Recent progress of cosmic shear cosmology

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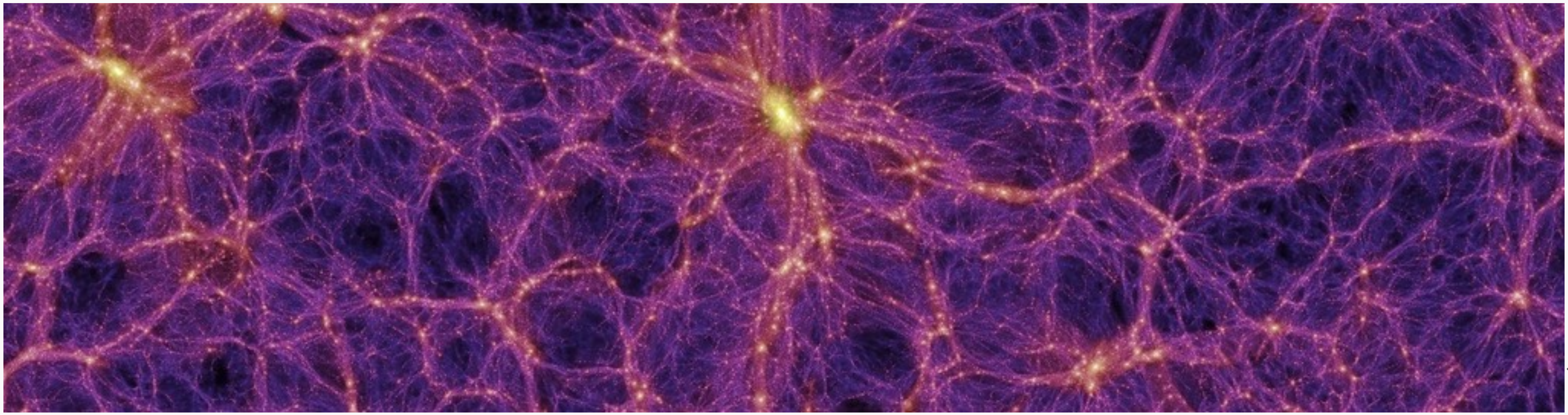
2020/1/22 Cosmological Structures in the Era of Large Surveys@KEK

Plan of this talk

- recap of basic cosmic shear theory
- analysis procedure
- ongoing cosmic shear surveys
- future prospect

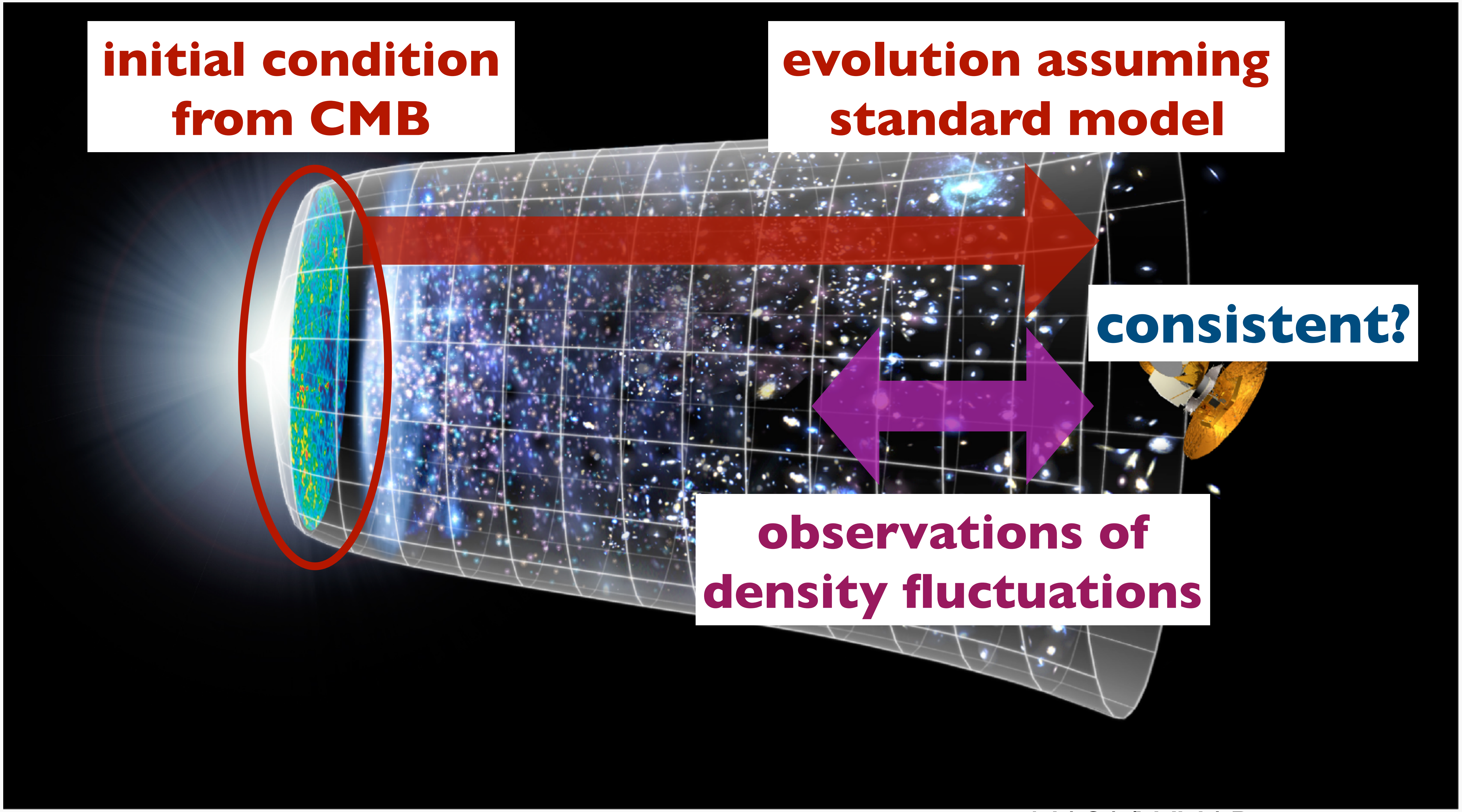
Why gravitational lensing?



- density fluctuations contain rich information

≈ **dark matter** density ⬅ **directly** probed by **gravitational lensing**!

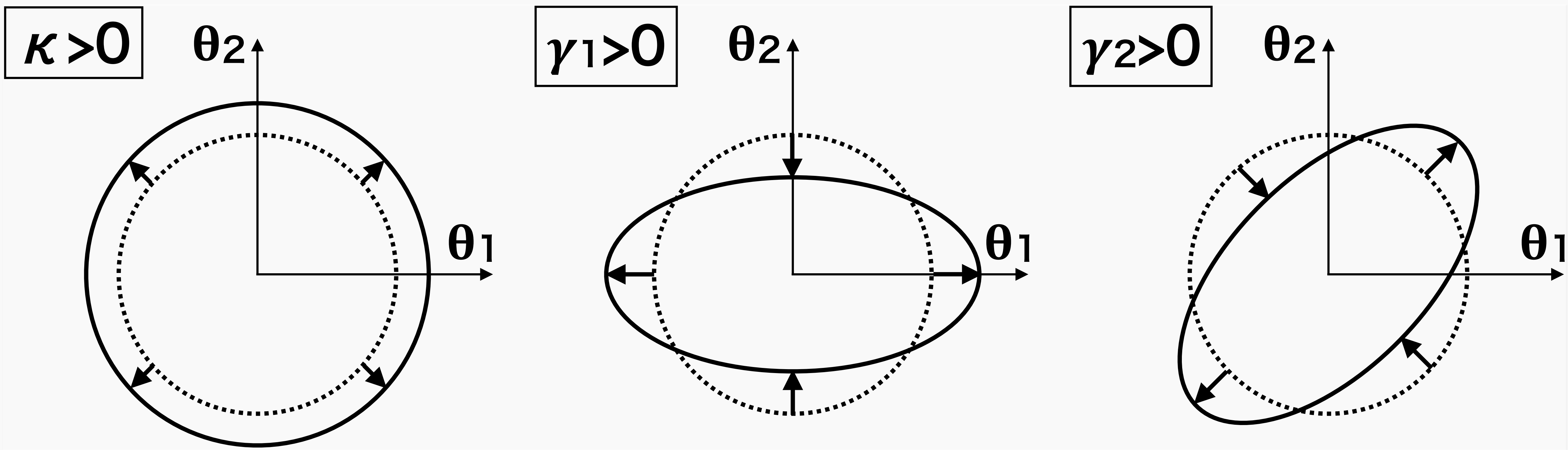
Consistency tests



NASA/WMAP science team

- clue to nature of dark matter/energy?

Weak lensing distortions



convergence κ

not easy to measure

shear γ

measured from galaxy shapes

Convergence and shear

lens potential (Born approximation)

$$\psi(\boldsymbol{\theta}) := \frac{2}{c^2}\int_0^{\chi_\mathrm{s}} d\chi \frac{f_K(\chi_\mathrm{s}-\chi)}{f_K(\chi) f_K(\chi_\mathrm{s})}\Phi(\chi,\boldsymbol{\theta})$$

2nd derivative

2nd derivative

$$\kappa := \frac{1}{2}\left(\psi_{,\theta_1\theta_1}+\psi_{,\theta_2\theta_2}\right)$$

related

$$\gamma_1 := \frac{1}{2}\left(\psi_{,\theta_1\theta_1}-\psi_{,\theta_2\theta_2}\right)$$

$$\gamma_2 := \psi_{,\theta_1\theta_2}$$

convergence κ

shear γ

Connection w/ density fluctuation

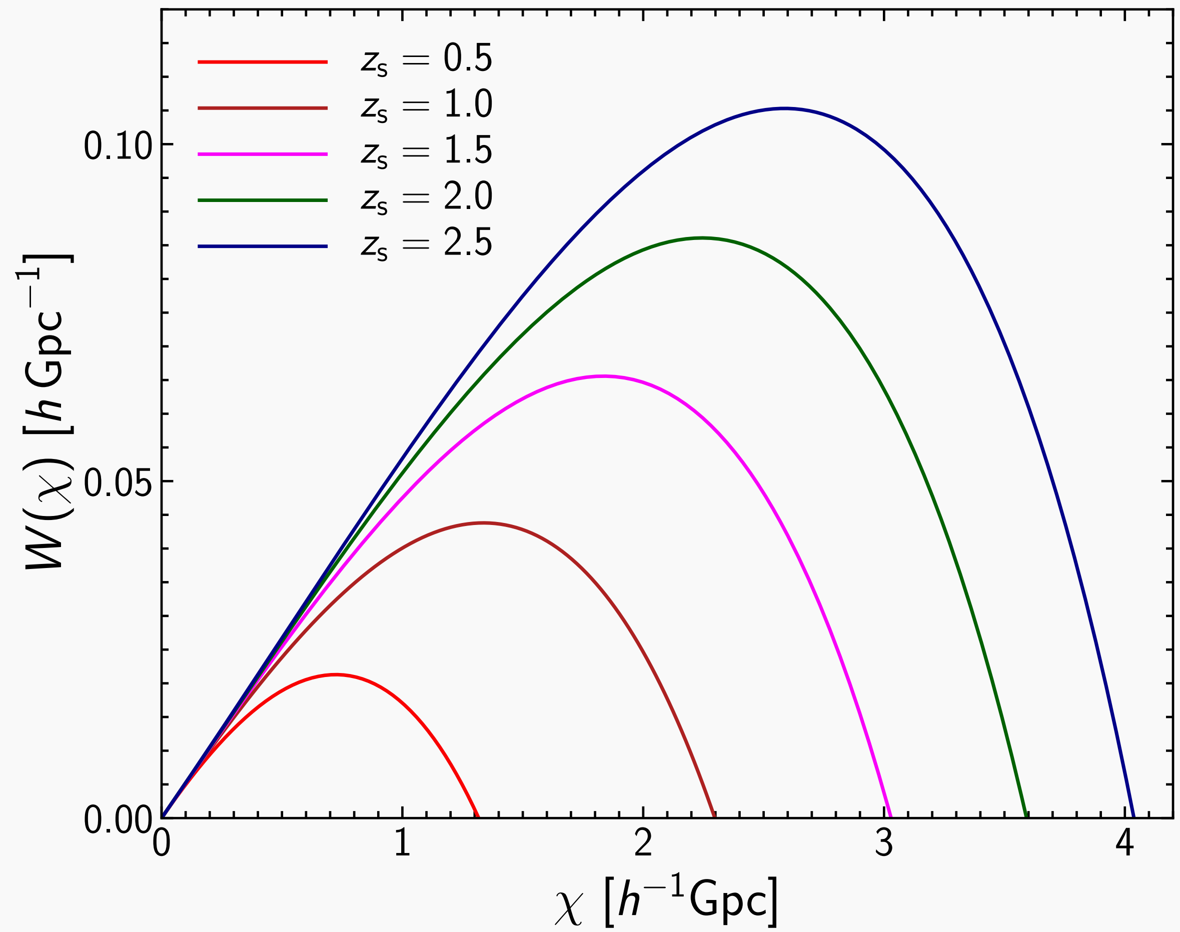
from **lens potential** + **Poisson equation**

$$\kappa(\boldsymbol{\theta}) = \int_0^{\chi_\mathrm{s}} d\chi\, W(\chi)\delta_\mathrm{m}(\chi, \boldsymbol{\theta})$$

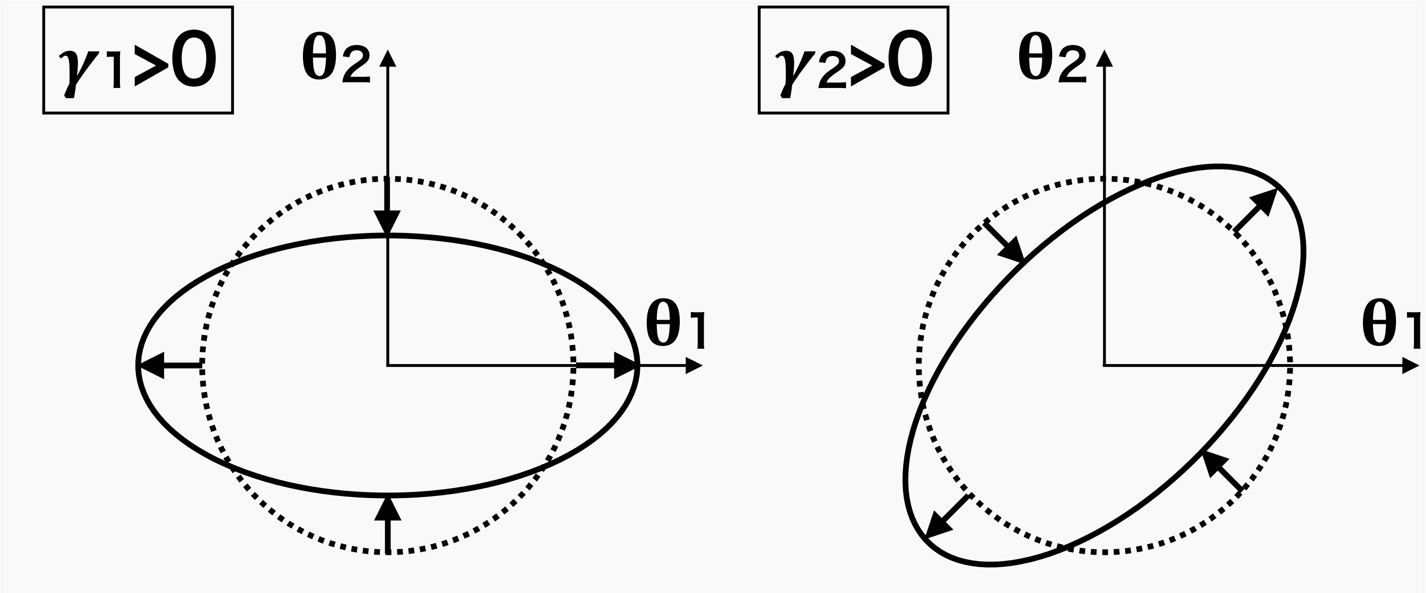
convergence
= projected surface density

$$W(\chi) := \frac{4\pi G}{c^4}\frac{f_K(\chi_\mathrm{s}-\chi)f_K(\chi)}{f_K(\chi_\mathrm{s})}\rho_\mathrm{m}a^2$$
$$= \frac{3\Omega_\mathrm{m0}H_0^2}{2c^2}\frac{f_K(\chi_\mathrm{s}-\chi)f_K(\chi)}{a\, f_K(\chi_\mathrm{s})}$$

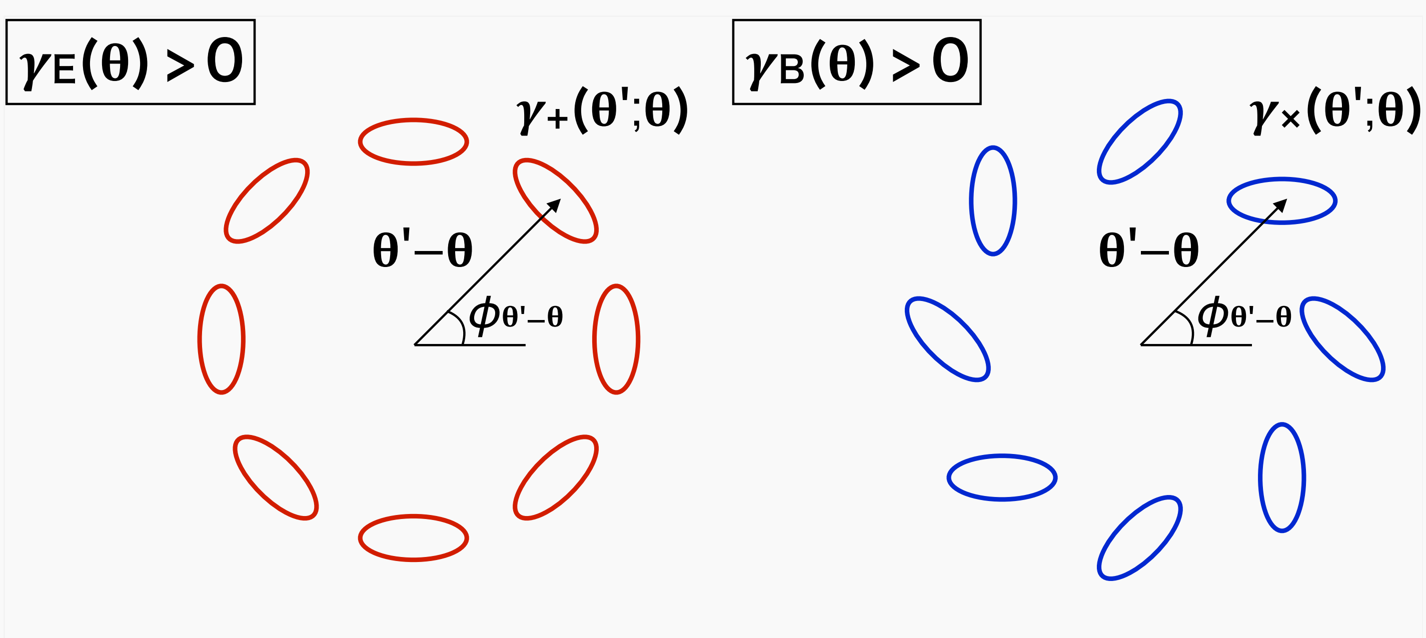
weight along line-of-sight



E/B decomposition



$$\tilde{\gamma}_{\rm E} + i\tilde{\gamma}_{\rm B} = e^{-2i\phi_{\ell}}\tilde{\gamma}$$



γ_1, γ_2

local

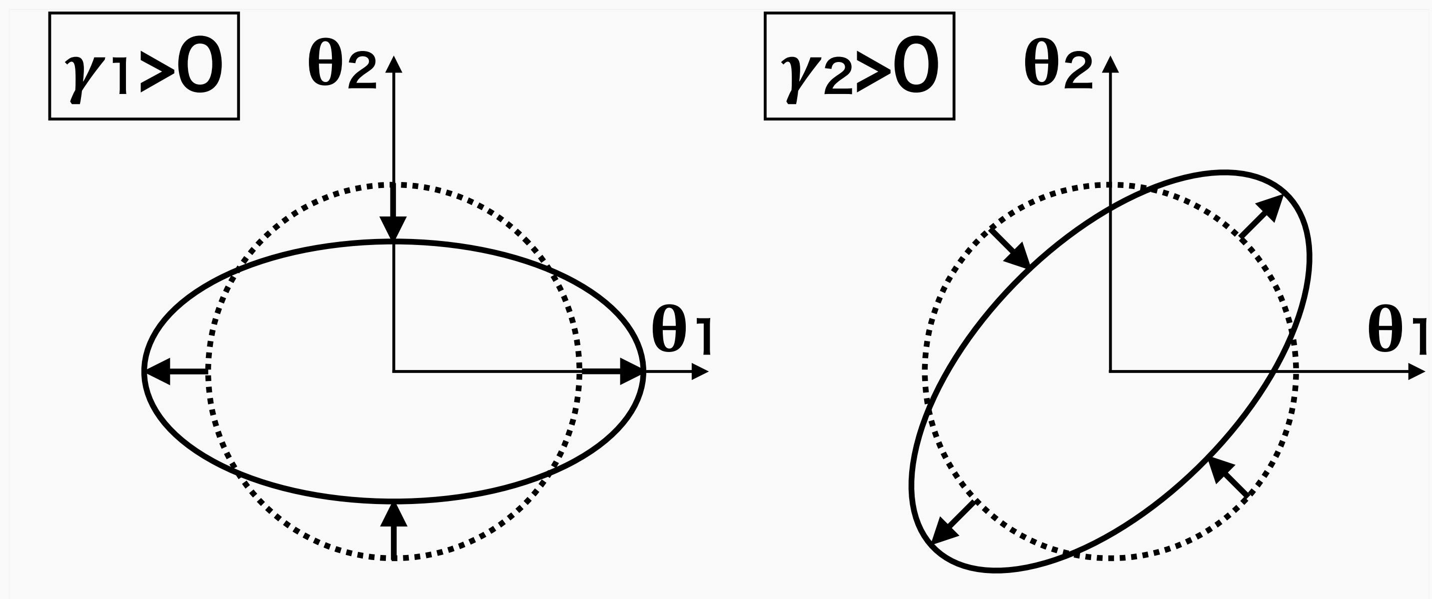
coordinate-dependent

γ_E, γ_B

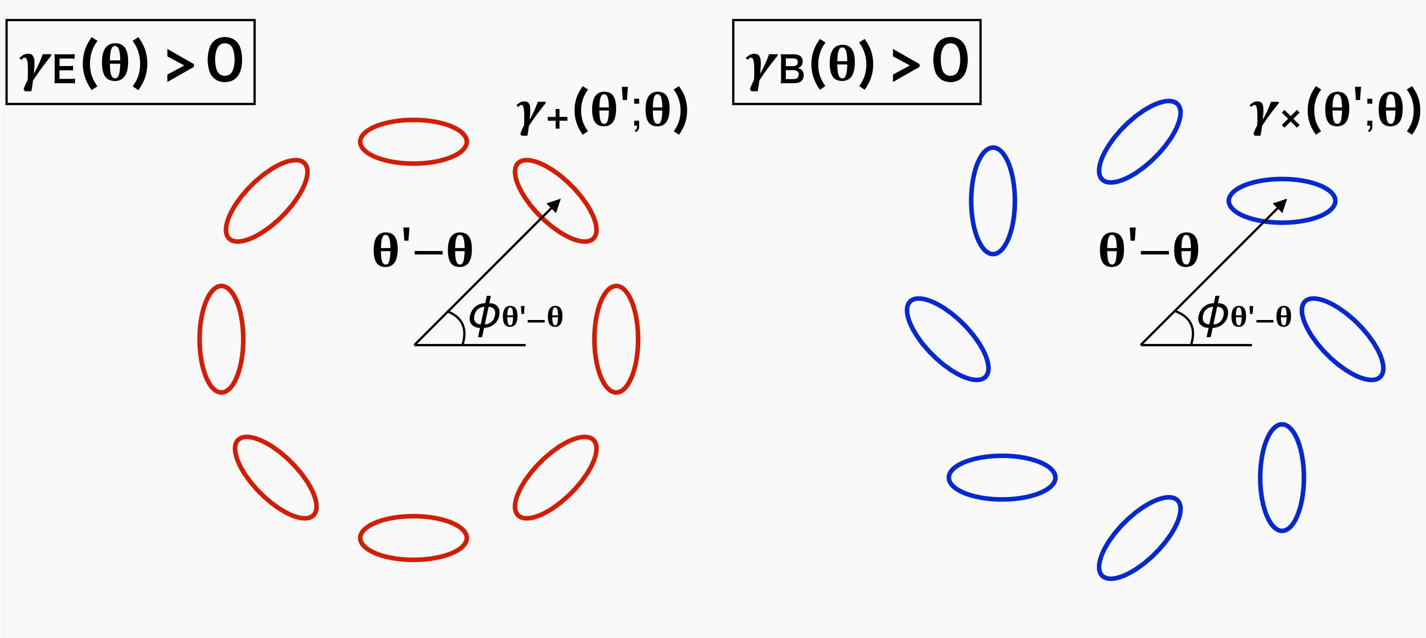
non-local

coordinate-independent

E/B decomposition



$$\tilde{\gamma}_{\mathrm{E}} + i\tilde{\gamma}_{\mathrm{B}} = e^{-2i\phi_{\ell}}\tilde{\gamma}$$



γ_1, γ_2

local

coordinate-dependent

(Born approximation)

$\gamma_E = \kappa$ $\gamma_B = 0$

γ_E, γ_B

non-local

coordinate-independent

Defining power spectrum

- angular power spectrum in Fourier space

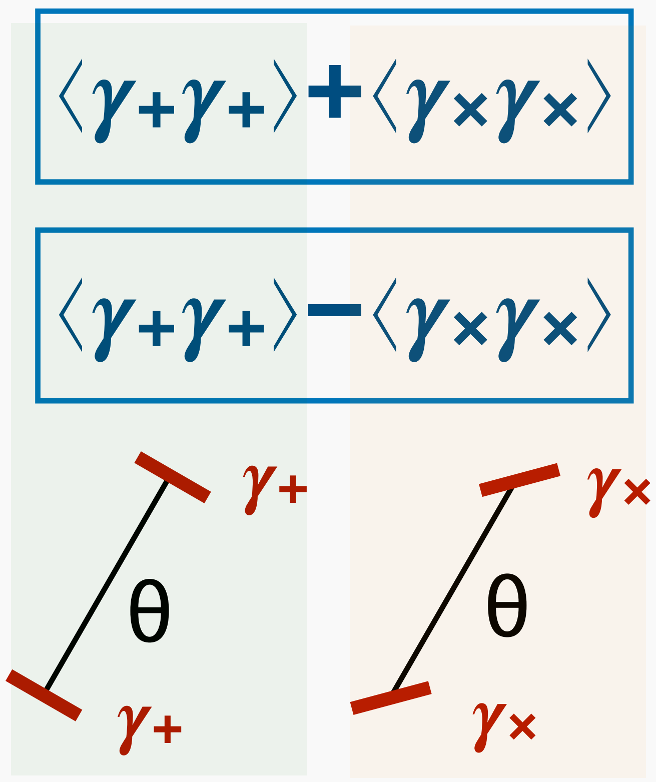
$$\langle \tilde{\kappa}(\boldsymbol{\ell})\tilde{\kappa}(\boldsymbol{\ell}')\rangle := (2\pi)^2 \delta^{\mathrm{D}}(\boldsymbol{\ell}+\boldsymbol{\ell}') C_\ell^{\kappa\kappa}$$

$$\langle \tilde{\gamma}_i(\boldsymbol{\ell})\tilde{\gamma}_j(\boldsymbol{\ell}')\rangle := (2\pi)^2 \delta^{\mathrm{D}}(\boldsymbol{\ell}+\boldsymbol{\ell}') C_{\boldsymbol{\ell}}^{\gamma_i\gamma_j}$$

- they are related to 2-point correlation func.

$$\xi_+(\theta) = \int_0^\infty \frac{\ell d\ell}{2\pi} \left(C_\ell^{\gamma_{\mathrm{E}}\gamma_{\mathrm{E}}} + C_\ell^{\gamma_{\mathrm{B}}\gamma_{\mathrm{B}}}\right) J_0(\ell\theta)$$

$$\xi_-(\theta) = \int_0^\infty \frac{\ell d\ell}{2\pi} \left(C_\ell^{\gamma_{\mathrm{E}}\gamma_{\mathrm{E}}} - C_\ell^{\gamma_{\mathrm{B}}\gamma_{\mathrm{B}}}\right) J_4(\ell\theta)$$



Cosmic shear power spectrum

- calculated under flat sky, Born, Limber approx.

$$C_\ell^{\kappa\kappa} = \int_0^{\chi_s} d\chi \frac{W^2(\chi)}{f_K^2(\chi)} P_m\left(\frac{\ell}{f_K(\chi)};\chi\right)$$

$=C_\ell^{\gamma_E\gamma_E}$

matter power spectrum

Cosmic shear power spectrum

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$$C_\ell^{\kappa\kappa} = \int_0^{\chi_s} d\chi \frac{W^2(\chi)}{f_K^2(\chi)} P_m\left(\frac{\ell}{f_K(\chi)};\chi\right)$$

$=C_\ell^{\gamma_E\gamma_E}$

matter power spectrum

$\ell \to \ell + 1/2$

improve accuracy at low-ℓ
(Loverde & Afshordi 2008)

Covariance

- measurement error under Gaussian approx.

$$\left[\mathrm{Cov}(\hat{C}_\ell^{\gamma_\mathrm{E}\gamma_\mathrm{E}})\right]_{ij} = \frac{2\delta_{ij}}{N_{\mathrm{mode},i}}\left(C_{\ell,i}^{\gamma_\mathrm{E}\gamma_\mathrm{E}} + \frac{\sigma_{\epsilon/2}^2}{2\bar{n}}\right)^2$$

cosmic variance **shape noise**

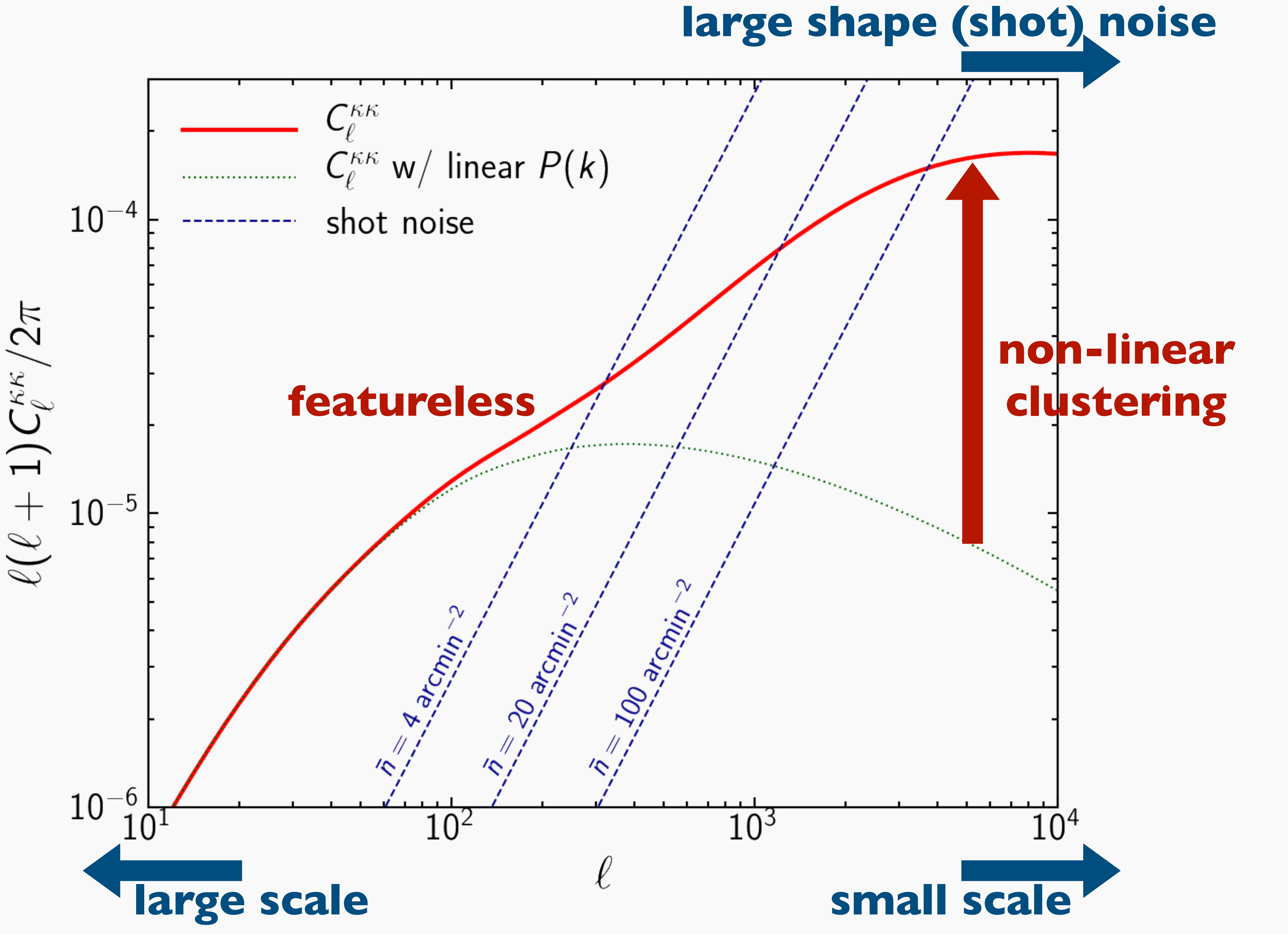
$$N_{\mathrm{mode},i} := \frac{\pi\left(\ell_{i,\mathrm{max}}^2 - \ell_{i,\mathrm{min}}^2\right)}{\Delta\ell^2} = f_\mathrm{sky}\left(\ell_{i,\mathrm{max}}^2 - \ell_{i,\mathrm{min}}^2\right)$$

$=\Omega_s/4\pi$ survey area

- non-Gaussian error also important

(e.g., Takada & Jain 2009; Takada & Hu 2013)

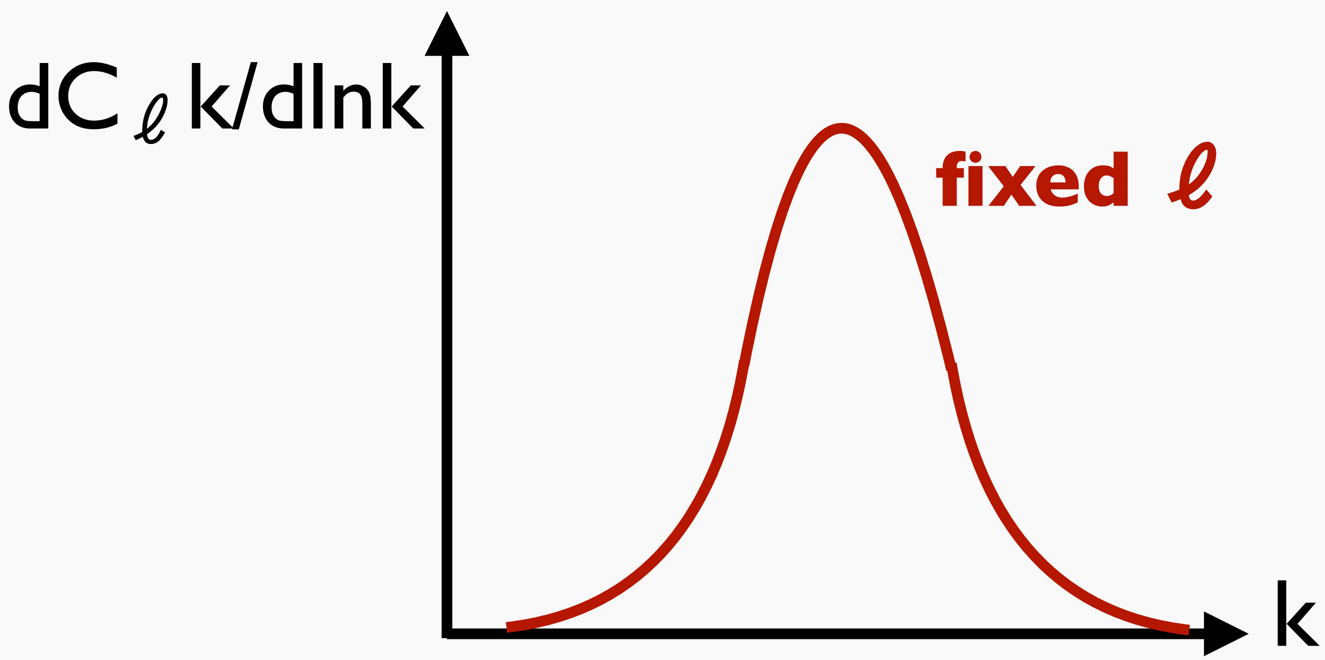
Example of C_ℓ

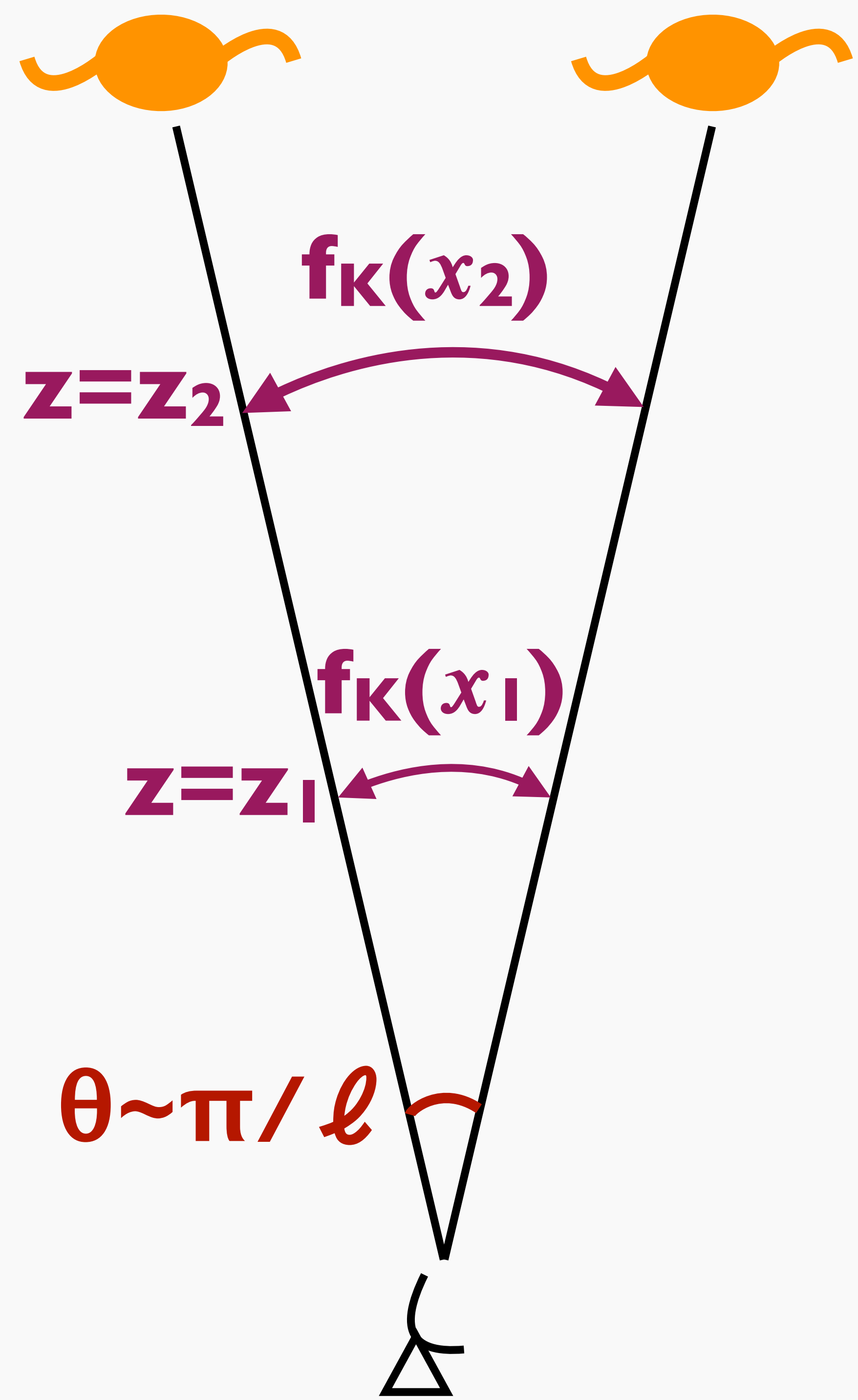


Mode mixing

wavenumber in $P_m(k)$

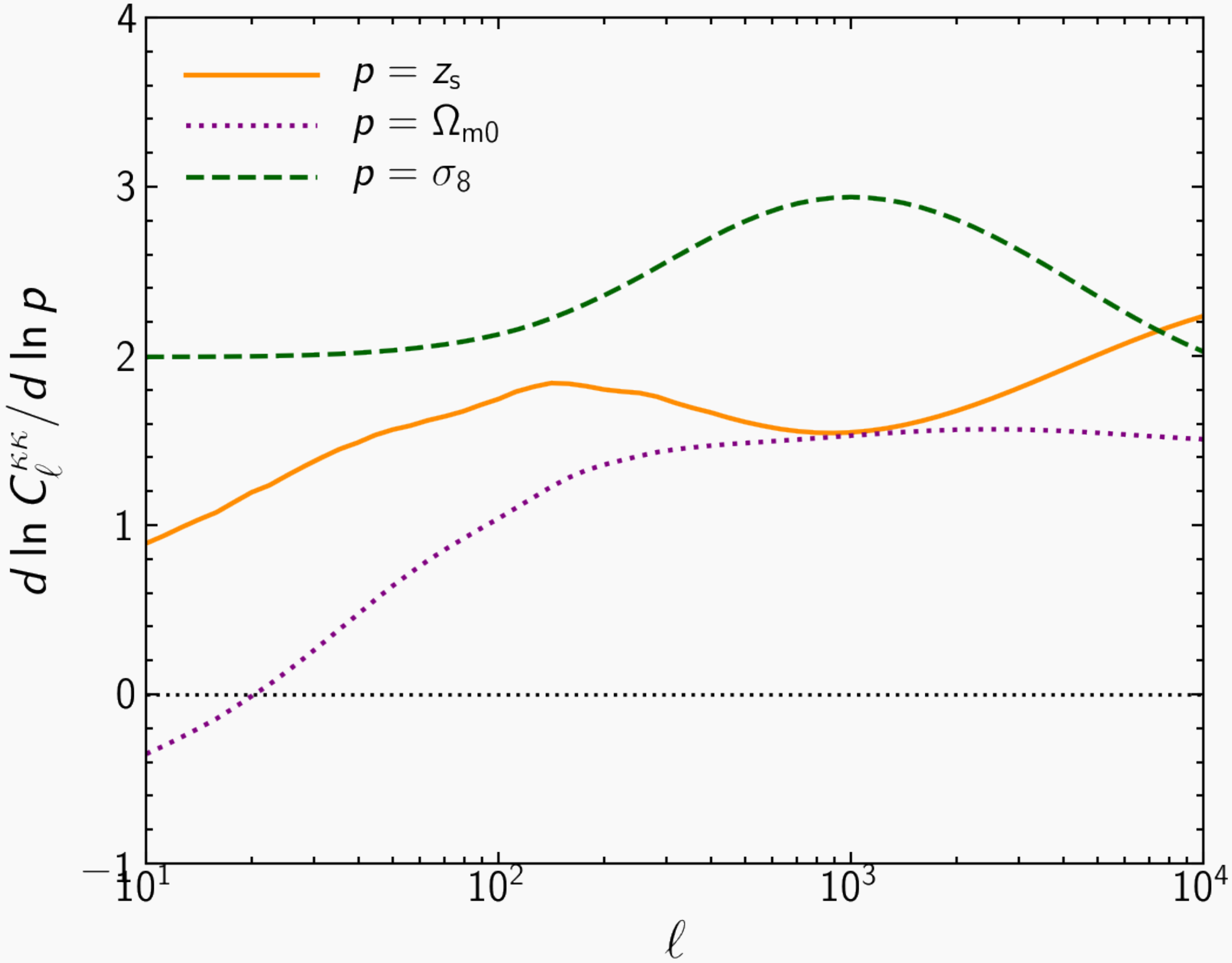
$$k = \frac{\ell}{f_K(\chi)}$$





→ smooth out features (BAO) in $P_m(k)$

Parameter dependence



$$C_{\ell=1000}^{\kappa\kappa} \propto z_s^{1.5} \Omega_{m0}^{1.5} \sigma_8^{2.9}$$

(around z_s=1, Planck cosmology)

Ω_{m0}–σ_8 degeneracy

z_s is important

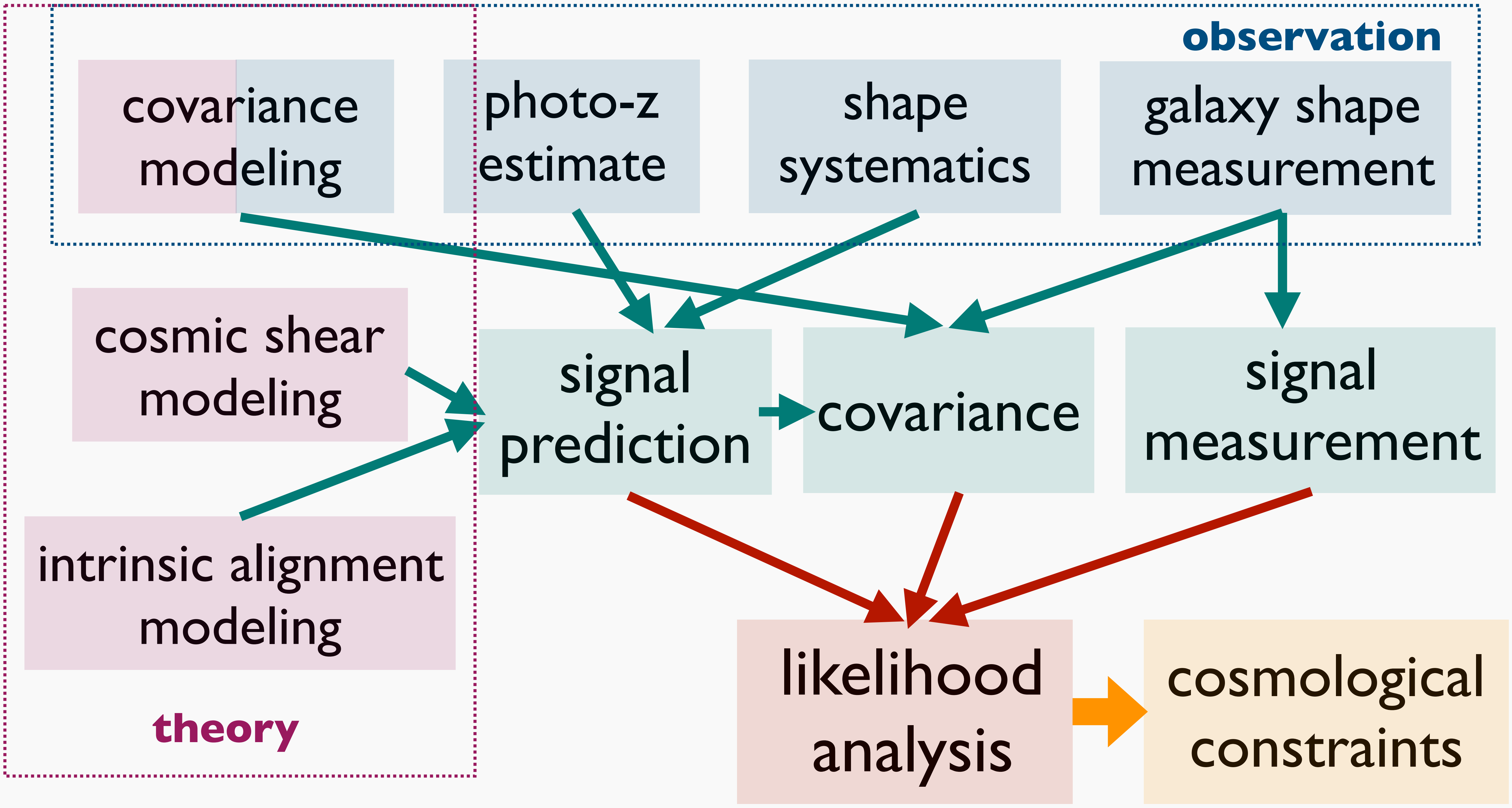
Analysis procedure

- real world is messy

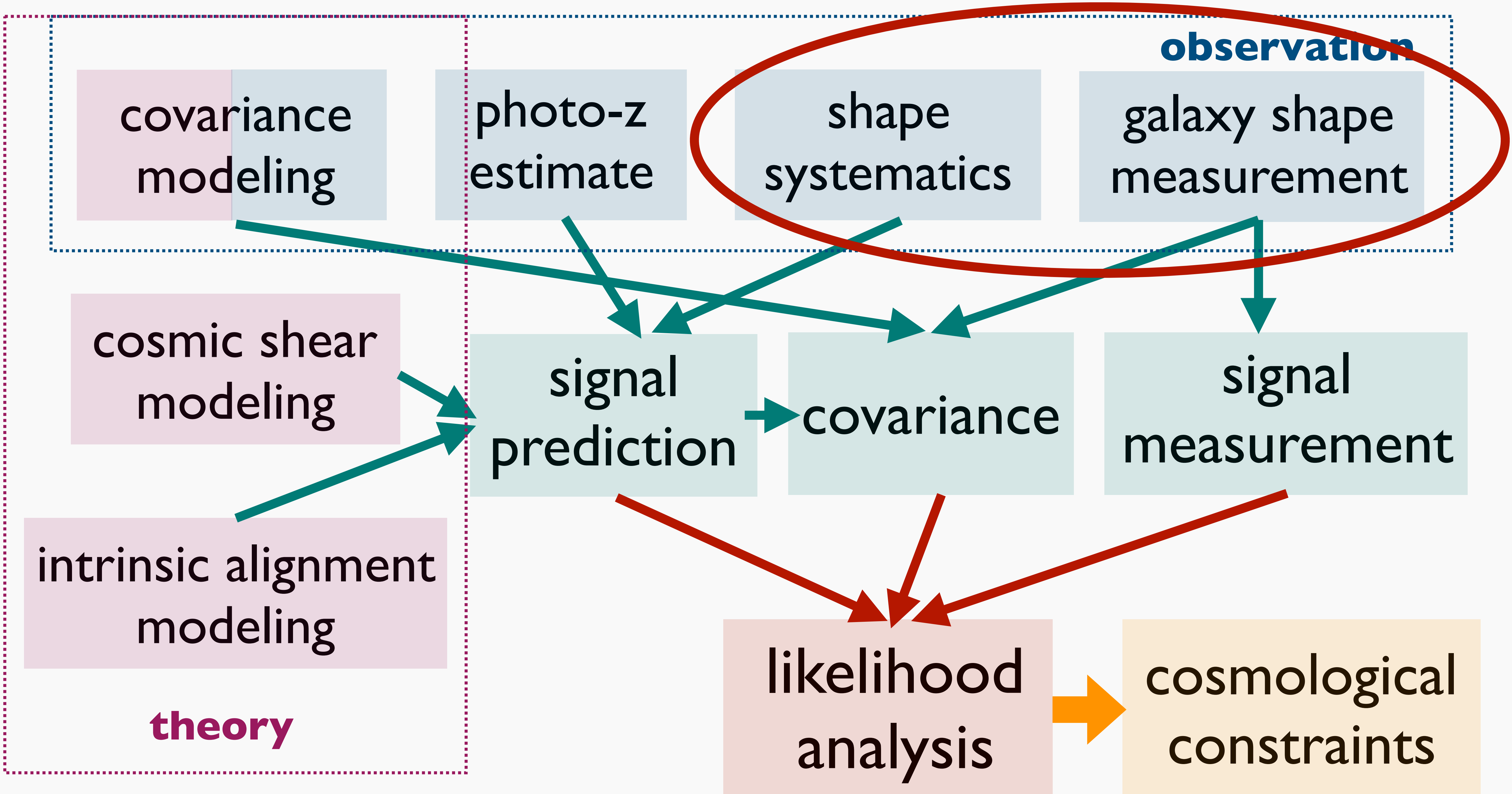
Real vs Fourier space

	Real space $\xi_\pm(\theta)$	**Fourier space** C_ℓ
measurement	**easy**	**difficult**
theoretical modeling	**difficult**	**easy**
popularity	(so far) **more popular**	(so far) **less popular**

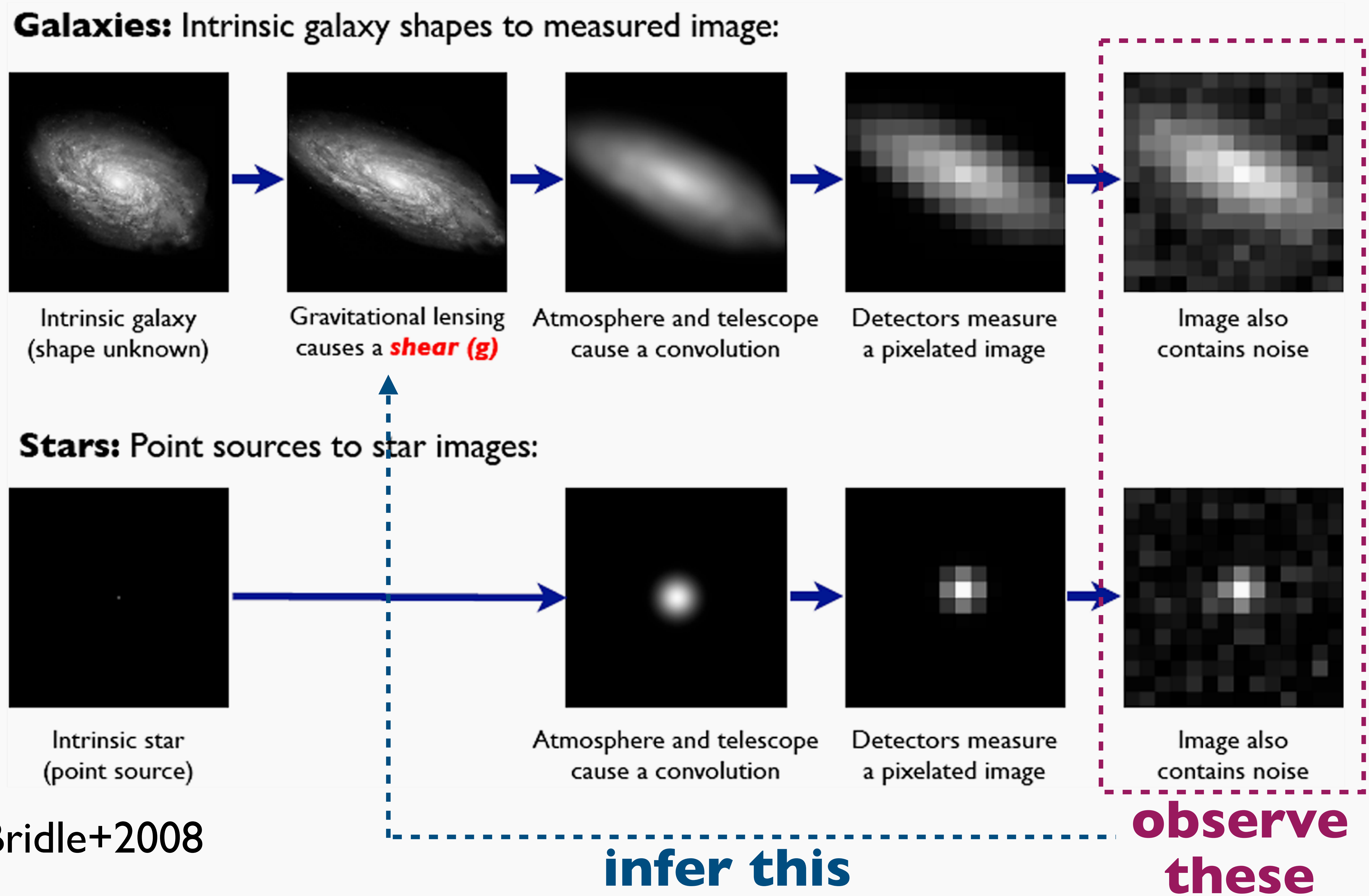
Analysis procedure: summary



Galaxy shape measurement



Shape measurement



Bridle+2008

Calibration by image simulations

mock images of galaxies and stars

↓

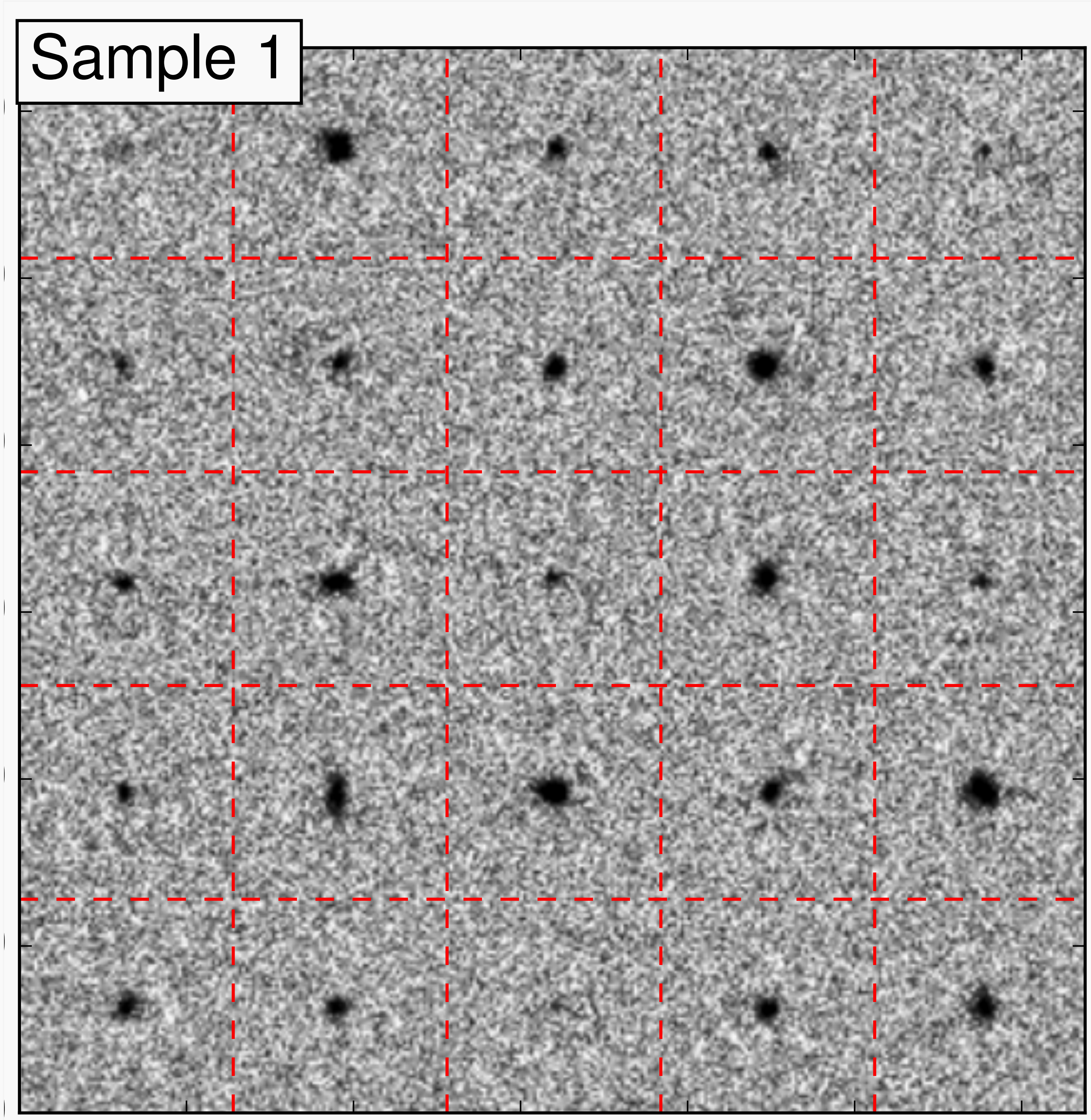
apply your shape measurements

↓

compare input γ and inferred γ

↓

calibrate residuals



Mandelbaum+2018

Checking systematics

- PSF leakage into measured shear

$$\underline{\gamma_{\rm obs}} = \gamma_{\rm true} + a\underline{e_{\rm PSF}}$$

from galaxy **$\approx e_{\rm star}$**

- checking by galaxy-star shape correlation

$$\underline{\langle \gamma_{\rm obs} e_{\rm star} \rangle} \approx a \underline{\langle e_{\rm star} e_{\rm star} \rangle}$$

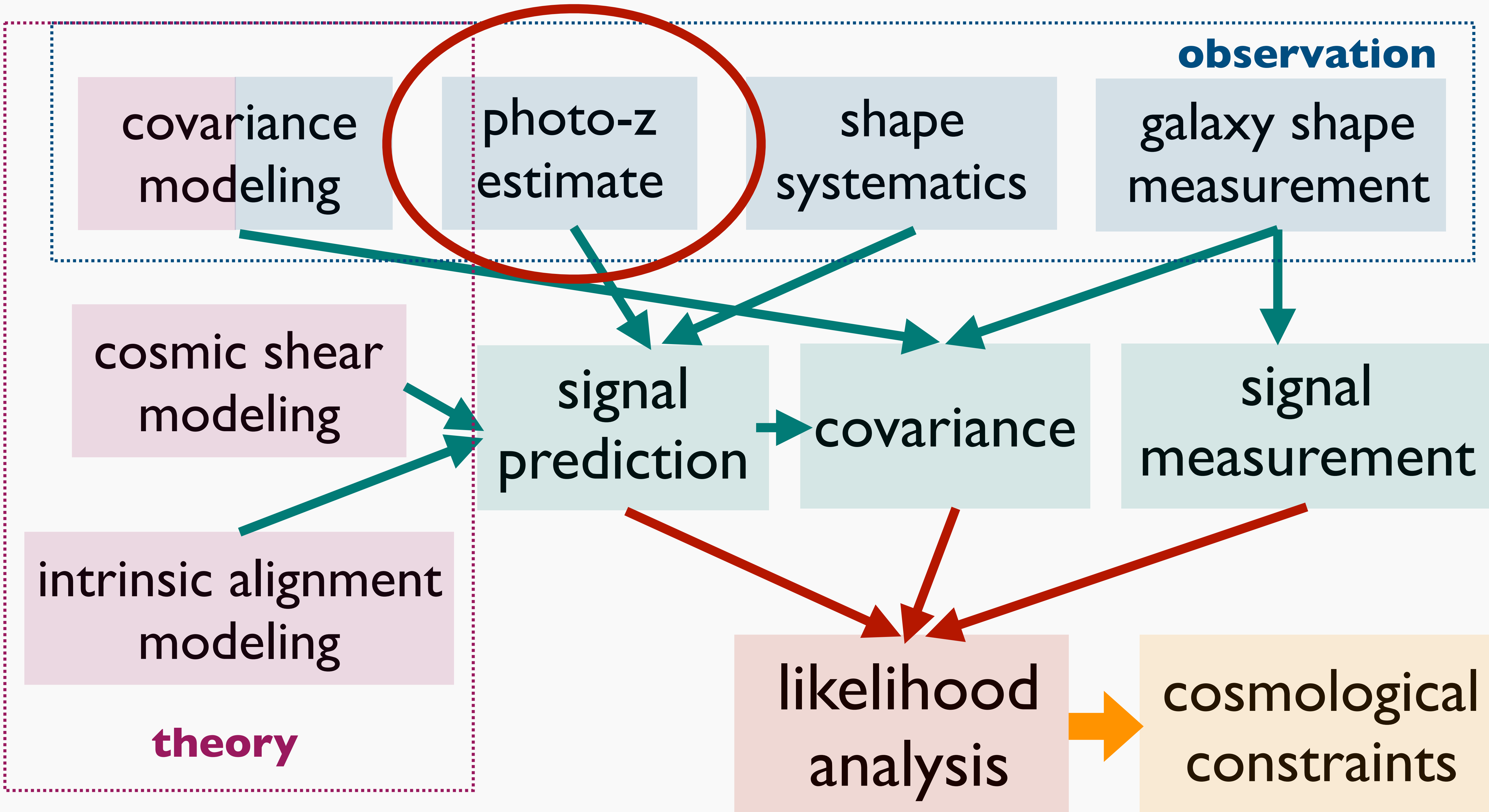
galaxy-star cross **star-star auto**

- estimate its impact on signal

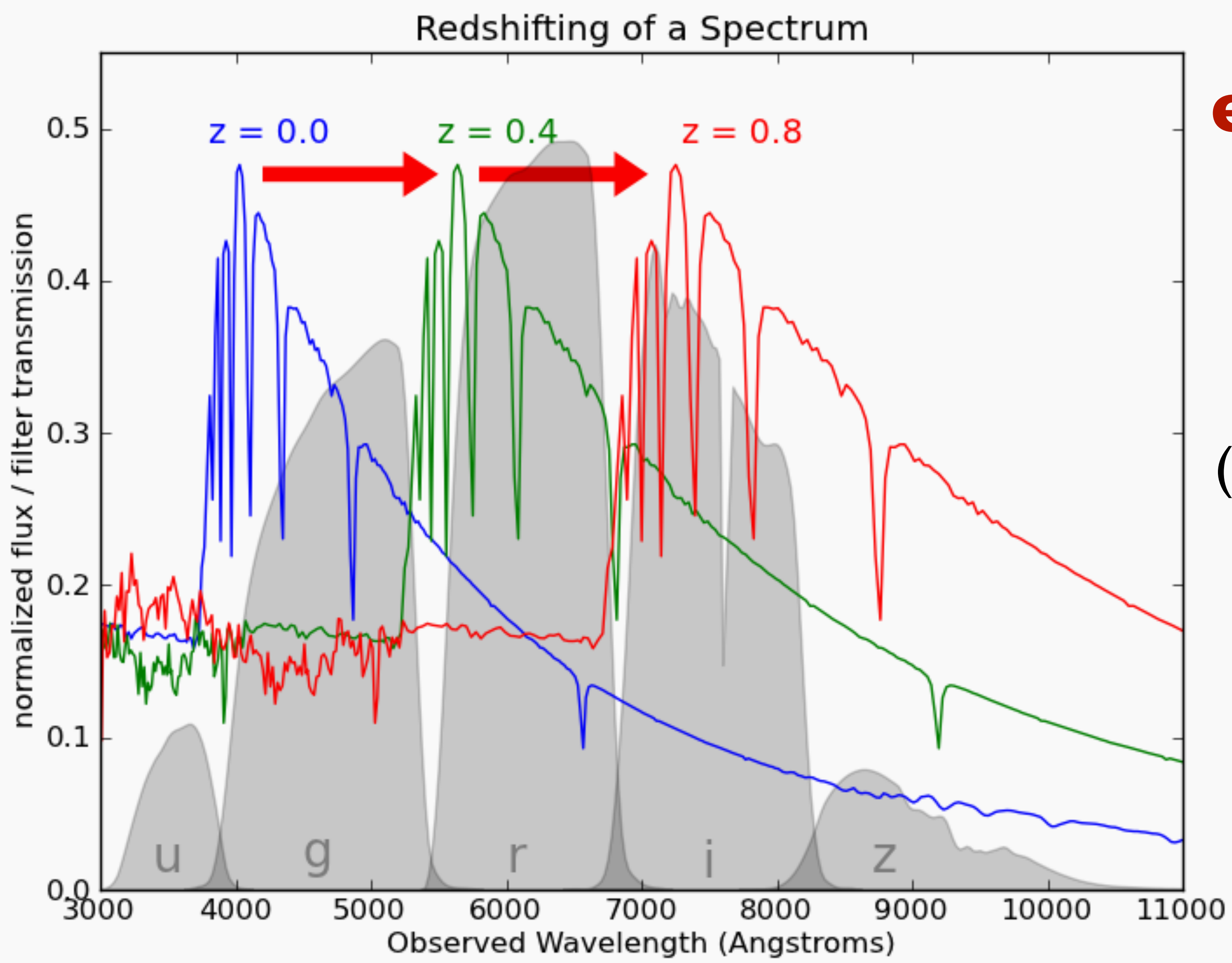
$$\langle \gamma_{\rm obs} \gamma_{\rm obs} \rangle = \langle \gamma_{\rm true} \gamma_{\rm true} \rangle + \underline{a^2} \langle e_{\rm PSF} e_{\rm PSF} \rangle$$

from galaxy-star/star-star

Photometric redshift



Photometric redshift estimate



estimate redshift by broadband colors

$$C_{\ell=1000}^{\kappa\kappa} \propto z_{\rm s}^{1.5}\Omega_{\rm m0}^{1.5}\sigma_8^{2.9}$$

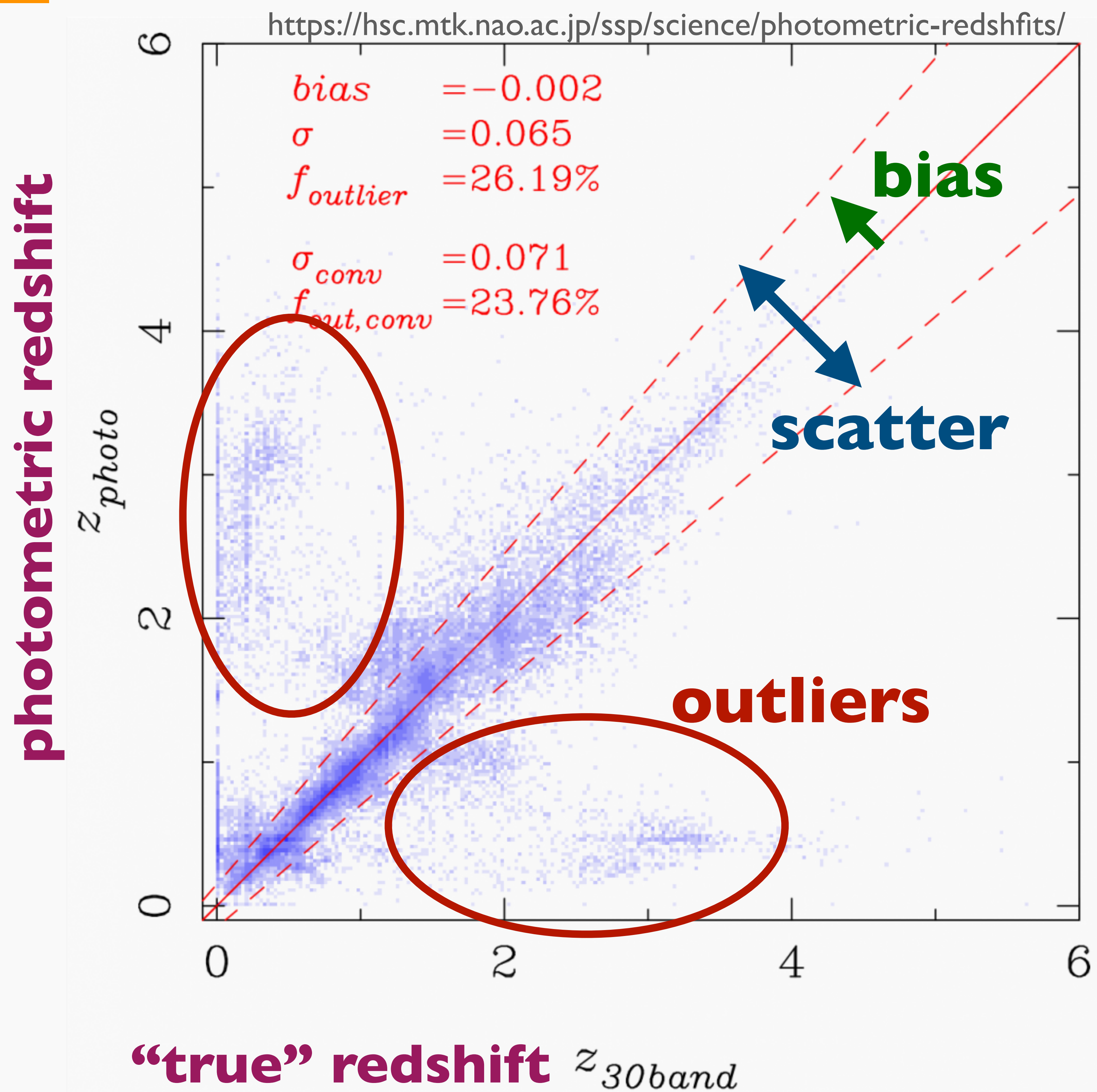
(around z_s=1, Planck cosmology)

3% σ_8 measurement

6% accuracy of z_s is needed

https://ogrisel.github.io/scikit-learn.org/sklearn-tutorial/tutorial/astronomy/regression.html

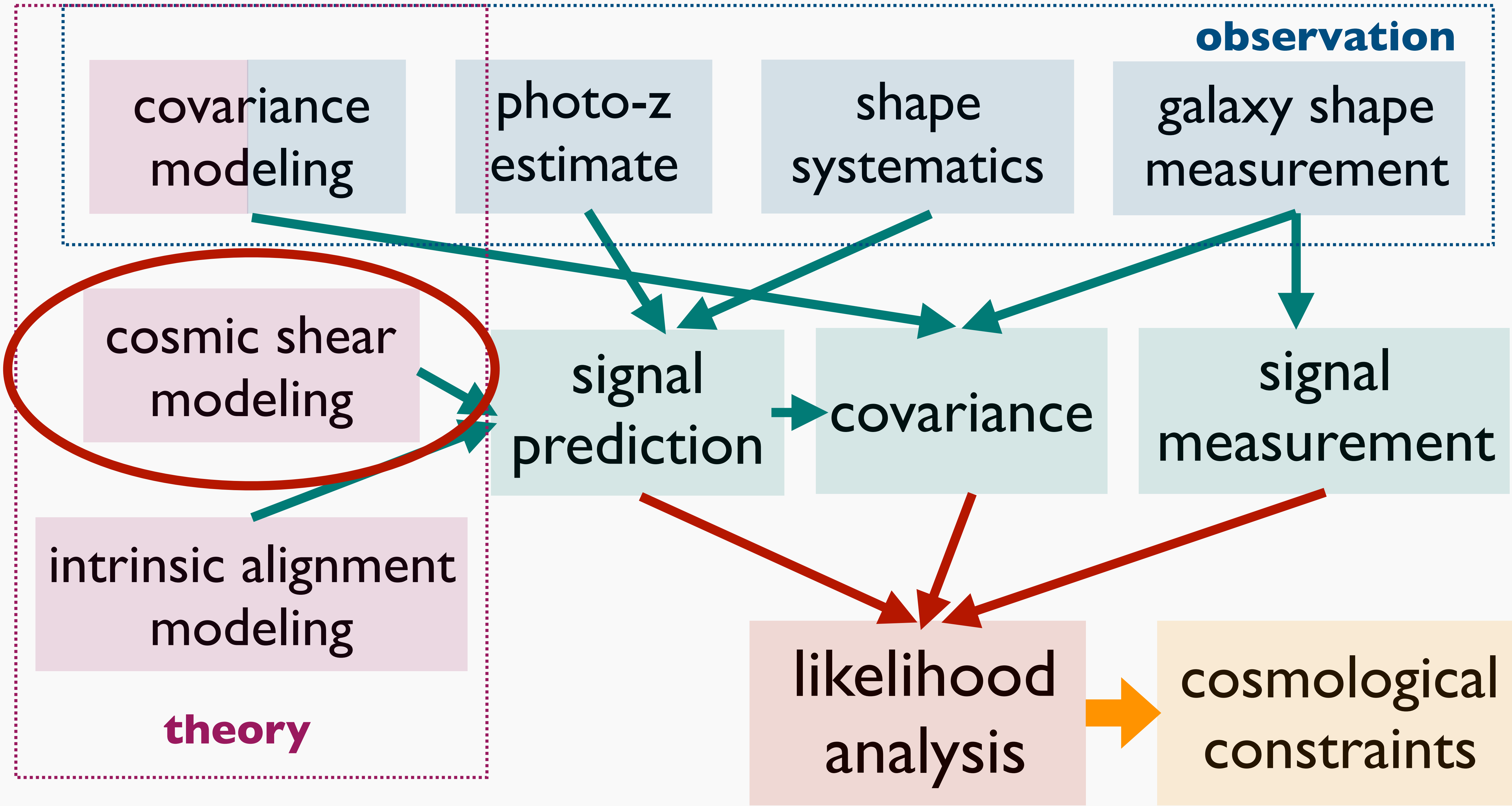
Photometric redshift error



$z_{photo} - z_{true}$ dist. is complicated

accurate error estimate/propagation is a big challenge

Cosmic shear modeling



Cosmic shear power spectrum

- calculated under flat sky, Born, Limber approx.

$$C_\ell^{\kappa\kappa} = \int_0^{\chi_{\rm s}} d\chi \frac{W(\chi)}{f_K^2(\chi)} P_{\rm m}\left(\frac{\ell}{f_K(\chi)};\chi\right)$$

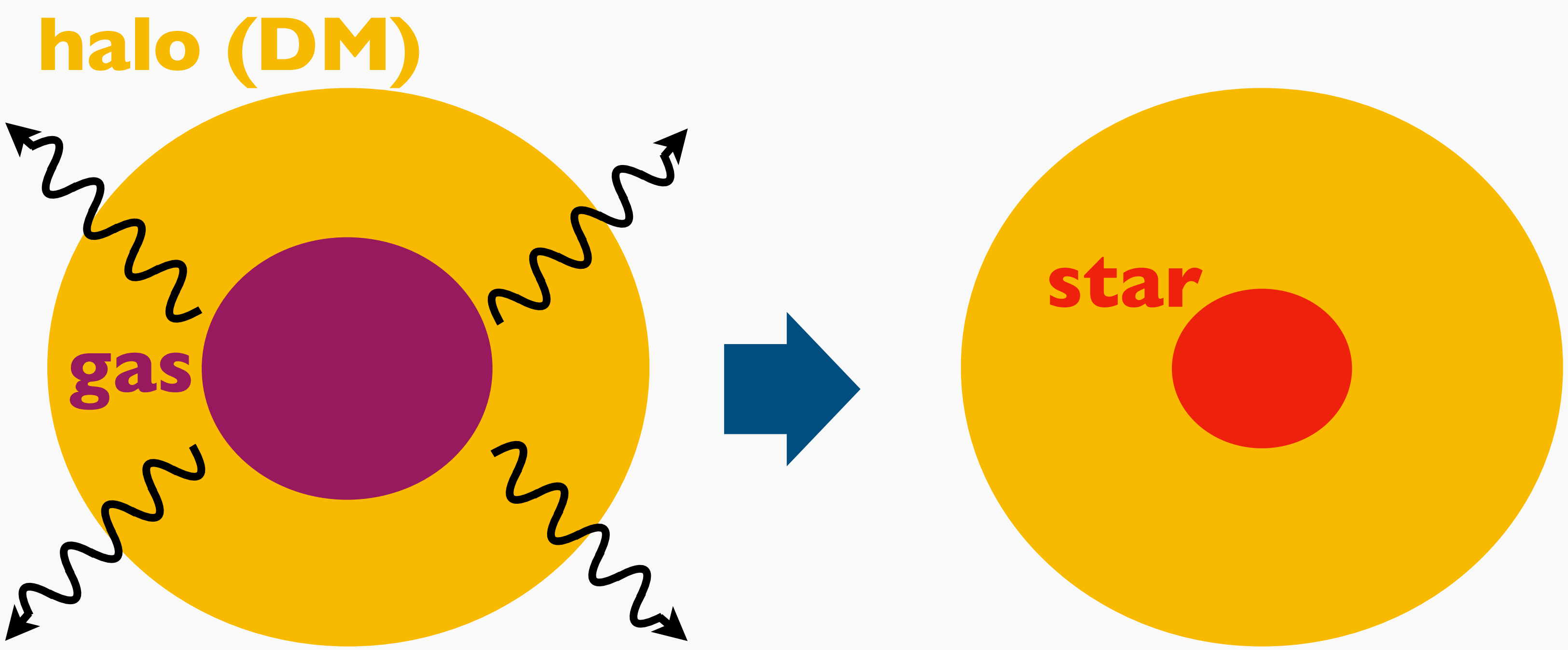
$= C_\ell^{\gamma_E \gamma_E}$

matter power spectrum

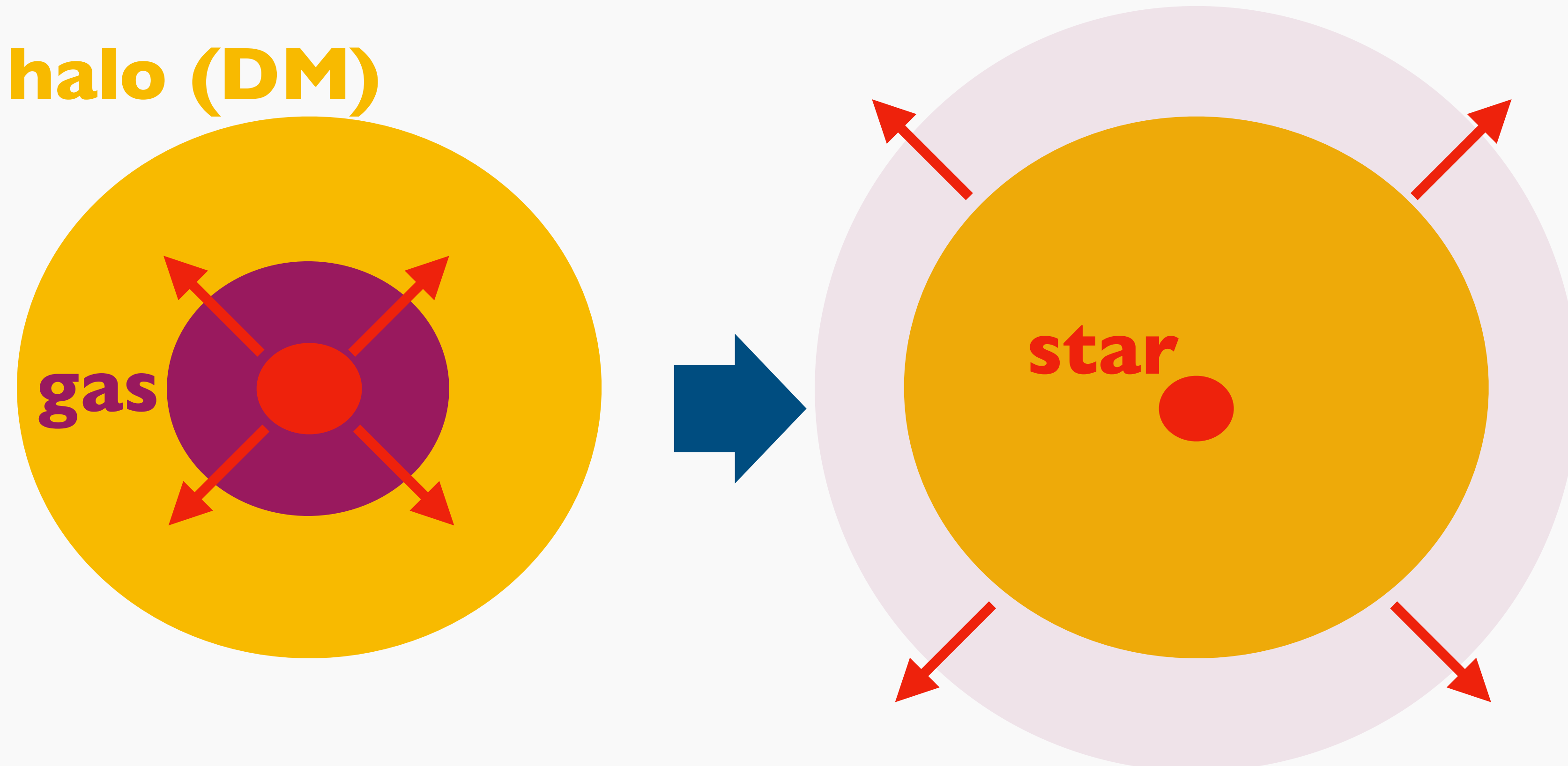
from N-body simulations

(fitting formula e.g., Takahashi+2012)

Effect of baryon physics

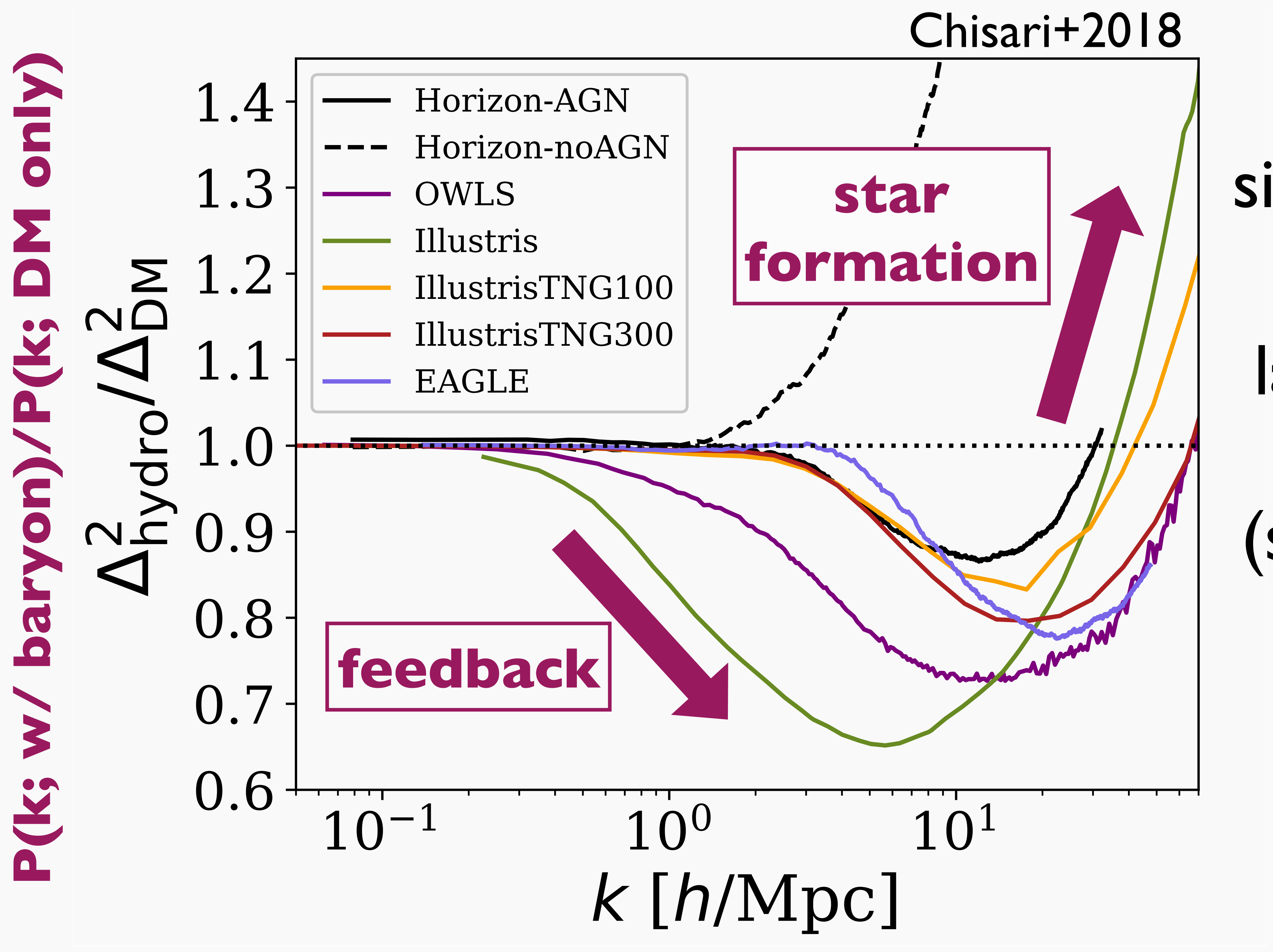


star formation by radiative cooling
P(k) increase



gas expelled by feedback
P(k) decrease

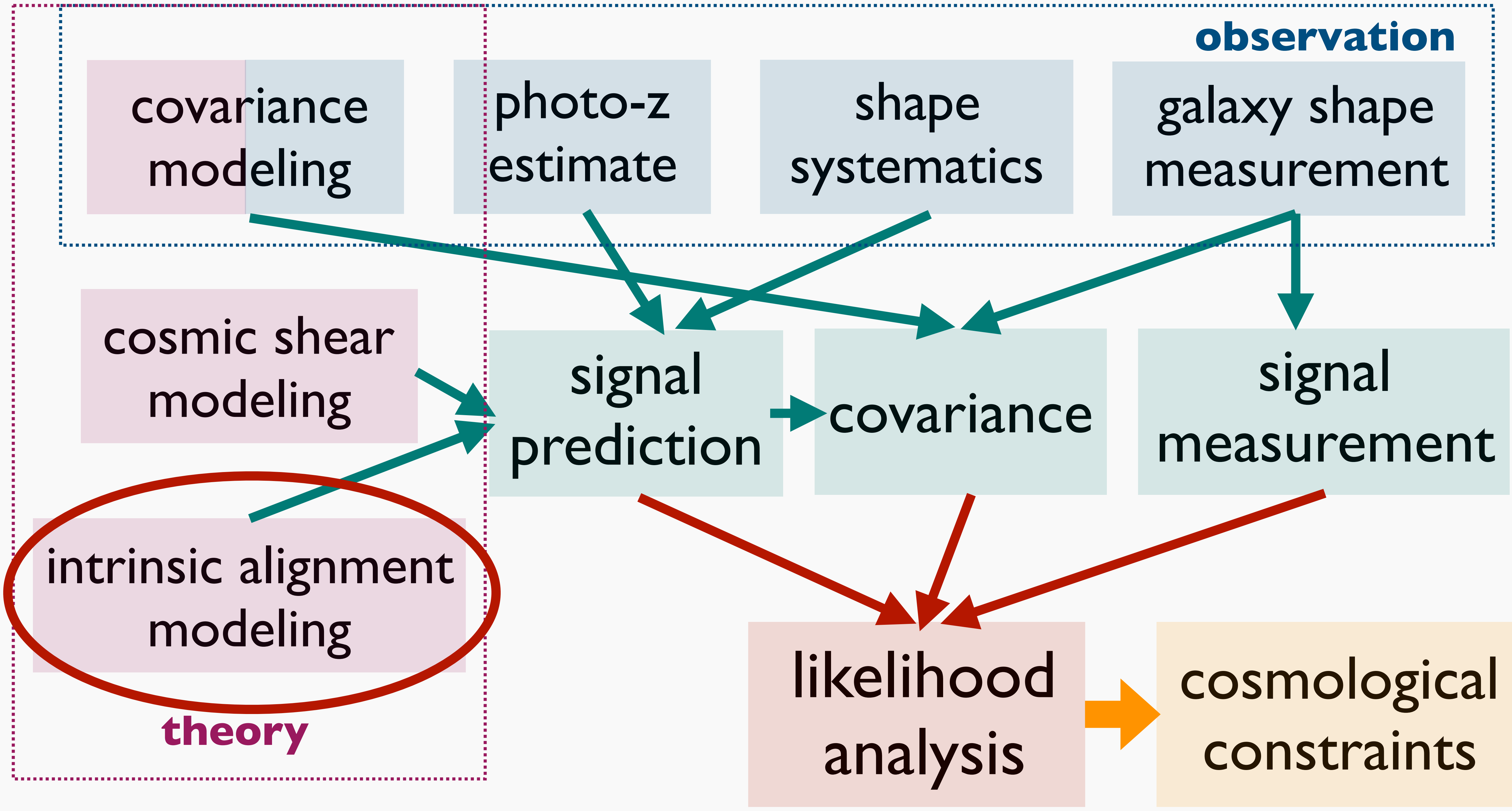
Modification of power spectrum



significant impact

large simulation dependence (subgrid physics)

Intrinsic alignment



What is intrinsic alignment?

- intrinsic galaxy orientations are **not** random

radial alignment

  - tidal torquing
  - merger/accretion along filament
  - …

- important systematics in cosmic shear

Effect of intrinsic alignment

$$\gamma_{\rm true} = \underbrace{\gamma_{\rm G}}_{\text{cosmic shear}} + \underbrace{\gamma_{\rm I}}_{\text{intrinsic alignment}}$$

cosmic shear **intrinsic alignment**

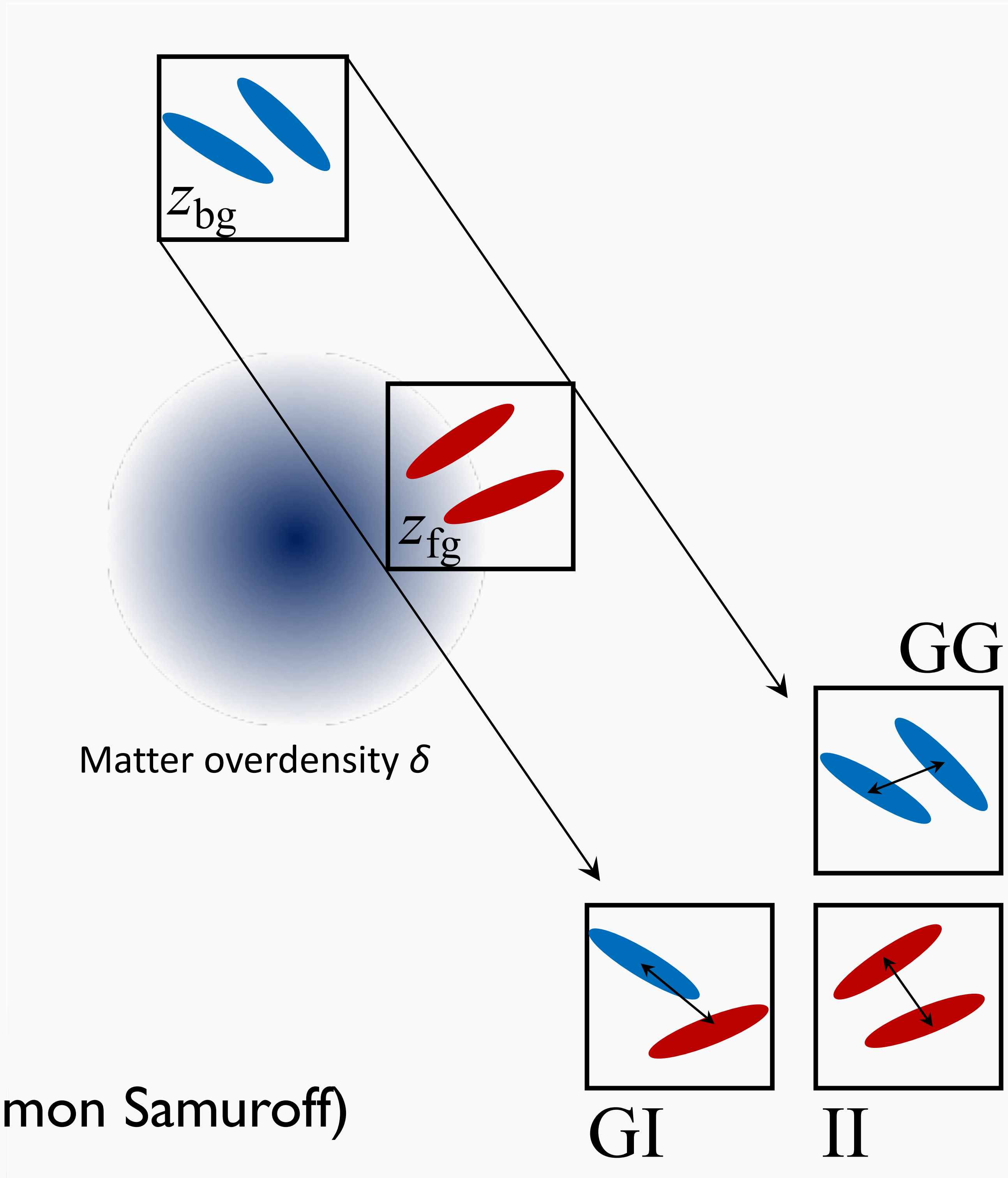
$$\langle \gamma_{\rm true} \gamma_{\rm true} \rangle = \langle \gamma_{\rm G} \gamma_{\rm G} \rangle + \langle \gamma_{\rm G} \gamma_{\rm I} \rangle + \langle \gamma_{\rm I} \gamma_{\rm G} \rangle + \langle \gamma_{\rm I} \gamma_{\rm I} \rangle$$

GG **GI** **GI** **II**

our main interest (GG)

marginalize over (GI, GI, II)

Effect of intrinsic alignment

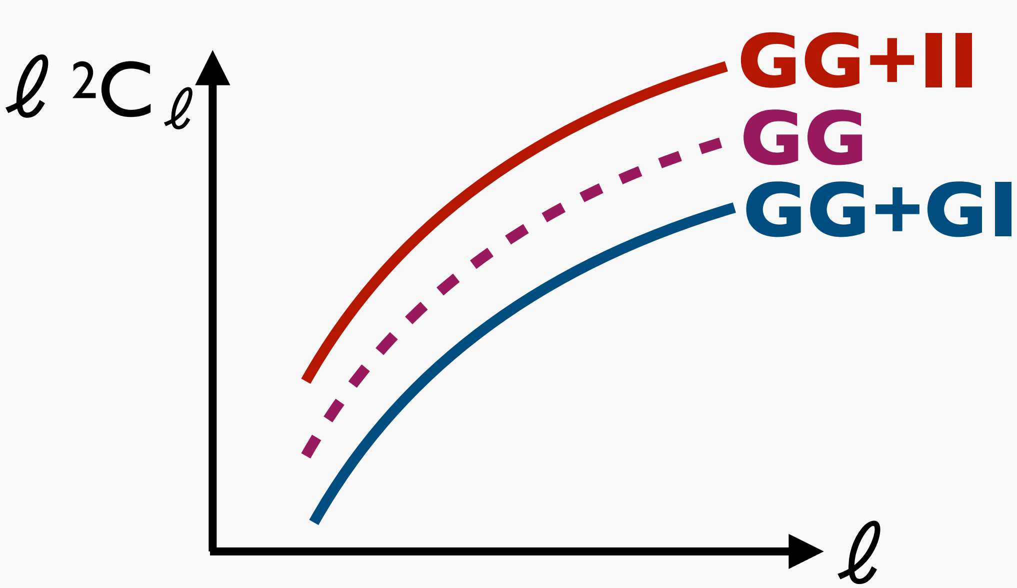


(Simon Samuroff)

GG
cosmic shear signal

II
same sign as GG

GI
opposite sign as GG



Model of intrinsic alignment

- nonlinear alignment model (Bridle & King 2007)

$$\gamma_{\rm I} \sim -C(\nabla^2_{\theta_1} - \nabla^2_{\theta_2} + 2i\nabla_{\theta_1}\nabla_{\theta_2})\Phi$$

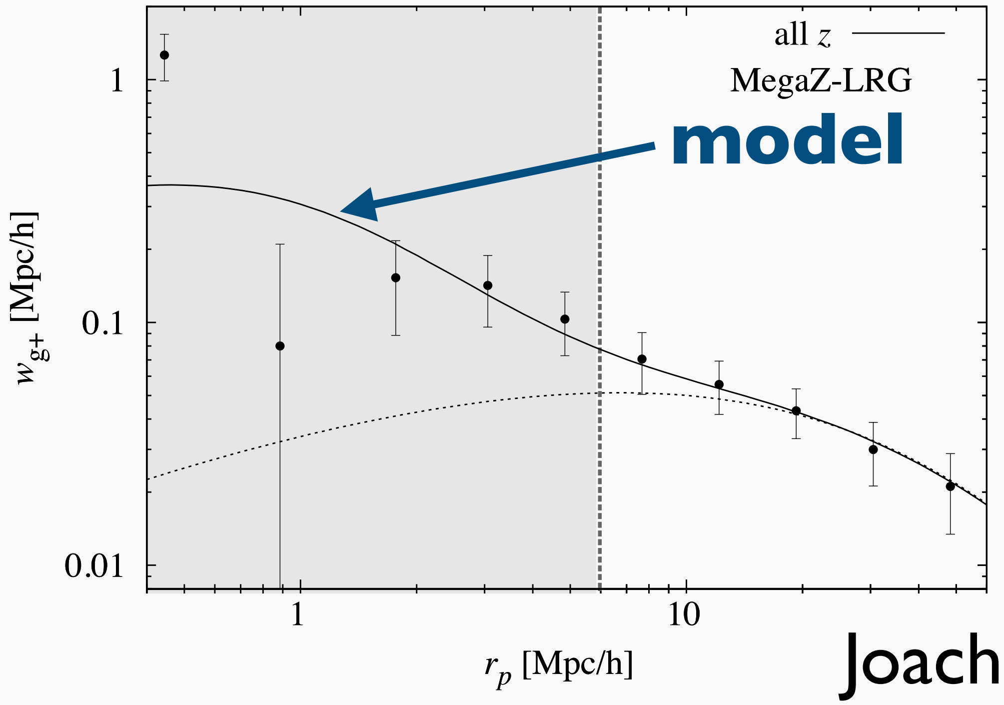
intrinsic shape align with tidal field

$$P_{\rm GI}(k) = -C' \underline{P_{\rm m}(k)}$$

$$P_{\rm II}(k) = C'^2 \underline{P_{\rm m}(k)}$$

(nonlinear) matter power spectrum

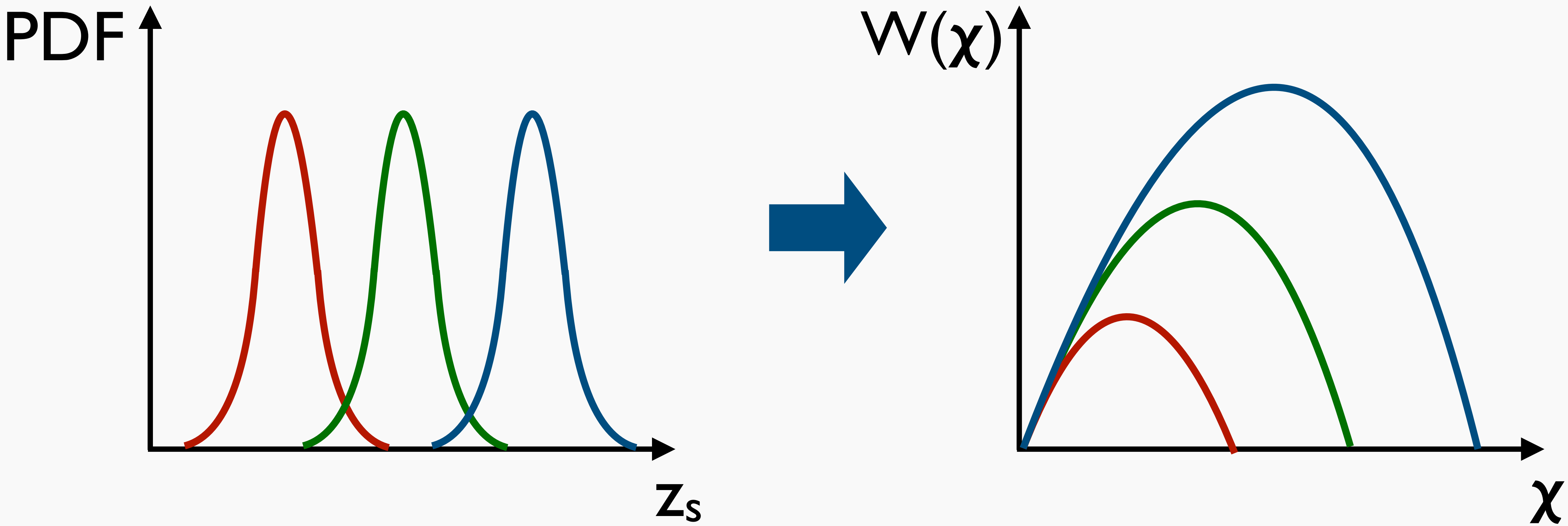
GI correlation



consistent with observations

Joachimi+2011

Cosmic shear tomography (Hu 1999)

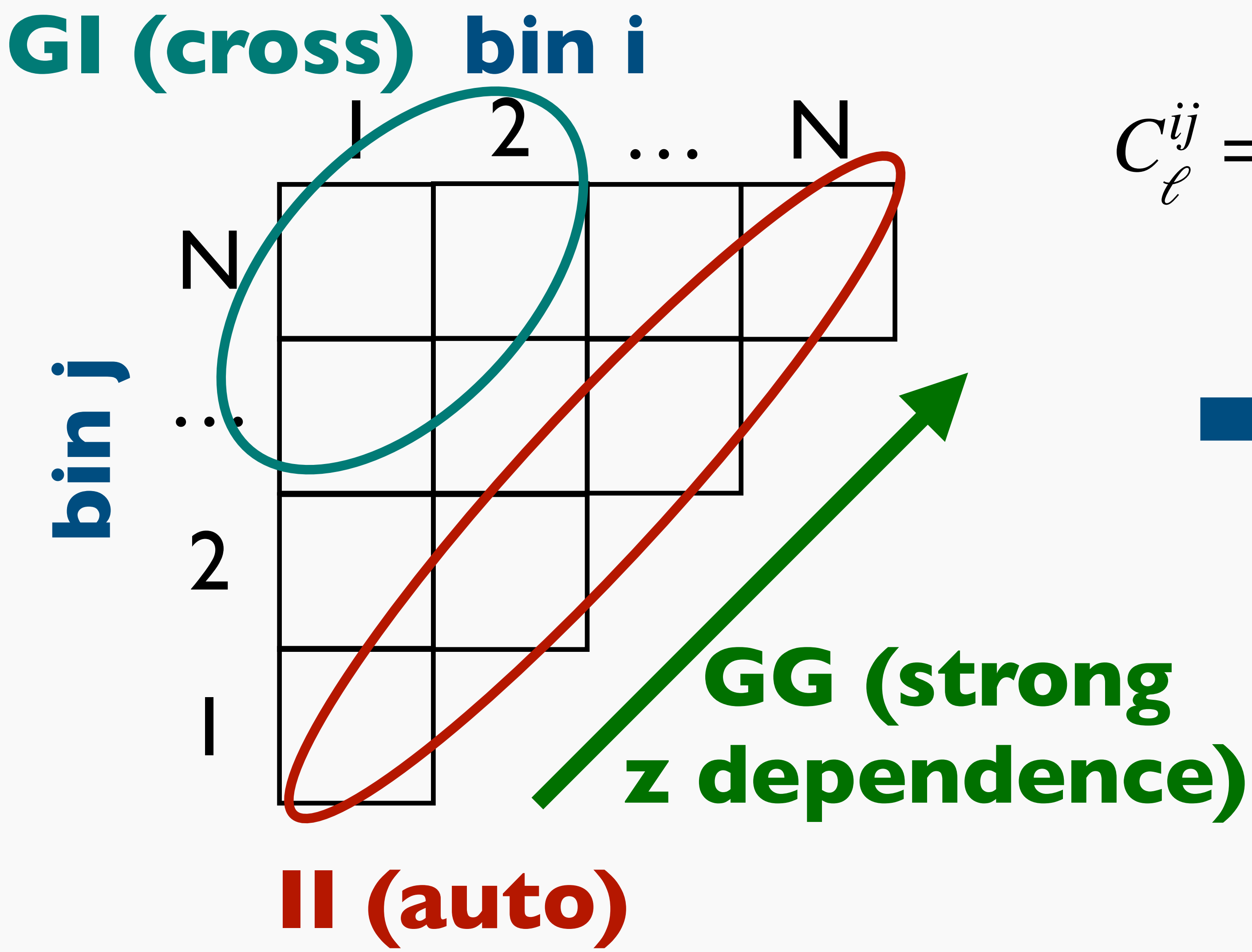


divide source galaxies into different z bins

probe different lens z

- evolution of δ_m
- mitigate intrinsic alignment

Intrinsic alignment w/ tomography



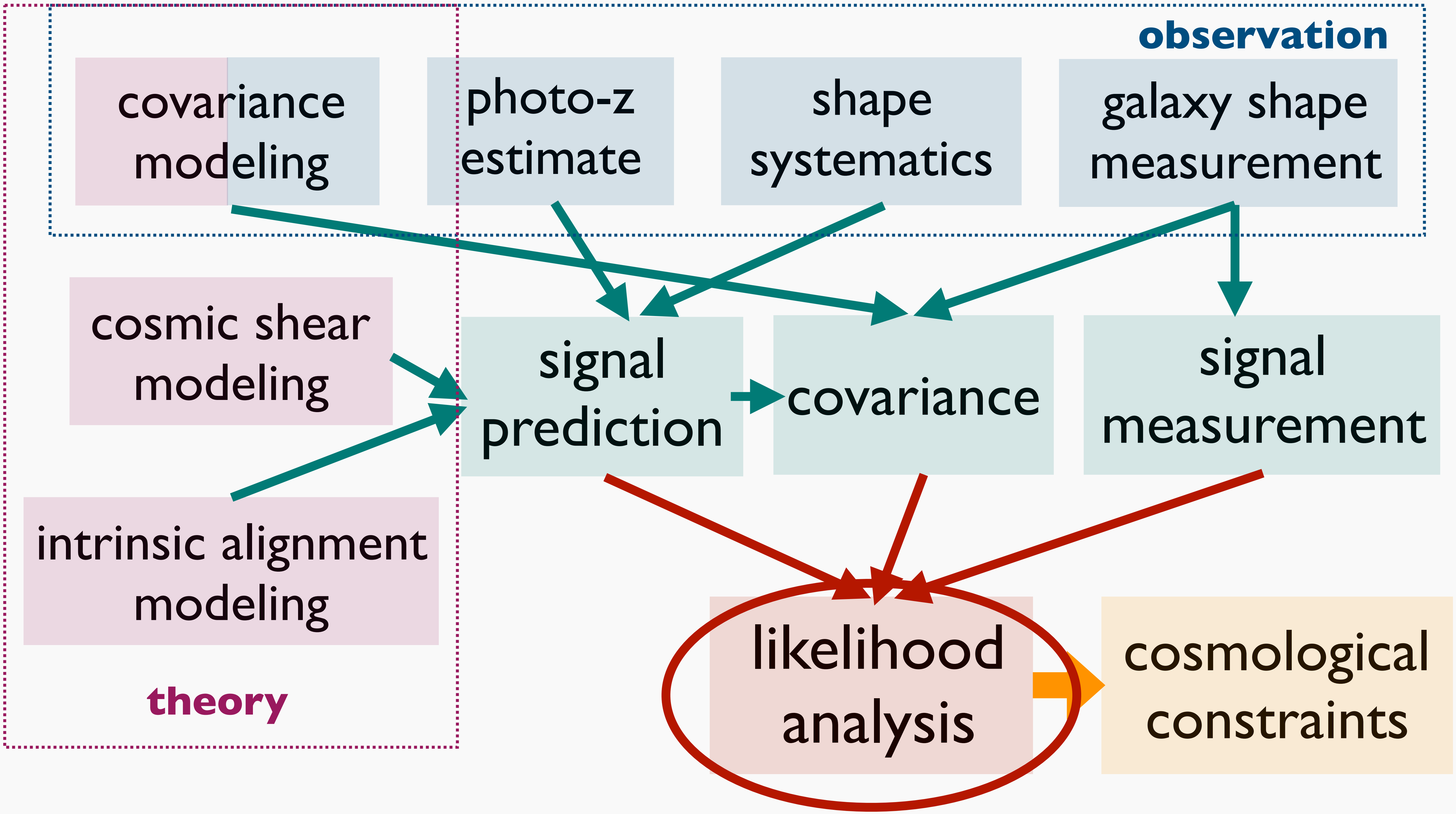
auto/cross power spectra

$$C_\ell^{ij} = \int d\chi \frac{W_i(\chi) W_j(\chi)}{f_K^2(\chi)} P_{\rm m}\left(\frac{\ell}{f_K(\chi)};\chi\right)$$

➡ help break degeneracy between cosmic shear and intrinsic alignment

(e.g., Heymans+2013)

Likelihood analysis



Likelihood analysis

model power spectrum

$$C_\ell^{\rm model} = C_\ell^{\kappa\kappa} + C_\ell^{\rm IA} + C_\ell^{\rm sys}$$

cosmic shear (incl. baryon effect) → $C_\ell^{\kappa\kappa}$

intrinsic alignment → $C_\ell^{\rm IA}$

systematics → $C_\ell^{\rm sys}$

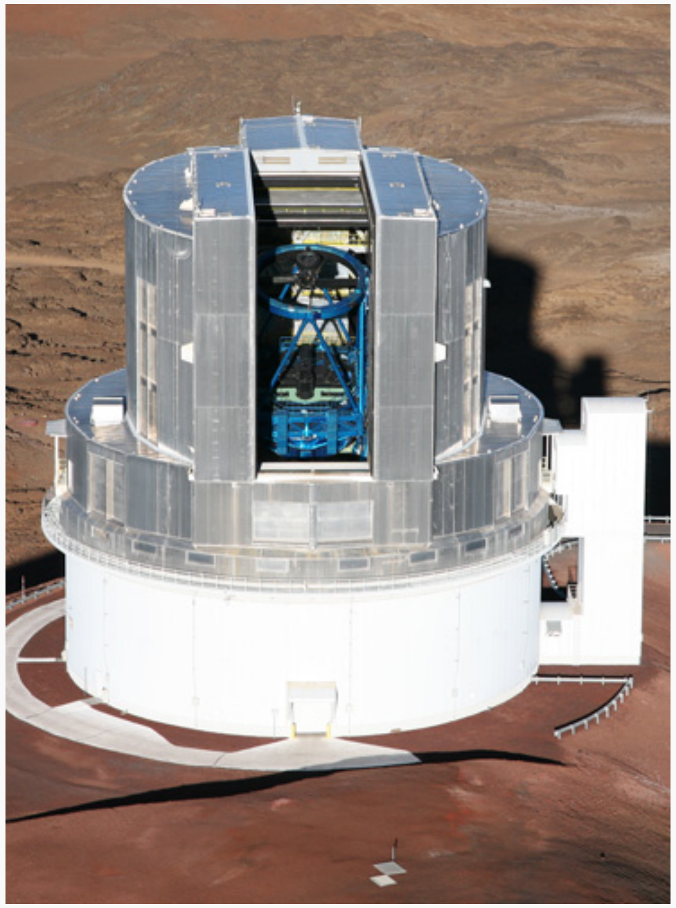
explore likelihood

$$\mathscr{L} \propto \exp\left[-\frac{1}{2}\left(C_\ell^{\rm model} - C_\ell^{\rm obs}\right)^T ({\rm Cov})^{-1}\left(C_\ell^{\rm model} - C_\ell^{\rm obs}\right)\right]$$

- Markov chain Monte Carlo
- nested sampling
- …

Ongoing cosmic shear surveys

- 'stage-III' dark energy surveys

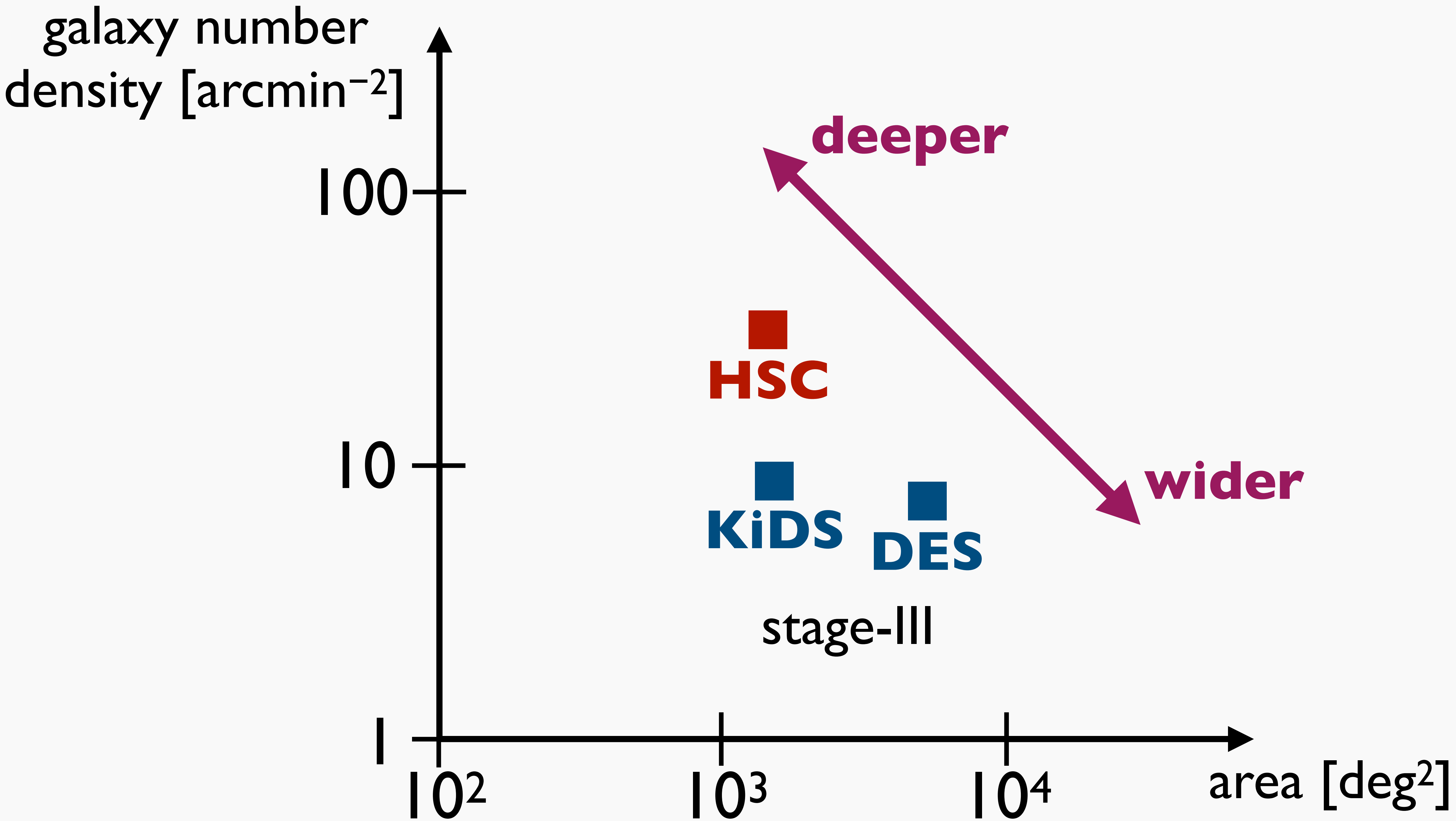


KiDS (2012-2019)
1500 deg², r_{lim}~25

DES (2013-2019)
5000 deg², r_{lim}~25

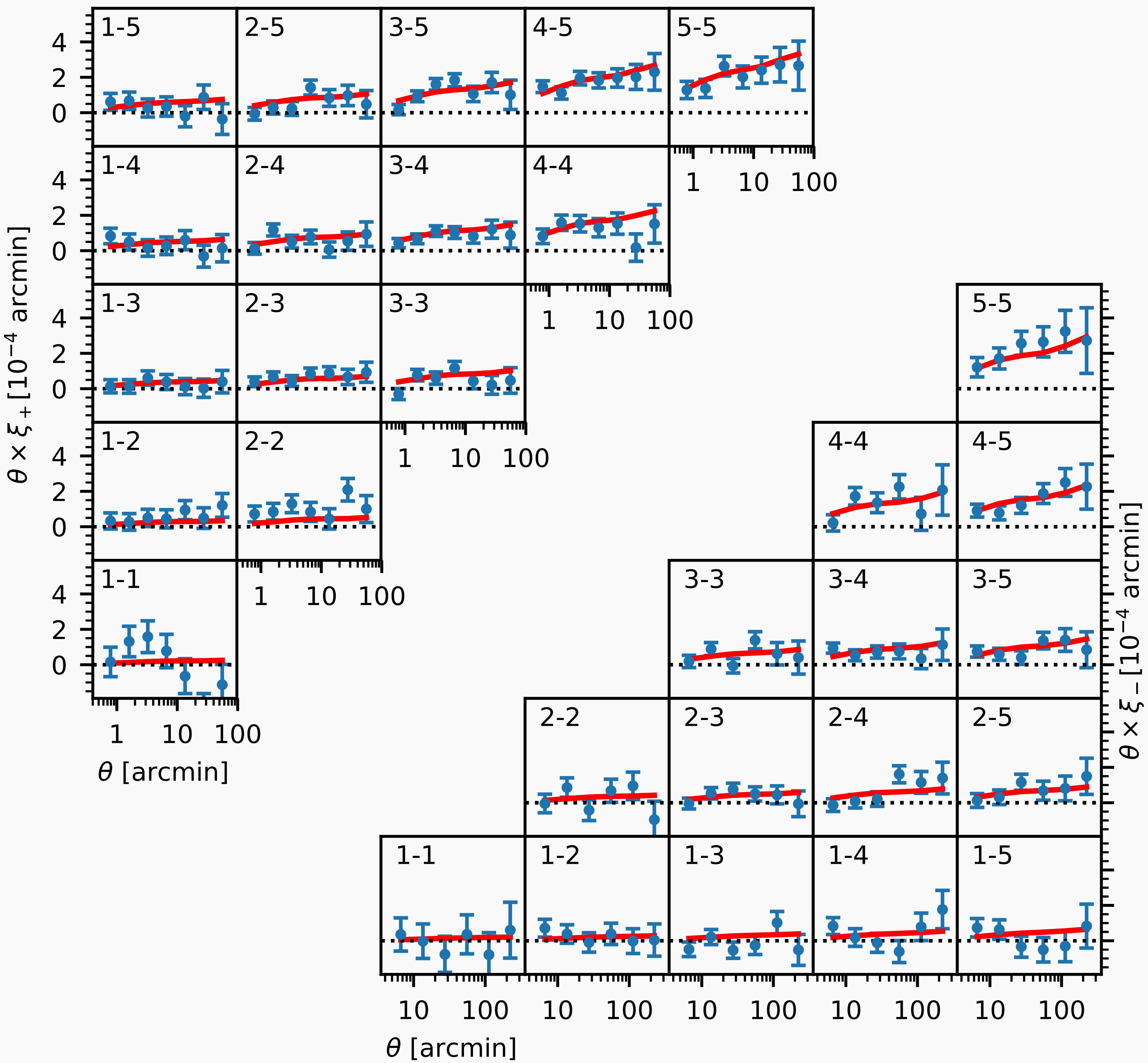
HSC (2014-2020)
1400 deg², r_{lim}~26

Weak lensing capability



Hildebrandt+ arXiv:1812.06076

KiDS+VIKING-450

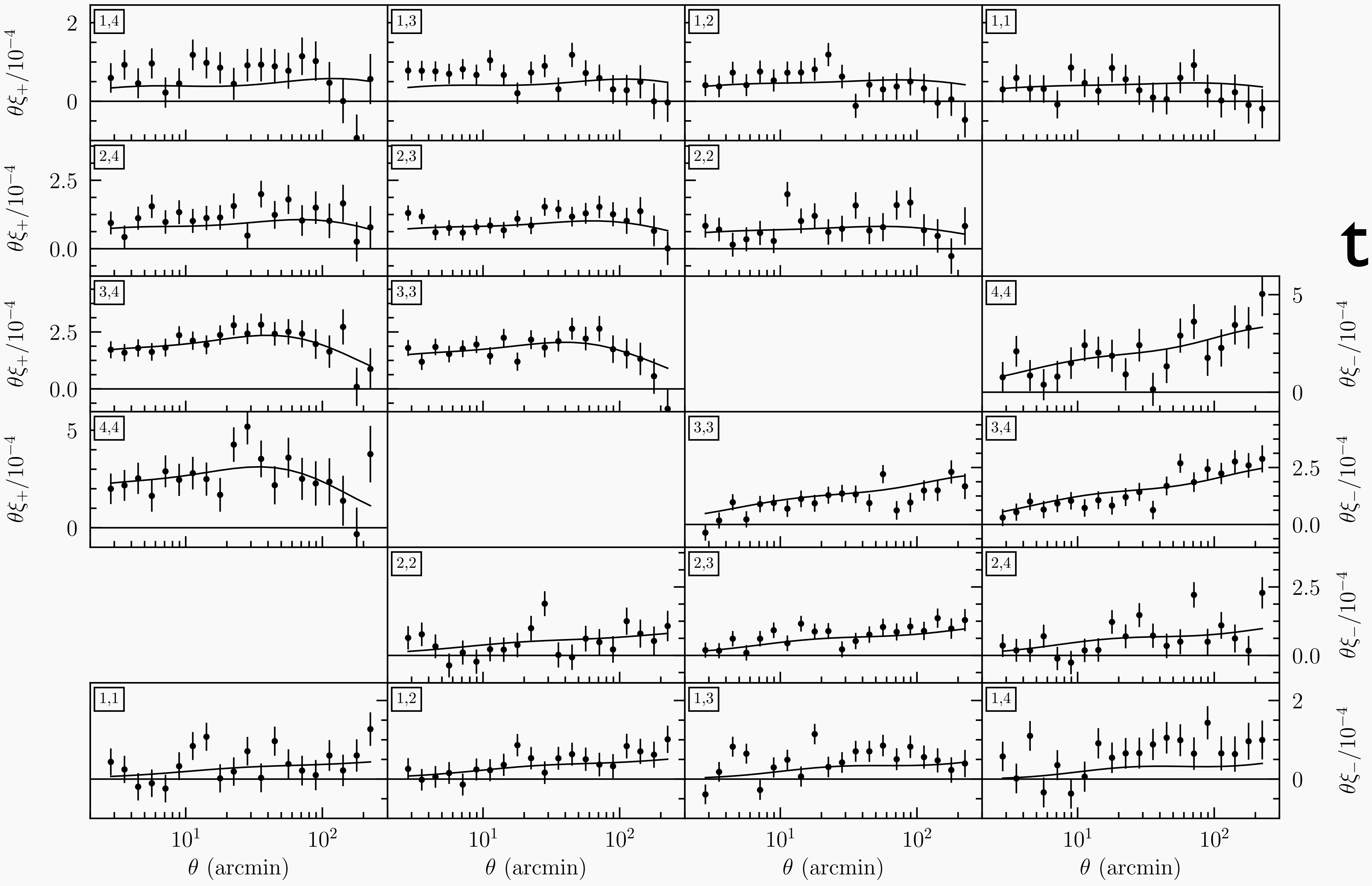


450 deg² data

near-IR data from VIKING

accurate photo-z

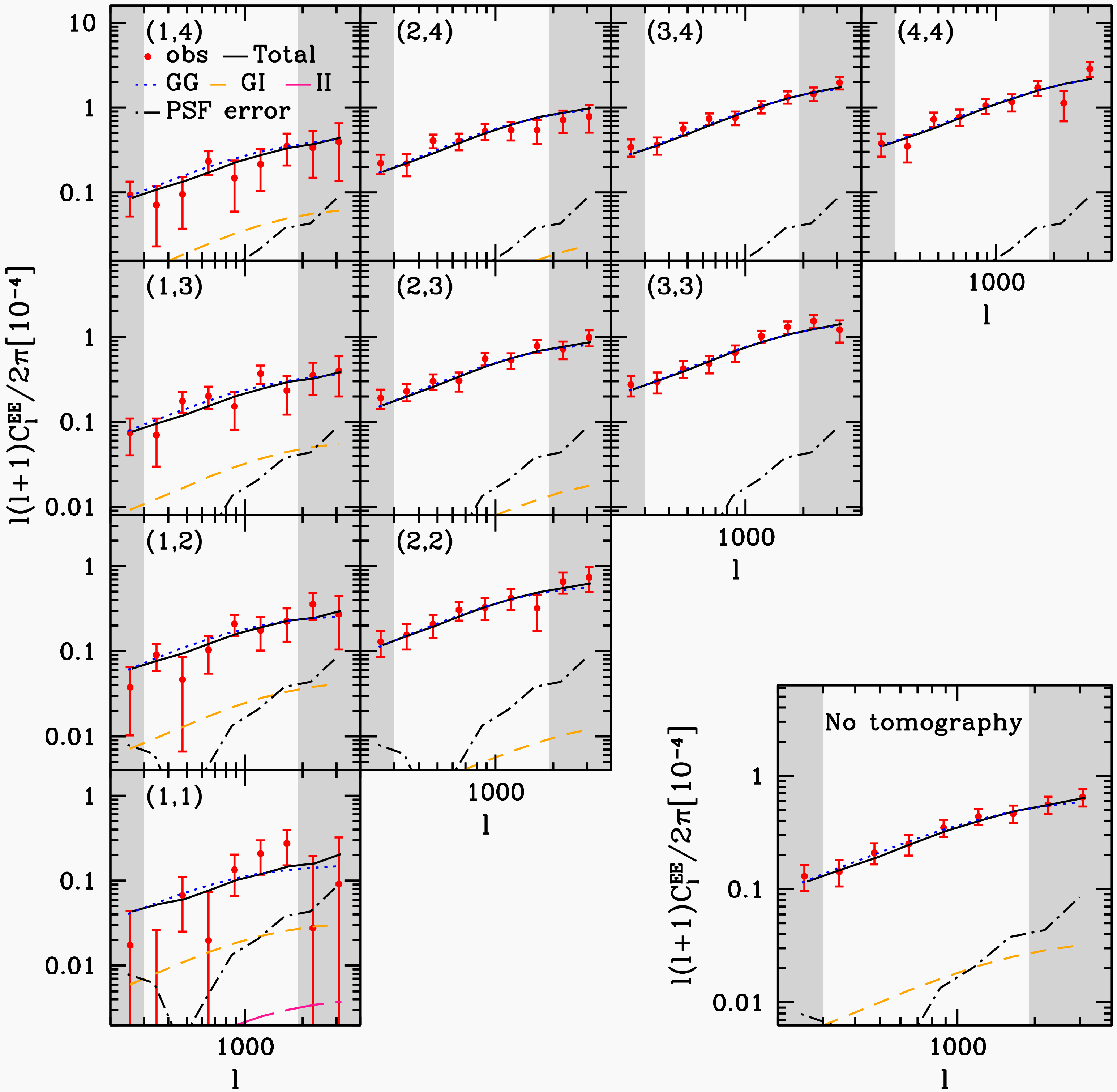
DES Year 1



~1300 deg^2, shallower than full depth

Hikage, MO+ PASJ **71** (2019)43

HSC Year 1 power spectrum

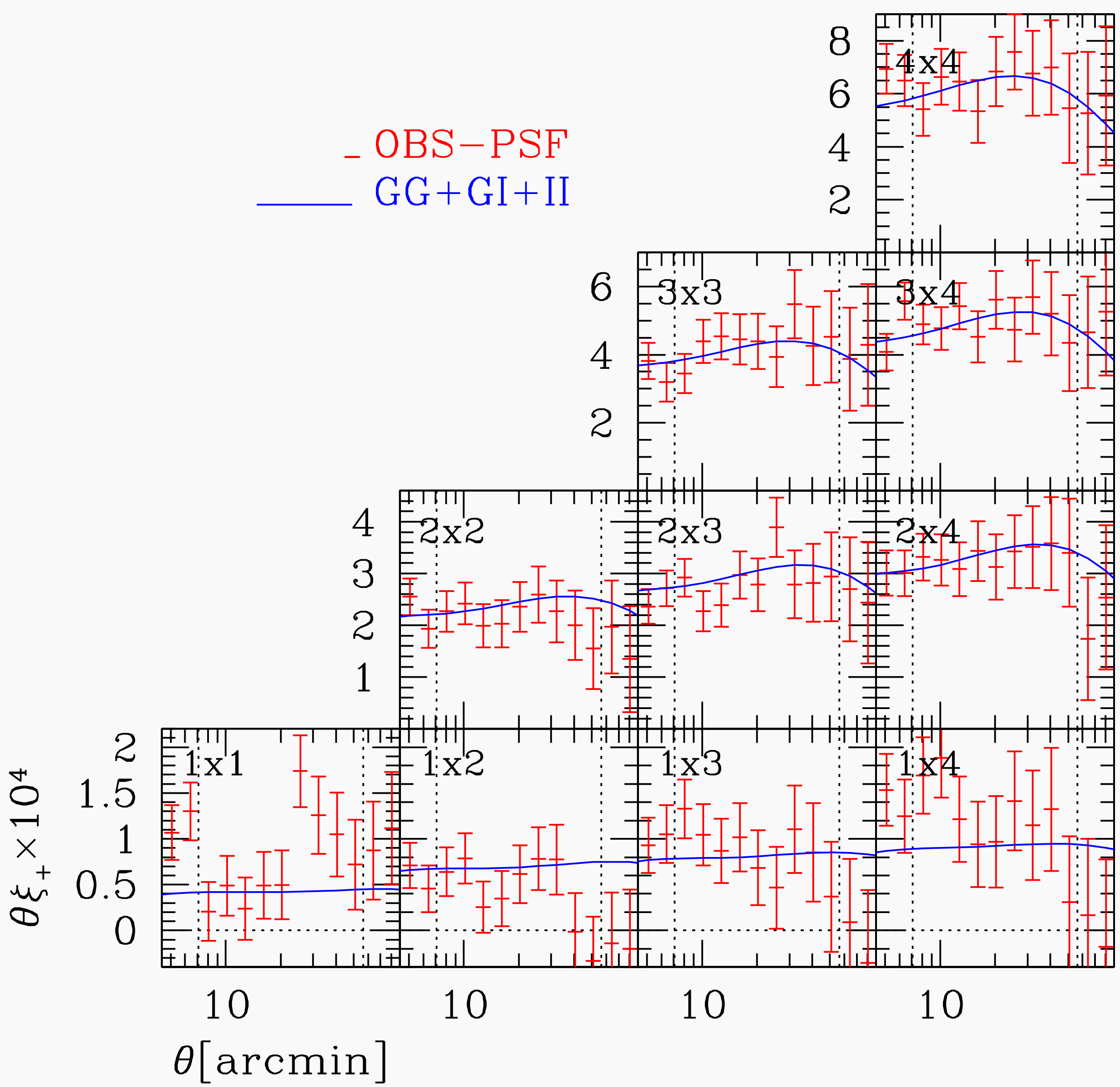


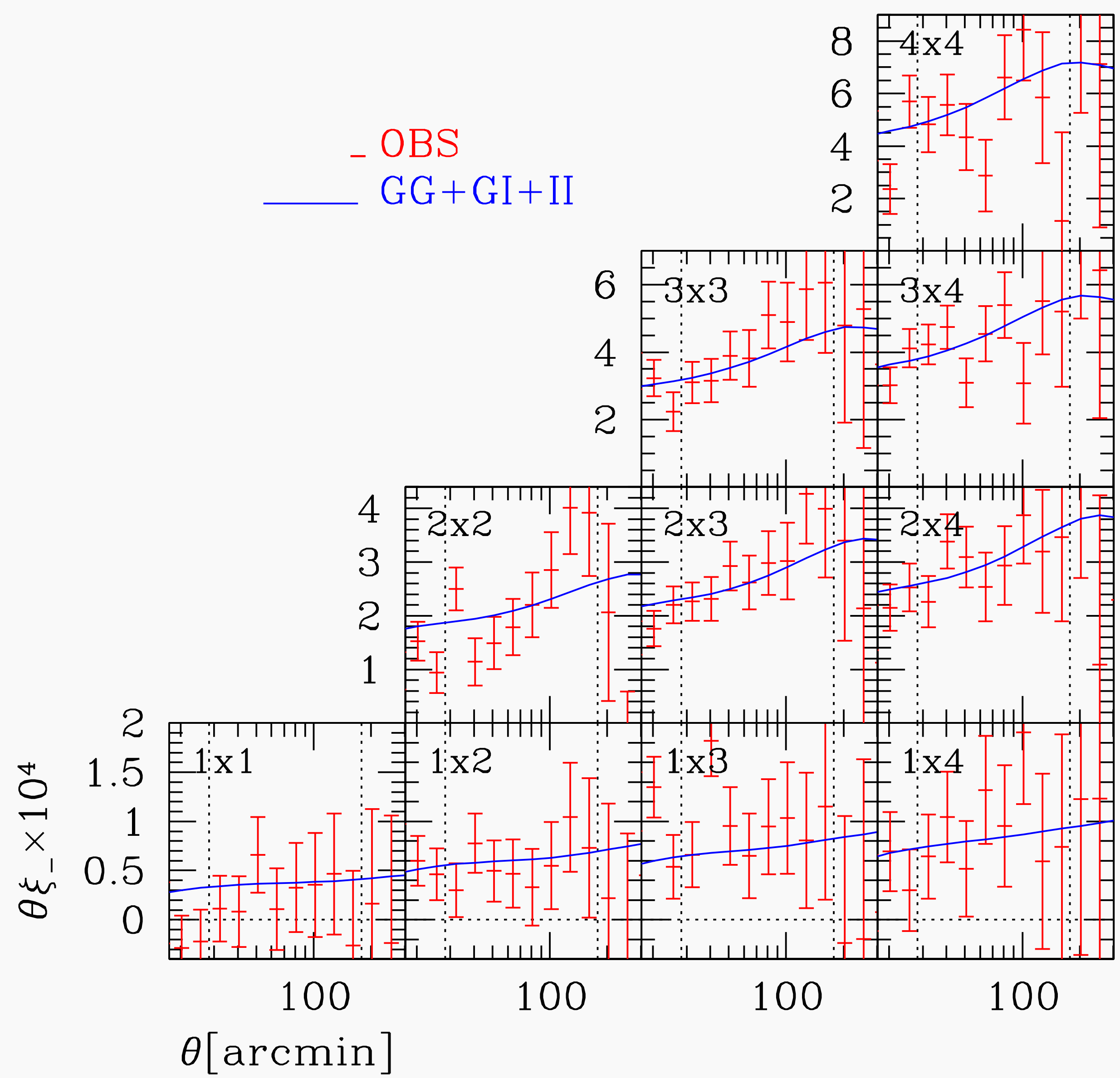
~140 deg², full depth

analysis in Fourier space

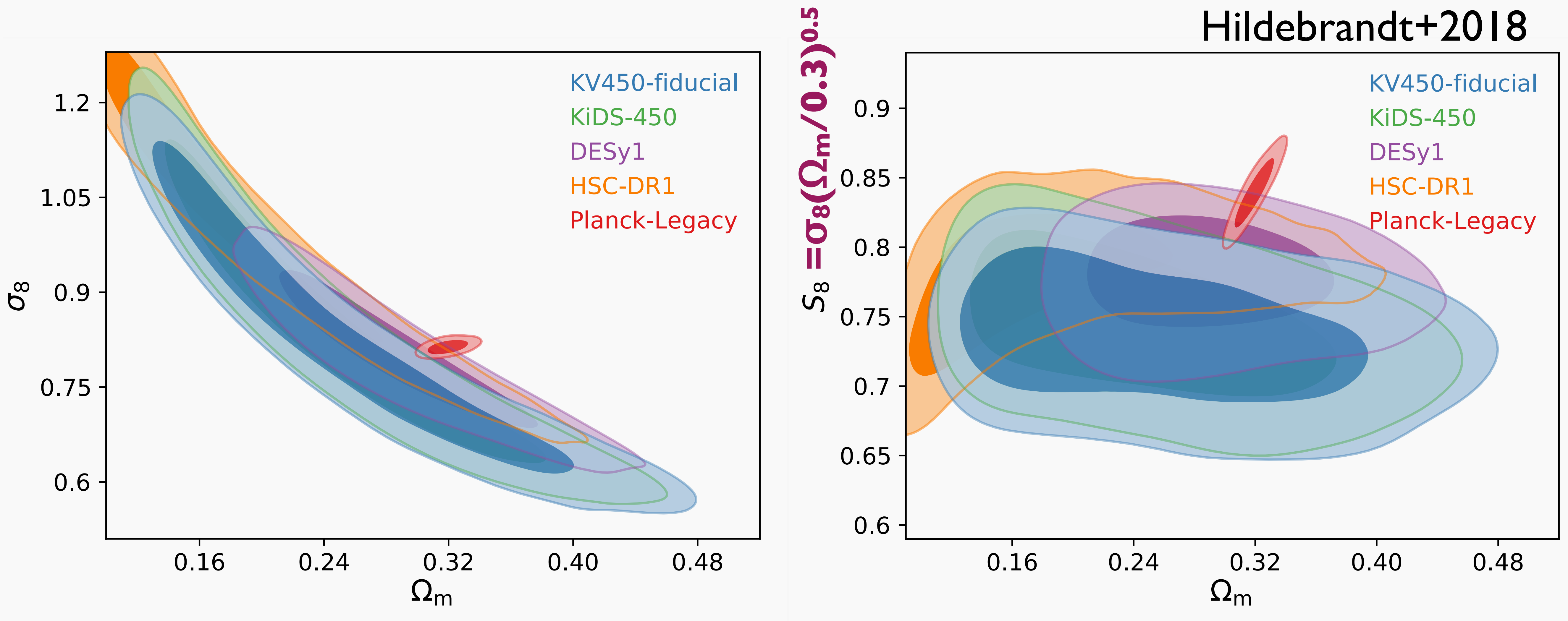
Hamana, .., MO+ arXiv:1906.06041

HSC Year 1 correlation function



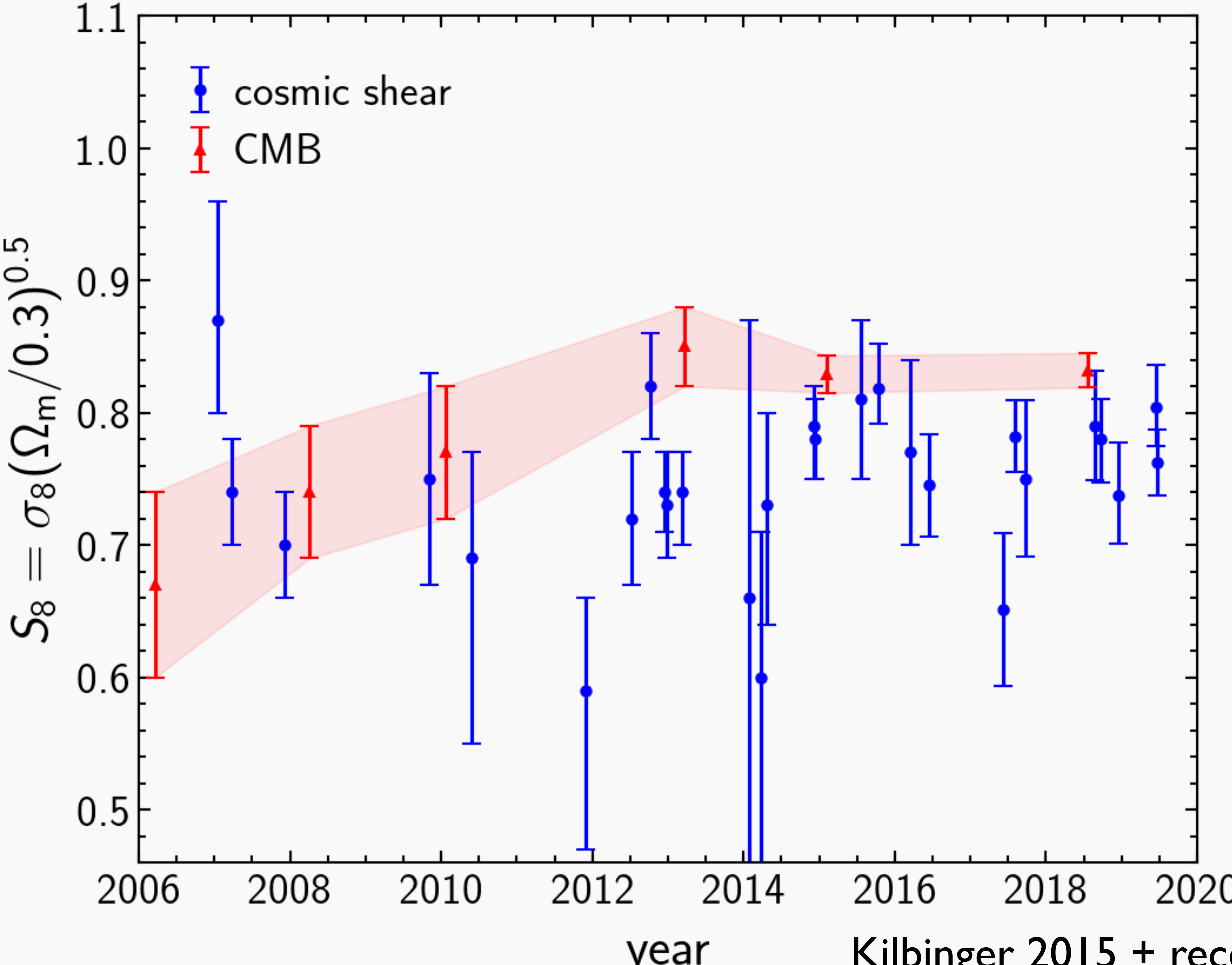


Constraints on Ω_m and σ_8



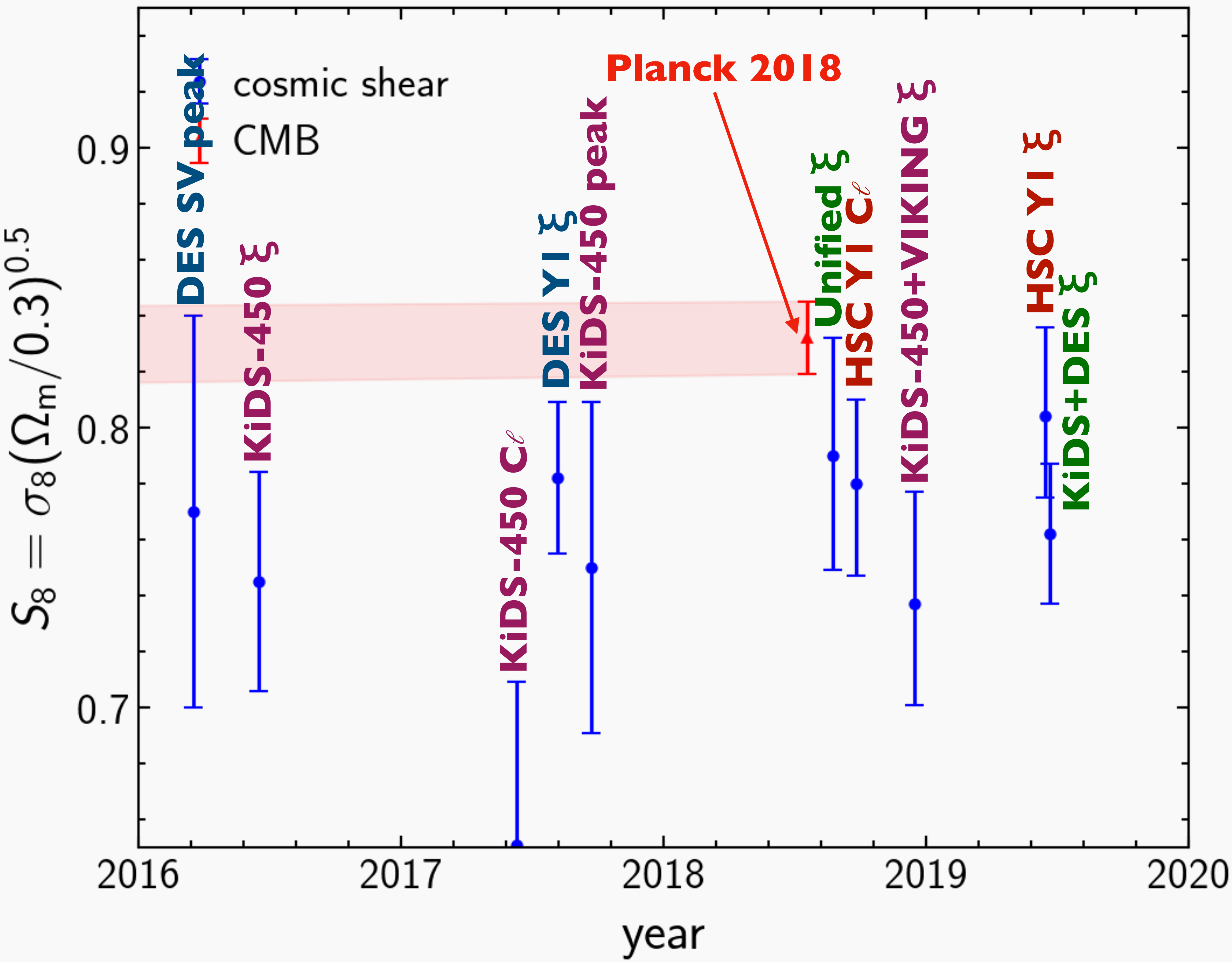
S_8 from cosmic shear consistently smaller than **Planck**

Cosmic shear: current status



Kilbinger 2015 + recent updates

Zoom-in



cosmic shear
CMB
Planck 2018
DES SV peak
KiDS-450 ξ
KiDS-450 Cℓ
DES Y1 ξ
KiDS-450 peak
Unified ξ
HSC Y1 Cℓ
KiDS-450+VIKING ξ
HSC Y1 ξ
KiDS+DES ξ
$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$
0.9
0.8
0.7
2016
2017
2018
2019
2020
year

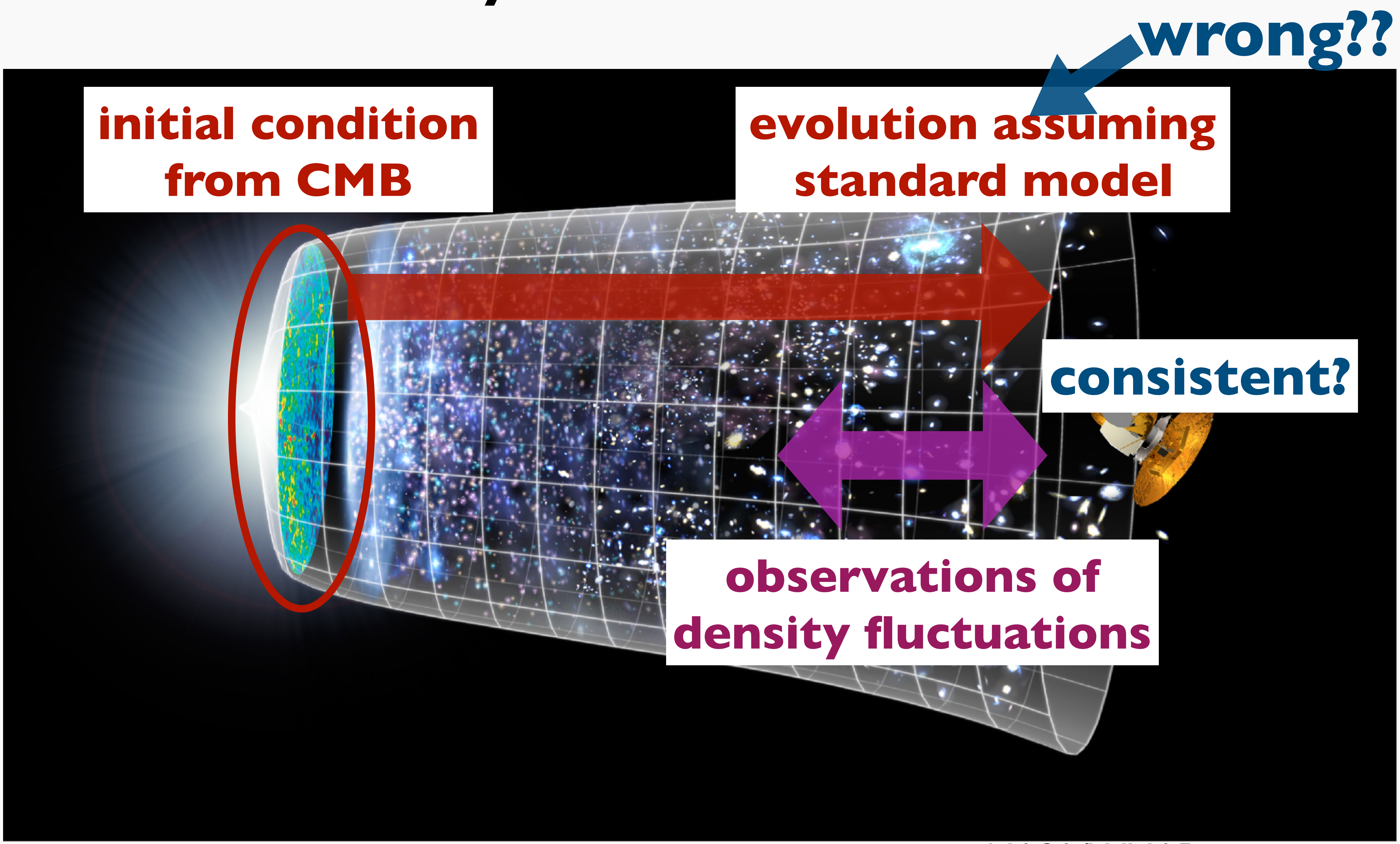
Origin of "σ_8 tension"

- **statistical fluctuations**
  − can be checked with larger datasets

- **common systematics**
  − z_{phot} calibrated by COSMOS (but see KiDS+VIKING)
  − theoretical model incl. $P_m(k)$, baryon, …
  − unknowns

- **ΛCDM is wrong**
  − most exciting!

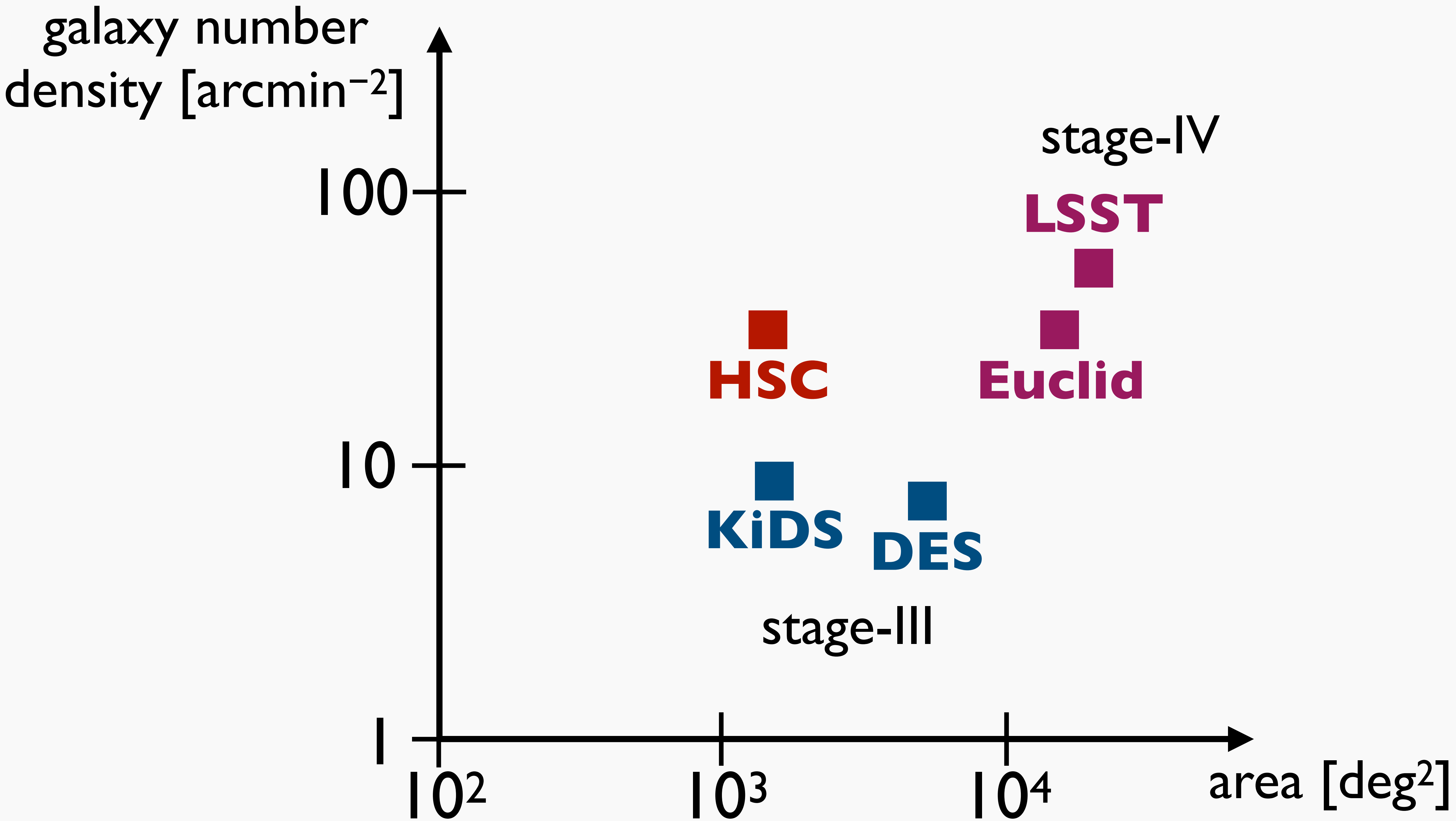
Consistency tests



NASA/WMAP science team

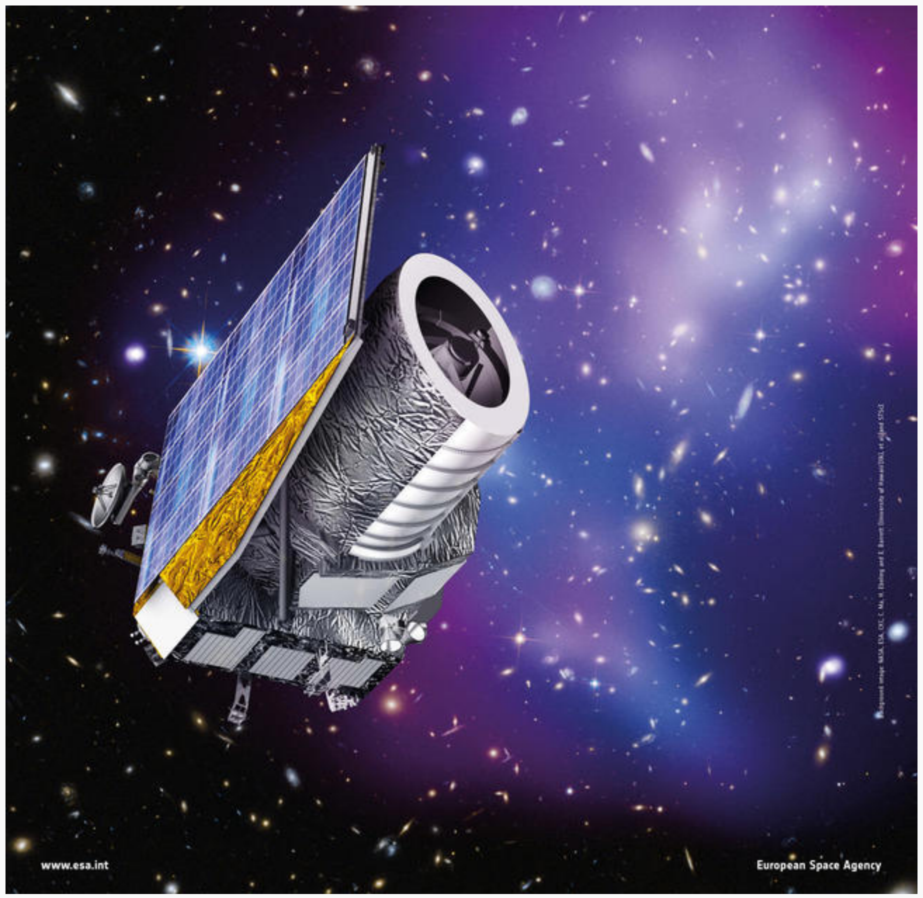
- clue to nature of dark matter/energy?

Future prospect



Euclid

https://www.euclid-ec.org

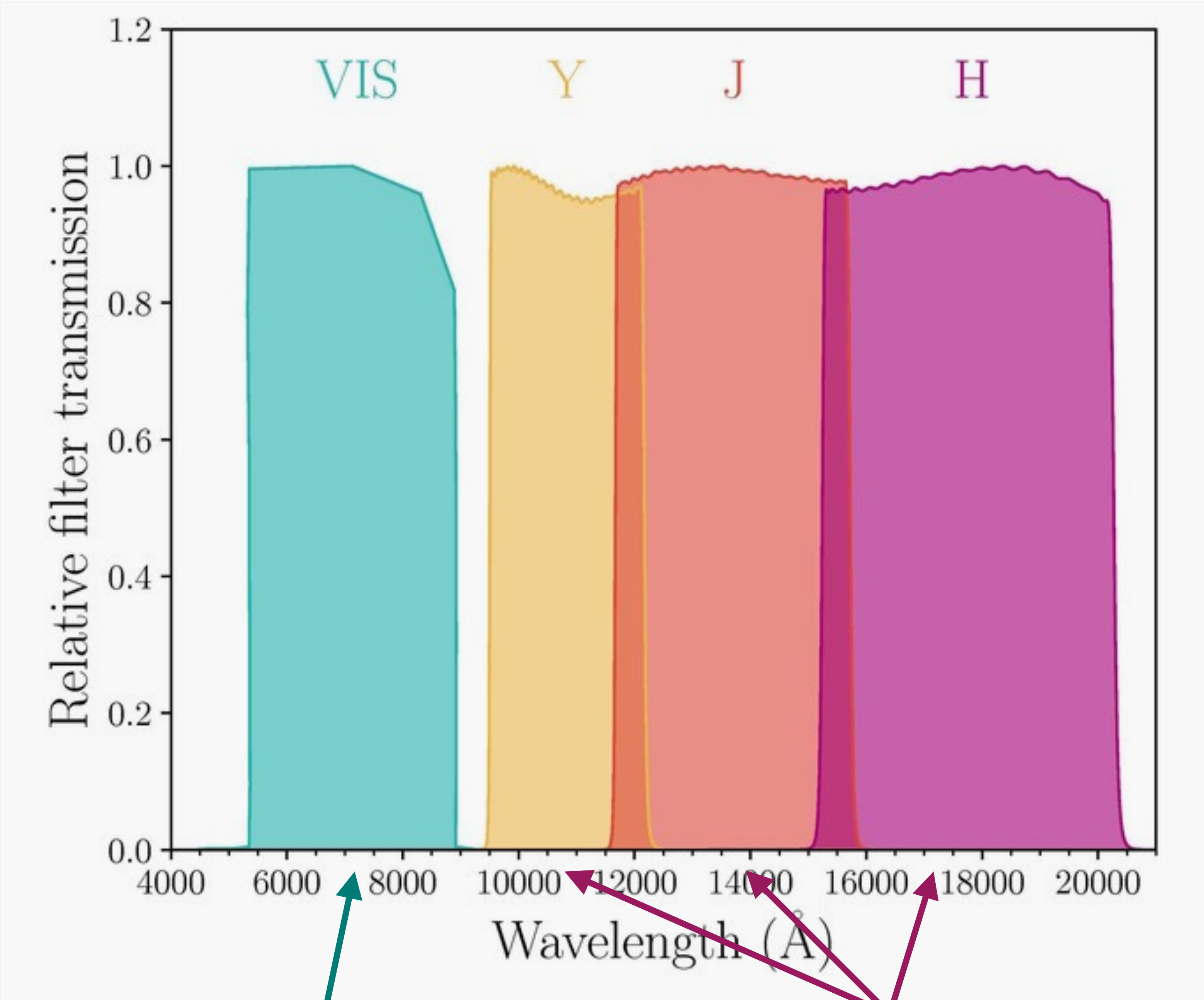


	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	*FoM*
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

(from the Euclid red book 2012)

- ESA satellite mission, launch 2022
- observes ~15,000 deg^2 of extragalactic sky

Euclid imaging survey

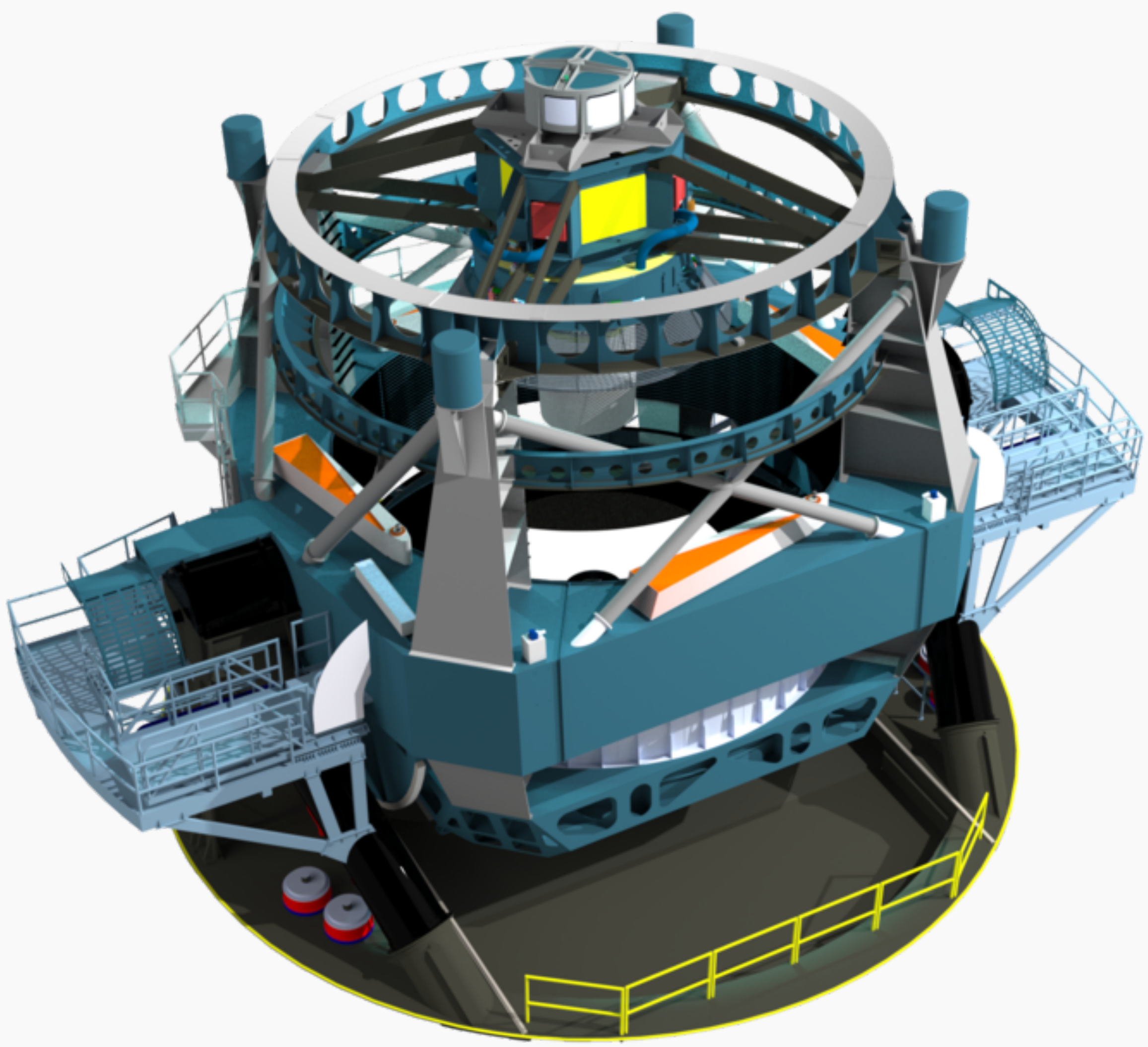


optical (ugriz) data from ground is crucial for photo-z

for galaxy shape measurements

for photo-z/ high-z science

Large Synoptic Survey Telescope



https://www.lsst.org

8.4-m telescope in Chile

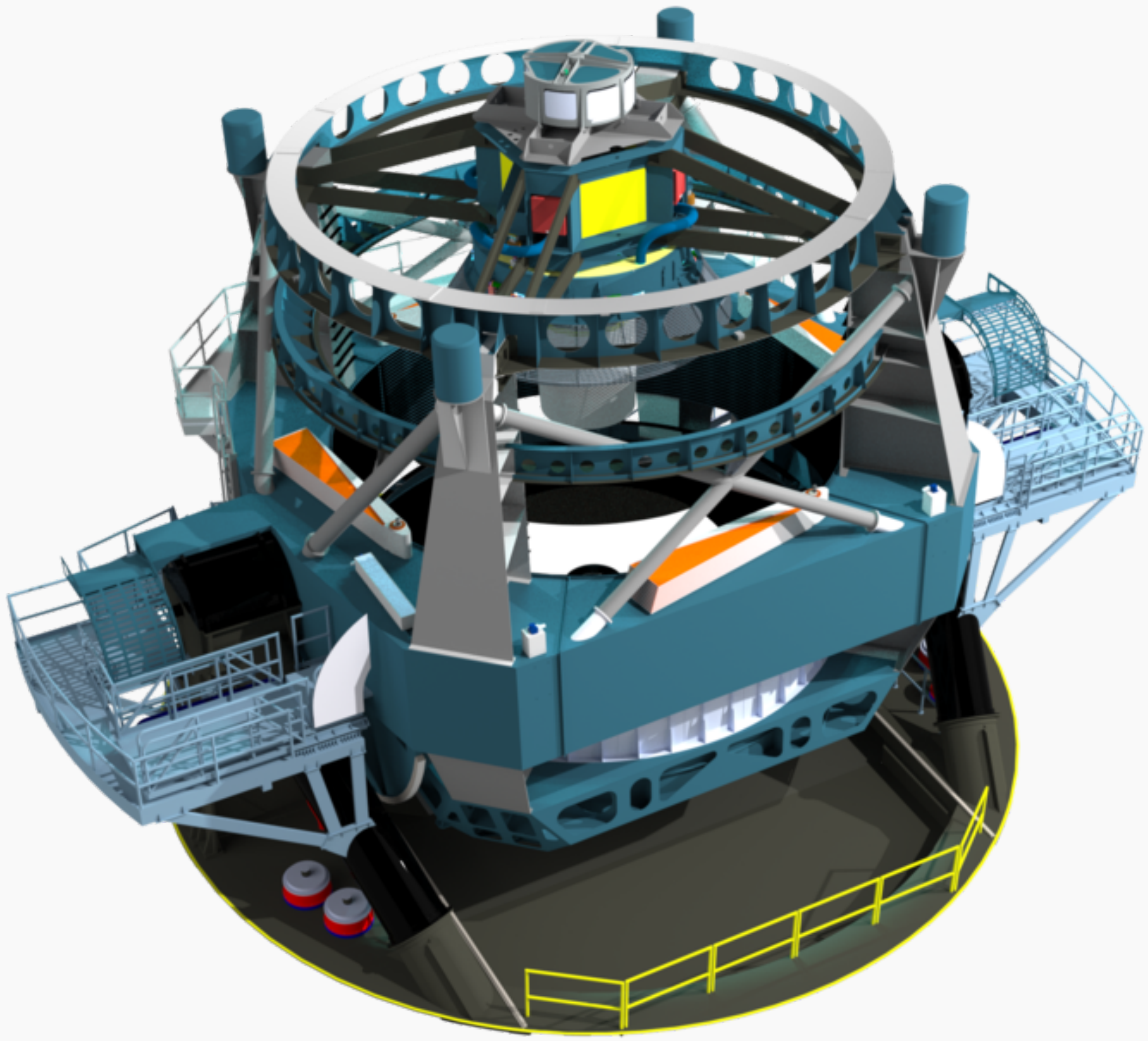
urgriz imaging, 30000 deg^2

time domain survey

survey from 2023

~~Large Synoptic Survey Telescope~~

Vera C. Rubin Observatory (VRO)/ Legacy Survey of Space and Time (LSST)



https://www.lsst.org

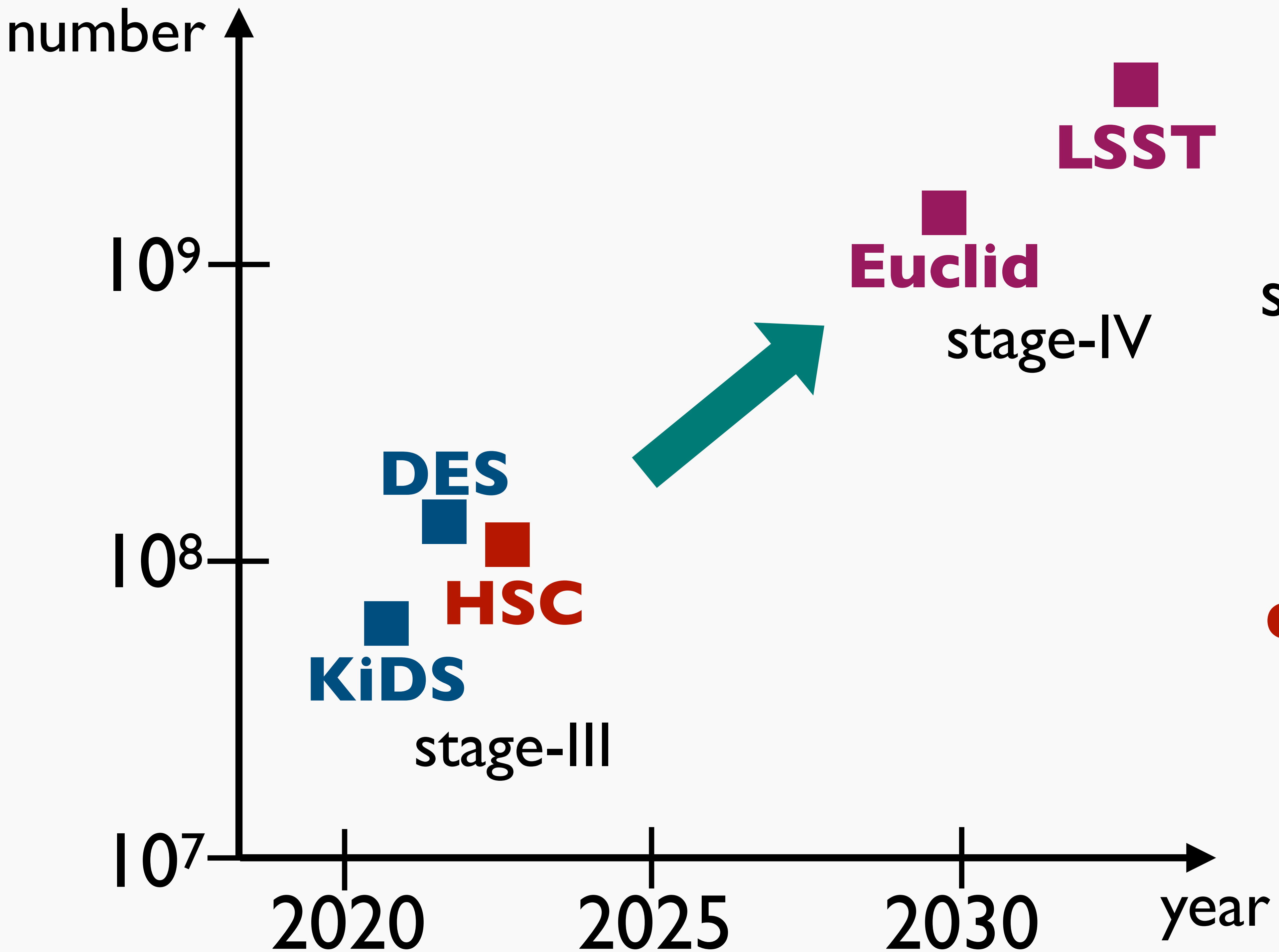
8.4-m telescope in Chile

urgriz imaging, 30000 deg^2

time domain survey

survey from 2023

Number of galaxies



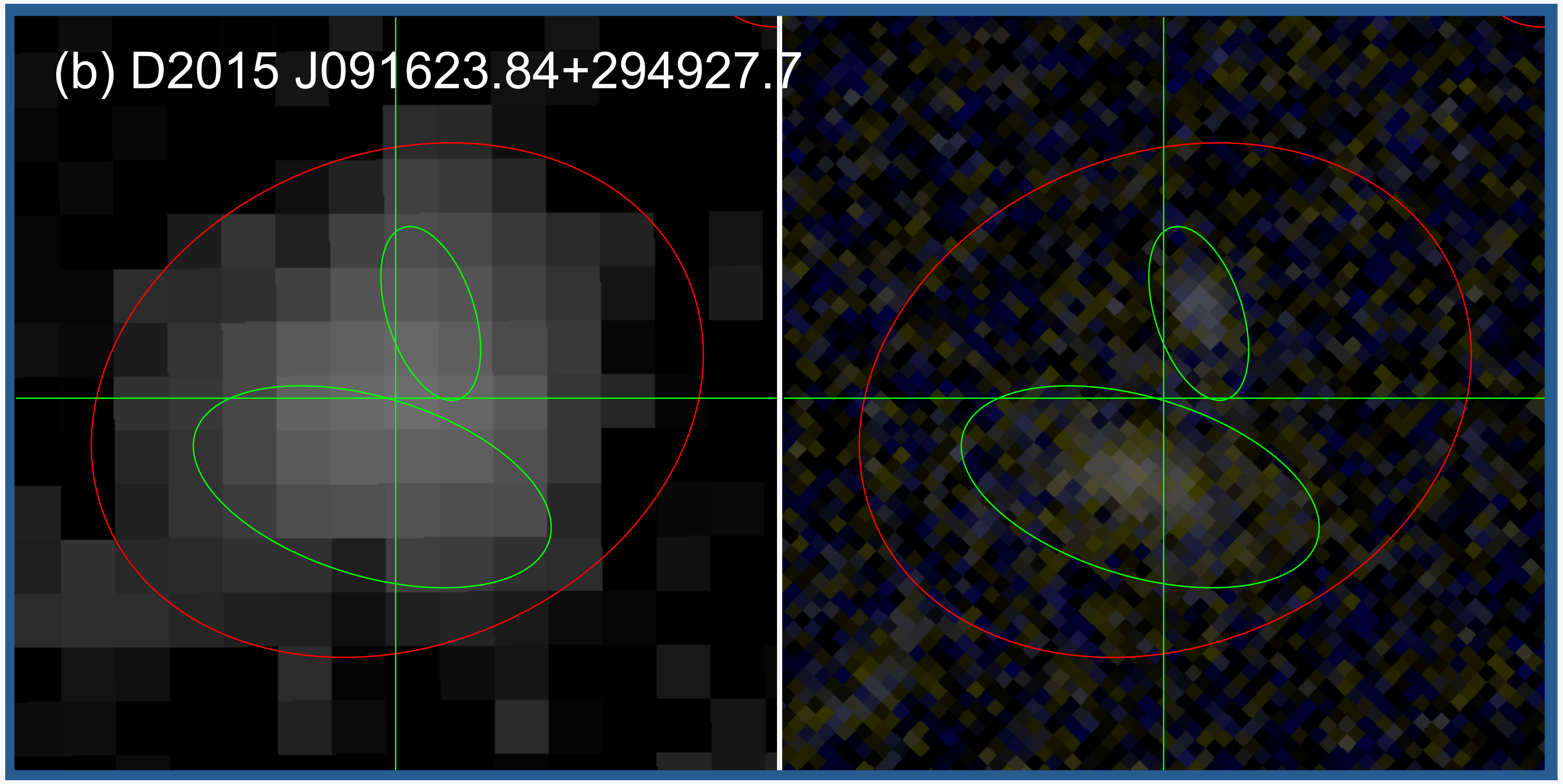
very small statistical errors

systematic errors have to be very small

Mitigating systematic errors

- **shape measurements** (blending)
  - extensive simulations incl. blending
  - calibrations with deeper/higher res. images
- **photometric redshifts**
  - near-IR images for improvements
  - deep spec-z sample for fair calibrations
  - clustering redshift?

Blending



Dawson+2016

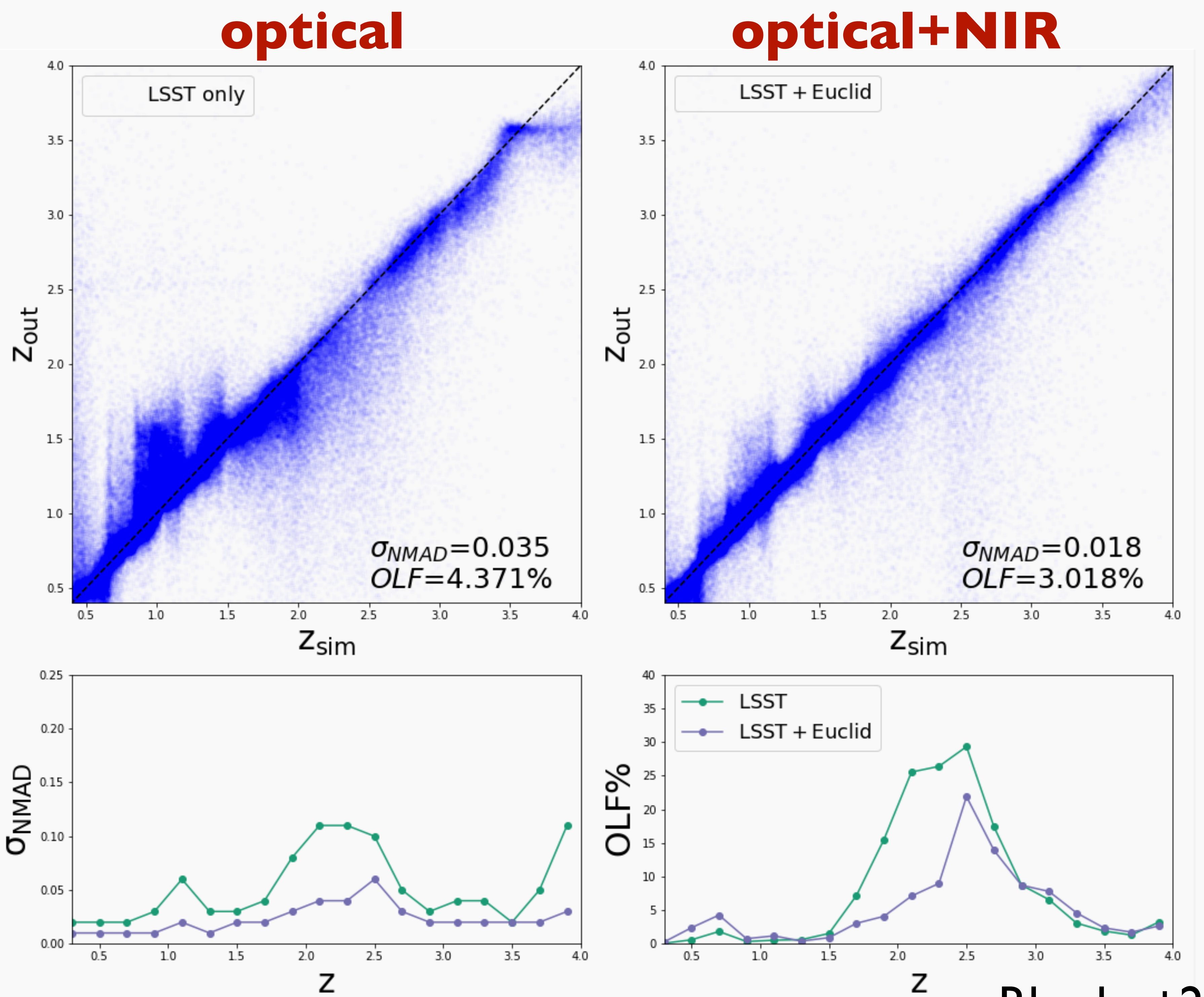
ground image (1 galaxy)

space image (2 galaxies)

very important for weak lensing with deep imaging

need more studies

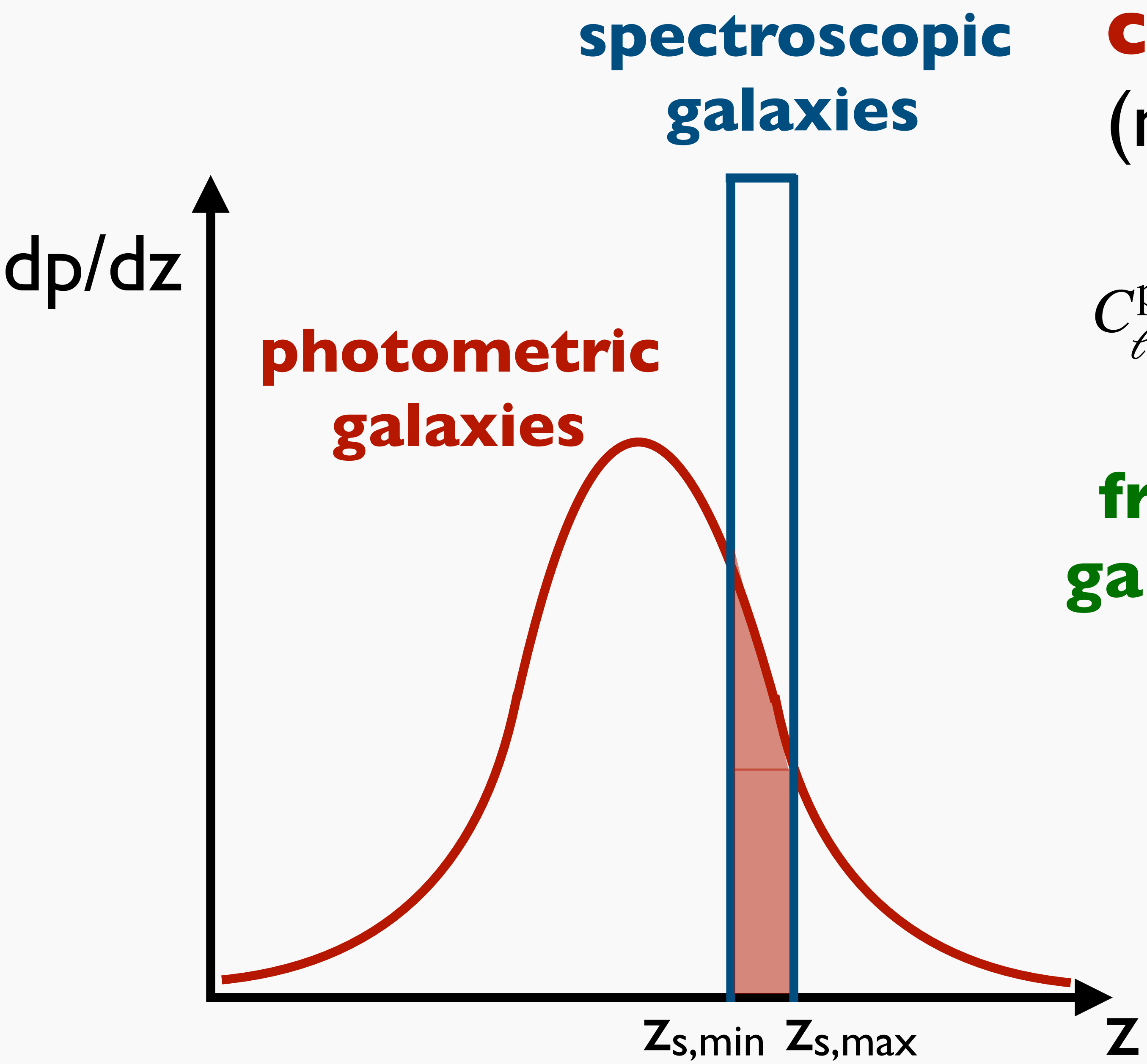
Near-infrared images



NIR important for good photo-z

Rhodes+2017

Clustering redshift



cross-correlation signal
(narrow spec-z bin)

$$C_\ell^{ps} \propto \frac{N_p(z_{s,min} < z < z_{s,max})}{N_{p,all}} \frac{1}{\Delta\chi} P_{gg}\left(\frac{\ell}{\chi}; \chi\right)$$

fraction of photometric galaxies within spec-z bin

reconstruct dp/dz of photometric galaxies
(e.g., Newman 2008)

Other challenges

- intrinsic alignments, measurement and model
- improved theory of $P_m(k)$ incl. baryon effect
- real versus Fourier space
- fast and accurate estimate of covariance
- model predictions in various cosmo. models
- analysis beyond 2-point statistics

Summary

- cosmic shear cosmology is getting one of the main probes of cosmology
- exciting future plans and challenges for them
- many other interesting related topic: cross-correlations, CMB lensing, …