Tightening geometric and dynamical constraints on dark energy and gravity with galaxy intrinsic alignment

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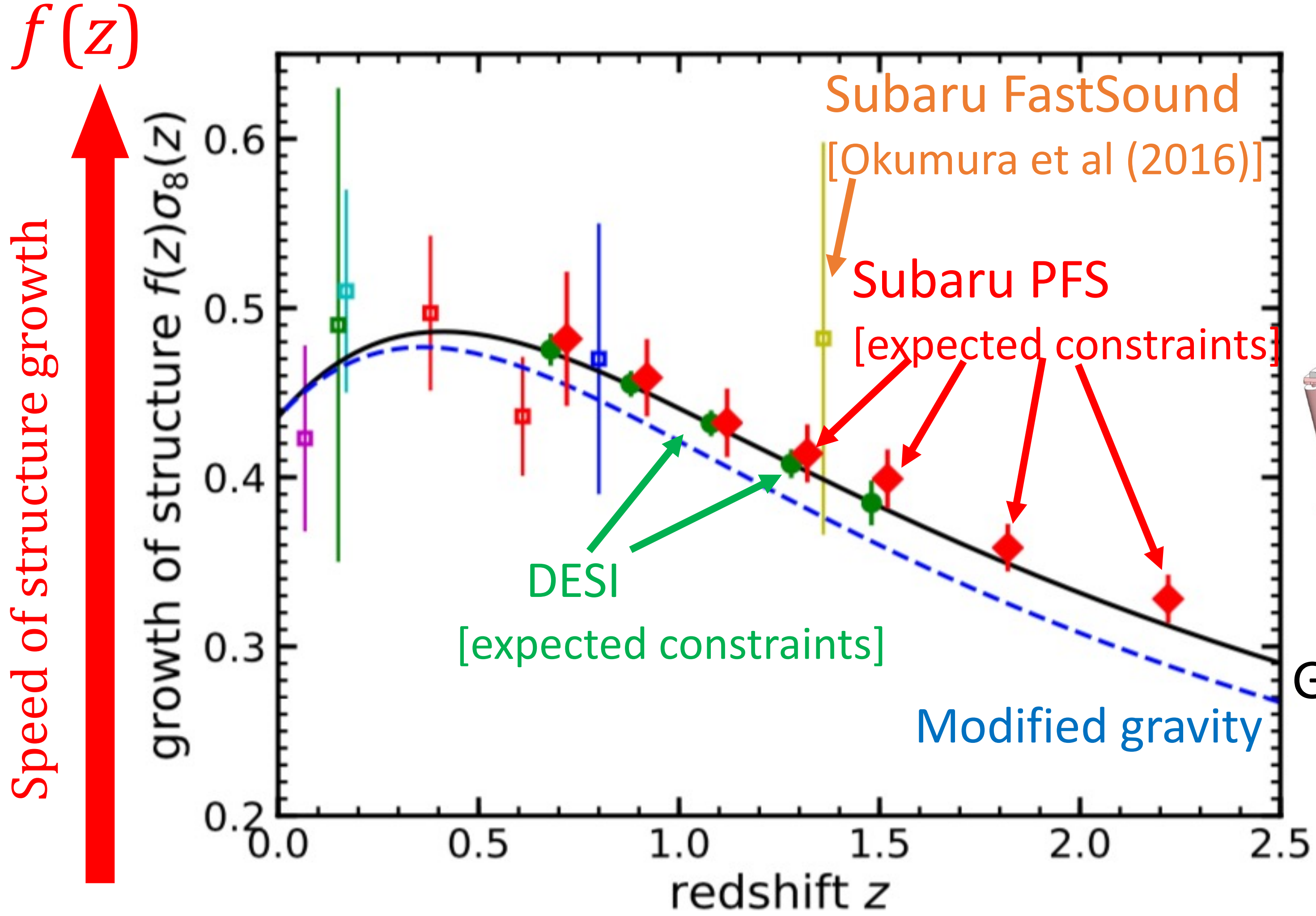
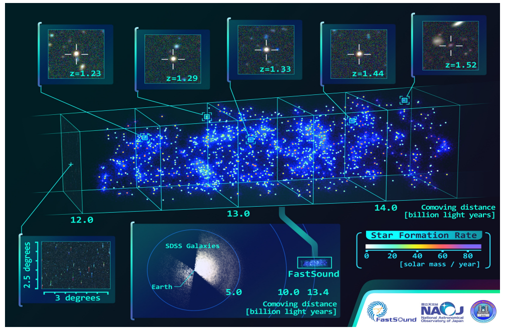
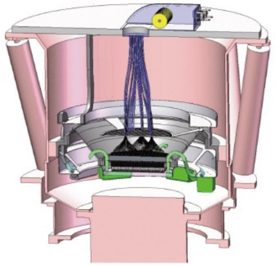
IA cosmology workshop, YITP, Nov. 29 – Dec. 3, 2021

References:
Okumura & Taruya, arXiv: 2110.11127
Tonegawa & **Okumura,** arXiv: 2109. 14297

Observational constraints on the growth and expansion history of the universe







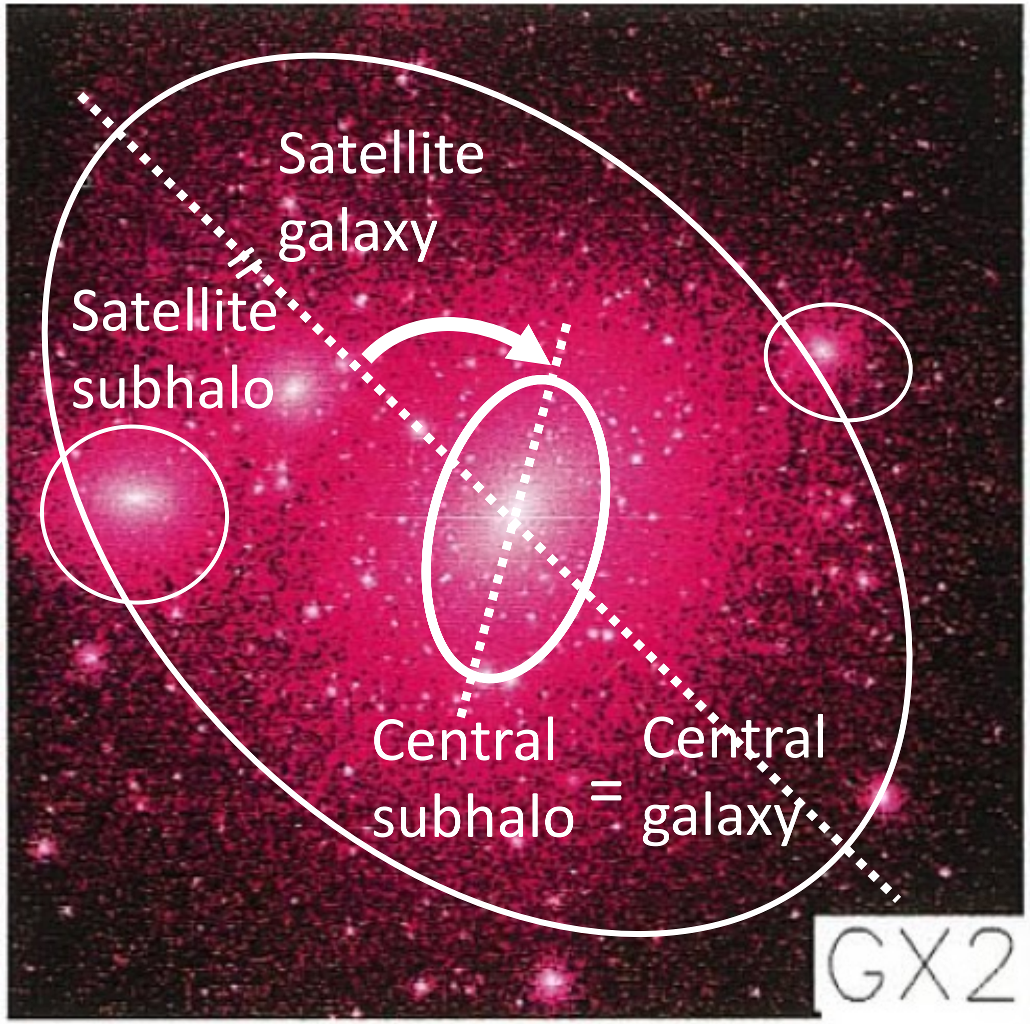
- $f(z)$ constraints
- $H(z)$ marginalized or fixed

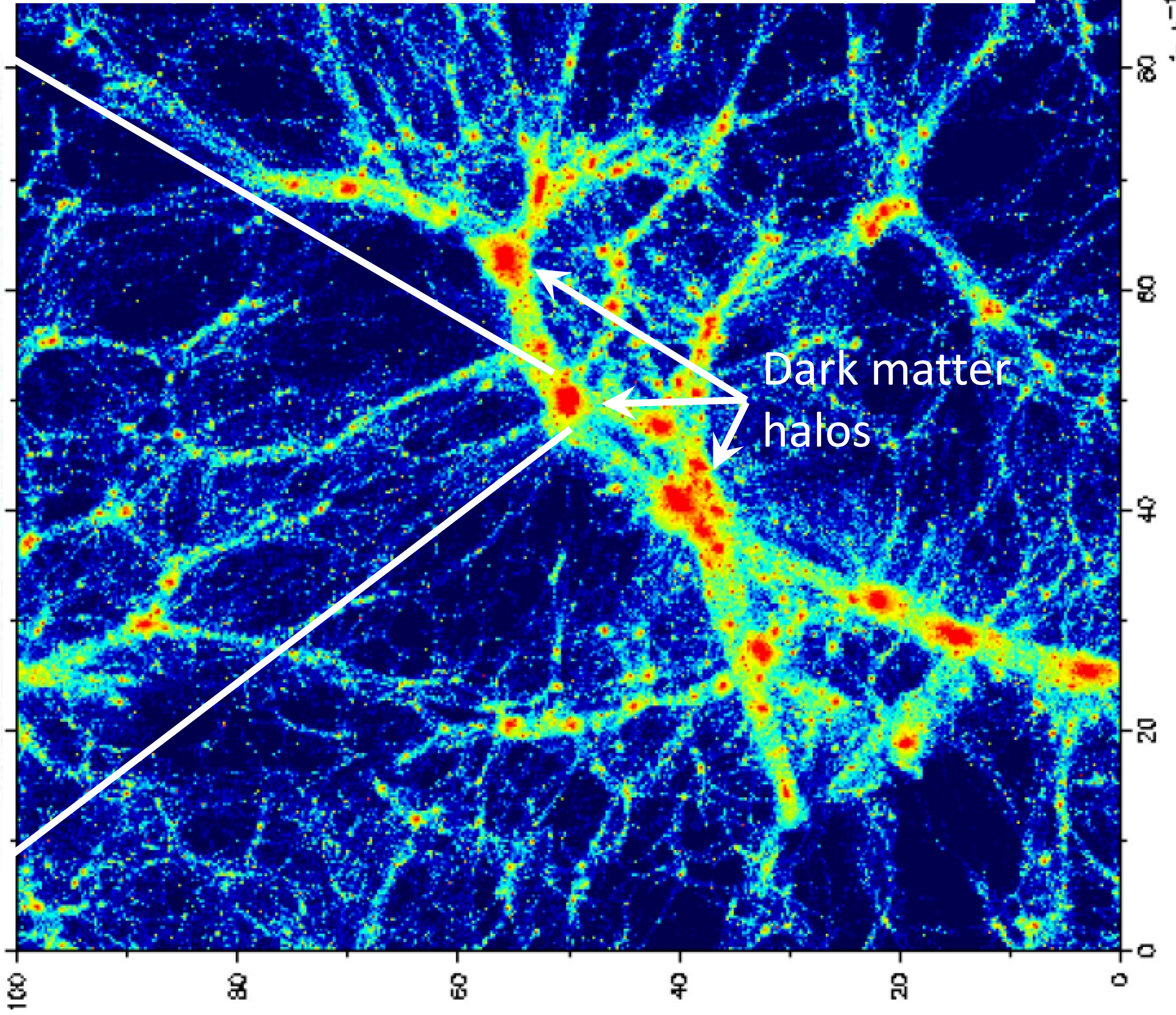
Figure made by Ryu Makiya at ASIAA
(PFS Cosmology WG chair)

Outline

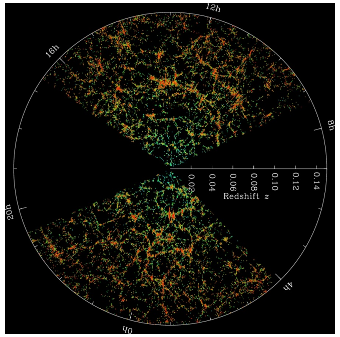
- Galaxy intrinsic alignment (IA) as a dynamical and geometric probe
- Kinetic Sunyaev-Zel'dovich (kSZ) effect as a dynamical and geometric probe
- Fisher matrix forecast with galaxy clustering + IA + kSZ
  - Geometric and dynamical constraints
  - Cosmological parameter constraints
  - Deep vs wide galaxy surveys
- Measurement of IA of red galaxies at $z > 1$

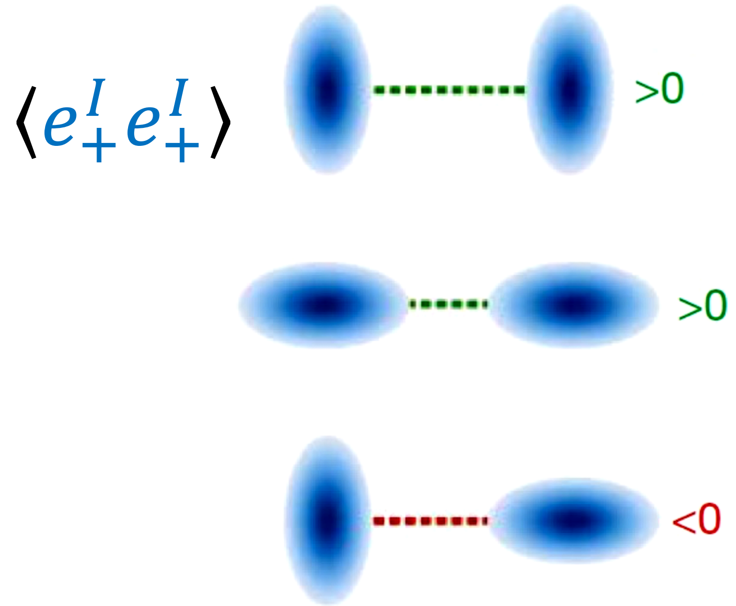
Intrinsic alignment (IA) of galaxy/halo shapes

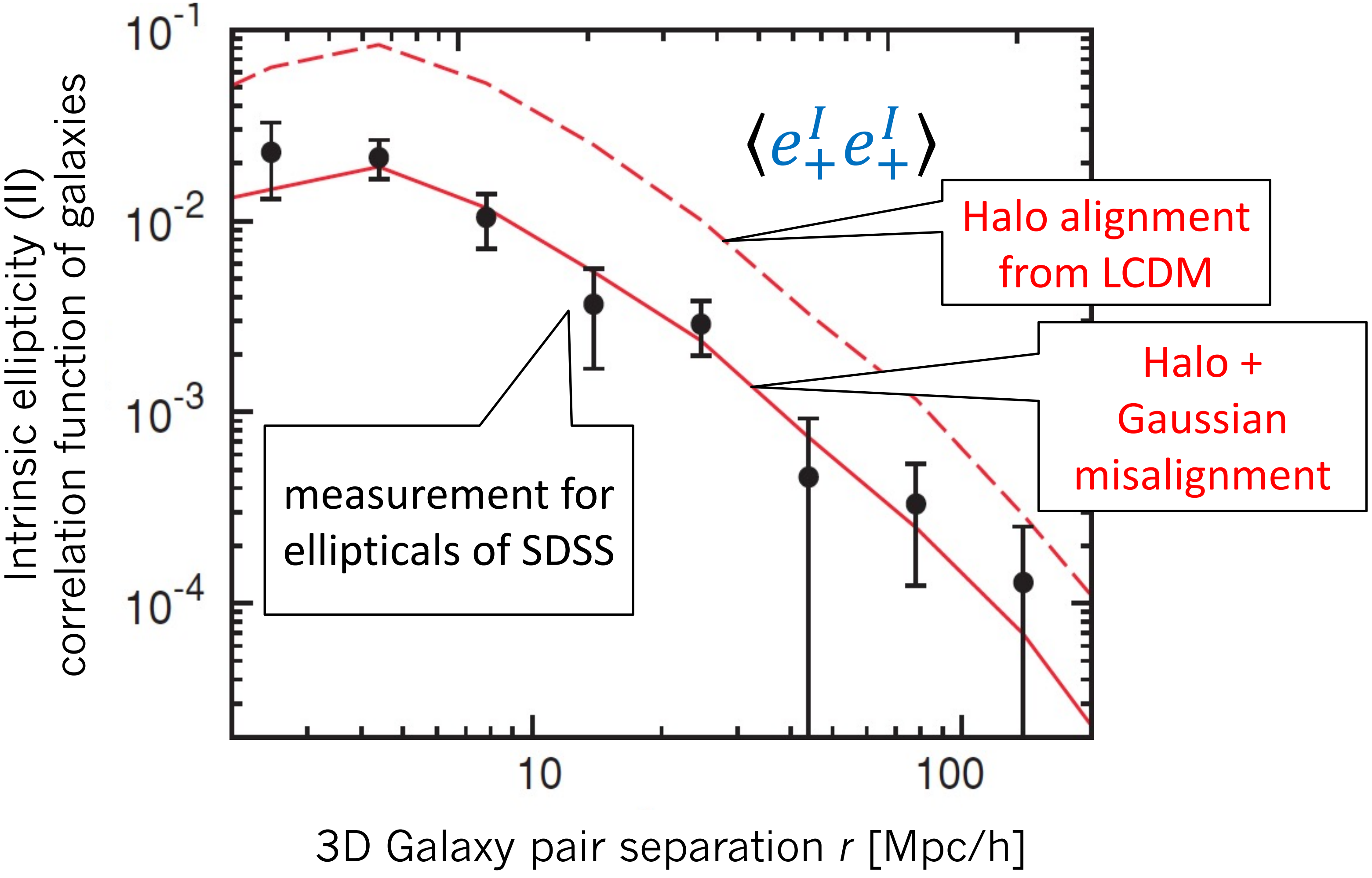




Intrinsic ellipticity auto correlation (II) of elliptical galaxies and the host halos

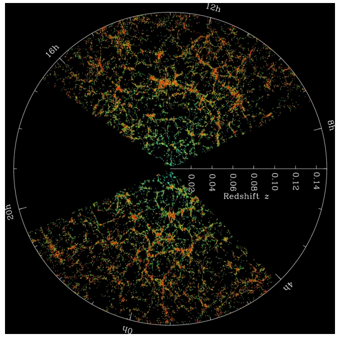




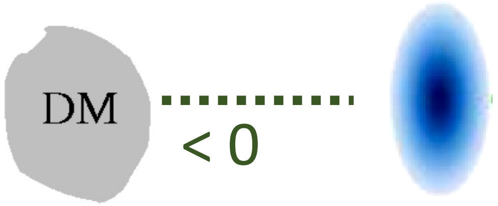


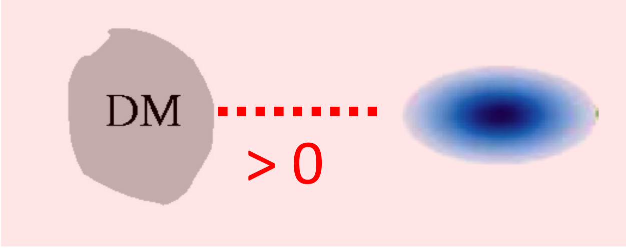
Okumura, Jing & Li (2009)

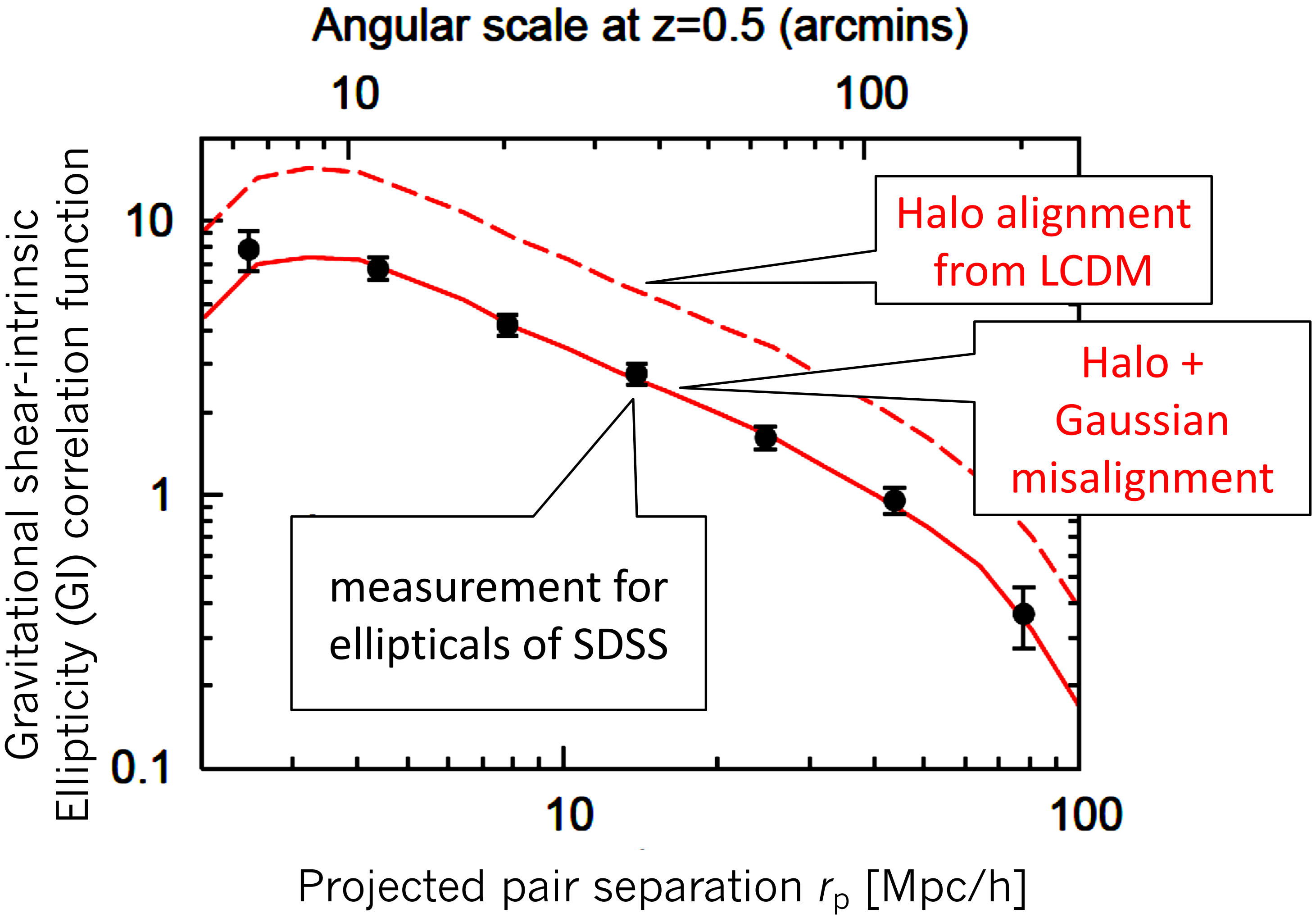
Cross-correlation function between ellipticity and density (GI)



$\langle \delta e_+^I \rangle$







Okumura & Jing (2009)

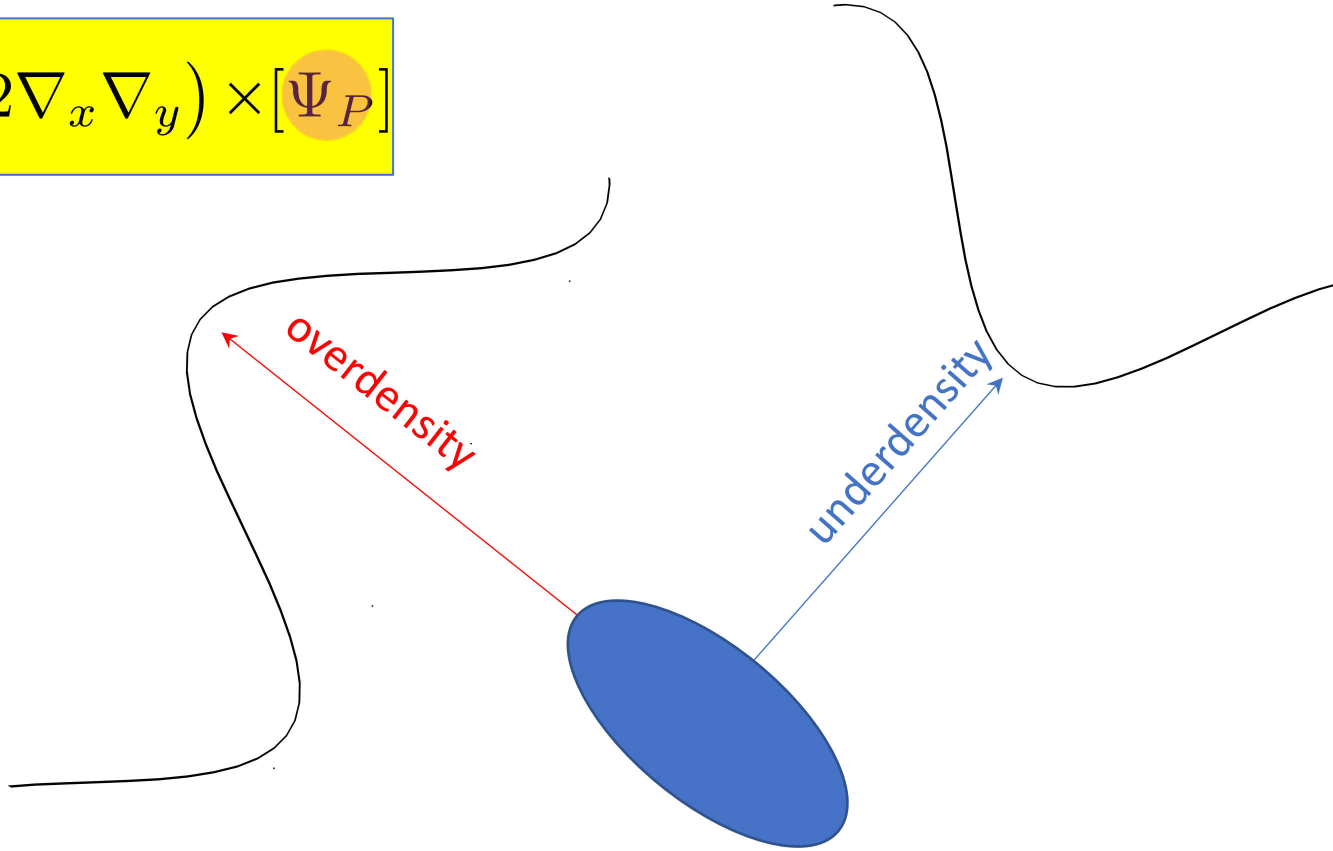
Linear alignment (LA) model

Catelan, Kamionkowski & Blandford (2001)
Hirata & Seljak (2004)

- Relates linear tidal field with galaxy/halo shape

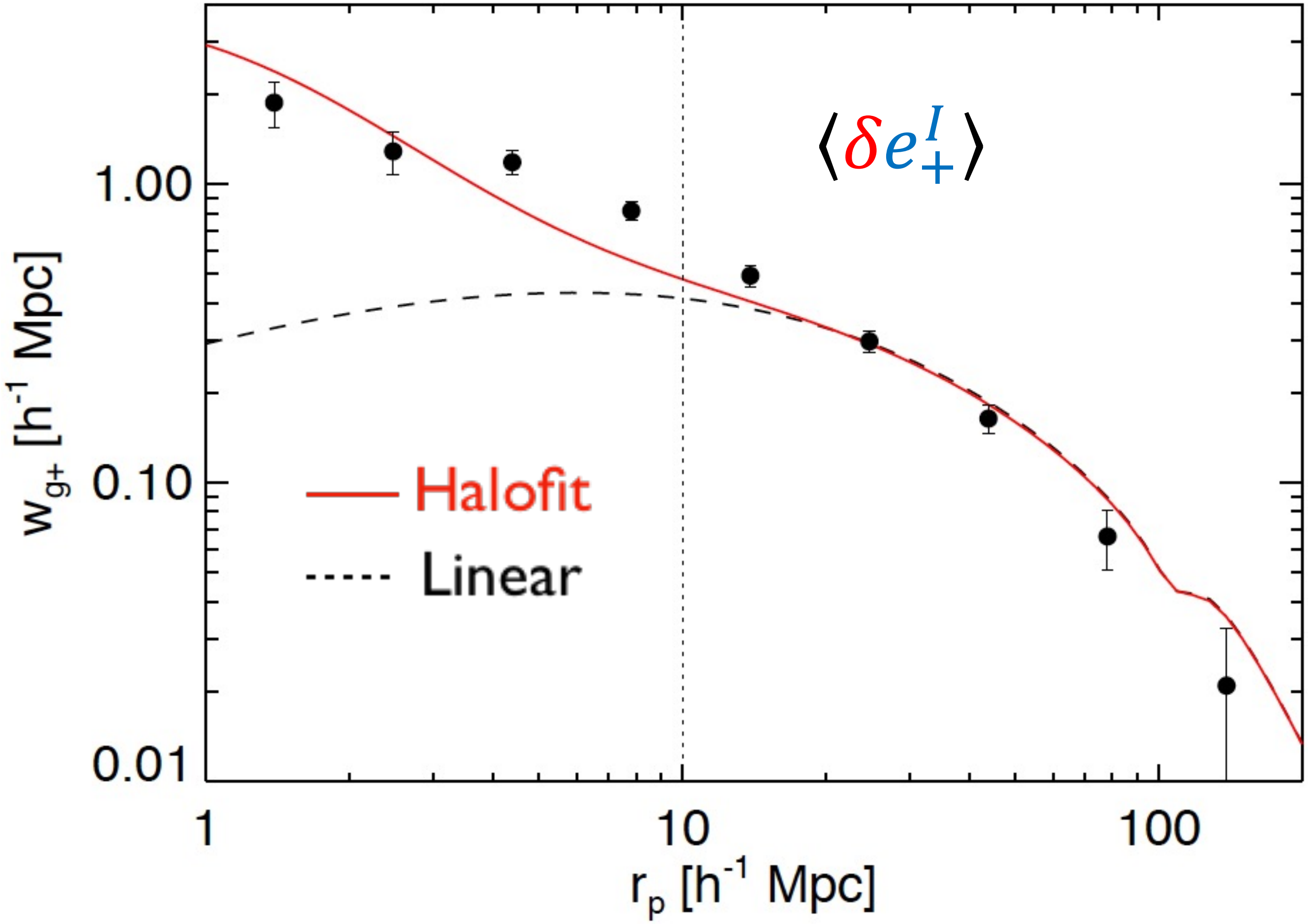
$$\gamma_{(+,\times)}(\mathbf{x}) = -\frac{C_1}{4\pi G}\left(\nabla_x^2 - \nabla_y^2, 2\nabla_x\nabla_y\right)\times[\Psi_P]$$

- Ψ_P: (Linear) Newton potential
- C_1 has to be determined by observation/simulation (this parameter absorbs misalignment and other uncertainties)



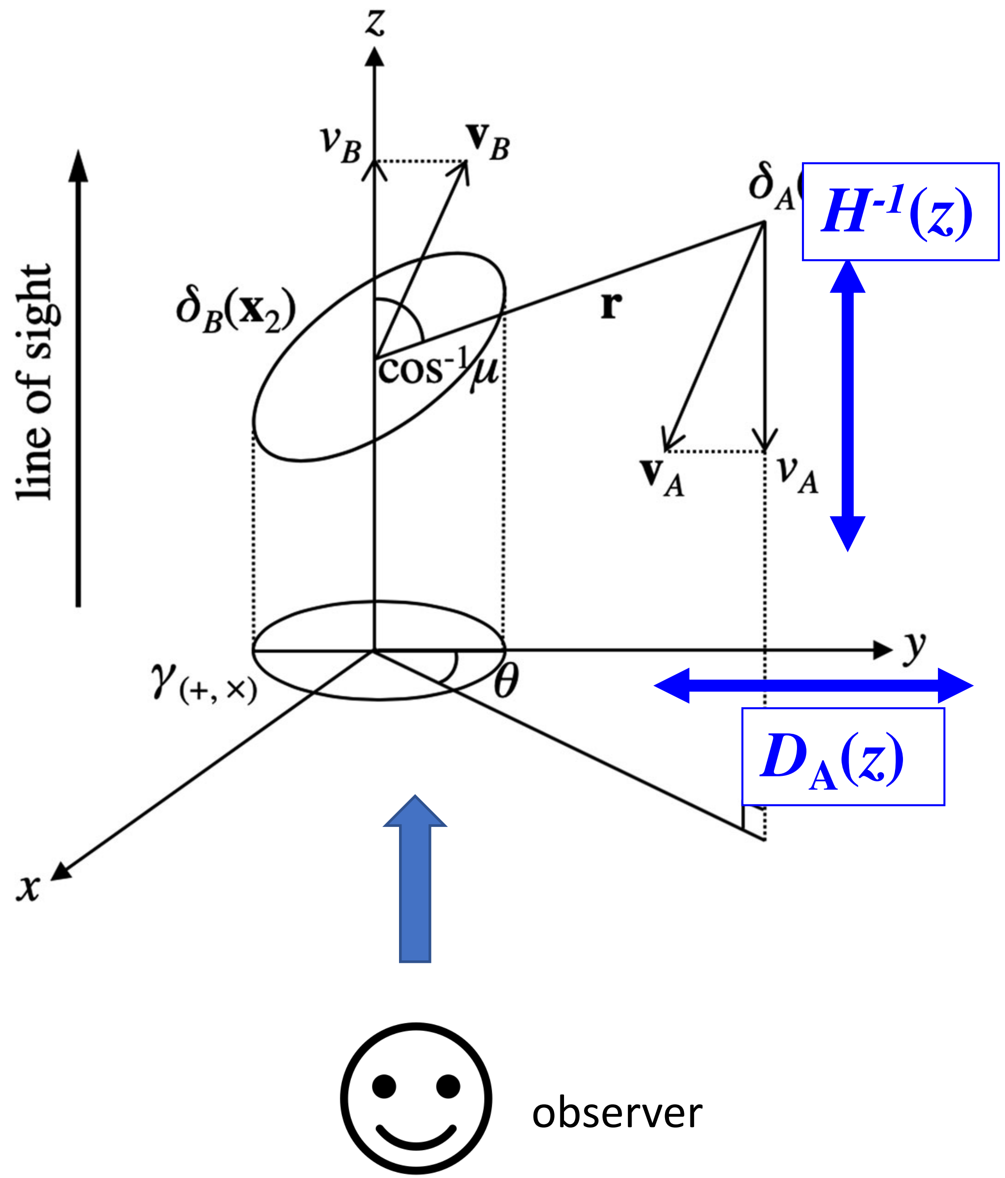
Testing galaxy-ellipticity correlation in LA model with observations

Blazek, McQuinn & Seljak (2011)



- LA model predicts the measurement of IA of the SDSS DR6 Luminous red galaxies by Okumura & Jing (2009)
- But this is the projected correlation function, not full 3D correlation.

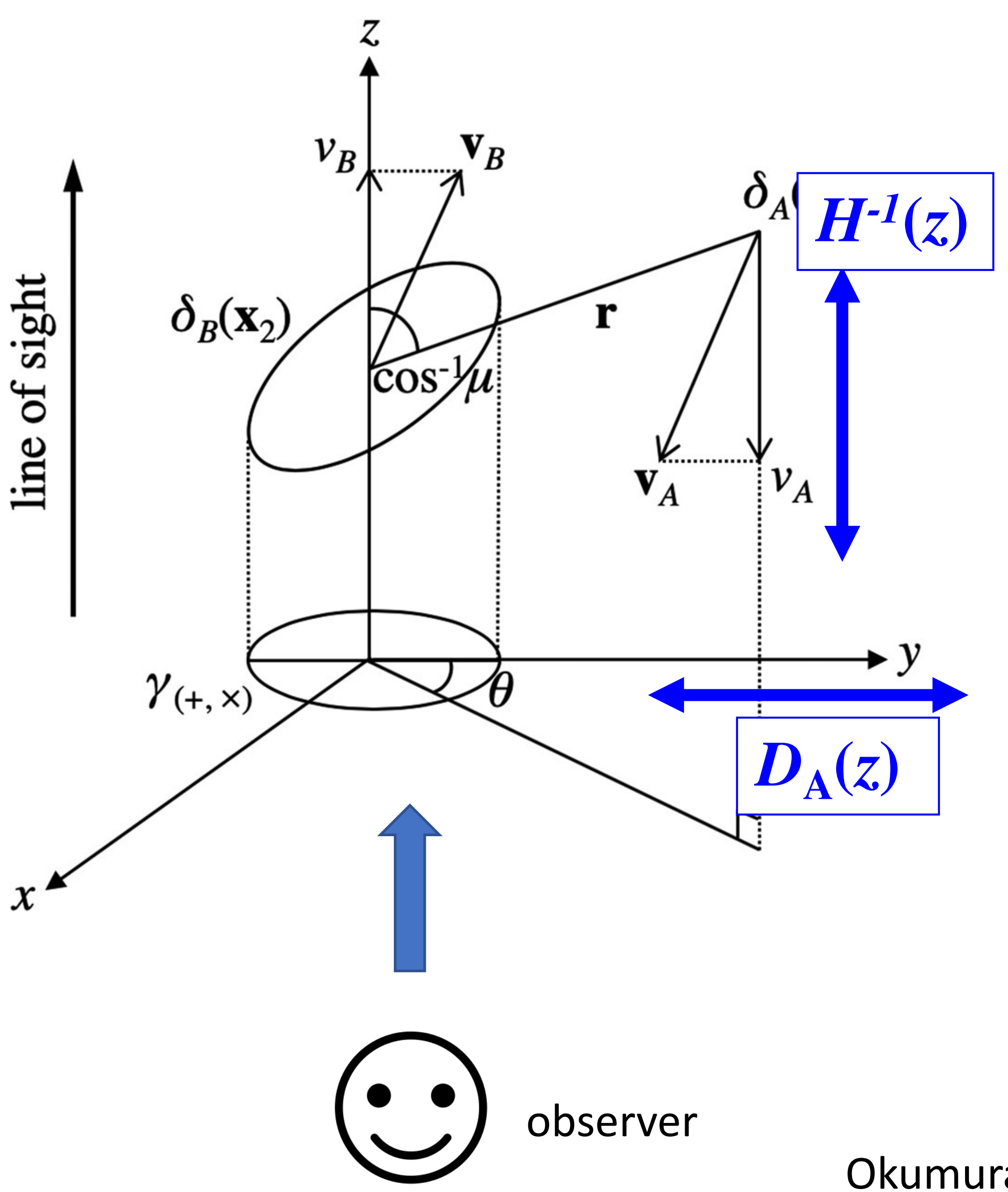
Formulating the IA statistics in redshift space



- Galaxy shapes/orientations are observed on the sky as 2-d projection (θ)
- The line-of-sight component of velocity (1-d) modulates galaxy positions (RSD)
- On the other hand, separation between two galaxies is described as 3-d, **r** = (r, μ)
- Original formula for the galaxy-intrinsic ellipticity (GI) correlation function (Hirata & Seljak 2004, Blazek et al 2011)

$$\xi_{g+}(\mathbf{r}) = \widetilde{C}_1 b_g \cos(2\phi) \int_0^\infty \frac{k_\perp dk_\perp}{2\pi^2} J_2(k_\perp r_\perp) \times \int_0^\infty dk_\parallel \frac{k_\perp^2}{k^2} P_{\delta\delta}(k) \cos(k_\parallel r_\parallel),$$

Formulating the IA statistics in redshift space



- Original formula for real-space GI correlation

$$\xi_{g+}(\mathbf{r}) = \widetilde{C}_1 b_g \cos(2\phi) \int_0^\infty \frac{k_\perp dk_\perp}{2\pi^2} J_2(k_\perp r_\perp) \times \int_0^\infty dk_\parallel \frac{k_\perp^2}{k^2} P_{\delta\delta}(k) \cos(k_\parallel r_\parallel),$$

- New, **equivalent** formula

$$\xi^R_{g+}(\mathbf{r}) = \widetilde{C}_1 b_g \cos(2\phi)(1-\mu^2)\Xi^{(0)}_{\delta\delta,2}(r)$$

$$\xi^R_{g+,0}(r) = -\xi^R_{g+,2}(r) = \frac{2}{3}\widetilde{C}_1 b_g \Xi^{(0)}_{\delta\delta,2}(r)$$

With RSD

$$\xi^S_{g+,0}(r) = \xi^R_{g+,0}(r) + \tfrac{2}{105}\widetilde{C}_1 f \left[5\,\Xi^{(0)}_{\delta\Theta,2}(r) - 2\,\Xi^{(0)}_{\delta\Theta,4}(r)\right],$$

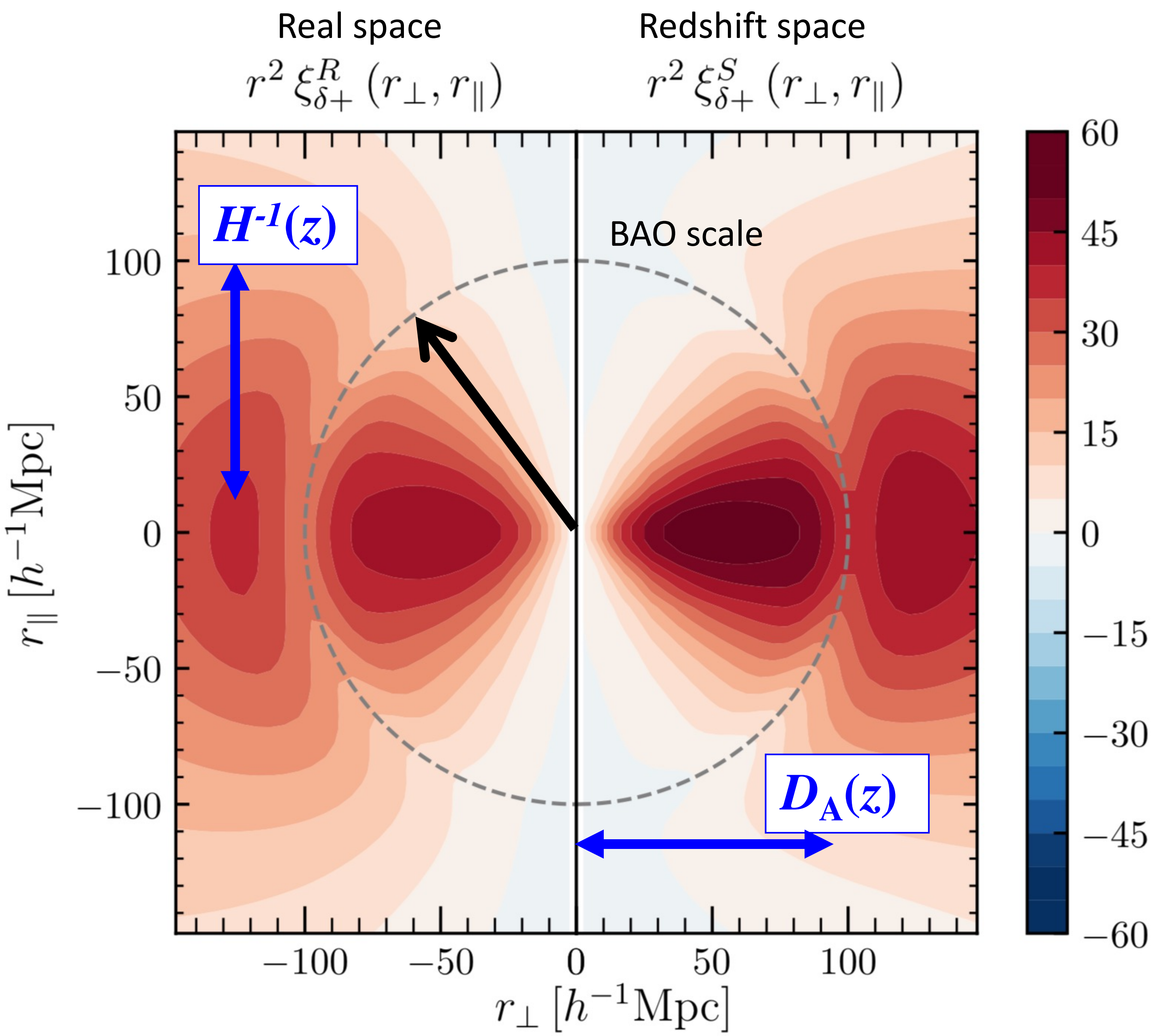
$$\xi^S_{g+,2}(r) = \xi^R_{g+,2}(r) - \tfrac{2}{21}\widetilde{C}_1 f \left[\Xi^{(0)}_{\delta\Theta,2}(r) + 2\,\Xi^{(0)}_{\delta\Theta,4}(r)\right],$$

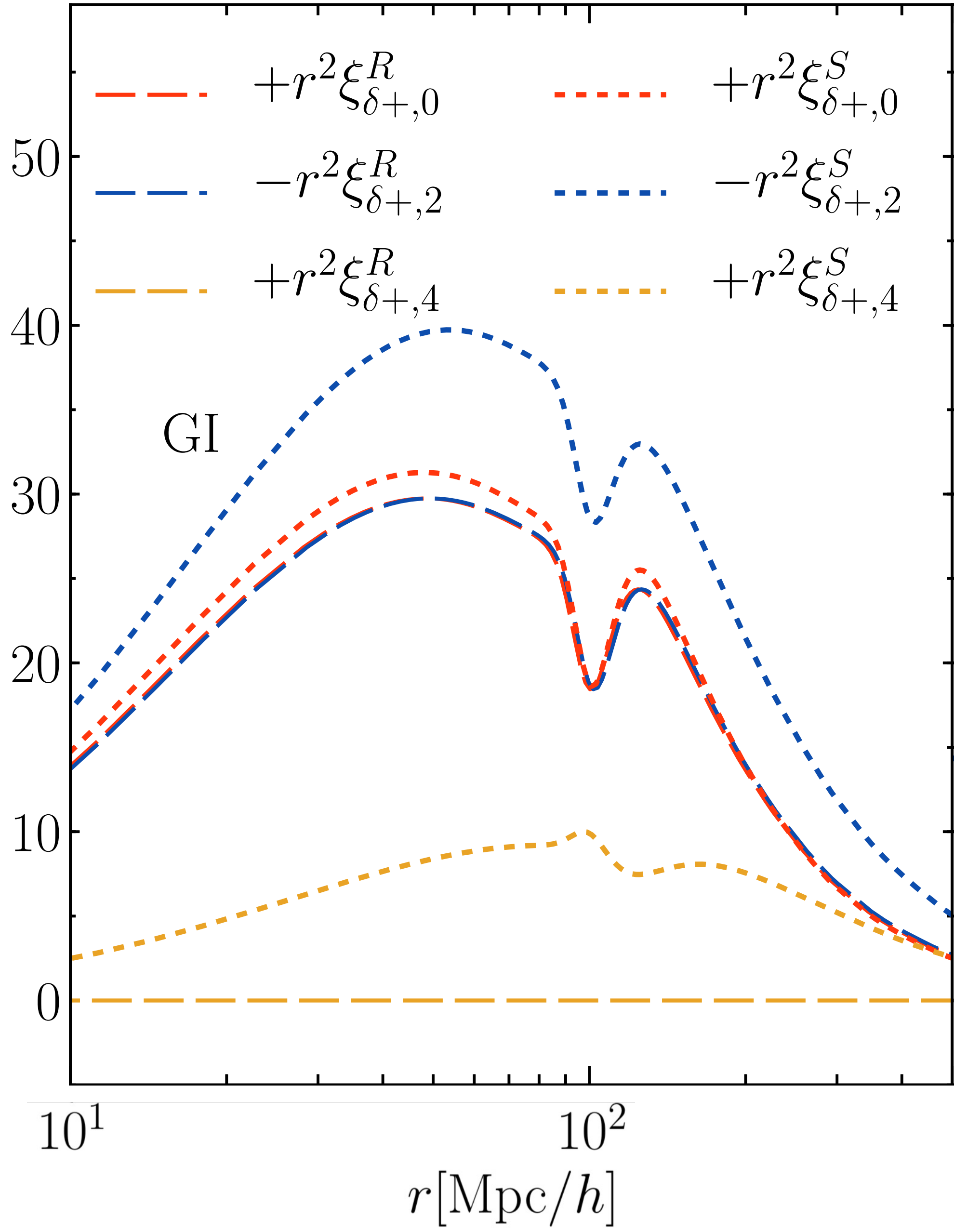
$$\xi^S_{g+,4}(r) = \tfrac{8}{35}\widetilde{C}_1 f\, \Xi^{(0)}_{\delta\Theta,4}(r).$$

$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^\infty \frac{k^{2-n}dk}{2\pi^2} P_{XY}(k) j_\ell(kr)$$

Okumura & Taruya (2020)

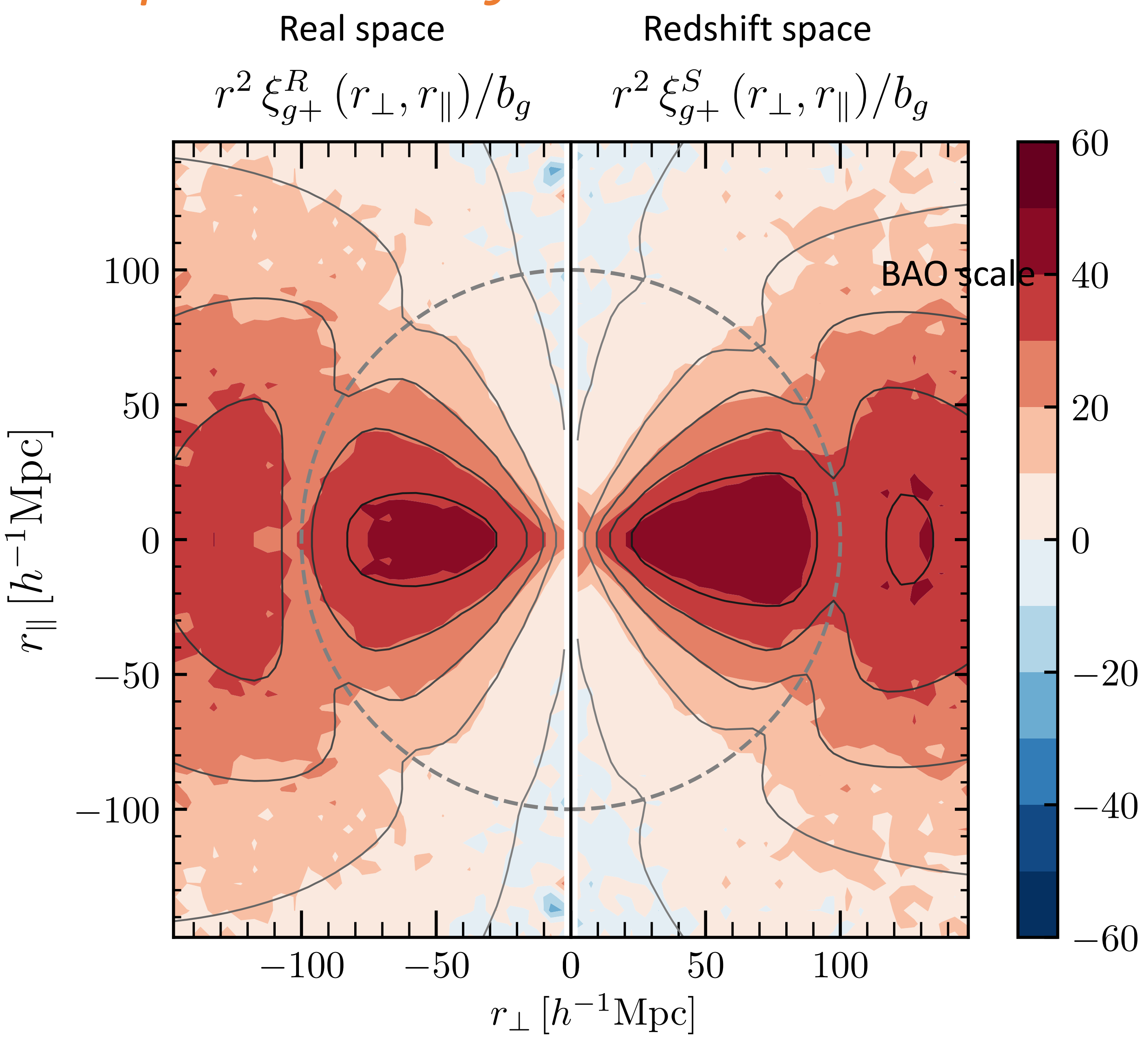
GI correlation in linear theory

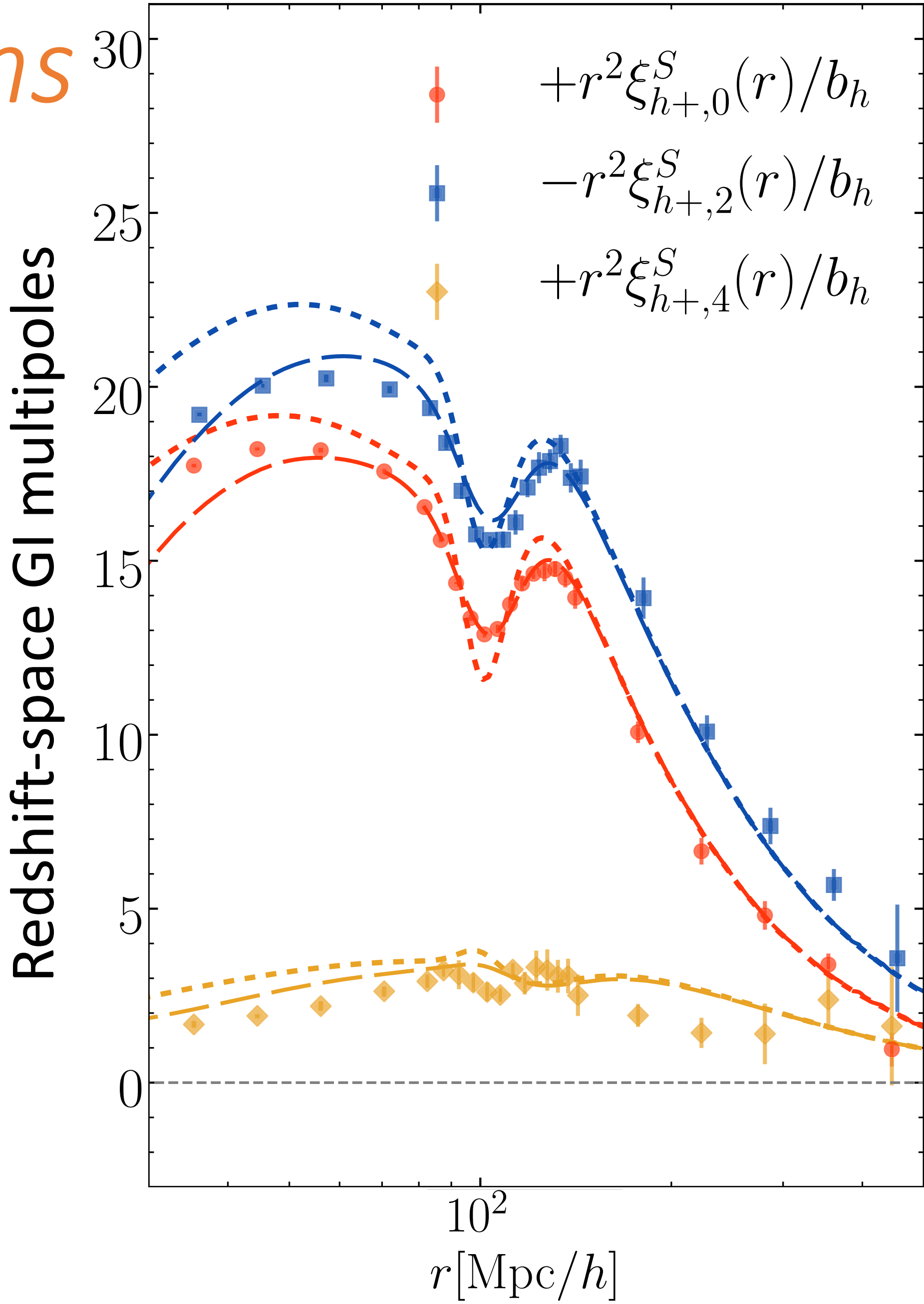




Okumura & Taruya (2020)

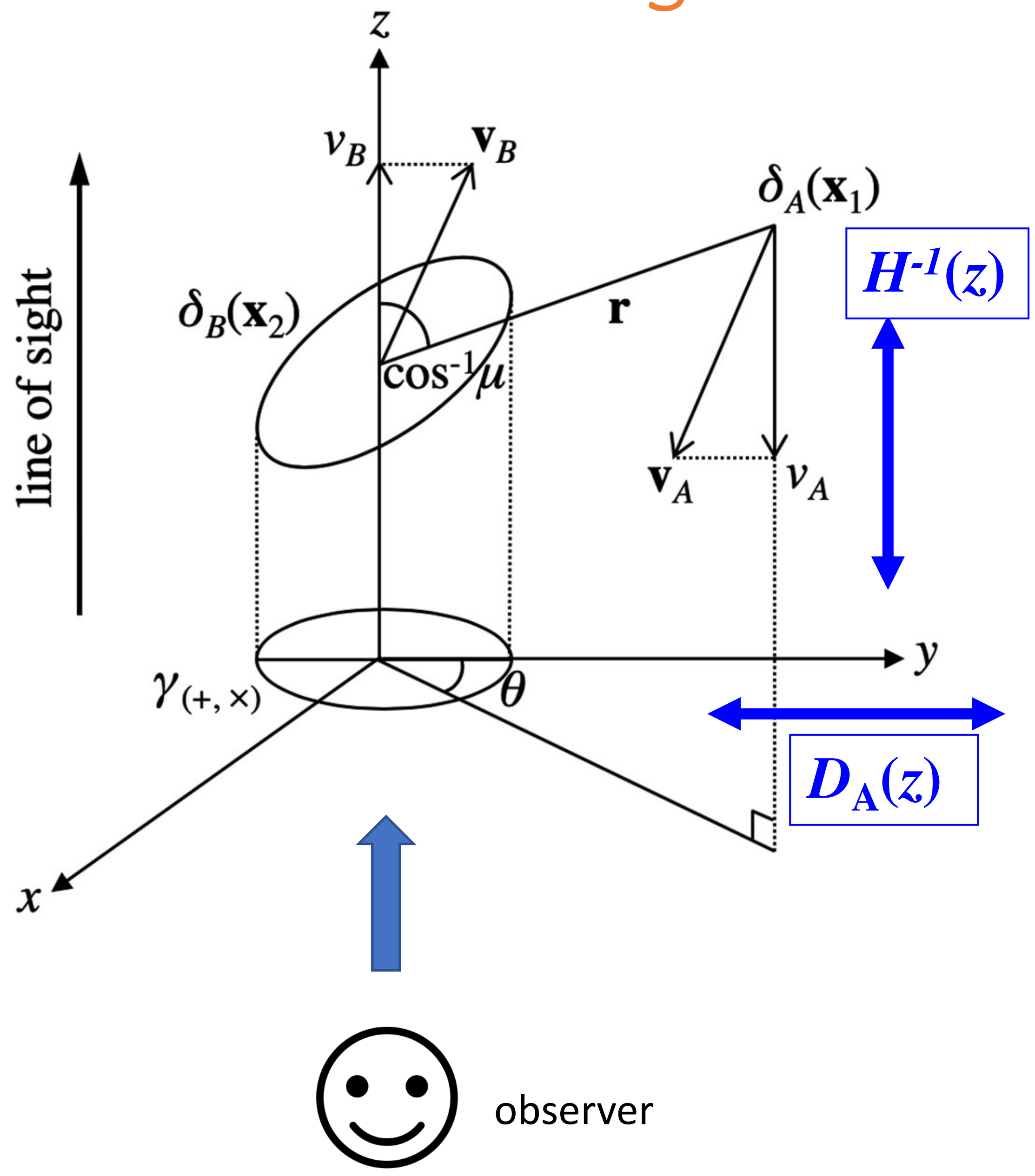
Comparison of 2-D GI to simulations





Okumura, Taruya and Nishimichi (2020)

Formulating the IA statistics in redshift space



- New formula for II correlation
  - See Xia+ (2017) for a similar expression for the isotropic moment

$$\xi_\pm(\mathbf{r}) = \xi_{++}(\mathbf{r}) \pm \xi_{\times\times}(\mathbf{r})$$

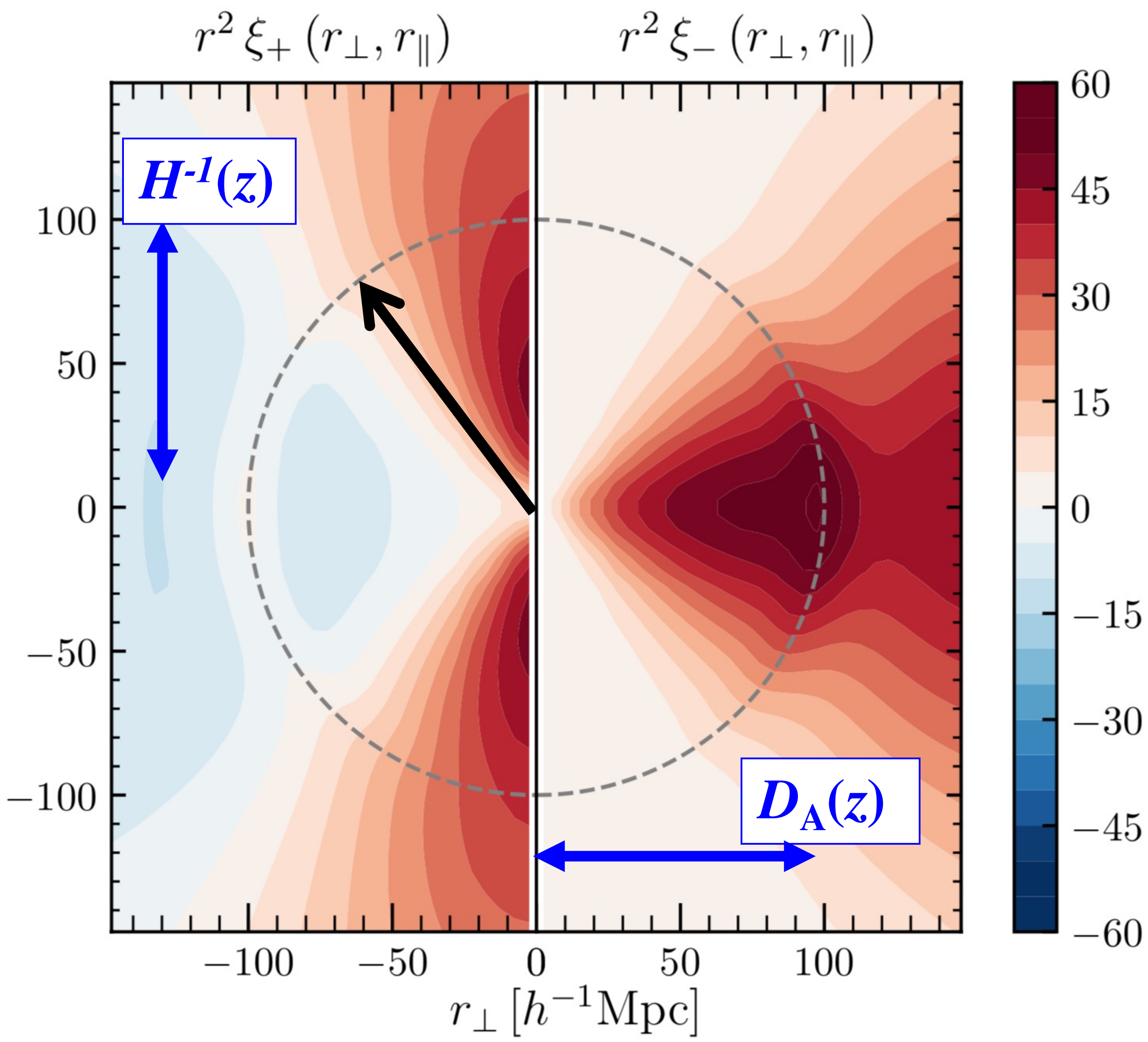
$$\xi_+(\mathbf{r}) = \frac{8}{105}\,\widetilde{C}_1^2\left[7\,\mathcal{P}_0(\mu)\,\Xi^{(0)}_{\delta\delta,0}(r) + 10\,\mathcal{P}_2(\mu)\,\Xi^{(0)}_{\delta\delta,2}(r) + 3\,\mathcal{P}_4(\mu)\,\Xi^{(0)}_{\delta\delta,4}(r)\right],$$

$$\xi_-(\mathbf{r}) = \widetilde{C}_1^2\cos(4\phi)\left(1-\mu^2\right)^2\,\Xi^{(0)}_{\delta\delta,4}(r) = \frac{8}{105}\,\widetilde{C}_1^2\cos(4\phi) \times \left[7\,\mathcal{P}_0(\mu) + 10\,\mathcal{P}_2(\mu) + 3\,\mathcal{P}_4(\mu)\right]\Xi^{(0)}_{\delta\delta,4}(r).$$

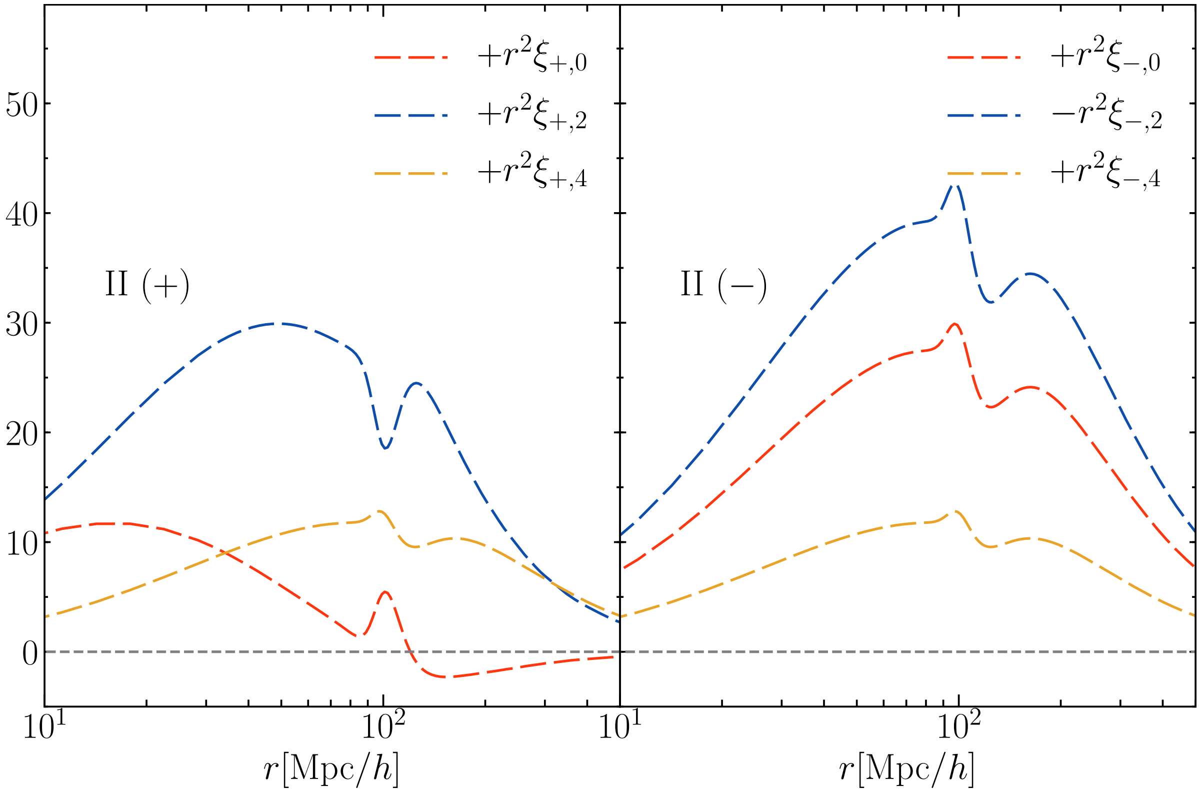
$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^\infty \frac{k^{2-n}dk}{2\pi^2} P_{XY}(k) j_\ell(kr)$$

Okumura & Taruya (2020)

II correlation in 2D

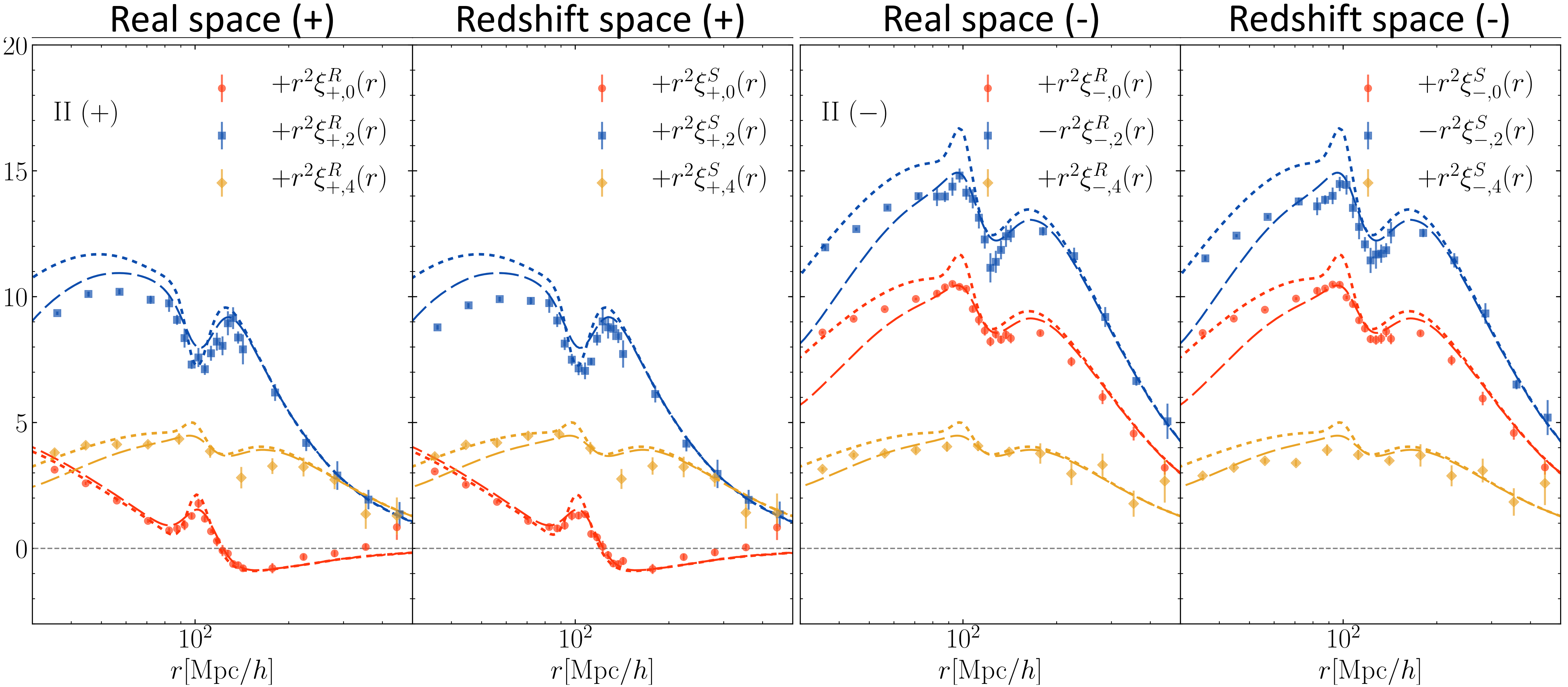


$$\xi_\pm(\mathbf{r}) = \xi_{++}(\mathbf{r}) \pm \xi_{\times\times}(\mathbf{r})$$



Okumura & Taruya (2020)

Comparison of II multipoles to simulations

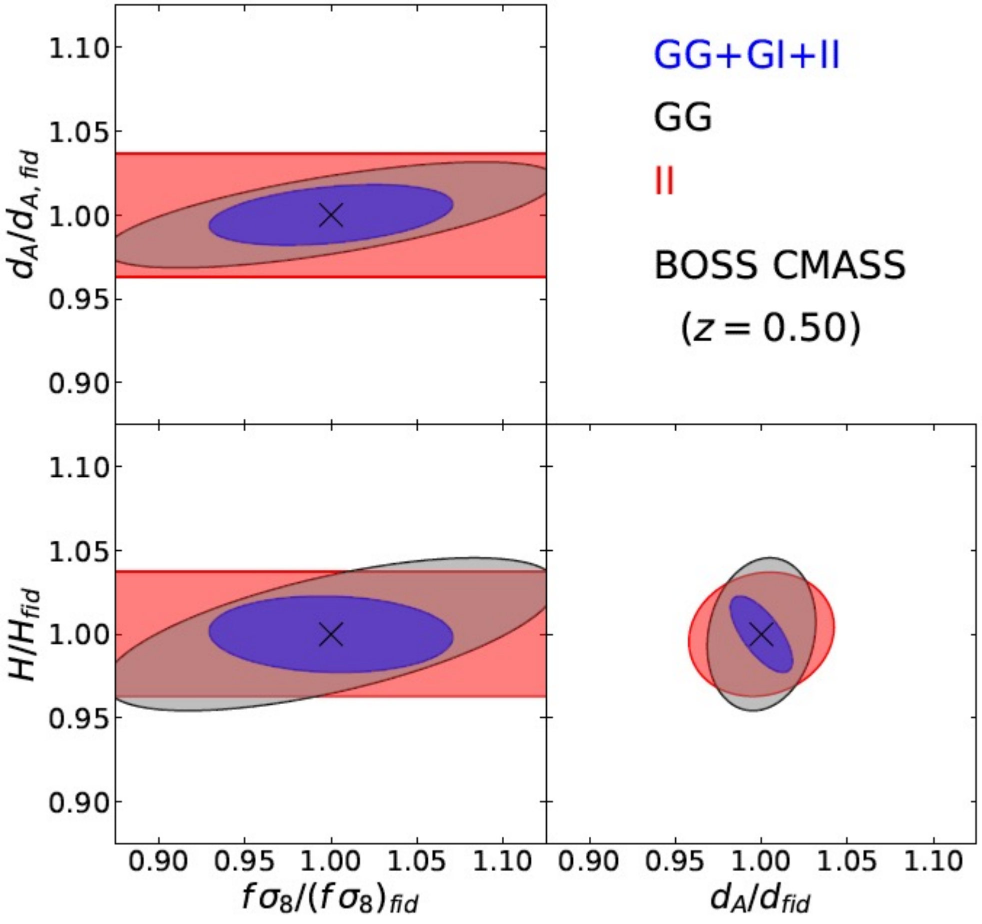


- dotted : linear-alignment
- dashed : nonlinear-alignment

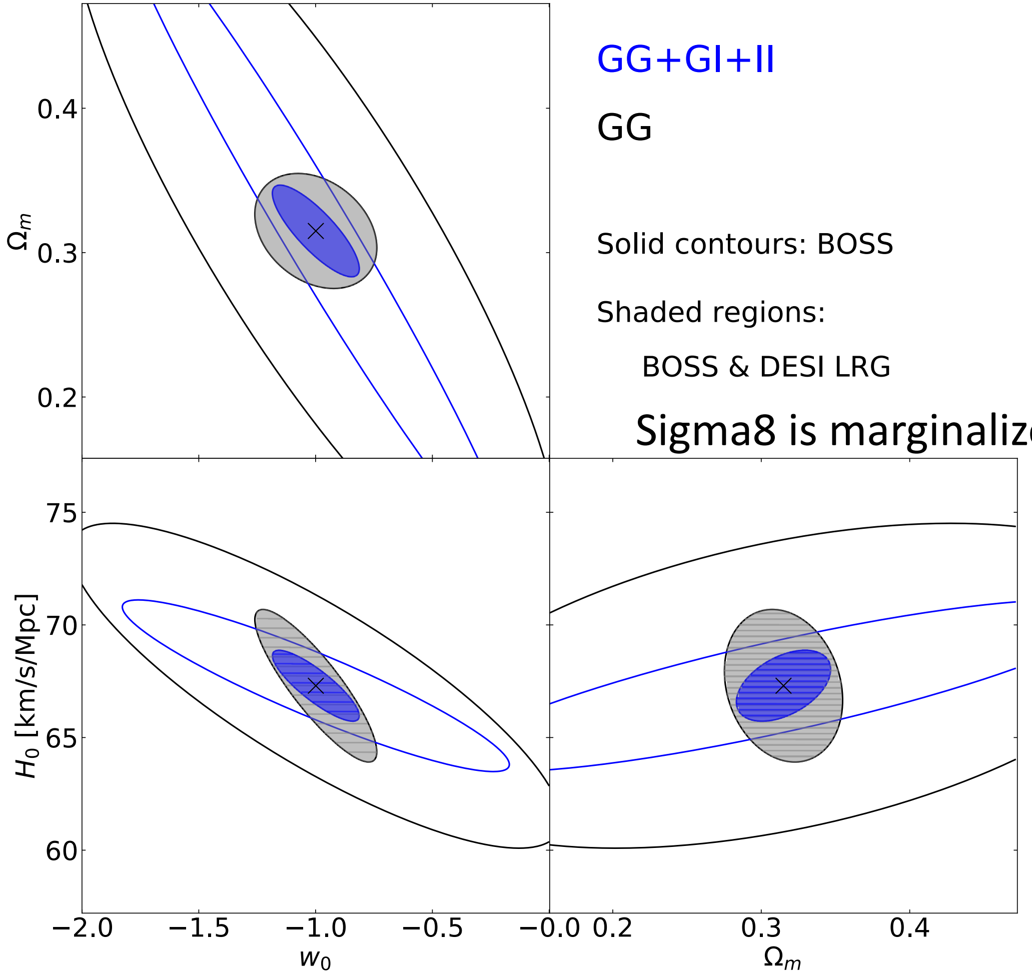
Okumura, Taruya and Nishimichi (2020)

IA measurements enhance the science return from galaxy redshift surveys

- Under the assumption that the linear alignment model describes the IA perfectly,



Clustering σ_8 and IA amplitude A_{IA} are marginalized over.



Sigma8 is marginalized over.

Taruya & Okumura (2020)

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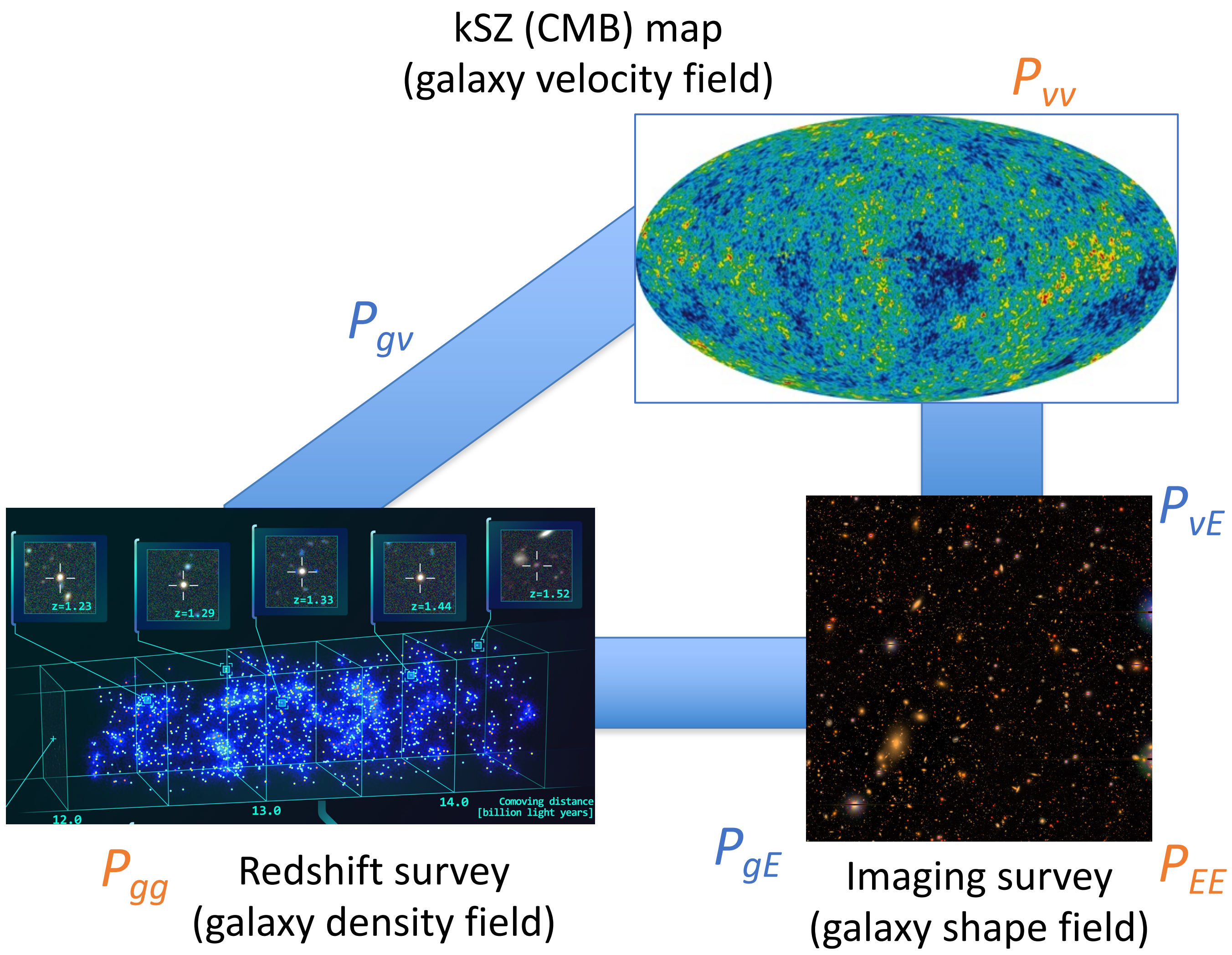
Synergies between galaxy redshift surveys and CMB



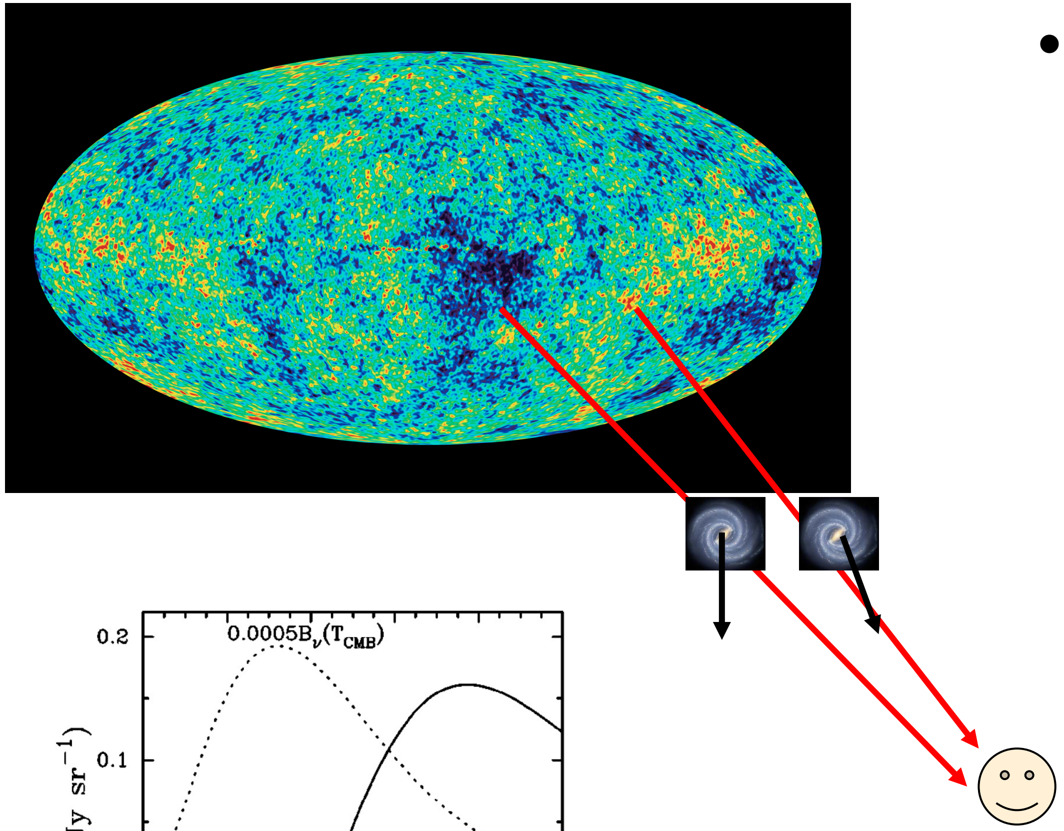
- Okumura, Nishimichi, Umetsu & Osato (2018)
- Okumura, Taruya & Nishimichi (2019, 2020)
- Okumura & Taruya (2020)
- van Gemeren & Chisari (2020)

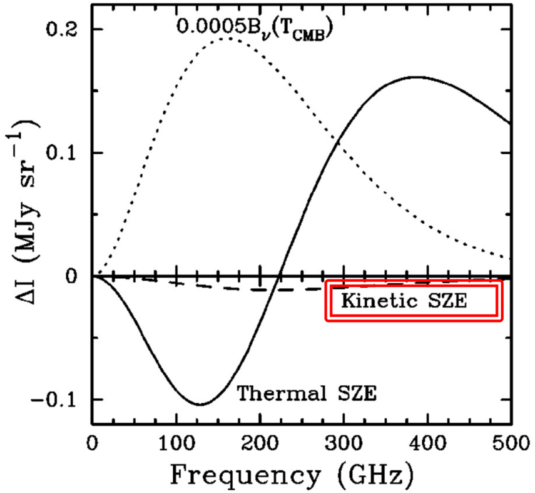
$$\xi_{v+}(\mathbf{r}) = \widetilde{C}_1 \cos(2\phi)\mu(1-\mu^2)\Xi^{(1)}_{\delta\Theta,3}(r)$$

$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^\infty \frac{k^{2-n}dk}{2\pi^2} P_{XY}(k) j_\ell(kr)$$

Direct measurement of velocities: Kinetic Sunyaev-Zeld'ovich (kSZ) effect

Cosmic microwave background



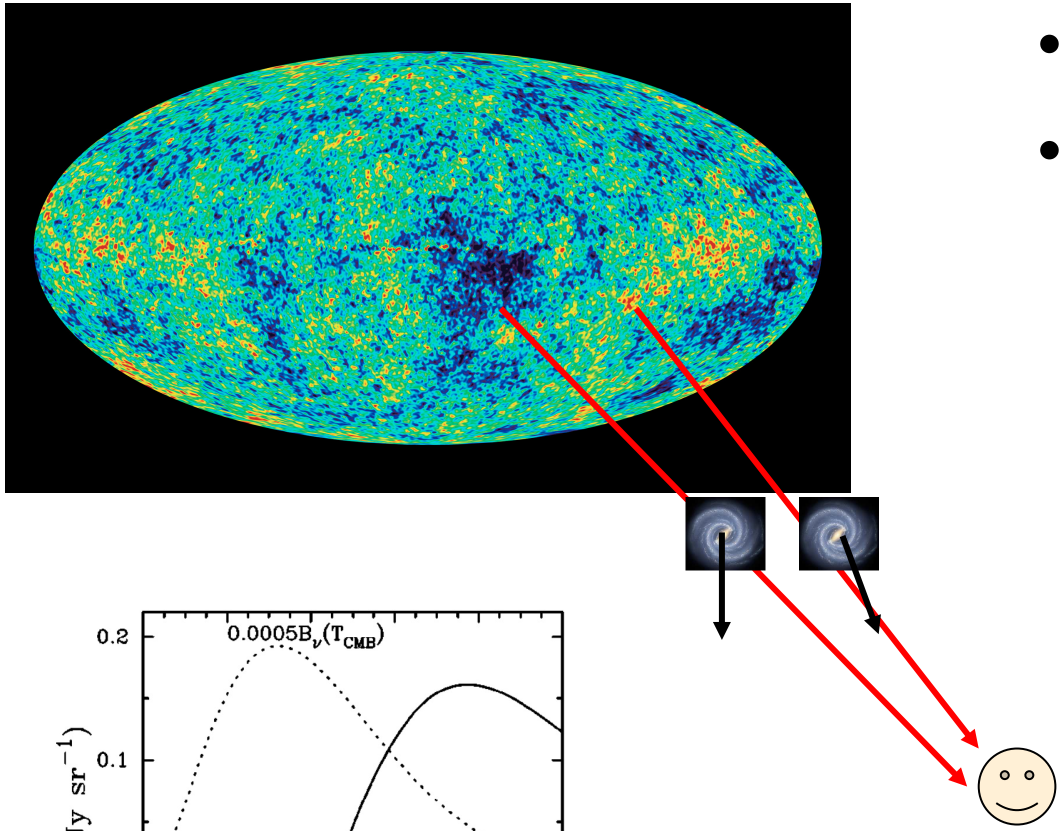


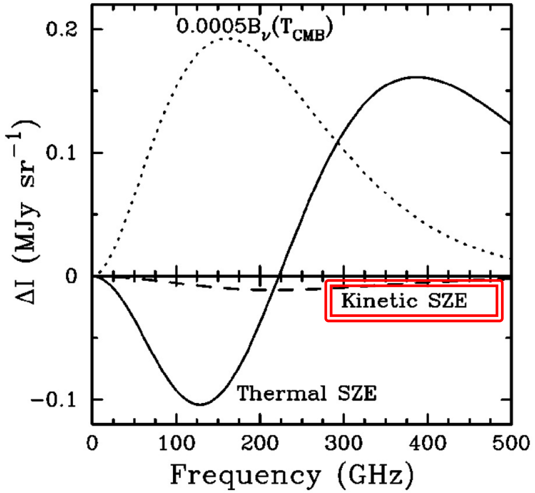
- Kinetic SZ (kSZ) effect (1980)
  - Doppler effect of cluster bulk velocity w.r.t. CMB rest frame

    $$\Delta T_{kSZ} / T_{CMB} = -\tau_e v_{//}$$ ($v_{//}$: line-of-sight velocity)
  - By measuring the temperature distortion, one can directly measure the velocity field of galaxy clusters, so it is a powerful observable to test modified gravity theories.
  - However, this effect is very tiny and hard to measure in observation.

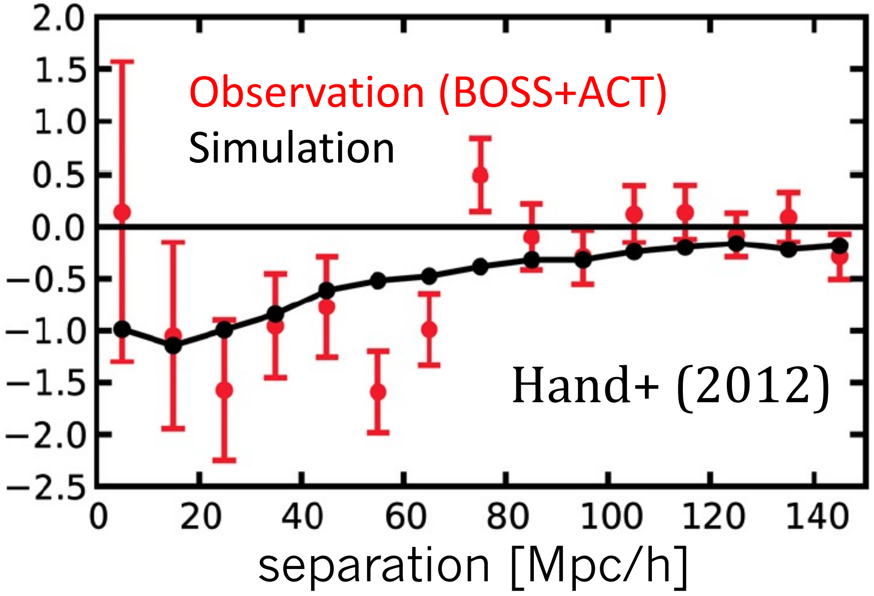
Direct measurement of velocities: Kinetic Sunyaev-Zeld’ovich (kSZ) effect

Cosmic microwave background





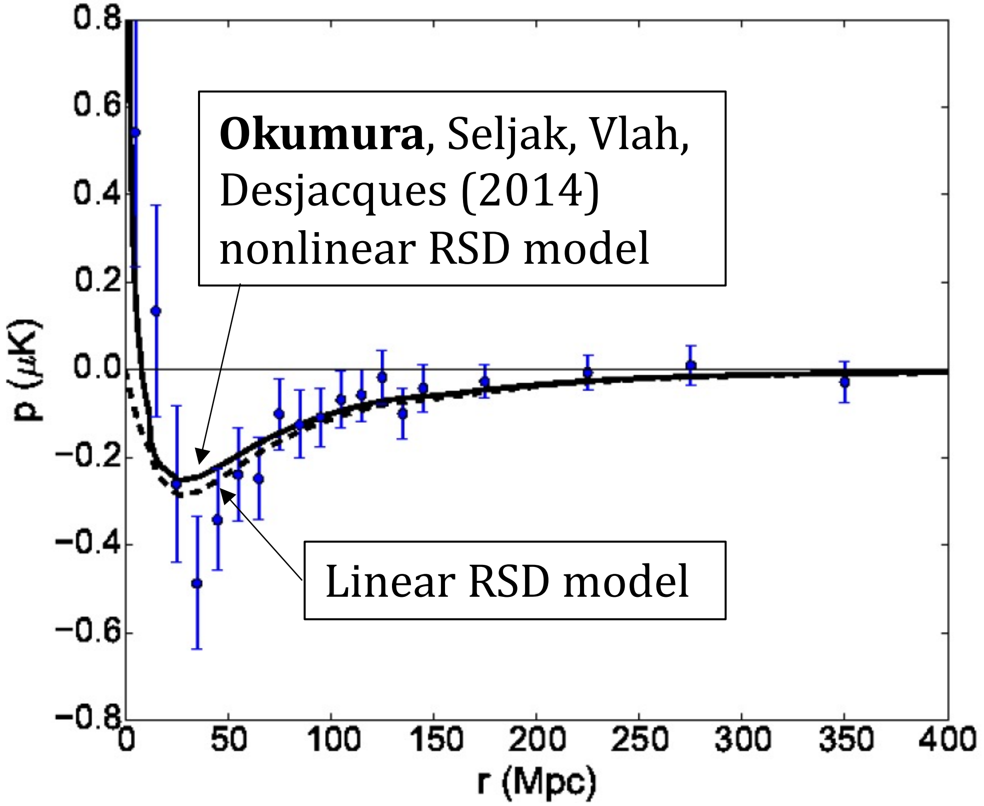
- Kinetic SZ (kSZ) effect (1980)
- First detection of kSZ effect (2012)



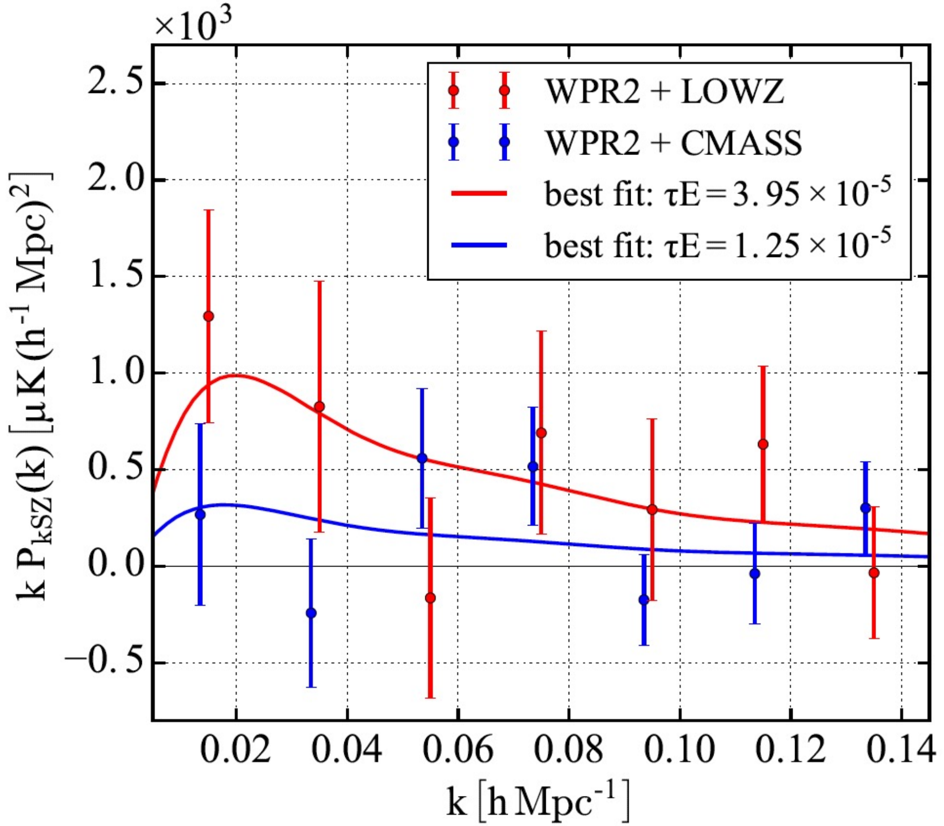
Large-scale velocity field probed via kSZ effect

$$P_{kSZ}(k) \propto P_{\delta\theta}(k) \propto P_{\delta\delta}(k)/k$$

- De Bernardis et al. (2016)
- Configuration space
- ACT x BOSS

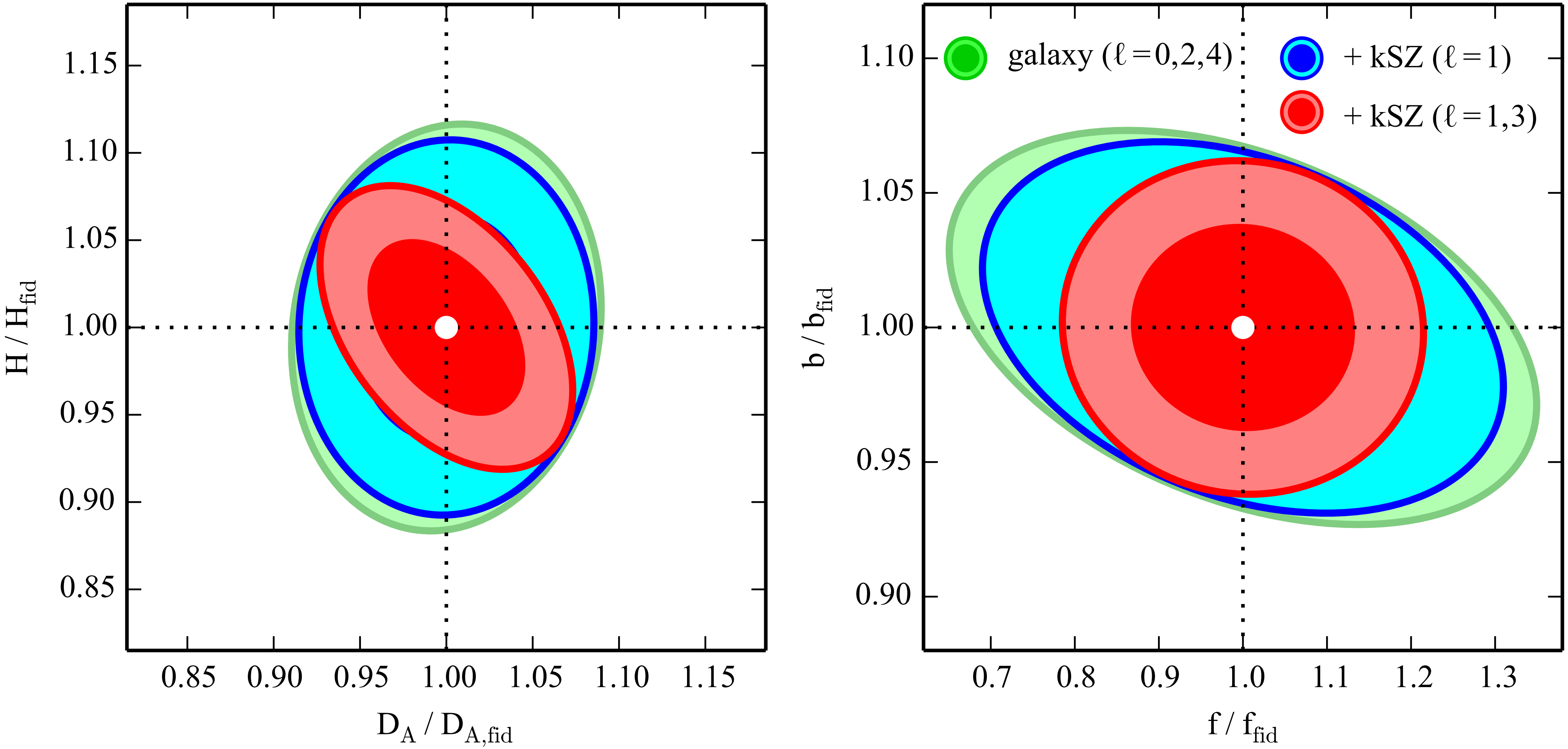


- Sugiyama, **Okumura**, Spergel (2018)
- Fourier space
- Planck x BOSS



kSZ measurements enhance the science return from galaxy redshift surveys

- Sugiyama, **Okumura**, Spergel (2017)
- CMB-S4 x DESI



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Galaxy density, velocity and ellipticity power spectra in linear theory

- Galaxy clustering: $\delta_g^S(\boldsymbol{k};z) = K_g(\mu;z)\delta_m(\boldsymbol{k};z)$

$$K_g(\mu;z) = b_g(z) + f(z)\mu^2$$

- kSZ: $\delta T(\boldsymbol{k};z) = (T_0\tau/c)v_{\parallel}(\boldsymbol{k};z) = K_v(\boldsymbol{k};z)\delta_m(k;z)$

$$K_v(k,\mu;z) = i\frac{T_0\tau}{c}\frac{f(z)\mu a H(z)}{k}$$

- IA: $\gamma_E(\boldsymbol{k};z) = K_E(\mu;z)\delta_m(\boldsymbol{k};z)$

$$K_E(\mu;z) = b_K(z)(1-\mu^2)$$

$$b_K(z) = 0.01344 A_{\mathrm{IA}}(z)\Omega_{\mathrm{m}}/D(z)$$

- Power spectra (6 in total)

$$P_{ij}(k,\mu;z) = K_i(k,\mu;z)K_j(k,\mu;z)P_{\mathrm{lin}}(k;z)$$

- Geometric distortions

$$P_{ij}^{\mathrm{obs}}\left(k_\perp^{\mathrm{fid}}, k_\parallel^{\mathrm{fid}}; z\right) = \frac{H(z)}{H^{\mathrm{fid}}(z)}\left\{\frac{D_{\mathrm{A}}^{\mathrm{fid}}(z)}{D_{\mathrm{A}}(z)}\right\}^2 P_{ij}\left(k_\perp, k_\parallel; z\right)$$

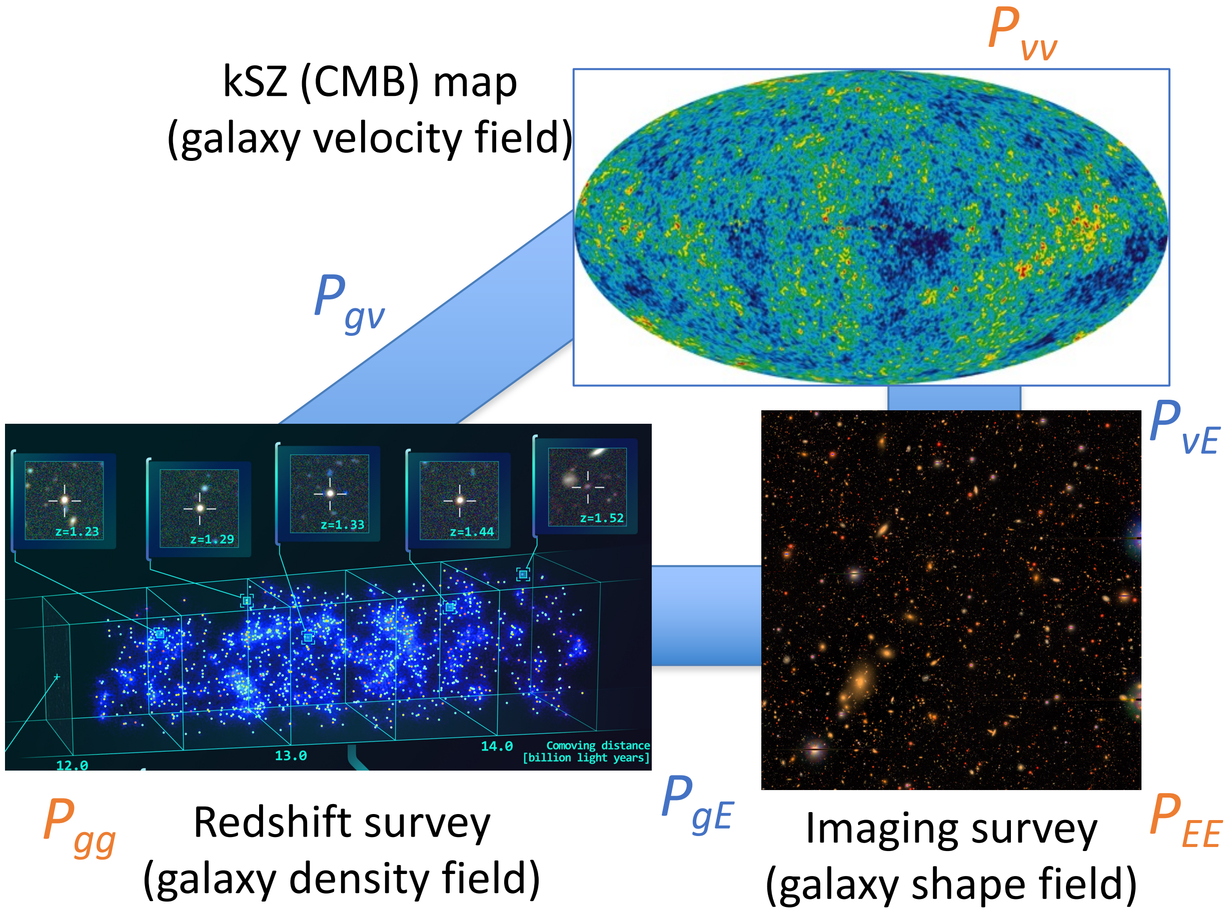
$$k_\parallel^{\mathrm{fid}} = k_\parallel H^{\mathrm{fid}}(z)/H(z) \text{ and } k_\perp^{\mathrm{fid}} = D_{\mathrm{A}}(z)/D_{\mathrm{A}}^{\mathrm{fid}}(z)$$

- Fitting parameters

$$\theta_\alpha = (b\sigma_8, A_{\mathrm{IA}}\sigma_8, \tau, f\sigma_8, H, D_{\mathrm{A}})$$

Amplitude (nuisance) parameters

Dynamical and geometric quantities



Fisher matrix formalism

$$F_{\alpha\beta} = \frac{V_s}{4\pi^2} \int_{k_{\min}}^{k_{\max}} dk k^2 \int_{-1}^{1} d\mu \sum_{a,b=1}^{N_P} \frac{\partial P_a(k,\mu)}{\partial \theta_\alpha} \left[\mathrm{Cov}^{-1}\right]_{ab} \frac{\partial P_b(k,\mu)}{\partial \theta_\beta}$$

- 6 x 6 Gaussian covariance matrix

Auto power: P_{gg} →, P_{EE} →, P_{vv} →

Cross power: P_{gE} →, P_{gv} →, P_{vE} →

$$\mathrm{Cov}_{ab}(k,\mu) = \begin{bmatrix}
2\{\widetilde{P}_{gg}\}^2 & 2\{P_{gE}\}^2 & 2\{P_{gv}\}^2 & 2\widetilde{P}_{gg}P_{gE} & 2\widetilde{P}_{gg}P_{gv} & 2P_{gv}P_{gE} \\
2\{P_{gE}\}^2 & 2\{\widetilde{P}_{EE}\}^2 & 2\{P_{vE}\}^2 & 2P_{gE}\widetilde{P}_{EE} & 2P_{gE}P_{vE} & 2\widetilde{P}_{EE}P_{vE} \\
2\{P_{gv}\}^2 & 2\{P_{vE}\}^2 & 2\{\widetilde{P}_{vv}\}^2 & 2P_{gv}P_{vE} & 2\widetilde{P}_{vv}P_{gv} & 2P_{vE}\widetilde{P}_{vv} \\
2\widetilde{P}_{gg}P_{gE} & 2P_{gE}\widetilde{P}_{EE} & 2P_{gv}P_{vE} & \widetilde{P}_{gg}\widetilde{P}_{EE} + \{P_{gE}\}^2 & \widetilde{P}_{gg}P_{vE} + P_{gE}P_{gv} & P_{gv}\widetilde{P}_{EE} + P_{gE}P_{vE} \\
2\widetilde{P}_{gg}P_{gv} & 2P_{gE}P_{vE} & 2\widetilde{P}_{vv}P_{gv} & \widetilde{P}_{gg}P_{vE} + P_{gE}P_{gv} & \widetilde{P}_{gg}\widetilde{P}_{vv} + \{P_{gv}\}^2 & P_{gE}\widetilde{P}_{vv} + P_{gv}P_{vE} \\
2P_{gv}P_{gE} & 2\widetilde{P}_{EE}P_{vE} & 2P_{vE}\widetilde{P}_{vv} & P_{gv}\widetilde{P}_{EE} + P_{gE}P_{vE} & P_{gE}\widetilde{P}_{vv} + P_{gv}P_{vE} & \widetilde{P}_{EE}\widetilde{P}_{vv} + \{P_{vE}\}^2
\end{bmatrix}$$

- Poisson shot noise

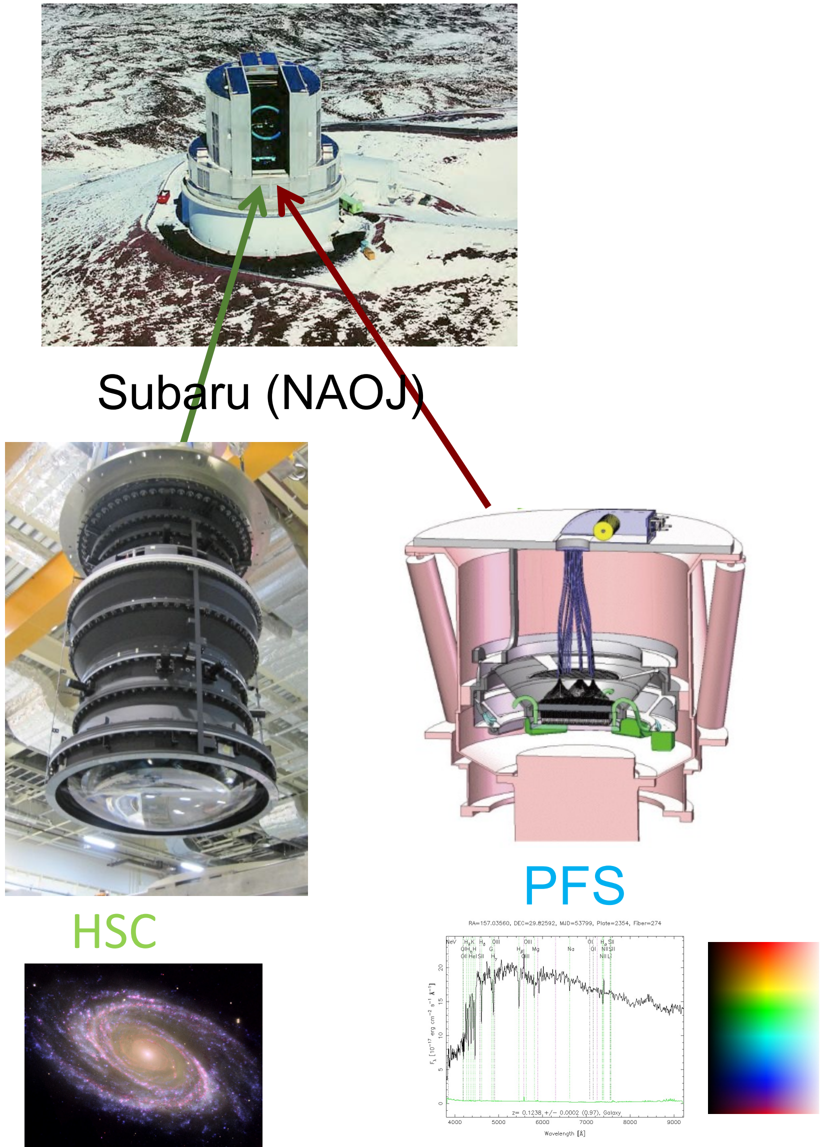
$$\widetilde{P}_{gg} = P_{gg} + \frac{1}{n_g}, \qquad \widetilde{P}_{vv} = P_{vv} + (1+R_N^2)\left(\frac{T_0\tau}{c}\right)^2 \frac{(f\sigma_v)^2}{n_v}, \qquad \widetilde{P}_{EE} = P_{EE} + \frac{\sigma_\gamma^2}{n_\gamma}$$

Survey setup

- Assume a PFS-like emission line galaxy (ELG) survey
  - Parameters from PFS white paper (Takada et al 2014)

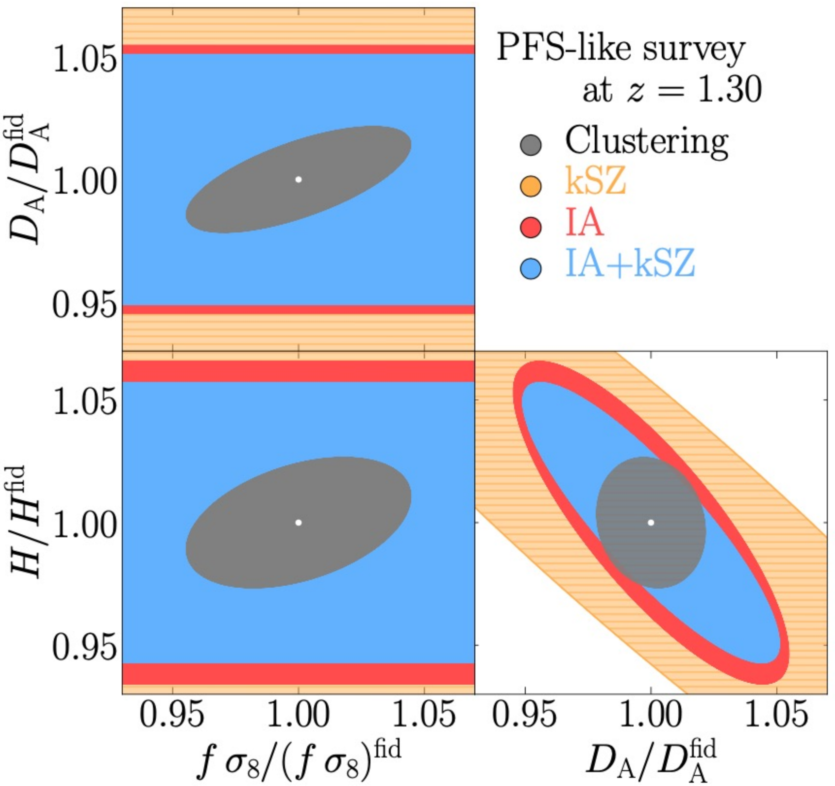
Redshift		Volume V_s	$10^4 n$	b_g
$z_{\rm min}$	$z_{\rm max}$	$(h^{-3}{\rm Gpc}^3)$	$(h^3{\rm Mpc}^{-3})$	
0.6	0.8	0.59	1.9	1.18
0.8	1.0	0.79	6.0	1.26
1.0	1.2	0.96	5.8	1.34
1.2	1.4	1.09	7.8	1.42
1.4	1.6	1.19	5.5	1.50
1.6	2.0	2.58	3.1	1.62
2.0	2.4	2.71	2.7	1.78

- Intrinsic alignment:
  - Beautiful galaxy images are obtained thanks to Hyper Suprime-Cam (HSC), σ_γ=0.2.
  - Shi et al (2021) proposed an estimator to directly detect IA of host halos using the observation of ELGs, $A_{\rm IA}$ = 18.
- kSZ:
  - CMB-S4, which is completely overlapped with the area of the PFS
  - Fiducial values: linear theory for σ_v, and the inverse S/N of the kSZ temperature fluctuations $R_{\rm N}$ = 10 (Sugiyama et al 2017).

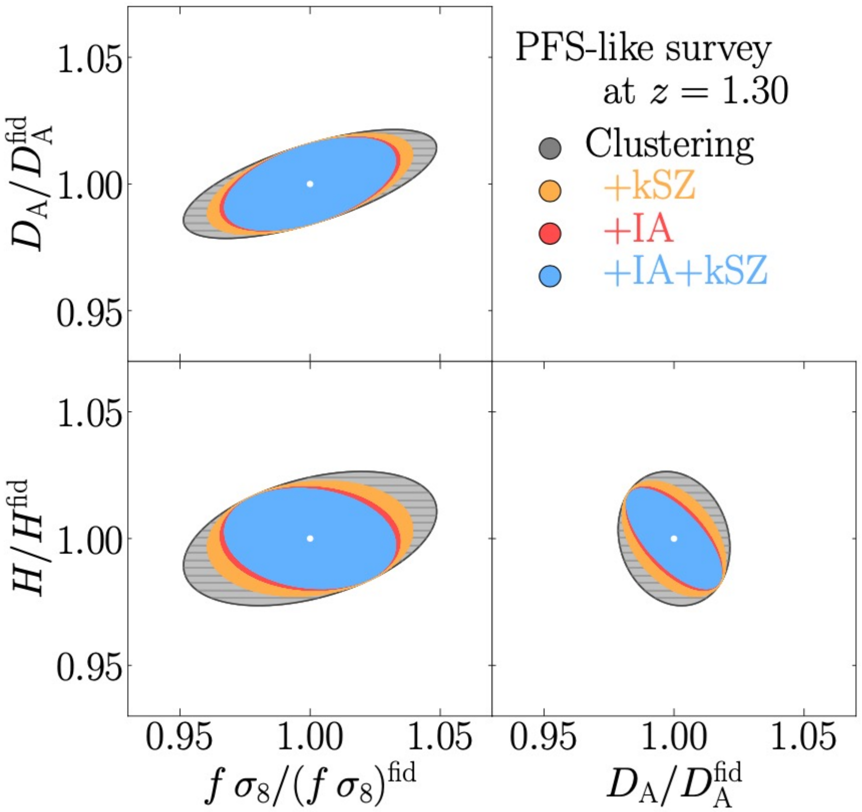


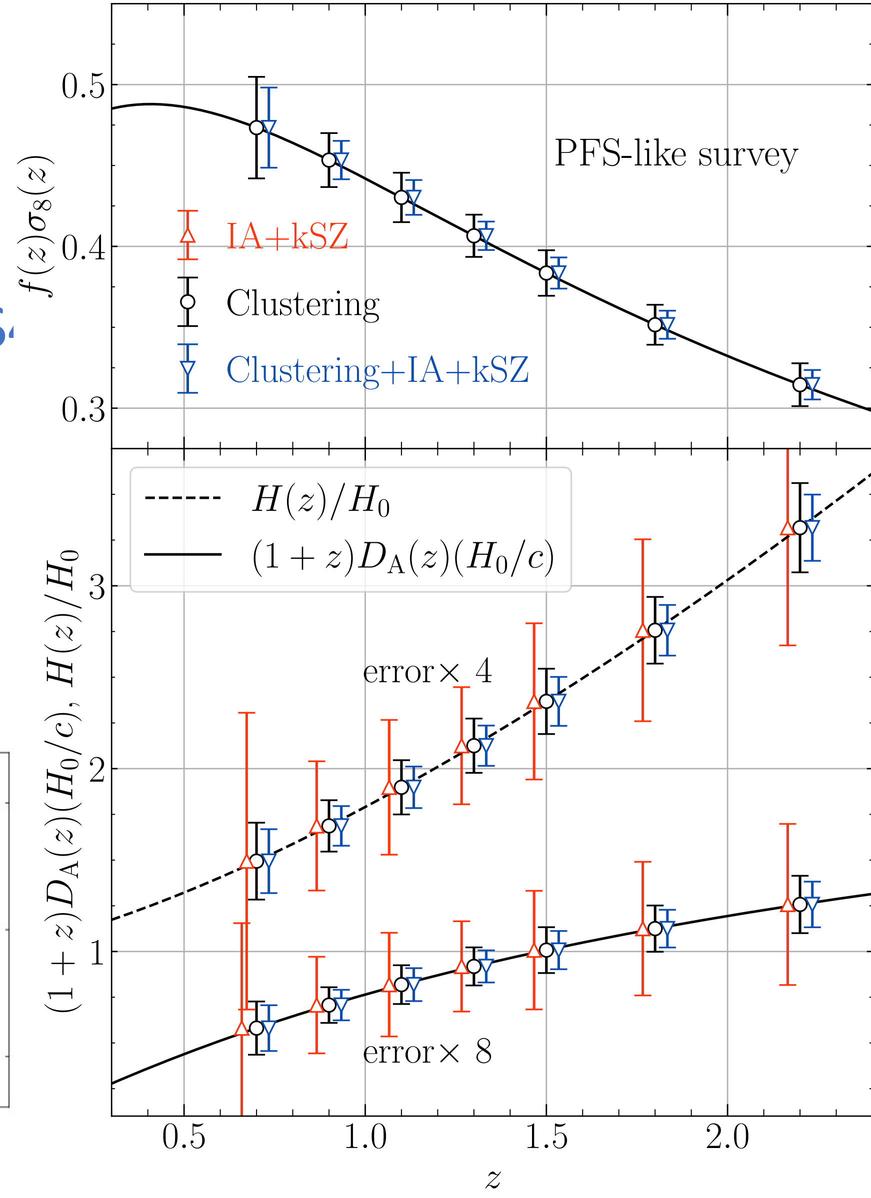
Geometric and dynamical constraints

- Clustering (PFS)
- kSZ (PFS + CMB-S4)
- IA (PFS + HSC)
- IA+kSZ (PFS + HSC + CMB-S4)



- Clustering (PFS)
- + kSZ (PFS + CMB-S4)
- + IA (PFS + HSC)
- + IA+kSZ (PFS + HSC + CMB-S





Cosmological constraints (1)

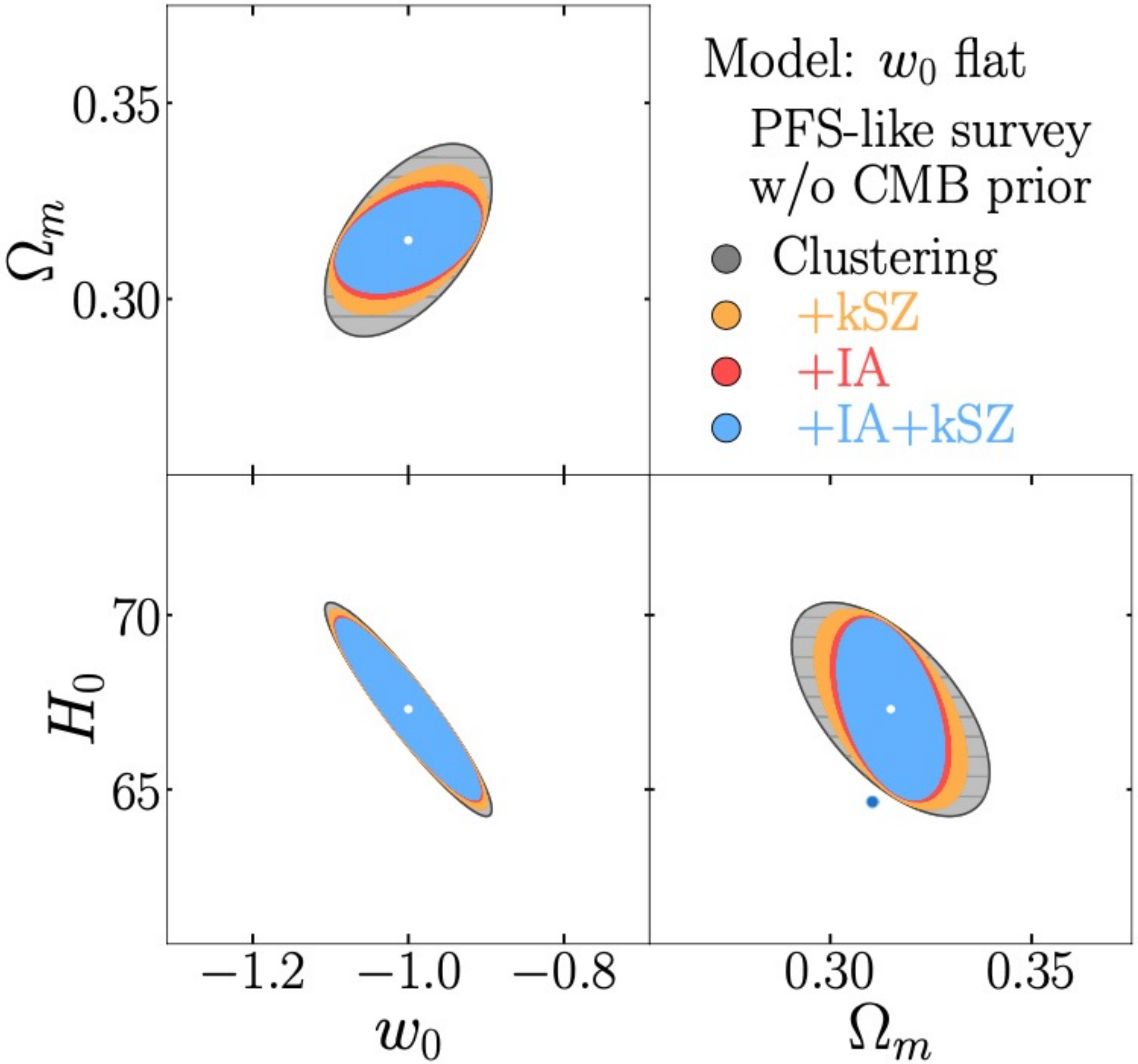
- Projection of the Fisher matrix to the cosmological parameter space:

$$S_{AB} = \sum_{\alpha,\beta} \frac{\partial \theta_\alpha}{\partial p_A} F_{\alpha\beta} \frac{\partial \theta_\beta}{\partial p_B}$$

$$\theta_\alpha = (b\sigma_8, A_{\rm IA}\sigma_8, \tau, f\sigma_8, H, D_{\rm A})$$

$$\rightarrow p_A = (\Omega_m, w_0, H_0, \sigma_8)$$

constant w, flat (Ω_K= 0) model



Cosmological constraints (2)

- Projection of the Fisher matrix to the cosmological parameter space:

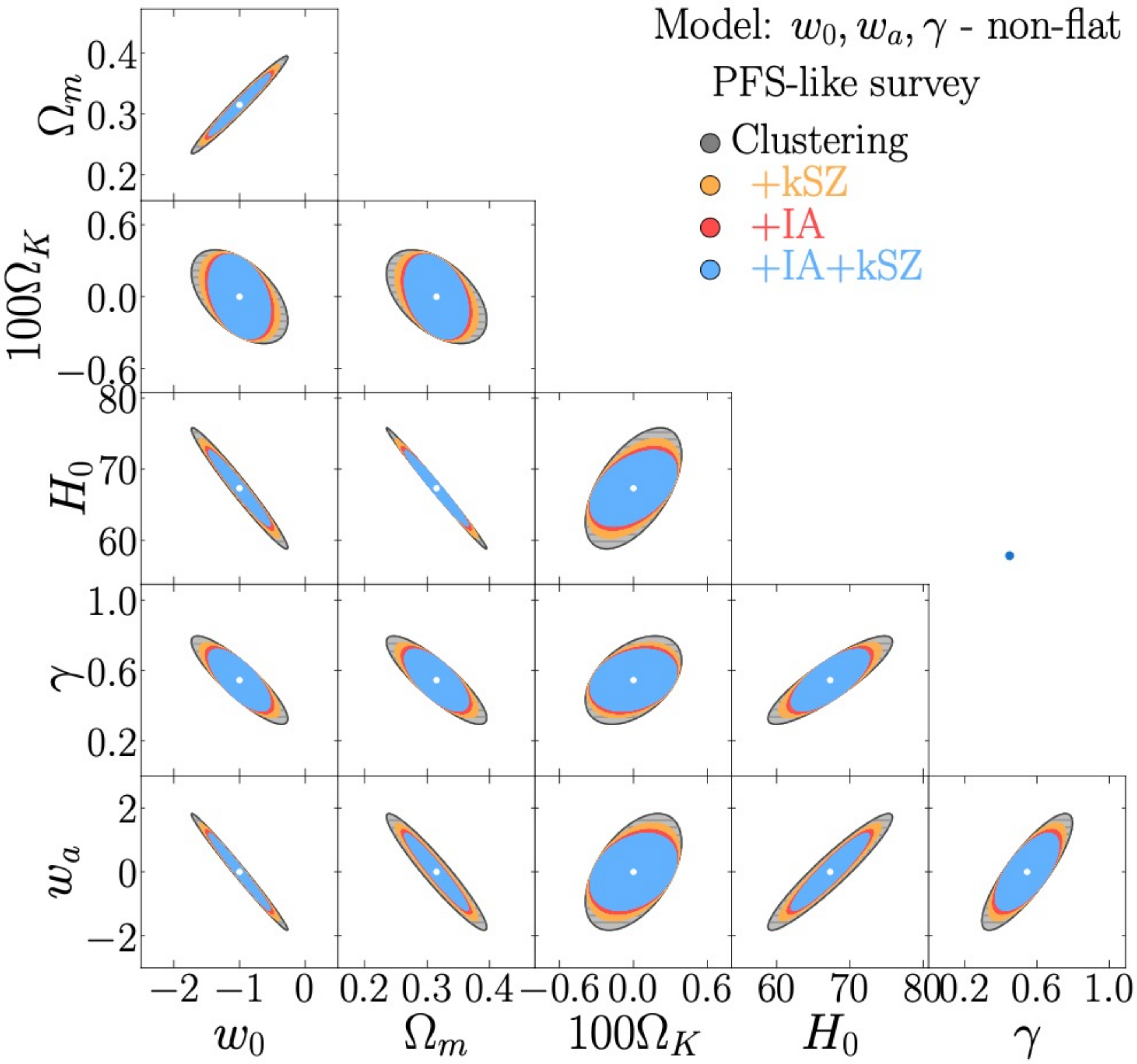
$$S_{AB} = \sum_{\alpha,\beta} \frac{\partial \theta_\alpha}{\partial p_A} F_{\alpha\beta} \frac{\partial \theta_\beta}{\partial p_B}$$

$$\theta_\alpha = (b\sigma_8, A_{\rm IA}\sigma_8, \tau, f\sigma_8, H, D_{\rm A})$$

$$\rightarrow p_A = (\Omega_{\rm m}, \Omega_K, w_0, w_a, H_0, \gamma, \sigma_8)$$

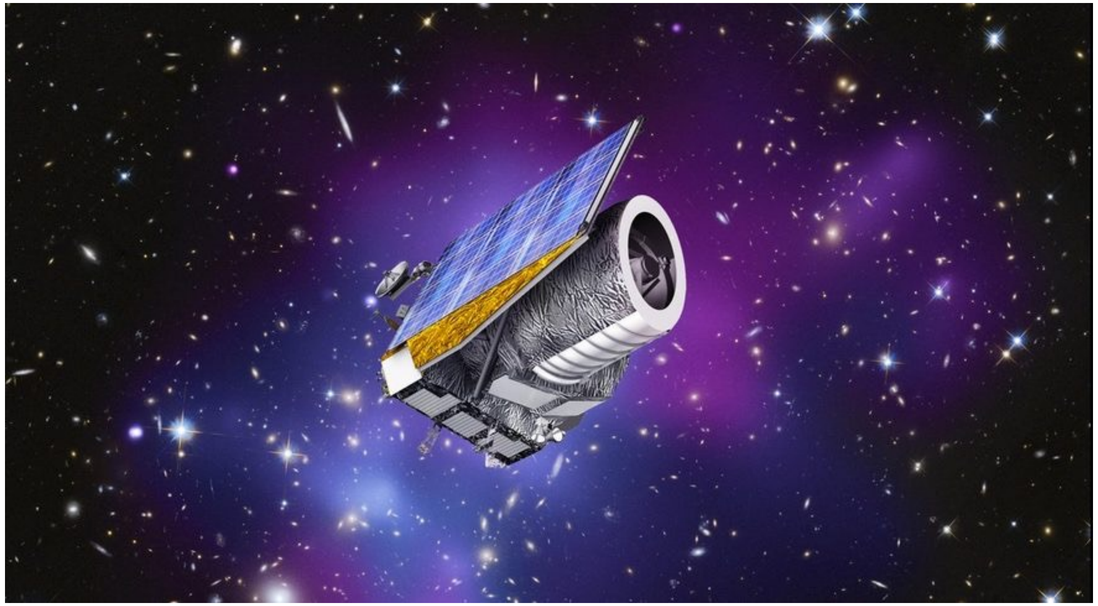
time-varying $w(a) = w_0 + (1-a)w_a$, non-flat ($\Omega_K \neq 0$) model with modified gravity parameter γ

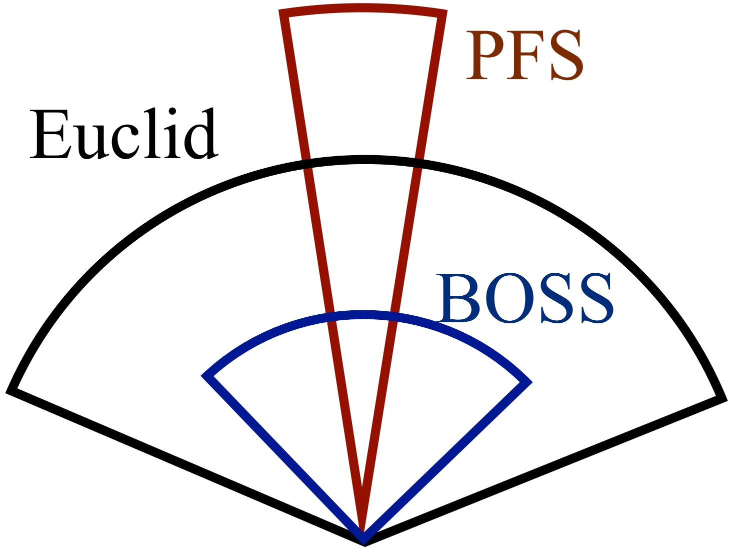
$$S_{AB} = S_{AB}^{\rm LSS} + S_{AB}^{\rm CMB}$$



Deep vs wide surveys

- Euclid satellite mission for galaxy surveys

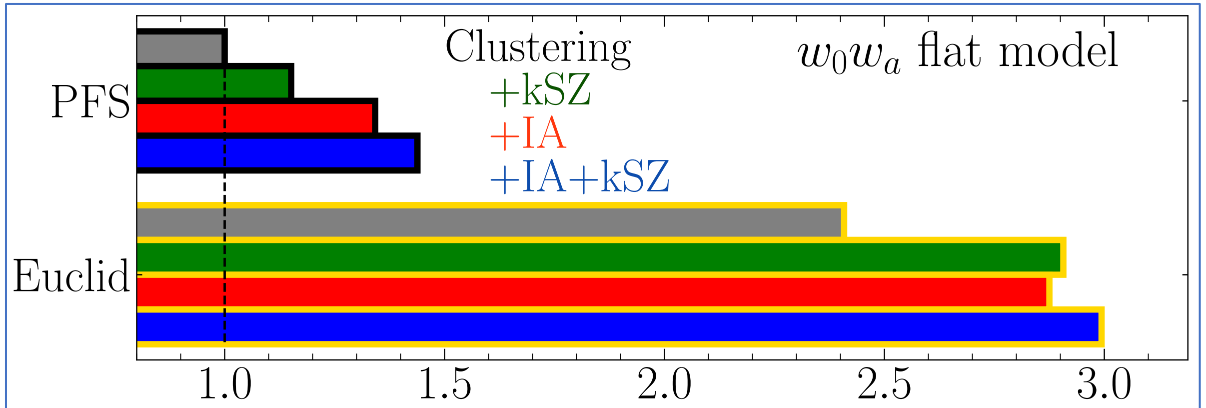




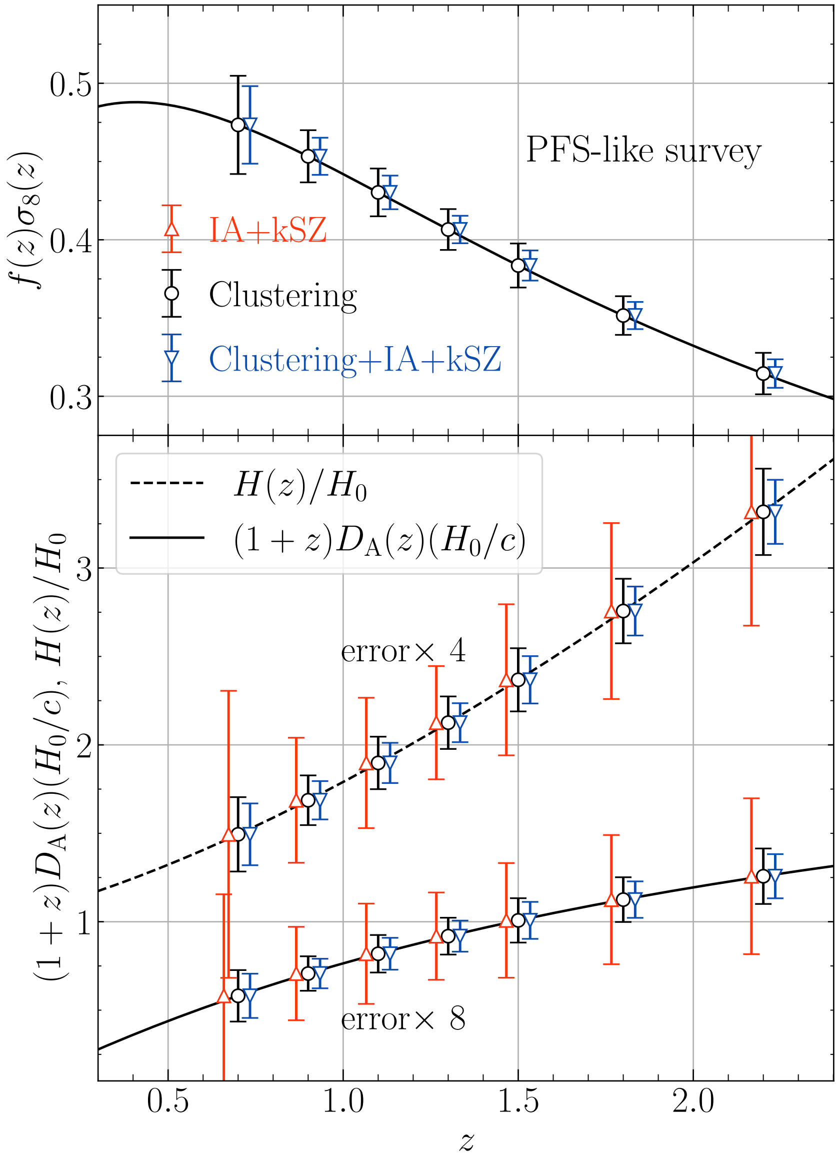
- Figure-of-Merit (FoM)

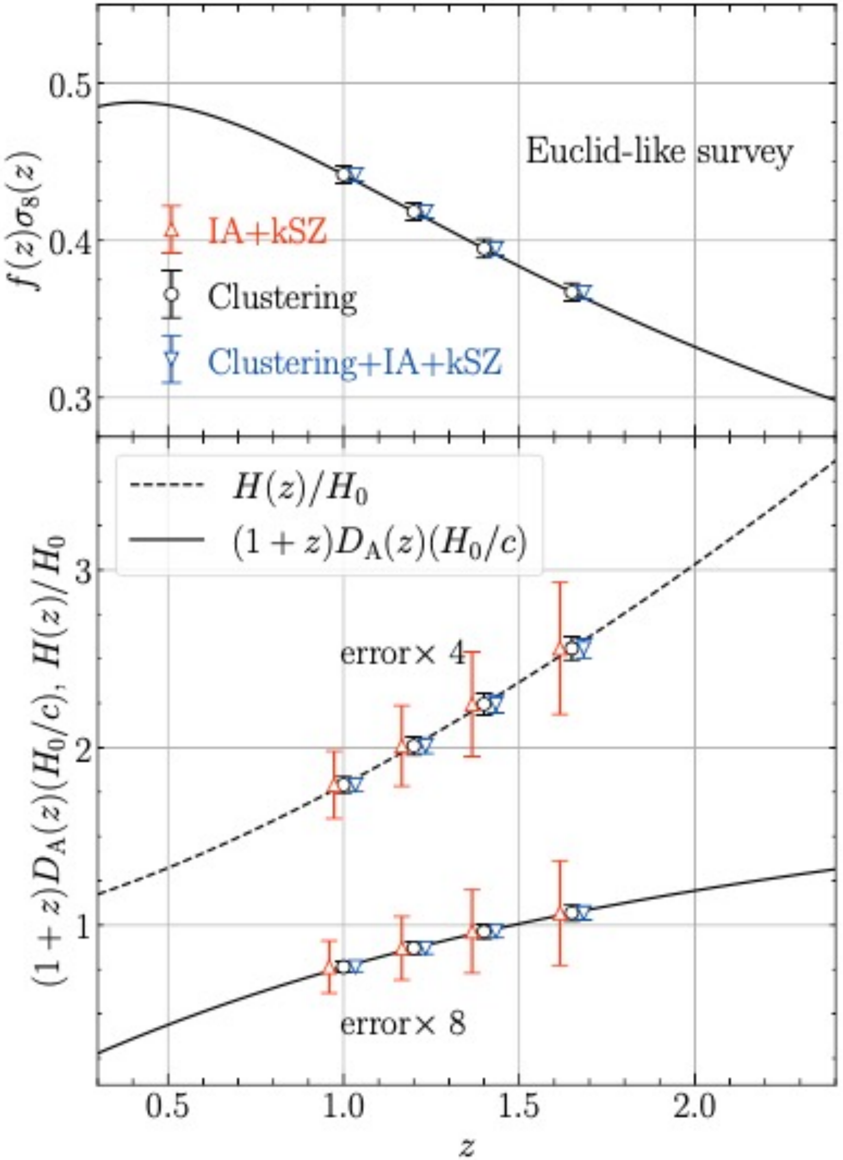
$$\mathrm{FoM} = \left\{\det(\overline{S}_{AB})\right\}^{1/N_p}$$

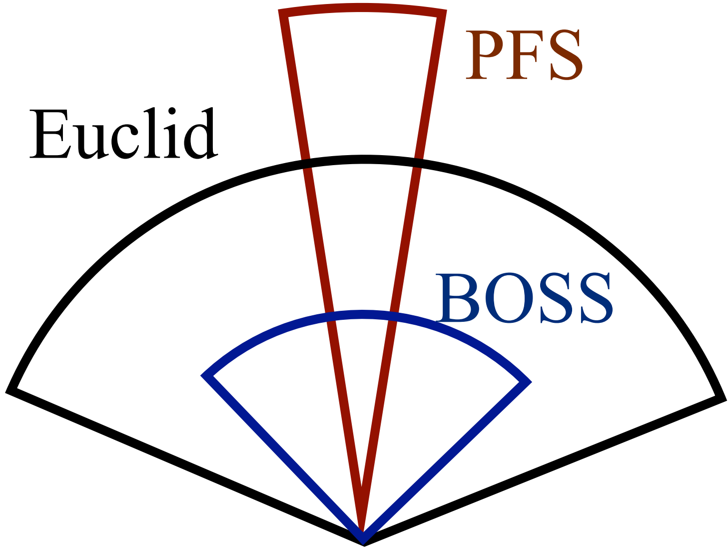
  - Normalize by the clustering-only case with PFS



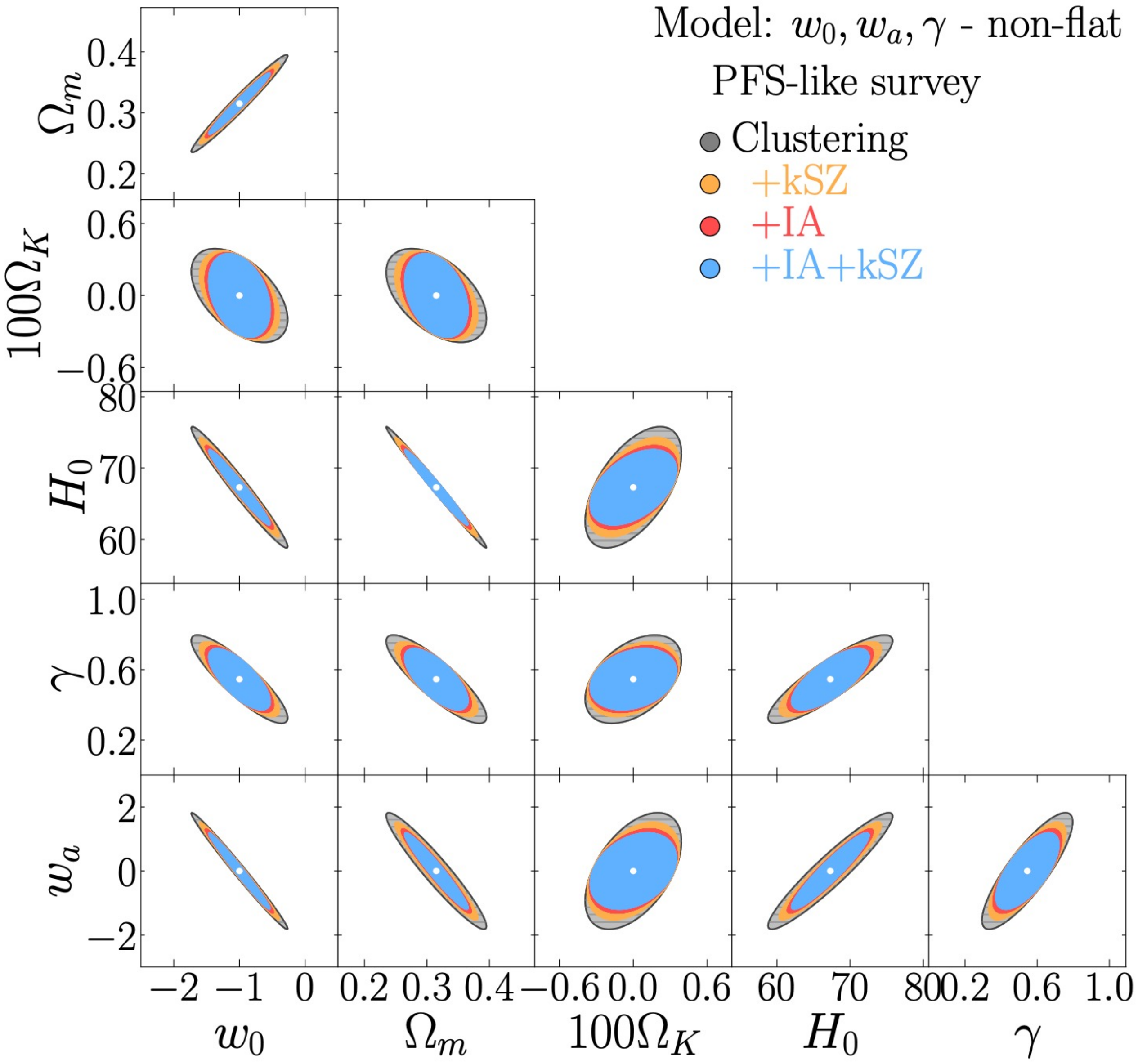
Deep vs wide surveys

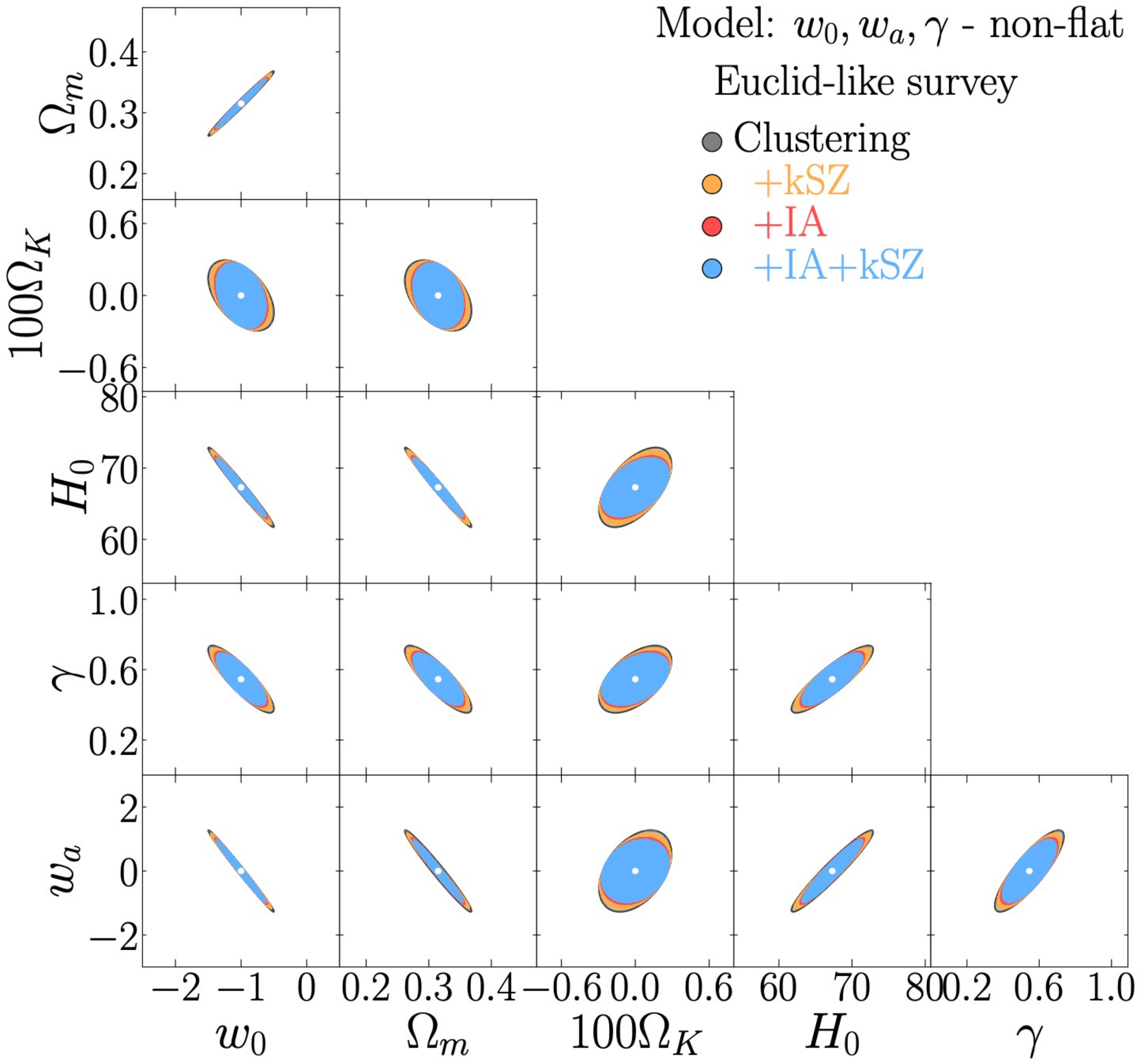




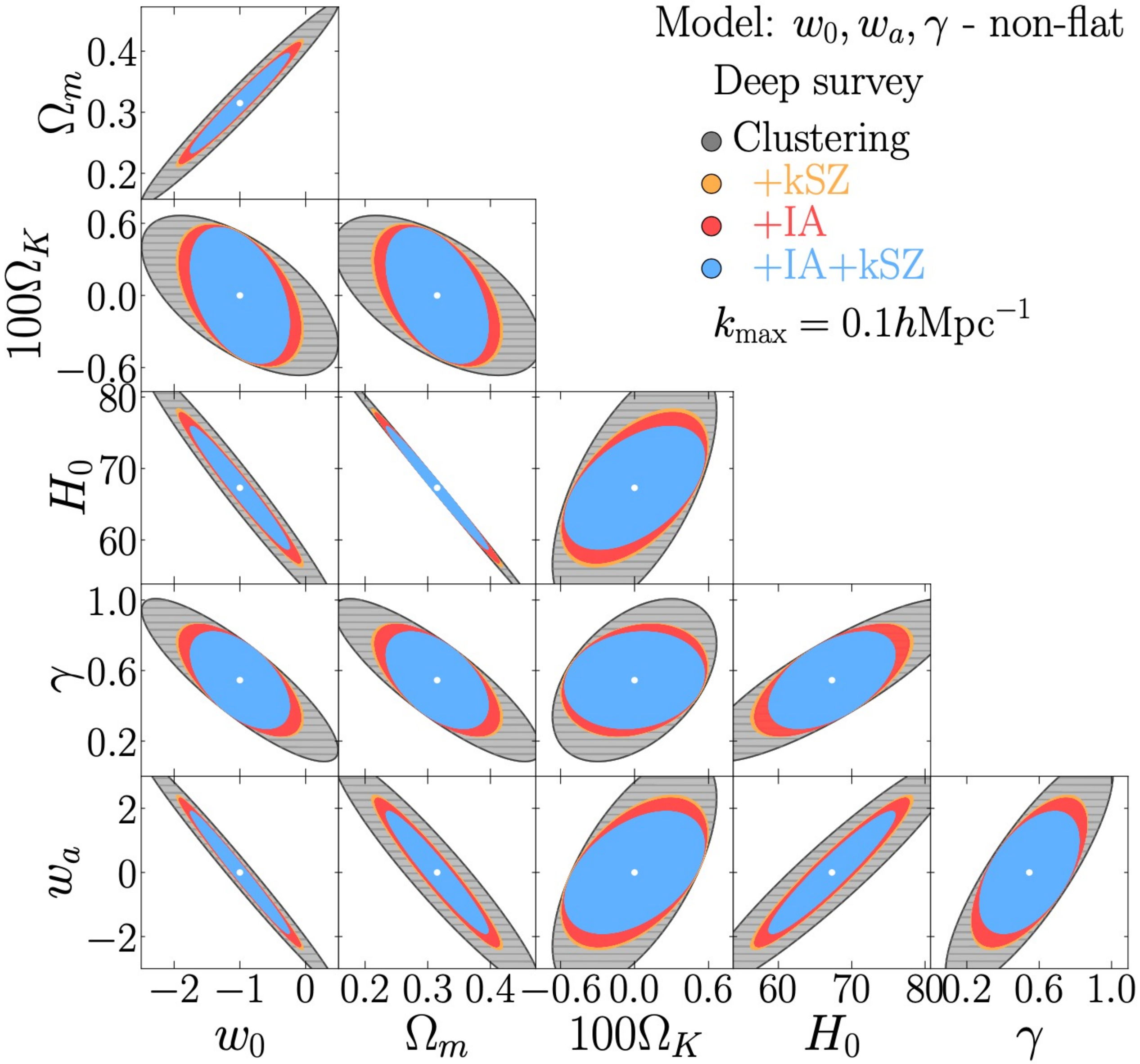


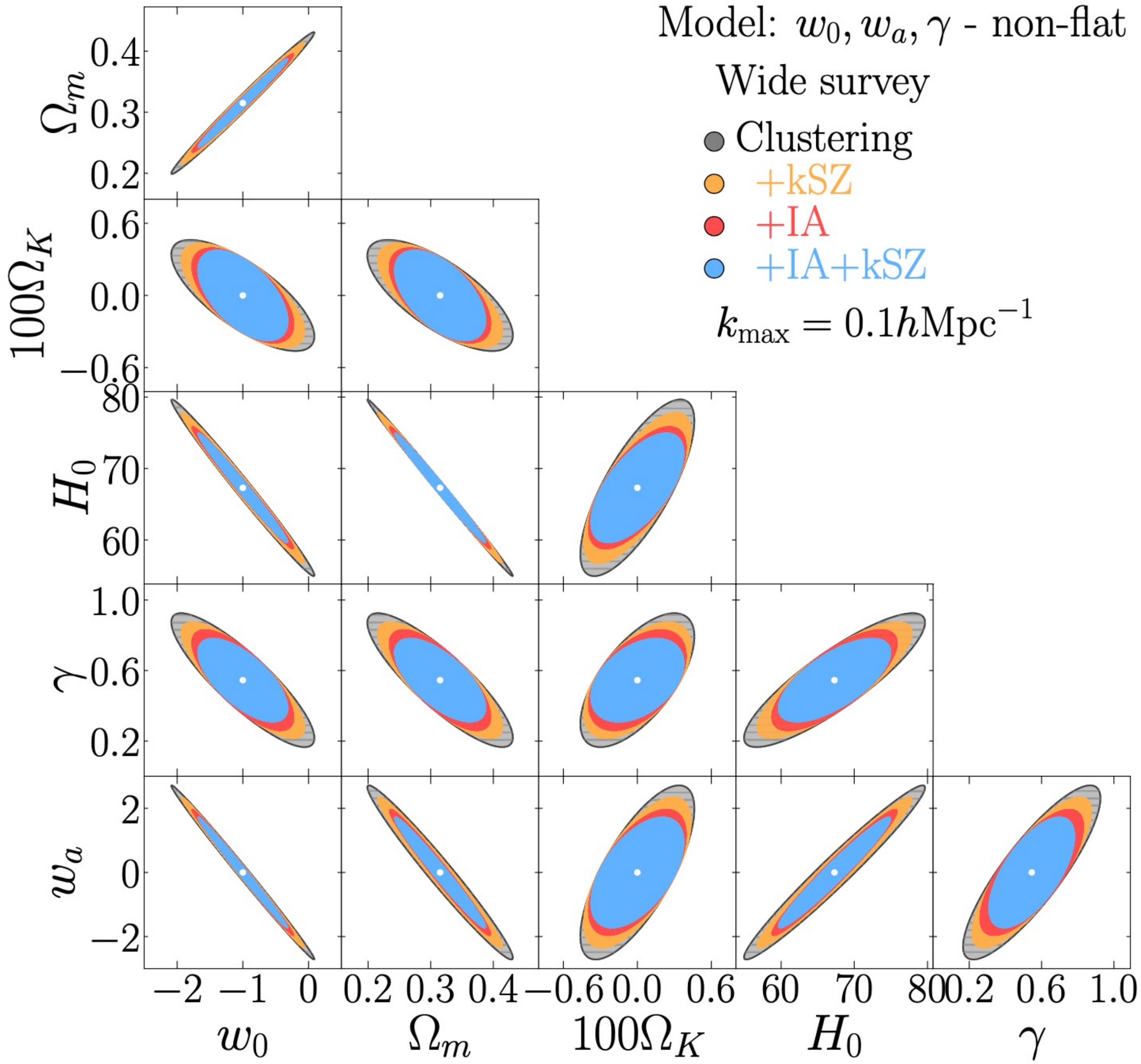
Deep vs wide surveys





Conservative analysis with cutoff of kmax = 0.10 h/Mpc





Outline

- Galaxy intrinsic alignment (IA) as a dynamical and geometric probe
- Kinetic Sunyaev-Zel'dovich (kSZ) effect as a dynamical and geometric probe
- Fisher matrix forecast with galaxy clustering + IA + kSZ
  - Geometric and dynamical constraints
  - Cosmological parameter constraints
  - Deep vs wide galaxy surveys
- Measurement of IA of red galaxies at $z > 1$

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First Evidence of Intrinsic Alignments of Red Galaxies at $z > 1$: Cross-correlation between CFHTLenS and FastSound Samples

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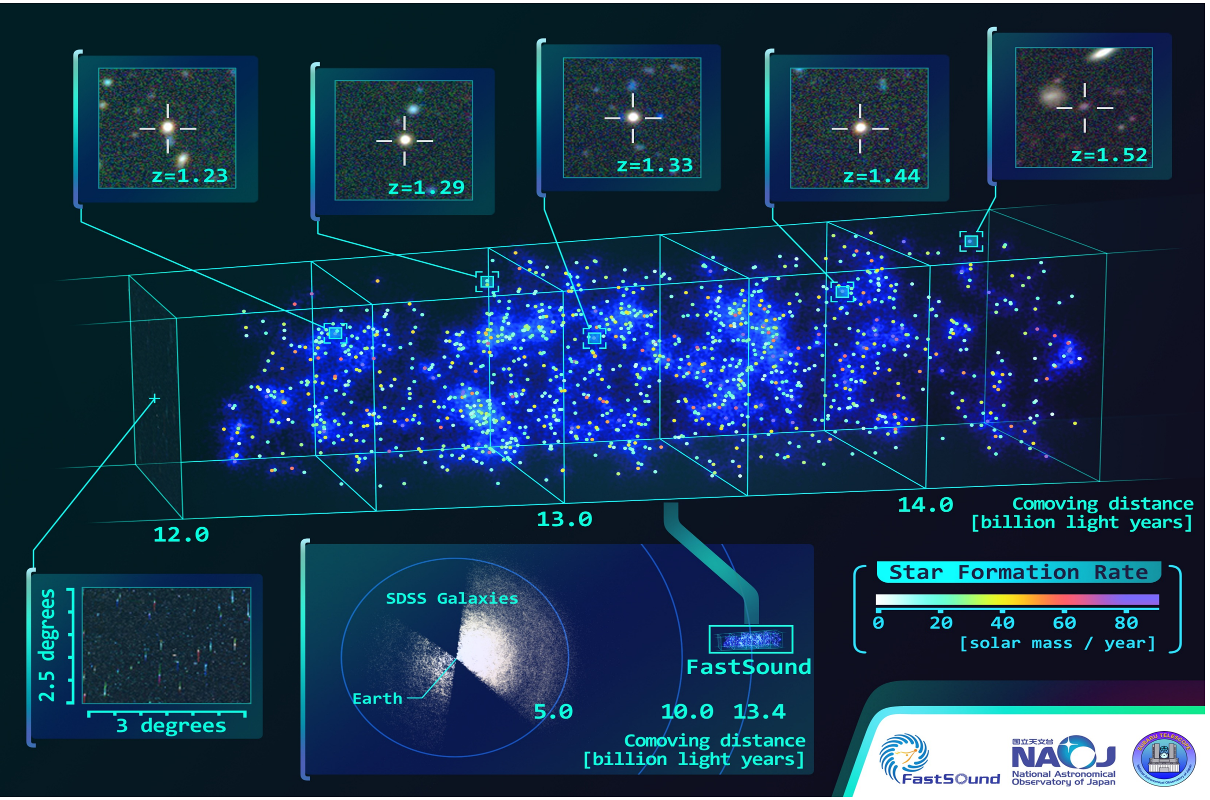
ABSTRACT

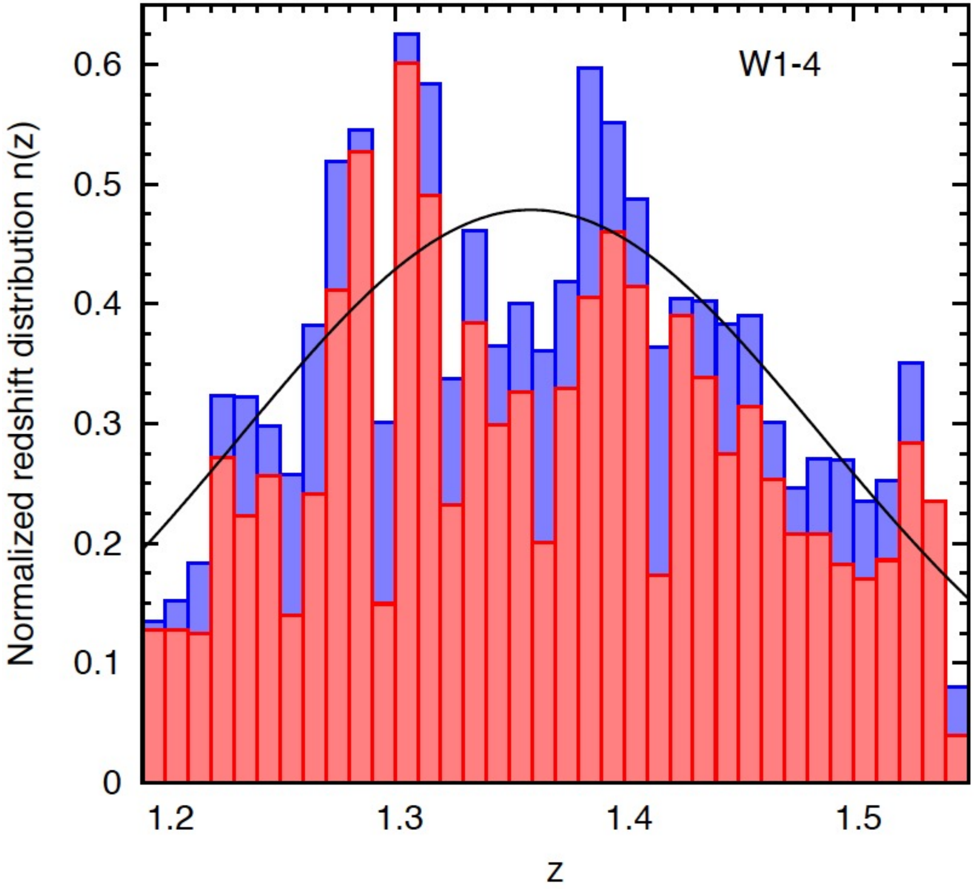
We report the first evidence of intrinsic alignment (IA) of red galaxies at $z > 1$. We measure the gravitational shear-intrinsic ellipticity (GI) cross-correlation function at $z \sim 1.3$ using galaxy positions from the FastSound spectroscopic survey and galaxy shapes from Canada-Hawaii-France telescope lensing survey data. Adopting the non-linear alignment model, we obtain a 2.4σ level detection of the IA amplitude, $A^{\rm LA} = 27.48^{+11.53}_{-11.54}$, larger than the value extrapolated from the constraints obtained at lower redshifts. Our measured IA is translated into a $\sim 20\%$ contamination to the weak lensing power spectrum for the red galaxies. This marginal detection of IA for red galaxies at $z > 1$ motivates the continuing investigation of the nature of IA for weak lensing studies. Furthermore, our result provides the first step to utilize IA measurements in future high-z surveys as a cosmological probe, complementary to galaxy clustering and lensing.

Keywords: Large-scale structure of the universe (902); Gravitational lensing (670)

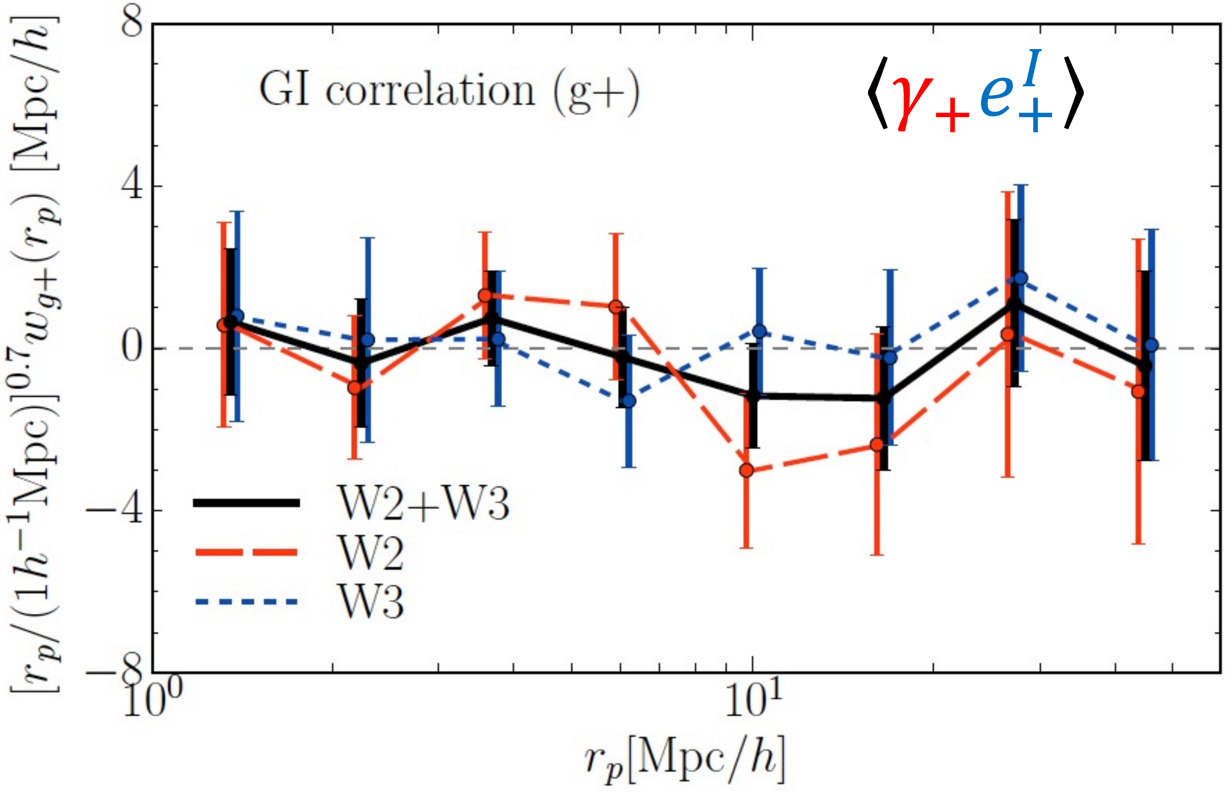
GI correlation measurement from CFHTLens-FastSound



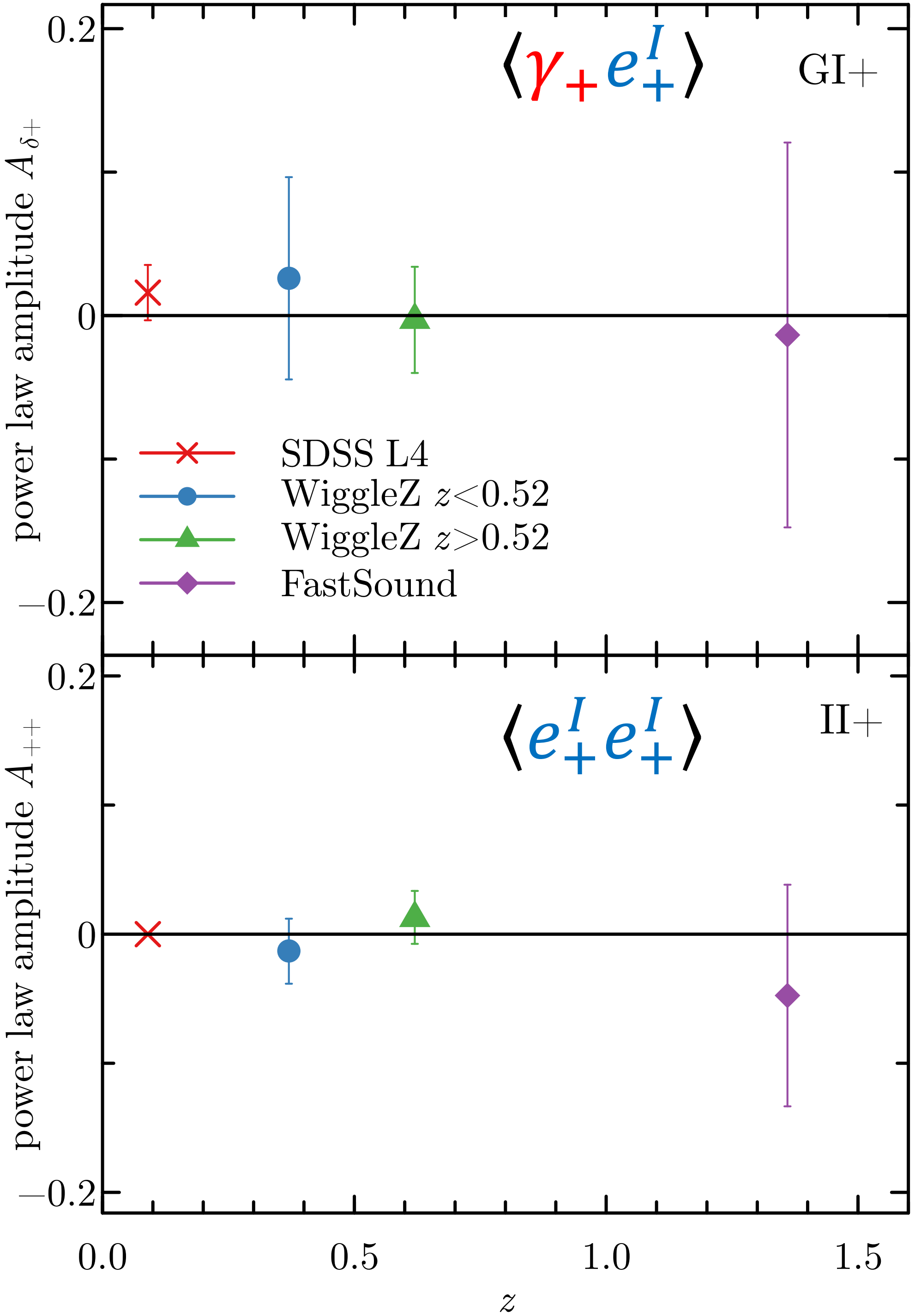
- z~1.2-1.5
- Shape sample: ~12000 LRGs from CFHTLenS
- Density sample: ~3000 Hα from FastSound



Previous result: No IA correlation for Hα



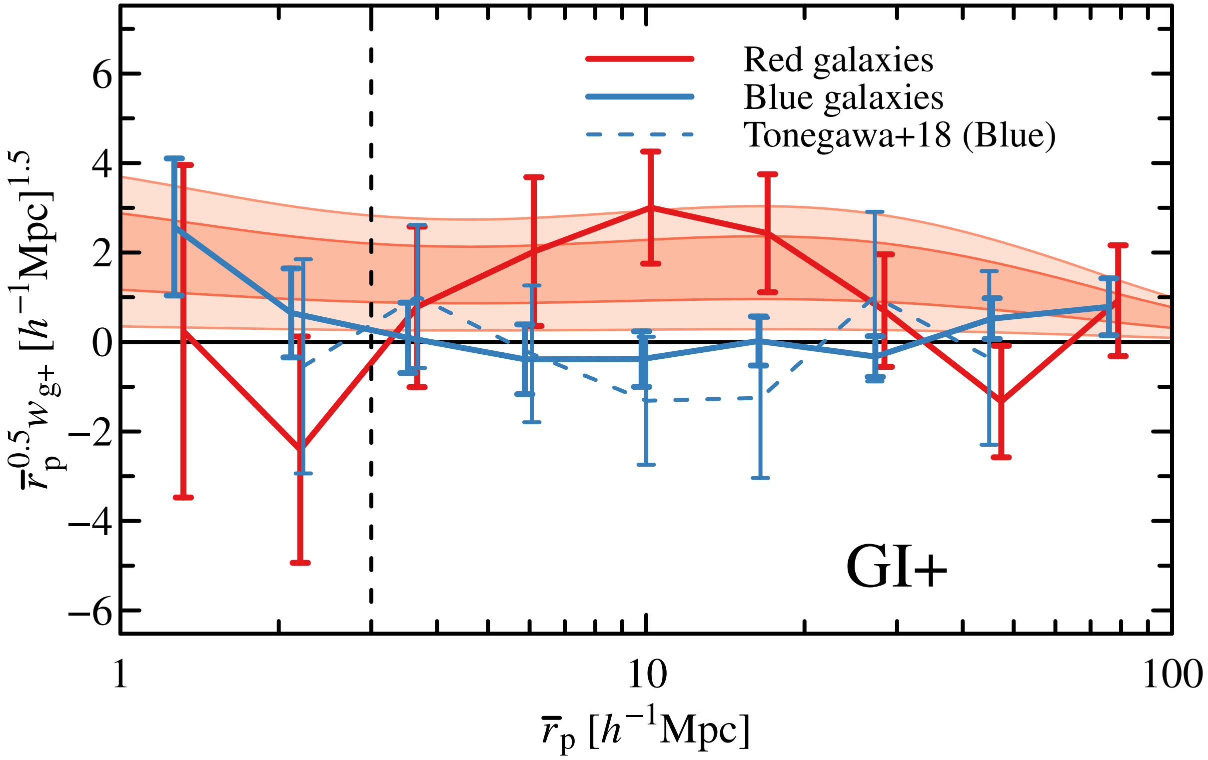
Projected separation

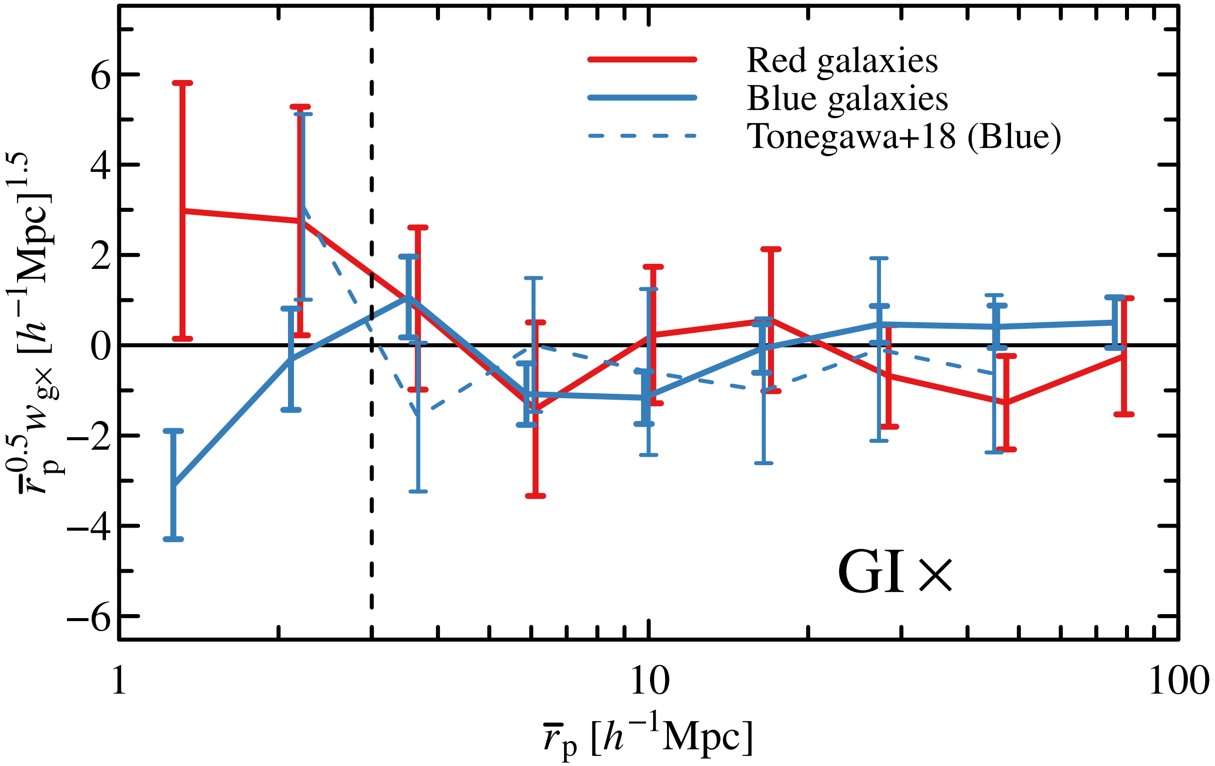


Tonegawa, Okumura, Totani, et al (2018)

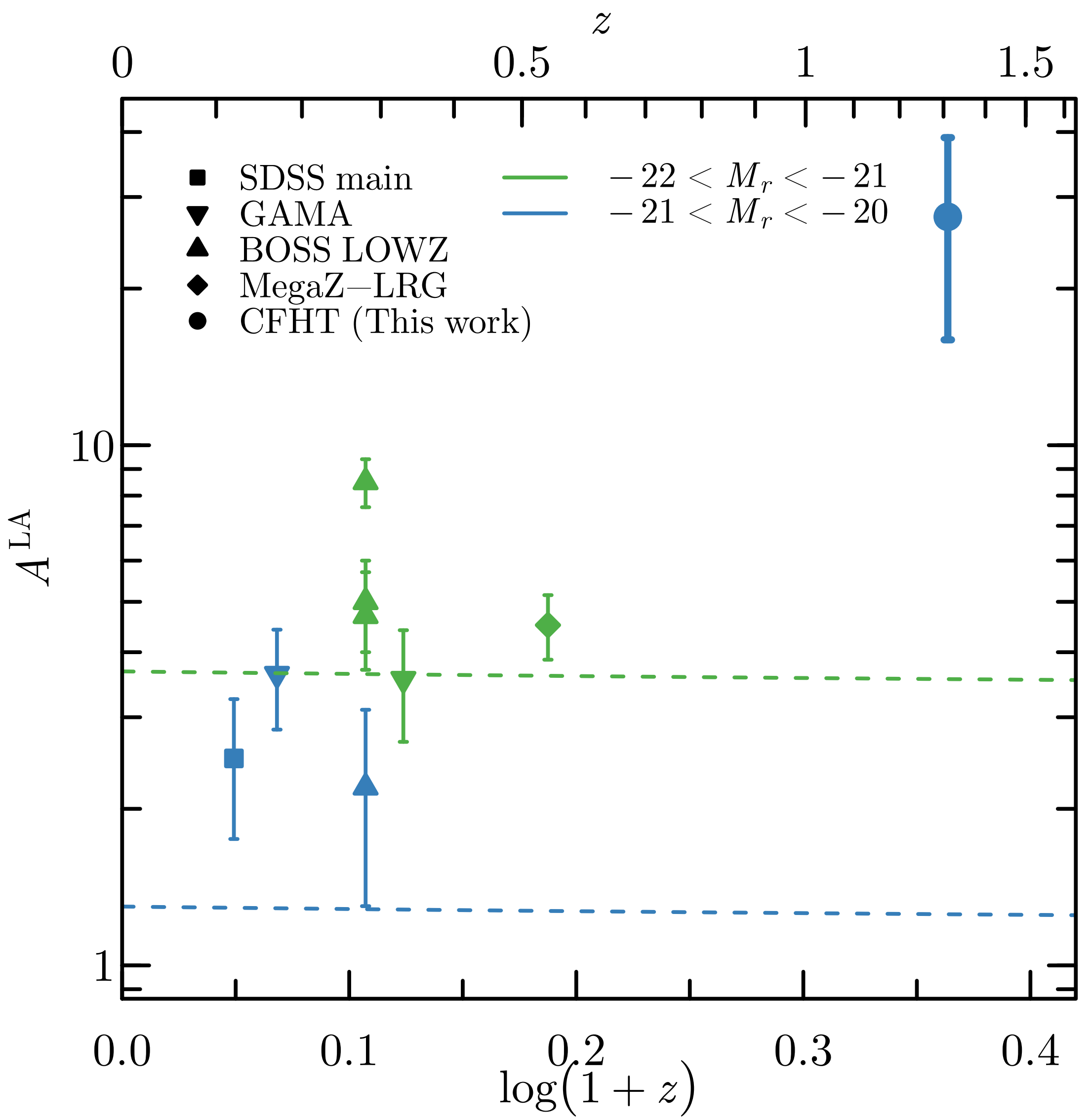
2.4-σ detection of IA for LRGs at z>1

- GI correlation function
  - Galaxy shape: CFHTlenS photo-z LRG
  - Galaxy position: FastSound spec-z Hα emitters





2.4-σ detection of IA for LRGs at z>1



- 2.4-σ (w/o shear and magnification)

  $A^{\rm LA} = 27.48^{+11.53}_{-11.54}$

- With gG and mG, the significance gets larger.
- It is straightforward to extend the analysis to HSC LRG shape – PFS [OII] emitter position cross-correlation.

Conclusions

- Conventionally, cosmological constraints on the growth and expansion history of the universe have been obtained from the measurements of RSD and BAO embedded in the galaxy distribution.
- We studied how well one can improve the cosmological constraints from the combination of the galaxy density field with velocity (kSZ) and ellipticity (IA) fields.
- For illustration, we consider the Subaru PFS whose survey footprint perfectly overlaps with the HSC and CMB-S4 experiment.
- We found adding the kSZ and IA effects significantly improves cosmological constraints.
- We measured the GI cross-correlation at $z>1$ and found the 2.4σ evidence of IA of elliptical galaxies, which can be greatly improved by upcoming surveys like DESI.