YITP molecule-type workshop on

YITP-T-21-06

Galaxy shape statistics and cosmology

29th November — 3rd December, 2021

Panasonic auditorium at YITP

& Online

Yukawa Institute for Theoretical Physics

Started in 1952 after Prof. H. Yukawa got Nobel physics prize

Research institute at Kyoto University (~30 faculty members):

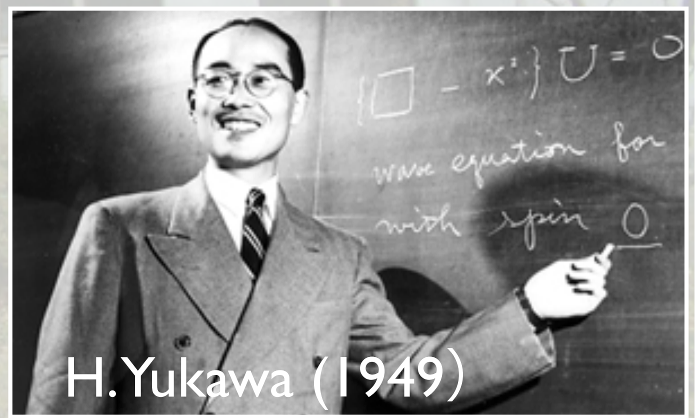
High energy physics, Nuclear physics, Astrophyics & cosmology, Condensed matter physics, Quantum information physics

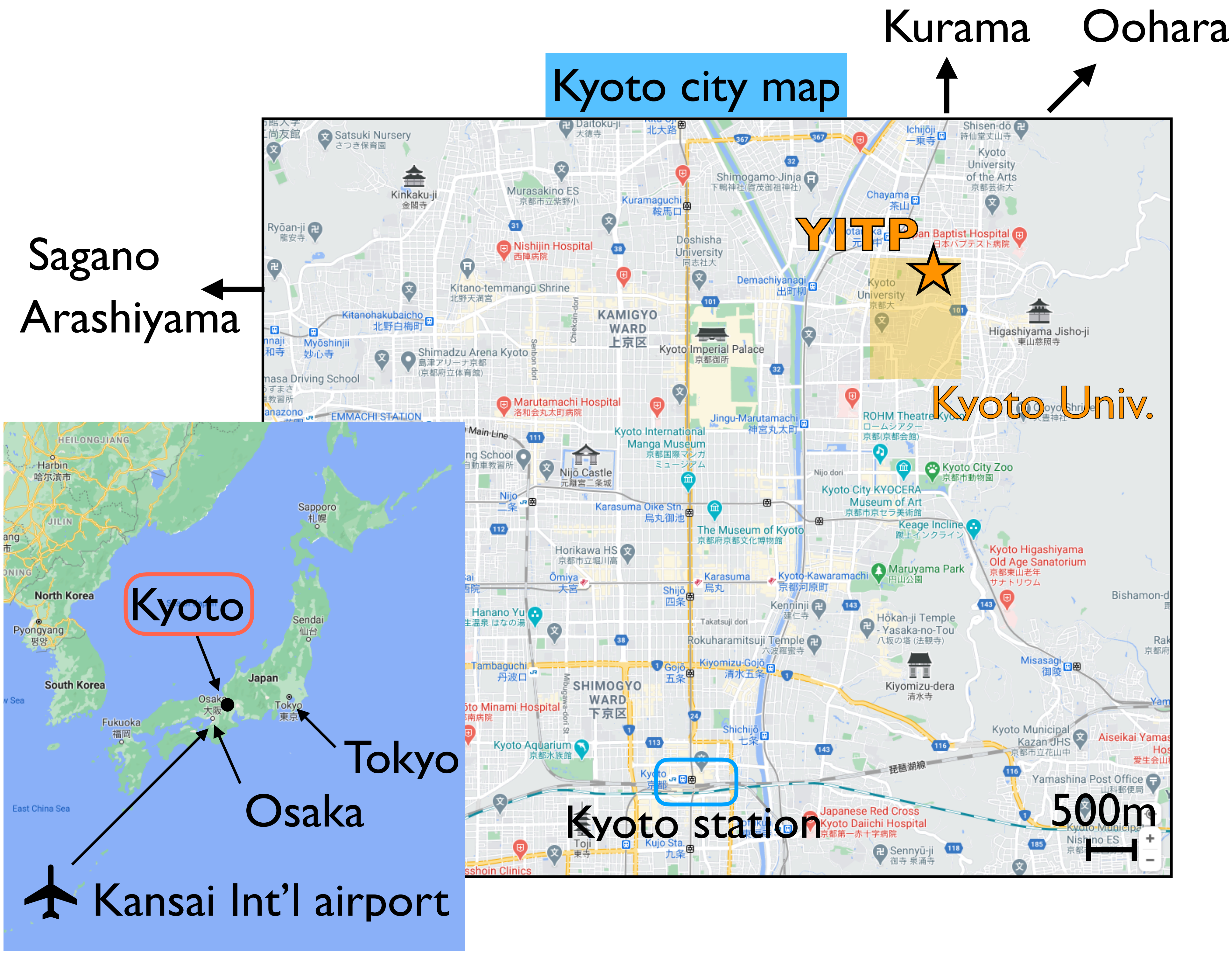
Promoting workshops/conferences on various topics related to fundamental physics and hosting domestic & overseas researchers


Panasonic auditorium


Research bldg.


Cherry blossom


H. Yukawa (1949)


Kyoto city map
Kurama
Oohara
Sagano
Arashiyama
YITP
Kyoto Univ.
Kyoto station
500m
Kyoto
Tokyo
Osaka
Kansai Int'l airport

Kinkaku-ji
Imperial Palace
Jisho-ji
YITP
Nijo castle
Kiyomizu-dera
Kyoto
Heian shrine
500m
North Korea
South Korea
Japan
Sendai
Pyongyang
KAMIGYO WARD 上京区
Kyoto Imperial Palace 京都御所
Nijō Castle
Kyoto University 京都大
Kinkaku-ji 金閣寺
Ryōan-ji 龍安寺
Nishijin Hospital 西陣病院
Marutamachi Hospital
Demachiyanagi 出町柳
Kyoto International Manga Museum 京都国際マンガミュージアム
Karasuma Oike Stn. 烏丸御池
The Museum of Kyoto 京都府京都文化博物館
Horikawa HS
Ōmiya 大宮
Karasuma 烏丸
Shijō 四条
Hanano Yu
Tambaguchi 丹波口
Gojō 五条
Kiyomizu-Gojō 清水五条
Rokuharamitsuji Temple 六波羅蜜寺
Kenninji 建仁寺
Maruyama Park 円山公園
Hōkan-ji Temple - Yasaka-no-Tou
ROHM Theatre Kyoto
Kyoto City KYOCERA Museum of Art
Keage Incline
Jingu-Marutamachi 神宮丸太町
Kuramaguchi 鞍馬口
Chayama 茶山
Ichijōji 一乗寺
SHIMOGYO WARD

Short history on this workshop

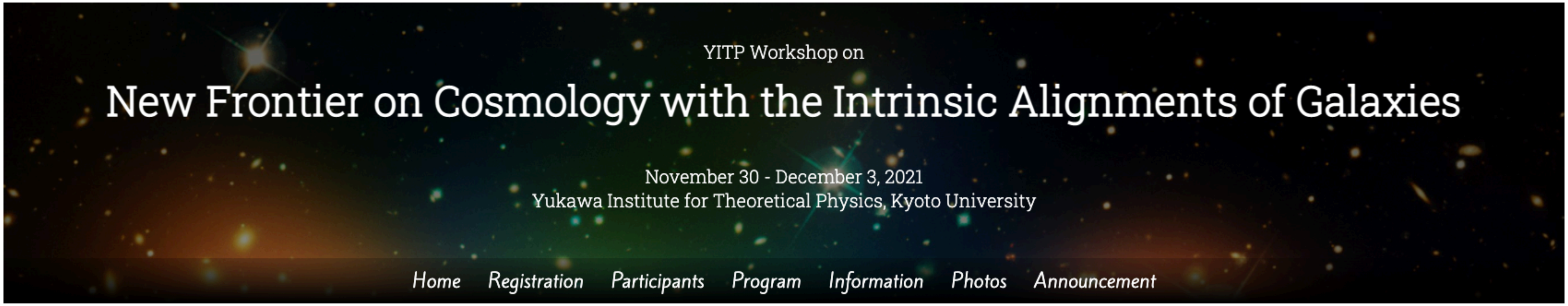
YITP international workshop on

In-person workshop

New Frontiers in Cosmology with the Intrinsic alignments of galaxies

Workshop page (hidden page)

Budget 1,750,000 JPY (≈15,000USD)



Overview

Mapping the large-scale structure of the universe with galaxy surveys is a key science driver for cosmology. It enables us to probe the late-time cosmic expansion, growth of structure, and even the primordial fluctuations. So far, the spatial distribution of galaxies has long been used as the major observable, ignoring the shapes and orientations of individual galaxies. While the orientations of distant galaxy images have been established as a promising tool to measure the weak gravitational lensing, intrinsic alignments (IAs) of galaxies are thought to be a contaminant to be removed in the cosmological data analysis. However, there is growing evidence that IAs are a good tracer of the gravitational tidal field, making themselves a unique channel to access the dynamics of the large-scale matter inhomogeneities. Therefore, it is expected that the use of IAs is beneficial, and with

Short history on this workshop

YITP international workshop on

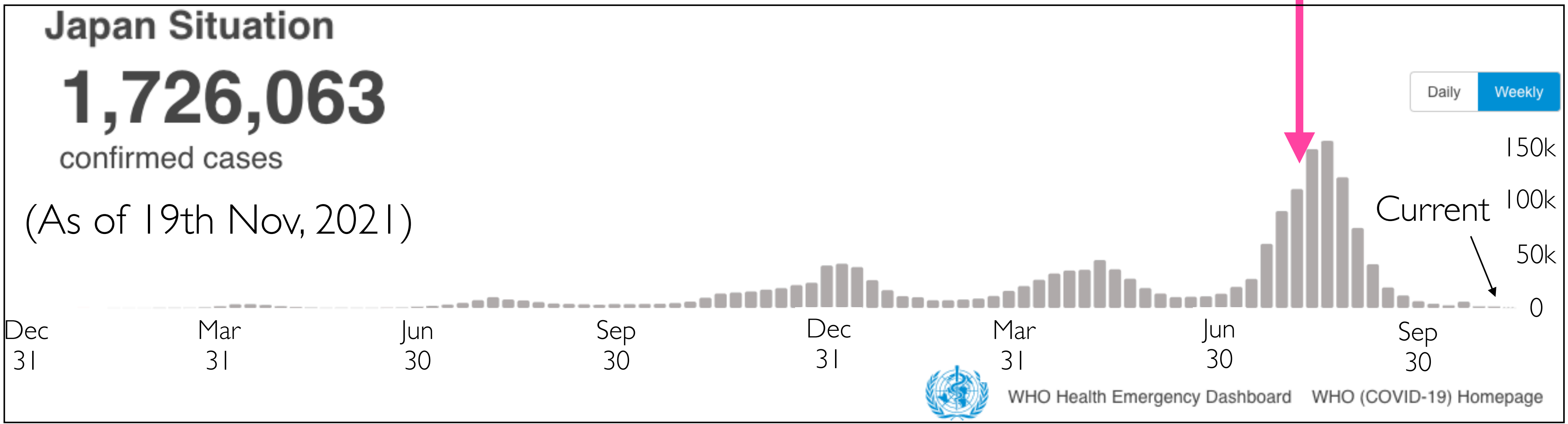
New Frontiers in Cosmology with the Intrinsic alignments of galaxies

Budget 1,750,000 JPY (≈15,000USD)

At an early August,

the covid-19 situation unfortunately got worse in Japan

Even now, quarantine measures are kept strengthened



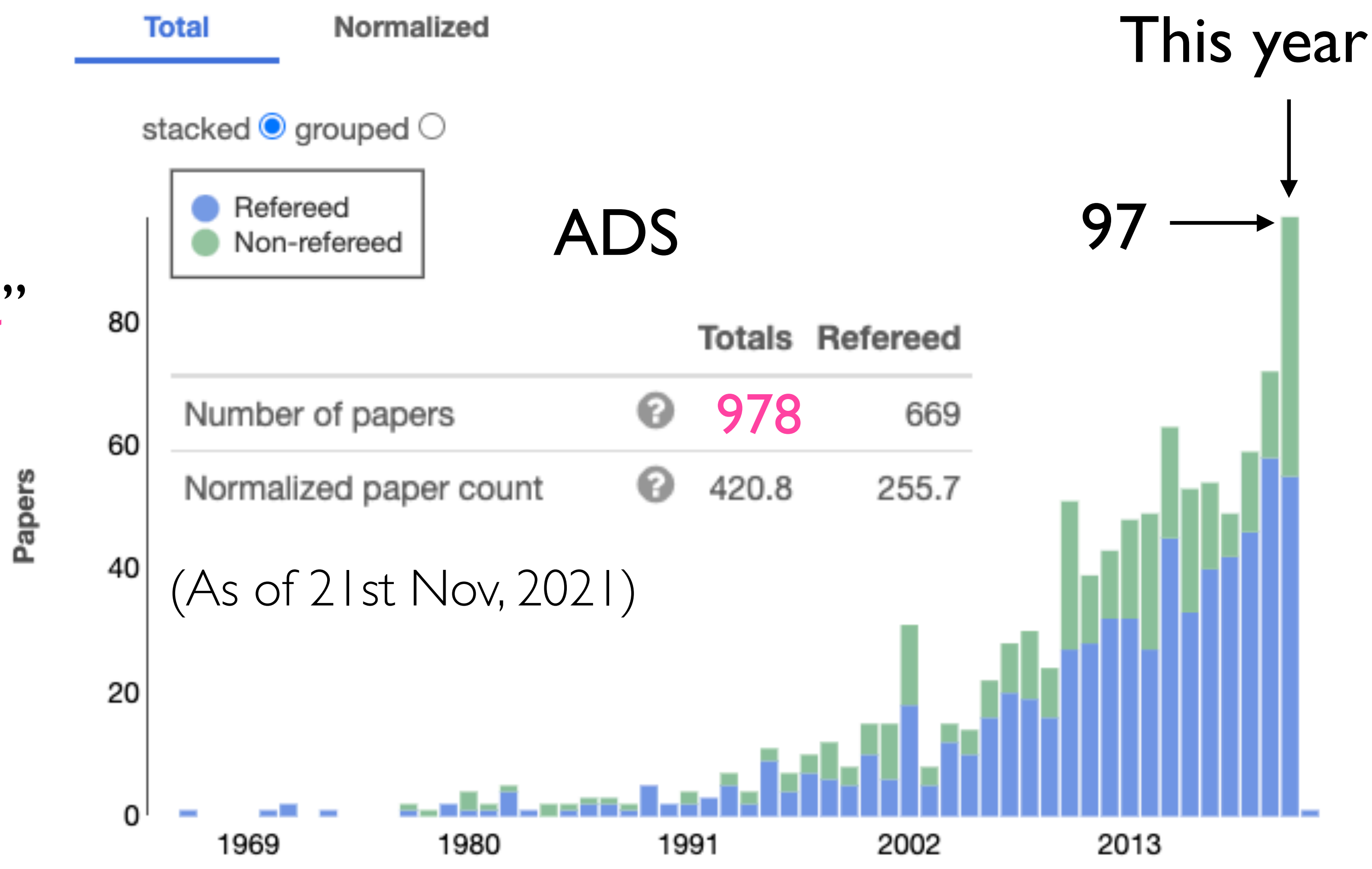
Short history on this workshop

Research activity on this subject is still expanding

No reason to stop discussions

Abstract/Keywords:

”intrinsic alignment”
"galaxy shape”
"galaxy spin"



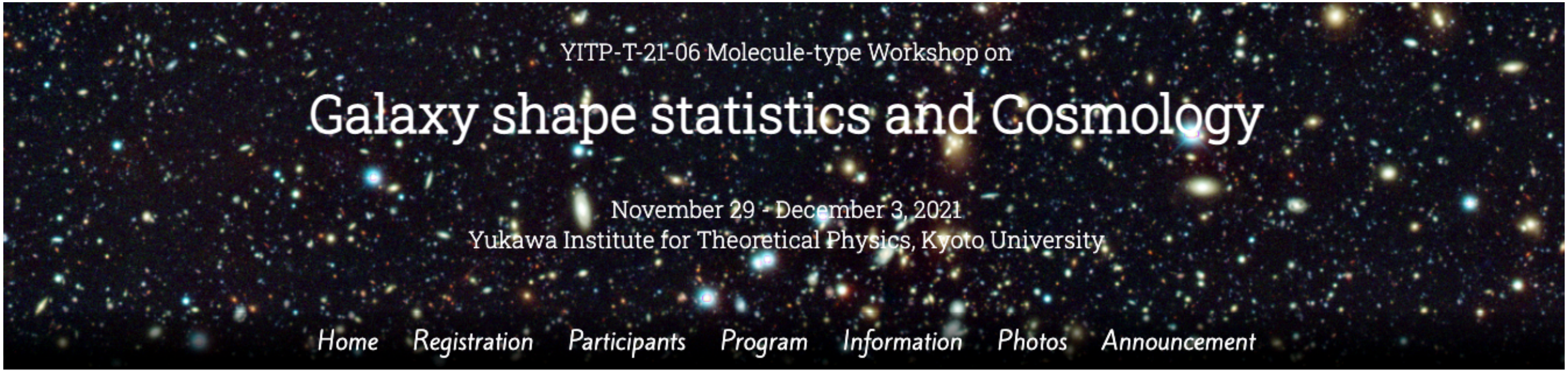
Short history on this workshop

Molecule-type workshop on

Galaxy shape statistics and cosmology

Budget 420,000 JPY

allowing on-site participation only for people in Japan



Overview

The aim of this workshop is to focus on the shape of galaxies as a potentially powerful cosmological probe, and to discuss future perspective on cosmology with large-scale structure surveys. The intrinsic galaxy shapes have been recently recognized as a good tracer of the gravitational tidal field, providing a unique

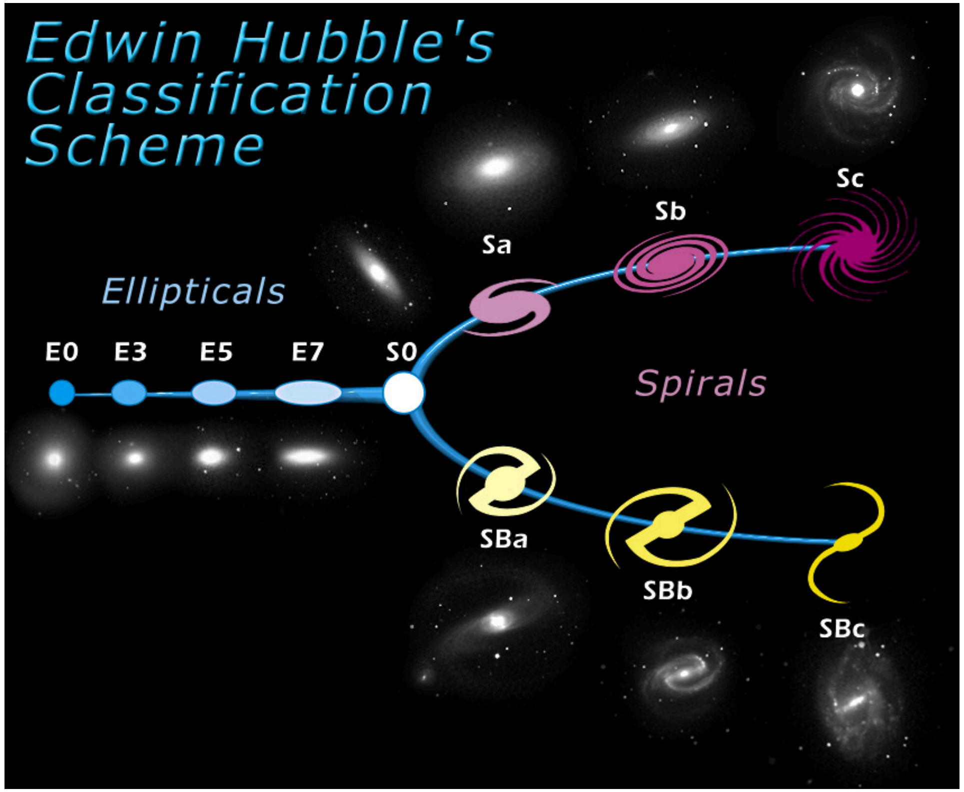
My personal

Overview and introduction

Galaxy shape & cosmology

Intrinsic shape of galaxies has been long discussed since the foundation of extragalactic astronomy

Hubble sequence



CLASSIFICATION OF NEBULAE

	Symbol	Example
I. Galactic nebulae:		
A. Planetaries	P	N.G.C. 7662
B. Diffuse	D	. . . .
1. Predominantly luminous	DL	N.G.C. 6618
2. Predominantly obscure	DO	Barnard 92
3. Conspicuously mixed	DLO	N.G.C. 7023
II. Extra-galactic nebulae:		
A. Regular:		
1. Elliptical (n=1, 2, ... , 7 indicates the ellipticity of the image without the decimal point)	En	N.G.C. 3379 E0 221 E2 4621 E5 2117 E7
2. Spirals:	Symbol	Example
a) Normal spirals	S	. . . .
(1) Early	Sa	N.G.C. 4594
(2) Intermediate	Sb	2841
(3) Late	Sc	5457
b) Barred spirals	SB	. . . .
(1) Early	SBa	N.G.C. 2859
(2) Intermediate	SBb	3351
(3) Late	SBc	7479
B. Irregular	Irr	N.G.C. 4449

Extra-galactic nebulae too faint to be classified are designated by the symbol "Q."

Hubble (1926)

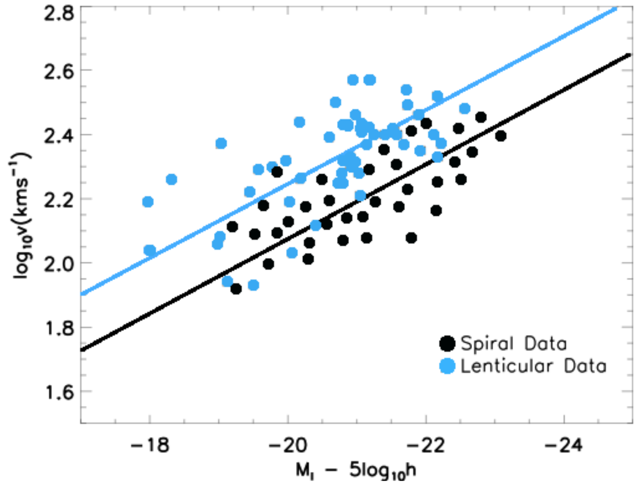
Galaxy shape & cosmology

Several empirical relations on galaxy shape have been found and used to estimate cosmological distance in cosmology

Spin

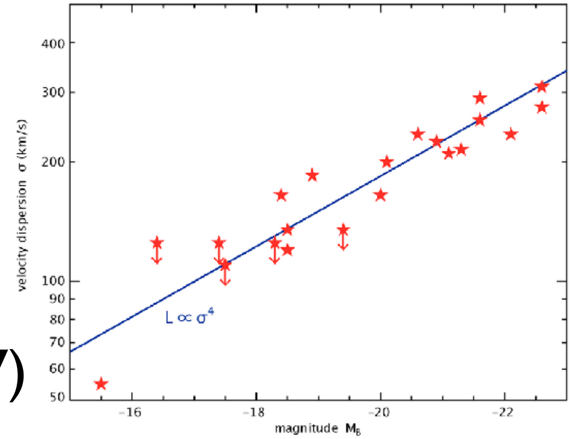
- **Tully-Fisher relation** (Tully & Fisher '77)

  Rotation velocity vs luminosity (magnitude) for spiral galaxies



- **Faber-Jackson relation** (Faber & Jackson'76)

  velocity dispersion vs luminosity (magnitude) for elliptical galaxies



➡ **Fundamental plane** (e.g., Djorgovski & Davis '87)

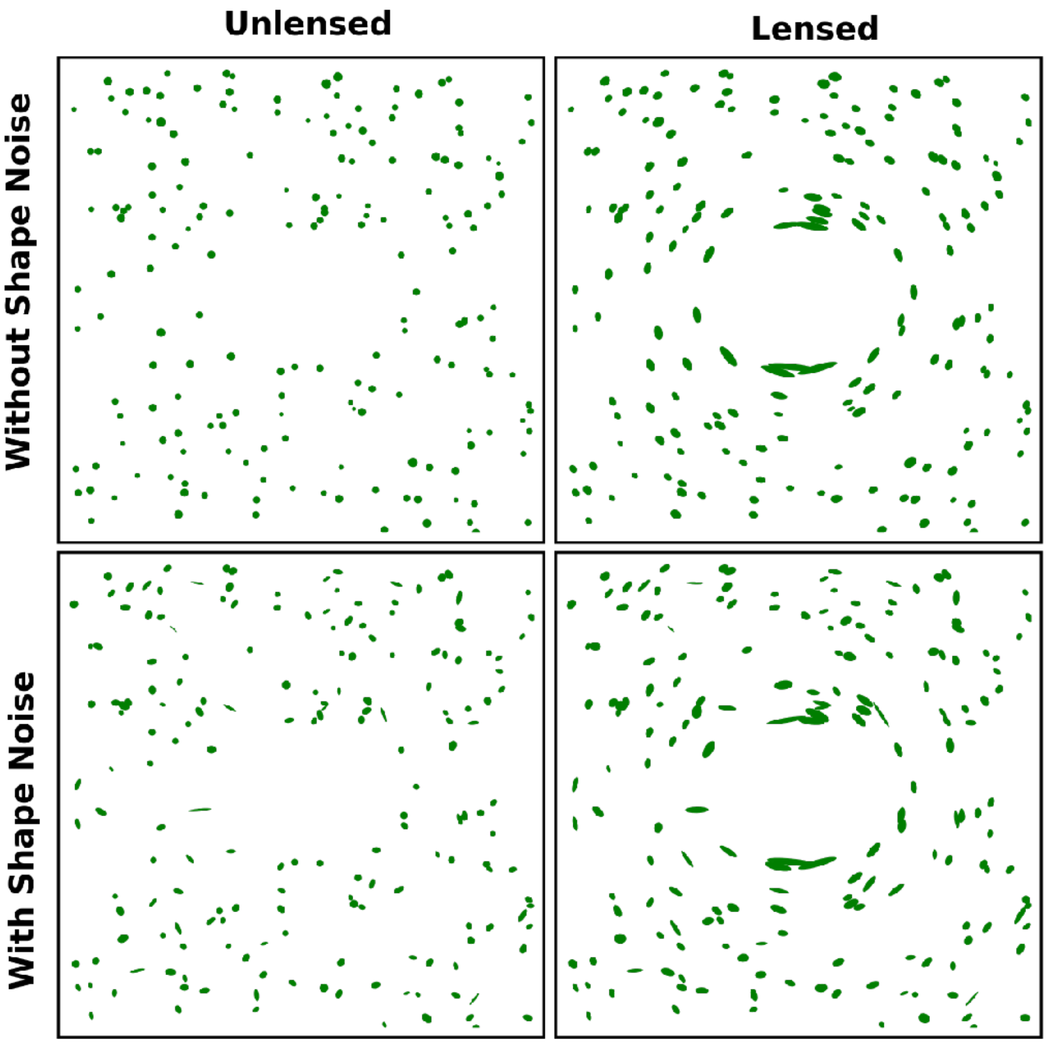
velocity dispersion — size — surface brightness

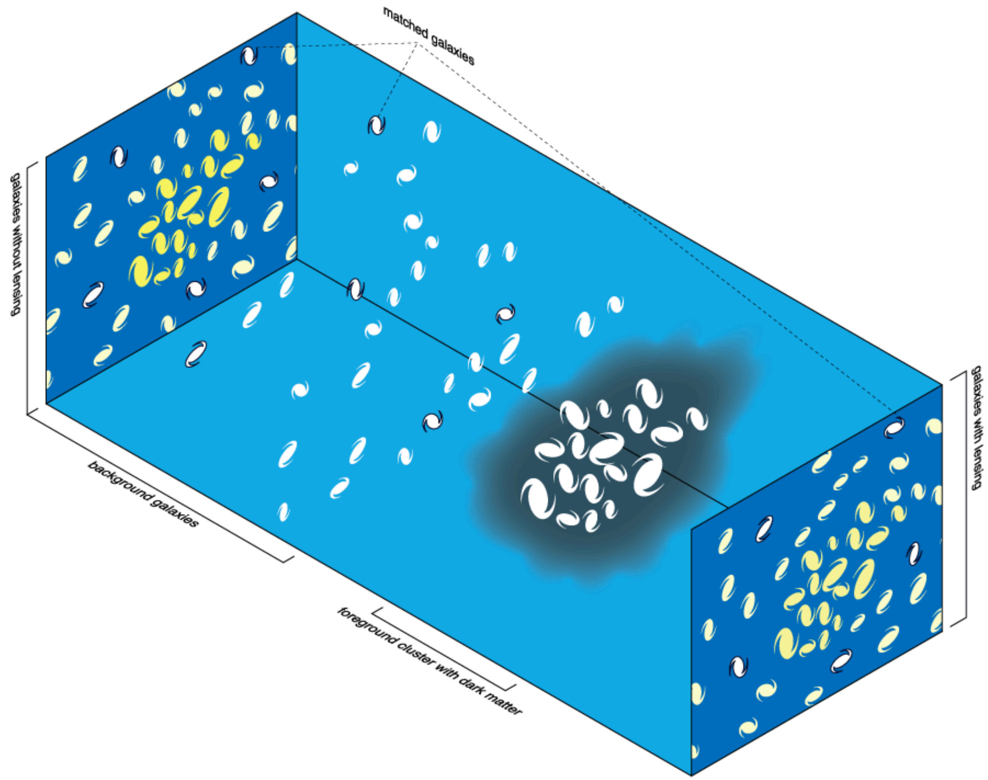
Size

(see e.g., Joachimi et al.'15 for spatial correlation)

Galaxy shape & cosmology

Shapes of distant galaxies as background light sources have now been extensively used to measure the weak lensing effect





Lensing induces spatial correlations between widely separated galaxy shapes

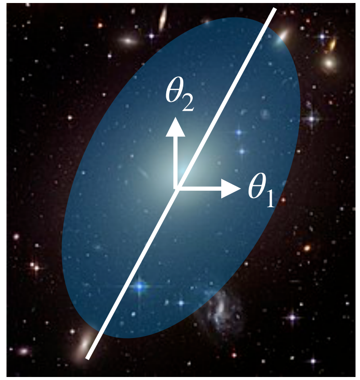
Galaxy shape & cosmology

Observation of weak lensing effect is made with measuring projected quadruple image of galaxies

Quadrupole moment of galaxy image

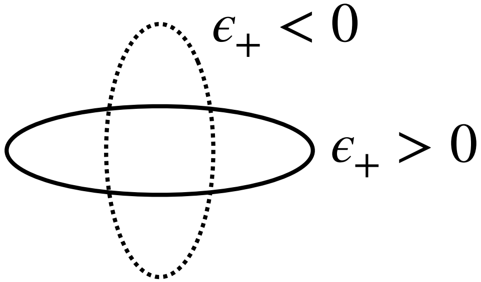
$$q_{ij}^{\rm obs} \equiv \frac{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})\, \theta_i \theta_j}{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})} \quad (i, j = 1{,}2)$$

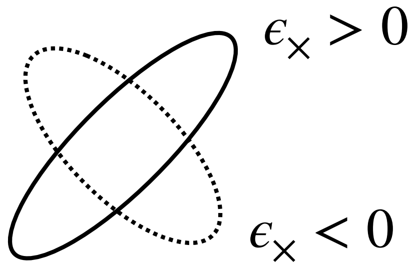
intensity

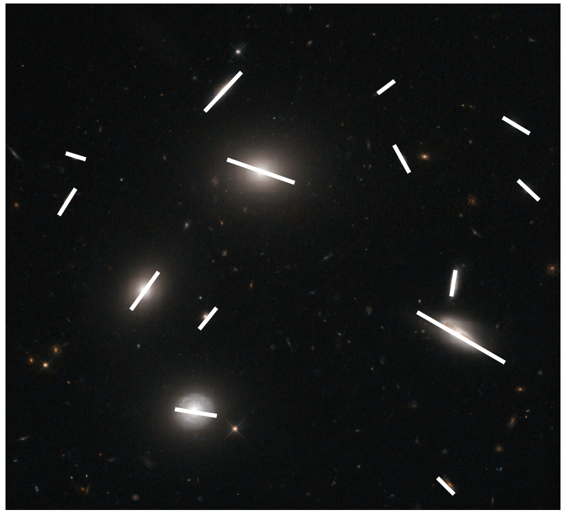


Ellipticity：

$$\epsilon_+ \equiv \frac{q_{11}^{\rm obs} - q_{22}^{\rm obs}}{q_{11}^{\rm obs} + q_{22}^{\rm obs}}, \qquad \epsilon_\times \equiv \frac{2q_{12}^{\rm obs}}{q_{11}^{\rm obs} + q_{22}^{\rm obs}}$$







Galaxy shape & cosmology

Non-zero ellipticity of distant galaxy consists of two contributions:

$$\epsilon_a \simeq \gamma_a^{\mathrm{I}} + 2\, g_a \qquad (a = + \text{ or } \times)$$

Intrinsic alignment (IA)

Lensing

$$g_a \equiv \frac{\gamma_a}{1-\kappa} \; (\ll 1)$$

Reduced shear

Lensing induces non-zero spatial correlation

⟶ A clue to detect lensing signal

However,

IA can have non-zero spatial correlation

(contaminant of lensing measurement)

Early studies on IA

Since the detection of weak lensing (cosmic shear) signals on 2000's, modeling and measuring IA have been a focused issue

Croft & Metzler ('00)

Heavens, Refregier & Heymans ('00)

Lee & Pen ('00, '01, '02, '08)

Lee, Pen & Seljak ('00)

Catelan, Kamionkowski & Blandford ('00)

Crittenden, Natarajan, Pen & Theuns ('01)

Brown, Taylor, Hambly & Dye ('02)

Jing ('02)

Hirata & Seljak ('04)

Heymans, Brown, Heavens, Meisenheimer, Taylor & Wolf ('04)

Incomplete

See

Troxel & Ishak, Phys.Rep. 558, 1 ('15)

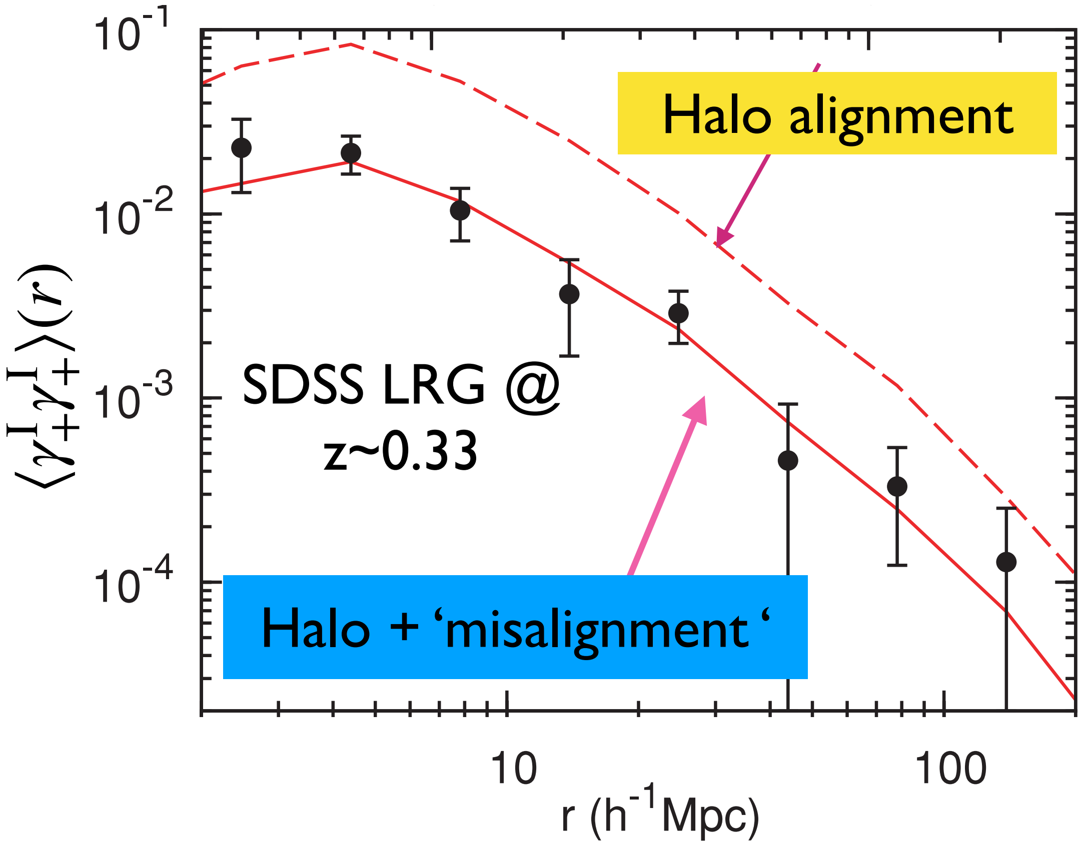
Joachimi et al. Space Sci. Rev. 193, 1 ('15)

For extensive reviews

3D intrinsic alignment (IA) correlation

Using the information on angular position (2D) + redshirt + shape

3D spatial correlation of luminous red galaxy (LRG) samples



Early-type

$\langle \gamma_+^{\rm I} \gamma_+^{\rm I} \rangle$ (II correlation)

Okumura, Jing & Li (’09)

Measured result resembles the halo ellipticity correlation in N-body simulations (solid & dashed) → IA of LRG traces *tidal fields of LSS*

Linear alignment model

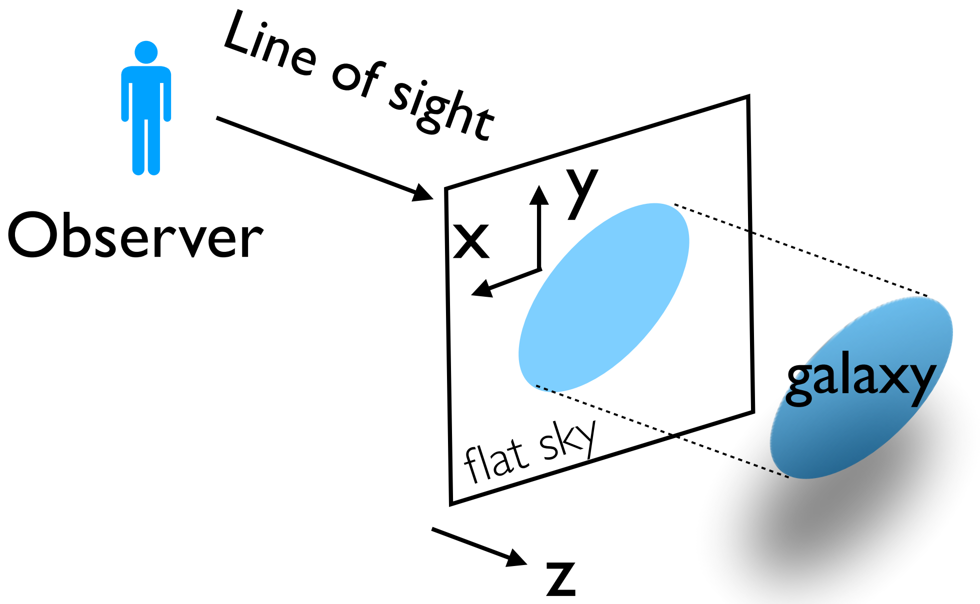
At first order,

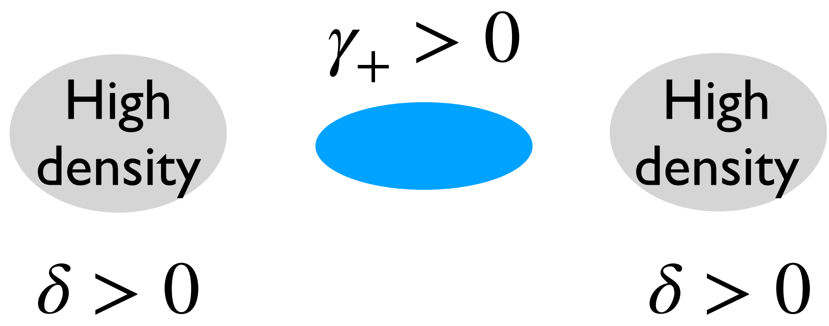
Suppose that the observed IA is *linearly* proportional to the tidal field of LSS

<u>A model for tidally-induced IA</u> (Catelan et al. '01, Hirata & Seljak '04)

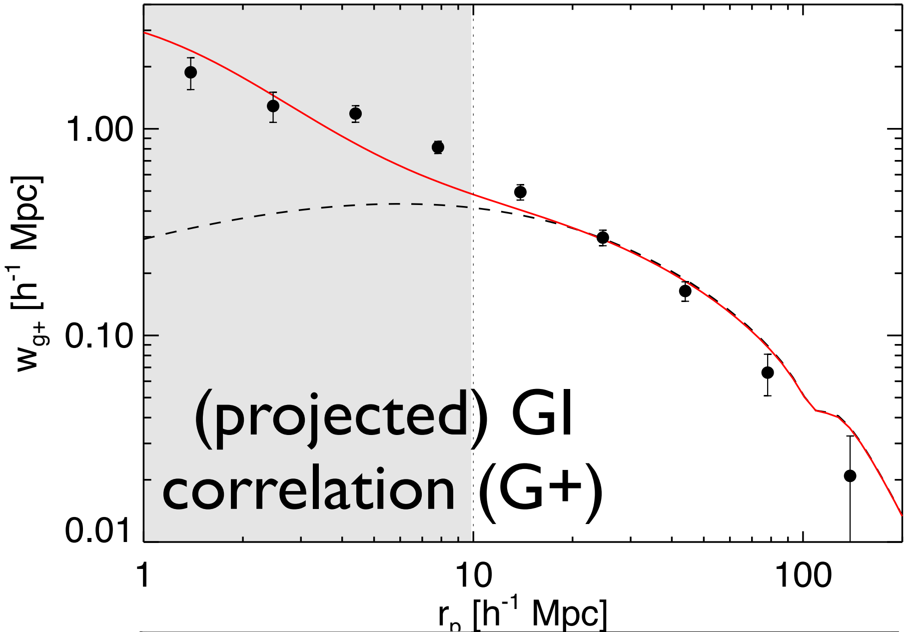
$$(\gamma_{+}^{\rm I},\, \gamma_{\times}^{\rm I}) \;\propto\; -\,(\nabla_x^2 - \nabla_y^2,\; 2\,\nabla_x \nabla_y)\,\Phi$$

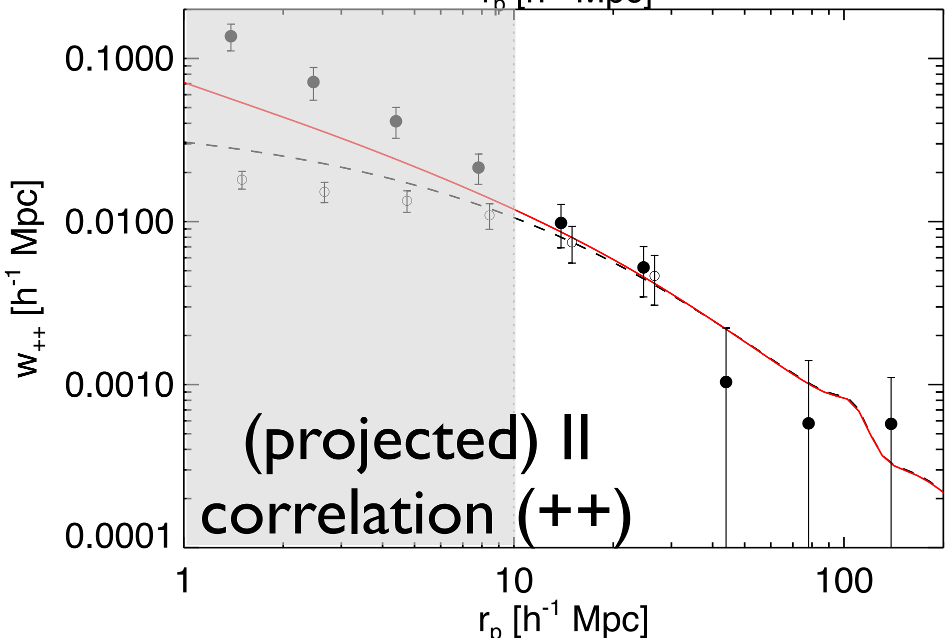
Gravitational potential





Testing LA model against observations





Blazek, McQuinn & Seljak ('11)

- Luminous red galaxies (LRGs) from SDSS DR6

Okumura, Jing & Li ('09);
Okumura & Jing ('09)

- 83,773 galaxies at $0.16<z<0.47$

Good agreement at $r_p>10\ h^{-1}$Mpc

LA model works well to describe IA of LRG at large scales

Anisotropic IA correlations

Interestingly,

Okumura & AT ('20)

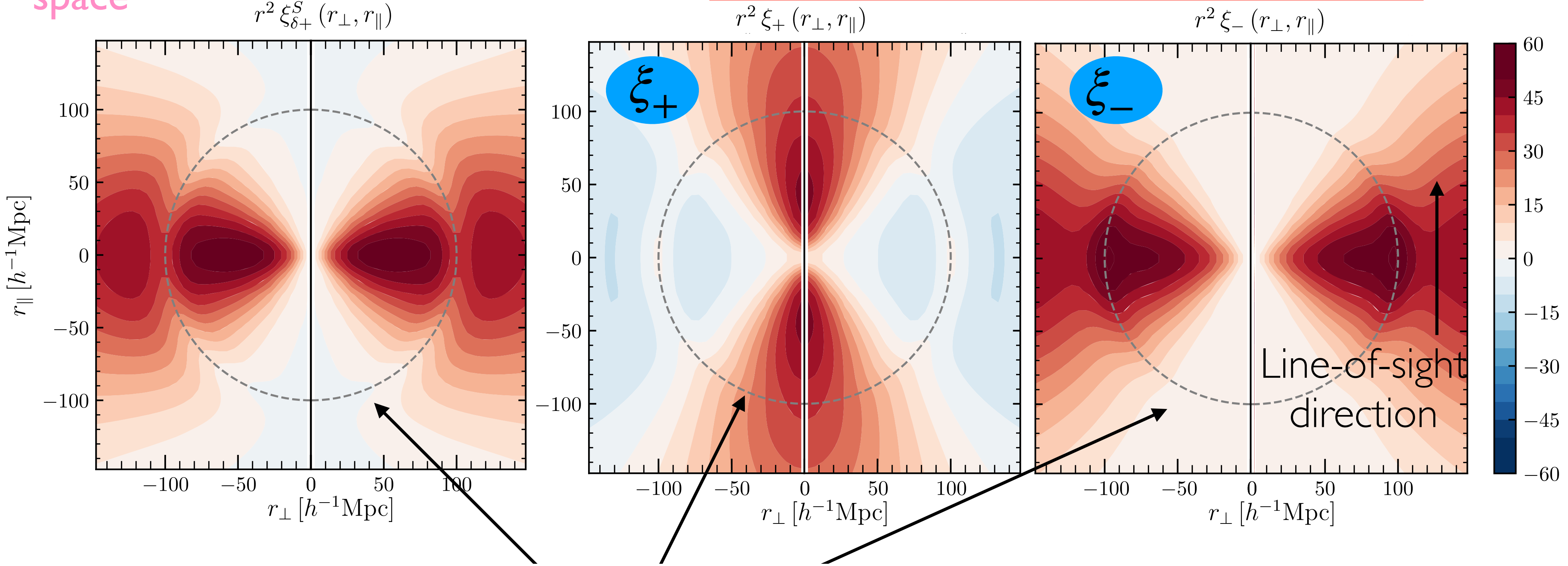
(see also, Croft & Metzler '00)

LA model predicts characteristic anisotropies in 3D correlations (described as function of $(r_\perp, r_\parallel)$)

Redshift space

GI correlation

II correlation $(\xi_\pm \equiv \xi_{++} \pm \xi_{\times\times})$



Baryon acoustic oscillation feature (appears as 'bump')

$r_\parallel$: line-of-sight separation

Analytical formulas

Okumura & AT ('20)

GI correlation

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

Real space

$\mu \equiv r_{\|}/r$

ϕ :azimuthal angle in $\vec{r}_{\perp}$

$$\xi^{S}_{g+}(\mathbf{r}) = \xi^{R}_{g+}(\mathbf{r}) + \frac{1}{7}\widetilde{C}_1 f \cos(2\phi)\left(1-\mu^2\right)\left[\Xi^{(0)}_{\delta\Theta,2}(r) - \left(7\mu^2-1\right)\Xi^{(0)}_{\delta\Theta,4}(r)\right]$$

Linear growth factor

Redshift space

II correlation

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

$$\xi_{-}(\mathbf{r}) = \widetilde{C}_1^2 \cos(4\phi)\left(1-\mu^2\right)^2\,\Xi^{(0)}_{\delta\delta,4}(r)$$

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

Expressions are identical in both real & redshift space

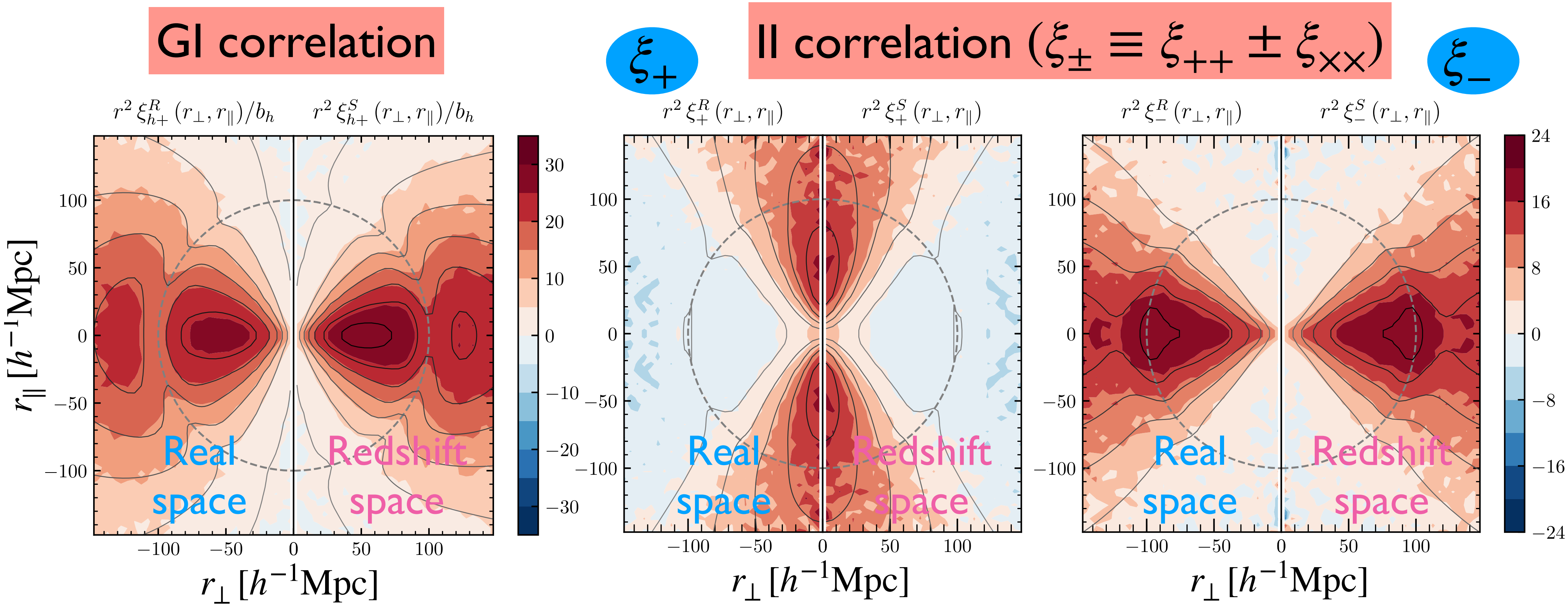
$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^\infty \frac{k^{2-n}\,\mathrm{d}k}{2\pi^2} P_{XY}(k)\, j_\ell(kr)$$

$\mathcal{P}_\ell(\mu)$:Legendre polynomials

Testing anisotropic IA correlations

Okumura, AT & Nishimichi ('20)

GI & II correlations measured @ z=0.3 from (sub-)halo catalog in N-body simulations



$M_\mathrm{h} \geq 10^{13}\,h^{-1}\,M_\odot$

Solid contours: LA model prediction

Testing anisotropic IA correlations

Okumura, AT & Nishimichi ('20)

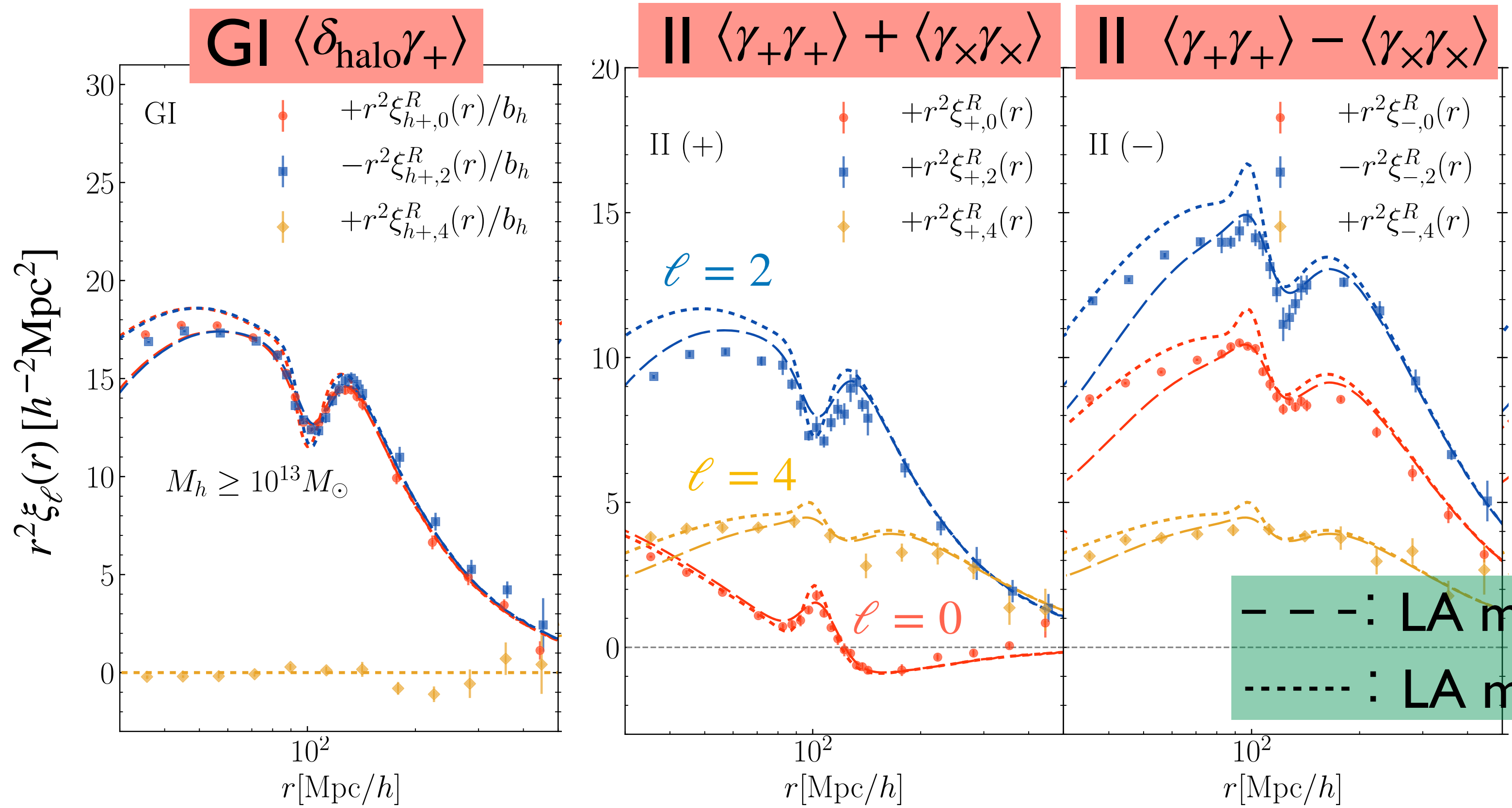
(for Fourier-space analysis, see Kurita et al. ('20) & his talk)

Using halos with $M>10^{13}\,M_{sun}/h$,

measured IA correlations are compared with LA model predictions:

Linear Alignment (LA) model $\gamma_+ \propto (\partial_x^2 - \partial_y^2)\,\Psi, \quad \gamma_\times \propto 2\partial_x\partial_y\,\Psi$

Ψ : Newton potential



Real space

Multipole expansion

$$\xi(\boldsymbol{r}) = \Sigma_\ell\, \xi_\ell(r) \times \mathscr{P}_\ell(r_\parallel/r)$$

Legendre polynomials

- - - : LA model w/ nonlinear P(k)

------ : LA model w/ linear P(k)

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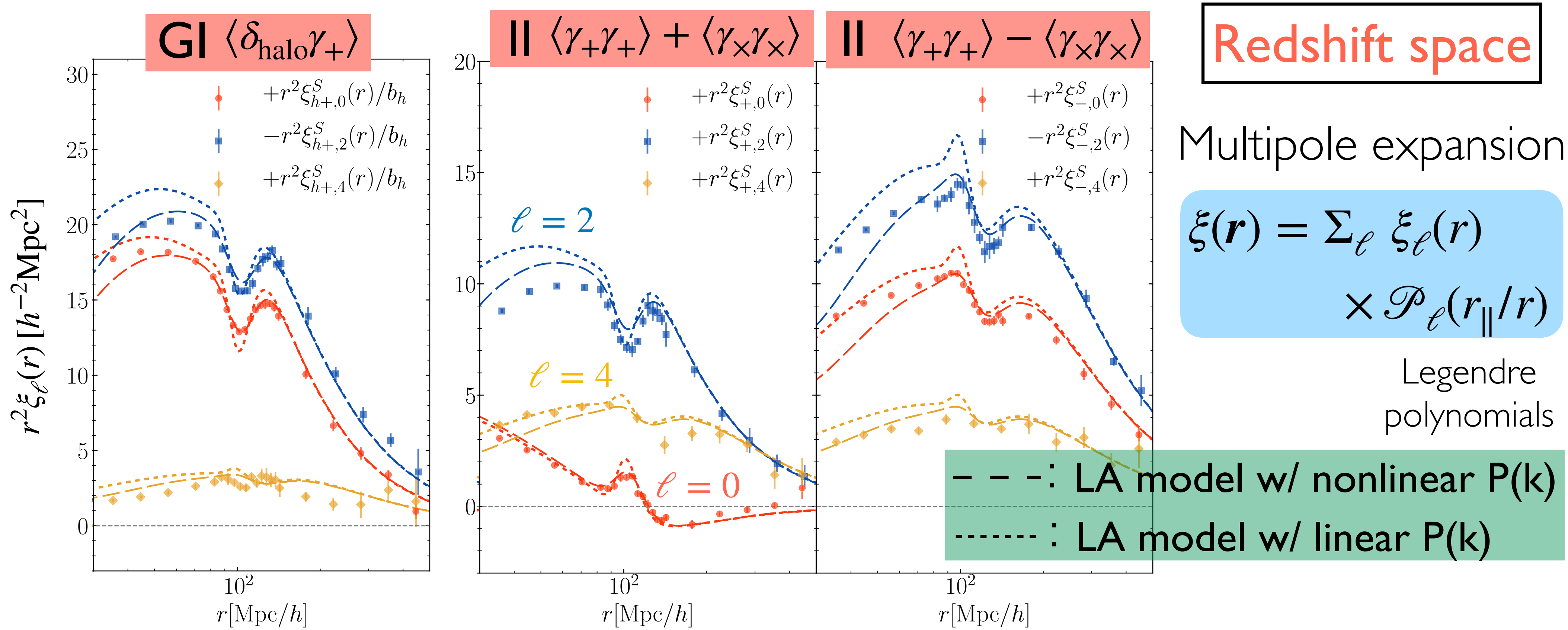


Redshift space

Multipole expansion

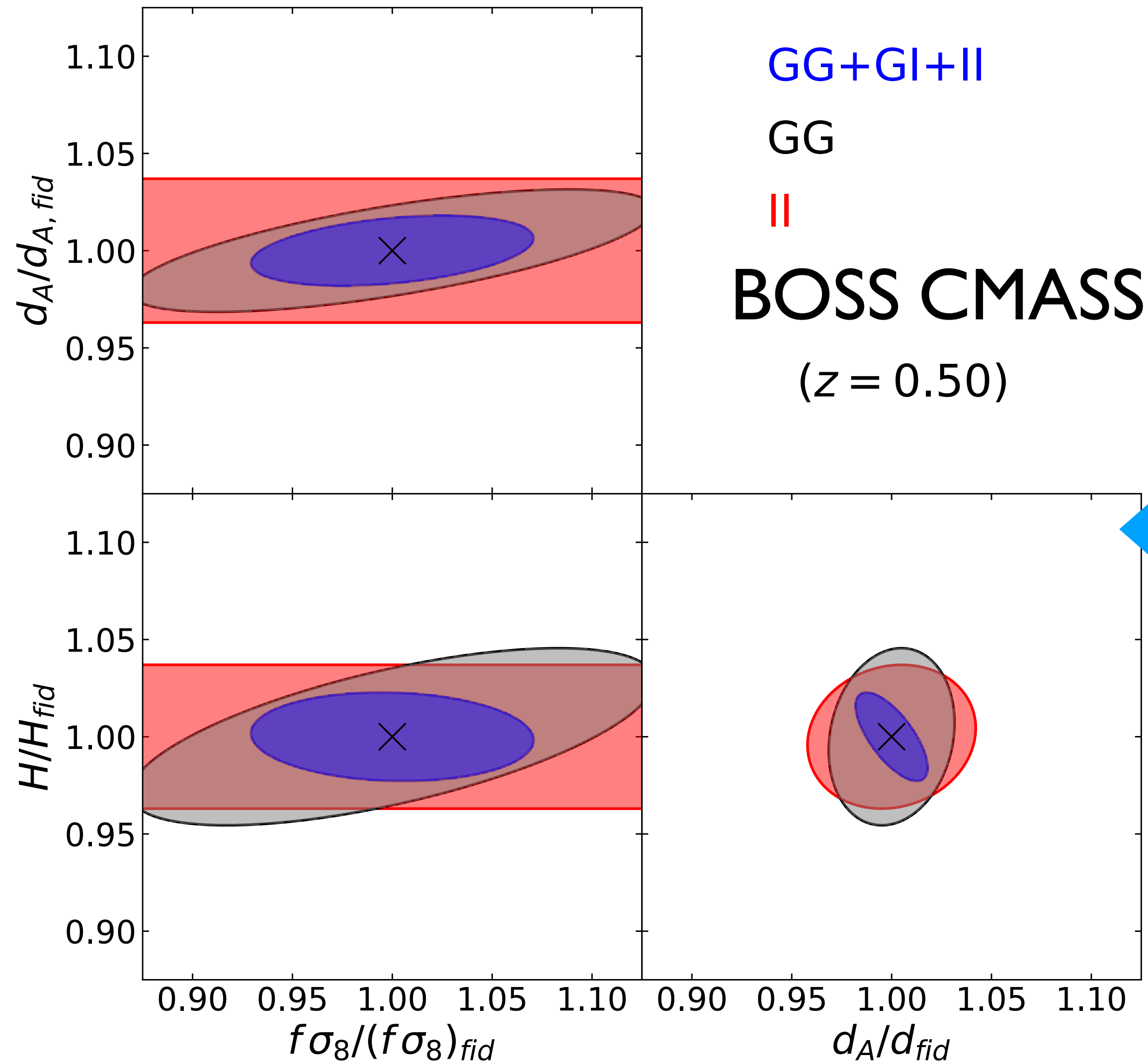
$$\xi(\boldsymbol{r}) = \Sigma_\ell\ \xi_\ell(r) \times \mathscr{P}_\ell(r_\parallel/r)$$

Legendre polynomials

Geometric & dynamical constraints

AT & Okumura ('20)

RSD & BAO can be measured from GI & II correlations → $\{d_\mathrm{A}(z_i), H(z_i), f\sigma_8(z_i)\}$



GG : galaxy clustering

II : IA statistics

GG+GI+II : both combined

Fisher matrix analysis

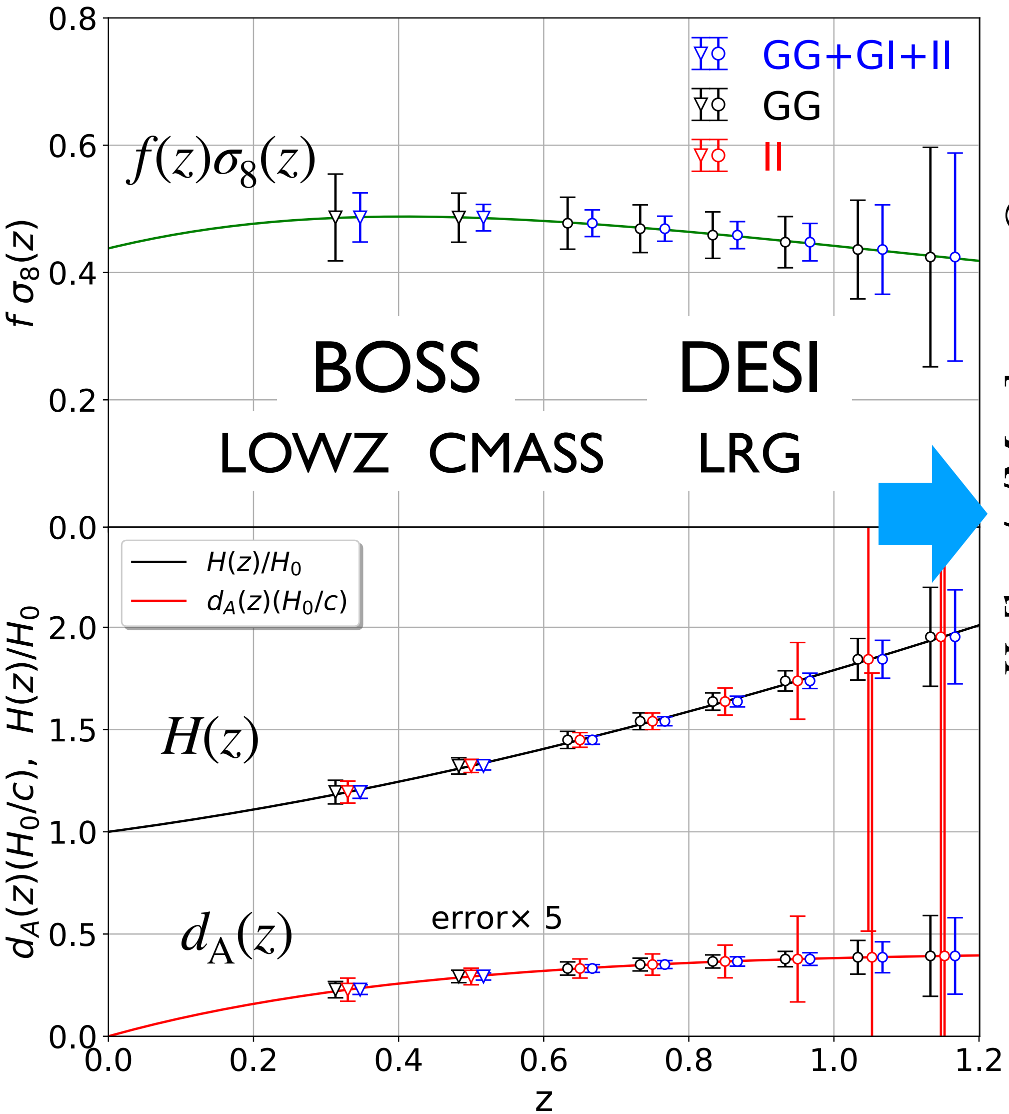
Combing conventional GG with IA correlations can improve constraints !

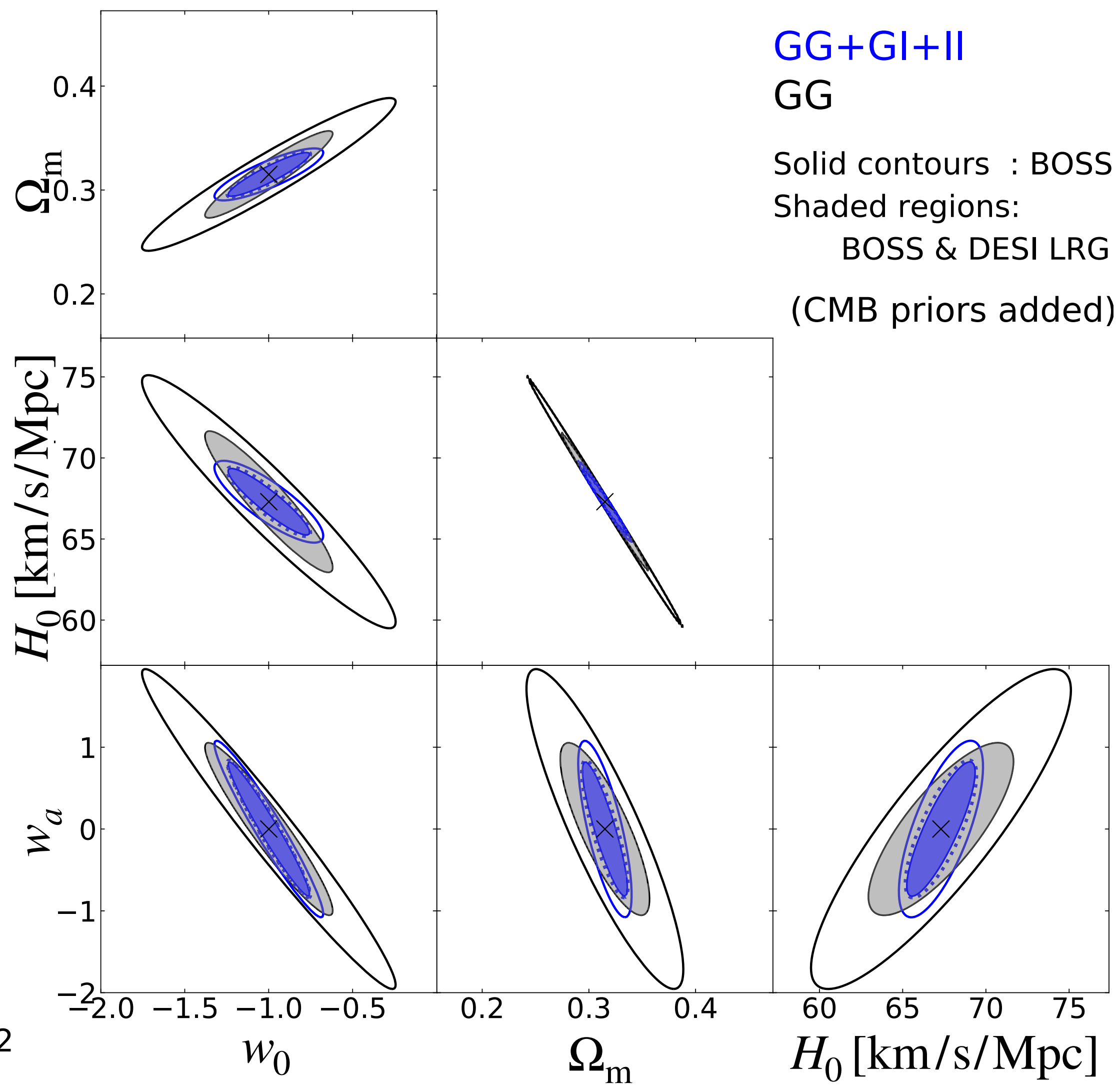
(with an optimistic IA amplitude)

Fisher forecast from IA statistics

AT & Okumura ('20)

Geometric & dynamical constraints at 0.3<z<1.2 (from BOSS & DESI) → flat $w_0 w_a$ CDM model





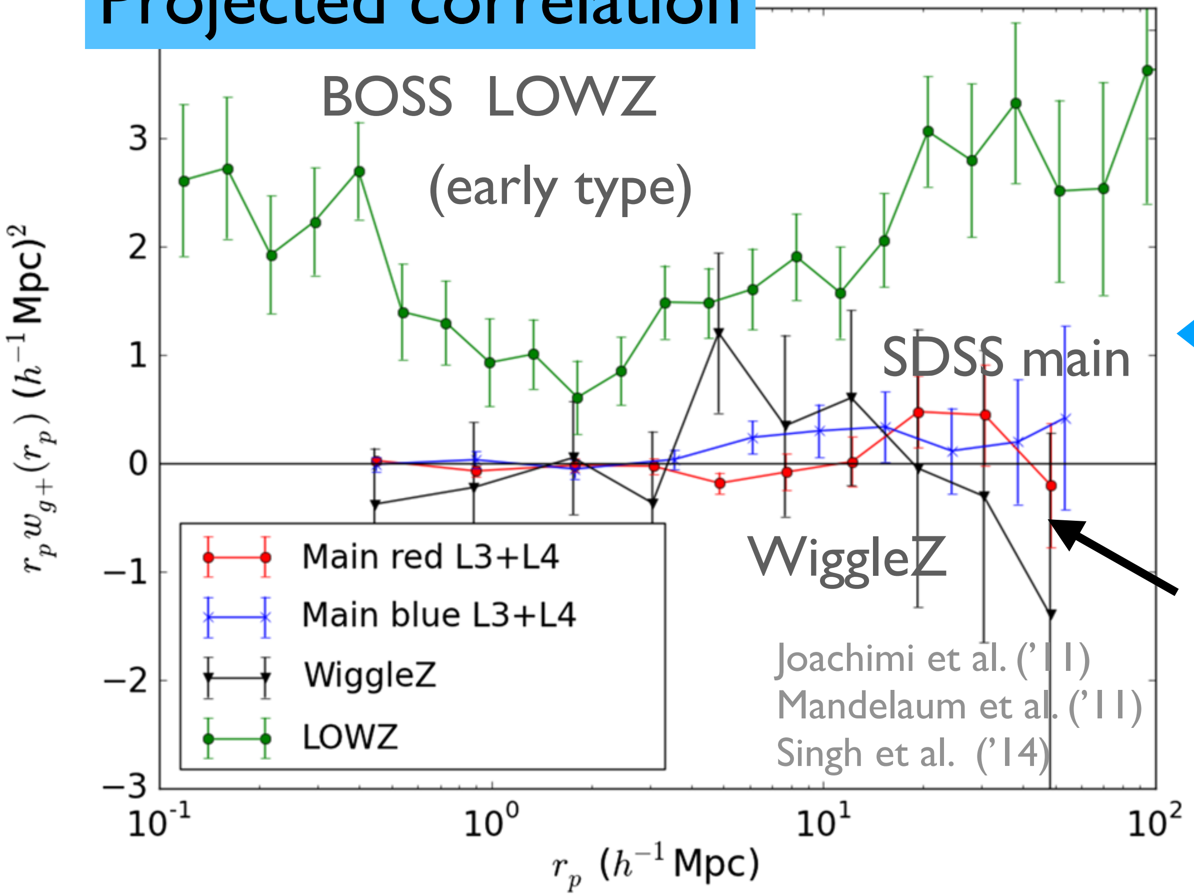
Caveats

Behaviors of IA correlations crucially depend on galaxy type

(So far we have focused on early-type galaxies)

→ Talk by J. Blazek based on lensing obs.

Projected correlation



Galaxy-IA correlation
(GI correlation)

$\langle \delta_{\rm g} \gamma_+^{\rm I} \rangle$

No clear correlation signal is detected for late-type galaxies

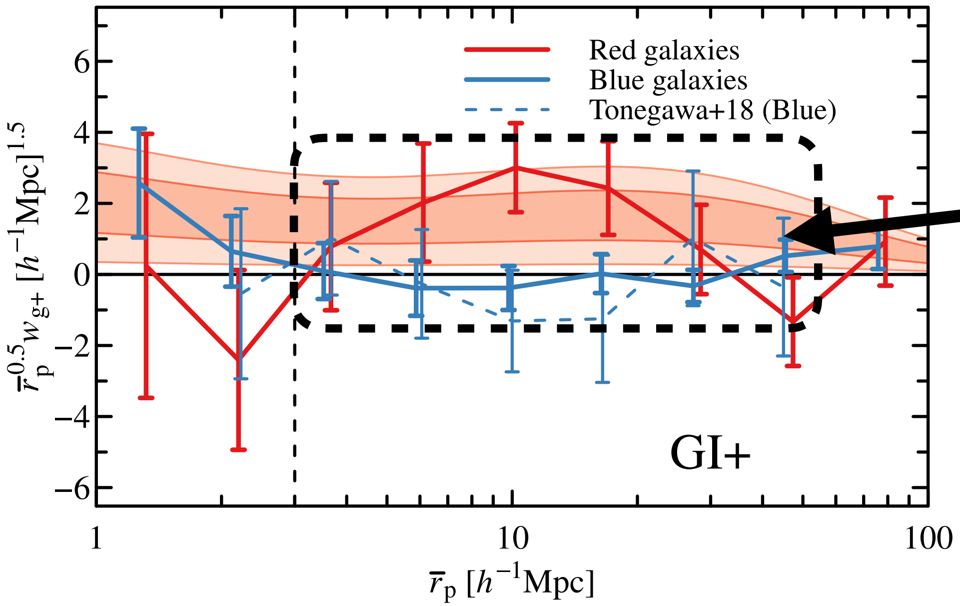
Also, no clear high-z signal has been so far detected

Joachimi et al. ('15)

But see Tonegawa & Okumura ('21) Shi et al. ('21)

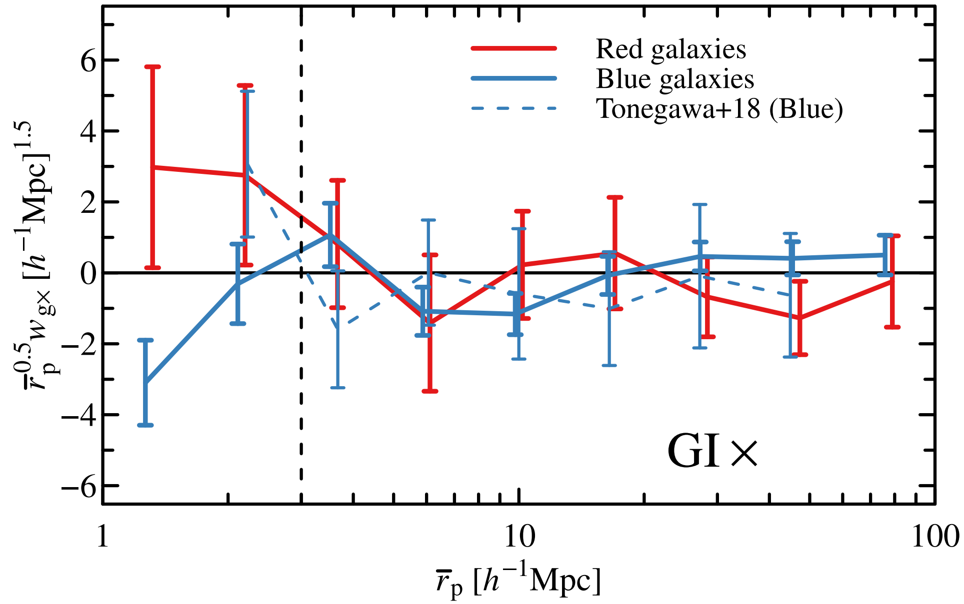
First evidence of IA signal at z>1

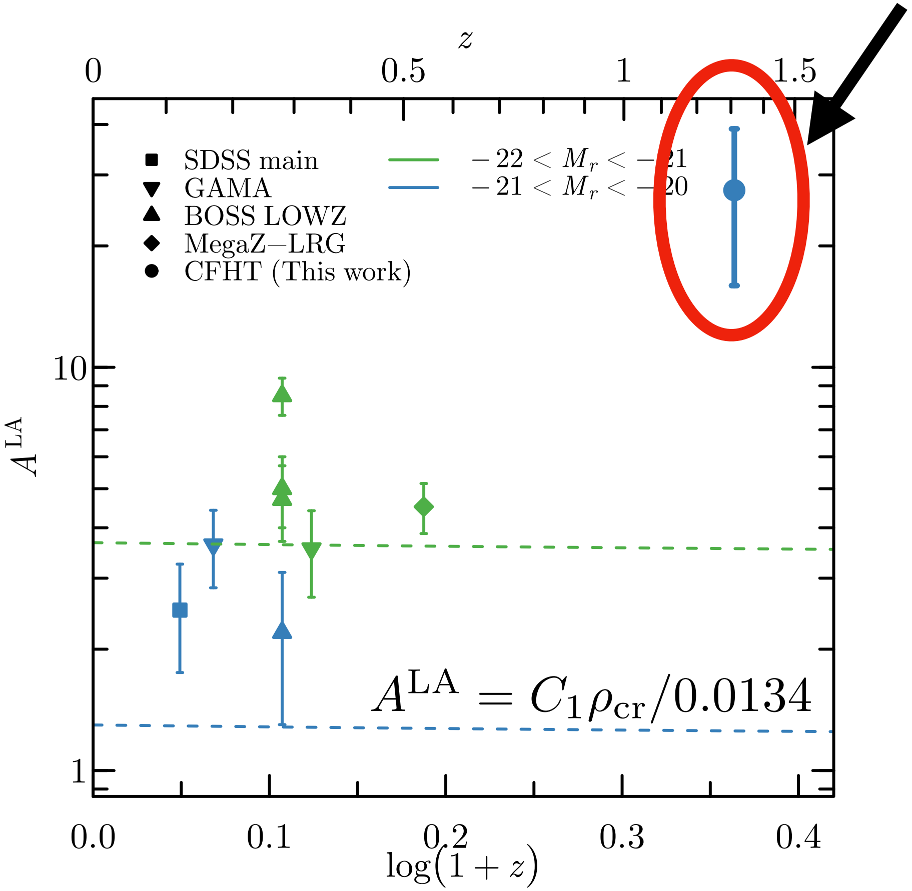
Tonegawa & Okumura ('21)
arXiv:2109.14297



Non-zero signal for GI correlation

Fastsound (G) x CFHT lens (I)





IA cosmology from star-forming galaxies

Shi, Osato, Kurita & Takada ('21)

→ Talk by J. Shi & K. Osato

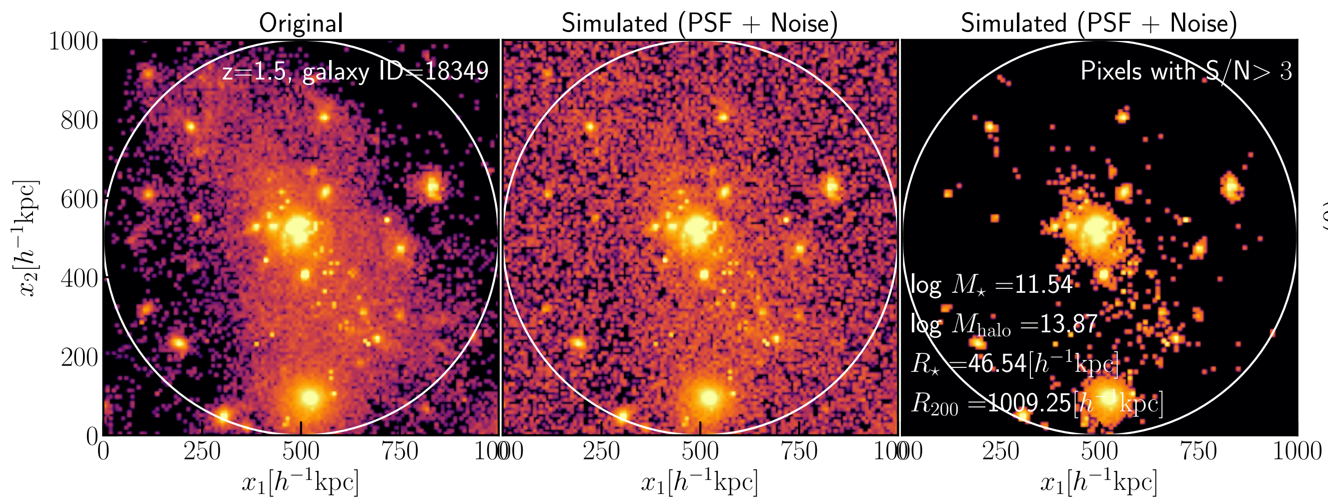
A clever way to enhance IA signals from non early-type galaxies:

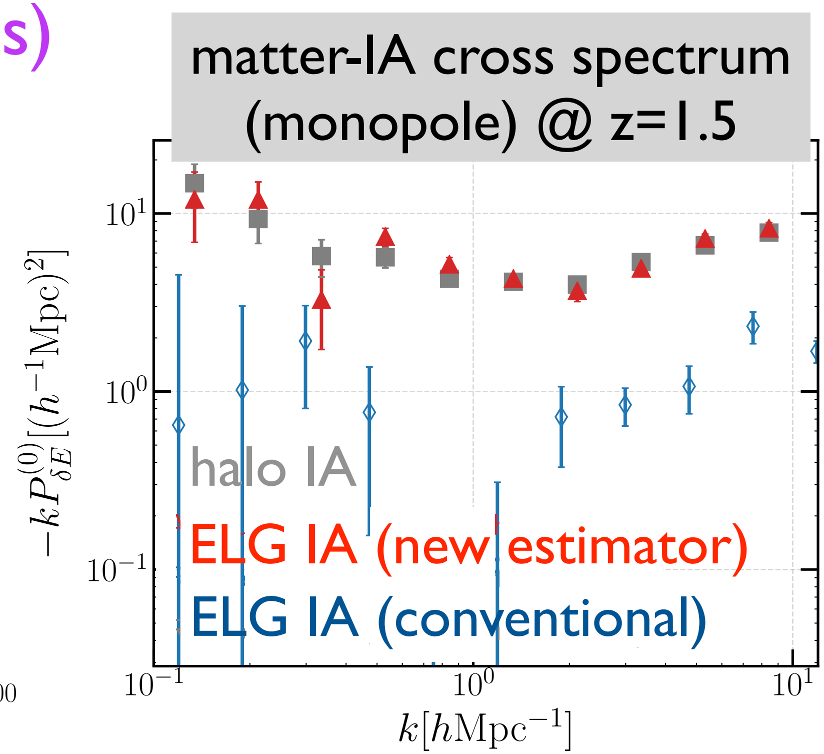
(New) aperture shape estimator

$$I_{ij}^{\rm ap} = \frac{\sum_{n;(S/N)_{\rm pix}>3; r_n^{\rm 2D}\le 500h^{-1}{\rm kpc}} f_n x_{ni} x_{nj}}{\sum_{n;(S/N)_{\rm pix}>3; r_n^{\rm 2D}\le 500h^{-1}{\rm kpc}} f_n}$$

Image simulations indicate that Subaru HSC/PFS can detect a strong IA signal from emission line galaxies (ELGs)

= "*star-forming*" galaxies





Extending cosmological science with IA

Beyond linear alignment model

Schmitz, Hirata, Blazek & Krause ('18)
Blazek, MacCrann, Troxel & Fang ('19)
Vlah, Chisari & Schmidt ('20ab) → Talk by Z. Vlah

Testing modified gravity models with IA statistics → Talk by Y-T. Chuang

Chuang, Okumura & Shirasaki ('21)

Synergy between imaging, spectroscopic & CMB observations

Okumura & AT ('21) → Talk by T. Okumura

Imprint of relativistic effects on IA signal → Talk by S. Saga

Saga et al. ('21, in prep.)

IA statistics as a sensible primordial non-Gaussianity probe

Schmidt, Chisari & Dvorkin ('15),
Kogai, Matsubara, Nishizawa & Urakawa ('18)
Kogai, Akitsu, Schmidt & Urakawa ('21)
Akitsu et al. ('20) → Talk by K. Kogai

and gravitational waves ? → Talk by K. Akitsu

More on galaxy shape statistics

Don't miss

Connection of galaxy spins & angular momenta with large-scale structure is also actively discussing !!

→ Talks by B. Zhang, U. Pen, P. Matloch, H-R. Yu & J. Lee

Spin-induced IA — Lee & Pen ('00, '01, '02, '08) Lee, Pen & Seljak ('00)
Crittenden, Natarajan, Pen & Theuns ('01)

Spin of cosmic filaments — Sheng, Li, Yu, Wang, Wang & Kang ('20)

Probing primordial chirality with galaxy spins
Yu, Motloch, Pen, Yu, Wang, Mo Yang & Jing ('20)
Wu, Yu, Liao & Du ('21)

Spin mode reconstruction — Motloch, Pen & Yu ('21a, b)

Neutrino & galaxy spins/shape — Yu, Pen, & Wang ('19)
Lee, Libeskind & Noam ('20) Lee & Noam ('20)

Galaxy spins & initial conditions — Motloch, Yu, Pen & Xie ('21)

Galaxy spins & dark energy — Lee & Libeskind ('20)

Scope of this workshop

Galaxy intrinsic shape & spin/angular momenta are not the systematics to be removed, but can be probes of large-scale structure and primordial universe

Also providing a unique channel that cannot be accessed by conventional galaxy clustering

Delivering a large scientific benefit from galaxy surveys:

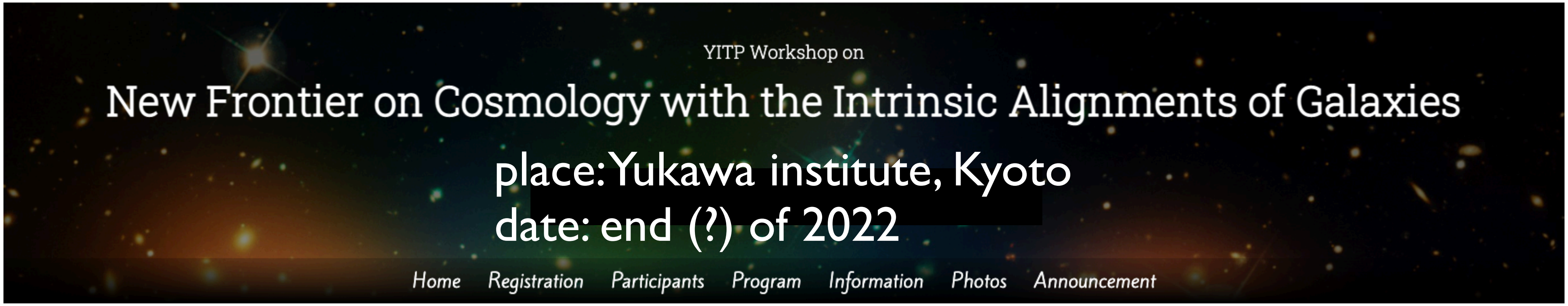
- New ideas to test/constrain cosmology (dark matter, dark energy, modified gravity, …)
- Development of techniques and methodologies
- Theoretical framework and its application to observations

Exchanging ideas and discussing recent progress

we hope to initiate new projects and to develop collaboration

Scope of this workshop

Galaxy intrinsic shape & spin/angular momenta are not the systematics to be removed, but can be probes of large-scale structure and primordial universe



Overview

Mapping the large-scale structure of the universe with galaxy surveys is a key science driver for cosmology. It enables us to probe the late-time cosmic expansion, growth of structure, and even the primordial fluctuations. So far, the spatial distribution of galaxies has long been used as the major observable, ignoring the shapes and orientations of individual galaxies. While the orientations of distant galaxy images have been established as a promising tool to measure the weak gravitational lensing, intrinsic alignments (IAs) of galaxies are thought to be a contaminant to be removed in the cosmological data analysis. However, there is growing evidence that IAs are a good tracer of the gravitational tidal field, making themselves a unique channel to access the dynamics of the large-scale matter inhomogeneities. Therefore, it is expected that the use of IAs is beneficial, and with

Hopefully we shall present our achievements at in-person workshop next year !

Acknowledgement

Report and publicizing the scientific achievements are our responsibility to demonstrate the activity of YITP

We would be grateful if you would acknowledge YITP in your papers initiated or motivated by discussions during the workshop

Please explicitly write YITP-T-21-06

Examples

The authors thank the Yukawa Institute for Theoretical Physics at Kyoto University, where this work was initiated [completed] during the YITP-T-21-06 on "Galaxy shape statistics and cosmology".

The authors thank the Yukawa Institute for Theoretical Physics at Kyoto University. Discussions during the YITP workshop YITP-T-21-06 on "Galaxy shape statistics and cosmology" were useful to complete this work.