Constraints On Dark Energy And Modified Gravity Models From CFHTLenS

ASIAA colloquium
2012 年 11 月 23 日

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www.cfhtlens.org

OUTLINE

- Weak gravitational lensing
- The CFHT Lensing survey; galaxy shape measurement, systematics
- CFHTLenS results: constraints on dark energy + Modified Gravity (+ Wiggle-Z)
- More CFHTLenS results: mass maps; galaxy bias
- Outlook, future lensing surveys

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 ≈ 0.1 and ≥ 1

epoch of acceleration

... measures the expansion history and growth rate

can distinguish between dark energy and modified gravity

HOW DOES IT WORK?

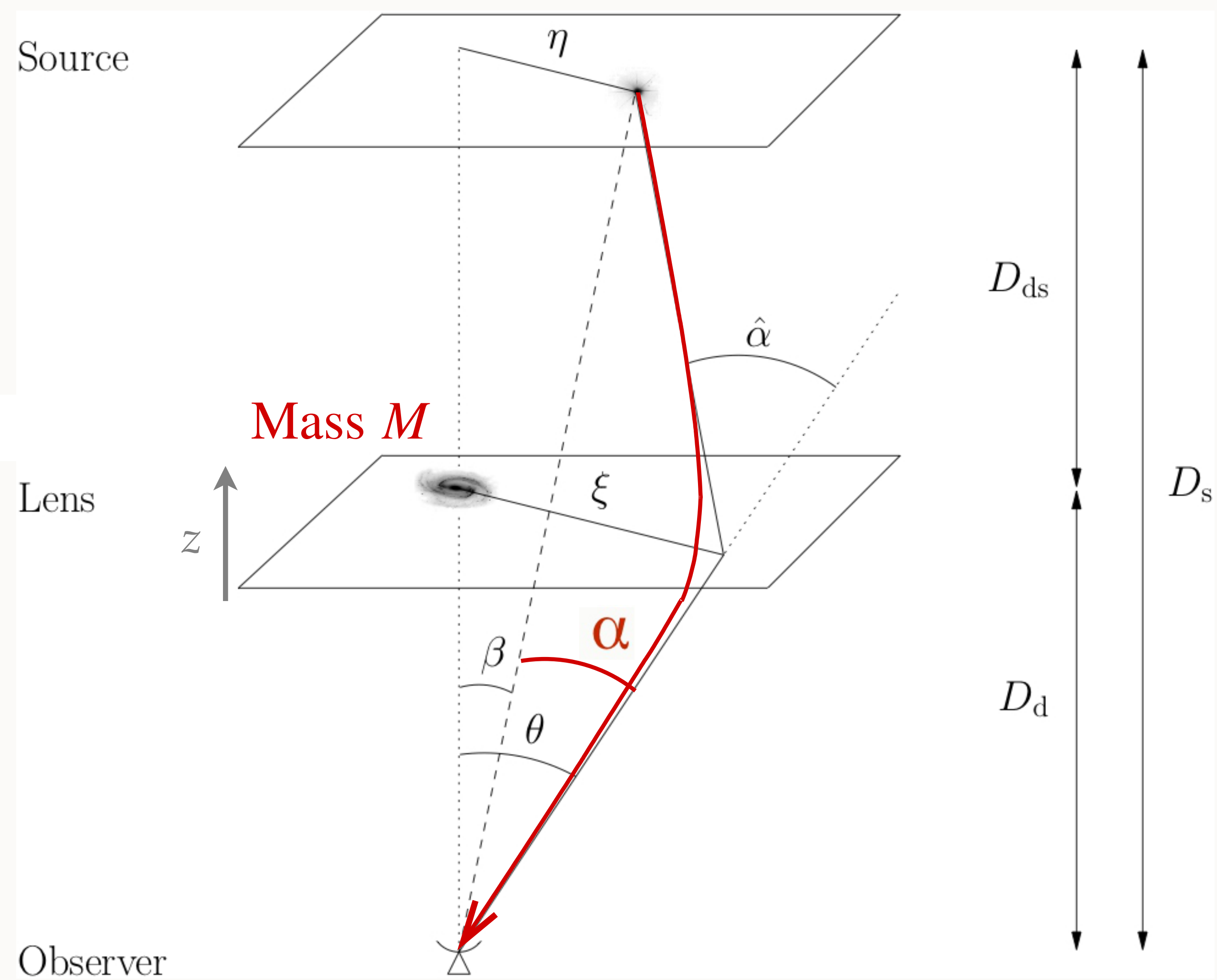
Mass deflects light (Einstein 1915)

Point mass:

Deflection angle

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

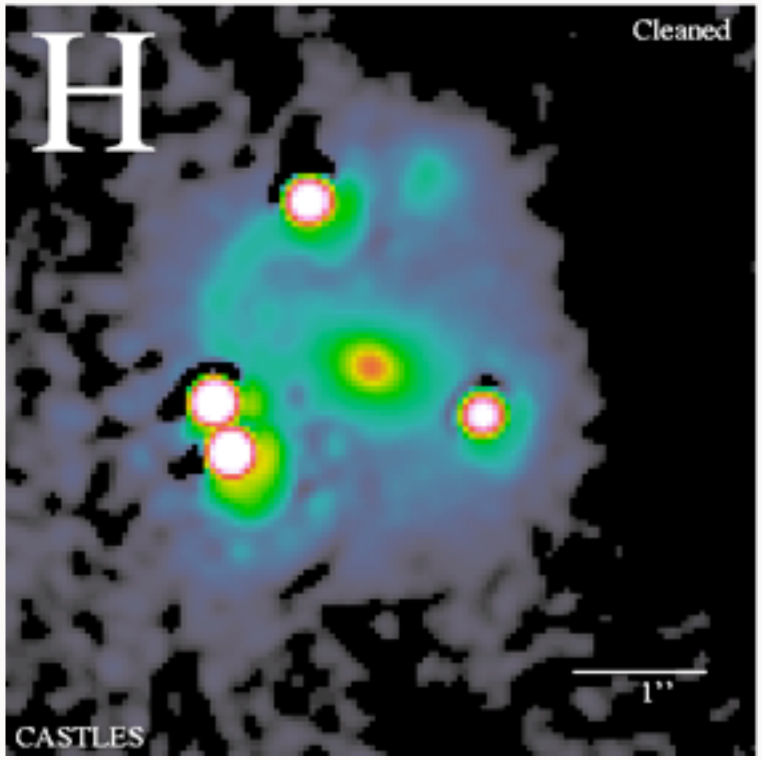
impact parameter

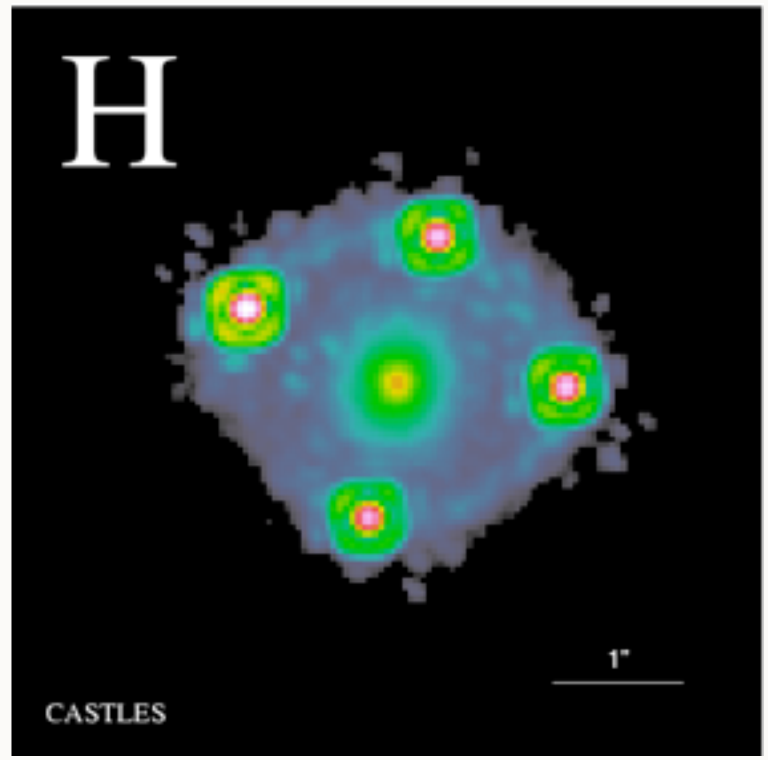


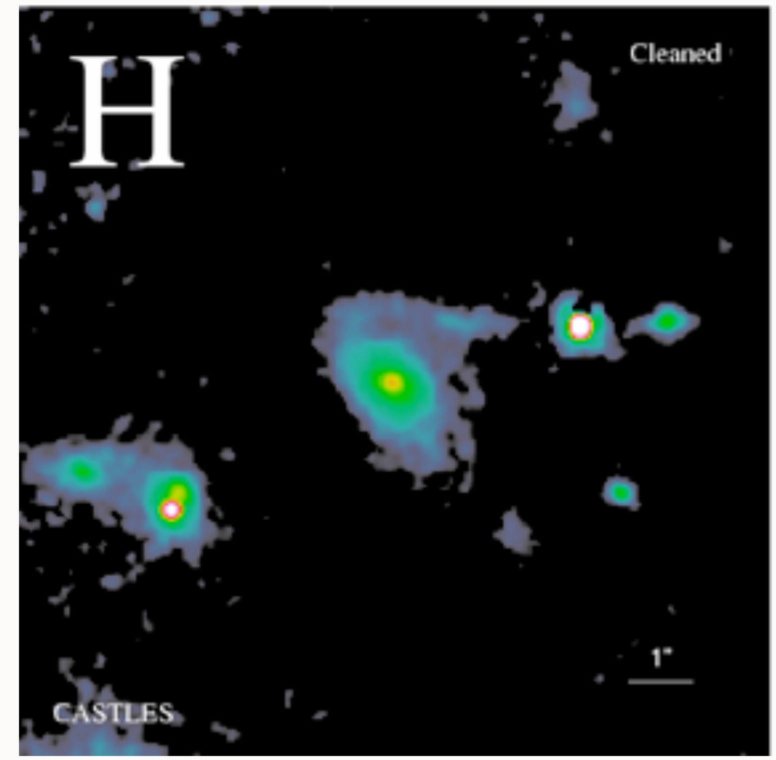
Extended mass distribution:

Deflection angle depends on integral over the projected mass distribution

LENSING MULTIPLICATION







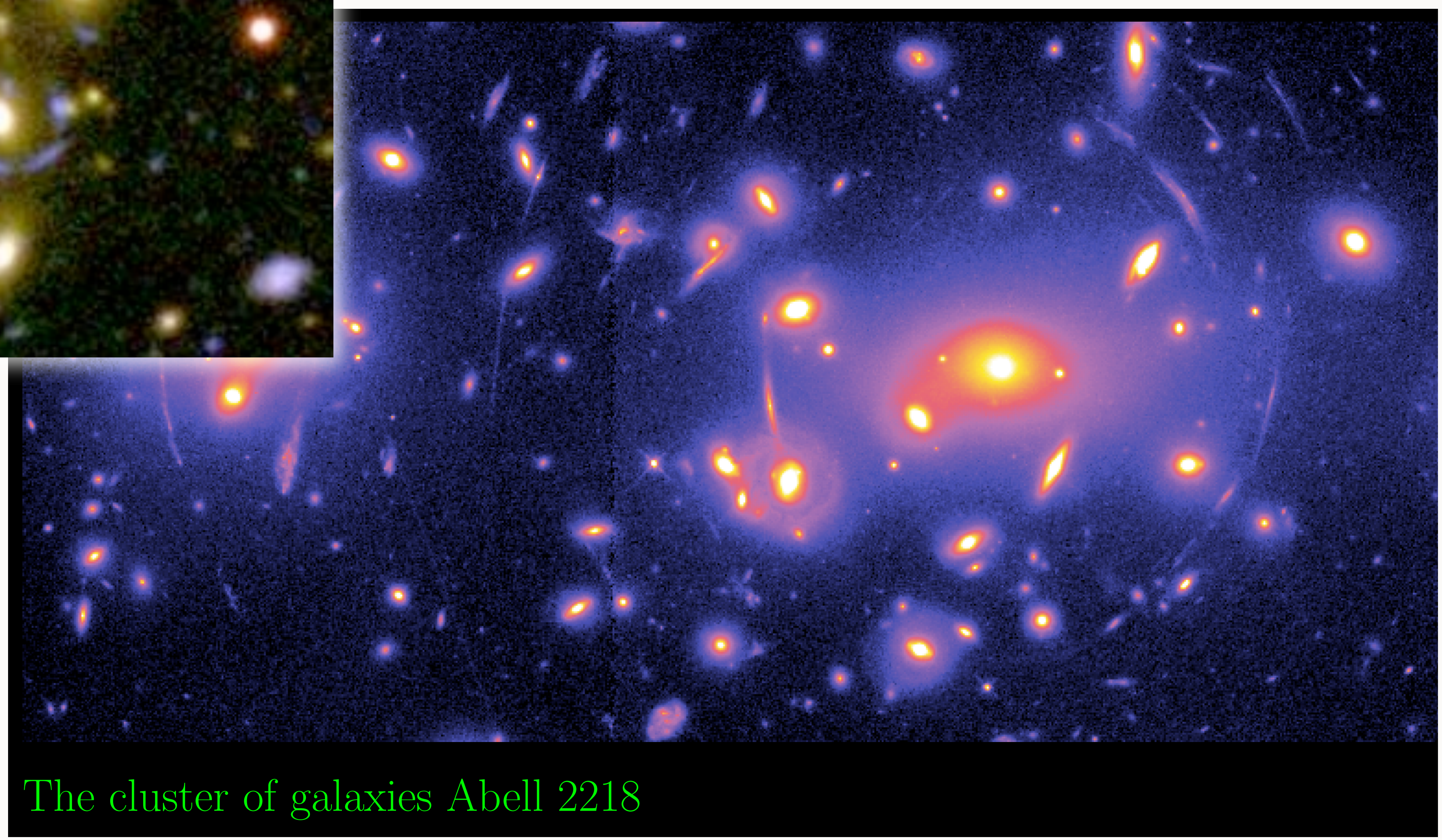
	MG0414+0534	HE0435-1223	RXJ0921+4529
z_{source}	2.64	1.689	1.65
z_{lens}	0.96	0.46	0.31

CASTLES survey,

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

LENSING DISTORTIONS

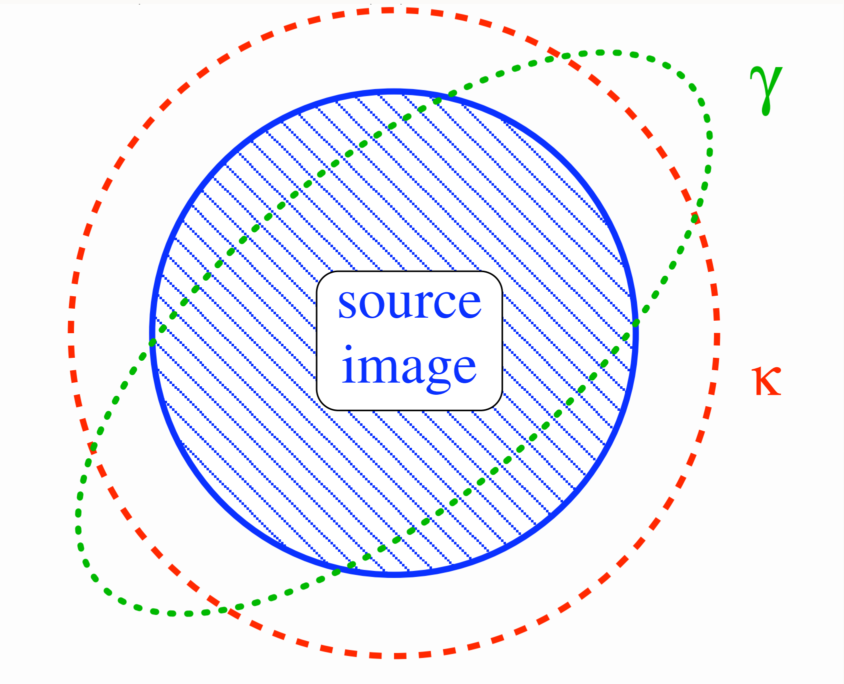
CFHTL12k lens candidate, Czoske et al. 2001,
$z_l = 0.49$, $z_s = ?$



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.



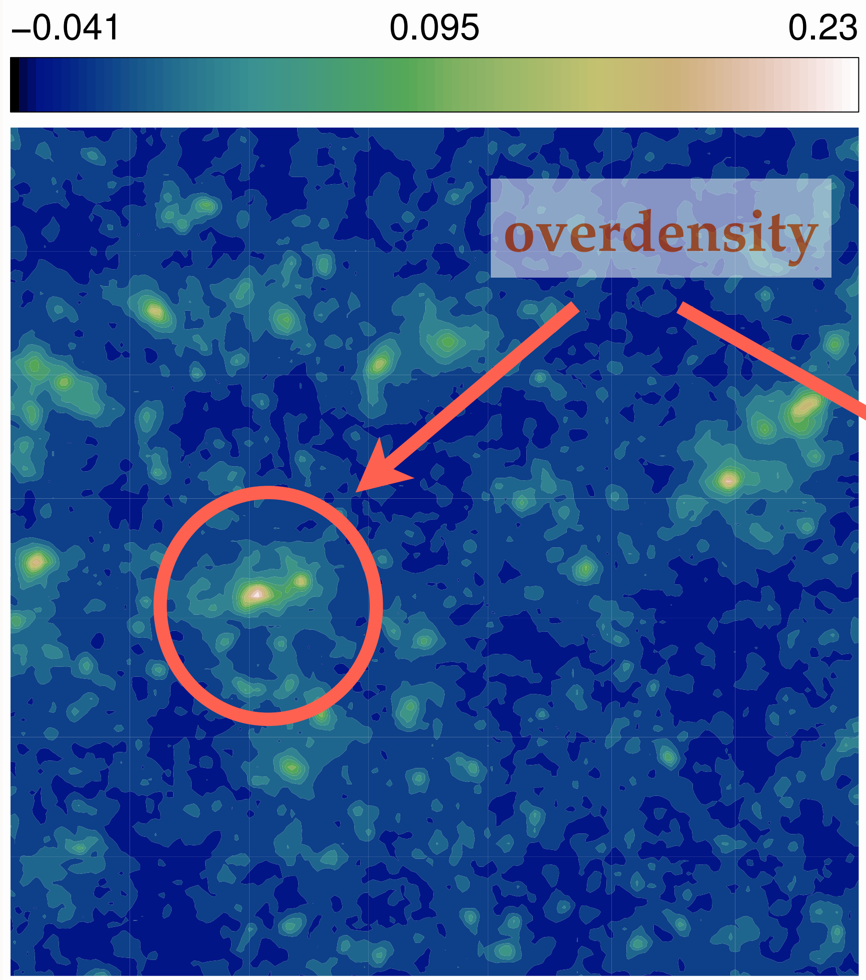
Typical in weak cosmological lensing: 3% distortion, $\gamma \approx 0.03$

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

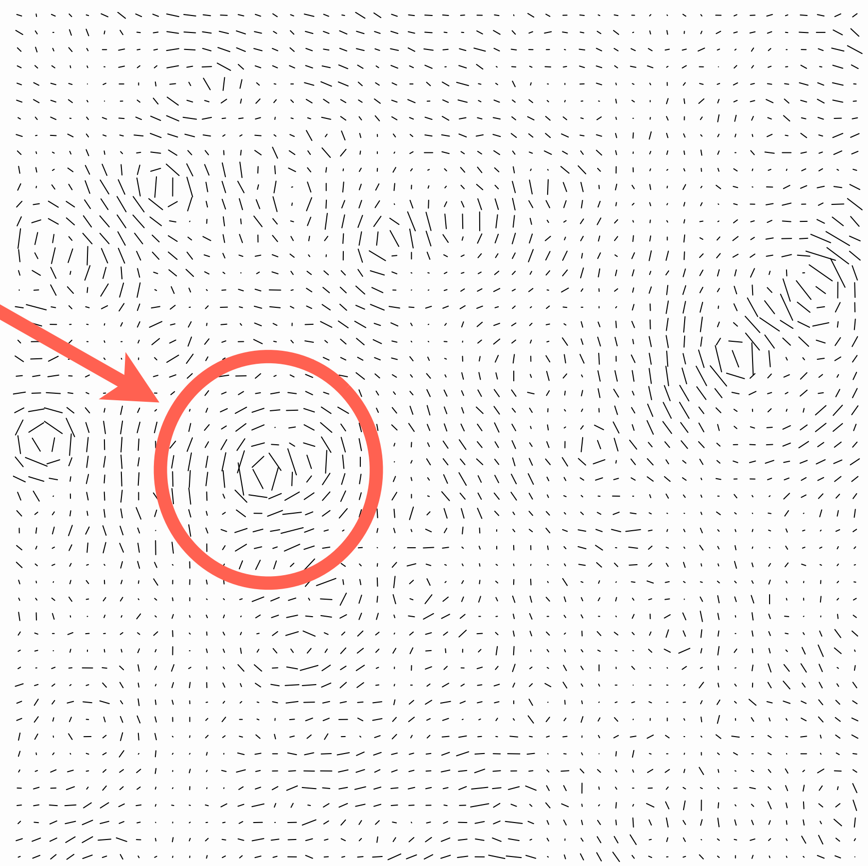
MASS AND SHEAR

Projected matter density
convergence κ

Distortion field
shear γ



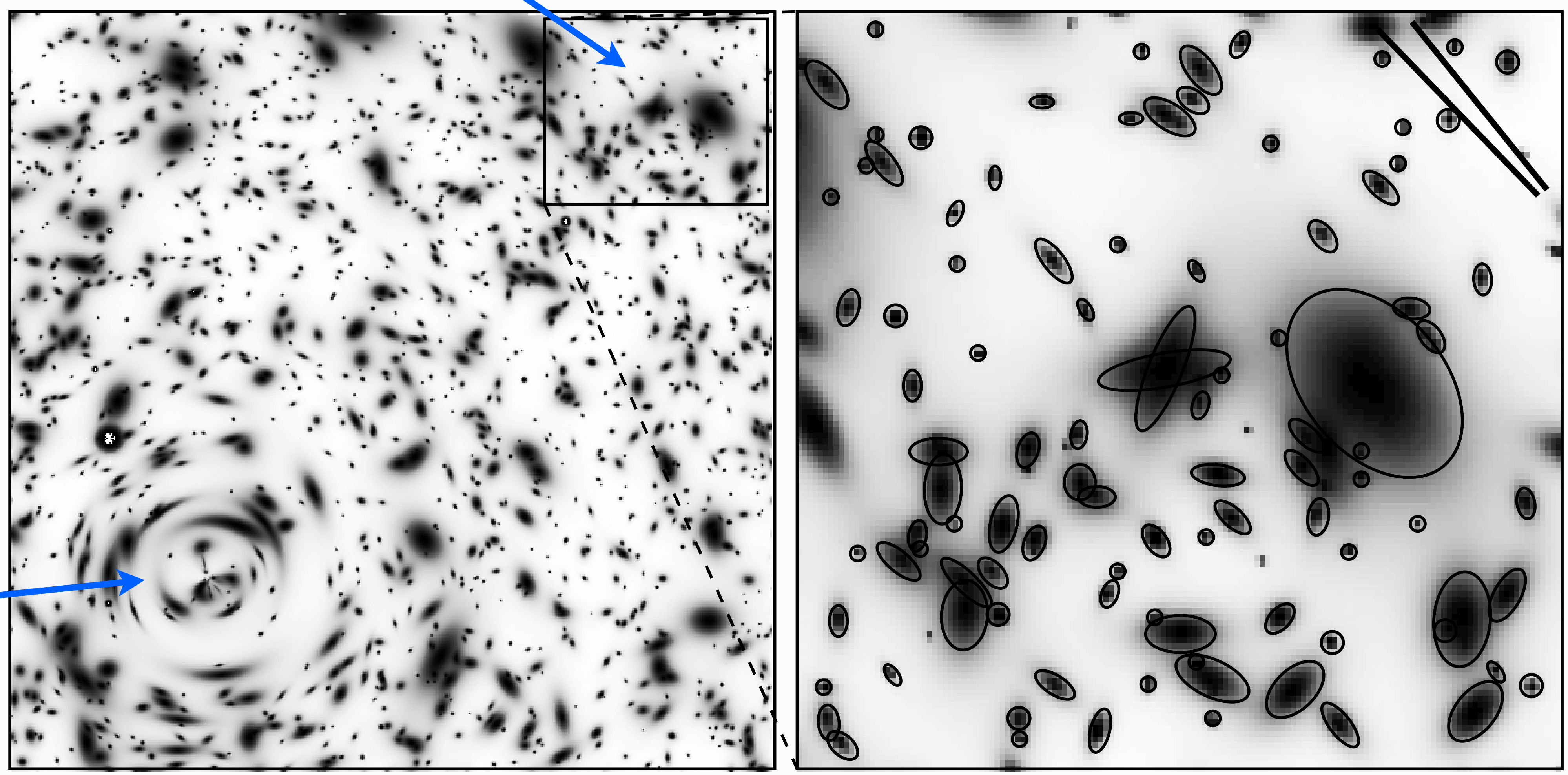
tangential distortions around mass peaks



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

GALAXIES ESTIMATE SHEAR

weak lensing $|\kappa|, |\gamma| \ll 1$



[from Y. Mellier]

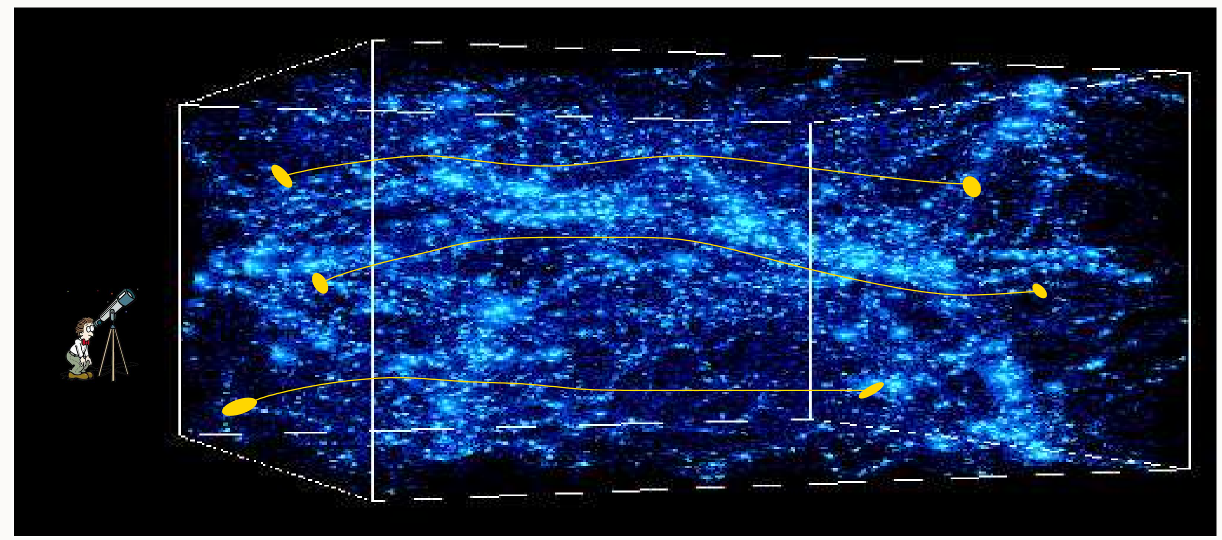
Galaxy ellipticities are an estimator of the local shear.

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

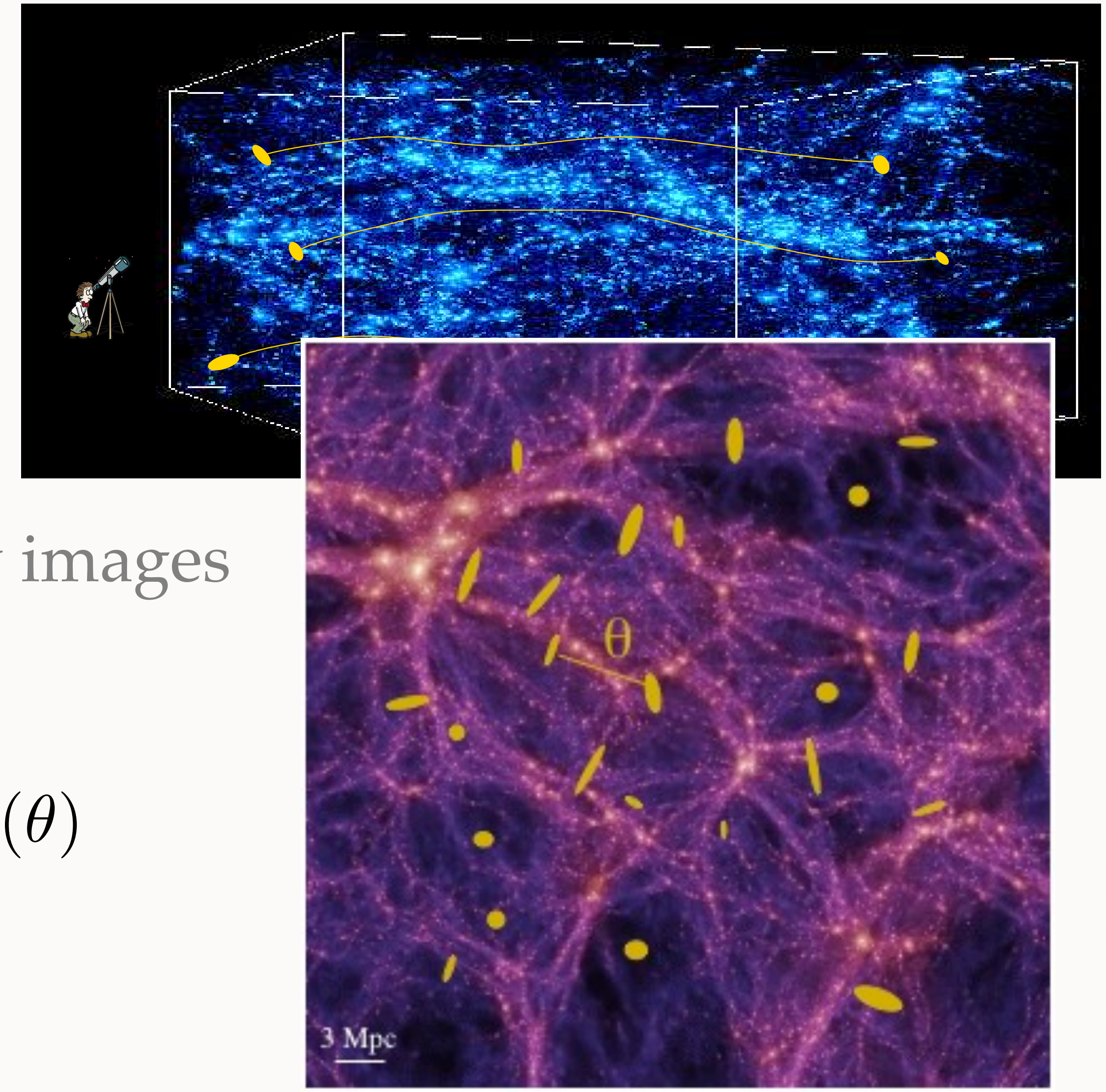
density contrast

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

redshift distribution of background galaxies

COSMIC SHEAR

Weak lensing by the large-scale structure



- Coherent distortions of galaxy images
  → measure shape correlations

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

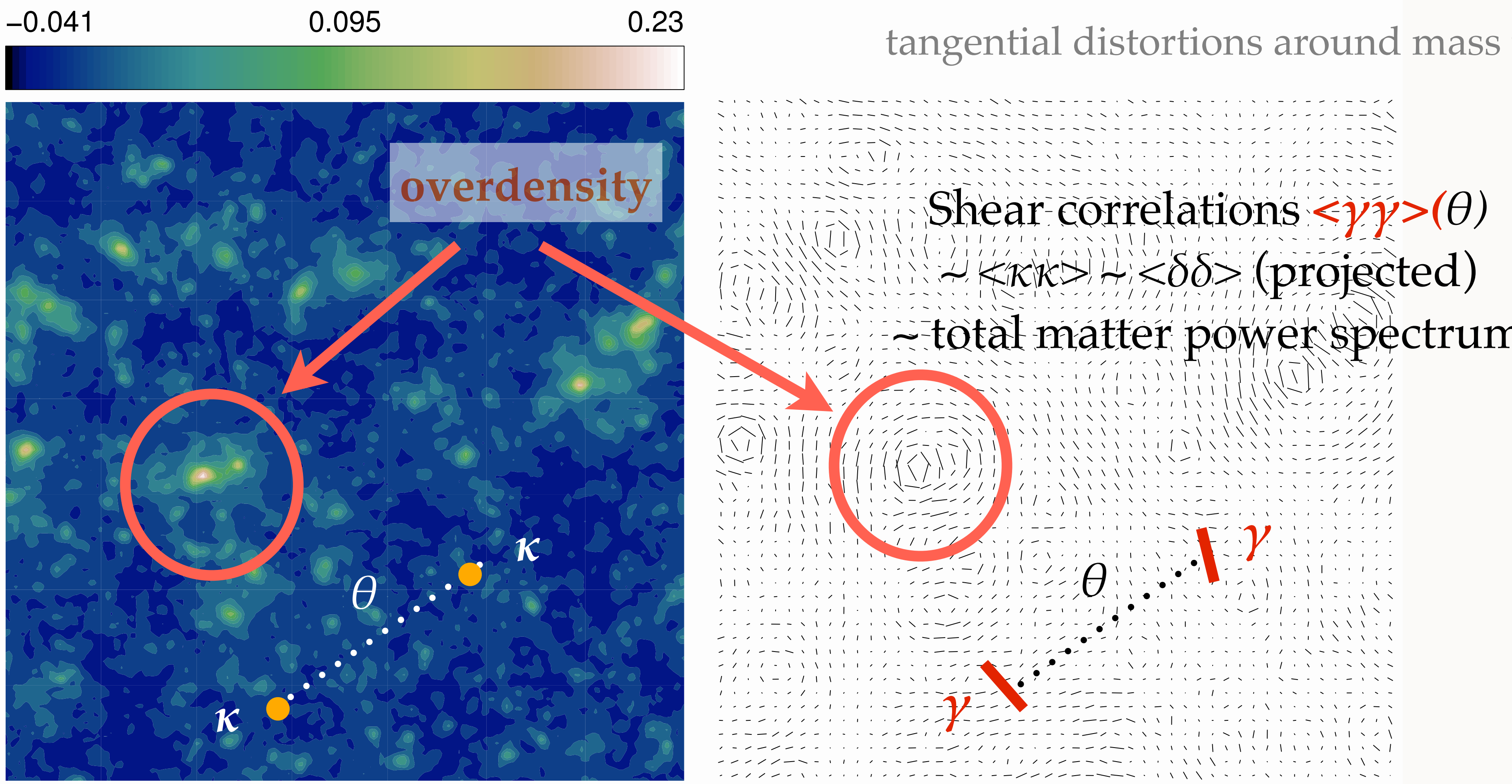
shear variance

MASS AND SHEAR

Projected matter density
convergence κ

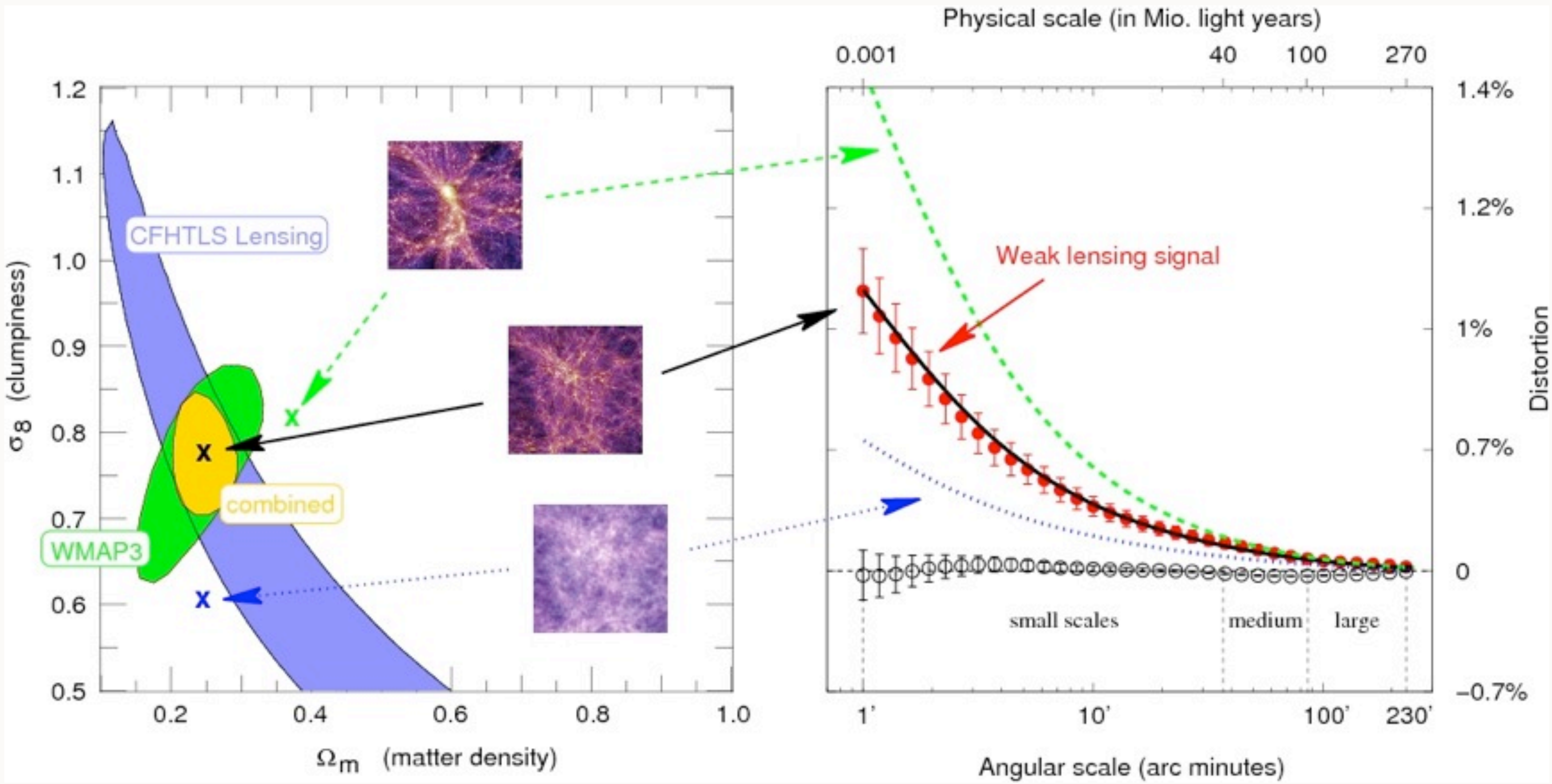
Distortion field
shear γ

tangential distortions around mass peaks



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

WEAK LENSING SUMMARY



[Fu et al. 2008]

σ_8 = density fluctuations rms in spheres of 8 Mpc/h
= density power spectrum amplitude

The CFHTLenS team

L. van Waerbeke (PI)
H. Hildebrandt
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R. Gavazzi

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T. Schrabback
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K. Kuijken
E. Semboloni
M. Smit

M. Hudson
B. Gillis

L. Miller
M. Velander

J. Coupon

B. Rowe

C. Bonnett

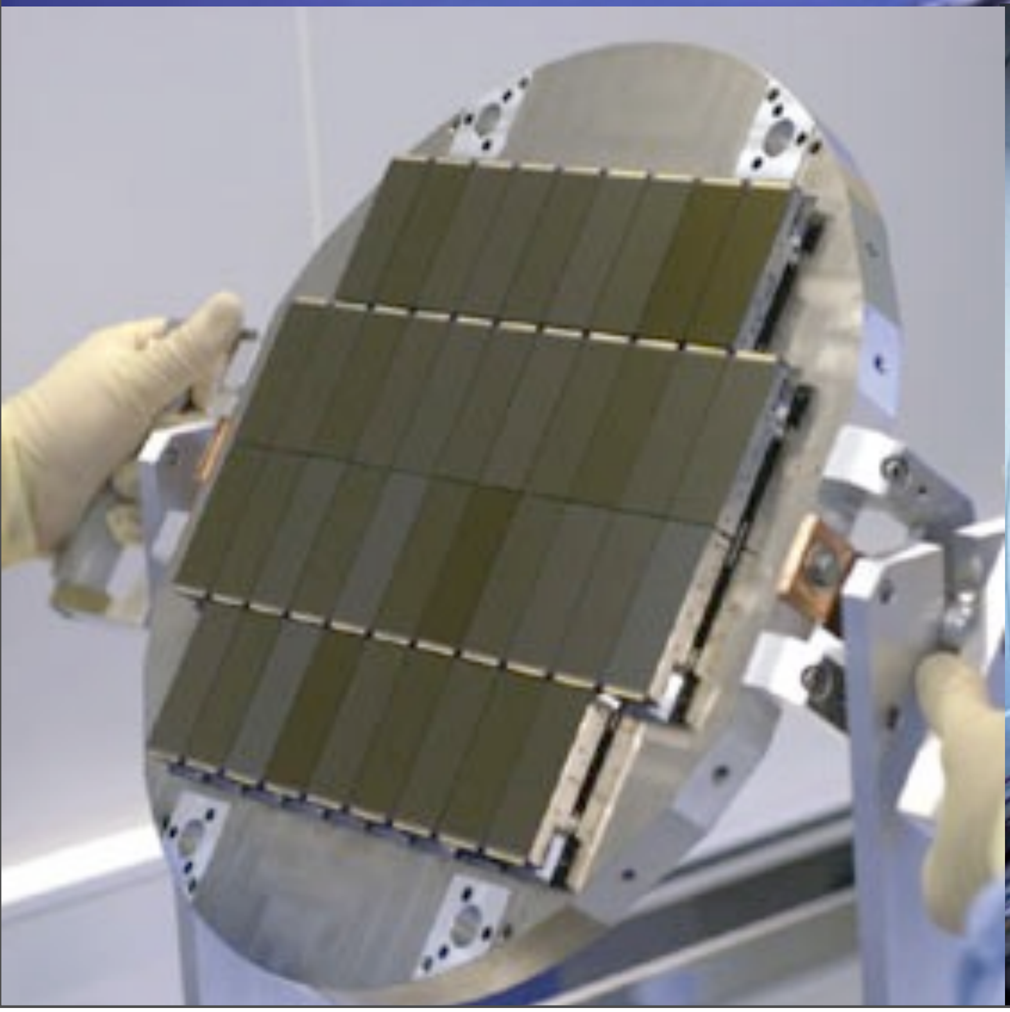
L. Fu

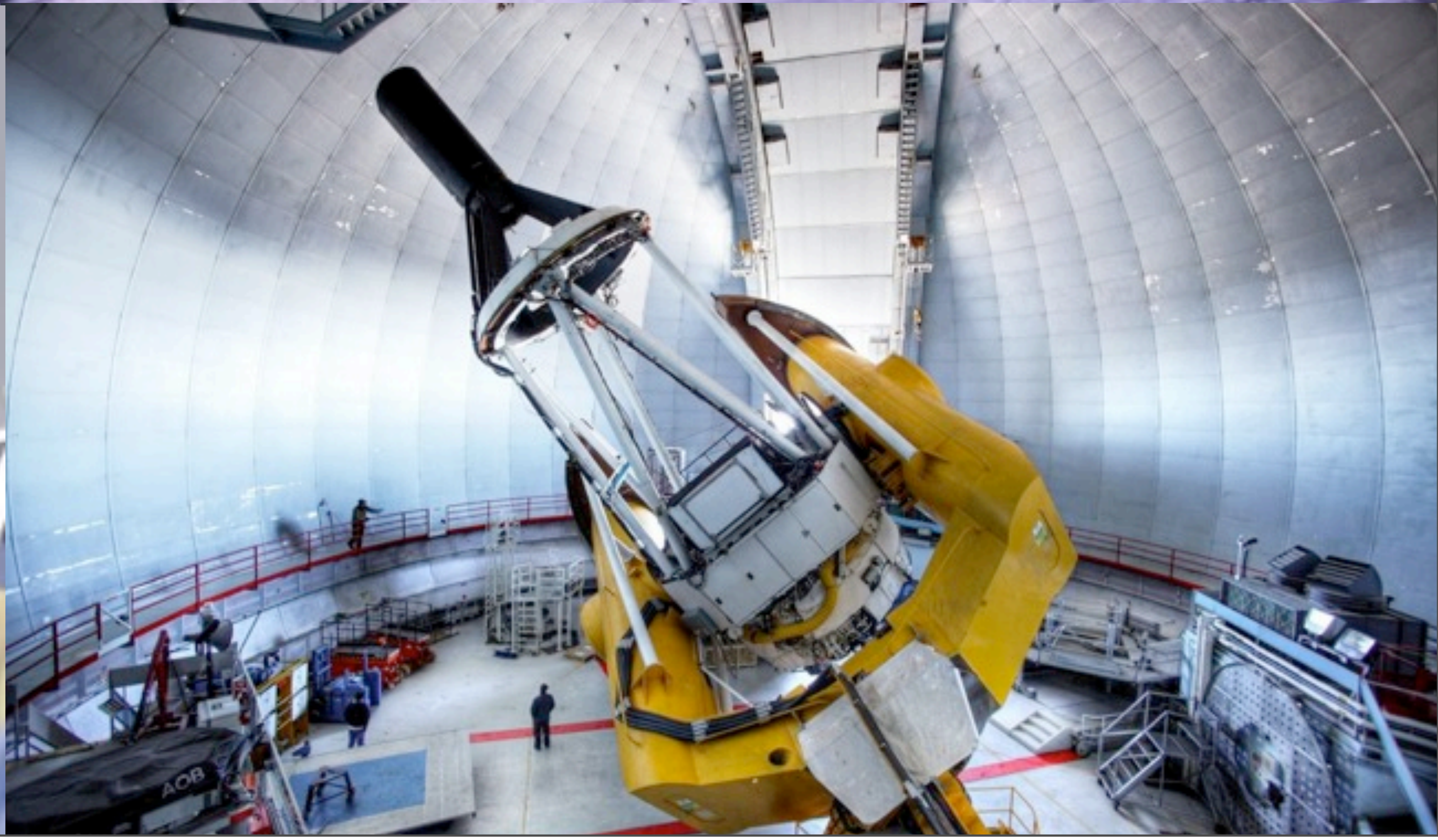
M. Kilbinger

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

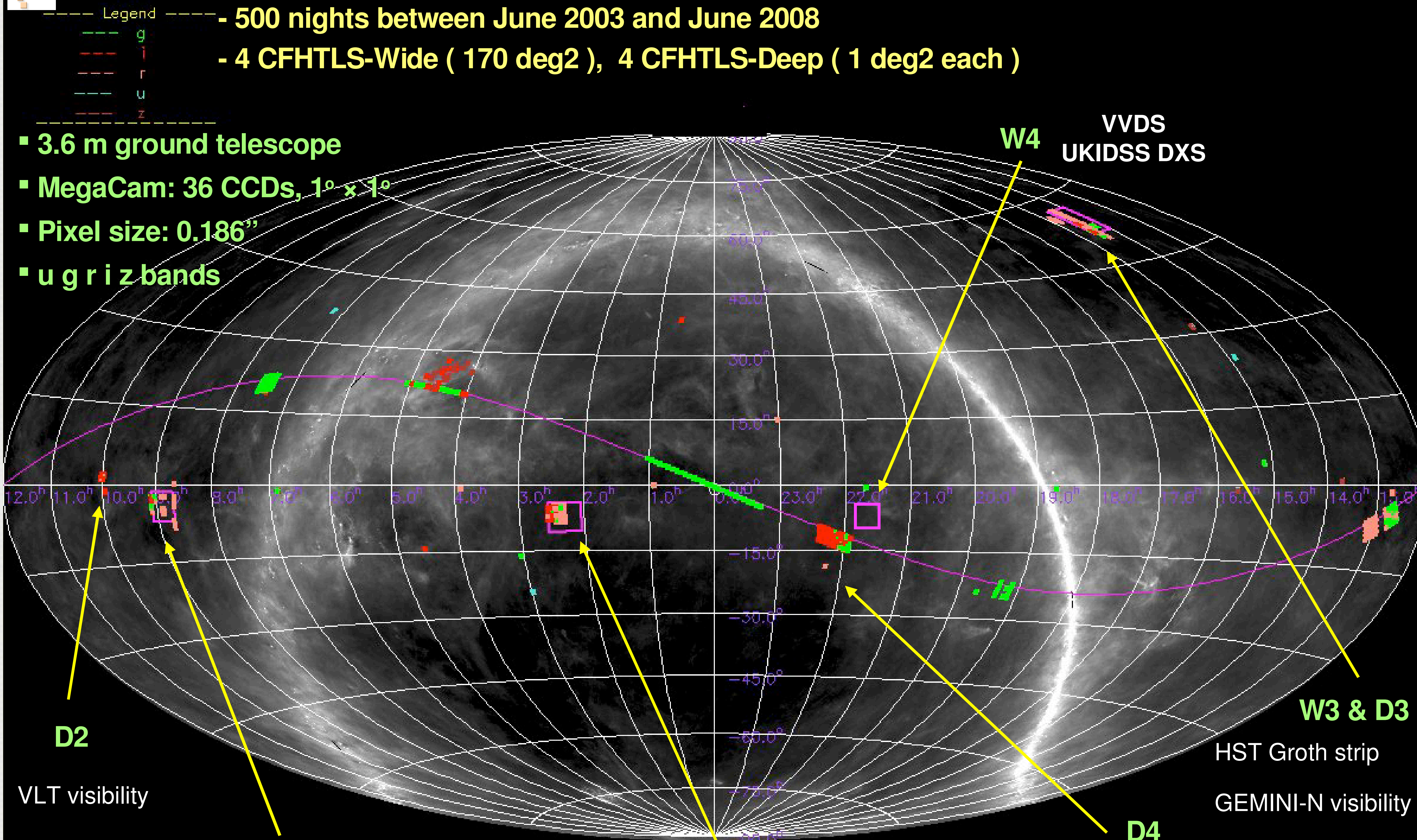




Canada-France-Hawaii Telescope Legacy Survey: Canada-France collaboration

- 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

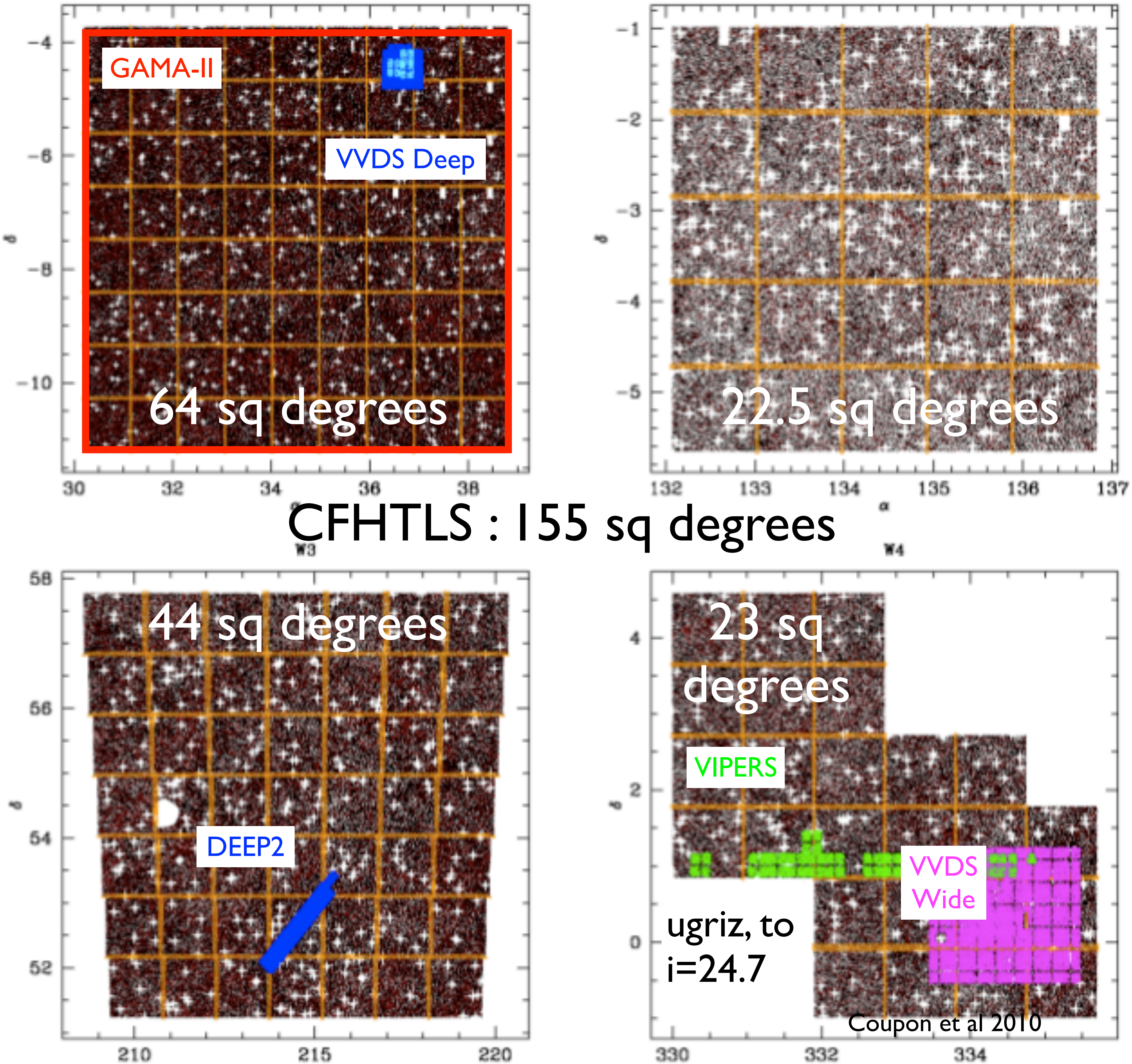
HST Groth strip

GEMINI-N visibility

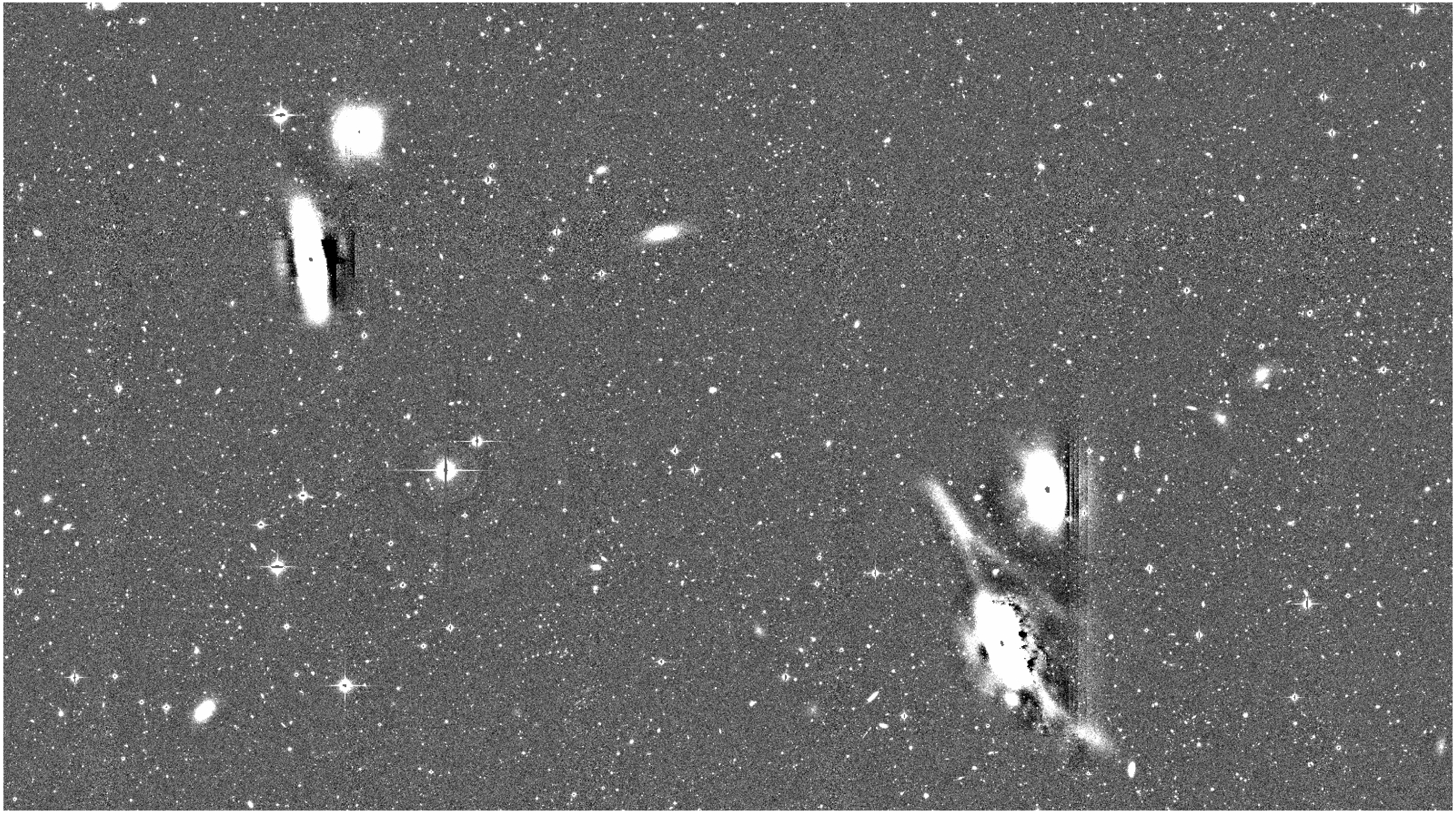
←command line : skywatcher

VVDS spectro. survey

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

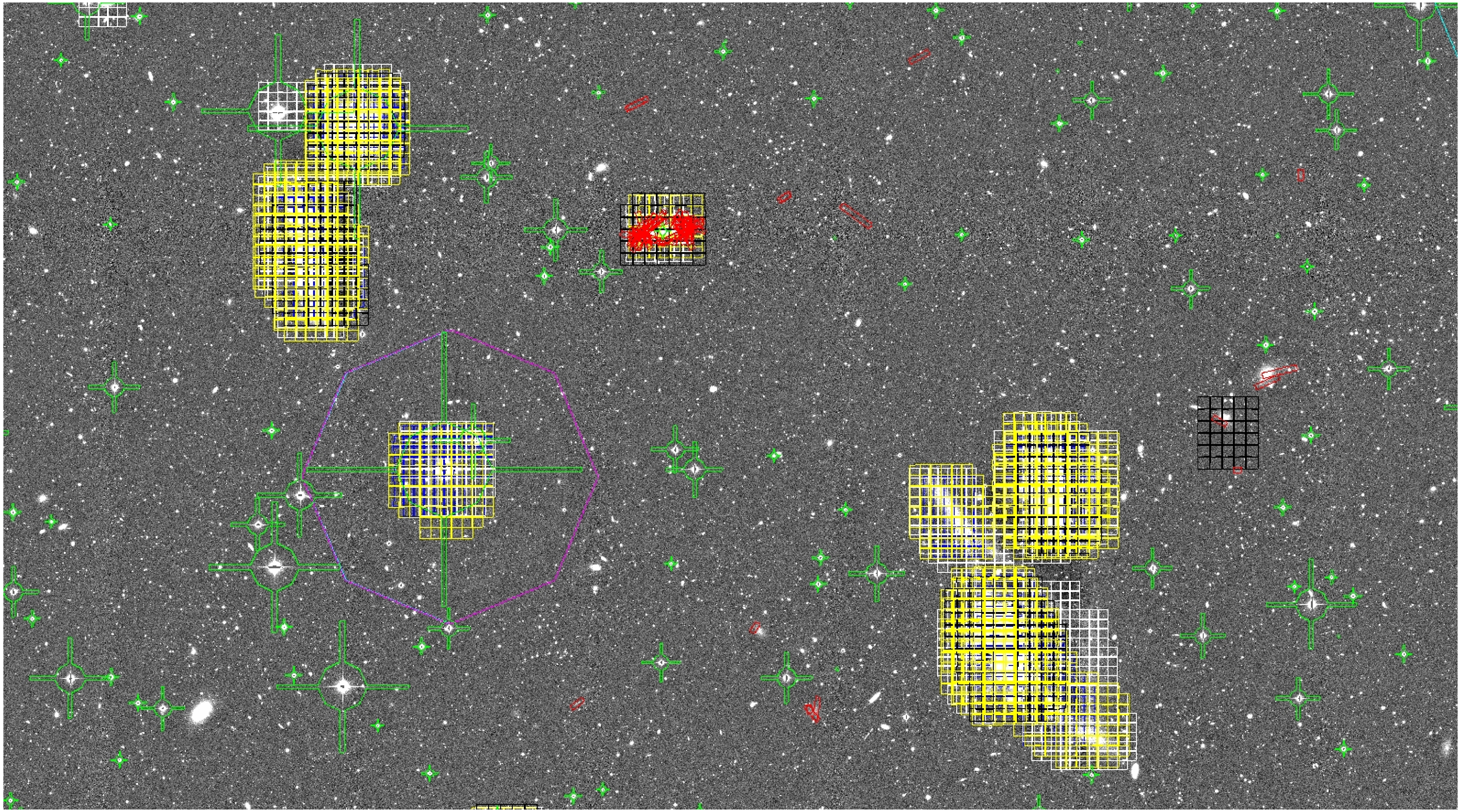

GAMA-II
VVDS Deep
64 sq degrees
22.5 sq degrees
CFHTLS : 155 sq degrees
44 sq degrees
DEEP2
23 sq
degrees
VIPERS
VVDS
Wide
ugriz, to
i=24.7
Coupon et al 2010

A MEGACAM@CFHT Image Section



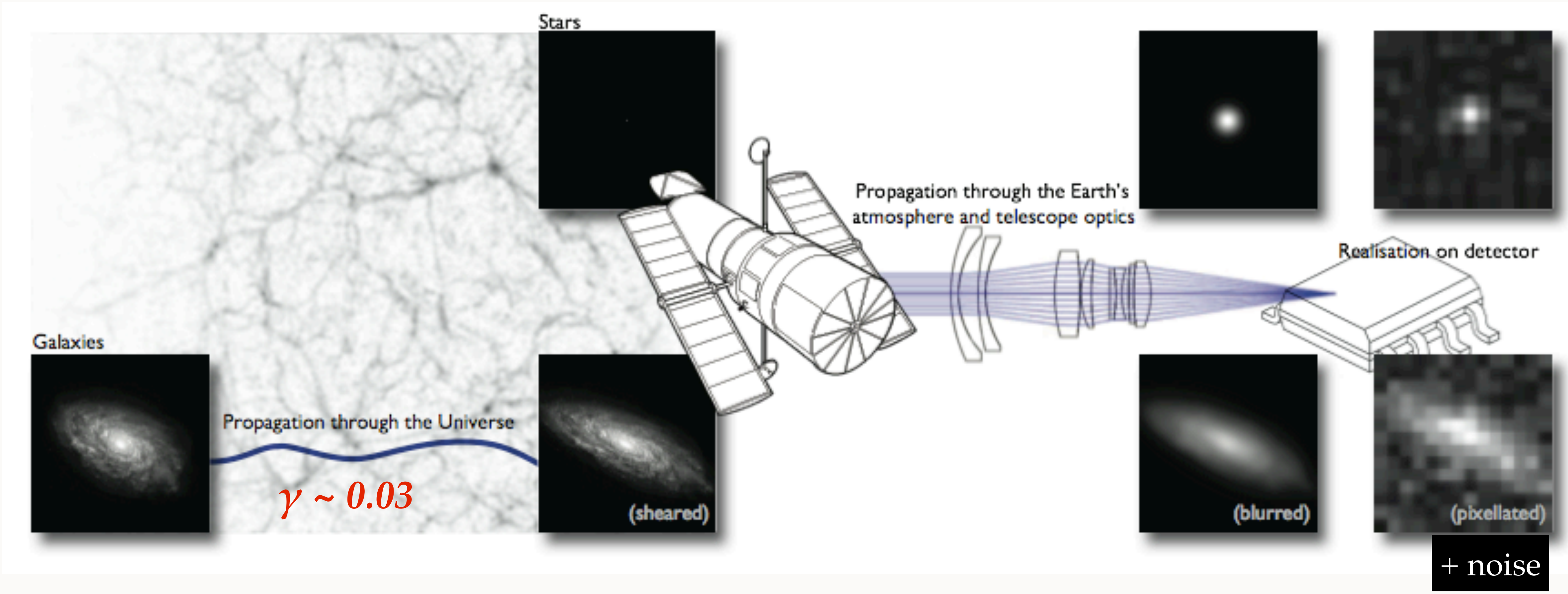
Regions around bright stars and big galaxies need to be excluded from our weak lensing studies.

Semi-Automatic Masking



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

SHAPE MEASUREMENT



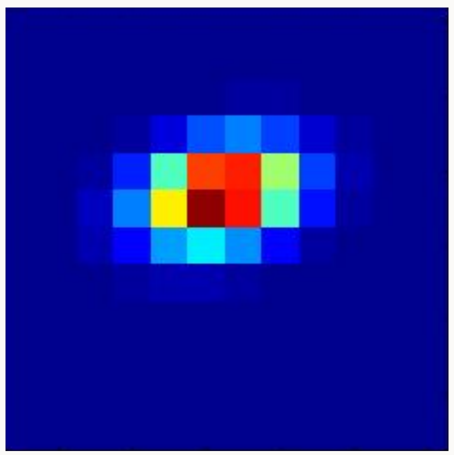
Bridle et al. 2008, great08 handbook

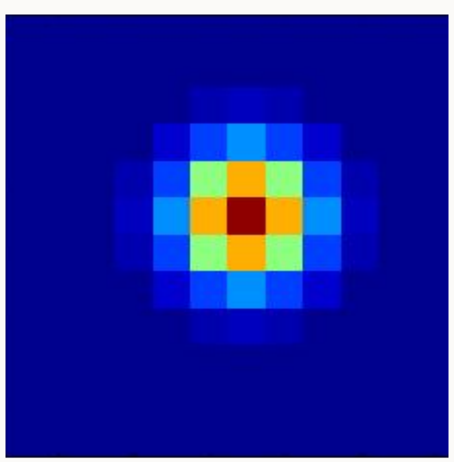
- Use stars to correct for instrumental and atmospheric distortions
- An individual galaxy shape cannot be well estimated, but need to measure the ensemble free from systematic bias

SHAPE MEASUREMENT: LENSFIT

[Miller et al 2007, Kitching et al 2008, Miller et al. 2012]

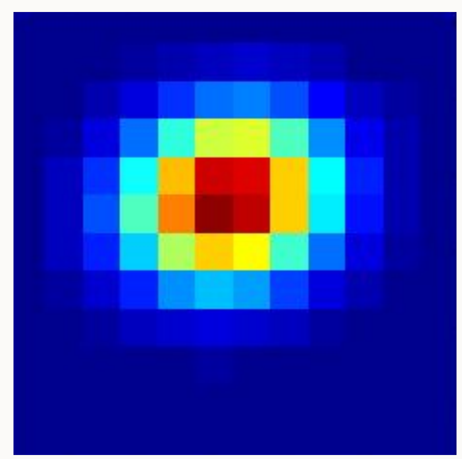
Model



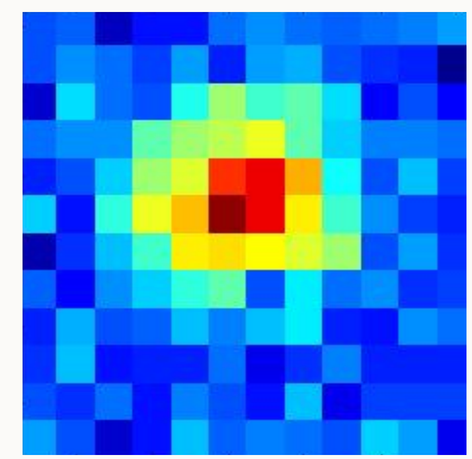


PSF
(Point Spread Function)

forward FFT,
multiply,
inverse FFT



Compare
data and
model to
maximise
likelihood



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

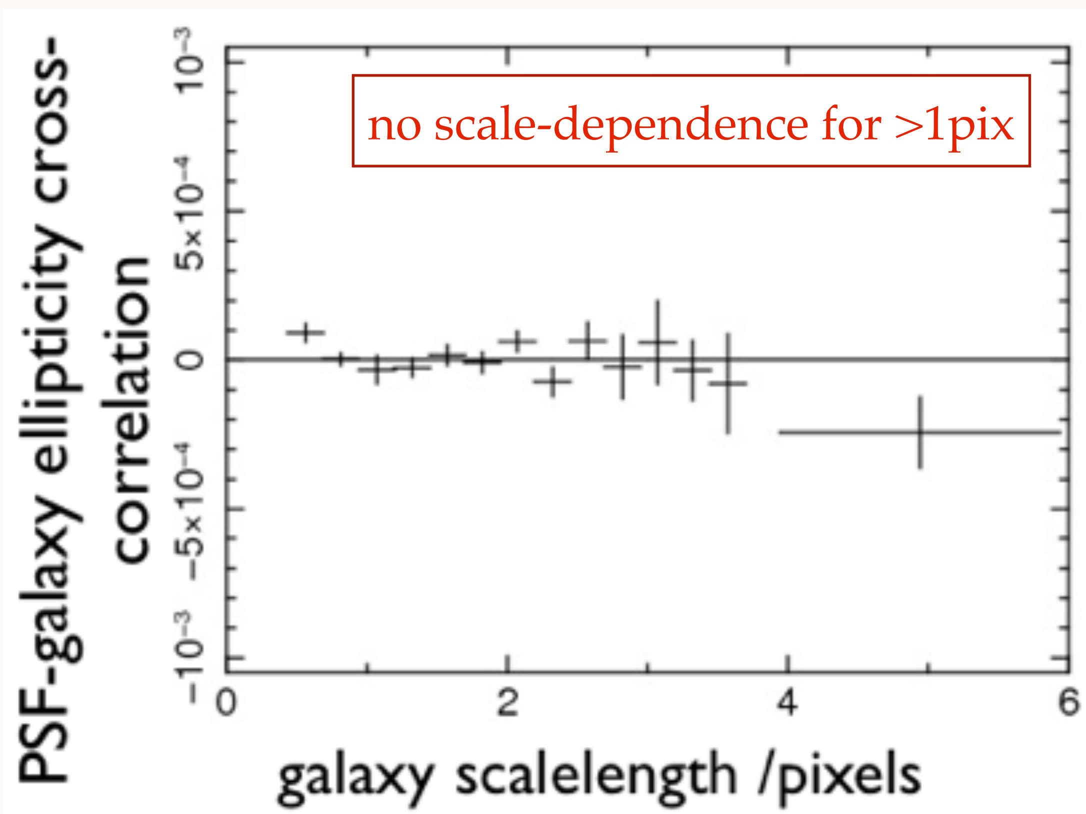
Avoids problems in co-added images.

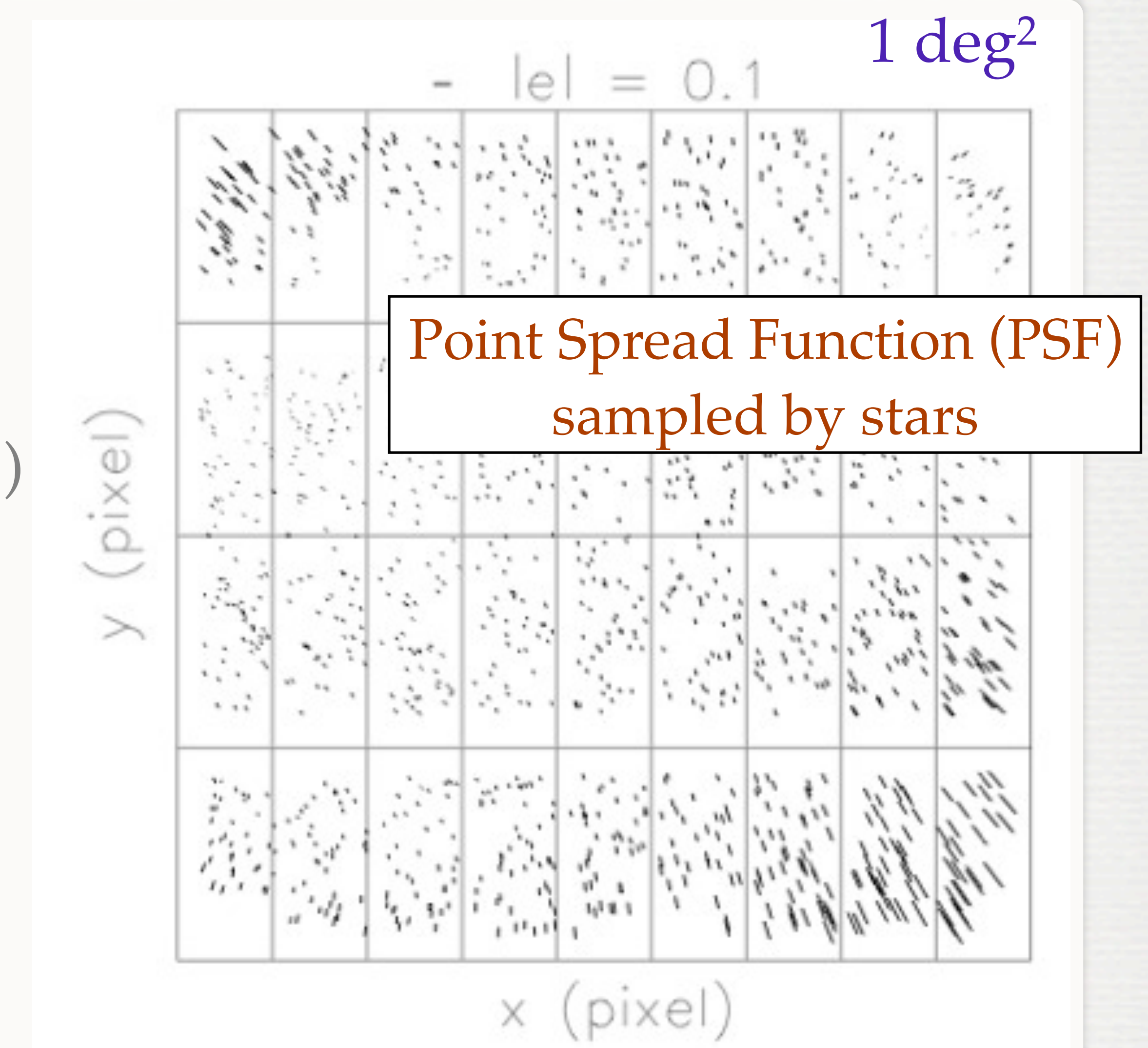
SHEAR MEASUREMENT: SYSTEMATICS (I)

- 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

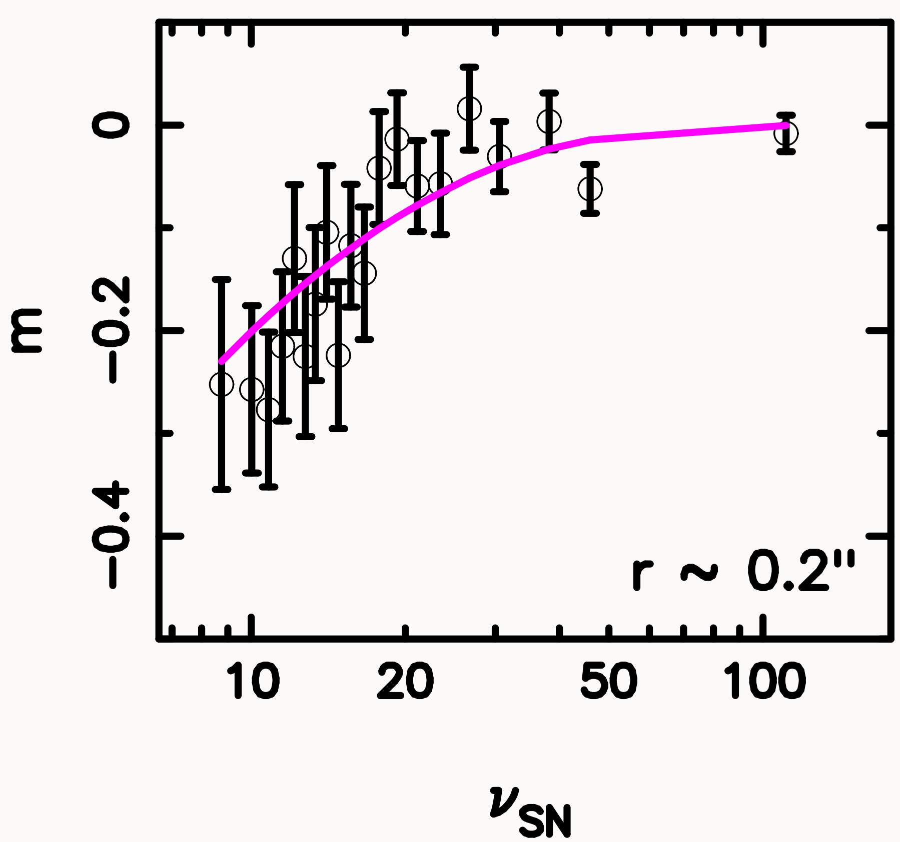
Thursday, December 13, 12

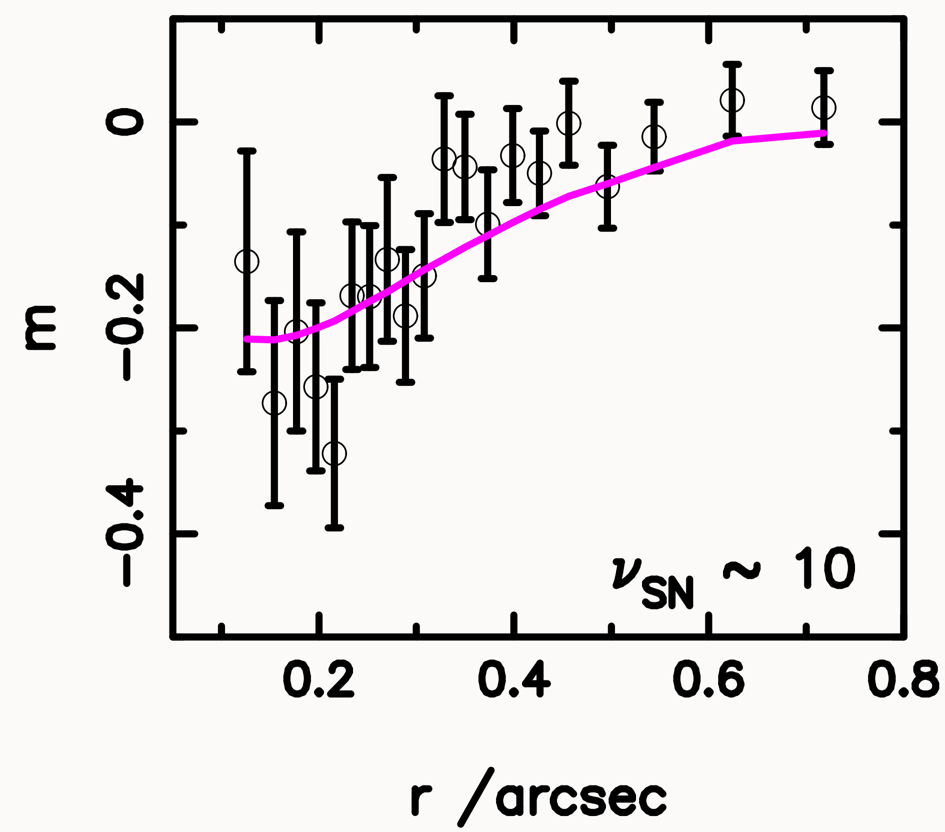
SHEAR MEASUREMENT: SYSTEMATICS (II)

Multiplicative and additive bias:

$$\gamma_{\rm measured} = (1+m)\gamma_{\rm true} + c$$

m depends on SN and galaxy size





[Miller et al. 2012]

SHEAR MEASUREMENT: SYSTEMATICS (II)

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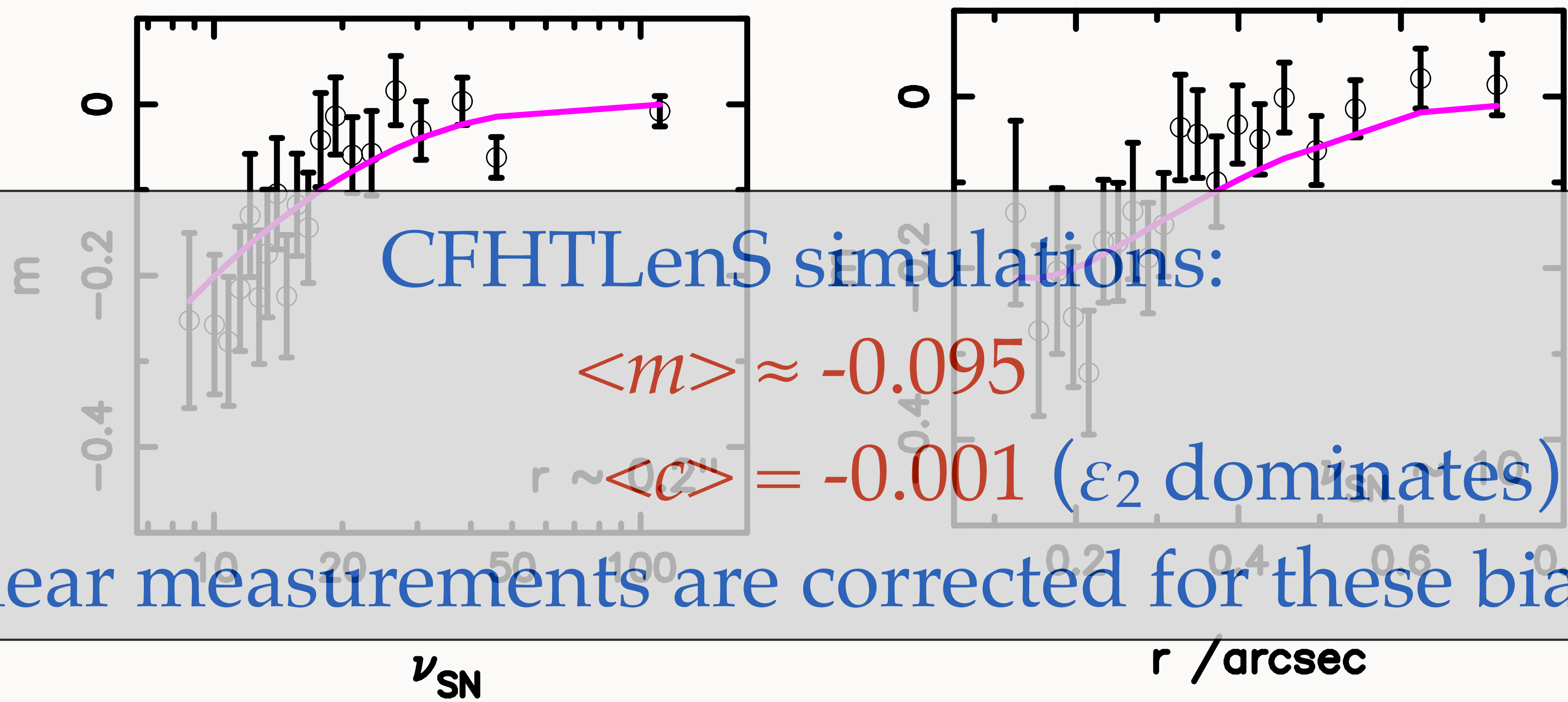


[Miller et al. 2012]

CFHTLenS simulations:

$\langle m \rangle \approx -0.095$

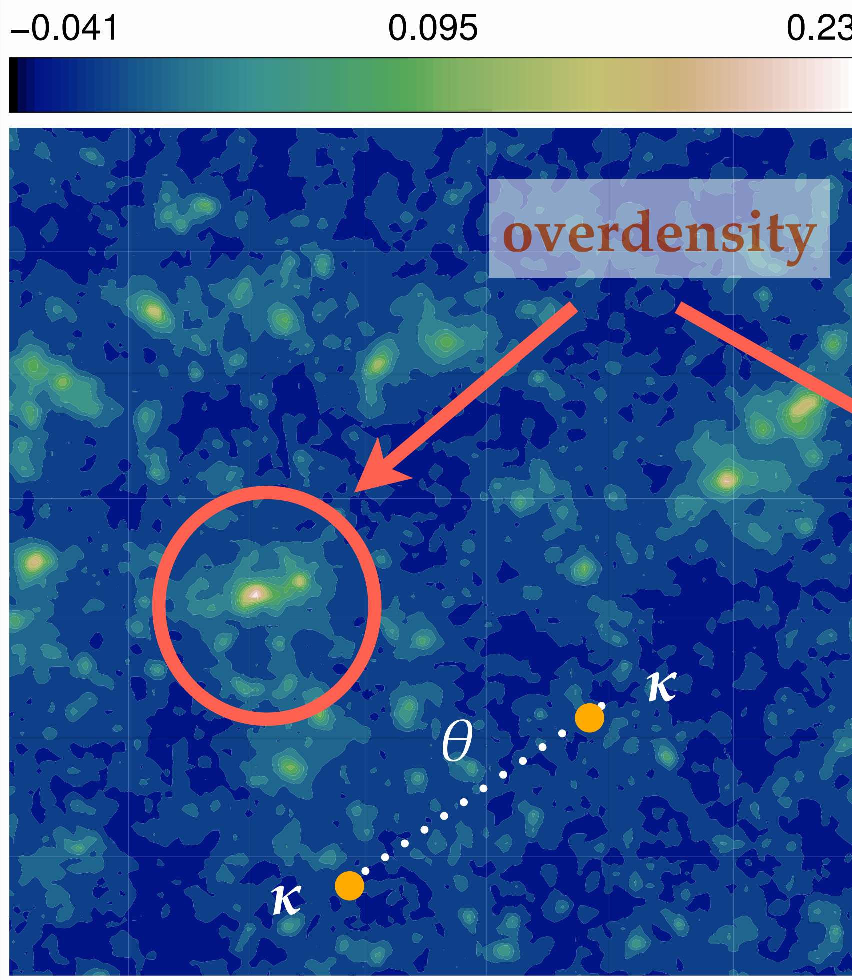
$\langle c \rangle = -0.001$ (ε_2 dominates)

Shear measurements are corrected for these biases

MASS AND SHEAR

Projected matter density

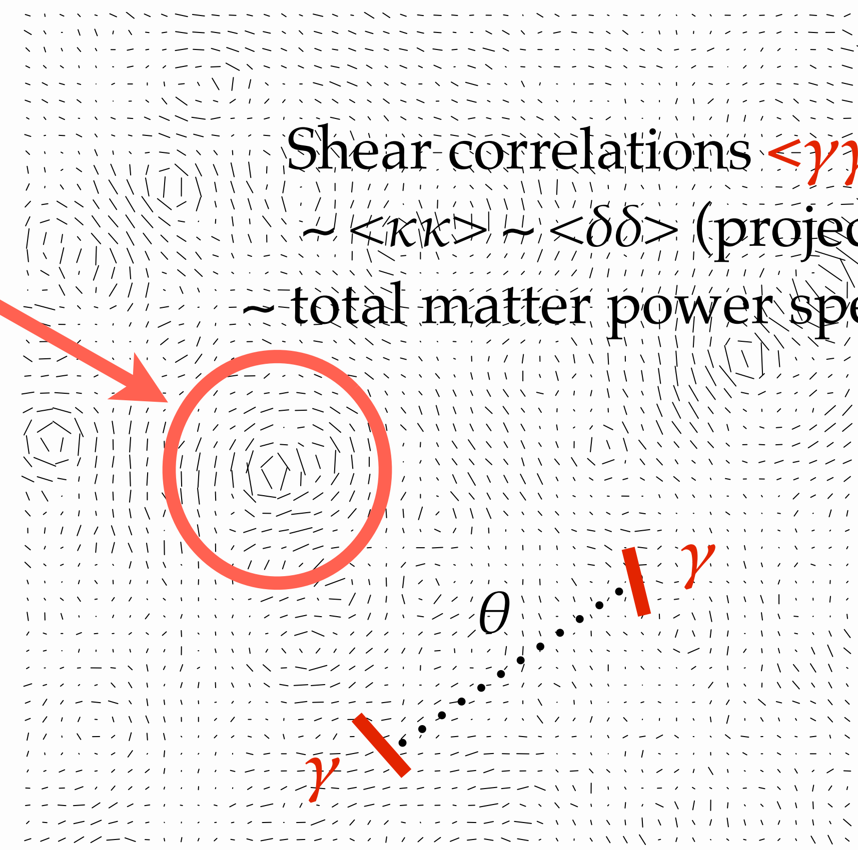
convergence κ



Distortion field

shear γ

tangential distortions around mass peaks



Shear correlations $<\gamma\gamma>(\theta)$

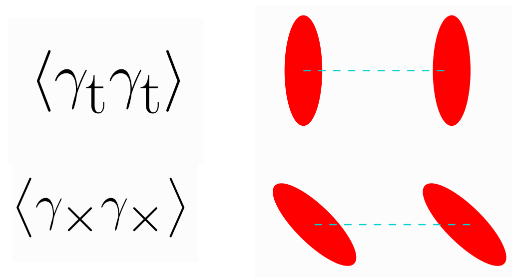
~ $<\kappa\kappa>$ ~ $<\delta\delta>$ (projected)

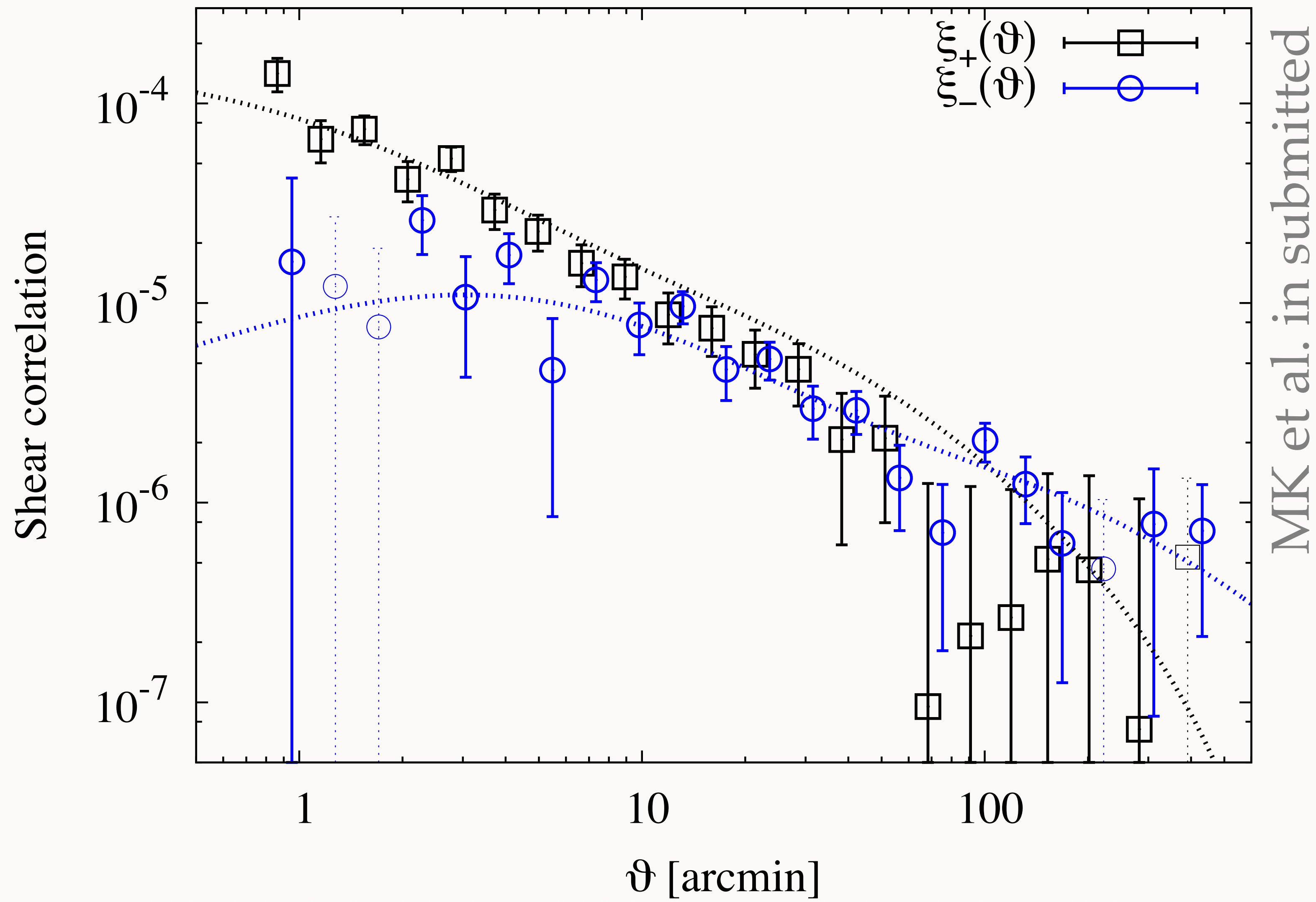
~ total matter power spectrum

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

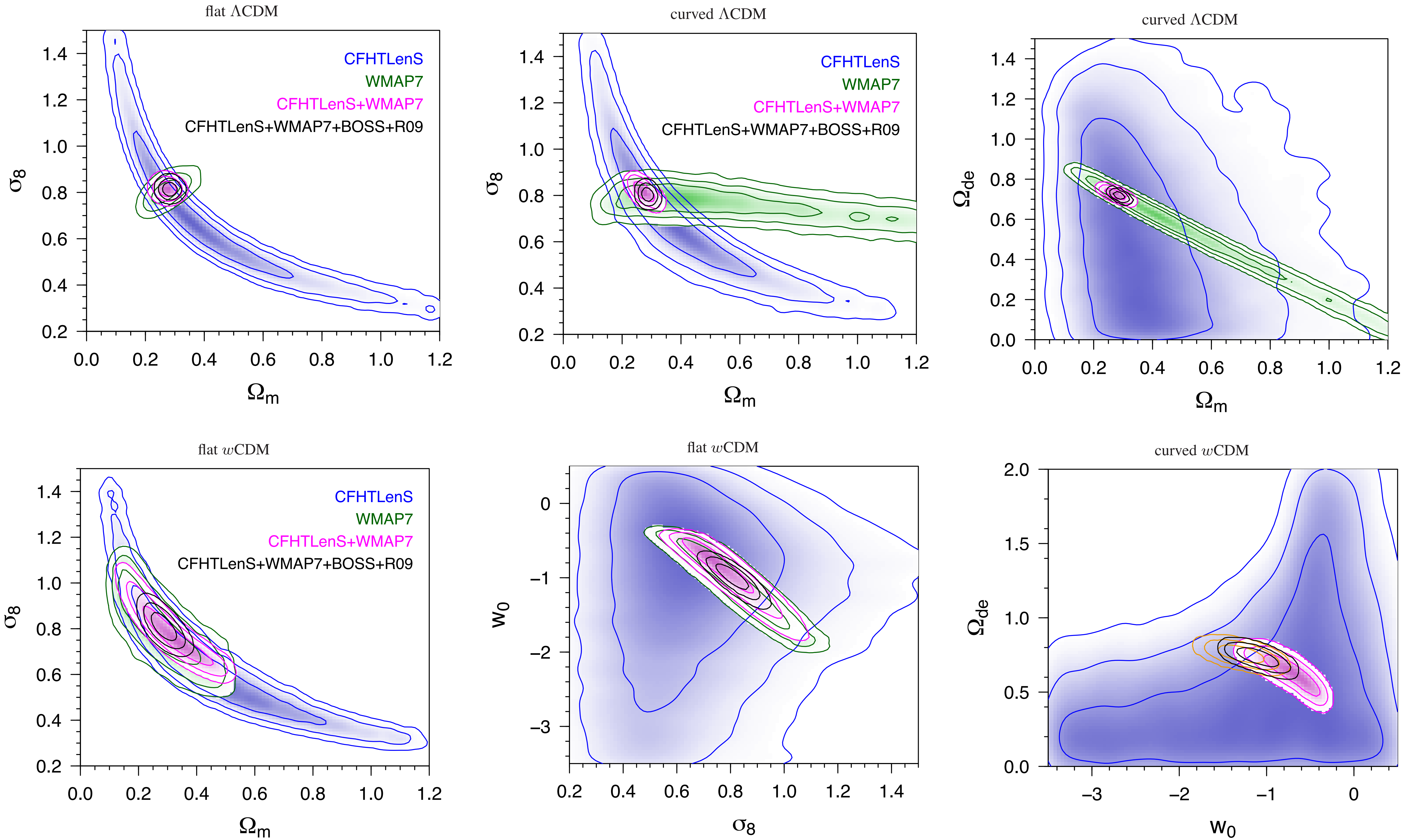
SHEAR CORRELATION

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



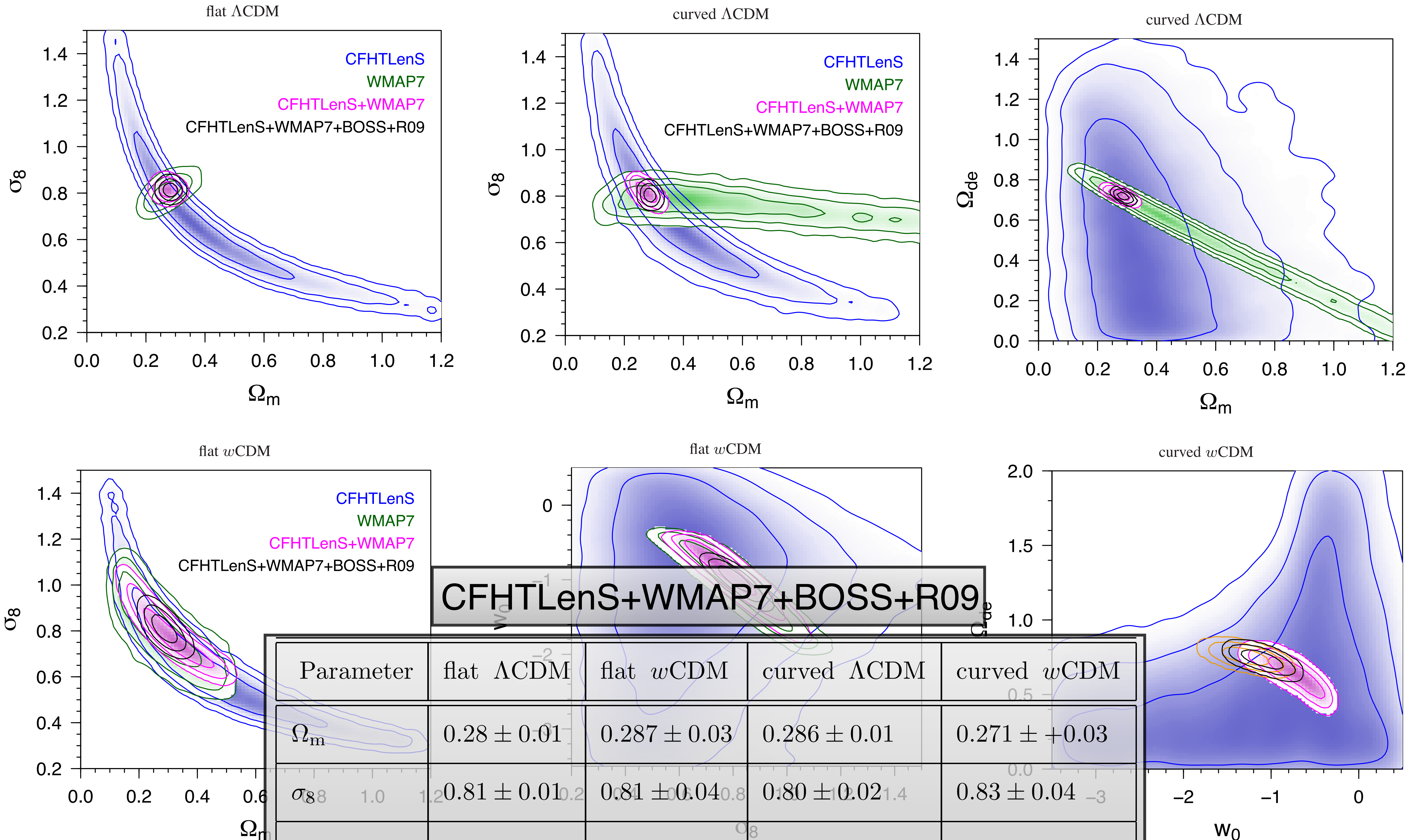


Prediction
(WMAP7 cosmology):
Flat Universe
$\Omega_m = 0.27$
$\sigma_8 = 0.8$
$w = -1$
Smith et al. (2003)
non-linear power spectrum



MK et al. in submitted

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	$-0.006^{+0.006}_{-0.005}$

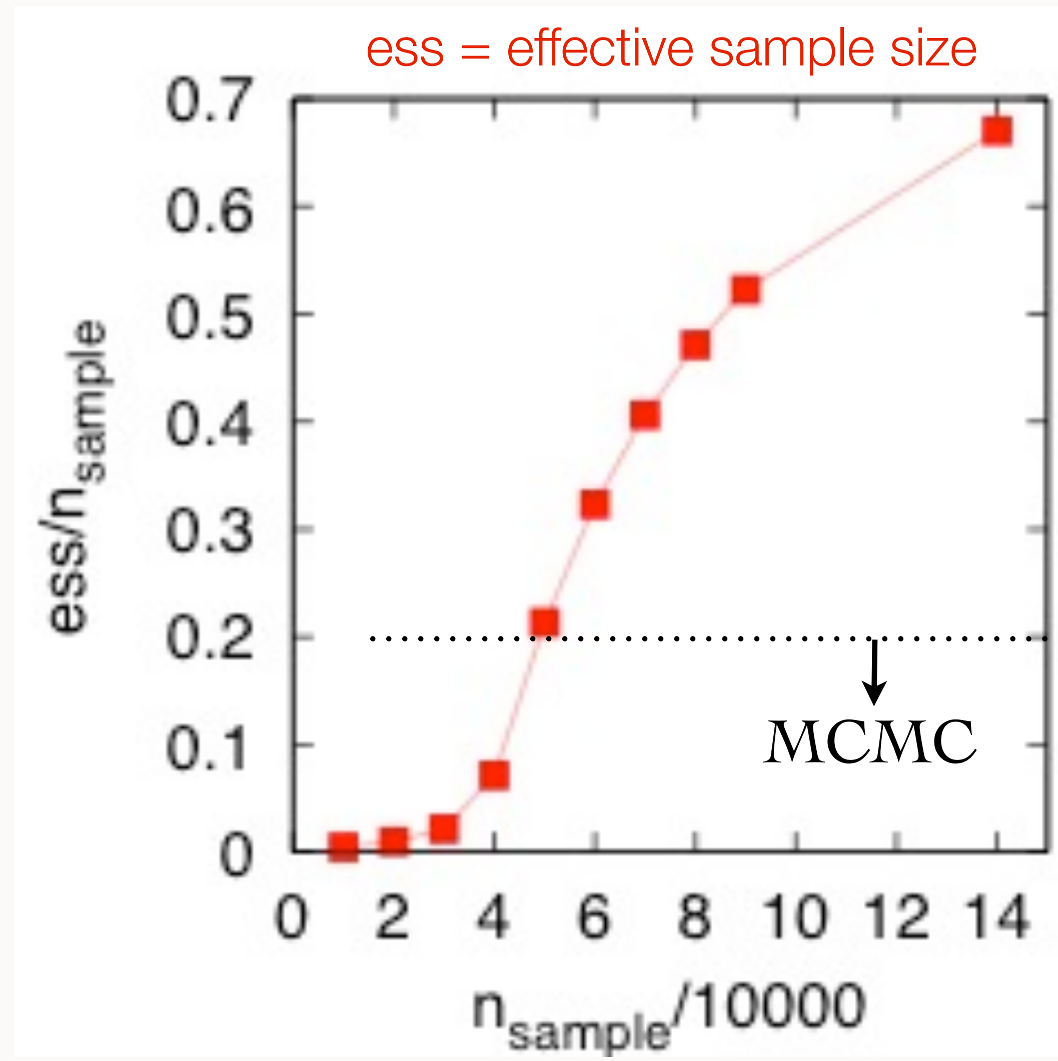
2d cosmic shear, no tomography

SAMPLING: POPULATION MONTE CARLO (PMC)

WMAP5 posterior, flat ΛCDM model, 6 parameters

- Exploring high-dimensional parameter space:
  Population Monte Carlo (PMC): Alternative to MCMC

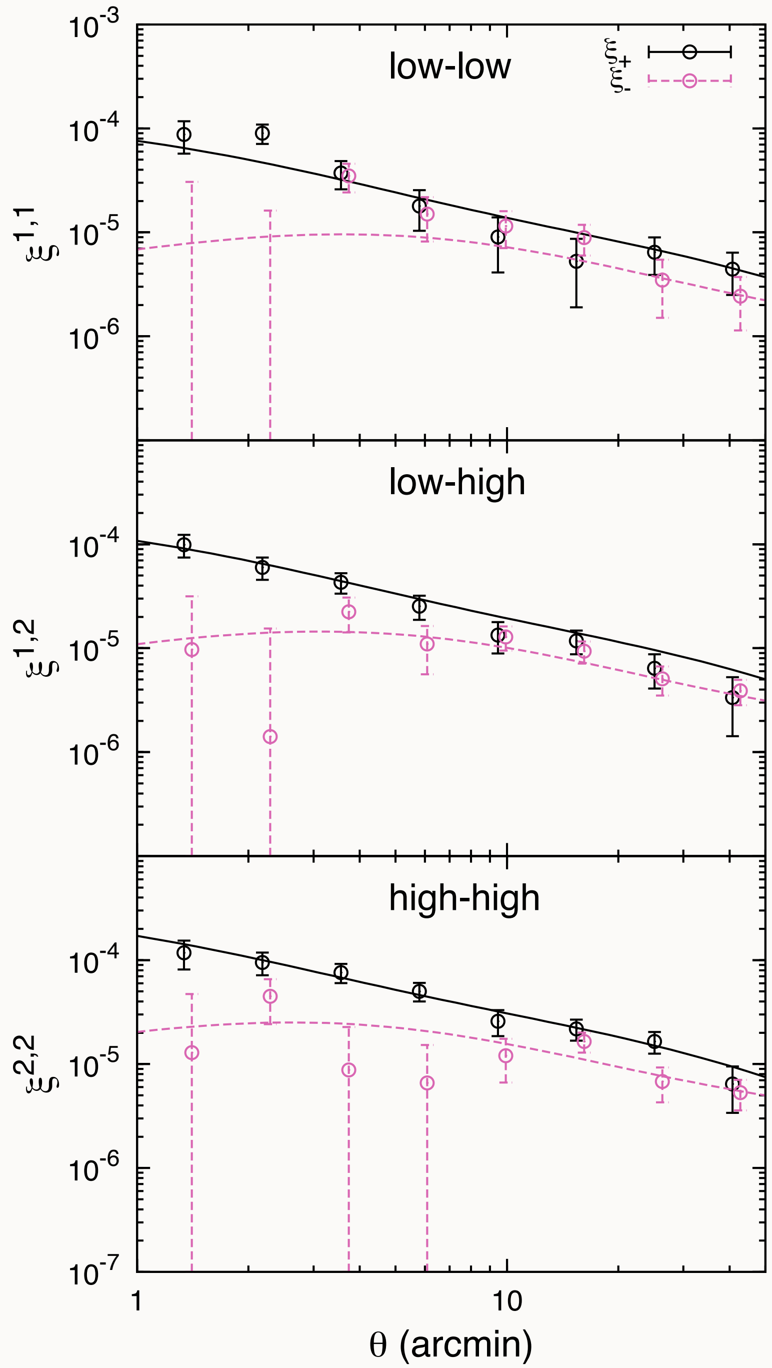
- PMC sample engine and cosmology
  modules, public code,
  www.cosmopmc.info,
  [Kilbinger et al. 2010, arXiv: 1101.0950]

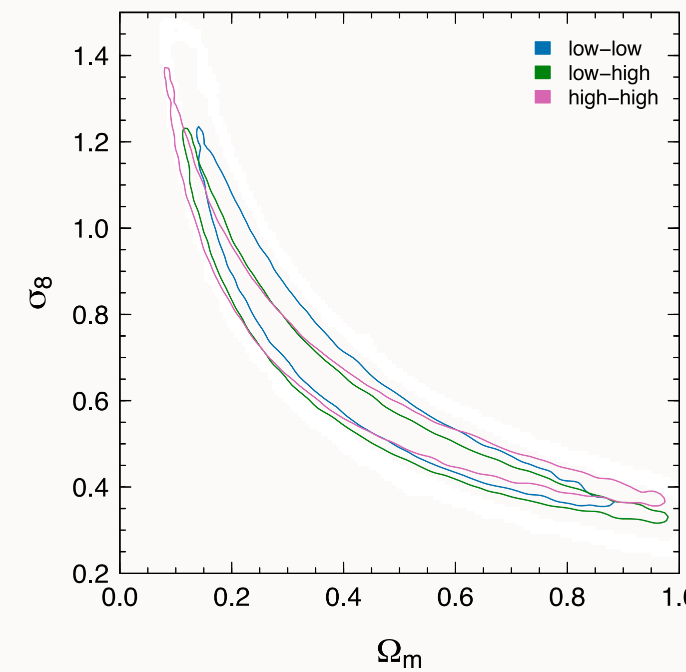


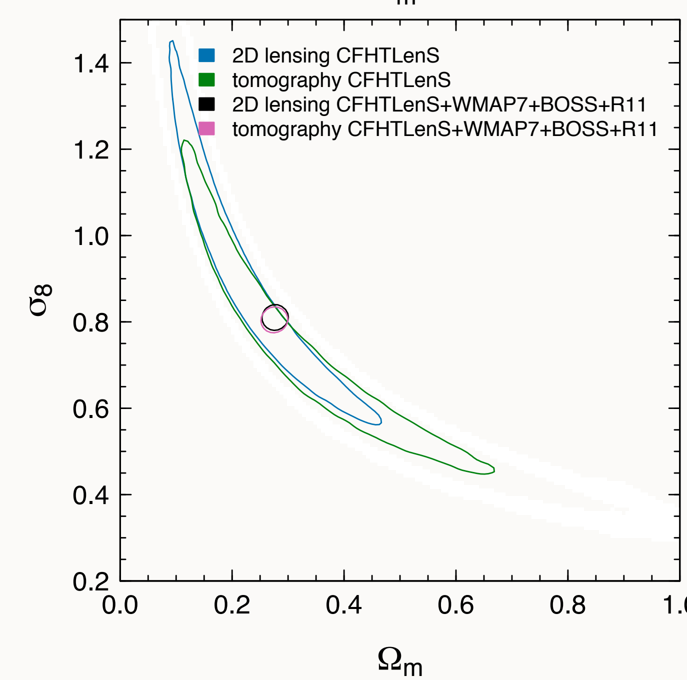
[Wraith, MK et al. (2009)]

LENSING TOMOGRAPHY

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

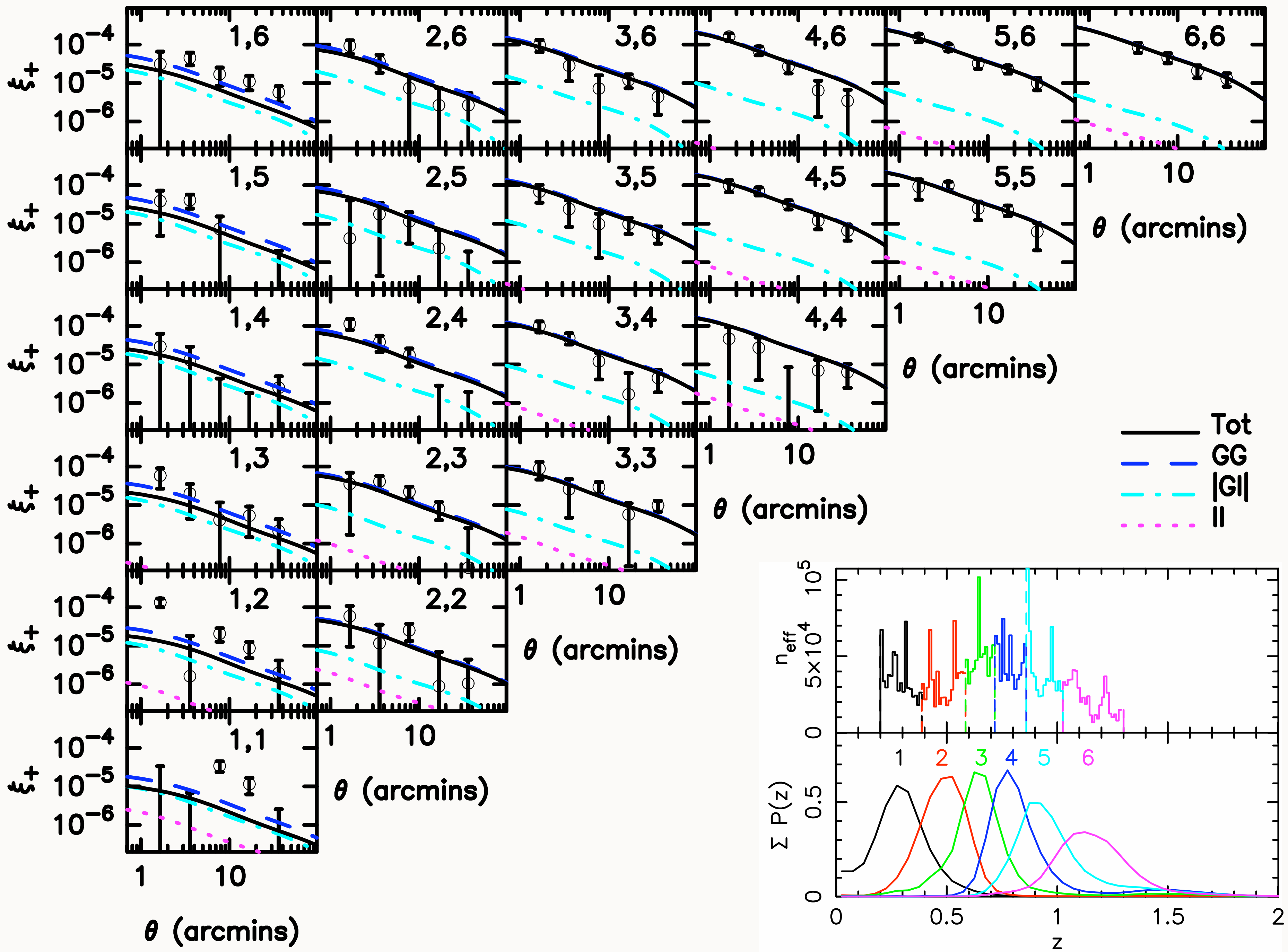






Benjamin et al. in prep.

LENSING TOMOGRAPHY

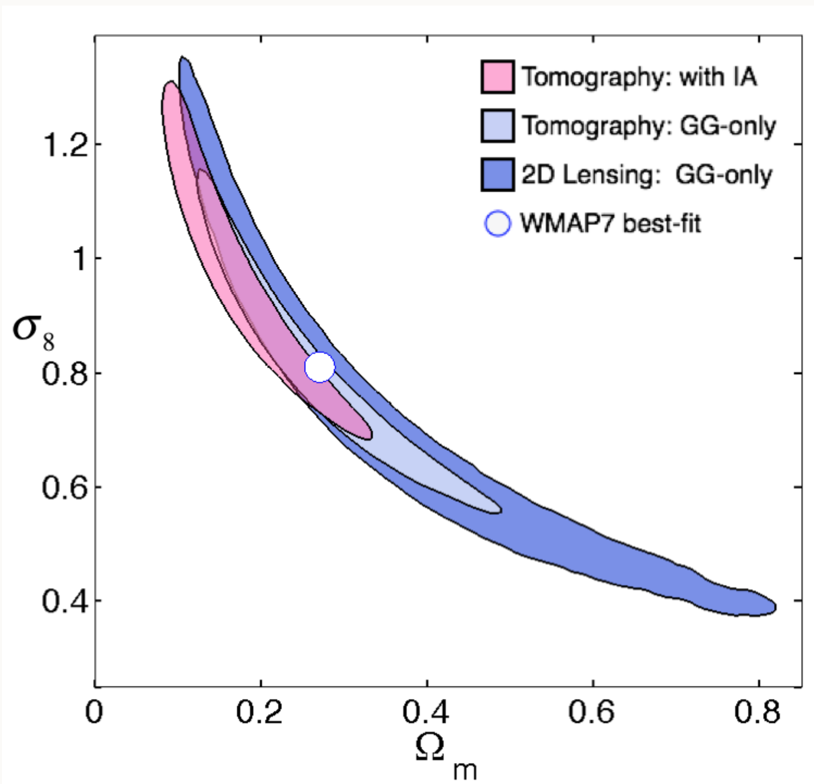


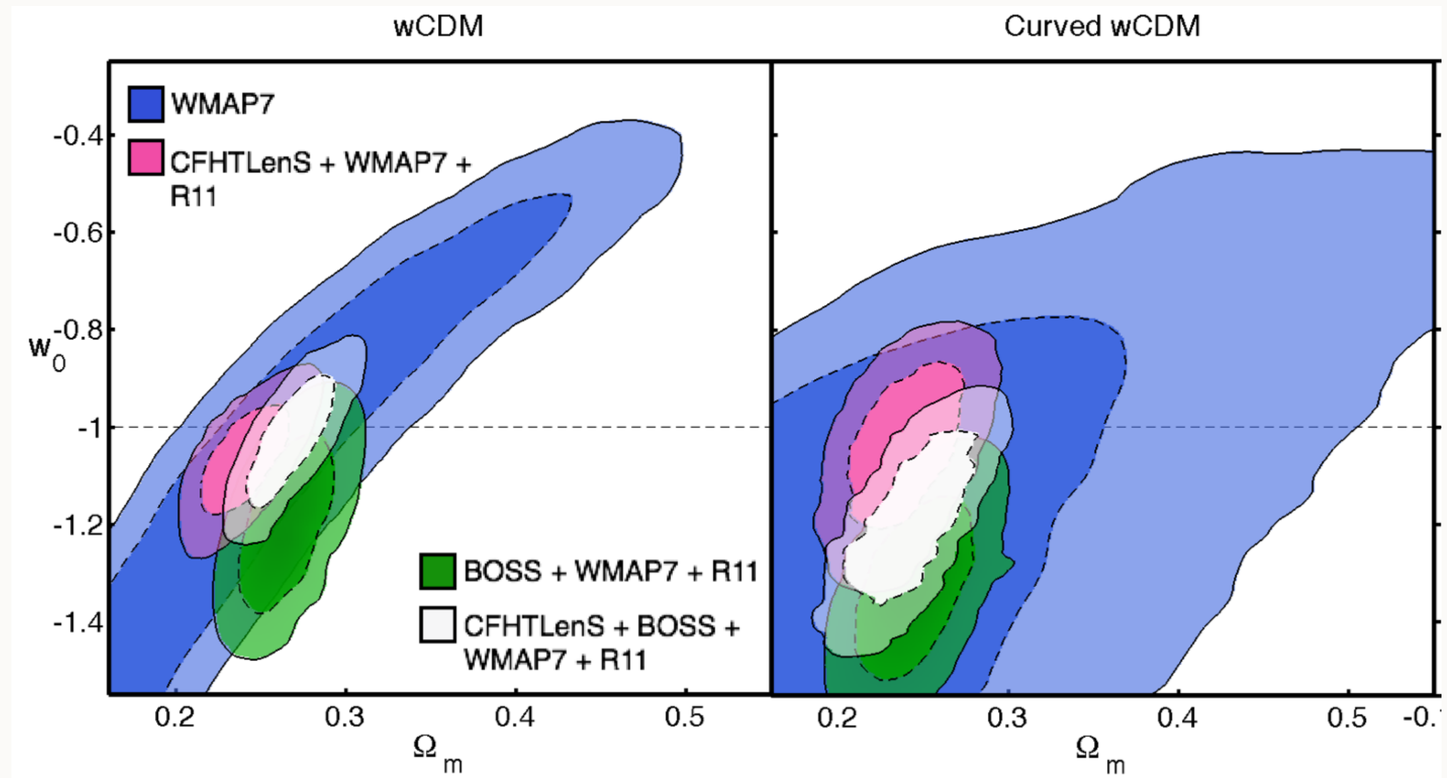
Bin	$z_{\rm BPZ}$	$z_{\rm m}$	$\bar{z}$
1	0.20 – 0.39	0.28	0.36
2	0.39 – 0.58	0.48	0.50
3	0.58 – 0.72	0.62	0.68
4	0.72 – 0.86	0.82	0.87
5	0.86 – 1.02	0.93	1.00
6	1.02 – 1.30	1.12	1.16

Heymans et al. in prep.

LENSING TOMOGRAPHY

Heymans et al. in prep.





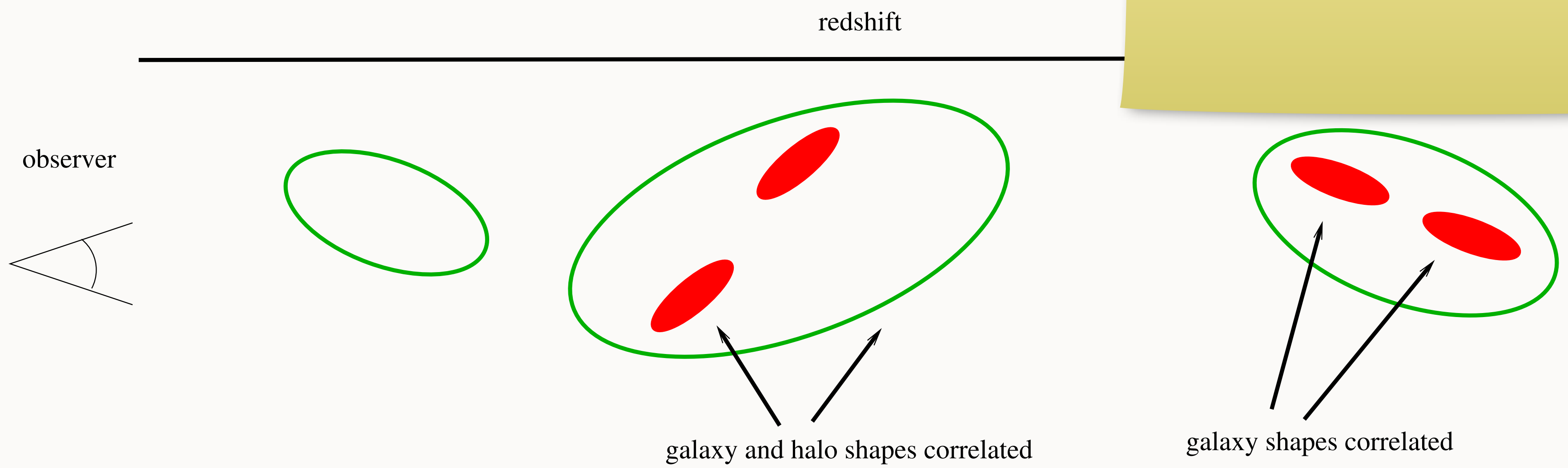
Tomography helps lifting the Ω_m - σ_8 degeneracy of 2D lensing.

CFHTLenS + WMAP7 + R11 + BOSS

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

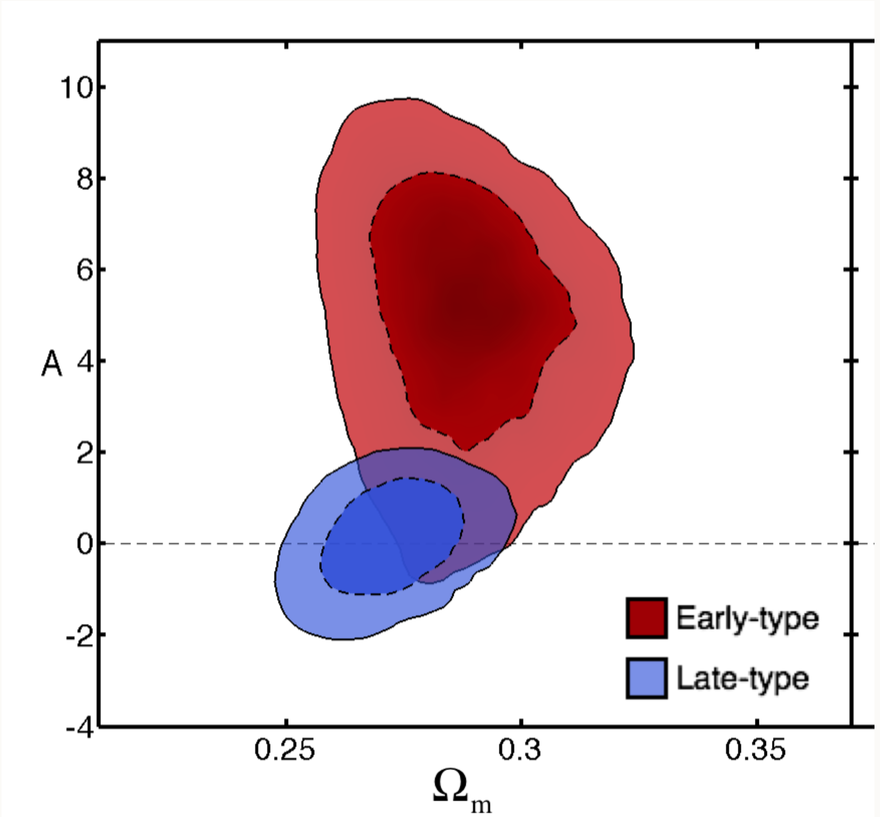
INTRINSIC ALIG

optimized: use all galaxies in background bins, not just early-type. All are dominated by late-type, whose II contribution is low (late-type have low IA + only in n(z) overlap region between bins)



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

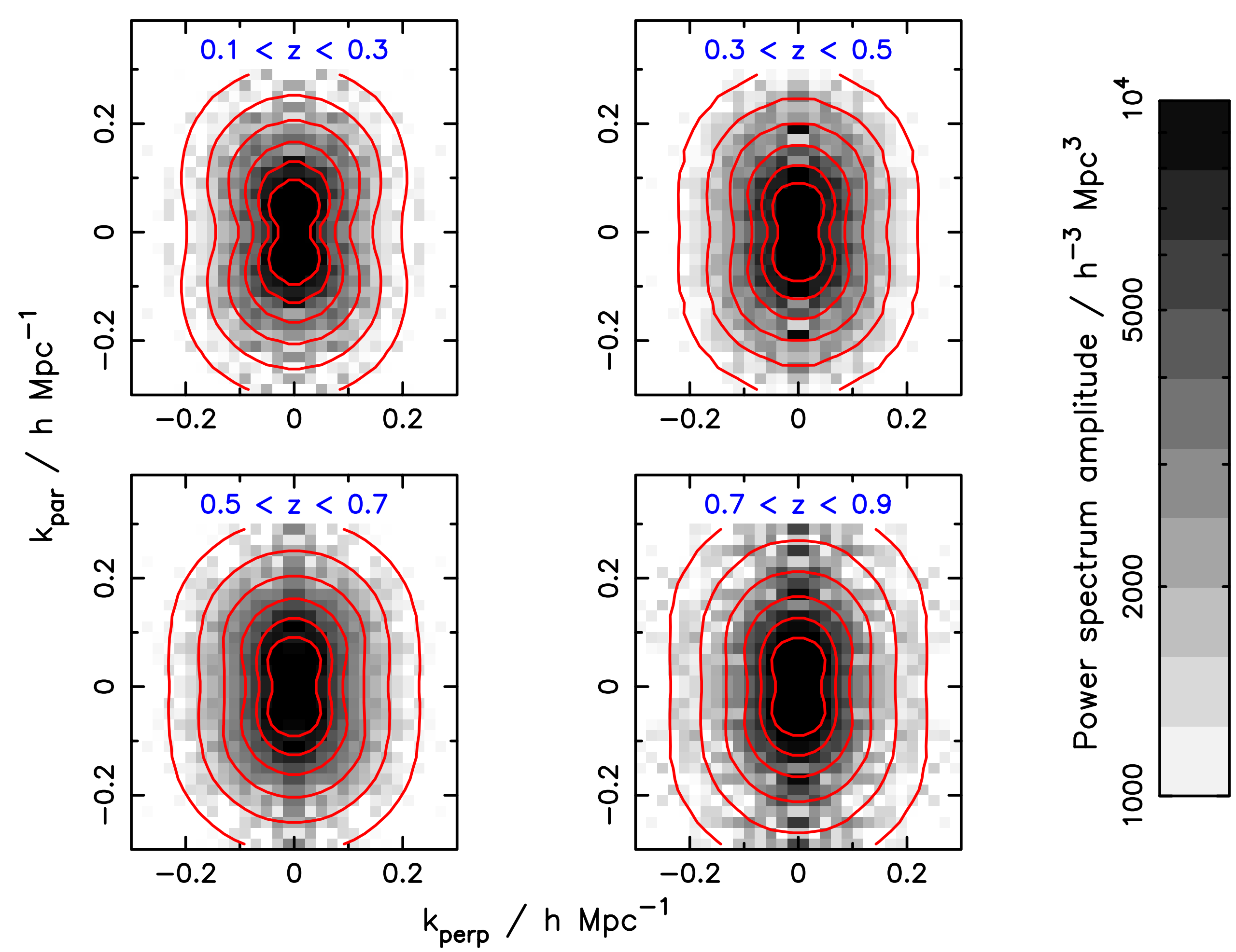
One free amplitude parameter *A*, fixed *z*-dependence.



Heymans et al. in prep.

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

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

ETRISATION

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

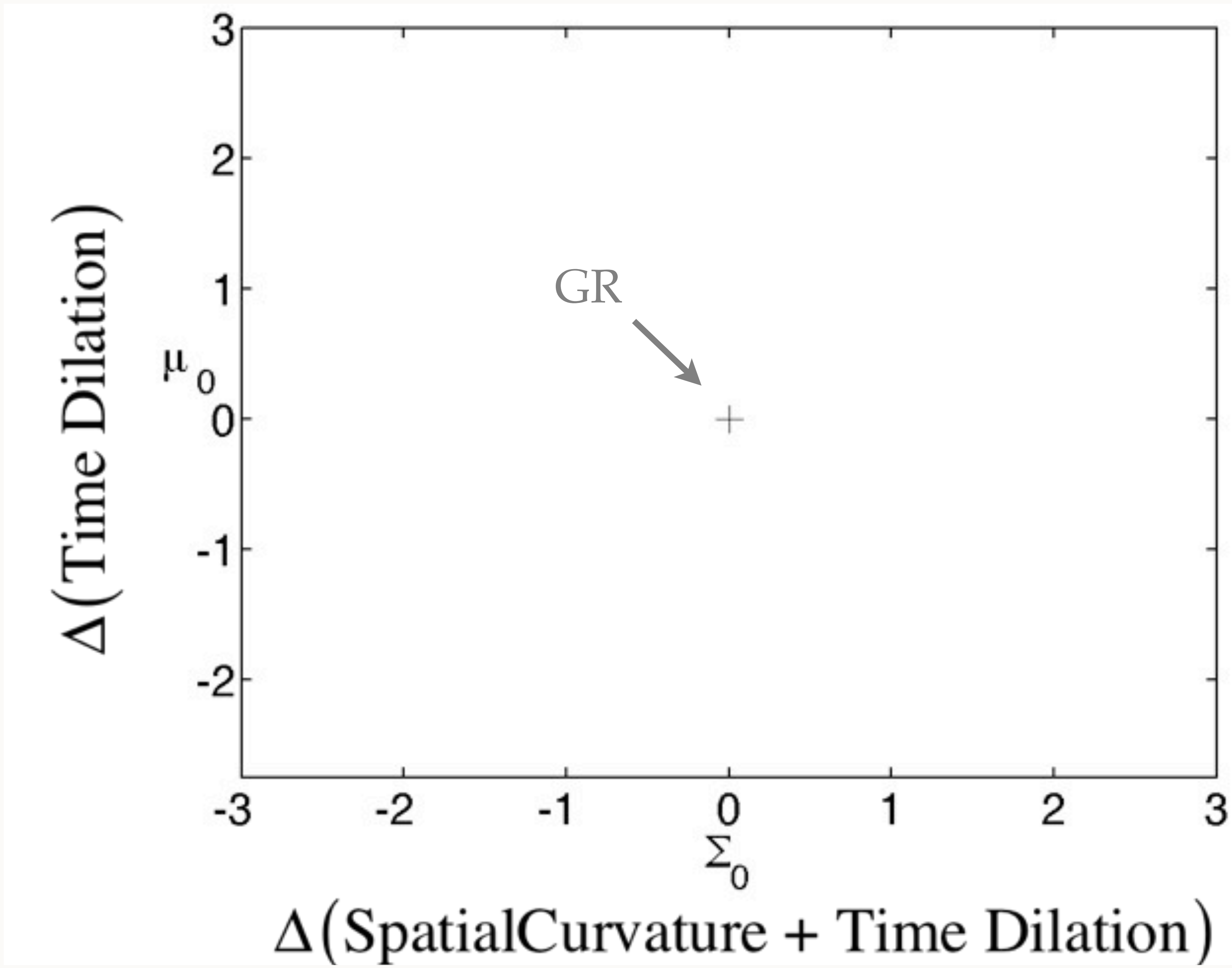
- Gravitational potential as experienced by galaxies:

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

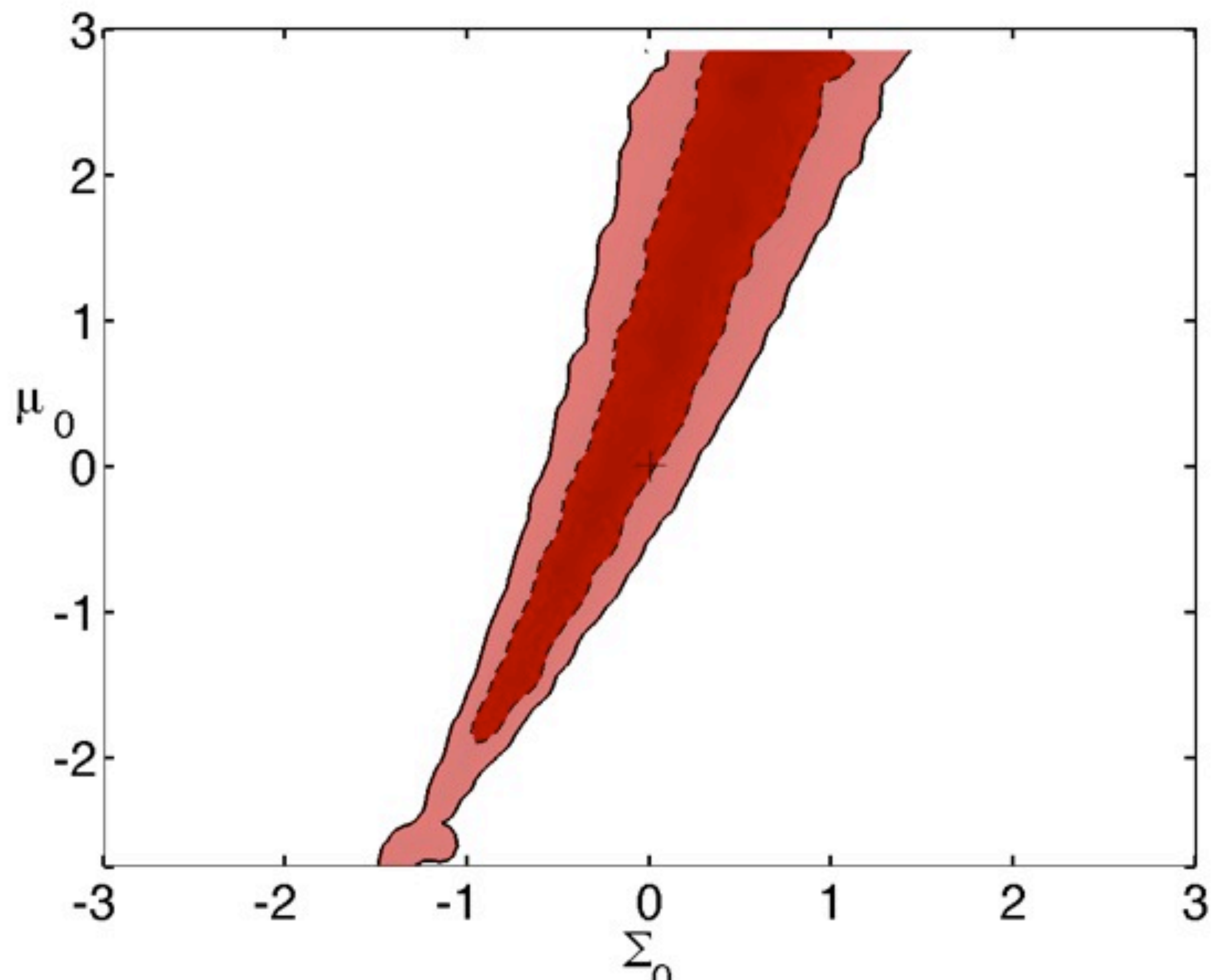
- Gravitational potential as experienced by photons:

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

PARAMETRISATION



PREVIOUS CONSTRAINTS

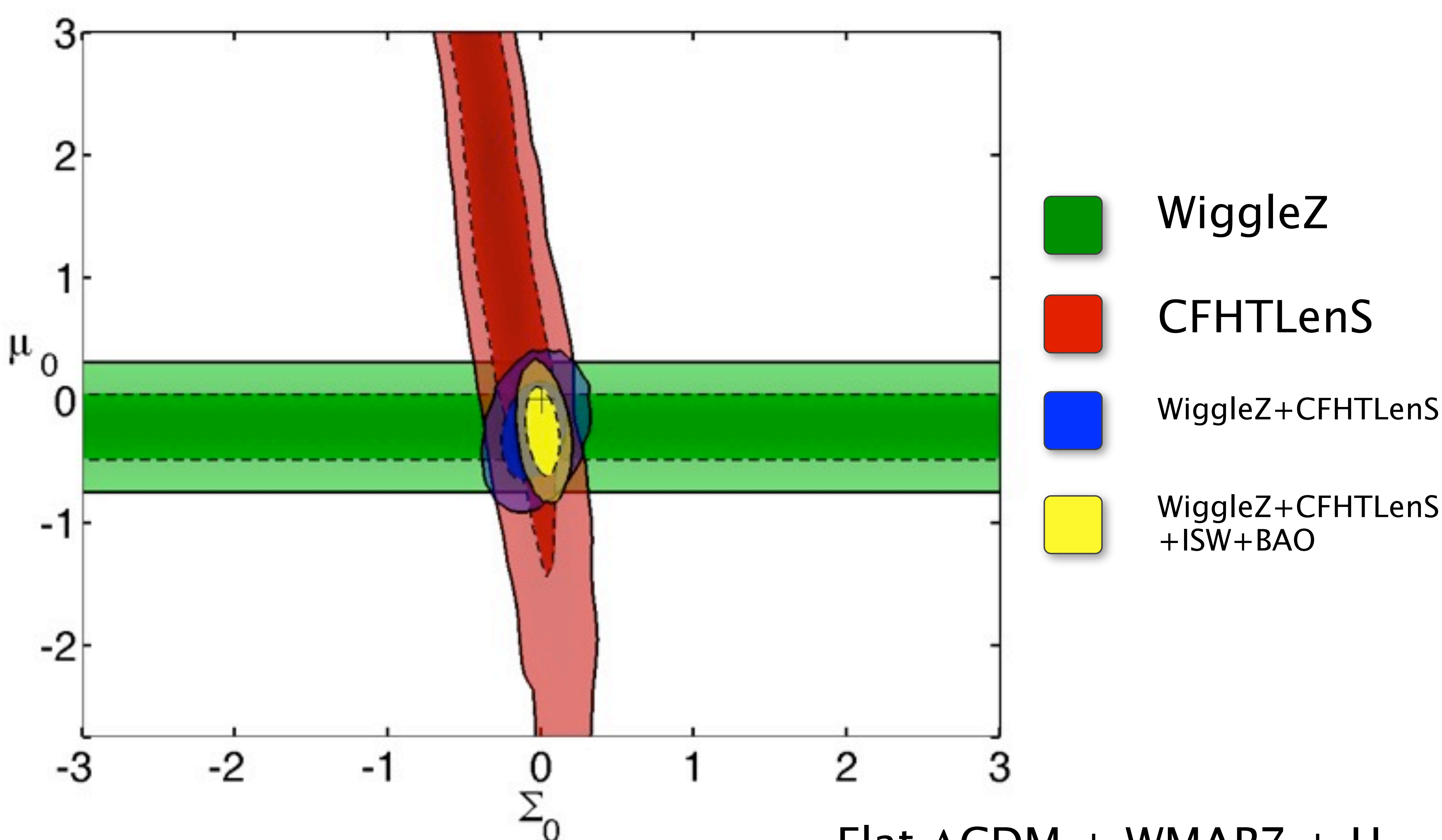


E_G (Reyes et al 2010) + BAO (Percival et al 2010)

Flat ΛCDM

CFHTLENS CONSTRAINTS

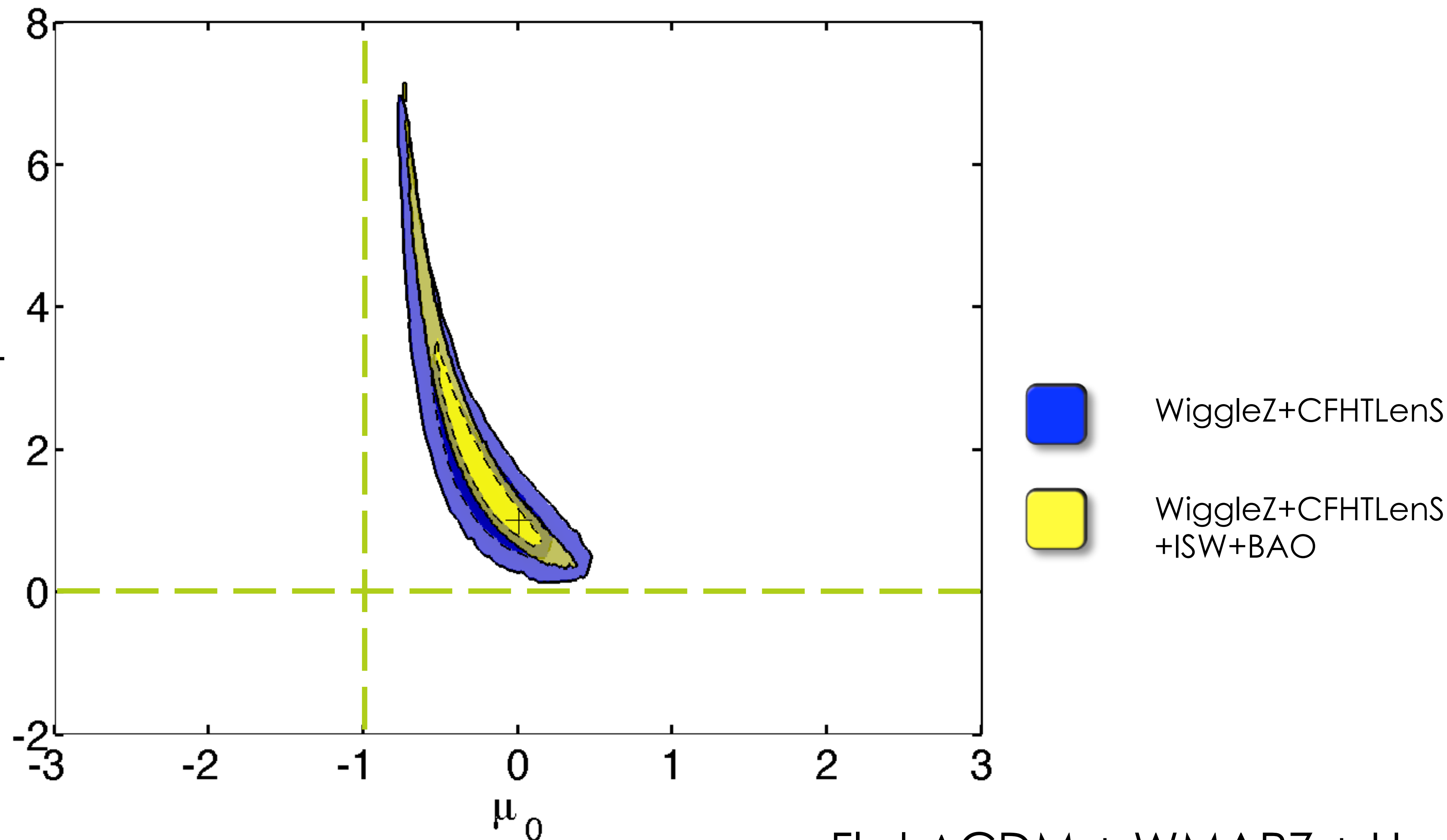
Simpson et al. submitted



Flat ΛCDM + WMAP7 + H_0

GRAVITATIONAL SLIP

Simpson et al. submitted



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

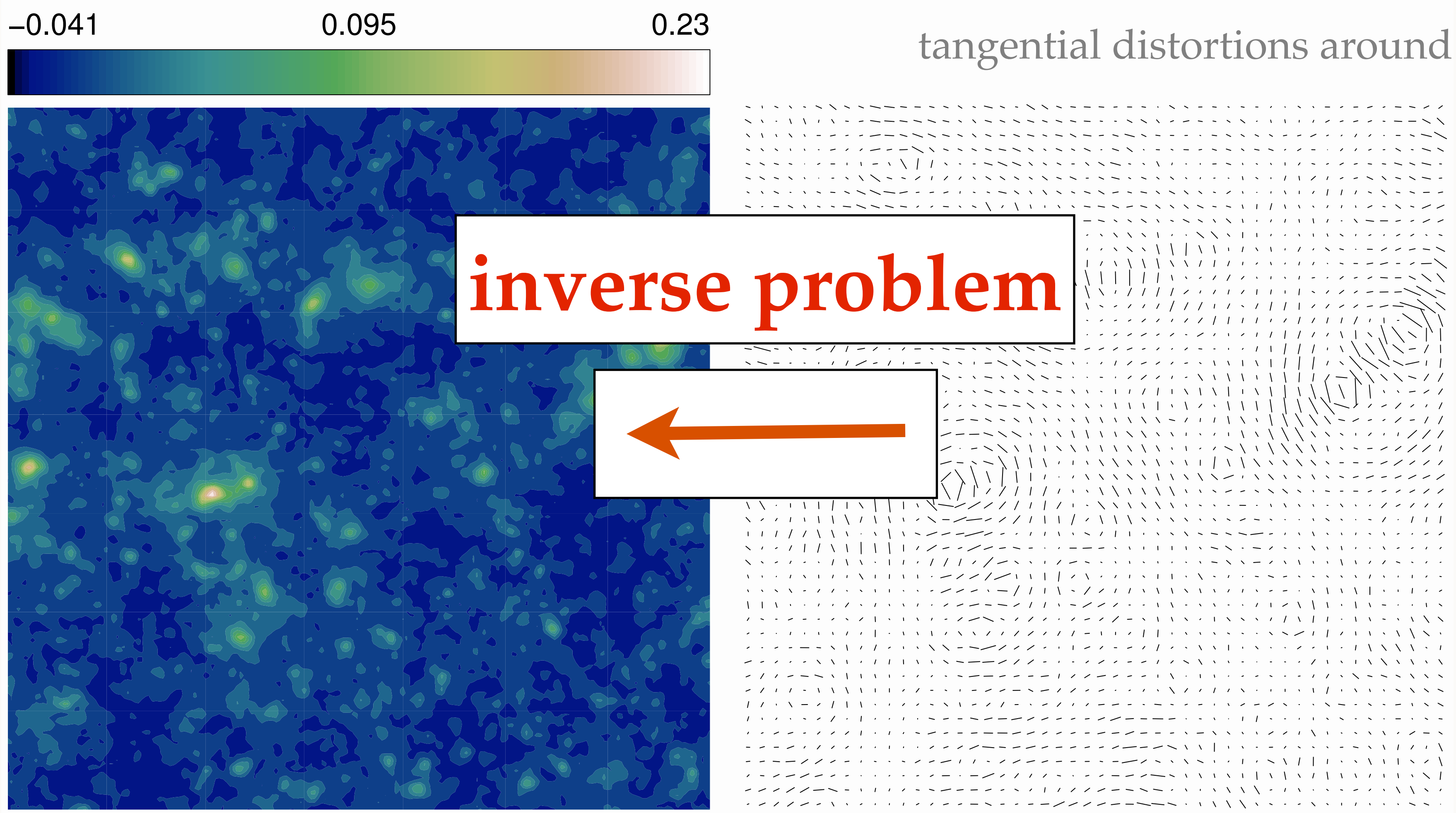
Flat ΛCDM + WMAP7 + H_0

LENSING MASS MAPS

Projected matter density
convergence κ

Distortion field
shear γ

tangential distortions around mass peaks



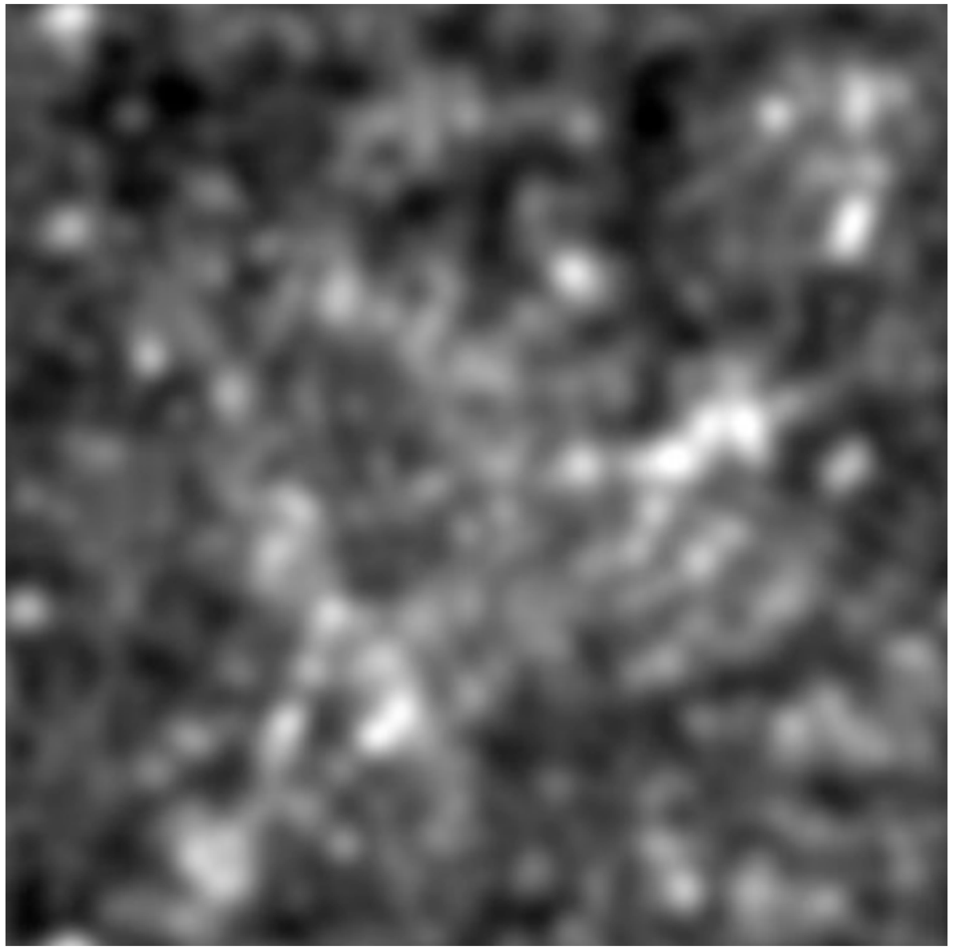
Source galaxies at $z = 1$, ray-tracing simulations by T. Hamana

LENSING MASS MAPS

van Waerbeke et al. prep.

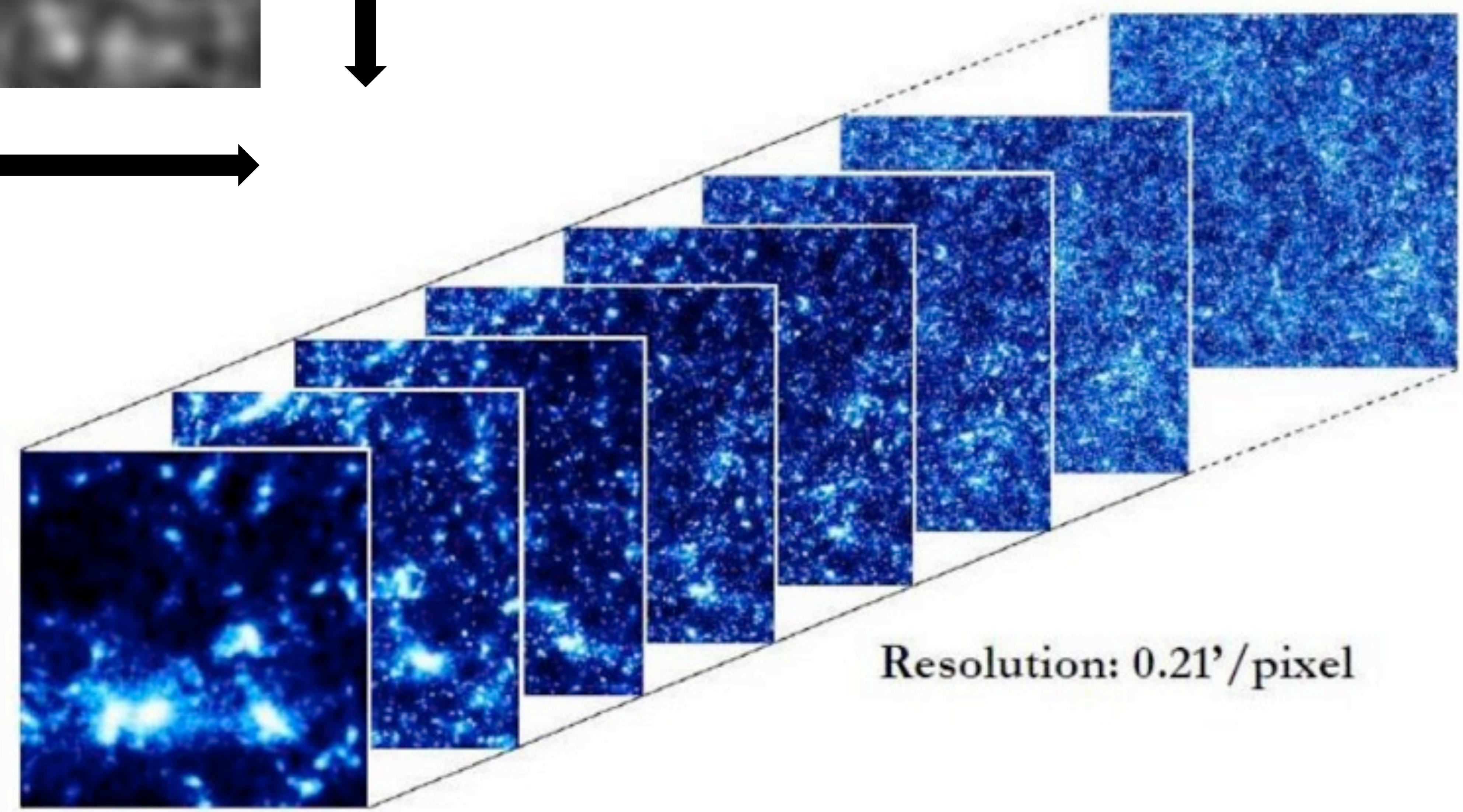
- Map dark-matter structures. Compare to optical (galaxies), X-ray (hot gas), SZ (gas)
- High-density regions trace non-linear structures
- Higher-order correlations, non-linear evolution
- 3D mass reconstruction, evolution of cosmic structures

Ray-tracing simulations
(Harnois-Deraps, Vafaei & van Waerbeke 2012)

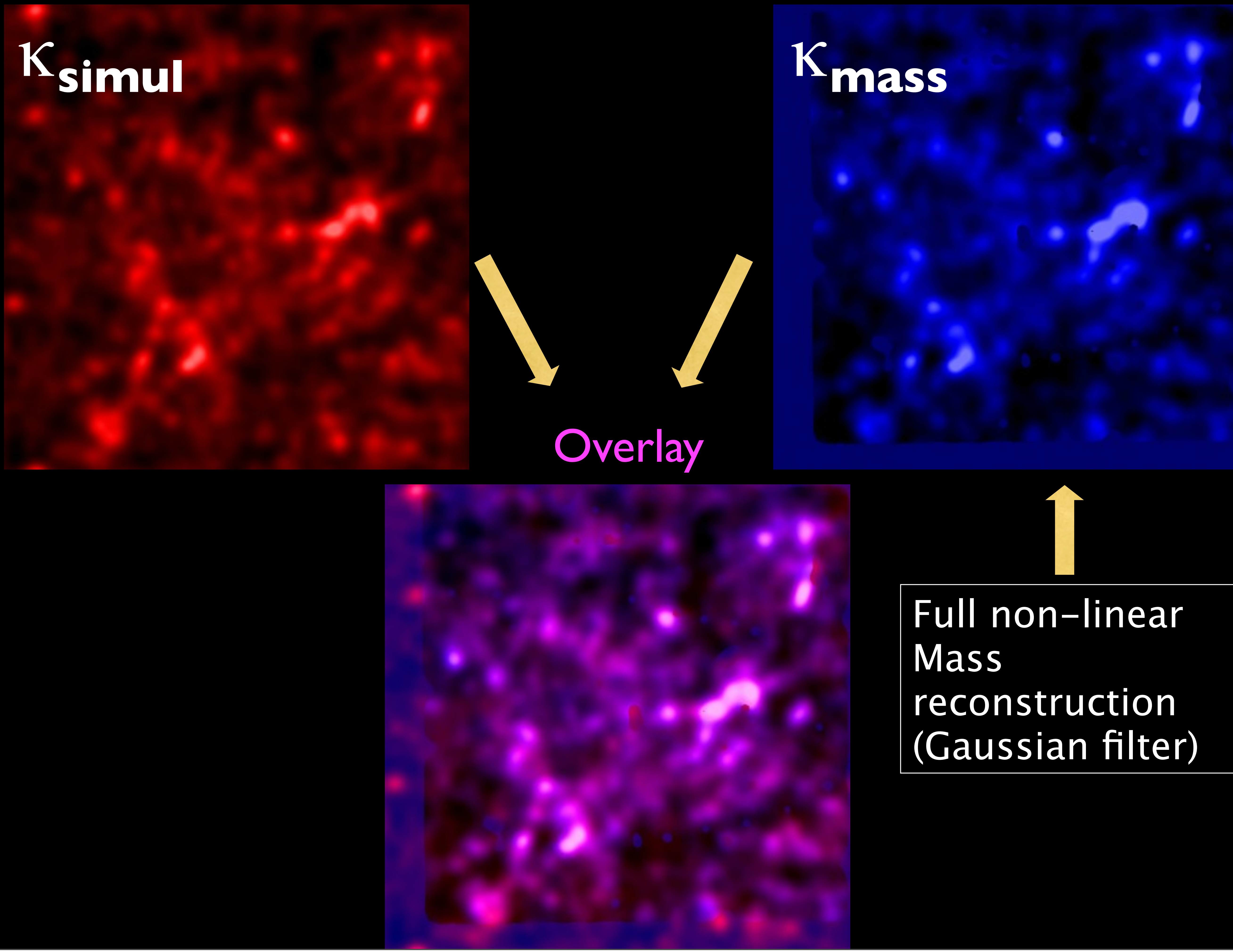


3.4 degrees

z=3



z=0.03



Thursday, December 13, 12

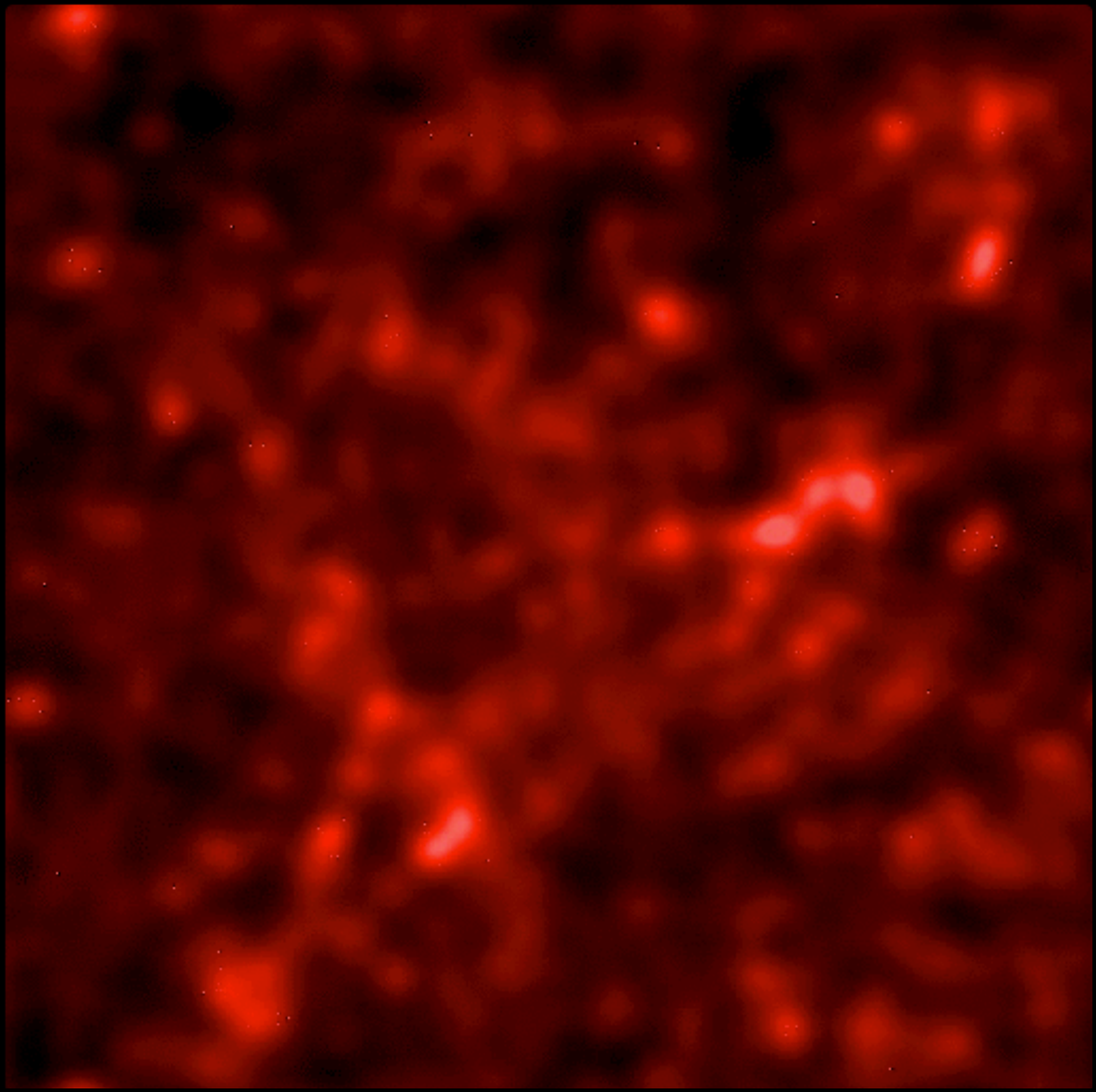
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

$\kappa_{\mathbf{mass}}$ NOISE FREE

Overlay

Perfect match!



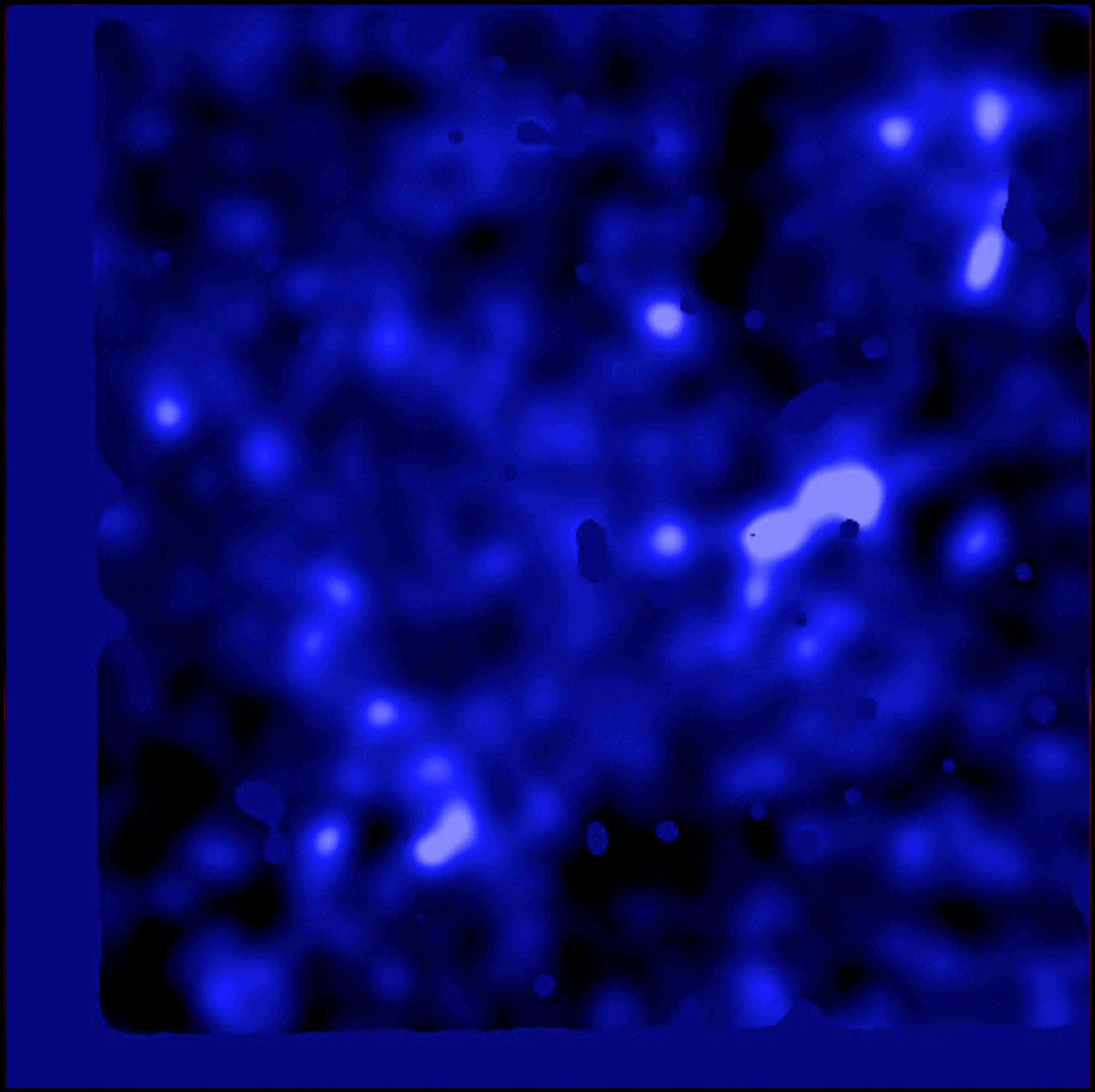
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

$\kappa_{\mathbf{mass}}$ NOISE FREE

Overlay

Perfect match!



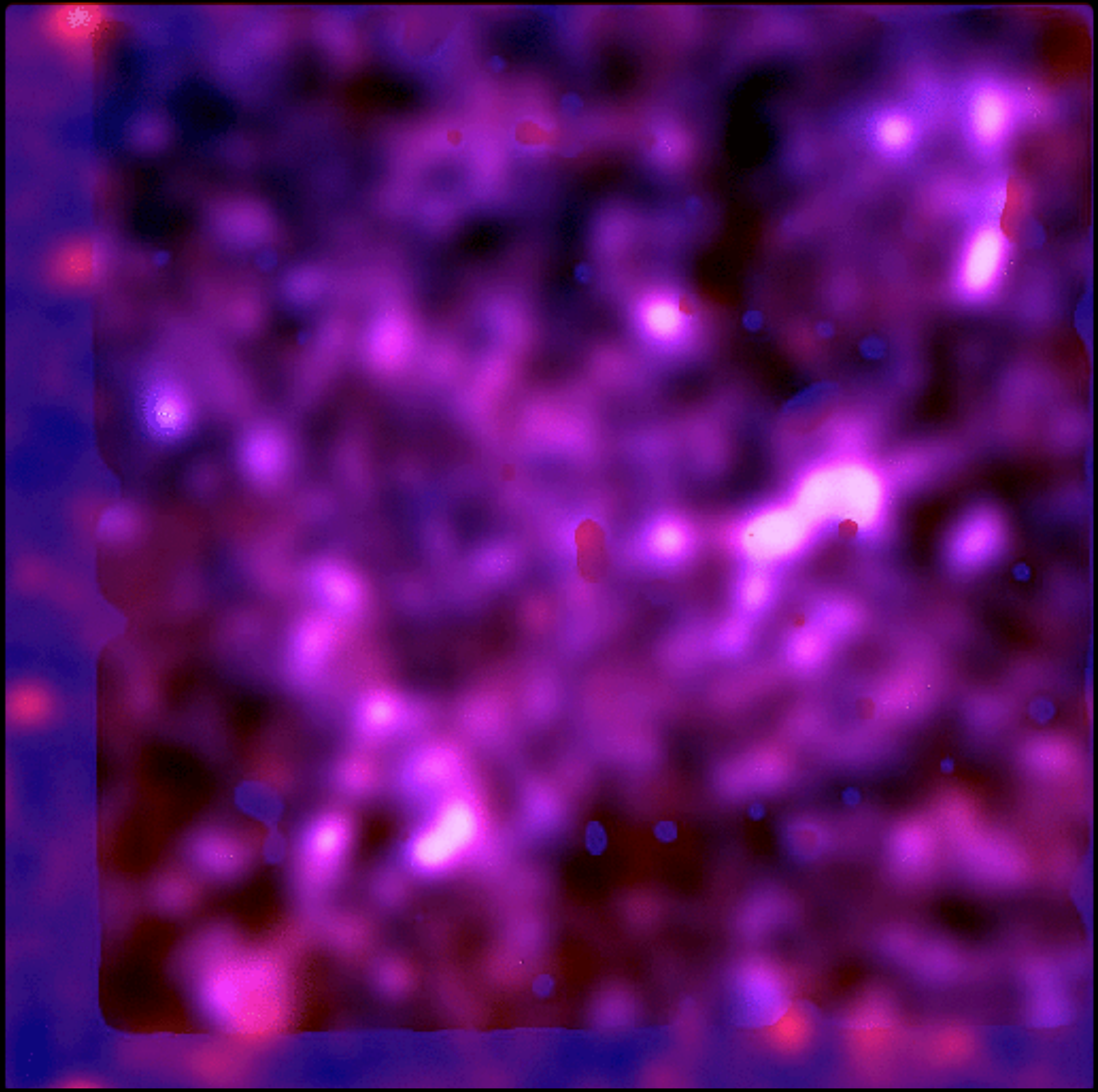
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

$\kappa_{\mathbf{mass}}$ NOISE FREE

Overlay

Perfect match!

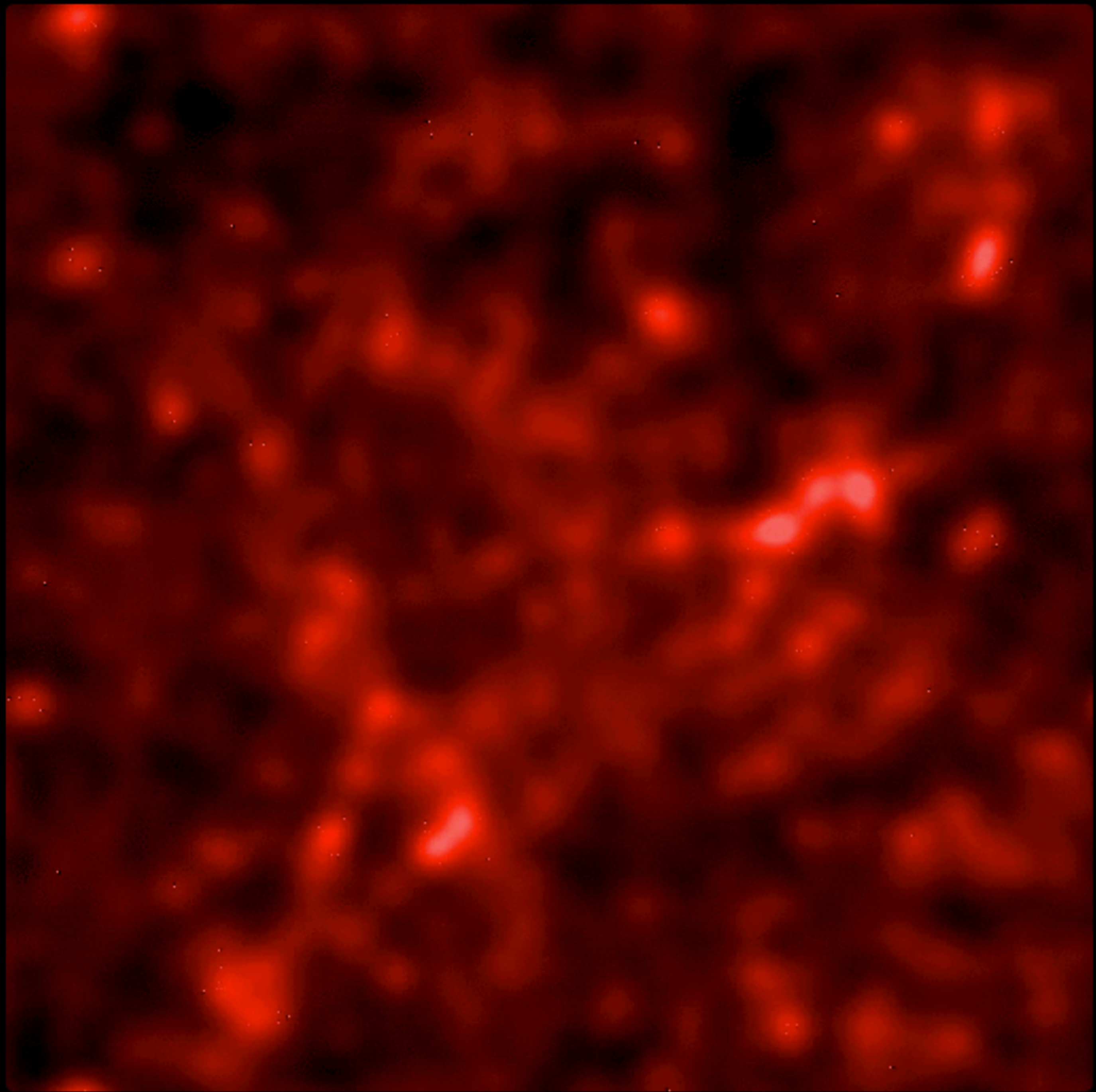


Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

$\kappa_{\mathbf{mass}}$ With NOISE

Overlay



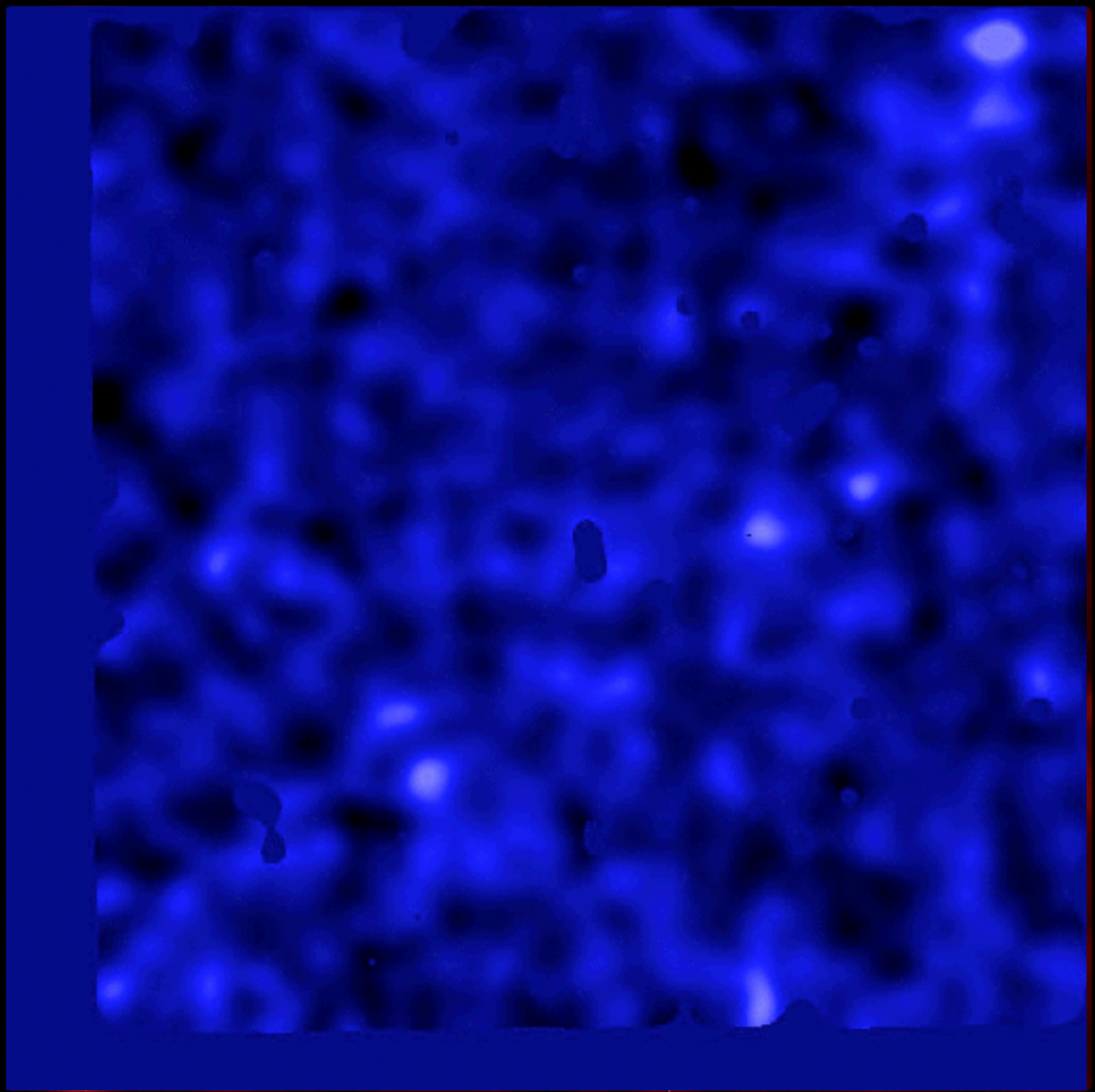
Very good match!
Peak and voids are well preserved

Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

$\kappa_{\mathbf{mass}}$ With NOISE

Overlay



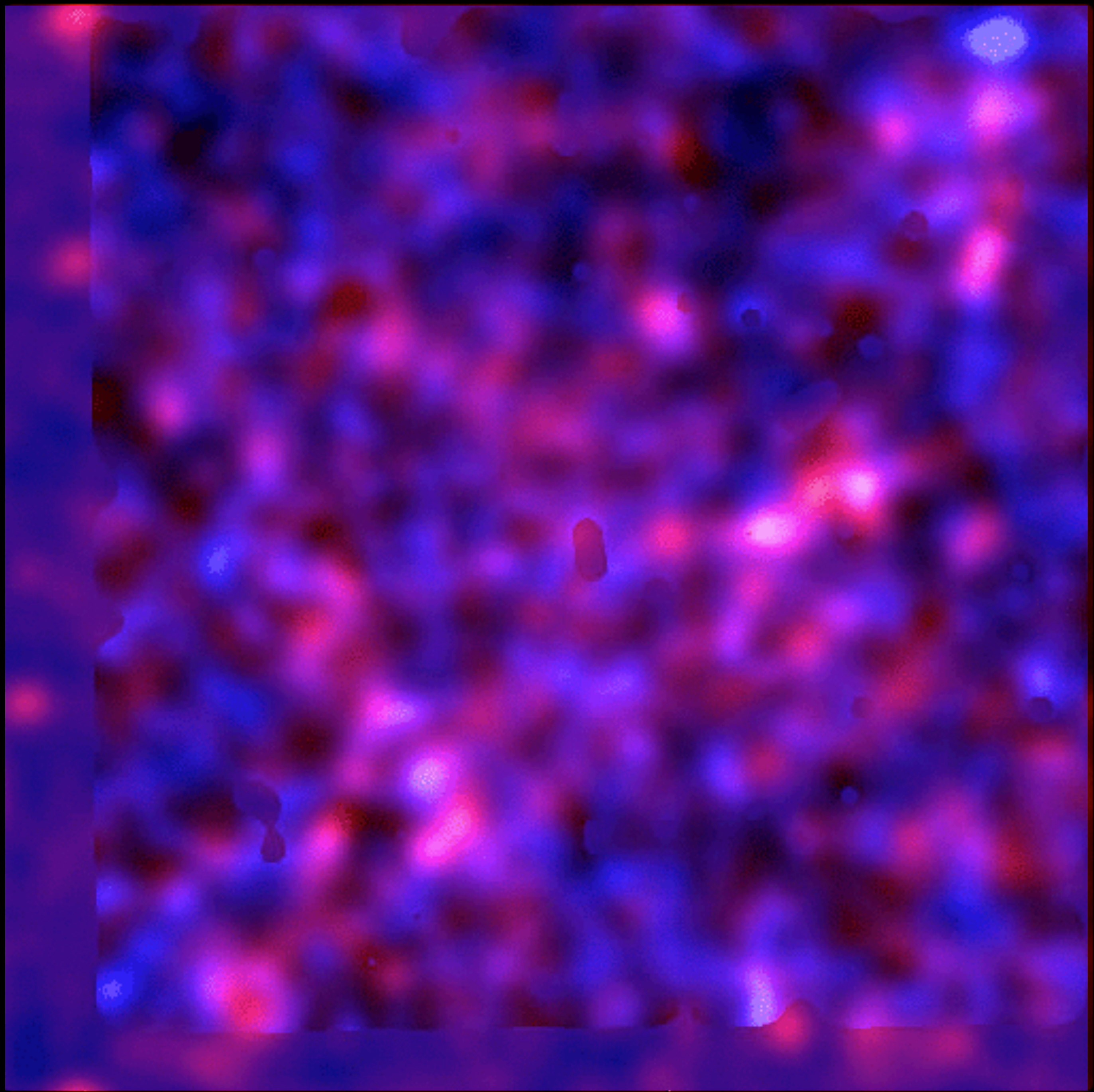
Very good match!
Peak and voids are well preserved

Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

$\kappa_{\mathbf{mass}}$ With NOISE

Overlay



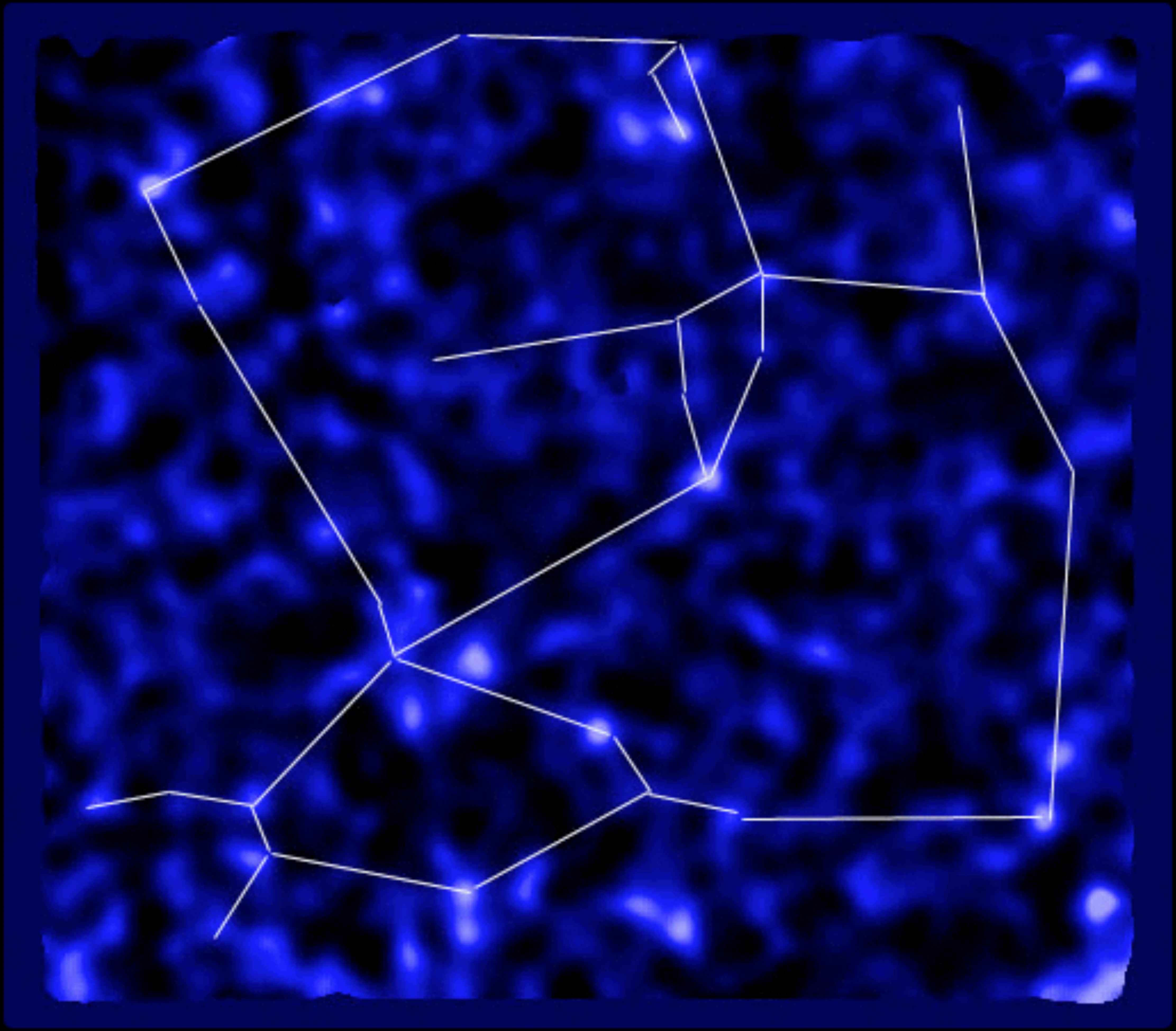
Very good match!
Peak and voids are well preserved

$\kappa_{\mathbf{mass}}$

$\kappa_{\mathbf{galaxies}}$

Overlay

3.5σ peaks

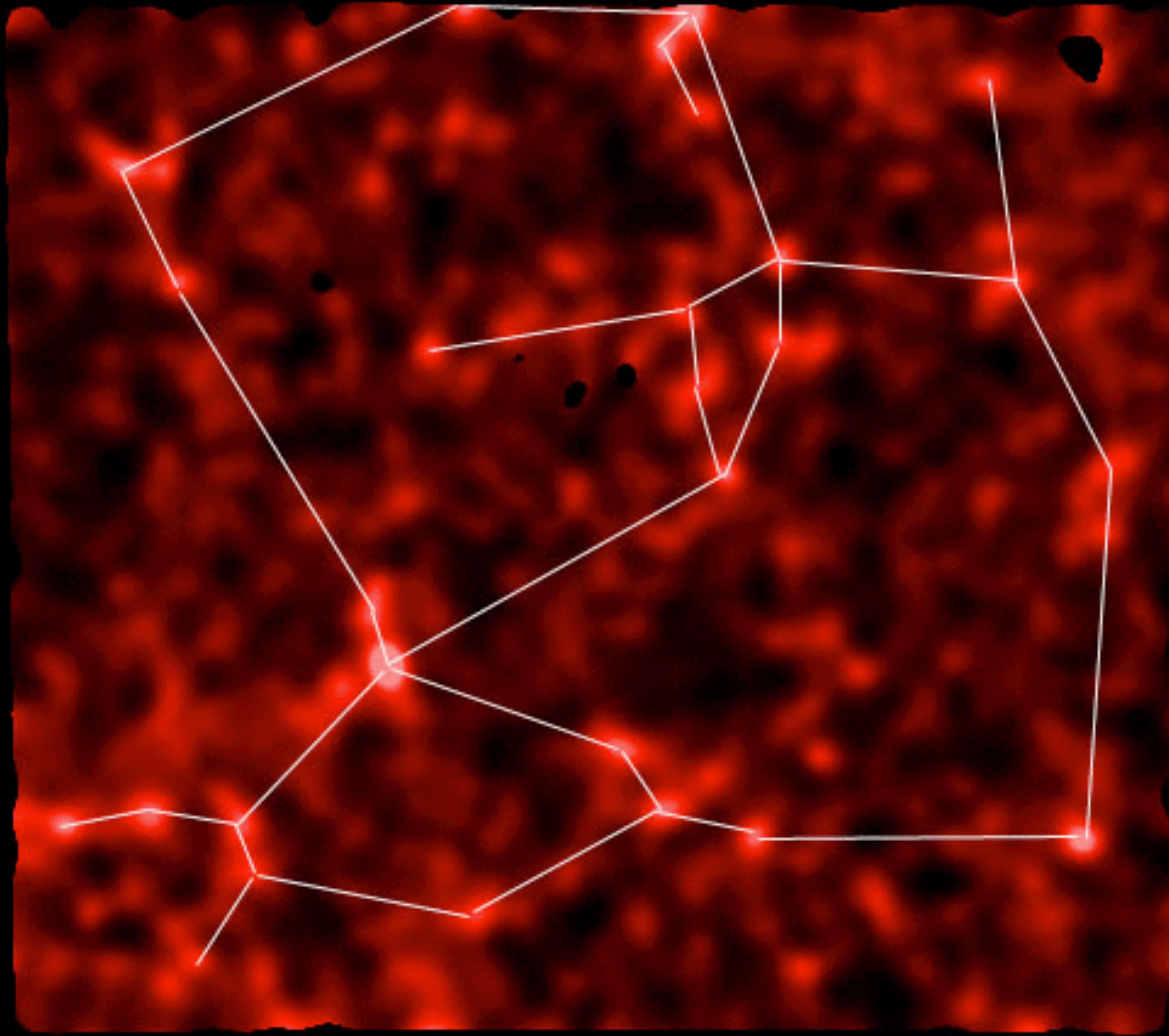


$\kappa_{\mathbf{mass}}$

$\kappa_{\mathbf{galaxies}}$

Overlay

3.5σ peaks

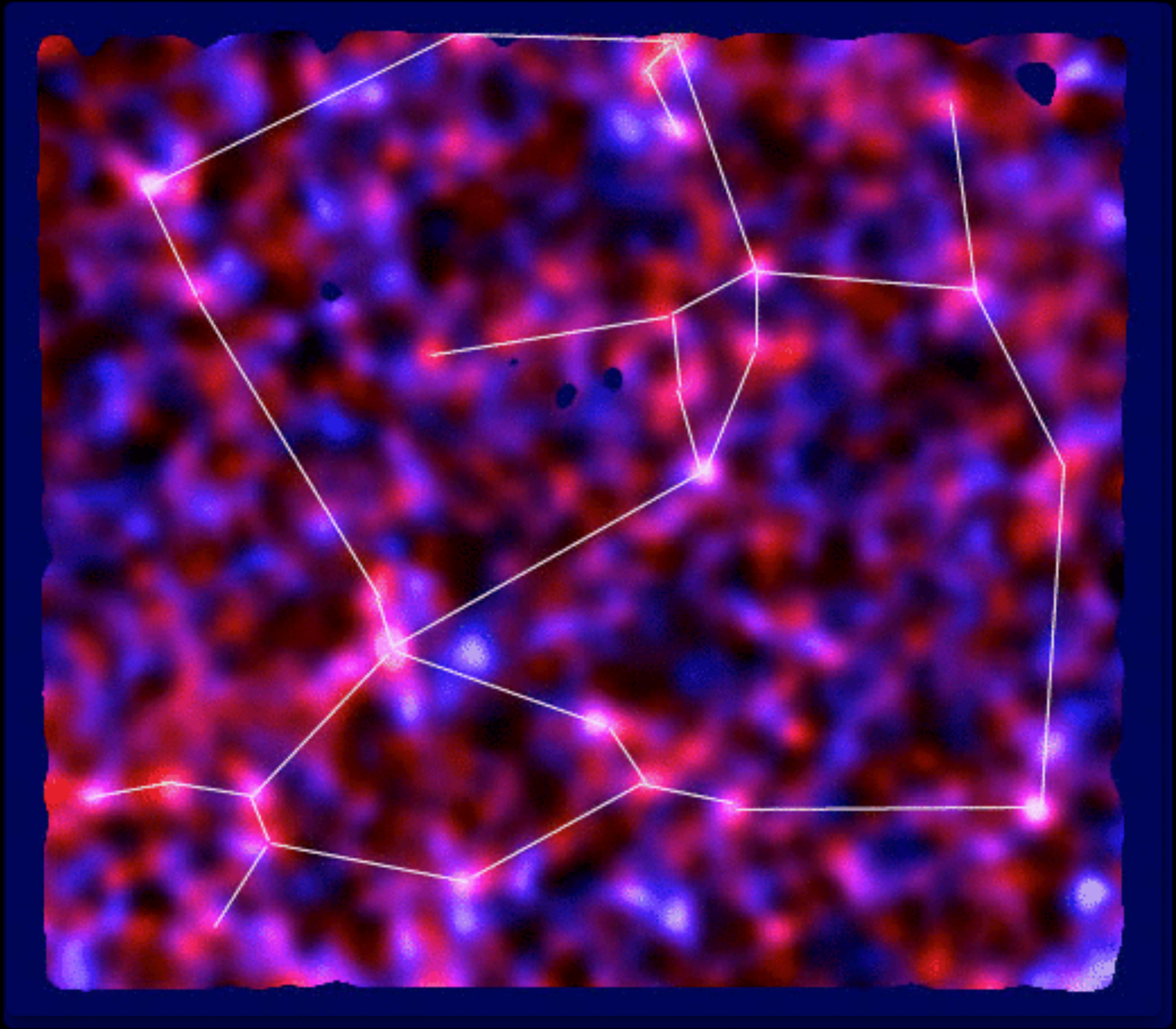


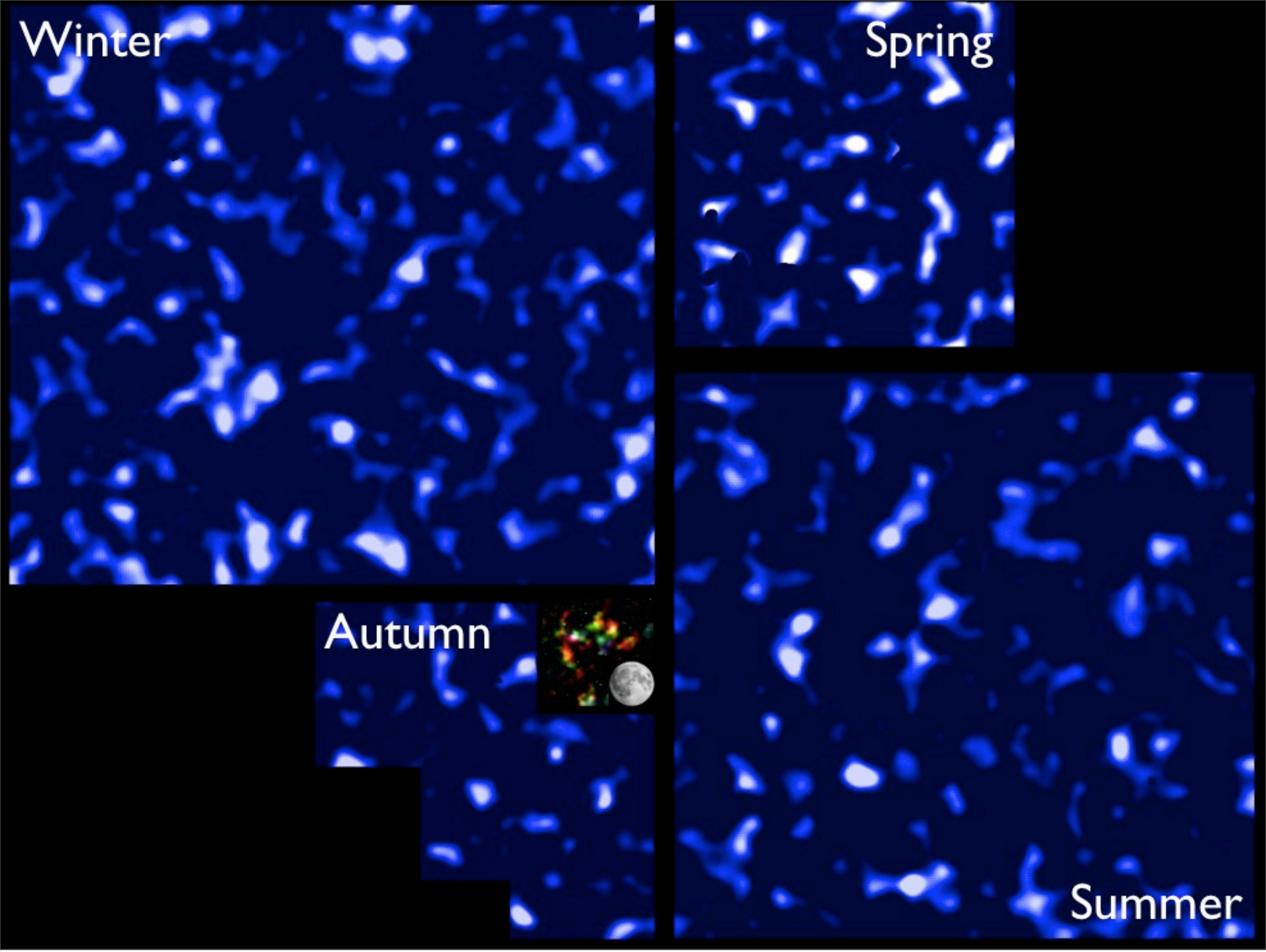
$\kappa_{\mathbf{mass}}$

$\kappa_{\mathbf{galaxies}}$

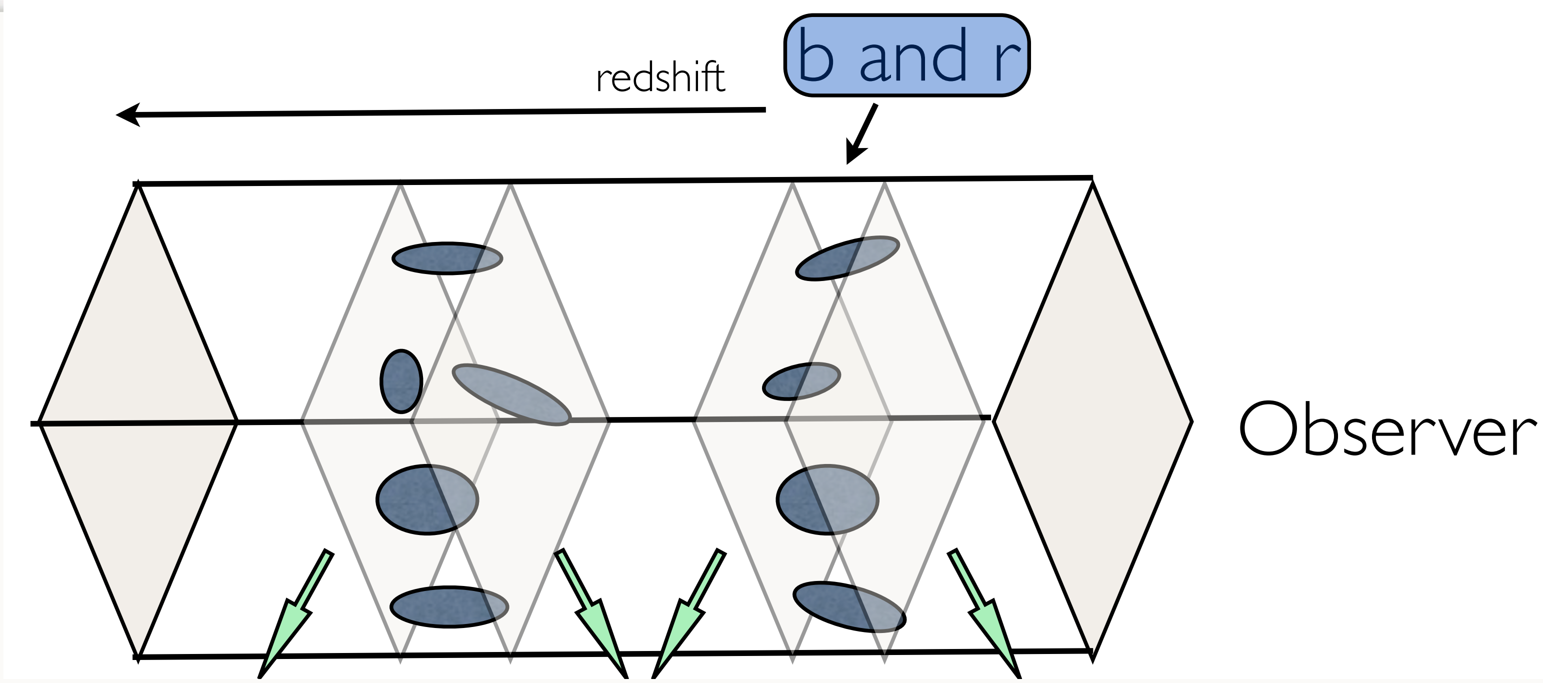
Overlay

3.5σ peaks




Winter
Spring
Autumn
Summer

LENSING & CLUSTERING



lensing

$\langle \delta_m \, \delta_m \rangle$

cross-corr.

$\langle \delta_m \, \delta_g \rangle$

clustering

$\langle \delta_g \, \delta_g \rangle$

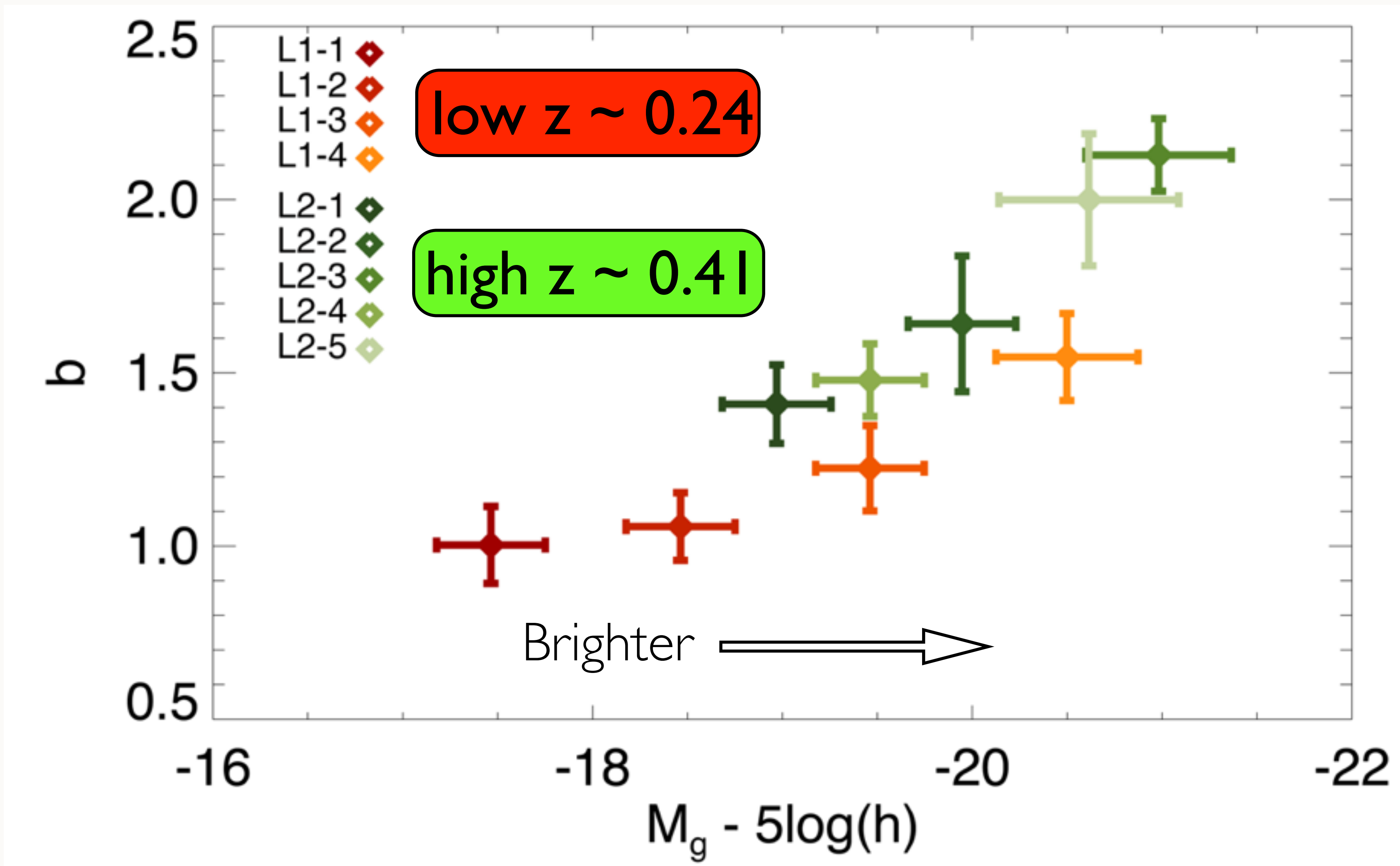
correlation factor :

$$r = \frac{\langle \delta_g \delta_m \rangle}{\sqrt{\langle \delta_g^2 \rangle \langle \delta_m^2 \rangle}}$$

bias factor :

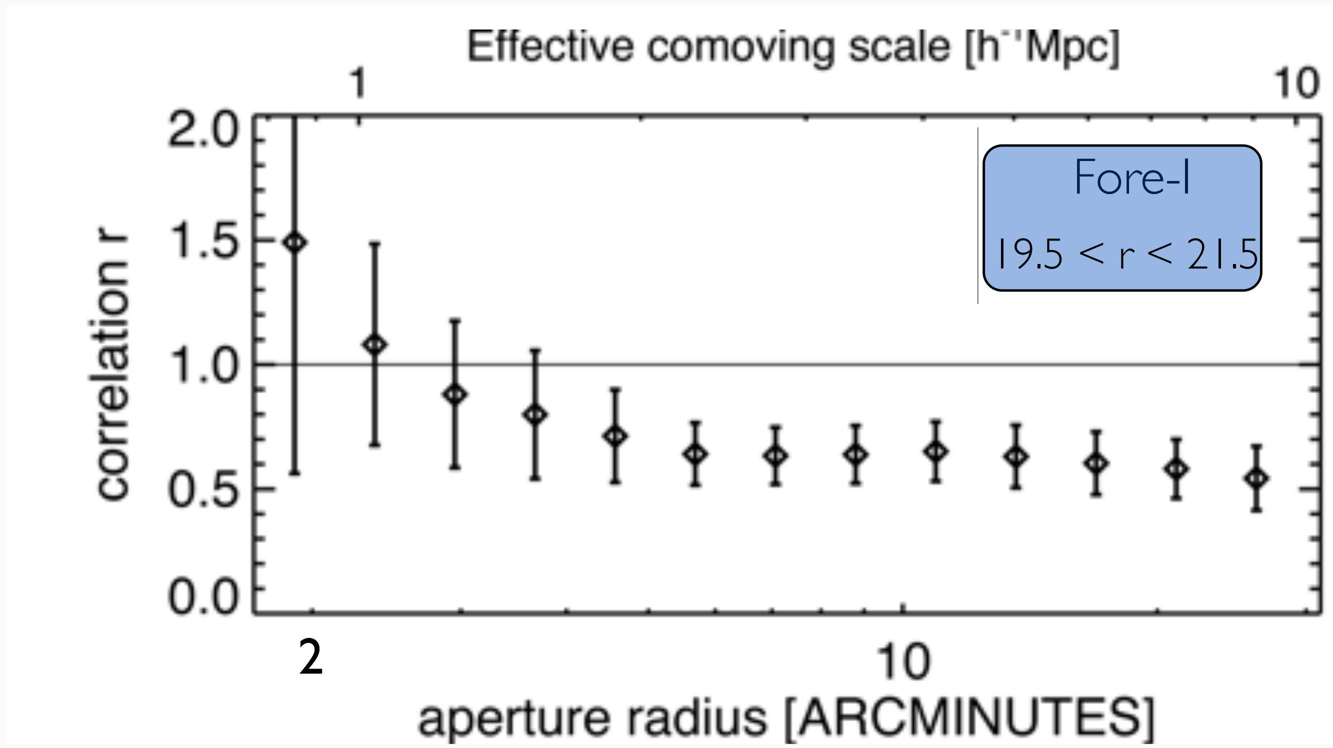
$$b = \sqrt{\frac{\langle \delta_g^2 \rangle}{\langle \delta_m^2 \rangle}}$$

GALAXY BIAS



c.f. clustering using HOD halo model, Coupon, MK et al. (2012)

CROSS-CORRELATION



- $r \to 1$ on large scales expected
- Roughly consistent with RCS [Hoekstra et al. 2002] & GaBoDS [Simon et al. 2006]
- Inconsistent with Millennium Simulations [Hartlap et al.]

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.

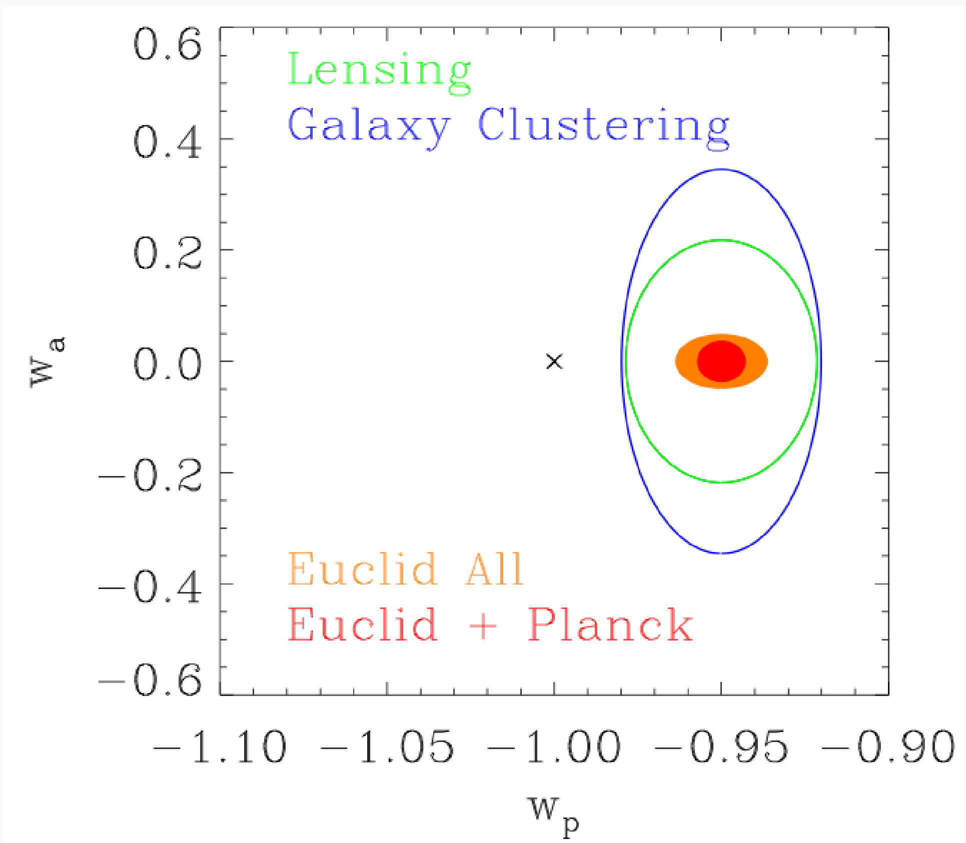
- CFHTLS. 2003 - 2009
  155 deg^2, MegCam/CFHT
  Science papers are being submitted and accepted. Catalogues have been made public on **Nov 1, 2012**. See www.cfhtlens.org .

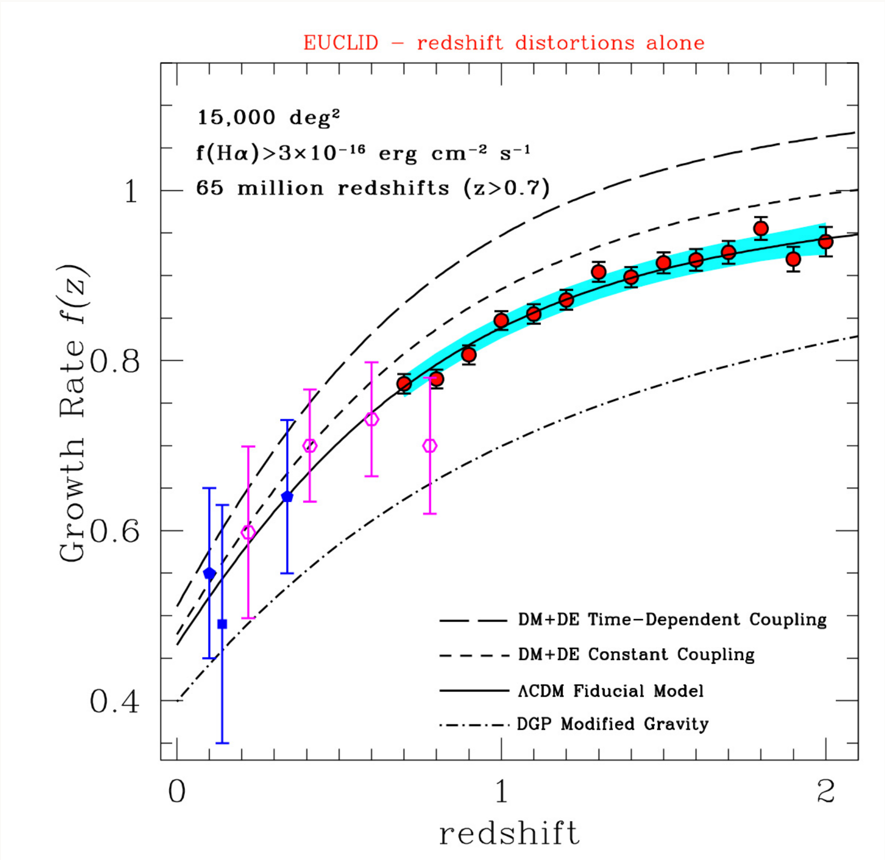
TIMELINE TO EUCLID

- 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.

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**





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

Technical papers:

The Canada-Hawaii Telescope Lensing Survey; Heymans & Van Waerbeke et al in prep
Bayesian galaxy shape measurement for weak lensing surveys –III. Miller et al in prep
CFHTLenS: Improving the quality of photometric redshifts with precision photometry; Hildebrandt et al,
CFHTLenS Data Release; Erben et al in prep
Impact of PSF modeling errors on cosmic shear analyses; Rowe et al in prep

Cosmology:

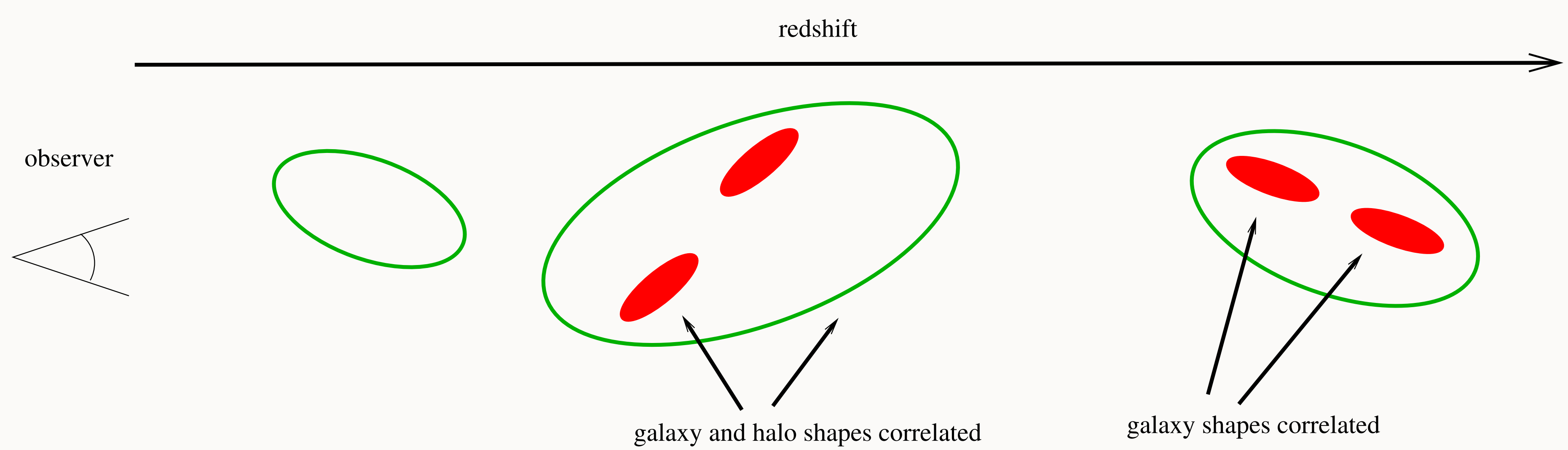
Cosmological constraints from cosmic shear; Kilbinger et al in prep
Tomographic cosmic shear with Photometric Redshifts; Benjamin et al in prep
Testing the laws of gravity with CFHTLenS and WiggleZ; Simpson et al in prep
Weak lensing magnification measurements in CFHTLenS; Hildebrandt et al in prep
Combined cosmic shear and intrinsic galaxy alignment constraints; Heymans & Grocutt et al in prep
3D weak lensing with CFHTLenS; Kitching et al in prep
Three-point cosmic shear analysis of CFHTLenS; Vafaei et al prep

Clusters and galaxies:

Mapping dark matter with CFHTLenS; Van Waerbeke & Heymans et al in prep.
Galaxy dark matter halo constraints in the CFHTLenS; Velander et al in prep
Galaxy-galaxy lensing in CFHTLenS; Hudson et al in prep
Third order galaxy-galaxy-galaxy lensing; Simon et al in prep
The scale dependent galaxy bias from CFHTLenS; Bonnett et al in prep
Galaxy halo shapes constrained by CFHTLenS; Schrabback et al in prep
CFHTLenS cluster mass scaling relations; Milkeraitis et al in prep
Galaxy groups in CFHTLenS; Gillis et al in prep

INTRINSIC ALIGNMENT

- Intrinsic alignment is a problem for future weak lensing surveys



- 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)

PSF CORRECTION

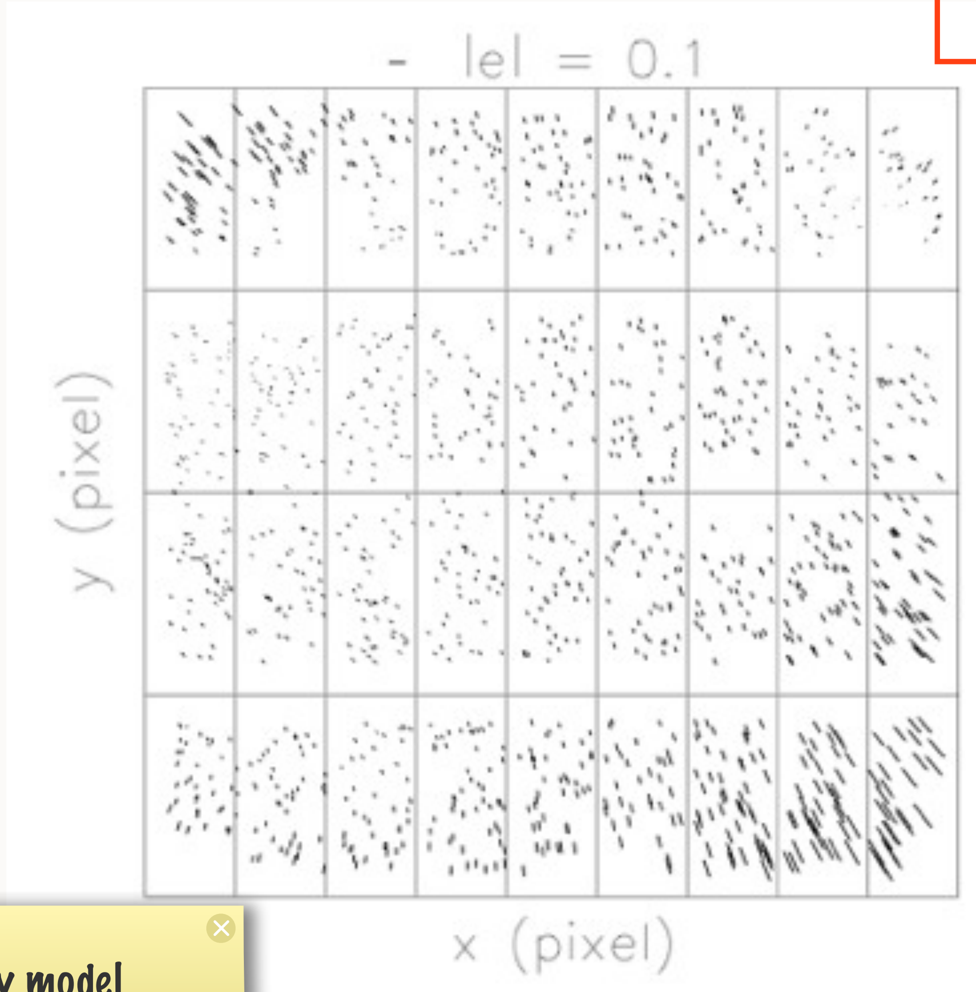
Telescope/Camera/Atmospheric distortions >> weak lensing

$\varepsilon < 0.1$ $\gamma < 0.01$

Euclid: measure to 1% accuracy!

Correct for PSF:

- Measure PSF for stars
- Model PSF
- Interpolate to galaxy positions
- Deconvolve/subtract/... estimated PSF



CFHTLS-Wide W_{3+2+O}
Fu et al. 2008

lensfit: multiply model with PSF in Fourier space

INTRINSIC ALIGNMENT

- MK et al. in submitted.: Broad redshift distribution, IA sub-dominant (see Fu et al. 2008)
- Simpson et al. submitted, Benjamin et al. in prep.: Exclude $z<0.5$, IA sub-dominant for high z
- Heymans et al. in prep.: Model simultaneously GG, GI and II

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 $\displaystyle\int {\rm d}^n\theta\, \boldsymbol{\theta}\, L(\boldsymbol{\theta})\pi(\boldsymbol{\theta})$

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

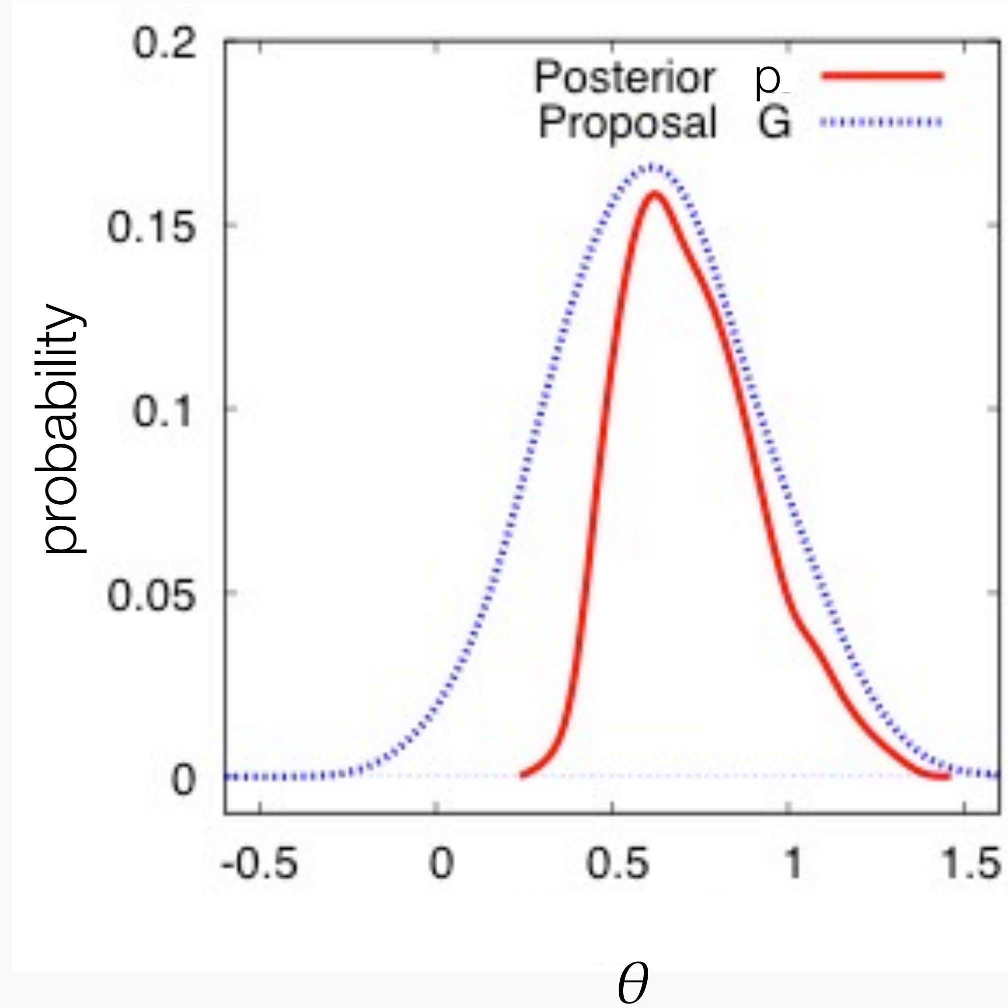
IMPORTANCE SAMPLING

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

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

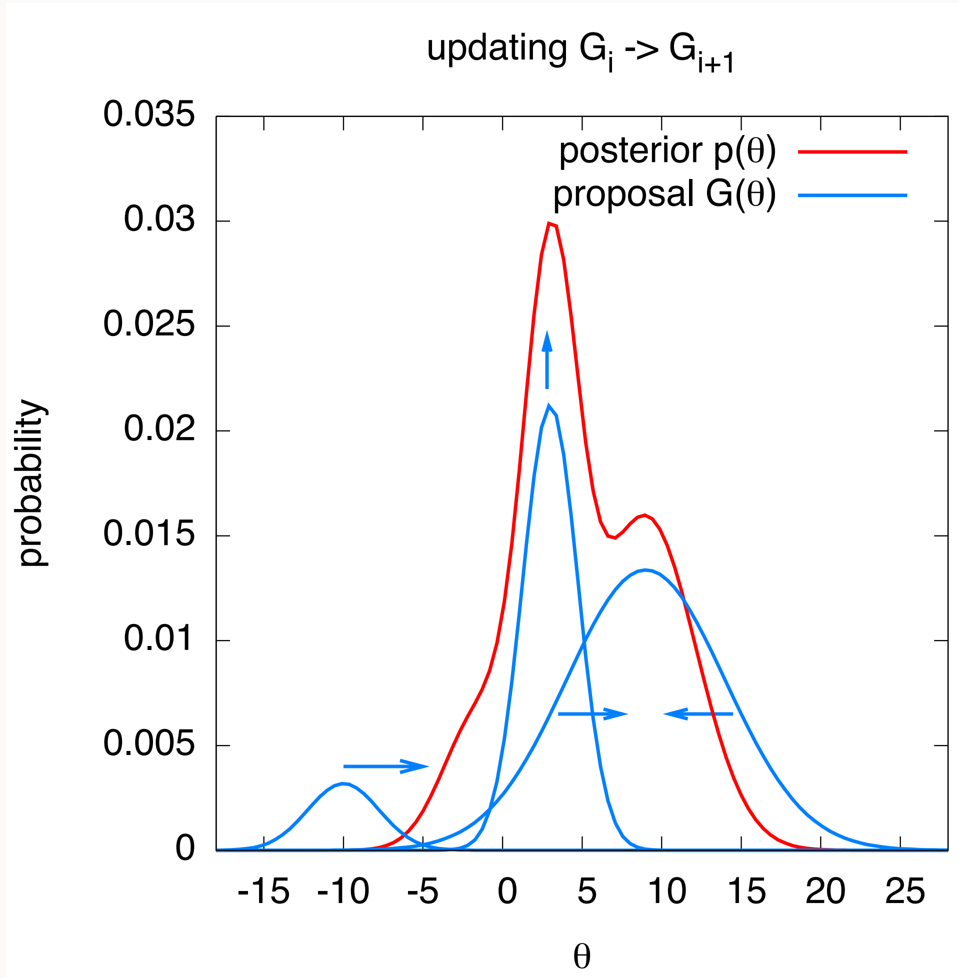
- Evaluation of posterior p (likelihood x prior) can be done in parallel

- Poor performance if proposal far from posterior



POPULATION MONTE CARLO (PMC)

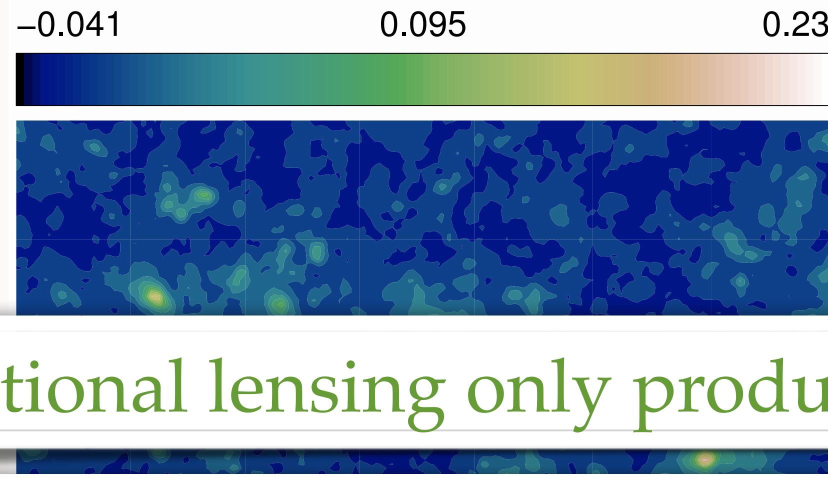
- Solution: Create adaptive importance samples ("populations") [Cappé et al. 2004, 2007]
- Iteration $G_i \rightarrow G_{i+1}$: Update mean, covariance and component weights
- PMC sample engine and cosmology modules, public code, www.cosmopmc.info, [Kilbinger et al. 2010, arXiv:1101.0950]
- Stop when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

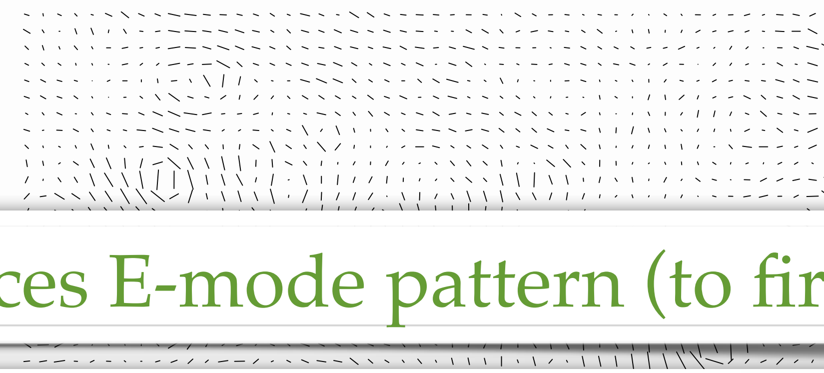


E- AND B-MODE

Projected matter density
convergence κ

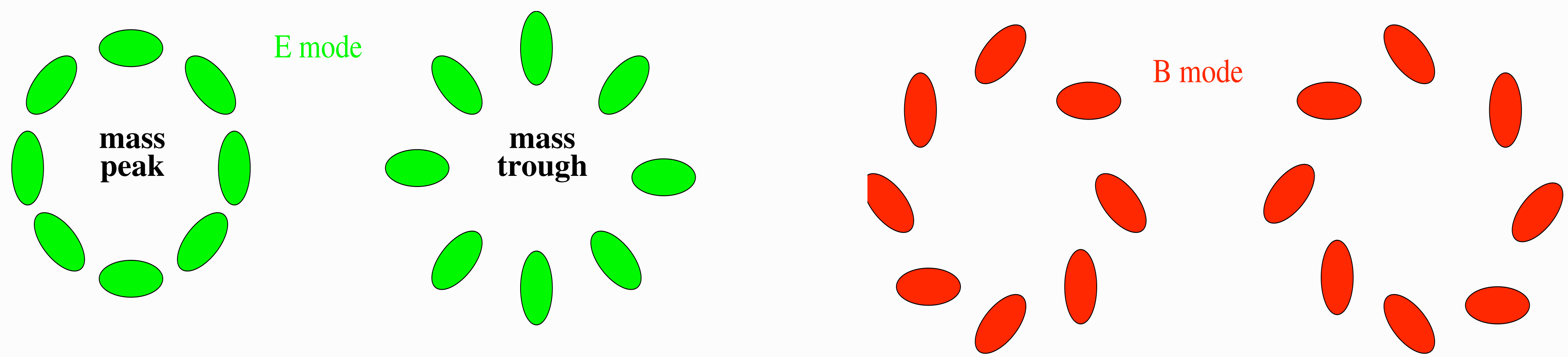
Distortion field
shear γ





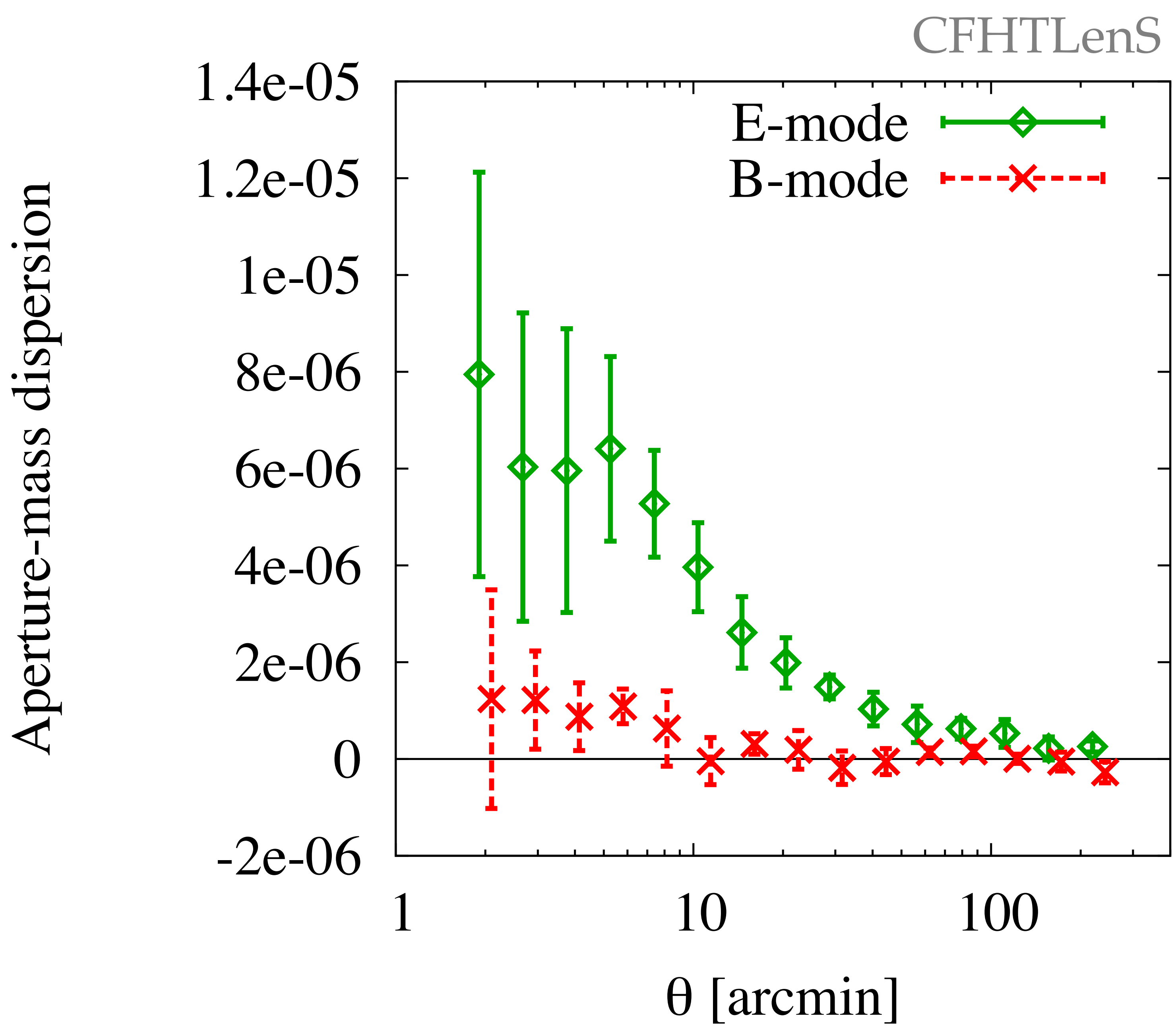
mass peaks

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



B-mode detected → hint for systematics in data

E- AND B-MODES



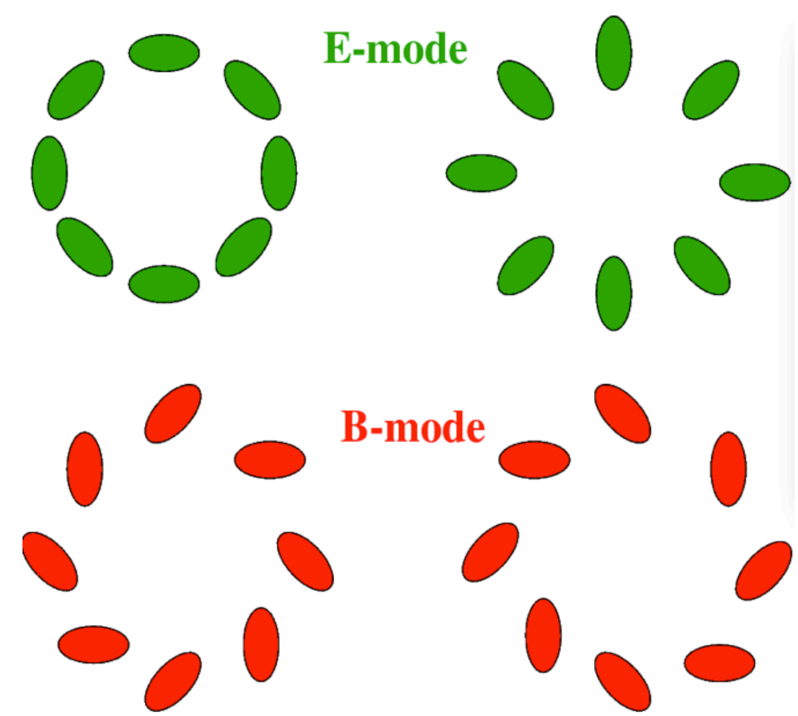
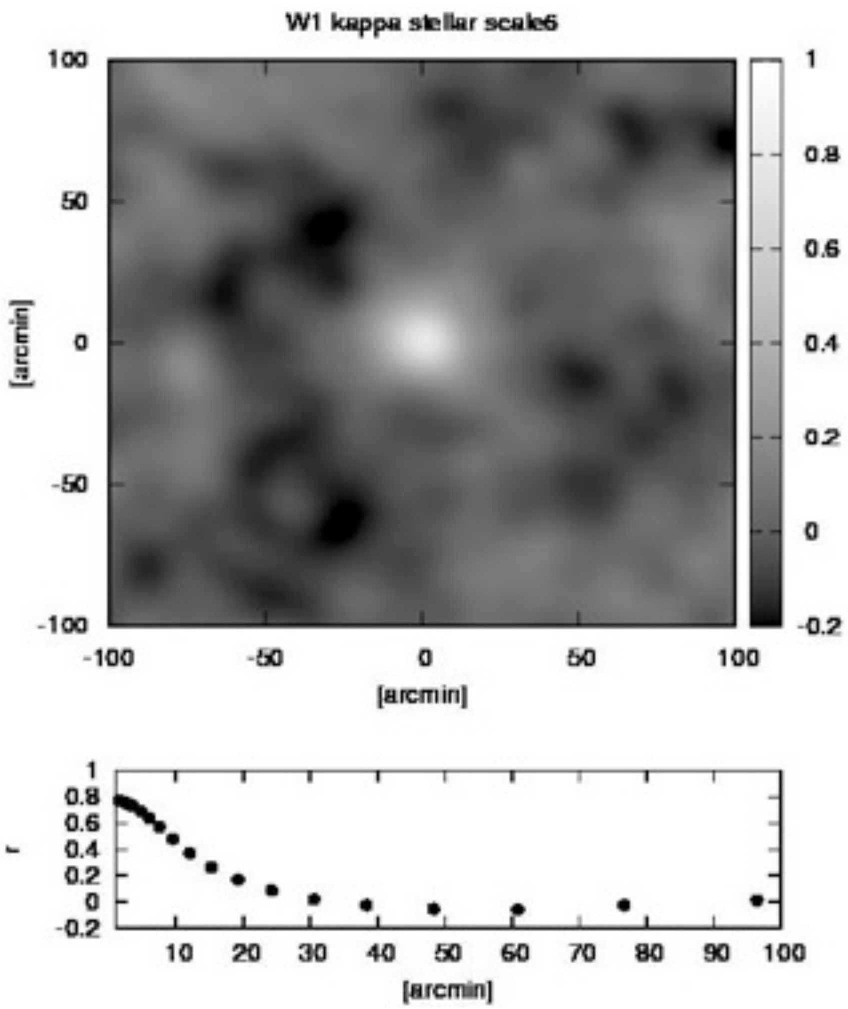
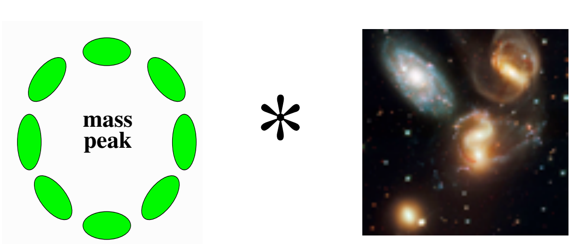


Fig.1. *Left*: E- and B-modes measured in CFHTLenS. *Right*: typical E- and B-mode shear patterns.

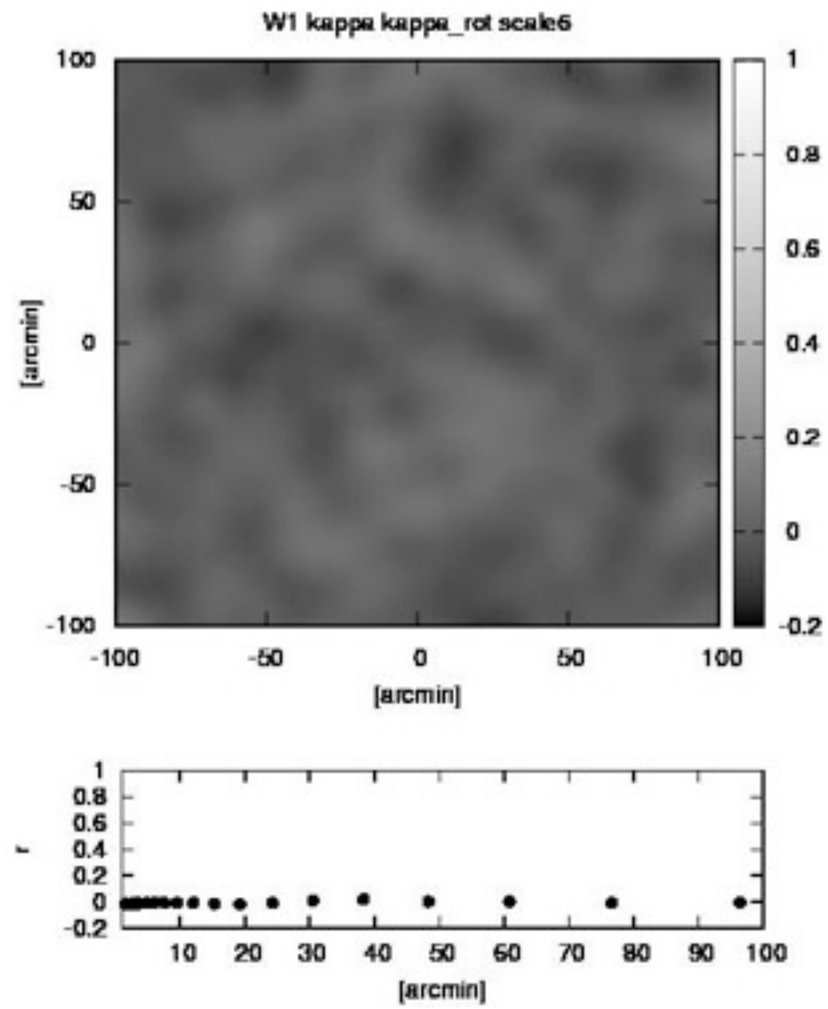
W1 cross-correlation analysis

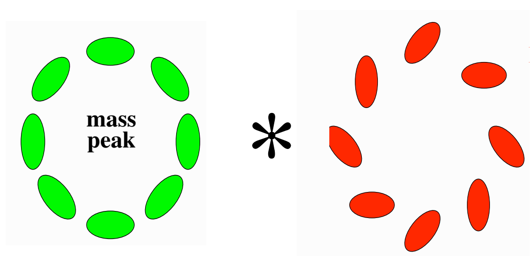
$\langle \kappa_{mass}\ \kappa_{galaxies} \rangle$



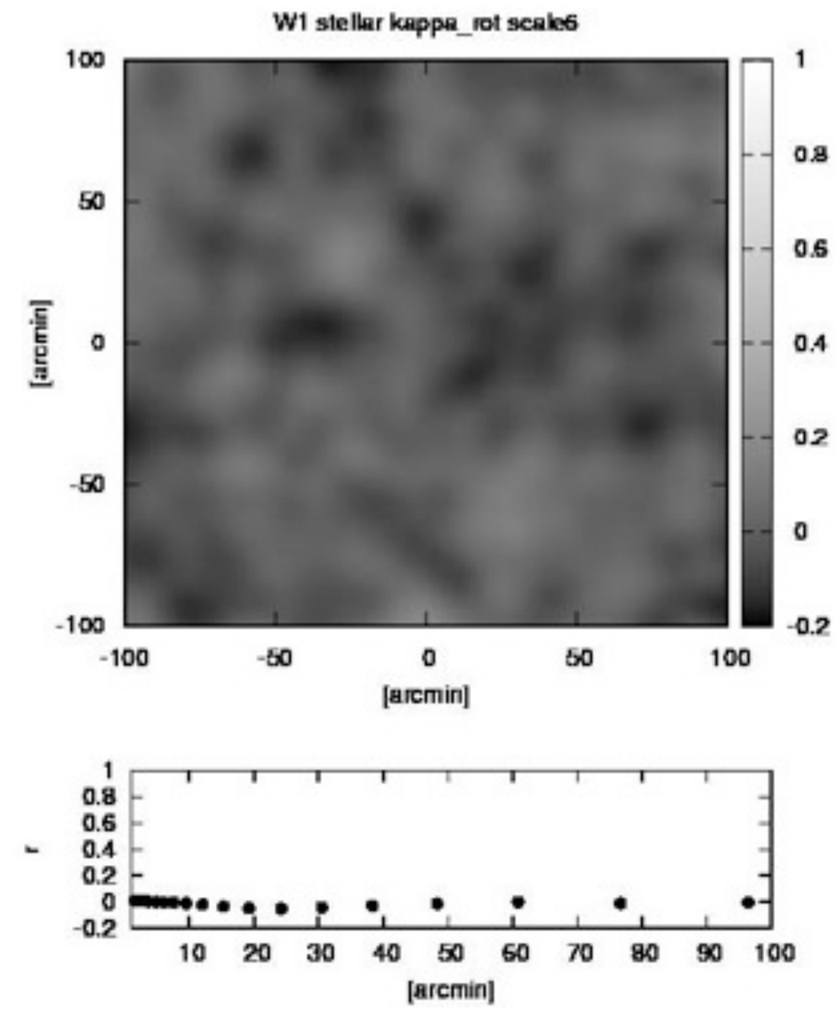


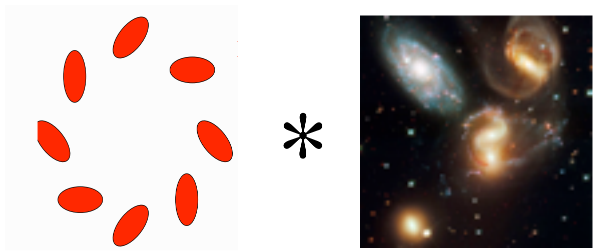
$\langle \kappa_{mass}\ \kappa_{rot} \rangle$



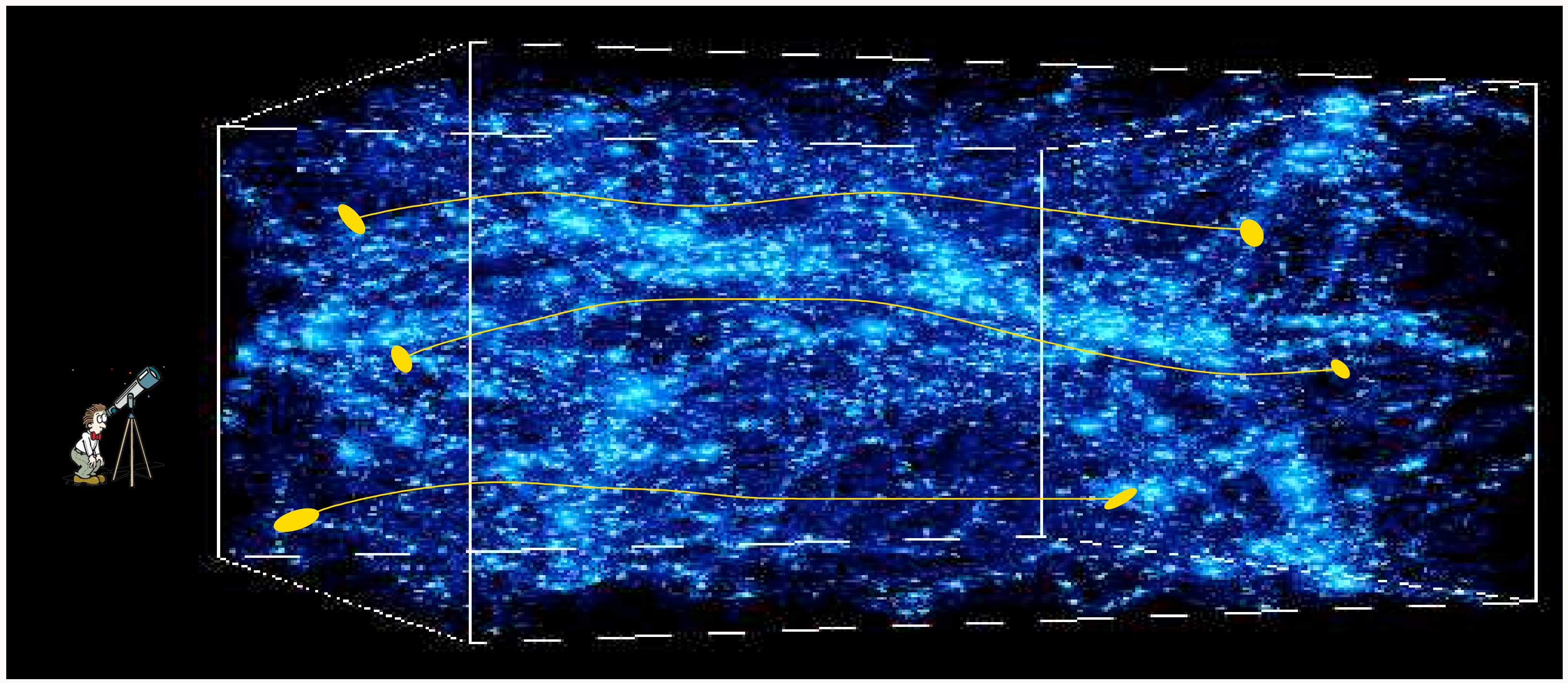


$\langle \kappa_{rot}\ \kappa_{galaxies} \rangle$





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