Physics of
Cosmic Acceleration

4. Chasing Down Cosmic Acceleration

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II Tiomno School (Rio 2012)

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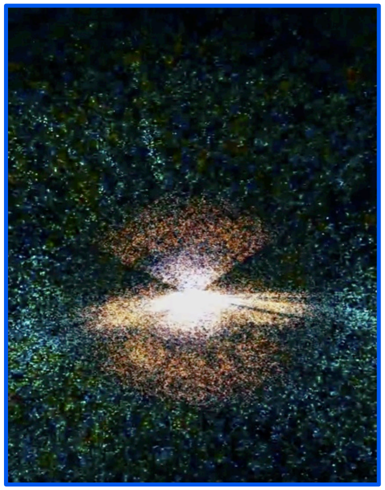


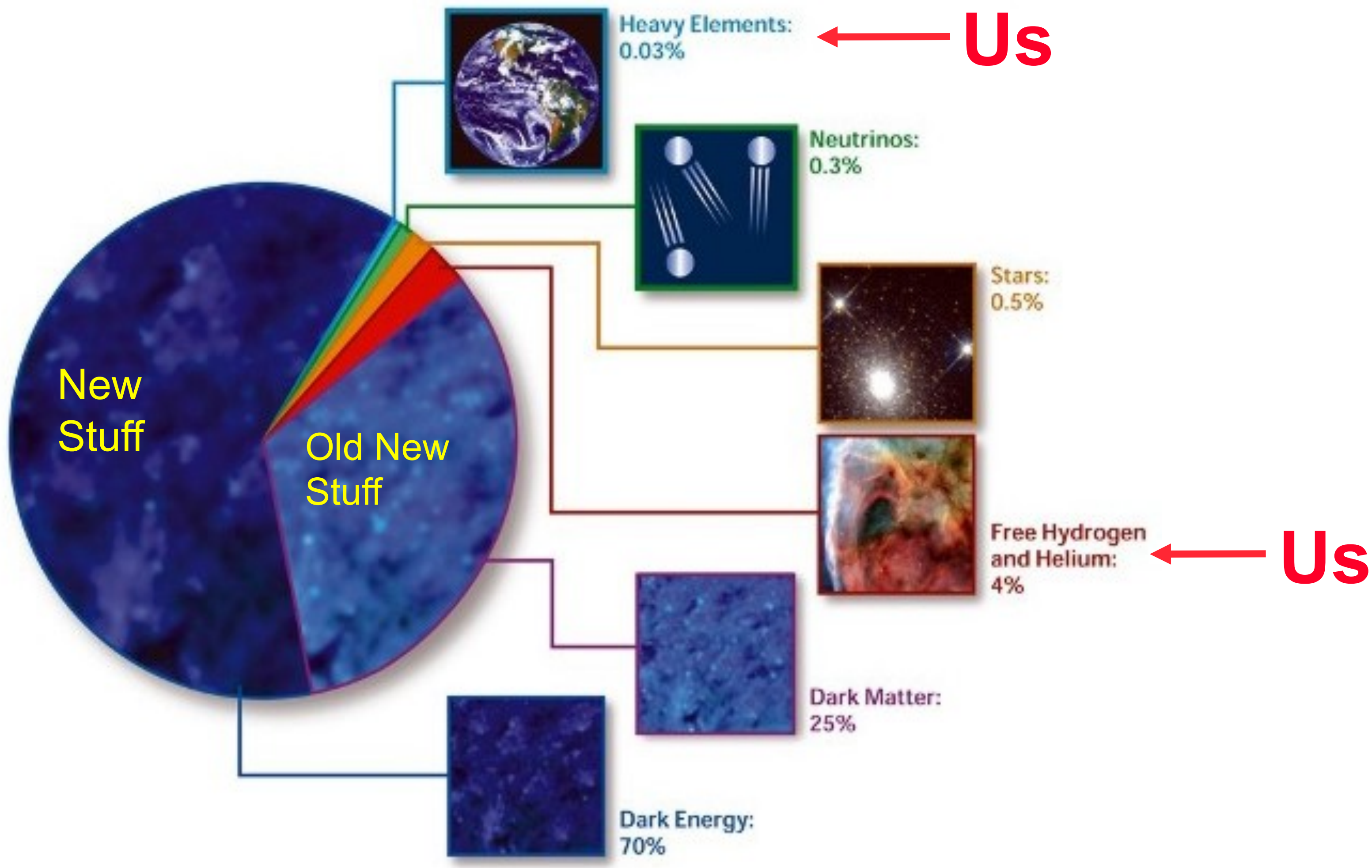
Role of Observations

O
Chapeuzinho
Vermelho

But Λ, what big teeth you have!

Before we jump into bed with Λ, we should be sure it is not something more beastly.

Describing Our Universe

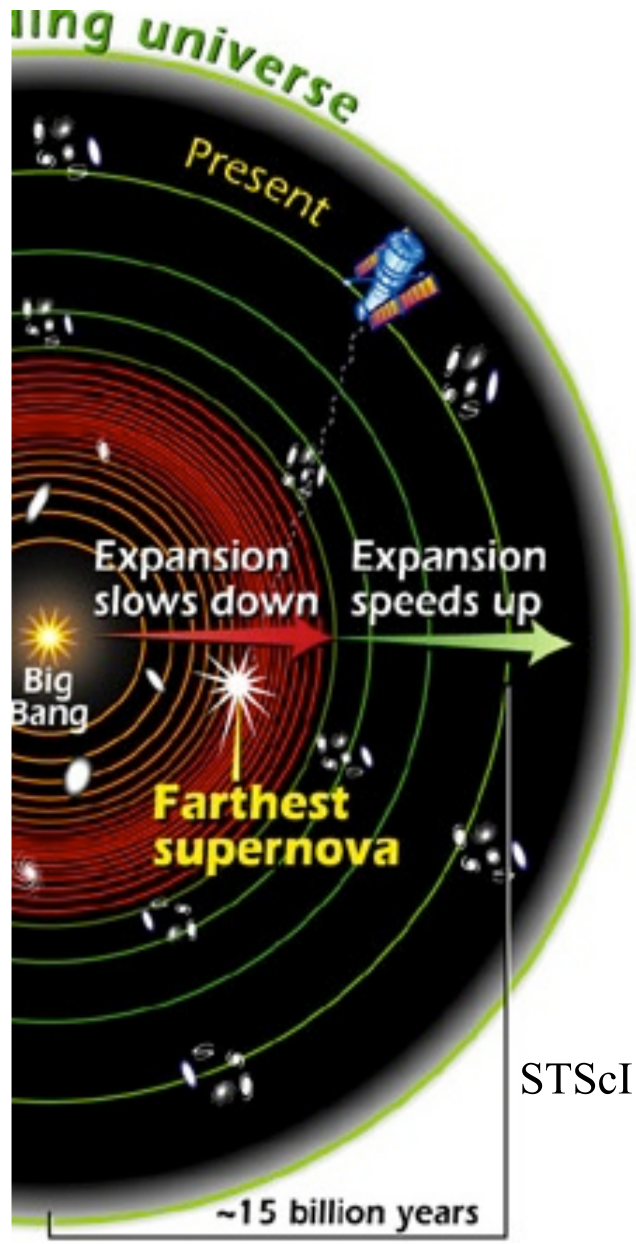


STScI

95% of the universe is unknown!

Mapping Our History

The subtle slowing down and speeding up of the expansion, of distances with time: a(t), maps out cosmic history like tree rings map out the Earth's climate history.



STScI

Dark Energy as a Teenager

14 years after discovery of the acceleration of the universe, where are we?

From 60 Supernovae Ia at cosmic distances, we now have ~800 published distances, with better precision, better accuracy, out to z=1.75.

CMB *and its lensing* points to acceleration. (Didn't even have acoustic peak in 1998.) Das+ 2011, Sherwin+ 2011, Keisler+ 2011, van Engelen+ 2012

BAO detected. Concordant with acceleration.

Weak lensing detected. Concordant with acceleration.

Cluster masses (*if* asystematic) ~1.5σ for acceleration.

Strong concordance among data: Ω_{DE}~0.73, w~-1.

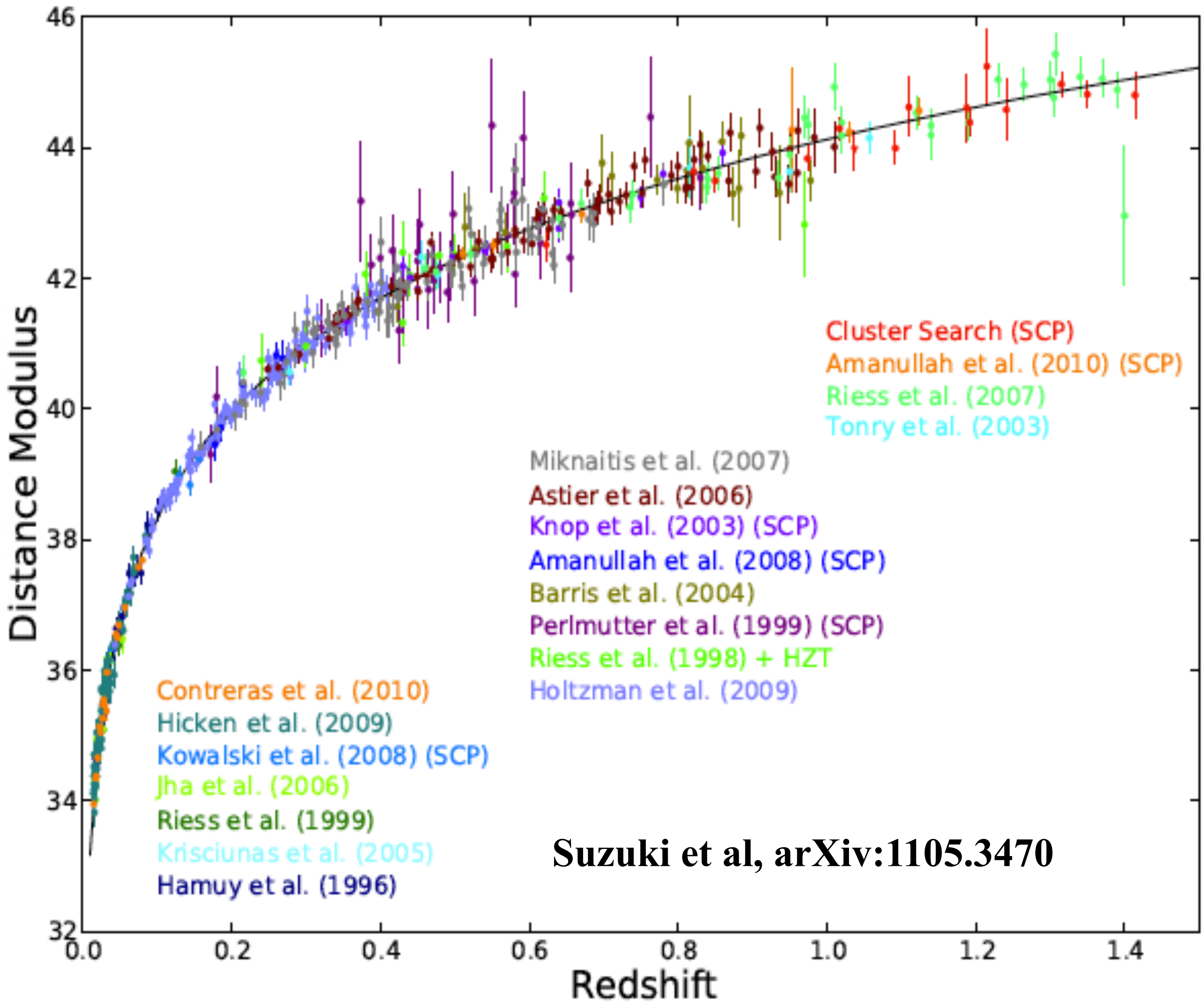
Latest Data

Union2.1 SN Set

- Complete SALT2 reanalysis, refitting 17 data sets
- 580 SNe Ia (166+414) - new z>1 SN, HST recalib
- Fit ΔM_i between sets and between low-high z
- Study of set by set deviations (residuals, color)
- Blind cosmology analysis!
- Systematic errors as full covariance matrix

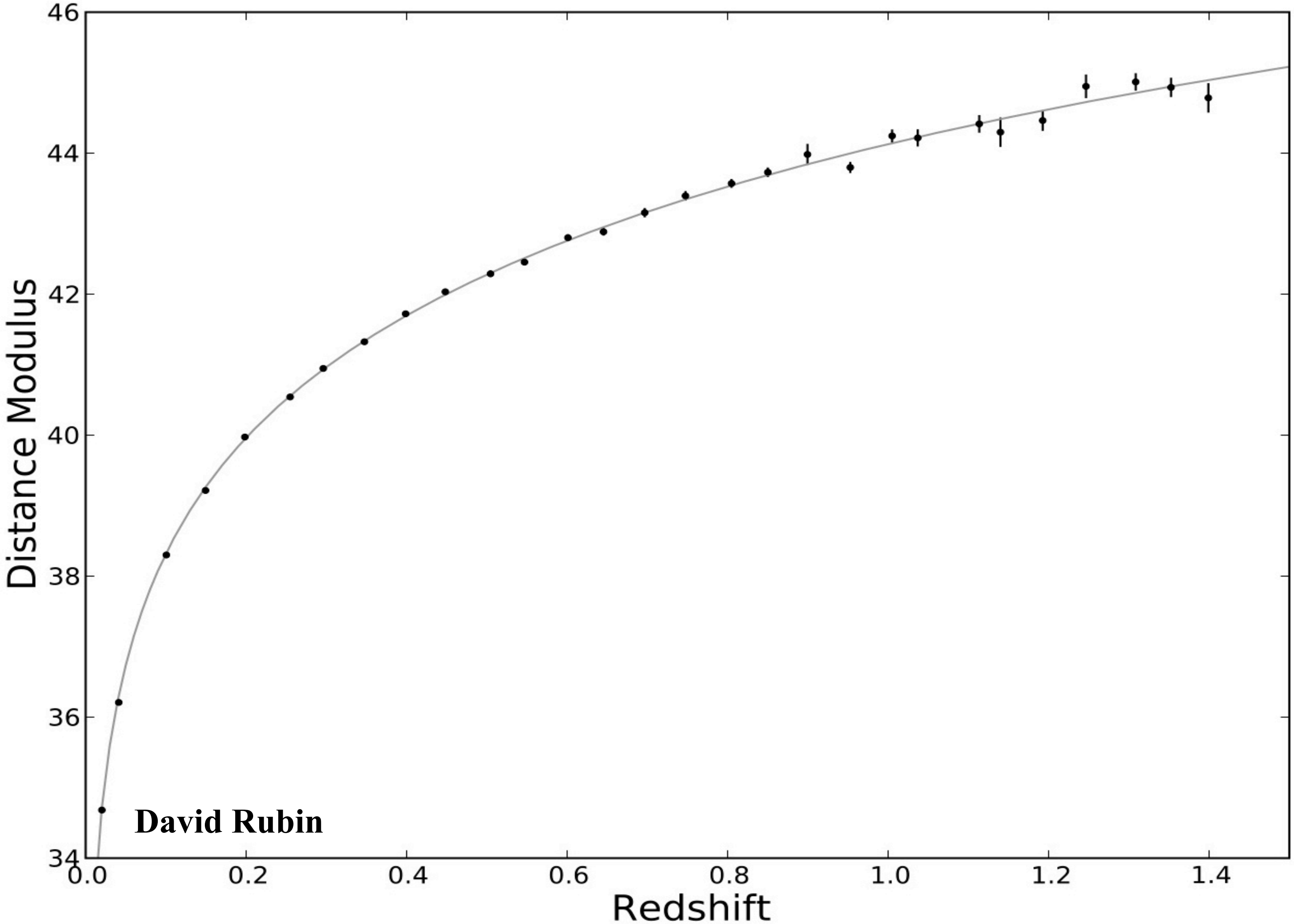
Suzuki et al, ApJ 2012, arXiv:1105.3470

Latest Data



Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
Suzuki et al, arXiv:1105.3470

Latest Data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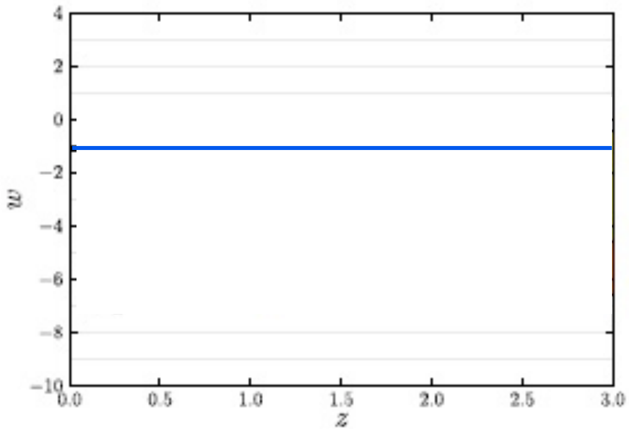
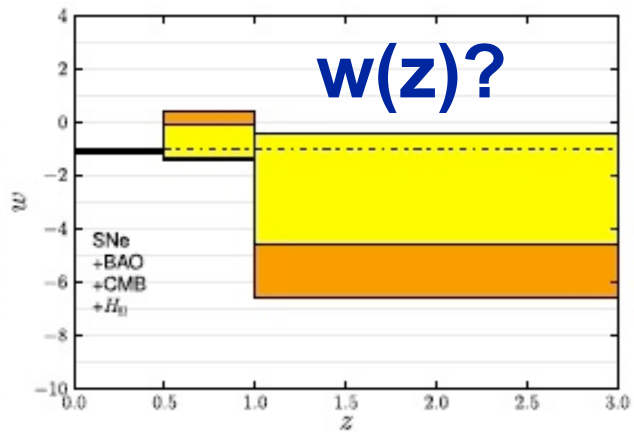
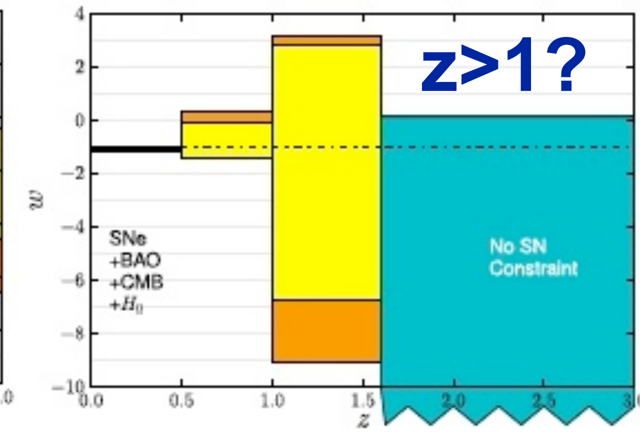
1.4
David Rubin

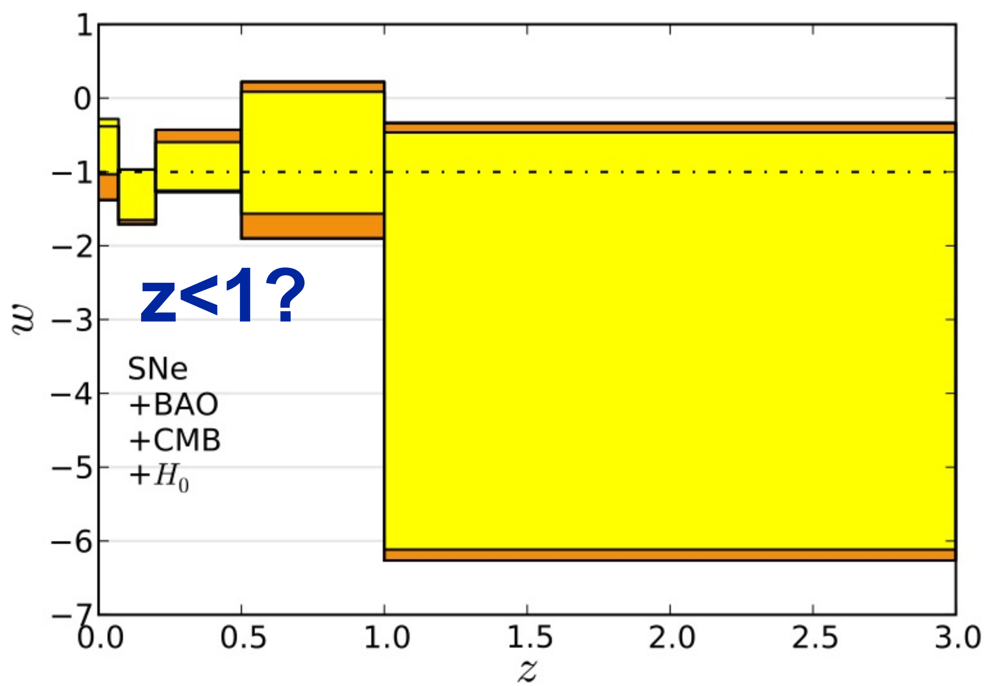
Are We Done?

$$w = -1.013^{+0.068}_{-0.073} \quad \text{(stat+sys)}$$





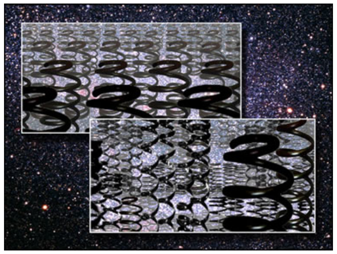




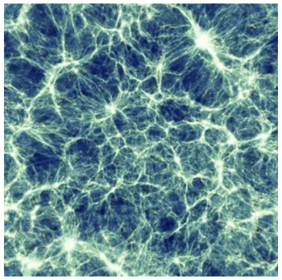
There is a long way to go still to say we have measured dark energy!

Dark Energy Properties

Dark energy is very much *not* the search for one number, "w".



Dynamics: Theories other than Λ give time variation $w(z)$. Form $w(z)=w_0+w_a z/(1+z)$ accurate to 0.1% in observable.



Degrees of freedom: Quintessence determines sound speed $c_s^2=1$. Barotropic DE has $c_s^2(w)$. But generally have $w(z)$, $c_s^2(z)$. Is DE cold ($c_s^2\ll 1$)? Cold DE enhances perturbations.

Persistence: Is there early DE (at $z\gg 1$)? $\Omega_\Lambda(z_{CMB})\sim 10^{-9}$ but observations allow 10^{-2}.

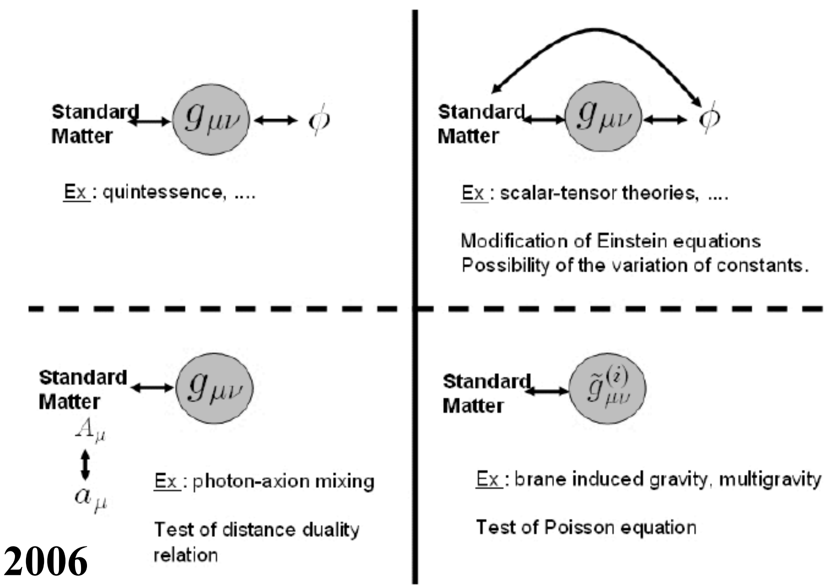
Beyond Einstein Gravity

Expansion is not the only determiner of growth of massive structure. "The Direction of Gravity"

Metric fluctuations: $\phi \xrightarrow{\text{Anisotropic Stress/Gravitational Slip}} \psi$

Energy-momentum: $\delta \xrightarrow{\text{Continuity equation}} v$

$$\begin{tikzcd} \phi \arrow[r, "\text{Anisotropic Stress/Gravitational Slip}"] \arrow[d, "\text{Poisson equations}"'] & \psi \arrow[d, "\text{Euler equation}"] \\ \delta \arrow[r, "\text{Continuity equation}"'] & v \end{tikzcd}$$



Uzan 2006

Need to know:

Expansion
DE perturbations
Couplings
Gravity

Observational Leverage

Dynamics: High+low redshift, complementarity (e.g. SN+SL, SN+CMB/BAO)

Degrees of freedom: Sensitivity to perturbations (CMB lensing, Galaxy clustering)

Persistence: High z probes (CMB lensing, Crosscorrelate CMB x Galaxies)

Test Gravity: Expansion vs growth (SN/BAO + CMBlens/Gal/WL)

Very much a *program*:
Multiple, complementary, diverse observations.
Equal weighting of Theory/Simulation/Observation essential.

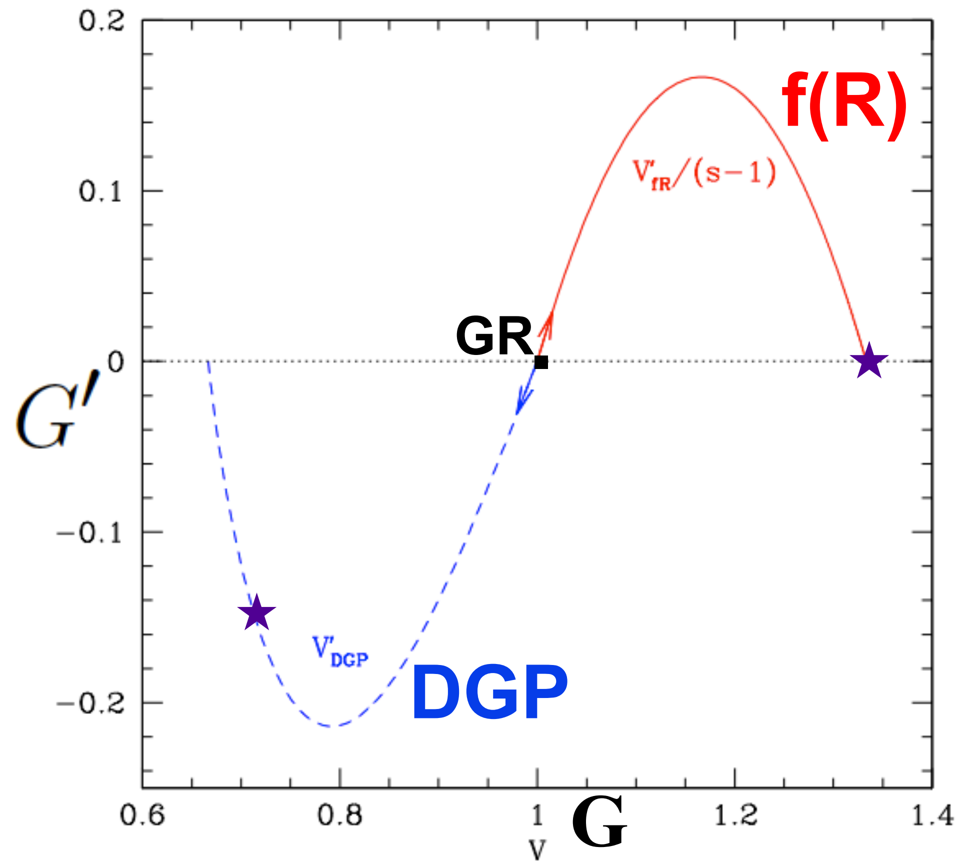
The Direction of Gravity

Scalar field dark energy (and Λ) have problems with **naturalness** of potential and high energy corrections.

Can avoid *both* problems by having a purely **geometric** object with no potential.

Galileon fields arise as geometric objects from higher dimensions and have shift symmetry protection (like DGP).

They also have **screening** (Vainshtein), satisfying GR on small scales.



Nicolis+ 2009, Deffayet+ 2009

Galileon Gravity

Scalar field π with shift symmetry $\pi \rightarrow \pi + c$, derivative self coupling, guaranteeing 2nd order field equations.

$$S = \int d^4x\,\sqrt{-g}\left[\left(1 - 2c_0\frac{\pi}{M_{\rm pl}}\right)\frac{M_{\rm pl}^2 R}{2} - \frac{c_2}{2}(\partial\pi)^2 - \frac{c_3}{M^3}(\partial\pi)^2\Box\pi - \frac{c_4\mathcal{L}_4}{2} - \frac{c_5\mathcal{L}_5}{2} - \frac{M_{\rm pl}}{M^3}c_G G^{\mu\nu}\partial_\mu\pi\partial_\nu\pi - \mathcal{L}_{\rm m}\right]$$

GR

Linear coupling

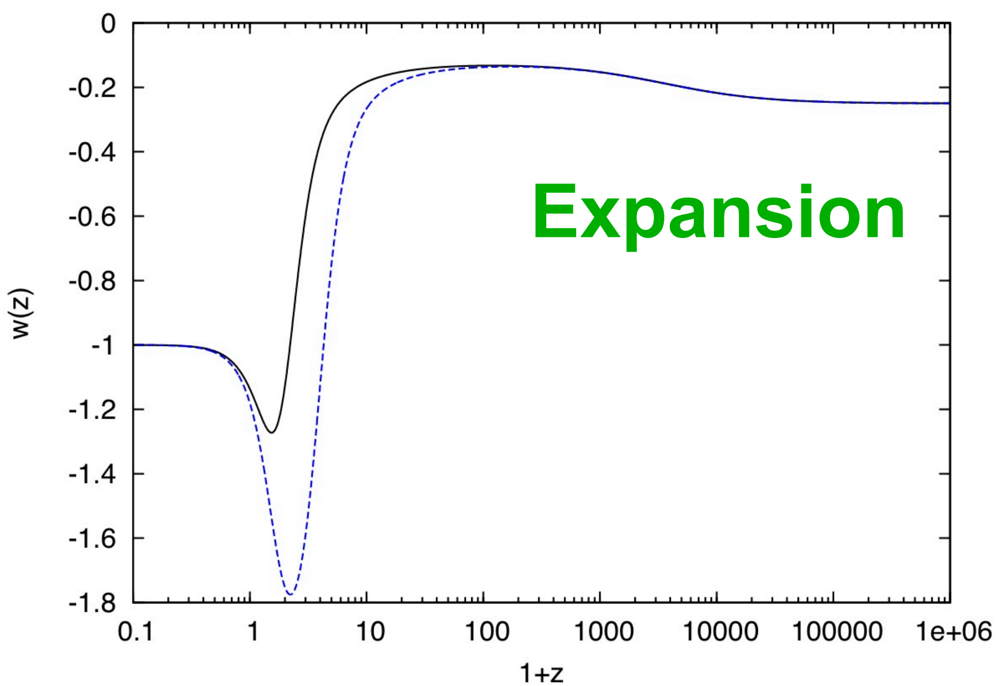
Standard Galileon

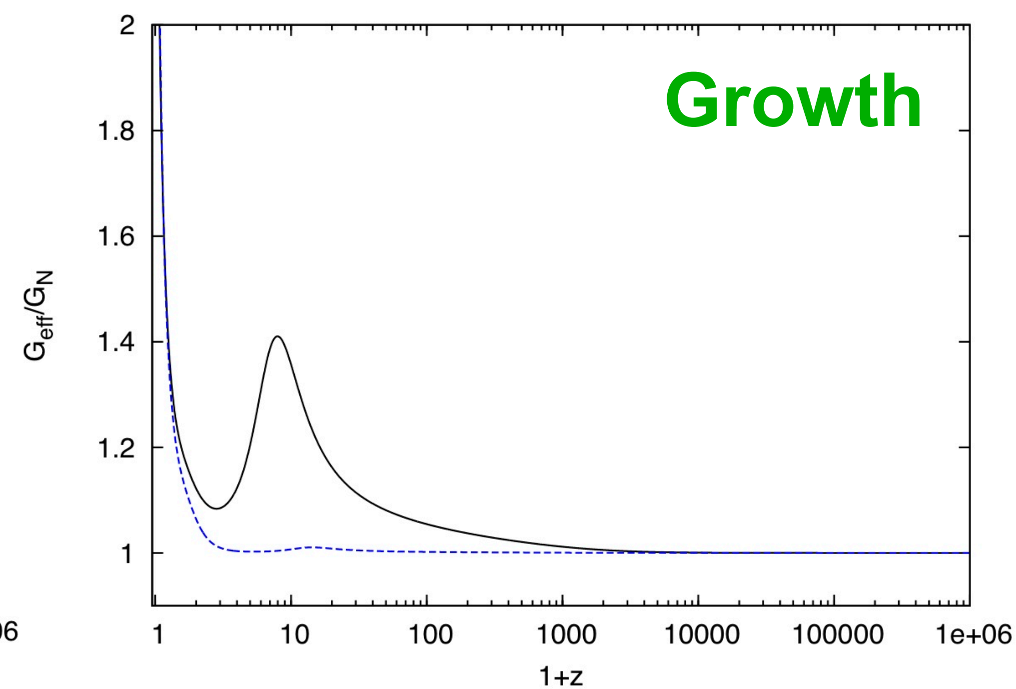
Derivative coupling

Coupled Galileons ruled out by Appleby & Linder 2012a **due to instabilities.**

Data vs Gravity

Galileon cosmology has early time tracker solutions (no fine tuning) and late time de Sitter attractor. Beautiful class of theories!





But Appleby & Linder 2012b **rule out Standard Galileon with $\Delta\chi^2_{LCDM}$>30 from current data. Data kill entire class of gravity!**

Chasing Down Cosmic Acceleration

How can we measure dark energy in detail – *in the next 5 years*?

New prospects in data (a partial, personal view):

- **Strong lensing time delays**
- **Redshift space distortions**
- **CMB polarization lensing**

New prospects in theory (a partial, personal view):

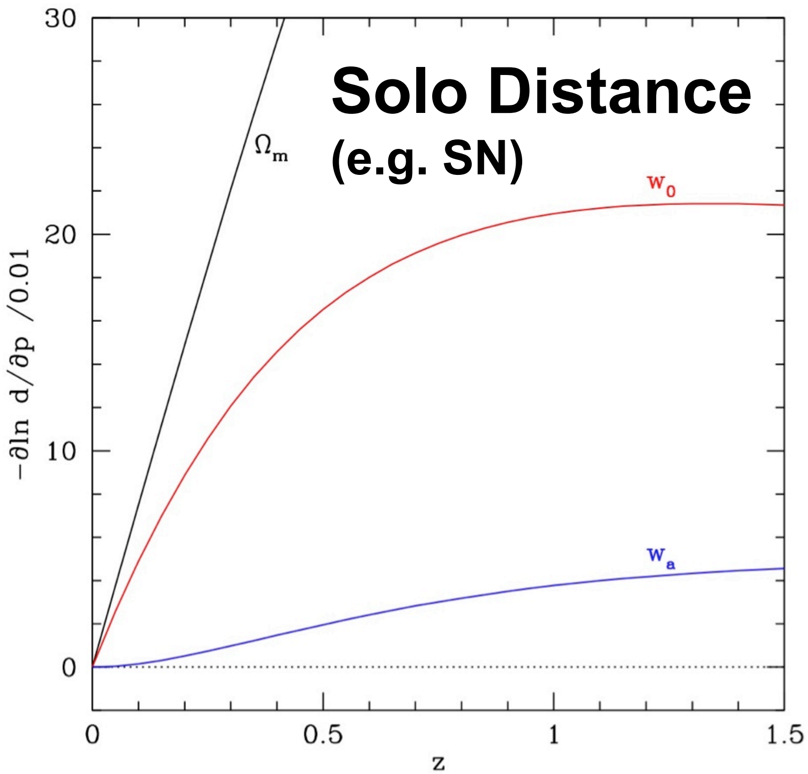
- **Higher dimensional gravity/field theory/symmetry**

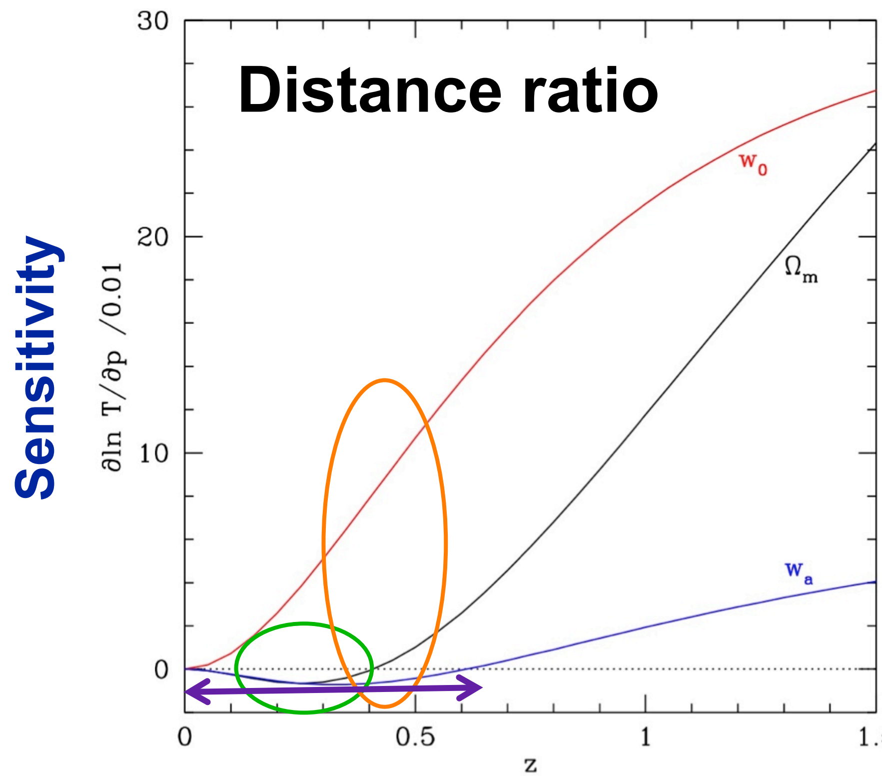
Old school leverage (a partial, personal view):

- **Enhanced low z supernova data**

Strong Lensing Time Delays

Strong gravitational lensing creates multiple images (light paths) of a source. Time delays between paths probe geometric path difference and lensing potential. Key parameter is distance ratio $T \equiv \frac{r_l r_s}{r_{ls}}$

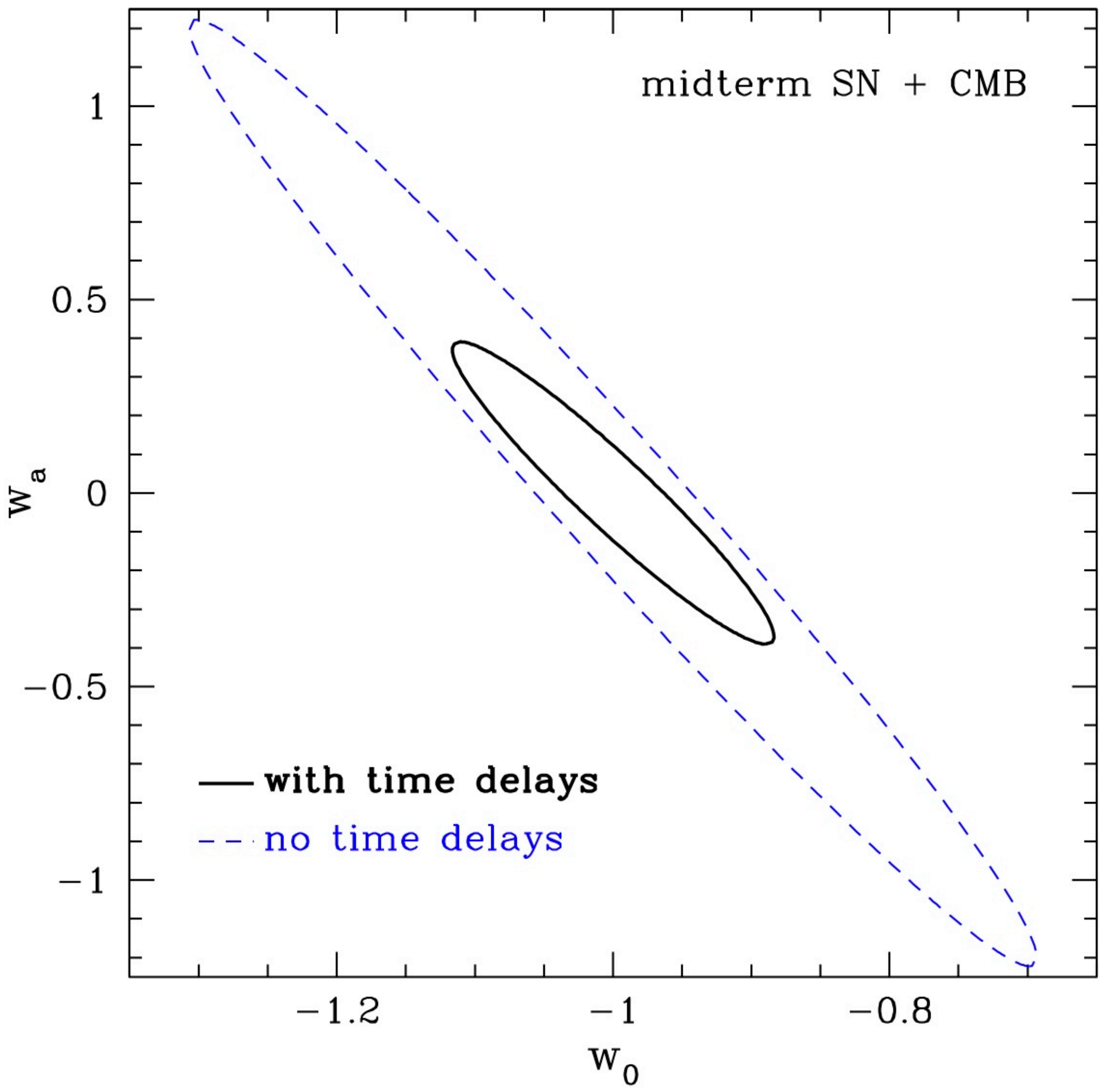




Strong complementarity first id'd by Linder 2004, first used by WMAP7 (Komatsu+ 2011), modeling advances now make it practical.

Time Delays + Supernovae

Lensing time delays give superb complementarity with SN distances plus CMB.



T to 1% for z=0.1, 0.2,… 0.6

SN to 0.02(1+z)mag for z=0.05, 0.15... 0.95

Factor 4.8 in area
Ω_m to 0.0044
h to 0.7%
w_0 to 0.077
w_a to 0.26

Time Delay Surveys

Best current time delays at 5% accuracy, 16 systems. 5 year aim: 38 systems, 5% accuracy = 230 orbits HST.

Need 1) high resolution imaging for lens mapping and modeling, 2) high cadence imaging, 3) spectroscopy for redshift, lens velocity dispersion, 4) wide field of view for survey.

Synergy: HST/Keck/VLT+ DES/BOSS. SN survey included. Only low redshift $z<0.6$ needed for lenses.

Systematics control via image separations, anomalous flux ratios (probe DM substructure!). Need good mass modeling, computationally intensive.

Higher Dimensional Data

Cosmological Revolution:

From 2D to 3D – CMB anisotropies to tomographic surveys of density/velocity field.

Data, Data, Data

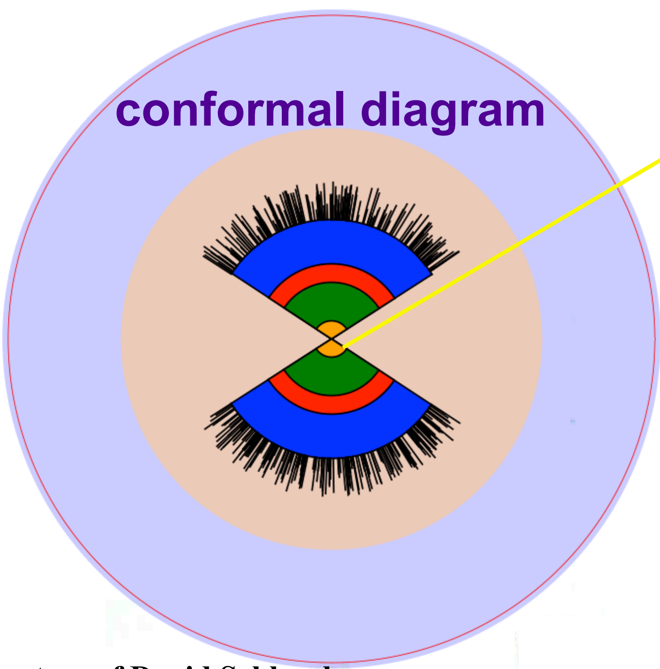
As wonderful as the CMB is, it is 2-dimensional.

The number of modes giving information is $l(l+1)$ or ~10 million.

BOSS (SDSS III) will map 400,000 linear modes.

N. Padmanabhan

BigBOSS will map 15 million linear modes.



courtesy of David Schlegel

SDSS I, II, 2dF

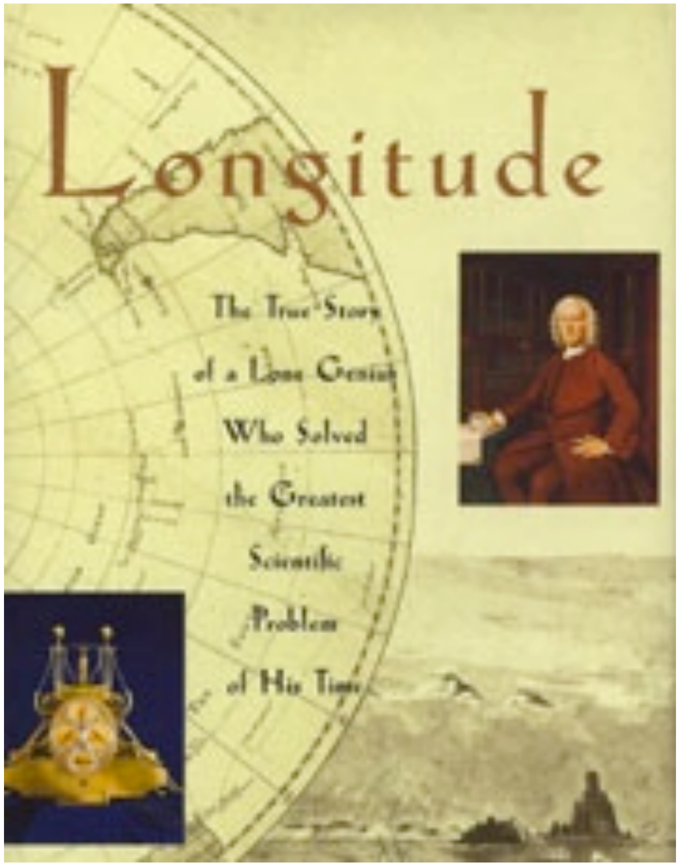
BOSS (SDSS III)

BigBOSS
18 million galaxies
z=0.2-1.5

600,000 QSOs
z=1.8-3

Maps of
density
velocity
gravity

"Greatest Scientific Problem"



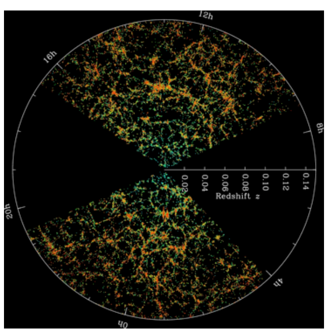
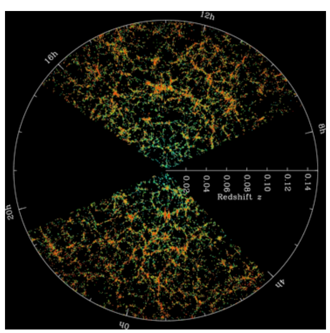
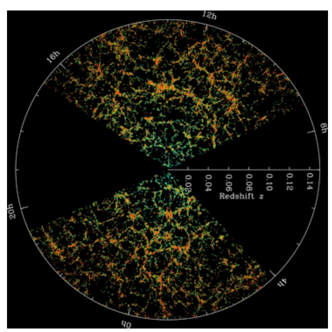
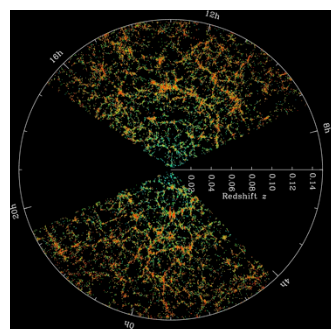
"When I'm playful I use the meridians of longitude and parallels of latitude for a seine, drag the Atlantic Ocean for whales."

– Mark Twain, ***Life on the Mississippi***

Cosmic Structure

Galaxy 3D distribution or power spectrum contains information on:

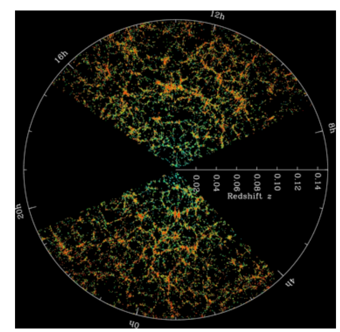
- **Growth - evolving amplitude**
- **Matter/radiation density, H - peak turnover**
- **Distances - baryon acoustic oscillations**
- **Growth rate - redshift space distortions**
- **Neutrino mass, non-Gaussianity, gravity, etc.**

x25

(x7 LRG)

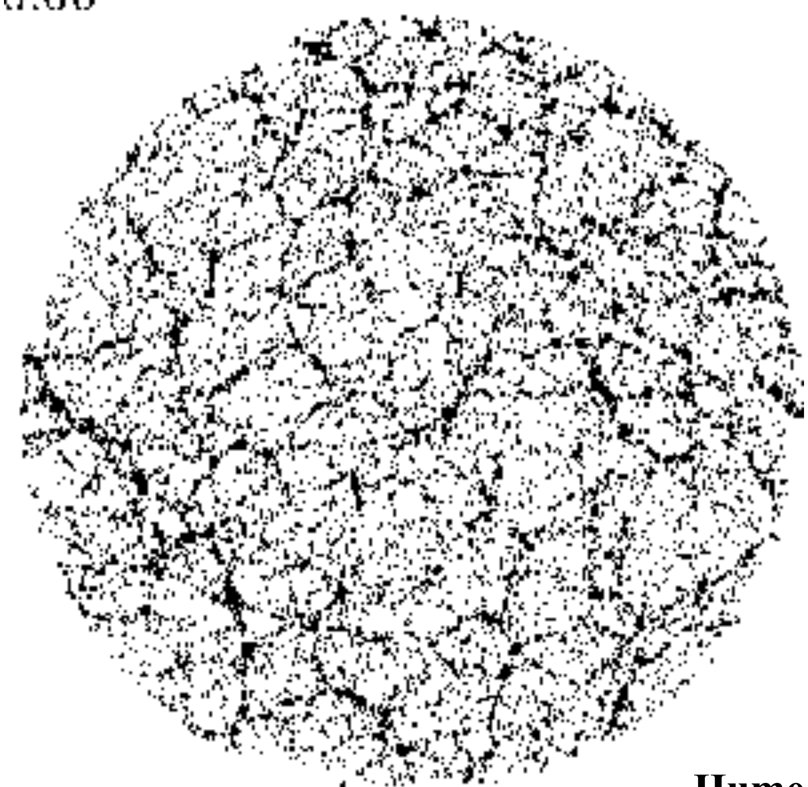
...



Redshift Space Distortions

Redshift space distortions (RSD) map velocity field along line of sight. Gets at growth rate f, one less integral than growth factor (like H vs d).

$\Omega_m = 0.00$



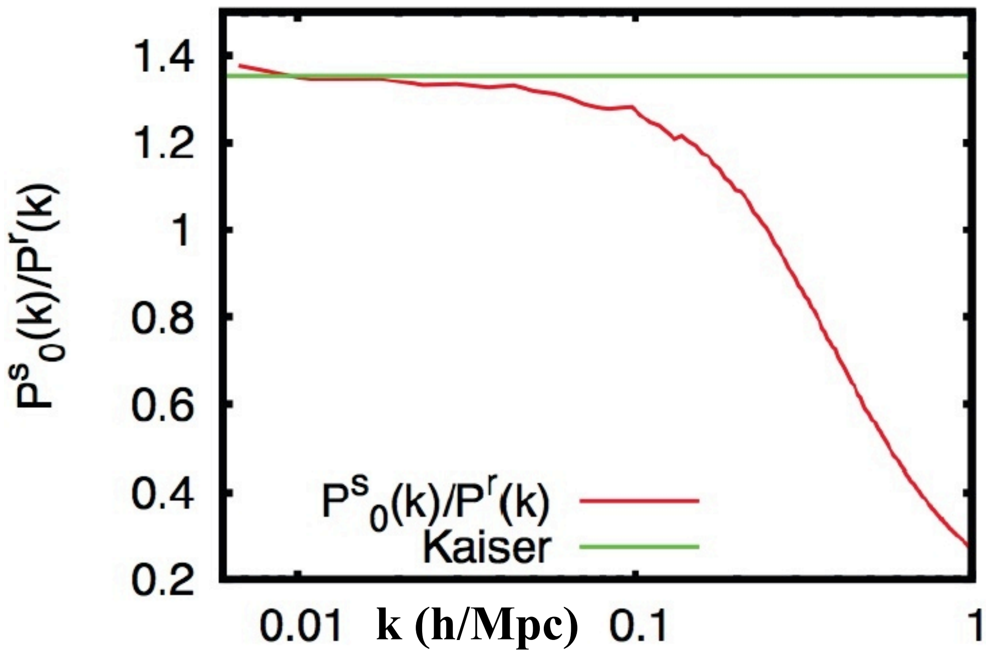
$$f = \frac{d\ln D}{d\ln a} \sim \Omega_m(a)^\gamma$$

gravitational growth index γ

Hume Feldman

Redshift Space Distortions

$$P_{gg}(k,z) = (b + f\mu^2)^2\, P_{\delta\delta}(k,z)$$ **Kaiser formula inaccurate**

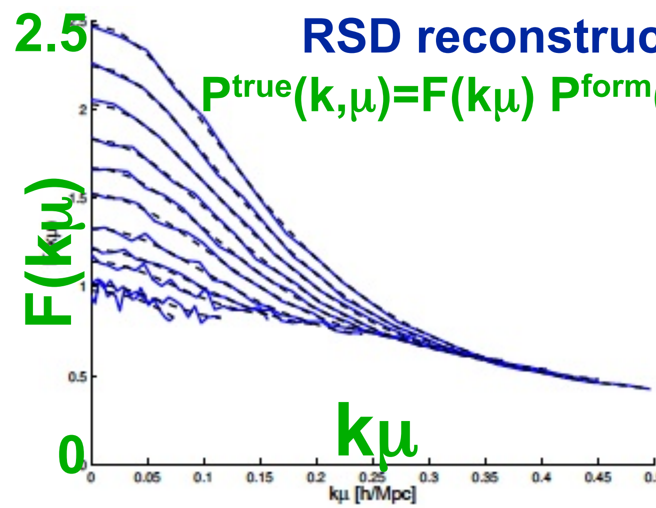


Even monopole (averaged over RSD) is poor.

Anisotropic redshift distortion hopeless – *without better theory*.

RSD reconstruction

$P^{true}(k,\mu)=F(k\mu)\ P^{form}(k,\mu)$



Simulation fitting function

Kwan, Lewis Linder 2011

highly accurate to higher kμ.

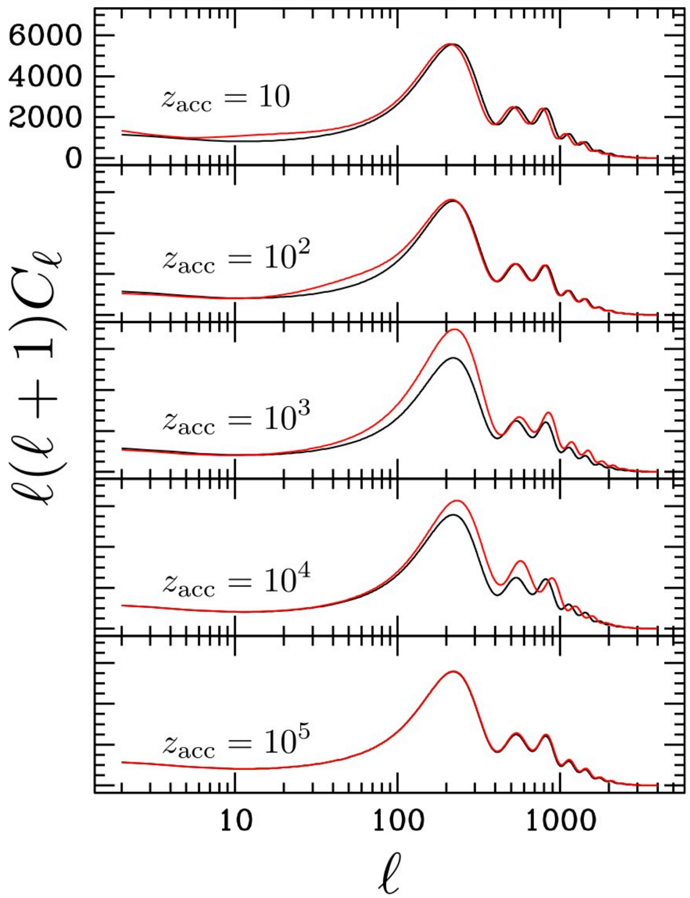
also see Okumura, Seljak, McDonald, Desjacques 2011; Reid & White 2011

CMB Probes of Acceleration

How well do we really know the standard picture of radiation domination → matter domination → dark energy domination?

Maybe acceleration is occasional. **(Solve coincidence)**

Effect of 0.1 e-fold of acceleration



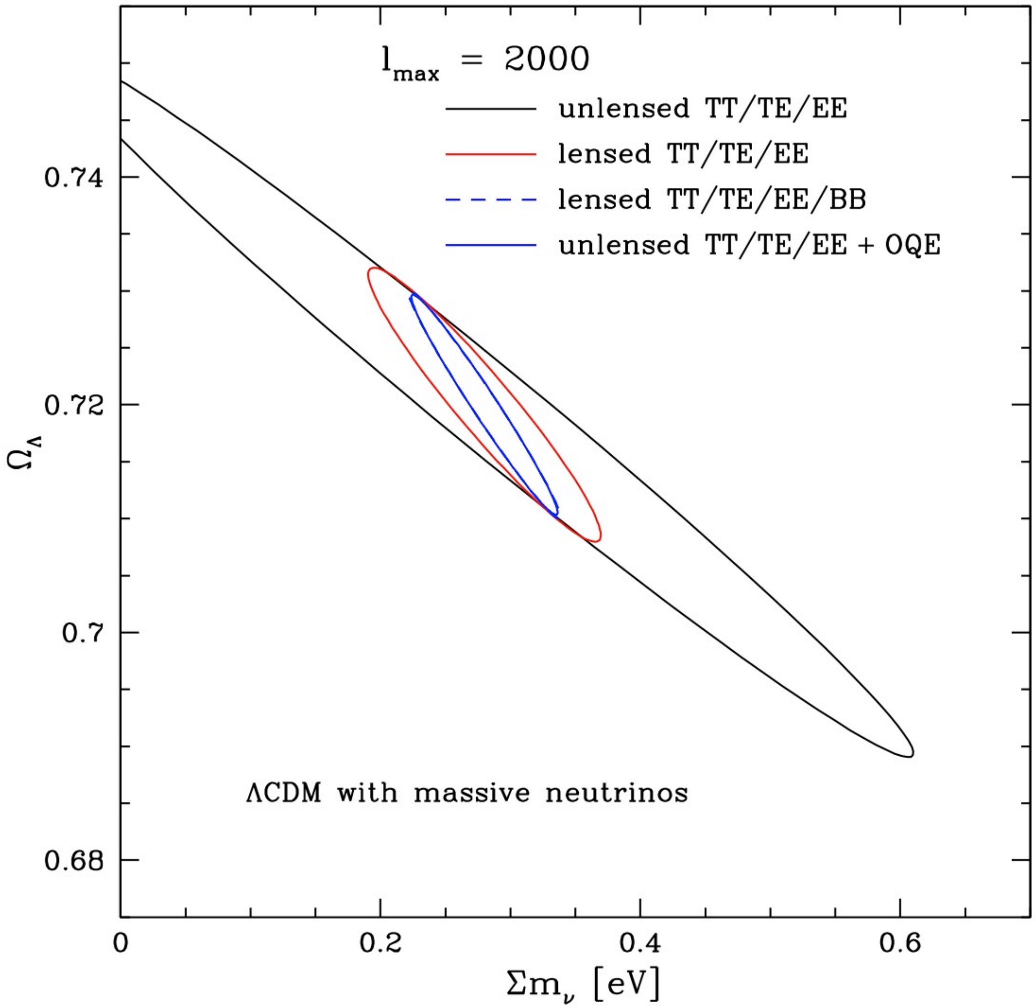
Linder & Smith 2010

Post-recombination, peaks → left and adds ISW.
Pre-recombination, peaks → right and adds SW.

Current acceleration unique within last factor 100,000 of cosmic expansion!

CMB Lensing

CMB as a source pattern for weak lensing. Probes z~1-5 effects, e.g. neutrino masses and early dark energy.



Model	Experiment	$\sigma(w_0)$	$\sigma(w_a)$	$\sigma(\Omega_e)$	$\sigma(\Sigma m_\nu)$ [eV]
ΛCDM	Planck	–	–	–	0.11
ΛCDM	CMBpol	–	–	–	0.037
w_0-w_a	Planck+SN	0.074	0.32	–	0.13
w_0-w_a	CMBpol+SN	0.068	0.27	–	0.044
w_0-Ω_e	Planck+SN	0.032	–	0.0042	0.15
w_0-Ω_e	CMBpol+SN	0.018	–	0.0020	0.050

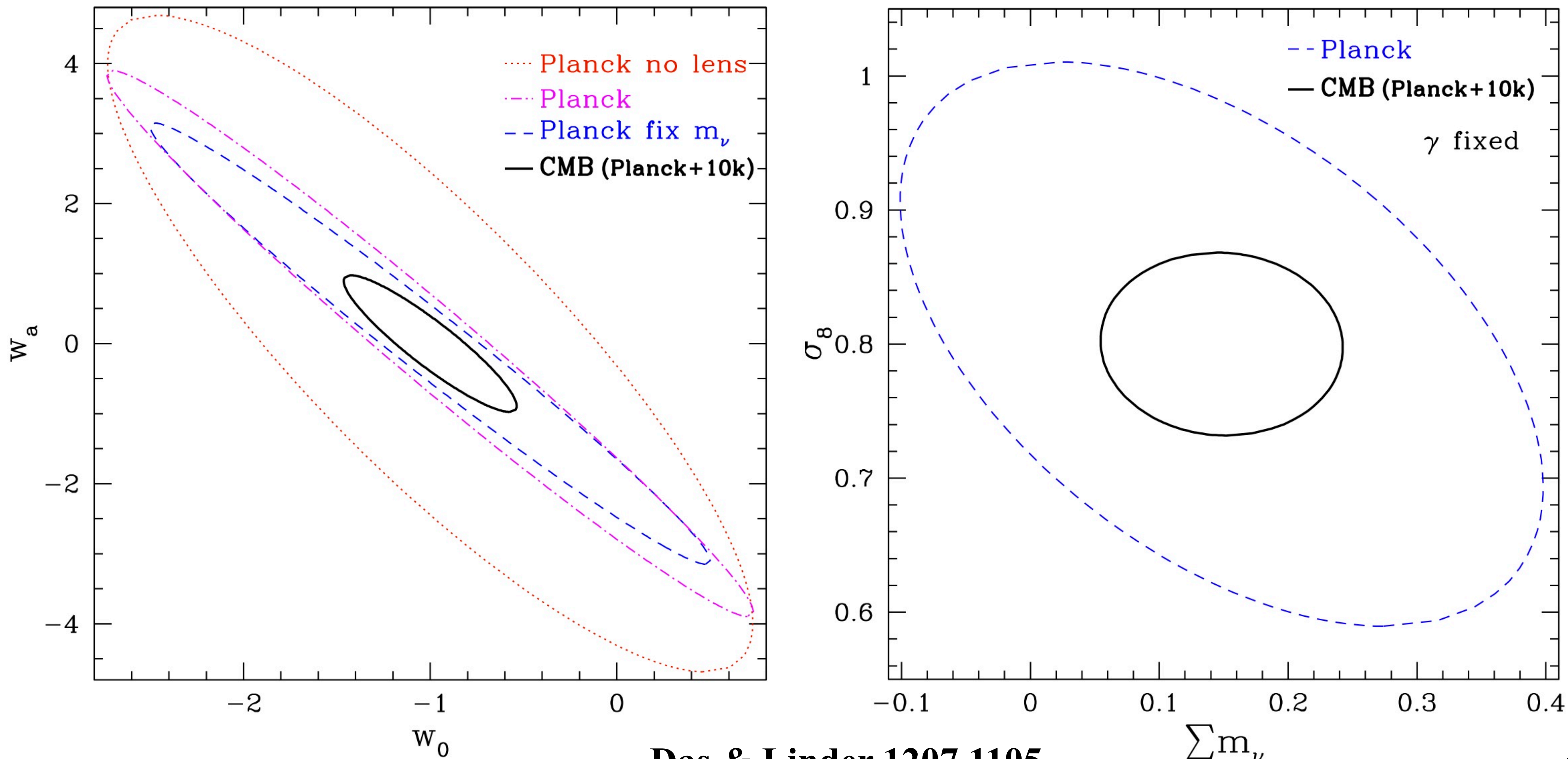
de Putter, Zahn, Linder 2009

SPT/ACT gets 8/3.2σ for Λ from CMB lensing.

van Engelen+ 2012, Sherwin+ 2011

Dawn's Early Light

Ground based experiments (ACTpol, Polarbear, SPTpol) are doing CMB lensing *now*. They strongly improve Planck constraints.



Das & Linder 1207.1105

CMB Polarization

We model the next 5 years of CMB polarization lensing experiments (ACTpol, POLAR, PolarBear, SPTpol) as: 10000 deg^2 at 5 μK-arcmin (7 pol), 1’ beam (insens if <4’), l_{max}=3000 (though 5000 pol possible).

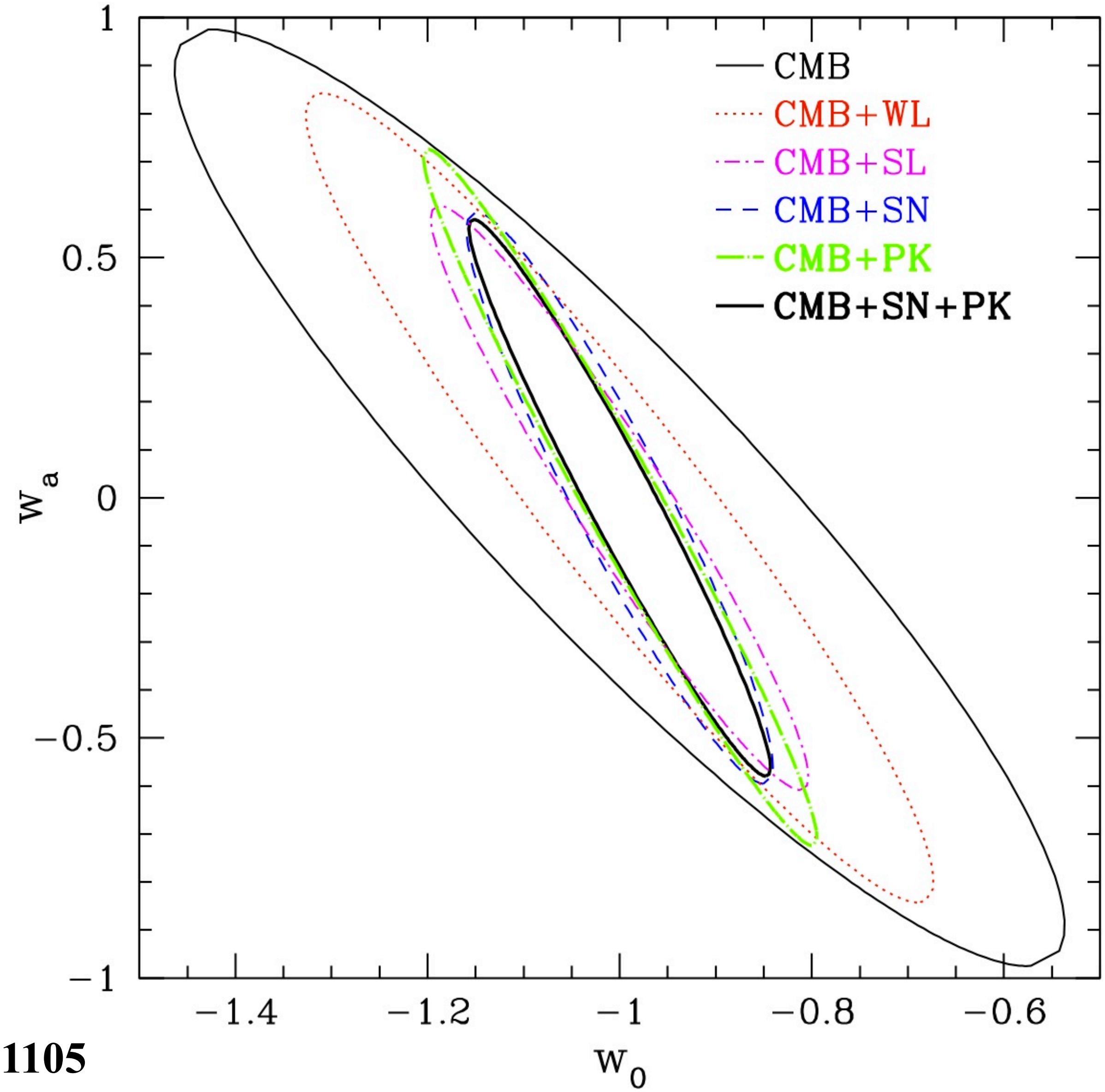
Lensing depends on mass power spectrum so include **all effects** on it, not just vanilla Ω_m. Expand parameter space to dynamical DE, neutrino mass, gravity/growth.

	ω_b	ω_c	ω_ν	Ω_{de}	n_s	τ	σ_8	w_0	w_a	γ
Fiducial	0.02258	0.1093	0.001596	0.734	0.963	0.086	0.8	-1	0	0.55
σ(Planck)	0.000137	0.00117	0.00175	0.124	0.00337	0.00426	d	1.10	2.48	d
σ(Planck+10k)	0.0000492	0.000682	0.000666	0.042	0.00207	0.00297	d	0.305	0.642	d
Gain	2.78	1.72	2.63	2.95	1.63	1.43	d	3.61	3.86	d

Improve m_ν constraint by 2.6, DE FOM by 6.6, m_ν-σ_8 FOM (fixing GR) by 5.2.

Dawn's Early Light

This changes the DE probe landscape.



Das & Linder 1207.1105

5 Year Realization

Consider near term (5 year), realistic landscape.

Supernovae (SN) ~ DES
Galaxy Clustering (PK) ~ BOSS
[Weak Lensing (WL) ~ DES]
[Strong Lensing (SL) ~ HST?]
SN: Linder; PK: Das, Linder; CMB: Das; WL: Das, de Putter, Linder, Nakajima; SL: Linder

Expand parameter space to all parameters affecting mass power spectrum, not just vanilla.

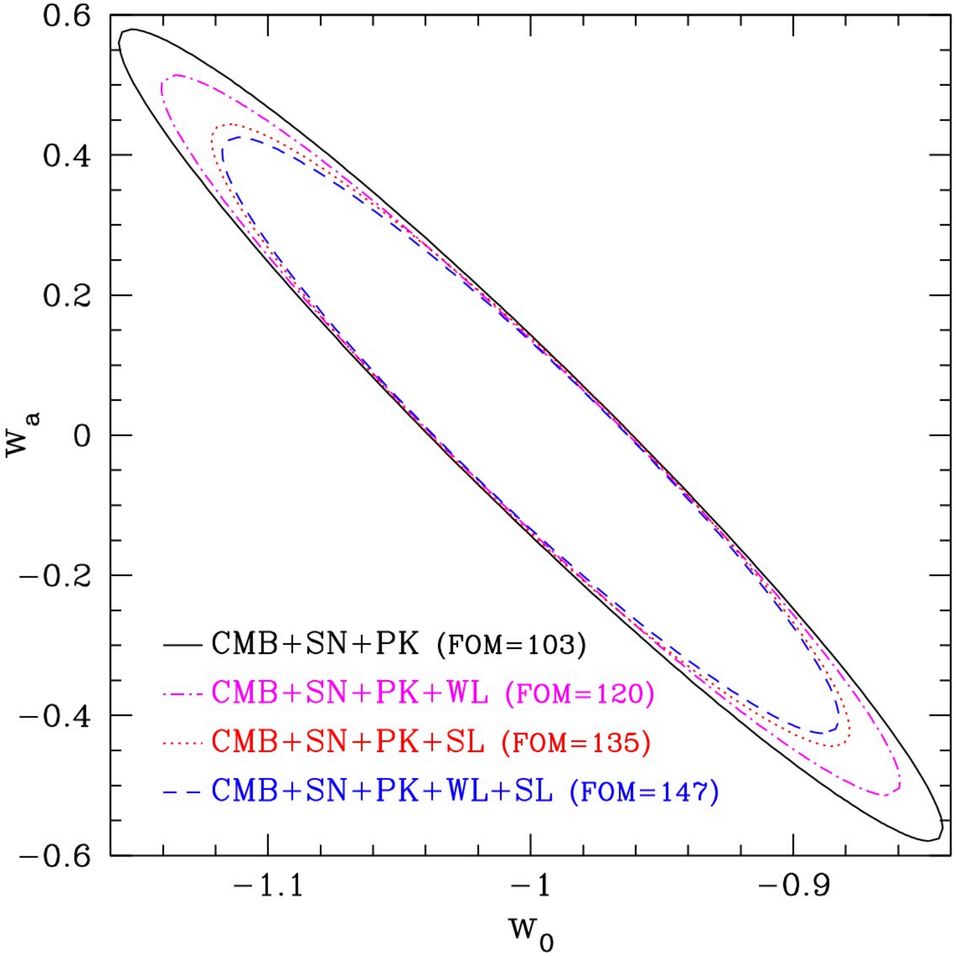
Dynamic dark energy: $w(z)=w_0+w_a z/(1+z)$

Neutrino mass: Σm_ν

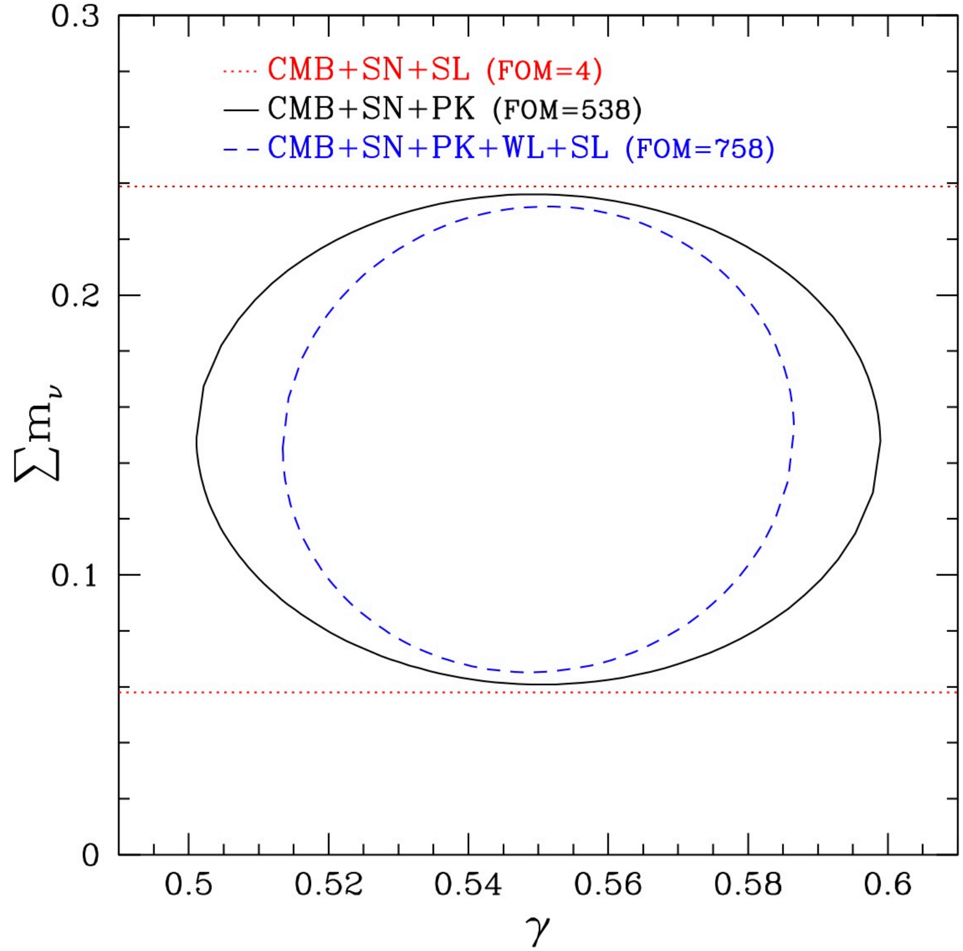
Gravitational growth index (GR test): γ

Cosmology 2017

Expansion



Growth



Strong program in place, but also easy to do better!

Baseline and Enhancements

FOMw=1/√det Cov[w_0,w_a] FOMν=1/√det Cov[m_ν,γ]

	$10^5\omega_b$	$10^4\omega_c$	$10^4\omega_\nu$	Ω_{de}	n_s	σ_8	w_0	w_a	γ	FOMw	FOMν
σ(CMB+SN+PK)	4.76	6.47	6.21	0.00507	0.00200	0.0110	0.103	0.382	0.0322	103	538
σ(CMB+SN+PK+WL)	4.71	5.85	5.97	0.00470	0.00192	0.00934	0.0927	0.339	0.0256	120	704
σ(CMB+SN+PK+SL)	4.74	6.03	6.12	0.00414	0.00195	0.0107	0.0801	0.292	0.0319	135	551
σ(CMB+SN+PK+WL+SL)	4.70	5.63	5.89	0.00403	0.00189	0.00808	0.0774	0.280	0.0241	147	758

SL program improves DE FOM by 32%.

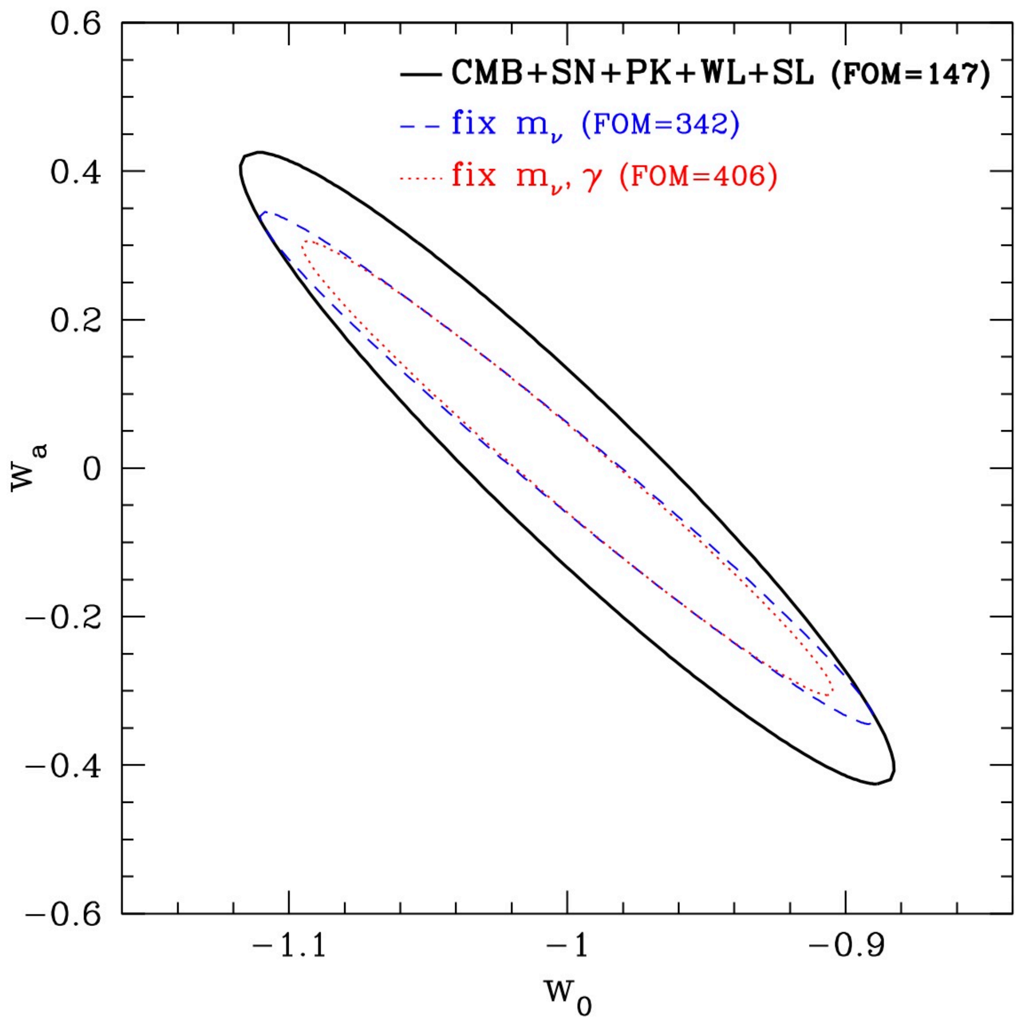
Enhanced z<0.1 SN program (150 SN → 300, 0.021^m → 0.008^m) **improves DE FOM by 26%.**

Theory/analysis: use of l_{max}>3000

Theory/analysis: use of k_{max}>0.125 h/Mpc

Beyond Vanilla

Fixing parameters – DE, neutrino, gravity – opens the door to bias, or is simply unrealistic (neutrinos do have mass and we don't know how much).



Fixing m_ν makes FOMw 2.3x higher than it should be.

(And SL then very strong, +76%) Strongest effect on w_p.

Fixing γ mostly affects σ_8.

Fixing both implies CMB+surveys gives FOMw = 406! (2.8x)

Ideas/Trends/Lessons

Very much a program: multiple, diverse surveys. Ground CMB adds +67% (FOMw), +134% (FOMν).

Strong program in place + easy improvements exist!

Lensing time delays improve FOM by 32%, cost 150-230 HST orbits.

Enhanced low z SN (300 with dm=0.008) improve FOM by 26%.

If weak lensing falters, we can still learn a lot.

Must be realistic: fixing m_ν, γ projects FOM x 2.77!

Can learn $\sigma(w_a)=0.25$, $\sigma(m_\nu)=0.055$ eV by 2017.

Summary

Much progress made: ruling out quintessence trackers, <w>~-1, robust GR tests/extensions.

Dark energy is not the search for one number “w”. Explore dynamics, degrees of freedom, persistence.

Gravity and particle physics informing DE models.

CMB polarization, mass power spectrum, (lensing time delays) are important upcoming probes.

Complementary probes: very much a program. Theory/simulate/observe equal weighting essential.

Data in next 5 years has us closing in on our chase of cosmic acceleration.

Exploring Cosmology

In theory, there is no difference between theory and practice. In practice, there is. **- Yogi Berra**

Astronomer Royal (Airy):
"I should not have believed it if I had not seen it!"

Astronomer Royal (Hamilton):
"How different we are! My eyes have too often deceived me. I believe it because I have proved it."