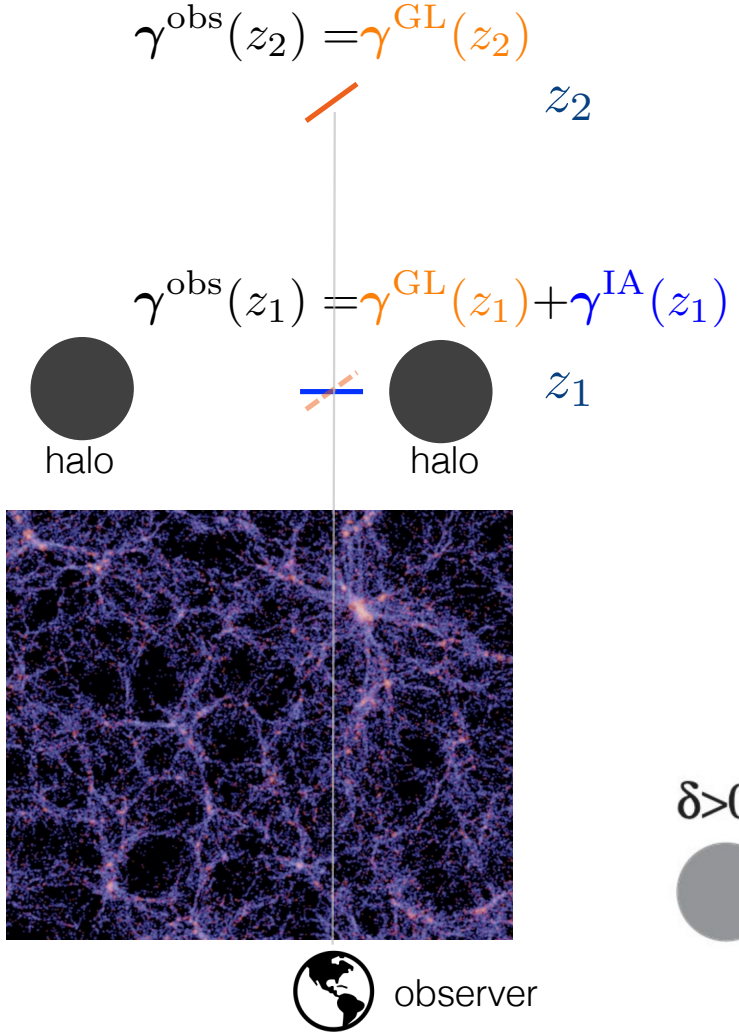
New Frontiers in Cosmology with the Intrinsic Alignments of Galaxies

Masahiro Takada (Kavli IPMU)

Intrinsic alignment (IA): signal vs. contamination?



- Hirata & Seljak (2004)

$$\langle \gamma^{\rm obs}(z_1)\gamma^{\rm obs}(z_2)\rangle = \langle \gamma^{\rm GL}(z_1)\gamma^{\rm GL}(z_2)\rangle + \langle \gamma^{\rm IA}(z_1)\gamma^{\rm GL}(z_2)\rangle$$

cosmic shear — IA contamination

$$\langle \gamma^{\rm IA}(z_1)\gamma^{\rm GL}(z_2)\rangle \neq 0 < 0$$

IA contamination needs to be considered in cosmic shear cosmology

- Galaxy-galaxy lensing is NOT contaminated by IA

$$\langle \delta_{\rm g}(\mathbf{x}; z_1)\gamma^{\rm GL}(z_2)\rangle$$

- IA cross-correlation function $\langle \delta_{\rm g}(\mathbf{x}; z_1)\gamma^{\rm IA}(\mathbf{x}'; z_1)\rangle$

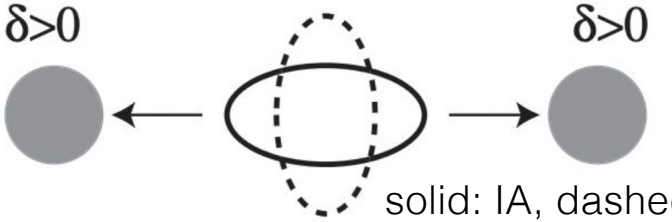
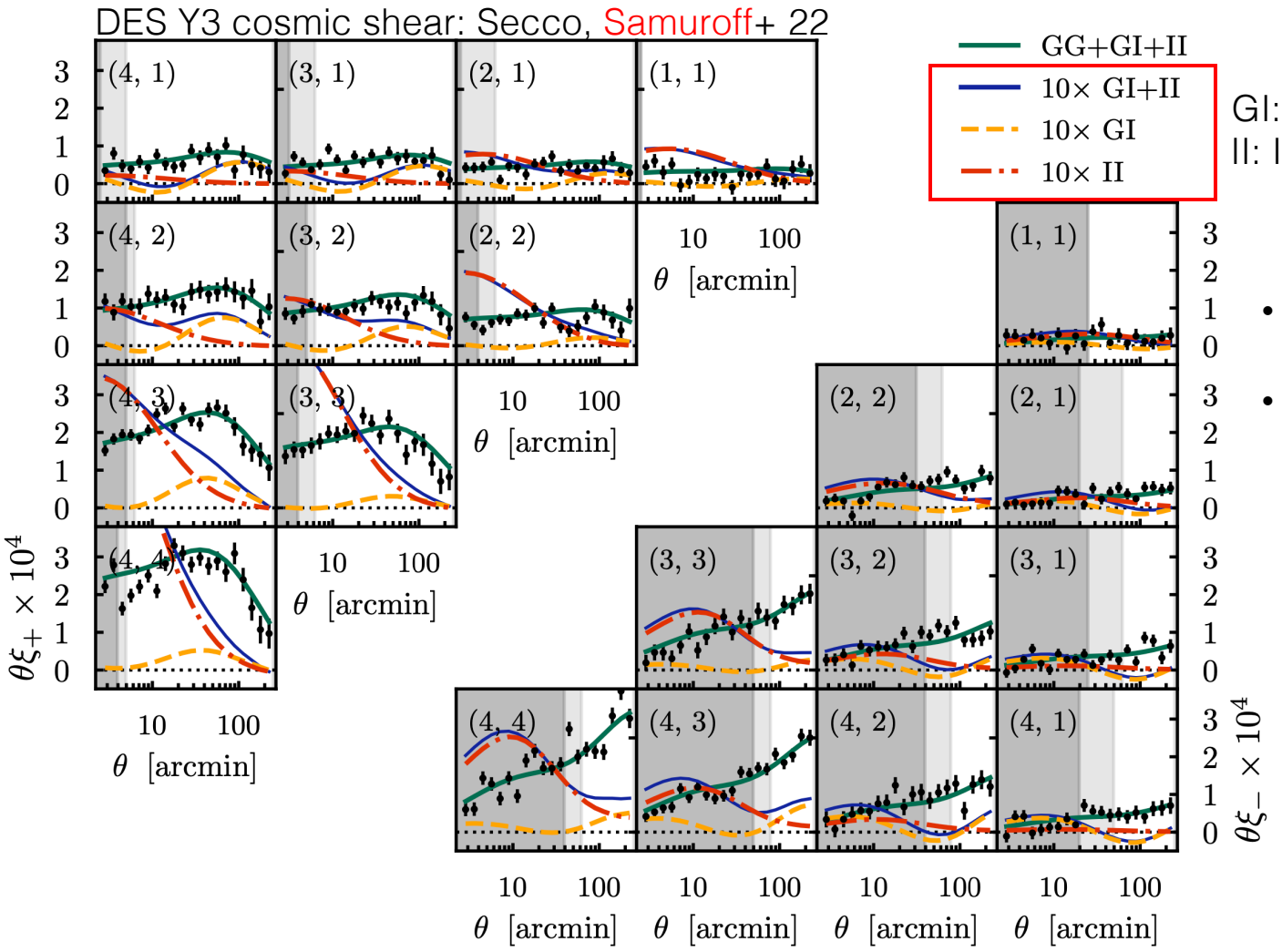


Image credit:
Hirata & Seljak (2004)

solid: IA, dashed: shear of background galaxies

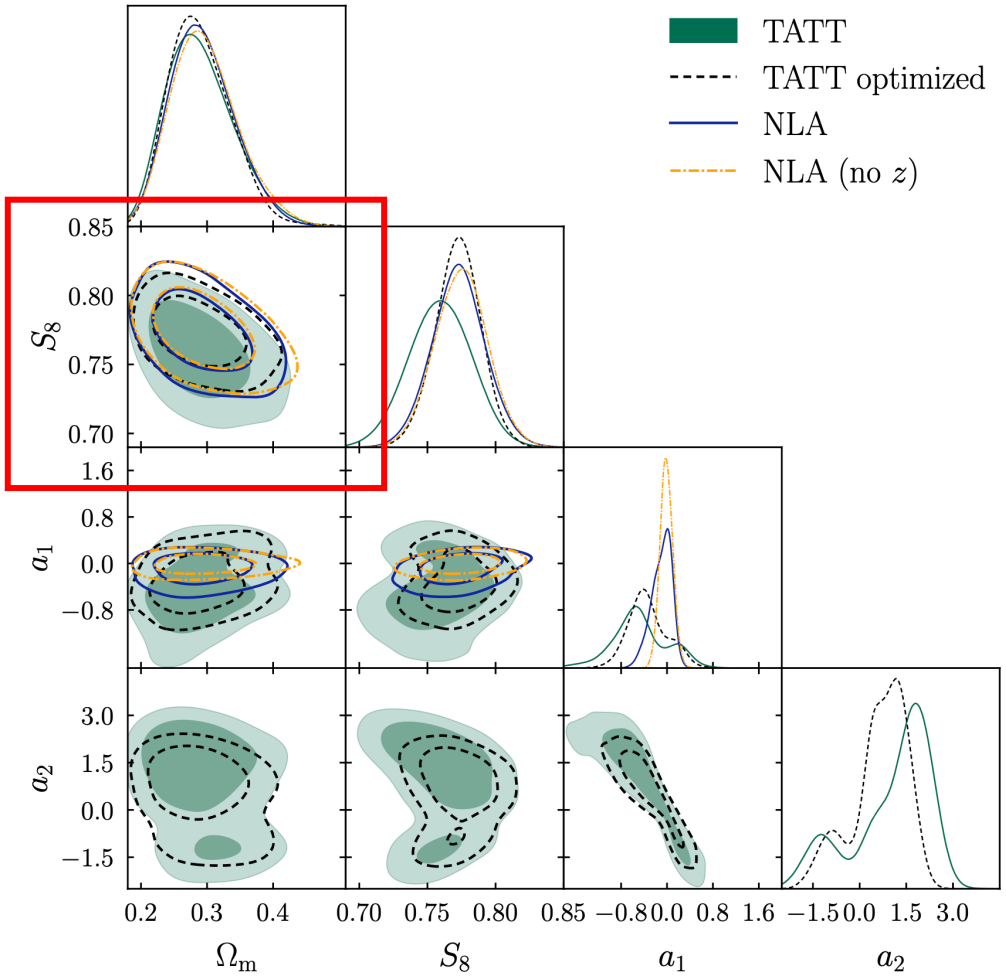
As contaminating effect in weak lensing cosmology



- Solid lines are best-fit model predictions
- So far, no clear signature of baryonic physics and IA contamination, down to scales below the scale cuts (this is true for HSC and KiDS too)

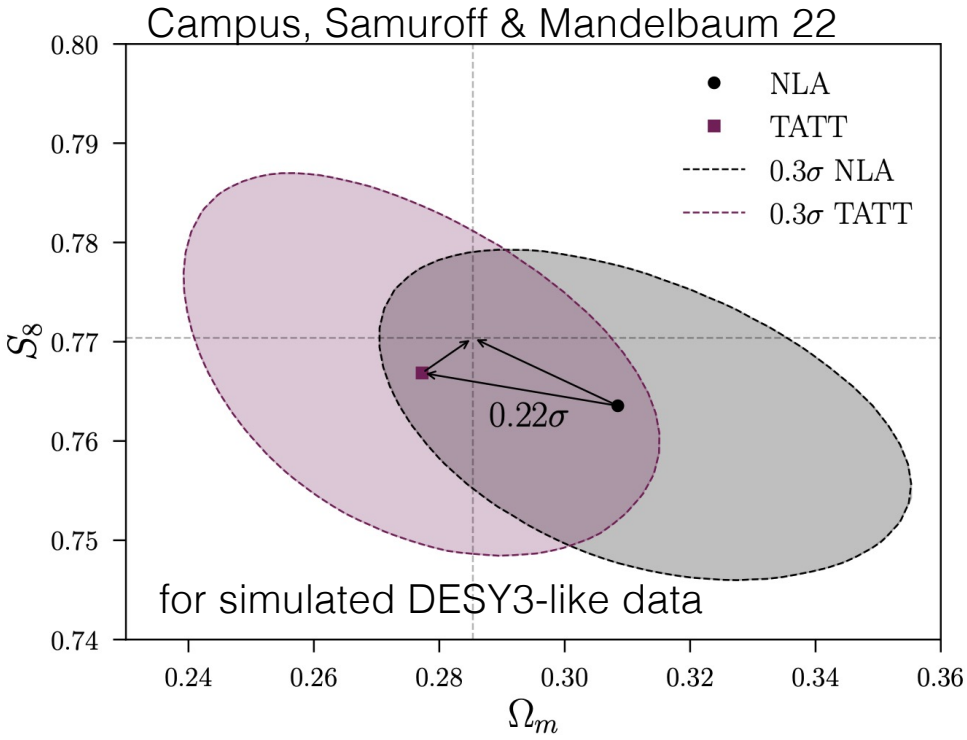
As contaminating effect in weak lensing cosmology

DES Y3 cosmic shear: Secco, Samuroff+ 22



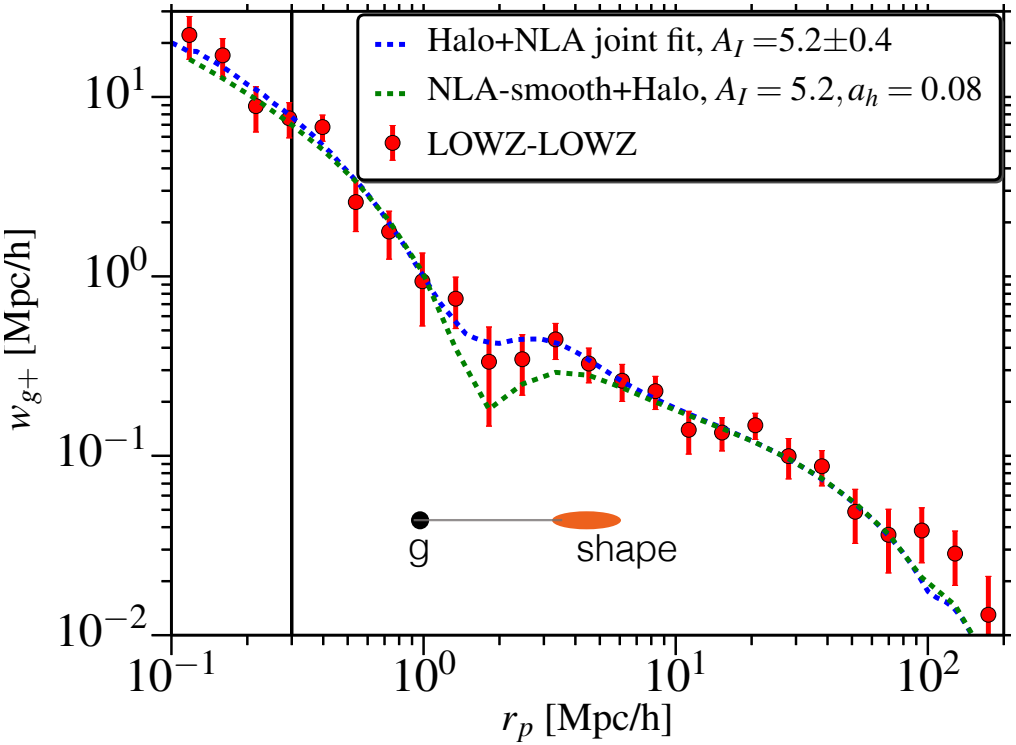
See Simon' and Rachel's talks

Campus, Samuroff & Mandelbaum 22

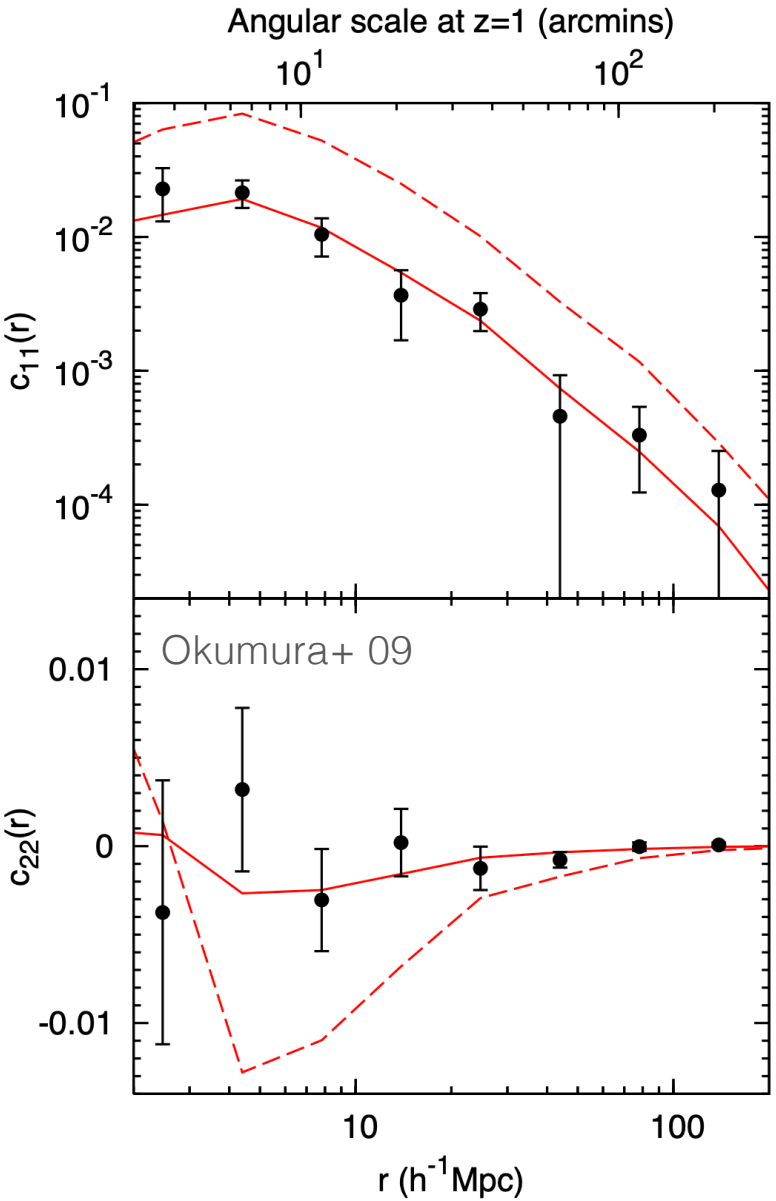


IA as “signal”

See Teppei, Sukhdeep, and Toshiki’s talks



Singh & Mandelbaum 15



Confusion: we should use “common” languages

- A_IA: linear/nonlinear alignment model

$$\gamma_{ij}(\mathbf{x};z) = -\frac{C_1}{4\pi G}\left(\partial_i\partial_j - \frac{\delta^K_{ij}}{3}\nabla^2\right)\Phi_P(\mathbf{x})$$

$$\rightarrow \boldsymbol{\gamma}^{\rm proj}(\mathbf{k};z) = -A_{\rm IA}C_1\rho_{\rm cr0}\frac{\Omega_{\rm m}}{D(z)}\frac{(k_x^2-k_y^2, 2k_xk_y)}{k^2}\delta_{\rm m}(\mathbf{k},z)$$

A_IA ~ 10-30 for halos
A_IA ~ 3 – 10 for galaxies

- b_K: linear shape bias parameter

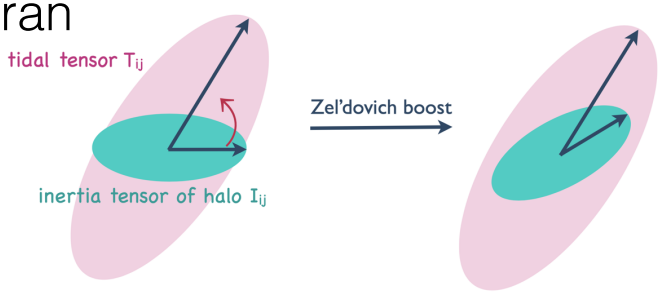
$$\gamma_{ij}(\mathbf{x}) = b_K\partial^{-2}\left(\partial_i\partial_j - \frac{\delta^K_{ij}}{3}\partial^2\right)\delta_{\rm m}(\mathbf{x})$$

b_K ~ 0.05-0.25 for halos
b_K ~ 0.05 for galaxies

should be compared to b_1 ~ O(1)

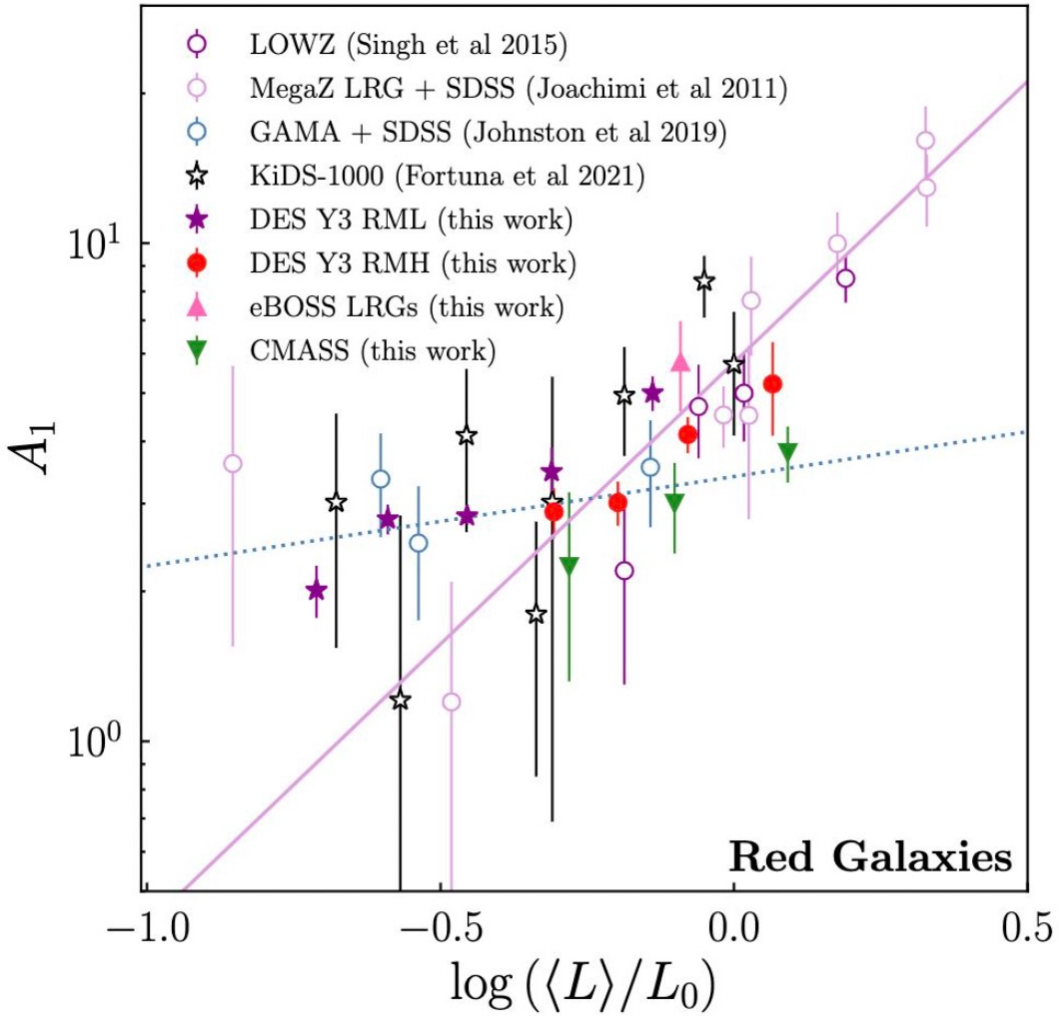
- According to Ue-Li & Haoran

$$L_K \propto \epsilon_{ijk}I_{li}T_{lj}$$



$$b_{L_i}(\mathrm{IC}\rightarrow\mathrm{final}) \sim O(0.4-0.6)$$

IA as signal



See Sukhdeep, Simon, Benjamin's talks
See Benjamin, Jingjing's talks for clusters

Note that there is no clear detection of IA for blue galaxies

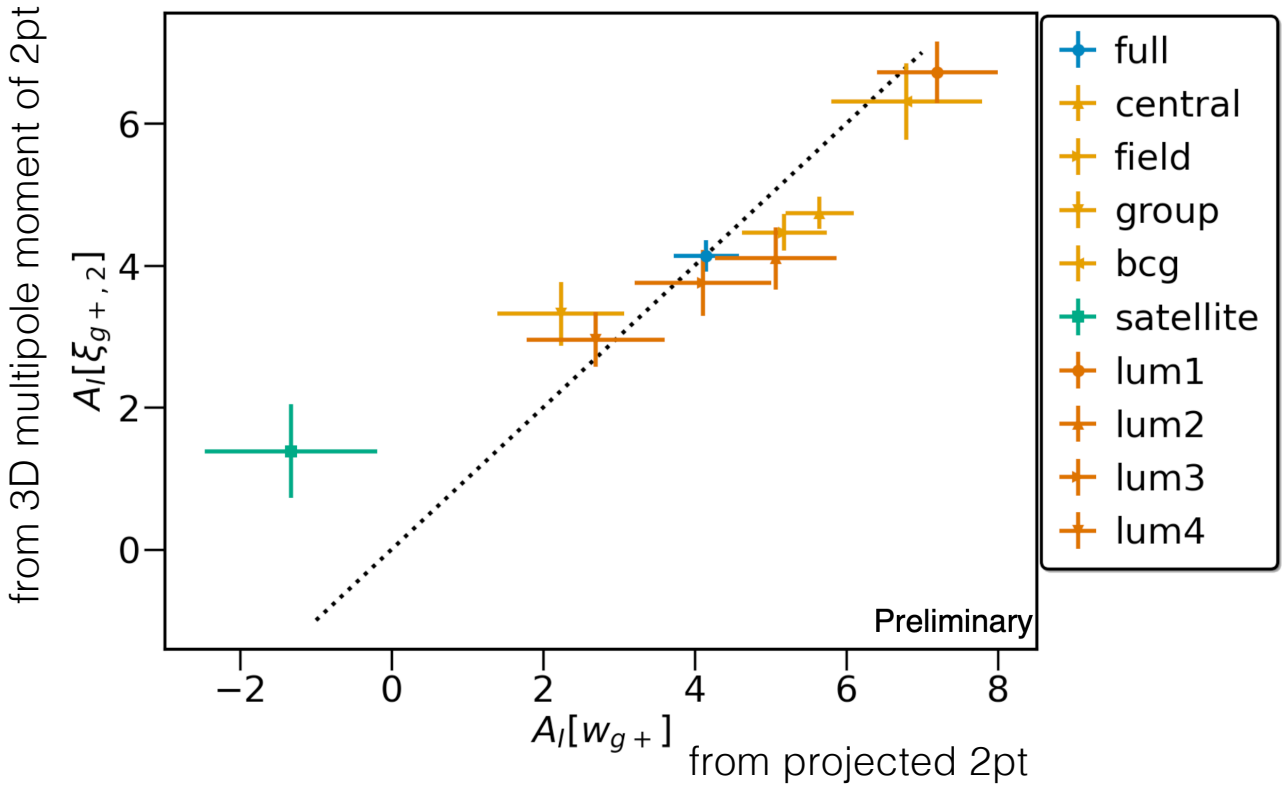
More optimal estimator of IA (e.g., see Sukhdeep, Jingjing and Ishikawa-san's talk)

The photometric sample, redMaGiC (DES), looks very promising; we should try with HSC (and KiDS) (see Hironao's talk)

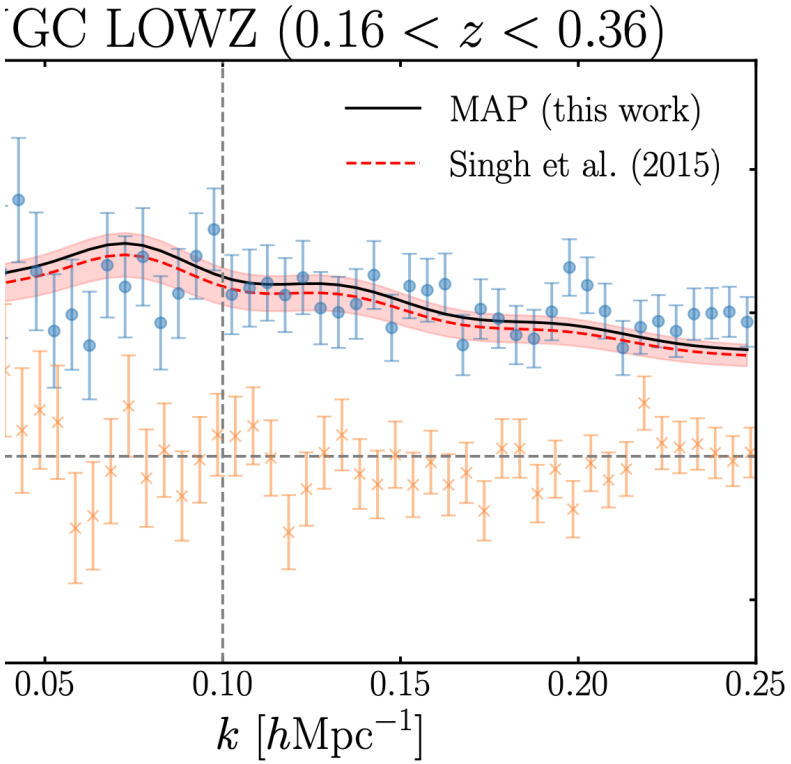
The use of "associated" Legendre polynomial, instead of Legendre polynomial, enables to extract most of the IA information from the lowest-order moment (the quadrupole in this case) (originally, Kurita & MT; now Sukhdeep as well)

$$A_{\rm IA} \simeq 4.4 \pm 0.5 \longrightarrow 4.4 \pm 0.25$$

Quadrupole vs Projected correlation function



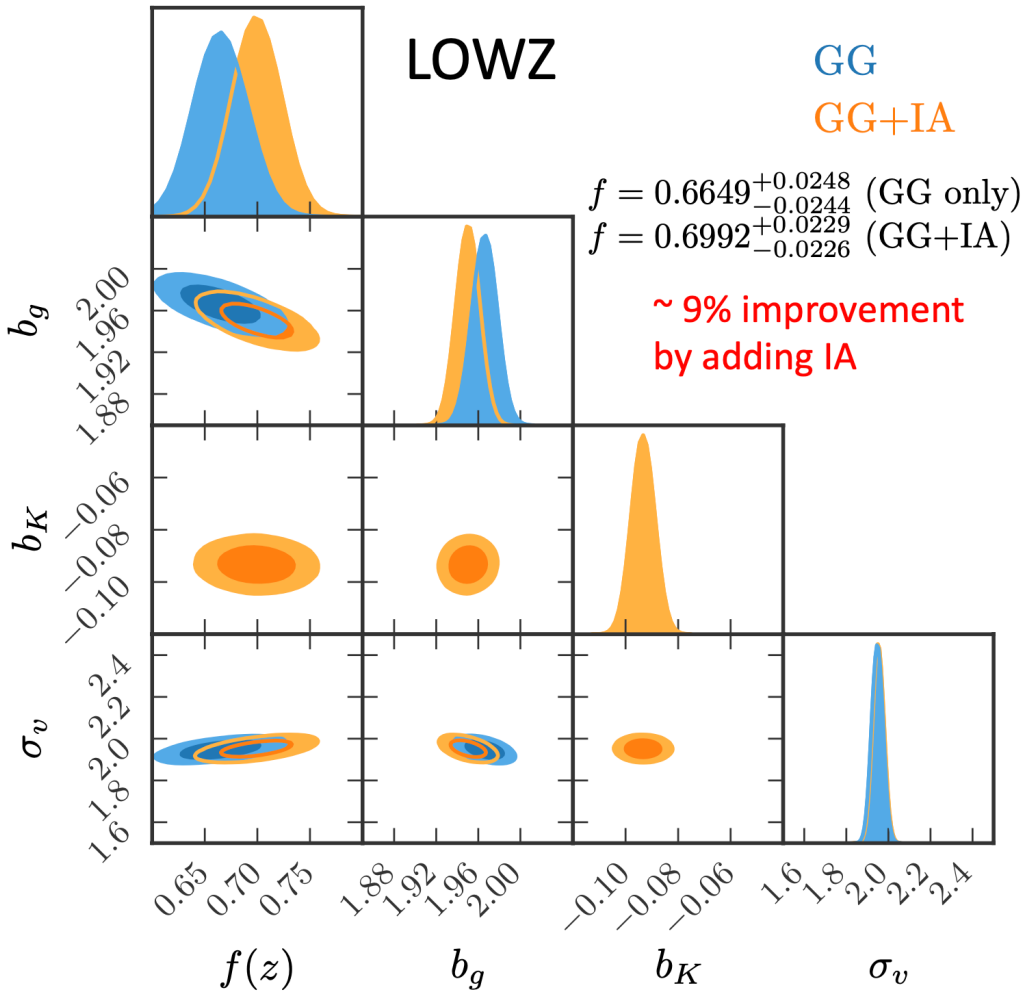
First measurement of IA power spectrum

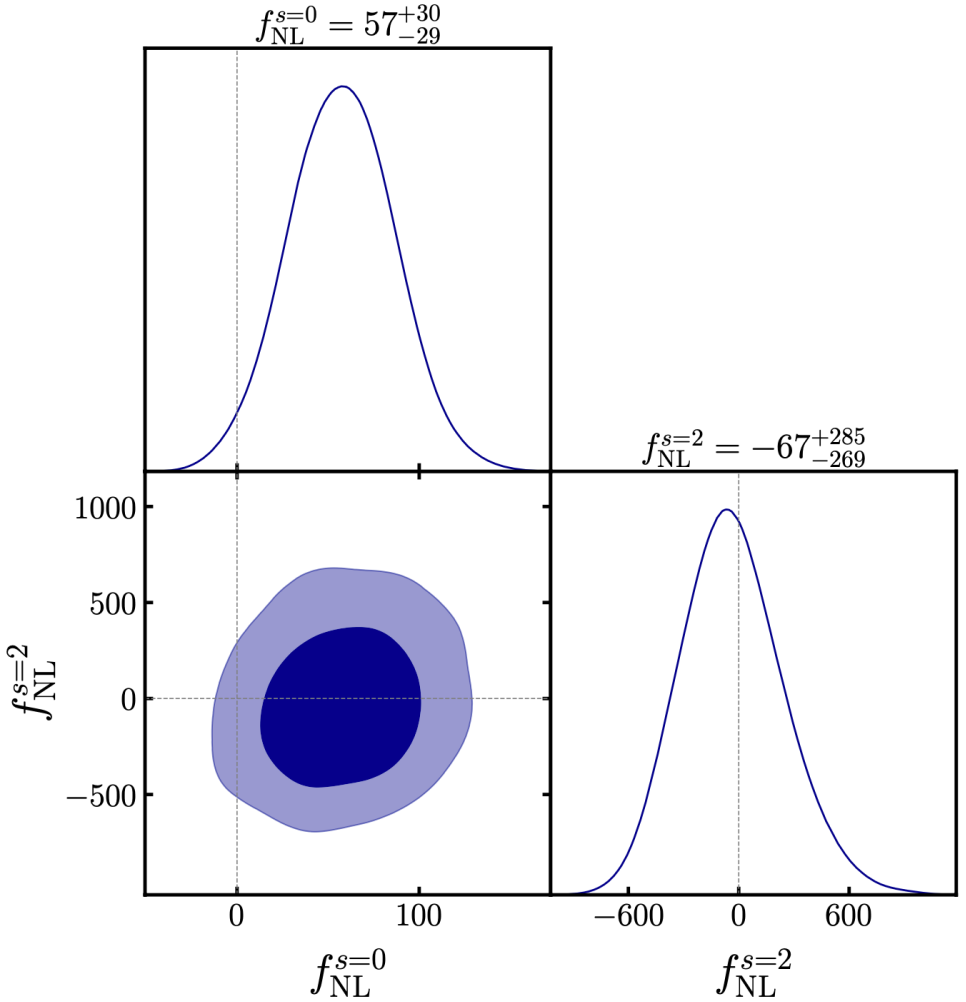


IA as “cosmology” probe

See Teppei and Toshiki’s talks

Very promising, exciting directions!



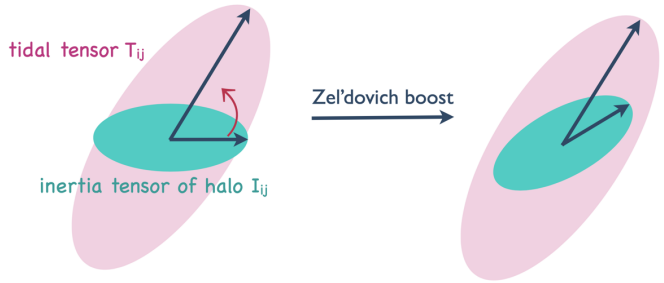


“Spin” and “tidal torque theory”

Ue-Li, Iye-san, Noam, Jounghun, Sandrine, …

- A lot of active discussion! Seems there is still some disagreement?
- Tidal torquing theory for the origin of galaxy spin (or filament spin)

$$L_K \propto \epsilon_{ijk} I_{li} T_{lj}$$

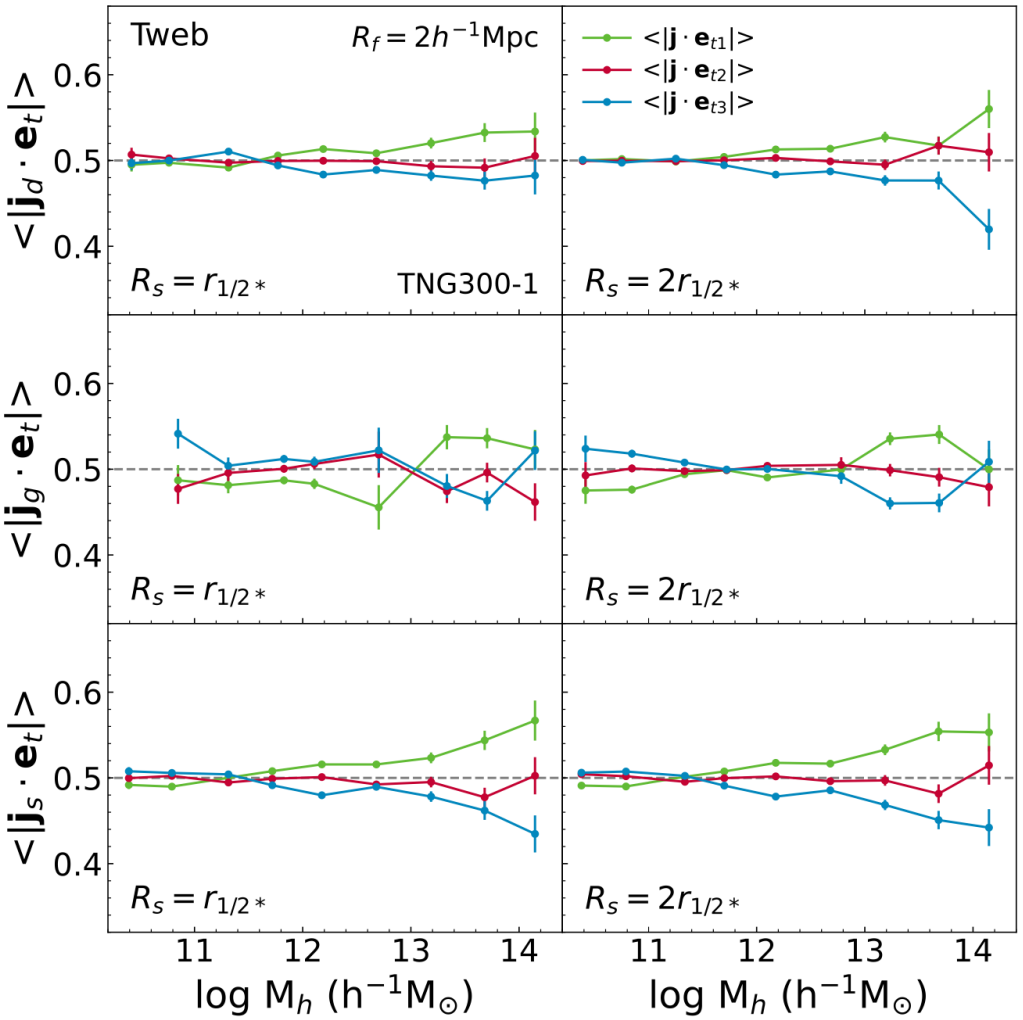


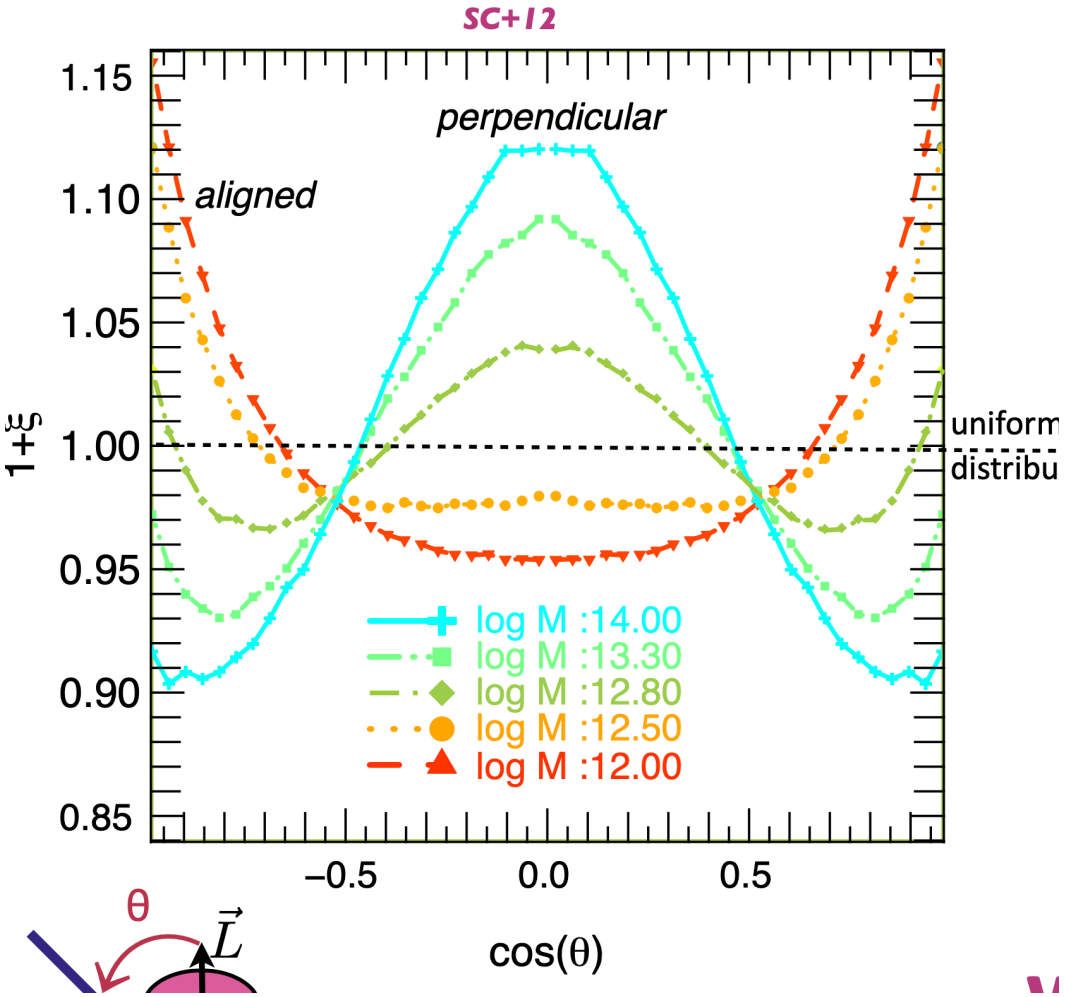
- Tidal alignment and tidal torquing theory (“TATT” model”): Jonathan, Simon, Kaz

$$\gamma_{ij} = b_K K_{ij} + b_{\delta K}\delta_{\rm m} K_{ij} + b_{KK}\left(K_{ia}K_{aj} - \frac{\delta^K_{ij}}{3}K^2\right) + b_T T_{ij} + \cdots$$

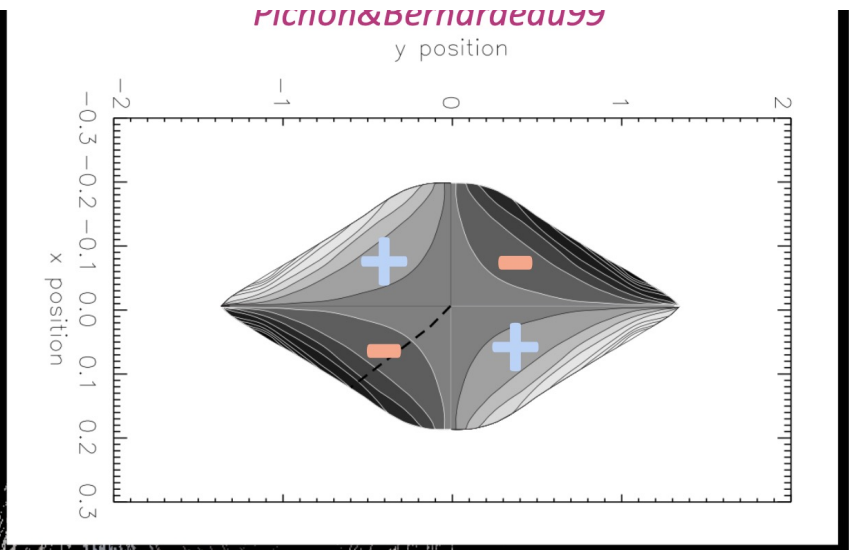
- Alignment cosine-angle $\langle \mathbf{j}\cdot\mathbf{e}_i \rangle$

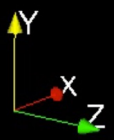
Spin flip? Involves galaxy formation physics in cosmic web



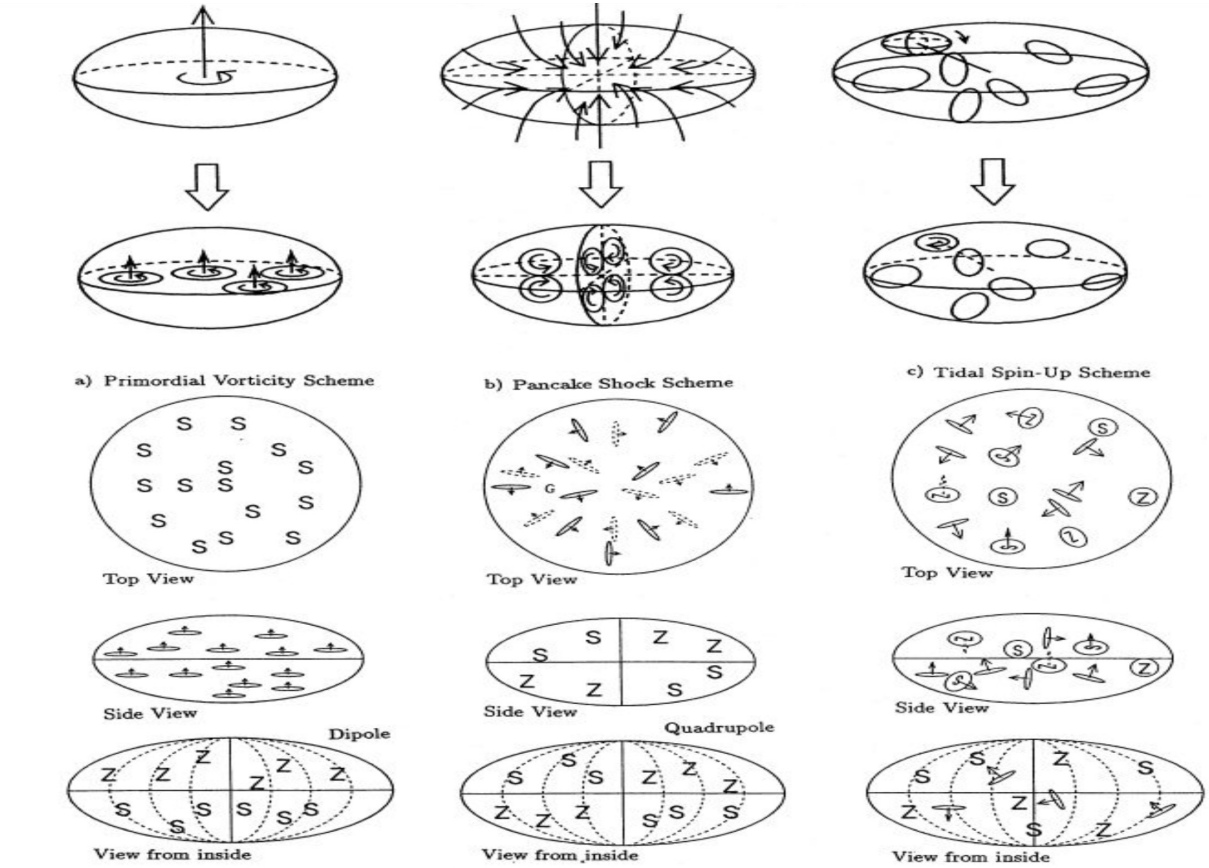


Nice visualization! (see Sandrine and Noam's talks)

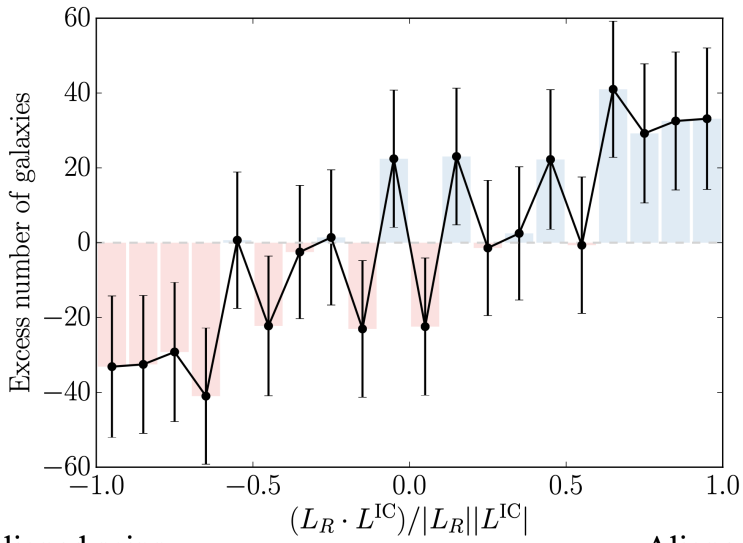




The universe's parity-symmetry violated? Fundamental question to be addressed



Motloch, Pen & Yu 22



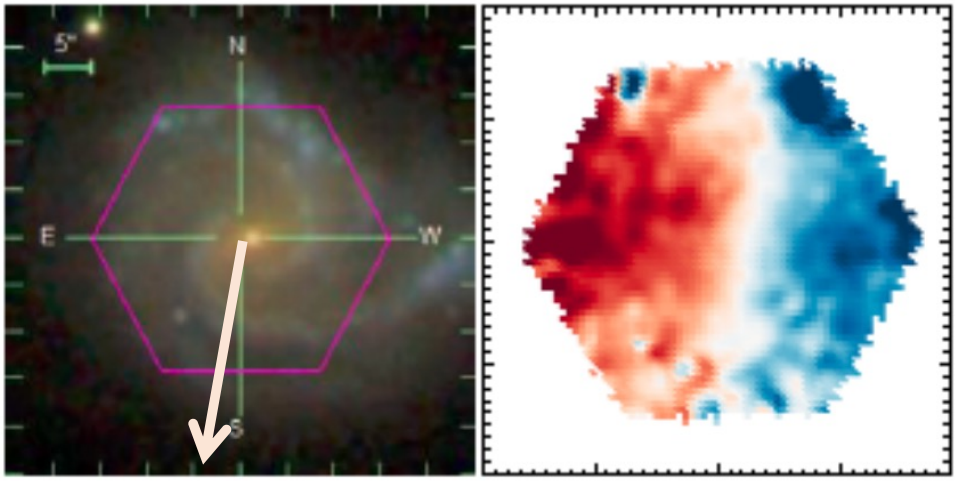
Anti-aligned spins

Aligned spins

$$\mu_{\rm exc} = (1.34 \pm 0.42) \times 10^{-2}$$

3σ hint of parity violation?

- So far, Iye-san's and Ue-Li's group's work are based on visual inspections of galaxy spins ("S" or "Z"-type galaxies): Galaxy Zoo vs. Iye-san's group (3 scientists) of 75k sample!
- We want to use more "auto-mated" or "objective" estimator of individual galaxy spin



MaNGA data

- Morphology (imaging) + Integral-field-unit-type spectroscopy (or slit-less spectroscopy from Euclid and Roman), or color-difference of broadband photometry (Doppler or dust extinction)? These are worth exploring

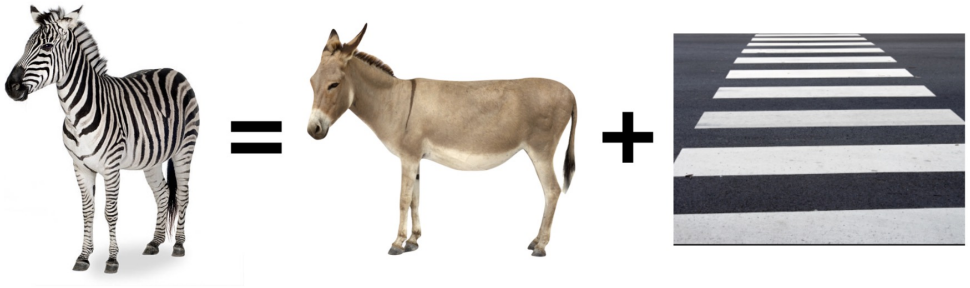
Theory of IA

- Development of an accurate model of IA is very important, for weak lensing cosmology and IA cosmology

$$
\begin{aligned}
P^{l_1 l_2; l\, l_z; L}_{X_1 X_2}(k,\mu) &= \frac{\Pi^2(k,\mu)}{\sqrt{4\pi}} P_{\rm L}(k) \\
&\times \left\{ \delta_{l_z 0}\delta_{lL}(-1)^{l_2} \begin{pmatrix} l_1 & l_2 & l \\ 0 & 0 & 0 \end{pmatrix} c^{(1)}_{X_1 l_1}(k) c^{(1)}_{X_2 l_2}(k) \right. \\
&\quad + \left(1+\frac{f}{3}\right) \frac{\delta_{l_z 0}\delta_{lL}}{\sqrt{\{l\}}} \Big[(-1)^l \delta_{l_1 l}\delta_{l_2 0} c^{(1)}_{X_1 l_1}(k) c^{(0)}_{X_2} \\
&\qquad\qquad + \delta_{l_1 0}\delta_{l_2 l} c^{(0)}_{X_1} c^{(1)}_{X_2 l_2}(k) \Big] \\
&\quad + \frac{2f}{3}\frac{\delta_{l_z 2}}{\sqrt{5}} \Big[\delta_{l_1 L}\delta_{l_2 0} \begin{pmatrix} 2 & l_1 & l \\ 0 & 0 & 0 \end{pmatrix} c^{(1)}_{X_1 l_1}(k) c^{(0)}_{X_2} \\
&\qquad\qquad + (-1)^l \delta_{l_1 0}\delta_{l_2 L} \begin{pmatrix} 2 & l_2 & l \\ 0 & 0 & 0 \end{pmatrix} c^{(0)}_{X_1} c^{(1)}_{X_2 l_2}(k) \Big] \\
&\quad + \delta_{L0}\delta_{l_1 0}\delta_{l_2 0}\delta_{l\, l_z} \Big[\delta_{l_z 0} \left(1 + \frac{2f}{3} + \frac{f^2}{5}\right) \\
&\qquad\qquad \left. + \frac{\delta_{l_z 2}}{5}\left(\frac{4f}{3} + \frac{4f^2}{7}\right) + \frac{\delta_{l_z 4}}{9}\frac{8f^2}{35} \Big] c^{(0)}_{X_1} c^{(0)}_{X_2} \right\}, \qquad (260)
\end{aligned}
$$

Of course, Matsubara-san and Zvonimir can solve everything …

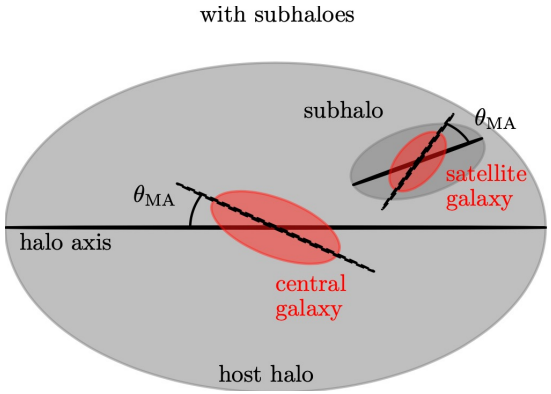
Scalar, vector and tensor (SVT) decomposition

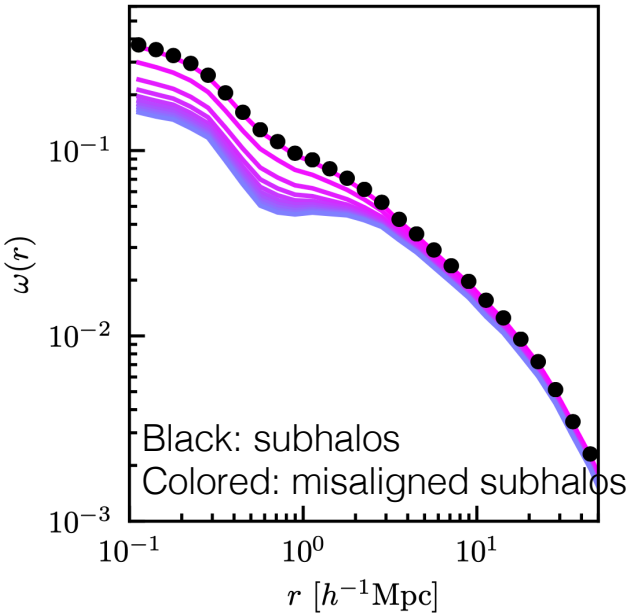


separation into "dynamics" + "symmetries"

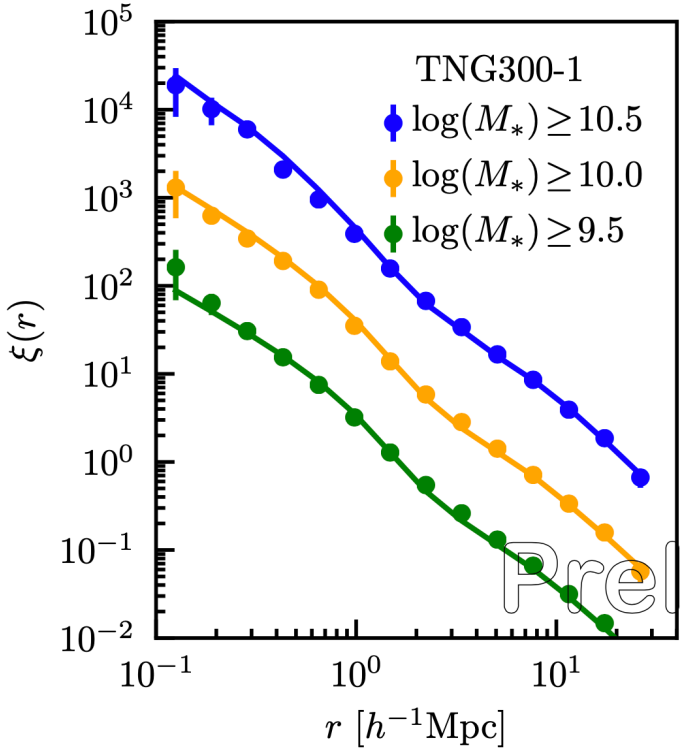
$$\langle S_1 S_2 \rangle = \langle \delta_1 \delta_2 \rangle + \{ \boldsymbol{Y}^{(\ell) m} \}$$

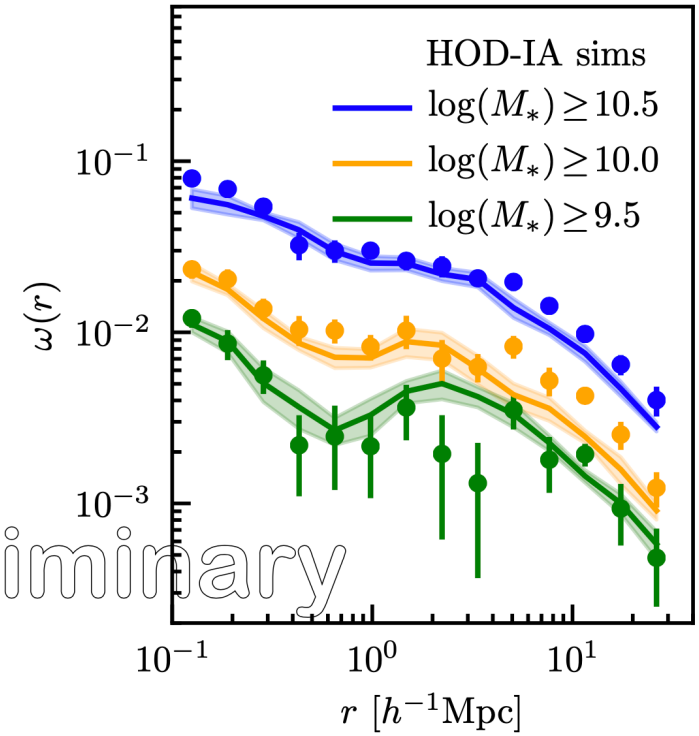
Theory of IA – halo model approach





See Teppei, Jonathan, Benjamin's talks





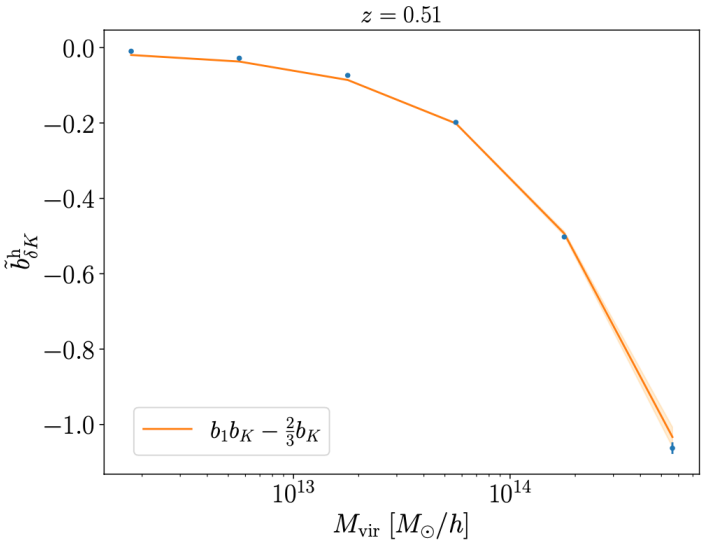
Preliminary

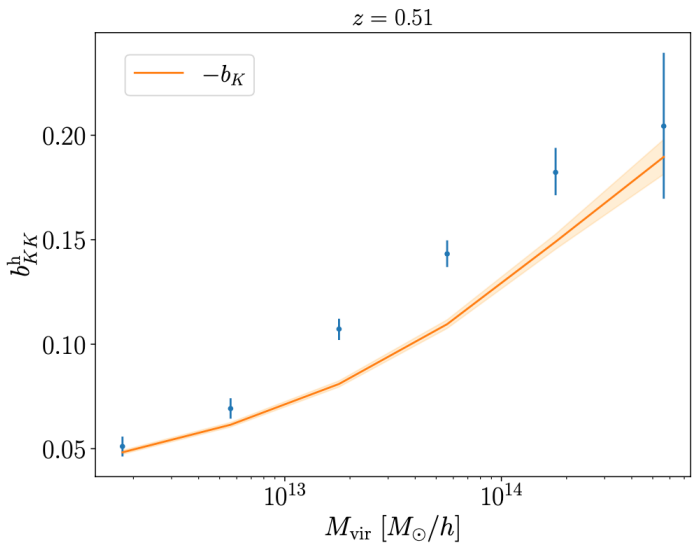
Halotools-IA seems very useful; make it public!

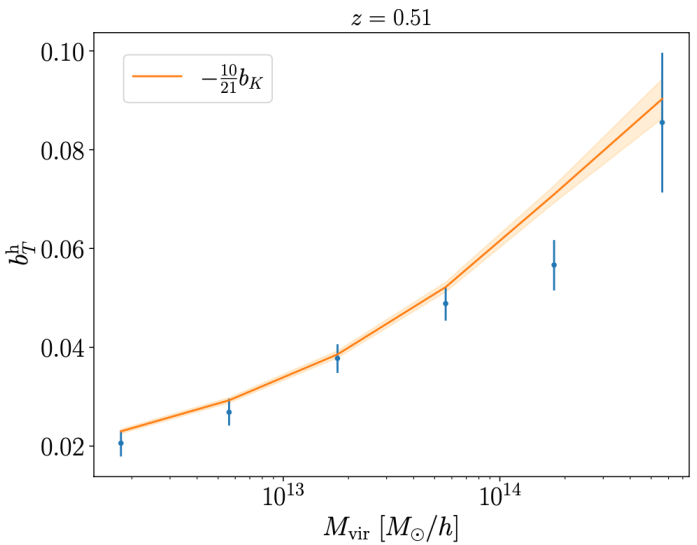
Theory of IA – perturbation theory approach

See Jonathan, Matsubara-san, Simon, Zvonimir, Kaz's talks

The first-time field-level calibration of the quadratic shape bias parameters (Kaz, congratulations!)





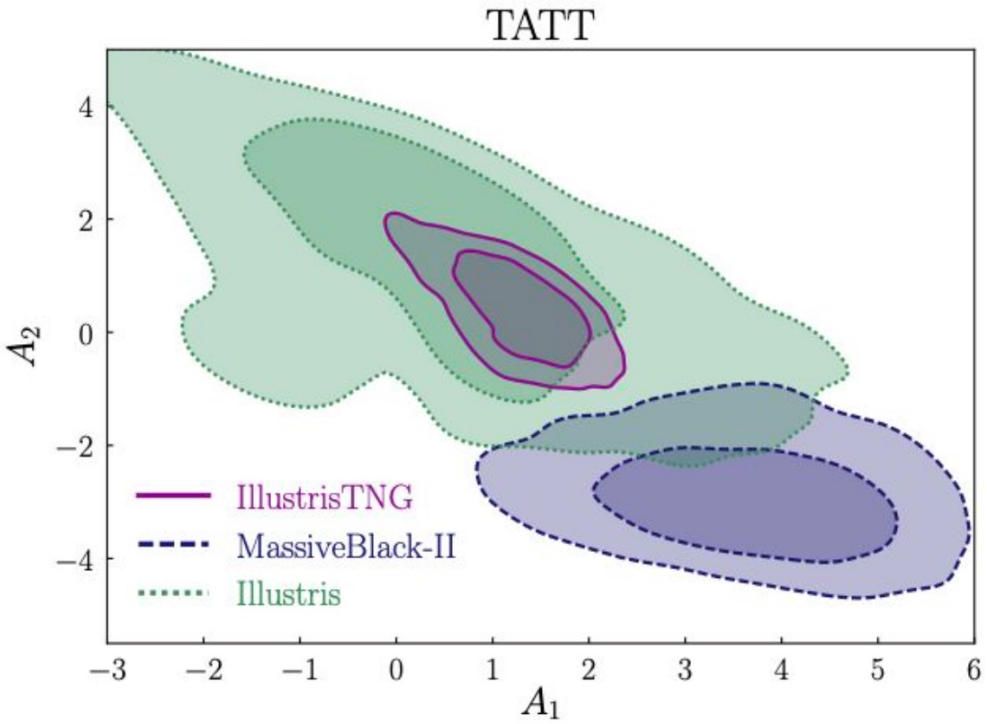


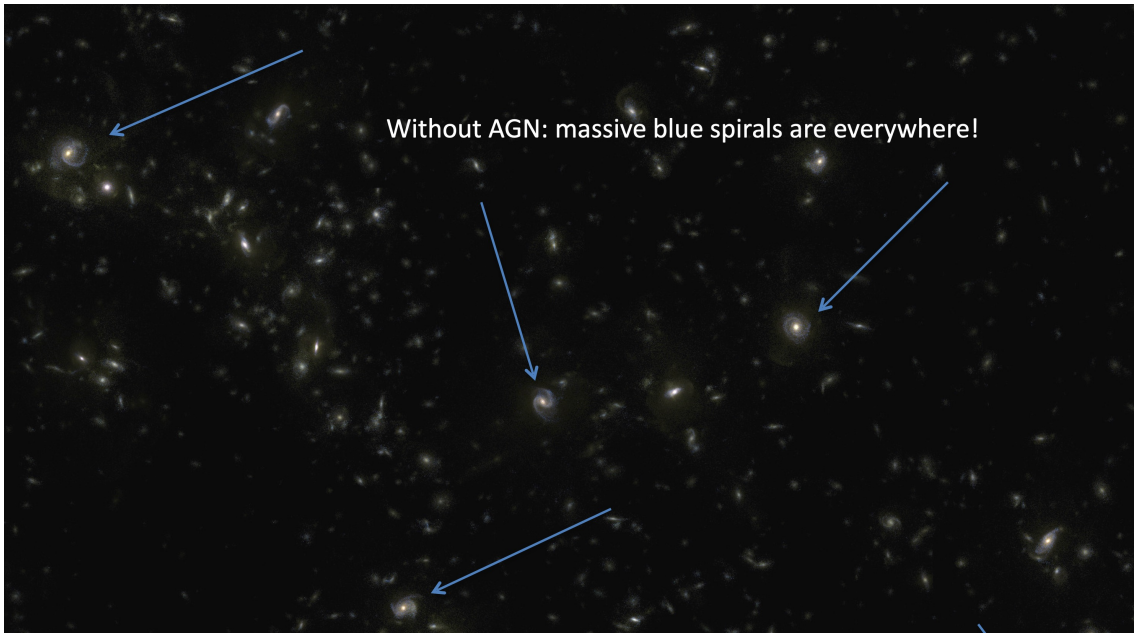
Nonlinear shape bias parameters seem simpler compared to the density case

Theory of IA – hydrodynamical simulations

See Rachel, Ken, Sandrine's talks

In principle, hydrodynamical simulations should give most accurate predictions, however, the results still depend on treatments of sub-grid physics





IA is really fun, exciting to work on!
Let's explore from **Subaru**, LSST, Euclid and Roman
Various opportunities!

We need more energy from junior colleagues; many thanks to Nakashima-san, Ishikawa-san^2, Toshiki, Saga-san, Osafune-san for your participations!

Of course, many thanks should go to LOC members (especially Taruya-san!)