Shedding Light on Dark Energy

Devdeep Sarkar
(dsarkar.org)
Center for Cosmology, UC Irvine

in collaboration with:

Scott Sullivan (UCI/UCLA), Shahab Joudaki (UCI), Alexandre Amblard (UCI),
Daniel Holz (Chicago/LANL), and Asantha Cooray (UCI)

ICTS/TIFR/IUCAA   Cosmology with the CMB and LSS   August 15, 2008

Probing Dark Energy

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A Little Bit of History

J. E. Gunn and B. M. Tinsley, Nature, 257, 454 (1975)

"New data on the Hubble diagram, combined with constraints on the density of the Universe and the ages of galaxies, suggest that the most plausible cosmological models have a positive cosmological constant, are closed, too dense to make deuterium in the big bang, and will expand for ever. Possible errors in the supporting arguments are discussed."

G. Efstathiou, W. J. Sutherland, and S. J. Maddox, Nature, 348, 705 (1990)

"...We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant ..."

J. P. Ostriker and P. J. Steinhardt, Nature, 377, 600 (1995)

"OBSERVATIONS are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe ... The observations do not yet rule out the possibility that we live in an ever-expanding open Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured."

J. S. Bagla, T. Padmanabhan, and J.V. Narlikar, Comments Astrophys., 18, 275 (1996)

"... the conclusion today is inescapable that the standard big bang models without the cosmological constant are effectively ruled out."

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7]
R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4]
NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]
Received 1998 March 13; revised 1998 May 6

ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.

Key words: cosmology: observations — supernovae: general

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THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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(THE SUPERNOVA COSMOLOGY PROJECT)
Received 1998 September 8; accepted 1998 December 17

ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is

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The Astrophysical Journal, 607:665–687, 2004 June 1 Ⓔ

TYPE Ia SUPERNOVA DISCOVERIES AT $z > 1$ FROM THE *HUBBLE SPACE TELESCOPE*: EVIDENCE FOR PAST DECELERATION AND CONSTRAINTS ON DARK ENERGY EVOLUTION[1]

Adam G. Riess,[2] Louis-Gregory Strolger,[2] John Tonry,[3] Stefano Casertano,[2] Henry C. Ferguson,[2] Bahram Mobasher,[2] Peter Challis,[4] Alexei V. Filippenko,[5] Saurabh Jha,[5] Weidong Li,[5] Ryan Chornock,[5] Robert P. Kirshner,[4] Bruno Leibundgut,[6] Mark Dickinson,[2] Mario Livio,[2] Mauro Giavalisco,[2] Charles C. Steidel,[7] Txitxo Benítez,[8] and Zlatan Tsvetanov[8]
Received 2004 January 20; accepted 2004 February 16

ABSTRACT

We have discovered 16 Type Ia supernovae (SNe Ia) with the *Hubble Space Telescope* (*HST*) and have used them to provide the first conclusive evidence for cosmic deceleration that preceded the current epoch of cosmic acceleration. These objects, discovered during the course of the GOODS ACS Treasury program, include 6 of the 7 highest redshift SNe Ia known, all at $z > 1.25$, and populate the Hubble diagram in unexplored territory. The luminosity distances to these objects and to 170 previously reported SNe Ia have been determined using empirical relations between light-curve shape and luminosity. A purely kinematic interpretation of the SN Ia sample provides evidence at the greater than 99% confidence level for a transition from deceleration to acceleration or, similarly, strong evidence for a cosmic jerk. Using a simple model of the expansion history, the transition between the two epochs is constrained to be at $z = 0.46 \pm 0.13$. The data are consistent with the cosmic concordance model of $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$ ($\chi^2_{\rm dof} = 1.06$) and are inconsistent with a simple model of evolution or dust as an alternative to dark energy. For a flat universe with a cosmological constant, we measure $\Omega_M = 0.29^{+0.05}_{-0.03}$ (equivalently, $\Omega_\Lambda = 0.71$). When combined with external flat-universe constraints, including the cosmic microwave background and large-scale structure, we find $w = -1.02^{+0.13}_{-0.19}$ (and $w < -0.76$ at the 95% confidence level) for an assumed static equation of state of dark energy, $P = w\rho c^2$. Joint constraints on both the recent equation of state of dark energy, w_0, and its time evolution, dw/dz, are a factor of ~8 more precise than the first estimates and twice as precise as those without the SNe Ia discovered with *HST*. Our constraints are consistent with the static nature of and value of w expected for a cosmological constant (i.e., $w_0 = -1.0$, $dw/dz = 0$) and are inconsistent with very rapid evolution of dark energy. We address consequences of evolving dark energy for the fate of the universe.

Subject headings: cosmology: observations — distance scale — galaxies: distances and redshifts — supernovae: general

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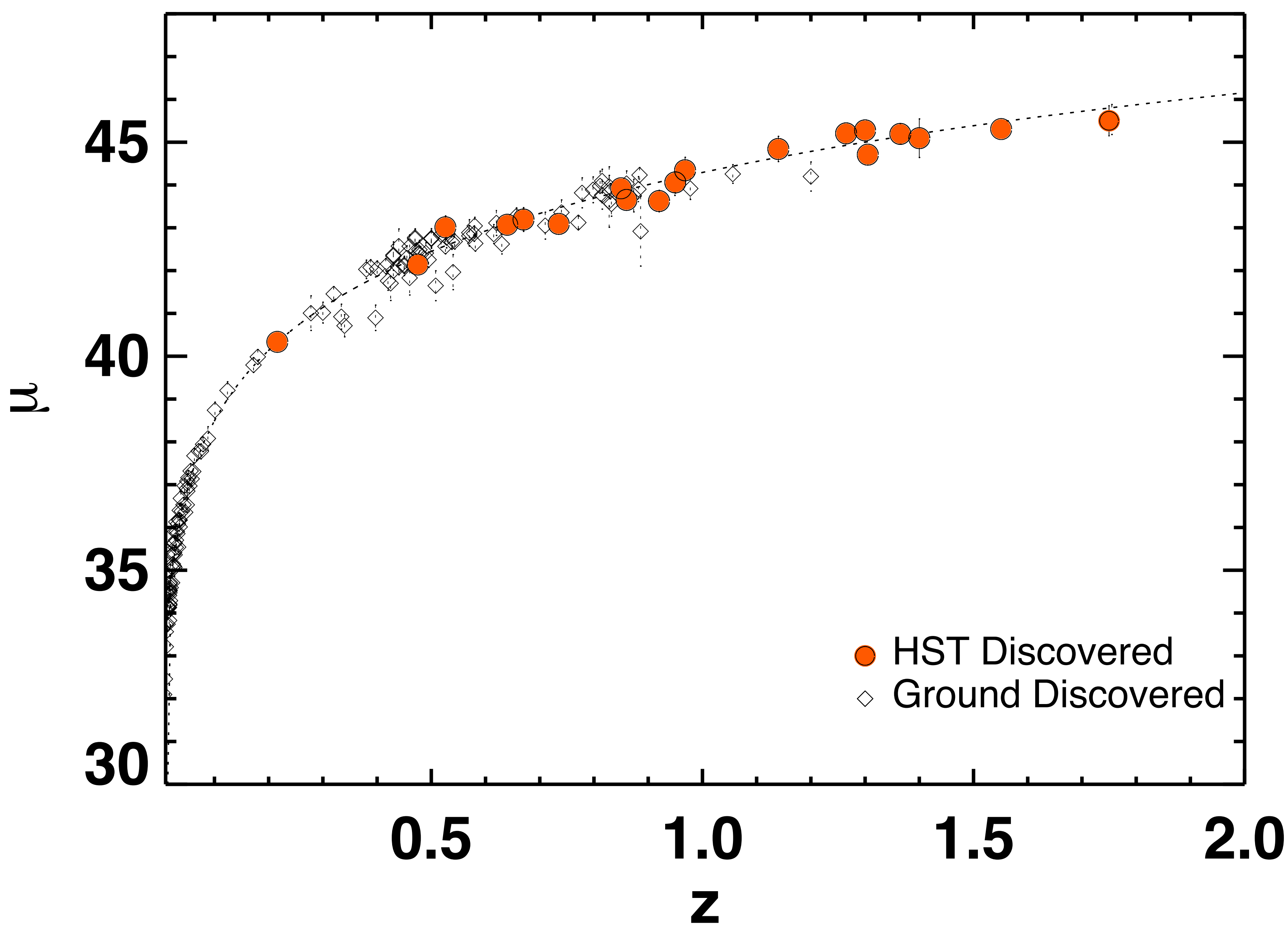

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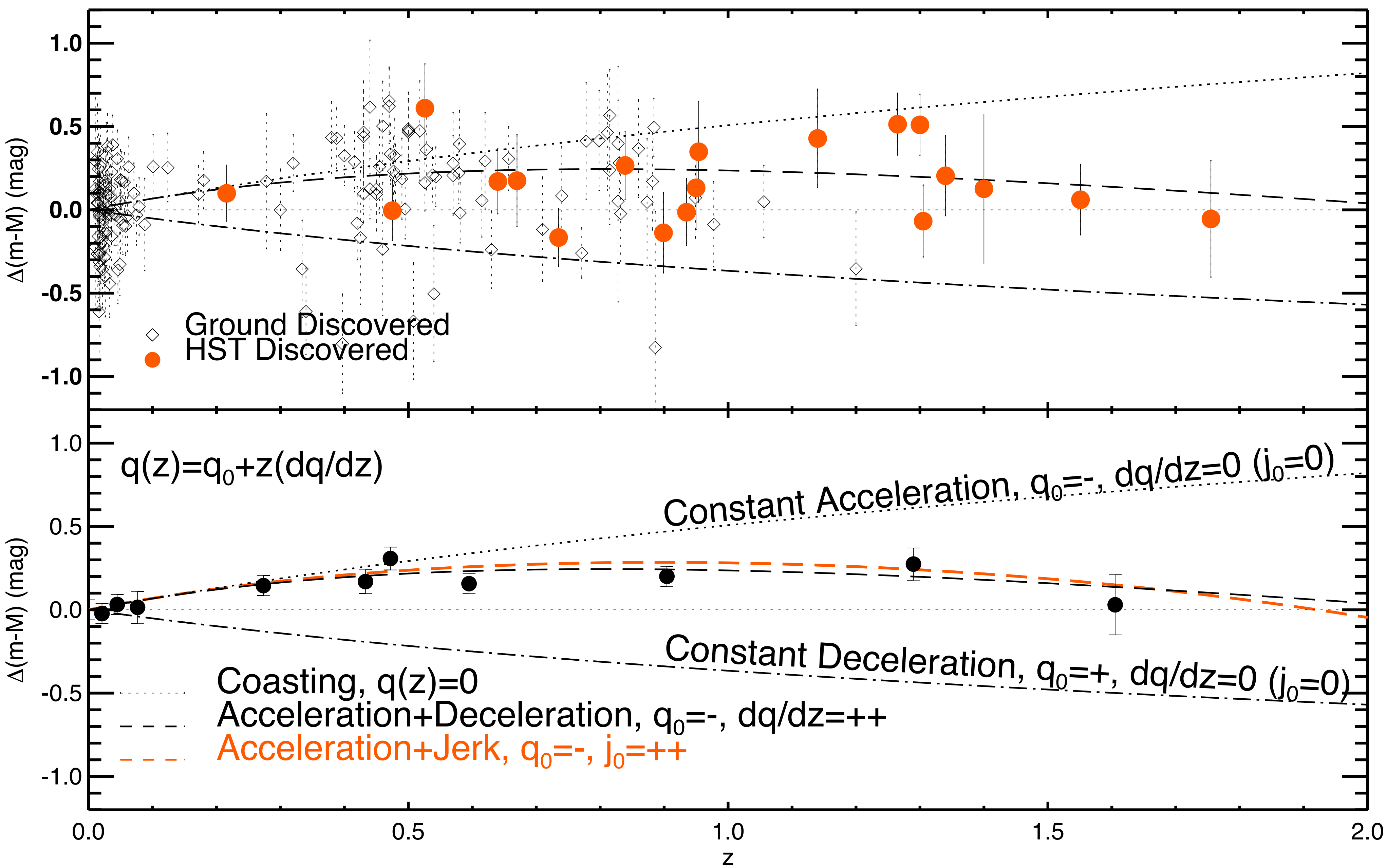
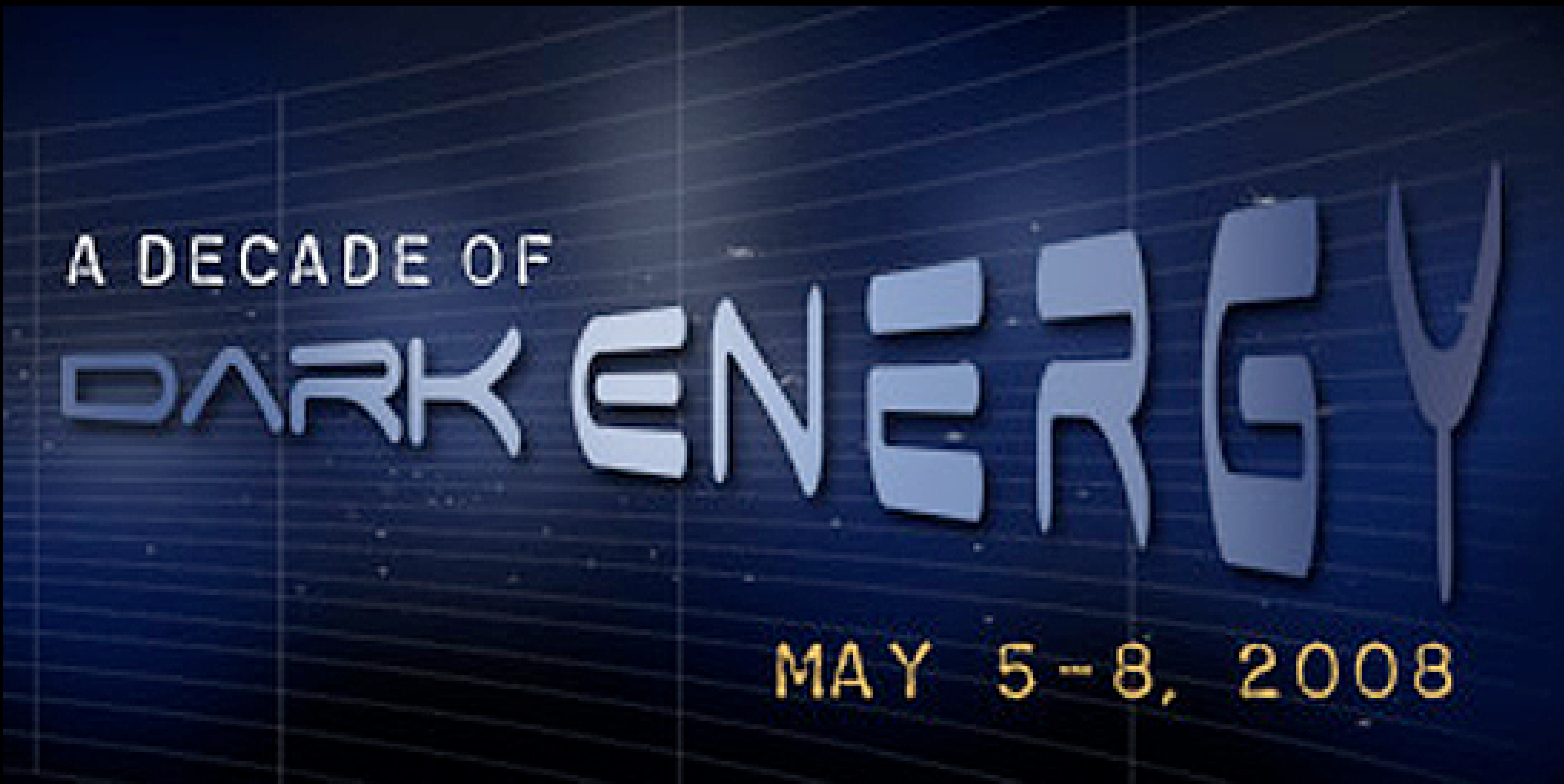


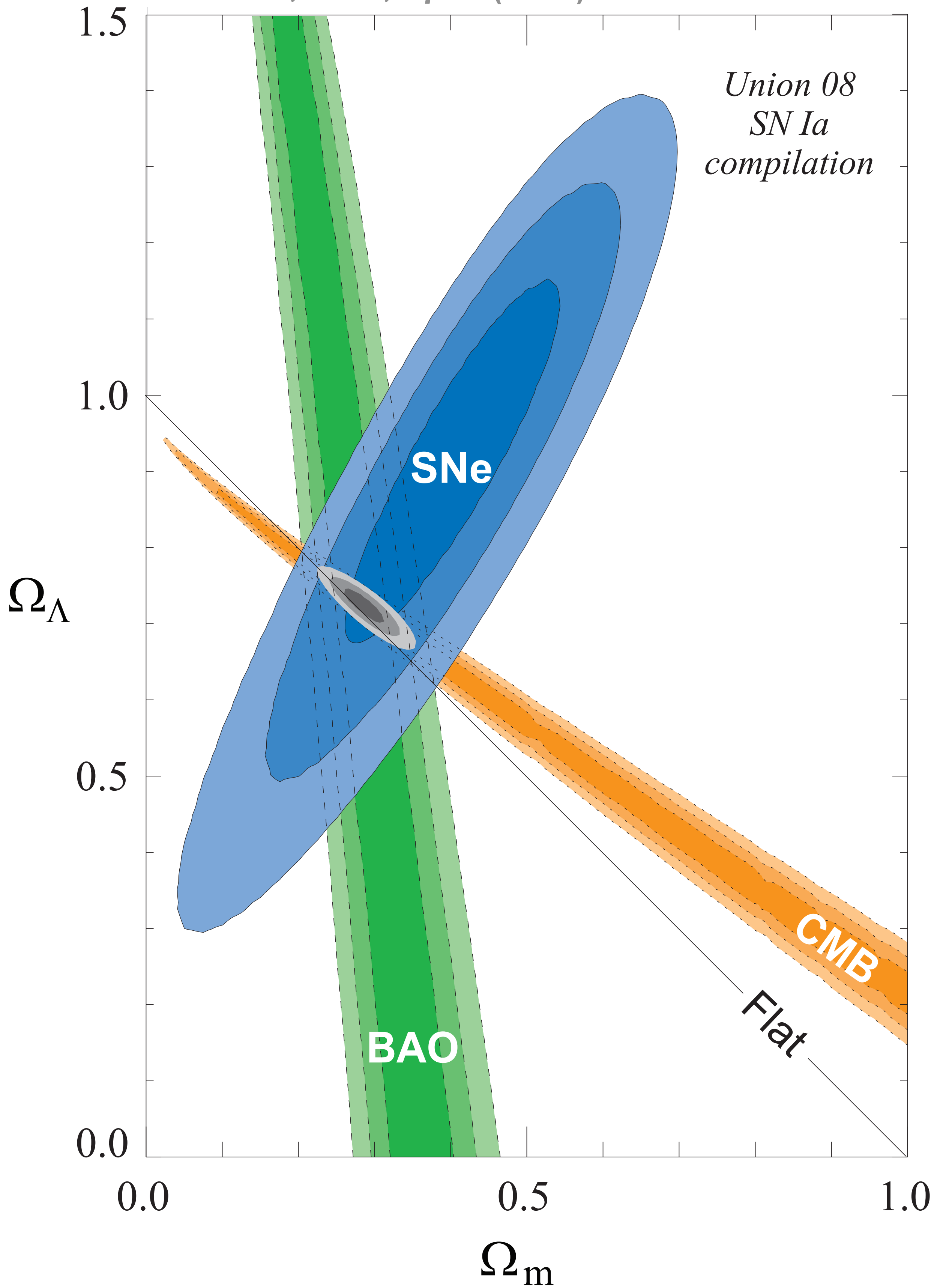
Where Do We Stand? After...

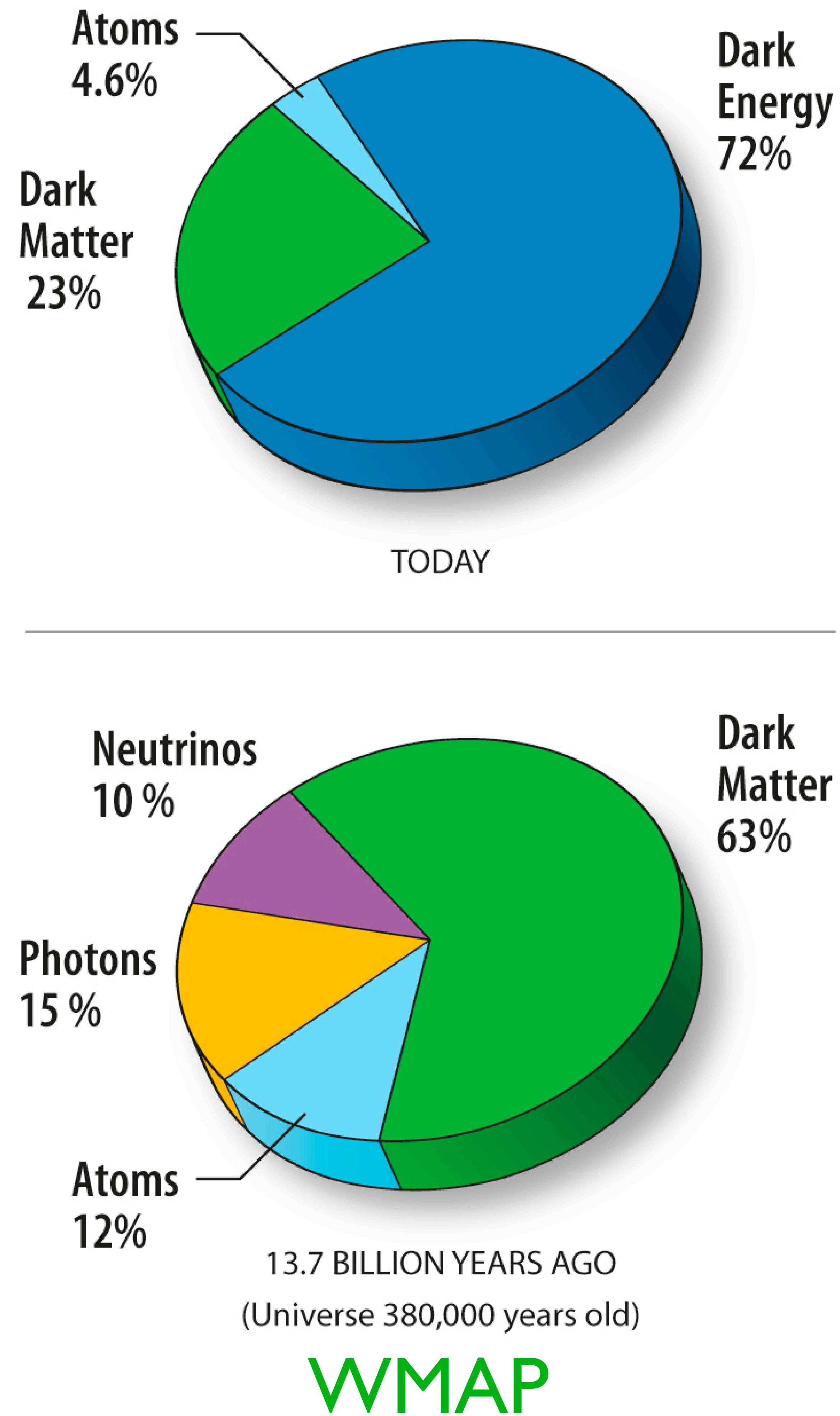


Space Telescope Science Institute, Baltimore, MD

$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$$

Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)





What is Dark Energy?

What is Dark Energy?

"Dark Energy is made from an exclusive blend of vital L-amino acids, beneficial vitamins and bionutrients that allows faster and greater ion penetration of the cell walls, visibly enhancing the rate of growth"

GrowLightSource.com

Cosmic Acceleration

Modified Gravity

Dark Energy

$$H^2 - \boxed{\frac{H}{r_c}} = \frac{8\pi G}{3}(\rho + \rho_V)$$

Modification of Friedmann equation (5D Gravity)

Phenomenological modification to the GR Lagrangian

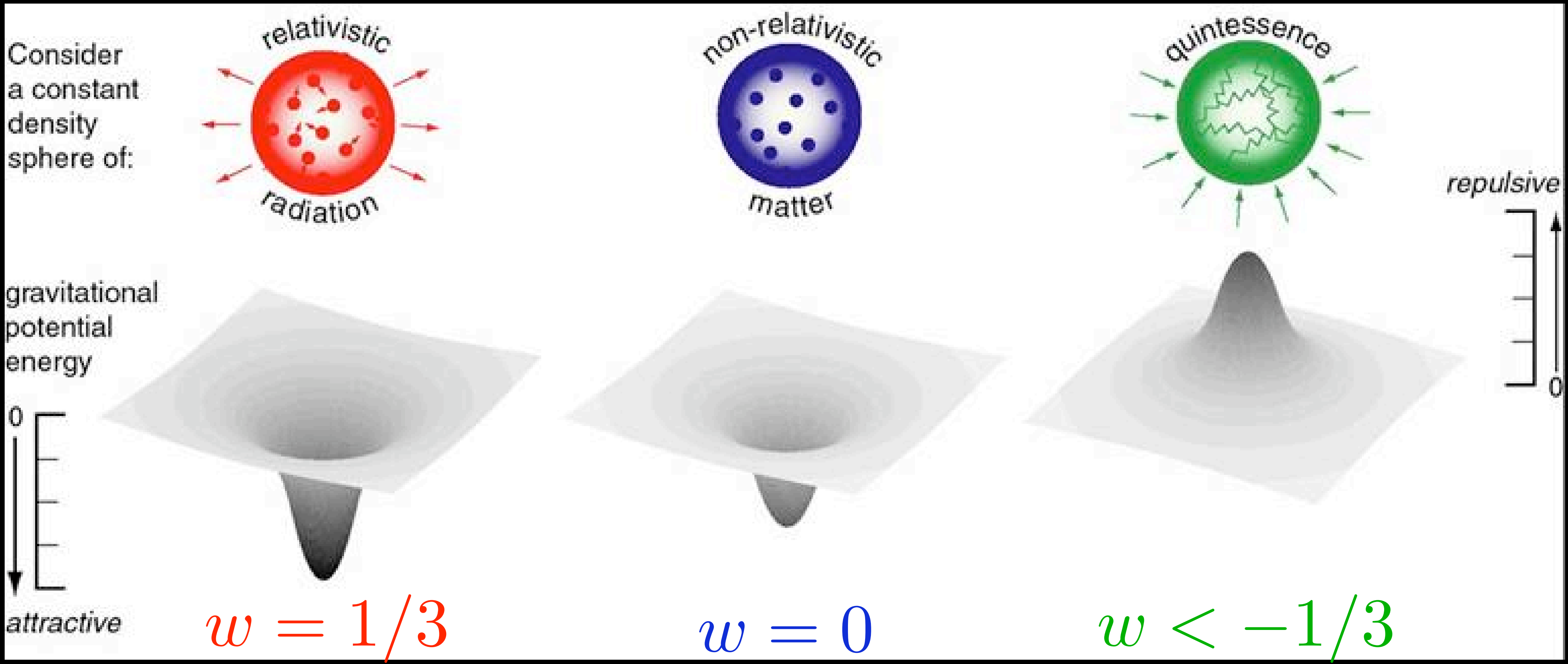
Vacuum Energy (Cosmological Constant)

Scalar Fields
Evolving Equation of State

New Physics/Surprises?

Dark Energy Equation Of State

$$T^{\nu}_{\mu} = diag(\rho, -p, -p, -p) \qquad p = w\rho$$



For Cosmological Constant... $w = -1$

“Seeing” The Dark Energy

"Seeing" The Dark Energy

...via its effect on the expansion of the Universe

$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + (1 - \Omega_k - \Omega_m) F(z)\right]^{1/2}$$

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Approaches...

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Approaches...

(1) Standard Candles: Luminosity Distance of SNe

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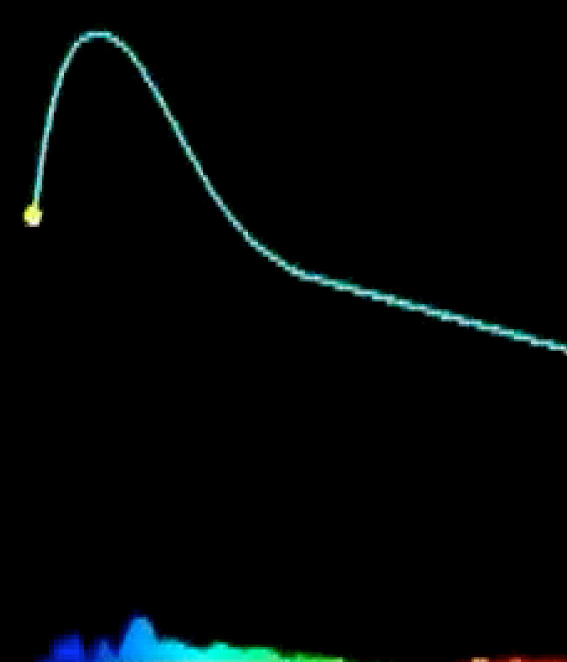

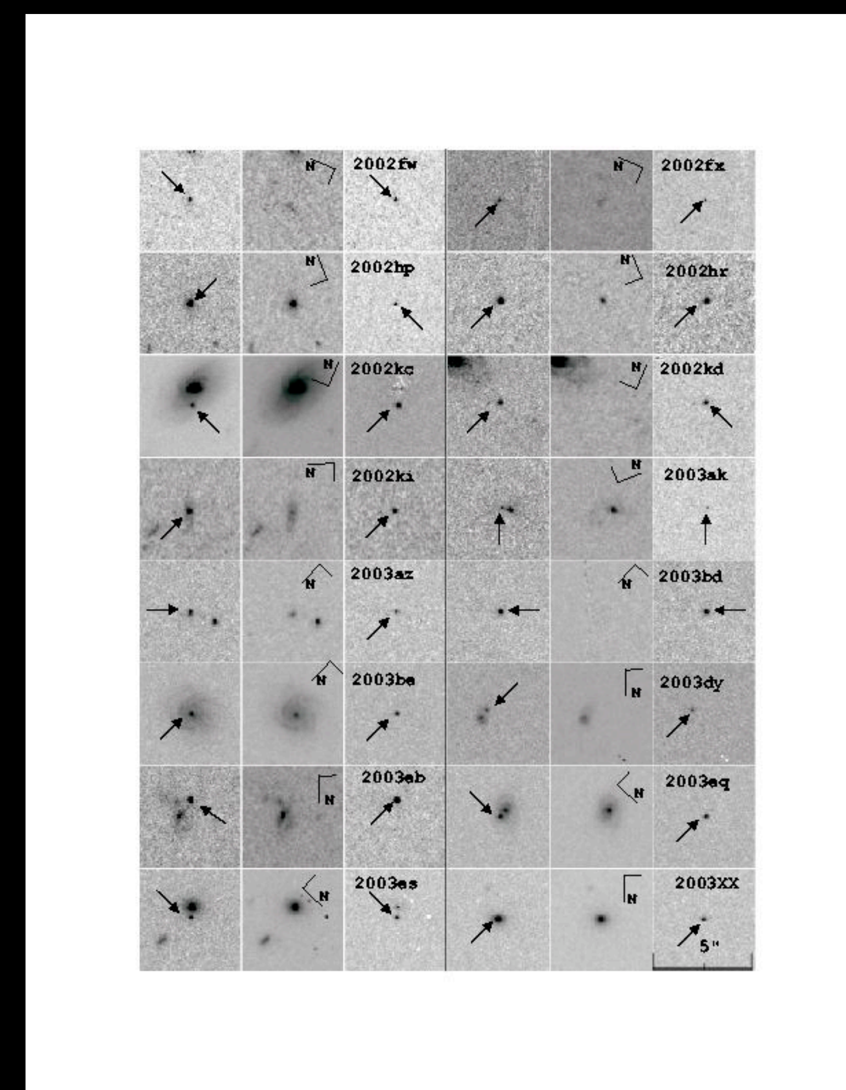

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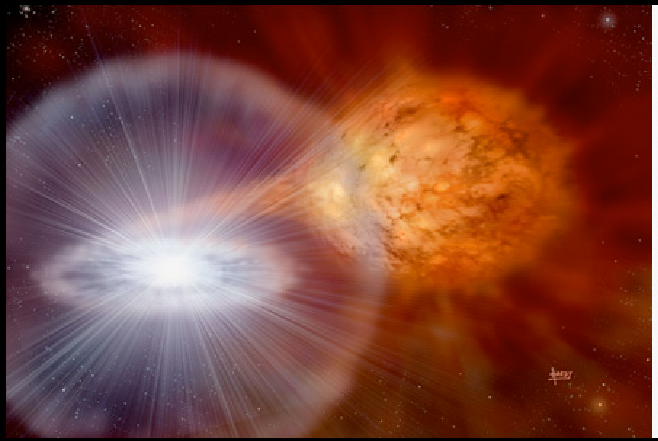
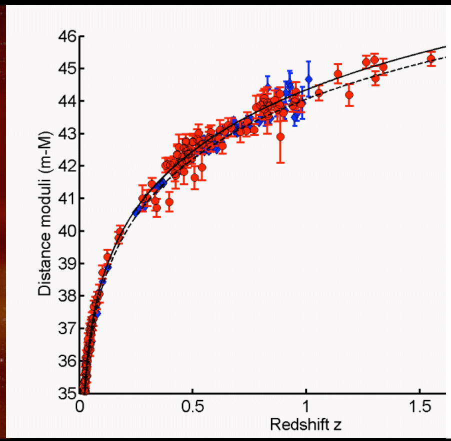

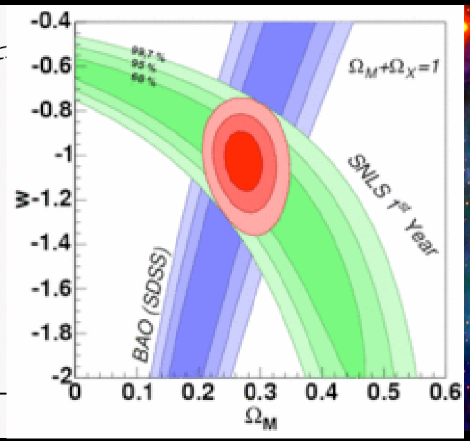

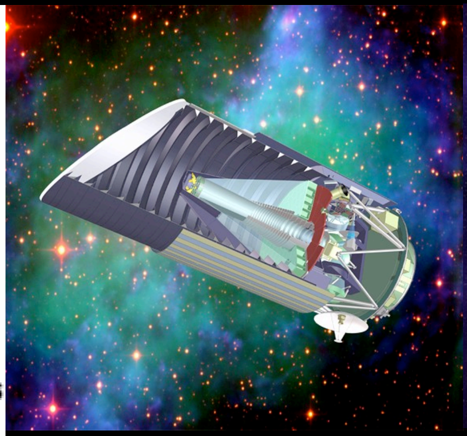


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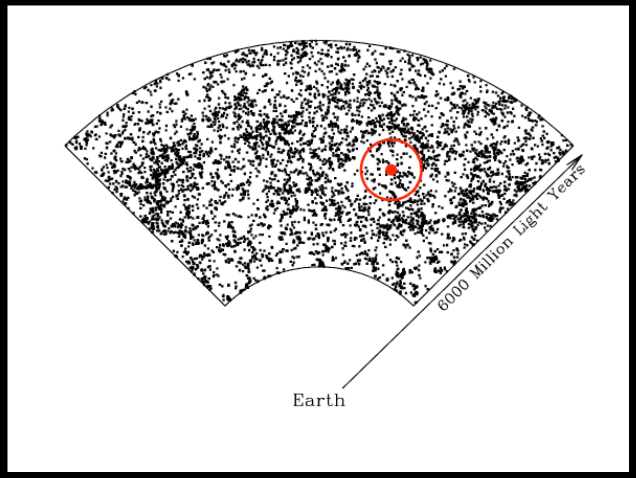
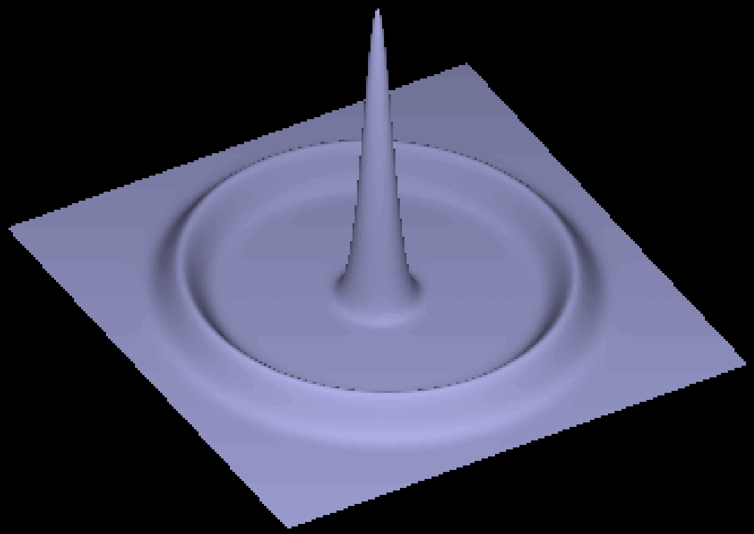
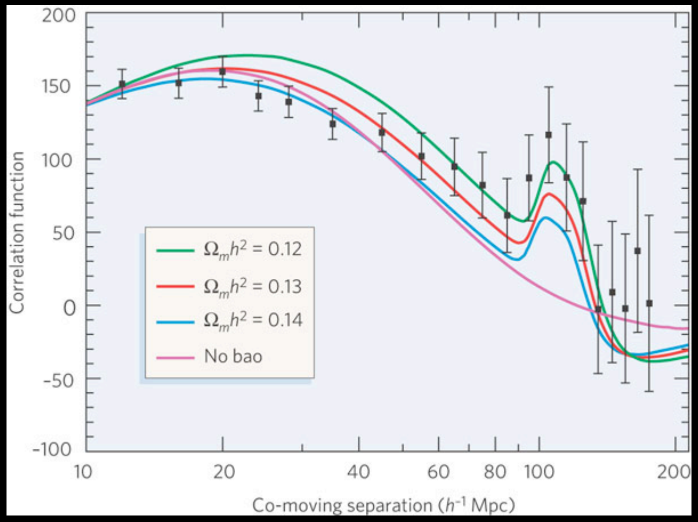
Approaches...

(2) Standard Rulers: Angular Diameter Distance via BAO







Eisenstein et al. (2005), Eisenstein, Seo, and White (2006)

Sunday: Nikhil's Talk

Gaztanaga, Miquel, and Sanchez (TODAY); arXiv:0808.1921

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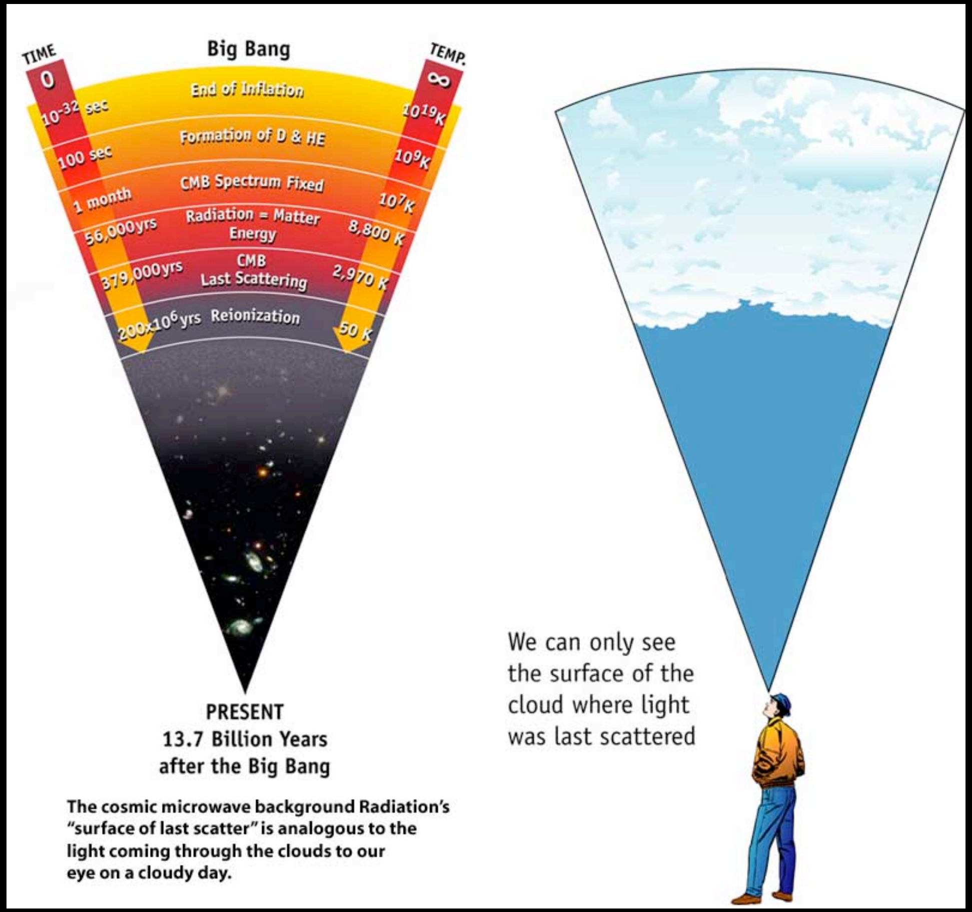
Approaches...

(3) Standard Rulers: Distance to Last Scattering Surface



$$R_{CMB} = \frac{\sqrt{\Omega_m H_0^2}}{c} r\left(z_{CMB}\right)$$

Wang and Mukherjee (2007)
Komatsu et al. (2008)

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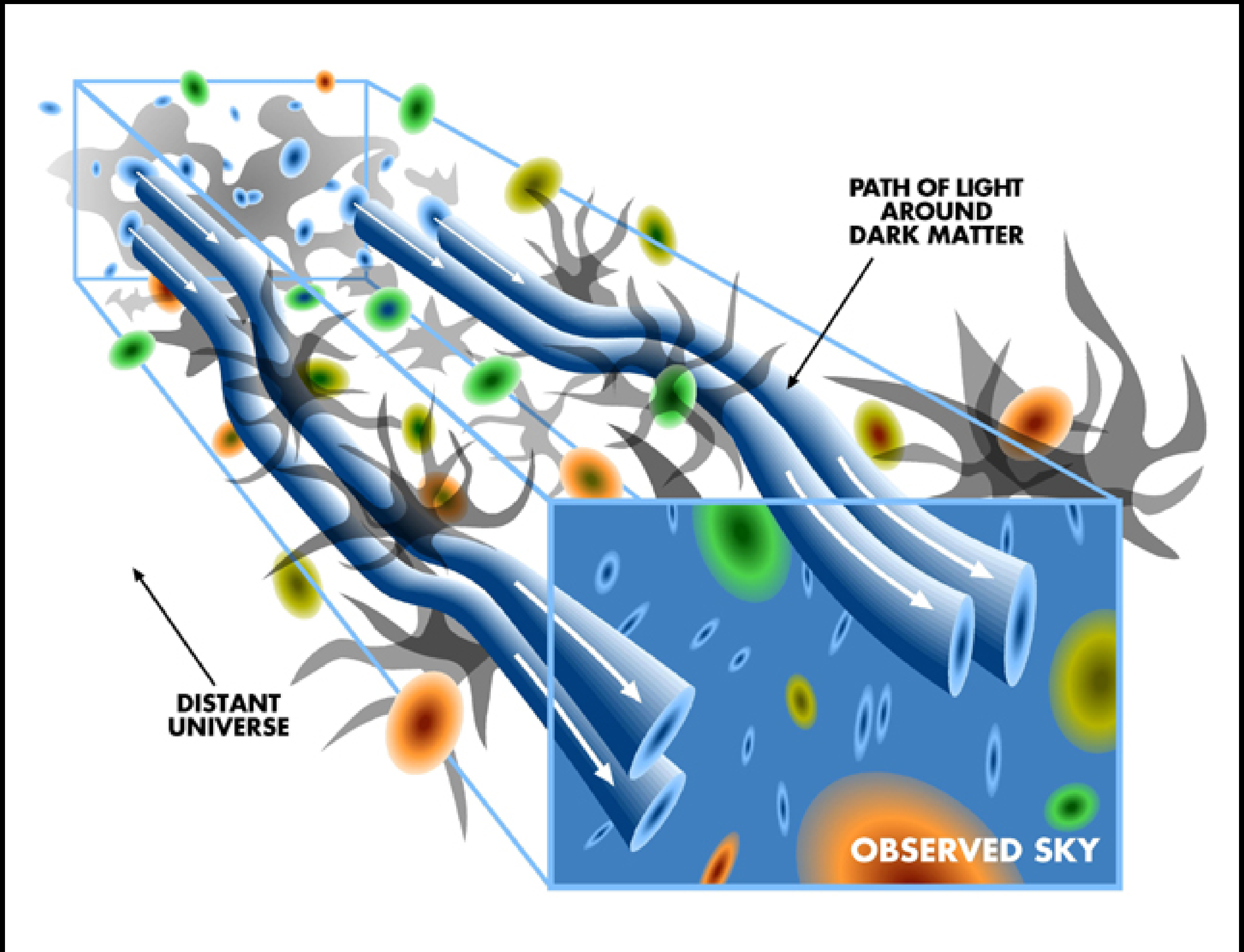
Approaches...

(4) Weak Lensing Tomography



☑ Galaxy Shear

☑ Photo-z

Wittman et al. (2001, 2002)
Hu and Keeton (2002

Ludovic's Talk this Morning

DE EOS Revisited: Different Approaches...

(A) Parameterize w(z) [Adopted by the DETF]

$$\boxed{w(a) = w_0 + (1-a)w_a}$$

Chevallier & Polarski (2001)
(Linder 2003)

DE EOS Revisited: Different Approaches...

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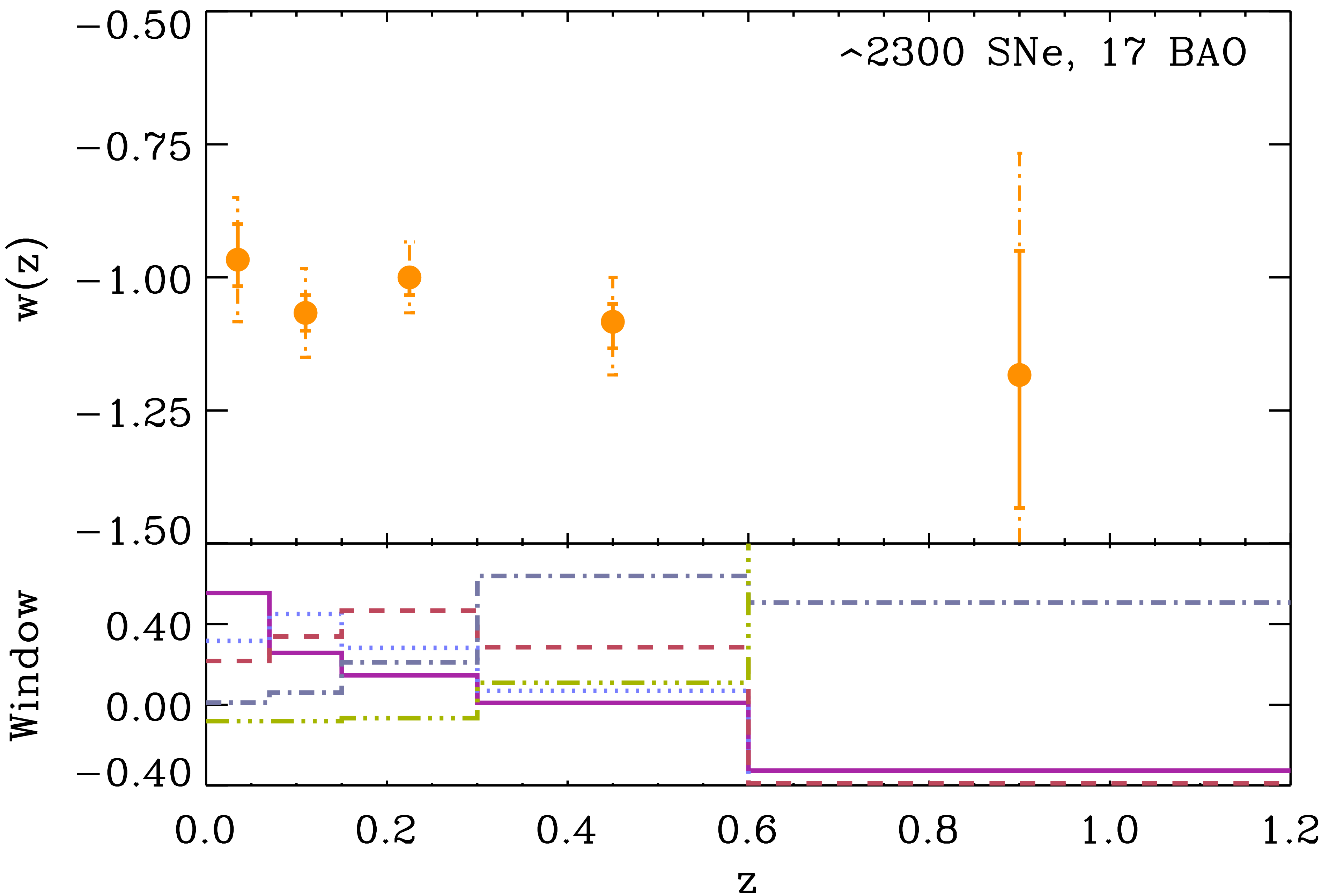
Chevallier & Polarski (2001)
(Linder 2003)

(B) Non-Parametric w(z)

- ✓ Unbiased Estimate of DE Density (Wang & Lovelace 2001)
- ✓ Principal Component Approach (Huterer & Starkman 2003)
- ✓ Uncorrelated Estimates (Huterer & Cooray 2005)
- ✓ Regularized Free Form Estimator (Saini 2003)
- ✓ Differential Method (Daly & Djorgovski 2003)
- ✓ Smoothing SNa data with Gaussian Kernel (Shafieloo et al. 2006)

For a review: Please see Sahni and Starobinsky (2006) [arXiv:astro-ph/0610026]

Binned Estimates: Future



w_1	0-.07
w_2	.07-.15
w_3	0.15-.3
w_4	0.3-0.6
w_5	0.6-1.2
w_6	1.2-2.0

D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, A. Cooray; PRL, 100, 241302 (2008)

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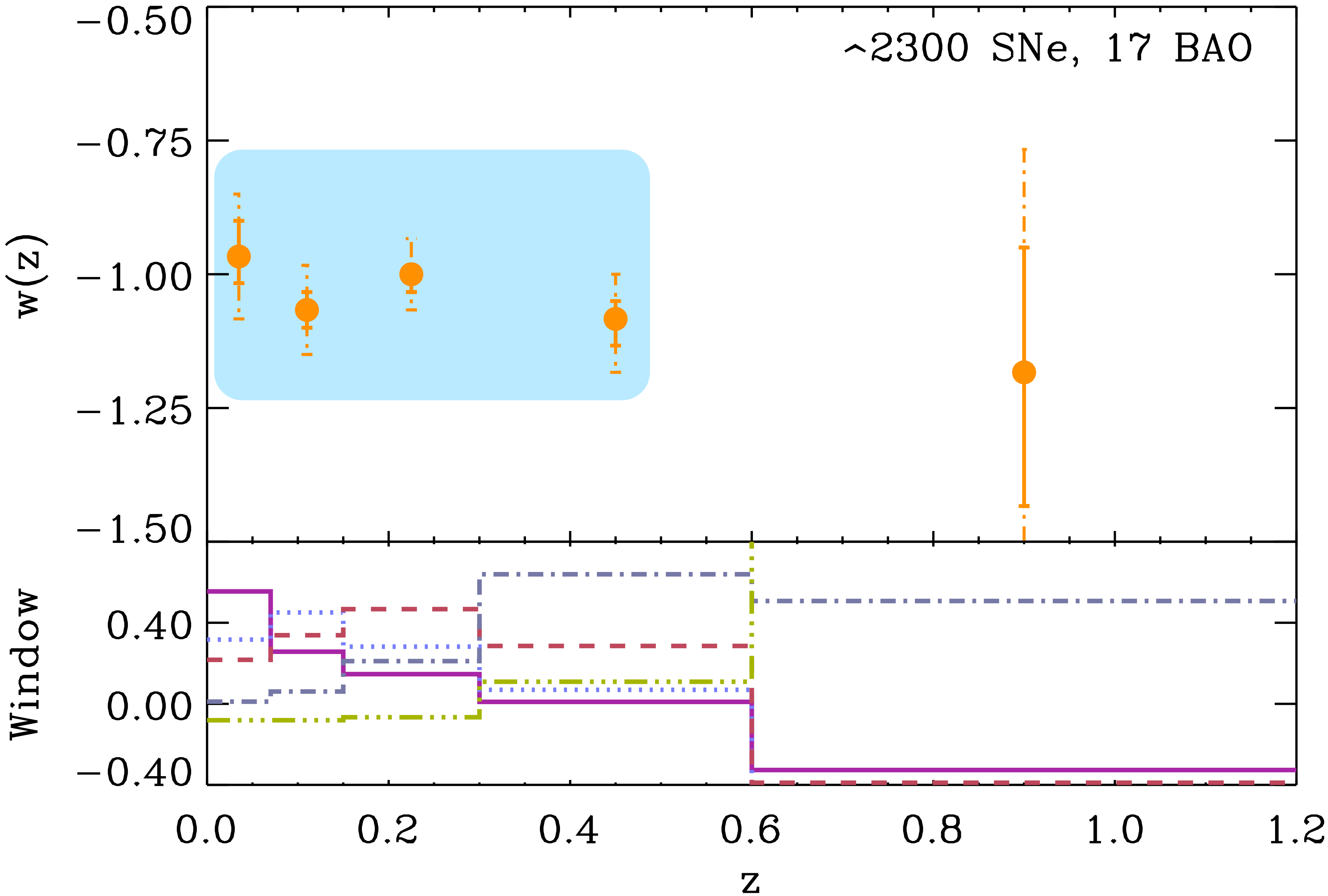

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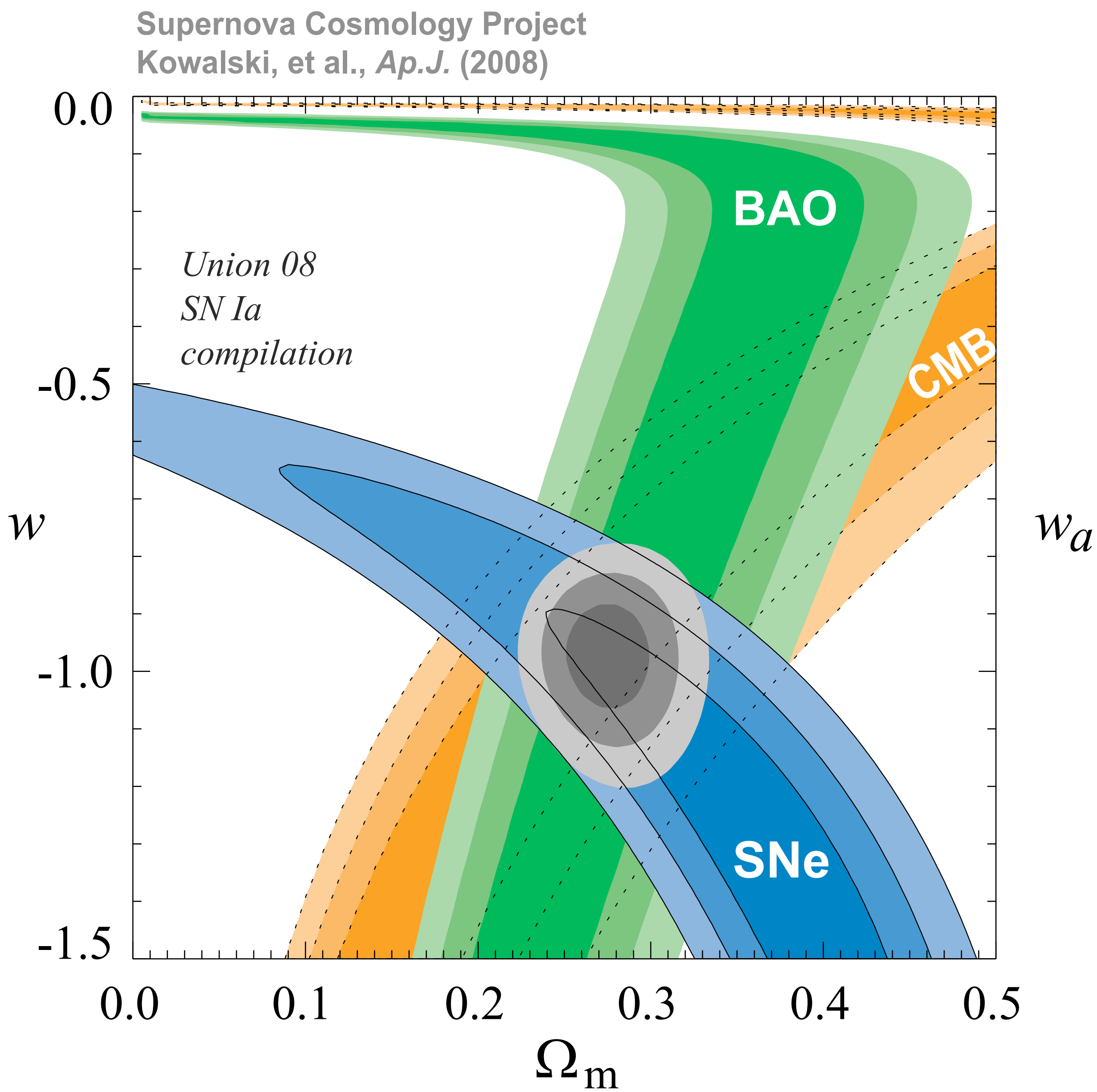
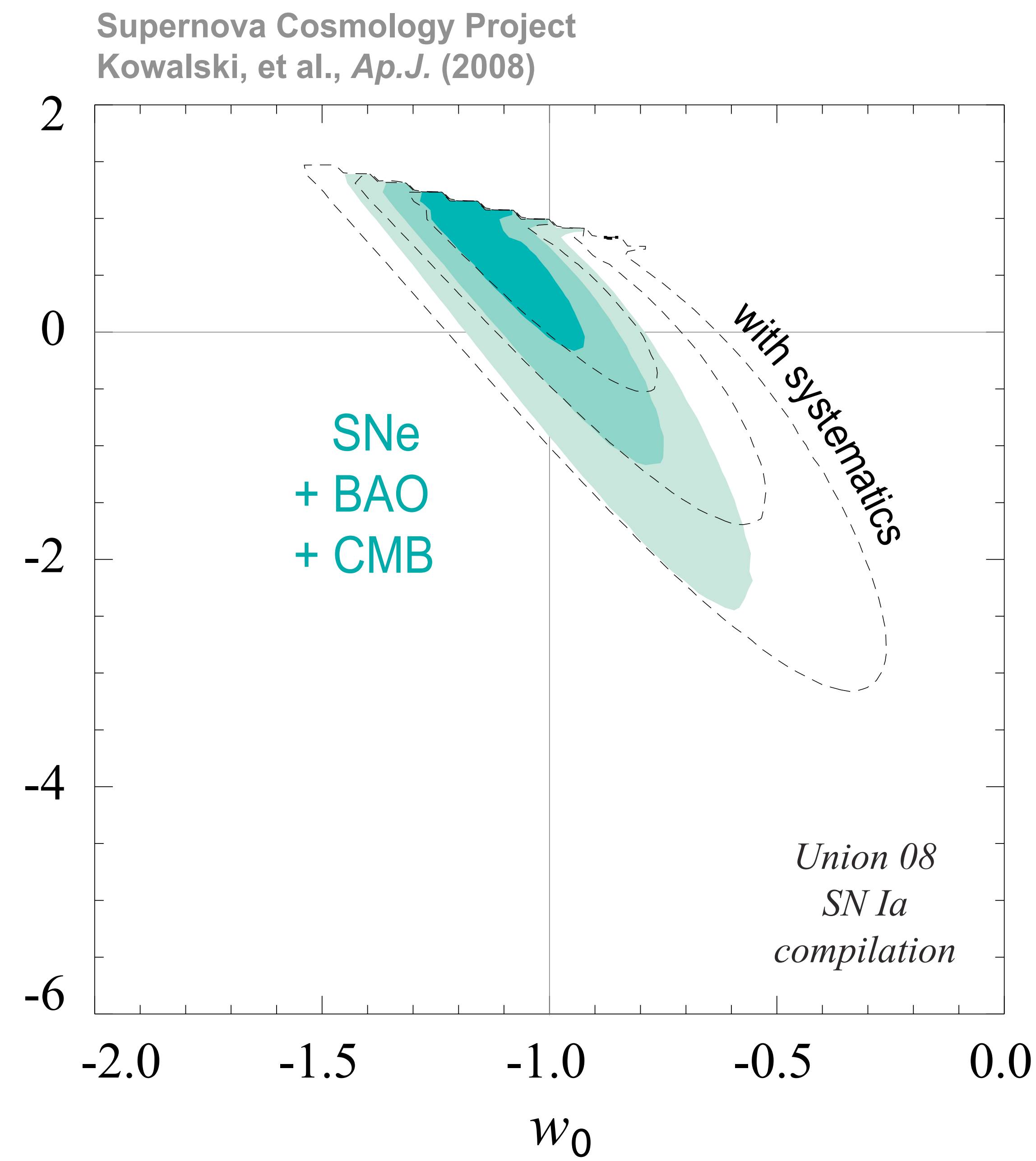
So Far So Good...

Systematic Matters!





$$\Omega_\Lambda = 0.713^{+0.027}_{-0.029}(\mathrm{stat})^{+0.036}_{-0.039}(\mathrm{sys})$$

$$w = -0.969^{+0.059}_{-0.063}(stat)^{+0.063}_{-0.066}(sys)$$

SNe Ia: Systematic Uncertainties

- ☑ Gravitational Lensing
- ☑ Evolution
- ☑ Photometric Calibration
- ☑ Malmquist Bias
- ☑ K-Correction
- ☑ Dust

SNe Ia: Systematic Uncertainties

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Influence of Gravitational Lensing?

$$\mathcal{F}^{\rm obs,lensed}(z,\hat{\mathbf{n}}) = \mu(z,\hat{\mathbf{n}})\mathcal{F}^{\rm obs,true}(z)$$

Weak lensing can modify the SNa flux & bias estimates of w

If a large # of SNe per redshift bin is available: Bias < 1%

D.S., A. Amblard, D. Holz, A. Cooray; ApJ, 678, 1 (2008)

SNe Ia: Systematic Uncertainties

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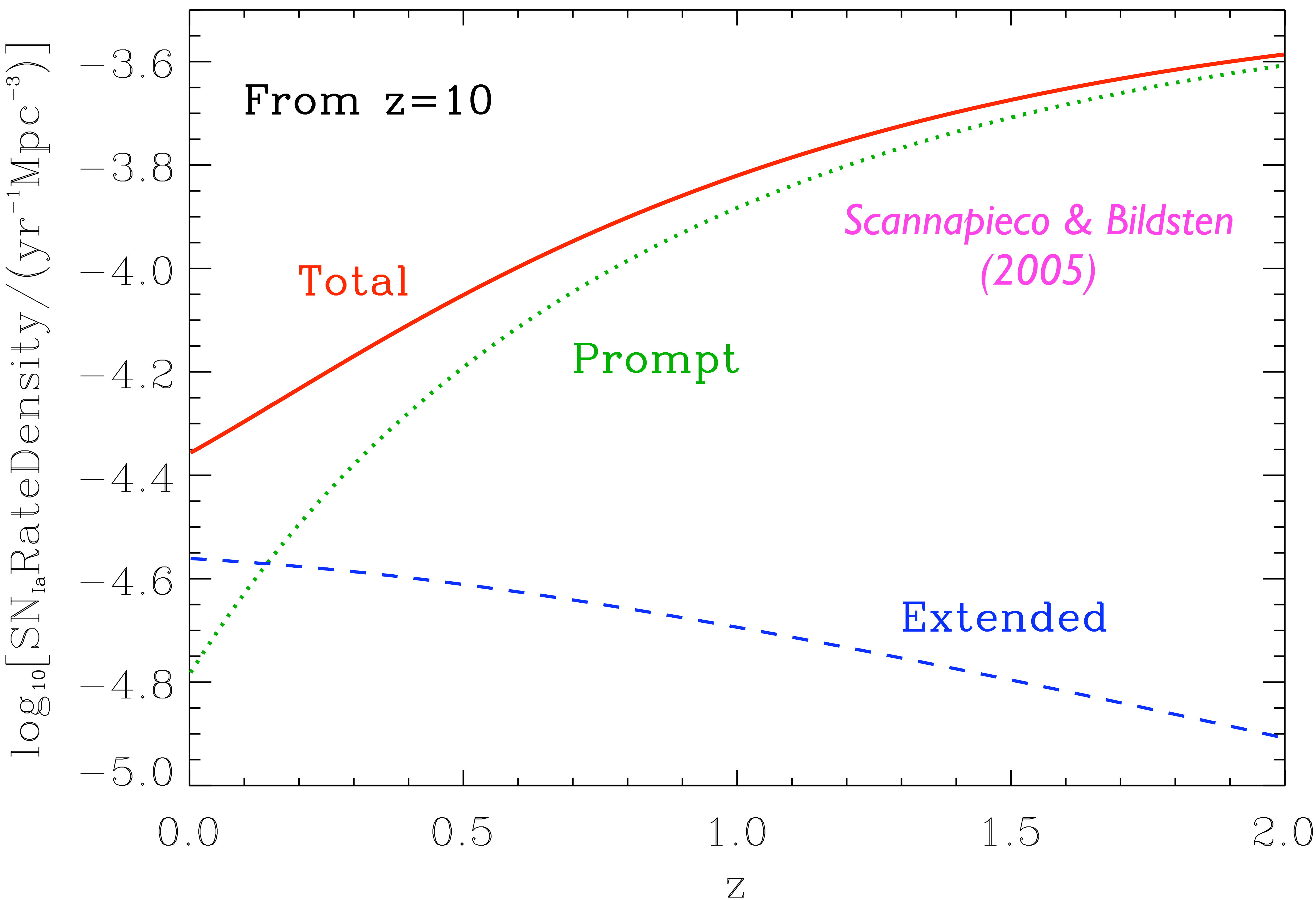
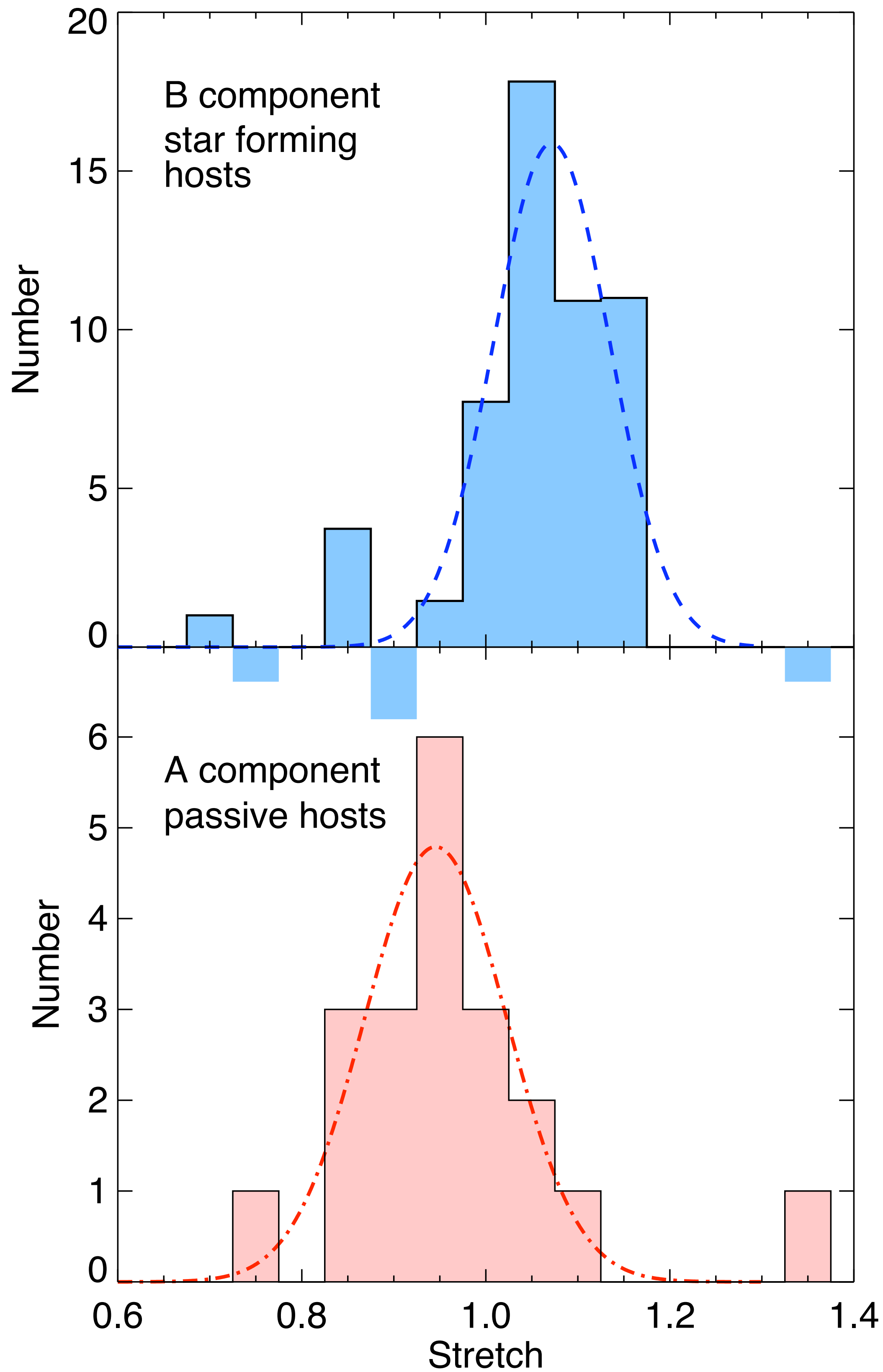
Evolution based on Two SN Populations



Evolution based on Two SN Populations



PROMPT

12% Dfference

in

Intrinsic Luminosity

$$\mathcal{L}_P = \mathcal{L}_E + \Delta\mathcal{L}$$

DELAYED

Howell et al. (2007)

Is there a Signature in the Hubble Diagram?

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$$m - M = 5\log\left(\frac{d_L}{\mathrm{Mpc}}\right) + 25 + \mathcal{M}$$

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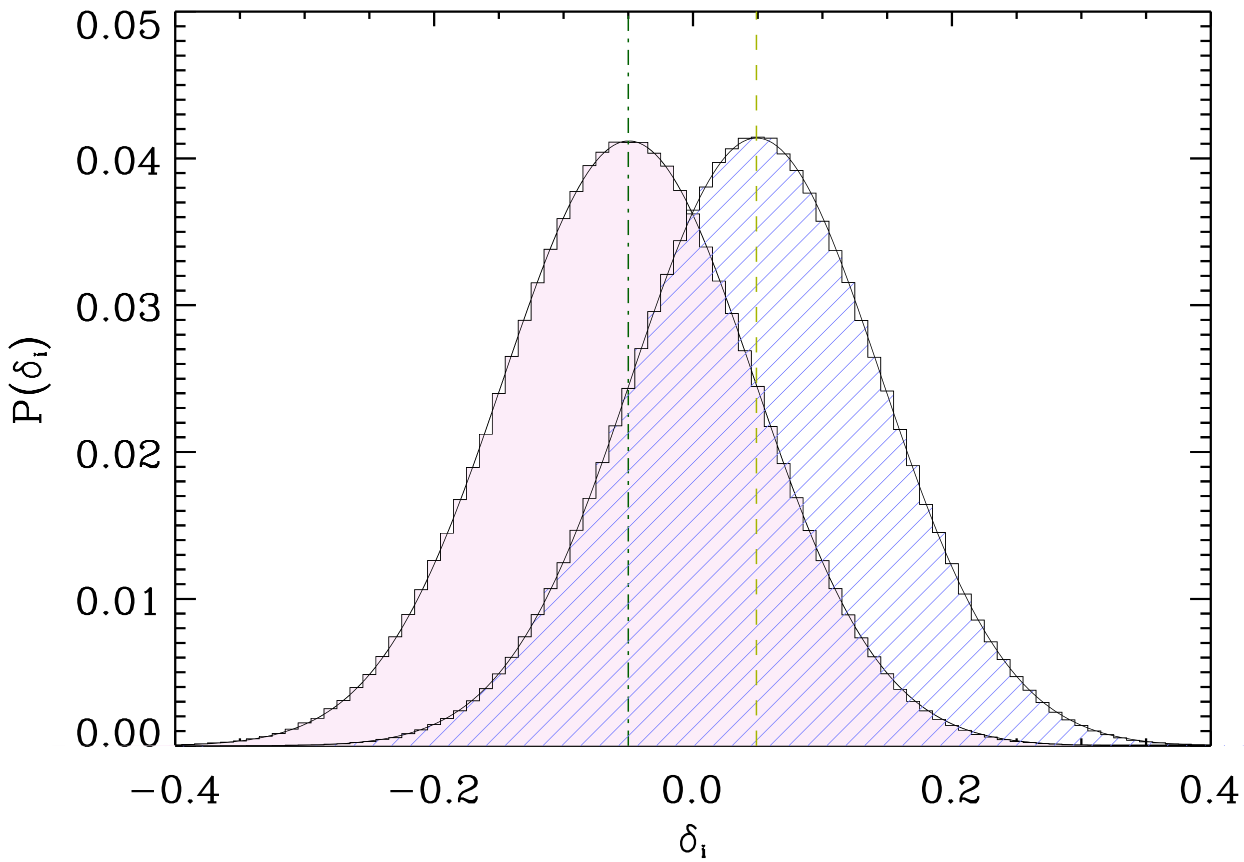


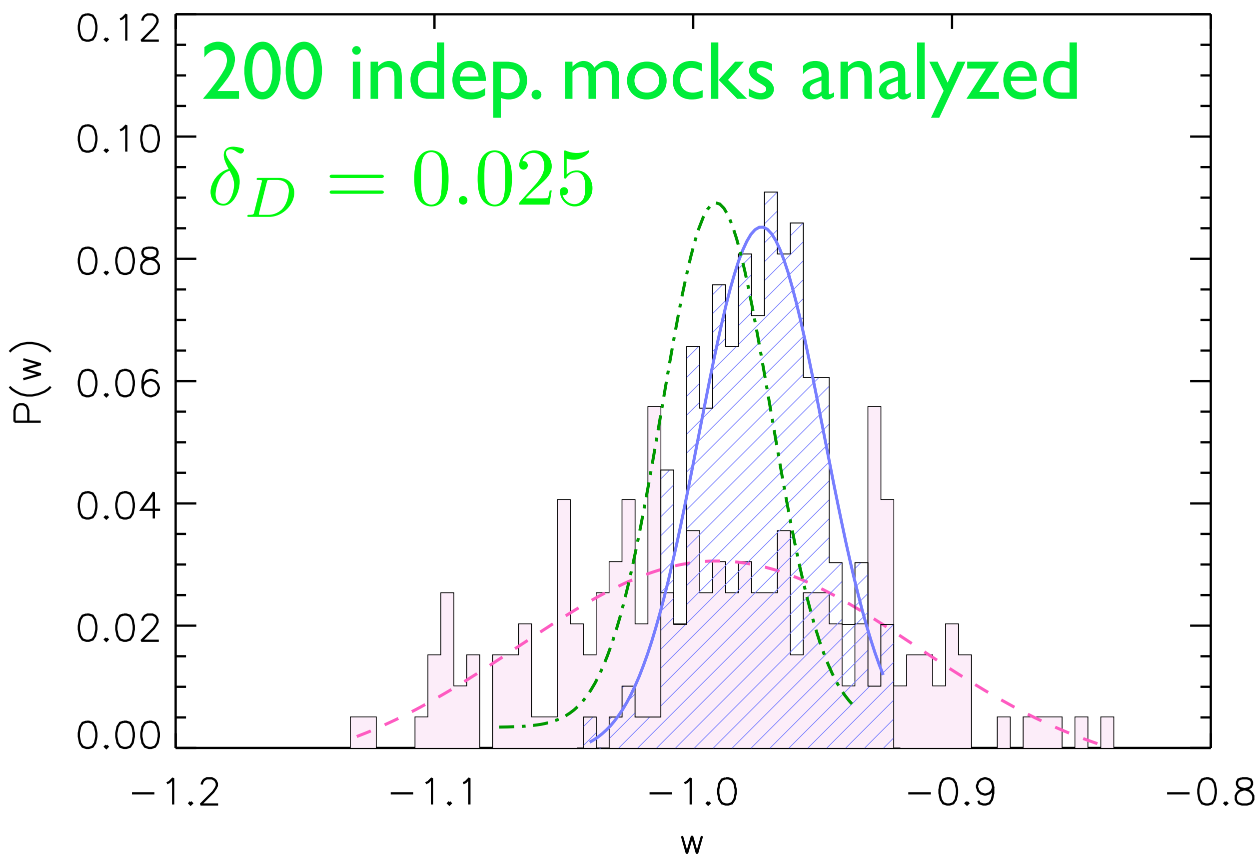
With current data (192 SNe from Davis et al. 2007), the residual is consistent with zero:

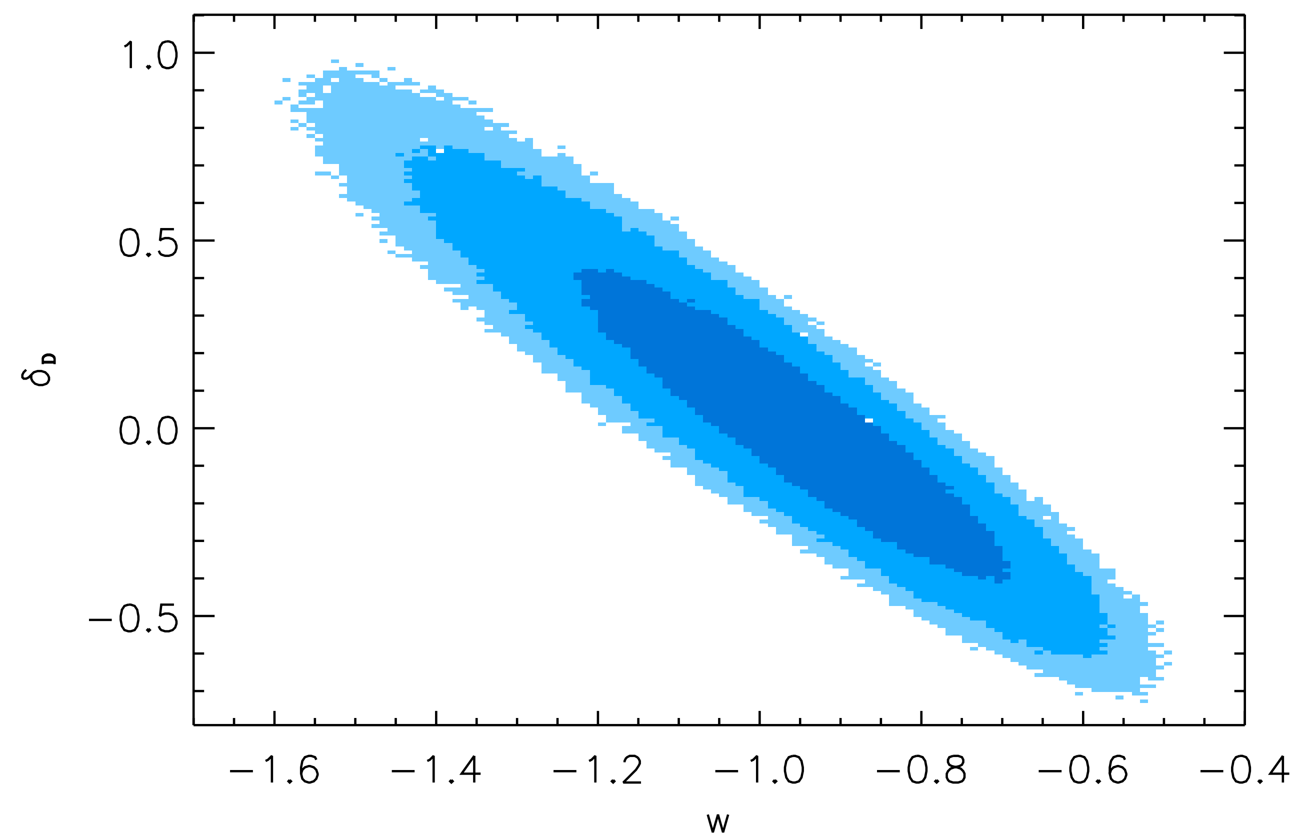
$$\delta_D \sim (5 \pm 9)\%$$

With future data, one will be able to constrain the residual much better.

D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)

Effect on the EOS Estimates: Bias in “w”



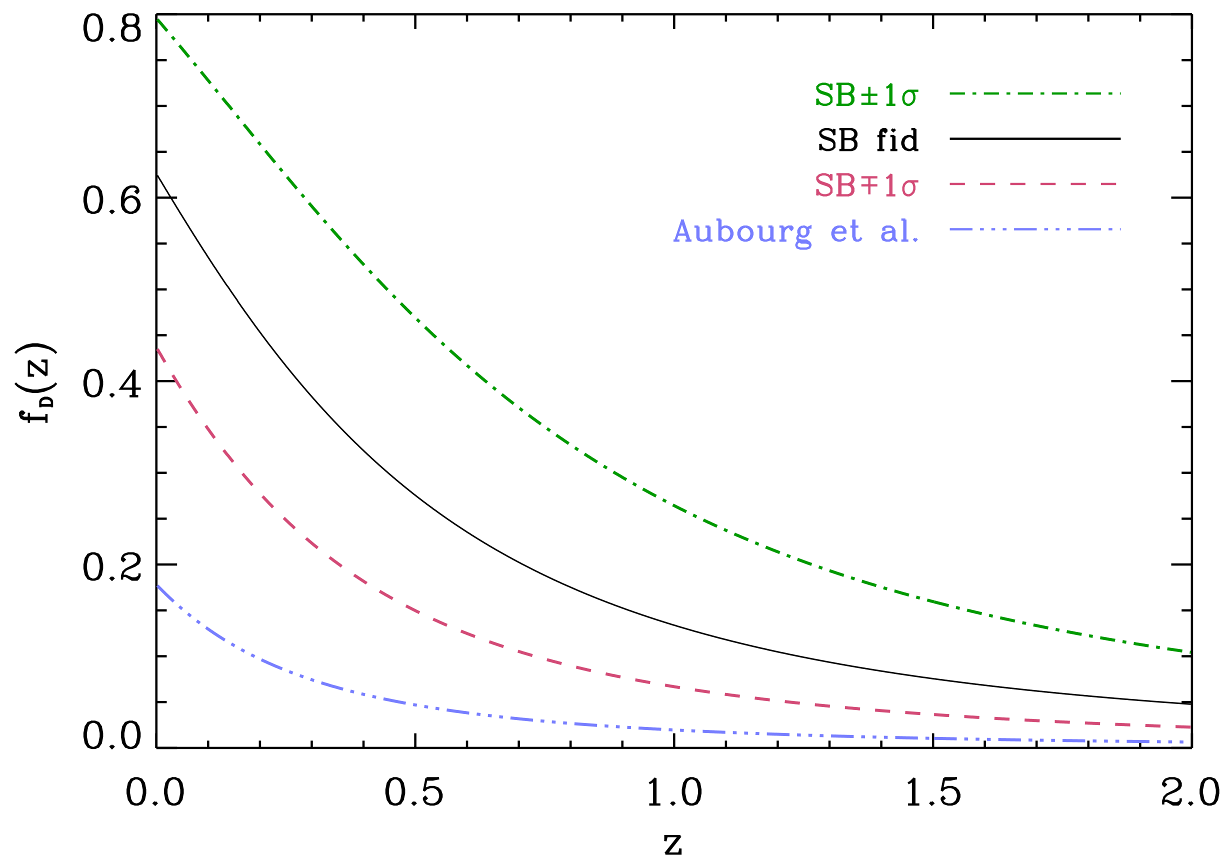


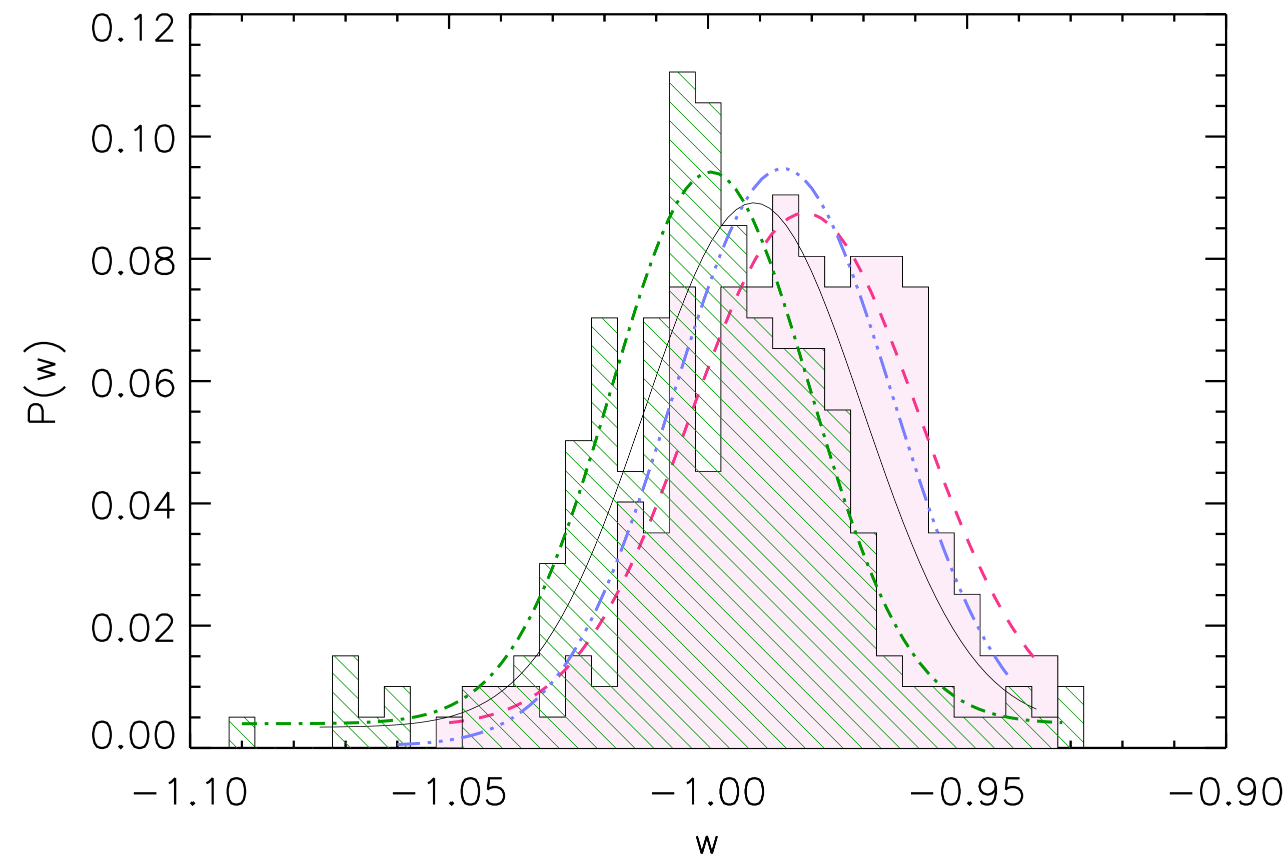
~1-sigma bias in “w”

Correlation

D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)

Uncertainty in Star Formation: Bias in "w"

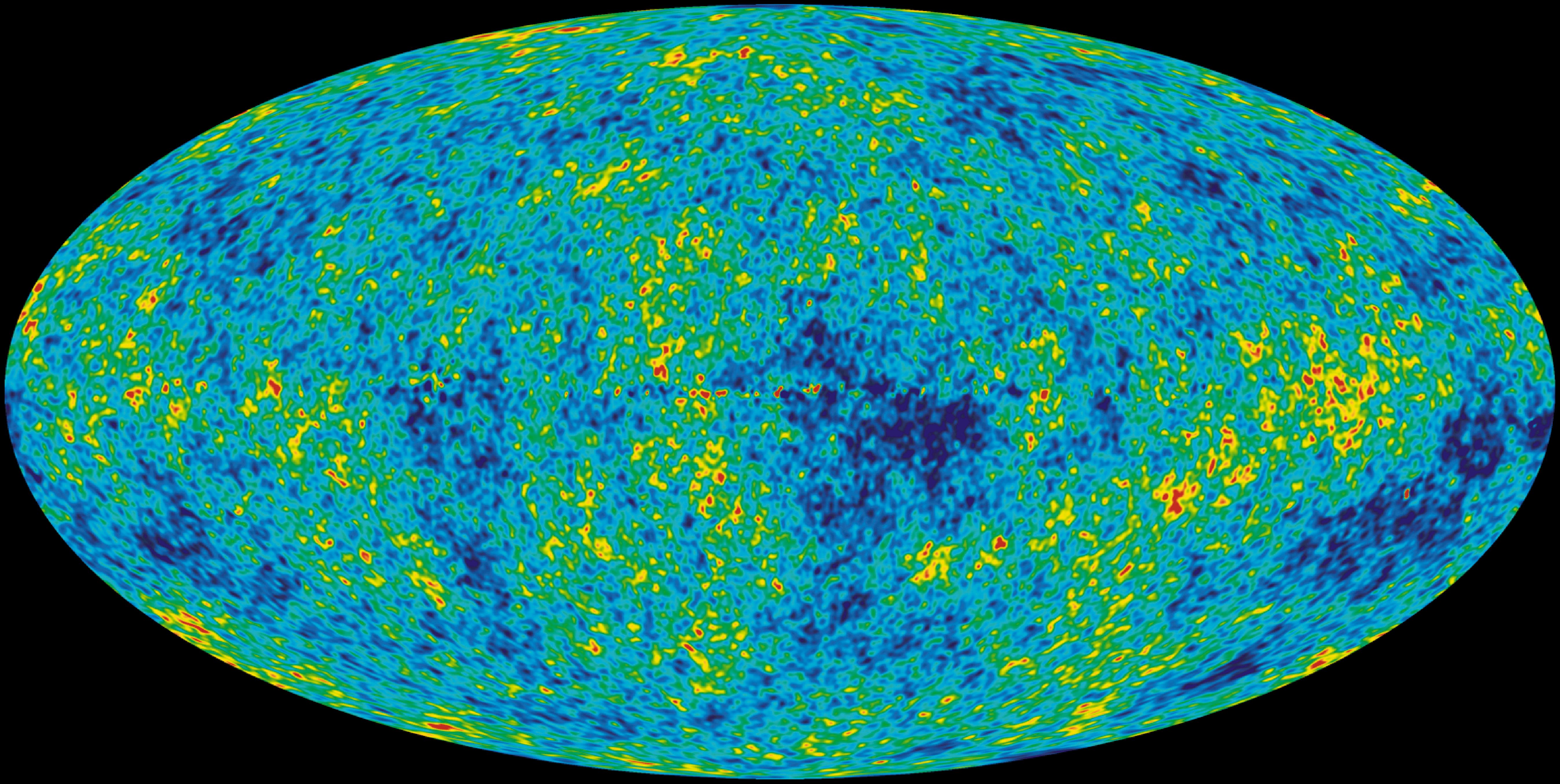




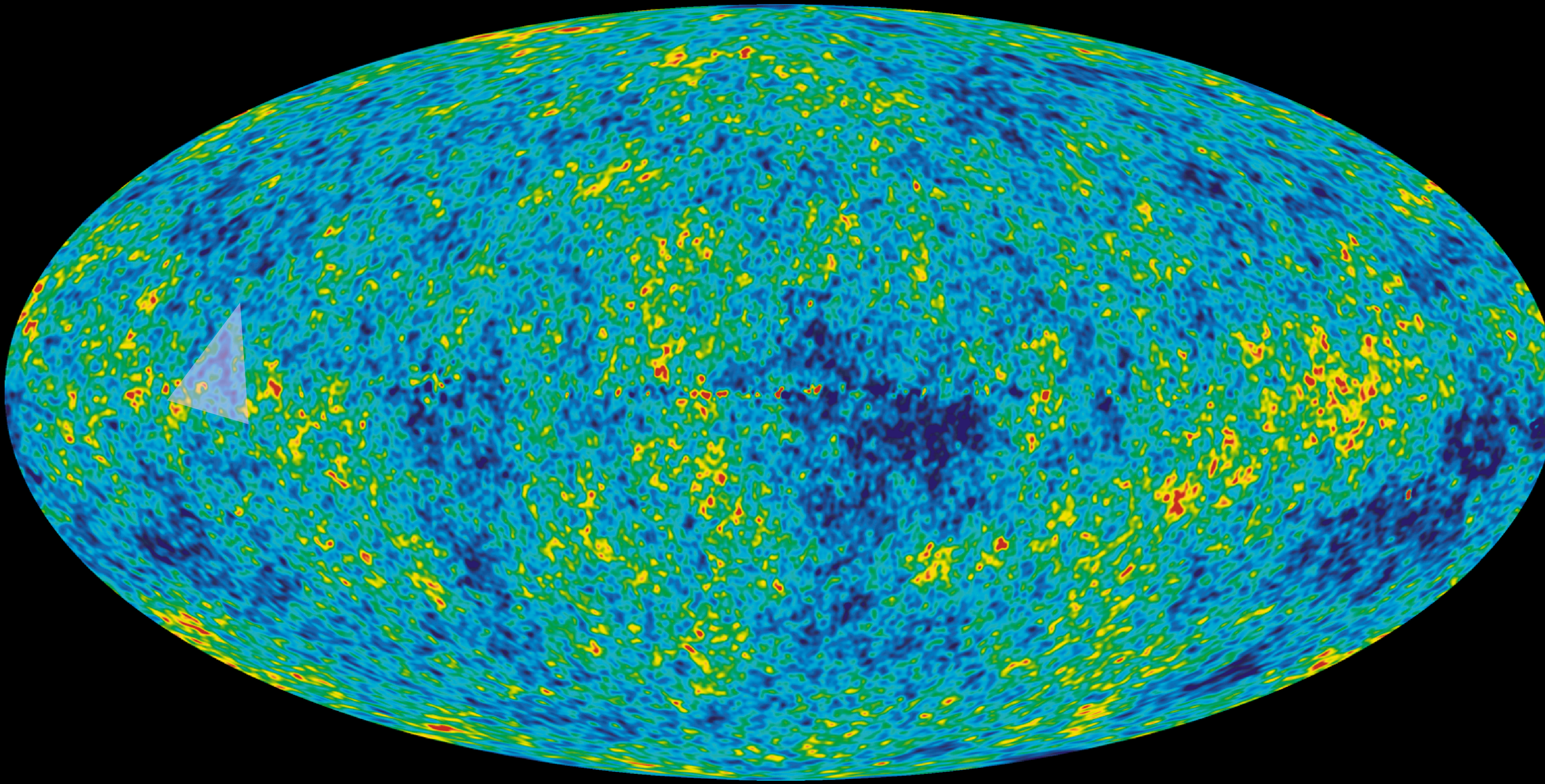
Delayed Fraction

Bias in "w"

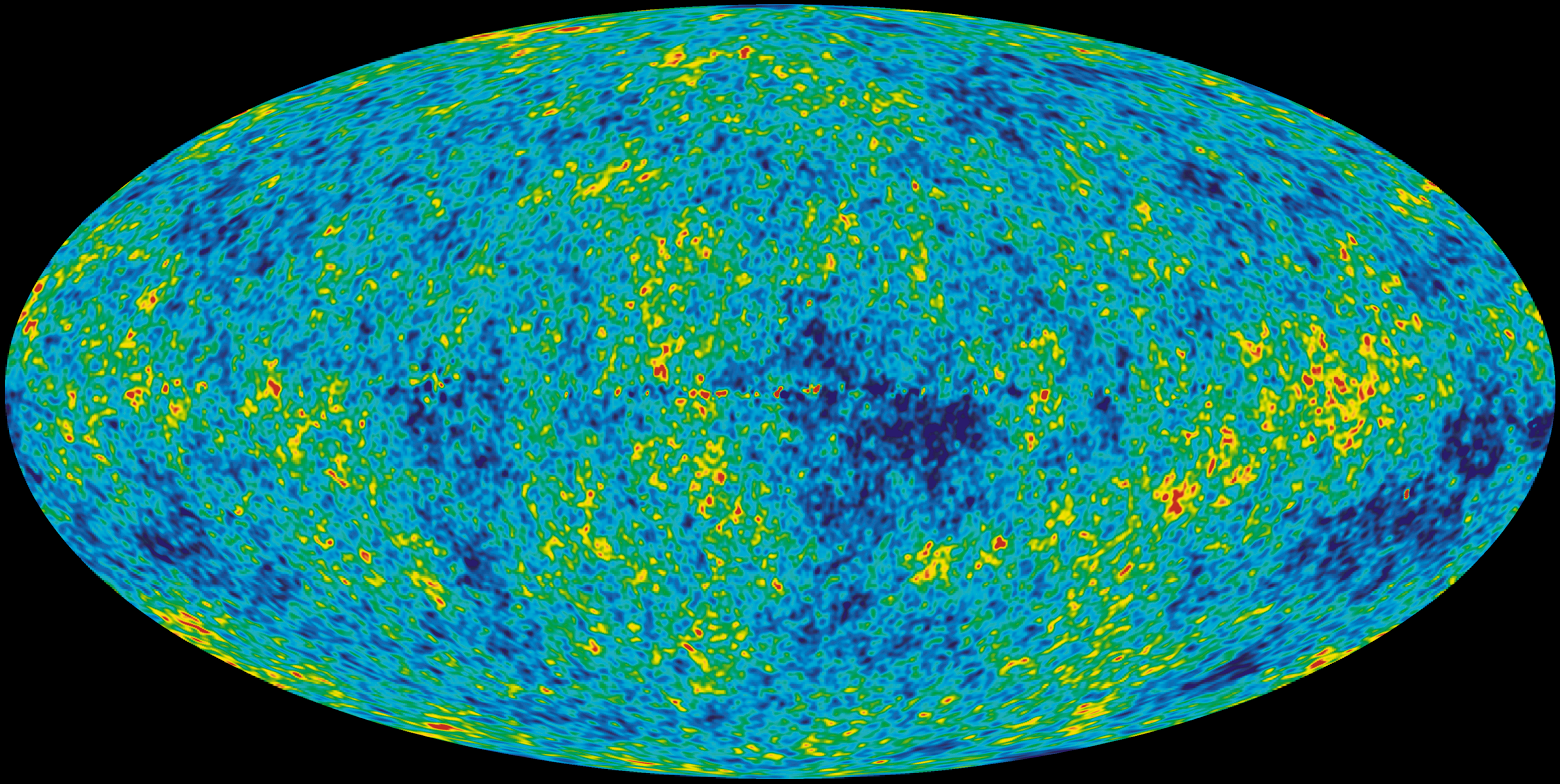
D.S., A. Amblard, A. Cooray, and D. Holz; ApJL, 684, L13 (2008)



Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team

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T
H
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O
U
WELLS FARGO
We're on Track
For a Cure