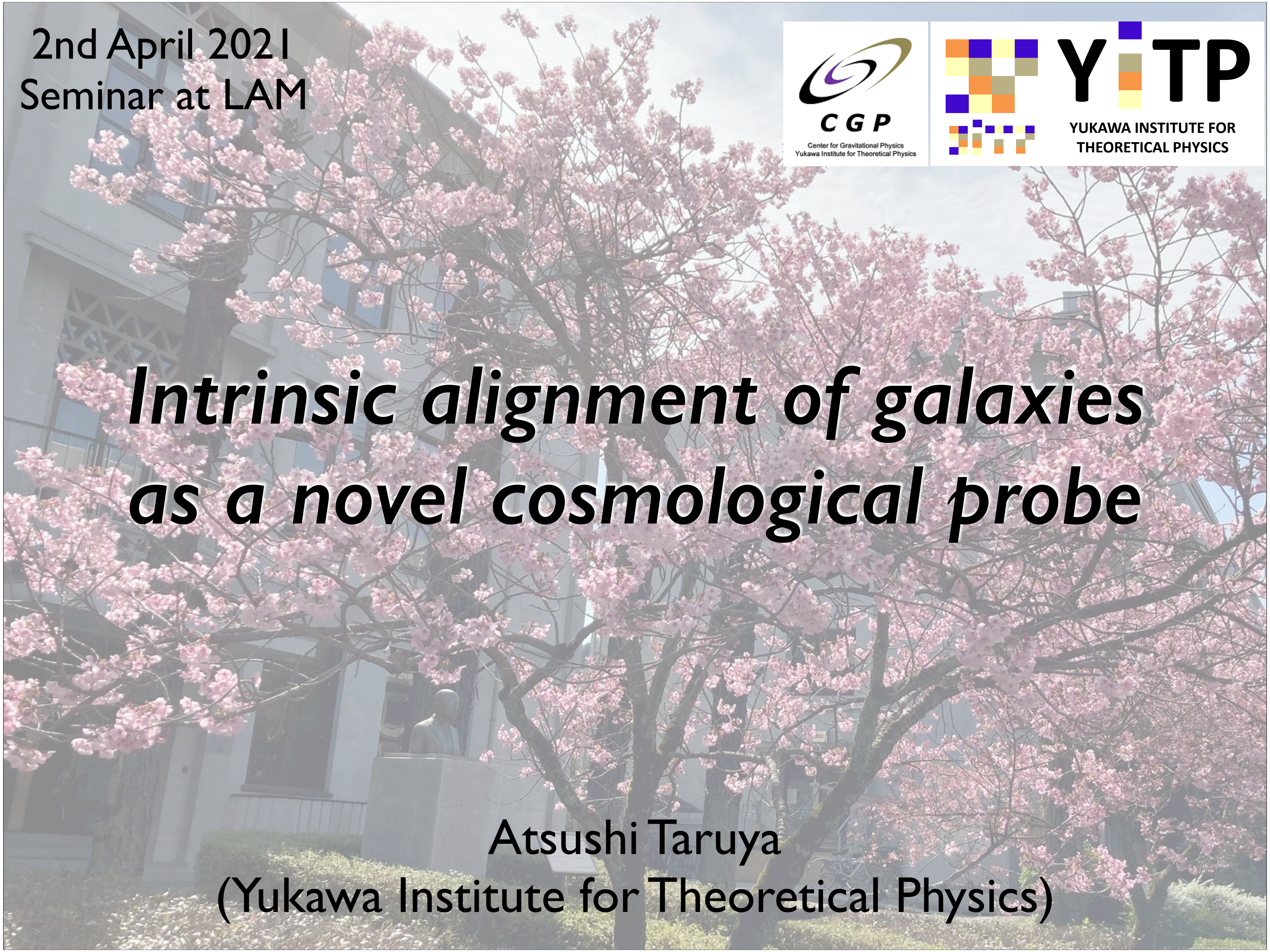


2nd April 2021
Seminar at LAM

CGP
Center for Gravitational Physics
Yukawa Institute for Theoretical Physics

YITP
YUKAWA INSTITUTE FOR
THEORETICAL PHYSICS

Intrinsic alignment of galaxies as a novel cosmological probe

Atsushi Taruya
(Yukawa Institute for Theoretical Physics)

Yukawa Institute for Theoretical Physics

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

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

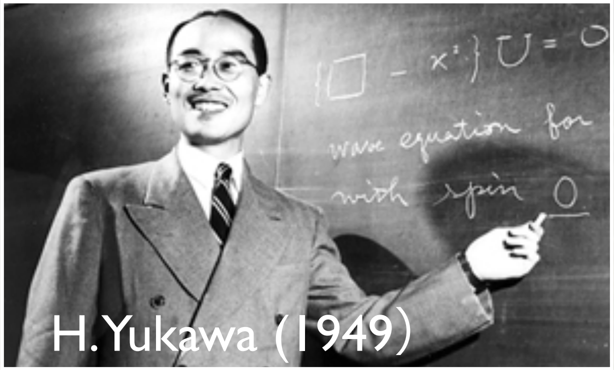
High energy physics, Nuclear physics, Astrophyics & cosmology, Condensed matter physics, Quantum information physics

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

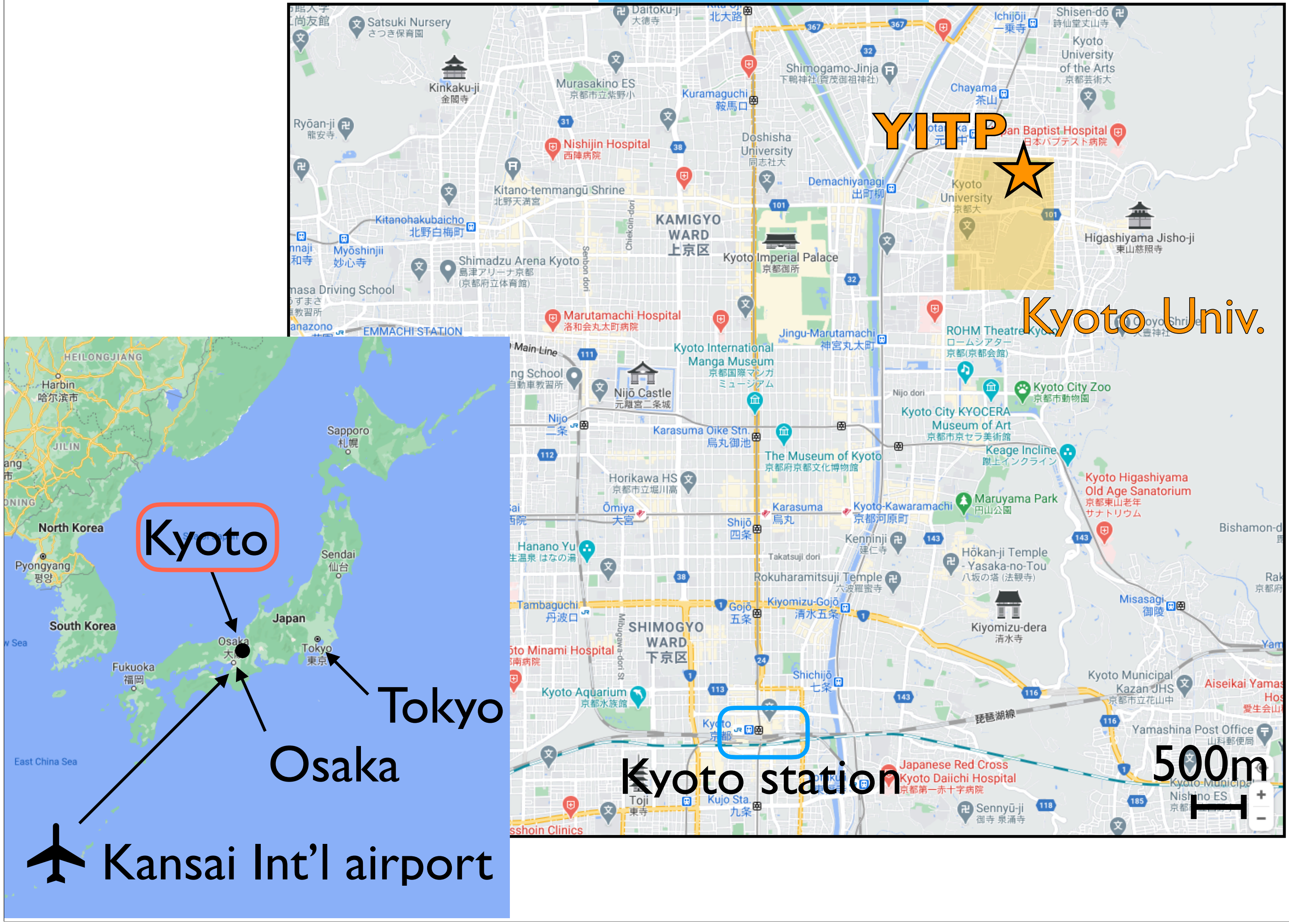

Panasonic auditorium

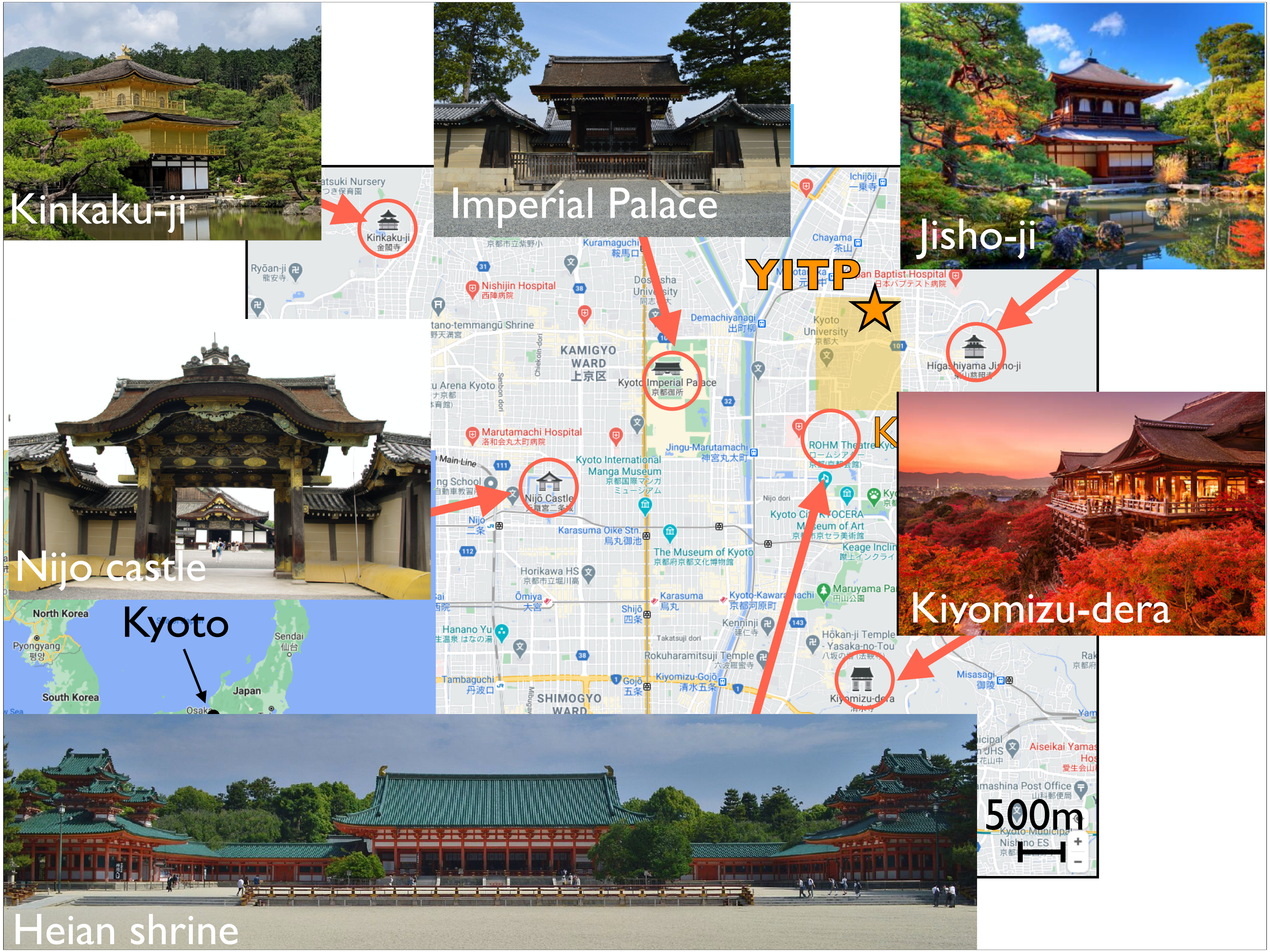

Research bldg.


Cherry blossom


H.Yukawa (1949)

Kyoto city map




Kinkaku-ji
Imperial Palace
Jisho-ji
YITP
Nijo castle
Kiyomizu-dera
Kyoto
North Korea
Pyongyang
South Korea
Japan
Sendai
Osaka
Heian shrine
500m
Kinkaku-ji
金閣寺
Ryōan-ji
龍安寺
Nishijin Hospital
KAMIGYO WARD
上京区
Kyoto Imperial Palace
京都御所
Doshisha University
Demachiyanagi
Kyoto University
京都大
Higashiyama Jisho-ji
Marutamachi Hospital
Kyoto International Manga Museum
Nijō Castle
ROHM Theatre Kyoto
Kyoto City KYOCERA Museum of Art
The Museum of Kyoto
Karasuma Oike Stn.
Horikawa HS
Ōmiya
Shijō
Karasuma
Kyoto-Kawaramachi
Maruyama Park
Kenninji
Hōkan-ji Temple - Yasaka-no-Tou
Rokuharamitsuji Temple
Kiyomizu-Gojō
Gojō
Tambaguchi
SHIMOGYO WARD
Kiyomizu-dera
Misasagi

Plan of talk

The intrinsic alignment (IA) of galaxies as a novel probe of precision cosmology

Introduction & motivation

Modeling intrinsic alignment signals

Forecast for cosmological constraints

Summary

Refs.

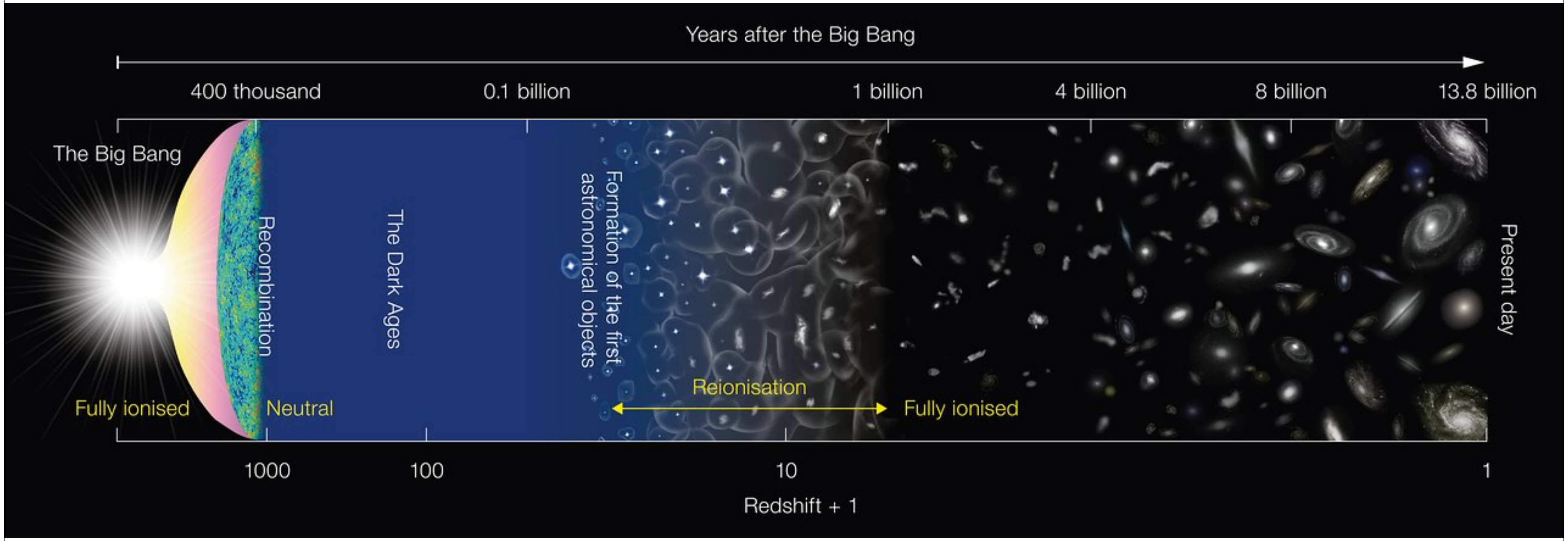
T. Okumura & A. Taruya & T. Nishimichi, MNRAS 494, 694-702 ('20)
A. Taruya & T. Okumura, ApJL 891, L42 ('20)
T. Okumura & A. Taruya, MNRAS 493, L124-L128 ('20)

Concordant picture of the Universe

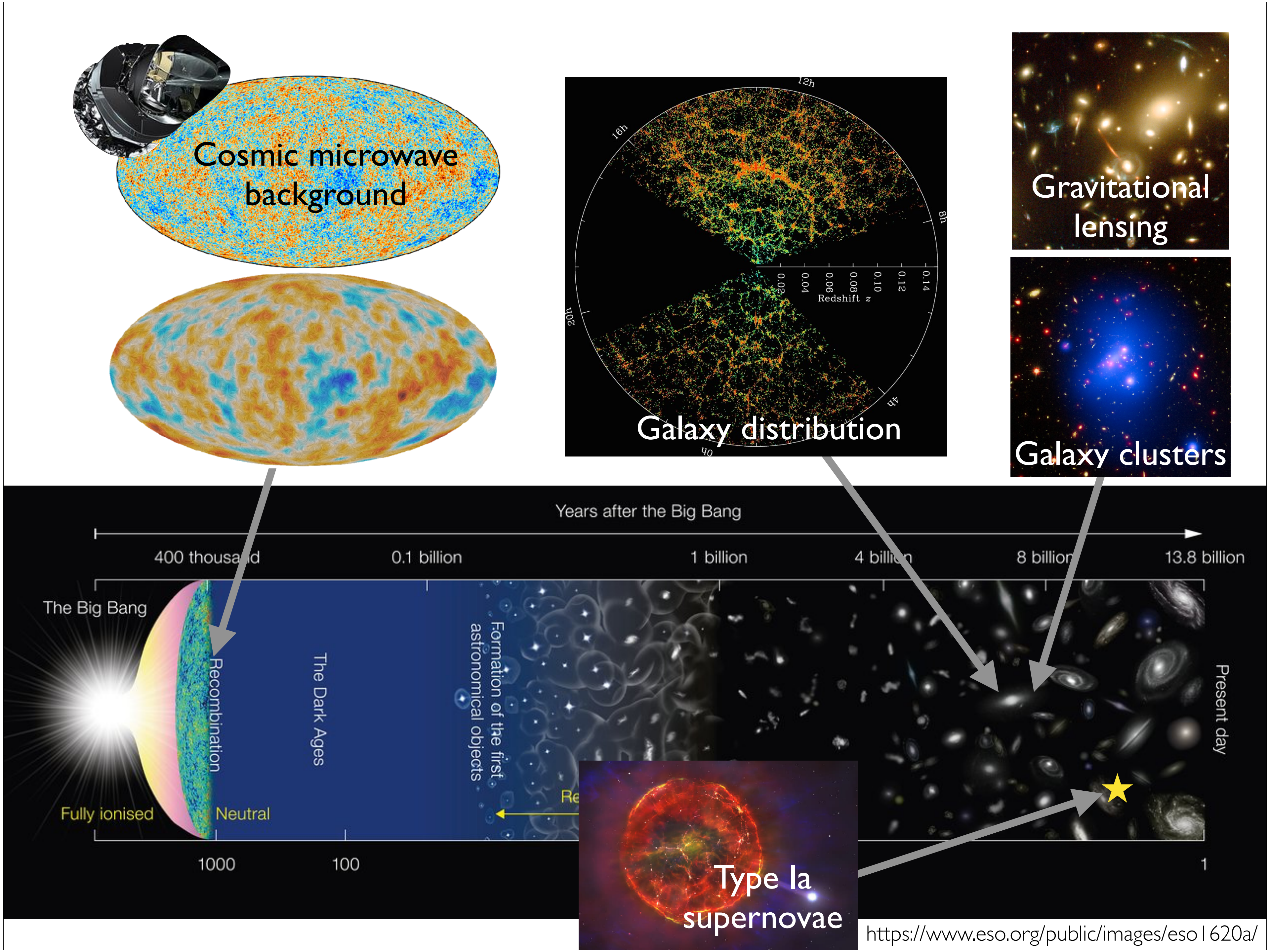
Lambda cold dark matter (ΛCDM) model

Minimal model characterized by 6 parameters

Model describes both cosmic expansion and structure formation over *13.8* billion years



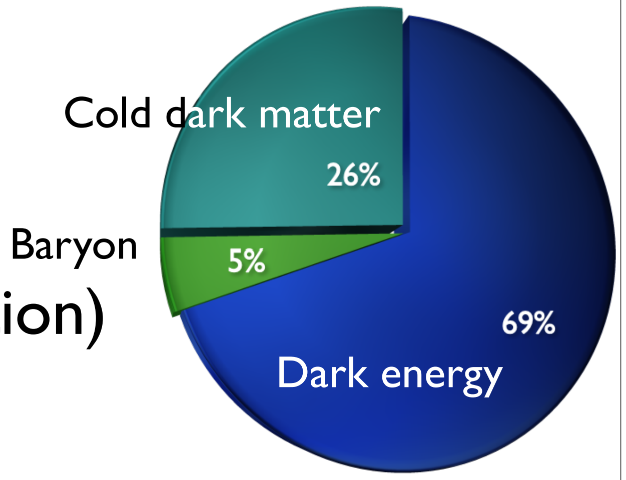
https://www.eso.org/public/images/eso1620a/



https://www.eso.org/public/images/eso1620a/

Unresolved issues

Success of minimal model does not imply model is convincing



Mysterious components

Dark matter

Dark energy (late-time cosmic acceleration)

Untested hypotheses

Cosmic inflation

General relativity on cosmological scales

Gaussianity of primordial fluctuations

Tensions

Discrepancy of Planck ΛCDM model parameters with those obtained from other observations (H_0, S_8, …)

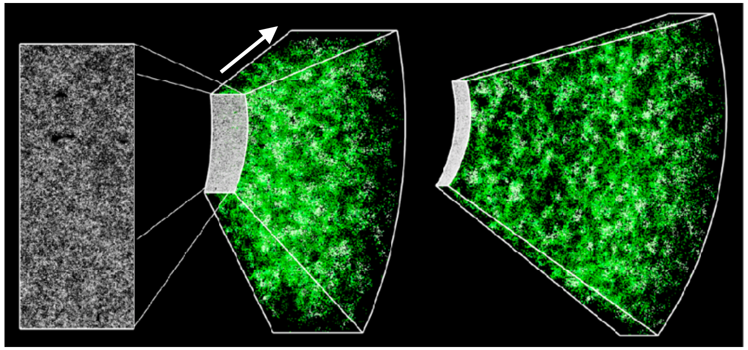
Large-scale structure

Large-scale matter inhomogeneities over Mpc~Gpc scales

evolved under the influence of gravity & cosmic expansion

Its statistical nature carries rich cosmological information

Using (mainly) galaxies as a tracer of LSS,



✓ Photometric/imaging surveys

(angular position + galaxy shape)

Weak lensing effect

✓ Spectroscopic surveys

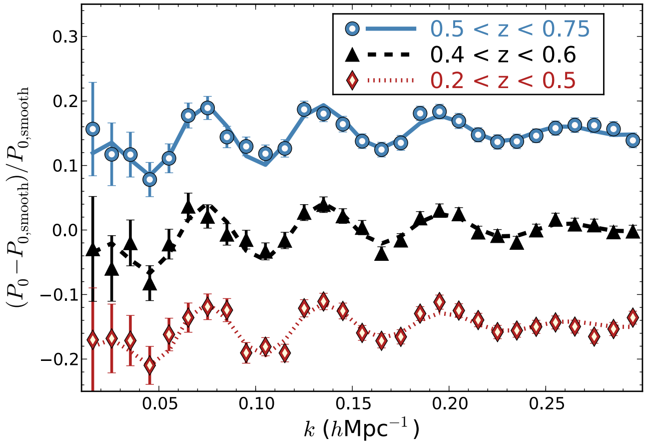
(angular position + redshift)

Baryon acoustic oscillation (BAO)

Redshift-space distortions (RSD)

A quick review of BAO & RSD

- ***BAO***: characteristic oscillatory feature of primeval baryon-photon fluid imprinted on galaxy clustering pattern at ~100Mpc

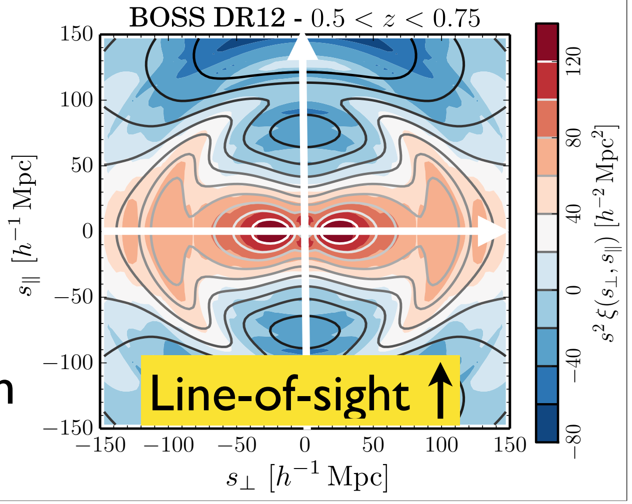


→ used as a standard ruler to measure

$d_A(z)$ & $H(z)$

Alam et al. ('16)

Alam et al. ('16)



Line-of-sight ↑

- ***RSD***: distortions of galaxy line-of-sight positions due to peculiar velocity of galaxies

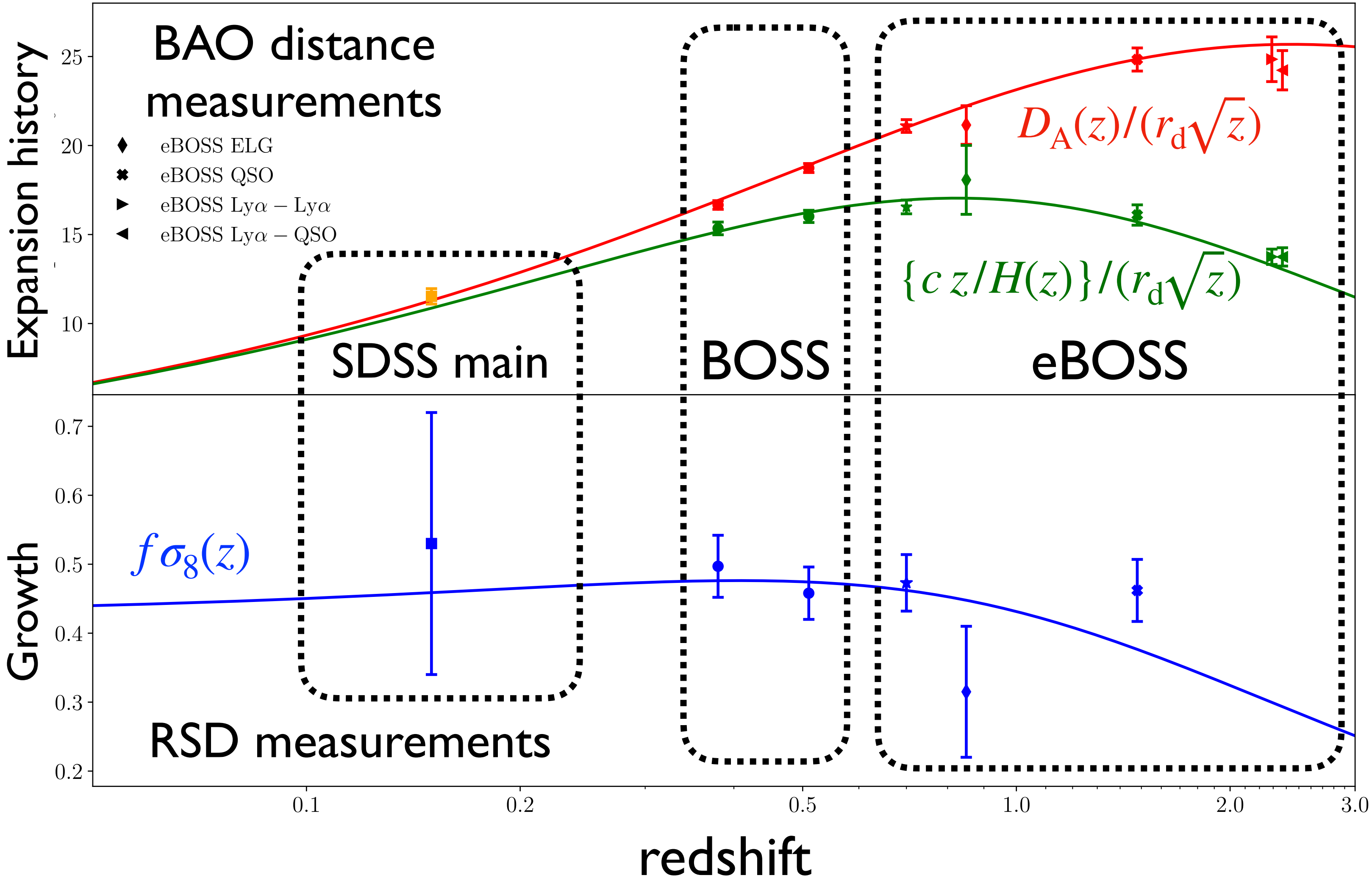
Strength of RSD (anisotropies) ∝ $f\sigma_8(z)$

Structure growth

→ cosmological test of gravity

Constraints from BAO & RSD

Alam et al. ('20)

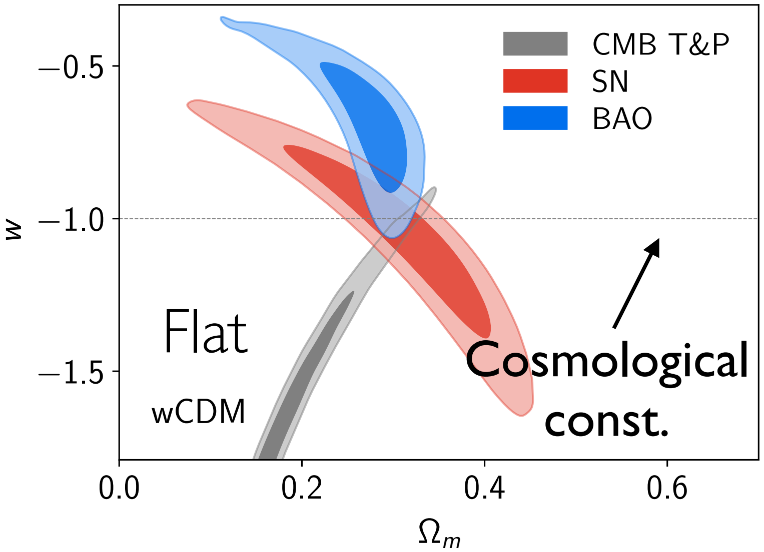


arXiv:2007.08991

Cosmological constraints

Alam et al. ('20)

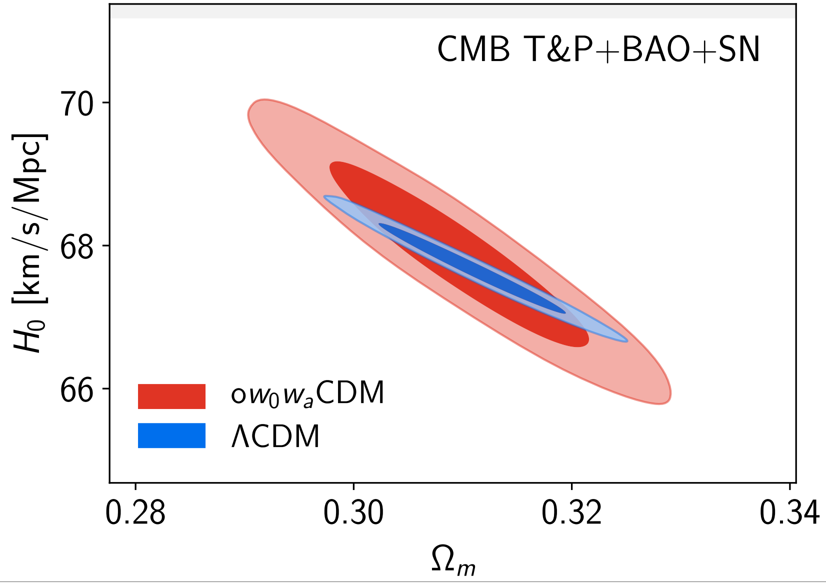
arXiv:2007.08991

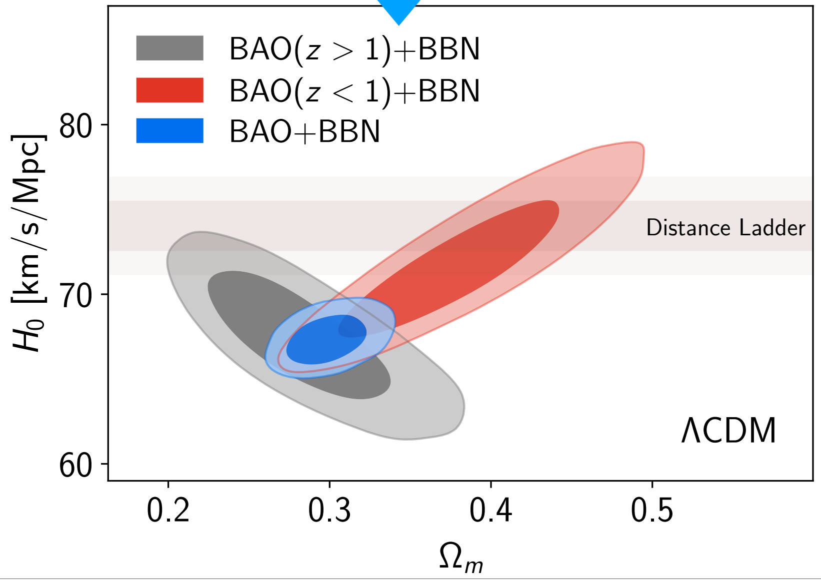


Dark energy equation-of-state

$$P_{\rm DE} = w\,\rho_{\rm DE}$$

Hubble parameter





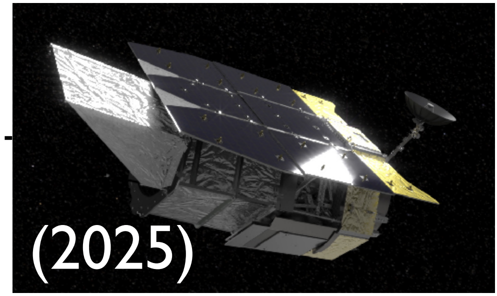
Ongoing/upcoming surveys

From stage III to stage IV-class surveys (ground & space)

Imaging surveys


VCRO (LSST)

(2021+)


(2025)

Nancy Grace Roman Space Telescope (WFIRST)


Euclid

(2023)

HSC

(2014~)

PFS

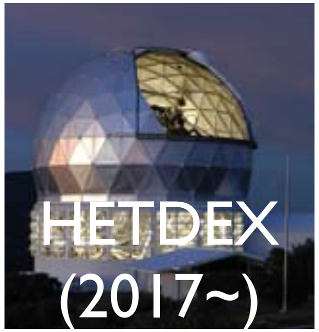
(2023~)


Subaru

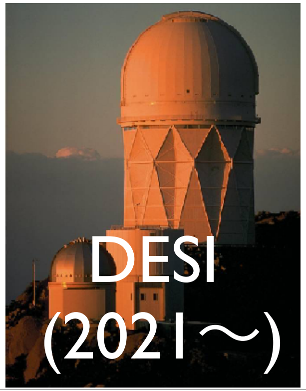
Spectroscopic surveys


SPHEREx

(2023)


HETDEX

(2017~)


DESI

(2021〜)

Improving cosmological constraints

Toward a better cosmological constraints,

without conducting extra surveys

Pushing available Fourier modes to a larger value $k_{\mathrm{max}} \nearrow$ (small scales)

Theoretical modeling far beyond linear regime is challenging

Using technique/method that maximizes cosmological information :

Combining several statistics such as bispectrum

Cross correlating multiple data set,

also utilizing the information that has been abandoned

Improving cosmological constraints

Toward a better cosmological constraints,
without conducting extra surveys

Pushing available Fourier modes to a larger value $k_{\rm max} \nearrow$ (small scales)

Focus of this talk

Intrinsic alignment (IA) of galaxies as a cosmological probe

BAO
Primordial gravitational waves
Primordial non-Gaussianity

Faltenbacher et al. ('12), Chisari & Dvorkin ('13), Okumura et al. ('19), Schmidt & Jeong ('12), Schmidt et al. ('12), Kogai et al. ('18, '20), Akitsu et al.('20)

Here, we particularly focus on

statistical properties of *3D correlations* (BAO & RSD)
& cosmological information

Intrinsic alignment (IA) of galaxy

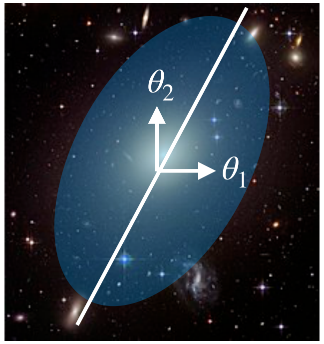
Projected shape of observed galaxies/dark matter halos

In general, galaxy/halo has elliptical shape, aligned to some directions:

Quadrupole moment of galaxy image

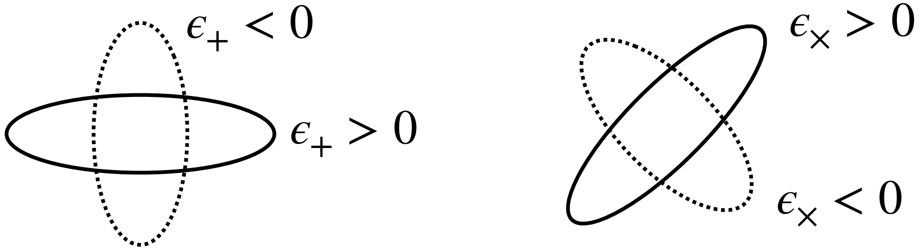
intensity

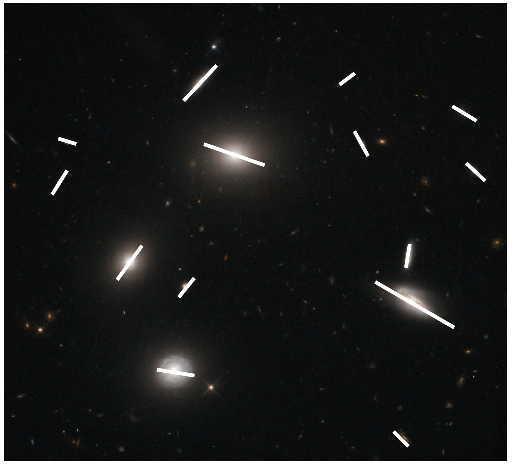
$$q_{ij}^{\rm obs} \equiv \frac{\displaystyle\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})\,\theta_i\,\theta_j}{\displaystyle\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})} \qquad (i,j=1,2)$$



Ellipticity :

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





Intrinsic alignment (IA) of galaxy

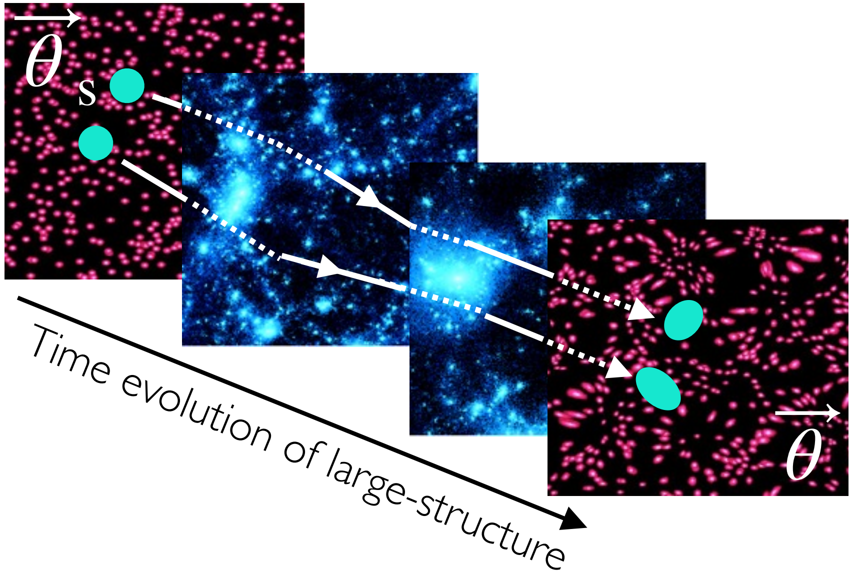
Ellipticity of distant galaxy is induced by the gravitational lensing of foreground large-scale structure :

$$\underbrace{\epsilon_a \simeq \gamma_a^{\mathrm{I}}}_{\text{IA}} + \underbrace{2\,g_a}_{\text{Lensing}}\ ; \qquad g_a \equiv \frac{\gamma_a}{1-\kappa}\,(\ll 1)$$

$(a = +\ \mathrm{or}\ \times)$ Reduced shear

IA

Lensing



Gravitational lensing induces non-zero spatial correlation

⟶ A clue to detect lensing signal

However,

IA can have non-zero spatial correlation

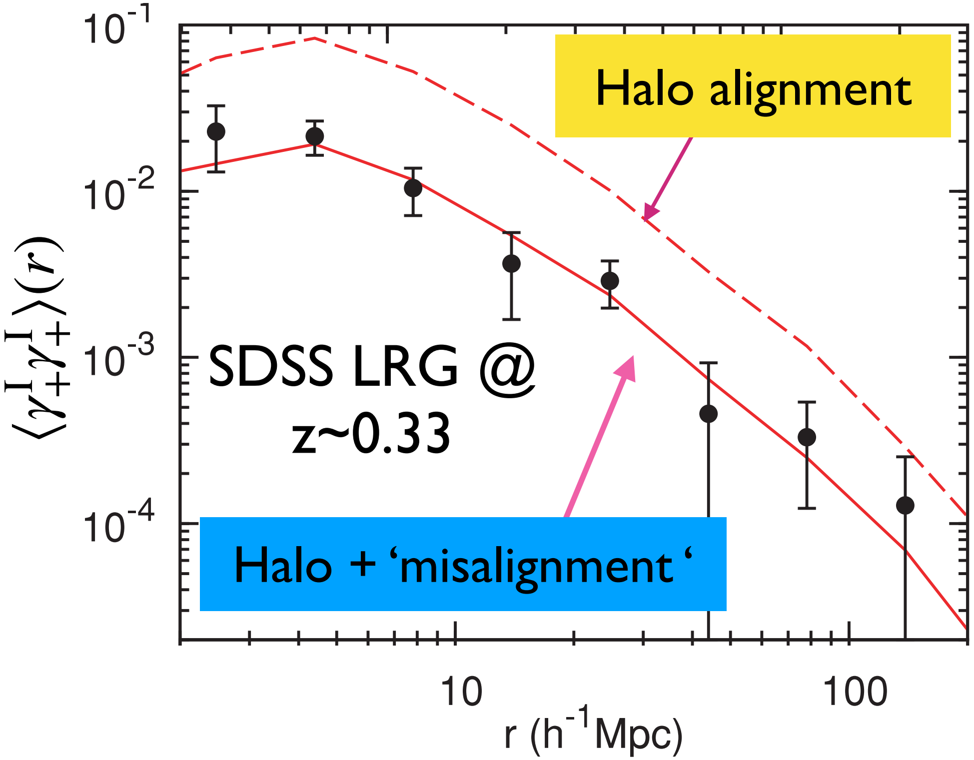
(contaminant of lensing measurement)

Troxel & Ishak ('15)
Joachimi et al. ('15)

Intrinsic alignment (IA) correlation

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

angular position (2D) + redshirt + shape



Halo alignment

SDSS LRG @
z~0.33

Halo + ‘misalignment ‘

Early type

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

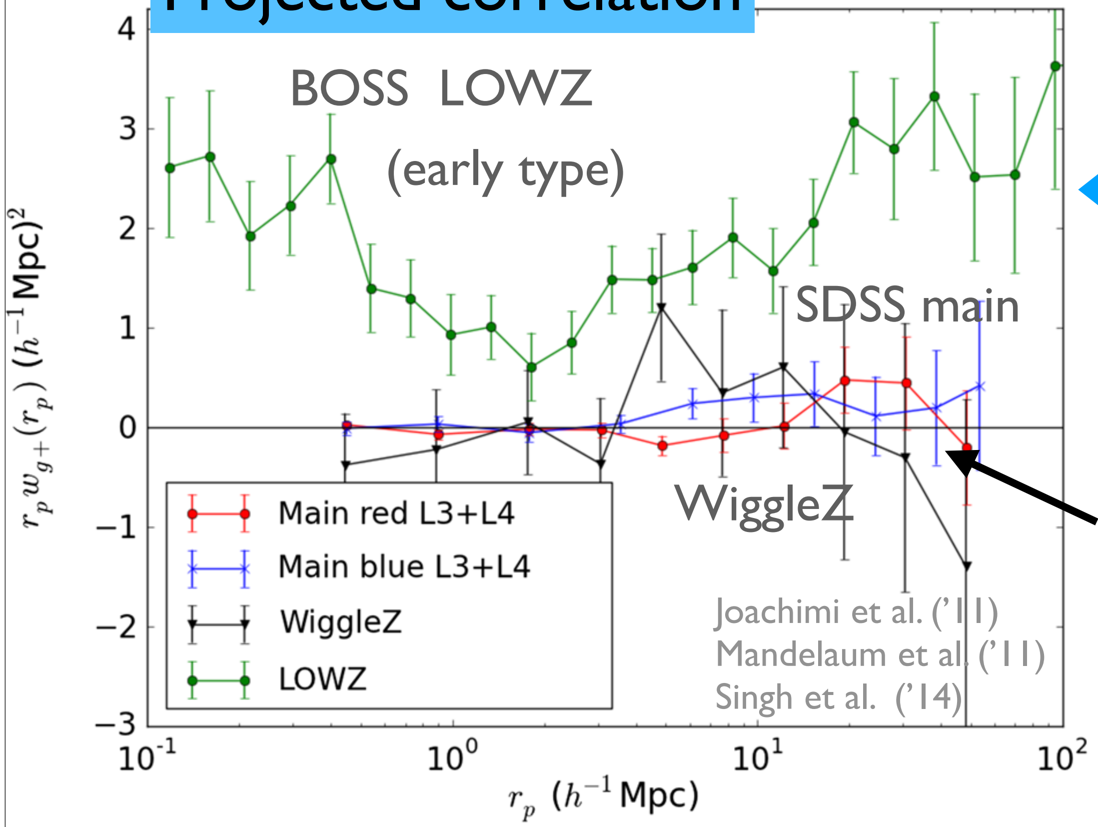
Okumura, Jing & Li (’09)

Measured result resembles the halo ellipticity correlation in N-body simulations (solid & dashed lines)

Intrinsic alignment (IA) correlation

Behaviors of IA correlation crucially depend on galaxy type

Projected correlation



Galaxy-IA correlation
(GI correlation)

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

No clear signal is detected
for late-type galaxies

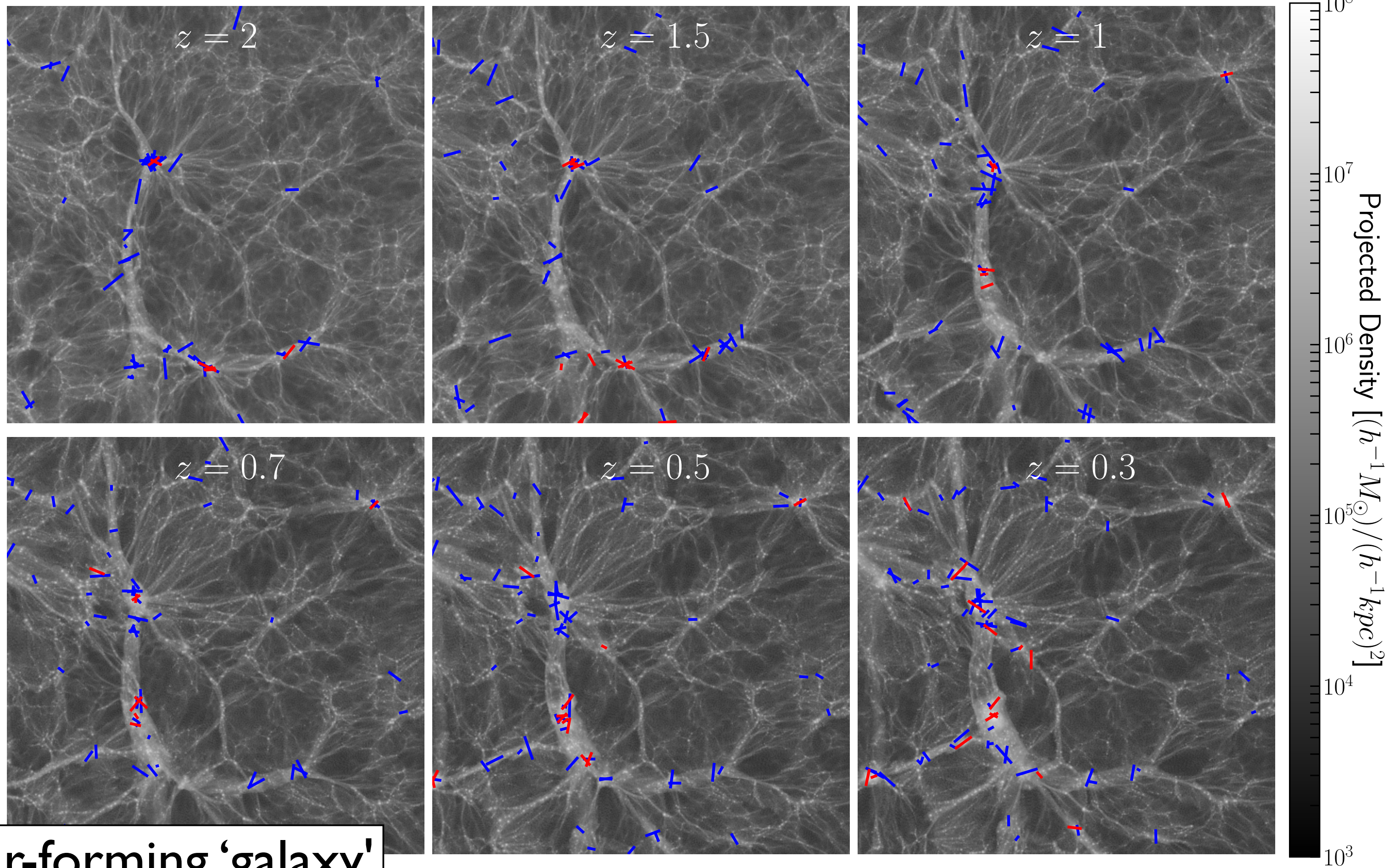
Joachimi et al. ('15)

IA in hydrodynamical simulations

Illustris-TNG300

40 x 40 $(h^{-1}\mathrm{Mpc})^2$

Shi et al. ('20)



Blue: star-forming 'galaxy'

Red: quiescent 'galaxy'

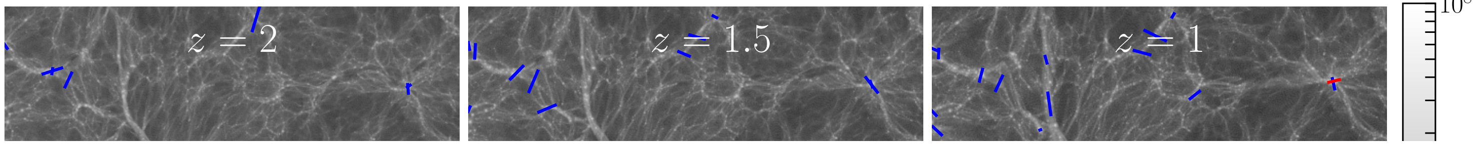
Blue seems to be randomly oriented

IA in hydrodynamical simulations

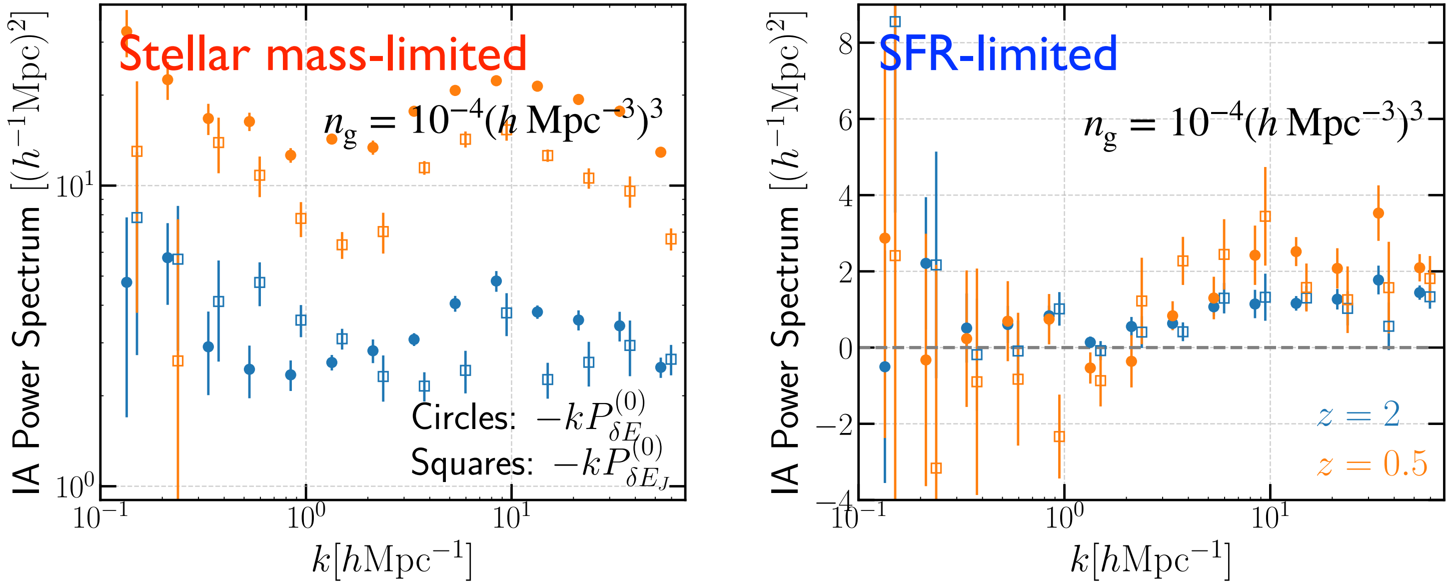
Illustris-TNG300

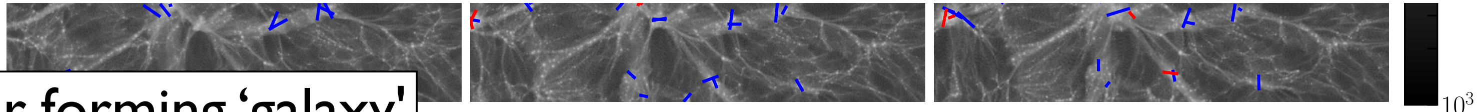
40 x 40 $(h^{-1}\mathrm{Mpc})^2$

Shi et al. ('20)



GI correlation (power spectrum)





Blue: star-forming 'galaxy'

Red: quiescent 'galaxy'

Blue seems to be randomly oriented

Mechanisms of IA correlation

Joachimi et al. ('15), Troxel & Ishak ('15)

Tidally induced alignment

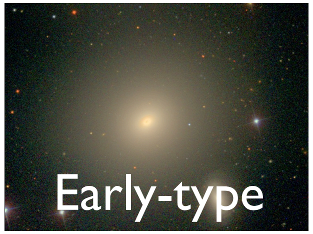
aligned along the tidal field induced by large-scale structure

$$\gamma_a^{\mathrm{I}} \propto \partial^2\Phi$$

Gravitational potential

Determined by large-scale structure

Strong correlation



Spin-induced alignment

aligned along the acquired angular momentum direction

$$\gamma_a^{\mathrm{I}} \propto \hat{J}^2$$

(Normalized) angular momentum

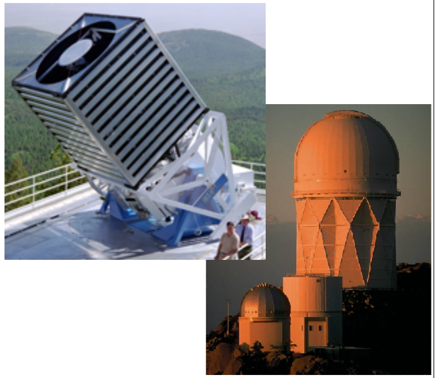
Determined mainly by local physics

Weak correlation

Cosmology with IA

Tidally-induced IAs look promising and measuring these can have a potential to improve cosmological constraints

Relevant surveys:



Done	BOSS†	LOWZ $(z \sim 0.3)$ & CMASS $(z \sim 0.5)$
Done	eBOSS*	LRG $(0.6 \leq z \leq 1)$
Ongoing	DESI★	LRG $(0.6 \leq z \leq 1.2)$

† Baryon Oscillation Spectroscopic Survey

* extended Baryon Oscillation Spectroscopic Survey

★ Dark Energy Survey Instrument

Q

- How well one can model/predict IA correlations ?

GI & II correlations: $\langle \delta_{\rm g} \gamma_a^{\rm I} \rangle$, $\langle \gamma_a^{\rm I} \gamma_b^{\rm I} \rangle$ $(a, b = +, \times)$

- Combining IAs with conventional GG correlation, how well one can improve the cosmological constraints ?

Linear alignment (LA) model

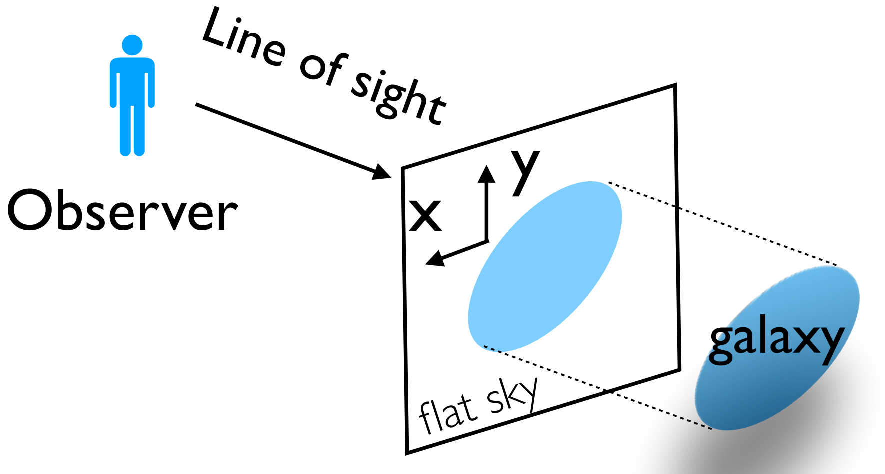
For cosmological purpose,

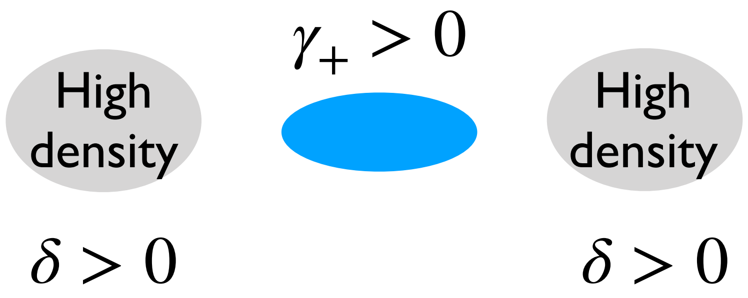
modeling IA of early-type galaxies is a crucial 1st step

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

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

Gravitational potential





In galaxy redshift surveys, one can measure 3D spatial correlation

IA statistics in 3D

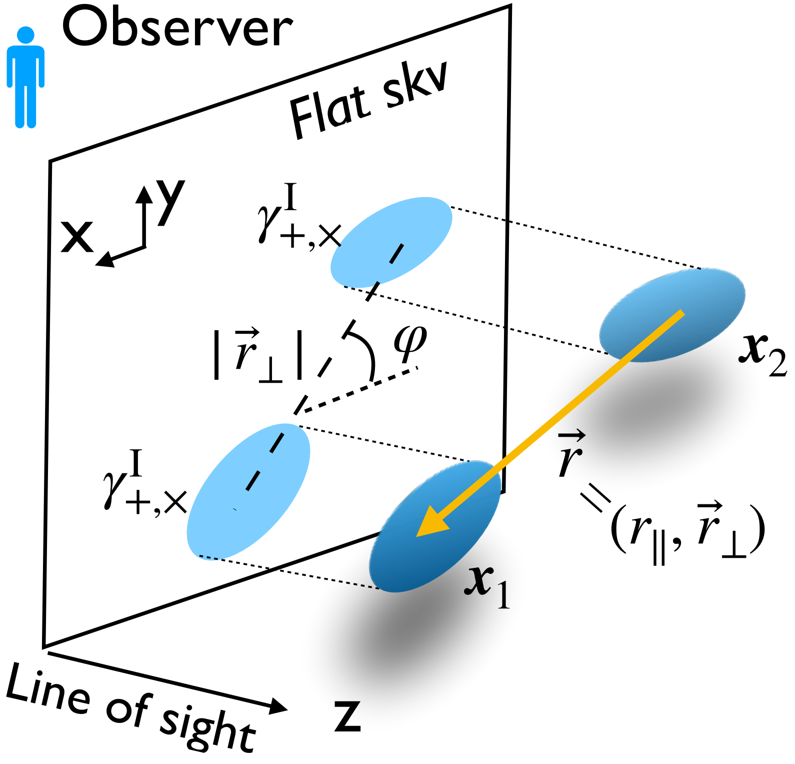
II correlation

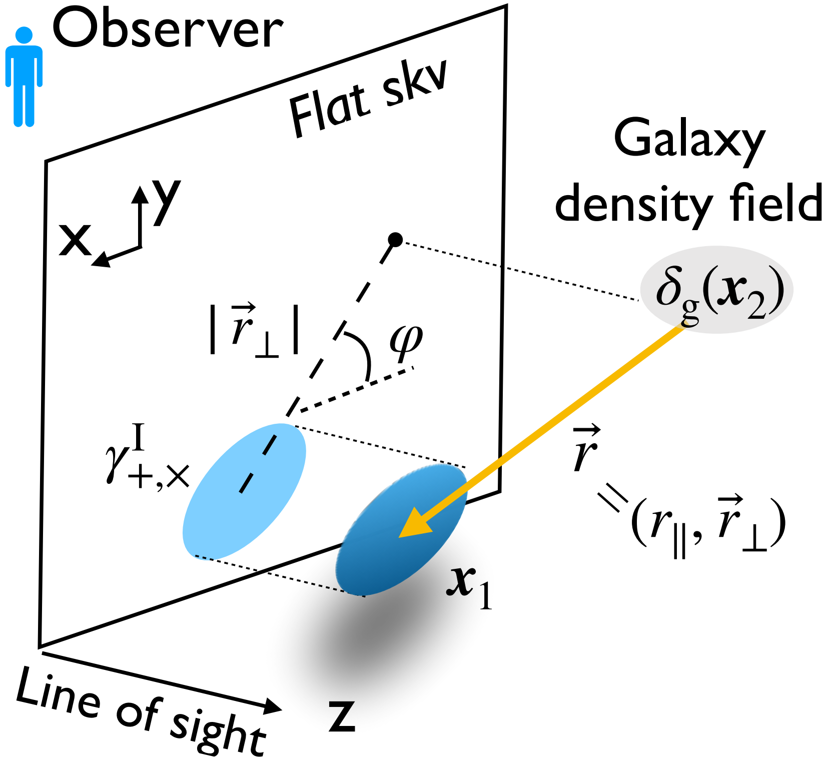
$\xi_{ab} \equiv \langle \gamma^{\rm I}_a(\boldsymbol{x}_1)\gamma^{\rm I}_b(\boldsymbol{x}_2)\rangle$

GI correlation

$\xi_{{\rm g},a} \equiv \langle \delta_{\rm g}(\boldsymbol{x}_1)\gamma^{\rm I}_a(\boldsymbol{x}_2)\rangle$

$(a, b = +, \times)$





With the IA defined by *projected* shape, their correlation becomes *anisotropic* along line of sight, characterized as a function of $(r_\parallel, r_\perp)$

Anisotropic GI & II correlations

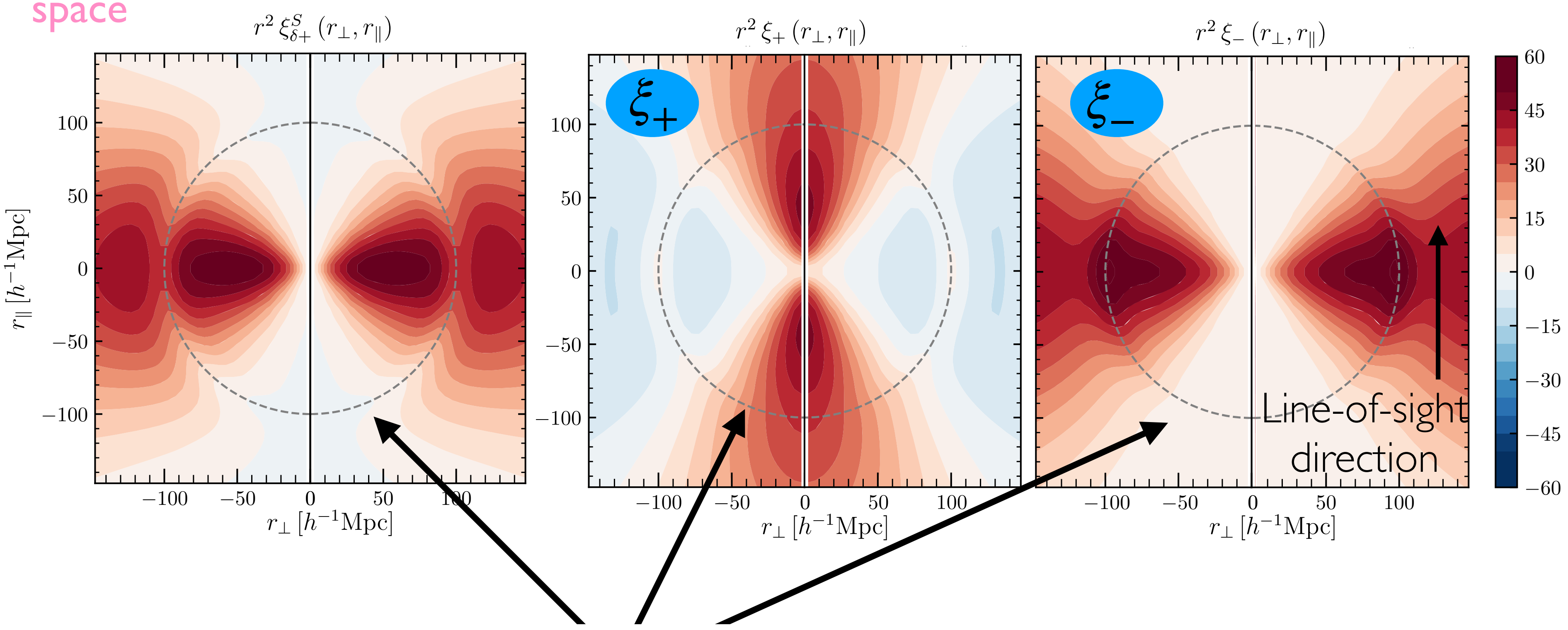
Okumura & AT ('20)

Anisotropic correlations characterized as function of $(r_\perp, r_\parallel)$

Redshift space

GI correlation

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



Line-of-sight direction

Baryon acoustic oscillation feature (appears as 'bump')

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

Analytical formulas

Okumura & AT ('20)

GI correlation

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

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

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

Real space

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

Linear growth factor

Redshift space

II correlation

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

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

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

Expressions are identical in both real & redshift space

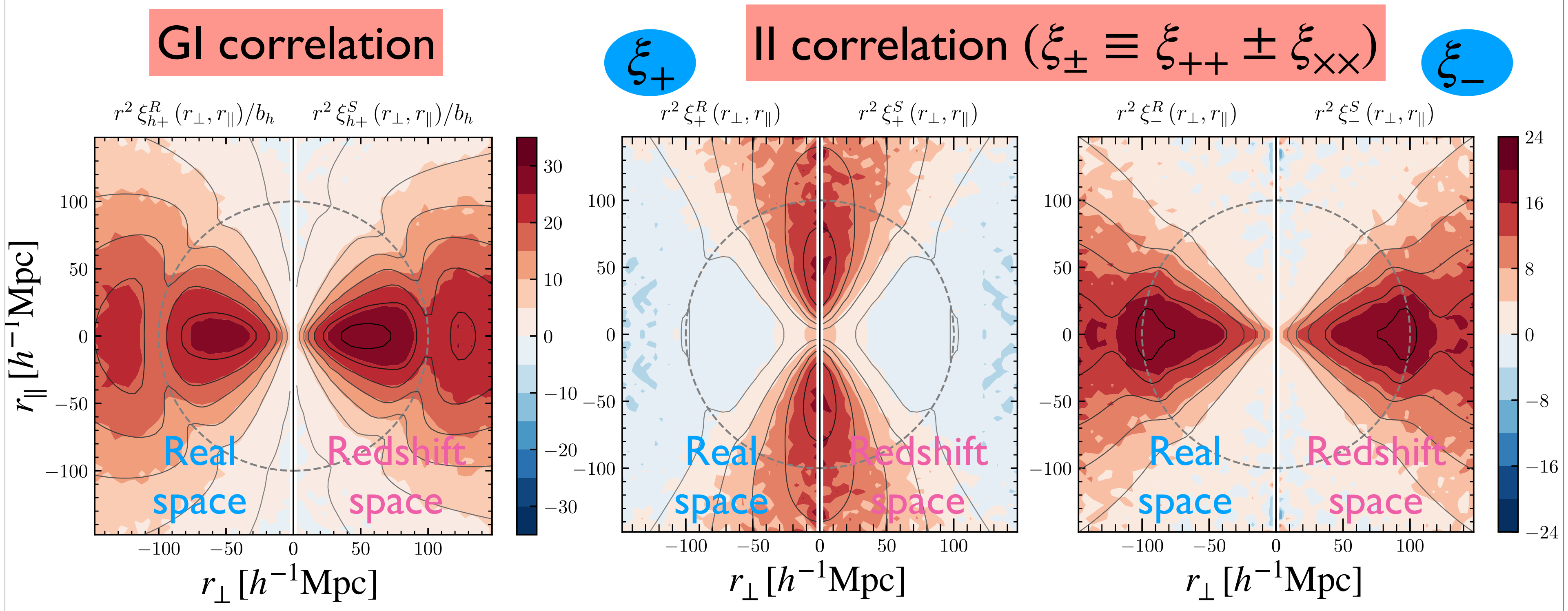
$$\Xi^{(n)}_{XY,\ell}(r) = (aHf)^n \int_0^\infty \frac{k^{2-n}{\rm d}k}{2\pi^2} P_{XY}(k)\,j_\ell(kr)$$

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

Testing LA model predictions

Okumura, AT & Nishimichi ('20)

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



GI correlation

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

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

Solid contours: LA model prediction

Testing LA model predictions

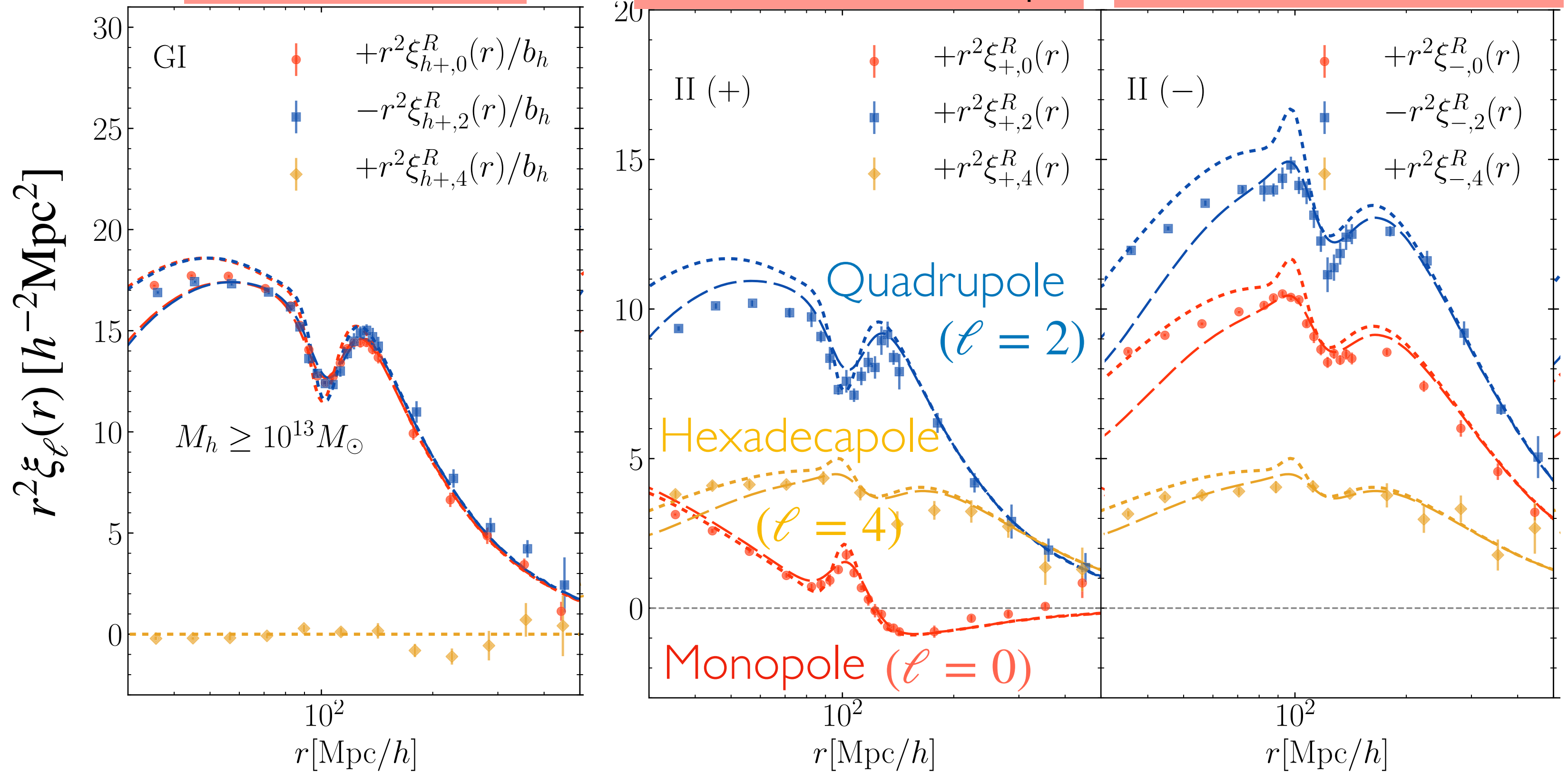
Okumura, AT & Nishimichi ('20)

Real space

Multipole expansion

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

GI correlation **II correlation (ξ_+)** **II correlation (ξ_-)**



dashed : LA model with non-linear P(k), dotted : LA model with linear P(k)

Testing LA model predictions

Okumura, AT & Nishimichi ('20)

Redshift space

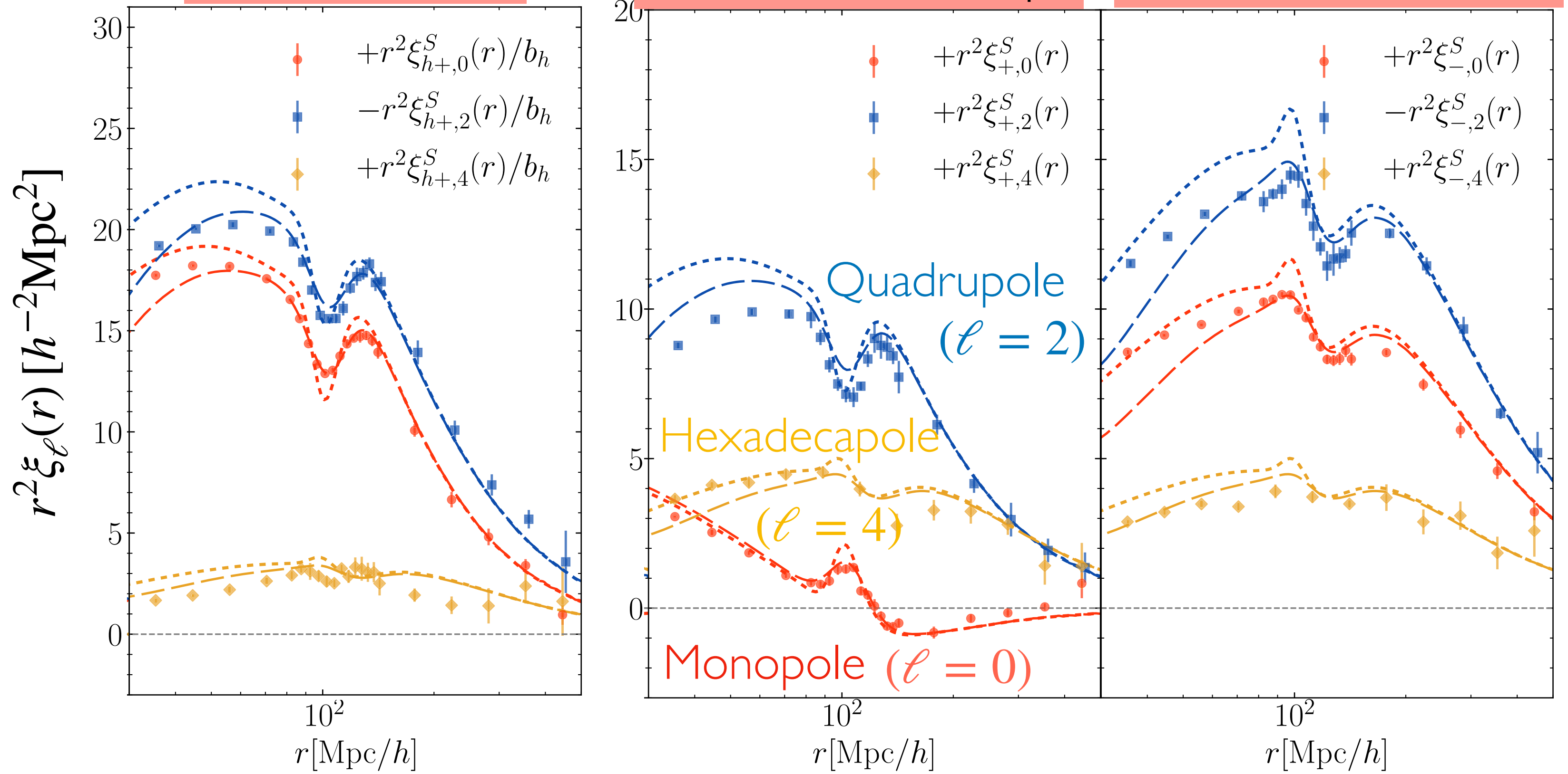
Multipole expansion

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

GI correlation

II correlation (ξ_+)

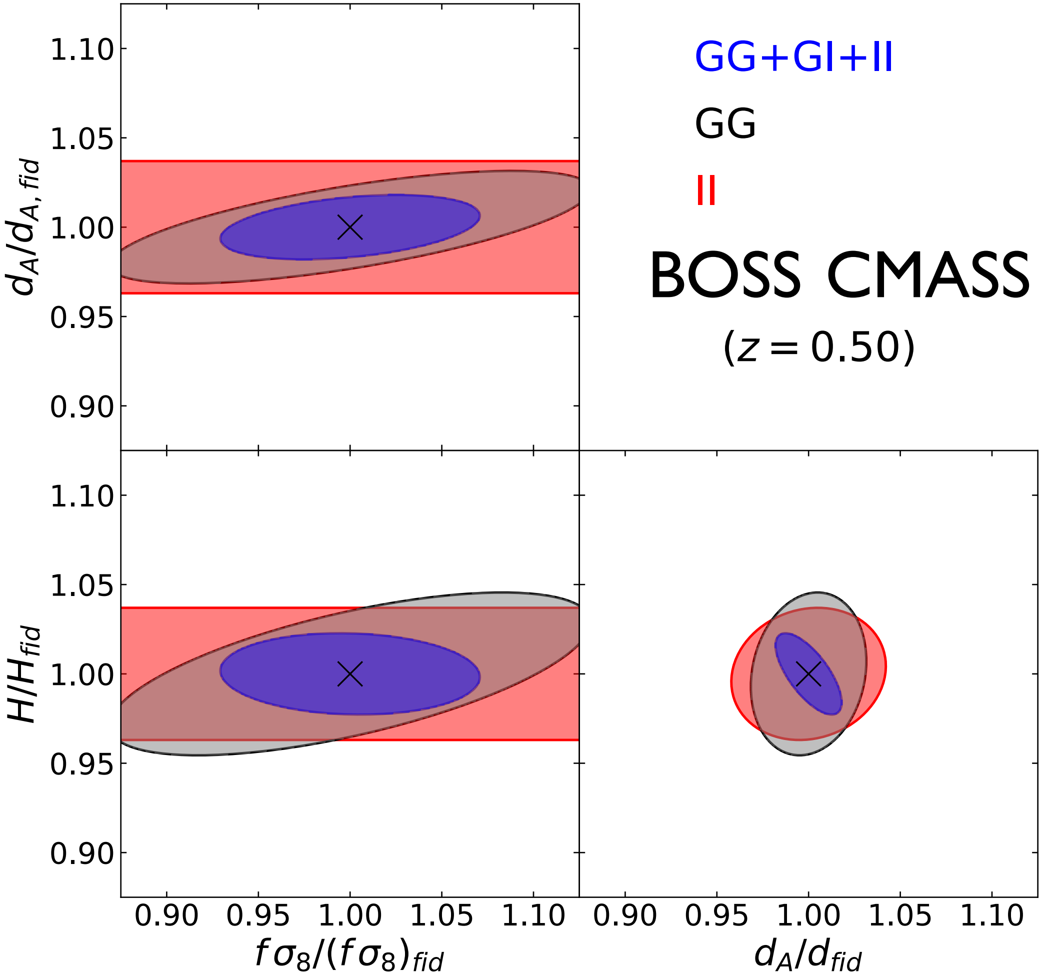
II correlation (ξ_-)



dashed : LA model with non-linear P(k), dotted : LA model with linear P(k)

Geometric & dynamical constraints

RSD & BAO can be measured from GI & II correlations $\xrightarrow[+GG]{}$ $\{d_{\rm A}(z_i), H(z_i), f\sigma_8(z_i)\}$



Expected constraints using large-scale info. at $k \leq 0.1\,h\,{\rm Mpc}^{-1}$

GG : galaxy clustering

II : IA statistics

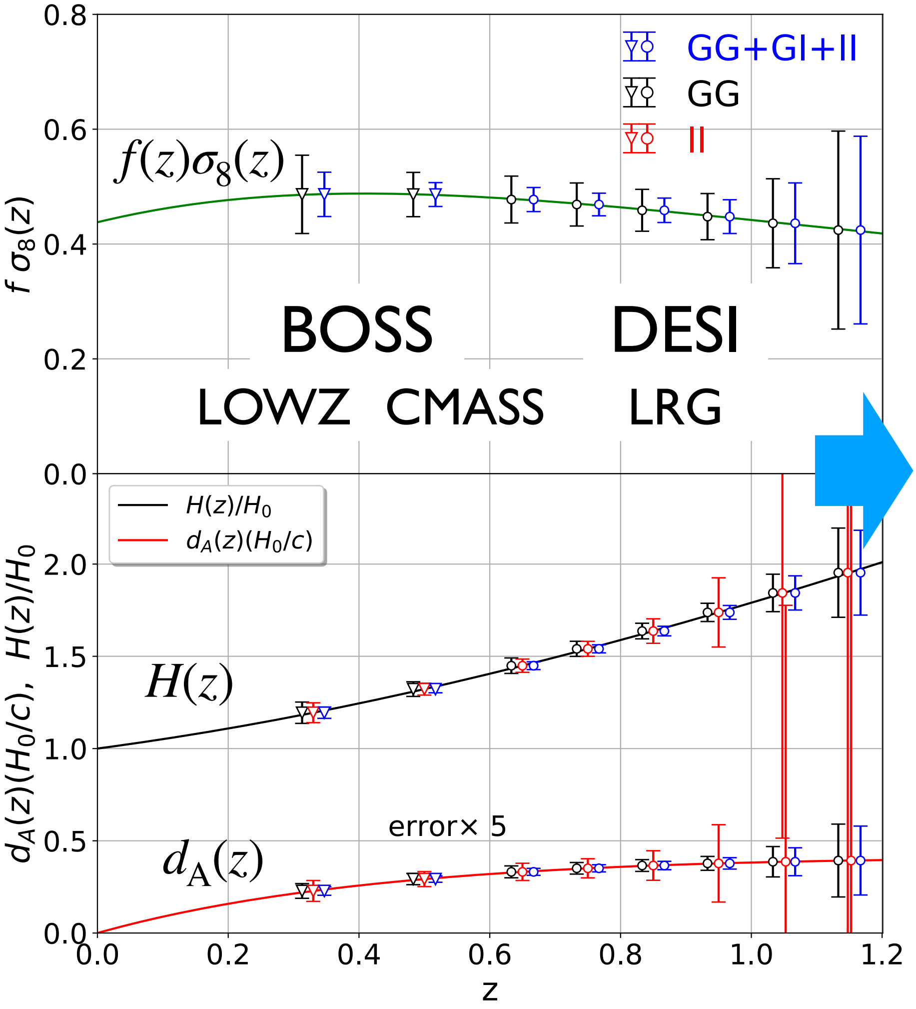
GG+GI+II : both combined

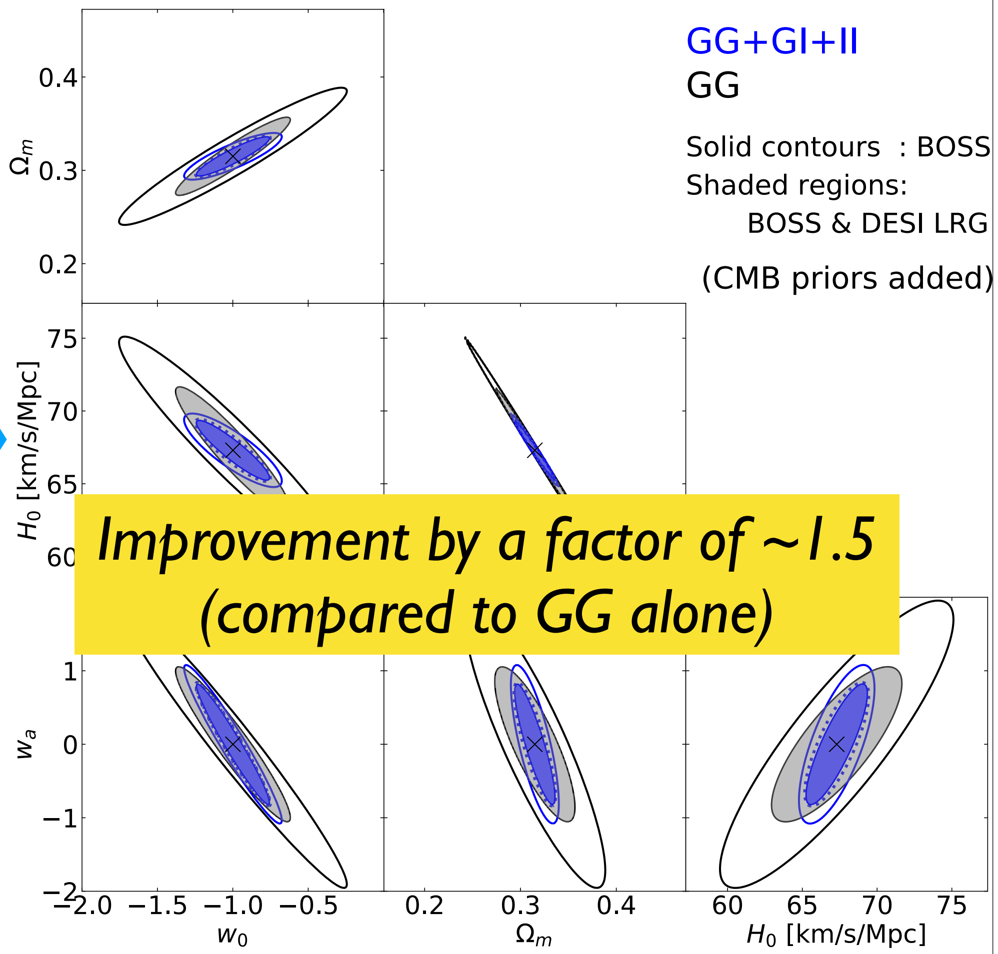
AT & Okumura ('20)
arXiv:2001.05962

Fisher forecast

AT & Okumura ('20)

BAO & RSD measurements from BOSS (finished) & DESI (upcoming)





GG+GI+II
GG

Solid contours : BOSS
Shaded regions:
BOSS & DESI LRG

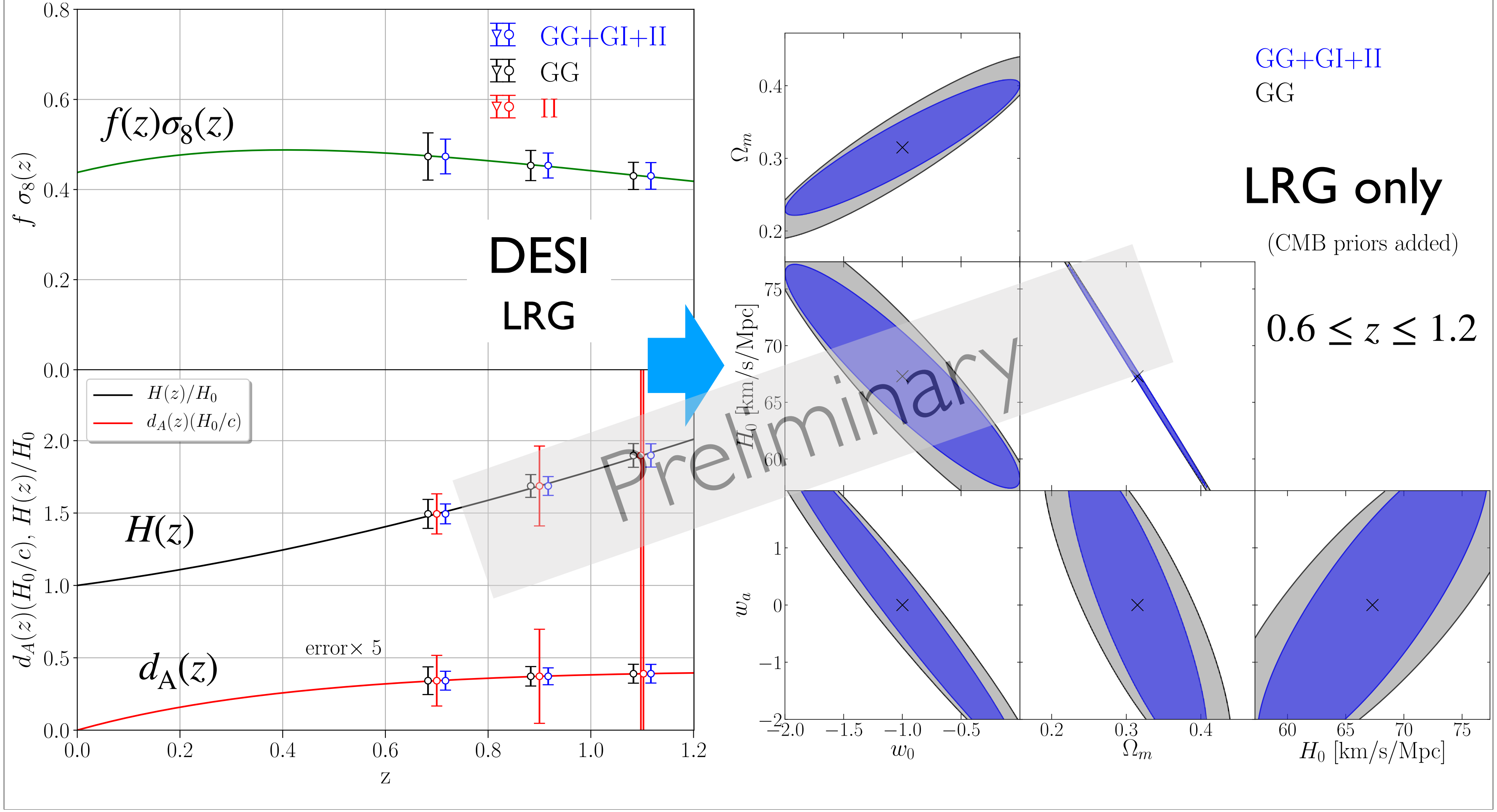
(CMB priors added)

Improvement by a factor of ~1.5
(compared to GG alone)

Fisher forecast

AT & Okumura ('20)

Synergy between DESI (spec-z) and subaru-HSC (shape info.)



LRG only

(CMB priors added)

$0.6 \leq z \leq 1.2$

Summary

The intrinsic alignment (IA) of galaxies as a novel probe of precision cosmology

The IA for late-type galaxies can be an ideal tracer of large-scale tidal fields

❖ Linear alignment (LA) model

- provide simple analytical formulas for IA correlations (GI & II)
- quantitatively explain anisotropies inherent in 3D correlations

⟶ BAO & RSD can be measured

❖ Forecast study of cosmological constraints

suggests combining GG with GI & II gives an improvement

by a factor of ~1.5

Observing IA delivers beneficial information, worth for further study