Cosmology Seminar

IfA Edinburgh

Cosmology with weak gravitational lensing

Chieh-An Lin (Linc)

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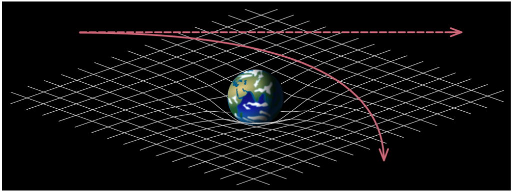
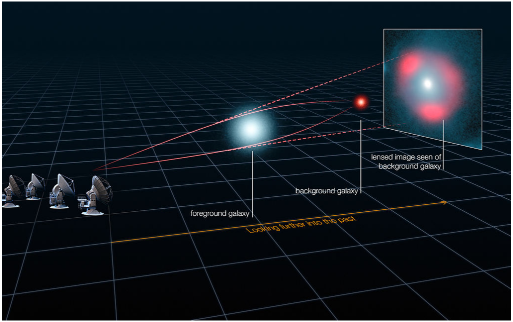
National Taiwan Normal University

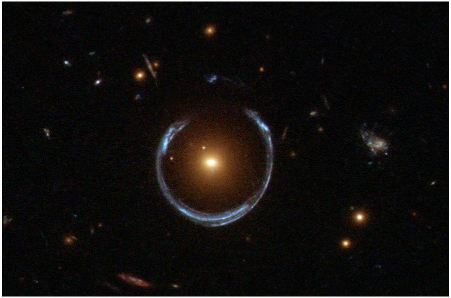
General relativity



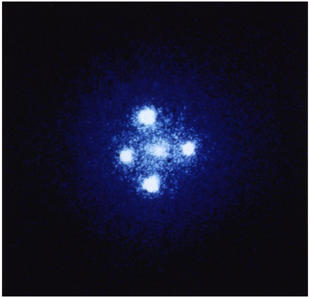
Gravitational lensing

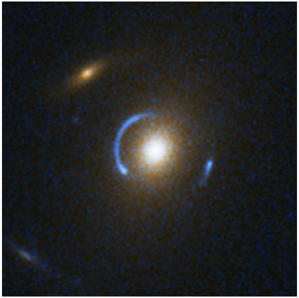


Source: ALMA

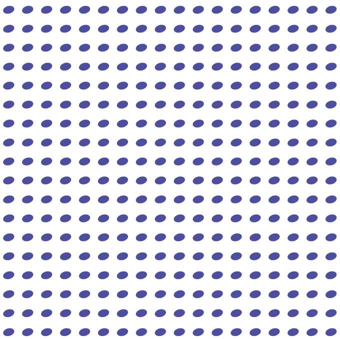


Strong lenses

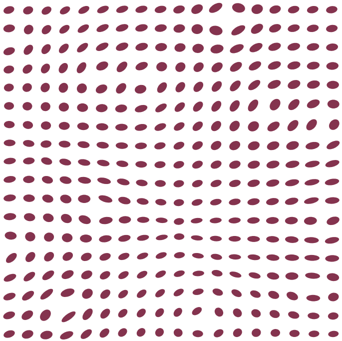




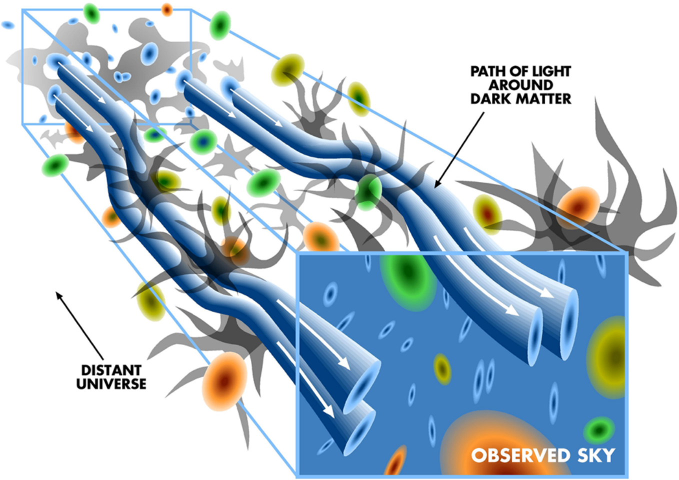
Source: SDSS, HST



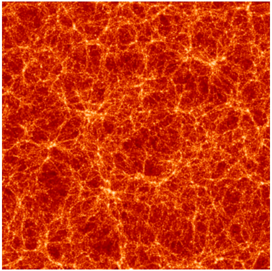
Unlensed sources



Weak lensing

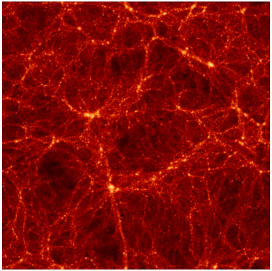

PATH OF LIGHT
AROUND
DARK MATTER
DISTANT
UNIVERSE
OBSERVED SKY

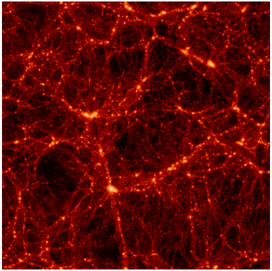
Source: LSST



SCDM

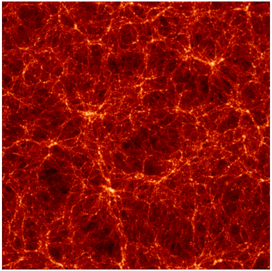
OCDM





ΛCDM

τCDM



Abundance $\Omega_{\rm m}$
Fluctuation σ_8

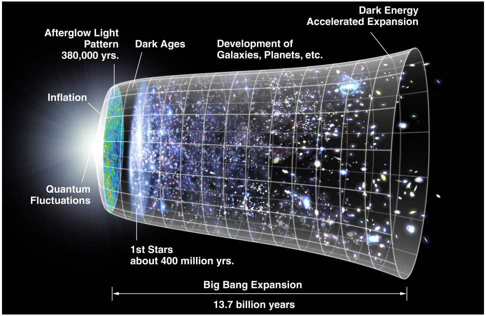
(Credit: J. Colberg, Virgo)

Outline

Scientific motivations	What to measure
Theoretical basis	How to measure
Observational challenges	What do we really measure
State of the art	What have been measured
Future perspectives	What will be measured

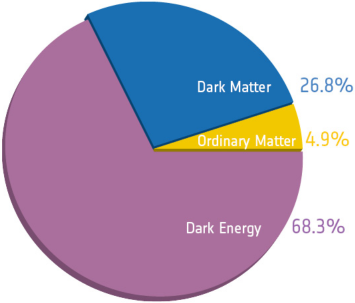
Scientific motivations

Cosmic timeline



(Source: NASA)

Cosmic recipe

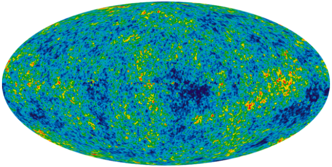


(Source: ESA)

"ΛCDM model"

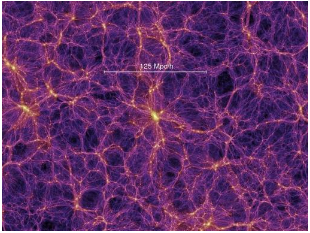
Cosmological probes

Cosmic microwave background



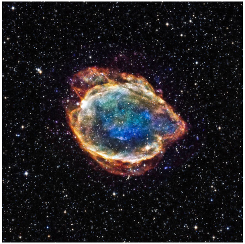
(Source: WMAP)

Large-scale structures



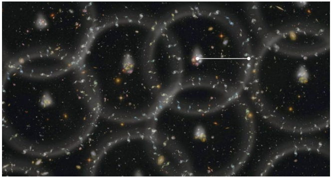
(Credit: Springel et al. 2005)

Type Ia supernovae

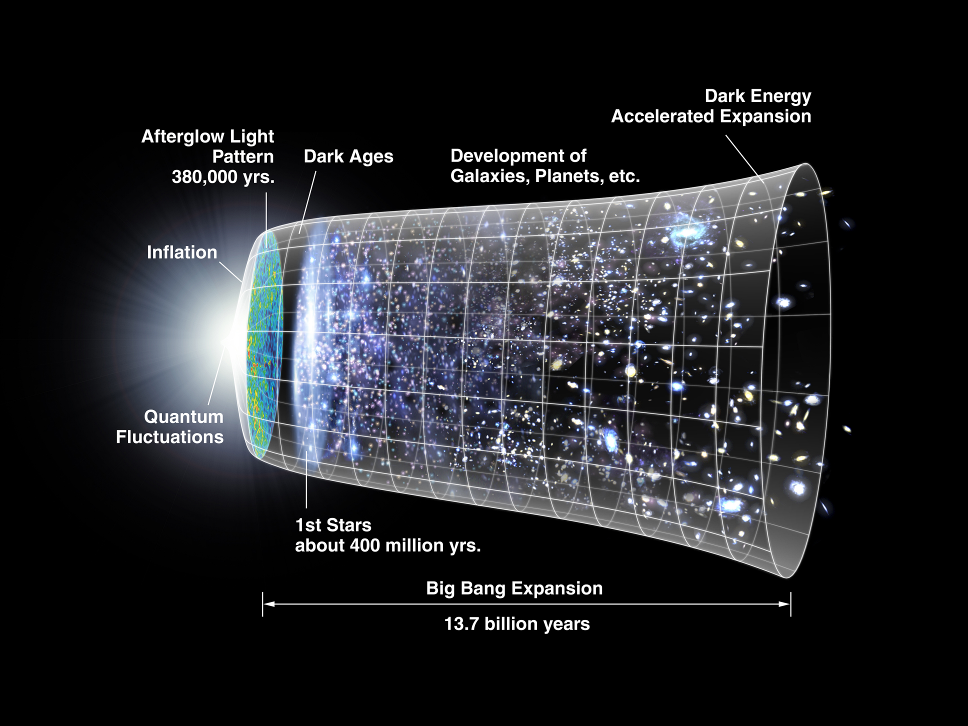


(Source: NASA)

Baryon acoustic oscillations



(Source: BNL)


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

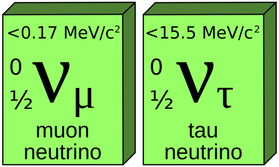
WL as a probe beyond ΛCDM

Modified gravity

(Source: NASA)

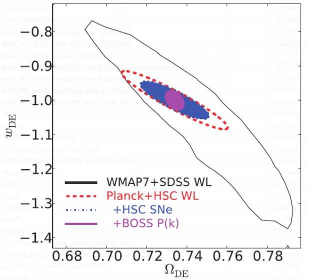
$$f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1}$$

Massive neutrinos



(Source: MissMJ@Wikimedia/CC BY 3.0)

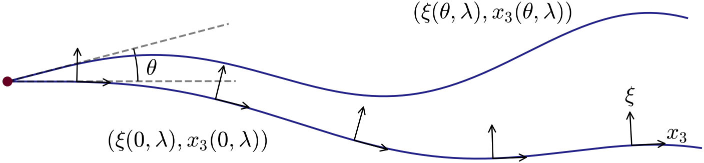
Dark energy



(HSC stratrgic survey proposal)

Theoretical basis

Geodesic deviation equation



Affine parameter λ

2D angular position $\boldsymbol{\theta}$

2D transverse vector $\boldsymbol{\xi} = (x_1, x_2)$

Optical tidal matrix $\mathcal{T}$

$$\frac{\mathrm{d}^2\boldsymbol{\xi}(\boldsymbol{\theta},\lambda)}{\mathrm{d}\lambda^2} = \mathcal{T}(x_1, x_2, x_3)\boldsymbol{\xi}(\boldsymbol{\theta},\lambda)$$

$\mathcal{T}$ can be related to the gravitational potential ϕ

Lensing potential

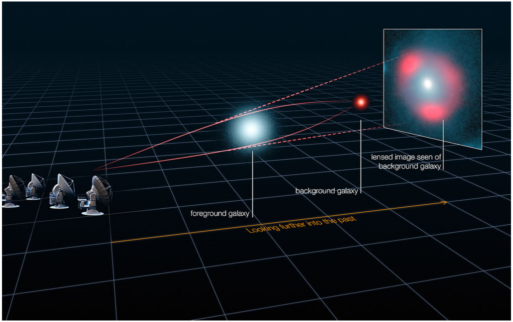
Gravitational potential ϕ
Lensing potential ψ
Comoving distances w, $f_K(w)$

$$\psi(\boldsymbol{\theta}) \equiv \frac{2}{\mathrm{c}^2} \int_0^w \mathrm{d}w' \; \frac{f_K(w-w')}{f_K(w) f_K(w')} \; \phi(f_K(w')\boldsymbol{\theta}, w')$$

First-order distortion:

$$\mathcal{A}_{ij}(\boldsymbol{\theta}) = \delta_{ij} - \partial_i \partial_j \psi(\boldsymbol{\theta})$$

Lensing potential

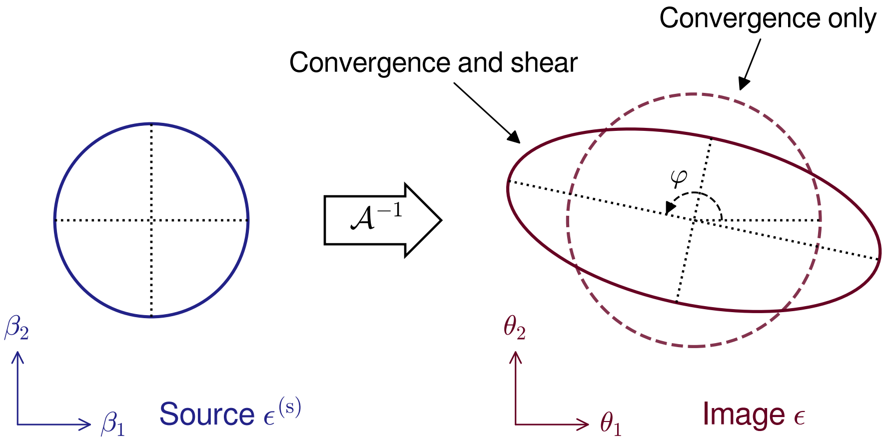


$$\psi(\boldsymbol{\theta}) \equiv \frac{2}{\mathrm{c}^2} \int_0^w \mathrm{d}w' \, \frac{f_K(w-w')}{f_K(w) f_K(w')} \, \phi(f_K(w')\boldsymbol{\theta}, w')$$

$$\mathcal{A}(\boldsymbol{\theta}) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

κ — convergence — “projected mass”

$\gamma = \gamma_1 + \mathrm{i}\gamma_2$ — shear — distortion



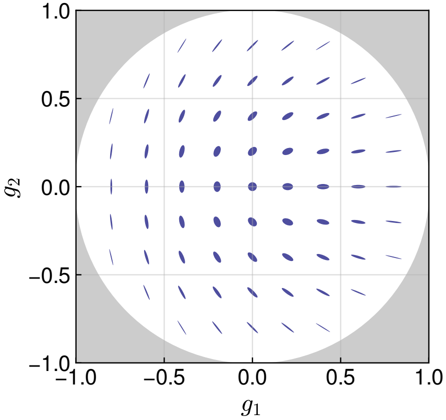
Projected mass

Matter density contrast δ
Scale factor a
Comoving distances w, $f_K(w)$
Various constants $\mathrm{c}, H_0, \Omega_\mathrm{m}$

$$\kappa(\boldsymbol{\theta}, w) = \frac{3H_0^2\Omega_\mathrm{m}}{2\mathrm{c}^2} \int_0^w \mathrm{d}w' \; \frac{f_K(w-w')f_K(w')}{f_K(w)} \frac{\delta\left(f_K(w')\boldsymbol{\theta}, w'\right)}{a(w')}$$

κ is a distance-weighted projection of δ

Shape and shear



Intrinsic ellipticity $\epsilon^{(\mathrm{s})}$ as a random variable

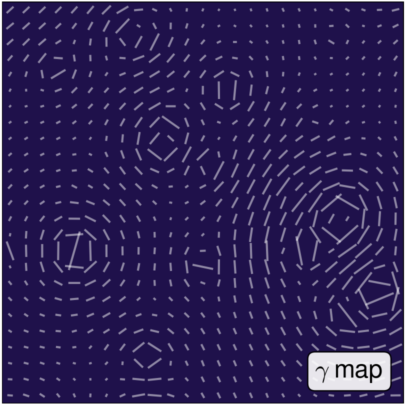
The observed one is
$\epsilon \approx \epsilon^{(\mathrm{s})} + g$

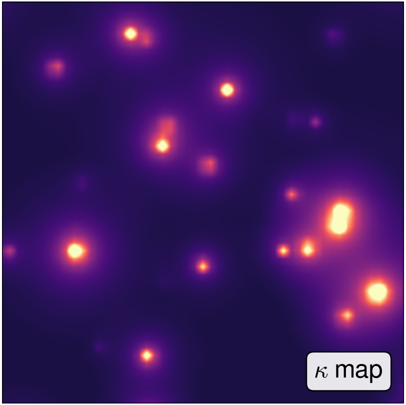
where $g \equiv \dfrac{\gamma}{1-\kappa} \approx \gamma$

$\sigma_{\epsilon^{(\mathrm{s})}} \approx 0.4$

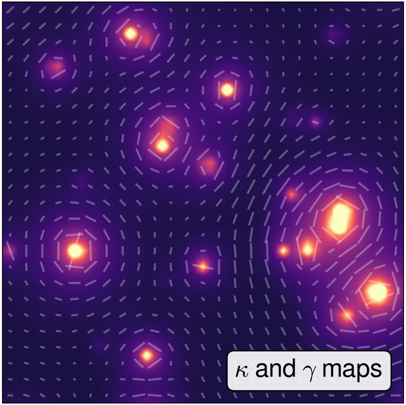
$|\gamma| \sim$ few percents

κ and γ are related quantities



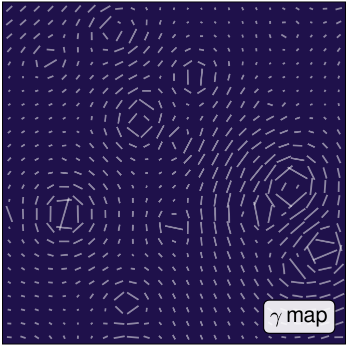


κ and γ are related quantities



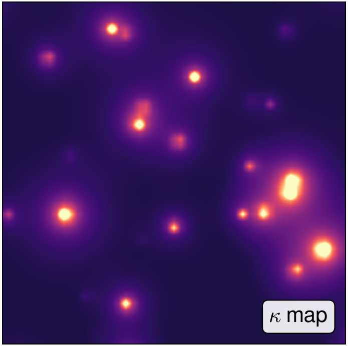
What to measure? Dark energy
How to measure?

Wake up if you fall asleep



Stretch of galaxy images induced by gravitation

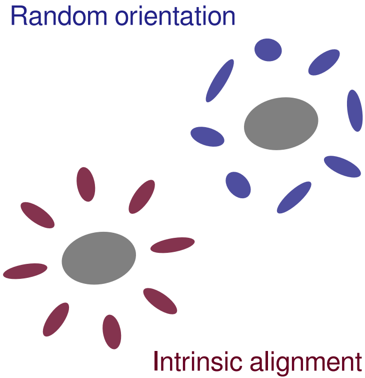
$\Leftrightarrow$



Underlying structures predicted by cosmological models

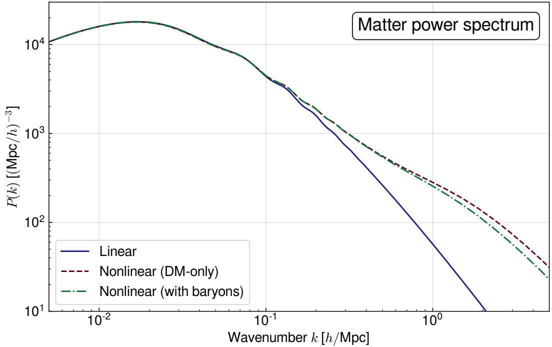
Modelling & observational challenges

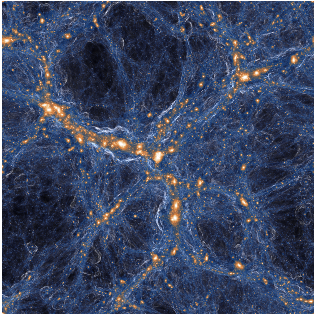
Intrinsic alignment



- IA mimics lensing signals
- Models exist
- Are they accurate enough?

Baryonic effects





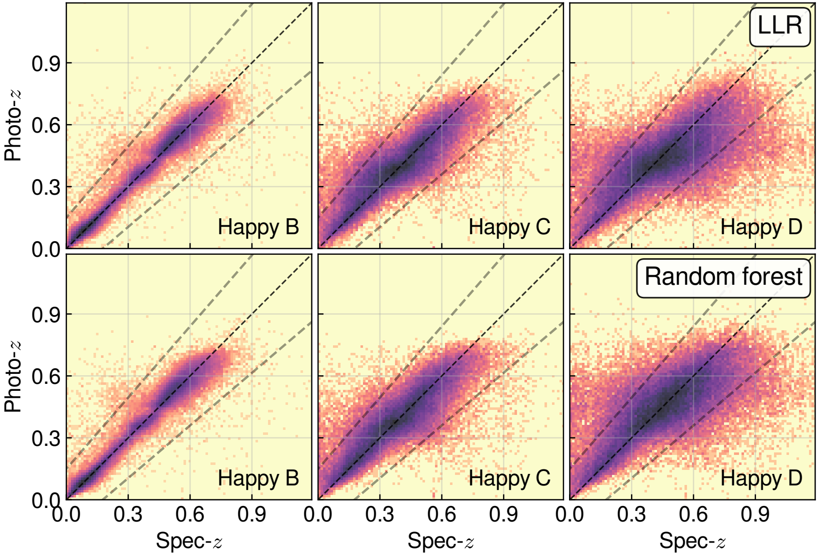
(Source: TNG Collaboration)

- Baryons contribute to lensing (of course!)
- Difficult to model

- We want to control the power spectrum at 2%
- Can cut scales, but will also lose data :(

Beck, Lin, et al. (2017)

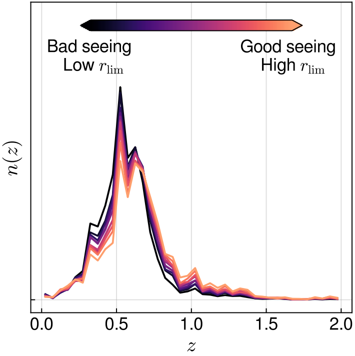
Photometric redshift errors

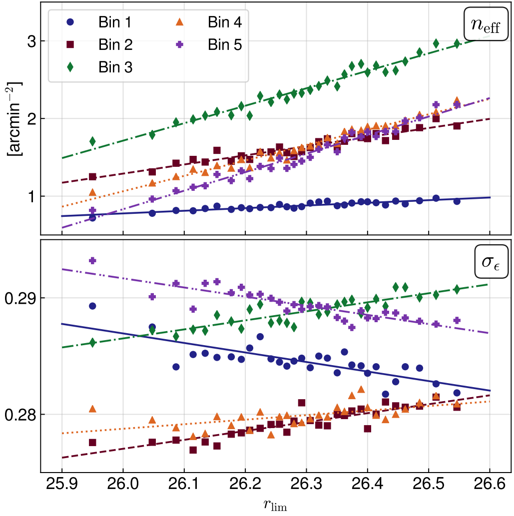


Joachimi, Lin, et al. in prep.

Variable depth effect

Redshift distributions $n(z)$, source density $n_{\rm eff}$, and shape noise σ_ϵ vary with r-band magnitude limit $r_{\rm lim}$.

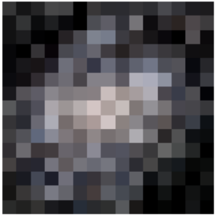




NGC 201 by ESA/Hubble

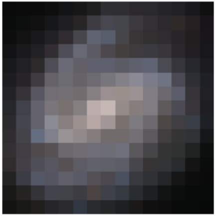
Galaxy shape in real life


Original galaxy

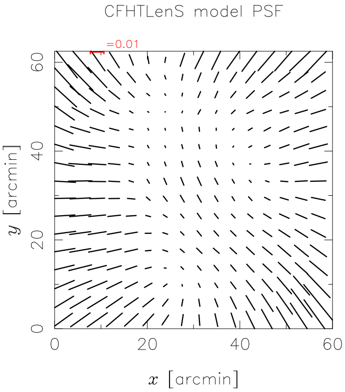

Instrumental noise


Lensing


PSF


Pixelization

Point spread function (PSF)

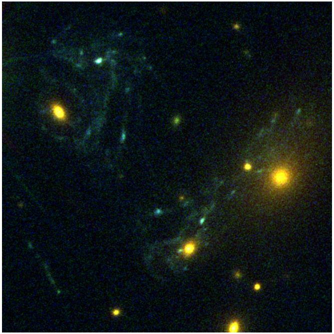


(van Uitert & Schneider 2016)

Shear: a percent-level effect

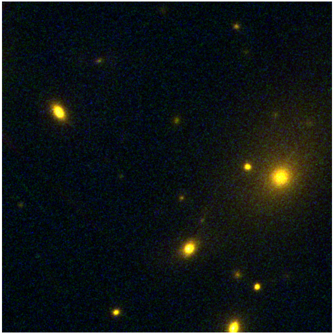
PSF: sub- to few percents

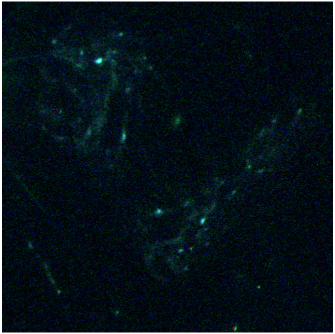
With state-of-the-art techniques, calibration of residuals is still needed



Galaxy blending

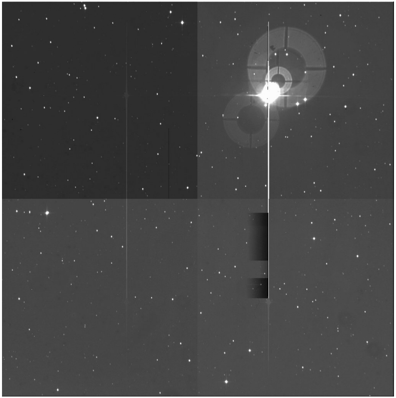
Joseph et al. (2016)

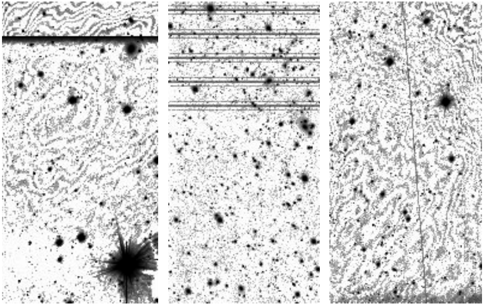


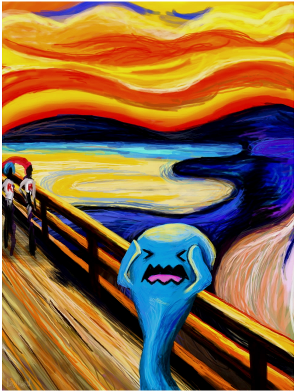


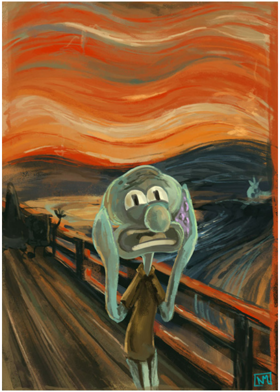
CCD defects

Source:
MDM Observatory
Amon et al. (2018a)

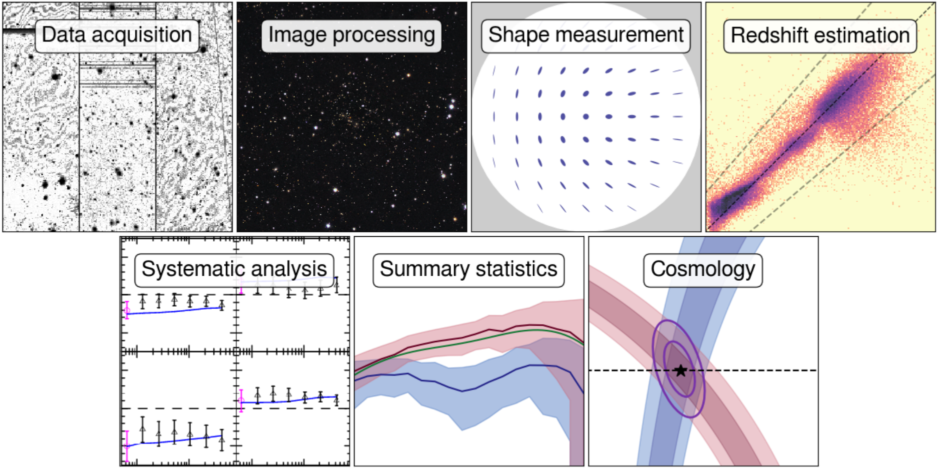








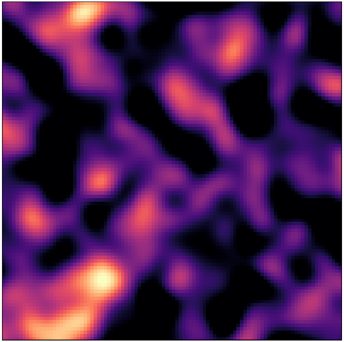
Weak-lensing pipeline



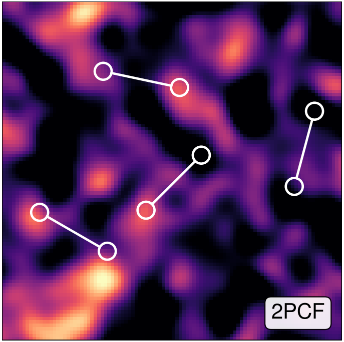
Amon et al. (2018a); Tudorica & KiDS; Beck, Lin, et al. (2017); Heymans et al. (2012)

State of the art

How to extract cosmological information?



How to extract cosmological information?



Two-point correlation functions:

$$\xi_\pm(\theta) \equiv \langle\gamma_+\gamma_+\rangle(\theta) \pm \langle\gamma_\times\gamma_\times\rangle(\theta)$$

$$\xi_+(\theta) = \int_0^{+\infty} \frac{\ell \mathrm{d}\ell}{2\pi} J_0(\ell\theta) P_\kappa(\ell)$$

$$\xi_-(\theta) = \int_0^{+\infty} \frac{\ell \mathrm{d}\ell}{2\pi} J_4(\ell\theta) P_\kappa(\ell)$$

Benchmark surveys

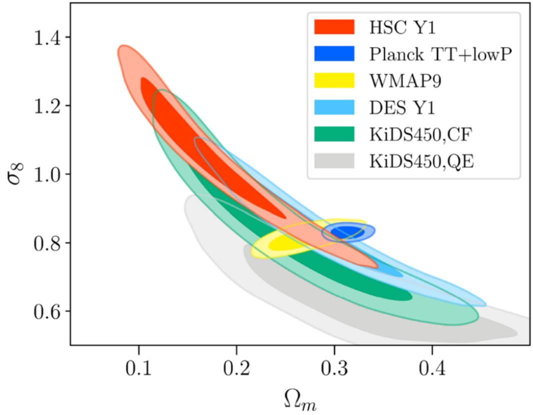
KiDS HSC

THE DARK ENERGY SURVEY

	KiDS	DES	HSC
Effective Area [deg^2]	360	1321	137
Magnitude limits*	24.9	24	26.4
Effective galaxy density [arcmin^{-2}]	8.5	5.5	16.5

*Respectively for i'-, r-, i-, and i-bands

Cosmological constraints

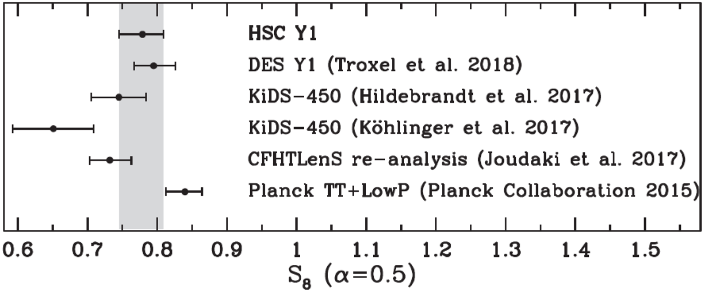


Ω_m = matter abundance
σ_8 = matter fluctuation

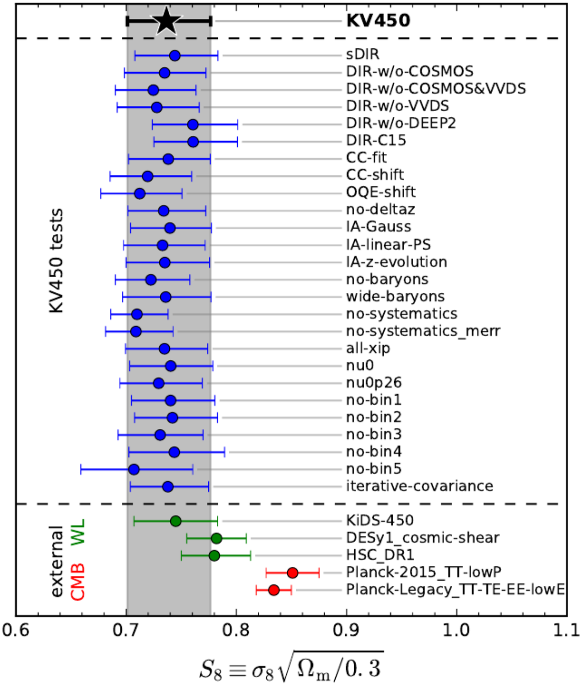
Hildebrandt et al. (2017)
Troxel et al. (2018)
Hikage et al. (2019)

Cosmological constraints

Hikage et al. (2019)



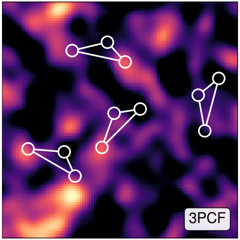
$$S_8 = \sigma_8(\Omega_\mathrm{m}/0.3)^\alpha$$

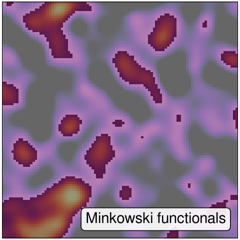


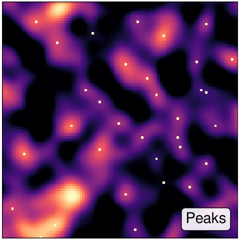
Systematic tests from WL

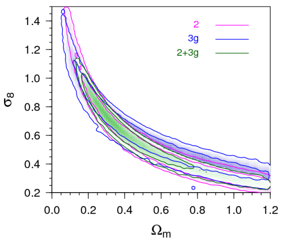
Hildebrandt et al. (2019)

Non-Gaussian estimators

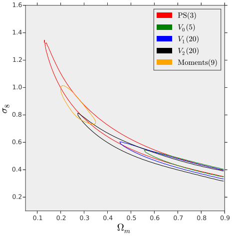




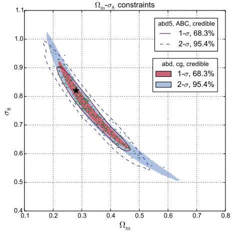




Fu et al. (2014)

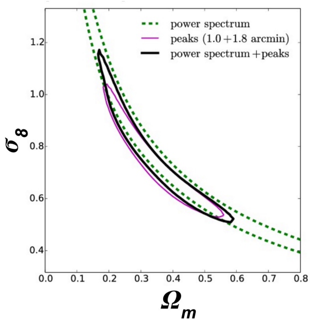


Petri et al. (2015)

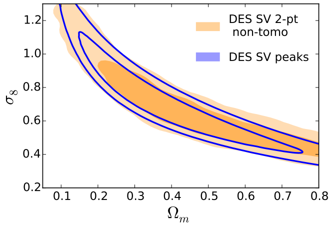


Lin & Kilbinger (2015b)

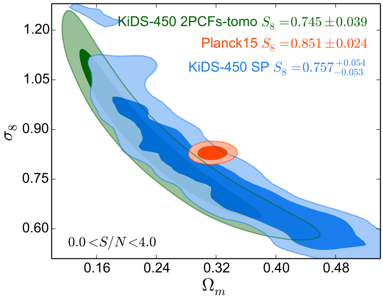
Results from lensing peaks



Liu et al. (2015)



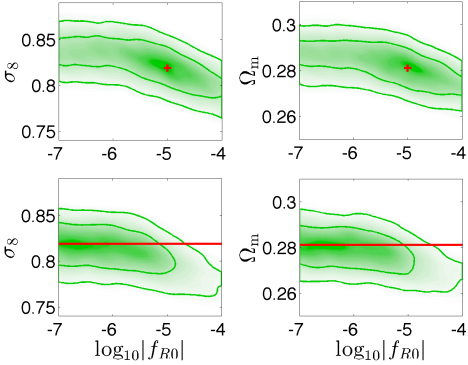
Kacprzak et al. (2016)



Martinet et al. (2018)

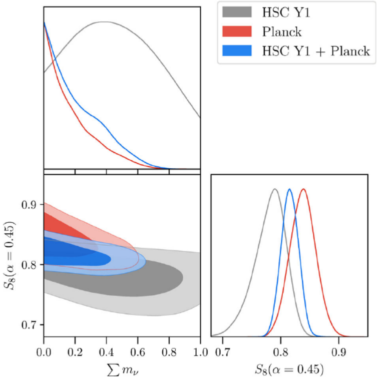
Constraints on extended physics

Modified gravity



Liu et al. (2016)

Massive neutrinos



Hikage et al. (2019)

Future perspectives

Ongoing surveys keep collecting data

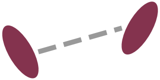
KiDS	Kilo-Degree Survey	$360 \Rightarrow 770 \Rightarrow 1000$ deg^2
THE DARK ENERGY SURVEY		$1321 \Rightarrow \cdots \Rightarrow 6000$ deg^2
HSC	Hyper Suprime-Cam	$130 \Rightarrow \cdots \Rightarrow 1000$ deg^2

$3\times$2pt analysis

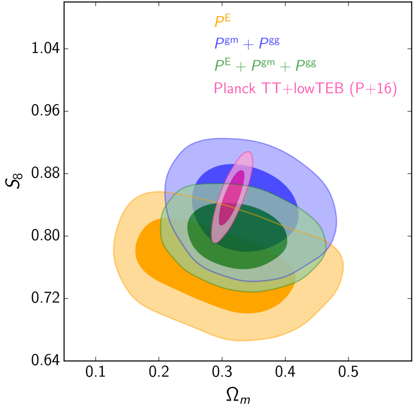
- Galaxy position: biased tracer of matter
- Galaxy shape: noisy tracer of projected matter

$\langle$ position position $\rangle$  galaxy clustering w

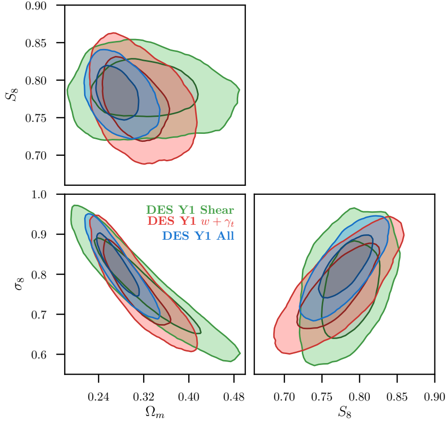
$\langle$ position shape $\rangle$  galaxy-galaxy lensing γ_+

$\langle$ shape shape $\rangle$  cosmic shear $\xi_\pm$

3×2pt: better constraints

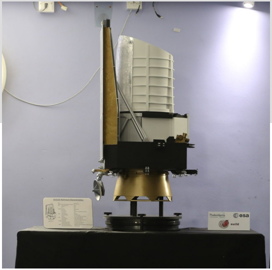


KiDS Collaboration
(van Uitert et al. 2018)



DES Collaboration (2018)

- Space mission at L2 point
- 1.2 meter entrance pupil & 609 Mpixel camera
- 3 infrared photometry bands: YJH
- Area = 15000 deg^2
- Visible band limit = 24.5



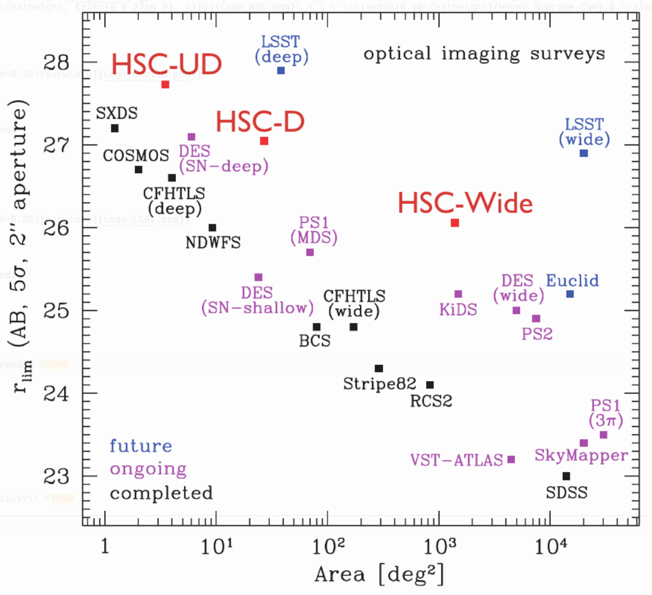
Euclid_NISP@Twitter

LSST
Large Synoptic Survey Telescope

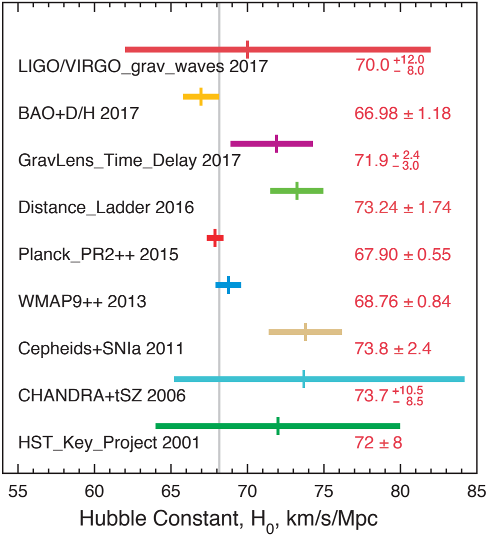
- Located at the sommet of Cerro Pachón in Chile
- 8.4 meter mirror & 3.2 Gpixel camera
- 6 photometry bands: ugrizy
- Area = 20000 deg^2
- i-band limit = 27.0

LSST@Twitter

Optical depth vs survey area

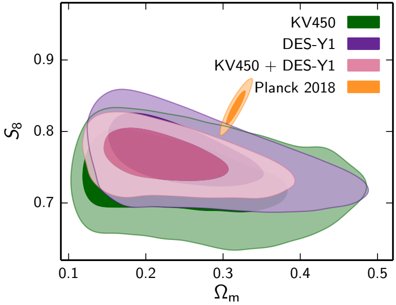


Tensions: systematics or new physics?



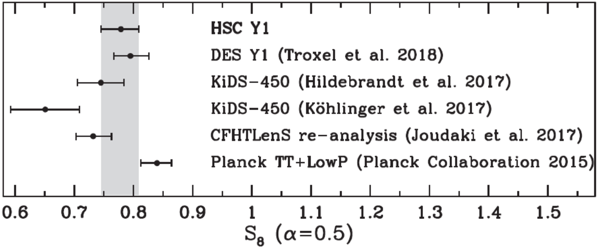
Source: NASA

Tensions: systematics or new physics?



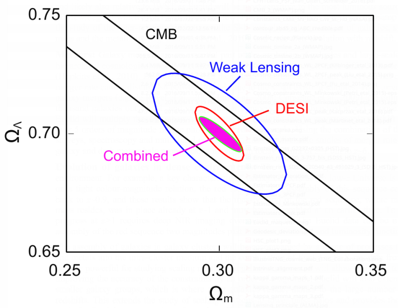
Joudaki et al. submitted

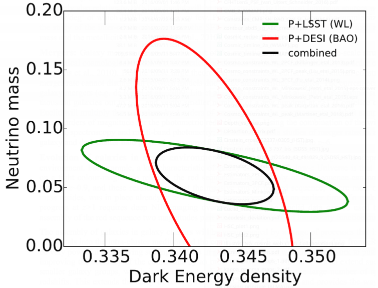
Hikage et al. (2019)

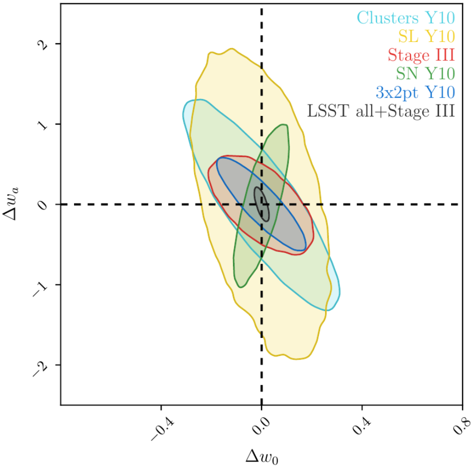


Synergy

Source:
LSST science requirements document
DESI final design report

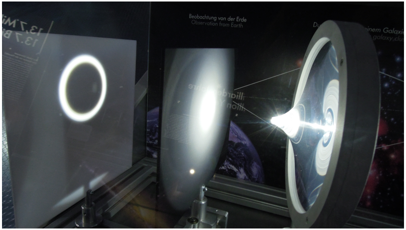


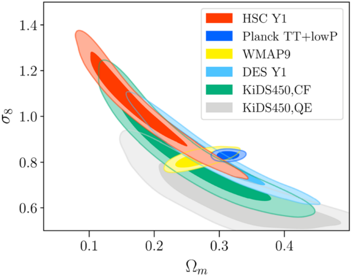




Summary

- What to measure?
- How to measure?
- What do we really measure?
- What have been measured?
- What will be measured?





- Dark energy
- From late-time evolution of cosmic structures
- Tiny distortions of galaxy images
- Some bananas
- Tiny bananas/potatoes or new discoveries!

http://linc.tw

Backup slides

Impact from variable depth