HYMALAIA: A Hybrid Lagrangian Model for IA

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HIGGS CENTER WORKSHOP ON LSS

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Intrinsic Alignments

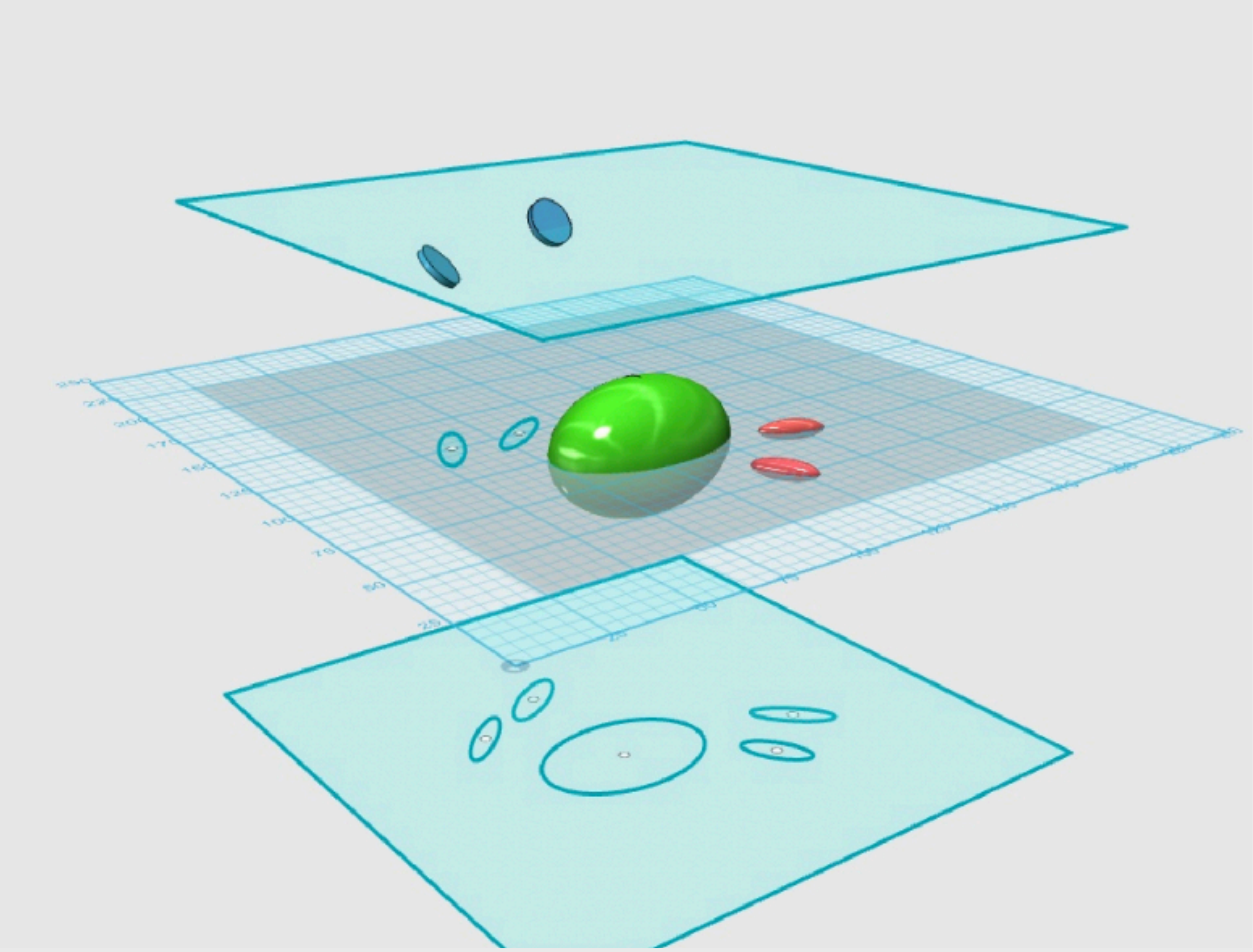
$$\langle \epsilon_i \epsilon_j \rangle = \underbrace{\langle g_i g_j \rangle}_{GG} + \underbrace{\langle \epsilon_i^{(s)} \epsilon_j^{(s)} \rangle}_{II} + \underbrace{\langle \epsilon_i^{(s)} g_j \rangle}_{IG} + \underbrace{\langle g_i \epsilon_j^{(s)} \rangle}_{GI} .$$

II term: Correlations between physically close galaxies

- Positive correlation

GI term: Correlations between one foreground galaxy and one background galaxy

- Negative correlation



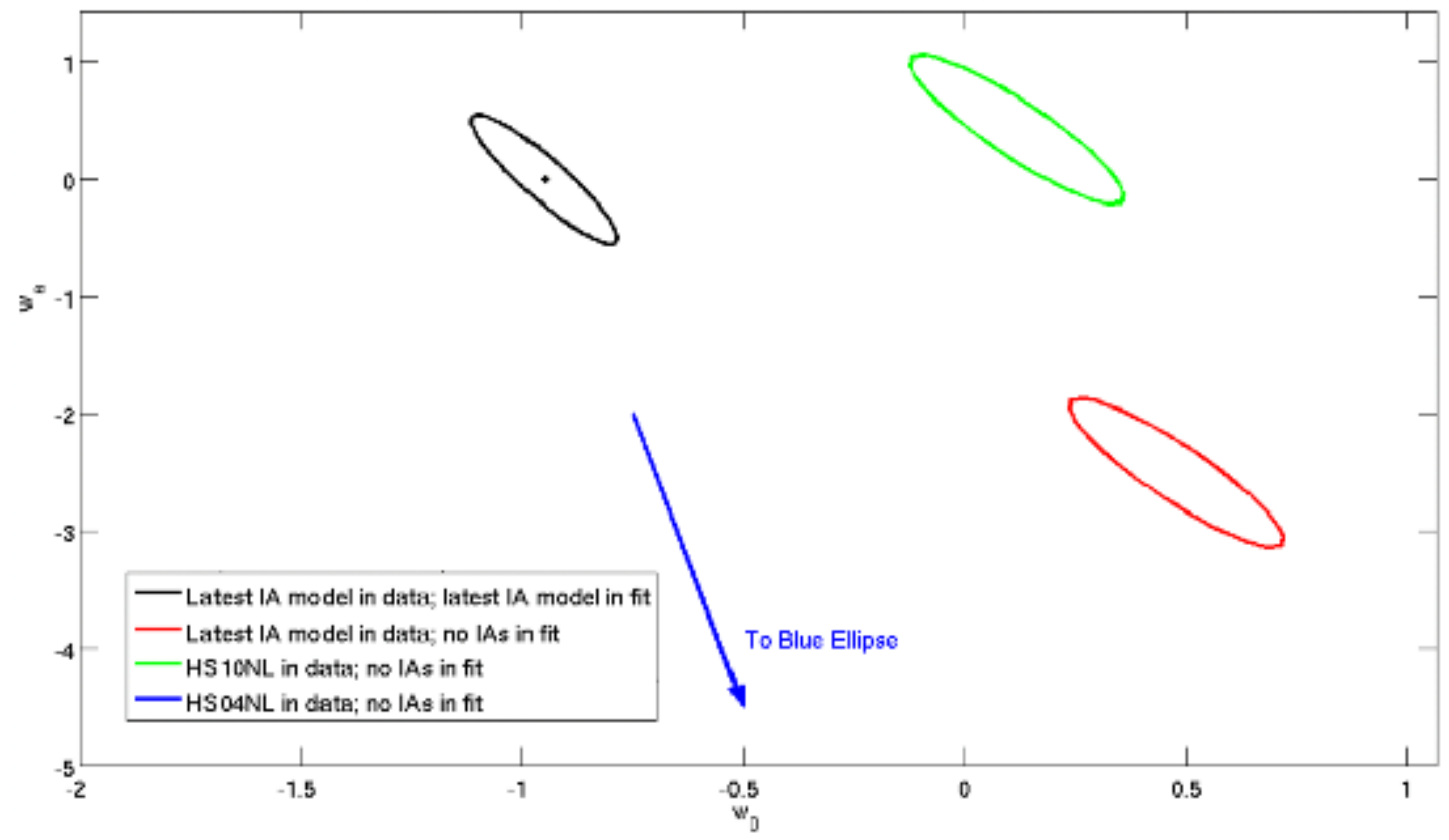
Credit: Joachimi et. al (2015)

WL Systematic

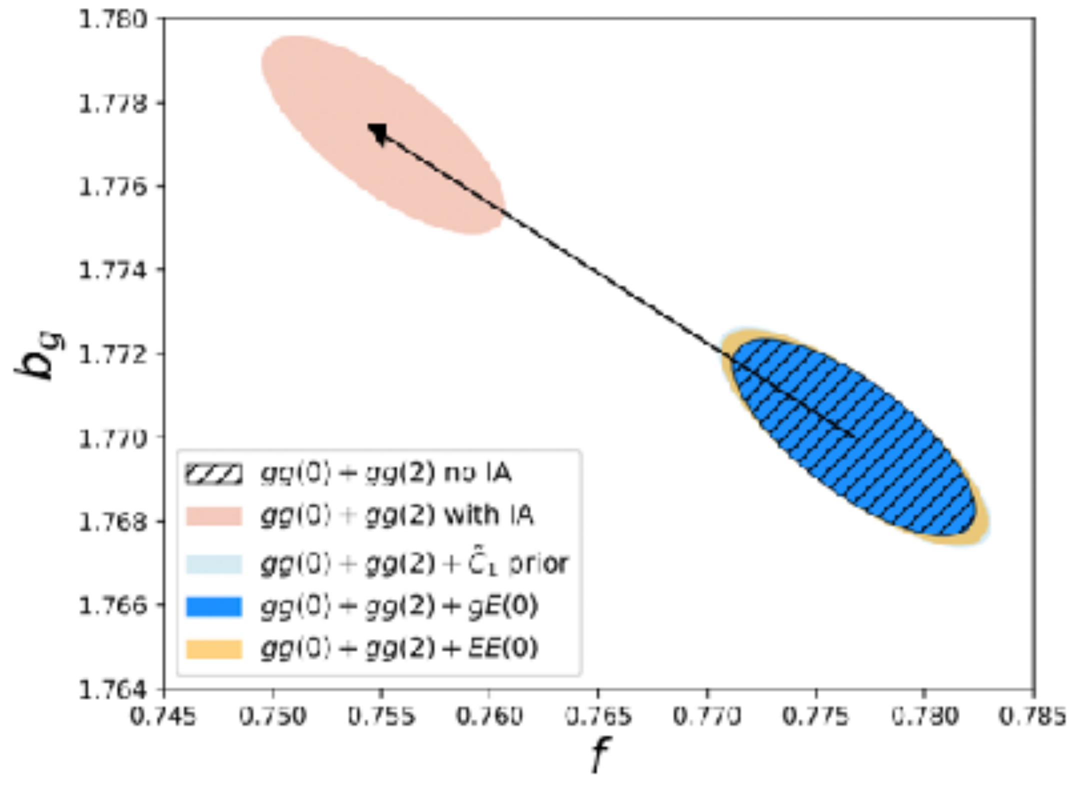
Dissolving constraining power with more IA parameters

Neglecting IA in cosmic shear analyses

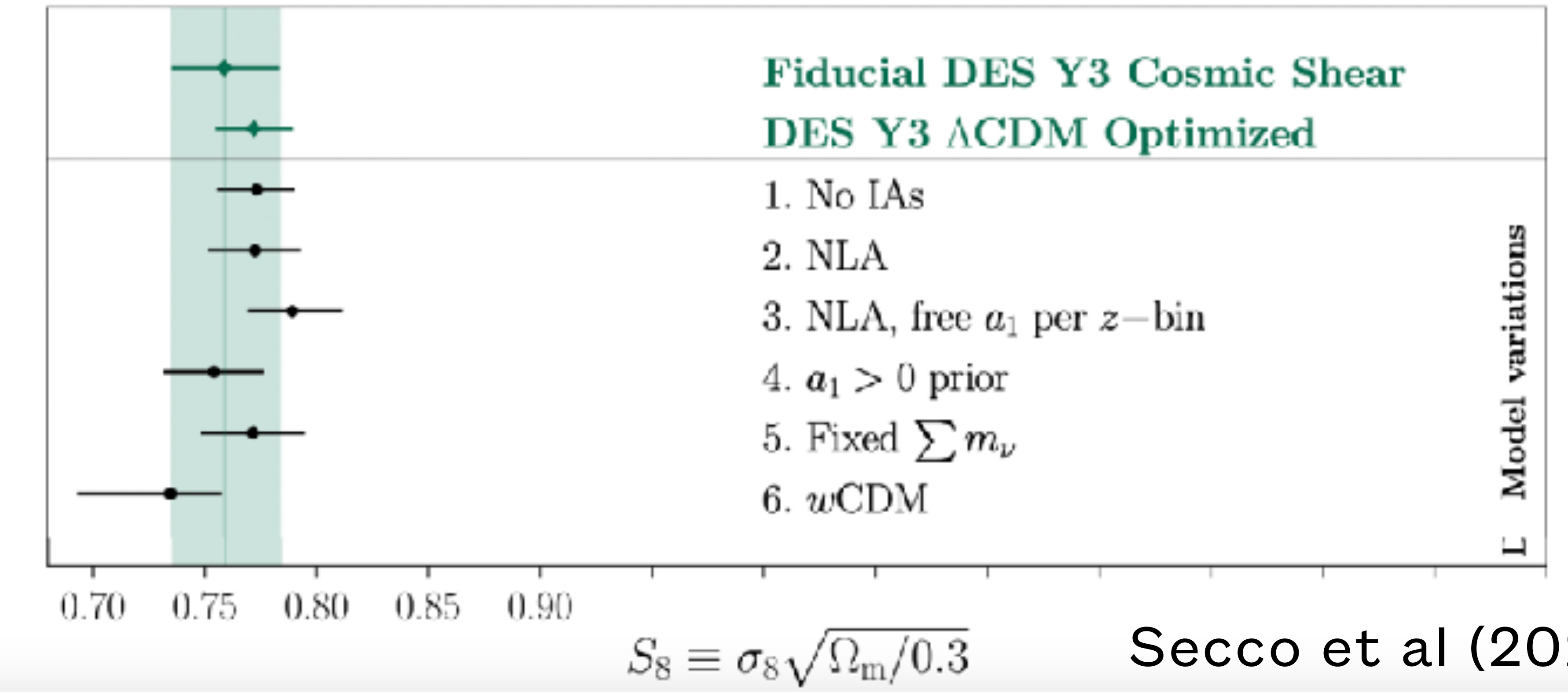
Neglecting IA as a selection effect in spectroscopic surveys



Kirk et. al (2012)



Zwetsloot & Chisari (2022)



Secco et al (2021)

Alignments probe cosmology

Many IA applications do not require modelling beyond the **linear regime.**

Physics	Proposed	Verified in sims	Constrained from LOWZ
Growth rate	Taruya & Okumura (2020)	X	Okumura & Taruya (2023)
Primordial (anisotropic) non-Gaussianity	Schmidt, Chisari, Dvorkin (2015)	Akitsu+ (2021)	Kurita & Takada (2023)
Primordial magnetic fields	Schmidt, Chisari, Dvorkin (2015) Saga+ (2023)	through PNG only	X
Isotropy	Shiraishi, Okumura, Akitsu (2023)	X	X
BAO	Chisari & Dvorkin (2013)	Okumura, Taruya & Nishimichi (2019)	Xu+ (2023)
Primordial gravitational waves	Schmidt, Pajer, Zaldarriaga (2014) Chisari, Dvorkin, Schmidt (2014)	Akitsu, Li & Okumura (2023)	X
Parity breaking	Biagetti & Orlando (2020)	X	X

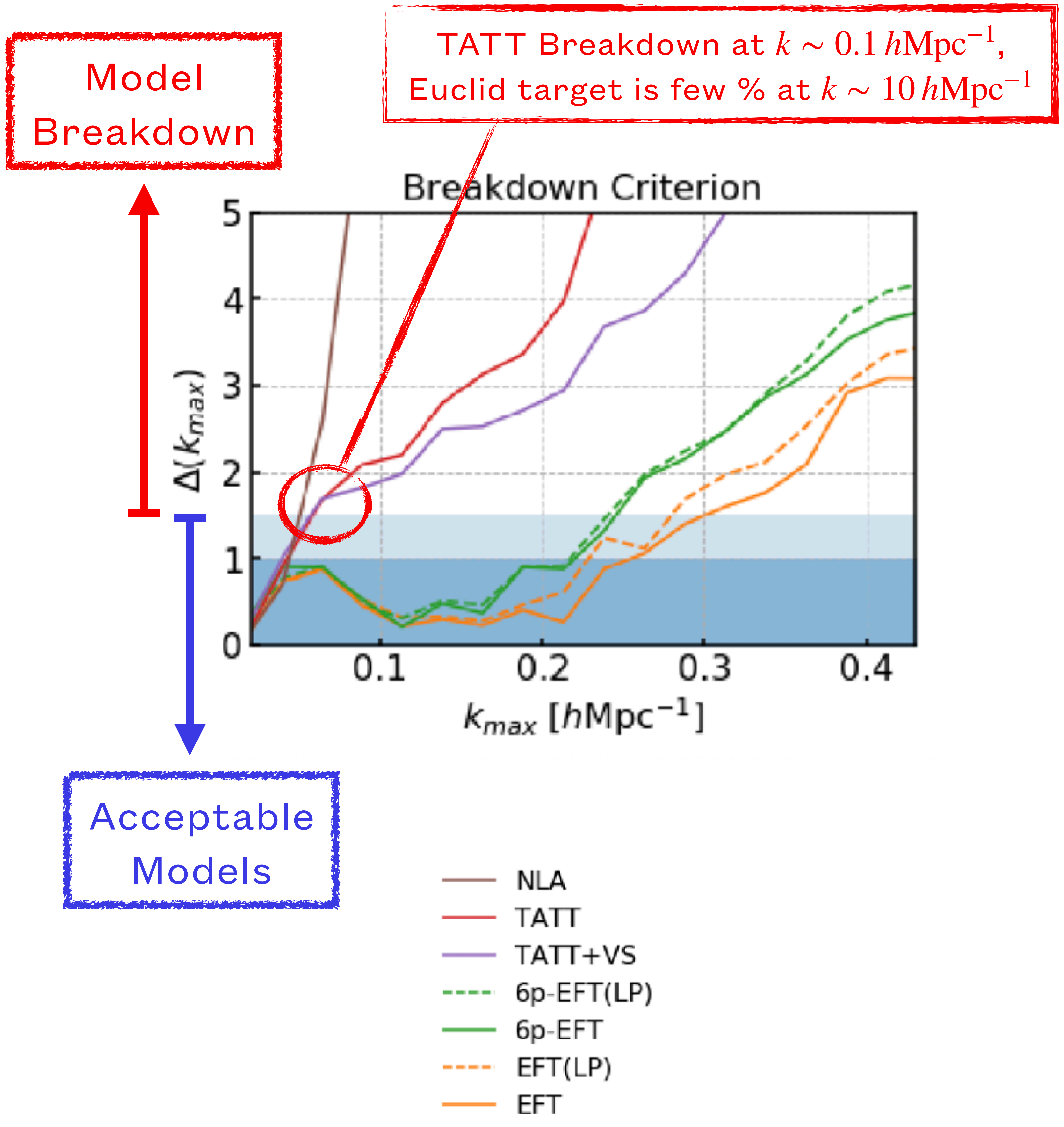
Tidal Alignment

To lowest order, the intrinsic shear of the galaxy shapes will be linearly related to the matter tidal field

$$\gamma^I = c_s s_{ij} = c_s \left(\partial_x^2 - \partial_y^2,\, 2\partial_x\partial_y\right) \nabla^{-2}\delta$$

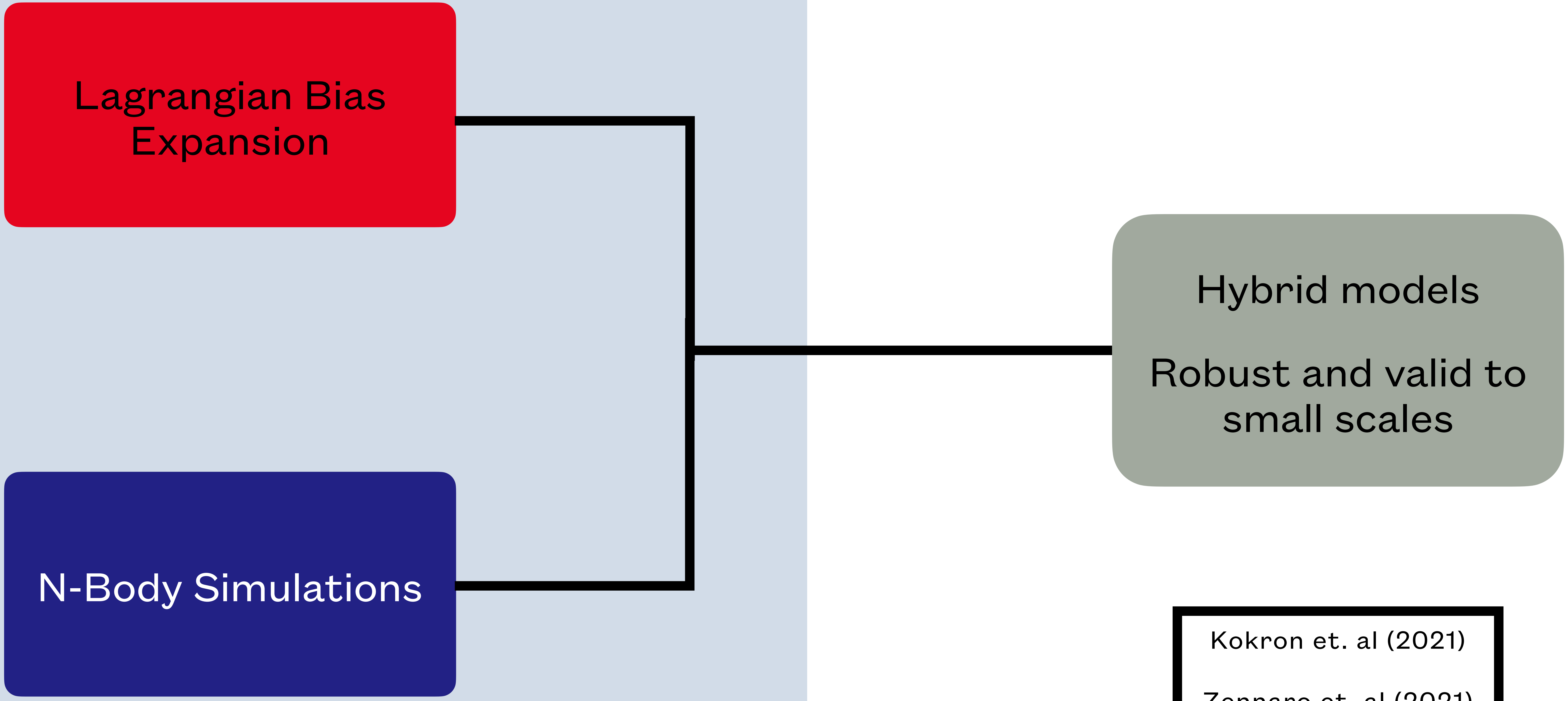
Breaks down quickly at small scales.

EFTofIA can reach $k_{max} = 0.28\, h/\mathrm{Mpc}$ at the expense of adding many free parameters



Credit: Bakx et. al (2023)

Hybrid Lagrangian Models



Kokron et. al (2021)

Zennaro et. al (2021)

Hadzhiyska et al (2021)

...

Bias Expansion - Density

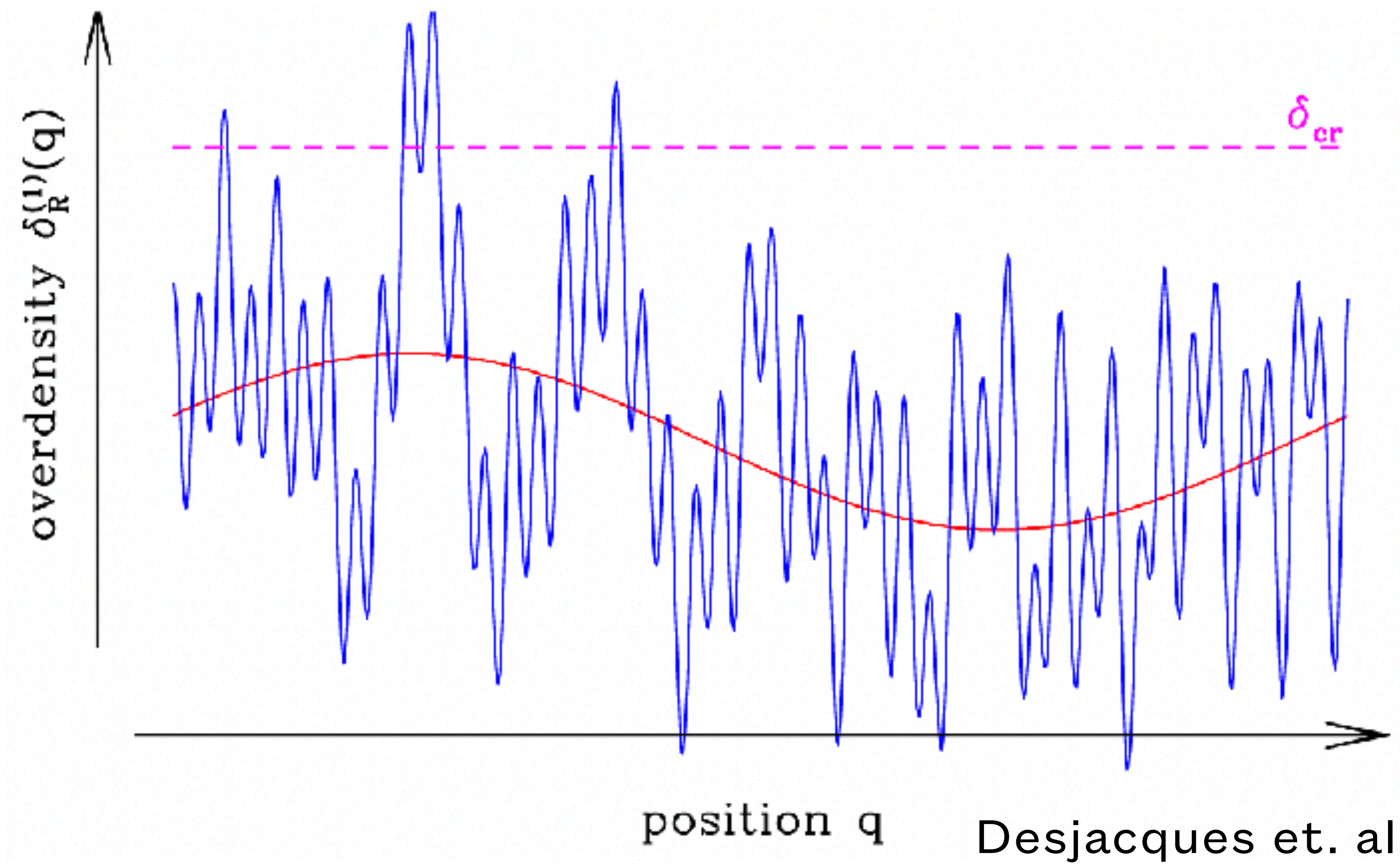
Symmetries and Physical Principles:

- Equivalence Principle (only $\partial^{2n}\Phi$ contributions allowed)
- Statistical Homogeneity
- Statistical Isotropy
- Scalar under rotations

Density:
$$\begin{cases} 1^{\text{st}} \text{ order} & : \delta \\ 2^{\text{nd}} \text{ order} & : \delta^2, s^2 \\ \text{Non-local} & : \nabla^2\delta \\ \text{Stochastic} & : \varepsilon \end{cases}$$

$$\delta_g = b_1\delta + b_2\delta^2 + b_{s^2}s^2 + b_{\nabla^2}\nabla^2\delta + \varepsilon$$

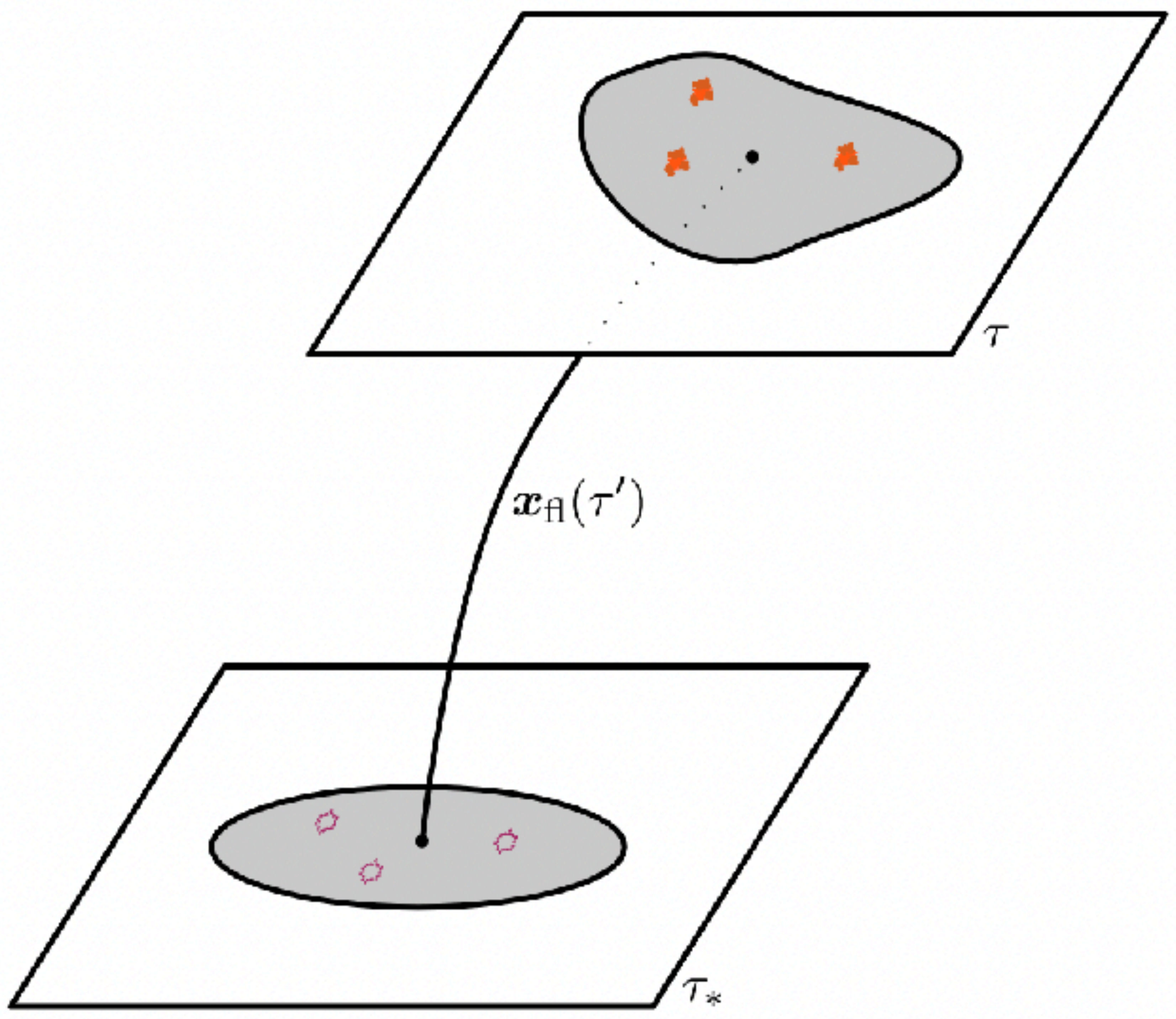
Correlations are setup very early in the universe



Desjacques et. al (2016)

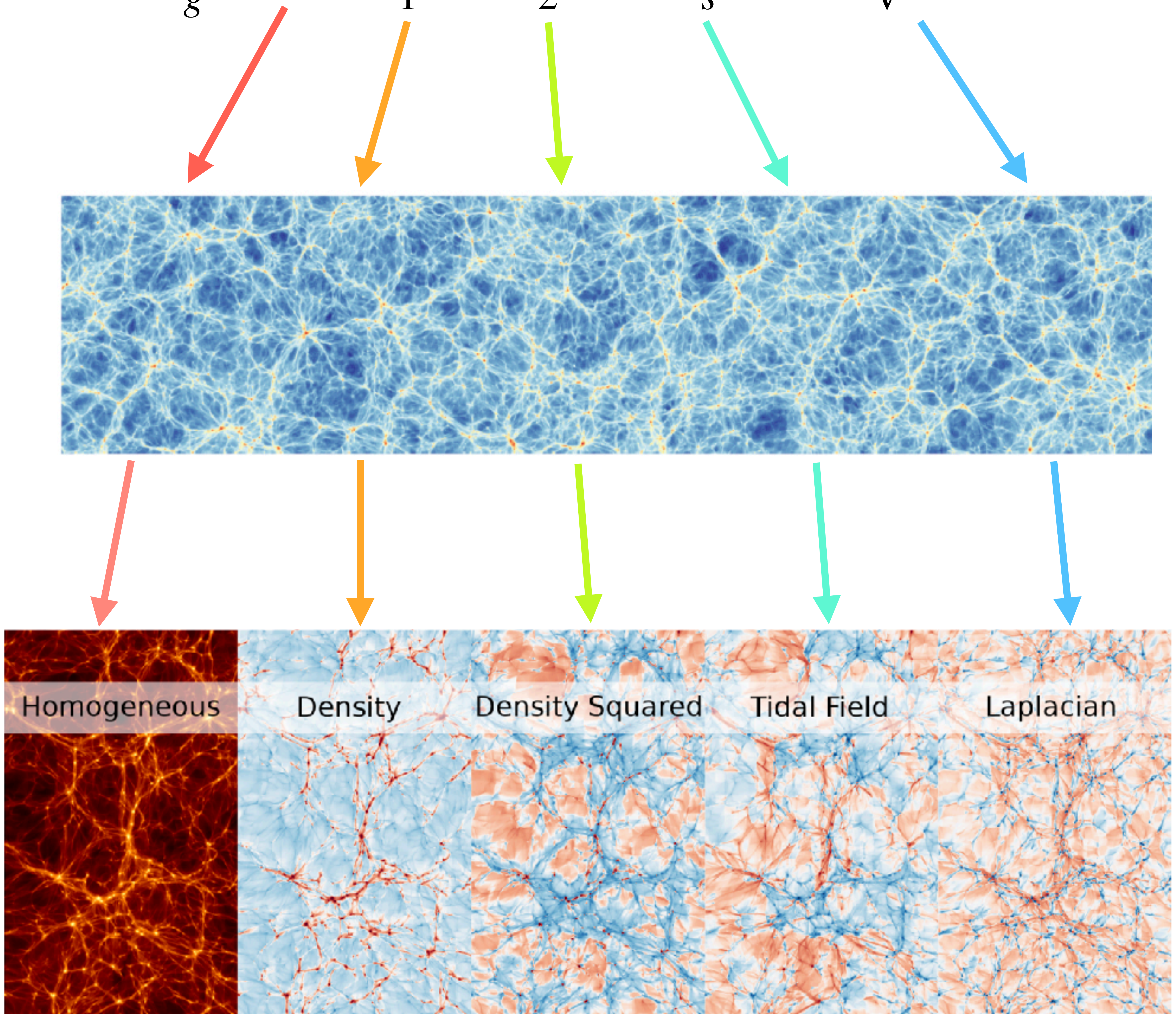
Advection - Density

The modelled galaxy field must be advected from Lagrangian to Eulerian space



Desjacques et. al (2016)

$$1 + \delta_g = 1 + b_1\delta + b_2\delta^2 + b_{s^2}s^2 + b_{\nabla^2}\nabla^2\delta + \varepsilon$$



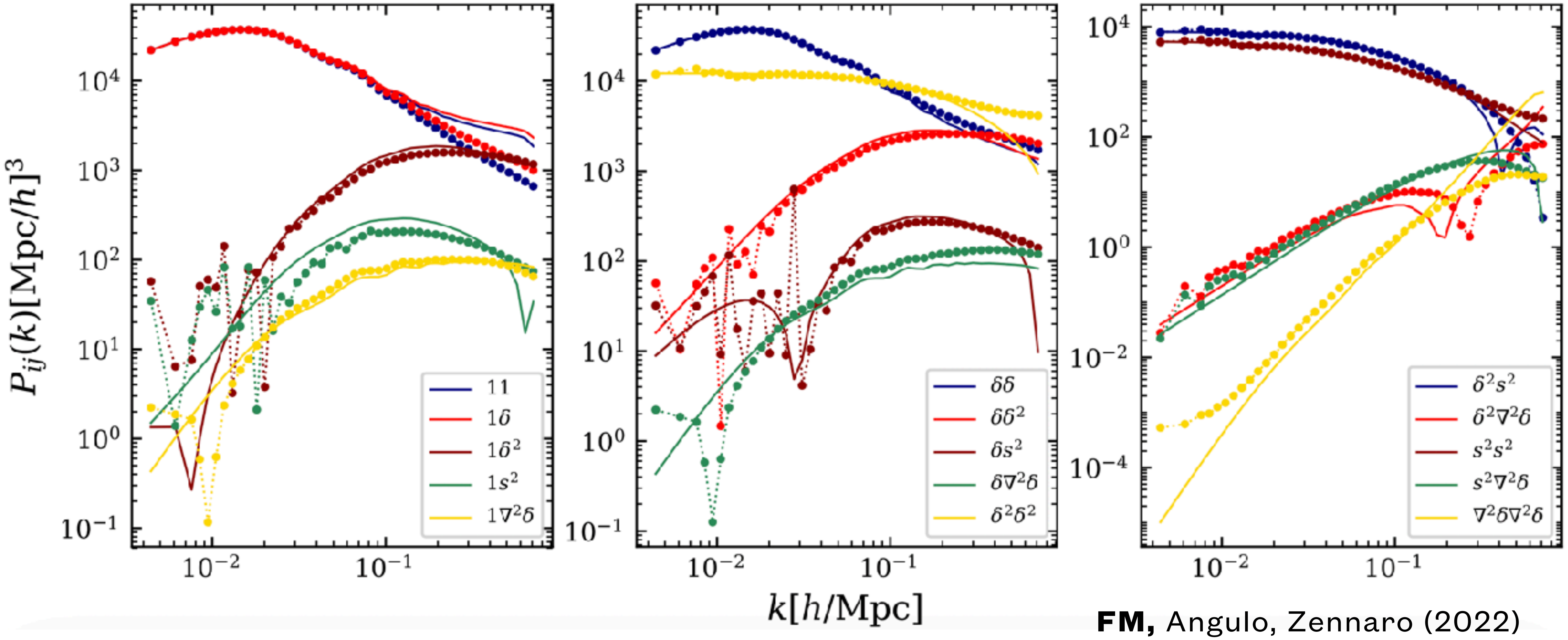
Zennaro et. al (2021)

Advection - Density

A set of 15 auto and cross-spectra will serve as basis for modelling of any biased tracer

$$P_{gg} = \sum_{i,j=1}^{4} b_i b_j P_{ij}(k) + P_\epsilon$$

$$i, j \in [1,\ 2,\ s^2,\ \nabla^2]$$



FM, Angulo, Zennaro (2022)

Bias Expansion - Shapes

Symmetries and Physical Principles:

- Equivalence Principle (only $\partial^{2n}\Phi$ contributions allowed)
- Statistical Homogeneity
- Statistical Isotropy
- Rank-2 tensor under rotations

$$g_{ij} = c_s s_{ij} + c_{s\delta}\delta s_{ij} + c_{s\otimes s}(s\otimes s)_{ij} + c_t t_{ij} + c_{\nabla^2}\nabla^2 s_{ij} + \varepsilon_{ij}$$

Shapes:

$$\begin{cases} 1^{\text{st}}\ \text{order} & : s_{ij} \\ 2^{\text{nd}}\ \text{order} & : (s\otimes s)_{ij}, \delta s_{ij}, t_{ij} \\ \text{Non-local} & : \nabla^2 s_{ij} \\ \text{Stochastic} & : \varepsilon_{ij} \end{cases}$$

$$(s\otimes s)_{ij} = \left(s_{il}s_{lj} - \delta^K_{ij}\frac{s^2}{3} \right)$$

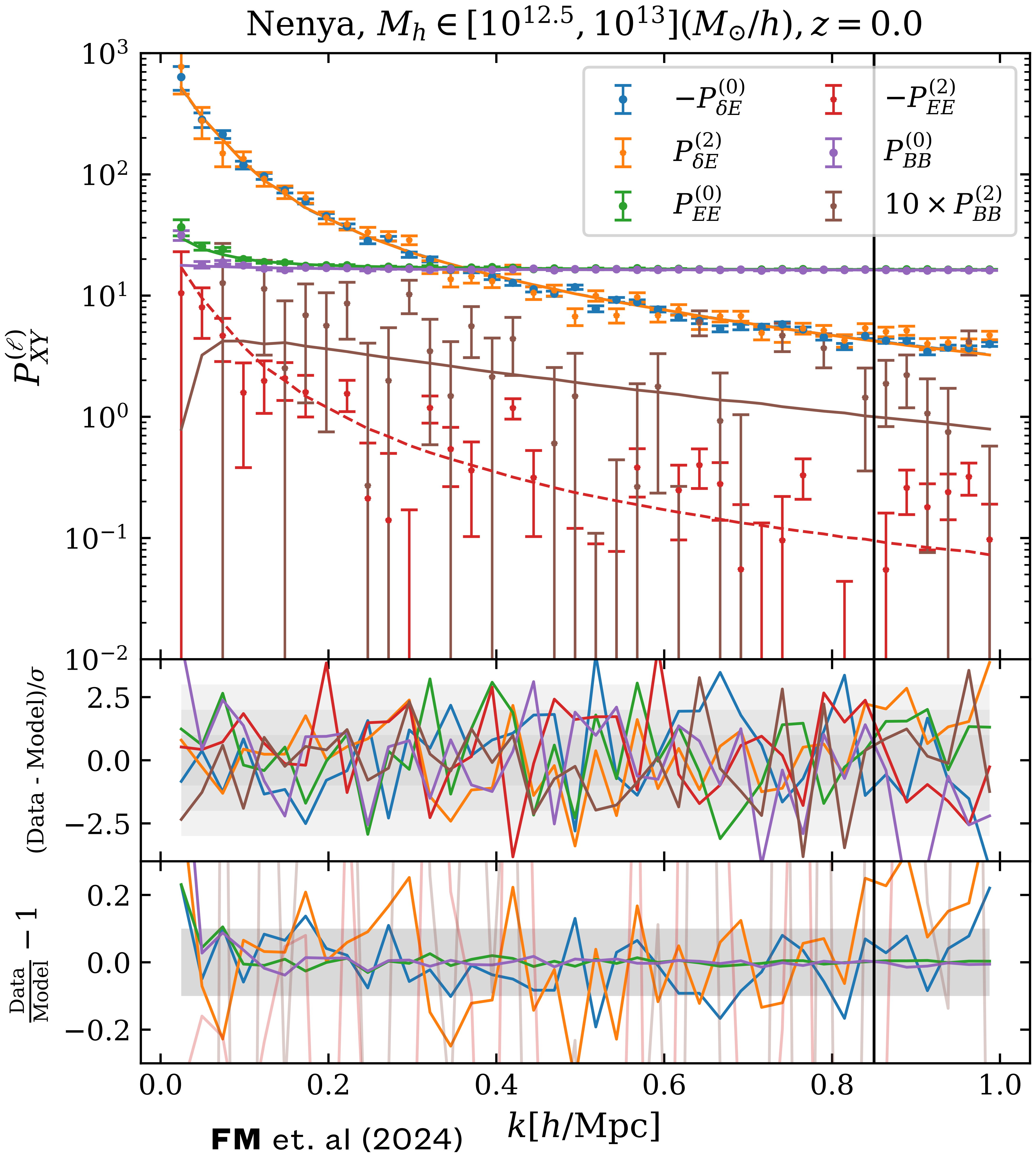
$$t_{ij} = \left(\frac{\partial_i\partial_j}{\nabla^2} - \frac{1}{3}\delta^K_{ij} \right)\left(\theta(\mathbf{x}) - \delta(\mathbf{x})\right)$$

Shape Power Spectra of Haloes

Compute the Legendre multipoles of their auto and cross spectra

$$P^{(\ell)}_{XY}(k) = \int \frac{d\Omega}{4\pi} \left\langle X(\mathbf{k}) Y(-\mathbf{k}) \mathscr{L}_\ell(\mu) \right\rangle$$

$$X, Y \in [\delta, E, B]$$



FM et. al (2024)

Model Validation

To evaluate the performance of the model we will use the reduced chi-squared,

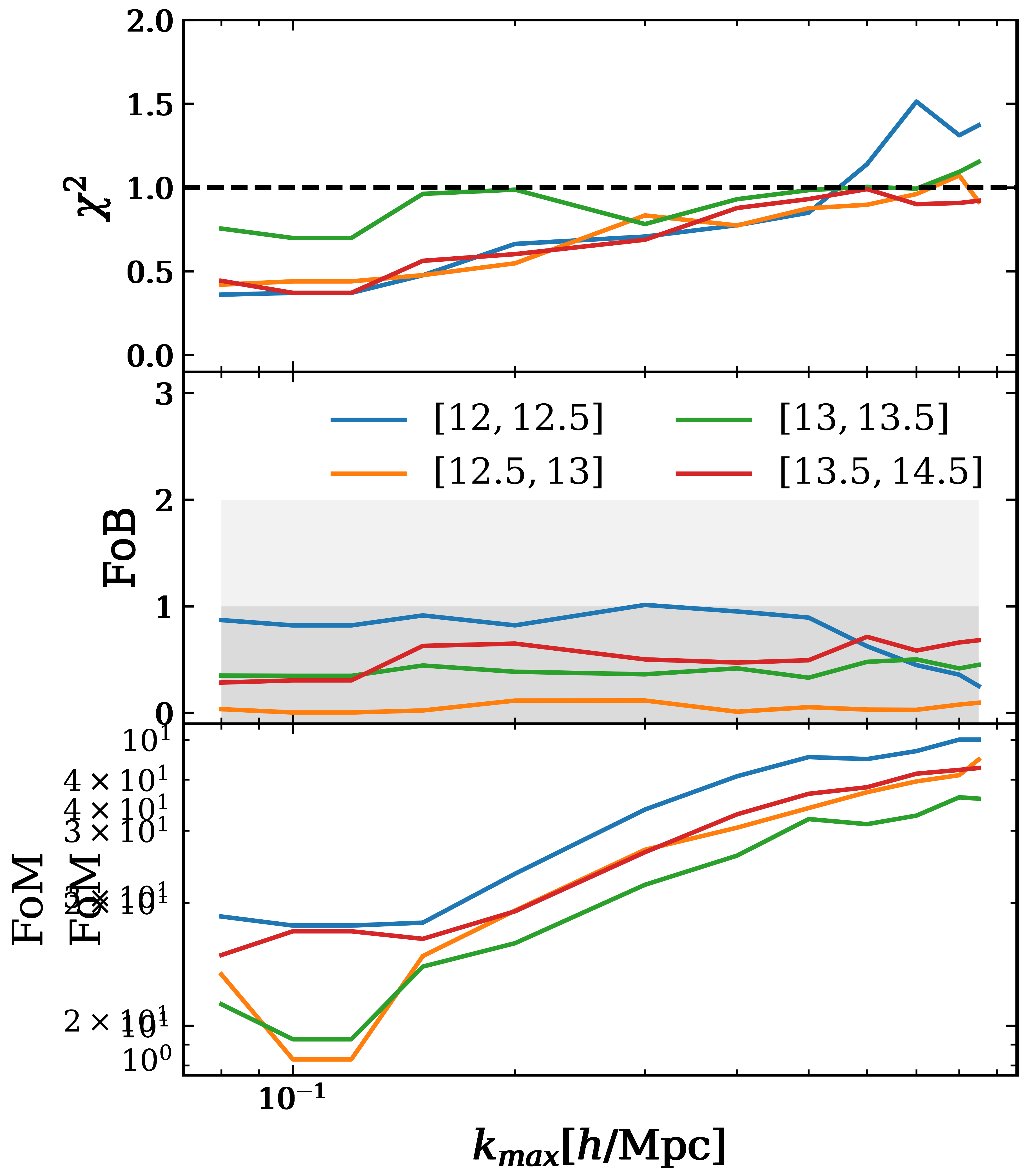
$$\chi^2_{\rm red} = \frac{1}{N_{\rm dof}} \sum_{\ell,\ell'=0,2} \sum_{\alpha,\beta} \sum_{i,j} \left(P_\alpha^{(\ell)}(k_i,\Theta) - \widehat{P}_\alpha^{(\ell)}(k_i)\right)\left[C_{\alpha,\beta}^{\ell,\ell'}\right]^{-1}_{ij}\left(P_\beta^{(\ell')}(k_j,\Theta) - \widehat{P}_\beta^{(\ell')}(k_j)\right)$$

the Figure of Bias, defined as

$$\mathrm{FoB}(\mathrm{k_{max}}) = \frac{\left|\mathrm{c_s^{fid}} - \mathrm{c_s(k_{max})}\right|}{\sqrt{\sigma^2_{\rm fid} + \sigma^2_{\rm c_s}(\mathrm{k_{max}})}}$$

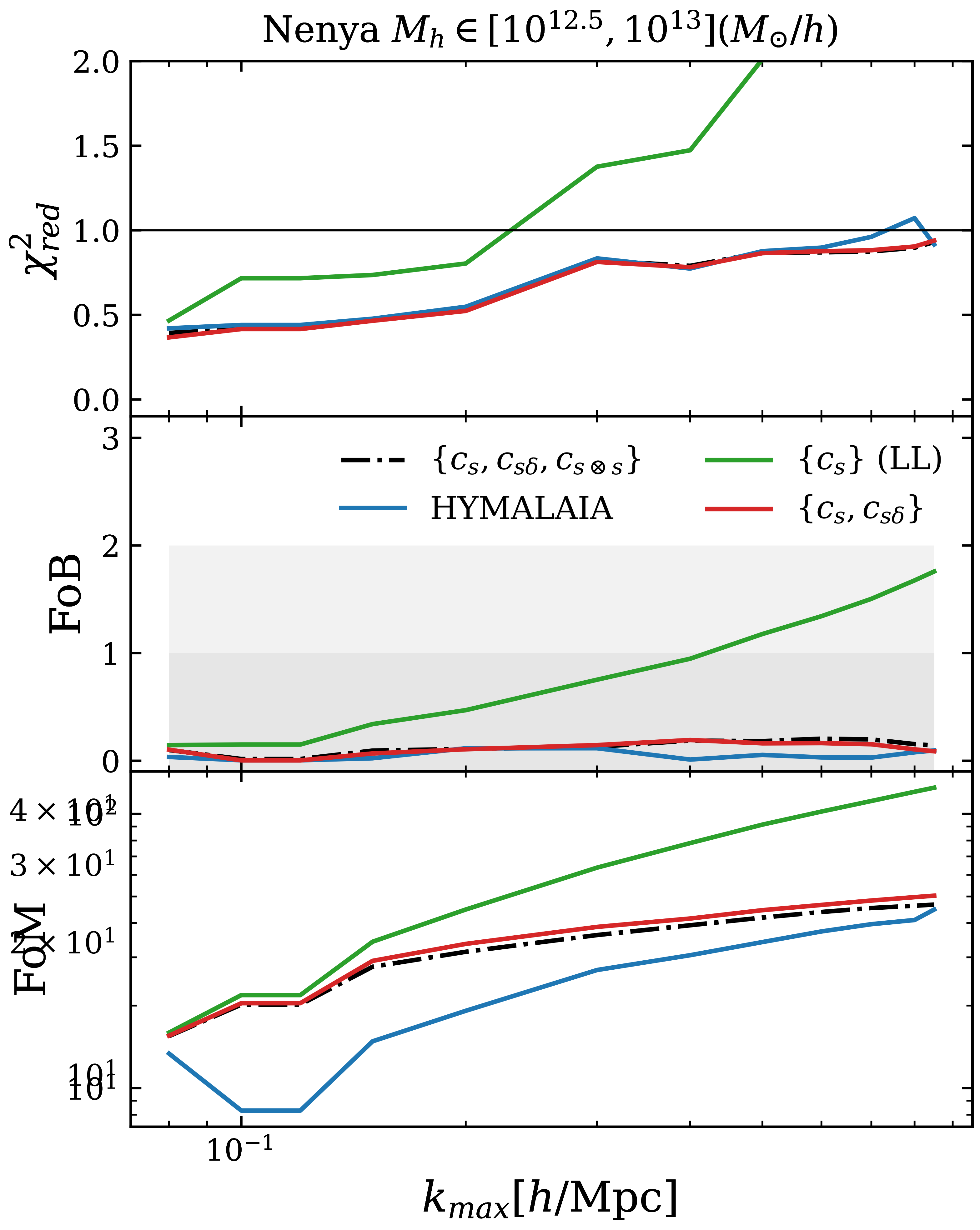
and the Figure of Merit, given by

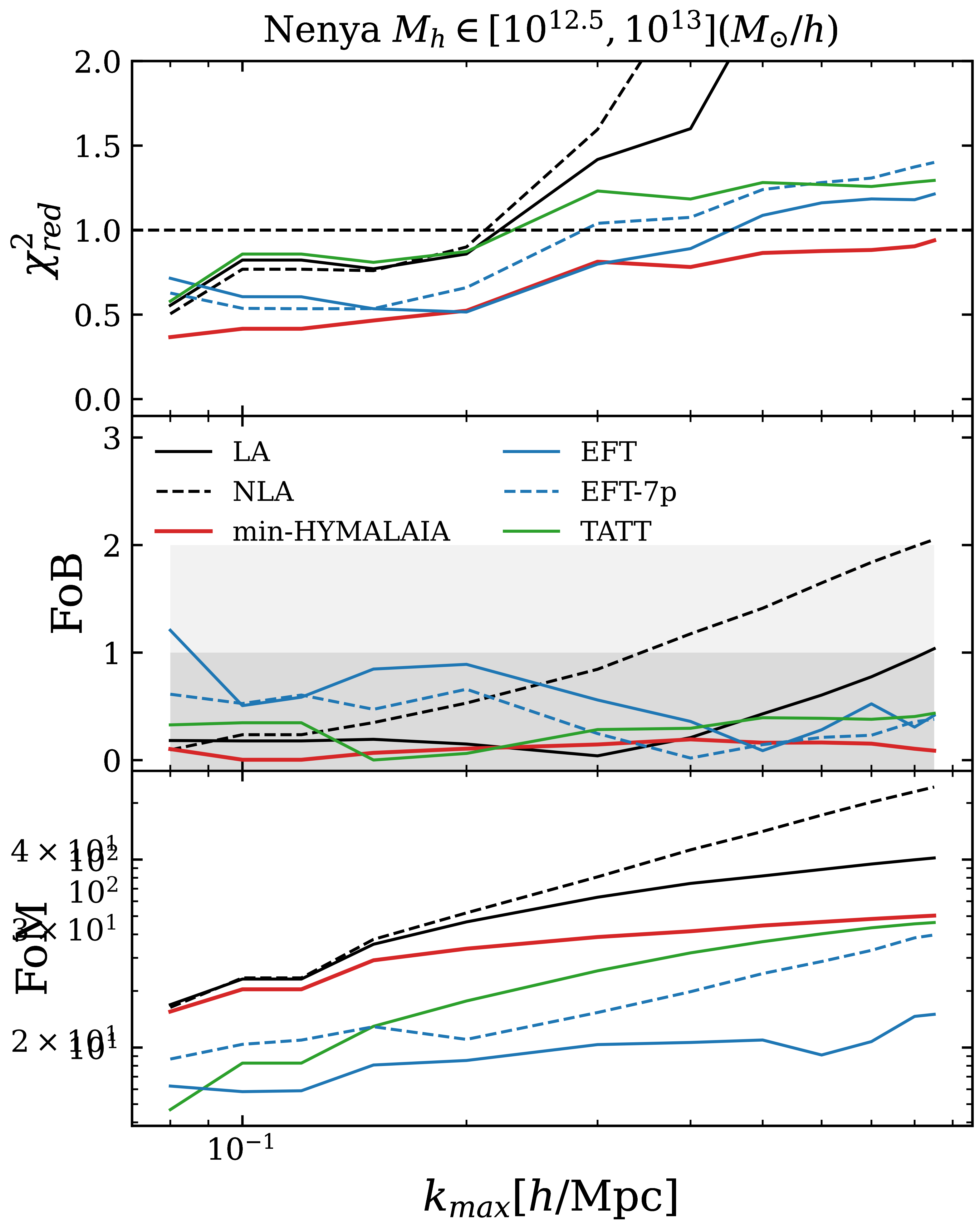
$$\mathrm{FoM} = \sqrt{\det\left[\frac{\Theta_{\alpha\beta}}{\theta_\alpha^{\rm fid}\theta_\beta^{\rm fid}}\right]^{-1}}$$



FM et. al (2023)

Comparison to Other Models





FM et. al (2023)

Density Weighting

$$\mathbf{I}(\mathbf{x}) = \sum_a I(\mathbf{x}_a)\delta^D(\mathbf{x} - \mathbf{x}_a)$$

$$I_n = \int d^3x W_{CIC}(\mathbf{x} - \mathbf{x}_i) I(\mathbf{x}) = \sum_{a\in i} I(\mathbf{x}_a) \approx n_{g,i}\langle I \rangle$$

$$\gamma_I = \left(1 + b_1\delta + \frac{1}{2}b_2(\delta^2 - \langle\delta^2\rangle) + \cdots\right)\left(c_s s_{ij} + c_{\delta s}\delta s_{ij} + \cdots\right)$$

$$\gamma_I = c_s s_{ij} + (c_{\delta s} + b_1 c_s)\delta s_{ij} + \cdots$$

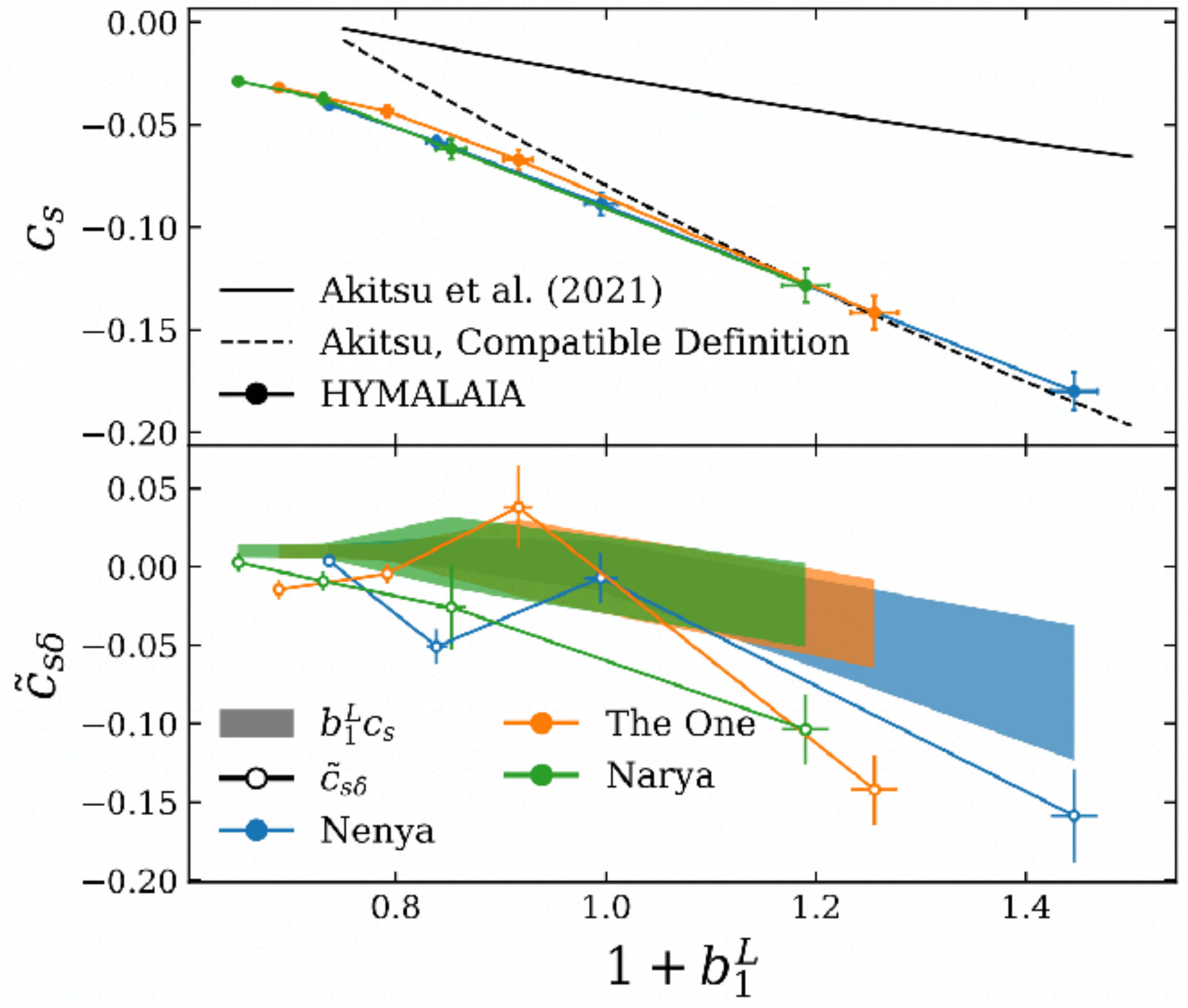
Bias Relations

Akitsu et. al (2021) have shown that there is an universal relation between c_s and b_1^E. We find compatible results.

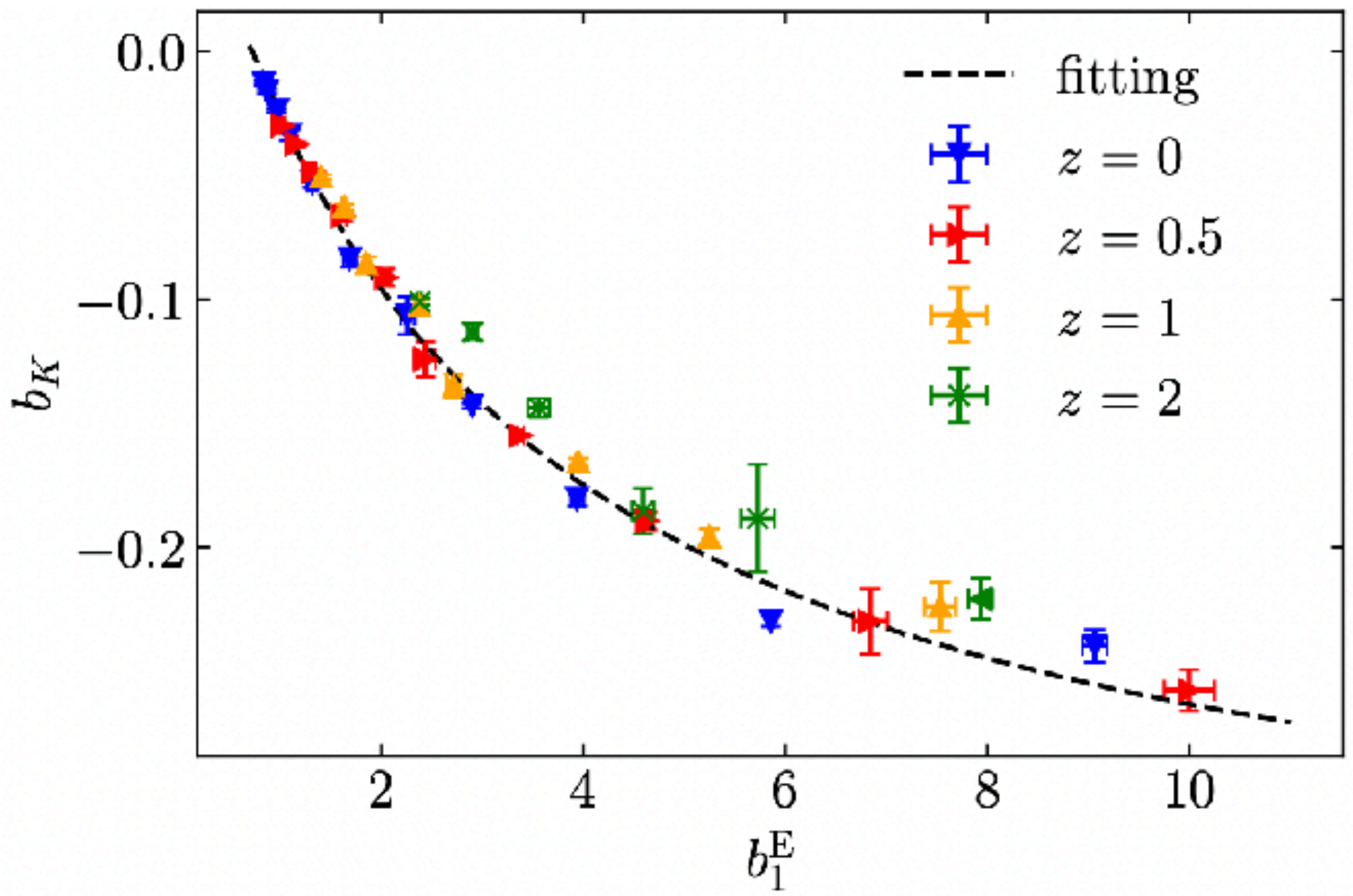
Under the assumption of a Linear Lagrangian bias model, $g_{ij}(\mathbf{q}) = c_s s_{ij}(\mathbf{q})$, density weighting the model introduces a non-zero $c_{s\delta}$ bias, given by

$$c_{s\delta} = b_1^L c_s$$

we find some qualitative agreement with this scenario



FM et. al (2023)



Akitsu et. al (2021)

Conclusions

- HYMALAIA is capable of describing shape power spectra of haloes
    - ✓ Consistent determination of linear bias parameter
    - ✓ Most accurate model until $k \sim 0.85\, h\mathrm{Mpc}^{-1}$
    - ✓ Small number of free parameters
- What's next?
    - Accuracy required for Euclid? Do we satisfy it?
    - Emulator of model in cosmological parameter space

Will defend my PhD in
Fall 2025

In the job market from
Fall 2024

Access
tinyurl.com/FM-articles
to see my publications

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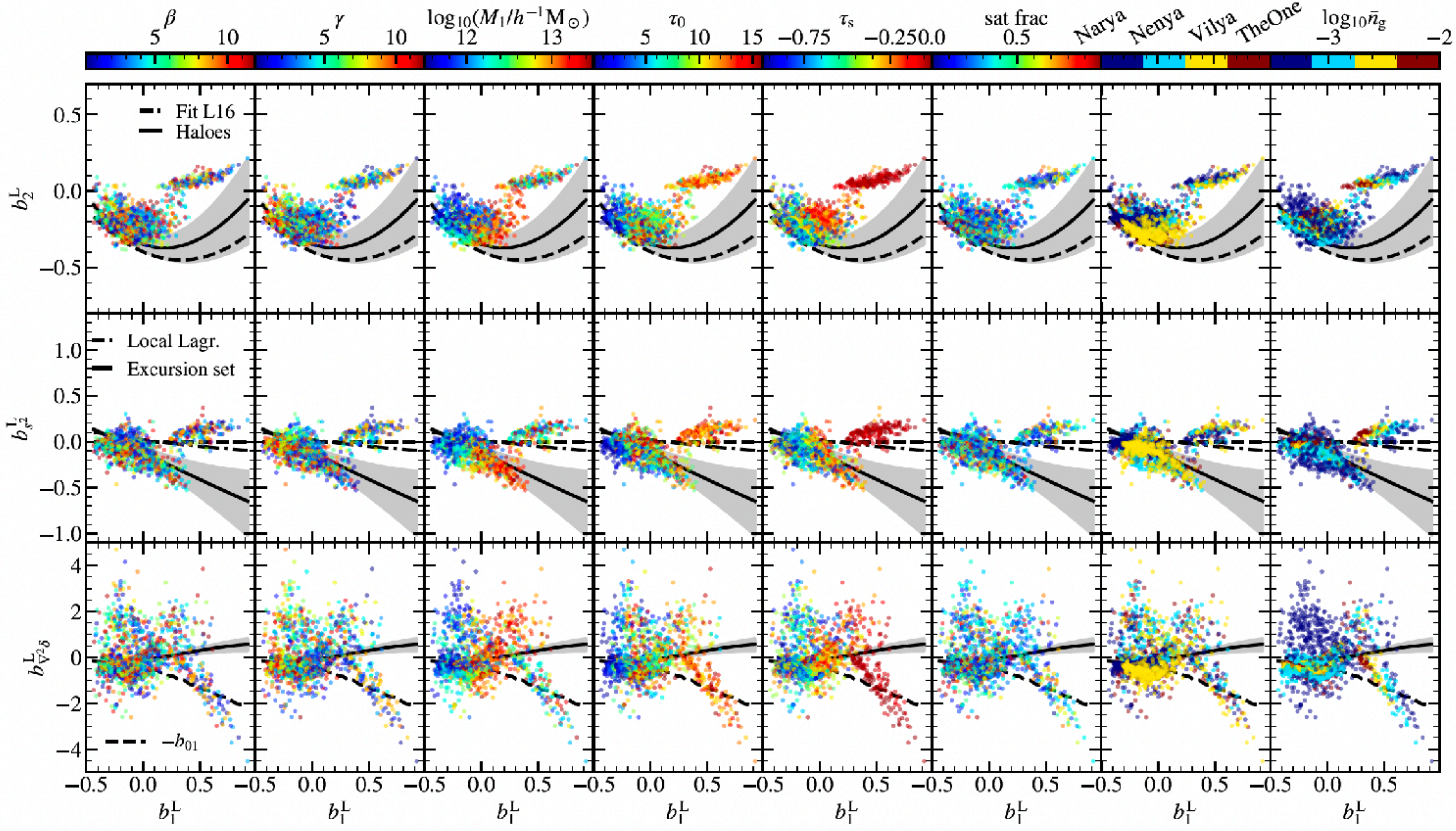
Extra Slides

Bias Expansion - Density



Zennaro, Angulo, Contreras, Pellejero-Ibañez, **FM** (2022)

Simulations

Three cold-matter only Fixed and Paired simulations with the following parameters:

	σ_8	Ω_m	Ω_b	n_s	h	M_ν	$L[h^{-1}\mathrm{Mpc}]$	$m_p\,[h^{-1}M_\odot]$	N_p	z
Nenya	0.9	0.315	0.05	1.01	0.60	0.0	[512, 1440]	3.2×10^9	$[1536^3, 4320^3]$	0
Narya	0.9	0.36	0.05	1.01	0.70	0.0	[512, 1440]	3.7×10^9	$[1536^3, 4320^3]$	−0.2
The One	0.9	0.307	0.05	0.96	0.68	0.0	[512, 1440]	3.2×10^9	$[1536^3, 4320^3]$	−0.2

From these, select four halo populations in increasing mass bins

	Mass Range $[\log_{10}(M/M_\odot)]$	$\bar{n}(z=0)\ [h^{-1}\mathrm{Mpc}]^{-3}$
M_1	[12, 12.5]	26.9×10^{-4}
M_2	[12.5, 13]	10.1×10^{-4}
M_3	[13, 13.5]	3.7×10^{-4}
M_4	[13.5, 14.5]	1.7×10^{-4}

Shape Power Spectra

From the simulations, one can get the shape tensor for each halo,

$$S_{ij} = \sum_{n=1}^{N} \left(x_i^{(n)} - \bar{x}_i\right)\left(x_j^{(n)} - \bar{x}_j\right),$$

Simulation of $L = 512\,h^{-1}\mathrm{Mpc}$

estimate the halo ellipticities

$$\begin{cases} \epsilon_1 & = \dfrac{S_{xx} - S_{yy}}{S_{xx} + S_{yy}} \\ \epsilon_2 & = \dfrac{2S_{xy}}{S_{xx} + S_{yy}} \end{cases}$$

Since this is a spin-2 field, one can define E and B modes, similarly as with light polarisation

$$E(\mathbf{k}) = \epsilon_1(\mathbf{k})\cos(2\phi_k) + \epsilon_2(\mathbf{k})\sin(2\phi_k)$$
$$B(\mathbf{k}) = -\epsilon_1(\mathbf{k})\sin(2\phi_k) + \epsilon_2(\mathbf{k})\cos(2\phi_k)$$

$$\phi_k = \tan^{-1}(k_y/k_x)$$