Modelling intrinsic alignments
in the Stage IV era

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Perspectives on LSS
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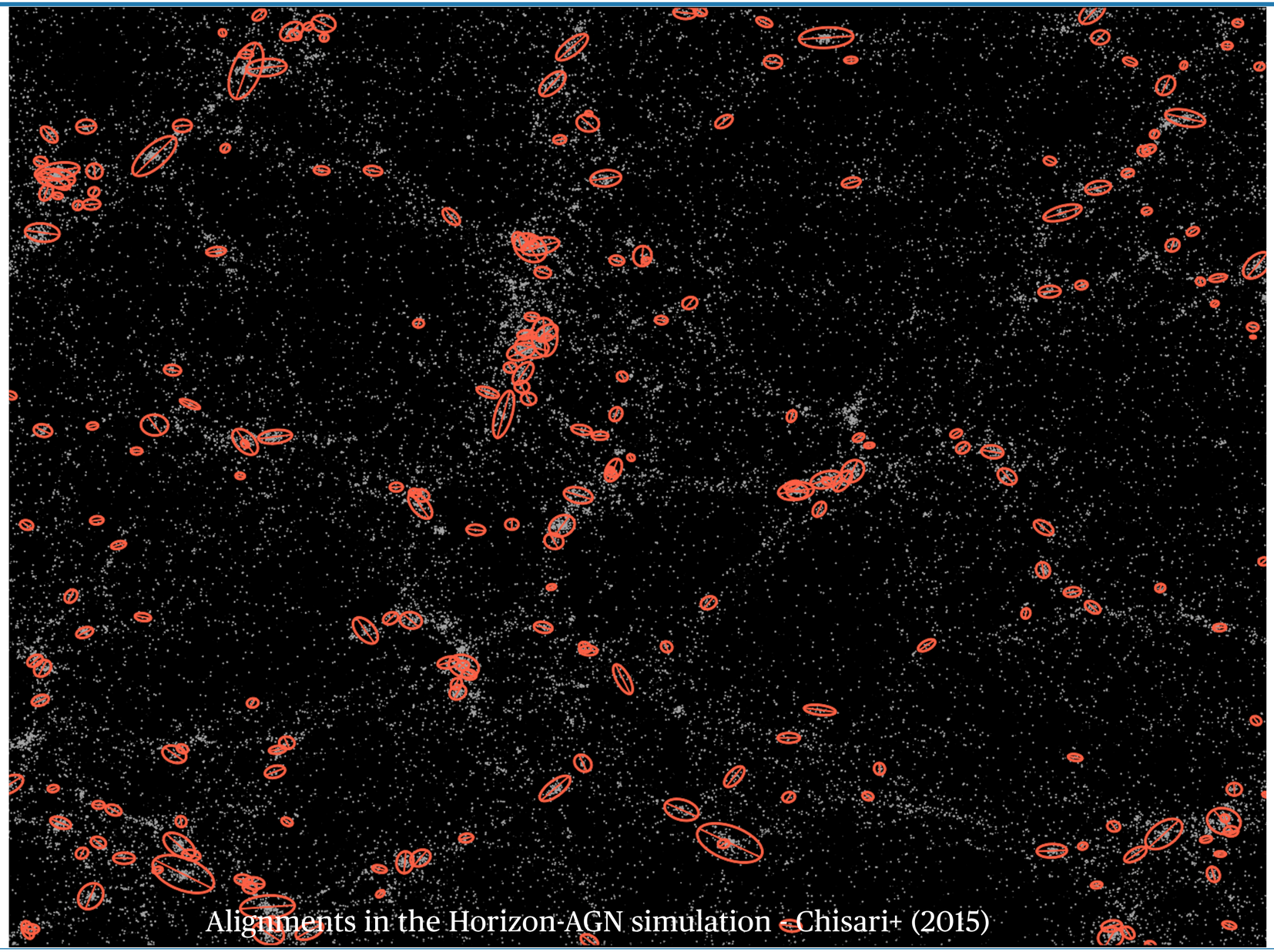
NWO

Universiteit Utrecht

Delta Institute for Theoretical Physics

Intrinsic galaxy alignments



Alignments in the Horizon-AGN simulation - Chisari+ (2015)

Modelling intrinsic alignments in the Stage IV era

1. **Weak lensing contamination**
2. **Clustering contamination**
3. **Modelling options (analytical)**
4. **Physics from intrinsic alignments**

Model-agnostic? *Self-calibration*

Exploits symmetry of IA behind and in front of the lens to remove contaminant.

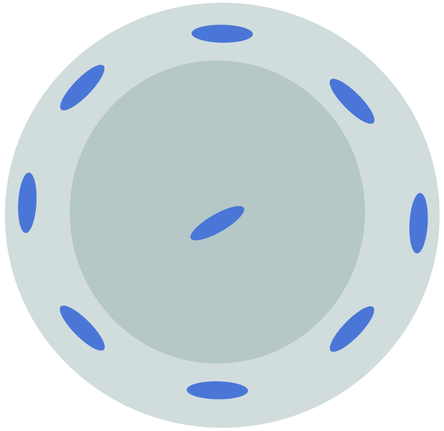
Zhang (2010), Yao+ (2019,2020a,2020b), Pedersen+ (2020)

Simulations of IA?

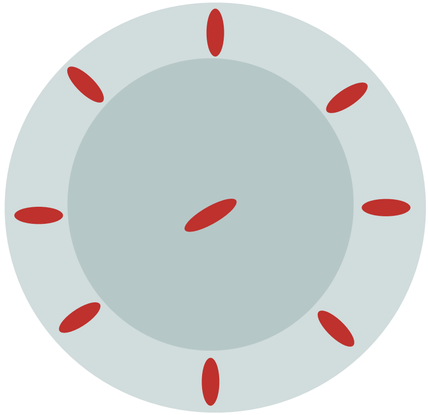
Help us go **very nonlinear** and/or add **baryons** to get **priors** but some discrepancies for blue galaxies.

Tenneti+, Velliscig+, Chisari+, Samuroff+, Hilvert+, Zjupa+, Delgado+, and many others.

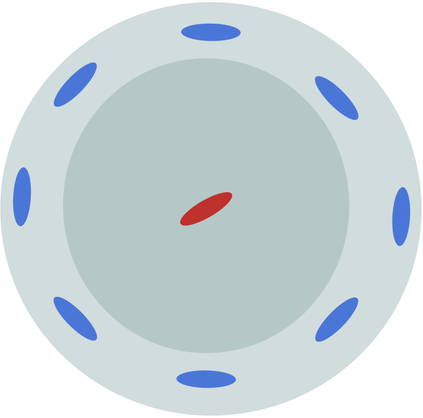
Weak lensing contamination



Gravitational lensing



Intrinsic alignments



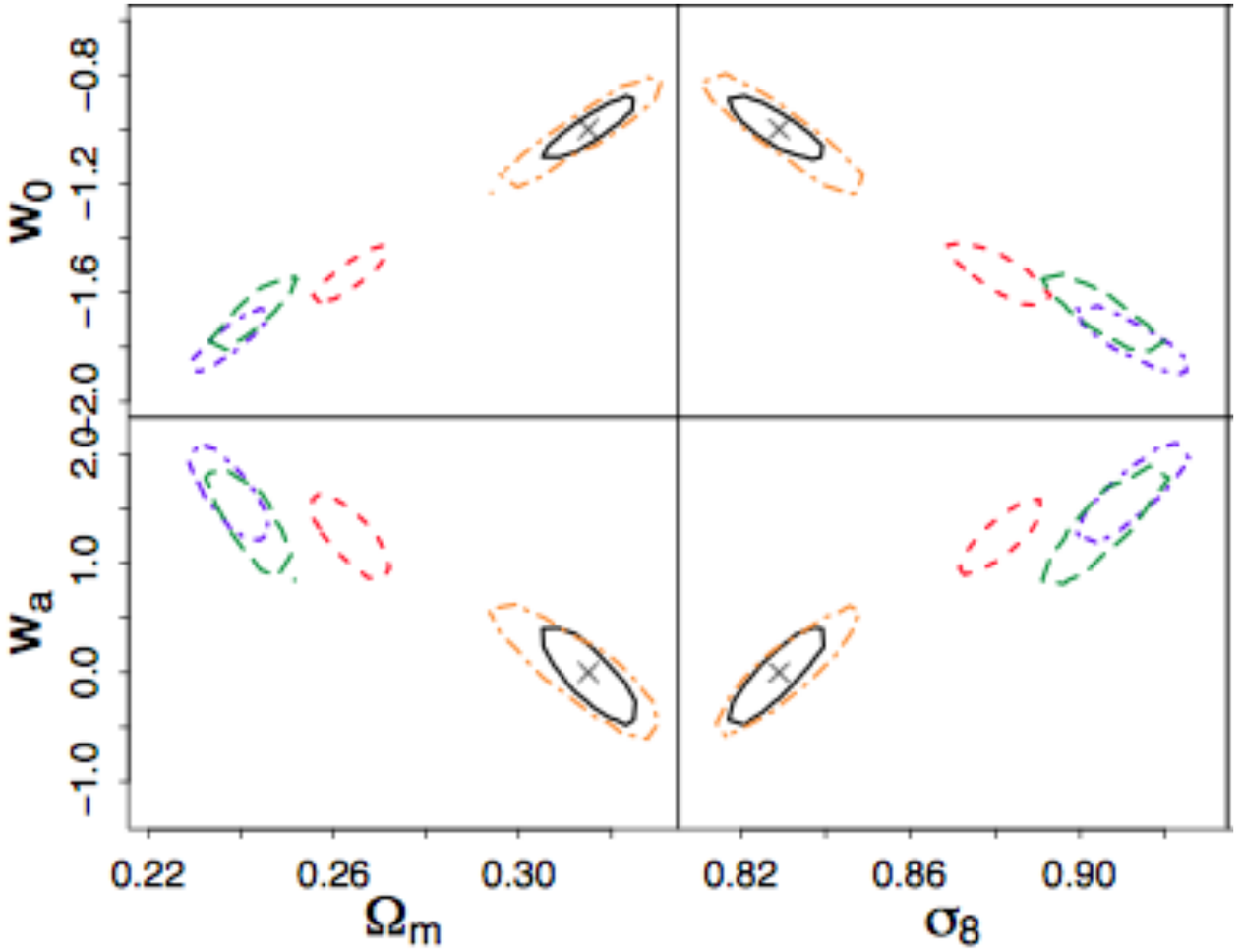
and their
cross-correlation

$$\xi_{++} \propto GG + GI + II + \text{Noise}$$

* degeneracies with photometric redshift quality

Weak lensing contamination

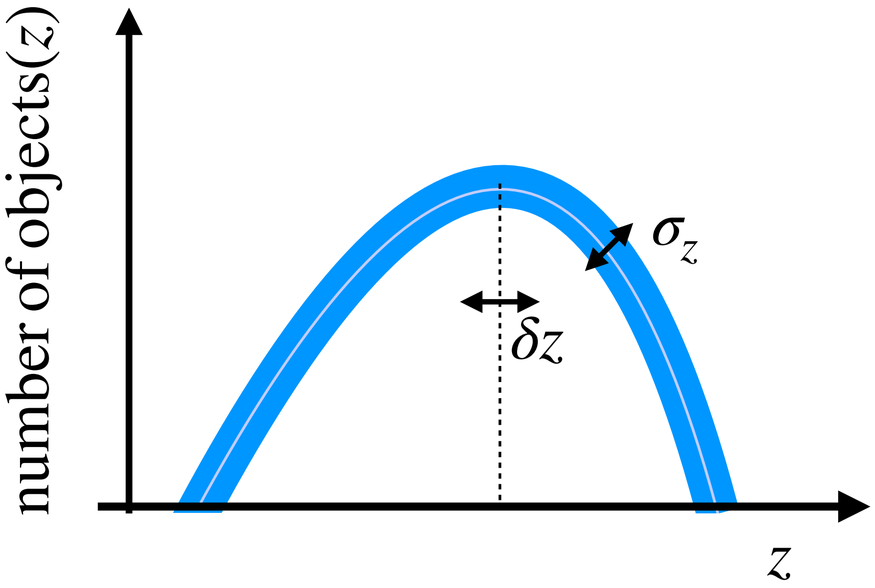
Bias induced by intrinsic alignments (LSST-like survey)

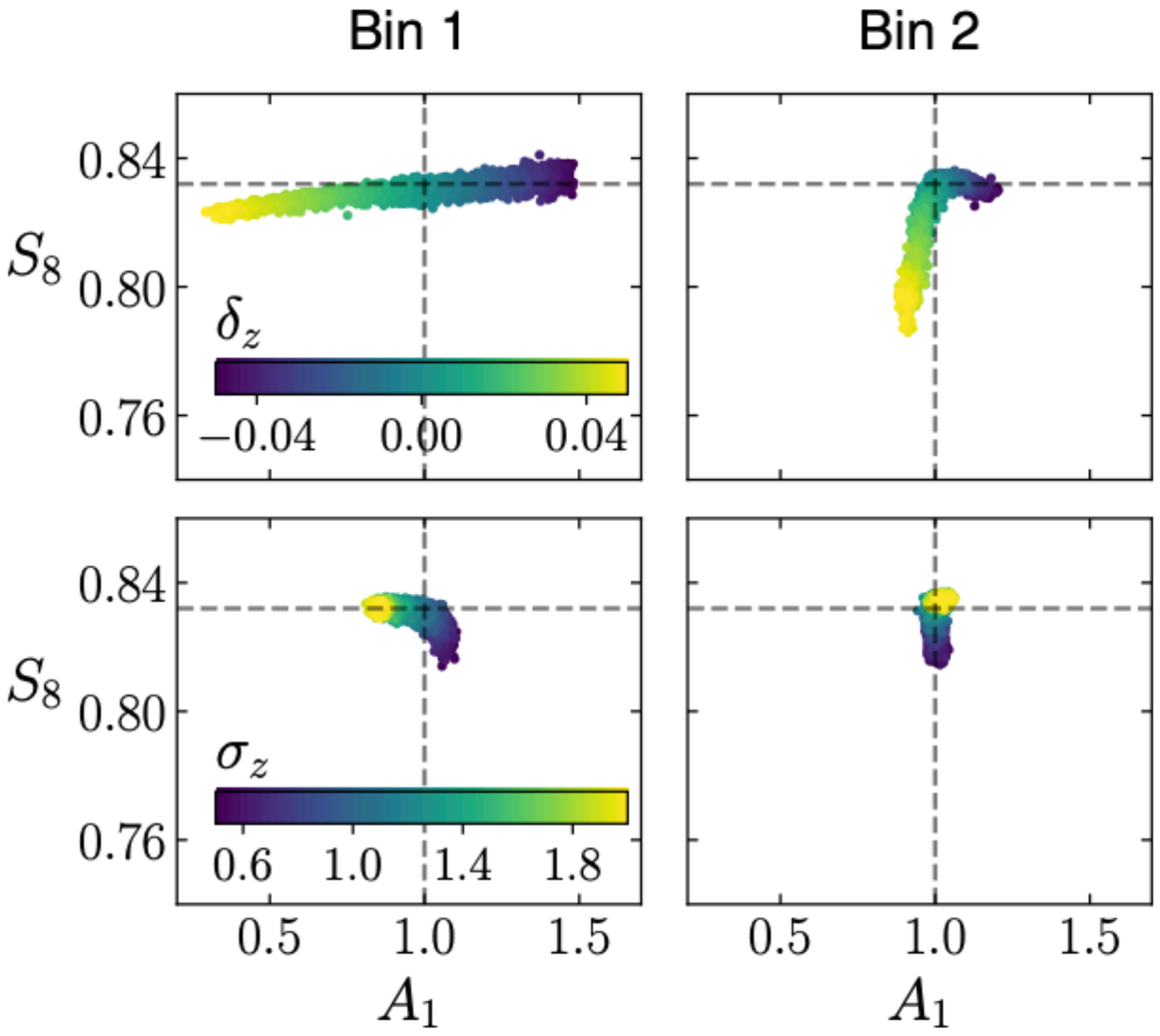


KRAUSE+ (2016)

Weak lensing contamination

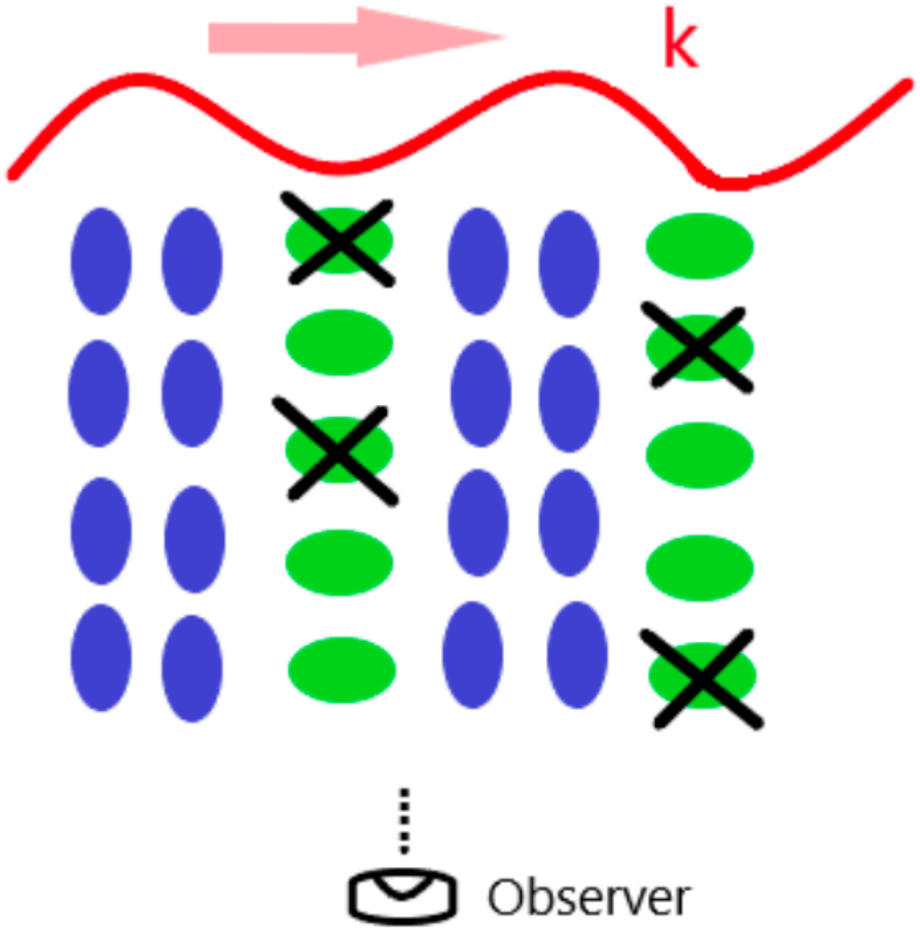
Photo-z uncertainty coupling





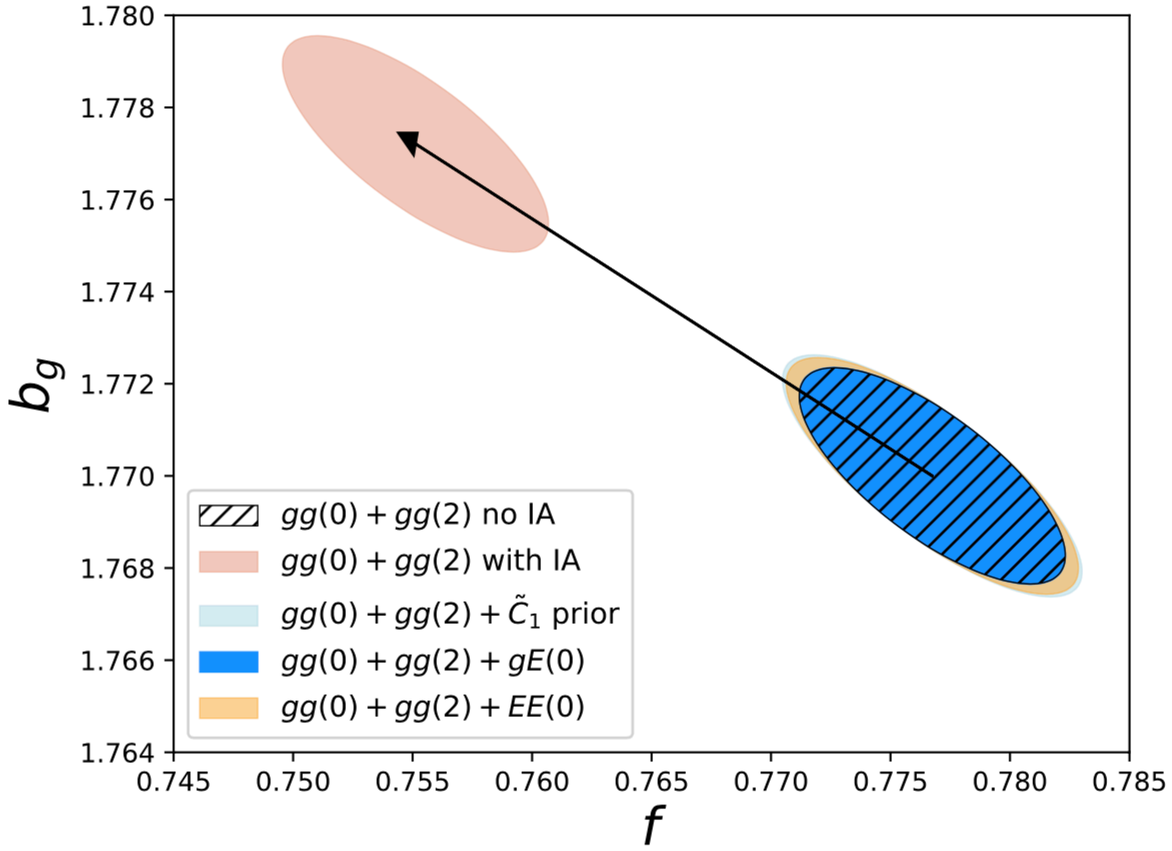
FISCHBACHER+ (2022)

Clustering contamination



HIRATA (2009), MARTENS+ (2018),
SINGH+ (2021), OBULJEN+ (2019)

LSST+spec (7,500 sq deg, LRG-like sample)



ZWETSLOOT & EC (2022, ARXIV:2208.07062)
SEE ALSO CHEN+ (2022)

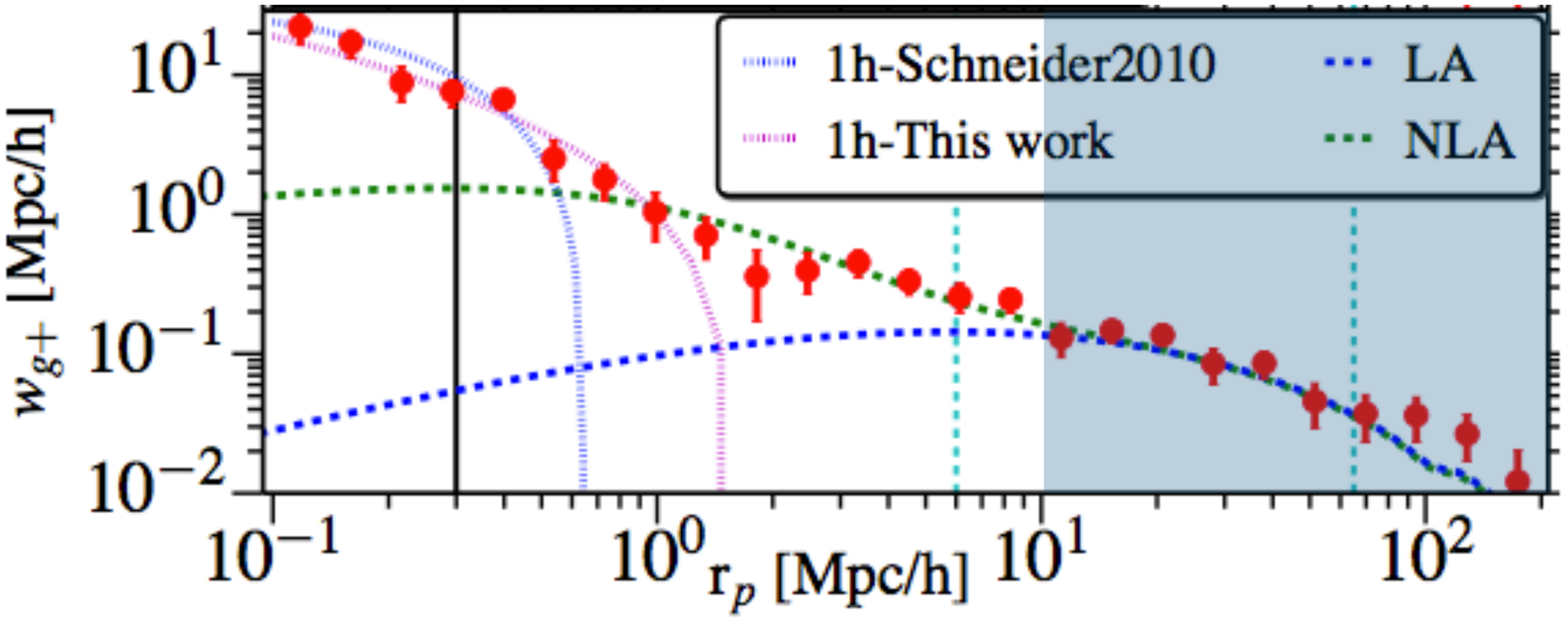
Linear modelling of intrinsic alignments

$$I \propto (\partial_x^2 - \partial_y^2)\Phi_p$$

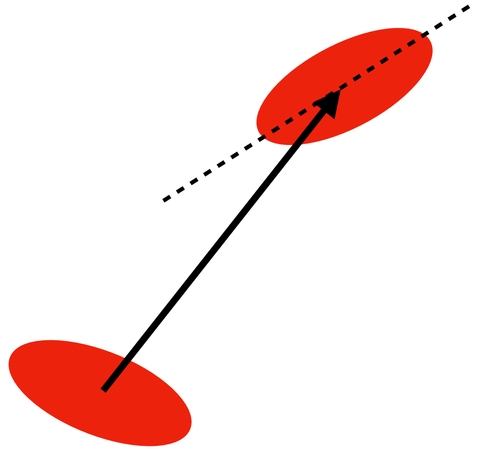
Projected shapes of galaxies $\propto$ Projected tidal field of matter in the Universe

CATELAN+ (2001)

* successful on linear scales
* sufficient for current data
* applies to ellipticals/red galaxies



SINGH+ (2015)



Linear modelling of intrinsic alignments

$$I \propto (\partial_x^2 - \partial_y^2)\Phi$$ *Instantaneous alignment* Catelan+ (2001)

vs. $$I \propto (\partial_x^2 - \partial_y^2)\Phi_p$$ *Primordial alignment* Hirata & Seljak (2004)

Instantaneous alignment is not enough

- Model (elliptical) galaxy as extended body $f_\star$
- Under the influence of external tides $U_{\rm ext}$
- Predict quadruple moments Q_{ij}
- Find instantaneous response $C_1 \ll C_1^{\rm obs}$

➡ *Formation & accretion play a role*

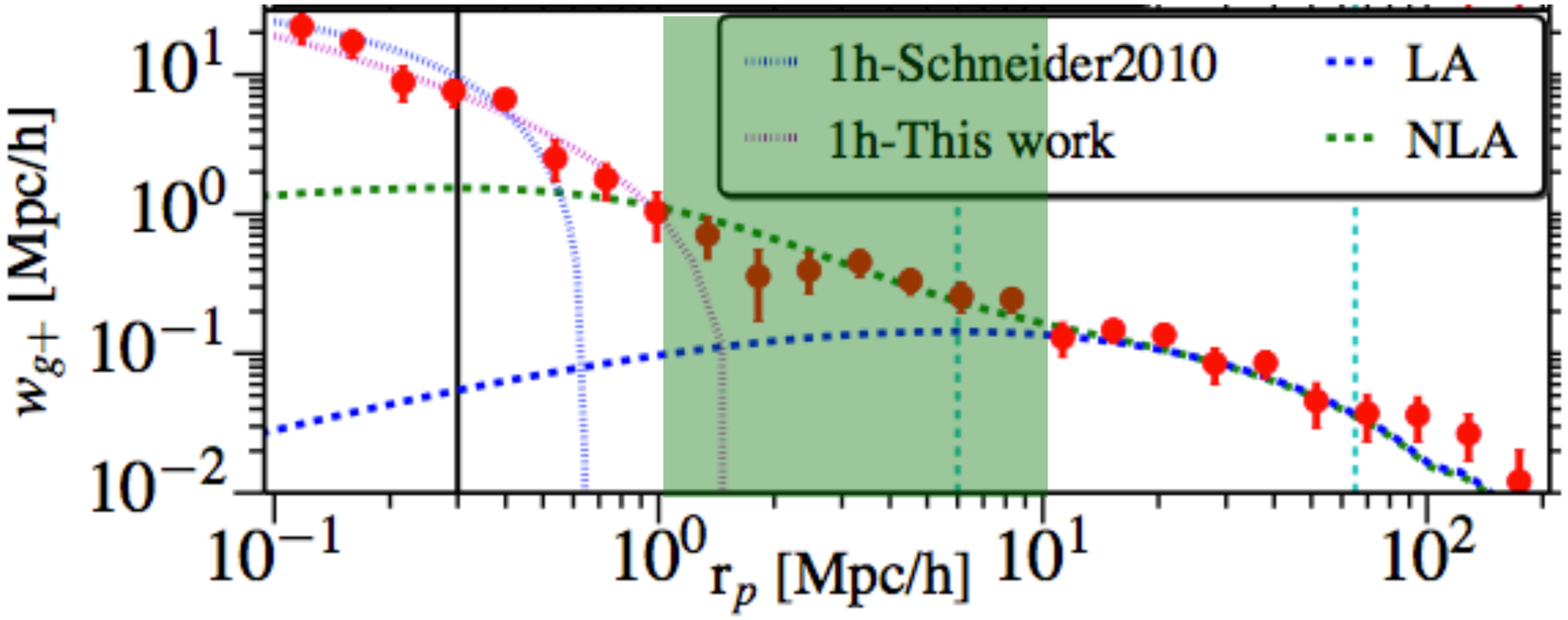
Camelio & Lombardi (2015)

Other modelling choices for intrinsic alignments

"NLA" **Empirical** recipe: replace any occurrence of $P_{\rm lin}(k,z)$ in linear alignment model by $P_{\rm NL}(k,z)$

BRIDLE & KING (2007)

* widely used in current surveys

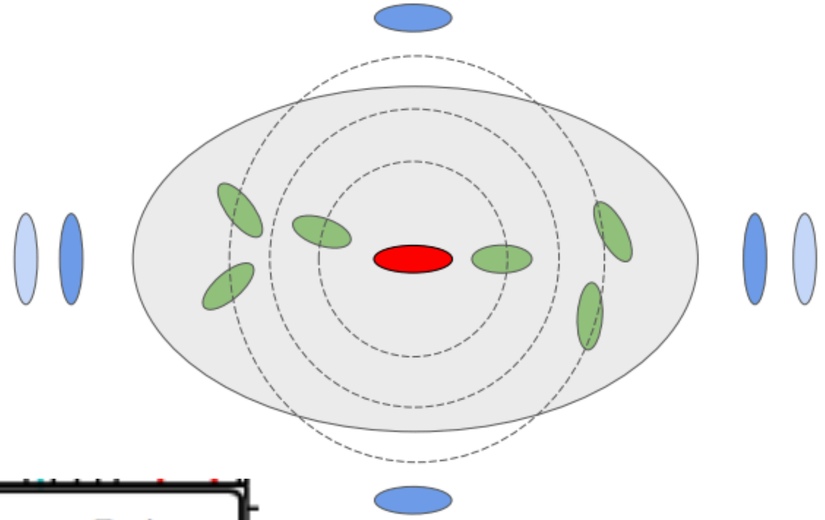


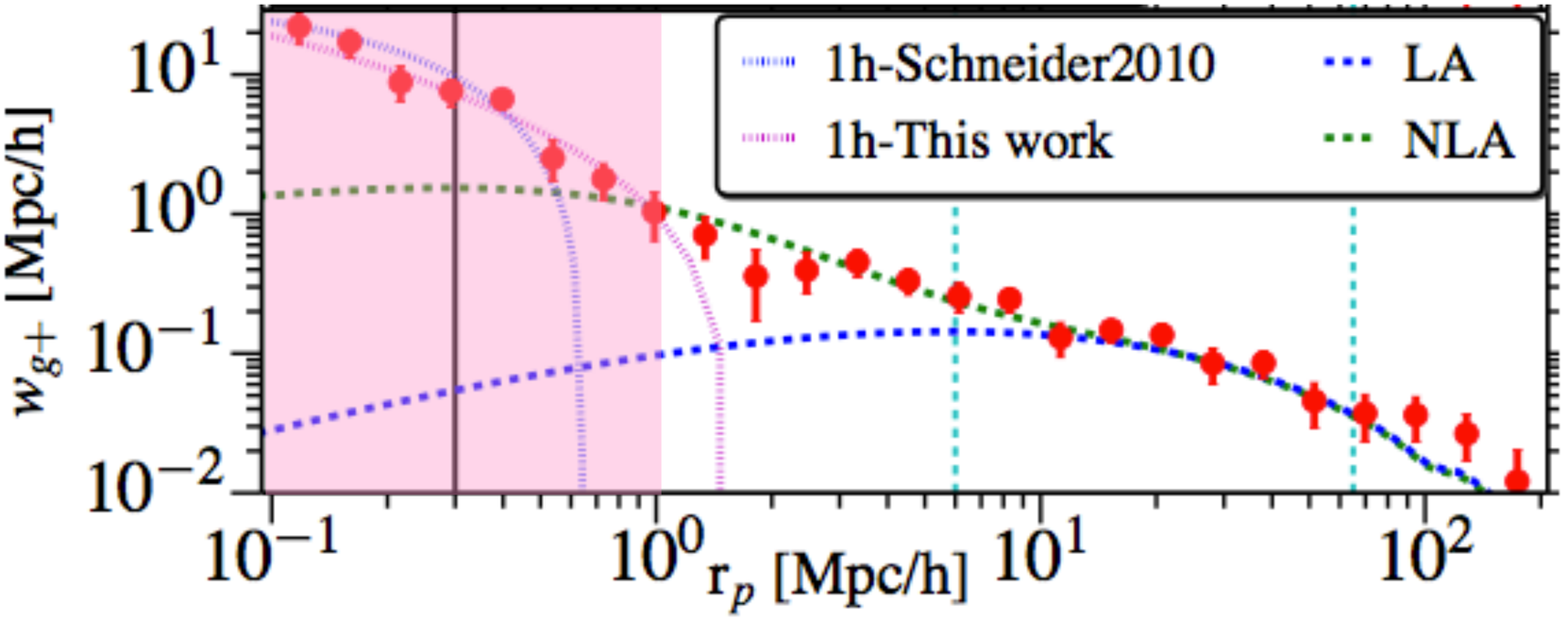
SINGH+ (2015)

Other modelling choices for intrinsic alignments

"halo model"

Galaxies live in **spherical** halos.
Intrinsic shapes **follow halo profile**
(+ additional radial/luminosity dependence from observations).





SINGH+ (2015)

SCHNEIDER & BRIDLE (2010)

FORTUNA+ (2021)

Other modelling choices for intrinsic alignments

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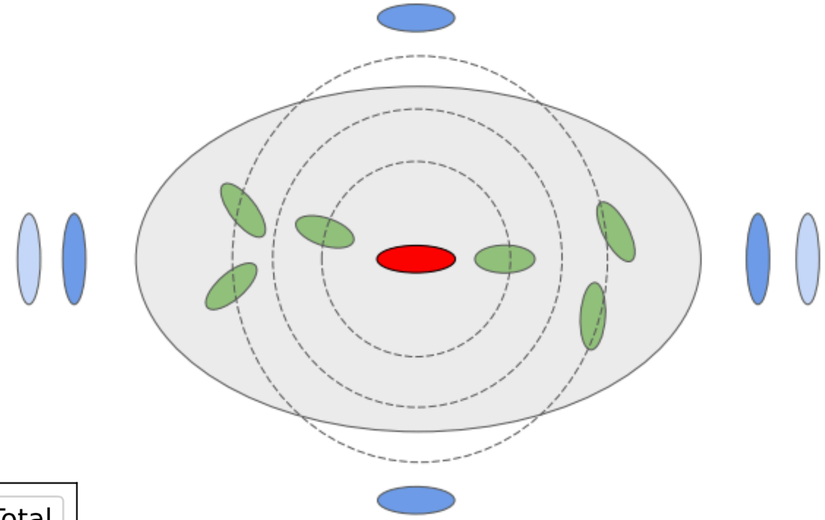
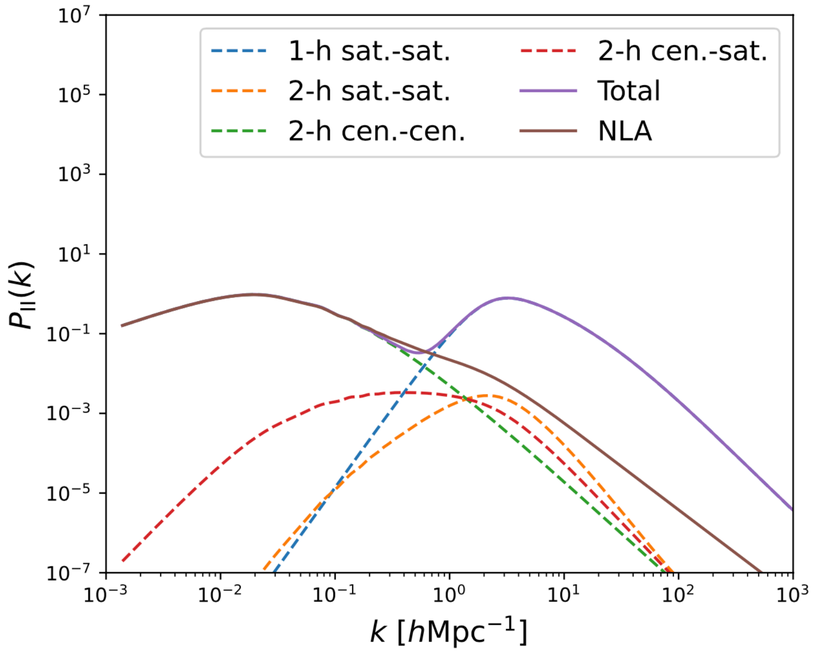
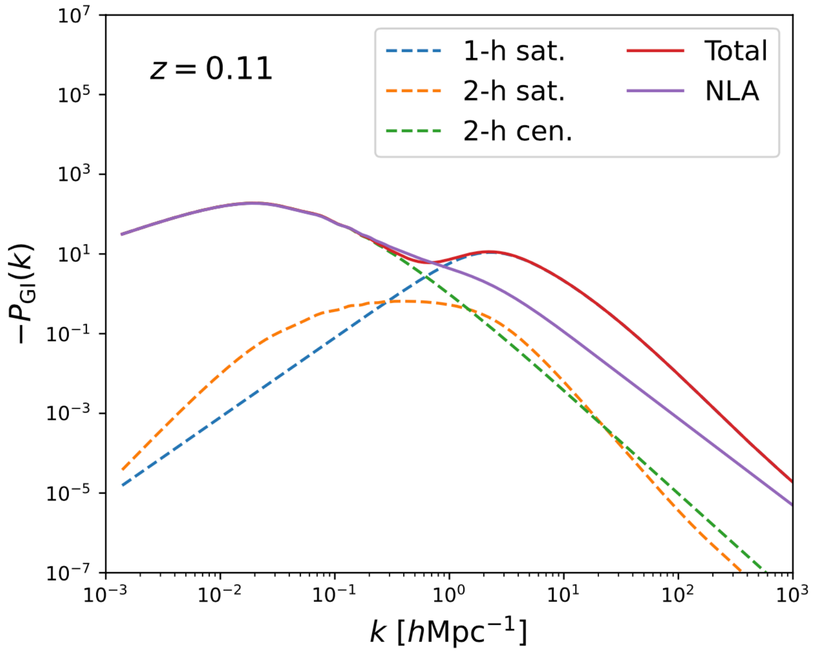






FORTUNA+ (2021)
GEORGIOU, VAN ZWOL, EC+- CCL IMPLEMENTATION

Other modelling choices for intrinsic alignments

"TATT" - STANDARD PERTURBATION THEORY AT ONE-LOOP

$$g_{ij}(\mathbf{x}) = C_1 T_{ij} + C_2 \left(T_{ij}T_{kj} - \frac{1}{3}\delta_{ij}T^2 \right) + C_{1\delta}(\delta T_{ij}) + C_t t_{ij} + \dots$$

write as many tensors consistent with GR

$$I_{E,B}(\mathbf{k}) = C_1 f_{(E,B)}(\hat{k})\delta(k) + C_{1\delta} \int \frac{d^3\mathbf{k}_1}{(2\pi)^3} f_{(E,B)}(\hat{k}_1)\delta(k_1)\delta(k_2) + \dots$$

project

$$\tilde{I}_{E,B} = (1 + \delta_g) I_{E,B}$$

weight

BLAZEK+ (2019), SCHMITZ+ (2018)

An EFT model for intrinsic alignments

$$g_{ij}(\mathbf{x}, z) = \sum_{\mathcal{O}} b_{\mathcal{O}}(z)\mathrm{TF}[\mathcal{O}_{ij}(\mathbf{x}, z)]$$

3D shapes of galaxies

Consistent way of building a complete basis of operators

write as many tensors consistent with GR

$$g_{ij}^{[\text{3rd order on } \delta]}(\mathbf{x}, z) = C_1 T_{ij}(\mathbf{x}, z) + C_{\delta T}(\delta K_{ij})(\mathbf{x}, z) + C_{K^2}\mathrm{TF}[(K_{ij})^2](\mathbf{x}, z) + \dots$$

$$I_{ij}(\mathbf{x}, z) = \mathcal{P}^{ijkl}(\hat{\mathbf{n}}) g_{ij}(\mathbf{x}, z)$$

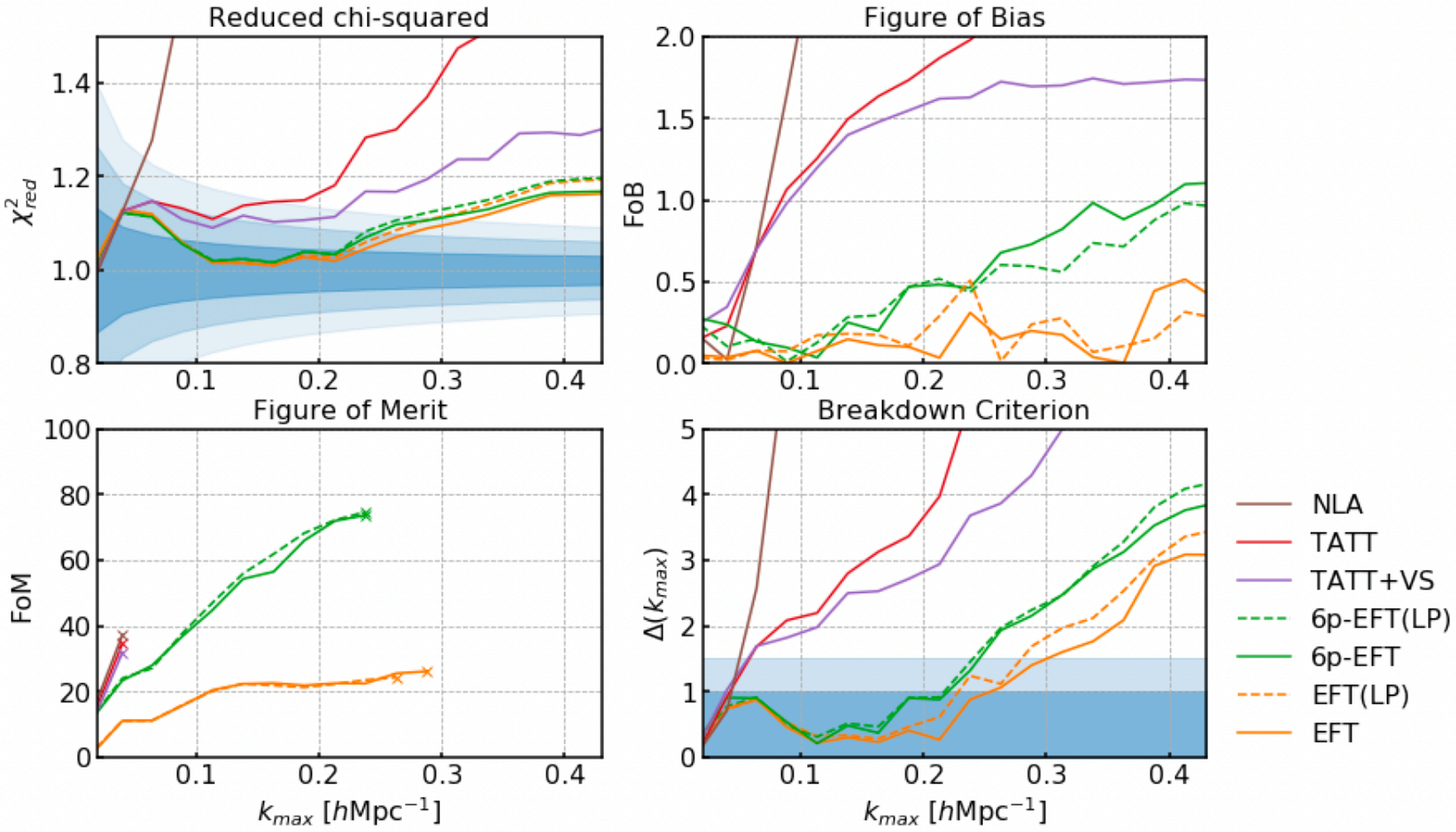
project

* 3D modelling and projection are decoupled
* Ensure complete at a given order
* 8 free parameters

EFTOFLSS - LEONARDO'S TALK
VLAH, EC, SCHMIDT (2020, 2021)
BAKX+, INCL. EC (ARXIV:2303.15565)

An EFT model for intrinsic alignments

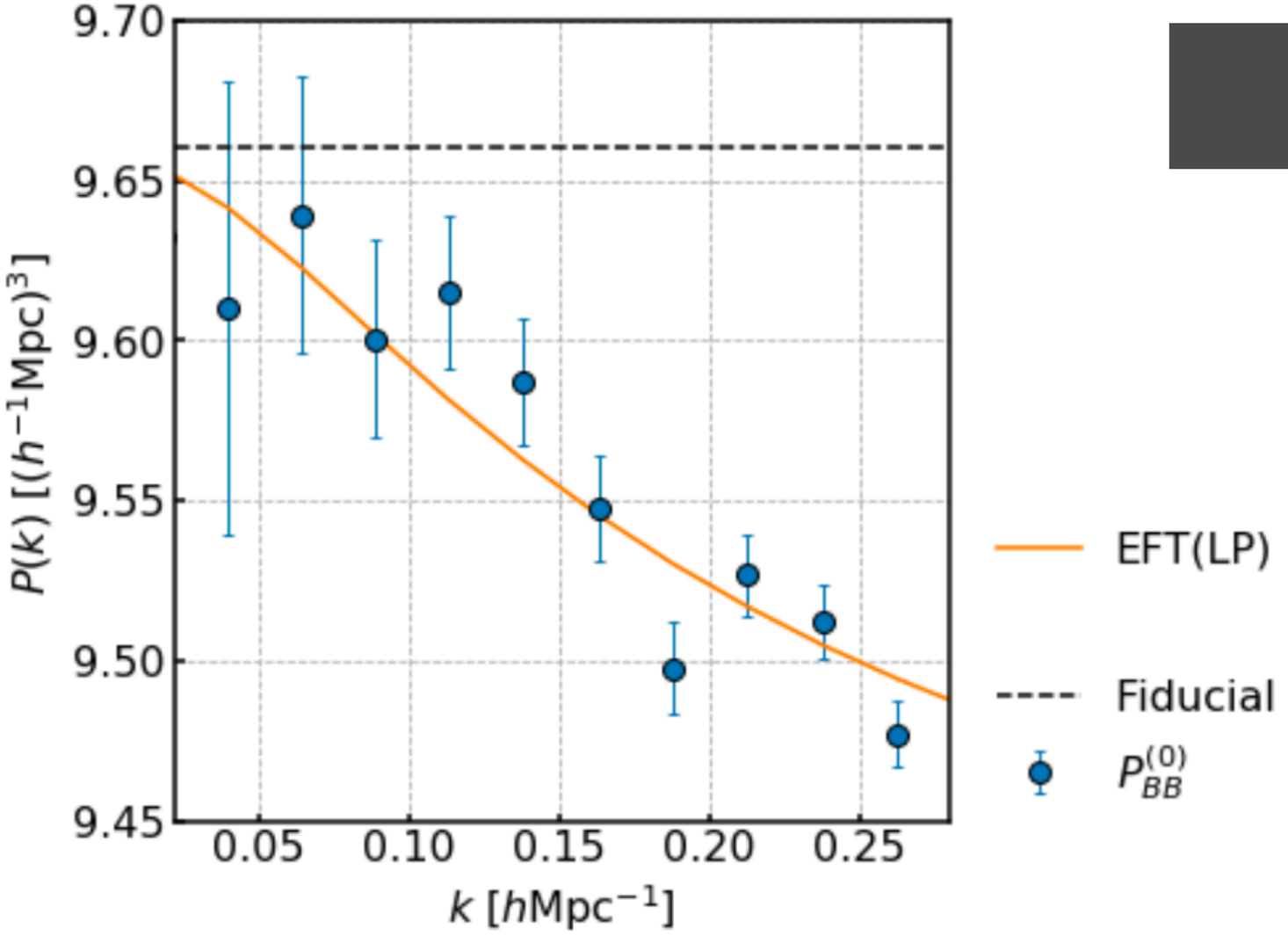
TESTS OF HALO ALIGNMENTS IN N-BODY SIMULATIONS



BAKX+, INCL. EC (ARXIV:2303.15565)

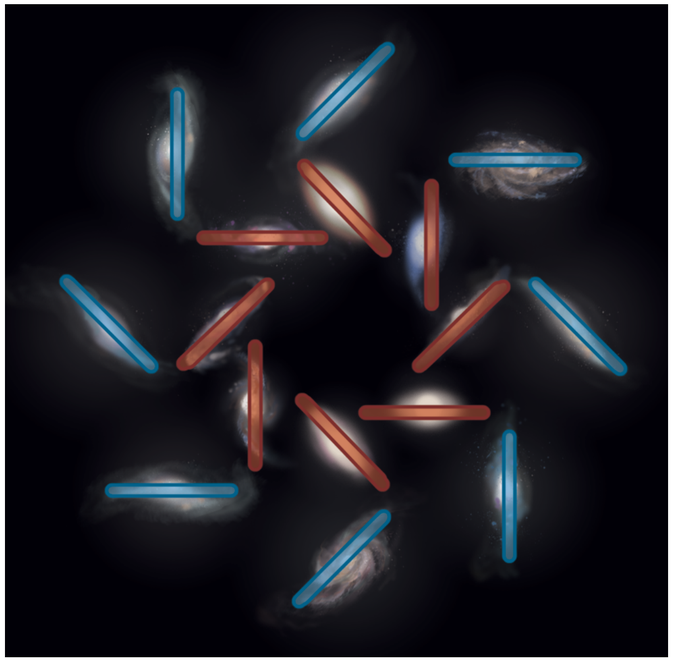
* need for forecasts in realistic mitigation scenarios

An EFT model for intrinsic alignments



BAKX+, INCL. EC (ARXIV:2303.15565)

B-MODES IN INTRINSIC ALIGNMENTS



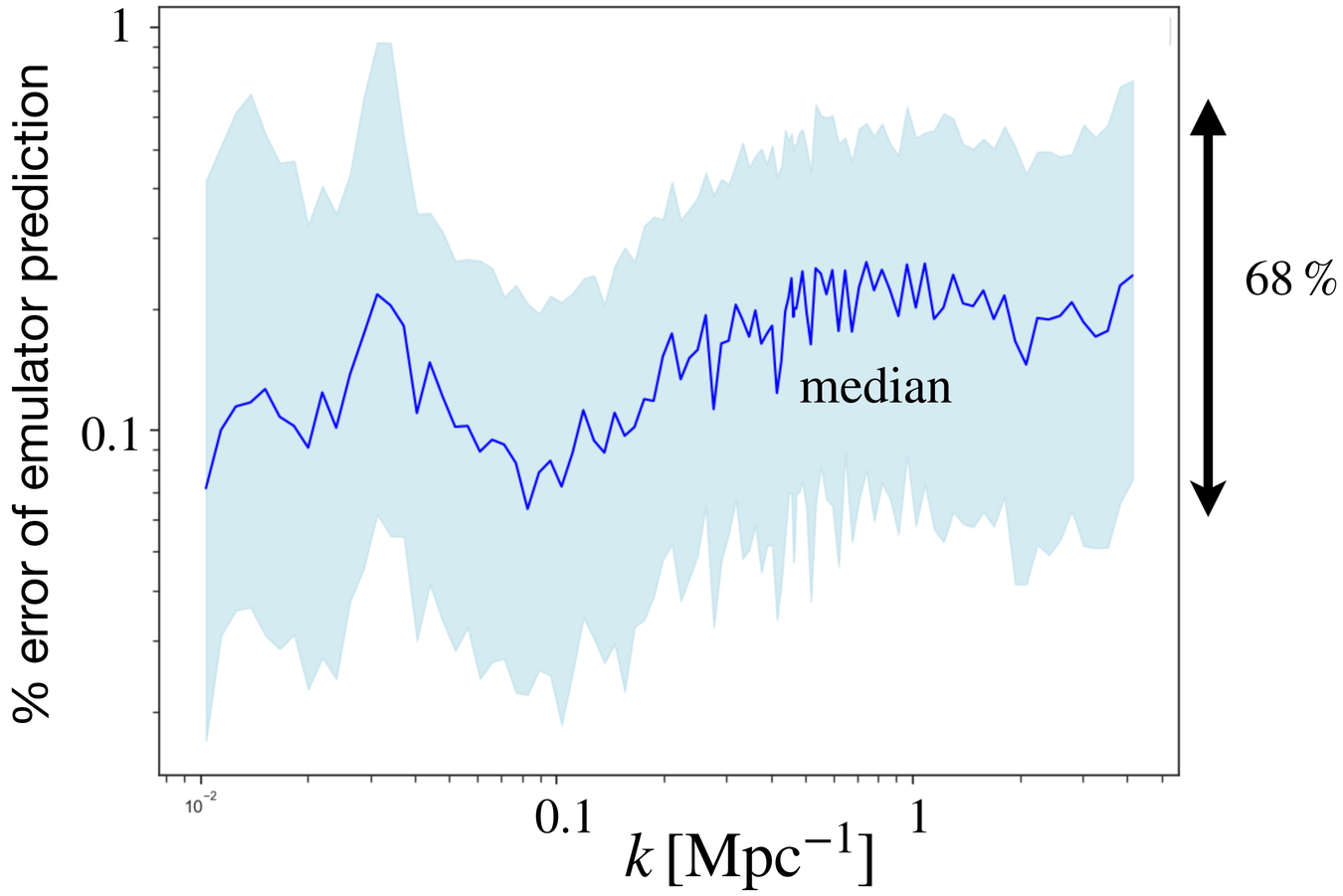
* exploring detectability

GEORGIOU+ (IN PREP.)

BASED ON VEDDER & EC (2022)

An EFT model for intrinsic alignments

AN EMULATOR FOR EFT PREDICTIONS



* 13 slow integrals made fast, <2% accurate

MONTES-ALVAREZ'S MASTER THESIS IN AI

Cosmology with intrinsic alignments

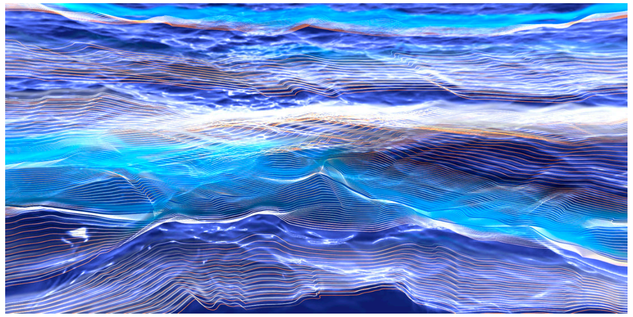
PRIMORDIAL GRAVITATIONAL WAVES

SCHMIDT+ (2014)

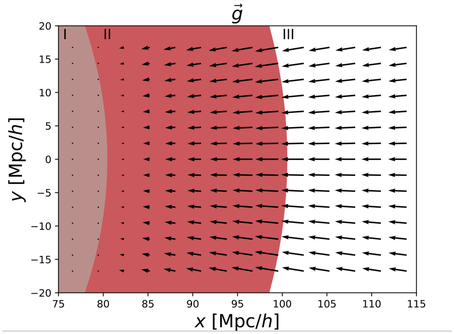
EC+ (2014)

BIAGETTI & ORLANDO (2020)

AKITSU+ (2022)



Credit: Carl Knox, OzGrav/Swinburne



BARYON ACOUSTIC OSCILLATIONS

EC & DVORKIN (2013)

VAN DOMPSELER, GEORGIOU & EC (2023)

XU+ (2023)

GROWTH RATE

TARUYA & OKUMURA (2020, **2023**)

VAN GEMEREN & EC (2020)

DM SELF-INTERACTION

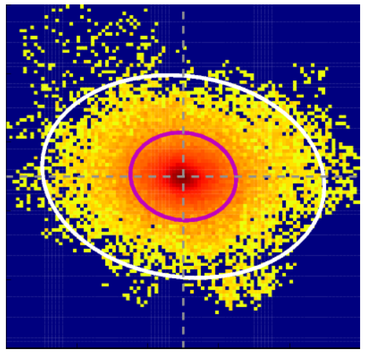
HARVEY, EC+ (2021)

PRIMORDIAL NON-GAUSSIANITY

SCHMIDT, EC & DVORKIN (2015)

EC+ (2016)

AKITSU+ (2021)



PARITY BREAKING

BIAGETTI & ORLANDO (2020)

FINAL REMARKS

- LA/NLA have done very well for current surveys. Are they sufficient for LSST/Euclid? Possibly, only with z-dependence (Fortuna+). Are they sufficient for clustering? Likely not.
- The halo model approach is the only viable option for fully non-linear.
  - ✦ Highly sensitive to fraction of satellites/blue alignment (poor priors).
  - ✦ The formalism suffers from some simplifications (symmetry, projection, halo exclusion).
- SPT/EFT are physical (perturbative) models. Play it safe: cut scales. But where to cut?
- Tests against sims/forecasting + better priors are needed.
- Alignments have many applications. Now starting to be used to constrain growth & PNG from surveys.

Thank you.

Collaborators: Thomas Bakx, Fabian Schmidt, Zvonimir Vlah, Christos Georgiou, Maria Cristina Fortuna, Toshiki Kurita, Ignacio Montes-Alvarez, David Harvey, Karel Zwetsloot, Bjorn van Zwol, Casper Vedder, Alex Eggemeier, ...

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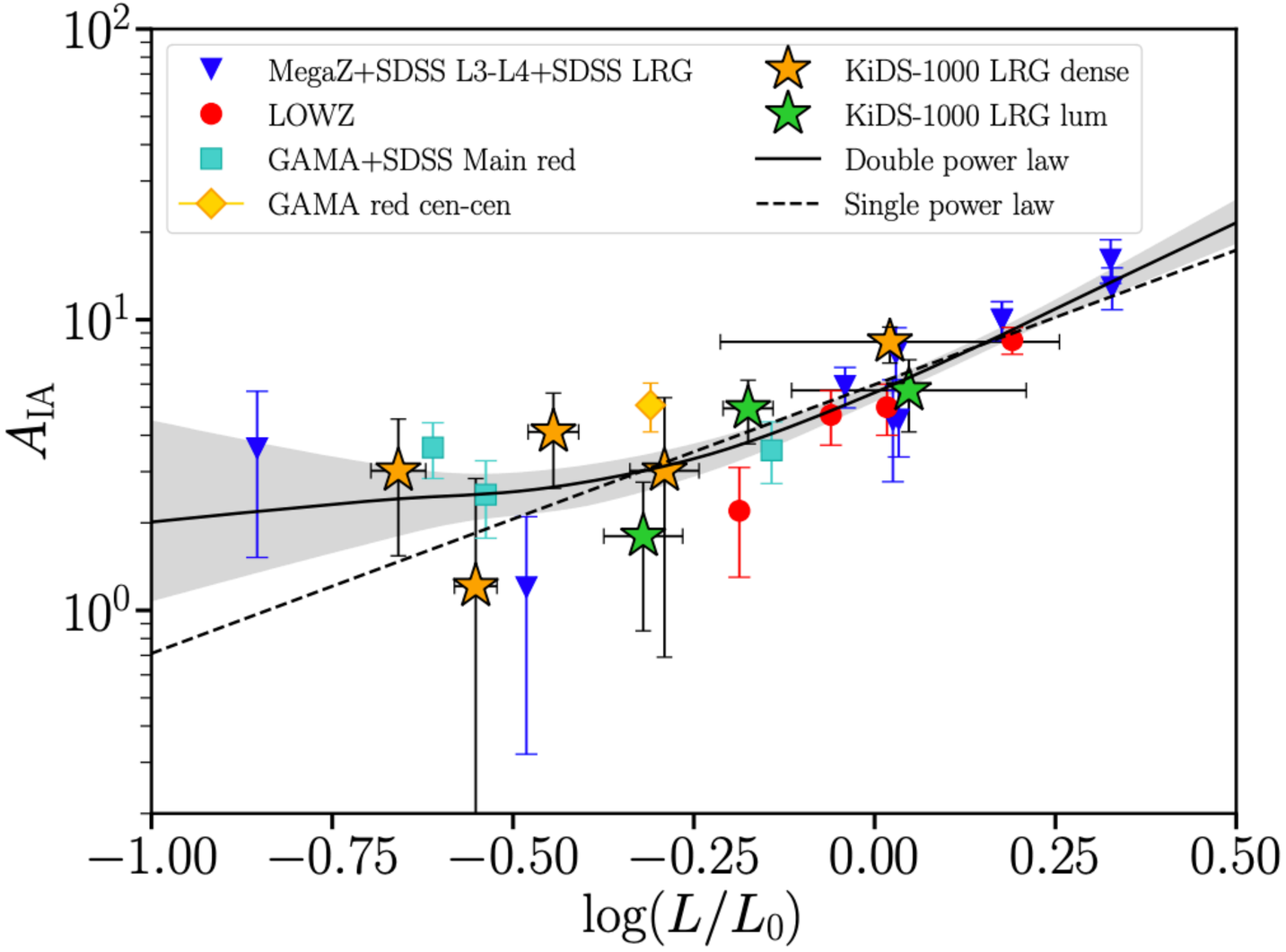
ALIGNMENT BIAS



A broken power-law?

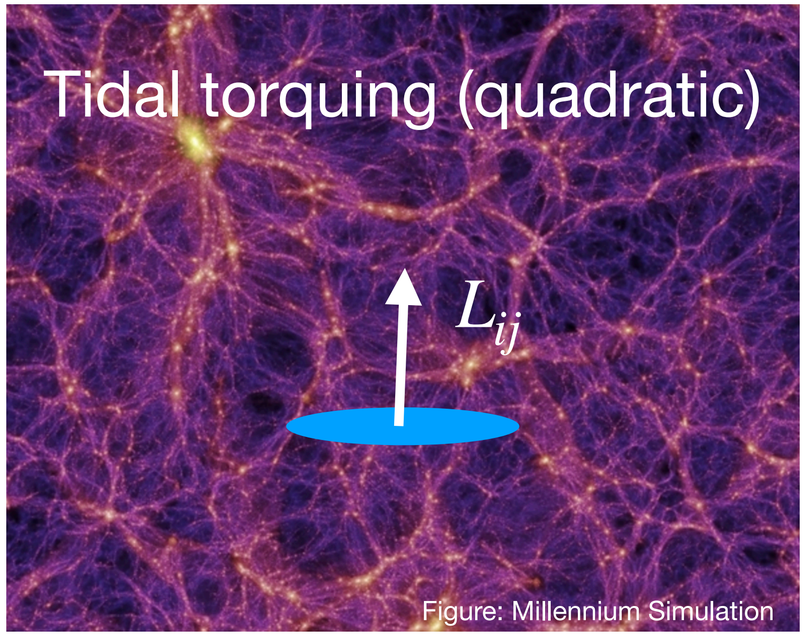
$$C_1 \rightarrow A_I(L) C_1^{\rm fid}$$

Fortuna+ (2021)

ALIGNMENT OF SPIRALS

$$g_{ij} \propto L_{ij}^2 \propto T_{ij}^2$$

Catelan+ (2001)
Crittenden+ (2001)



Perfect disk - Torquing naturally included in SPT/EFT. Does not appear at the linear level: LA/NLA not justified.

Imperfect disk - Expect a linear term. (Important because we don't select on morphology!)