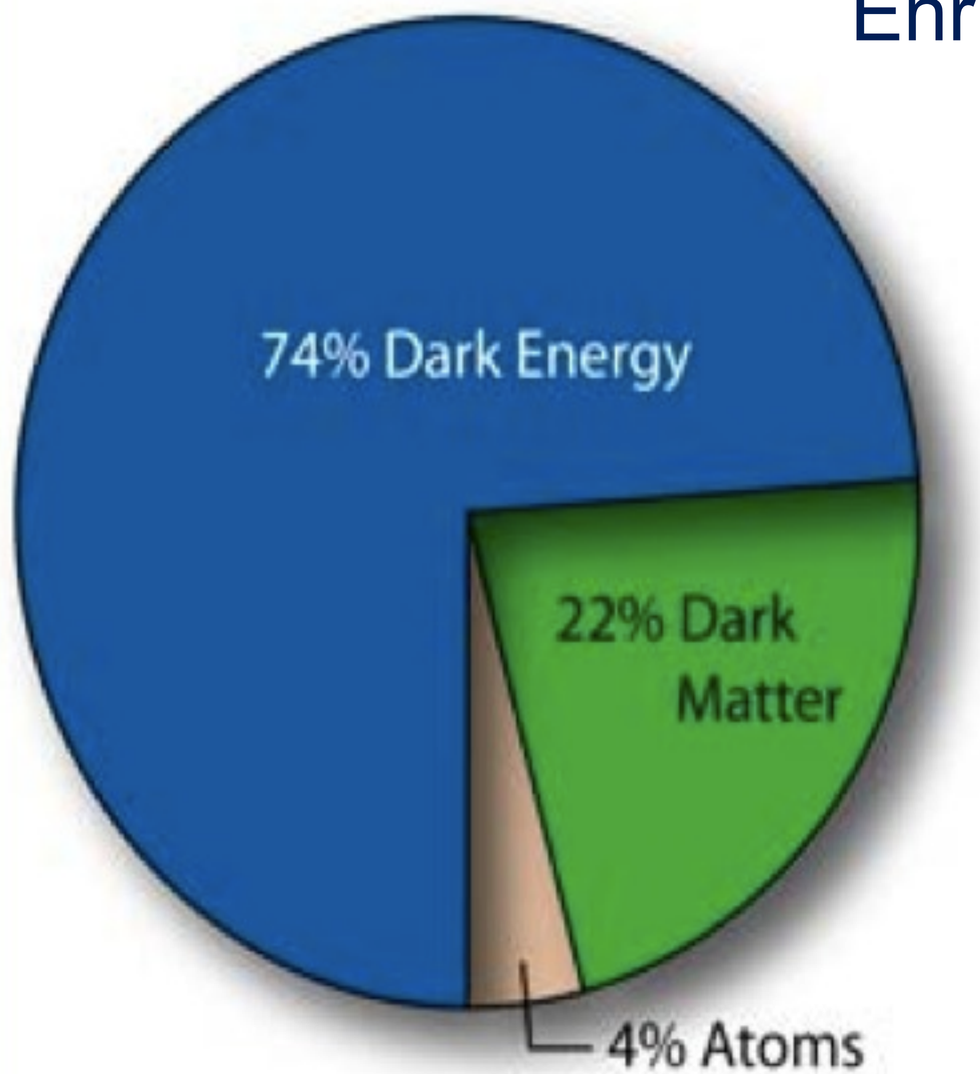
Dark Energy with Galaxy Surveys

INSTITUT D'ESTUDIS ESPACIALS DE CATALUNYA
IEEC
CSIC
INSTITUTO DE CIENCIAS DEL ESPACIO
ICE

Enrique Gaztañaga



○ ○ ○ ○ ○ bottom line

astro-ph:1109.4852

MORE EFFICIENT WAY OF USING GALAXY SURVEYS:

UNDERSTANDING GALAXY BIAS CAN BRING > X100 REWARD IN COSMOLOGICAL PARAMETER MEASUREMENTS

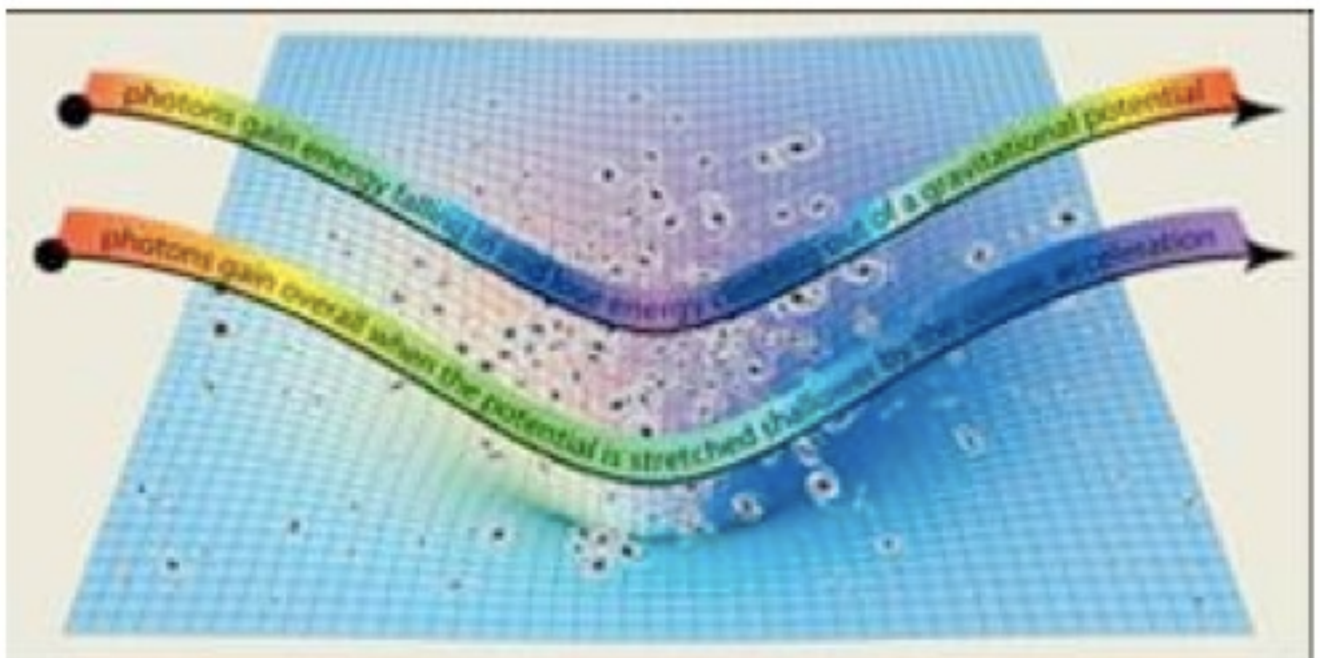
Dark Energy (DE) from Galaxy Surveys

Contents

- *What is DE? Evidence and goals*
- *Need for statistical approach*
- *Different DE probes*
- *Current and future DE surveys*
- *Some spanish contributions: SPADES network*
- *The Dark Energy Survey, an update*
- *DE and galaxy formation (biasing)*
- *Xtalks as a way to observe DE*

What is Dark Energy (DE)?

Einstein's Field Eq. DO NOT seem to work



$$R_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)$$

1) Energy content of Universe has a missing ingredient: DE

so far all data is compatible with <u>cosmological constant</u>

2) the Eq. is wrong (Modify Gravity =>DM=> Galaxy formation)

3) wrong assumptions (homogeneity, perfect fluid, model)

Observing Dark Energy: H(z) & D(z)

- ***Expansion rate history:***

$$R_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right)$$

$$H^2(z) = H^2_0 \; [\; \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)} \;]$$

matter radiation curvarure dark energy $w=p/\rho$

$w=-1$ cosmological constant $\Omega_\Lambda = \Omega_{DE}$

- Measurements are usually integrals over H(z) $r(z) = \int dz/H(z)$
- Standard Candles (supernova) $d_L(z) = (1+z)\, r(z)$
- Standard Rulers (BAO) $d_a(z) = (1+z)^{-1}\, r(z)$ or $H(z)=cdz/r$ directly
- Volume Markers (clusters) $dV/dzd\Omega = r^2(z)/H(z)$

- ***Growth rate history:***

$$\delta T^{\mu\nu}_{;\nu} = 0$$

$$\frac{d^2\delta_k}{d\tau^2} + \mathcal{H}\frac{d\delta_k}{d\tau} - \left(\frac{3}{2}\mathcal{H}^2\Omega_m - k^2 v_s^2\right)\delta_k = 0$$

$\delta = D(z)\, \delta_0$

DARK ENERGY (DE)

Challenge for Observational Cosmology:

Can we use data to confirm
or falsify the cosmological constant model?

-> show that w (DE equation of state) is different from unity

If deviations are found, can we distinguish between
DE and modified gravity (why is G so weak)?

-> show relation between
H(z) expansion history & growth history D(z)

$$\ddot{\delta}(a,k) + 2H(a)\dot{\delta}(a,k) - \frac{g(k)}{\eta(k)} 4\pi G\bar{\rho}\delta(a,k) = 0.$$

Modified:
Poison Eq. & Metric potentials

Evidence for DE:

Flat universe: $\Omega_{DE} = 1 - \Omega_M$ (WMAP+ H_0)

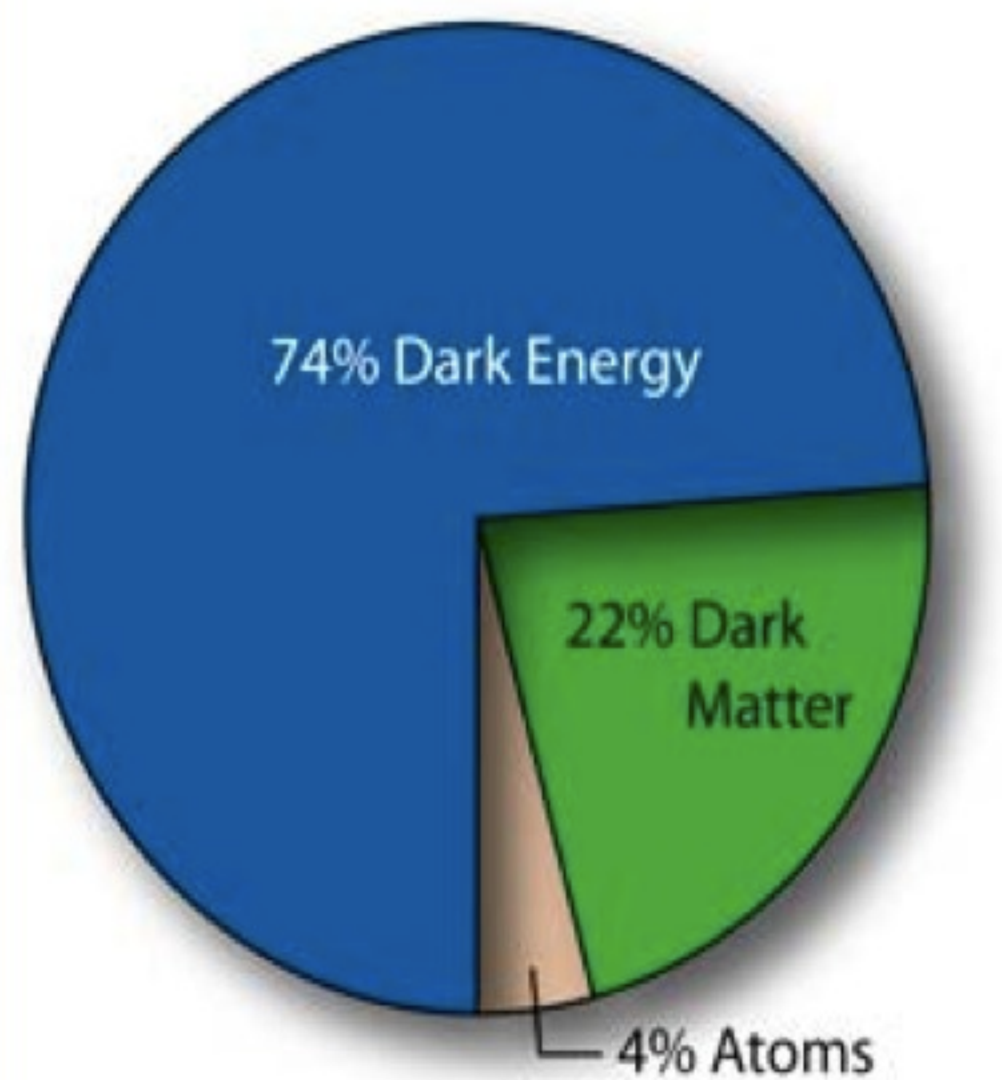
w=-1 cosmological constant $\Omega_\Lambda = \Omega_{DE}$

Acceleration: $w < -1/(3\ \Omega_{DE})$ (Supernovae)

$$H^2(z) = H^2_0\ [\ \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_K (1+z)^2 + \Omega_{DE} (1+z)^{3(1+w)}\ ]$$

Concordance with:

BAO (volume)
Cluster Abundance (mass)
WL (2D)
P(k) in Galaxy Surveys (3D but bias)
RSD (ratios)
ISW (2D)



Need for Statistical Approach

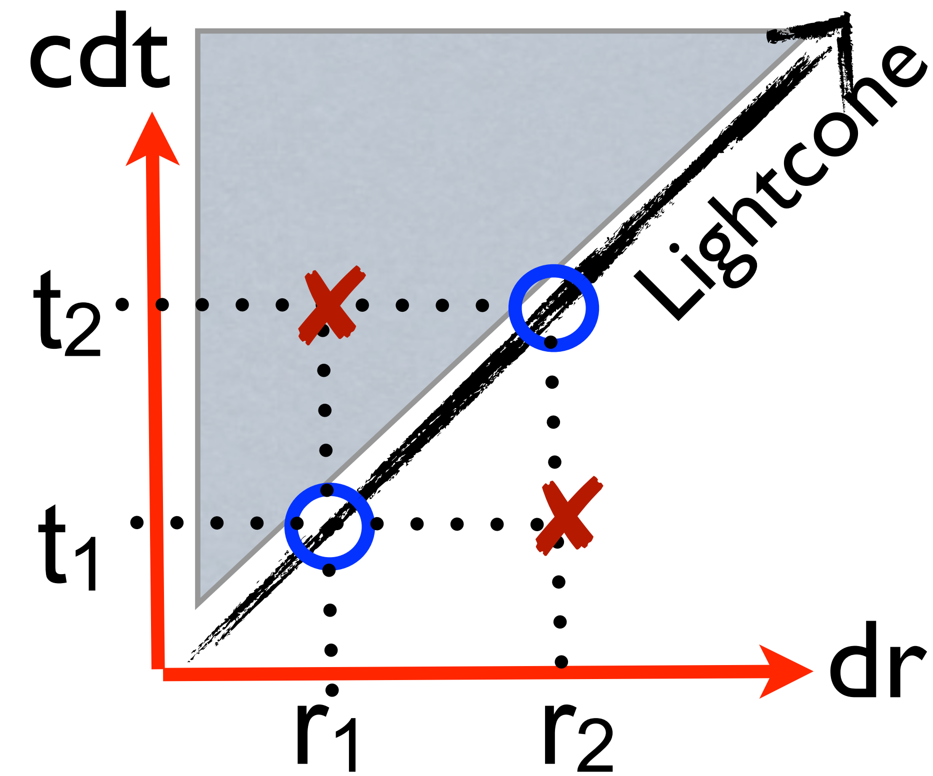
$$\frac{d^2\delta_k}{d\tau^2} + \mathcal{H}\,\frac{d\delta_k}{d\tau} - \left(\frac{3}{2}\,\mathcal{H}^2\,\Omega_m - k^2\;v_s^2\right)\;\delta_k = 0$$

This is a initial condition problem, we need:

$$\delta(r_2,t_2) = D(t_1,t_2)\;\delta(r_2,t_1)$$

$$\delta(r_1,t_2) = D(t_1,t_2)\;\delta(r_1,t_1)$$

but we can only measure: $\delta(r_1,t_1)$ & $\delta(r_2,t_2)$



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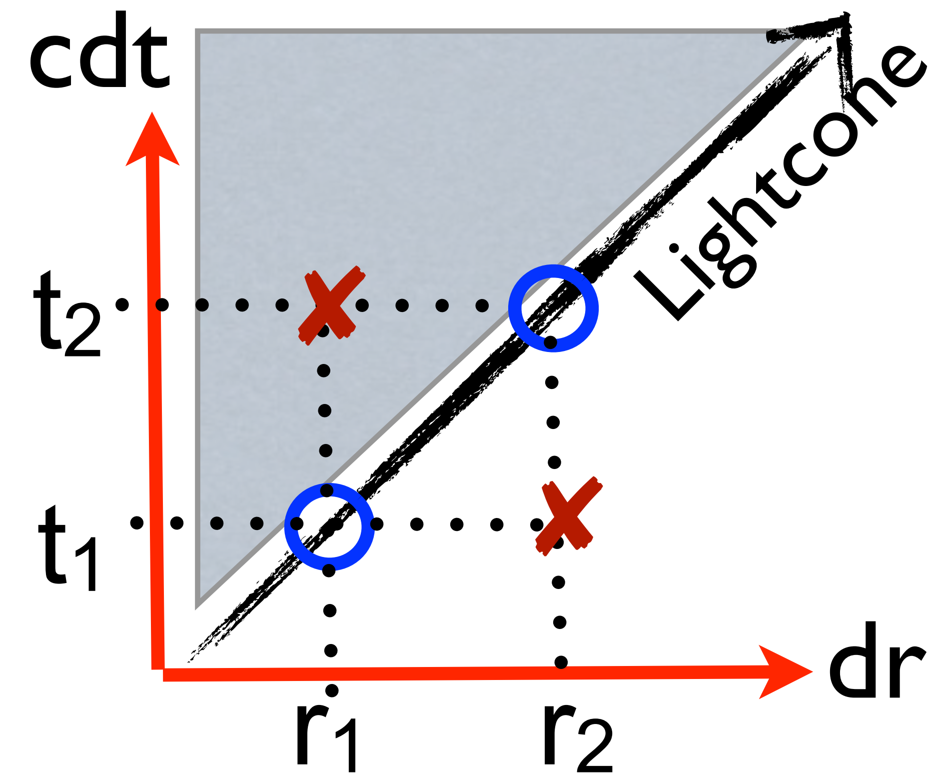

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but we can only measure: $\delta(r_1,t_1)$ & $\delta(r_2,t_2)$

Statistically this is possible (in homogeneous universe):

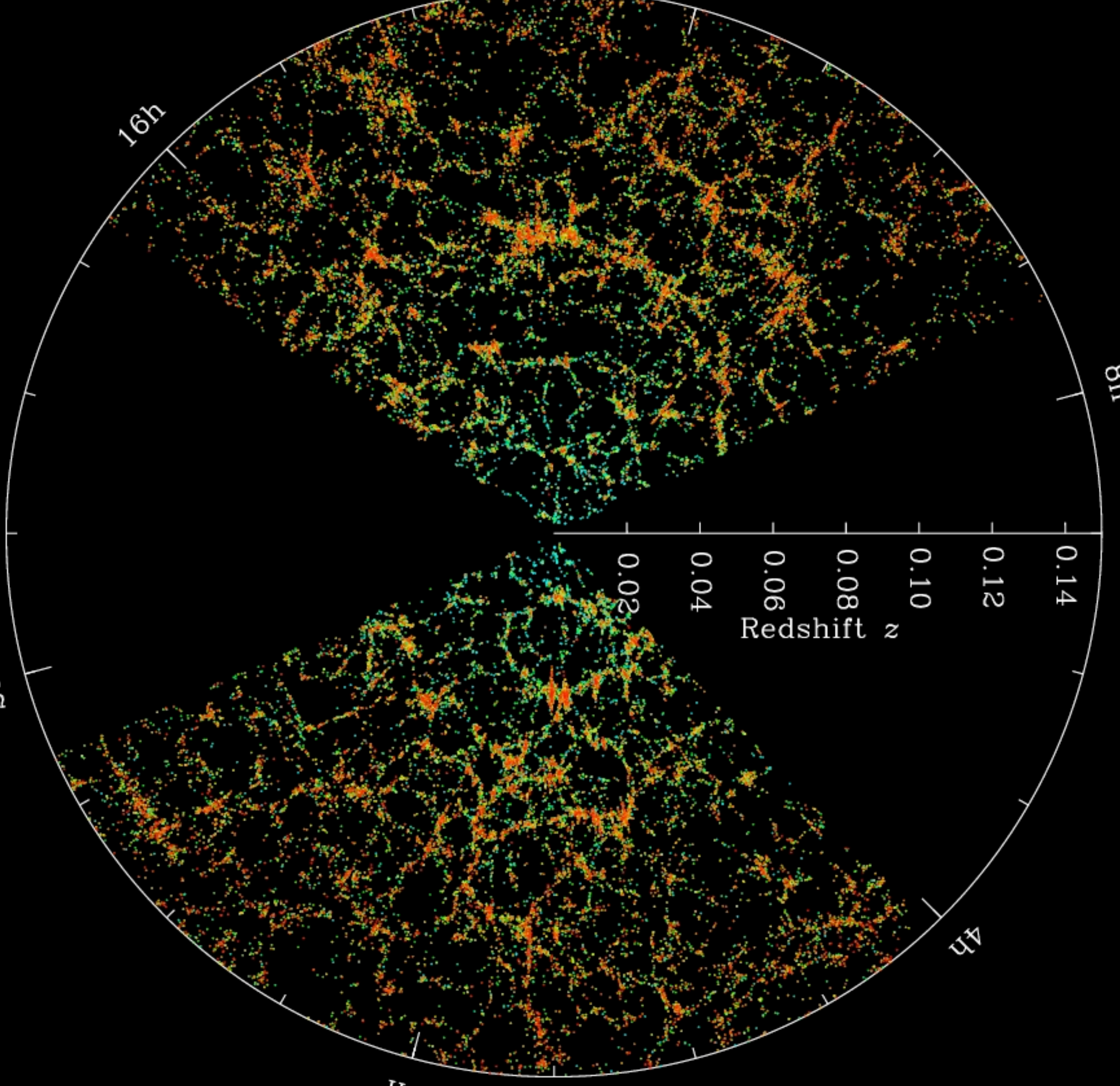
$$\xi_2(r,t_2) \equiv \langle\delta(x,t_2)\delta(y,t_2)\rangle_{xy} = D^2(t_1,t_2)\ \langle\delta(x,t_1)\delta(y,t_1)\rangle_{xy} = D^2(t_1,t_2)\ \xi_2(r,t_1)$$

$r=|x-y|$

$$P(k,z) = D^2(z)\ P(k,0)$$

This is limited by *sampling variance*: need large Volume (3D)

Can produce ***biases*** in statistical measures



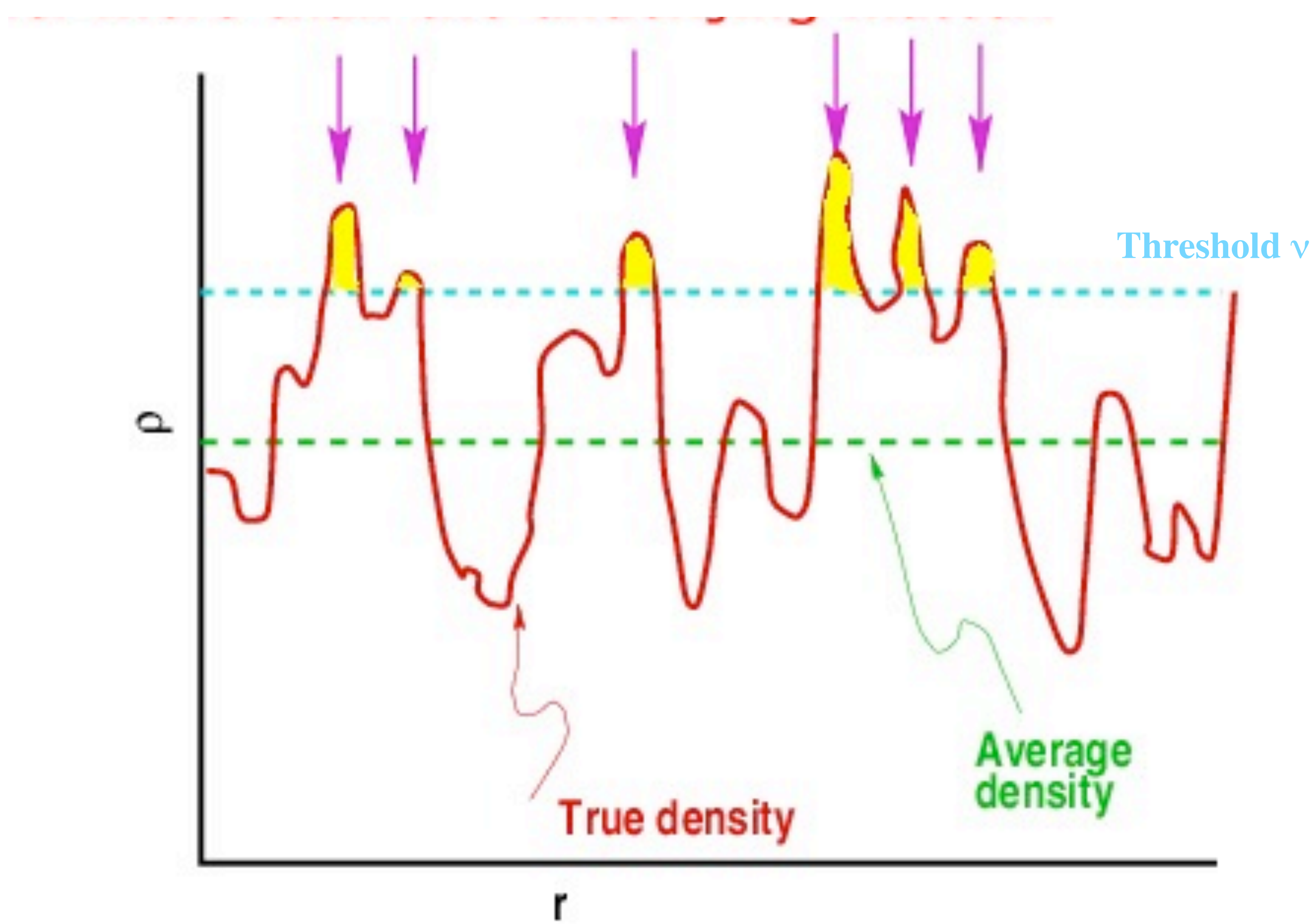
16h
8h
4h
20h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

Bias: lets take a very simple model.

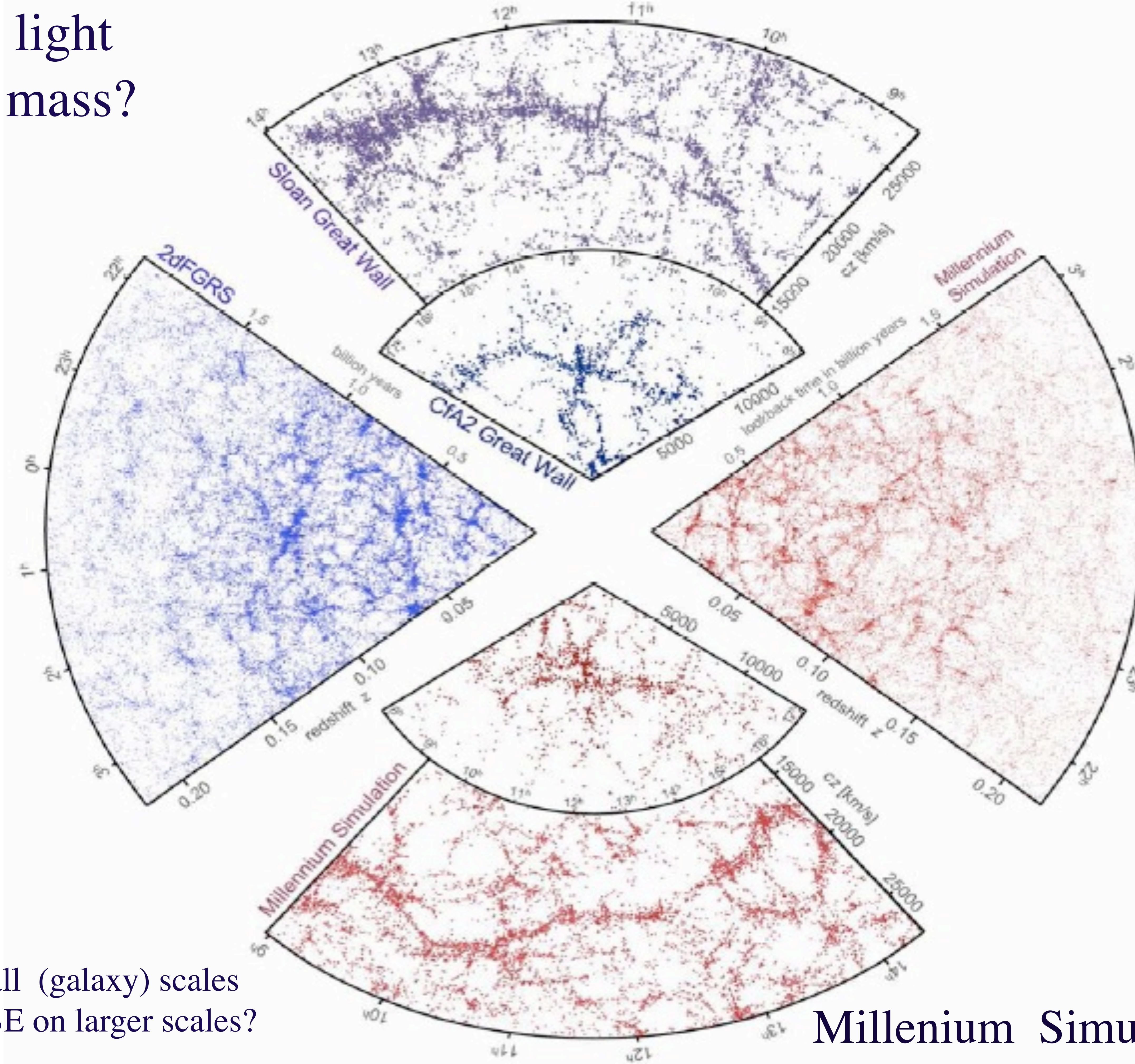
rare peaks in a Gaussian field (Kaiser 1984, BBKS)

Linear bias "b": $\delta\,(\mathrm{peak}) = b\ \delta(\mathrm{mass})$ with $b = \nu/\sigma$ (SC: $\nu=\delta_c/\sigma$)

$$\rightarrow \xi_2\,(\mathrm{peak}) = b^2\,\xi_2\,(m)$$



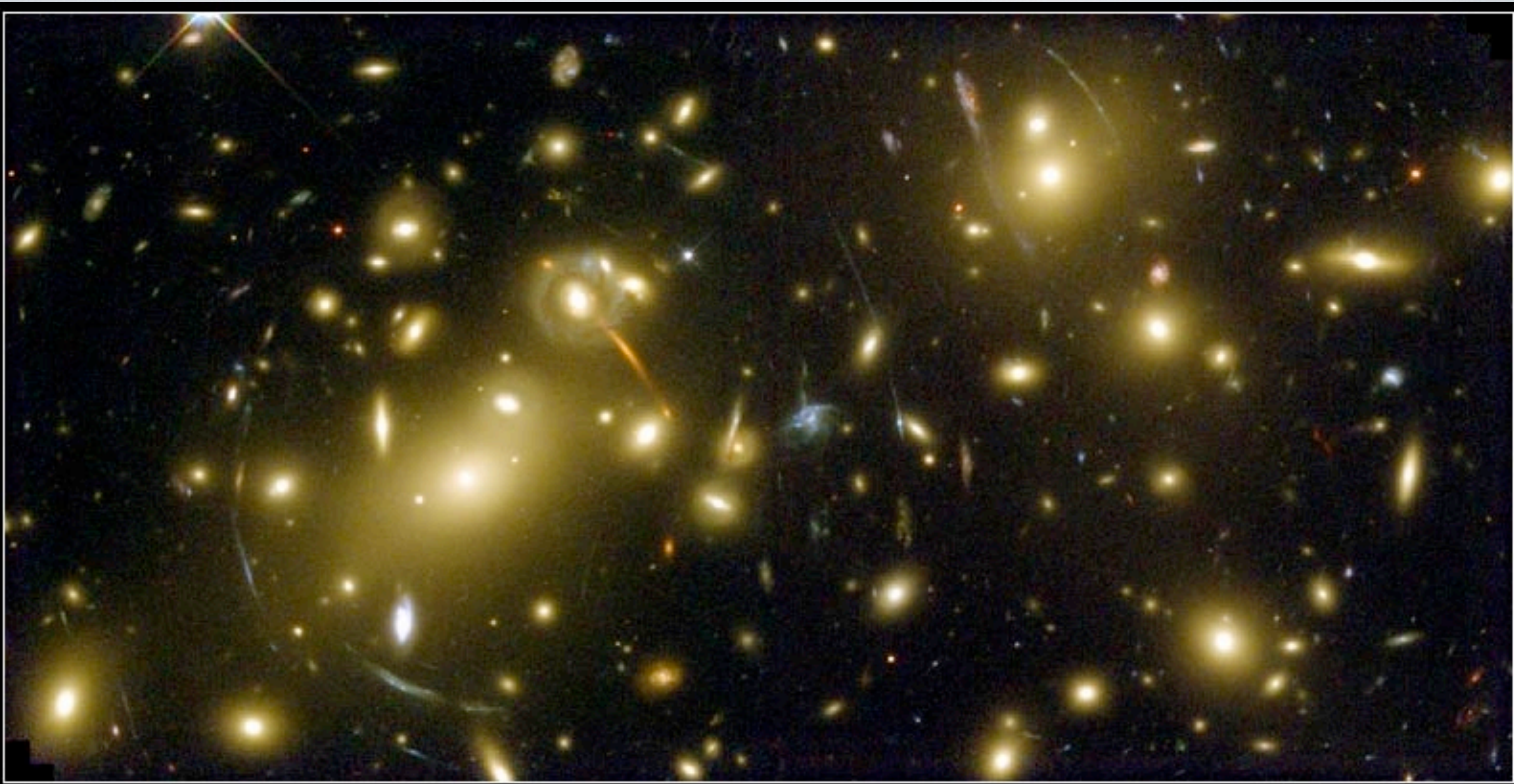
Does light traces mass?



Not on small (galaxy) scales
but MAY BE on larger scales?

Millenium Simulation

Strong and Weak Gravitational Lenses

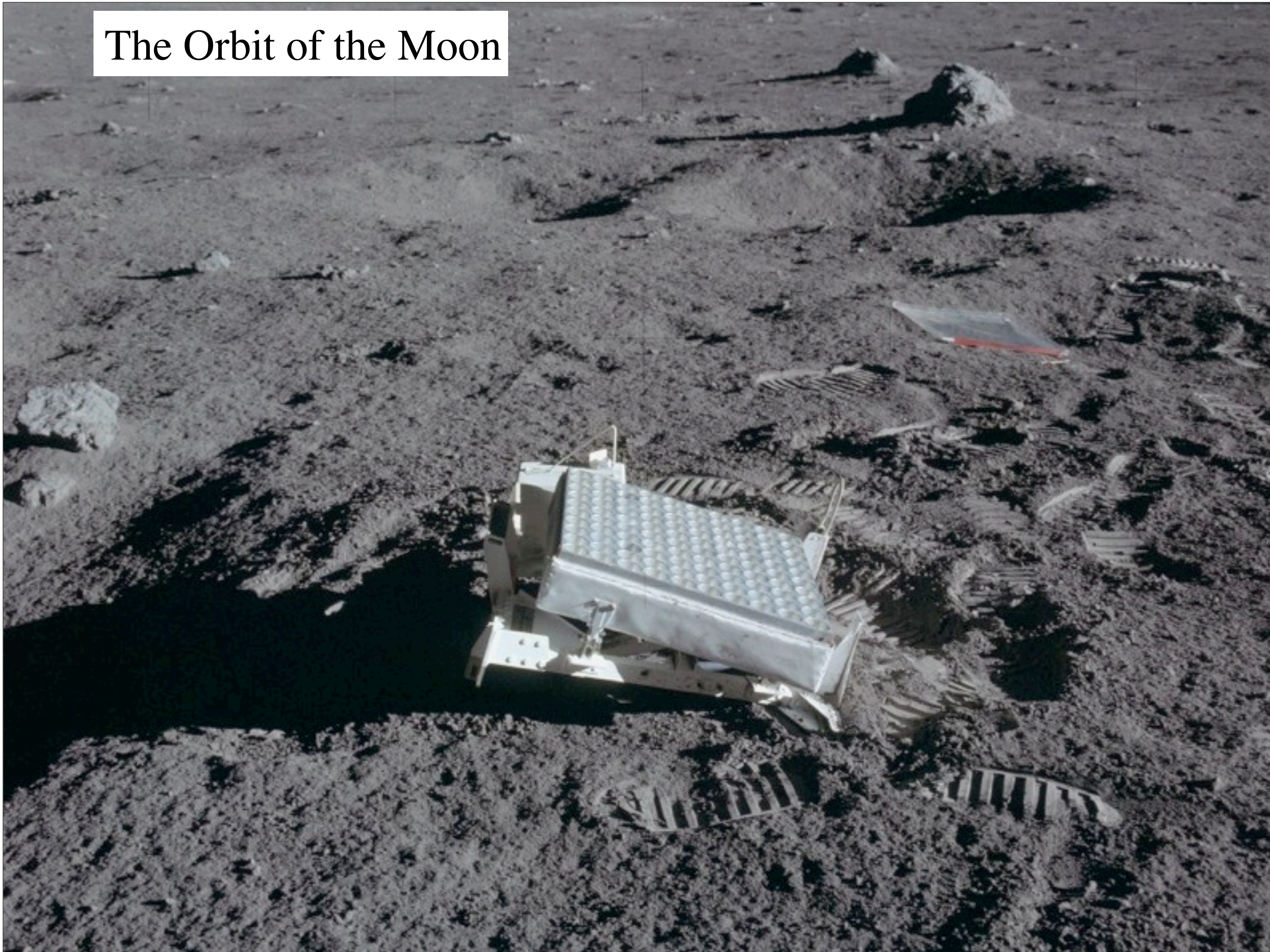


Galaxy Cluster Abell 2218 HST • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Can be used to measure distances and growth history in the universe

The Orbit of the Moon

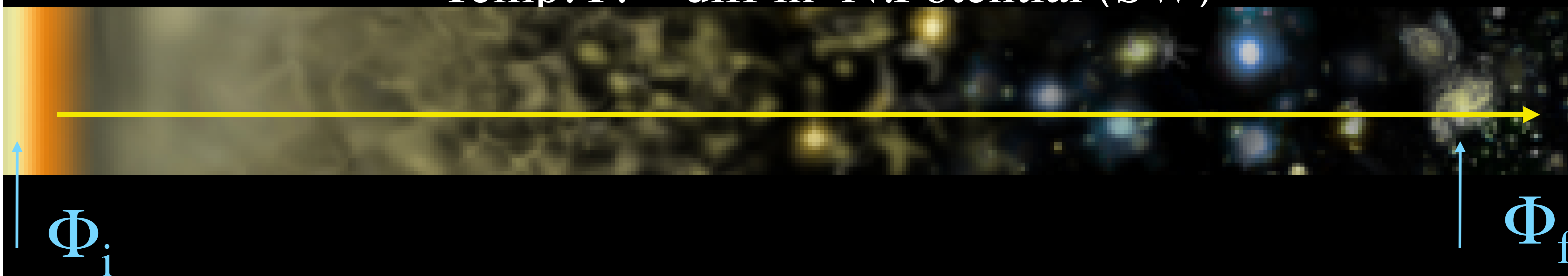


PRIMARY CMB ANISOTROPIES

Sachs-Wolfe (ApJ, 1967)

$$\Delta T/T(n) = [\Phi\ (n)\ ]_i^f$$

Temp. F. = diff in N.Potential (SW)



$$\left.\begin{aligned} \Delta T/T = (SW) = \Delta\Phi\ /c^2 \\ \Delta\Phi\ = GM\ (\delta/\ R)\ /c^2 \end{aligned}\right\} \Delta T/T = G\ \rho_m\ 4/3\ \pi\ (R/c)^2\ \delta$$

$$\boxed{\Delta T/T\ = \Omega_m\ /2\ \ (H_0 R/c)^2\ \delta\ \ \sim\ \ \Omega_m/2\ \ (R/3000\mathrm{Mpc})^2\ \delta}$$

$<\Delta T/T>_{rms} \sim 10^{-5}\ \sigma_8$ for $(R \sim 8$ Mpc , $<\delta> \sim 1)$

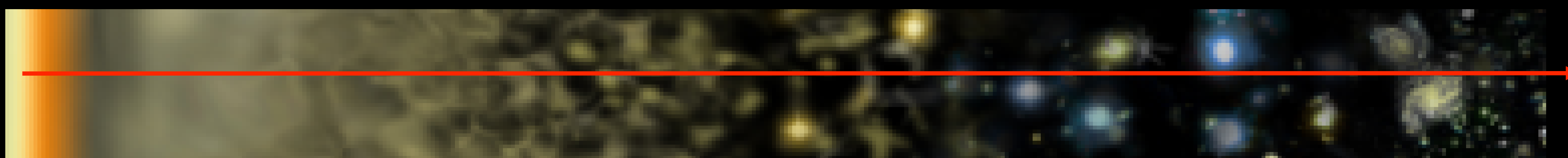
PRIMARY & SECONDARY ANISOTROPIES

Sachs-Wolfe (ApJ, 1967) & Rees-Sciama (Nature, 1968) non-linear

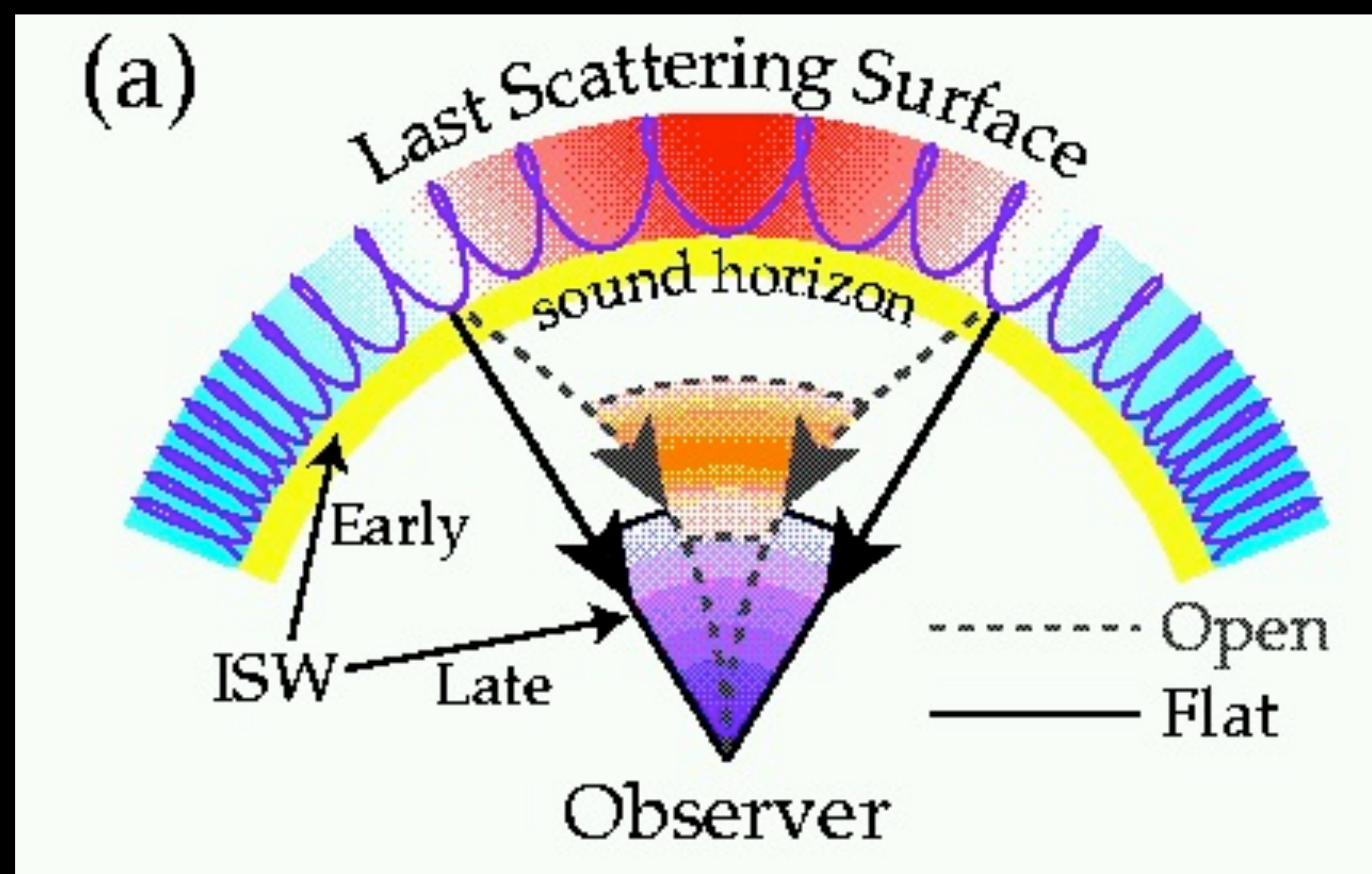
$$\Delta T/T(n) = \left[\; 1/4\;\delta\gamma\;(n) \;+\; v.n \;+\; \Phi\;(n)\;\right]_i^f \;+\; 2\int_i^f d\tau\;\; d\Phi/d\tau\;(n)$$

Temp. F. = Rad-baryon fluid + Doppler + N.Potential (SW) + Integrated Sachs-Wolfe (ISW)

Φ_i



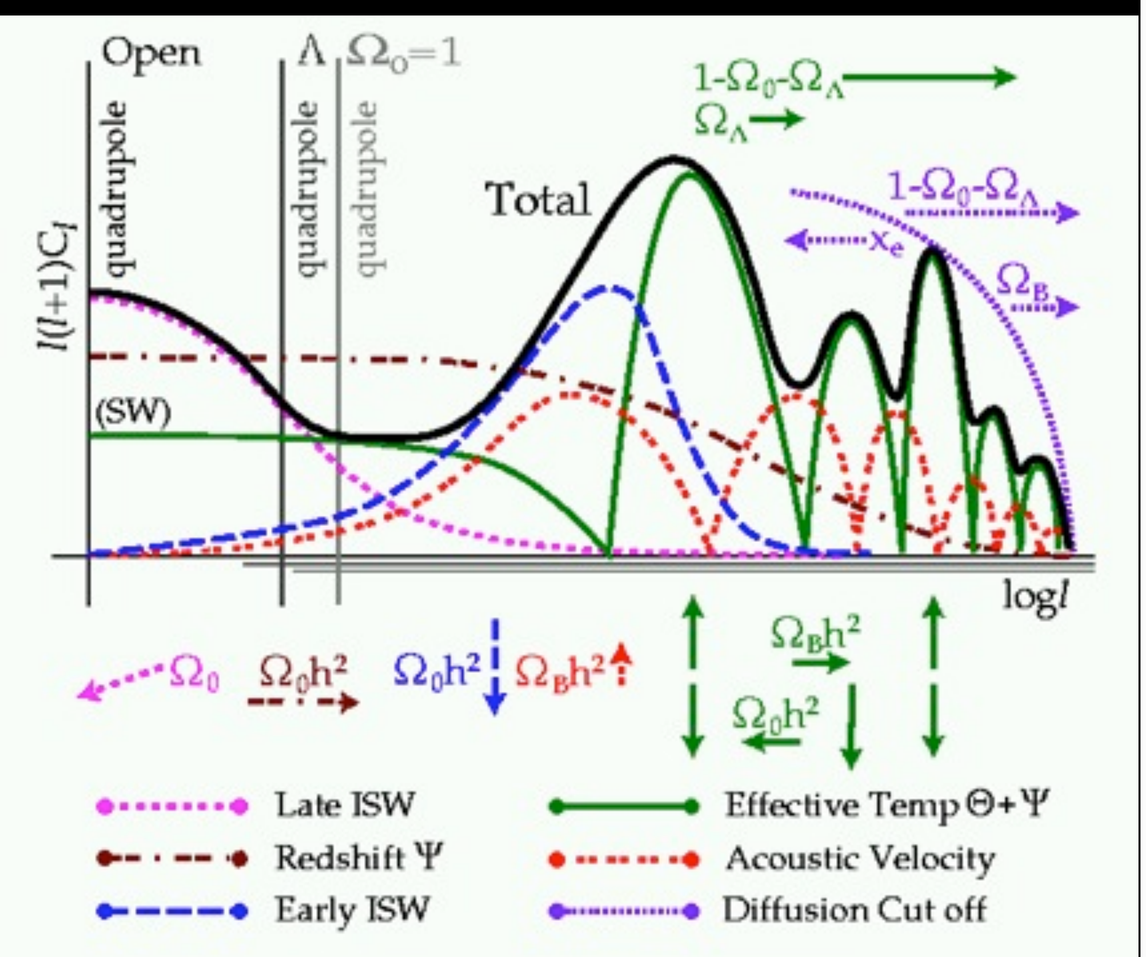
Φ_f

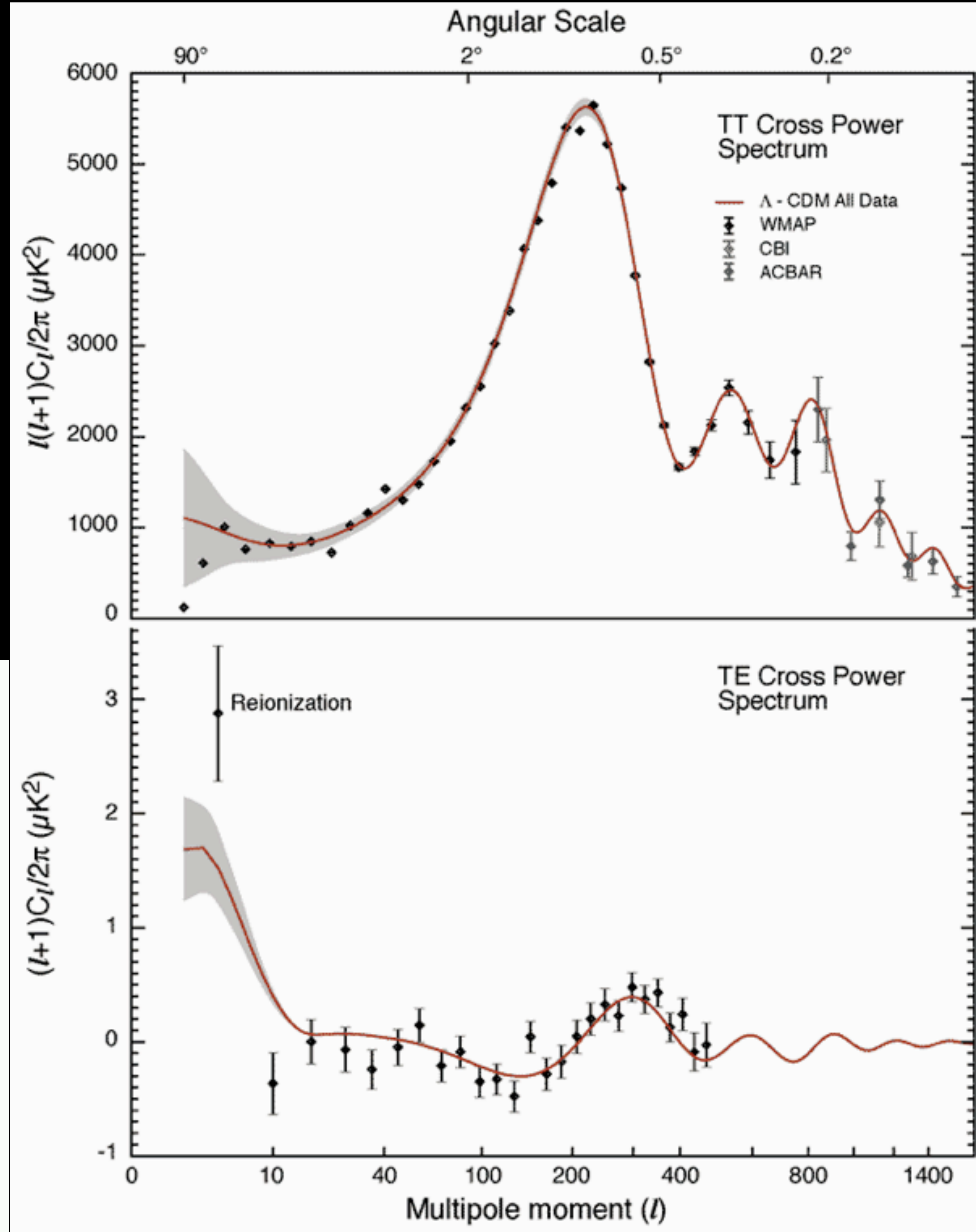


A geometrical test for space:

Measure the angular scale that
Corresponds to the sound horizon

WMAP1
+
Planck is comming

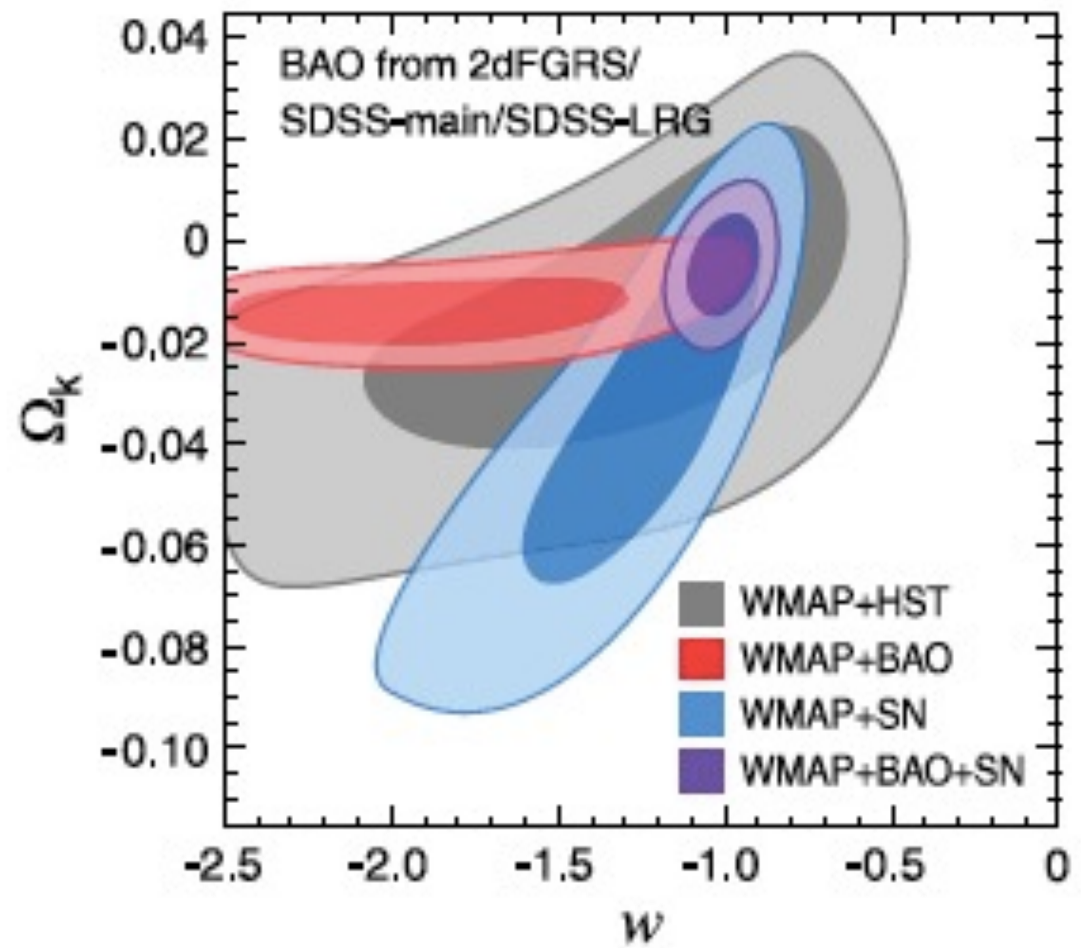


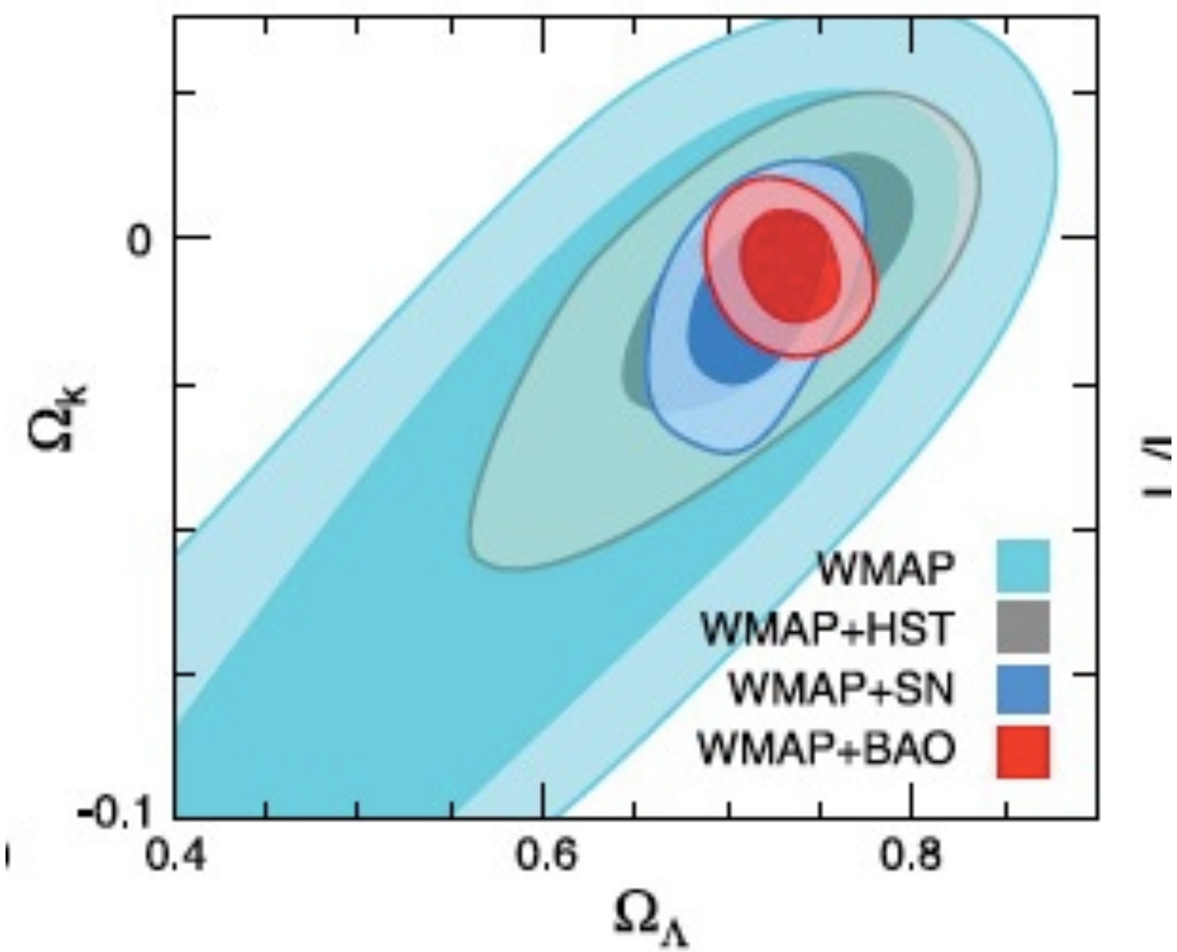


Constraints from CMB

Komatsu etal 0803.0547

	5-year ML[a]	5-year Mean[b]	Error, σ
$l_A(z_*)$	302.10	302.45	0.86
$R(z_*)$	1.710	1.721	0.019
z_*[e]	1090.04	1091.13	0.93





Acustic scale $\theta_A \equiv \pi / l_A = r_s / d_A$

$Z_* = 1090$ is z at decoupling

Shift parameter $R = d_A H(z_*) / c$

DARK ENERGY (DE)

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$$\ddot{\delta}(a,k) + 2H(a)\dot{\delta}(a,k) - \frac{g(k)}{\eta(k)} 4\pi G \bar{\rho} \delta(a,k) = 0.$$

Modified:
Poison Eq. & Metric potentials

Figure of Merit $\mathrm{FoM}_{w\gamma} \times 10^3$: Expansion x Growth

$$H = H(w)$$

w(z) -> Expansion History (background metric)
we will use w0 and wa

$$f \equiv \frac{d\ln D}{d\ln a} = \frac{\dot\delta}{\delta} \equiv \Omega_m^\gamma(a)$$

γ -> Growth History (metric perturbations)
probably need one more parameter here

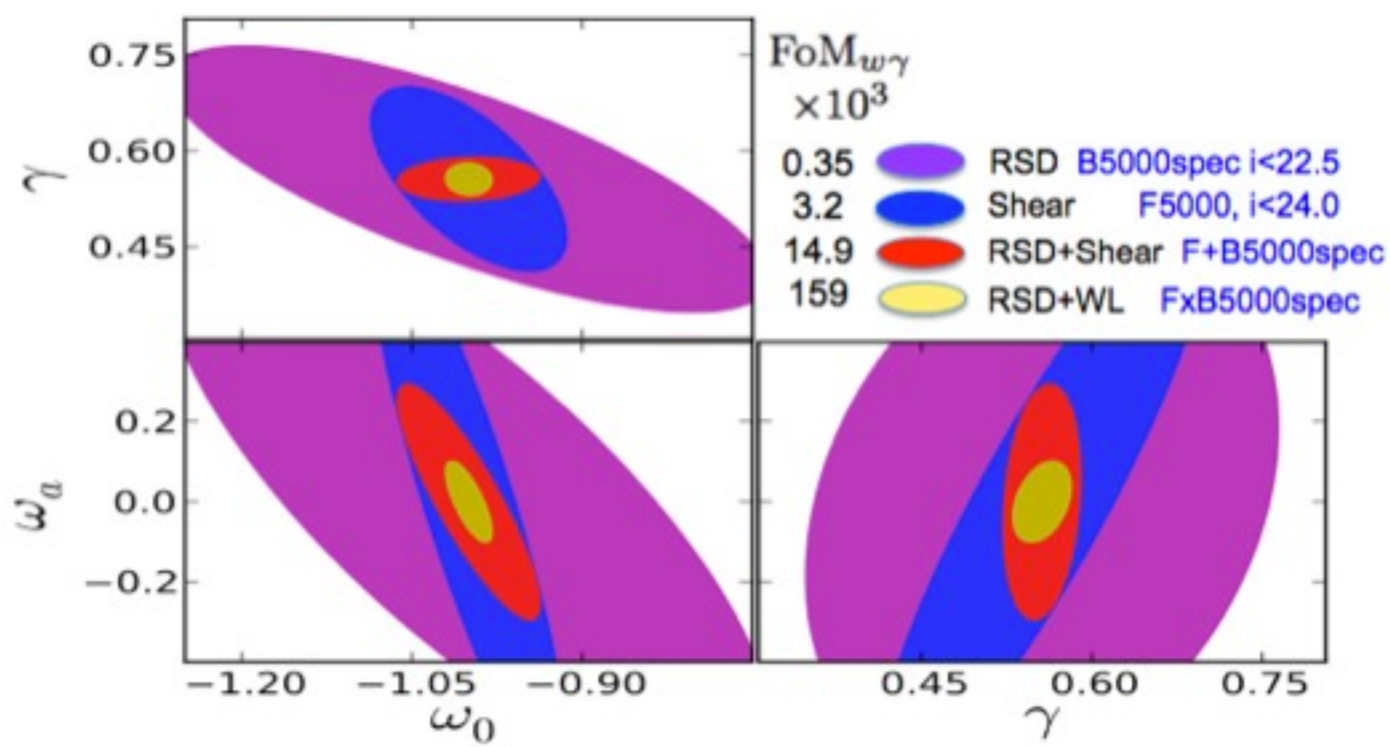
$$\delta = D(a)\delta(0)$$

Linear Theory: P(k,z) ~D^2(z) P(k,0)

+
mass conservation

$$\dot\delta = -H\theta$$

θ = – f(Ω) δ

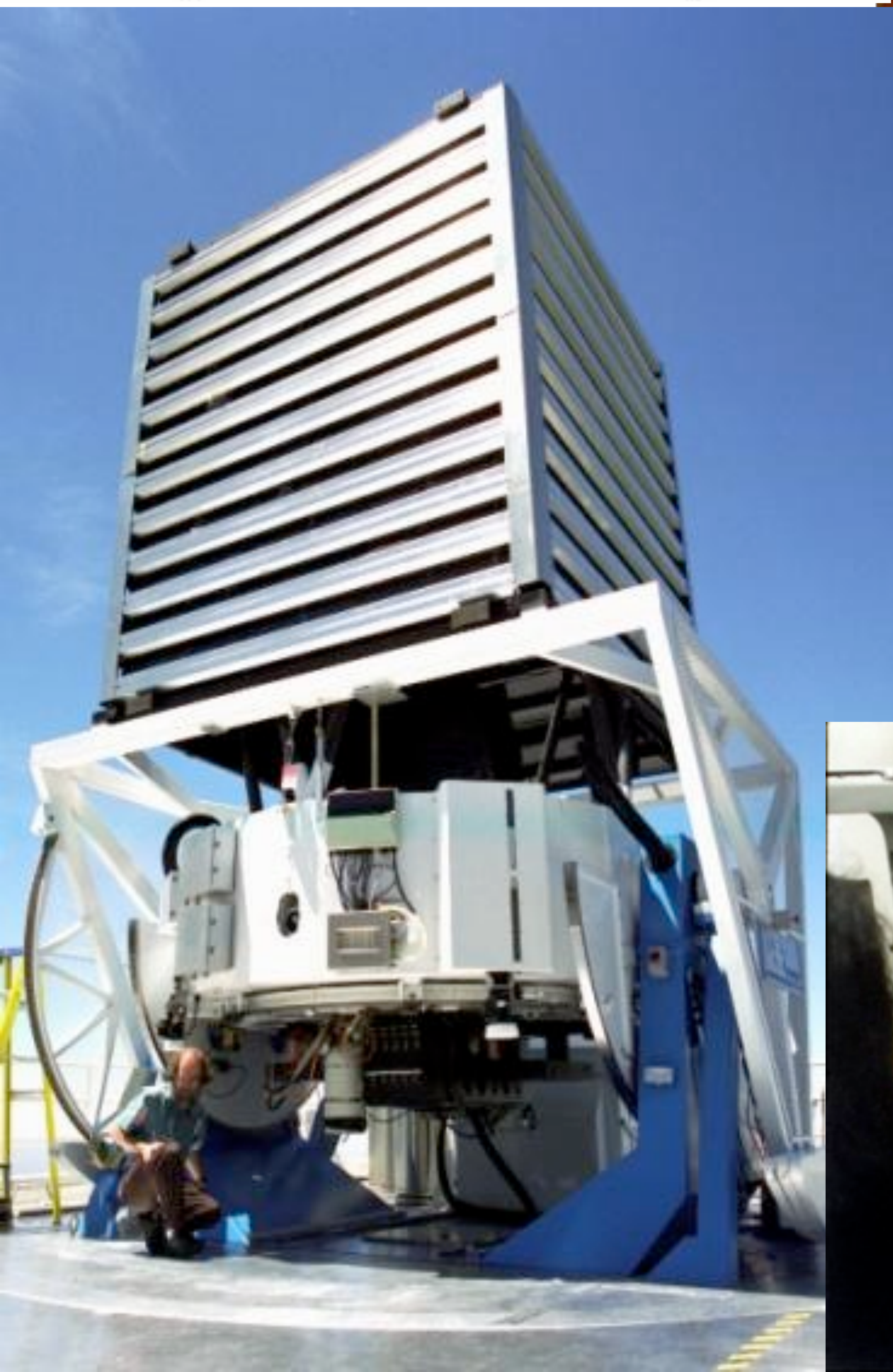


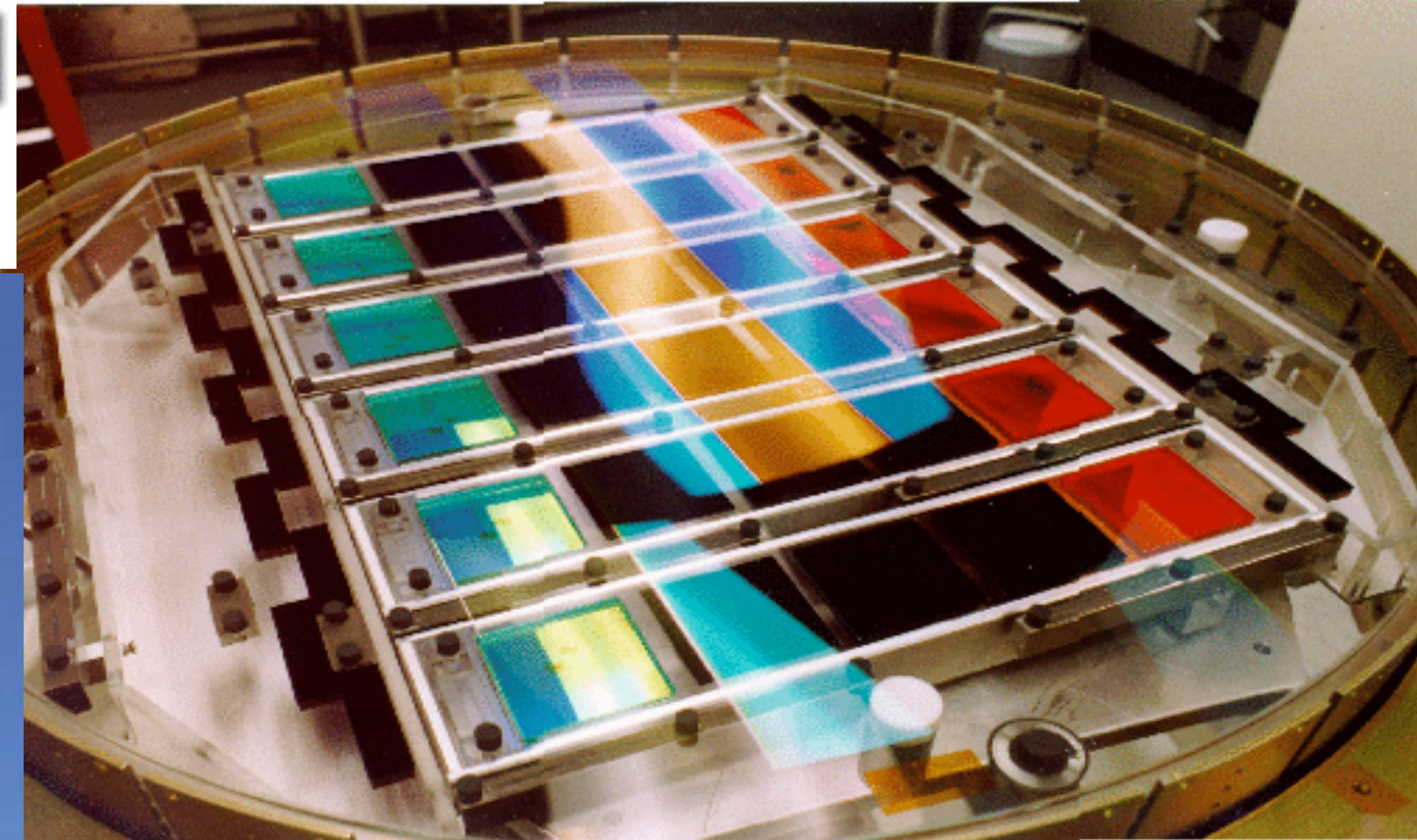
f = Velocity growth factor: tell us if gravity is really responsible for structure formation!
Could also tell us about cosmological parameters or Modify Gravity

$$FoM_S = \sqrt{\frac{1}{det[F^{-1}]_S}} = \frac{1}{\sigma(w0)\ \sigma(wa)\ \sigma(\gamma)}$$

Om - ODE - h - sig8 - Ob - **w0 - wa -**γ- ns - bias(z)

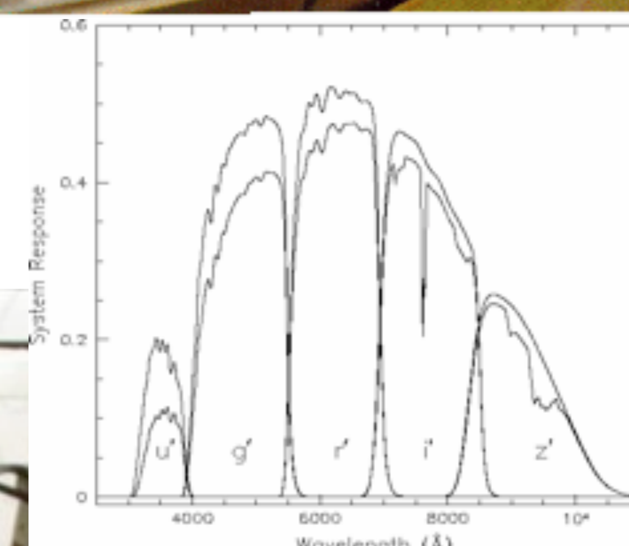
Sloan Digital Sky Survey





5x6 x 2048 x 2048 = 5 color

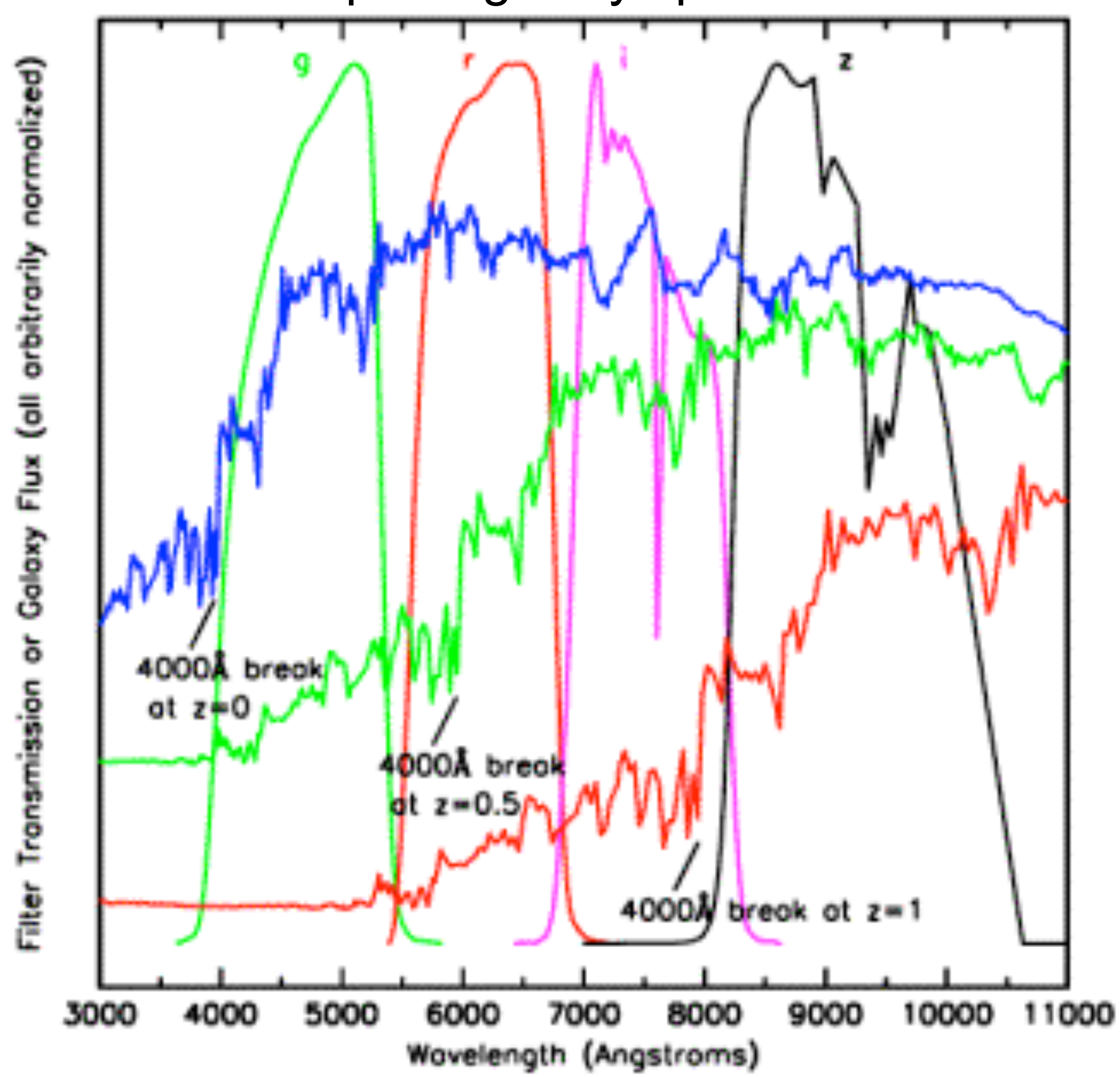
24 x 400 x 2048 astrometry /focus



Photometric Redshifts

- Measure relative flux in multiple filters: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Precision is sufficient for Dark Energy probes, provided error distributions well measured.
- Good detector response in *z* band filter needed to reach z>1

Elliptical galaxy spectrum



DARK ENERGY PROBES

PROBE	Photometric Survey	Spectroscopic Survey (z<1)	Spectroscopic Follow-up	CMB
SNe-Ia	X		X	
BAO	Y	Y		X
WL	X		Y	
z-distortions		X		
clusters	X	Y	X	Y
ISW	X		Y	X

Y = OPTIONAL

X = REQUIRED

BAO Surveys Padmanabhan

Spectroscopic: WiggleZ, HETDEX, WFMOS, BOSS LRG + QSO

Photo-z 40-filter: PAU-BAO

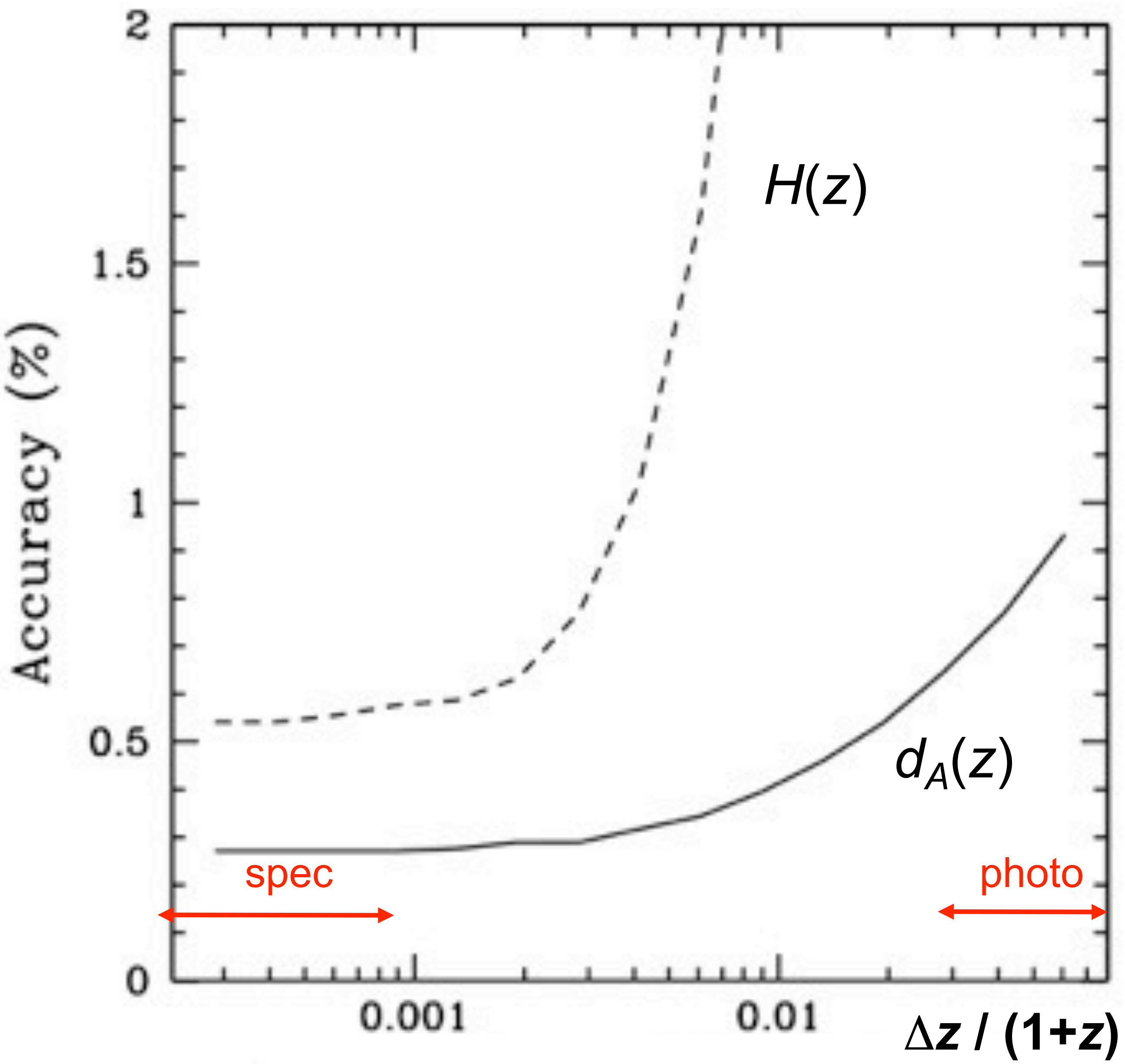
Photo-z 5-filter: Pan-STARRS*, DES*, LSST*

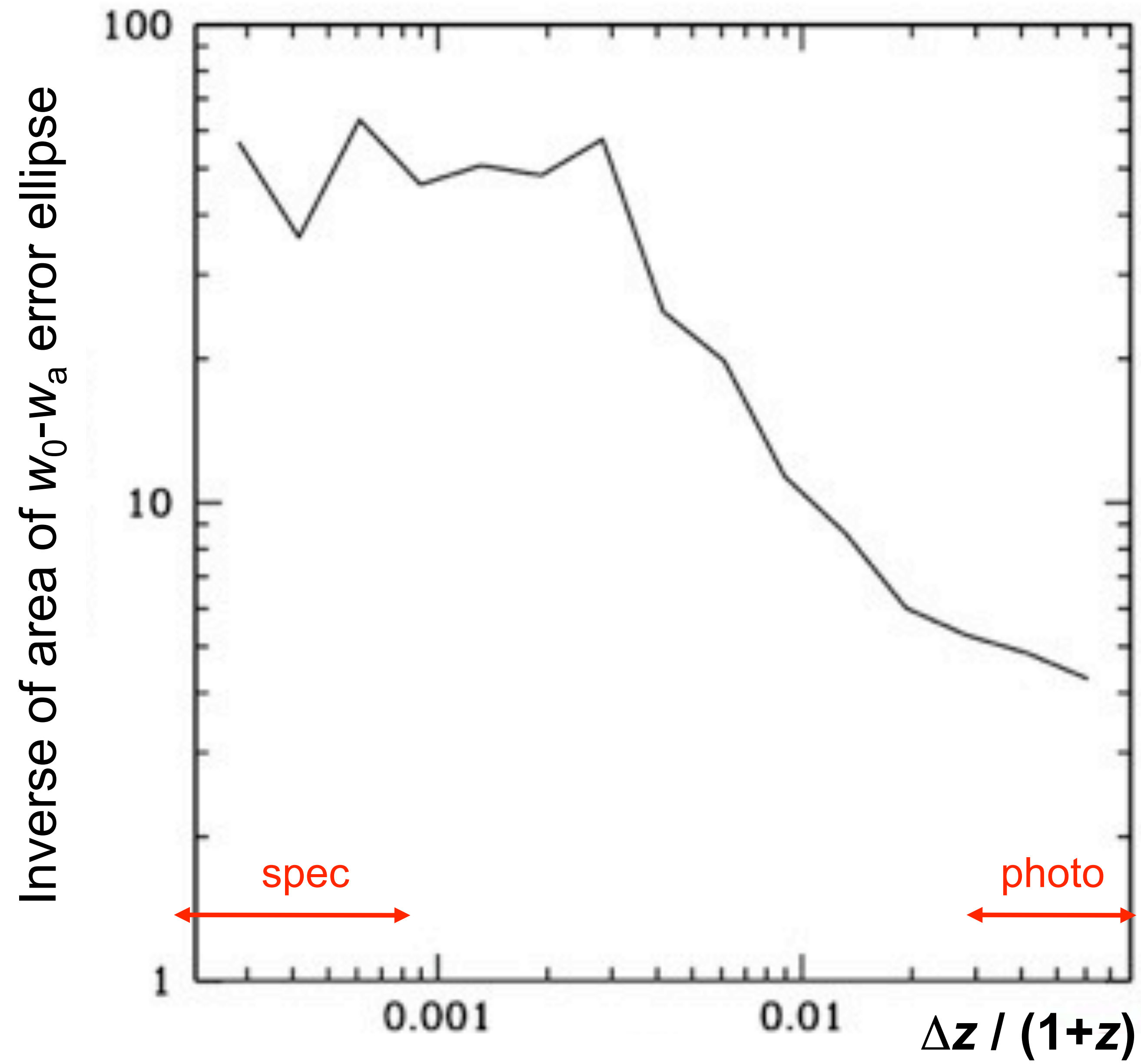
Project	Redshift	Area (deg^2)
WiggleZ	0.4-1.0	1000
HETDEX	2.0-4.0	350
WFMOS	0.5-1.3 2.3-3.3	2000 300
BOSS LRG + QSO	0.1-0.8 2.0-3.0	10000 8000
PAU-BAO	0-1	10000
Pan-STARRS*	0-1?	20000
DES*	0-1.5?	4000
LSST*	0-1.5?	20000

Requirements on Redshift Precision

$$\frac{\sigma}{P} = \sqrt{\frac{2}{n_{\rm modes}}}\left(1 + \frac{1}{P\bar{n}}\right)$$

$$n_{\rm modes} = V 4\pi k^2 \delta k / (2\pi)^3$$





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Spectroscopic accuracy is not needed: trade-off with number density

Requirements on Redshift Precision

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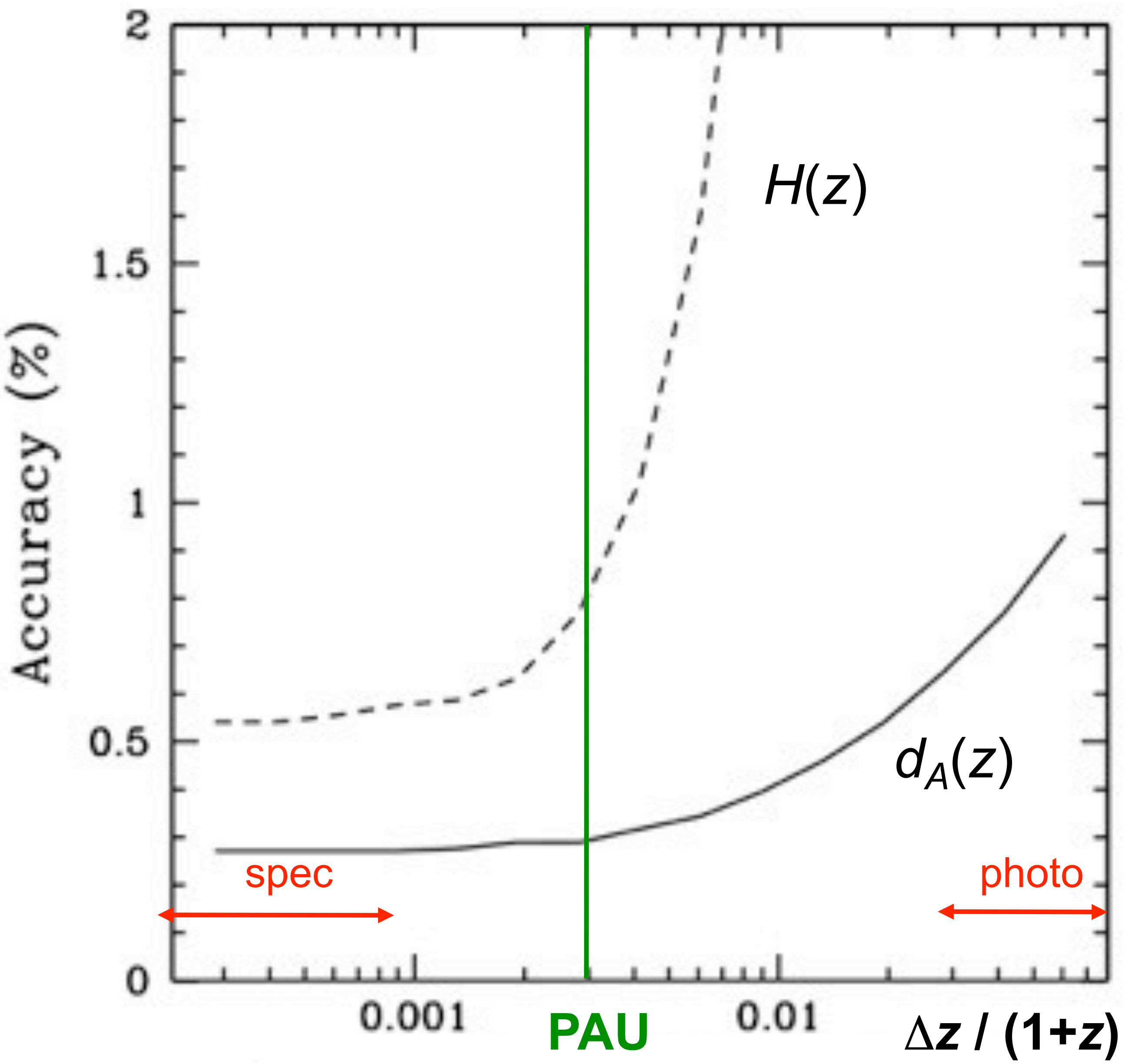
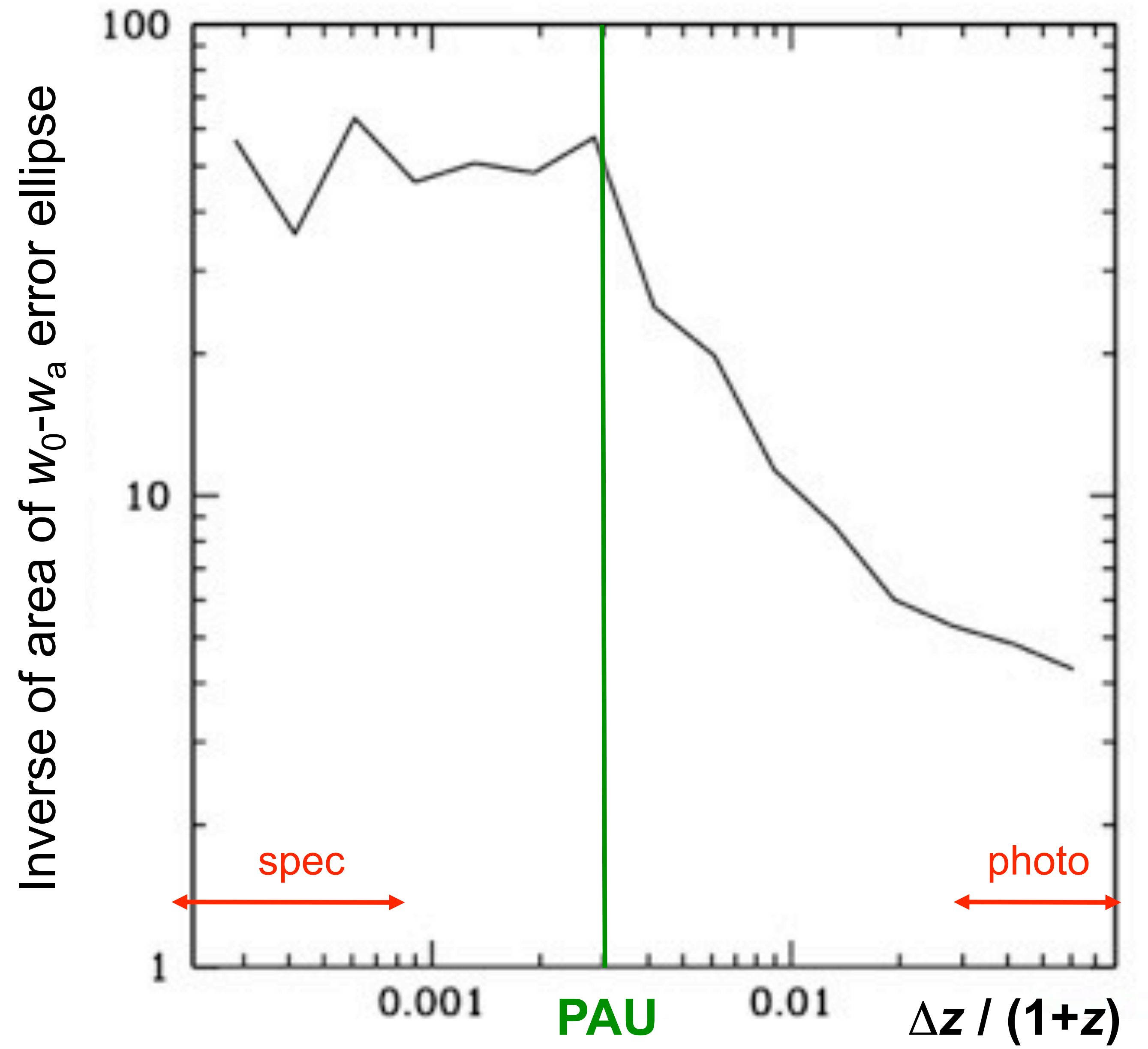




Padmanabhan

Spectroscopic accuracy is not needed: trade-off with number density

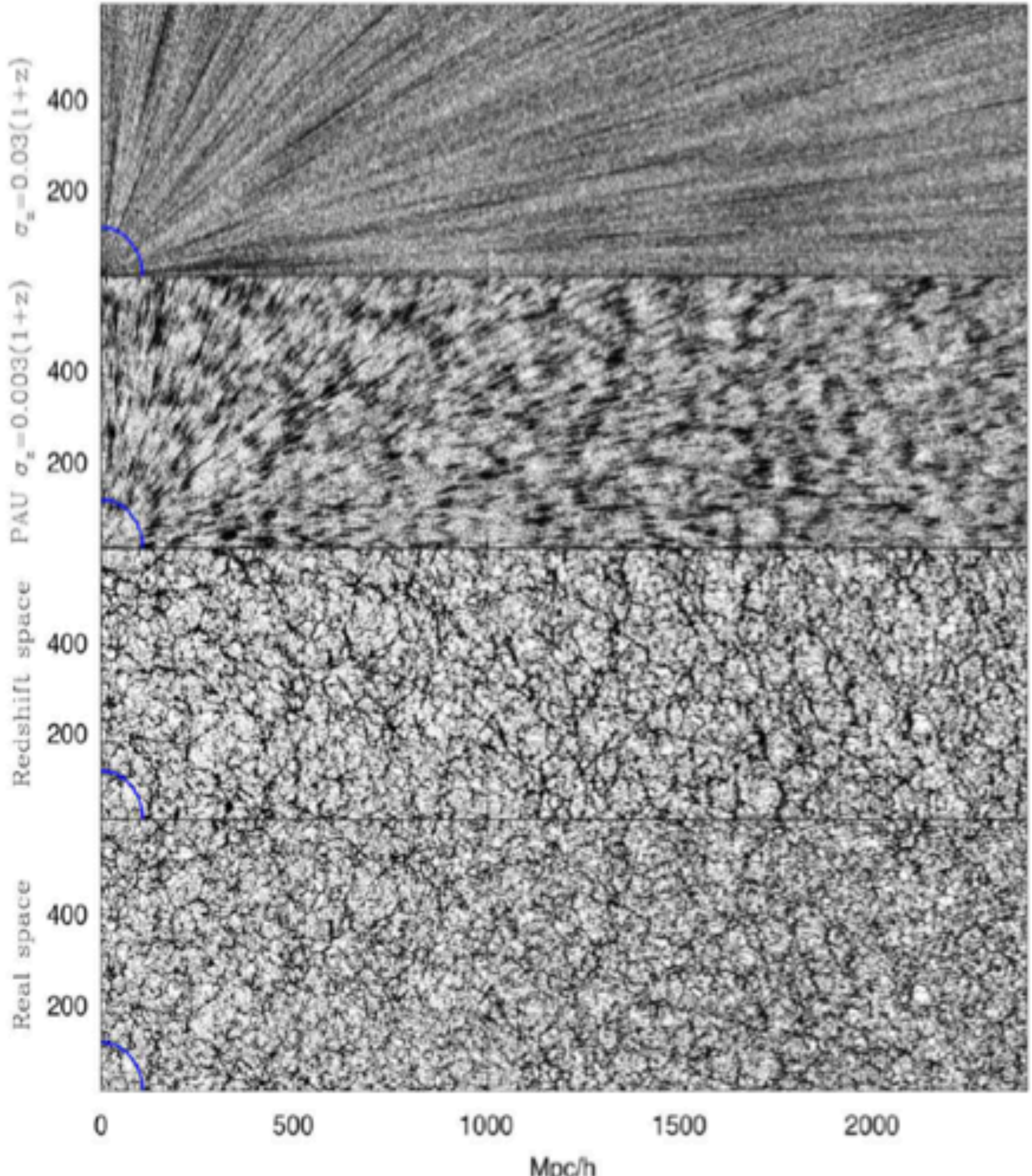
Visual illustration of the importance of z resolution

z-space, Δz = *0.03(1+z)* + peculiar velocities

z-space, Δz = *0.003(1+z)* + peculiar velocities

z-space, perfect z-resolution + peculiar velocities

Real space, perfect resolution



Galaxy Surveys

Photometric:

poor radial (redshift) resolution (~300 Mpc/h) but more Volume

DES, VISTA, Pan-STARRS, Subaru/HSC, Skymapper, LSST

PAU

Spectroscopic:

good or very good radial resolution (1-20Mpc/h), smaller Volume

WiggleZ, BOSS, e-BOSS, Subaru/Sumire, BiggBOSS, DESpec, HETDEX, SKA, VISTA/Spec

SPADES network

Surveys for Physics of Acceleration and Dark Energy Science

to participate in DES, PAU & Euclid

(MICE/Planck, DESpec, e-BOSS)

Senior Scientists
Post-docs
Engineers
Doctoral Students
Technicians

CIEMAT

E. Sánchez, F. J. Rodríguez, I. Sevilla
J. Castilla, J. de Vicente R. Ponce, F. J. Sánchez

ICE/IEEC

F. J. Castander, E.Gaztañaga, P. Fosalba, A. Bauer, C. Bonnett, M.Crocce, S. Farrens, S.Jouvel R. Casas, J. Jiménez, F. Madrid, S. Serrano
J. Asorey, M. Eriksen, A. Izard, K. Hoffman, C.López, A. Pujol

IFAE

E. Fernández, R. Miquel, C. Padilla, A. Pacheco, (S. Heinis, starting in September)
O. Ballester, L. Cardiel, F. Grañena, C. Hernández, L. López, M. Maiorino, C. Pio
P. Martí, C. Sánchez C. Arteche, J. Gaweda

PIC

M. Delfino, V. Acín, J. Carretero, M. Caubet, J.Flix, C. Neissner, P. Tallada, N. Tonello, E. Planas

UAM

J. García-Bellido, D. Sapone, S. Nesseris Alicia Bueno, David Alonso

DES= Dark Energy Survey
Spain: CIEMAT, ICE/IEEC, IFAE, UAM

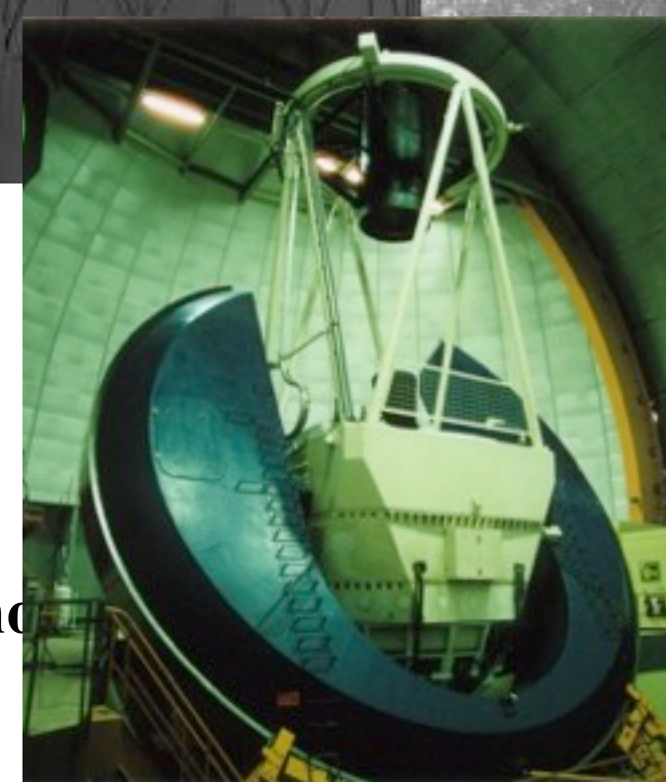
DARK ENERGY SURVEY

- Study Dark Energy using
  4 complementary* techniques:
  I. Cluster Counts
  II. Weak Lensing
  III. Baryon Acoustic Oscillations
  IV. Supernovae

- Two multiband surveys:
  5000 deg^2 *g, r, i, Z, Y* to *i~24*
  9 deg^2 repeat (SNe)

- Build new 3 deg^2 camera
  and Data management system
  Survey 30% of 5 years
  Response to NOAO AO

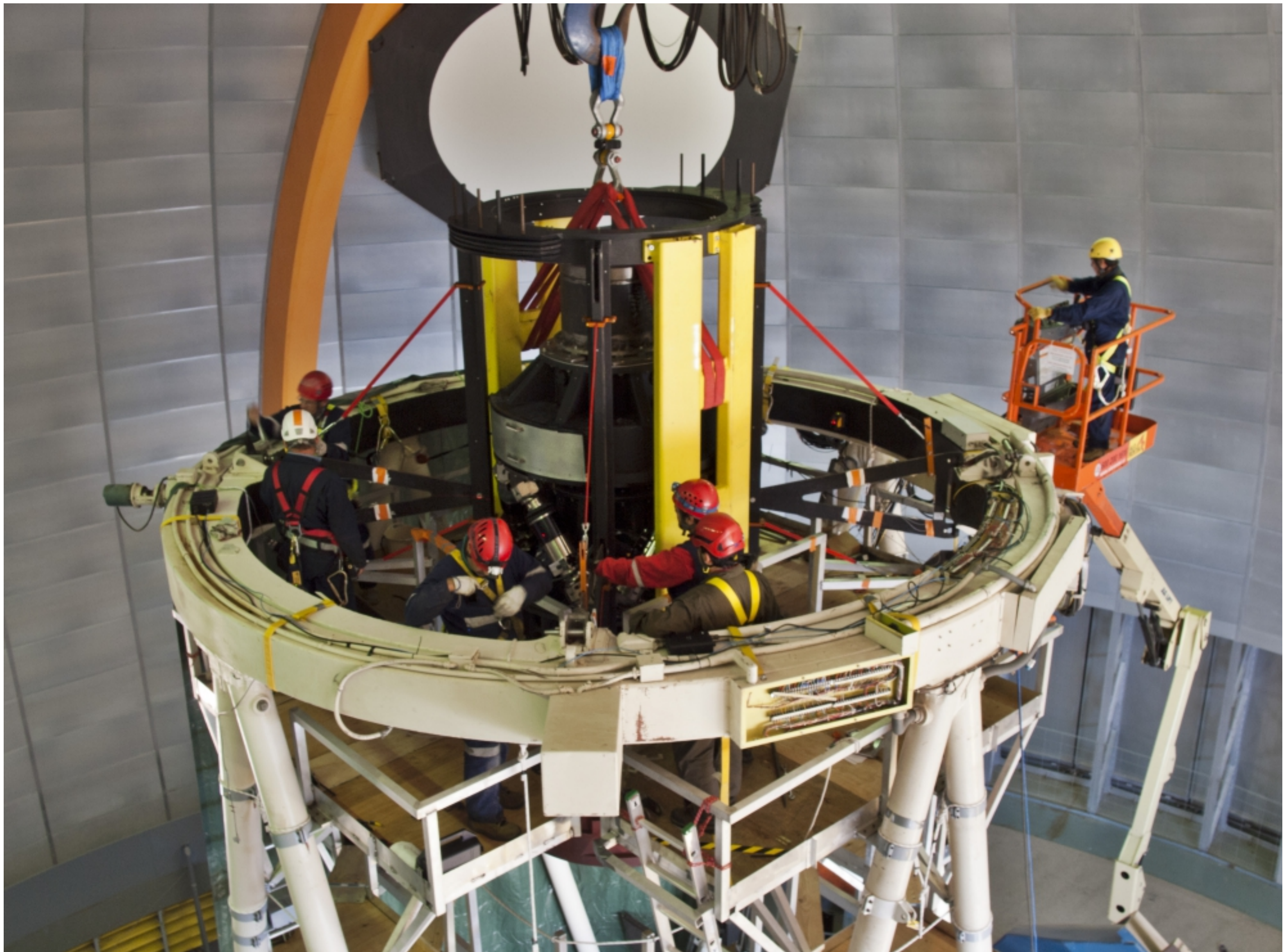
DES Forecast: FoM =4.6x



Blanco 4m Telescope Cerro-Tololo Observatorio Inter-Americano CTIO

Dark Energy Survey Status

DARK ENERGY SURVEY



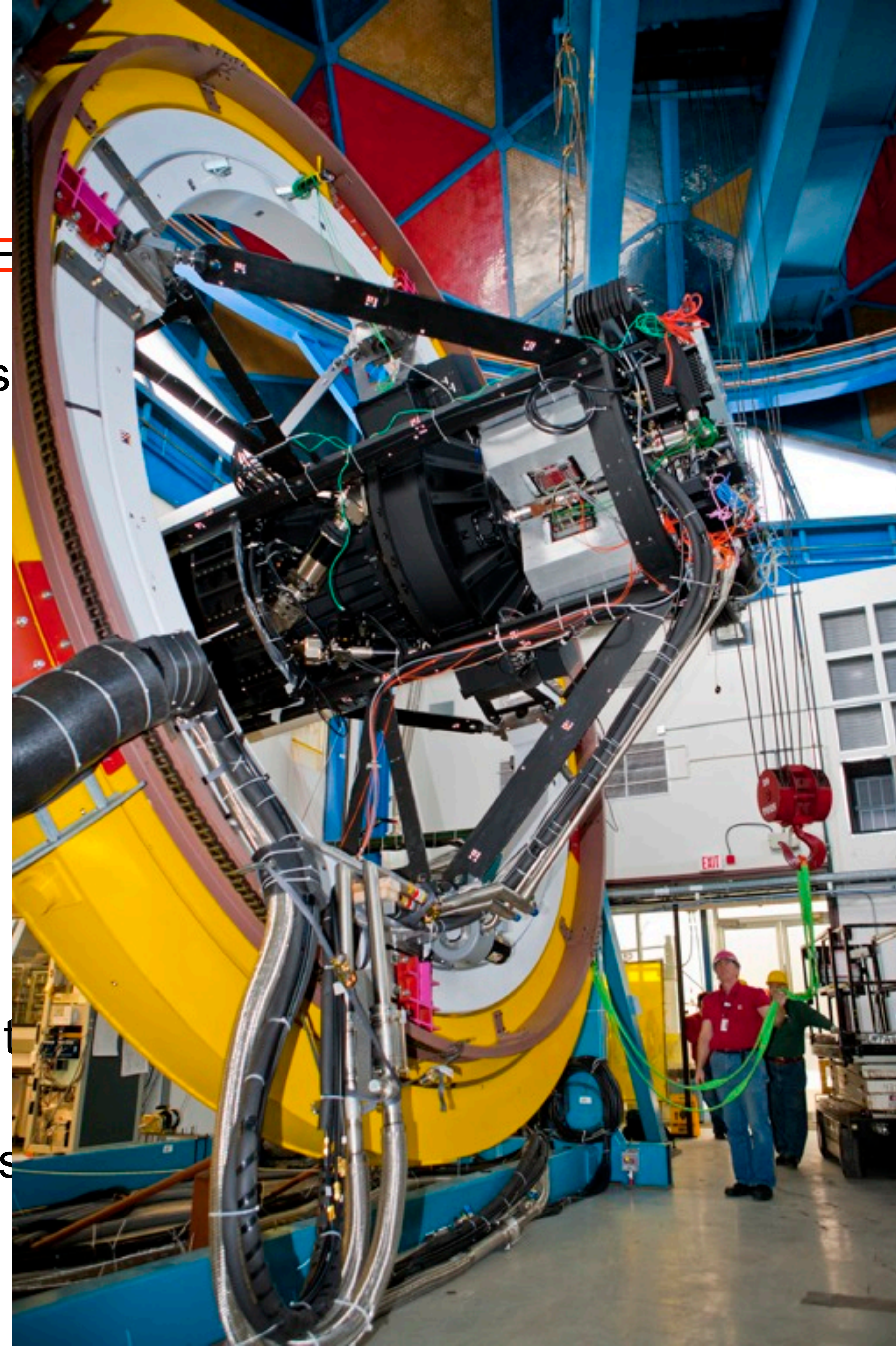
16th DES Collaboration Meeting, Munich, May 2012

Dec. 2010

DARK ENERGY SURVEY

- Most DECam systems complete and full system tests (except the optics) on telescope simulator

  Imager with 28 CCDs installed, Filter changer, shutter, hexapod, LN2 cooling, CCD readout crate cooling, all exercised in multiple positions.
- Mock Observing Feb. 2011
- Rest of 2011:
  - Packing, shipping, checkout in Chile
  - Installation of science CCDs in imager



DARK ENERGY SURVEY

I. Clusters and Dark Energy

- Requirements
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy that can be used as cluster mass estimate

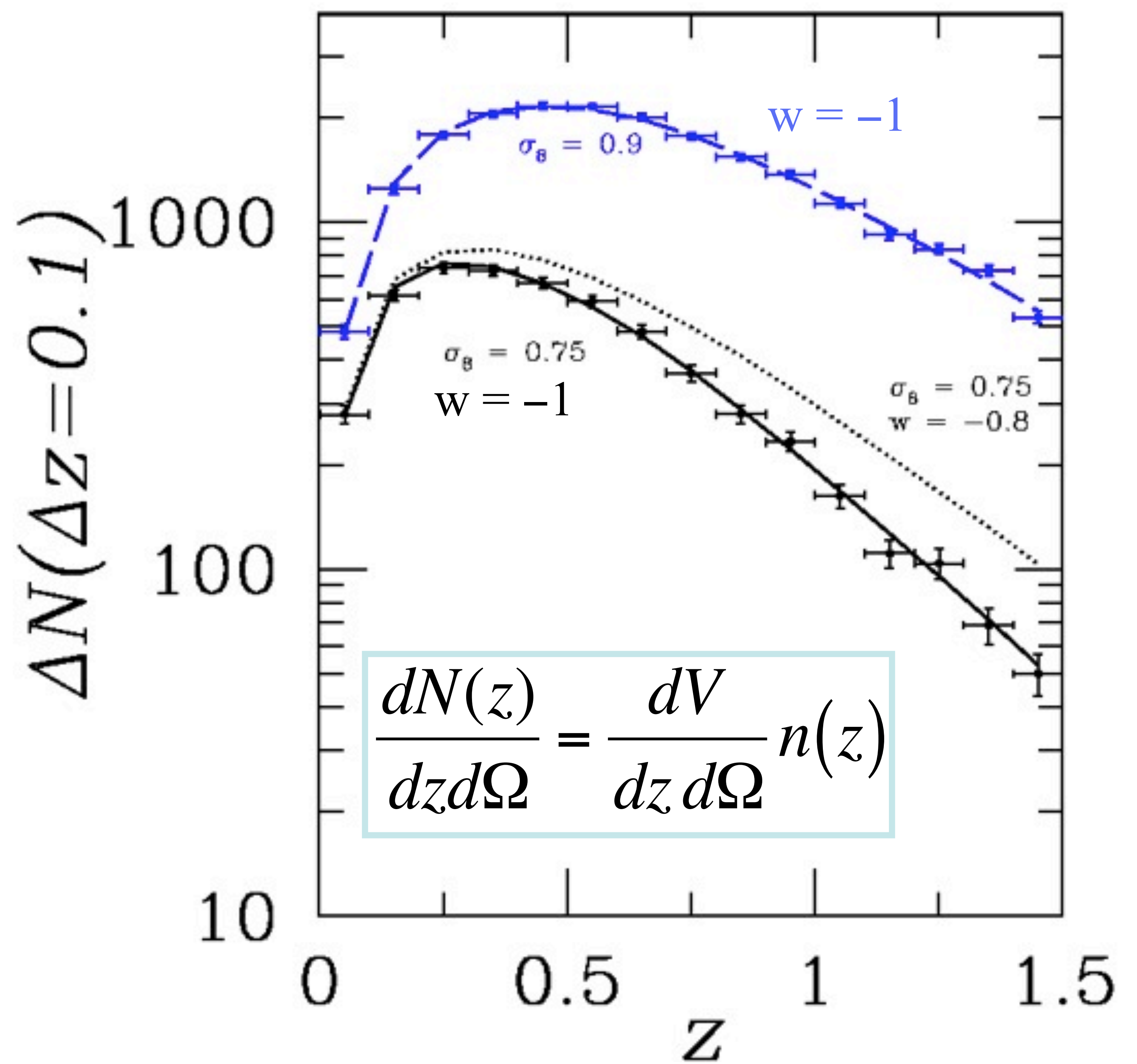
     g(O|M,z)

Primary systematics:

Uncertainty in *g* (bias & scatter)

Uncertainty in *O* selection fn.

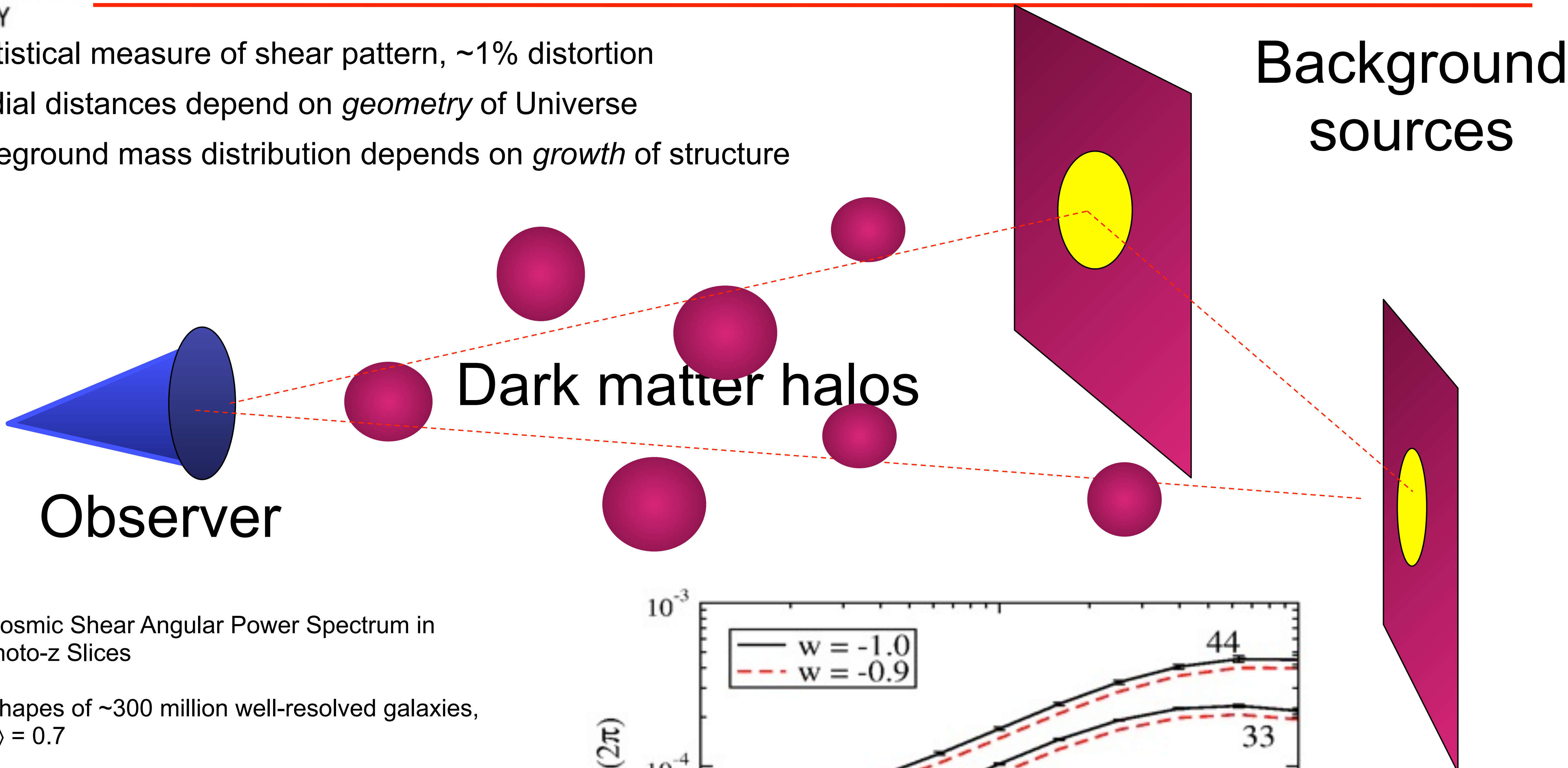
Number of Clusters vs. Redshift



II. Weak Lensing: Cosmic Shear

DARK ENERGY SURVEY

- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

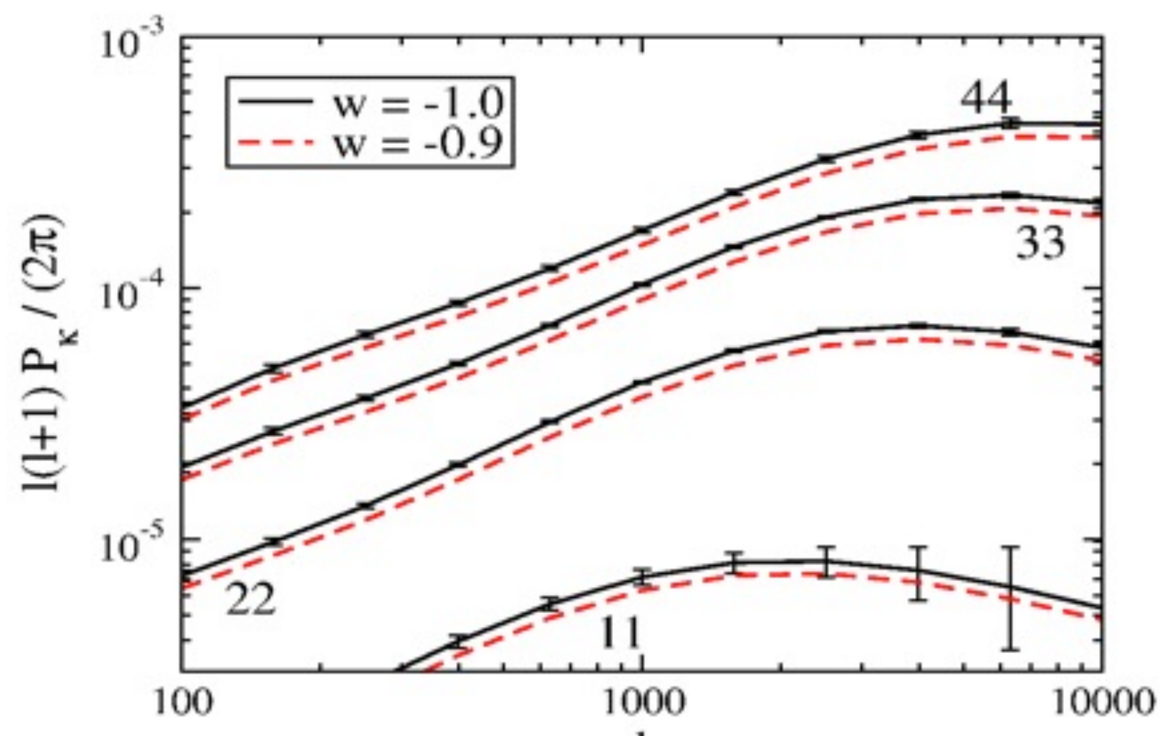


•Cosmic Shear Angular Power Spectrum in Photo-z Slices

•Shapes of ~300 million well-resolved galaxies, $\langle z \rangle = 0.7$

•Primary Systematics:
photo-z's,
PSF anisotropy,
shear calibration

•Extra info in bispectrum & galaxy-shear: robust

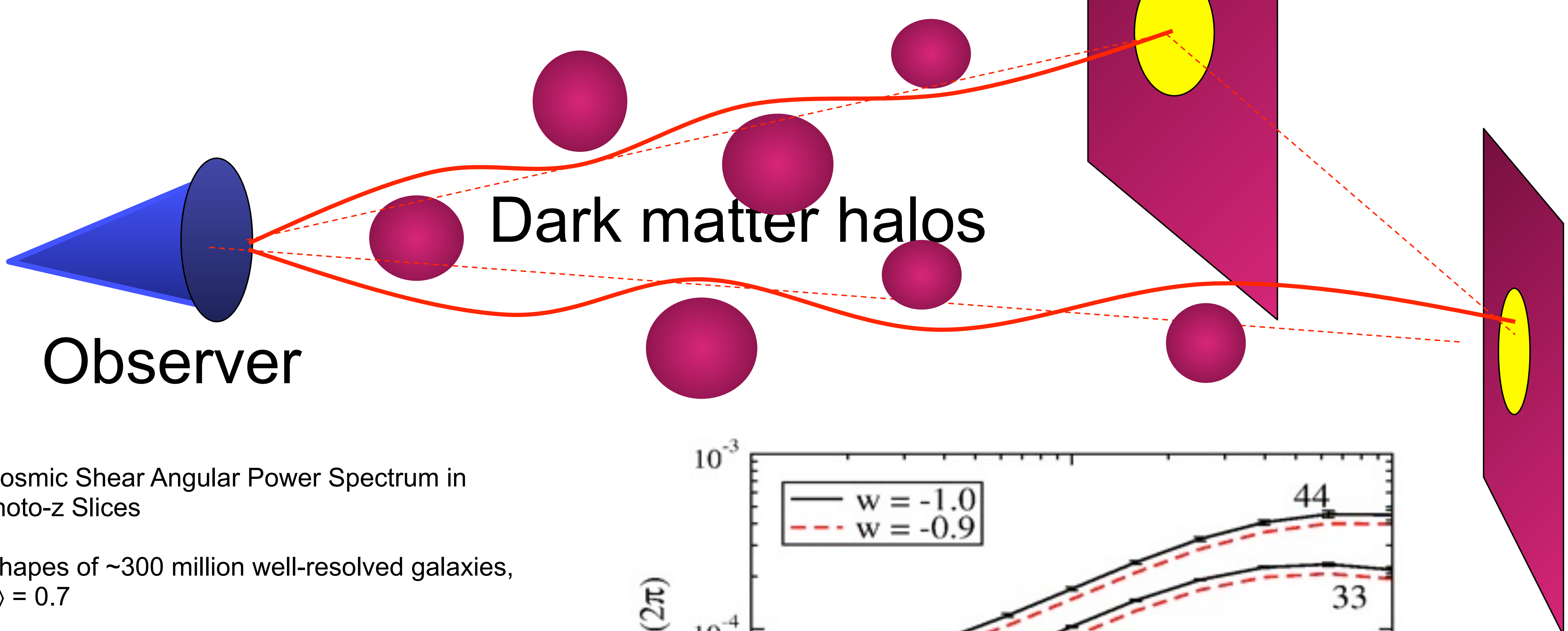


II. Weak Lensing: Cosmic Shear

DARK ENERGY SURVEY

- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

Background sources



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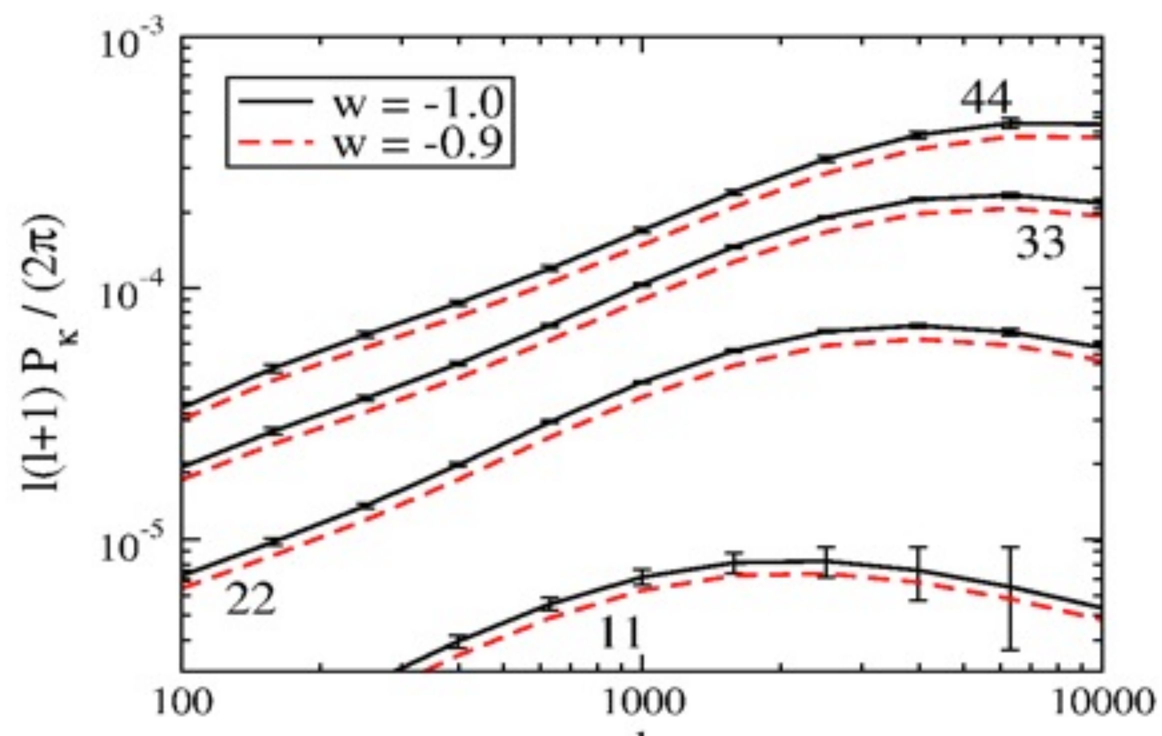


$$\frac{d^2\delta_k}{d\tau^2} + \mathcal{H}\,\frac{d\delta_k}{d\tau} - \left(\frac{3}{2}\,\mathcal{H}^2\,\Omega_m - k^2\,v_s^2\right)\,\delta_k = 0$$

III. Baryon wiggles

Angular

Spectrum

For single redshift slice:

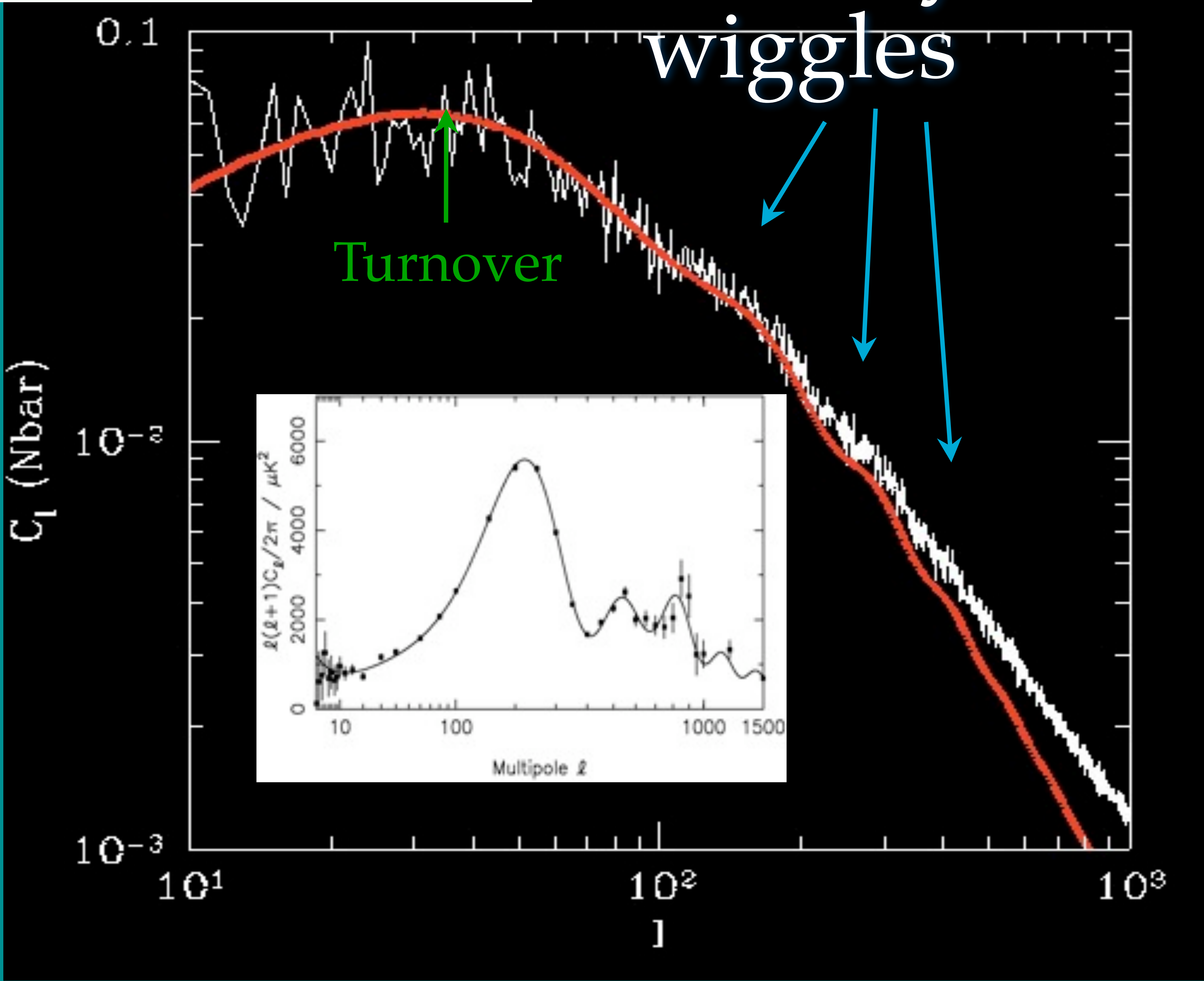
z =0.9-1.0

Of MICE

Simulation

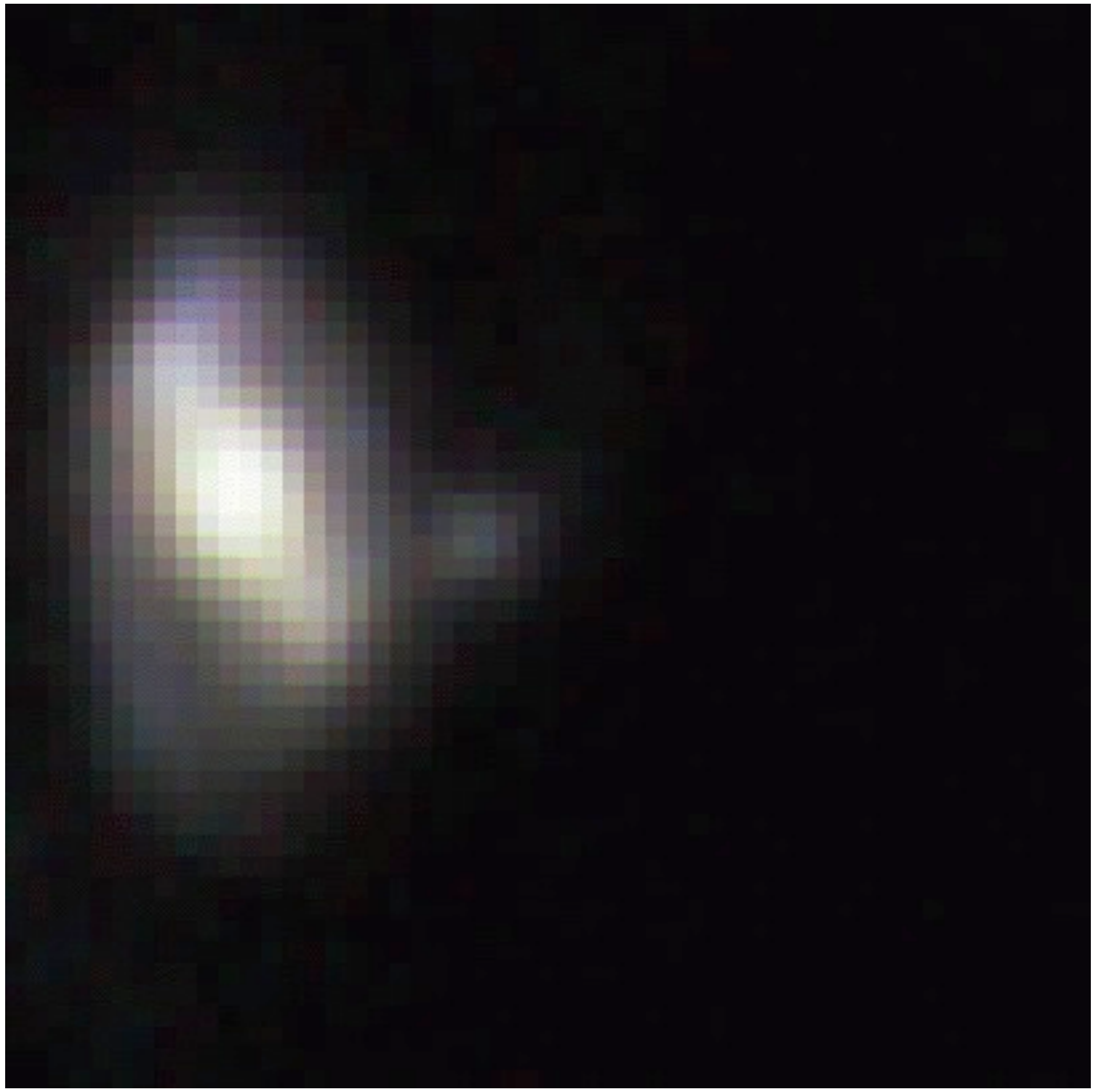
www.ice.cat/mice

DARK ENERGY Survey



IV. Supernovae

- Geometric Probe of Dark Energy
- Baseline: repeat observations of 9 deg^2 using 10% of survey time: 5 visits per lunation in *riz*
- ~1100-1400 well-measured SN Ia lightcurves to z~1
- Larger sample, improved *z*-band response (fully depleted CCDs) compared to ESSENCE, SNLS: reduce dependence on rest-frame *u*-band and Malmquist bias
- Spectroscopic follow-up of large SN subsample +host galaxies (LBT, Magellan, Gemini, Keck, VLT, …) e.g., focus on ellipticals (low dust extinction)



SDSS

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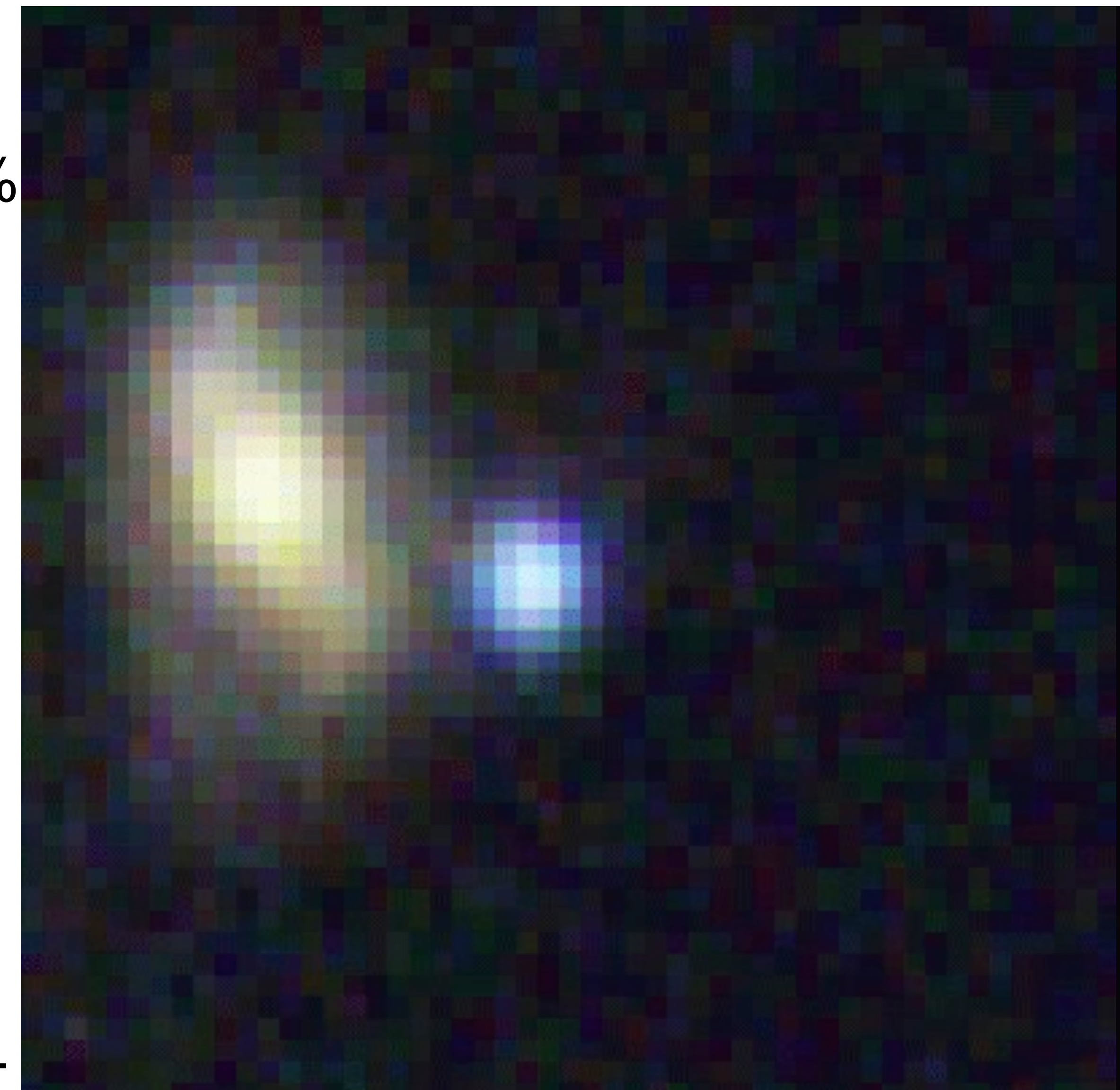

SDSS

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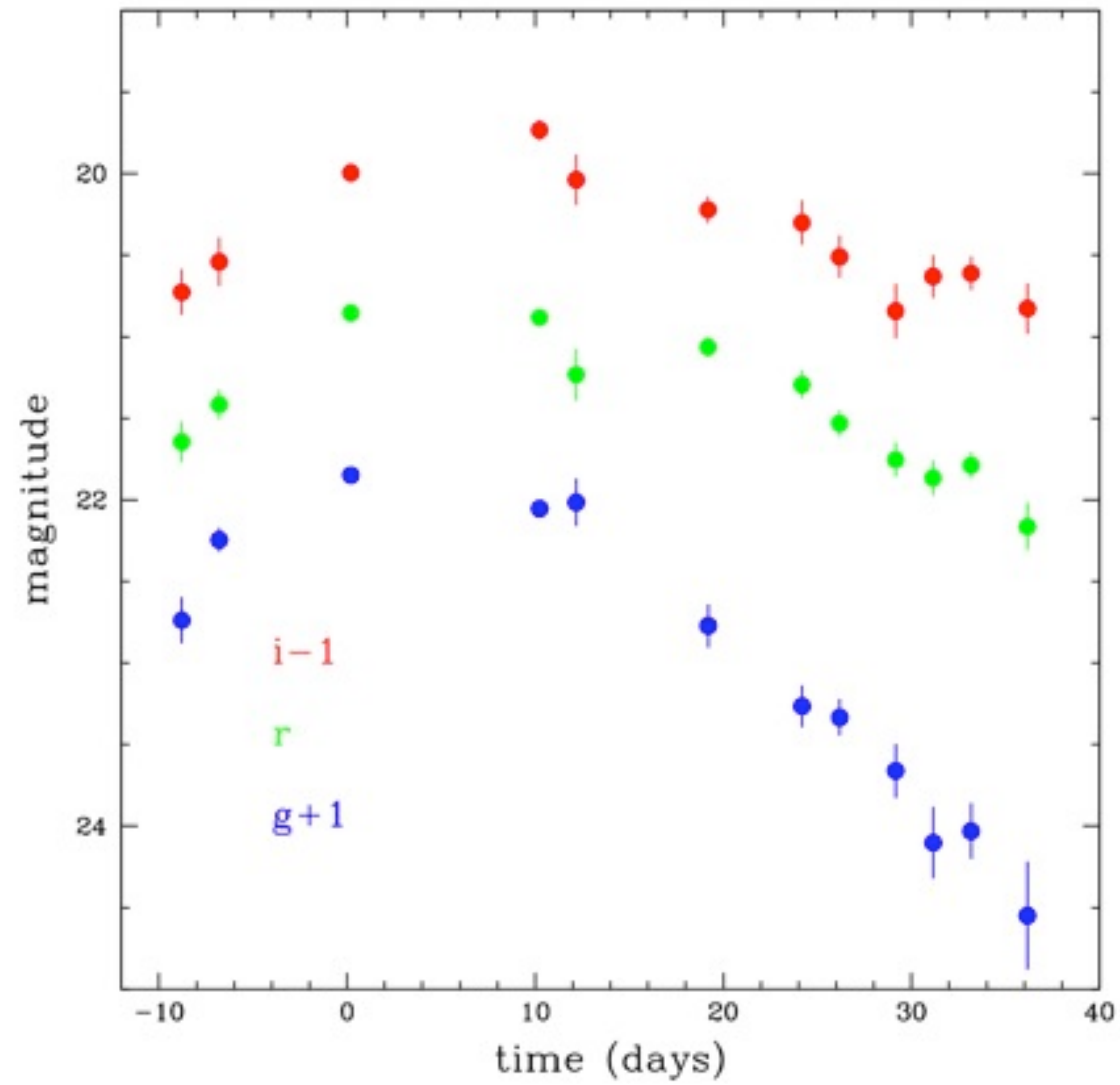


SDSS

DES Forecasts: Power of Multiple Techniques

DARK ENERGY SURVEY

Assumptions:

Clusters:

σ_8=0.75, z_{max}=1.5,

WL mass calibration

(no clustering)

BAO: ℓ_{max}=300

WL: ℓ_{max}=1000

(no bispectrum)

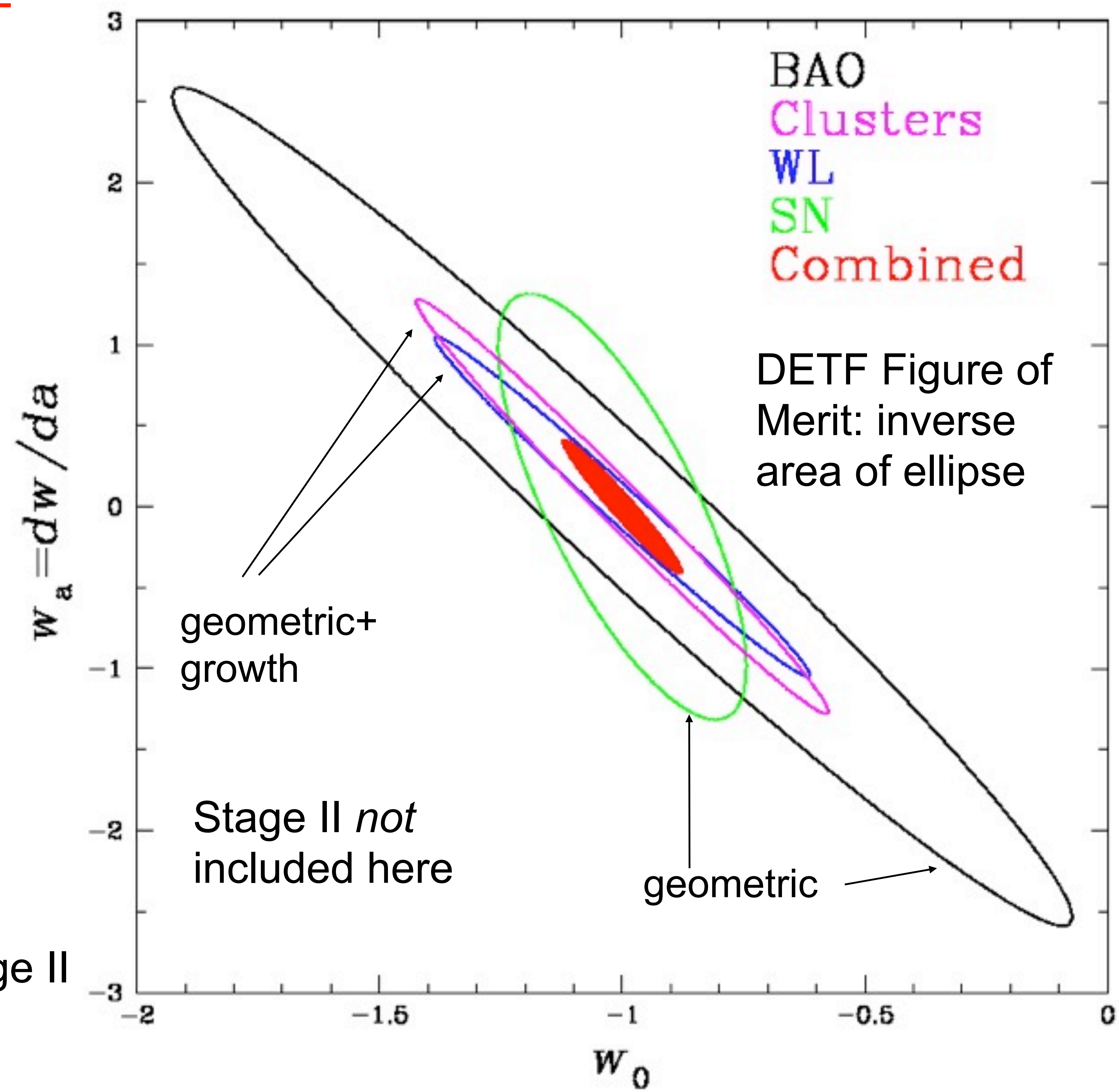
Statistical+photo-z systematic errors only

Spatial curvature, galaxy bias marginalized,

Planck CMB prior

Factor 4.6 improvement over Stage II

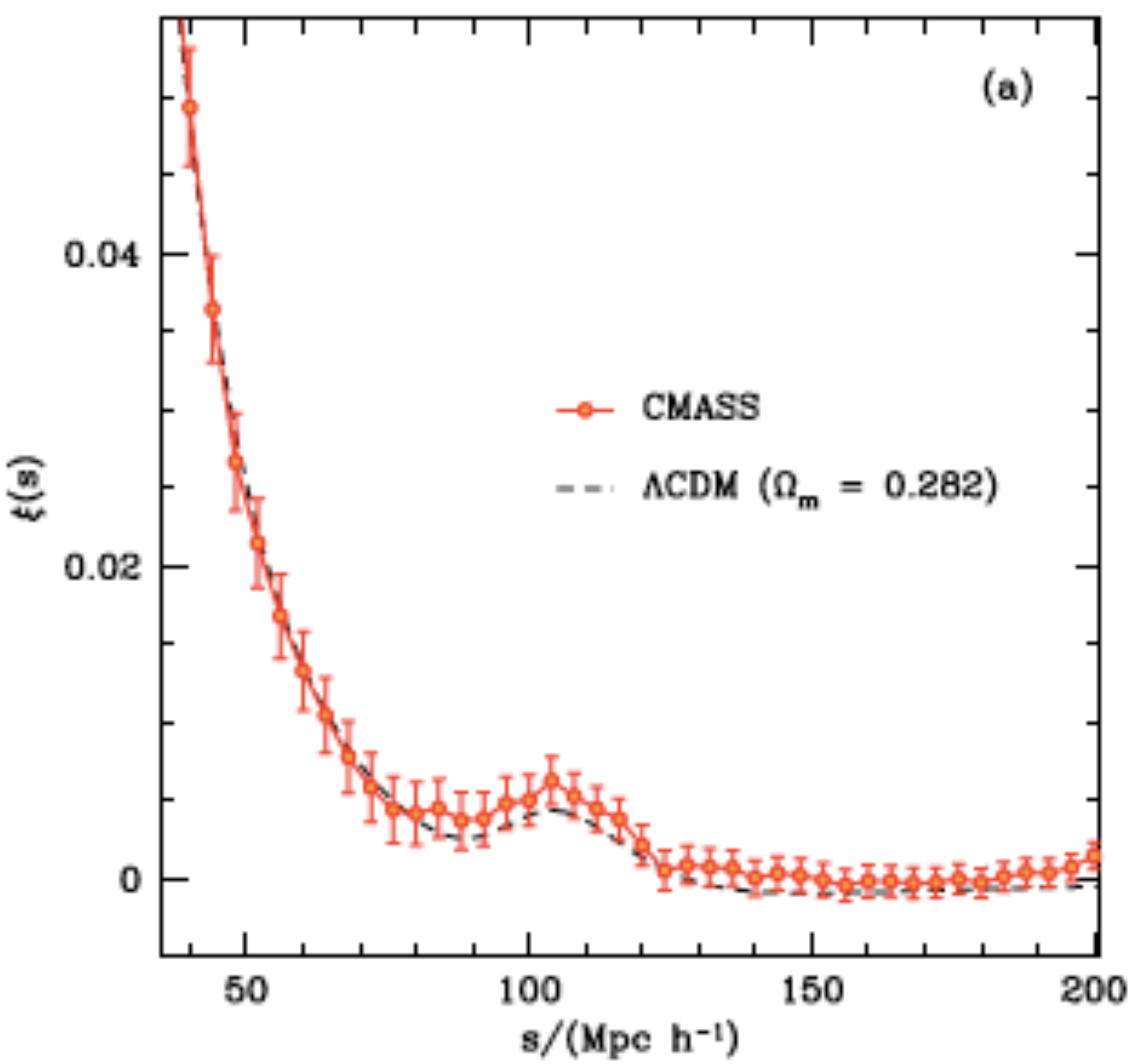
$w(z) = w_0 + w_a(1-a)$ 68% CL

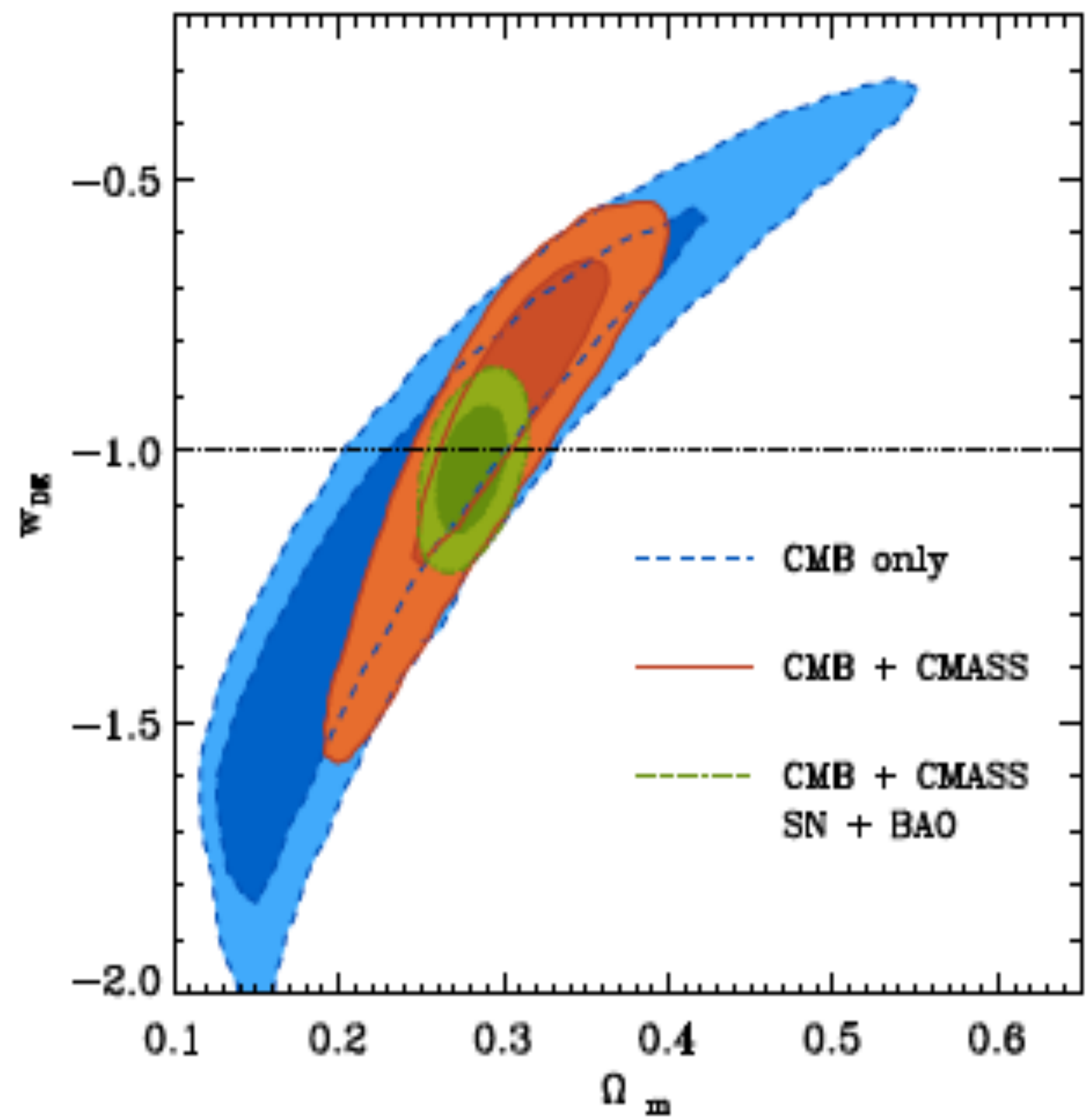


Concluding Remarks

- **DES project** has made great progress over the last year, though with some schedule slippage.
- **DECam** complete.
- **Installation** well underway.
- **Commissioning and transition to survey operations** this year: commissioning and operations plans exist, details being refined, Year-1 science program/strategy mature & flexible.
- **Data Management system** has made good recent progress, but needs support to deliver on science requirements and operational readiness; will need to phase in functionality.
- **SWG activity** continuing to ramp up and will be critical during commissioning, Science Verification, and early operations.
- We will soon have a fantastic instrument on a world-class telescope and embark on a great, discovery-filled survey.

New Results - BOSS





basic parameters can be specified by $\Omega_m = 0.285 \pm 0.009$, $100\,\Omega_b = 4.59 \pm 0.09$, $n_s = 0.961 \pm 0.009$, $H_0 = 69.4 \pm 0.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\sigma_8 = 0.80 \pm 0.02$. The

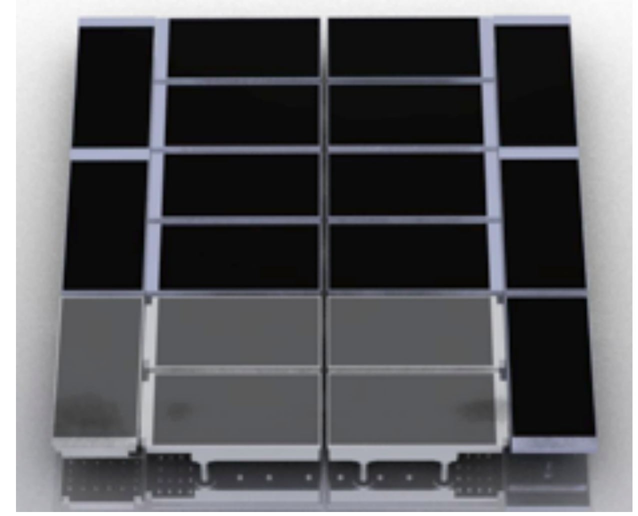
w =-1.03 +- 0.07

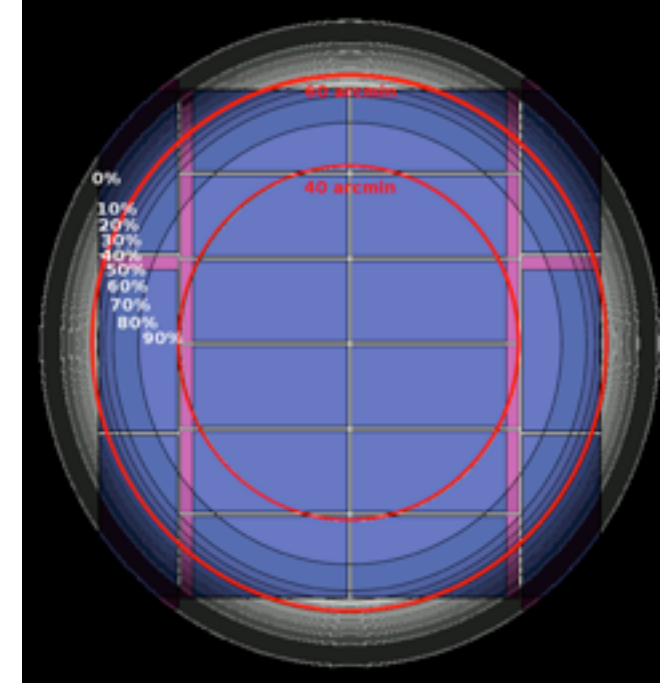
Sanchez et al. 2012

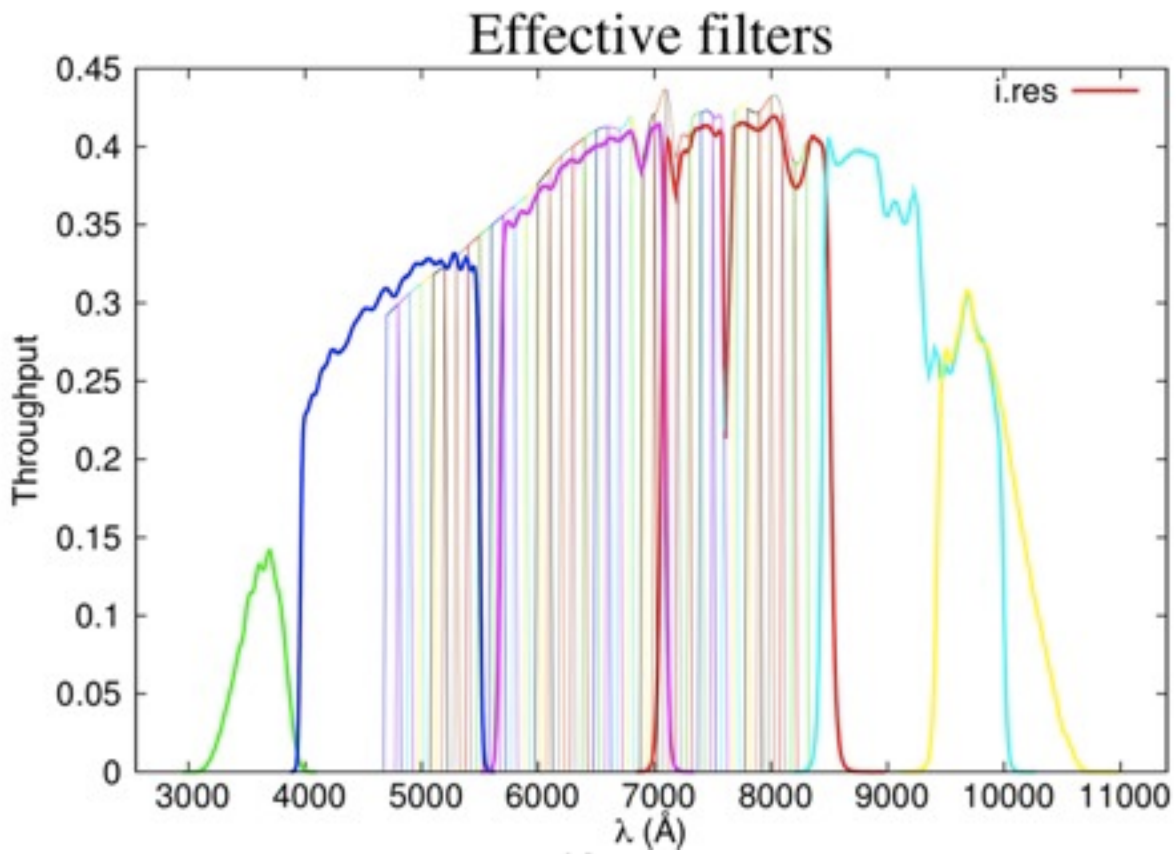
Spain lead (SPADES)

PAU Survey @WHT

18+4 Hamamatsu CCD





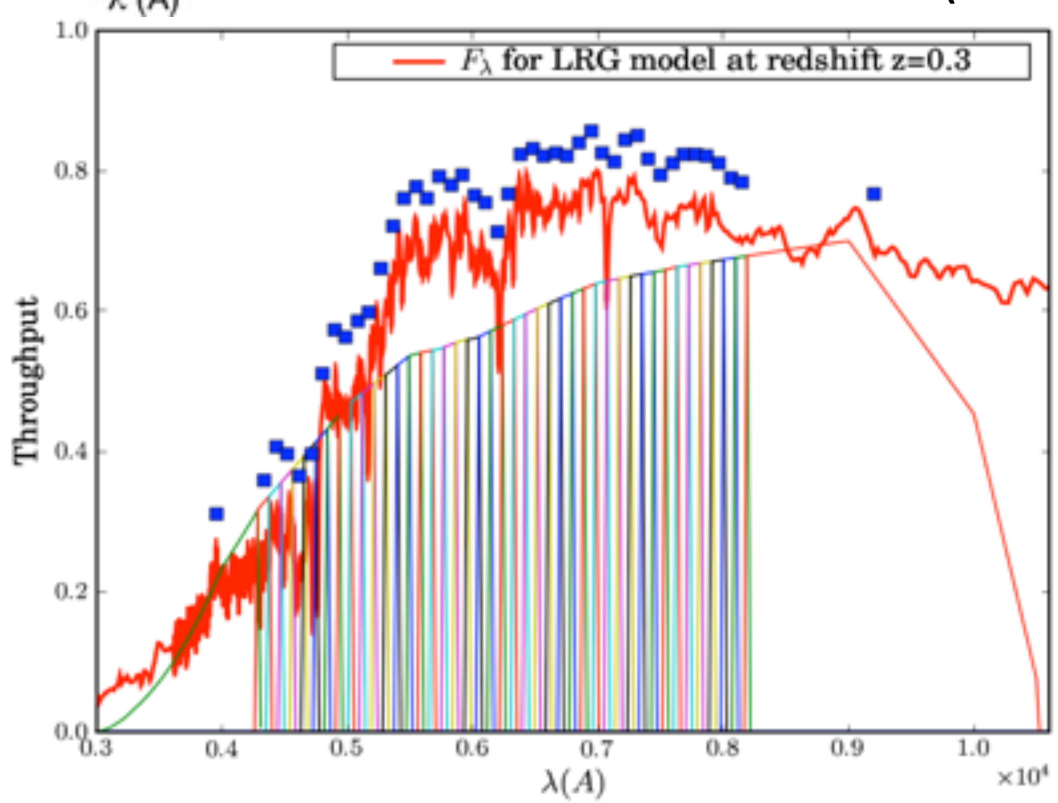


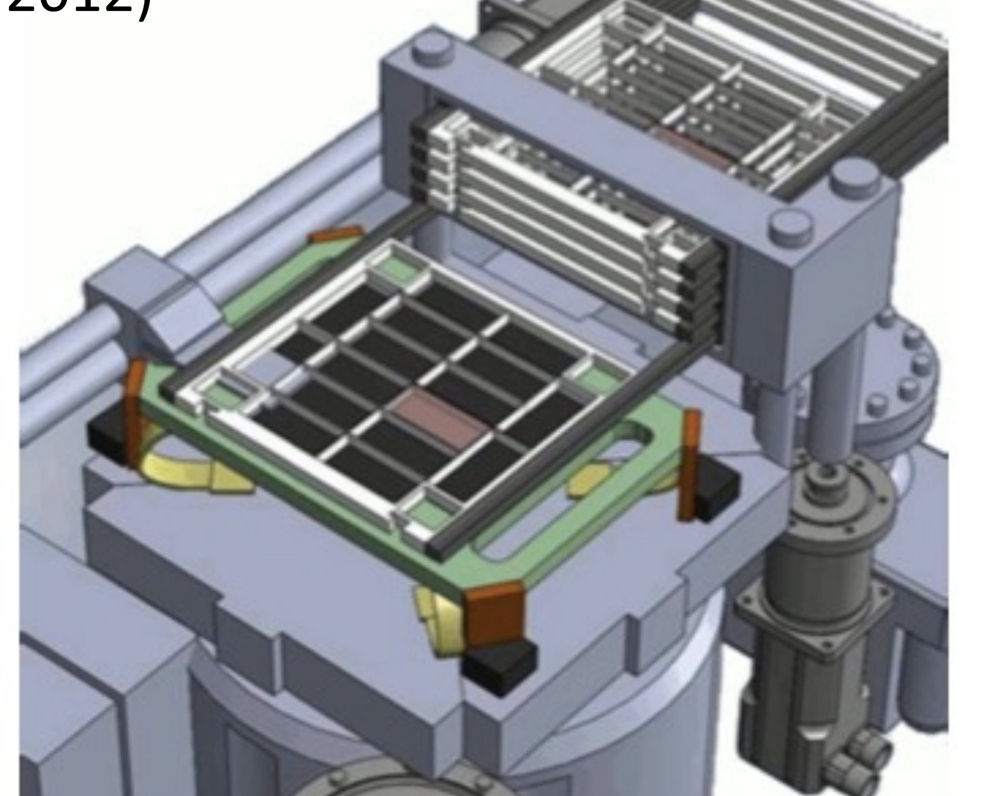
In 1 night can do 2(4) sqr.deg. to i~22.5
in 36 narrow + 6x2 broad (i~24 survey)
To get R=1/100 spectra (900 Km/s)
for 30,000 galaxies (15,000/sd)
And R=1/10 photo-z for 120,000 galaxies
No galaxy selection effects
(end 2012)

Simultaneous
Photometric (i~24)
& Spectroscopic (i~22.5)
Surveys

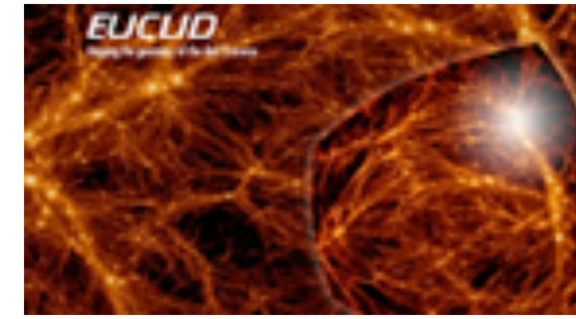
Photo-z of 0.03/0.003
(10/100Mpc)

For linear P(k)
reconstruction

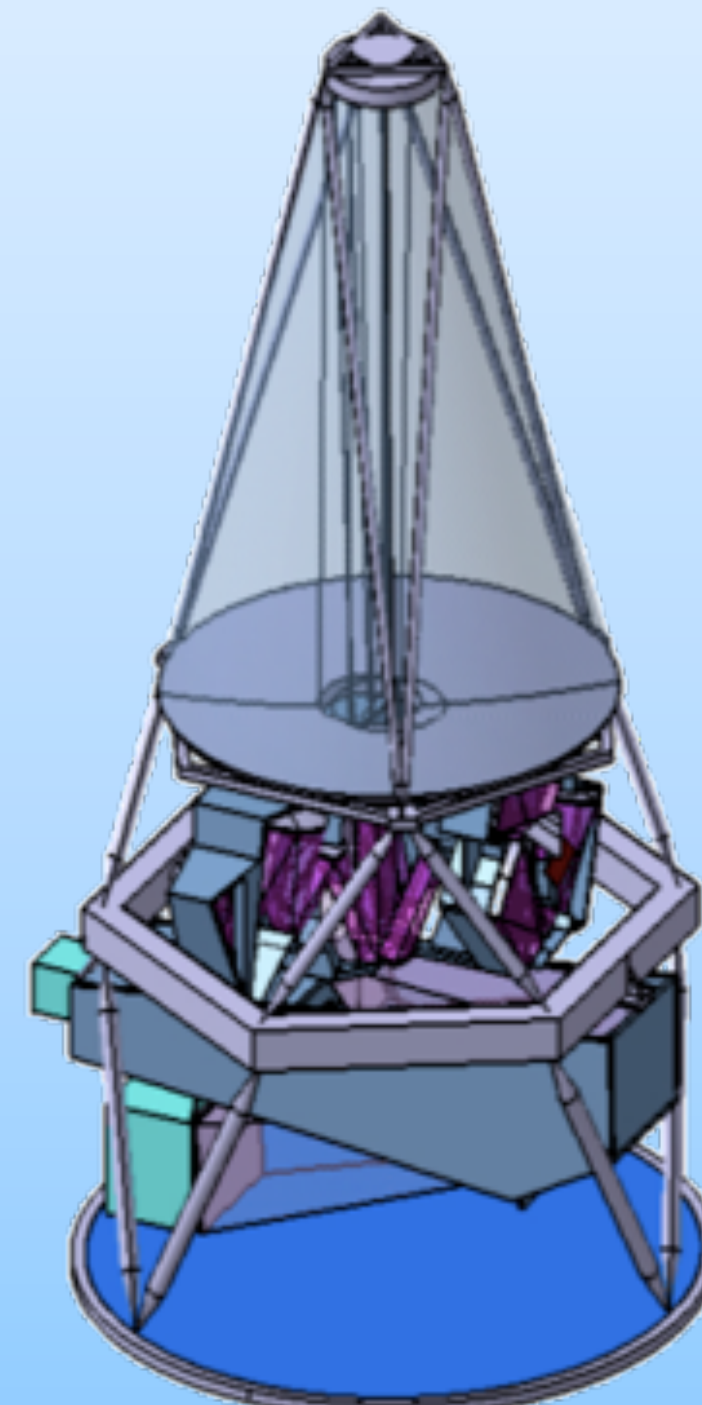




Euclid



- ESA Cosmic Vision satellite proposal (600M€, M-class mission)
- 5 year mission, L2 orbit
- 1.2m primary mirror, 0.5 sq. deg FOV
- $\Omega = 20{,}000 deg^2$ imaging and spectroscopy
- slitless spectroscopy:
  - 100,000,000 galaxies (direct BAO)
  - ELGs (H-alpha emitters): z~0.5-2.1
- imaging:
  - deep broad-band optical + 3 NIR images
  - 2,900,000,000 galaxies (for WL analysis)
  - photometric redshifts
- Space-base gives robustness to systematics
- Final down-selection due mid 2011
- nominal 2017 launch date
- See also: LSST, WFIRST



Problem Using Galaxy Surveys:

they are biased tracers of DM

Possible Solutions:

Avoid bias:

CMB, SNIa

Clusters, BAO

Use redshift space distortions <= only sensitive to ratios

Do weak lensing (to avoid bias) <= is 2D

Measure bias

learn about galaxy formation => put priors on bias

higher order correlations

Combine the best of both: Do cross-correlations

astro-ph:1109.4852

Forecast: Planck+SNII priors

5000 sq.deg.

$\mathrm{FoM}_{w\gamma} \times 10^3$	RSD	RSD +BAO	WL Shear-Shear	Galaxy-Galaxy (including magnification to measure bias)	Galaxy-Galaxy WHEN BIAS IS KNOWN
Photometric (i<24)			**3.2**	**0.3**	**8.4**
Spectroscopic (i<22.5)	**0.5**	**2.7**		**0.1**	**17**

Motivation to learn about bias

Cosmology with Galaxy Clustering

Focus here only on large scales, where bias is only weaky no-linear (and r~1) but evolves with redshift and luminosity b=b(z)

1. Galaxy Clustering 2pt: 3D, all info but biased

2. Galaxy Clustering 3pt: 3D (bias can be roughly measured)

3. Weak Lensing: 2D (unbiased but degenerate)

4. Redshift Space Distortions: ratios, (unbiased but degenerate)

5. BAO: 1.5 D (unbiased)

Combine (cross-correlate) Photometric & Spectroscopic Surveys

astro-ph:1109.4852

4. Redshift Space Distortions

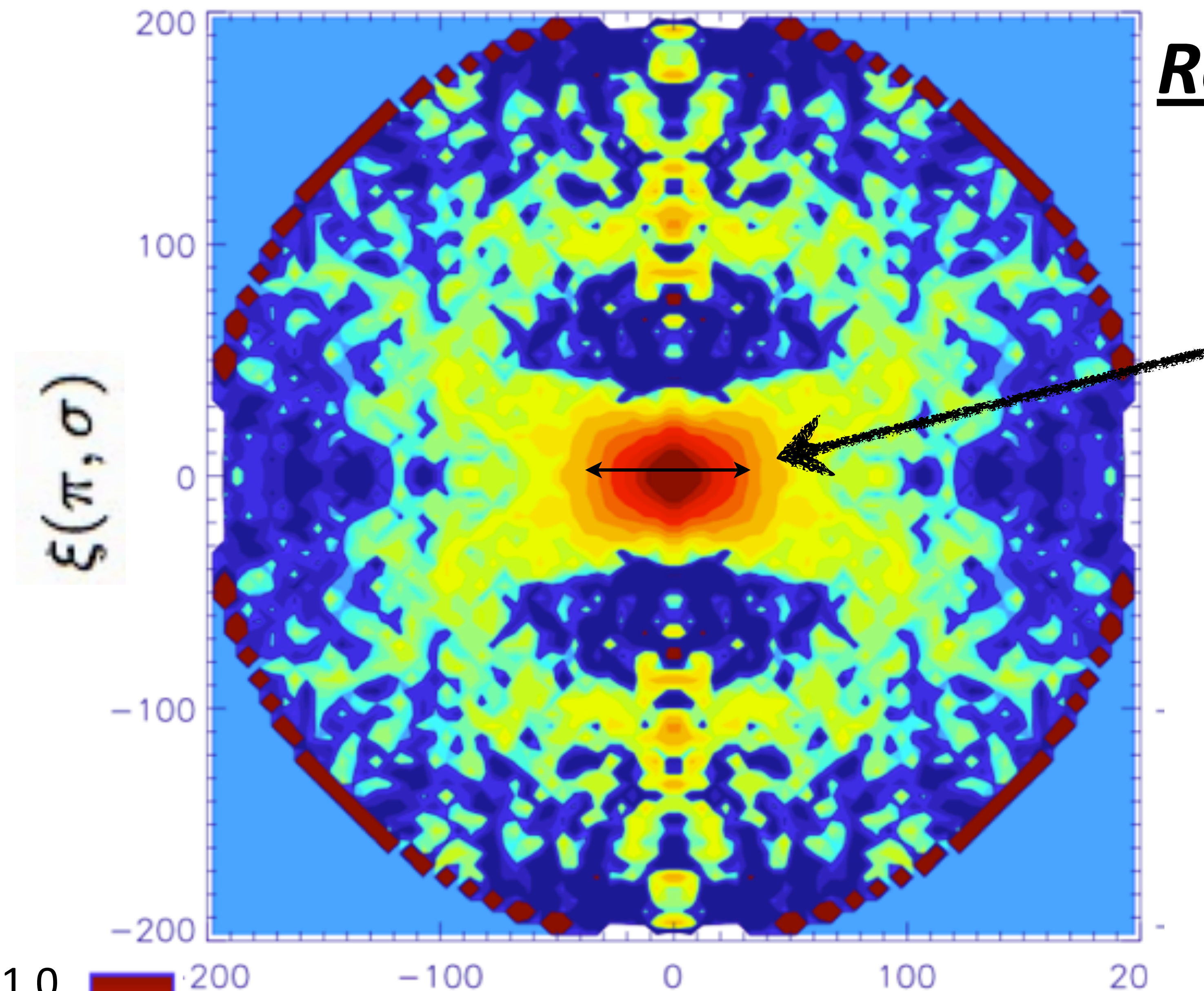
- Depends on bias
- But also has a term that only depends on velocity divergence
- f can be separated by comparison of transverse to radial modes

5. BAO (Baryon Acoustic Oscillations)

- Independent on bias
- 1-2 D

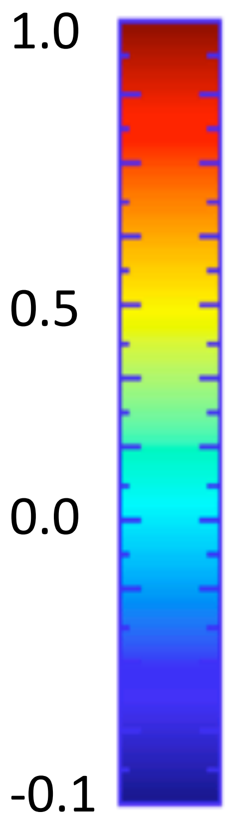
Redshift Space Distortions (RSD)

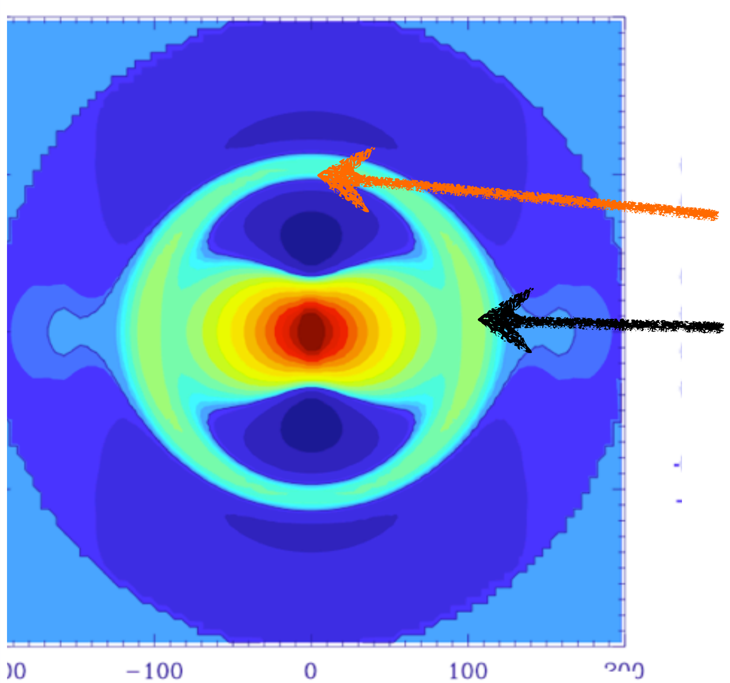
$$\delta_g(k,\mu) = (b + f\mu^2)\delta(k)$$

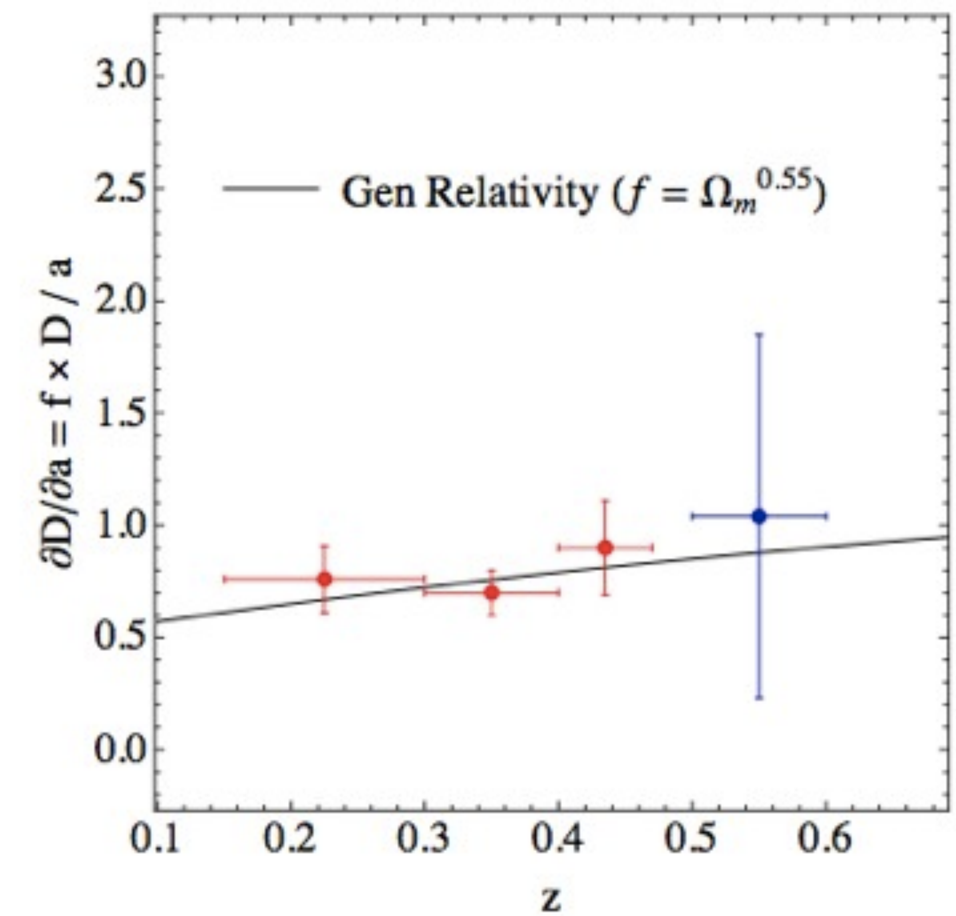


μ=0
π=0

Anna Cabré's PhD Thesis arXiv:0807.3551







$$\gamma = 0.54 \pm 0.17$$

FoMγ= 6   Crocce etal 2011

(Forecast for DES: Ross etal 2011)

BAO: $\xi(\pi,\sigma)$

radial H(z)

H(z=0.34) = 83.8 ±3.0± 1.6

EG, Cabre & Hui (2009)

Transverse $\int$ cdz/H(z)

θ(z=0.34) = 3.90 ± 0.38

Carnero etal 2011

XTalks in Galaxy Clustering

1. Galaxy Clustering 2pt: 3D, all info but biased
2. Galaxy Clustering 3pt: 3D (bias can be roughly measured)
3. Weak Lensing: 2D (unbiased but degenerate)
4. Redshift Space Distortions: ratios, (unbiased but degenerate)
5. BAO: 1.5 D (unbiased)

Combine (cross-correlate) Photometric & Spectroscopic Surveys
and all different probes: XTalks

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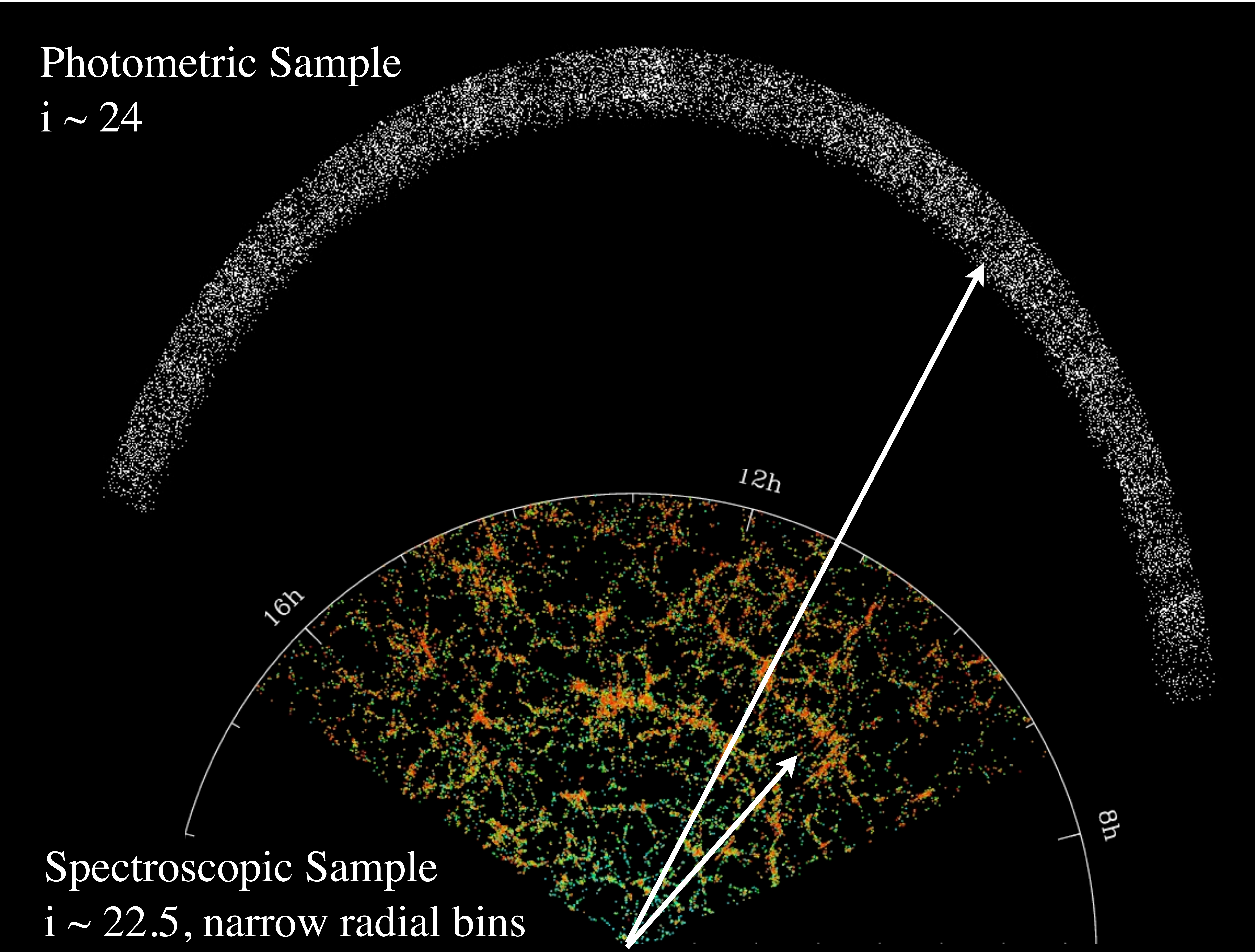

Photometric Sample
i ~ 24
12h
16h
8h
Spectroscopic Sample
i ~ 22.5, narrow radial bins

Forecast Cross-correlations: narrow bins

$$\delta_{A_i}(\vec{\theta}) = \int dz\, p_{A_i}(z)\delta_m(r\vec{\theta}, z) \qquad C_{A_iB_j}(\ell) = \int_0^\infty dz\, p_{A_i}(z)\, p_{B_j}(z)\, \mathcal{P}(k,z)$$

Galaxy-galaxy Magnification
or
Galaxy-shear
are 3D with z

$$\left.\begin{aligned} C_{GiKj} &\simeq b_{n_i} p_{ij} \mathcal{P}_i \\ C_{GiGj} &\simeq b_{n_i}^2 \frac{\delta_{ij}}{\Delta_i} \mathcal{P}_i \end{aligned}\right\}$$

Cross-correlation Ratios:

Measure bias, ie from Cii/Cij
Measure pij, ie from Cij/Cik
Measure P(k) ie from Cij^2/Cii

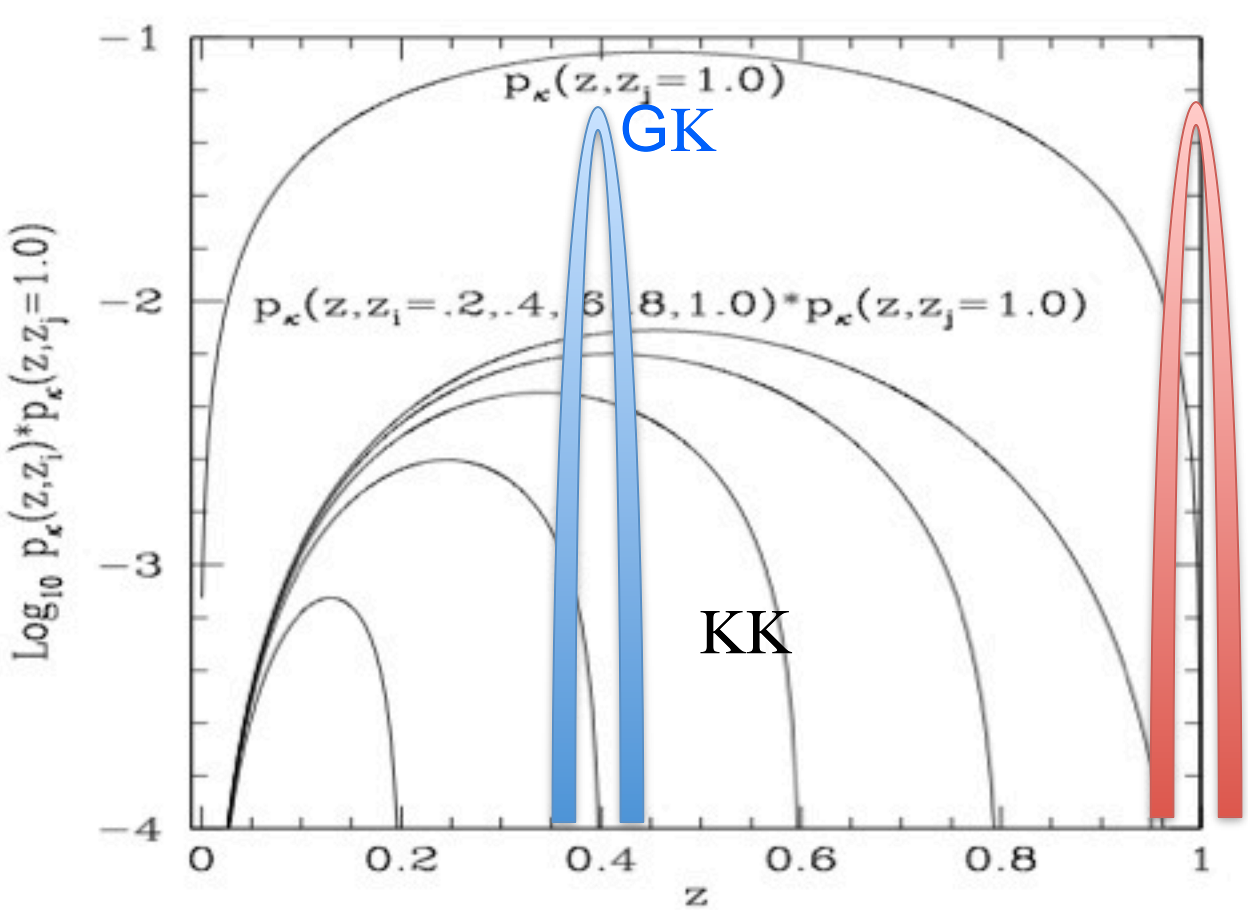


FIG. 2.— Weak lensing efficiency for shear-shear power $p_\kappa(z,\bar{z}_i)p_\kappa(z,\bar{z}_j)$ for $\bar{z}_j = 1.0$ and $\bar{z}_i = 0.2, 0.4, 0.6, 0.8$ and 1.0. Top line corresponds to $p_\kappa(z,\bar{z}_j = 1.0)$, for galaxy-shear lensing.

$$\mathcal{P}_i \equiv \frac{P(k_i, \bar{z}_i)}{\chi_i^2 \chi_{H_i}} \qquad k_i = l/\chi_i$$

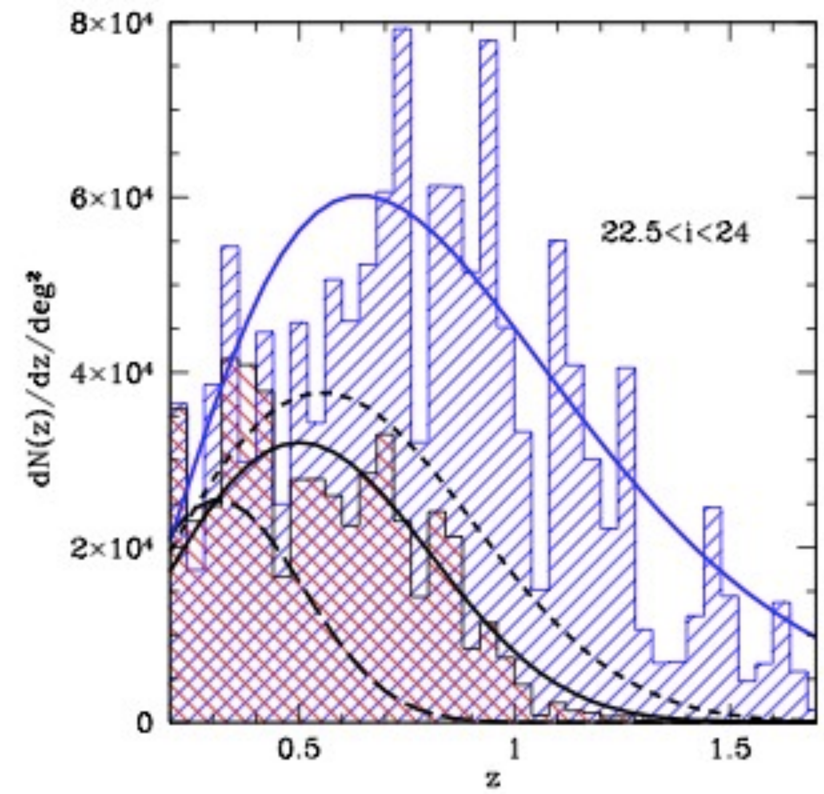
$$p_{ij} \equiv p_{\kappa_j}(z_i) \simeq \begin{cases} \frac{3\Omega_m H_0}{2H(z_i)a_i} \frac{\chi_i(\chi_j - \chi_i)}{\chi_{H0}\chi_j} & \text{for} \quad i < j \\ 0 & \text{for} \quad i \geq j \end{cases}$$

$$\chi_H(z) \equiv c/H(z)$$

WE IGNORE RSD HERE

$$F_{\mu\nu} = \sum_{\ell \text{ or } k_i} \sum_{ij,mn} \frac{\partial C_{ij}}{p_\mu} \Theta^{-1}_{ij;mn} \frac{\partial C_{mn}}{p_\nu}$$

Forecast	RSD(BAO)	WLxG
Spectroscopic (B=Bright)	✔	✘
Photometric (F=Faint)	✘	✔
Combined as independent: B+F	B	F
Cross-correlate same Area: BxF	B (+F)	BxF



Observables:

WLxG: Angular clustering of Shear-Shear; Galaxy-Shear; Galaxy-Galaxy

RSD: f(z)D(z); b(z)D(z) from P(k,z) in 3D with

Fisher Matrix of RSD and WLxG are added: transverse modes+radial ratios

Nuisance parameters: bias (4 for each B & F), photo-z transitions (rij), noise (σ/n)

Cosmological: Om - ODE - h - sig8 - Ob - **w0 - wa - γ** - ns - bias(z)

$$FoM_{w\gamma} \simeq 2700\ \bar{A}^{0.89}\ \eta^{0.22}\ 1.4^{m_l-22.5}\ e^{-\bar{\sigma}_z^2-\bar{\Delta}_r\bar{A}^{0.05}}$$

astro-ph:1109.4852

Forecast: Planck+SNII priors 5000 sq.deg.

$\mathrm{FoM}_{w\gamma} \times 10^3$	RSD	RSD + BAO	WL Shear-Shear	WLxG + RSD + BAO	**RSD + WLxG** or just **MAG** **(den/mag)**	**RSD + WLxG** or just **MAG** **(den/mag)**	**RSD+ WLxG** + **BIAS IS KNOWN** (eg 3pt)
Photometric DES (i<24)			**3.2**				
Spectroscopic eBOSS+ (i<22.5)	**0.5**	**2.7**					
Combine both as Independent				**40**			
PAU: Cross Correlated over same Area					**251** **30/72**	**5.2** **1.8/2.5**	**26** **7.7/10**

← 5000 sq.deg. → (RSD through RSD + WLxG or just MAG columns)

← 200 sq.deg. → (last two columns)

WLxG: shear-shear, galaxy-shear, galaxy-galaxy (including MAG from counts)

astro-ph:1109.4852

Conclusion

astro-ph:1109.4852

- Combining Spectroscopic and Photometric samples and different probes can bring a boost of x100 in FoM (roughly 2-5 times smaller errors)
  - Req: Photo-z error transitions need to be known to 1% accuracy
  - Req: Bias evolves on timescales>1Gyr
  - Thanks to measurement of galaxy bias
- Spectroscopic follow-up: is better to measure spectra of lenses than doing BAO
- Magnification can be as usefull as shear
- If more is known of bias another x5