Cosmology from Large Scale full-shape analyses combining 2PCF and 3PCF

ALMA MATER STUDIORUM
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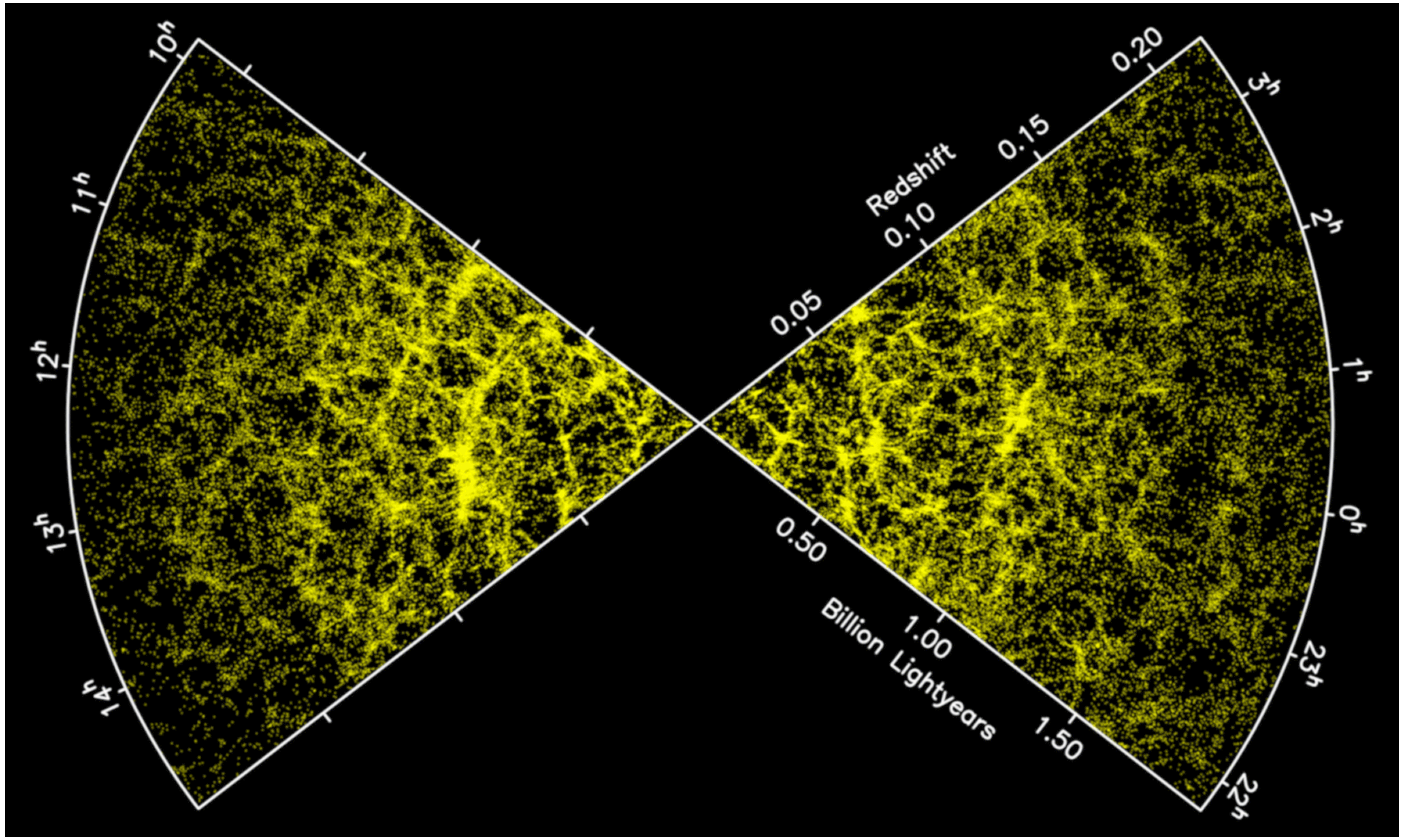
Redshift surveys provide a description of the Large Scale Structure of the Universe

Large observational campaigns (such as SDSS, BOSS, DESI, Euclid, …) aim to unveil the Dark Universe:

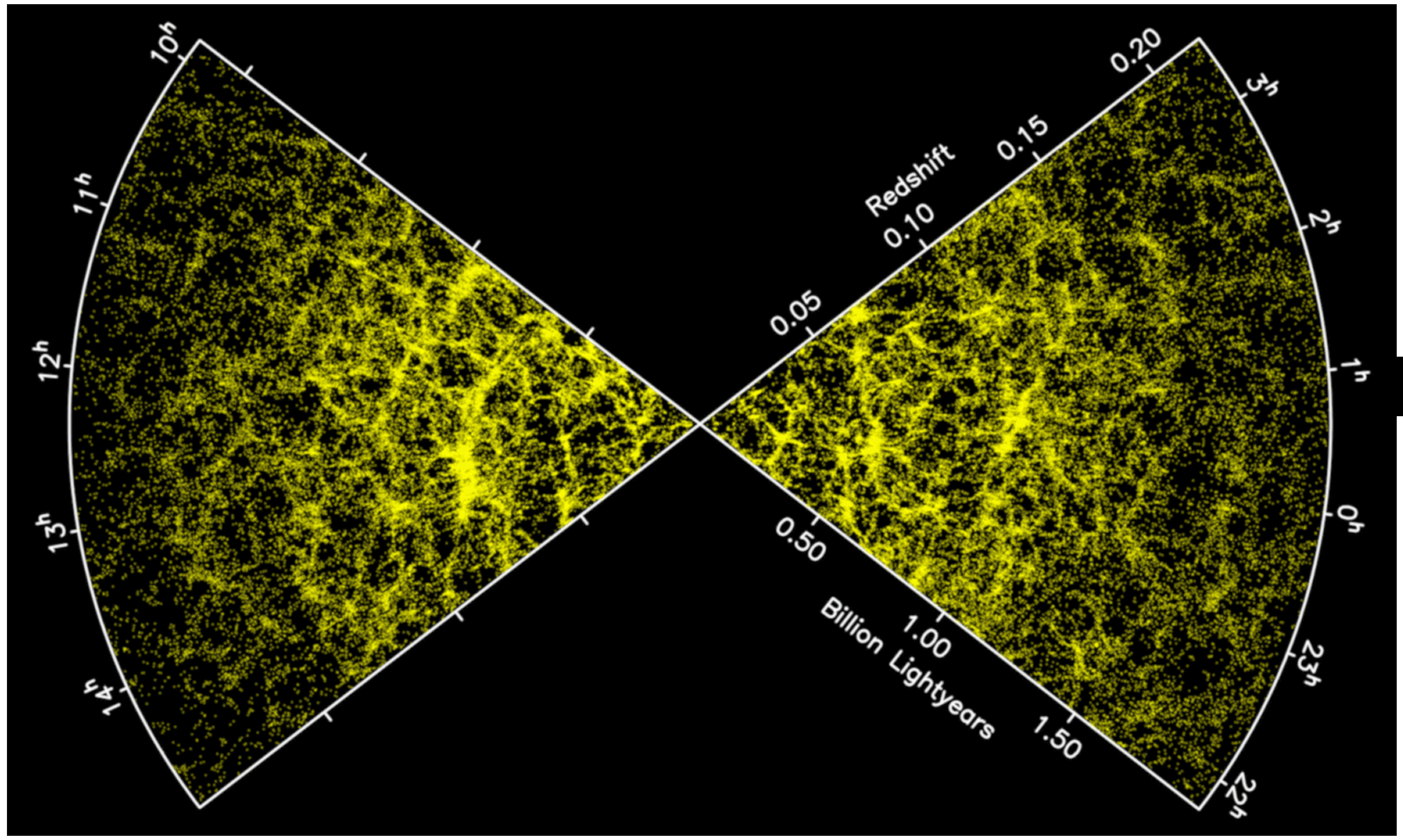
- Dark energy
- Dark matter
- Beyond LCDM (Inflation, General Relativity, Neutrinos, …)



Credits: Institute for Computational Cosmology of Durham

Baryonic acoustic oscillations

How to extract cosmological information from redshift surveys?



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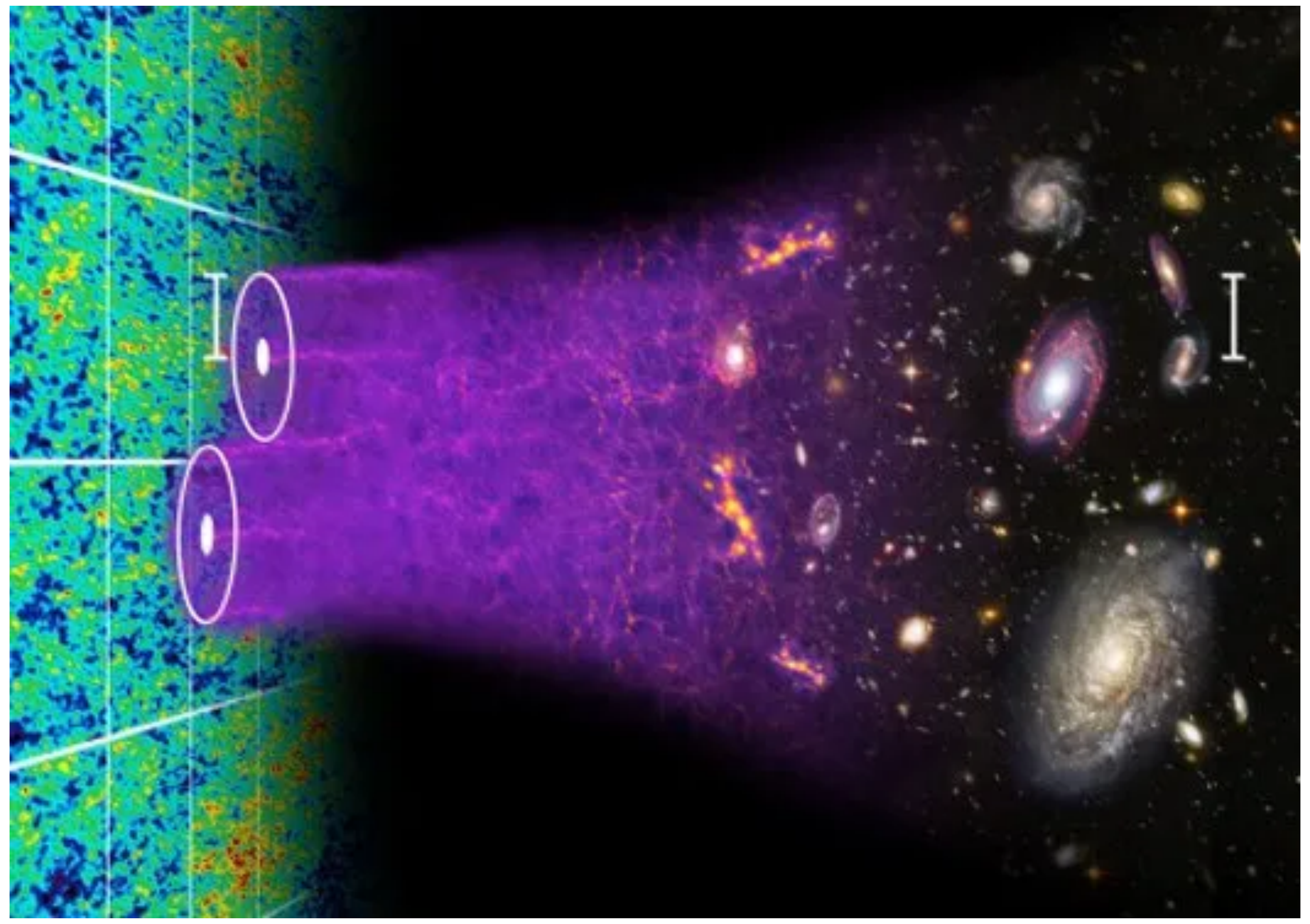
Baryonic acoustic oscillations after decoupling act as a **standard ruler** during the expansion history…



…like an expanding wave with an associated frequency

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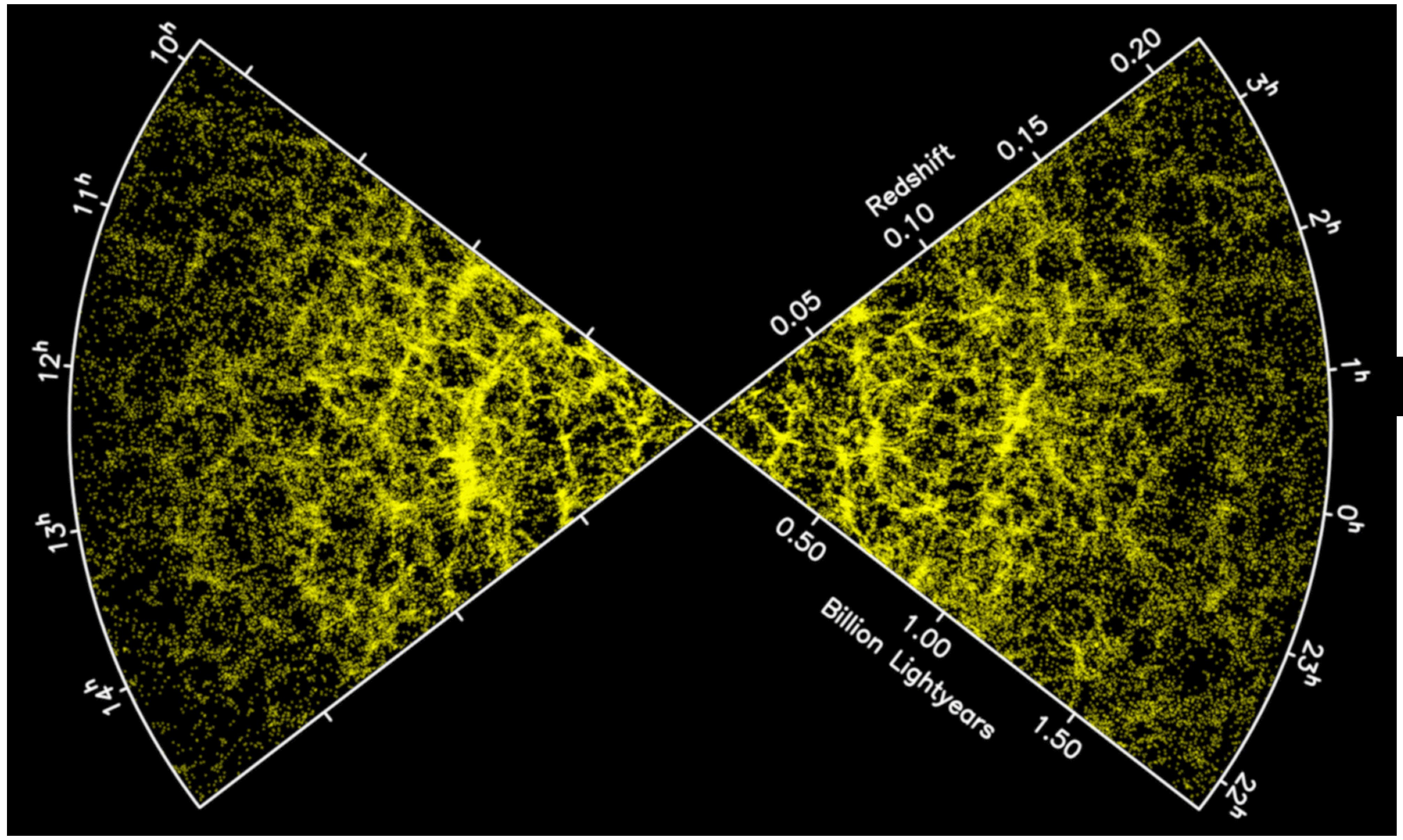
How to extract cosmological information from redshift surveys?

When converting redshifts to physical distances, neglecting the effect of peculiar velocities gives raise to a distortion of clustering signal along the line of sight introducing observational **anisotropies**…



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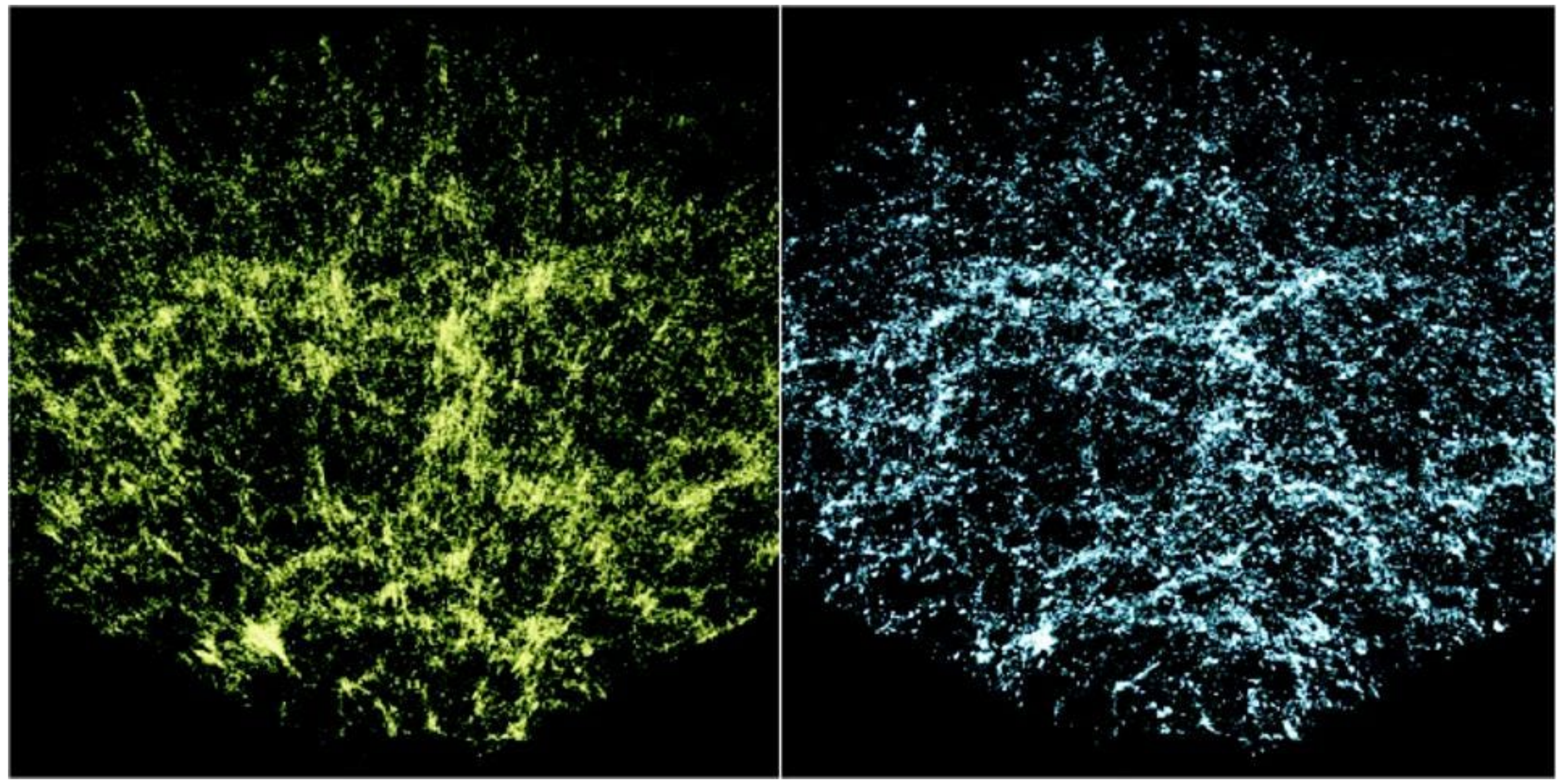
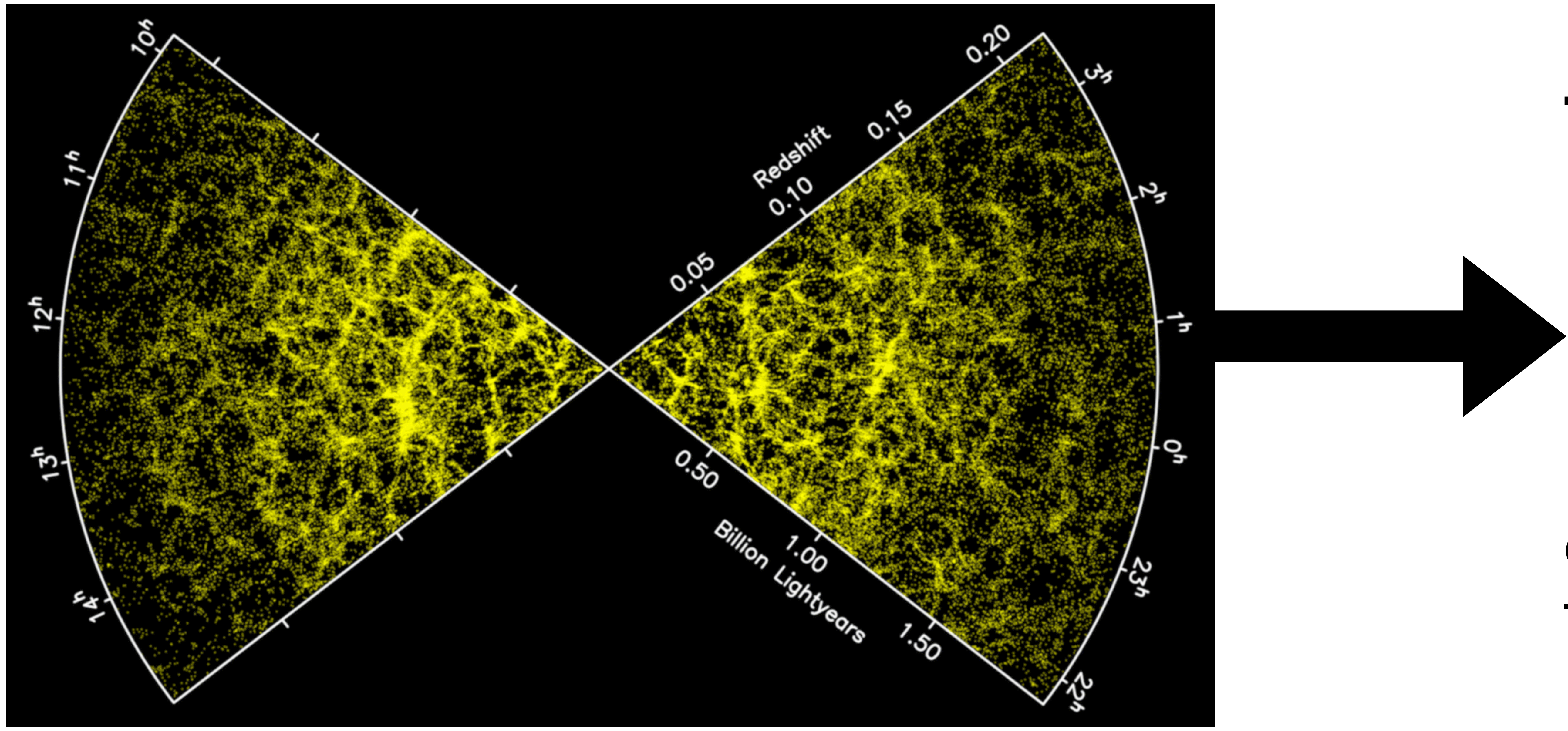


…degrading the quality of extraction of information from the BAO peak, but adding **extra information** depending on the **growth factor** of cosmic structures!

How to extract cosmological information from redshift surveys?



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Template fitting: Alcock-Paczynski parameters (BAO) + growth factor (RSD)

Full-shape: direct sampling of the posterior distribution of cosmological parameters by fitting the shape dependance on cosmological parameters themselves

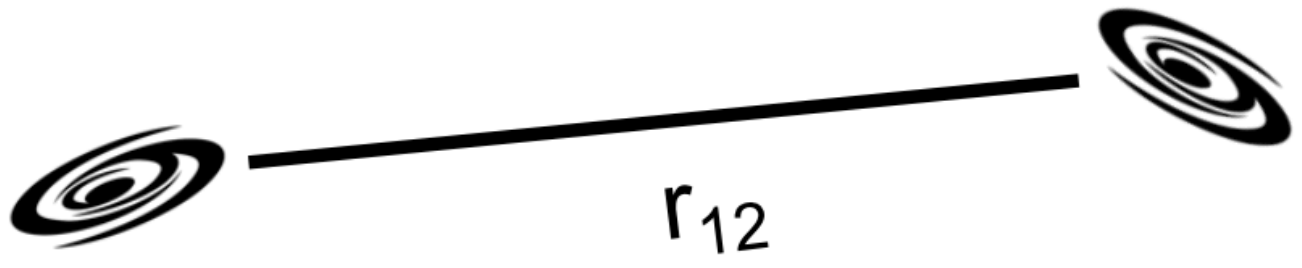
Correlation functions - Two-Point Correlation Function (2PCF) or Power spectrum

Probability of finding **pairs** of galaxies at a given *r* with respect to a random distribution: $\mathrm{d}P = n^2[1 + \xi(r)]dV_1 dV_2$

2PCF estimator:

Landy & Szalay (1993)

$$\xi(r) = \frac{DD - 2DR + RR}{RR}$$



Peebles (1993)

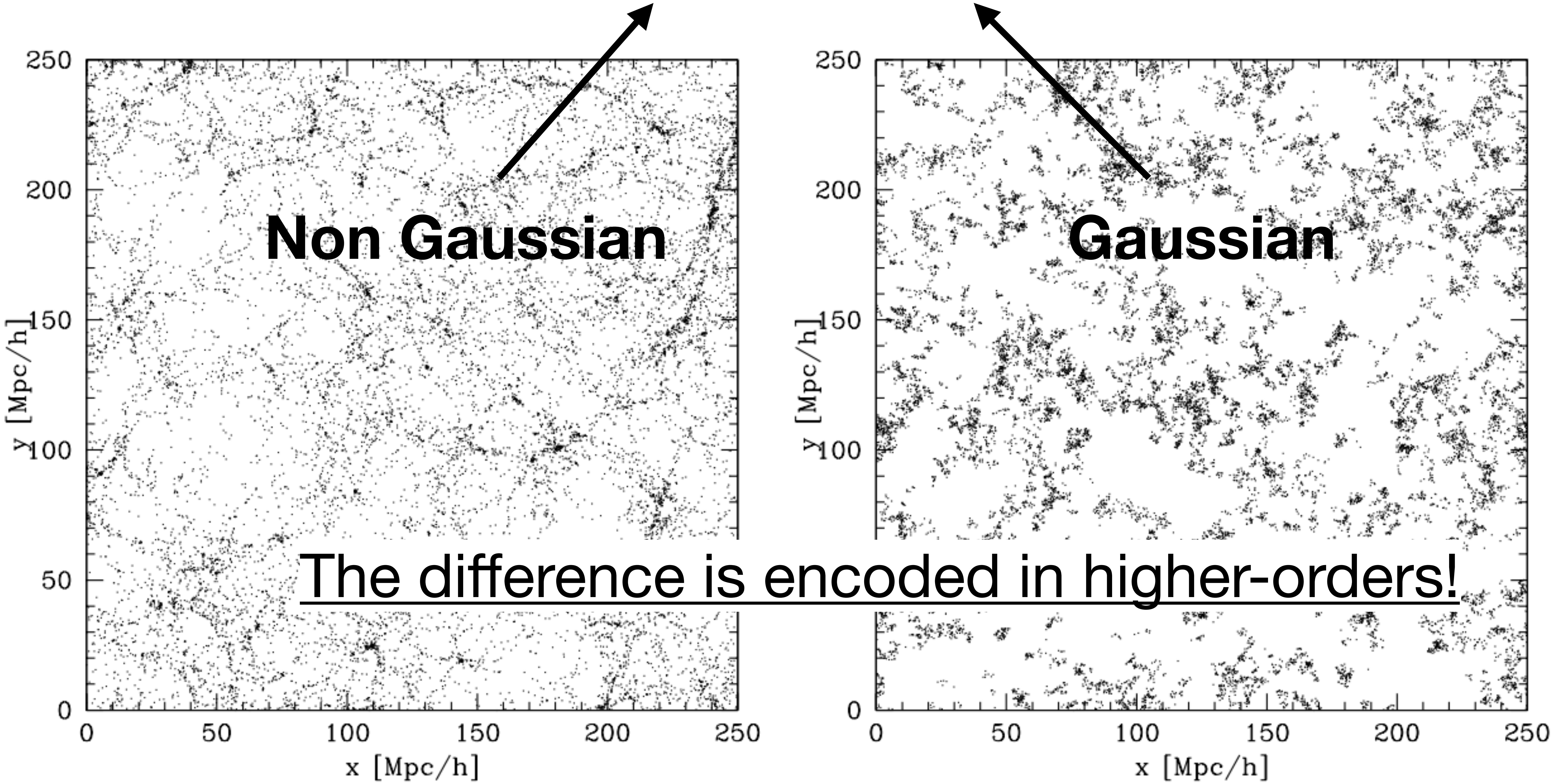
$$\xi(r) = \frac{DD}{RR} - 1$$

For a **Gaussian** Random Field, two-point statistics are enough to completely describe the distribution…

… but this is far from the large scale structure of the universe!

Higher-order correlation functions

Same 2-point statistics



Slices of thickness 50 Mpc/h of a mock galaxy distributions for SDSS (left) and a realisation of a Rayleigh-Lèvy flight (right)

Sefusatti & Scoccimarro, 2005

Non-Gaussianity:

- Nonlinear *gravitational* evolution
- Nonlinear relation between luminous tracers and dark matter perturbation (*galaxy biasing*)
- *Primordial* Non-Gaussianity

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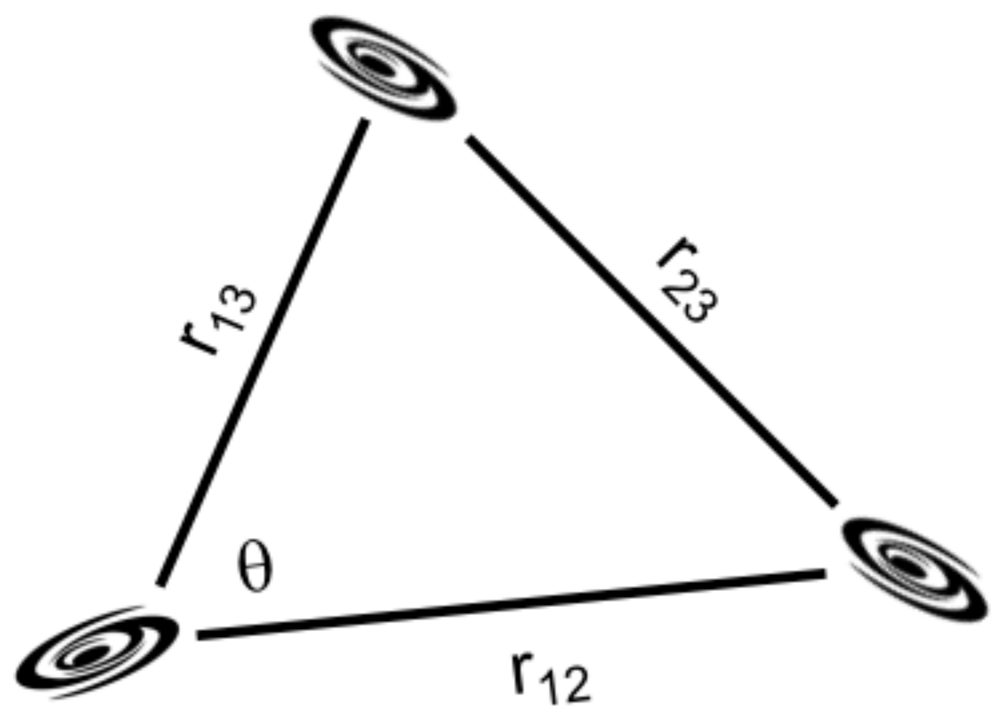
Probability of finding **triplets** of galaxies at a given *triangle* with respect to a random distribution: $\mathrm{d}P = n^3[1 + \xi(r_{12}) + \xi(r_{13}) + \xi(r_{23}) + \zeta(r_{12}, r_{13}, r_{23})]dV_1 dV_2 dV_3$

3PCF estimator:

Szapudi & Szalay (1998)

$$\zeta(r_{12}, r_{13}, r_{23}) = \frac{DDD - 3DDR + 3DRR - RRR}{RRR}$$



Spherical Harmonic Decomposition:

Slepian & Eisenstein (2015, 2017)

$$\zeta(r_{12}, r_{13}, r_{23}) = \sum_{0}^{\ell_{\max}} \zeta_\ell(r_{12}, r_{13}) \mathscr{L}(\hat{r}_{12} \cdot \hat{r}_{13})$$

$$\zeta_\ell(r_{12}, r_{13}) = \frac{DDD_\ell - 3DDR_\ell + 3DRR_\ell - RRR_\ell}{RRR_0}$$

Correlation function - 3PCF or Bispectrum

Probability of finding **triplets** of galaxies at a given *triangle* with respect to a random distribution: $\mathrm{d}P = n^3[1 + \xi(r_{12}) + \xi(r_{13}) + \xi(r_{23}) + \zeta(r_{12}, r_{13}, r_{23})]dV_1 dV_2 dV_3$

Configuration space

Estimator:

- Now feasible thanks to Spherical Harmonic Decomposition
- Survey footprint: just random distribution needed

Modelling (2PCF + 3PCF):

- Template fitting (BAO, BAO + RSD), computational intensive!
- No full-shape yet! **Gap** with Fourier space

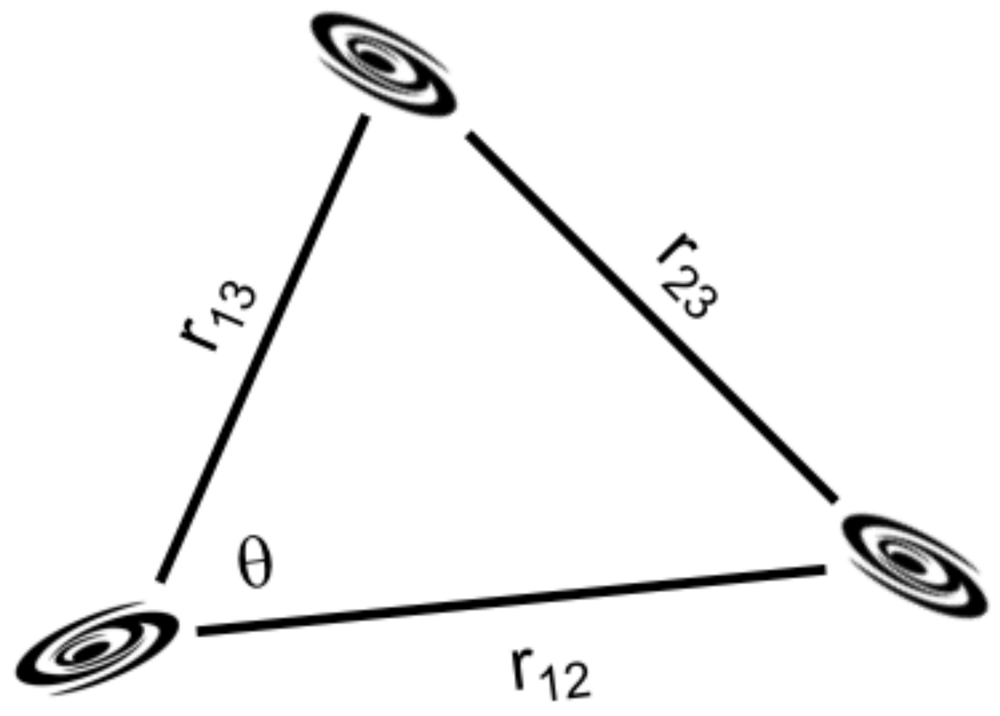
Fourier space

Estimator:

- Survey footprint requires window function to model mode coupling

Modelling (P + B):

- Accessible modeling: template fitting and full-shape (tree-level B)



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Recap

- Extraction of **cosmological information** from redshift survey
    - Probes: BAO, RSD
    - Methods: Template fitting, Full-shape

- **Higher-order**: important as they add **constraining power,** configuration space data better deal with systematics due to the **footprint**, but both modelling and measuring have a **high computational cost**

How modelling the 3PCF?

3PCF multipoles
(isotropic or anisotropic)

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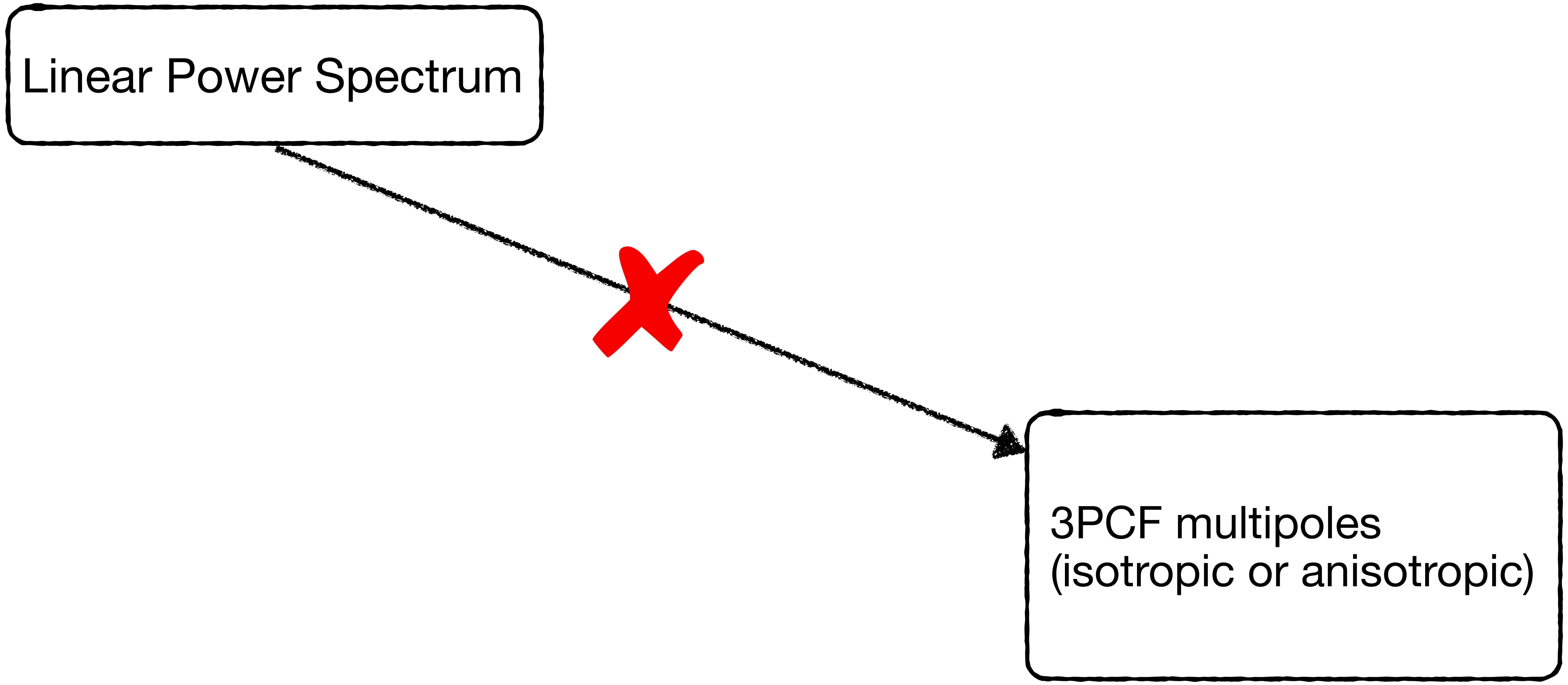
How modelling the 3PCF?



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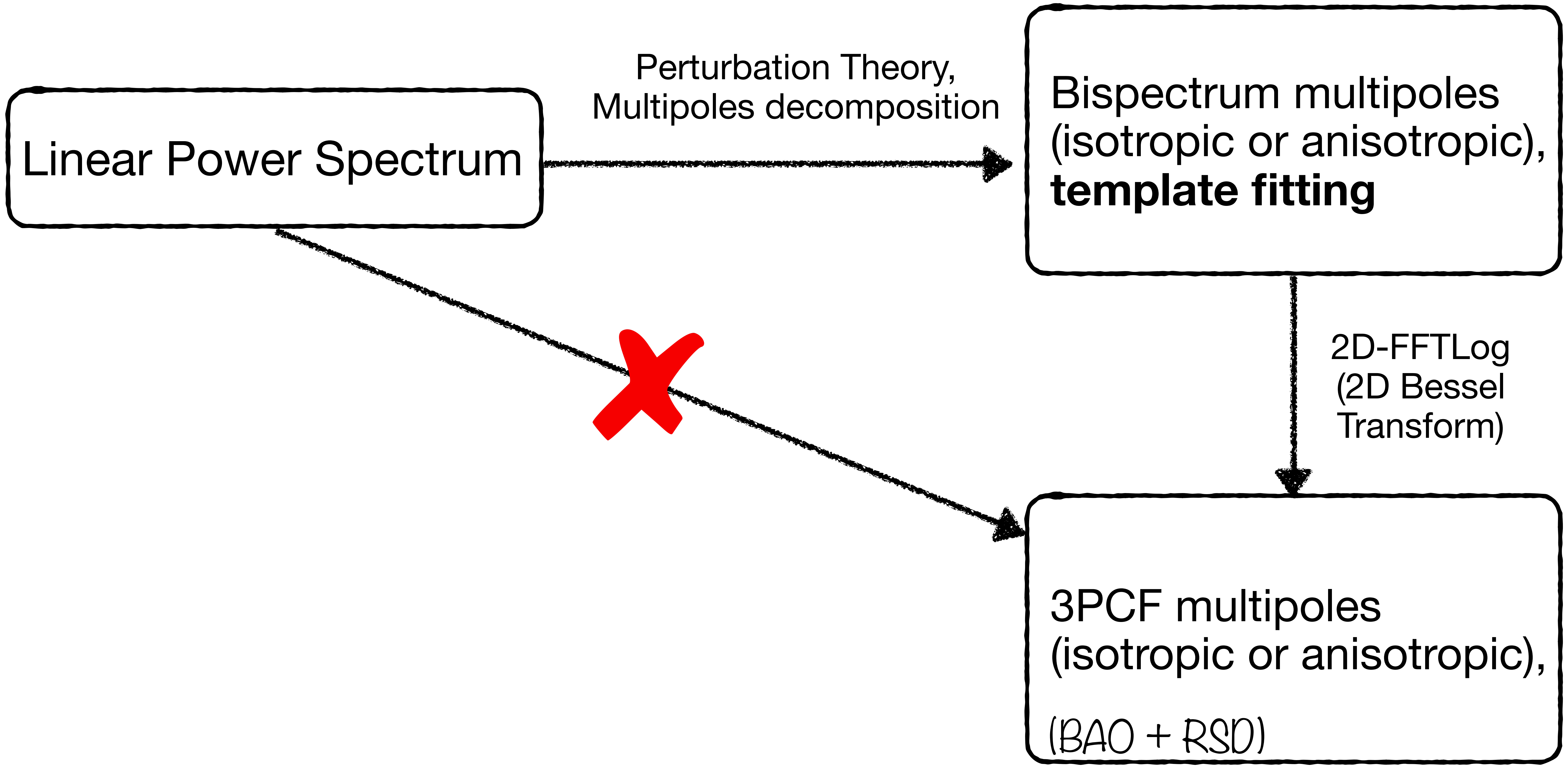
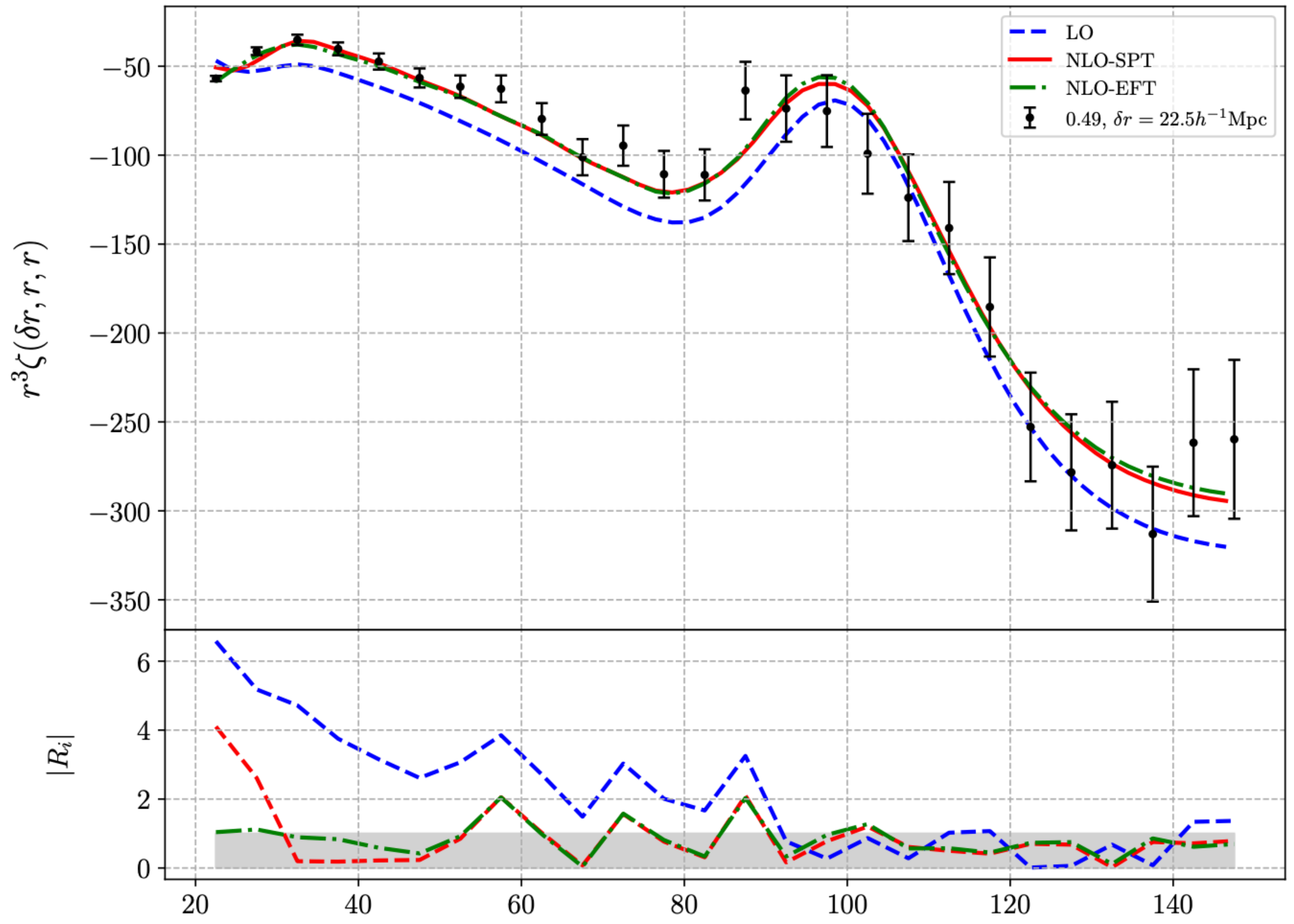
How modelling the 3PCF?



How modelling the 3PCF?

A squeezed isosceles triangle BAO configuration in the small-scale regime:



One-loop (red and green) and tree-level 3PCF matter models compared with measurements from the DEMNUni N-Body simulation

Bispectrum multipoles (isotropic or anisotropic), **template fitting**

2D-FFTLog (2D Bessel Transform)

3PCF multipoles (isotropic or anisotropic),

(BAO + RSD)

(2023) Reaching the small-scale regime

Some related works:

Umeh et al, 2020
Veropalumbo et al, 2022
Guidi et al, 2023
Farina et al, 2024
Pugno et al, 2024

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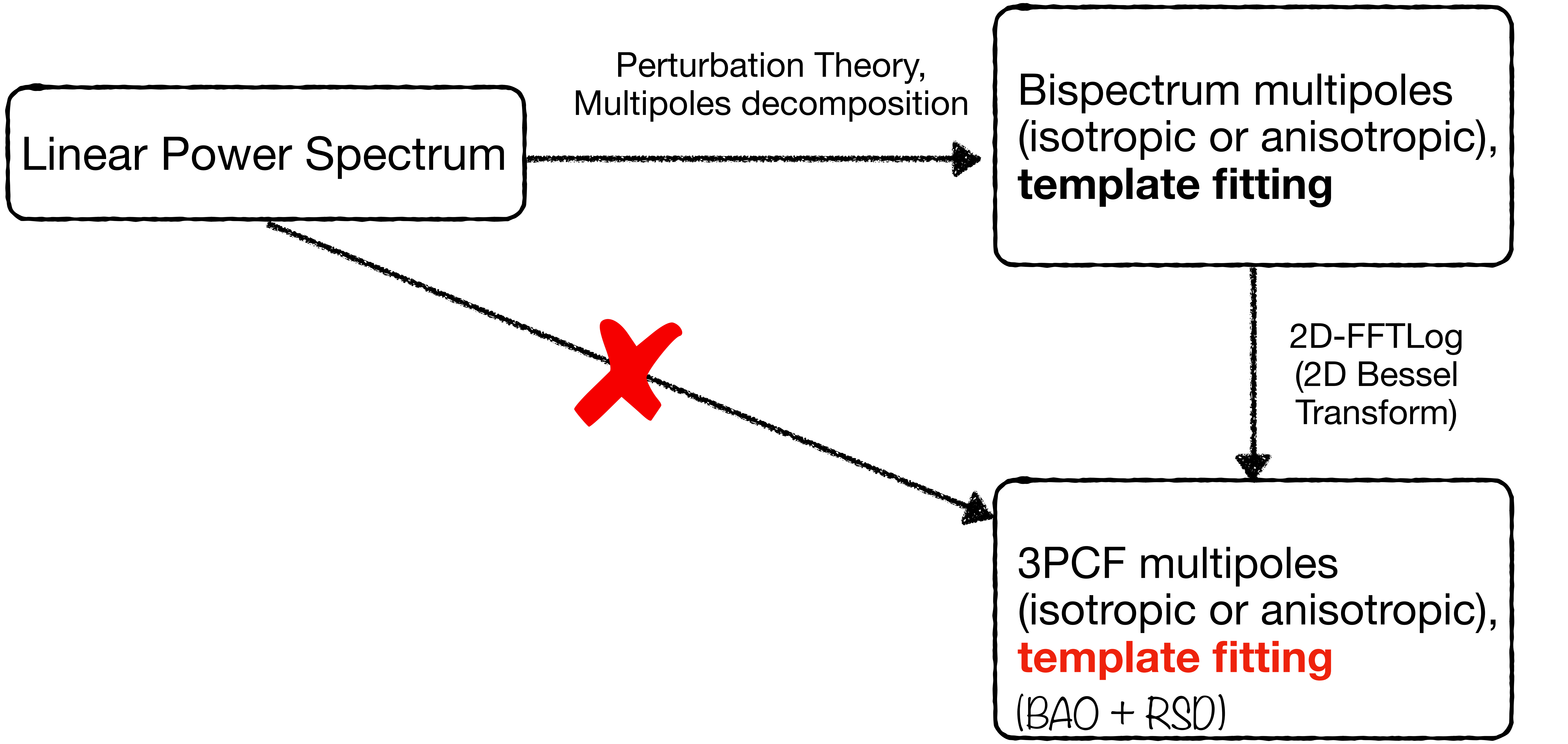
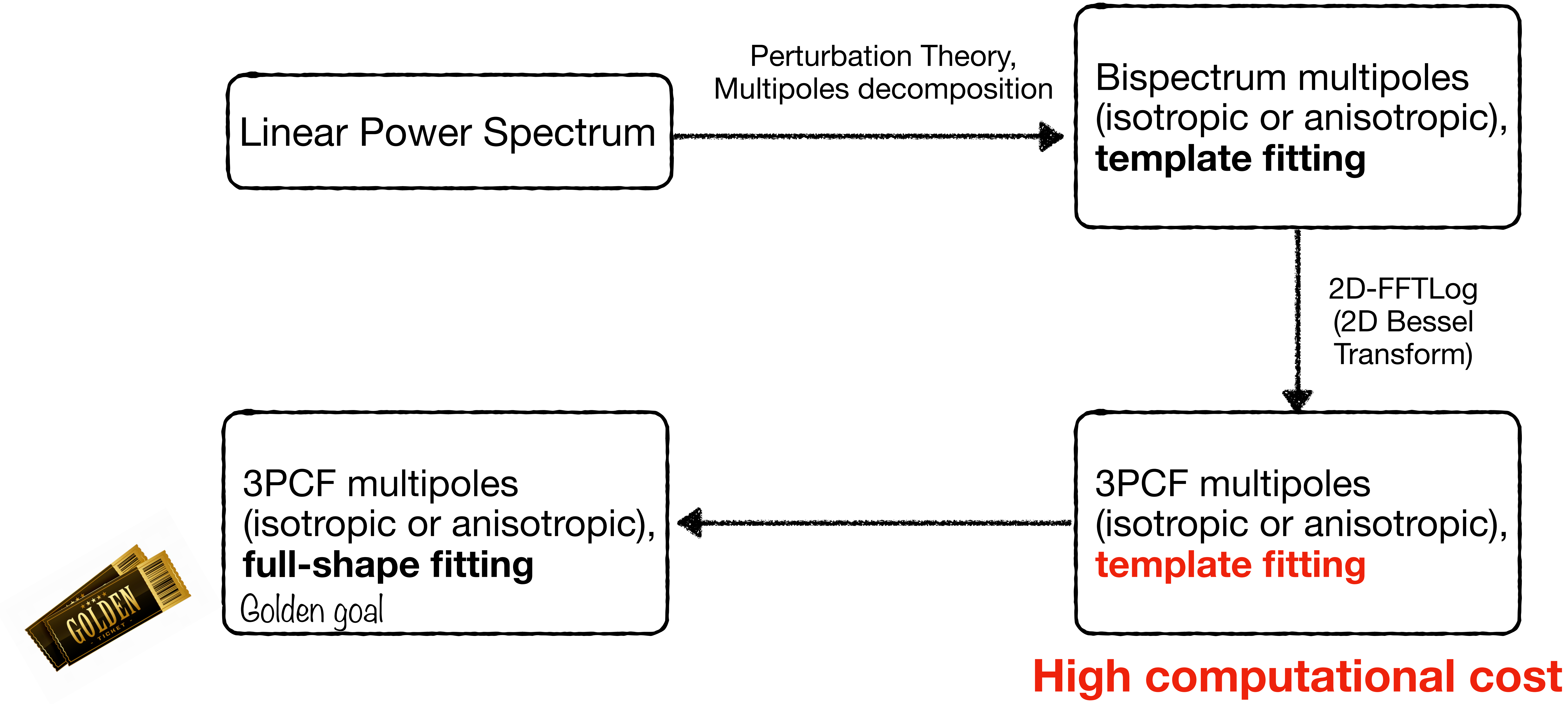
How modelling the 3PCF?



High computational cost

How modelling the 3PCF?



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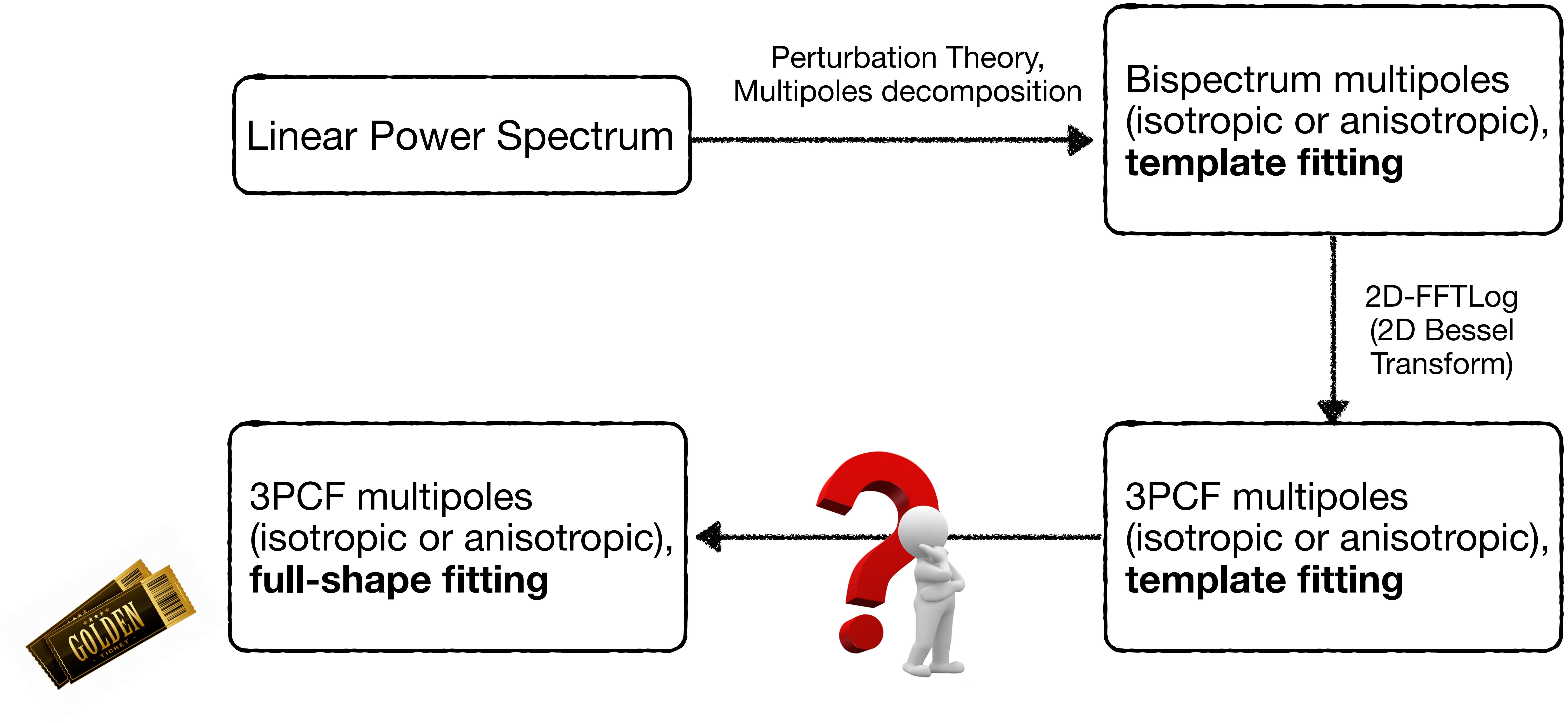
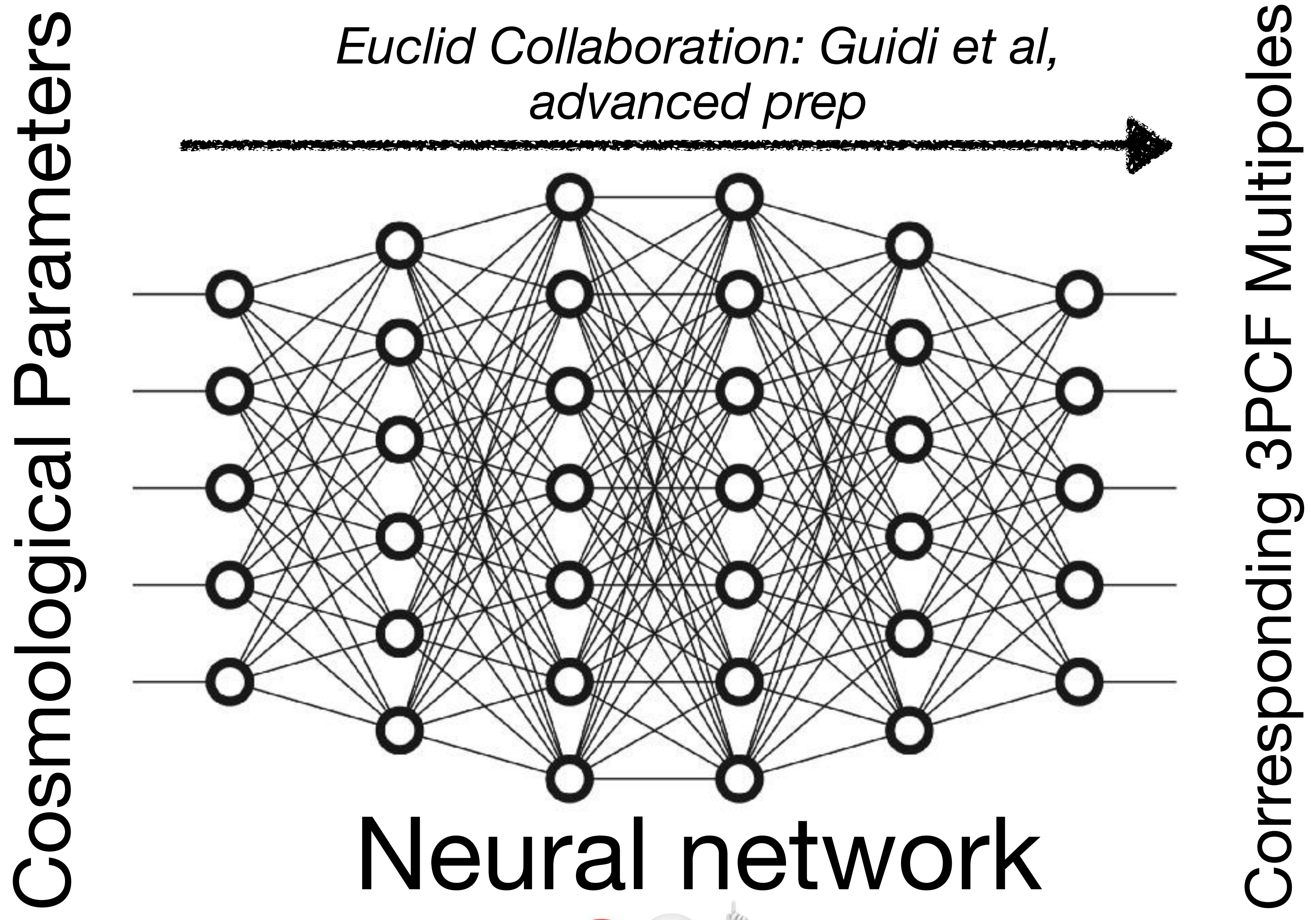
How modelling the 3PCF?



How modelling the 3PCF?

Euclid Collaboration: Guidi et al, advanced prep



3PCF multipoles (isotropic or anisotropic), **full-shape fitting**

3PCF multipoles (isotropic or anisotropic), **template fitting**

Training set!

First higher-order full-shape analysis in configuration space in the literature

arXiv:2506.22257v1 [astro-ph.CO] 27 Jun 2025

Euclid preparation. Full-shape modelling of 2-point and 3-point correlation functions in real space

Euclid Collaboration: M. Guidi★[1,2], A. Veropalumbo[3,4,5], A. Pugno[6], M. Moresco[7,2], E. Sefusatti[8,9,10], C. Porciani[6], E. Branchini[5,4,3], M.-A. Breton[11,12,13], B. Camacho Quevedo[9,14,8,15,11], M. Crocce[11,15], S. de la Torre[16], V. Desjacques[17], A. Eggemeier[6], A. Farina[5,3,4], M. Kärcher[16,18,19], D. Linde[20], M. Marinucci[21,22], A. Moradinezhad Dizgah[23], C. Moretti[14,24,8,9,10], K. Pardede[20], A. Pezzotta[25,26], E. Sarpa[14,24,10], A. Amara[27], S. Andreon[3], N. Auricchio[2], C. Baccigalupi[9,8,10,14], D. Bagot[28], M. Baldi[1,2,29], S. Bardelli[2], P. Battaglia[2], A. Biviano[8,9], M. Brescia[30,31], S. Camera[32,33,34], G. Cañas-Herrera[35,36,37], V. Capobianco[34], C. Carbone[38], V. F. Cardone[39,40], J. Carretero[41,42], M. Castellano[39], G. Castignani[2], S. Cavuoti[31,43], K. C. Chambers[44], A. Cimatti[45], C. Colodro-Conde[46], G. Congedo[47], L. Conversi[48,49], Y. Copin[50], F. Courbin[51,52], H. M. Courtois[53], A. Da Silva[54,55], H. Degaudenzi[56], G. De Lucia[8], H. Dole[57], M. Douspis[57], F. Dubath[56], X. Dupac[49], S. Dusini[22], S. Escoffier[58], M. Farina[59], R. Farinelli[2], F. Faustini[39,60], S. Ferriol[50], F. Finelli[2,61], P. Fosalba[15,11], S. Fotopoulou[62], M. Frailis[8], E. Franceschi[2], M. Fumana[38], S. Galeotta[8], B. Gillis[47], C. Giocoli[2,29], J. Gracia-Carpio[26], A. Grazian[63], F. Grupp[26,64], L. Guzzo[19,3,65], S. V. H. Haugan[66], W. Holmes[67], F. Hormuth[68], A. Hornstrup[69,70], K. Jahnke[71], M. Jhabvala[72], B. Joachimi[73], E. Keihänen[74], S. Kermiche[58], A. Kiessling[67], B. Kubik[50], M. Kümmel[64], M. Kunz[75], H. Kurki-Suonio[76,77], A. M. C. Le Brun[78], S. Ligori[34], P. B. Lilje[66], V. Lindholm[76,77], I. Lloro[79], G. Mainetti[80], D. Maino[19,38,65], E. Maiorano[2], O. Mansutti[8], S. Marcin[81], O. Marggraf[6], K. Markovic[67], M. Martinelli[39,40], N. Martinet[16], F. Marulli[7,2,29], R. Massey[82], E. Medinaceli[2], S. Mei[83,84], M. Melchior[85], Y. Mellier[86,87], M. Meneghetti[2,29], E. Merlin[39], G. Meylan[88], A. Mora[89], B. Morin[13], L. Moscardini[7,2,29], E. Munari[8,9], C. Neissner[90,42], S.-M. Niemi[35], C. Padilla[90], S. Paltani[56], F. Pasian[8], K. Pedersen[91], W. J. Percival[92,93,94], V. Pettorino[35], S. Pires[13], G. Polenta[60], M. Poncet[28], L. A. Popa[95], F. Raison[26], R. Rebolo[46,96,97], A. Renzi[21,22], J. Rhodes[67], G. Riccio[31], E. Romelli[8], M. Roncarelli[2], R. Saglia[64,26], Z. Sakr[98,99,100], A. G. Sánchez[26], D. Sapone[101], B. Sartoris[64,8], J. A. Schewtschenko[47], P. Schneider[6], T. Schrabback[102], M. Scodeggio[38], A. Secroun[58], G. Seidel[71], M. Seiffert[67], S. Serrano[15,103,11], P. Simon[6], C. Sirignano[21,22], G. Sirri[29], A. Spurio Mancini[104], L. Stanco[22], J. Steinwagner[26], P. Tallada-Crespí[41,42], D. Tavagnacco[8], A. N. Taylor[47], I. Tereno[54,105], N. Tessore[73], S. Toft[106,107], R. Toledo-Moreo[108], F. Torradeflot[42,41], A. Tsyganov[109], I. Tutusaus[99], L. Valenziano[2,61], J. Valiviita[76,77], T. Vassallo[64,8], G. Verdoes Kleijn[110], Y. Wang[111], J. Weller[64,26], G. Zamorani[2], F. M. Zerbi[3], E. Zucca[2], V. Allevato[31], M. Ballardini[112,113,2], M. Bolzonella[2], E. Bozzo[56], C. Burigana[114,61], R. Cabanac[99], M. Calabrese[115,38], A. Cappi[2,116], D. Di Ferdinando[29], J. A. Escartin Vigo[26], L. Gabarra[117], J. Martín-Fleitas[118], S. Matthew[47], M. Maturi[98,119], N. Mauri[45,29], R. B. Metcalf[7,2], A. A. Nucita[120,121,122], M. Pöntinen[76], I. Risso[123], V. Scottez[86,124], M. Sereno[2,29], M. Tenti[29], M. Viel[9,8,14,10,24], M. Wiesmann[66], Y. Akrami[125,126], I. T. Andika[127,128], S. Anselmi[22,21,12], M. Archidiacono[19,65], F. Atrio-Barandela[129], A. Balaguera-Antolinez[46,130], D. Bertacca[21,63,22], M. Bethermin[131], L. Blot[132,78], H. Böhringer[26,133,134], S. Borgani[135,9,8,10,24], M. L. Brown[136], S. Bruton[137], A. Calabro[39], F. Caro[39], C. S. Carvalho[105], T. 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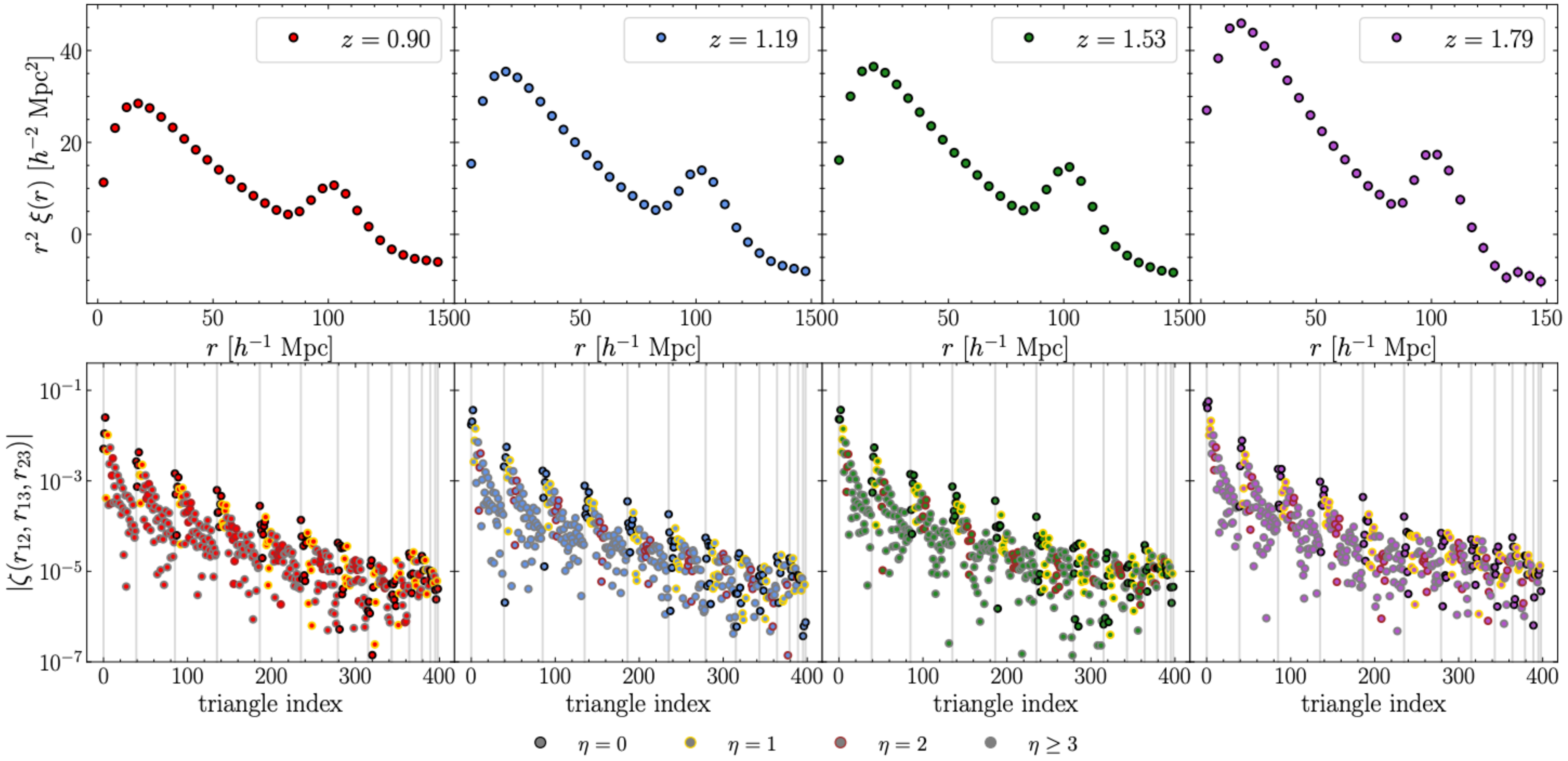
Magliocchetti[59], F. Mannucci[161], R. Maoli[162,39], C. J. A. P. Martins[163,164], L. Maurin[57], M. Miluzio[49,165], P. Monaco[135,8,10,9], G. Morgante[2], S. Nadathur[143], K. Naidoo[143], A. Navarro-Alsina[6], S. Nesseris[125], L. Pagano[112,113], F. Passalacqua[21,22], K. Paterson[71], L. Patrizii[29], A. Pisani[58], D. Potter[154], S. Quai[7,2], M. Radovich[63], P. Reimberg[86], P.-F. Rocci[57], G. Rodighiero[21,63], S. Sacquegna[120,121,122], M. Sahlén[166], D. B. Sanders[44], A. Schneider[154], D. Sciotti[39,40], E. Sellentin[167,37], L. C. Smith[168], J. G. Sorce[169,57], K. Tanidis[117], C. Tao[58], G. Testera[4], R. Teyssier[170], S. Tosi[5,4,3], A. Troja[21,22], M. Tucci[56], C. Valieri[29], A. Venhola[171], D. Vergani[2], F. Vernizzi[172], G. Verza[173], P. Vielzeuf[58], and N. A. Walton[168]

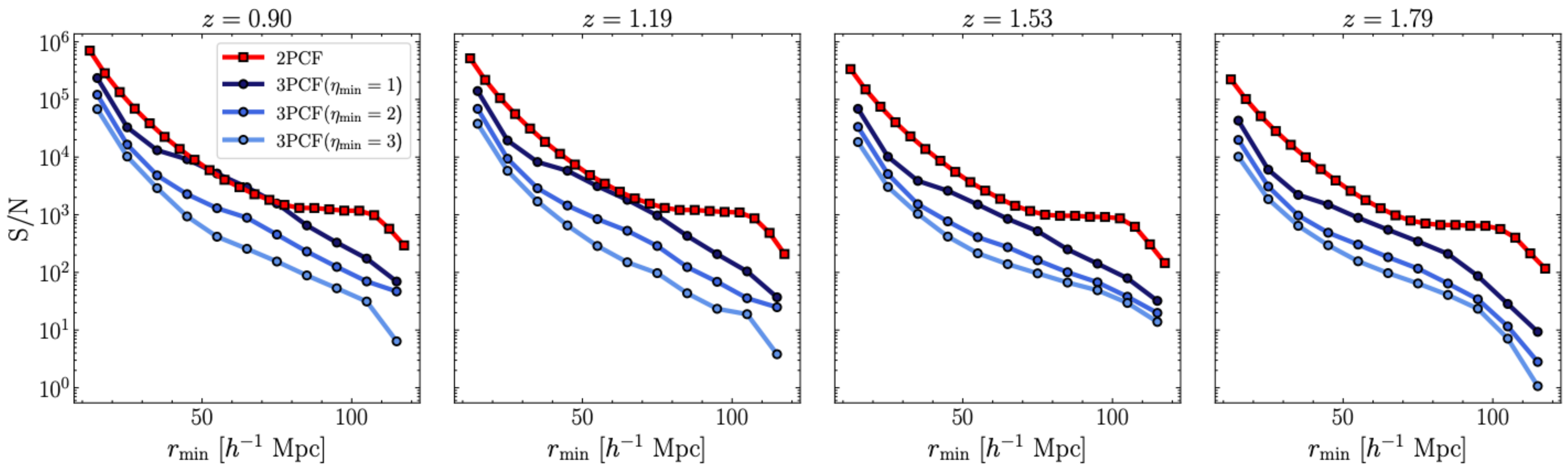
(Affiliations can be found after the references)

Euclid Preparation: Full-shape modelling of 2PCF and 3PCF in real space

- Four coming snapshots, $54\ (\mathrm{Gpc/h})^3$ coming volume
- **Real space** measurements
  - 2PCF
  - 3PCF: All triangle configurations, parametrised by $\eta_{\min} = \dfrac{r_{13} - r_{12}}{\Delta}$, where Δ bin size
  - Cumulative SNR reveals how important is reaching the small-scale regime in the modeling



Top: 2PCF measurements at different four redsfhit snapshots. *Bottom:* as the top panel, but for the 3PCF



Cumulative SNR as a function of the minimum scale, for the 2PCF and the 3PCF (parametrised by different choices of $\eta_{\min}$)

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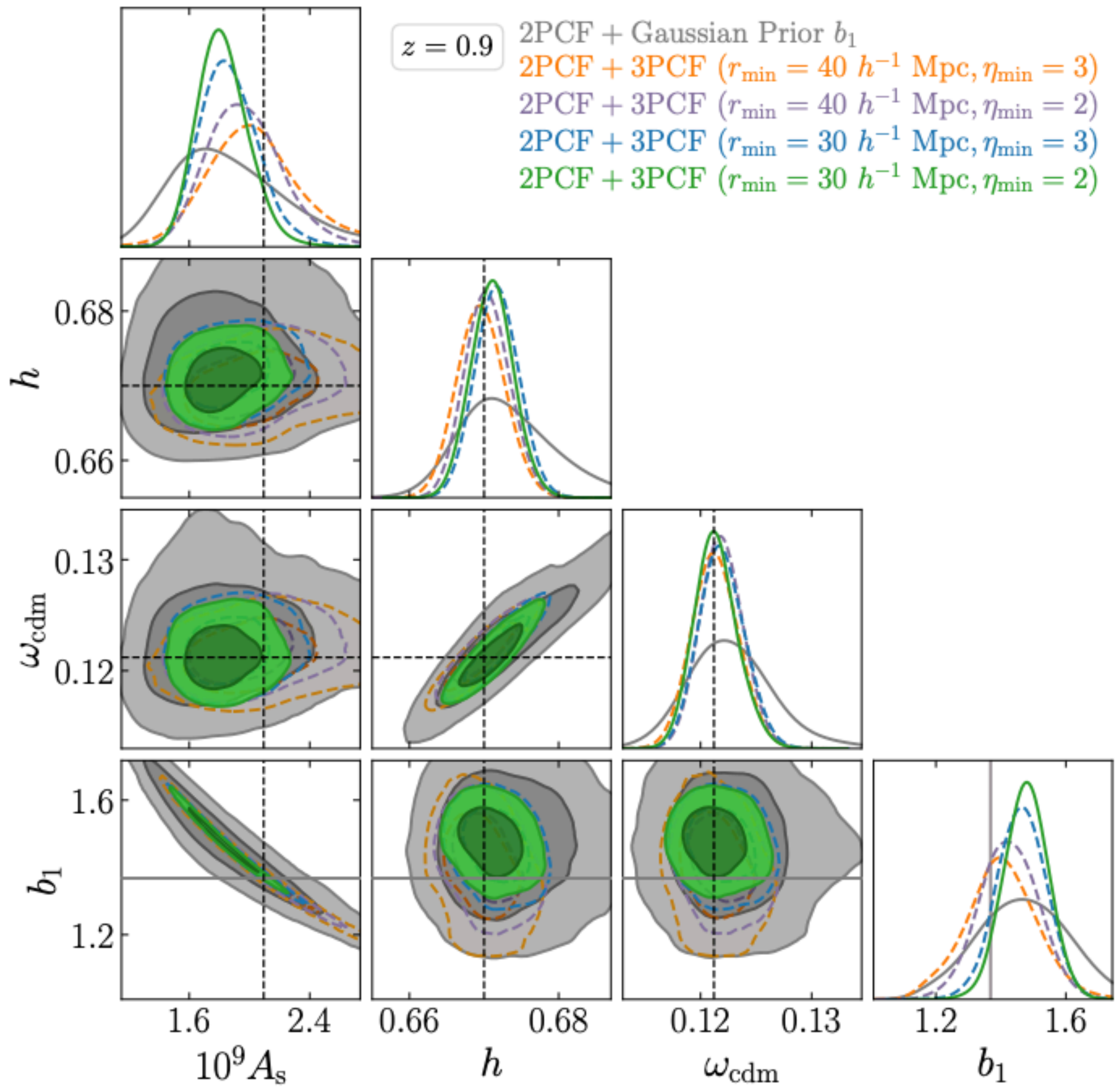
Euclid Preparation: Full-shape modelling of 2PCF and 3PCF in real space

First higher-order full-shape analysis in configuration space in the literature

- Theoretical Gaussian Covariance
- 2PCF galaxy 1-loop model, 3PCF galaxy tree level. Parameter set: $\{A_s, h, \omega_{cdm}\} + \{b_1, b_2, b_{\mathcal{G}_2}, b_{\Gamma_3}, c_0\}$
- 2PCF + 3PCF significantly improves the **constraining power** with respect to only 2PCF
- Full-shape **minimum scale** for constraining cosmological parameters consistent with template fitting and methodological studies (Veropalumbo et al, 2022)

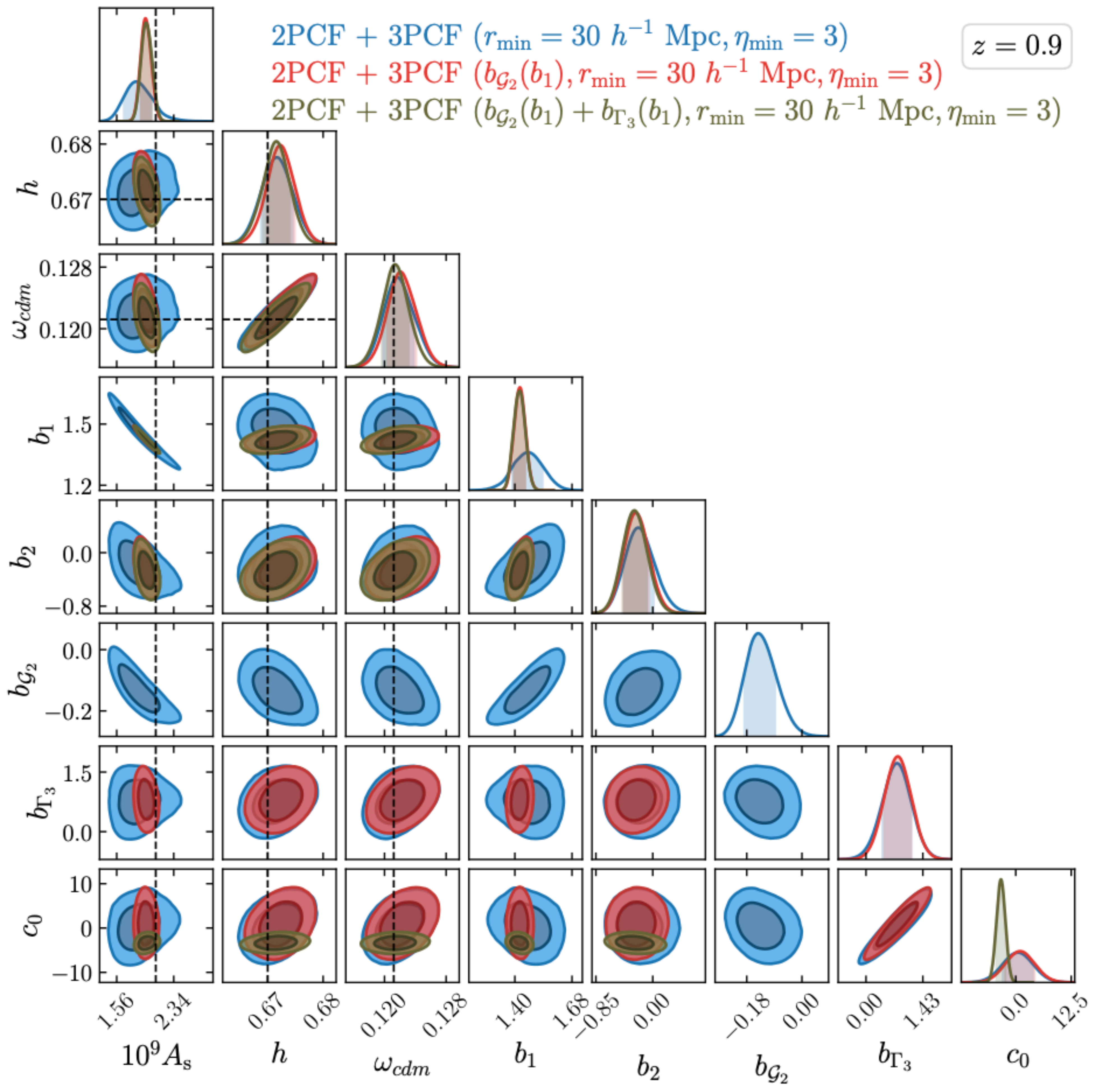


2D Posterior distribution of cosmological parameters + linear bias from a 2PCF + Gaussian prior on linear bias (grey) and a joint 2PCF + 3PCF analysis as a function of different r_{min} and η_{min} (different colors and linestyles) at z = 0.9

Euclid Preparation: Full-shape modelling of 2PCF and 3PCF in real space

First higher-order full-shape analysis in configuration space in the literature

- Theoretical Gaussian Covariance
- 2PCF galaxy 1-loop model, 3PCF galaxy tree level. Parameter set: $\{A_s, h, \omega_{\rm cdm}\} + \{b_1, b_2, b_{\mathcal{G}_2}, b_{\Gamma_3}, c_0\}$
- **Bias relations help in constraining A_s and b_1**
- Full-shape minimum scale for constraining cosmological parameters consistent with template fitting and methodological studies (Veropalumbo et al, 2022)



2D Posterior distribution of cosmological parameters + galaxy bias parameters from a joint 2PCF + 3PCF analysis as a function of different relations between bias parameters (different colors)

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Conclusions

- 3PCF as a powerful statistical tool combined with 2PCF, important to constrain physics responsible to non-Gaussianity in the density field

- **Unlocked** first full-shape 2PCF + 3PCF in real space in a simulated dataset. It maximise the extraction of cosmological information in a configuration space higher-order analysis and fills the gap with Fourier space modelling (power spectrum + bispectrum)

- Just the beginning, research line unfolding in many directions, some of them:

  - Exploring the full-shape information content of the **redshift space** (isotropic and anisotropic) 3PCF (Nagainis, *Guidi*, Moresco et al, in prep) ⟶ see Kristers' talk!

  - First analysis in redshift space with real data (BOSS, *Guidi* et al, in prep) + application to Stage IV upcoming datasets ⟶ (using of MEICorr code, see Alfonso's talk!)

  - Addressing beyond LCDM cosmologies, and the information content of the full-shape 3PCF. Role of massive neutrinos current ongoing (Labate, *Guidi*, et al in prep) ⟶ see Michele's talk!

- **Higher-order correlation** function will be fundament to **maximise the extraction of cosmological information**

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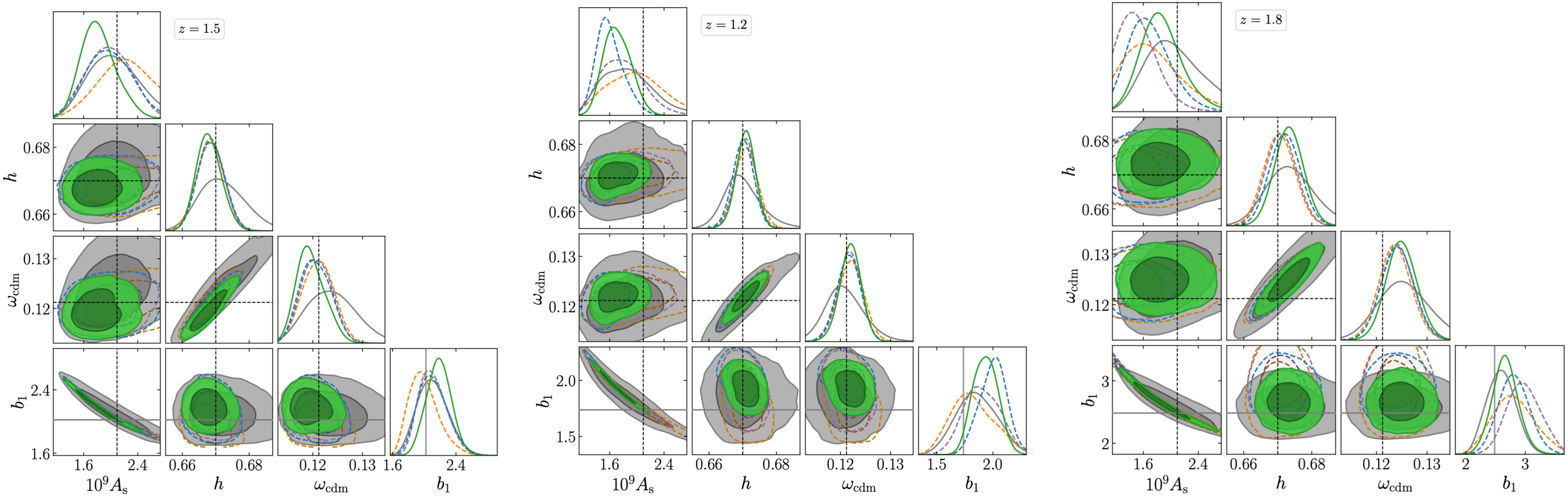
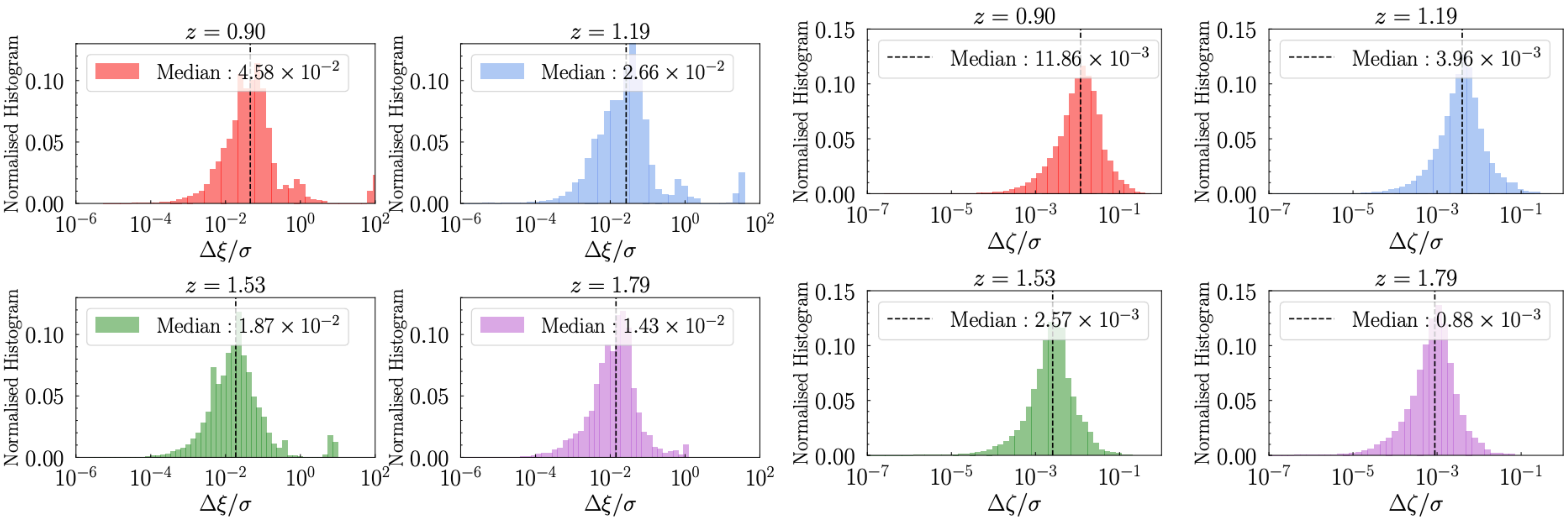
Appendix: Full-shape modelling of 2PCF and 3PCF in real space



2D Posterior distribution of cosmological parameters + linear bias from a 2PCF + Gaussian prior on linear bias (grey) and a joint 2PCF + 3PCF analysis as a function of different $r_{\rm min}$ and $\eta_{\rm min}$ (different colors and linestyles). Different panels show different redsfhit snapshots

Appendix: Emulator Validation



Normalised histogram of the ratio between the difference between emulated and exact modelling 2PCF (left), 3PCF (right) predictions and the corresponding uncertainty