Shedding Light on the Dark Sector

Devdeep Sarkar
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in collaboration with:
Scott Sullivan (UCI/UCLA), Shahab Joudaki (UCI), Alexandre Amblard (UCI),
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Drexel University Cosmology/Astrophysics Seminar May 09, 2008

A Little Bit of History

A. Einstein, Sitzungsber. Preuss. Akad. Wiss. phys.-math. Klasse VI, 142 (1917)

"In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It has to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars."

A. Friedmann, Z. Phys. 10, 377 (1922); 21, 326 (1924)

G. E. Lemaitre, Ann. Soc. Sci. Brux. A 47, 49 (1927)

Einstein to H. Weyl (1923):

"If there is no quasi-static world, then away with the cosmological term"

A. Einstein, S.B. Preuss. Akad. Wiss. (1931) 235

THE ASTROPHYSICAL JOURNAL, **284**:439–444, 1984 September 15
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TESTS OF COSMOLOGICAL MODELS CONSTRAINED BY INFLATION

P. J. E. PEEBLES
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Received 1984 February 6; accepted 1984 March 23

ABSTRACT

The inflationary scenario requires that the universe have negligible curvature along constant-density surfaces. In the Friedmann-Lemaître cosmology that leaves us with two free parameters, Hubble's constant H_0 and the density parameter Ω_0 (or, equivalently, the cosmological constant Λ). I discuss here tests of this set of models from local and high-redshift observations. The data agree reasonably well with $\Omega_0 \sim 0.2$.

Subject heading: cosmology

THE ASTROPHYSICAL JOURNAL, **325**:L17–L20, 1988 February 15
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COSMOLOGY WITH A TIME-VARIABLE COSMOLOGICAL "CONSTANT"

P. J. E. PEEBLES AND BHARAT RATRA
Joseph Henry Laboratories, Princeton University
Received 1987 October 20; accepted 1987 November 23

ABSTRACT

If the potential $V(\phi)$ of the scalar field that drove inflation had a power-law tail at large ϕ, $V \approx \phi^{-\alpha}$, the mass density, ρ_ϕ, associated with ϕ would act like a cosmological constant that decreases with time less rapidly than the mass densities of matter and radiation. If ρ_ϕ were appreciable at the present epoch it could help reconcile the low dynamical estimates of the mean mass density with the negligibly small space curvature preferred by inflation.

Subject headings: cosmology — early universe

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September
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OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] 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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Key words: cosmology: observations — supernovae: general

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1
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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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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 Ⓔ
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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 $\sim$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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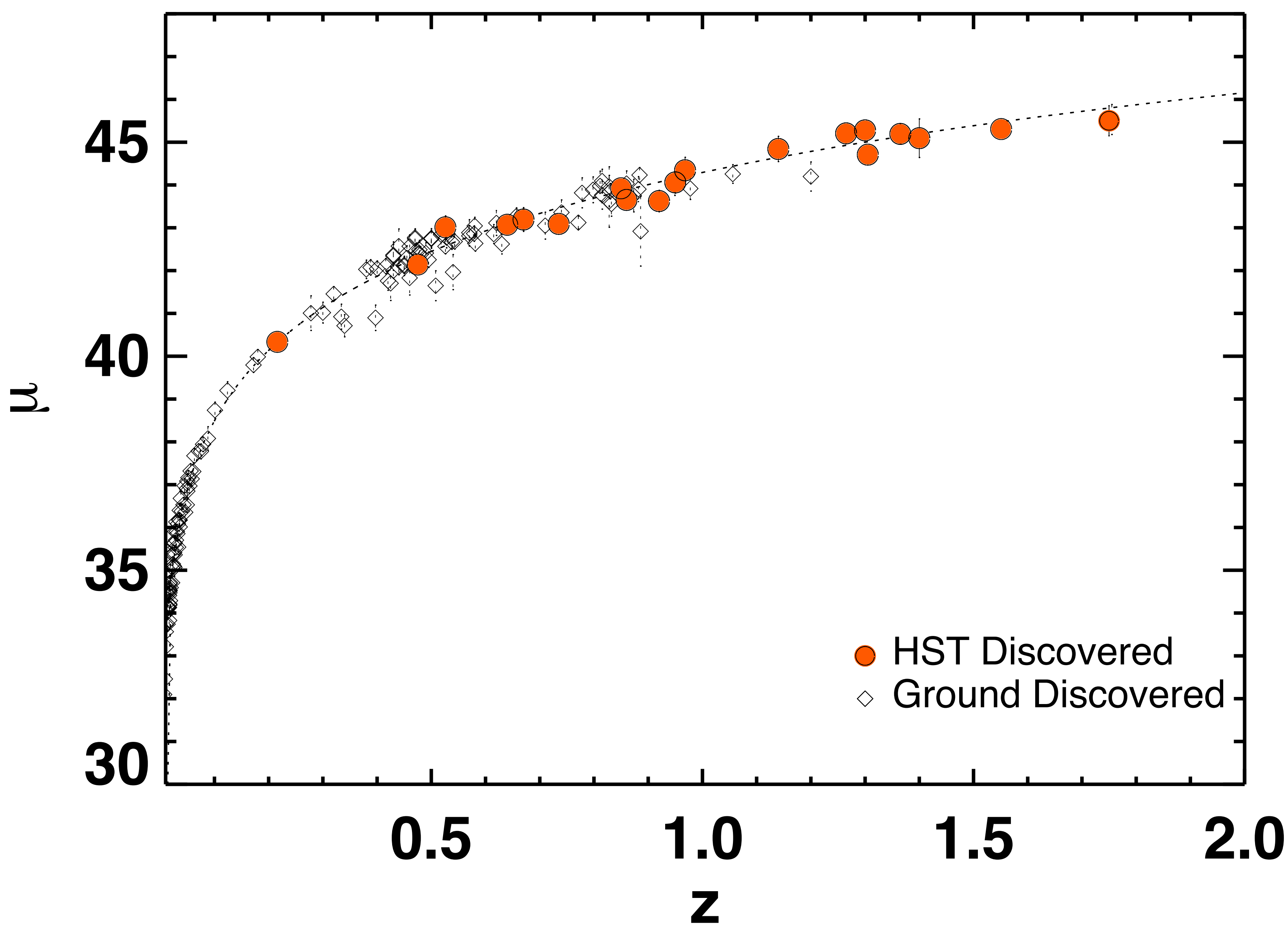

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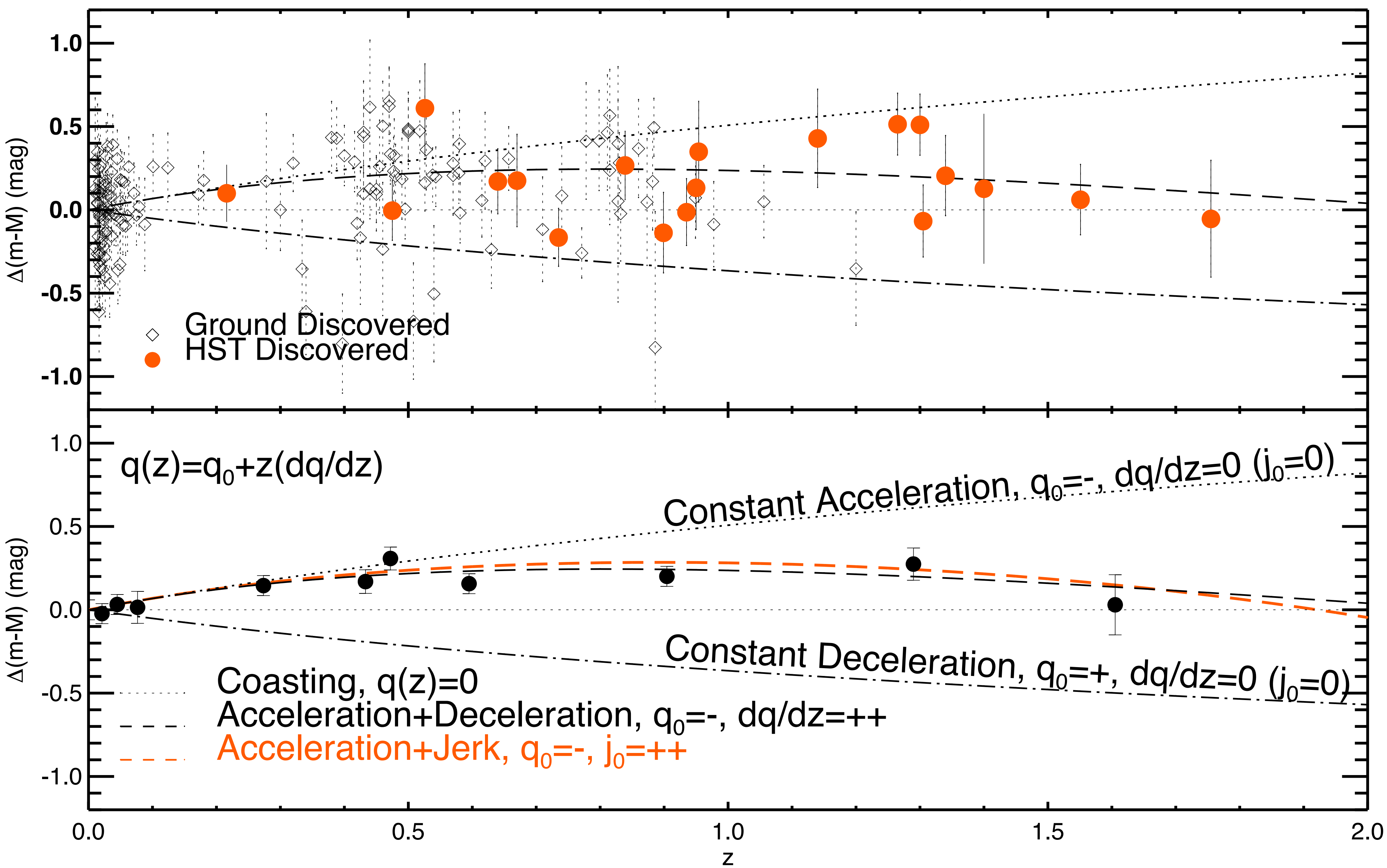
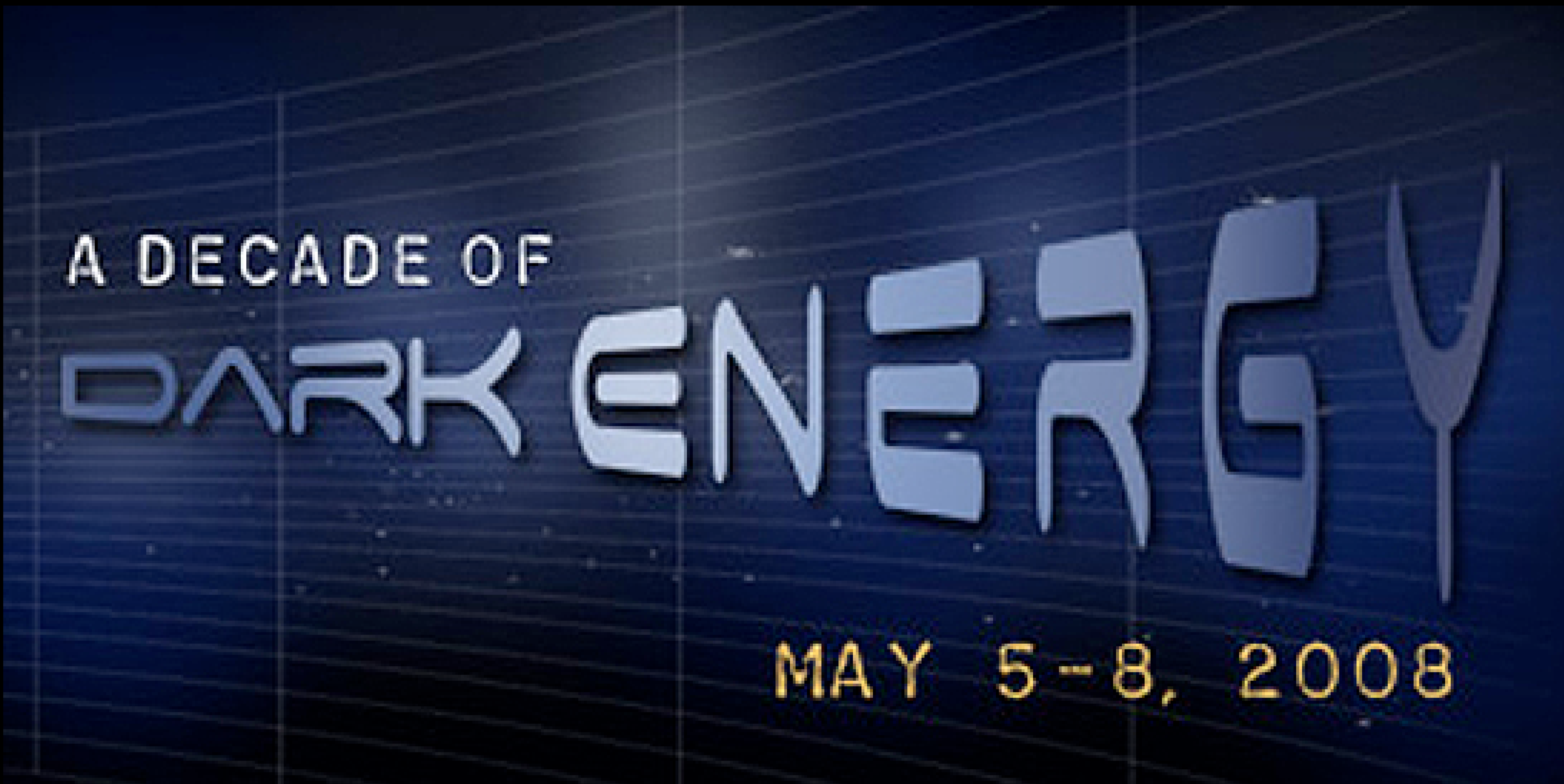
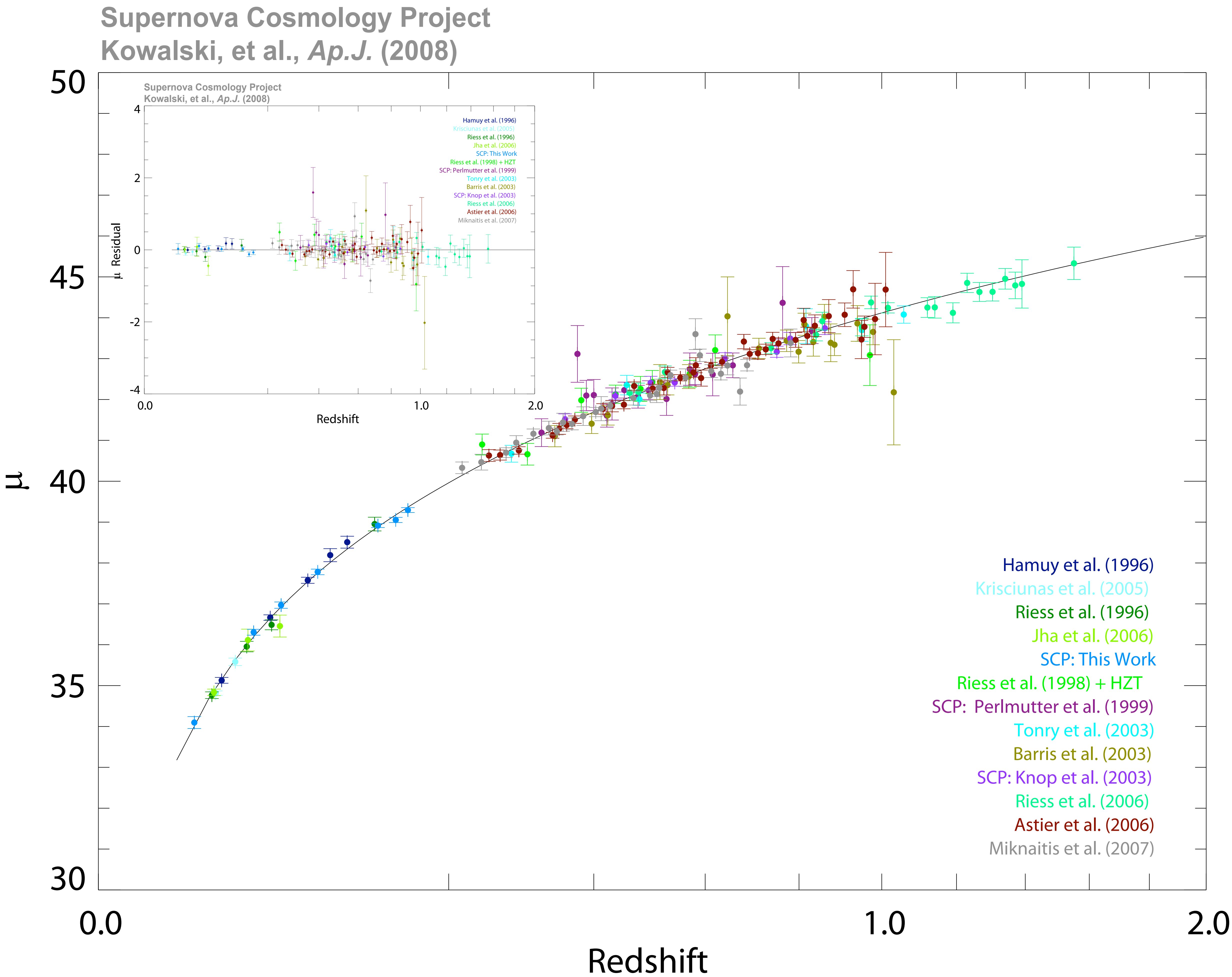


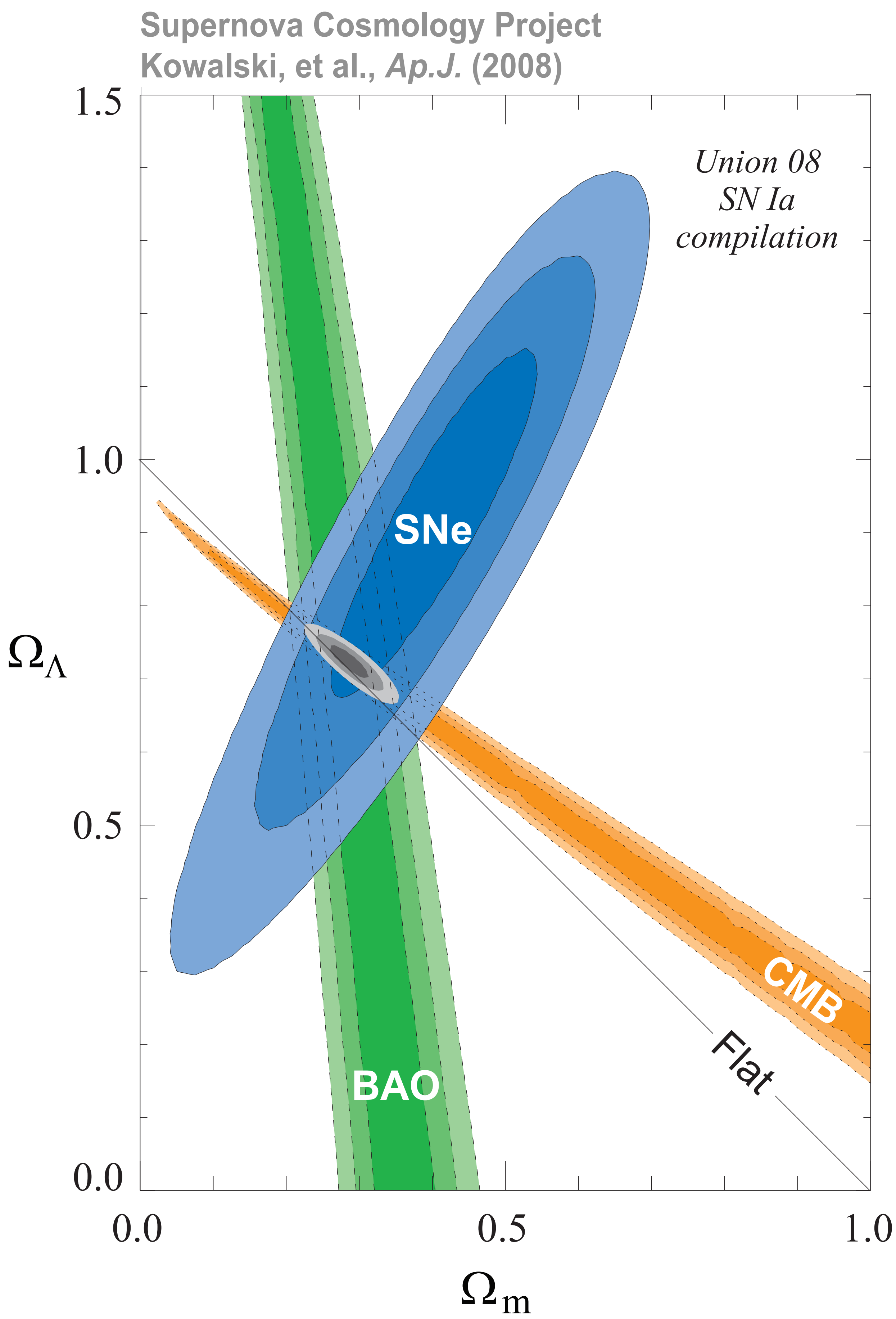
Where Do We Stand?
After...



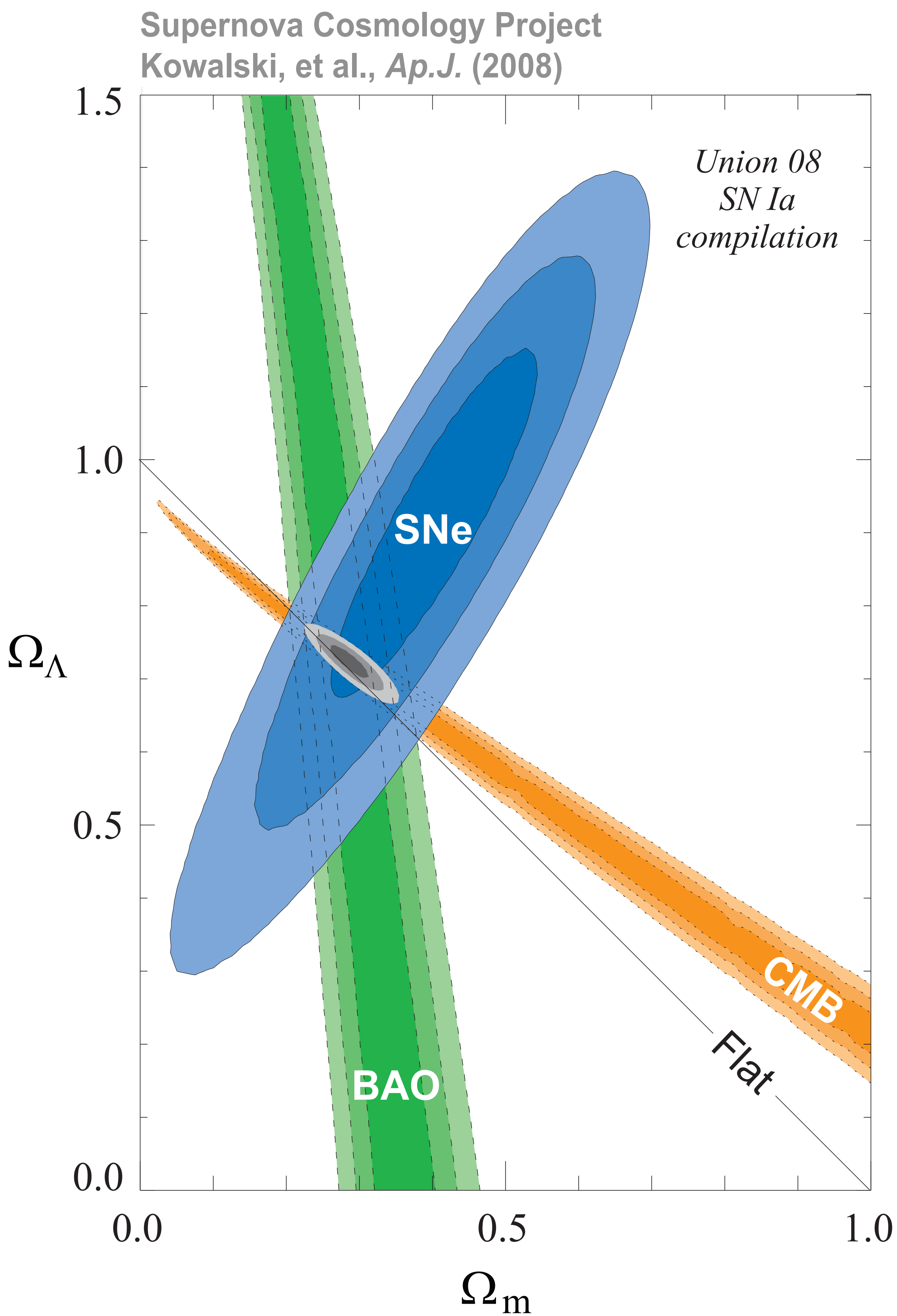
Space Telescope Science Institute, Baltimore, MD



Supernova Cosmology Project
Kowalski, et al., Ap.J. (2008)
μ Residual
Redshift
Hamuy et al. (1996)
Krisciunas et al. (2005)
Riess et al. (1996)
Jha et al. (2006)
SCP: This Work
Riess et al. (1998) + HZT
SCP: Perlmutter et al. (1999)
Tonry et al. (2003)
Barris et al. (2003)
SCP: Knop et al. (2003)
Riess et al. (2006)
Astier et al. (2006)
Miknaitis et al. (2007)
μ
Redshift
0.0
1.0
2.0
30
35
40
45
50


Supernova Cosmology Project
Kowalski, et al., *Ap.J.* (2008)
Union 08
SN Ia
compilation
SNe
BAO
CMB
Flat
1.5
1.0
0.5
0.0
0.0
0.5
1.0
Ω_Λ
Ω_m

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



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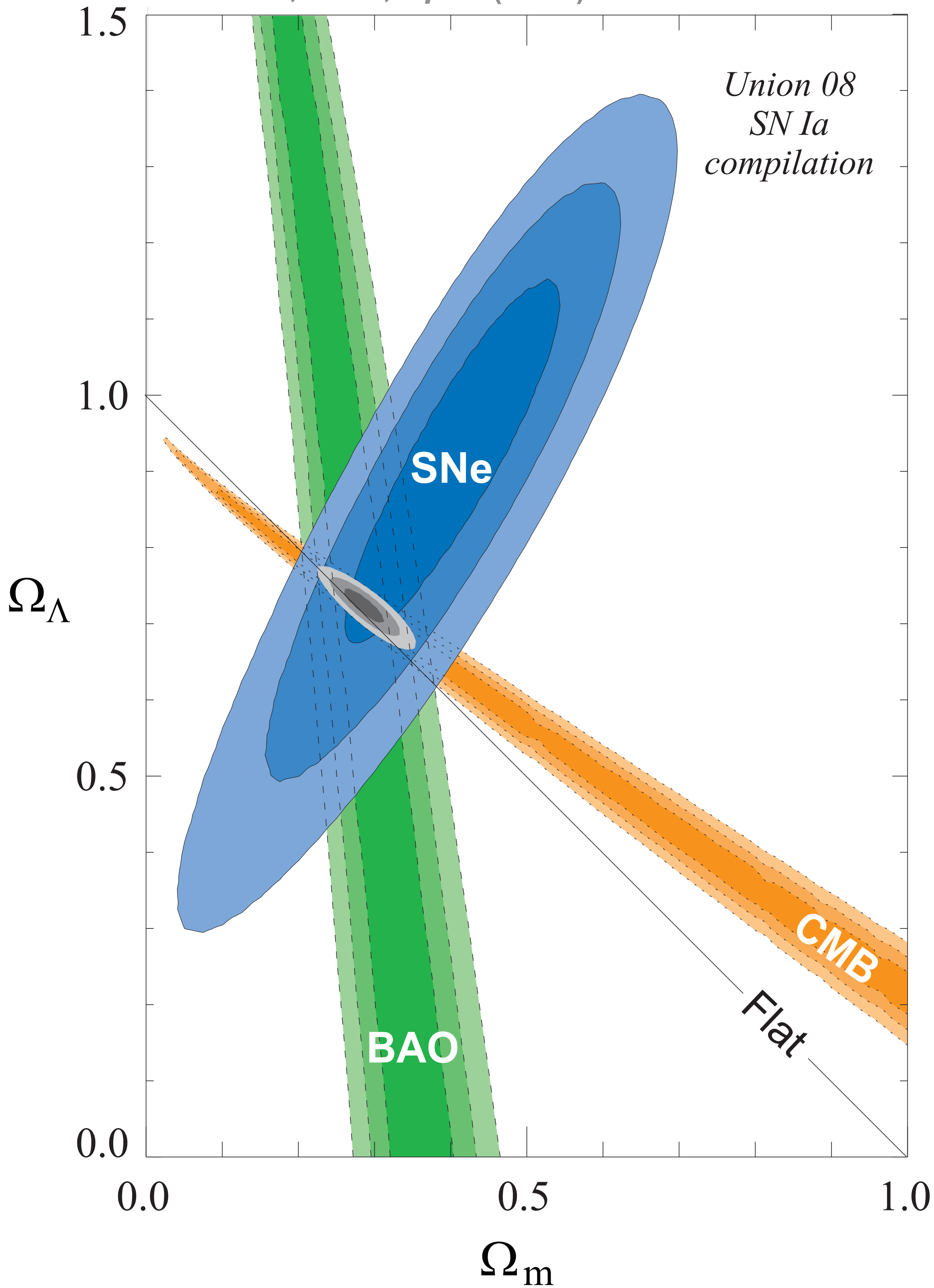
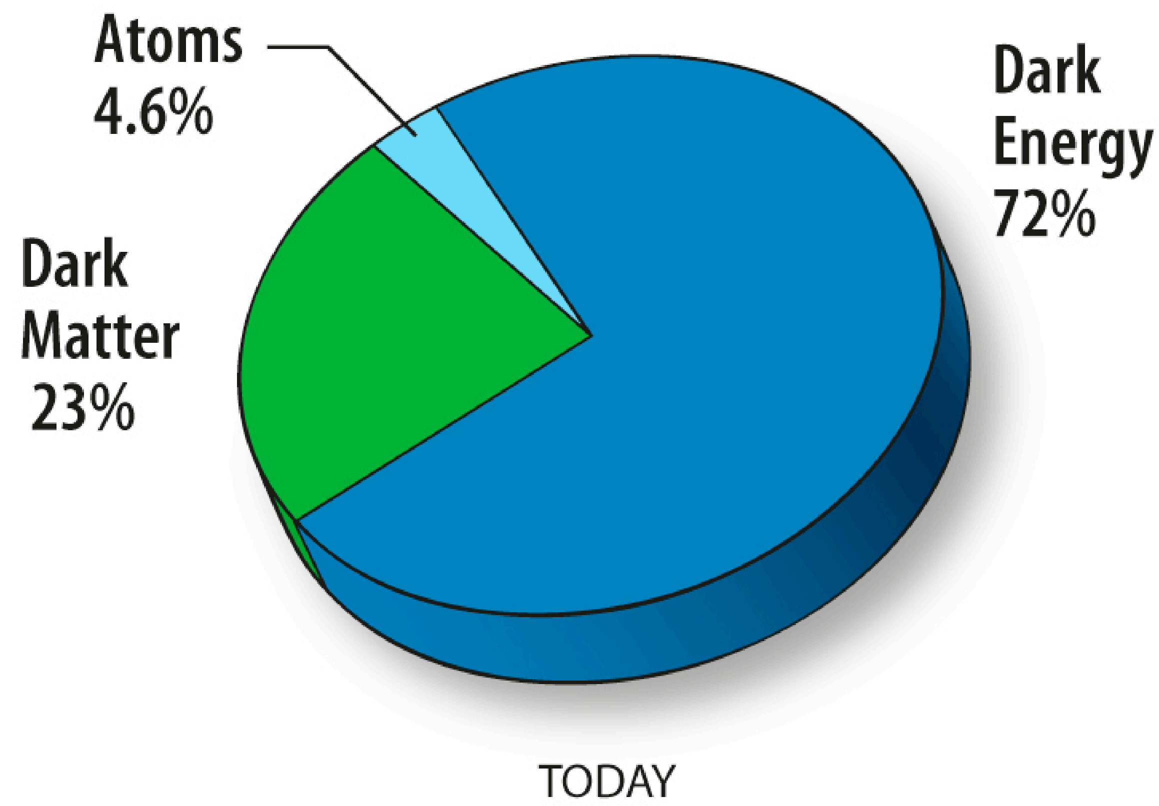
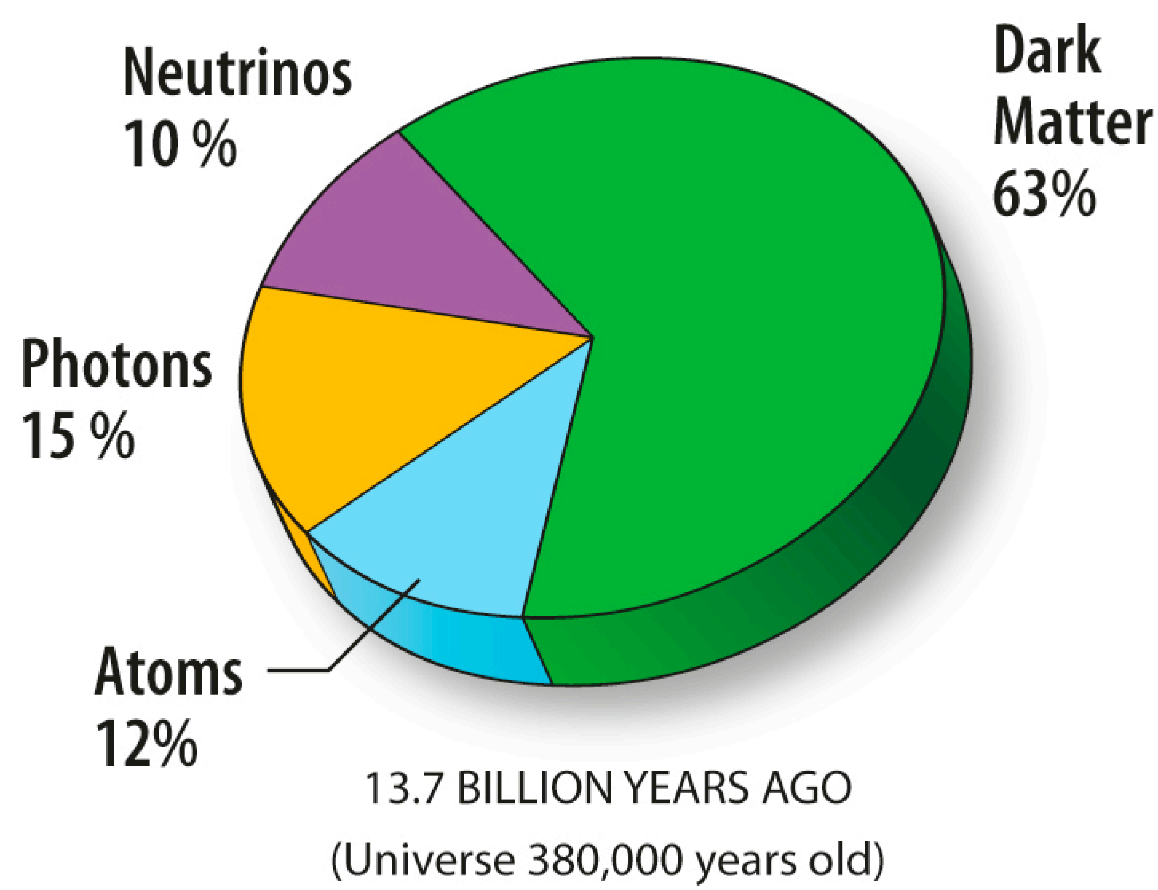






WMAP

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)

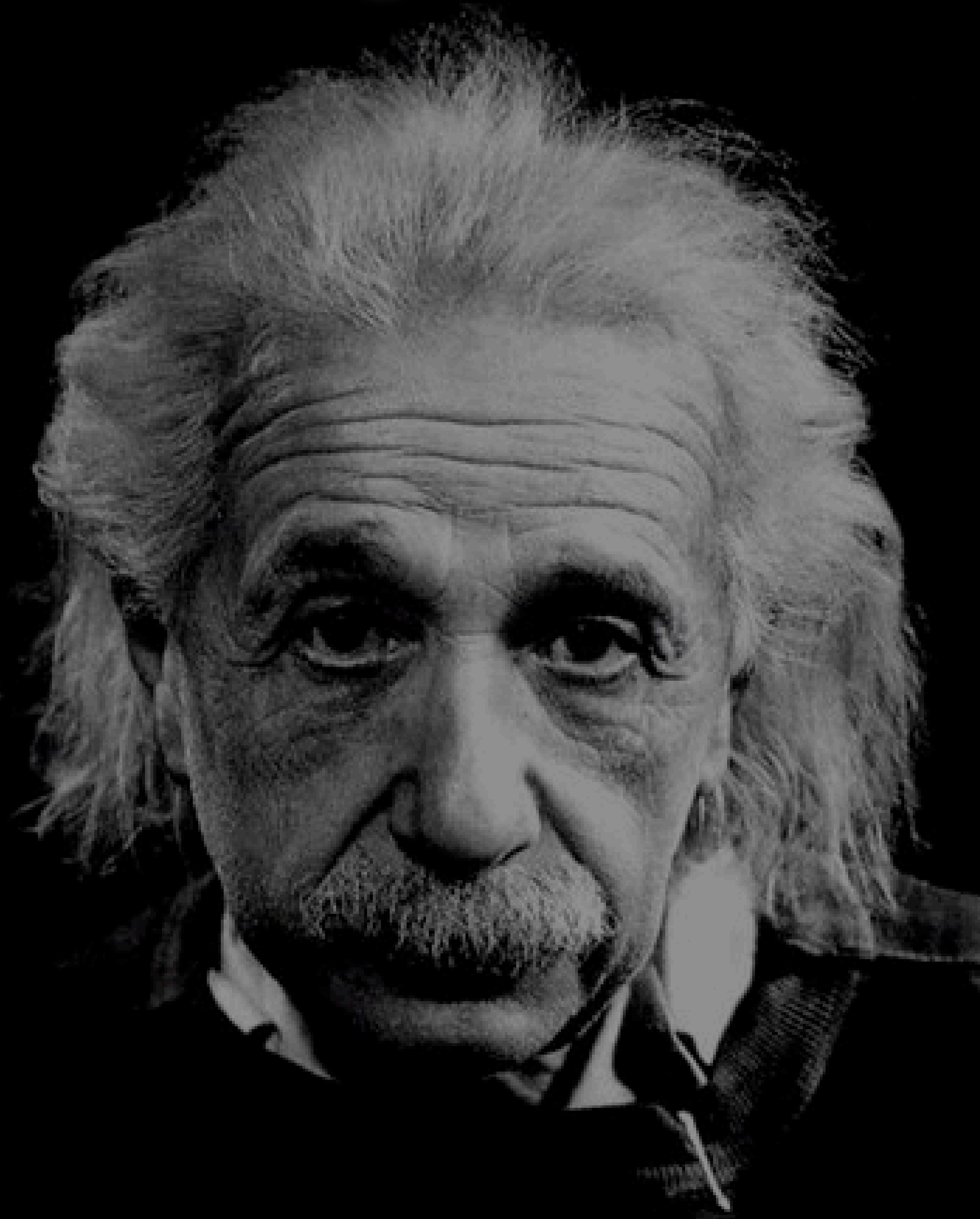
Phenomenological modification to the GR Lagrangian

Vacuum Energy (Cosmological Constant)

Scalar Fields
Evolving Equation of State

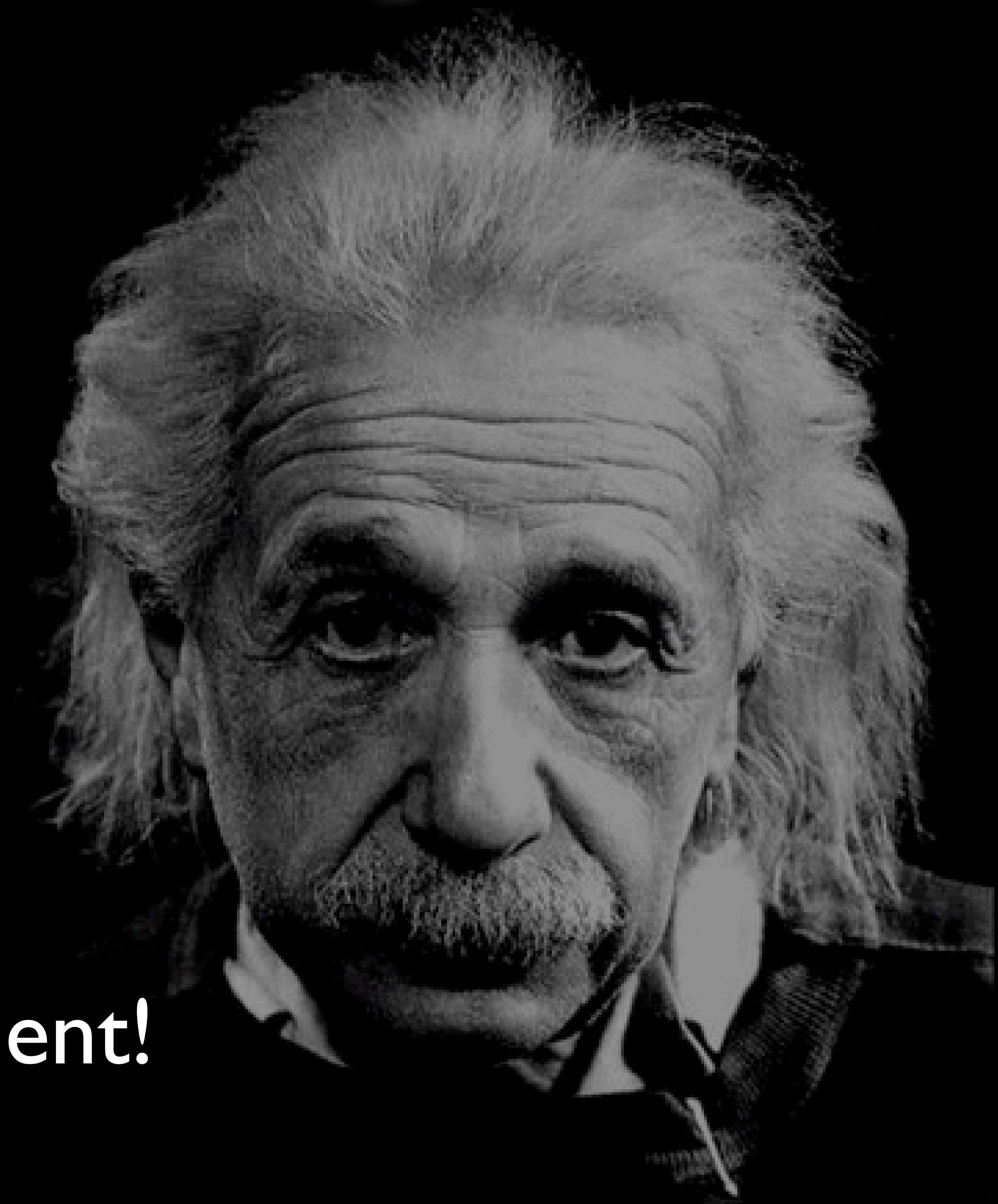
New Physics/Surprises?

Agenda



Agenda

- “Seeing” the Dark Energy
- Evolving (or Constant?) EOS?
- How many Parameters?
- Go Independent! Bin It!!!



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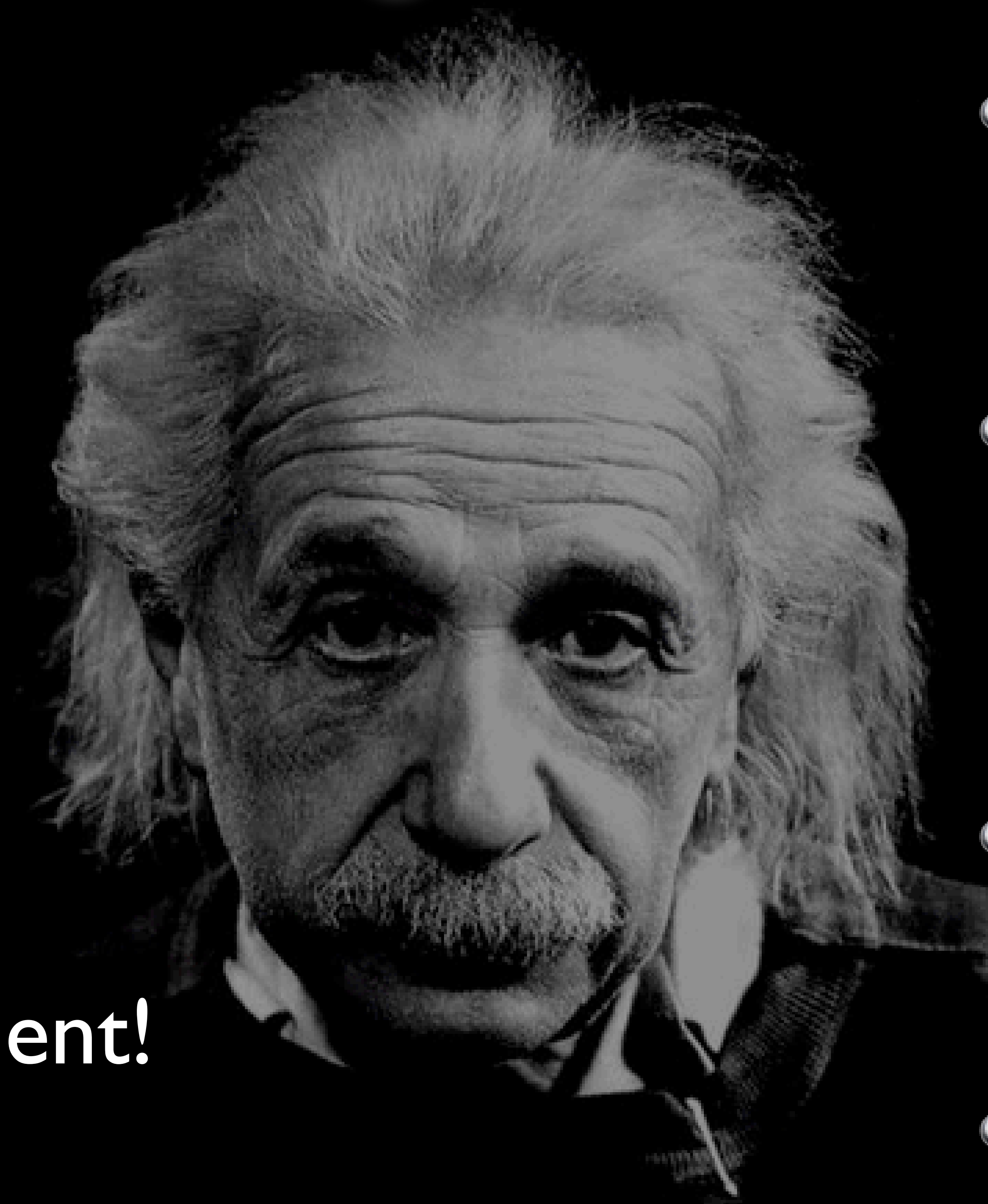

- Those damn systematics
- Evolution? Two supernova Populations?
- Gravitational Lensing!
- What to do?

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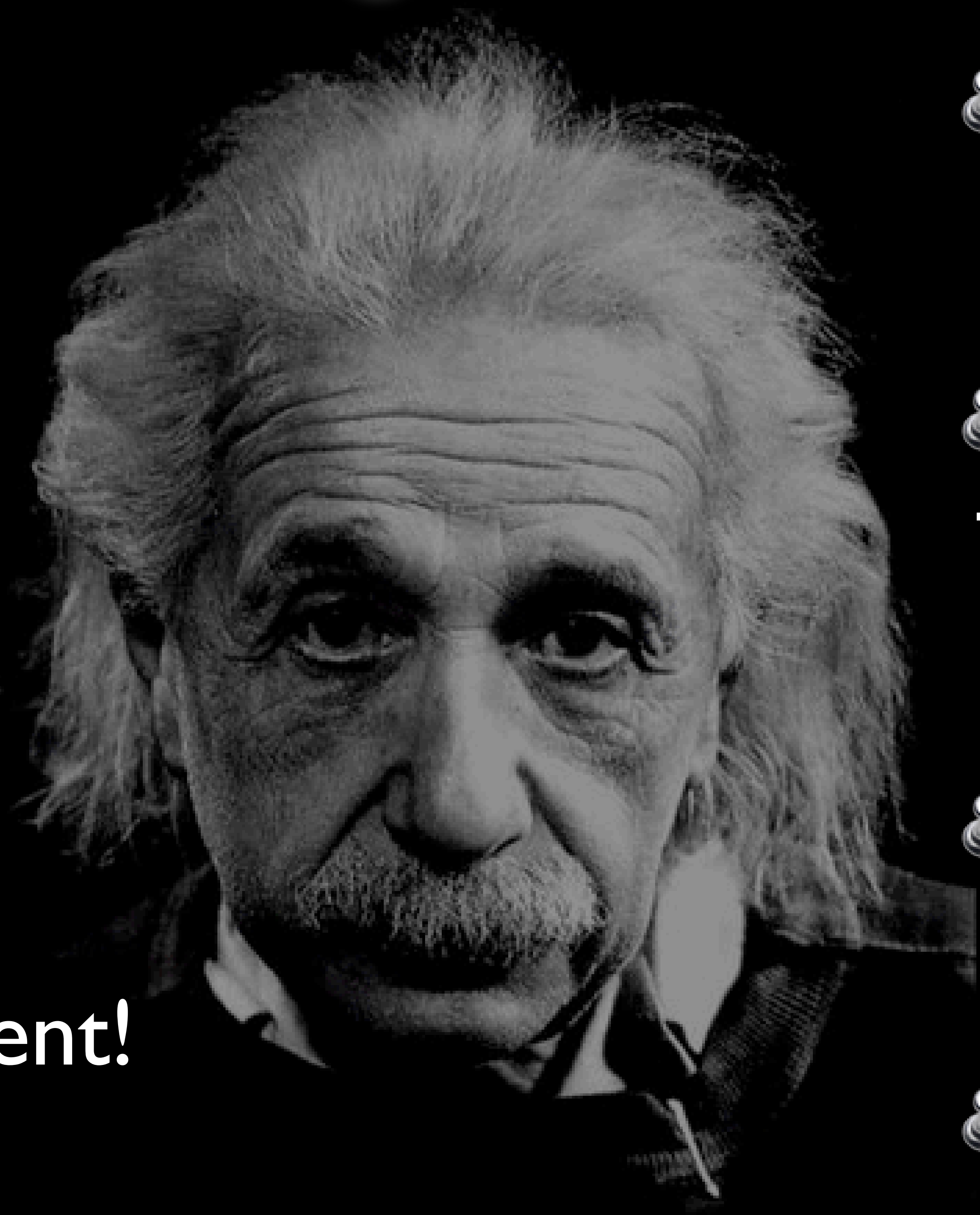
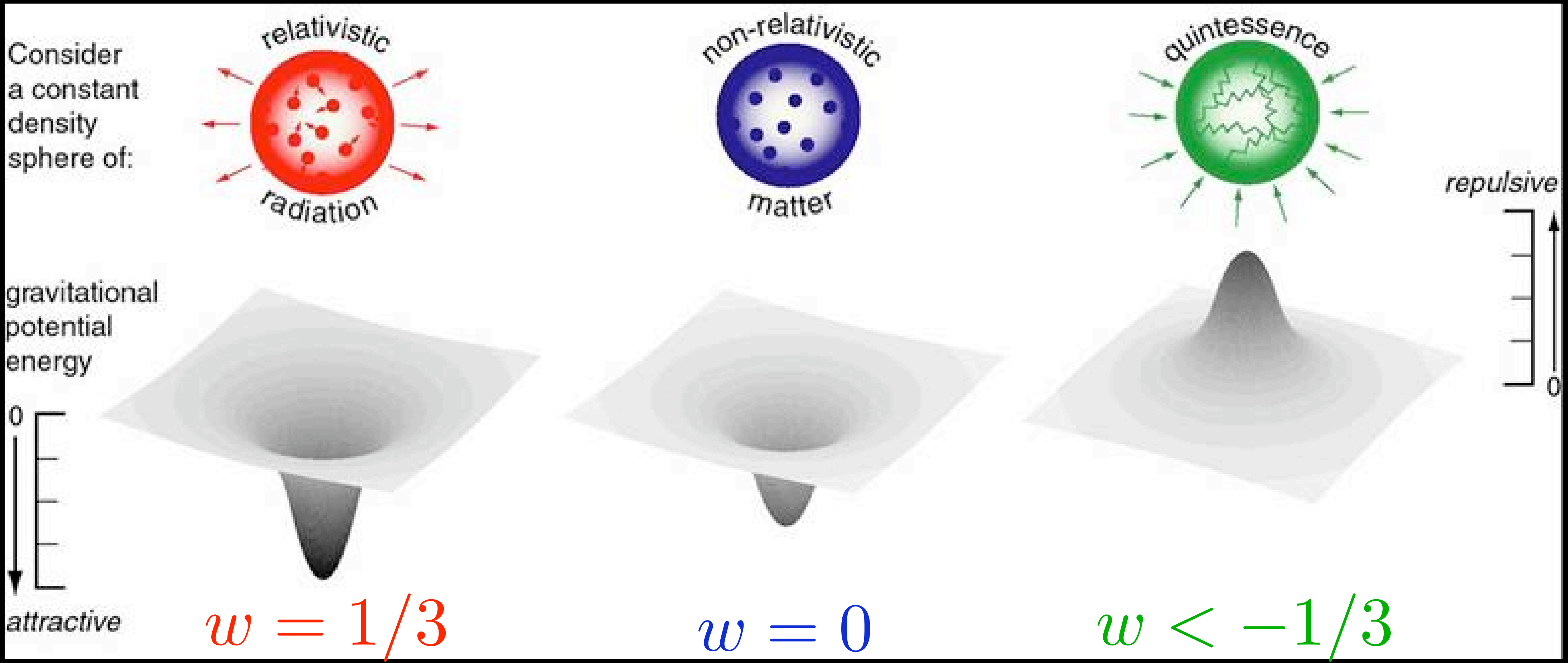


- Those damn systematics
- Evolution? Two supernova Populations?
- Gravitational Lensing!
- What to do?

A peek into the future: the next decade...

Dark Energy Equation Of State

$$T_\mu^\nu = diag(\rho, -p, -p, -p) \qquad p = w\rho$$



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

“Seeing” The Dark Energy

"Seeing" The Dark Energy

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

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

"Seeing" The Dark Energy

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

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

Approaches...

“Seeing” The Dark Energy

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

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

Approaches...

(1) Standard Candles: Luminosity Distance of SNe

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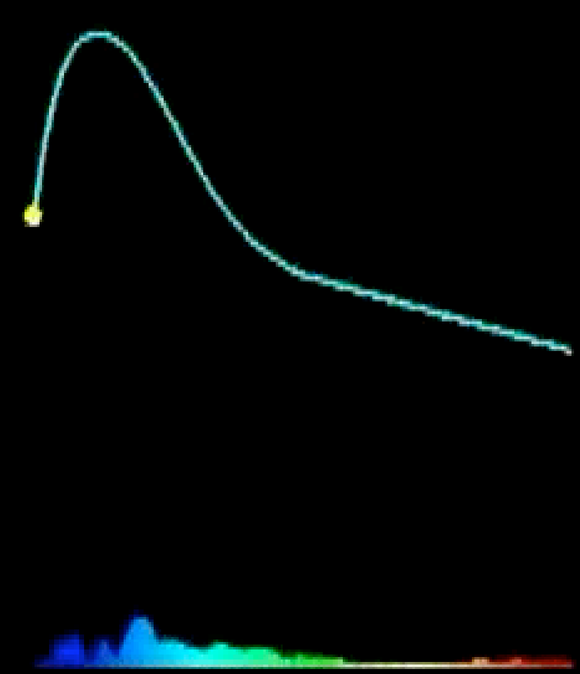

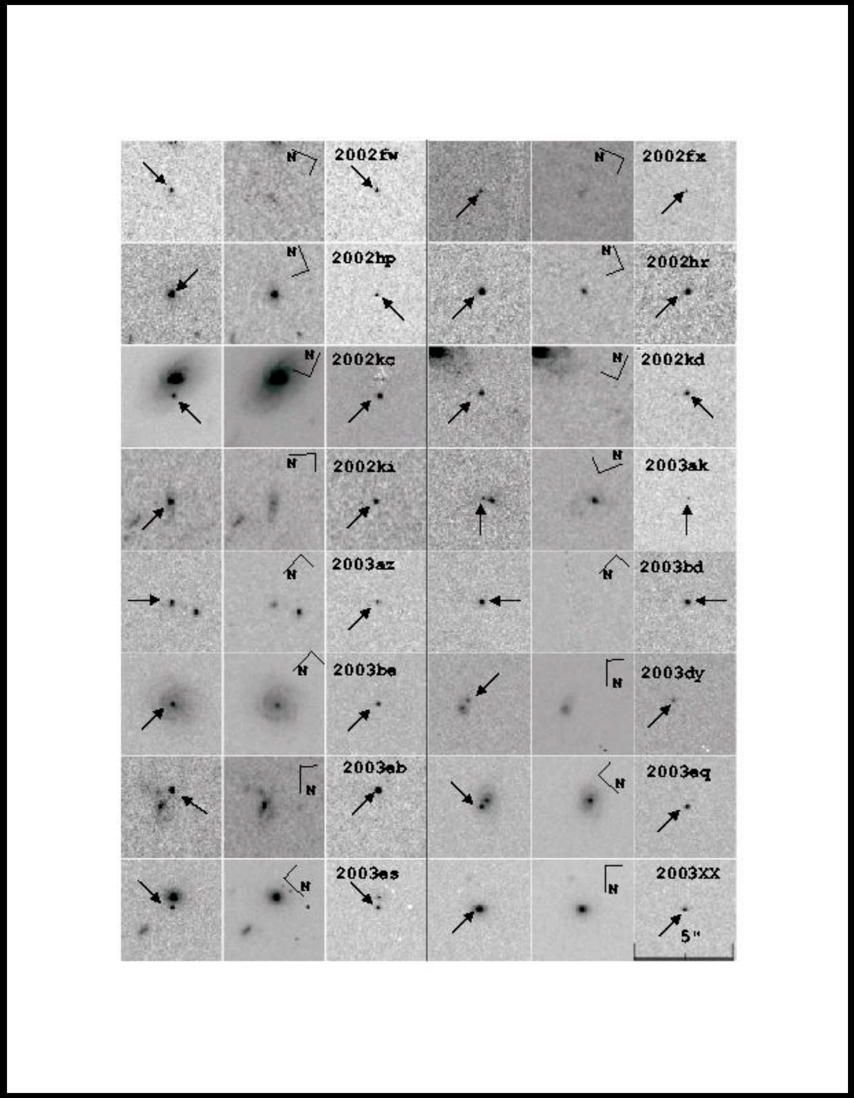

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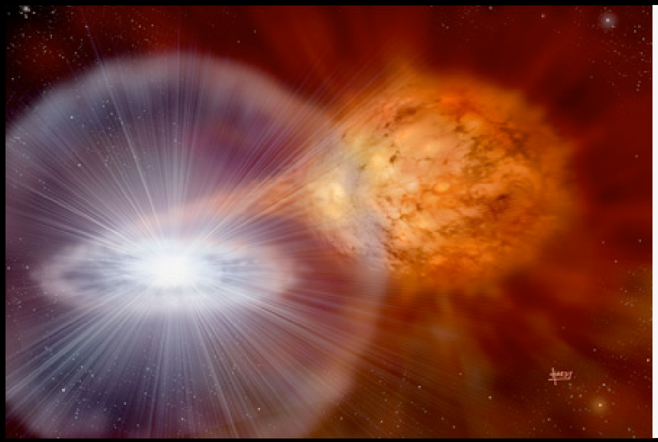

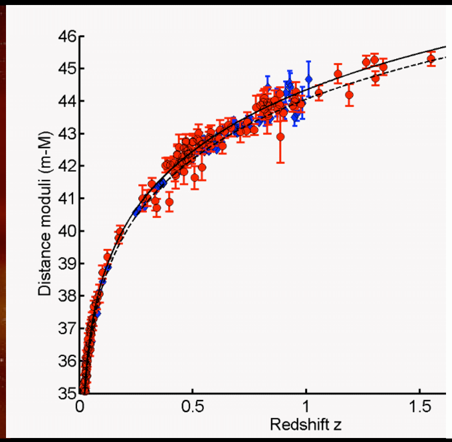

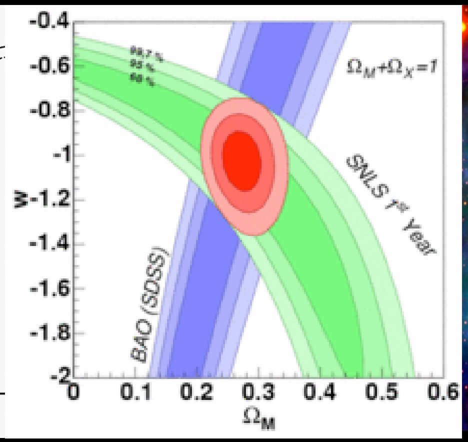

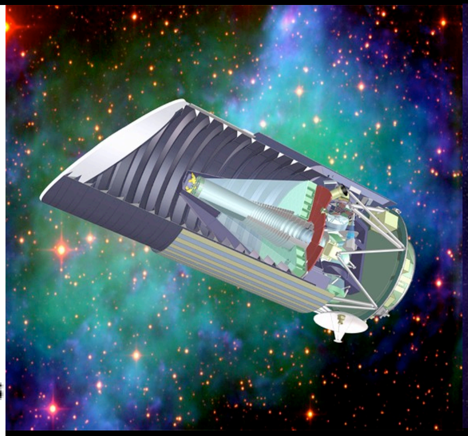

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(2) Standard Rulers: Angular Diameter Distance via BAO

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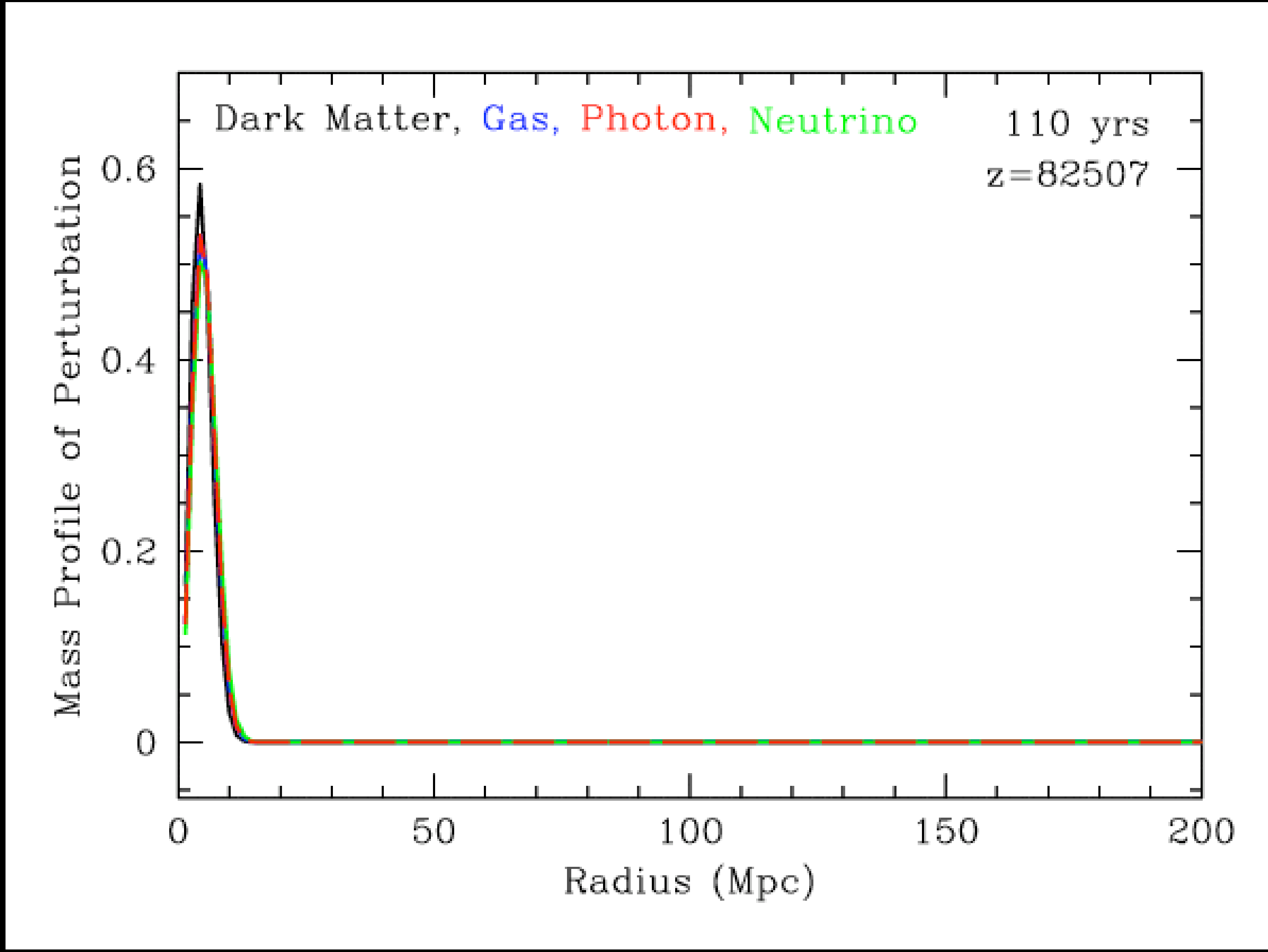

courtesy: D. Eisenstein

“Seeing” The Dark Energy

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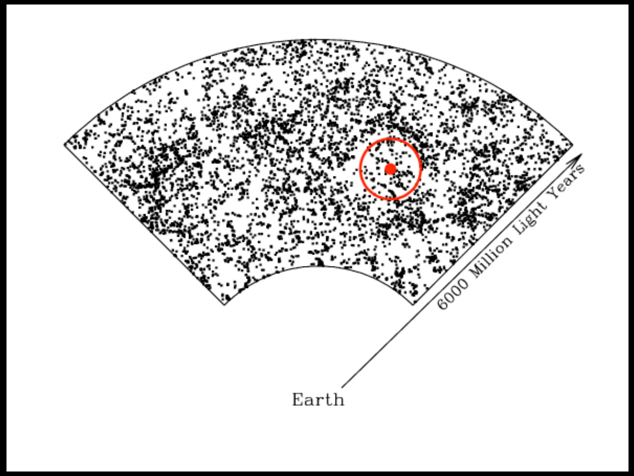

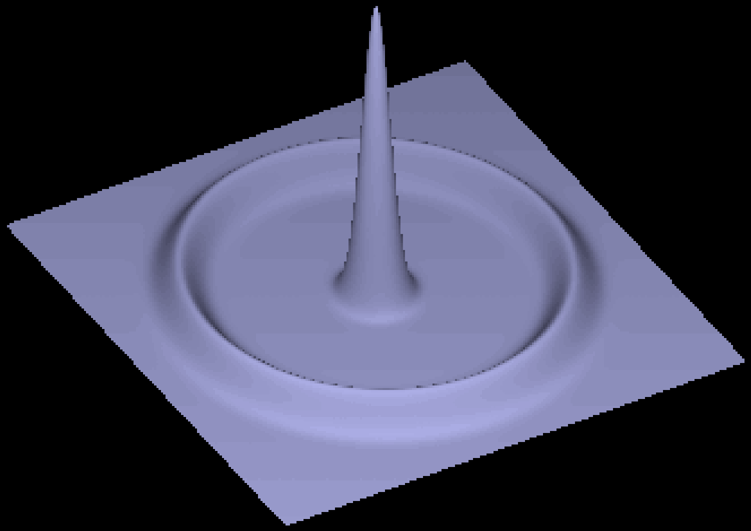

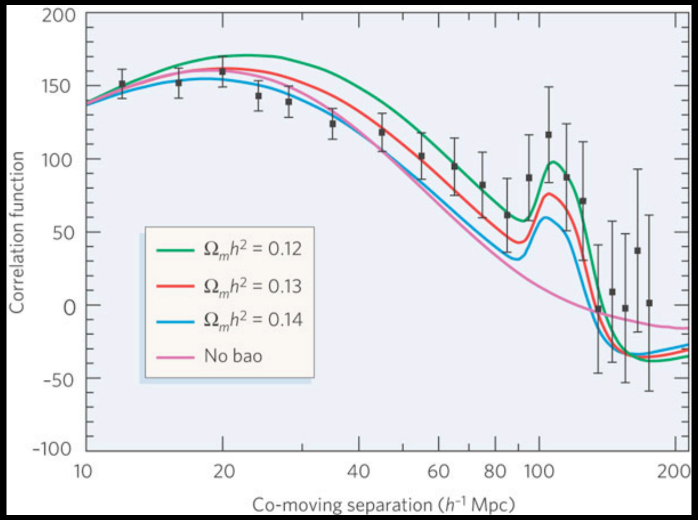

Eisenstein et al. (2005)

“Seeing” The Dark Energy

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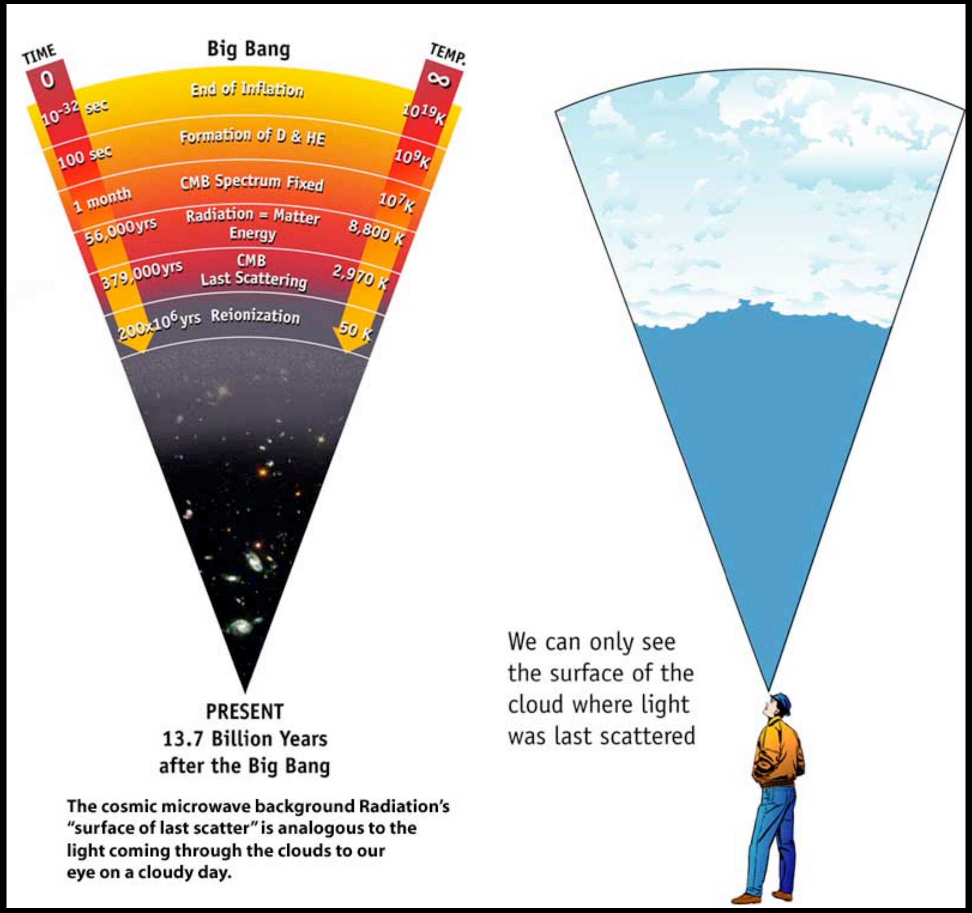
Approaches...

(3) Standard Rulers: Distance to Last Scattering Surface



The cosmic microwave background Radiation's “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.

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

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

“Seeing” The Dark Energy

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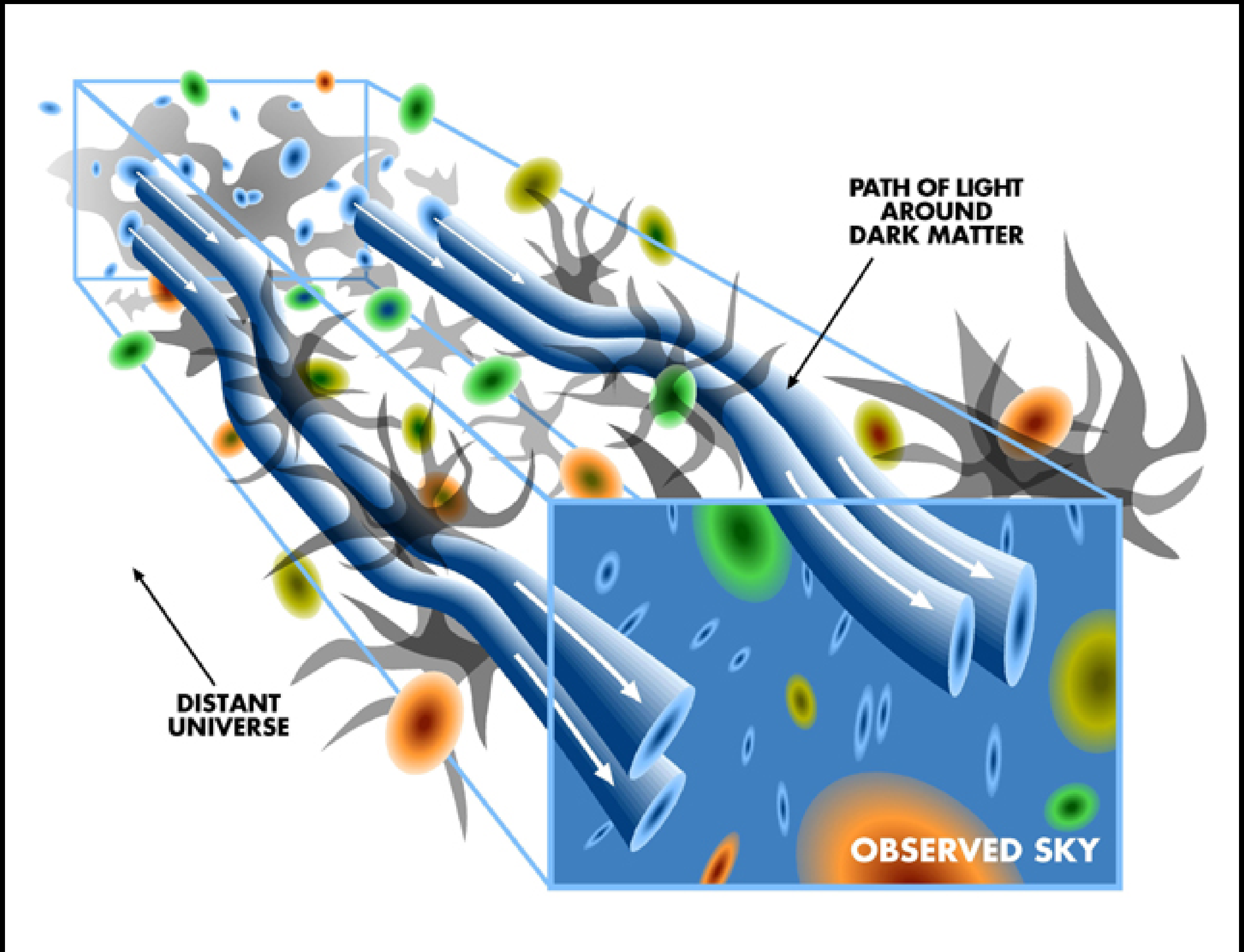
$$H(z) = H_0 \left[\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + (1 - \Omega_k - \Omega_m) F(z)\right]^{1/2}$$

Approaches...

(4) Weak Lensing Tomography



- ☑ Galaxy Shear
- ☑ Photo-z

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

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)

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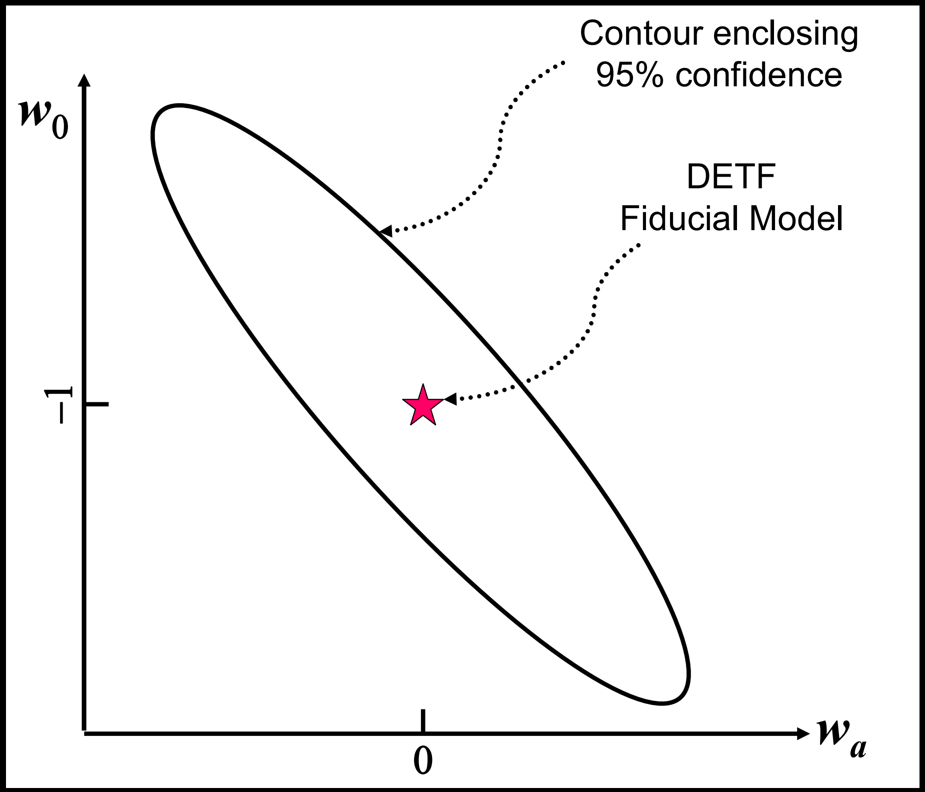
Chevallier & Polarski (2001)
(Linder 2003)

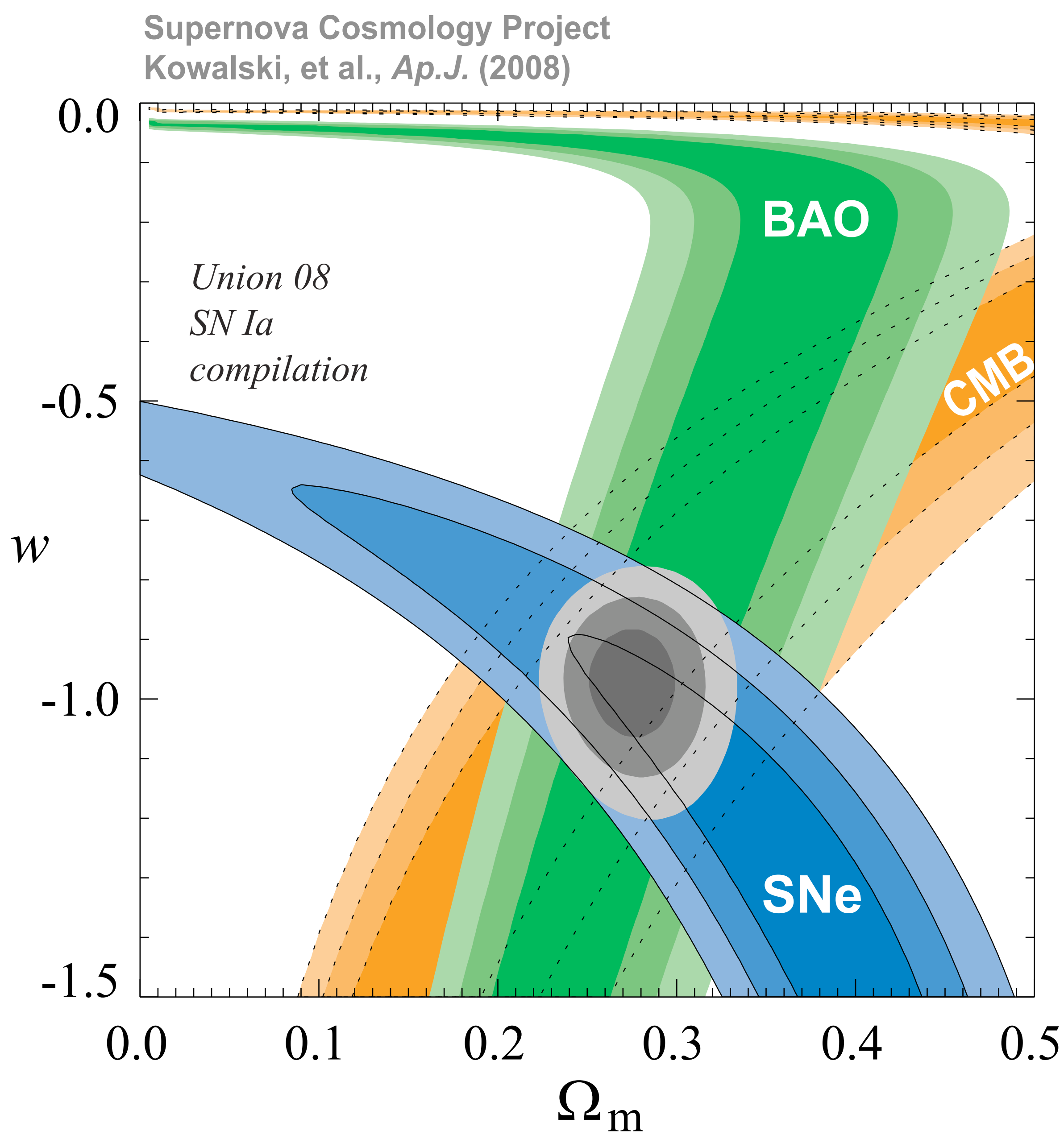
DETF Figure of Merit (FoM)

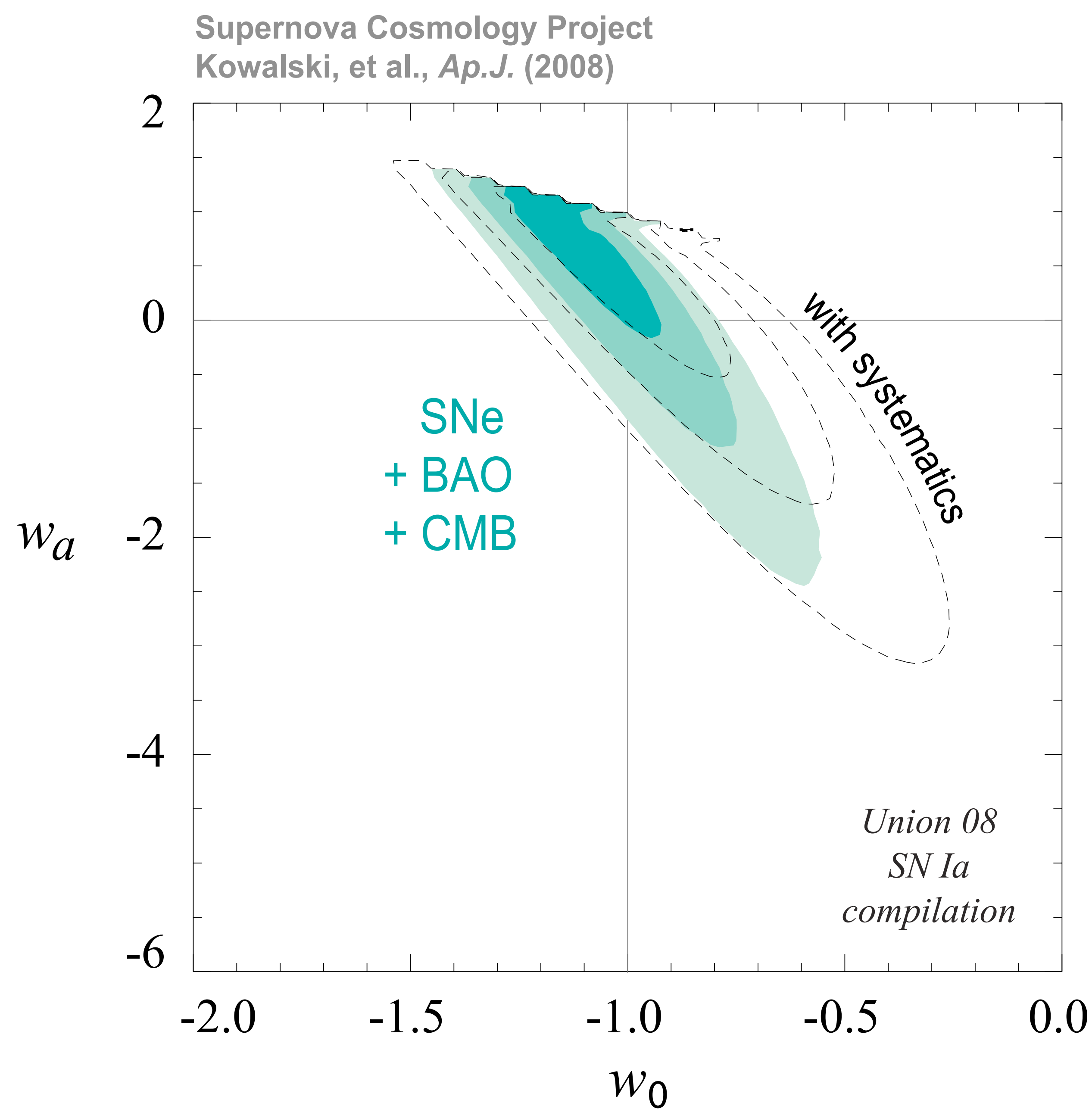
Reciprocal of the Area of the Error Ellipse enclosing the 95% Confidence Limit in the $w_0 - w_a$ Plane.



Larger Value of the FoM ⟷ Greater Accuracy

Union Dataset





Consistent with a Cosmological Constant

DE EOS Revisited: Beyond Two Param...

(B) Model-Independent Redshift-Binning of w(z)

DE EOS Revisited: Beyond Two Param...

(B) Model-Independent Redshift-Binning of w(z)

bin	$w_1(z)$	$w_2(z)$	$w_3(z)$	$w_4(z)$	$w_5(z)$	$w_6(z)$
z-ran	0-0.07	0.07-0.15	0.15-0.3	0.3-0.6	0.6-1.2	1.2-2.0

DE EOS Revisited: Beyond Two Param...

(B) Model-Independent Redshift-Binning of w(z)

$$F(z_n > z > z_{n-1}) = (1+z)^{3(1+w_n)} \prod_{i=0}^{n-1} (1+z_i)^{3(w_i - w_{i+1})}$$

DE EOS Revisited: Beyond Two Param...

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Covariance Matrix

$$C = \left\langle \mathbf{w}\mathbf{w}^T \right\rangle - \left\langle \mathbf{w} \right\rangle \left\langle \mathbf{w}^T \right\rangle$$

DE EOS Revisited: Beyond Two Param...

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(C) Decorrelated Estimates of w(z)

(Huterer & Cooray 2005)

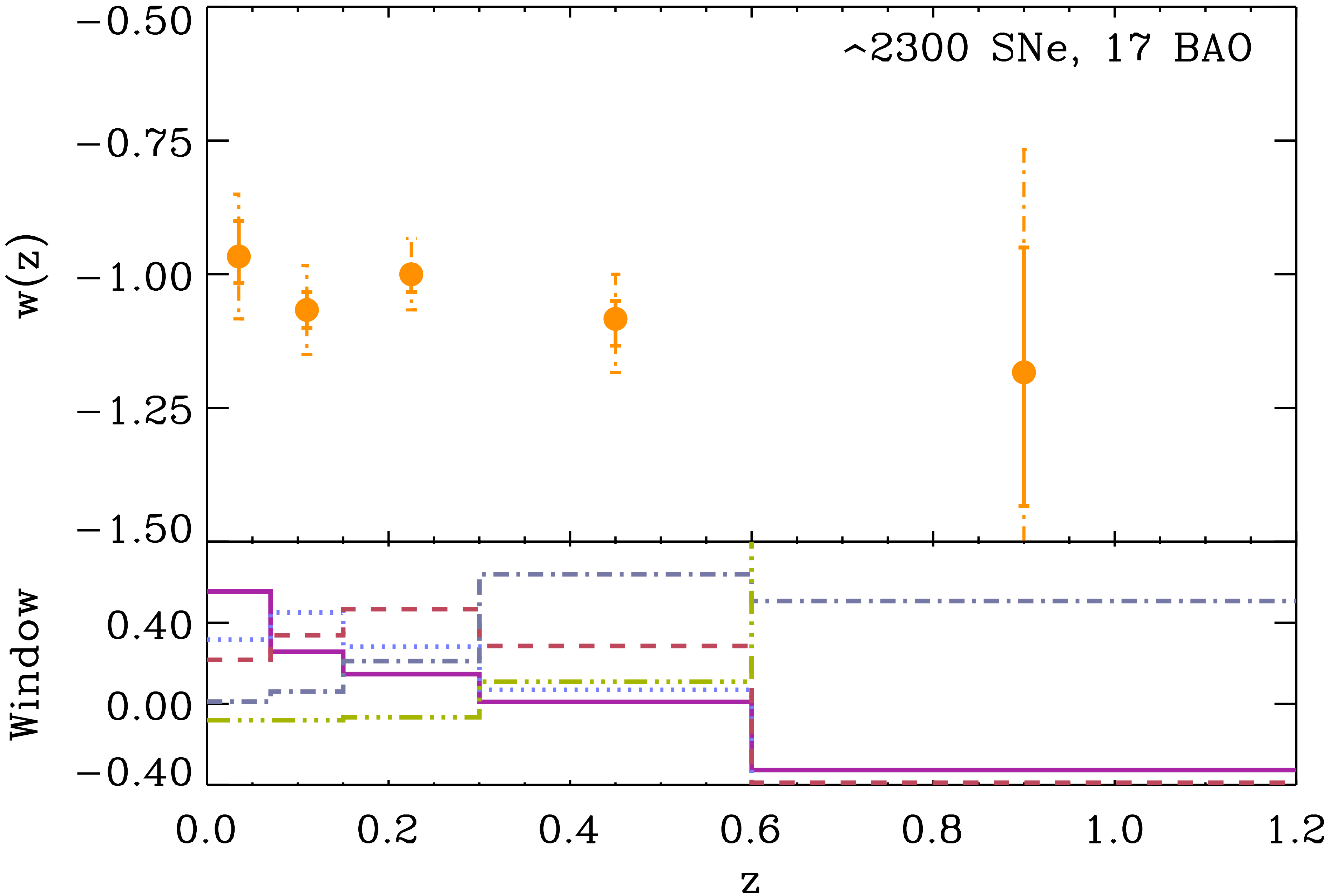
Diagonalize The Fisher Matrix

$$\mathbf{F} \equiv \mathbf{C}^{-1} = \mathbf{O}^T \mathbf{\Lambda} \mathbf{O}$$

Our Analyses: Six Mock Scenarios

- Case A: 200 SNe up to z=1.8; 2 BAO estimates
- Case B: 300 SNe out to z=0.1 & 2000 SNe in the range 0.1<z<1.8; 7 BAO estimates
- Case C: Same as (B)... with 10 new BAO constraints
- Case D: 10,000 SNe out to z=2.0, 7 BAO estimates
- Case E: 10,000 SNe out to z=2.0; 17 BAO estimates
- Case F: 200 SNe as in (A); 17 BAO estimates

Results



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
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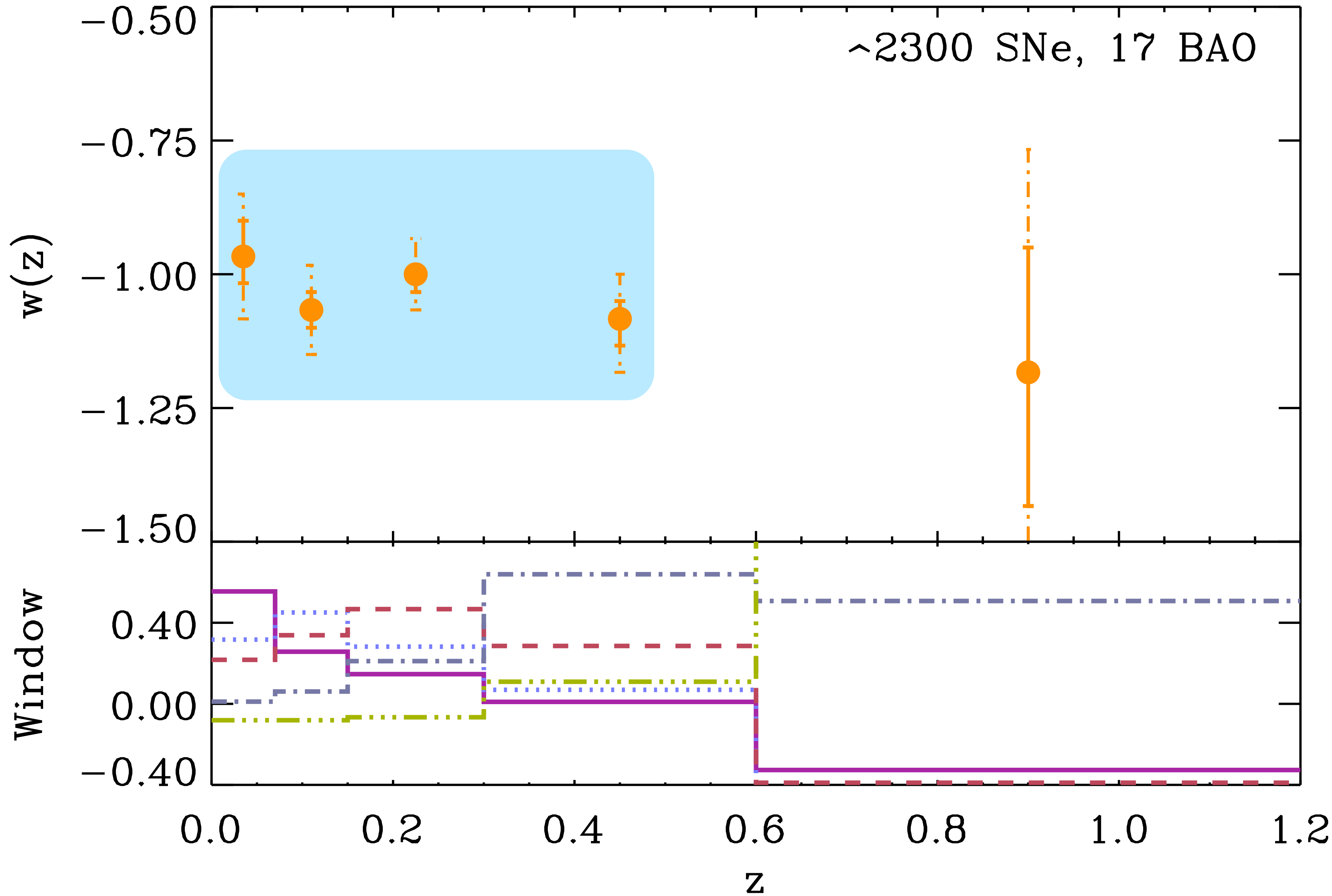
D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, A. Cooray (2007)

Results



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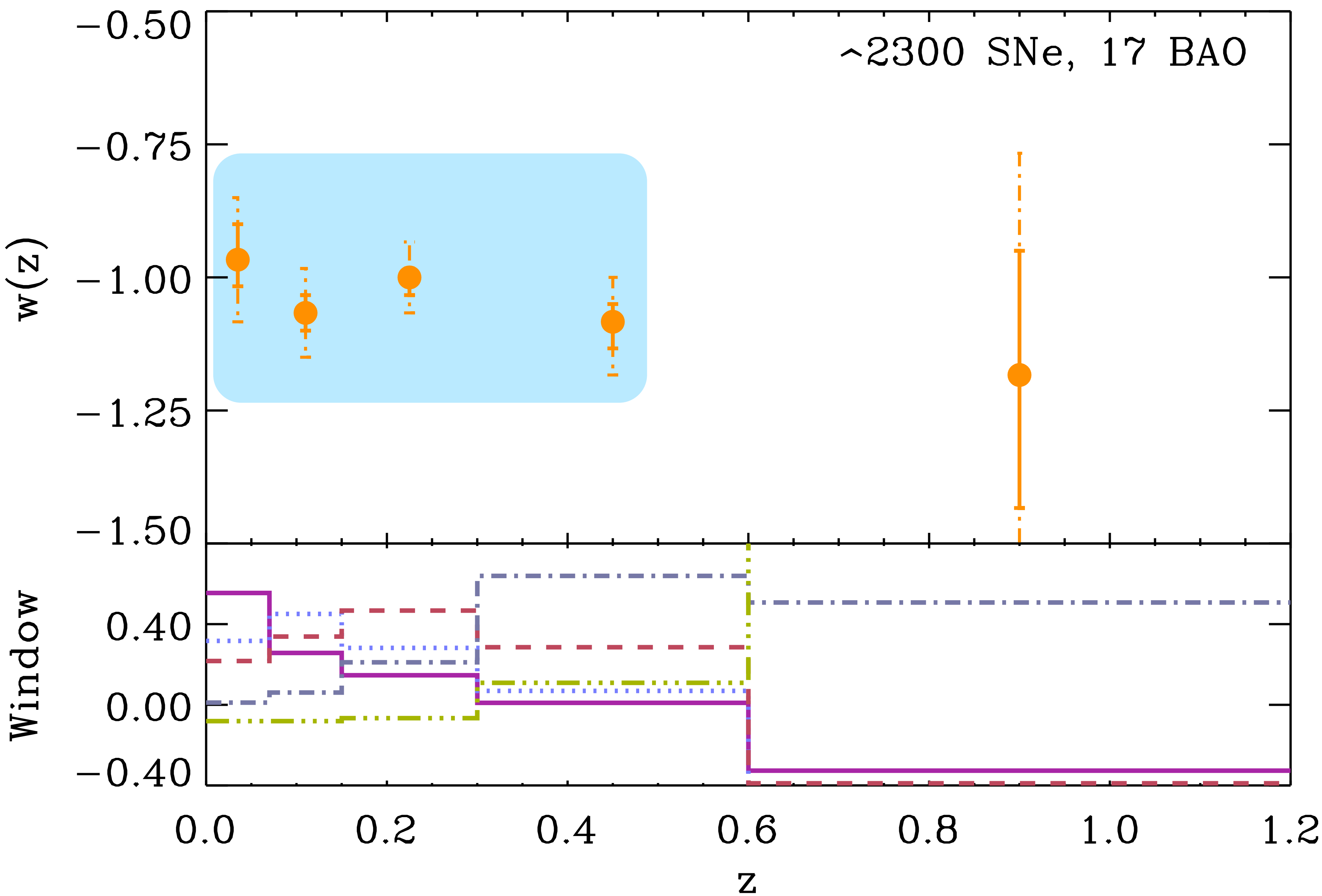
D.S., S. Sullivan, S. Joudaki, A. Amblard, D. Holz, A. Cooray (2007)

Results

$$\mathrm{FoM} = \left[\sum_i \frac{1}{\sigma^2(w(z_i))}\right]^{1/2}$$



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w_2	.07-.15
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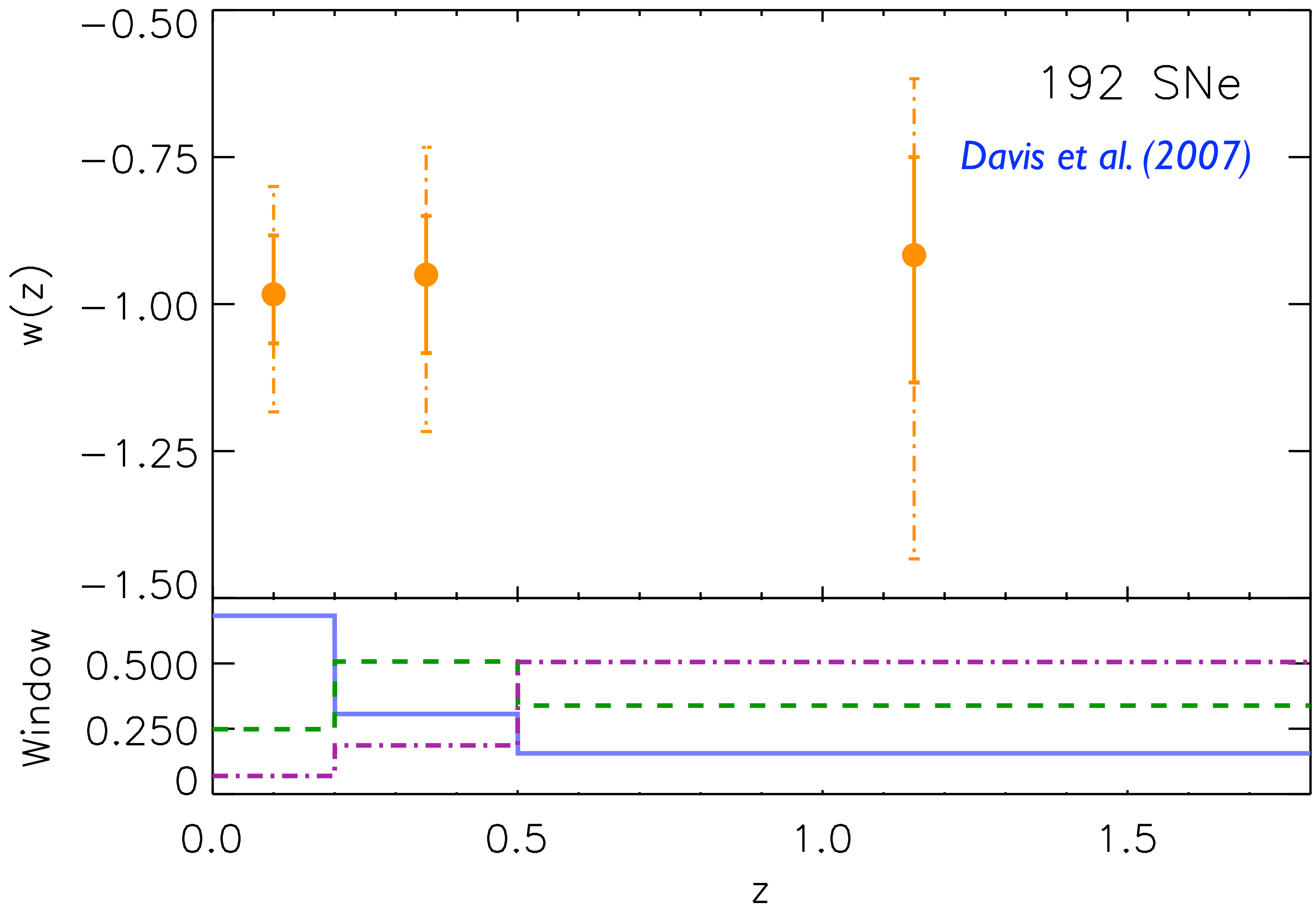
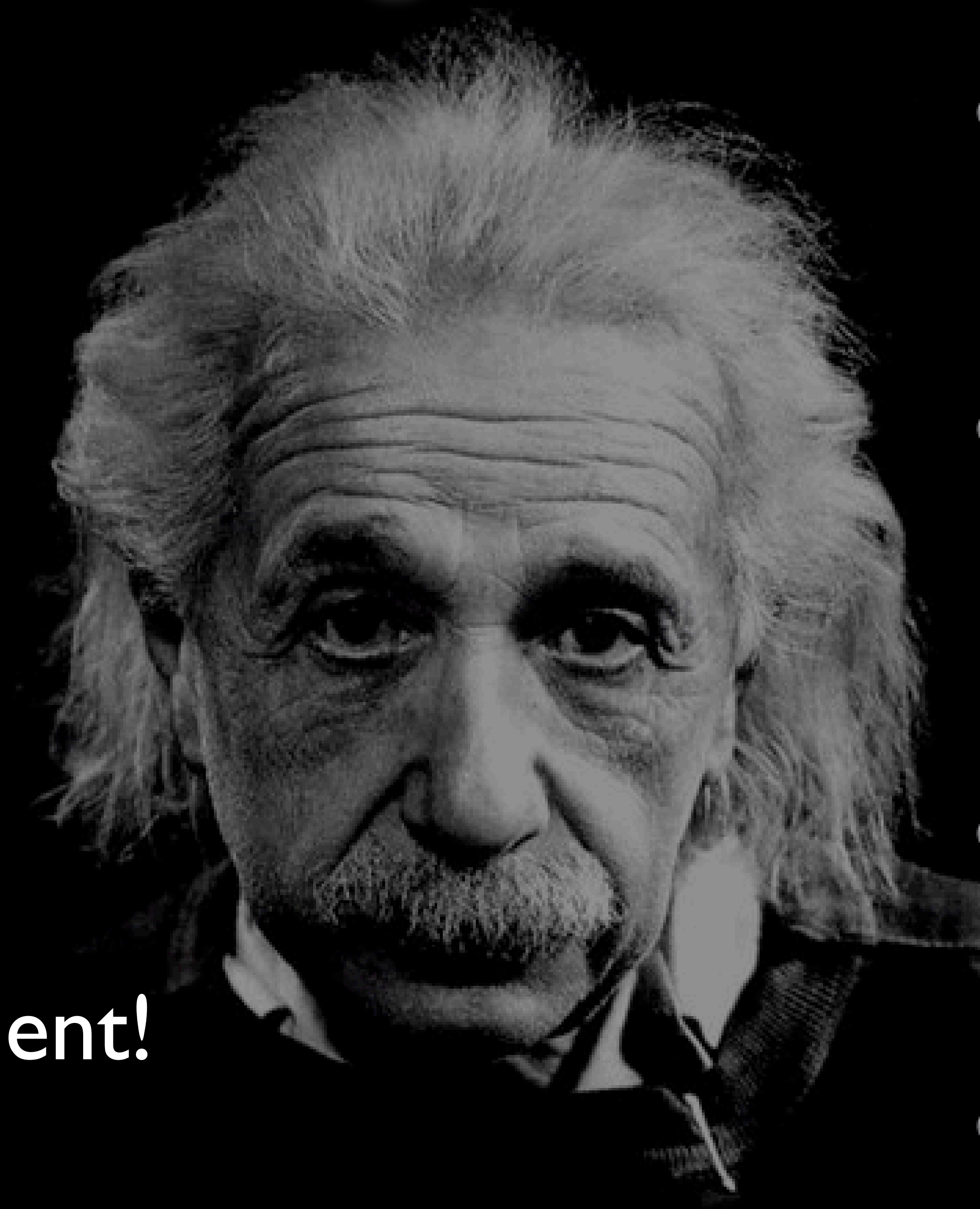


w_1	0-0.2
w_2	0.2-0.5
w_3	0.5-1.8

S. Sullivan, A. Cooray, and D. Holz (2007)

Agenda

- “Seeing” the Dark Energy
- Evolving (or Constant?) EOS?
- How many Parameters?
- Go Independent! Bin It!!!



- Those damn systematics
- Evolution? Two supernova Populations?
- Gravitational Lensing!
- What to do?

A peek into the future: the next decade...

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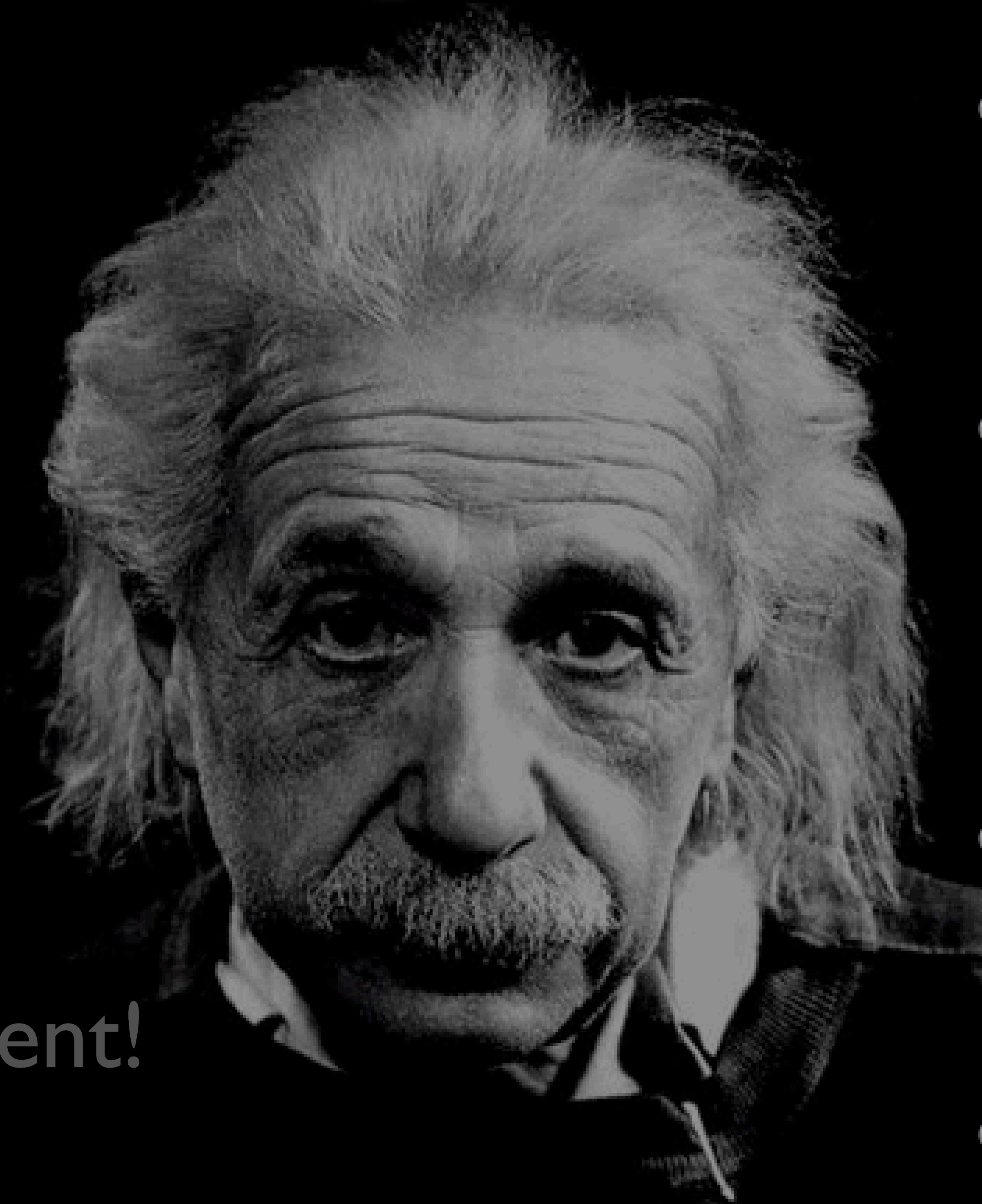

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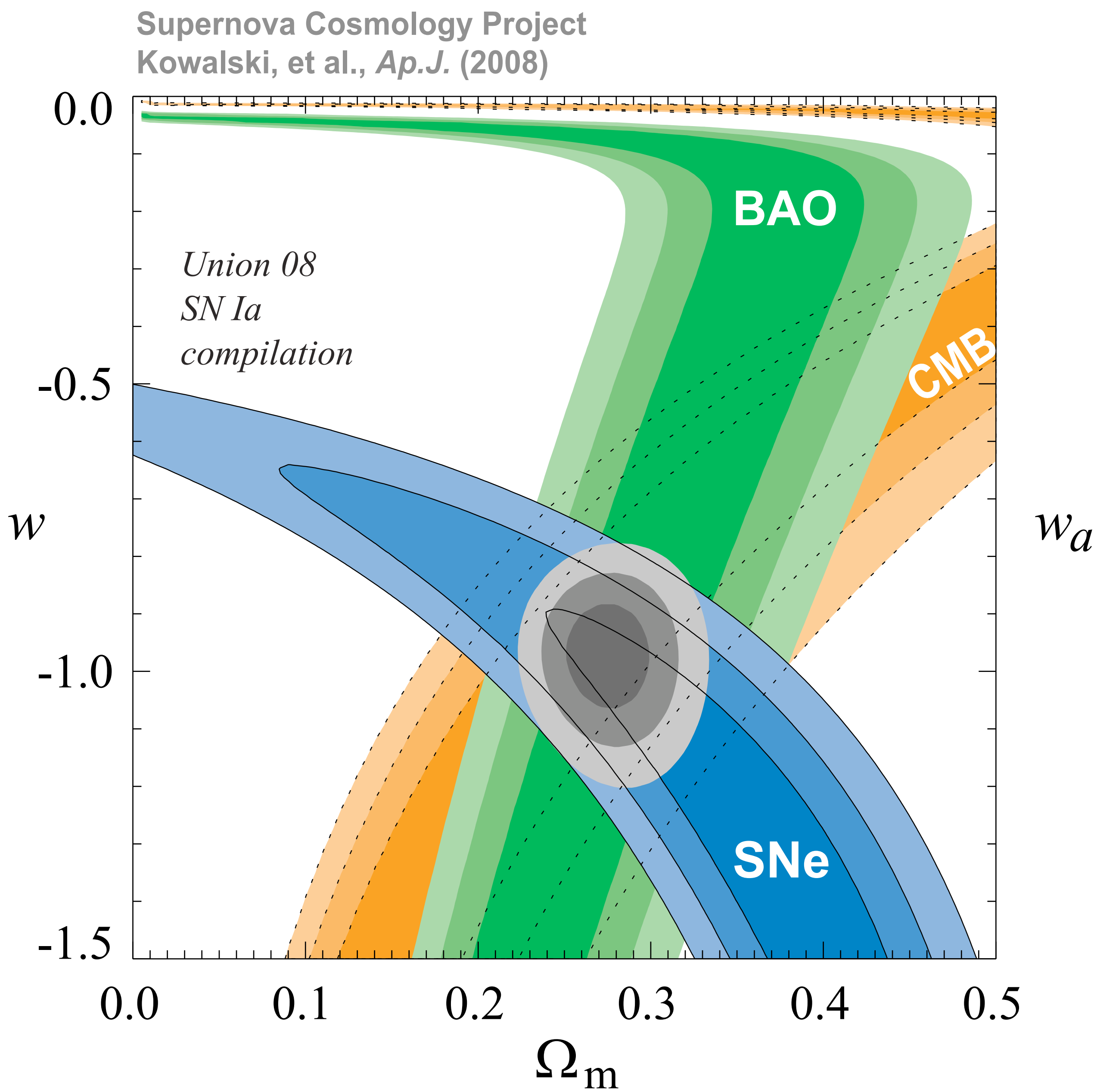
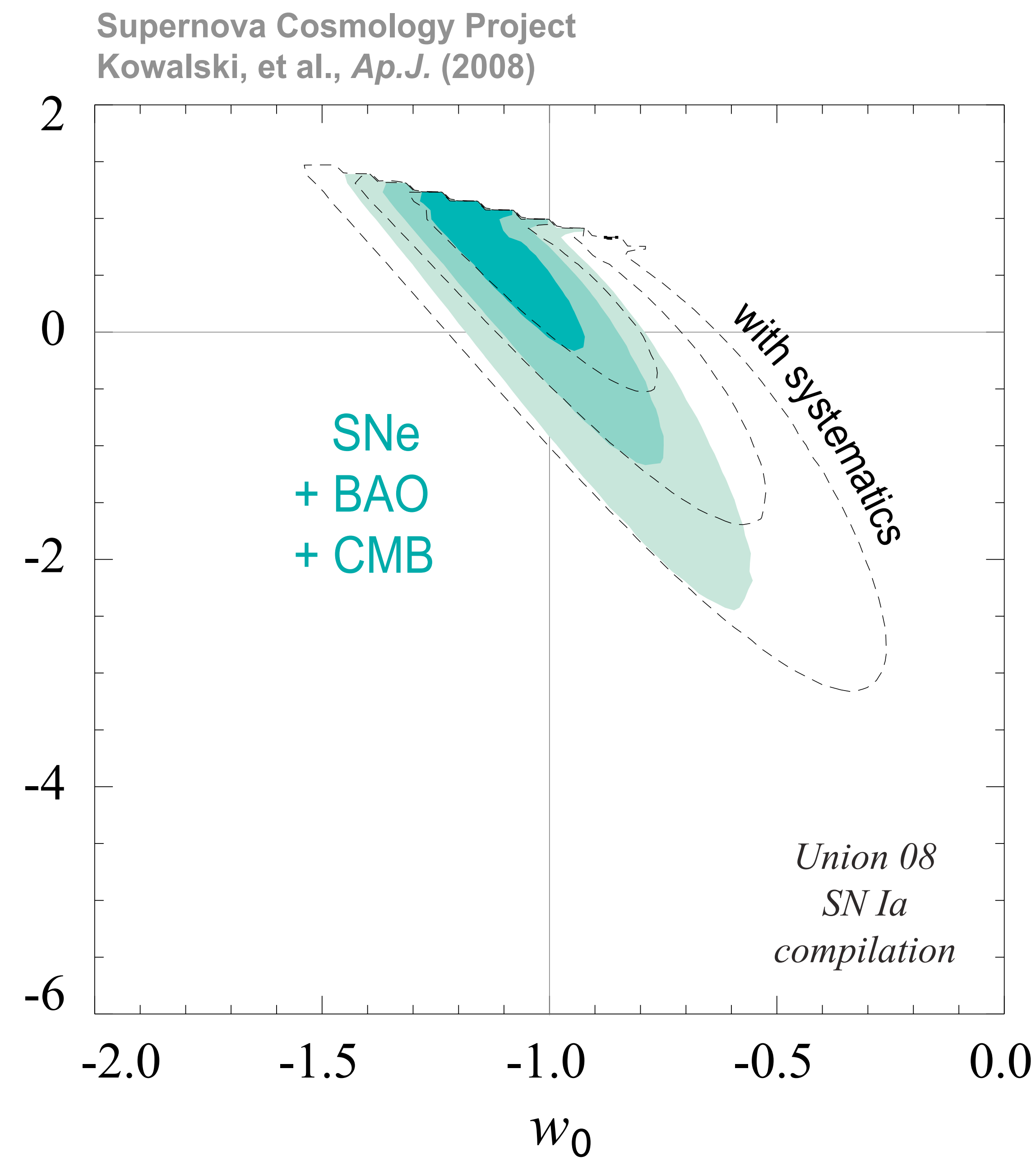
Systematic Matters!





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

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

SNe Ia: Systematic Uncertainties

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

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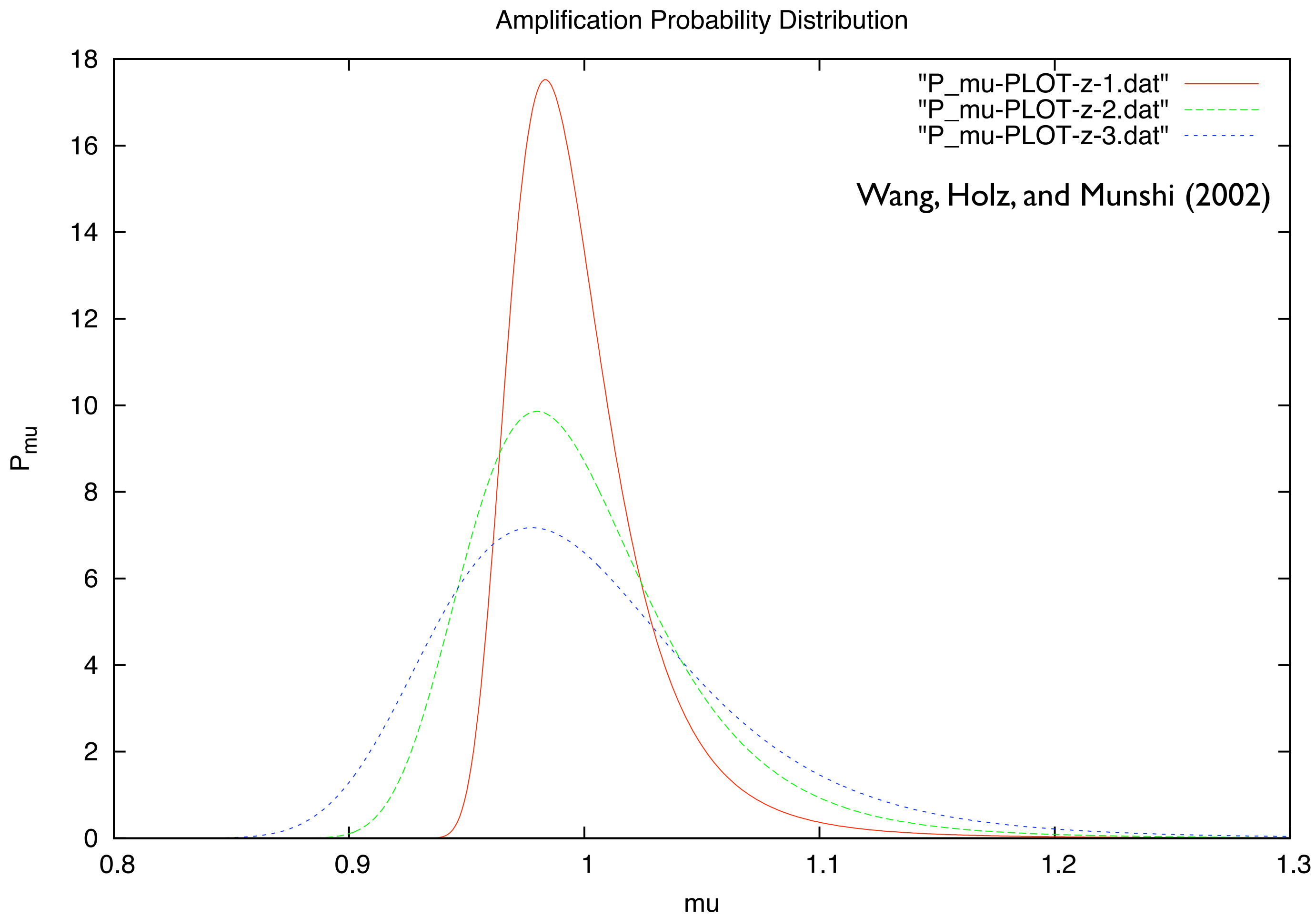
Influence of Gravitational Lensing?

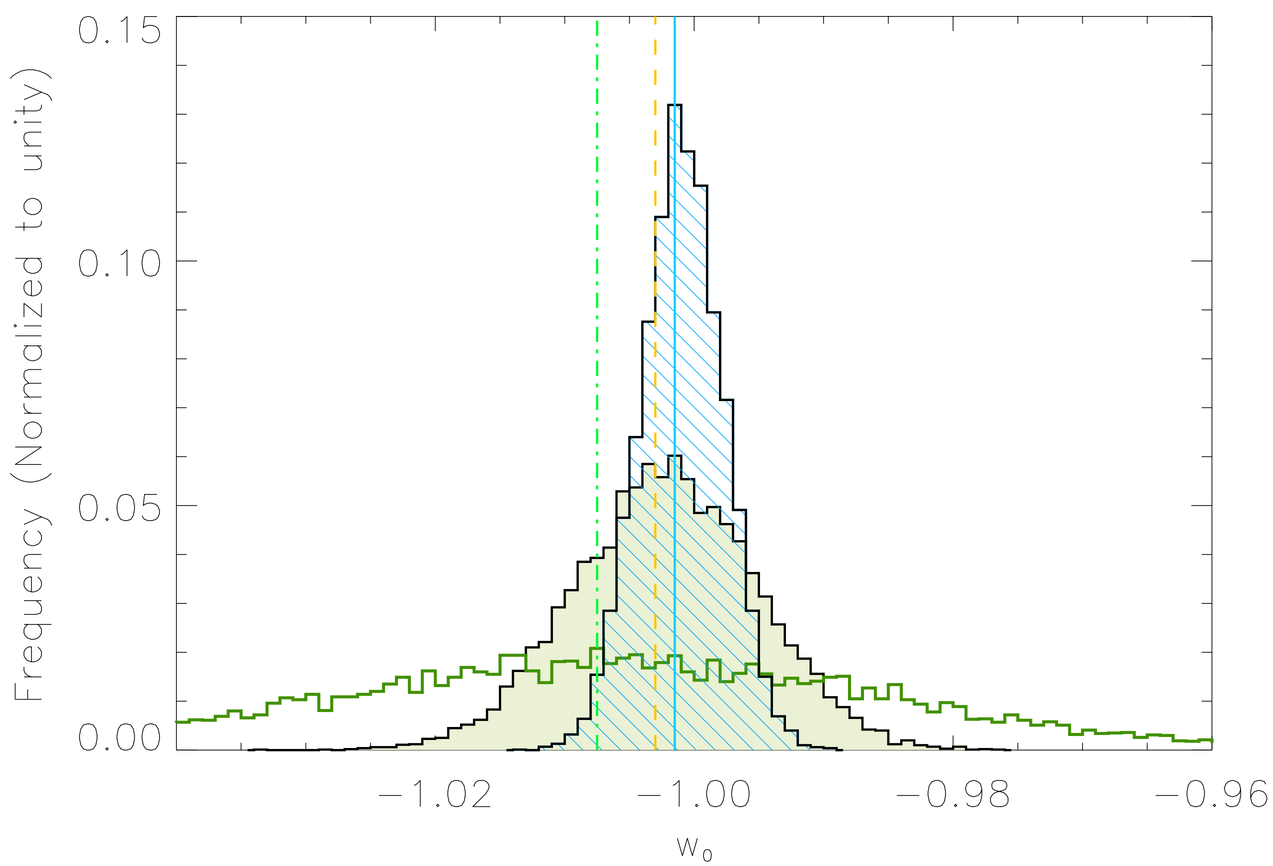
Lensing Galaxy

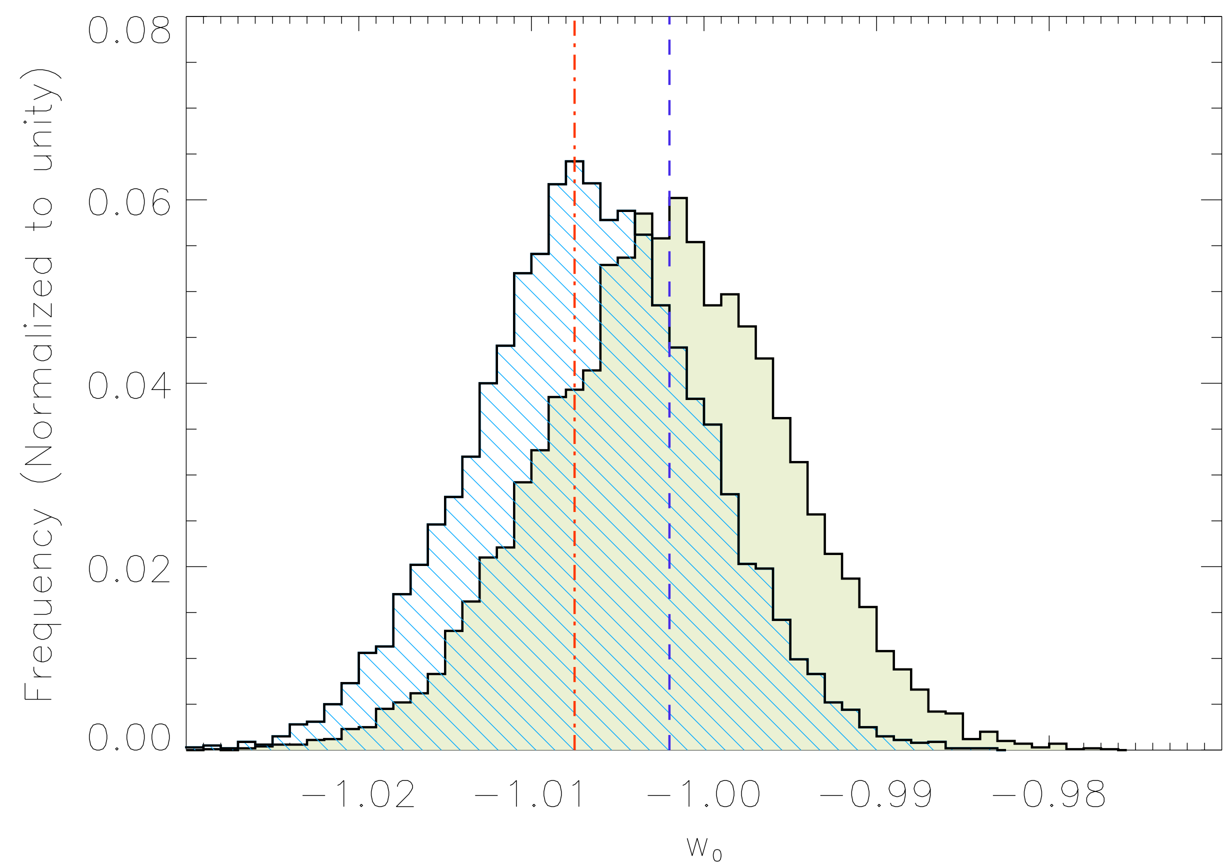
Influence of Gravitational Lensing?

Thus Lensing can Modify Supernova Flux

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

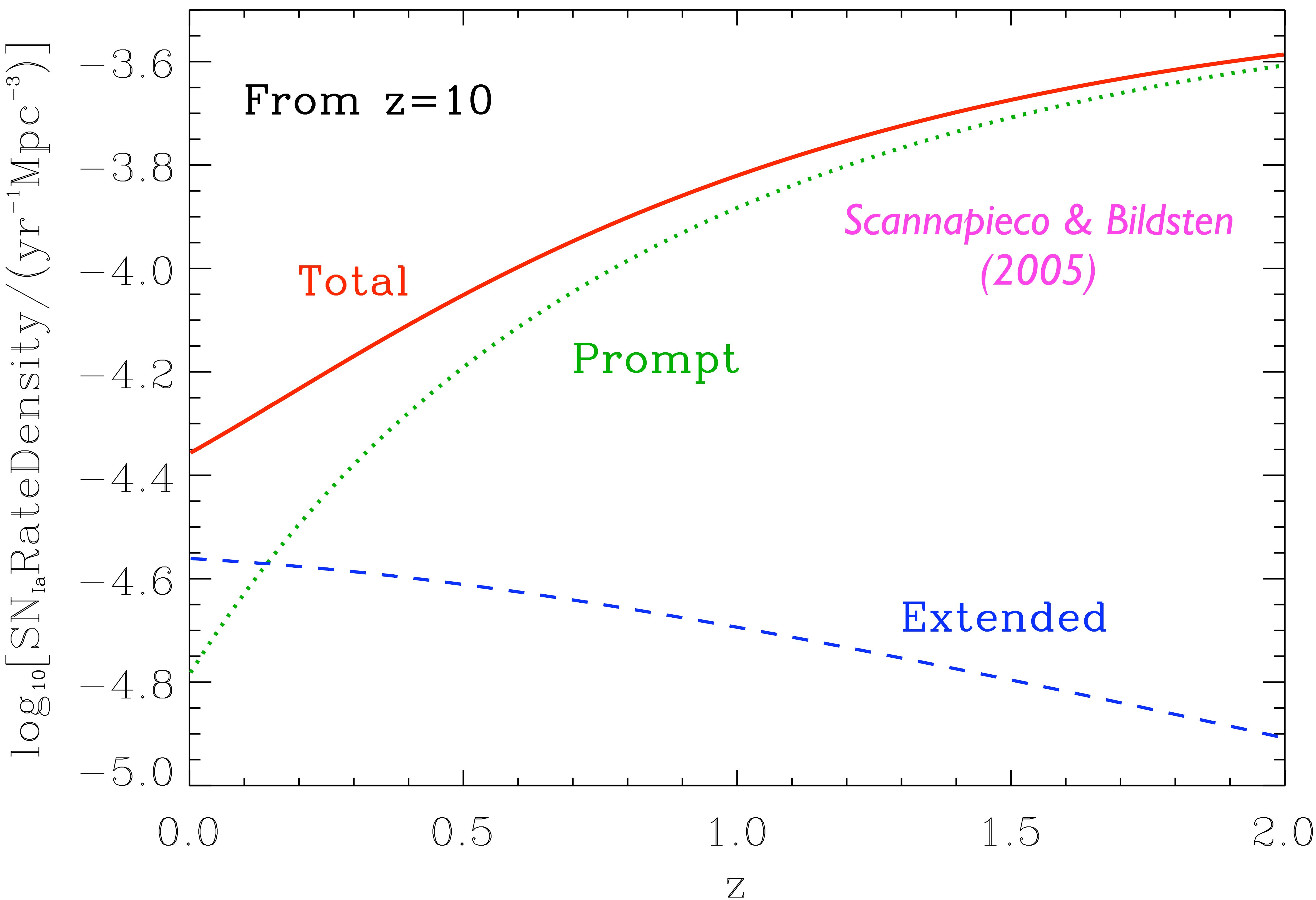






D.S., A. Amblard, D. Holz, A. Cooray (2008)

Evolution based on Two SN Populations



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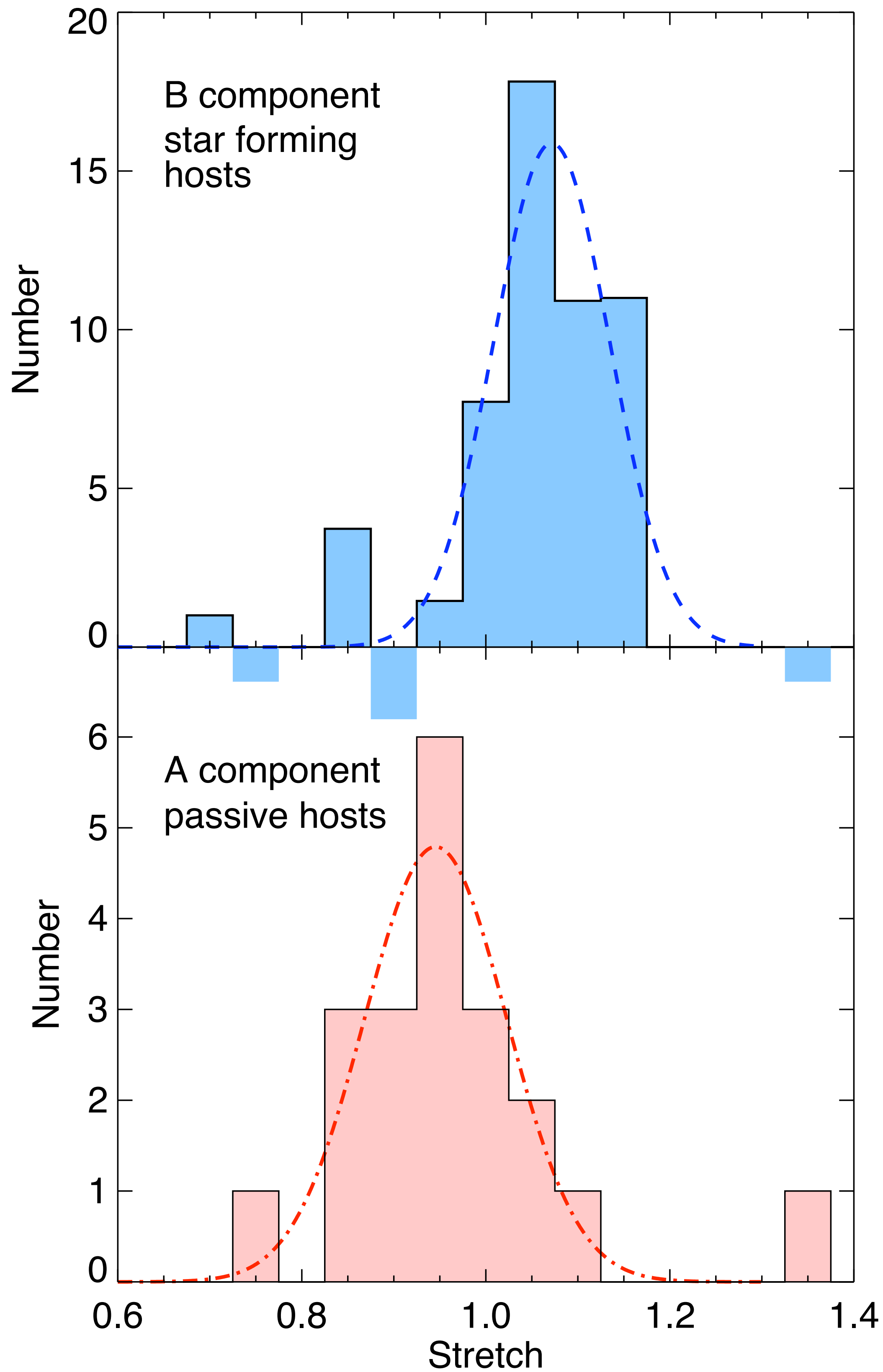

12% Dfference

in

Intrinsic Luminosity

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

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

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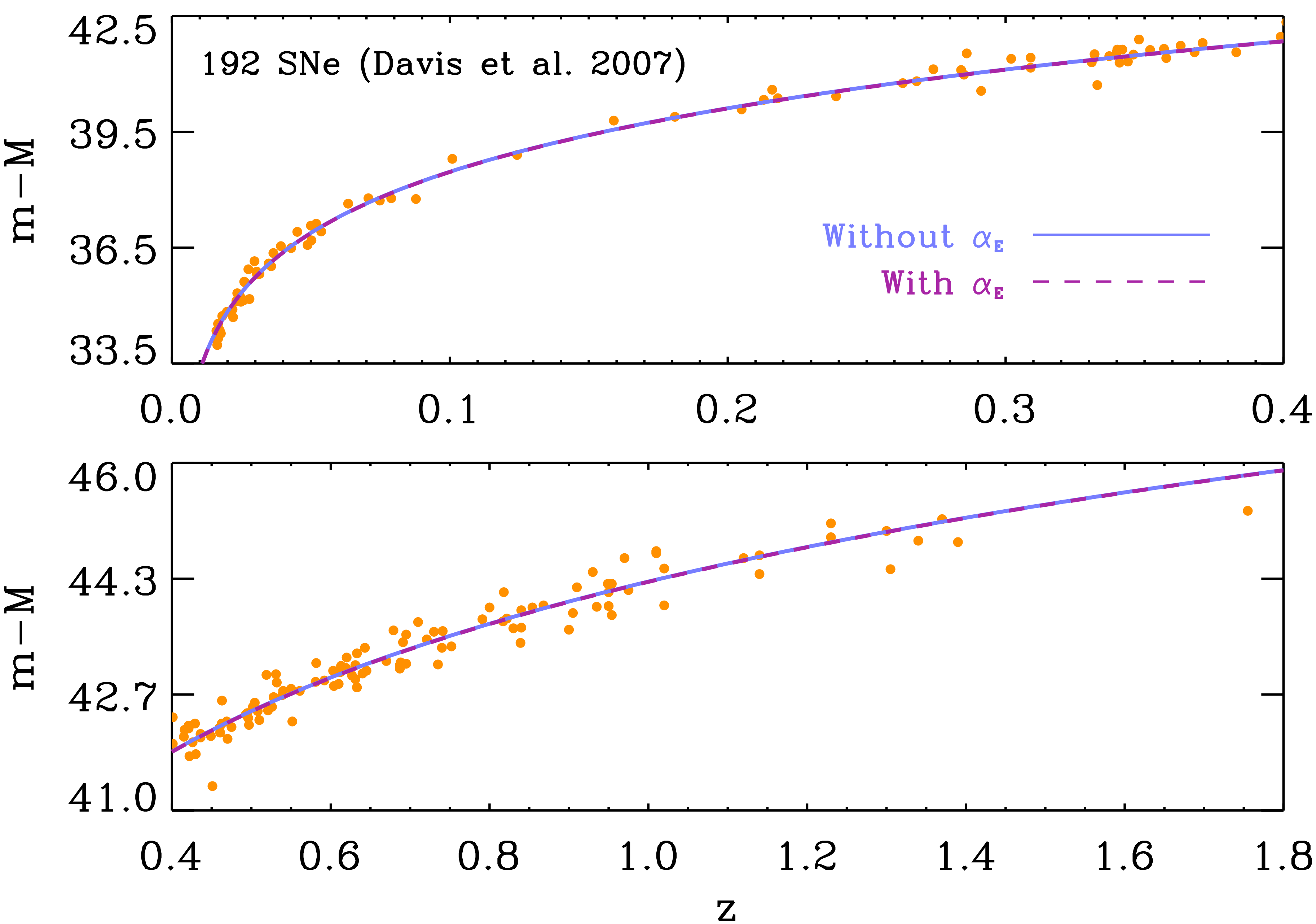

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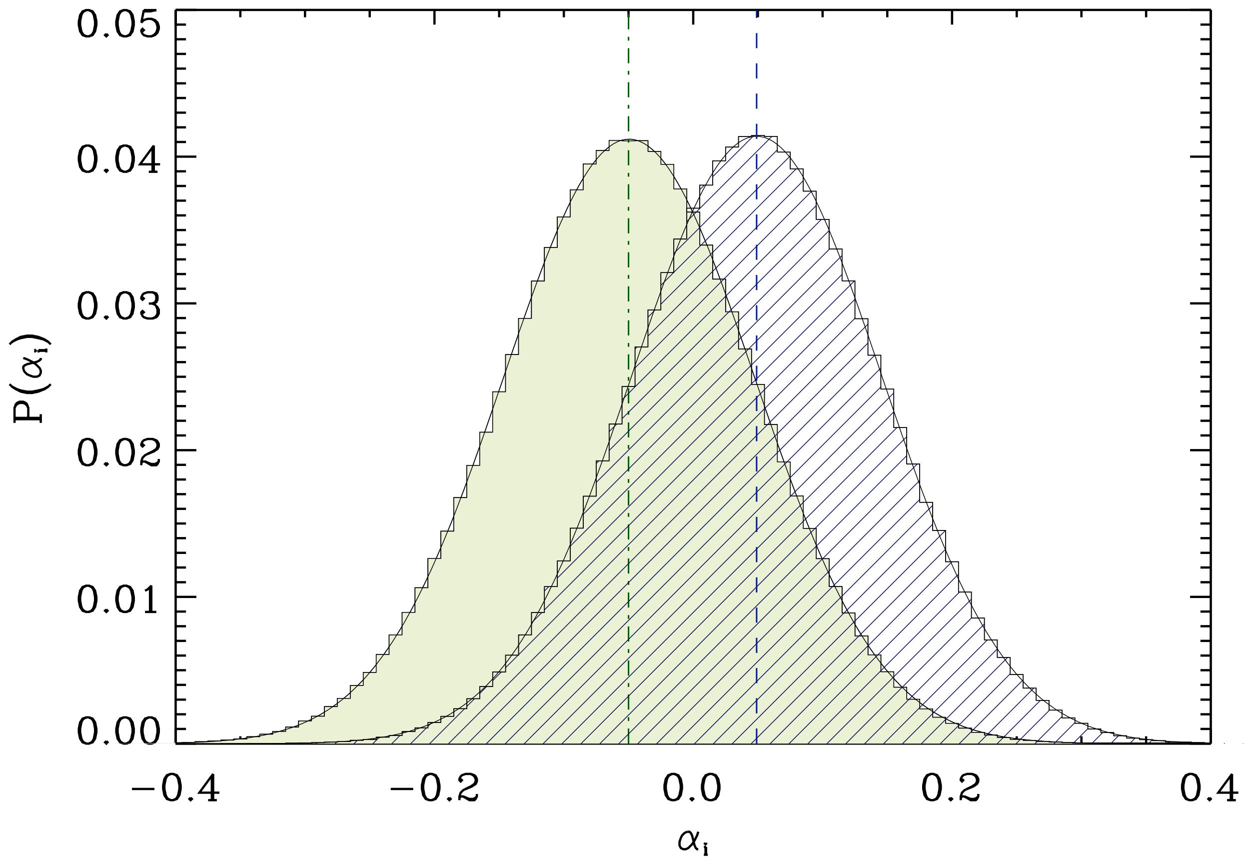
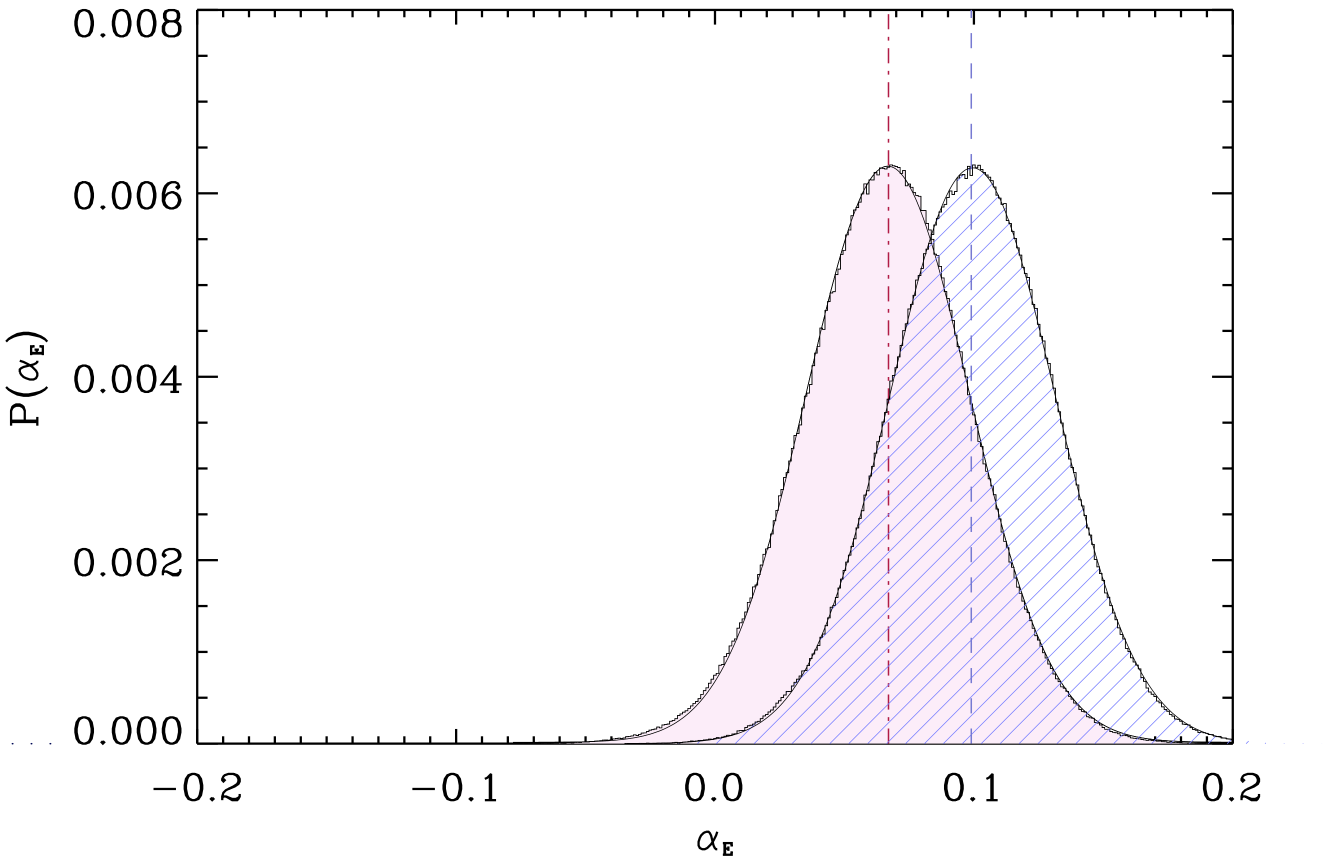


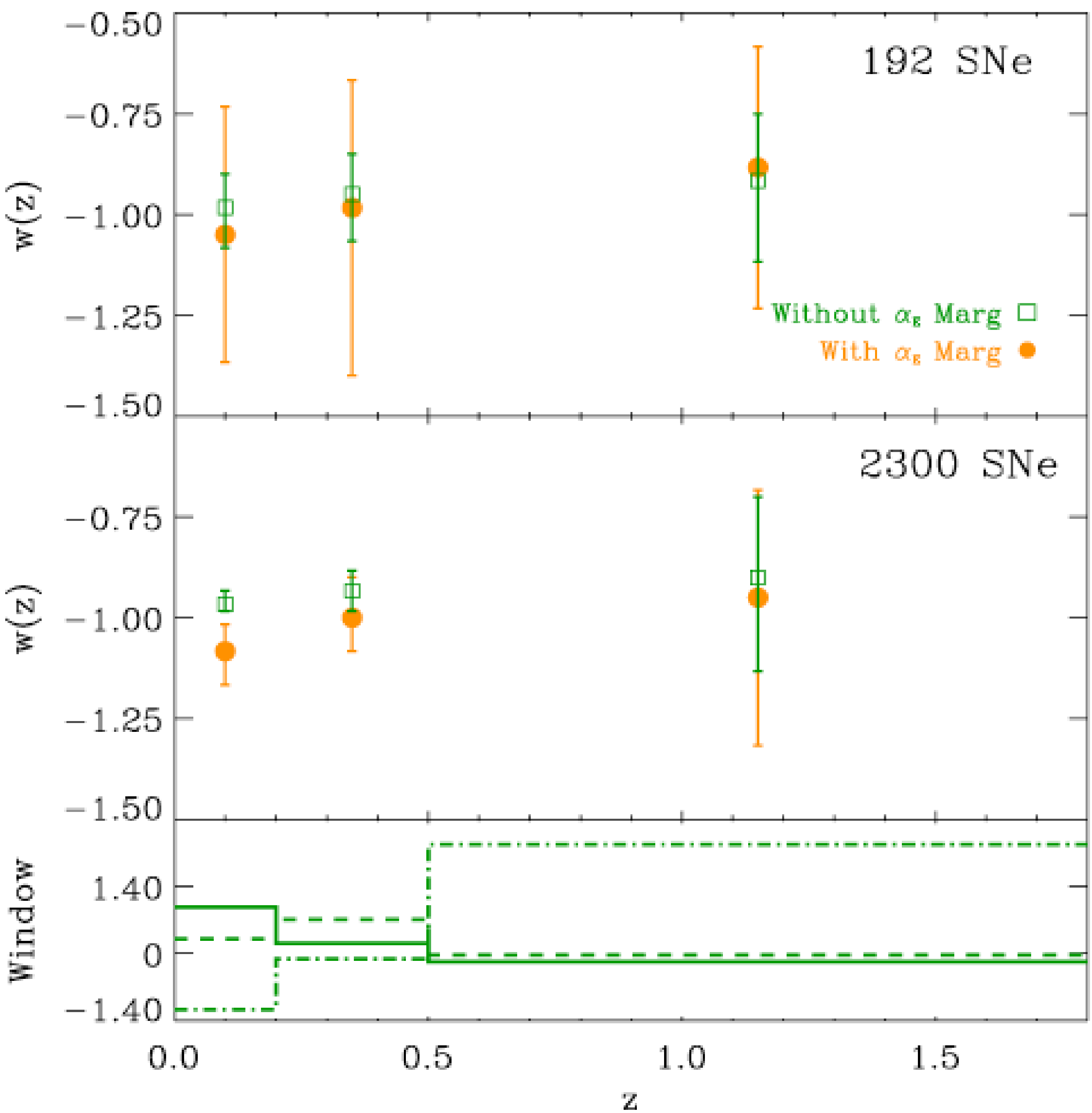


Current Data

Futuristic Data

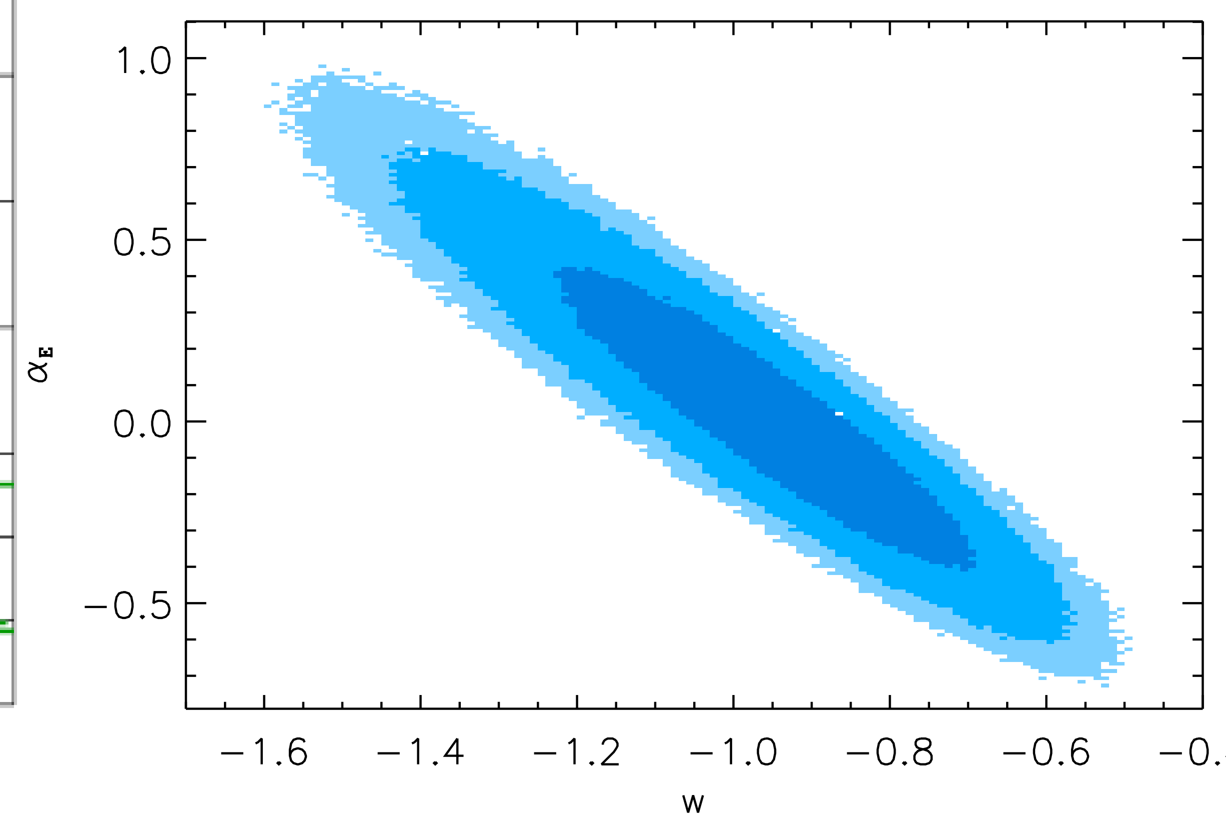
D.S., A. Amblard, A. Cooray, and D. Holz (in prep.)

Effect on Parameter Estimation



N	Bin z range	$w_1(z)$ 0-0.2	$w_2(z)$ 0.2-0.5	$w_3(z)$ 0.5-1.8
192	$\alpha_E = 0$	-0.983±0.102	-0.950±0.126	-0.917±0.226
	With α_E	-1.050±0.327	-0.983±0.383	-0.883±0.438

N	Bin z range	$w_1(z)$ 0-0.2	$w_2(z)$ 0.2-0.5	$w_3(z)$ 0.5-1.8
2300	$\alpha_E = 0$	-0.967±0.036	-0.933±0.053	-0.900±0.242
	With α_E	-1.083±0.083	-1.000±0.100	-0.950±0.341



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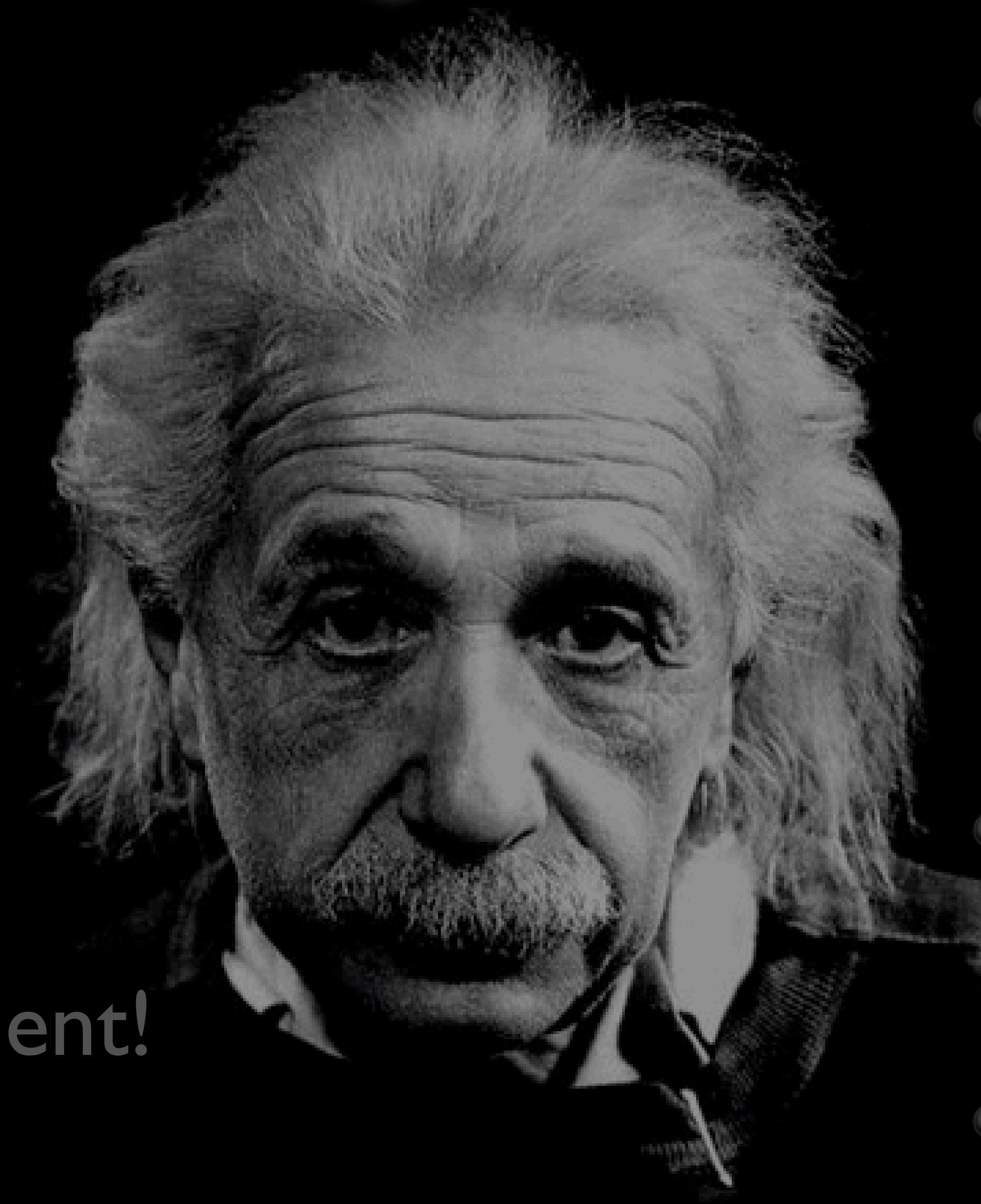

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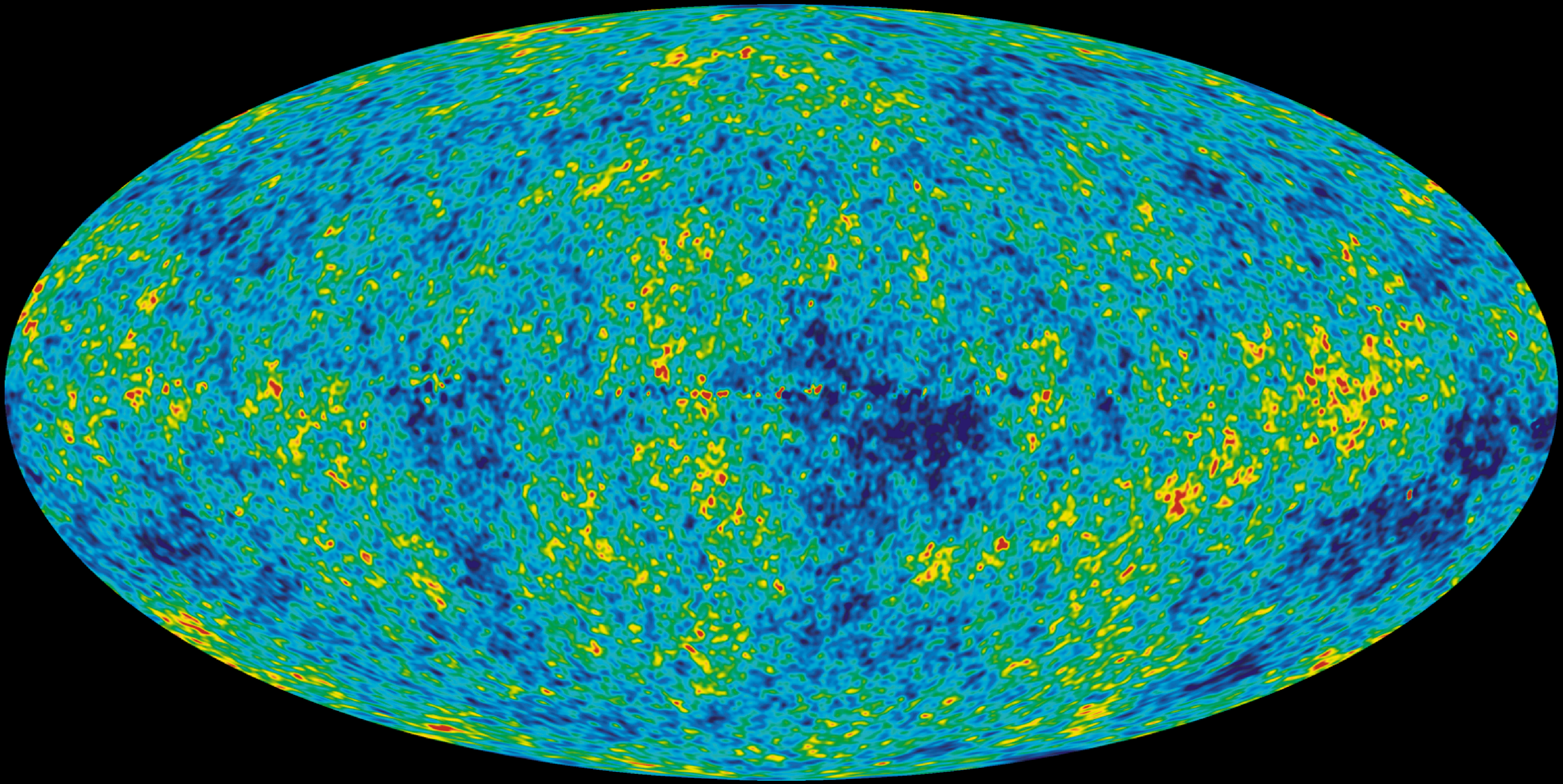
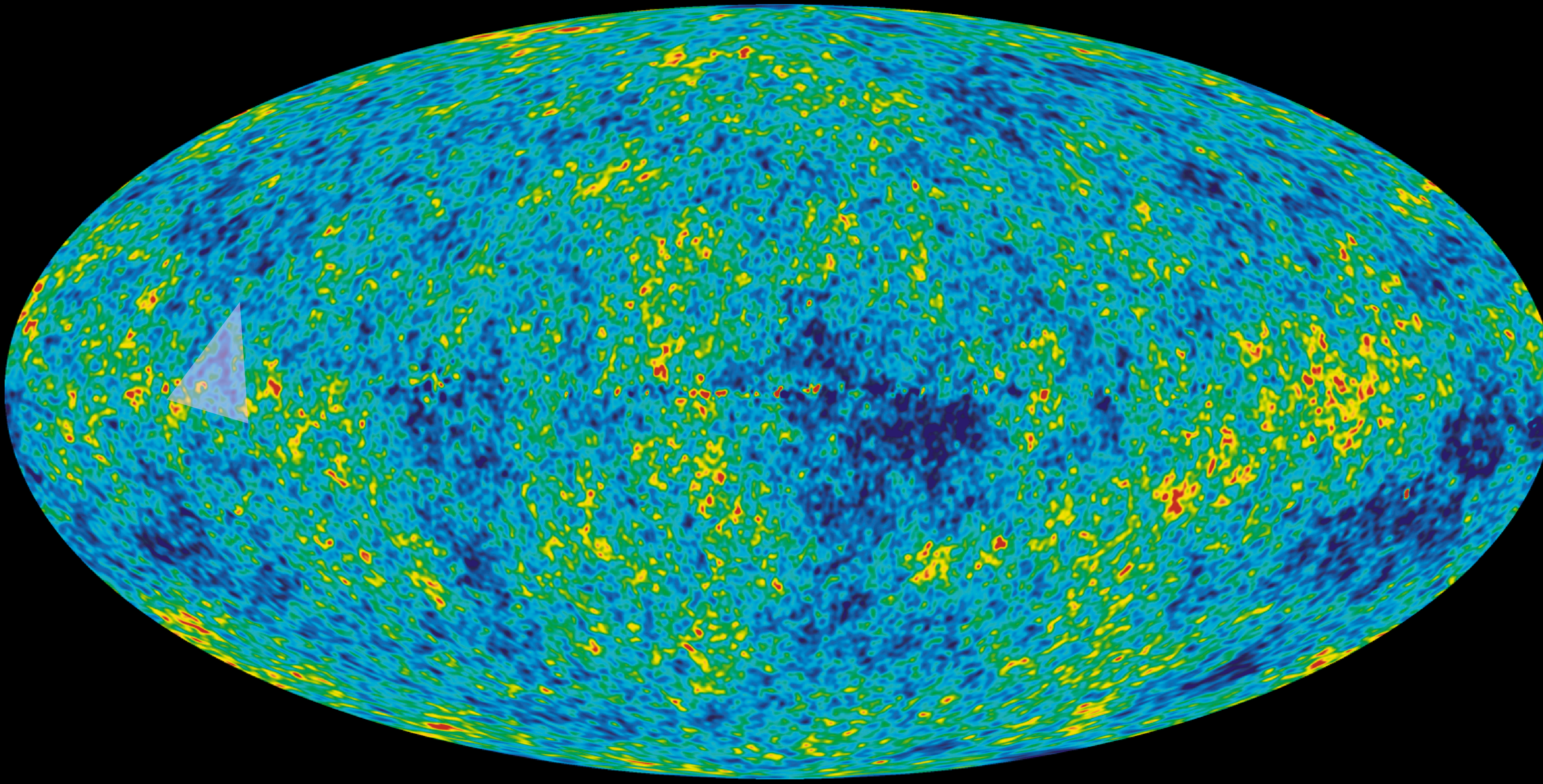


Credit: NASA/WMAP Science Team



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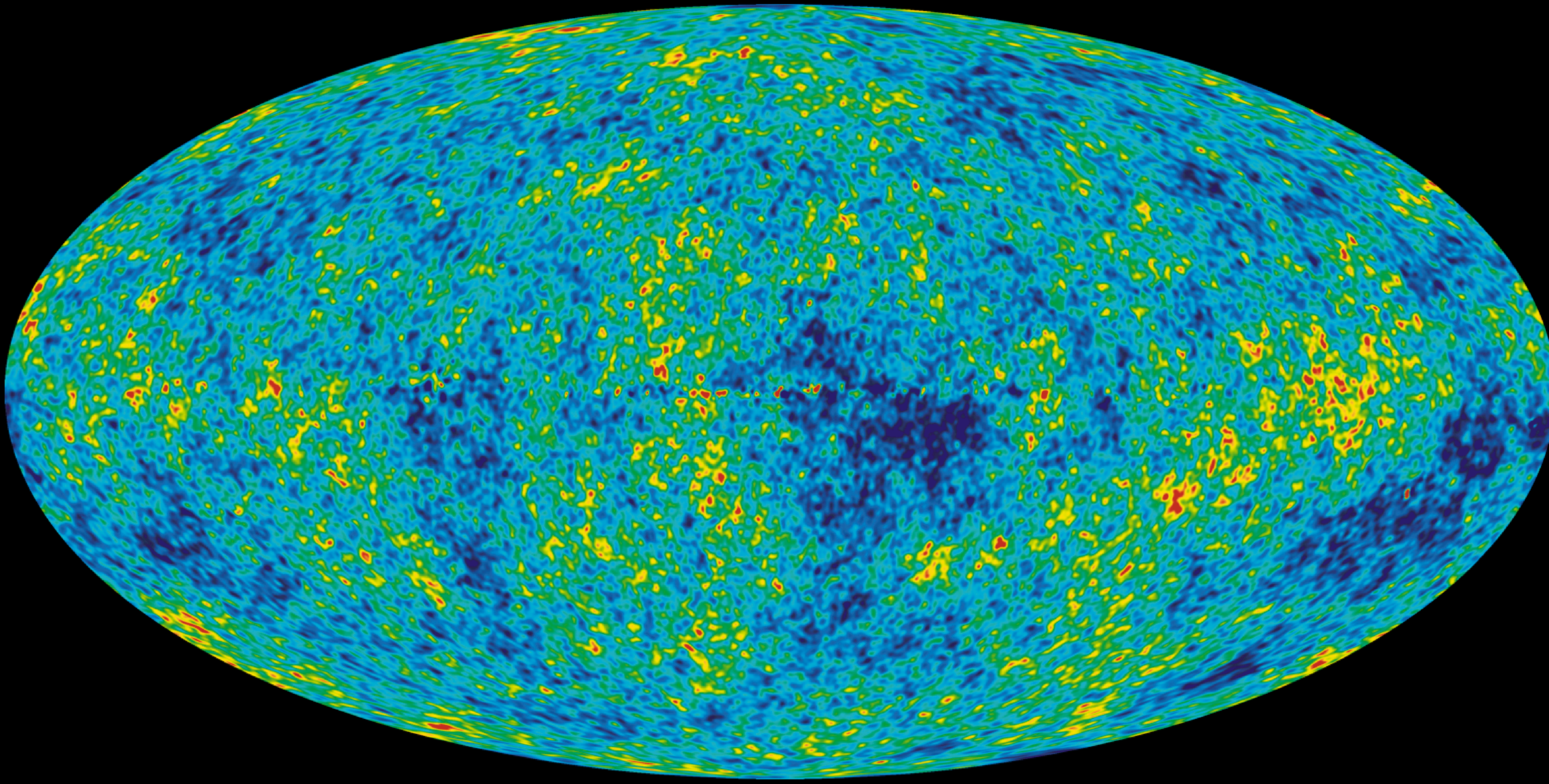

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THANK YOU
WELLS FARGO
We're on Track
For a Cure