Constraints On Dark Energy And Modified Gravity Models From CFHTLenS

SPP seminar, 11 June 2012

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www.cfhtlens.org

OUTLINE

- Weak gravitational lensing
- The CFHT Lensing survey; galaxy shape measurement, systematics
- Monte-Carlo sampling (PMC)
- CFHTLenS results: constraints on dark energy + Modified Gravity (+ Wiggle-Z); 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 $z \approx 0.1$ 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:

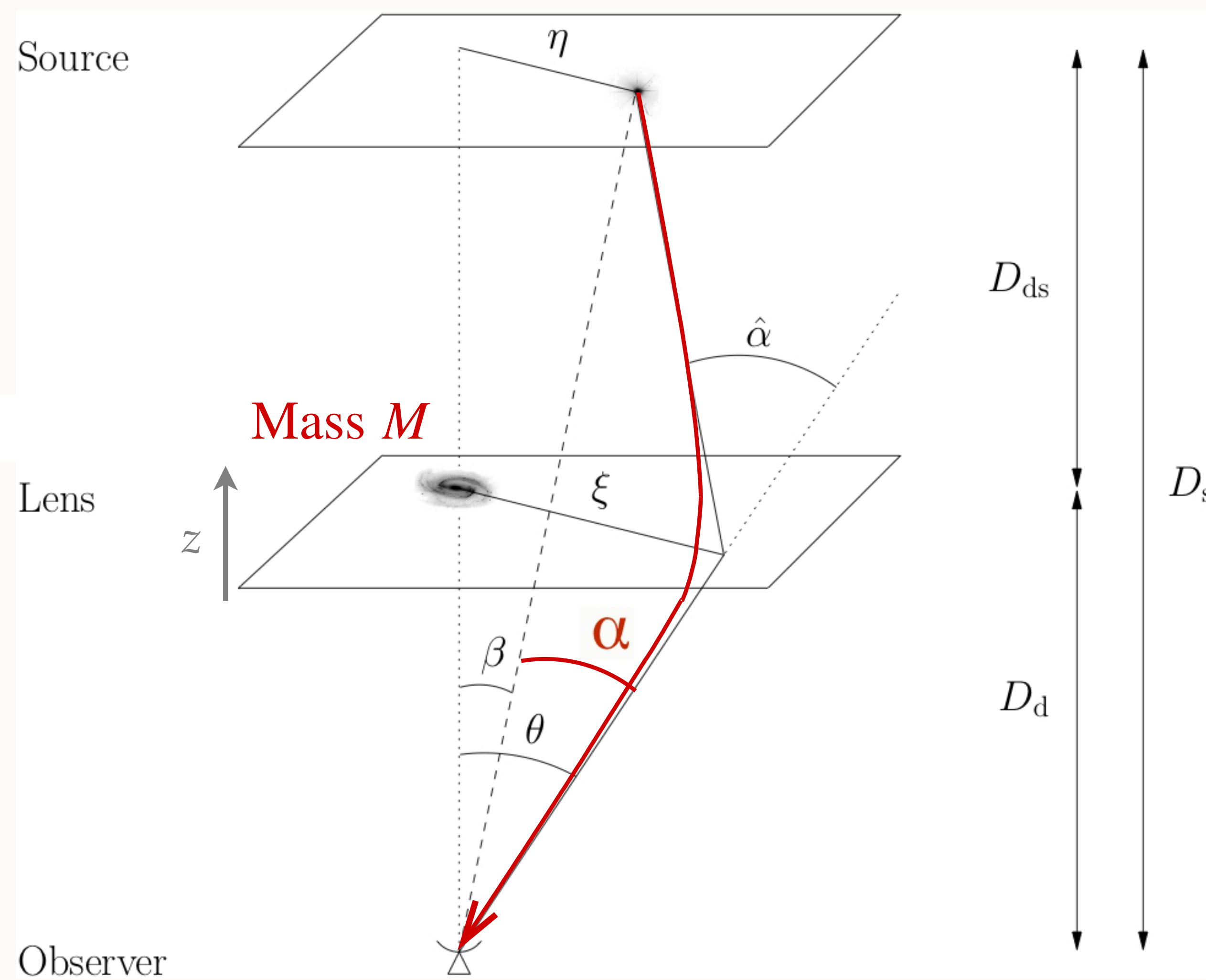
Deflection angle

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

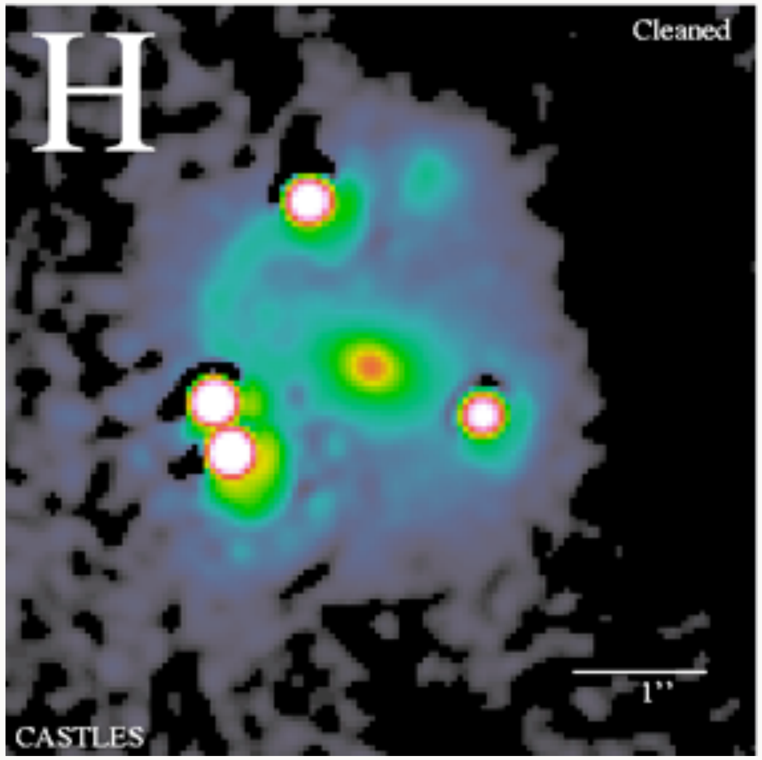
impact parameter

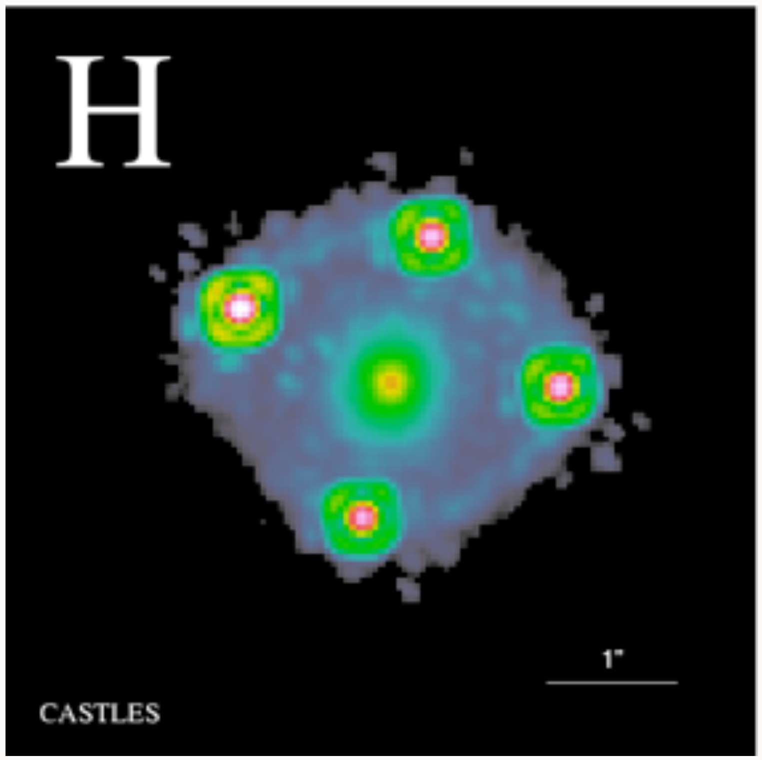
Extended mass distribution:

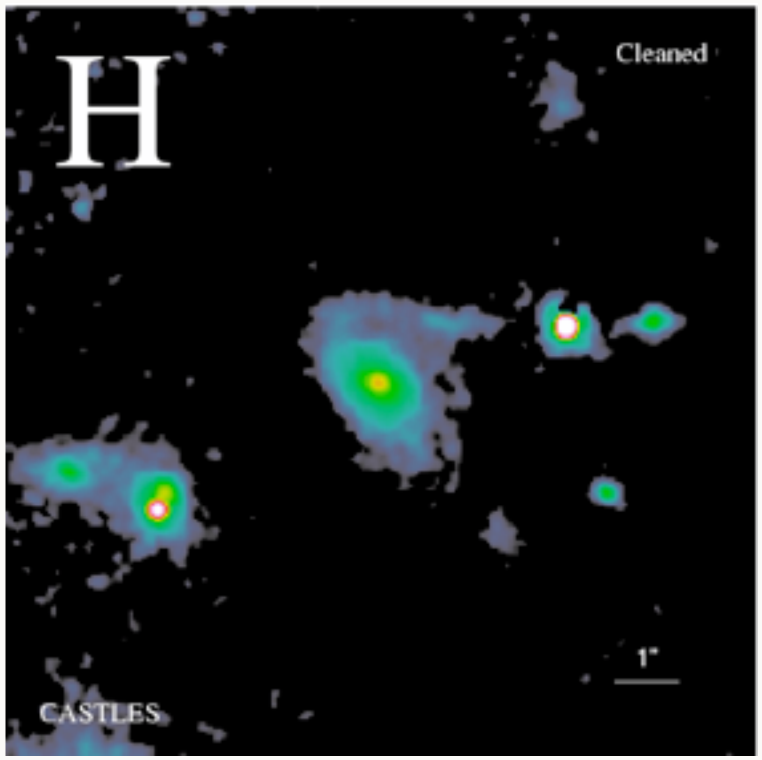
Deflection angle depends on integral over the projected mass distribution



GALACTIC LENSES







	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

- Lens equation:

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

(2D angular coordinates)

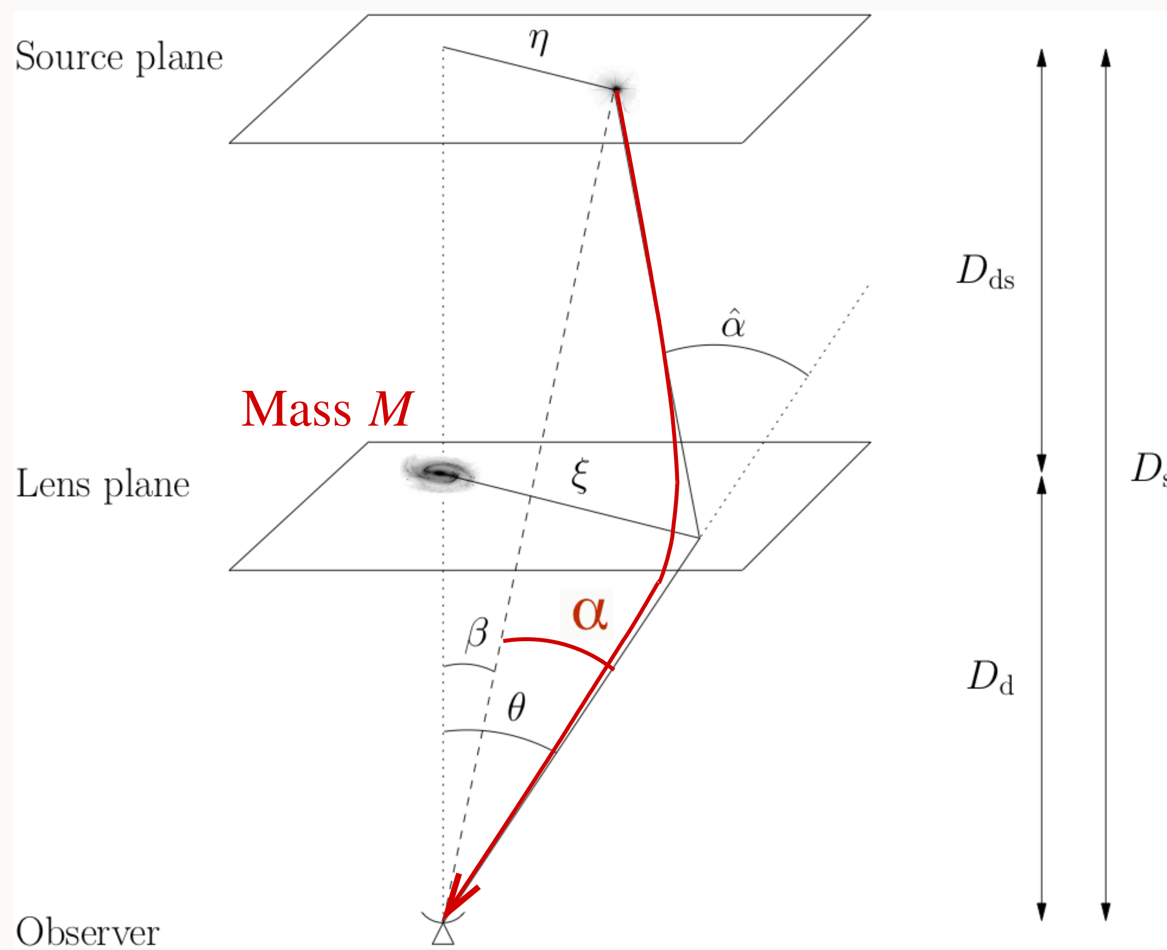
- Deflection angle is a gradient:

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

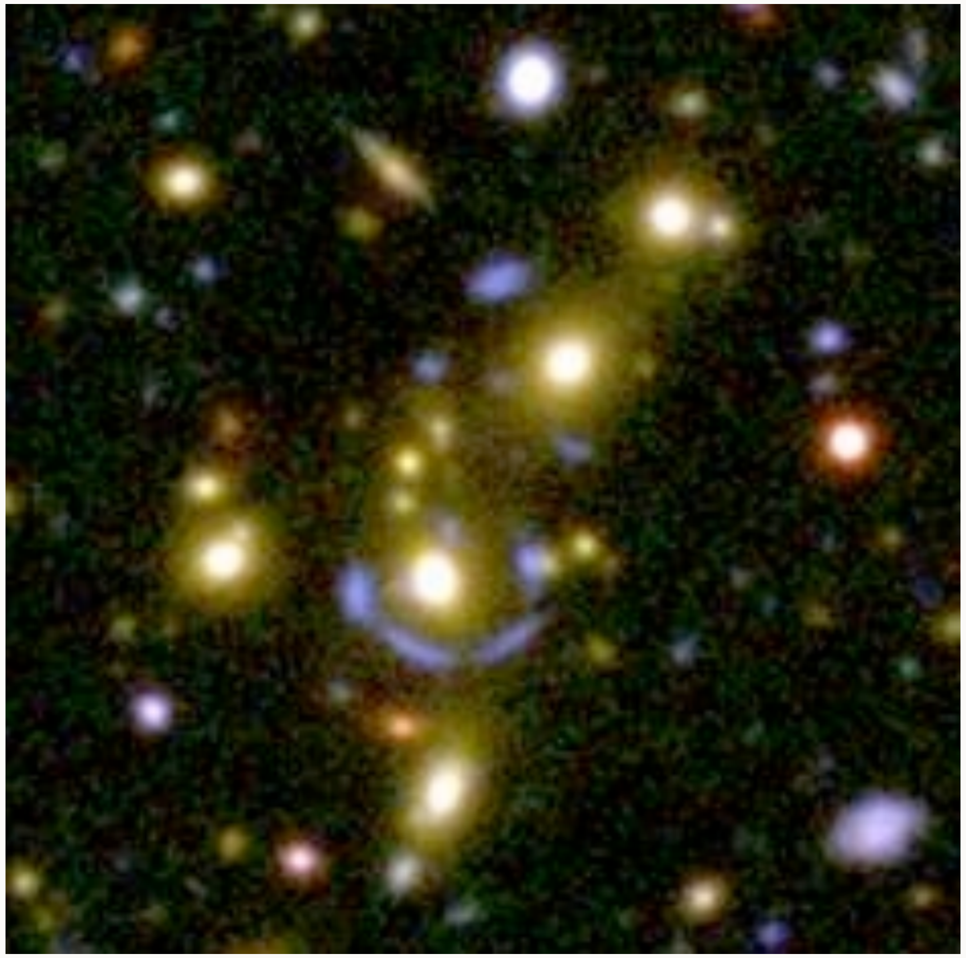
2D lensing potential

- First order effect: Deflection of a point source

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



LENSING DISTORTIONS



z_{source}	0.47	?
z_{lens}	0.21	0.49

SLACS (Sloan lens ACS Survey)
Bolton et al. 2009

CFHTL12k image
Czoske et al. 2001

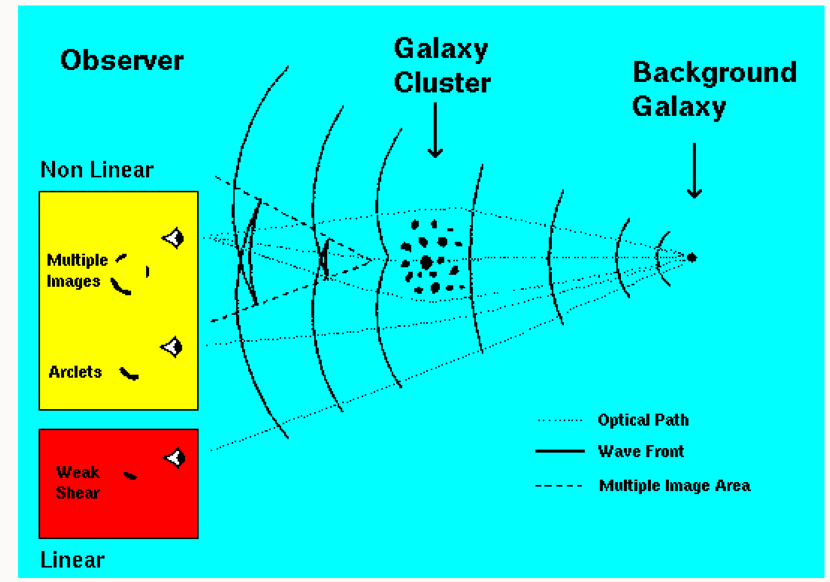
CLUSTER LENSING

The cluster of galaxies Abell 2218

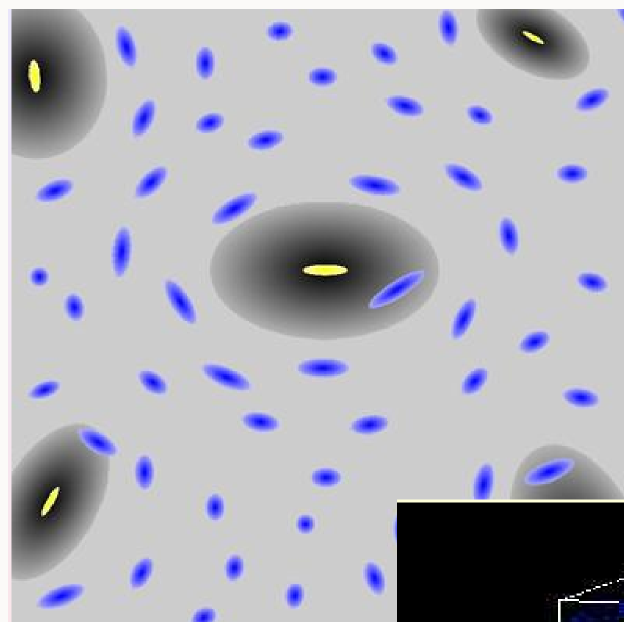
APPLICATIONS OF WEAK LENSING

Weak lensing

- … by clusters
  Mass, profile, substructure



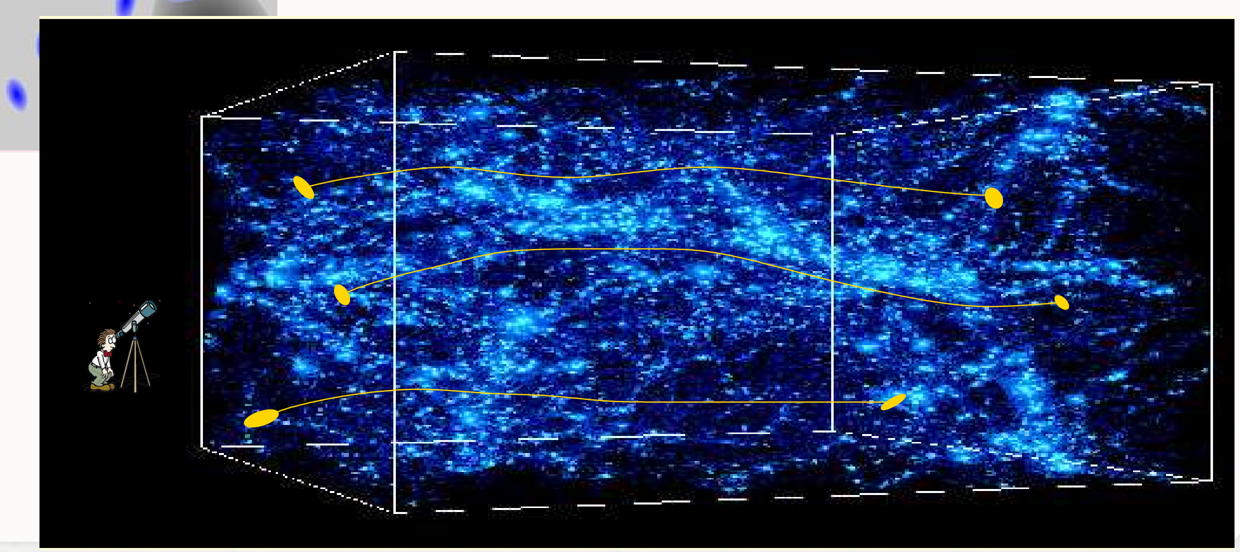
- … by galaxies
  Average mass, halos, bias



background galaxy

foreground galaxy

- … by the large-scale structure
  Cosmology



A CLOSER LOOK

- The lens equation

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

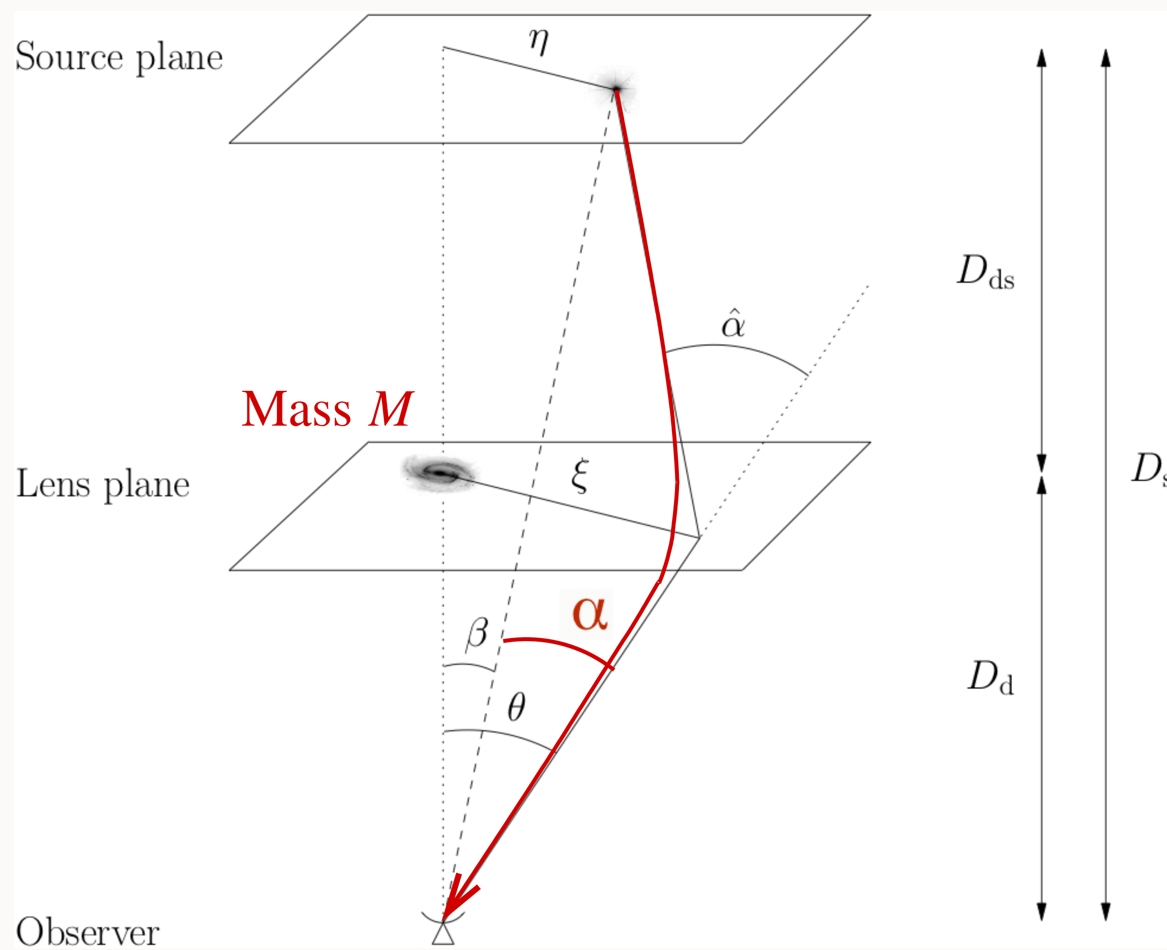
is a mapping from the image plane (θ) to the source plane (β)

mapping of light distribution

- Linearize this mapping, define Jacobian $\mathcal{A}$:

$$\frac{\partial \beta_i}{\partial \theta_j} = \mathcal{A}_{ij} = \frac{\partial \theta_i}{\partial \theta_j} - \frac{\partial \alpha_i}{\partial \theta_j}$$

$$= \delta_{ij} - \begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix}$$

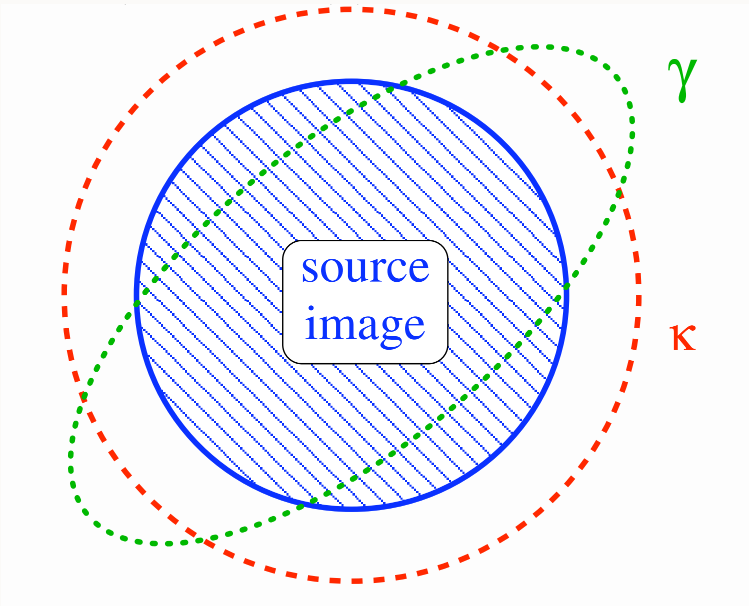


CONVERGENCE & SHEAR

Lensing mapping is given to first order by Jacobian

$$\begin{pmatrix} \kappa + \gamma_1 & \gamma_2 \\ \gamma_2 & \kappa - \gamma_1 \end{pmatrix}$$

- Convergence κ: isotropic magnification
- Shear γ: anisotropic stretching
- κ and γ are second derivatives of the lensing potential Φ.



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

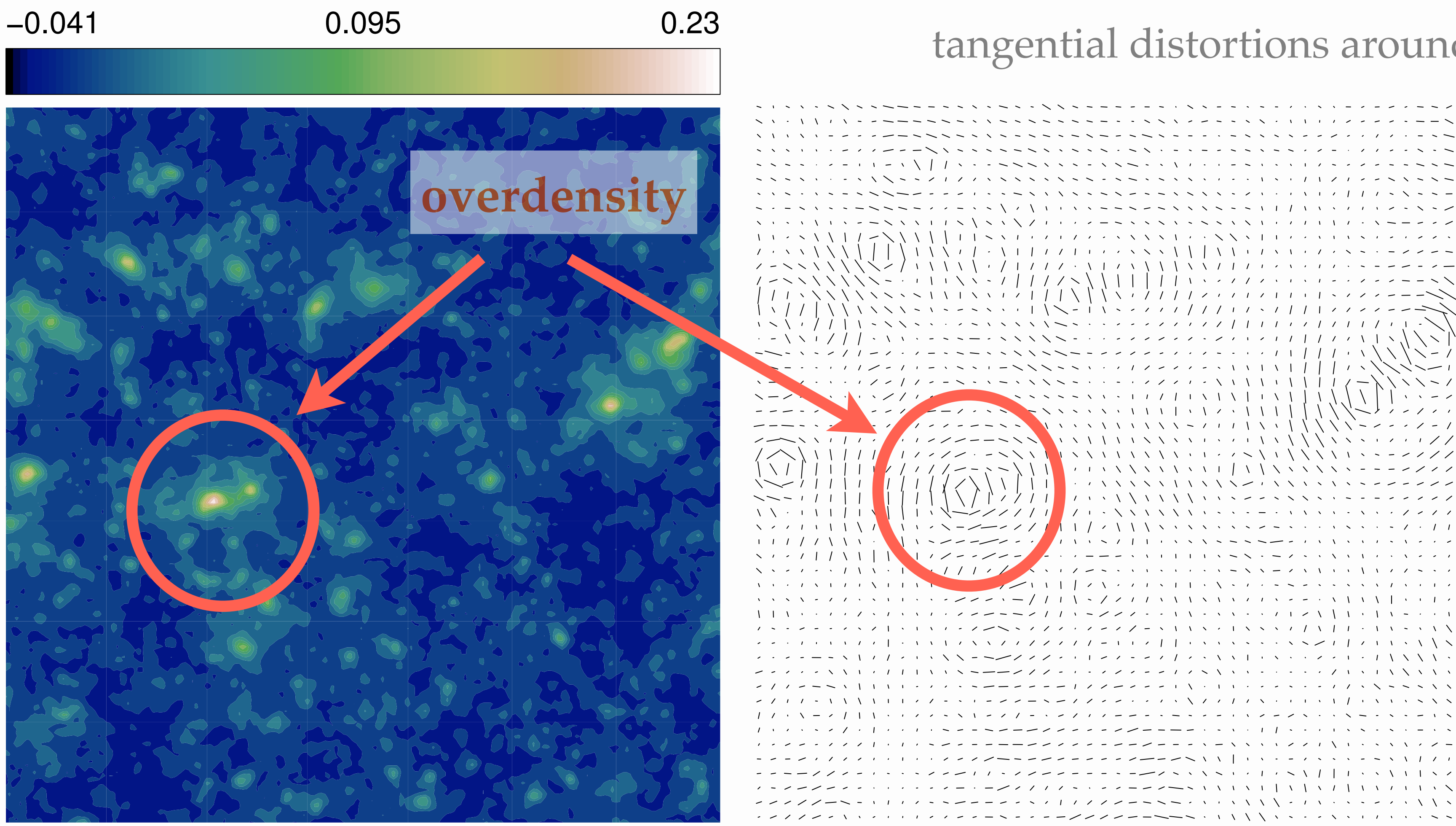
[Actually, κ is the scaled projected mass density, related to Φ via a Poisson equation: $2\kappa = \Delta\Phi$]

MASS AND SHEAR

Projected matter density
convergence κ

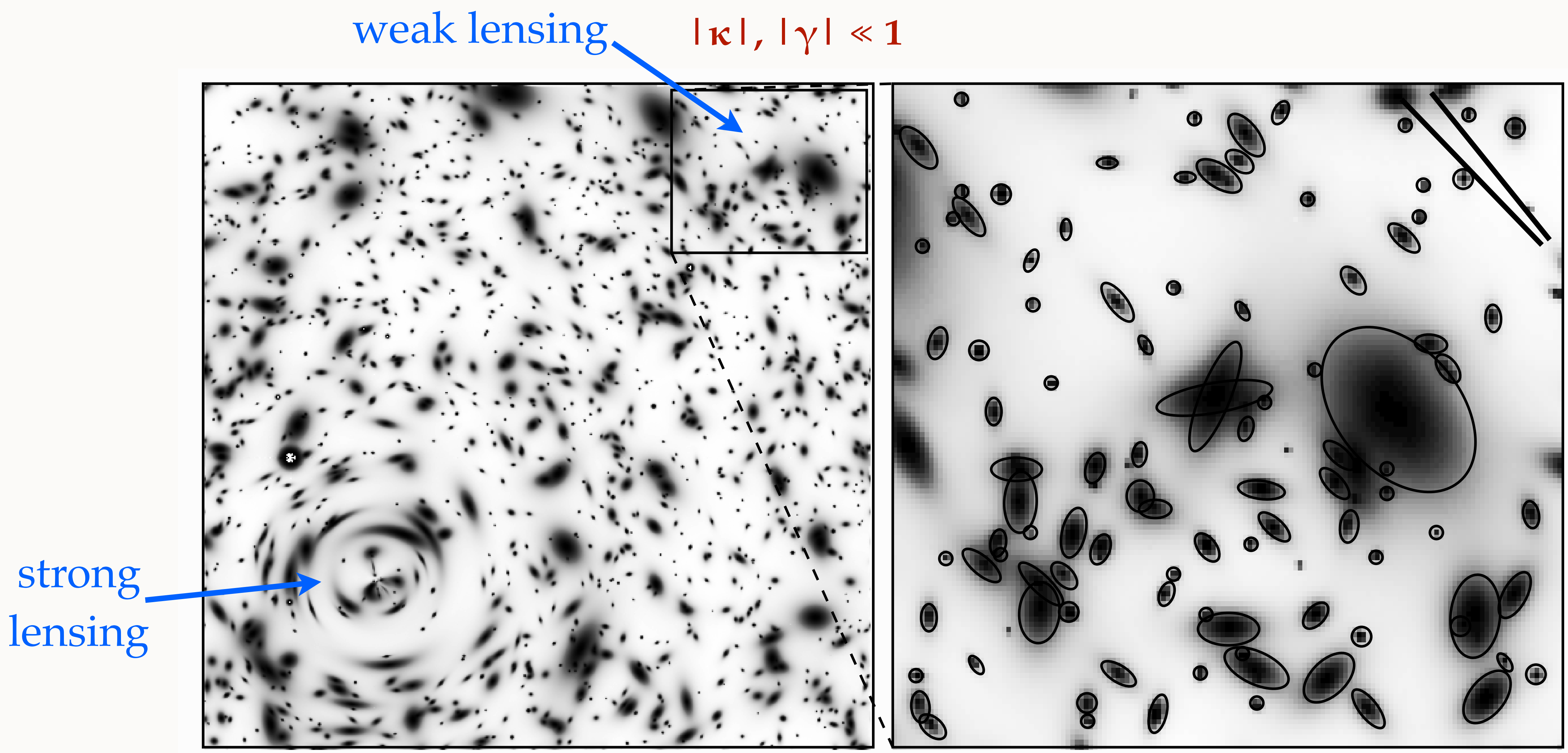
Distortion field
shear γ

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

Geometry
Growth (<delta^2>)

Weak lensing by the large-scale structure

- Continuous distortion along light ray path

comoving coordinates

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

lensing efficiency

density contrast

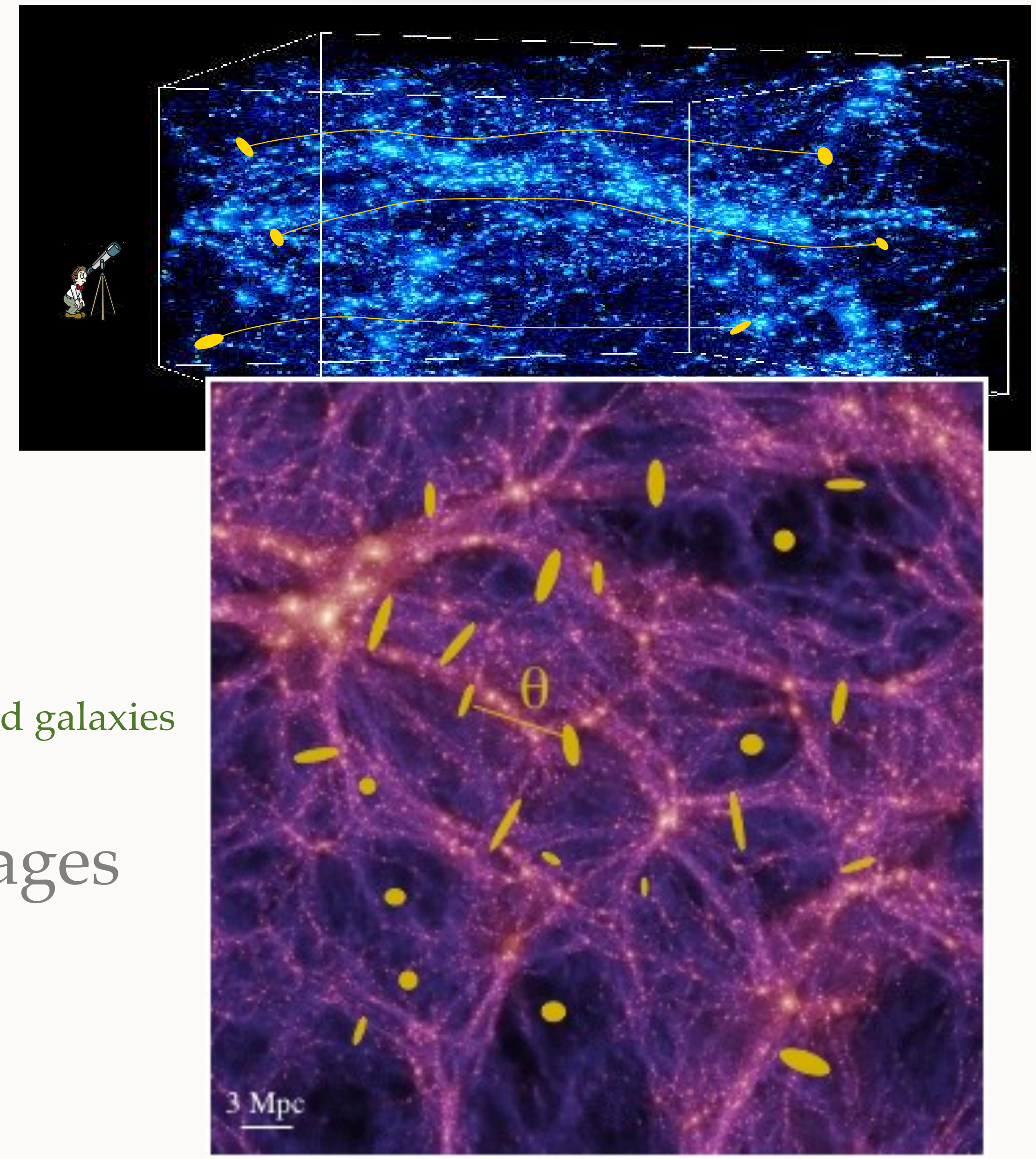
$$G(\chi) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \frac{\Omega_{\rm m}}{a} \int_{\chi}^{\chi_{\rm lim}} \mathrm{d}\chi' \, p(\chi') \frac{\chi(\chi'-\chi)}{\chi'}$$

redshift distribution of background galaxies

- Coherent distortions of galaxy images → measure shape correlations

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

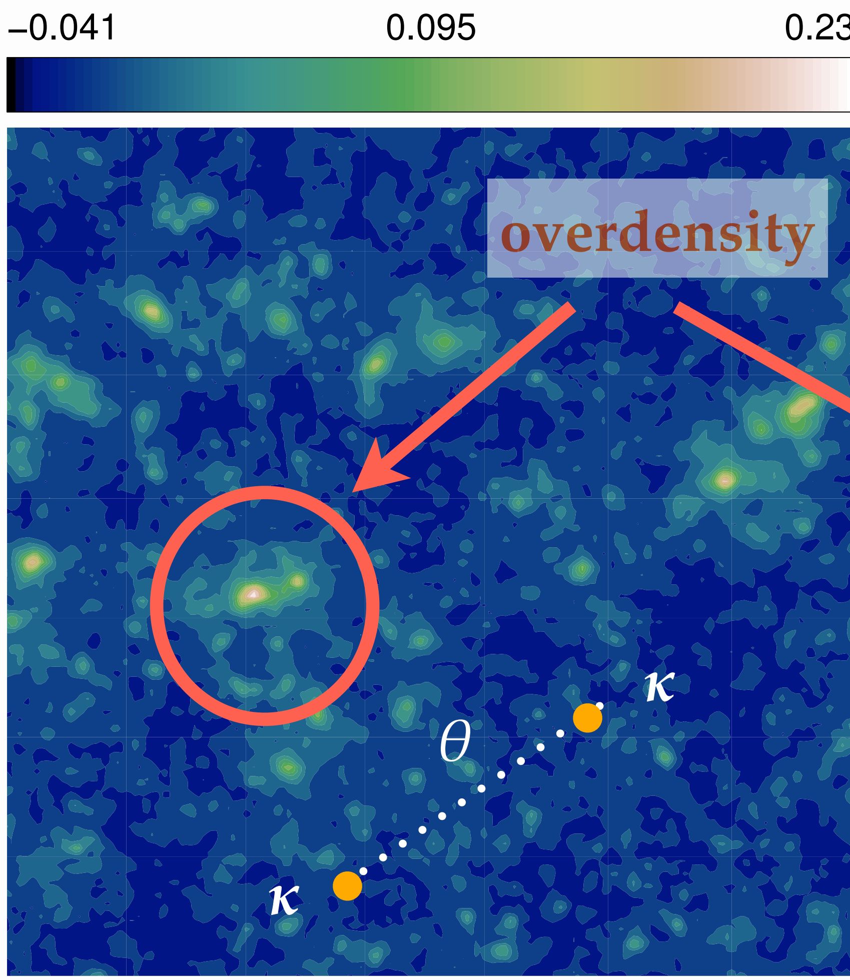
shear variance



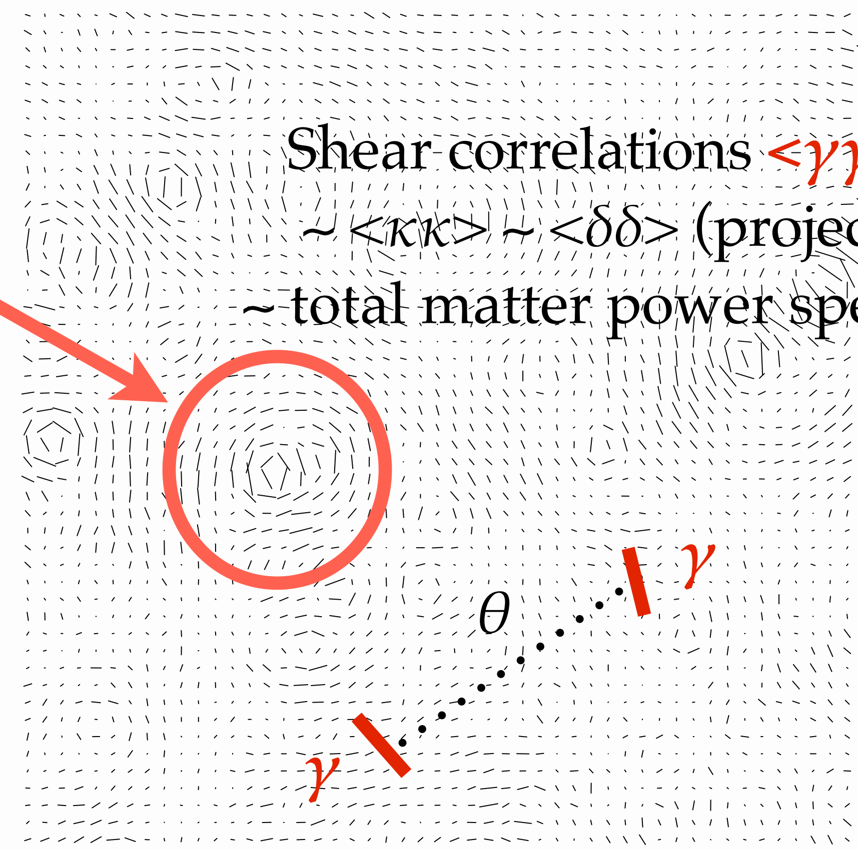
MASS AND SHEAR

Projected matter density
convergence κ

Distortion field
shear γ



tangential distortions around mass peaks

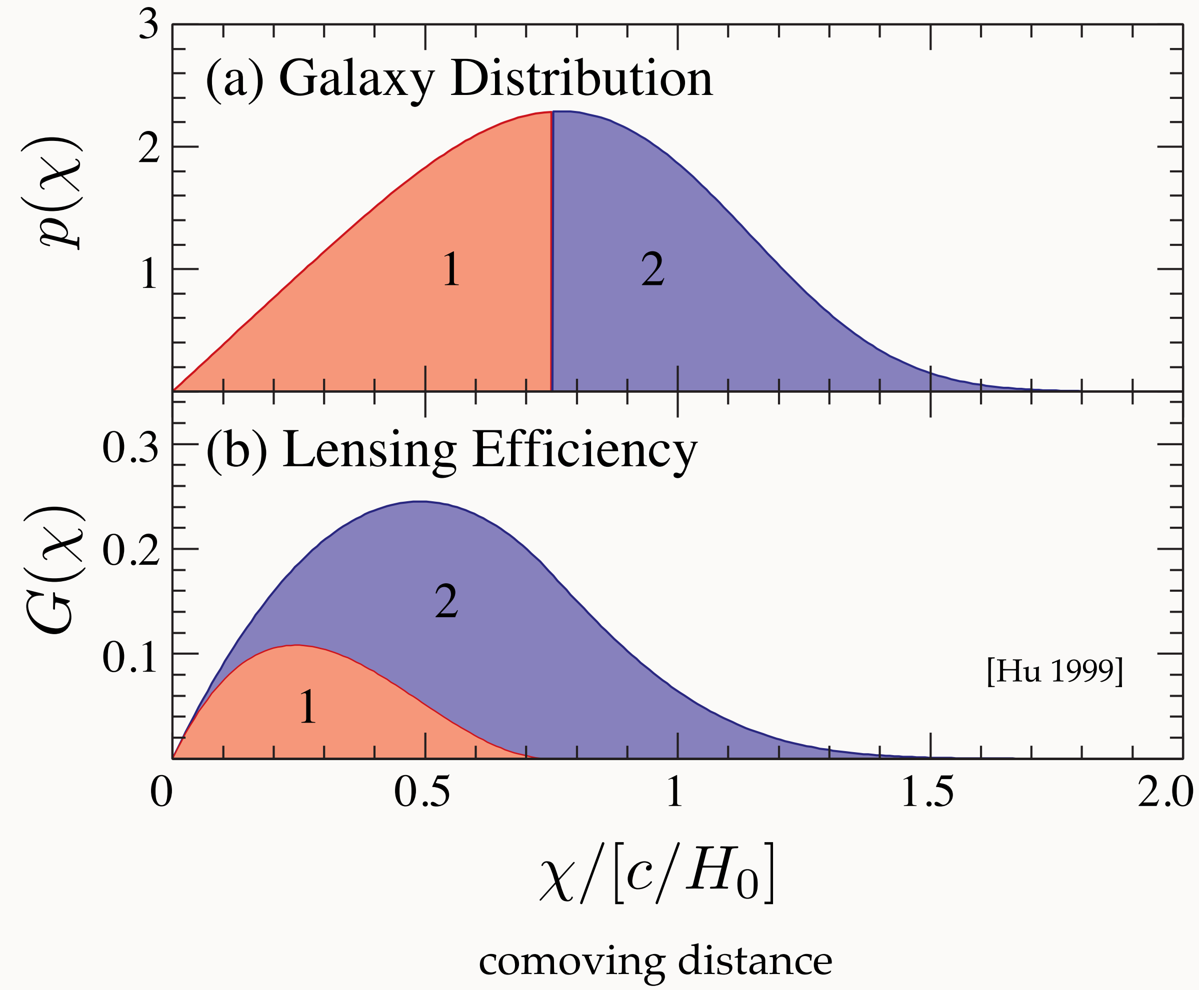


Shear correlations $<\gamma\gamma>(\theta)$
~ $<\kappa\kappa>$ ~ $<\delta\delta>$ (projected)
~ total matter power spectrum

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

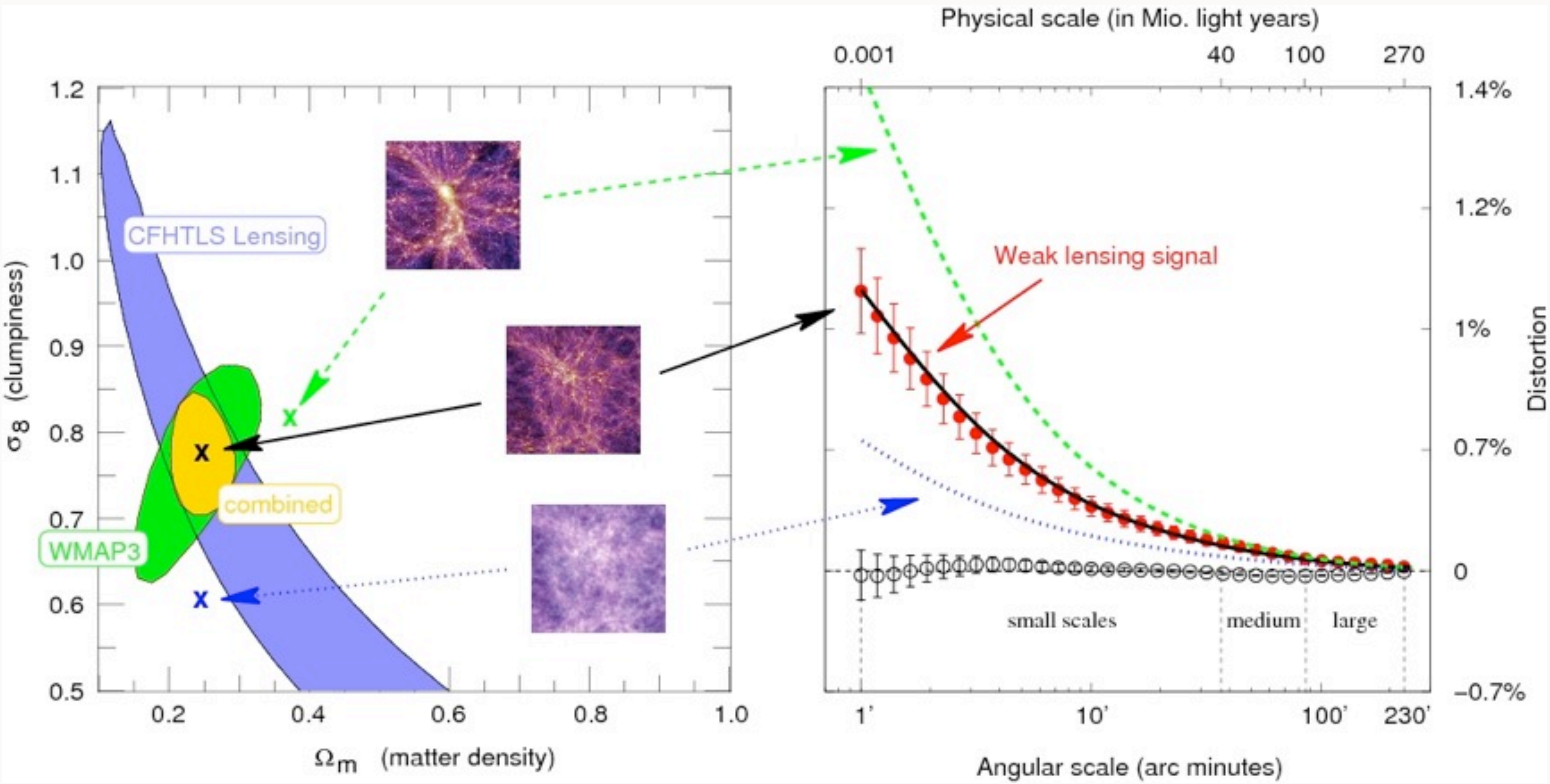
SHEAR TOMOGRAPHY

- Lensing efficiency depends on redshift distribution
- Split galaxies into redshift bins: measure growth of structure
- For ΛCDM models: 2-3 bins already sufficient. But (many?) more bins desired: *w(z)*, modified gravity, intrinsic alignment



- Need accurate photometric redshifts

WEAK LENSING SUMMARY



[Fu et al. 2008, CNRS press release]

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

= density power spectrum amplitude

The CFHTLenS team

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M. Hudson
B. Gillis

L. Fu

Y. Mellier
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L. Miller
M. Velander

M. Kilbinger

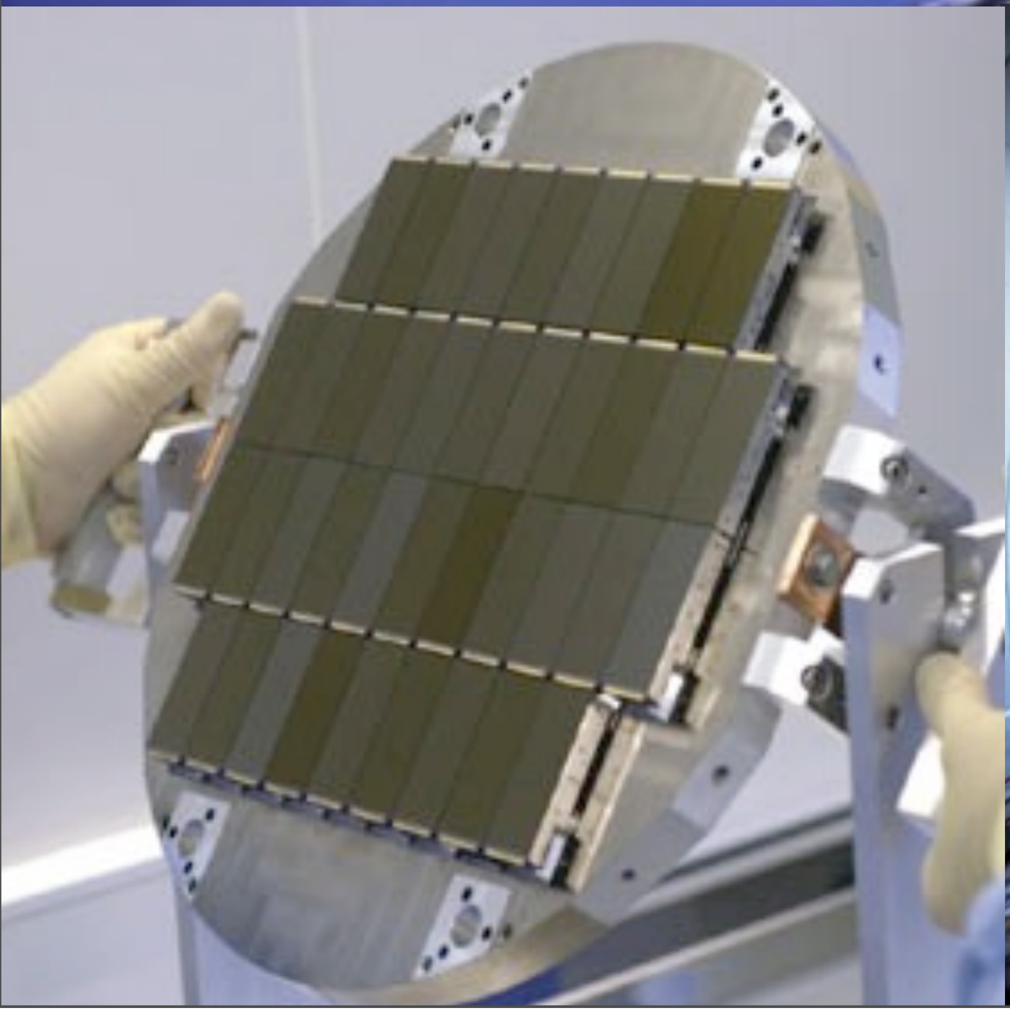
T. Erben
P. Simon
T. Schrabback
E. van Uitert

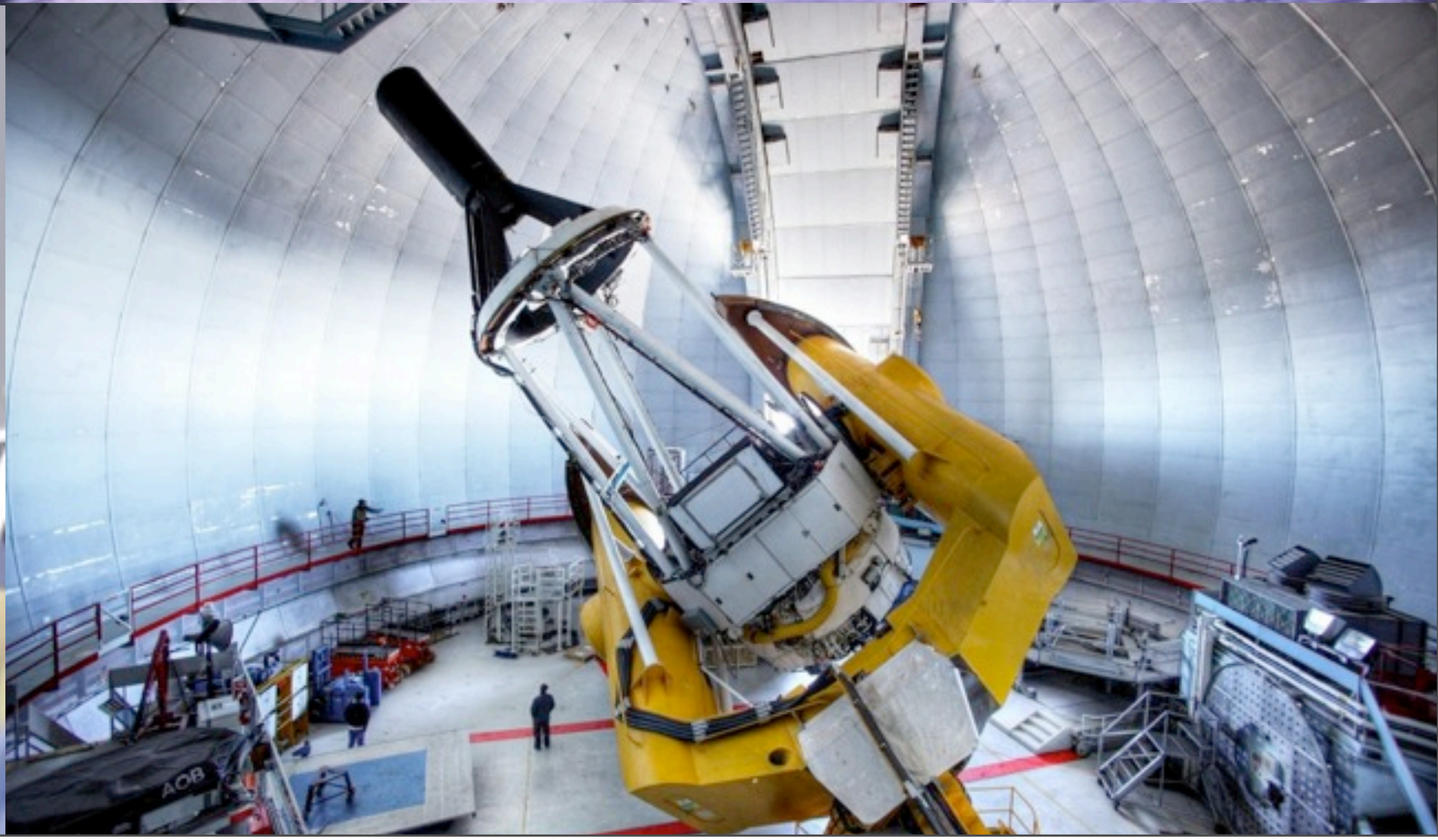
J. Coupon

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

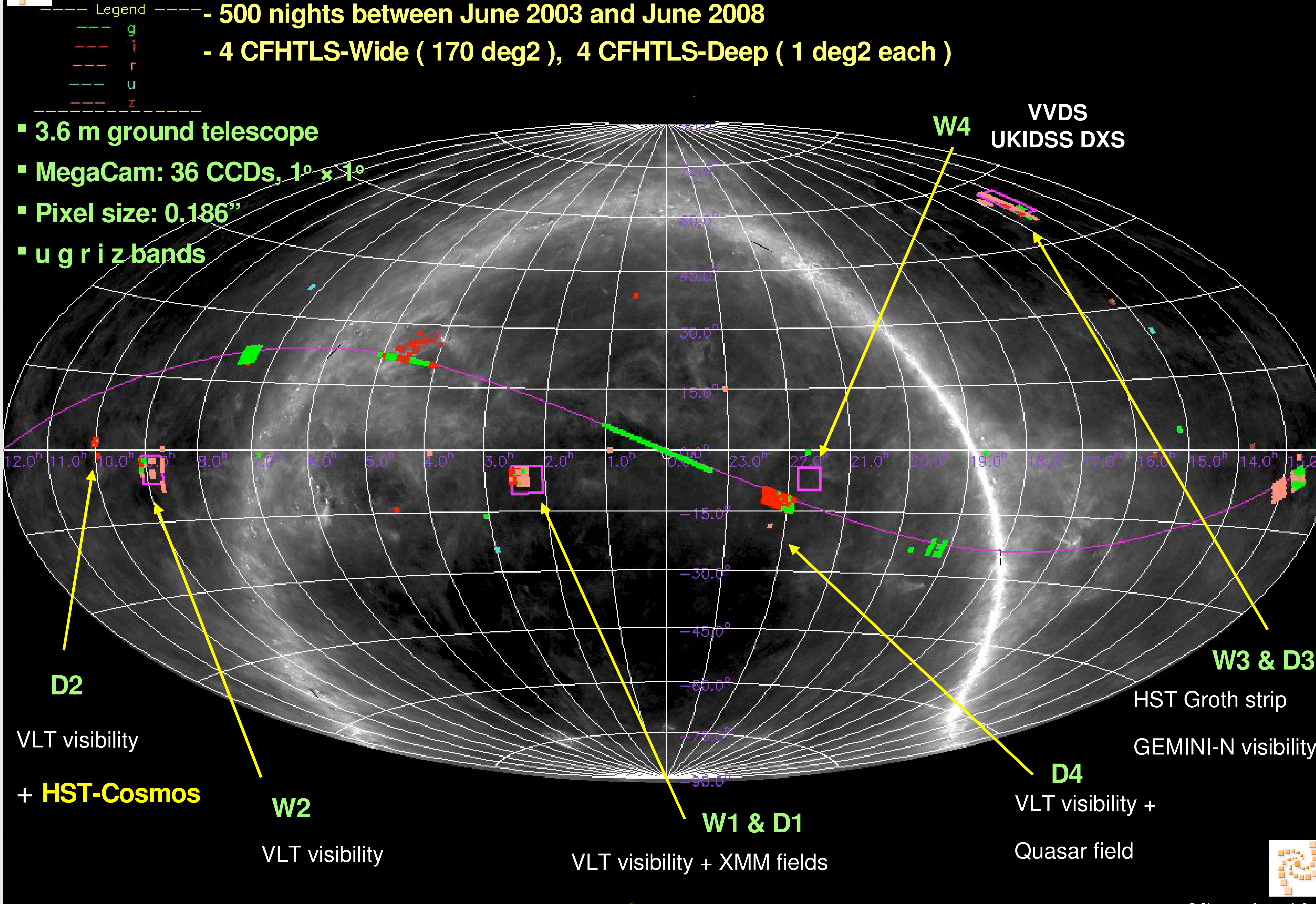




Canada-France-Hawaii Telescope Legacy Survey: Canada-France collaboration

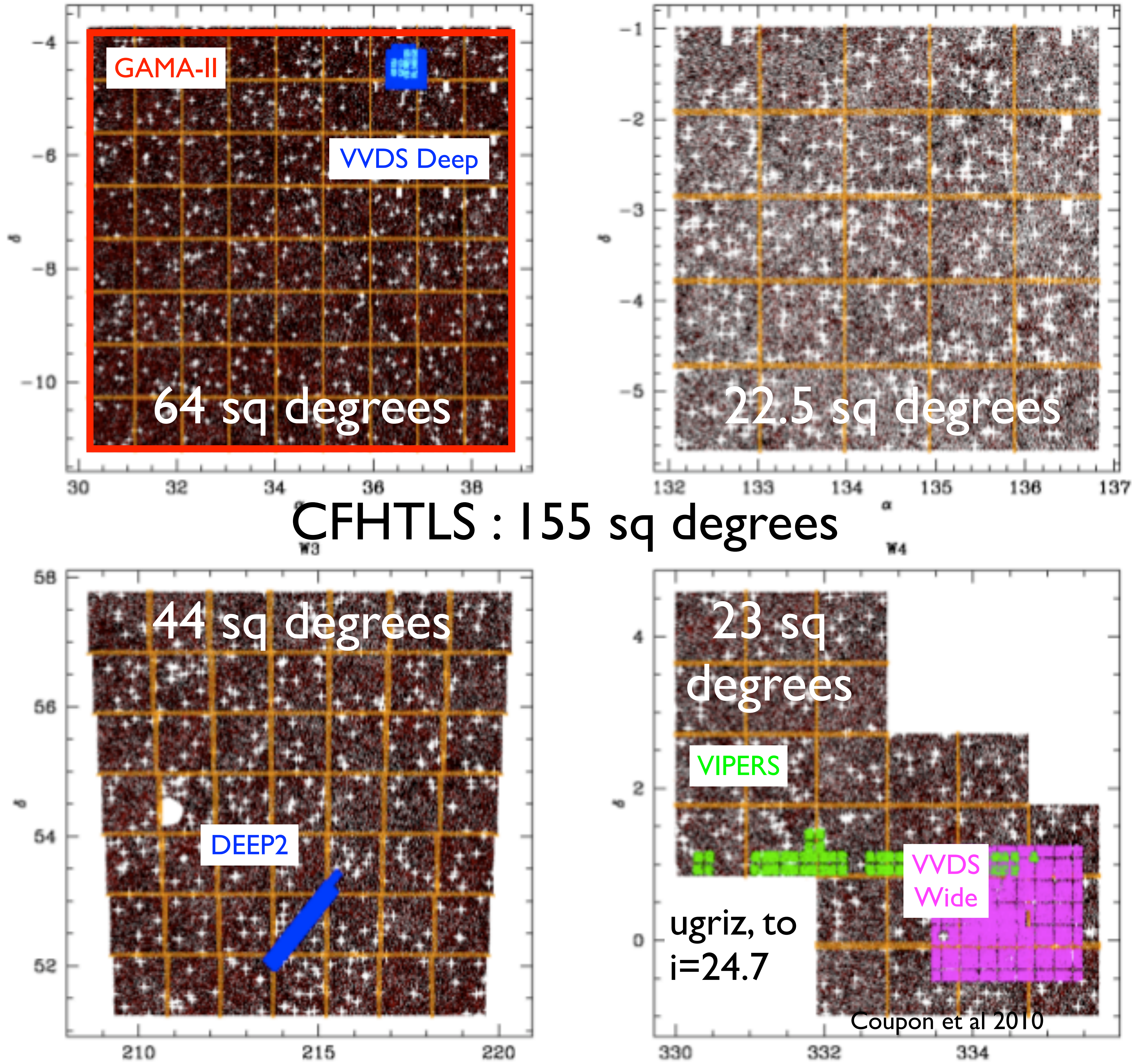
- 500 nights between June 2003 and June 2008
- 4 CFHTLS-Wide (170 deg2), 4 CFHTLS-Deep (1 deg2 each)

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

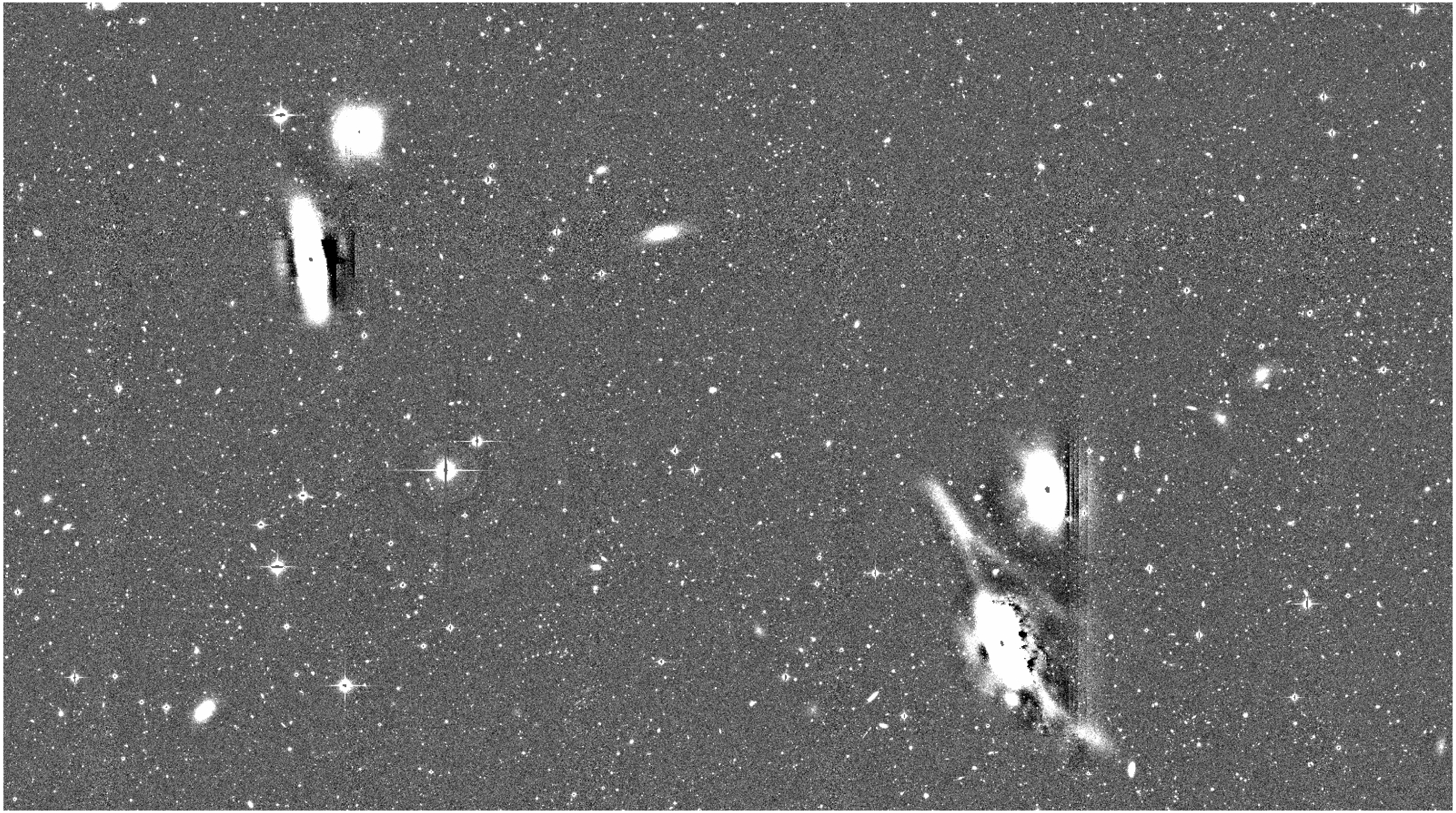


VVDS spectro. survey

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

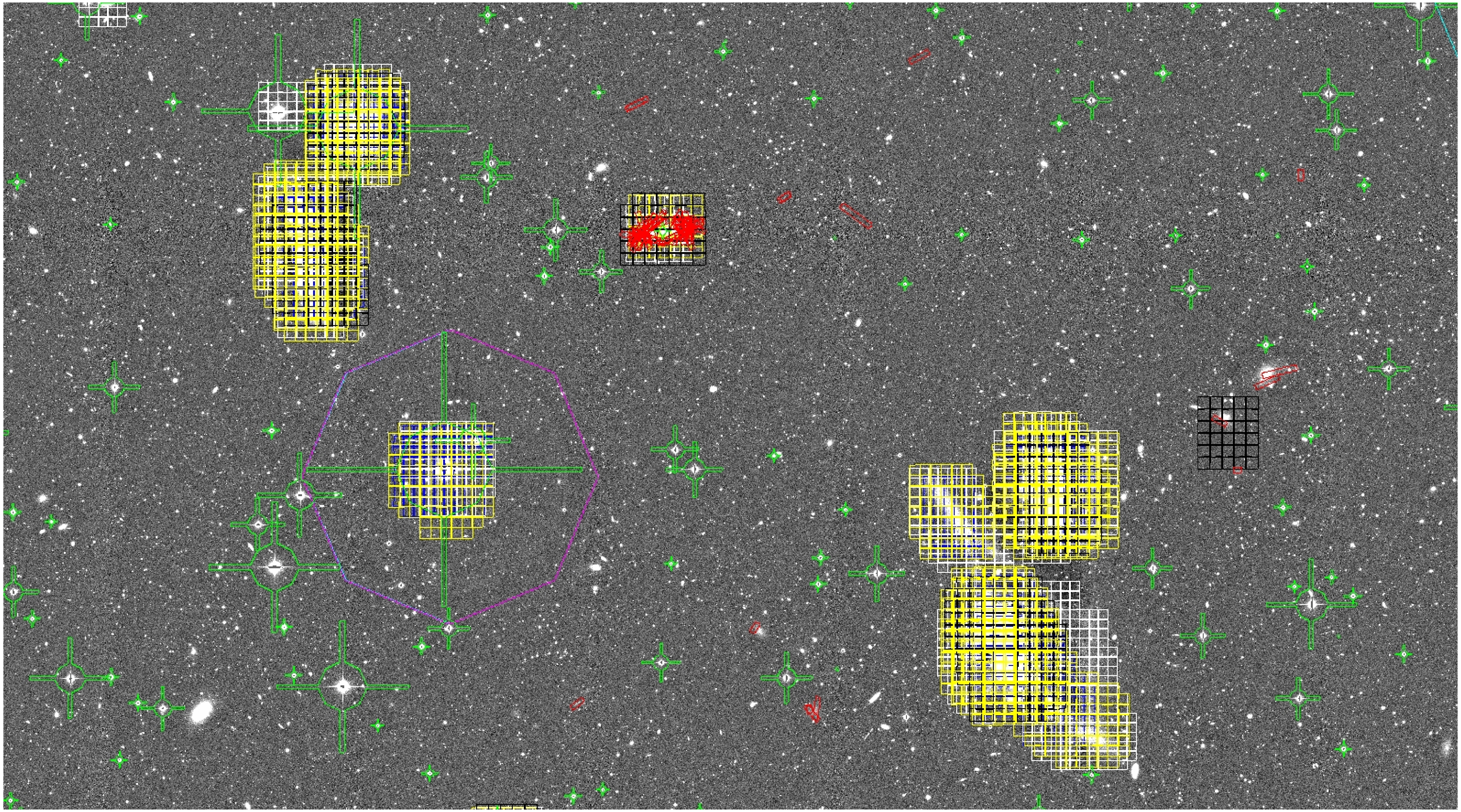

GAMA-II
VVDS Deep
64 sq degrees
22.5 sq degrees
CFHTLS : 155 sq degrees
44 sq degrees
DEEP2
23 sq degrees
VIPERS
VVDS Wide
ugriz, to i=24.7
Coupon et al 2010

A MEGACAM@CFHT Image Section



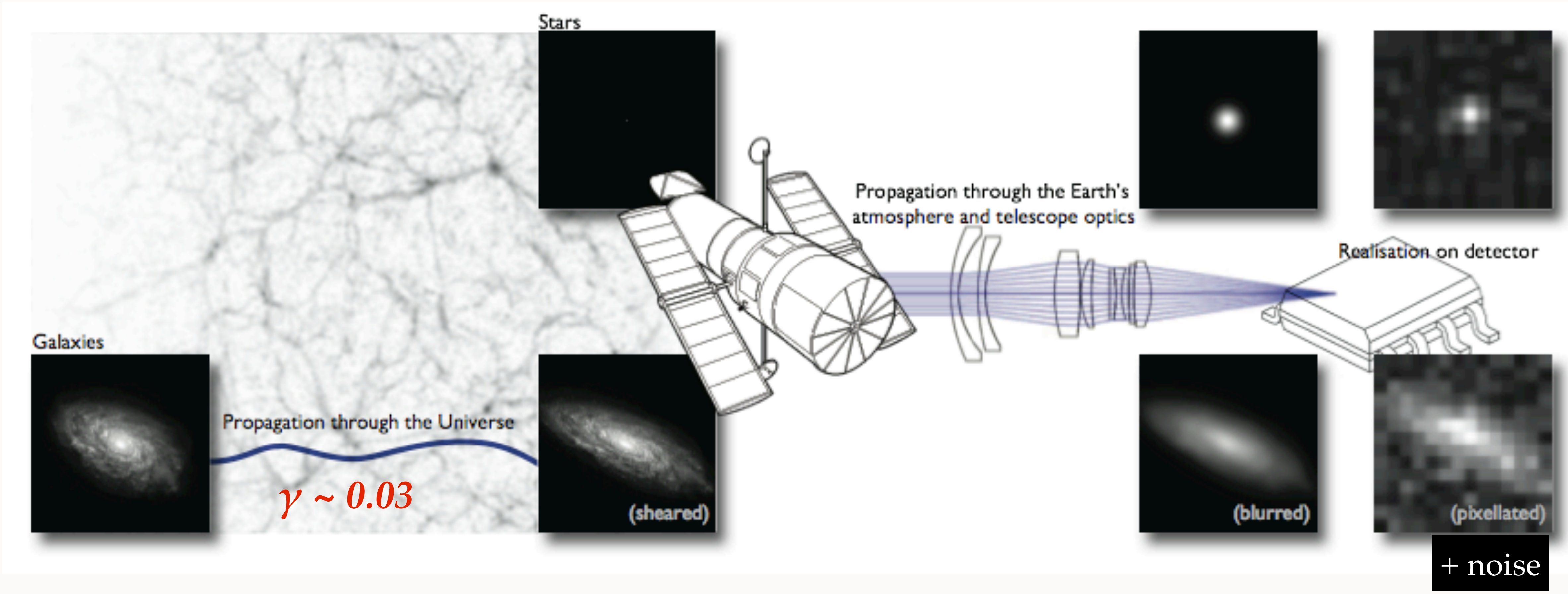
Regions around bright stars and big galaxies need to be excluded from our weak lensing studies.

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

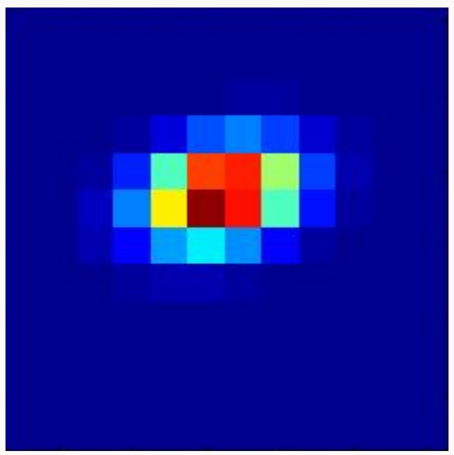
SHAPE MEASUREMENT: LENSFIT

[Miller et al 2007, Kitching et al 2008]

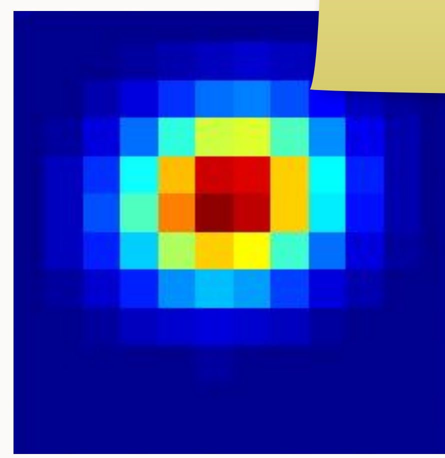
Problems:
- correlated noise
- stacked PSF complicated, e.g. twisted isophotes
- interpolation = smoothing

Bayesian lensfit: lossless, capturing all information

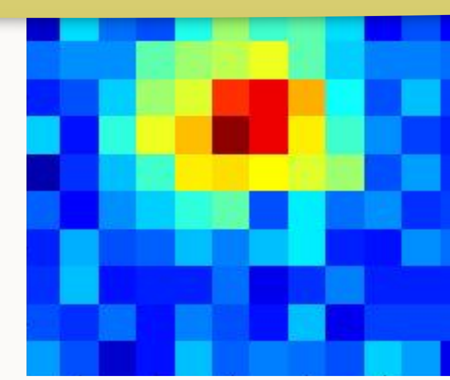
Model

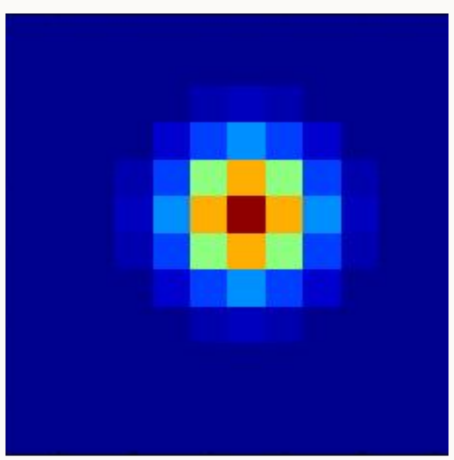


forward FFT, multiply, inverse FFT



Compare data and model to maximise likelihood





PSF
(Point Spread Function)

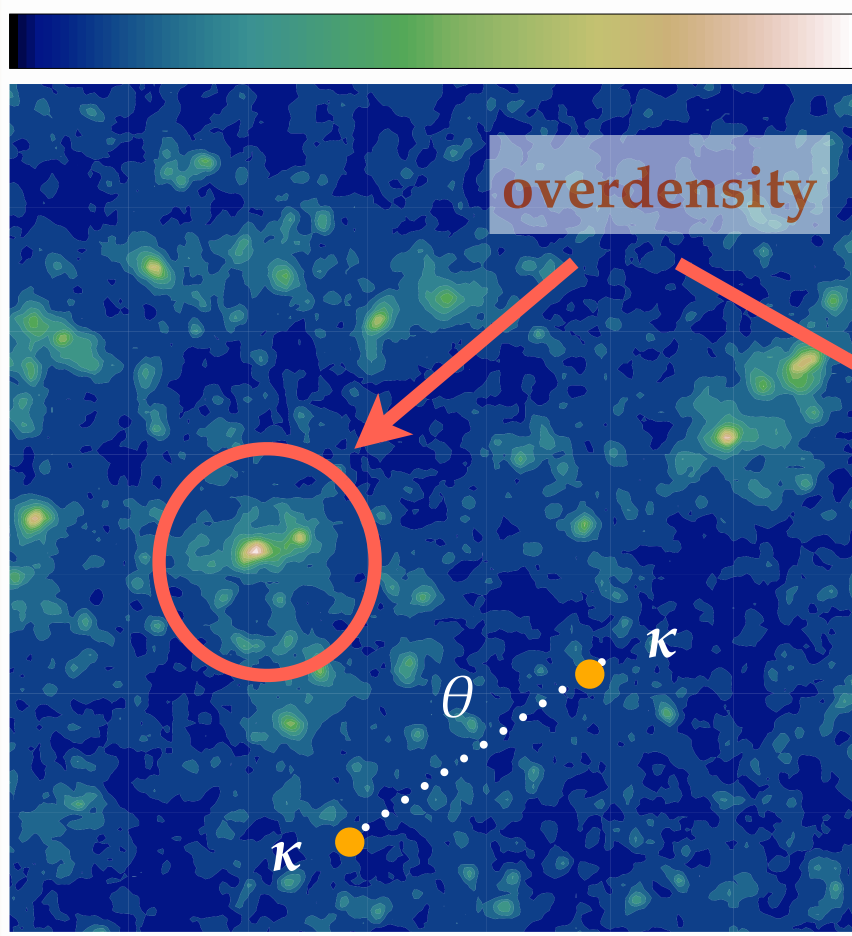
Measure shapes on individual exposures, combines ellipticity posteriors in Bayesian way.

Avoids problems in co-added images.

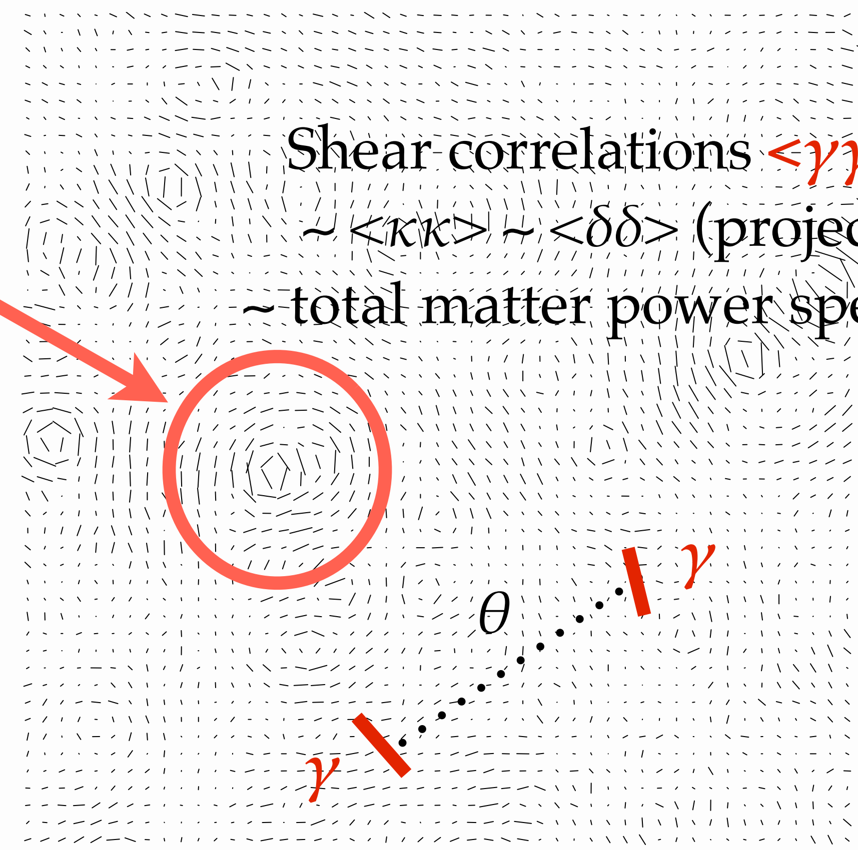
MASS AND SHEAR

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

LIKELIHOOD FUNCTION

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

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

$\boldsymbol{d}^{\mathsf{obs}}$: 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. $\Omega_{\mathsf{m}}, \sigma_{\mathsf{8}}, h, w \ldots$

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

Beyond Gaussian likelihood:
- Hartlap et al. (2009): Sample likelihood from *N*-body simulations
- Schneider & Hartlap (2009): non-linear transformation of variables
- Benabed et al. (2009): Inverse-Gamma distribution for low ell (CMB)

LIKELIHOOD FUNCTION

The likelihood is a high-dimensional function.

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

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

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

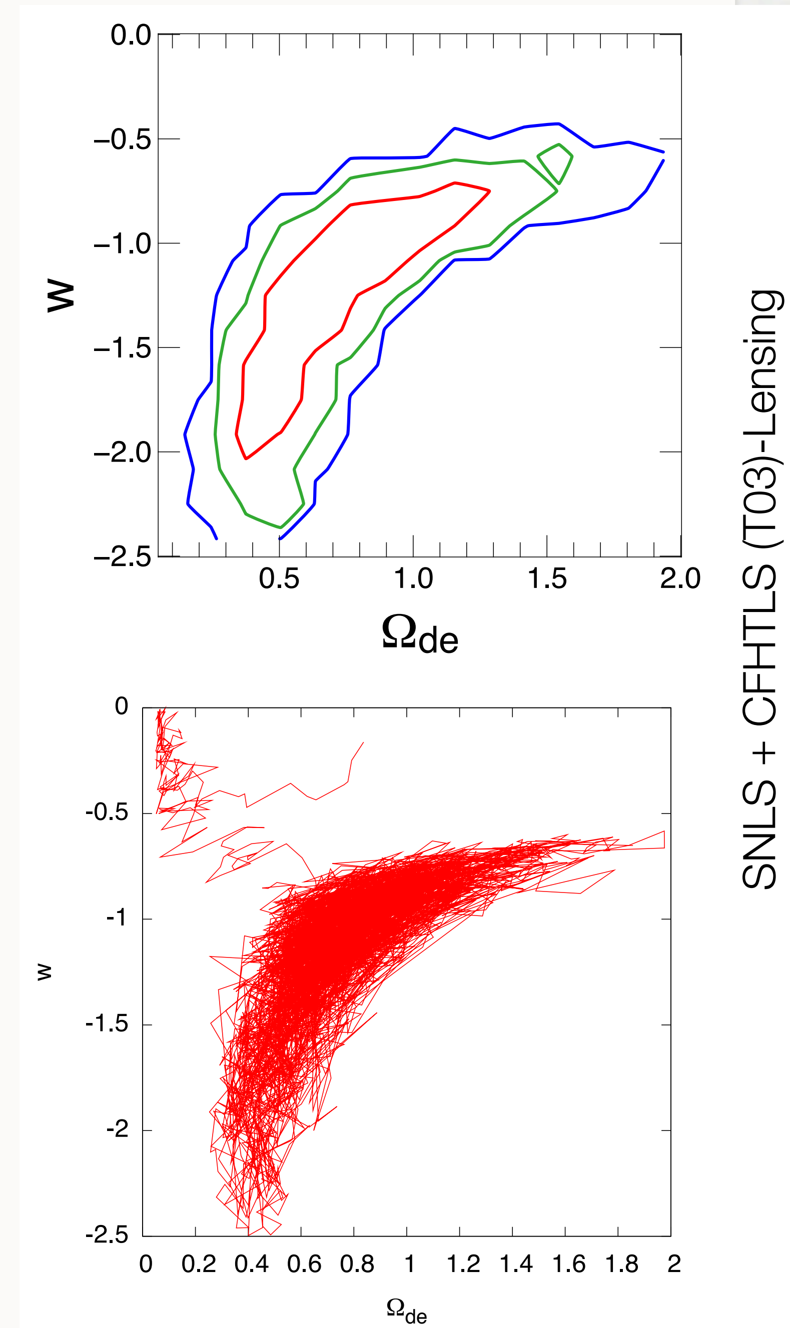
MONTE-CARLO SAMPLING

- Sample of points from the posterior (likelihood × prior).
  Aka Monte-Carlo integration.

- E.g.: Monte Carlo Markov Chain

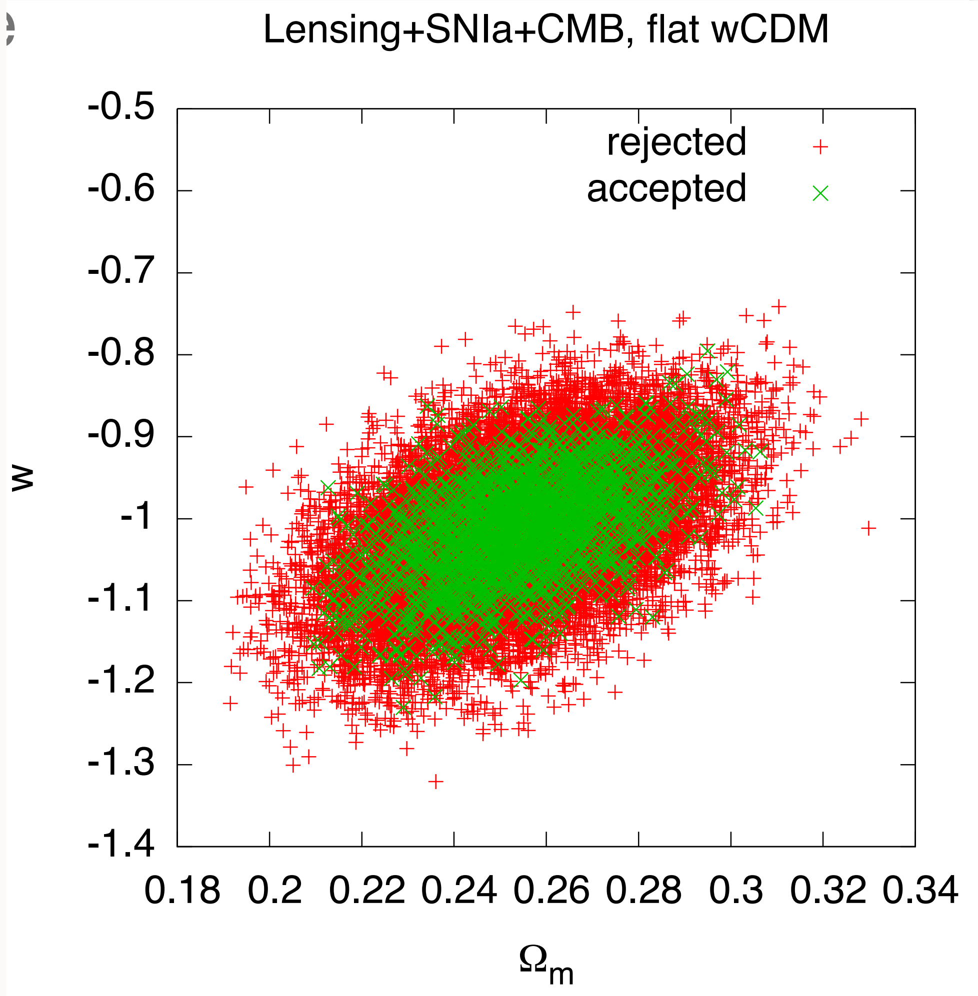
$$\theta_i \sim p \qquad\qquad p(\theta) \propto \mathcal{L}(\theta)\pi(\theta)$$

likelihood — prior



MCMC DRAWBACKS

- Difficult to reach & determine chain convergence
- Acceptance rate ≤ 25%
- Not easily or efficiently parallelisable
- For model comparison: Bayesian evidence difficult to estimate



CFHTLS (T03)-Lensing

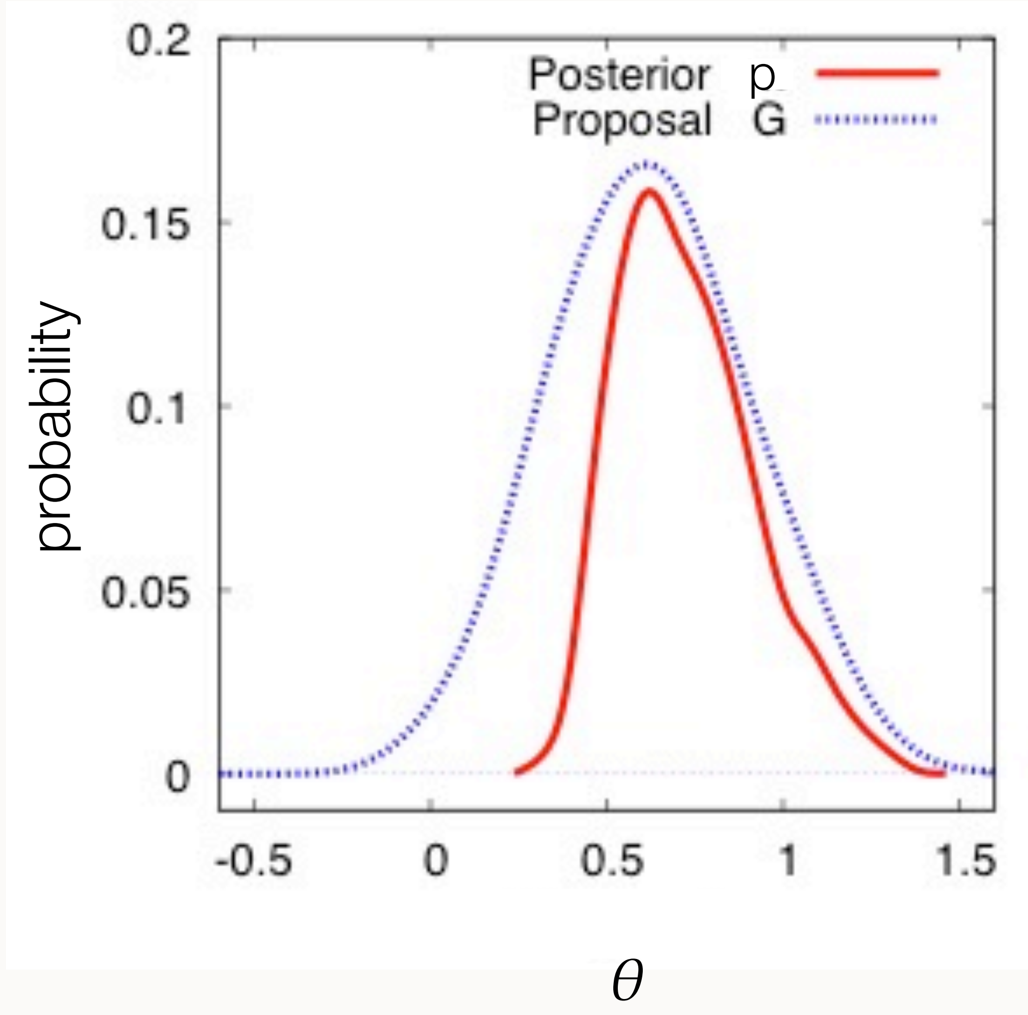
IMPORTANCE SAMPLING

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

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

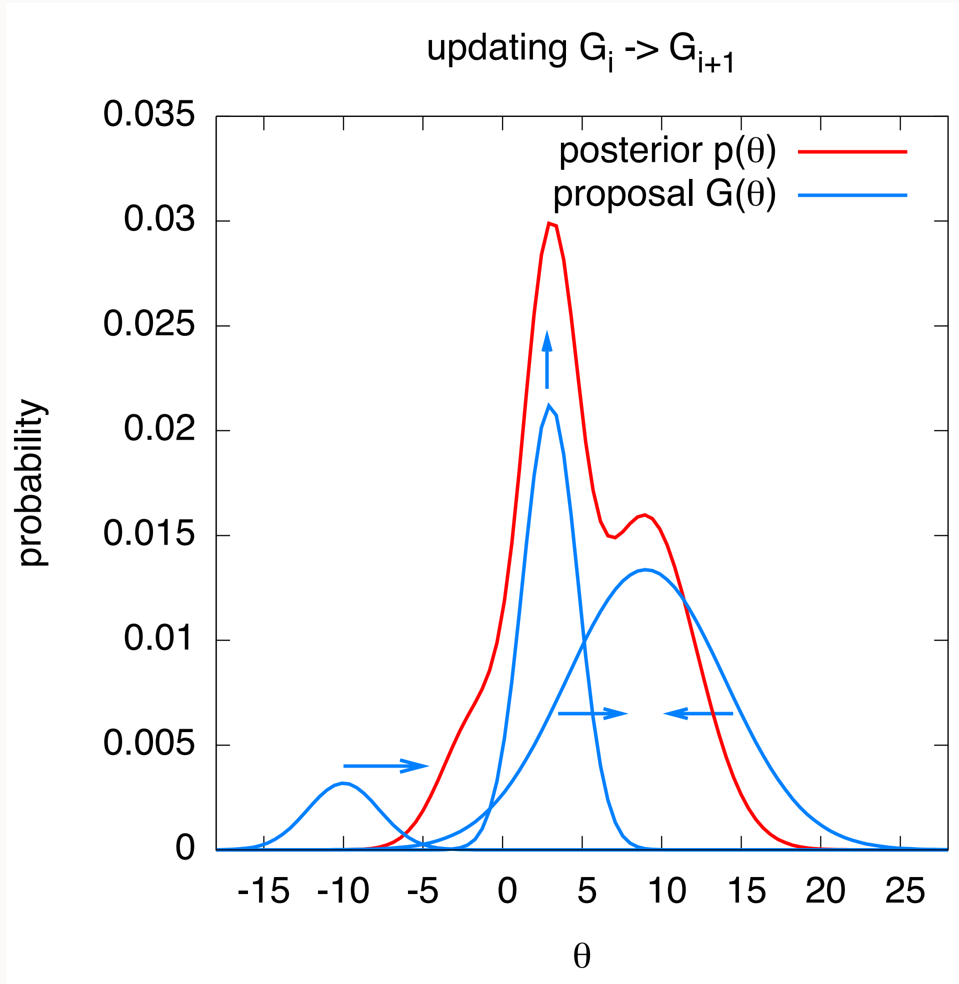
- Evaluation of posterior p (likelihood x prior) can be done in parallel

- Poor performance if proposal far from posterior



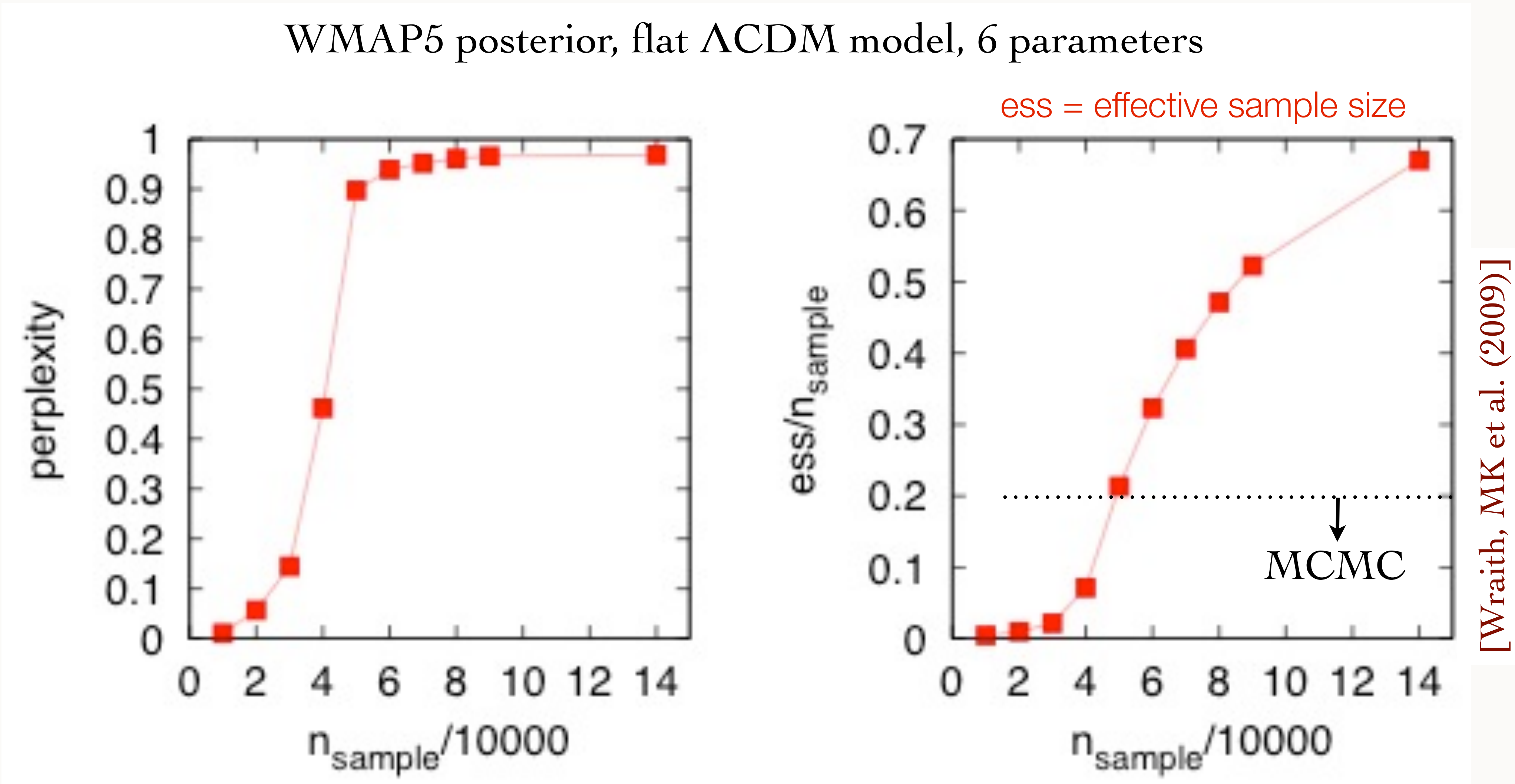
POPULATION MONTE CARLO (PMC)

- 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



PMC PERFORMANCE

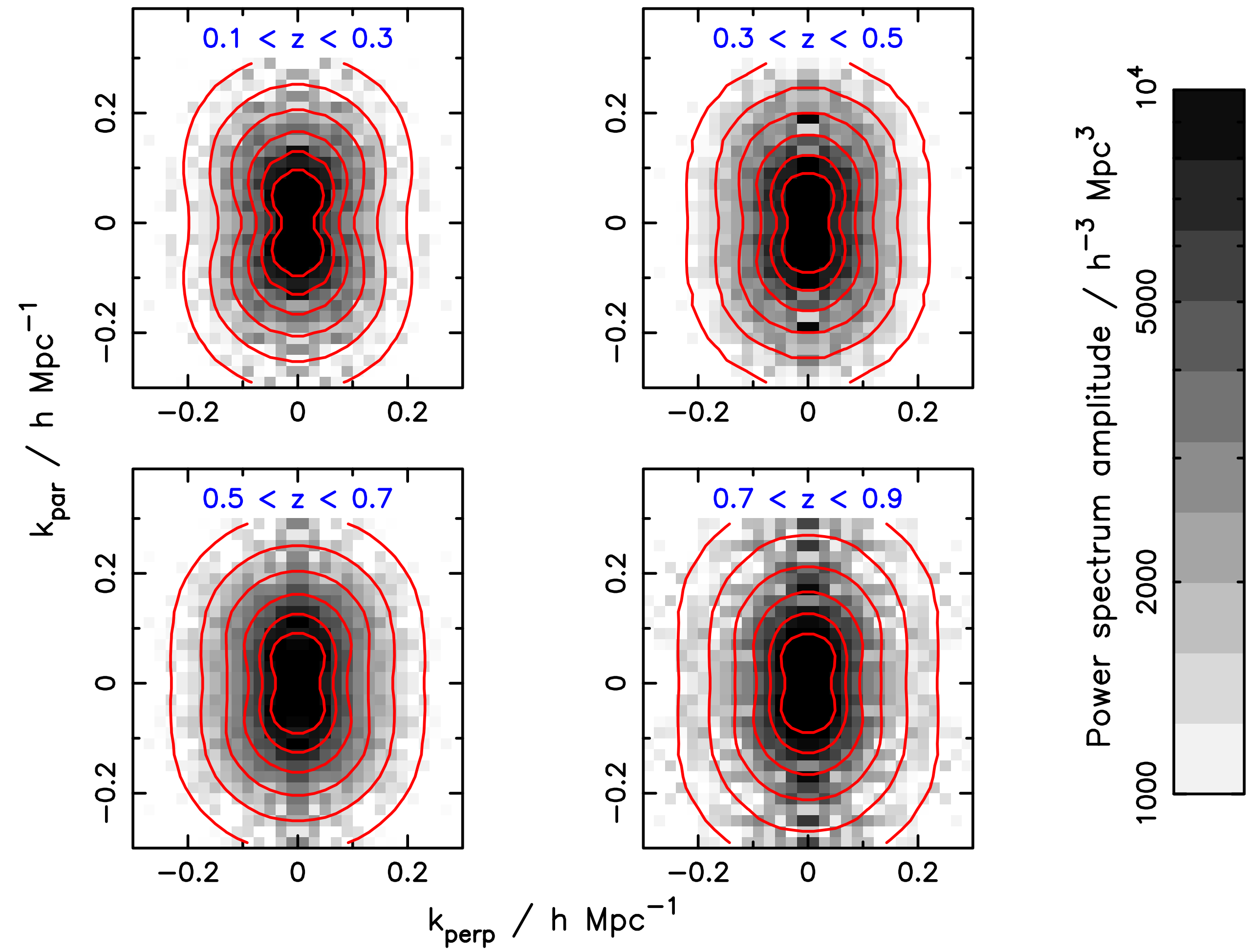
- Perplexity: Measures distance between posterior *p* and proposal *G*



10 iterations

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

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

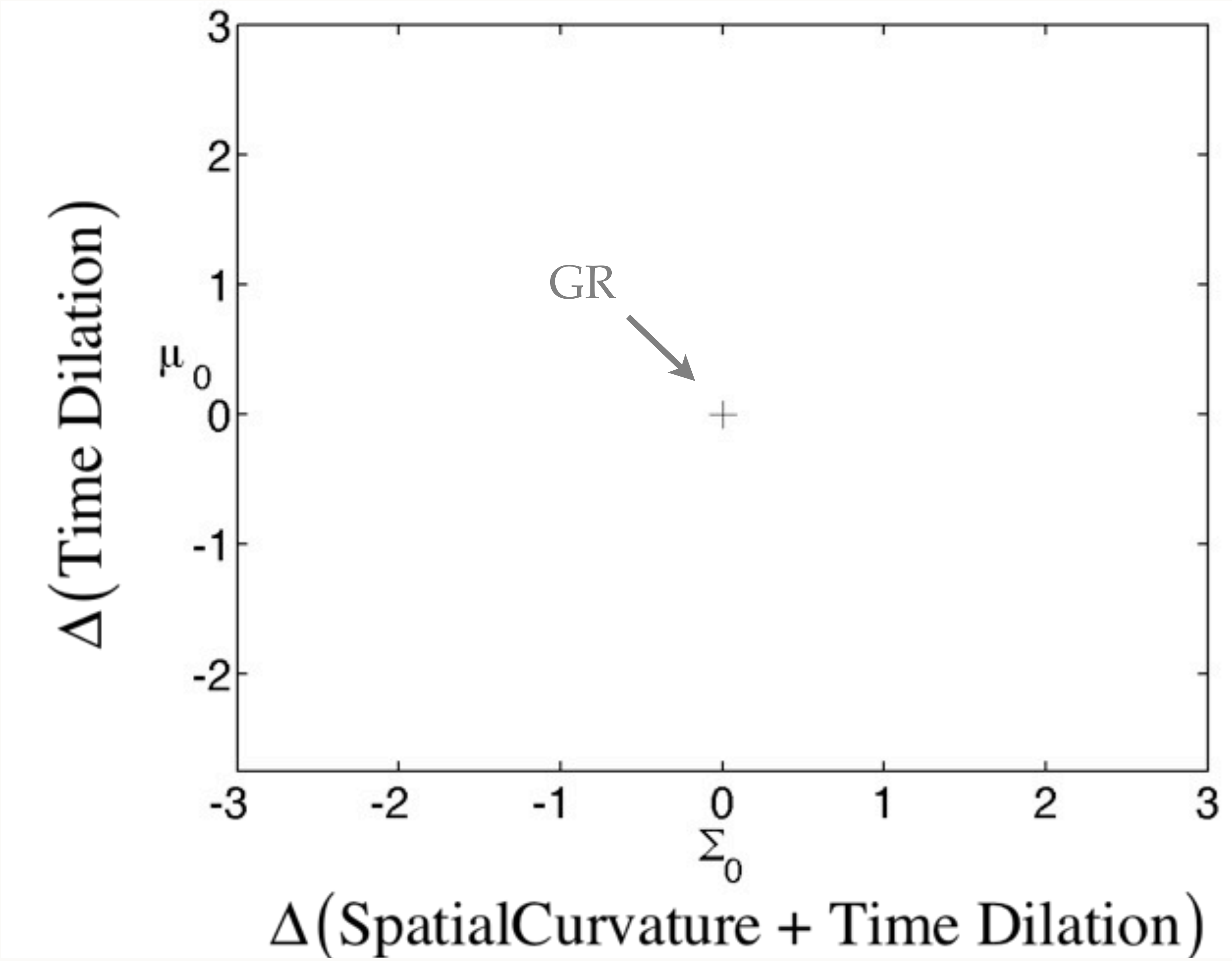
- Gravitational potential as experienced by galaxies:

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

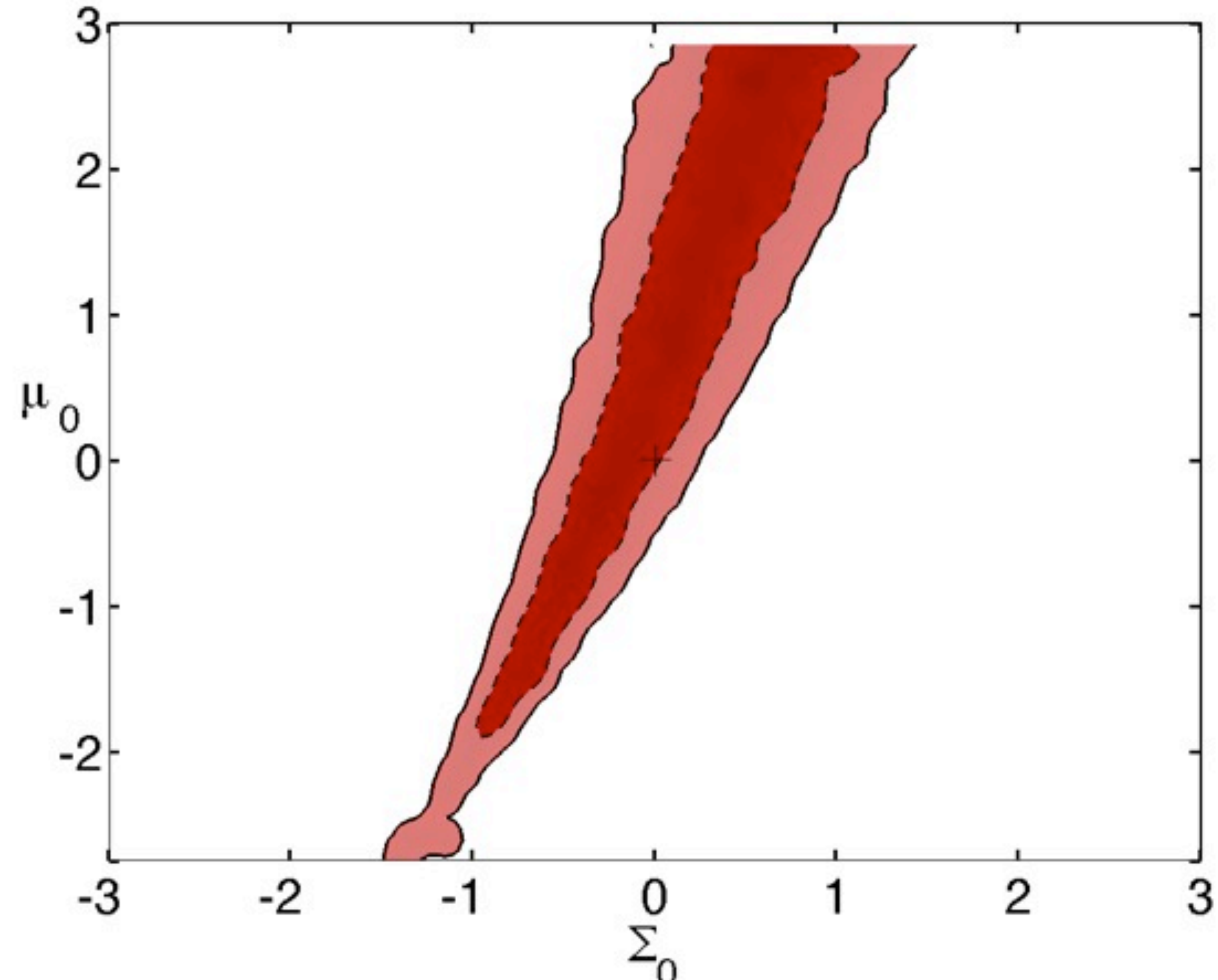
- Gravitational potential as experienced by photons:

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

PARAMETRISATION



PREVIOUS CONSTRAINTS



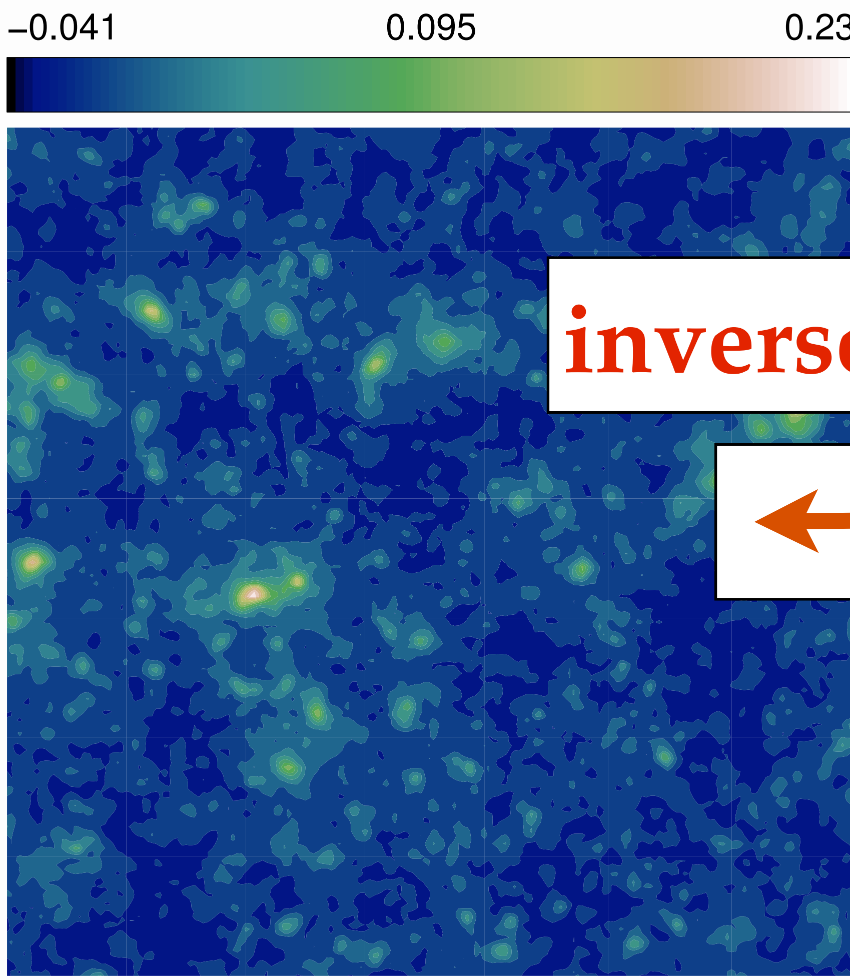
E_G (Reyes et al 2010) + BAO (Percival et al 2010)

Flat ΛCDM

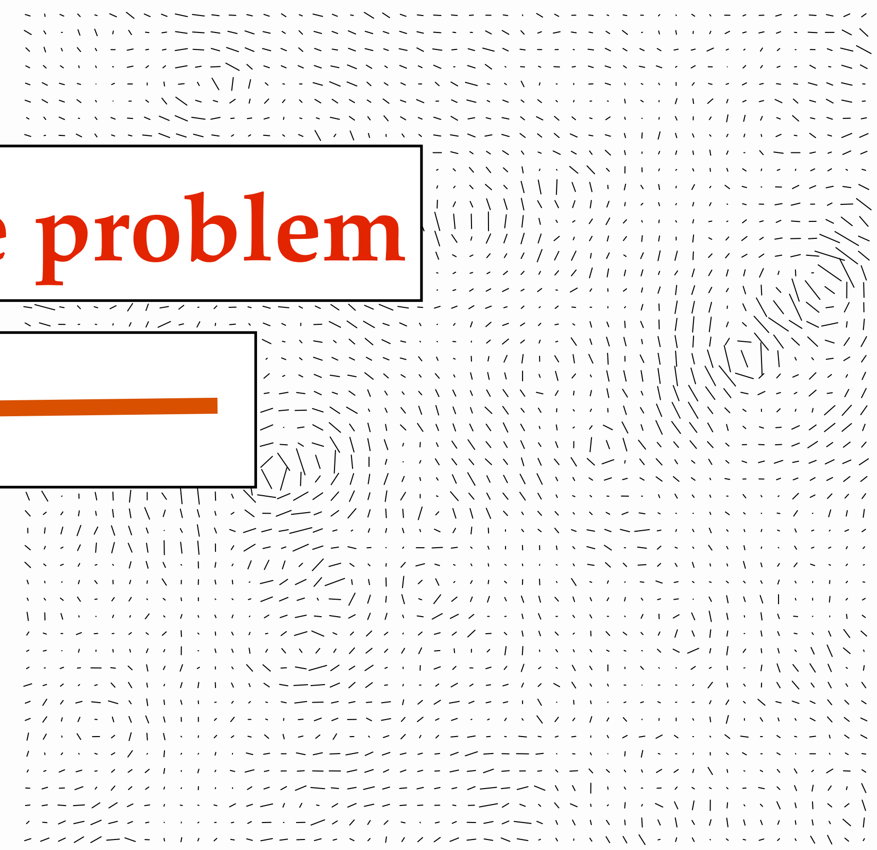
LENSING MASS MAPS

Projected matter density
convergence κ

Distortion field
shear γ



tangential distortions around mass peaks

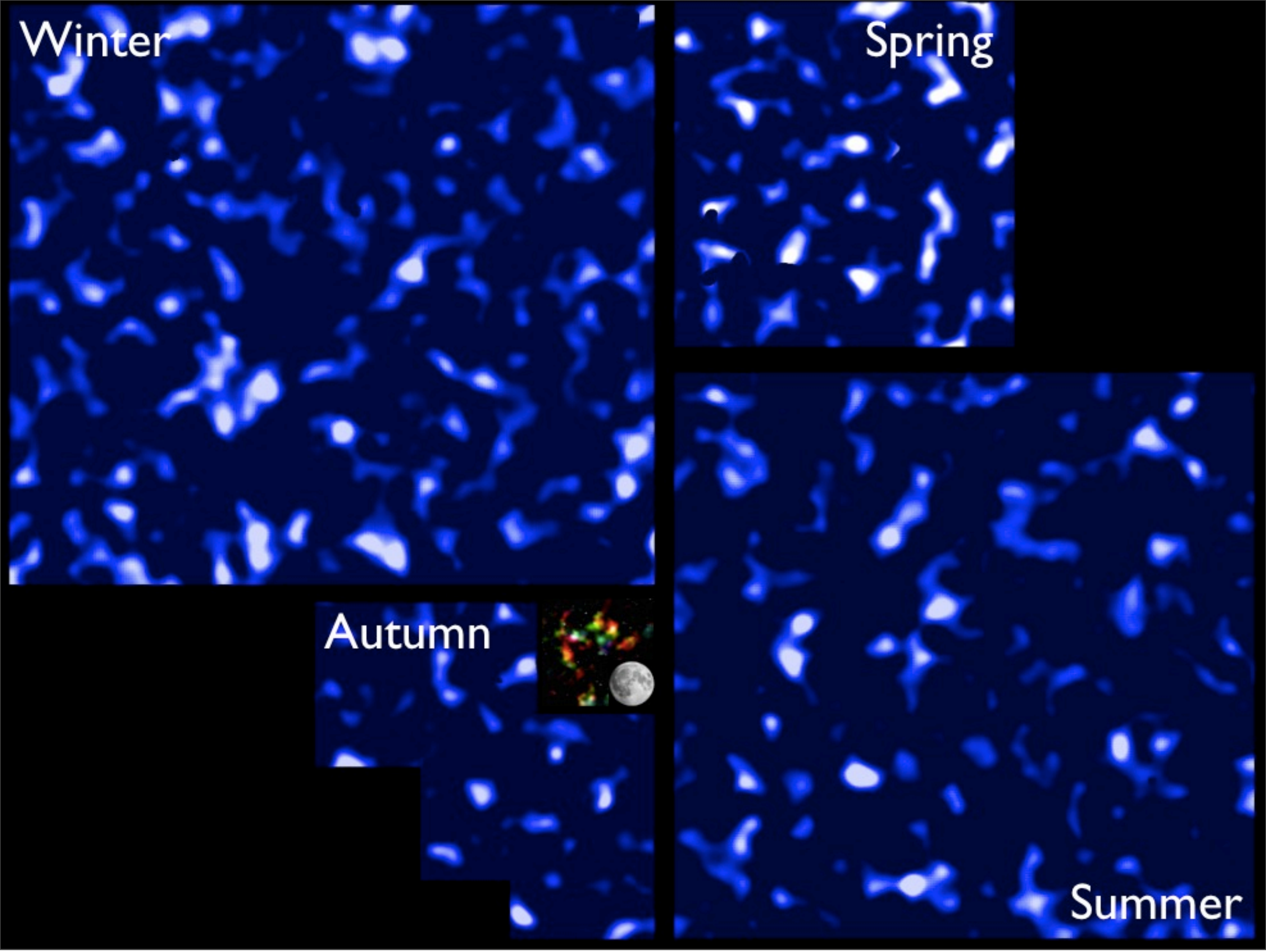


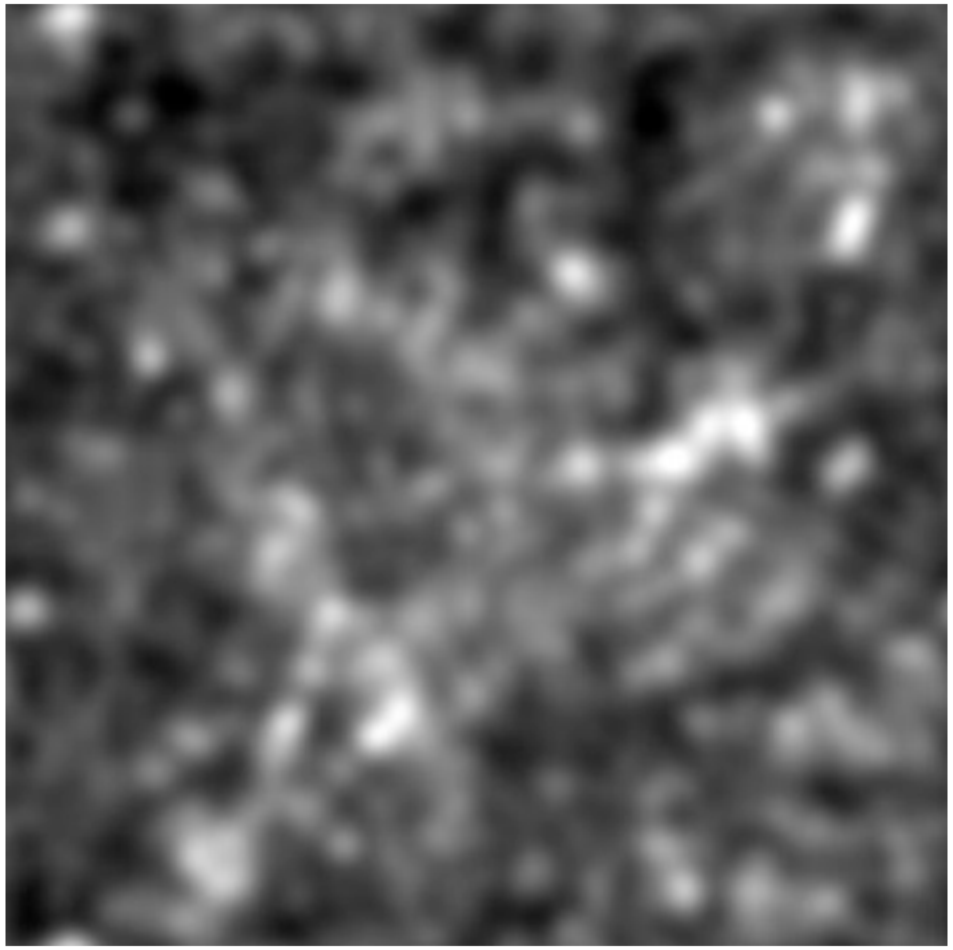
inverse problem

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

LENSING MASS MAPS

- 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

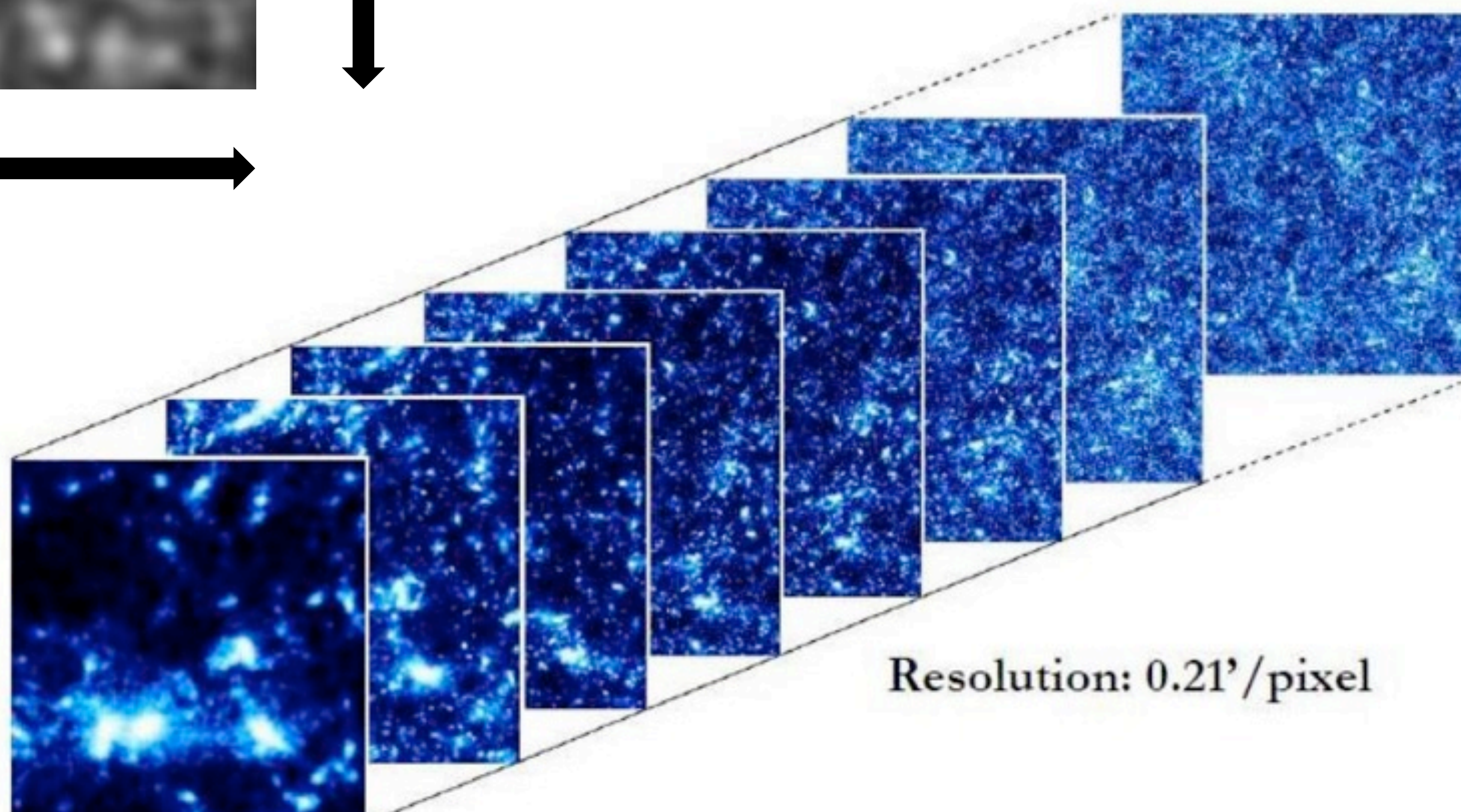

Winter
Spring
Autumn
Summer



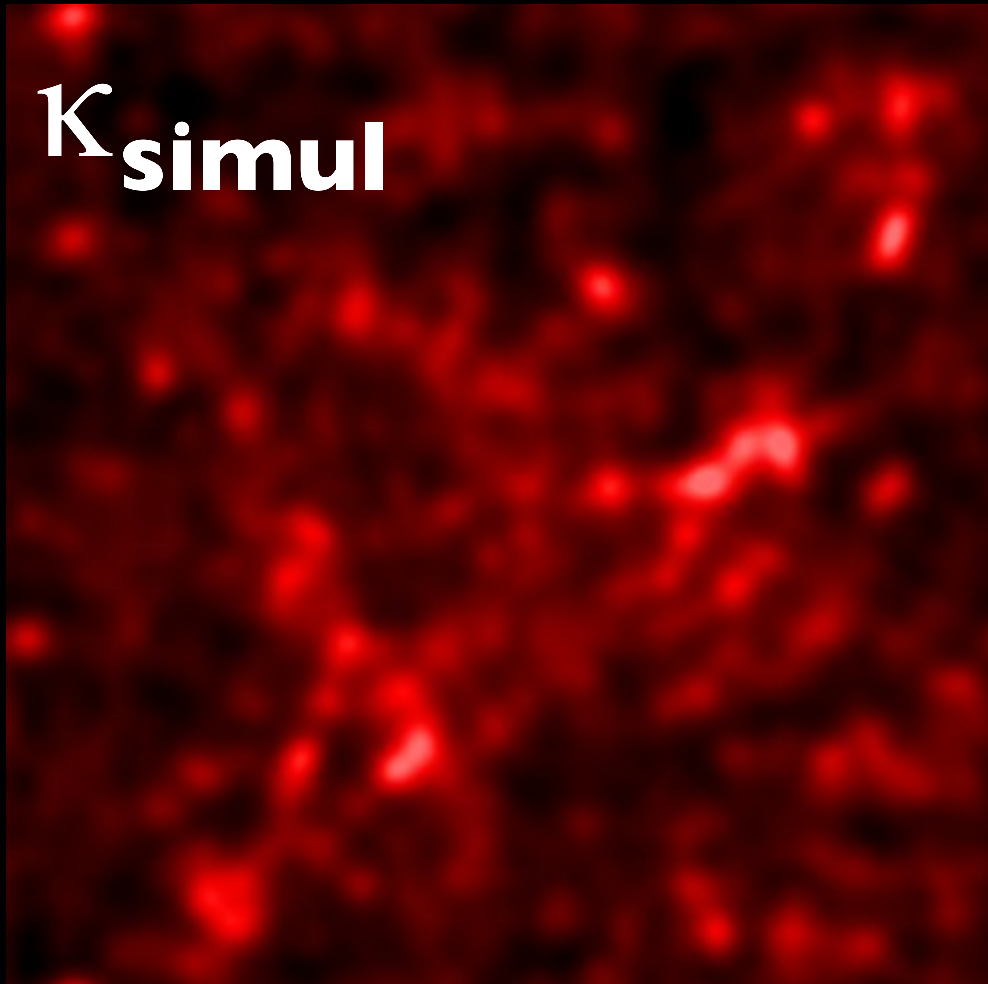
Ray-tracing simulations
(Harnois-Deraps, Vafaei & van Waerbeke 2012)

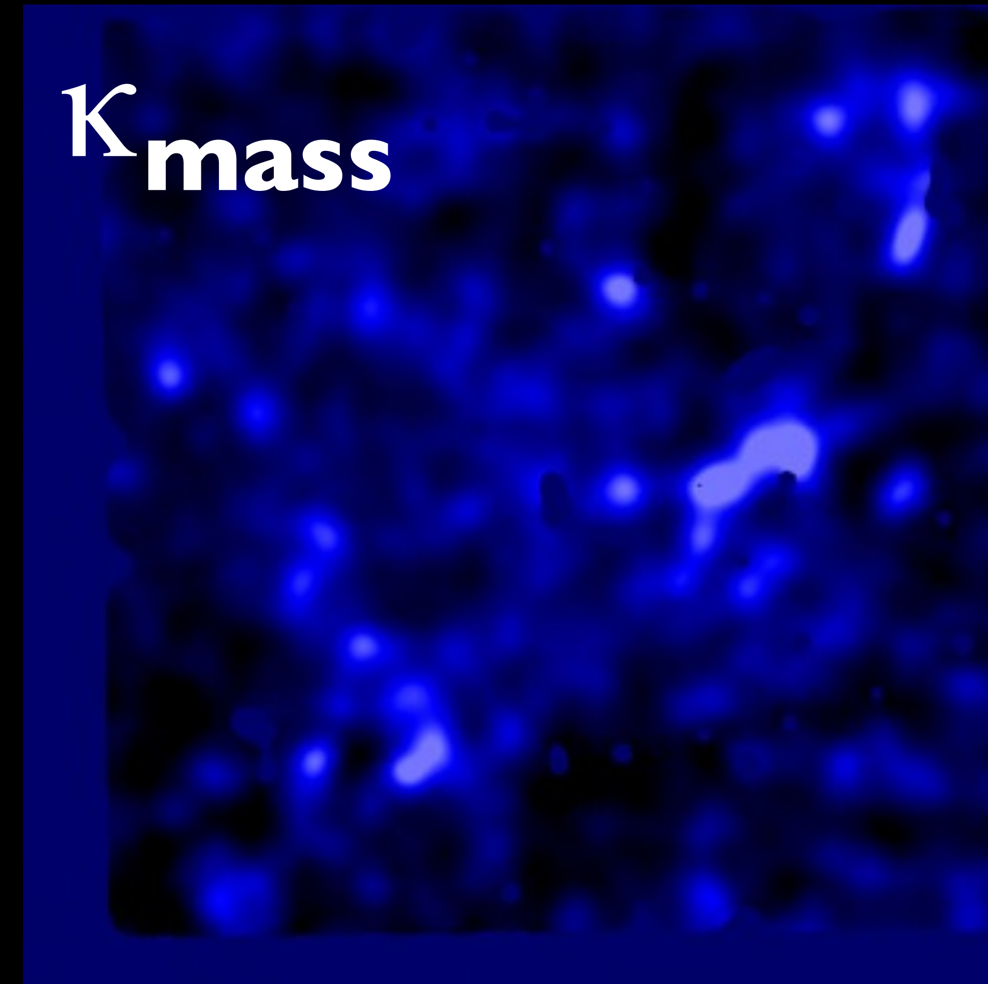
3.4 degrees

z=3

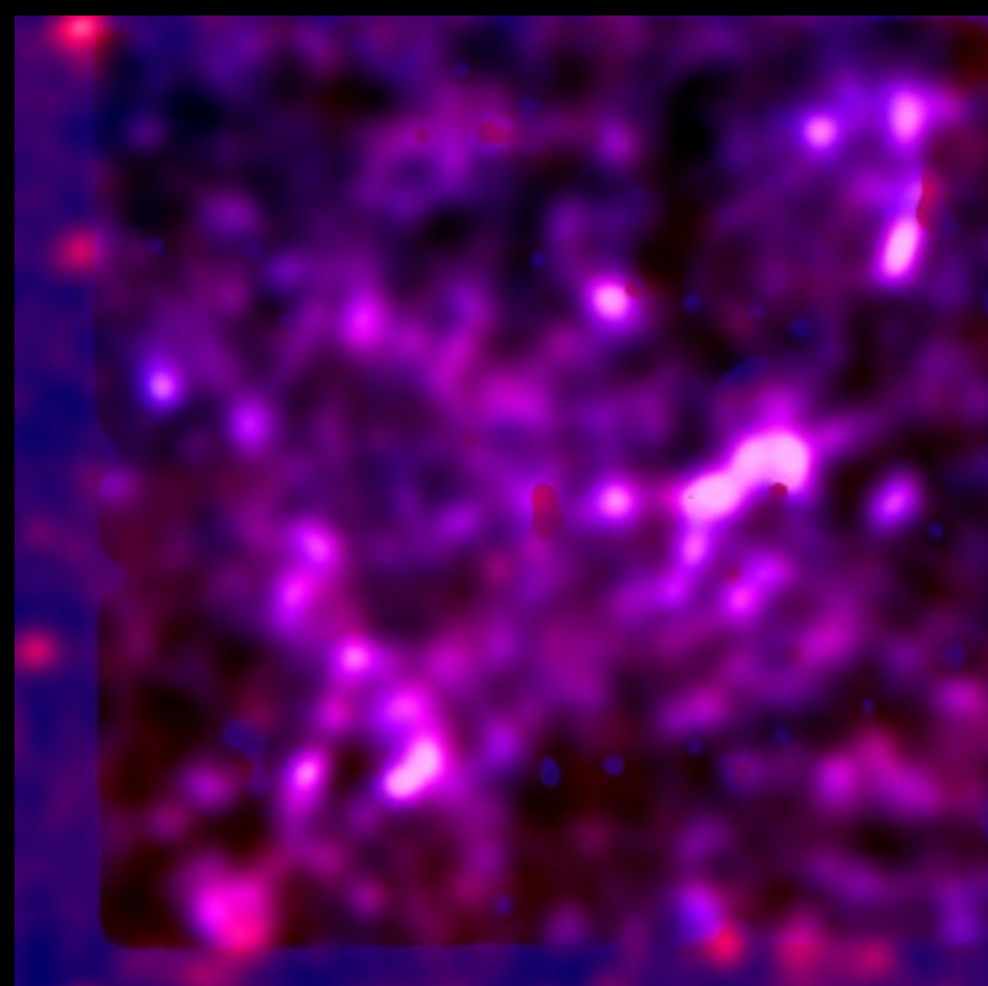


z=0.03





Overlay



Full non-linear Mass reconstruction (Gaussian filter)

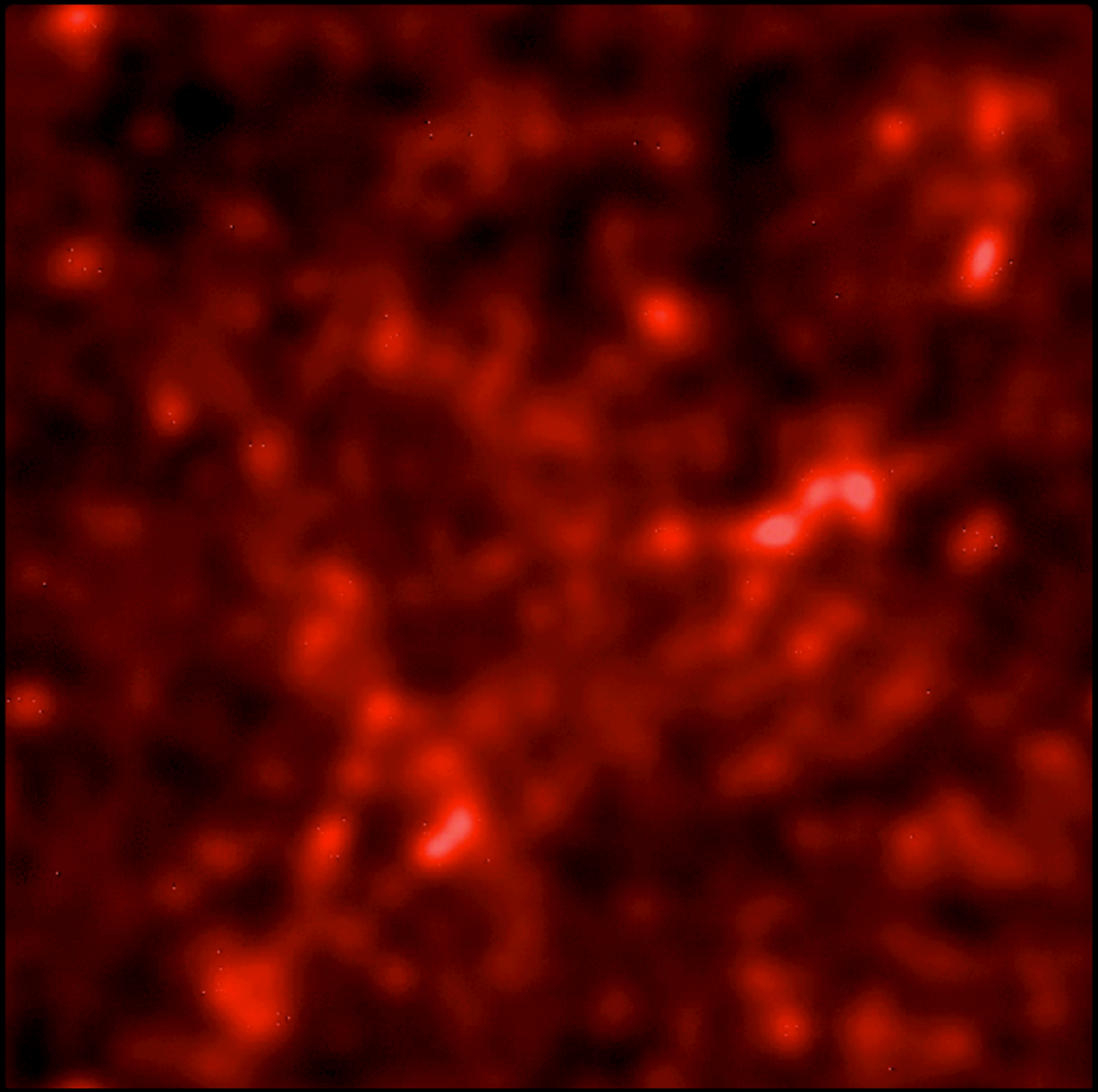
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

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

Overlay

Perfect match!



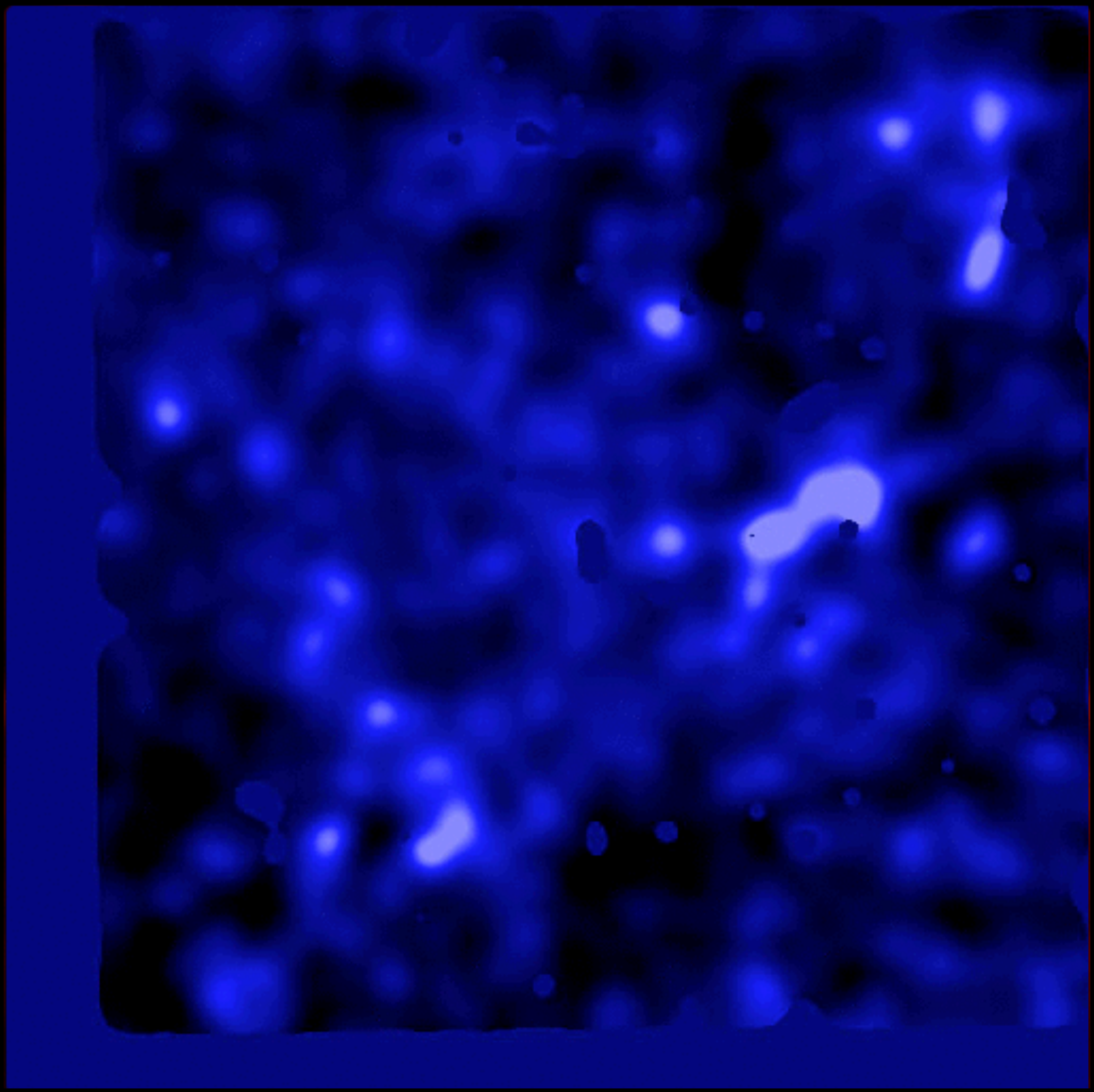
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

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

Overlay

Perfect match!



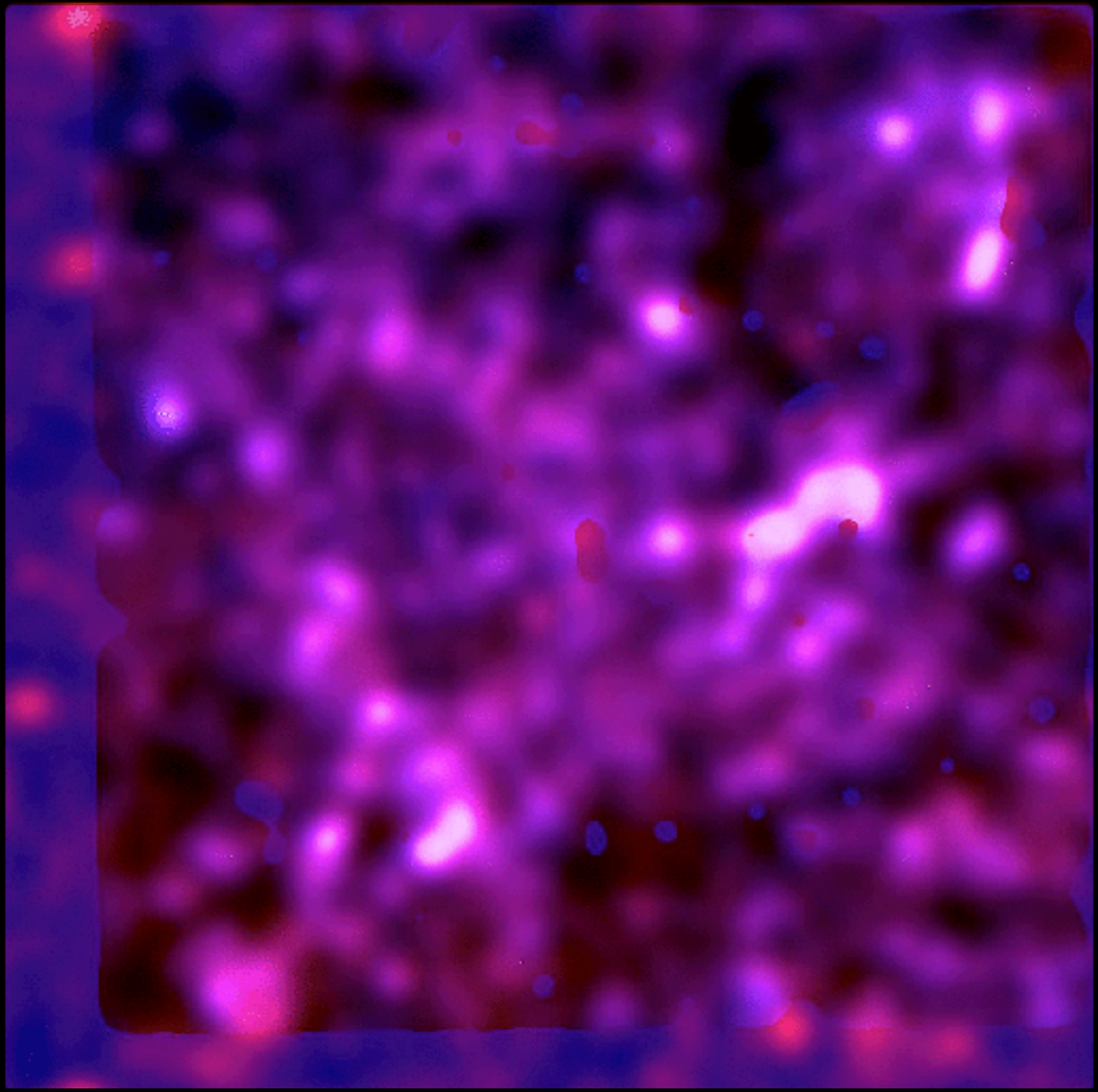
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

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

Overlay

Perfect match!

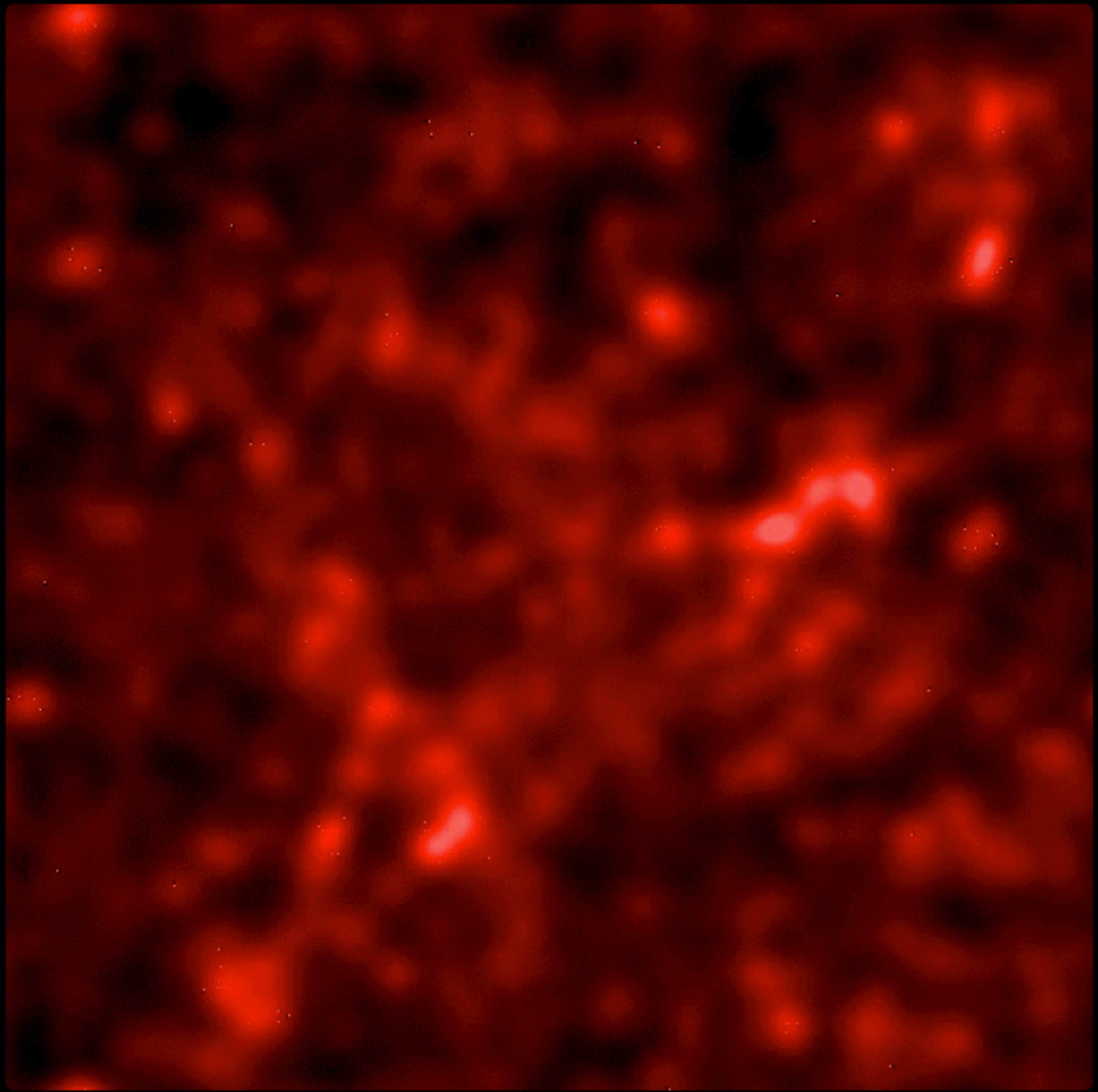


Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

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

Overlay



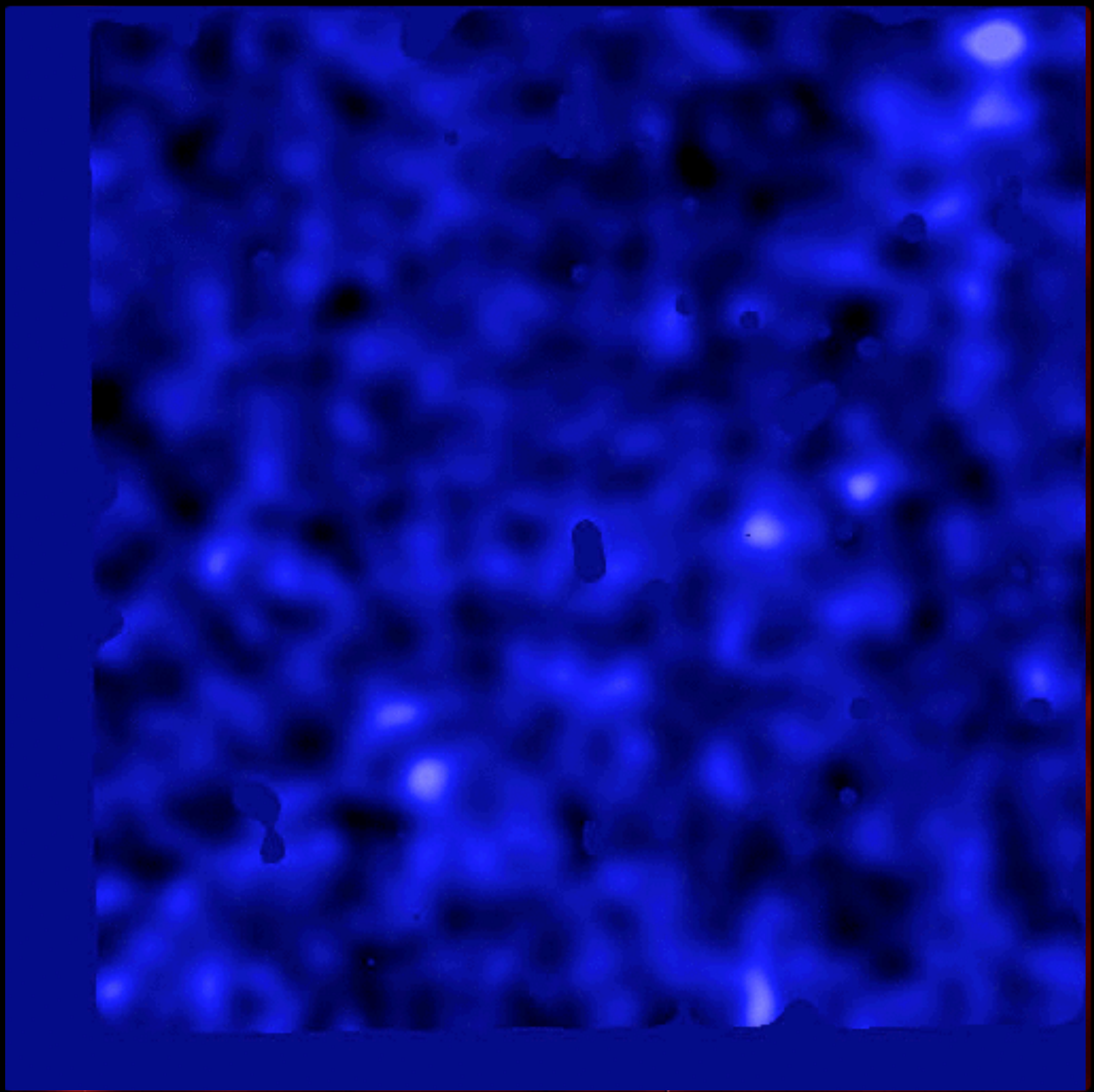
Very good match!
Peak and voids are well preserved

Mass reconstruction from mock catalogue

κ_{simul}

κ_{mass} With NOISE

Overlay



Very good match!
Peak and voids are well preserved

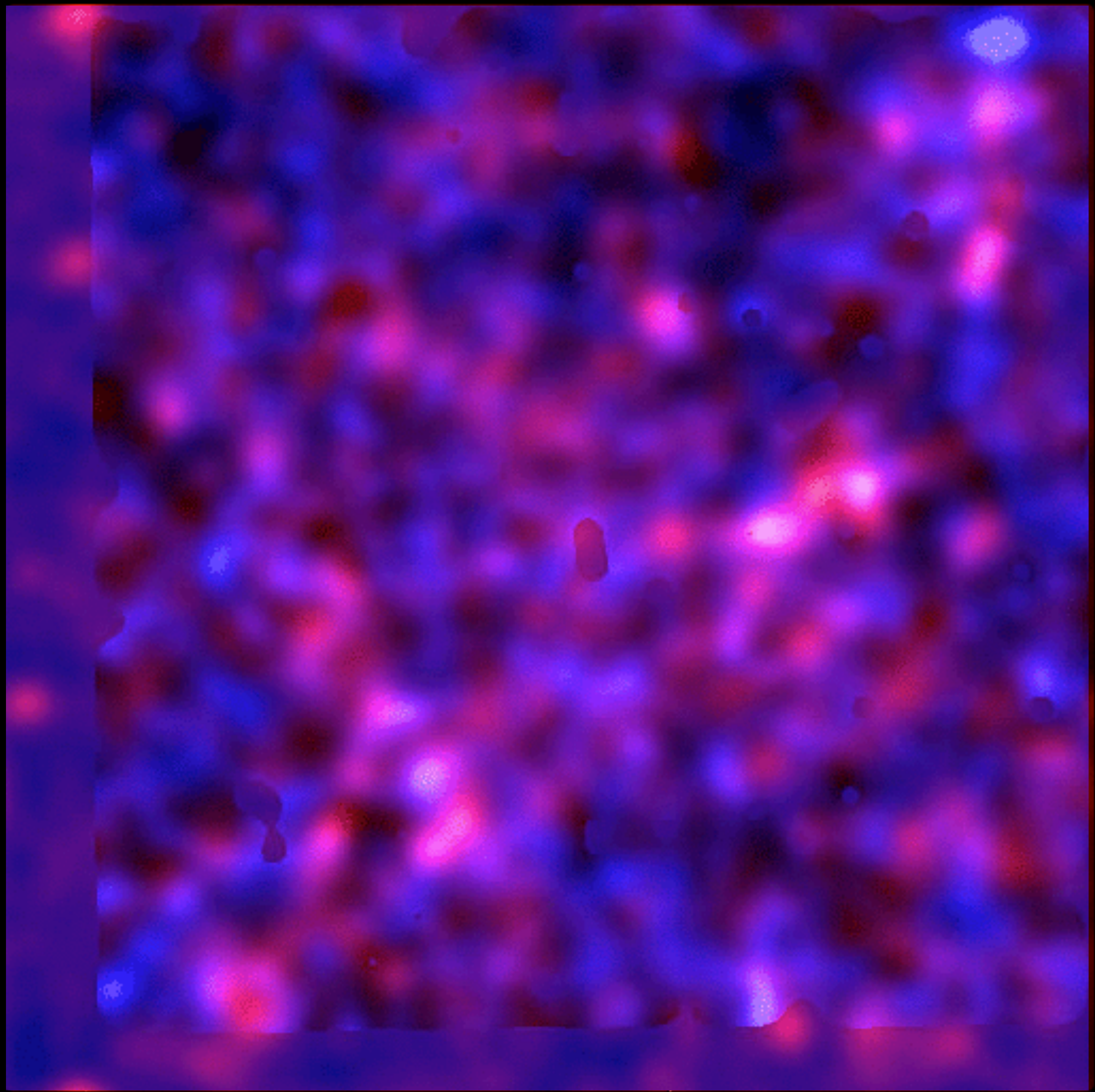
Mass reconstruction from mock catalogue

$\kappa_{\mathbf{simul}}$

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

Overlay

Very good match!
Peak and voids are well preserved



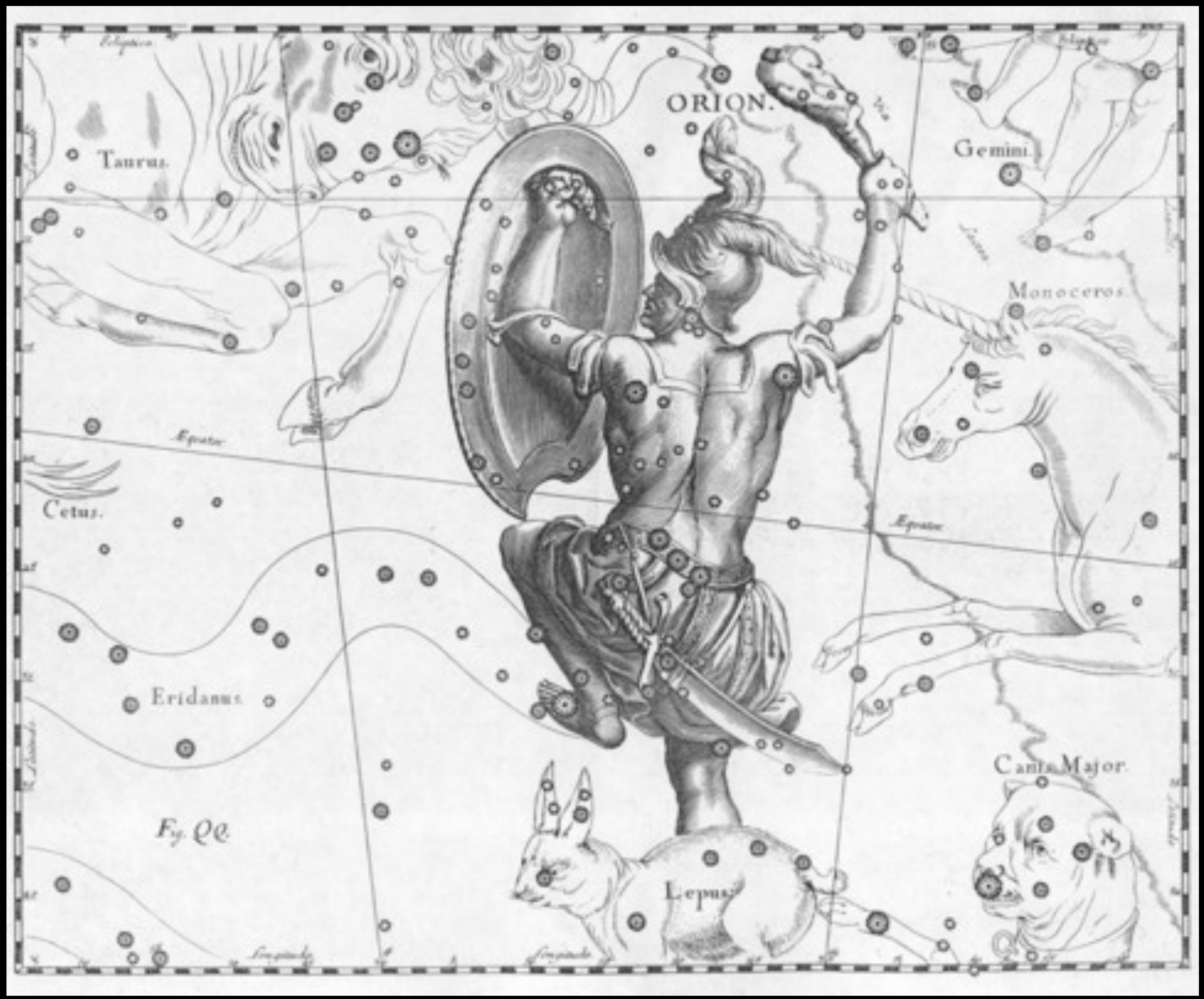
W1 mass reconstruction

$\kappa_{\mathbf{mass}}$

$\kappa_{\mathbf{galaxies}}$

Overlay

$\kappa_{\mathbf{clusters}}$

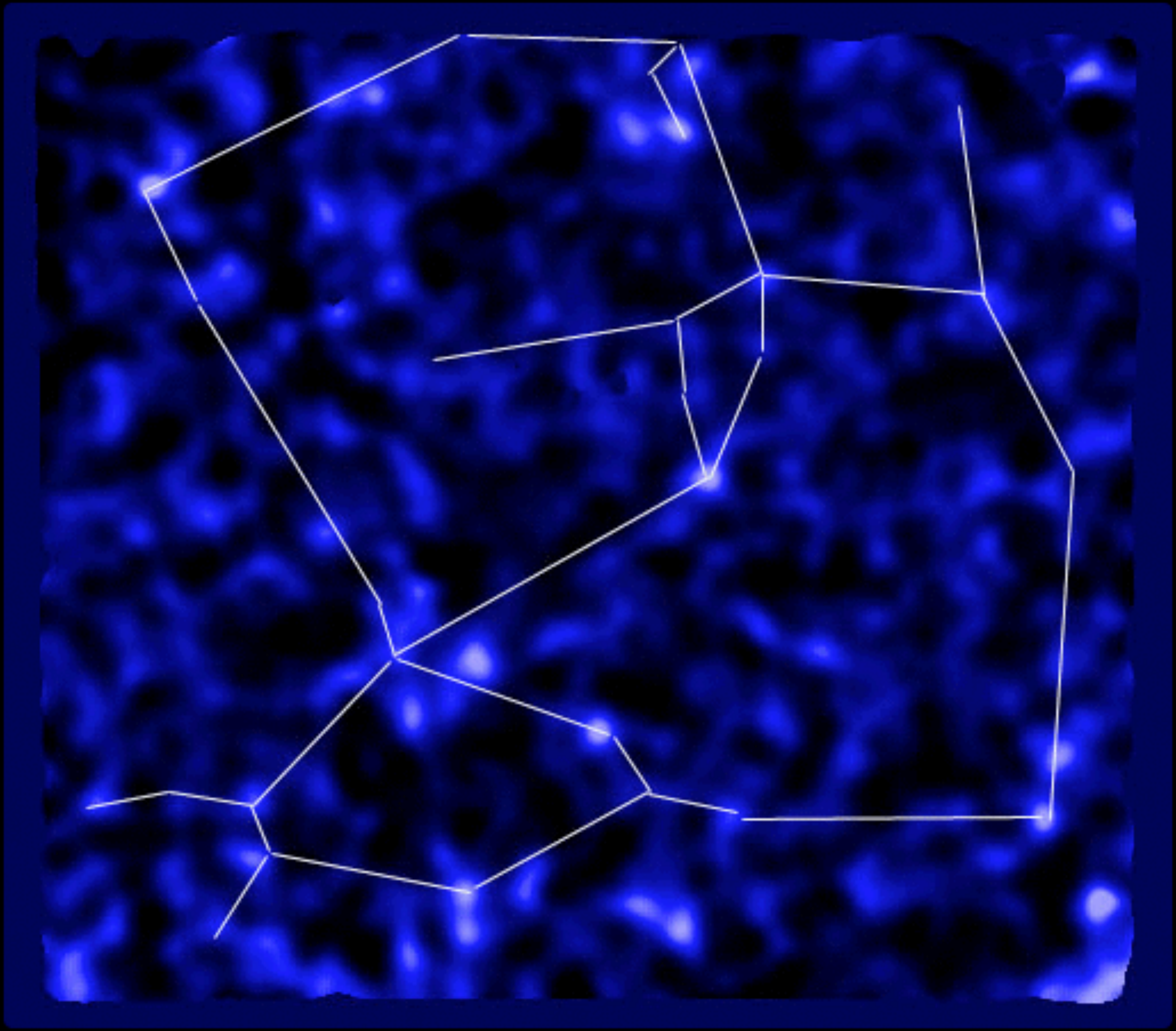


κ**mass**

κ**galaxies**

Overlay

3.5σ peaks

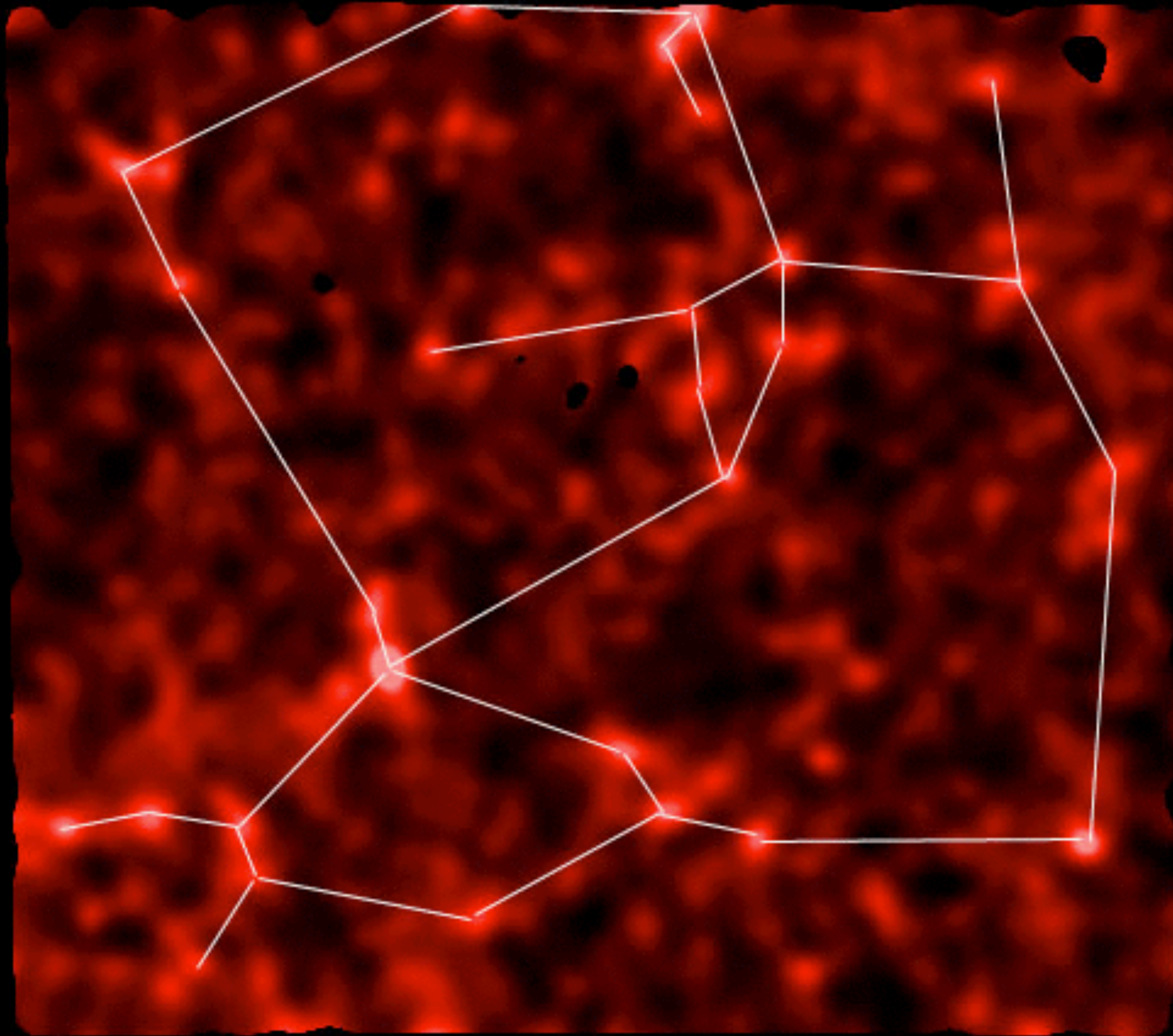


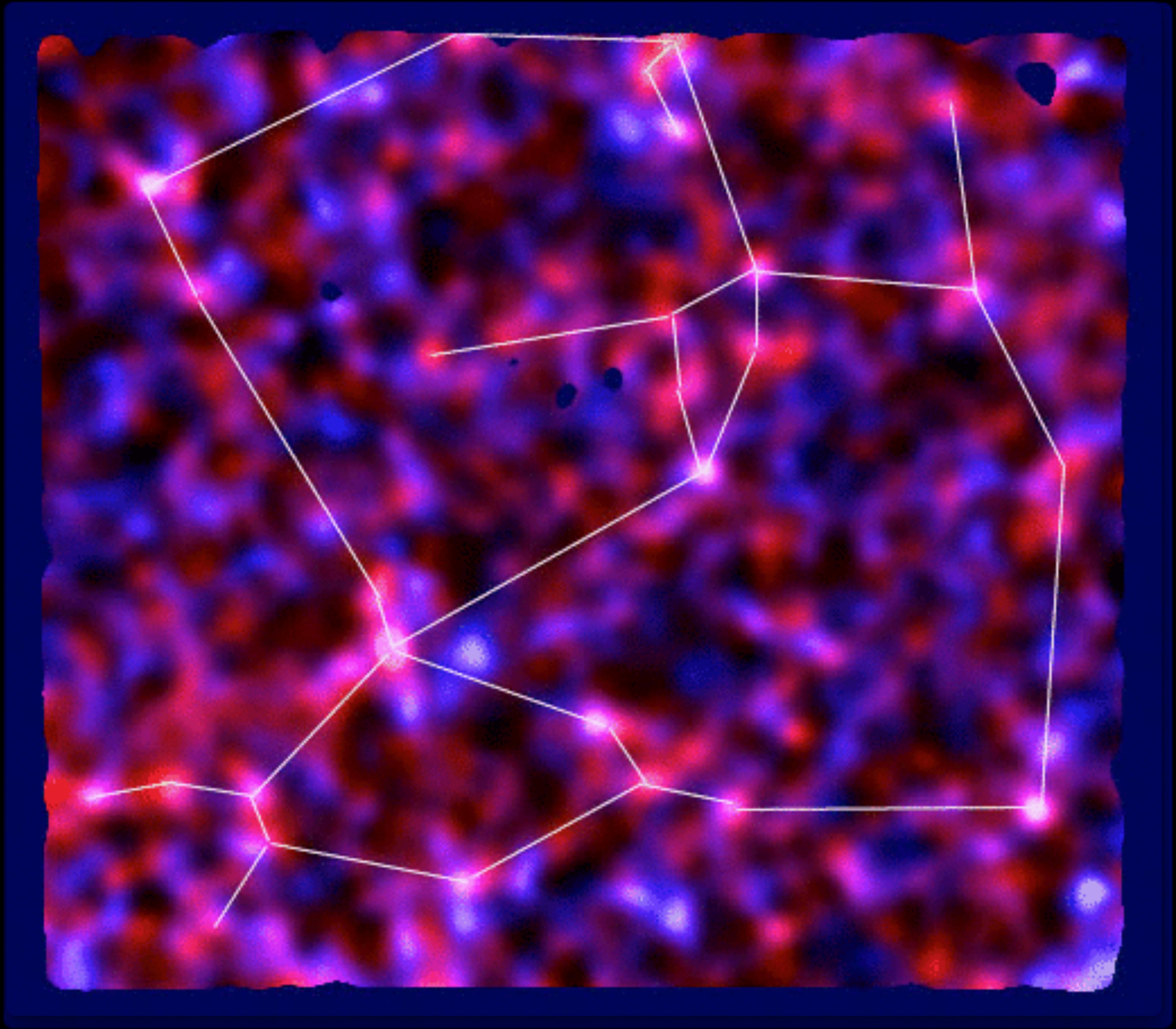
κ_{mass}

$\kappa_{galaxies}$

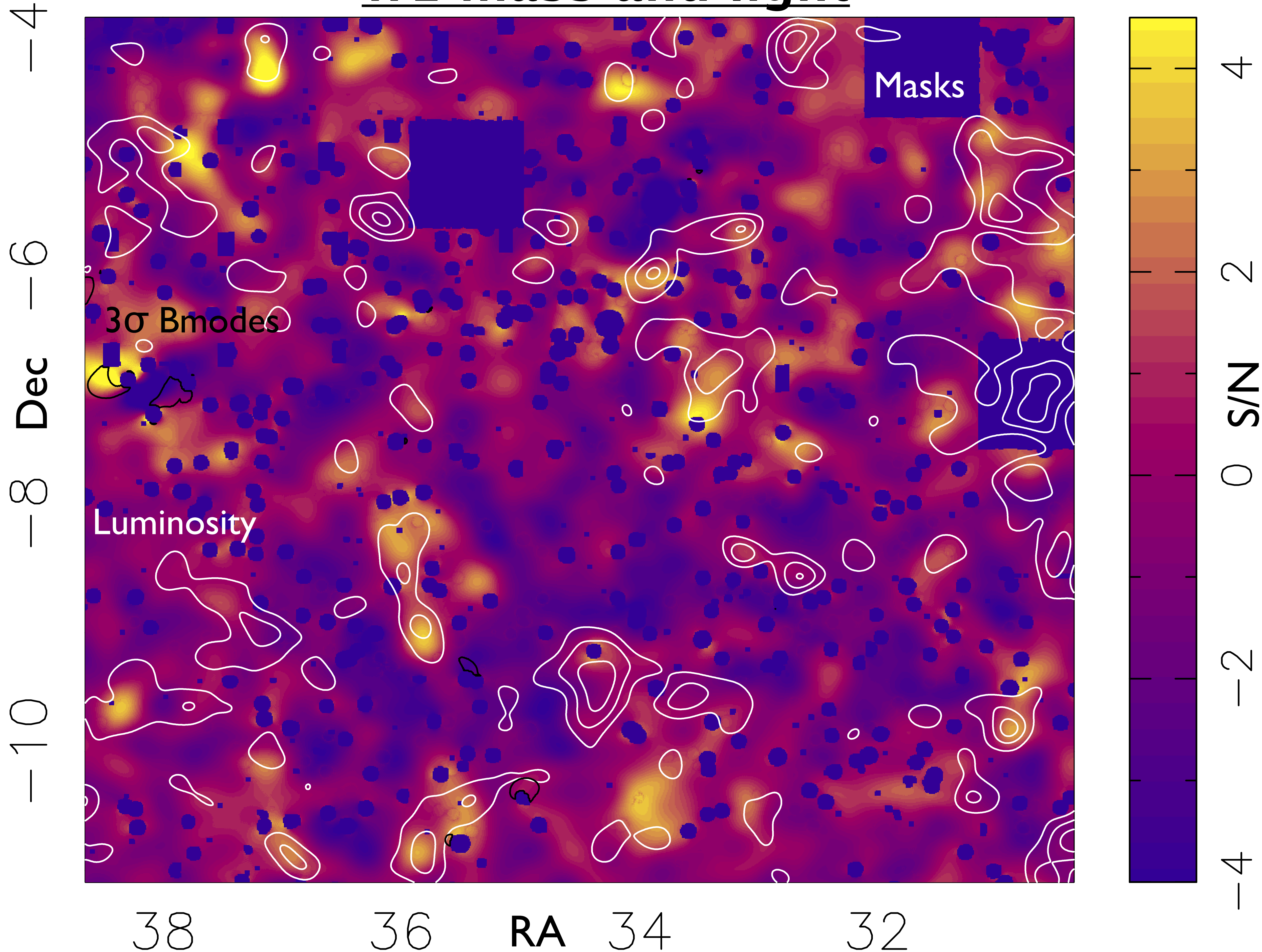
Overlay

3.5σ peaks

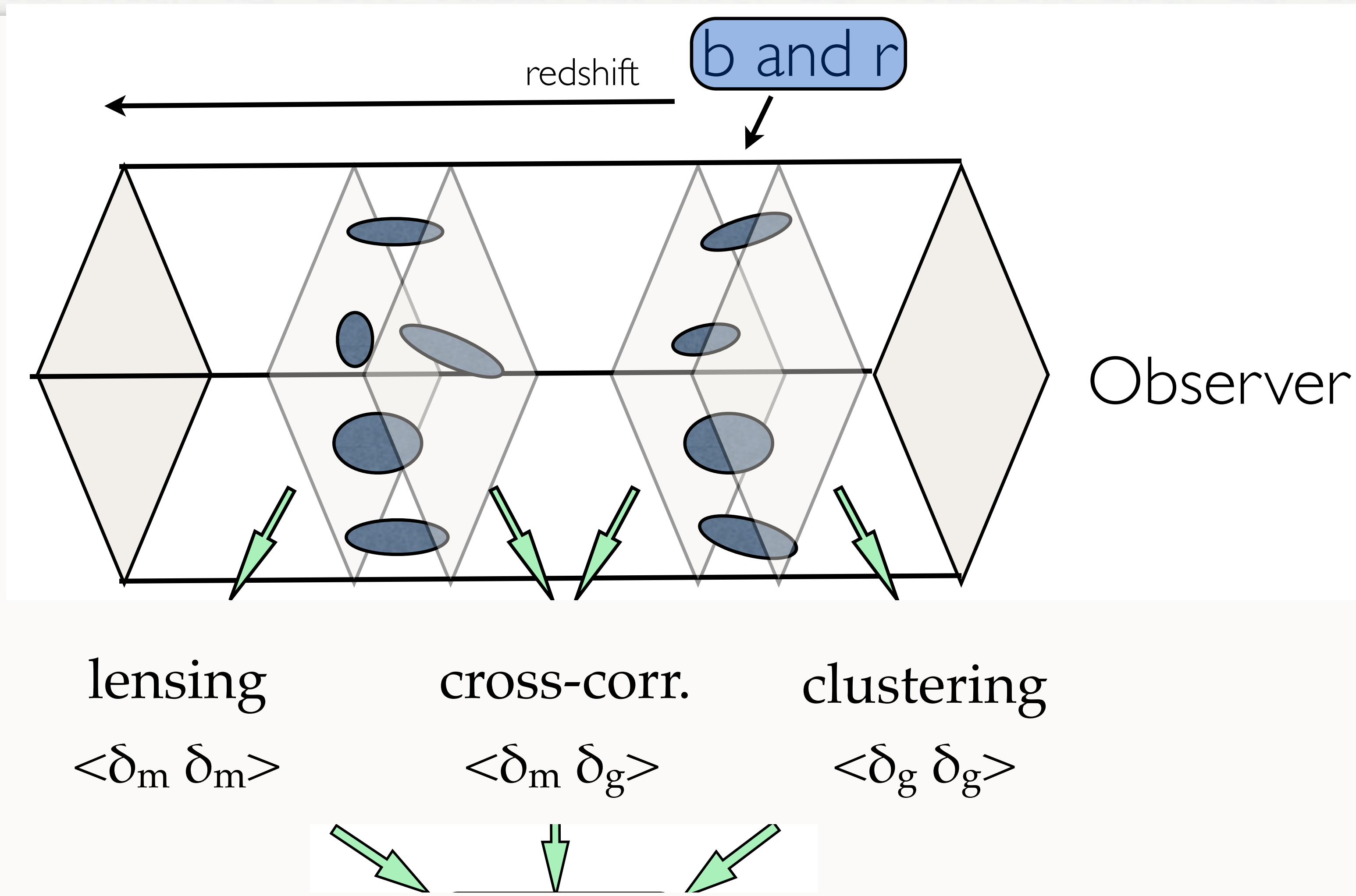



κ_{mass}
$\kappa_{galaxies}$
Overlay
3.5σ peaks

W1 mass and light



LENSING & CLUSTERING



correlation factor :

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

bias factor :

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

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 results in 2012. Catalogues will be made public on **Nov 1, 2012**.

TIMELINE TO EUCLID

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

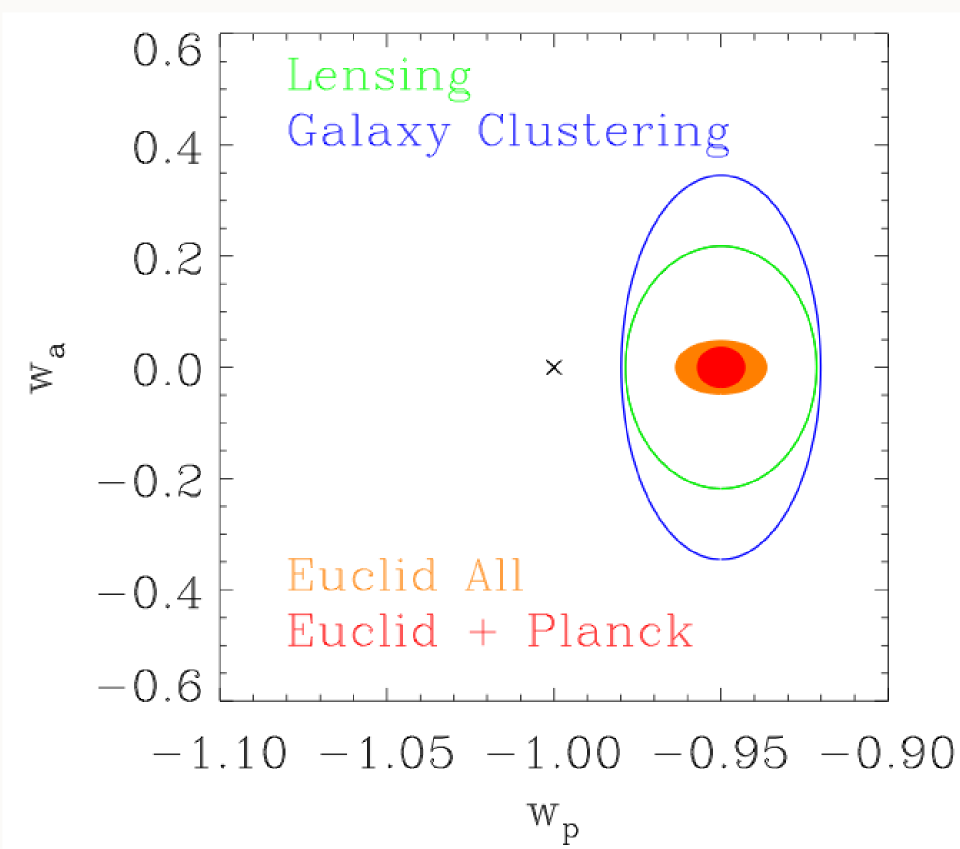
- DES. 2012 -
  5,000 deg^2 , DECam / CTIO
  Large area, IR coverage. Large spectro-follow up planned (DESpec)

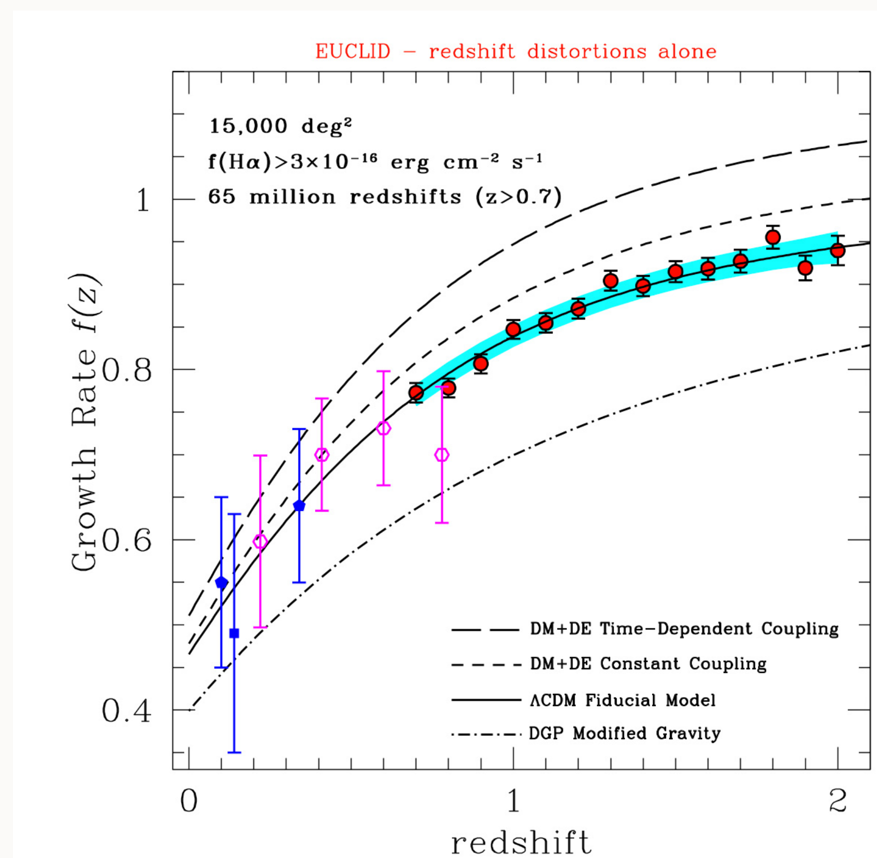
- LSST. ≥ 2018 -
  20,000 deg^2

- 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

SUMMARY

- CFHTLenS: best lensing results to date. 3 years + of work
- New data reduction, shear measurement, photo-z
- Systematics can be quantified
- Systematics tests cosmology-blind
- Data and catalogue public release on Nov 1, 2012.

www.cfhtlens.org

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:

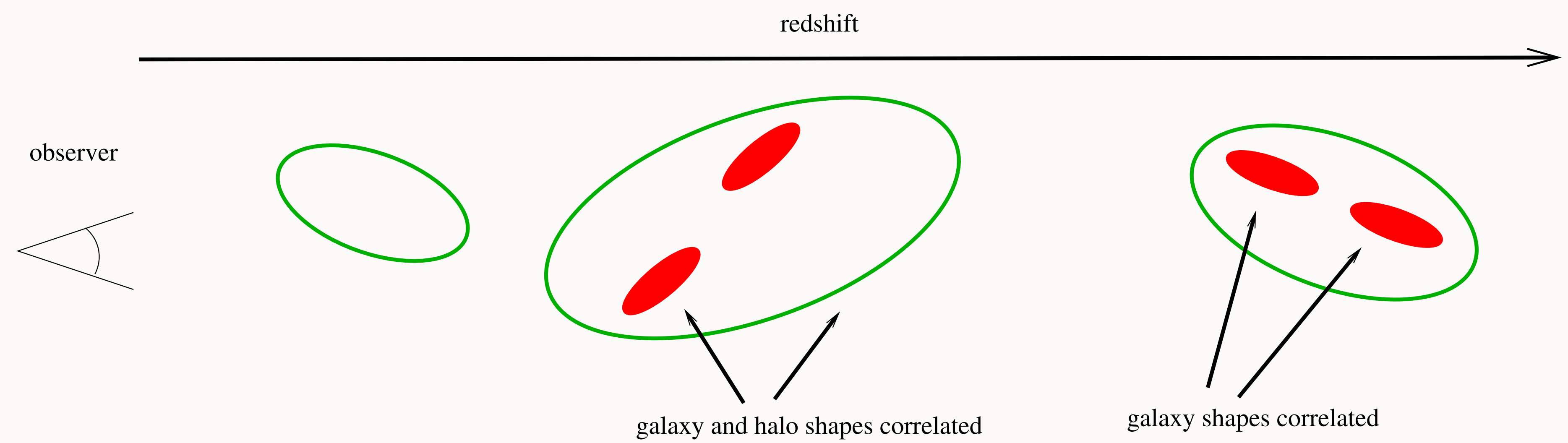
- **Cosmological constraints from cosmic shear;** Kilbinger et al in prep
- **Tomographic cosmic shear with Photometric Redshifts;** Benjamin et al in prep
- **Testing the laws of gravity with CFHTLenS and WiggleZ;** Simpson et al in prep
- **Weak lensing magnification measurements in CFHTLenS;** Hildebrandt 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

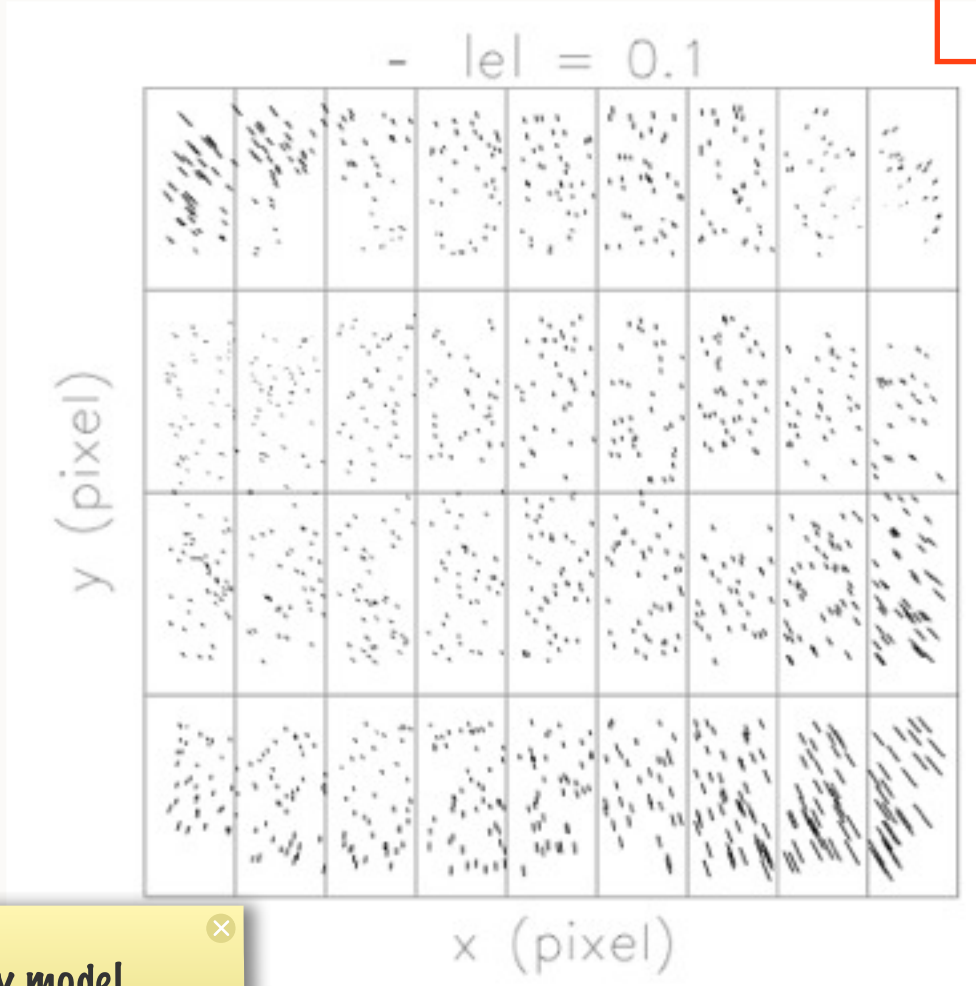
Telescope / Camera / Atmospheric distortions >> weak lensing

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

Euclid: measure to 1% accuracy!

Correct for PSF:

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



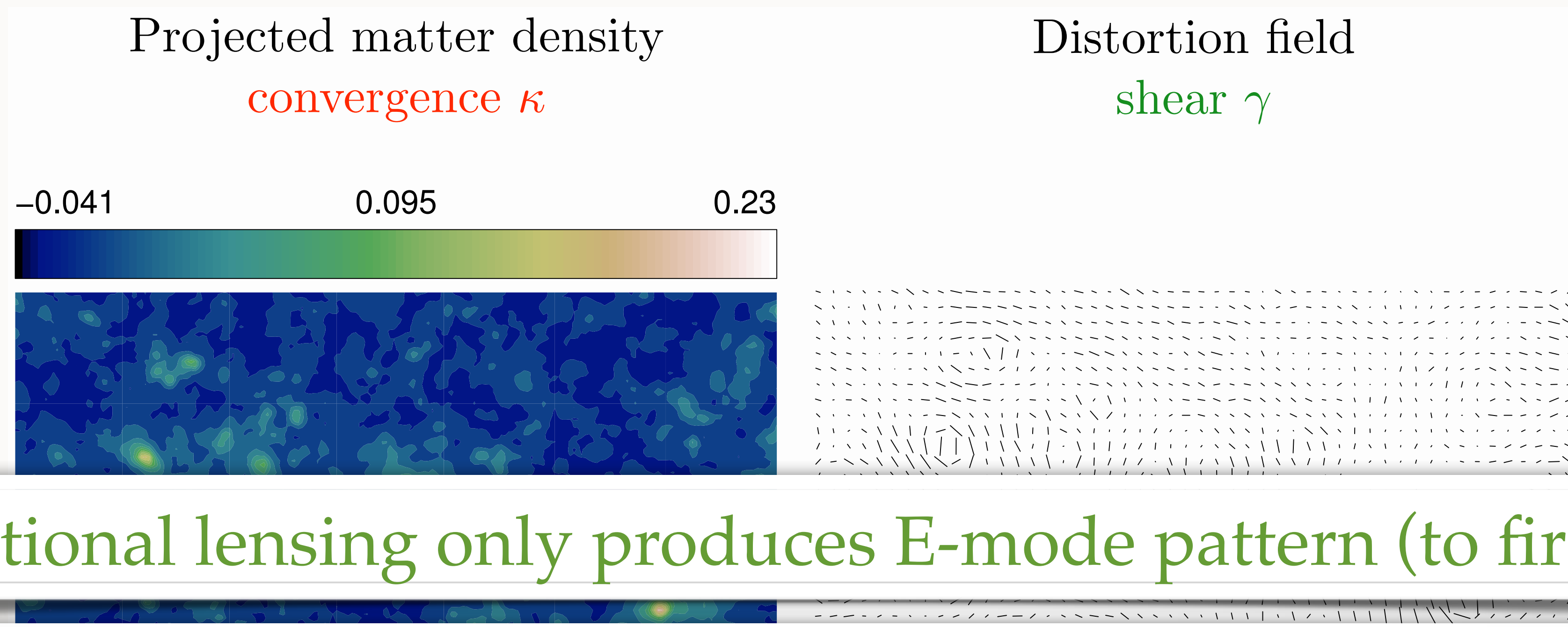
CFHTLS-Wide W_{3+2+0}
Fu et al. 2008

lensfit: multiply model with PSF in Fourier space

INTRINSIC ALIGNMENT

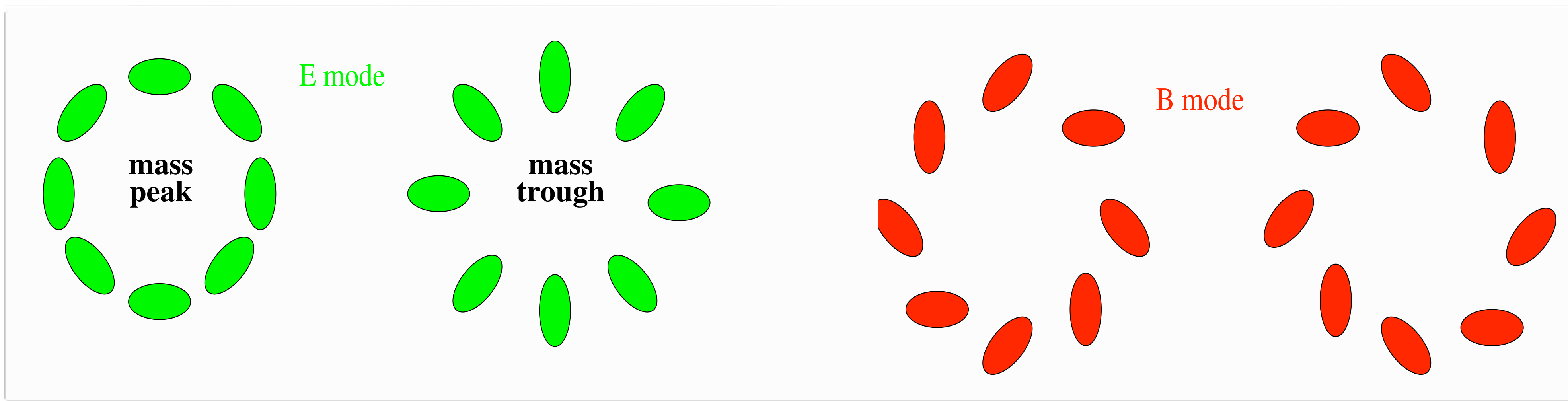
- MK et al. in prep.: Broad redshift distribution, IA sub-dominant (see Fu et al. 2008)
- Simpson et al, Benjamin et al. in prep.: Exclude z<0.5, IA sub-dominant for high z
- Grocutt et al. in prep.: Model simultaneously GG, GI and II

E- AND B-MODE



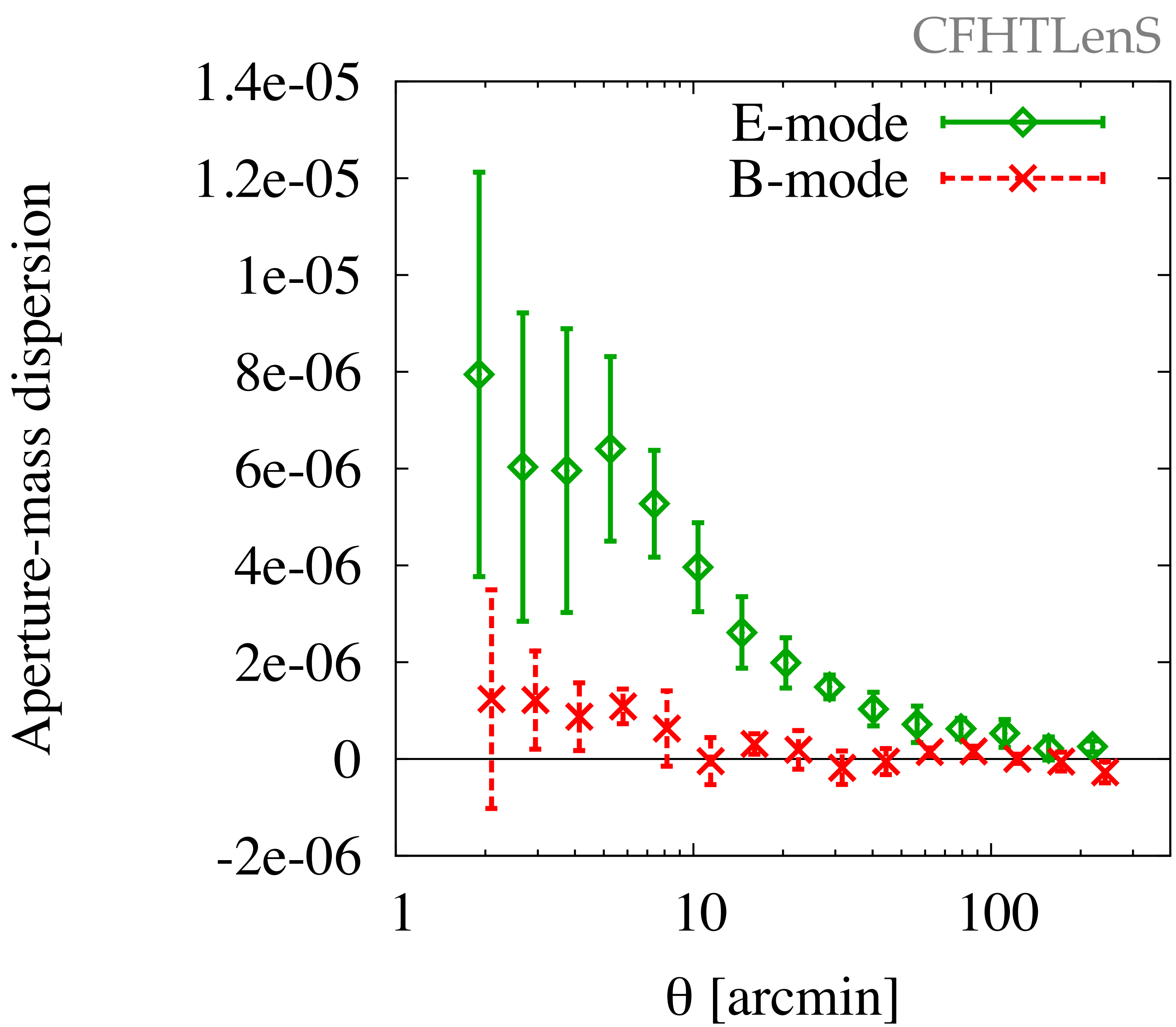
mass peaks

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



B-mode detected → hint for systematics in data

E- AND B-MODES



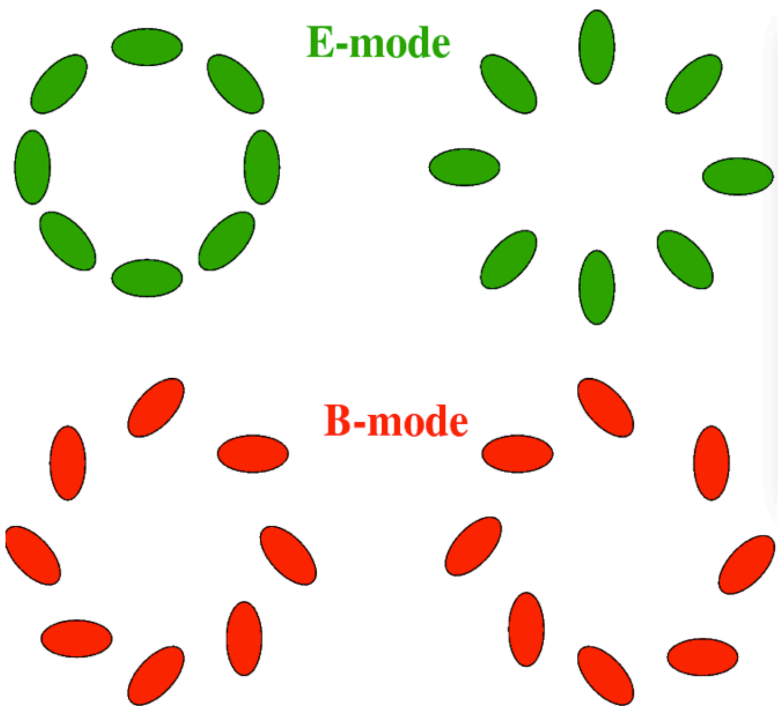


Fig.1. *Left*: E- and B-modes measured in CFHTLenS. *Right*: typical E- and B-mode shear patterns.