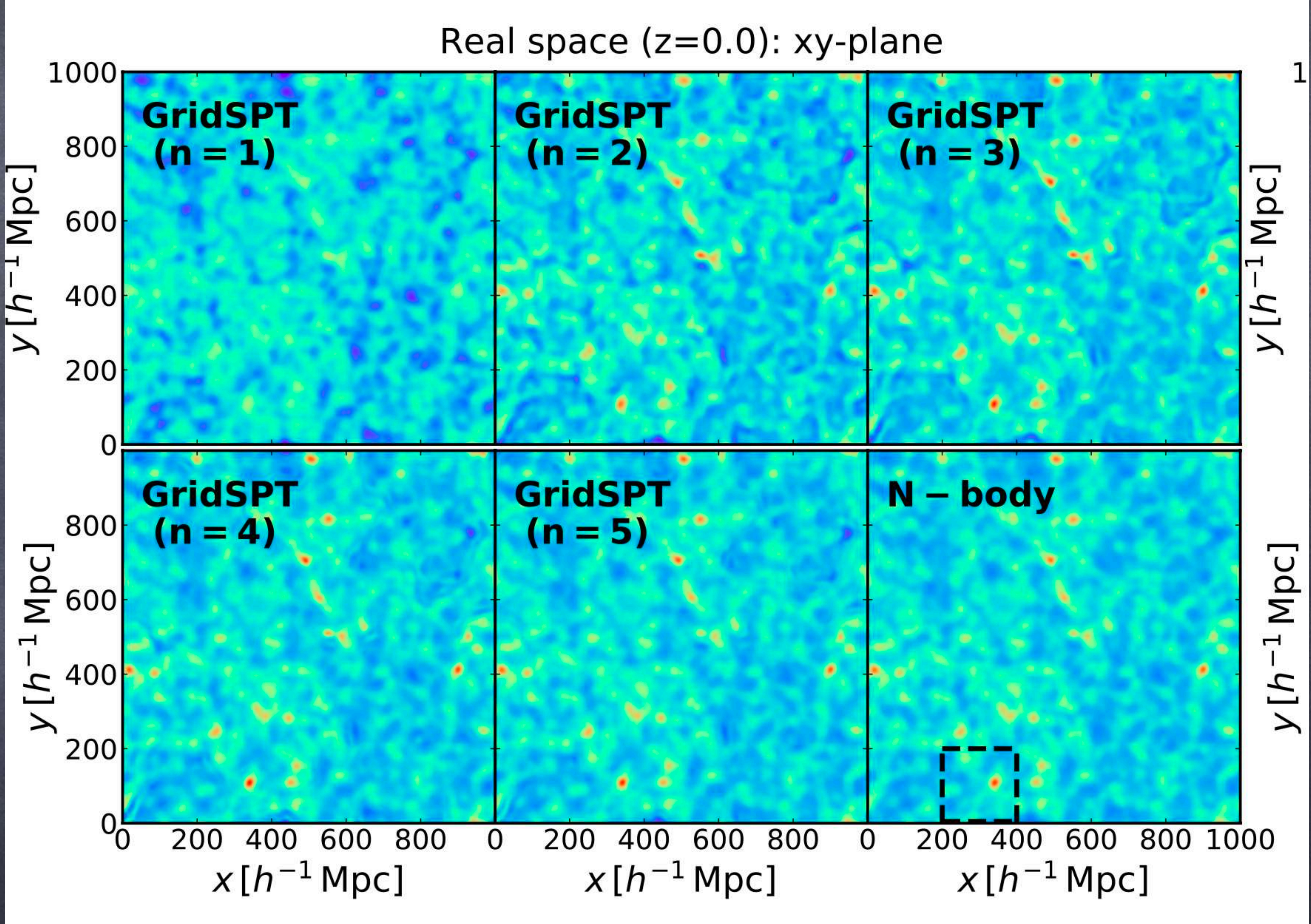
Is there more information in the LSS than can be extracted reliably?

From field correlators to the field itself





F. Schmidt++ 1808.02002, 2004.06702, 2403.03220...

G. Cabass++ 2307.04706

A.Obuljen++ 2207.12398

N. Kokron++ 2112.00012

Taruya, Nishimichi, Jeong, 2109.06734

LSS on the lattice

box: $L=1000$ Mpc/h, $\Lambda_{uv} = 2\pi N_{grid}/[L(N+1)]$

LSS on the lattice

box: L=1000 Mpc/h, $\Lambda_{uv} = 2\pi N_{grid}/[L(N+1)]$

PT expansion

model:

$$\delta^{[N]}(\mathbf{k}) = \delta^{[N],\mathrm{PT}}_{\Lambda_{\mathrm{uv}}}(\mathbf{k}) + \Delta\delta^{[N]}_{\Lambda_{\mathrm{uv}}}(\mathbf{k}) \,,$$

$$\delta^{[N],\mathrm{PT}}_{\Lambda_{\mathrm{uv}}}(\mathbf{k}) \equiv \sum_{n=1}^{N} \delta^{(n)}_{\Lambda_{\mathrm{uv}}}(\mathbf{k}) \,, \quad \Delta\delta^{[N]}_{\Lambda_{\mathrm{uv}}}(\mathbf{k}) \equiv \sum_{n=1}^{N} \Delta\delta^{(n)}_{\Lambda_{\mathrm{uv}}}(\mathbf{k}) \,,$$

UV correction

LSS on the lattice

box: $L = 1000$ Mpc/h, $\Lambda_{uv} = 2\pi N_{grid}/[L(N+1)]$

PT expansion

model:

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UV correction

likelihood:

$$\log P_N[\delta|\delta_{in}](k_{\max};\Lambda,\{\alpha^i_\Lambda\}) = -\frac{1}{2}\sum_{\mathbf{n}}^{n_{\max}}\left[\log\left(L^{-3}p_\epsilon(k_{\mathbf{n}})\right) + \frac{\left|\delta(\mathbf{k_n}) - \delta^{[N]}(\mathbf{k_n})\right|^2}{L^3\,p_\epsilon(k_{\mathbf{n}})}\right]$$

LSS on the lattice

box: L=1000 Mpc/h, $\Lambda_{uv} = 2\pi N_{grid}/[L(N+1)]$

PT expansion

model:

$$\delta^{[N]}(\mathbf{k}) = \delta^{[N],\mathrm{PT}}_{\Lambda_{\rm uv}}(\mathbf{k}) + \Delta\delta^{[N]}_{\Lambda_{\rm uv}}(\mathbf{k}),$$

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likelihood:

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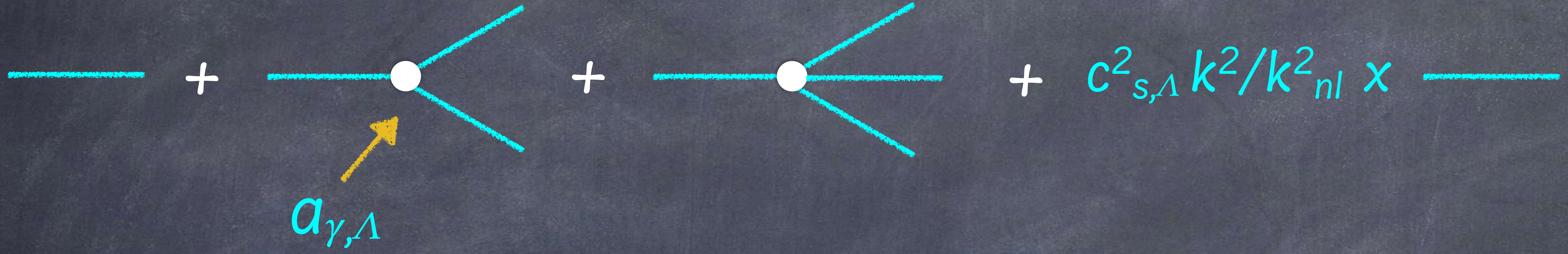
PT computations with GridSPT: A.Taruya, T. Nishimichi, D. Jeong

1807.04215, 2007,05504, 2109.06734…

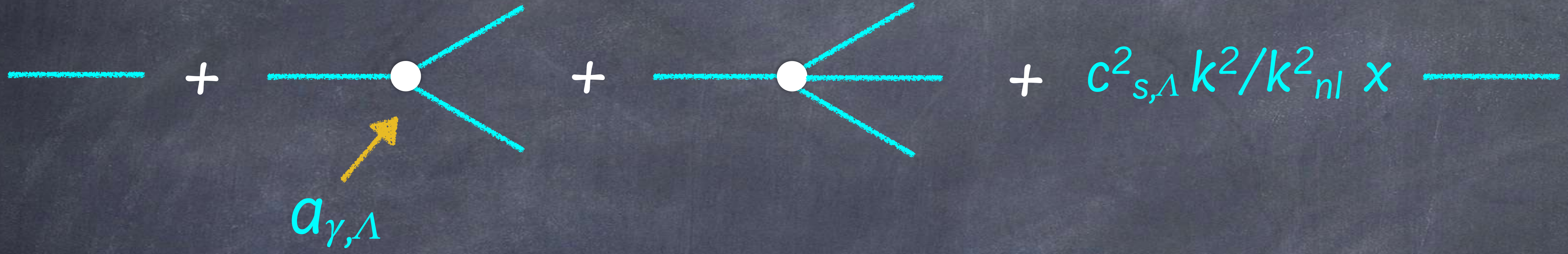
Running of the bootstrap parameters

Model: truncated field in the theory with the cutoff:

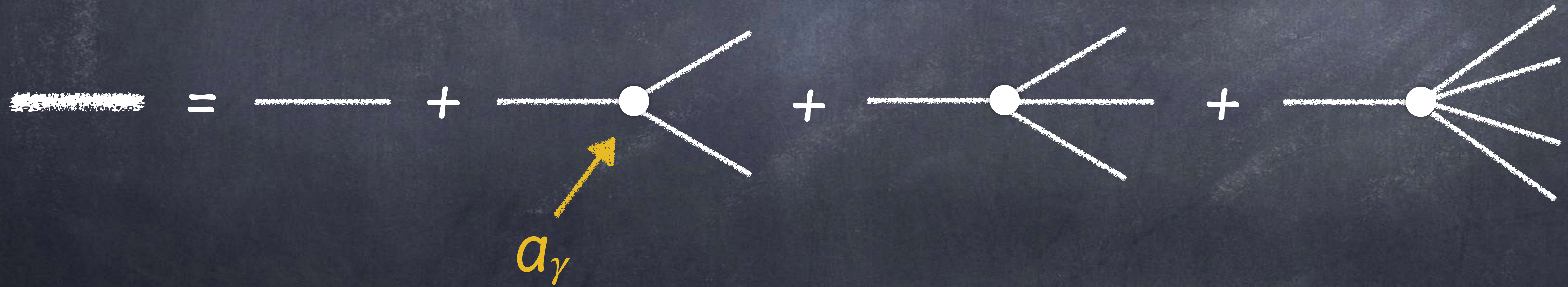


Running of the bootstrap parameters

Model: truncated field in the theory with the cutoff:

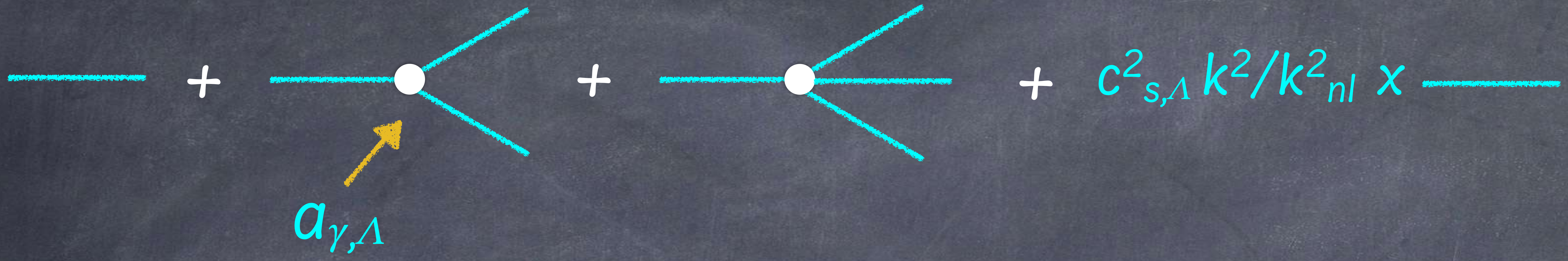


Data: field of the full theory in the continuum (data/nBody, no cutoff):

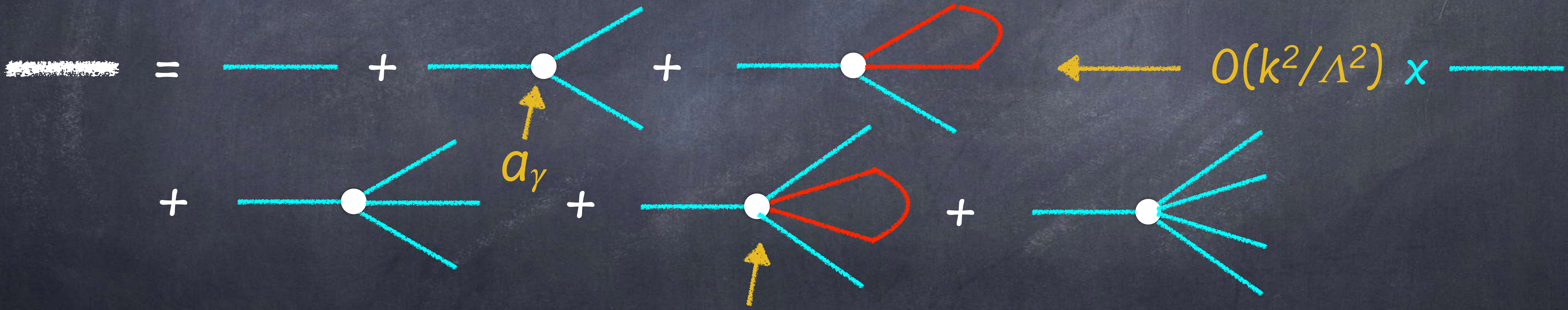


+ higher PT + non-perturbative

Model: truncated field in the theory with the cutoff: $k = k<\Lambda + k>\Lambda$



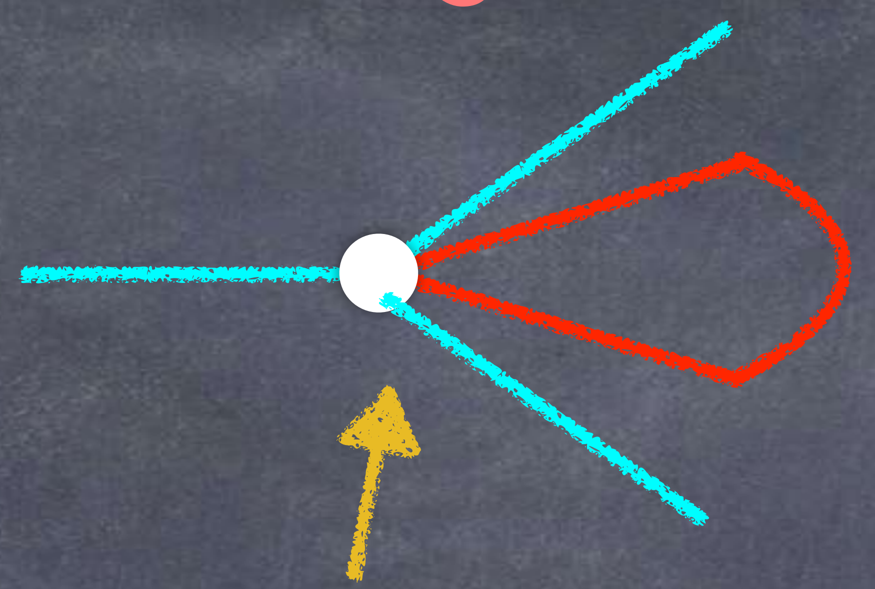
Data: field of the full theory in the continuum (data/nBody, no cutoff): $k<k_{nl}<\Lambda$



$O(k^2/\Lambda^2)\, a_\gamma + O(k^2/\Lambda^2) = \delta a_{\gamma,\Lambda}$

\+ higher PT + “finite” + “stochastic” $O(k^2/k^2_{nl})$

Running is calculable



$O(k^2/\Lambda^2)\ a_\gamma + O(k^2/\Lambda^2) = \delta a_{\gamma,\Lambda}$

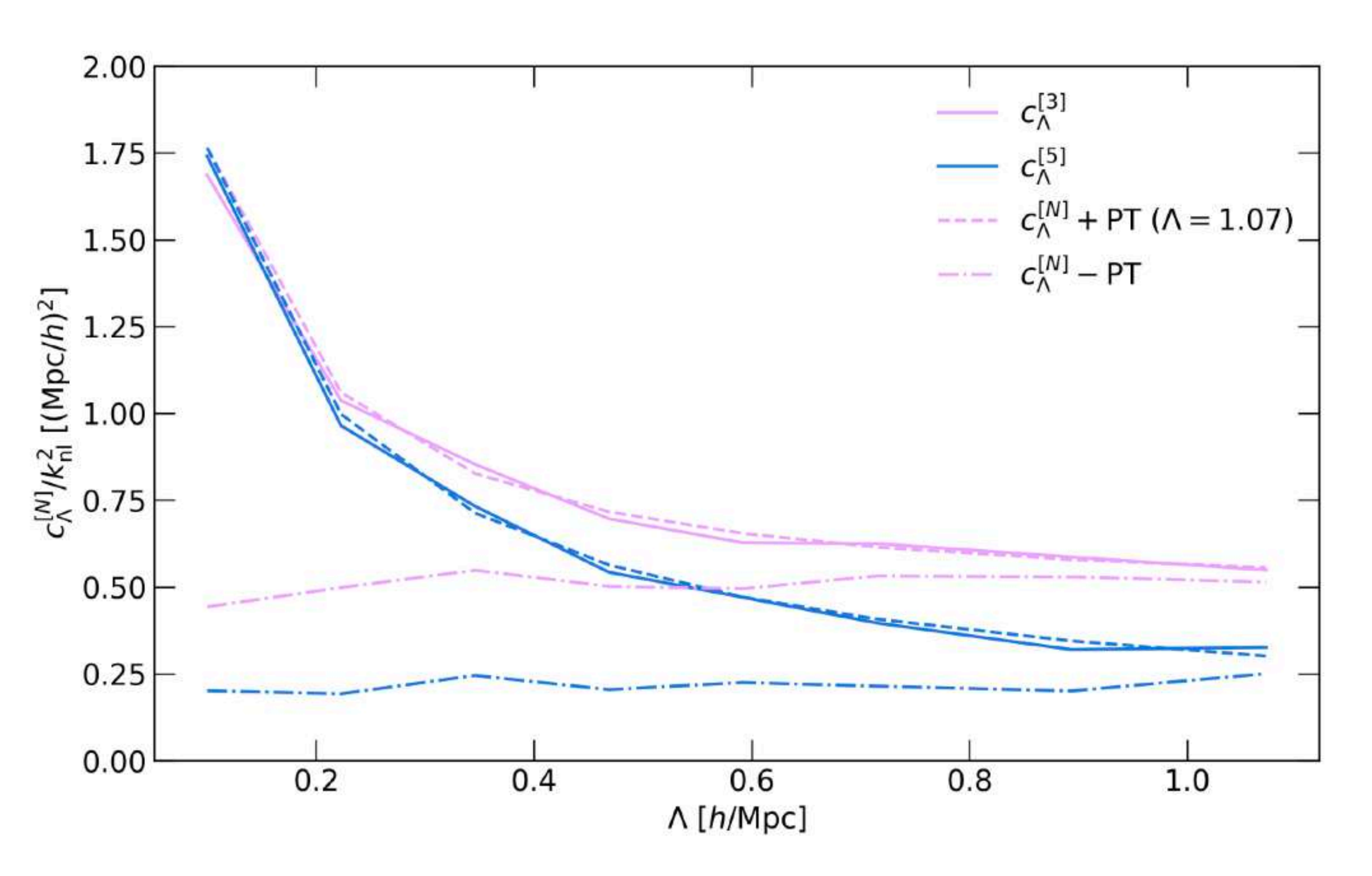
Finite contribution expected

$\delta a_{\gamma,fin} = O(k^2/k^2_{nl})$

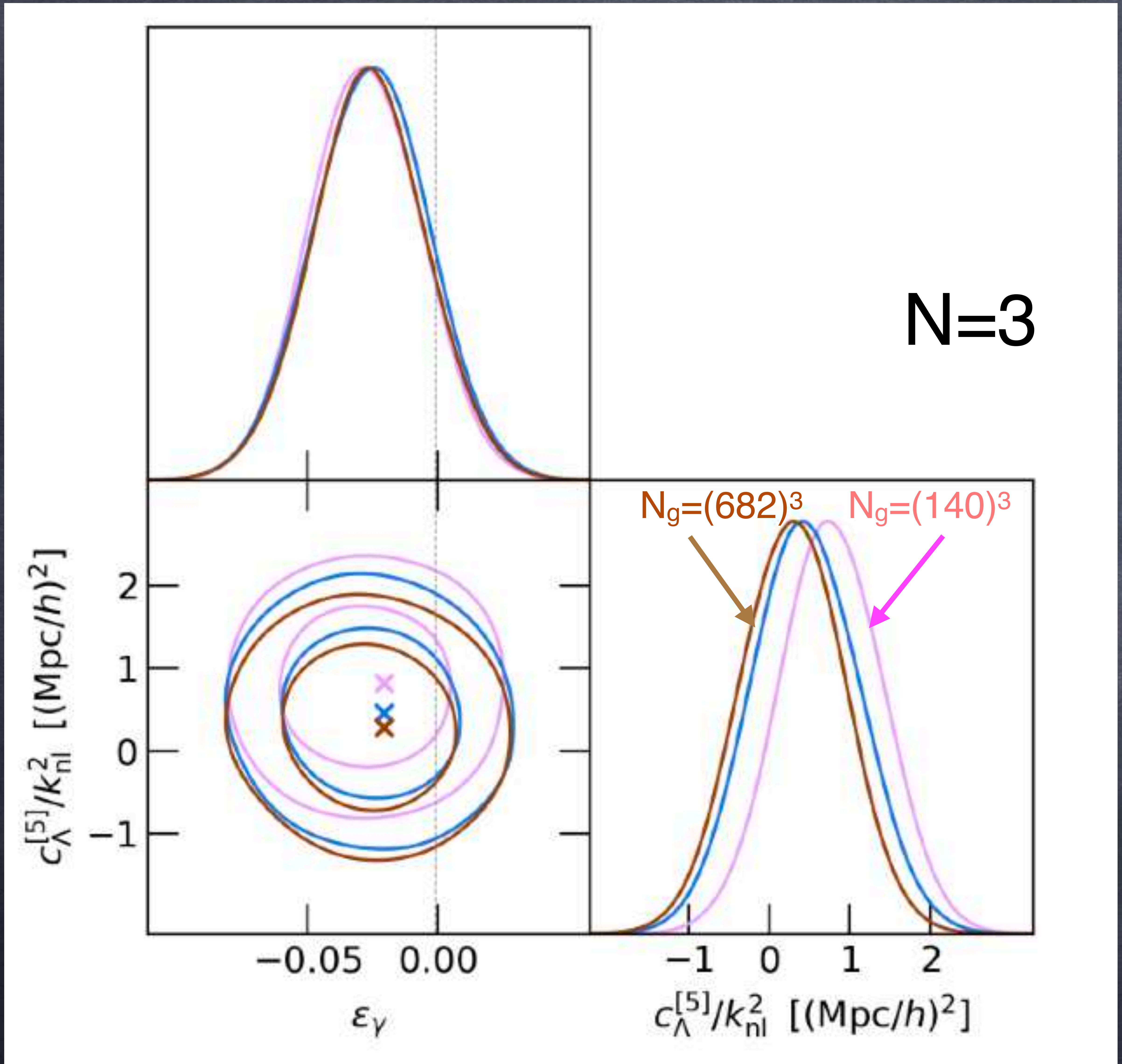
Evades non-renormalization th. of galileon operators

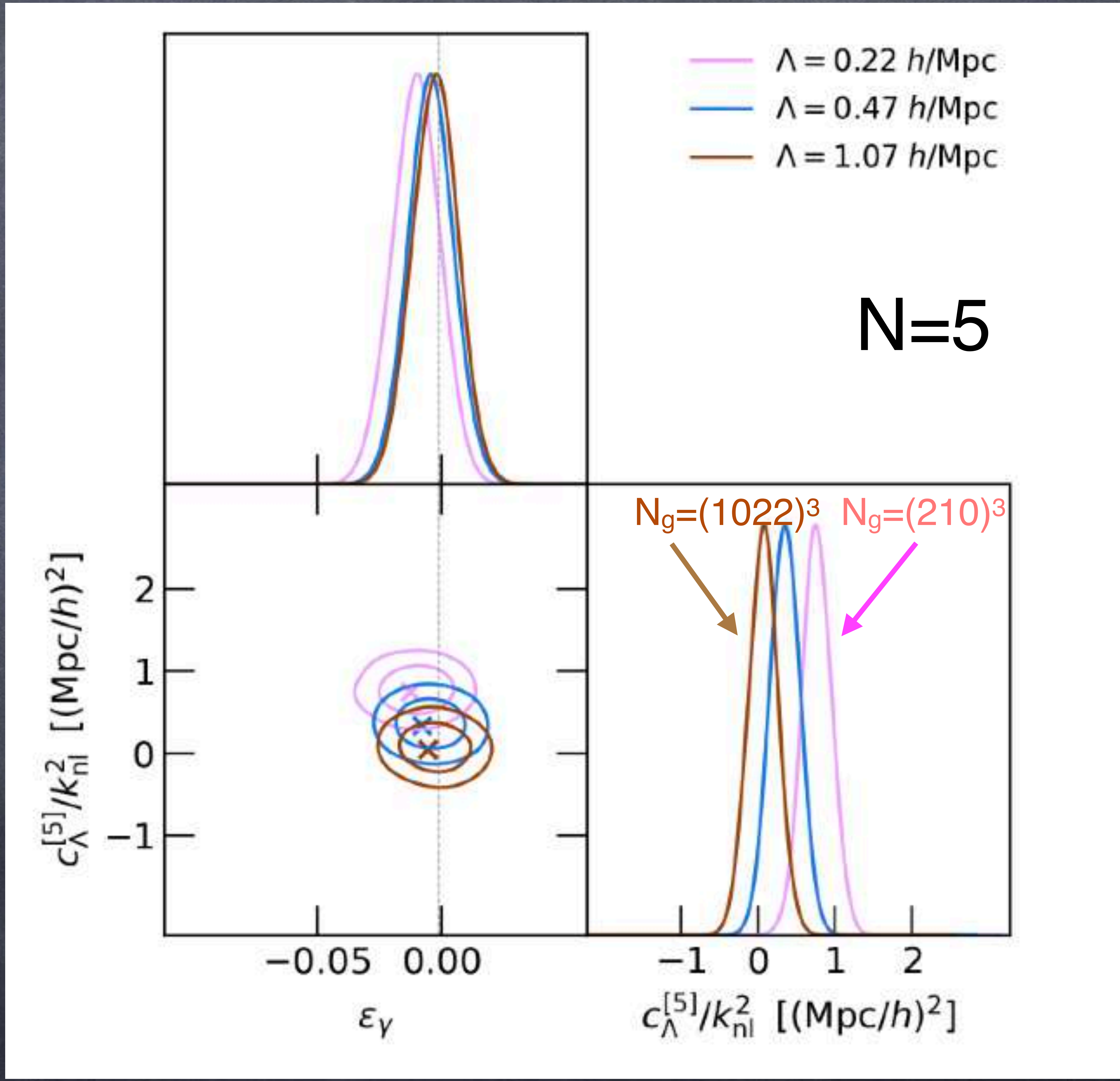
Asassi, Baumann, Green, Zaldarriaga, 2014

Running of the Wilson coefficients

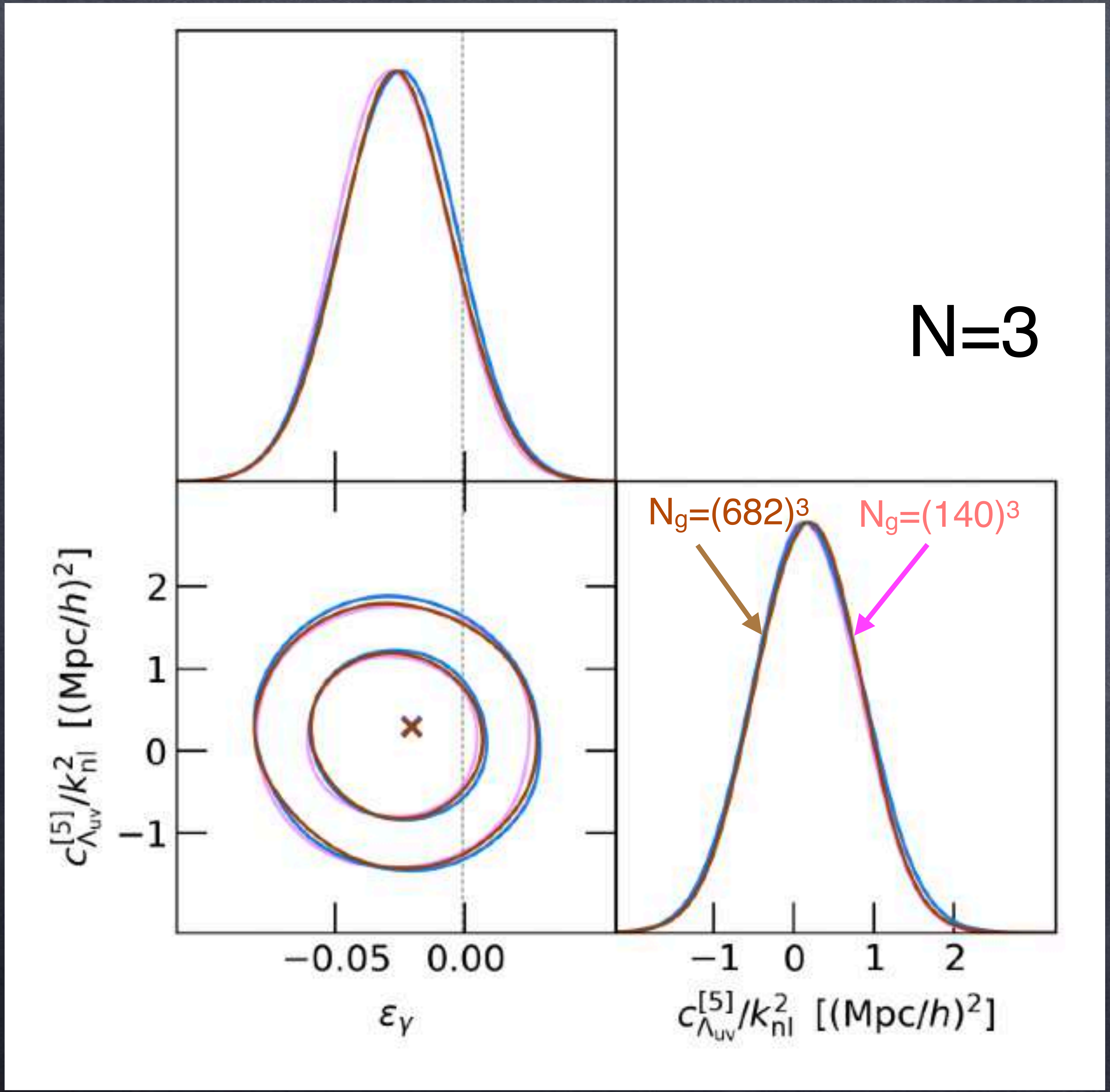


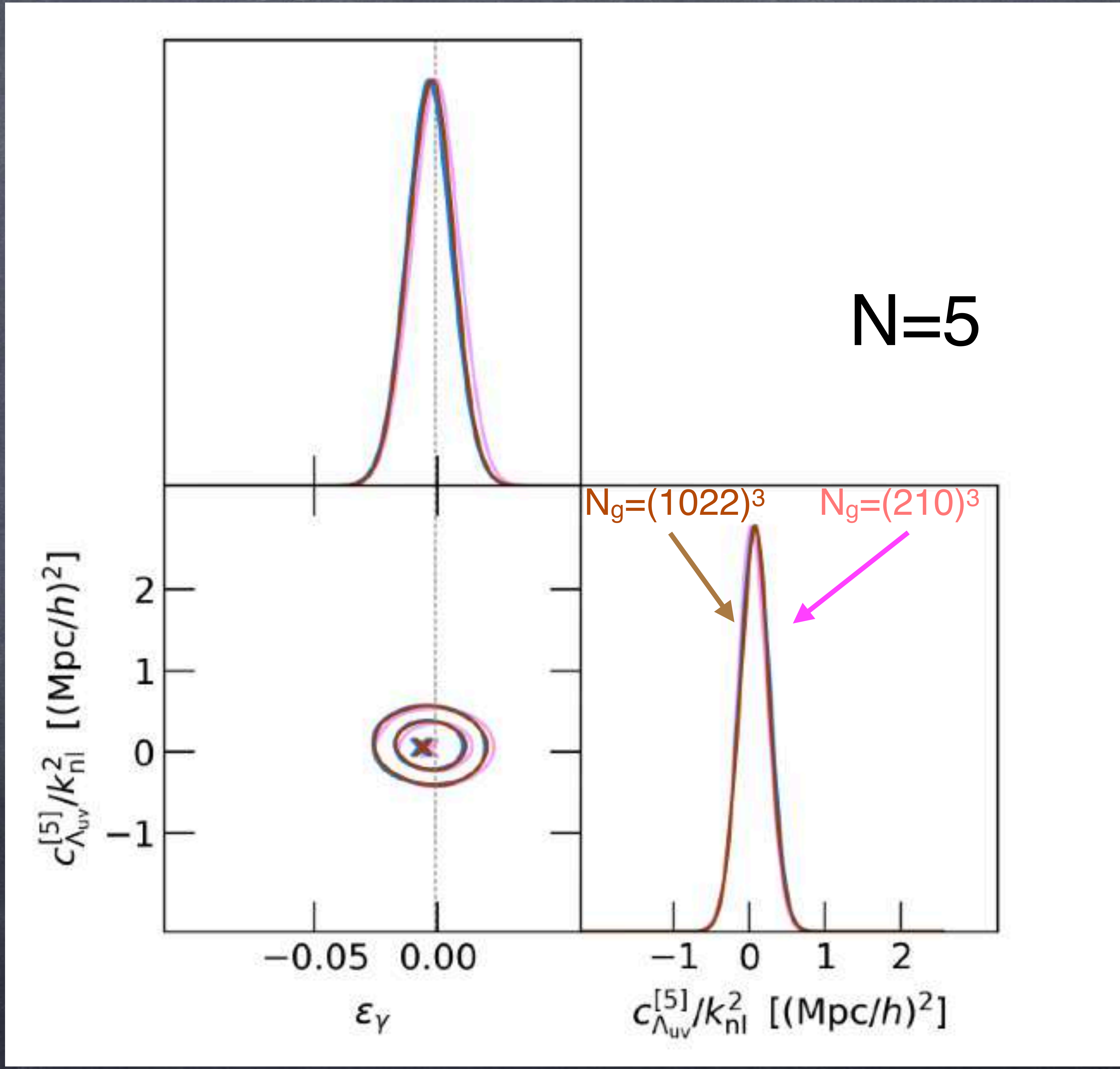
From Λ-dependent parameters…





… to renormalized ones





Summary

- The LSS is a source of information on physics beyond ΛCDM
- Model-independent nonlinearities beyond ΛCDM: LSS bootstrap
- From O(10%) to O(1 %): beyond field correlators (P and B)
- Field-level approaches: treat renormalization properly
- Towards real data: redshift space, bias (lagrangian vs eulerian), observational systematics...

Antonio’s Magic Powers

Antonio's Magic Powers

THANK YOU ANTONIO !!!

Bootstrap at field level

D. Jeong, T. Nishimichi, M. Peron, MP, A. Taruya, preliminary

2nd order

$$\delta_2(\mathbf{x},\eta) = \varphi^{(2)}_\beta(\mathbf{x}) + \frac{a^{(2)}_\gamma(\eta)}{2}\varphi^{(2)}_\gamma(\mathbf{x})$$

$$\theta_2(\mathbf{x},\eta) = \varphi^{(2)}_\beta(\mathbf{x}) + \frac{d^{(2)}_\gamma(\eta)}{2}\varphi^{(2)}_\gamma(\mathbf{x})\,,$$

$$\varphi^{(2)}_\beta(\mathbf{x}) \equiv \partial_i\varphi^{(1)}(\mathbf{x})\left(\frac{\partial_i}{\partial^2}\varphi^{(1)}(\mathbf{x})\right) + \left(\frac{\partial_i\partial_j}{\partial^2}\varphi^{(1)}(\mathbf{x})\right)\left(\frac{\partial_i\partial_j}{\partial^2}\varphi^{(1)}(\mathbf{x})\right)\,,$$

$$\varphi^{(2)}_\gamma(\mathbf{x}) \equiv \left(\varphi^{(1)}(\mathbf{x})\right)^2 - \left(\frac{\partial_i\partial_j}{\partial^2}\varphi^{(1)}(\mathbf{x})\right)\left(\frac{\partial_i\partial_j}{\partial^2}\varphi^{(1)}(\mathbf{x})\right)\,,$$

New summary statistics

Wavelets:

Valogiannis, Dvorkin, '22

Eickenberg et al, '22

Blancard et al, '23

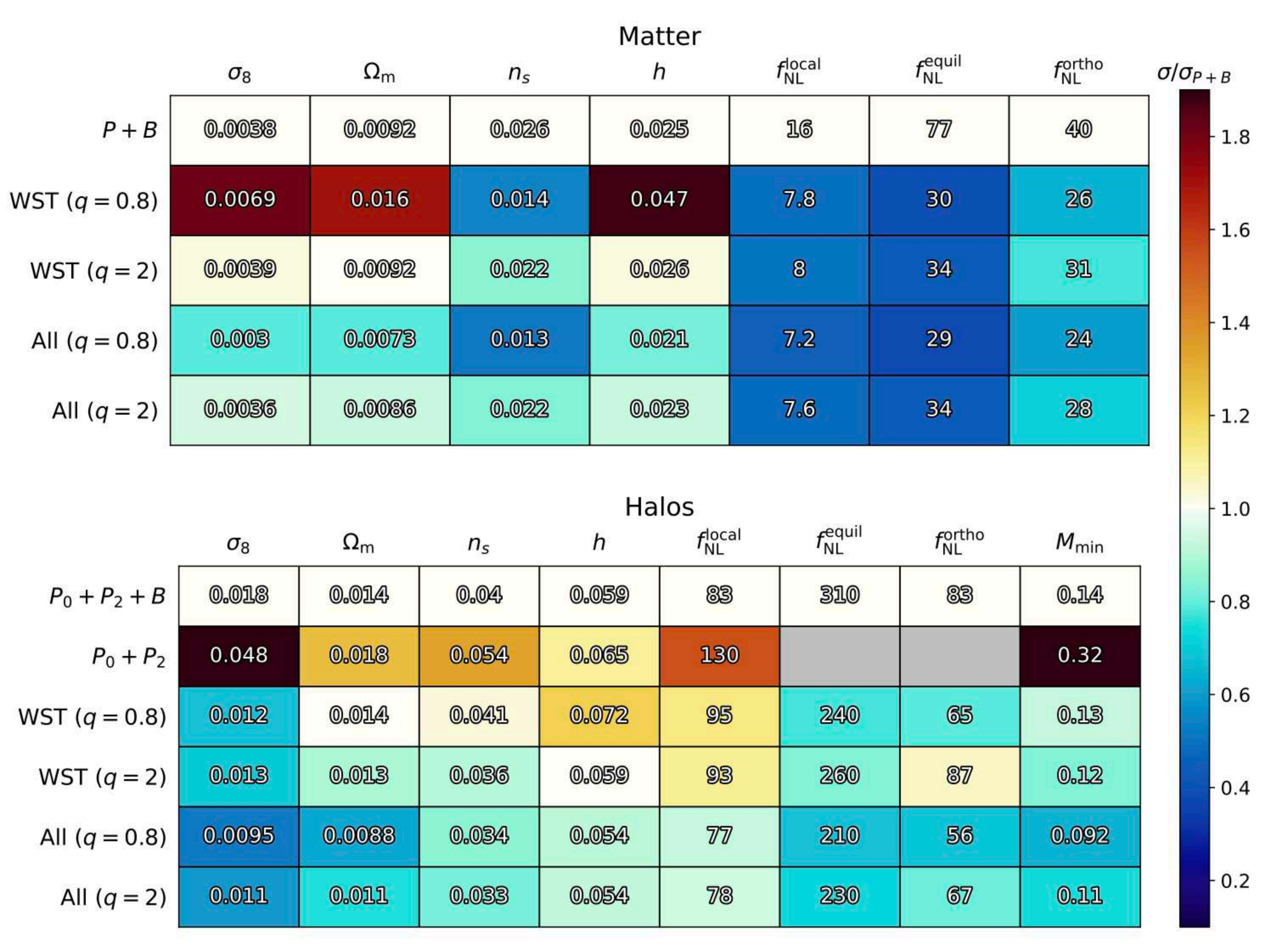
Peron, Jung, Liguori, MP '24

Marked PS:

White, '16

Massara et al, '21

Marinucci et al, '24



2403.17657

KNN:

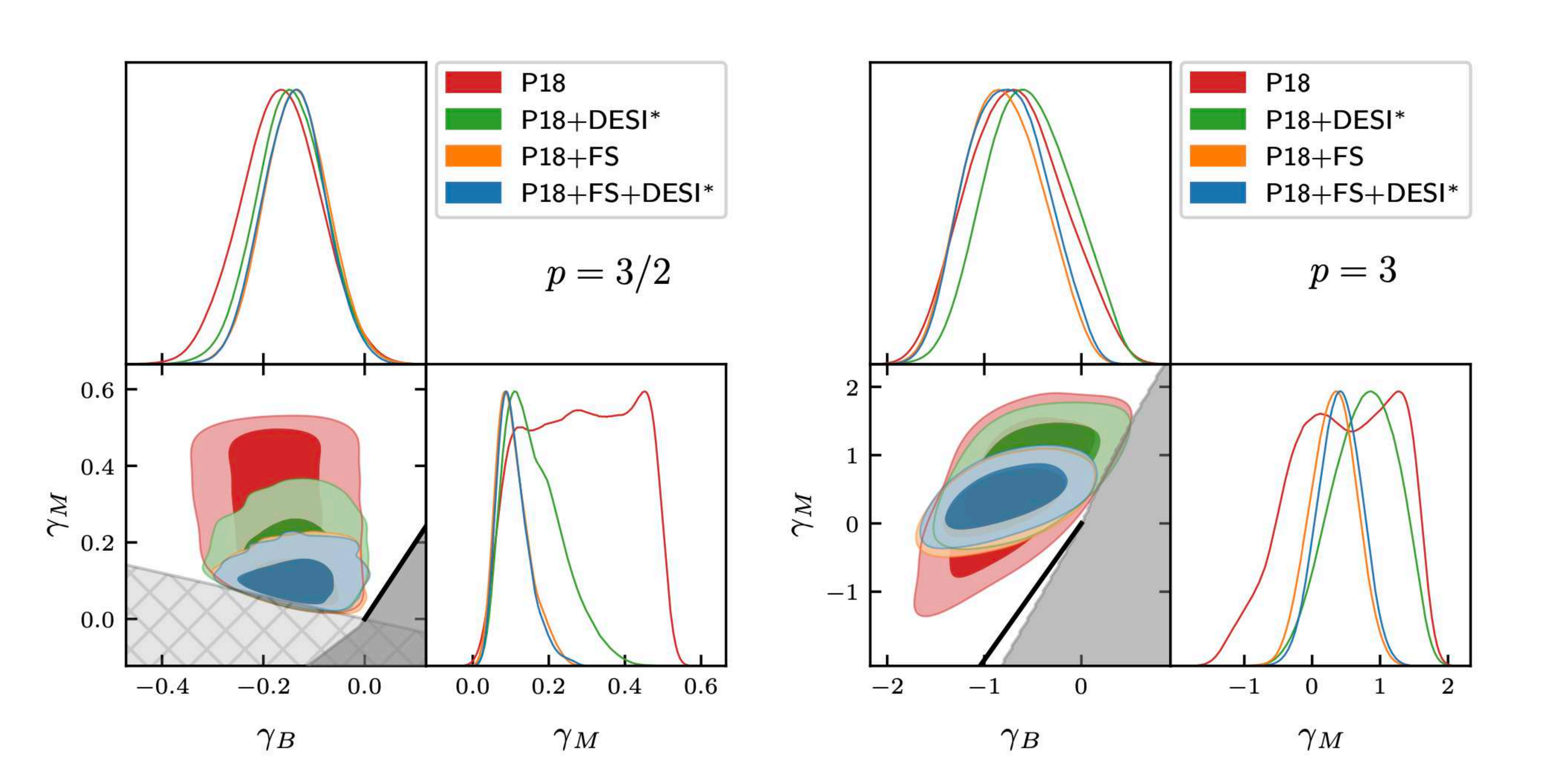
Coulton, Banerjee, Abel, '22

Skew spectra:

Schmittfull, Dizgah, '20

to combine constraints from CMB+LSS: assume a time-dependence

$$\alpha_{\rm B}(a) = \gamma_{\rm B} \left(\frac{a}{a_0}\right)^p , \qquad \alpha_{\rm M}(a) = \gamma_{\rm M} \left(\frac{a}{a_0}\right)^p ,$$



Taule, Marinucci, Biselli, MP, Vernizzi, 2409.08971

different time-dependence corresponds to different models!

Extension beyond ΛCDM: the case of nDGP

$$H^2 + \frac{H}{r_c} = \frac{8\pi G}{3} \sum_i \rho_i$$

r_c : cross-over scale between 4d and 5d cosmology

$$H(a) = H_0\sqrt{\Omega_{\rm m}(a/a_0)^{-3} + 1 - \Omega_{\rm m}}$$

DE component fine-tuned to have ΛCDM background evolution

$$\dot\delta + a^{-1}\partial_i\left((1+\delta)v^i\right) = 0\,,$$
$$\dot v^i + Hv^i + \frac{1}{a}v^j\partial_j v^i + \frac{1}{a}\partial_i\Phi = -\frac{1}{a\rho_{\rm m}}\partial_j\tau^{ij}\,,$$

continuity and Euler equations

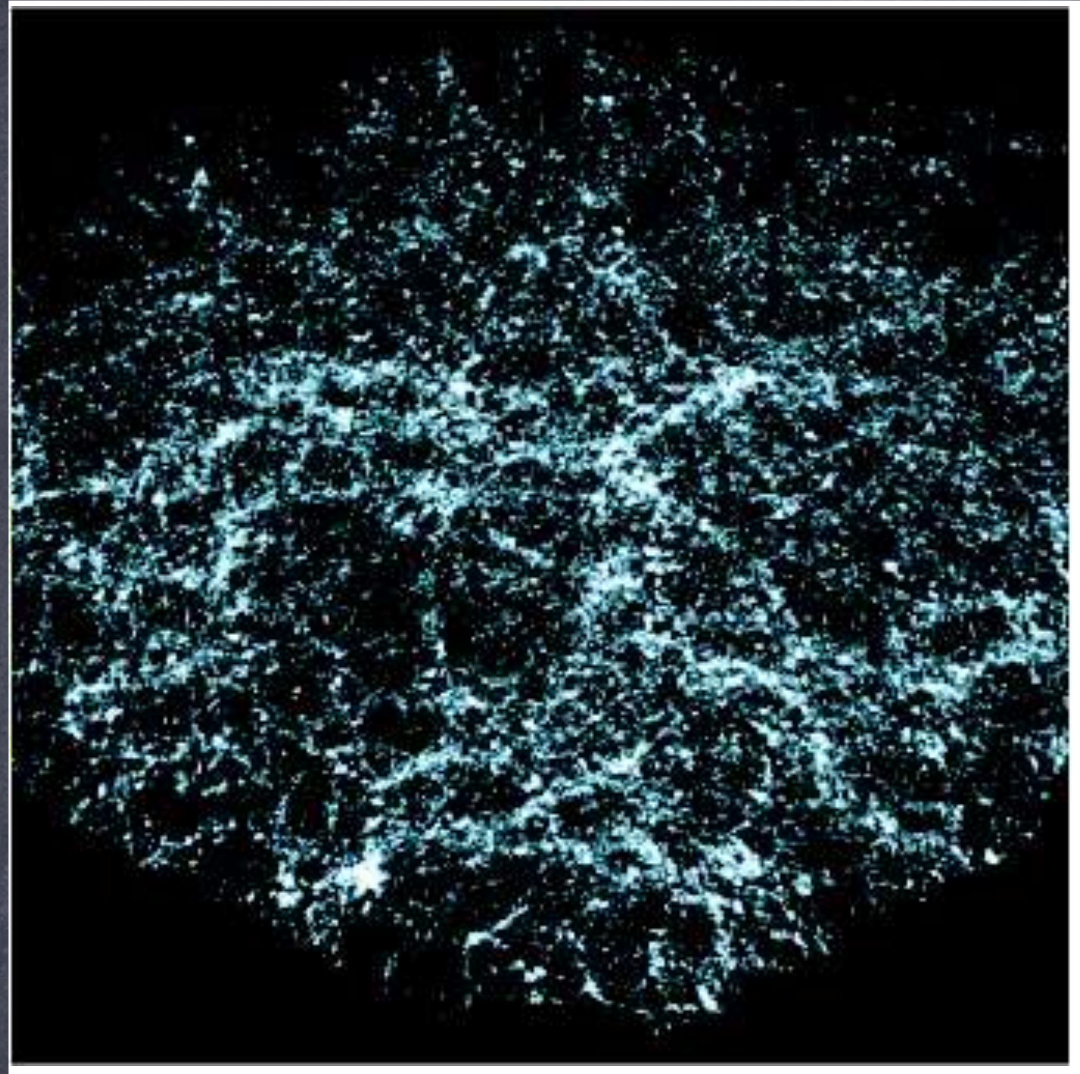
$$\frac{\partial^2\Phi}{H^2a^2} = \frac{3\,\Omega_{{\rm m},a}}{2}\mu\,\delta + \left(\frac{3\,\Omega_{{\rm m},a}}{2}\right)^2\mu_2\left[\delta^2 - \left(\partial^{-2}\partial_i\partial_j\delta\right)^2\right]$$
$$+\left(\frac{3\,\Omega_{{\rm m},a}}{2}\right)^3\mu_{22}\left[\delta - \left(\partial^{-2}\partial_i\partial_j\delta\right)\partial^{-2}\partial_i\partial_j\right]\left[\delta^2 - \left(\partial^{-2}\partial_k\partial_l\delta\right)^2\right]$$
$$+\left(\frac{3\,\Omega_{{\rm m},a}}{2}\right)^3\mu_3\left[\delta^3 - 3\delta\left(\partial^{-2}\partial_i\partial_j\delta\right)^2 + 2(\partial^{-2}\partial_i\partial_j\delta)(\partial^{-2}\partial_k\partial_j\delta)(\partial^{-2}\partial_i\partial_k\delta)\right] + \mathcal{O}(\delta^4)$$

μ, μ_2, μ_{22}, μ_3

controlled by r_c

modified Poisson equation

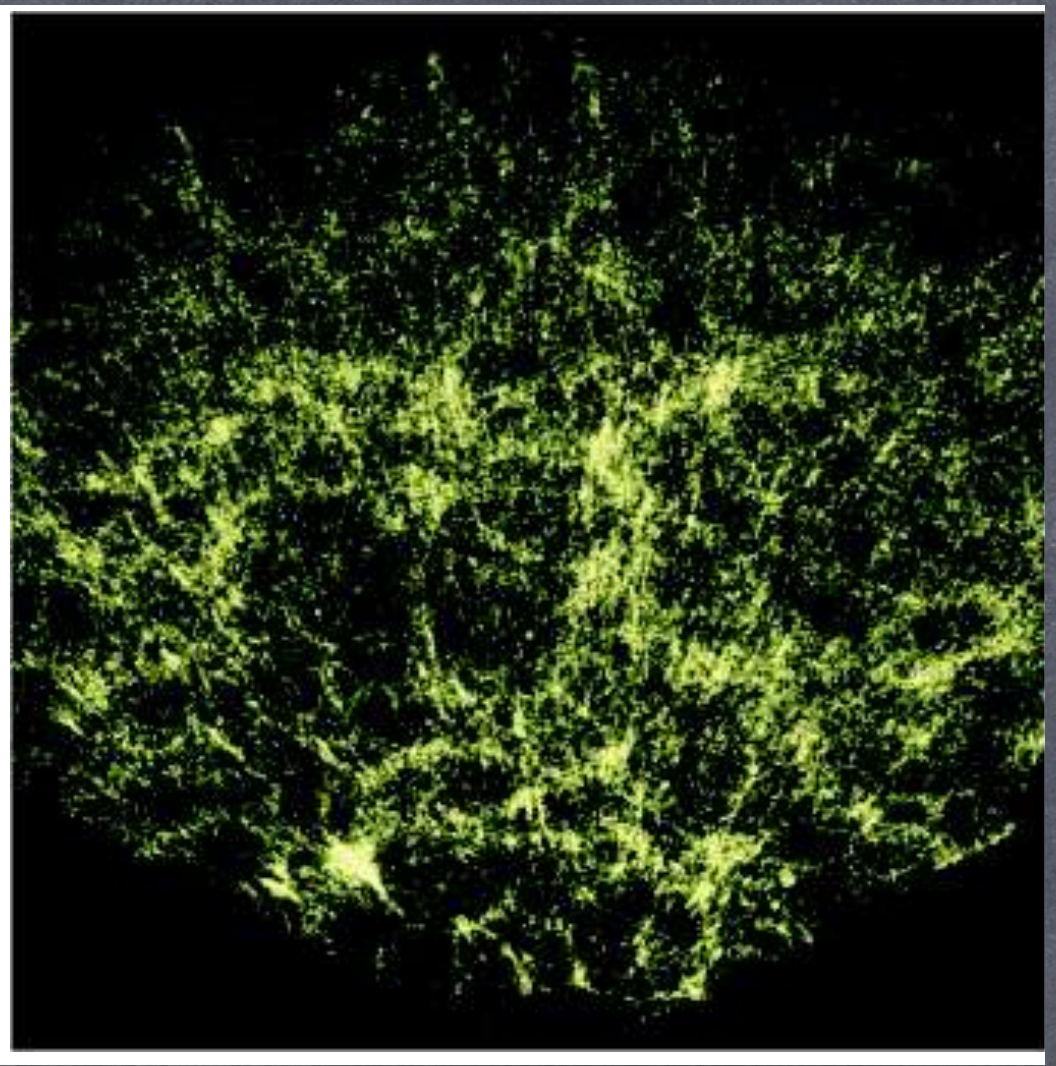
Redshift space



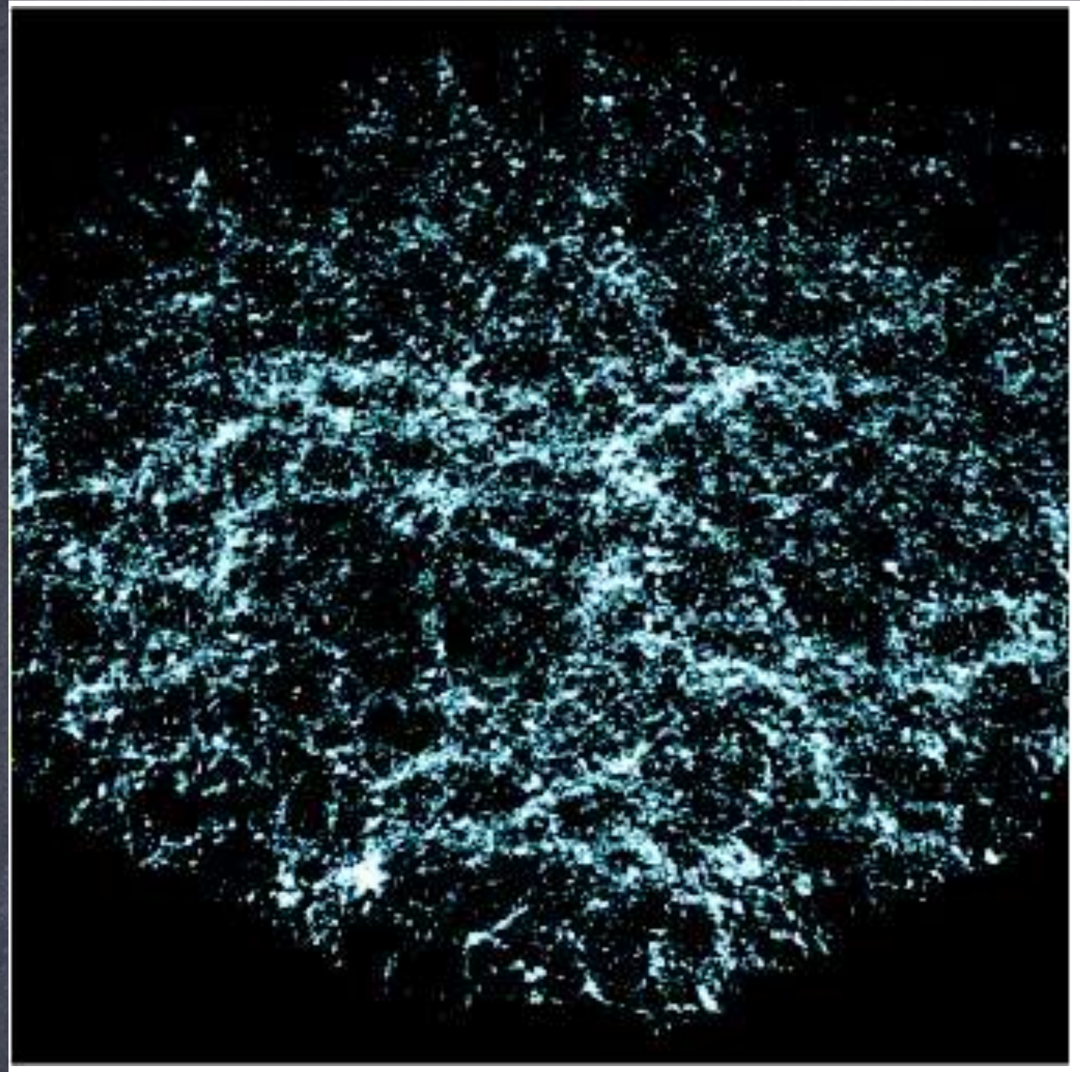
$$1 + \delta_s(\vec{x}_s) = [1 + \delta(\vec{x}(\vec{x}_s))] \left| \frac{\partial \vec{x}_s}{\partial \vec{x}} \right|^{-1}_{\vec{x}(\vec{x}_s)}$$

$$\vec{x}_s = \vec{x} + \frac{\vec{v} \cdot \hat{z}}{H_0} \hat{z}$$

Kaiser ‘87



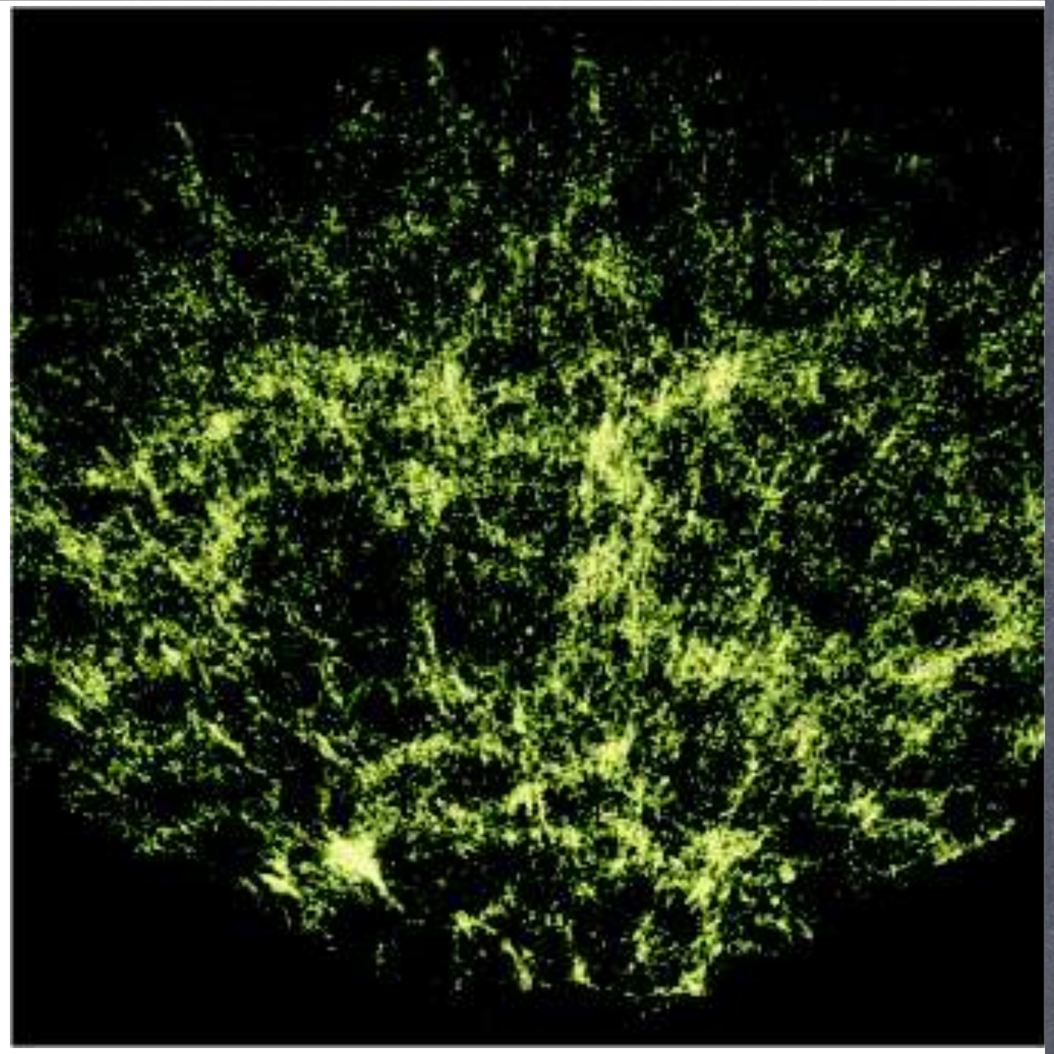
Redshift space



$$1 + \delta_s(\vec{x}_s) = [1 + \delta(\vec{x}(\vec{x}_s))] \left| \frac{\partial \vec{x}_s}{\partial \vec{x}} \right|^{-1}_{\vec{x}(\vec{x}_s)}$$

$$\vec{x}_s = \vec{x} + \frac{\vec{v} \cdot \hat{z}}{H_0} \hat{z}$$

Kaiser '87



$$P_g(k,\mu) = Z_1(\mu)^2 P_{11}(k) + 2\int \frac{d^3q}{(2\pi)^3}\, Z_2(\boldsymbol{q}, \boldsymbol{k}-\boldsymbol{q}, \mu)^2 P_{11}(|\boldsymbol{k}-\boldsymbol{q}|) P_{11}(q) + 6 Z_1(\mu) P_{11}(k) \int \frac{d^3q}{(2\pi)^3}\, Z_3(\boldsymbol{q}, -\boldsymbol{q}, \boldsymbol{k}, \mu) P_{11}(q)$$

Cosmology information is encoded in velocity: nonlinear Kaiser effect

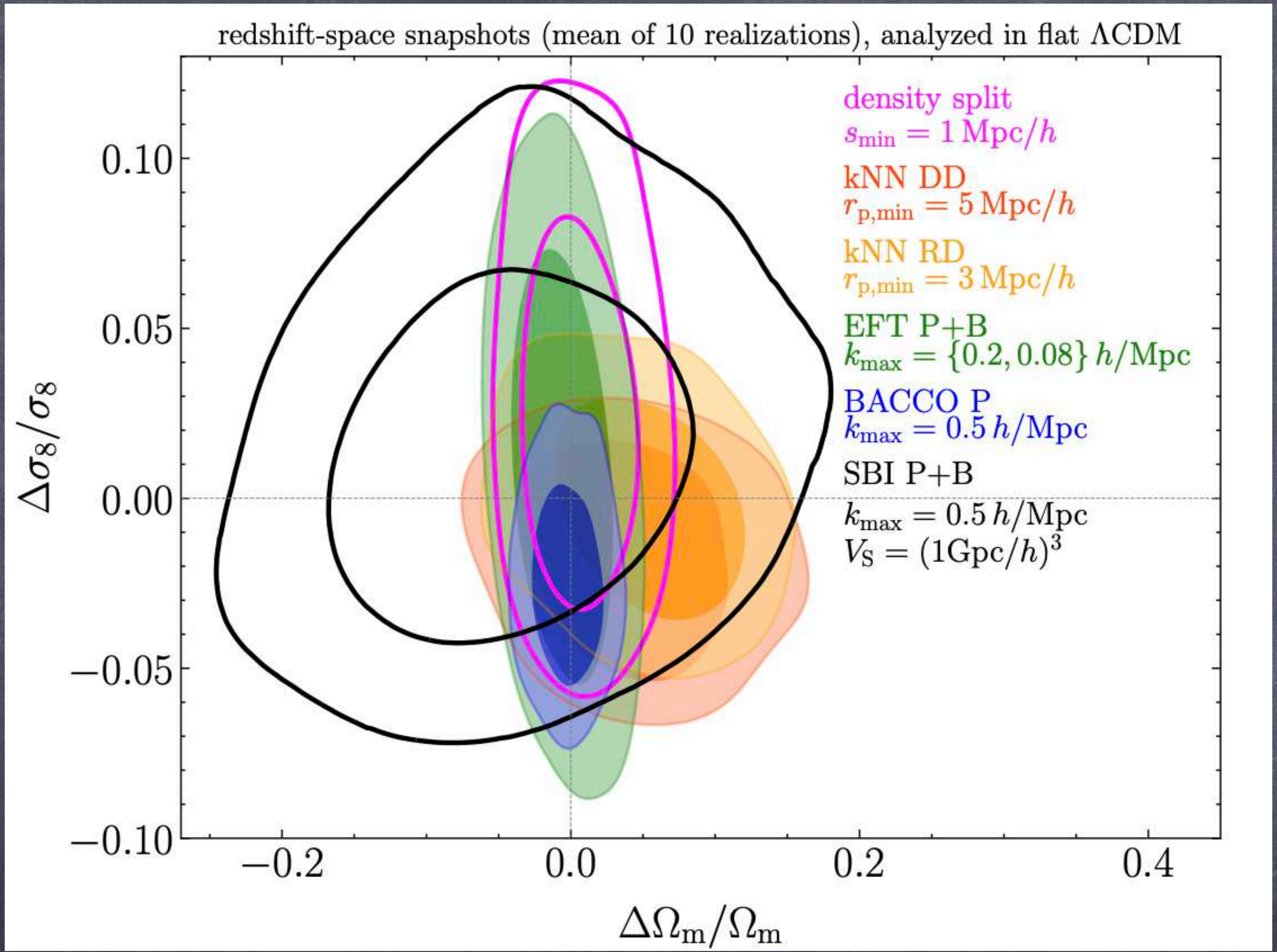
$$Z_g^{(1)}(\mathbf{q}) = c_0^{(1)} + f\mu_k^2\,,$$

$$Z_g^{(2)}(\mathbf{q}_1,\mathbf{q}_2) = K_g^{(2)}(\mathbf{q}_1,\mathbf{q}_2) + f\mu_k^2\, G^{(2)}(\mathbf{q}_1,\mathbf{q}_2) + c_0^{(1)} f\mu_k\, k\left(\frac{\mu_{q_1}}{q_1} + \frac{\mu_{q_2}}{q_2}\right) + f^2\mu_k^2\, k^2\, \frac{\mu_{q_1}\mu_{q_2}}{q_1 q_2}\,,$$

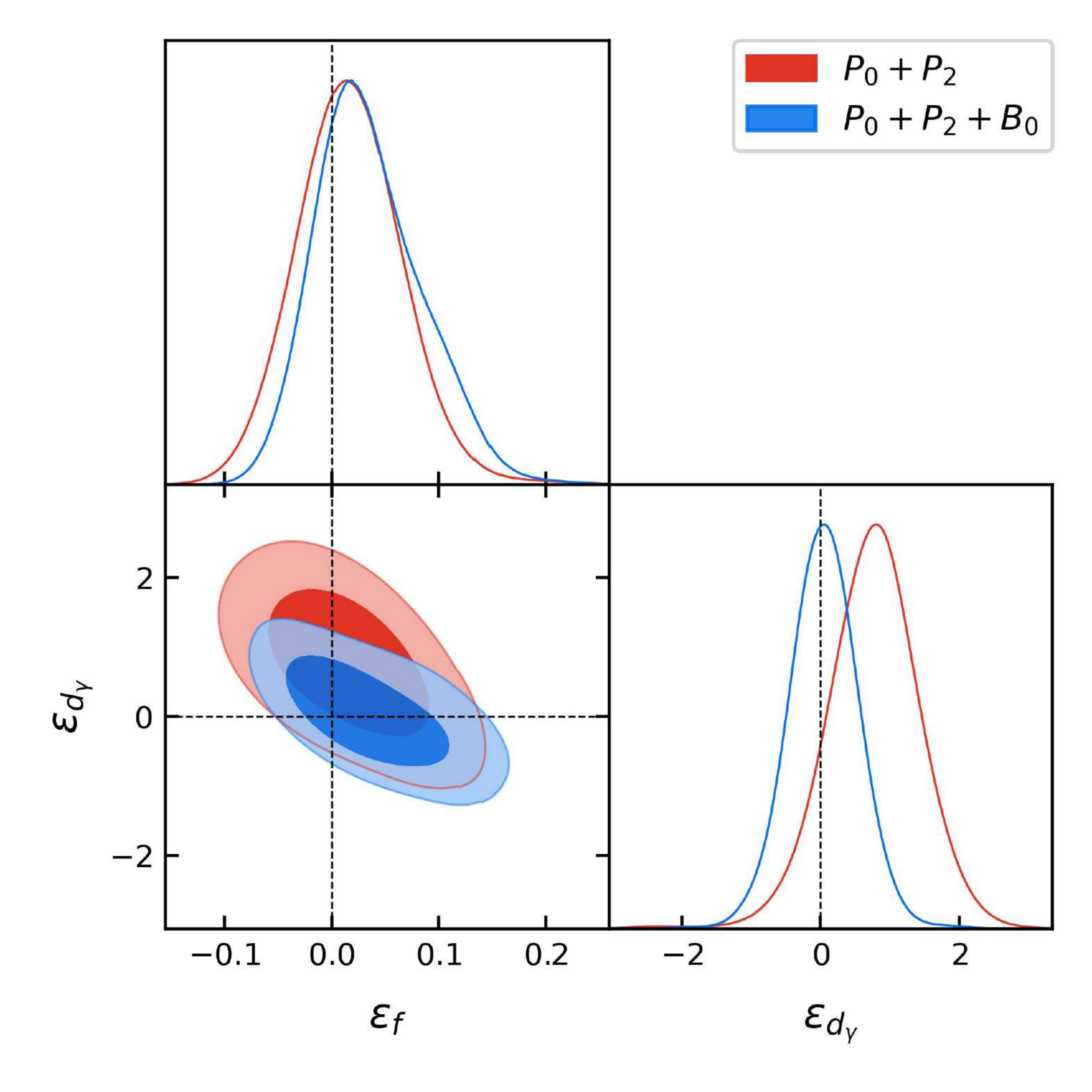
$$\begin{aligned} Z_g^{(3)}(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3) = {} & K_g^{(3)}(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3) + f\mu_k^2\, G^{(3)}(\mathbf{q}_1,\mathbf{q}_2,\mathbf{q}_3) \\ & + f\mu_k\, k\left[\frac{\mu_{q_1}}{q_1} K_g^{(2)}(\mathbf{q}_2,\mathbf{q}_3) + \frac{\mu_{q_{23}}}{q_{23}} G^{(2)}(\mathbf{q}_2,\mathbf{q}_3)\left(c_0^{(1)} + f\mu_k\, k\,\frac{\mu_{q_1}}{q_1}\right)\right. \\ & \left. + c_0^{(1)} f\mu_k\, k\,\frac{\mu_{q_2}\mu_{q_3}}{q_2 q_3} + 2\text{ cyclic}\right] \\ & + f^3\mu_k^3\, k^3\,\frac{\mu_{q_1}\mu_{q_2}\mu_{q_3}}{q_1 q_2 q_3}\,, \end{aligned}$$

$d_1^{(2)}$

From Fisherland towards real world...



"Beyond 2pt Mock challenge": Krause et al 2405.02252



$P_0 + P_2$
$P_0 + P_2 + B_0$
2
0
−2
ε_{d_γ}
−0.1
0.0
0.1
0.2
ε_f
−2
0
2
ε_{d_γ}