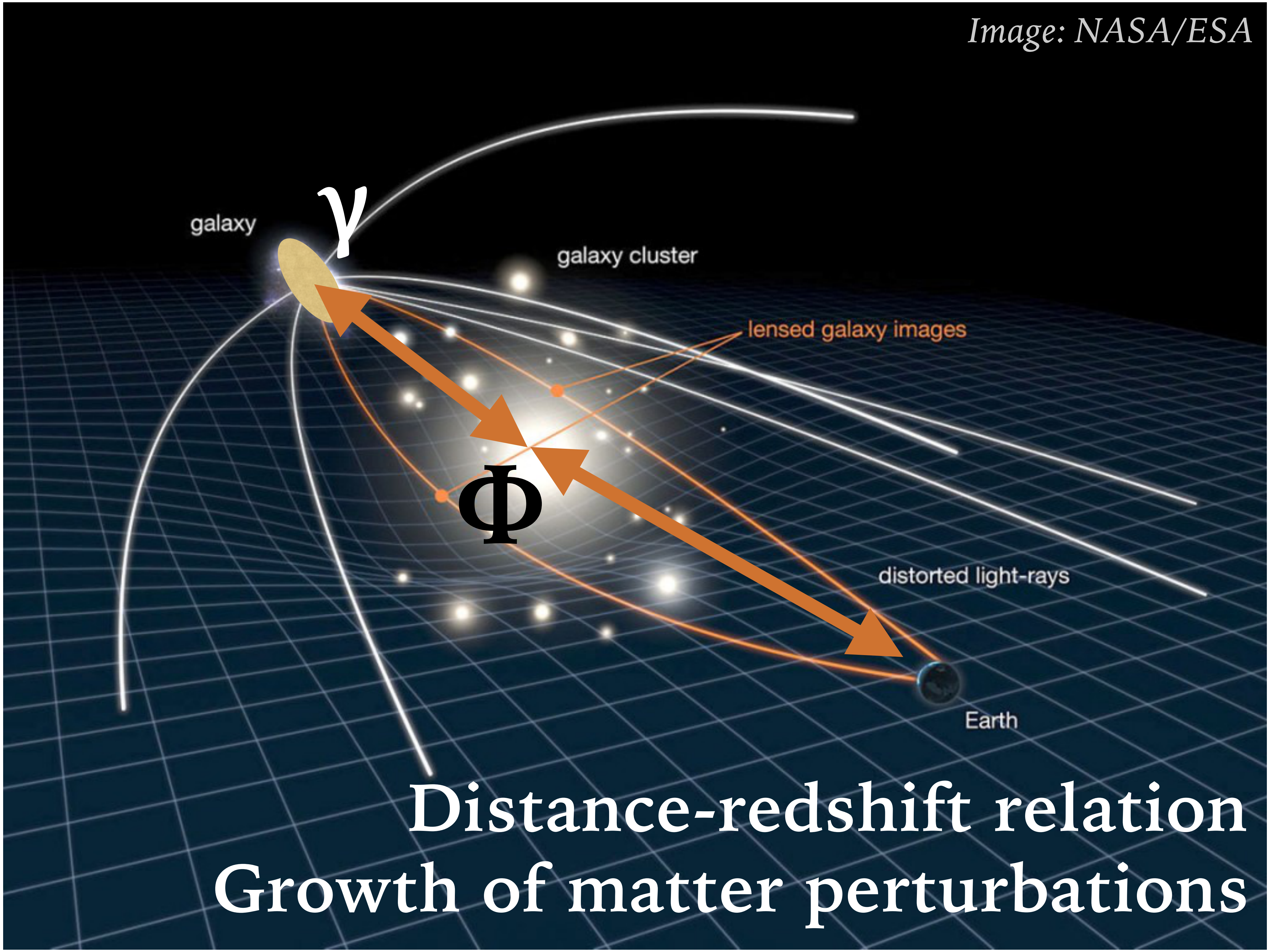
OUTLINE

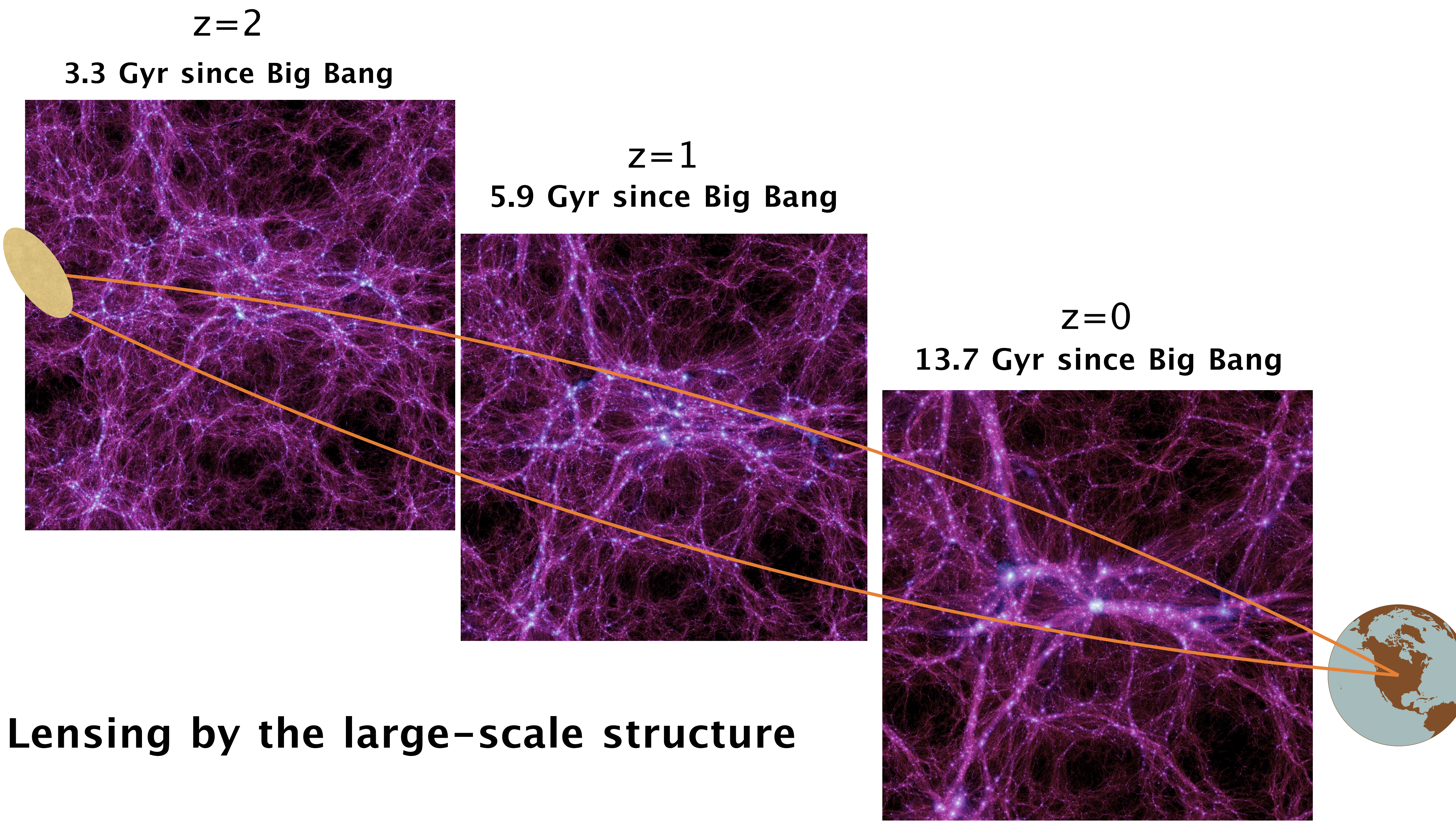
* Galaxy shapes
  * Gravitational lensing
  * Intrinsic alignments (IA)
    - Contamination
    - Simulations & modelling
* Opportunities with intrinsic alignments
  * Cosmology: the early Universe
  * Galaxy evolution: AGN feedback & mergers

GALAXY SHAPES

GRAVITATIONAL LENSING



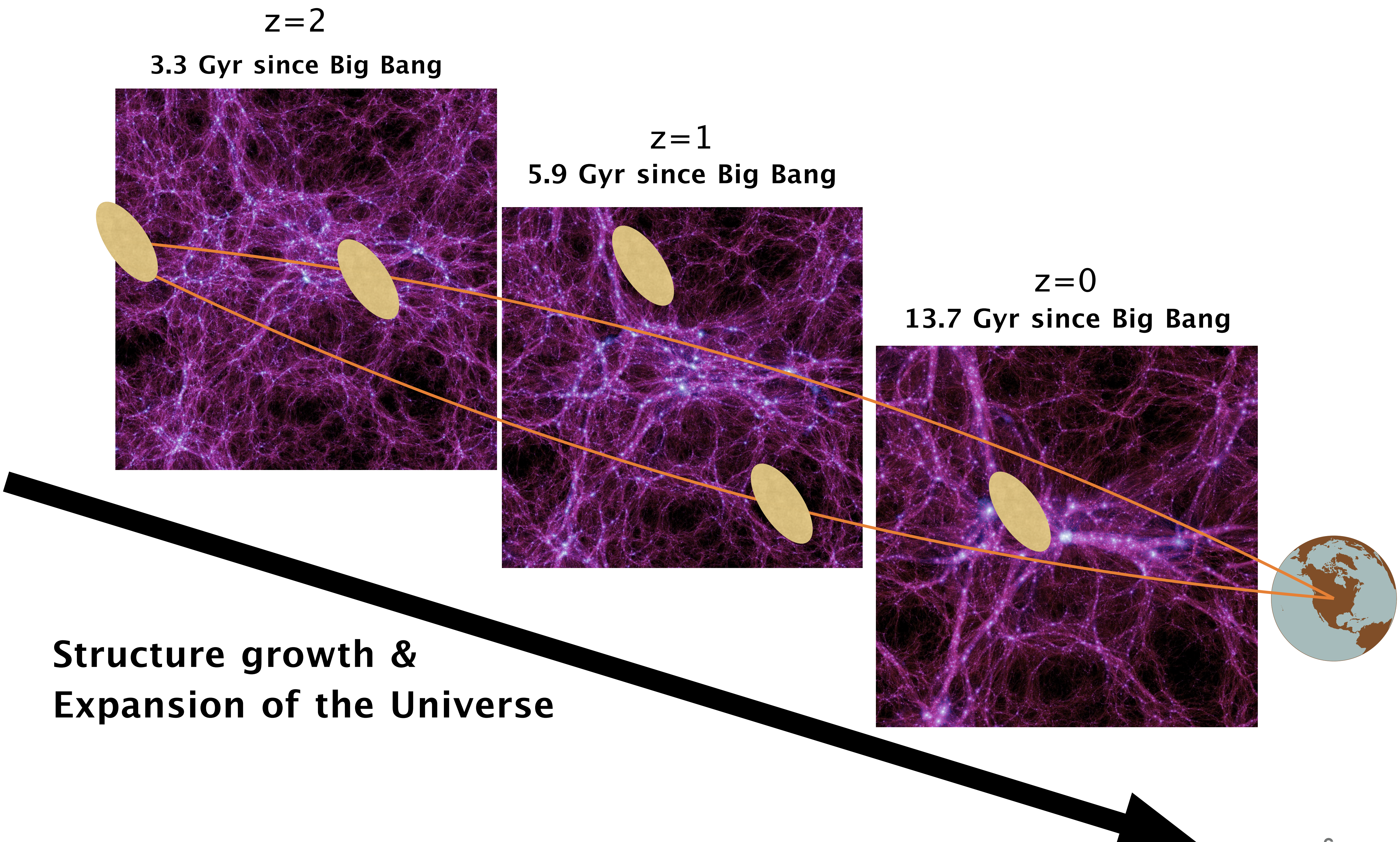
GRAVITATIONAL LENSING



Lensing by the large-scale structure

Credit: M. Boylan-Kolchin et al. (2009) - Millennium-II

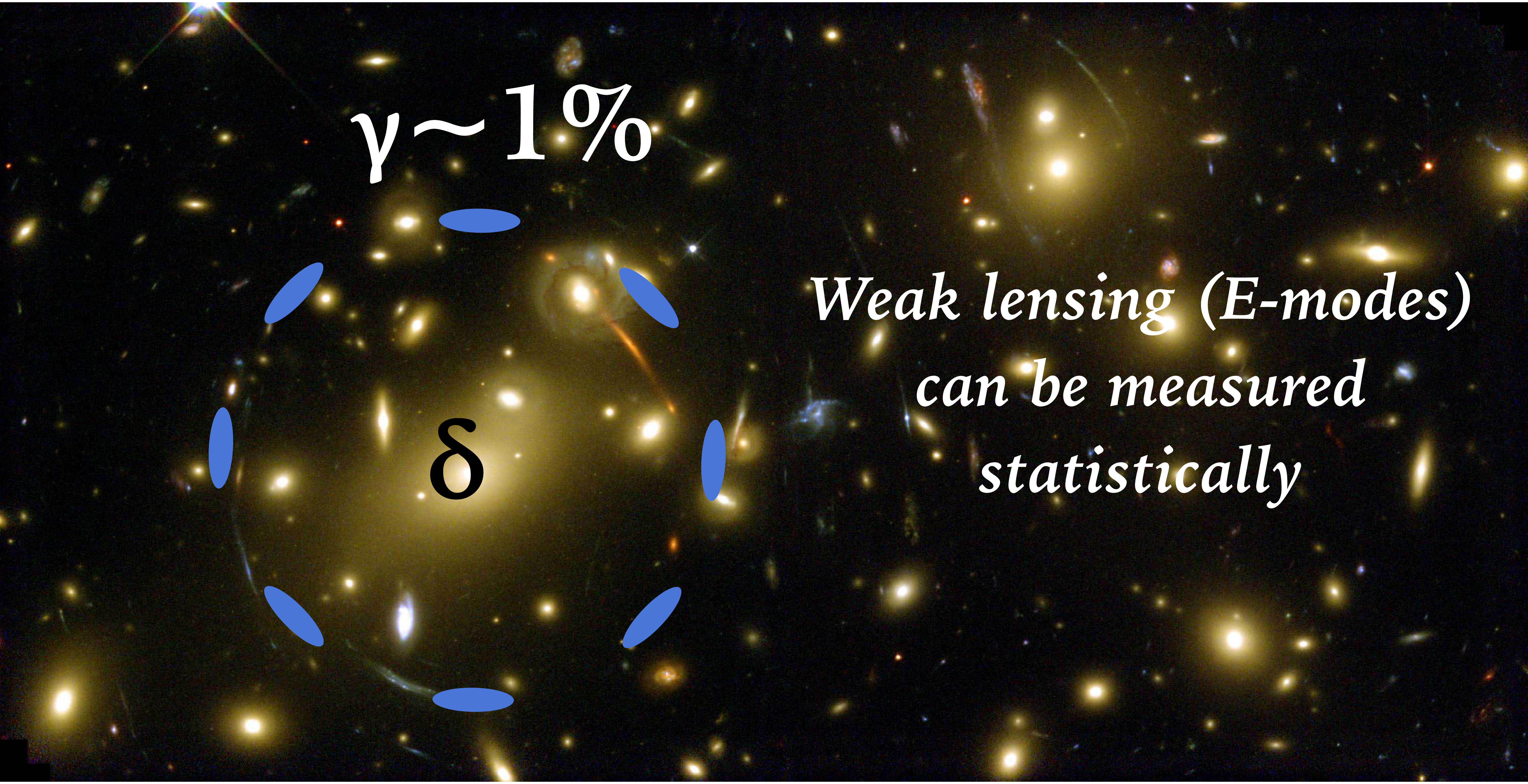
GRAVITATIONAL LENSING



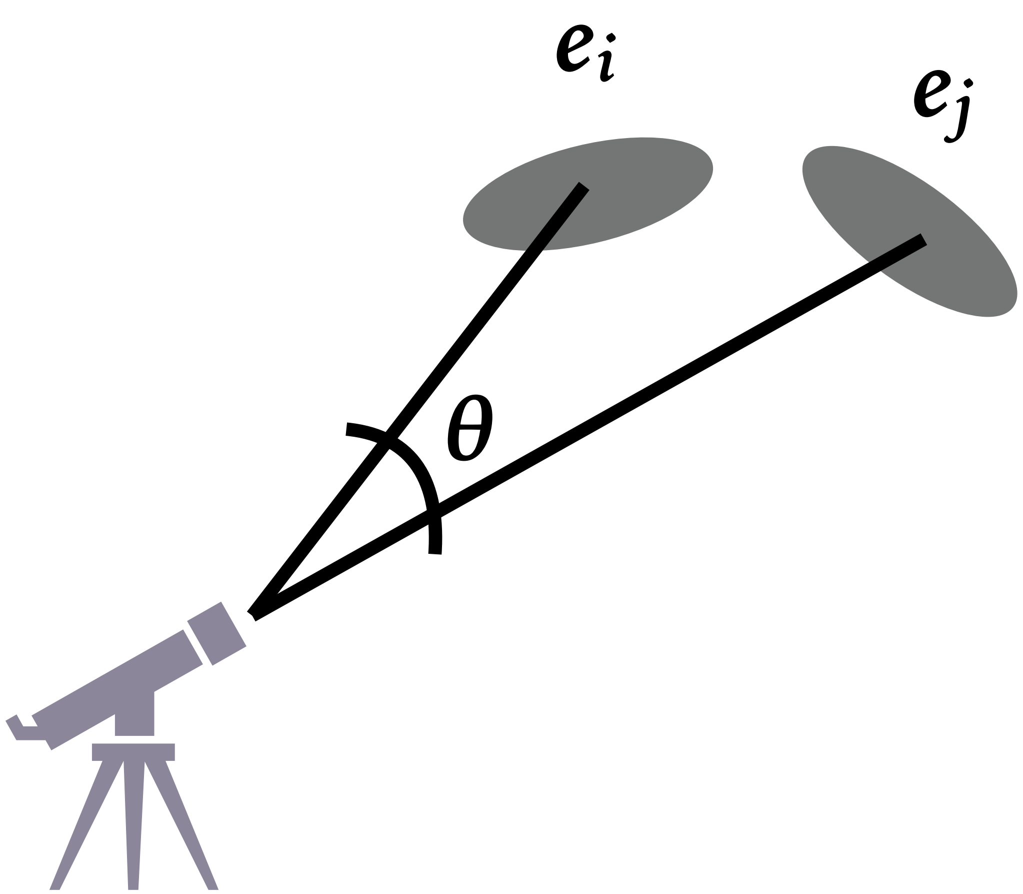
Credit: M. Boylan-Kolchin et al. (2009) - Millennium-II

GRAVITATIONAL LENSING

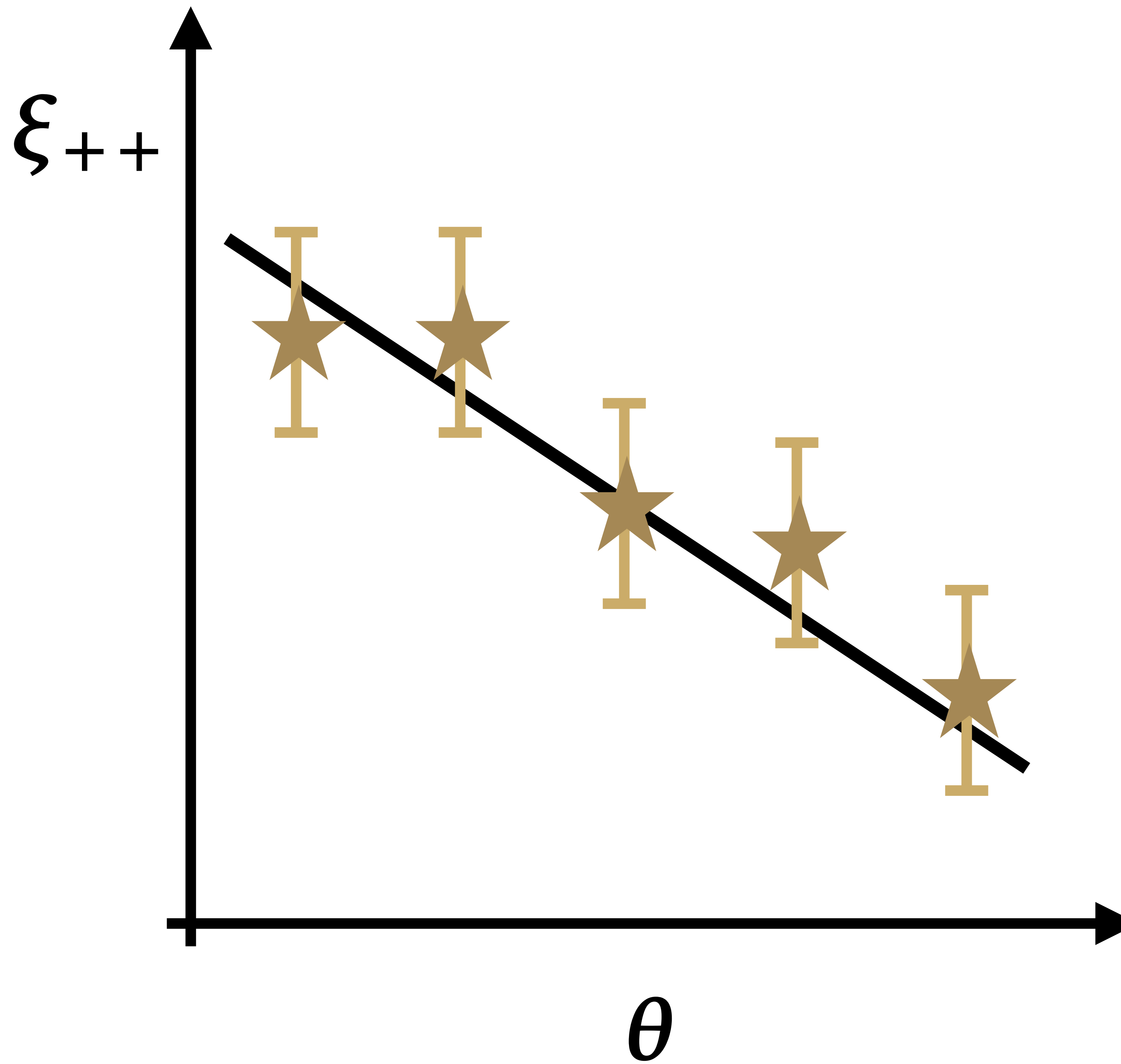
Image: Abell 2218, NASA/ESA



GRAVITATIONAL LENSING



Correlation function



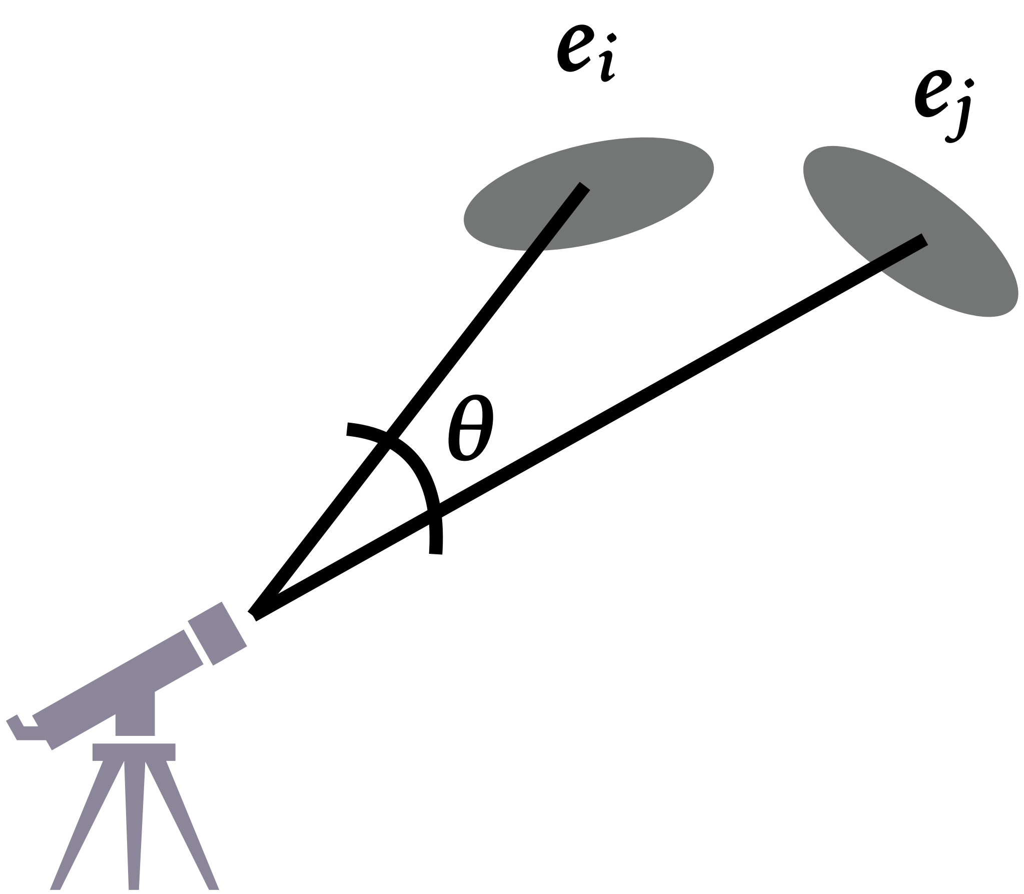
e.g.

$$\xi_{++}(\theta) = \frac{\sum_{ij} w_i w_j e_{i+} e_{j+}}{\sum_{ij} w_i w_j}$$

GRAVITATIONAL LENSING

Cosmological model parameters

$\Omega_m = \Omega_{DM} + \Omega_b$, Ω_Λ , w, h, σ_8 , Σm_ν



e.g.

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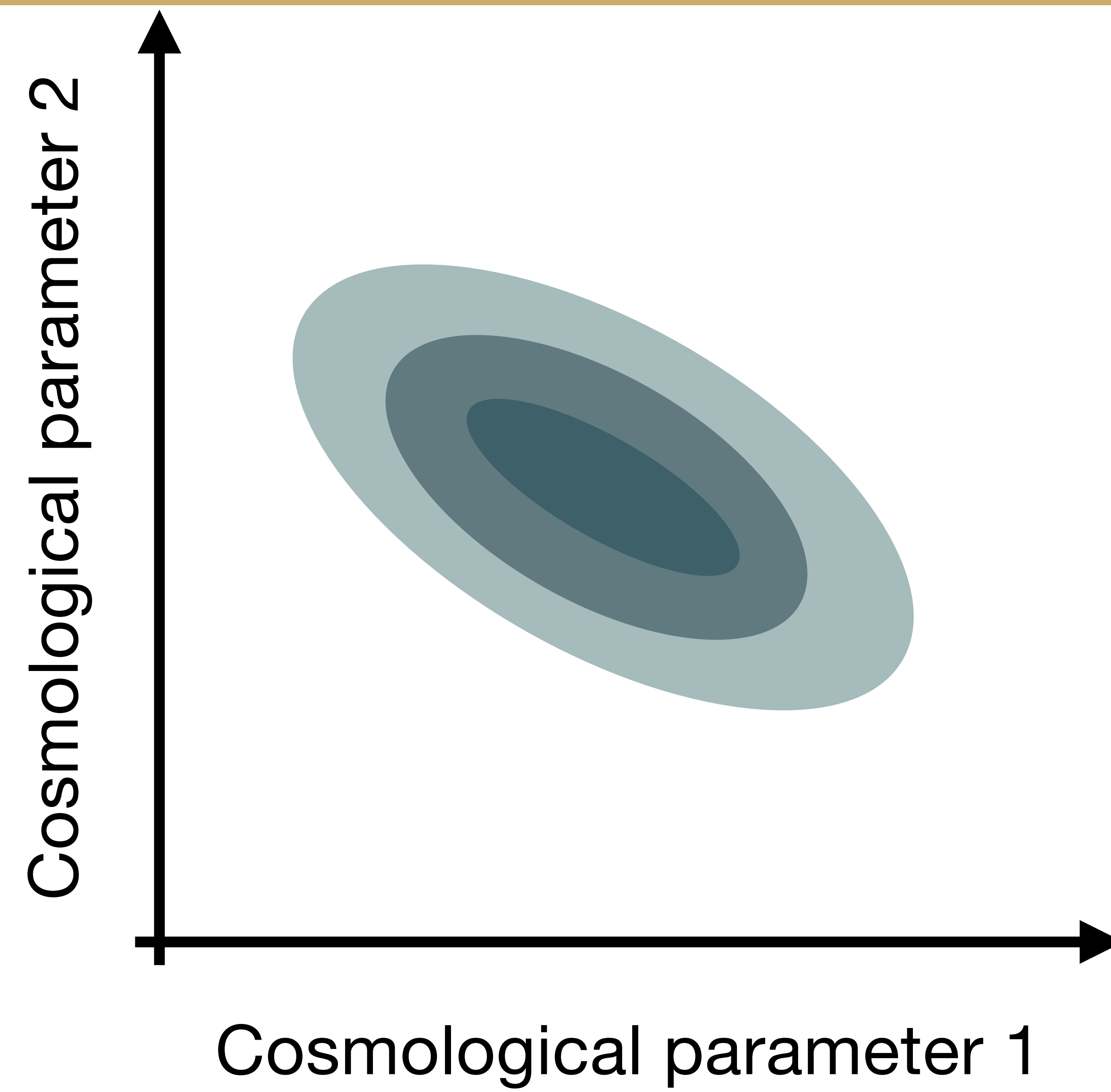
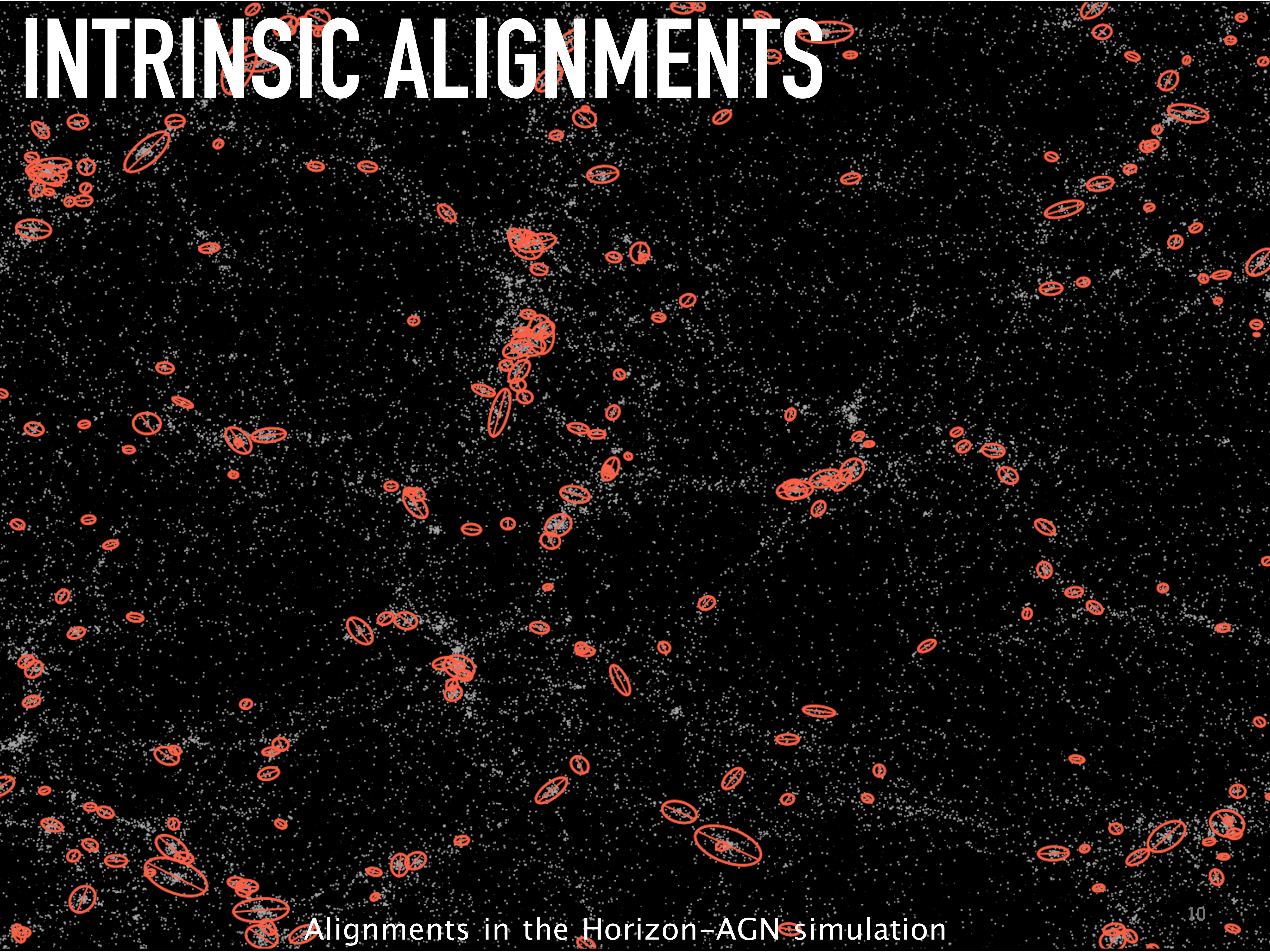
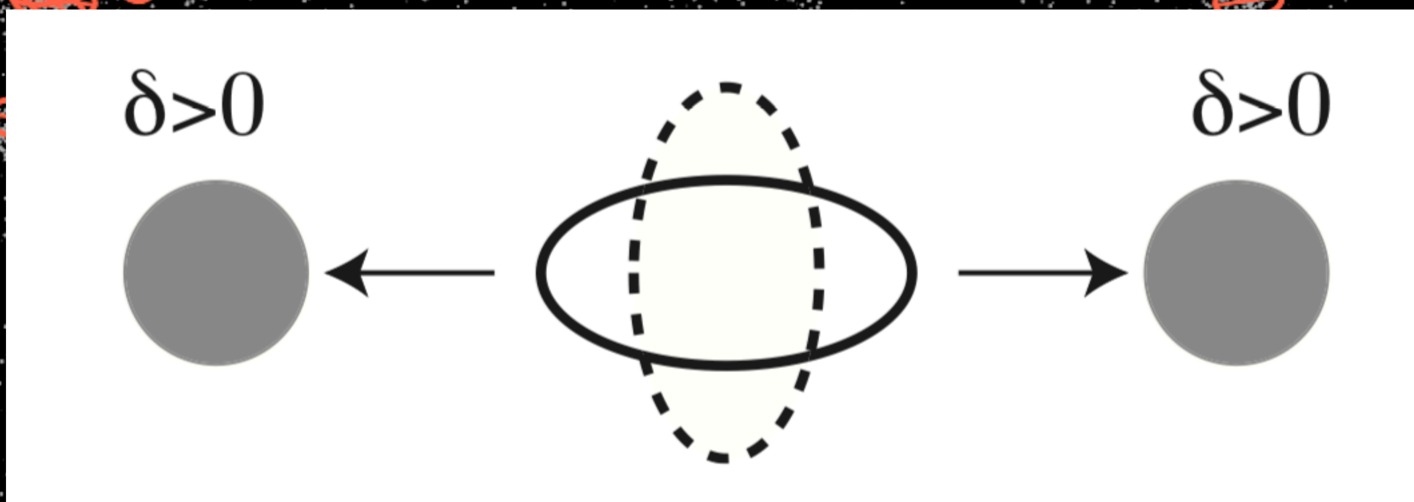


INTRINSIC ALIGNMENTS



Alignments in the Horizon-AGN simulation

INTRINSIC ALIGNMENTS



Lensing and alignments are coupled

$$e_+ \propto \gamma + I + \text{Noise}$$

$$\Downarrow$$

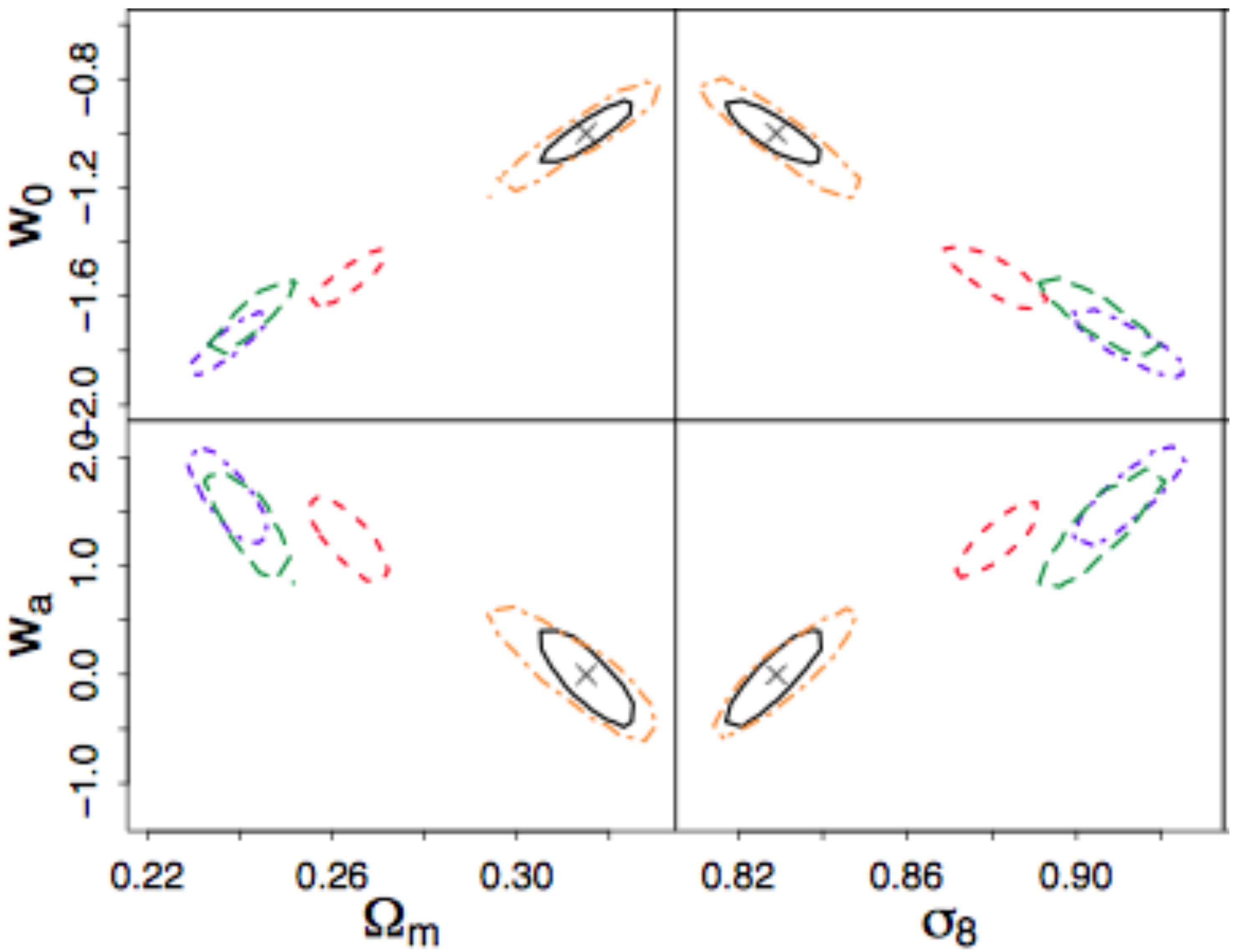
$$\xi_{++} \propto \gamma\gamma + \gamma I + II + \text{Noise}$$

Alignments in the Horizon-AGN simulation

IA AS CONTAMINATION

Bias in lensing cosmology due to alignments

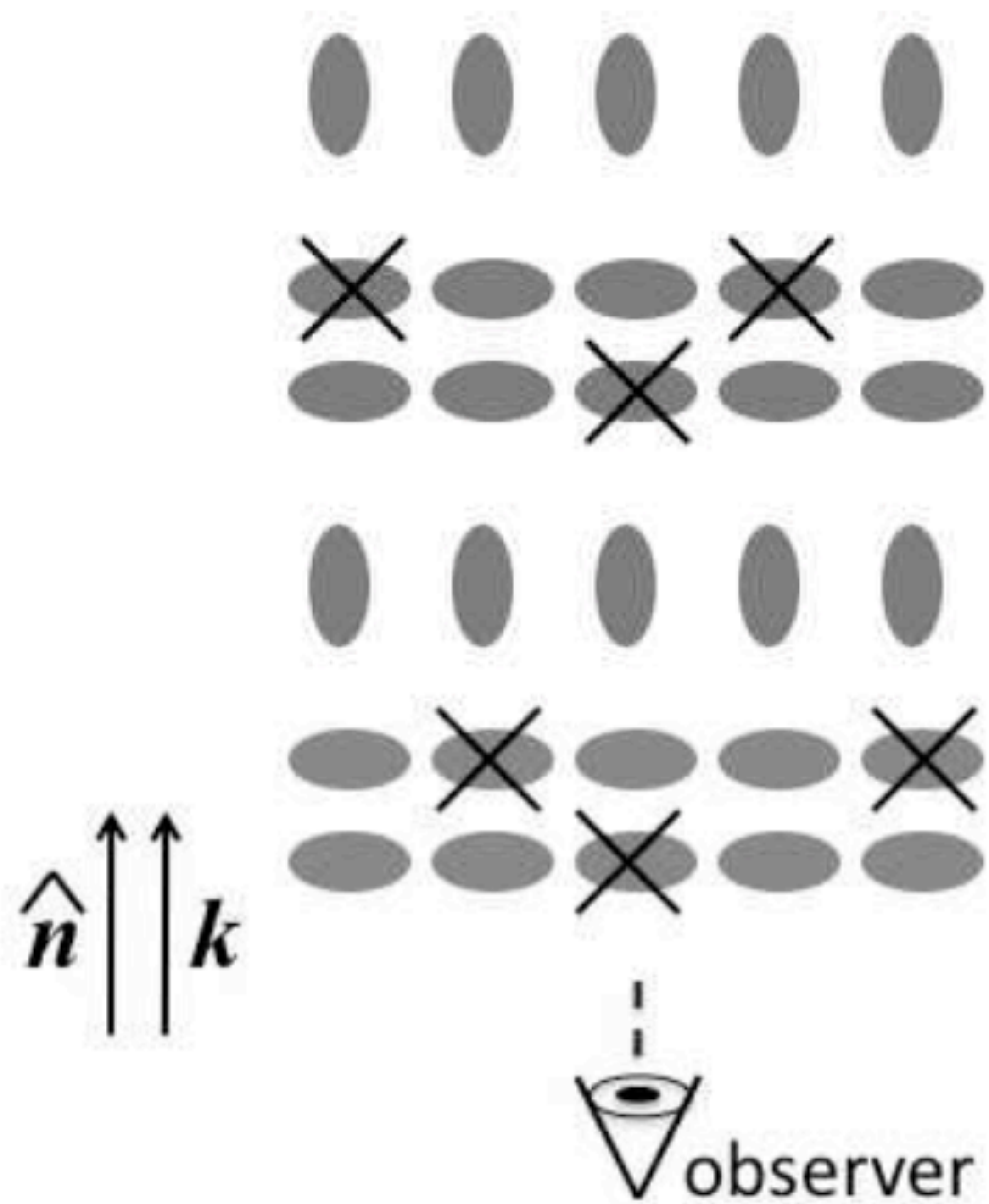
Krause+ (2015) - LSST-like experiment



*not responsible for current tensions

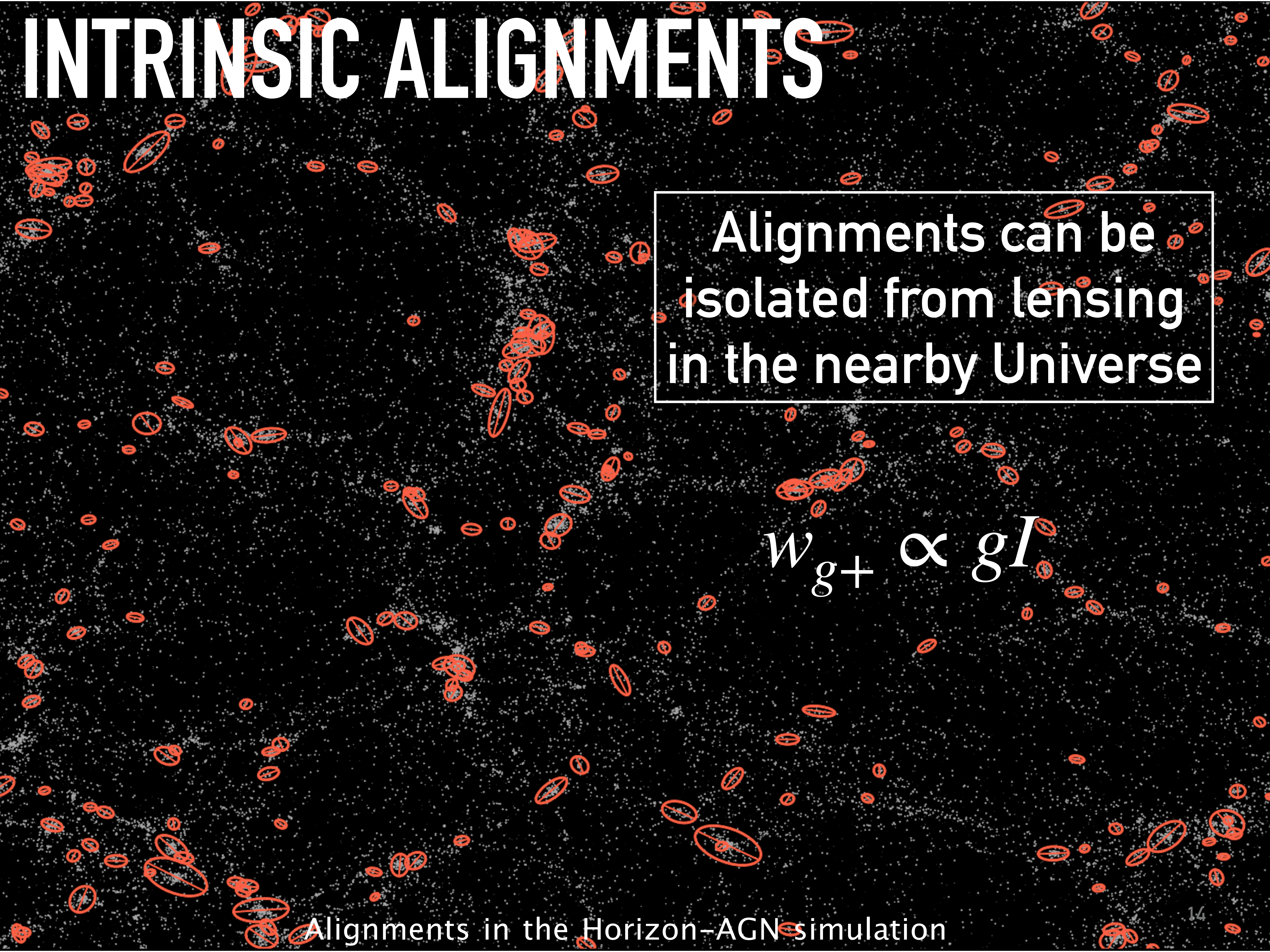
IA AS CONTAMINATION

Clustering (RSD) surveys are also affected due to selection effects imposed by alignments (at 3σ in BOSS).



Hirata (2009), Martens (2019)

INTRINSIC ALIGNMENTS



Alignments can be isolated from lensing in the nearby Universe

$$w_{g+} \propto gI$$

Alignments in the Horizon-AGN simulation

CROSS-CORRELATIONS

$w_{g+} \propto gI$ *galaxy position-galaxy shape*

$\gamma I \propto mI$ *matter-galaxy shape, lensing-galaxy shape*

II *shape-shape*

CROSS-CORRELATIONS

$w_{g+} \propto gI$ *galaxy position-galaxy shape*

$\gamma I \propto mI$ *matter-galaxy shape, lensing-galaxy shape*

II *shape-shape*

vI *velocity-shape*

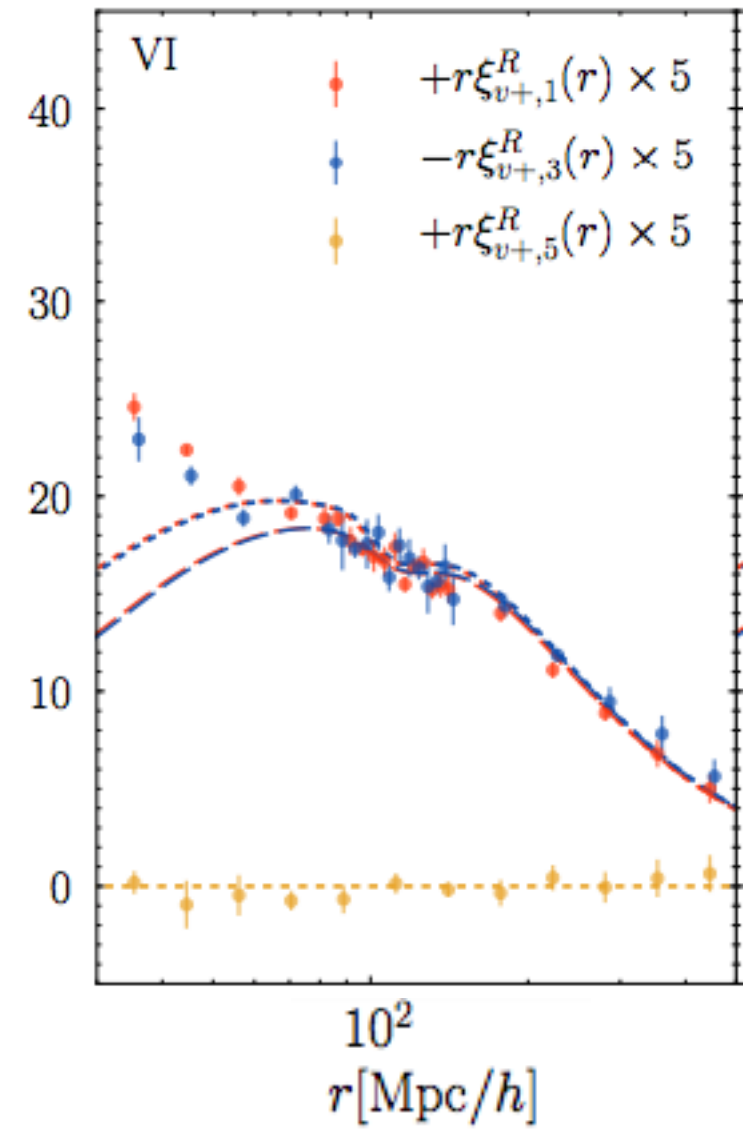
> measured in **simulations**

> **detectable** in cross-correlation with kSZ velocity reconstruction (e.g. LSST+CMB S4+4MOST)

> can **break degeneracy** of IA in RSD contamination

van Gemeren & EC (to appear)

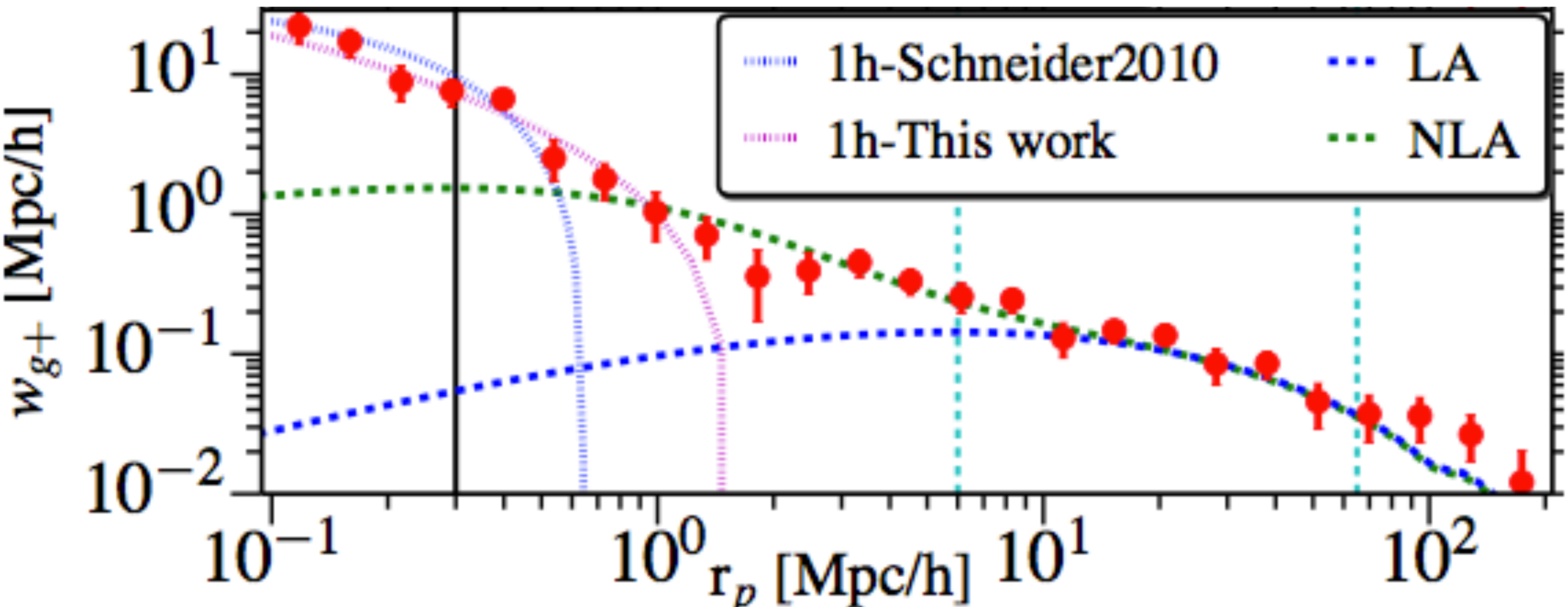
Okumura+ (2020)



MODELLING IA

$$w_{g+} \propto gI$$

SDSS LOWZ sample - Singh+ (2014)

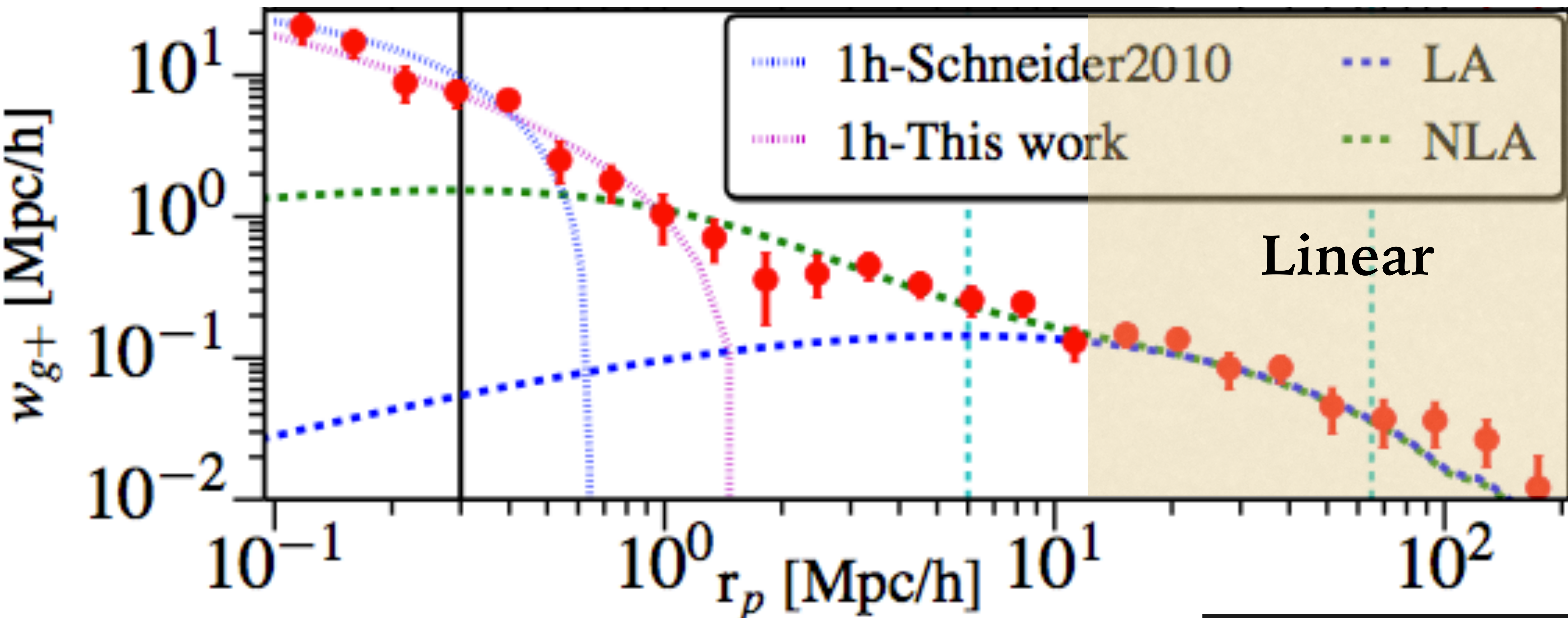


Red galaxies align strongly in the Universe

MODELLING IA

$$w_{g+} \propto gI$$

SDSS LOWZ sample - Singh+ (2014)



Red galaxies align strongly in the Universe

MODELLING IA

Linear alignment model (small alignment regime)

$$\boxed{I \propto (\partial_x^2 - \partial_y^2)\Phi}$$

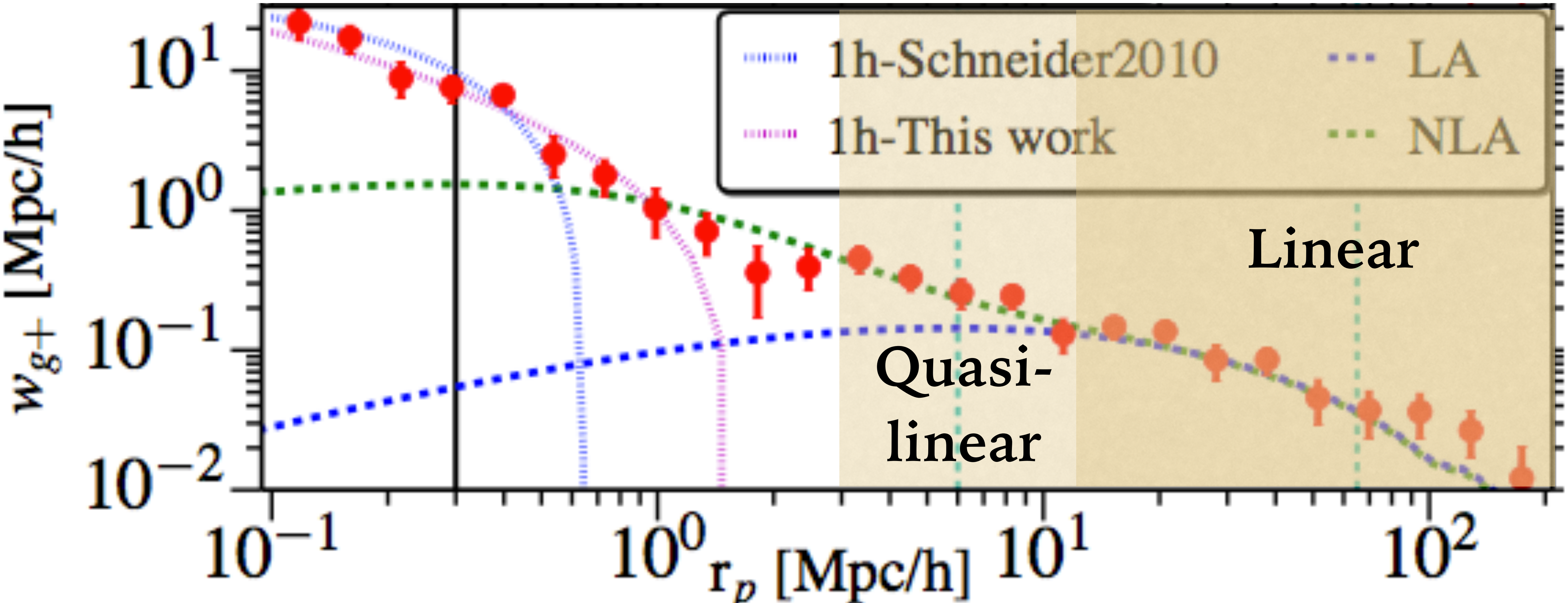
Projected shapes of galaxies $\propto$ *Projected tidal field of matter in the Universe*

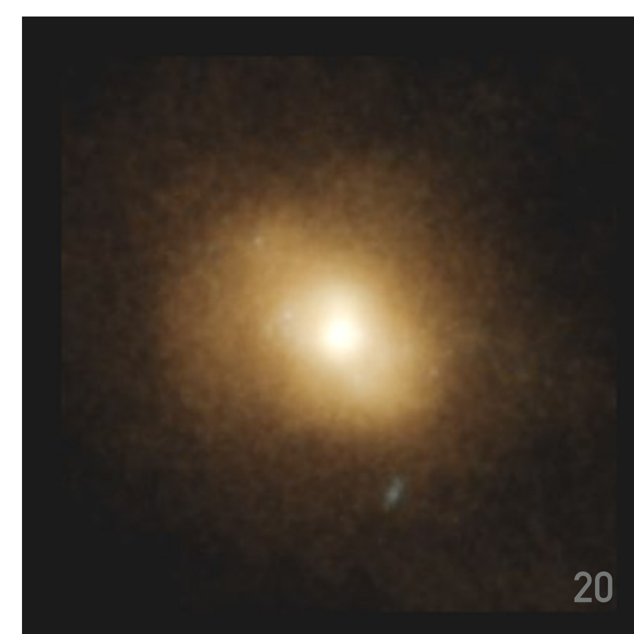
Catelan+ (2001)

MODELLING IA

$$w_{g+} \propto gI$$

SDSS LOWZ sample - Singh+ (2014)





Red galaxies align strongly in the Universe

MODELLING IA

Quasi-linear regime: EFT of the Large-Scale Structure

$$\boxed{I_{ij} = \sum_{\mathcal{O}} b_{\mathcal{O}} \mathcal{O}_{ij}}$$

Small-scale physics

Three-dimensional shapes of galaxies $\propto$ *All gravitational observables consistent with symmetry of trace-free rank-2 tensor*

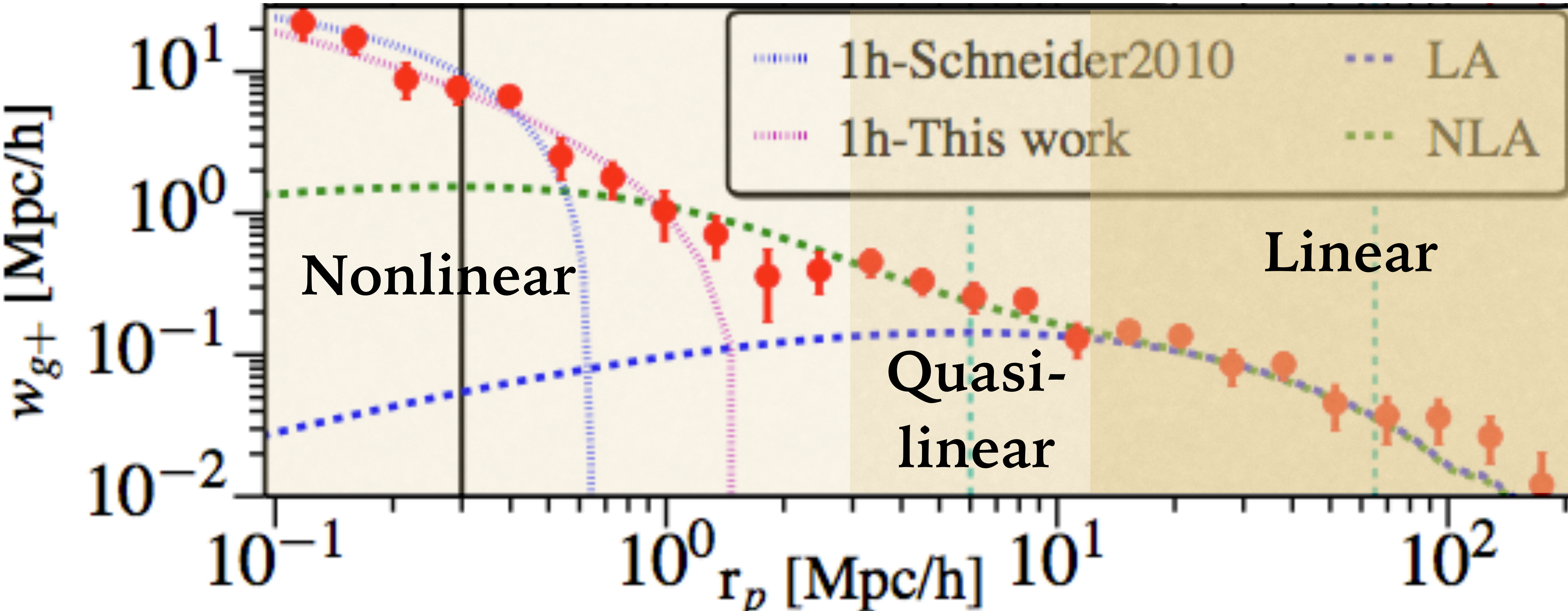
Vlah, EC, Schmidt (2019, in prep.)

See also Blazek+ (2019), Samuroff+ (2019) for a similar SPT expansion.

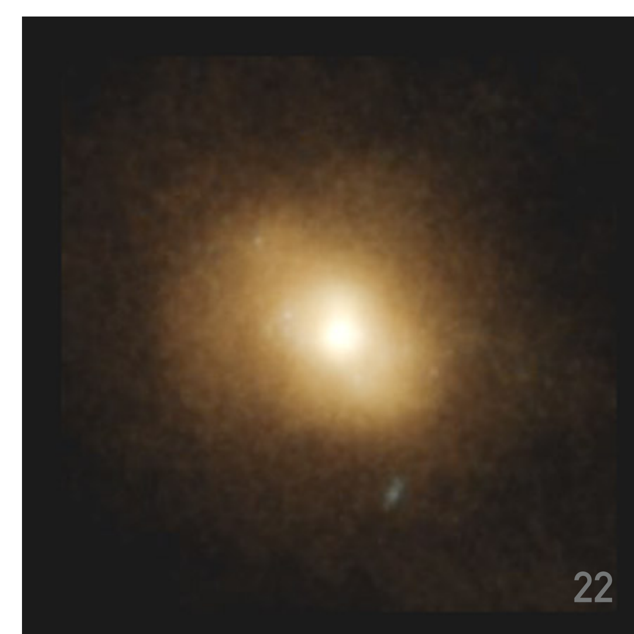
MODELLING IA

$$w_{g+} \propto gI$$

SDSS LOWZ sample - Singh+ (2014)



Red galaxies align strongly in the Universe

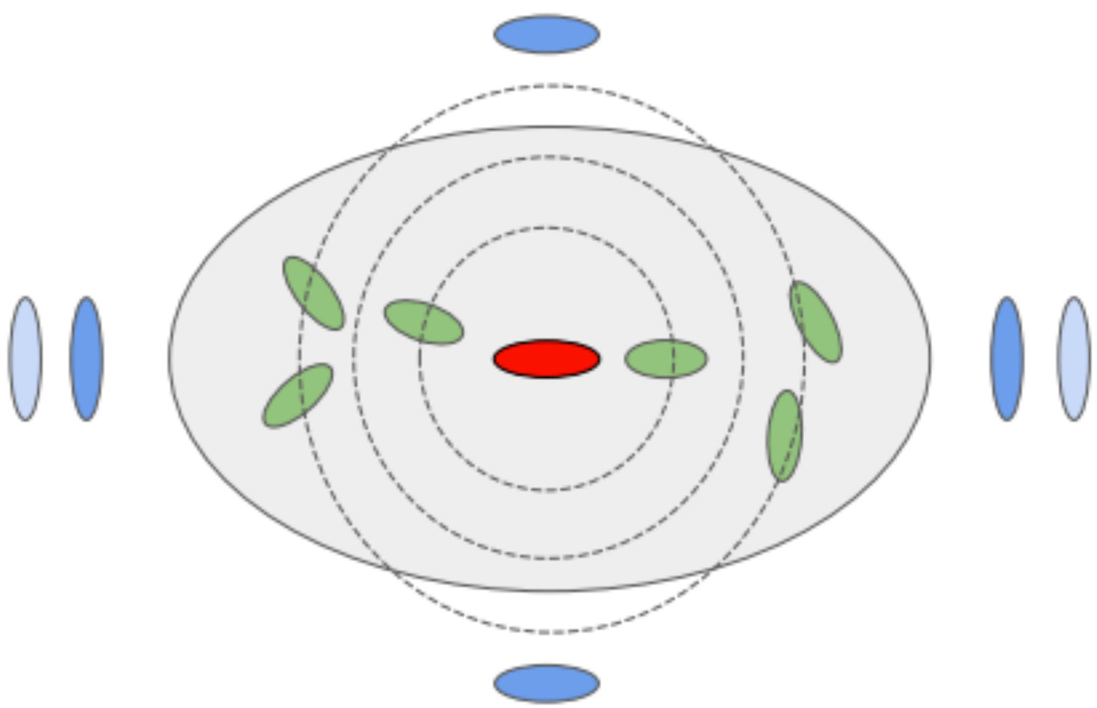


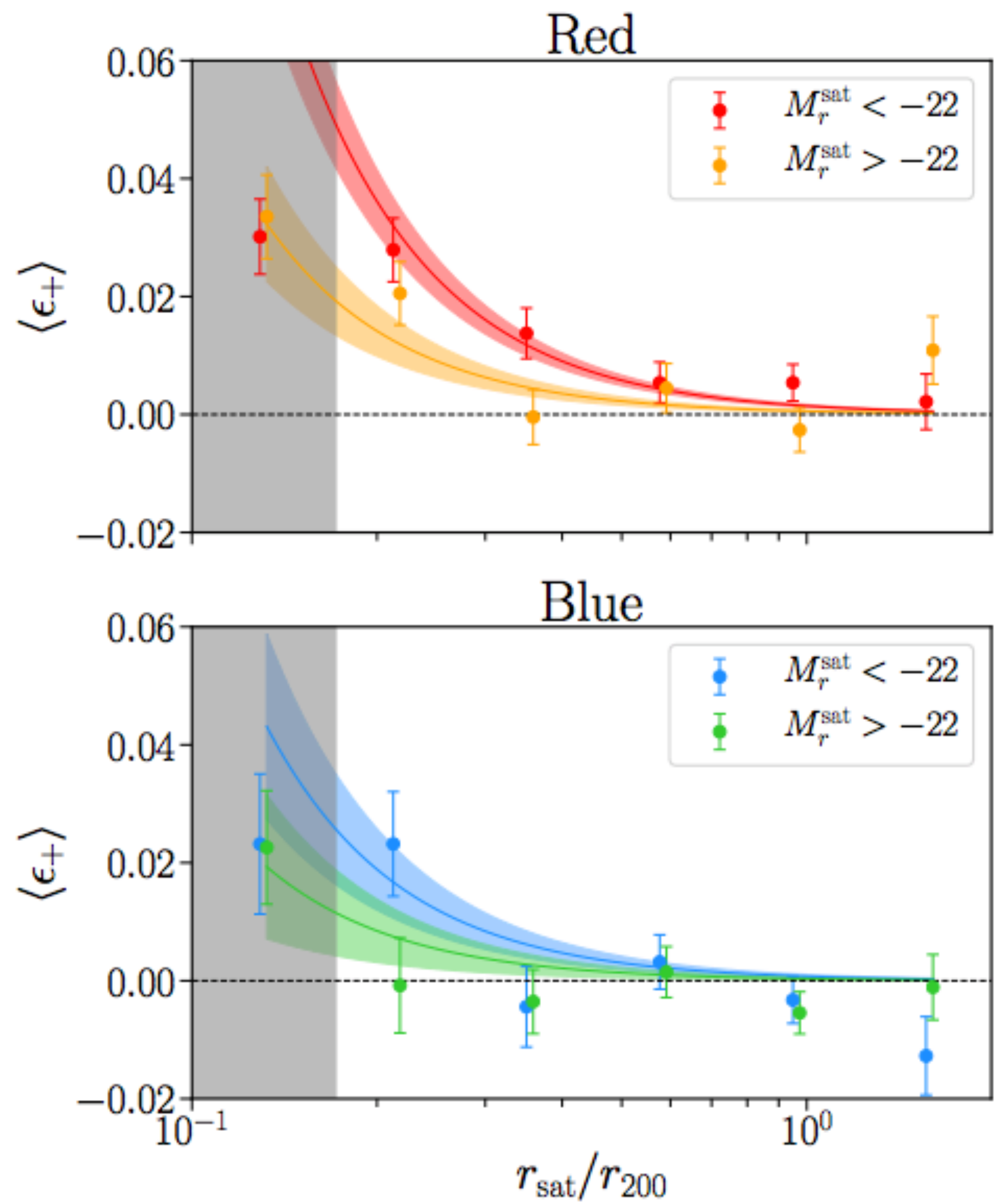
MODELLING IA

Non-linear regime: Halo model (large alignment regime)

Projected shapes of galaxies

$\propto$ *Observationally-motivated power-law profile*





Schneider & Bridle (2010)
Georgiou+ (2019a,b)
Fortuna+, incl. EC (submitted)

SIMULATING IA

Non-linear regime

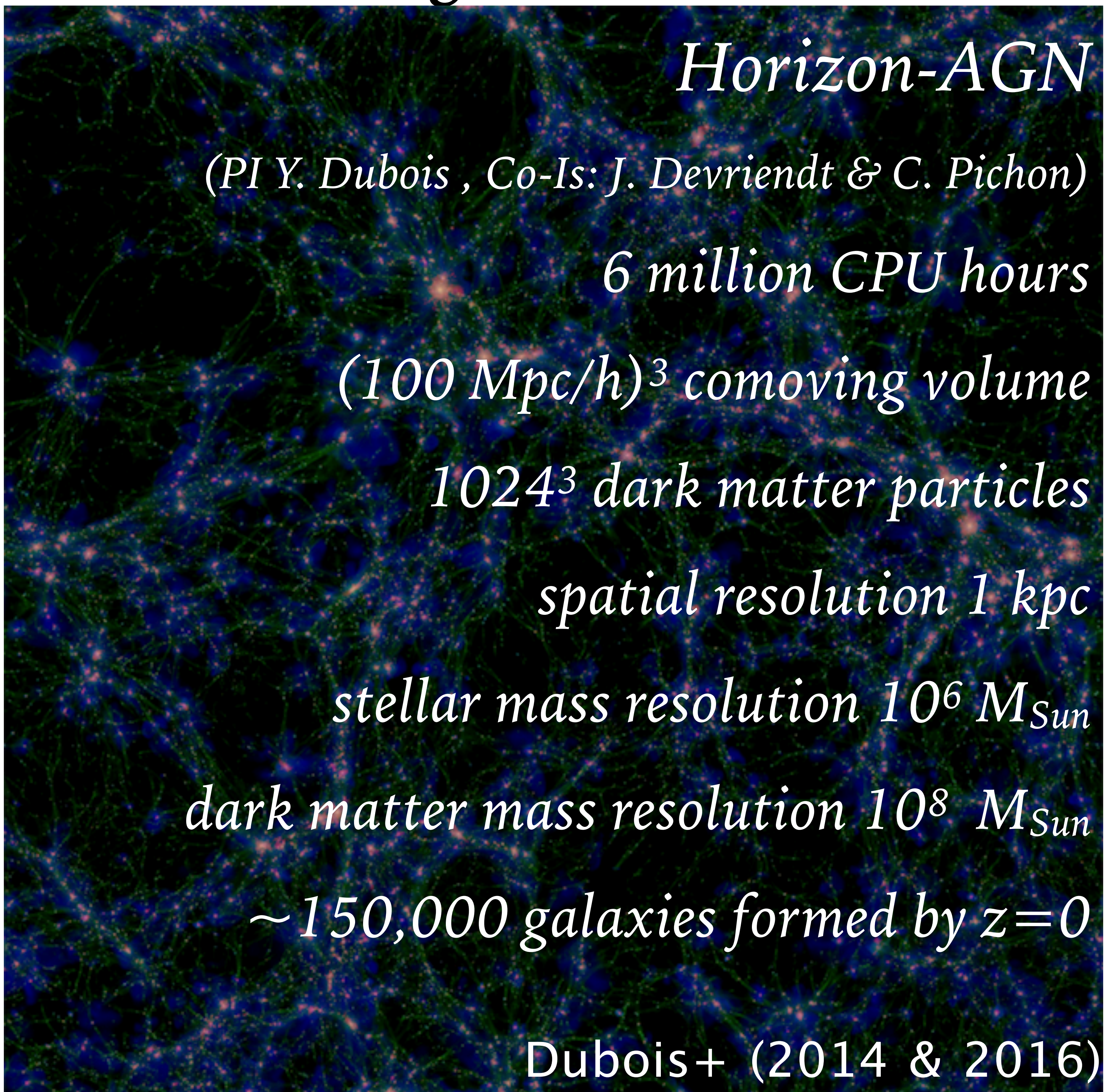
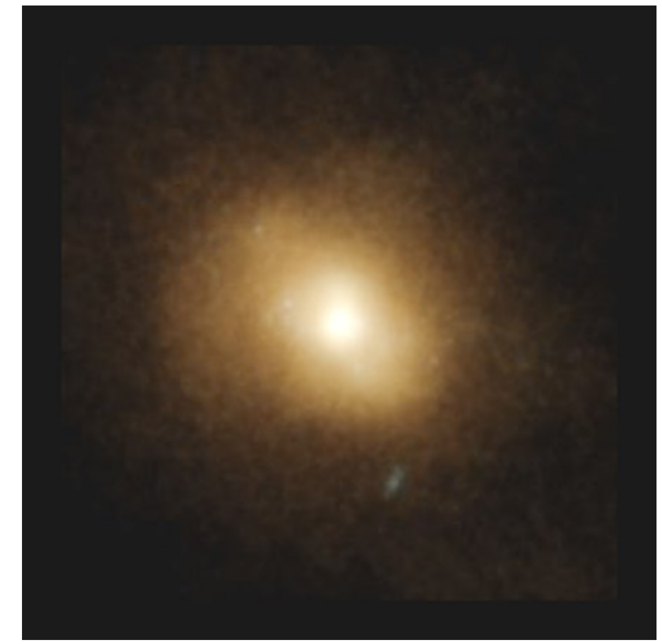
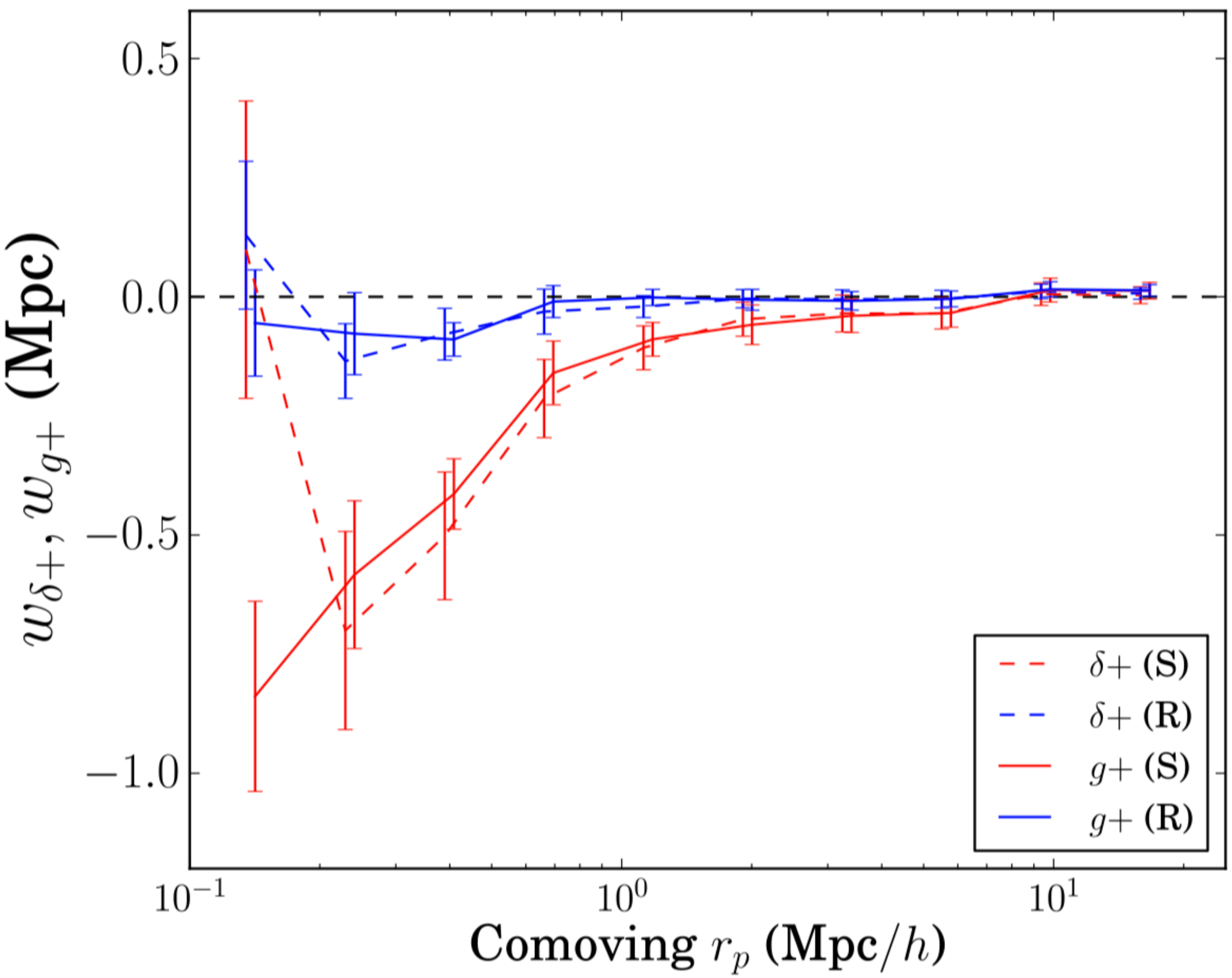


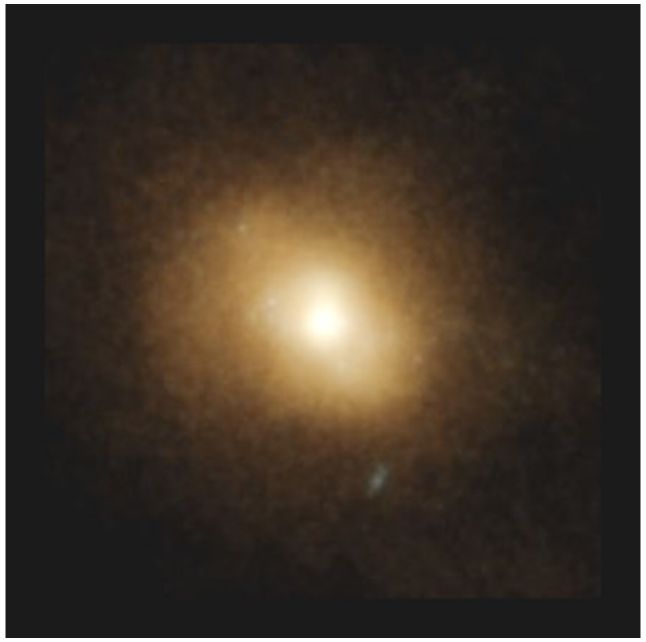
Image: J. Devriendt, Horizon-AGN



SIMULATING IA

Red elliptical galaxies align

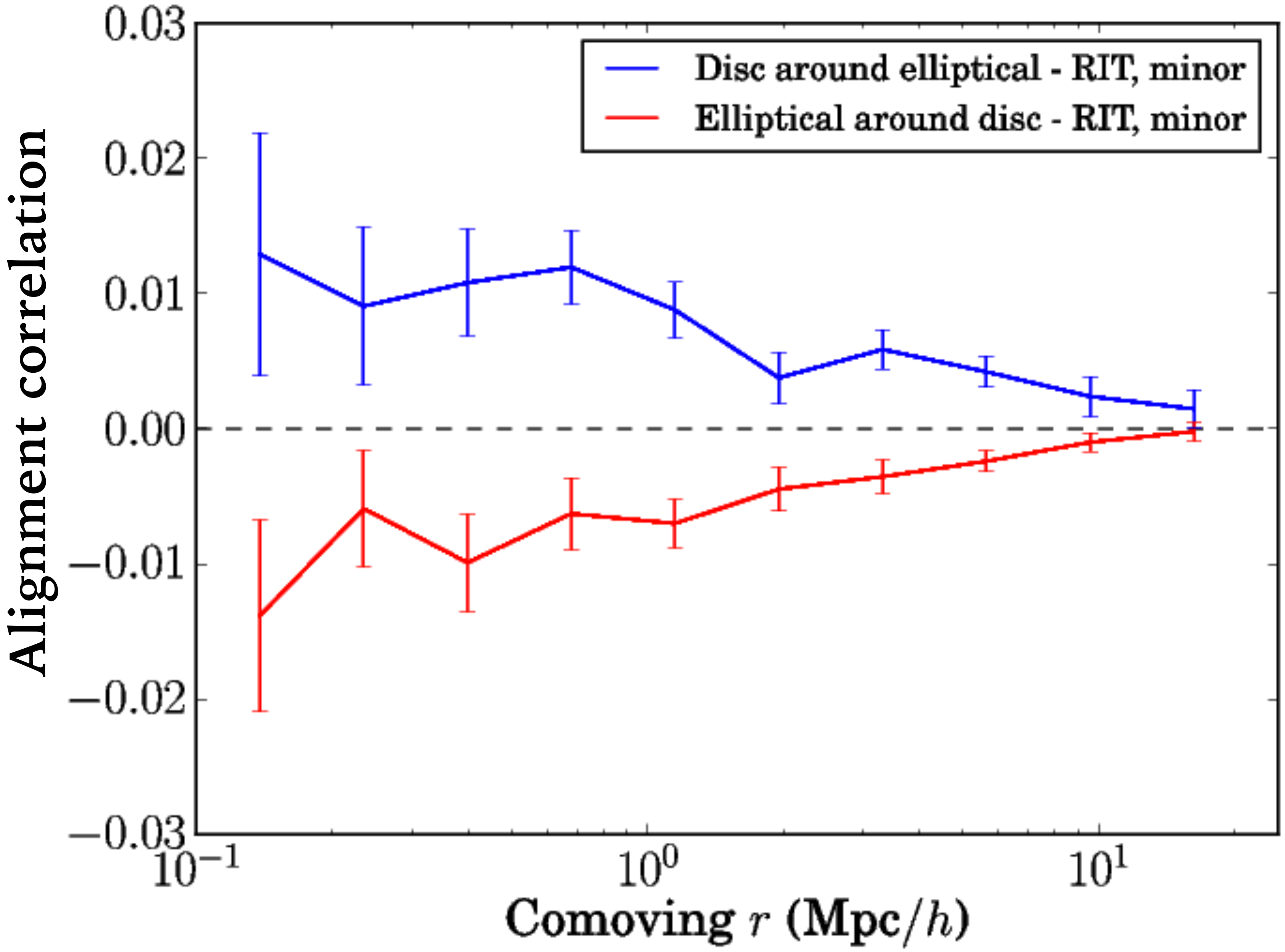


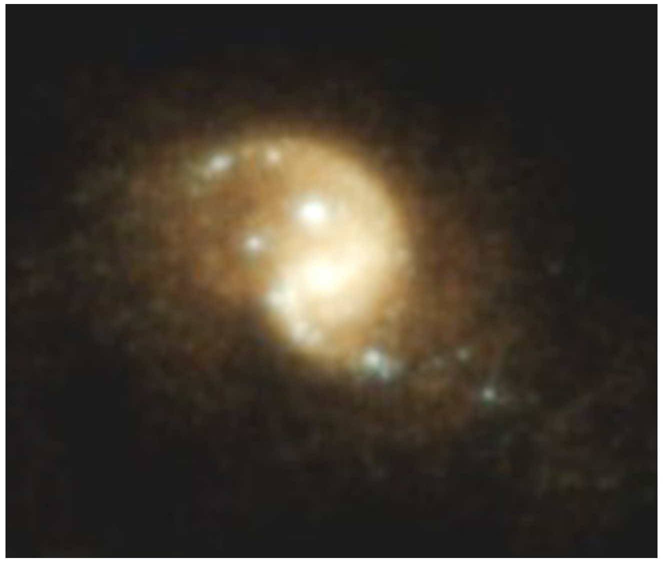


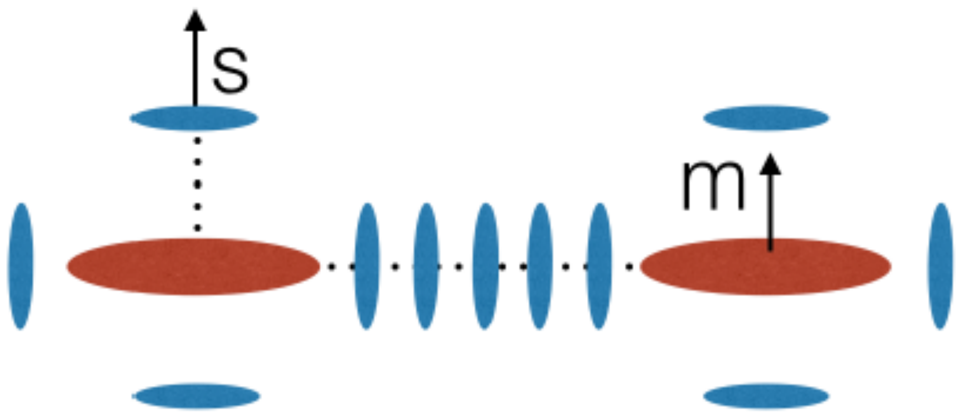
EC+(2015)

SIMULATING IA

Blue disc alignments: a puzzle

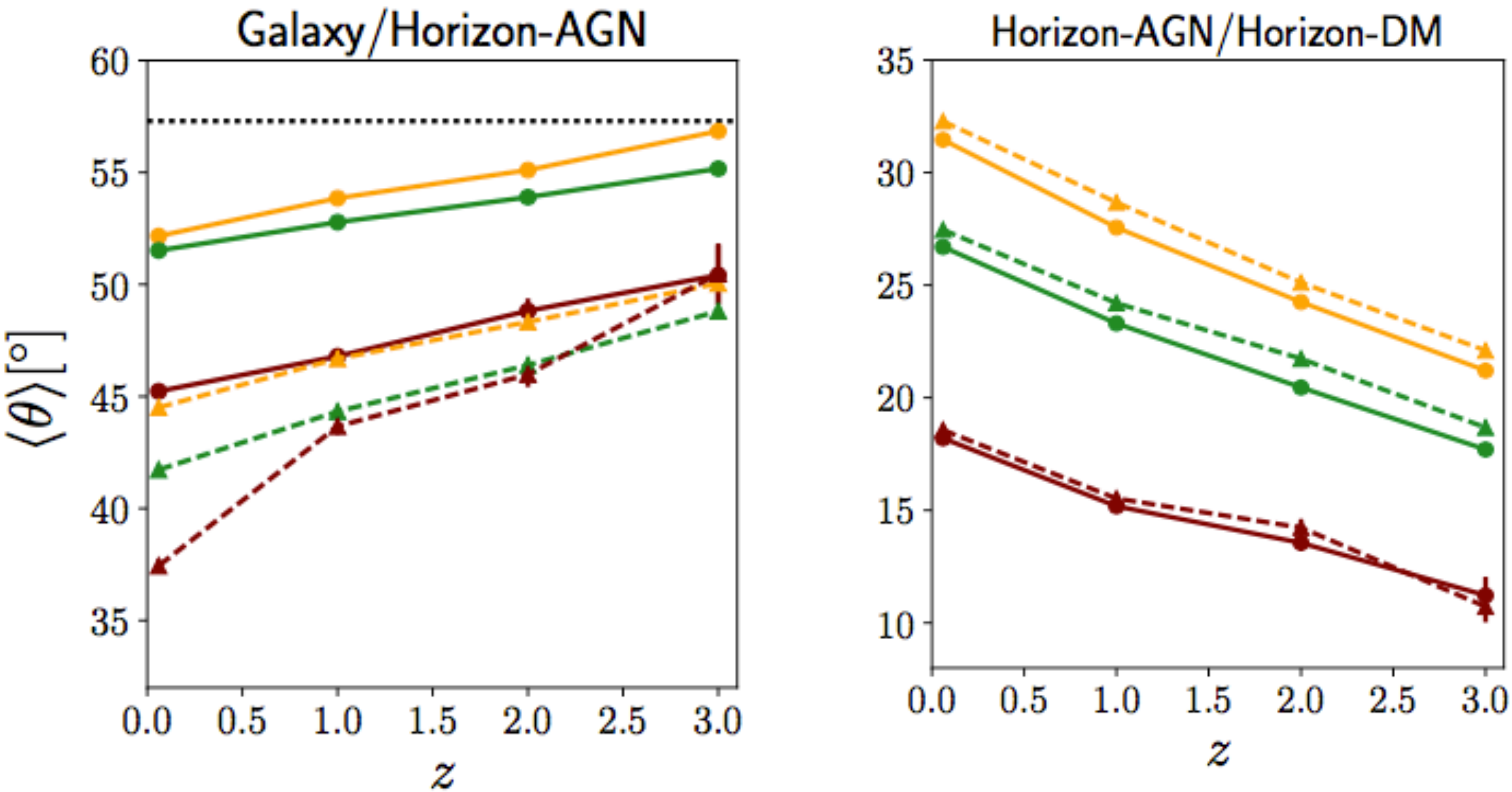






EC+ (2015)
Tenneti+ (2016)
Velliscig+ (2015)
Hilbert+ (2017)
Kraljic+ (2019)

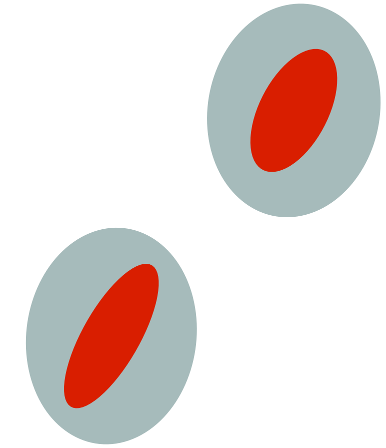
SIMULATING IA



GALAXY-HALO MISALIGNMENT AS A FUNCTION OF REDSHIFT

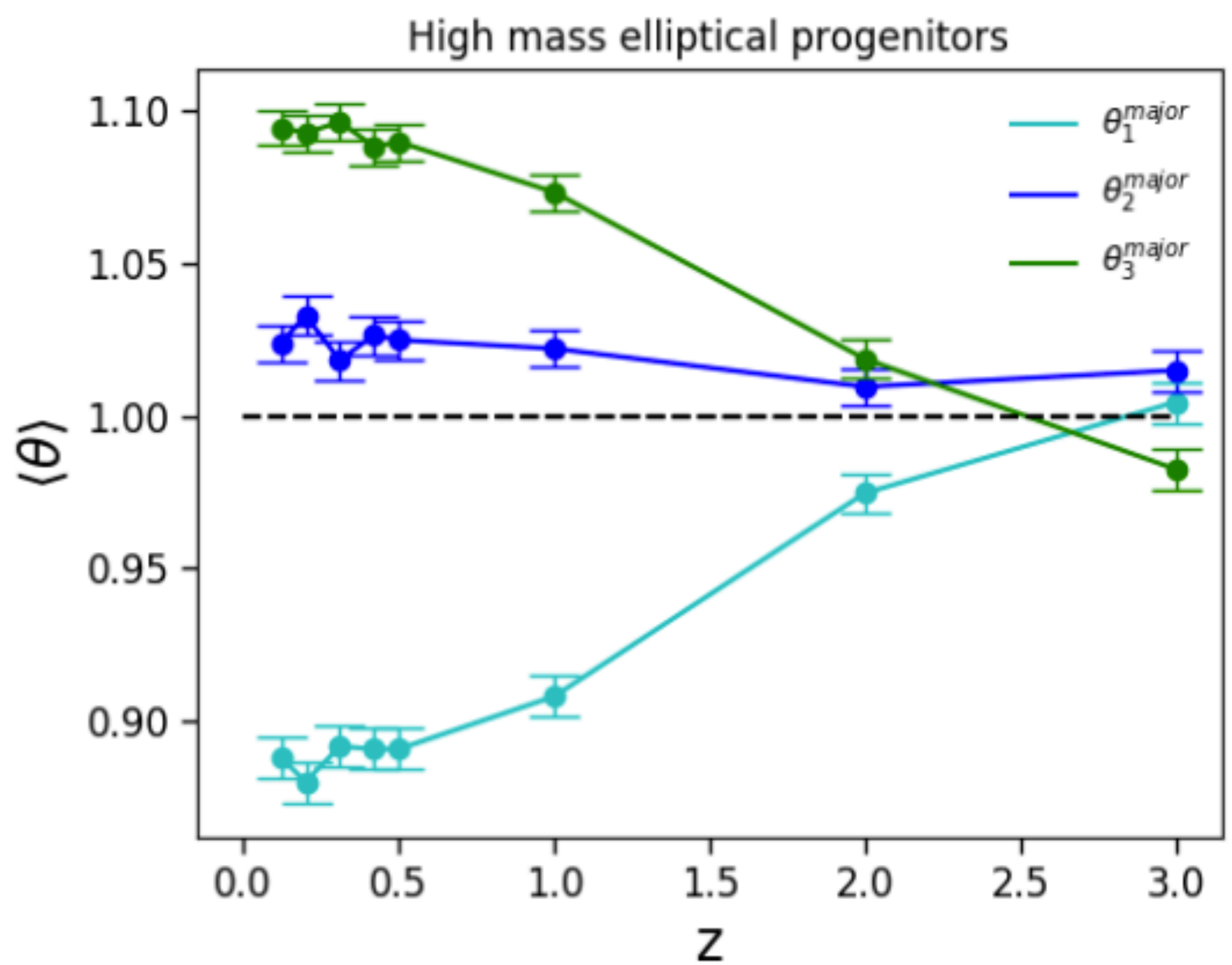
EC, Koukoufilippas+ (2017)
see also Bowhmick+ (2019)

SIMULATING IA



WHEN DO GALAXIES ALIGN?

THE ALIGNMENTS OF MASSIVE ELLIPTICAL PROGENITORS



Aligned

Misaligned

Aligned

Bate, EC+ (2020)

OPPORTUNITIES FROM INTRINSIC ALIGNMENTS

COSMOLOGY

Linear alignment model (small alignment regime)

$$\boxed{I \propto (\partial_x^2 - \partial_y^2)\Phi}$$

Catelan+ (2001)

BARYON ACOUSTIC OSCILLATIONS

EC & Dvorkin (2013)
Okumura+ (2019)

PRIMORDIAL GRAVITATIONAL WAVES

EC, Dvorkin & Schmidt (2016)
Biagetti & Orlando (2020)

TESTING THEORIES OF INFLATION

EC+ (2016)
Schmidt, EC & Dvorkin (2015)

COSMOLOGY

Linear alignment model (small alignment regime)

$$\boxed{I \propto (\partial_x^2 - \partial_y^2)\Phi}$$

Catelan+ (2001)

TESTING THEORIES OF INFLATION

$$w_{g+} \propto gI \boxed{+ \text{new terms}}$$

$$\xi_{++} \propto \gamma\gamma + \gamma I + II \boxed{+ \text{new terms}}$$

Spin-2 particles during inflation

Magnetic fields

Solid inflation

(any anisotropic primordial non-Gaussianity)

EC+ (2016)

Schmidt, EC & Dvorkin (2015)

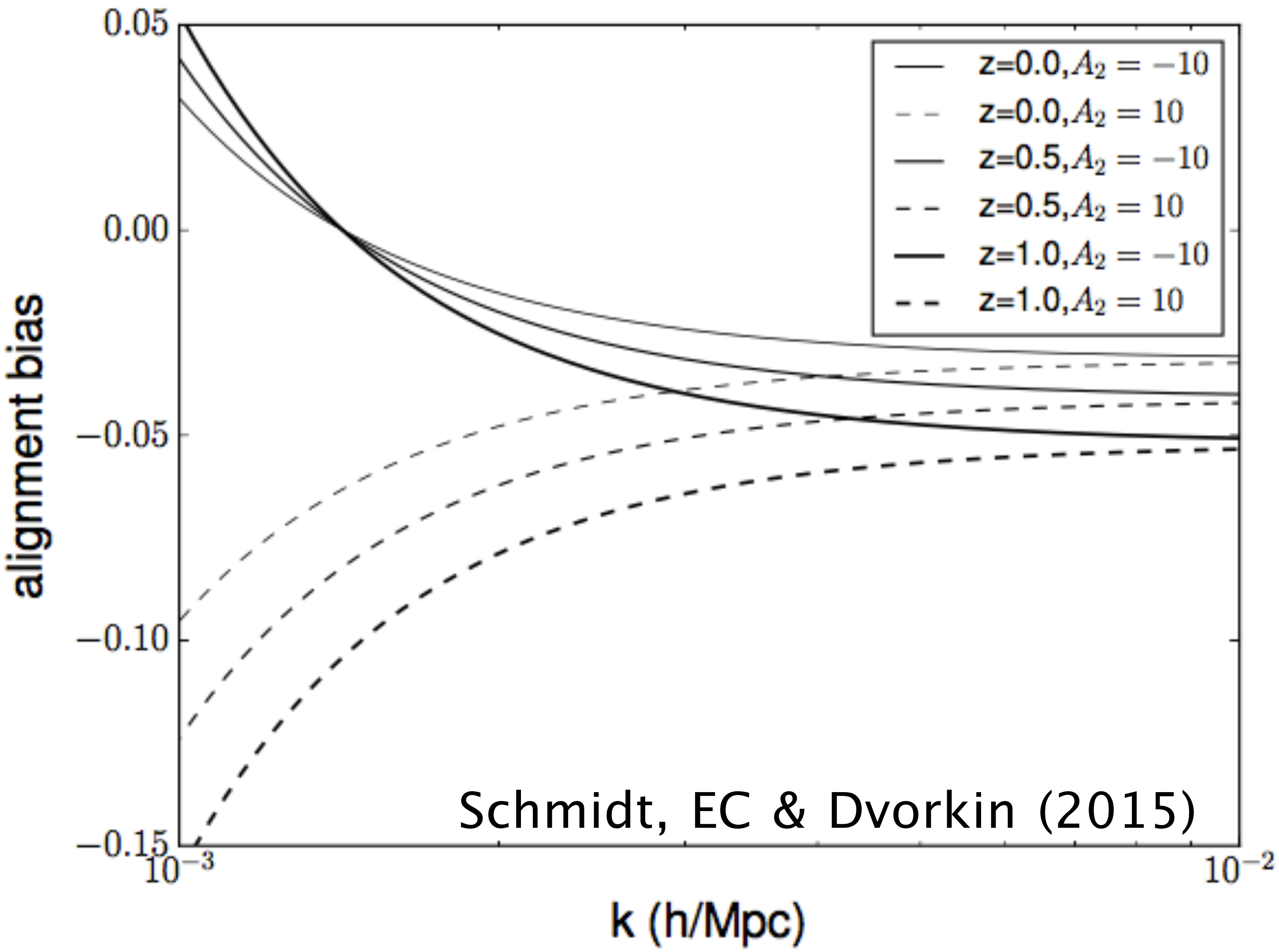
COSMOLOGY

Scale-dependent bias of galaxy shapes

$$\langle \delta(\mathbf{k}') I_{ij}(\mathbf{k}) \rangle = \left(\frac{k_i k_j}{k^2} - \frac{1}{3}\delta_{ij} \right) \left\{ b_1^I + 3 b_{\rm NG}^I A_2 \, \mathcal{M}^{-1}(k) \right\} P_m(k) \, (2\pi)^3 \delta_D(\mathbf{k} + \mathbf{k}')$$

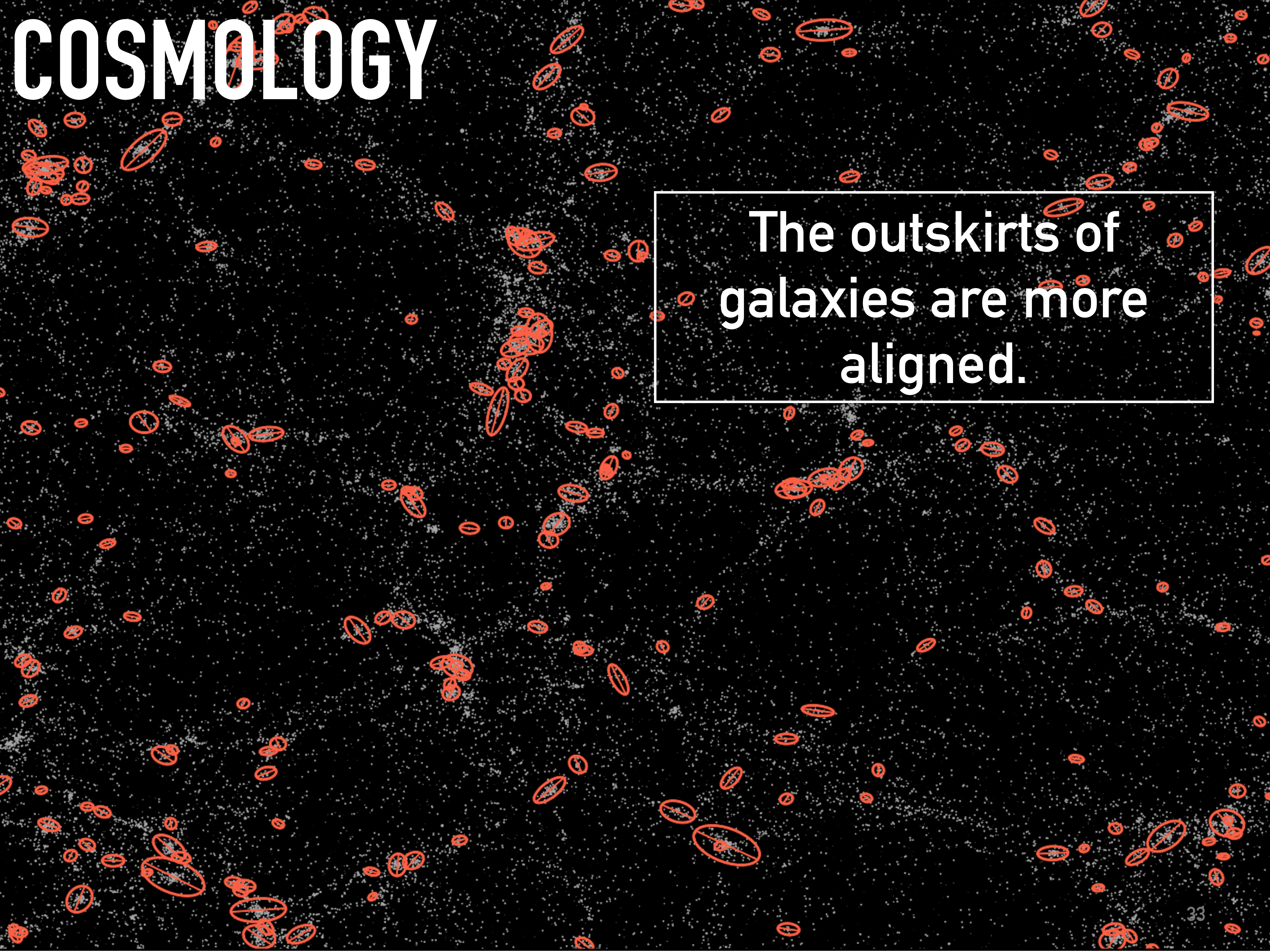
Analogy with scale-dependent bias in clustering

$$\langle \delta(\mathbf{k}') \delta_n(\mathbf{k}) \rangle = \left\{ b_1^n + \frac{1}{2} b_{\rm NG}^n A_0 \, \mathcal{M}^{-1}(k) \right\} P_m(k) \, (2\pi)^3 \delta_D(\mathbf{k} + \mathbf{k}')$$



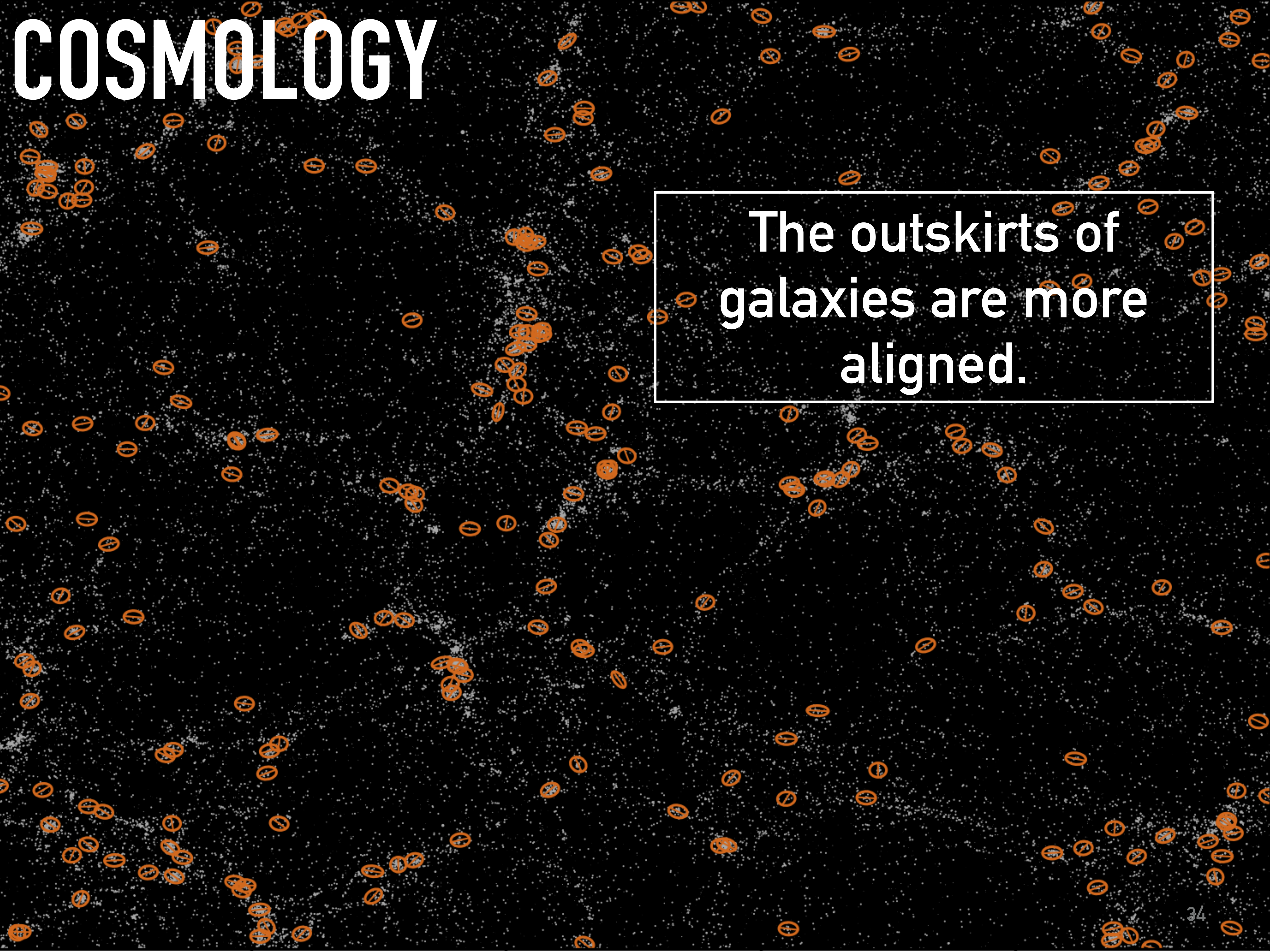
new terms $\propto k^{-2}$

COSMOLOGY



The outskirts of galaxies are more aligned.

COSMOLOGY

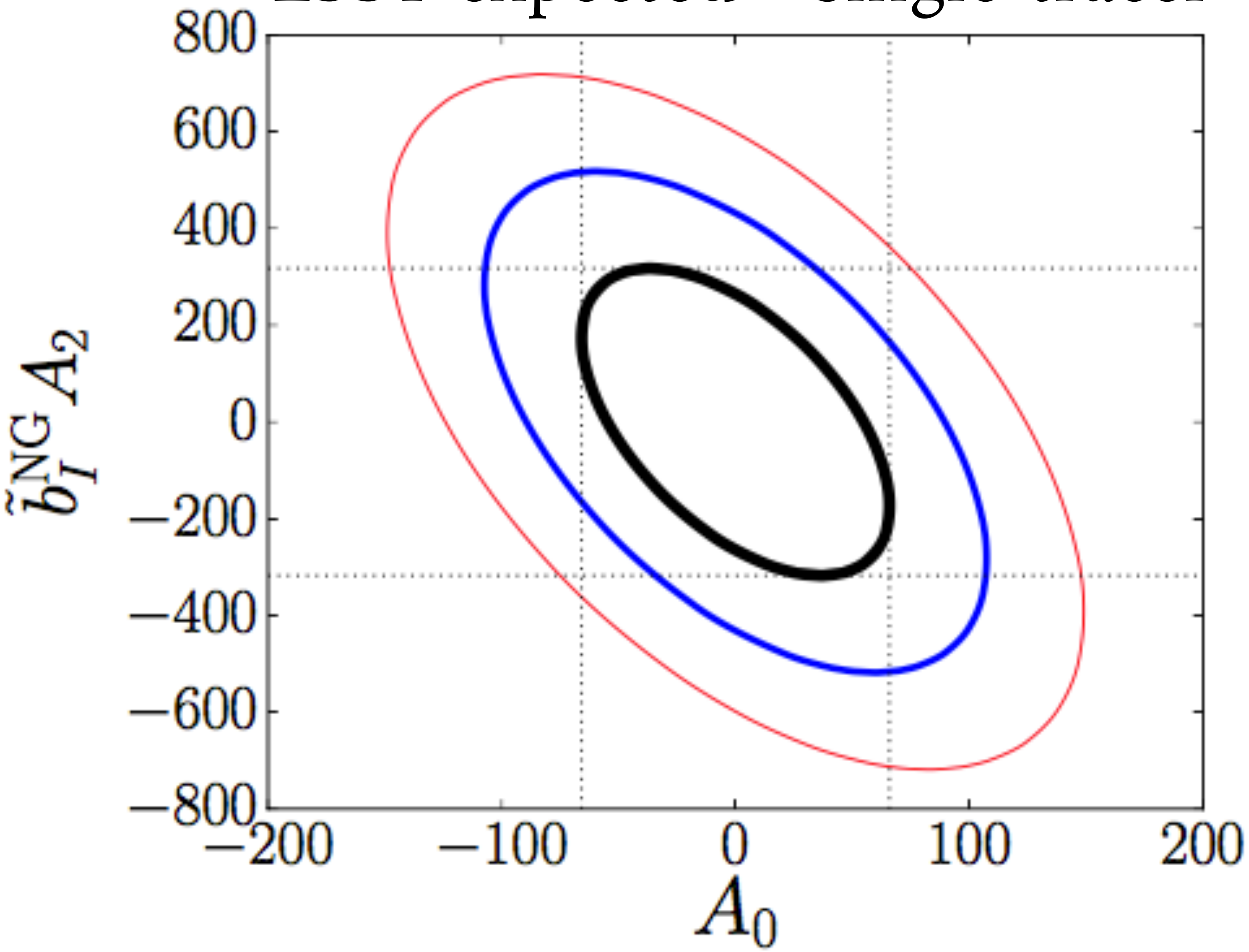


The outskirts of galaxies are more aligned.

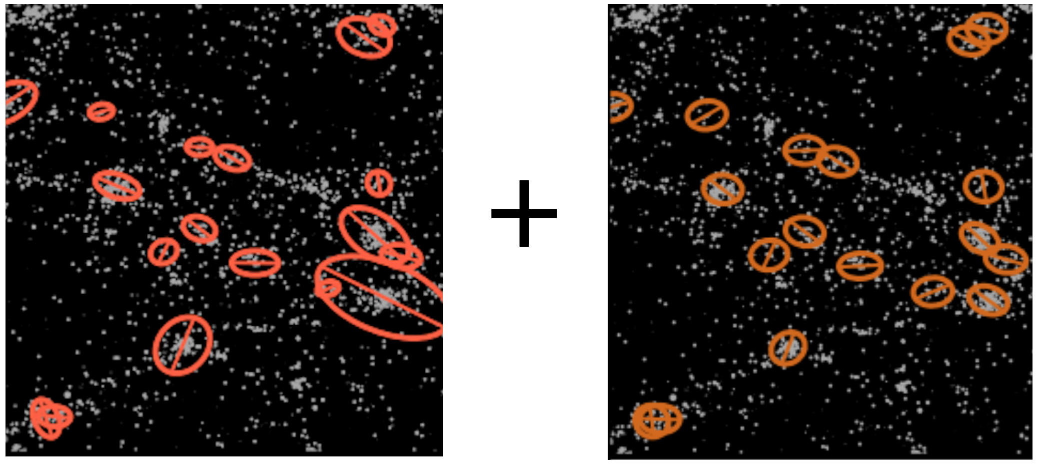
COSMOLOGY

Inflationary model parameters **A_0, A_2, ...**

LSST expected – single-tracer



Multi-shape



Schmidt, EC & Dvorkin (2015)
EC+ (2016)

COSMOLOGY

Inflationary model parameters **$A_0, A_2, \ldots$**

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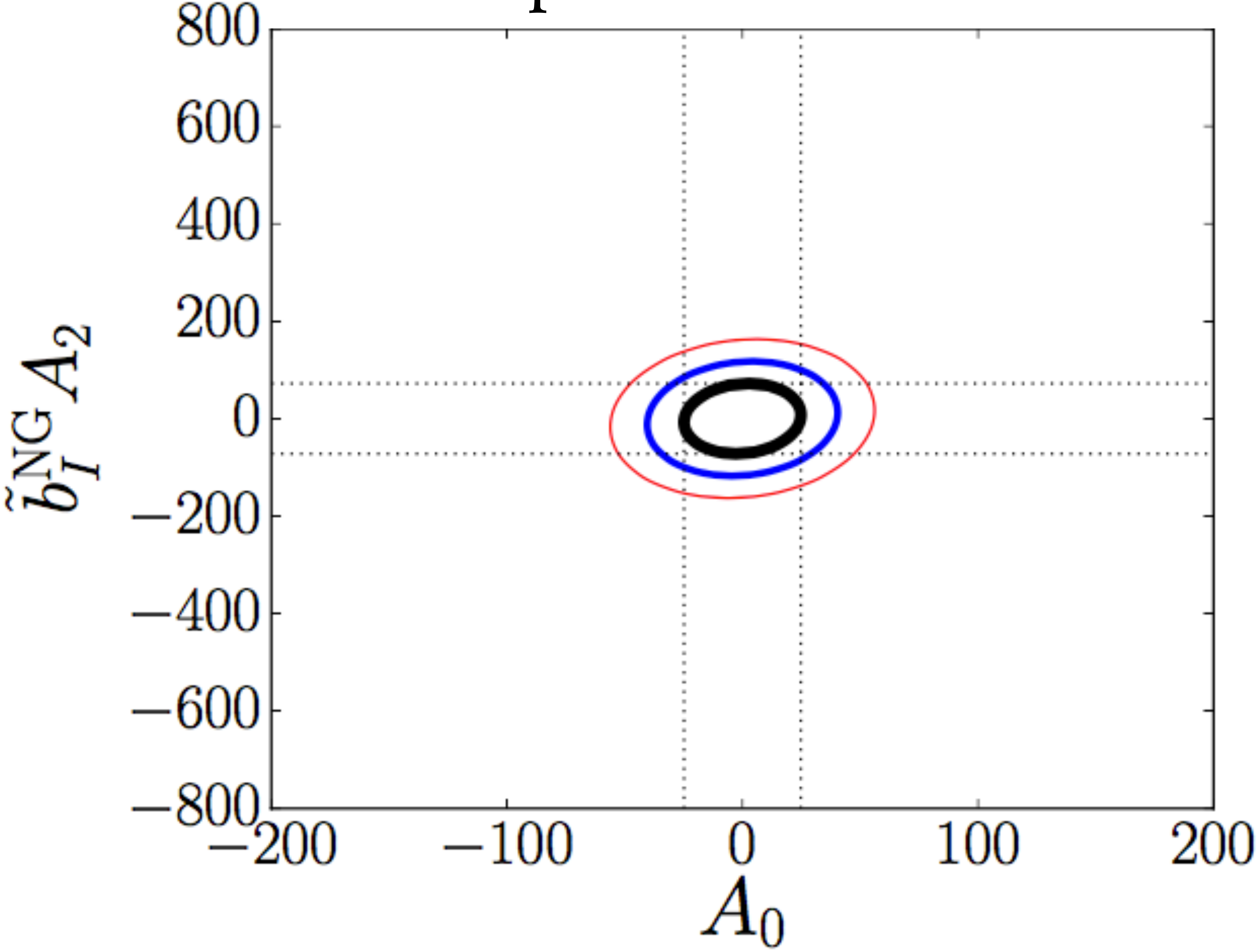

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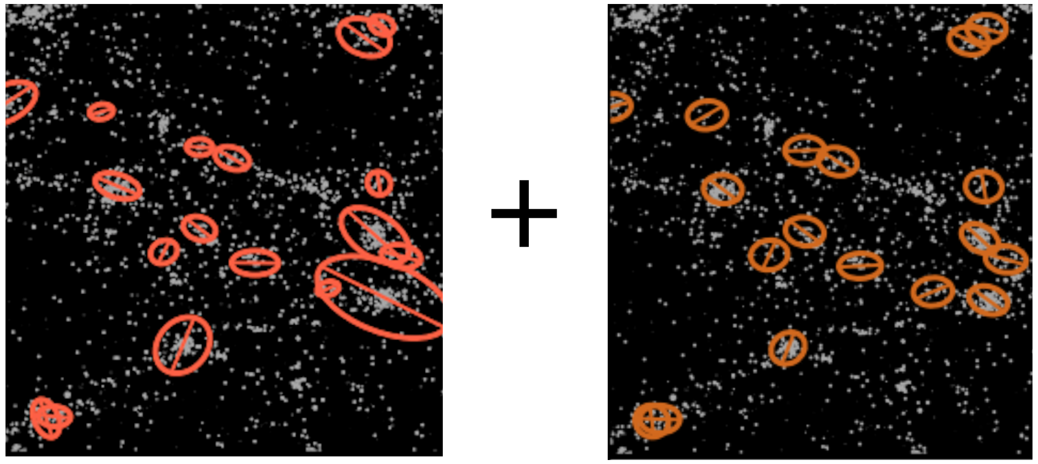
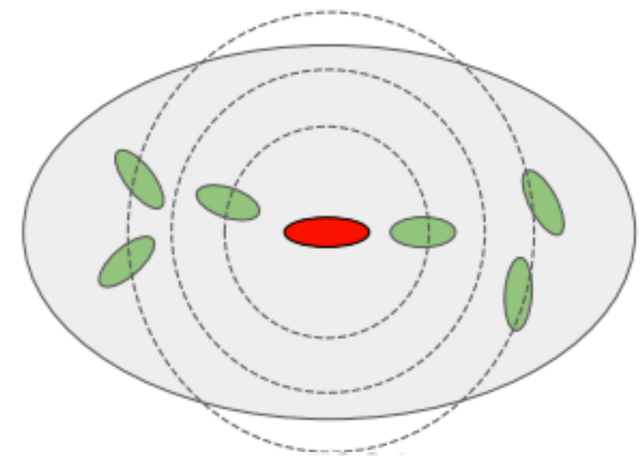


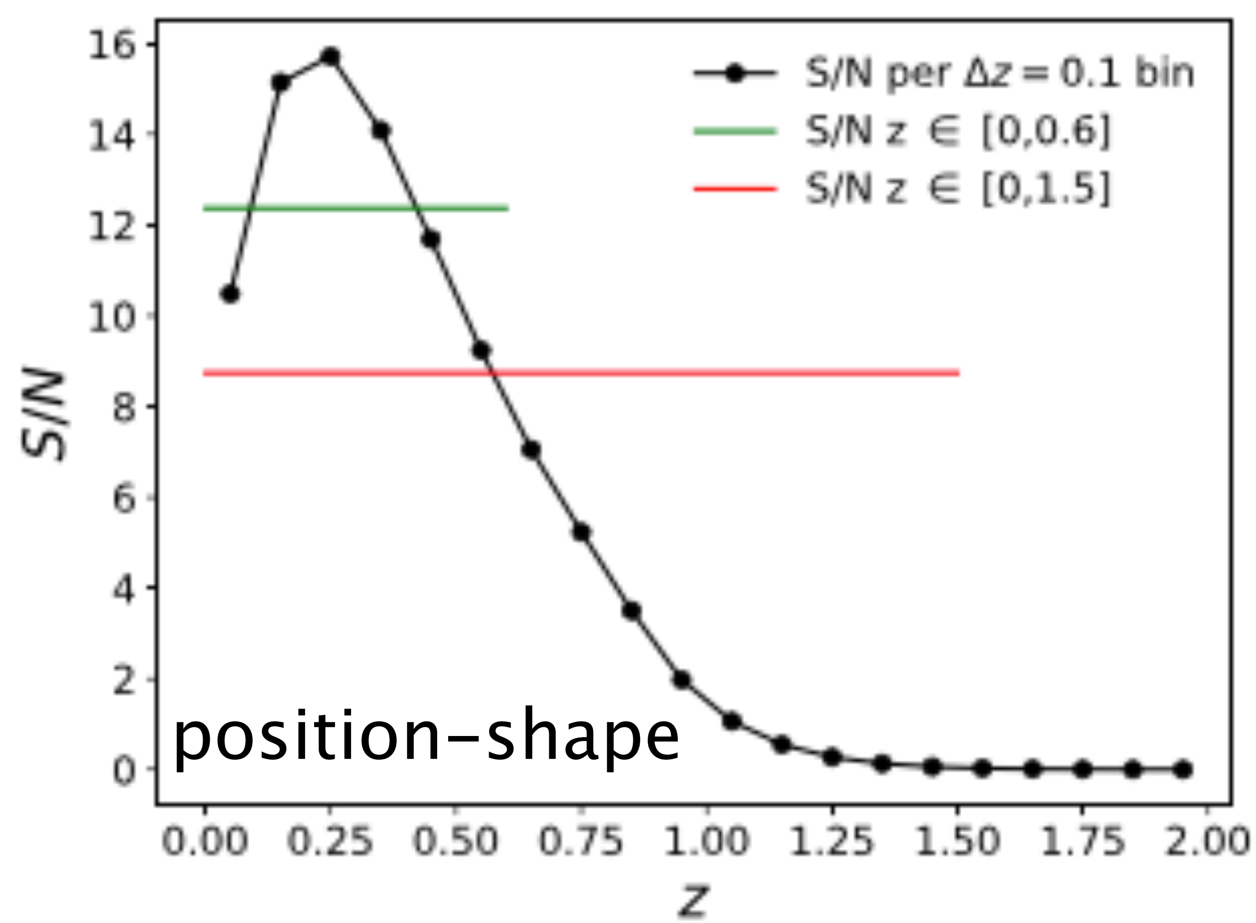
Schmidt, EC & Dvorkin (2015)
EC+ (2016)

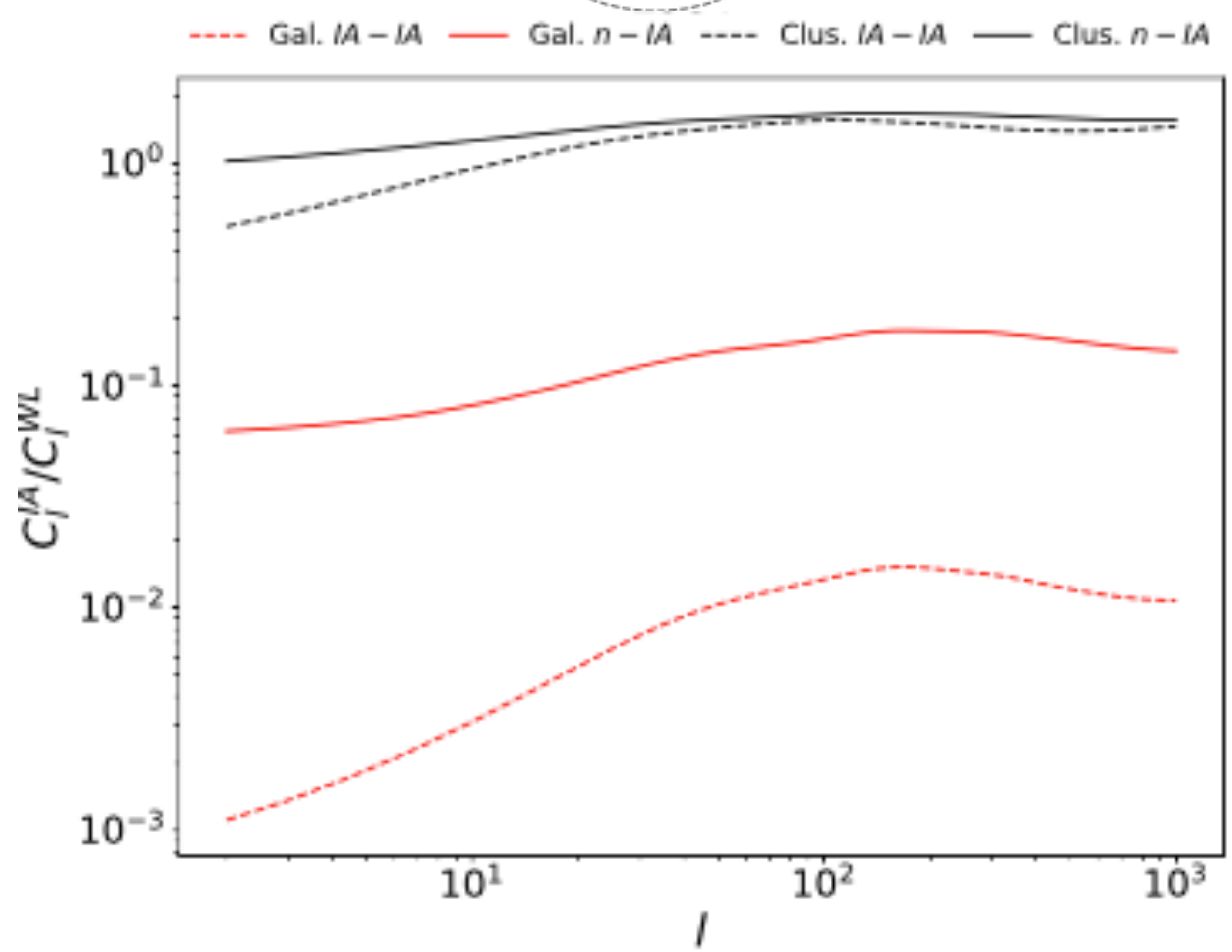
EXPLORING NEW OBSERVABLES

Cluster shapes are also aligned
(most recently van Uitert & Joachimi, 2017)



Forecast for LSST

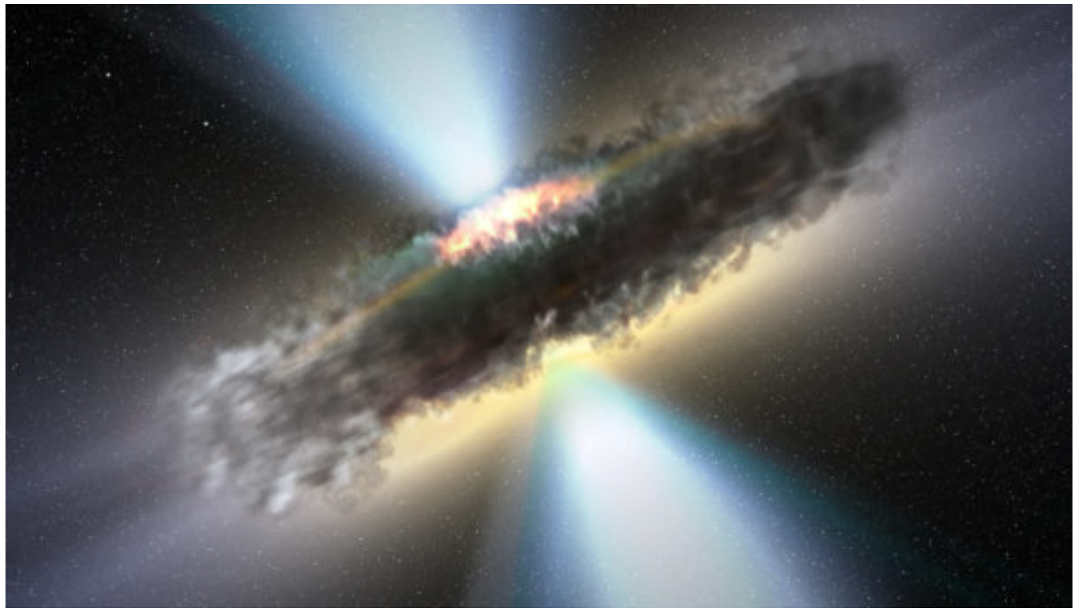




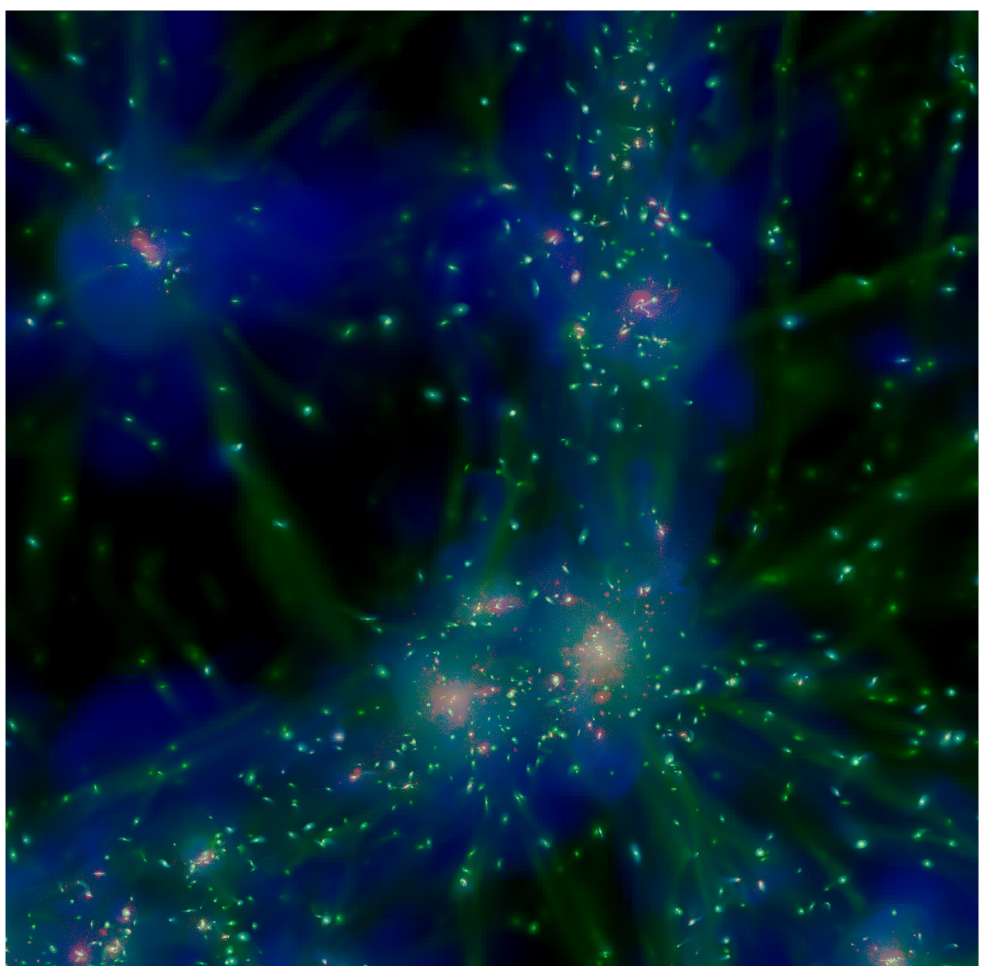
Cluster alignments are detectable and can be more easily recovered than galaxy alignments from future surveys

Vedder & EC (to appear)

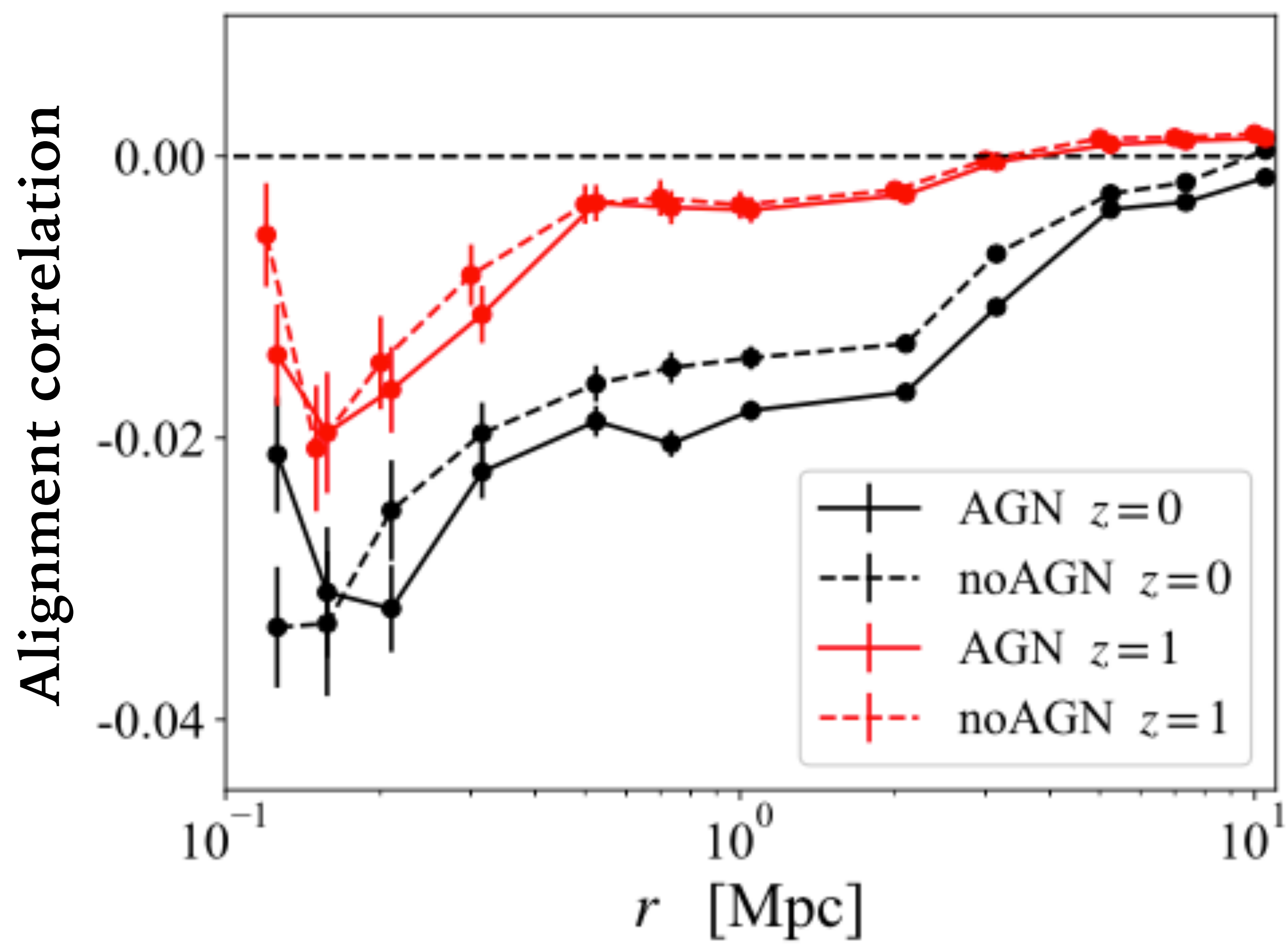
GALAXY EVOLUTION



Credit: ESA / V. Beckmann (NASA-GSFC)



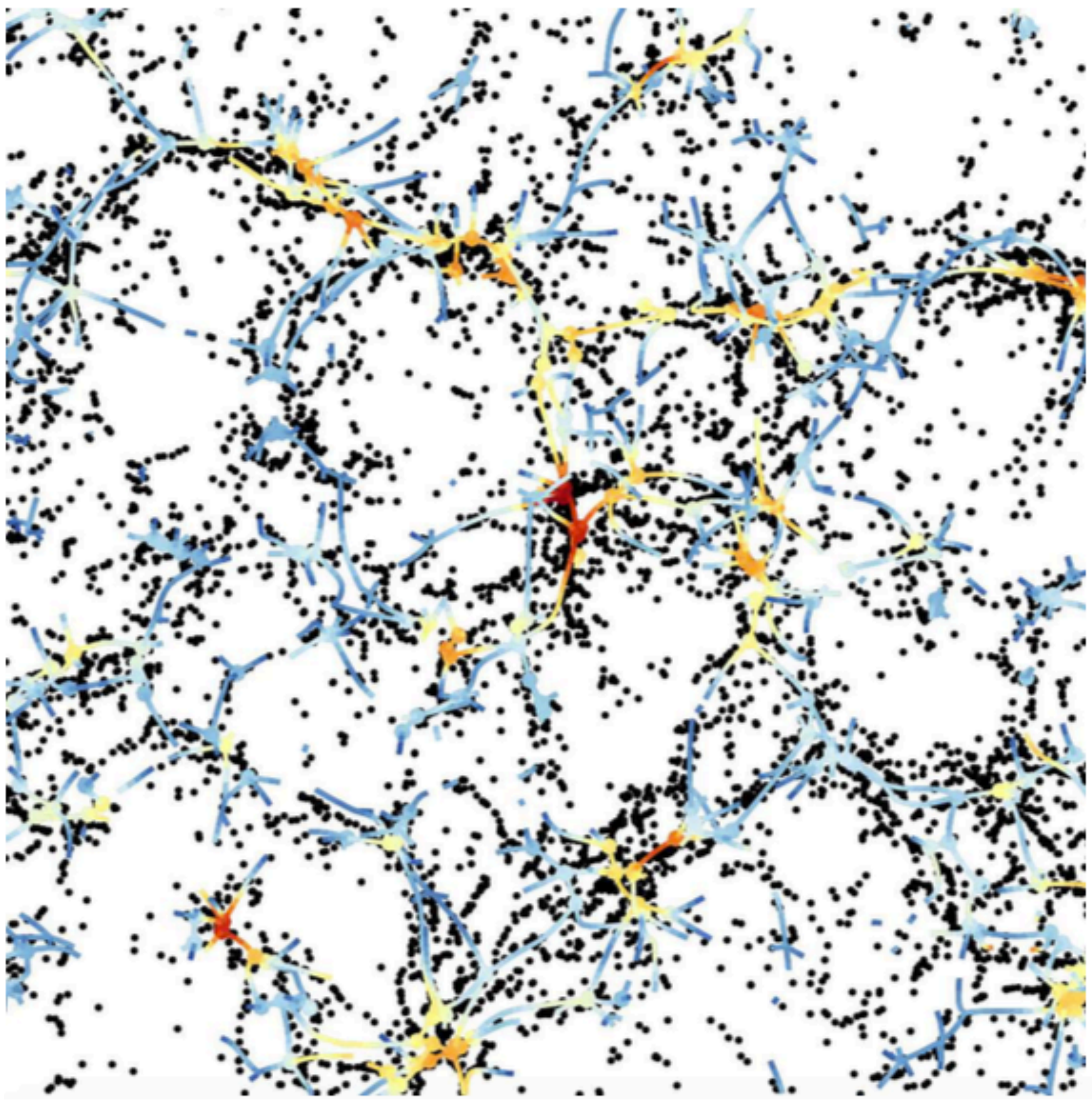
Credit: J. Devriendt (Horizon-AGN)

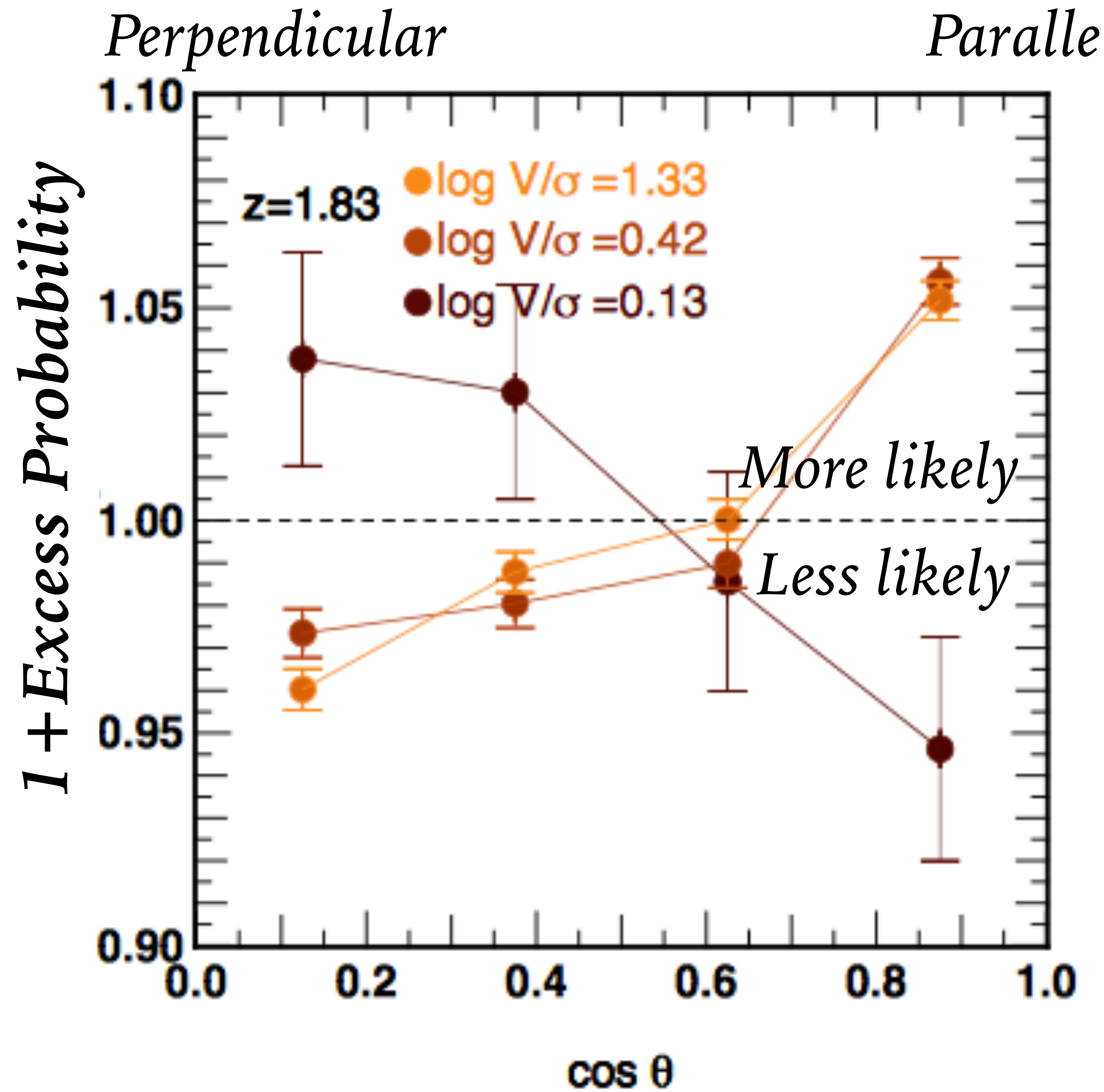


A significant impact of Active Galactic Nuclei on galaxy alignments.

Soussana, EC+ (2020)

GALAXY EVOLUTION

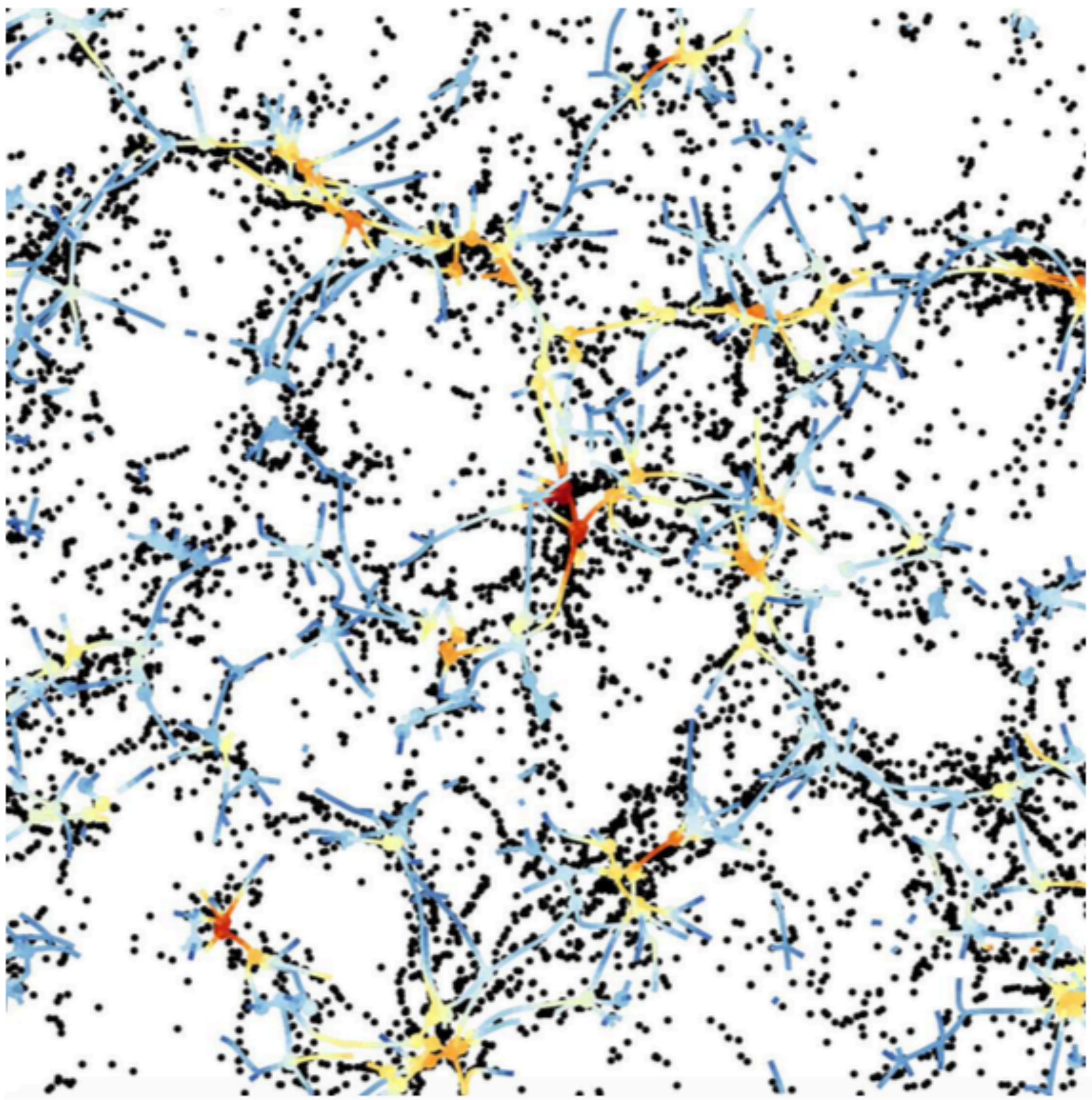


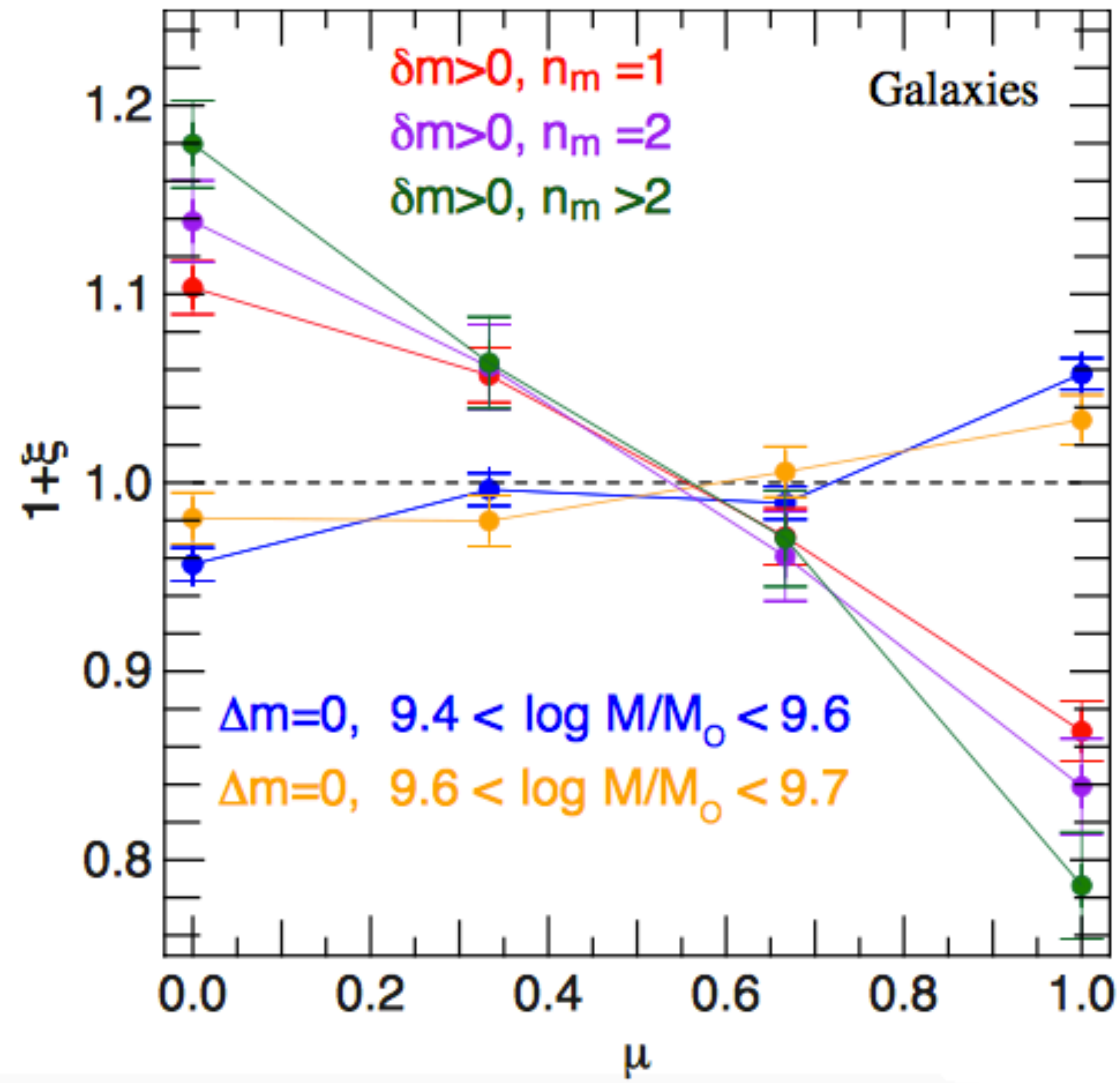


SPIN SWINGS IN THE COSMIC WEB

Dubois+ (2014)
Codis+, incl. EC (2018)

GALAXY EVOLUTION





MERGERS AS DRIVERS OF SPIN SWINGS
A CONNECTION TO GALAXY SHAPES?

Dubois+ (2014)
Welker+ (2014)

CONCLUSIONS

Intrinsic alignments show a link between galaxies and the tidal field of the Universe at linear scales.

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Alignments of galaxies and clusters at different scales, and cross-correlations with other fields, open opportunities for cosmology.

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Intrinsic alignments show a link between galaxies and the tidal field of the Universe at linear scales.

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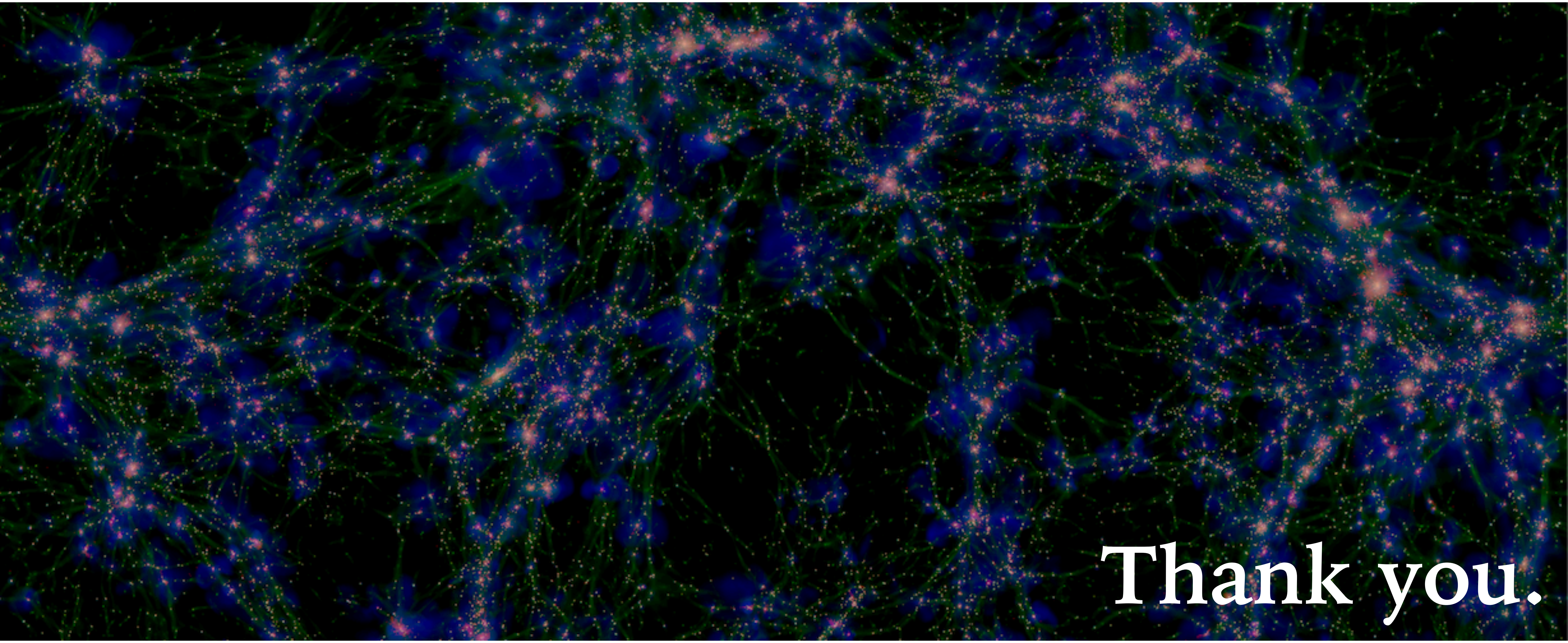
Alignments of galaxies and clusters at different scales, and cross-correlations with other fields, open opportunities for cosmology.

Intrinsic alignments are now known to be sensitive to galaxy evolution processes.



n.e.chisari@uu.nl