Constraints On Dark Energy And Modified Gravity Models From CFHTLenS

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OUTLINE

- Weak gravitational lensing
- The CFHT Lensing survey; data, galaxy shape measurement, systematics
- CFHTLenS results: constraints on dark energy, modified gravity (+ Wiggle-Z), mass maps
- Outlook, future lensing surveys, Euclid

ALL THE FUSS ABOUT LENSING

From the CFHTLS web page:

[The CFHTS Wide] allows the study of the large scale structures and matter distribution in the universe through weak lensing and galaxy distribution, as well as the study of clusters of galaxies through morphology and photometric properties of galaxies.

From the ESO description of KiDS:

The primary science driver for the design of this project has been weak gravitational lensing.

From Sanchez et al. (2011), "The Dark Energy Survey":

will start in the fall of 2011 and will study the dark energy properties using four independent methods: galaxy clusters counts and distributions, weak gravitational lensing tomography, baryon acoustic oscillations and supernovae Ia distances. Obtaining the four measurements

From the Euclid Red Book:

Main Scientific Objectives
Understand the nature of Dark Energy and Dark Matter by:
• Reach a dark energy *FoM* > 400 using only weak lensing and galaxy clustering; this roughly corresponds to 1 sigma errors on w_p and w_a of 0.02 and 0.1, respectively.

WHY ALL THE FUSS?

Weak gravitational lensing

... probes the matter distribution on large scales

outskirts of galaxies, clusters, large-scale structure, cosmology

... is sensitive to the total (dark + baryonic) mass

no assumption needed for relation between galaxies and dark matter

... probes the Universe between $z \approx 0.1$ and ≥ 1

epoch of acceleration

... measures the expansion history and growth rate

can distinguish between dark energy and modified gravity


WEAK LENSING OVERVIEW

HOW DOES IT WORK?

Mass deflects light (Einstein 1915)

Point mass:

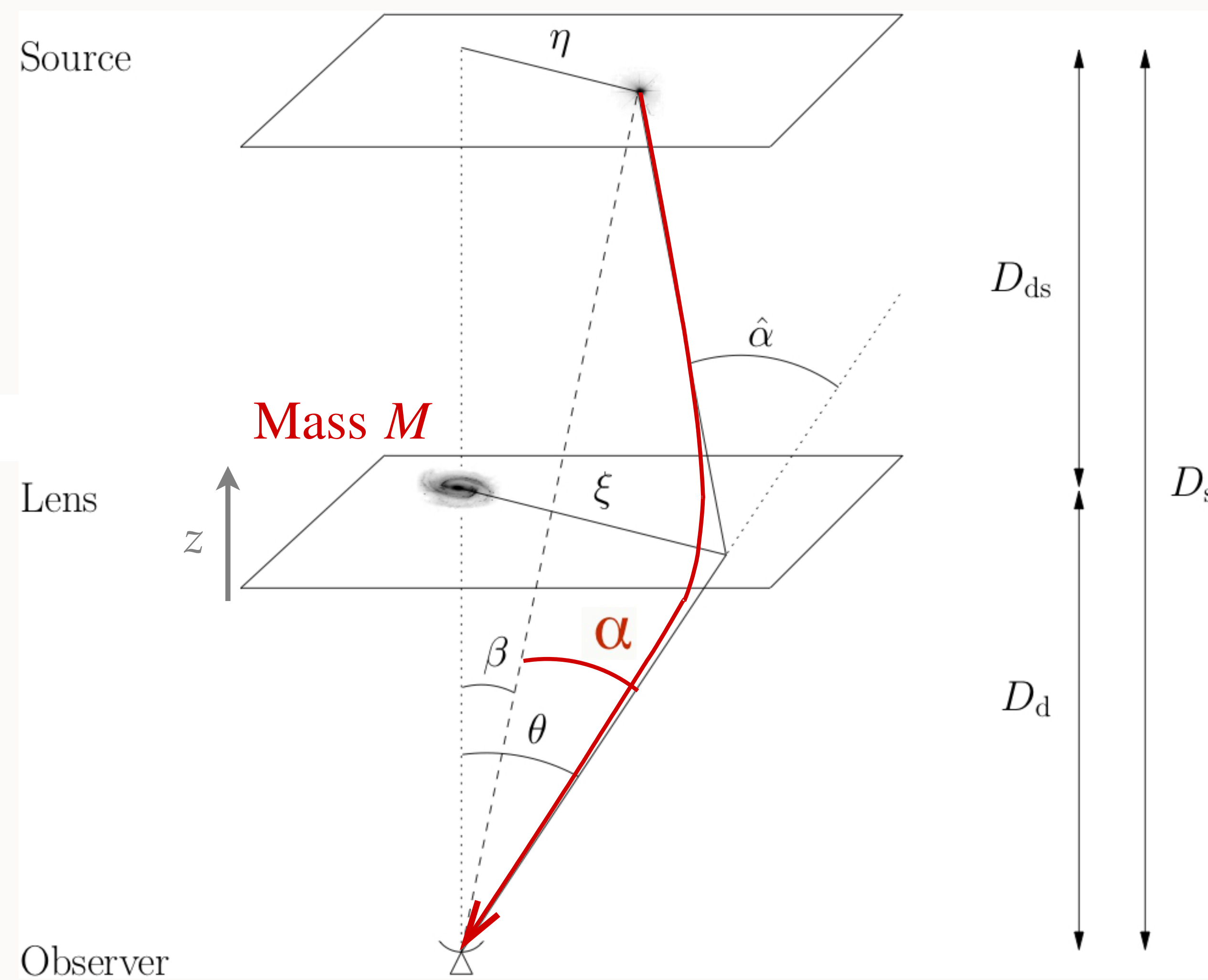
Deflection angle

$$\hat{\alpha} = \frac{4GM}{c^2\xi}$$

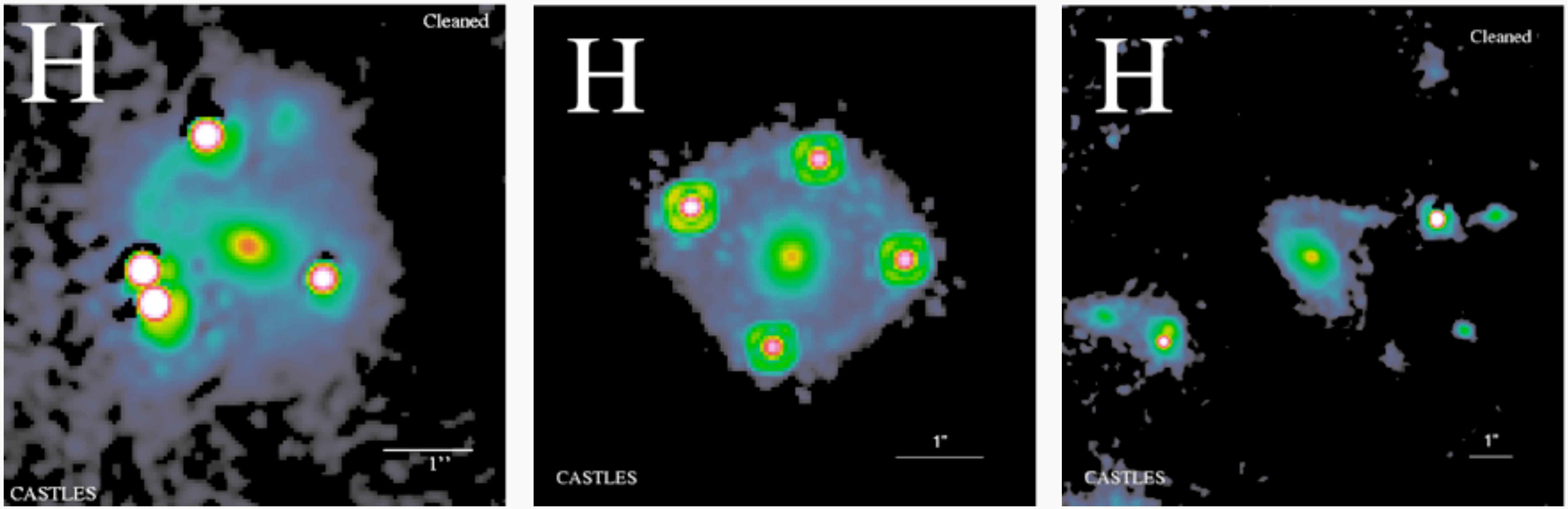
impact parameter

Extended mass distribution:

Deflection angle depends on integral over the projected mass distribution



LENSING MULTIPLICATION



	MG0414+0534	HE0435-1223	RXJ0921+4529
z_{source}	2.64	1.689	1.65
z_{lens}	0.96	0.46	0.31

CASTLES survey,

http://www.cfa.harvard.edu/castles

A CLOSER LOOK

- First order effect: Deflection of a point source

- Second order effect: Differential deflection of an extended source, distortion,

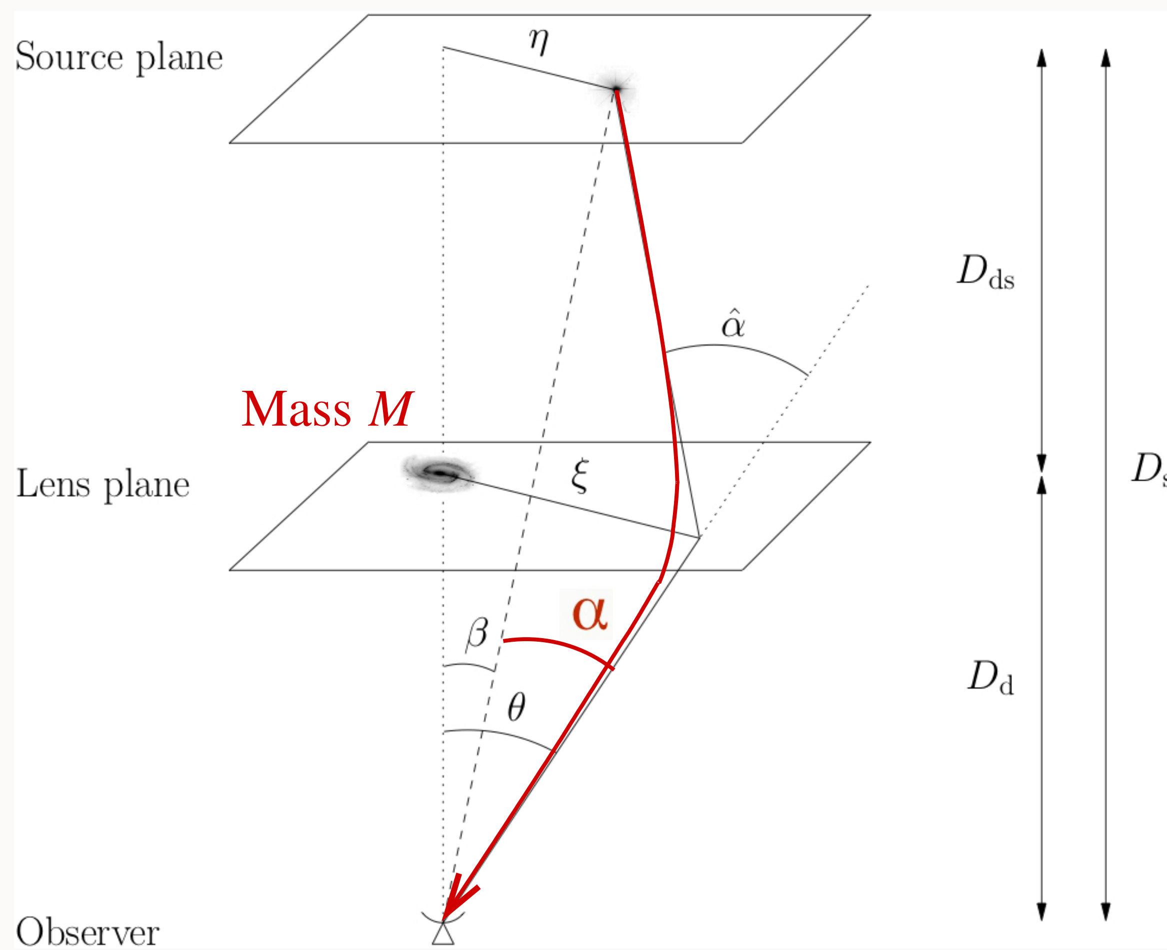
$$\vec{\alpha} = \vec{\alpha}(\vec{\theta})$$

2D angular coordinates

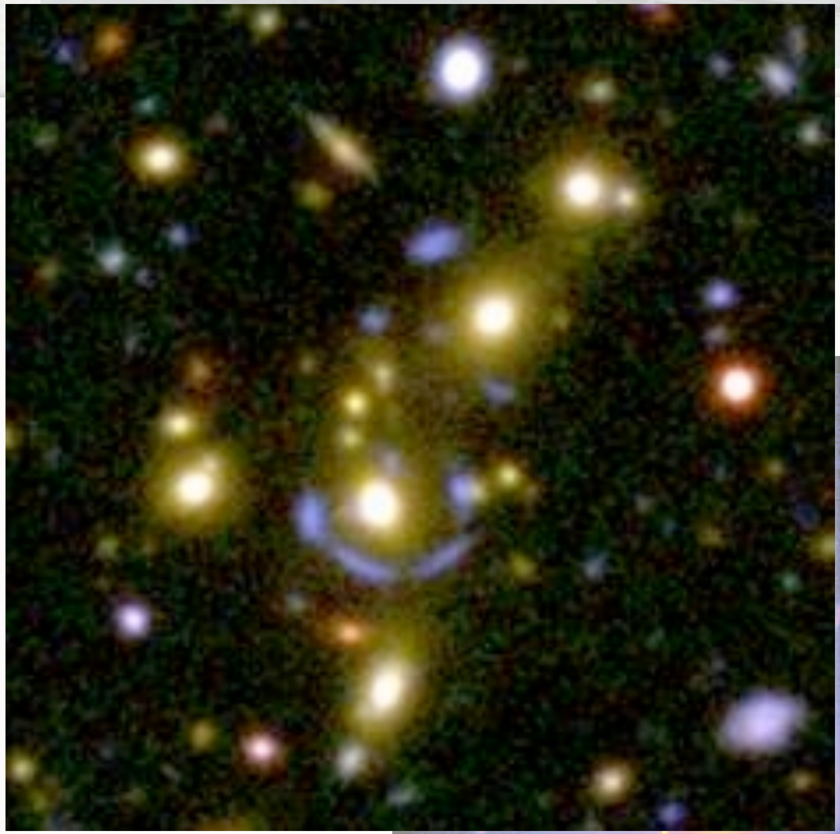
- Deflection angle is a gradient:

$$\vec{\alpha} = \vec{\nabla}\phi$$

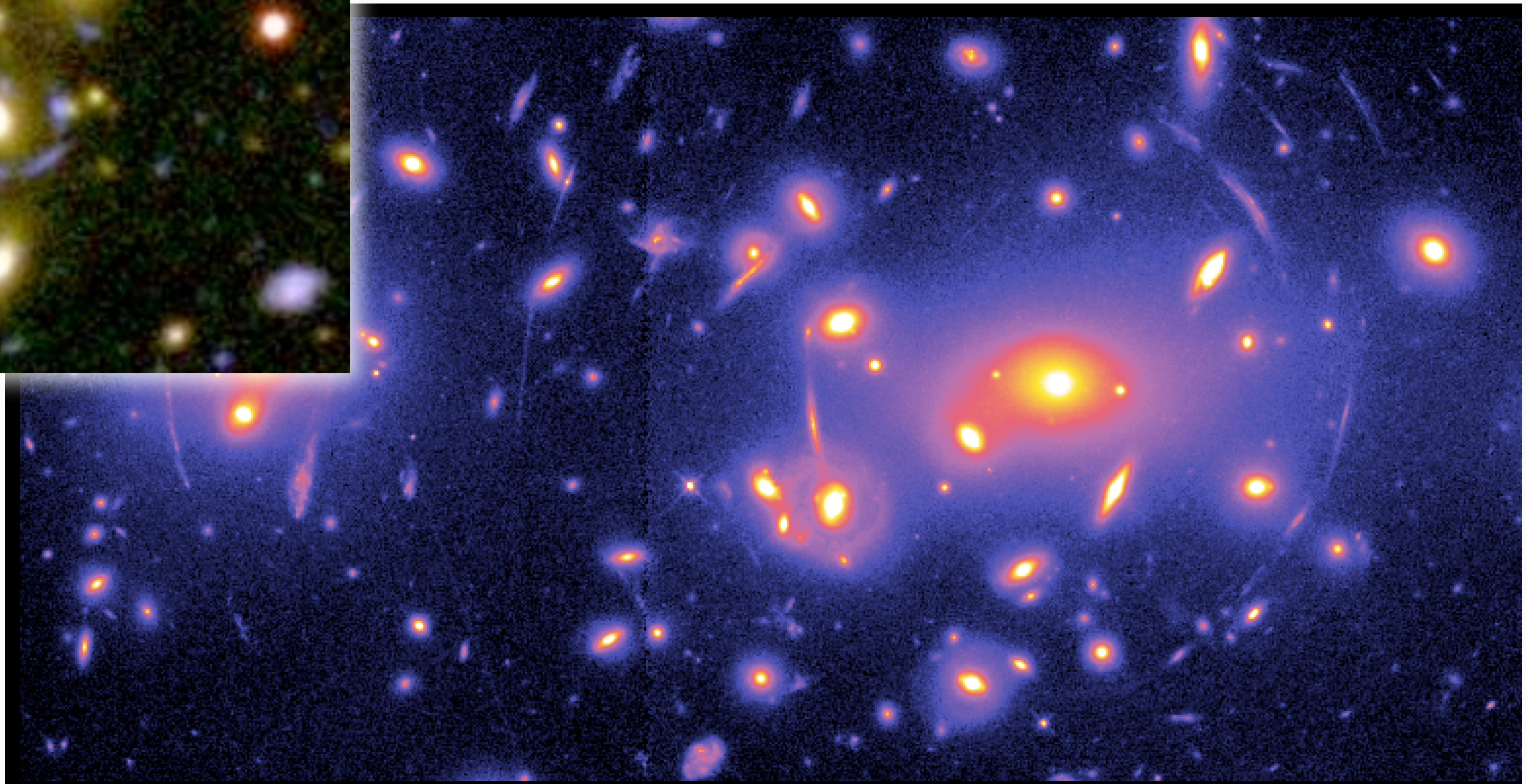
2D lensing potential



LENSING DISTORTIONS



CFHTL12k lens candidate, Czoske et al. 2001,
$z_l = 0.49$, $z_s = ?$



The cluster of galaxies Abell 2218

A CLOSER LOOK

- Deflection angle is a gradient:

$$\vec{\alpha} = \vec{\nabla}\phi$$

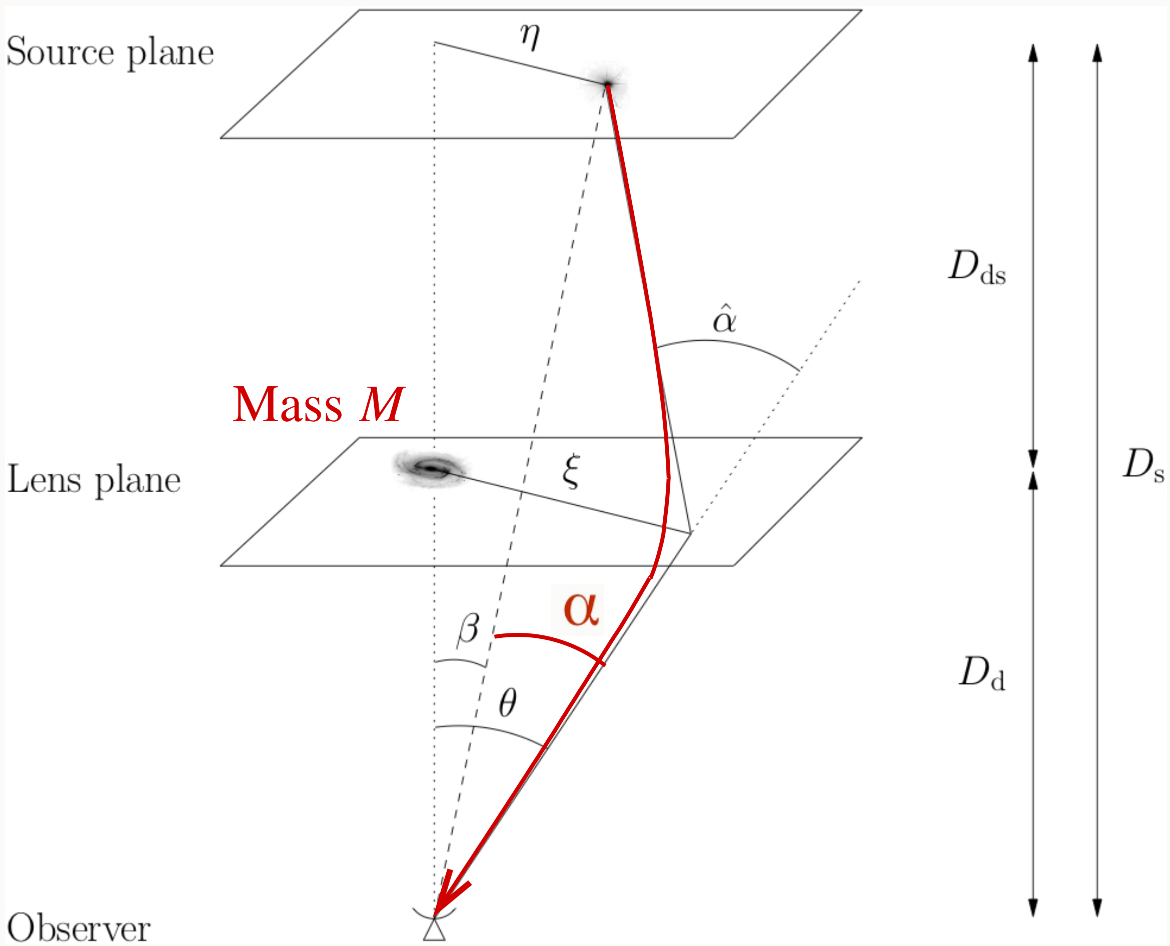
2D lensing potential

- Second order effect: Differential deflection of an extended source, distortion, $\vec{\alpha} = \vec{\alpha}(\vec{\theta})$

2D angular coordinates

- Linearize deflection:

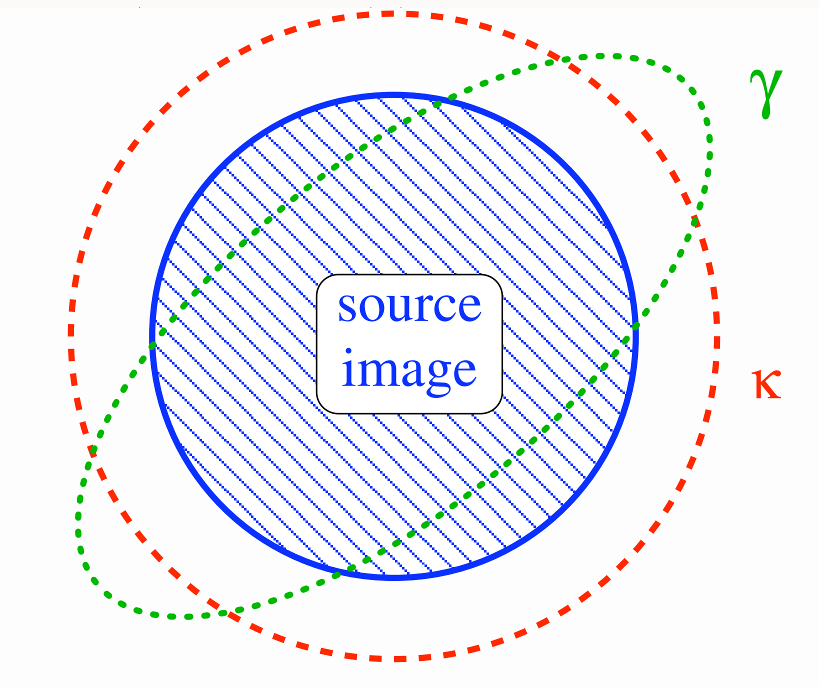
$$\frac{\partial \alpha_i}{\partial \theta_j} = \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix}$$



CONVERGENCE & SHEAR

Gravitational lensing effect, locally:

- Convergence κ: isotropic magnification
- Shear γ: anisotropic stretching
- κ and γ are second derivatives of the "lensing potential" Φ, which describes the projected 2D mass distribution.



Typical in weak cosmological lensing: 3% distortion, $\gamma \approx 0.03$

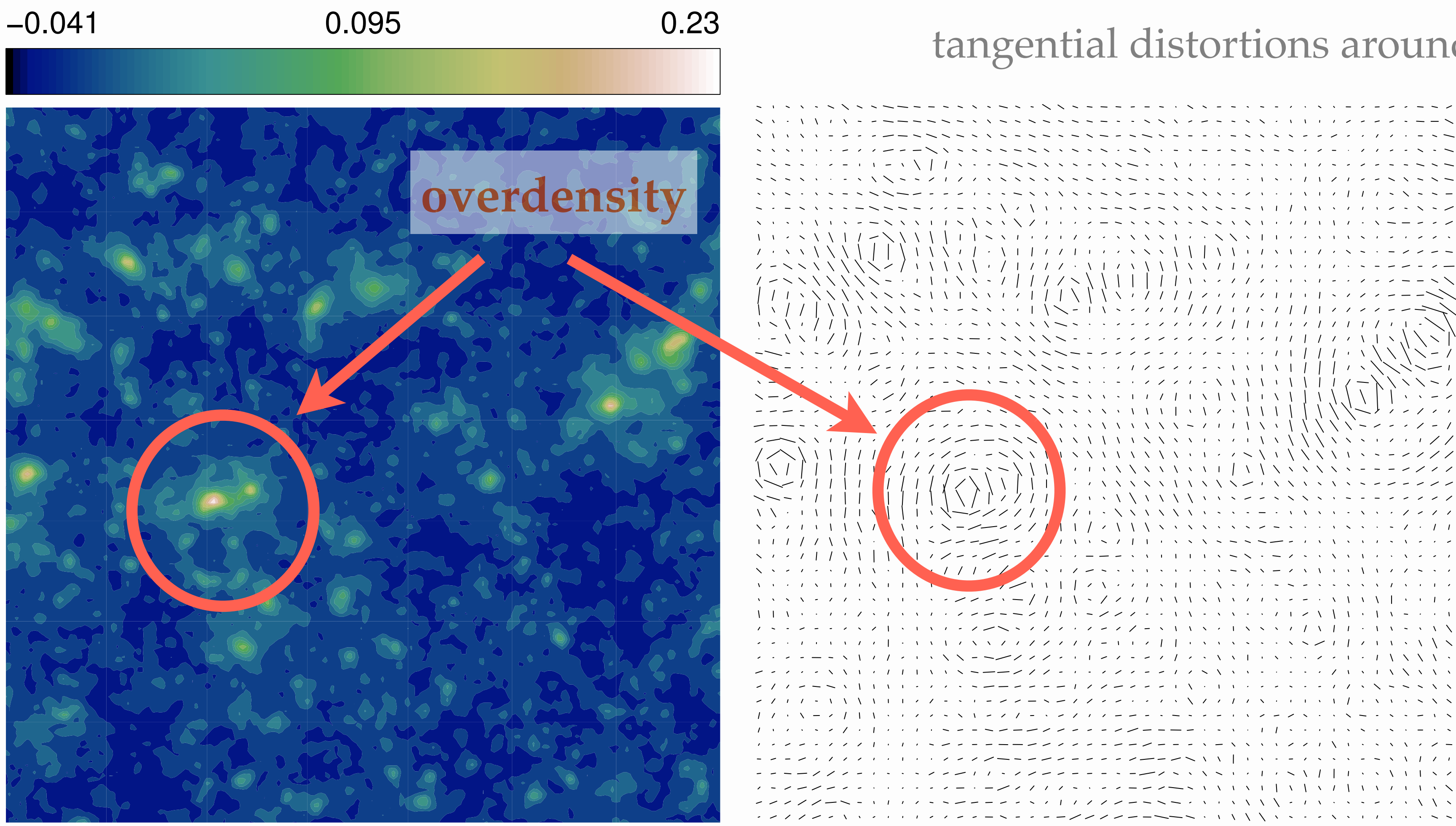
[In particular, κ is the scaled projected mass density, related to Φ via a Poisson equation: $2\kappa = \Delta\Phi$]

MASS AND SHEAR

Projected matter density
convergence κ

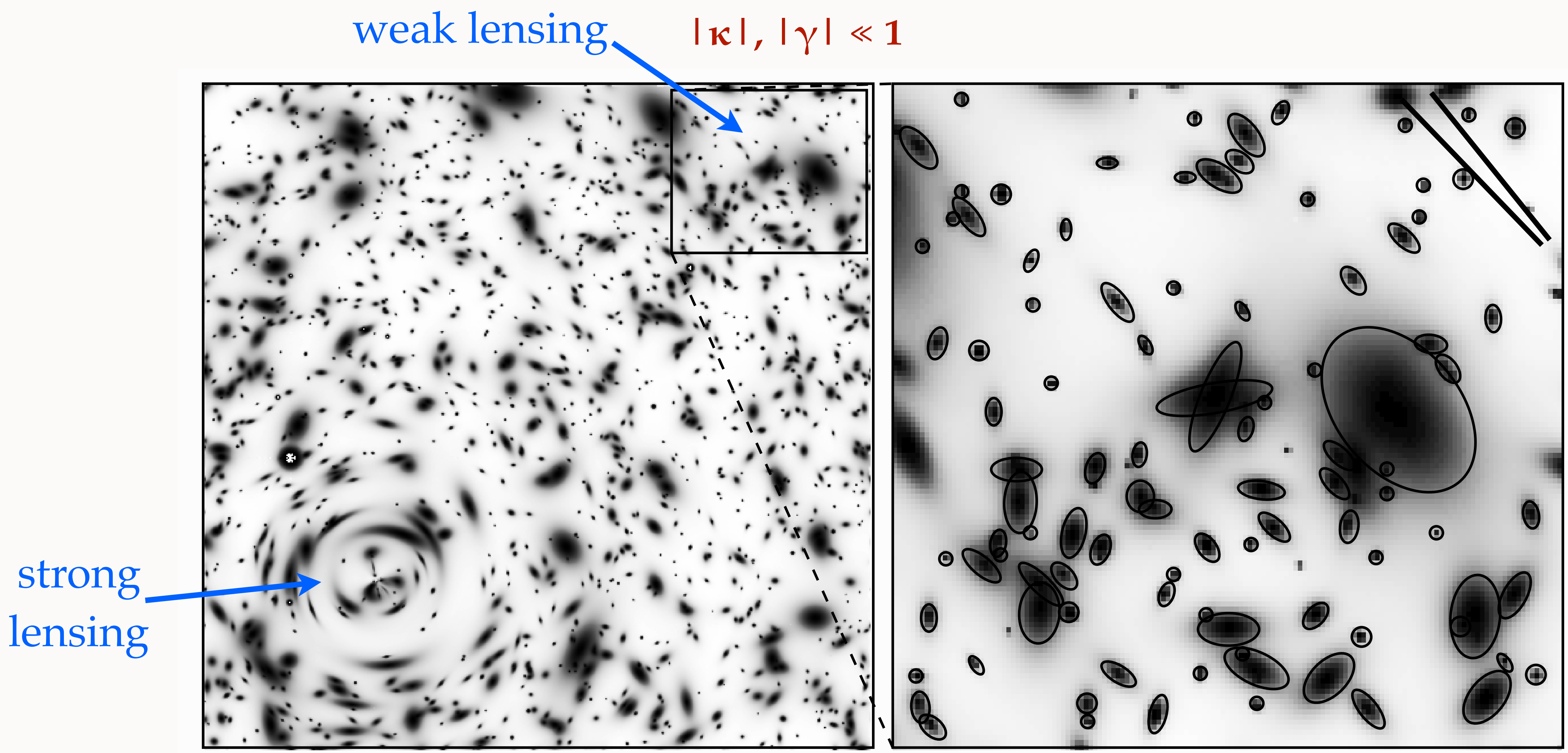
Distortion field
shear γ

tangential distortions around mass peaks



Source galaxies at $z = 1$, ray-tracing simulations by T. Hamana

GALAXIES ESTIMATE SHEAR



[from Y. Mellier]

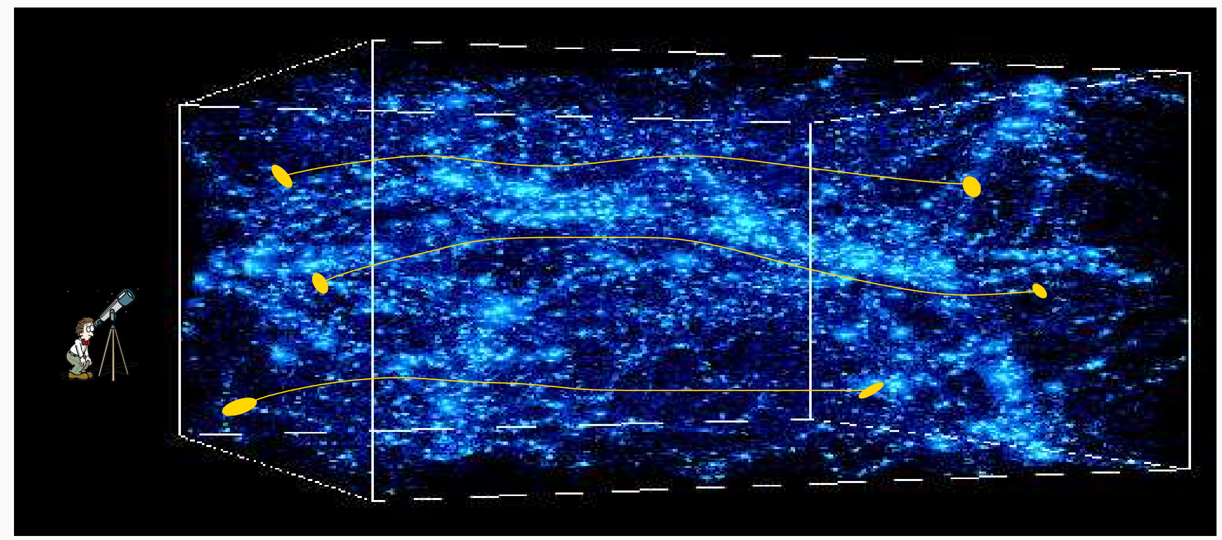
Galaxy ellipticities are an estimator of the local shear.

Noise: intrinsic galaxy shapes

COSMIC SHEAR

Weak lensing by the large-scale structure

- Continuous distortion along light ray path
- Lensing distortion strength depends on properties of projected 2D density contrast
- Sensitive to geometry of the Universe and growth of structures



comoving coordinates

$$\kappa(\vec{\theta}) = \int_0^{\chi_{\rm lim}} \mathrm{d}\chi\, G(\chi)\delta(\chi\vec{\theta}, \chi)$$

lensing efficiency

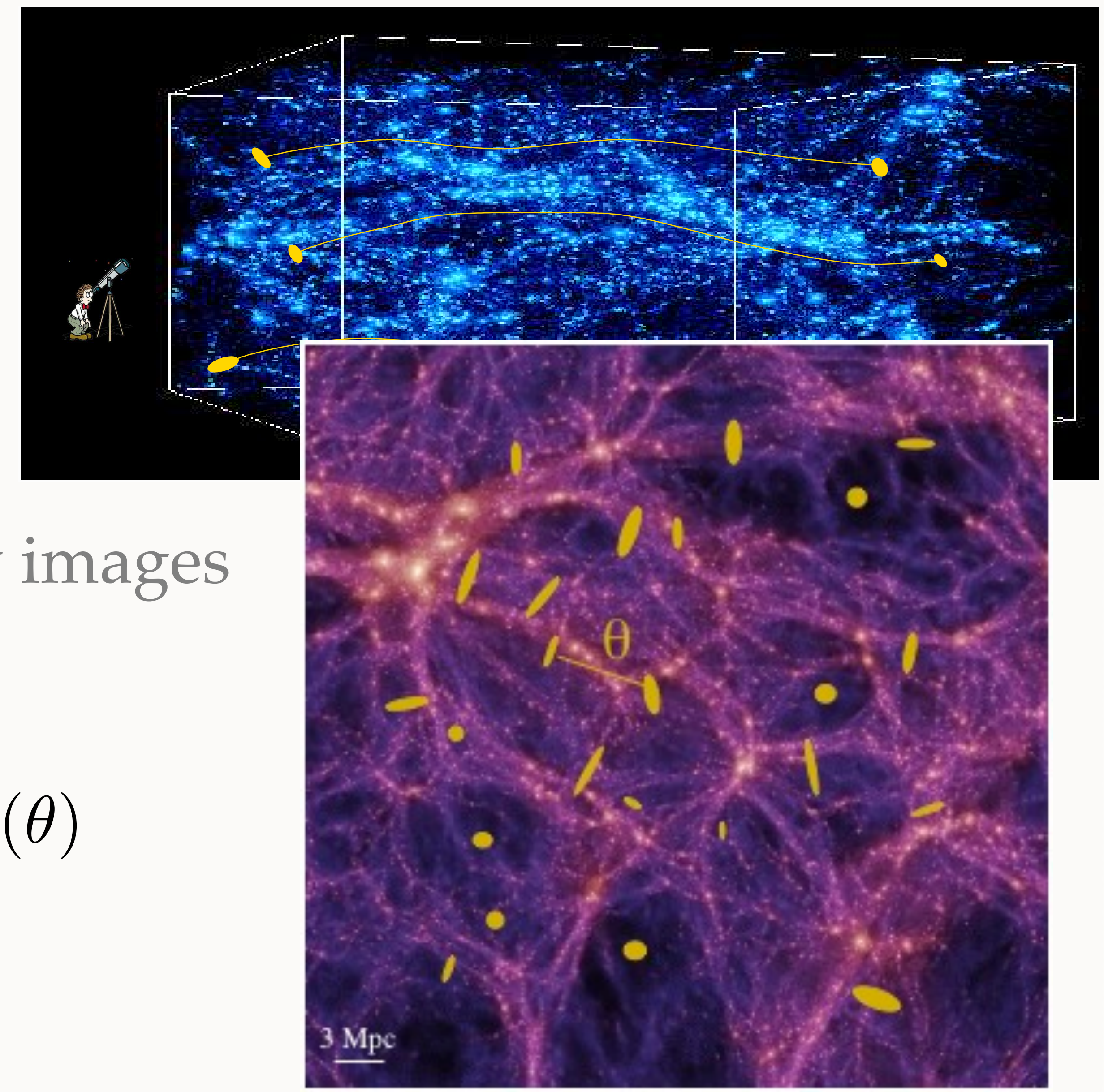
density contrast

$$G(\chi) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \frac{\Omega_{\rm m}}{a} \int_{\chi}^{\chi_{\rm lim}} \mathrm{d}\chi'\, p(\chi') \frac{\chi(\chi'-\chi)}{\chi'}$$

redshift distribution of background galaxies

COSMIC SHEAR

Weak lensing by the large-scale structure



- Coherent distortions of galaxy images
  → measure shape correlations

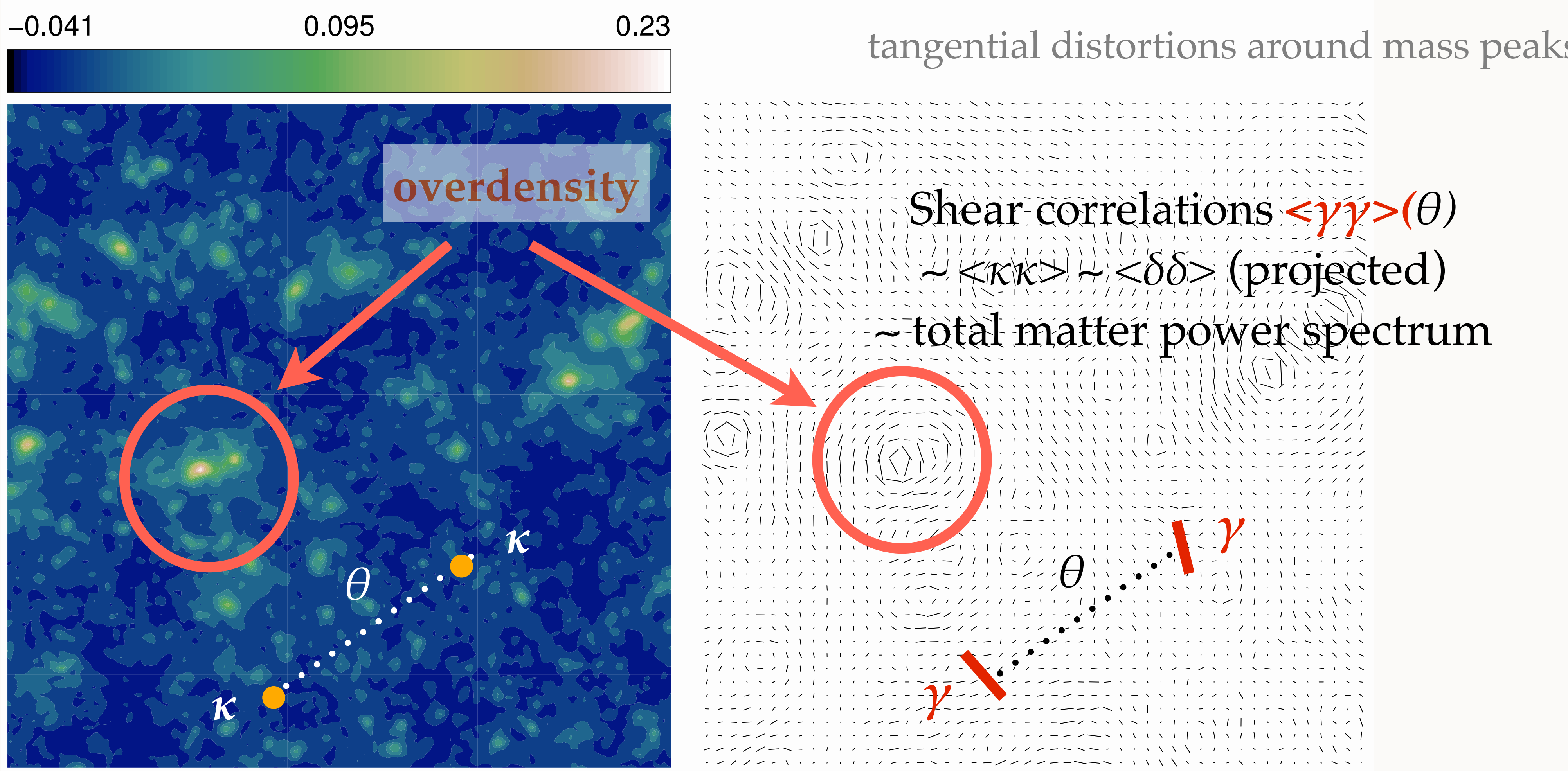
$$\langle |\gamma|^2 \rangle (\theta) = \langle \kappa^2 \rangle (\theta) \propto \langle \delta^2 \rangle (\theta)$$

shear variance

MASS AND SHEAR

Projected matter density
convergence κ

Distortion field
shear γ



Source galaxies at $z = 1$, ray-tracing simulations by T. Hamana

CFHT LENSING SURVEY

The CFHTLenS team

L. van Waerbeke (PI)
H. Hildebrandt
M. Milkeraitis
S. Vafaei
J. Benjamin

C. Heymans (PI)
T. Kitching
F. Simpson
E. Grocutt

Y. Mellier
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T. Erben
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K. Kuijken
E. Semboloni
M. Smit

M. Hudson
B. Gillis

L. Miller
M. Velander

J. Coupon

B. Rowe

C. Bonnett

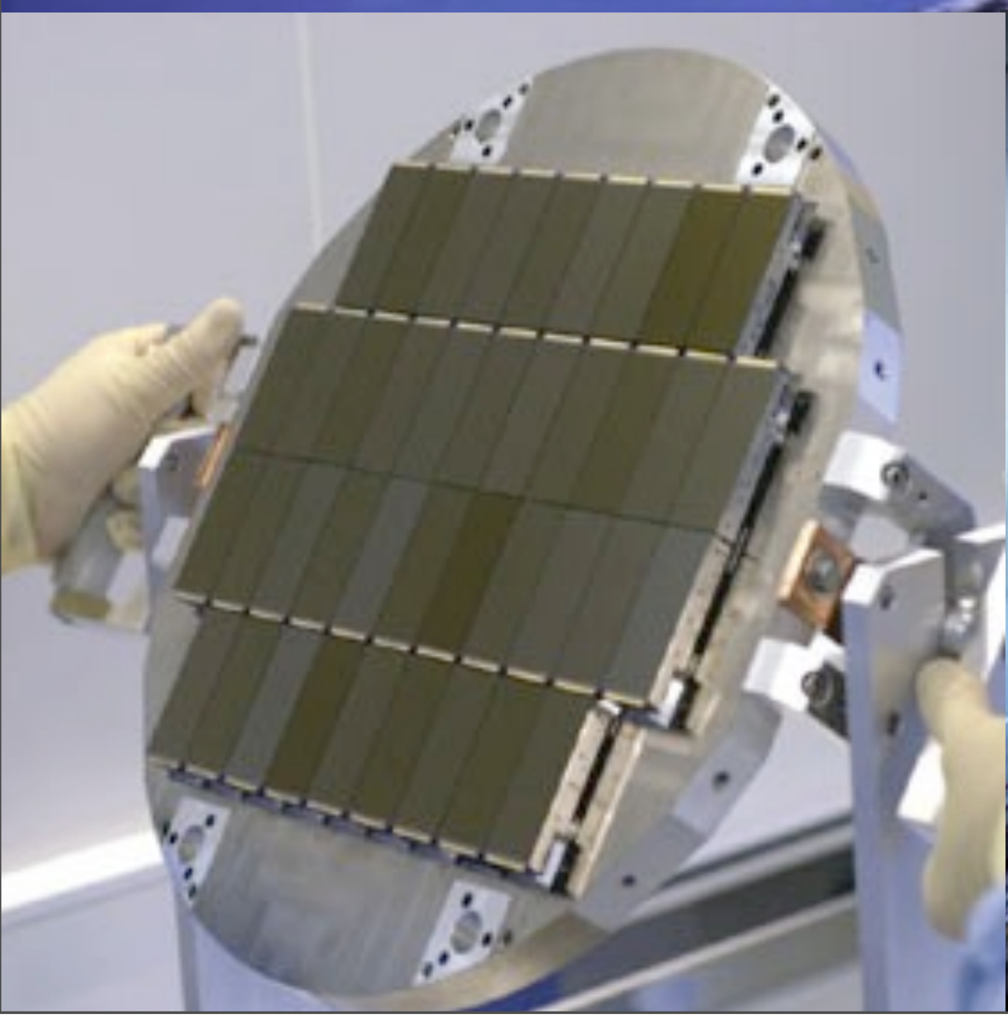
L. Fu

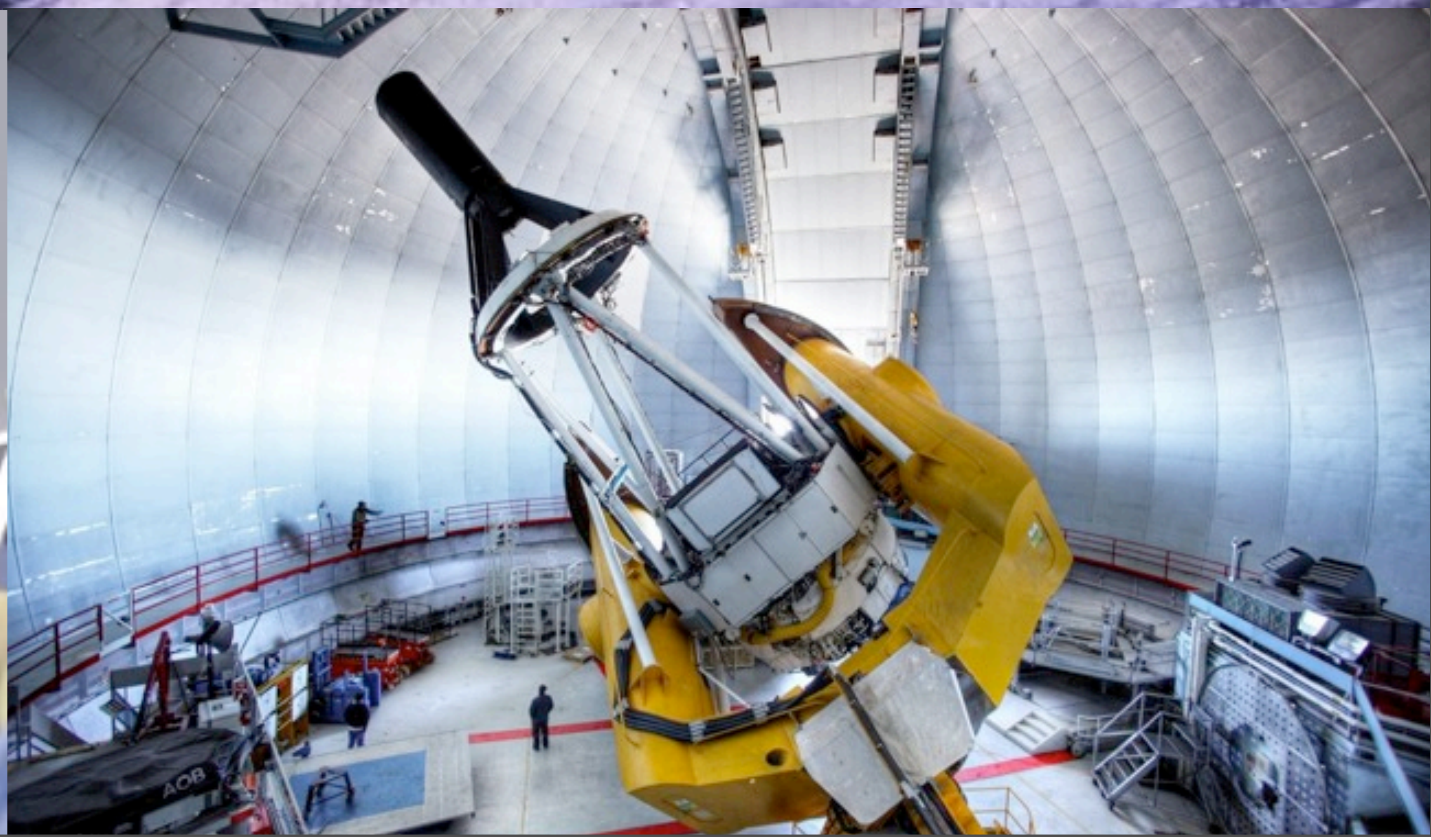
M. Kilbinger

K. Holhjem

CFHTLenS

- The state-of-the-art cosmological survey with 155 sq degrees, ugriz to i<24.7 (7σ extended source)
- Uses 5 yrs of data from the Deep, Wide and Pre-survey components of the CFHT Legacy Survey

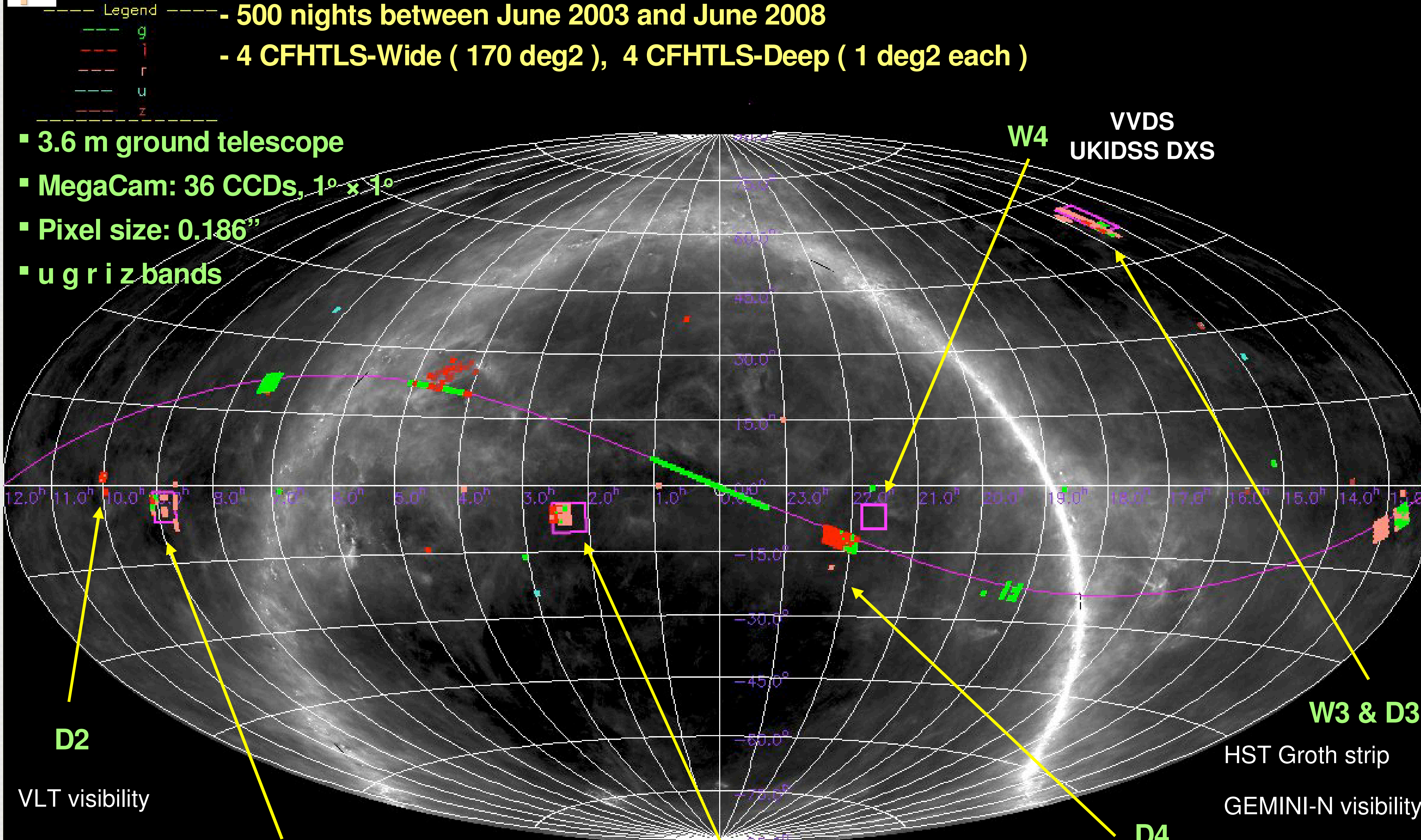




Canada-France-Hawaii Telescope Legacy Survey: Canada-France collaboration

- 500 nights between June 2003 and June 2008
- 4 CFHTLS-Wide (170 deg2), 4 CFHTLS-Deep (1 deg2 each)

- 3.6 m ground telescope
- MegaCam: 36 CCDs, 1° x 1°
- Pixel size: 0.186”
- u g r i z bands



W4
VVDS
UKIDSS DXS

D2
VLT visibility
+ HST-Cosmos

W2
VLT visibility

W1 & D1
VLT visibility + XMM fields

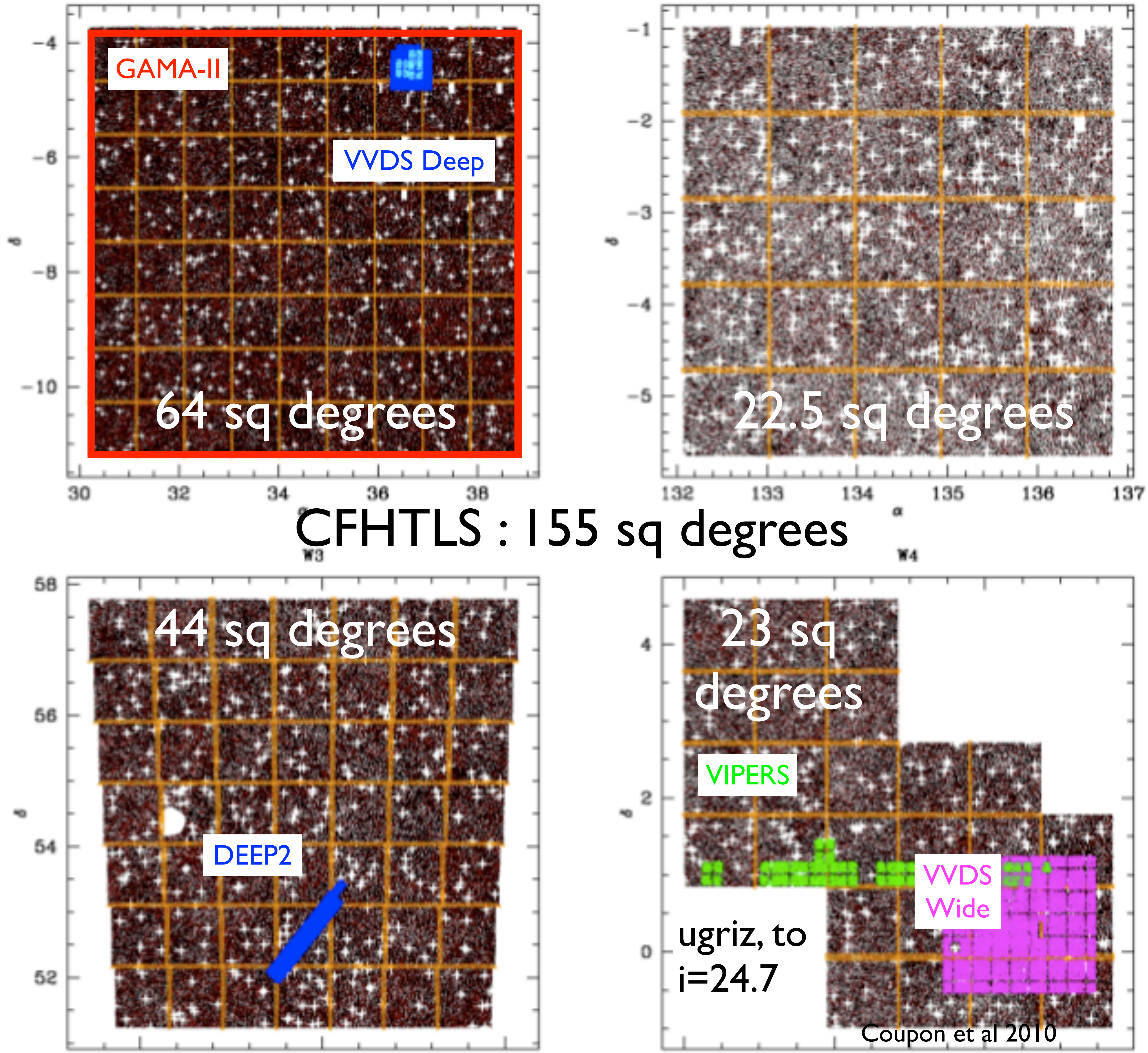
D4
VLT visibility +
Quasar field

W3 & D3
HST Groth strip
GEMINI-N visibility

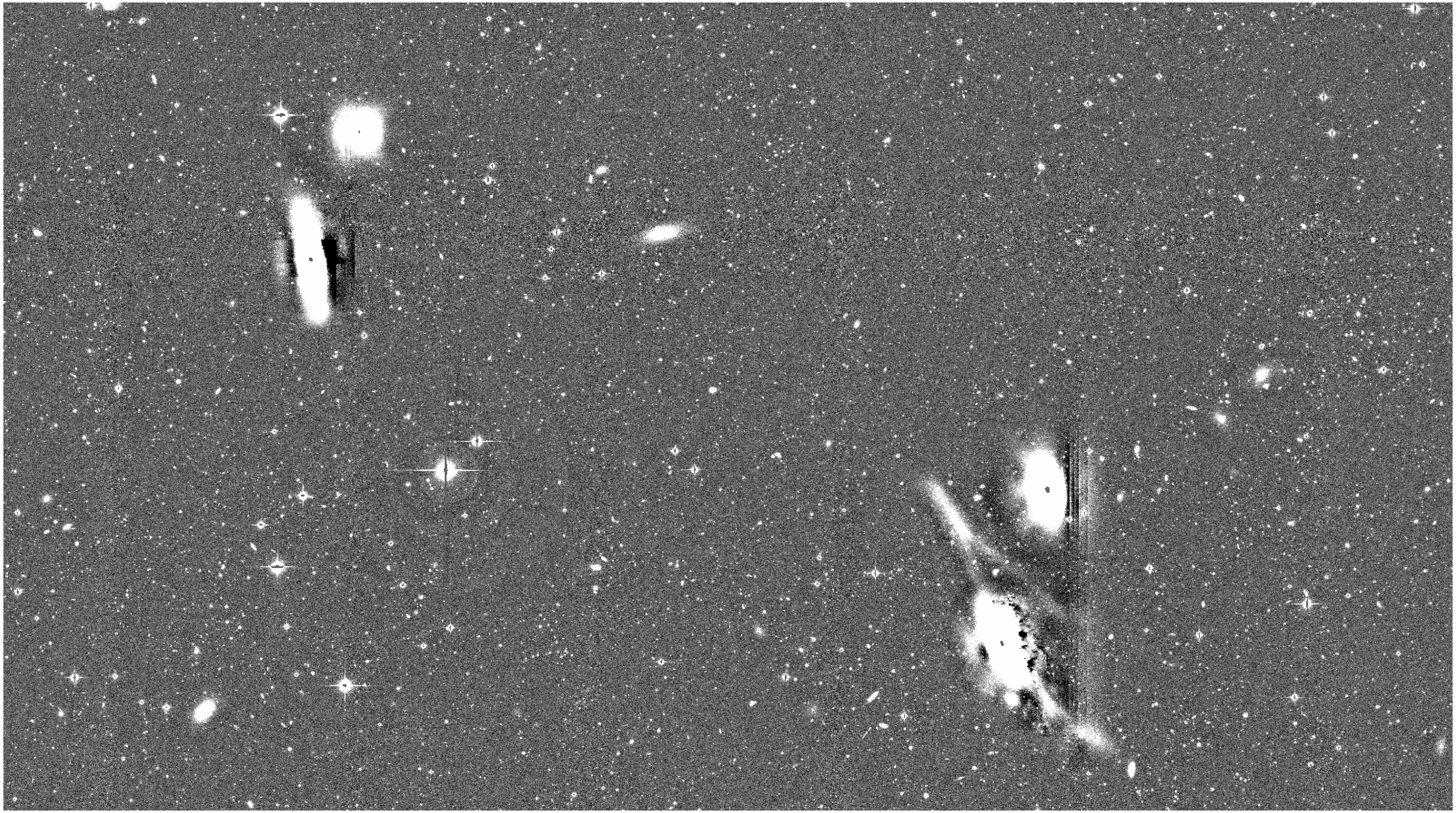
VVDS spectro. survey

←command line : skywatcher

Terapix/Skywatcher : all data 03A-05A : 20000 Megacam images

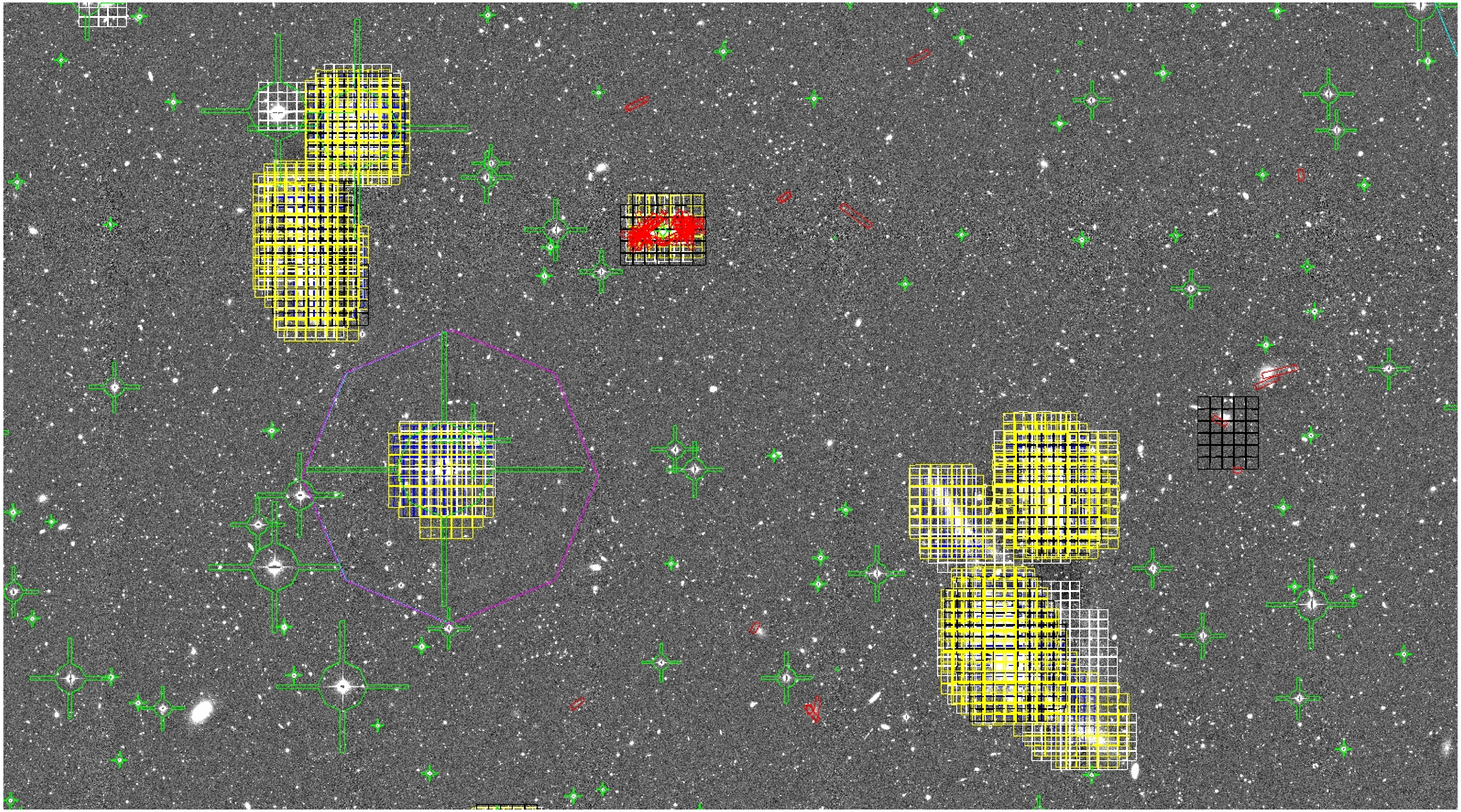

GAMA-II
VVDS Deep
64 sq degrees
22.5 sq degrees
CFHTLS : 155 sq degrees
44 sq degrees
DEEP2
23 sq degrees
VIPERS
VVDS Wide
ugriz, to i=24.7
Coupon et al 2010

A MEGACAM@CFHT Image Section



Regions around bright stars and big galaxies need to be excluded from our weak lensing studies.

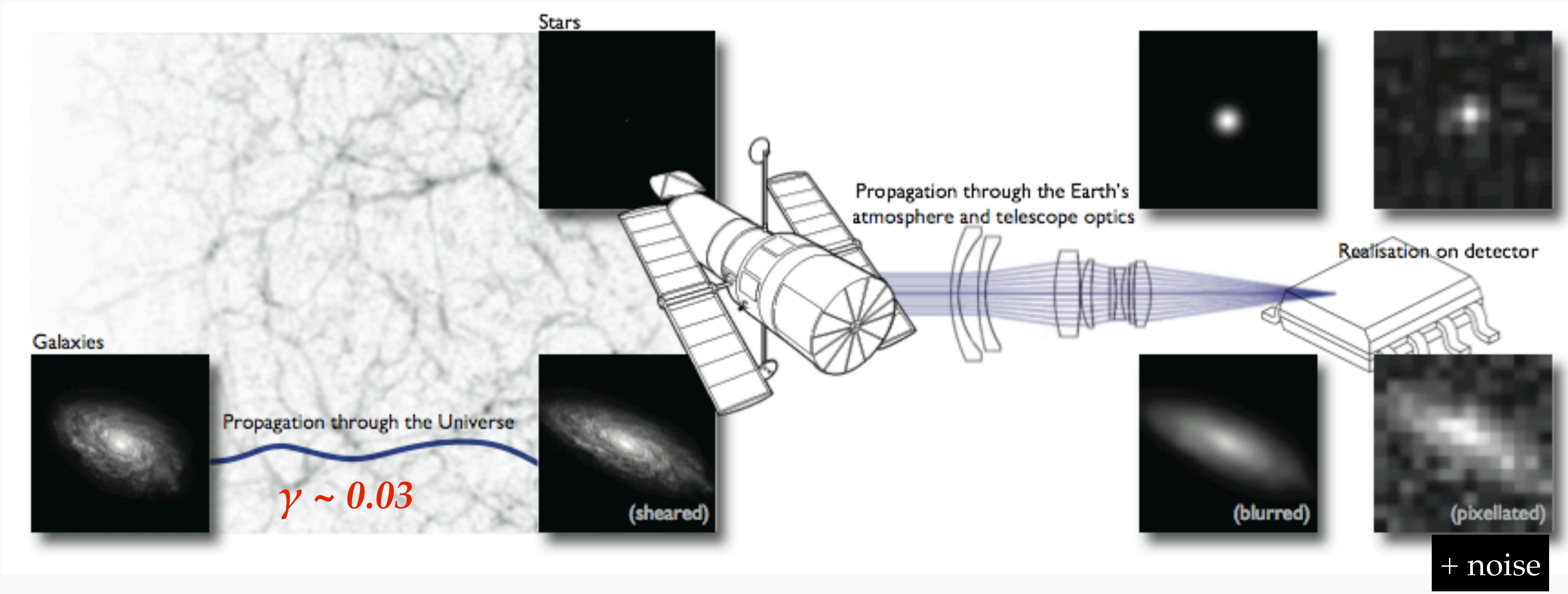
Semi-Automatic Masking



Moderately bright Stars are masked with template masks; large scale defects produce significant jumps in the object number density

[Erben et al. in 2013]

SHAPE MEASUREMENT



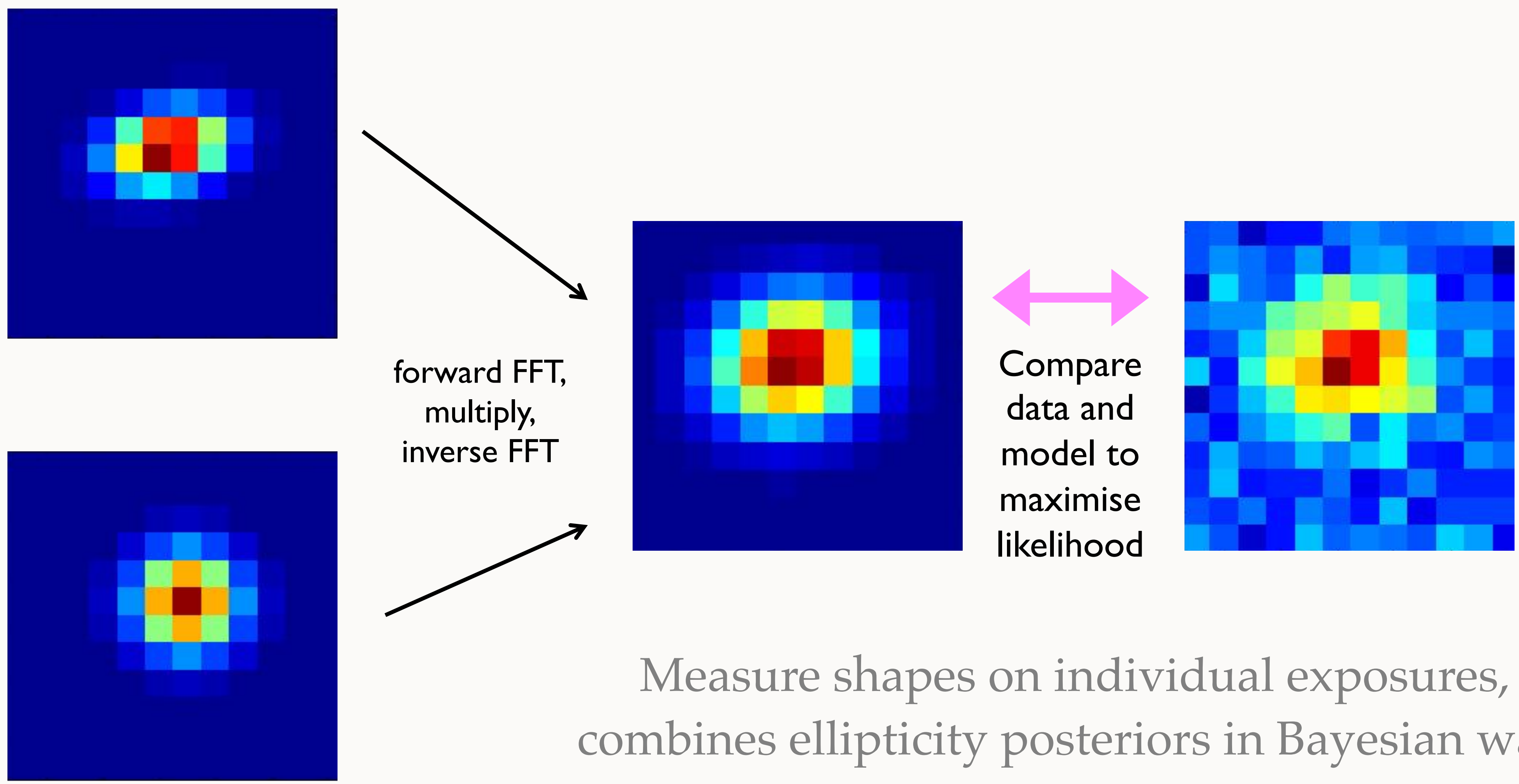
[Bridle et al. 2008, great08 handbook]

- Use stars to correct for instrumental and atmospheric distortions
- An individual galaxy shape cannot be well estimated, but need to measure the ensemble free from systematic bias

SHAPE MEASUREMENT: LENSFIT

[Miller et al 2007, Kitching et al 2008, Miller et al. 2013]

Model



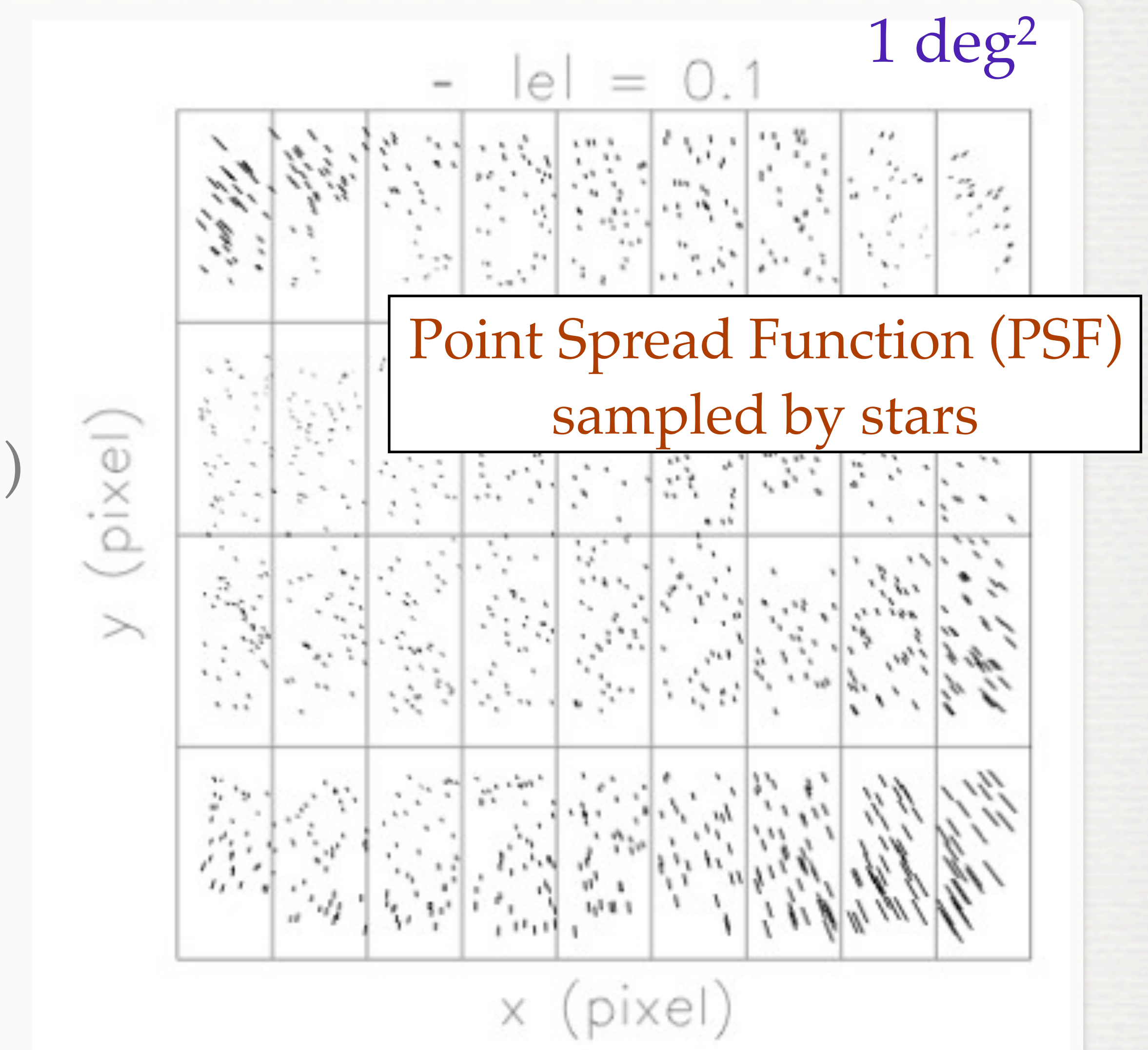
PSF
(Point Spread Function)

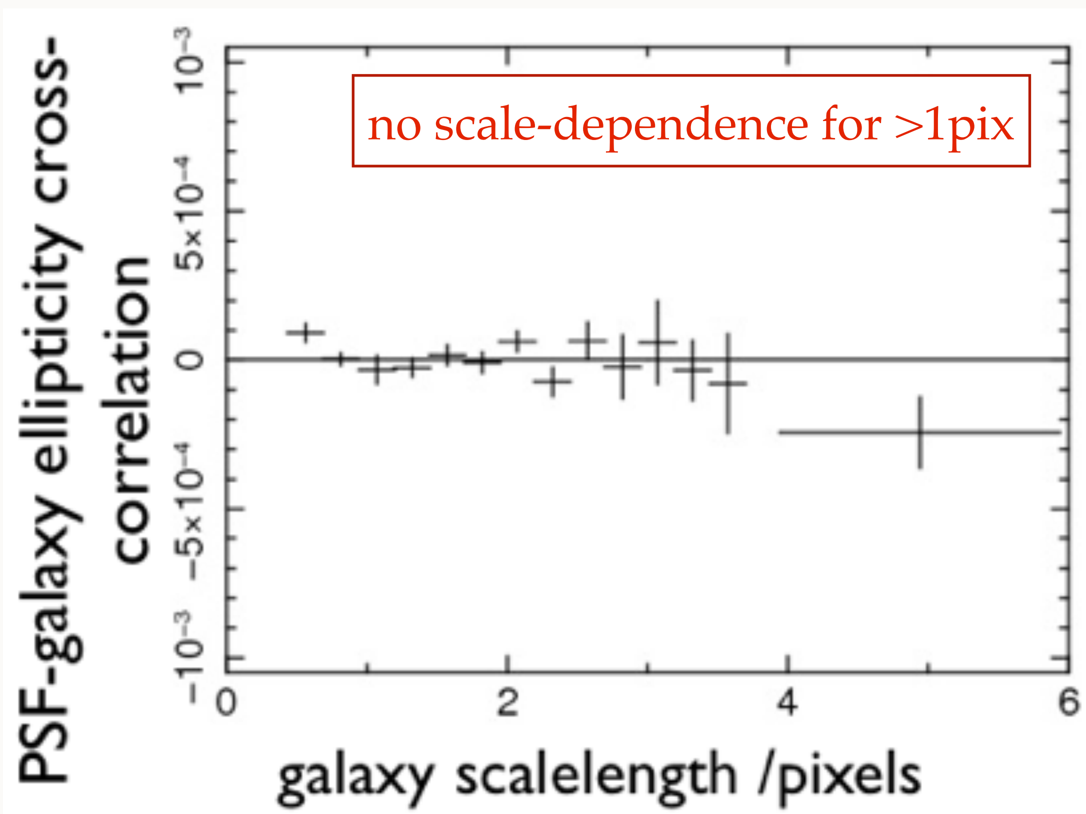
Measure shapes on individual exposures, combines ellipticity posteriors in Bayesian way.

Avoids problems in co-added images.

SHEAR MEASUREMENT: SYSTEMATICS

- Correlation between
  - galaxy shapes (after correction)
  - star shapes (uncorrected)
  non-zero ⇔ PSF residuals
- Compare to noise simulations (incl. LSS)



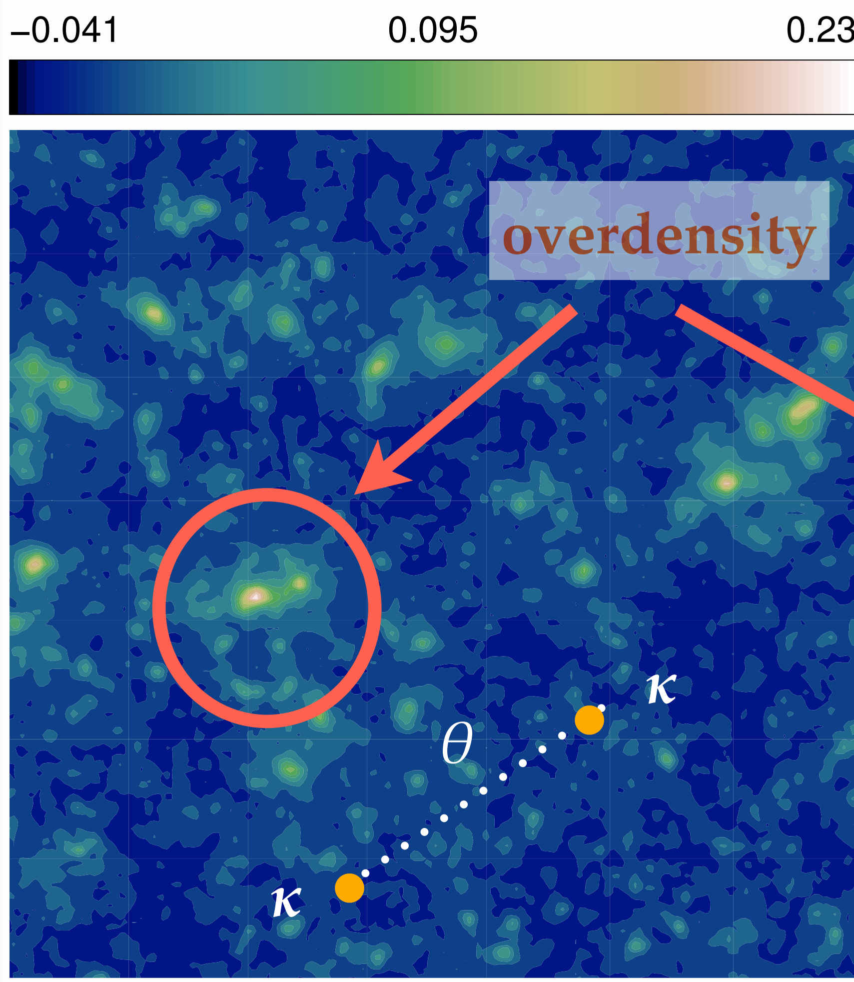


- Cosmology-blind
- 80% of data pass

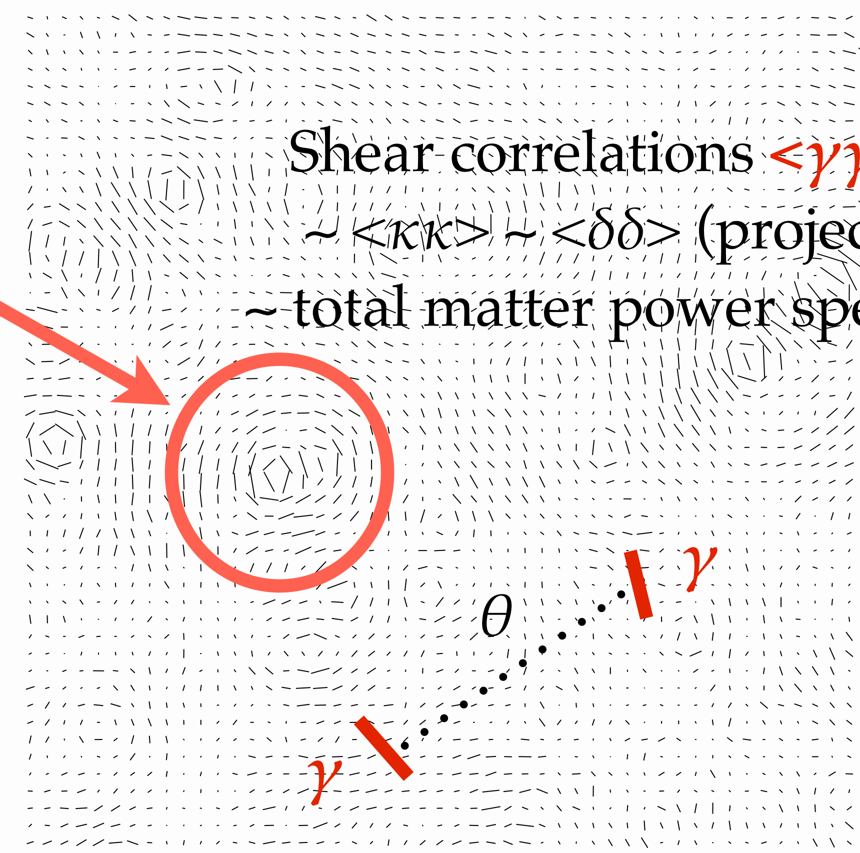
MASS AND SHEAR

Projected matter density
convergence κ

Distortion field
shear γ



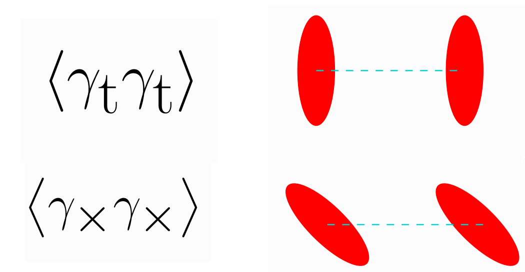
tangential distortions around mass peaks

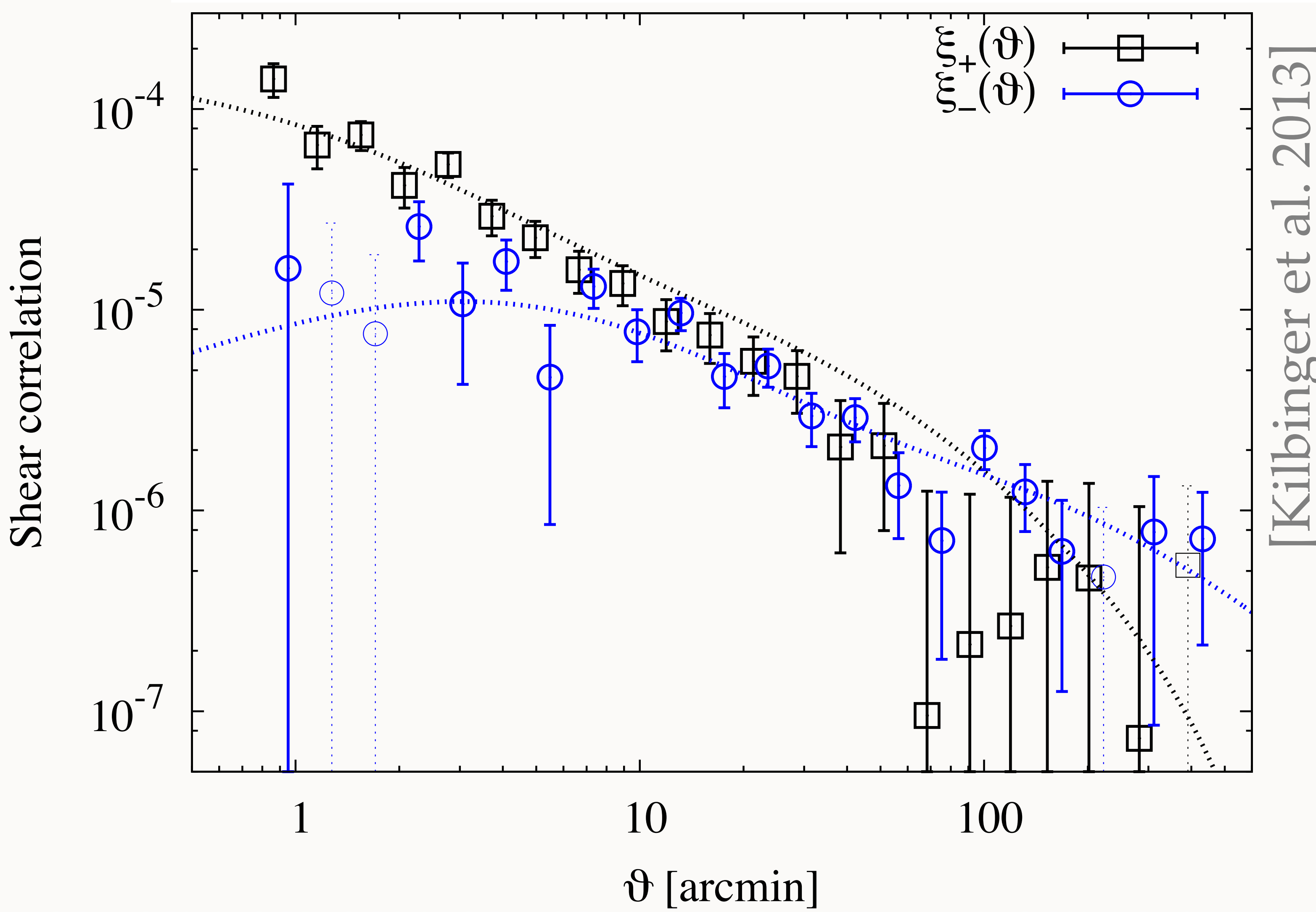


Source galaxies at $z = 1$, ray-tracing simulations by T. Hamana

SHEAR CORRELATION

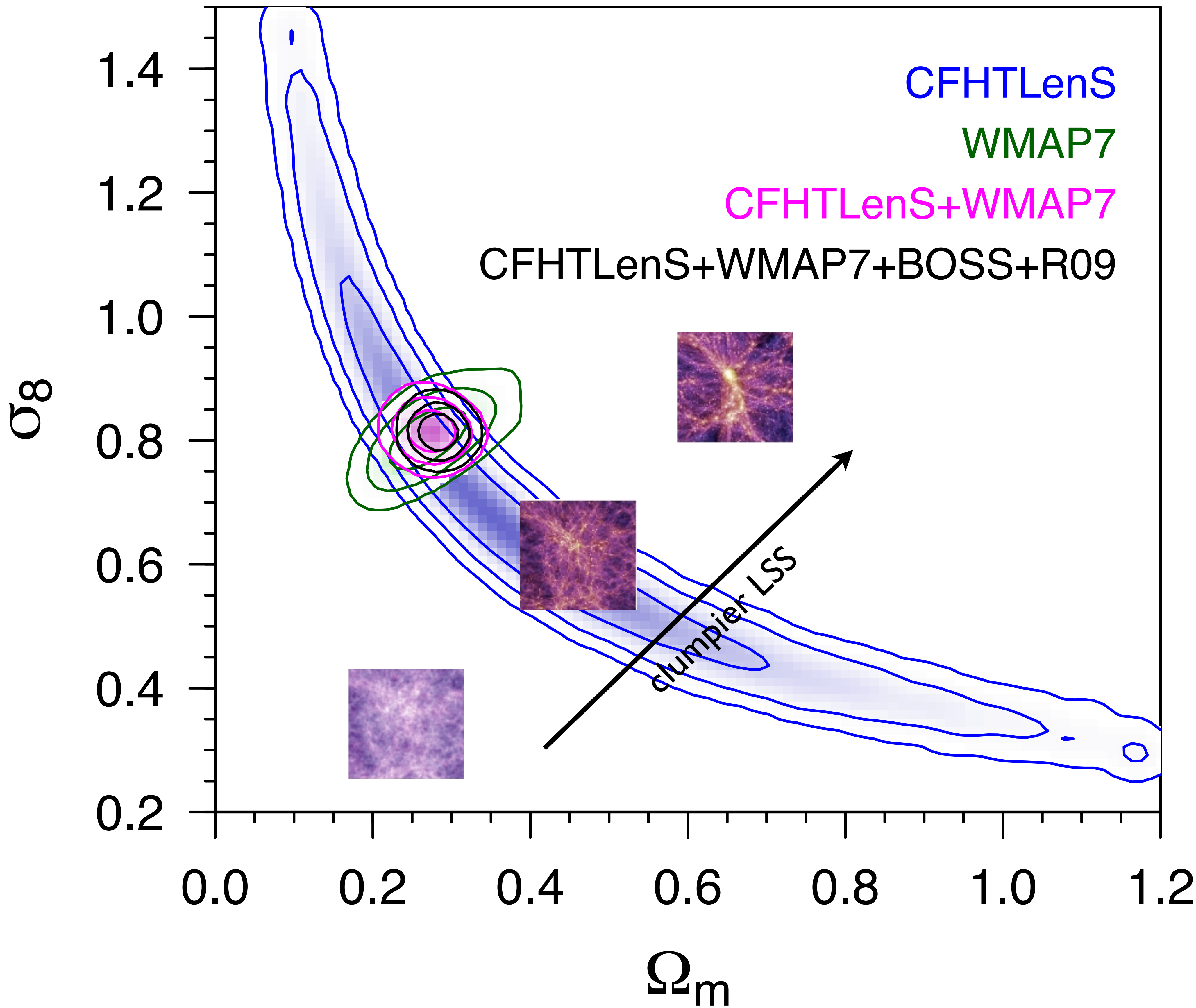
$$\xi_+(\vartheta) = \langle \gamma_t \gamma_t \rangle (\vartheta) + \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$
$$\xi_-(\vartheta) = \langle \gamma_t \gamma_t \rangle (\vartheta) - \langle \gamma_\times \gamma_\times \rangle (\vartheta)$$

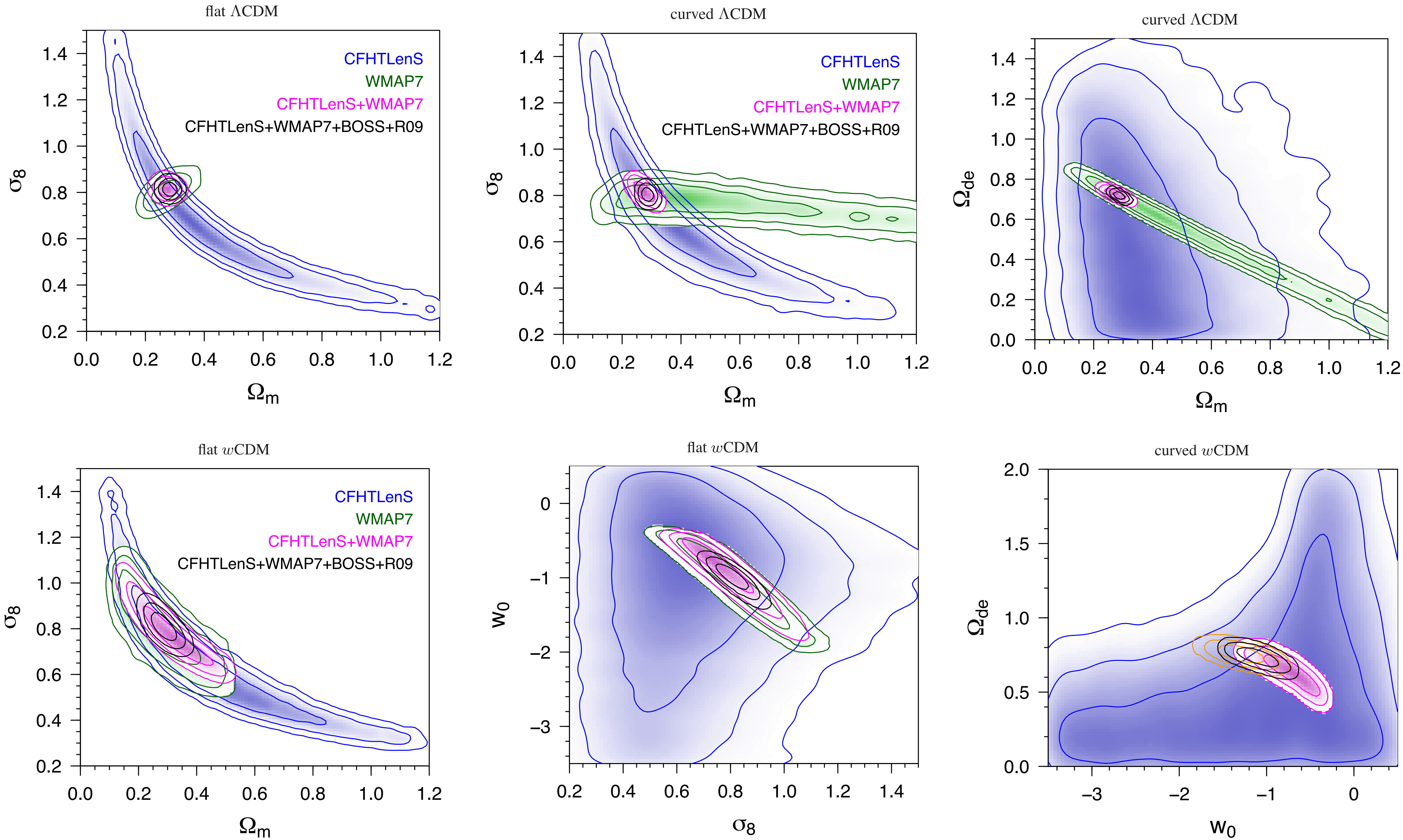




Prediction
(WMAP7 cosmology):
Flat Universe
$\Omega_m = 0.27$
$\sigma_8 = 0.8$
$w = -1$
Smith et al. (2003)
non-linear power spectrum

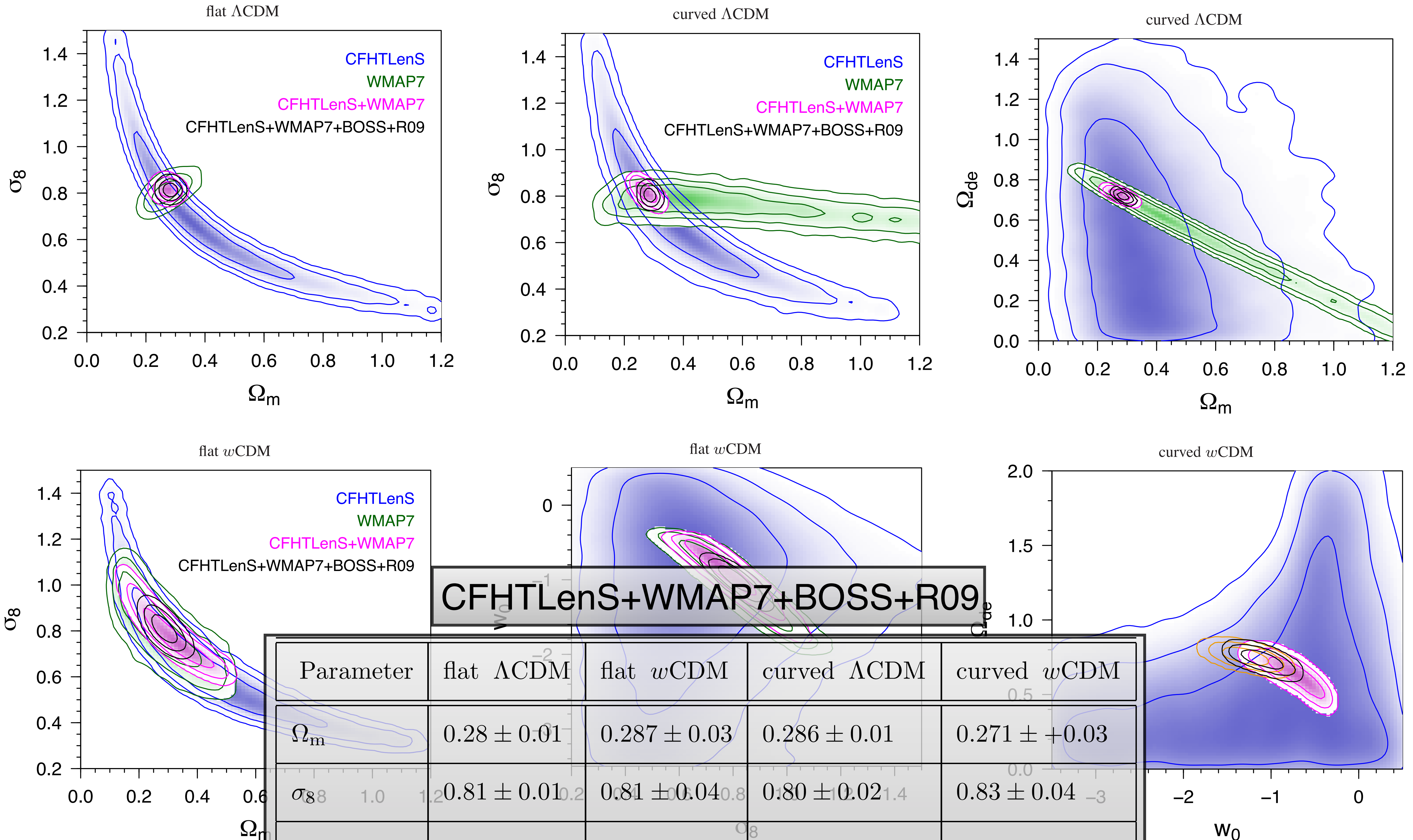
flat ΛCDM


CFHTLenS
WMAP7
CFHTLenS+WMAP7
CFHTLenS+WMAP7+BOSS+R09
clumpier LSS
σ_8
Ω_m
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.0
0.2
0.4
0.6
0.8
1.0
1.2



[Kilbinger et al. in 2013]

2d cosmic shear,
no tomography

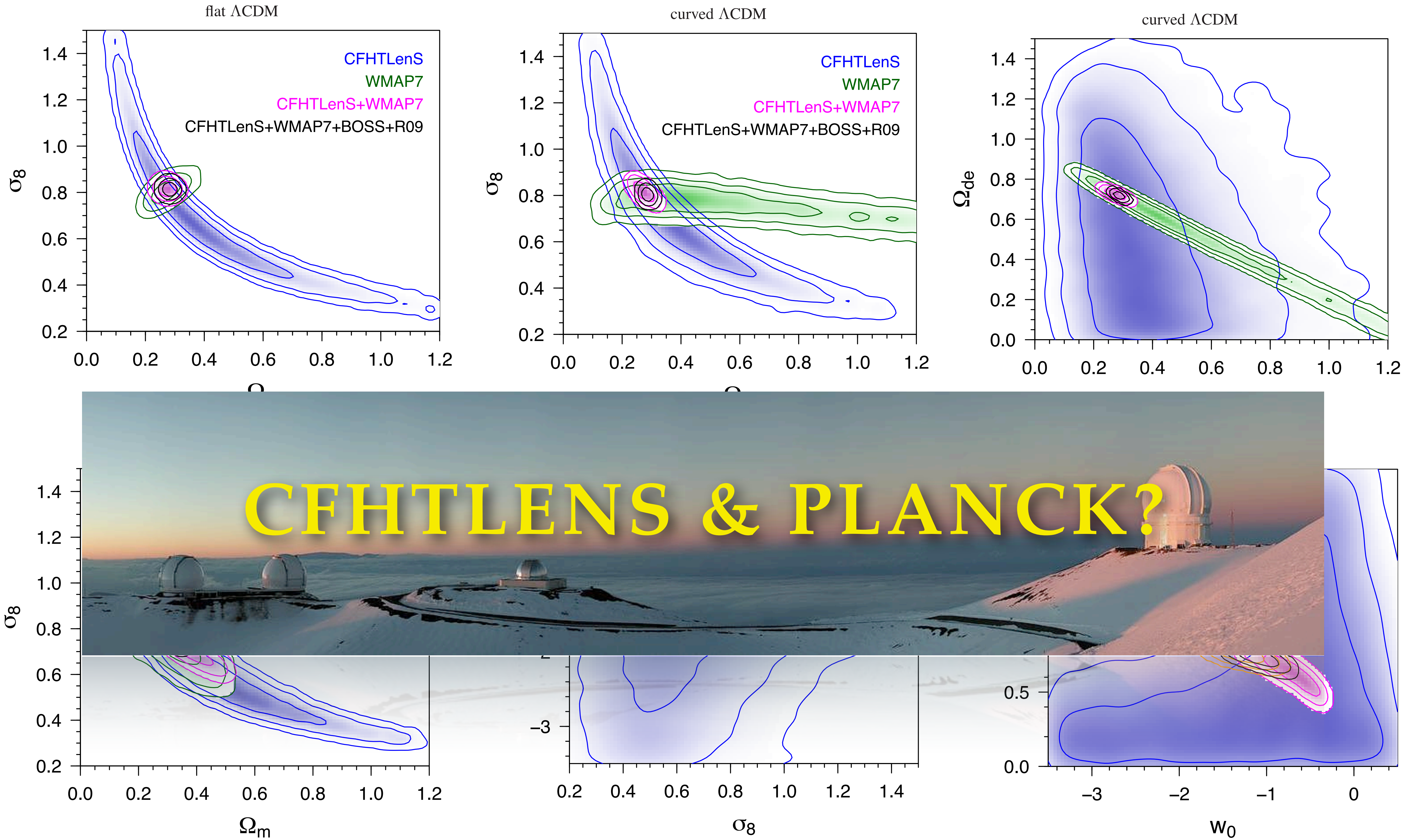


CFHTLenS+WMAP7+BOSS+R09

Parameter	flat ΛCDM	flat wCDM	curved ΛCDM	curved wCDM
$\Omega_{\rm m}$	0.28 ± 0.01	0.287 ± 0.03	0.286 ± 0.01	$0.271 \pm +0.03$
σ_8	0.81 ± 0.01	0.81 ± 0.04	0.80 ± 0.02	0.83 ± 0.04
w_0	-1	-1.0 ± 0.1	-1	-1.1 ± 0.2
$\Omega_{\rm de}$	$1 - \Omega_{\rm m}$	$1 - \Omega_{\rm m}$	0.72 ± 0.01	0.74 ± 0.03
Ω_K	0	0	-0.005 ± 0.005	$-0.006^{+0.006}_{-0.005}$

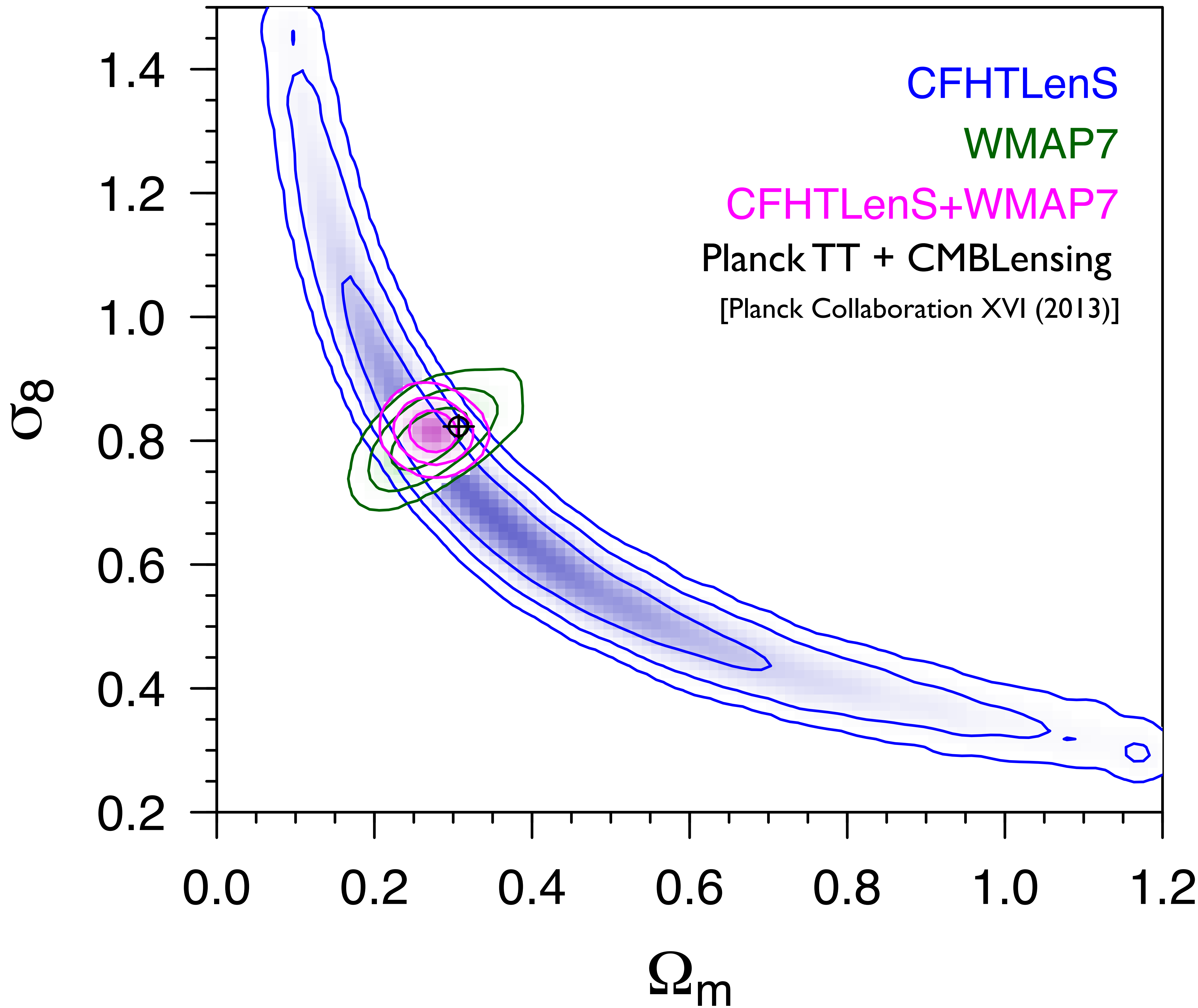
2d cosmic shear,
no tomography

CFHTLENS & PLANCK?



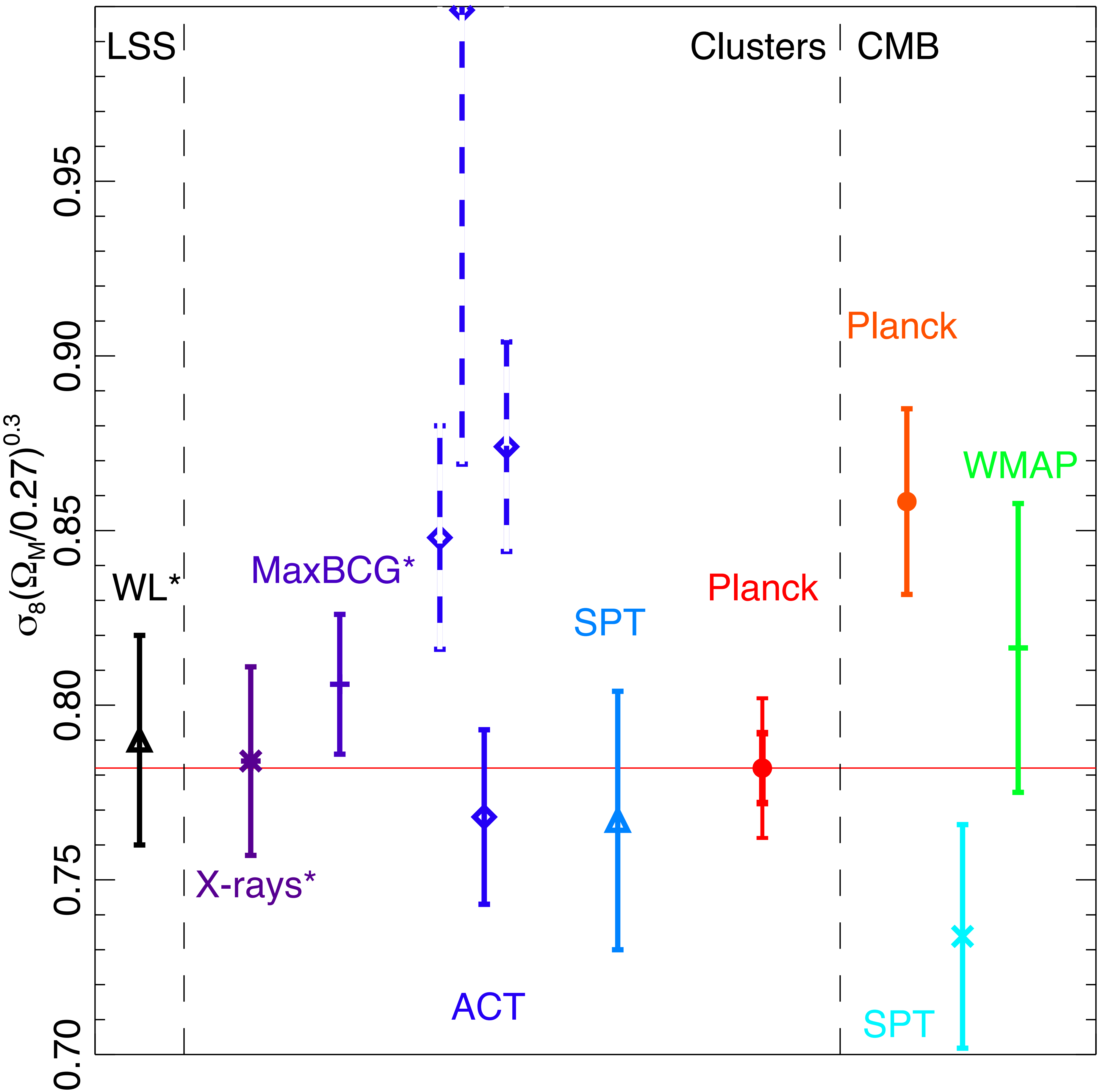
2d cosmic shear,
no tomography

flat ΛCDM

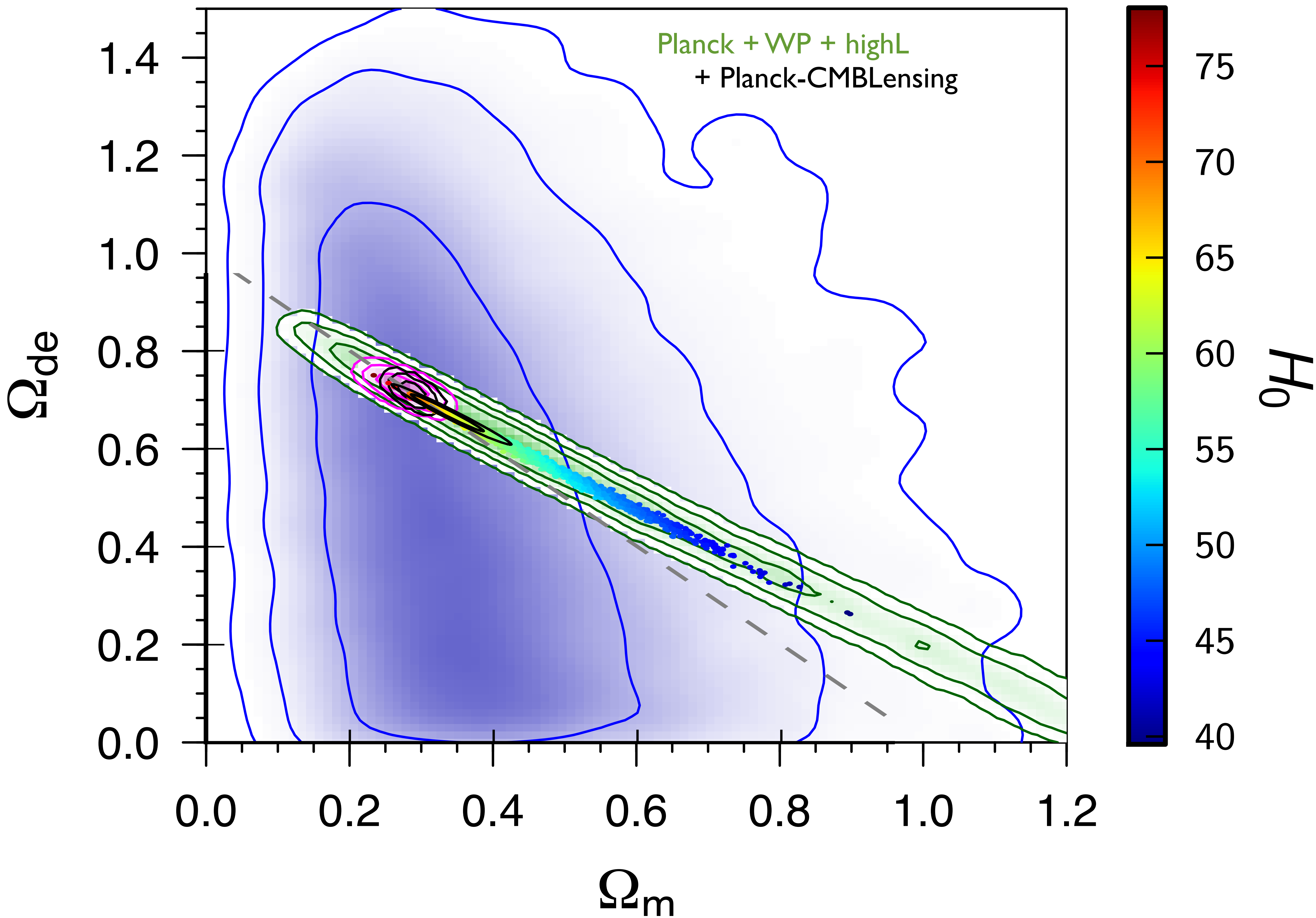


CFHTLenS
WMAP7
CFHTLenS+WMAP7
Planck TT + CMBLensing
[Planck Collaboration XVI (2013)]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
σ_8
Ω_m

[Planck Collaboration XX (2013)]

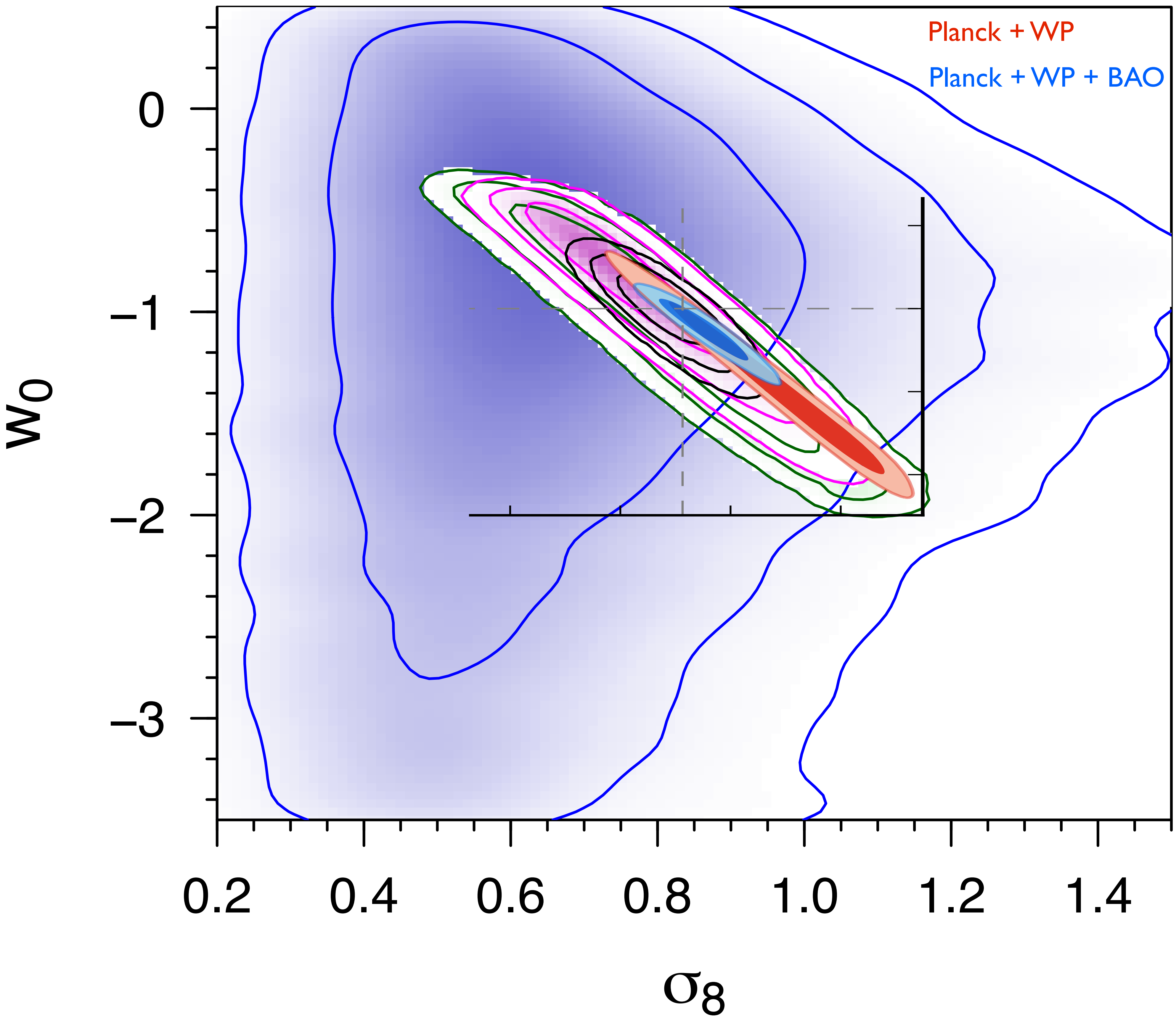


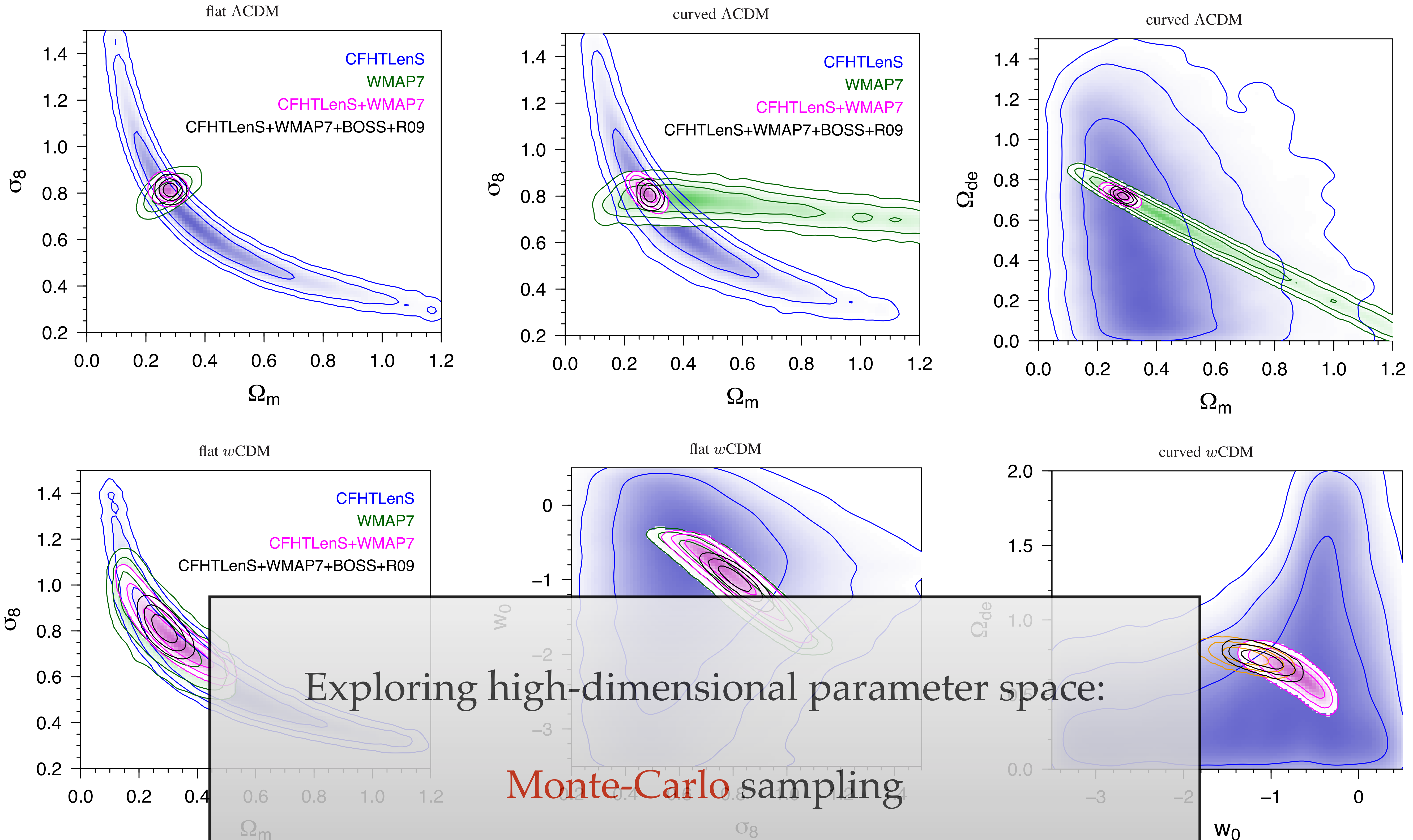
curved ΛCDM



Planck + WP + highL
+ Planck-CMBLensing
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Ω_{de}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_m
75
70
65
60
55
50
45
40
H_0

flat wCDM





Exploring high-dimensional parameter space:

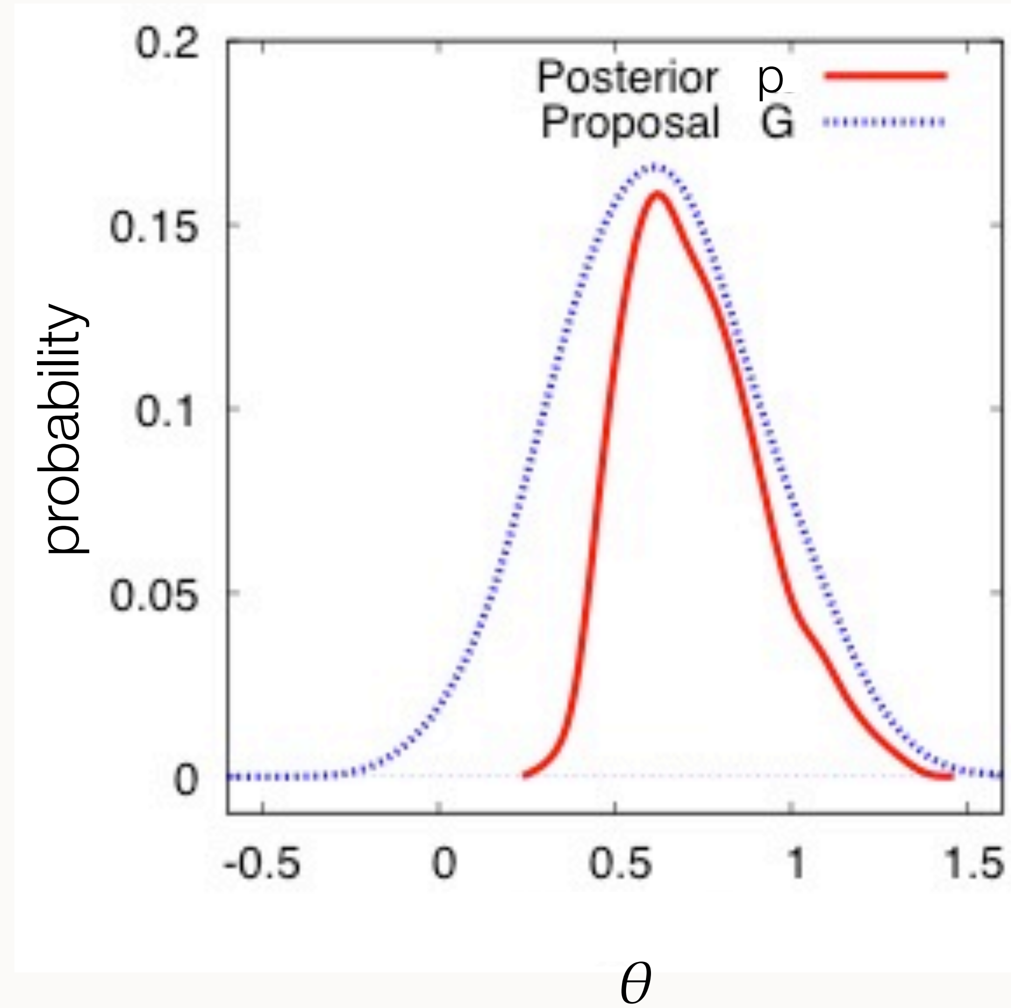
Monte-Carlo sampling

Population Monte Carlo (PMC): Alternative to MCMC

2d cosmic shear,
no tomography

IMPORTANCE SAMPLING

- Sample from proposal distribution G (importance function). E.g. mixture of Gaussians



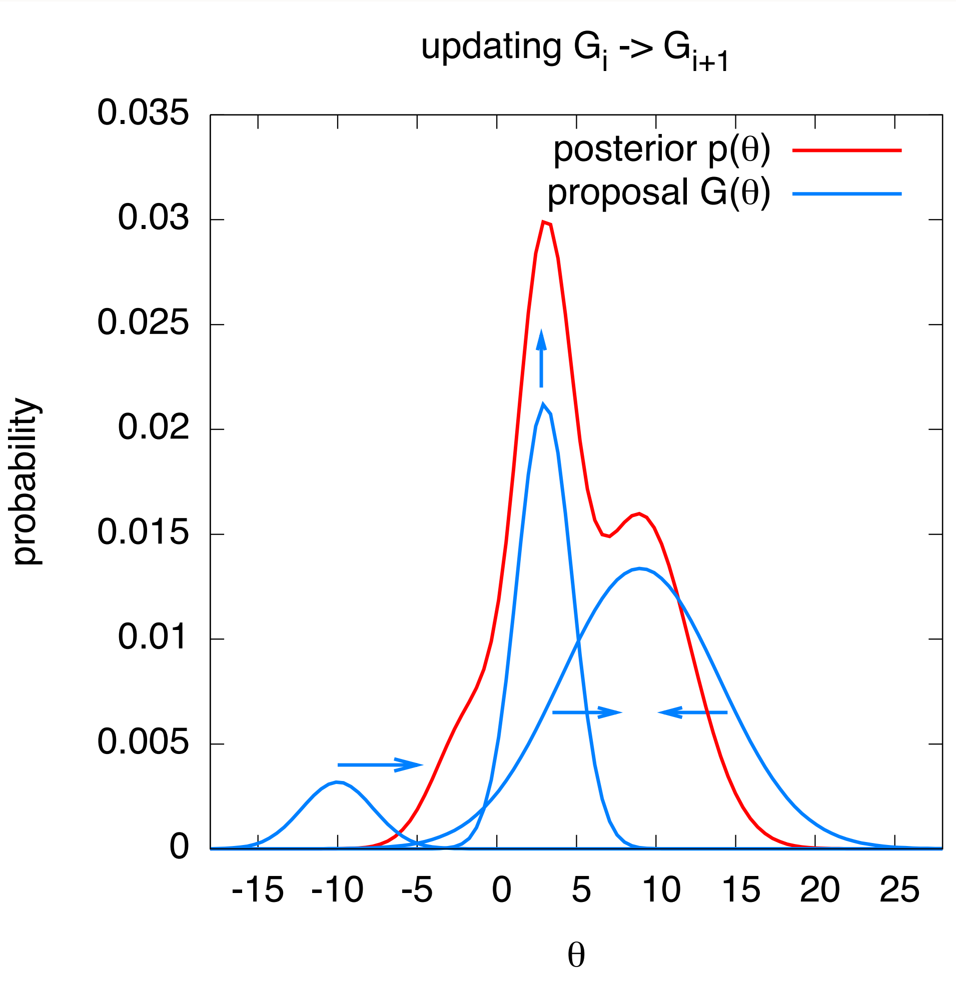
- Weigh each sample point θ by ratio (importance weight) $w = p(\theta)/G(\theta)$

- Evaluation of posterior p (likelihood x prior) can be done in parallel

- Poor performance if proposal far from posterior

POPULATION MONTE CARLO (PMC)

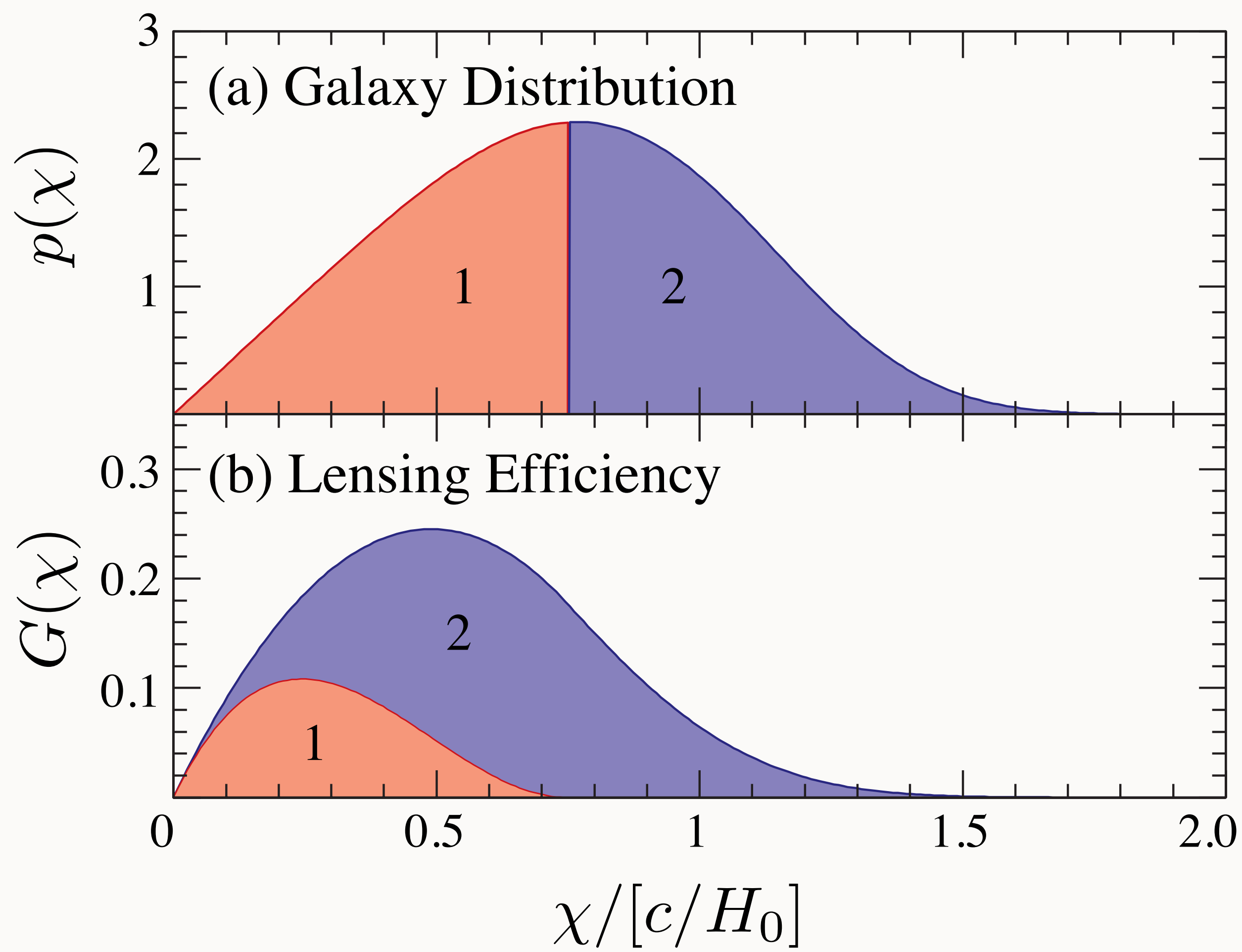
- Solution: Create adaptive importance samples ("populations") [Cappé et al. 2004, 2007]
- Iteration $G_i \rightarrow G_{i+1}$: Update mean, covariance and component weights
- Stop when proposal p 'close enough'
- PMC sample engine and cosmology modules, public code, www.cosmopmc.info, [Kilbinger et al. 2010, arXiv:1101.0950]



Thursday, April 4, 13

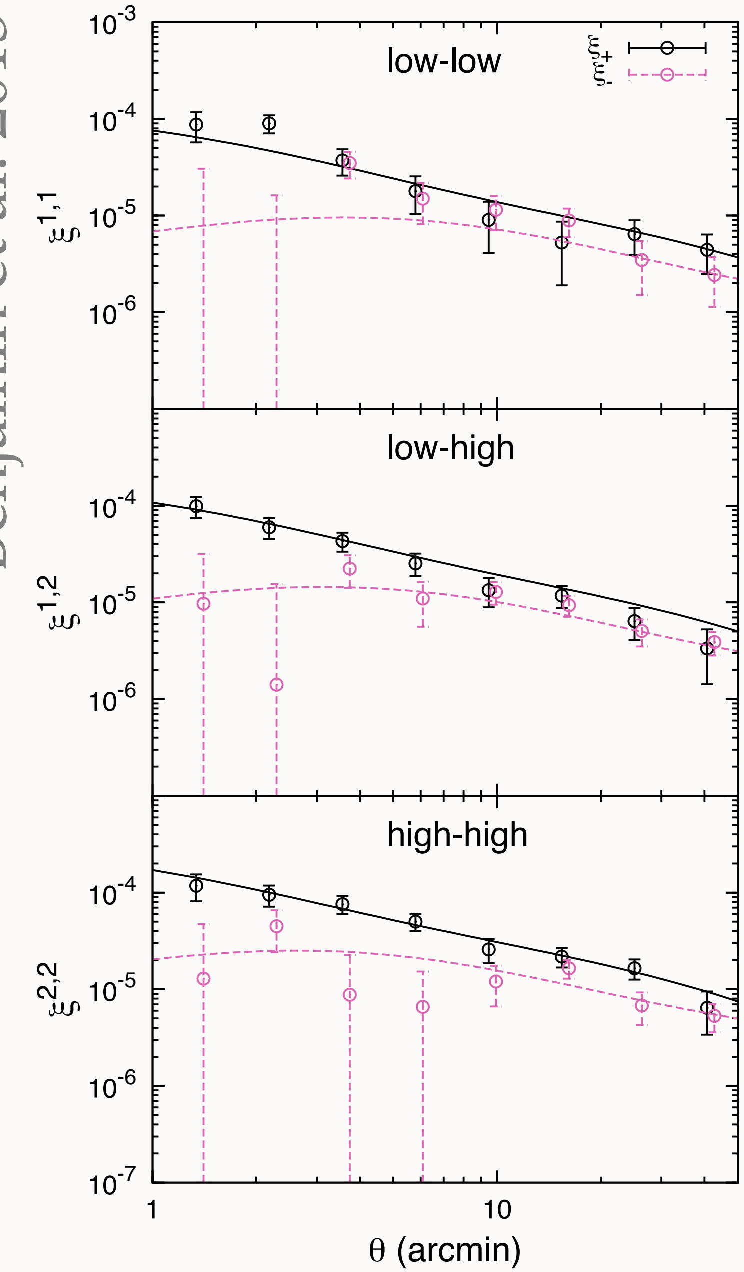
LENSING TOMOGRAPHY

3d cosmic shear:
low: z = [0.5; 0.85]
high: z = [0.85; 1.3]

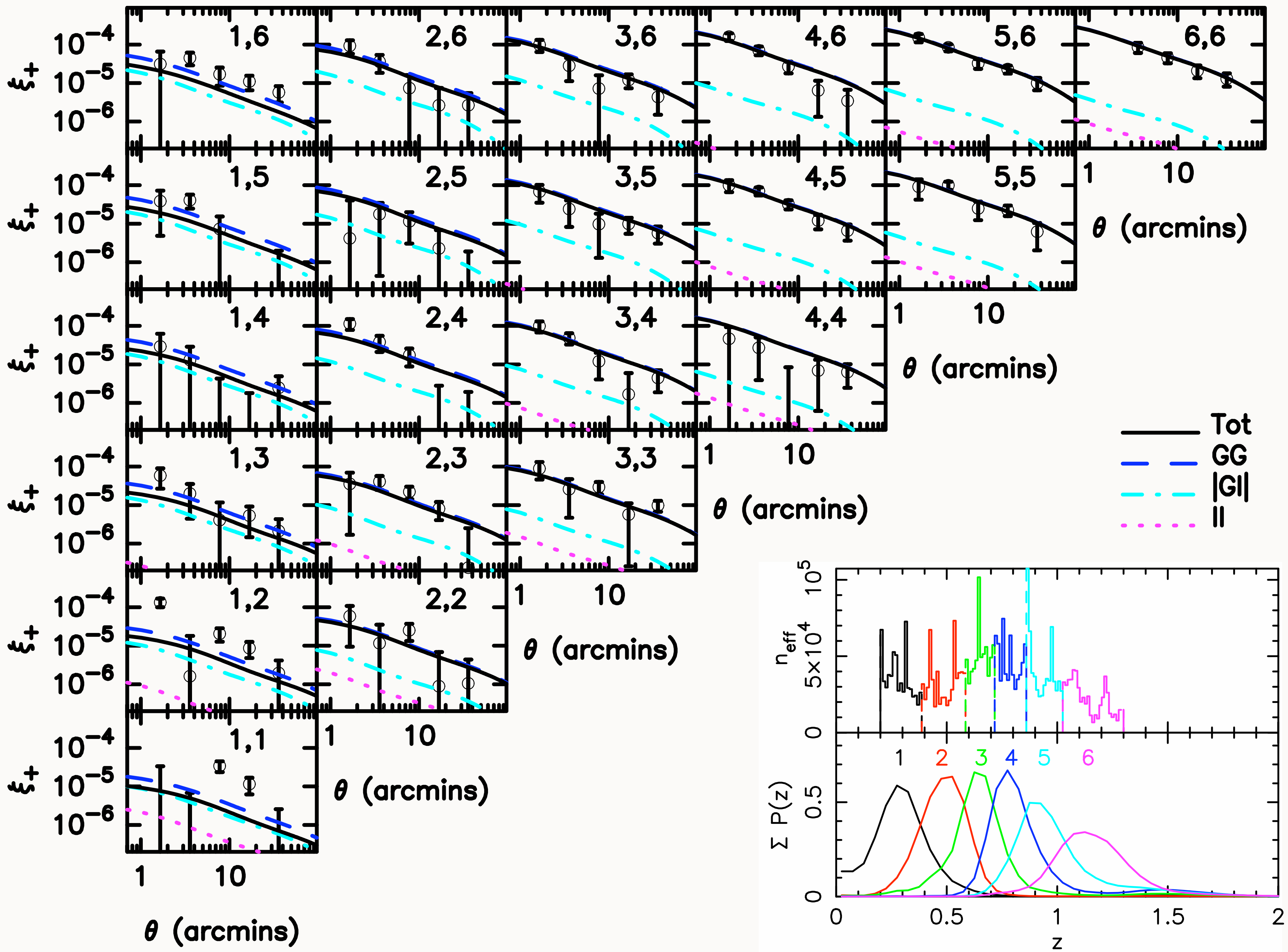


comoving distance

Benjamin et al. 2013



LENSING TOMOGRAPHY

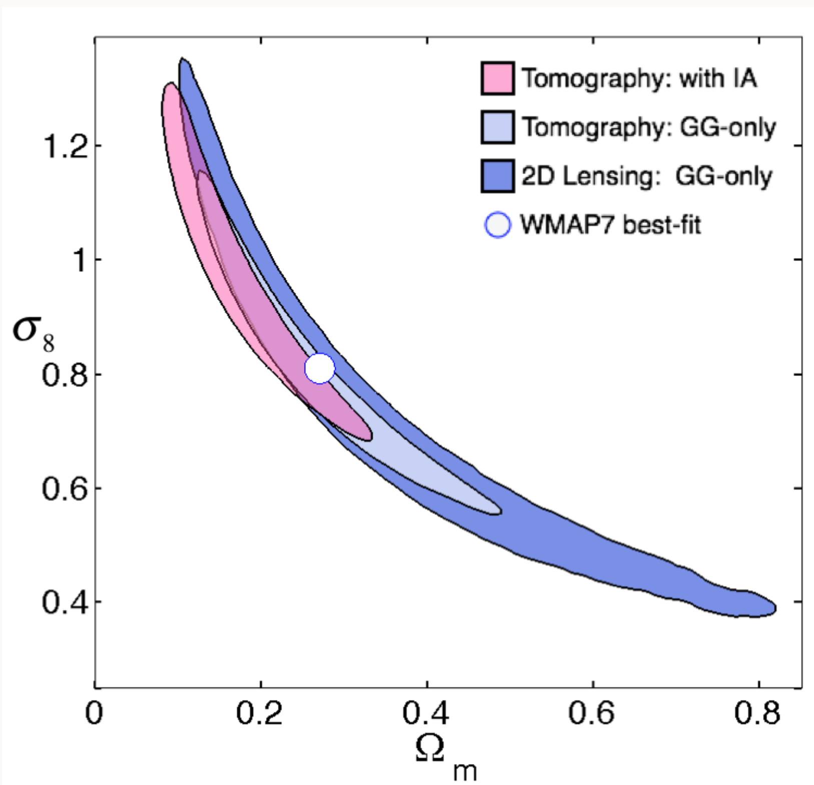


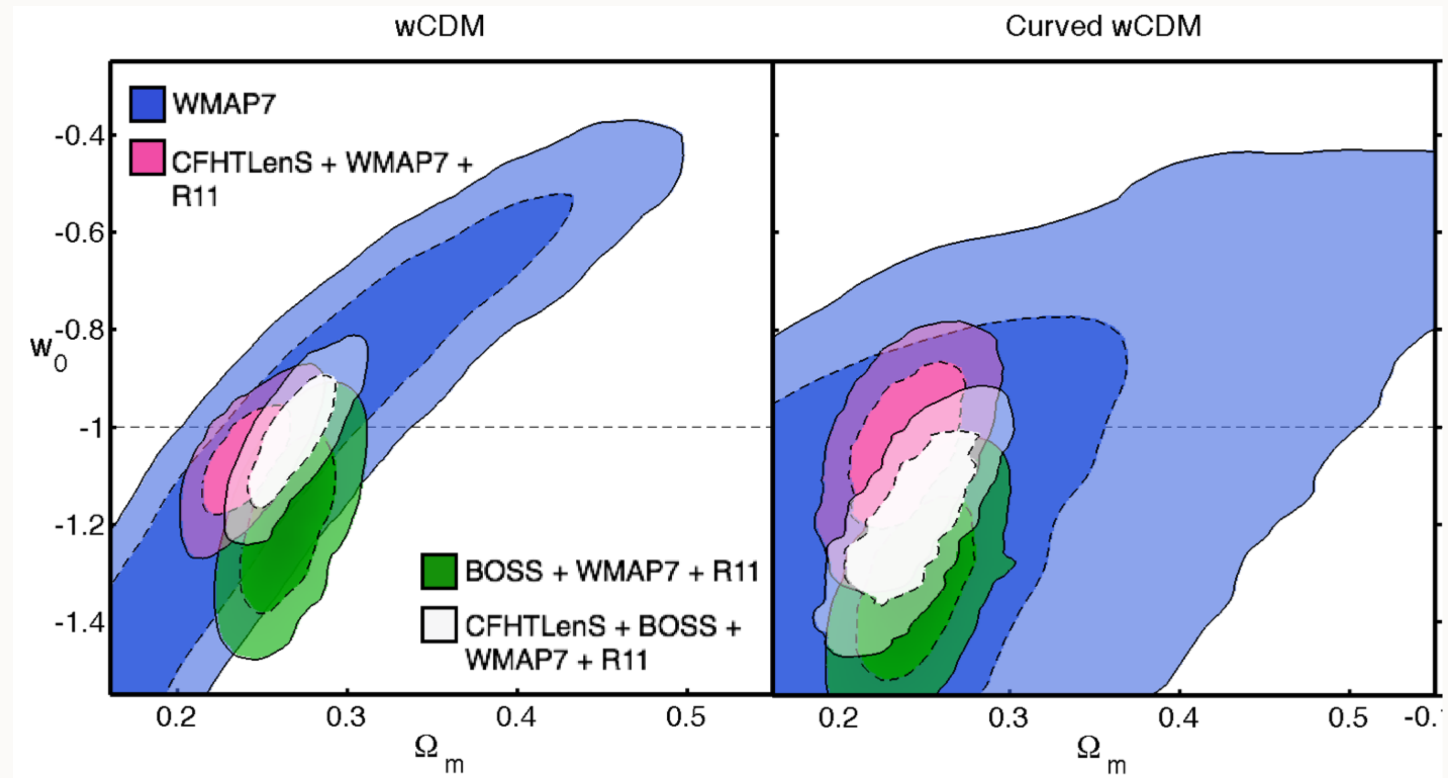
Bin	z_{BPZ}	z_m	$\bar{z}$
1	0.20 − 0.39	0.28	0.36
2	0.39 − 0.58	0.48	0.50
3	0.58 − 0.72	0.62	0.68
4	0.72 − 0.86	0.82	0.87
5	0.86 − 1.02	0.93	1.00
6	1.02 − 1.30	1.12	1.16

[Heymans et al. 2013]

LENSING TOMOGRAPHY

[Heymans et al. 2013]





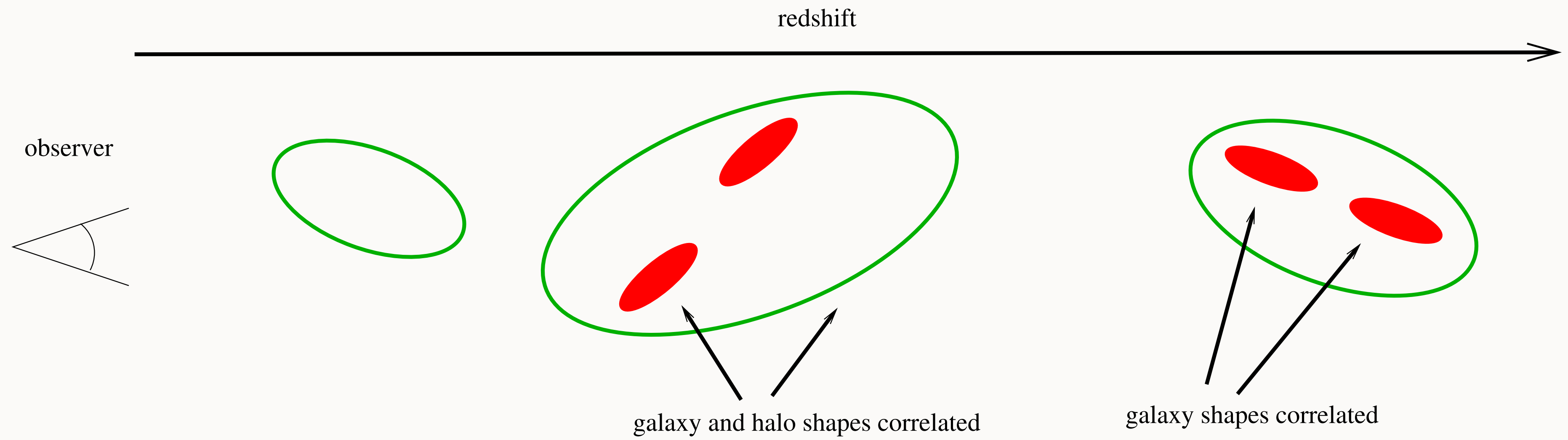
Tomography helps lifting the Ω_m - σ_8 degeneracy of 2D lensing.

CFHTLenS + WMAP7 + R11 + BOSS

	flat wCDM	curved wCDM
w_0	$-1.02^{+0.09}_{-0.09}$	$-1.19^{+0.14}_{-0.11}$

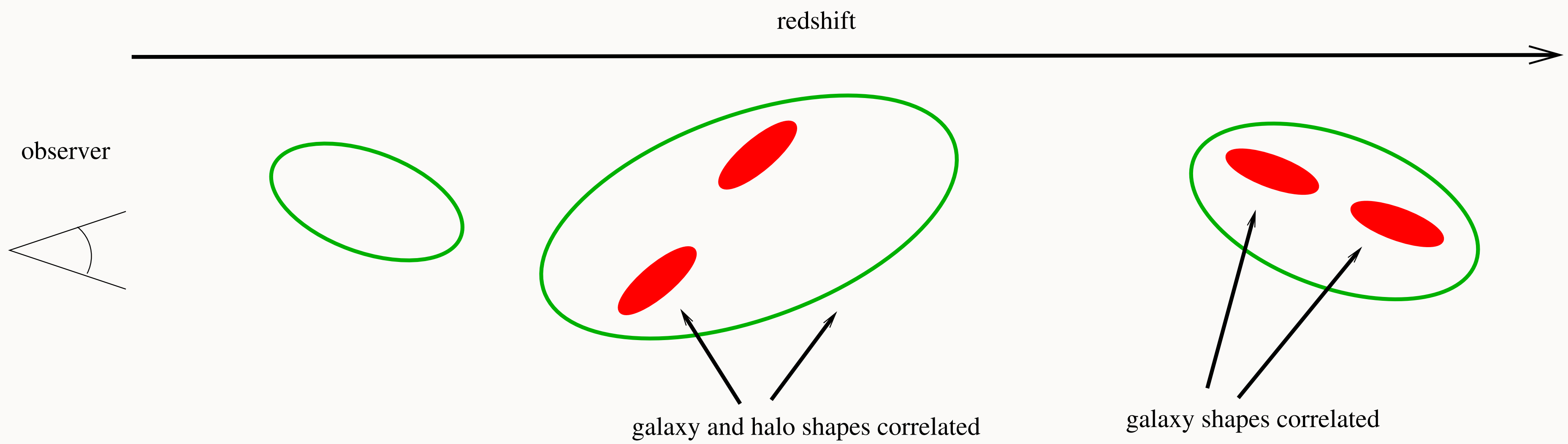
INTRINSIC ALIGNMENT

- Galaxy shapes correlated with environment, e.g. dm halo shape



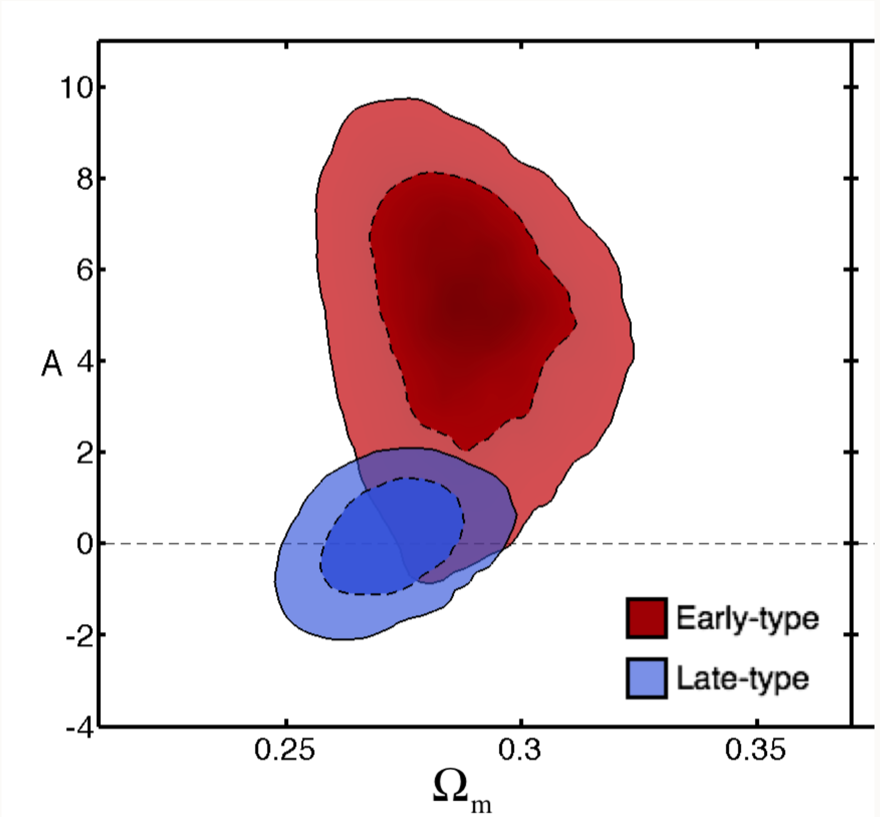
- Galaxies at same z: remove from analysis
- Galaxies @ different z:
  - Nulling (model-independent): scan through z (Benjamini, Schneider)
  - Fitting shear + alignment models: many parameters (Bridle, King, Kirk)

INTRINSIC ALIGNMENT



Simple intrinsic alignment model:
Galaxy ellipticity linearly related to tidal field
[Hirata & Seljak 2004, Bridle & King 2007].

One free amplitude parameter *A*, fixed *z*-dependence.

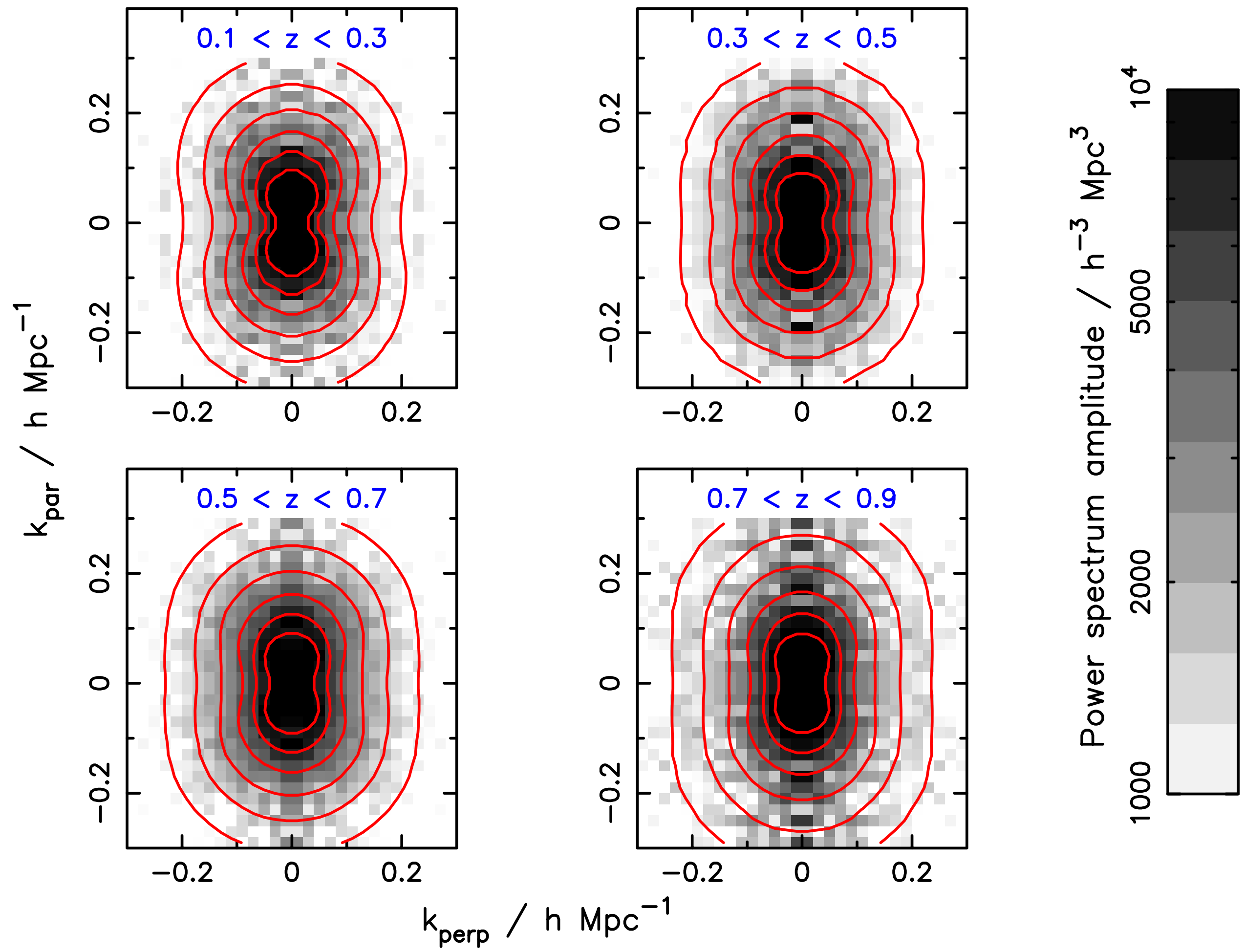


[Heymans et al. 2013]


MODIFIED GRAVITY

WIGGLE-Z DATA

- CFHTLenS Cosmic Shear
  - Two redshift bins; $1 < \theta < 100$ arcmin
- WiggleZ Redshift Space Distortions (Blake et al. 2011)
- Auxiliary Data
  - WMAP7 ($l > 100$)
  - $H_0 = 73.8 \pm 0.024$ km s^{-1} Mpc^{-1} (Riess et al. 2011)
- Utilise CosmoPMC, MGCAMB, WMAP Likelihood, CosmoloGUI



Blake et al 2011

Thursday, April 4, 13

- non-constant Sigma, mu: only late-time effect. Time-dependence like DE. CMB would dominate constraint on const S, m

ETRISATION

$$ds^2 = -(1+2\varphi)dt^2 + (1-2\phi)a^2 d\vec{x}^2$$

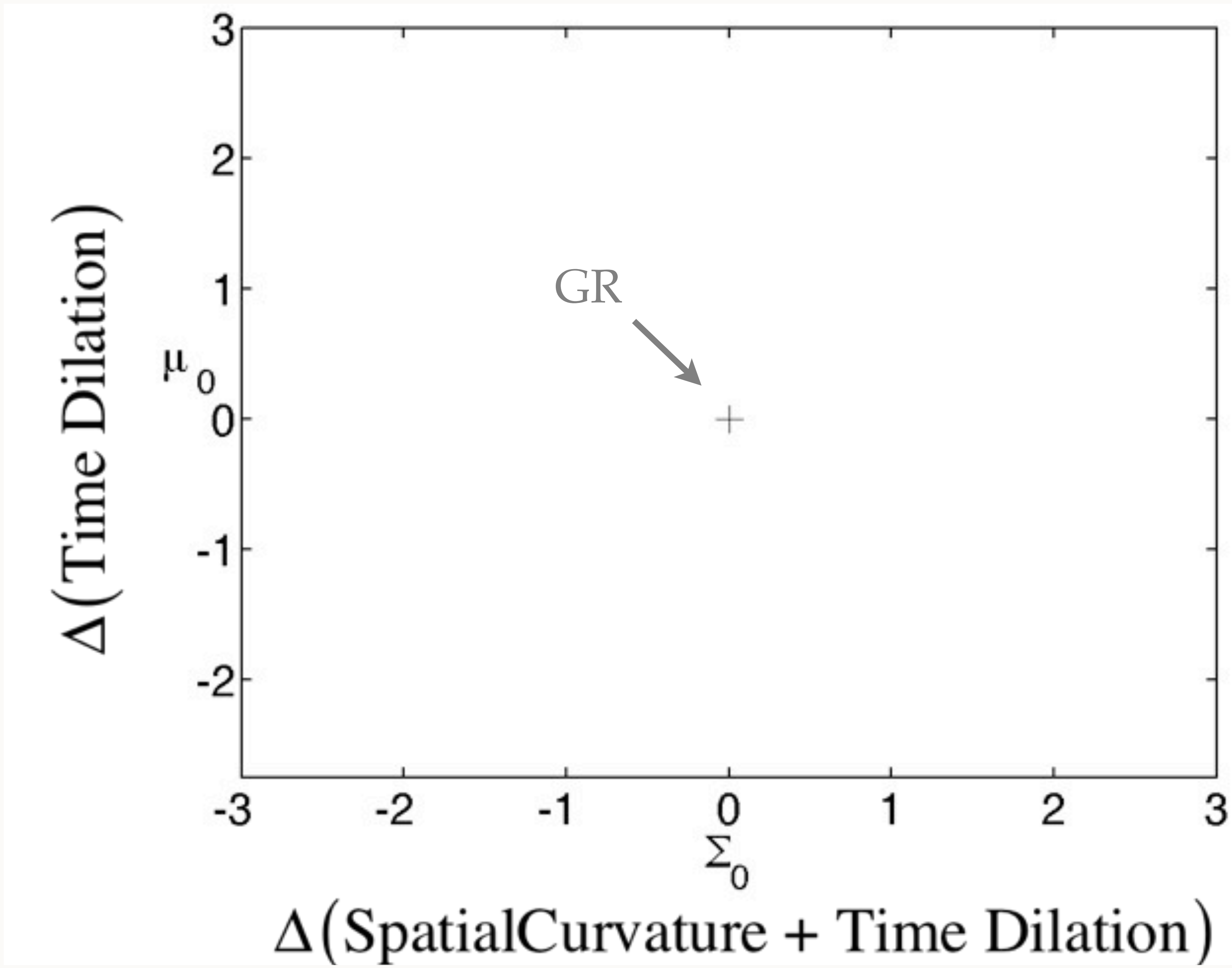
- Gravitational potential as experienced by galaxies:

$$\nabla^2\varphi = 4\pi G a^2 \bar{\rho}\delta\left[1+\mu\right] \qquad \mu(a) \propto \Omega_\Lambda(a)$$

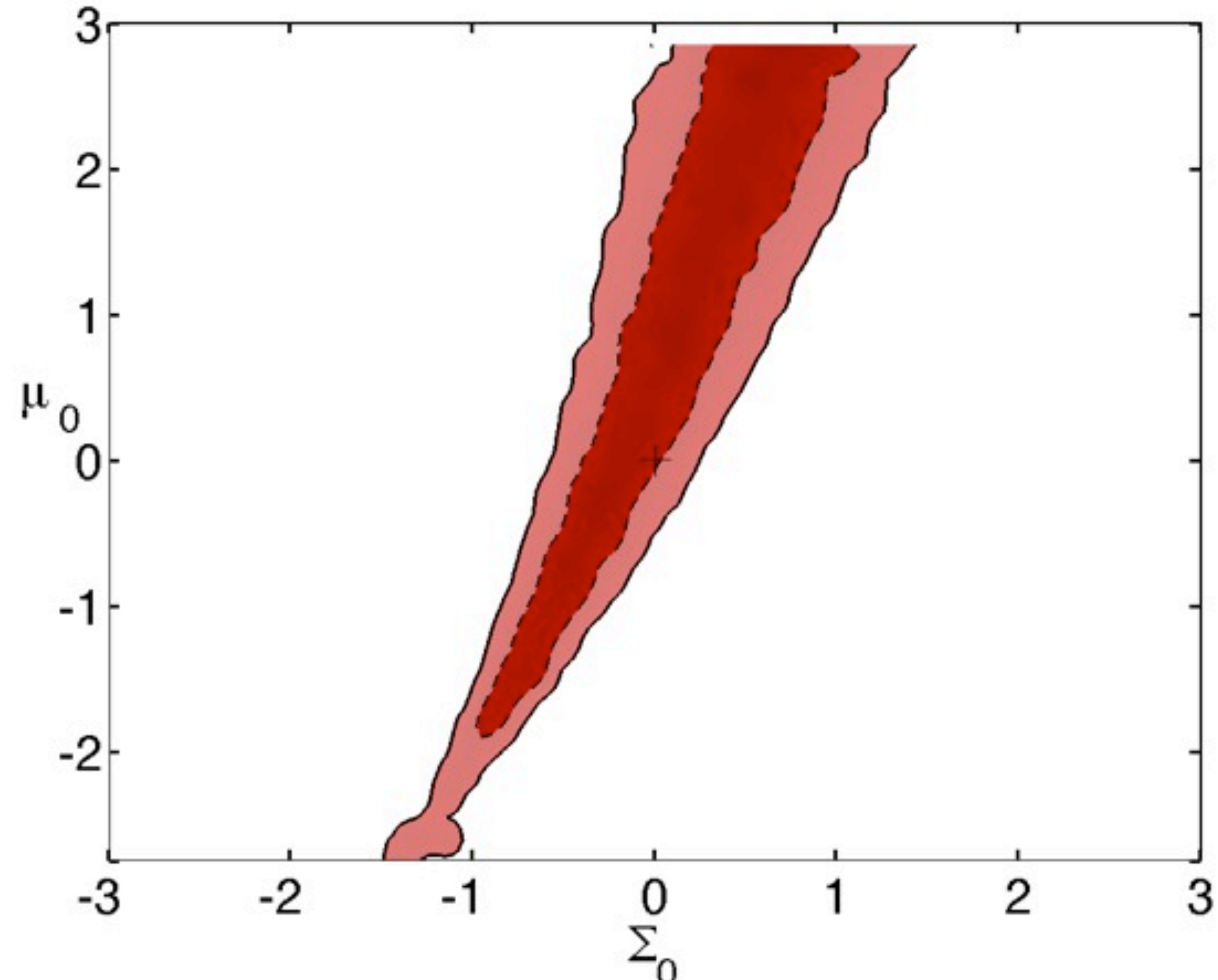
- Gravitational potential as experienced by photons:

$$\nabla^2(\varphi+\phi) = 8\pi G a^2 \bar{\rho}\delta\left[1+\Sigma\right] \qquad \Sigma(a) \propto \Omega_\Lambda(a)$$

PARAMETRISATION



PREVIOUS CONSTRAINTS

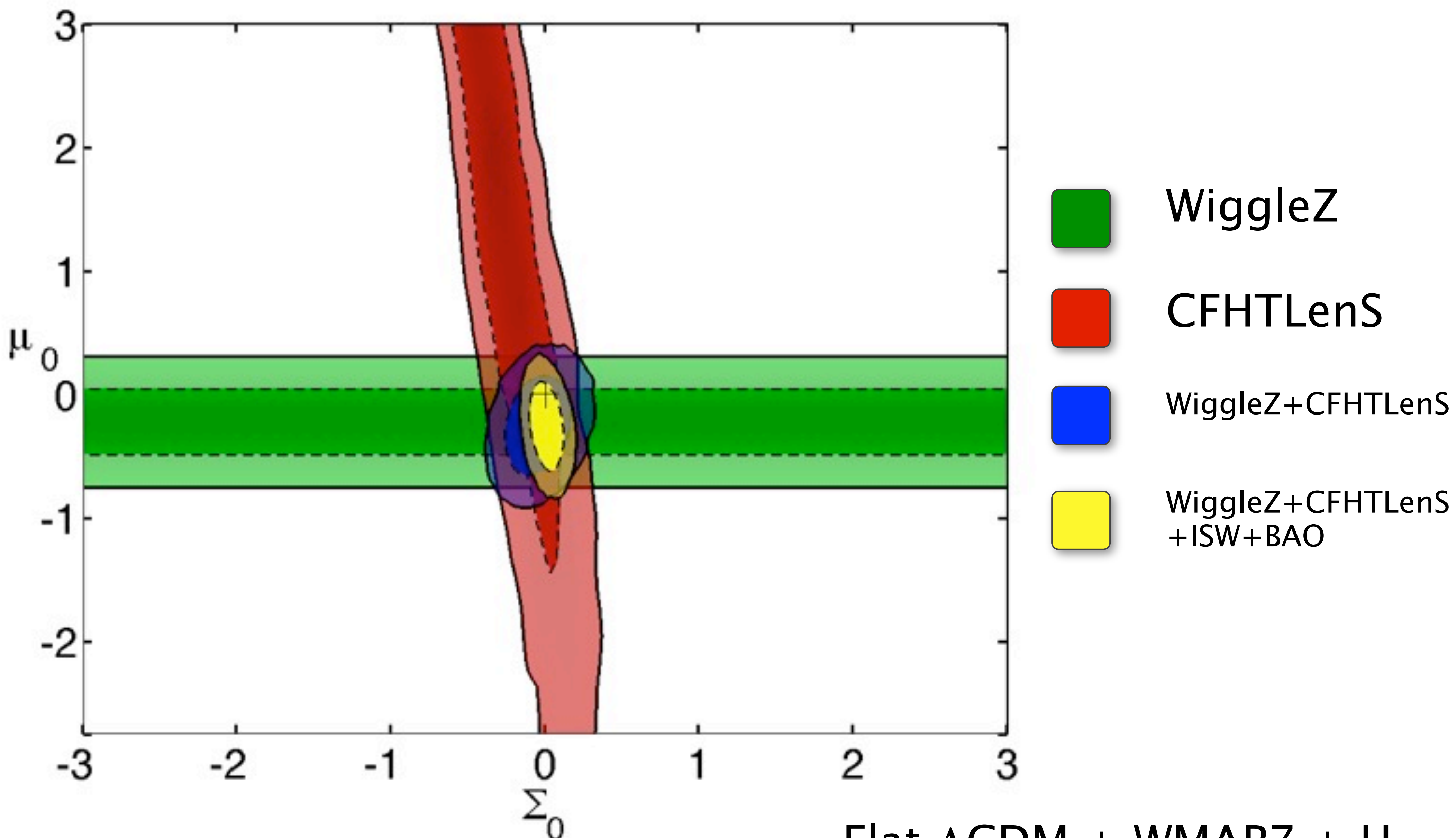


E_G (Reyes et al 2010) + BAO (Percival et al 2010)

Flat ΛCDM

CFHTLENS CONSTRAINTS

Simpson et al. 2013

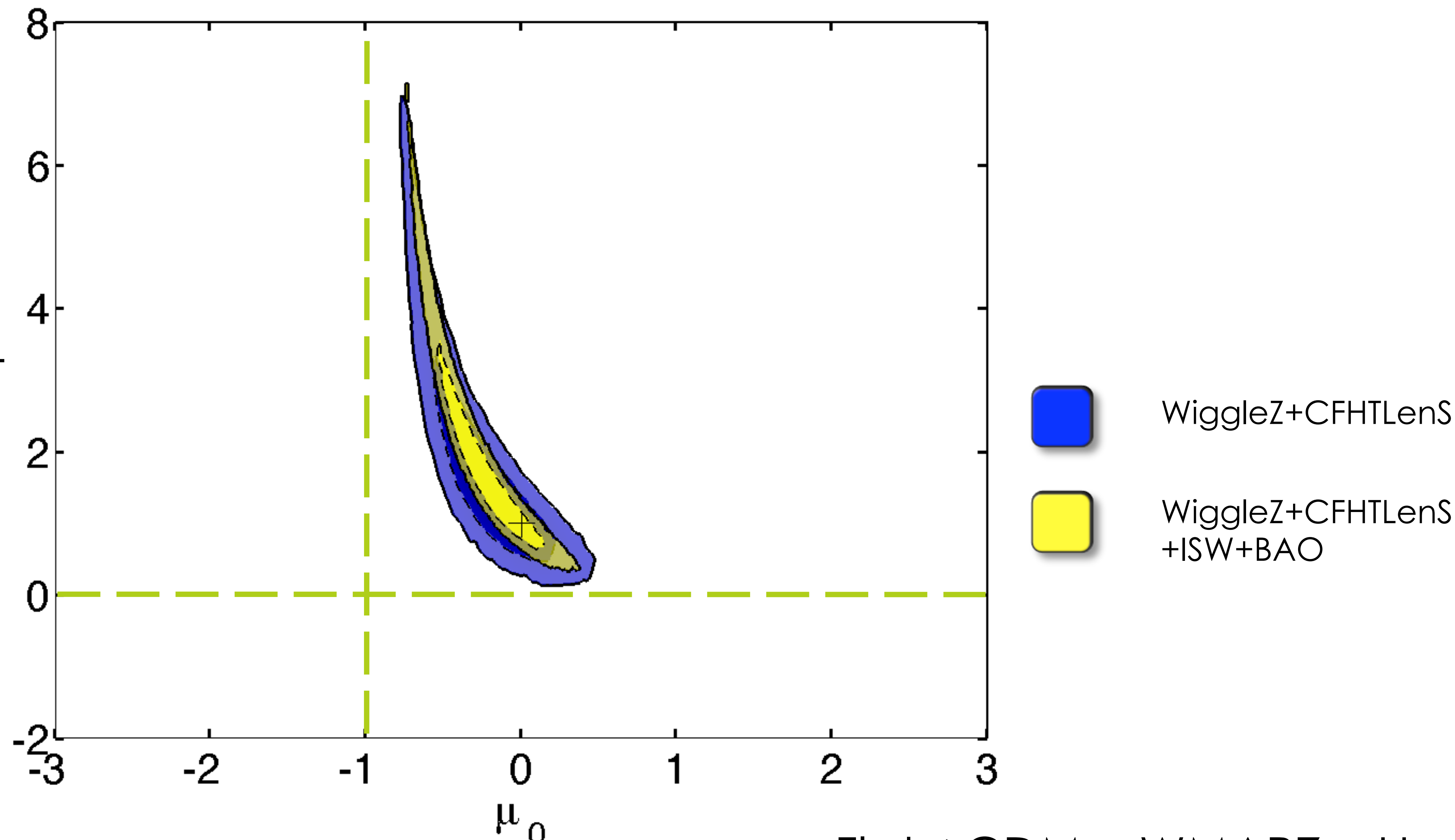


Flat ΛCDM + WMAP7 + H_0

GRAVITATIONAL SLIP

[Simpson et al. 2013]

$$\eta = \frac{\phi}{\varphi}$$



Flat ΛCDM + WMAP7 + H_0

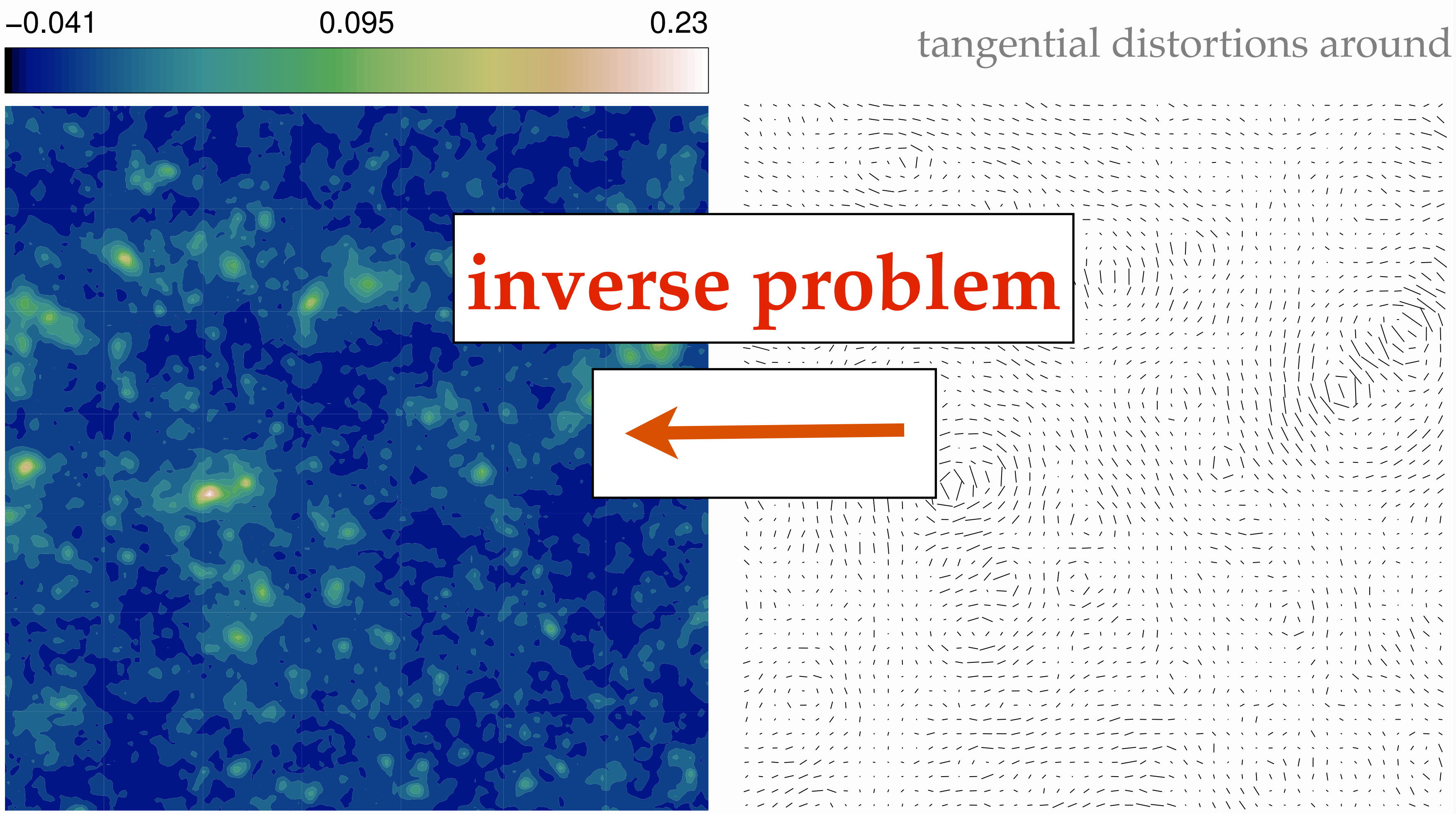
MASS MAPS

LENSING MASS MAPS

Projected matter density
convergence κ

Distortion field
shear γ

tangential distortions around mass peaks

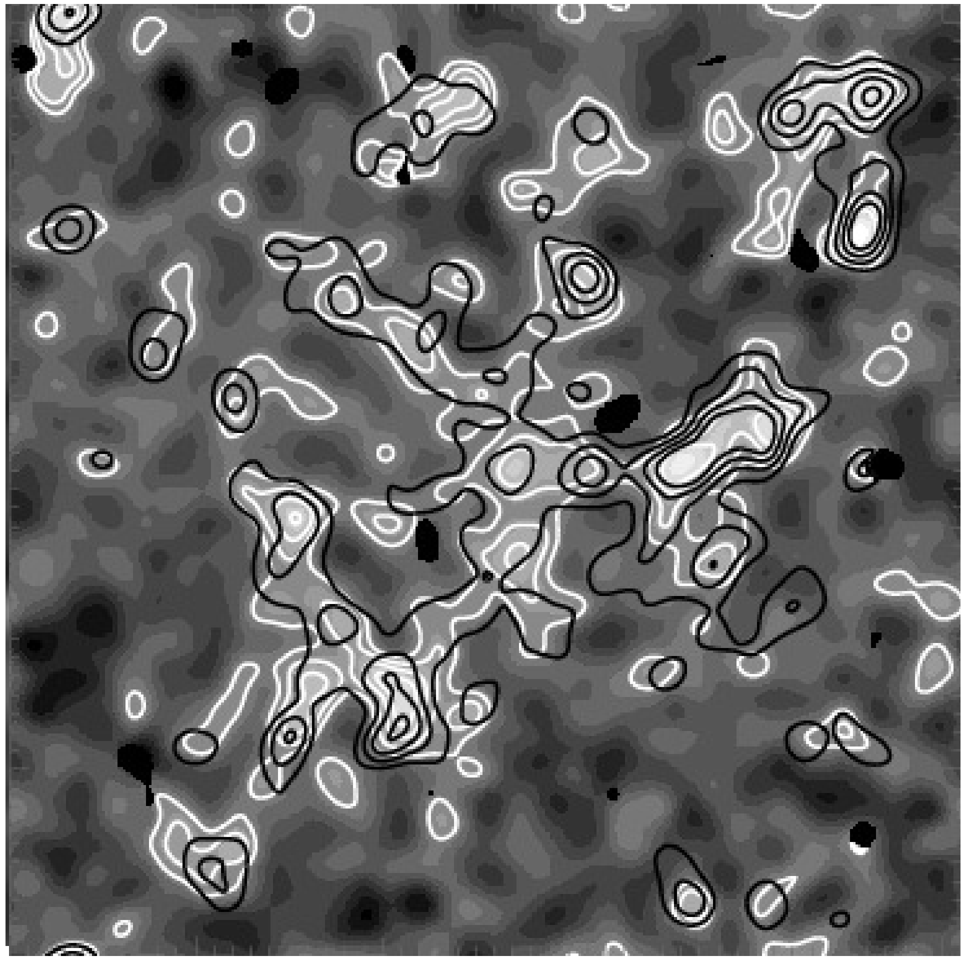


Source galaxies at $z = 1$, ray-tracing simulations by T. Hamana

LENSING MASS MAPS

[van Waerbeke et al. 2013]

- Map dark-matter structures. Compare to optical (galaxies), X-ray (hot gas), SZ (gas)
- High-density regions trace non-linear structures
- Higher-order correlations, non-linear evolution of LSS
- 3D mass reconstruction, evolution of cosmic structures



3.4 degrees

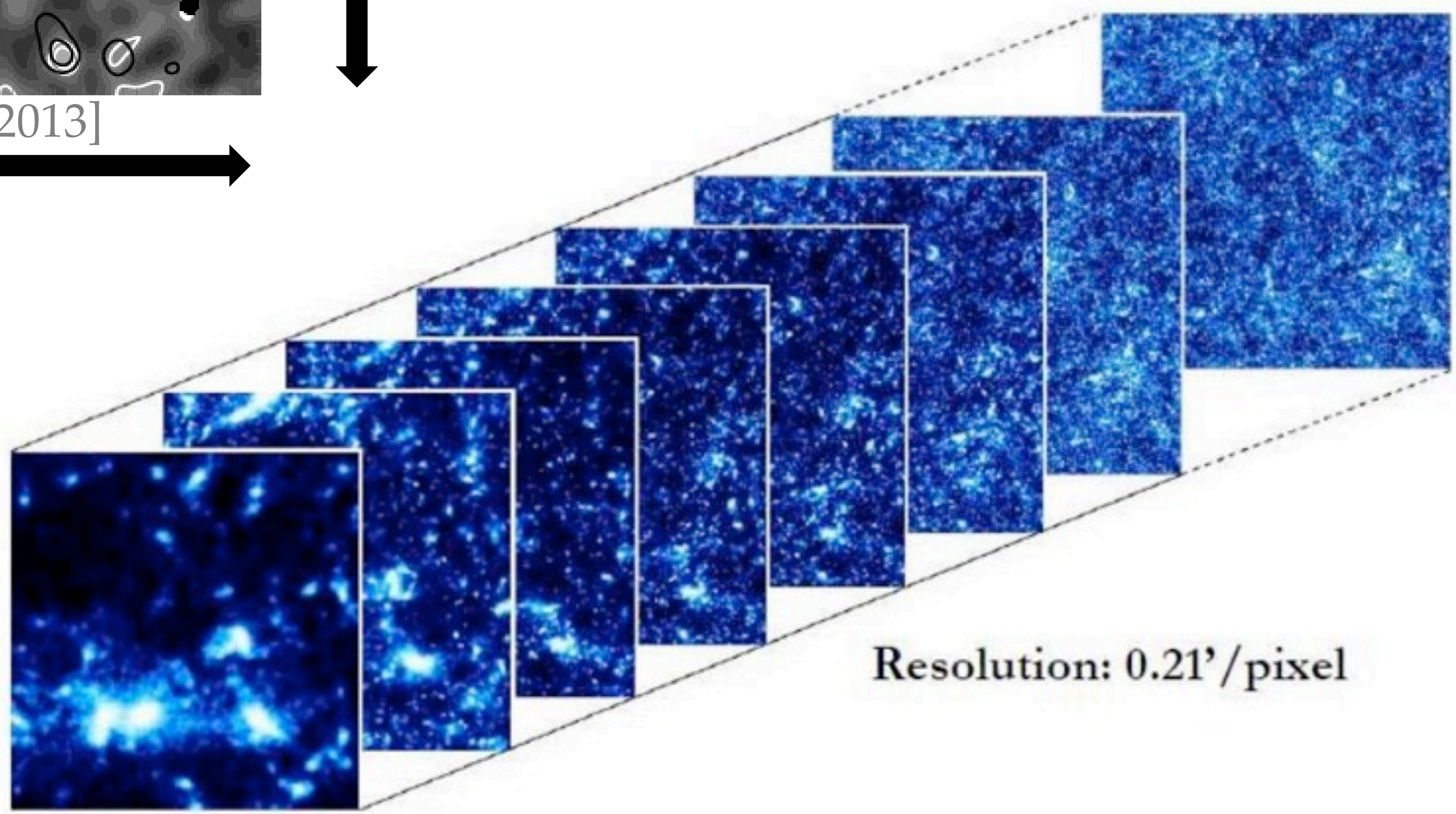
Black contours: Input

White contours + background map: Reconstruction

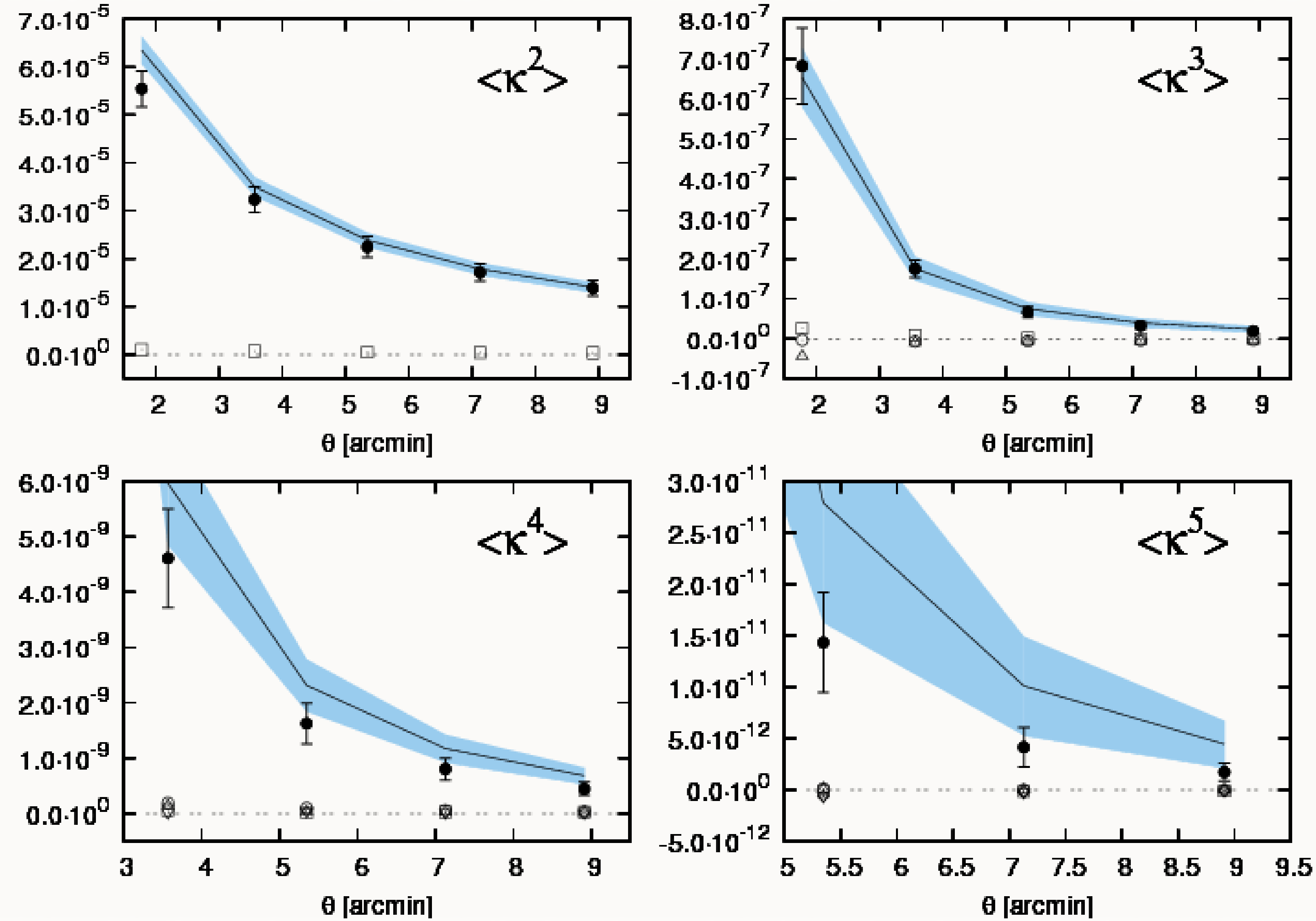
Ray-tracing simulations
[Harnois-Deraps, Vafaei & van Waerbeke 2012]

z=3

z=0.03

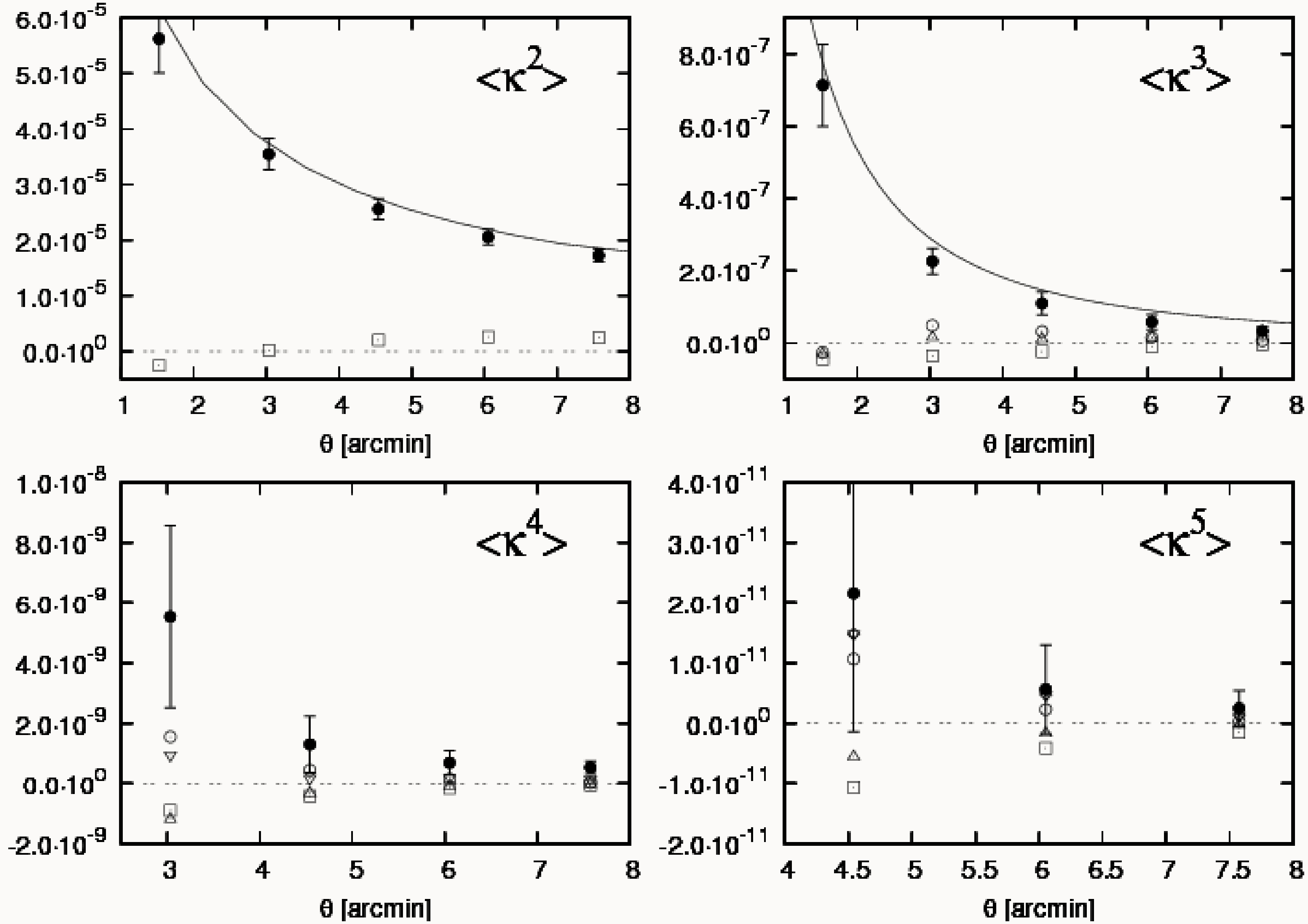


MOMENTS: SIMULATIONS



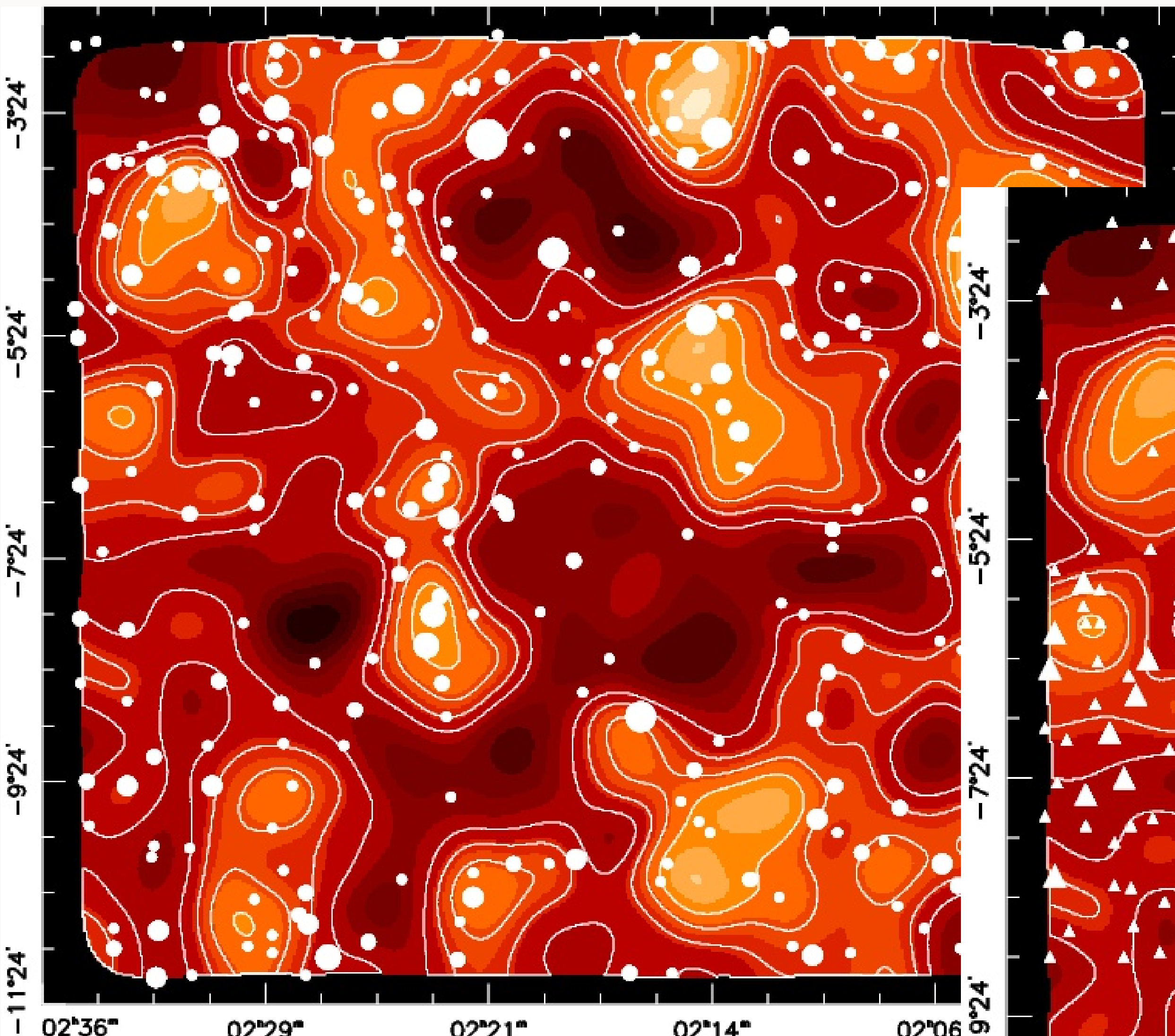
[van Waerbeke et al. 2013]

MOMENTS: CFHTLENS

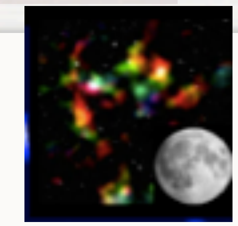


[van Waerbeke et al. 2013]

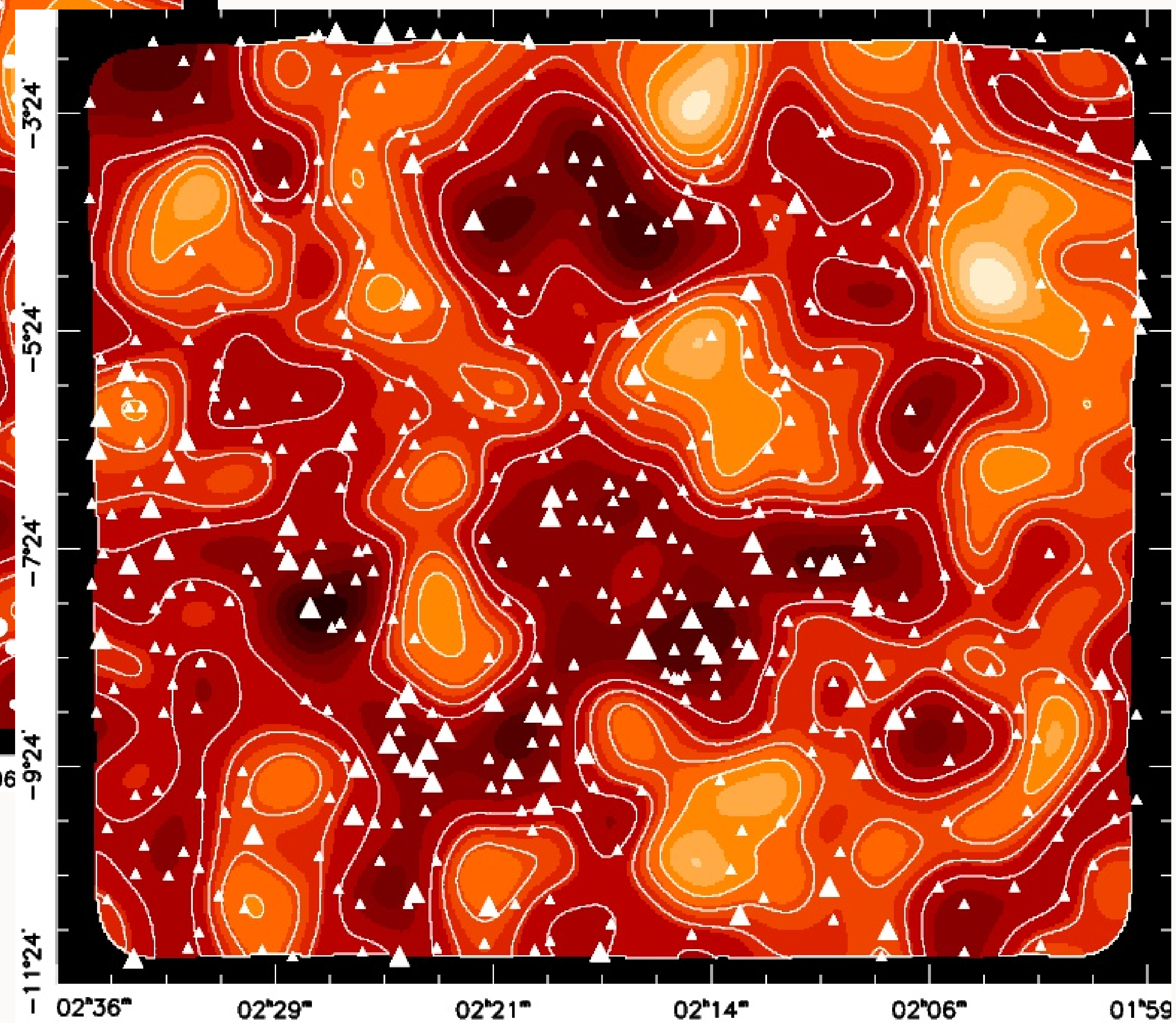
LOOKING FOR PEAKS



positive peaks



negative peaks



CFHTLenS W1
[van Waerbeke et al. 2013]


OUTLOOK

TIMELINE TO EUCLID

- CTIO 75 deg^2, DLS 25 deg^2, SDSS stripe-82 168 deg^2

- COSMOS. 2003 - 2005
  1.64 deg^2, ACS/HST
  Excellent photometric redshifts (30 bands from UV to IR), very deep. Space-based.

- CFHTLS. 2003 - 2009
  155 deg^2, MegCam/CFHT
  Science papers are being submitted and accepted. Catalogues have been made public on **Nov 1, 2012**. See www.cfhtlens.org .

TIMELINE TO EUCLID

- KiDS. 2011 -
  1,500 deg^2, OmegaCam/VST
  Excellent image quality and seeing. Deep IR coverage (VISTA) + u-band

- DES. 2012 -
  5,000 deg^2 , DECam/CTIO
  Large area, IR coverage. Large spectro-follow up planned (DESpec)

- HSC survey. ≥ 2013 -
  1,200 deg^2, HyperSuprimeCam/Subaru.
  Excellent image quality and seeing, very deep (8m telescope!). Deep and Ultra-deep field

- LSST. ≥ 2018 -
  20,000 deg^2

- Euclid. ≥ 2019 -
  15,000 deg^2
  Very stable PSF, space-based.

THE EUCLID MISSION

SURVEYS In ~5.5 years

	Area (deg2)	Description
Wide Survey	**15,000 deg^2**	Step and stare with 4 dither pointings per step.
Deep Survey	**40 deg^2**	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

PAYLOAD

Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3 10^{-16} erg cm-2 s-1 3.5σ unresolved line flux
	Shapes + Photo-z of *n* = 1.5 x10^9 galaxies ?			**z of *n*=5x10^7 galaxies**	
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

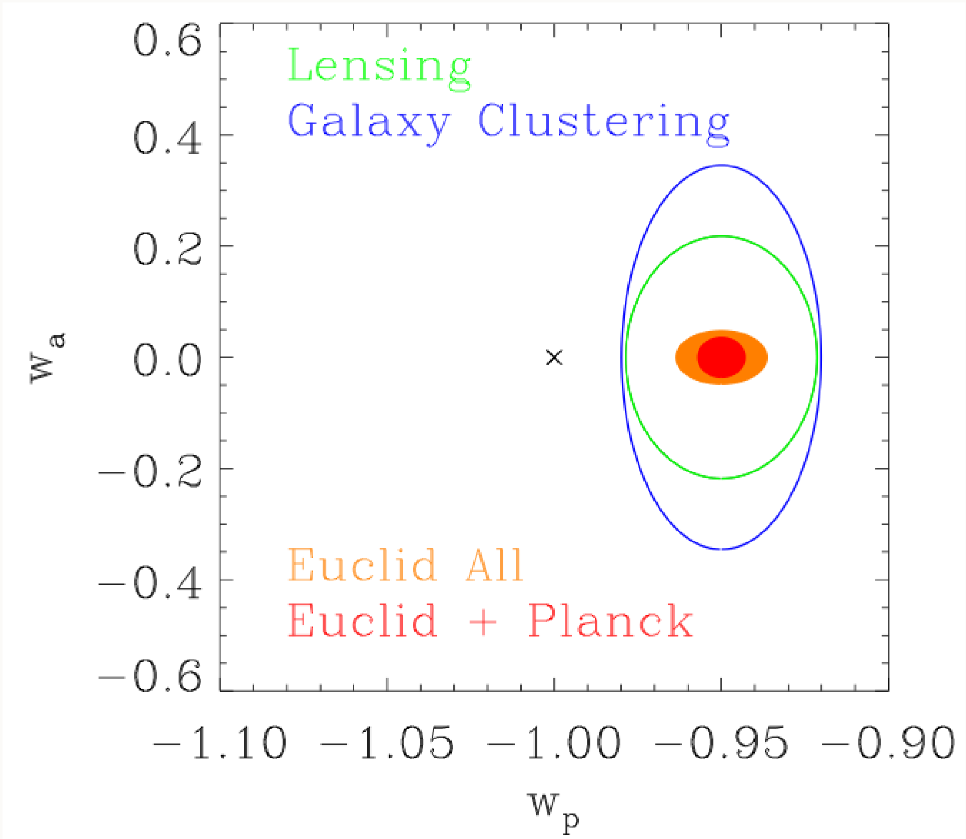
Possibility to propose other surveys: SN and/or μ-lens surveys, Milky Way ?

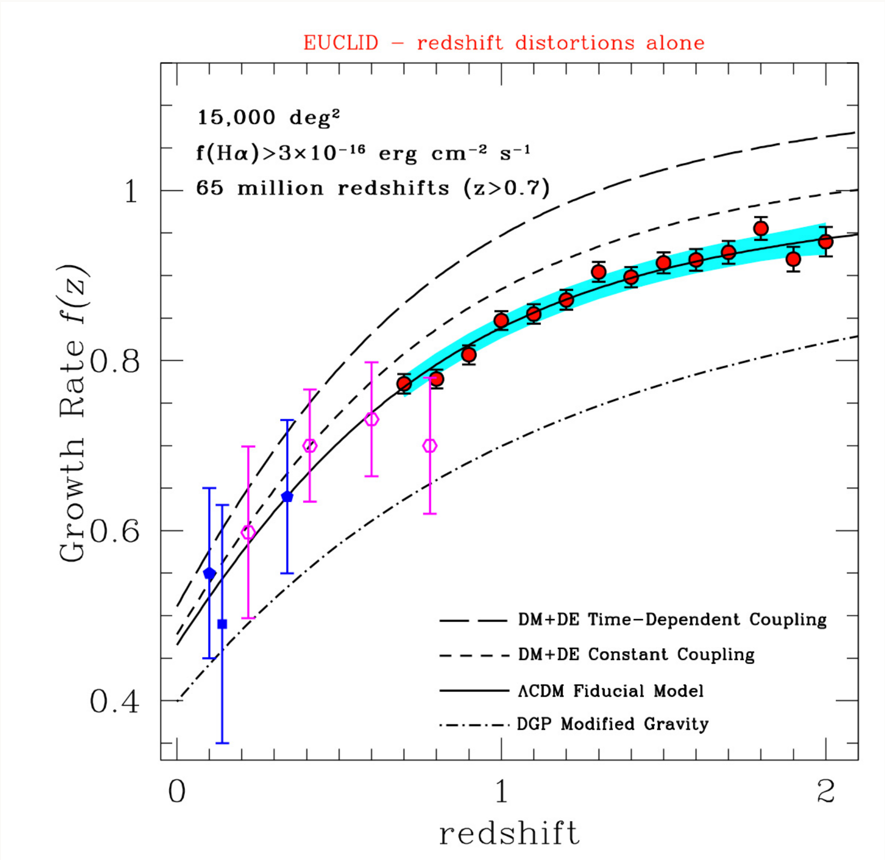
EUCLID FORECASTS

	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**

CFHTLenS + WiggleZ + WMAP5 + H0:

$\gamma = 0.52 \pm 0.09$





M51

SDSS @ z=0.1   Euclid @ z=0.1   Euclid @ z=0.7

- Euclid images of z~1 galaxies: same resolution as SDSS images at z~0.05 and at least 3 magnitudes deeper.
- Space imaging of Euclid will outperform any other surveys of weak lensing.

FUTURE LENSING SURVEYS

- Order of magnitude more area → dominated by systematic errors!
- No current shape measurement method accurate enough for future surveys
- Space-based weak lensing challenges (CTI, PSF undersampling, color gradients)
- No show-stopper for weak lensing found yet

LIKELIHOOD FUNCTION

$$L(\boldsymbol{d}^{\rm obs};\boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^n \det C}} \exp[-\chi^2(\boldsymbol{d}^{\rm obs};\boldsymbol{\theta})/2]$$

$$\chi^2(\boldsymbol{d}^{\rm obs};\boldsymbol{\theta}) = \left(\boldsymbol{d}(\boldsymbol{\theta}) - \boldsymbol{d}^{\rm obs}\right)^{\rm t} C^{-1} \left(\boldsymbol{d}(\boldsymbol{\theta}) - \boldsymbol{d}^{\rm obs}\right)$$

$\boldsymbol{d}^{\sf obs}$: data vector of ellipticity correlations, e.g. $d_i = \xi(\vartheta_{j(i)}, z_{k(i)})$

$\boldsymbol{d}(\boldsymbol{\theta})$: model vector

$\boldsymbol{\theta}$: vector of cosmological parameters, e.g. $\Omega_{\sf m}, \sigma_8, h, w \ldots$

C : covariance matrix, $C = \langle d d^{\sf t}\rangle - \langle d\rangle\langle d^{\sf t}\rangle$

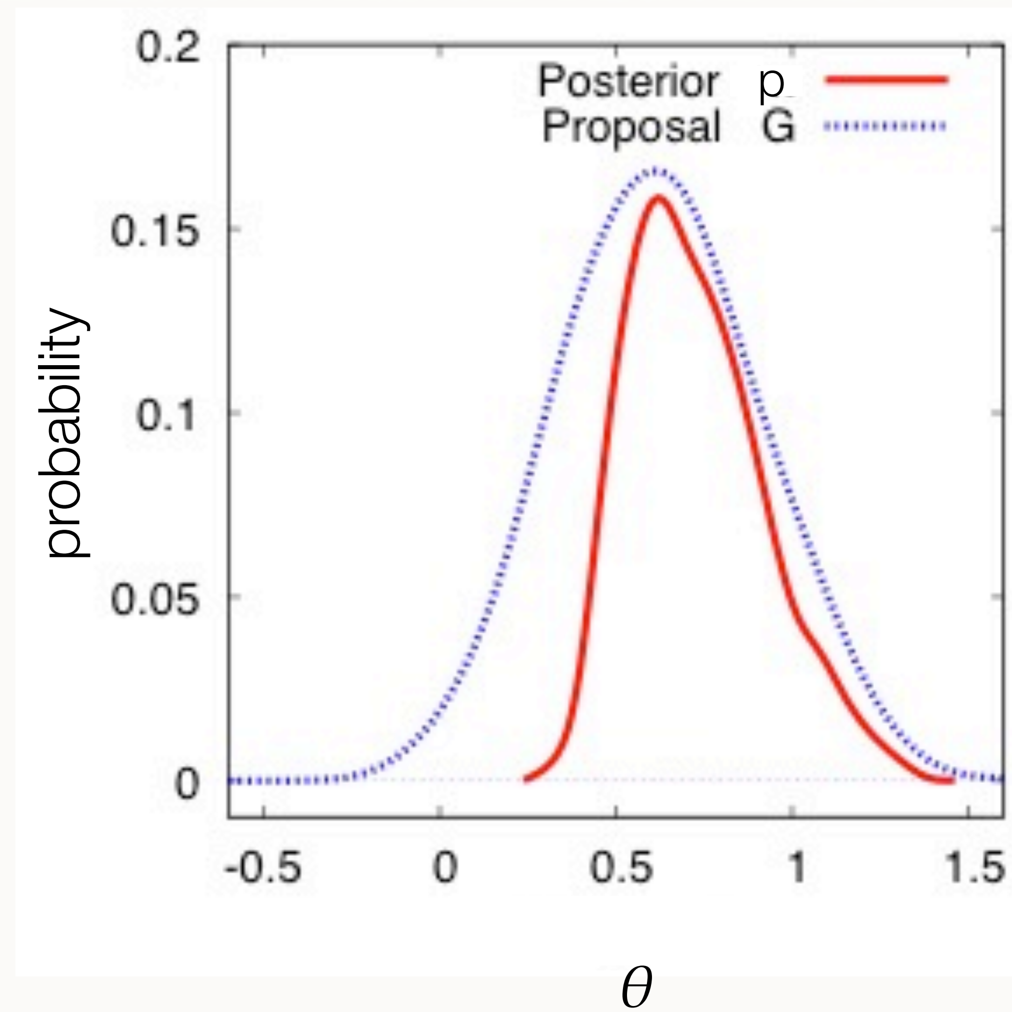
We need integrals over the likelihood:

mean of parameter vector $\int {\rm d}^n\theta \, \boldsymbol{\theta} \, L(\boldsymbol{\theta})\pi(\boldsymbol{\theta})$

68% confidence region $\int {\rm d}^n\theta \, 1_{68\%} \, L(\boldsymbol{\theta})\pi(\boldsymbol{\theta})$

IMPORTANCE SAMPLING

- Sample from proposal distribution G (importance function). E.g. mixture of Gaussians



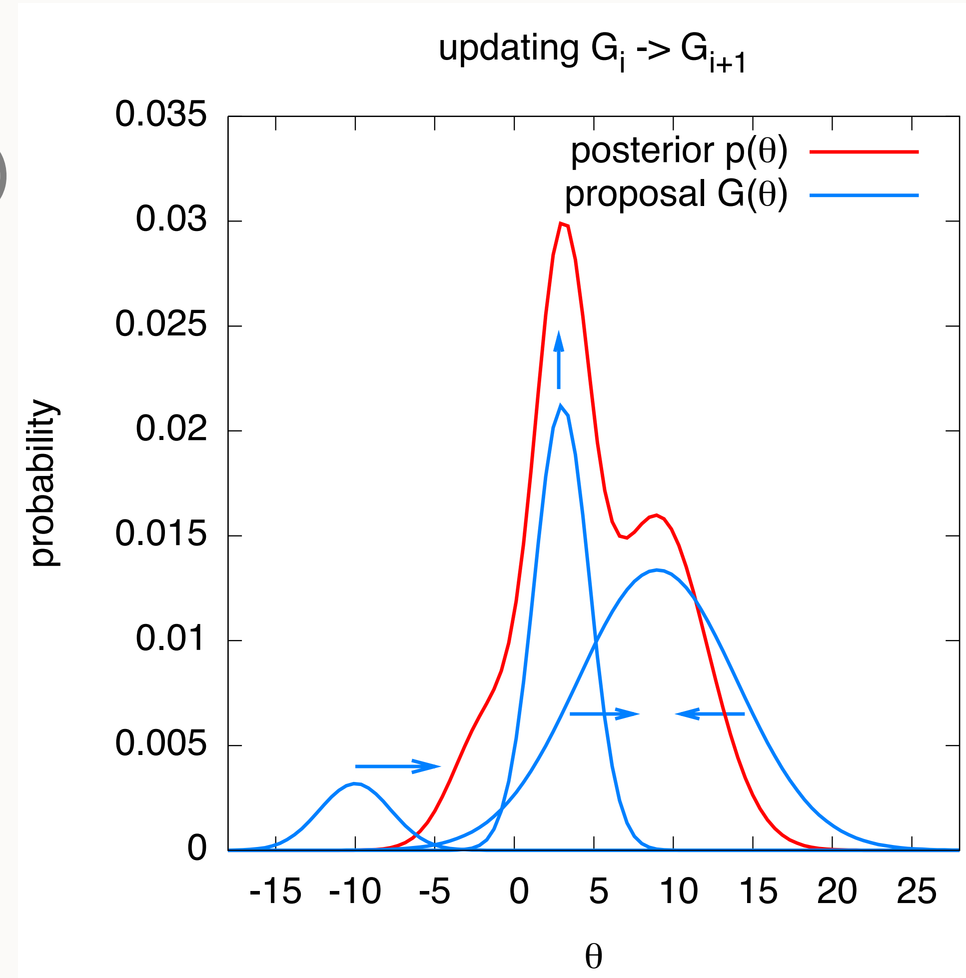
- Weigh each sample point θ by ratio (importance weight) $w = p(\theta)/G(\theta)$

- Evaluation of posterior p (likelihood x prior) can be done in parallel

- Poor performance if proposal far from posterior

POPULATION MONTE CARLO (PMC)

- Solution: Create adaptive importance samples ("populations") [Cappé et al. 2004, 2007]



- Iteration $G_i \rightarrow G_{i+1}$: Update mean, covariance and component weights

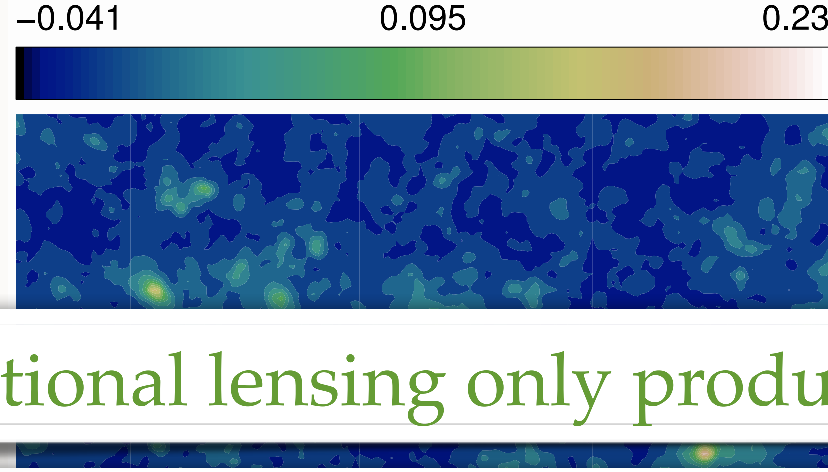
- PMC sample engine and cosmology modules, public code, www.cosmopmc.info, [Kilbinger et al. 2010, arXiv:1101.0950]

- Stop when proposal p 'close enough' to posterior G

E- AND B-MODE

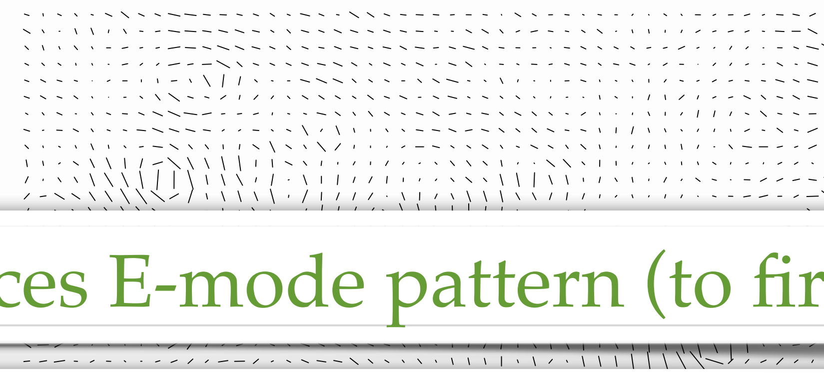
Projected matter density

convergence κ



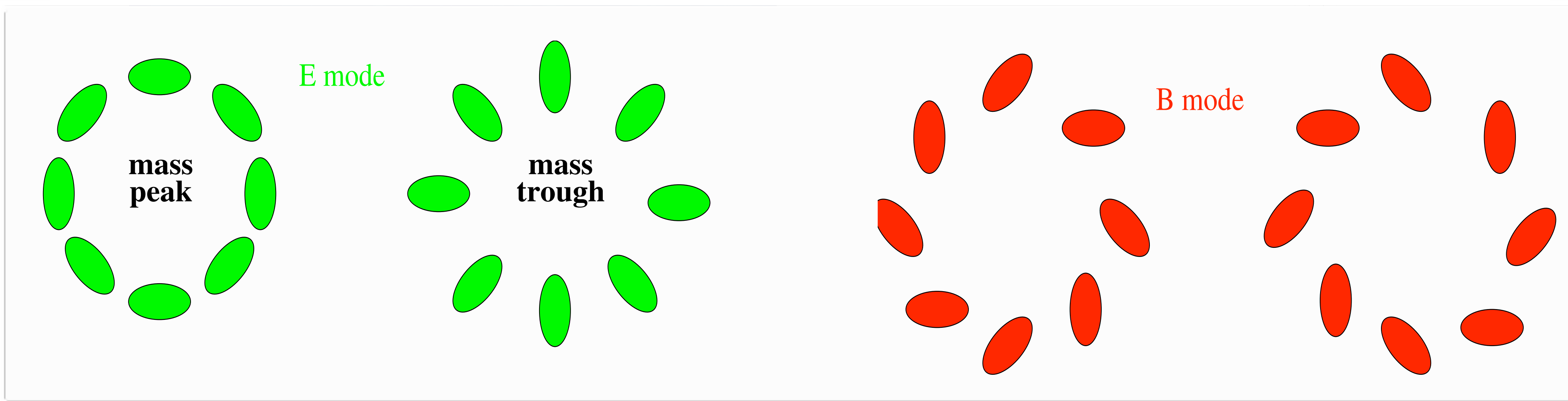
Distortion field

shear γ



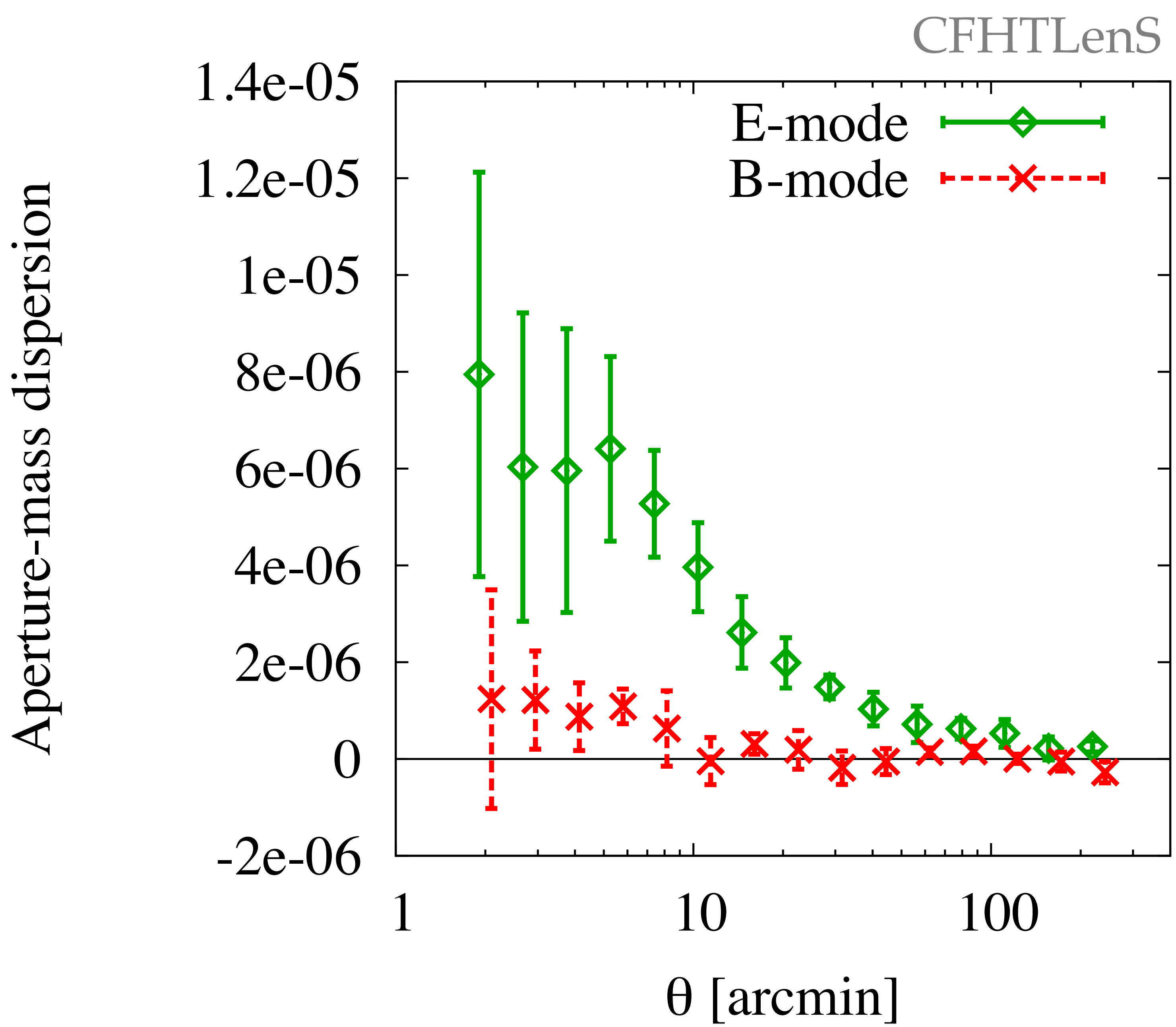
mass peaks

Gravitational lensing only produces E-mode pattern (to first order)



B-mode detected → hint for systematics in data

E- AND B-MODES



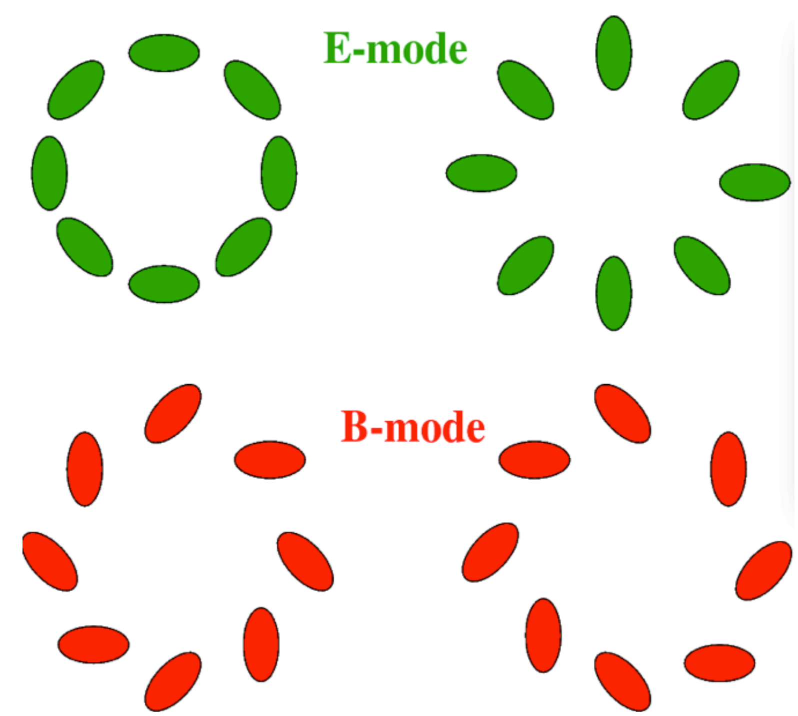
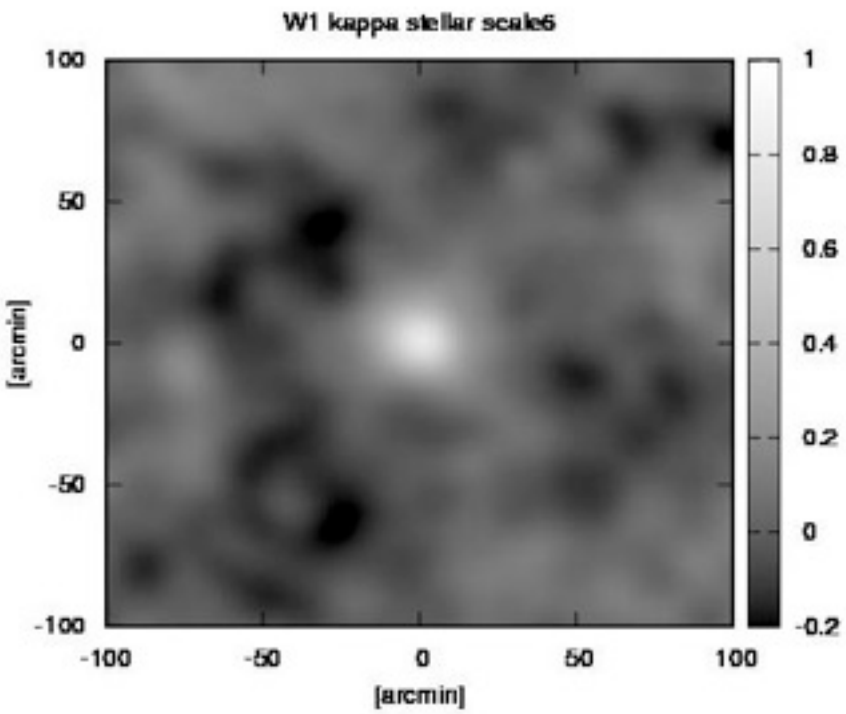
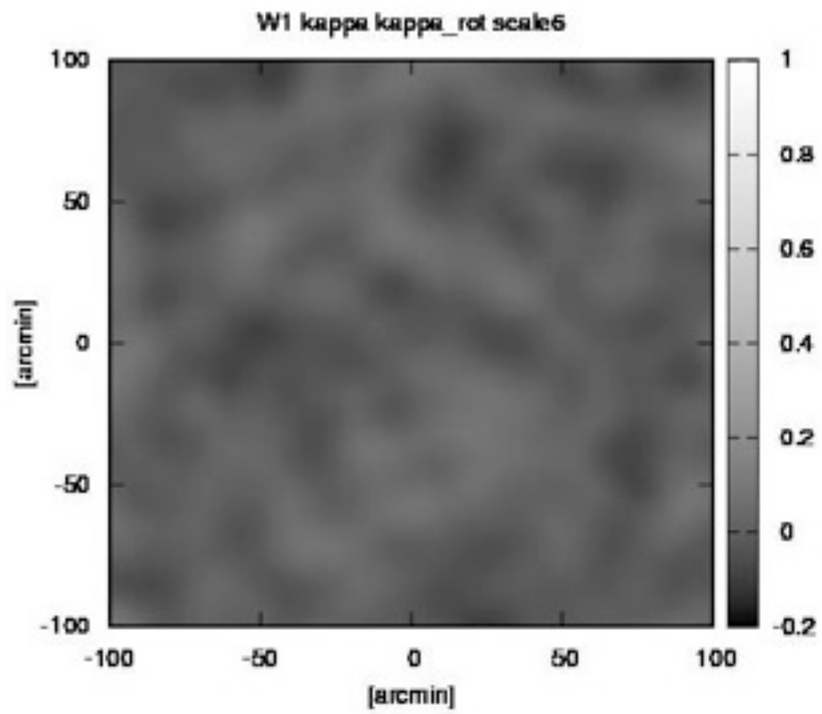


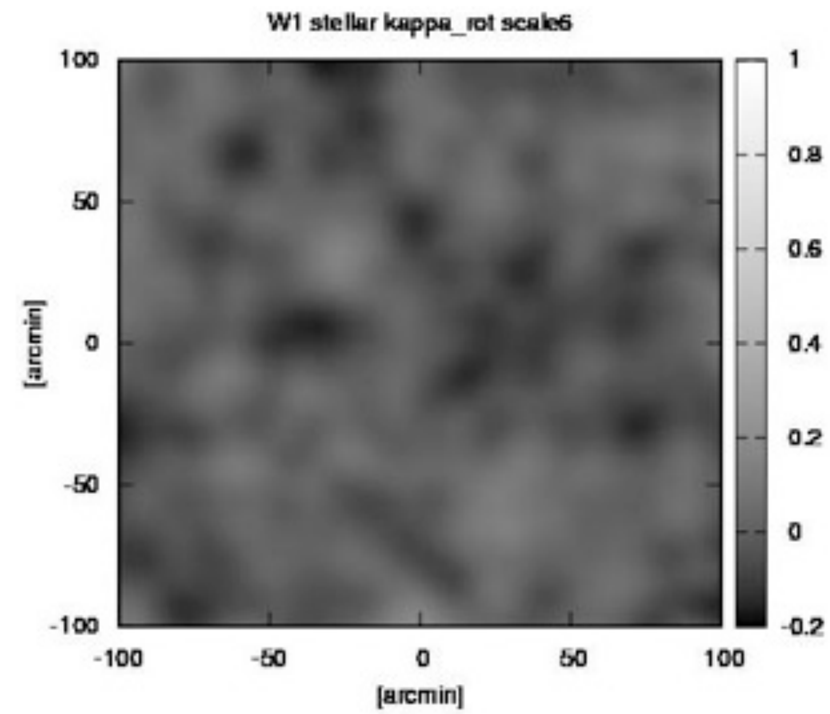
Fig.1. *Left*: E- and B-modes measured in CFHTLenS. *Right*: typical E- and B-mode shear patterns.

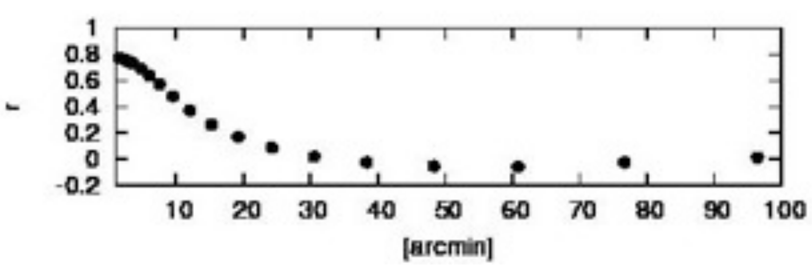
W1 cross-correlation analysis

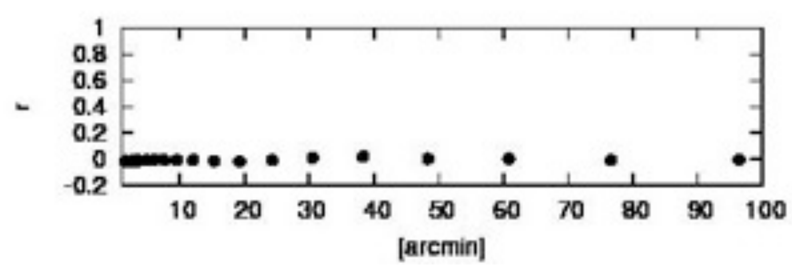
$\langle \kappa_{mass}\ \kappa_{galaxies} \rangle$ $\langle \kappa_{mass}\ \kappa_{rot} \rangle$ $\langle \kappa_{rot}\ \kappa_{galaxies} \rangle$

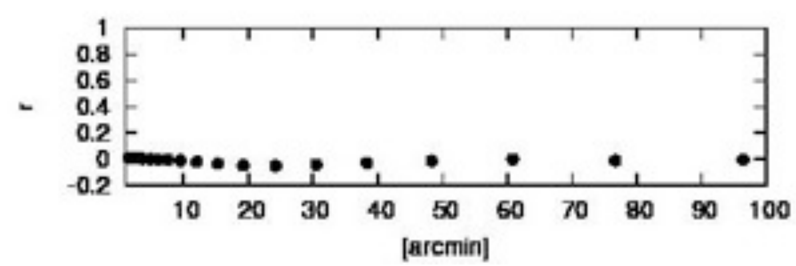


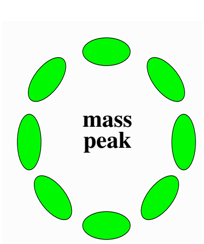












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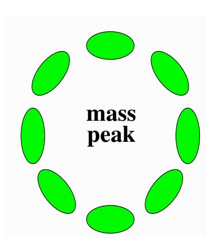

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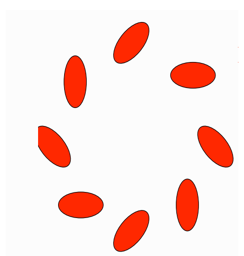

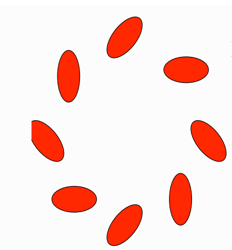

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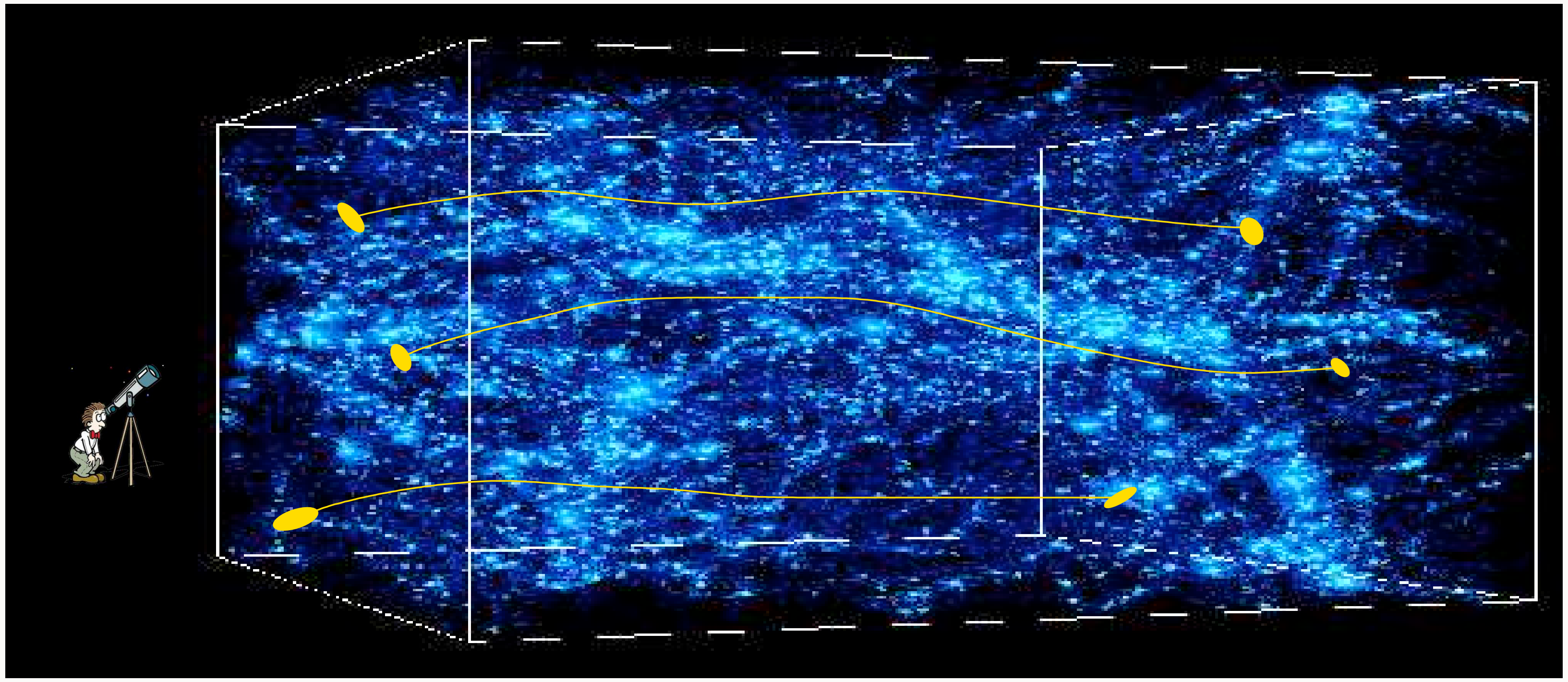
WEAK LENSING SUMMARY



- Galaxy shape correlations measure 'lumpiness' of large-scale structure (LSS)
- Sensitive to both geometry and growth, $z = 0.2 \ldots 1$, acceleration epoch; dark energy, modified gravity
- Weak lensing regime: need huge number of galaxies to measure statistically & excellent image quality