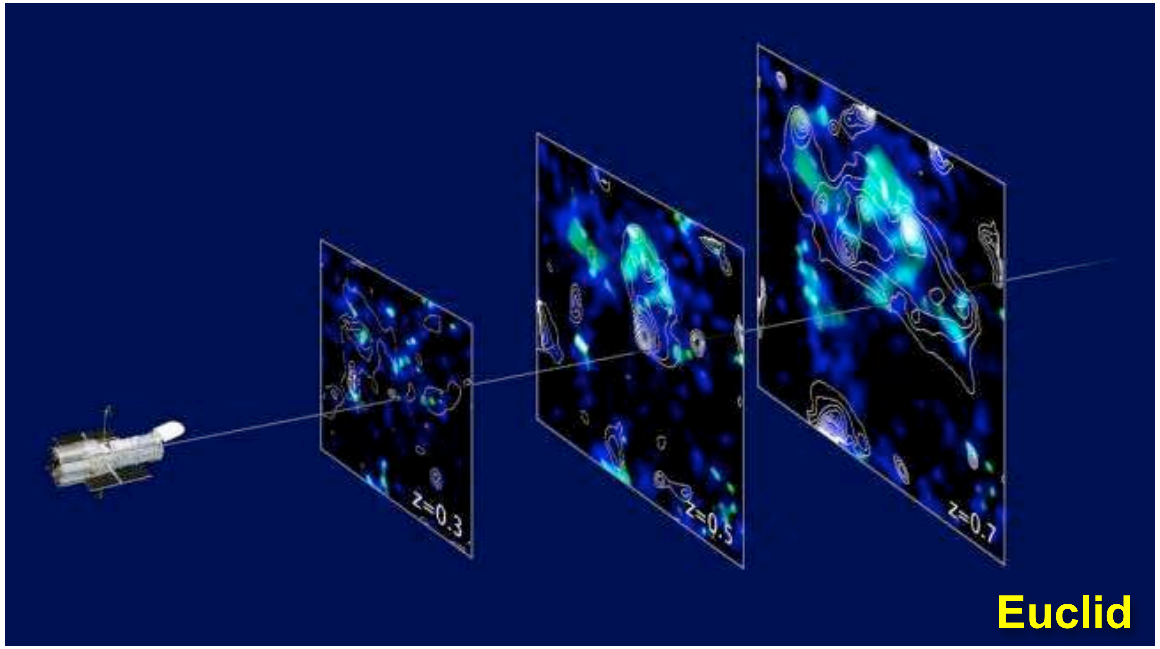
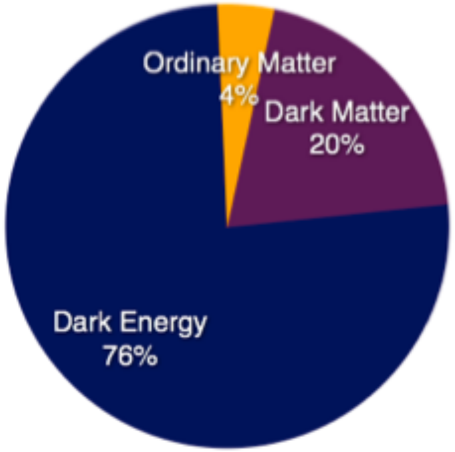
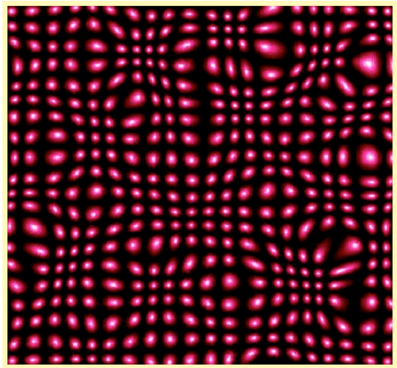
Weak Lensing

Saclay Weak Lensing Team: **J.-L. Starck, S. Paulin-Henriksson, S. Pires, A. Leonard , M. Kilbinger, S. Beckouche**

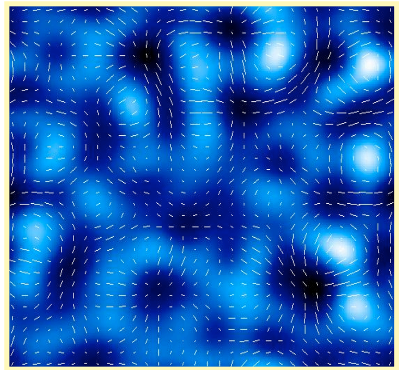


Weak Lensing

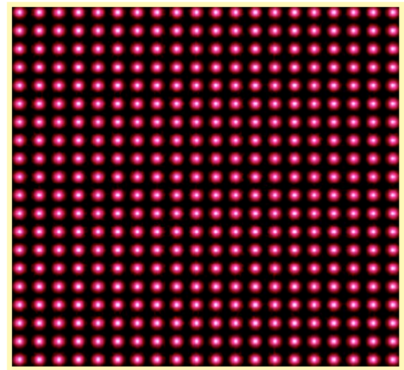




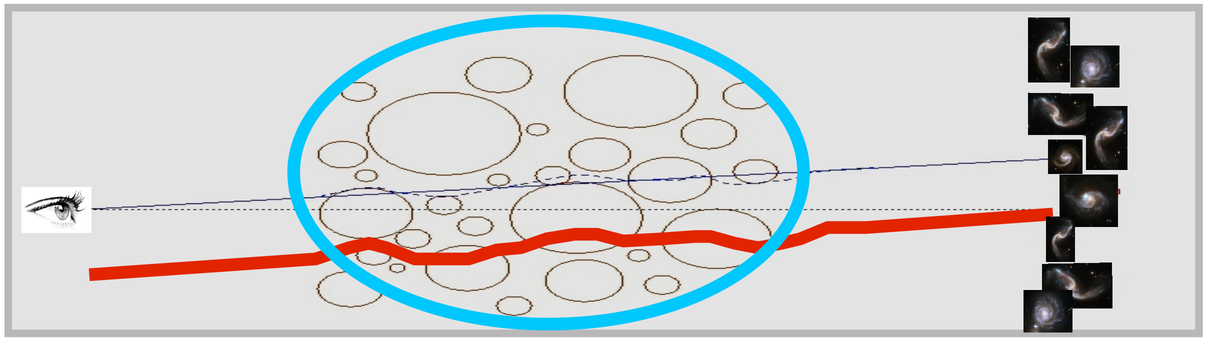
OBSERVER



GRAVITATIONAL LENS

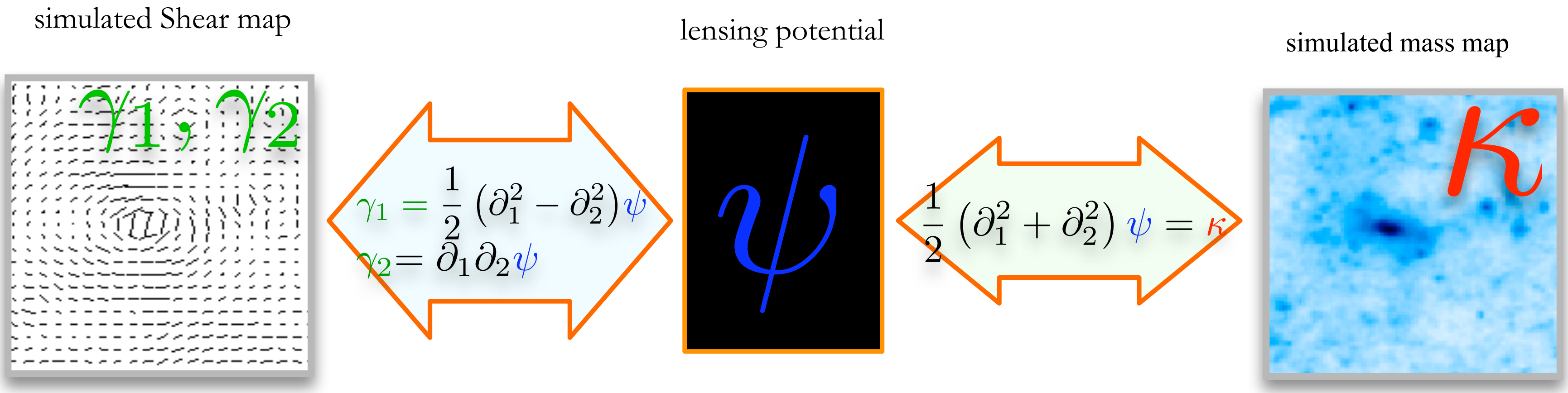


BACKGROUND GALAXIES



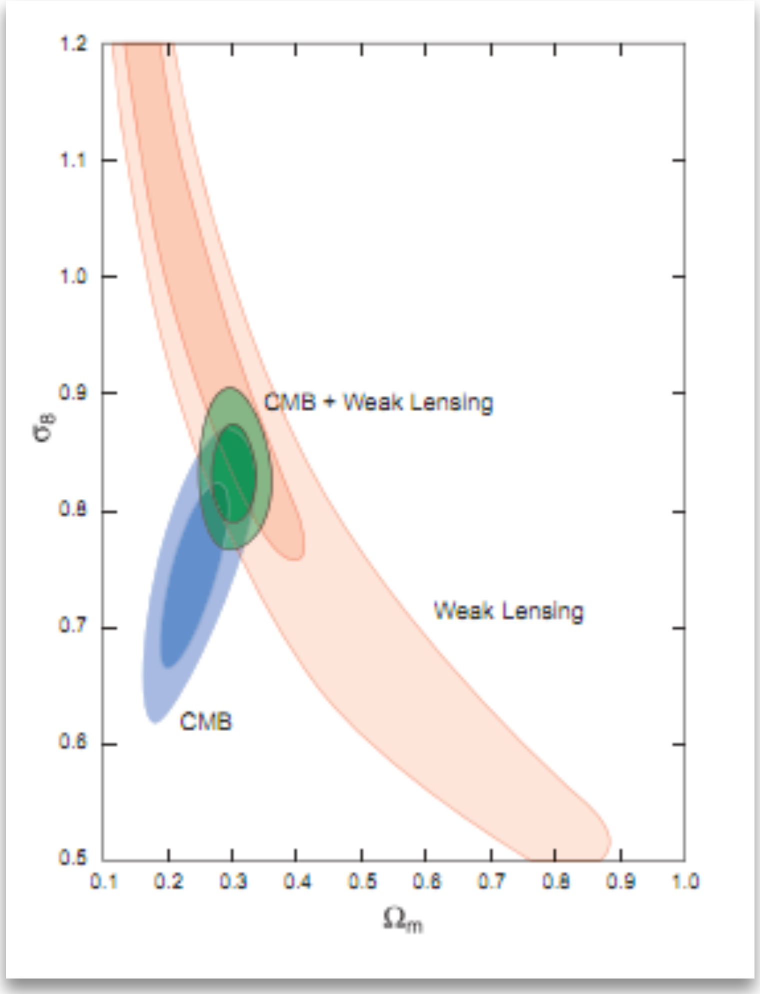
gravitational lens

Weak Lensing

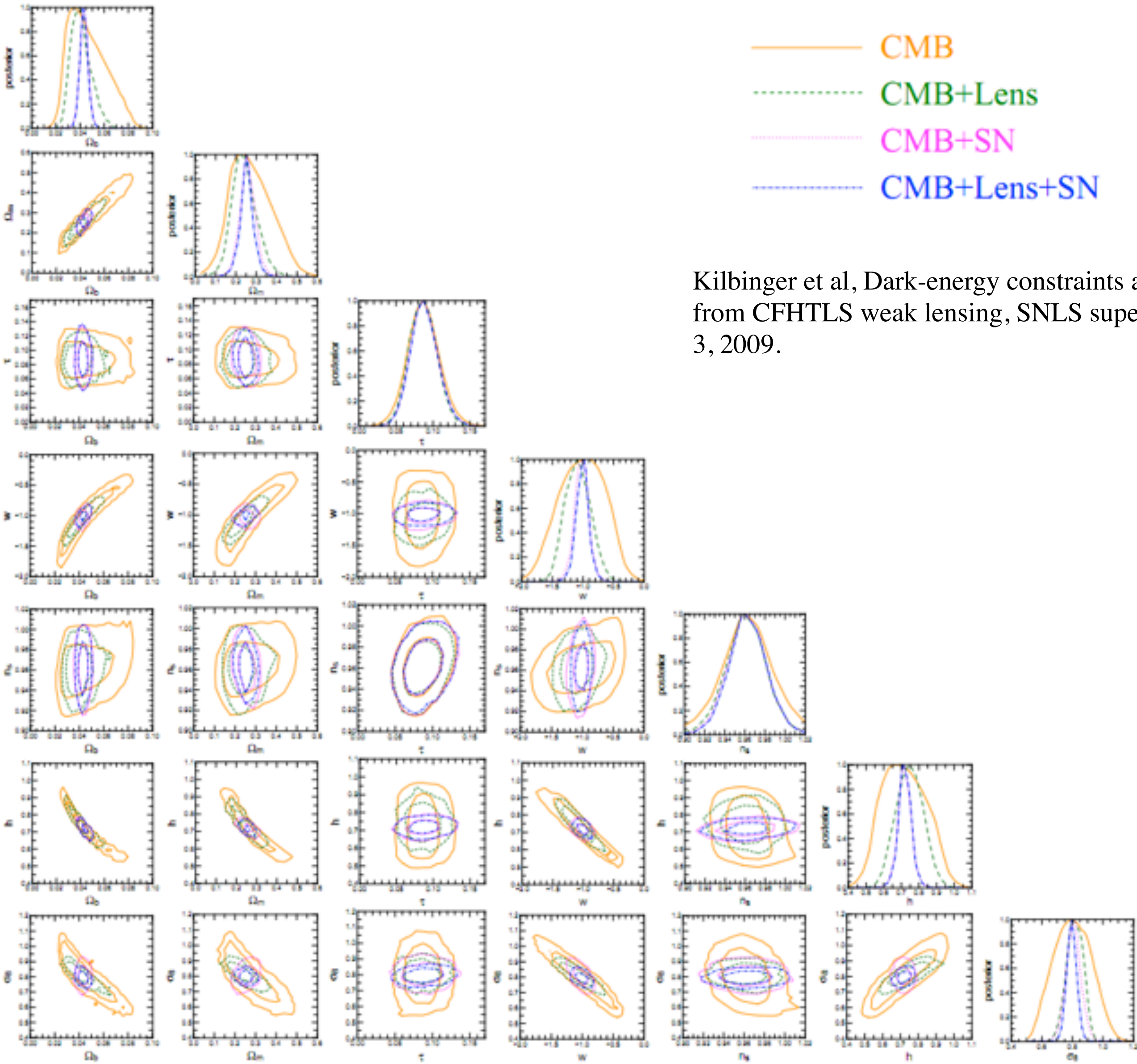


$$\begin{pmatrix} \hat{E}(\boldsymbol{k}) = \hat{\kappa}(\boldsymbol{k}) \\ \hat{B}(\boldsymbol{k}) \end{pmatrix} = \underbrace{\frac{1}{|\boldsymbol{k}|^2} \begin{pmatrix} k_1^2 - k_2^2 & 2k_1k_2 \\ 2k_1k_2 & -k_1^2 + k_2^2 \end{pmatrix}}_{A_{\boldsymbol{\kappa}}} \begin{pmatrix} \hat{\gamma}_1(\boldsymbol{k}) \\ \hat{\gamma}_2(\boldsymbol{k}) \end{pmatrix}$$

Weak Lensing



Massey et al, “The dark matter of gravitational lensing”,Reports on Progress in Physics, 73, 8, 2010.



Kilbinger et al, Dark-energy constraints and correlations with systematics from CFHTLS weak lensing, SNLS supernovae Ia and WMAP5, AA, 497, 3, 2009.

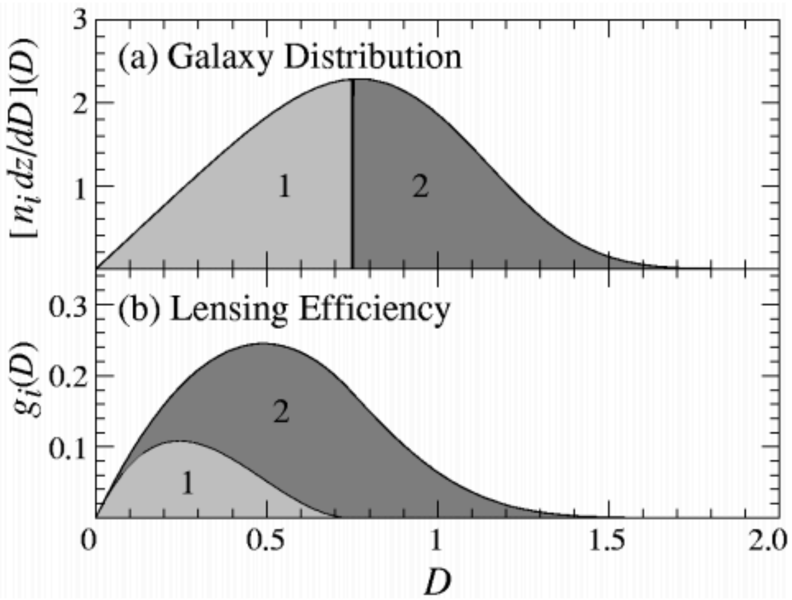
Fig. 9. 68% and 95% confidence levels for CMB (orange, solid lines), CMB+lensing (green dashed), CMB+SNIa (magenta dotted) and CMB+lensing+SNIa (blue dash-dotted). Systematics are ignored in this plot.

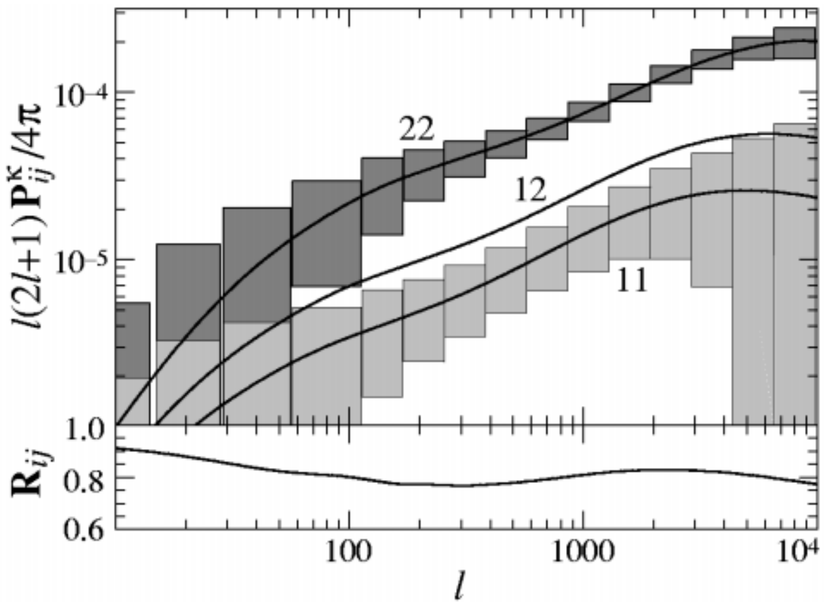
Tomographic Weak Lensing

THE ASTROPHYSICAL JOURNAL, 522:L21–L24, 1999 September 1

POWER SPECTRUM TOMOGRAPHY WITH WEAK LENSING

WAYNE HU
Institute for Advanced Study, Princeton, NJ 08540
Received 1999 April 13; accepted 1999 June 30; published 1999 July 21





Euclid Red Book

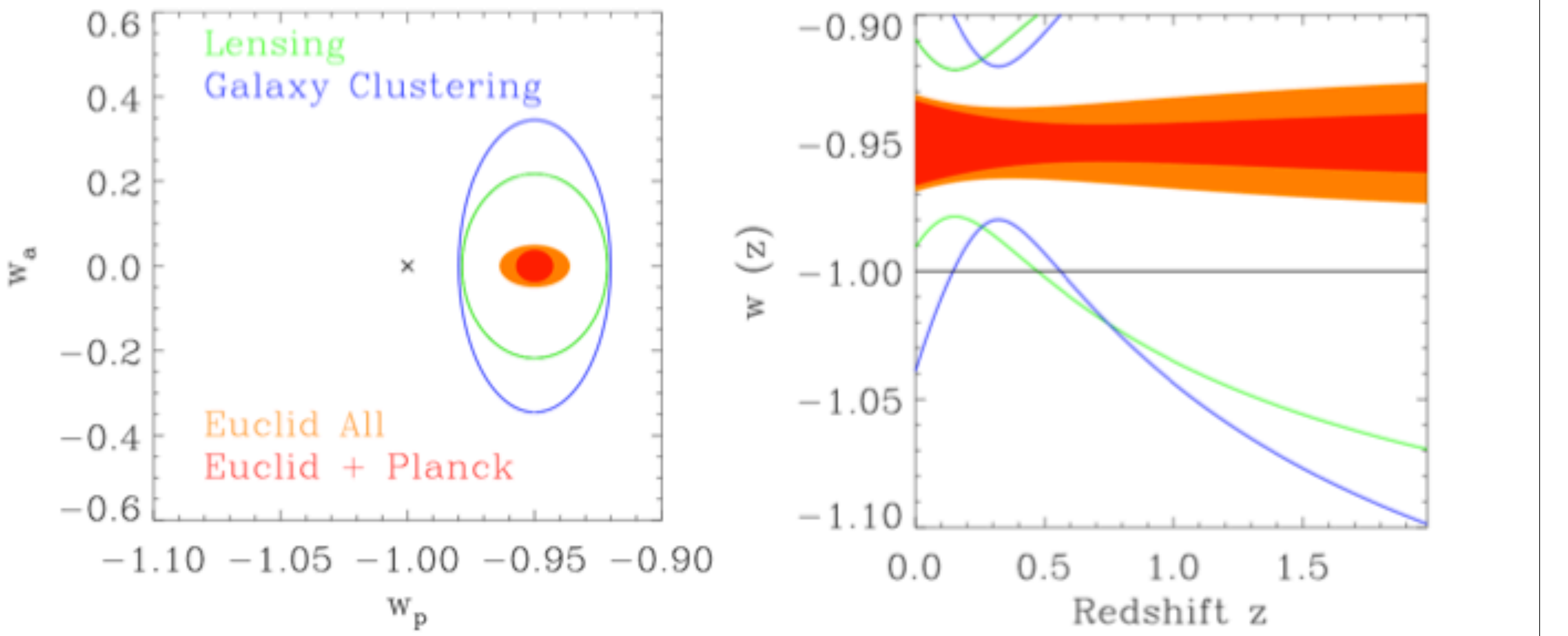
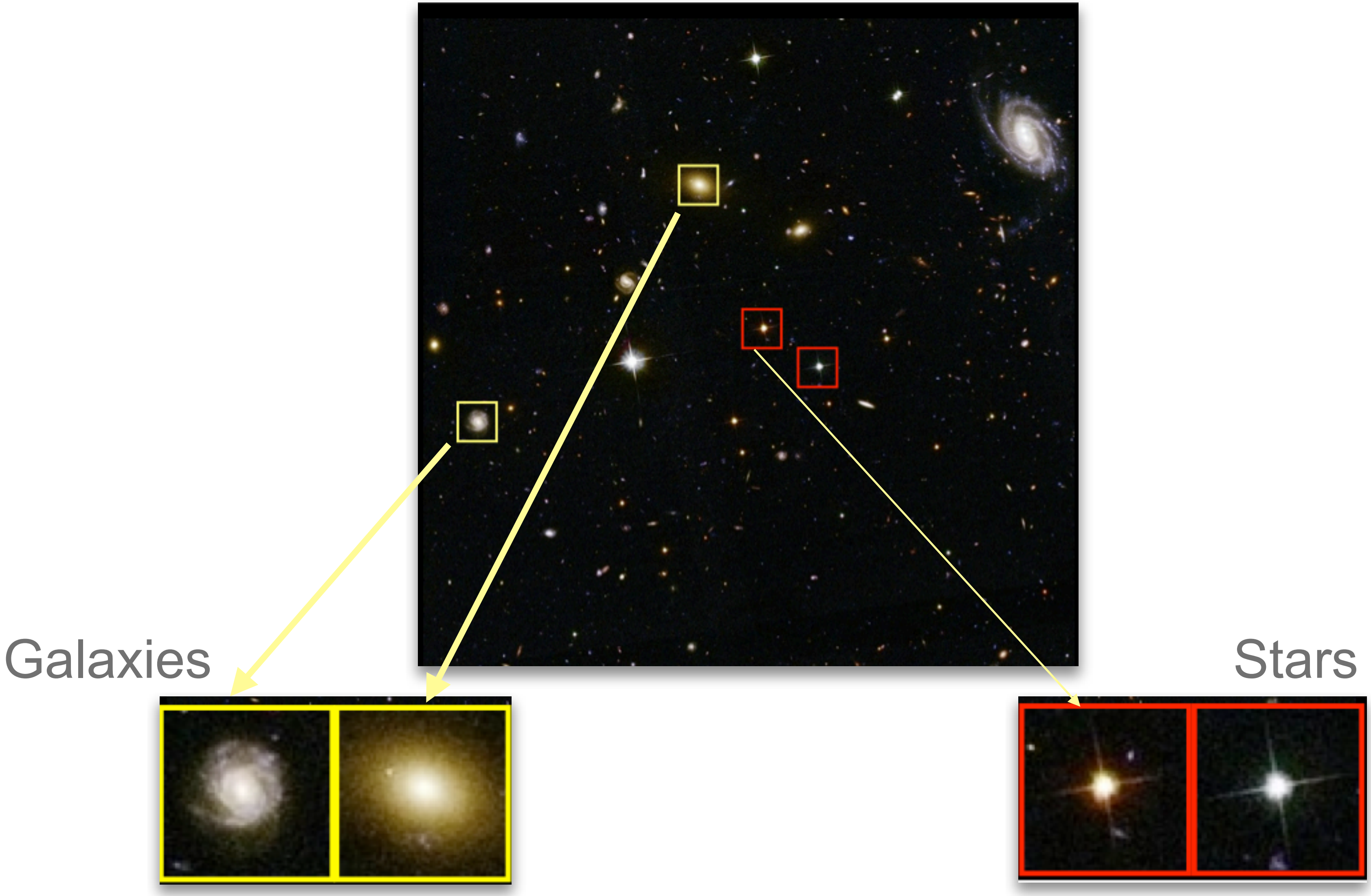


Figure 2.4: The expected constraints from Euclid in the dynamical dark energy parameter space. We show lensing only (green), galaxy clustering only (blue), all the Euclid probes (lensing+galaxy clustering+clusters+ISW; orange) and all Euclid with Planck CMB constraints (red). The cross shows a cosmological constant model. Left panel: the expected 68% confidence contours in the (w_p, w_a). Right panel: the 1σ constraints on the function w(z) parameterised by (w_p, w_a) as a function of redshift (green-lensing alone, blue-galaxy clustering alone, orange-all of the Euclid probes, red-Euclid combined with Planck).

Detection + Classification stars/galaxies

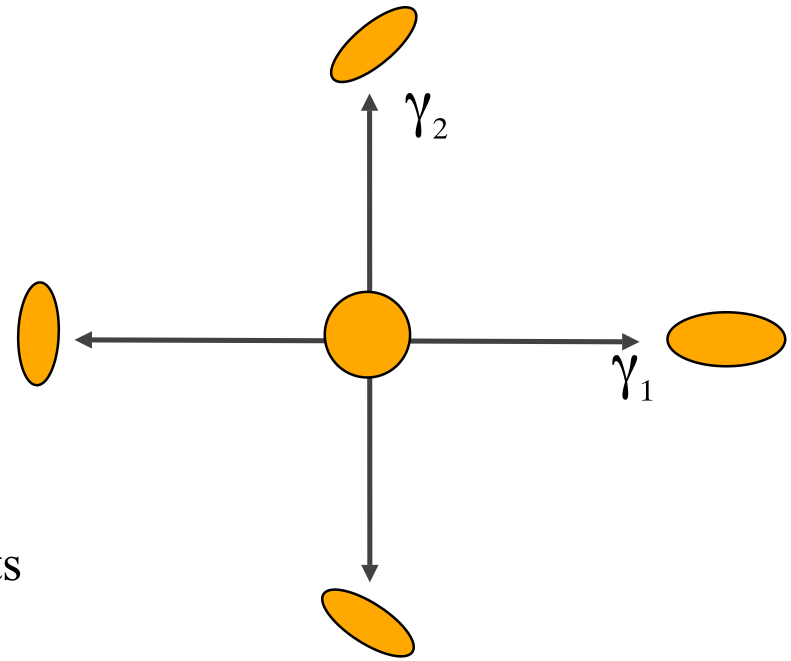


Shape Parameters

The shear map (γ_1, γ_2)

γ_1 = deformation along the x-axis,
and γ_2 at 45 degrees from it.

$$\gamma = \gamma_1 + i\gamma_2 = |\gamma| e^{2i\theta}$$



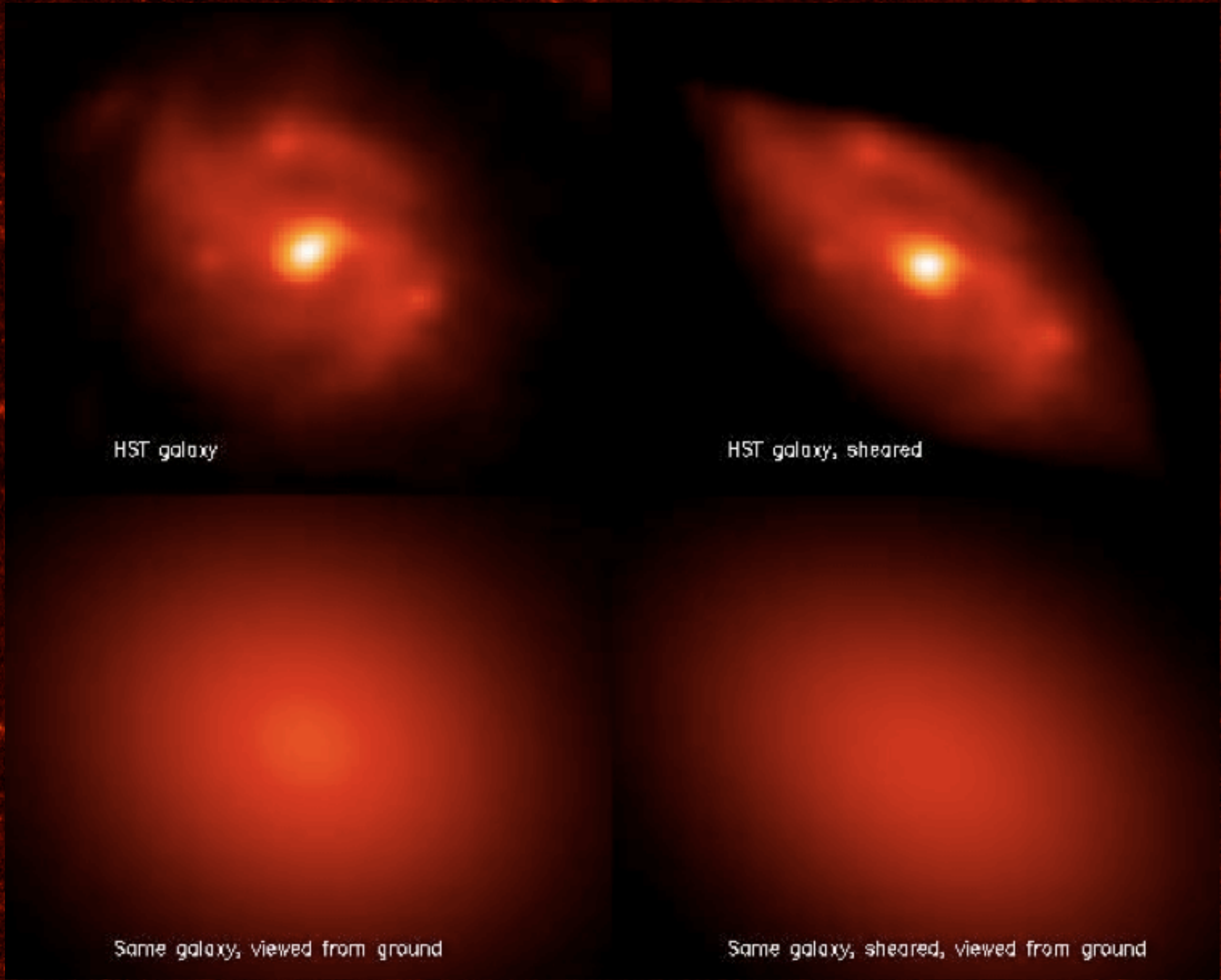
Where the modulus represents the amount of shear and the phase represents its direction.

$$\gamma_1 = \frac{M_{1,1} - M_{2,2}}{M_{1,1} + M_{2,2}}, \gamma_2 = \frac{2M_{1,2}}{M_{1,1} + M_{2,2}}, \quad M_{i,j} = \int \theta_i \theta_j S(\theta) w(\theta) d\theta^2$$

$M_{1,1} - M_{2,2}$ and $2M_{1,2}$ correspond respectively to the flattening along the x axis and the 45° axis. $M_{1,1} + M_{2,2}$ is related to the size.

PB 1: We need accurate measurements from noisy data

Motivation for spatial observations

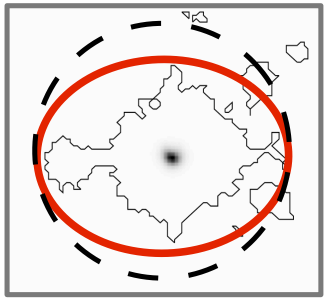


Massey, MGA

Convolution with an isotropic PSF circularises galaxies.
Convolution with an anisotropic PSF also changes their shapes... coherently!
Worst from ground (large PSF, with unpredictable spatial / temporal variation).

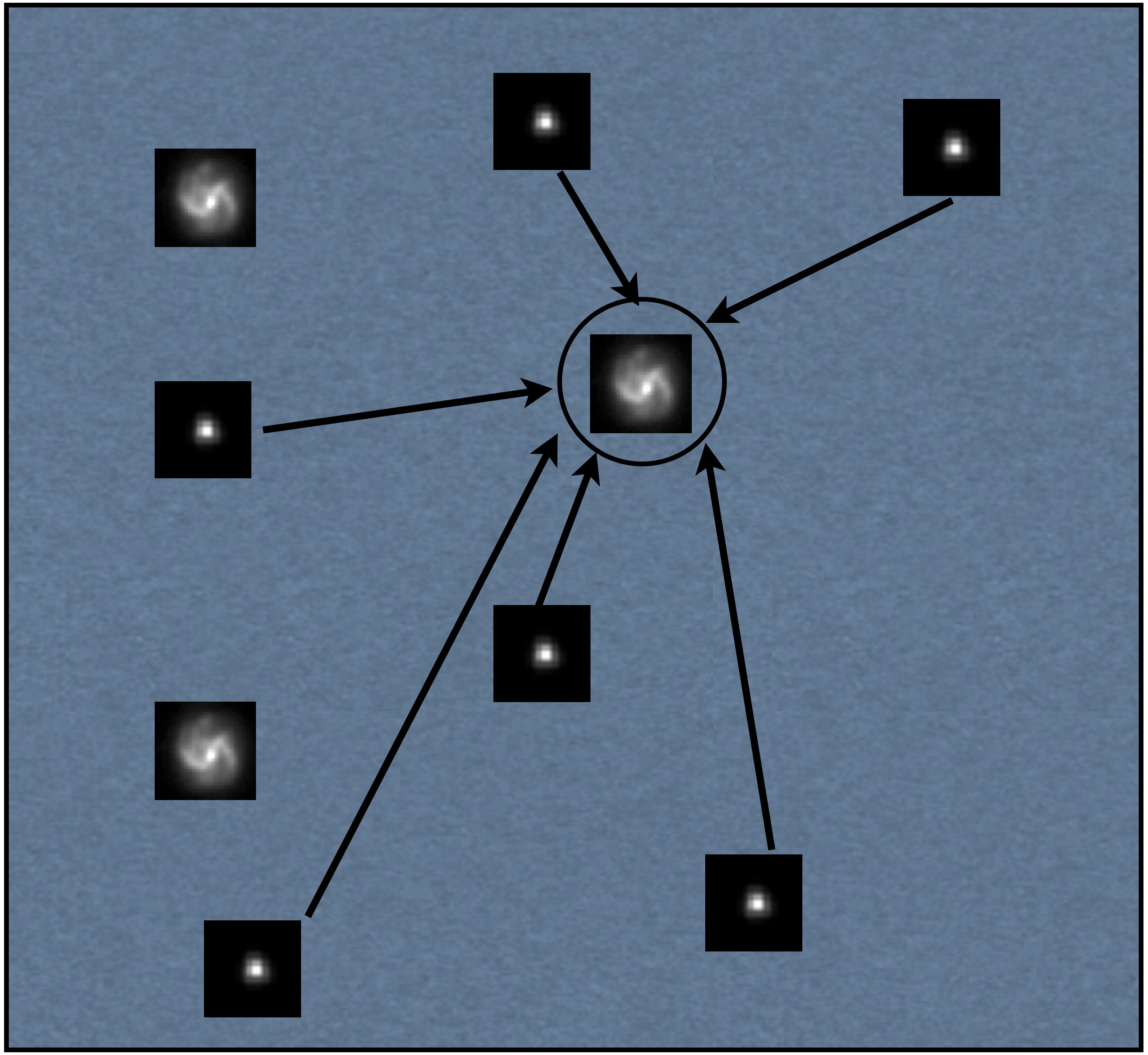
Point Spead Function

Galaxies are convolved by an asymetric PSF



PB 2: Shape measurements must be deconvolved

Space Variant PSF



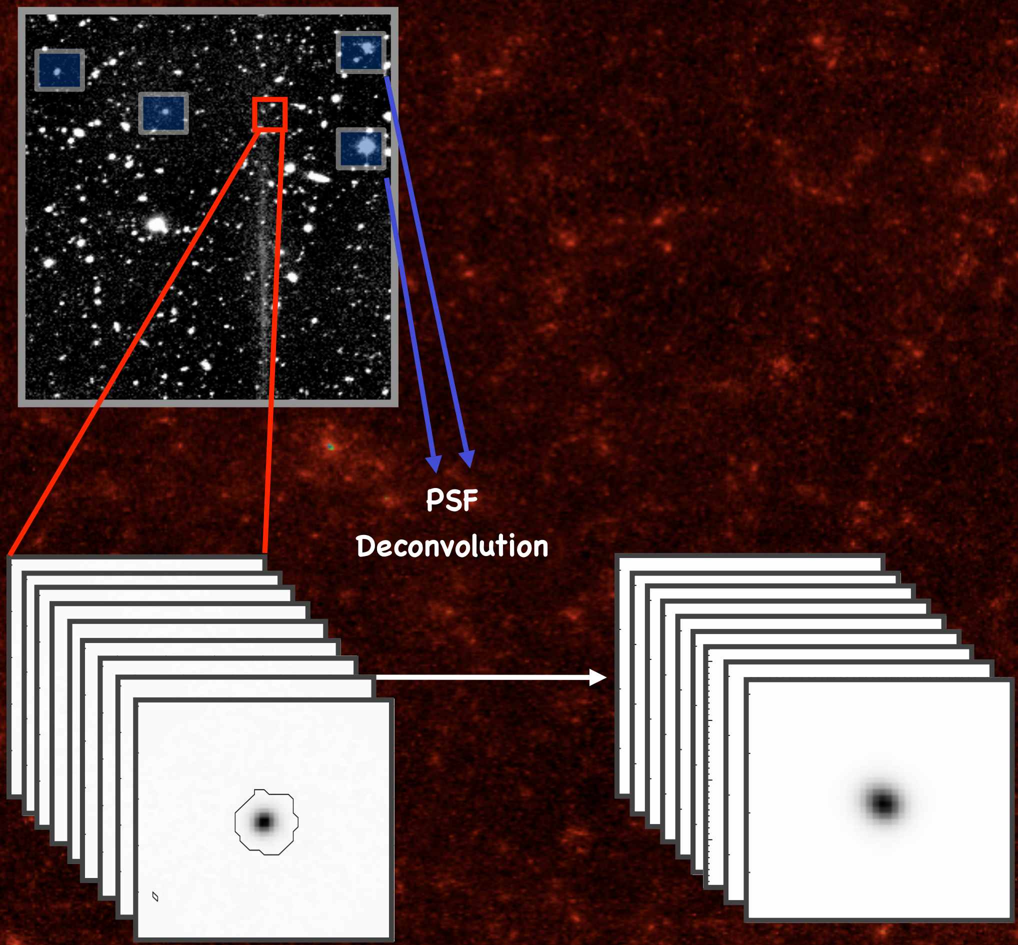
PB 3: We need to interpolate the PSF shape !

Intrinsic Ellipticities

✓ Galaxies have an intrinsic ellipticipty

PB 4: We need to correct the measurements from the intrinsic ellipticity

From Shear Measurements to Shear Map



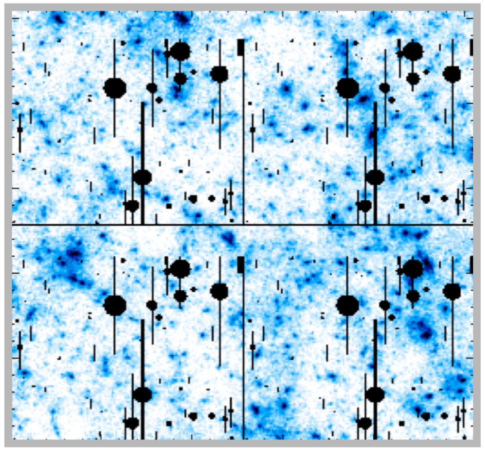
We need to solve a triple inverse problem !!!

Determine the PSF at any position from the measured PSF.

Correct the galaxy shear from the PSF shear.

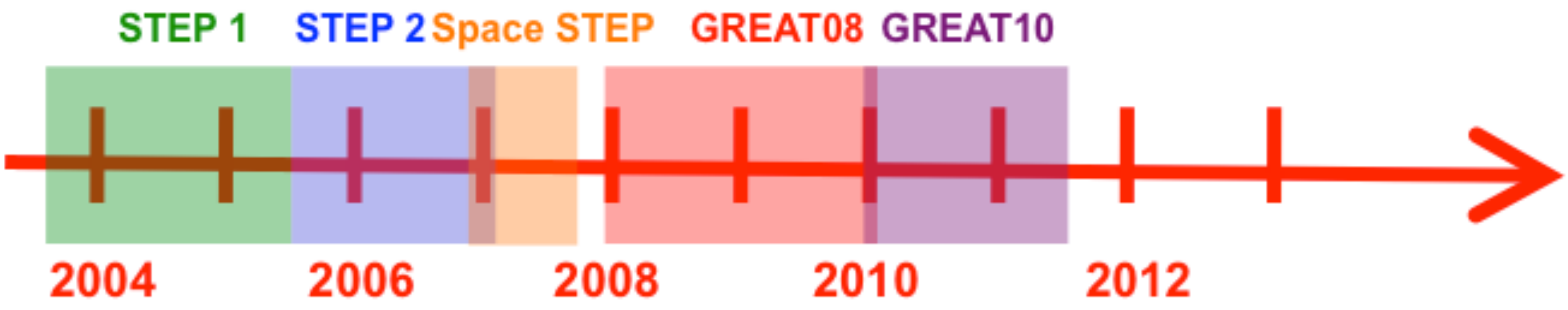
Correct the shear from intrinsic ellipticities

+ noise and missing data!!!



Missing data

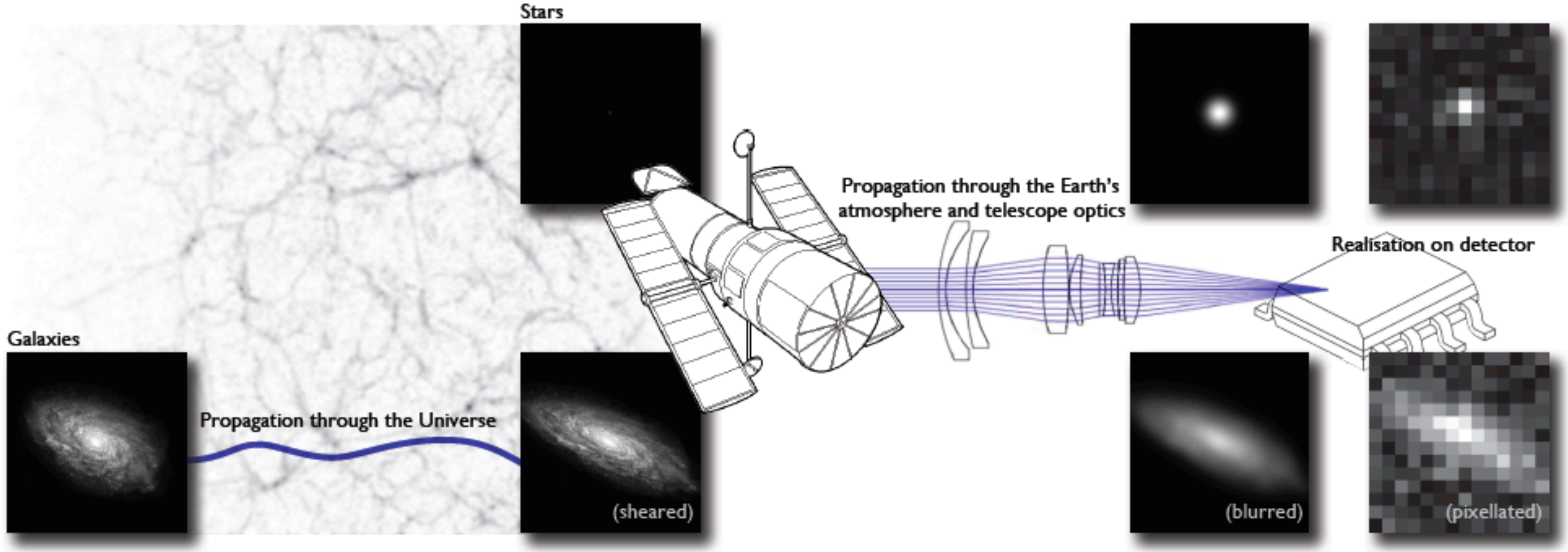
Shape measurement techniques: chronology of challenges



~3 more challenges should be organised before 2020

In GREAT10, there were 3 sub-challenges:

1. the main (galaxy) challenge: to measure the ellipticity of galaxies, assuming the PSF is known
2. a star challenge: to estimate the PSF and interpolate it at the position of galaxies
3. a 'light' challenge (named 'kaggle') to attract more people



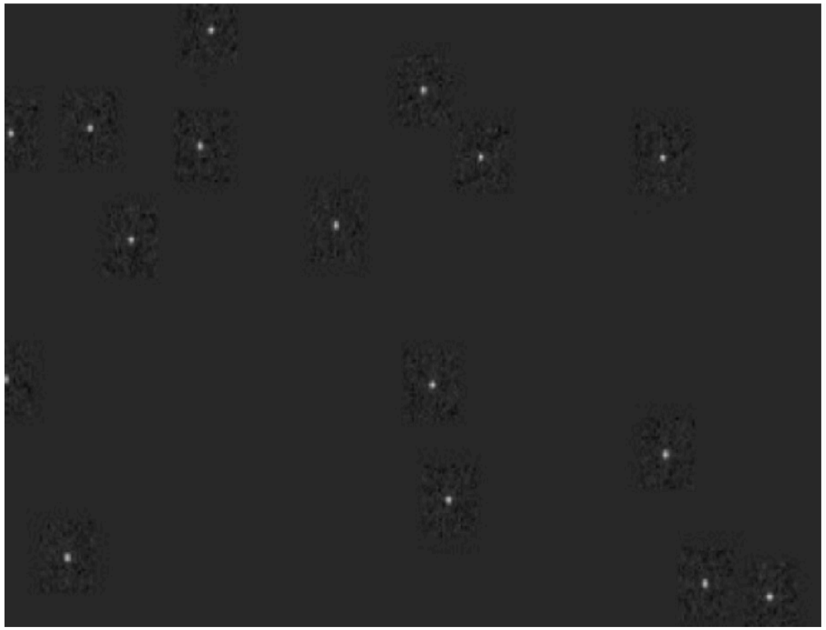
Need to measure the shear (which is of ~10^{-2}) with an accuracy of 10^{-2}

➔Need an absolute accuracy of ~10^{-4} in the measure of the shear

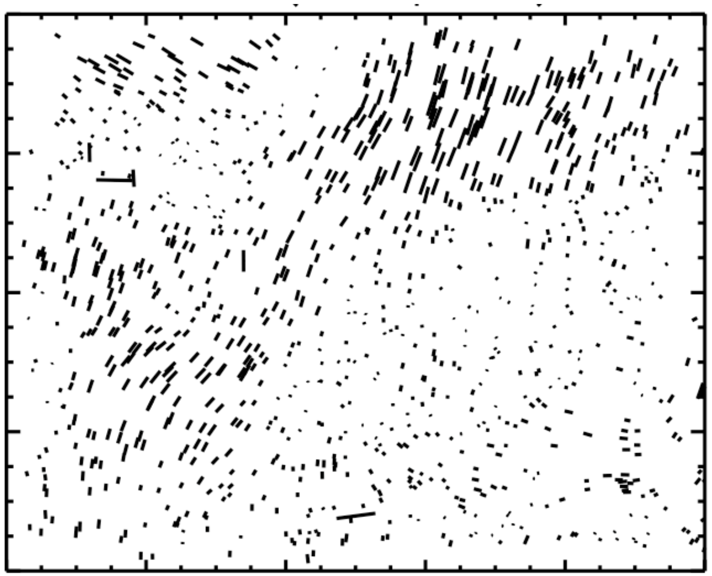
➔Need an absolute accuracy of ~sqrt(Ngal)*10^{-4} in the measure of the ellipticity for individual galaxies

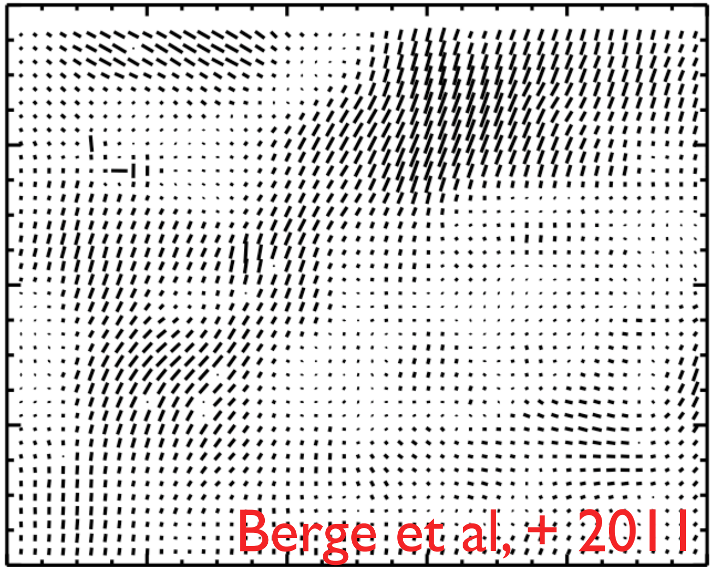
Star Challenge

Estimate the PSF and interpolate it at the position of galaxies



around 40000 stars





Drawbacks:

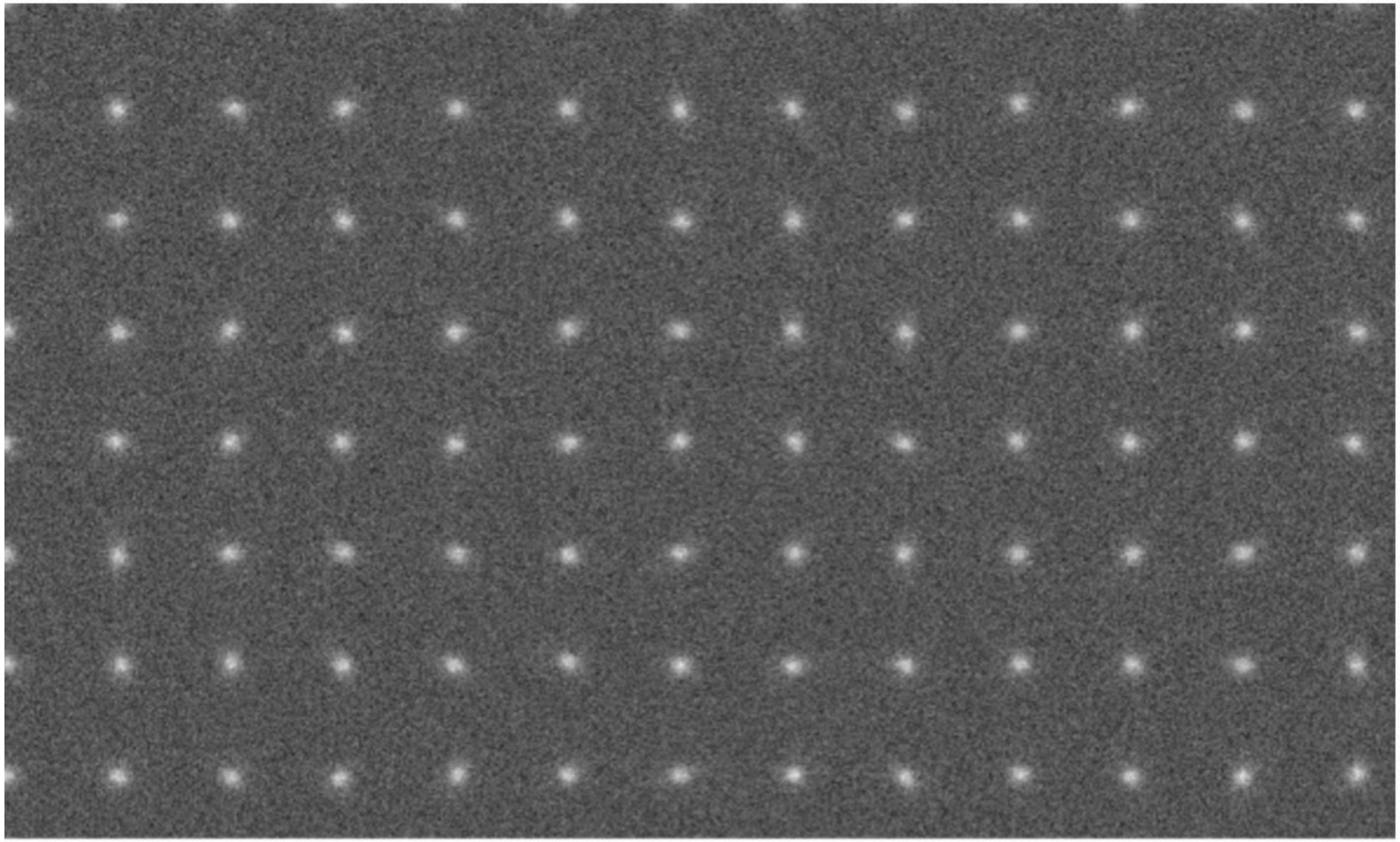
1.unrealistically simple PSF (could be easily modeled with a profile).

2.the SNR of stars was high and the noise unrealistically simple.

Winner: EPFL(Lausanne) ==> PSF model (moffat, 8 parameters: position, amplitude and 5 shape parameters) + interpolation (spline, kriging, etc).

Rank	Group Name	Method Name	Submission Date	Q	Sigma Sys
1	EPFL LASTRO	B-Splines	Aug. 25, 2011, 3:17 p.m.	13.3	7.52602E-05
2	EPFL LASTRO	IDW	July 18, 2011, 12:38 p.m.	13.2	7.59258E-05
3	EPFL LASTRO	RBF	Aug. 15, 2011, 4:42 p.m.	12.7	7.86296E-05
4	EPFL LASTRO	RBF-thin	Aug. 16, 2011, 4:33 p.m.	12.6	7.92756E-05
5	EPFL LASTRO	IDW	June 23, 2011, noon	8.7	0.000114747
6	EPFL LASTRO	IDW	June 2, 2011, 7:07 p.m.	7.2	0.000138215
7	EPFL LASTRO	Kriging	June 3, 2011, 4:13 p.m.	7.2	0.000138215
8	Purdue	Gaussianlets	July 19, 2011, 11:32 p.m.	4.1	0.000245255
9	EPFL LASTRO	IDW Stk	Aug. 25, 2011, 3:17 p.m.	4.0	0.000249888
10	AstrOmatic	PSFEx 3.10 baseline	Sept. 1, 2011, 4:40 p.m.	4.0	0.000252947
11	UPenn/USM	PSFEx	April 28, 2011, 4:45 p.m.	3.7	0.000268701
12	U. Penn	Shapelets	Sept. 1, 2011, 7:27 p.m.	3.5	0.000287593
13	Purdue	PCA+kriging	July 6, 2011, 9:34 p.m.	2.9	0.000342539
14	Purdue	PAC+kriging	July 20, 2011, 2:46 p.m.	2.1	0.000476479
15	AstrOmatic	PSFEx 3.10 tuned lo-mid	Sept. 2, 2011, 3:25 p.m.	1.9	0.00052613
16	AstrOmatic	PSFEx 3.10 baseline scaled	Sept. 2, 2011, 4:34 p.m.	1.9	0.00052613
17	AstrOmatic	PSFEx 3.10 tuned lo-hi	Sept. 2, 2011, 10:20 a.m.	1.9	0.000533332
18	AstrOmatic	PSFEx 3.10 tuned mid-hi	Sept. 2, 2011, 2:02 p.m.	1.8	0.000545185
19	InfEd	MoffatGP	Sept. 1, 2011, 4:39 p.m.	1.2	0.000800598
20	GREAT10		Dec. 7, 2010, 11:15 a.m.	1.0	0.00104465
21	BayesPSF	Basic SEx retry	May 2, 2011, 8:42 a.m.	1.0	0.00104465
22	InfEd	PcaGP	Aug. 31, 2011, 2:28 a.m.	0.8	0.00120245
23	I2PRG-ITB	Thin Plate	June 29, 2011, 12:27 p.m.	0.8	0.00125409
24	I2PRG-ITB	Correction of Thin-Plate	Aug. 23, 2011, 6:12 a.m.	0.7	0.00136537
25	I2PRG-ITB	SimpleQM+Thin Plate	Aug. 5, 2011, 10:39 a.m.	0.6	0.00155256
26	I2PRG-ITB	Thin-Plate (revised)	Aug. 25, 2011, 6:33 a.m.	0.5	0.00199096
27	I2PRG-ITB	Sparse Random Field	Aug. 25, 2011, 10:43 a.m.	0.5	0.00199158
28	I2PRG-ITB	Thin Plate (V.2.0)	Aug. 28, 2011, 10:18 a.m.	0.5	0.00207088
29	Purdue	Moffatlets	July 20, 2011, 7:05 a.m.	0.2	0.00496487

Galaxy challenge: to measure the ellipticity of galaxies, assuming the PSF is known



volume : 10^4 galaxies x 10^3 images ~ 1 TB

GREAT10 Challenge

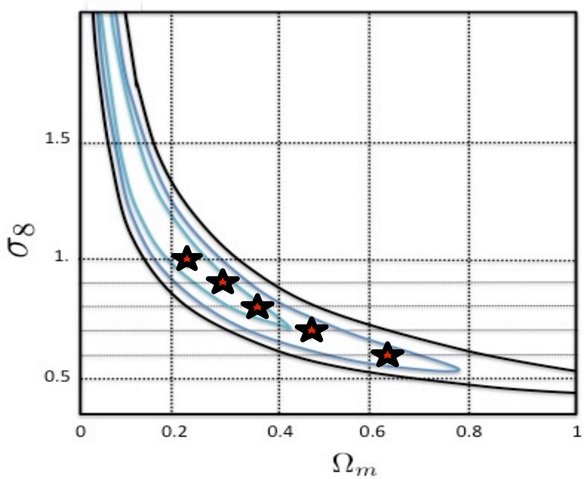
Winner: DeepZot (KSB + galaxy model fitting + bias correction from MC using Neural Network)

Rank	Group Name	Method Name	Submission Date	Q	Sigma Sys
1	DeepZot	fit2-unfold (ps)	Sept. 1, 2011, 4:53 p.m.	319.5	3.12987E-06
2	DeepZot	fit1-unfold (ps)	Sept. 1, 2011, 4:51 p.m.	291.5	3.4304E-06
3	Ohio State University	KSB	Aug. 29, 2011, 10:58 p.m.	119.6	8.36359E-06
4	EPFL LASTRO	gfit_den_cs	Sept. 2, 2011, 10:05 a.m.	118.8	8.4204E-06
5	Ohio State University	ARES	Sept. 2, 2011, 6:22 a.m.	115.5	8.6578E-06
6	Ohio State University	ARES2	Sept. 2, 2011, 4:36 p.m.	114.0	8.76837E-06
7	mpi-is	method04 (set21)	Sept. 2, 2011, 11:16 a.m.	109.7	9.11972E-06
8	mpi-is	method04	Sept. 1, 2011, 2:25 p.m.	109.3	9.15092E-06
9	mpi-is	method04 (set_21 corrected)	Sept. 1, 2011, 5:53 p.m.	109.3	9.15092E-06
10	mpi-is	method05 (set21)	Sept. 2, 2011, 1:33 p.m.	96.4	1.03681E-05
11	mpi-is	method05	Sept. 2, 2011, 10:18 a.m.	95.0	1.05228E-05
12	Ohio State University	KSB_BSA (ps)	Sept. 1, 2011, 11:38 a.m.	92.0	1.08703E-05
13	UCL CoGS	Im3shape NBC0	Aug. 31, 2011, 12:54 p.m.	89.1	1.12279E-05
14	UCL CoGS	Im3shape NBC1	Sept. 2, 2011, 1:37 a.m.	88.9	1.12478E-05
15	UCL CoGS	Im3shape NBC0XS	Sept. 2, 2011, 3:12 p.m.	88.6	1.12827E-05
16	UCL CoGS	Im3shape Uncalibrated	Aug. 30, 2011, 11:57 p.m.	87.6	1.14111E-05
17	UCL CoGS	Im3shape Uncalibrated XS	Sept. 2, 2011, 4:11 p.m.	87.2	1.14683E-05
18	Ohio State University	KSB analytic	Sept. 2, 2011, 4:07 p.m.	81.0	1.23428E-05
19	Ohio State University	DEIMOS C6	Aug. 24, 2011, 12:14 a.m.	79.9	1.251E-05
20	Ohio State University	DEIMOS C4	Aug. 23, 2011, 12:16 a.m.	77.9	1.28418E-05
21	UCL CoGS	Im3shape NBC0	Aug. 29, 2011, 6:13 p.m.	75.7	1.32041E-05
22	mpi-is	method01	Aug. 30, 2011, 9:29 p.m.	74.1	1.34928E-05
23	EPFL LASTRO	gfit	Sept. 2, 2011, 9:52 a.m.	73.8	1.35452E-05
24	EPFL LASTRO	gfit_cs	Sept. 2, 2011, 10:12 a.m.	73.8	1.35452E-05
25	UCL CoGS	Im3shape Uncalibrated	Aug. 27, 2011, 11:52 a.m.	73.5	1.36001E-05
26	UCL CoGS	Im3shape Uncalibrated	Aug. 23, 2011, 1:21 a.m.	73.2	1.36676E-05
27	UCL CoGS	Im3shape NBC1XS	Sept. 2, 2011, 2:27 p.m.	72.2	1.38468E-05
28	mpi-is	method02	Aug. 31, 2011, 6:05 p.m.	71.8	1.39286E-05
29	UCL CoGS	Im3shape Uncalibrated	Sept. 2, 2011, 10:55 a.m.	71.7	1.39533E-05
30	GREAT10	None	Dec. 3, 2010, 5:43 p.m.	67.6	1.47931E-05
31	Ohio State University	DEIMOS C6 analytic	Sept. 1, 2011, 9:51 a.m.	64.6	1.54684E-05
32	Ohio State University	DEIMOS C8 analytic	Sept. 1, 2011, 8:16 p.m.	63.1	1.58405E-05
33	Oxford/Malta	LensfitG10 -uses incorrect PSF due to FUNCPSF form	Aug. 31, 2011, 1:15 p.m.	63.1	1.58555E-05
34	Ohio State University	DEIMOS C4 analytic	Sept. 1, 2011, 9:15 p.m.	62.8	1.59281E-05
35	Oxford/Malta	LensfitG10 -uses incorrect PSF due to FUNCPSF form	Aug. 31, 2011, 5 p.m.	61.7	1.6215E-05

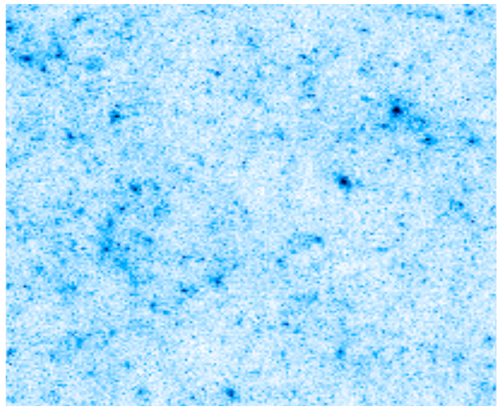
EPFL (Lausanne)

GREAT08 winner

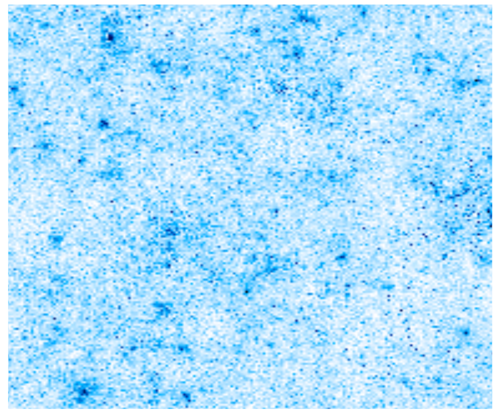
Cosmological Parameters Constraints and High Order Statistics



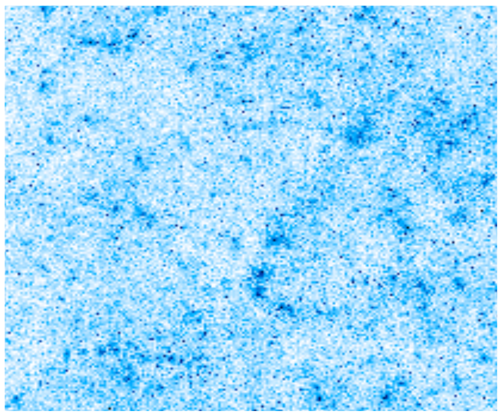
Model1 (σ_8=1, Ω_m=0.23)



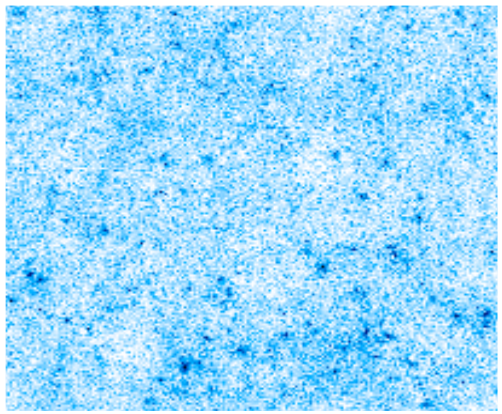
Model2 (σ_8=0.9, Ω_m=0.3)



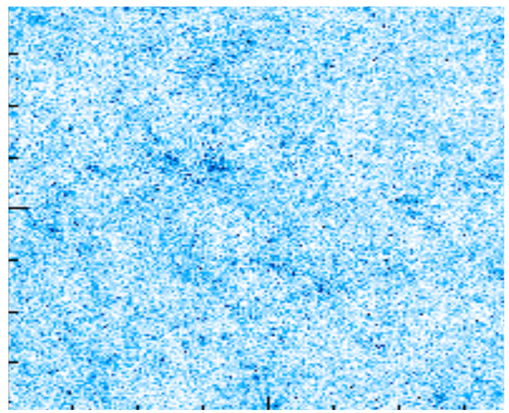
Model3 (σ_8=0.8, Ω_m=0.36)



Model4 (σ_8=0.7, Ω_m=0.47)

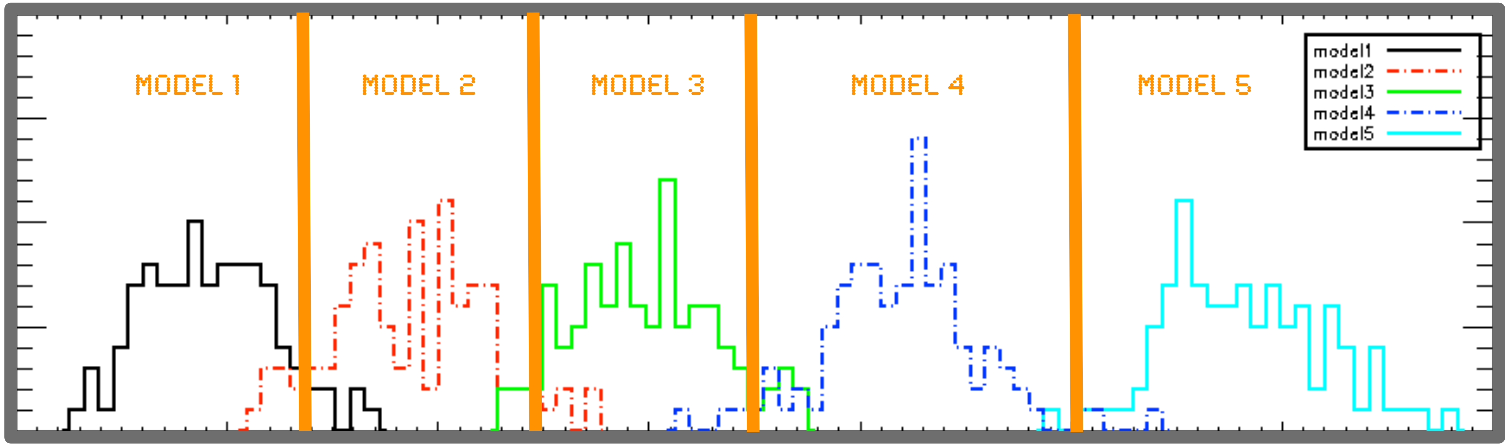


Model5 (σ_8=0.6, Ω_m=0.64)



Cosmological Parameters Constraints and High Order Statistics

- S. Pires, J.-L. Starck, A. Amara, A. Refregier, R. Teyssier, "Cosmological models discrimination with Weak Lensing", 505, A&A, pp 969-979, 2009.
- S. Pires, J.-L. Starck and A. Refregier, "Light on Dark Matter with Weak Gravitational Lensing", IEEE Signal Processing Magazine, 27, 1, pp 76--85, 2010.
- S. Pires, J.-L. Starck, A. Amara, A., R. Teyssier, A. Refregier and J. Fadili, "FASTLens (FAst STatistics for weak Lensing) : Fast method for Weak Lensing Statistics and map making", MNRAS , 395, 3, pp. 1265-1279, 2009.
- S. Pires, A. Leonard, J.-L. Starck, "Cosmological Parameters Constraint from Weak Lensing Data", MNRAS, submitted, 2011.
- A. Leonard, S. Pires, J.-L. Starck, "Fast Calculation of the Weak Lensing Aperture Mass Statistic", MNRAS, submitted, 2011.

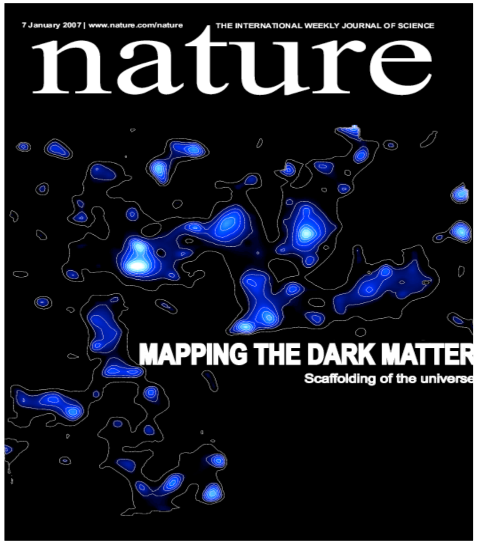


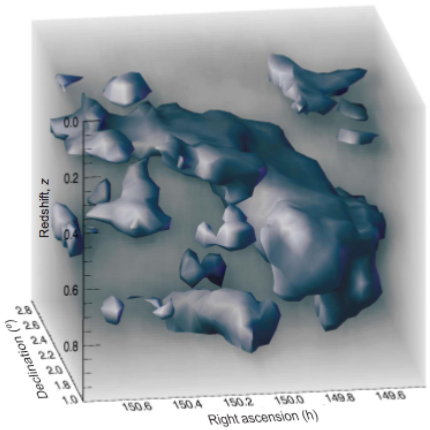
WAVELET PEAK COUNTING ON MRLENS FILTRED MAPS (AT SCALE OF ABOUT 1 ARCMIN)

Mass Map Reconstruction and High Order Statistics

J.-L. Starck, S. Pires and A. Réfrégier, Astronomy and Astrophysics, 451, 3, 2006, pp.1139-1150 , 2006
S. Pires, J.-L. Starck, A. Amara, R. Teyssier, A. Refregier and J. Fadili, MNRAS, Volume 395, Issue 3, pp. 1265-1279, 2009.
R. Massey et al, Maps of the Universe's Dark matter scaffolding,, Nature, Vol. 445, pp. 286-290, 2007

$$\gamma_i \rightarrow \boxed{\min_\kappa \|\Phi^t\kappa\|_{l_0} \ \text{subject to} \ \sum_i \|\gamma_i - M(P_i * \kappa)\|_{l_2}^2 \le \varepsilon} \rightarrow \kappa$$

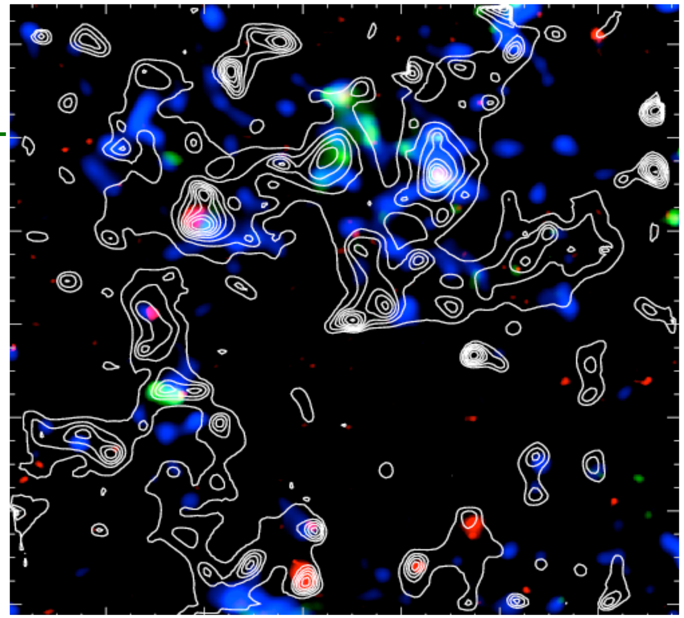




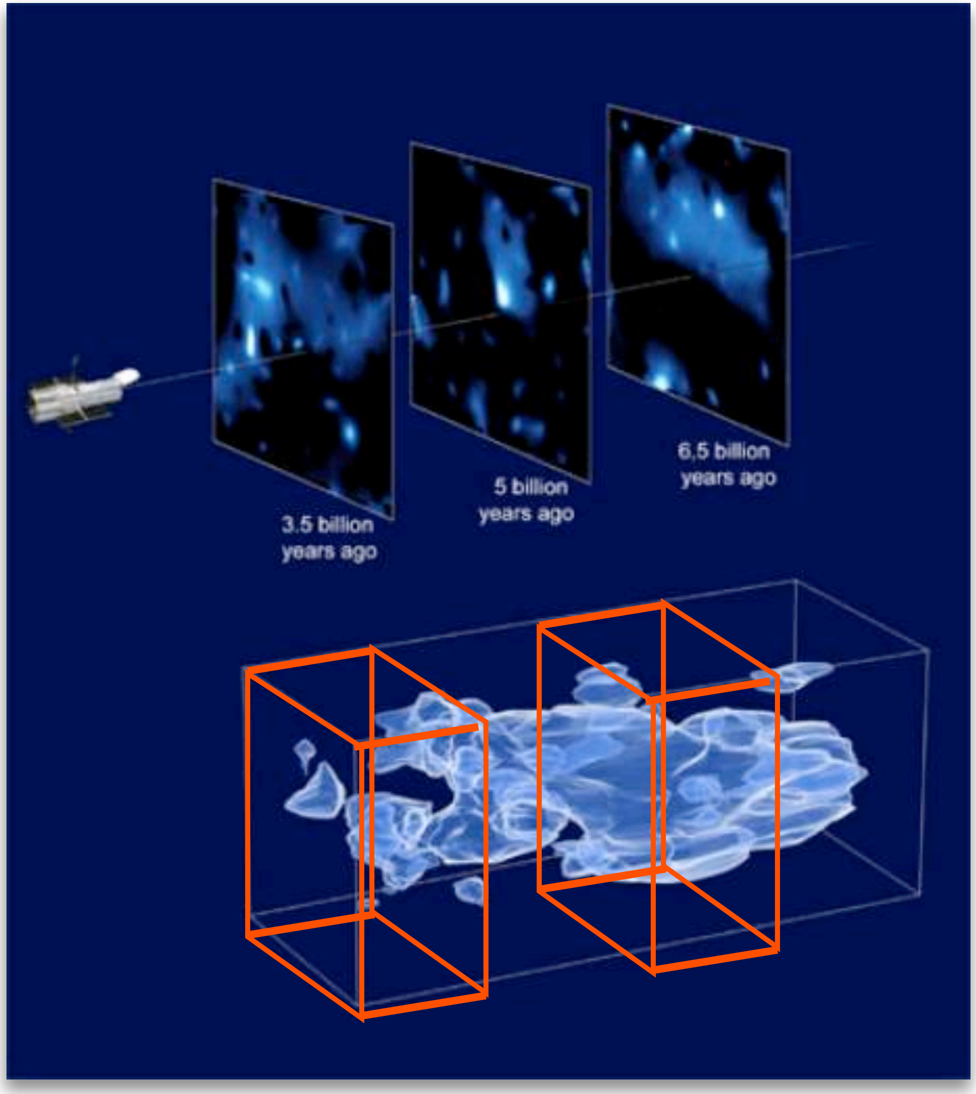
Stellar mass

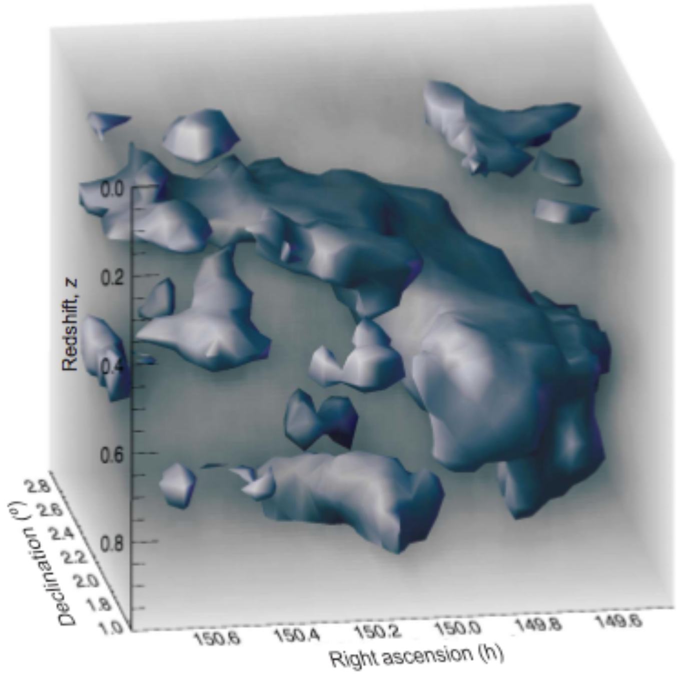
Galaxy density and WL

Hot gas

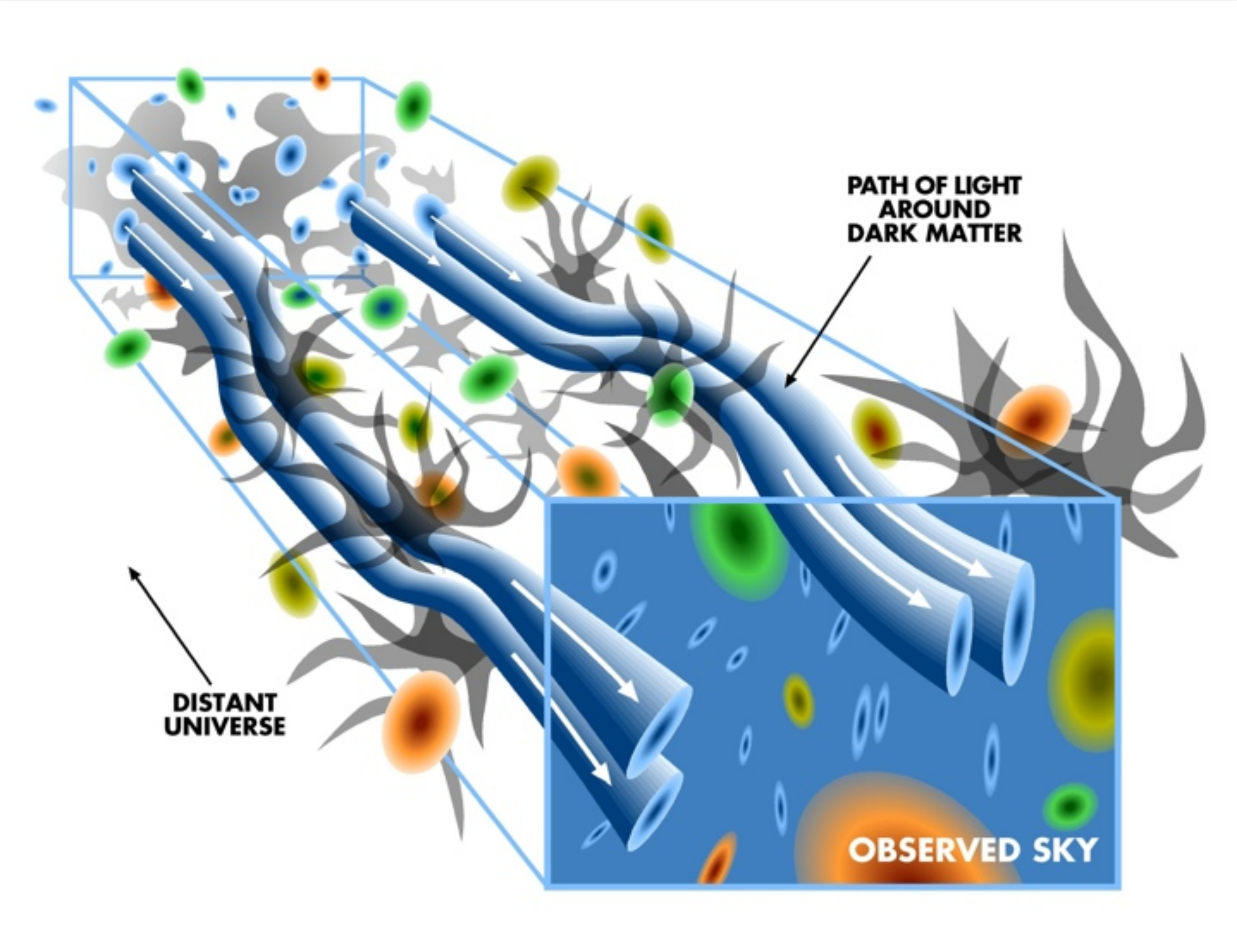


Pseudo-3D Weak Lensing





3D Weak Lensing



3D Weak Lensing

The convergence κ, as seen in sources of a given redshift bin, is the linear transformation of the matter density contrast, δ, along the line-of-sight (Simon et al 2009):

$$\kappa = Q\delta + N$$

with $\delta(r) \equiv \rho(r)/\overline{\rho} - 1$

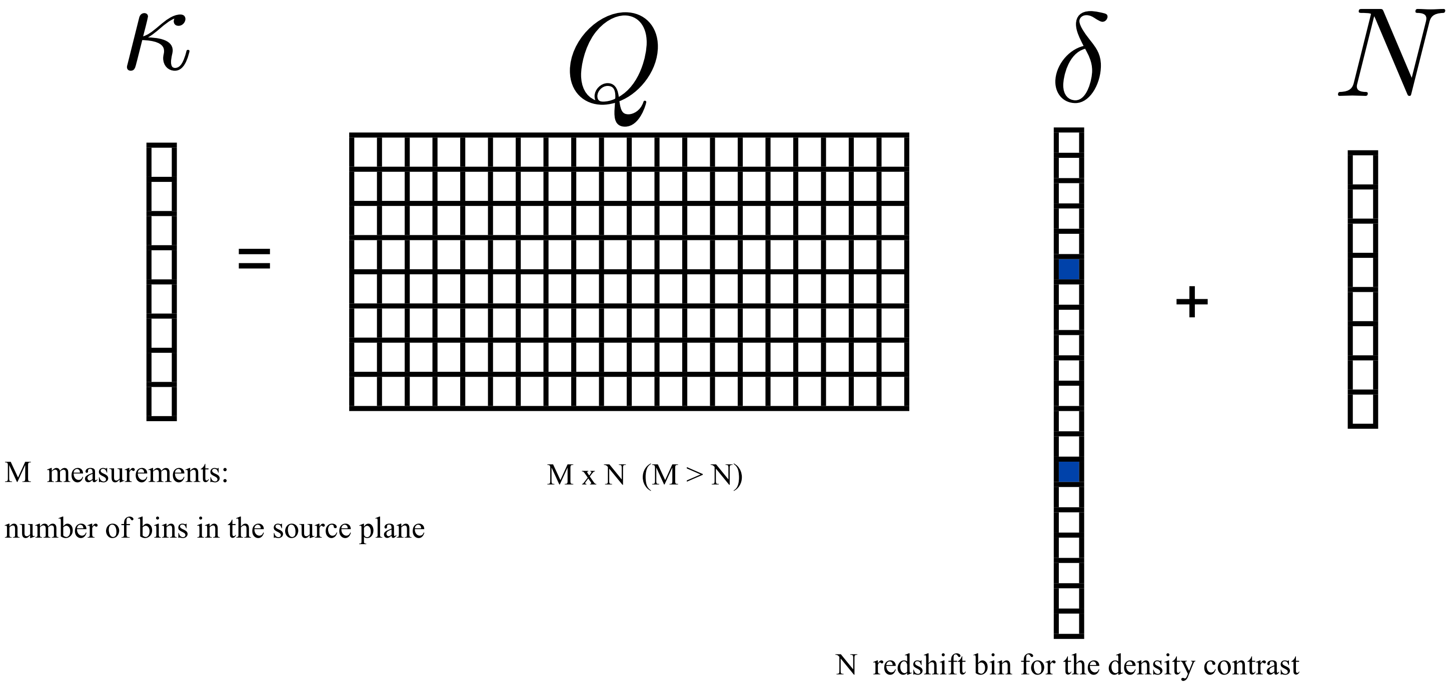
$$Q_{i\ell} = \frac{3H_0^2\Omega_M}{2c^2}\int_{w_\ell}^{w_{\ell+1}} dw \frac{\overline{W}^{(i)}(w) f_K(w)}{a(w)}\,, \quad \overline{W}^{(i)}(w) = \int_0^{w^{(i)}} dw' \frac{f_K(w-w')}{f_K(w')}\left(p(z)\frac{dz}{dw}\right)_{z=z(w')}$$

where H_0 is the hubble parameter, Ω_M is the matter density parameter, c is the speed of light, $a(w)$ is the scale parameter evaluated at comoving distance w, and

$$f_K(w) = \begin{cases} K^{-1/2}\sin(K^{1/2}w), & K > 0 \\ w, & K = 0 \\ (-K)^{-1/2}\sinh([-K]^{1/2}w) & K < 0 \end{cases}\,,$$

gives the comoving angular diameter distance as a function of the comoving distance and the curvature, K, of the Universe.

3D Weak Lensing



δ is sparse.

Q spreads out the information in δ along κ bins.

More unkown than measurements

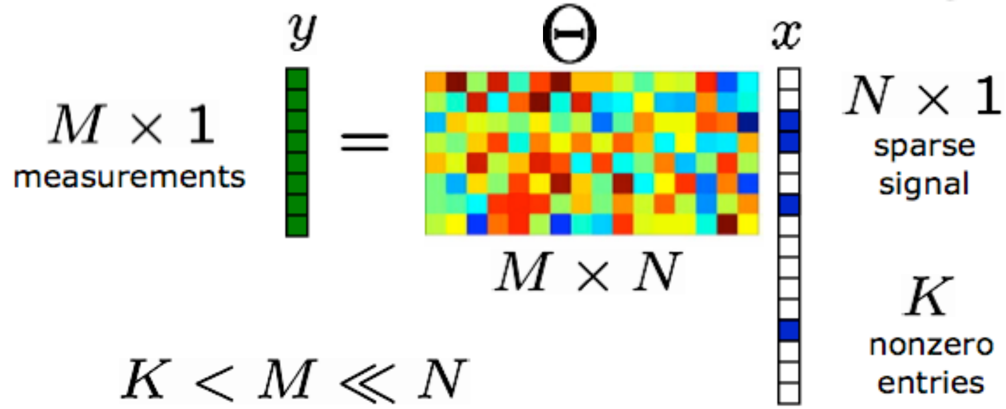
Compressed Sensing

* E. Candès and T. Tao, "Near Optimal Signal Recovery From Random Projections: Universal Encoding Strategies? ", IEEE Trans. on Information Theory, 52, pp 5406-5425, 2006.
* D. Donoho, "Compressed Sensing", IEEE Trans. on Information Theory, 52(4), pp. 1289-1306, April 2006.
* E. Candès, J. Romberg and T. Tao, "Robust Uncertainty Principles: Exact Signal Reconstruction from Highly Incomplete Frequency Information", IEEE Trans. on Information Theory, 52(2) pp. 489 - 509, Feb. 2006.

<u>A non linear sampling theorem</u>

"Signals with exactly K components different from zero can be recovered perfectly from ~ K log N incoherent measurements"

Replace samples with *few linear projections* $y = \Theta x$



$$y = \Theta x$$

$$K < M \ll N$$

Reconstruction via non linear processing: $\min_x \|x\|_1 \quad \text{s.t.} \quad y = \Theta x$

⇒Application: Compression, tomography, ill posed inverse problem.

3D Weak Lensing

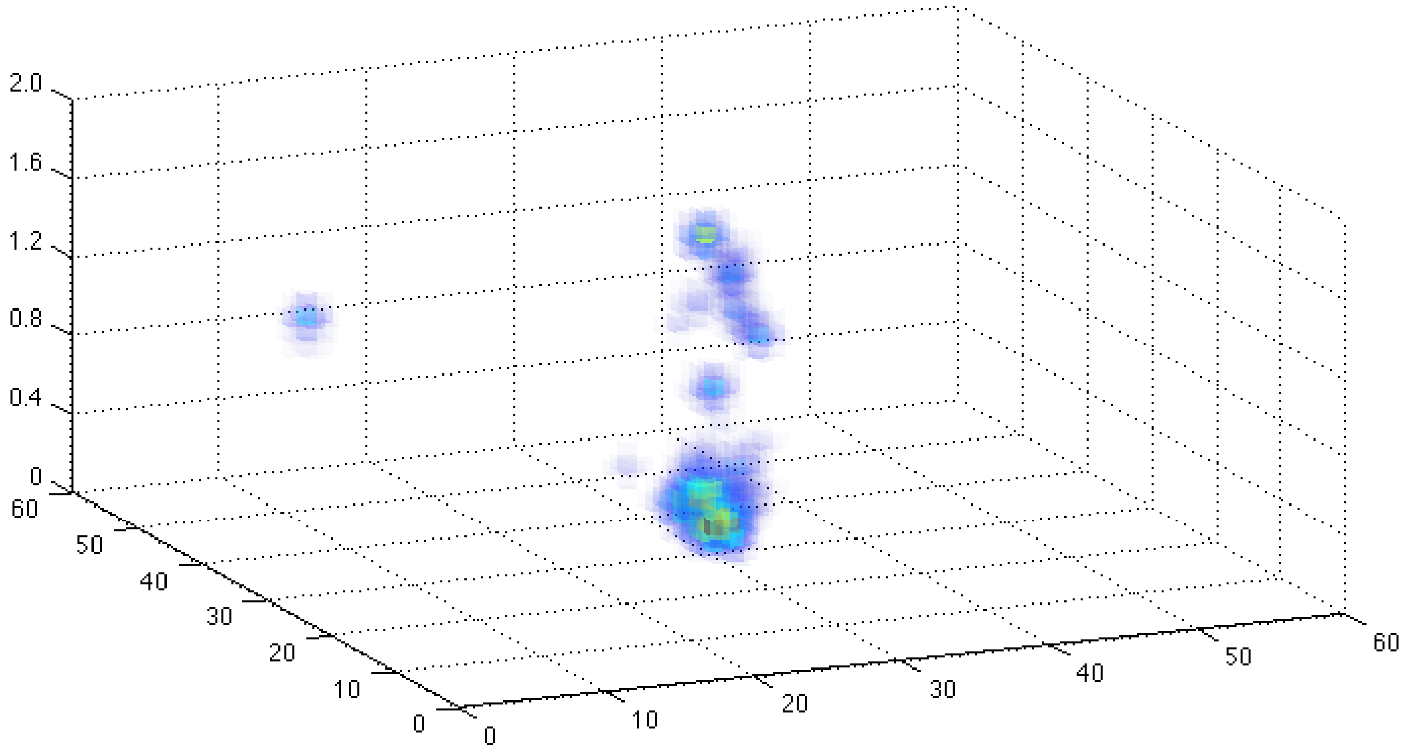
Matter in the Universe as a Natural Compressed Sensing Operator

$$\min_{\delta} \parallel \delta \parallel_1 \quad s.t. \ \frac{1}{2} \parallel \kappa - Q\delta \parallel^2_{\mathbf{\Sigma}^{-1}} \leq \epsilon$$

Recent optimization method, based on proximal theory, such as Chambolle & Pock (2010) can be used to find the solution.

A. Leonard, F.-X. Dupe, J.-L. Starck, "A compressed sensing approach to 3D weak lensing", Astronomy and Astrophysics, arXiv:1111.6478, A&A, in press.

3D Weak Lensing



Reconstructions of two clusters along the line of sight, located at a redshift 0.2 and 1.0 (data binned into Nsp = 20 redshift bins, but aim to reconstruct onto Nlp = 25 redshift bins).

Conclusions/Perspectives

- Weak Lensing is a powerful technique to measure large-scale structure

- It directly measures the mass (as opposed to light

- But require tight control of systematic

- Algorithms need clearly to be improved in order to meet EUCLID scientific requirements.

  * Psf measurements
  * Shear on individual galaxies
  * Lensing statistics.

- High order statistics should be used to better constraint the cosmological parameters

- Compressed sensing theory useful to recover the 3D density map.
  * l1 norm minimization is required to find the best solution with such operator.
  * Compressed Sensing approach may allow us to map the cosmic web in far greater detail than what has previously been achieved.