Dark Energy and WFIRST-AFTA

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Fermilab and the University of Chicago

Wide-field Infrared Surveys: Science & Techniques
Pasadena, Nov. 2014

Dark Energy Sessions

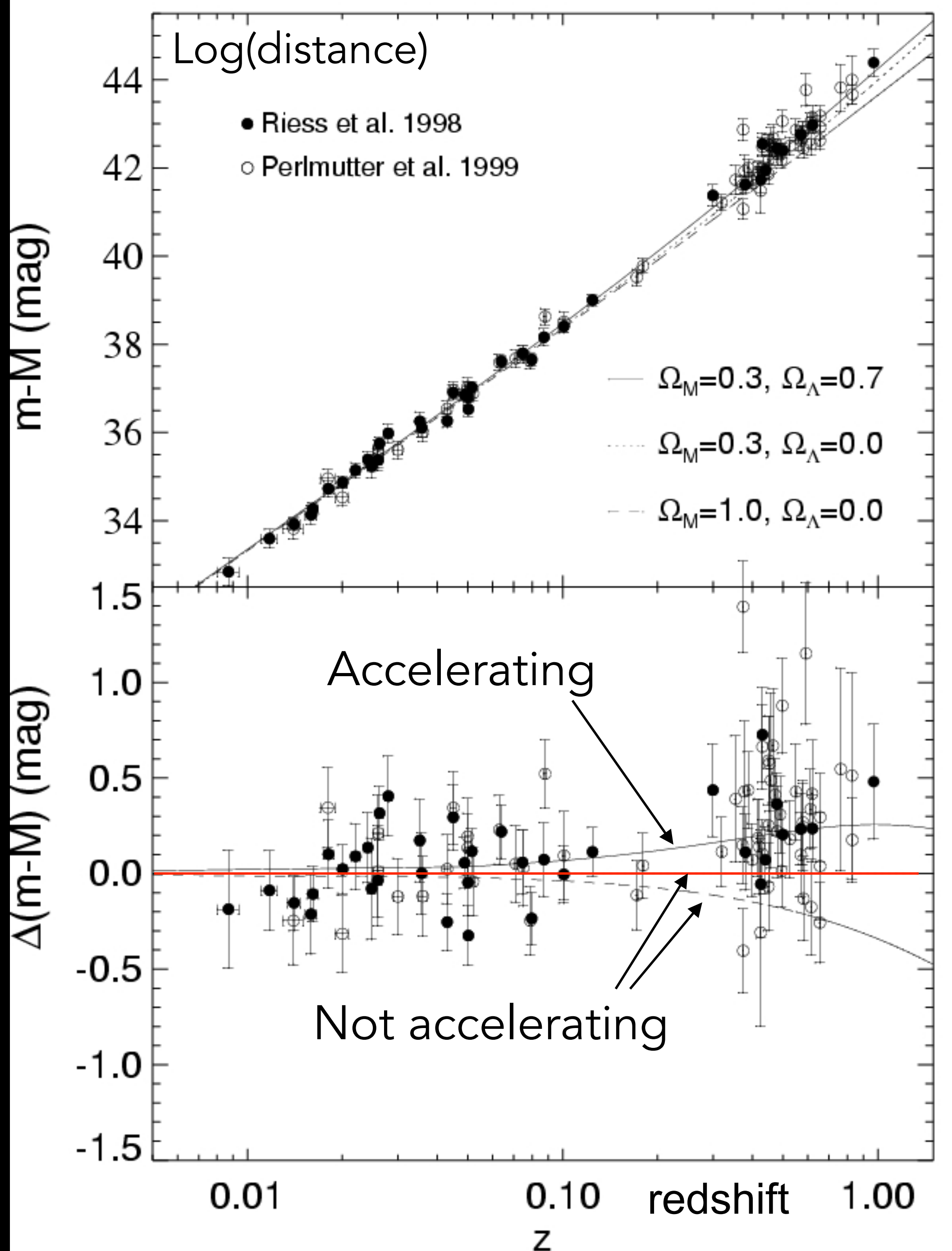
- Monday PM:
  - B. Jain: Dark Energy & Modified Gravity
  - S. Ho: Current constraints
  - D. Weinberg: BOSS results and WFIRST requirements
  - J. Newman: Photo-z Challenges & Synergies
  - M. Schneider: Joint image analysis of LSST & WFIRST
  - R. Bean: Weak Lensing
  - R. Kirshner: Type Ia Supernovae
  - N. Padmanabhan: Redshift Distortions and BAO
  - E. Krause: Combining DE Probes
  - H. Dole: High-redshift Clusters from Planck

Dark Energy Sessions

- Tuesday PM:
  - C. Hirata: WFIRST High-latitude survey
  - D. Scolnic: Simulating the WFIRST SN survey
  - C. Baltay: WFIRST SN survey
  - R. Foley: SNe and the WFIRST IFU
  - T. Eifler: Controlling WL systematics
  - M. Takada: SuMIRe
  - J. Rhodes: Euclid
  - A. Rettura: High-z clusters with Spitzer
  - A. Prakash: Optical/IR selection of LRGs
  - P. Eisenhardt: High-redshift Clusters from WISE

Discovery of Cosmic Acceleration from High-redshift Supernova Data

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

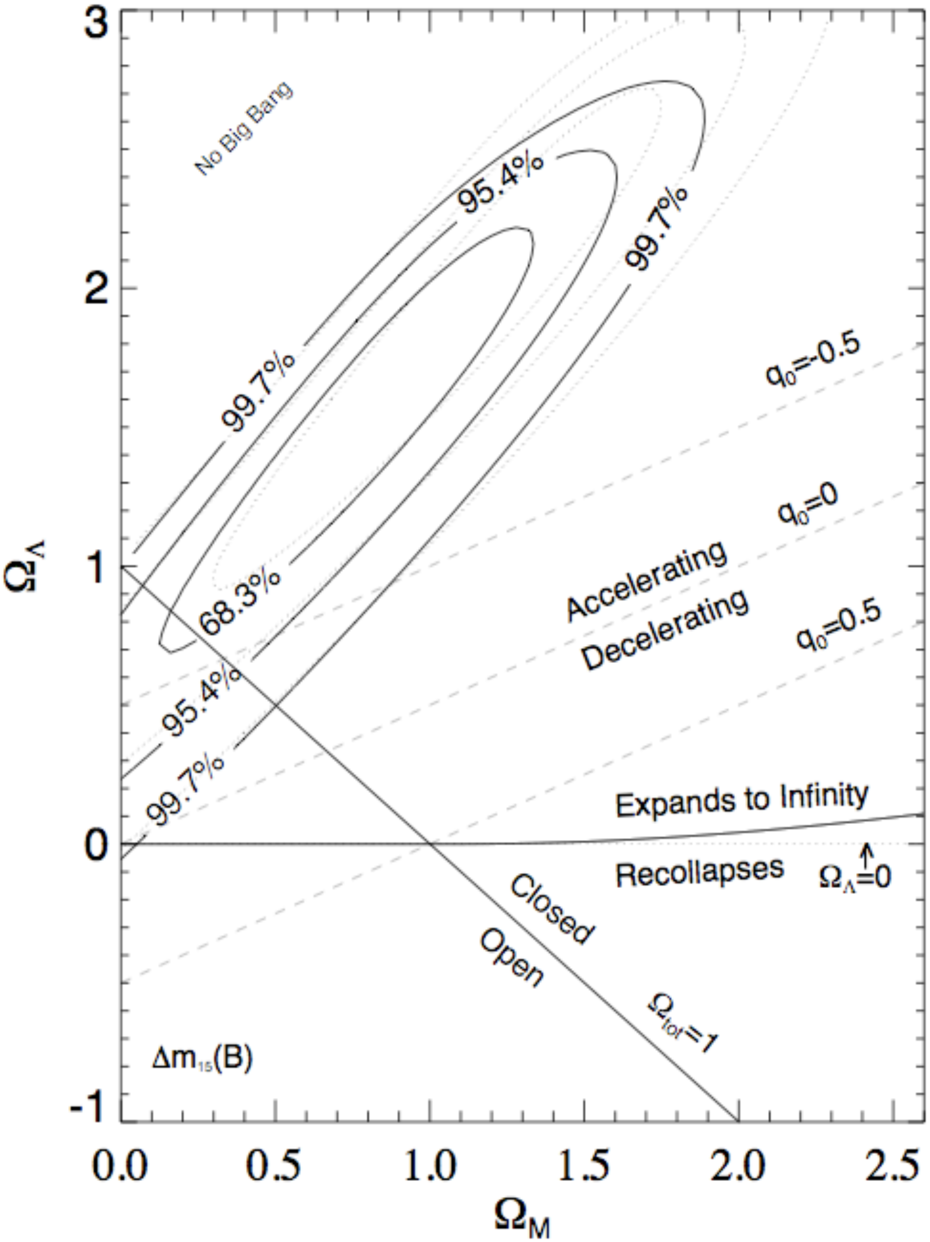


$\Omega_\Lambda = 0.7$

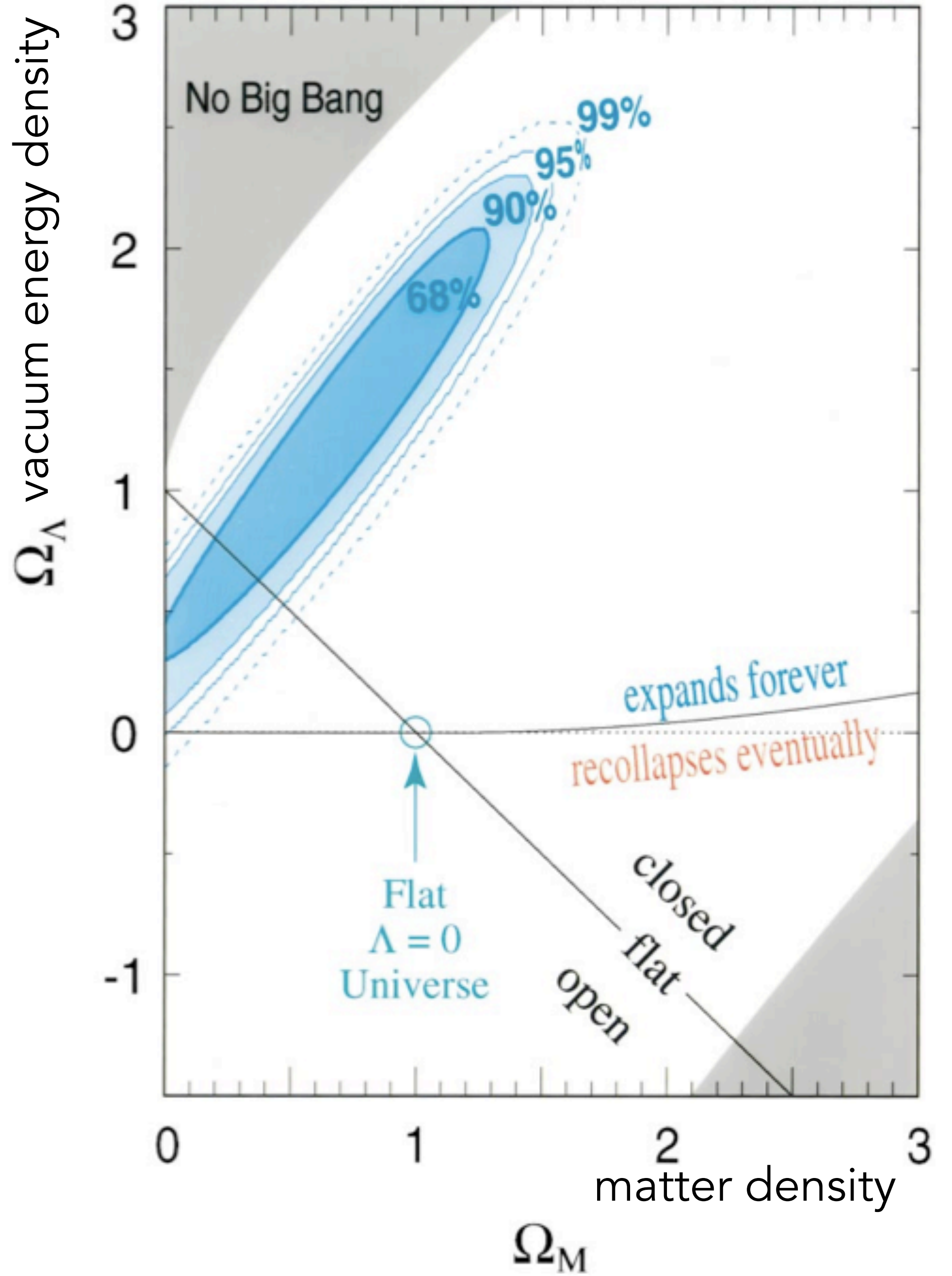
$\Omega_\Lambda = 0.$

$\Omega_m = 1.$

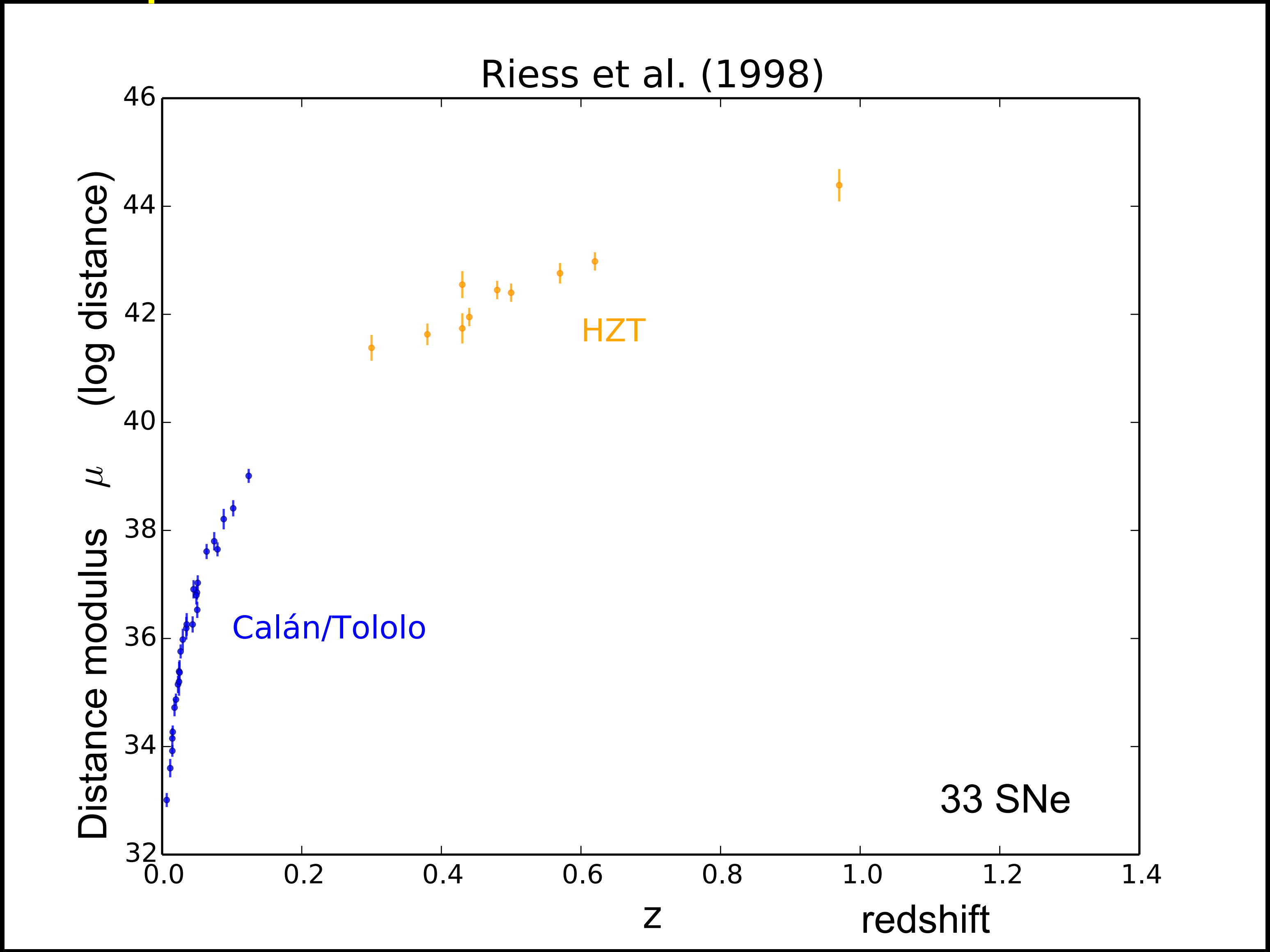
Riess et al. (1998, AJ)



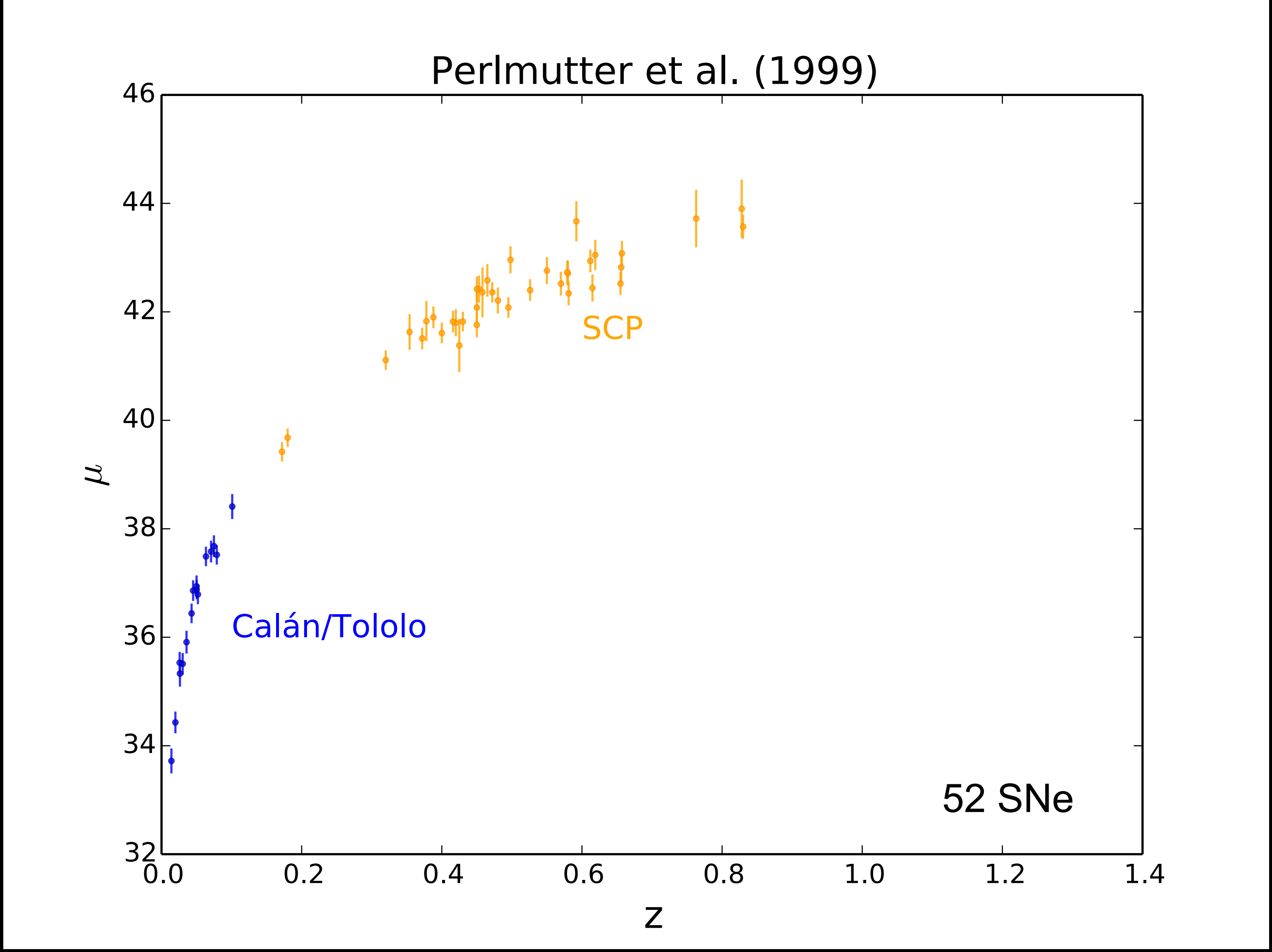
Perlmutter et al. (1999, ApJ)



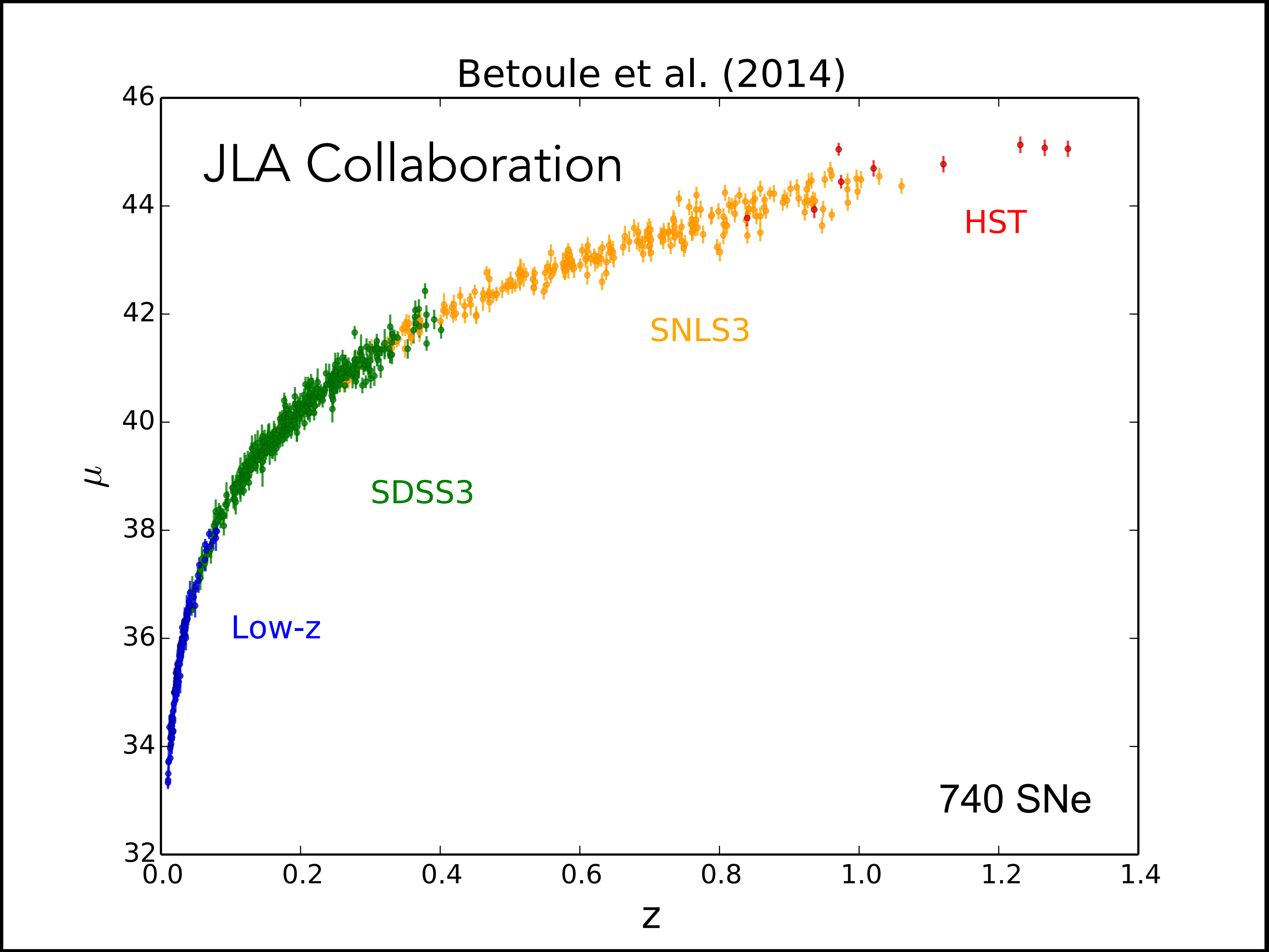
Supernova Ia Hubble Diagram



figures by A. Conley



Perlmutter et al. (1999)
46
44
42
40
38
36
34
32
μ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z
SCP
Calán/Tololo
52 SNe


Betoule et al. (2014)
JLA Collaboration
HST
SNLS3
SDSS3
Low-z
740 SNe
μ
z
46
44
42
40
38
36
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32
0.0
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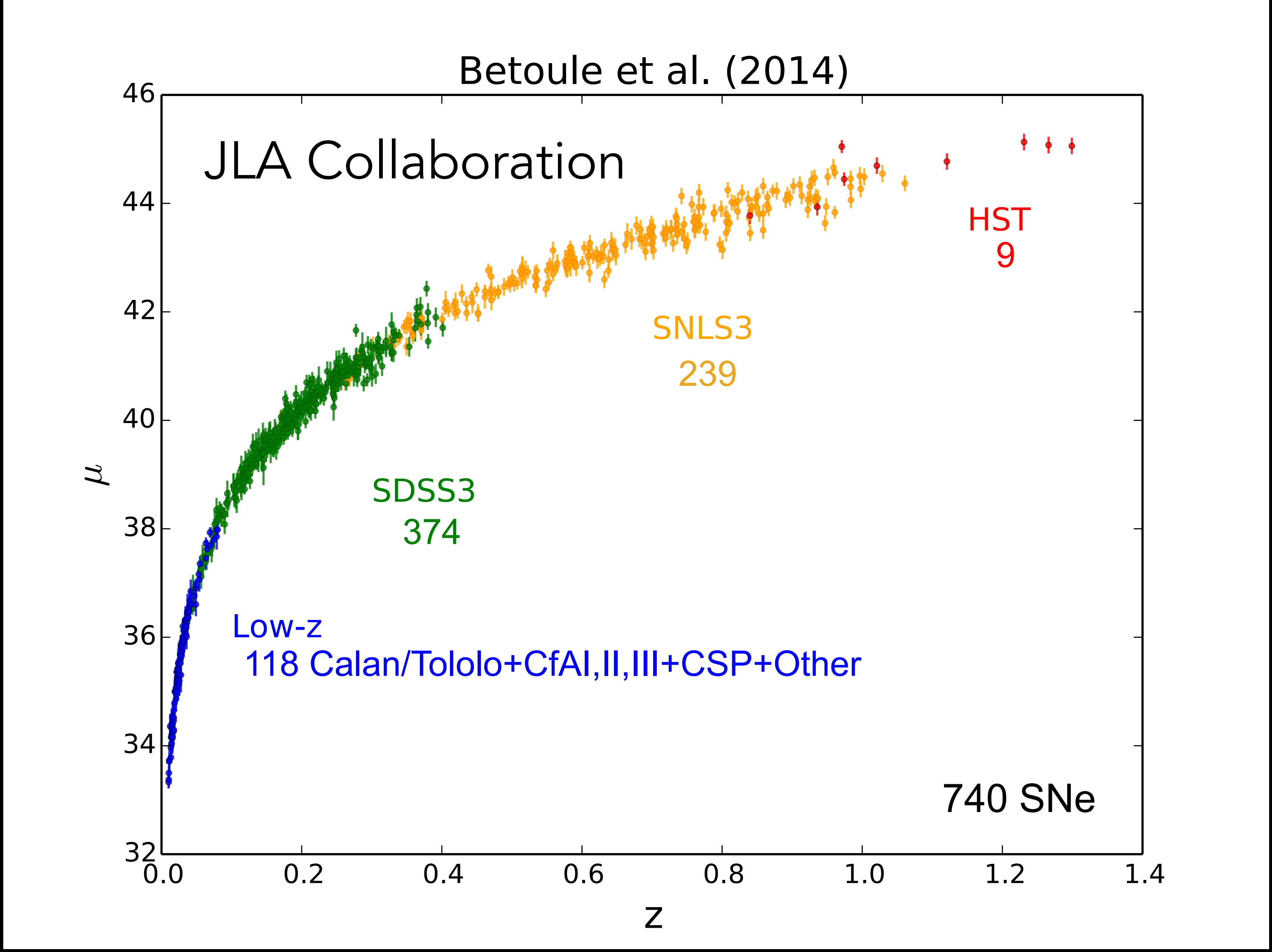
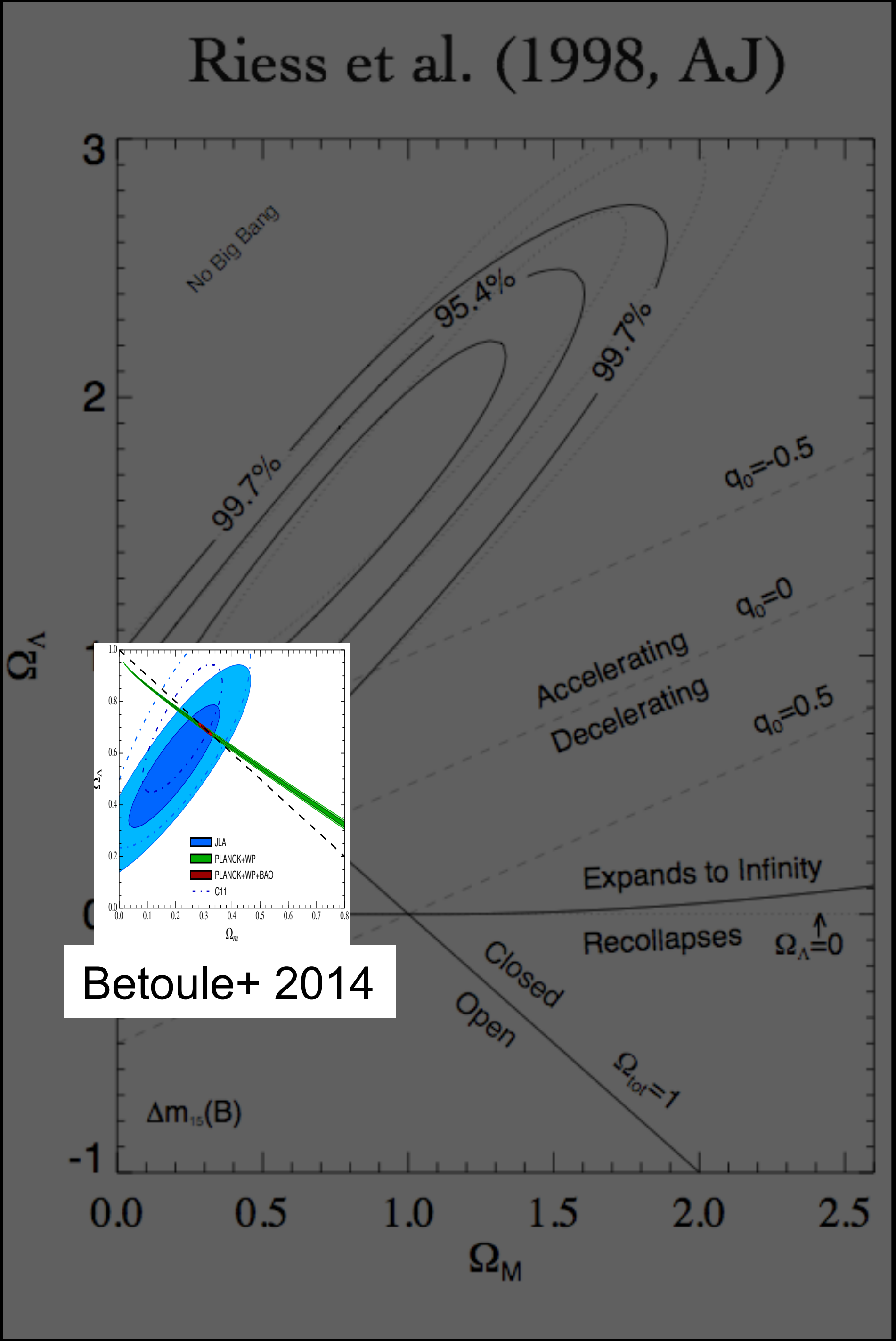
1.0
1.2
1.4



This is NOT a compilation of all SN Ia distance measurements

Progress over the last 16 years



Supernovae

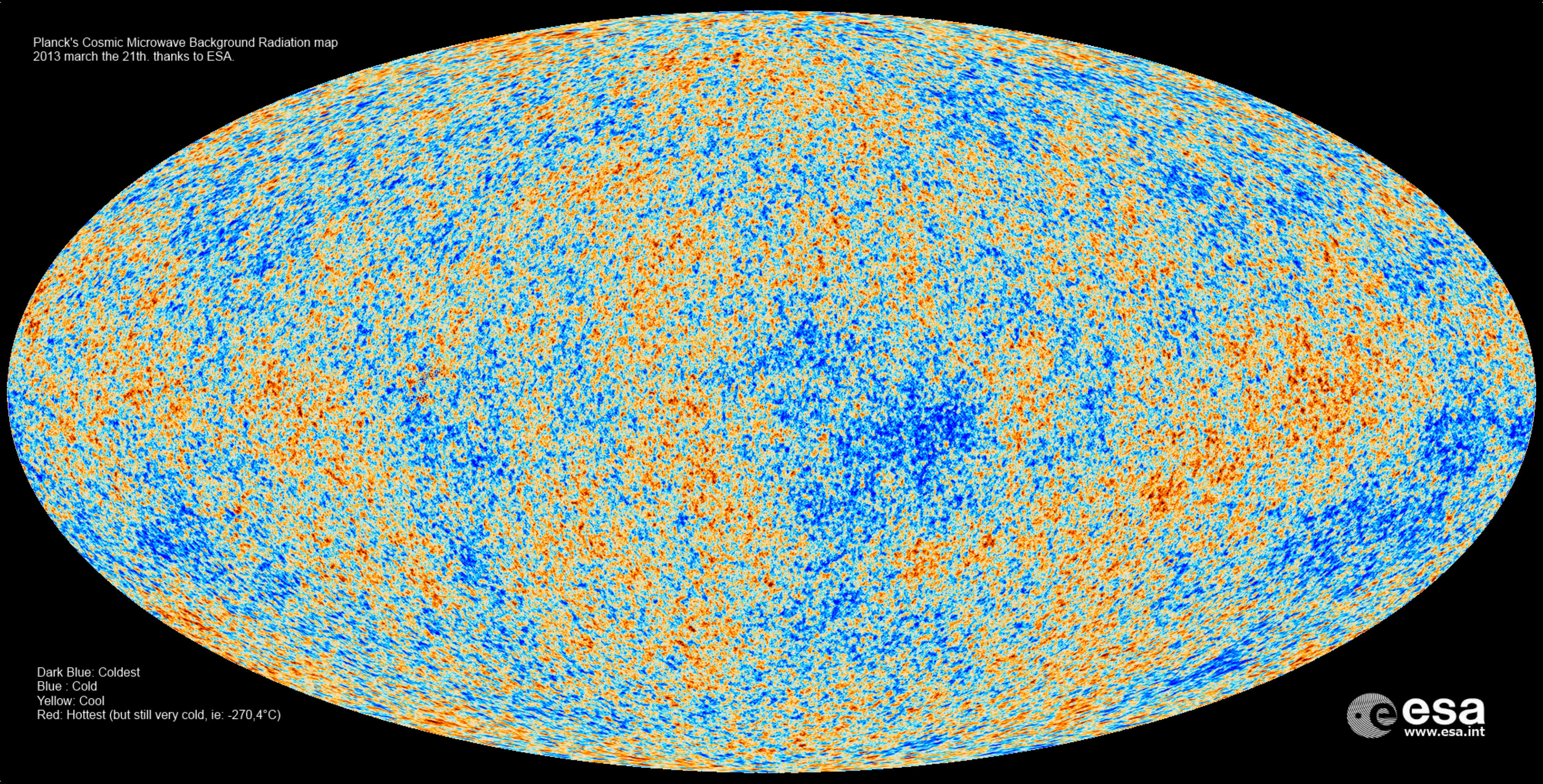
Cosmic Microwave Background (Planck, WMAP)

CMB+BAO

Cosmology 2014

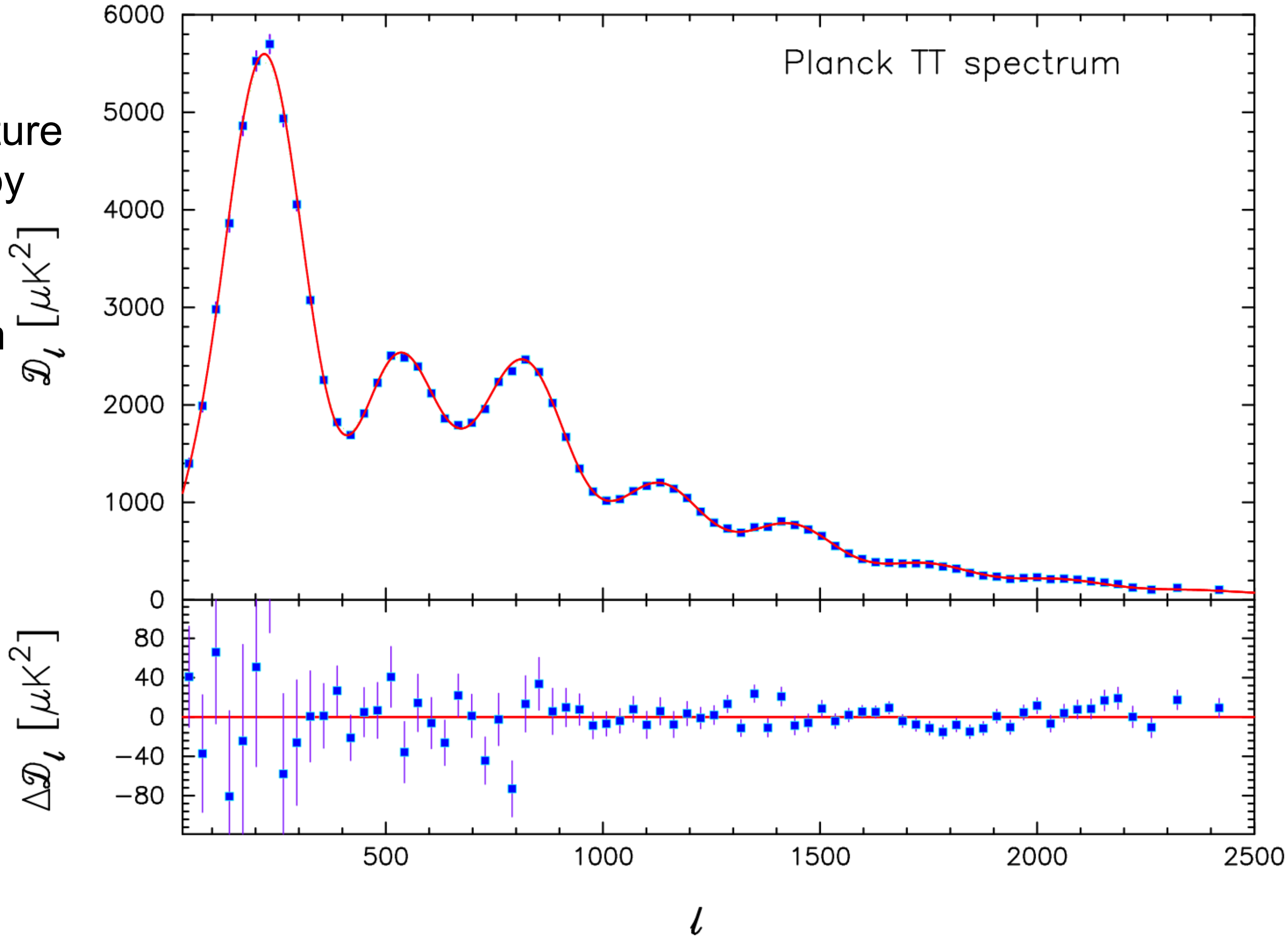
- A well-tested cosmological model:
  - two epochs of cosmic acceleration (inflation and now)
  - hot, dense early phase (Big Bang)
  - nearly scale-invariant, nearly Gaussian density perturbations (and perhaps tensor perturbations) from quantum fluctuations during inflation
  - structure formation from gravitational instability of cold dark matter in currently Λ-dominated universe
- consistent with all data from the CMB, large-scale structure, galaxies, supernovae, clusters, light element abundances,…

Planck CMB Temperature Anisotropy



LCDM FIT

Temperature Anisotropy Angular Power Spectrum

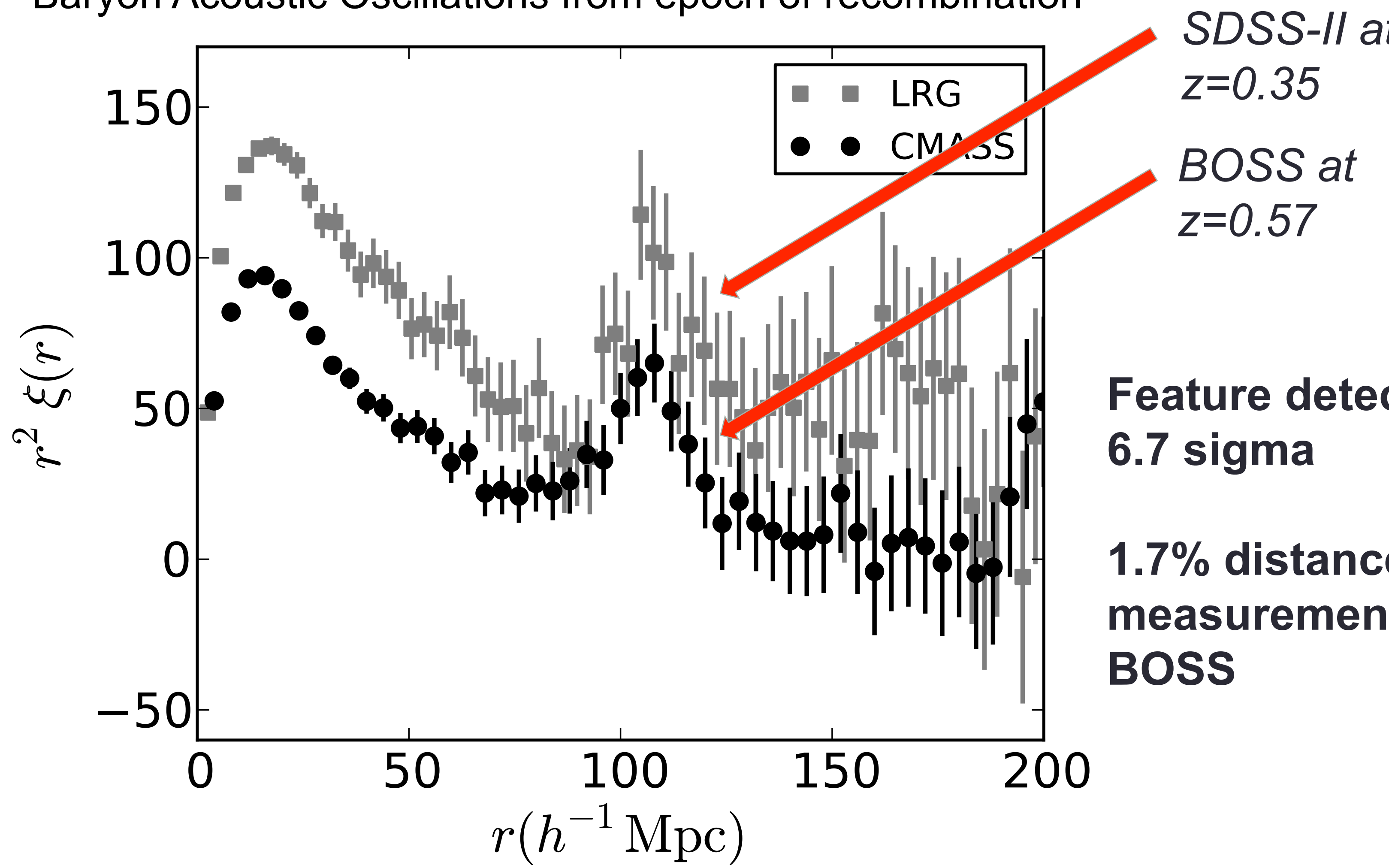


- Acceptable fit to channel spectra and composite spectrum: χ^2 compatible with LCDM to 1.6 σ

Challinor

The BAO Feature in SDSS/BOSS

Baryon Acoustic Oscillations from epoch of recombination



Feature detected at 6.7 sigma

1.7% distance measurement from BOSS

slide from N. Padmanabhan

Anderson et al, 2012

Cosmology 2014

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

Friedmann Equation from General Relativity

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 (vacuum energy): $w_\Lambda = -1$

Cosmology 2014

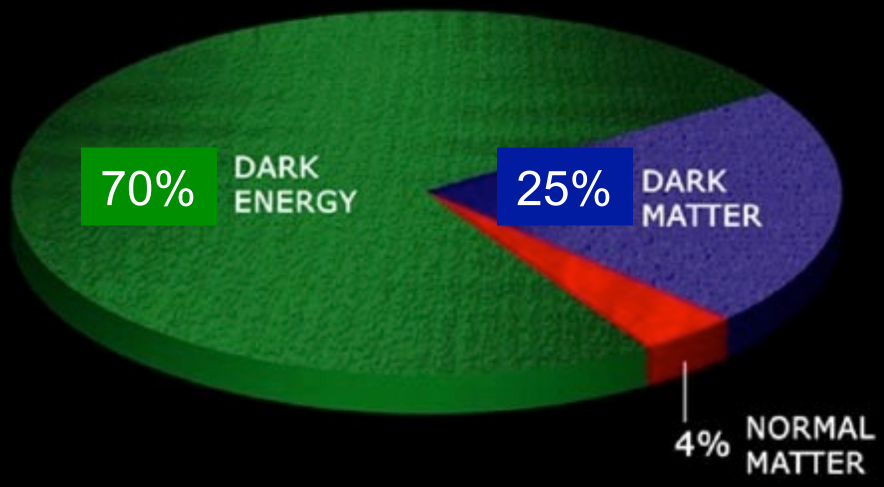
$$\frac{\ddot{a}}{a} + f(a, \dot{a}, \ddot{a}, \ldots) = -\frac{4\pi G}{3}\rho_m$$

Modify
General Relativity

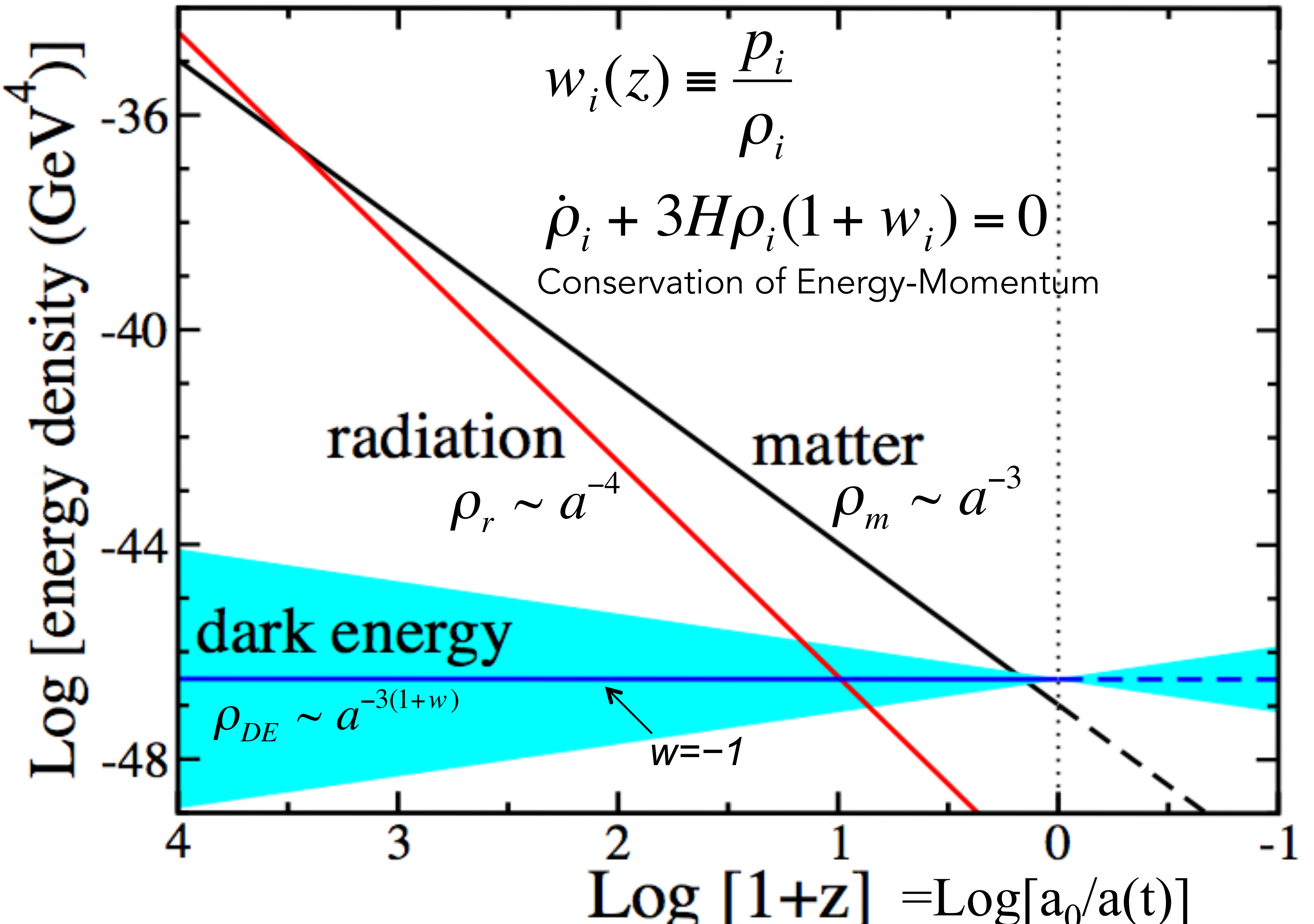
Replace GR dynamics with another gravity theory

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?



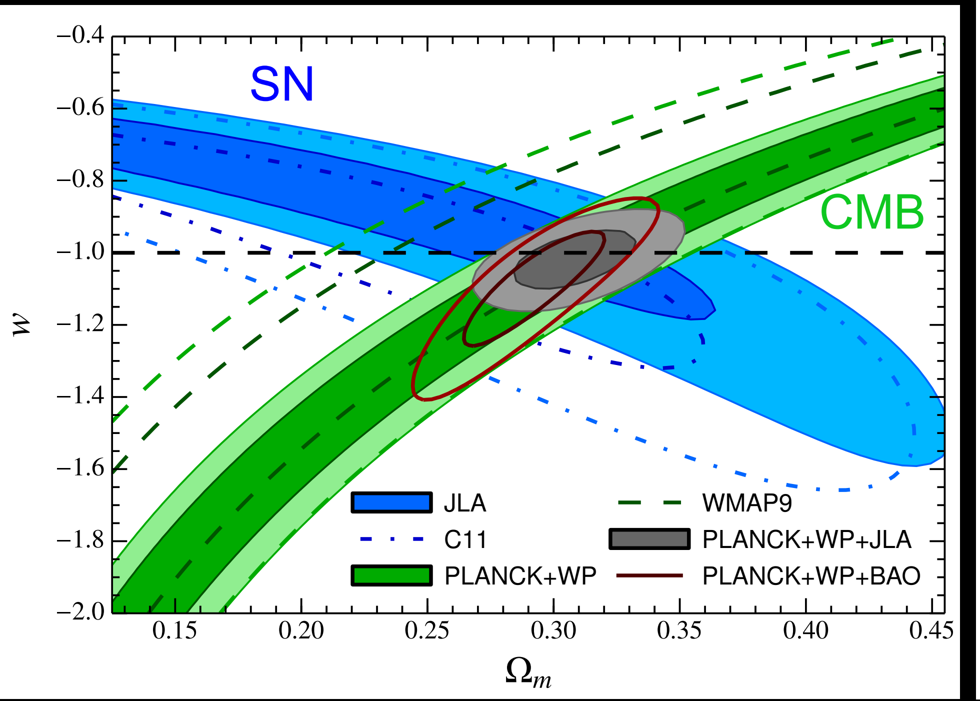
Equation of State parameter *w* determines Cosmic Evolution

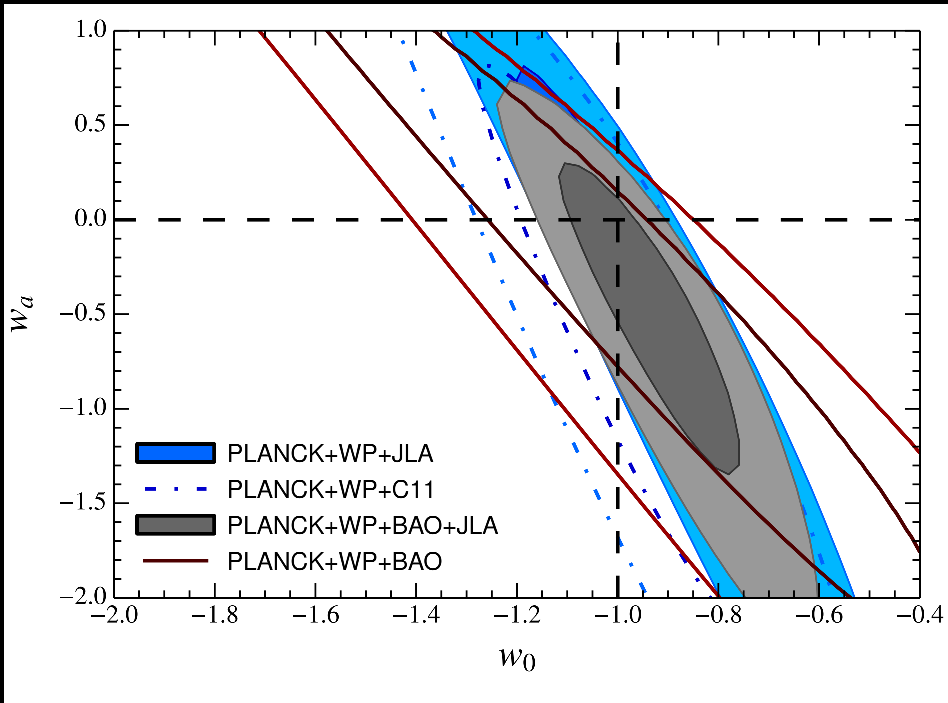


Current Dark Energy Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*: $w = -1.027 \pm 0.055$

Assuming $w = w_0 + w_a(1-a)$: $w_0 = -0.957 \pm 0.124$ $w_a = -0.336 \pm 0.552$





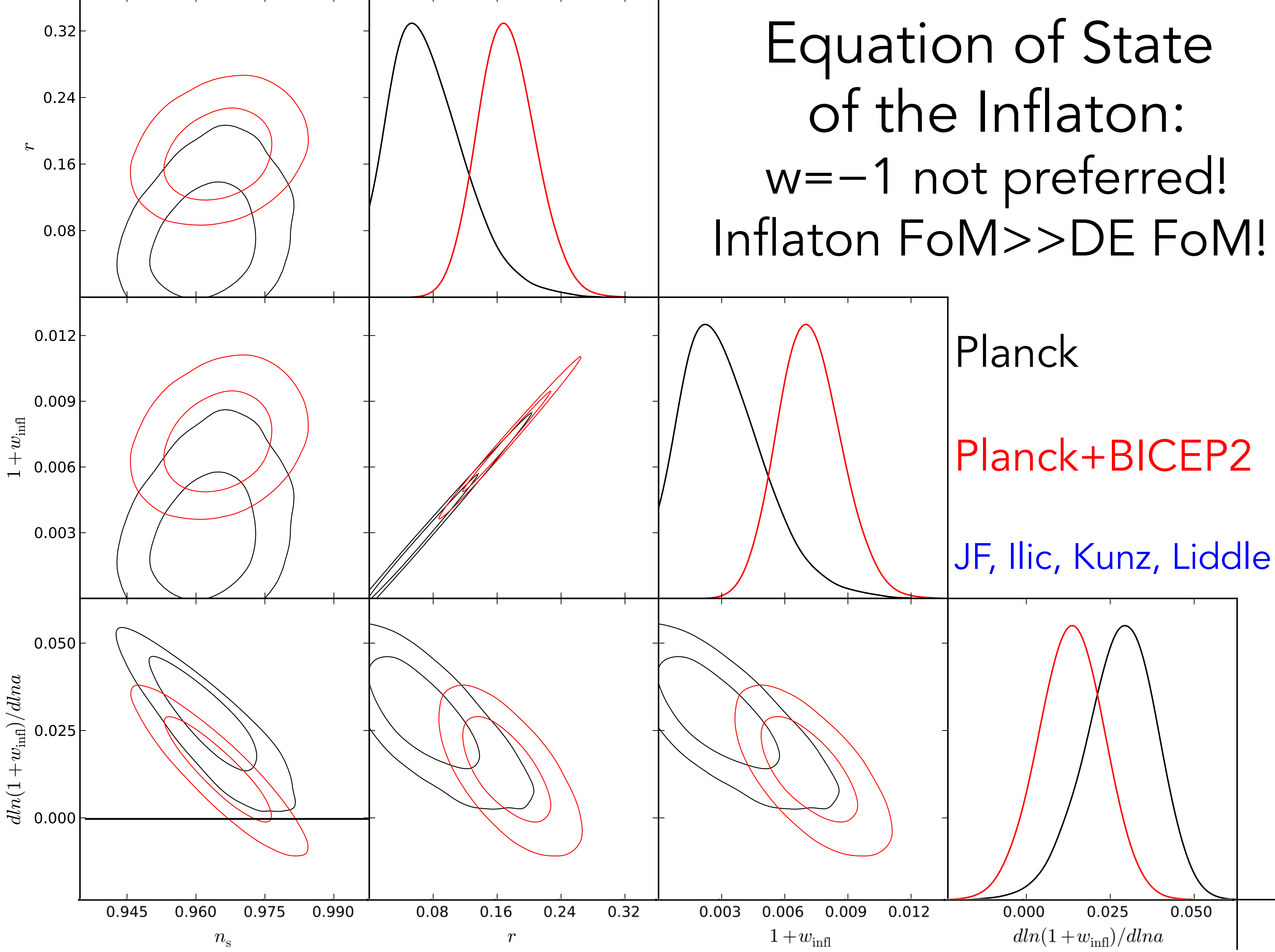
Betoule etal 2014: JLA

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

Cosmological Constant and Acceleration

- What is the justification for theoretical prejudice in favor of Λ as origin of current acceleration?
- Imagine particle theorists sitting around 10^{-35} sec after the Big Bang, when inflation had just started.
  - They would have said the Universe was becoming Λ-dominated.
  - They would have been wrong: inflation ended.
- Being wrong once is not necessarily a strong argument in favor of it the 2^{nd} time around.

Equation of State of the Inflaton: w=−1 not preferred! Inflaton FoM>>DE FoM!



Alternatives to Λ

Perhaps the Universe is not yet in its ground state. The `true' vacuum energy (Λ) could be zero (for reasons yet unknown). Transient vacuum energy can exist if there is a field that takes a cosmologically long time to reach its ground state. This was the reasoning behind inflation. For this reasoning to apply now, we must postulate the existence of an extremely light scalar field, since the dynamical evolution of such a field is governed by

$$t_d \sim \frac{1}{m} \ , \ t_d > 1/H_0 \ \Rightarrow \ m < H_0 \sim 10^{-33}\,\mathrm{eV}$$

JF, Hill, Stebbins, Waga 1995

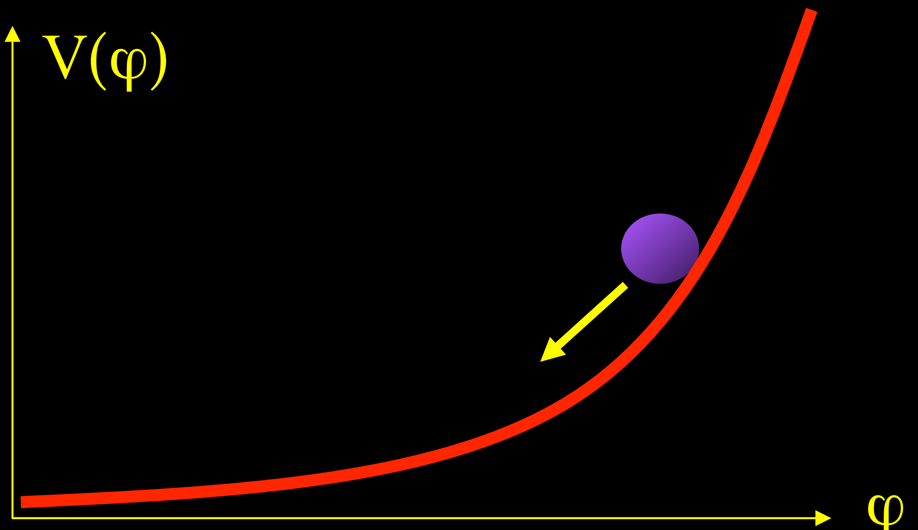
Scalar Field Dark Energy
(aka quintessence)

- Dark Energy could be due to a very light scalar field φ, slowly evolving in a potential, V(φ):

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

- Density & pressure:

$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$

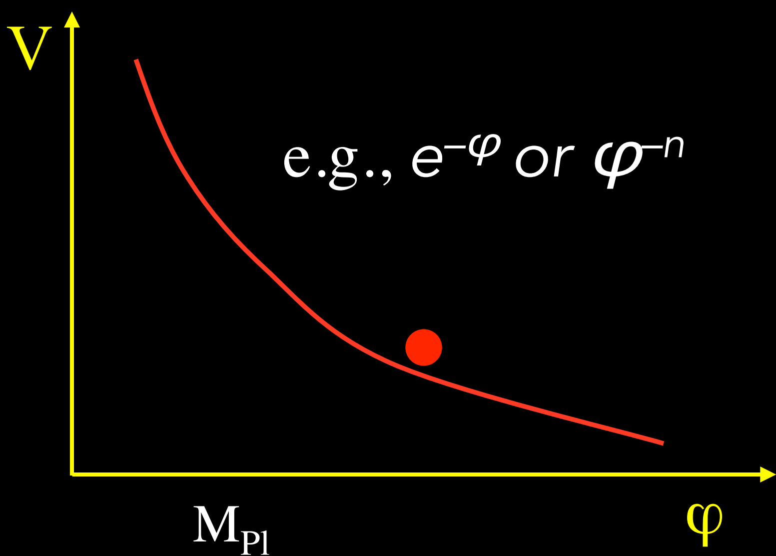


- Slow roll:

$$\tfrac{1}{2}\dot{\varphi}^2 < V(\varphi) \Rightarrow P < 0 \Leftrightarrow w < 0 \text{ and time - dependent}$$

Scalar Field Models

Freezing models



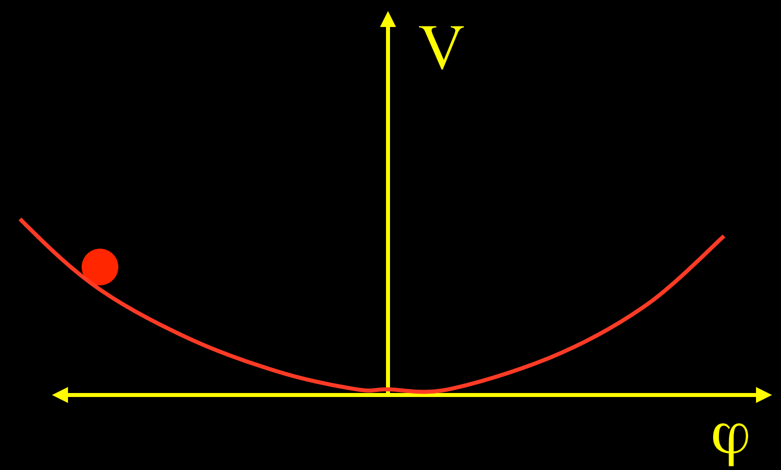
Runaway potentials

DE/matter ratio constant

(Tracker Solution)

Ratra & Peebles; Caldwell, etal

Thawing models



Pseudo-Nambu Goldstone Boson

Low mass protected by symmetry

(Cf. axion)

JF, Hill, Stebbins, Waga

Dynamical Evolution of Freezing vs. Thawing Models

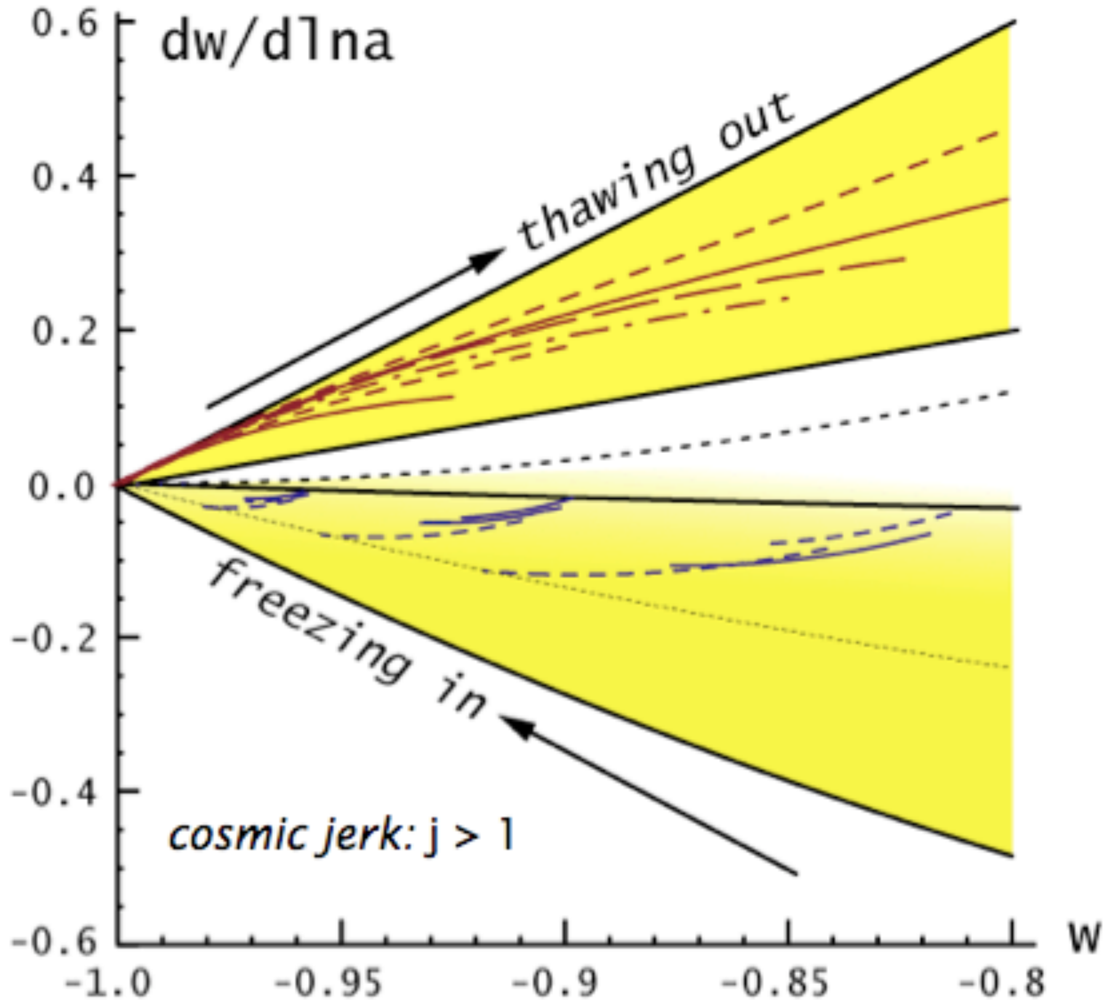
scalar field models

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

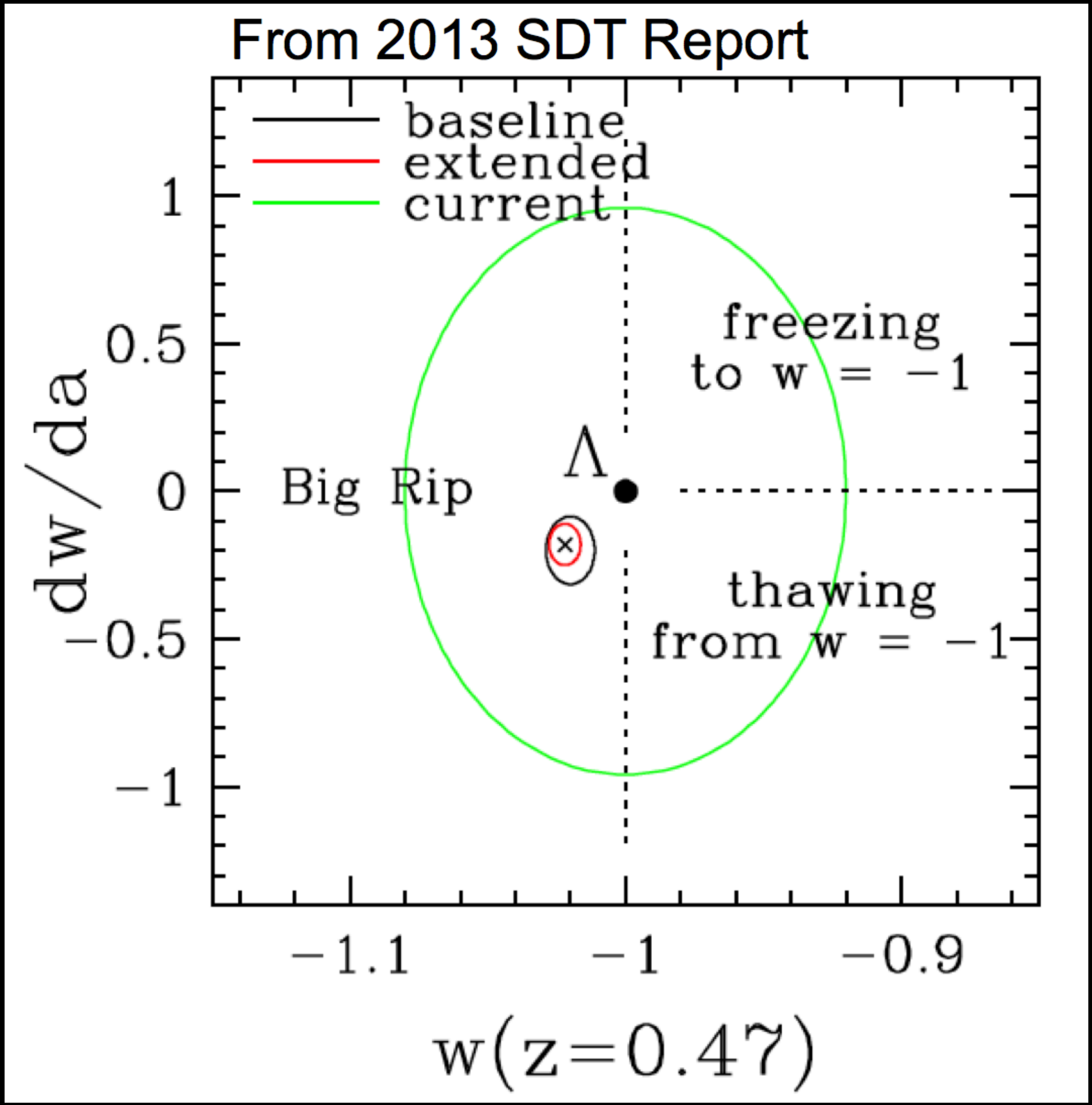
$V \propto \cos^2(\Phi/2f)$
solid

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

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

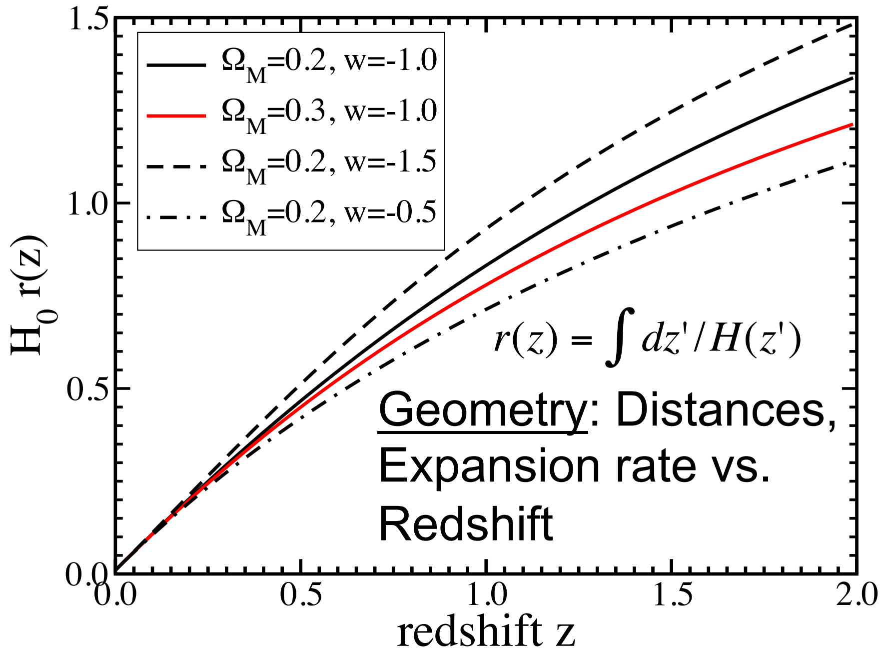


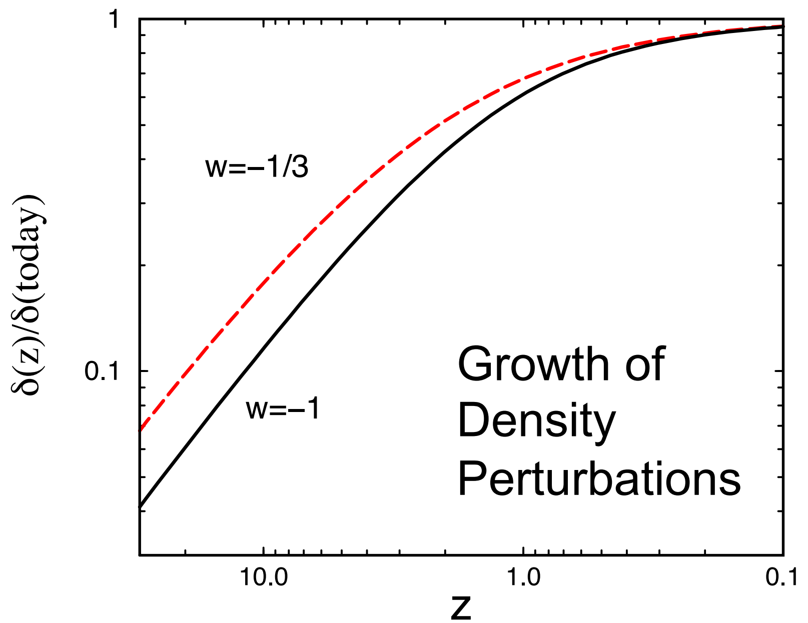
Measuring *w* and its evolution can potentially distinguish between physical models for acceleration



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

What can we probe?





Expansion History

Growth of Structure

GR: H(z) determines perturbation growth.
Measure both: consistency test of GR+DE, smoking gun for Modified Gravity

Probes of Dark Energy

- Galaxy Clusters
  - Counts of Dark Matter Halos: Clusters as Halo Proxies
  - Sensitive to growth of structure and geometry
  - Also Cluster gas fraction and pressure profiles
- Weak Lensing
  - Correlated Galaxy Shape and magnification measurements
  - Sensitive to growth of structure and geometry
- Large-scale Structure
  - Baryon Acoustic Oscillations: feature at ~150 Mpc
    - Sensitive to geometry
  - Redshift-space Distortions due to Peculiar Velocities
    - Sensitive to growth of structure
- Supernovae
  - Hubble diagram: standard candle distance vs. redshift
  - Sensitive to geometry
- Strong Lensing
  - Time Delays sensitive to geometry

Complementarities:
RSD x WL

Dark Energy Surveys

- Spectroscopic (3D):
  - Completed: BOSS/SDSS-III, WiggleZ, 2dFGRS
  - Starting now: eBOSS, HETDEX
  - Future: PFS, DESI, 4MOST,…
- Photometric (2D):
  - Current: PanSTARRS, DES, HSC, KIDS
  - Future: LSST
- Narrow-band Photometric (2.5D):
  - JPAS, PAU
- Both:
  - Space: Euclid, WFIRST

- X-ray:
  - XMM, Chandra
  - eROSITA
- SZ:
  - ACT, SPT, Planck

The Dark Energy Survey (DES)

- Use all DE probes
  - Distance vs. redshift
  - Growth of Structure
- Two multicolor surveys:

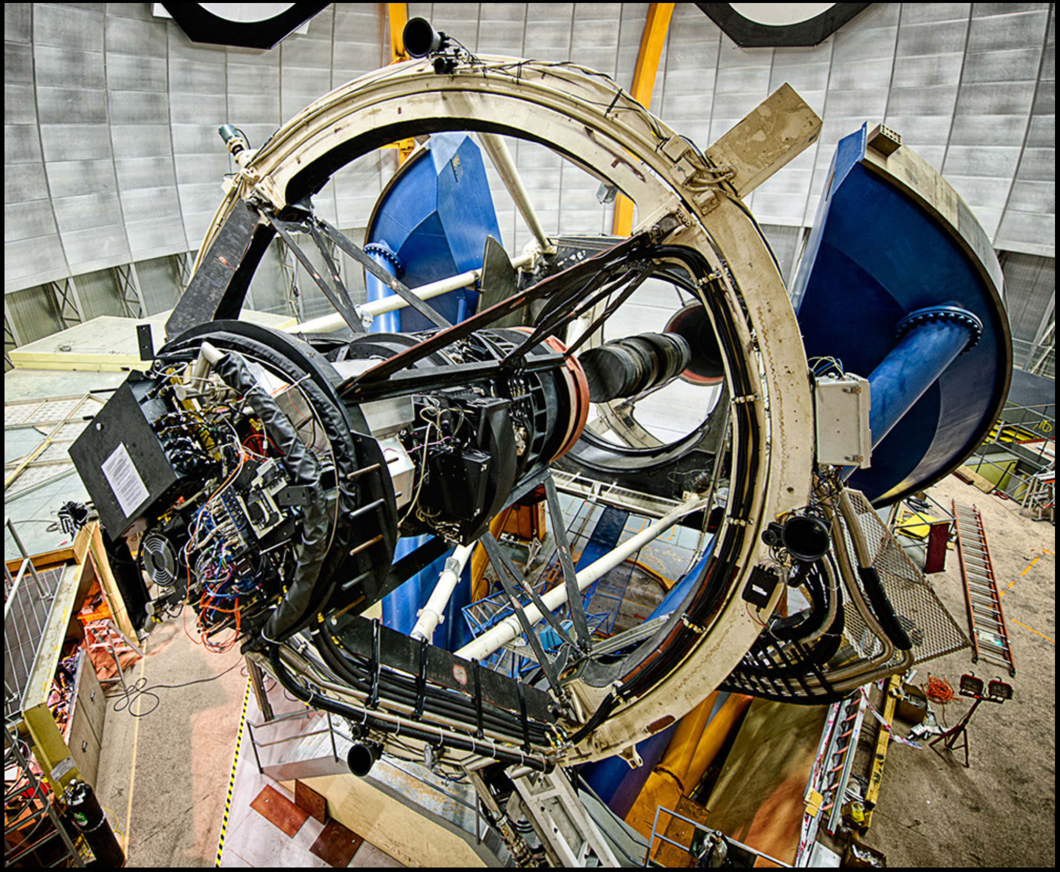
  300 M galaxies over 5000 sq deg, grizY to ~24^{th} mag

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

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

  525 nights (Sept.-Feb.)

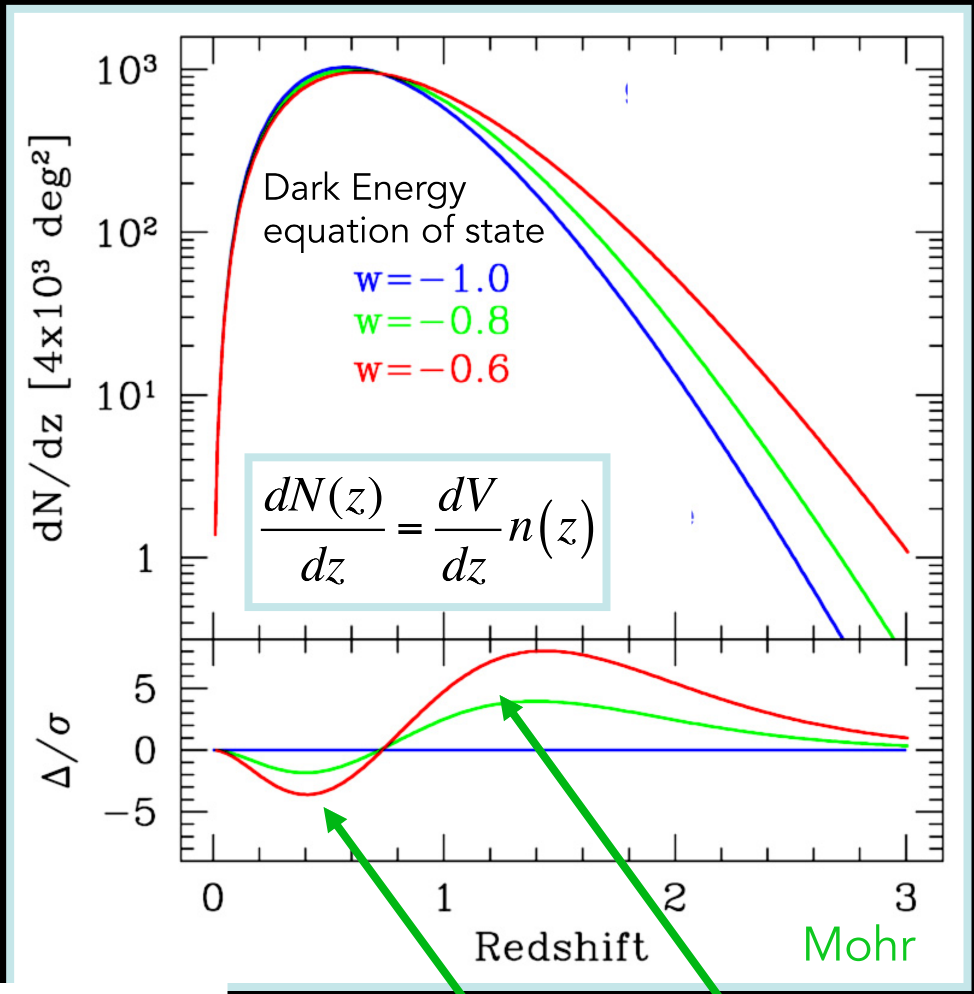
DECam on the CTIO Blanco 4m



www.darkenergysurvey.org
www.darkenergydetectives.org

I. Clusters

Number of clusters above mass threshold



- Clusters are proxies for massive dark 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 <u>p(O|M,z)</u> with sufficient precision
- Multiple observable proxies *O* for cluster mass: optical richness, SZ flux, weak lensing mass, X-ray flux, velocity dispersion

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

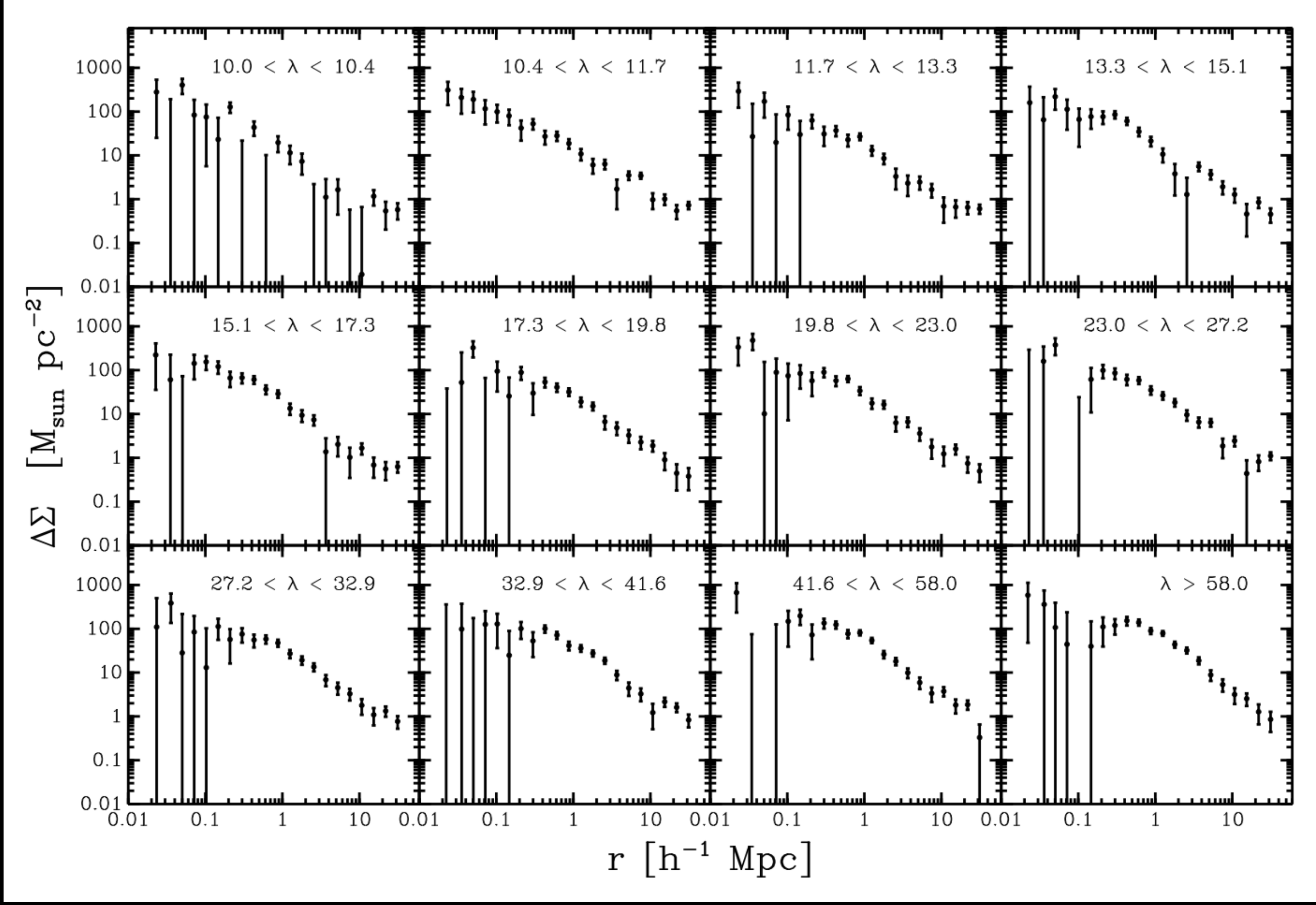
Volume

Growth

Statistical Weak Lensing by Galaxy Clusters

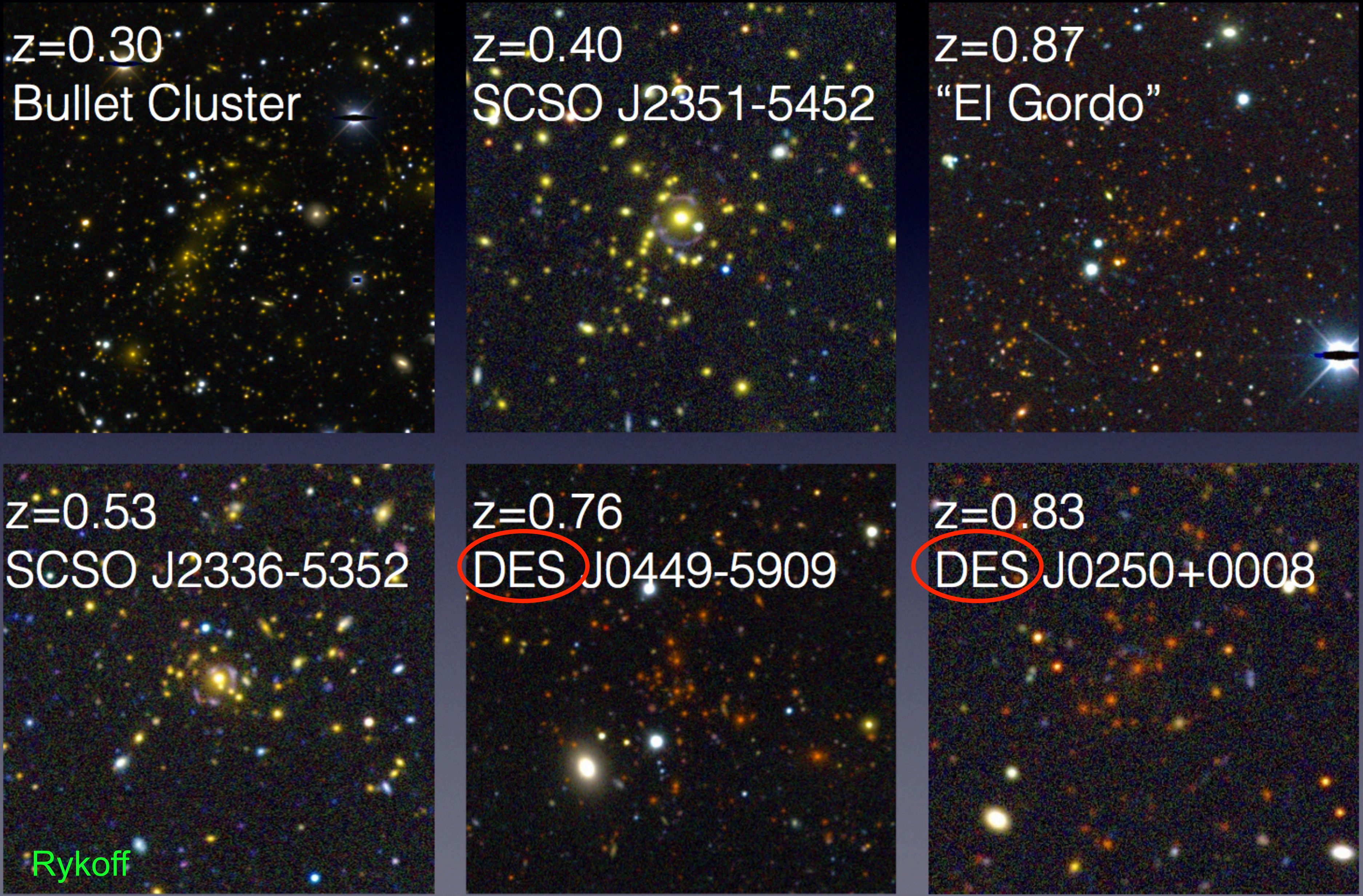
Mean Tangential Shear Profile in Optical Richness Bins

Calibrate Mass-Observable relations

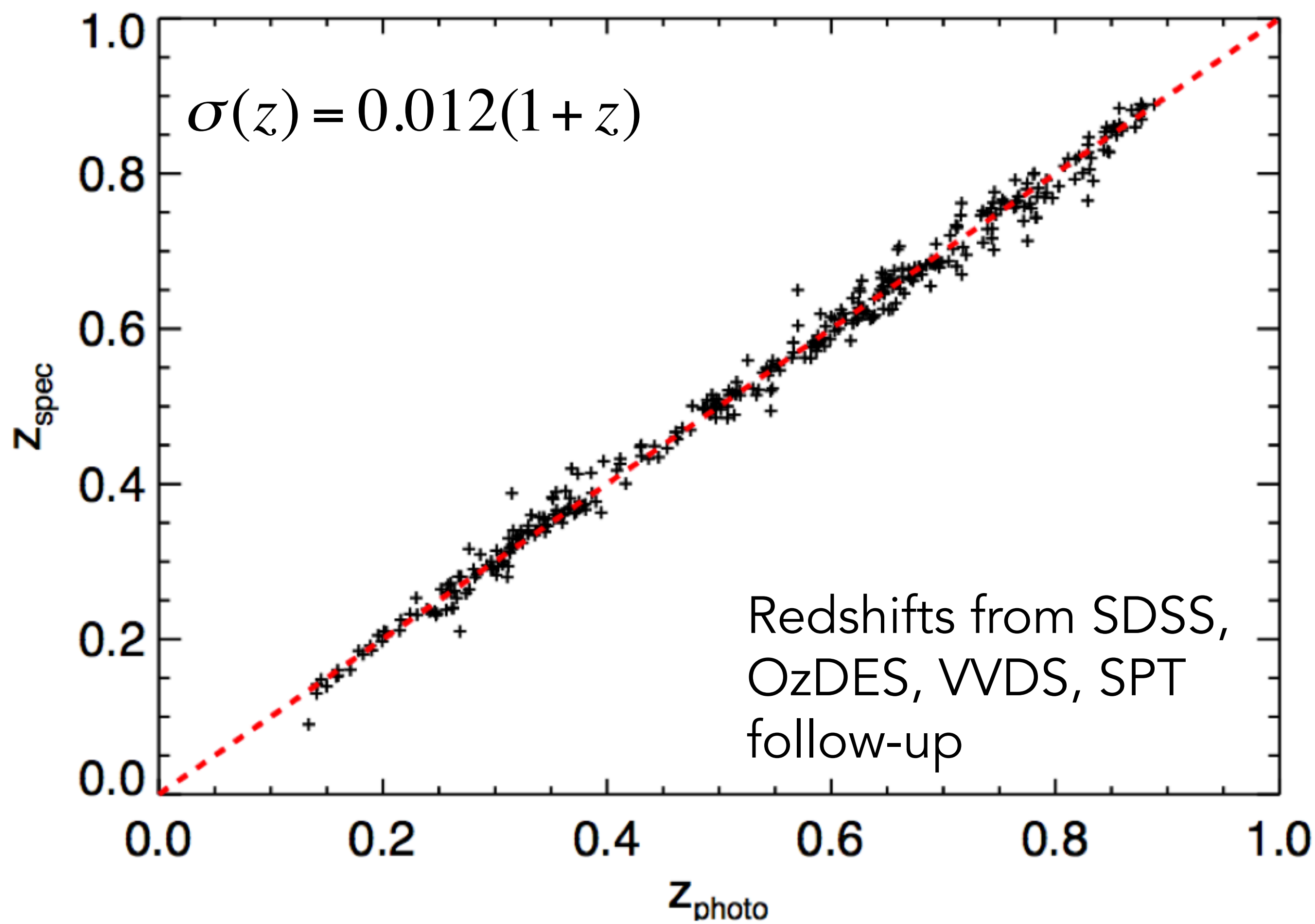


Sheldon, Rykoff, etal SDSS + Redmapper

Galaxy Clusters in early DES data



DES Cluster Photometric Redshifts



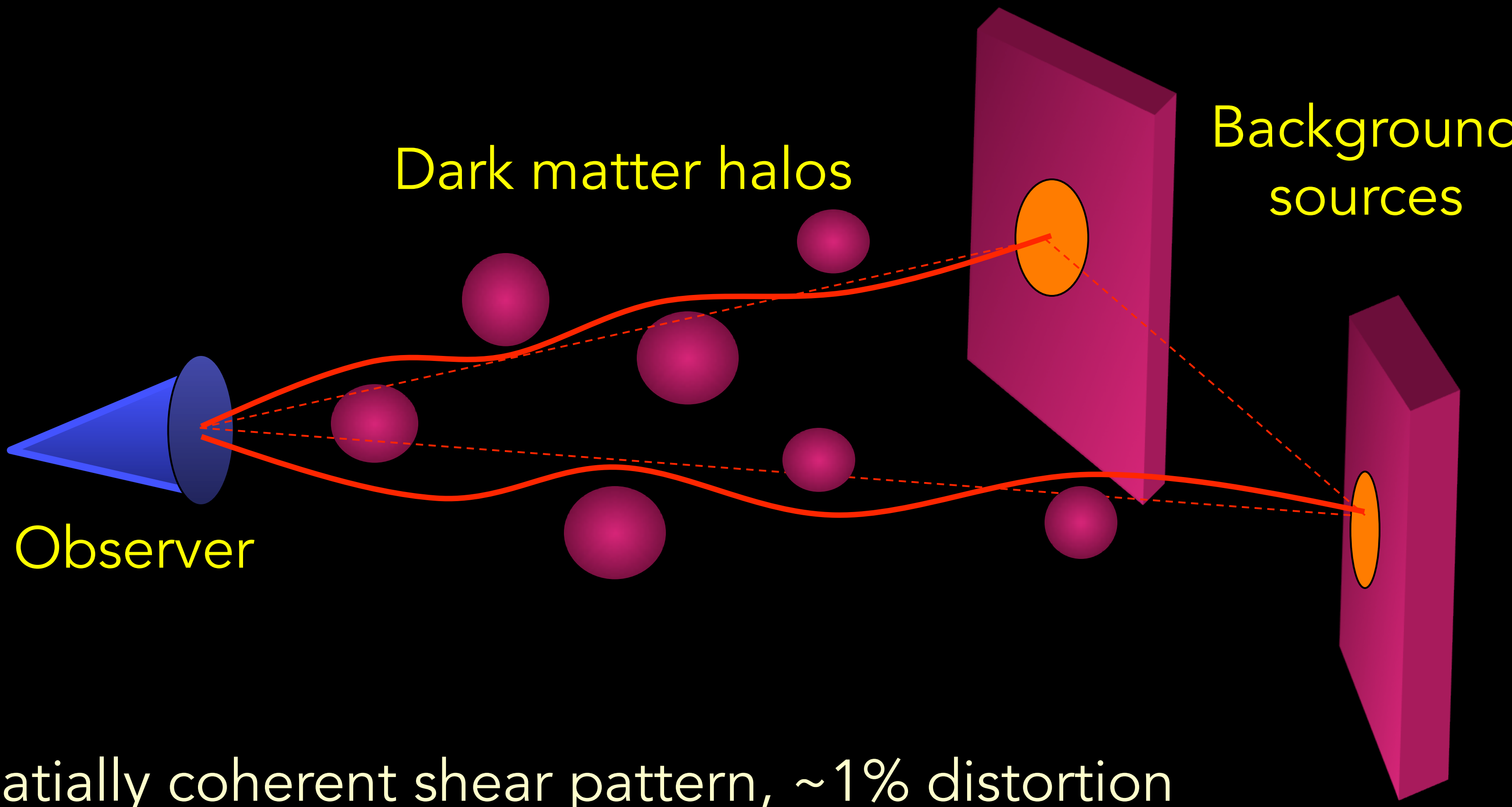
Rykoff, Rozo, etal

Clusters in Science Verification

RXC J2248.7-4431
(z=0.35)

preliminary mass map contours: significance

II. 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

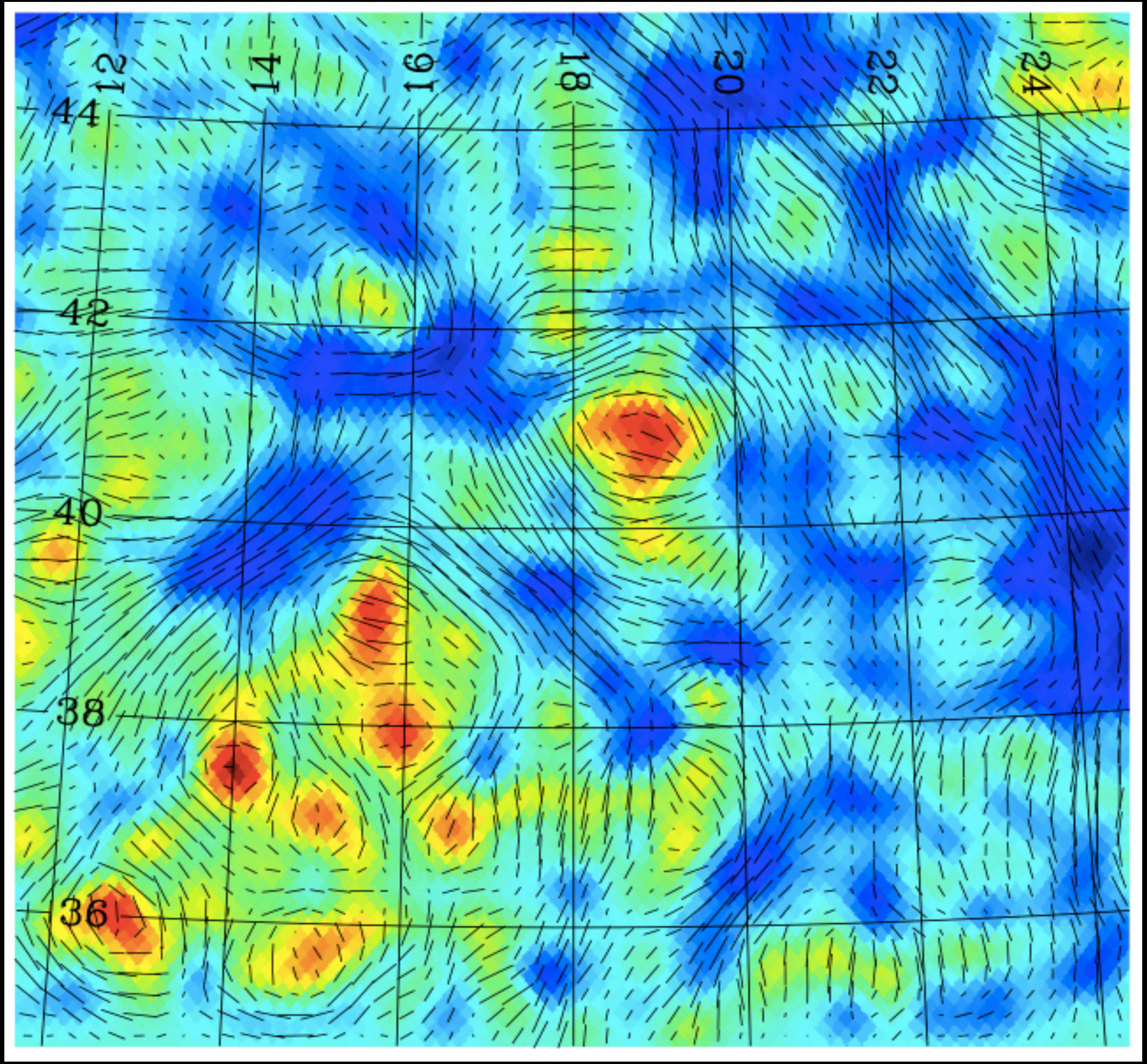
Weak Lensing Mass and Shear

DES Simulation

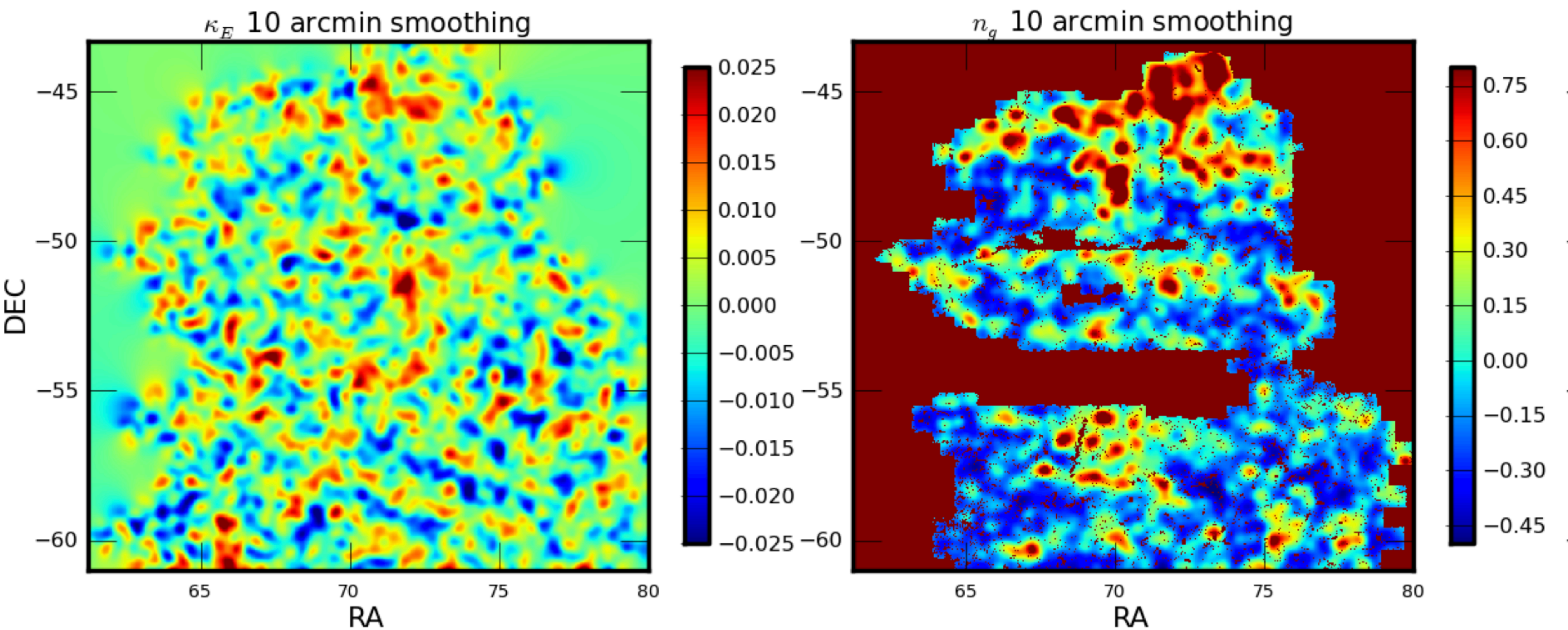
Tick marks: shear

Colors: projected mass density

Becker, Kravtsov, etal



DES Large-scale Weak Lensing



Mass Map

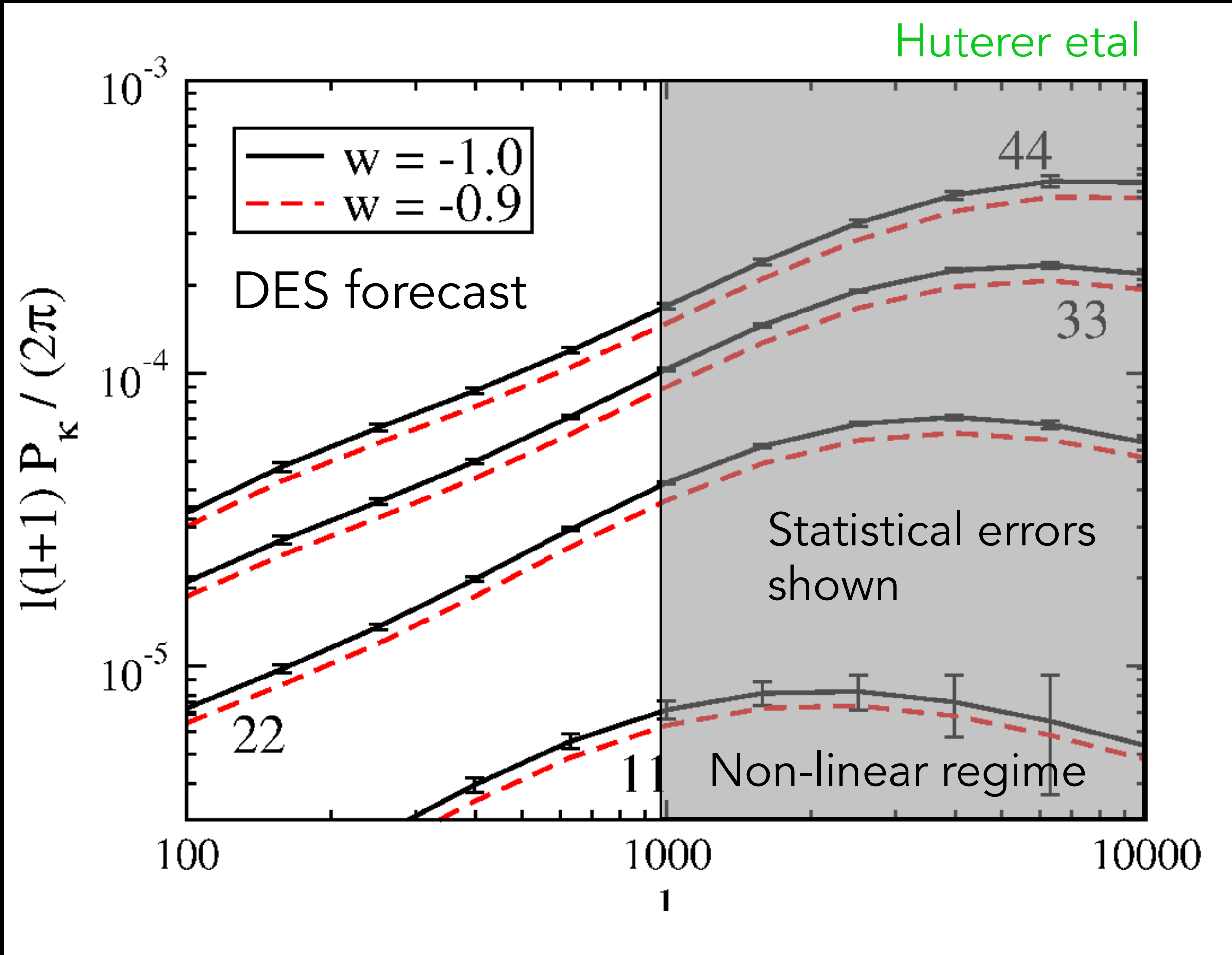
Luminous Red Galaxy overdensity

Vikram, et al

Weak Lensing Tomography

- Cosmic Shear Angular Power Spectrum in 4 Photo-z Slices

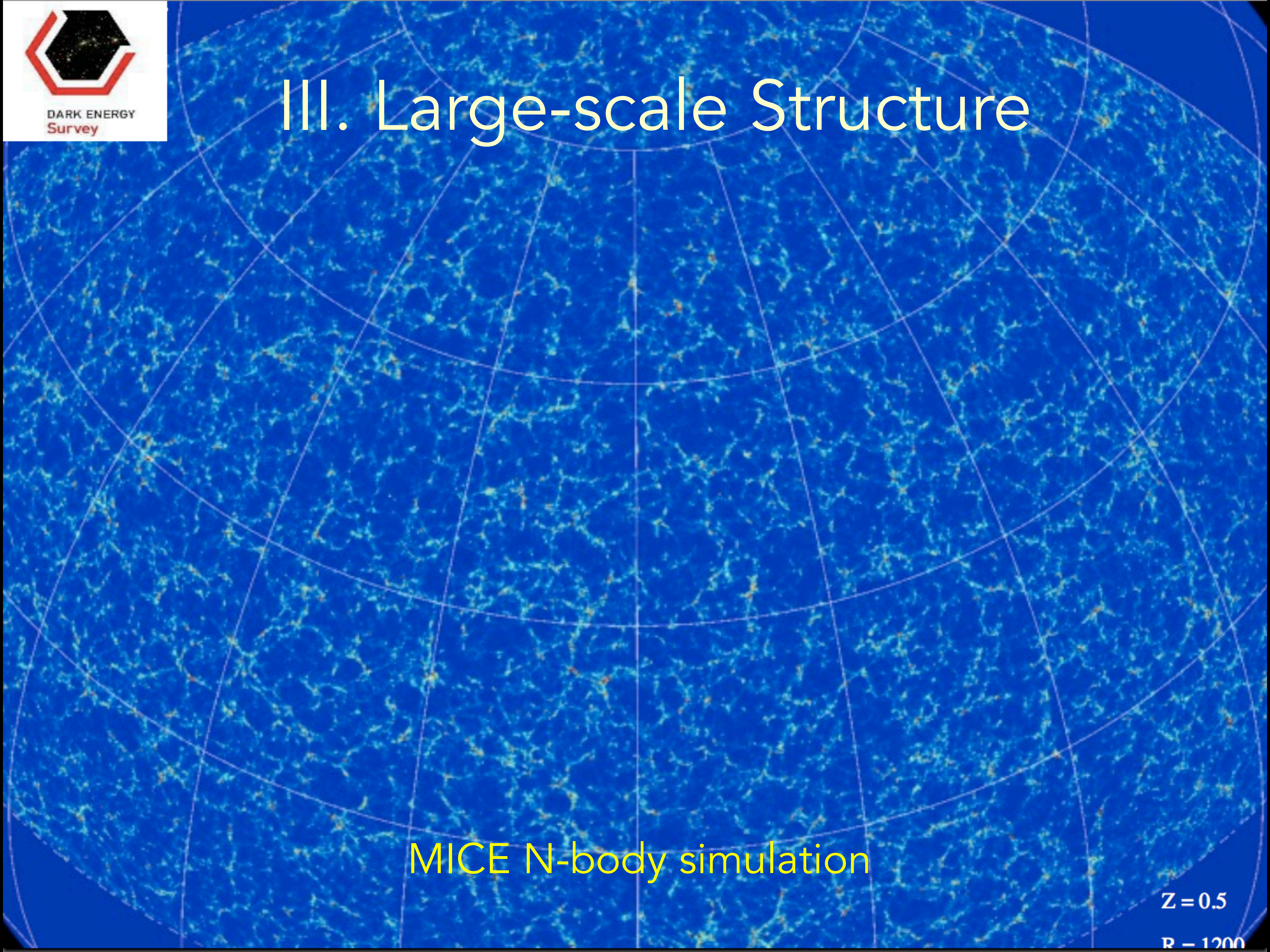
- Systematics Challenges: photo-z's, intrinsic alignments, PSF anisotropy, shear calibration, nonlinear +baryon *P(k)* effects



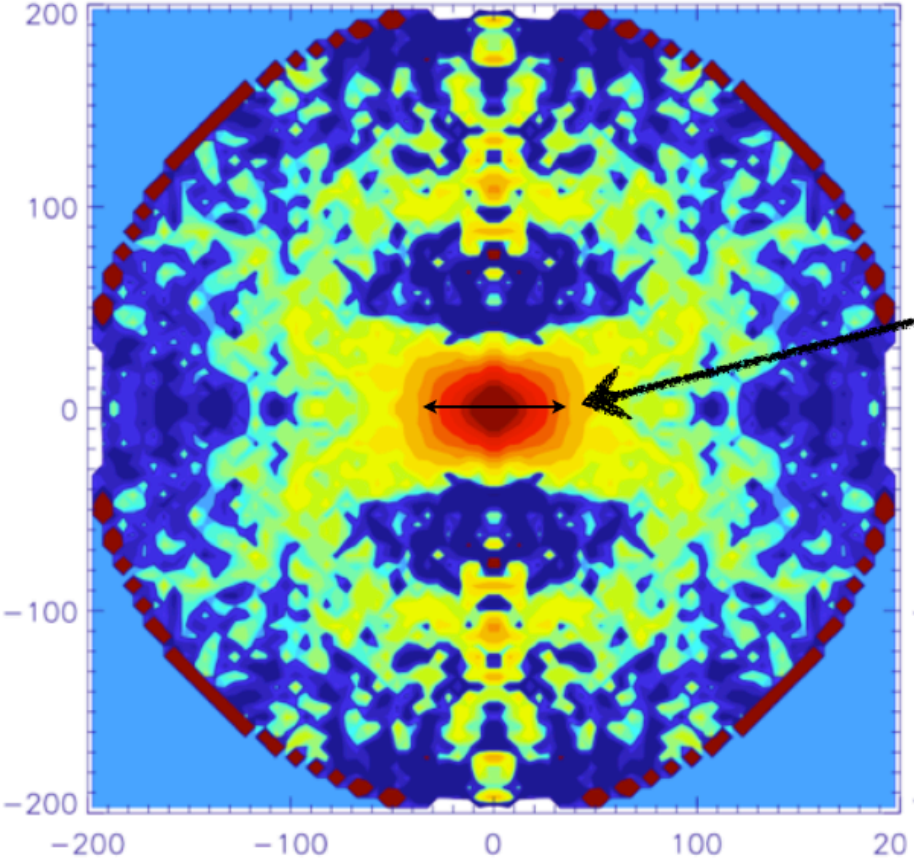
$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

$$\Delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

III. Large-scale Structure



MICE N-body simulation



Redshift Space Distortions (RSD)

$$\delta_g(k,\mu) = (b + f\mu^2)\delta(k)$$

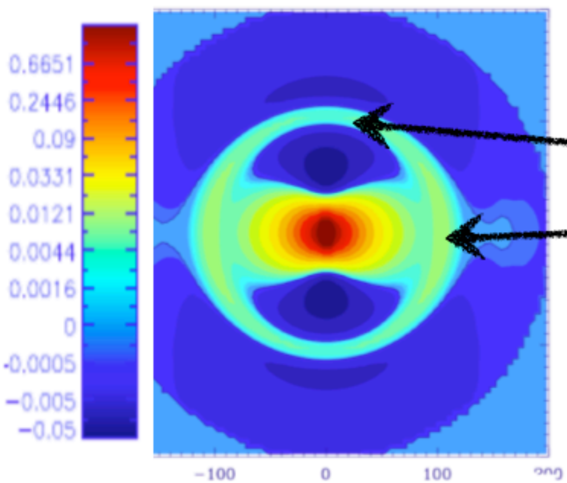
μ=0

Anistropy of clustering in redshift space

$f \equiv d\ln\delta / d\ln a = \Omega_m^{\gamma}$ growth rate

γ=0.55 in GR, can differ in modified gravity

$b =$ galaxy bias



BAO:

radial H(z)

Transverse $\int$ cdz/H(z)

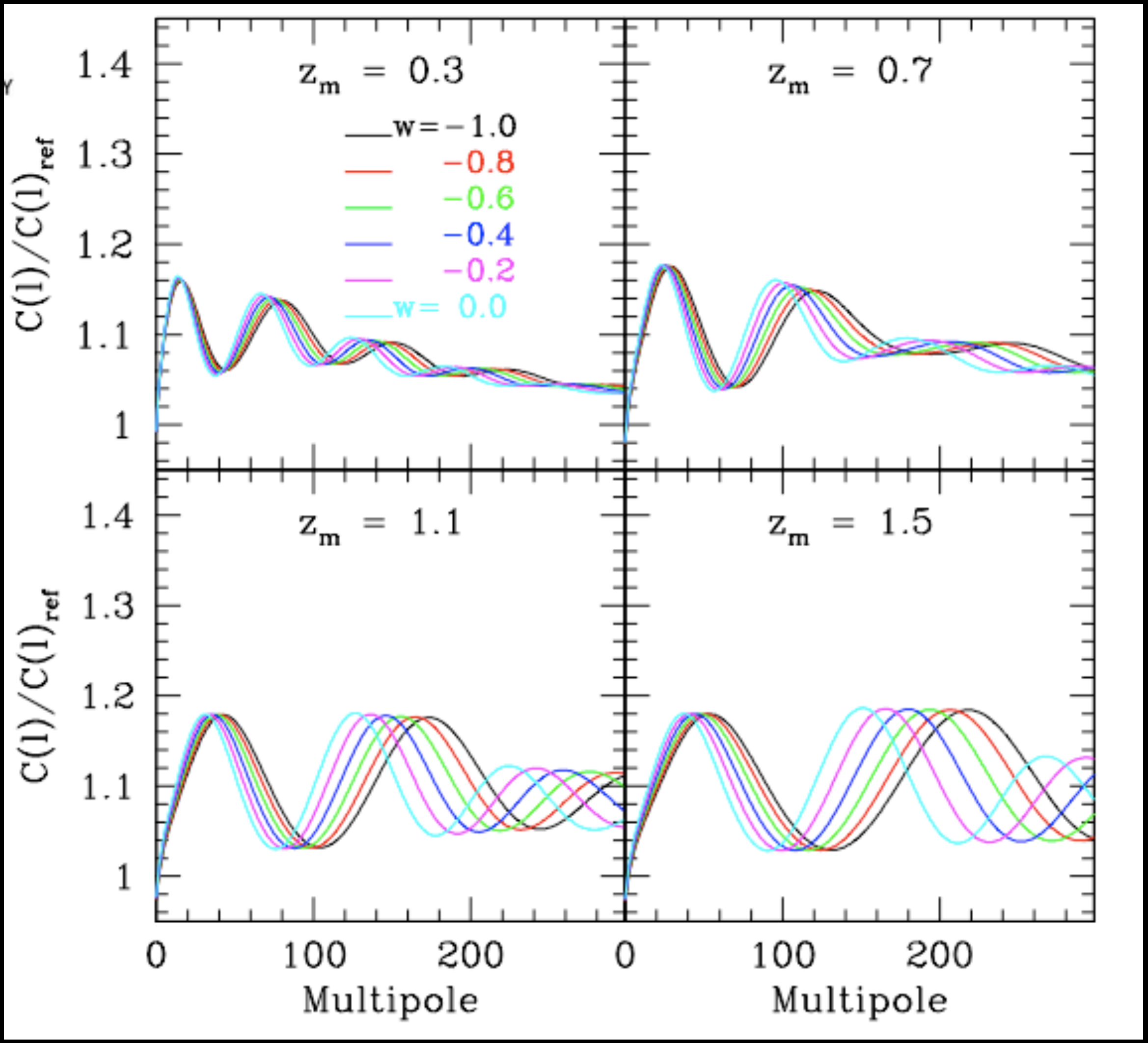
slide from Enrique Gaztanaga

Baryon Acoustic Oscillations

Galaxy angular power spectrum in photo-z bins
(relative to model without BAO)

Photometric surveys provide this angular measure

Spectroscopic surveys add radial measure: H(z), much more powerful



Fosalba & Gaztanaga

LSS – First Measurements

Many people working on that!!

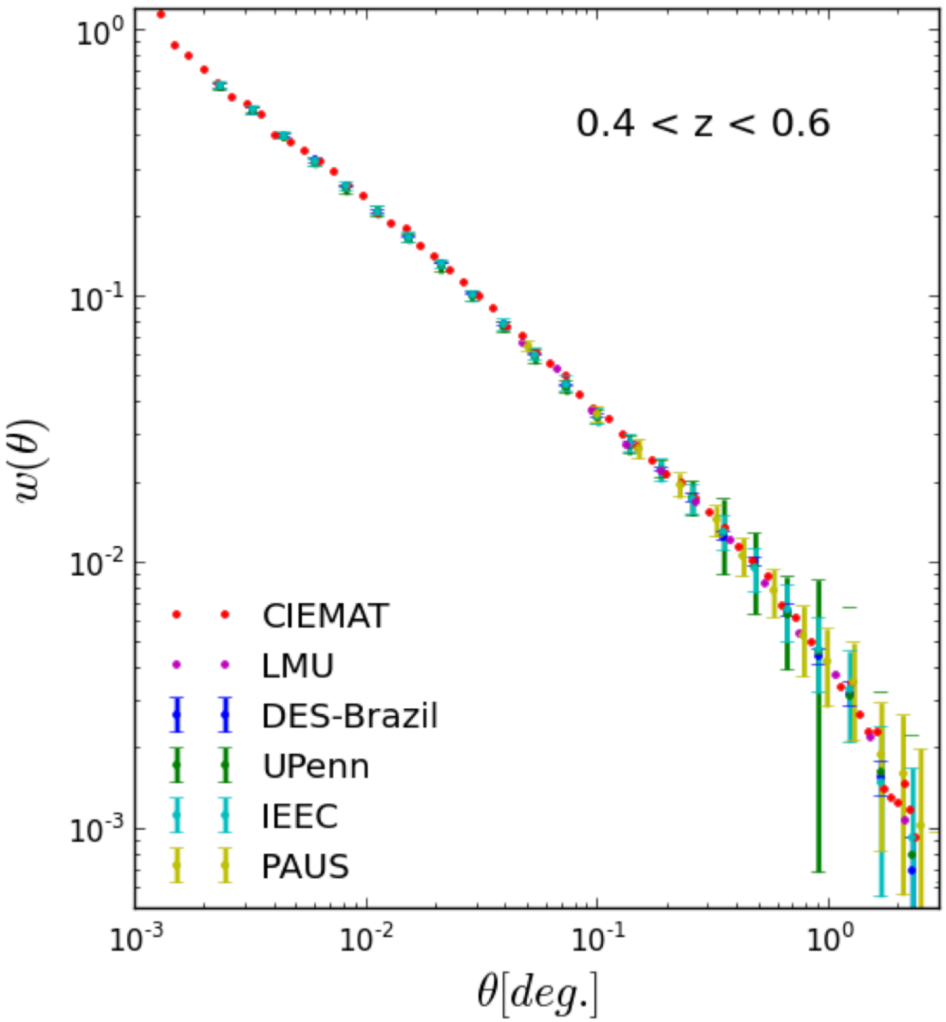
Separate galaxies in redshift shells and estimate $w(\theta)$

18 < mag_i < 22.5

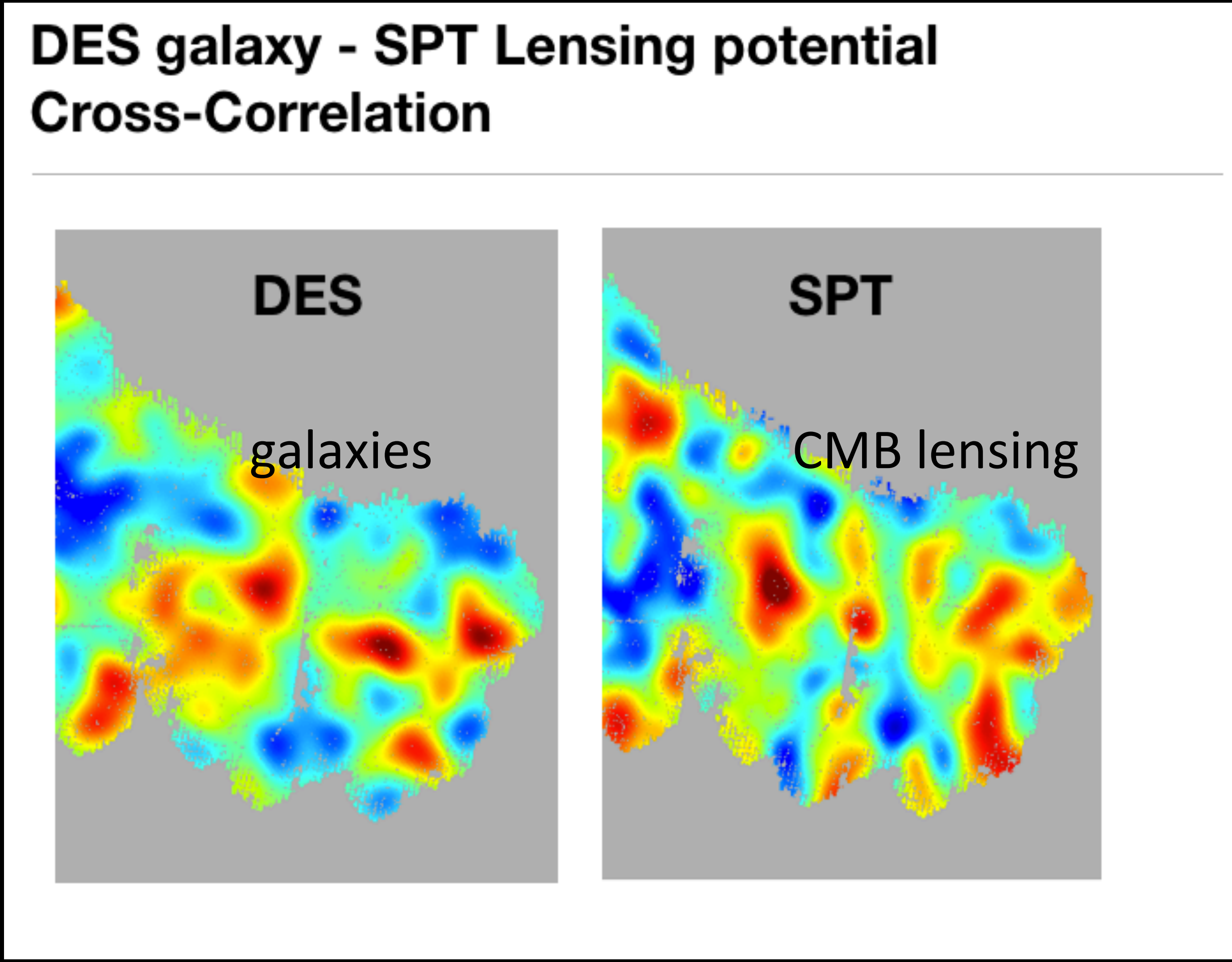
SPTE-Field

60 < RA < 95
-61 < DEC < -40

3540268 galaxies



DES-SPT Joint Analysis



Multi-wavelength cross-correlations can help constrain nuisance parameters

Fosalba, Giannantonio, Cawthon et al

IV. Supernovae

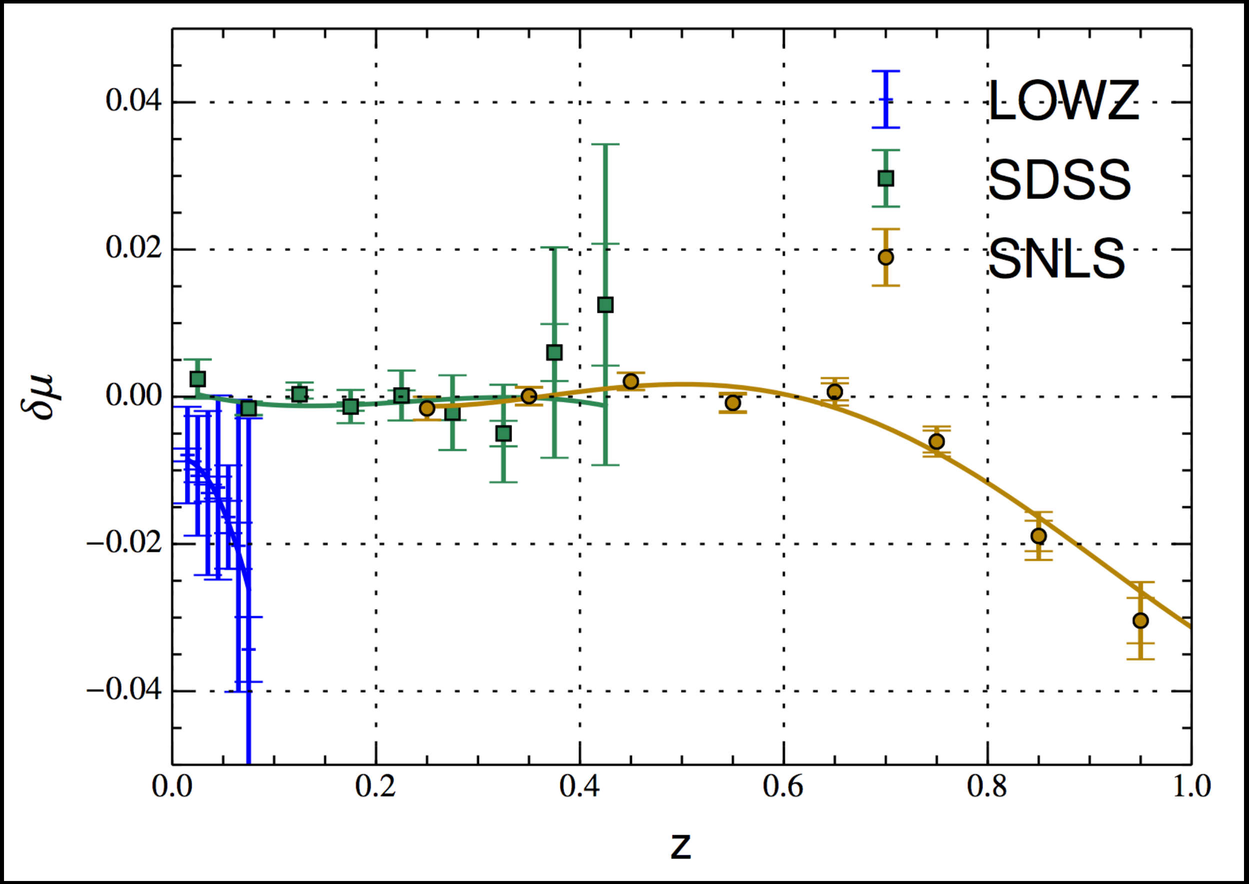
B. Dilday

SDSS-II: 500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III

Bias and Scatter

- Reducing scatter less important than controlling bias.
- Bias doesn't always need to be eliminated, but needs to be measured and modelled.

Bias due to sample selection effects



Betoule et al

JLA Errors

Uncertainty sources	$\sigma_x(\Omega_m)$	% of $\sigma^2(\Omega_m)$
Calibration	0.0203	36.7
Milky Way extinction	0.0072	4.6
Light-curve model	0.0069	4.3
Bias corrections	0.0040	1.4
Host relation[a]	0.0038	1.3
Contamination	0.0008	0.1
Peculiar velocity	0.0007	0.0
Stat	0.0241	51.6

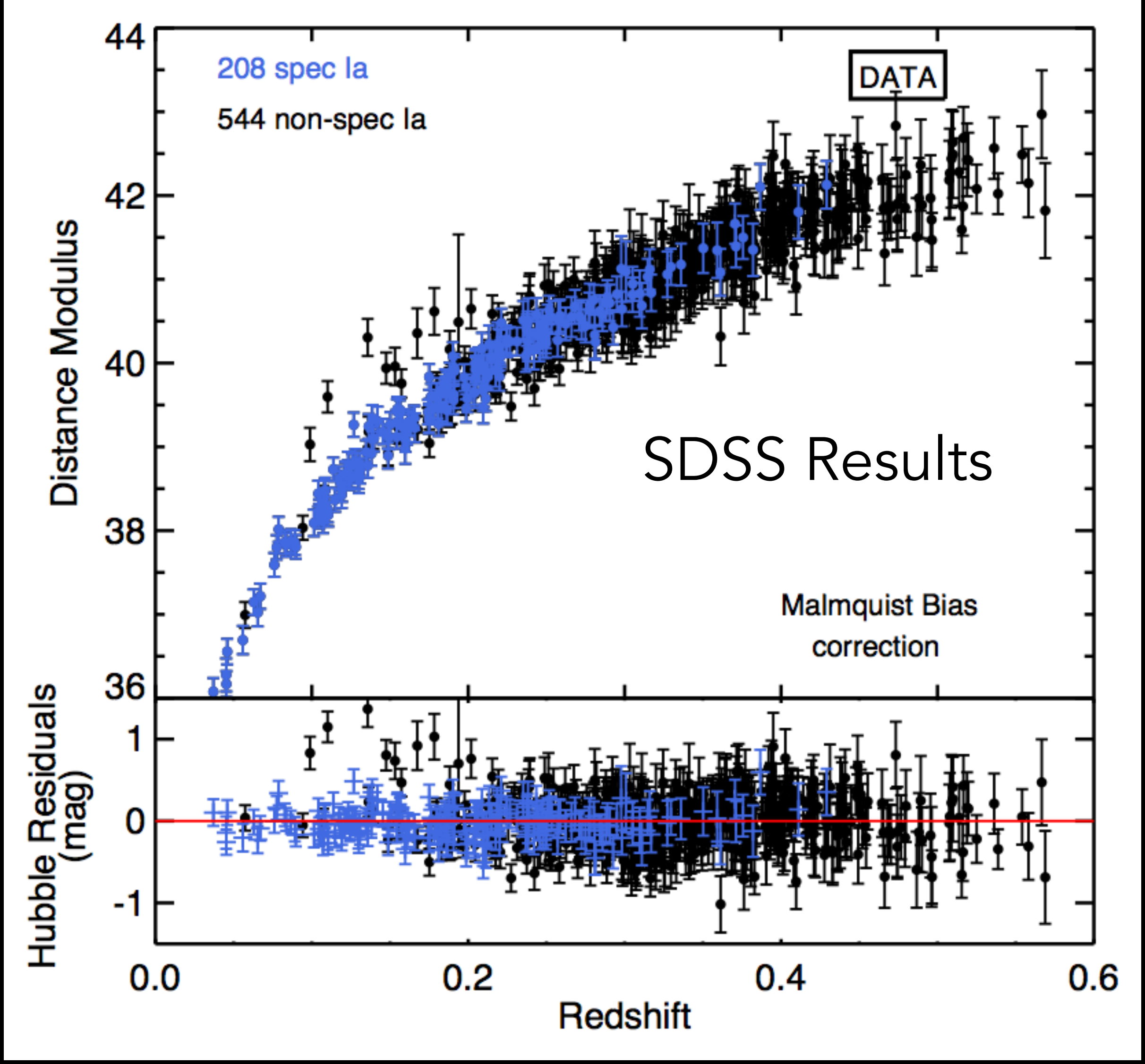
Betoule et al

Into the Era of Photometric SN Cosmology

- Supernova cosmology results to date (largely) based on spectroscopically confirmed SNe Ia, with samples in the 100s
- Present (PanSTARRS, DES) and future (LSST) photometric SN samples from large ground-based surveys will harvest 1000s to 100s of 1000s of SN Ia light curves. Very limited SN spectroscopic follow-up (limited telescope resources)
- WFIRST will mark a return to spectroscopic SN cosmology after a decade

Photometric SN Cosmology with SDSS

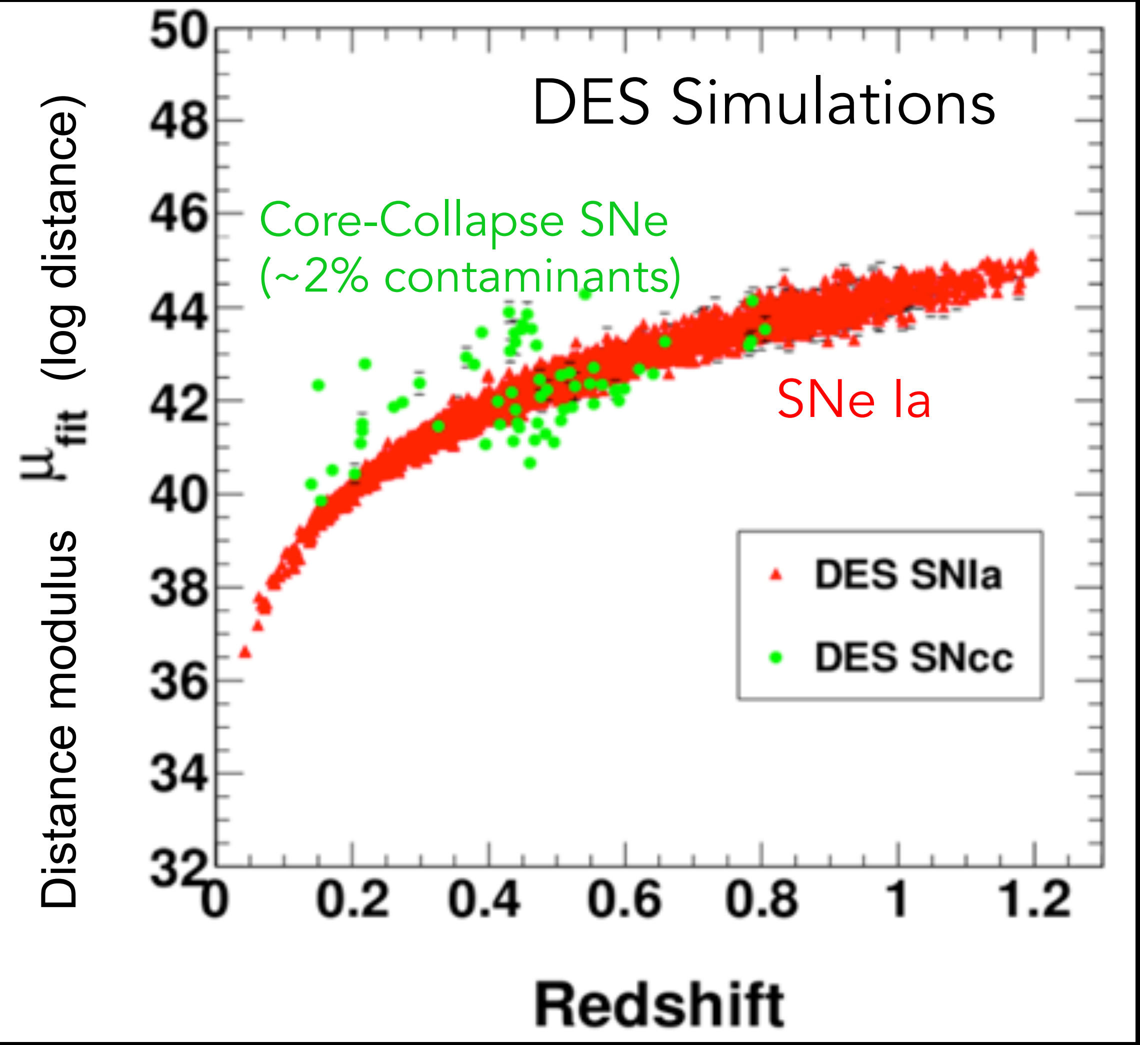
- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy spectroscopic redshifts



Campbell, etal

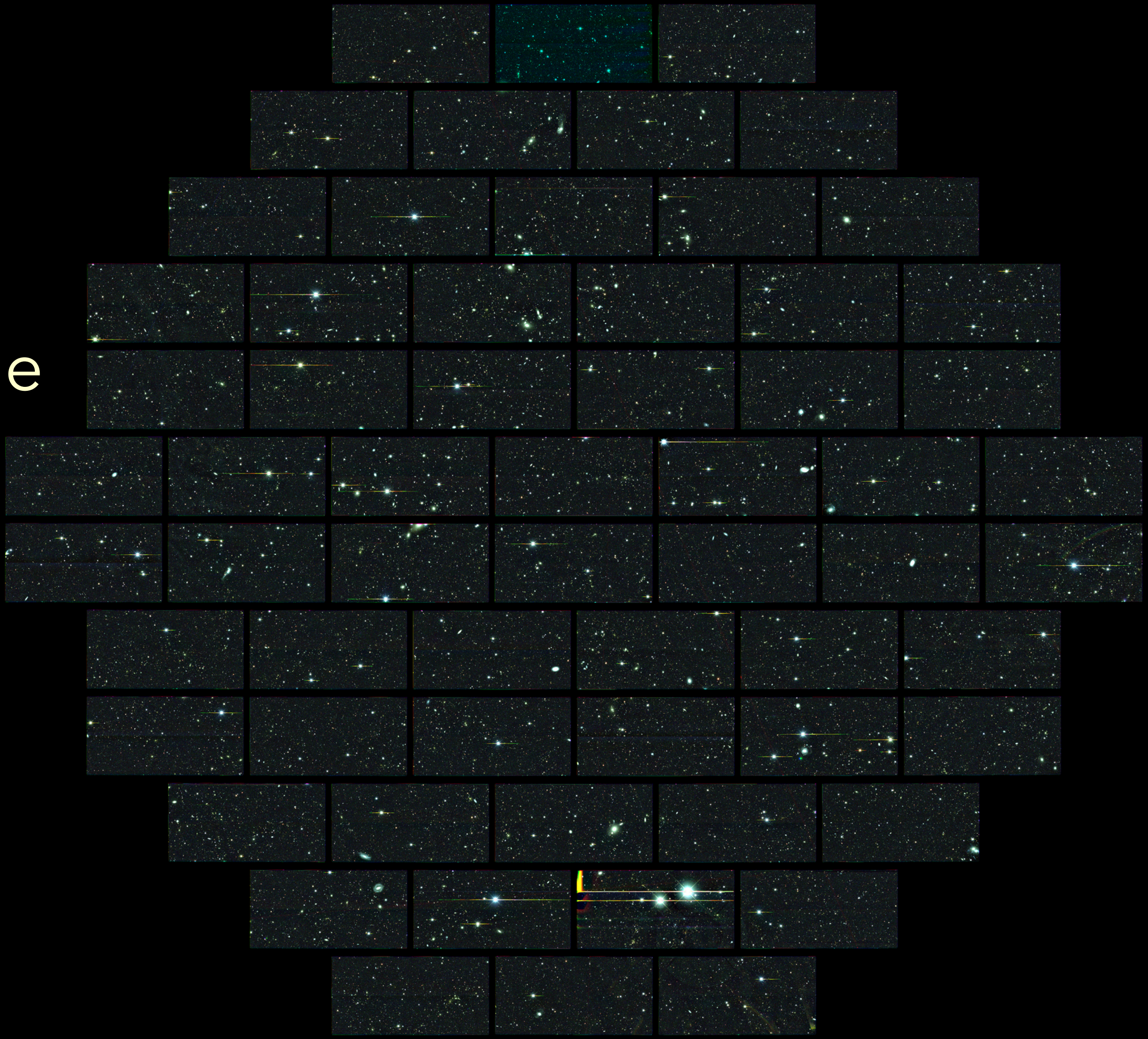
Photometric SN Cosmology with DES

- Hubble diagram of simulated DES SNe Ia
- Expected contamination from Core Collapse SNe appears to be subdominant cosmology systematic, but CC templates are limited



Bernstein, etal

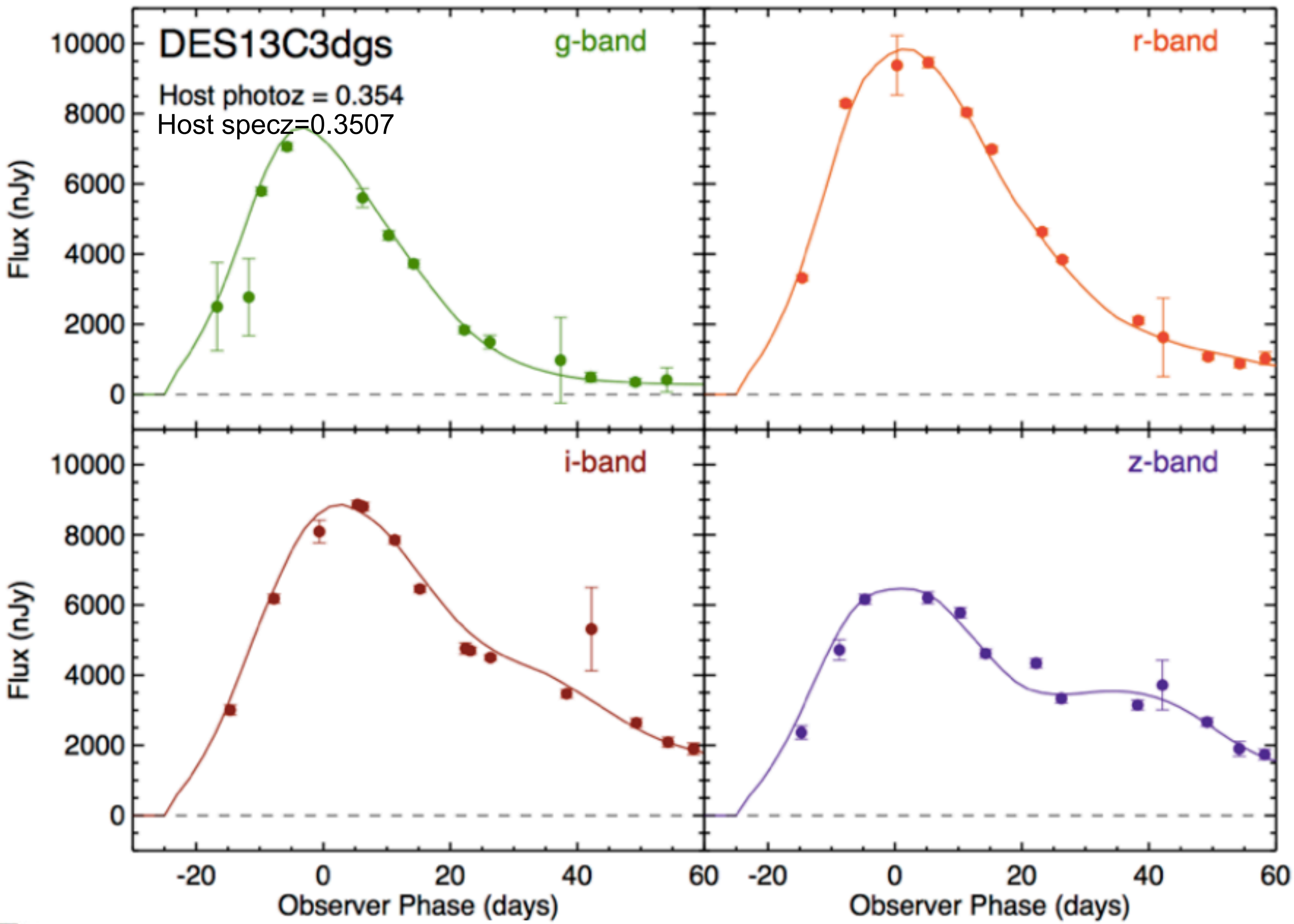
DES image of a deep SN field



DES image of a deep SN field

DES image of a deep SN field

A deep field DES SN light curve z=0.35



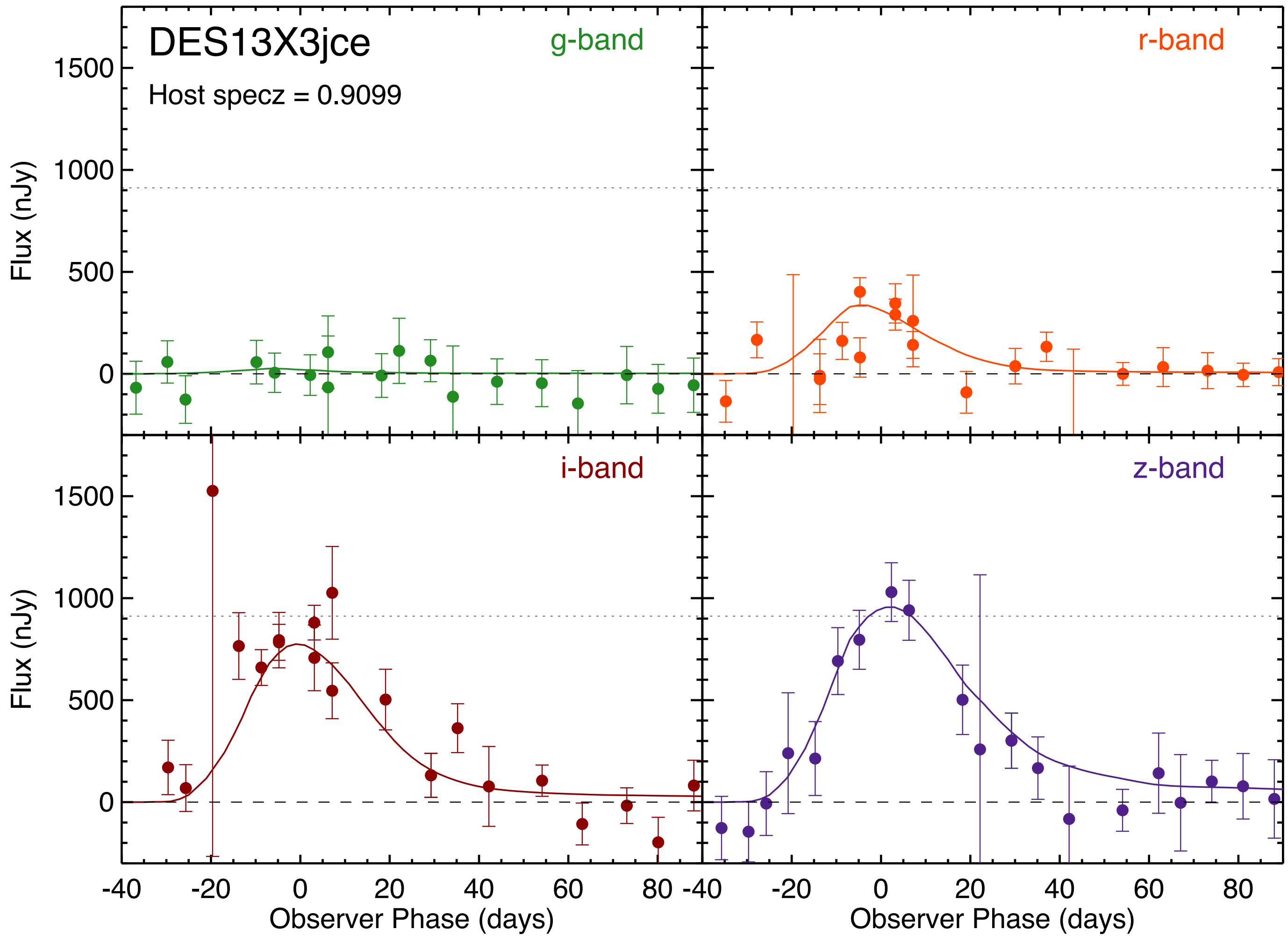
Data points: search photometry from subtracted DES images.

Solid lines: Fit to SALT2 light curve model.

THE DARK ENERGY SURVEY

Graphics: C. D'Andrea

A high redshift DES SN light curve: z=0.9



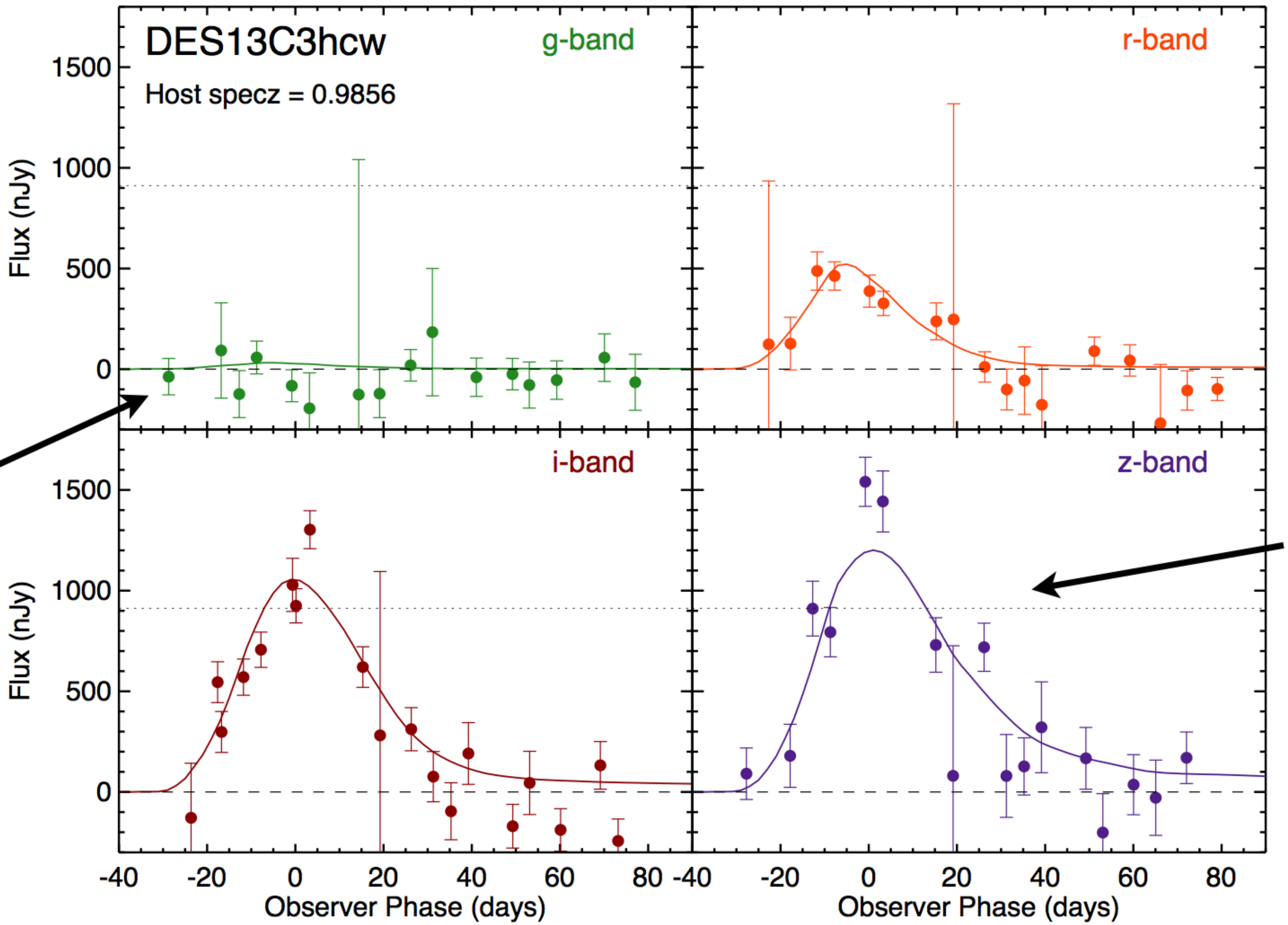
Data points: search photometry from subtracted DES images.

Solid lines: Fit to SALT2 light curve model.

THE DARK ENERGY SURVEY

Graphics: C.D'Andrea

A high redshift DES SN light curve: z=1.0



Good signal-to-noise ratio in the z band

THE DARK ENERGY SURVEY

Graphics: C.D'Andrea

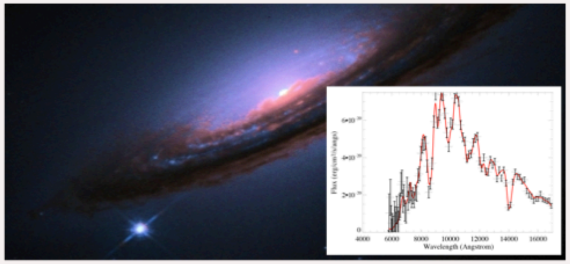
WFIRST-AFTA Dark Energy Roadmap

Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



High Latitude Survey

spectroscopic: galaxy redshifts

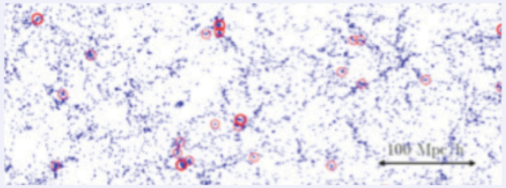
20 million Hα galaxies, z = 1–2
2 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

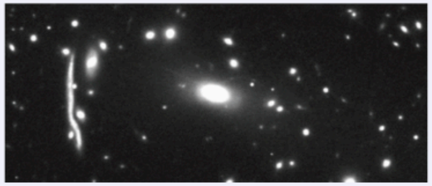
400 million lensed galaxies
40,000 massive clusters

standard ruler

distances	**expansion rate**
z = 1–2 to 0.4%	z = 1–2 to 0.72%
z = 2–3 to 1.3%	z = 2–3 to 1.8%

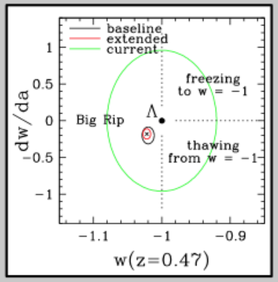


dark matter clustering
z < 1 to 0.16% (WL); 0.14% (CL)
z > 1 to 0.54% (WL); 0.28% (CL)
1.2% (RSD)



history of dark energy
+
deviations from GR

$w(z)$, $\Delta G(z)$, Φ_{REL}/Φ_{NREL}

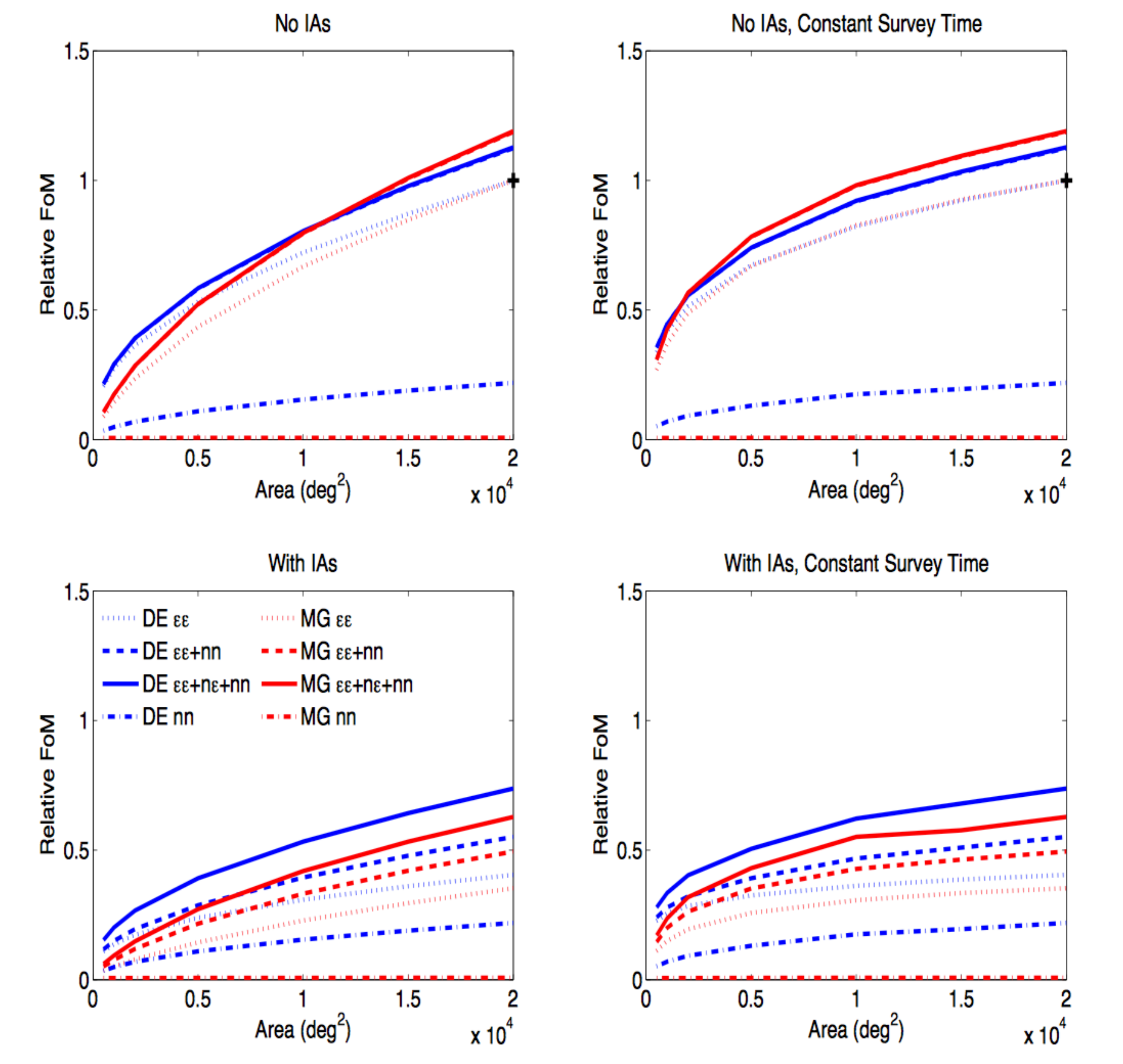


Complementarity of Ground & Space

- Ground offers:
  - Wide area coverage (long mission times)
  - *Optical* multi-band surveys, photo-z's necessary for NIR space surveys
  - Adequate for shapes to m~25 and z~1 (beyond that, majority of sources poorly resolved and/or blended)
- Space advantages:
  - Infrared → High-redshift → larger volumes → reduced cosmic and systematic errors
  - Deeper, pristine imaging (small, stable PSF)
- Potentially substantial gains from coordinating operations and data analysis from ground+space surveys
  - Optical (ground) + NIR (space) improves ground-based photo-z's but necessary for space-based photo-z's

Systematics & Area vs Depth

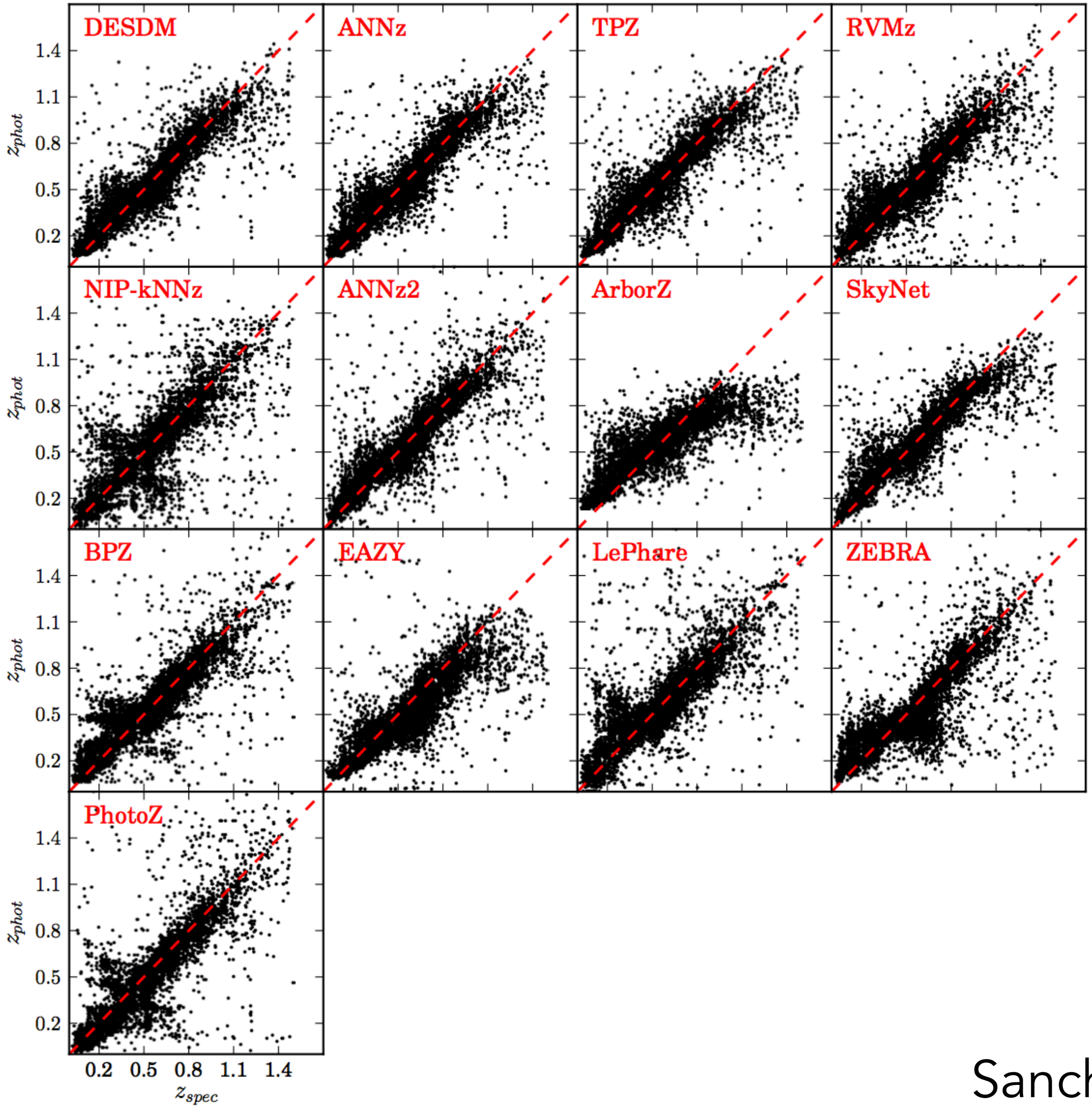
- Stage IV WL+LSS +galaxy-galaxy lensing forecast
- Inclusion of intrinsic alignment systematic error alters trade optimization of area vs depth: WFIRST vs Euclid
- SN systematics also favor z leverage (depth)



Kirk, et al 2012

Photo-z comparison test

Results for Early DES Data



consistent with expectations

Sanchez, et al 2014

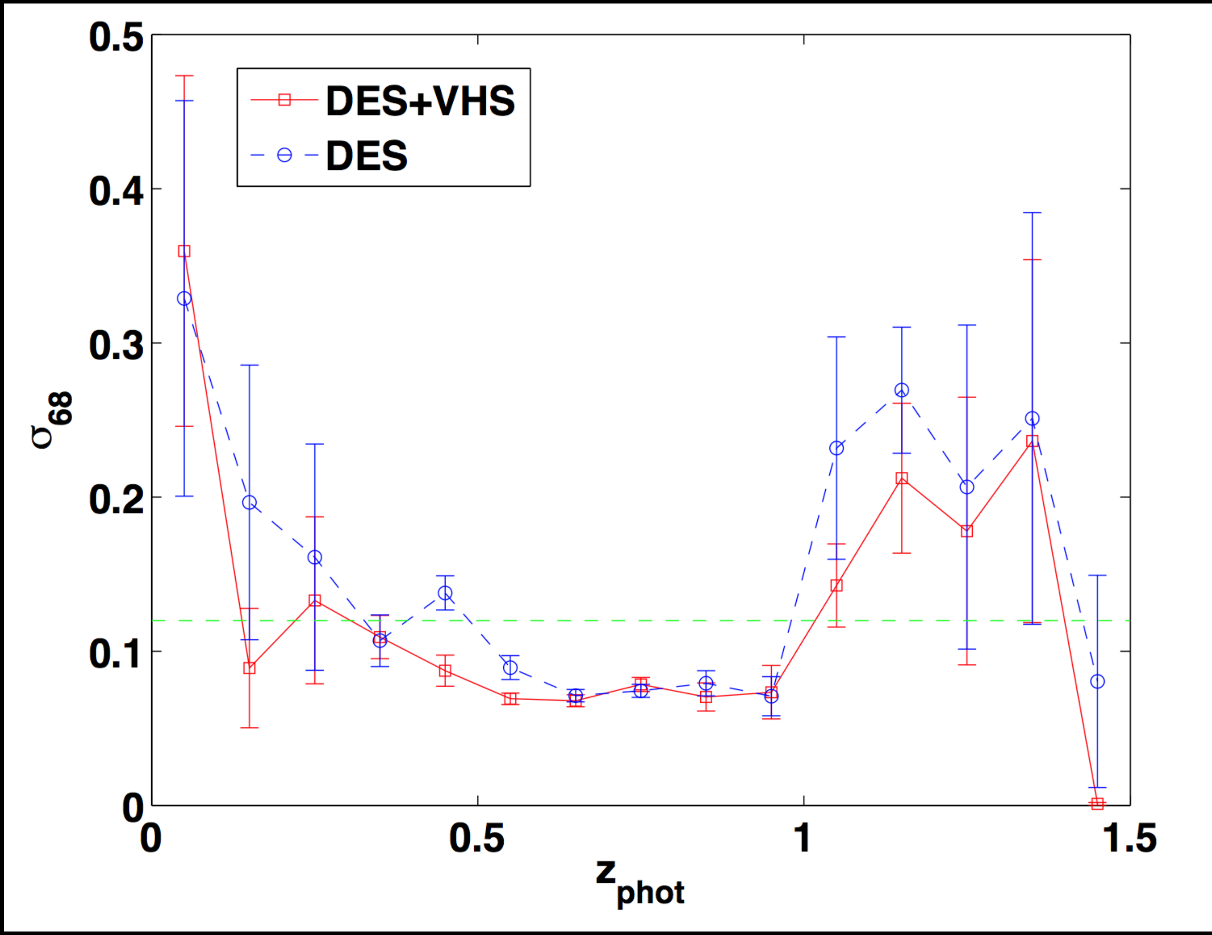
Photometric Redshifts: Optical+NIR

- Combine optical grizY imaging from DES with JK near-infrared imaging from the overlapping Vista Hemisphere Survey (ESO 4m)

- Expect improved photo-z precision, particularly for z>1.

- Results from early data over 150 sq. deg shown

- Model for LSST optical +WFIRST NIR



Banerji, et al 2014

Photo-z Bias and Figure of Merit

- Stage IV WL+LSS +galaxy-galaxy lensing forecast
- Controlling bias at ~10^{-3} requires ~10^5 spectroscopic galaxies
- Inclusion of intrinsic alignments can weaken dependence on photo-z bias

Kirk, et al 2012

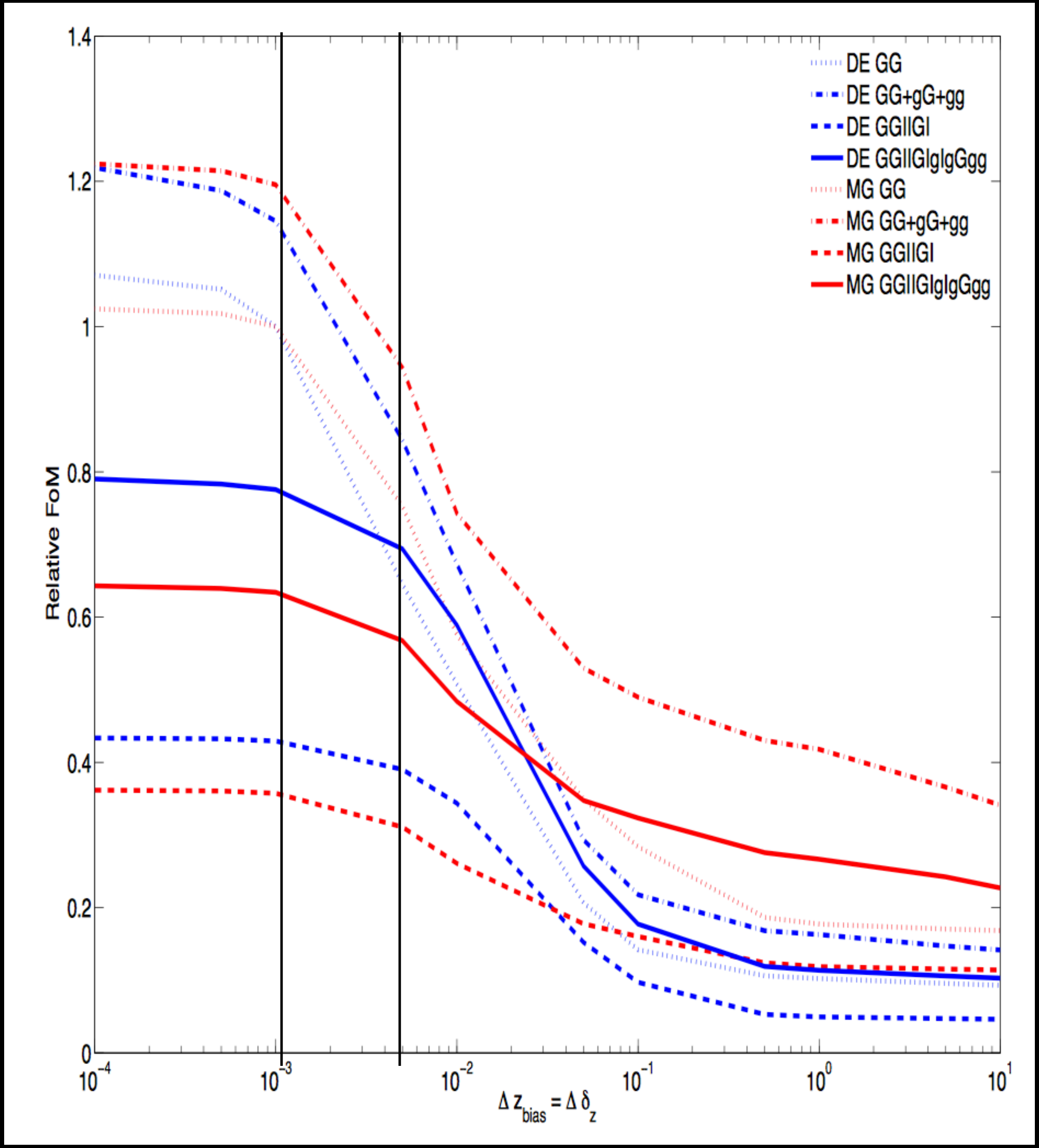


Photo-z Training & Validation

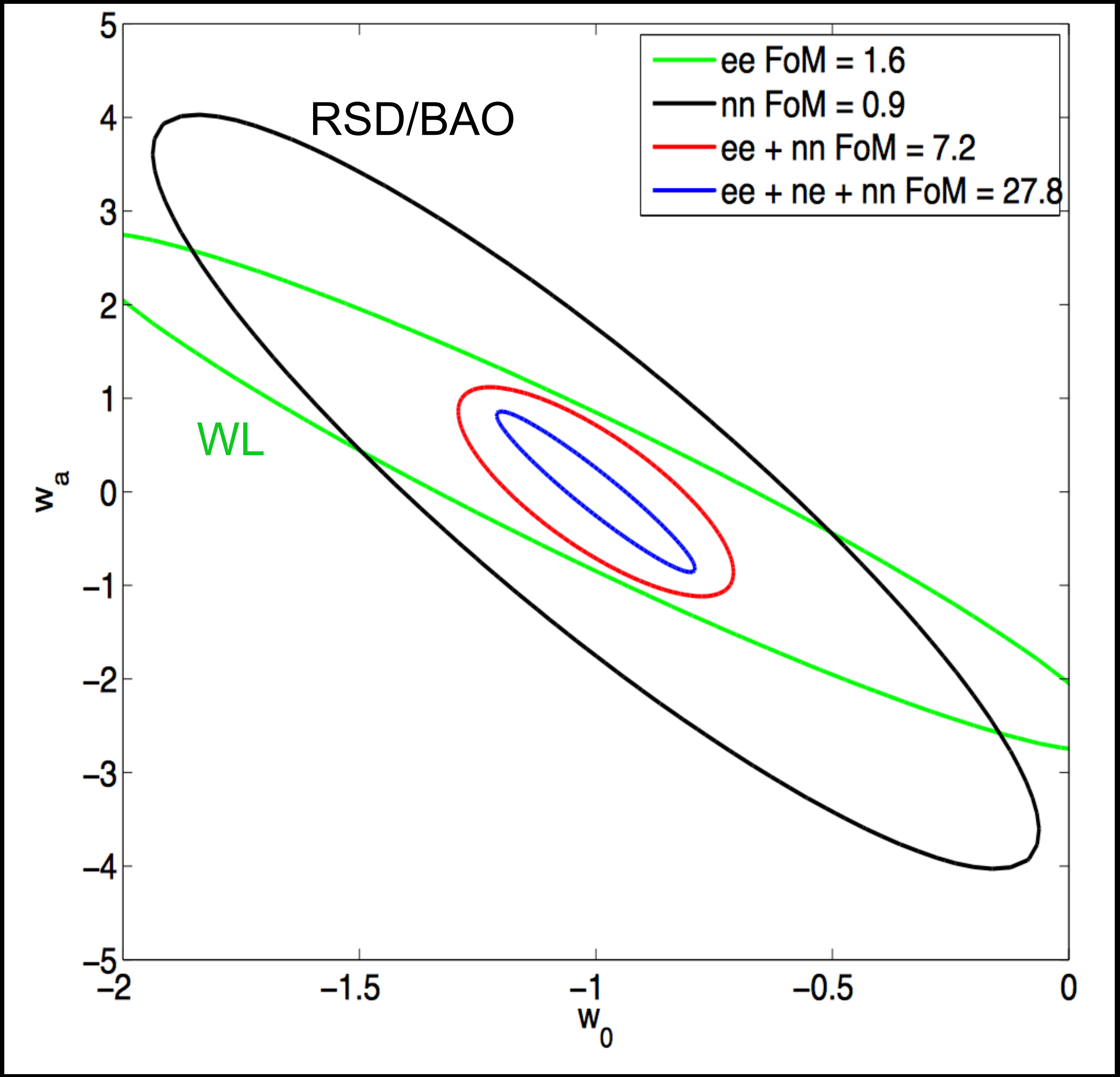
- Uncertainties in photo-z bias and error (or N(z)) potentially dominant sources of systematics for ground- and space-based DE projects
- Current spectroscopic samples incomplete at faint magnitudes
  - Training of machine-learning photo-z methods
  - Calibration of photo-z errors & bias
- Training samples to LSST/WFIRST depth would require large amounts of 10-30m time: global coordination?
- Angular cross-correlation method promising but not yet battle-tested at faint magnitudes
- Are multiplexed narrow-band surveys a useful alternative?
- WFIRST IFU galaxy spectroscopy?

See talk by Jeff Newman

Combining Covariant Probes

- Break degeneracies by constraining nuisance parameters
- Magnitude of effect may depend on assumptions

Kirk, et al 2013



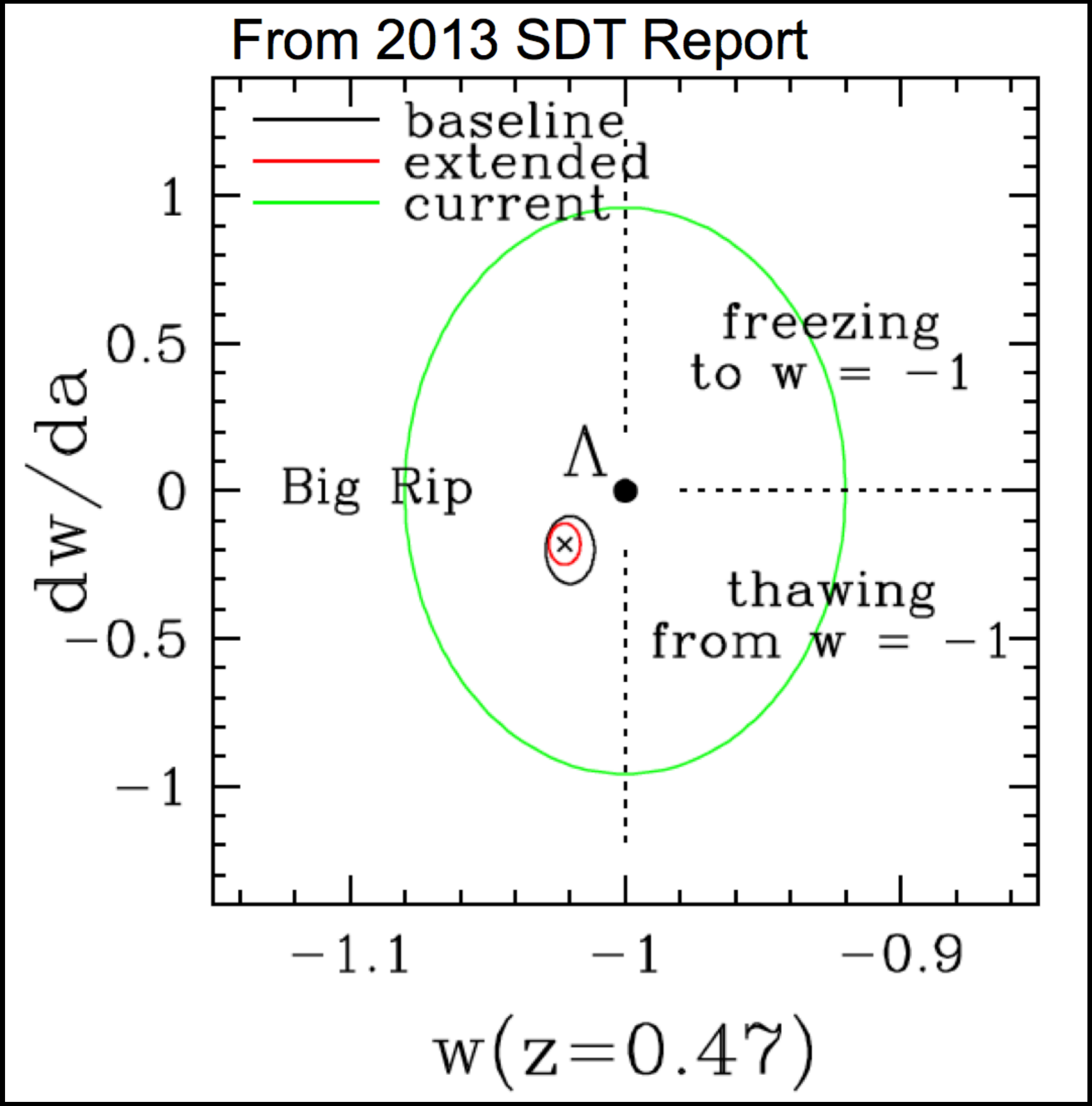
Late-night Questions for SDT

- Does complementarity of methods (e.g., RSD and WL) impact imaging and spectroscopic survey optimization for WFIRST Dark Energy or Modified Gravity FoM?
- Supernova Survey Strategy optimization:
  - Model of systematics error floor in z-bins argues for high-z
  - Complementarity with BAO argues for mid-z
  - Reduction of scatter/dust argues for mid-z (rest-frame NIR)
  - IFU synthetic photometry vs imaging?
  - Will SN constraints be limited by low-z sample systematics?

See talks by Dan Scolnic, Ryan Foley

Dark Energy Landscape in 2024

- DES, HSC long done
- DESI, PFS wrapping up
- LSST in ~3rd year of survey operations
- Euclid in mature operation
- WFIRST launches
  - Is WFIRST to Euclid as Planck is to WMAP?
  - Multiplicity of experiments and probes suggests there will be a number of tensions to resolve, due to systematics and/or departures from ΛCDM.



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