Dark Energy at the Crossroads

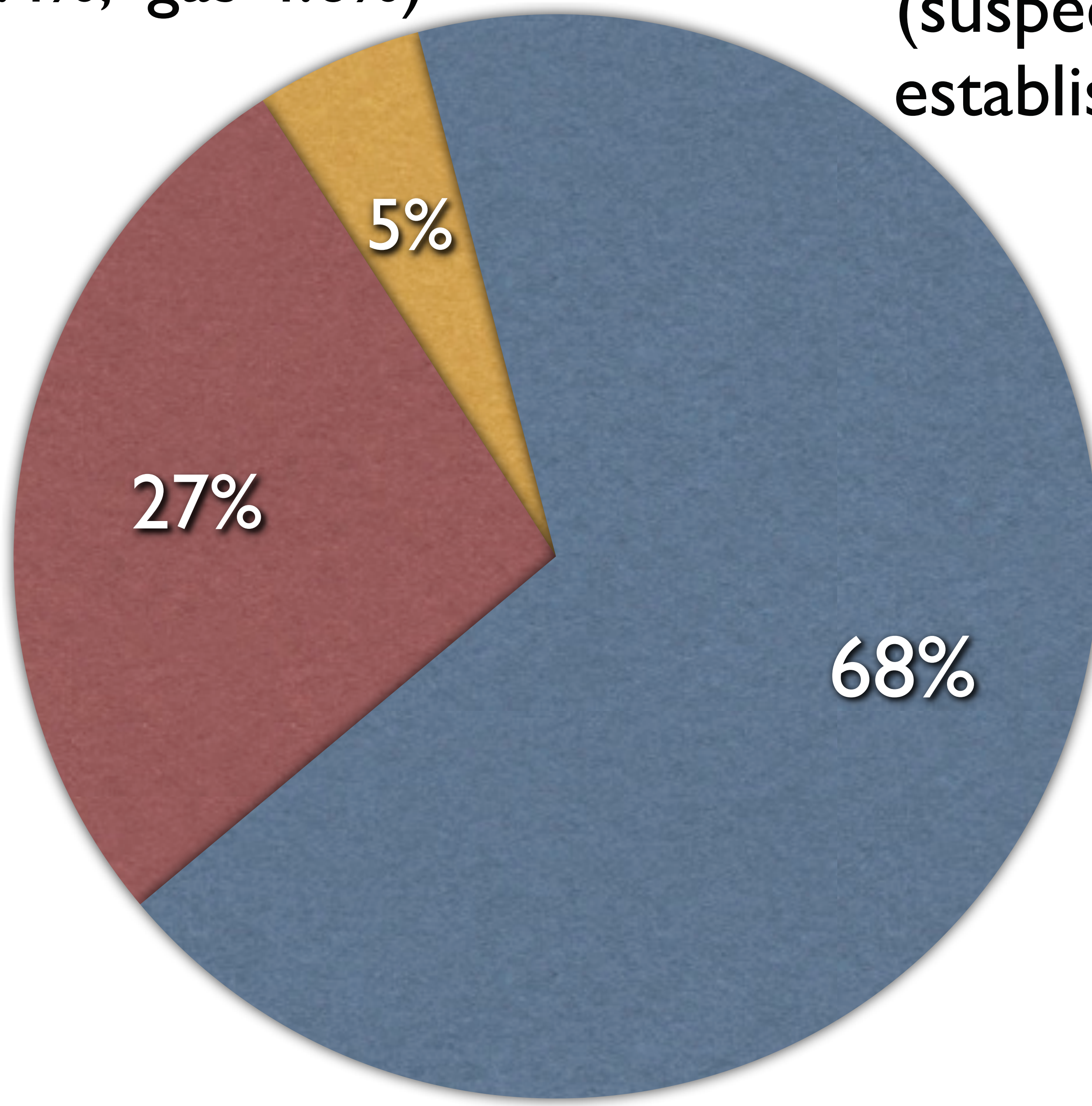
Dragan Huterer
Physics Department
University of Michigan

Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 4.6%)

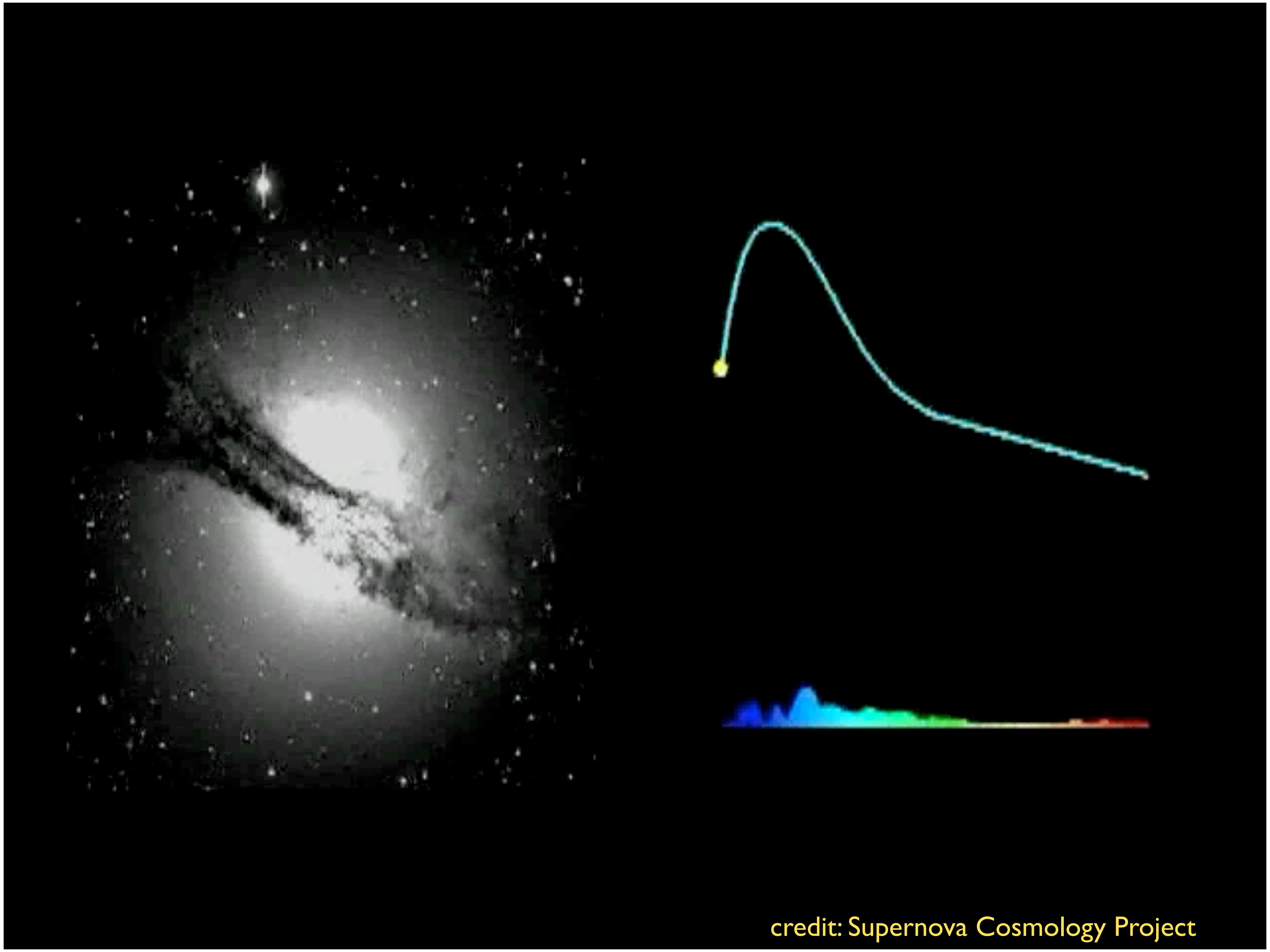
Dark Energy
(suspected since 1980s
established since 1998)

Dark Matter
(suspected since 1930s
established since 1970s)



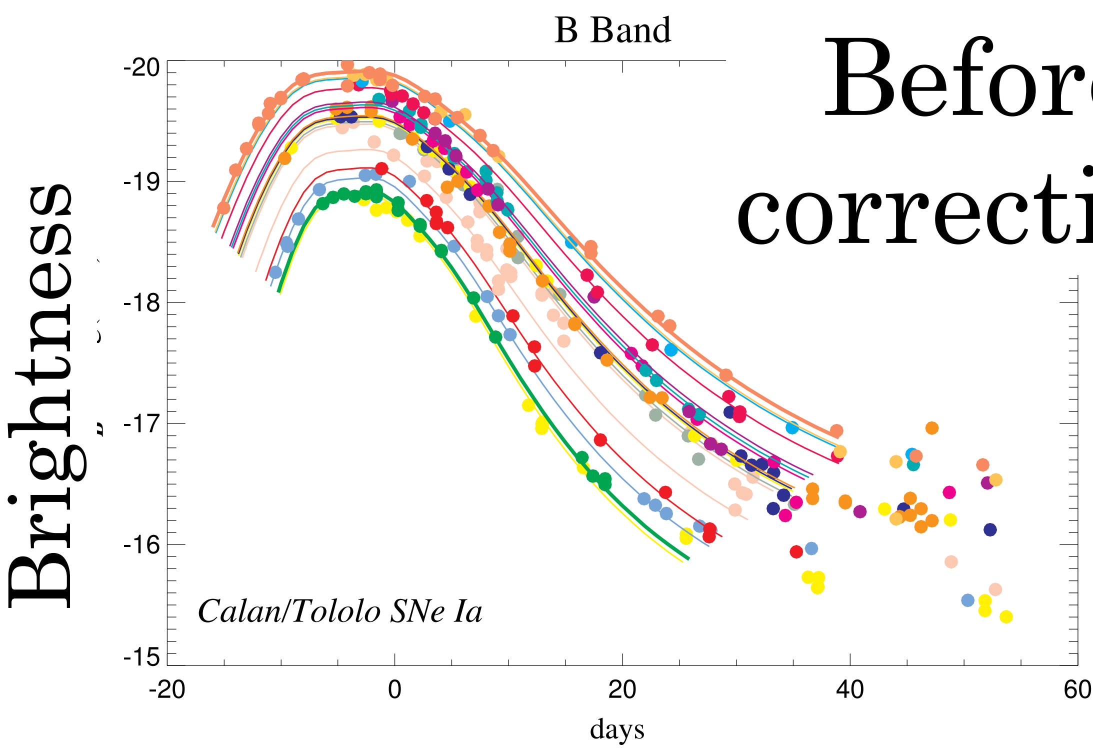
Also:
radiation (0.01%)

Type Ia Supernovae

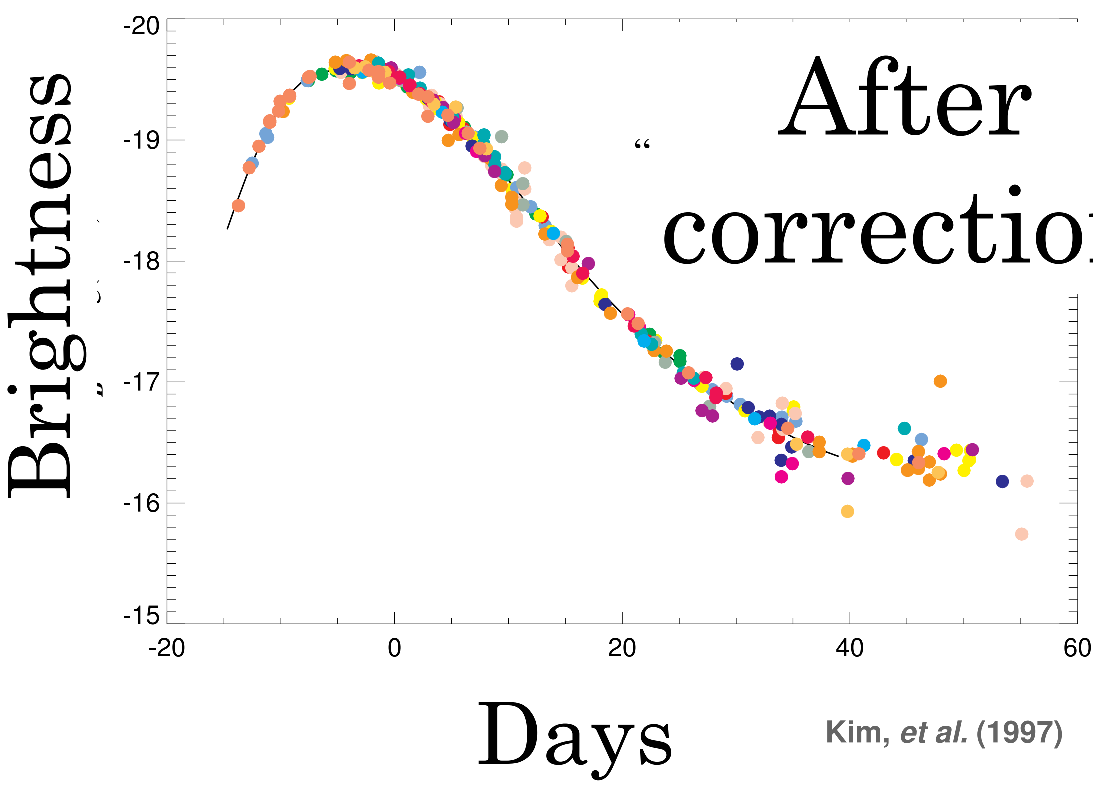


(Nearly) standard candles, so get $d_L = (L/4\pi F)^{1/2}$

Standardizing the candles



Before correction

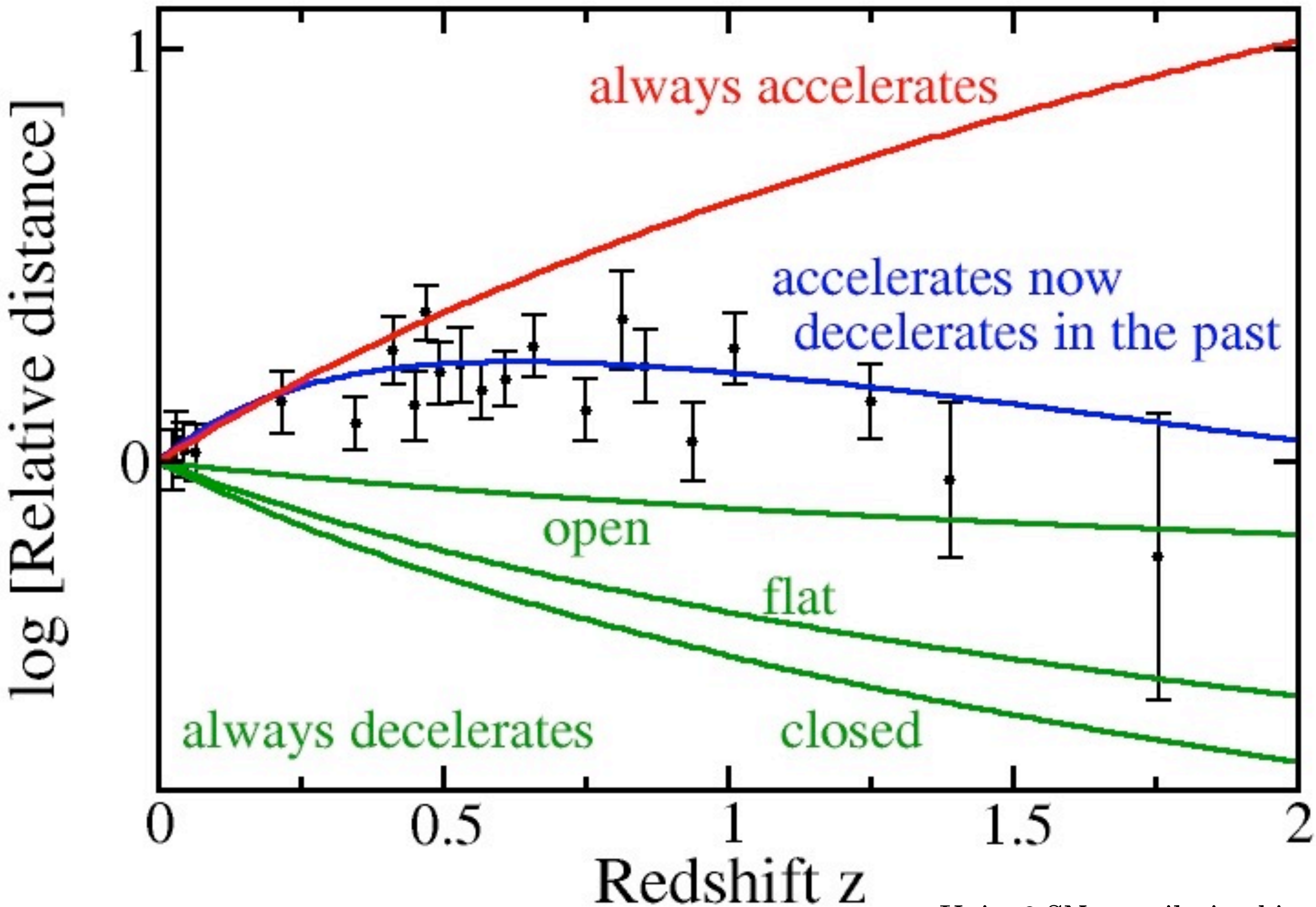


After correction

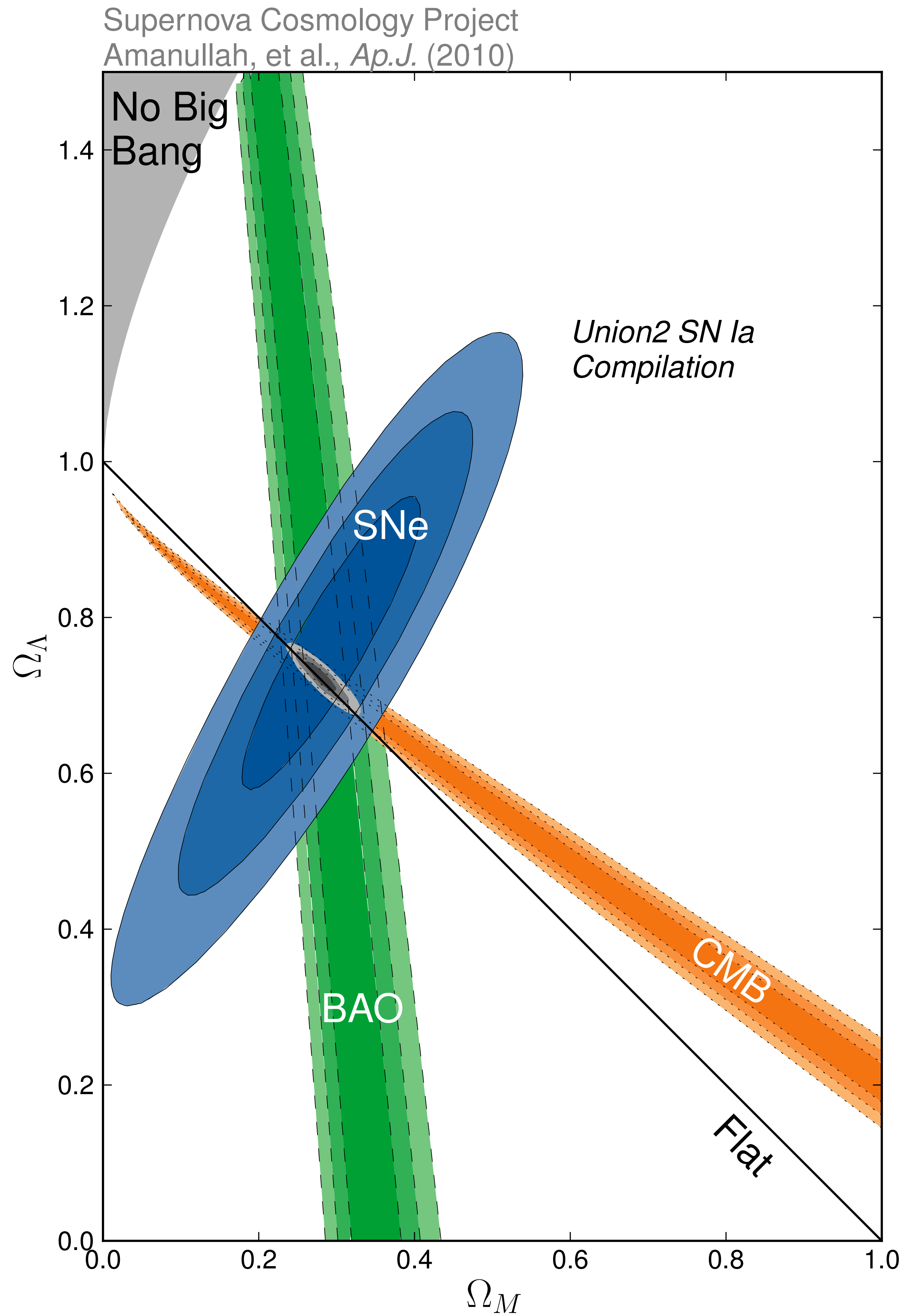
"Broader
is
(intrinsically) Brighter"

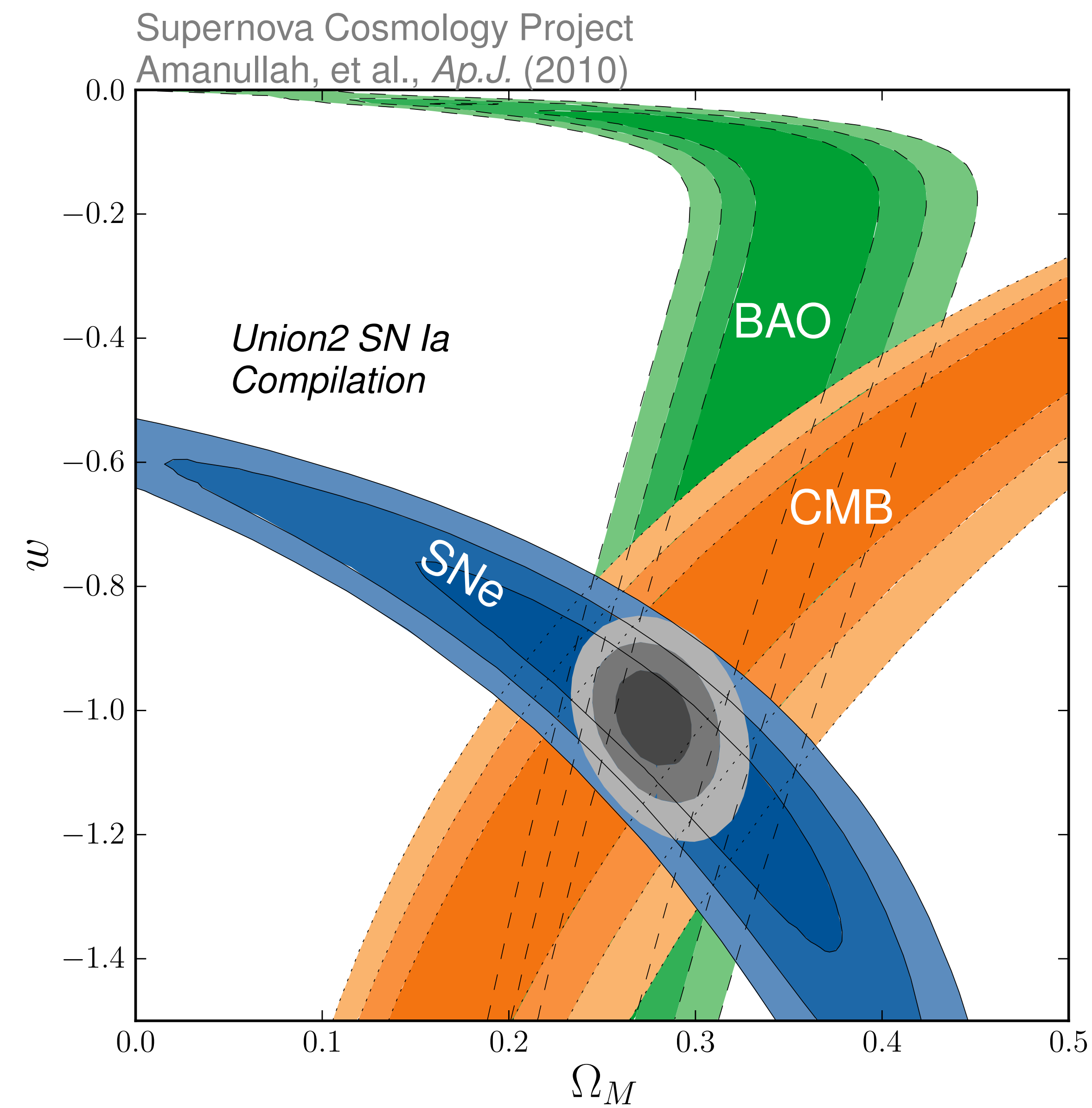
Key insight:
M. Phillips, ApJ, 413, L105, 1993

Evidence for Dark energy from type Ia Supernovae



Union2 SN compilation binned in redshift





$$\Omega_{\mathrm{DE}} \equiv \frac{\rho_{\mathrm{DE}}}{\rho_{\mathrm{crit}}}$$

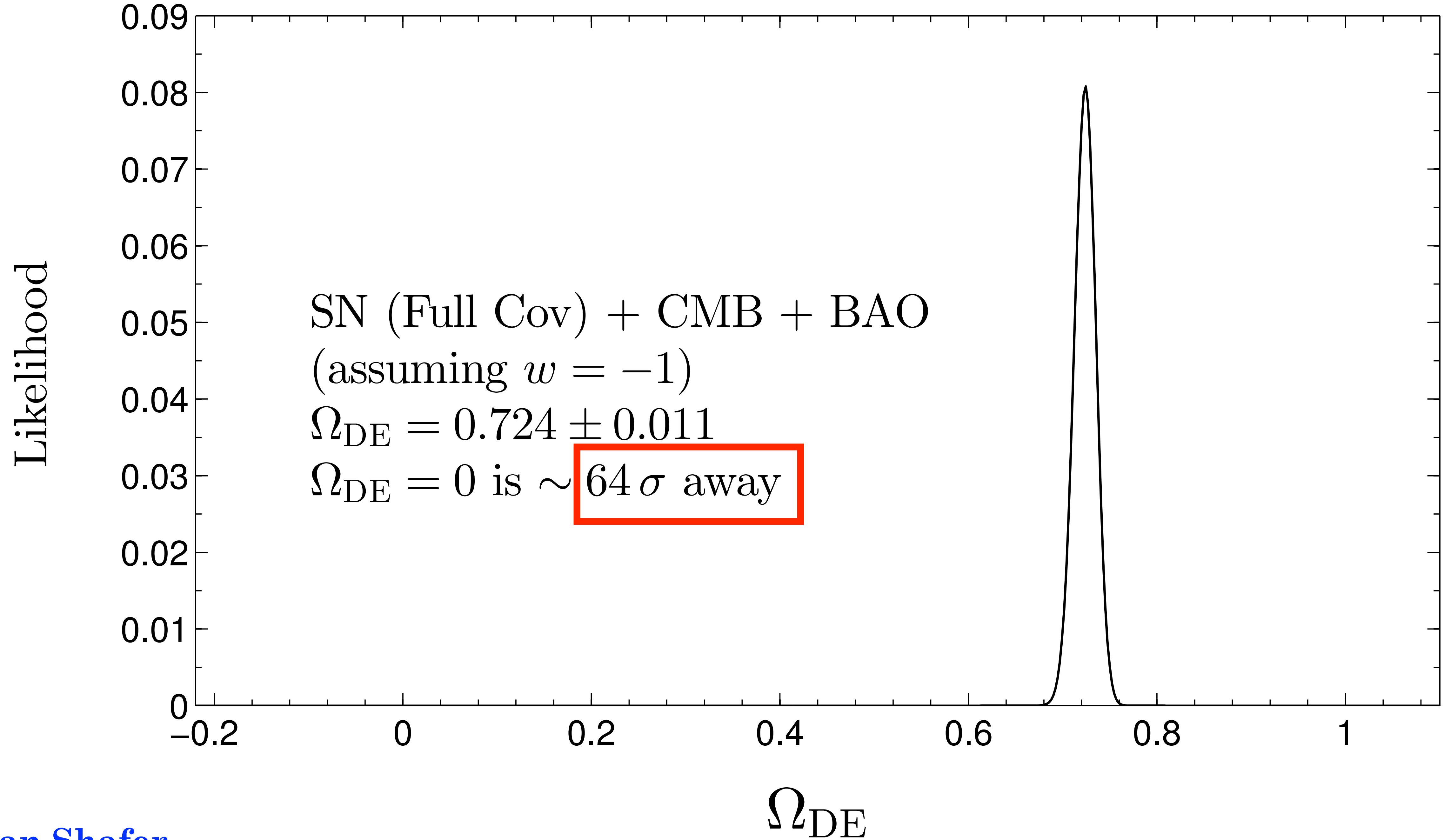
$$w \equiv \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

Dark Energy

Michael Turner
University of Chicago

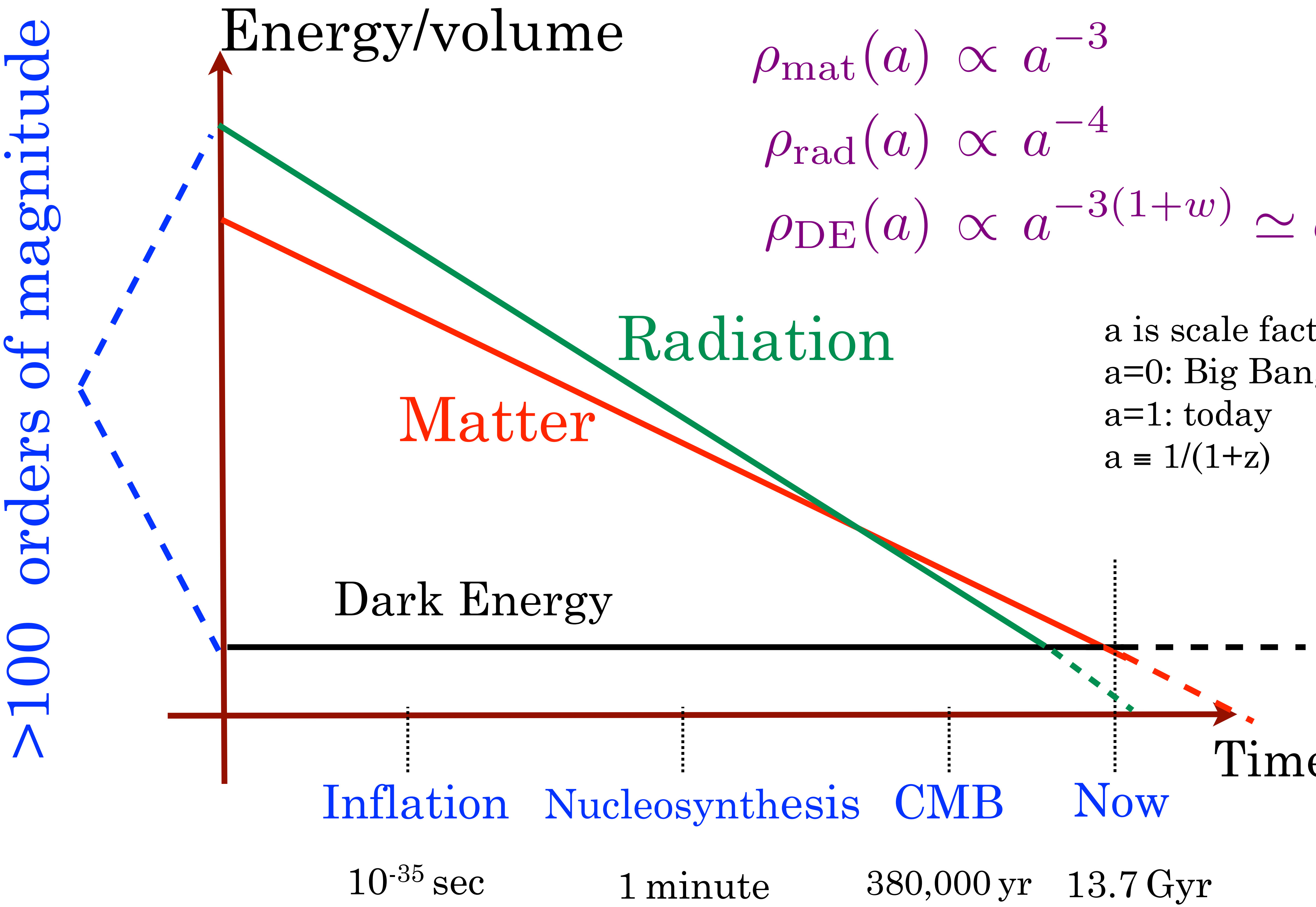
- Universe is dominated by something other than dark matter
- This new component - “dark energy” - makes the universe undergo accelerated expansion
- This new component is largely smooth
- Other than that, we don’t know much!

Current evidence for dark energy is impressively strong



Dan Shafer

Coincidence problem



$$\rho_{\rm mat}(a) \propto a^{-3}$$
$$\rho_{\rm rad}(a) \propto a^{-4}$$
$$\rho_{\rm DE}(a) \propto a^{-3(1+w)} \simeq a^{0}$$

a is scale factor
a=0: Big Bang
a=1: today
a ≡ 1/(1+z)

Cosmological constant problem

Vacuum Energy: QFT predicts it to be cutoff scale

$$\rho_{\mathrm{VAC}} = \frac{1}{2}\sum_{\mathrm{fields}} g_i \int_0^\infty \sqrt{k^2+m^2}\,\frac{d^3k}{(2\pi)^3} \simeq \sum_{\mathrm{fields}} \frac{g_i k_{\mathrm{max}}^4}{16\pi^2}$$

$$\left.\begin{array}{ll} \text{Measured:} & \boxed{(10^{-3}\mathrm{eV})^4} \\ \text{SUSY scale:} & (1\,\mathrm{TeV})^4 \\ \text{Planck scale:} & (10^{19}\,\mathrm{GeV})^4 \end{array}\right\}$$

60-120 orders of magnitude smaller than expected!

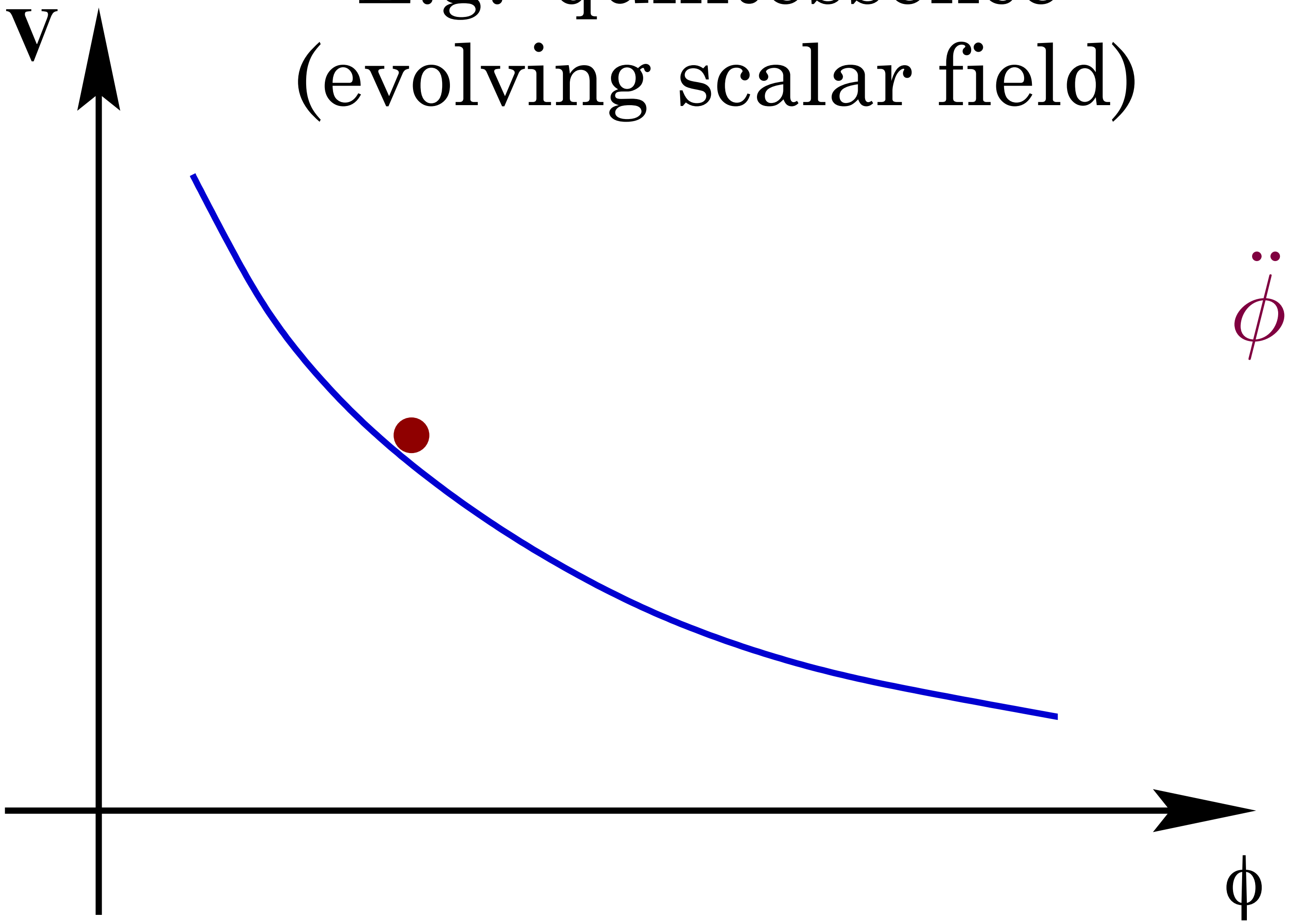
"The mother of all Physics problems" (Susskind)

Reviews: A. Padilla, "Lectures on the Cosmological Constant Problem", arXiv:1502.05296
J. Martin, "Everything you wanted to know about the CC but didn't dare to ask", arXiv:1205.3365

Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE **naturally**

E.g. ‘quintessence’
(evolving scalar field)



$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$m_\phi \simeq H_0 \simeq 10^{-33}\ \mathrm{eV}$$

String landscape?

Bousso & Polchinski 2000

$0 \quad 10^{-120}\, M_{PL}^4 \qquad\qquad M_{PL}^4 \quad \rho_\Lambda$

Among the ~10^{500} minima,

we live in one that allows structure/galaxies to form

(selection effect) (anthropic principle)

Pam Jeffries

Landscape postdicts $w = -1$

Big questions

1. Is the cosmic acceleration due to something other than vacuum energy?

2. Does GR self-consistently describe the acceleration?

Wish List

Goals:

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

$$\Omega_{\rm DE} = \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

Measure $\Omega_{\rm DE}, w$

Measure $\rho_{\rm DE}(z)$ or $w(z)$

Measure any clustering of DE

Wish List

Goals:

$$w = \frac{p_{\rm DE}}{\rho_{\rm DE}}$$

$$\Omega_{\rm DE} = \frac{\rho_{\rm DE}}{\rho_{\rm crit}}$$

Measure $\Omega_{\rm DE}, w$

Measure $\rho_{\rm DE}(z)$ or $w(z)$

Measure any clustering of DE

Difficulties:

$w(z)$ enters the observables via integral relations

$$r(z) = \int_0^z \frac{dz'}{H(z')}$$

$$H^2(z) = H_0^2 \left[\Omega_M (1+z)^3 + \Omega_{DE} \exp\left(3\int_0^z (1+w(z'))\, d\ln(1+z')\right)\right]$$

DE clustering is negligible except perhaps on scales $\simeq H_0^{-1}$

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

1. Neutrino masses:

$$\left.\begin{aligned}(\Delta m^2)_{sol} &\simeq 8\times10^{-5}\ eV^2\\ (\Delta m^2)_{atm} &\simeq 3\times10^{-3}\ eV^2\end{aligned}\right\}$$

$\sum m_i = 0.06\ eV^*$ (normal)

vs.

$\sum m_i = 0.10\ eV^*$ (inverted)

*(assuming m_3=0)

A difficulty:

DE theory target accuracy, in e.g. w(z), not known *a priori*

Contrast this situation with:

1. Neutrino masses:

$$\left.\begin{array}{l}(\Delta m^2)_{sol} \simeq 8\times10^{-5}\ \mathrm{eV}^2 \\ (\Delta m^2)_{atm} \simeq 3\times10^{-3}\ \mathrm{eV}^2\end{array}\right\} \quad \begin{array}{c}\sum m_i = 0.06\ \mathrm{eV}^* \ \text{(normal)} \\ \text{vs.} \\ \sum m_i = 0.10\ \mathrm{eV}^* \ \text{(inverted)}\end{array}$$

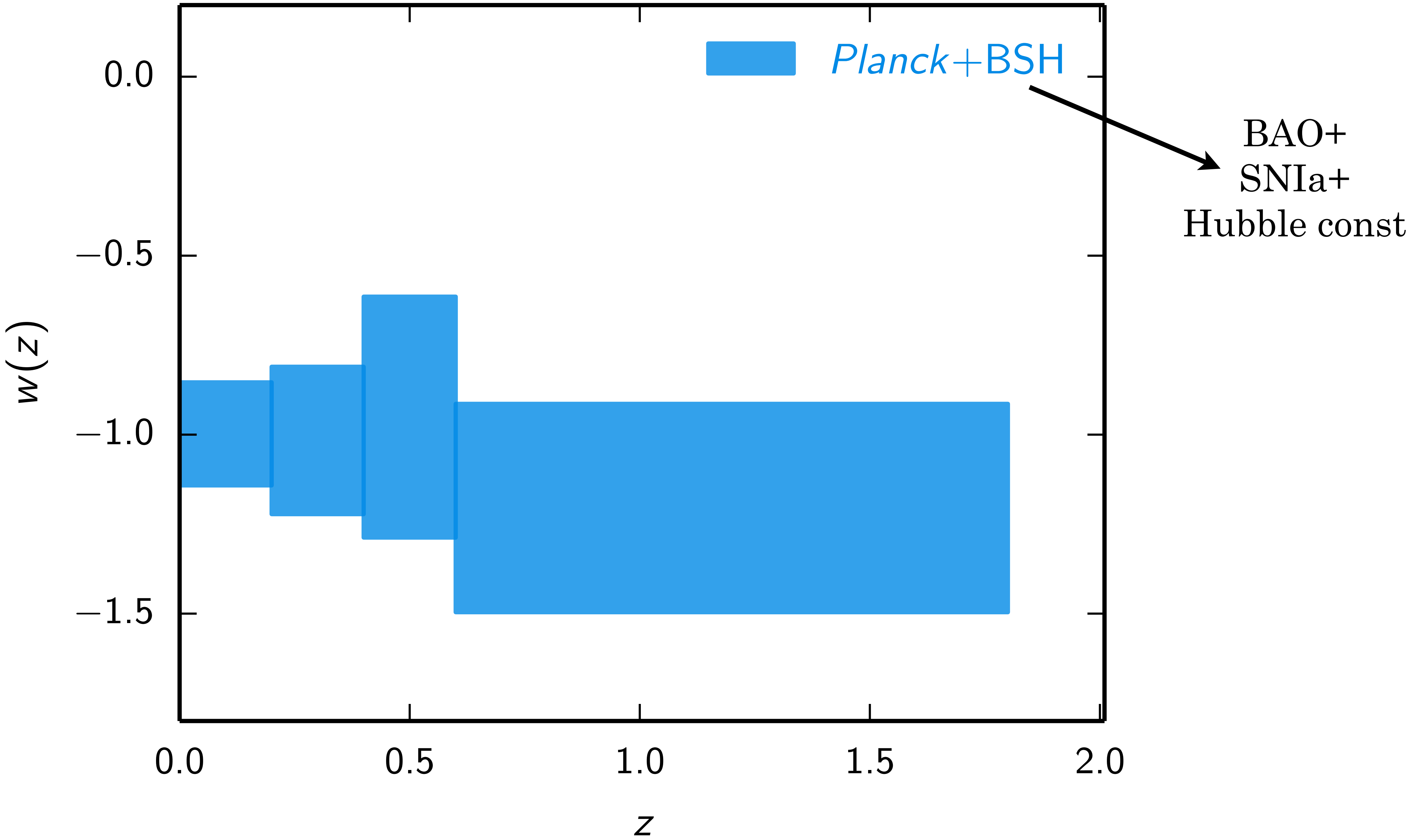
*(assuming $m_3=0$)

2. Higgs Boson mass (before LHC 2012):

$$m_H \lesssim O(200)\ \mathrm{GeV}$$

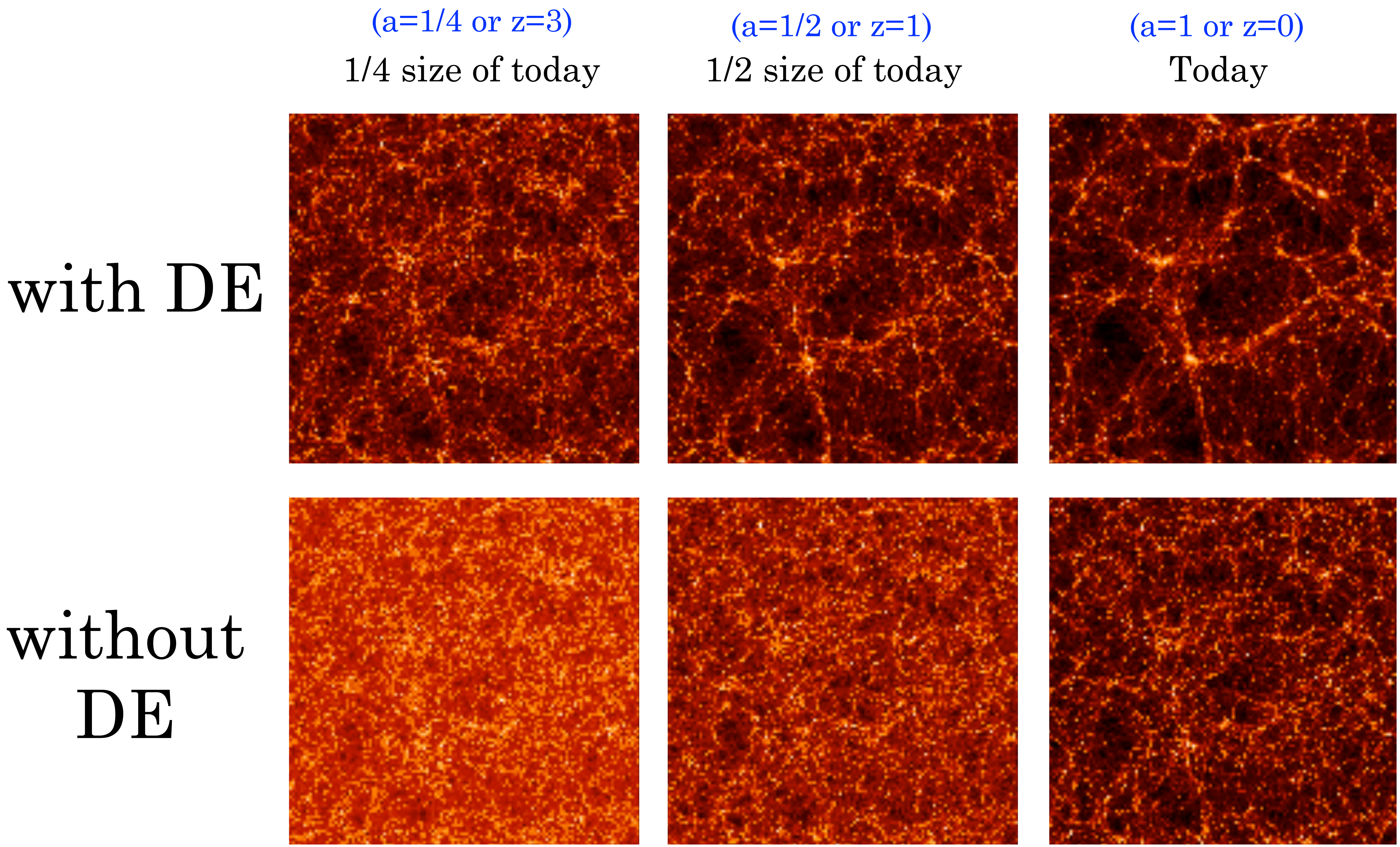
(assuming Standard Model Higgs)

Current constraints on w(z): **largely from geometrical measures**



Planck XIV, “Dark Energy and Modified Gravity”, arXiv:1502.01590

Dark Energy suppresses the growth of density fluctuations



Huterer et al, Snowmass report, 1309.5385

The Virgo Consortium (1996)

Using growth to separate GR from MG:

For example:

$$H^2 - F(H) = \frac{8\pi G}{3}\rho, \qquad \text{or} \qquad H^2 = \frac{8\pi G}{3}\left(\rho + \frac{3F(H)}{8\pi G}\right)$$

Modified gravity

GR + dark energy

Growth of density fluctuations can decide:

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_M\delta = 0$$ (assuming GR)

LSS tracers and their statistical probes

- Clusters of galaxies
  - 1-point function - cluster counts (dn/dlnM), sens to DE
  - 2-pt function - sensitive to primordial NG
- Galaxies: LRG, ELG, also quasars
  - 2-point function: pretty well understood, easily measured
  - anisotropic 2-pt function - Redshift Space Distortions (RSD)
  - 3-pt function: powerful, but issues in predicting $b_G(k, a, env)$
  - also galaxy-CMB cross-correlation
- Weak Lensing Shear:
  - 2-point function: measurements systematics dominated
  - 3-pt function: future; systematics a huge challenge
  - also gal-gal (γ-g), shear peaks, ...

Counting galaxy clusters

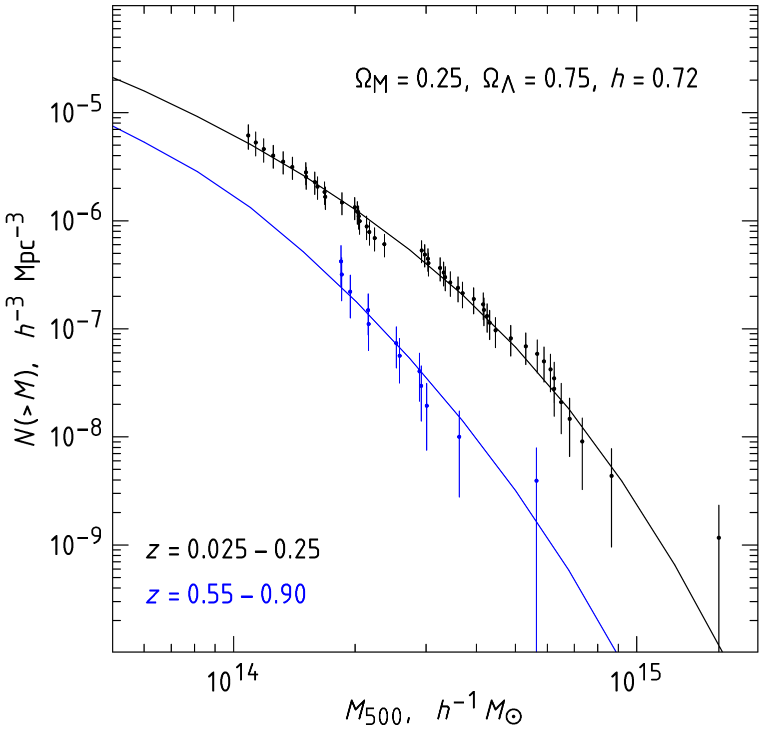
Allen, Evrard & Mantz review, 2011

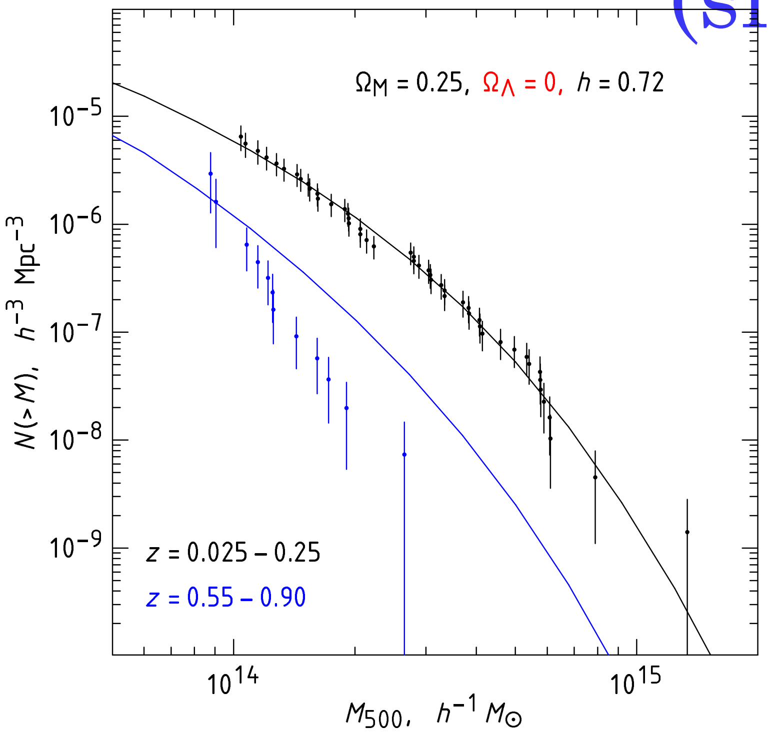
cluster number
(measure)

$$\frac{d^2N}{d\Omega\, dz} = n(z)\,\frac{r(z)^2}{H(z)}$$

cluster num. density
(simulations)

distance factors
(theory)

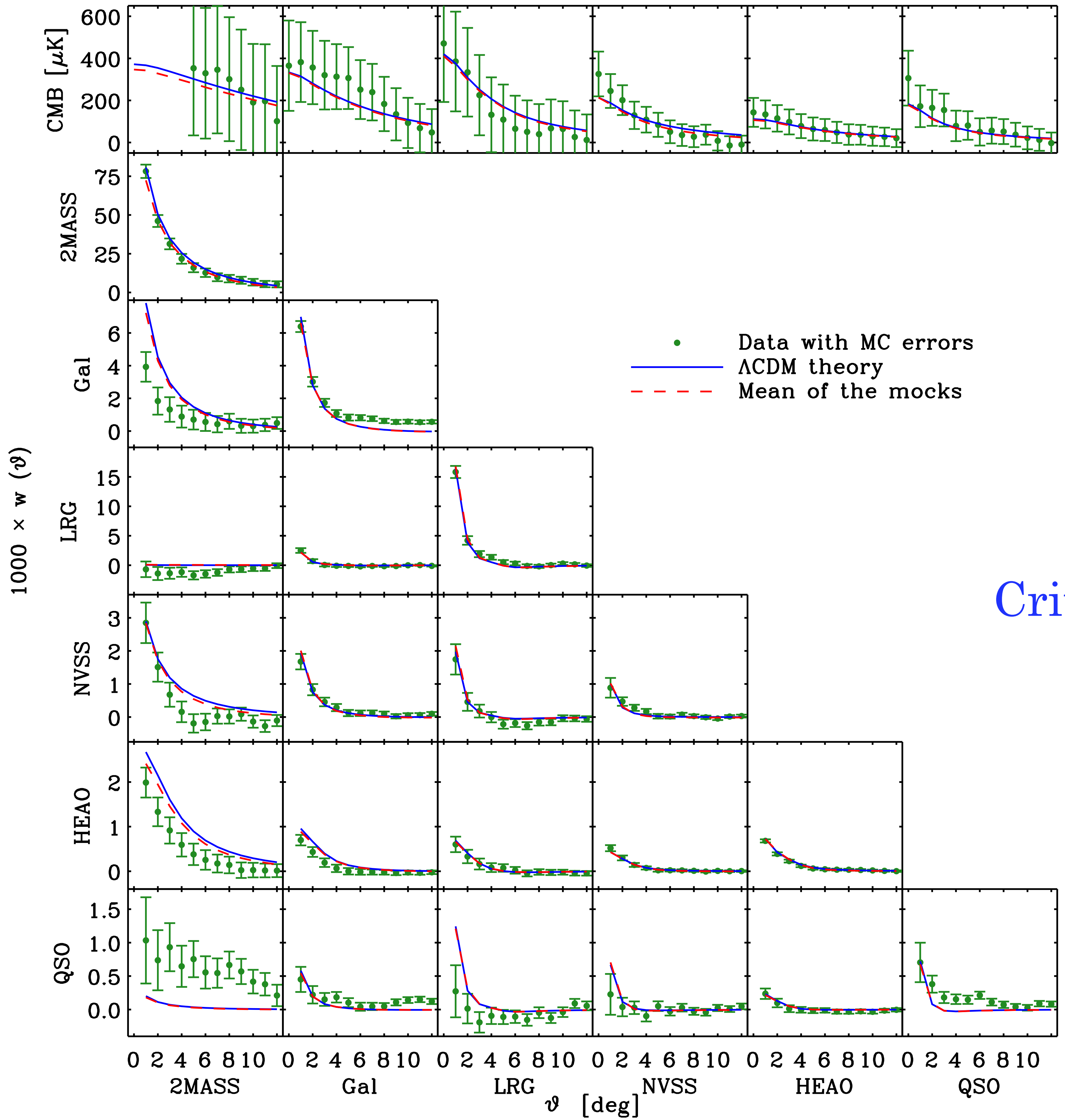




Vikhlinin et al, 2009

“Cross - correlations”:

galaxy - galaxy
galaxy - QSO
galaxy - CMB
shear -shear
shear-galaxy
apple - orange
.....

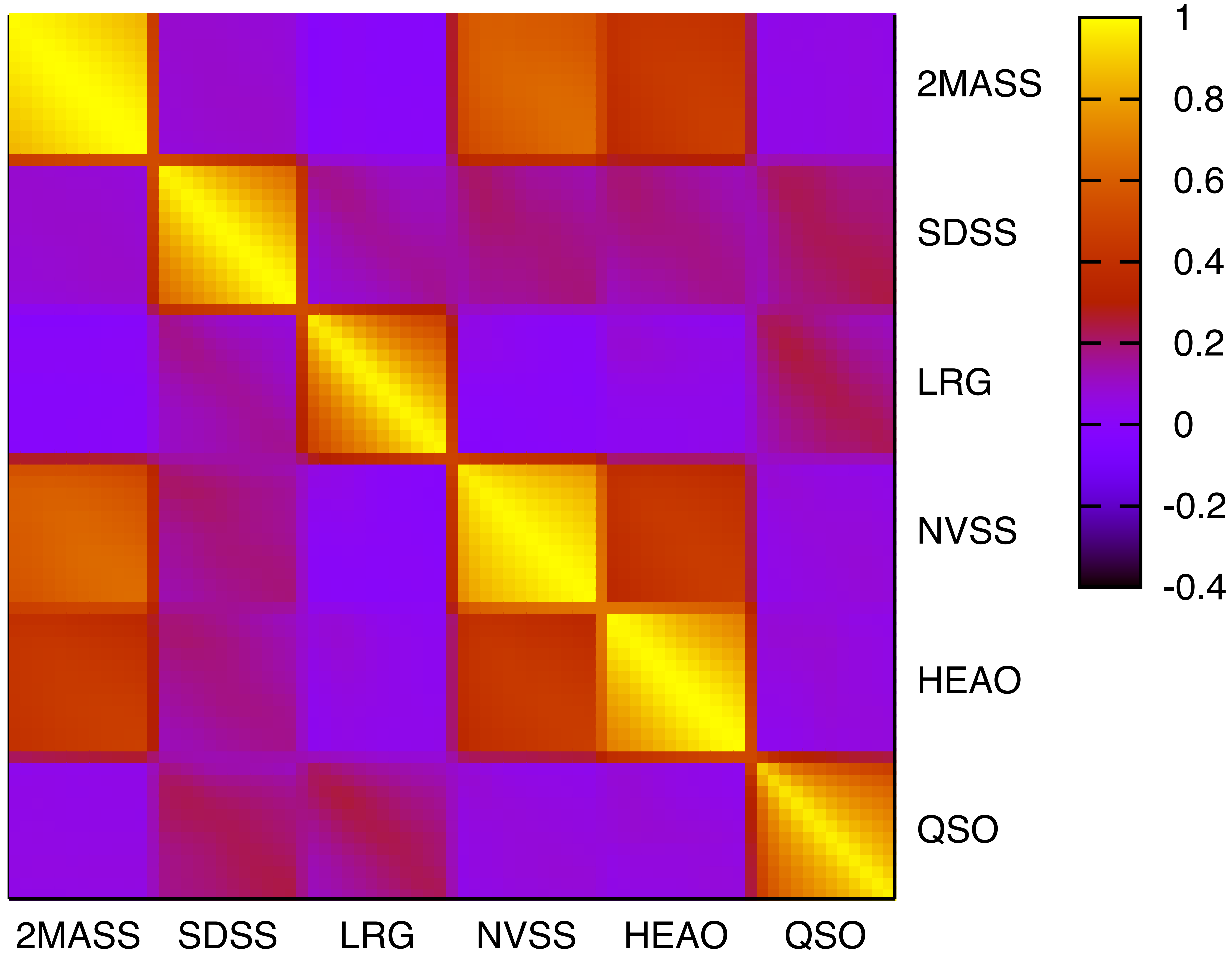


Key insight:
Crittenden & Turok, 1996

Giannantonio et al. 2013

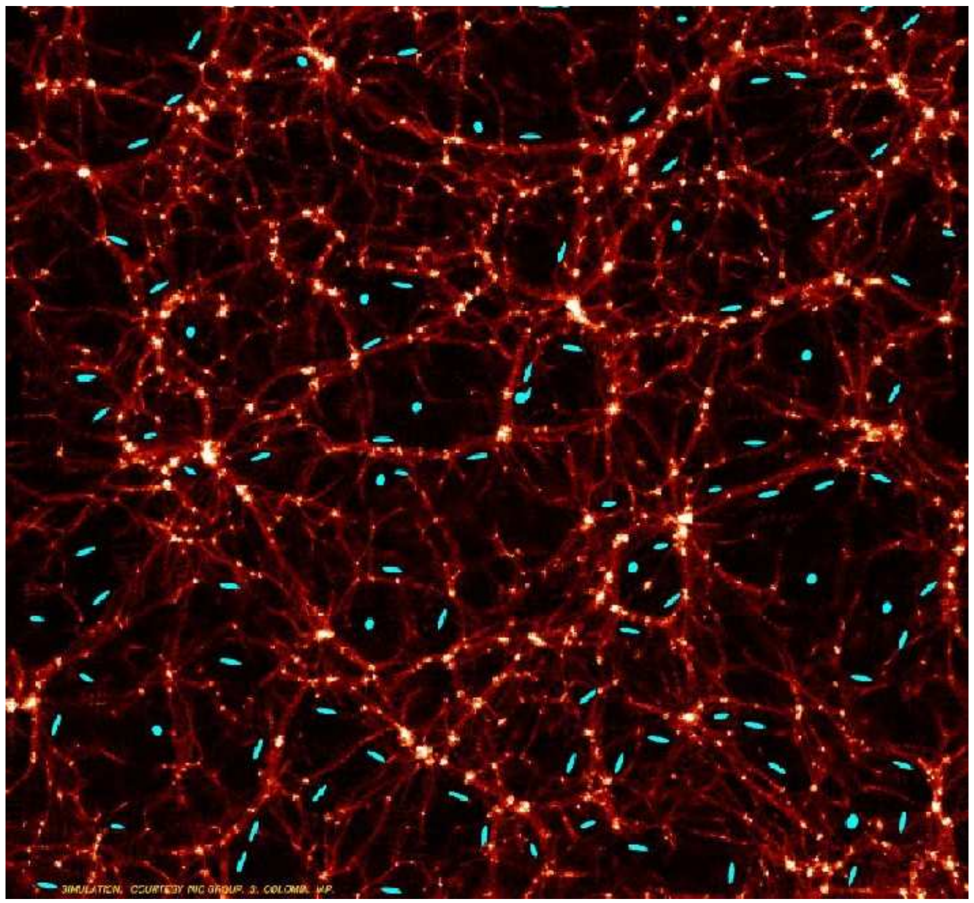
Hardest part of this: simulating/calculating the covariance matrix

(that is: clustering in nonlinear regime)

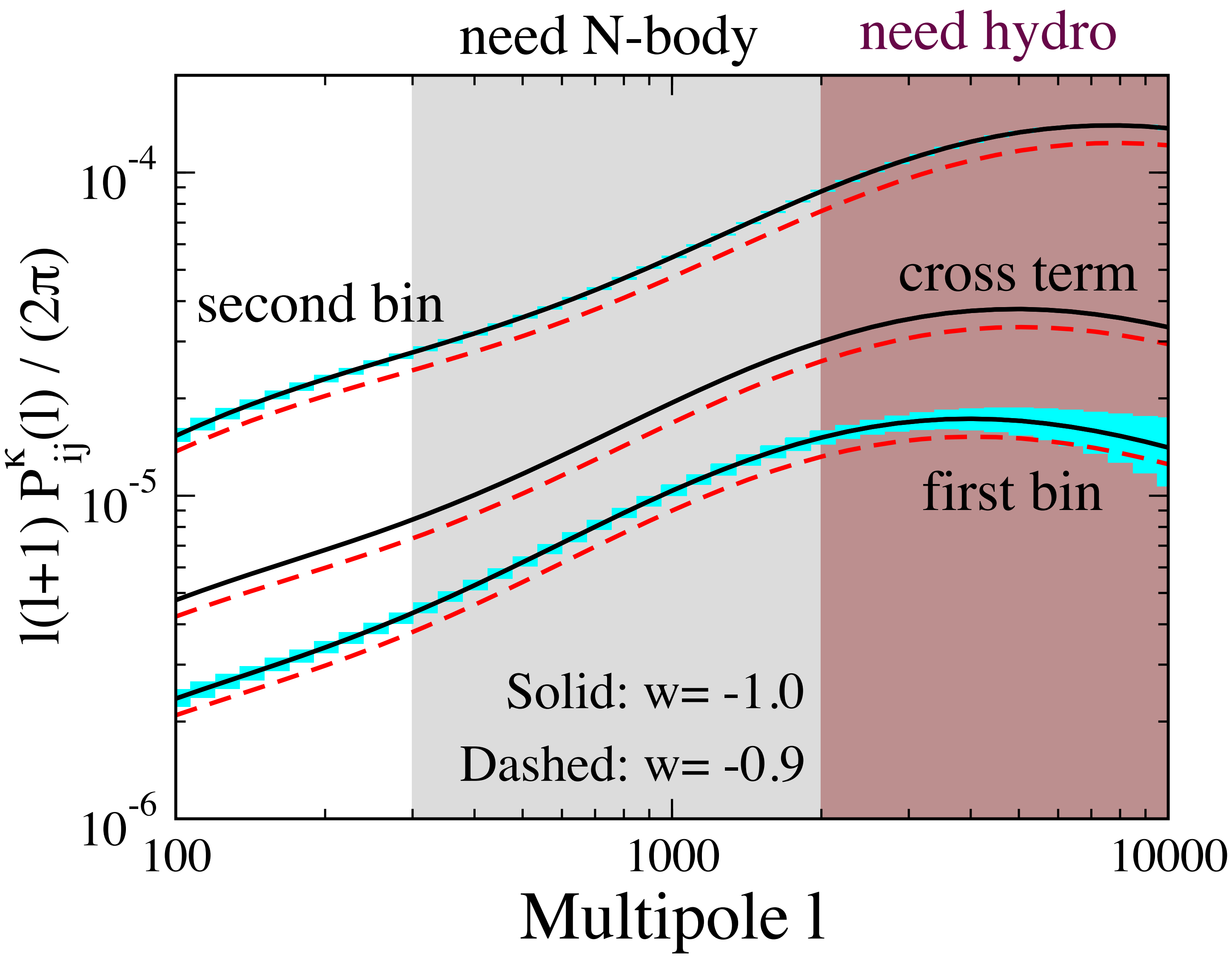


Giannantonio et al. 2013

Weak Gravitational Lensing



Takashi Hamana

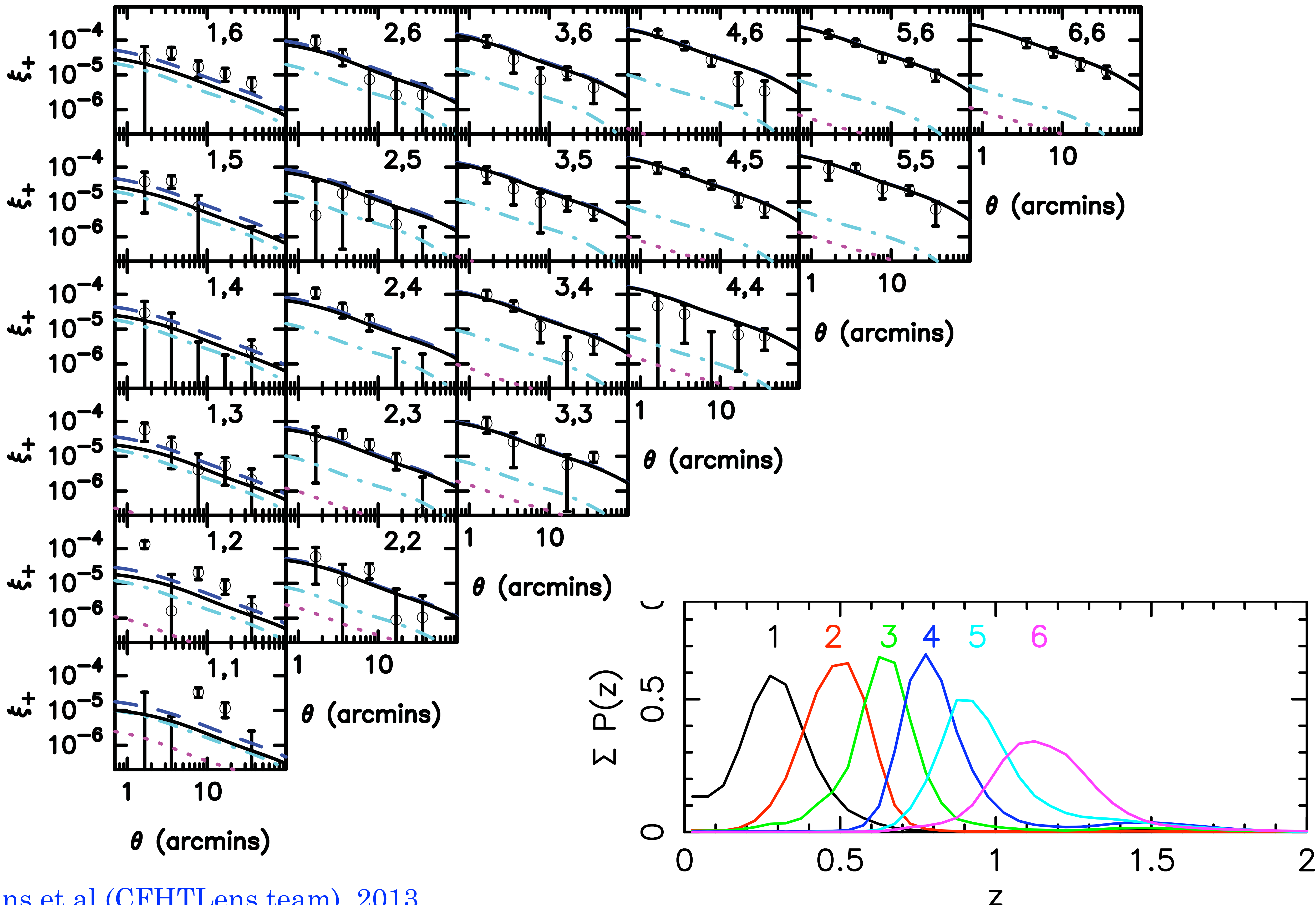


Huterer et al, Snowmass report, 1309.5385

WL systematics are very challenging:

$$\gamma^{\rm obs} = \gamma^{\rm true}(1+m) + \gamma^{\rm add} + \gamma^{\rm noise}$$

Measured 2-pt correlation func from CFHTLens



Heymans et al (CFHTLens team), 2013

Next Frontier: **Growth (+geom) from LSS**

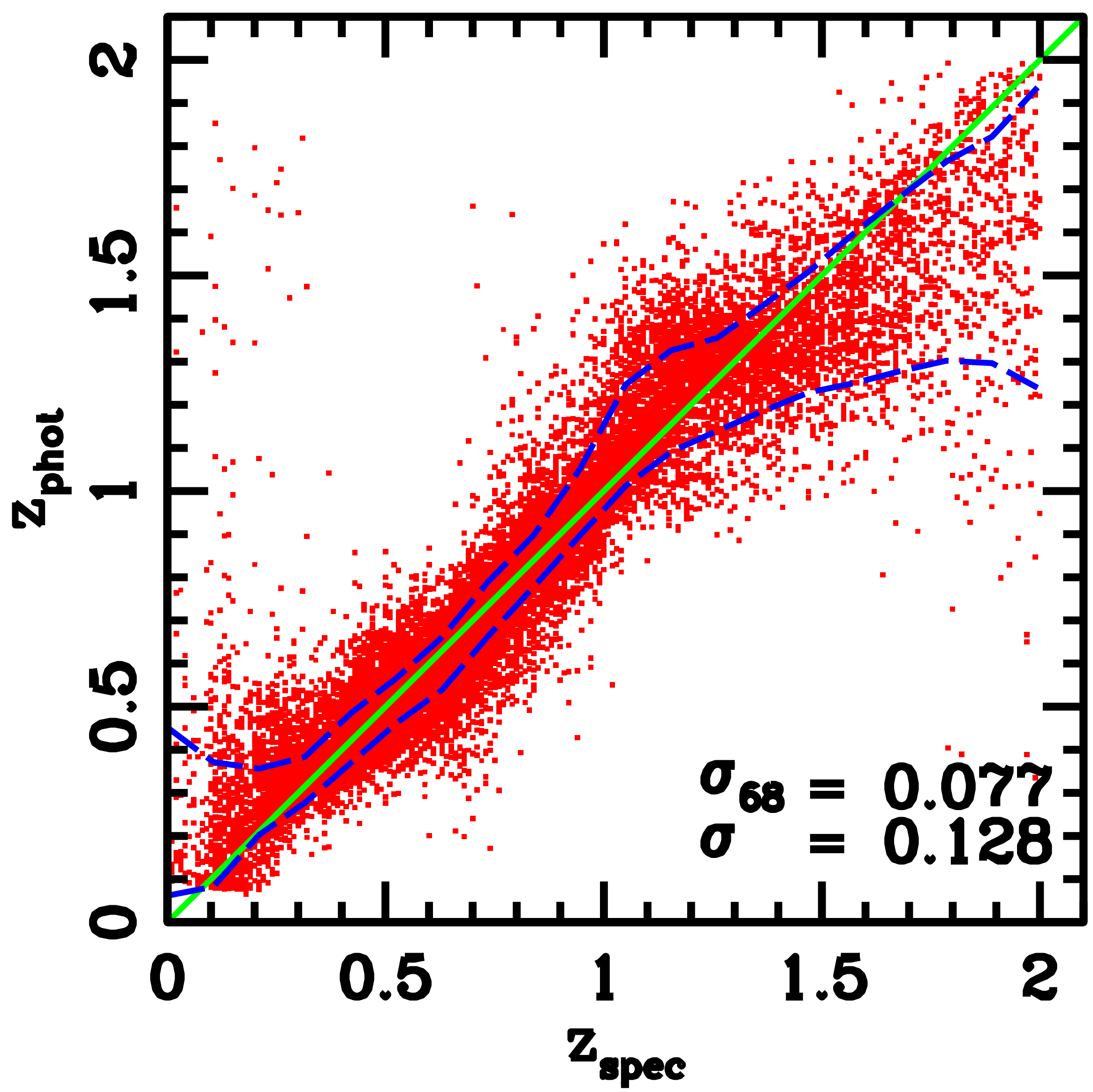
	CMB	LSS
dimension	2D	3D
# modes	$\propto l_{max}{}^2$	$\propto k_{max}{}^3$
can slice in	λ only	λ, M, bias...
temporal evol.	no	yes
systematics?	relatively clean	relatively messy
theory modeling	easy	can be hard

Systematic Errors, top two:

1. **Photometric Redshift errors**
2. **(photometric) Calibration errors**

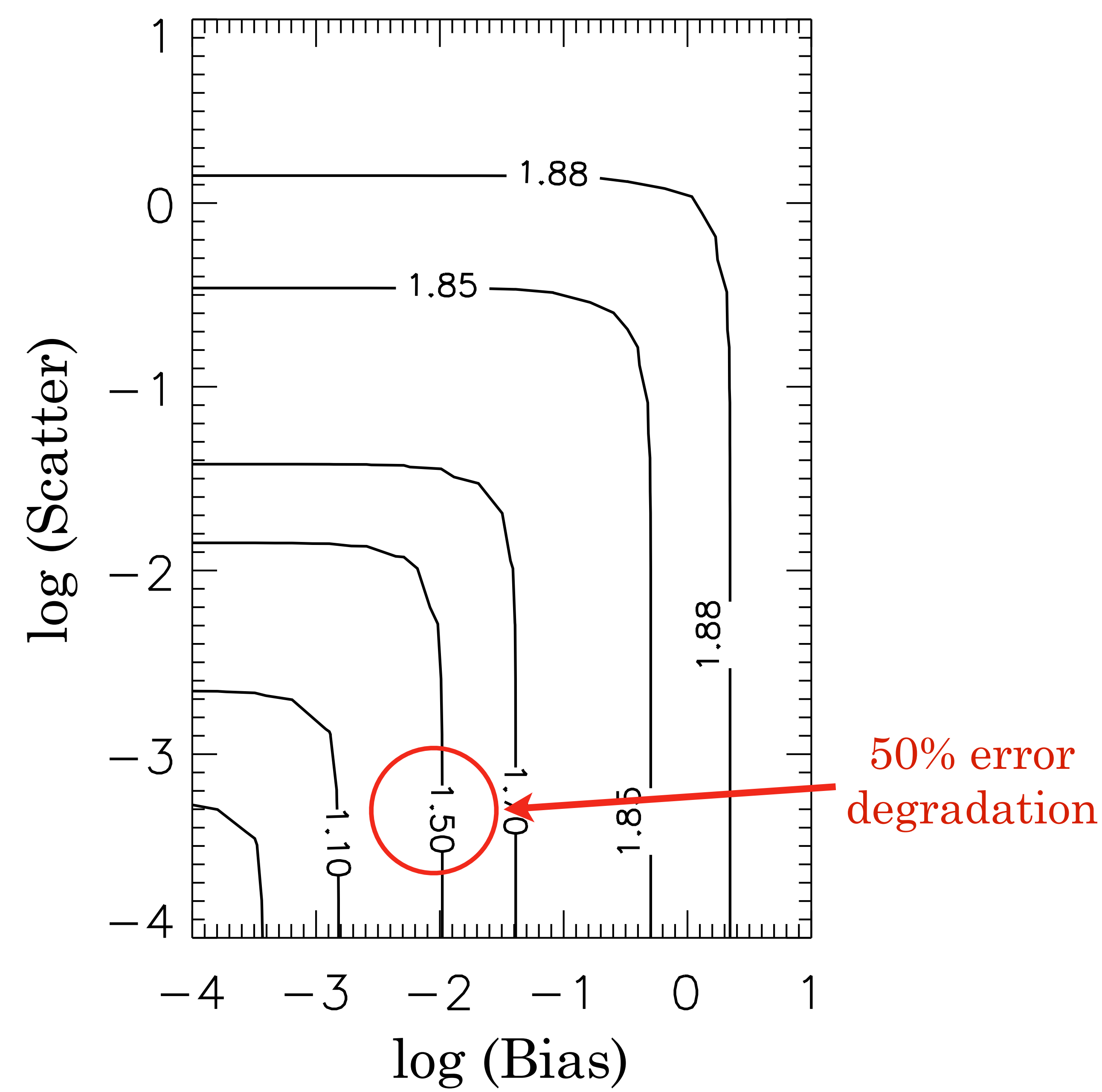
Poster child for the systematics: photometric redshift errors

z_{phot}-z_{spec}
from "training set"



C. Cunha

Requirements

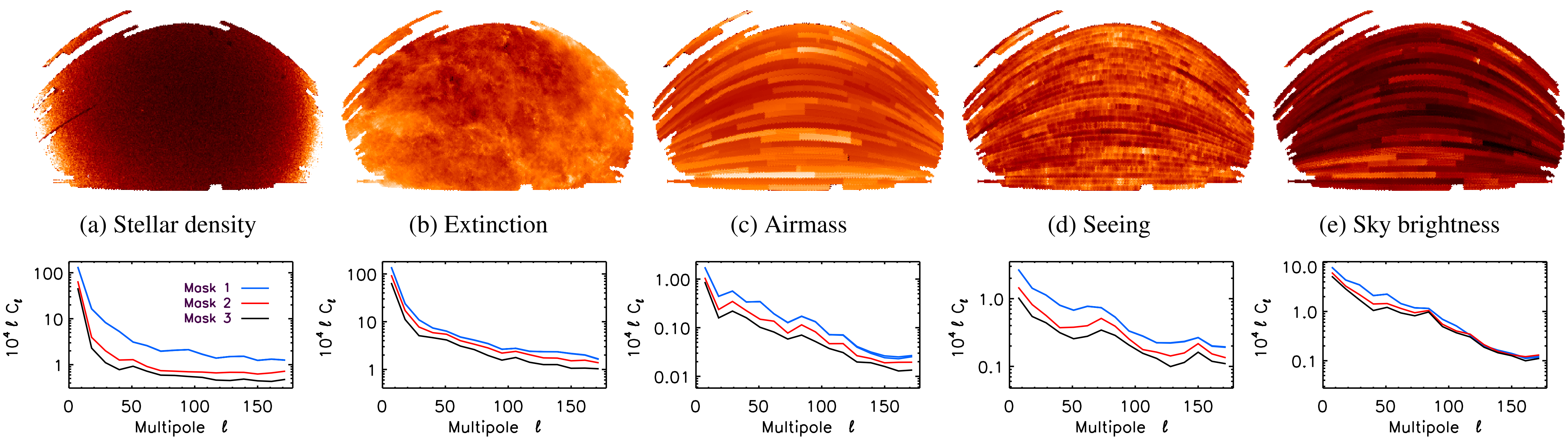


Ma, Hu & Huterer 2006

(Photometric) **calibration** errors

- **Detector sensitivity**: sensitivity of the pixels on the camera vary along focal plane.
- **Observing conditions**: spatial and temporal variations.
- **Bright objects**: The light from foreground bright stars and galaxies.
- **Dust extinction**: Dust in the MW absorbs light from the distant galaxies.
- **Star-galaxy separation**: Faint stars erroneously included in the galaxy sample.
- **Deblending**: Galaxy images can overlap.

Huterer, Cunha & Fang 2013
Shafer & Huterer 2015



Leistedt et al 2013

Explicitly separating information from growth and geometry using current data

Ruiz & Huterer, PRD 2015, arXiv:1410.5832

Sensitivity to geometry and growth

Cosmological Probe	Geometry	Growth
SN Ia	$H_0 D_L(z)$	—
BAO	$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$	—
CMB peak loc.	$R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$	—
Cluster counts	$\frac{dV}{dz}$	$\frac{dn}{dM}$
Weak lens 2pt	$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$	$P\left(k = \frac{\ell}{r(z)}\right)$
RSD	$F(z) \propto D_A(z) H(z)$	$f(z)\sigma_8(z)$

Idea: compare geometry and growth

e.g. Wang, Hui, May & Haiman 2007

Our approach:

Double the standard DE parameter space

($\Omega_M=1-\Omega_{DE}$ and w):

$\Rightarrow \Omega_M^{\rm geom}, w^{\rm geom}\ \Omega_M^{\rm grow}, w^{\rm grow}$

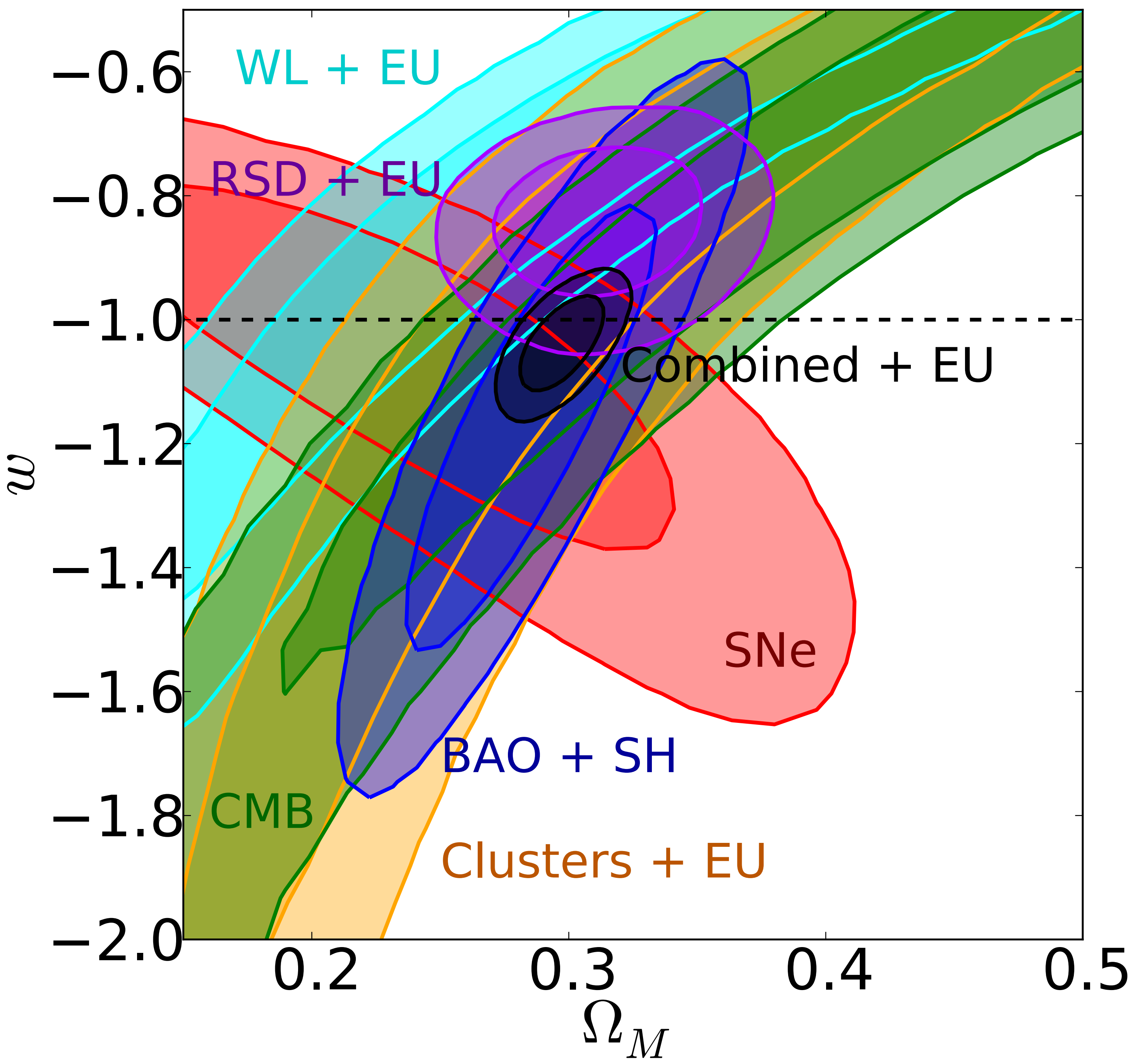
[In addition to other:

standard parameters: $\Omega_M h^2\ \Omega_B h^2$, n_s, A)

nuisance parameters: probe-dependent]

Ruiz & Huterer, 2015

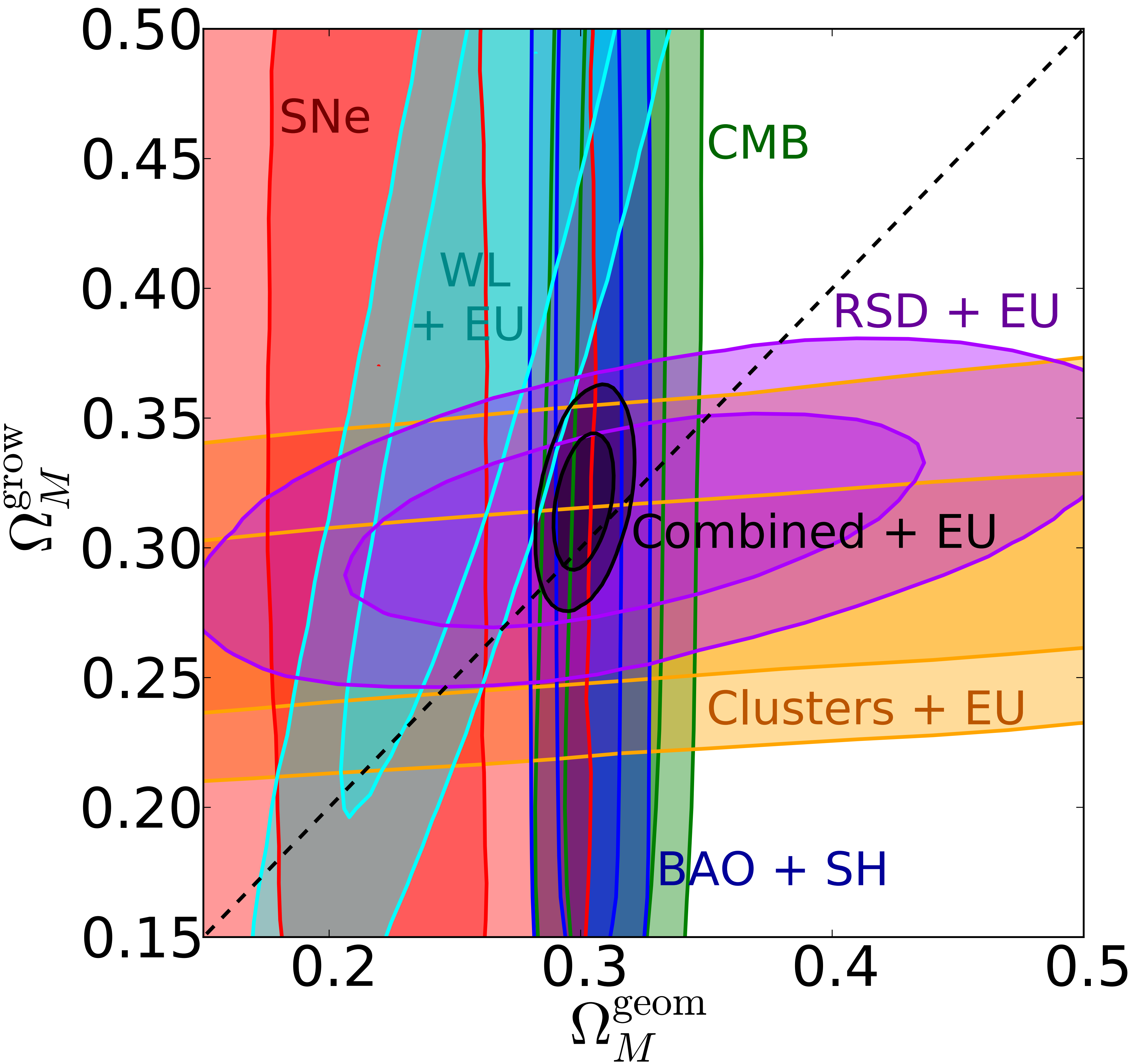
Standard parameter space



EU = Early Universe prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$, n_s, A)

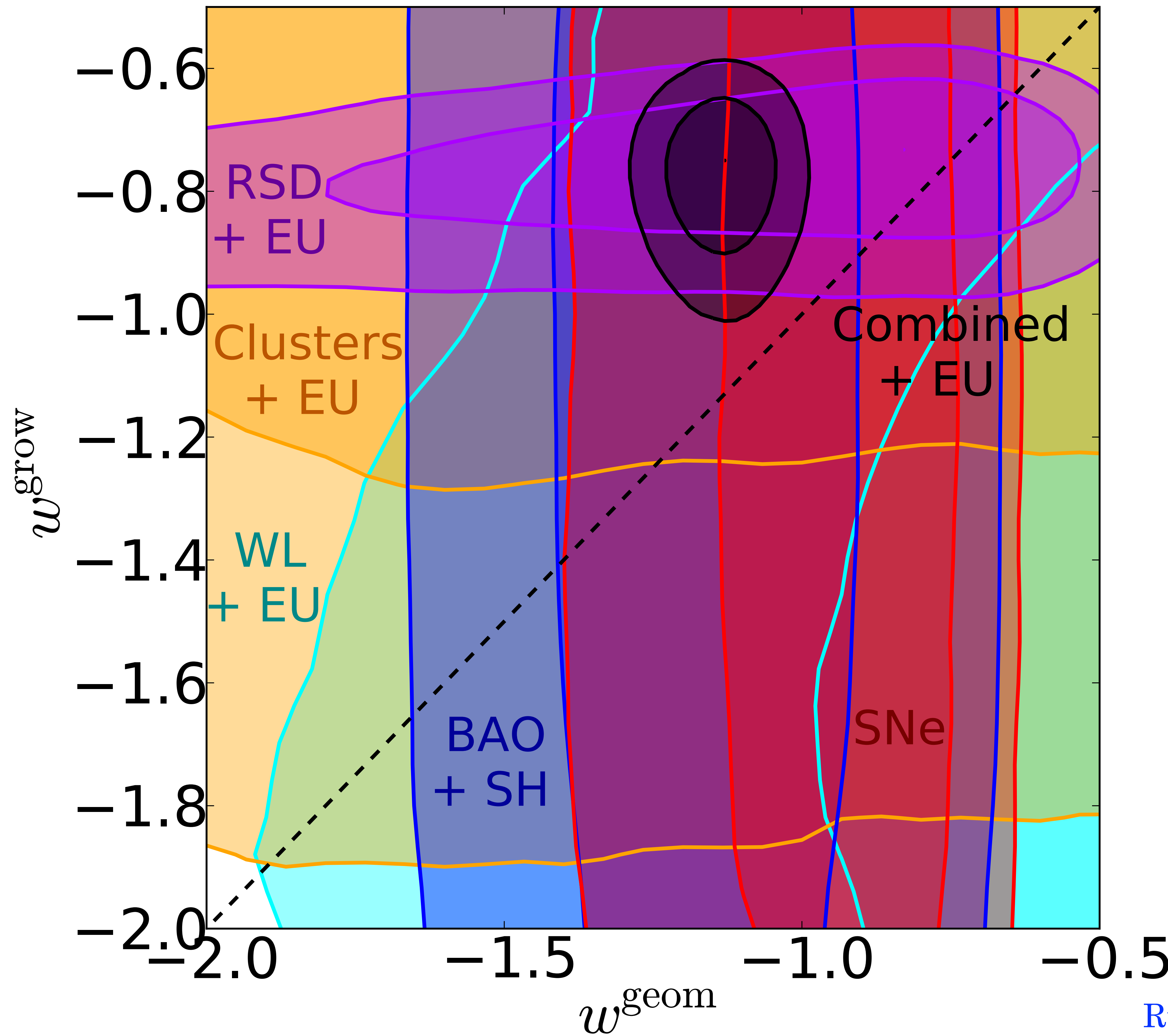
SH = Sound Horizon prior from Planck ($\Omega_M h^2$, $\Omega_B h^2$)

Omega matter: geometry vs. growth



* SN not the recalibrated JLA compilation - need to update; will move $\Omega_M{}^{\rm grow}$ up

w (eq of state of DE): geometry vs. growth



Evidence for $\mathrm{w}^{\mathrm{grow}} > \mathrm{w}^{\mathrm{geom}}$: 3.3-σ

Ruiz & Huterer, 2015

Therefore:
growth probes point to even less growth than LCDM with ~Planck parameters
(i.e. $w^{grow} > -1$)

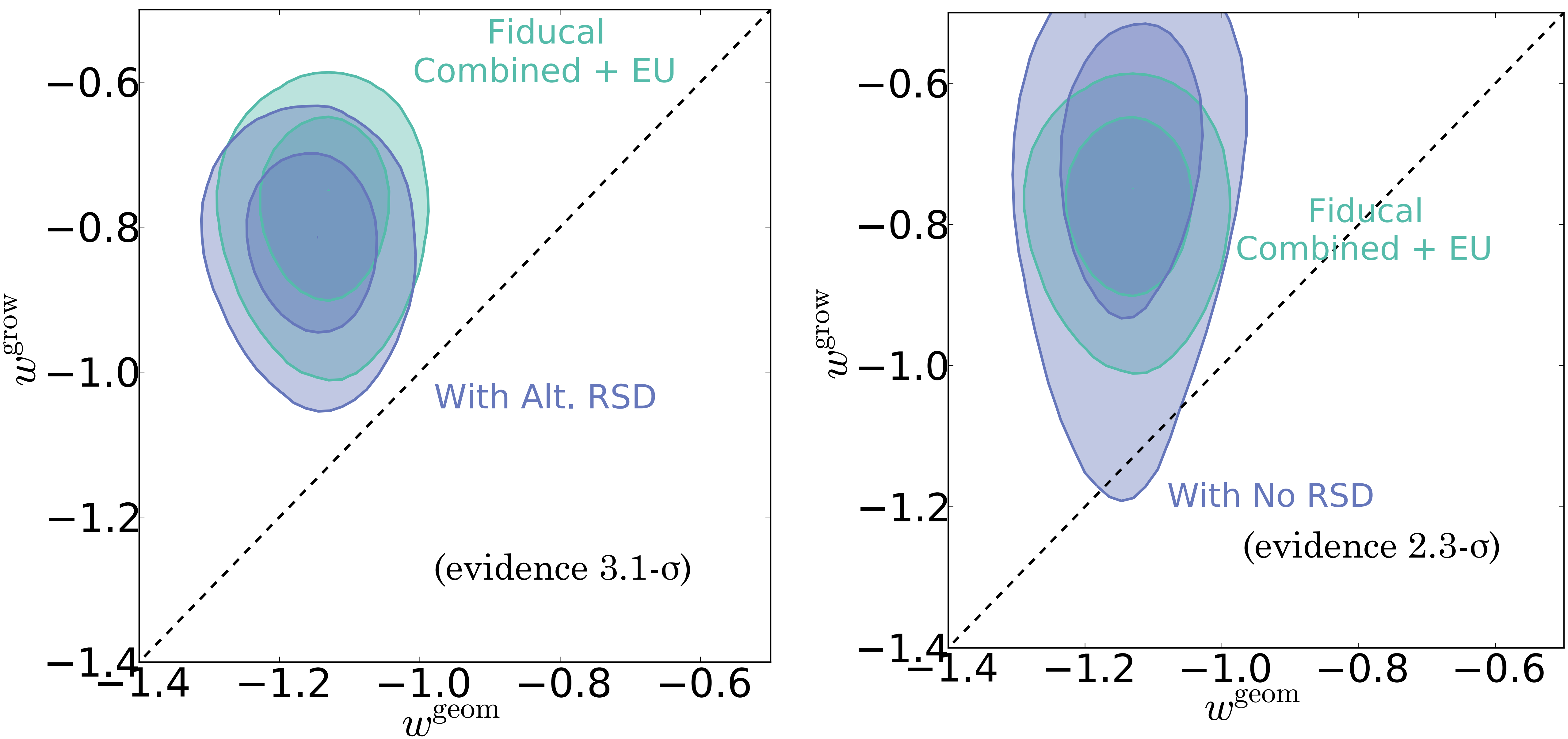
(but the evidence is still not ironclad...)

Probably equivalent to these recent findings:

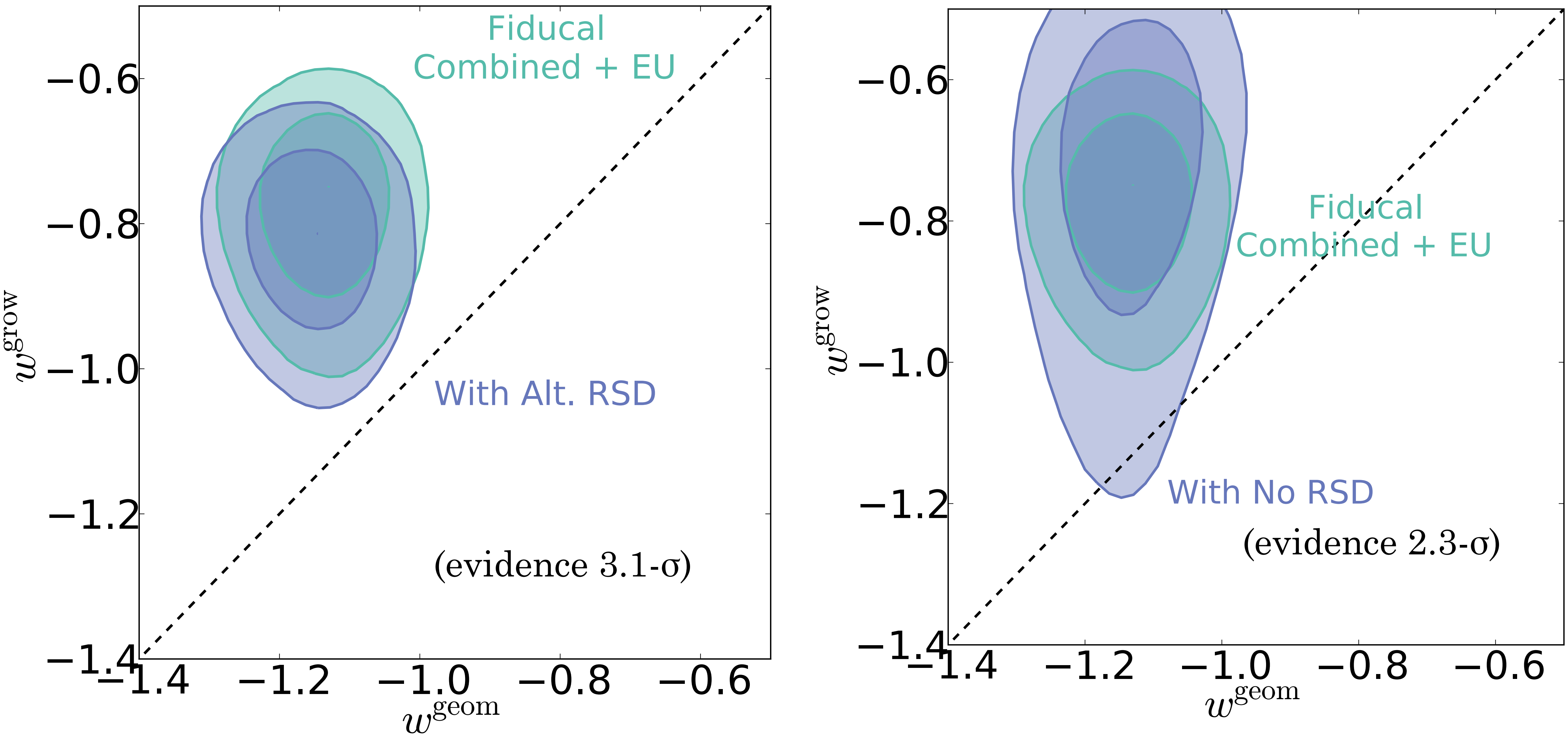
- σ_8 from clusters is lower than that from CMB (eg. Chon & Bohringer, Hou et al, Bocquet et al, Costanzi et al)
- σ_8 from WL is lower than that from CMB (eg. MacCrann et al)
- evidence for neutrino mass (eg. Beutler et al, Dvorkin et al)
- evidence for interactions in the dark energy sector (eg. Salvatelli et al)

also: Battye, Charnock & Moss 2015; Wednesday talk by Tom Charnock

RSD prefer $w^{grow} > -1$ (slower growth than in LCDM)

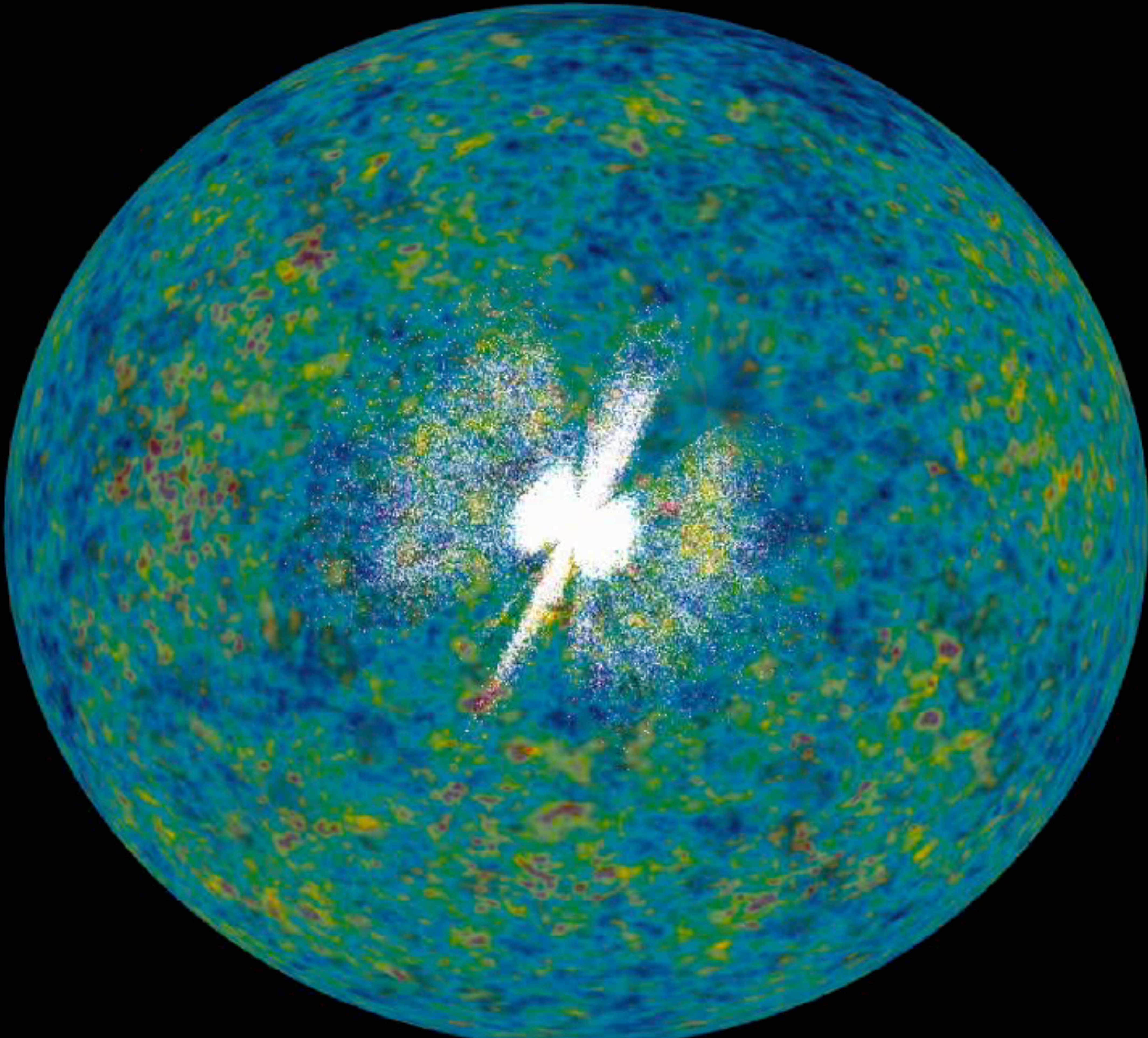


RSD prefer $\mathrm{w}^{\mathrm{grow}} > -1$ (slower growth than in LCDM)

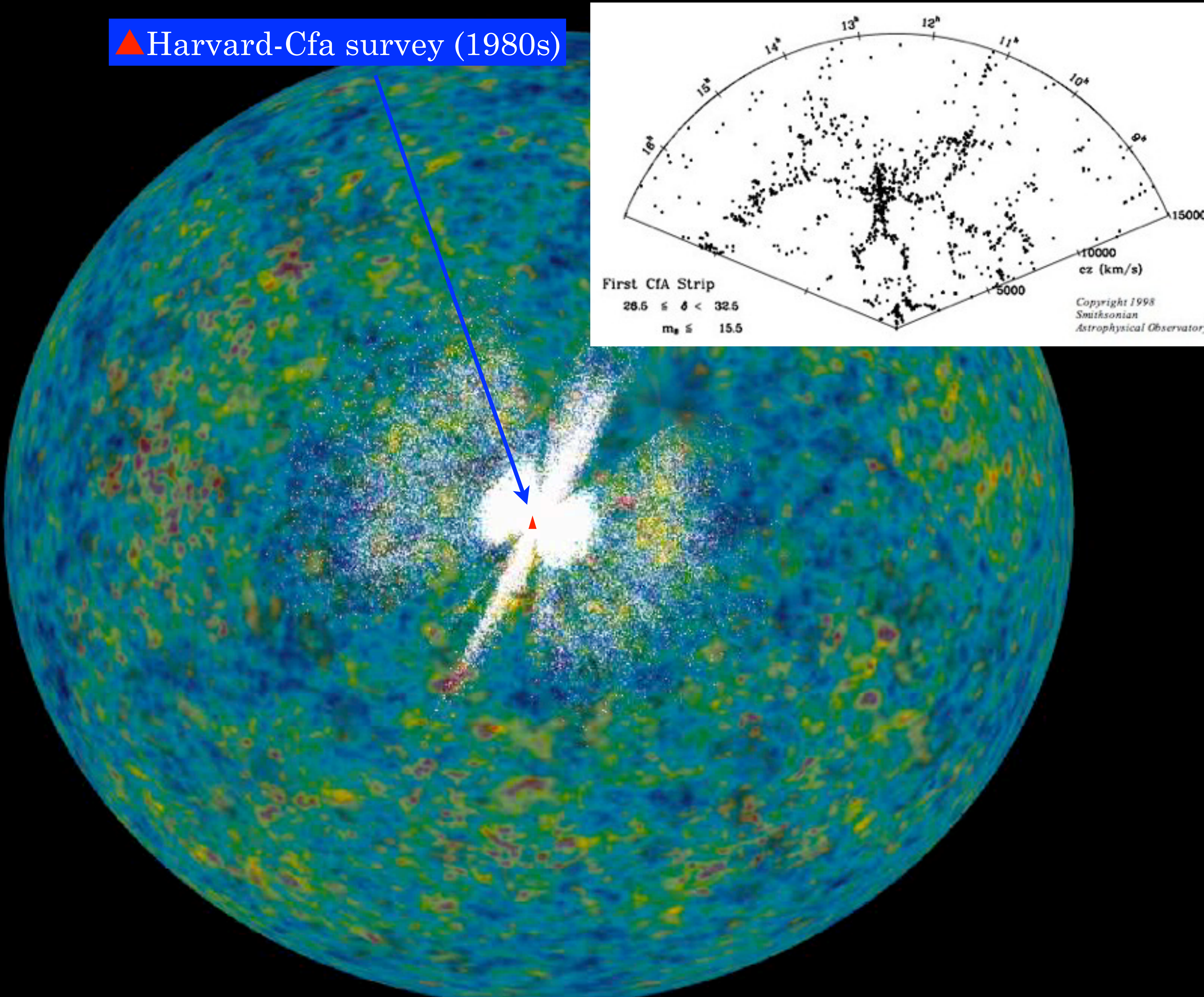


"Are there cracks in the Cosmic Egg?"

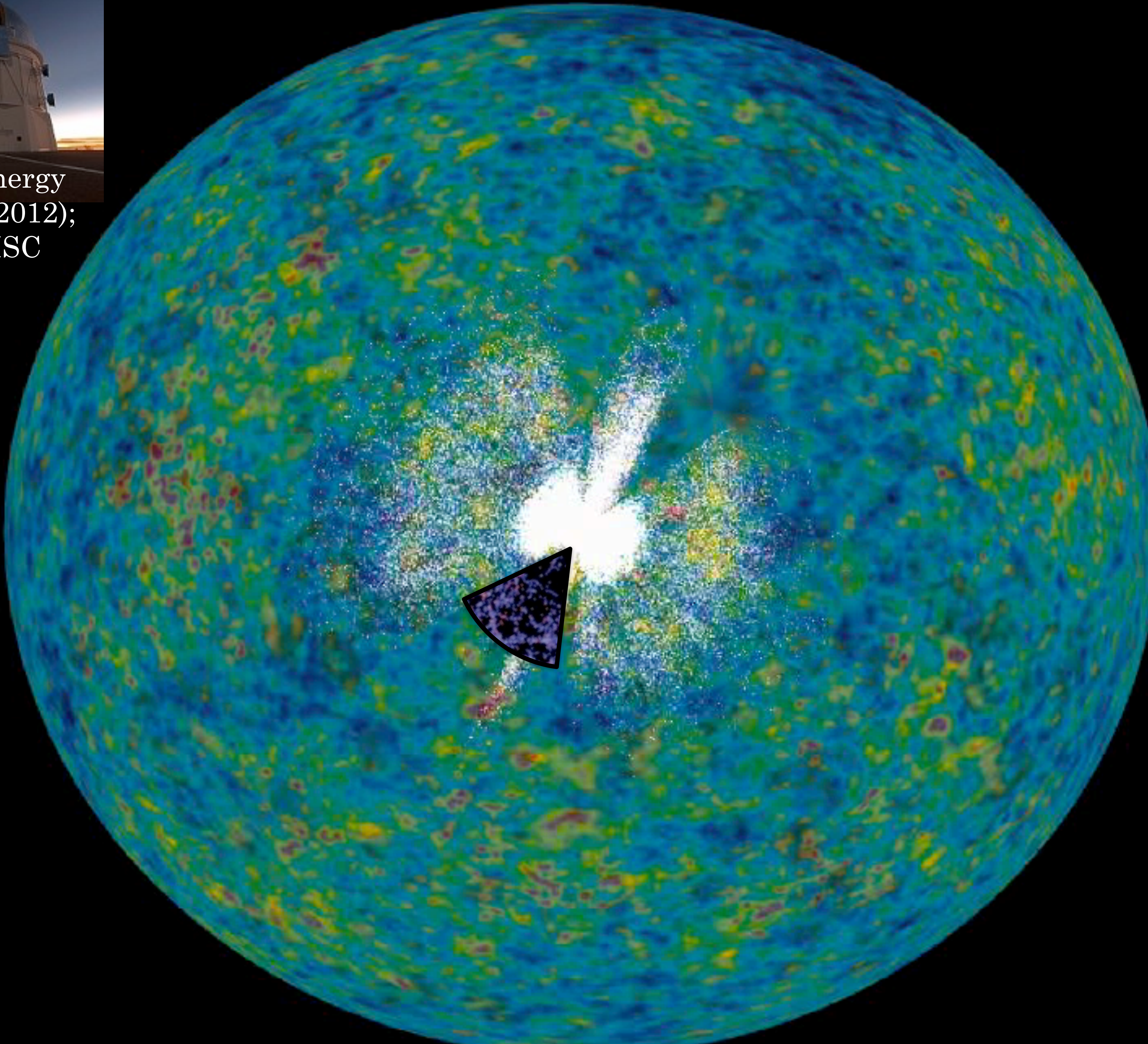
Michael Turner, Aspen, summer 2014



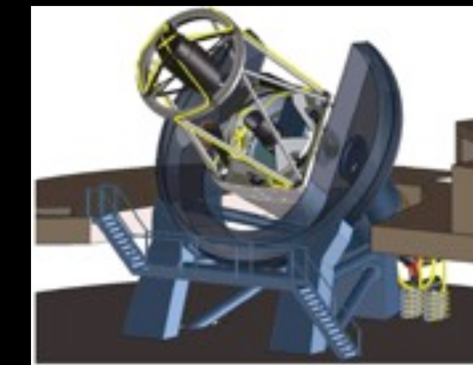
Harvard-Cfa survey (1980s)



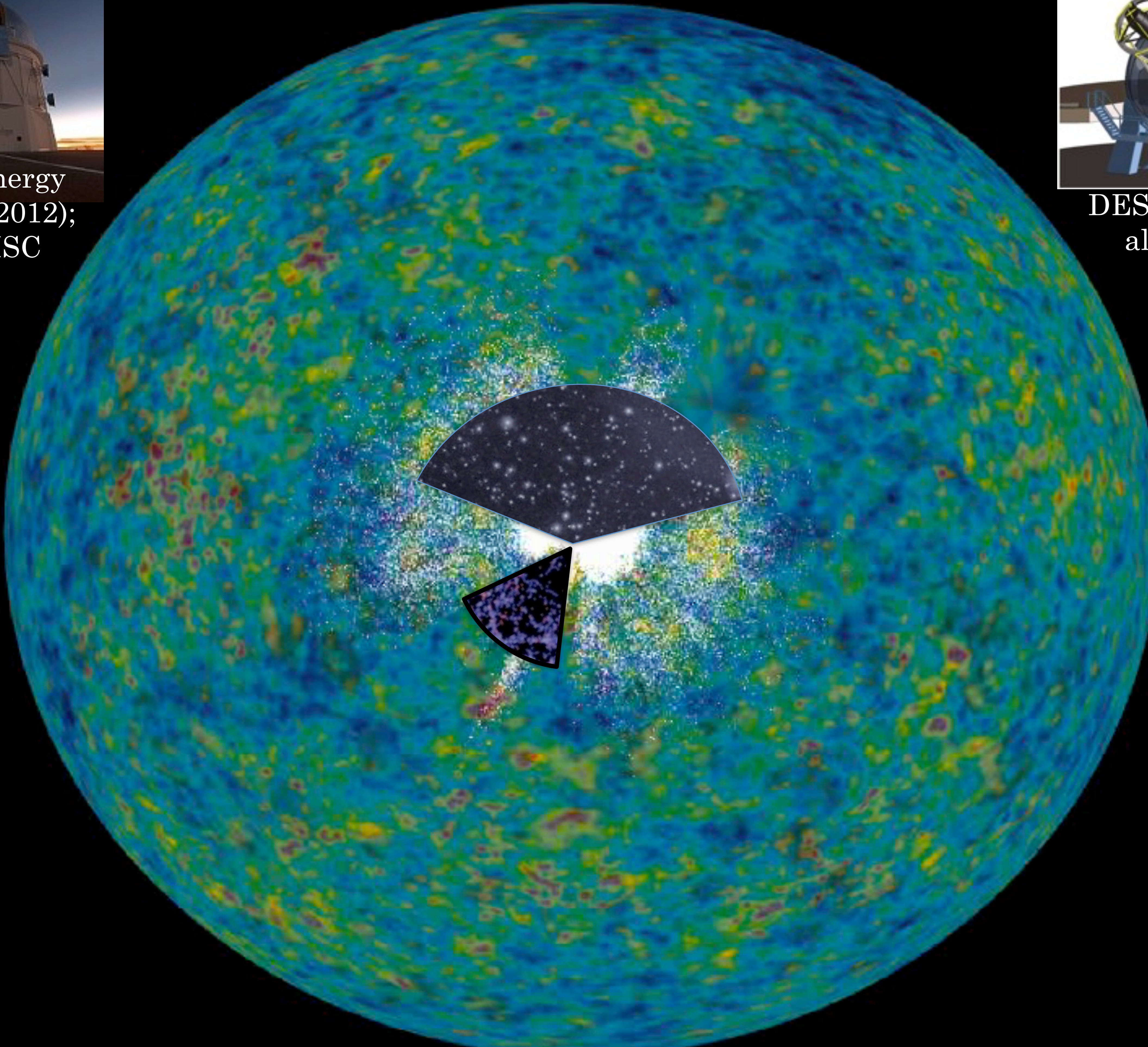
Dark Energy Survey (2012); also HSC



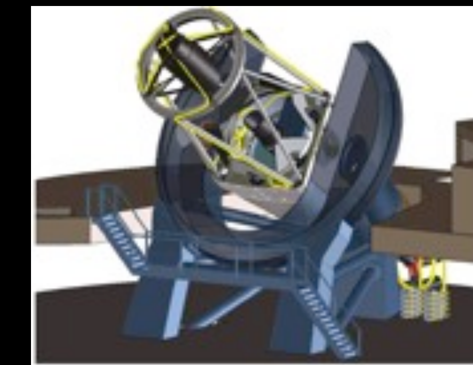
Dark Energy Survey (2012); also HSC



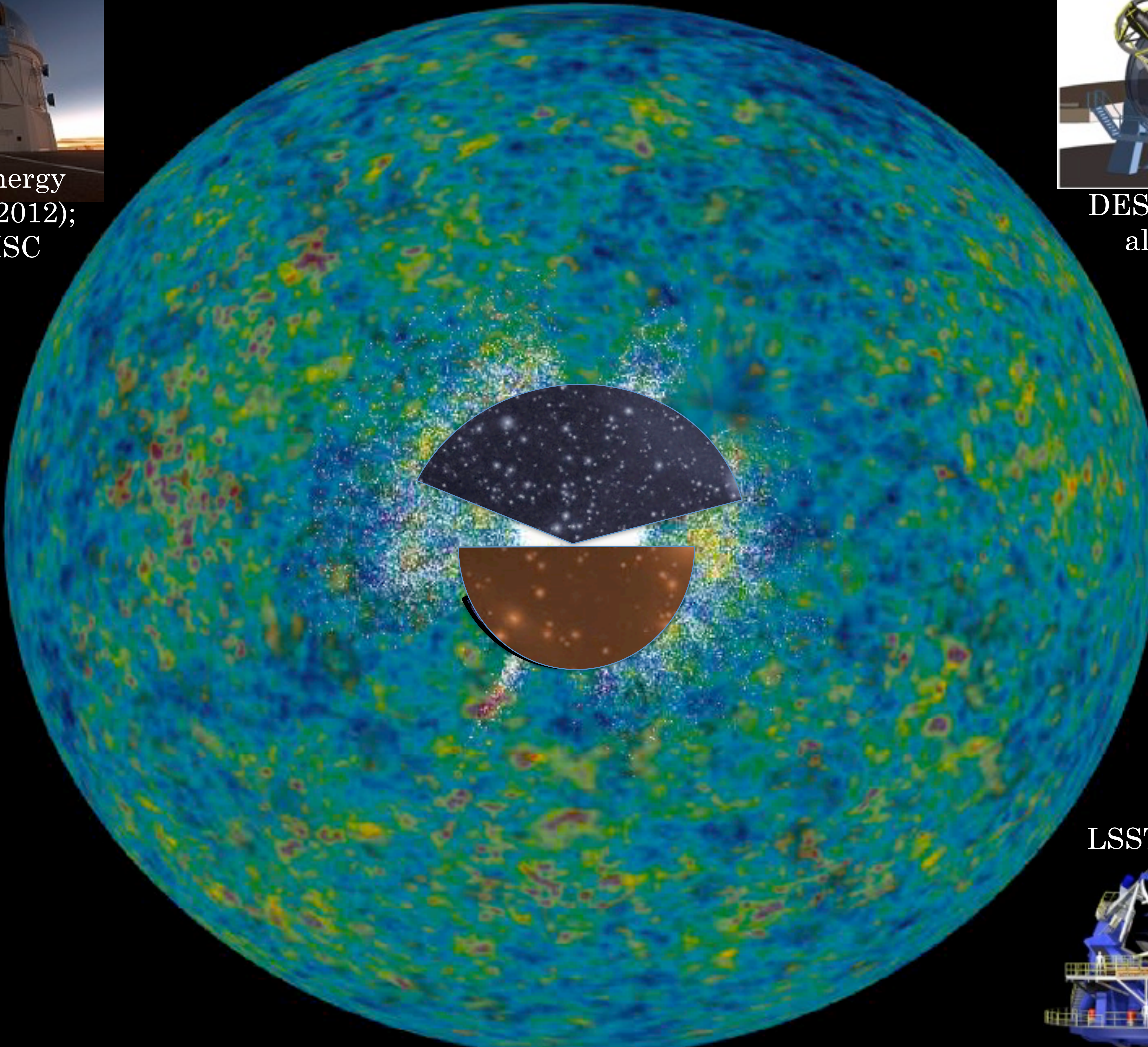
DESI (~2017); also PFS



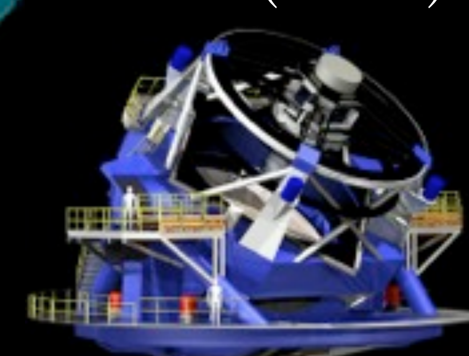
Dark Energy Survey (2012); also HSC

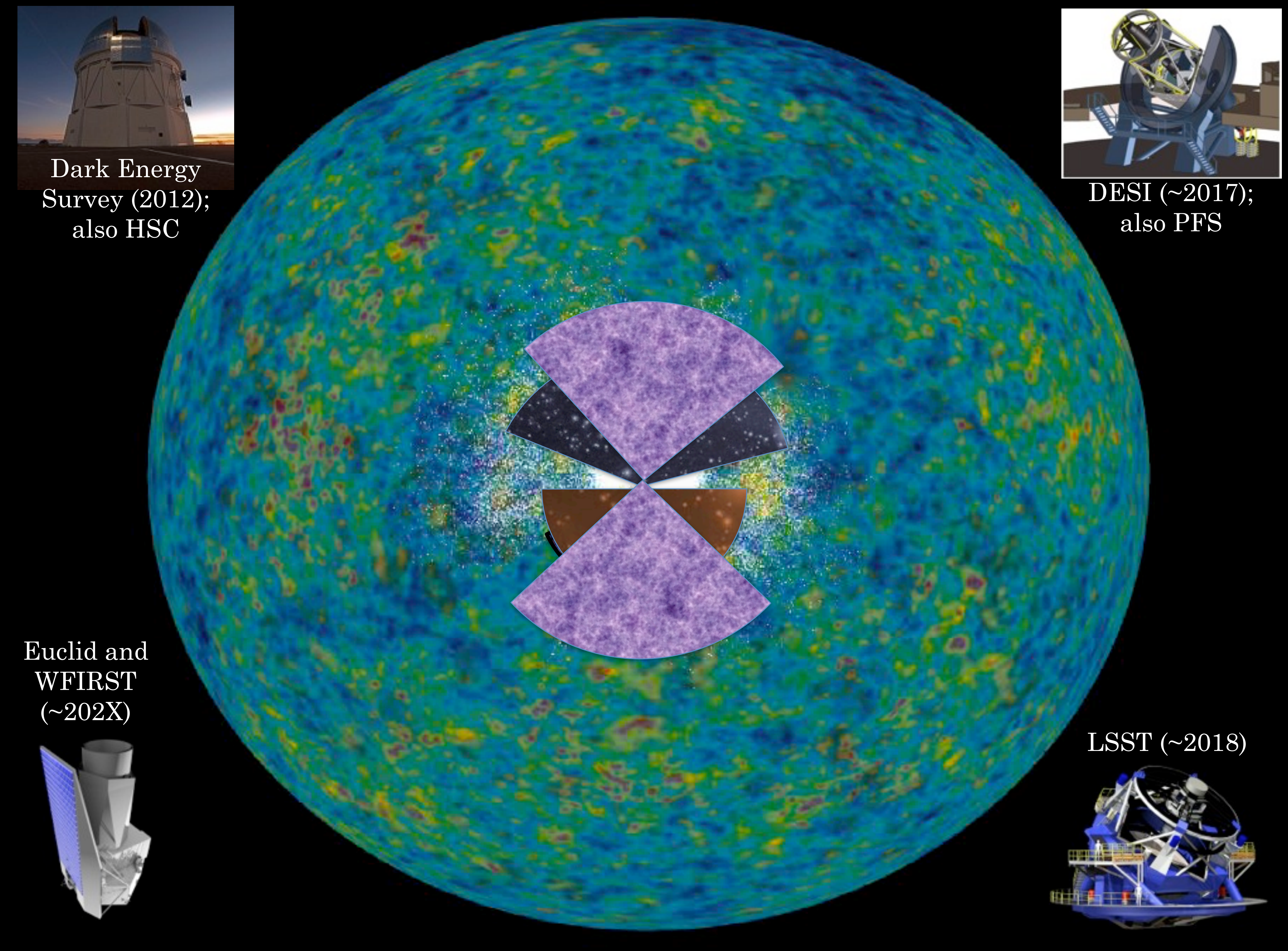


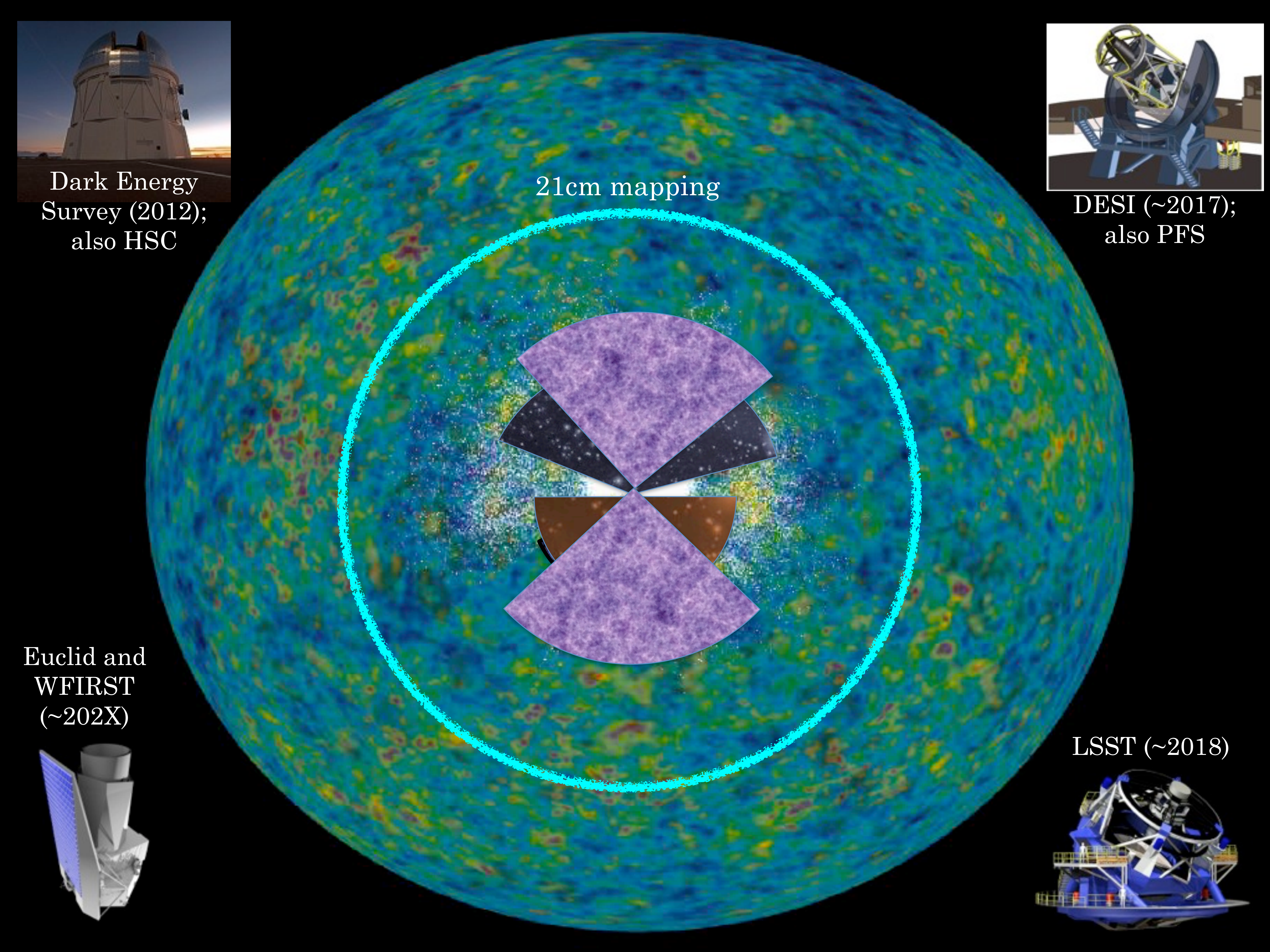
DESI (~2017); also PFS



LSST (~2018)




Dark Energy Survey (2012); also HSC
DESI (~2017); also PFS
Euclid and WFIRST (~202X)
LSST (~2018)



Dark Energy Survey (2012); also HSC
21cm mapping
DESI (~2017); also PFS
Euclid and WFIRST (~202X)
LSST (~2018)

Dark Energy Survey Instrument (**DESI**)

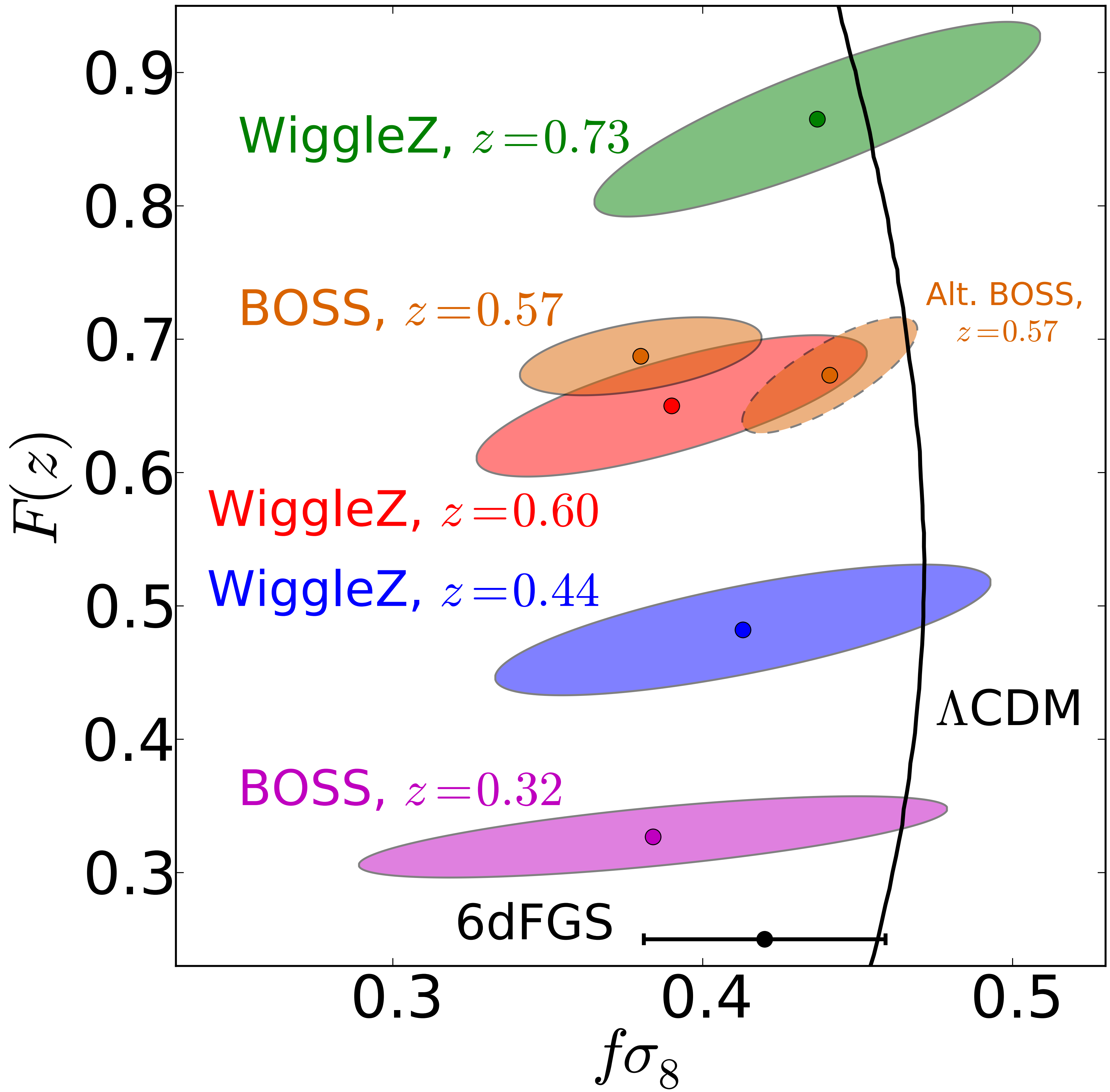
- Huge spectroscopic survey on Mayall telescope (Arizona)
- ~5000 fibres, ~15,000 sqdeg, ~30 million spectra
- LRG in $0 < z < 1$, ELG in $0 < z < 1.5$, QSO $2.2 < z < 3.5$
- Great for dark energy (RSD, BAO)
- Great for primordial non-Gaussianity - $P(k, z)$, bispectrum...
- Start ~2018, funding DOE + institutions

Conclusions

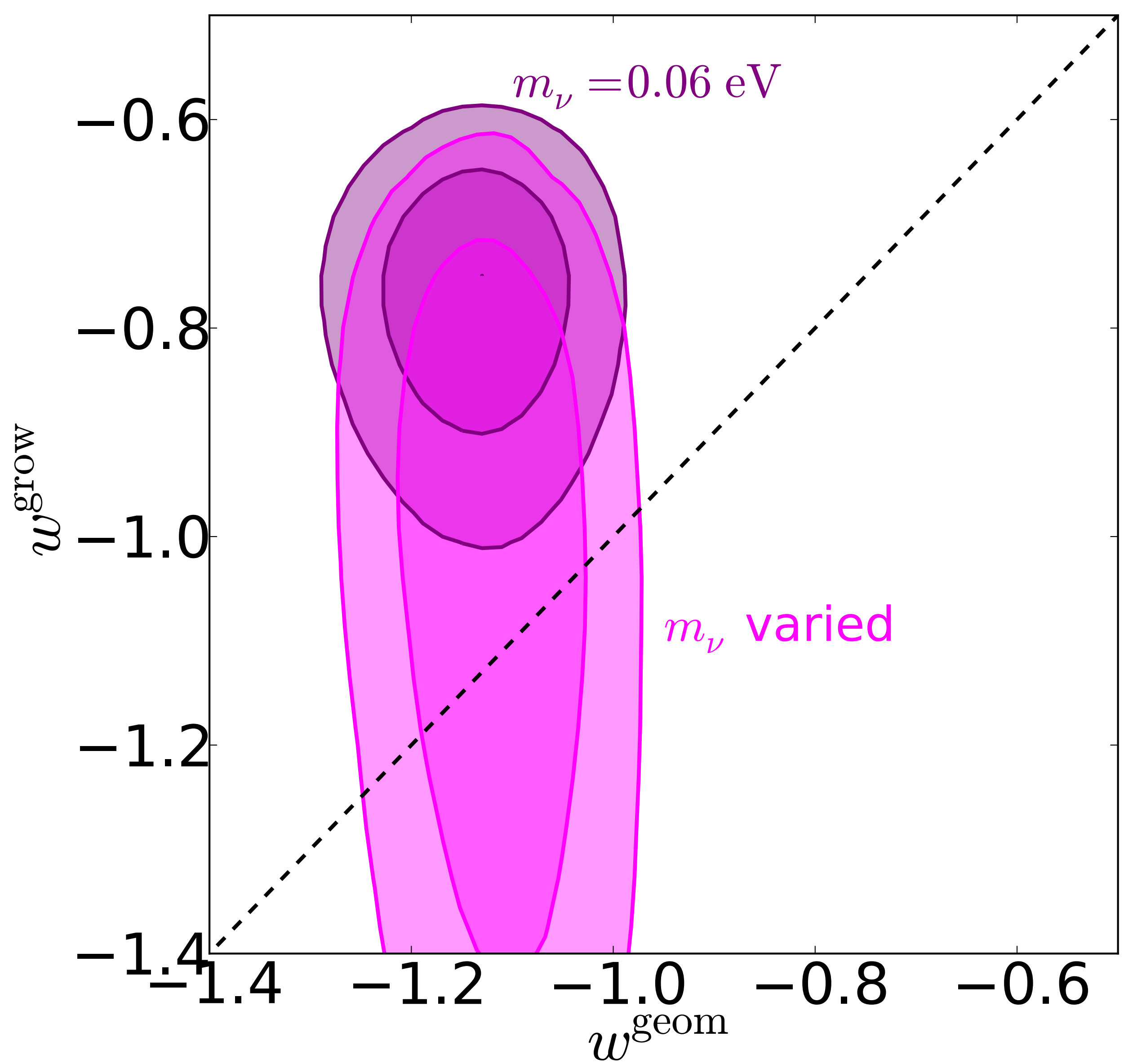
- The physical mechanism behind the accelerating universe is a major mystery linking cosmology, particle physics and astrophysics
- So far, all measurements are in excellent agreement with Lambda* (i.e. $w = -1$)   * except some evidence for growth≠geom
- Separating growth from geometry is a good way to get a) DE constraints b) insights into what data is telling us
- "We shouldn't be afraid of null tests!" (E. Komatsu)

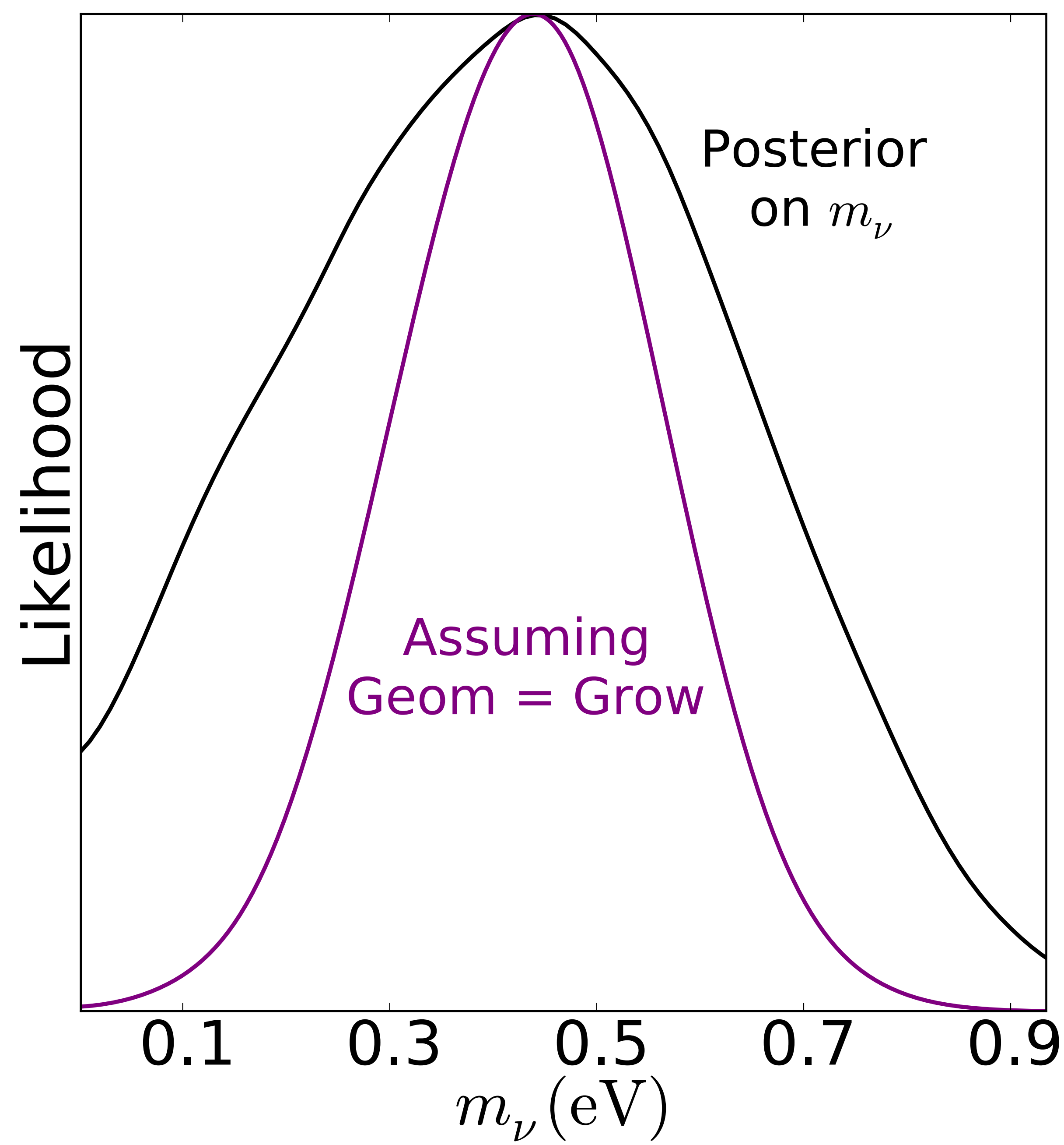
EXTRA SLIDES

Redshift Space Distortion data



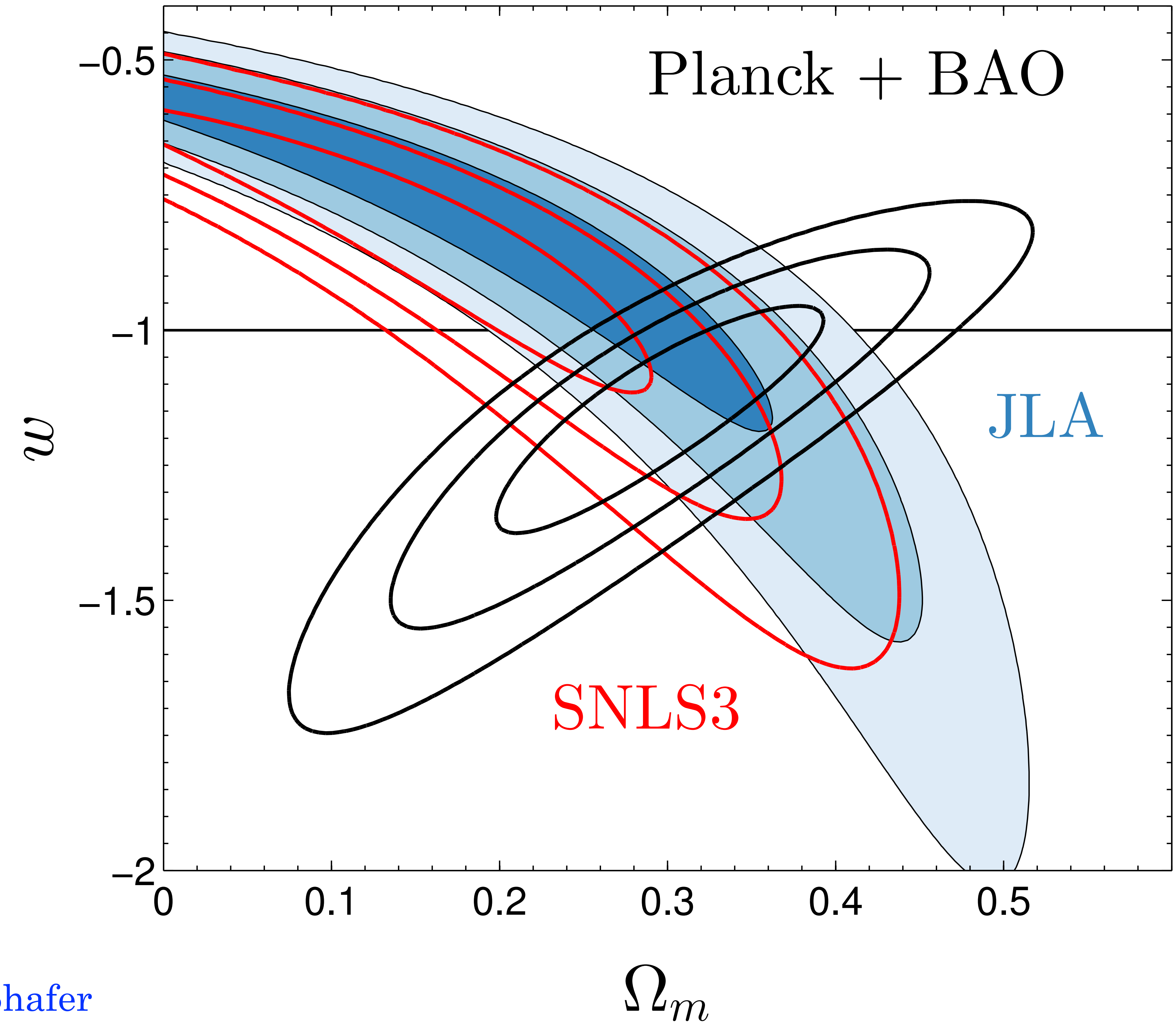
(Pretty high) neutrino mass can relieve the tension





Ruiz & Huterer, arXiv:1410.5832

SN datasets and dark energy constraints



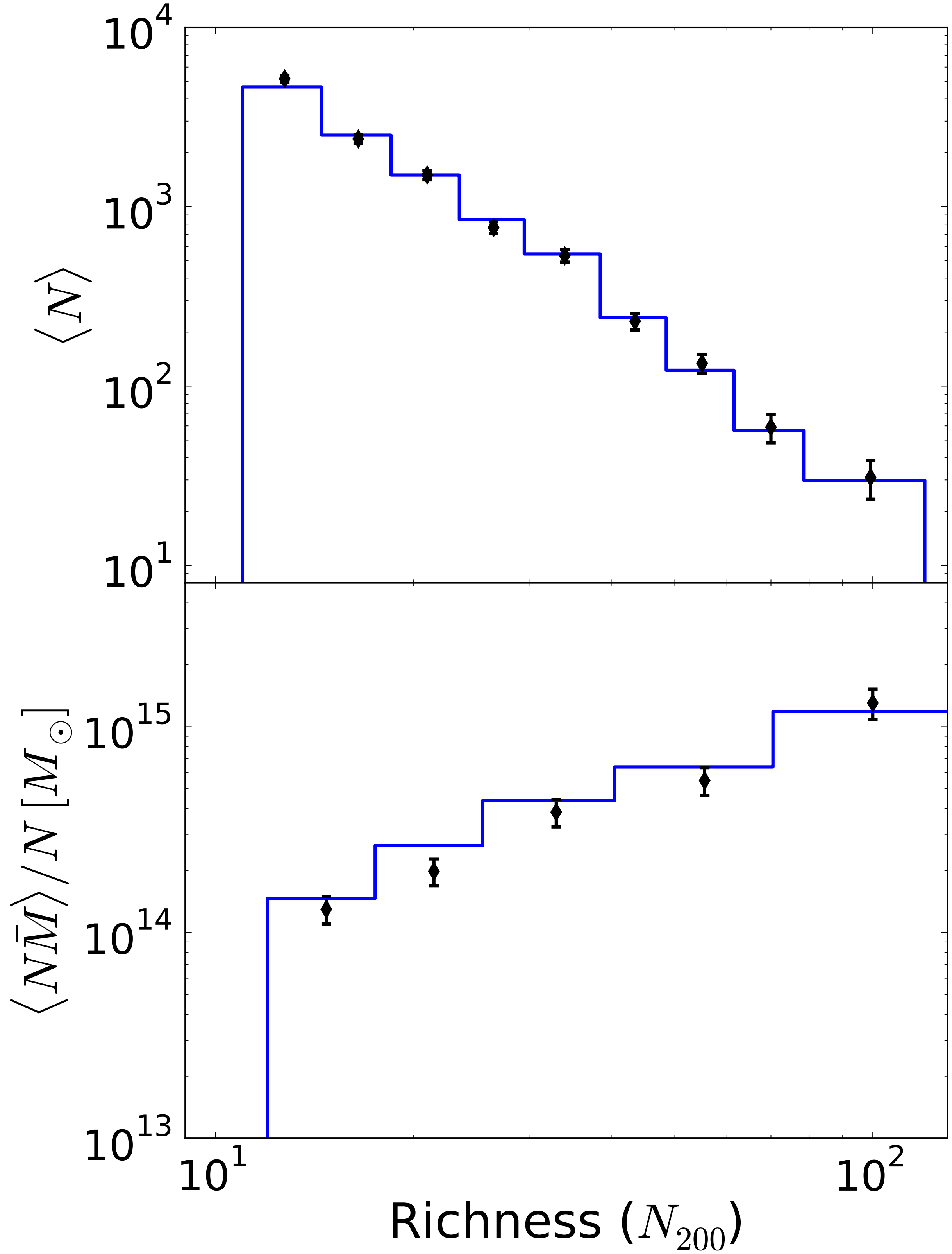
Dan Shafer

BAO data

Survey	$z_{\rm eff}$	Parameter	Measurement
6dFGS [33]	0.106	r_s/D_V	0.336 ± 0.015
SDSS LRG [34]	0.35	D_V/r_s	8.88 ± 0.17
BOSS CMASS [35]	0.57	D_V/r_s	13.67 ± 0.22

TABLE III. BAO data measurements used here, together with the effective redshift for the corresponding galaxy sample.

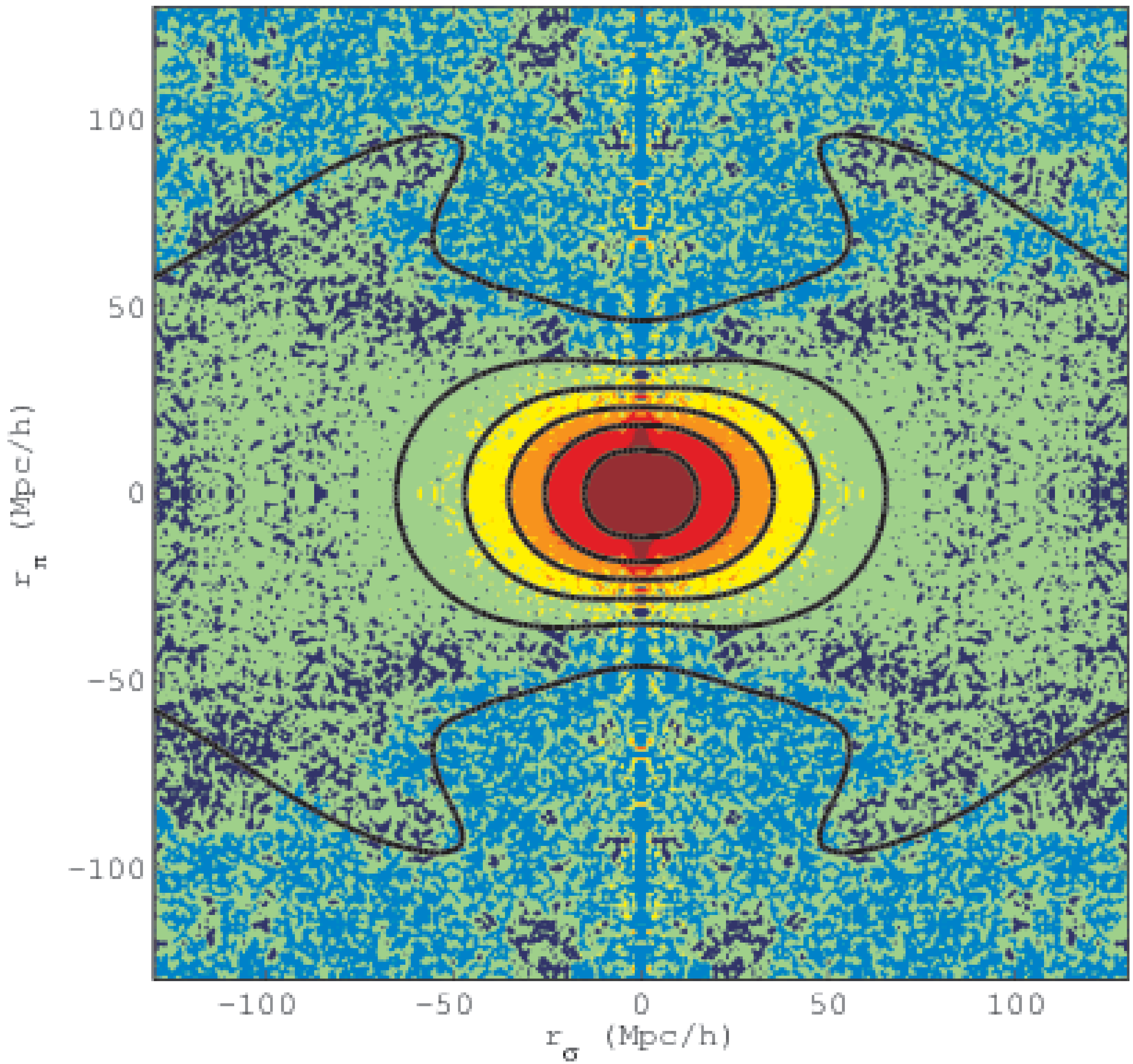
Cluster data



Richness bin	No. of Clusters	$\langle M_{200b} \rangle [10^{14} M_\odot]$
12-17	5651	1.298
18-25	2269	1.983
26-40	1021	3.846
41-70	353	5.475
71+	55	13.03

TABLE IX. Mean mass (and their number) of clusters with a
richness within the given bin.

RSD (BOSS paper)



Parameter		Unsplit, $w=-1$	Unsplit, w free	Split, $w=-1$	Split, w free
Ω_M	Ω_M^{geom}	0.303 ± 0.008	0.299 ± 0.010	0.302 ± 0.008	0.283 ± 0.011
	Ω_M^{grow}			0.321 ± 0.017	0.311 ± 0.017
$\Omega_M h^2$		0.140 ± 0.001	0.141 ± 0.002	0.140 ± 0.001	0.142 ± 0.002
$\Omega_b h^2$		0.0221 ± 0.0002	0.0220 ± 0.0003	0.0221 ± 0.0002	0.0221 ± 0.0003
w	w^{geom}	—	-1.03 ± 0.05	—	-1.13 ± 0.06
	w^{grow}			—	-0.77 ± 0.08
$10^9 A$		1.95 ± 0.09	1.91 ± 0.10	1.96 ± 0.09	2.17 ± 0.13
n_s		0.961 ± 0.005	0.959 ± 0.006	0.962 ± 0.005	0.961 ± 0.006
σ_8		0.786 ± 0.015	0.788 ± 0.016	0.782 ± 0.016	0.771 ± 0.017
h		0.680 ± 0.006	0.687 ± 0.012	0.661 ± 0.017	0.677 ± 0.018
α_s		1.44 ± 0.11	1.44 ± 0.11	1.44 ± 0.11	1.44 ± 0.11
β_c		3.26 ± 0.11	3.26 ± 0.11	3.26 ± 0.11	3.27 ± 0.11
$\ln(N\|M_1)$		2.36 ± 0.06	2.37 ± 0.06	2.29 ± 0.08	2.33 ± 0.08
$\ln(N\|M_2)$		4.15 ± 0.09	4.16 ± 0.09	4.09 ± 0.11	4.15 ± 0.11
σ_{NM}		0.359 ± 0.057	0.357 ± 0.057	0.378 ± 0.059	0.367 ± 0.060
β		1.041 ± 0.050	1.045 ± 0.051	1.018 ± 0.054	1.036 ± 0.055
σ_{MN}		0.462 ± 0.081	0.459 ± 0.082	0.486 ± 0.085	0.464 ± 0.084