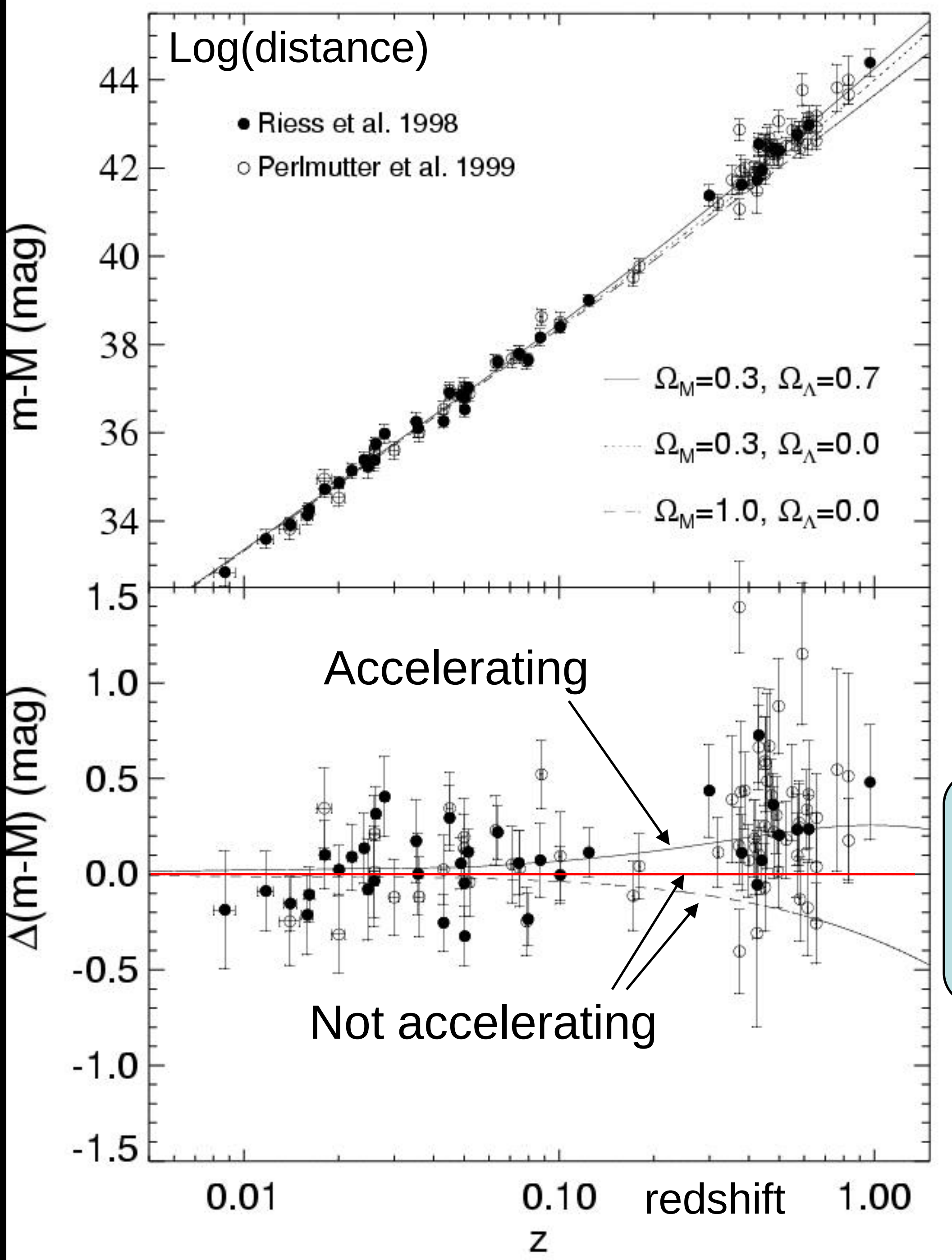
Dark Energy: Status and Outlook

David Gerdes
University of Michigan

XXXIV Physics in Collision
Indiana University
September 20, 2014

Discovery of Cosmic Acceleration from High-redshift Supernovae

Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected



$W_L = 0.7$
$W_L = 0.7$
$W_m = 1.0$

Cosmological Dynamics

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \sum_i \rho_i \left(1 + 3w_i\right)$$

Friedmann Equation from GR

Equation of state parameter: $w_i = p_i / \rho_i c^2$

Non-relativistic matter: $p_m \sim \rho_m \mathrm{v}^2, \quad w \approx 0$

Relativistic particles: $p_r = \rho_r c^2 / 3, \qquad w = 1/3$

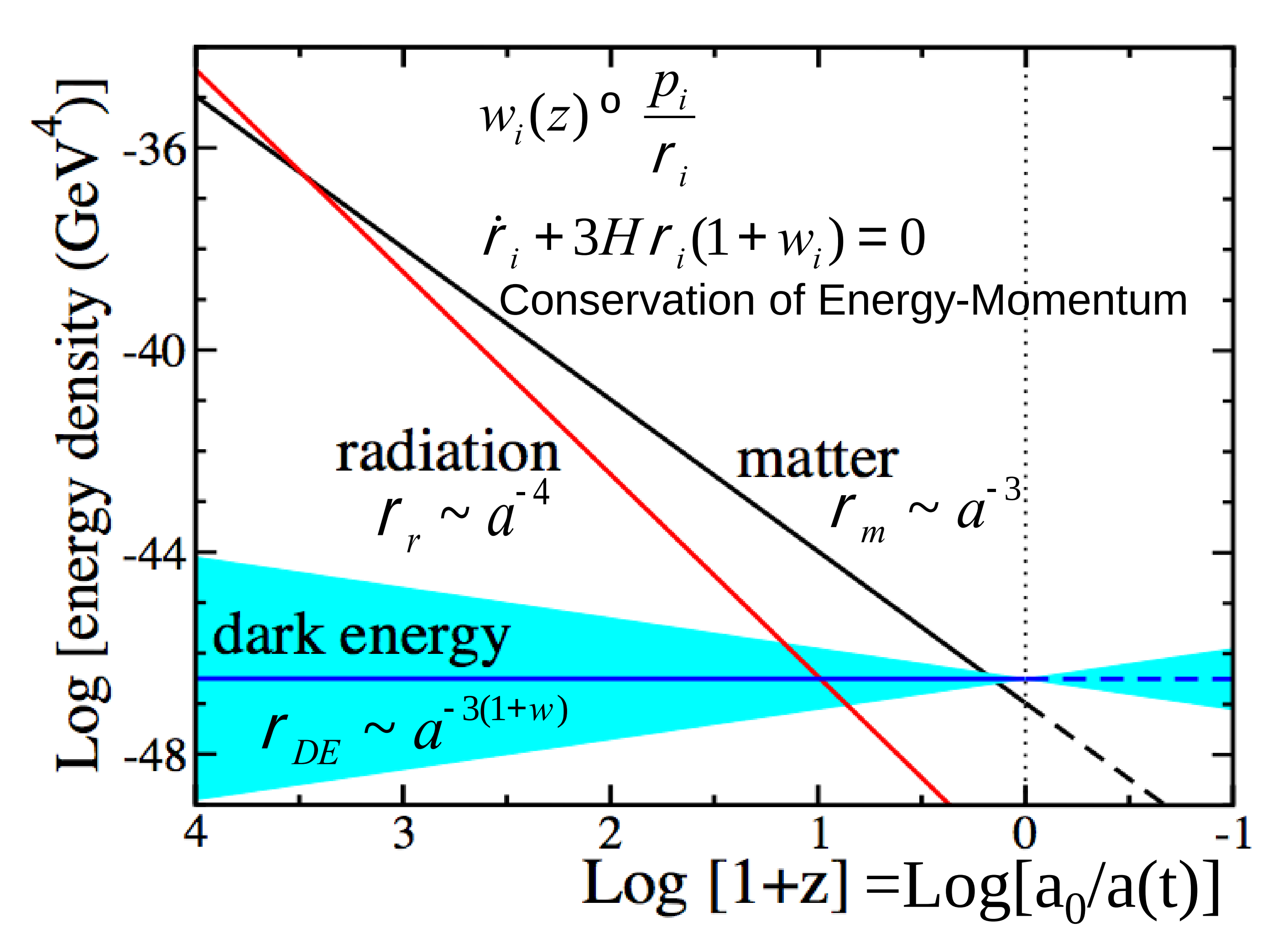
Acceleration ($\ddot{a} > 0$) requires component with negative pressure:

Dark Energy: $w_{DE} < -1/3$

Cosmological Constant: $w_\Lambda = -1$

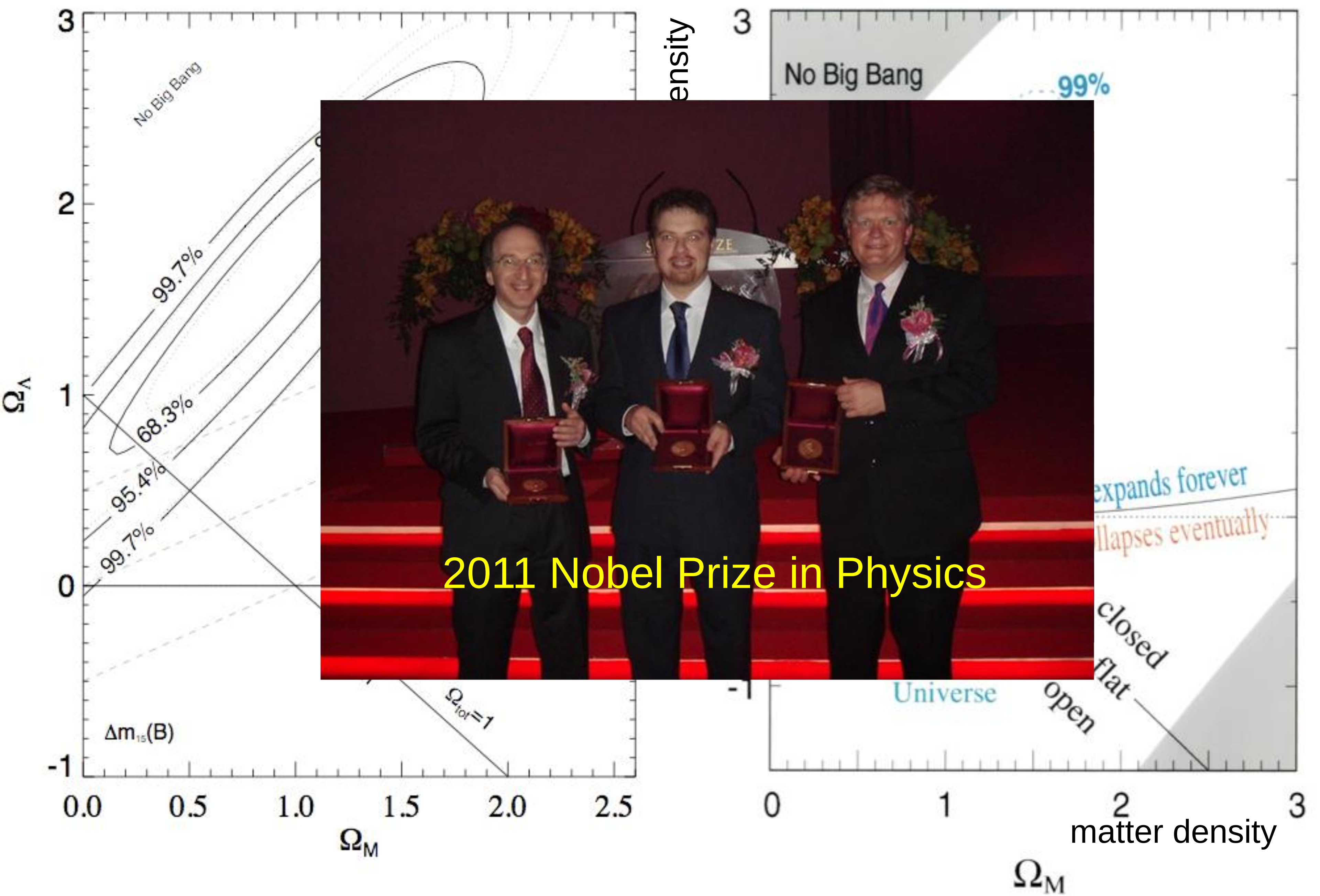
or Replace GR dynamics with another gravity theory

Equation of state parameter w determines cosmic evolution

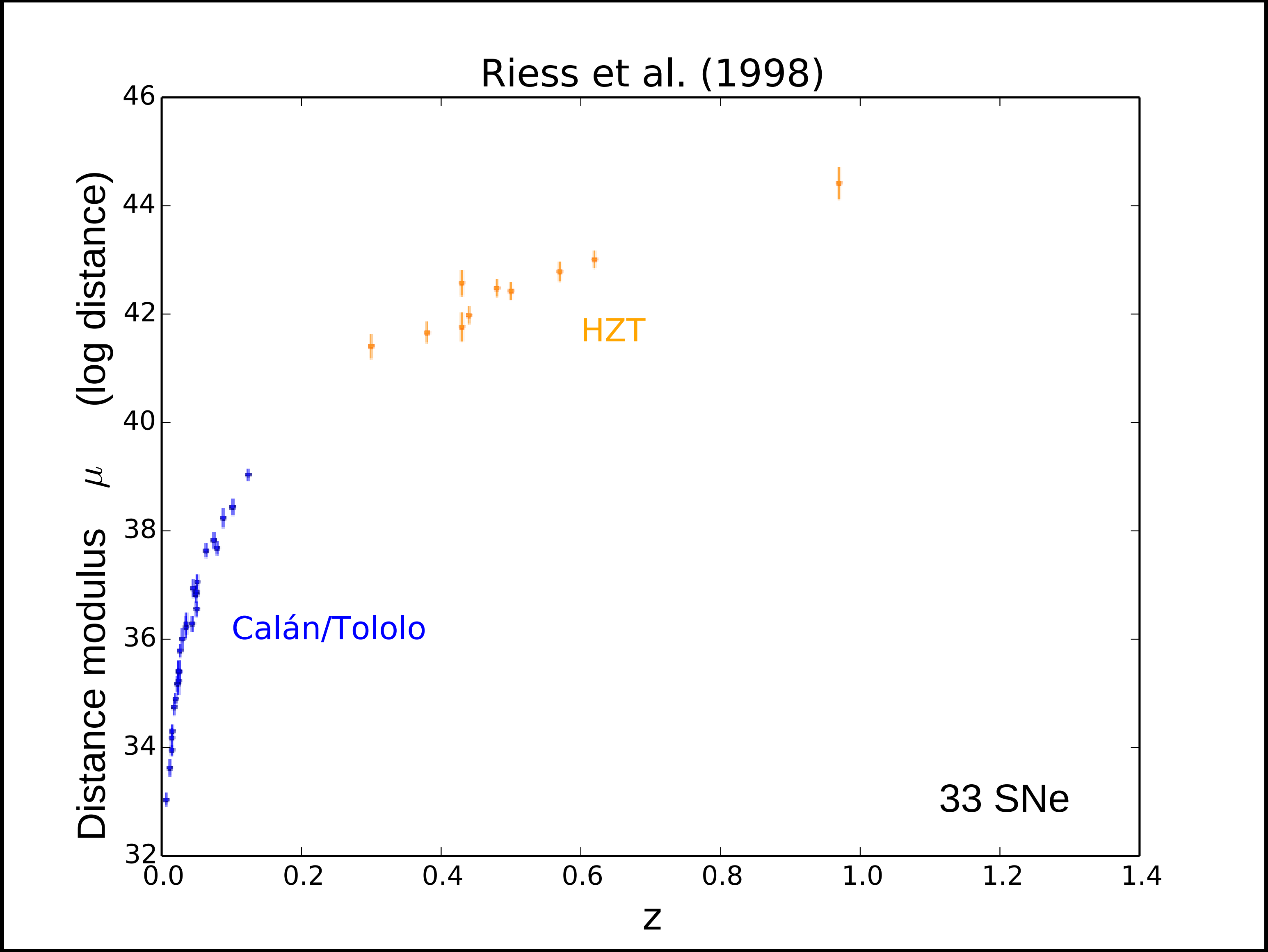


Riess et al. (1998, AJ)

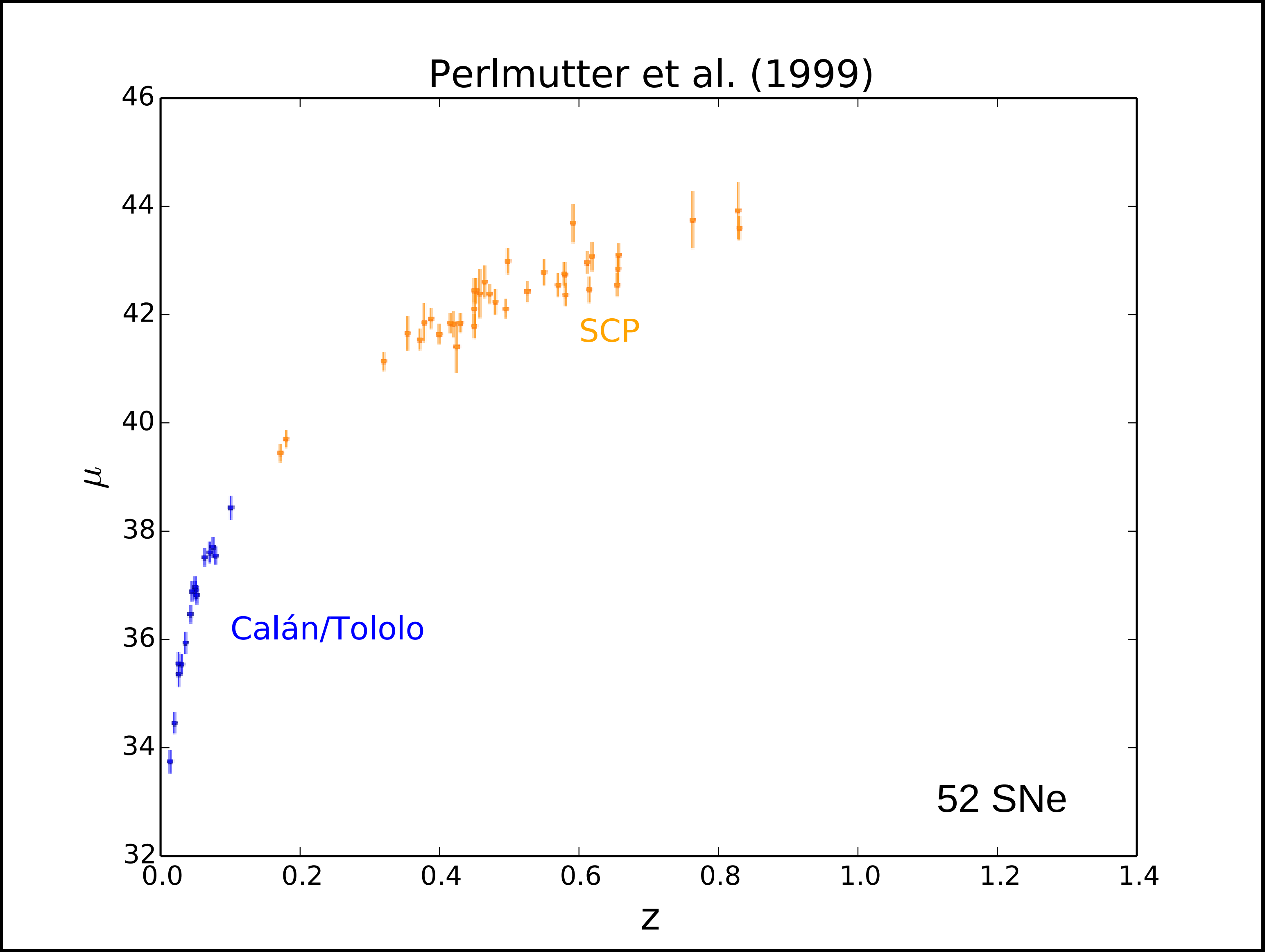
Perlmutter et al. (1999, ApJ)



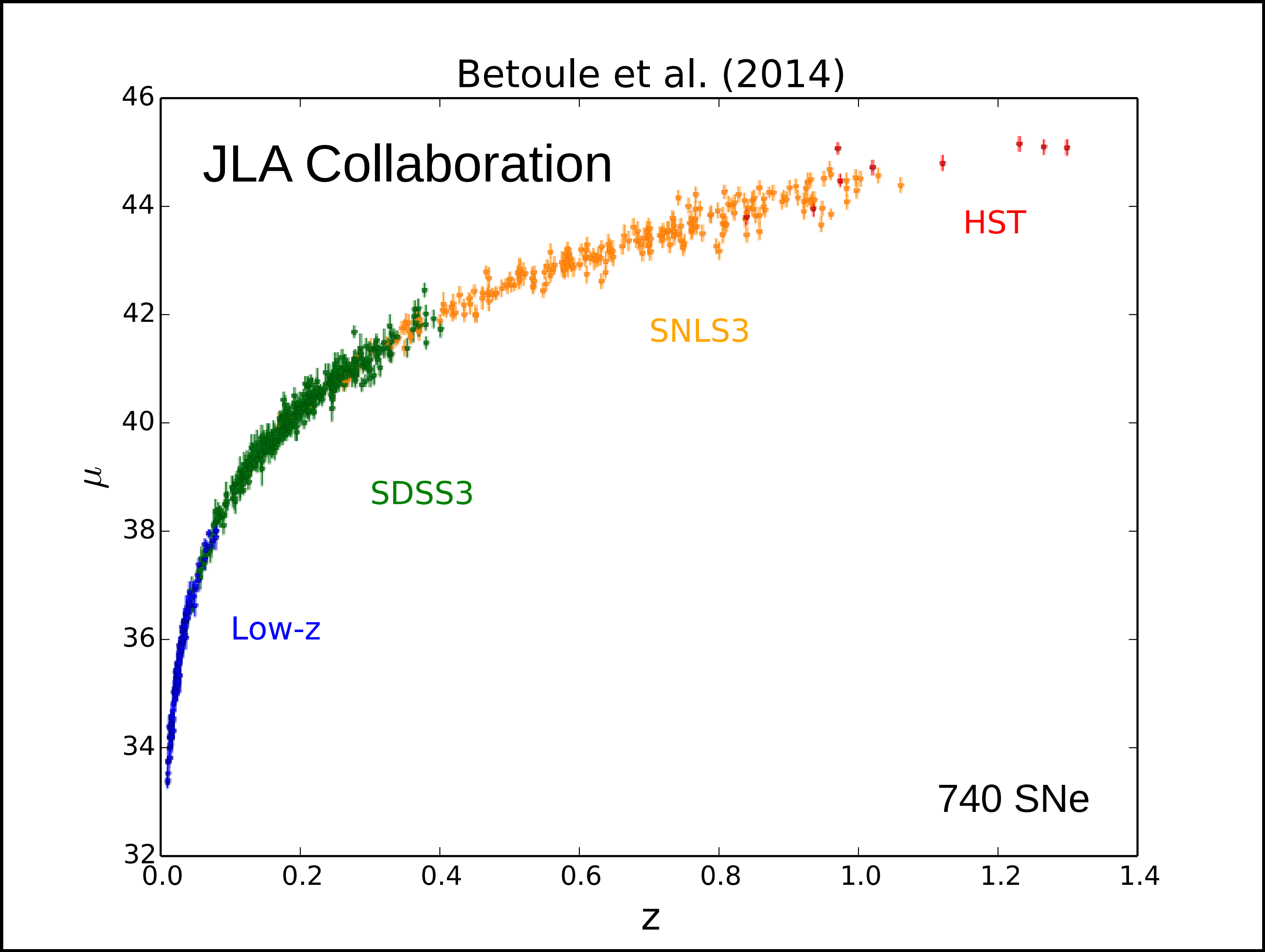
Supernova Ia Hubble Diagram



figures by A. Conley

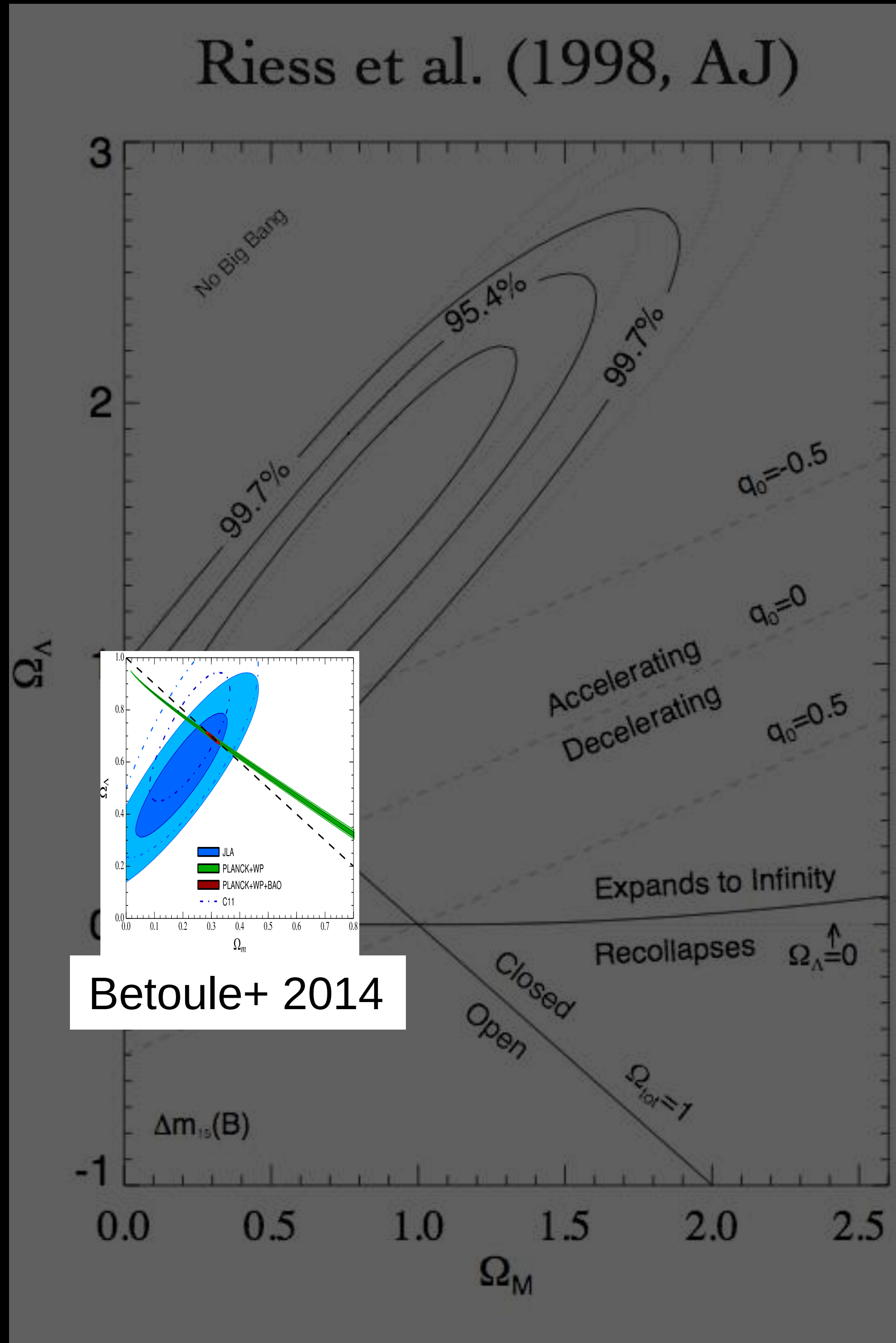


Perlmutter et al. (1999)
μ
z
SCP
Calán/Tololo
52 SNe



arXiv:1401.4064

Progress over the last 16 years



Supernovae

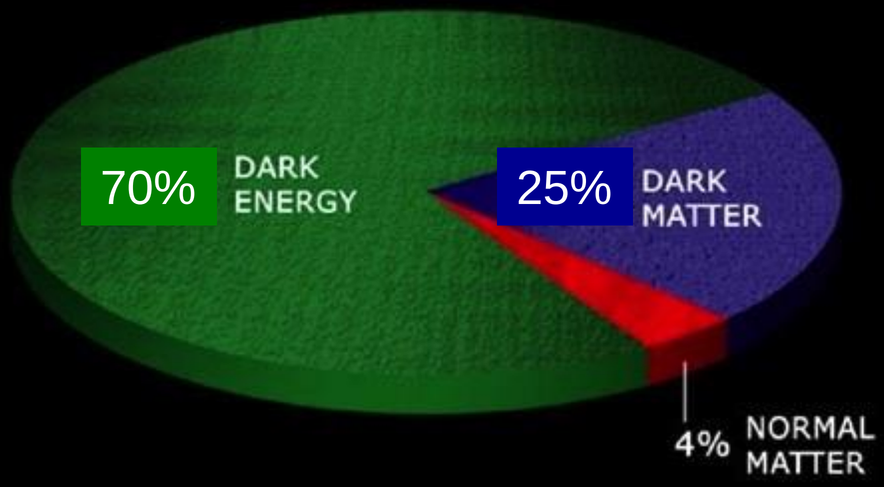
Cosmic Microwave Background (Planck, WMAP)

CMB+BAO

Here assuming $w=-1$

From Discovery to Physics

- What is the physical cause of cosmic acceleration?
  - Dark Energy or modification of General Relativity?
    - If Dark Energy, is it Λ (the vacuum) or something else?
      - What is the DE equation of state parameter *w* and (how) does it evolve?



No consensus on dynamical DE or modified gravity models

- Theoretical prejudice in favor of cosmological constant (vacuum energy) with $w=-1$ was probably wrong once (Cf. inflation): not a strong argument for it being correct now
- Cosmological constant problem (why is vacuum energy density not 120 orders of magnitude larger?) is not necessarily informative for model-building
- Some alternatives to Λ (Cf. quintessence) rely on notion that a very light degree of freedom can take ~current Hubble time to reach its ground state.
- Modified gravity models predict scale-dependent departures from GR on cosmological (and sometimes galactic) scales.

Dynamical Evolution of Freezing vs. Thawing Models

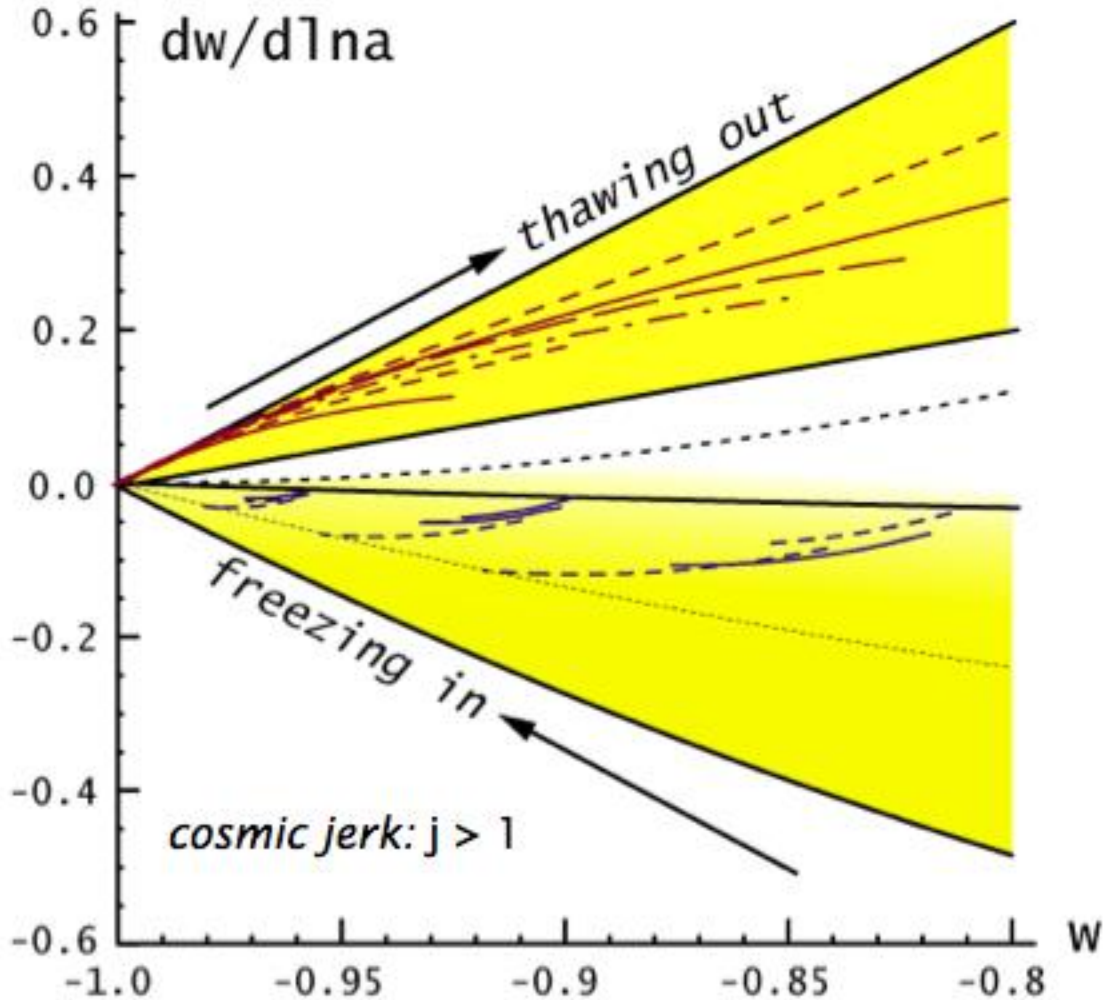
scalar field models

$V \propto \Phi^n,\ n = 1, 2, 4$
short-, dot-, long-dashed

$V \propto \cos^2(\Phi/2f)$
solid

$V \propto \Phi^{-n}$
solid

$V \propto \Phi^{-n} e^{\alpha\Phi^2}$
dashed

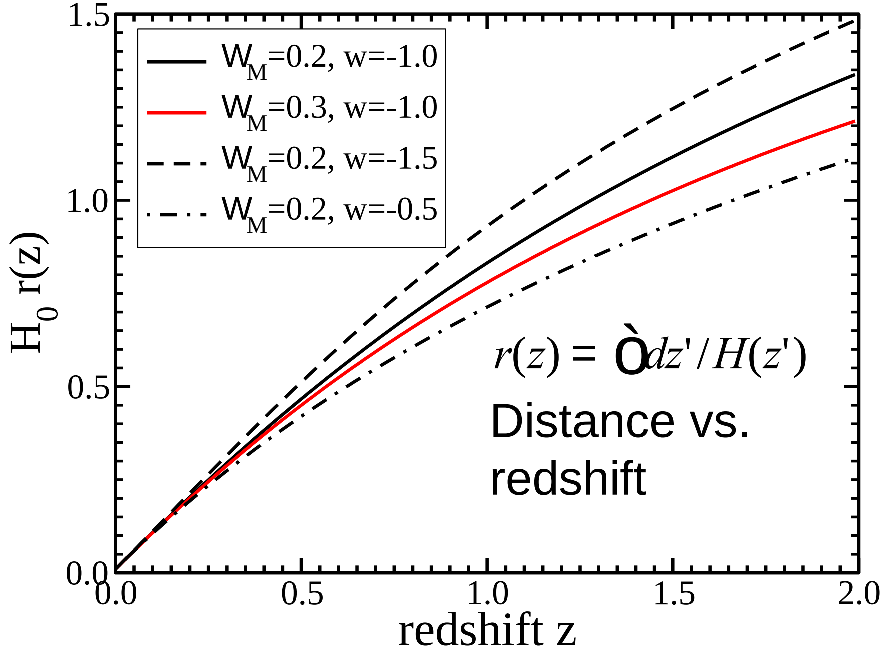


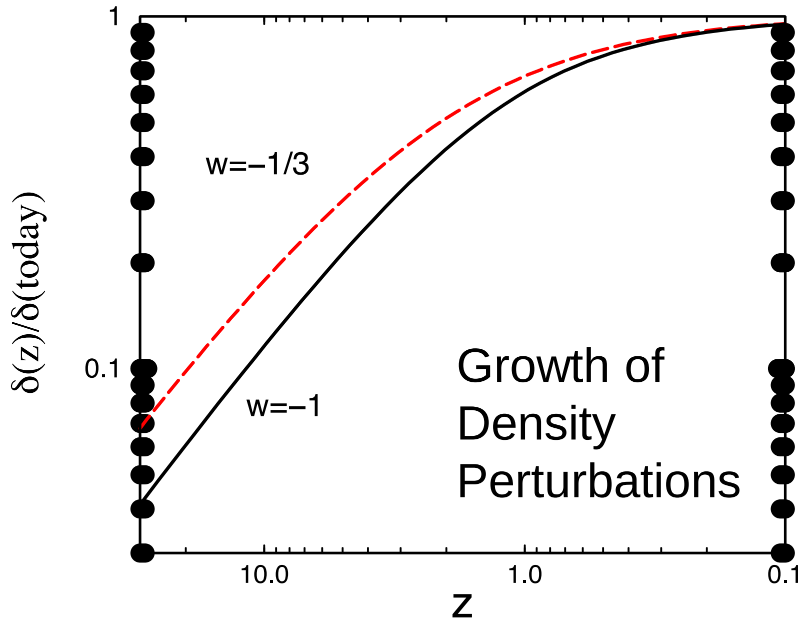
Caldwell & Linder

Measuring *w* and its evolution can potentially distinguish between physical models for acceleration

What can we probe?

Require both to disentangle Dark Energy from Modified Gravity





- Supernovae — Distances
- Weak Lensing cosmic shear — Distances+growth
- Baryon Acoustic Oscillations — Distances and H(z)
- Cluster counts — Distances+growth
- Redshift-Space Distortions — Growth

Constraints from the CMB (Planck)

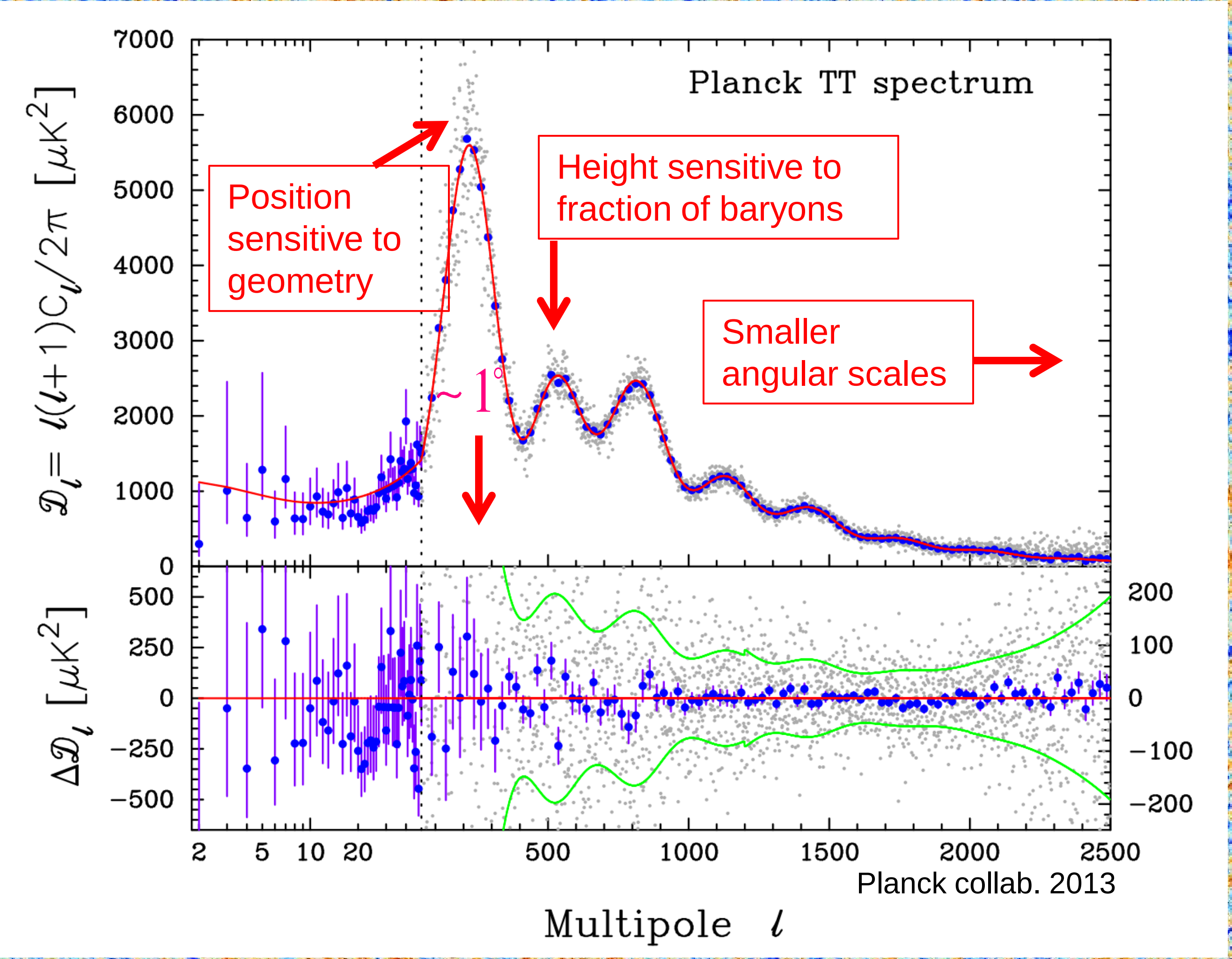
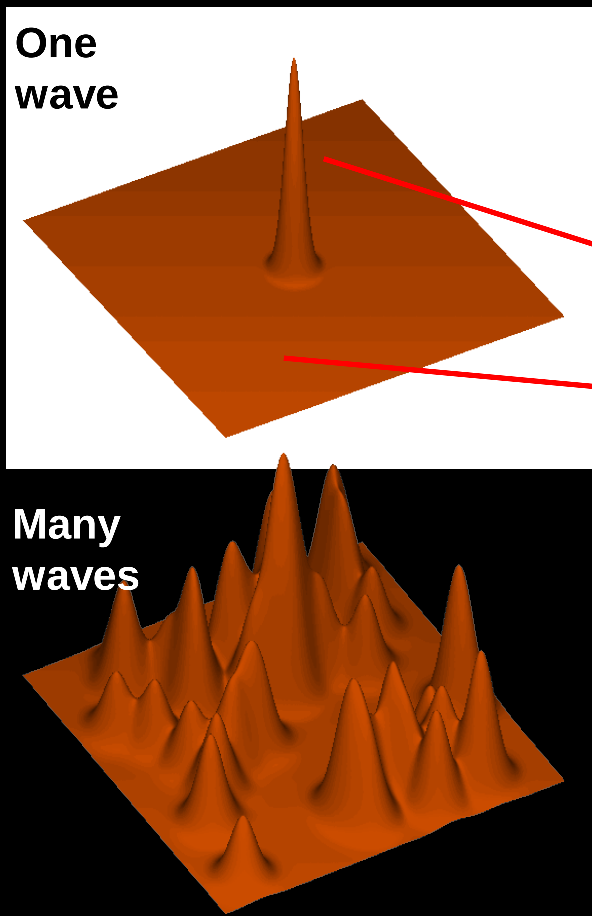


Image: Planck Science Team

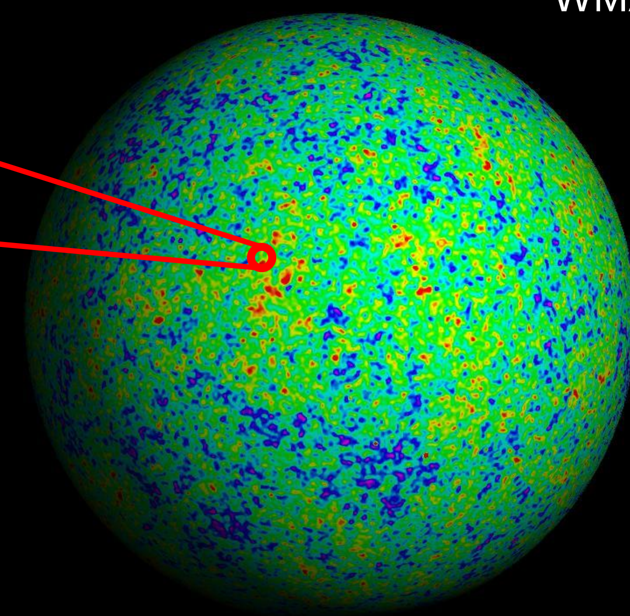
Baryon Acoustic Oscillations

Sound waves travel at $v=c/\sqrt{3}$ until recombination. The sound horizon at recombination sets the ~1° characteristic angular scale of the CMB.



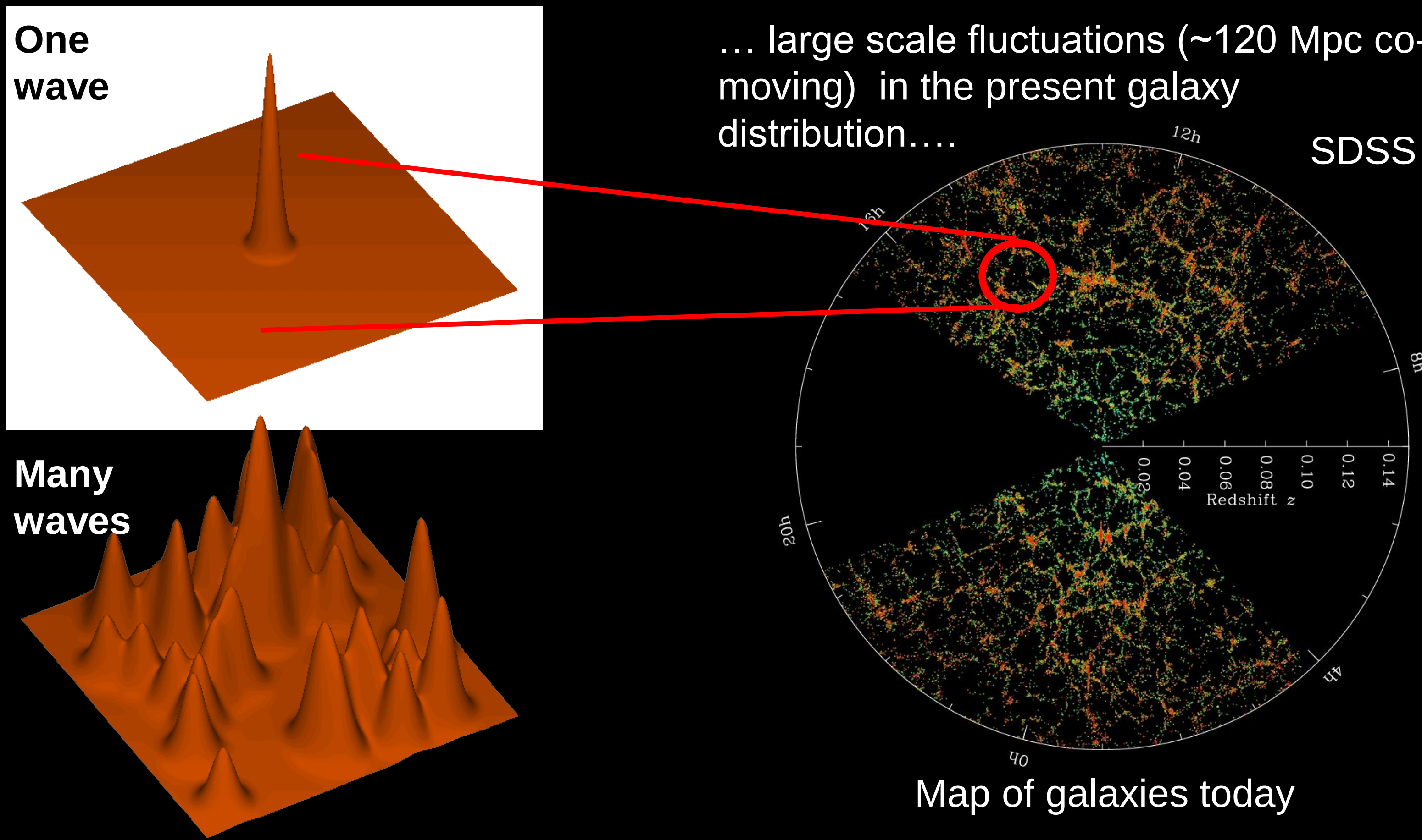
At the surface of last scattering (z=1088) this is a "standard ruler" used to establish the flatness of the universe. These $1/10^5$ level fluctuations grow into…

WMAP

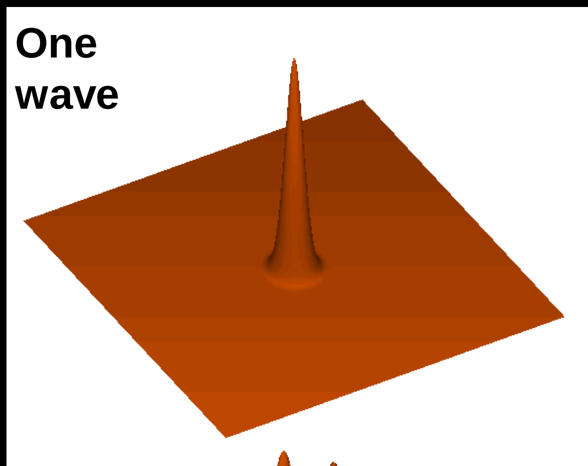


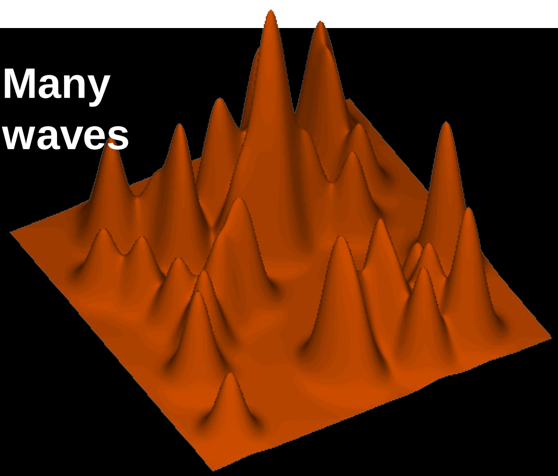
Map of Universe at 380,000 years (CMB)

Baryon Acoustic Oscillations

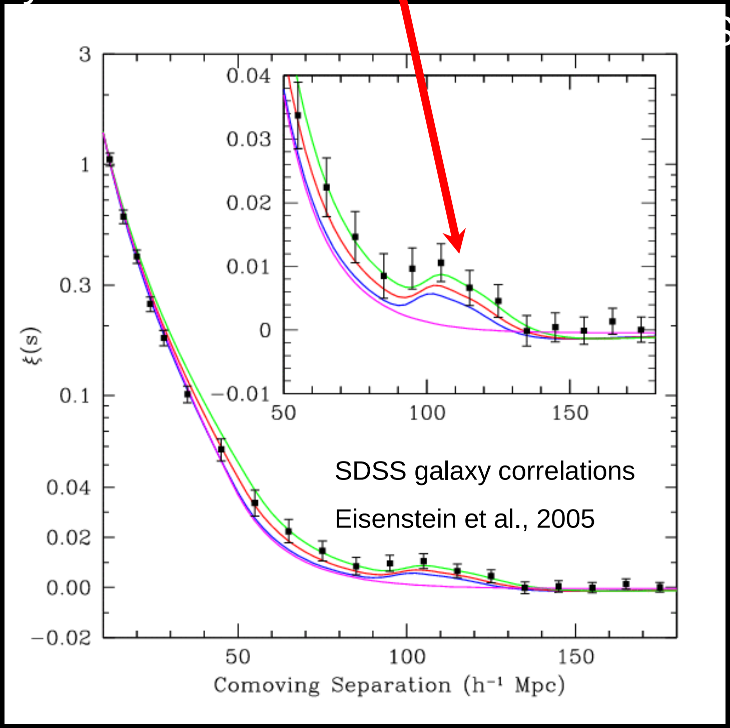


Baryon Acoustic Oscillations





… and can be seen as a peak in the power spectrum of the galaxy correlation function today.



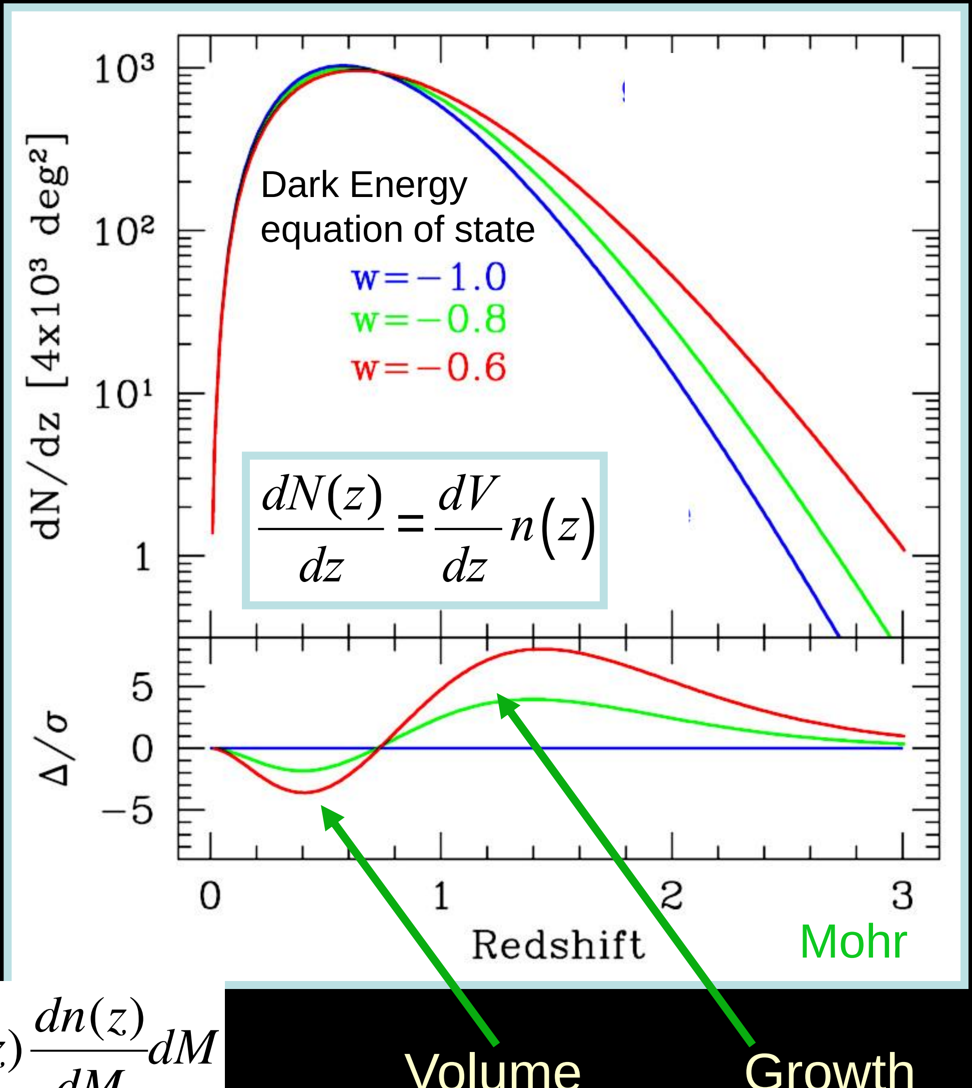
Map of galaxies today

Galaxy Clusters

DARK ENERGY SURVEY

- Clusters are proxies for massive halos and can be identified to redshifts z>1
- Galaxy colors provide photometric redshift estimates for each cluster, σ(z)~0.01
- Challenge: determine mass-observable relation *p(O|M,z)* with sufficient precision
- Multiple observable proxies *O* for cluster mass: optical richness, SZ flux, weak lensing mass, X-ray flux, velocity dispersion

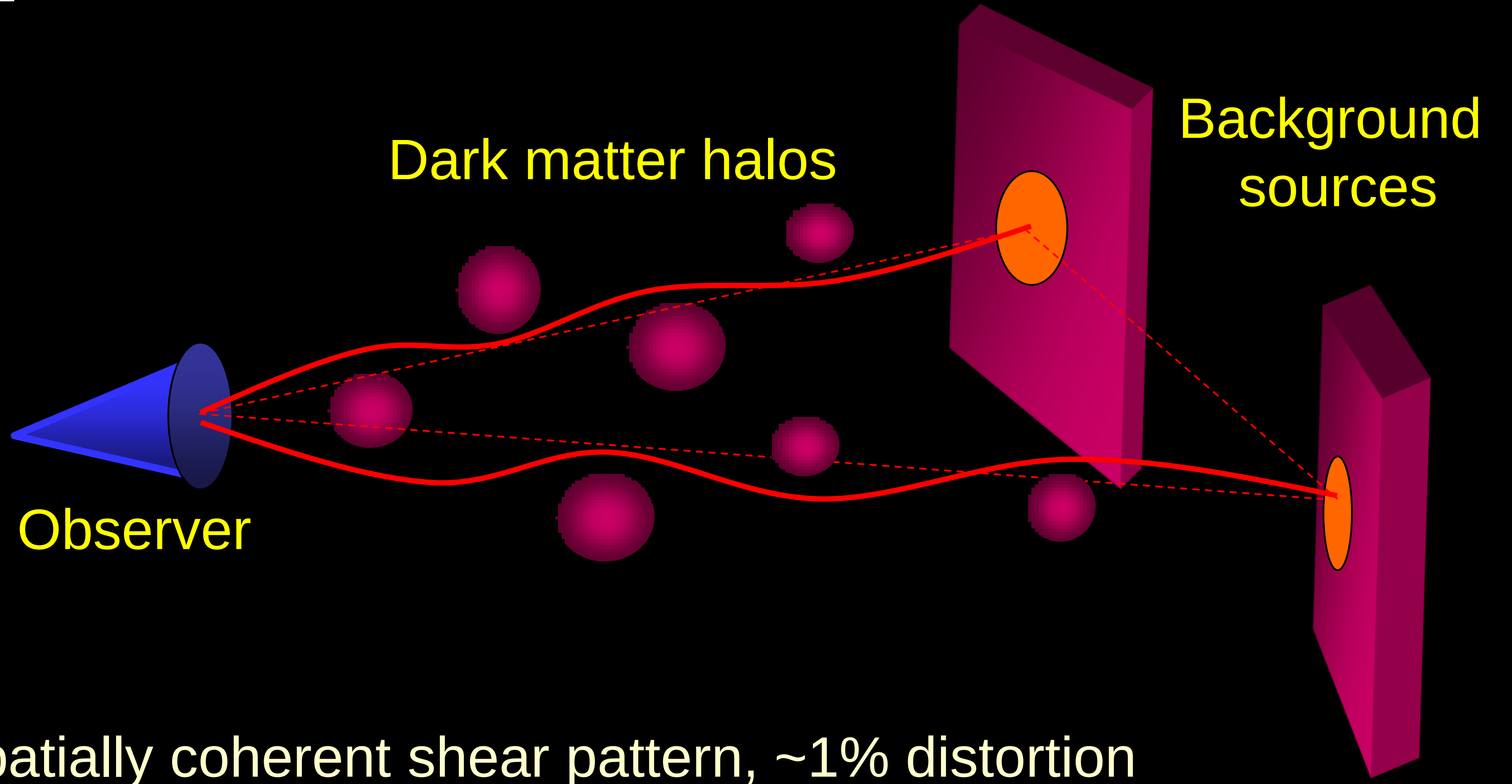
Number of clusters above mass threshold



$$\frac{dN(z)}{dz} = \frac{dV}{dz} n(z)$$

$$\frac{d^2N}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z) dO \int \underline{p(O \mid M,z)} \frac{dn(z)}{dM} dM$$

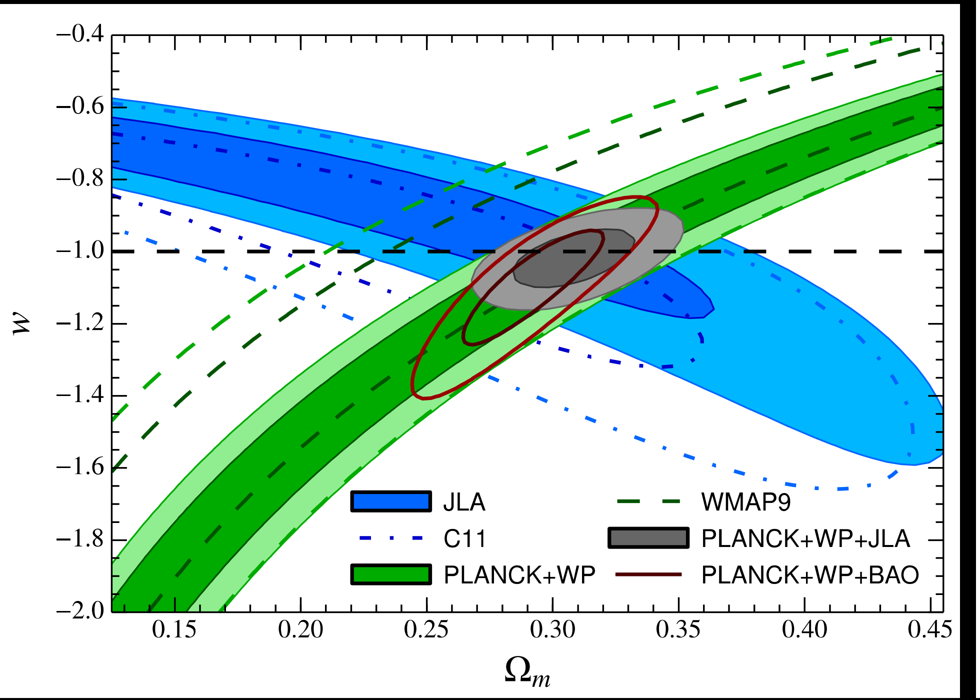
Weak Lensing: Cosmic Shear



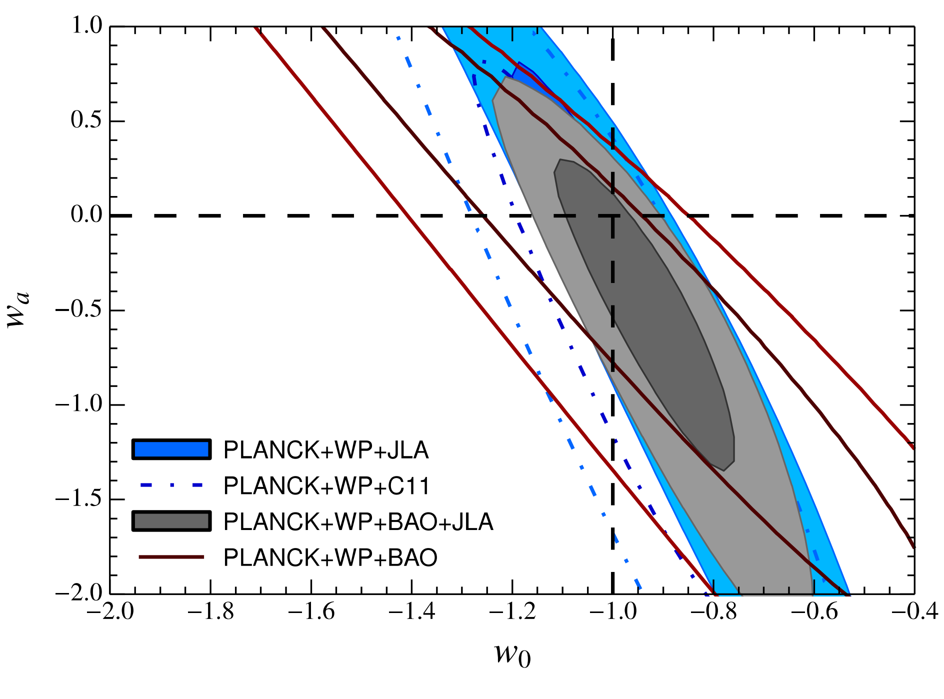
- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure

Current Dark Energy Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*



Assuming $w=w_0+w_a(1-a)$



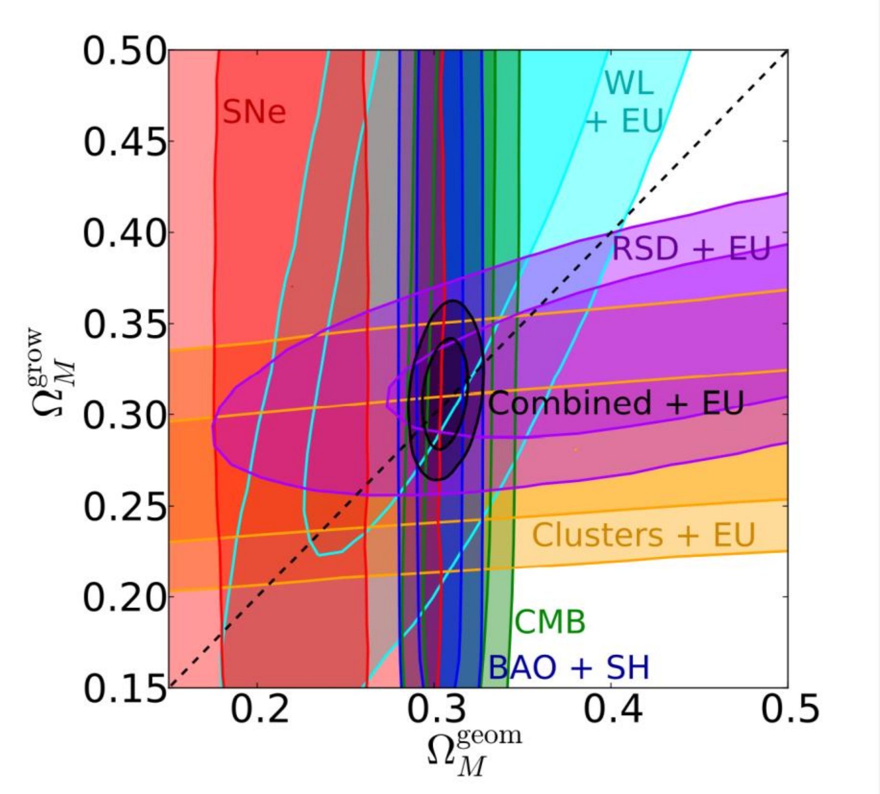
Betoule et. al 2014

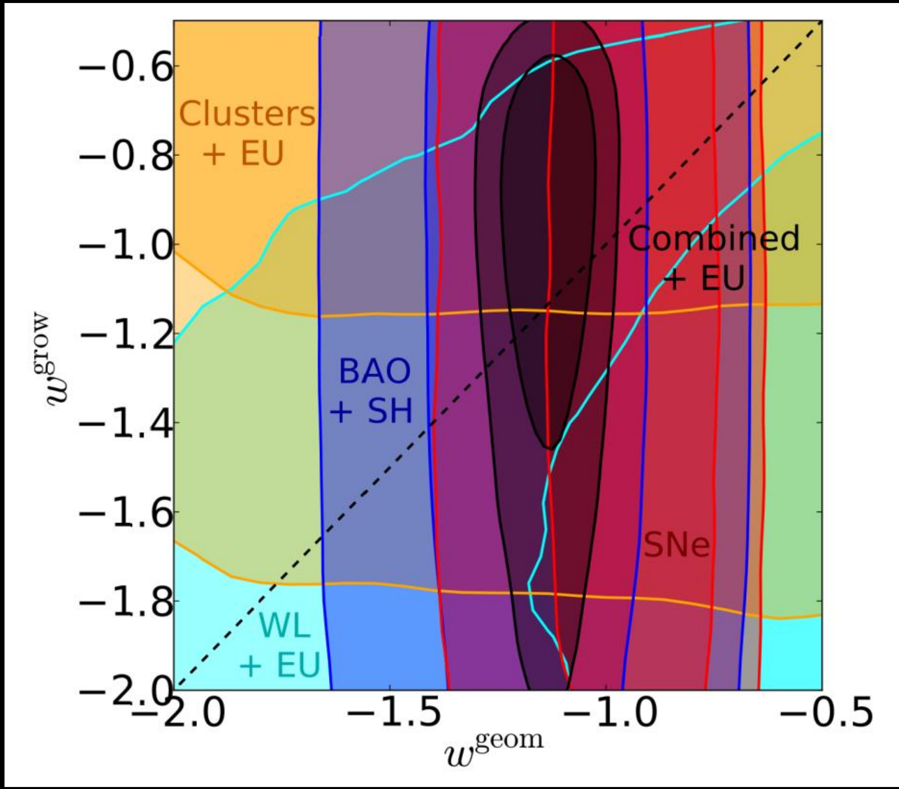
Consistent with vacuum energy (Λ): $w_0=-1$, $w_a=0$

Complementarity of probes

Probe	Geometry	Growth
SNe Ia	$D_L(z)$	---
BAO	$(D_A^2(z)/H(z))^{1/3}$	---
CMB peak location	$D_A(z \approx 1100)$	---
Cluster counts	dV/dz	dn/dM
Weak lensing 2pt	$r^2(z)/H(z)$	$P(k)$
RSD	$F(z)=D_A(z)H(z)$	$f(z)\sigma_8$

Consistency(?) between geometry and growth measures





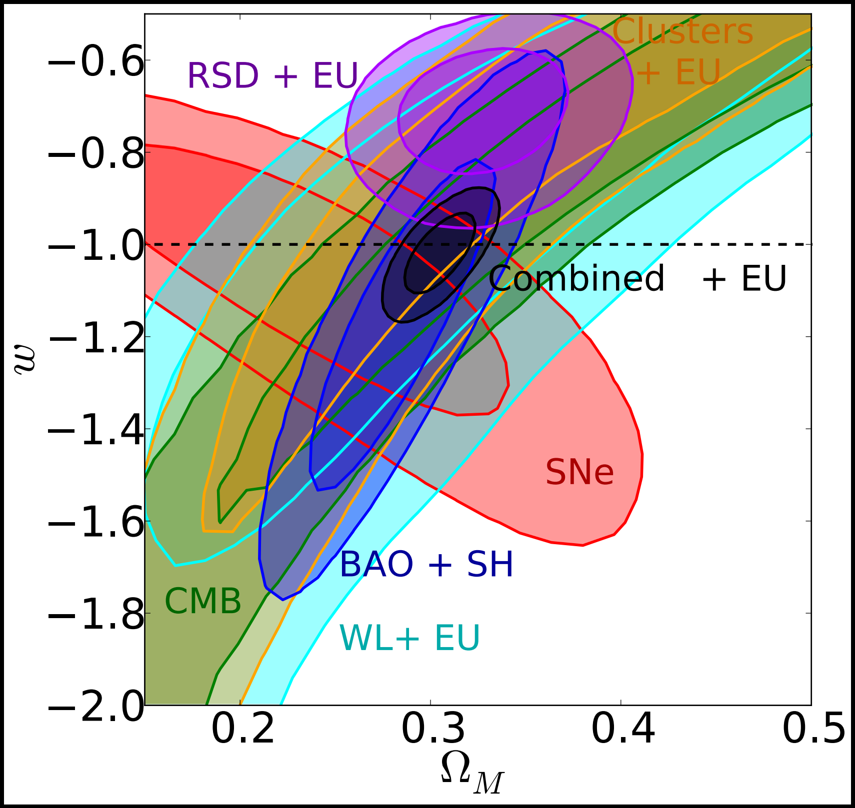
$$\mathrm{W}_M^{geom} = 0.307 \pm 0.008$$
$$\mathrm{W}_M^{growth} = 0.315 \pm 0.019$$
assuming $w = -1$

$$w^{geom} = -1.10 \pm 0.06$$
$$w^{growth} = -0.72 \pm 0.08$$

Ruiz & Huterer, 2014

Putting it all together

- A remarkably consistent picture emerges!
- RSD measurements in tension with others… systematics?
- SNe, CMB, BAO now very well established
- RSD, lensing, and clusters under development



Complementarity between probes with different systematics bodes well for future multi-probe surveys.

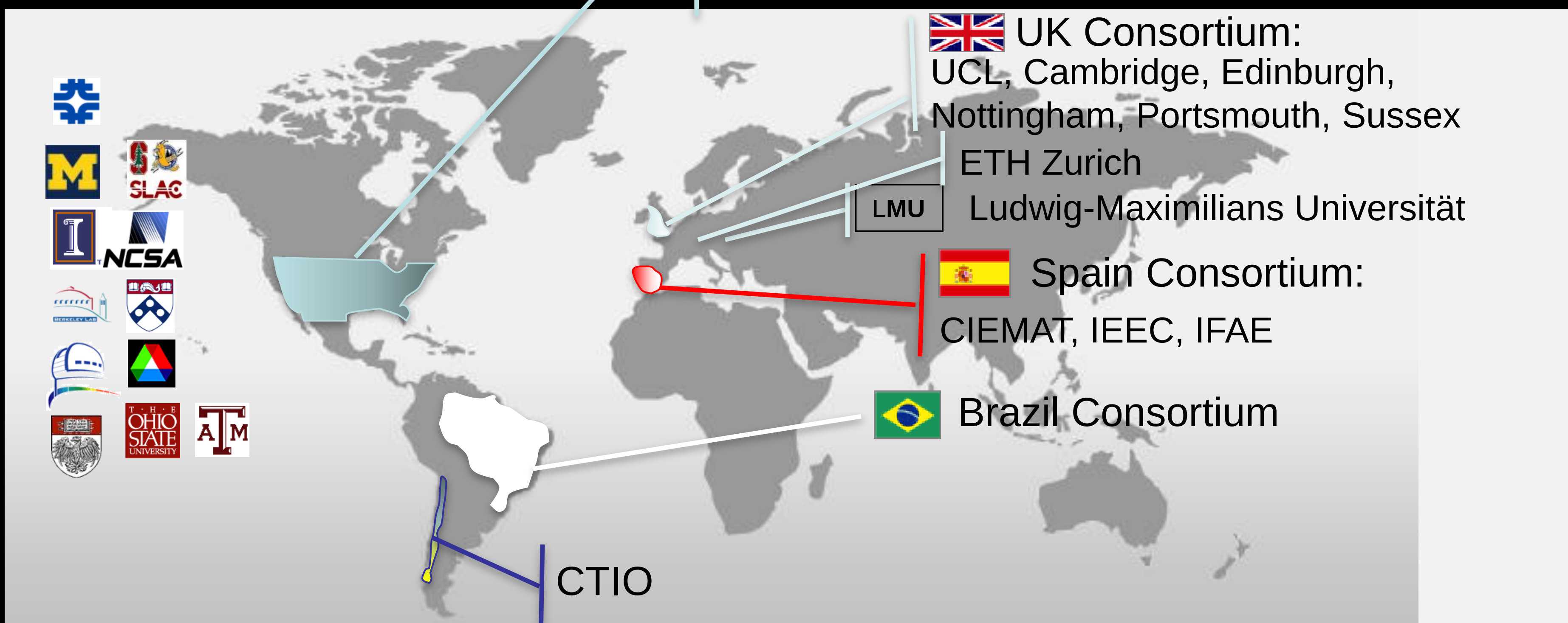
Cerro Tololo Inter-American Observatory

- Excellent astronomical site in Chilean Andes:
  - good seeing: ~0.75” median for site
  - high, dry: high percentage of clear, photometric nights
- Late 2003: NOAO Announcement of Opportunity for new facility instrument on the Blanco 4-meter telescope
- DES collaboration formed to build Dark Energy Camera and carry out Dark Energy Survey

Dark Energy Survey Collaboration

~300 scientists
US support from DOE+NSF

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M



The Dark Energy Survey

- Probe Dark Energy and the origin of Cosmic Acceleration:
  - Distance vs. redshift
  - Growth of Structure
- Two multicolor surveys:

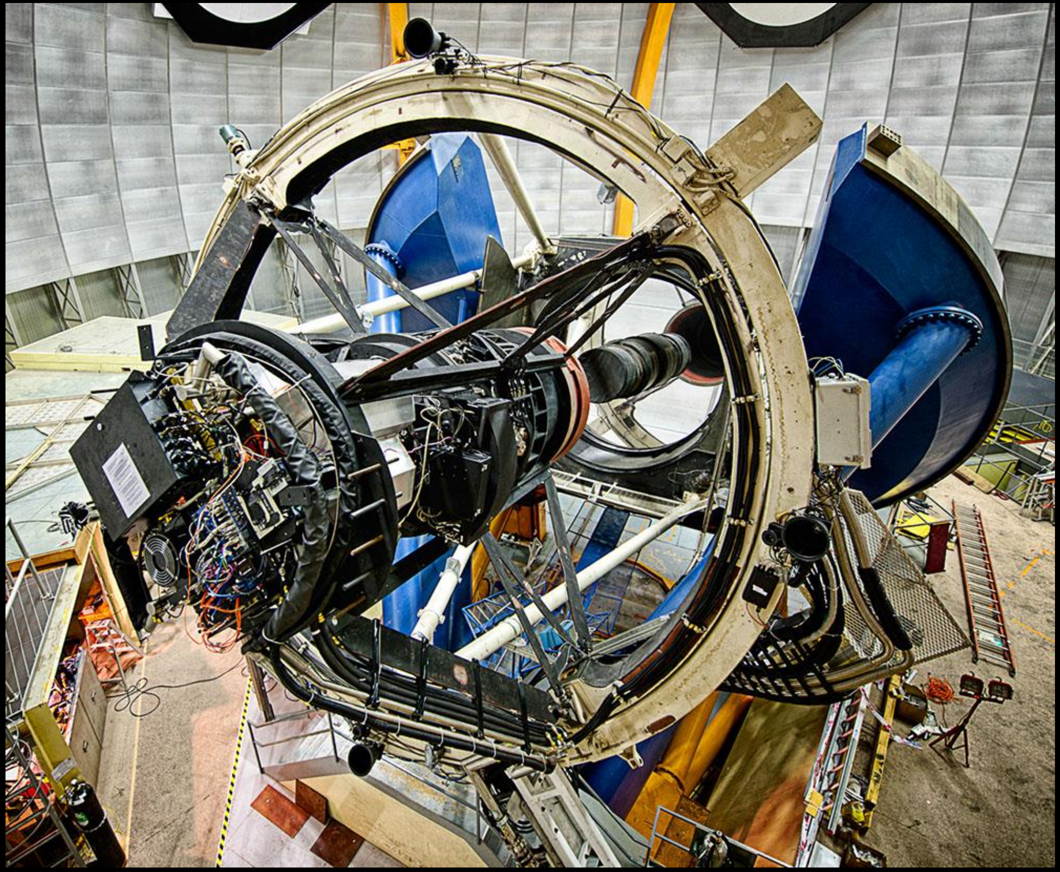
  300 M galaxies over 1/8 sky

  3500 supernovae (30 sq deg)
- Built new camera for CTIO Blanco telescope

  Facility instrument
- Five-year Survey started Aug. 31, 2013

  525 nights (Aug.-Feb.)

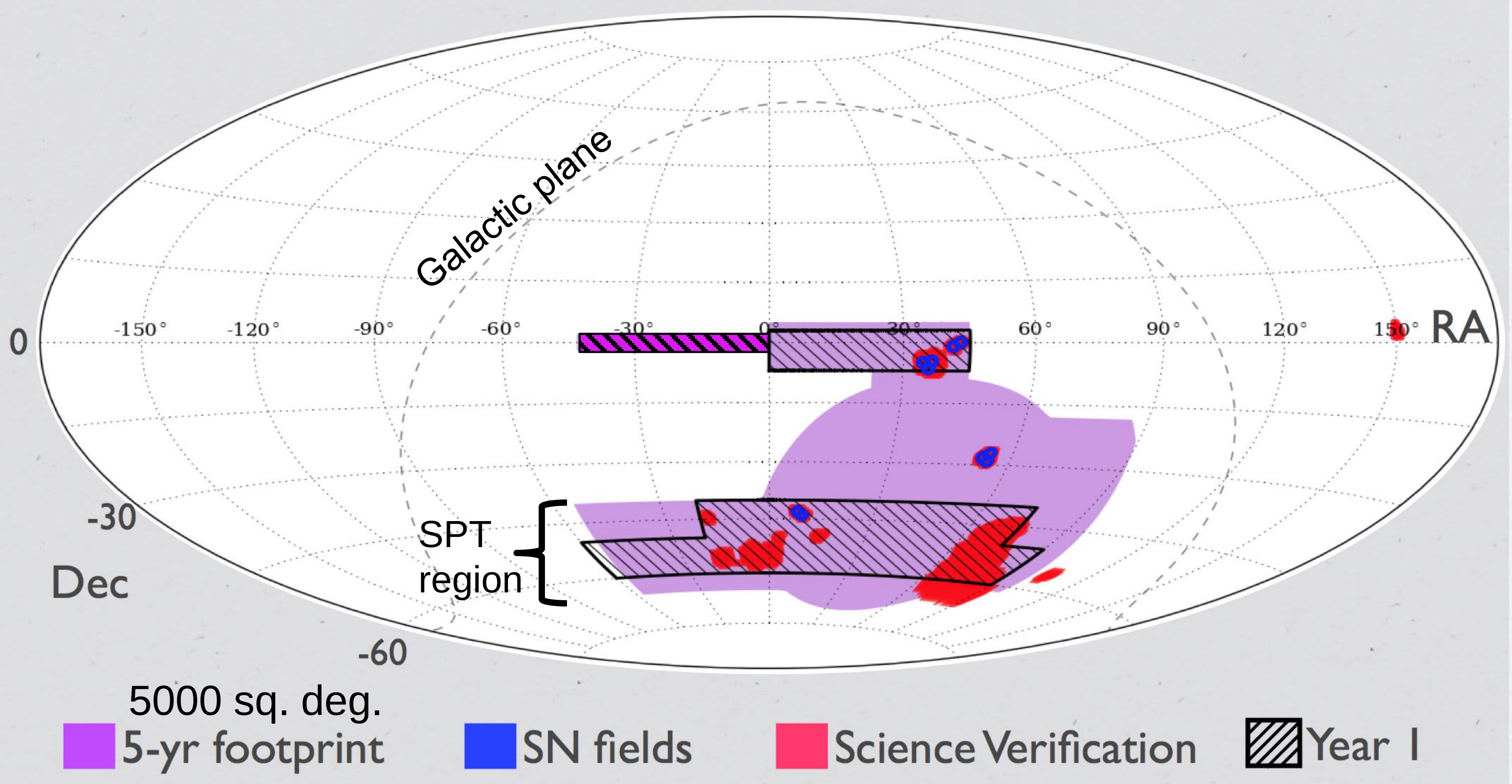
DECam on the Blanco 4m



www.darkenergysurvey.org

www.darkenergydetectives.org

DES Survey Footprint



- Science Verification: ~250 sq. deg. to ~full depth; 45 M objects
- Year 1: ~2000 sq. deg. overlap SPT, SDSS: 4/10 tilings; 140 M objects

Early Image taken with the Dark Energy Camera

DARK ENERGY SURVEY

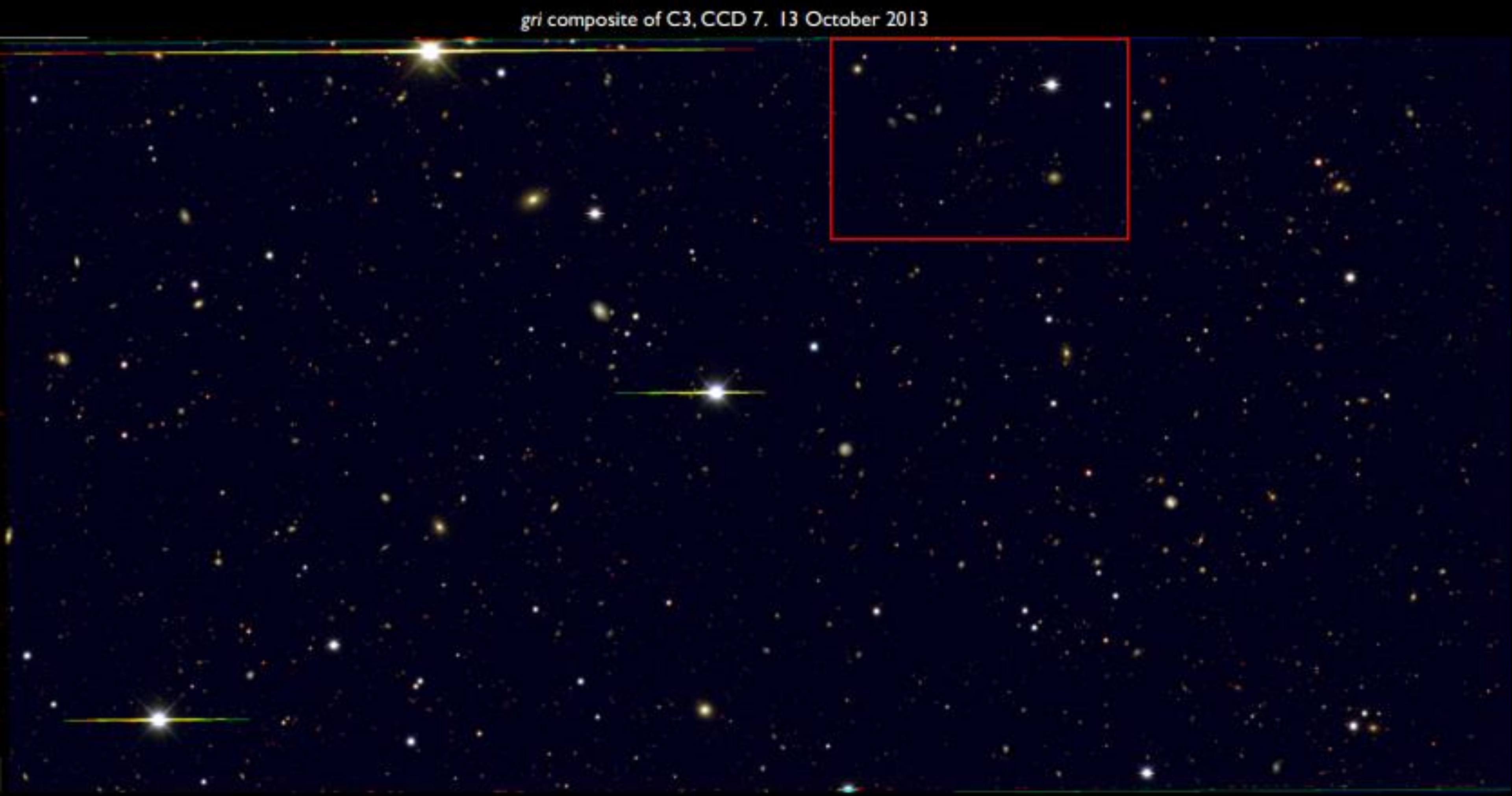
DES SV image of a deep SN field

Focal plane: 62 2k x 4k deep-depleted red-sensitive CCDs (LBNL)

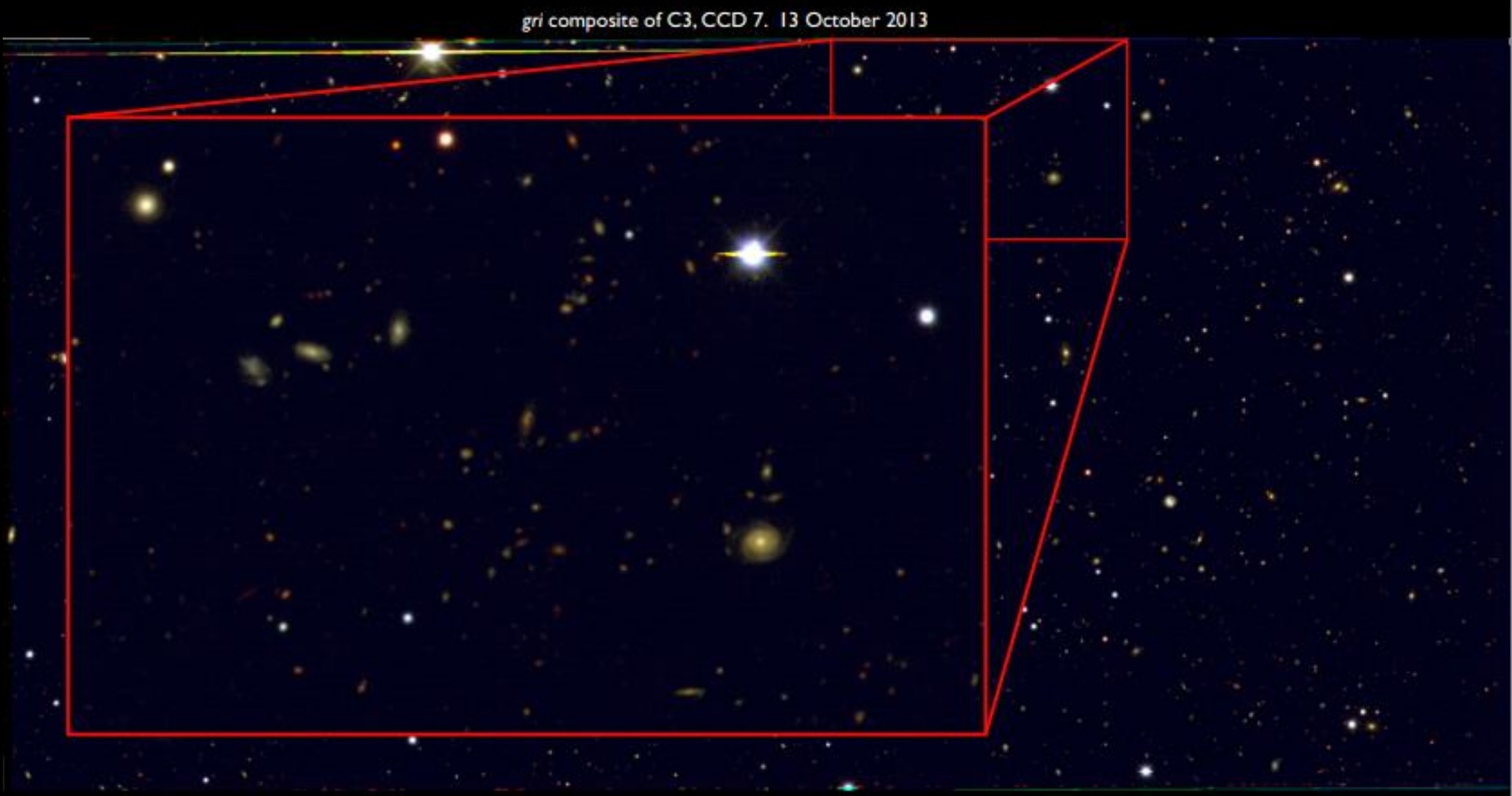
Supernova DES13C3hwb, SN-Ia at z=0.606

gri composite of C3, CCD 7. 13 October 2013

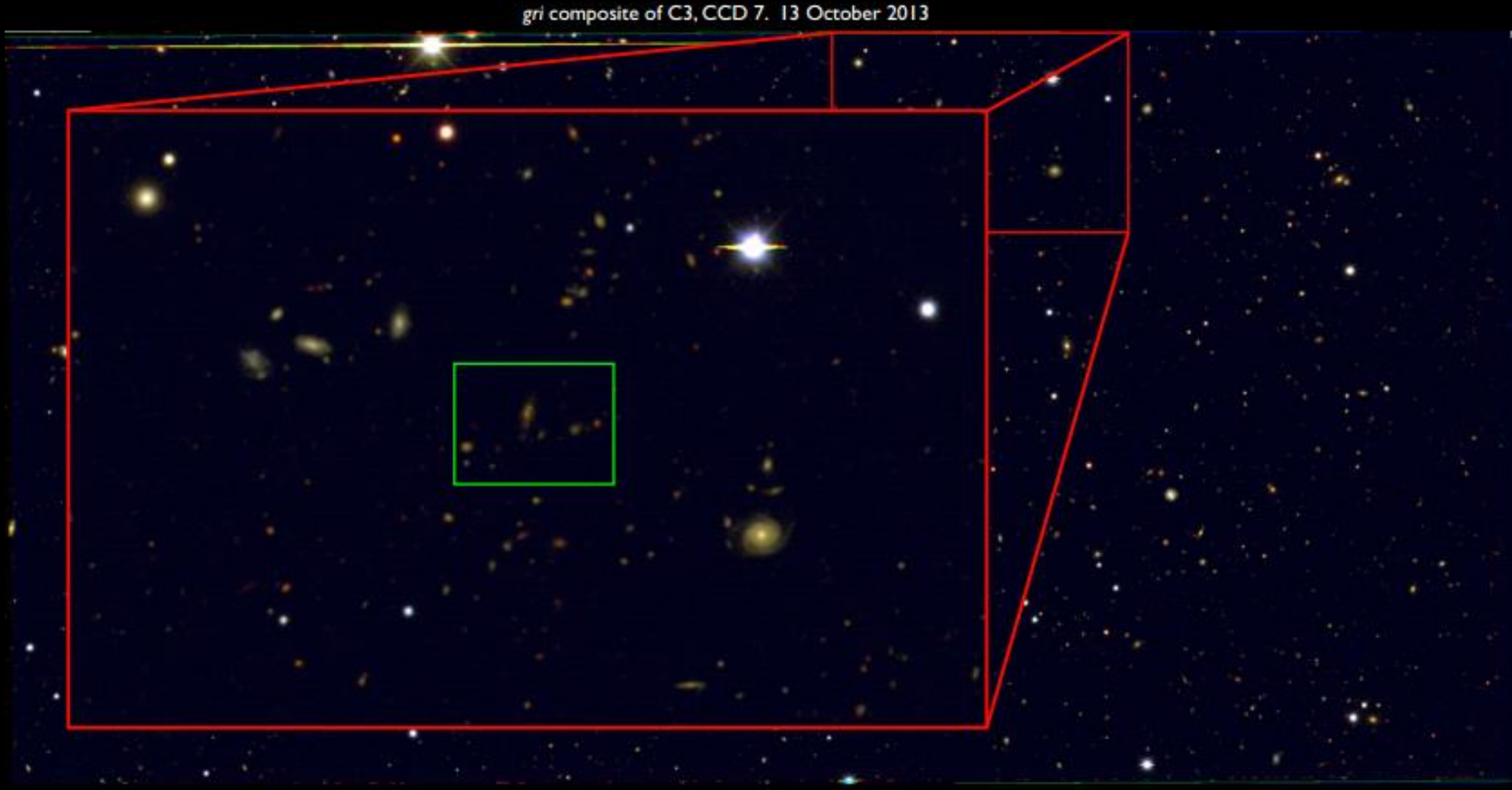
Supernova DES13C3hwb, SN-Ia at z=0.606



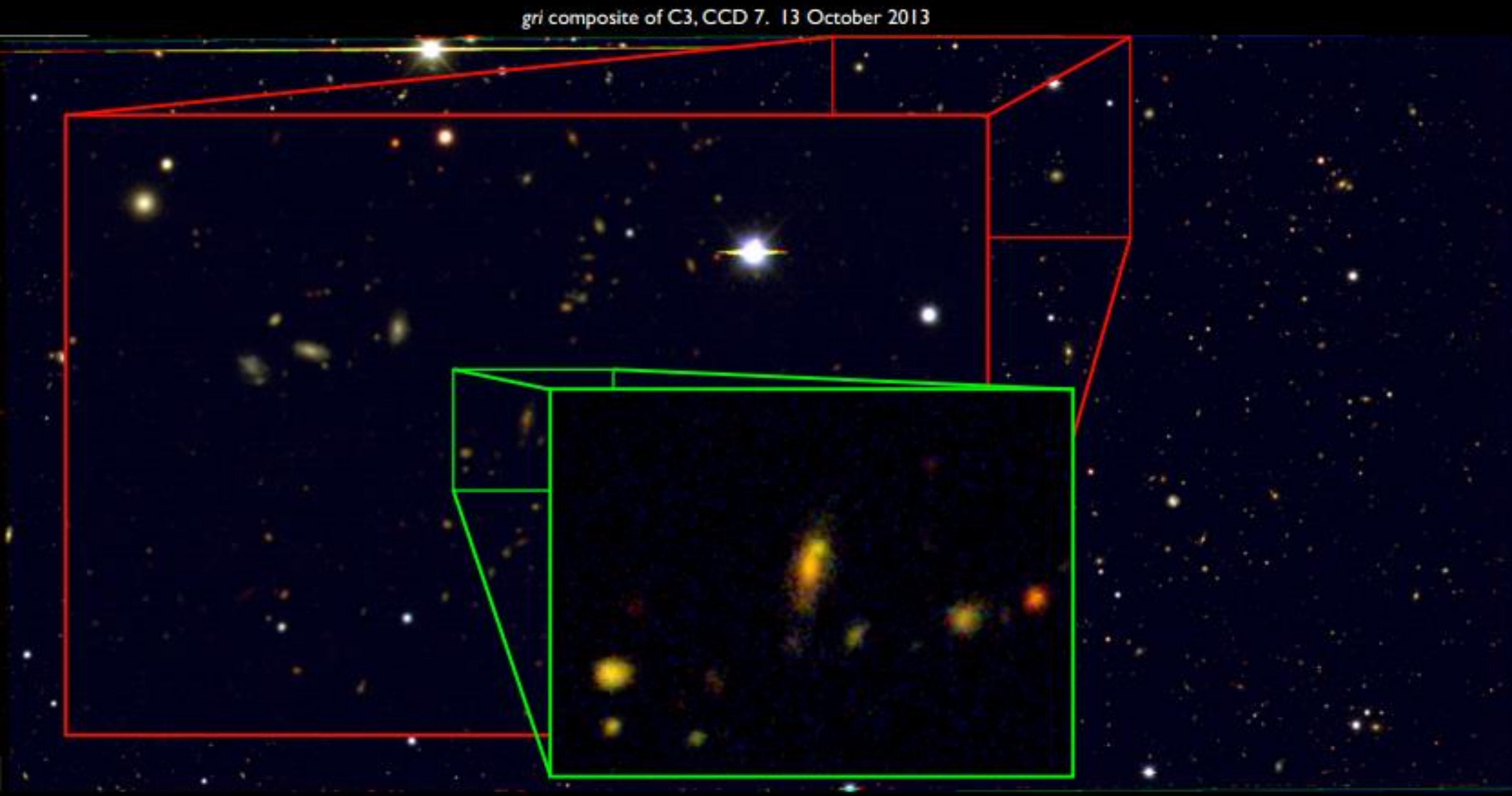
Supernova DES13C3hwb, SN-Ia at z=0.606



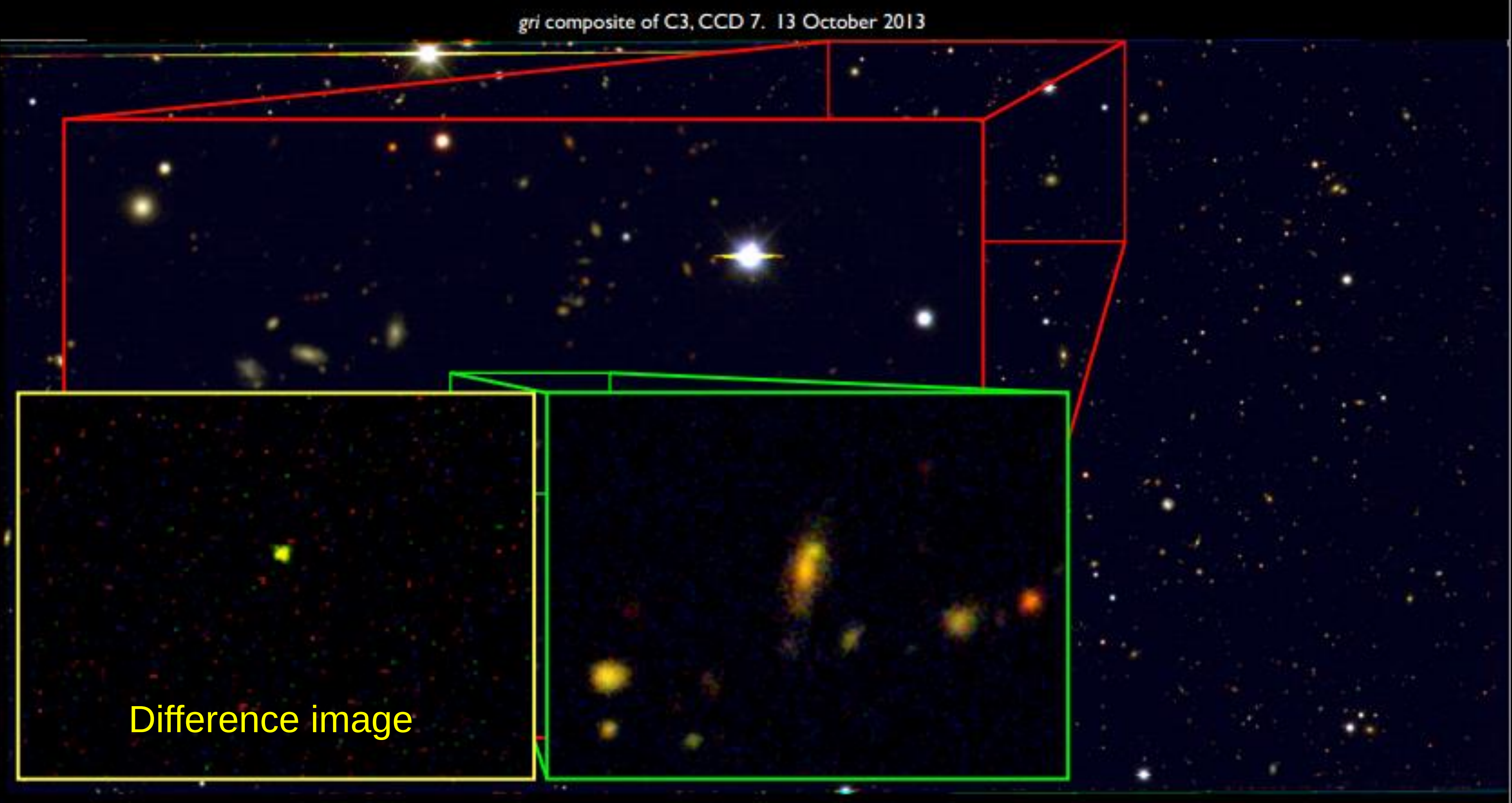
Supernova DES13C3hwb, SN-Ia at z=0.606



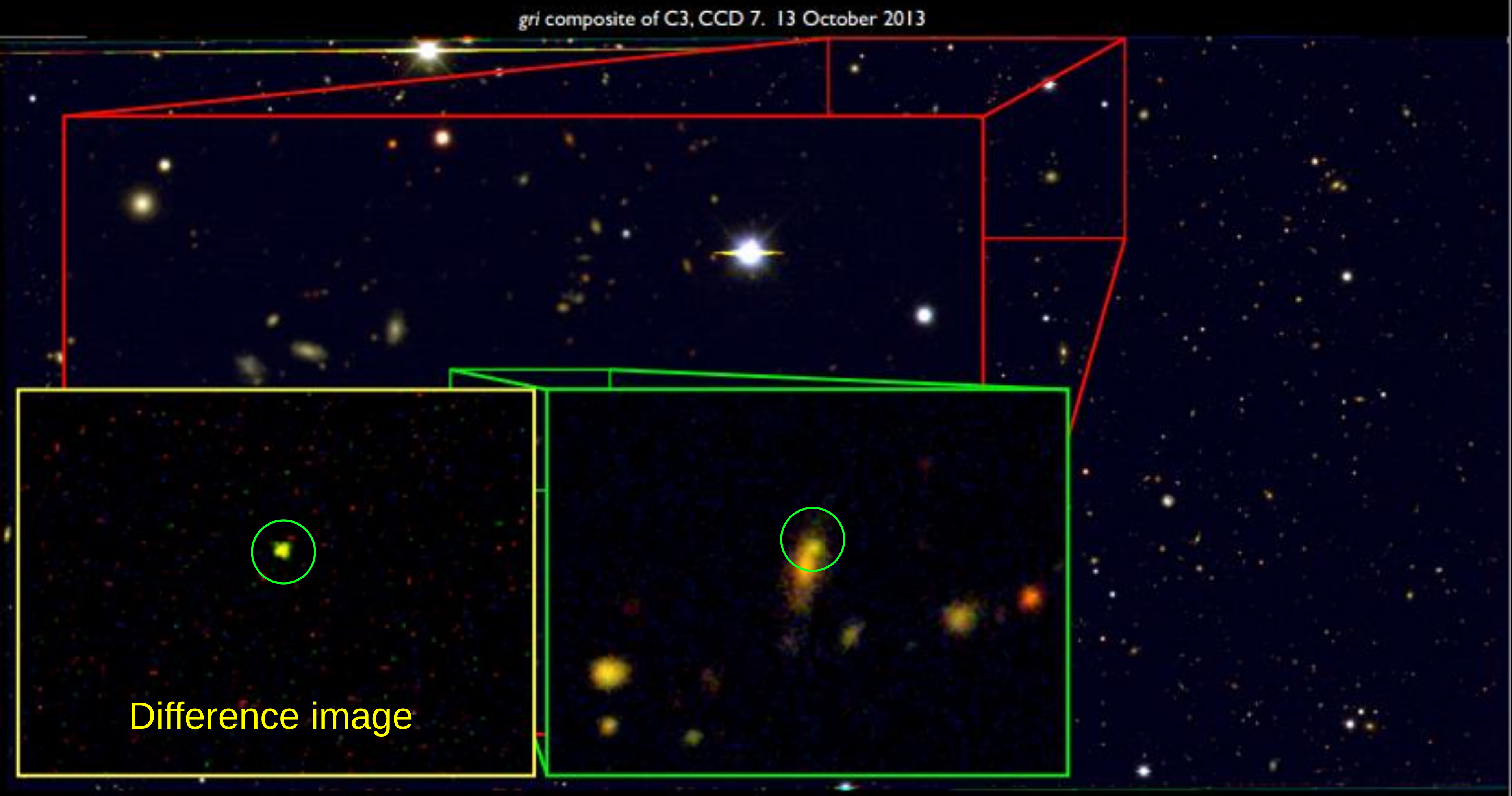
Supernova DES13C3hwb, SN-Ia at z=0.606



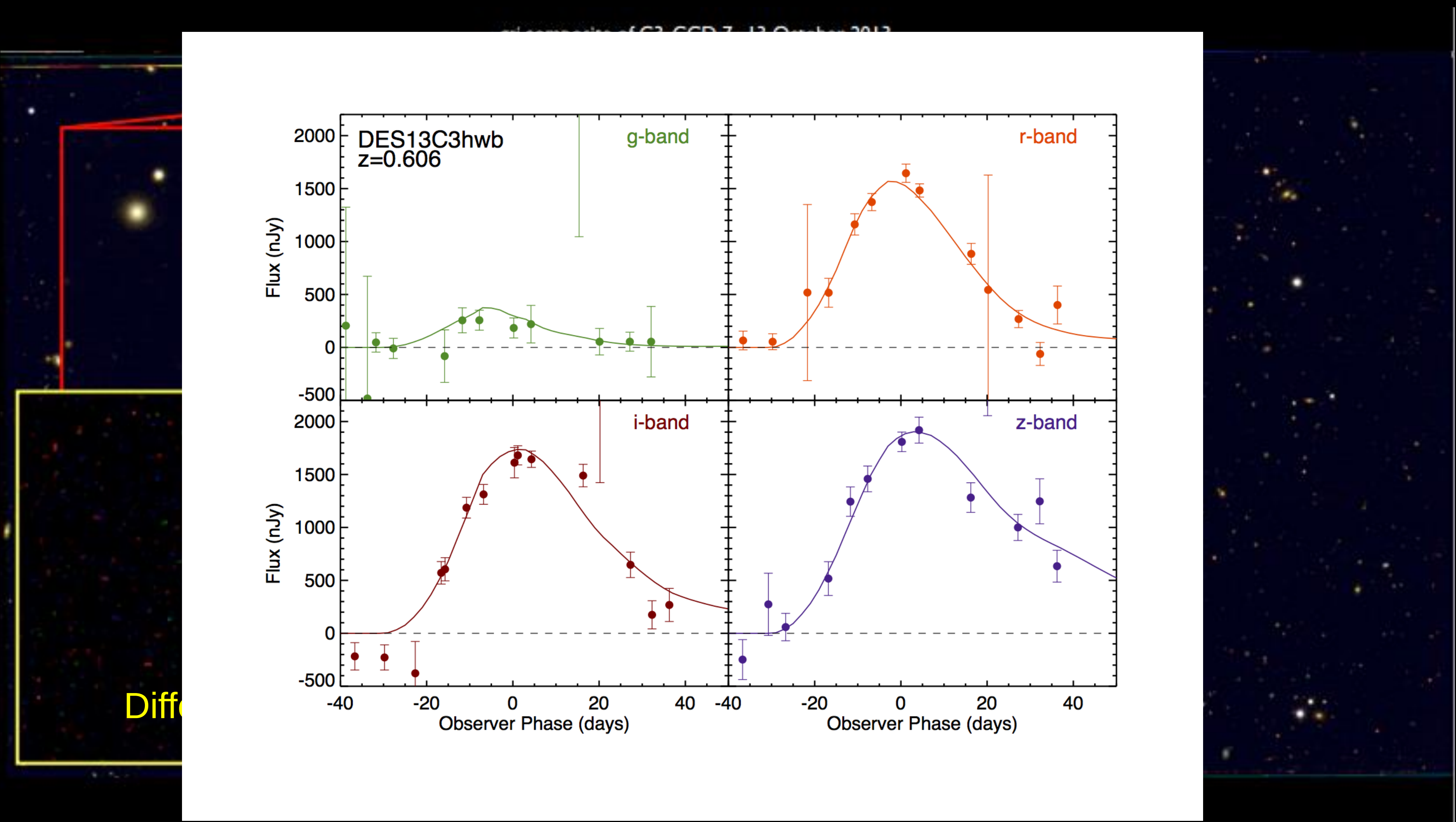
Supernova DES13C3hwb, SN-Ia at z=0.606



Supernova DES13C3hwb, SN-Ia at z=0.606



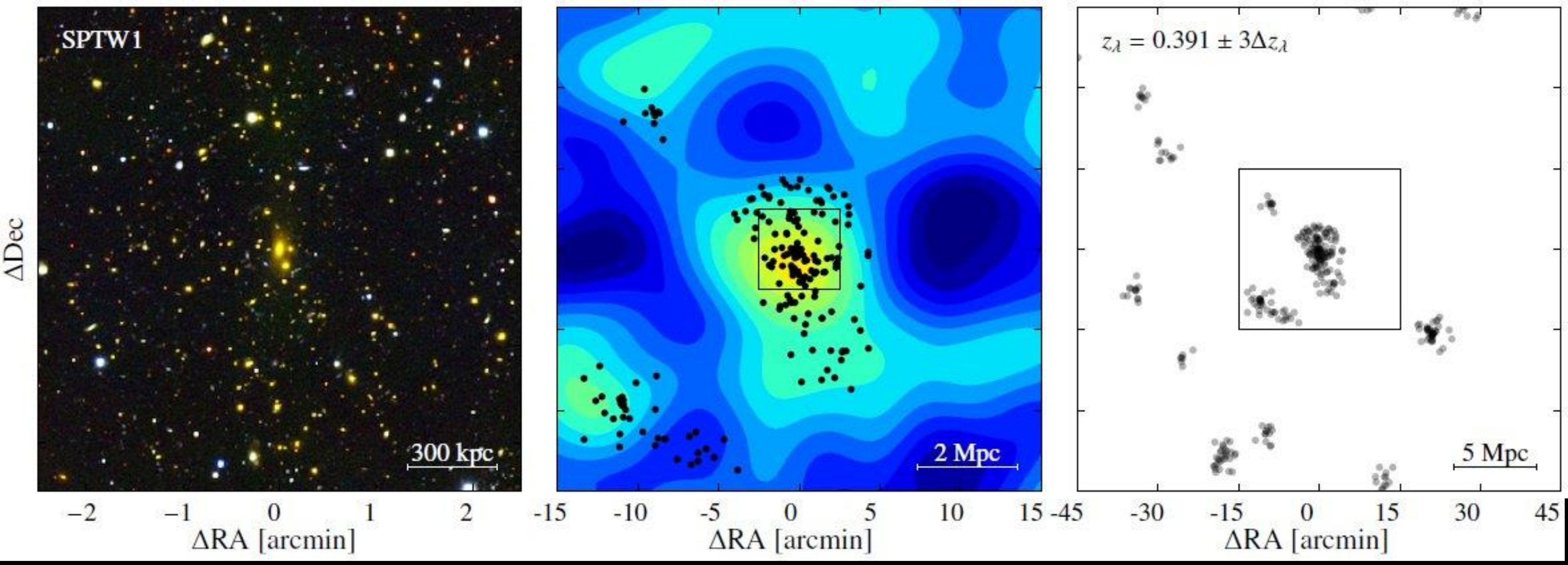
Supernova DES13C3hwb, SN-Ia at z=0.606



Individual Cluster Masses

arXiv:1405.4285

4 known massive clusters at z ~ 0.2–0.4. One example:



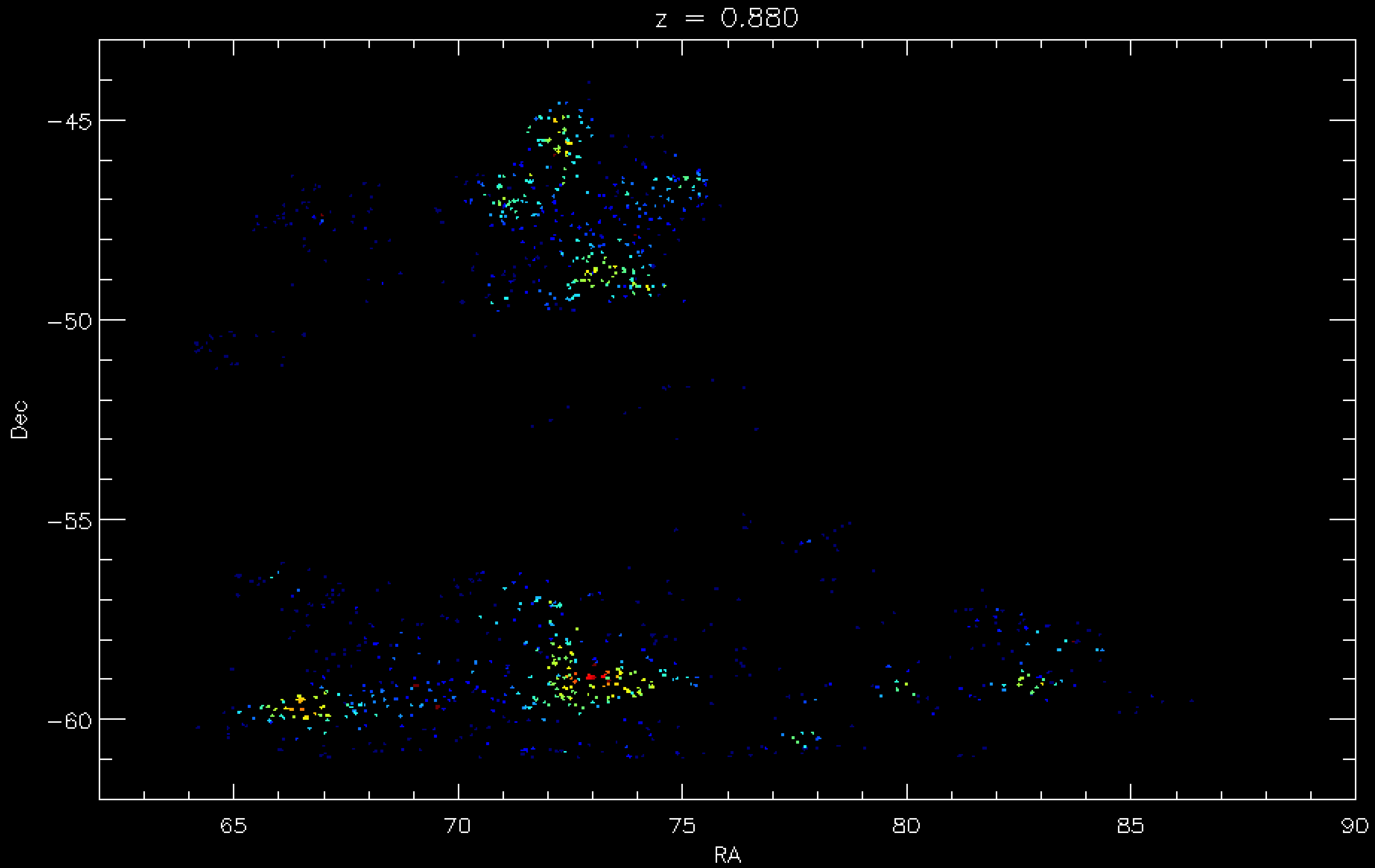
Multi-color image (inner 5″)

Weak lensing mass significance map overlaid with galaxies
WL aperture (inner 30″)

Same galaxies, entire useable FoV (90″)

DES Galaxy Clusters (new clusters at high redshift (z > 0.7)

redMaPPer clusters in DES SV (Plot courtesy of Eli Rykoff)

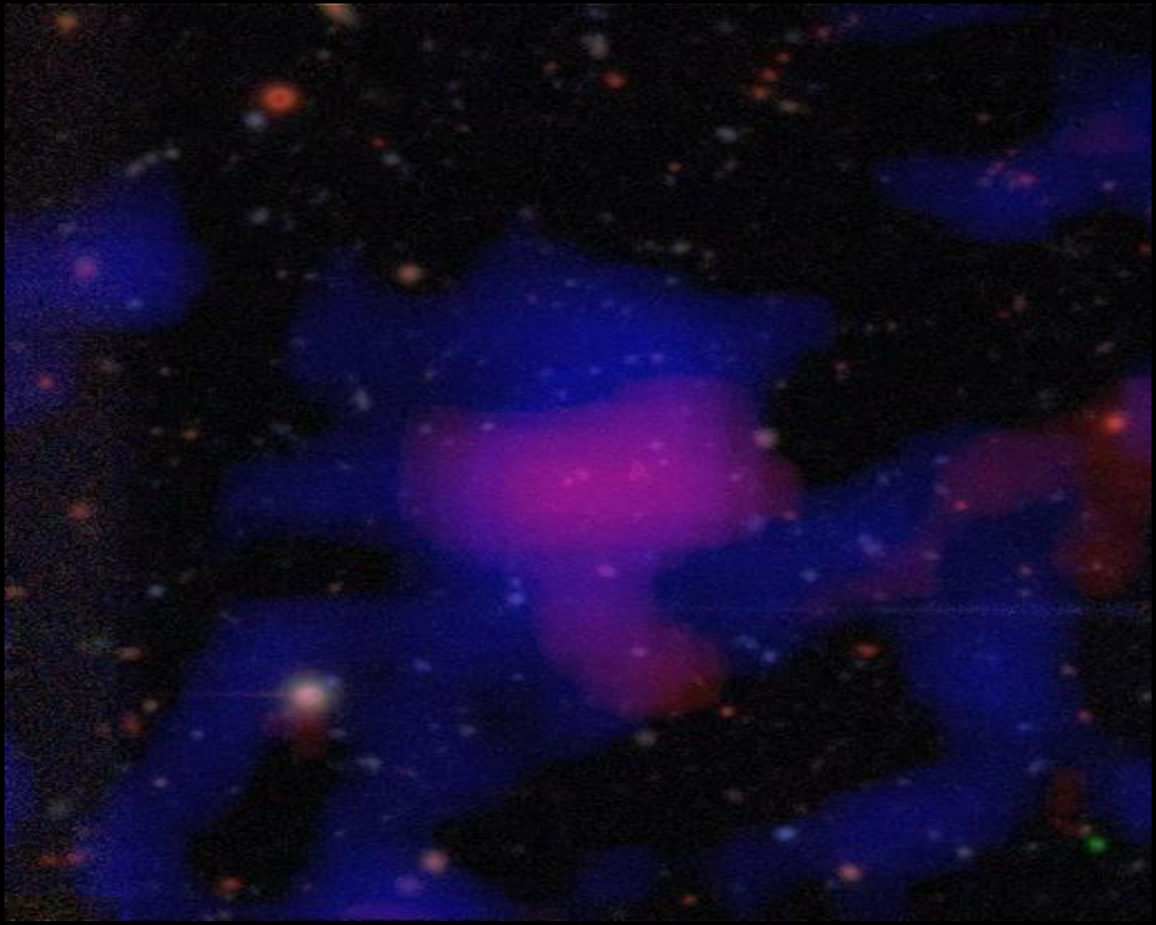


Movie courtesy of Eli Rykoff and RedMaPPer team

Local density encoded in color: high density low density

X-ray + Optical Clusters

- 120 X-ray clusters confirmed by DES-SV data (Movie courtesy of Kathy Romer)
- XMM data **pink**/**blue** (Phil Rooney)

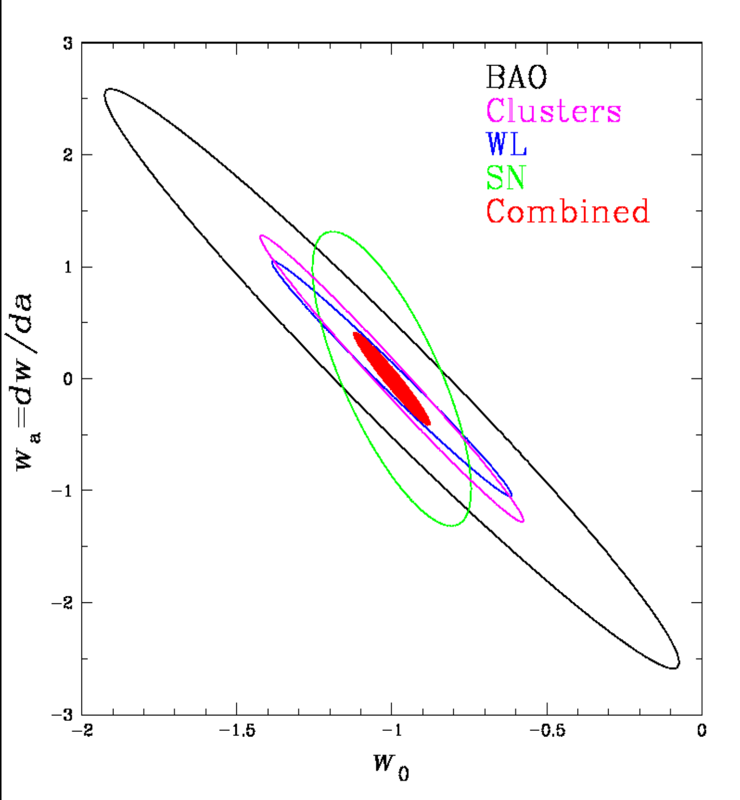


DES Science Summary

DARK ENERGY SURVEY

Forecast Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t))$$



DES forecast

Four Probes of Dark Energy

- Galaxy Clusters
  - Tens of thousands of clusters to z~1
  - Synergy with SPT, VHS
- Weak Lensing
  - Shape and magnification measurements of 200 million galaxies
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
- Supernovae
  - 30 sq deg time-domain survey
  - 3500 well-sampled SNe Ia to z ~1

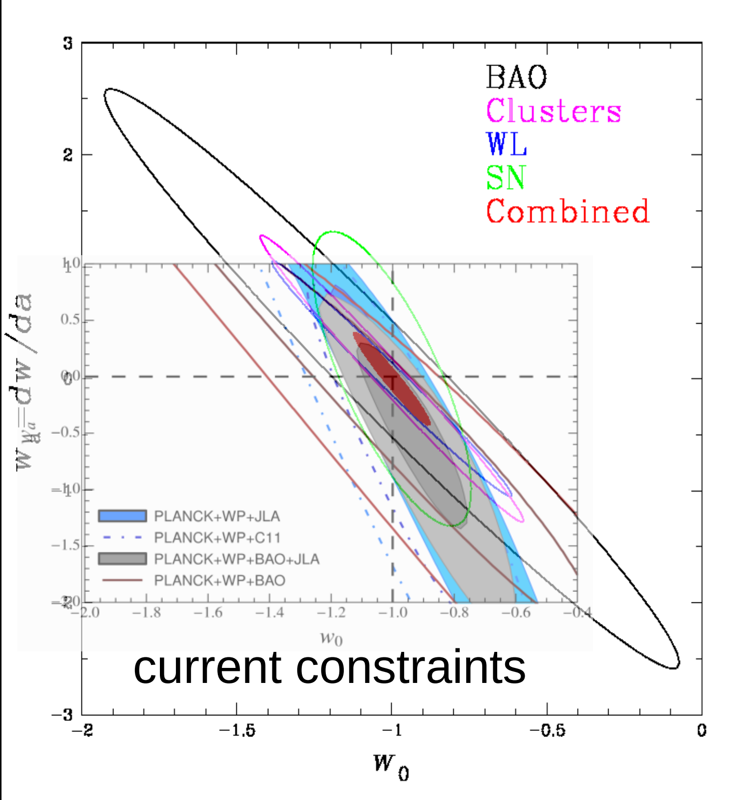
DES Science Summary

Four Probes of Dark Energy

- Galaxy Clusters
  - Tens of thousands of clusters to z~1
  - Synergy with SPT, VHS
- Weak Lensing
  - Shape and magnification measurements of 200 million galaxies
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
- Supernovae
  - 30 sq deg time-domain survey
  - 3500 well-sampled SNe Ia to z ~1

Forecast Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t))$$



DES forecast

DES in the Service of Humanity

Subject: urgent request for DDT observations of a near-Earth object candidate
Date: Mon, 3 Feb 2014 19:03:07 +0000
From: Mainzer, Amy (3266) <Amy.Mainzer@jpl.nasa.gov>
To: director@ctio.noao.edu <director@ctio.noao.edu>

Dear Dr Silva,

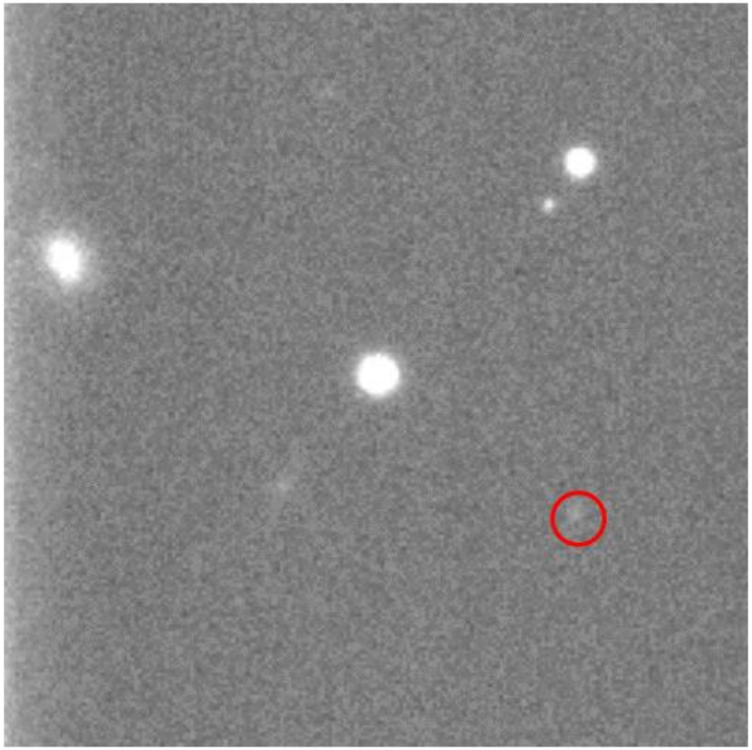
I am writing you today to request a set of Director's Discretionary Time ToO images from CTIO/ DECam for a critical near-Earth object that has been recently discovered by NEOWISE that may be on a potentially hazardous orbit. However, no other ground-based surveys have been able to recover the object due to bad weather. This object is currently moving to lower solar elongations and thus will soon be lost without immediate followup. Additionally, the uncertainty region for the position of this object currently spans nearly 1 deg in RA. The expected magnitude of this object is V=21-22, and it is currently moving at about 2" per minute.

Given the large uncertainty region, the object cannot feasibly be recovered with our Gemini DDT allocation – its astrometric uncertainty has now grown too large, unfortunately.

The object is currently in the evening sky, and sets shortly after the Sun, so observations will need to be taken in evening twilight (UT~1:30)

We are requesting a series of 5 thirty-second DECam exposures, centered on the uncertainty region. If the images are tiled to avoid chip gaps we should have sufficient coverage to get three astrometric measurements of this object. A map of the uncertainty region is attached.

Near-Earth Asteroid of **DOOM!**



Feb. 3, 2014

Turned out to miss us by 18 million miles, posing no threat to DES operations
(and no threat to planet Earth).

Conclusions

- Dark energy represents nearly ¾ of the universe, yet we have no real understanding of its nature.
- Multiple probes consistent with the ΛCDM “Standard Model of Cosmology”.
- Next steps: study the evolution of DE over cosmic time using multiple probes sensitive to geometry and growth.
- Dark Energy Survey is starting its second of five years and is performing beautifully.
- Stay tuned for exciting new results!

Thank you!