# *Tightening geometric and dynamical constraints on dark energy and gravity: galaxy clustering, intrinsic alignment and kinetic Sunyaev-Zel'dovich effect*

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観測的宇宙論ワークショップ, Nov. 17-19, 2021

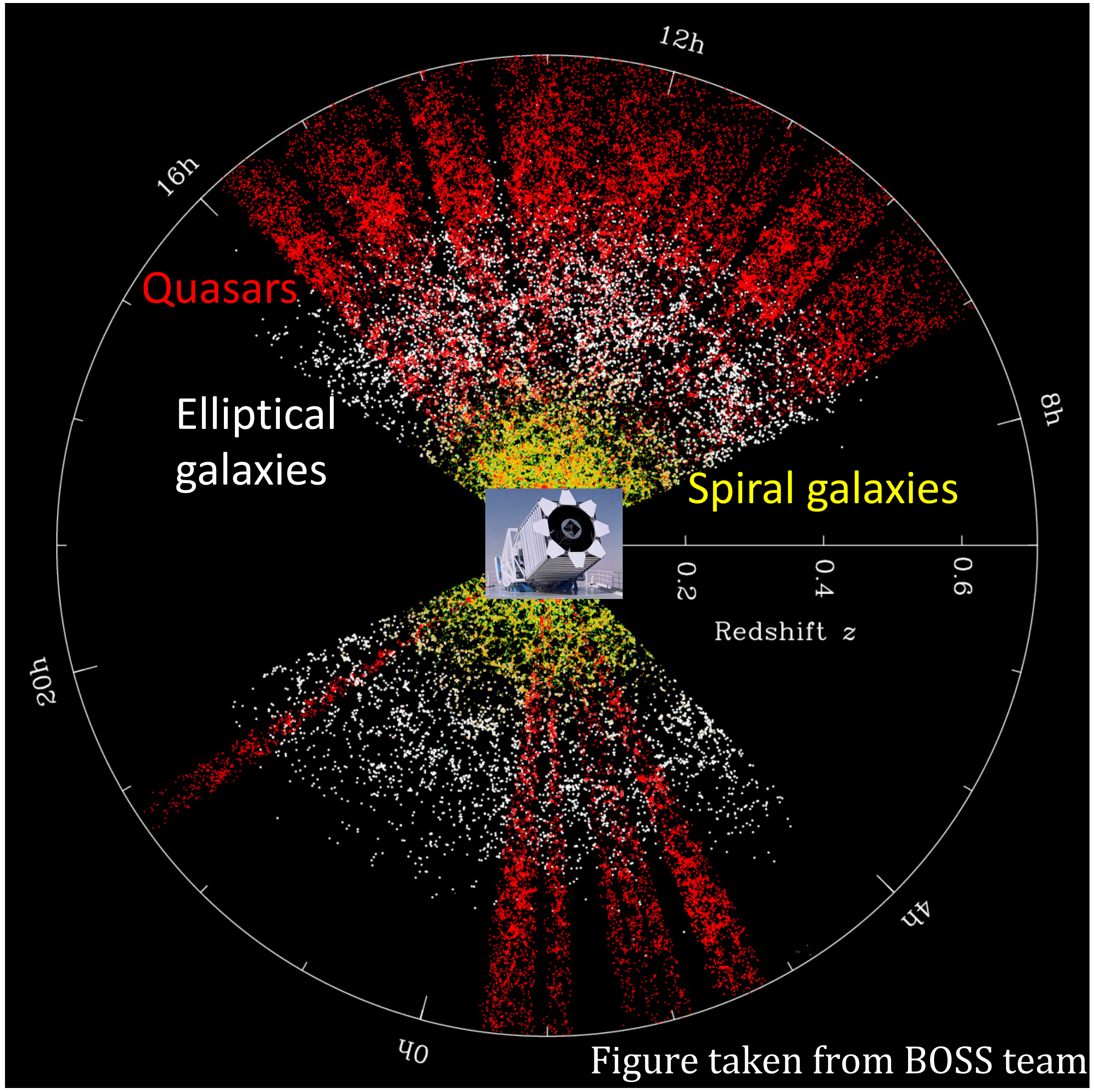
References:
**Okumura** & Taruya, submitted to PRD (arXiv: 2110.11127)
Chuang, **Okumura** & Shirasaki, submitted to MNRAS Letters (arXiv: 2111.01417)

# Outline

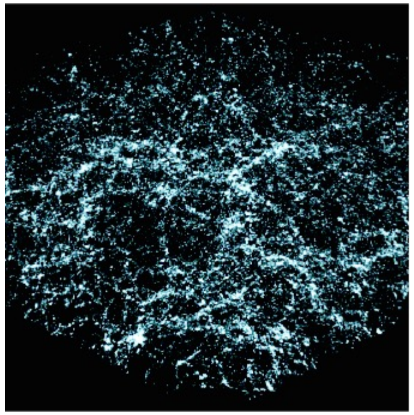
- Galaxy redshift surveys
  - Dynamical distortions: redshift-space distortions (RSD)
  - Geometric distortions: baryon acoustic oscillations (BAO)
- Kinetic Sunyaev-Zel'dovich (kSZ) effect
- Galaxy intrinsic alignment (IA)
- Fisher matrix forecast with galaxy clustering + IA + kSZ
  - Geometric and dynamical constraints
  - Cosmological parameter constraints
  - Deep vs wide galaxy surveys
- IA in $f(R)$ gravity simulations

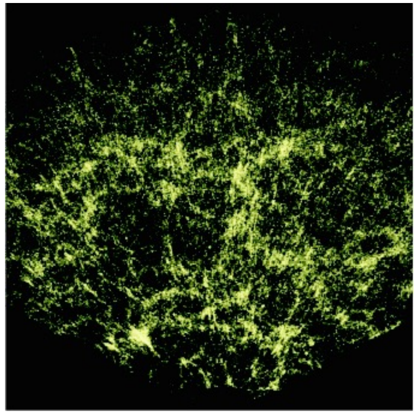
# *Galaxy redshift surveys as geometric and dynamical probes*

- In galaxy surveys, measurements of baryon acoustic oscillations (BAO) and redshift-space distortions (RSD) embedded in the large-scale galaxy distribution enable us to constrain the growth and expansion history of the universe.



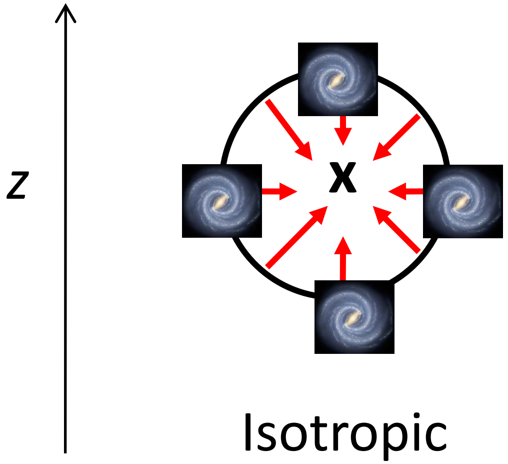
# *RSD tells velocity field (= speed of growth)*





redshift $cz = aH(a)r + v_{//}$

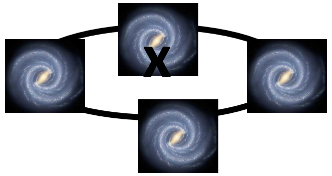
Real-space to redshift-space mapping




Isotropic

$\nabla \cdot v = -aHf\delta(x)$

$v \sim d\sigma_8/d\ln a = f\sigma_8$




Squashed along LoS

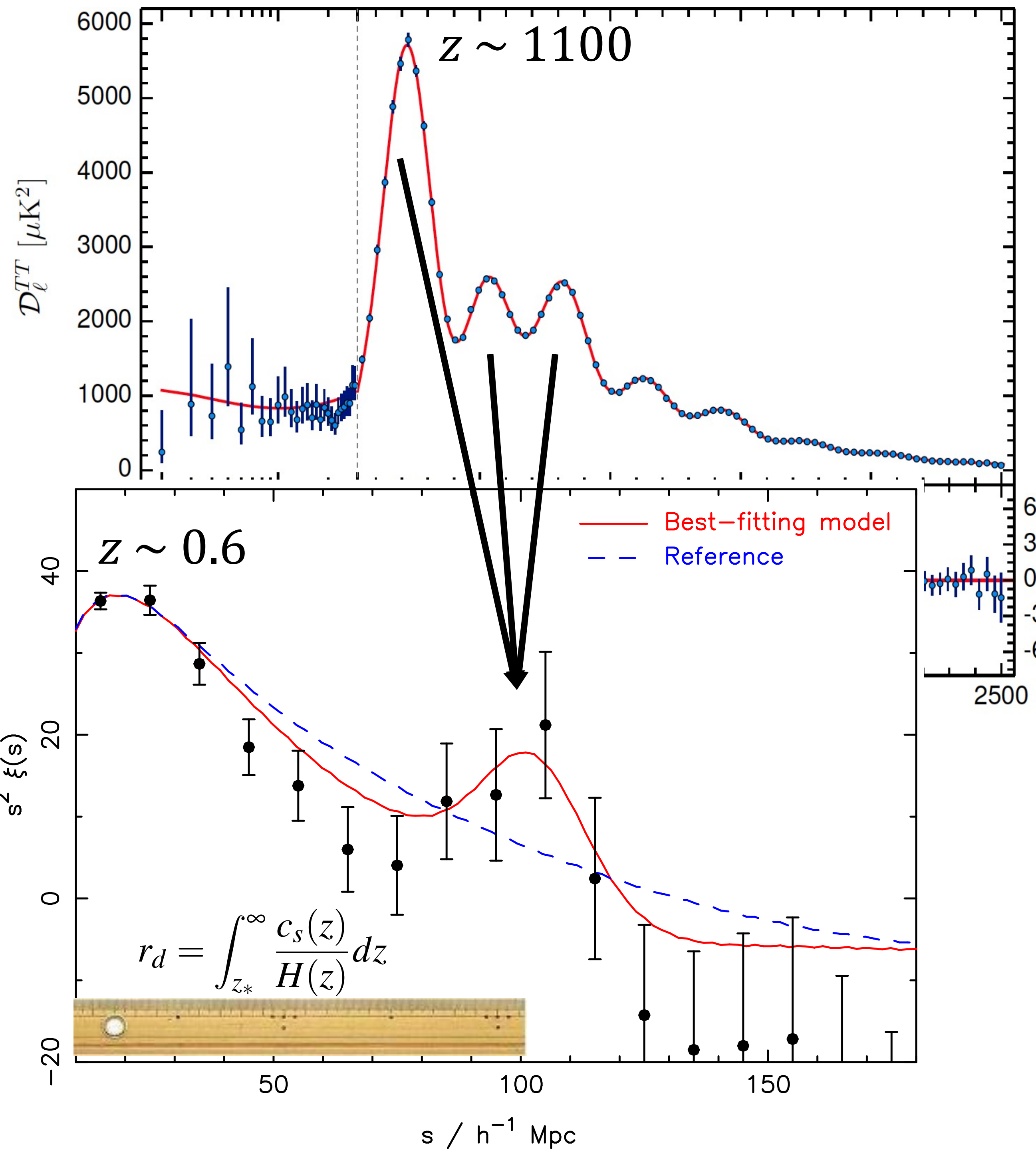
$f = d\ln\delta/d\ln a = \Omega_m{}^{\gamma}$

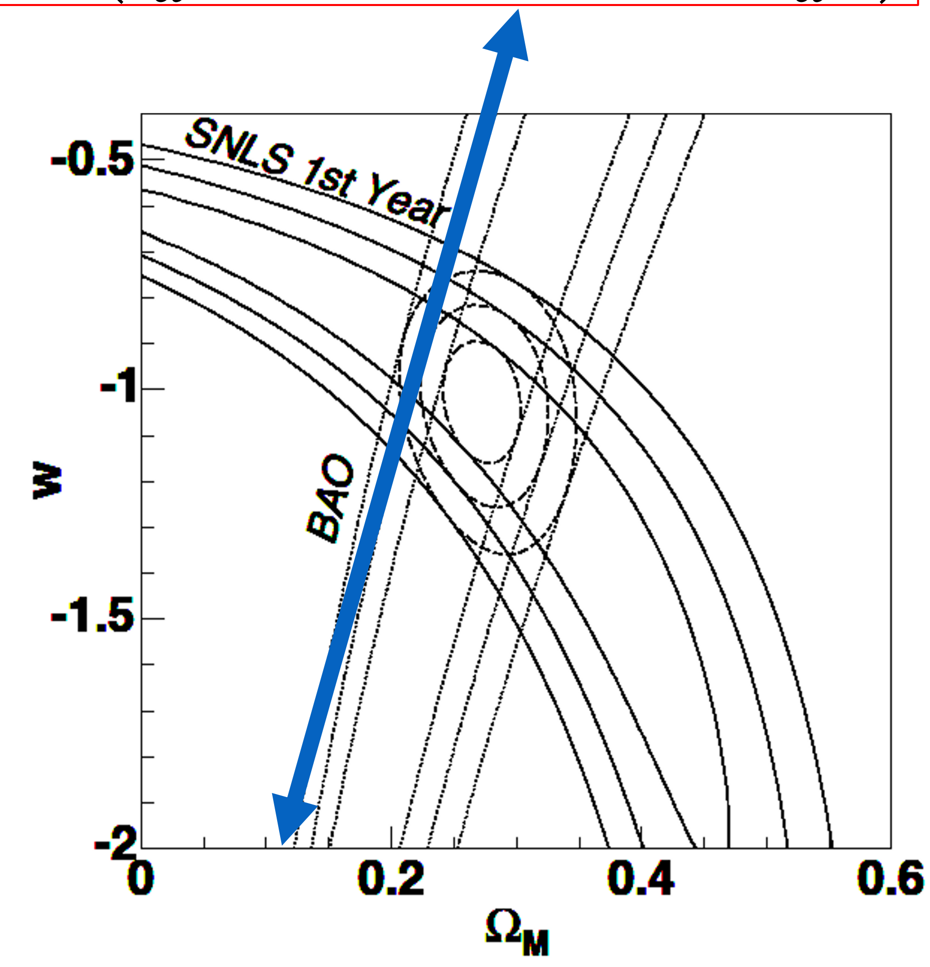
$\gamma$=0.556 (GR)

$\gamma$=0.683(DGP gravity)

# *Baryon acoustic oscillations (BAO)*

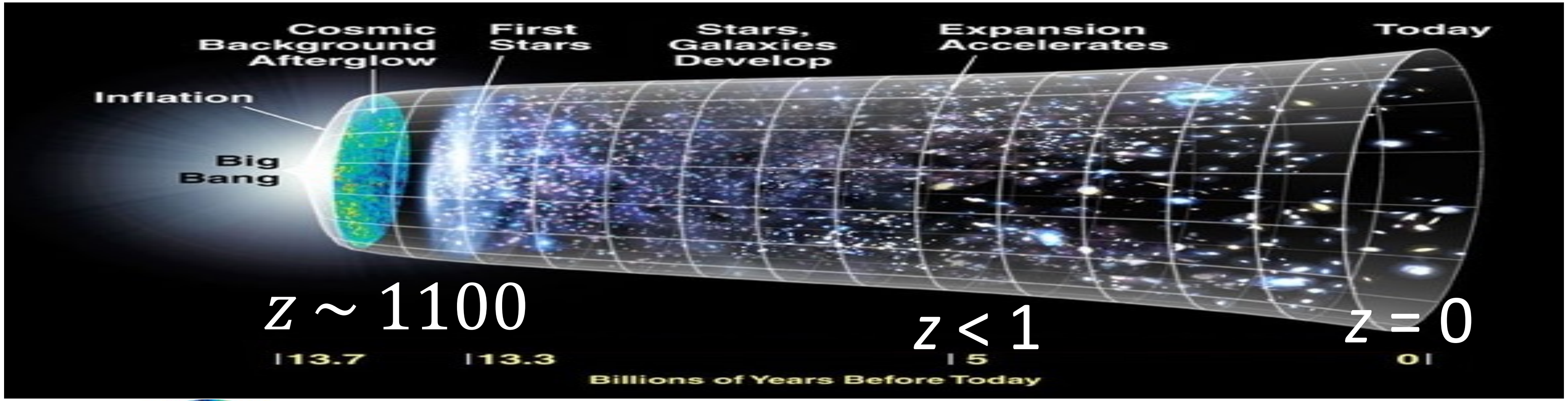
$$H^2(a) = H_0^2\left(\frac{\Omega_{m0}}{a^3} + \Omega_{DE0}a^{-3(1+w)} - \frac{\Omega_{K0}}{a^2}\right)$$

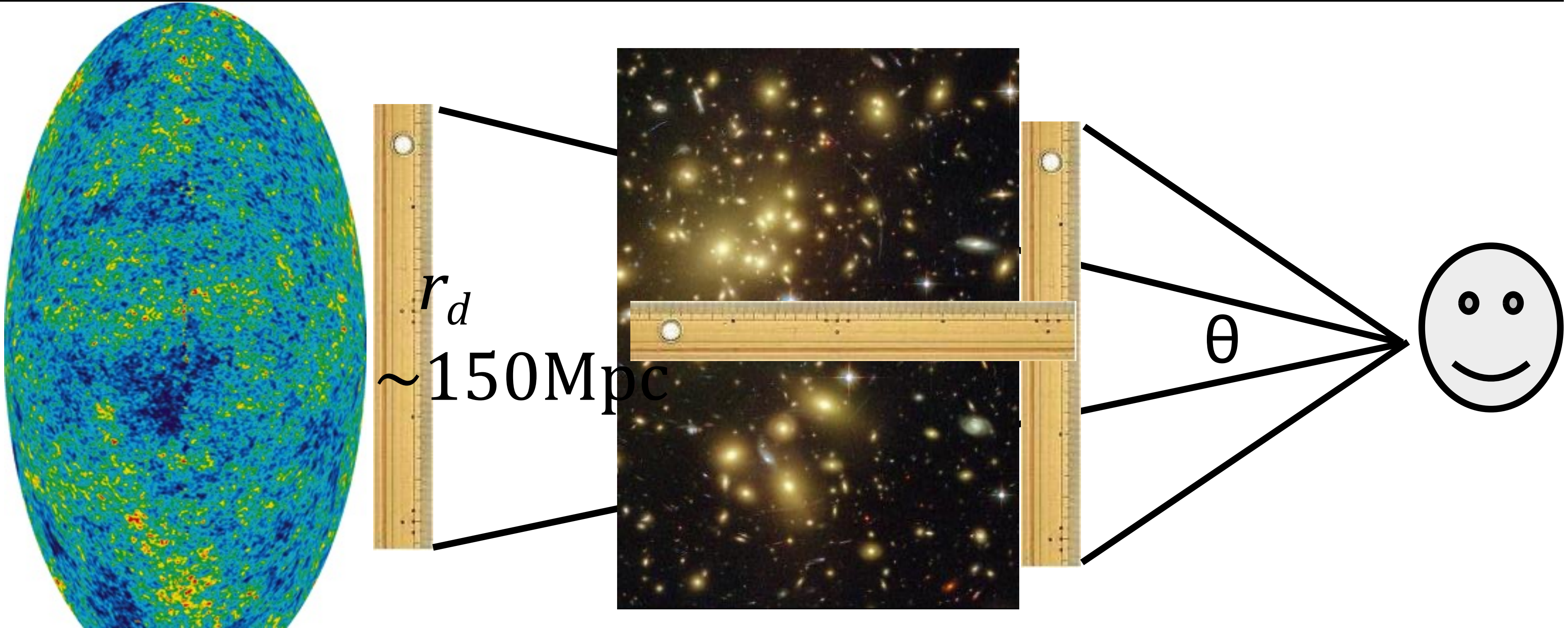


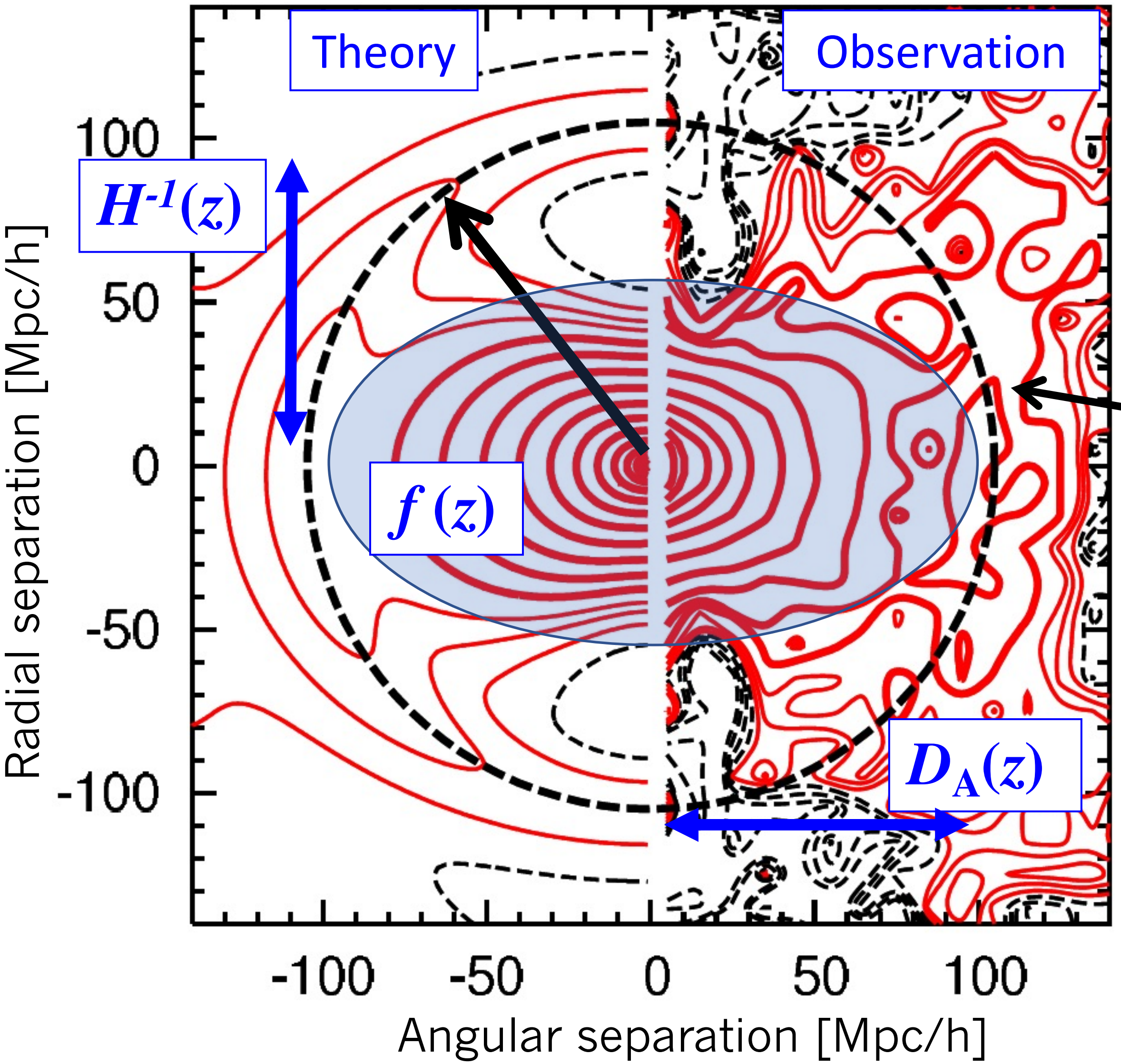

Constant acoustic scale

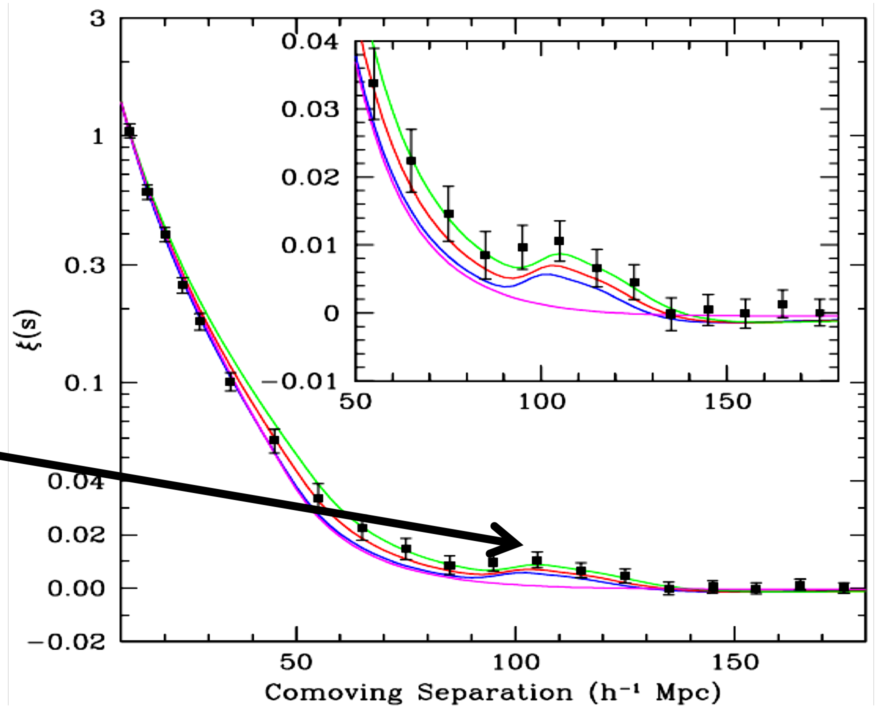
# Anisotropy of BAO



# *Anisotropy of BAO and RSD in the redshift-space galaxy correlation function*



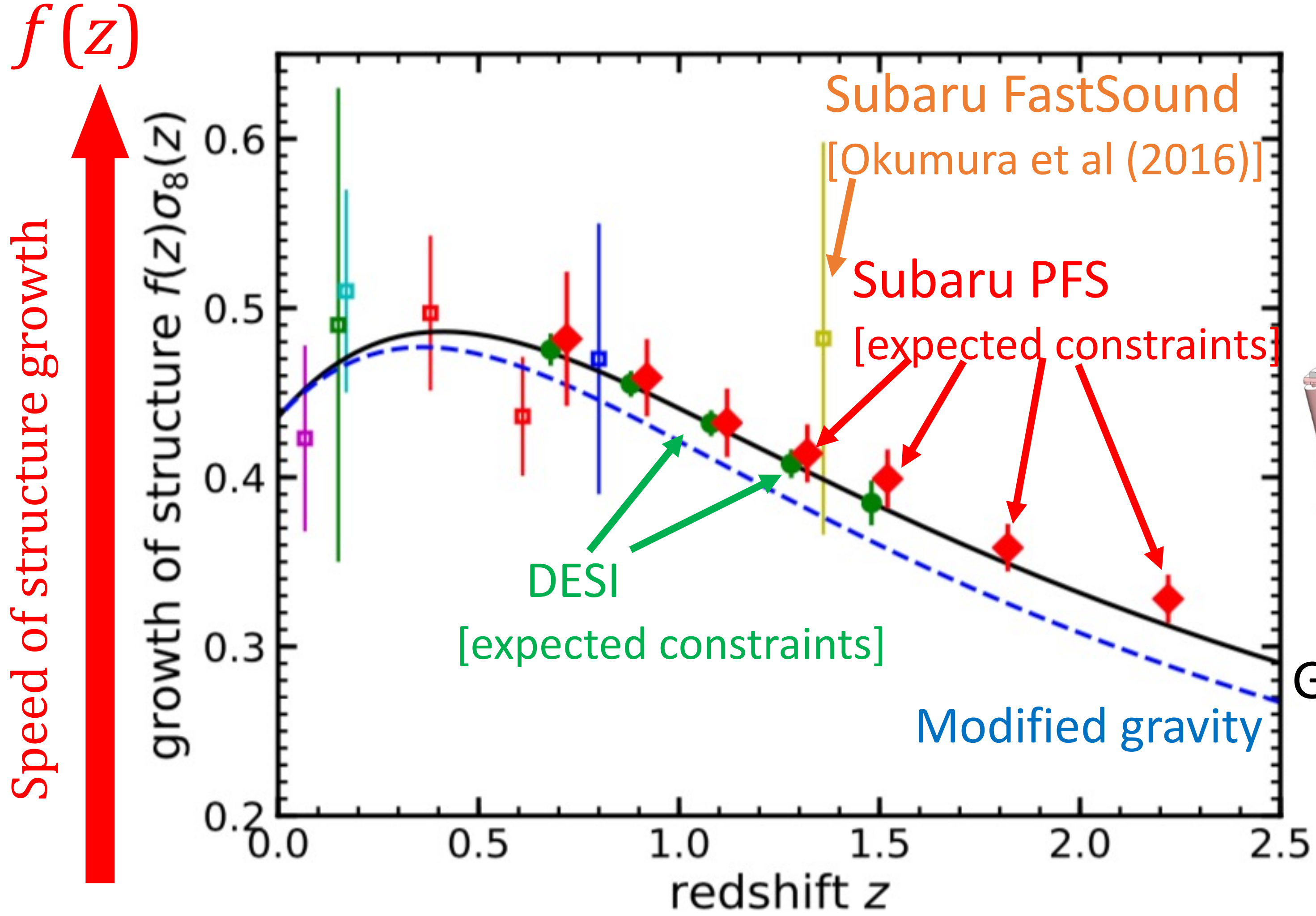

$$f(z) = \frac{d\ln\delta}{d\ln a}$$

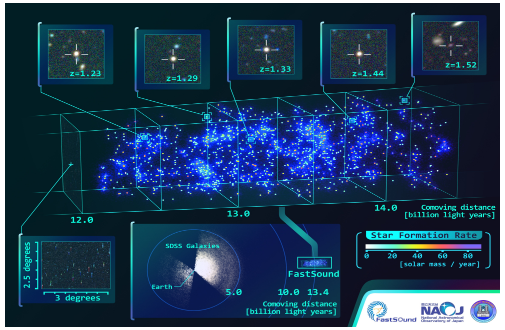
$$H(z) = H_0\sqrt{(1+z)^3\Omega_m + (1+z)^{3(1+w)}\Omega_{DE}}$$

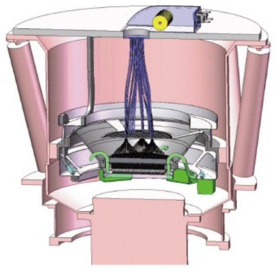
$$D_A(z) = (1+z)^{-1}\int_0^z \frac{dz'}{H(z')}$$

Okumura, Matsubara, Eisenstein, Kayo, Hikage et al (2008)

# *Observational constrants: Cosmological constant? Dark energy? Or modified gravity?*





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

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

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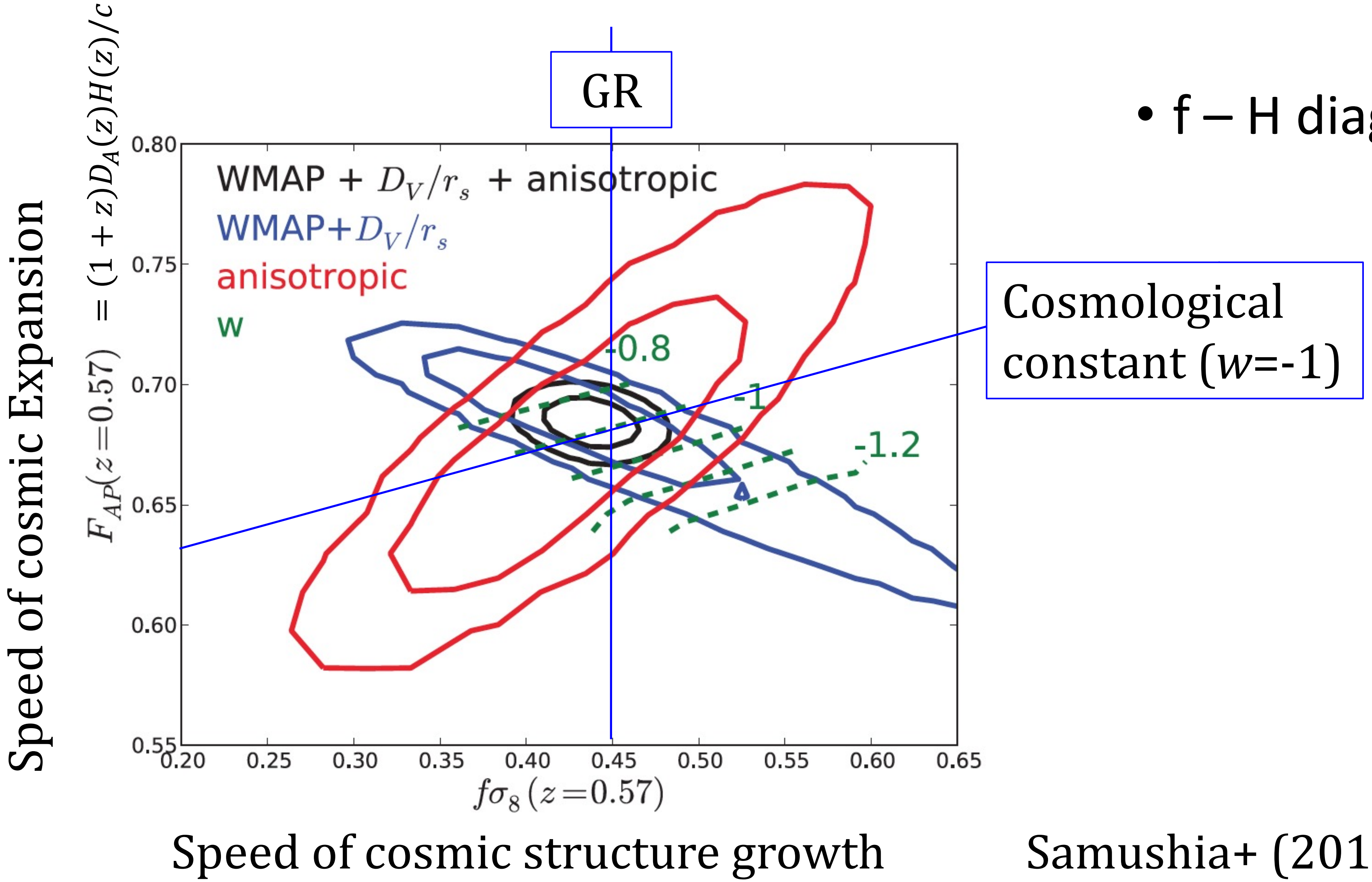
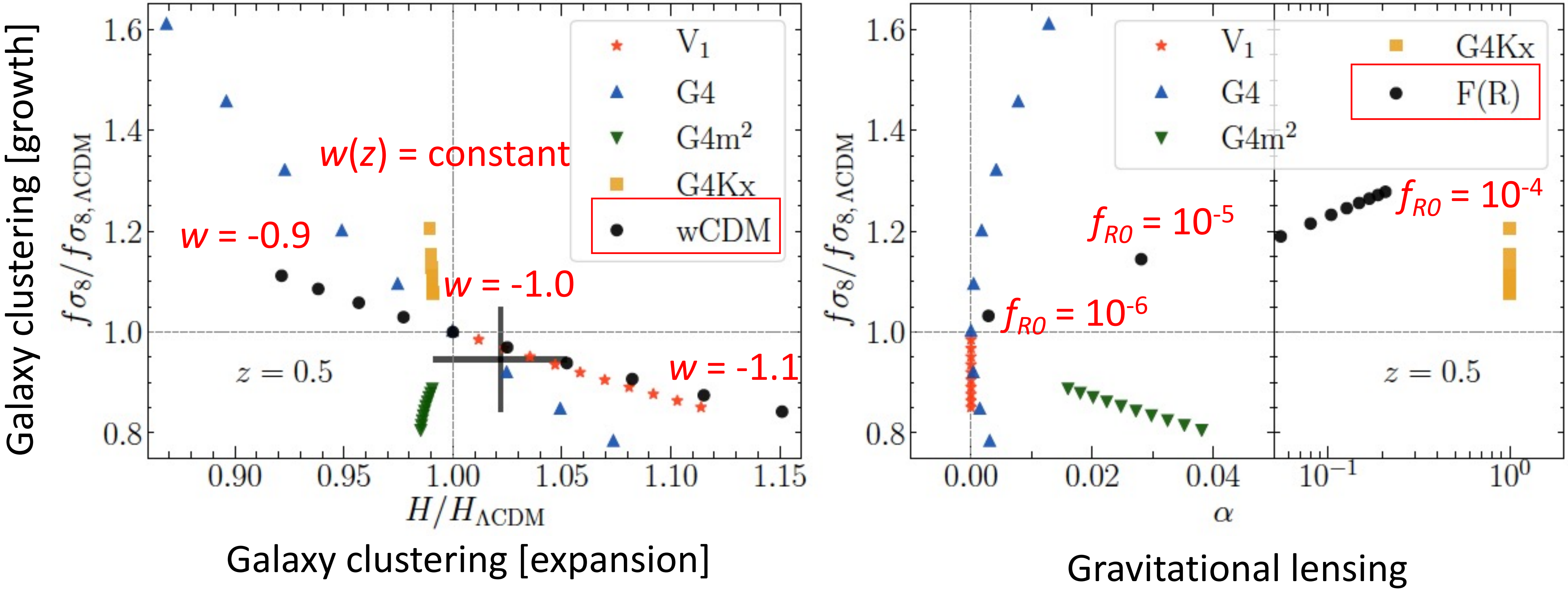



- f – H diagram

Samushia+ (2013)

# New measures to distinguish modified gravity models: $f\sigma_8 - H - \alpha$ diagram




Matsumoto, Okumura & Sasaki (2020)

$$\Psi + \Phi = -\alpha\,\Phi$$

# *Three key quantities in galaxy surveys: $H(z)$, $D_A(z)$ and $f(z)$*

- Geometric quantities $H(z)$, $D_\mathrm{A}(z)$ : Expansion rate of the Universe
- Dynamical quantity $f(z)$ : Growth rate of the Universe

Gravity/geometry $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$ Matter/energy

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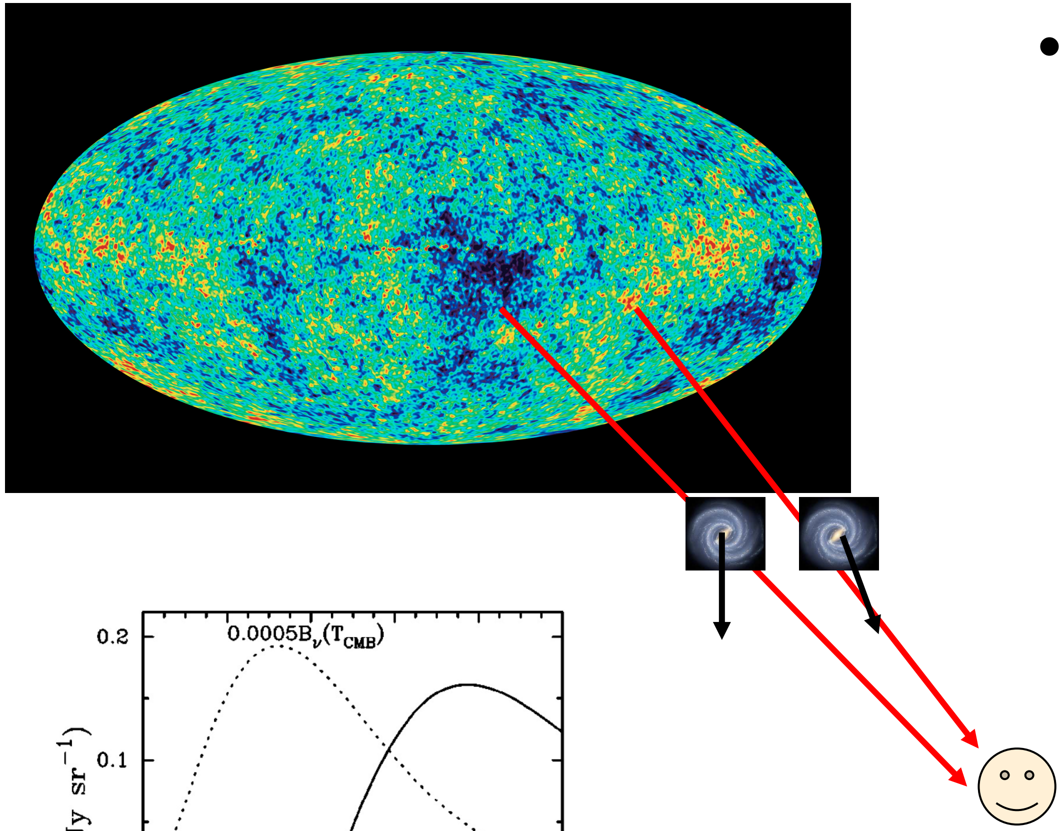
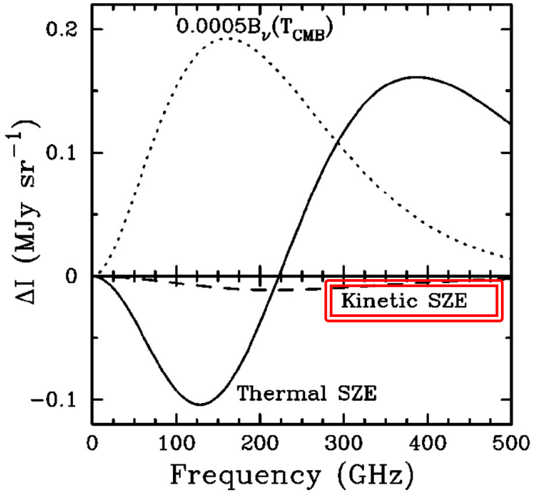
# Direct measurement of velocities: Kinetic Sunyaev-Zeld'ovich (kSZ) effect

Cosmic microwave background






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

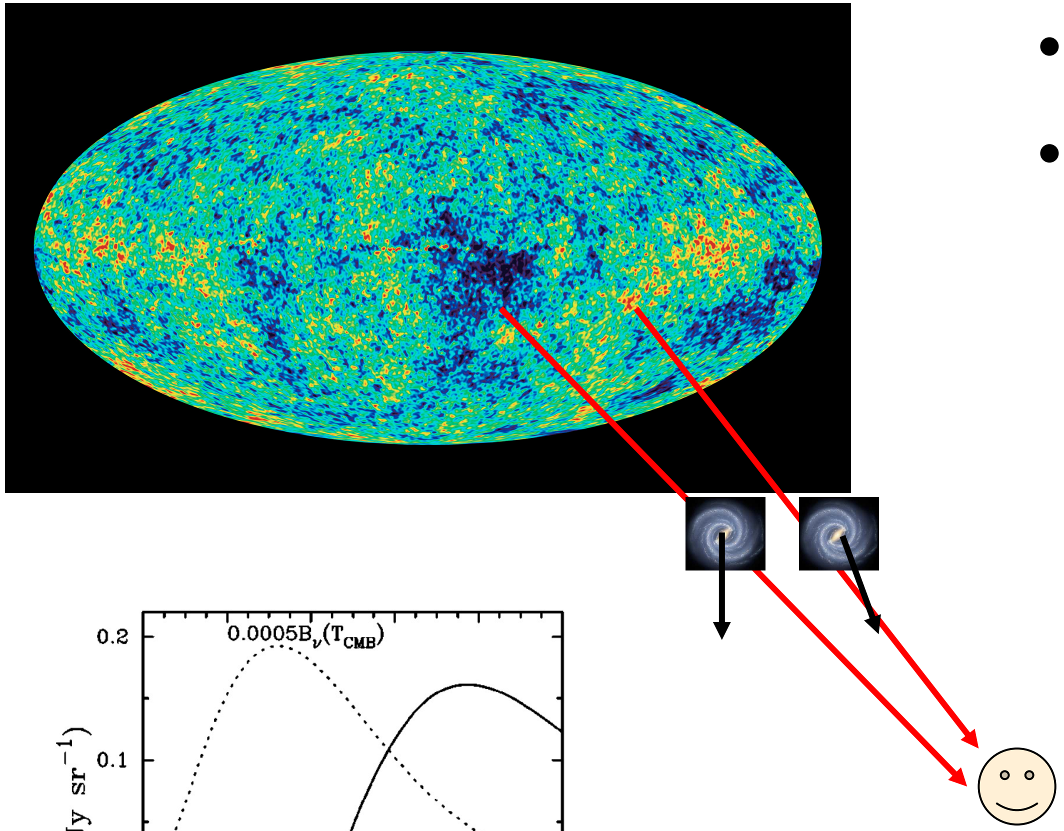
$$\Delta T_{kSZ}/T_{CMB} = -\tau_e v_{//}$$

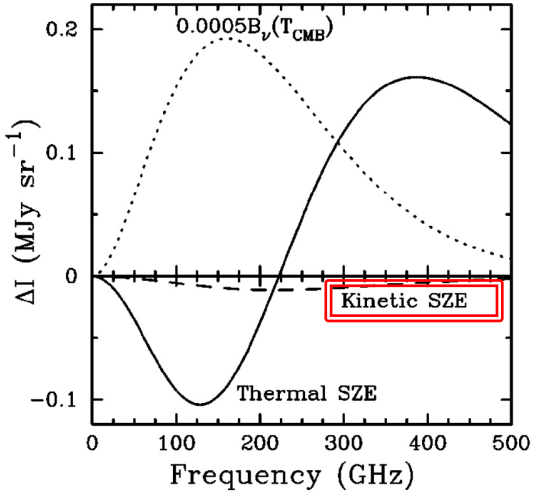
($v_{//}$: line-of-sight velocity)

  - 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.

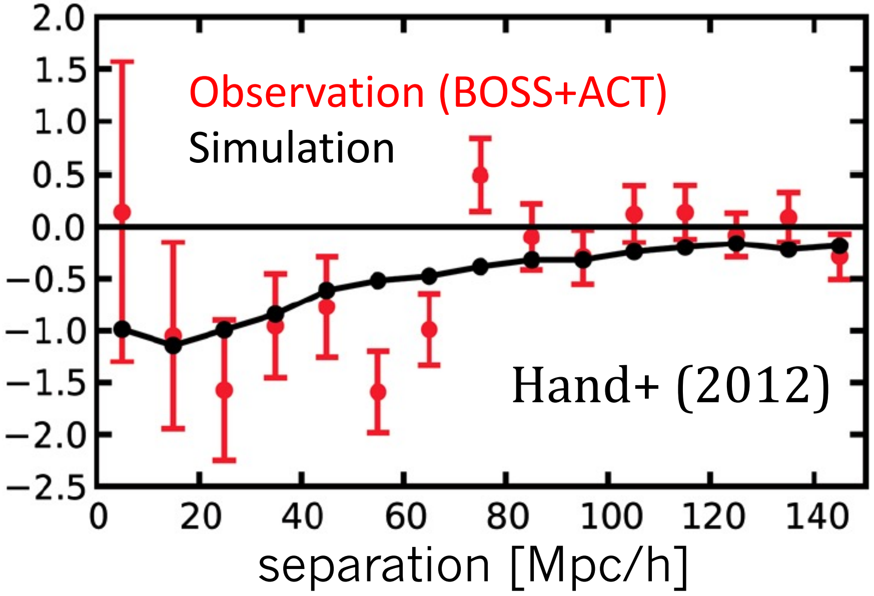
# *Direct measurement of velocities:*
# *Kinetic Sunyaev-Zeld'ovich (kSZ) effect*

Cosmic microwave background





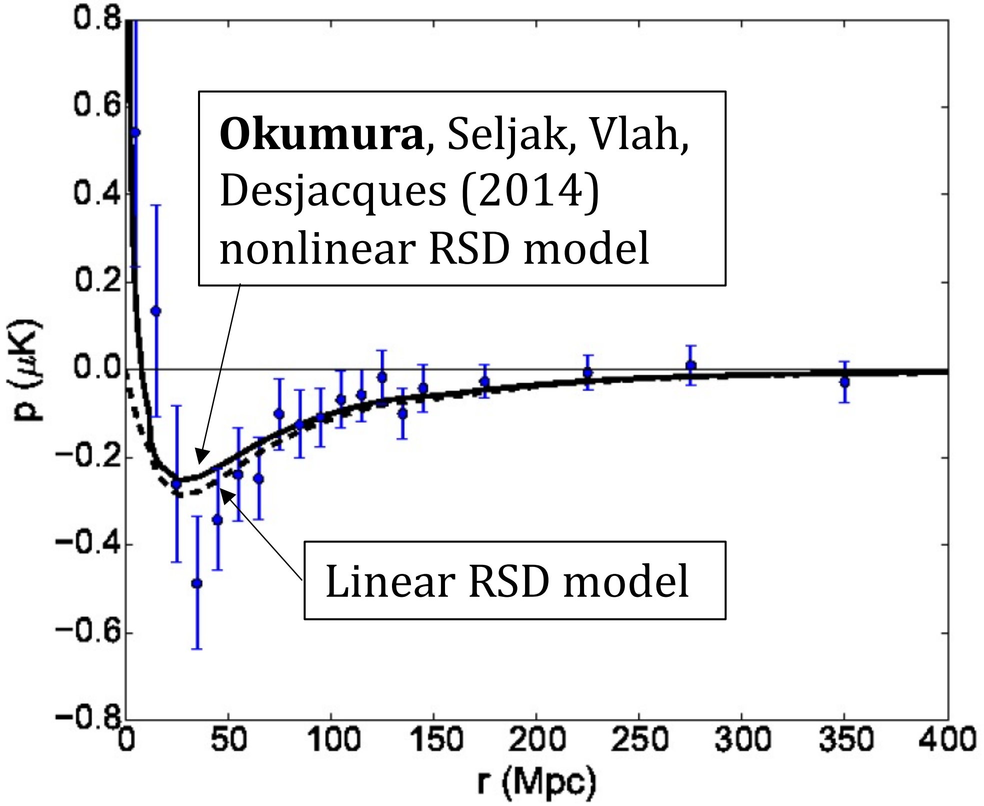

- Kinetic SZ (kSZ) effect (1980)
- First detection of kSZ effect (2012)



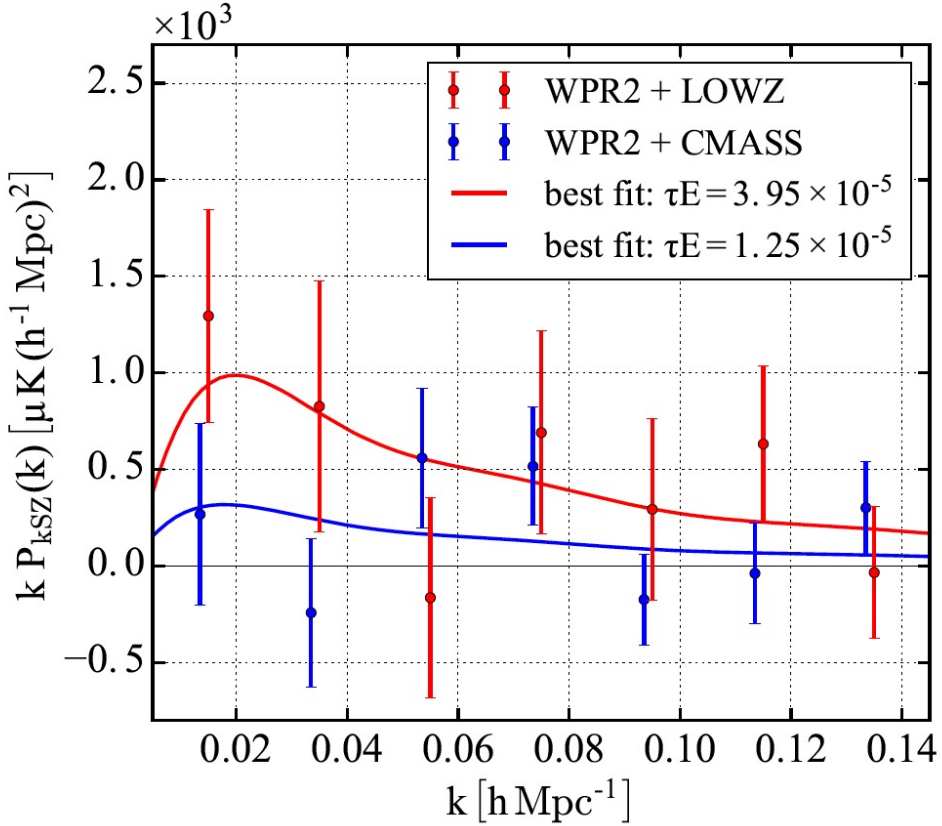
# Large-scale velocity field probed via kSZ effect

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

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

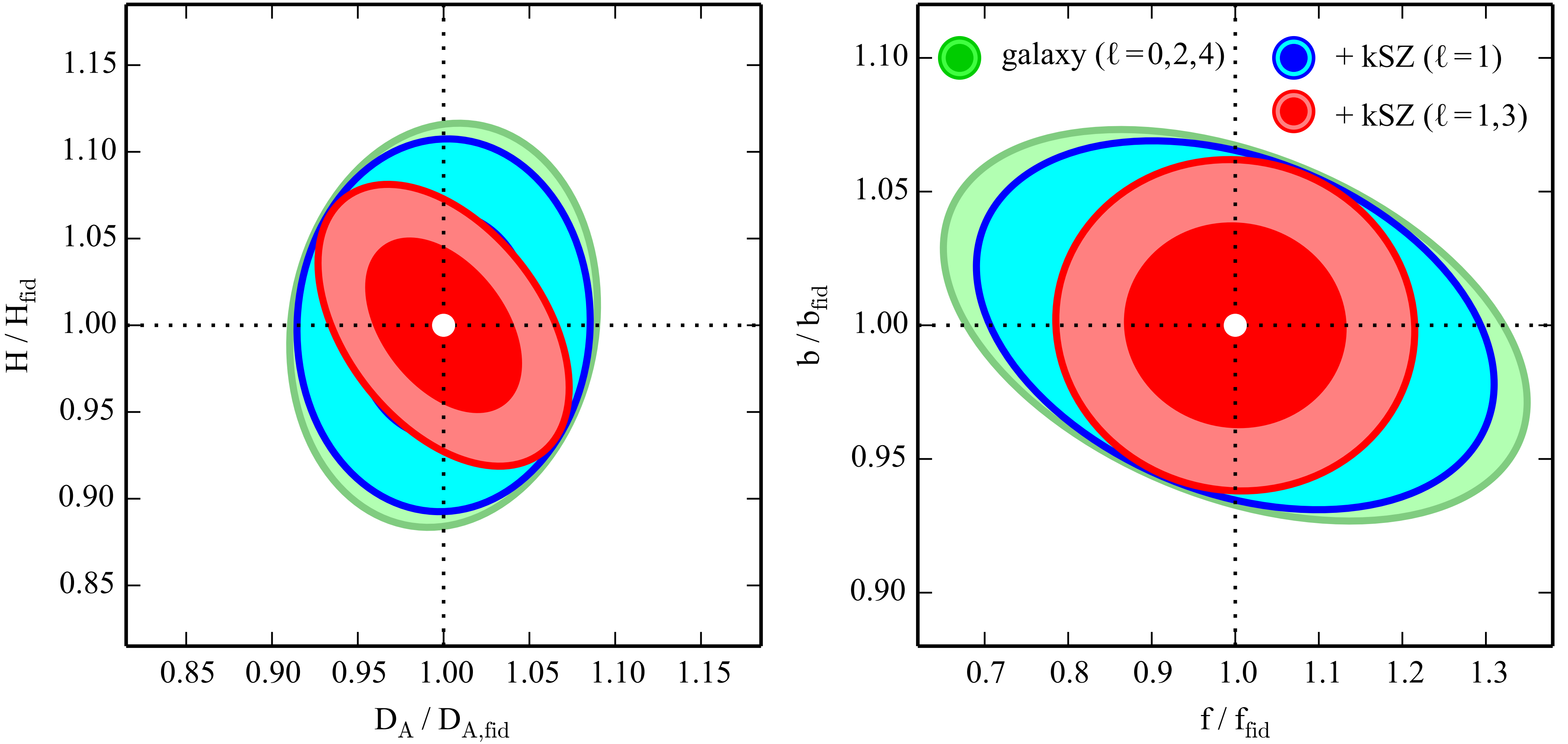



- Sugiyama, **Okumura**, Spergel (2018)
- Fourier space
- Planck x BOSS



# *kSZ measurements enhance the science return from galaxy redshift surveys*

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



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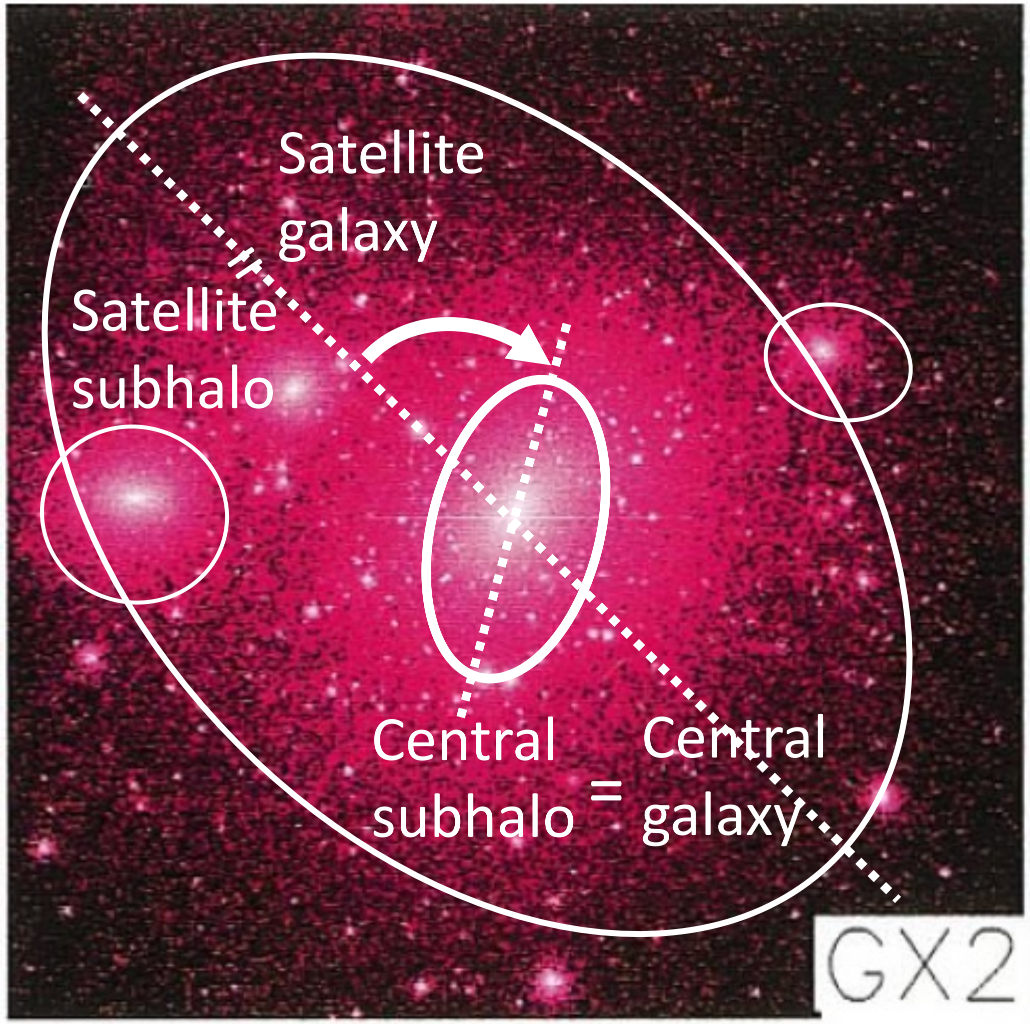
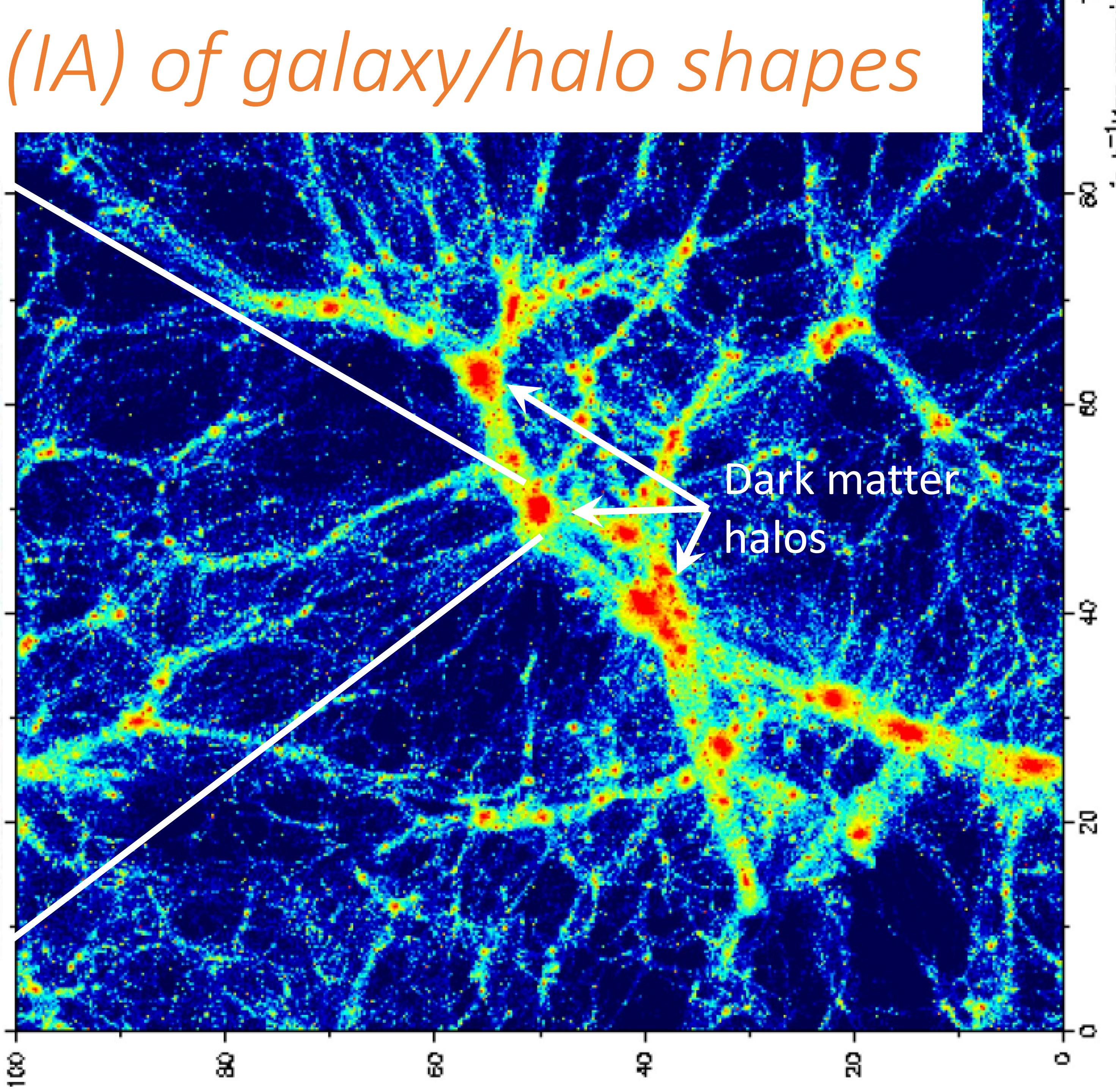
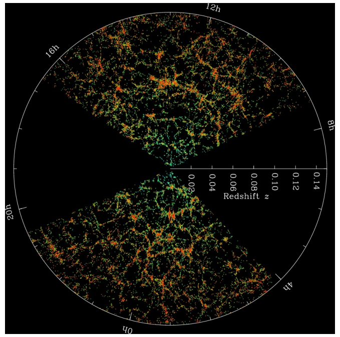
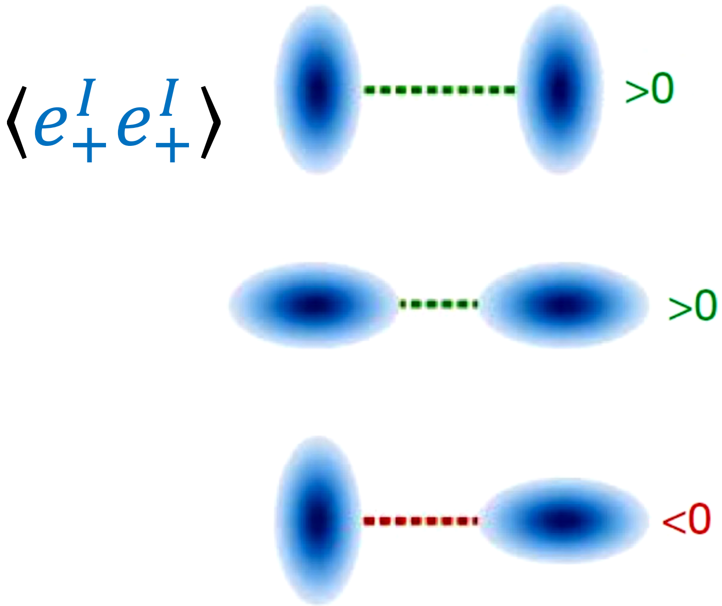
# Intrinsic alignment (IA) of galaxy/halo shapes

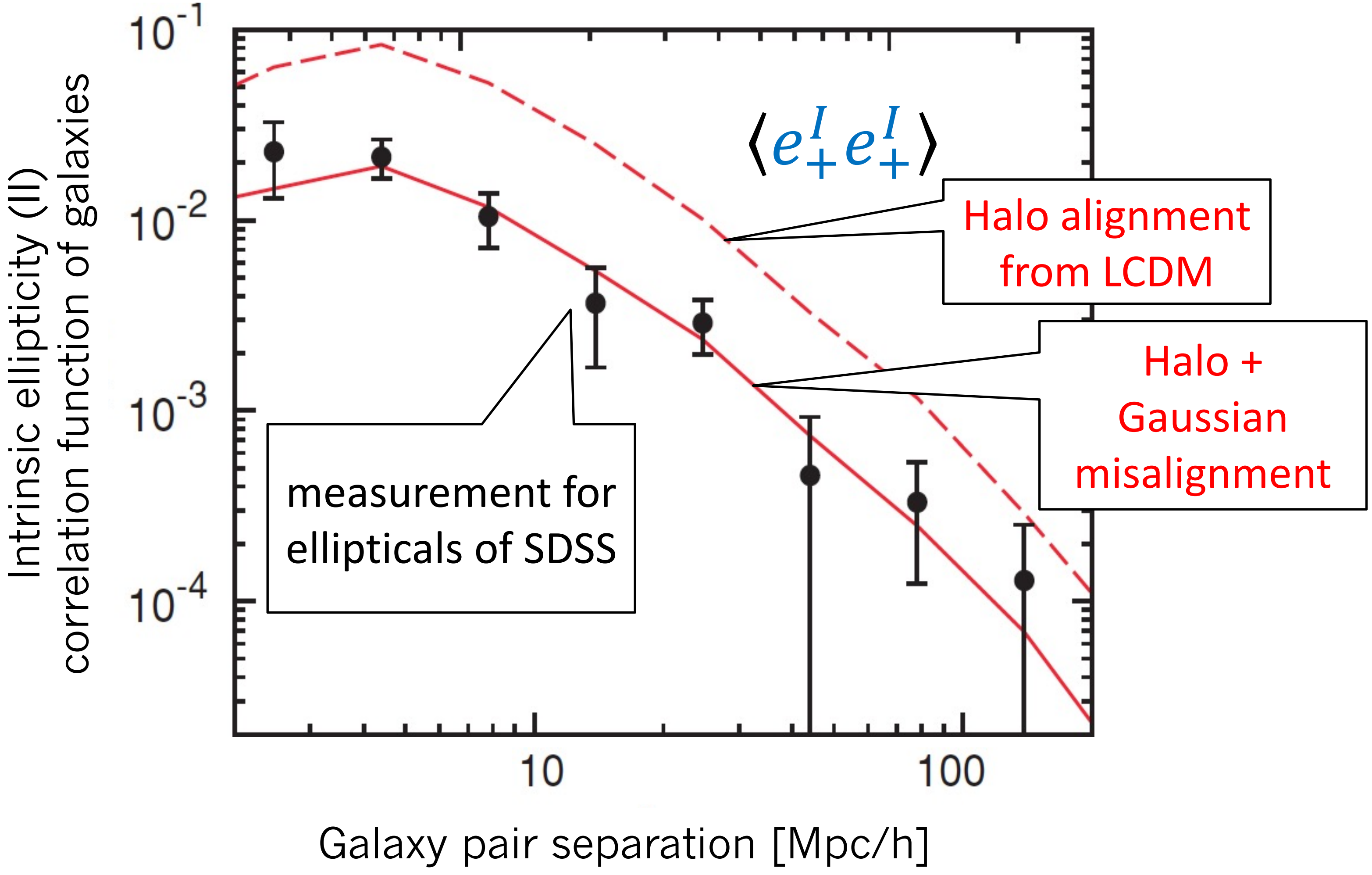


# *Intrinsic ellipticity auto correlation (II) of elliptical galaxies and the host halos*

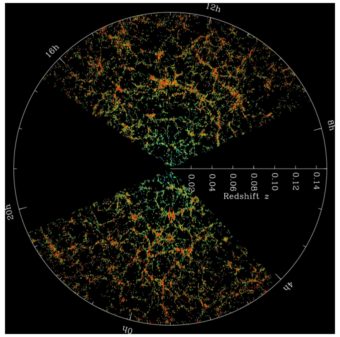




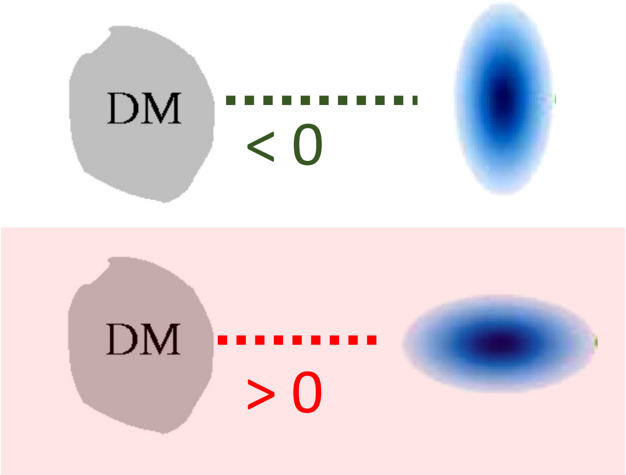



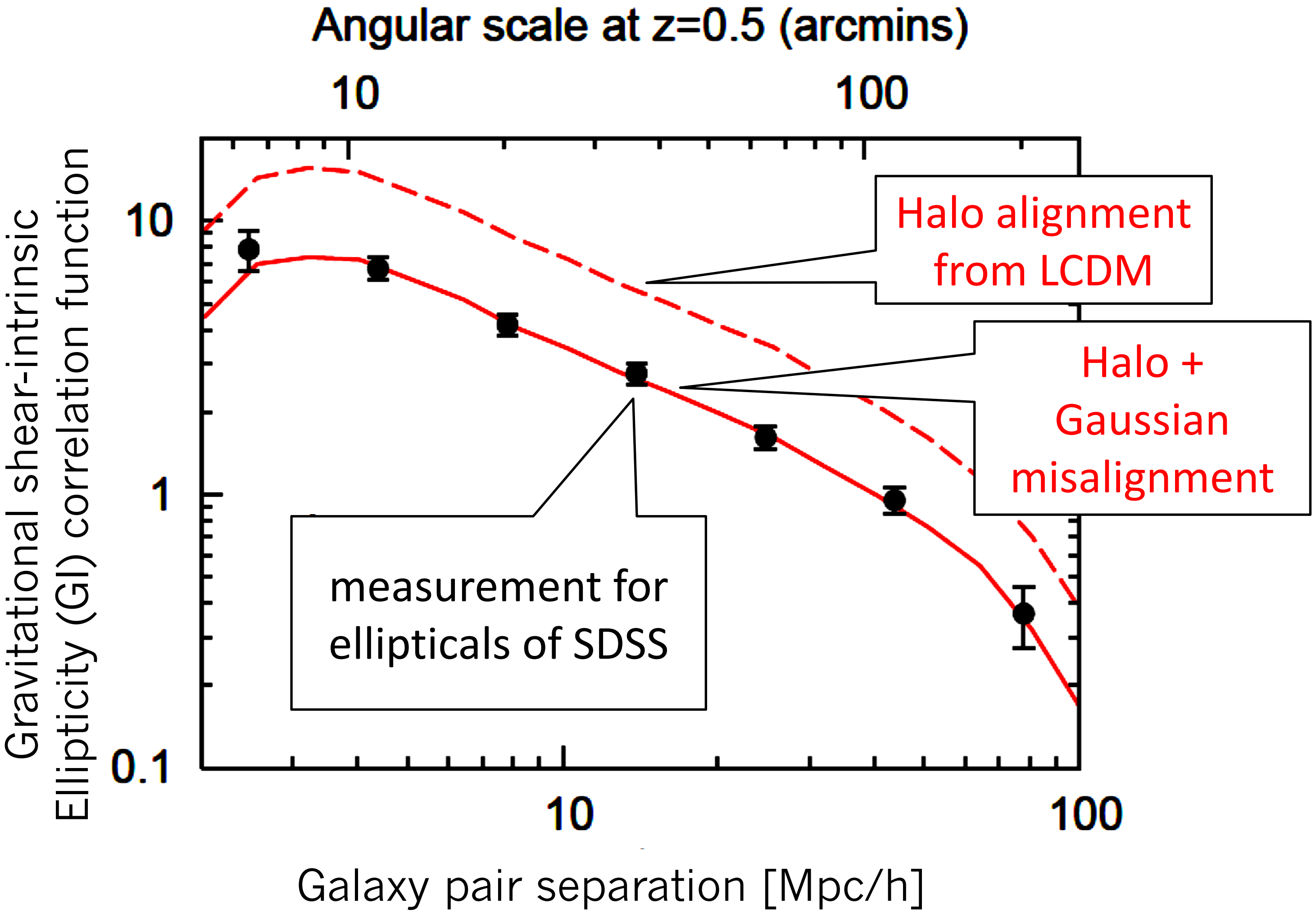

Okumura, Jing & Li (2009)

# Cross-correlation function between ellipticity and density (GI)



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




Okumura & Jing (2009)

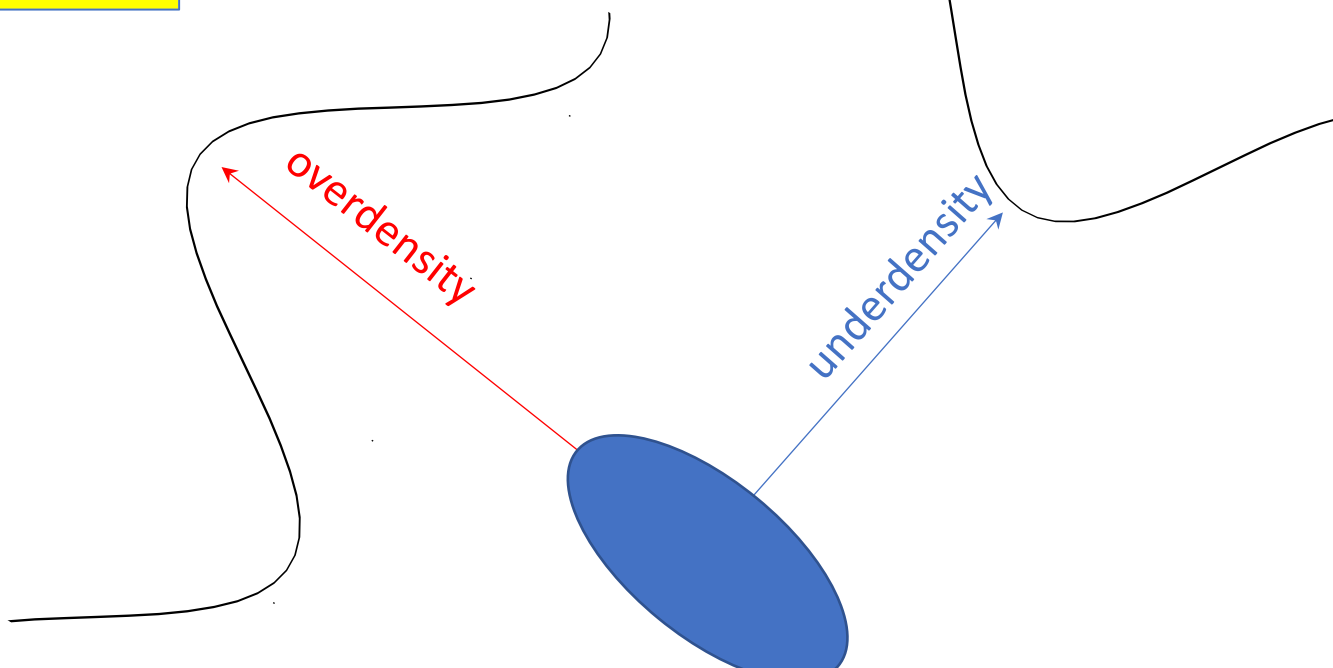
# *Linear alignment (LA) model*

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

- First-principle approach to compute IA is difficult
- Consider a model relating linear tidal field with galaxy/halo shape

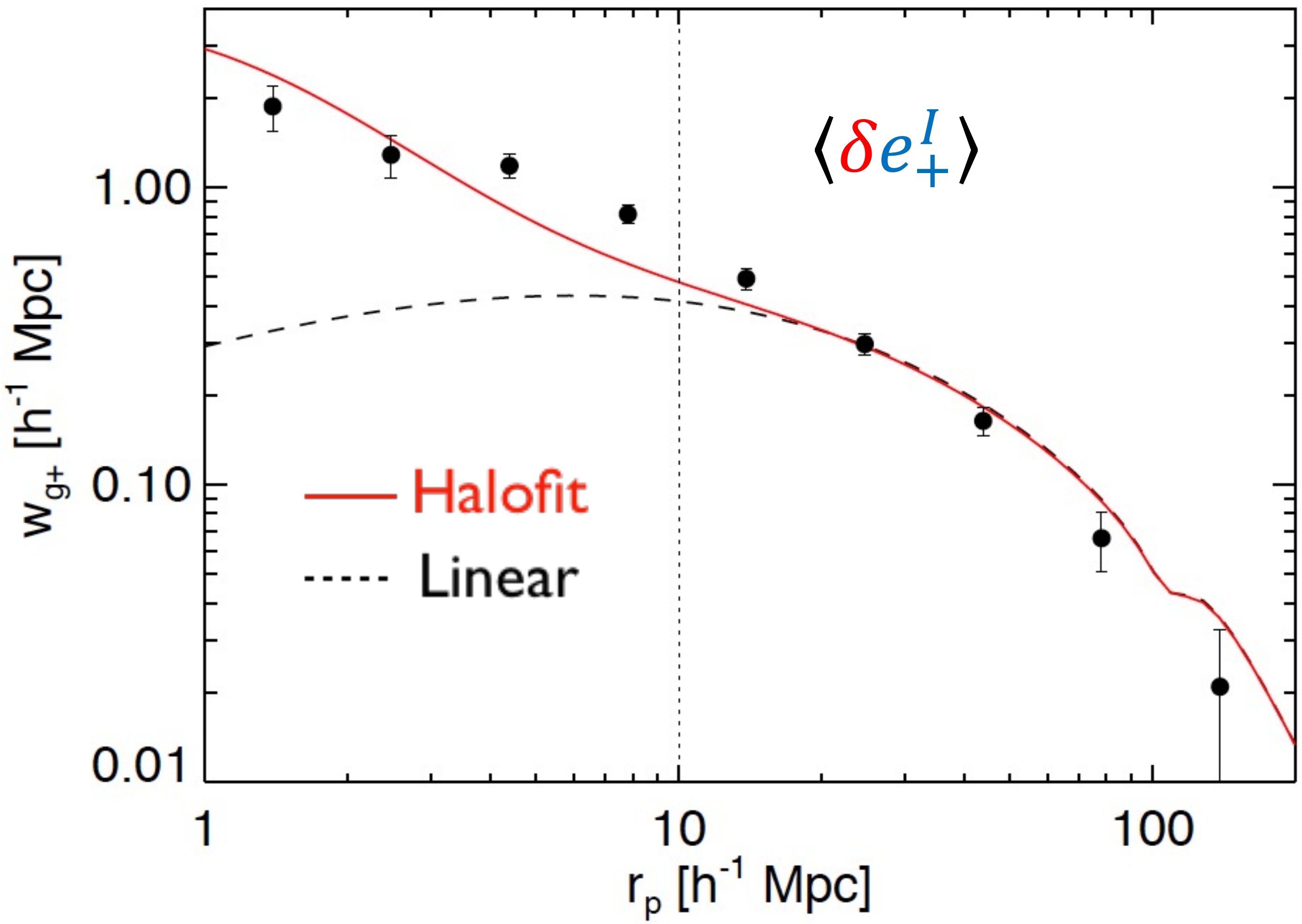
$$\gamma_{(+,\times)}(\mathbf{x}) = -\frac{C_1}{4\pi G}\left(\nabla_x^2 - \nabla_y^2, 2\nabla_x\nabla_y\right)\times[\Psi_P] \longleftrightarrow \delta = \frac{1}{4\pi G}(\nabla_x^2 + \nabla_y^2 + \nabla_z^2)\Psi$$

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



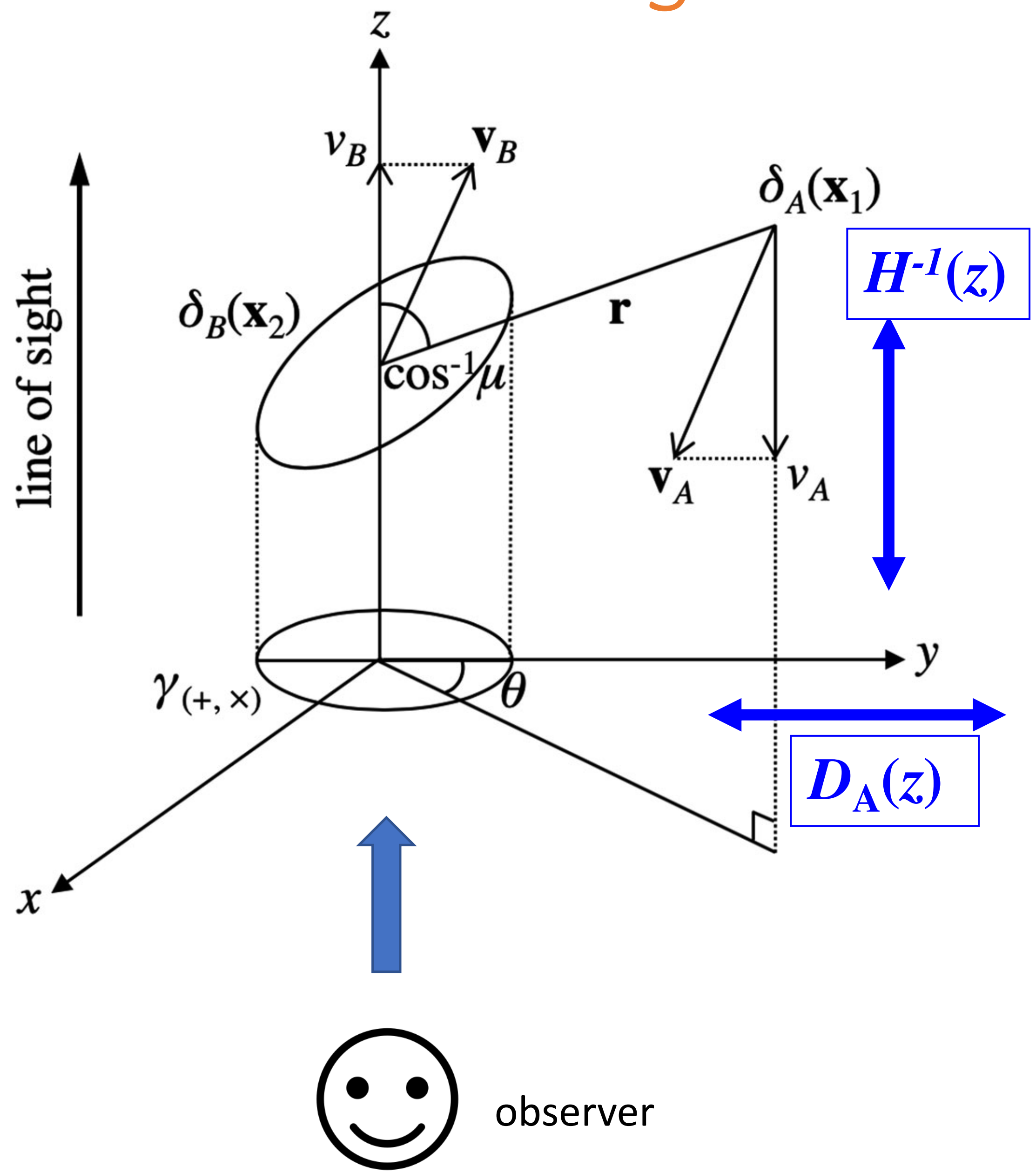
# Testing galaxy-ellipticity correlation in LA model with observations

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.

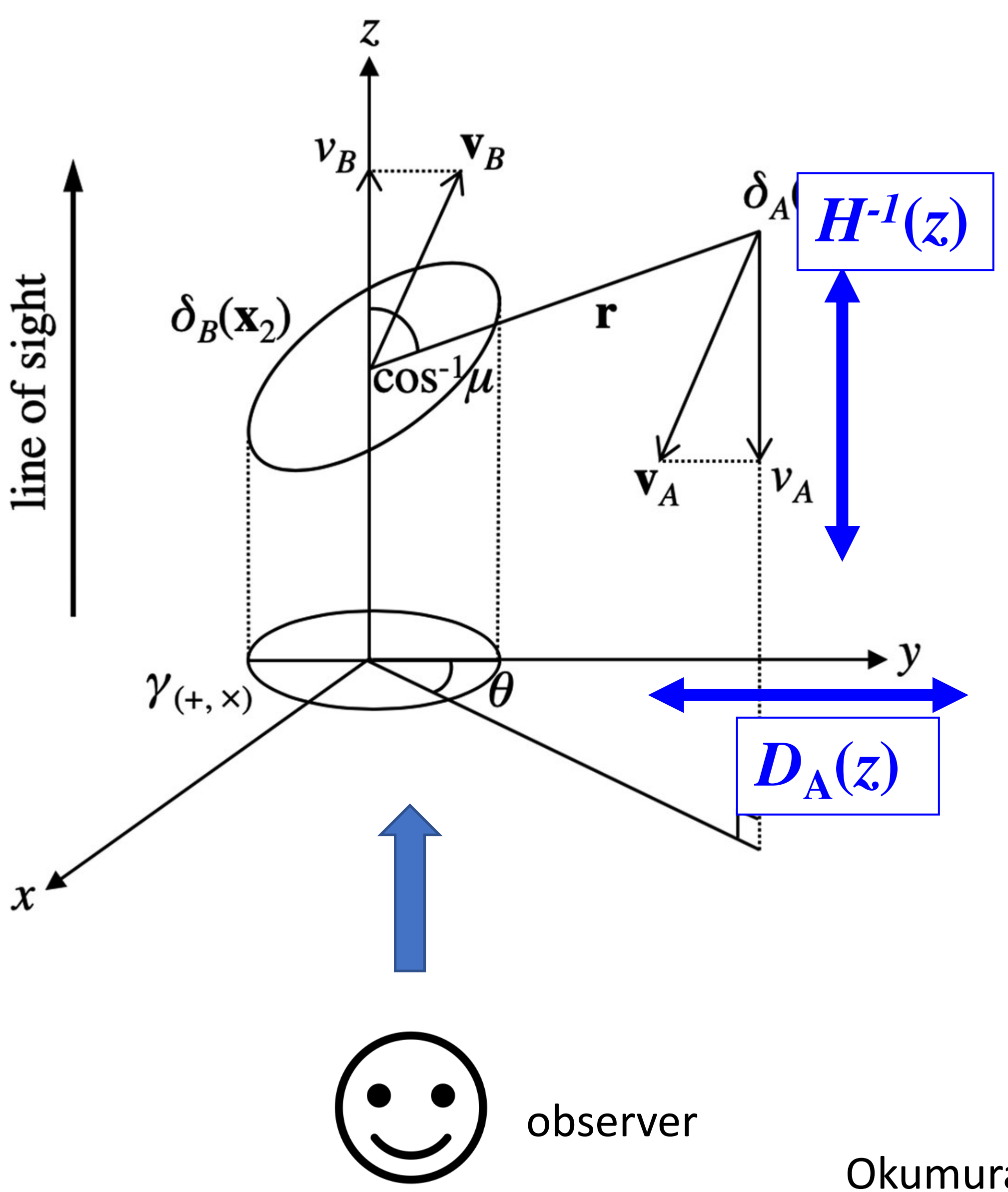
# Formulating the IA statistics in redshift space




- 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, $\mathbf{r} = (r, \mu)$
- 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*

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

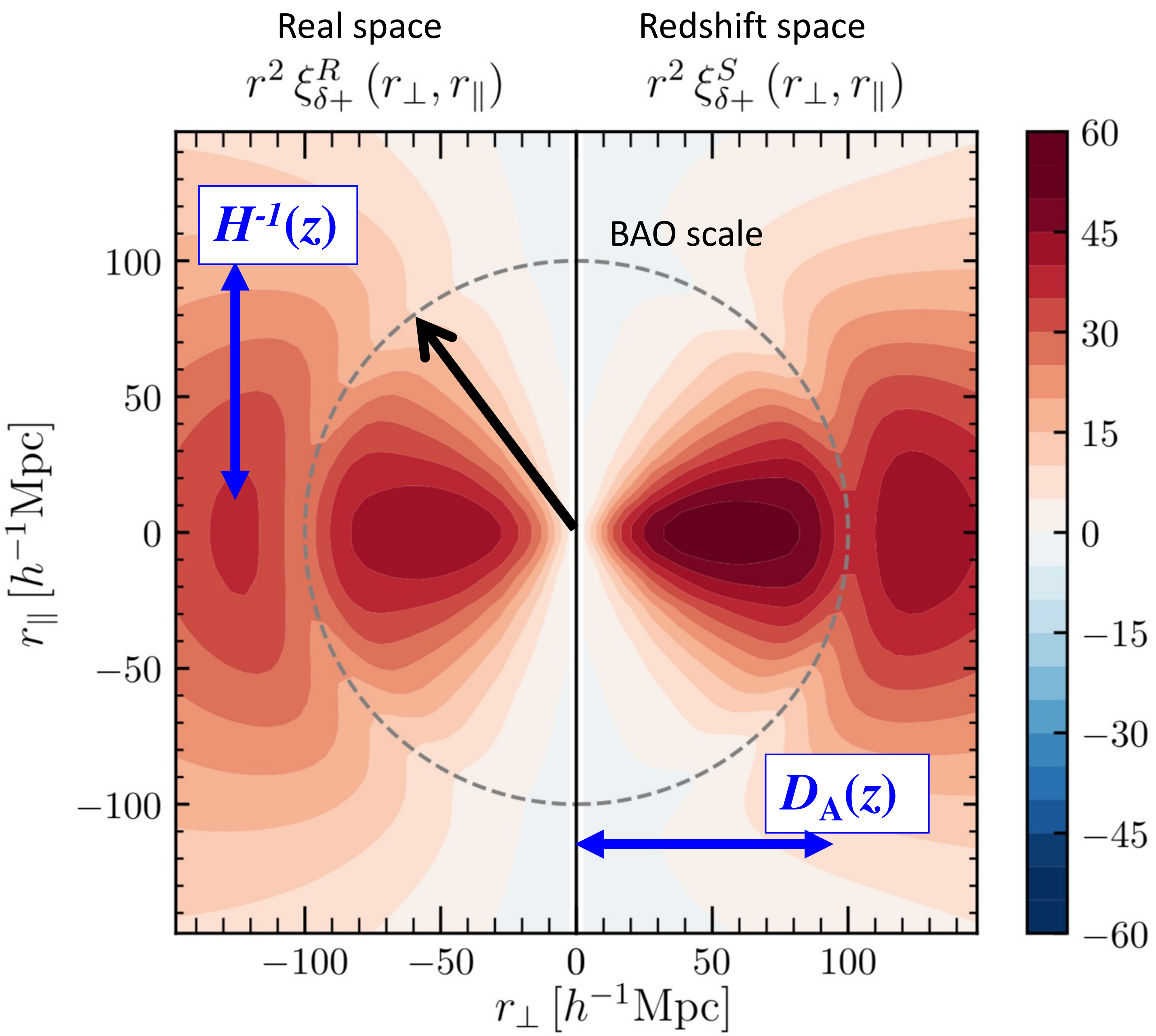
$$\xi^S_{g+,2}(r) = \xi^R_{g+,2}(r) - \frac{2}{21}\widetilde{C}_1 f \left[\Xi^{(0)}_{\delta\Theta,2}(r) + 2\,\Xi^{(0)}_{\delta\Theta,4}(r)\right],$$

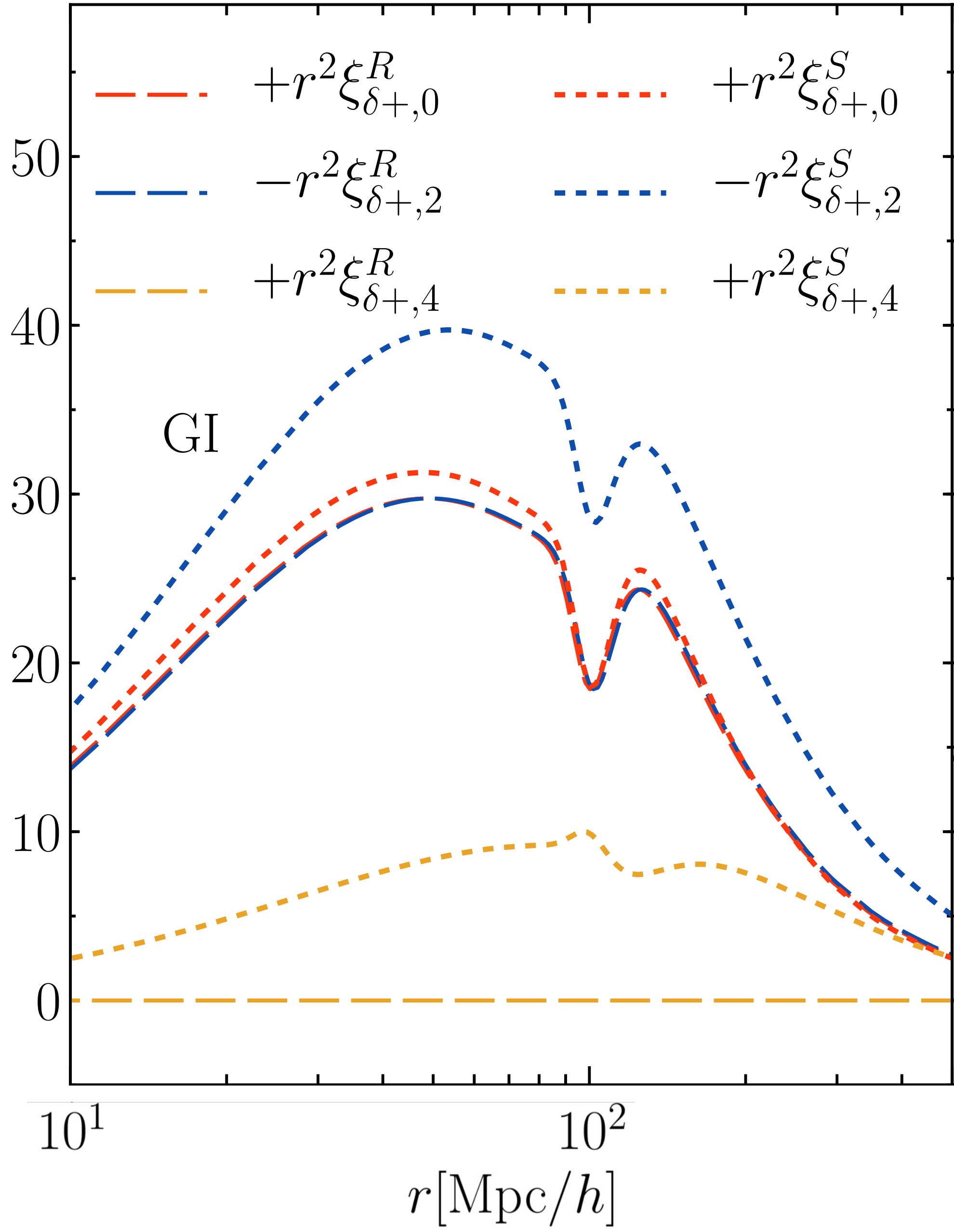
$$\xi^S_{g+,4}(r) = \frac{8}{35}\widetilde{C}_1 f\, \Xi^{(0)}_{\delta\Theta,4}(r).$$

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

Okumura & Taruya (2020)

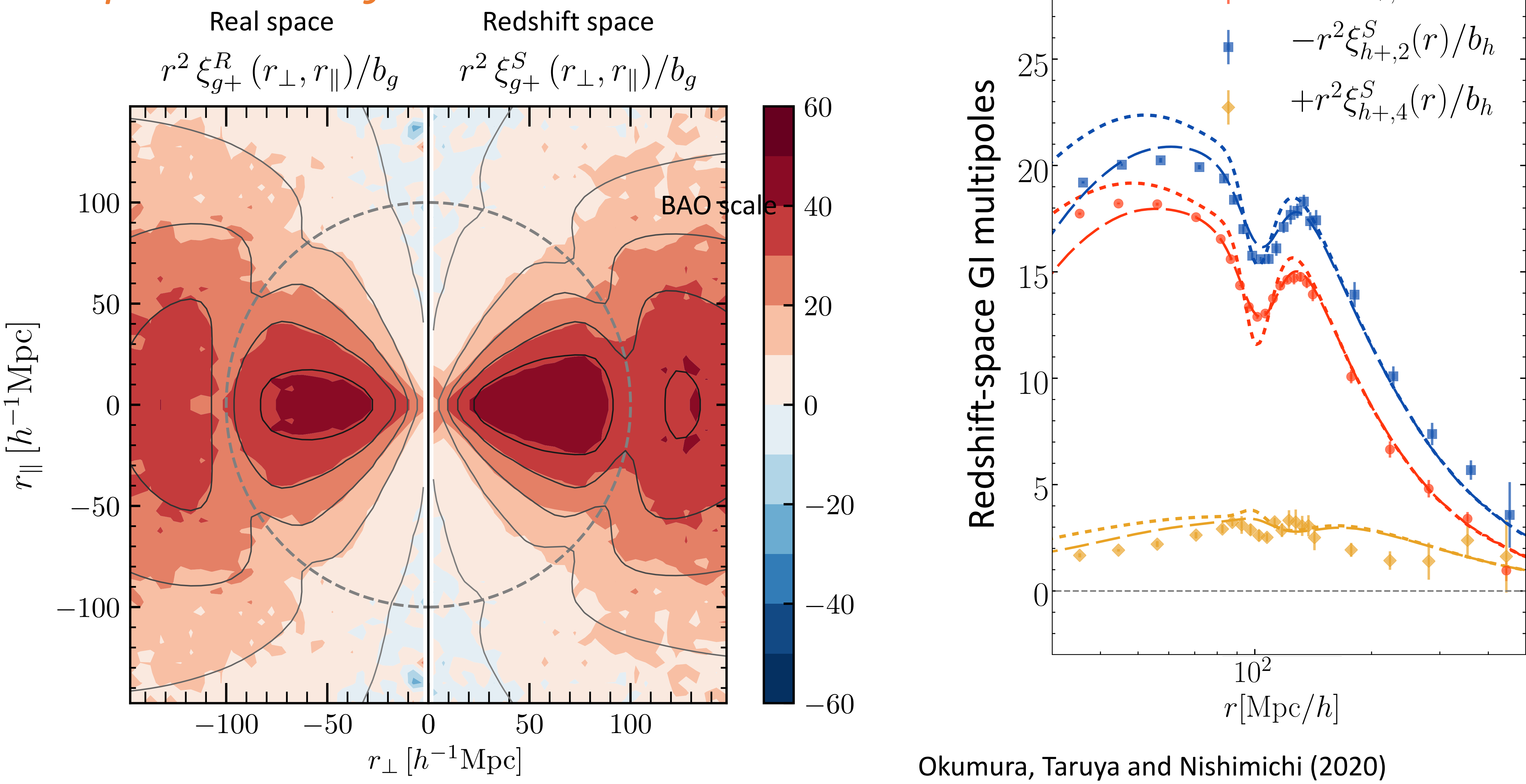
# GI correlation in linear theory



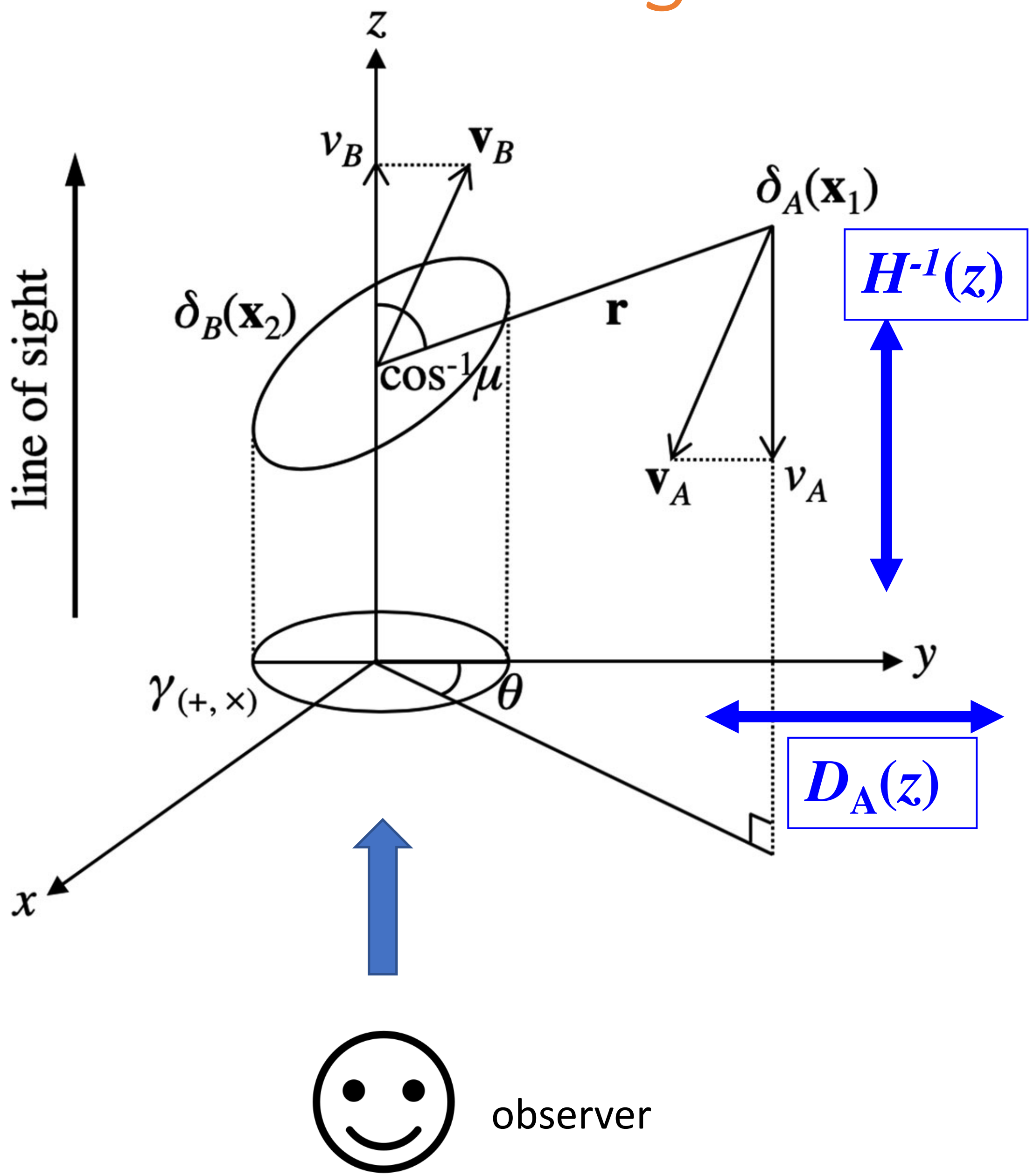

Okumura & Taruya (2020)

# 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

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

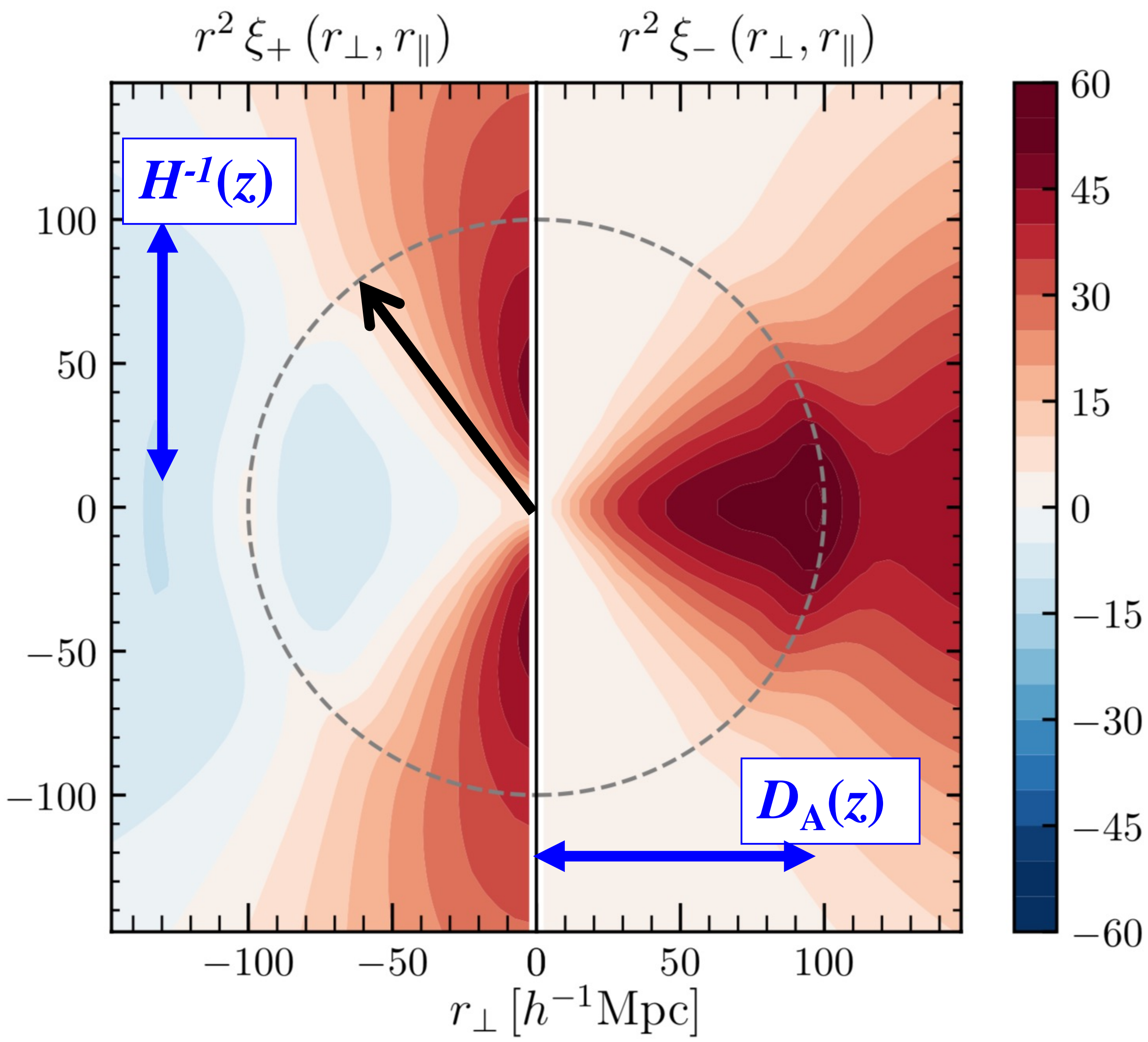
$$\xi_+(\mathbf{r}) = \frac{8}{105}\,\widetilde{C}_1^2\left[7\,\mathcal{P}_0(\mu)\,\Xi^{(0)}_{\delta\delta,0}(r) + 10\,\mathcal{P}_2(\mu)\,\Xi^{(0)}_{\delta\delta,2}(r) + 3\,\mathcal{P}_4(\mu)\,\Xi^{(0)}_{\delta\delta,4}(r)\right],$$

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

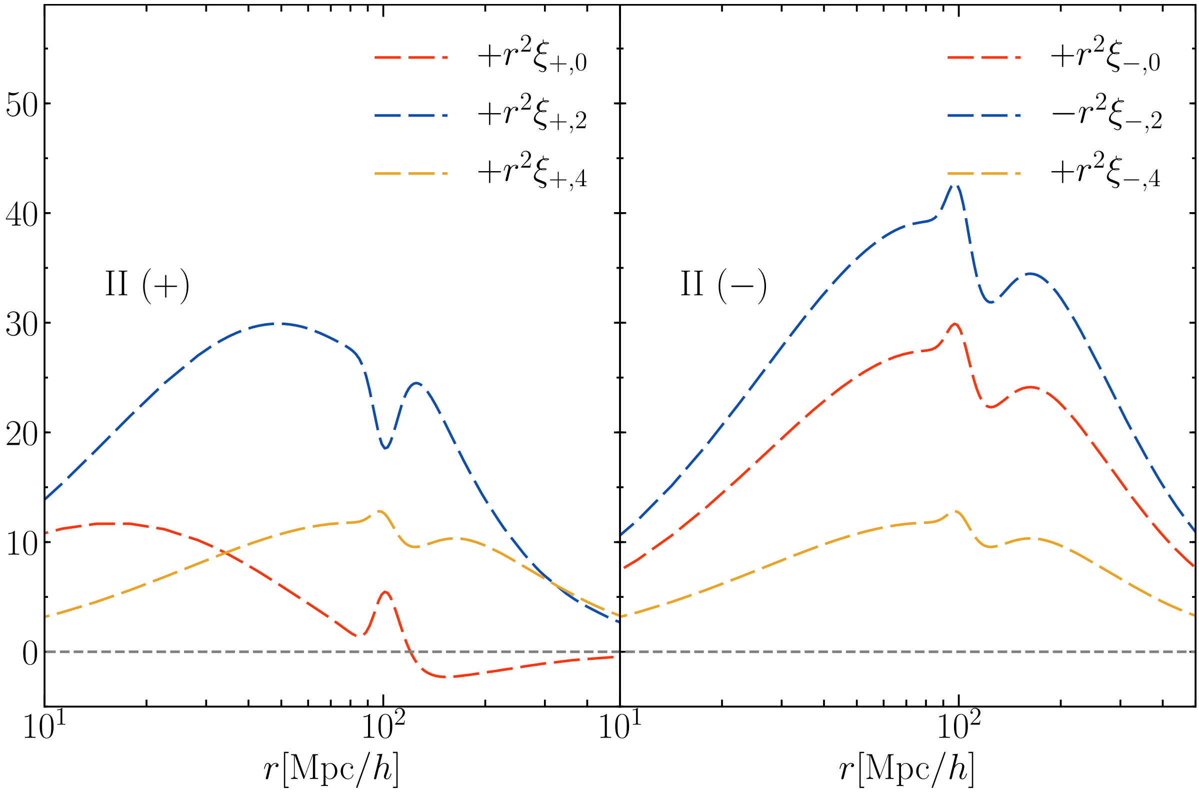
$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^\infty \frac{k^{2-n}dk}{2\pi^2} P_{XY}(k) j_\ell(kr)$$

Okumura & Taruya (2020)

# II correlation in 2D



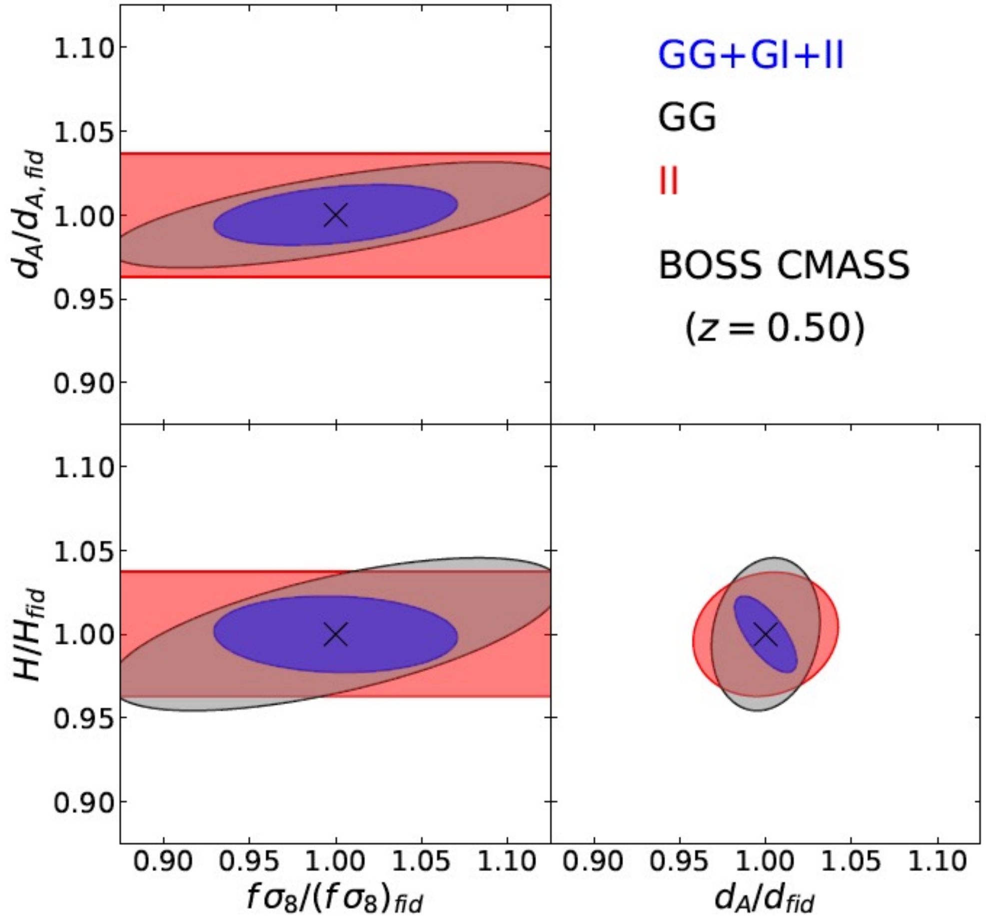

$$\xi_\pm(\mathbf{r}) = \xi_{++}(\mathbf{r}) \pm \xi_{\times\times}(\mathbf{r})$$



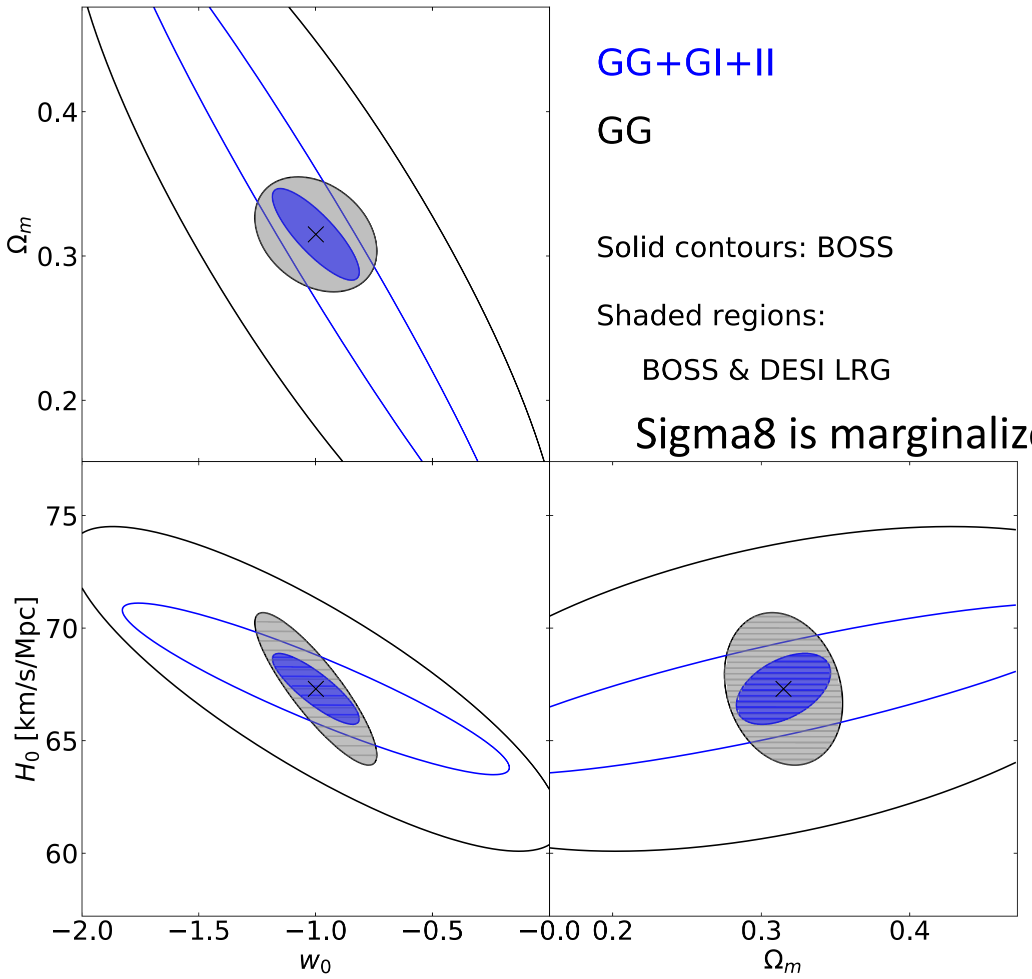

Okumura & Taruya (2020)

# IA measurements enhance the science return from galaxy redshift surveys

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




Clustering $\sigma_8$ and IA amplitude $A_{IA}$ are marginalized over.




Sigma8 is marginalized over.

Taruya & Okumura (2020)

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

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

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

- Power spectra (6 in total)

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

- Geometric distortions

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

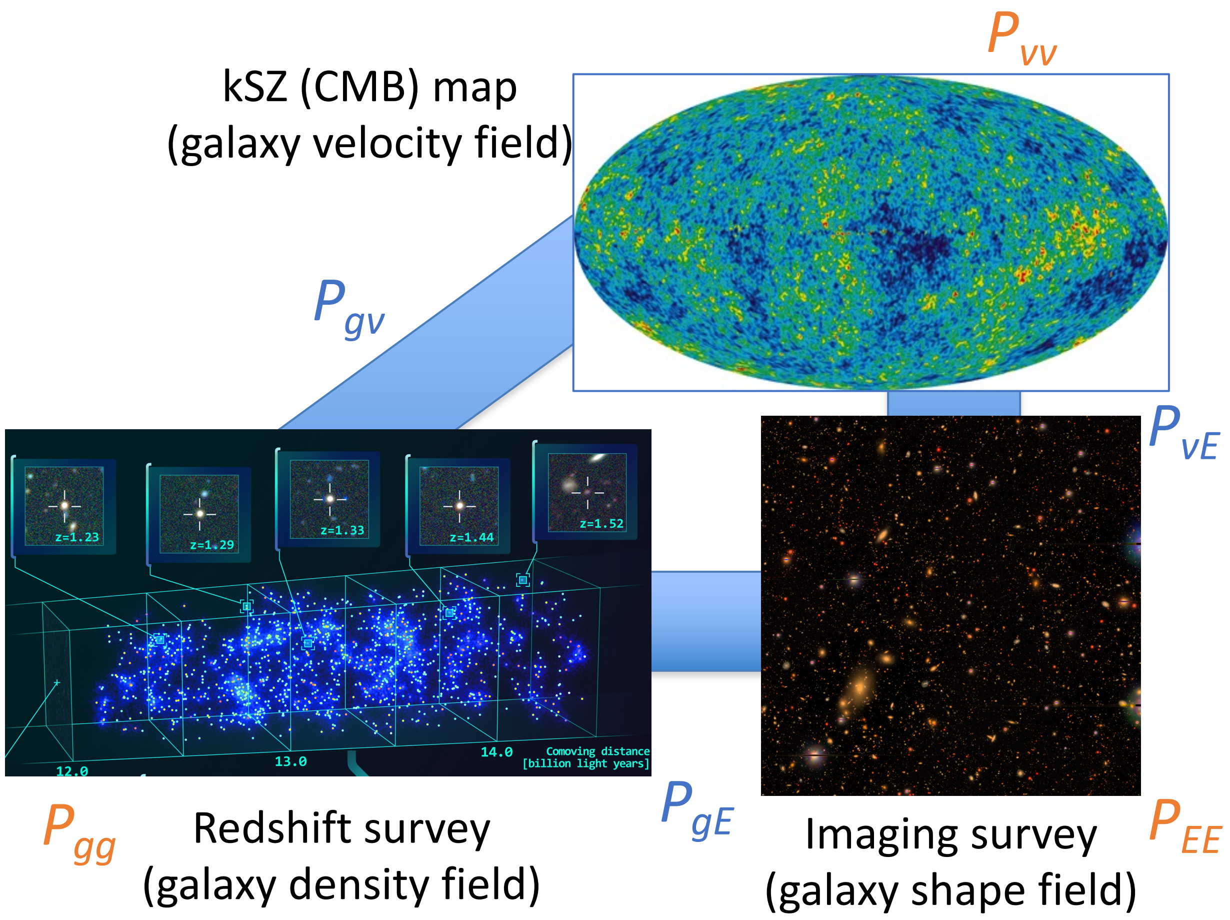
$$k_\parallel^{\rm fid} = k_\parallel H^{\rm fid}(z)/H(z) \text{ and } k_\perp^{\rm fid} = D_{\rm A}(z)/D_{\rm A}^{\rm fid}(z)$$

- Fitting parameters

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

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

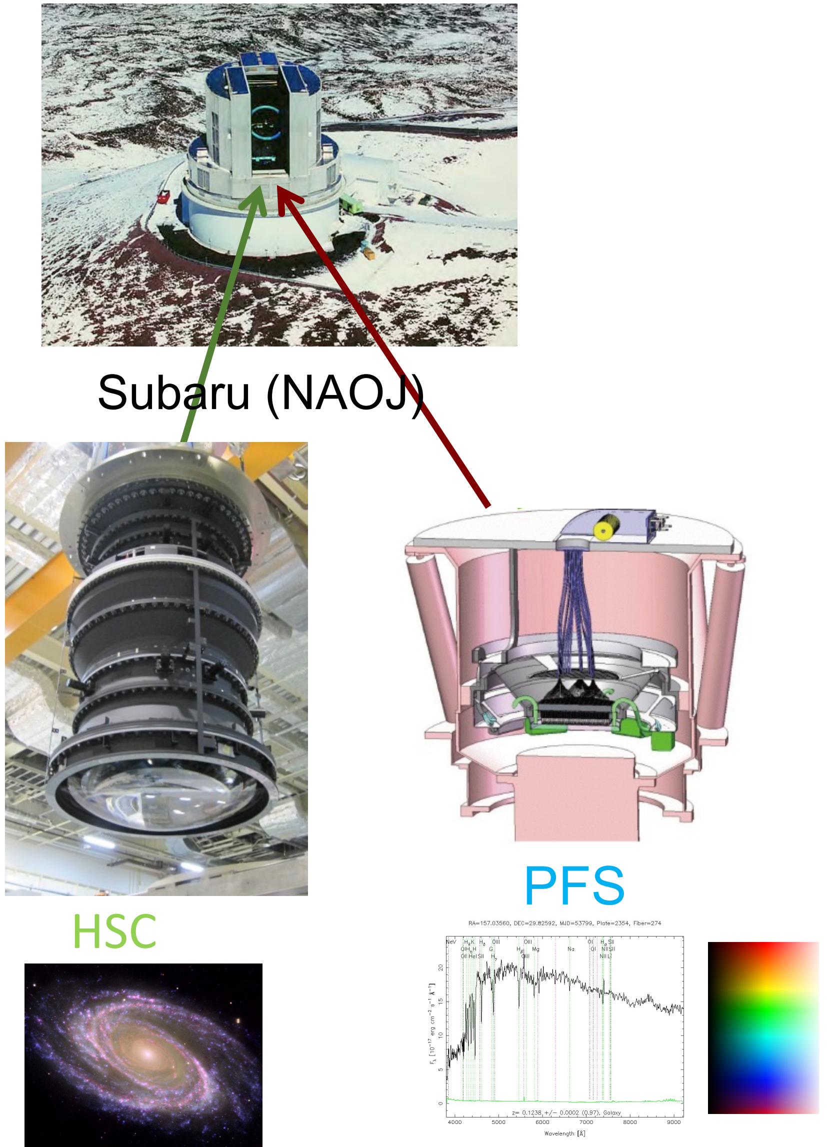
$$\widetilde{P}_{gg} = P_{gg} + \frac{1}{n_g}, \qquad \widetilde{P}_{vv} = P_{vv} + (1+R_N^2)\left(\frac{T_0\tau}{c}\right)^2 \frac{(f\sigma_v)^2}{n_v}, \qquad \widetilde{P}_{EE} = P_{EE} + \frac{\sigma_\gamma^2}{n_\gamma}$$

# Survey setup

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

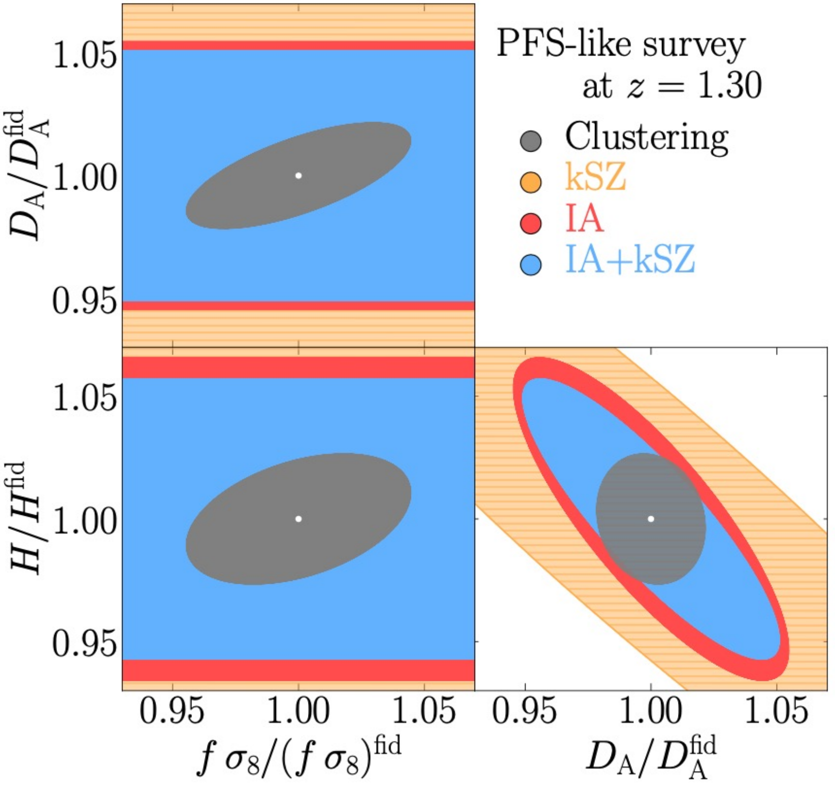
| Redshift $z_{\mathrm{min}}$ | $z_{\mathrm{max}}$ | Volume $V_s$ ($h^{-3}\mathrm{Gpc}^3$) | $10^4 n$ ($h^3\mathrm{Mpc}^{-3}$) | $b_g$ |
|---|---|---|---|---|
| 0.6 | 0.8 | 0.59 | 1.9 | 1.18 |
| 0.8 | 1.0 | 0.79 | 6.0 | 1.26 |
| 1.0 | 1.2 | 0.96 | 5.8 | 1.34 |
| 1.2 | 1.4 | 1.09 | 7.8 | 1.42 |
| 1.4 | 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), $\sigma_\gamma$=0.2.
  - Shi et al (2021) proposed an estimator to directly detect IA of host halos using the observation of ELGs, $A_{\mathrm{IA}}$ = 18.
- kSZ:
  - CMB-S4, which is completely overlapped with the area of the PFS
  - Fiducial values: linear theory for $\sigma_v$, and the inverse S/N of the kSZ temperature fluctuations $R_{\mathrm{N}}$ = 10 (Sugiyama et al 2017).

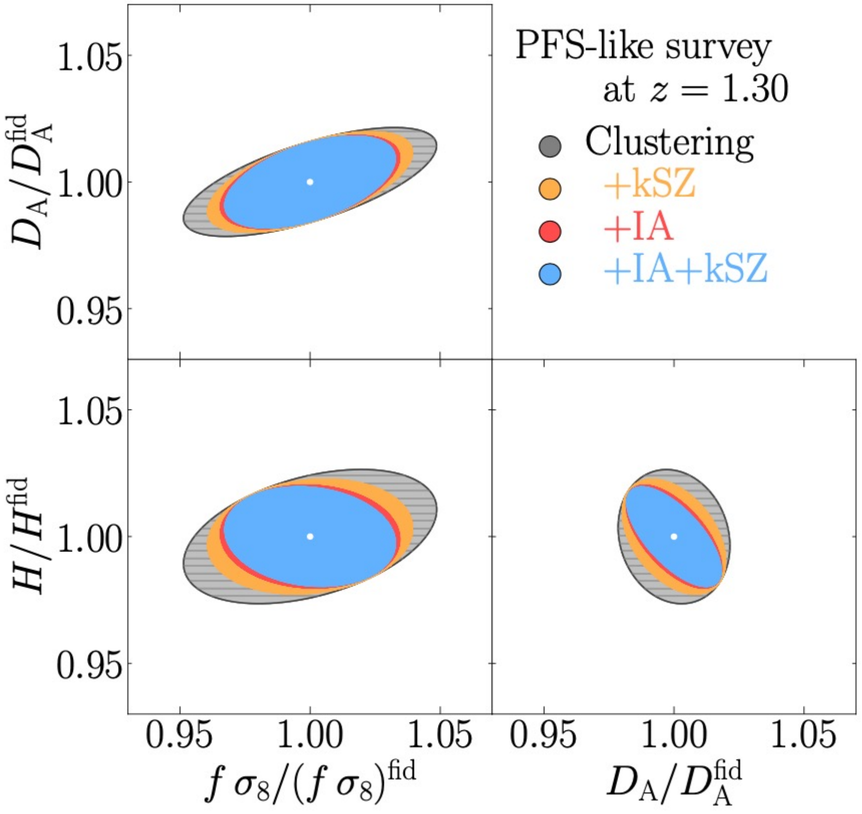


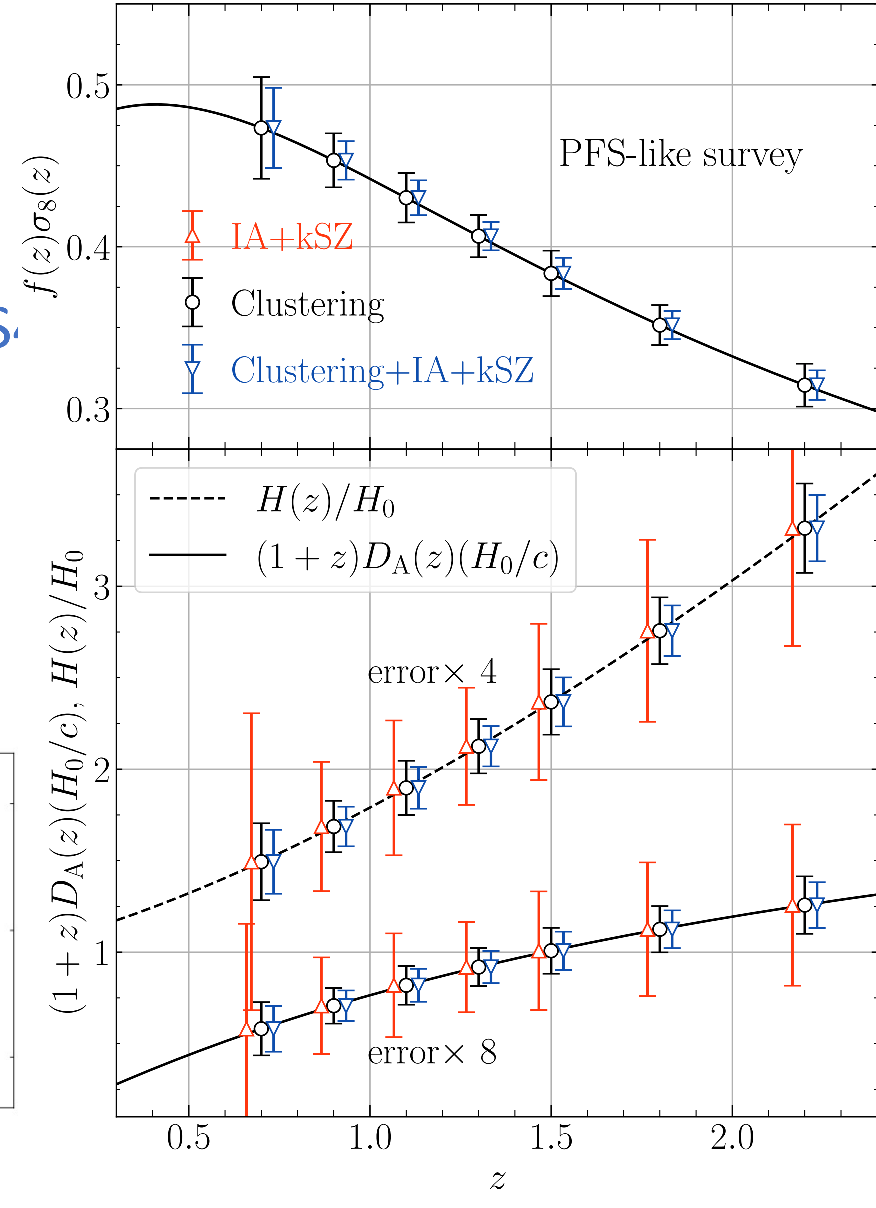
# Geometric and dynamical constraints

- 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-S4)



# Cosmological constraints (1)

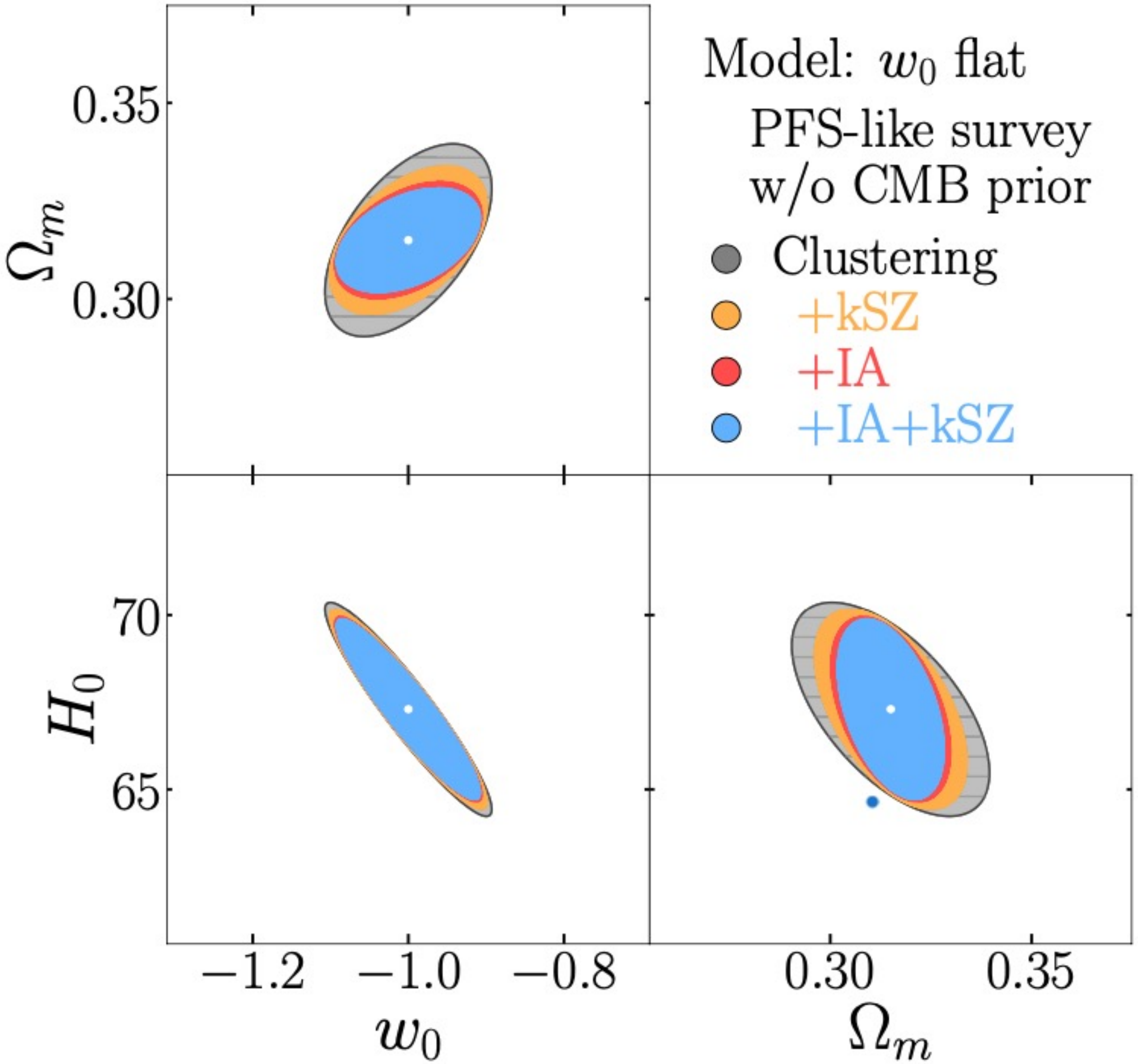
- Projection of the Fisher matrix to the cosmological parameter space:

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

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

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

constant w, flat ($\Omega_K$= 0) model



# Cosmological constraints (2)

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

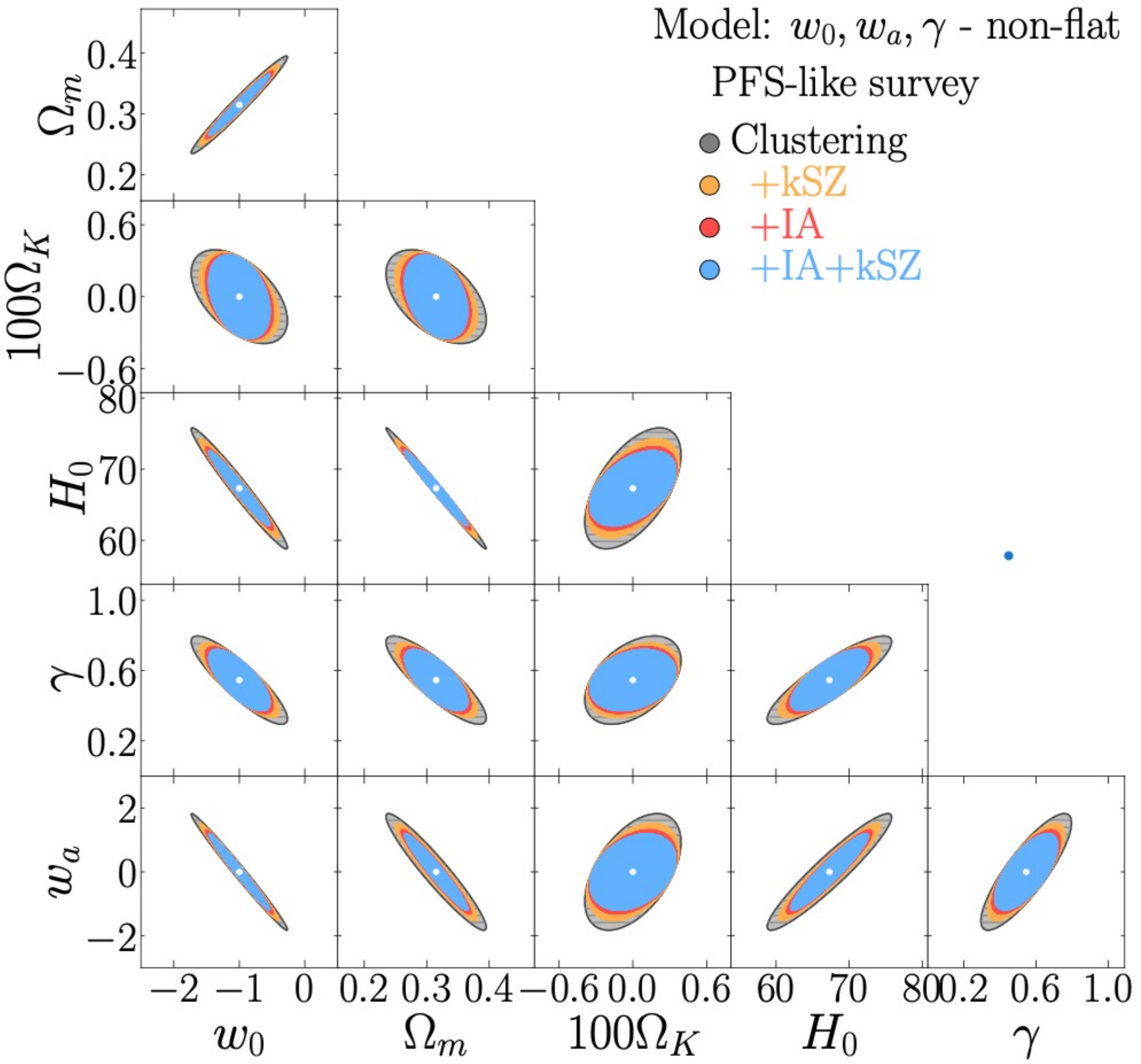
$$S_{AB} = \sum_{\alpha,\beta} \frac{\partial \theta_\alpha}{\partial p_A} F_{\alpha\beta} \frac{\partial \theta_\beta}{\partial p_B}$$

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

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

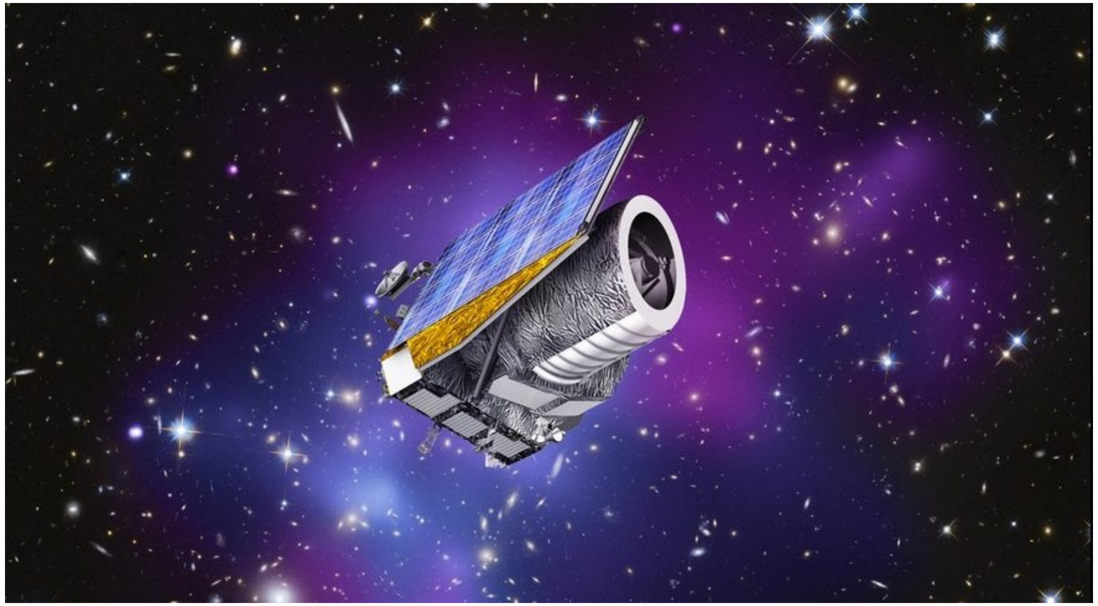
time-varying $w(a) = w_0 + (1-a)w_a$, non-flat ($\Omega_K \neq 0$) model with modified gravity parameter γ

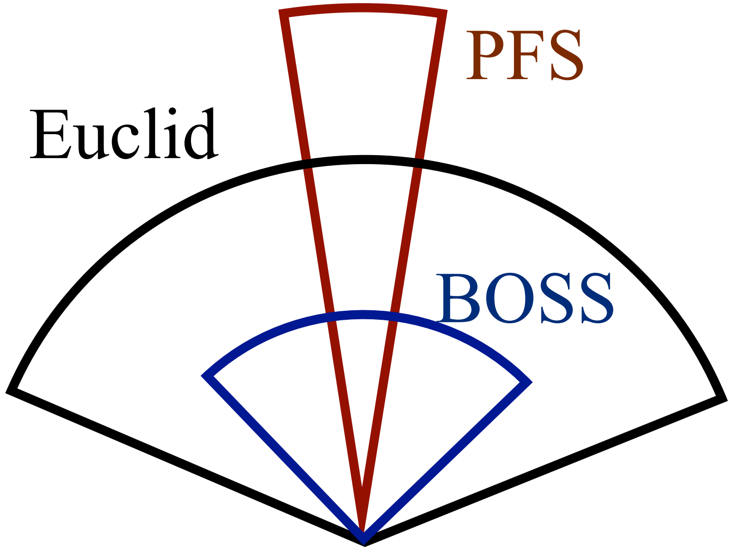
$$S_{AB} = S_{AB}^{\rm LSS} + S_{AB}^{\rm CMB}$$



# *Deep vs wide surveys*

- Euclid satellite mission for galaxy surveys

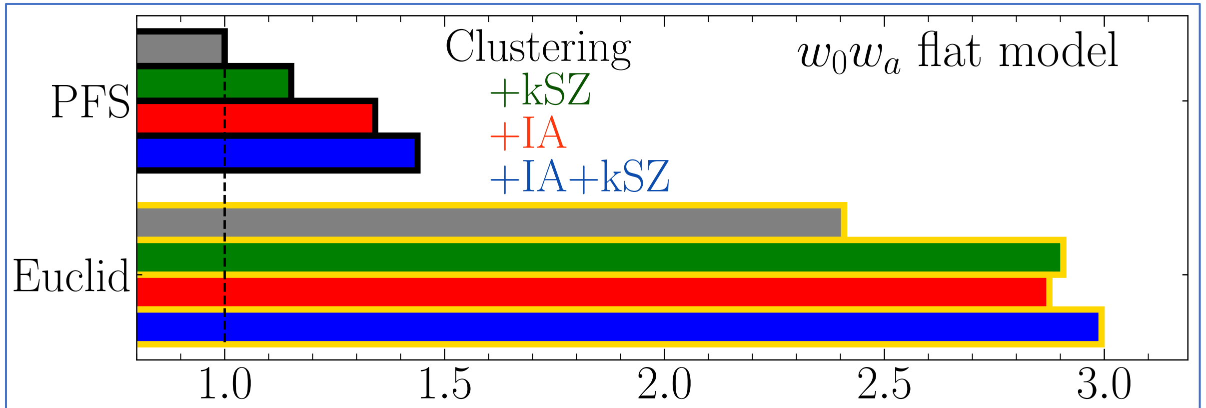




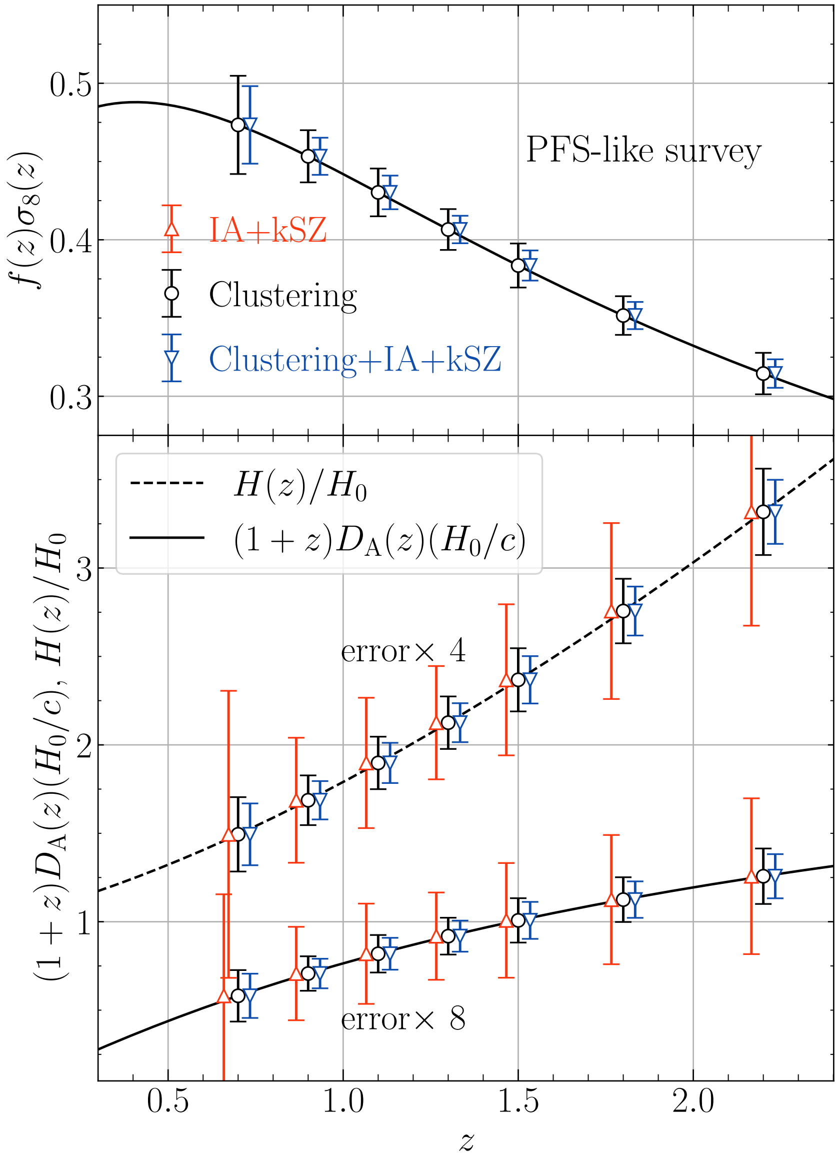

- Figure-of-Merit (FoM)

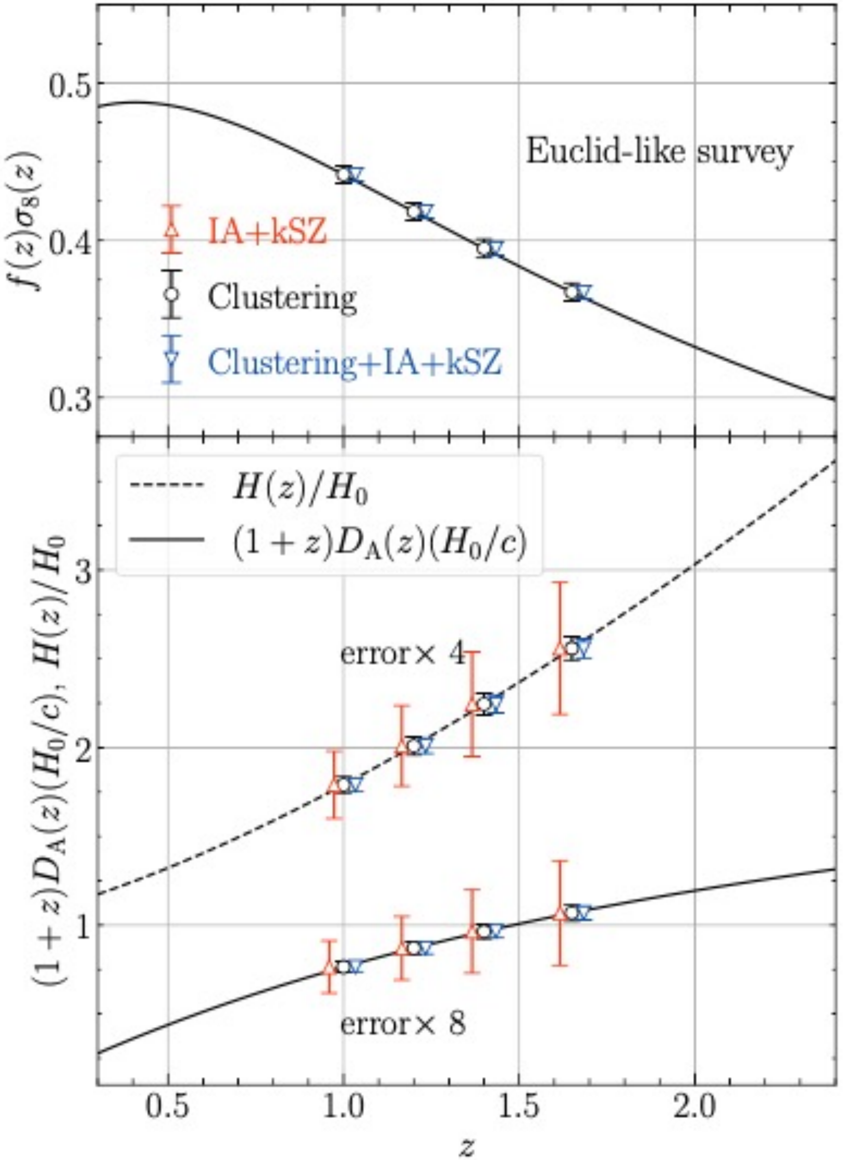
$$\mathrm{FoM} = \left\{\det(\overline{S}_{AB})\right\}^{1/N_p}$$

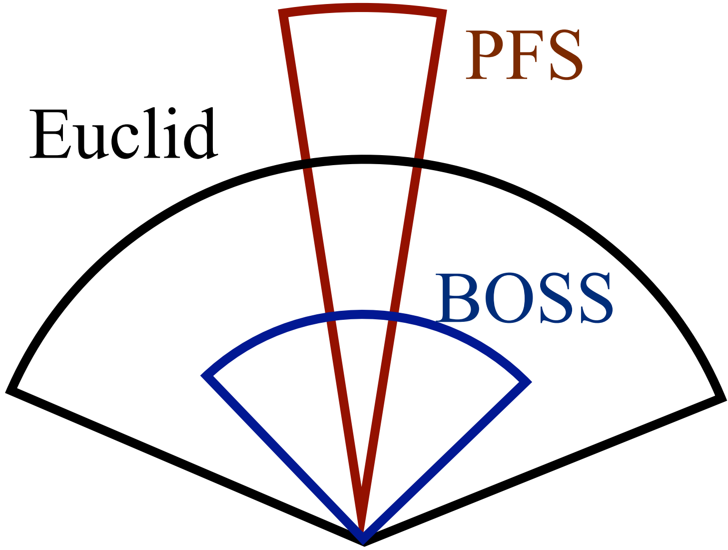
  - Normalize by the clustering-only case with PFS



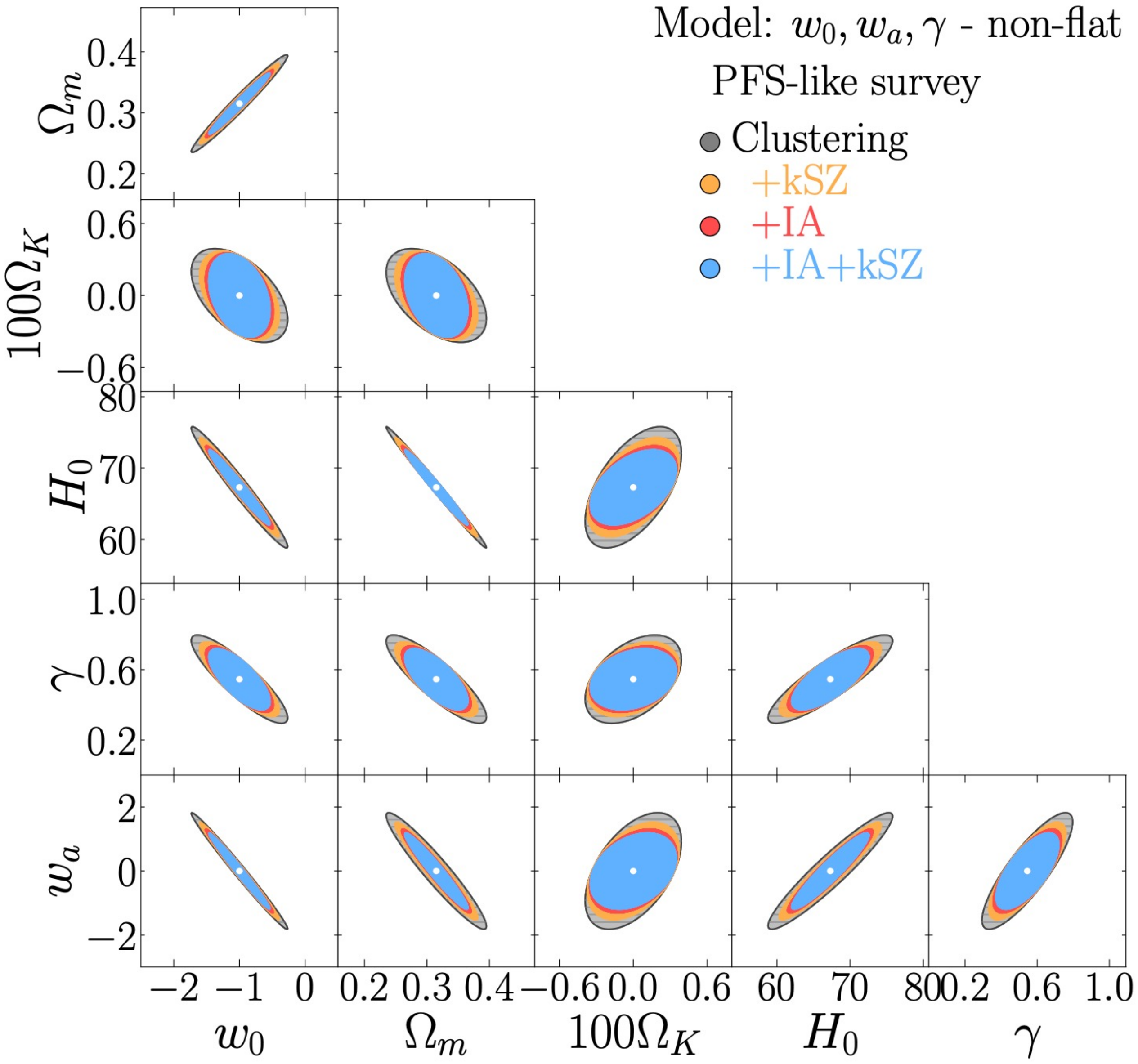
# Deep vs wide surveys

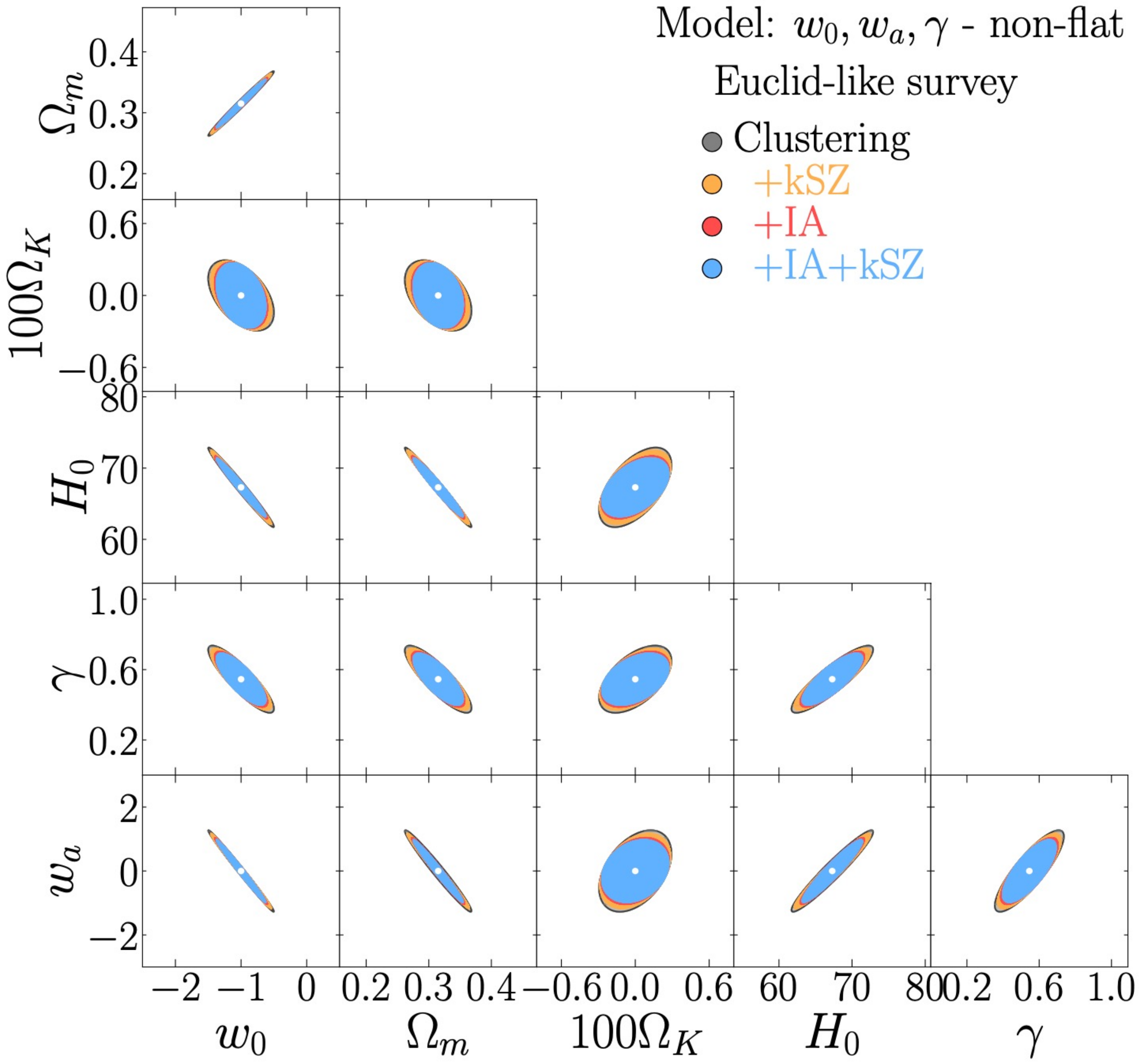


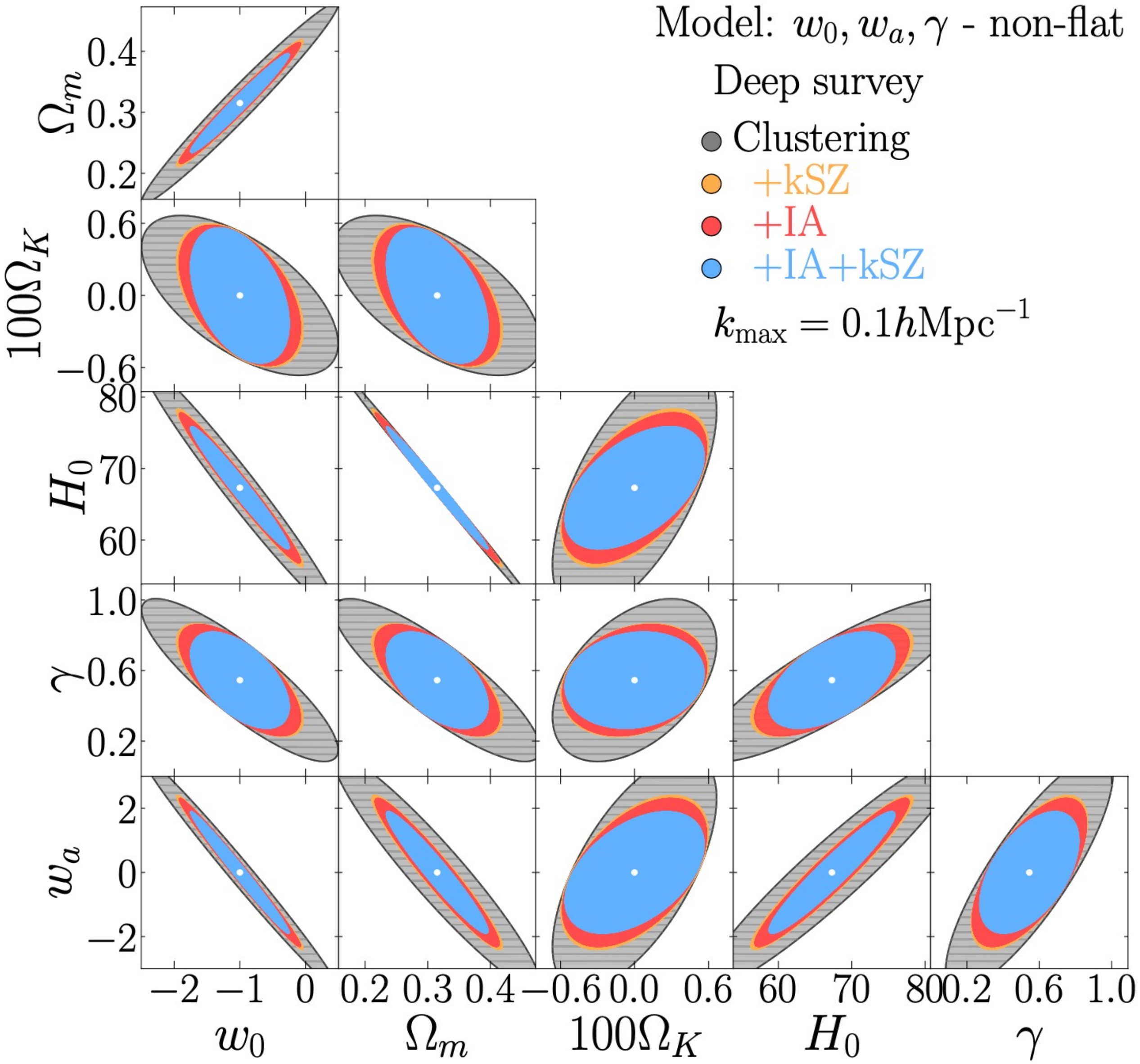



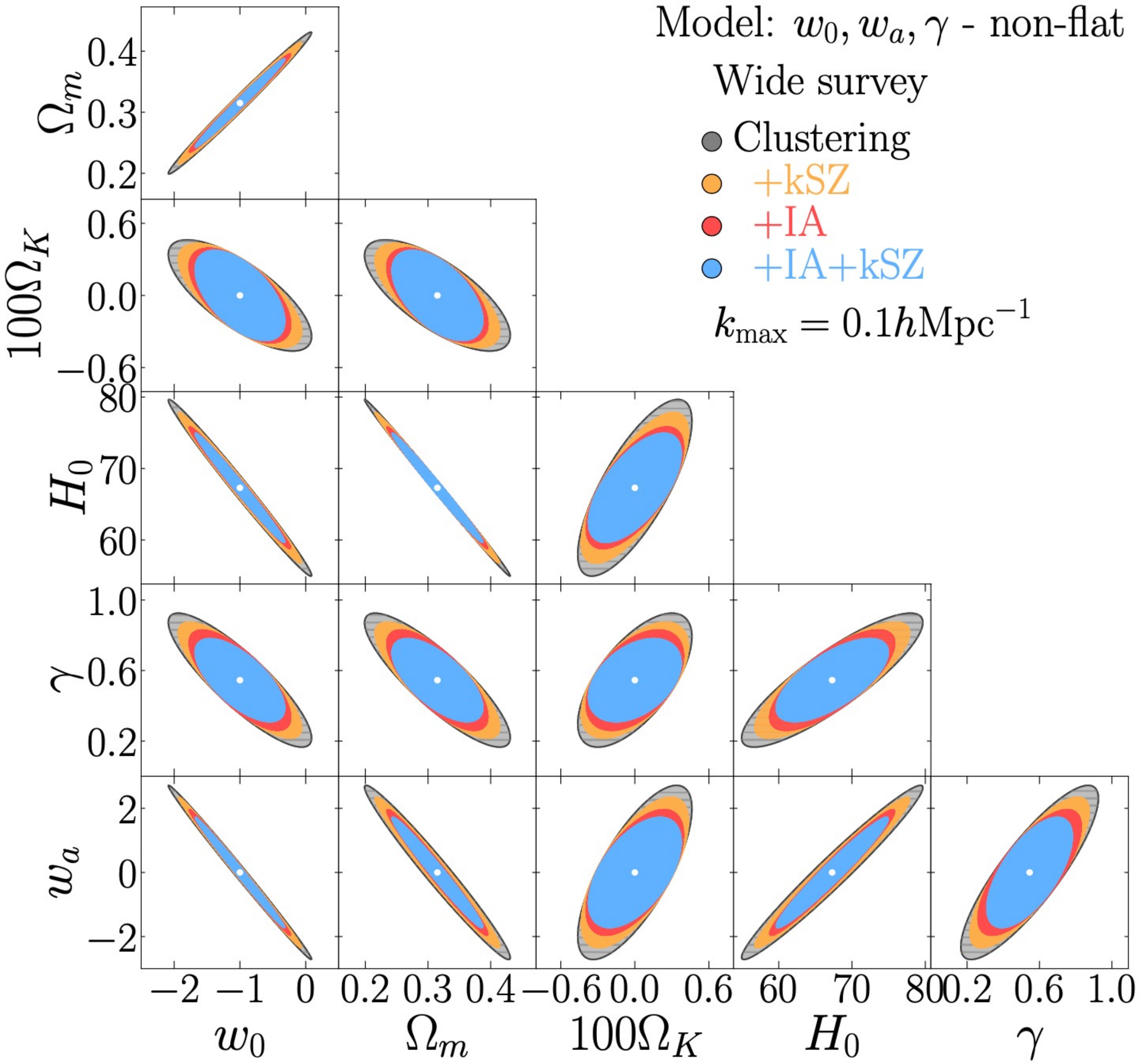
# Deep vs wide surveys



# Conservative analysis with cutoff of kmax = 0.10 h/Mpc



# *Outline*

- Galaxy redshift surveys
  - Dynamical distortions: redshift-space distortions (RSD)
  - Geometric distortions: baryon acoustic oscillations (BAO)
- Kinetic Sunyaev-Zel'dovich (kSZ) effect
- Galaxy intrinsic alignment (IA)
- Fisher matrix forecast with galaxy clustering + IA + kSZ
  - Geometric and dynamical constraints
  - Cosmological parameter constraints
  - Deep vs wide galaxy surveys
- IA in $f(R)$ gravity simulations

MNRAS 000, 1–5 (2021) Preprint 3 November 2021 Compiled using MNRAS LATEX style file v3.0

arXiv: 2111.01417

# Intrinsic alignments of dark matter halos in $f(R)$ gravity simulations

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Accepted XXX. Received YYY; in original form ZZZ

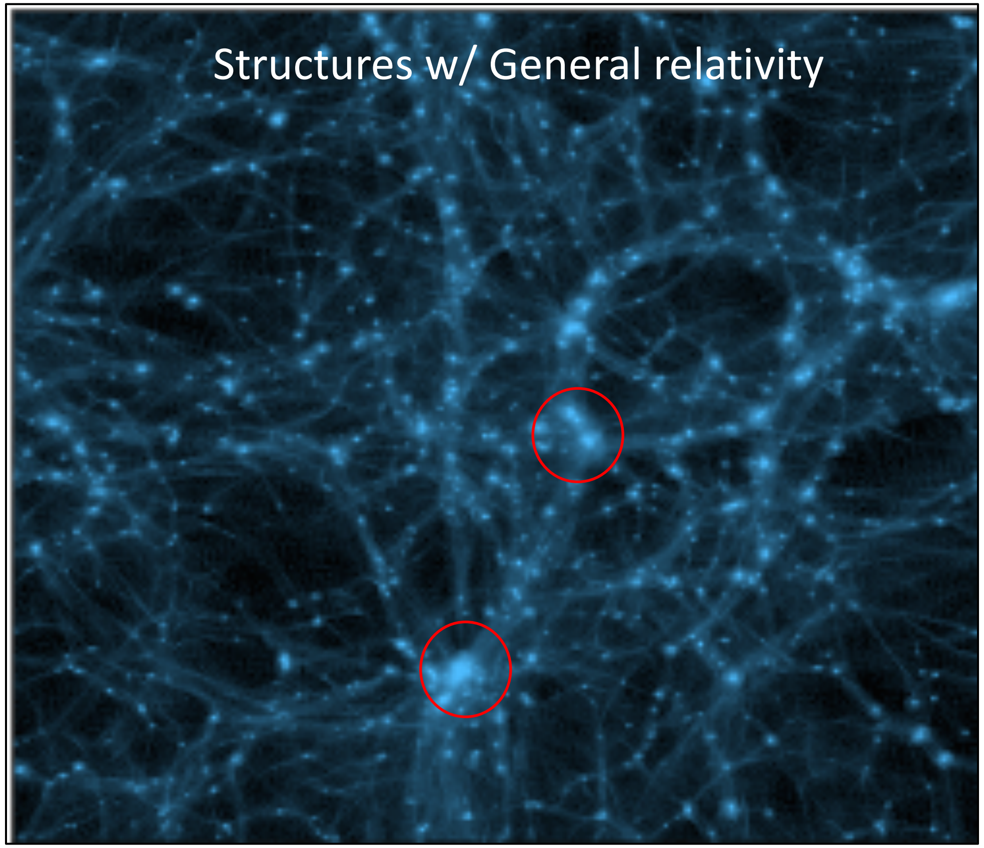
**ABSTRACT**

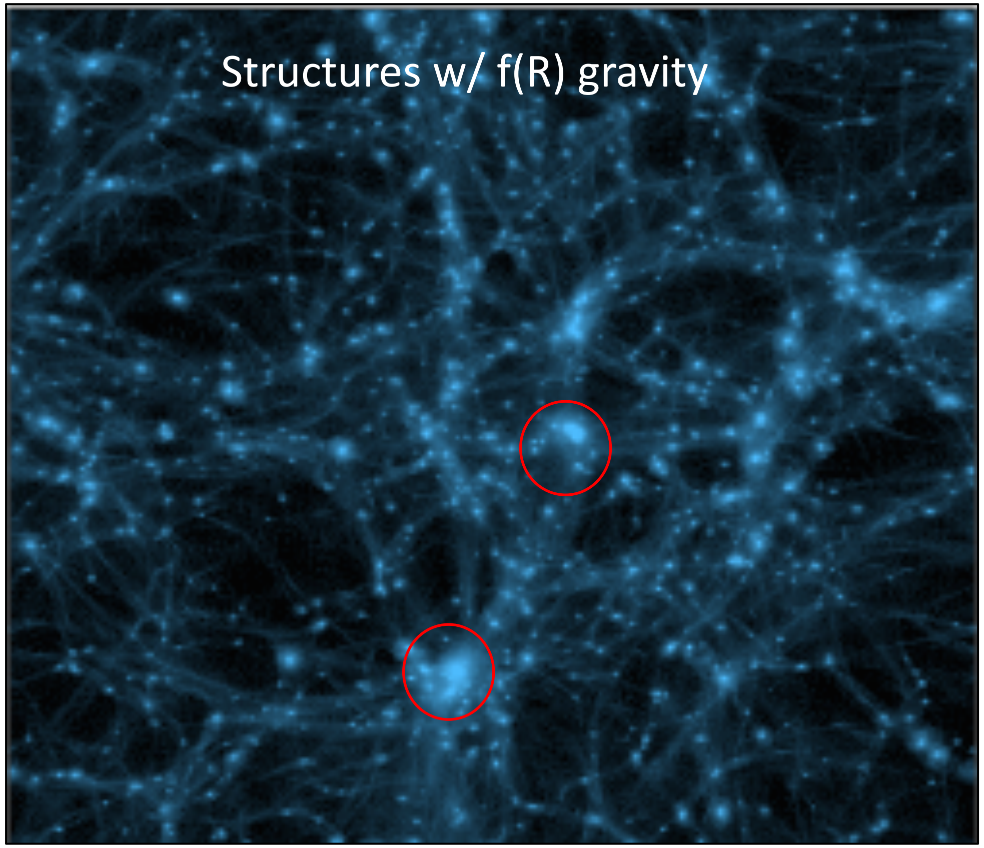
There is a growing interest of utilizing intrinsic alignment (IA) of galaxy shapes as a geometric and dynamical probe of cosmology. In this paper we present the first measurements of IA in a modified gravity model using the gravitational shear-intrinsic ellipticity correlation (GI) and intrinsic ellipticity-ellipticity correlation (II) functions of dark-matter halos from $f(R)$ gravity simulations. By comparing them with the same statistics measured in ΛCDM simulations, we find that the IA statistics in different gravity models show distinguishable features, with a trend similar to the case of conventional galaxy clustering statistics. Thus, the GI and II correlations are found to be useful in distinguishing between the ΛCDM and $f(R)$ gravity models. More quantitatively, IA statistics enhance detectability of the imprint of f(R) gravity on large scale structures by $\sim 20\%$ when combined with the conventional halo clustering in redshift space. Our results demonstrate the usefulness of IA statistics as a probe of gravity beyond a consistency test of ΛCDM and general relativity.

**Key words:** methods: statistical – cosmology: theory – dark energy – large-scale structure of Universe.

# *Measuring IA statistics in f(R) gravity simulations*

- Simulations run by Shirasaki-san

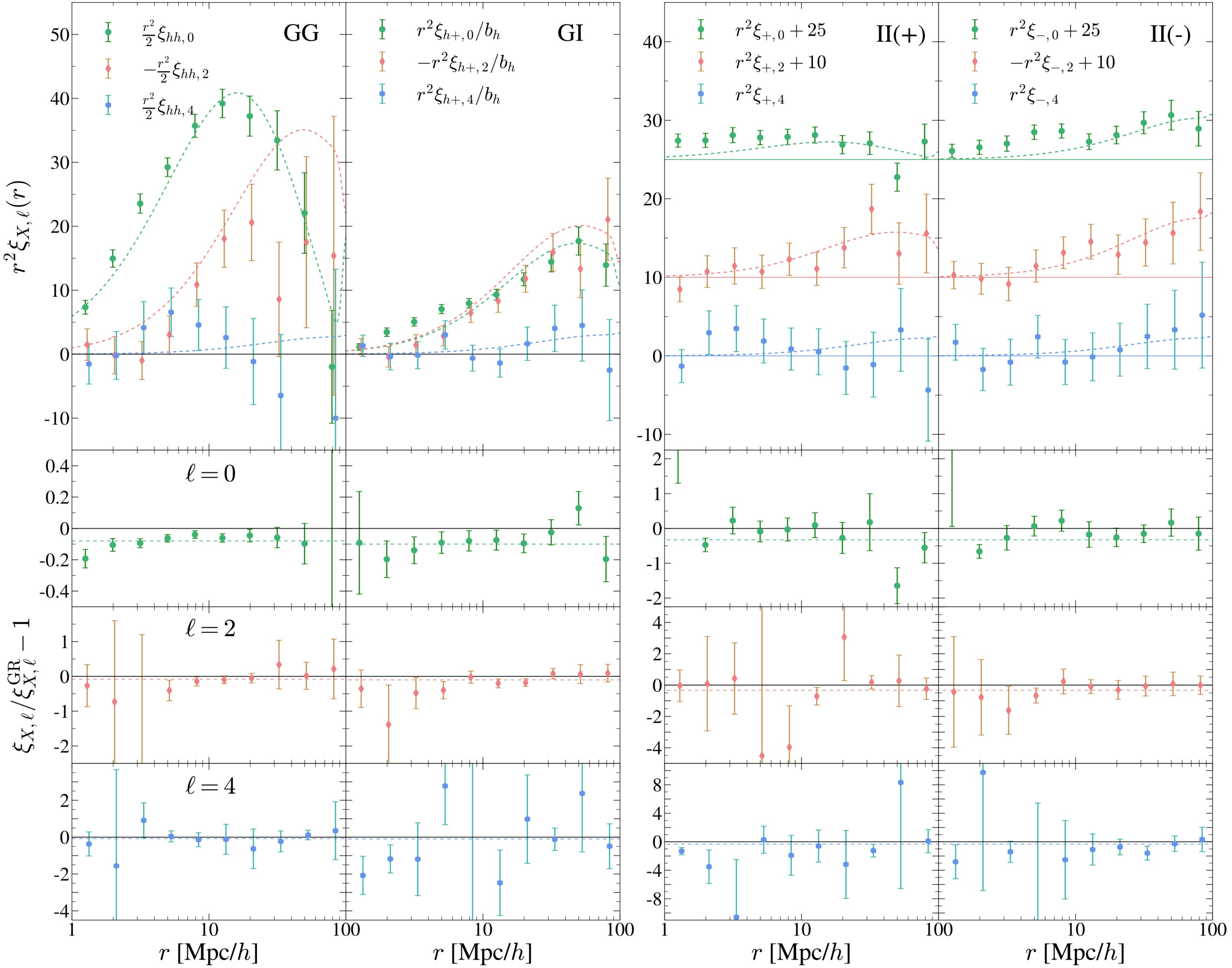



This vidualization made by
Gongbo Zhao (NAOC)

# *Non-zero multipoles of GG, GI and II correlation functions (l=0,2,4)*

- $M > 10^{13}$ halos
- $z$=0
- $L$ = 316Mpc/$h$
- $|f_{\mathrm{R0}}| = 10^{-5}$

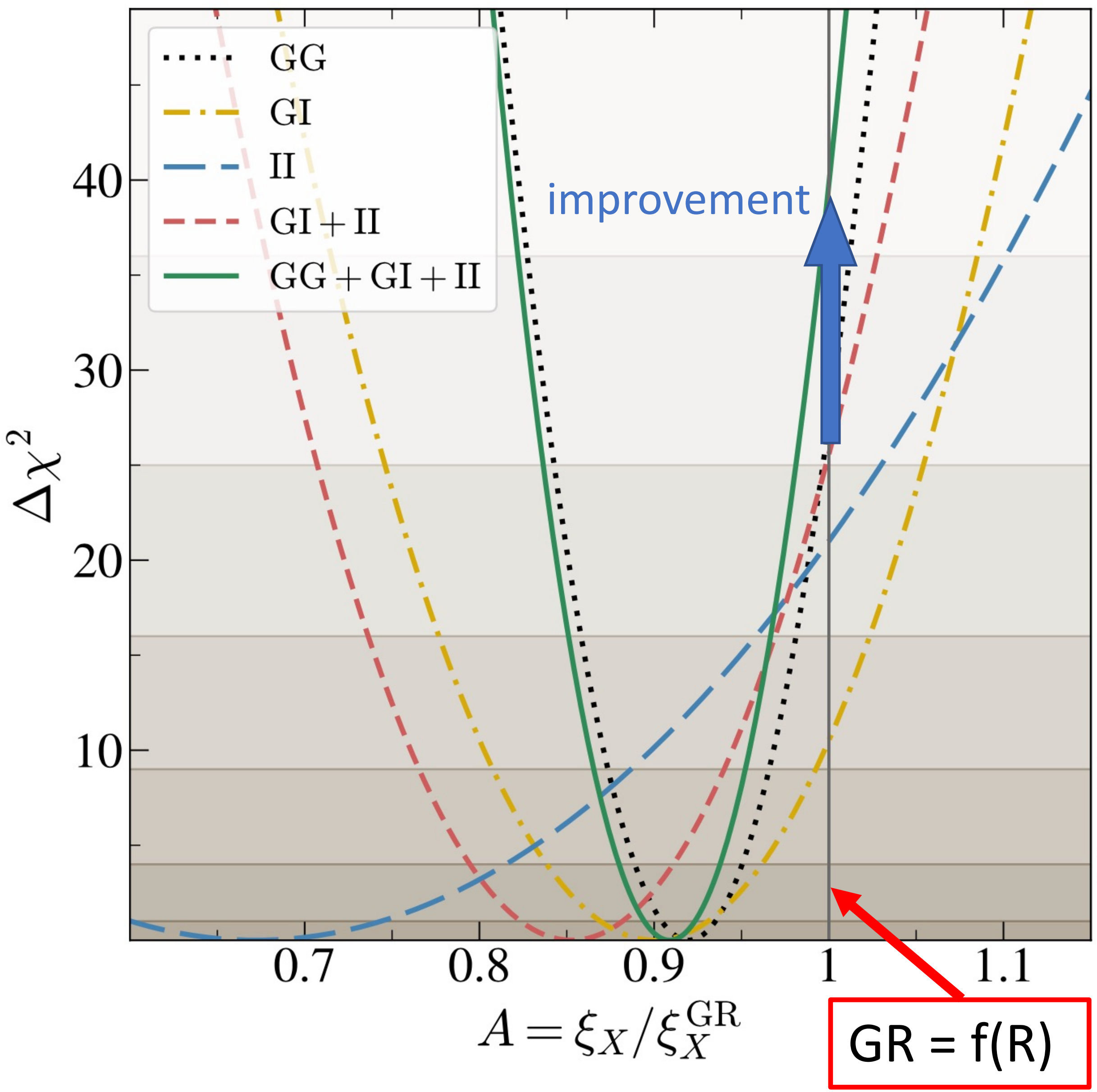


# *Distingusihability of different gravity models using galaxy shapes*

- The constraint gets ~20% tighter, but

- The analysis is too simple:
- The difference comes from not only *f*(z) but also *b*(z), $b_K$(z), *D*(z) and $\sigma_8$.
- Thus, the actual improvement is not so significant as obtained here.
- The *P*(*k*) shape is not used.
- The scale dependence is ignored.
- So the constraints can be tighter as well.

- The more realistic constraint will be given in the upcoming paper.



# 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.
- IA of galaxies is useful as a probe of gravity even beyond a consistency test of LCDM and GR.