Cosmology and the Dark Energy Survey

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ETH Zurich

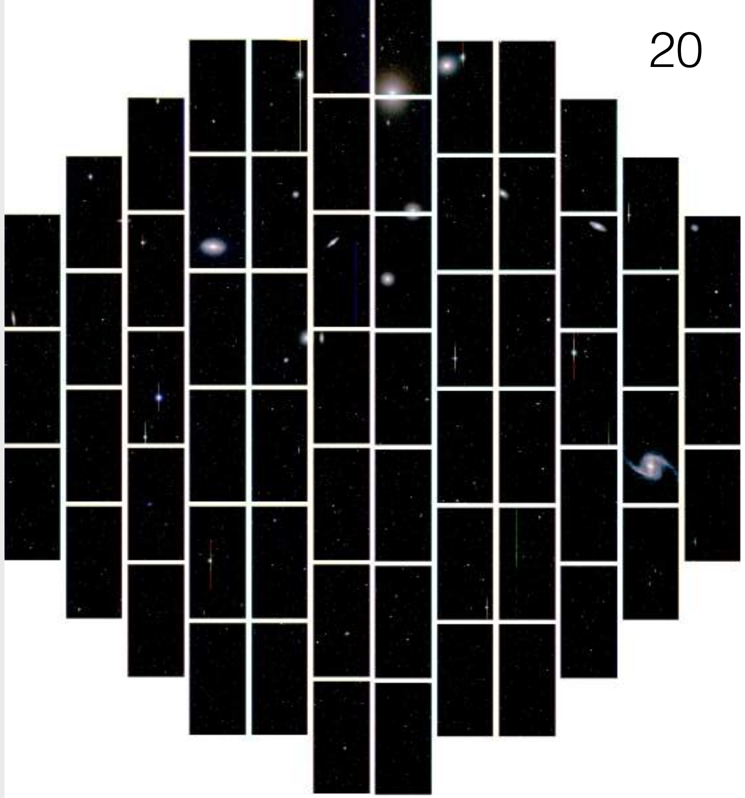
Dark Energy Survey
&
Latest Results

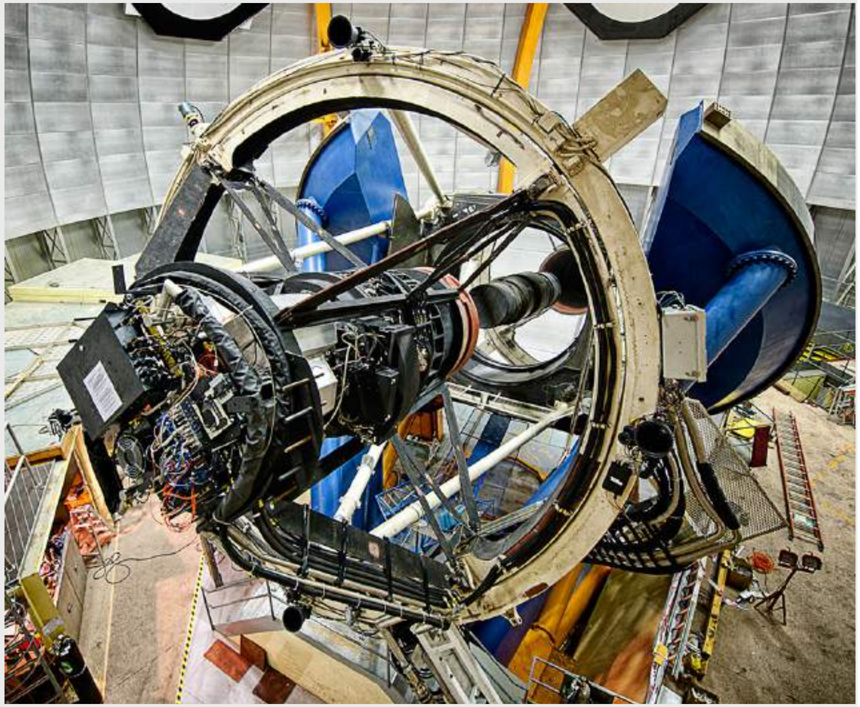
Cosmic Concordance?

Precision Measurements
Looking Forward

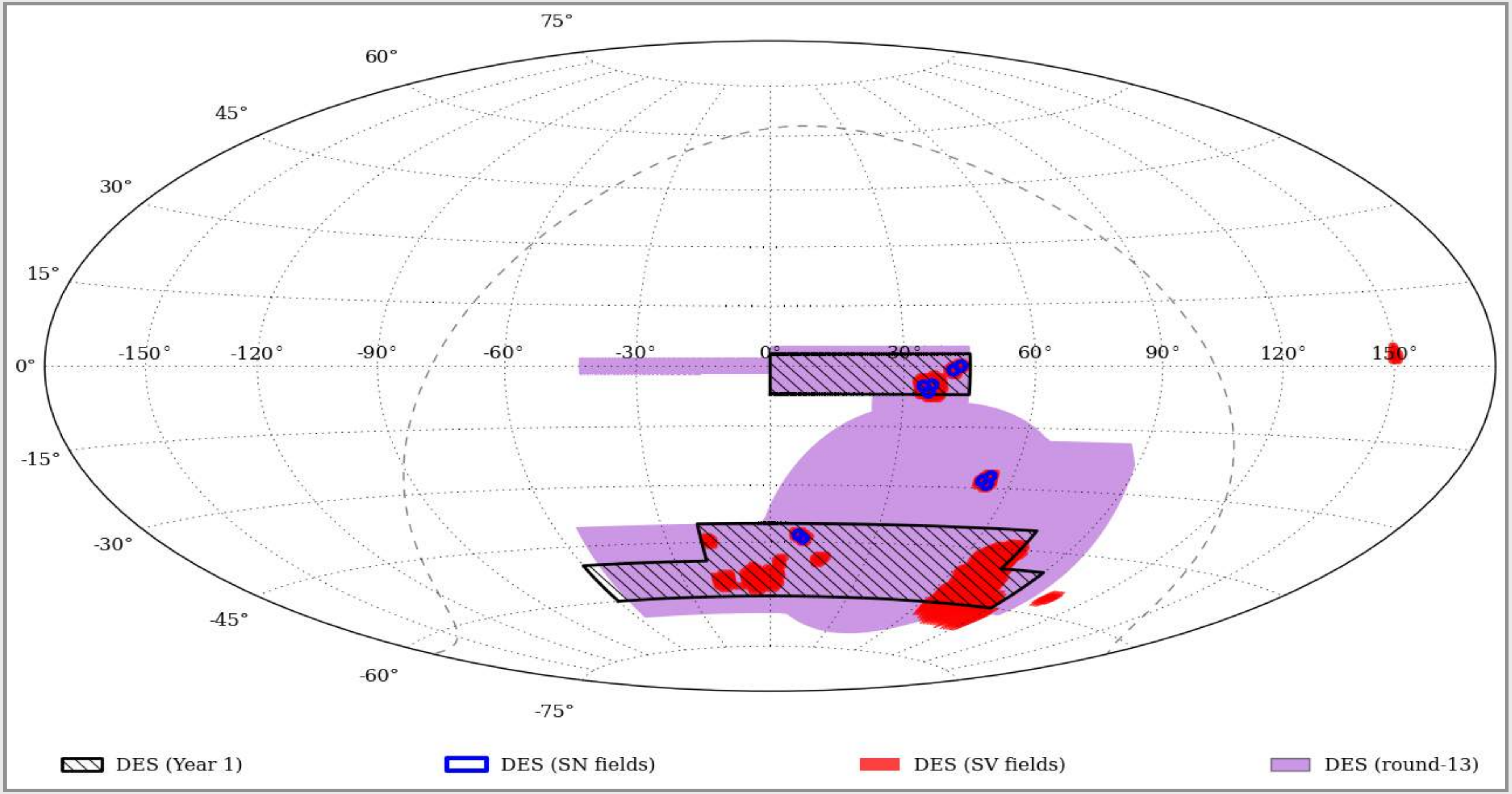
The Dark Energy Survey

DES First Light
12 September 2012





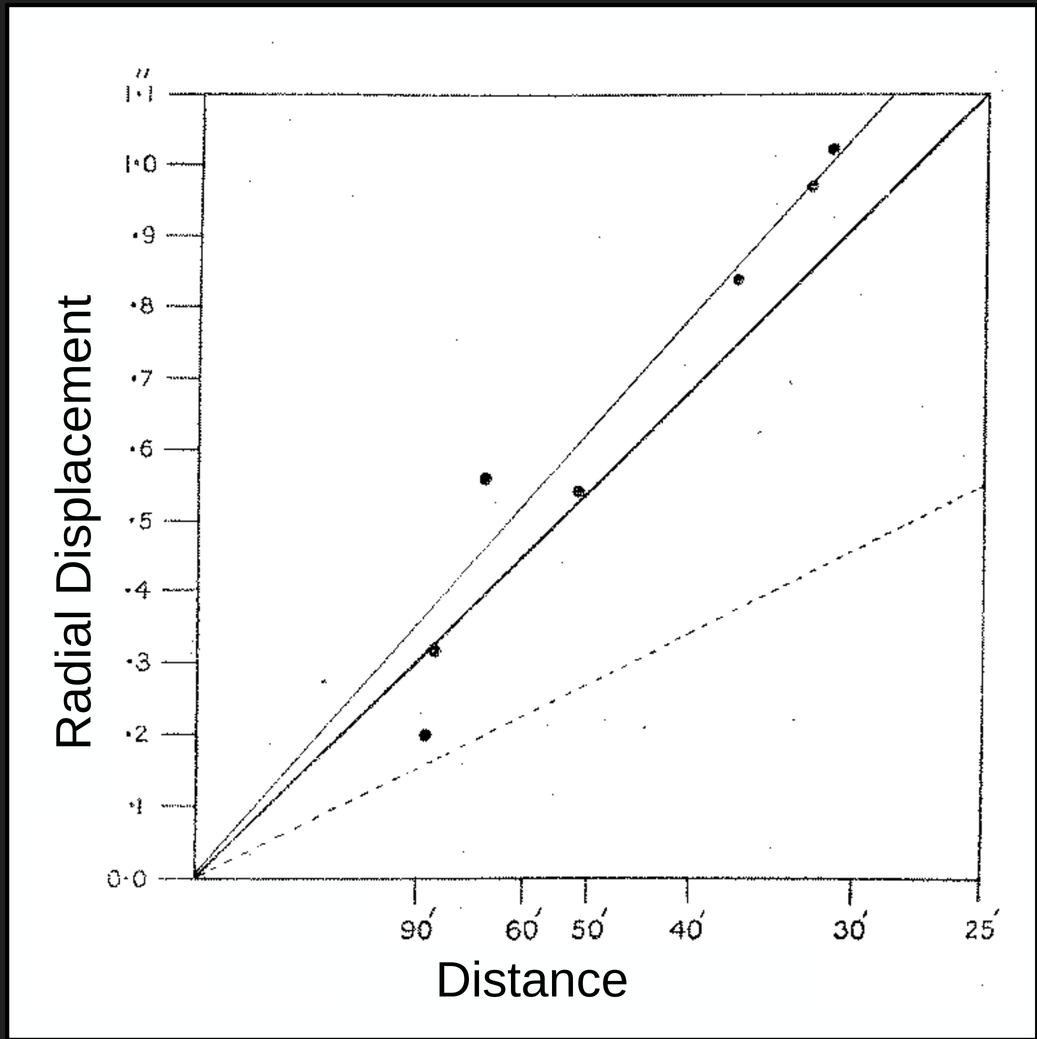
Footprint



year 0 (science validation) - 180 deg^2 (full depth)
year 1 - 2500 deg^2 (half depth)
5 years - 5000 deg^2

History of Light Bending

Dyson, Eddington & Davidson 1919



1915: General Relativity

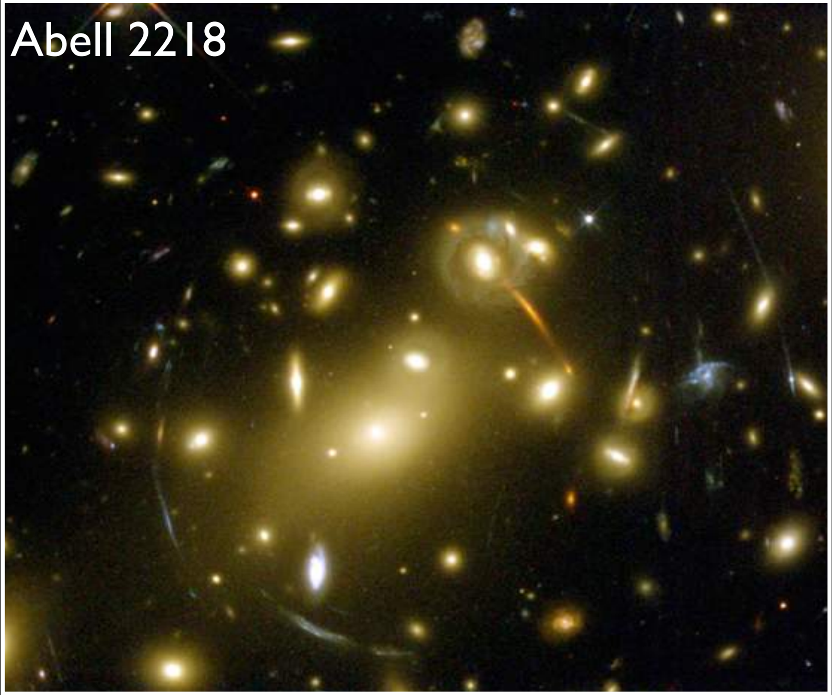
1919: Eclipse Experiment

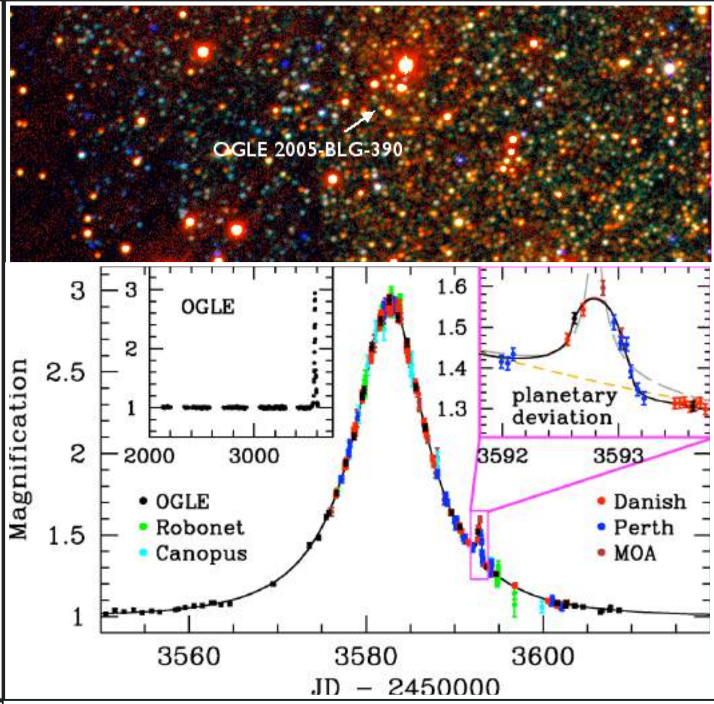
1937: Galaxies as Lens (*Zwicky*)

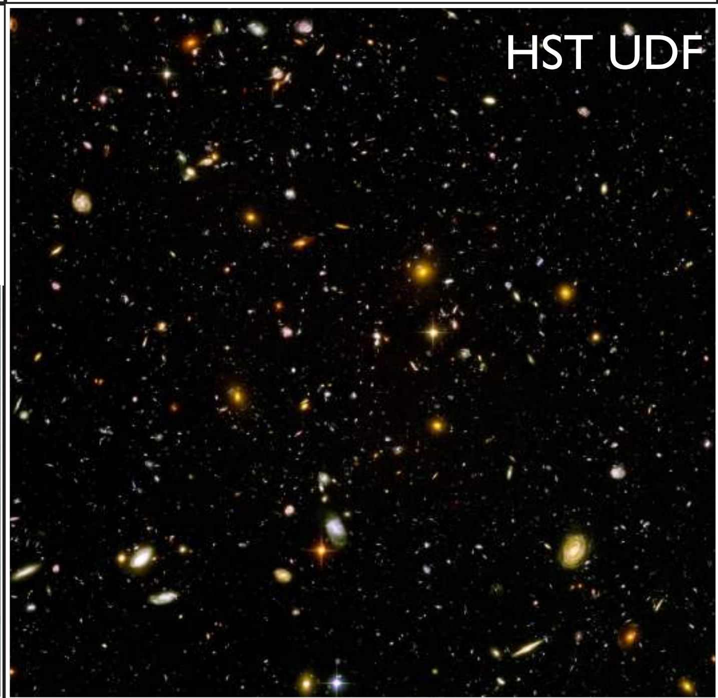
1979: First Galaxy Lens

$$\alpha = \frac{4G}{c^2}\frac{M}{r}$$

Examples of Gravitational Lenses

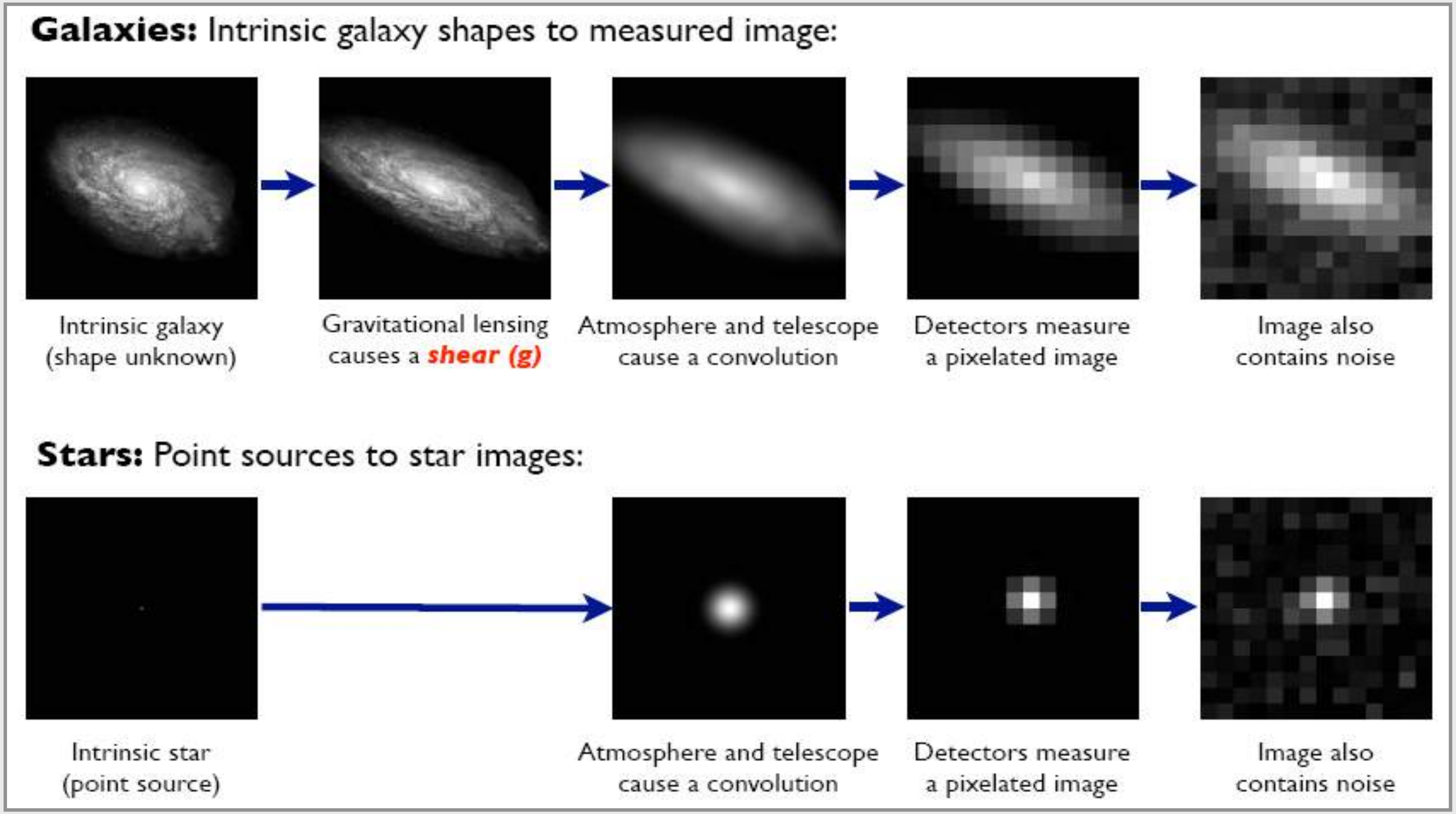






Bridle, AA + 2008
AA 2011

Galaxy Shapes

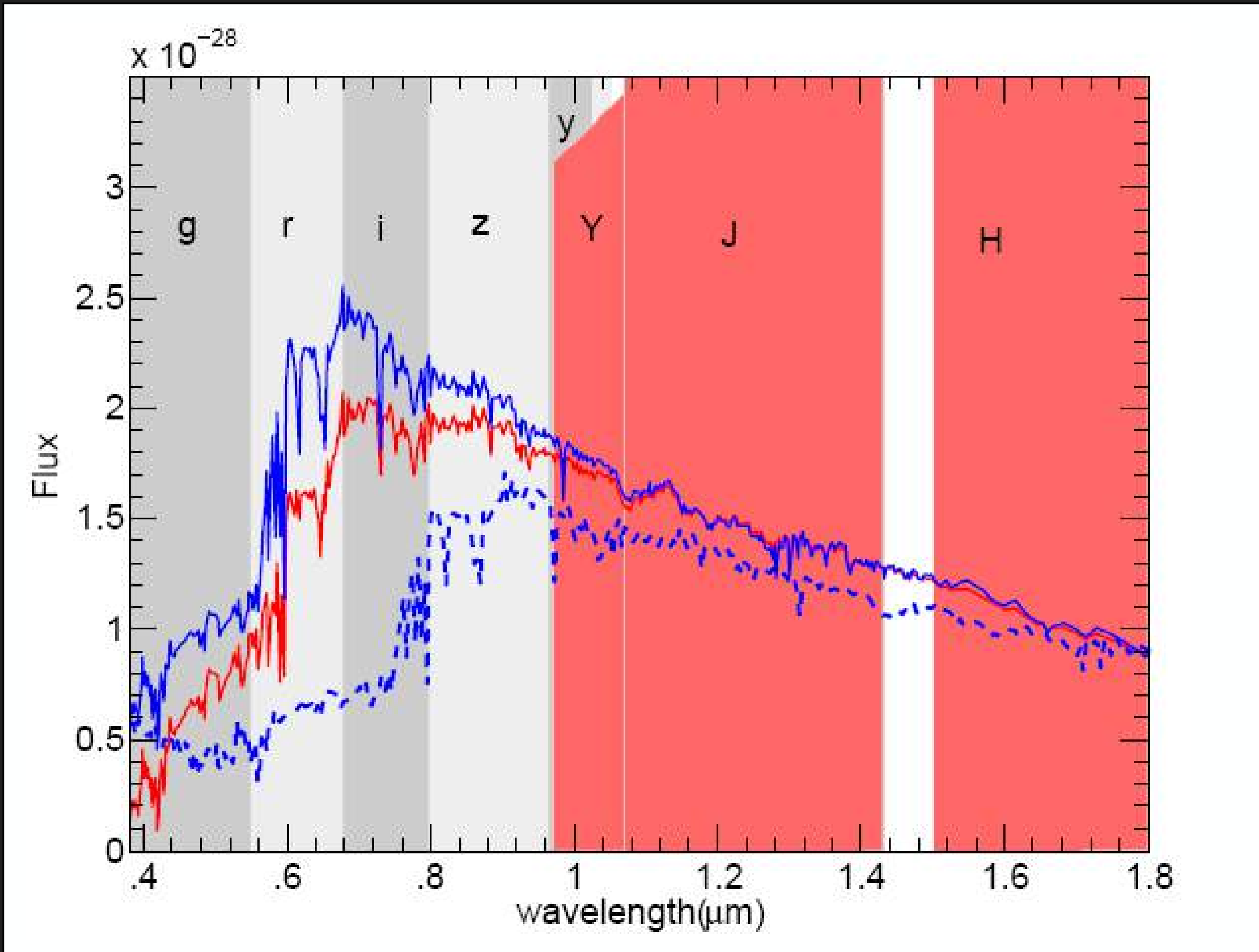


- Key is a well-behaved PSF
- Precisions hardware
- Analysis methods

Voigt, Bridle, AA+2012
Kacprzak,…, AA+2012
Refregier, Kacprzak, AA+ 2012
Refregier & AA 2014

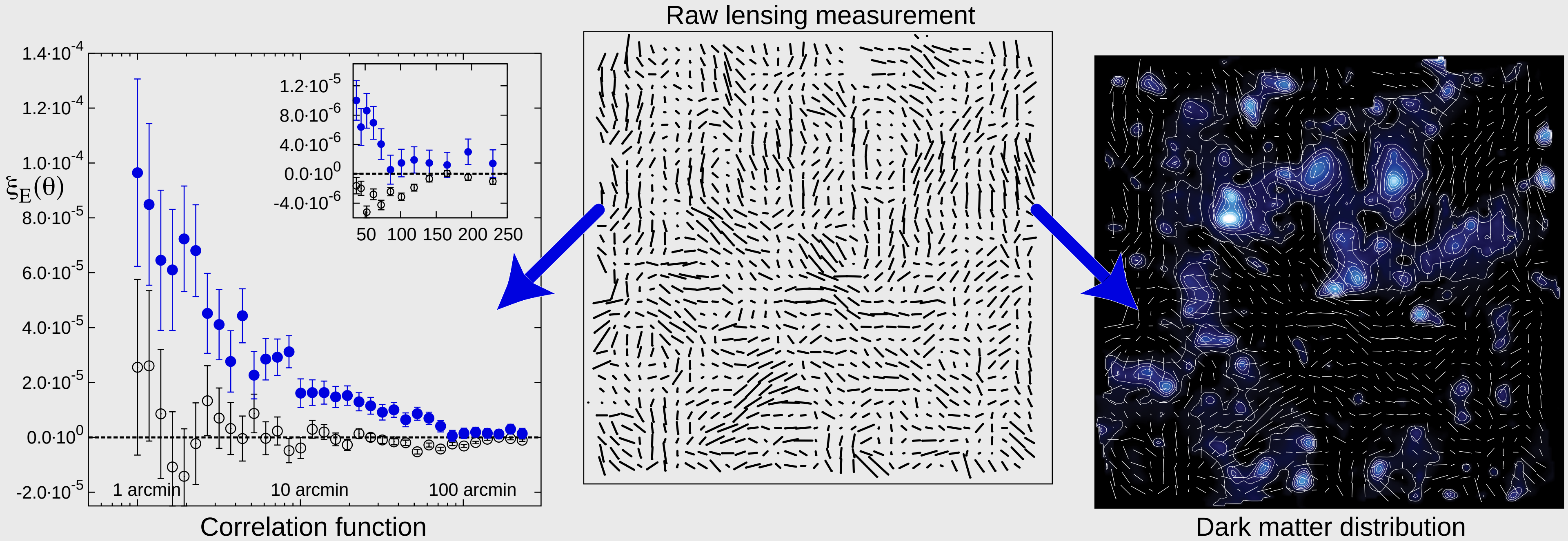
AA+ 2010
Cypriano, AA+ 2010
Paulin-Henriksson, Refregier & AA 2009
Paulin-Henriksson, AA+ 2008

Photometric Redshifts



AA & Refregier 2007
Abdalla, *AA*+ 2008
Bordoloi, *AA* & Lilly 2010
Bordoloi, *AA* & Lilly 2012
Bonnett, Troxel, Hartley, *AA*+ 2015

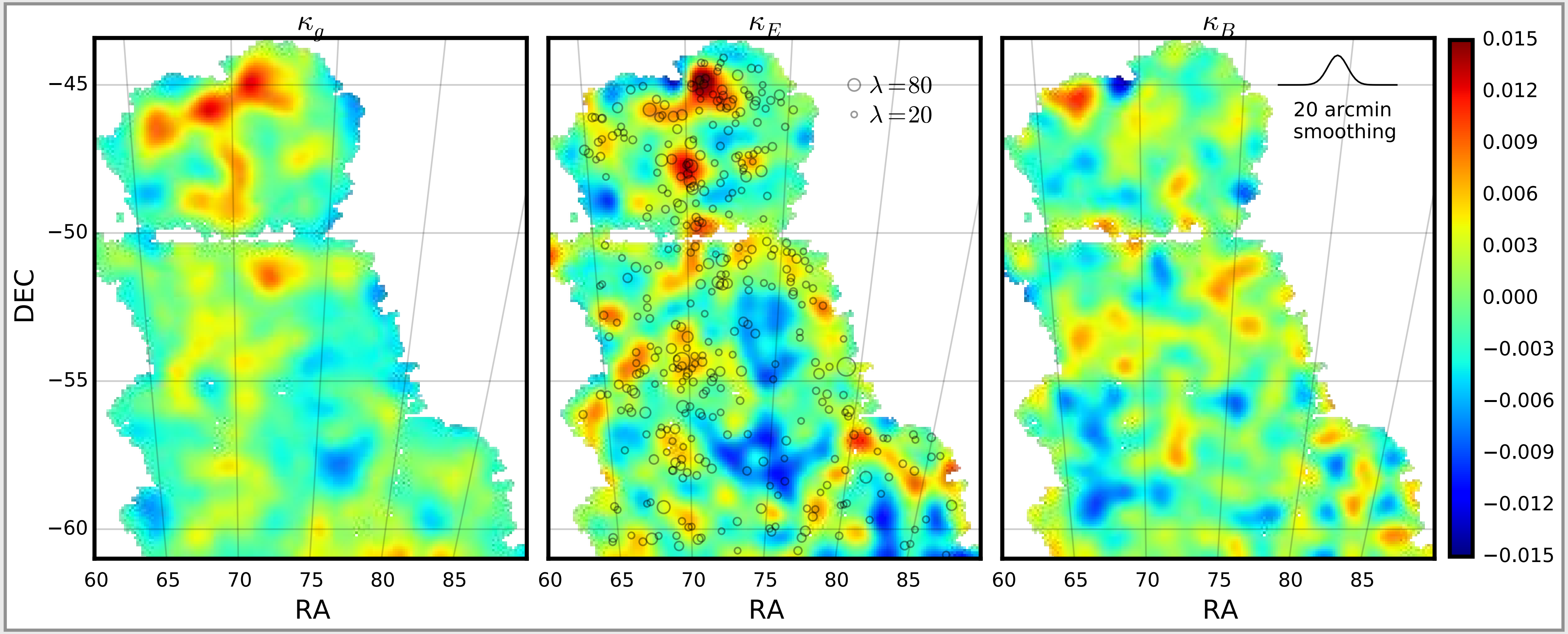
Weak Lensing Correlations and Mass Reconstruction



Fu et al 2007 - CFHTLS

Massey et al 2007 - COSMOS

DES: Dark Matter Mapping

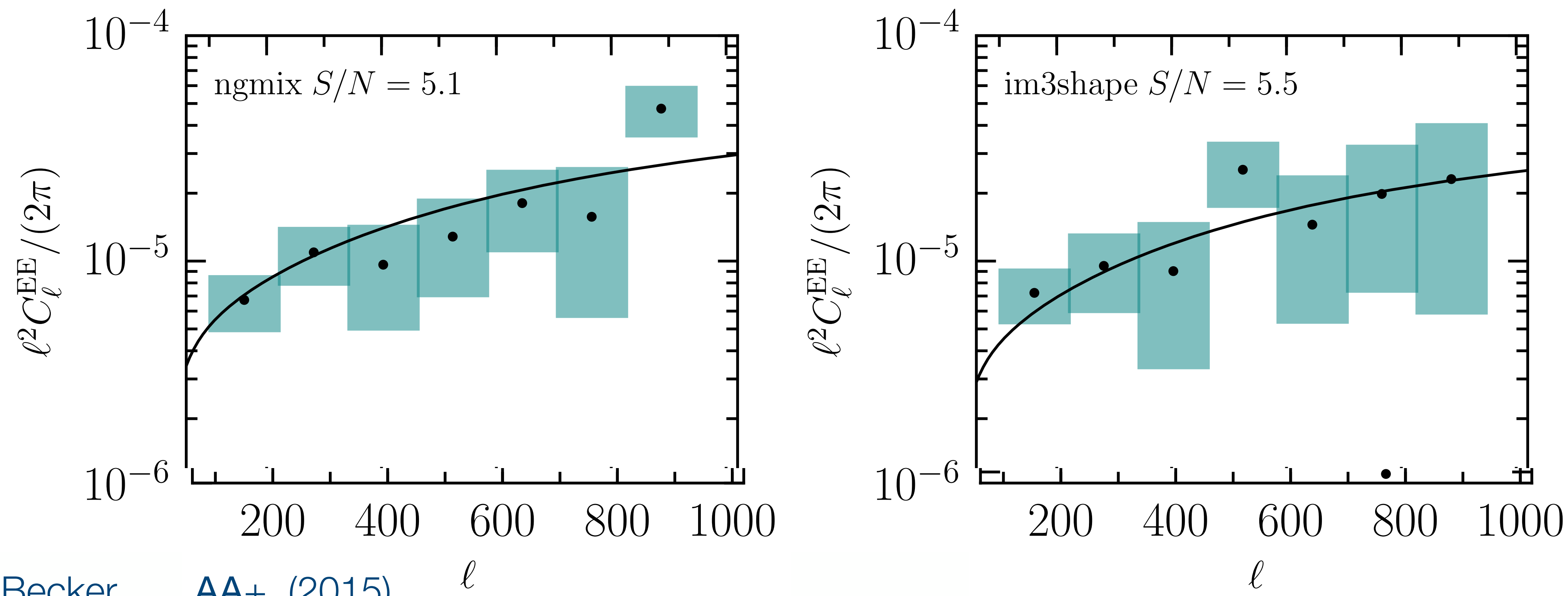


Chang,…, *AA*+ PRL (2015)
Vikram, Chang…, *AA*+ PRD (2015)
Chang, Pujol, Gaztañaga, *AA*+ (2016)
Pujol, Chang, Gaztañaga, *AA*+ (2016)

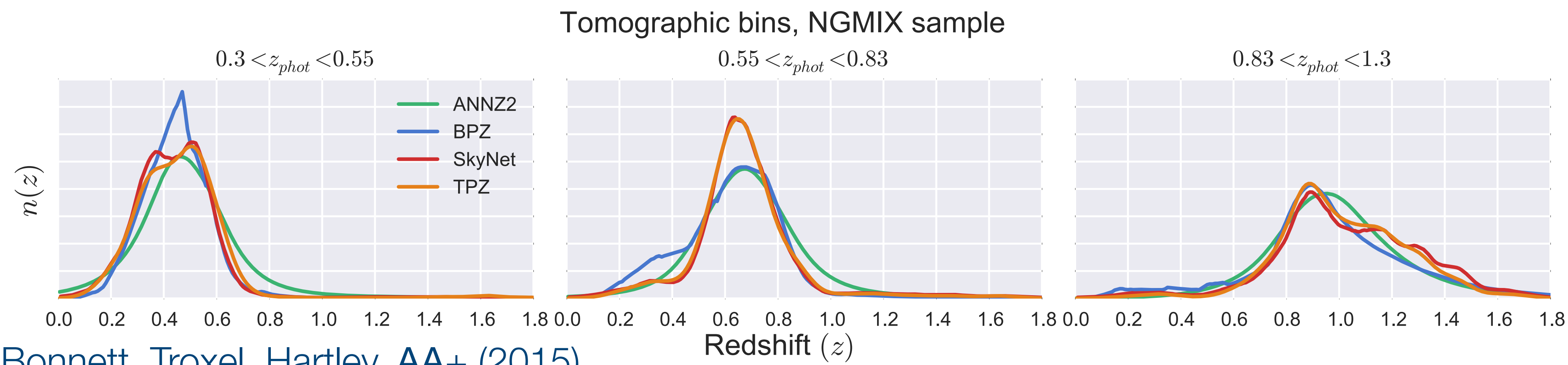
Science Verification Results

Cosmlogy	DES Collaboration (arXiv:1507.05603)
Shear Catalogs	Jarvis et al (arXiv:1507.05603)
Photometric redshift	Bonnett et al (arXiv:1507.05909)
Systematics maps	Leistedt et al (arXiv:1507.05647)
Shear Power Spectra	Becker et al (arXiv:1507.05598)

DES: Dark Matter Statistics

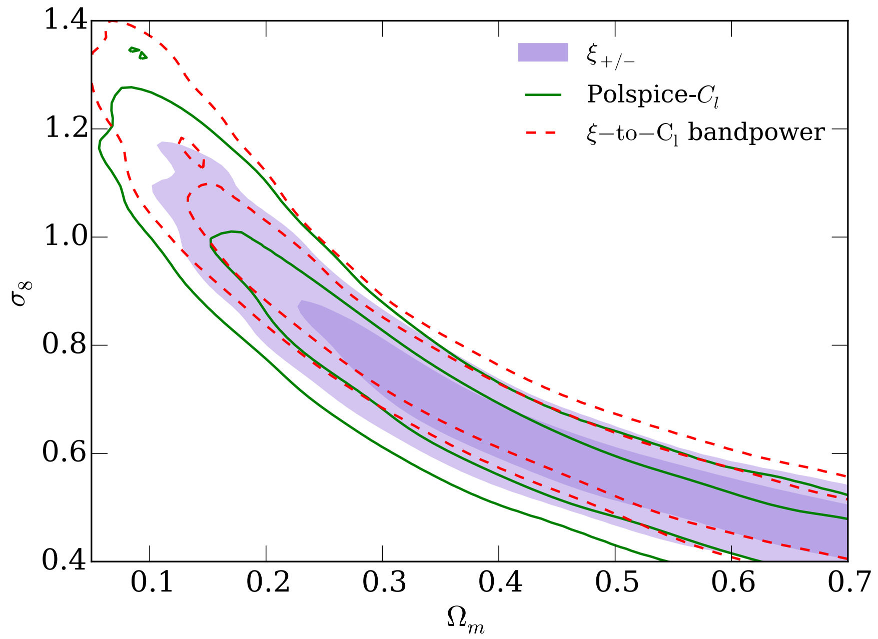


Becker, …, AA+ (2015)

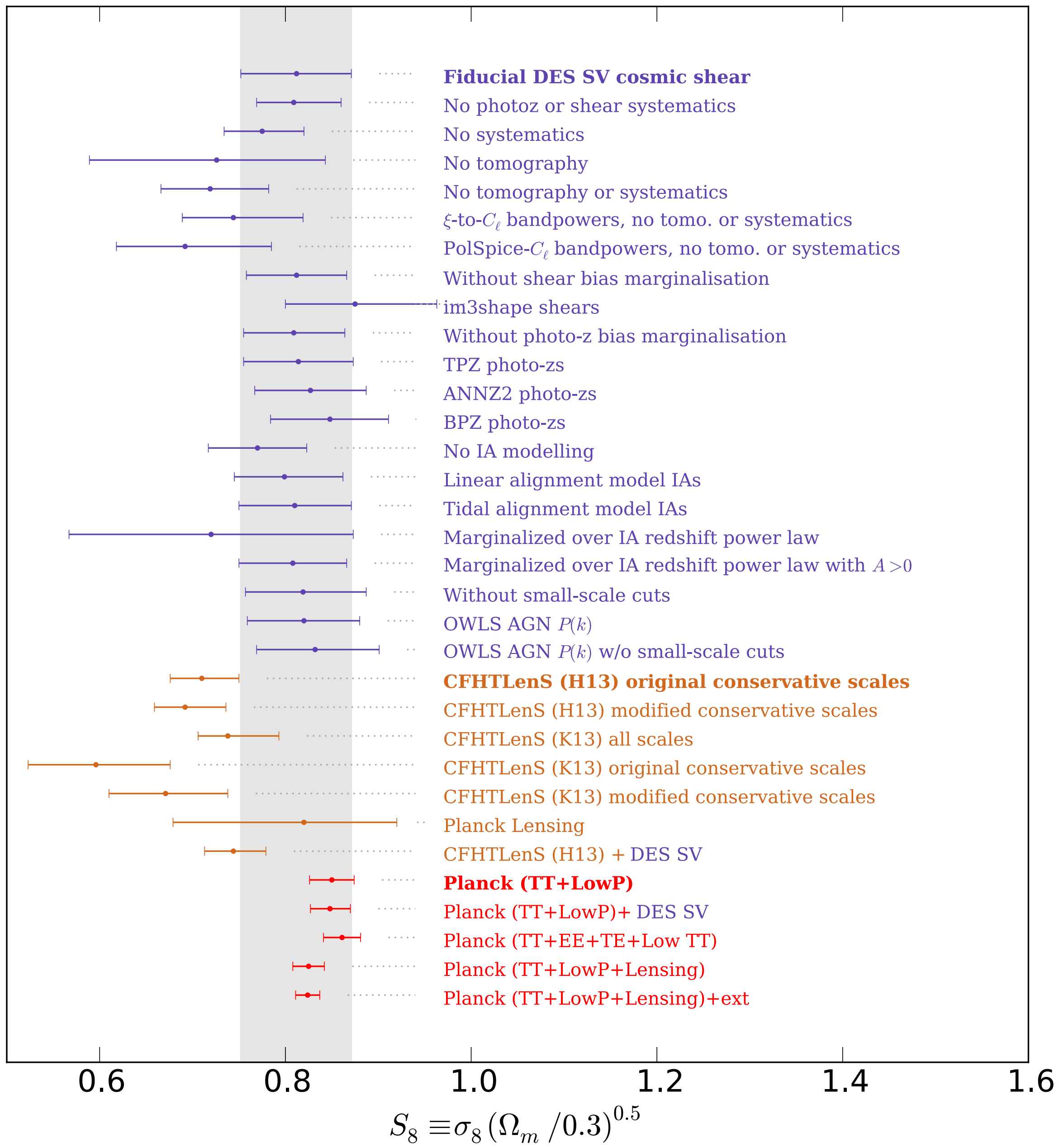


Bonnett, Troxel, Hartley, AA+ (2015)

Robustness

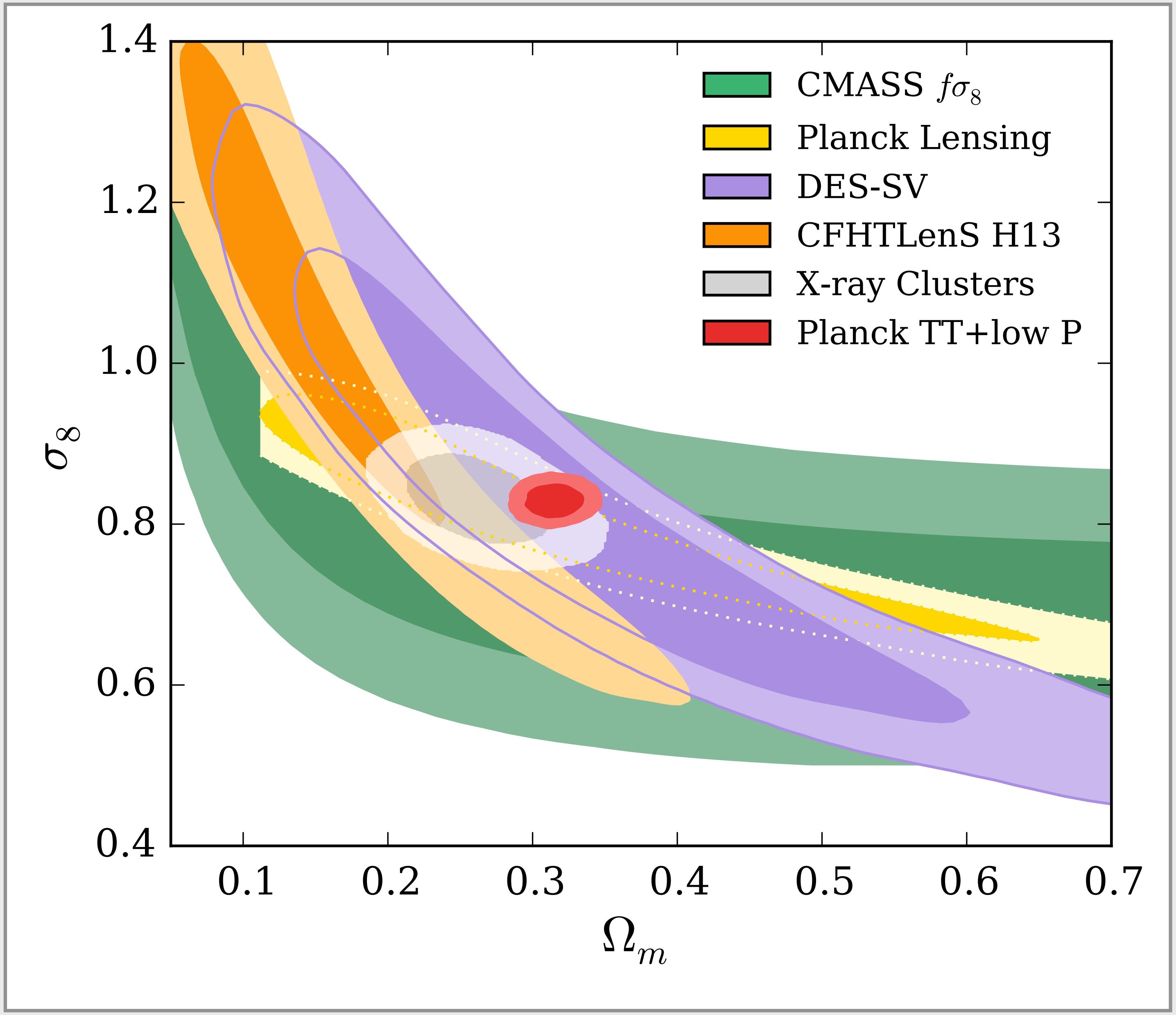


$\xi_{+/-}$
Polspice-C_l
ξ–to–C_l bandpower
σ_8
Ω_m
1.4
1.2
1.0
0.8
0.6
0.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7



Fiducial DES SV cosmic shear
No photoz or shear systematics
No systematics
No tomography
No tomography or systematics
ξ-to-C_ℓ bandpowers, no tomo. or systematics
PolSpice-C_ℓ bandpowers, no tomo. or systematics
Without shear bias marginalisation
im3shape shears
Without photo-z bias marginalisation
TPZ photo-zs
ANNZ2 photo-zs
BPZ photo-zs
No IA modelling
Linear alignment model IAs
Tidal alignment model IAs
Marginalized over IA redshift power law
Marginalized over IA redshift power law with $A>0$
Without small-scale cuts
OWLS AGN $P(k)$
OWLS AGN $P(k)$ w/o small-scale cuts
CFHTLenS (H13) original conservative scales
CFHTLenS (H13) modified conservative scales
CFHTLenS (K13) all scales
CFHTLenS (K13) original conservative scales
CFHTLenS (K13) modified conservative scales
Planck Lensing
CFHTLenS (H13) + DES SV
Planck (TT+LowP)
Planck (TT+LowP)+ DES SV
Planck (TT+EE+TE+Low TT)
Planck (TT+LowP+Lensing)
Planck (TT+LowP+Lensing)+ext
0.6
0.8
1.0
1.2
1.4
1.6
$S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5}$

Cosmology Parameters



The Dark Energy Survey Collaboration (2015)

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Precision Measurements
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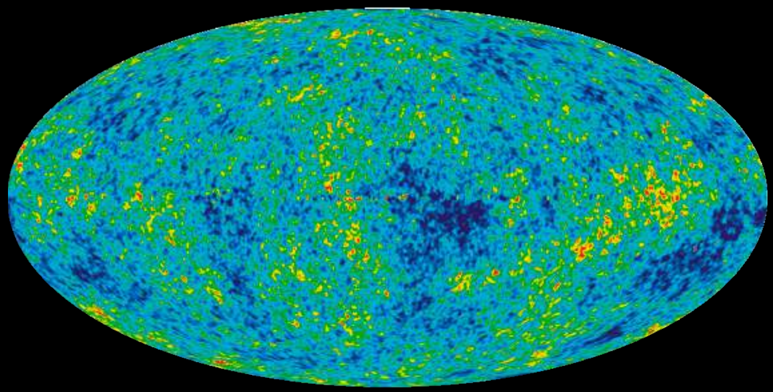
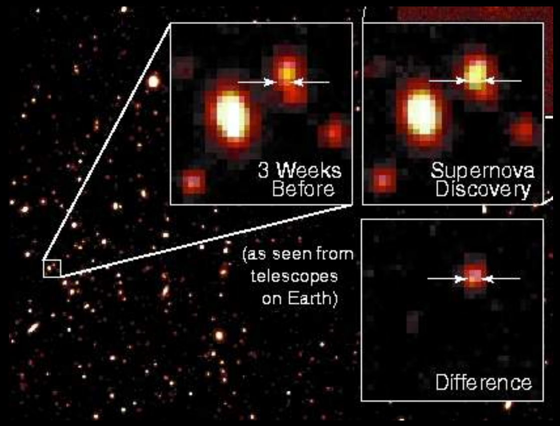
Cosmological Probes

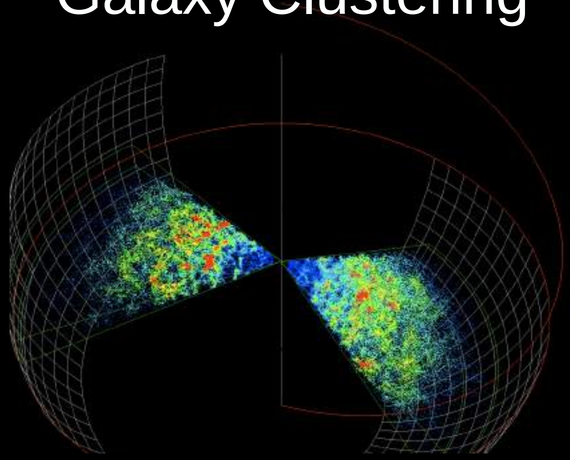
Cosmic Microwave Background



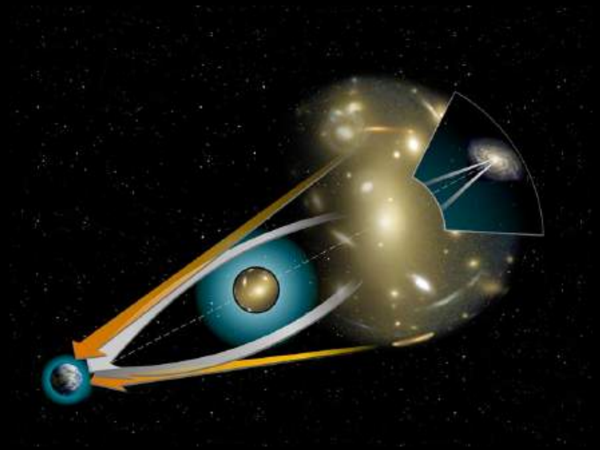
Supernovae



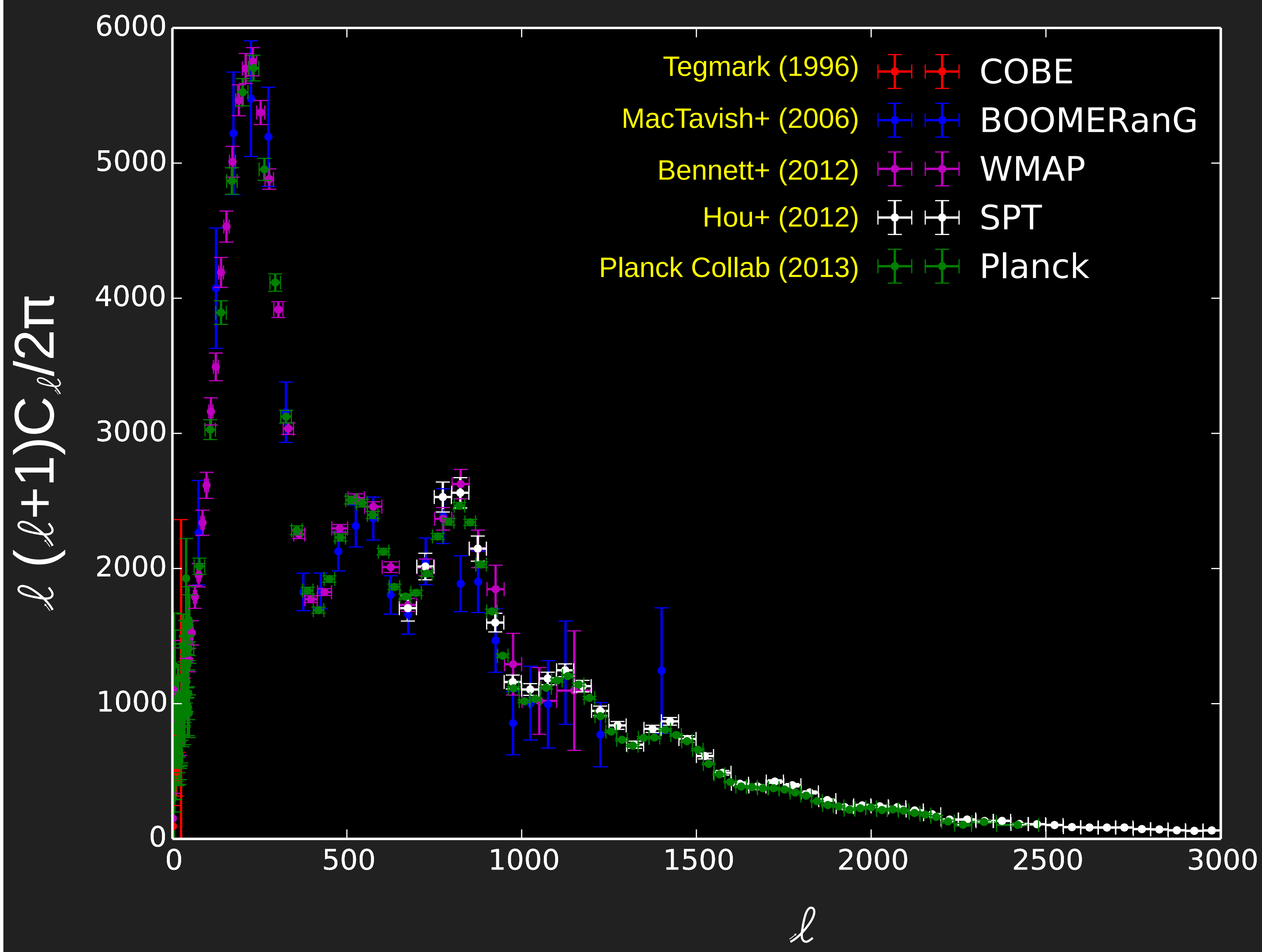
Galaxy Clustering

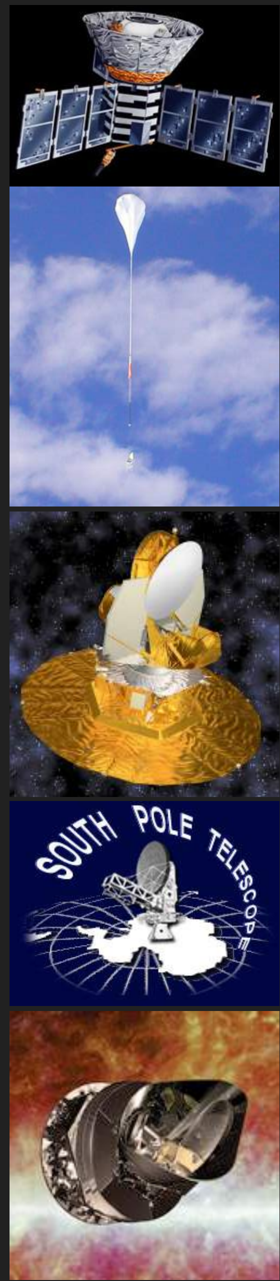


Gravitational Lensing



Cosmic Microwave Background





COBE (1989)

BOOMERanG (1997)

WMAP (2001)

SPT (2006)

Planck (2009)

WMAP 9

Hinshaw+ (2013)

Parameter	*WMAP*	+eCMB	+eCMB+BAO	+eCMB+H_0	+eCMB+BAO+H_0
Fit parameters					
$\Omega_b h^2$	0.02264 ± 0.00050	0.02229 ± 0.00037	0.02211 ± 0.00034	0.02244 ± 0.00035	0.02223 ± 0.00033
$\Omega_c h^2$	0.1138 ± 0.0045	0.1126 ± 0.0035	0.1162 ± 0.0020	0.1106 ± 0.0030	0.1153 ± 0.0019
Ω_Λ	0.721 ± 0.025	0.728 ± 0.019	0.707 ± 0.010	0.740 ± 0.015	$0.7135^{+0.0095}_{-0.0096}$
$10^9\Delta^2_\mathcal{R}$	2.41 ± 0.10	2.430 ± 0.084	$2.484^{+0.073}_{-0.072}$	$2.396^{+0.079}_{-0.078}$	2.464 ± 0.072
n_s	0.972 ± 0.013	0.9646 ± 0.0098	$0.9579^{+0.0081}_{-0.0082}$	$0.9690^{+0.0091}_{-0.0090}$	0.9608 ± 0.0080
τ	0.089 ± 0.014	0.084 ± 0.013	$0.079^{+0.011}_{-0.012}$	0.087 ± 0.013	0.081 ± 0.012
Derived parameters					
t_0 (Gyr)	13.74 ± 0.11	13.742 ± 0.077	13.800 ± 0.061	13.702 ± 0.069	13.772 ± 0.059
H_0 (km s^{-1} Mpc^{-1})	70.0 ± 2.2	70.5 ± 1.6	68.76 ± 0.84	71.6 ± 1.4	69.32 ± 0.80
σ_8	0.821 ± 0.023	0.810 ± 0.017	$0.822^{+0.013}_{-0.014}$	0.803 ± 0.016	$0.820^{+0.013}_{-0.014}$
Ω_b	0.0463 ± 0.0024	0.0449 ± 0.0018	0.04678 ± 0.00098	0.0438 ± 0.0015	0.04628 ± 0.00093
Ω_c	0.233 ± 0.023	0.227 ± 0.017	0.2460 ± 0.0094	0.216 ± 0.014	$0.2402^{+0.0088}_{-0.0087}$
$z_{\rm eq}$	3265^{+106}_{-105}	3230 ± 81	3312 ± 48	3184 ± 70	3293 ± 47
$z_{\rm reion}$	10.6 ± 1.1	10.3 ± 1.1	10.0 ± 1.0	10.5 ± 1.1	10.1 ± 1.0

Planck

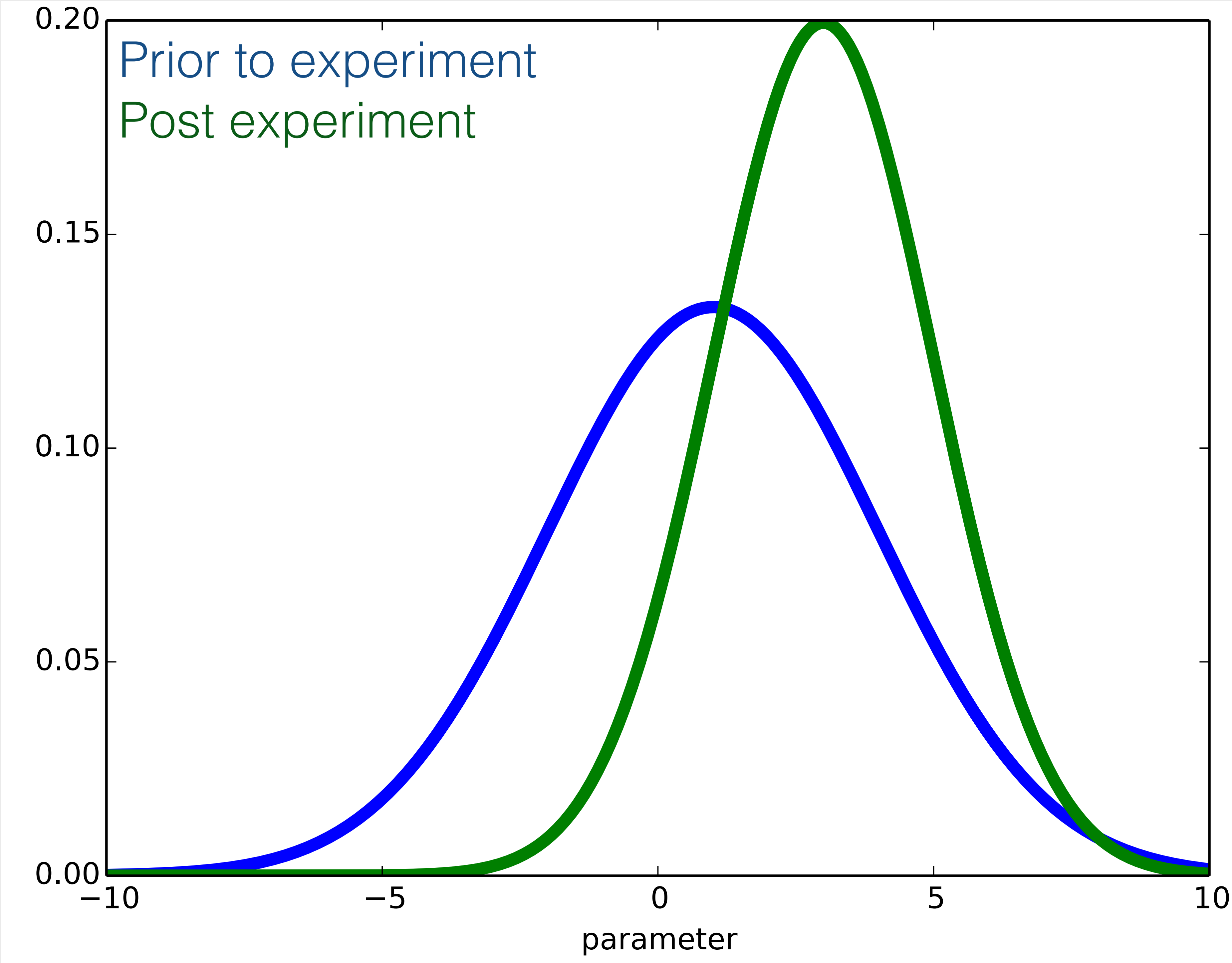
(2013)

	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{\rm MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10}A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
$z_{\rm re}$	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
$r_{\rm drag}$	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

What are the central values?

Have things changed?

Are things consistent?


Prior to experiment
Post experiment
0.20
0.15
0.10
0.05
0.00
−10
−5
0
5
10
parameter

RELATIVE ENTROPY

Constraints from Data A neter transformations

$$D(P_1||P_2) = \int_{\mathcal{S}} dX\, P_1(X) \log \frac{P_1(X)}{P_2(X)}$$

≧0

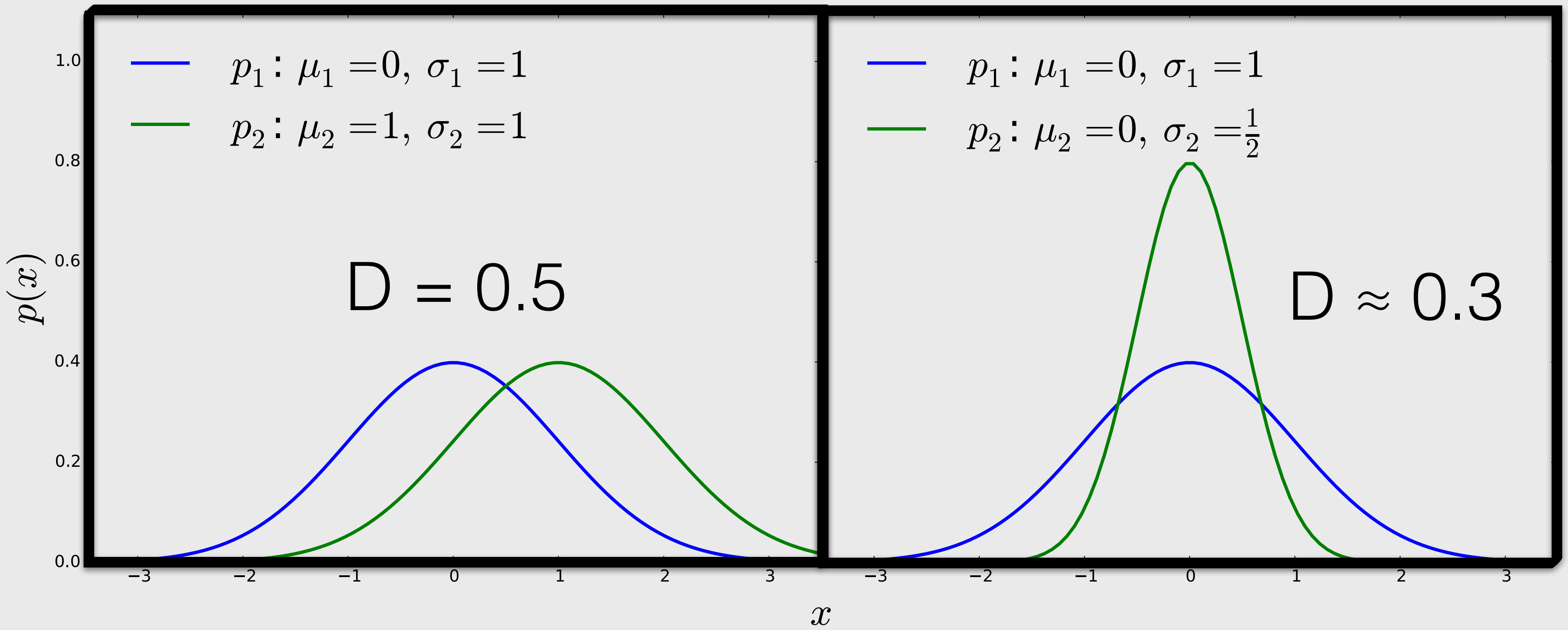
Constraints from Data A and B equals P_2

Kullback & Leibler (1951)

Seehars et al (2014)

NORMAL DISTRIBUTIONS

$$D(P_2||P_1) = \frac{1}{2}\left(\left(\frac{\mu_1 - \mu_2}{\sigma_1}\right)^2 + \left(\frac{\sigma_1}{\sigma_2}\right)^2 - \log\left(\frac{\sigma_1}{\sigma_2}\right)^2 - 1\right)$$



NORMAL DISTRIBUTIONS & LINEAR MODEL

Surprise ⟷ $S = D(p_2||p_1) - \langle D \rangle$

$$D(p_2||p_1) = \frac{1}{2}\left((\mu_1 - \mu_2)^T \Sigma_1^{-1}(\mu_1 - \mu_2) + \mathrm{tr}(\Sigma_2\Sigma_1^{-1}) - d - \log\det\left(\Sigma_2\Sigma_1^{-1}\right)\right)$$

$\langle D \rangle$ ⟷ Expected relative entropy

Seehars et al (2014)

WMAP 9

Hinshaw+ (2013)

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$\Omega_b h^2$	0.02264 ± 0.00050	0.02229 ± 0.00037	0.02211 ± 0.00034	0.02244 ± 0.00035	0.02223 ± 0.00033
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Planck

(2013)

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{\rm MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
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n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
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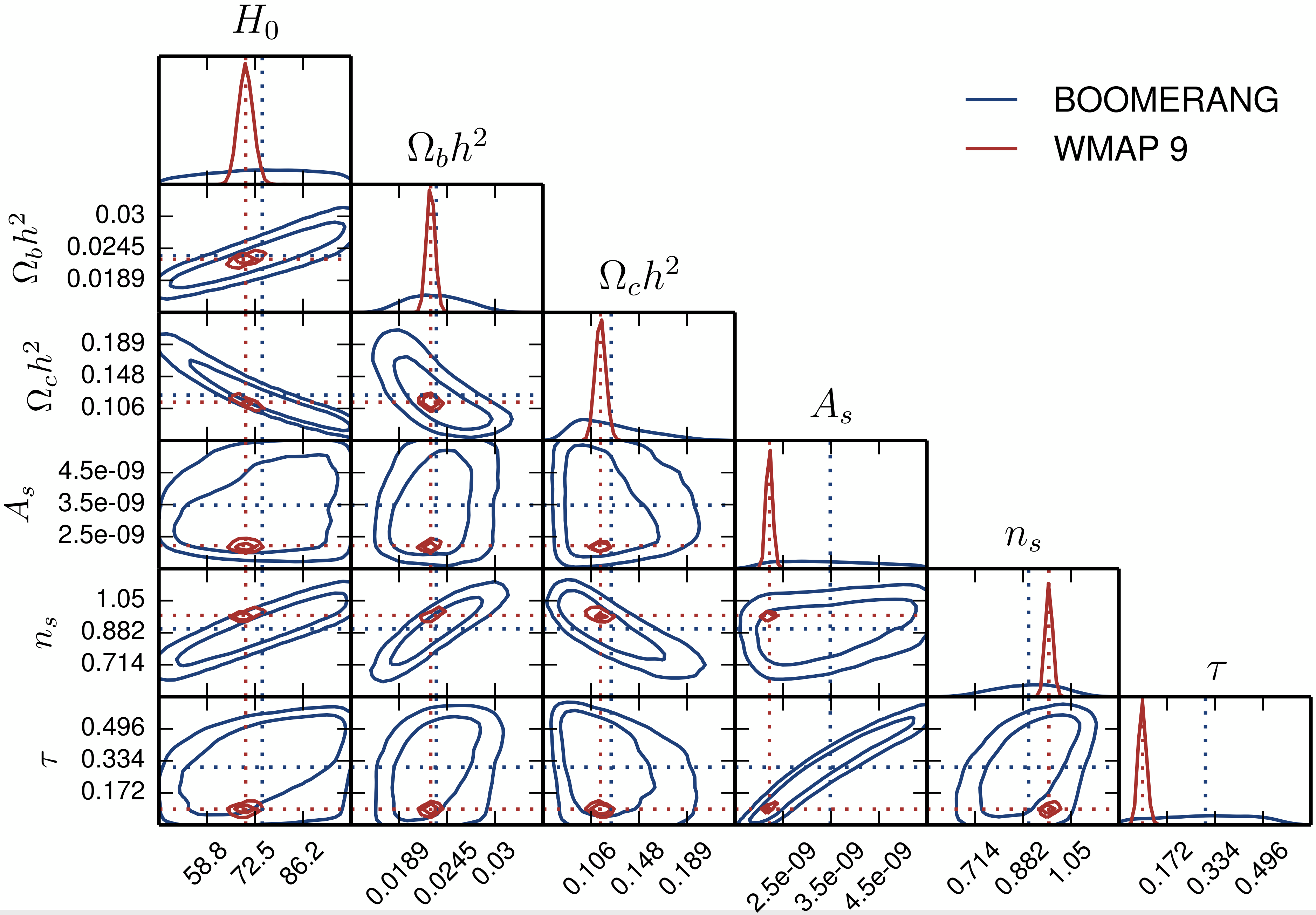
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
$r_{\rm drag}$	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

			D	$\langle D \rangle$	S	$S/\sigma(D)$	p-value[d]
BOOMERANG	$\rightarrow$	WMAP 9	22.5	18.4	4.1	1.6	0.07
WMAP 9	$\rightarrow$	WMAP 9 + SPT	4.3	2.1	2.2	2.1	0.04
WMAP 9	$\rightarrow$	Planck + WP	29.8	7.9	21.9	6.5	0.0002

Unit of bits

BOOMERANG: MacTavish et al. (2003)
WMAP 3, 5, 7, 9: Spergel et al. (2007), Dunkley et al. (2009), Larson et al. (2011), and Bennett et al. (2013)
WP: WMAP 9 polarisation data
SPT: Story et al. (2013)
Planck: Ade et al. (2013)

Seehars et al (2014)

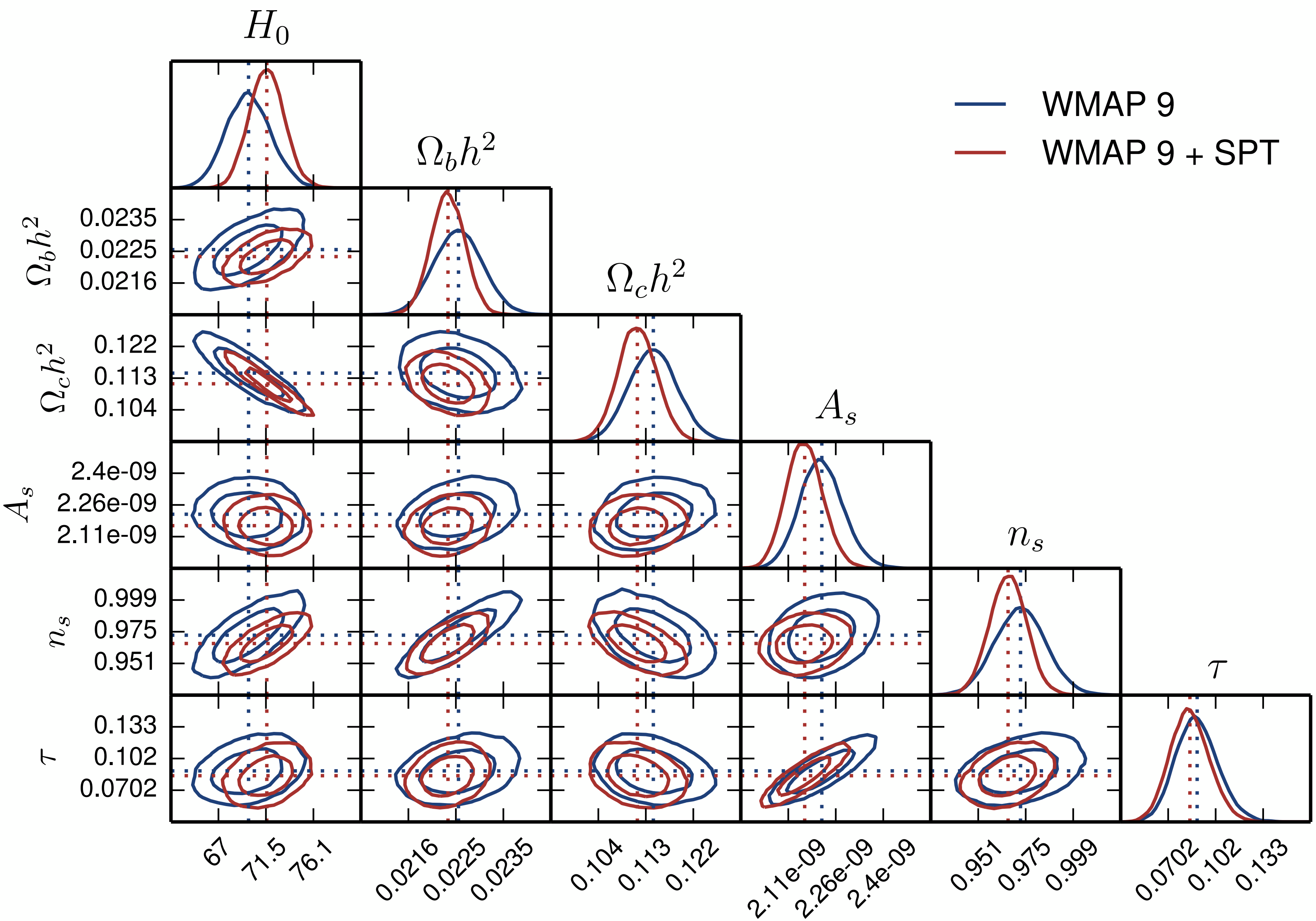


Seehars et al (2014)

			D	$\langle D \rangle$	S	$S/\sigma(D)$	p-value[d]
BOOMERANG	$\to$	WMAP 9	22.5	18.4	4.1	1.6	0.07
WMAP 9	$\to$	WMAP 9 + SPT	4.3	2.1	2.2	2.1	0.04
WMAP 9	$\to$	Planck + WP	29.8	7.9	21.9	6.5	0.0002

BOOMERANG: MacTavish et al. (2003)
WMAP 3, 5, 7, 9: Spergel et al. (2007), Dunkley et al. (2009), Larson et al. (2011), and Bennett et al. (2013)
WP: WMAP 9 polarisation data
SPT: Story et al. (2013)
Planck: Ade et al. (2013)

Seehars et al (2014)



Seehars et al (2014)

			D	$\langle D \rangle$	S	$S/\sigma(D)$	p-value[d]
BOOMERANG	$\rightarrow$	WMAP 9	22.5	18.4	4.1	1.6	0.07
WMAP 9	$\rightarrow$	WMAP 9 + SPT	4.3	2.1	2.2	2.1	0.04
WMAP 9	$\rightarrow$	Planck + WP	29.8	7.9	21.9	6.5	0.0002

BOOMERANG: MacTavish et al. (2003)
WMAP 3, 5, 7, 9: Spergel et al. (2007), Dunkley et al. (2009), Larson et al. (2011), and Bennett et al. (2013)
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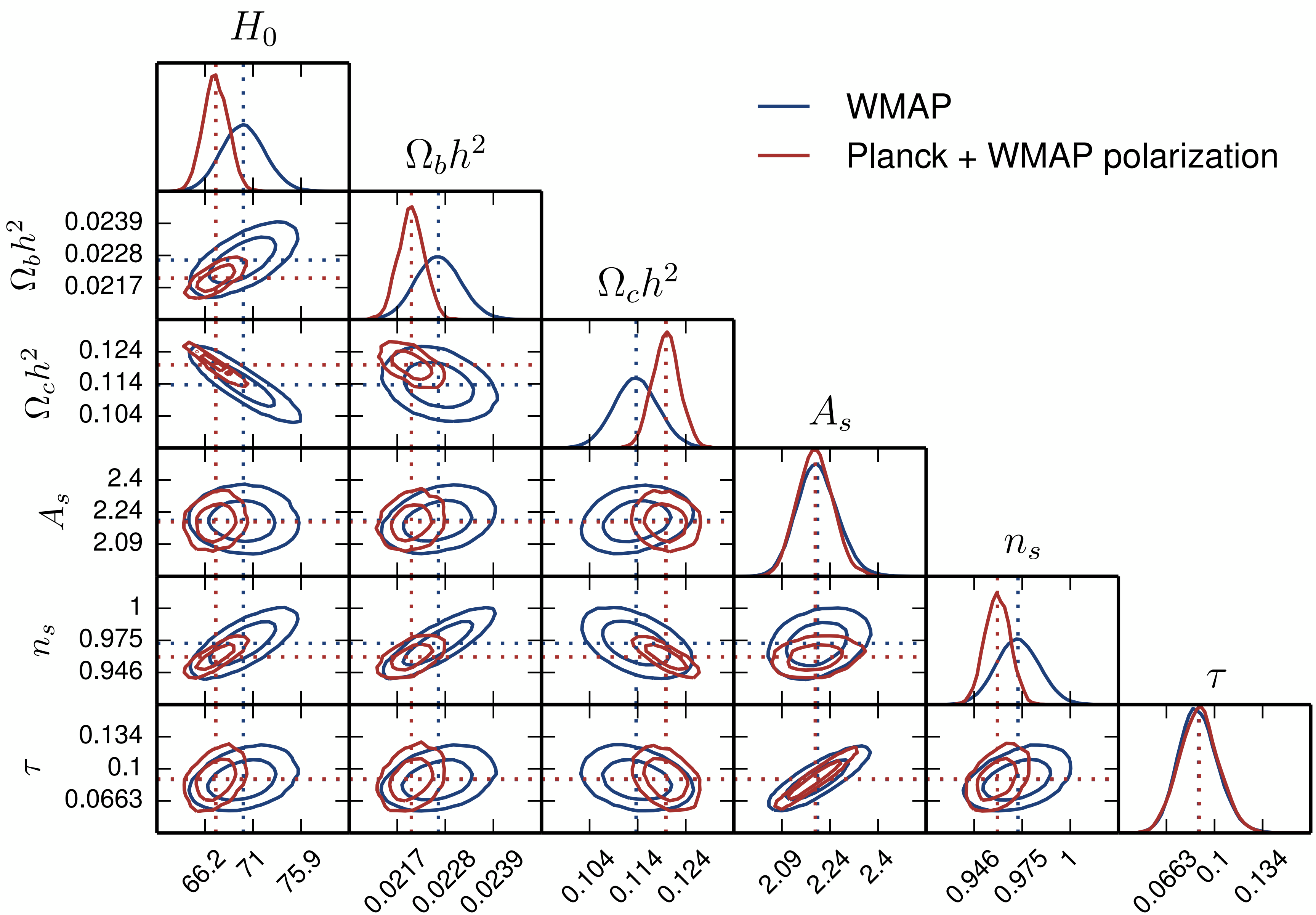
Seehars et al (2014)



Seehars et al (2014)

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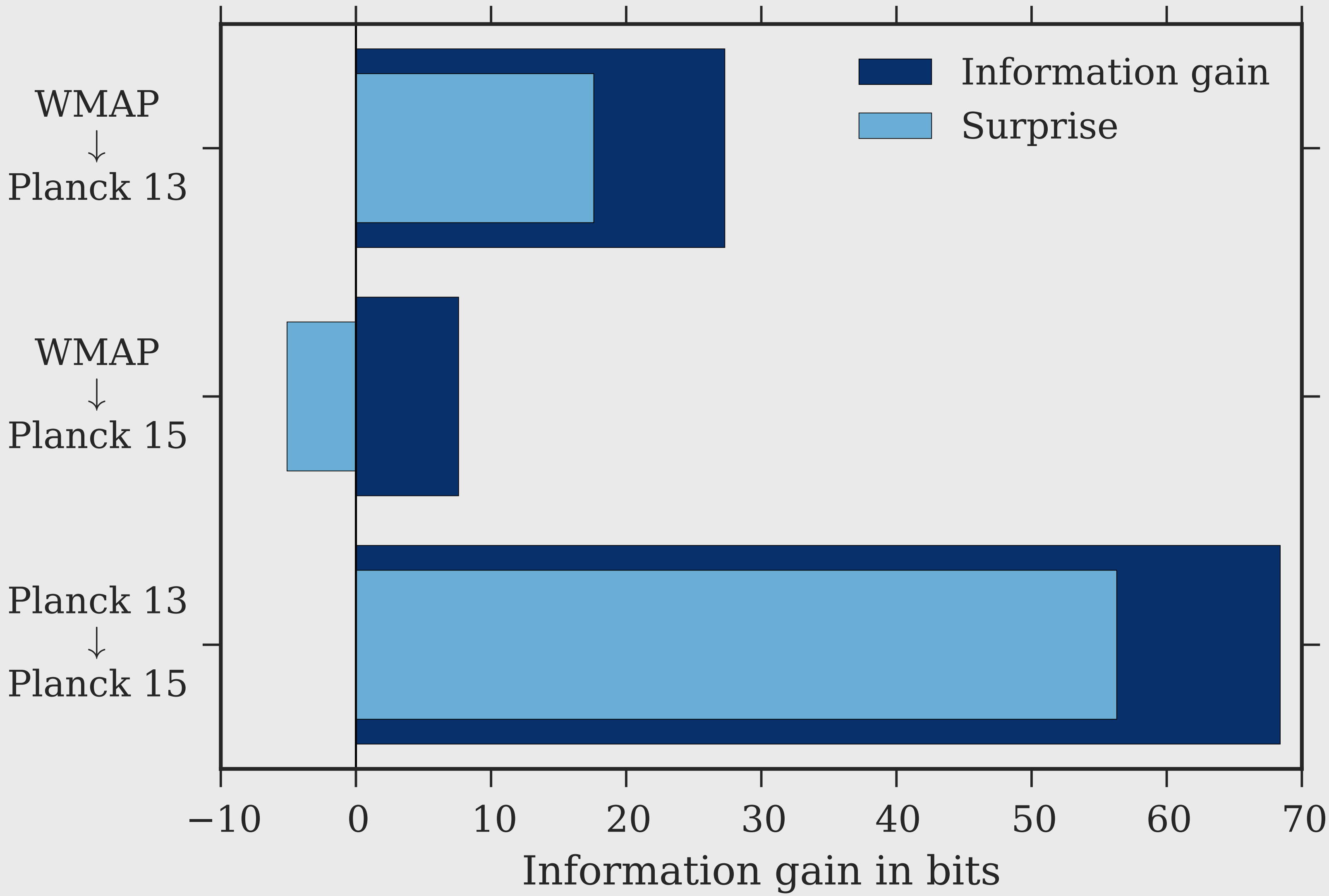
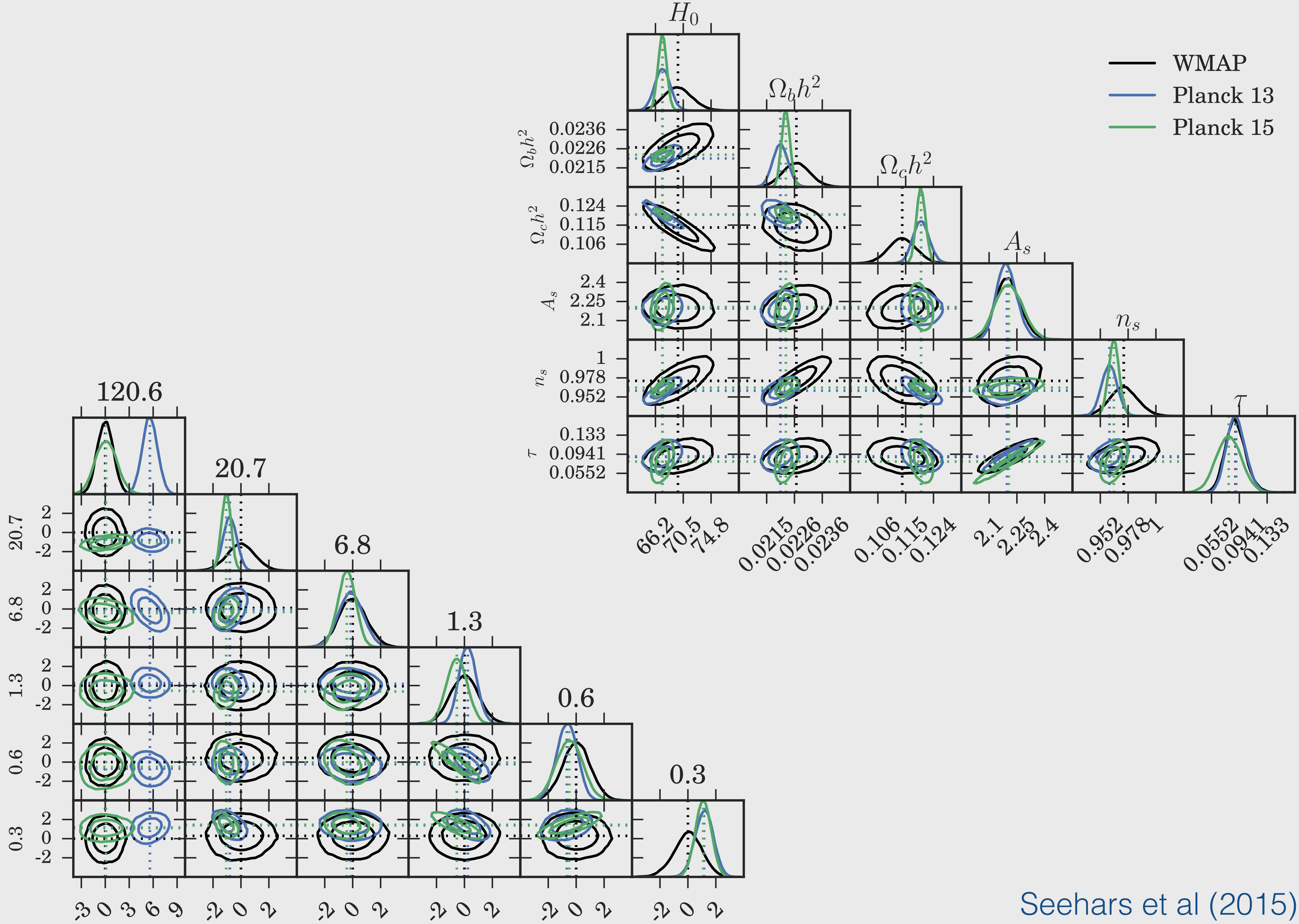
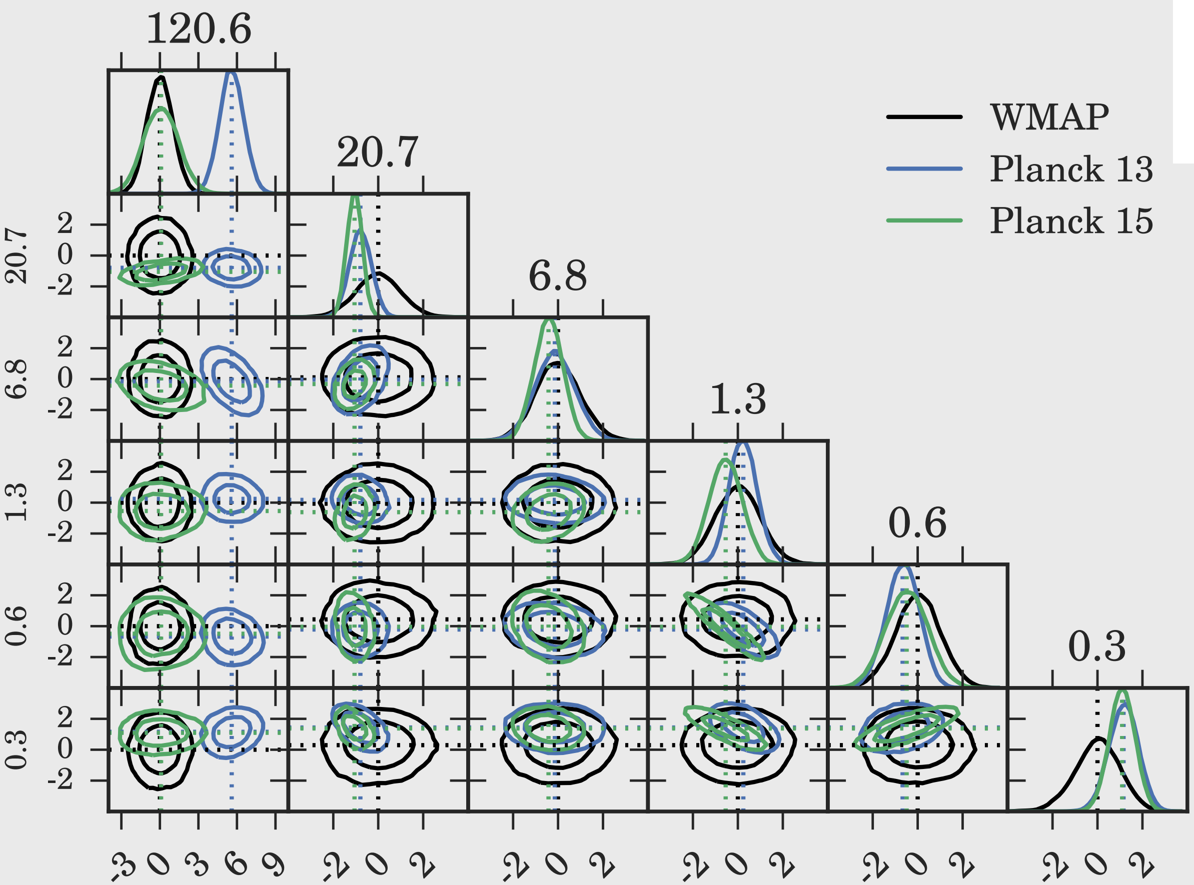
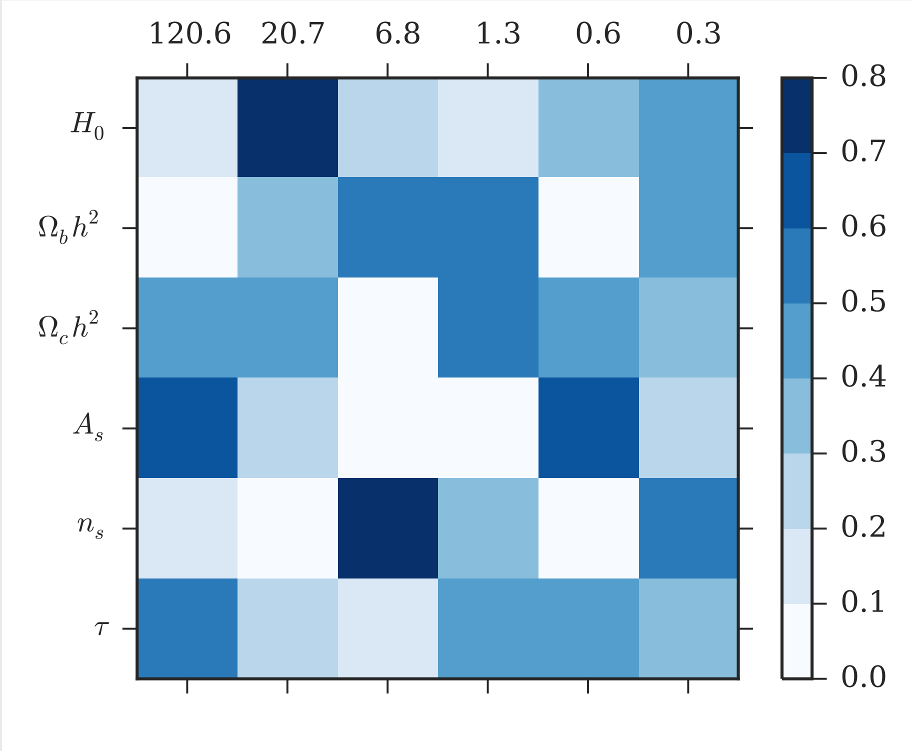


Seehars et al (2015)



Seehars et al (2015)

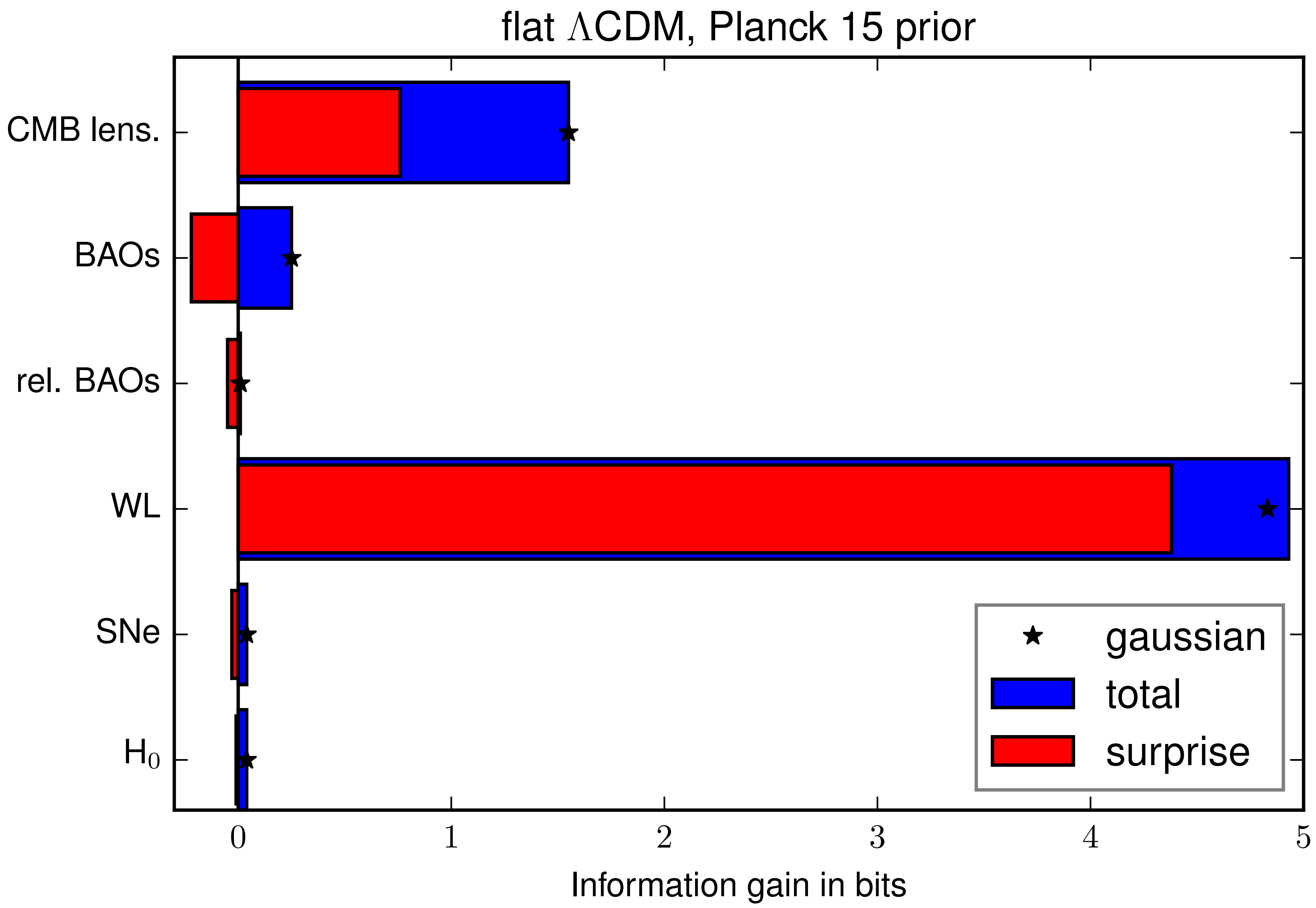




Seehars et al (2015)

What about the other probes?

Grandis et al (2015)



Dark Energy Survey
&
Latest Results

Cosmic Concordance?

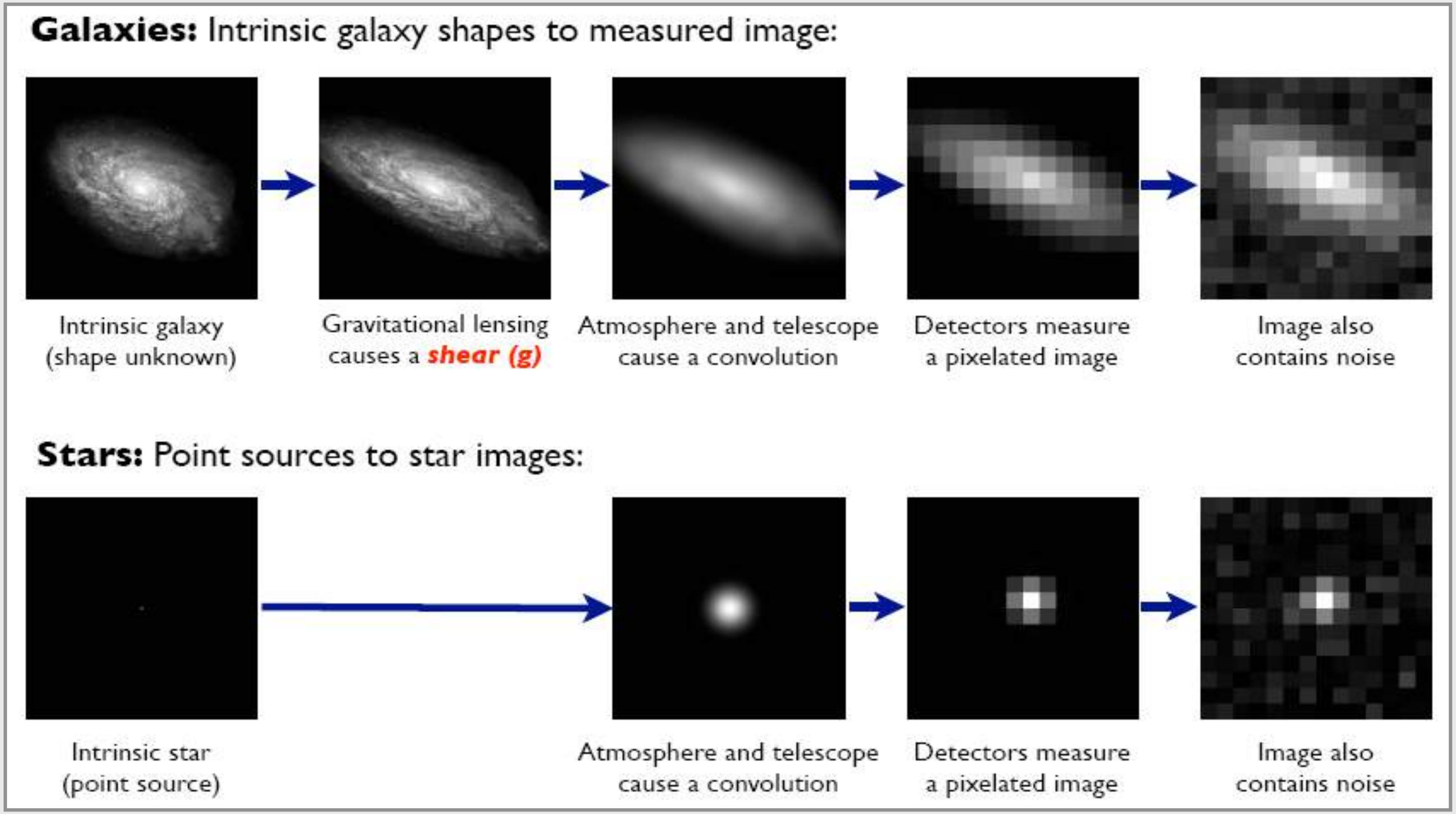
Precision Measurements
Looking Forward

Current and Planned Experiments

Survey	Start (rough dates)
COSMOS*	2003
CFHTLS	2003
Pan-STARRS1	2009
KIDS	2011
DES*	2012
HALO (balloon)*	>2020
LSST*	>2020
Euclid*	>2020
WFIRST	>2020

*Bridle, **Amara**+ 2008*
***Amara** 2011*

Galaxy Shapes

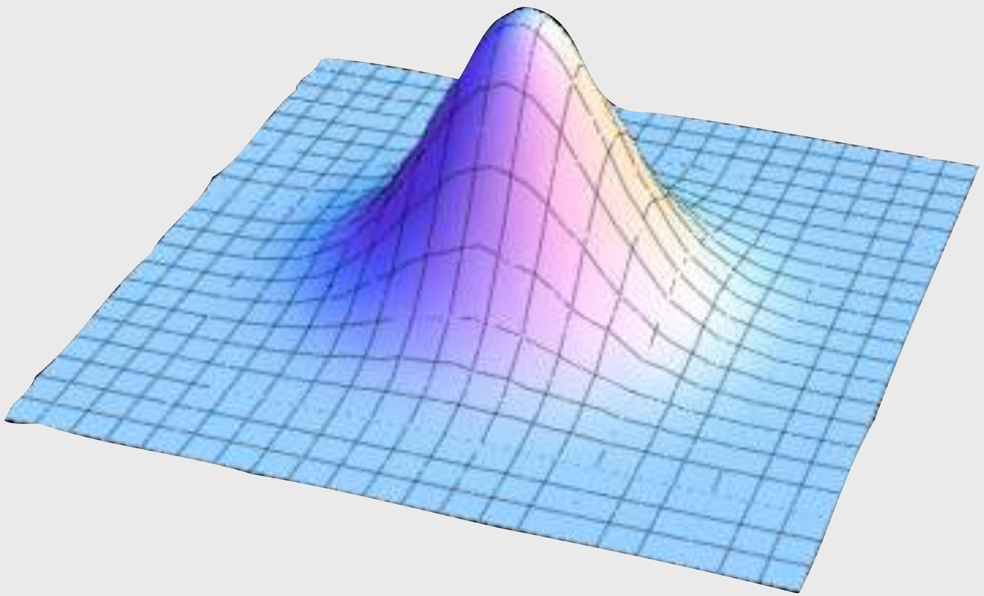


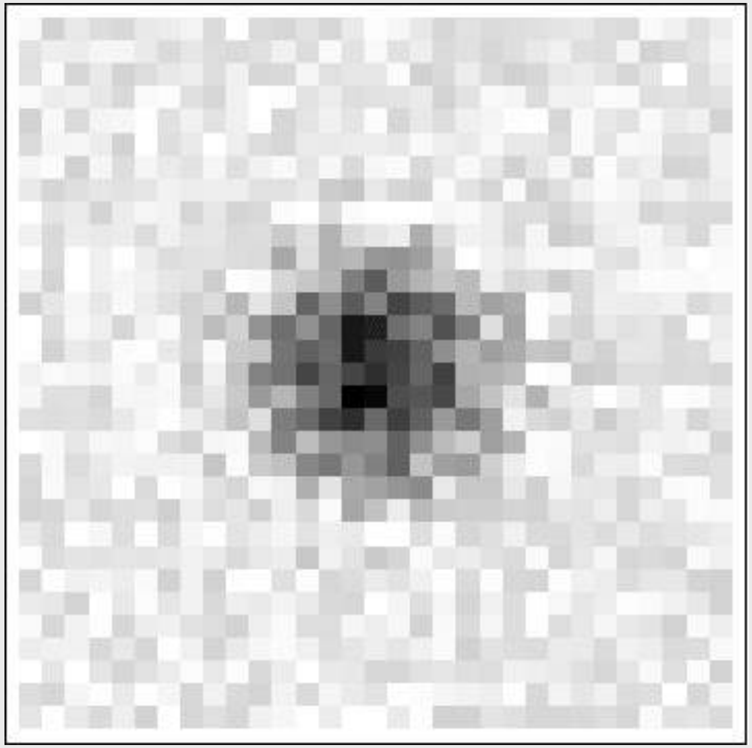
- Key is a well-behaved PSF
- Precisions hardware
- Analysis methods

*Voigt, Bridle, **Amara**+2012*
*Kacprzak,…, **Amara**+2012*
*Refregier, Kacprzak, **Amara**+ 2012*
*Refregier & **Amara** 2014*

***Amara**+ 2010*
*Cypriano, **Amara**+ 2010*
*Paulin-Henriksson, Refregier & **Amara** 2009*
*Paulin-Henriksson, **Amara**+ 2008*

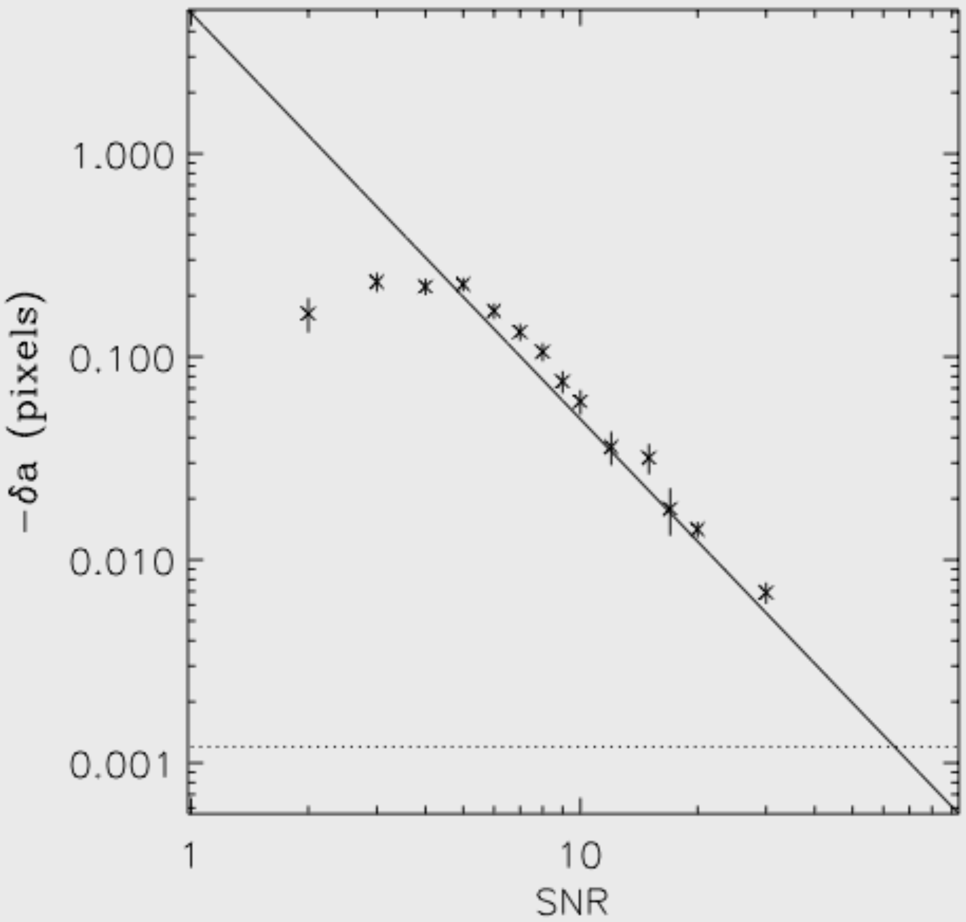
Toy Model: Measuring the Size of a 2D Gaussian





Refregier, AA, + 2013

Measurement Biases



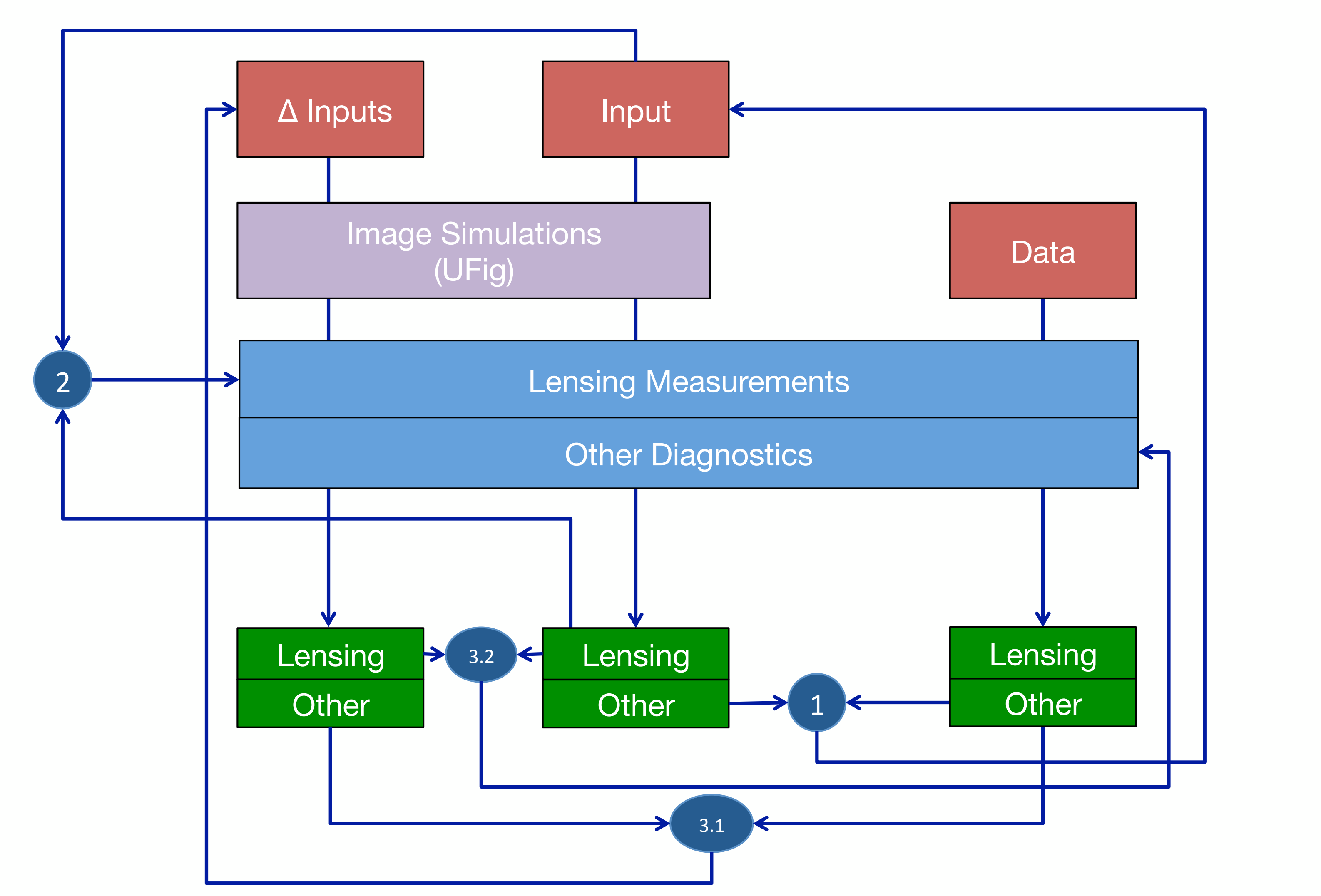
$$\delta a_i \simeq -\frac{1}{2} F_{ij} F_{kl} B_{jkl} \propto 1/\mathrm{SNR}^2$$

$$F_{ij} = \sum_p \frac{1}{\sigma_p^2} \frac{\partial f}{\partial a_i} \frac{\partial f}{\partial a_j}$$

$$B_{ijk} = \sum_p \frac{1}{\sigma_p^2} \frac{\partial f}{\partial a_i} \frac{\partial^2 f}{\partial a_j \partial a_k}$$

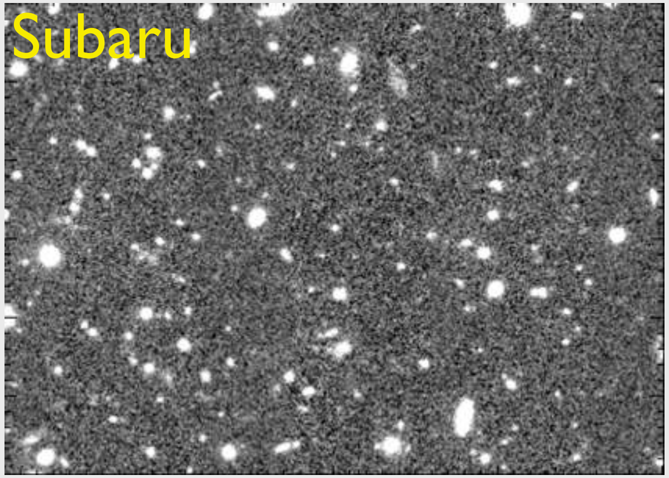
Refregier, AA, + 2013

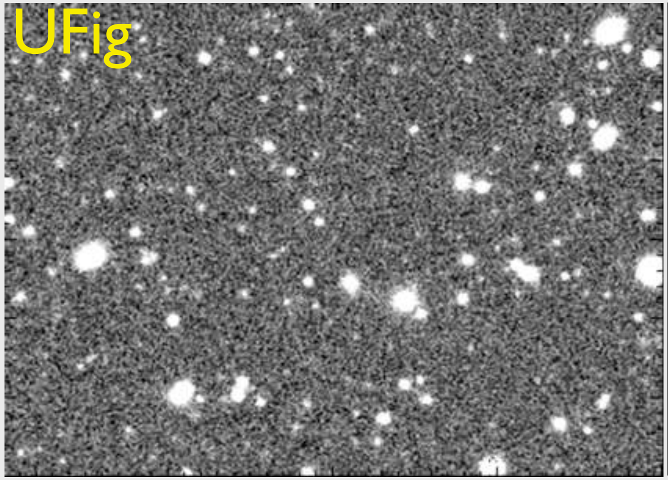
Monte Carlo Control Loops



Refregier & Amara (2013)

Ultra Fast Image Generator (UFig)





Speed the driving factor

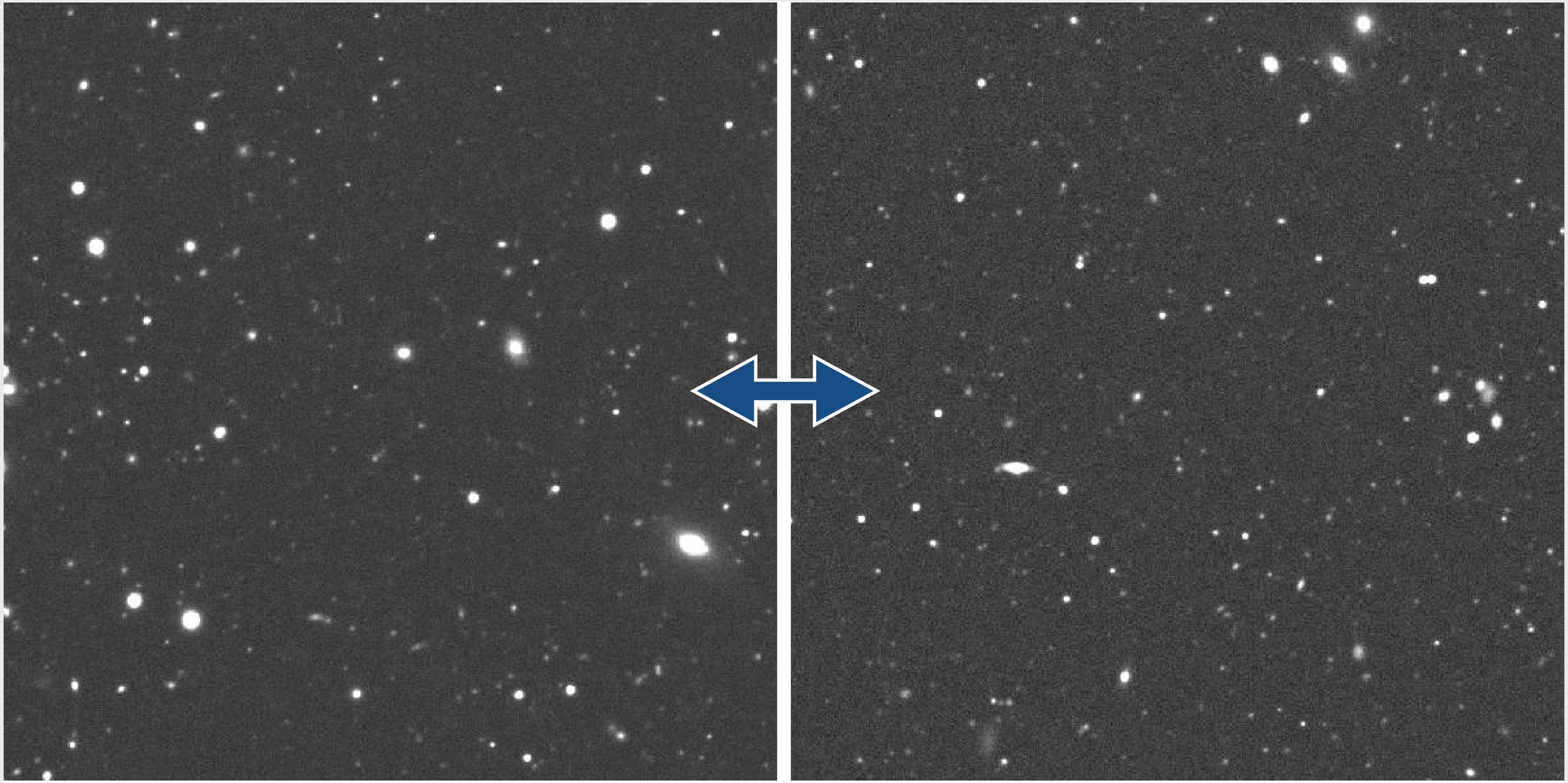
As fast as SExtractor (or faster)
Subaru Image (0.25 deg2,R~26,10k×8k) generated in:
- 30sec on a laptop
- 30μsec per galaxy

HOPE: A Python Just-In-Time compiler for astrophysical computations

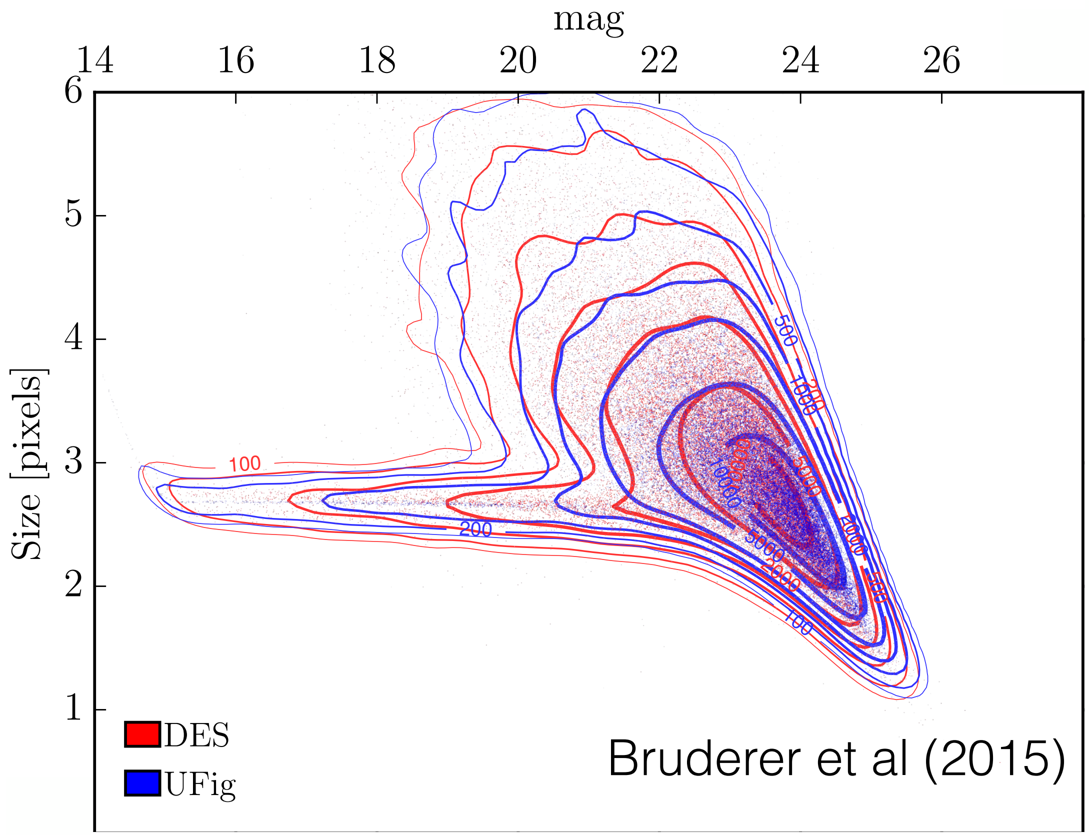
Akeret et al 2014
http://hope.phys.ethz.ch

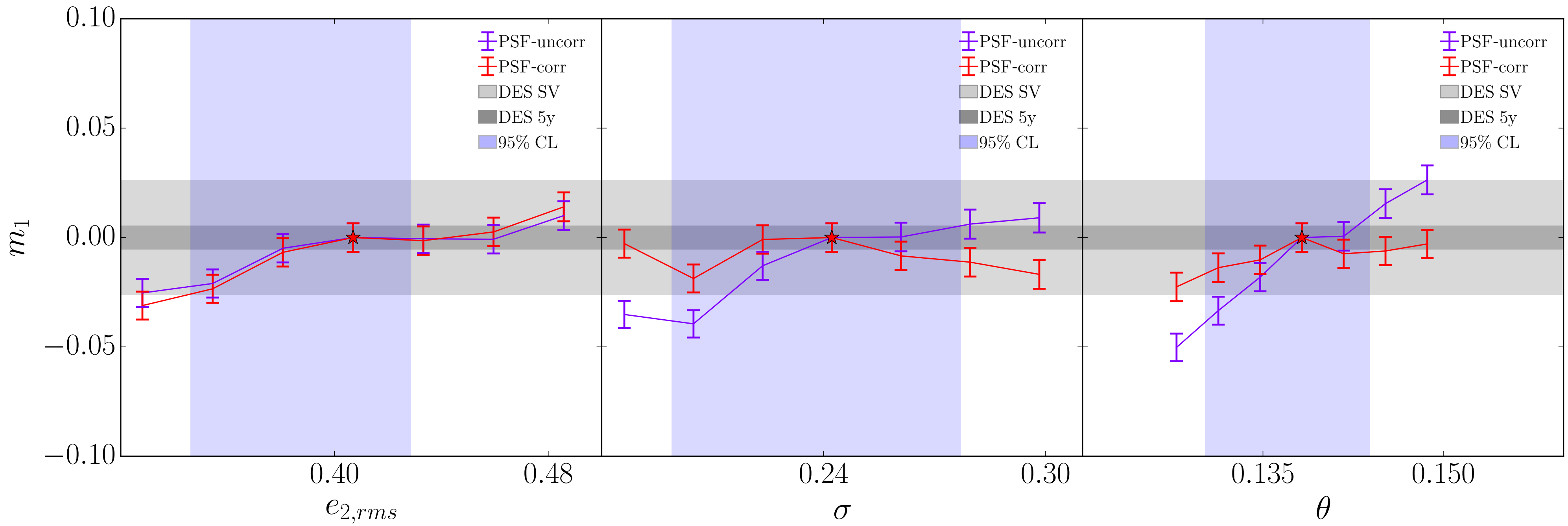
	Python (NumPy)	Numba	Cython	Nuitka (NumPy)	PyPy (NumPy)	numexpr (8 cores)	HOPE	C++
Fibonacci	57.4	65.7[a]	1.1	26.7	21.1	—	1.1	**1.0**
Quicksort	79.4	—[b]	4.6	61.0	45.8	—	1.1	**1.0**
Pi sum	27.2	**1.0**	1.1	13.0	**1.0**	—	**1.0**	**1.0**
10^{th}order	2.6	2.2	2.1	1.2	12.1	1.4	1.1	**1.0**
Simplify	1.4	1.5[ab]	1.8	1.4	23.2	0.6	**0.015**	1.0
Pairwise distance	1357.8 (8.7)	1.8	**1.0**	1247.7 (9.5)	277.8 (60.4)	—	1.7	**1.0**
Star PSF	265.4	250.4[a]	46.2	234.6	339.5	—	2.2	**1.0**

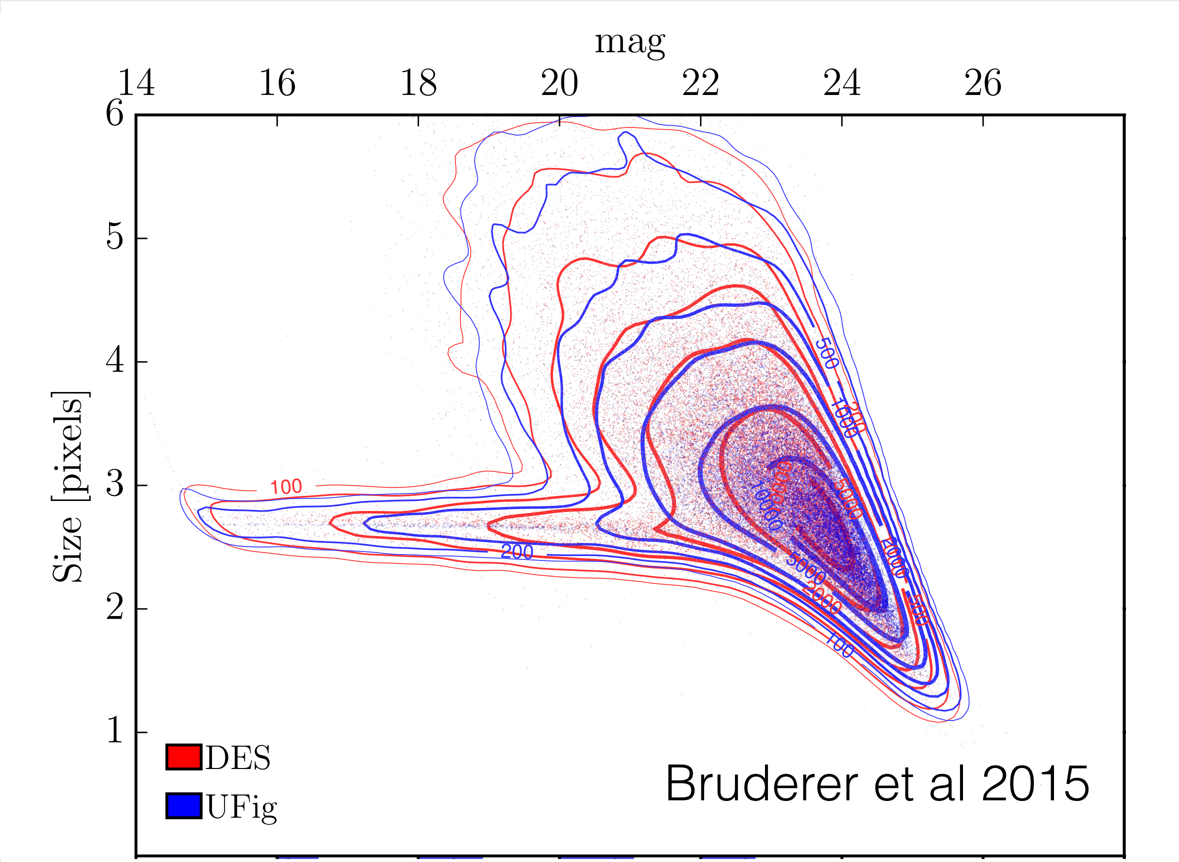
Calibrating Shear measurement

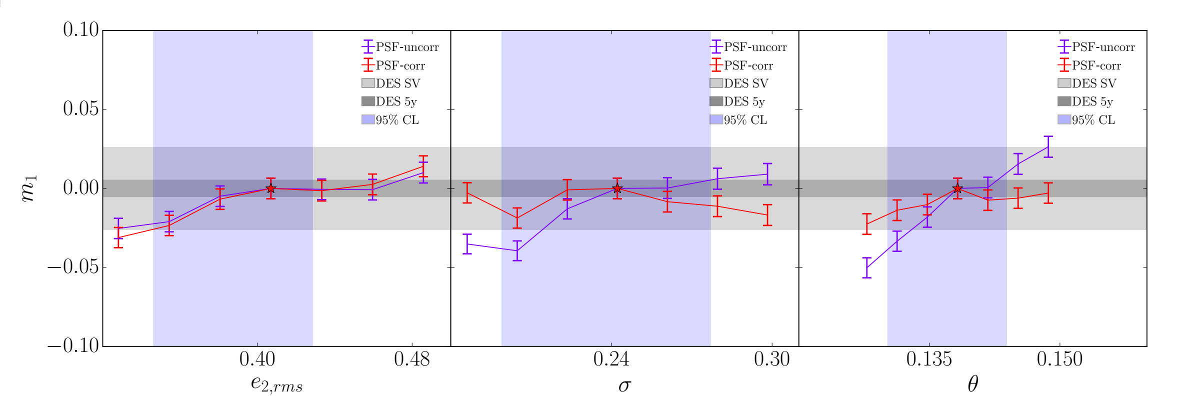


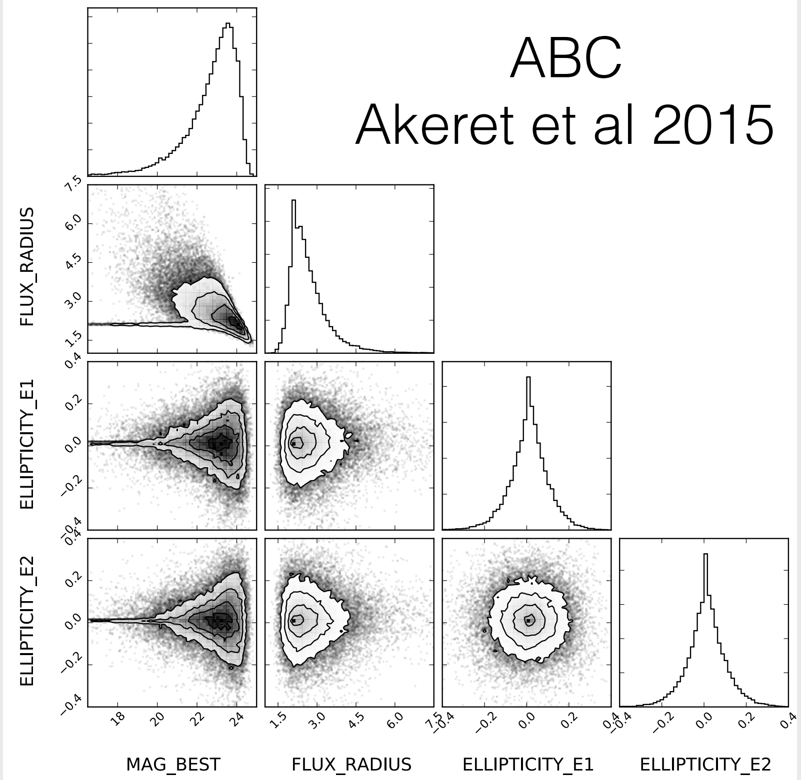
Bruderer et al (2015)

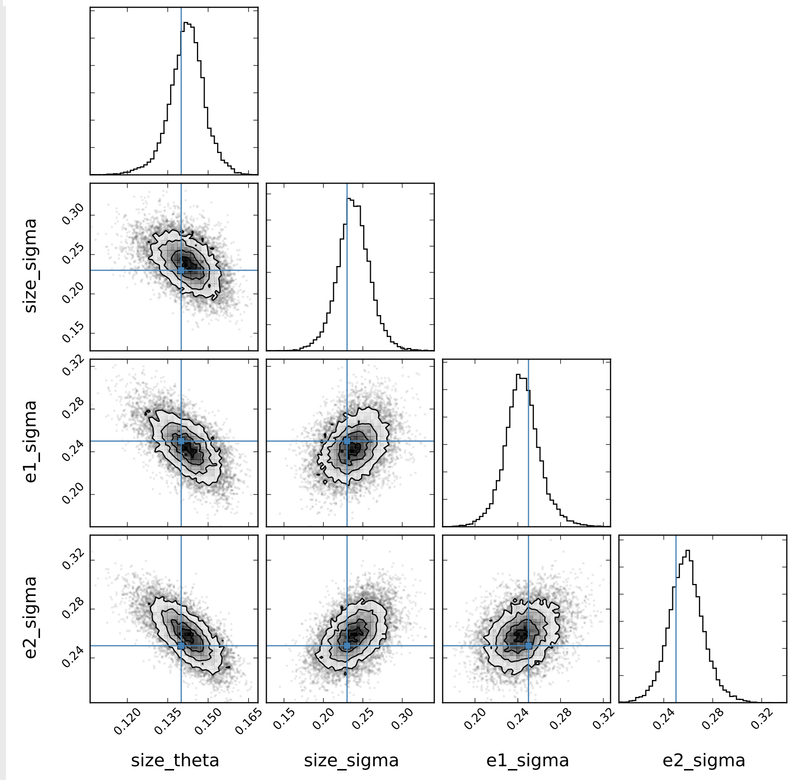

mag
Size [pixels]
DES
UFig
Bruderer et al (2015)


PSF-uncorr
PSF-corr
DES SV
DES 5y
95% CL
m_1
$e_{2,rms}$
σ
θ


mag
14
16
18
20
22
24
26
Size [pixels]
6
5
4
3
2
1
100
200
500
1000
2000
3000
5000
10000
DES
UFig
Bruderer et al 2015


0.10
0.05
0.00
−0.05
−0.10
m_1
PSF-uncorr
PSF-corr
DES SV
DES 5y
95% CL
0.40
0.48
$e_{2,rms}$
0.24
0.30
σ
0.135
0.150
θ


ABC
Akeret et al 2015
FLUX_RADIUS
ELLIPTICITY_E1
ELLIPTICITY_E2
MAG_BEST
FLUX_RADIUS
ELLIPTICITY_E1
ELLIPTICITY_E2


size_sigma
e1_sigma
e2_sigma
size_theta
size_sigma
e1_sigma
e2_sigma

Dark Energy Survey
&
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→ Science Verification phase was enormously successful. First results are consistent with expectations and first science survey results are due this year.

Cosmic Concordance?

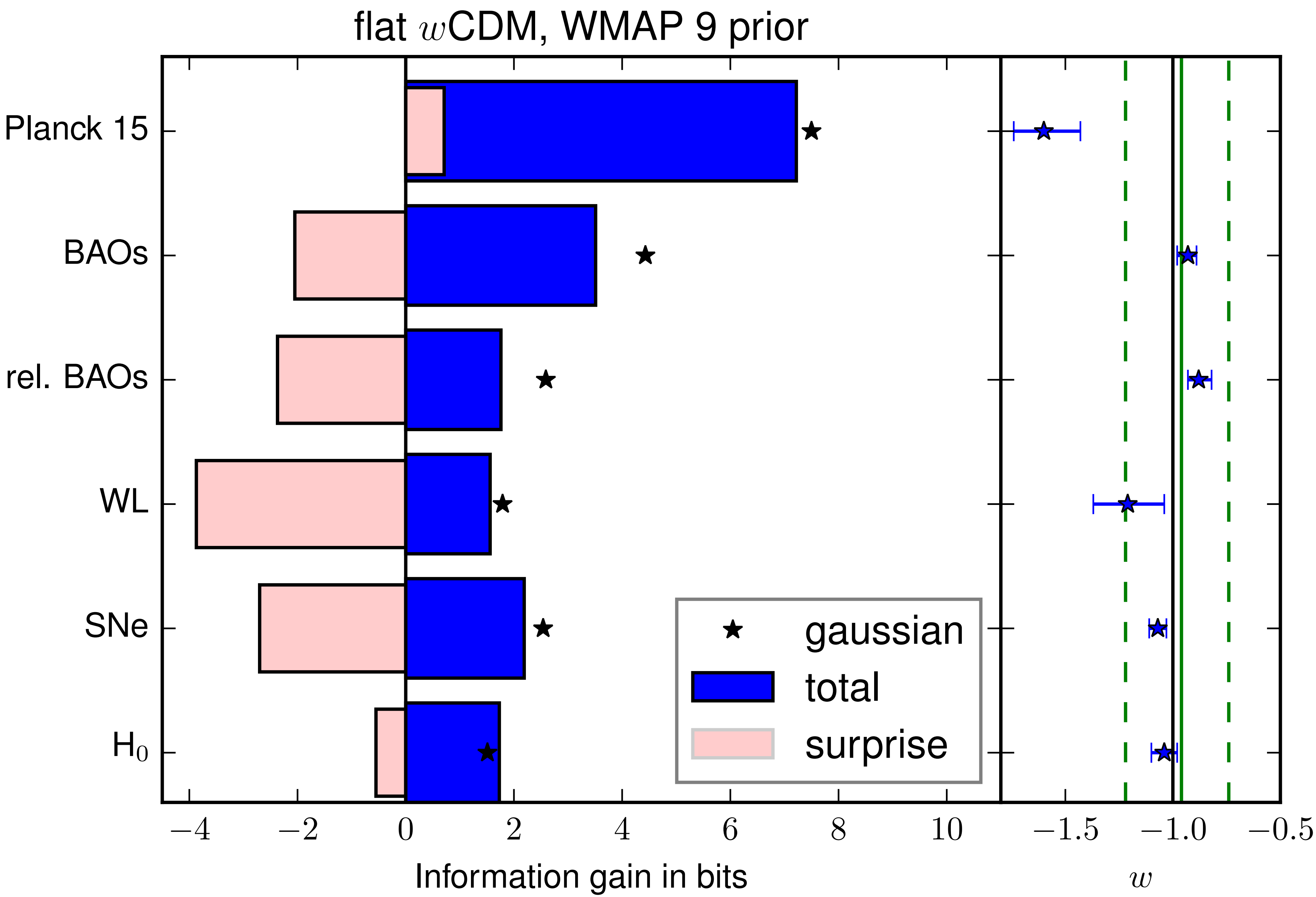
→ In the era of precision multiple probes, concordance of the model needs to be tested in a consistent way. Relative entropy is simple and powerful tool for this

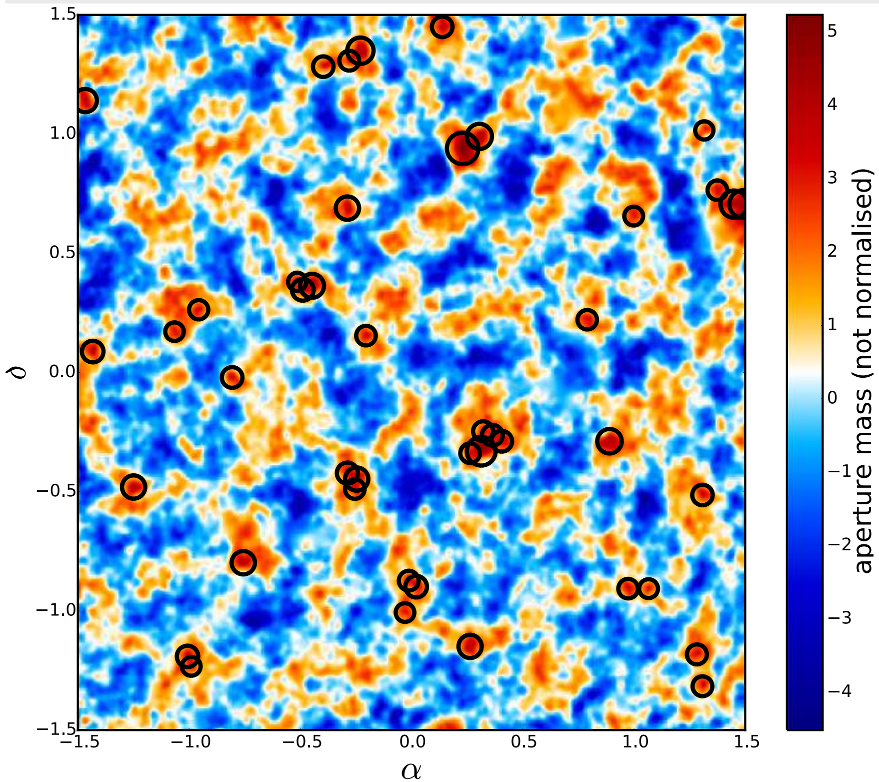
Precision Measurements
Looking Forward

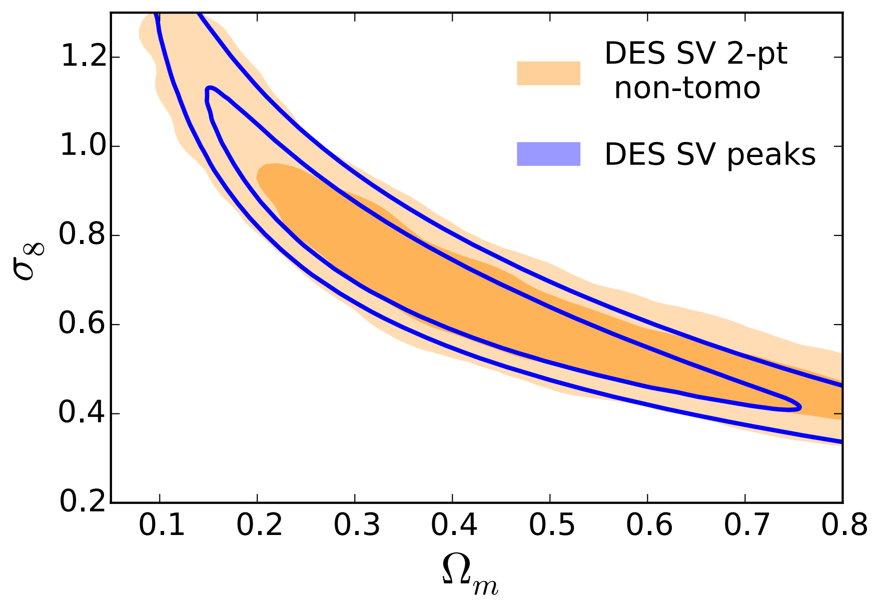
→ Ambitious hardware driven projects need to be matched by sophisticated analysis methods. In particular systematic use of simulations and forward modelling is crucial.

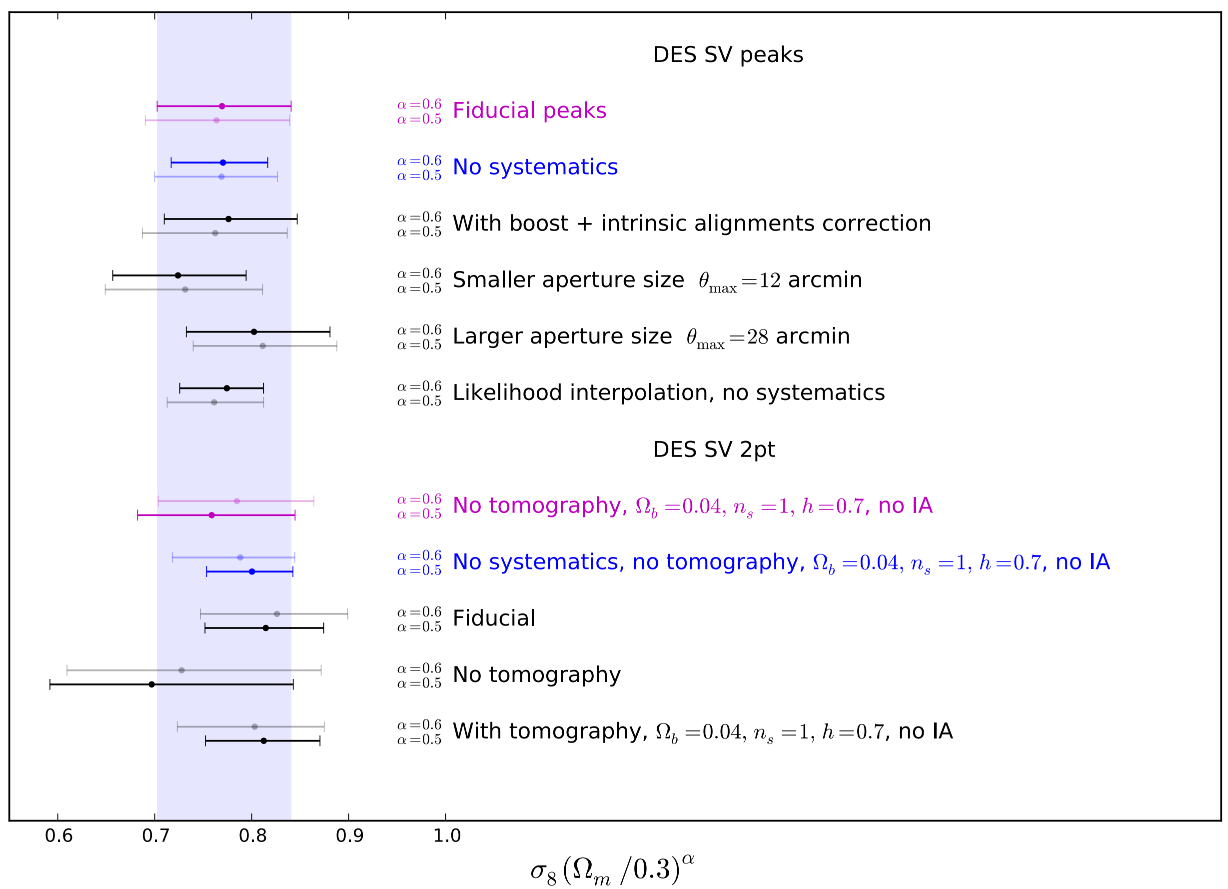
End

Grandis et al (2015)









Kacprzak 2016