The Non-Gaussian Universe @ Heraklion, Crete

Three-point intrinsic galaxy alignments in FLAMINGO

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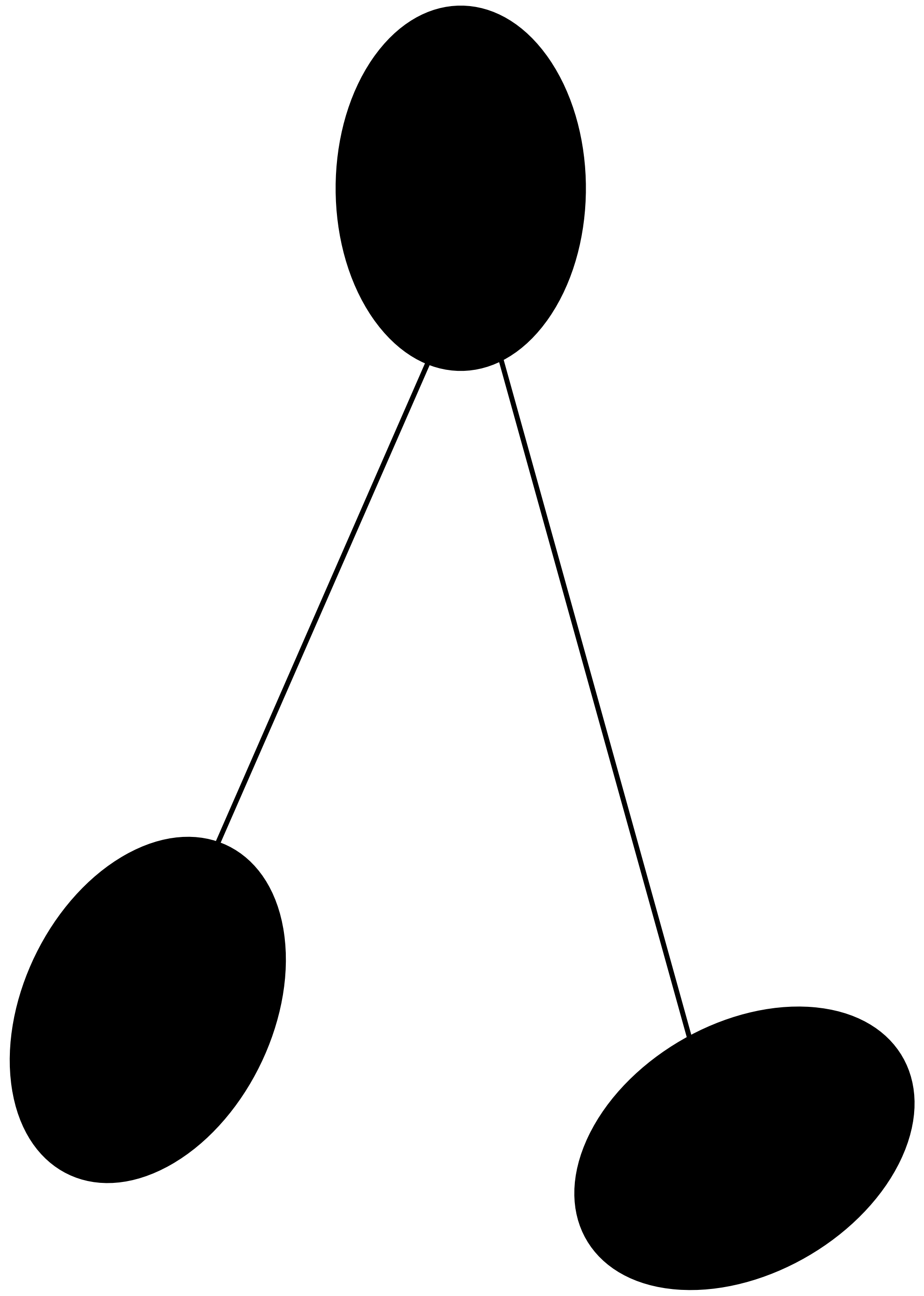
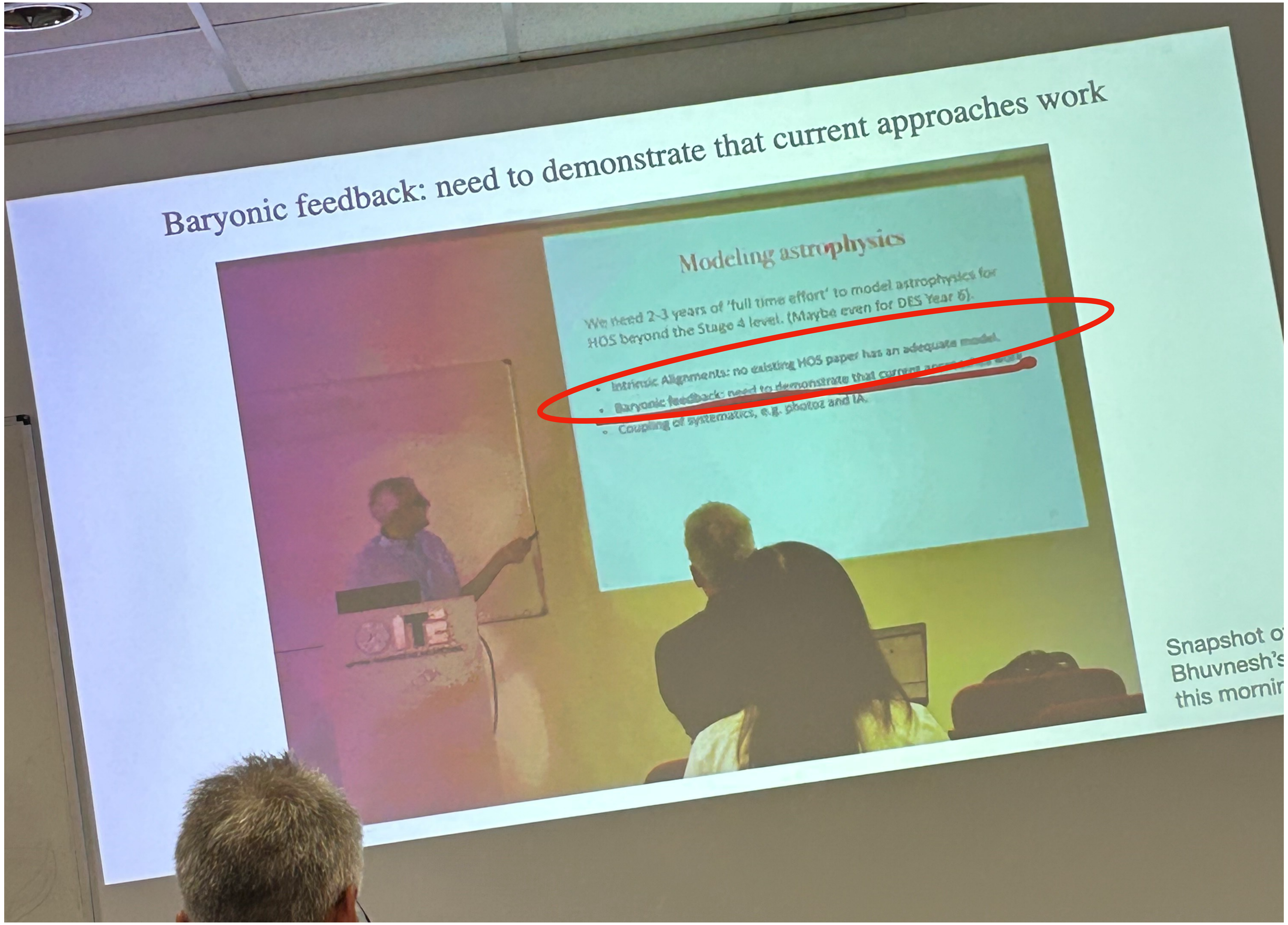
Based on 2601.17914 with Thomas Bakx, Elisa Chisari, Henk Hoekstra



Modeling astrophysics: IA



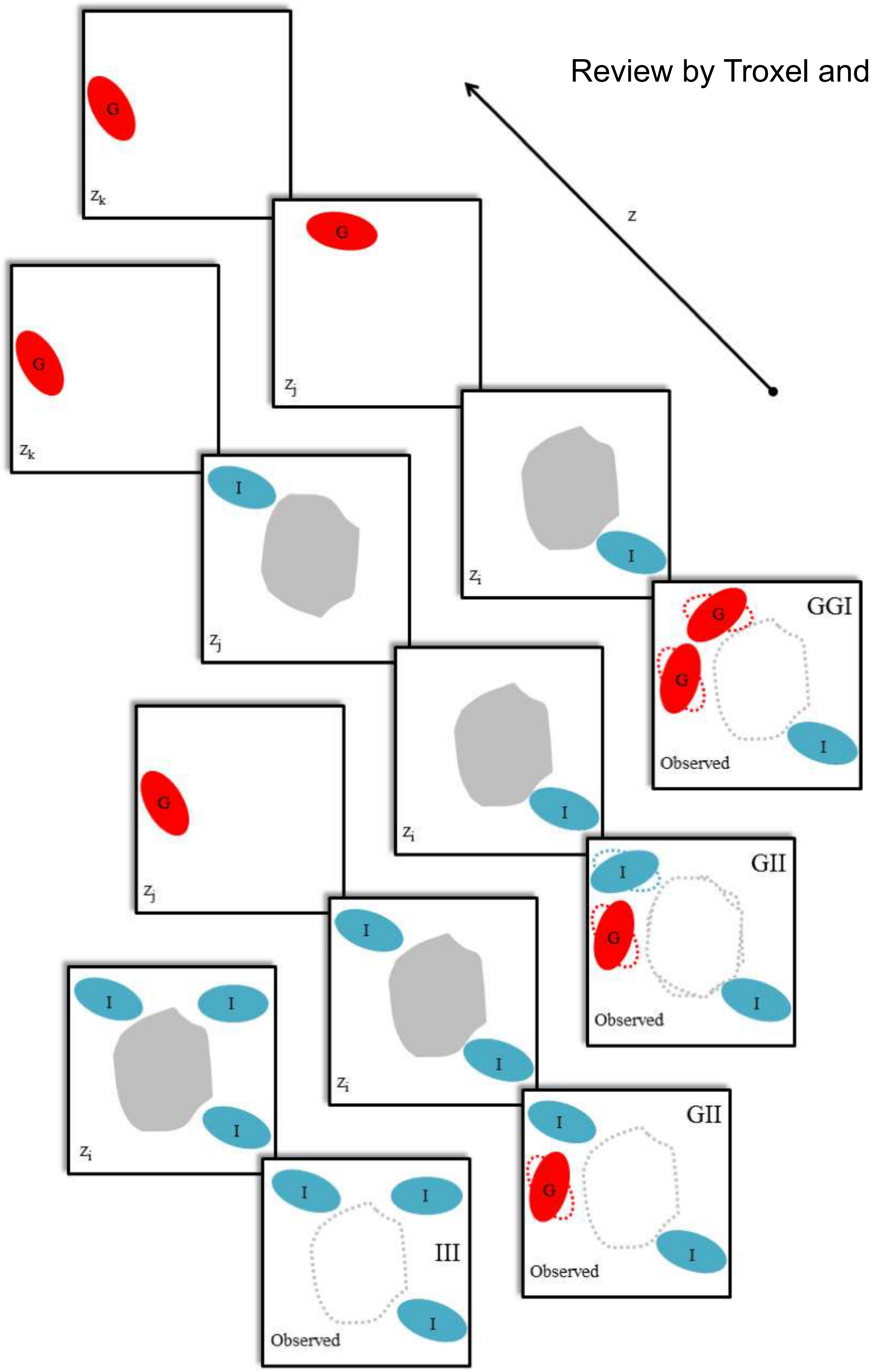
Snapshot of Bhuvnesh's talk in Giovanni's talk yesterday

Intrinsic Alignments

Challenges for (higher order) lensing*

- Tighter constraints give more stringent demands for modeling
- We specifically target non-linear information

Review by Troxel and Ishak 2014



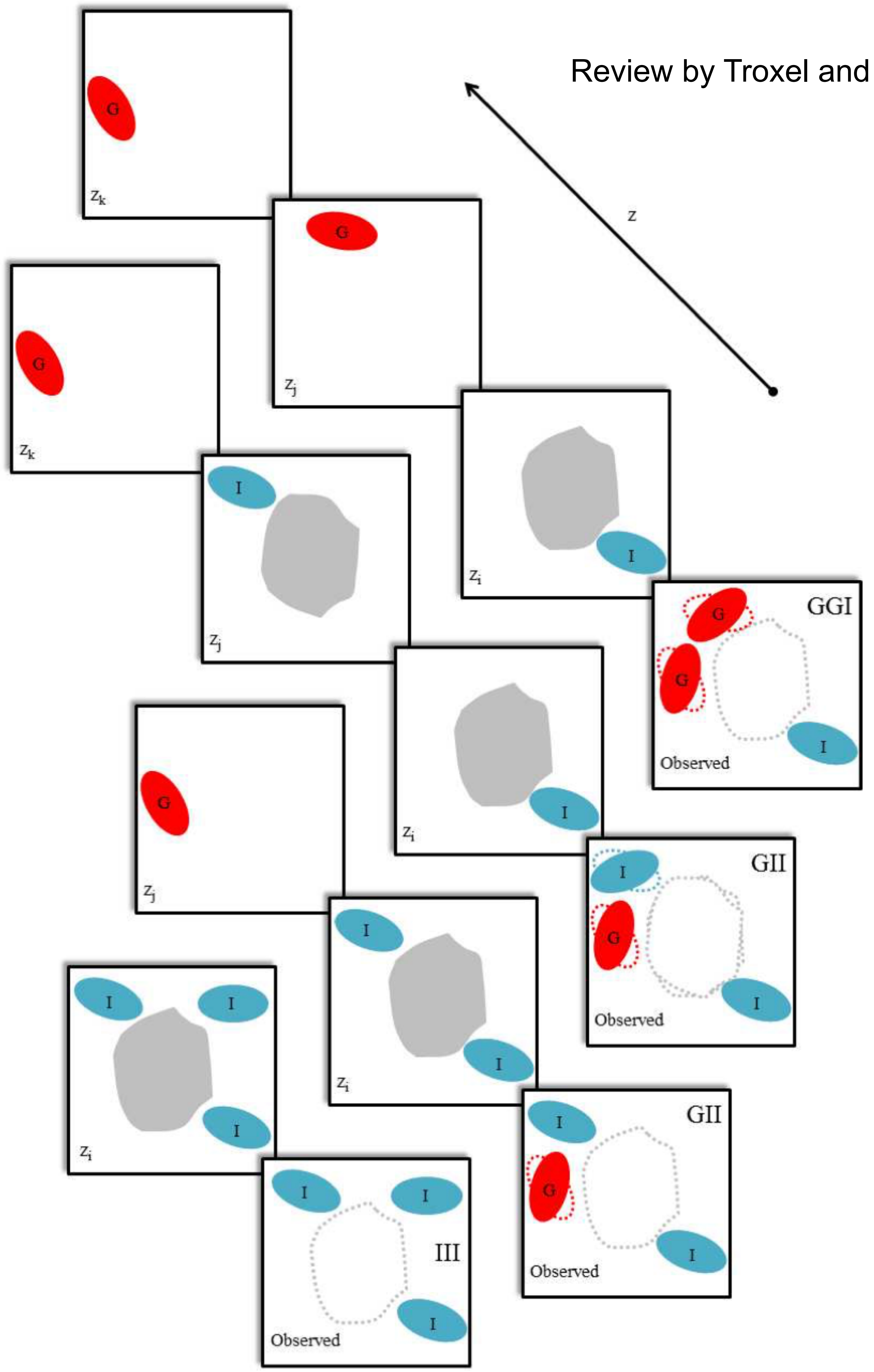
*but many more applications of IA!

Intrinsic Alignments

Challenges for (higher order) lensing*

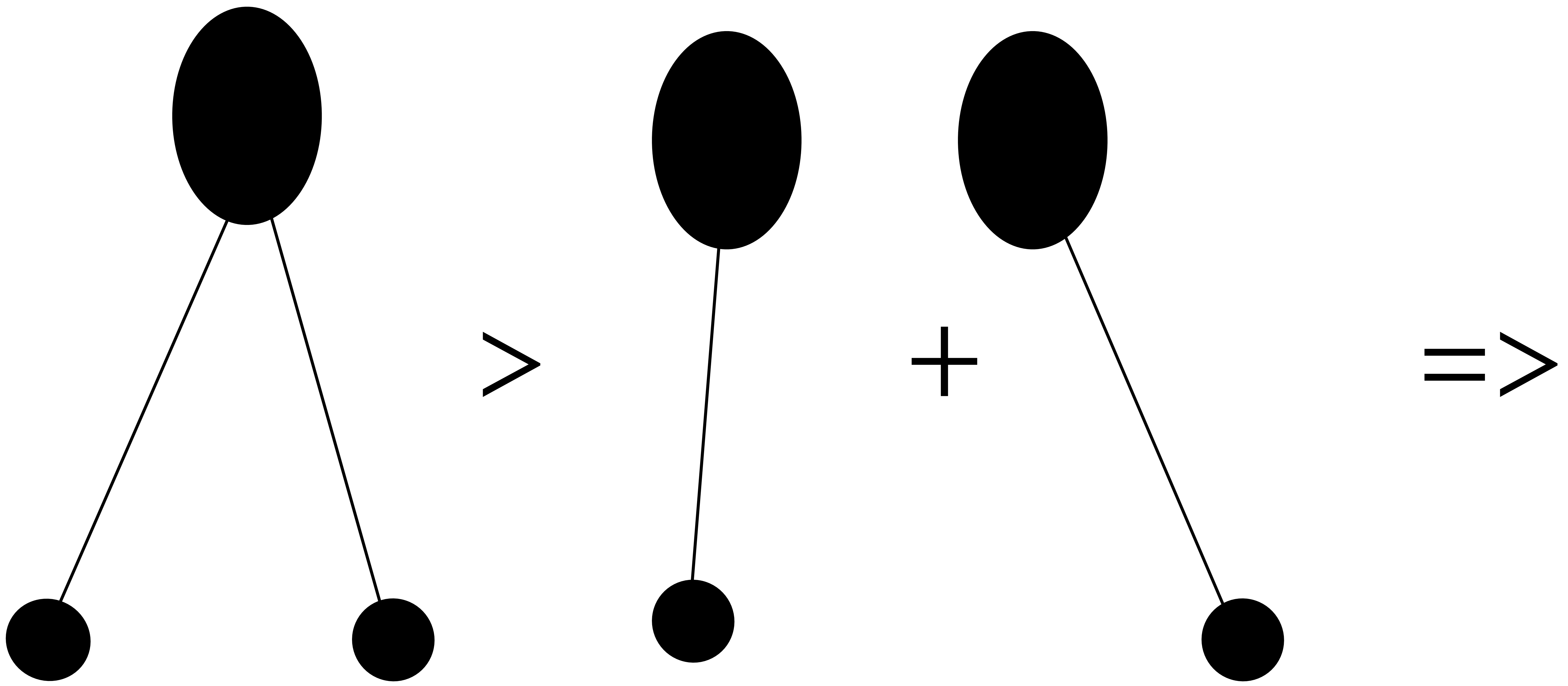
- Tighter constraints give more stringent demands for modeling
- We specifically target non-linear information
  - Models from 2-pt. might not suffice
  - Important to test our models and assumptions

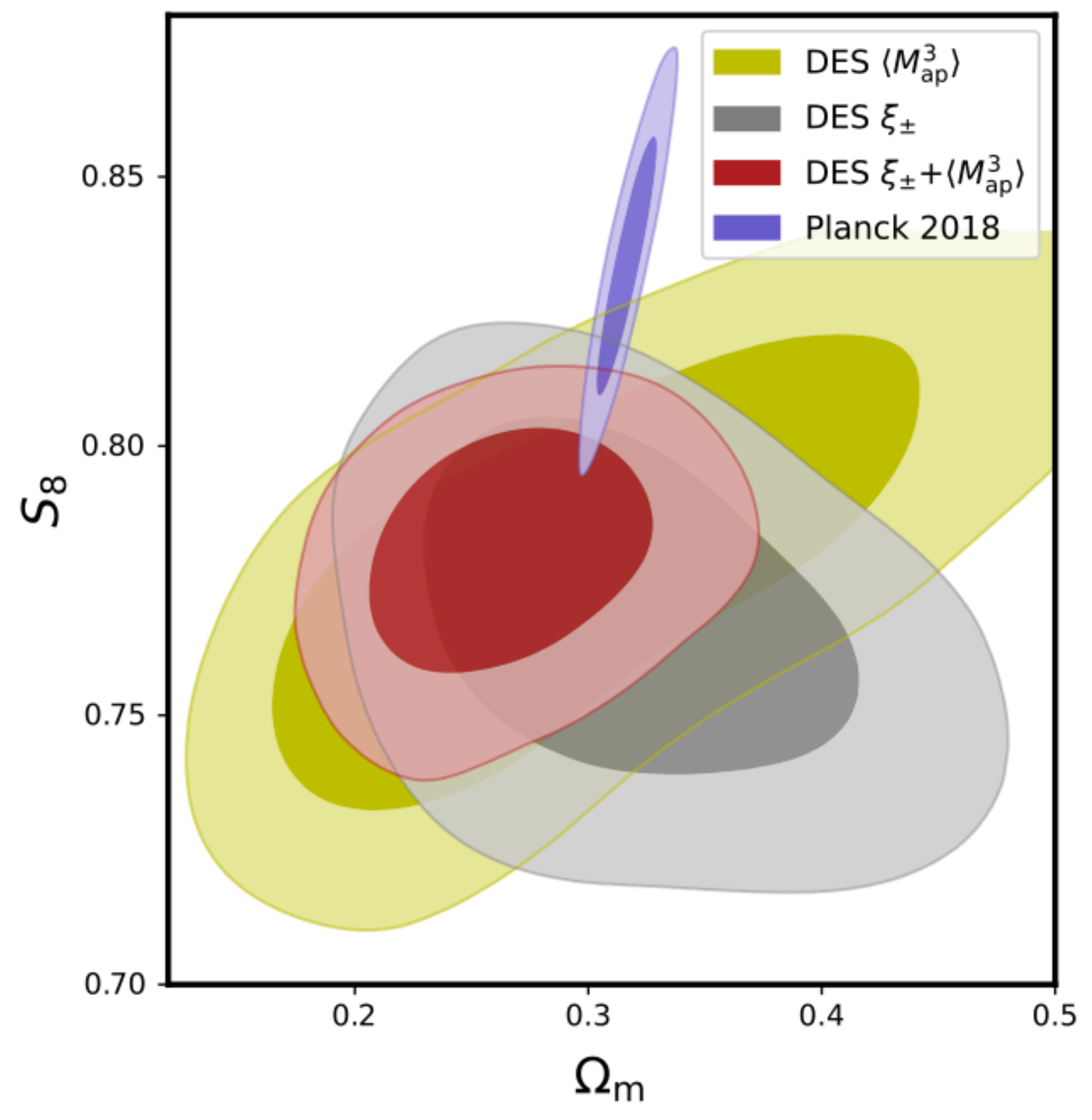
Review by Troxel and Ishak 2014



*but many more applications of IA!

Three-point statistics and cosmic shear



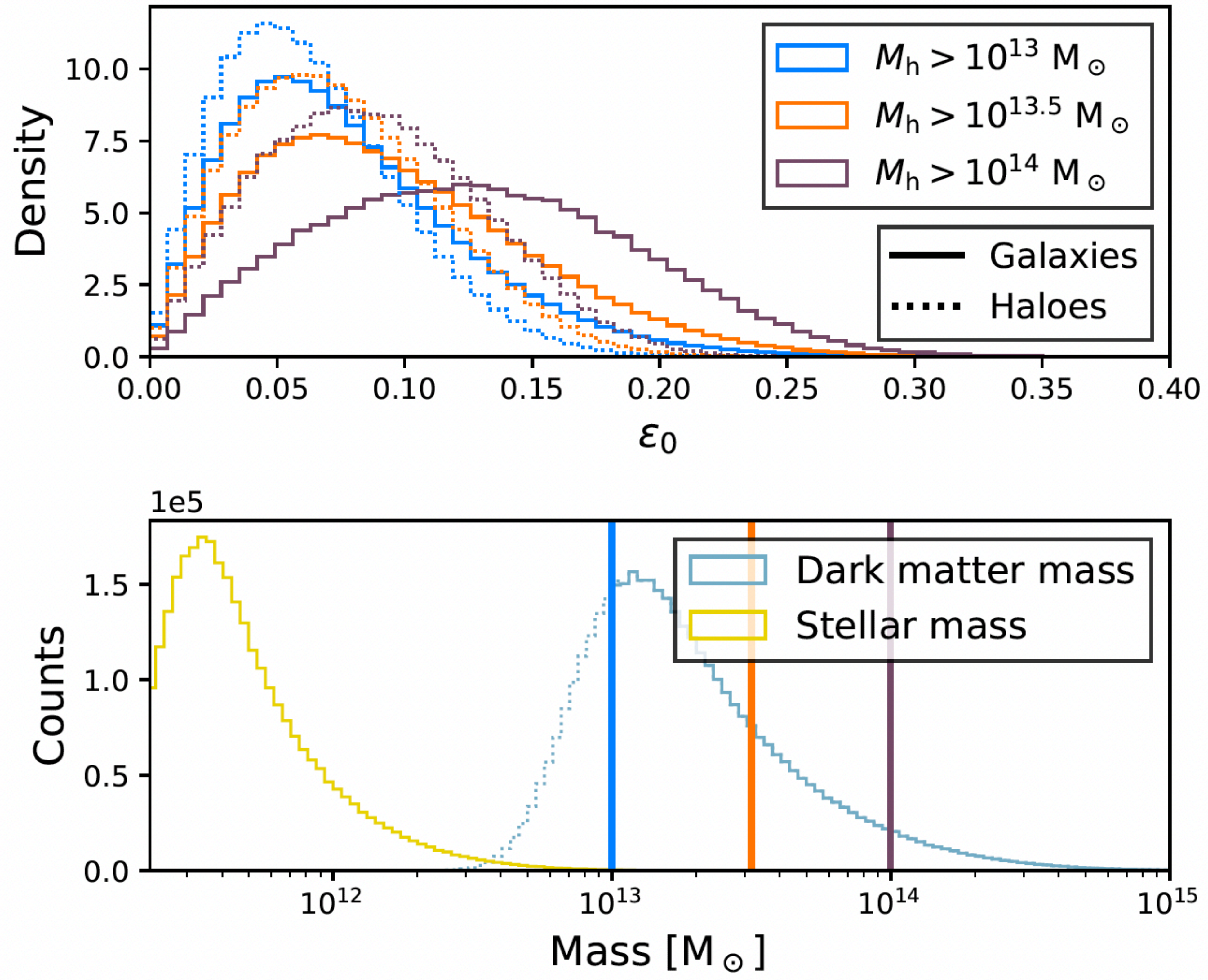


DES y3: Gomes et al, 2025, 2508.14018

- Benefit of 3-pt: **analytical modeling** on large scales (EFT) + **some intuition**
- Obtained directly from a shape catalogue
- Many insights and challenges will carry over, so natural bridge to higher order stats!

FLAMINGO

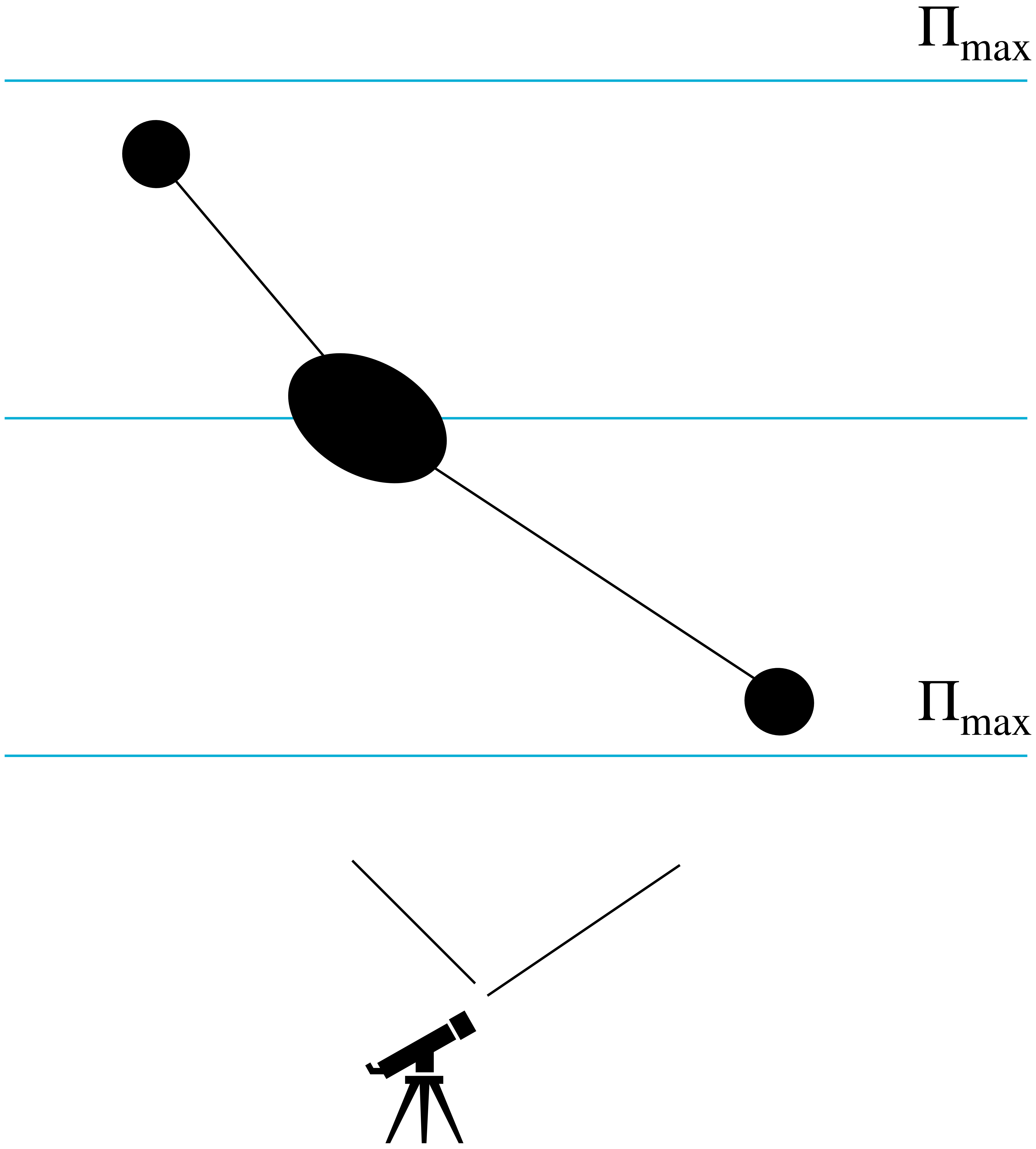
- One of the largest hydro sims to date
  - $(2.8\,\mathrm{Gpc})^3$, ‘m9 resolution’
- Construct a galaxy catalogue of about 3 mln LRG’s
- Obtain shapes via inertia tensors and project into (ϵ_1, ϵ_2)
- Measure and model 3PCF of IA on this sample



3PCF of IA

- **Natural components:** complex valued correlation functions
- Isolate and project tracers within **LOS distance of < 20 Mpc** from one specific galaxy
- Measured efficiently with a multipole algorithm (Porth et al, 2024), using *TreeCorr* (Jarvis et al, 2004)
- ggI, gII, III

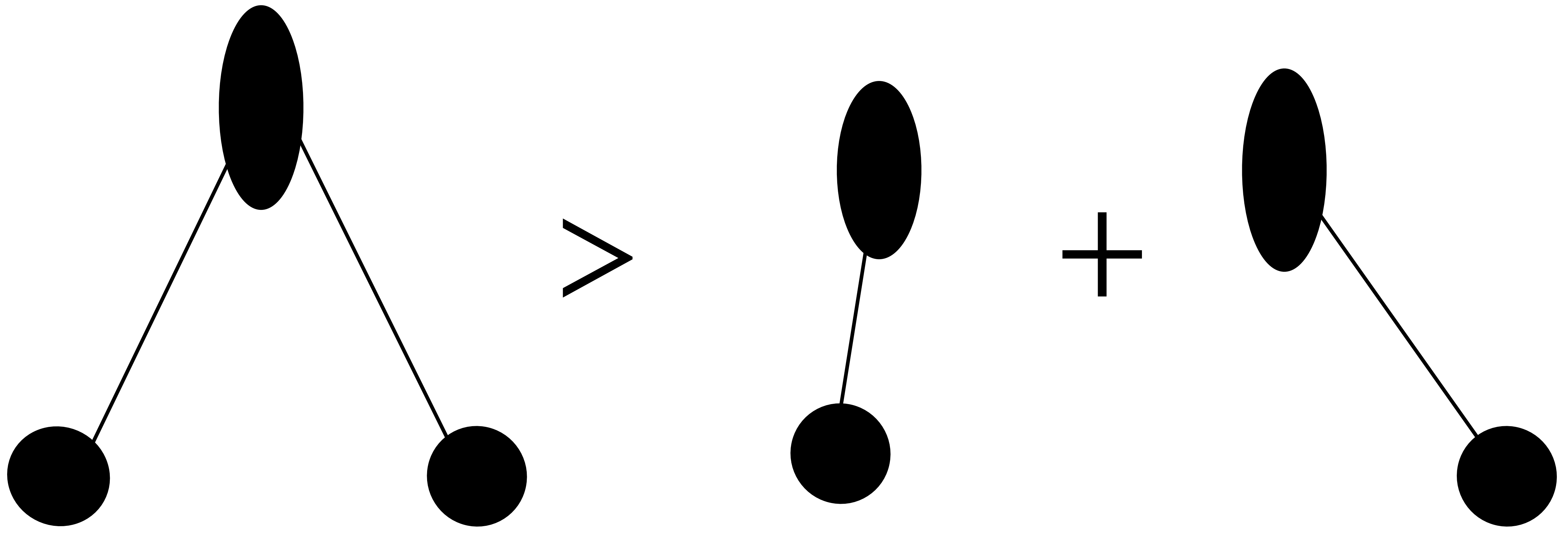
$$\text{ggI} = \frac{DDS - 2DRS + RRS}{RRR}$$

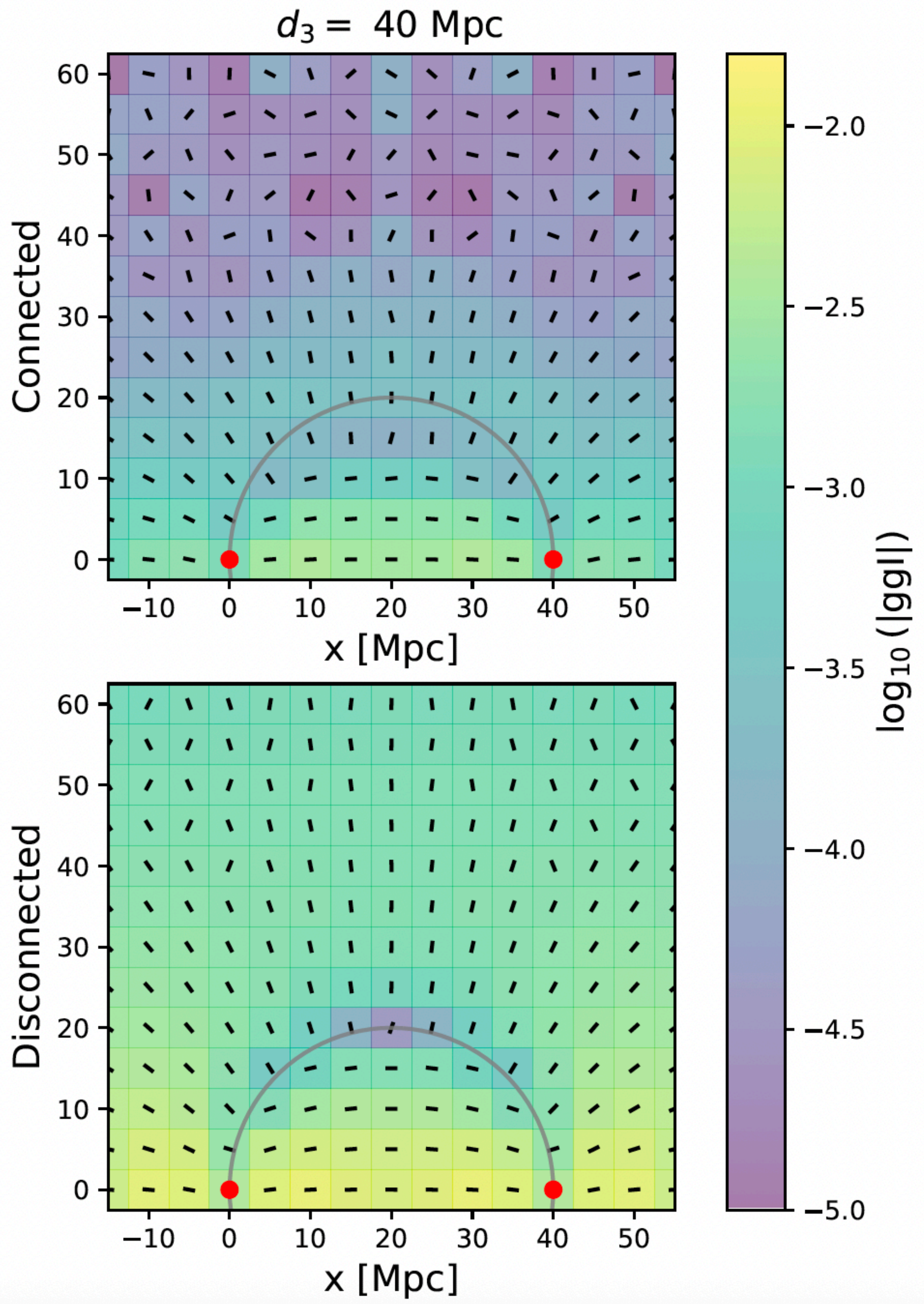


3PCF of IA

Example

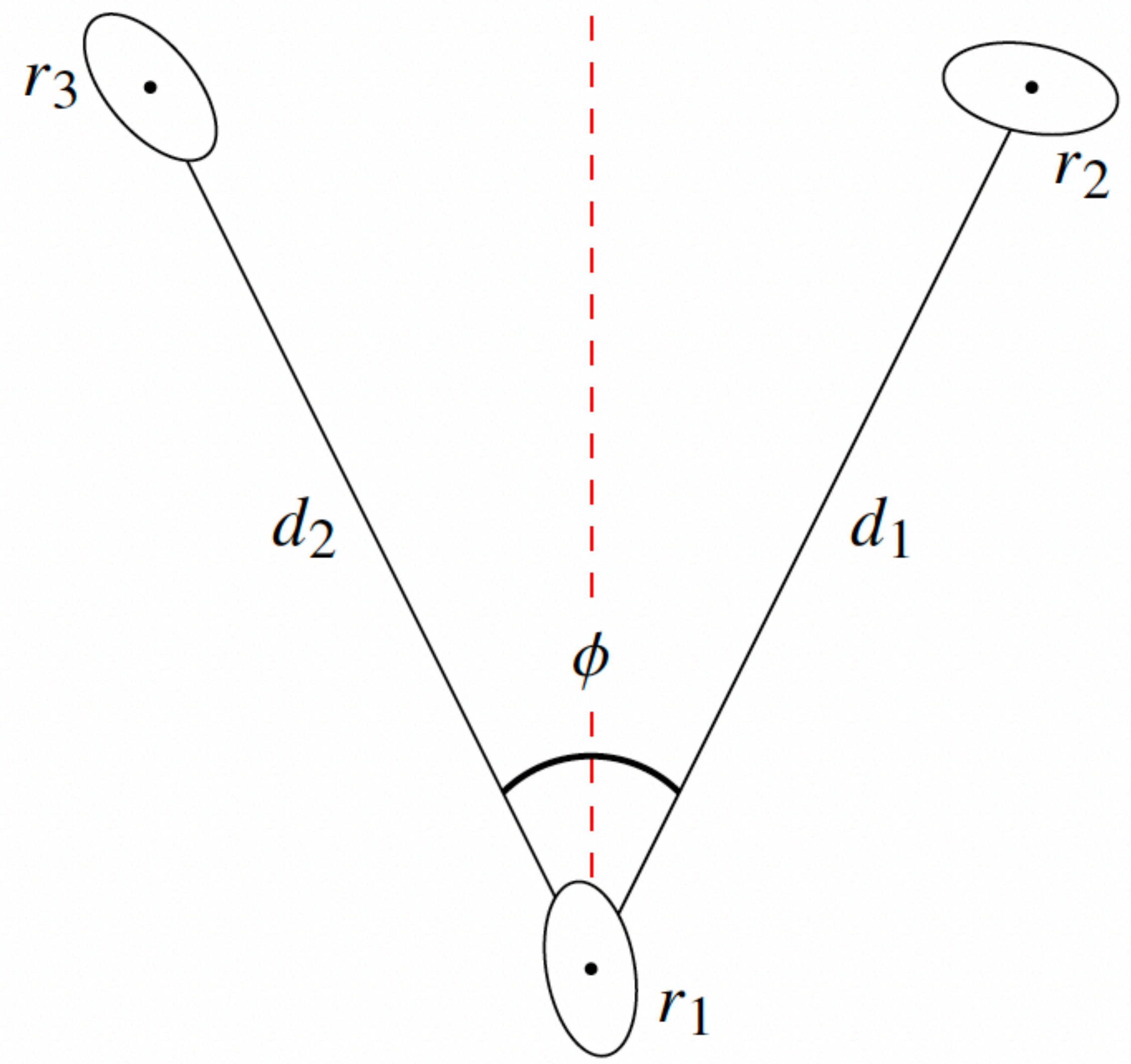
- “Excess alignment around galaxy pairs”
- $$\mathrm{ggI} = \frac{DDS - 2DRS + RRS}{RRR}$$

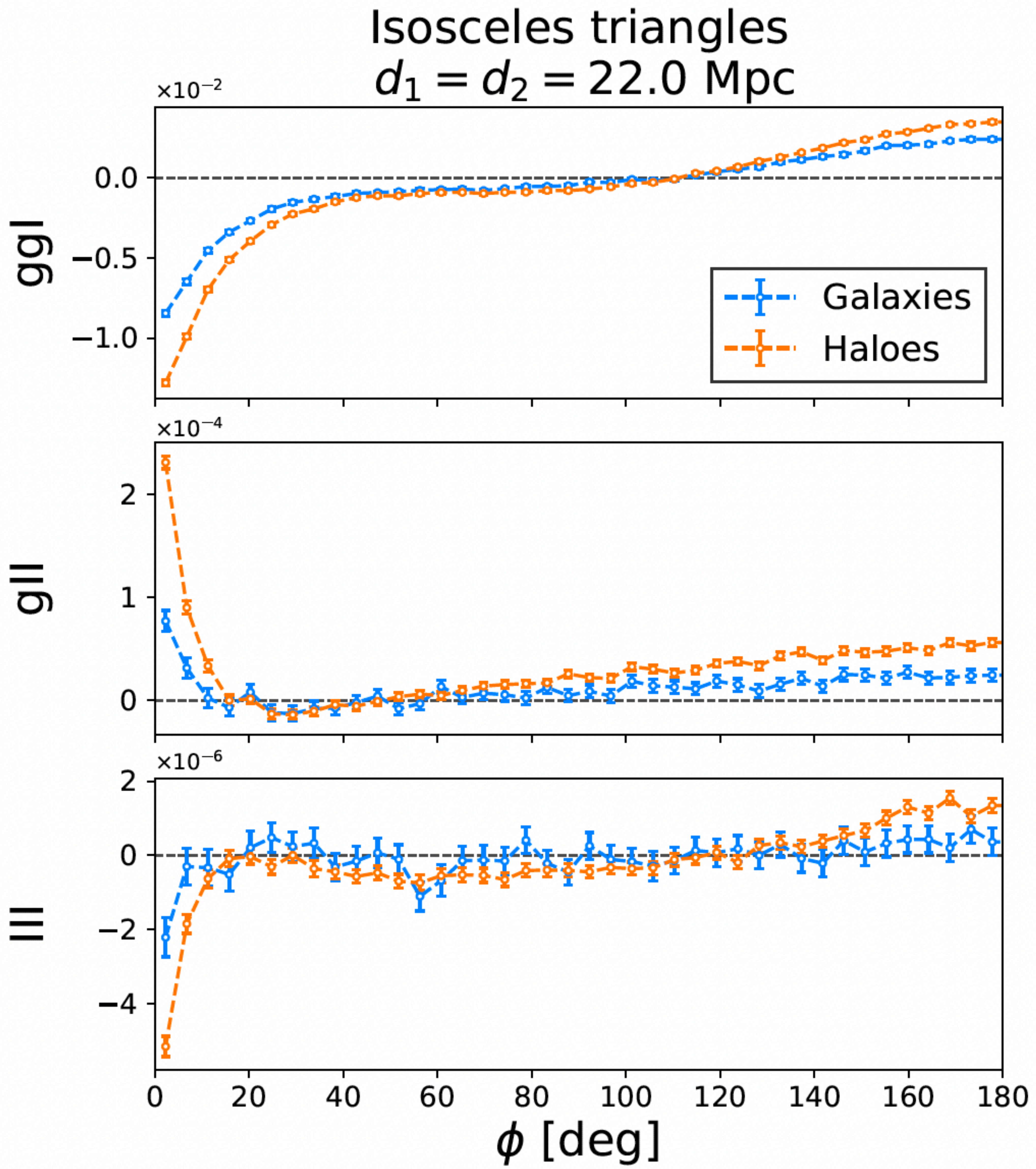




3PCF of IA

- **Tangential components** of 3PCF
- Most signal in collinear triangles

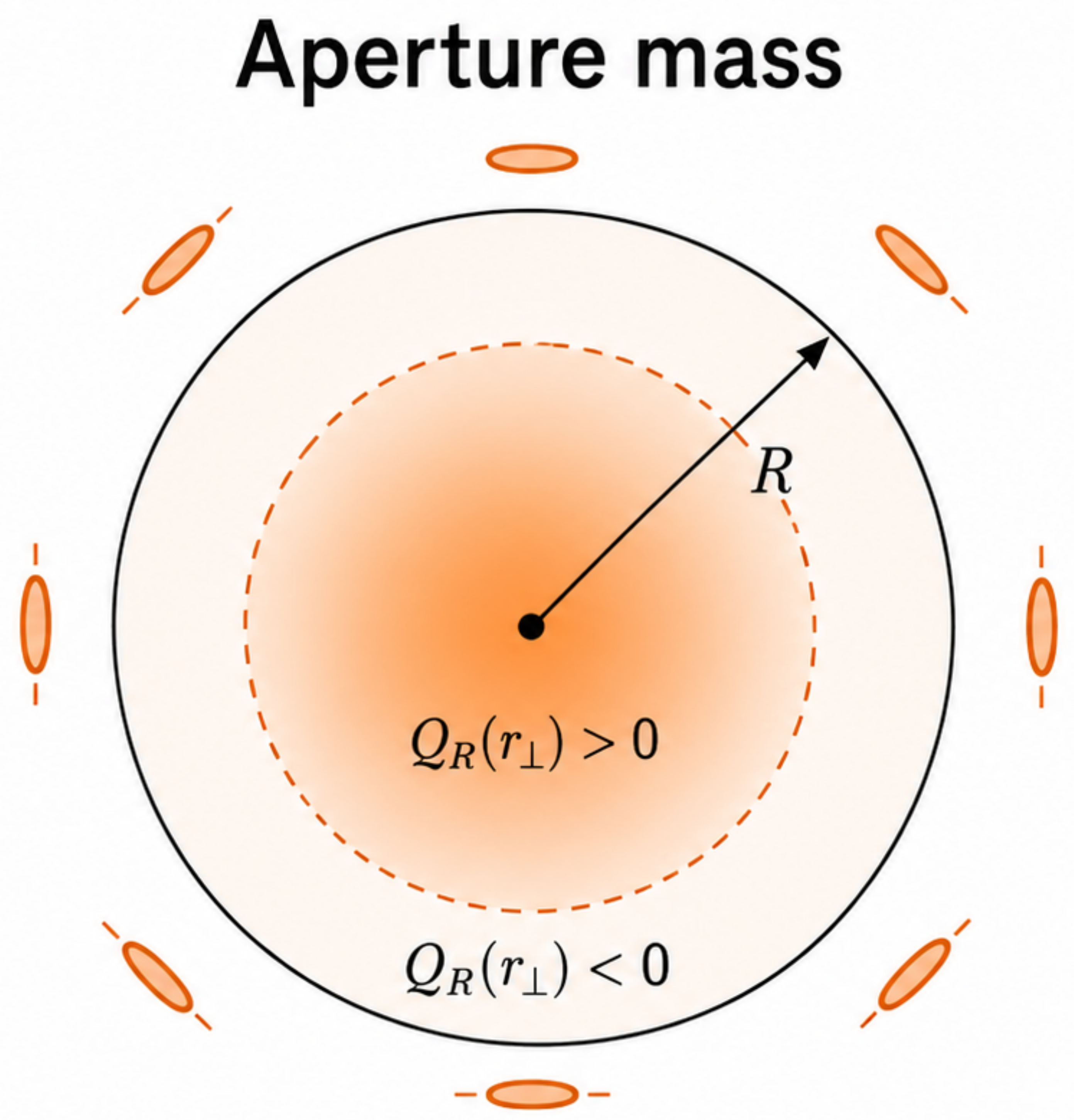




Aperture mass statistics

Practical compression

- 3PCF is rich in information, but somewhat unwieldy, apertures provide several benefits
  - Easier to model
  - **E/B separation**
  - Randoms subtraction automatically due to **compensated filter**
  - Relatively local probe of the bispectrum
- Integral transform of 3PCF, and easy to connect to the bispectrum
  - $\langle NNM_{\rm ap}\rangle \sim \int 3\mathrm{PCF} \sim \int B_{\delta\delta E}$



$$M_{ap}(R) = \int d^2r_\perp \; Q_R(r_\perp) \; \varepsilon_t(r_\perp)$$

$$M_\times(R) = \int d^2r_\perp \; Q_R(r_\perp) \; \varepsilon_\times(r_\perp)$$

*notable other options: hybrid or halo models

Modeling the bispectrum

Shapes and the bias expansion*

- Bias expansion

See review by Desjacques, Jeong and Schmidt (2018), see Vlah et al (2020) for IA

  - $g_{ij} = \sum_{\mathcal{O}} b_{\mathcal{O}} \mathcal{O}_{ij} = b_K K_{ij} + b_{\delta K} \delta K_{ij} \ldots$

- Bias parameters encode our ignorance of galaxy evolution and formation

- Tree-level bispectrum is then obtained via $\langle \delta \delta g_{ij} \rangle \sim \langle \delta^{(1)} \delta^{(2)} g_{ij}^{(1)} \rangle + \langle \delta^{(2)} \delta^{(1)} g_{ij}^{(1)} \rangle + \langle \delta^{(1)} \delta^{(1)} g_{ij}^{(2)} \rangle$

  - So no $\langle \delta^{(1)} \delta^{(1)} g_{ij}^{(1)} \rangle$ due to Wicks theorem

  - **Hence, always non-linear bias terms**

  - Therefore we have $B_{mmE} \neq b_K B_{mmm}$ even at tree level. Additional bias terms contribute on all scales. This is fundamentally different from the 2-point function!

*In Fourier space also add stochastic contributions!

IA - Shape bias expansion

For bispectrum: Schmitz et al (2018), Vlah et al (2020), Bakx et al (2025a, 2025b)

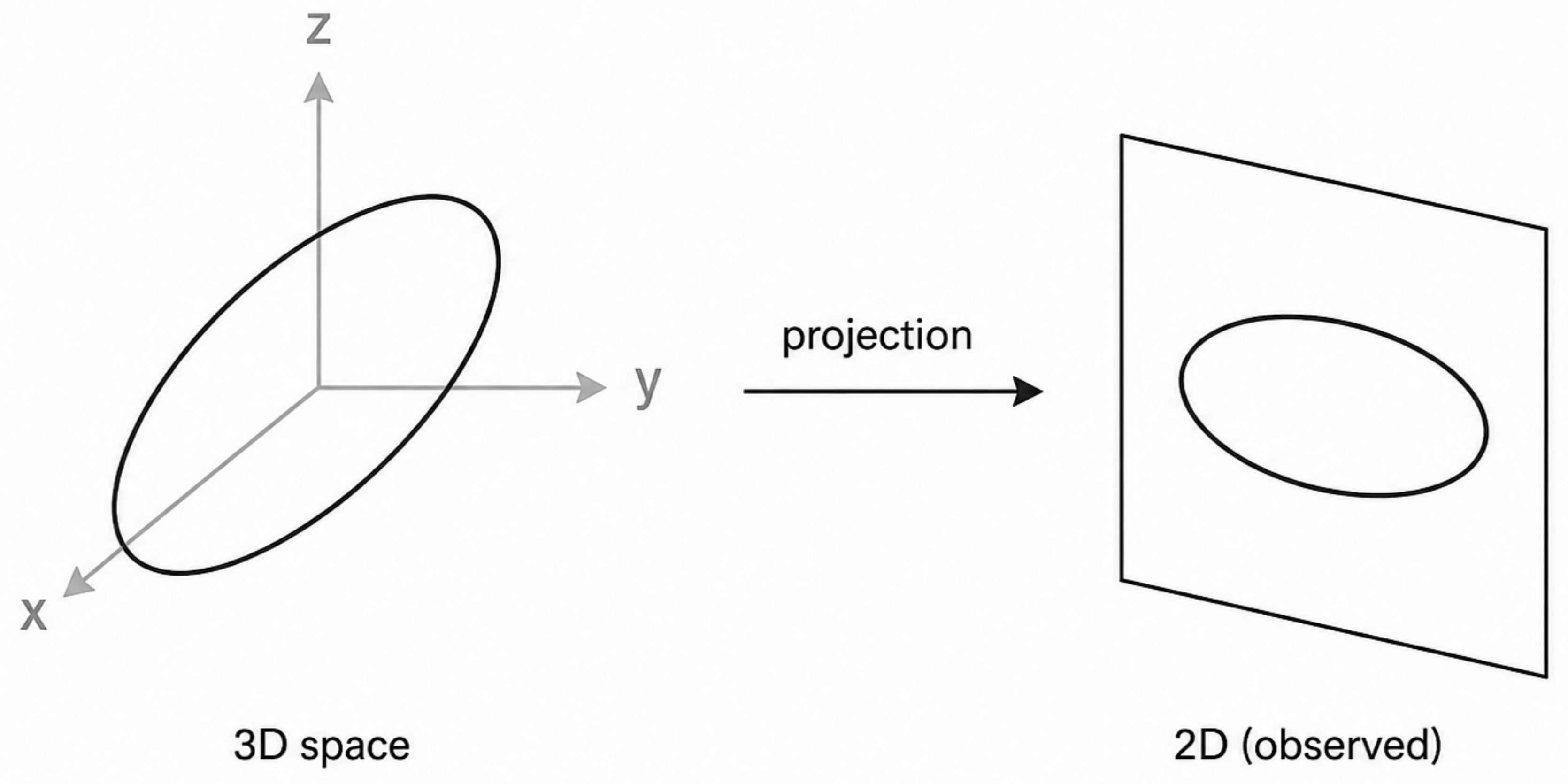
- 4 operators relevant at tree-level, which can all be relevant
- **Models we use are a subset of this tree-level EFT**
  - NLA: Assume only b_K, expand matter-field to all orders
  - EFT - no VS/TATT: velocity shear set to 0
  - EFT - LLB, using co-evolutions relations based on linear Lagrangian bias

Akitsu et al (2023)

$$b_{KK} = -b_K,$$
$$b_{\delta K} = (b_1 - \frac{2}{3})b_K,$$
$$b_t = \frac{5}{2}b_K.$$

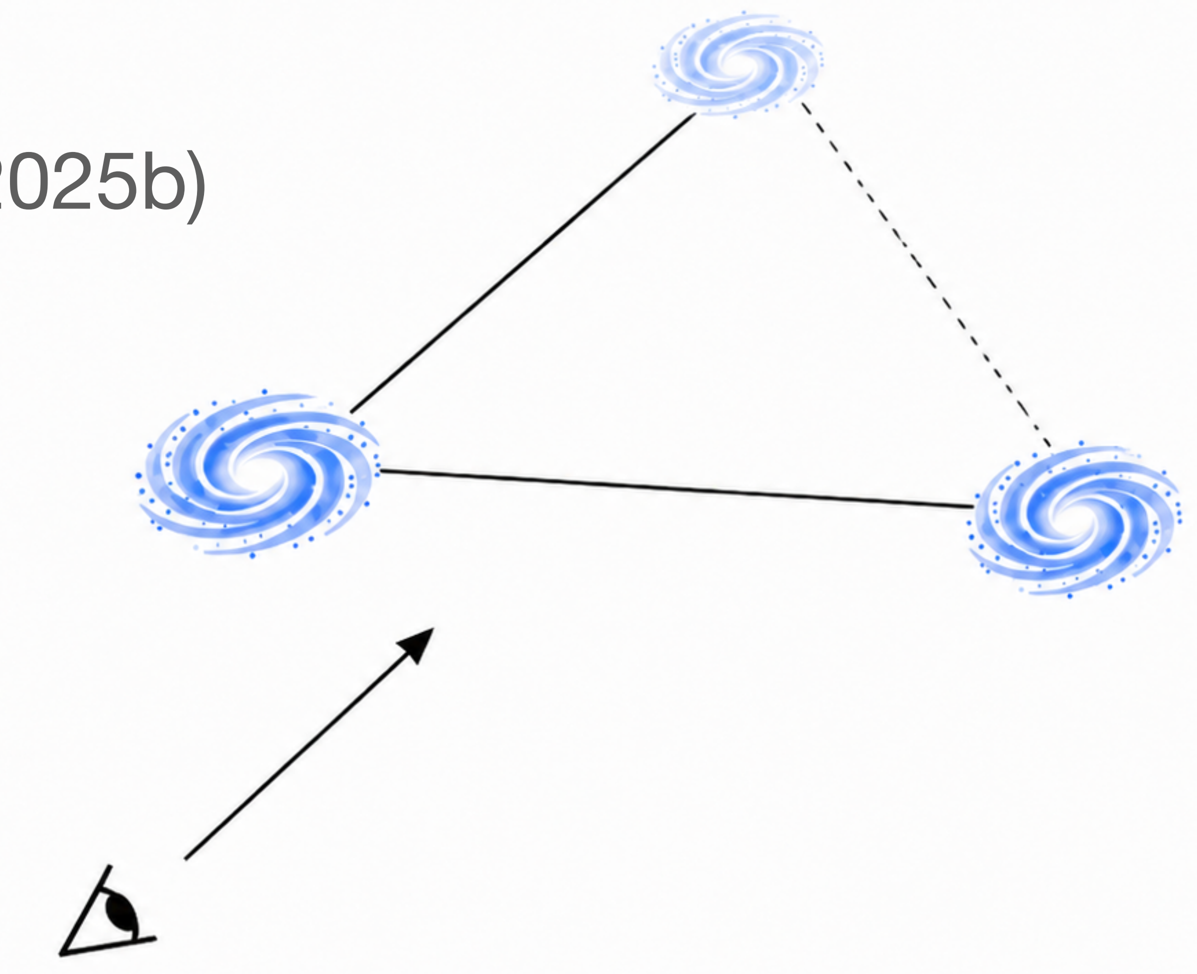
$$g_{ij} \approx b_K K_{ij} + b_{\delta K}\delta K_{ij} + b_{KK}\mathrm{TF}\left(K^2\right)_{ij} + b_t t_{ij} + \ldots,$$

Projecting the shapes to the plane

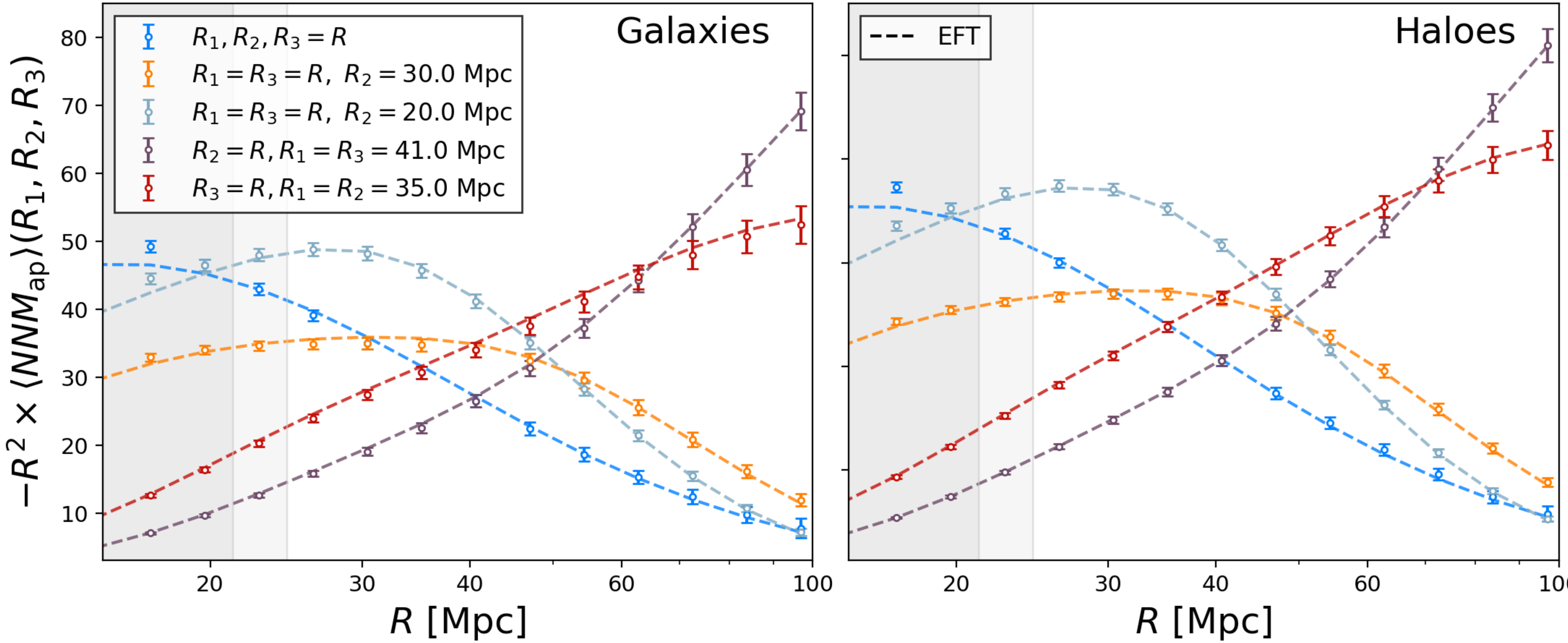


- 3D shapes need to be projected to E and B modes
  - $B_{\delta\delta g} \sim \langle \delta\delta g_{ij} \rangle \rightarrow B_{\delta\delta E} \sim \langle \delta\delta \epsilon_E \rangle \rightarrow \langle NNM_{\rm ap} \rangle$
- Triangle depends on 5 variables, 3 k's and 2 angles for the line of sight dependence

Bakx et al (2025a, 2025b)



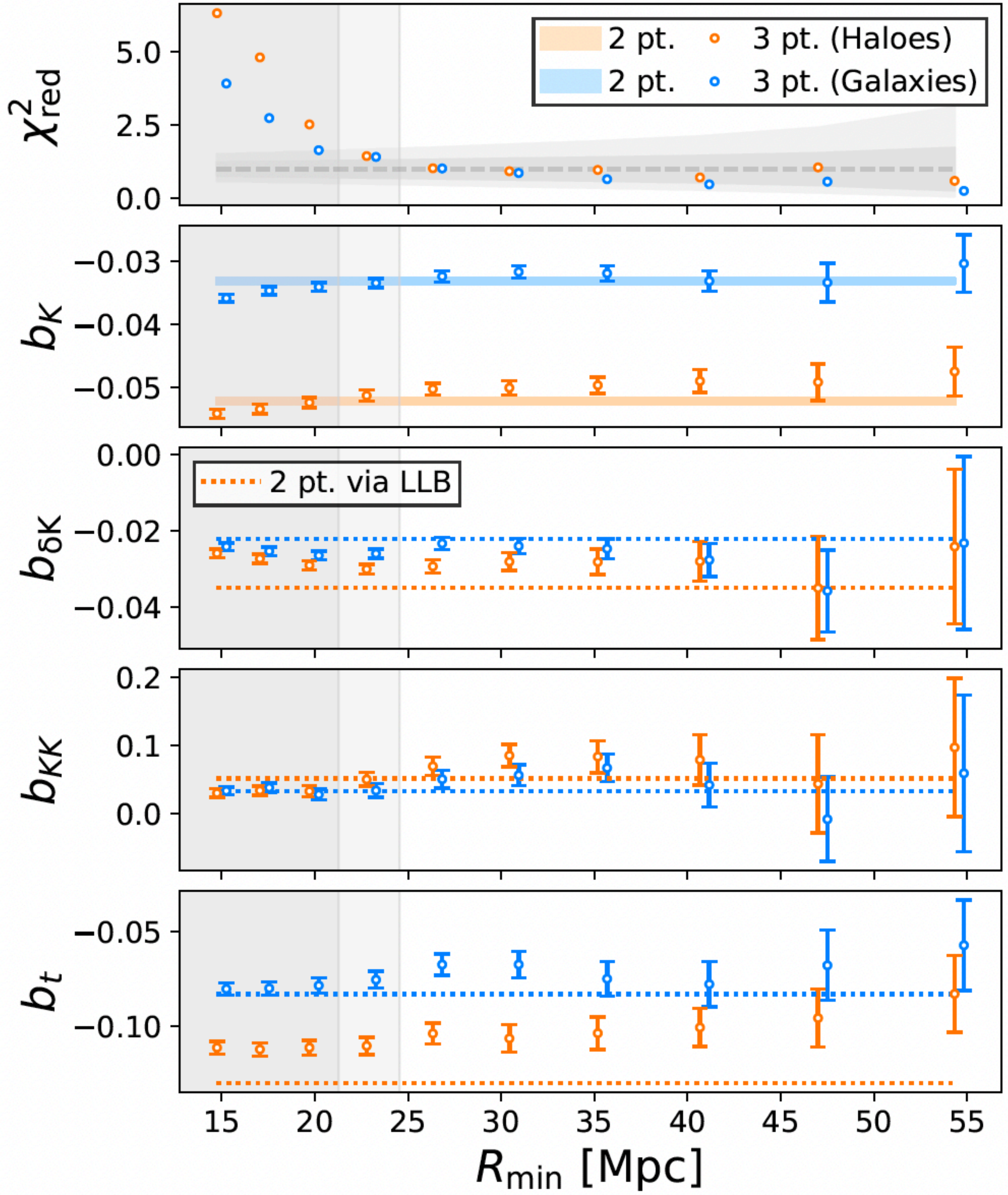
EFT vs data (1)



- Correlate shapes with matter instead of galaxies position to avoid galaxy biasing
- Unequal aperture scale add information and are needed to break degeneracies

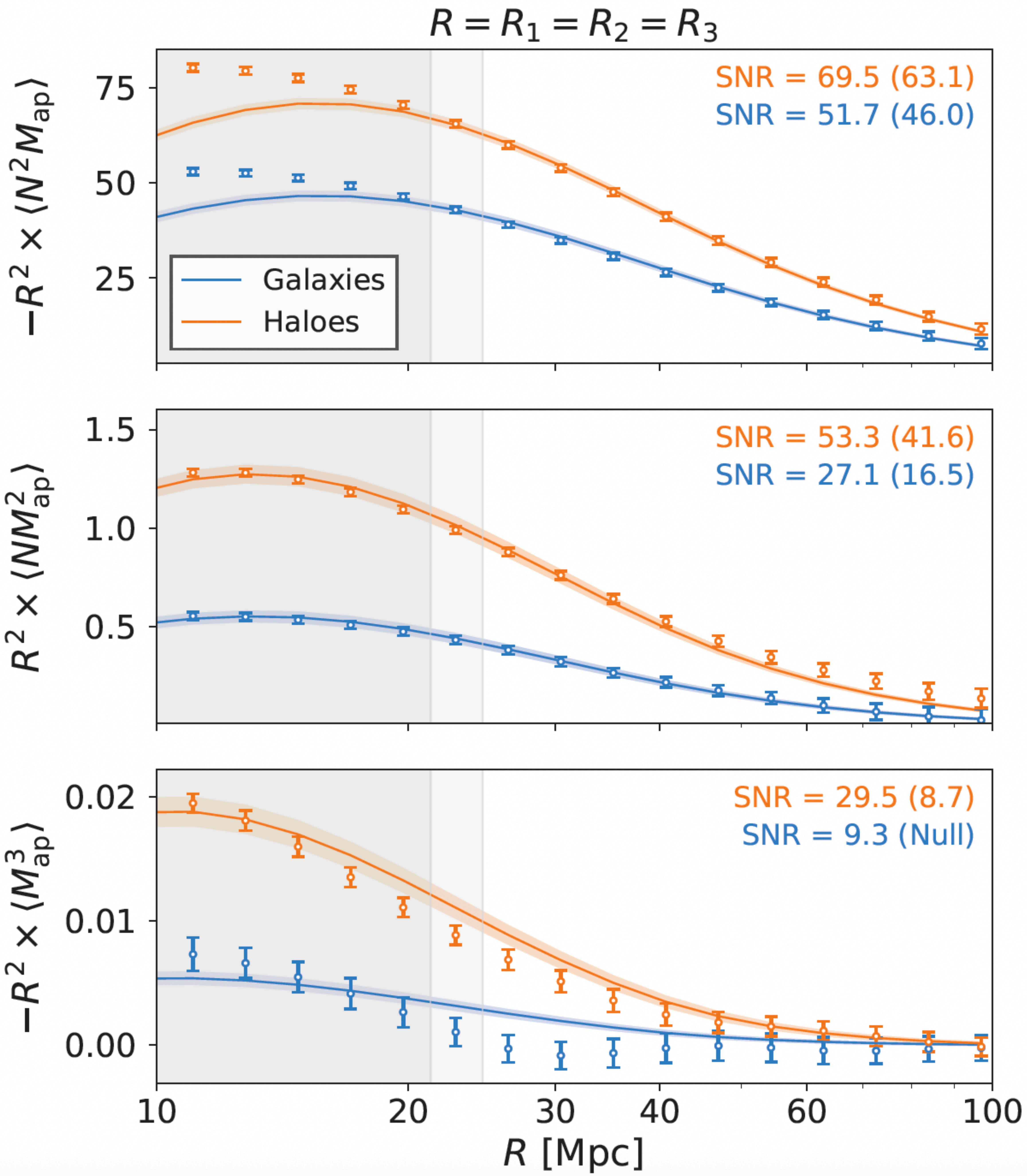
EFT vs data (2)

- All parameters are detected at several sigma
- EFT fits the data well until 22 Mpc
- Matches large scale 2 pt. b_K
- Co-evolution relations capture general trends



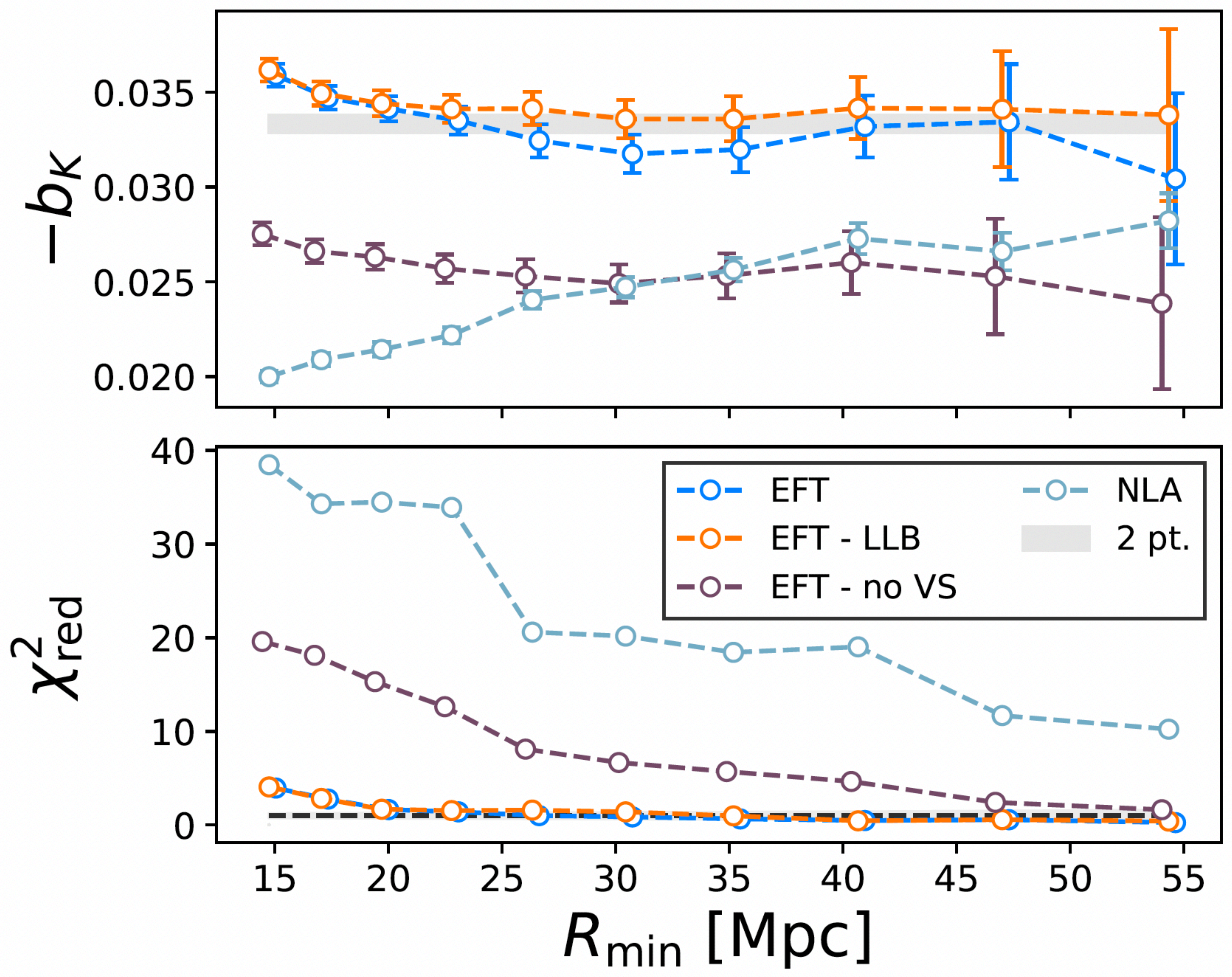
EFT vs data (3)

- Best fitting $\langle NNM_{\rm ap} \rangle$ parameters consistent with $\langle NM_{\rm ap}^2 \rangle$ and $\langle M_{\rm ap}^3 \rangle$



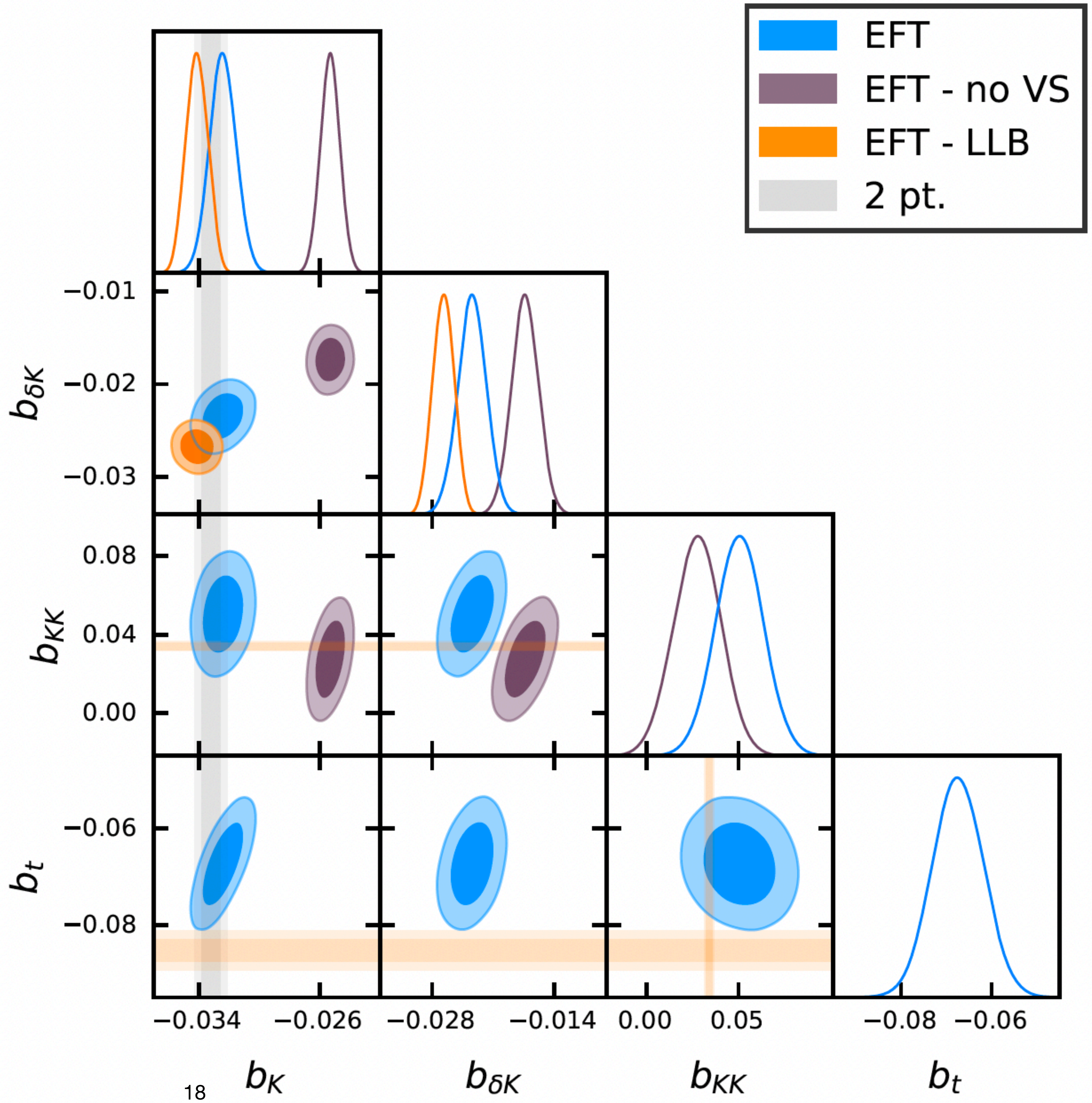
Model comparison

- All parameters relevant
  - **Also at large scales**
- Co-evolution gives a similar fit to data!

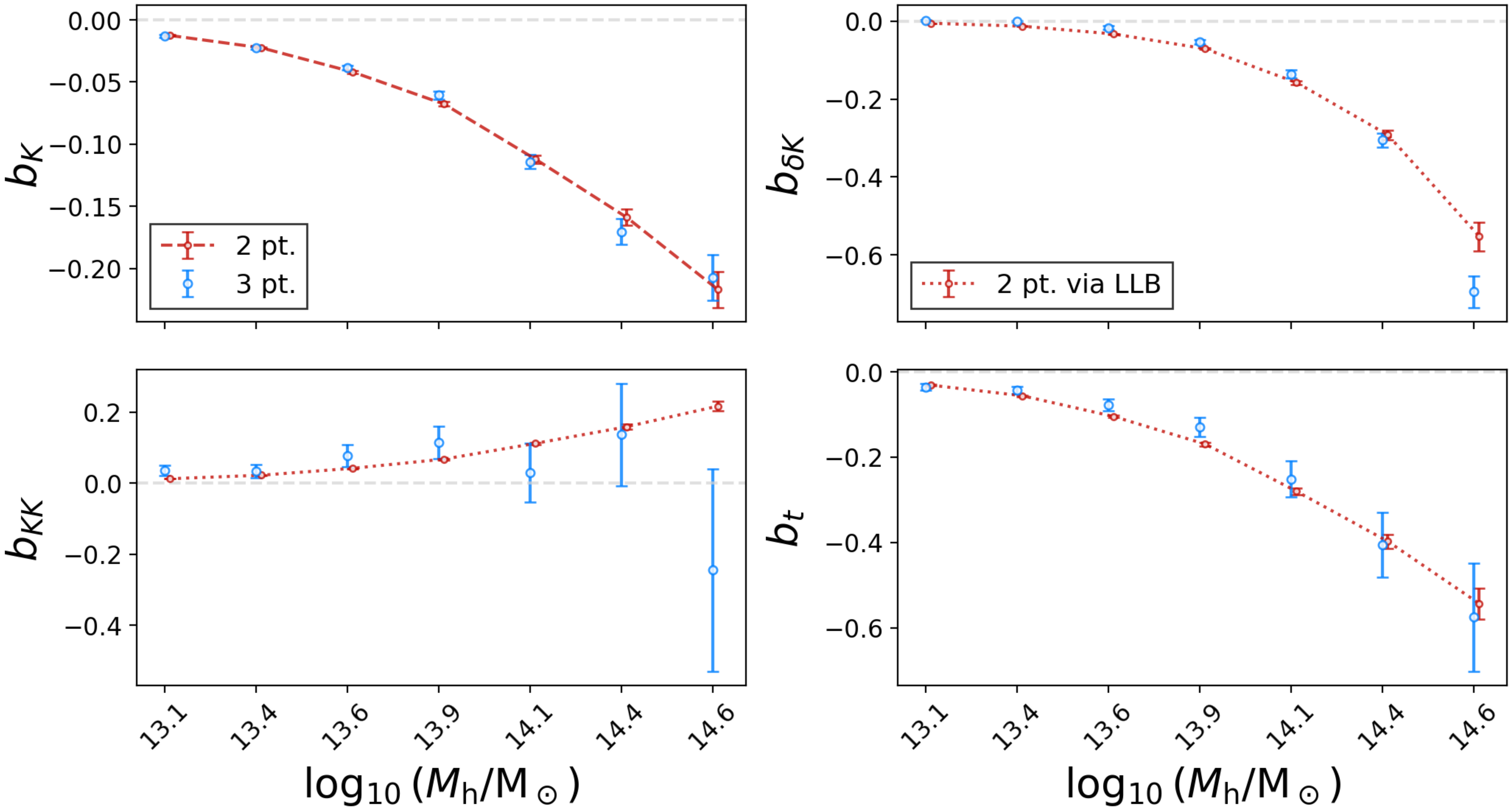


Contours

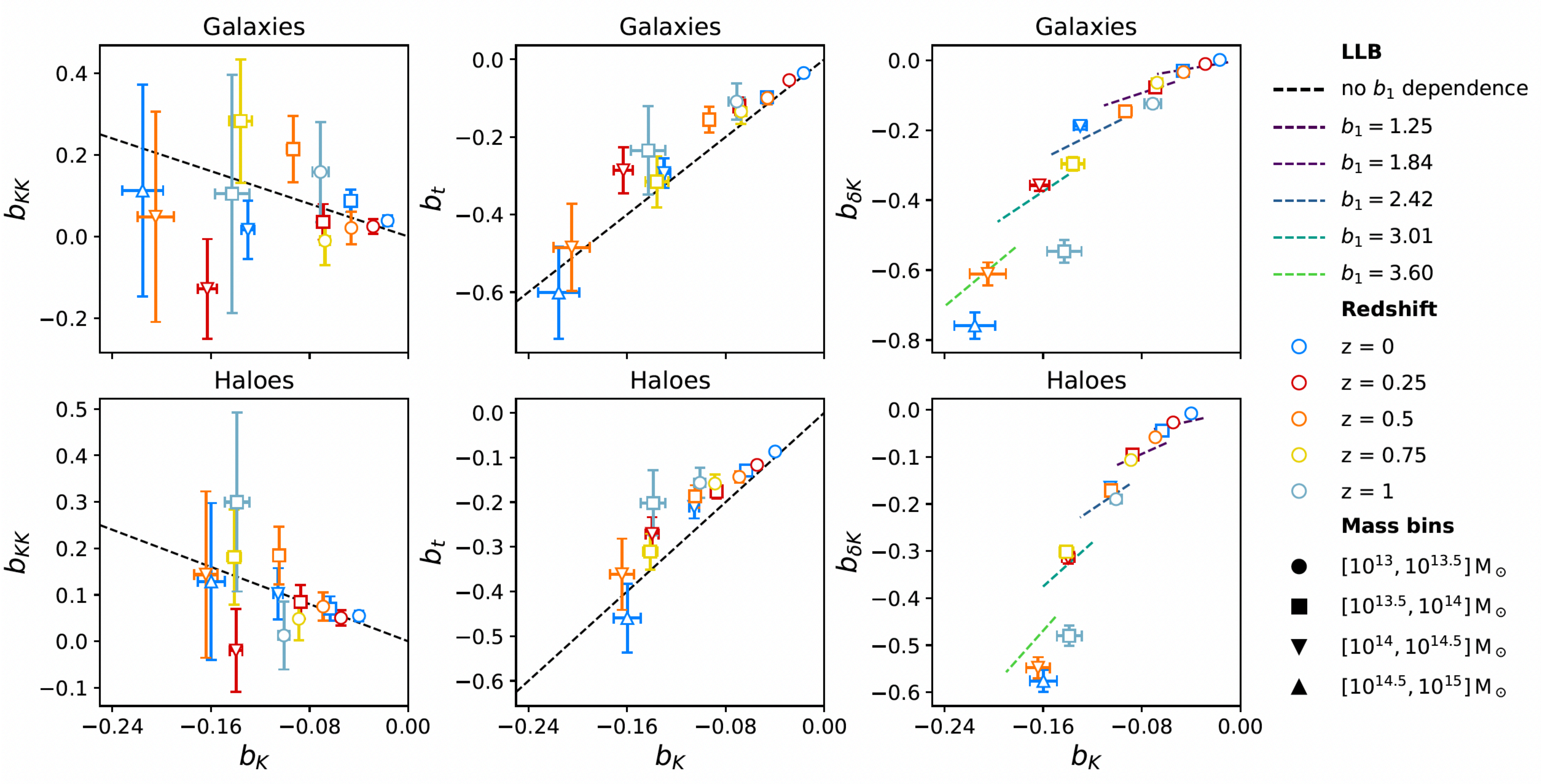
- Omission of velocity shear especially biasing to the results
- Forms a pair with b_K
    - if one goes up, the other goes down



Mass - scaling and co-evolution



Co-evolution relations across mass and redshift



*echoIA workshop in Utrecht on IA, Aug 31–Sep 4, https://echo-ia.github.io/UtrechtIA/

Conclusions

- 3-pt IA of FLAMINGO galaxies can be accurately described using the EFT of IA, yielding consistent results
- Fixing parameters to co-evolutions reduces the parameter space without significant biases: likely a good option for lensing mitigations
- Neglecting parameters can lead to **significant biases** with respect to 2-pt.
    - Also a **cautionary tale** for higher order stats in general!

Open questions

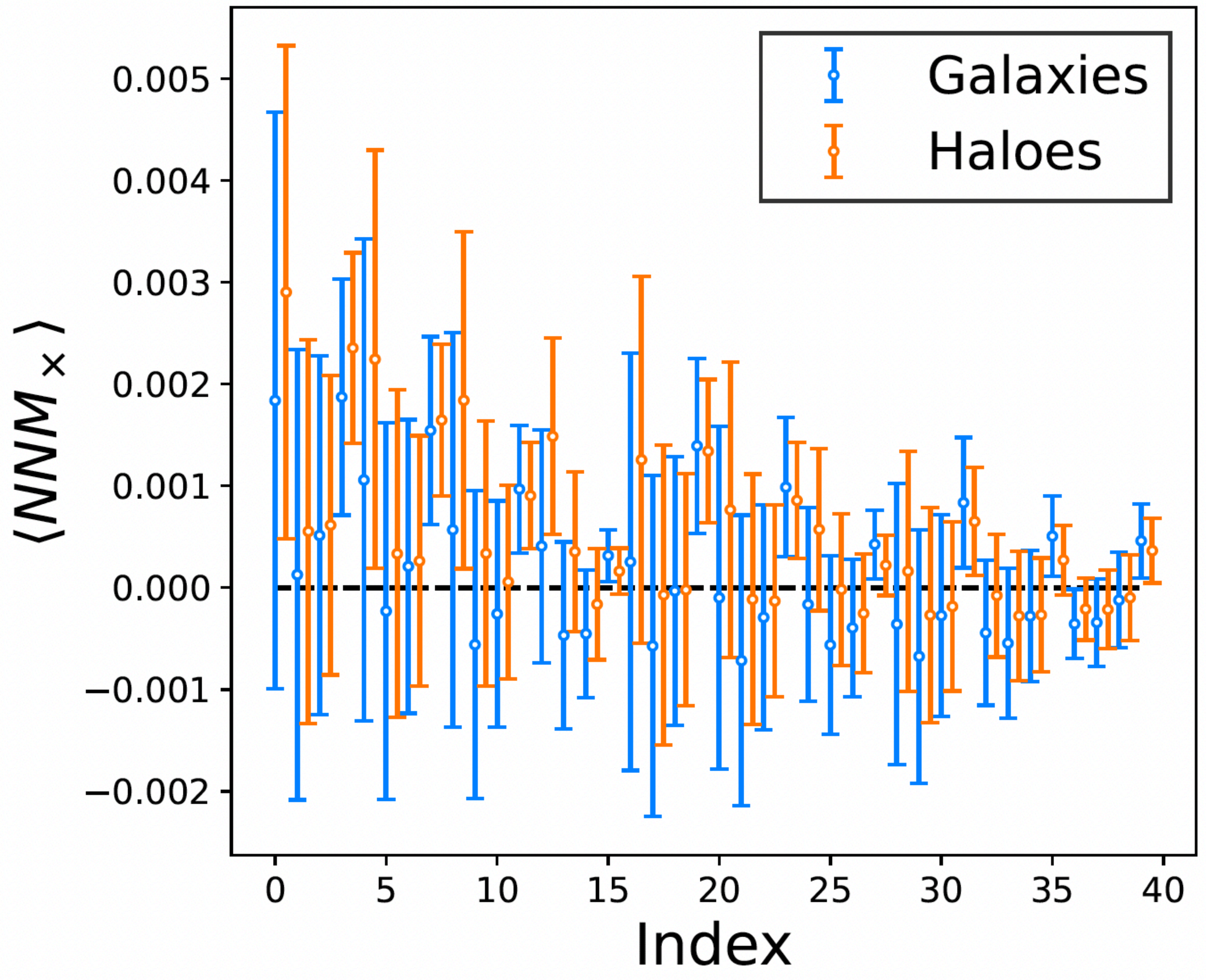
- Can we push to **smaller scales**?
- How does this affect **cosmological inference** at stage IV? (Some work already by Gomes et al, 2026)
- Plenty more! (Redshift dependence, interplay with other systematics, …)

Extra slides

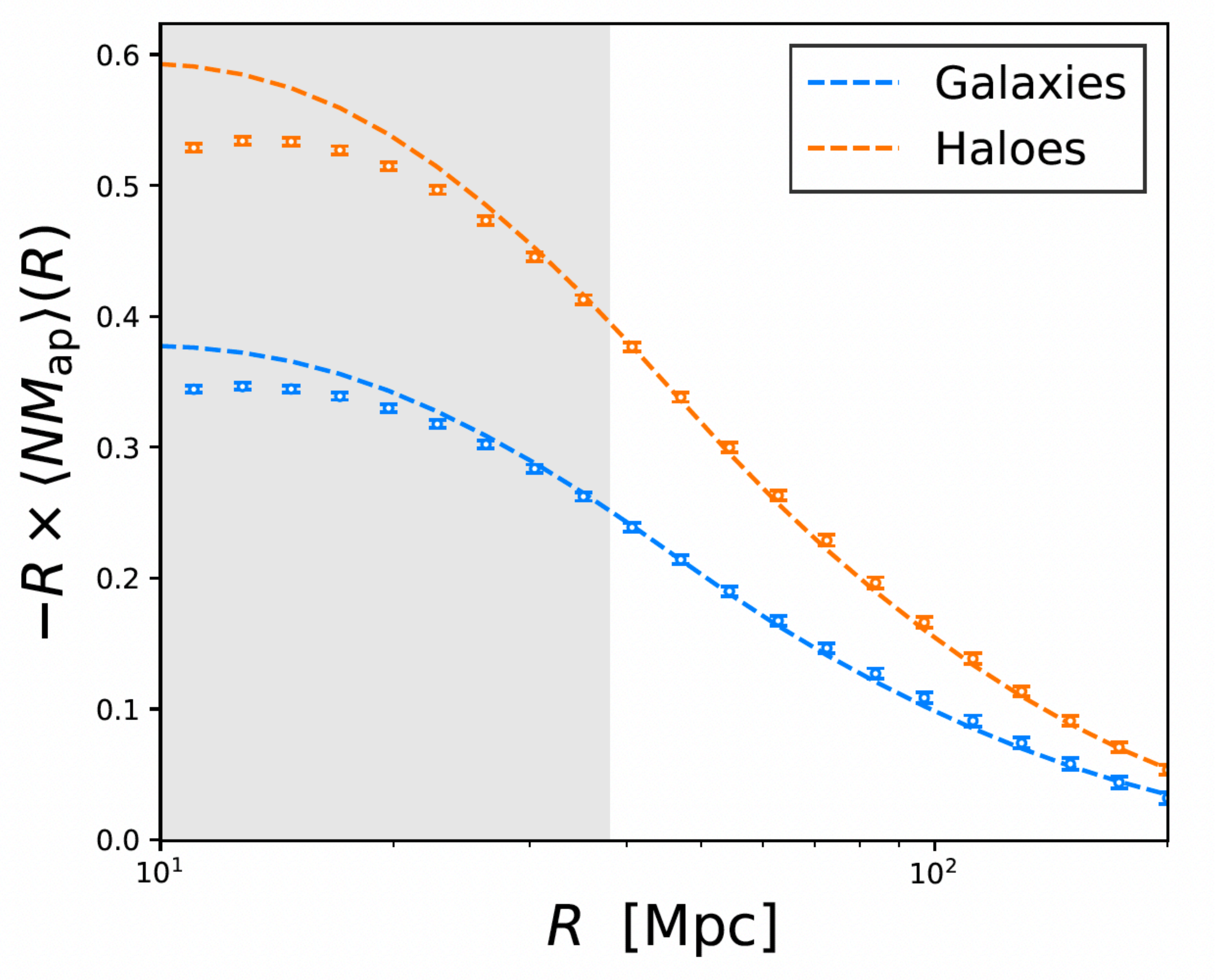
B-modes

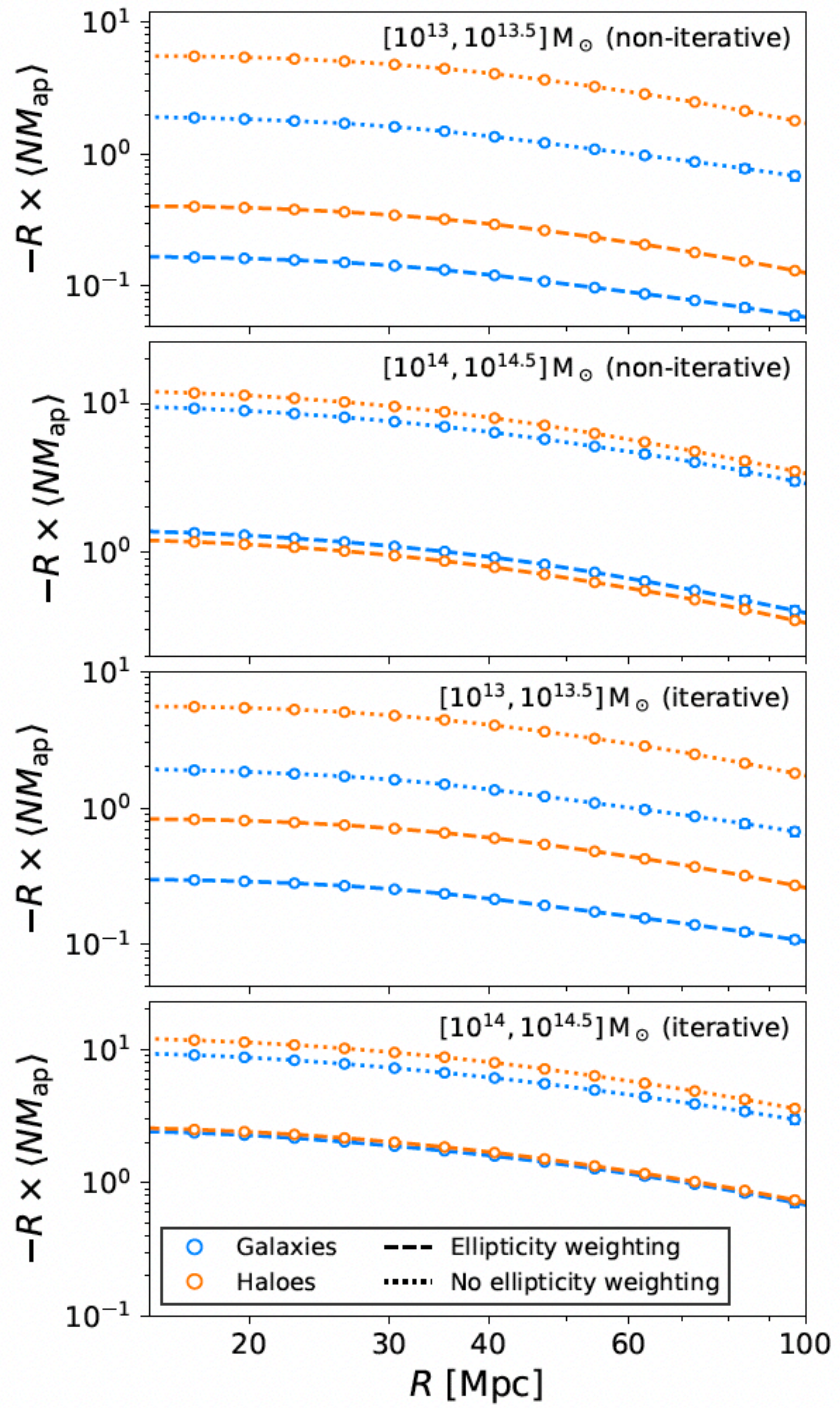
- $\langle NNM_\times \rangle$ vanishes by construction due to angular averaging

$$\langle NNM_\times \rangle = \frac{1}{(2\pi)^5} \int_0^\infty k_\perp^{(1)}\, \mathrm{d}k_\perp^{(1)} \int_0^\infty k_\perp^{(2)}\, \mathrm{d}k_\perp^{(2)} \times \int_{-\infty}^{\infty} \mathrm{d}k_\parallel^{(1)} \int_{-\infty}^{\infty} \mathrm{d}k_\parallel^{(2)} \boxed{\int_0^{2\pi} \mathrm{d}\phi}\; \tilde{W}_\Pi(k_\parallel^{(1)})\, \tilde{W}_\Pi(k_\parallel^{(2)}) \times \tilde{U}_{R_1}(k_\perp^{(1)})\, \tilde{U}_{R_2}(k_\perp^{(2)})\, \tilde{U}_{R_3}(||\mathbf{k}_\perp^{(1)} + \mathbf{k}_\perp^{(2)}||) \boxed{\times B_{\delta\delta B}\left(k_\perp^{(1)}, k_\perp^{(2)}, k_\parallel^{(1)}, k_\parallel^{(2)}, \phi\right),}$$

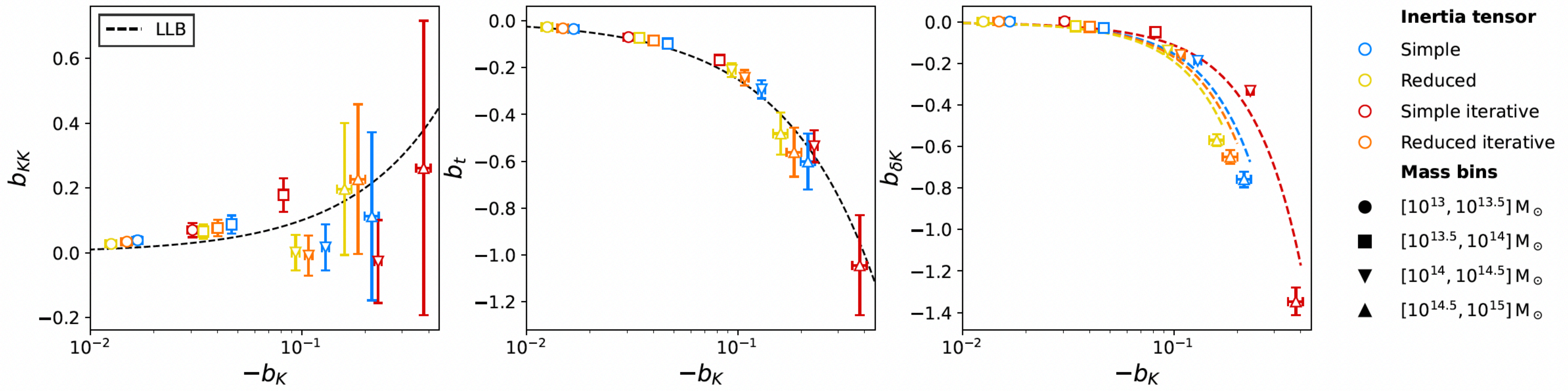


2-pt. Measurements





Dependence on inertia tensor



Projections