DARK ENERGY SURVEY

Dark Energy Survey

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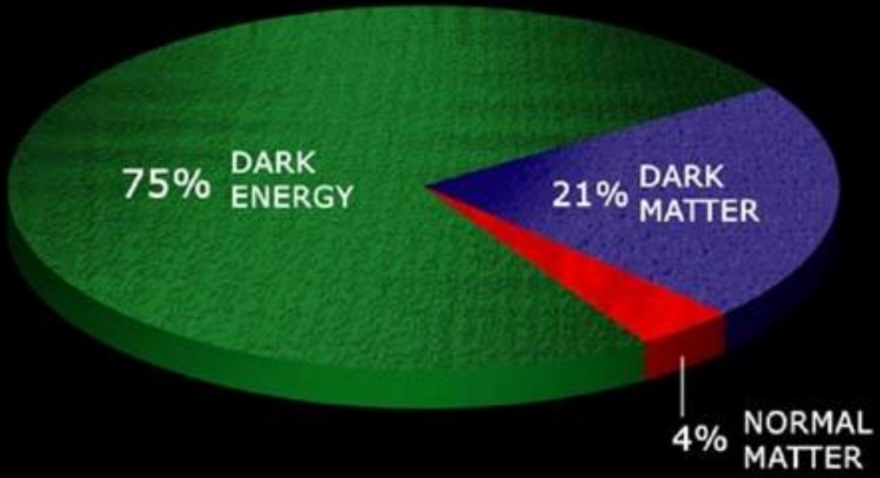
DES Project Director
Fermilab and the University of Chicago

Seeing the Big Picture:
DECam Community Workshop
Tucson, August 2011

www.darkenergysurvey.org

Dark Energy

- 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*?



Cosmological Constant and Acceleration

Einstein:

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Zel'dovich and Lemaitre:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

$$\equiv 8\pi G\left(T_{\mu\nu}(\mathrm{matter}) + T_{\mu\nu}(\mathrm{vacuum})\right)$$

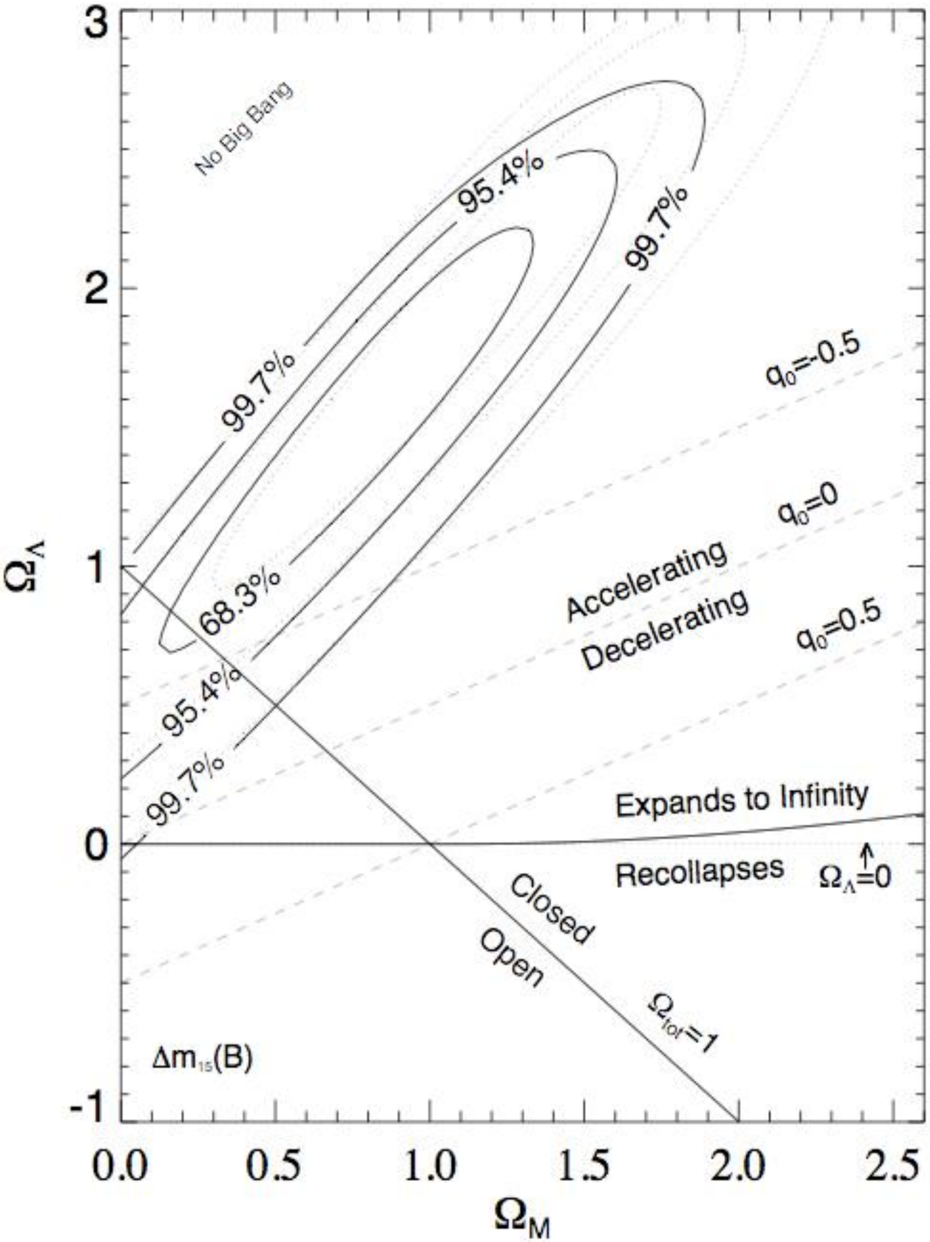
Vacuum Energy:

$$T_{\mu\nu}(\mathrm{vac}) = \frac{\Lambda}{8\pi \mathrm{G}} g_{\mu\nu}$$

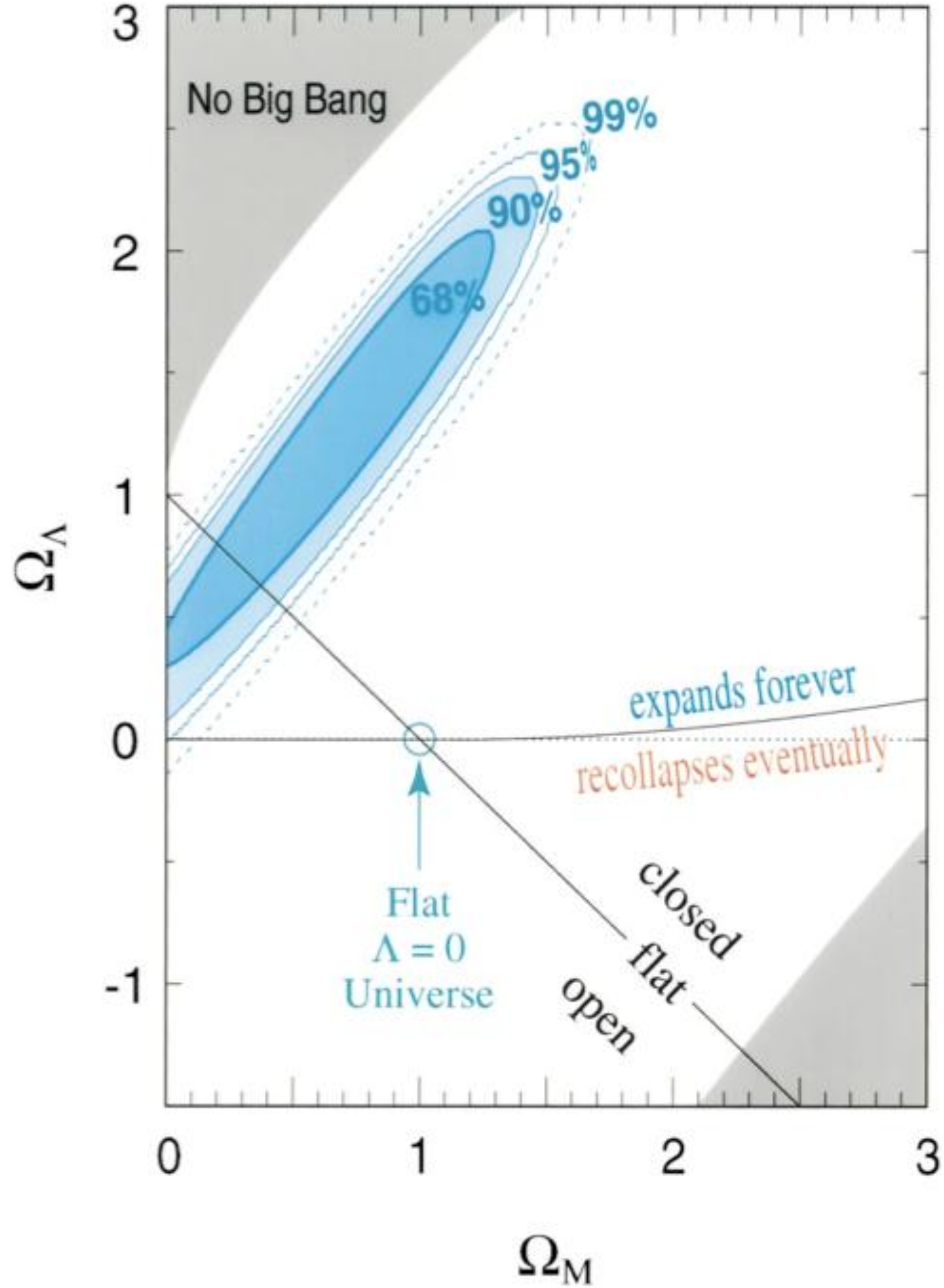
$$\rho_{\mathrm{vac}} = T_{00} = \frac{\Lambda}{8\pi \mathrm{G}}, \quad p_{\mathrm{vac}} = T_{ii} = -\frac{\Lambda}{8\pi \mathrm{G}}$$

$$w_{\mathrm{vac}} \equiv p_{\mathrm{vac}} / \rho_{\mathrm{vac}} = -1 \;\Rightarrow\; H = \mathrm{constant} \;\Rightarrow\; a(t) \propto \exp(Ht)$$

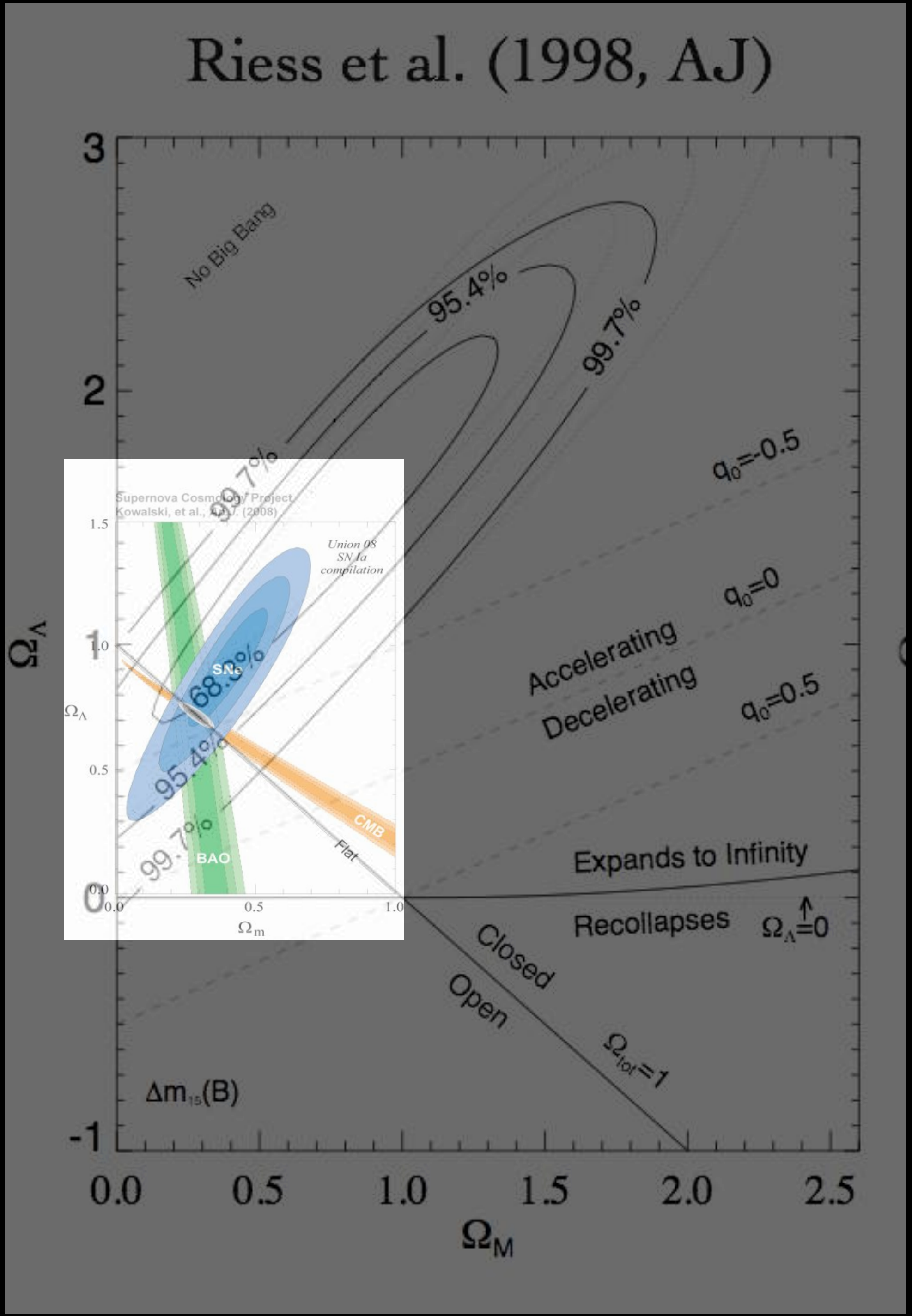
Riess et al. (1998, AJ)



Perlmutter et al. (1999, ApJ)



Progress over the last 12 years



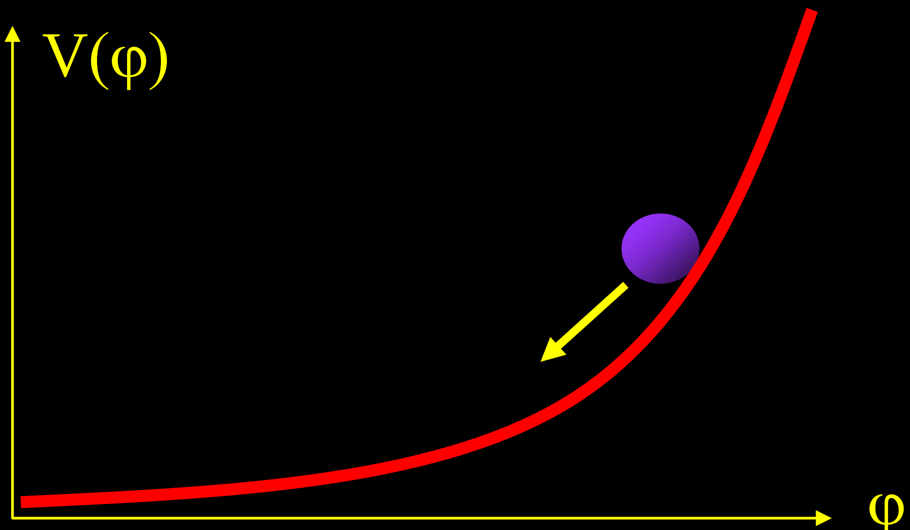
Scalar Field Dark Energy
(aka quintessence)

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

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

- Density & pressure:

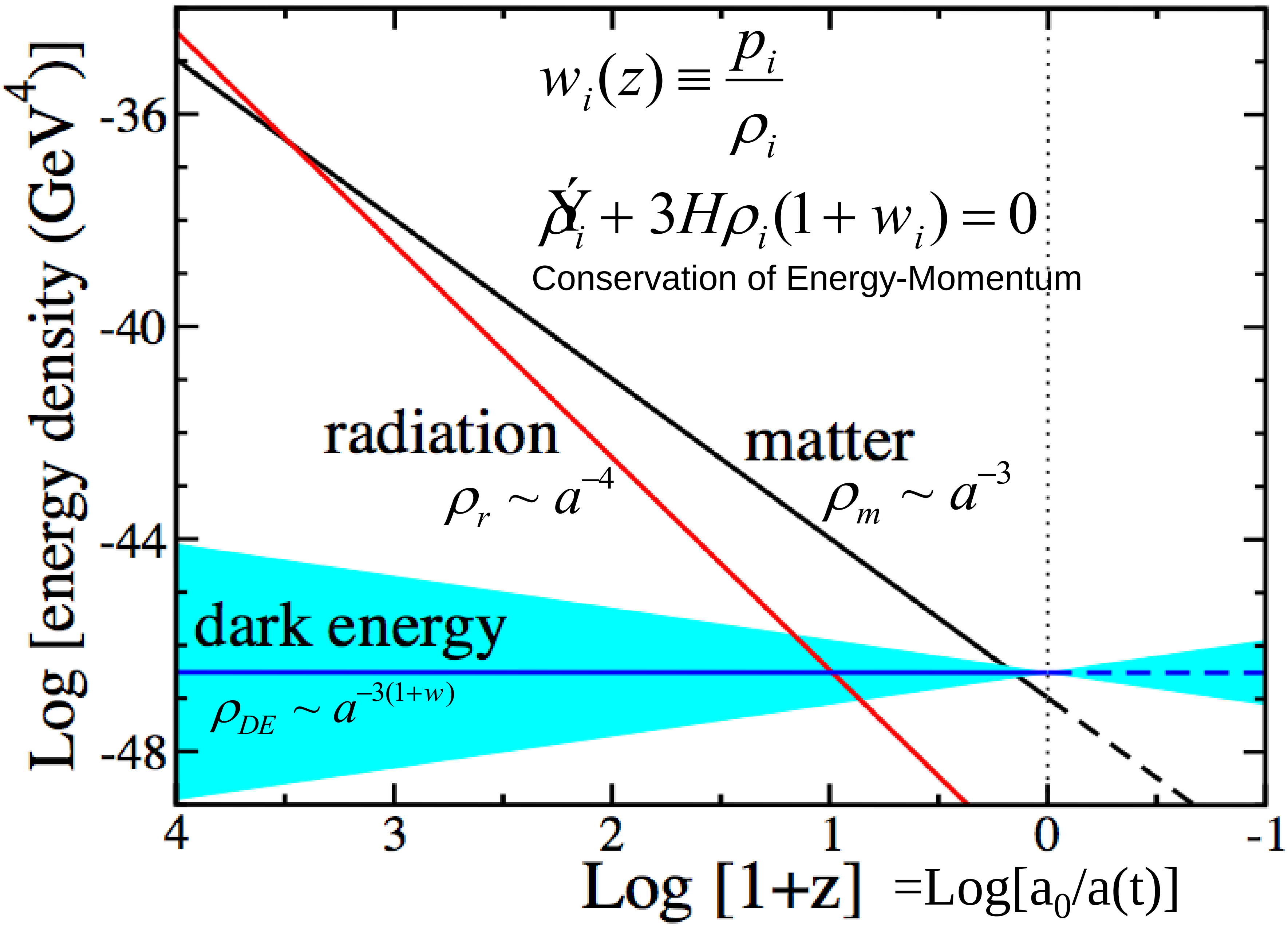
$$\rho = \tfrac{1}{2}\dot{\varphi}^2 + V(\varphi)$$
$$P = \tfrac{1}{2}\dot{\varphi}^2 - V(\varphi)$$



- Slow roll:

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

Equation of State parameter *w* determines Cosmic Evolution



What can we probe?

- Probe dark energy through the history of the expansion rate:

$$\frac{H^2(z)}{H_0^2} = \Omega_m (1+z)^3 + \Omega_{DE} \exp\left[3\int (1+w(z))\, d\ln(1+z)\right] + (1-\Omega_m-\Omega_{DE})(1+z)^2$$

- and the growth of large-scale structure: $\frac{\delta\rho(a)}{\rho}$

- Distances are indirect proxies for *H(z)*:
  Form of *F* depends on spatial curvature

$$r(z) = F\left[\int \frac{dz}{H(z)}\right]$$

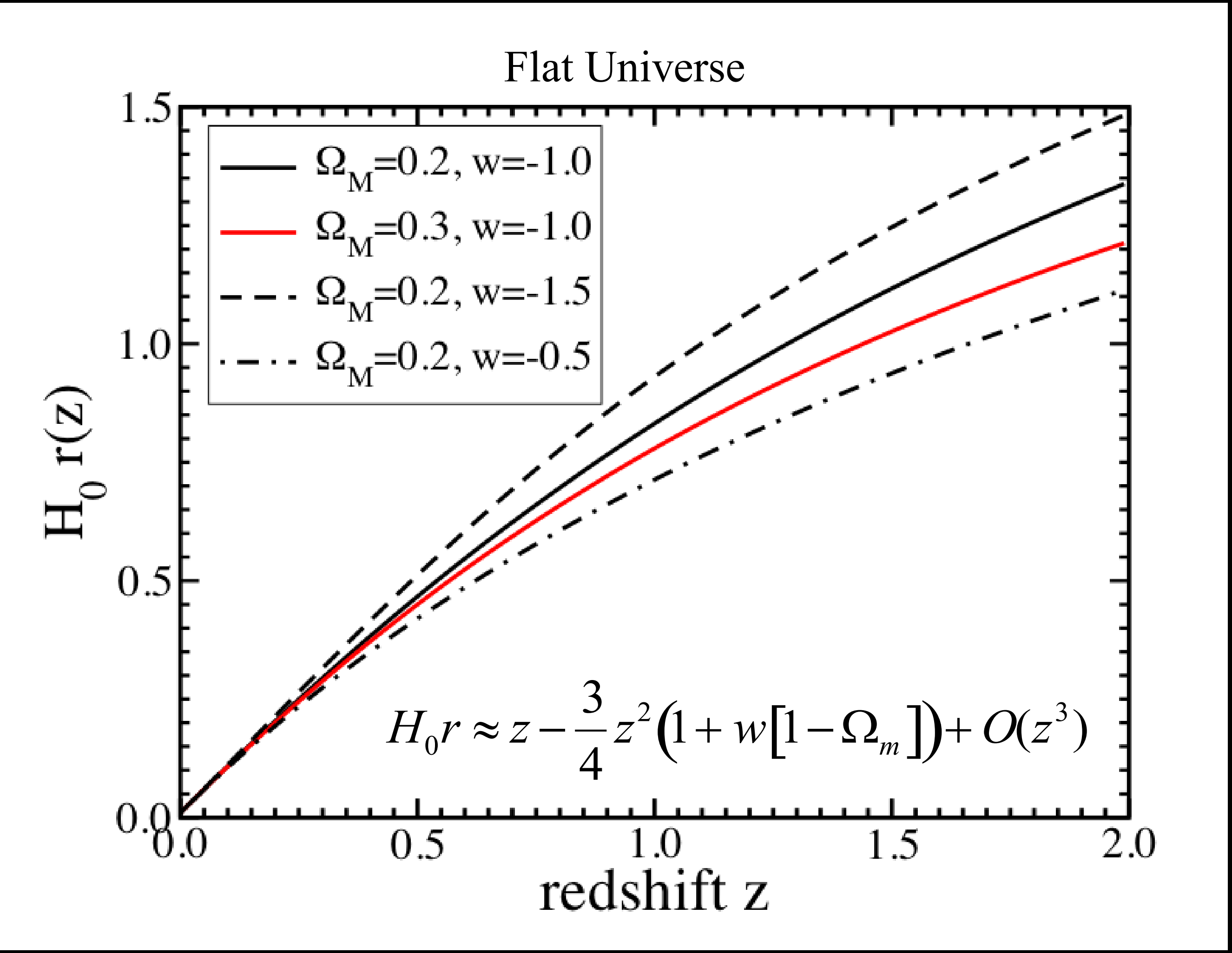
$$d_L(z) = (1+z)r(z)$$

$$d_A(z) = (1+z)^{-1} r(z)$$

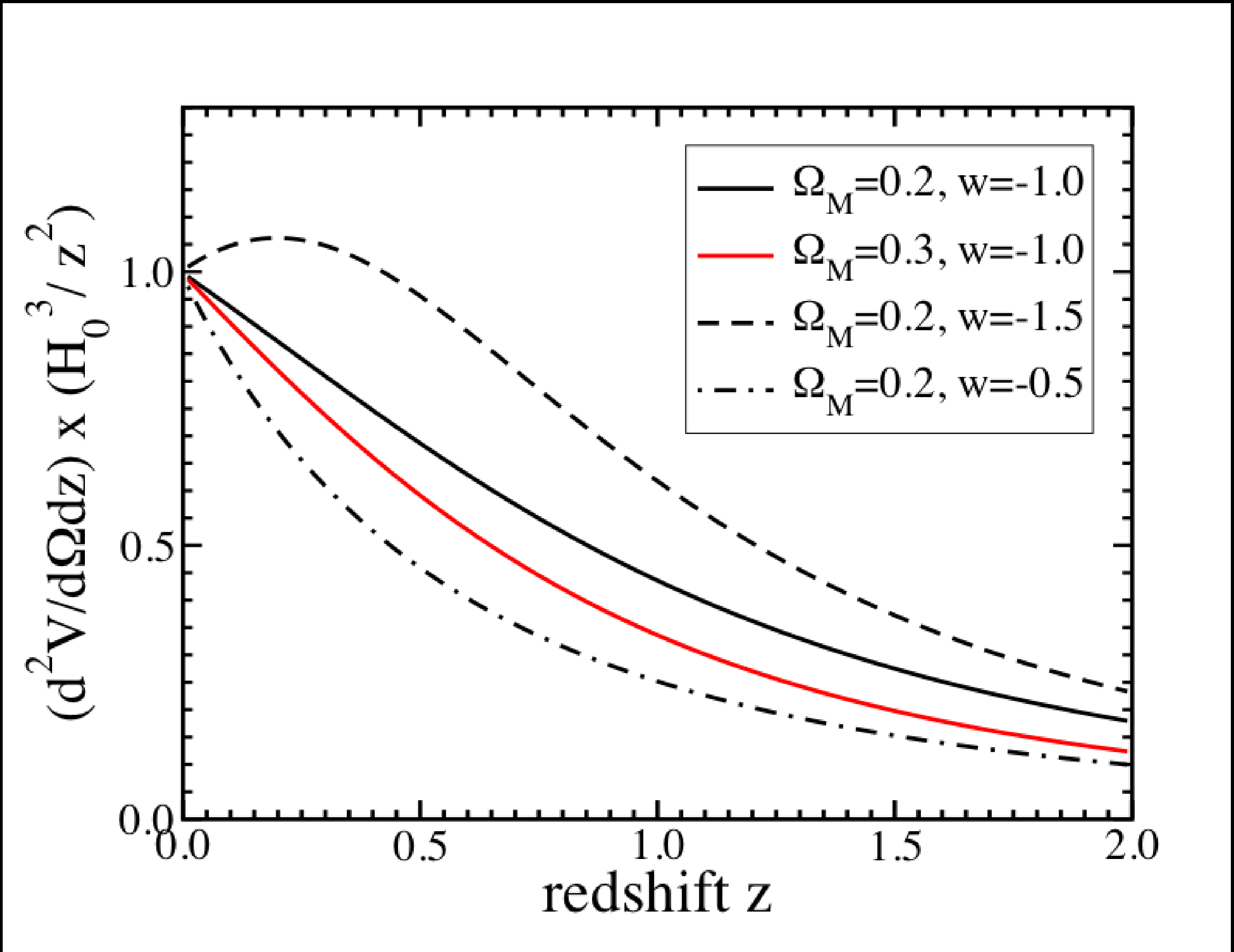
$$\frac{d^2V}{dz\,d\Omega} = \frac{r^2(z)}{H(z)}$$

- Weak Lensing cosmic shear — Distance+growth
- Supernovae — Distance
- Baryon Acoustic Oscillations — Distance+*H(z)*
- Cluster counting — Distance (volume)+growth

Coordinate Distance



Volume Element



Growth of Density Perturbations

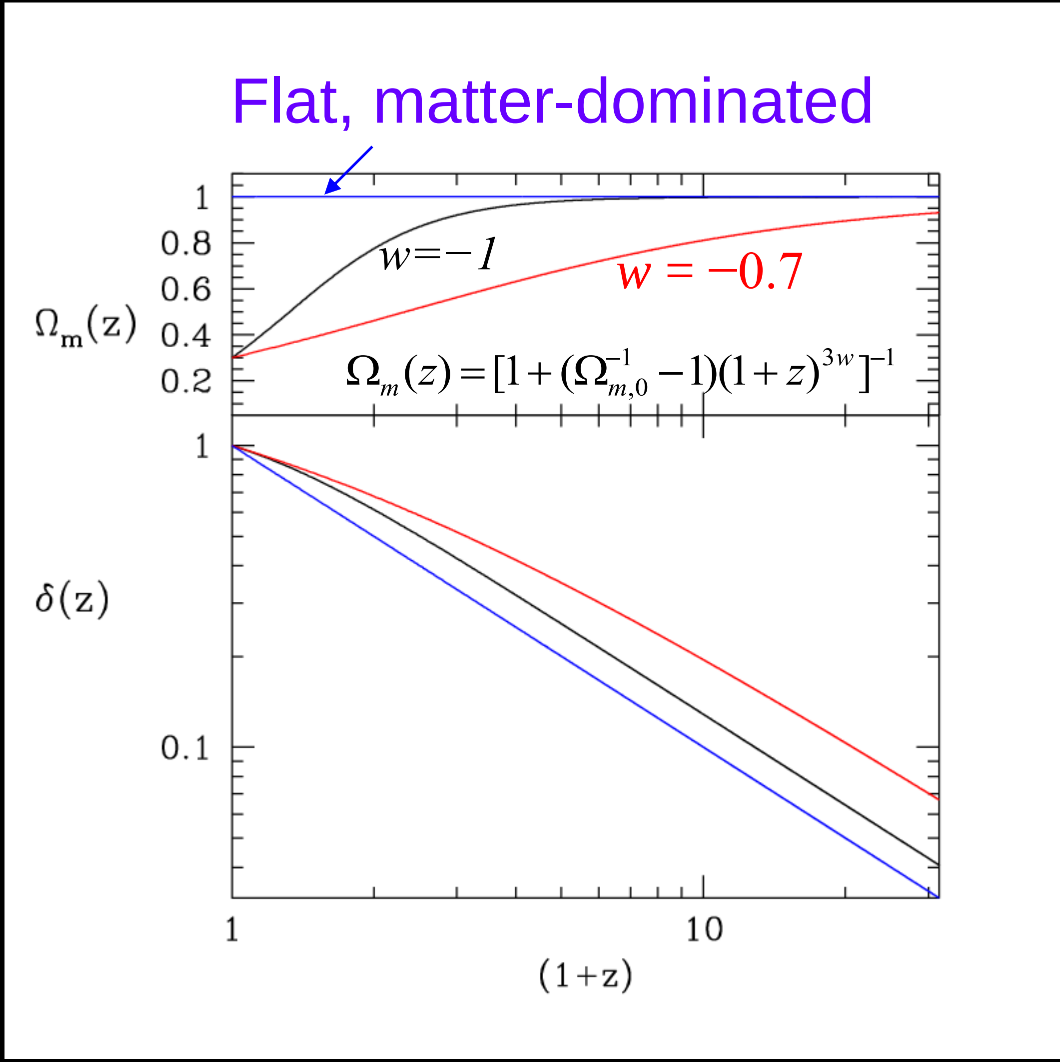
Linear growth of perturbations:

$$\delta_m(x,t) \equiv \frac{\rho_m(x,t) - \bar{\rho}_m(t)}{\bar{\rho}_m(t)}$$

$$\ddot{\delta}_m + 2H(t)\dot{\delta}_m - \frac{3}{2}\Omega_m(t)H^2(t)\delta_m = 0$$

Damping due to expansion

Growth due to gravitational instability



Testing General Relativity

- Metric for perturbed FRW Universe:

$$ds^2 = -[1+2\Psi(\vec{x},t)]dt^2 + a^2(t)[1-2\Phi(\vec{x},t)][d\chi^2 + r^2(\chi)d\Omega^2],$$

- Poisson equation for Modified Gravity:

$$k^2\Psi = 4\pi G a^2 \mu(a,k)\bar{\rho}\delta(k,a)$$

- Growth of Perturbations:

$$\ddot{\delta}(a,k) + 2H(a)\dot{\delta}(a,k) - \frac{k^2}{a^2}\Psi = 0$$

- GR: $\Psi = \Phi$ (no anisotropic stress), $\mu=1$, $d\ln\delta/d\ln a=\Omega_m^{0.6}$
- Weak Lensing: $\alpha = \nabla_\perp(\Phi + \Psi)$
- Need to probe growth *δ(a)* and *H(a)*.

The Dark Energy Survey

- Survey project using 4 complementary techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat (SNe)
- Build new 3 deg^2 FOV camera and Data management system
  - Survey 2012-2017 (525 nights)
  - Facility instrument for Blanco

Blanco 4-meter at CTIO

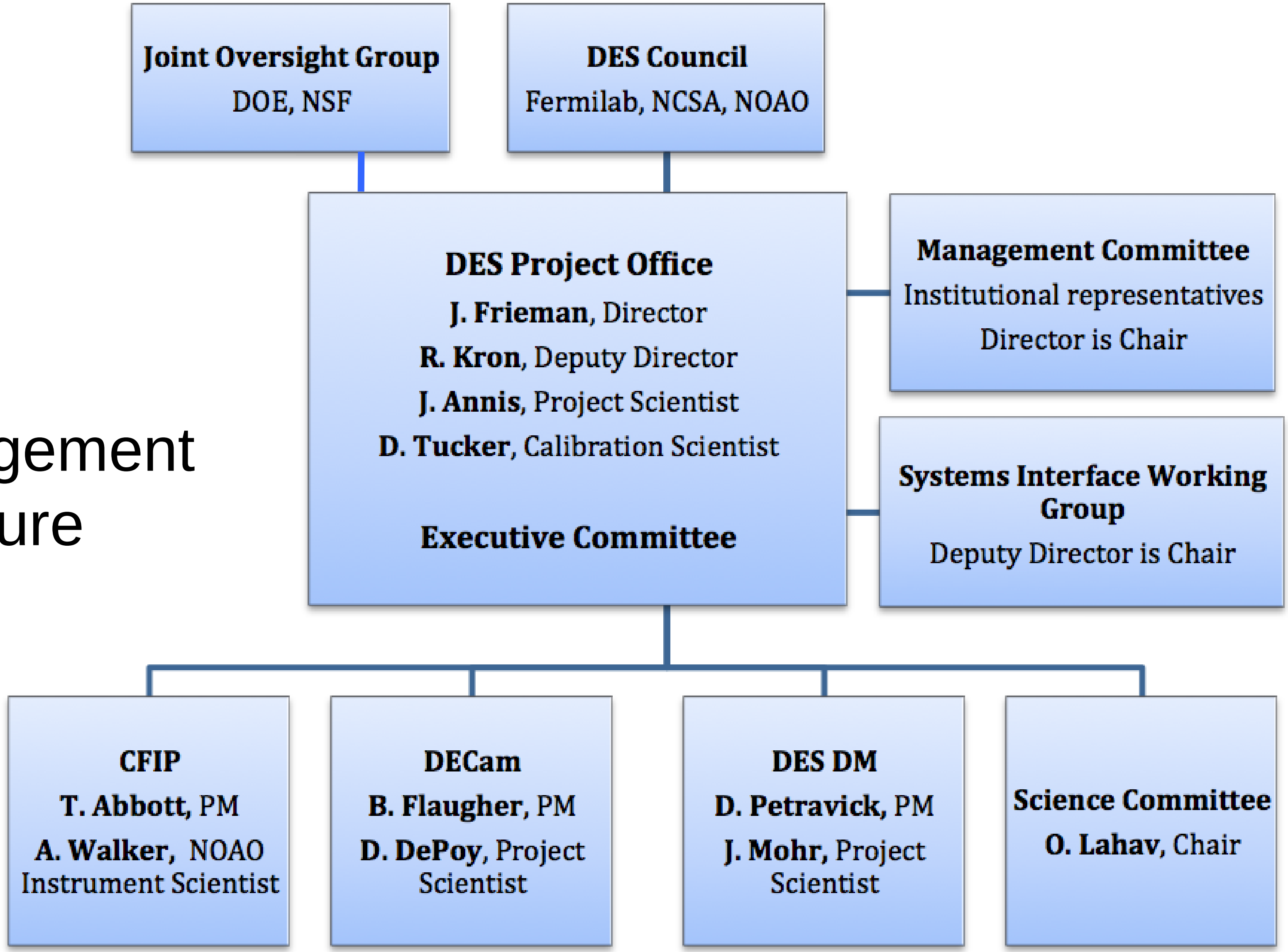
The DES Collaboration

Fermilab
University of Illinois at Urbana-Champaign/NCSA
University of Chicago
Lawrence Berkeley National Lab
NOAO/CTIO
DES Spain Consortium
DES United Kingdom Consortium
University of Michigan
Ohio State University
University of Pennsylvania
DES Brazil Consortium
Argonne National Laboratory
SLAC-Stanford-Santa Cruz Consortium
Universitats-Sternwarte Munchen
Texas A&M University
plus Associate members at: Brookhaven National Lab, U. North Dakota, Paris, Taiwan

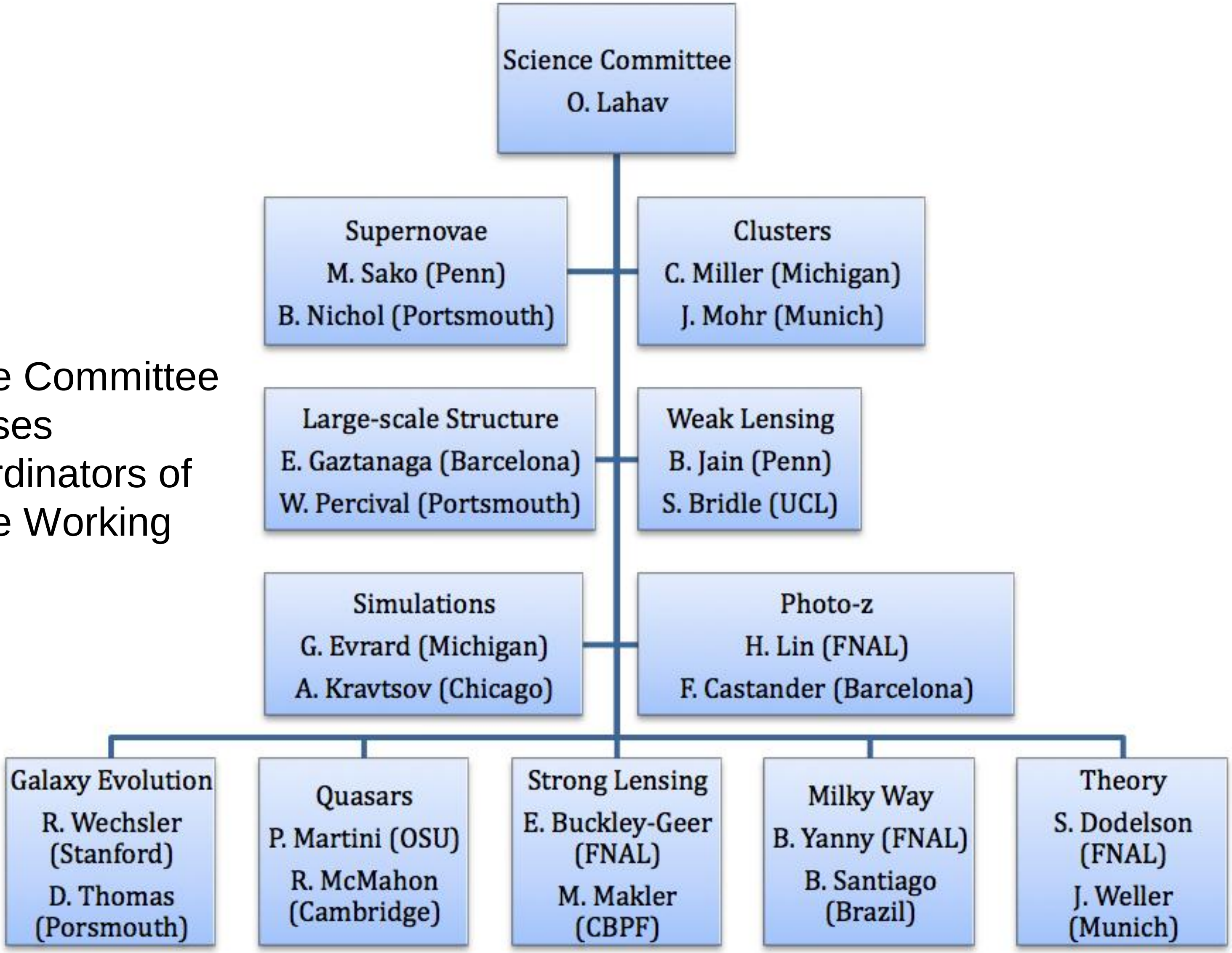
Over 120 members plus students & postdocs

Funding: DOE, NSF; UK: STFC, SRIF; Spain Ministry of Science, Brazil: FINEP, Ministry of Science, FAPERJ; Germany: Excellence Cluster; collaborating institutions

DES Management Structure



Science Committee comprises co-coordinators of Science Working Groups



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Project Structure & Timeline

- 3 Construction Projects:
  - DECam (hosted by FNAL; DOE supported)
  - Data Management System (NCSA; NSF support)
  - CTIO Facilities Improvement Project (NSF/NOAO)
    - NOAO Blanco Announcement of Opportunity 2003
    - DECam R&D 2004-8
    - Camera construction 2008-11
    - Final testing, integration now on-going
    - Shipping components to Chile this year
    - Installation on telescope begins Jan 2012
    - First light DECam on telescope: ~June 2012
    - Commissioning and Science Verification: June-Aug. 2012
    - Survey operations begin: Sept 2012

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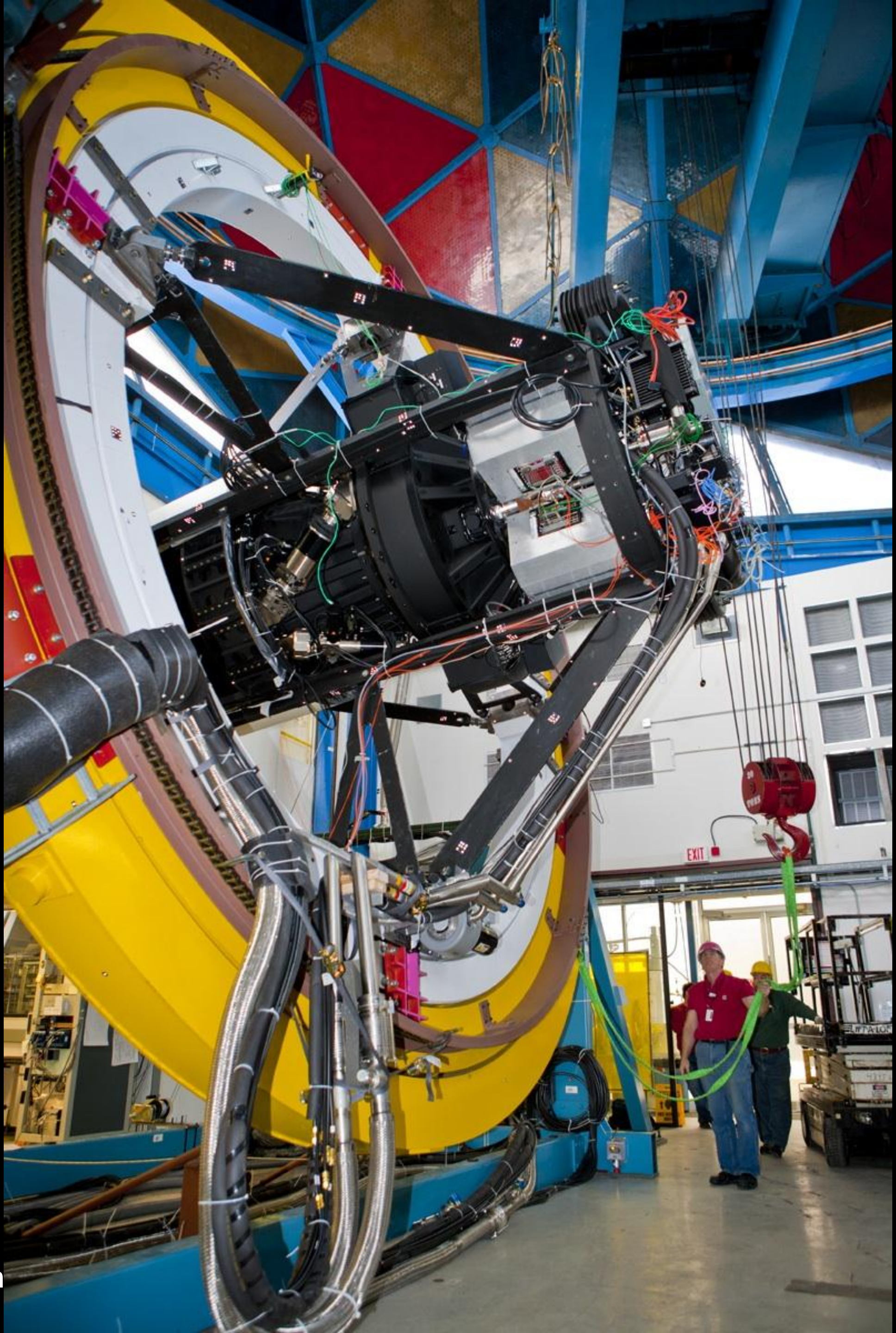
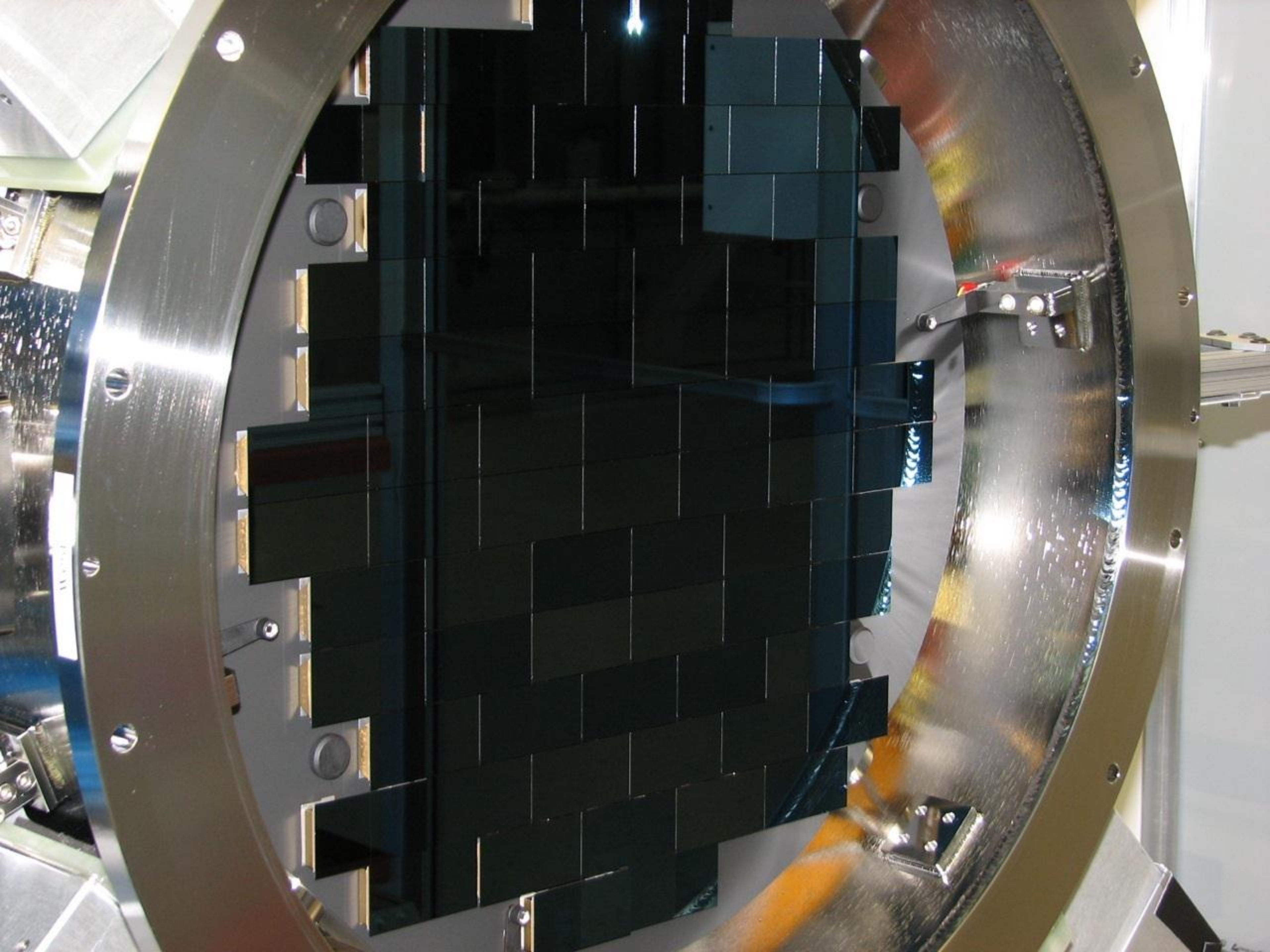
- DECam mounted on Telescope Simulator at Fermilab in early 2011

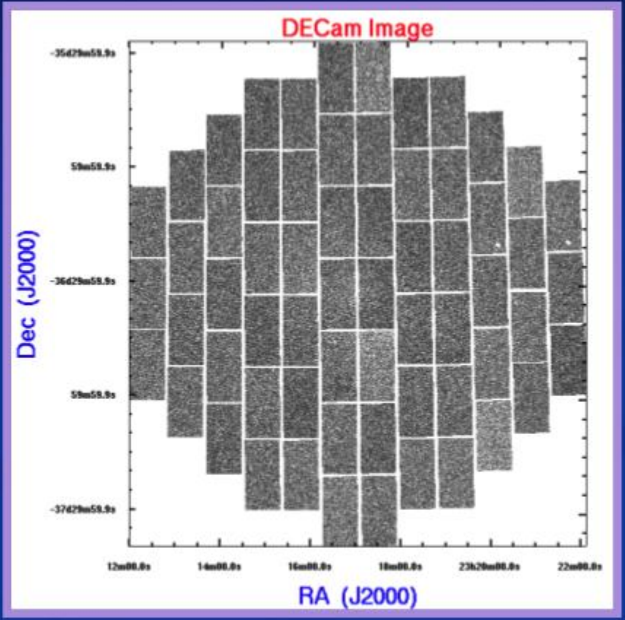




DES Data Management

http://cosmology.illinois.edu/DES/

- The DESDM system:
  - Process DES data at NCSA
  - Archive DES data over the long term
    - ~4PB total, ~350TB database
  - Distribute data to Collaboration
  - Distribute data to public
    - NOAO — Raw/reduced data after 1 yr
    - NCSA — Co-adds/catalogs at midpoint and end of survey



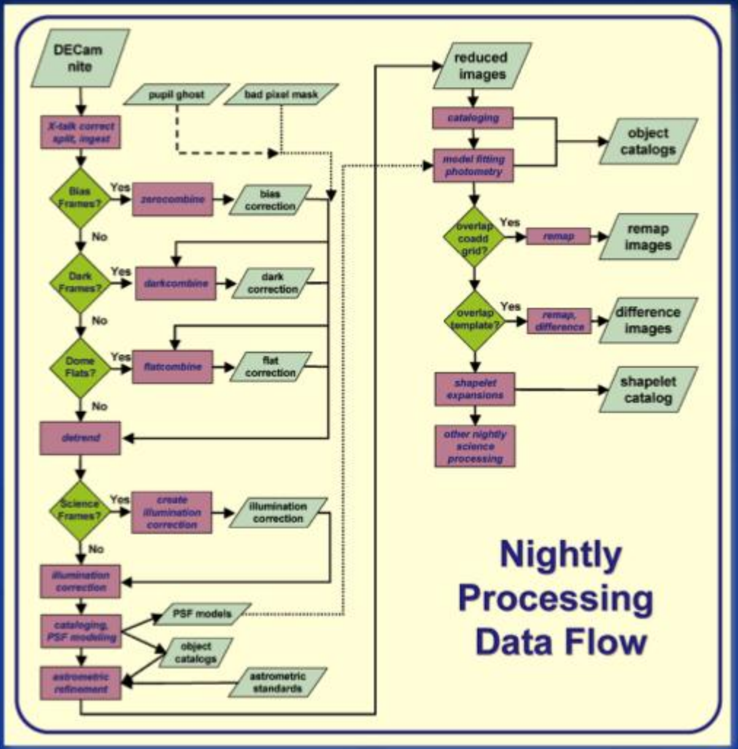
Exposure consists of 62 2kX4k CCD images - 3deg^2

Survey is ~150,000 exposures over 525 nights

For details, ask Brian Yanny, DES Data Coordinator, or Robert Gruendl, UIUC

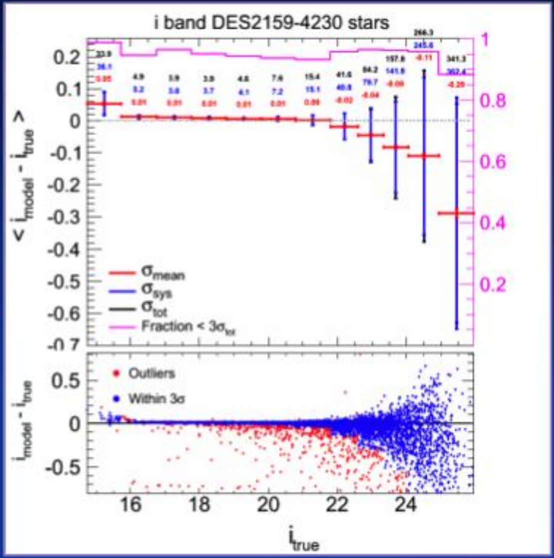
DESDM Processing

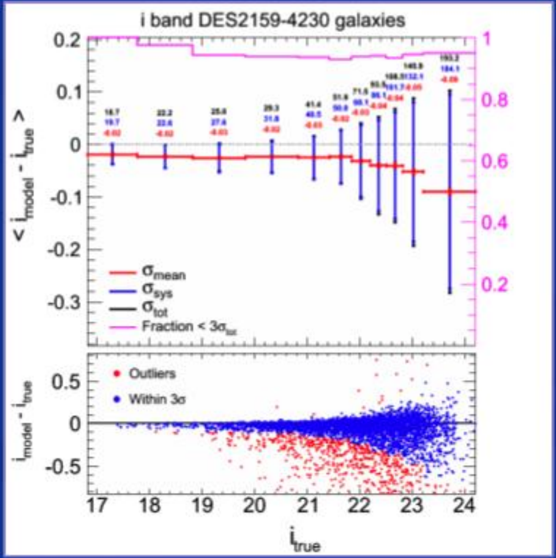
- DESDM processing includes:
  - Nightly processing
    - Detrending, astrometric refinement, remapping for coaddition and difference imaging, cataloging, ingestion to DES Archive and photometric calibration
  - Coaddition (w/PSF Homogenization)
    - Build and catalog deeper images of the sky
  - Weak Lensing
    - Extract shear measurements from the survey data (both single epoch and multi-epoch)
  - Difference Imaging
    - Support SNe science within dedicated fields
  - Photo-z, Survey Mask, etc



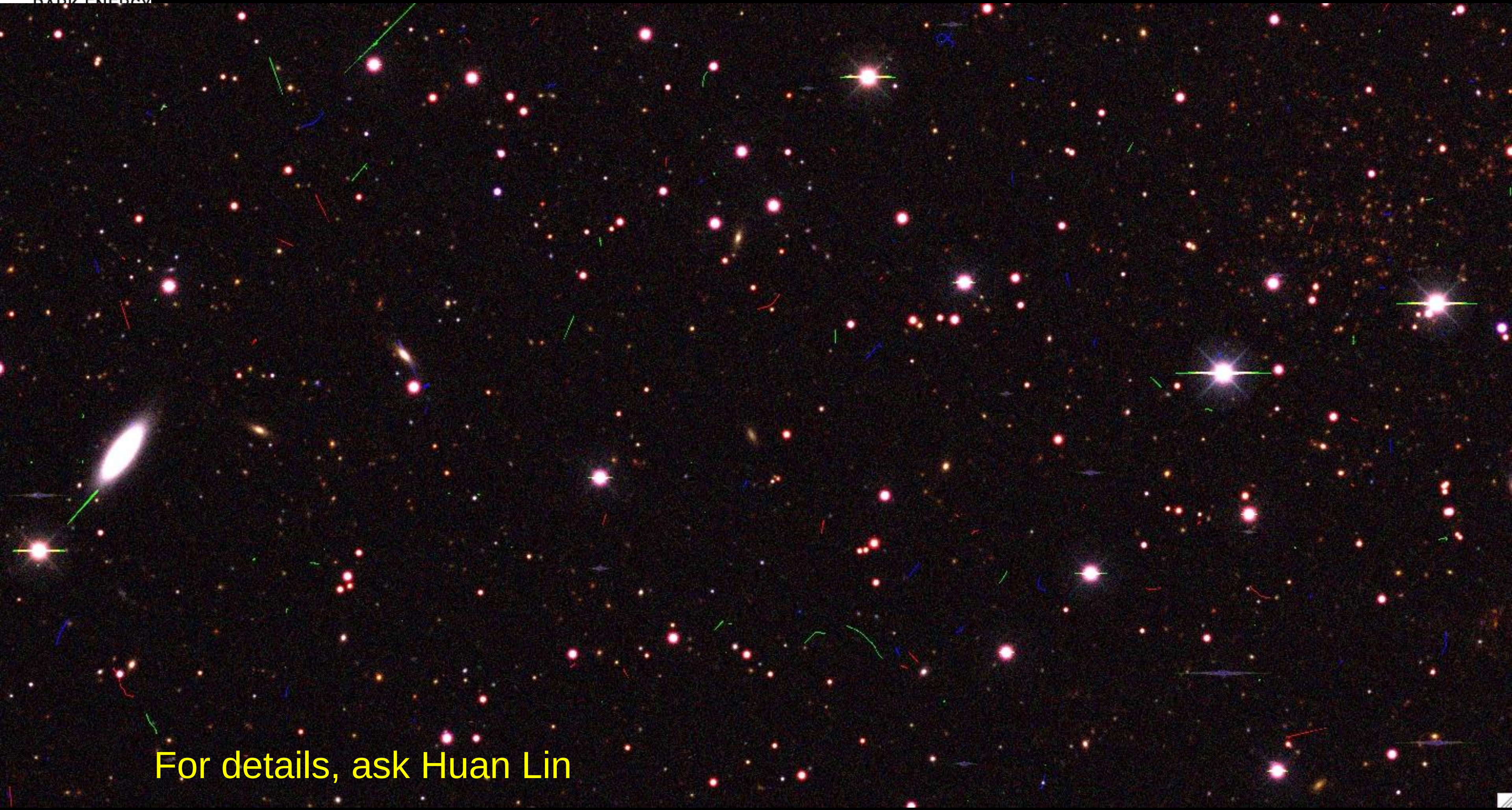
DES Data Quality

- Requirements:
  - <2% accurate photometric zeropoints
  - <100mas astrometry
  - Spatially uniform and accurate star-galaxy classification
- Strategy:
  - Develop DES specific detrending/calibration codes
  - Build upon existing AstroMatic toolkit from Bertin
- PSF Corrected Model Fitting Photometry
  - PSFEx used to model PSF variation across images
  - SExtractor extended to do PSF corrected model fitting
- PSF Homogenization for Coadds
  - Use PSFEx and tools that will be integrated into SWarp to build uniform median seeing coadds





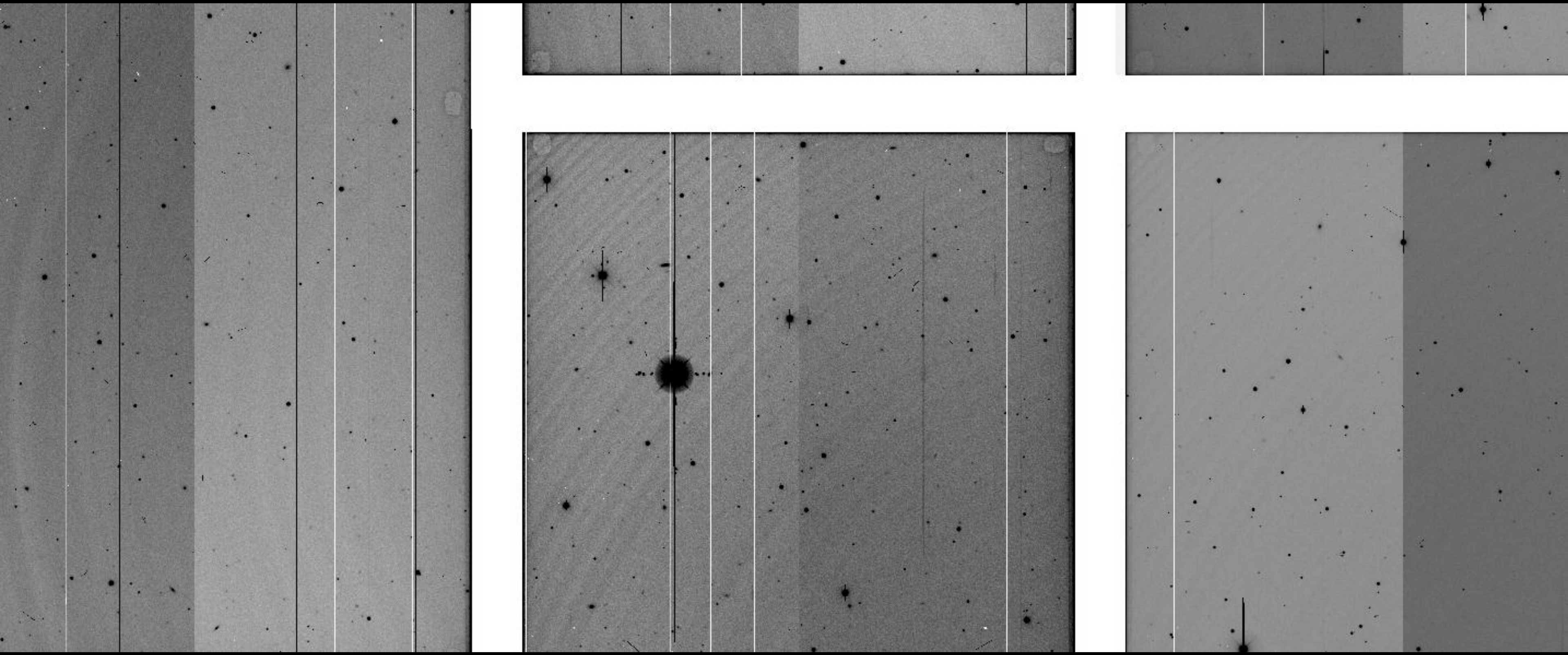
DECam Image Simulations



Populate N-body sims w/ galaxies drawn from SDSS+evolution+shapes

DECam Image Simulations

Series of Data Challenges to test Data Management System

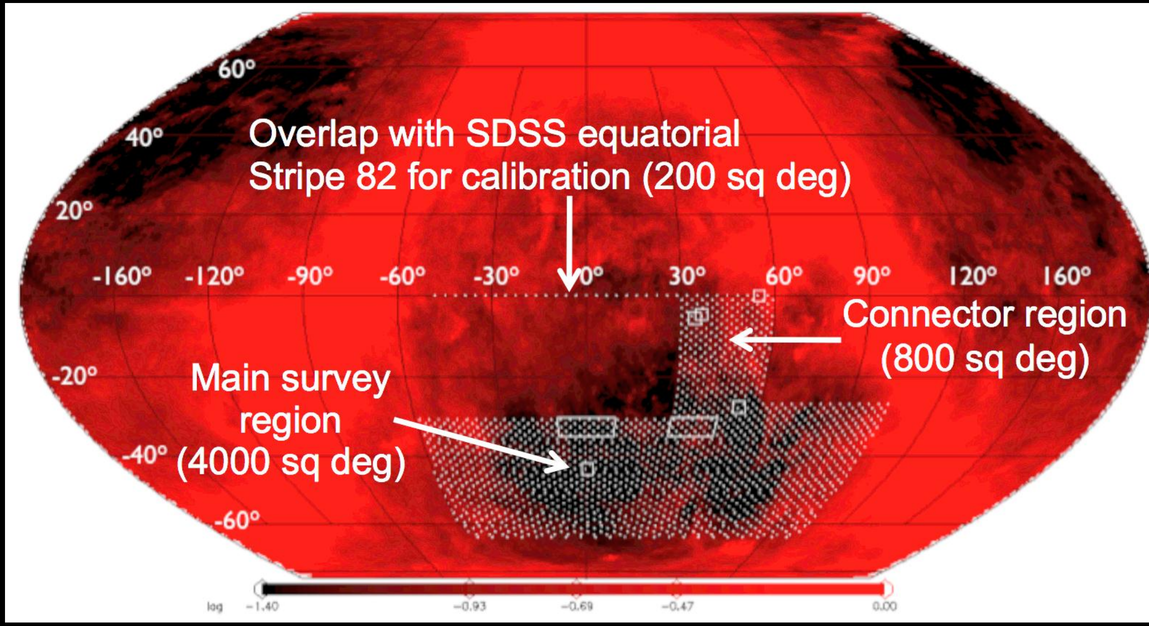


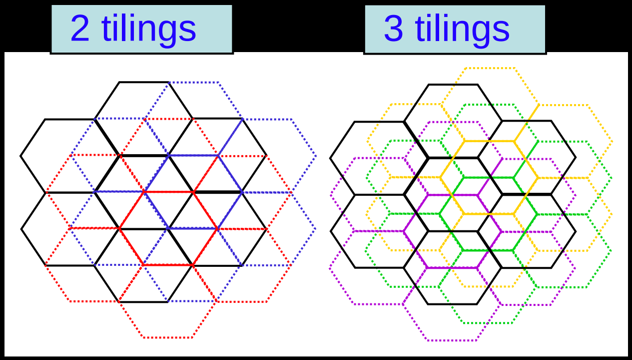
- Note bright star artifacts, cosmic rays, cross talk, glowing edges, flatfield (“grind marks”, tape bumps), bad columns, 2 amplifiers/CCD.
- Working groups analyze DM outputs→ feedback to pipeline

DES Observing Strategy

- Sept-Feb observing seasons
- 80-100 sec exposures
- 2 filters per pointing (typically)
  - *gr* in dark time
  - *izy* in bright/grey time
- Photometric calibration: overlap tilings, standard stars, spectrophotometric calibration system, preCAM
- 2 survey tilings/filter/year
- Interleave 10 SN fields in *griz* if non-photometric or bad seeing or time gap (aim for ~5 day cadence)

Survey Area   5000 sq deg

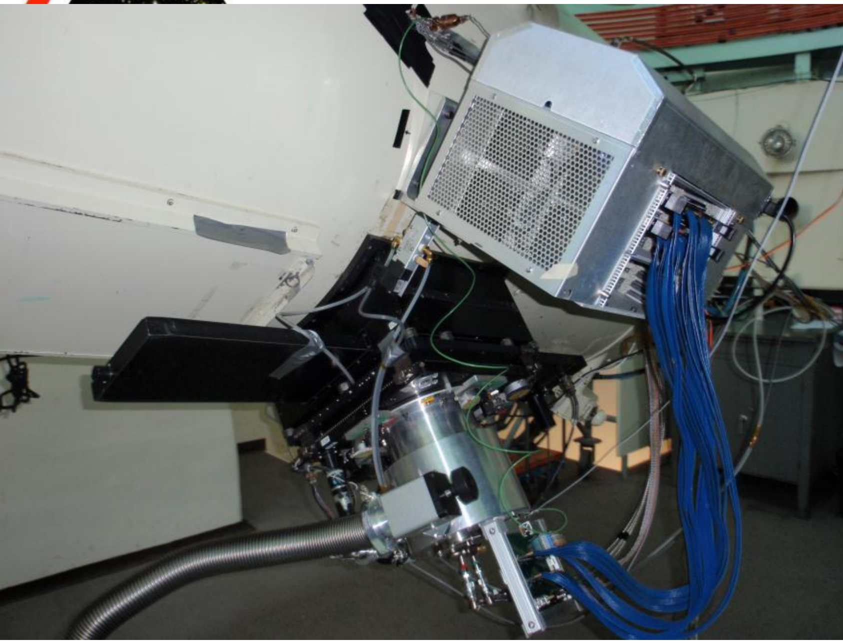




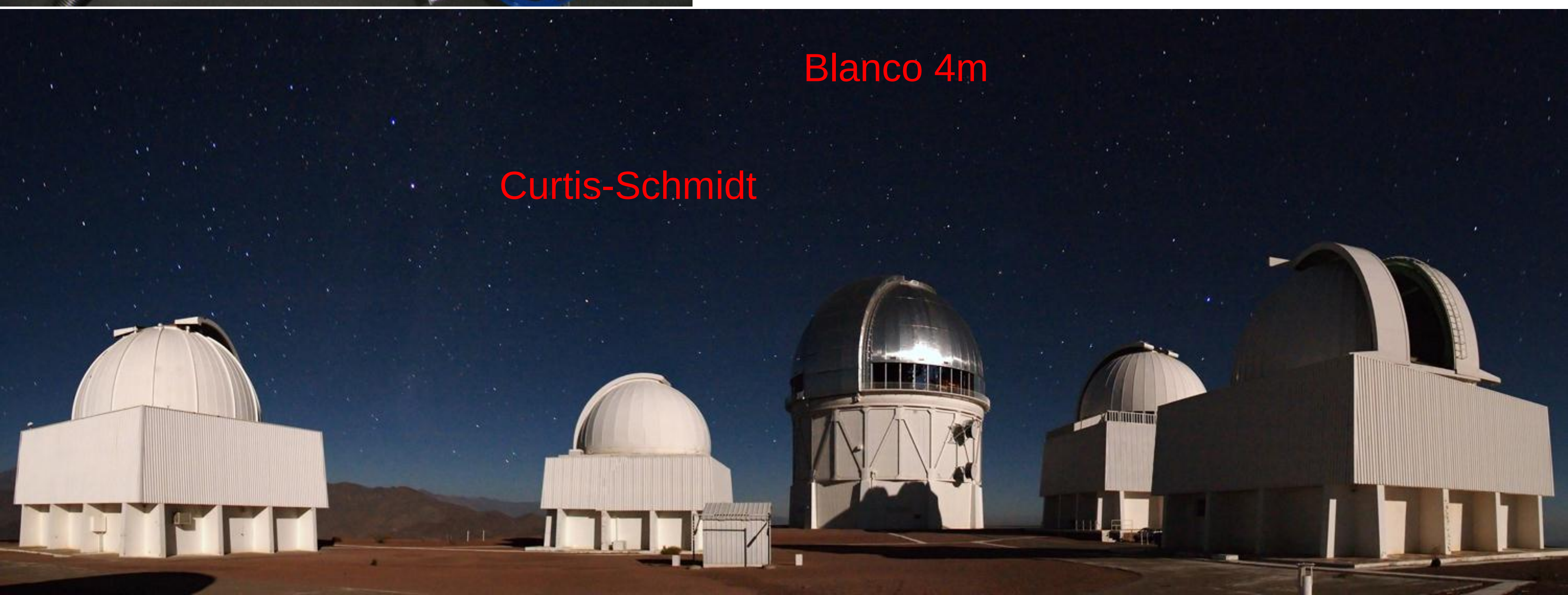
DES Calibration Plan

1. Instrumental Calibration (Nightly & Periodic): Create biases, dome flats, linearity curves, cross-talk coefficients, system response maps.
2. Photometric Monitoring: Monitor sky with new 10μm All-Sky Cloud Camera.
3. Nightly and Intermediate Calibrations: Observe standard star fields with DECam during evening and morning twilight and at least once in the middle of the night; fit photometric equation; apply the results to the data.
4. Global Relative Calibrations: Use the extensive overlaps between exposures over multiple tilings to tie together the DES photometry onto an internally consistent system across the entire DES footprint.
5. Global Absolute Calibrations: Use DECam observations of spectro-photometric standards in combination with periodic measurements of the full DECam system response map to tie the DES photometry onto an AB magnitude system.
6. PreCam Survey: Use *grizy* standards from PreCam Survey for nightly calibrations and calibrated PreCam fields to improve the DES Global Relative Calibrations. May monitor atm transmission as well

PreCAM



- Built by Argonne, uses 2 DECam CCDs
- Deployed on U. Michigan Curtis-Schmidt at CTIO



PreCam Survey Strategy

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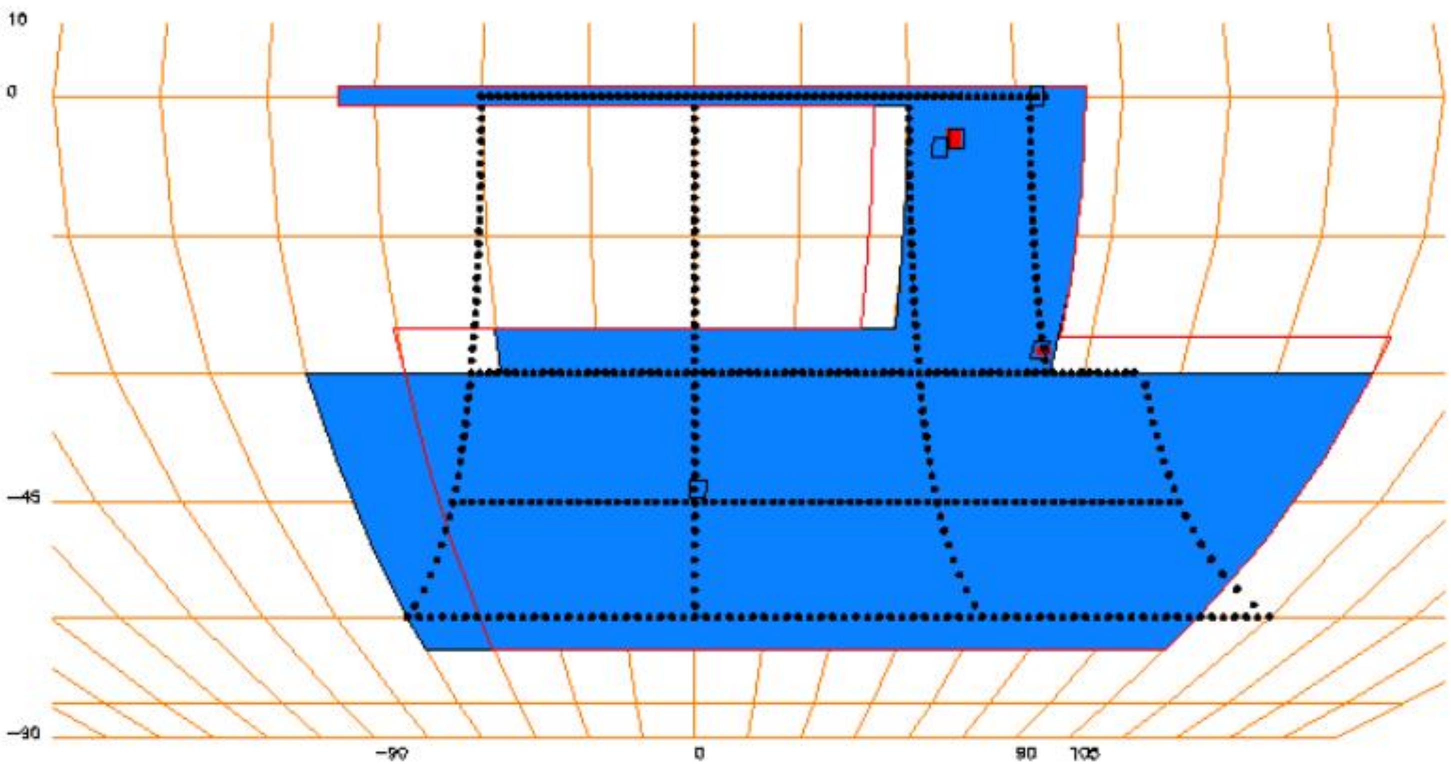
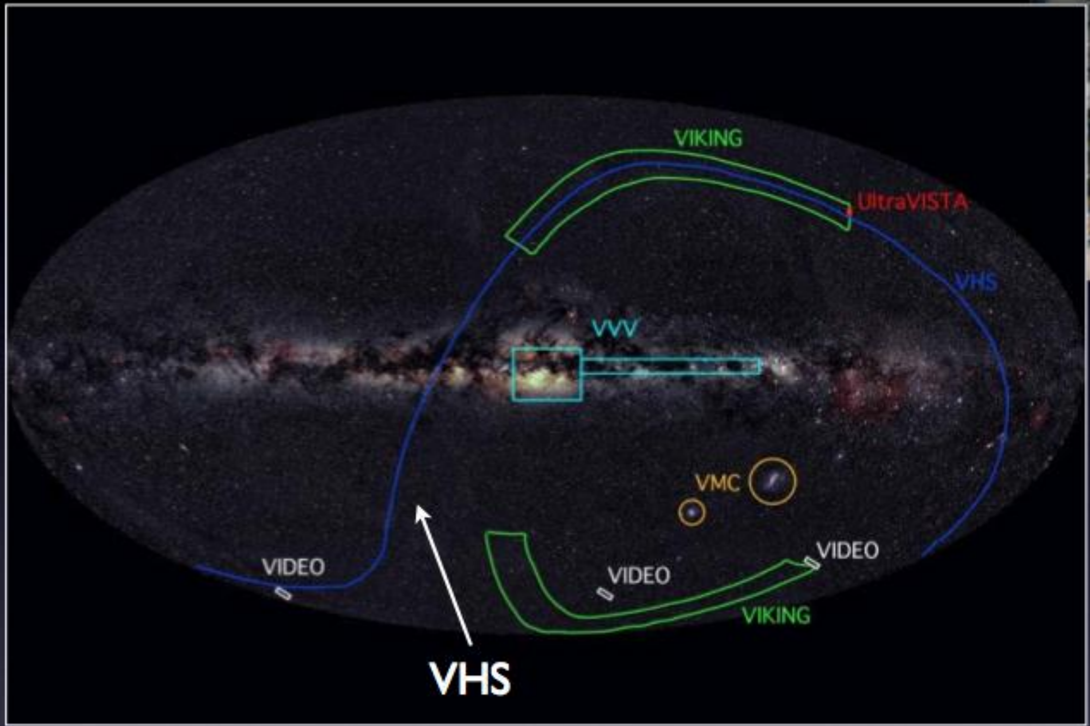
- Rigid grid of calibration stars throughout DES footprint
- Observations carried out late 2010-early 2011: analysis on-going



VISTA Hemisphere Survey



120 sec JHK exposures

VISTA

4.1m primary mirror
1.5deg field of view
16 2kx2k HgCdTe

VHS

380 nights over 5 yrs
120 sec JHK exposures
Richard McMahon, PI

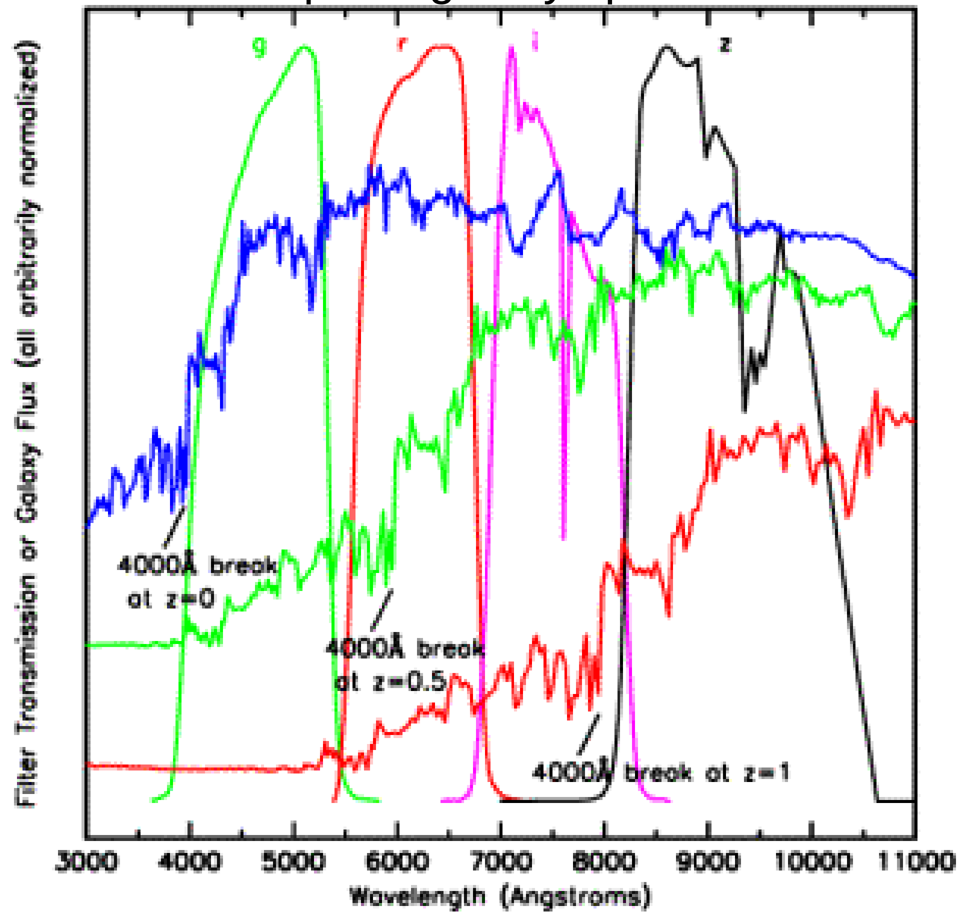
VHS limiting magnitudes [AB system; 5σ]	deg²	Y	J	H	K
VHS-DES	5000	**21.9**	21.2	20.8	20.2

DES collaborates with VHS: DES acquires Y imaging, VHS shares JHK data

Photometric Redshifts

- Measure relative flux in multiple filters: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Precision is sufficient for Dark Energy probes, provided error distributions well measured.

Elliptical galaxy spectrum



Galaxy Photo-z Simulations

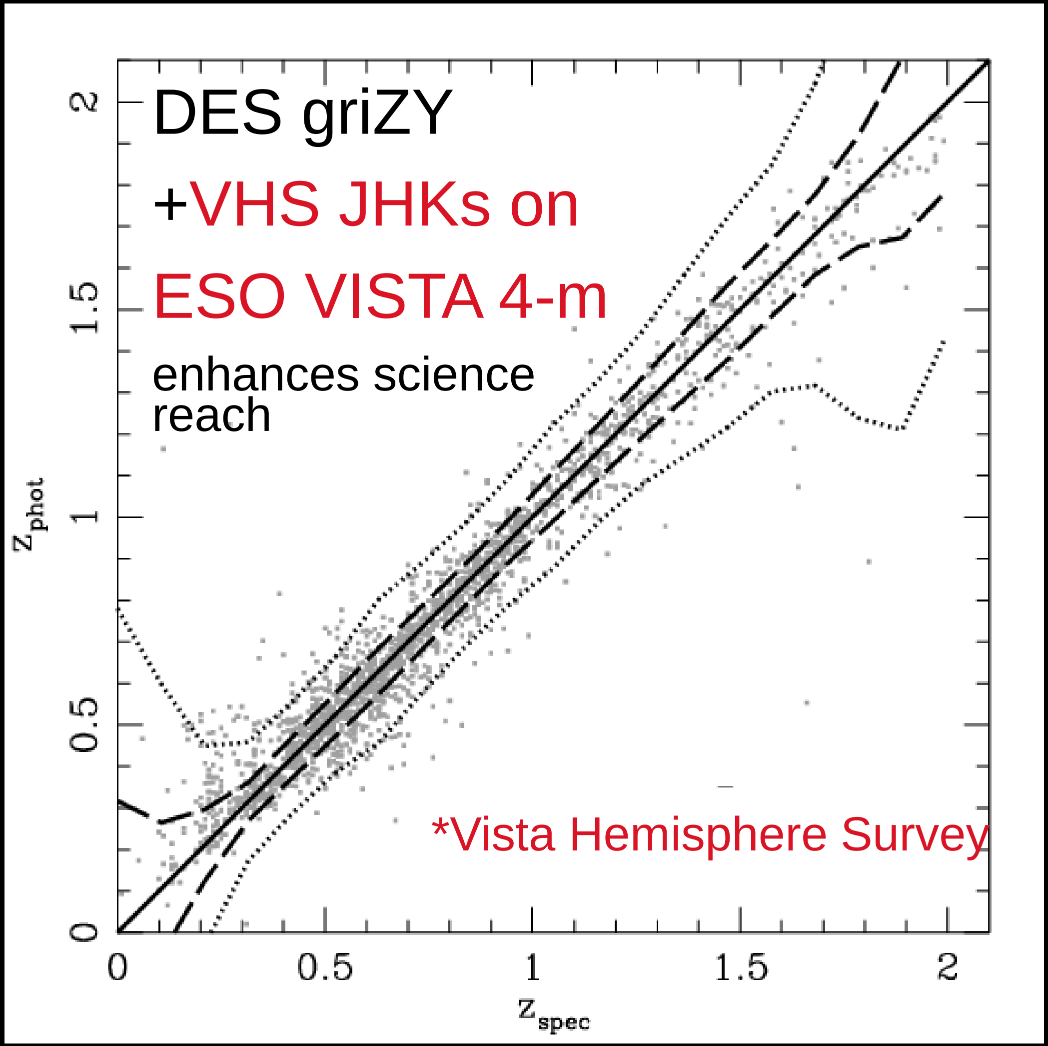
DES +VHS*

10σ Limiting Magnitudes

g	24.6		
r	24.1		
i	24.0	J	20.3
z	23.8	H	19.4
Y	21.6	Ks	18.3

+2% photometric calibration error added in quadrature

Spectroscopic training sets comparable to DES depth exist

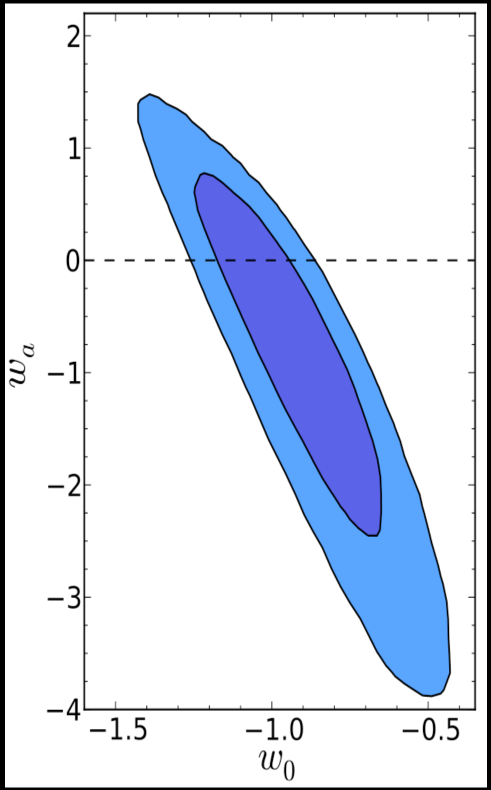


DES Science Summary

Four Probes of Dark Energy

- Galaxy Clusters
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- Supernovae
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Current Constraints on DE Equation of State



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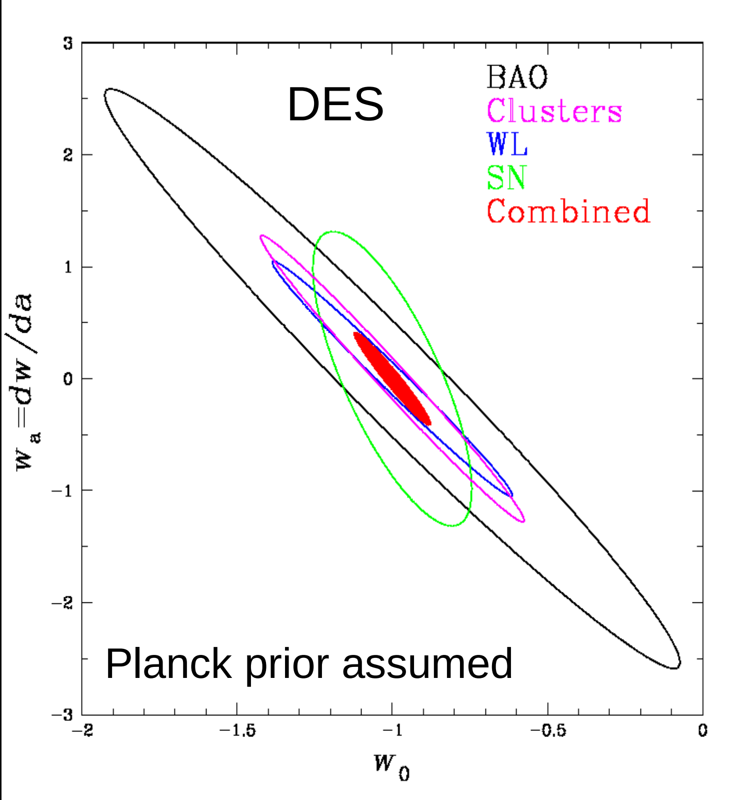
Forecast Constraints on DE Equation of State



Factor 3-5 improvement over Stage II DETF Figure of Merit

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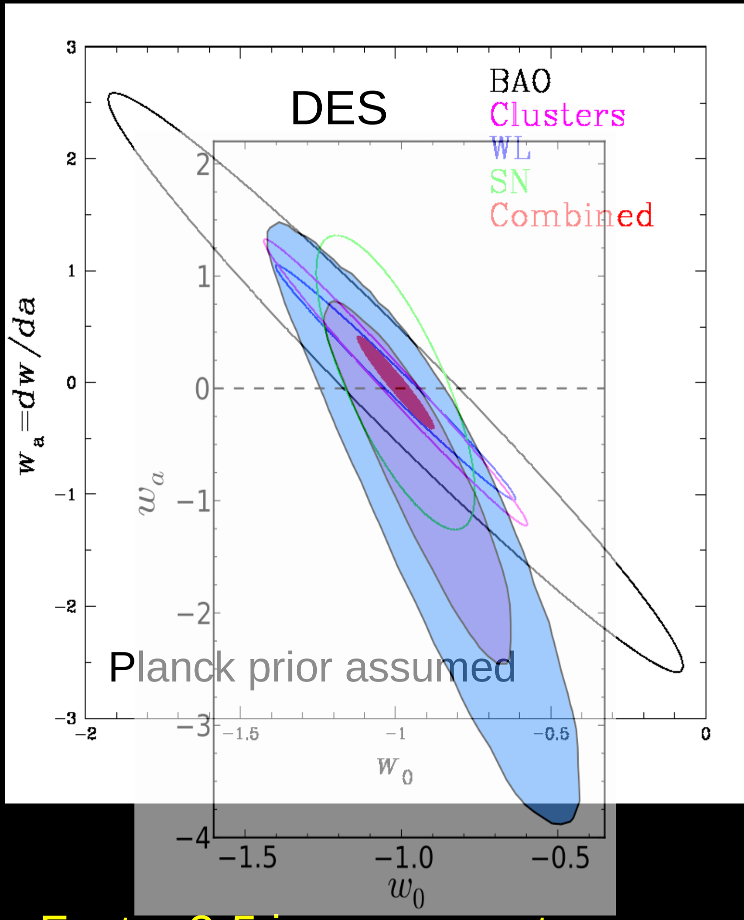


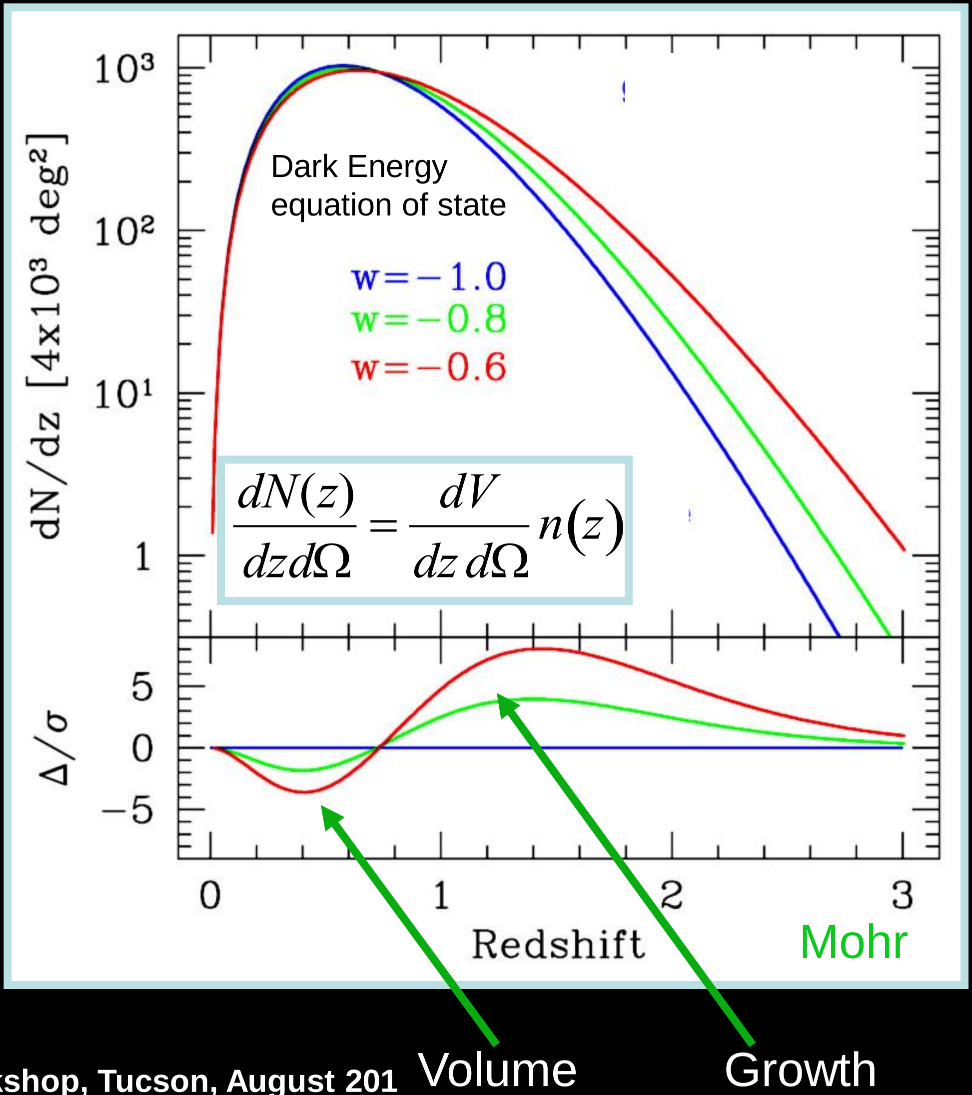
Factor 3-5 improvement over Stage II DETF Figure of Merit

DARK ENERGY SURVEY

I. Clusters

- Elements of the Method:
  - Clusters are proxies for massive halos and can be identified optically to redshifts z>1
  - Galaxy colors provide photometric redshift estimates for each cluster
  - Observable proxies for cluster mass: optical richness (DES), SZ flux decrement (SPT), weak lensing mass (DES), X-ray flux (eRosita)
  - Cluster spatial correlations help calibrate mass estimates

Number of clusters above mass threshold



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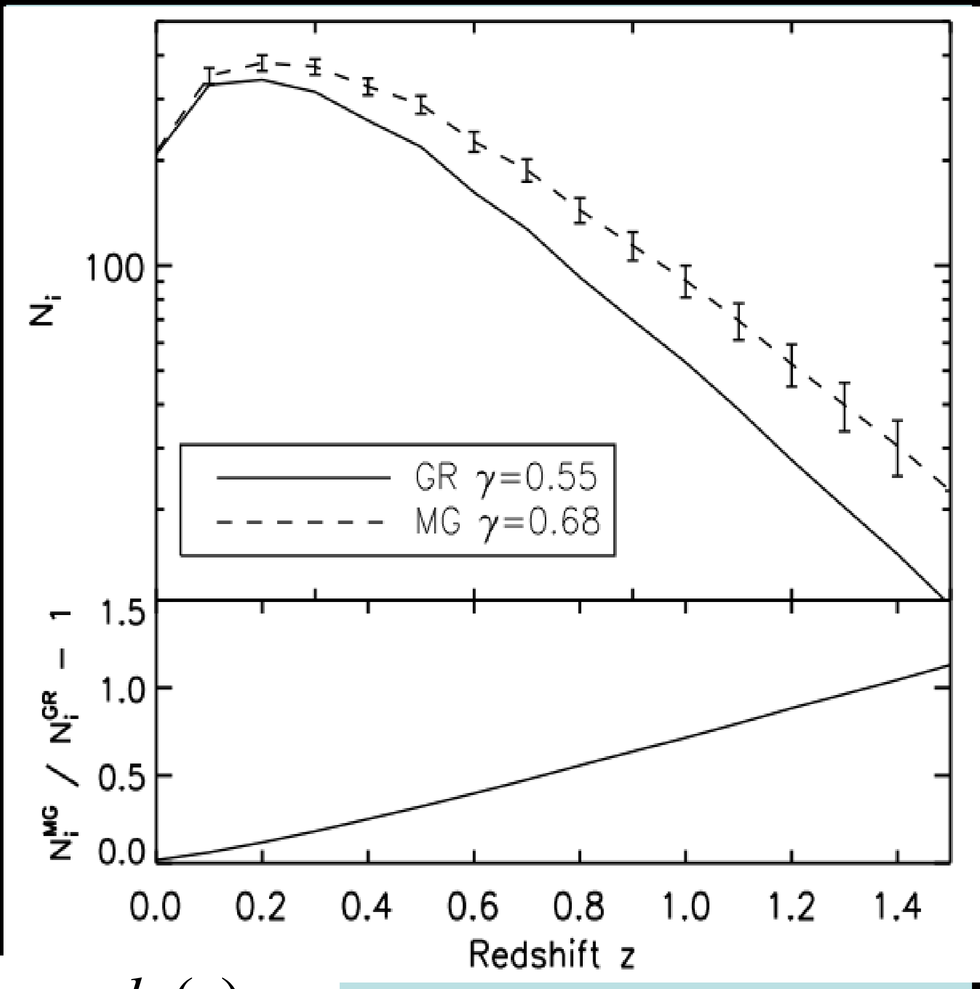
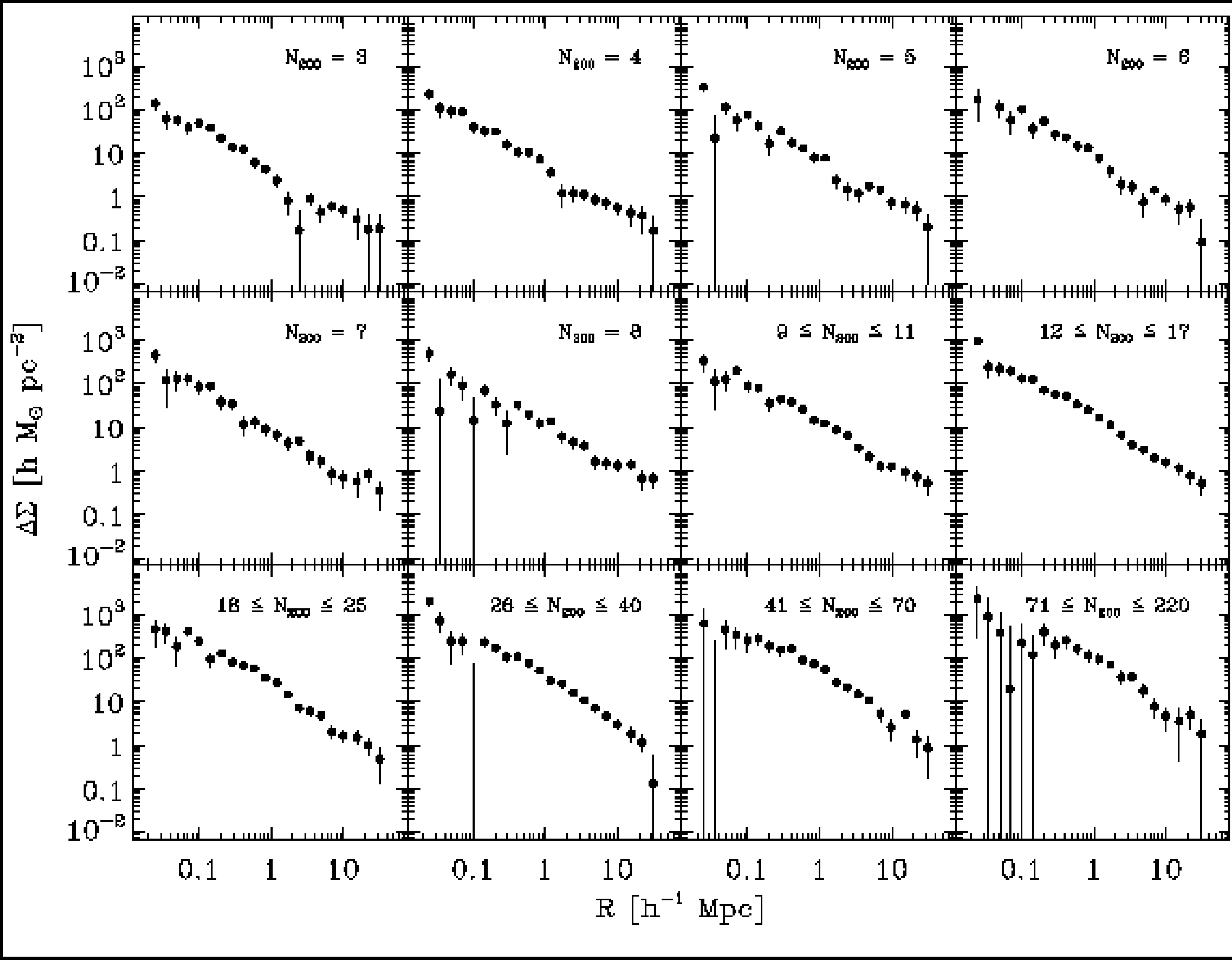


$$\frac{d^2N}{dz\,d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z)\,dO \int p(O\,|\,M,z)\,\frac{dn(z)}{dM}\,dM$$

Statistical Weak Lensing by Galaxy Clusters

Mean Tangential Shear Profile in Optical Richness (N_{gal}) Bins to 30 h^{-1}Mpc



Sheldon, Johnston, etal SDSS

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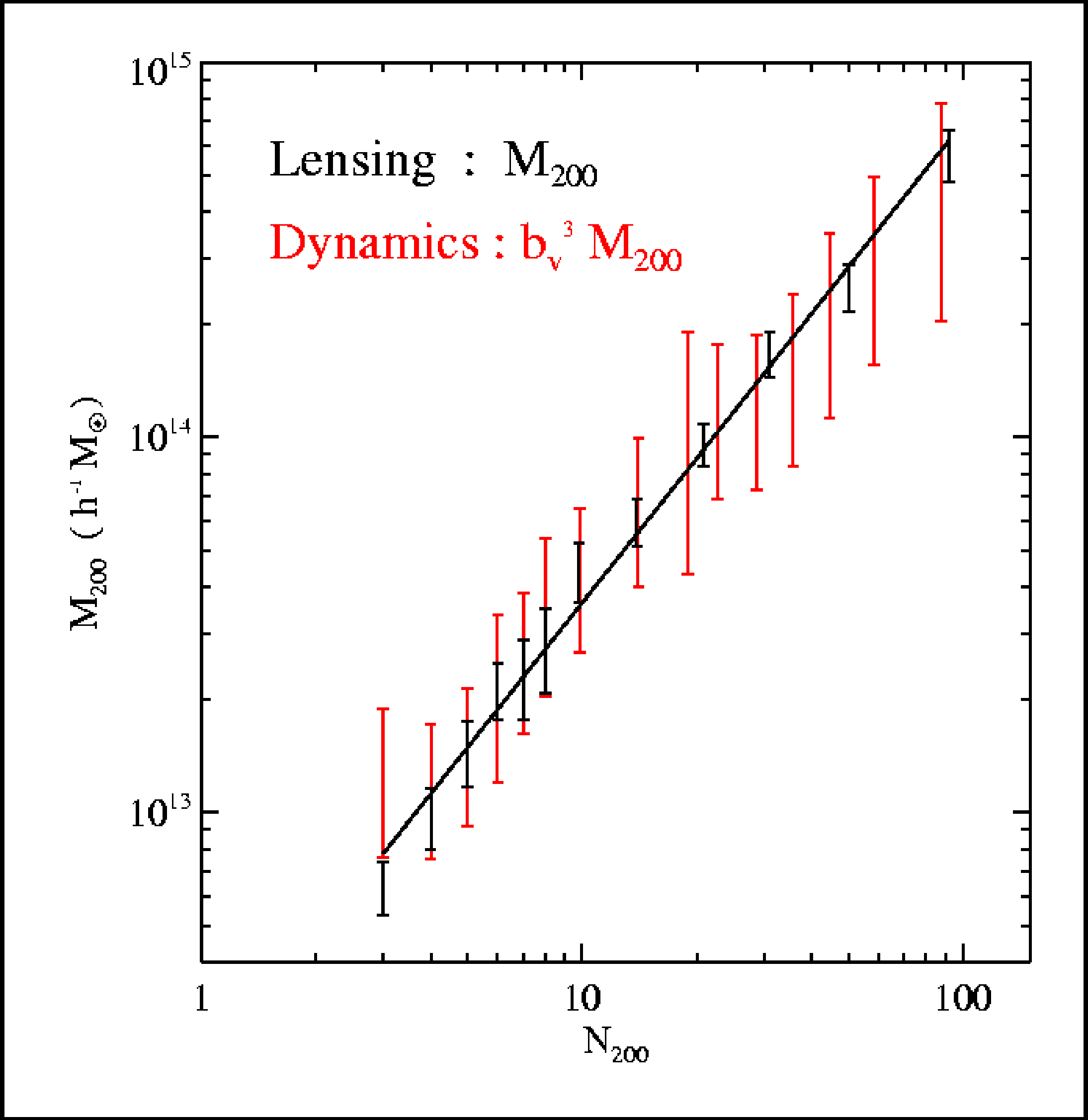
Statistical Weak Lensing Calibrates Cluster Mass vs. Observable Relation

Cluster Mass vs. Number of galaxies they contain (richness)



Statistical Lensing controls projection effects of individual cluster mass estimates

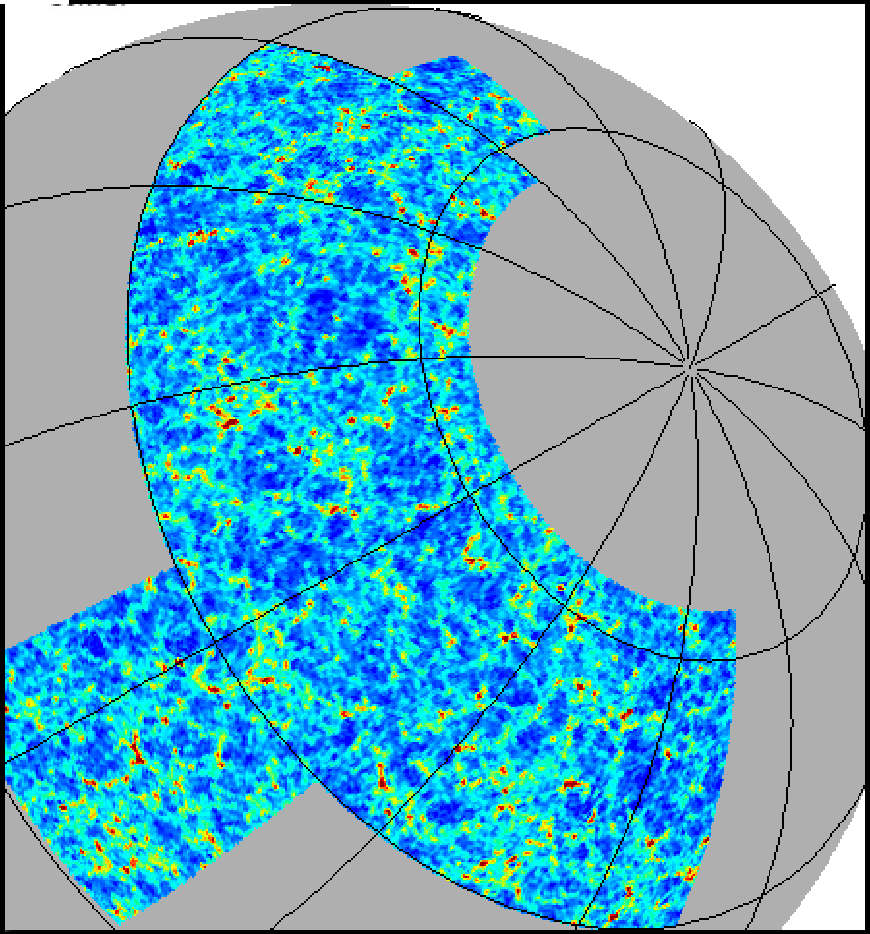
Improved red-sequence richness estimator reduces scatter in mass vs optical richness to ~20-30%

Rykoff etal

Johnston, Sheldon, etal

Synergy with South Pole Telescope

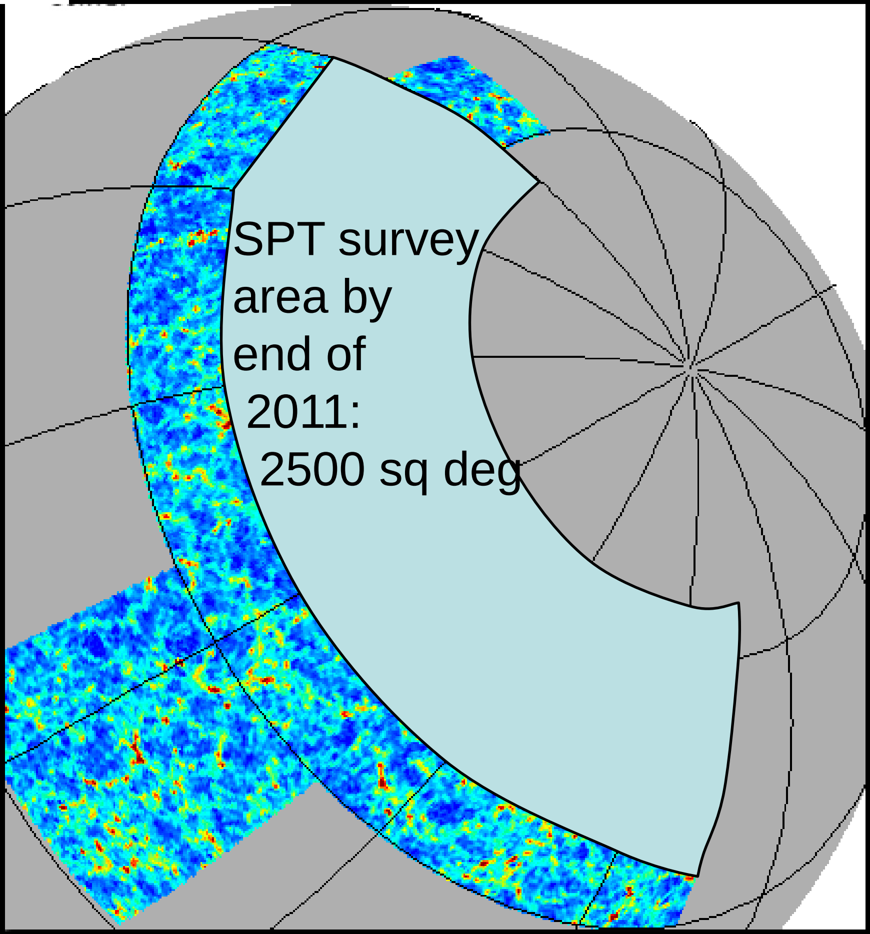
DES footprint: 5000 sq deg



DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey

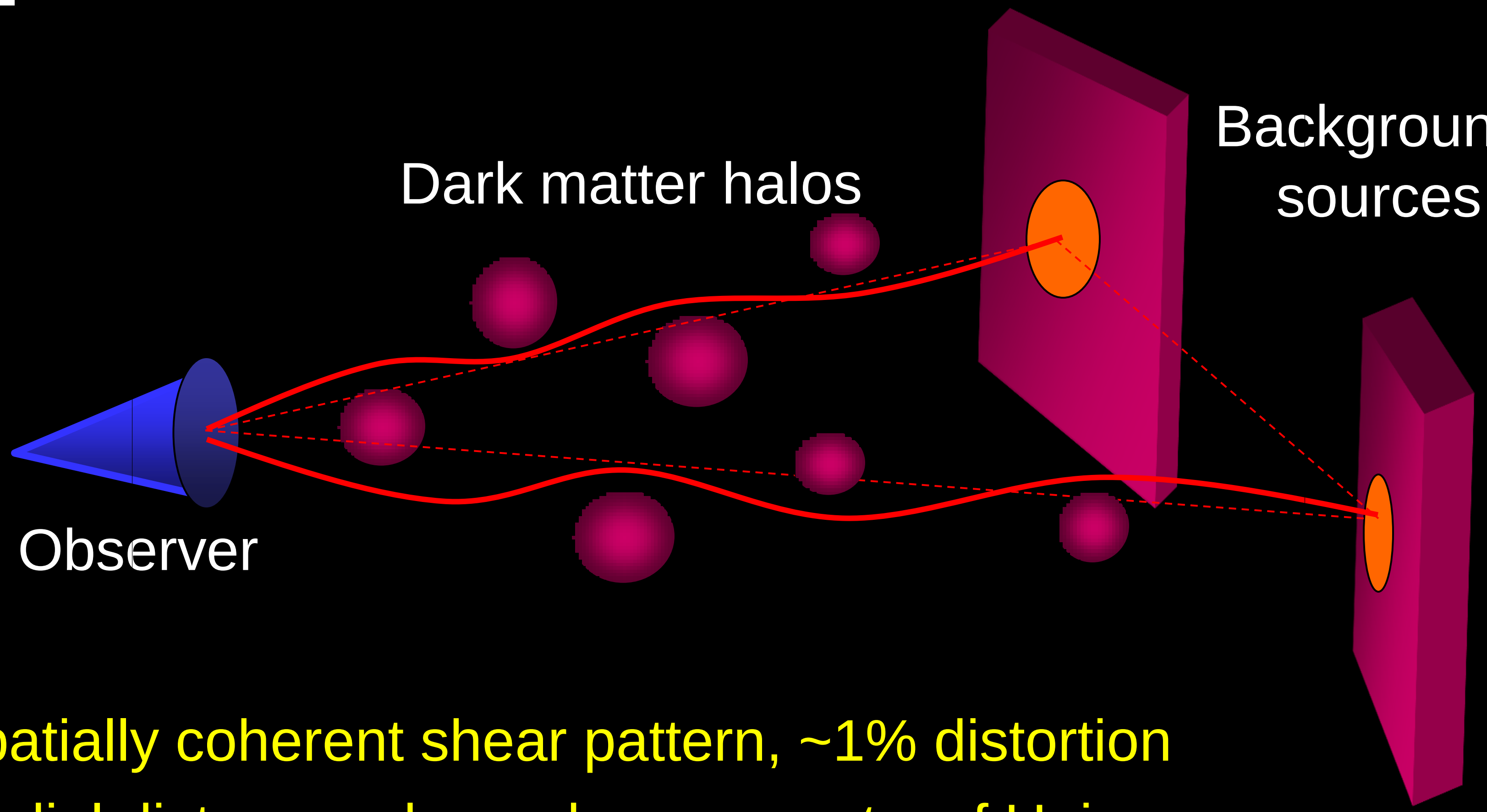
Synergy with South Pole Telescope

DES footprint: 5000 sq deg



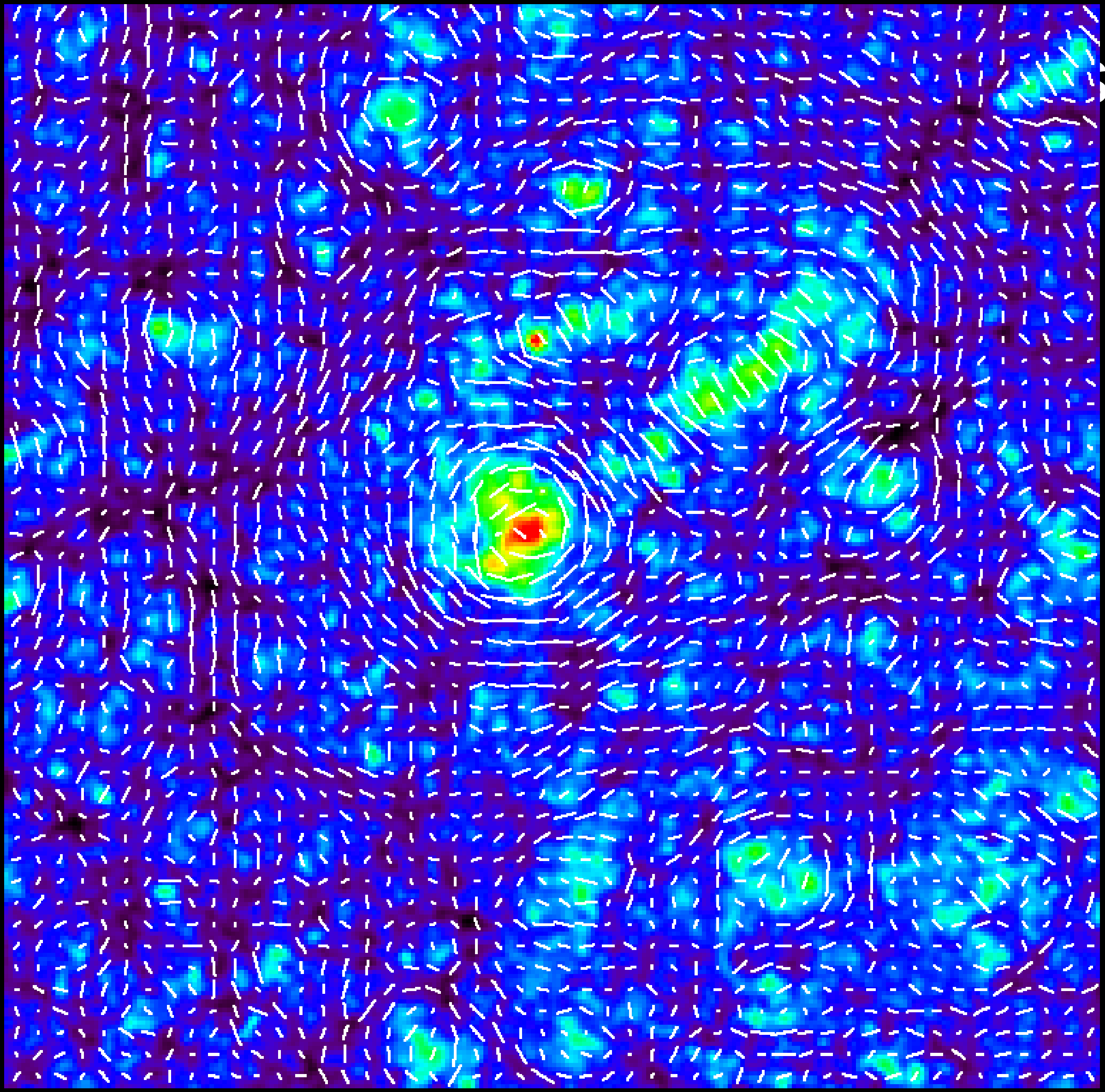
DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey
SZ flux correlates with cluster halo mass with ~10% scatter

II. Weak Lensing: Cosmic Shear



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

Weak Lensing Mass and Shear



Takada

DARK ENERGY SURVEY

Weak Lensing Tomography

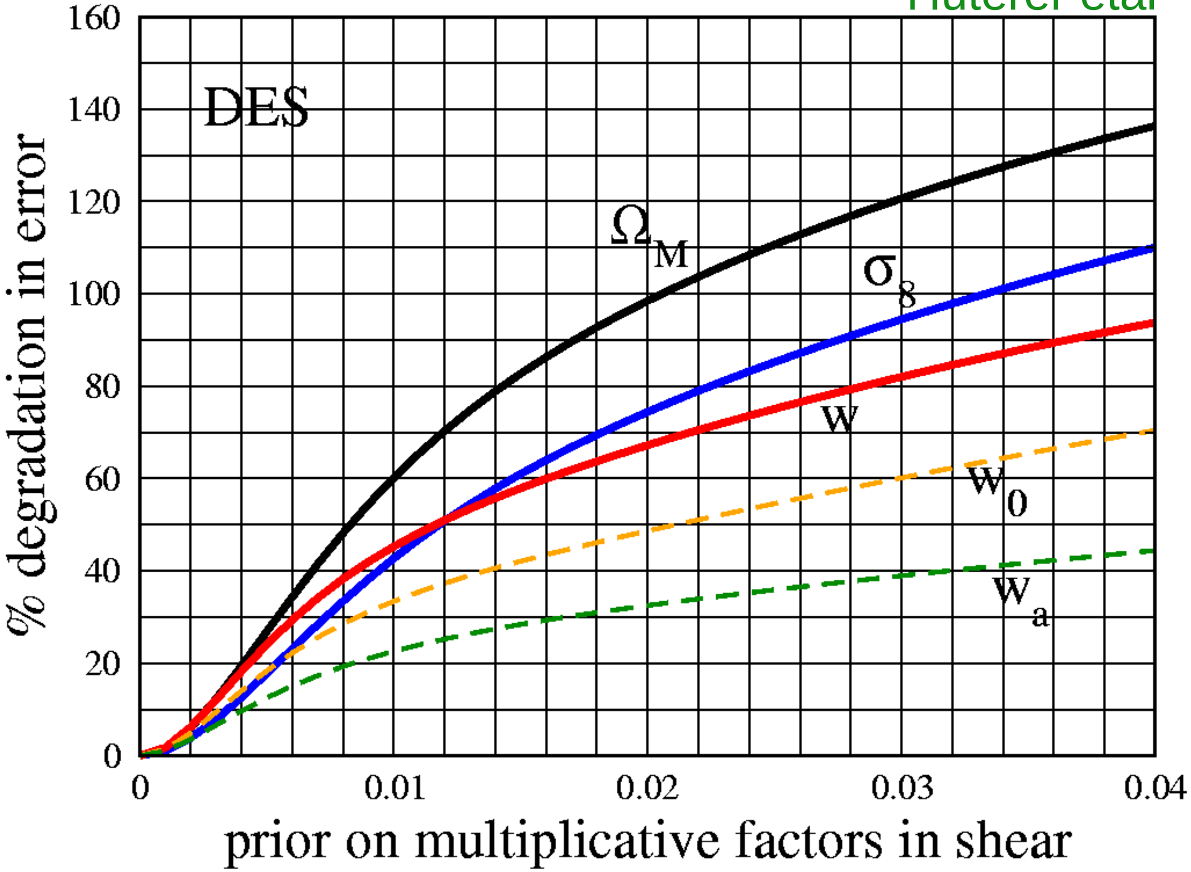
- Cosmic Shear Angular Power Spectrum in Photo-z Slices

- Shapes of ~300 million well-resolved galaxies, $\langle z \rangle = 0.7$

- Primary Systematics: photo-z's, intrinsic alignments, PSF anisotropy, shear calibration, NL+baryon effects

- Extra info in bispectrum & galaxy-shear: robust

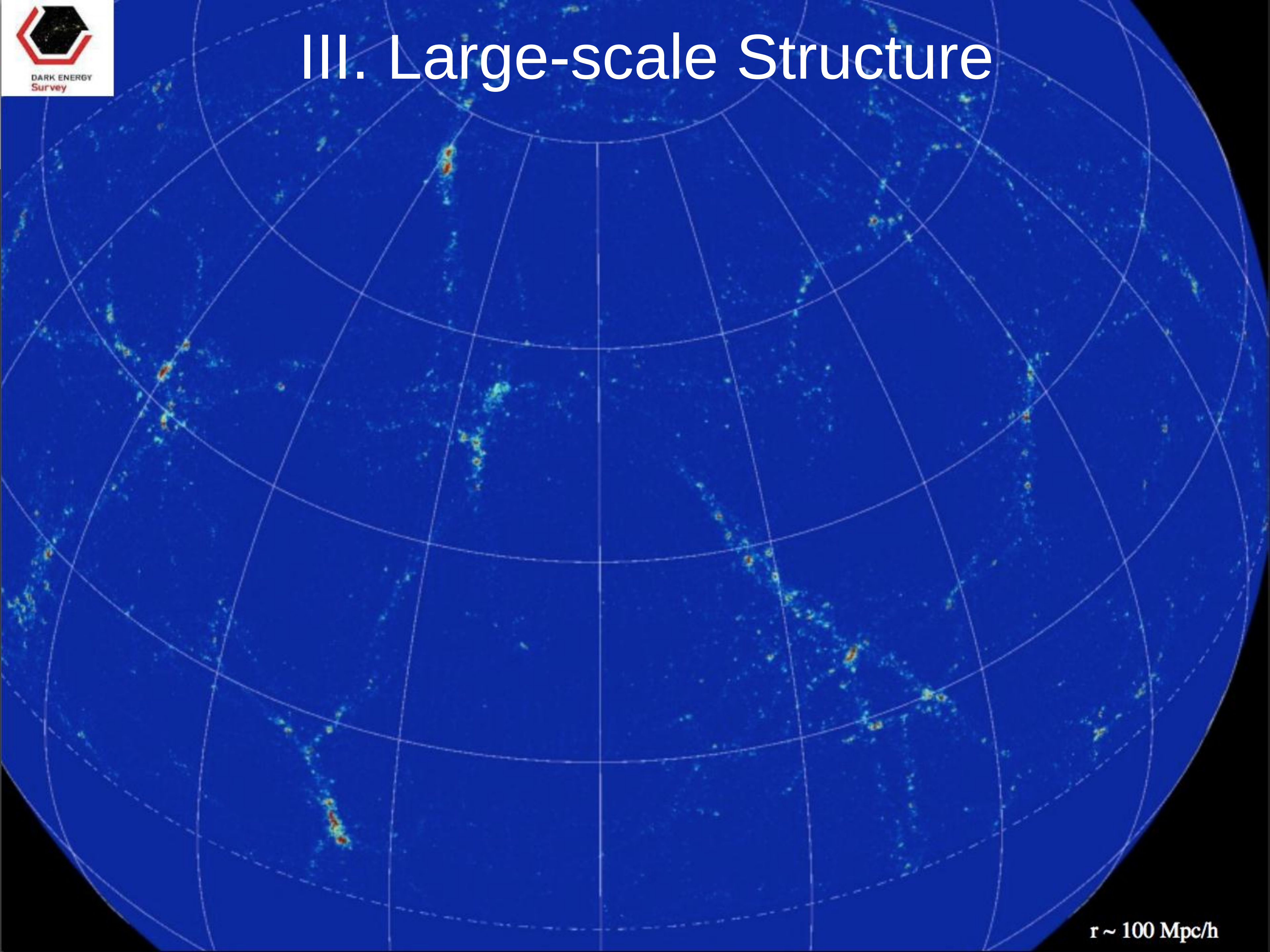
Huterer etal



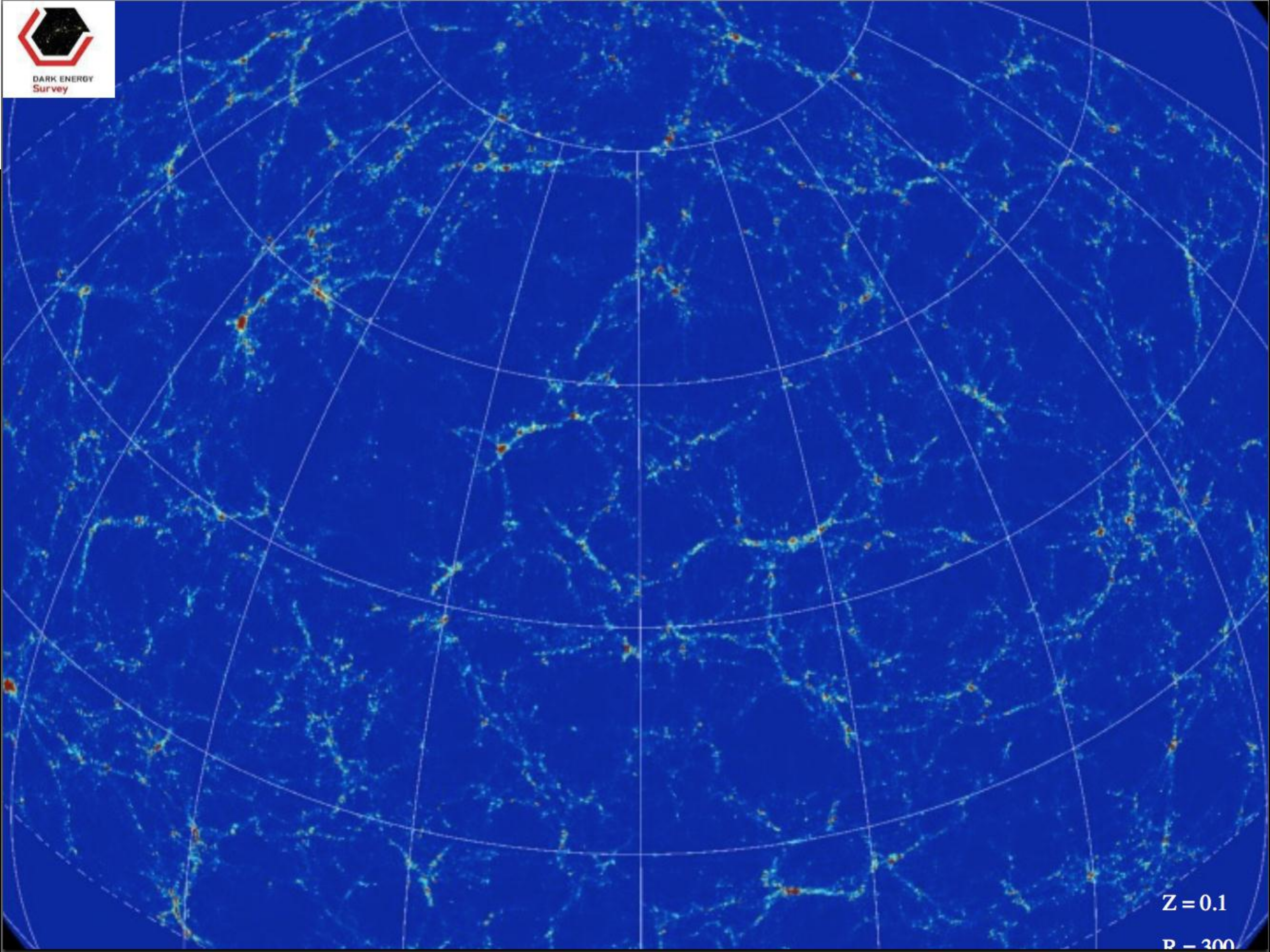
Expect n_{eff}~10/arcmin^2 for median 0.9" PSF

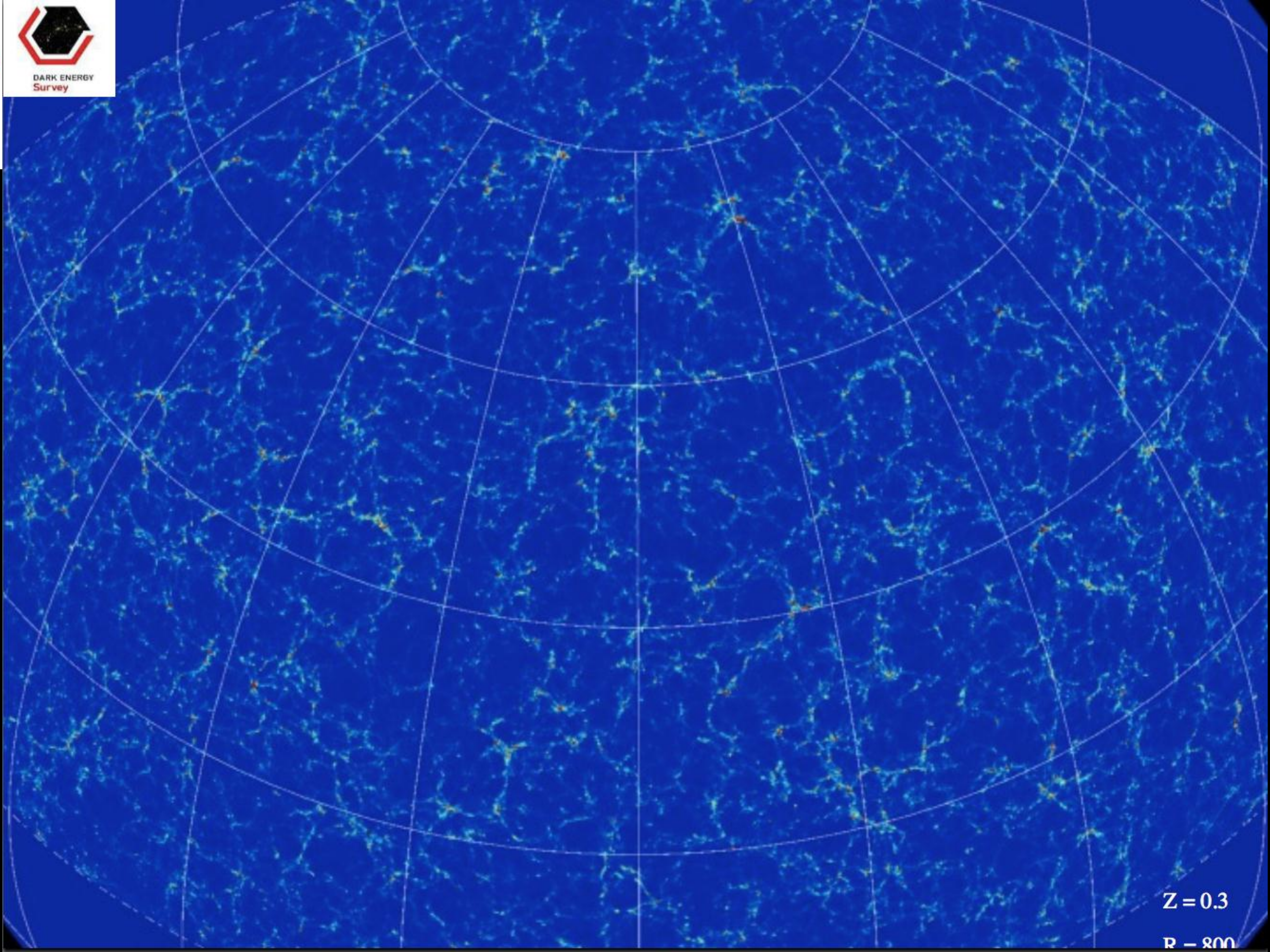
$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z) \quad \Delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

III. Large-scale Structure

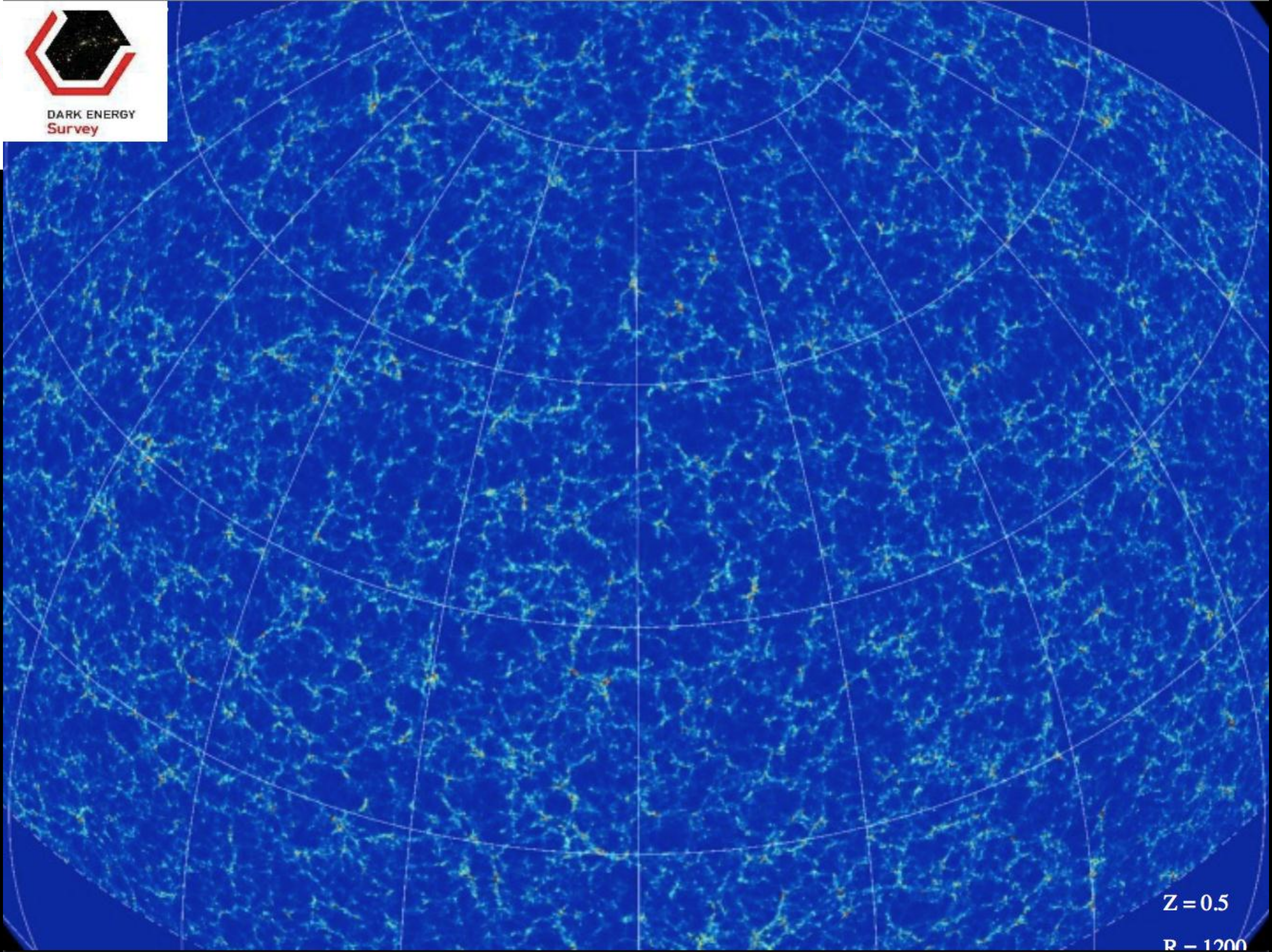


DARK ENERGY
Survey



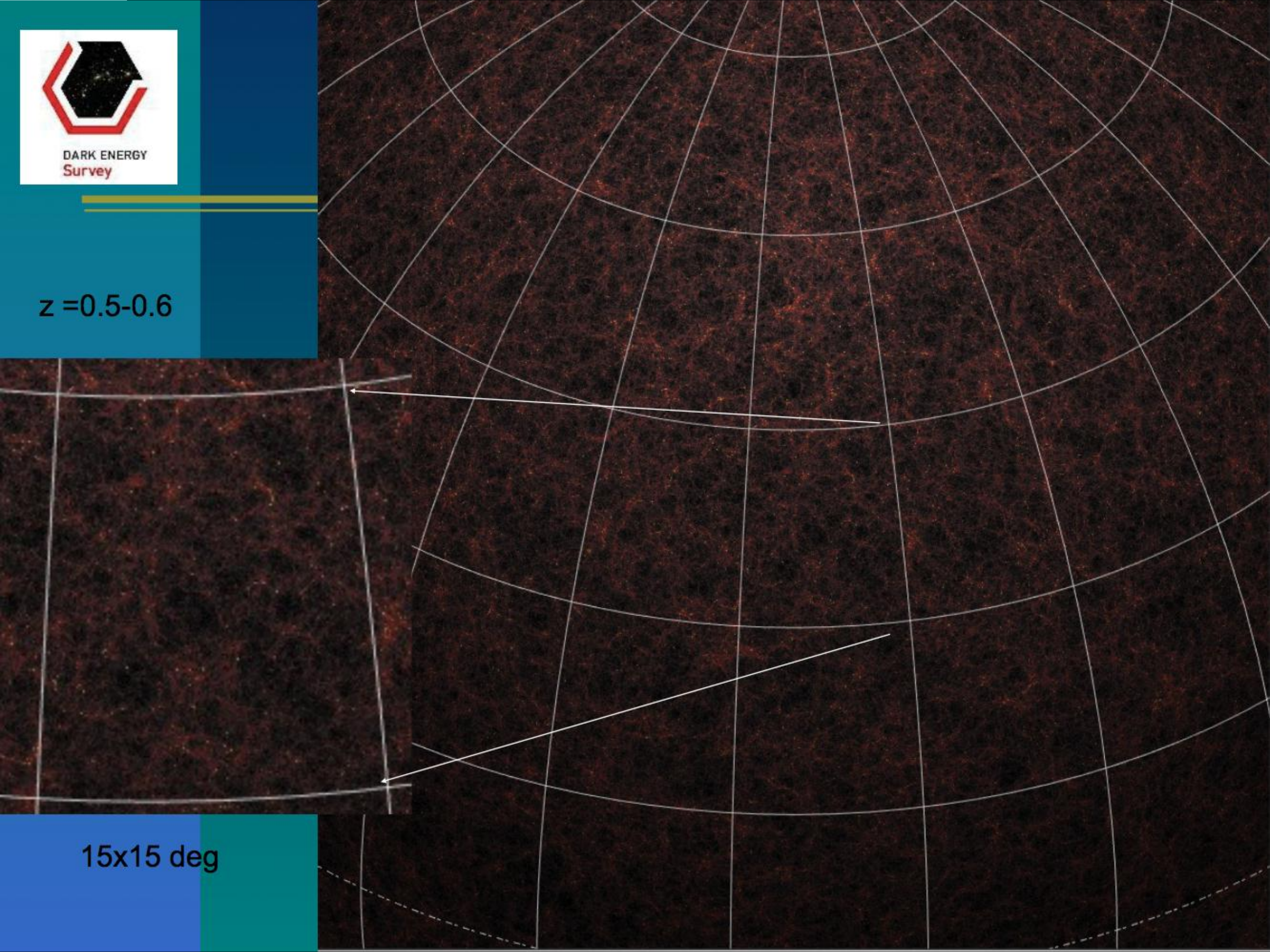

DARK ENERGY
Survey
Z = 0.3

DARK ENERGY
Survey



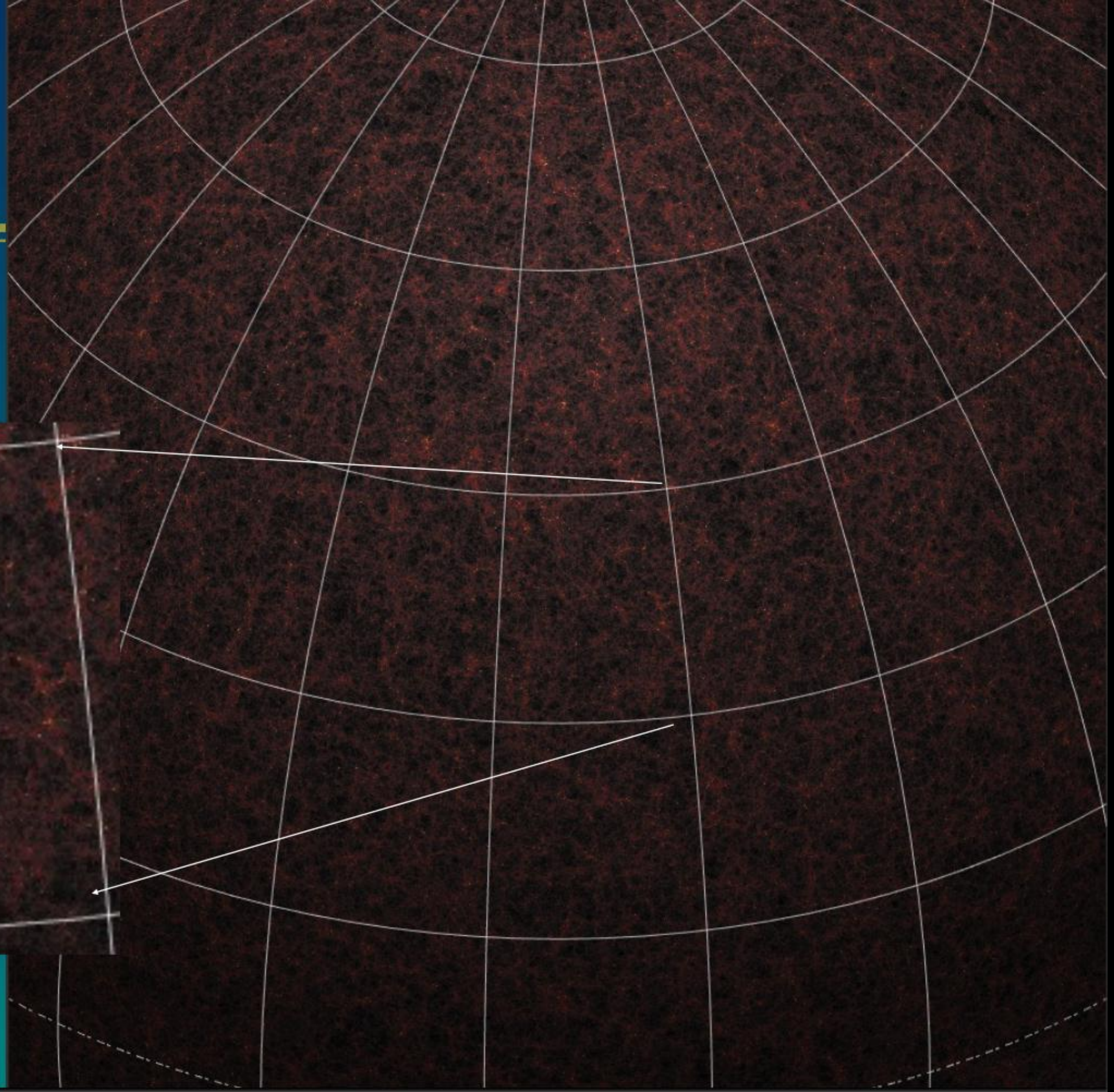
DARK ENERGY Survey

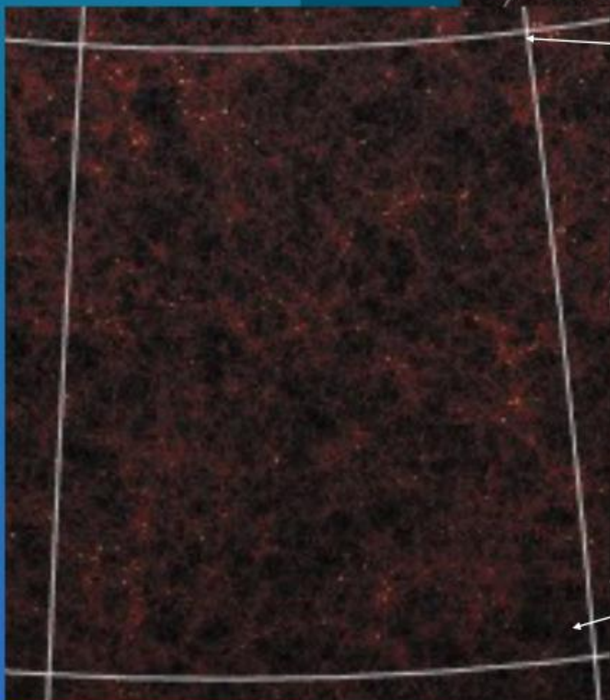
z =0.5-0.6



15x15 deg

z =0.9-1.0





15x15 deg

DARK ENERGY Survey

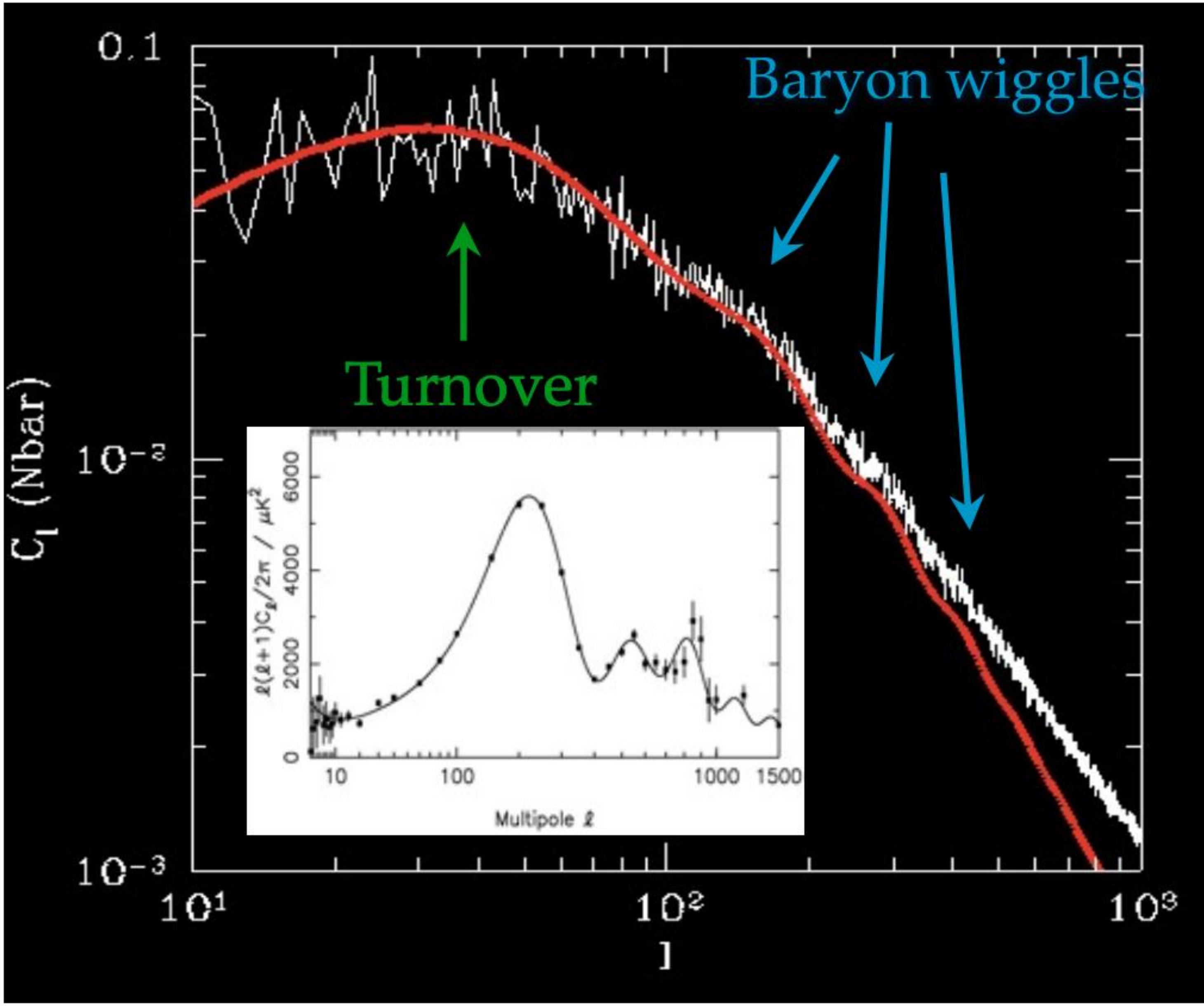
Angular Spectrum

For single redshift slice:

z =0.9-1.0

Out of MICE Simulation

www.ice.cat/mice



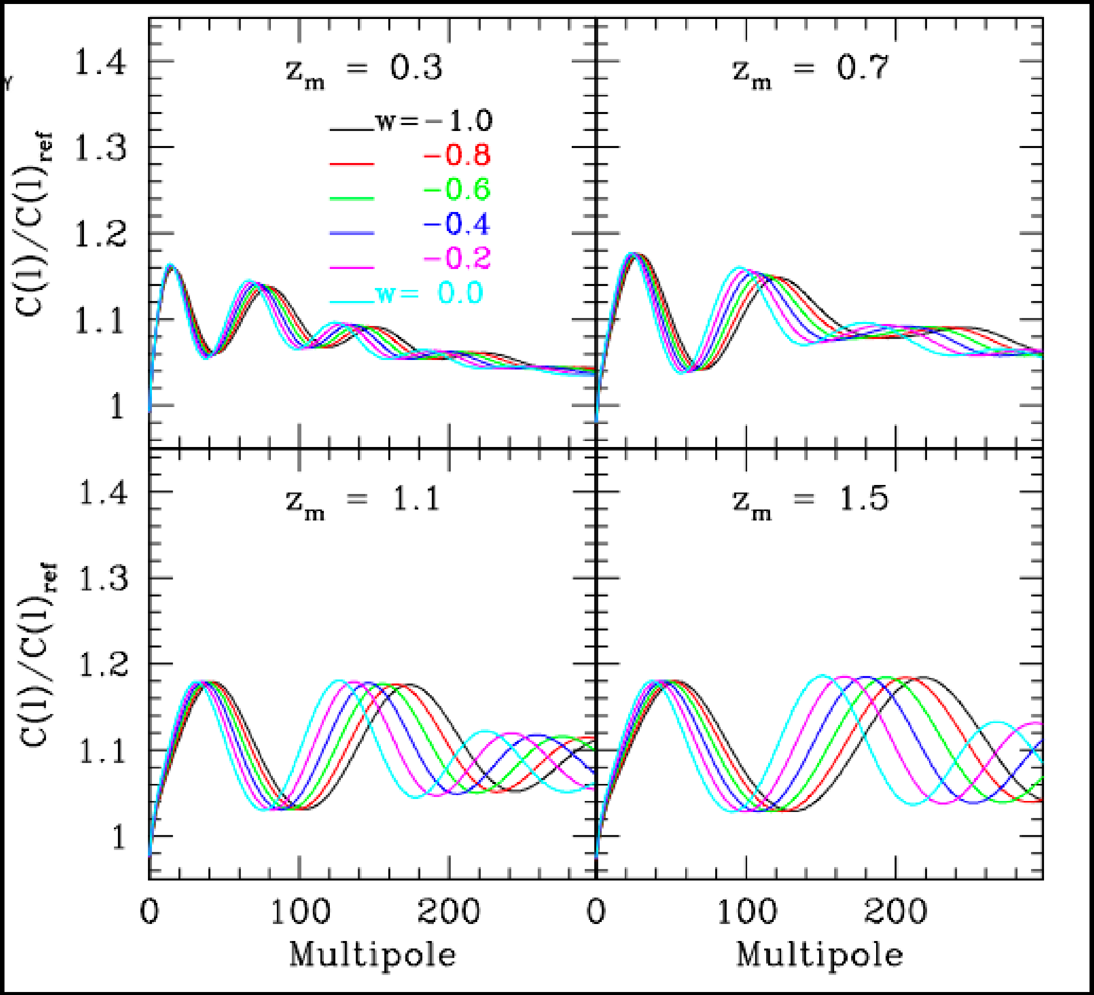
Measurements can provide both with:

1. BAO scale (DM & Baryon density)
2. distance to BAO scale (DE)

$$c\Delta z_{BAO} = r_{BAO} H(z) \qquad \Delta\theta_{BAO} = \frac{r_{BAO}}{d_A(z)}$$

Baryon Acoustic Oscillations

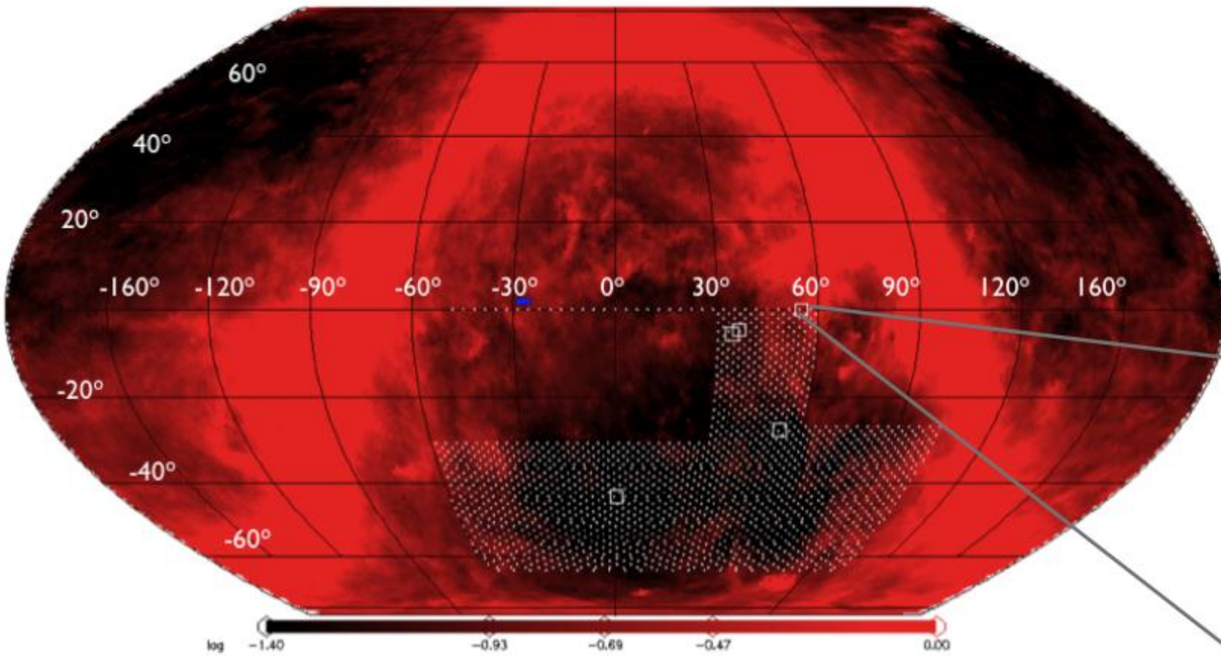
Galaxy angular power spectrum in photo-z bins (relative to model without BAO)



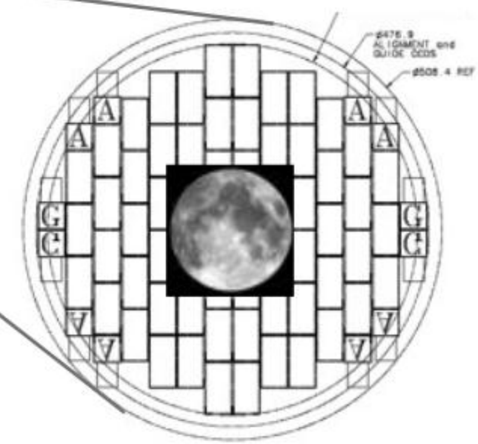
Fosalba & Gaztanaga

IV. DES SN Survey

DARK ENERGY SURVEY



Fields to overlap with existing and near-future deep imaging (e.g., CDF-S, SNLS, VIDEO) and spectroscopic surveys (DEEP2, VIPERS, VVDS, WiggleZ, GAMA I/II).



10 DES fields

Visit once every ~4 days.

2 deep + 8 shallow (30 deg^2)

deep: 6600 sec per visit (*griz*)

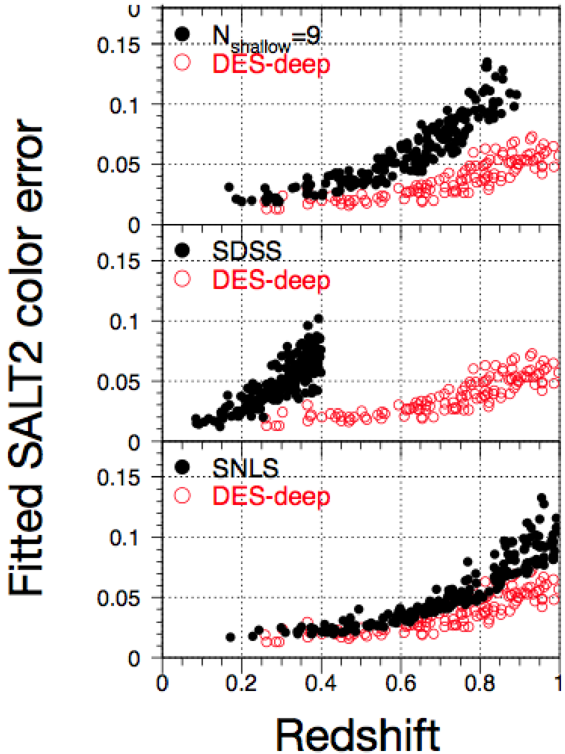
shallow: 800 sec per visit (*griz*)

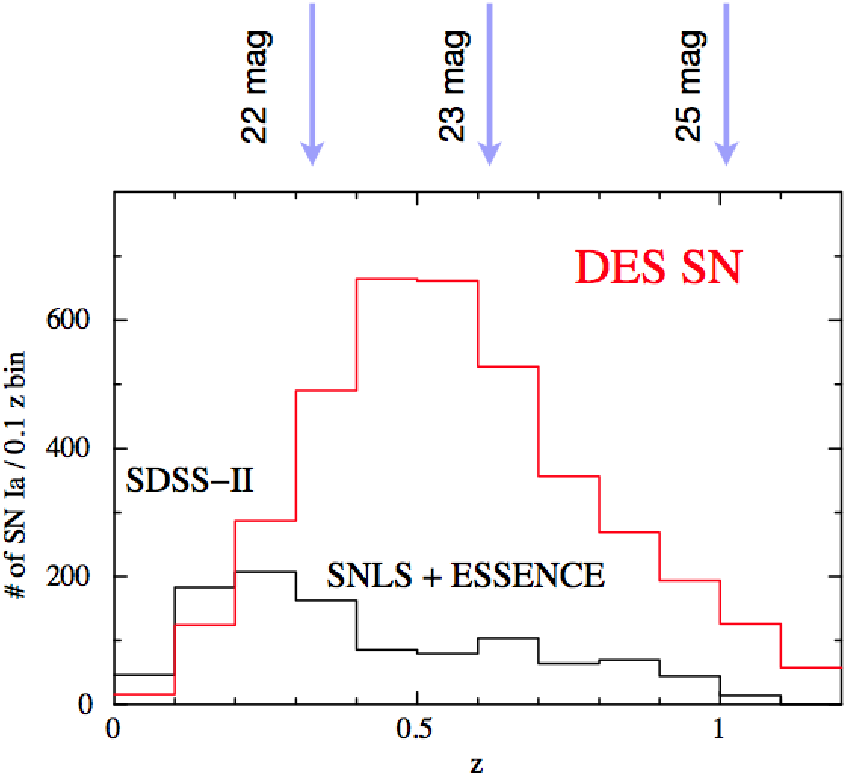
good z-band efficiency (~4x higher than CFHT/MegaCam) and target high-z SN Ia

→ good rest-frame *g*-band light curves of z~1 SN Ia.

SN Search Strategy

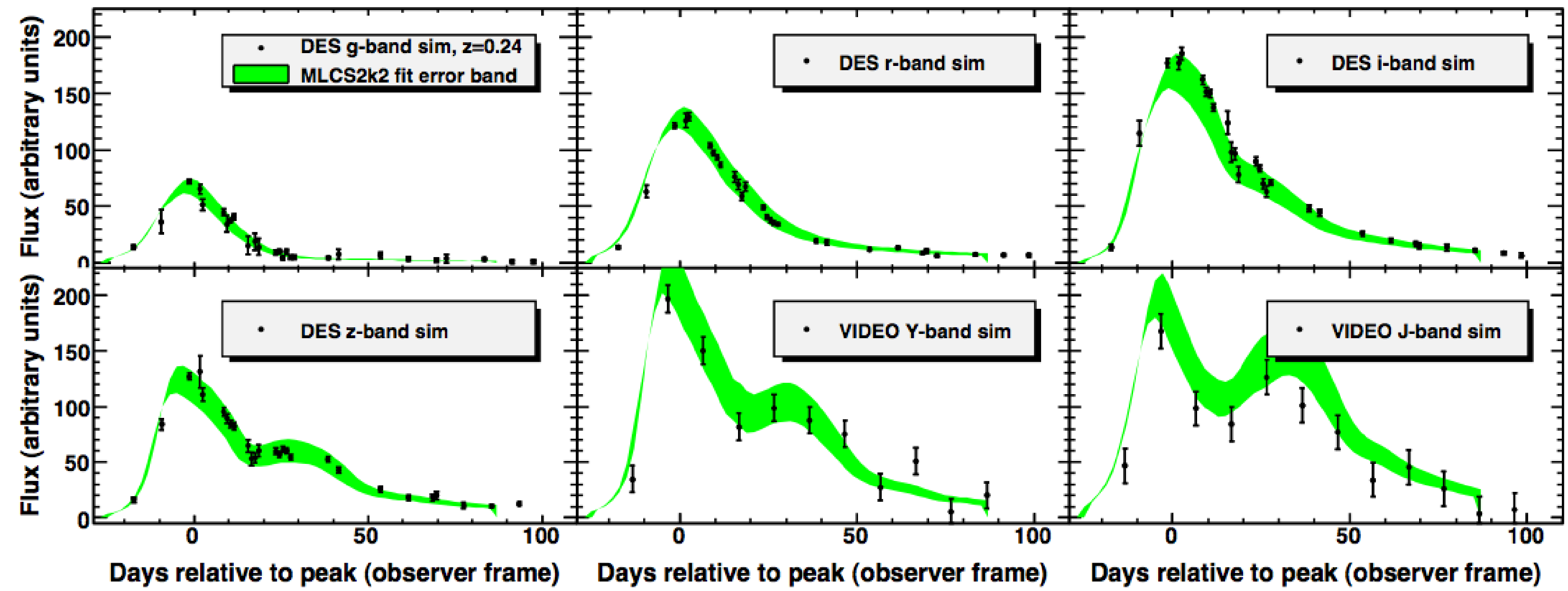
- 6-month search and follow-up campaigns
- Use <u>1000+ hours</u> of total DES observing time.





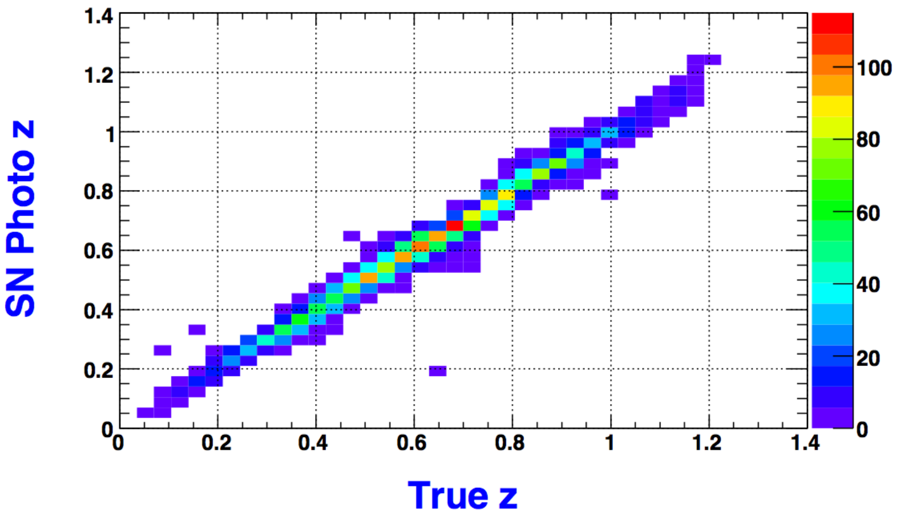
- Will discover ~6000 SN Ia at $0.1 < z < 1.0$.
  - **~3800 SN Ia** with "good" light curves

Supernova Light Curves

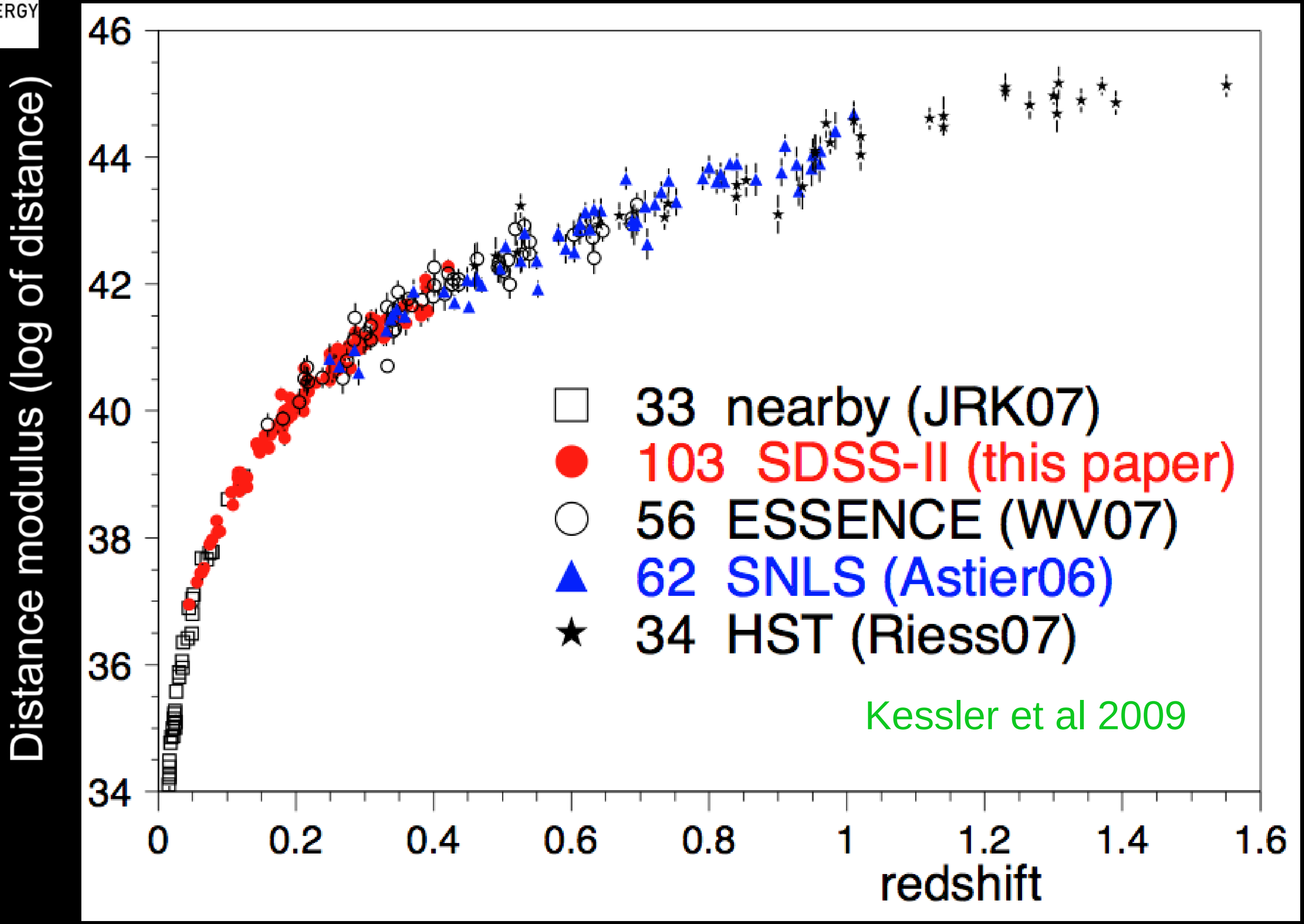


Bernstein et al

- Broader redshift range than SDSS SN
- Higher S/N in red passbands than SNLS
- Add NIR from VISTA VIDEO survey
- Factor ~10x statistics vs. current samples

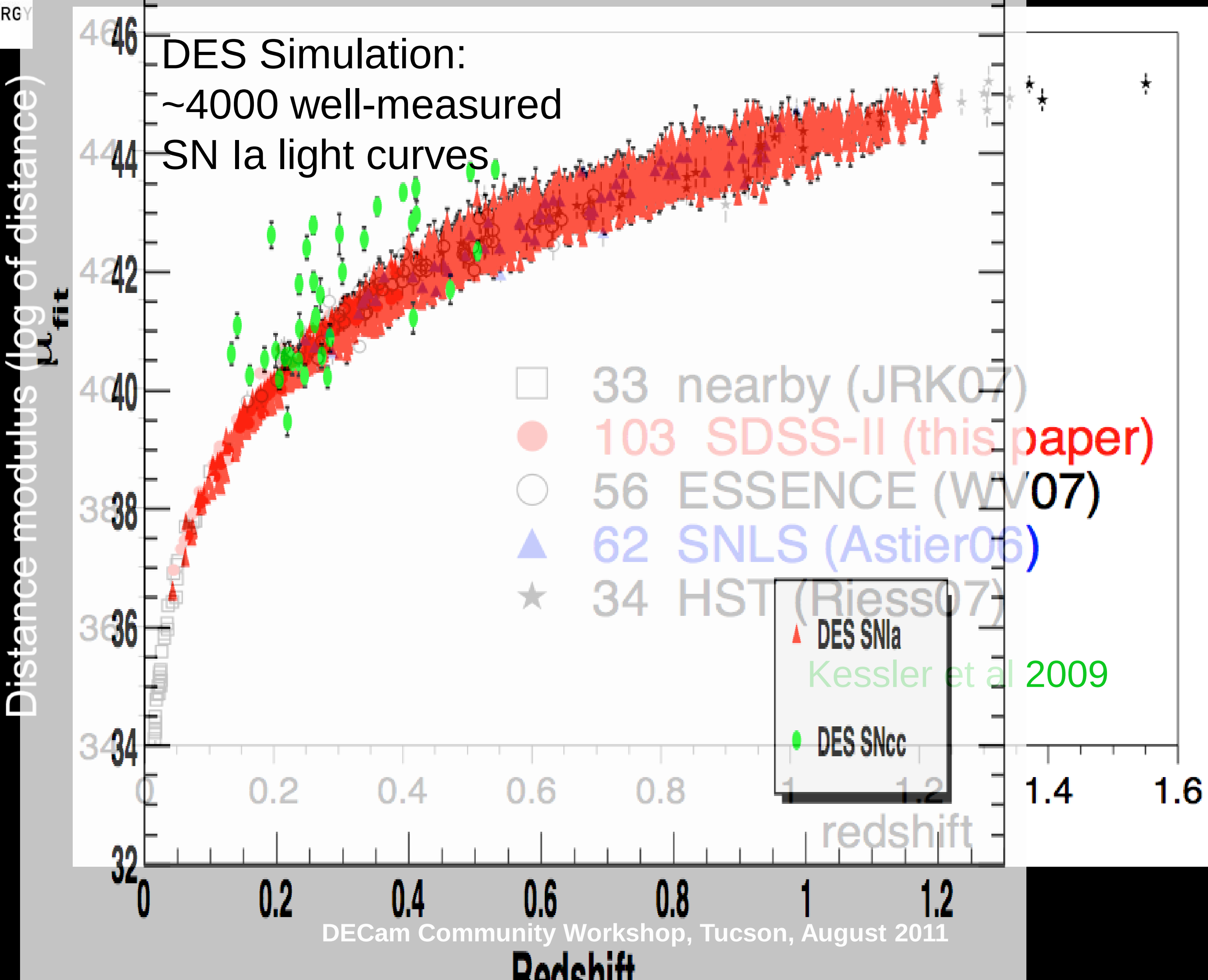


Supernova Hubble Diagram



Supernova Hubble Diagram

DES Simulation:
~4000 well-measured
SN Ia light curves



Kessler et al 2009

SN Spectroscopy

- 1) DES/VIDEO sample - grizYJ(HK) = ~**60** SN Ia
- 2) "Random" sample of all types of SN candidates = ~**500 - 1000** candidates for studying sample purity and photometric SN typing
- 3) SN Ia in faint hosts (>25 mag) = ~**200** SN Ia
- 4) Post-search host galaxy spectroscopy of all SN Ia candidates = ~**5000+** galaxies

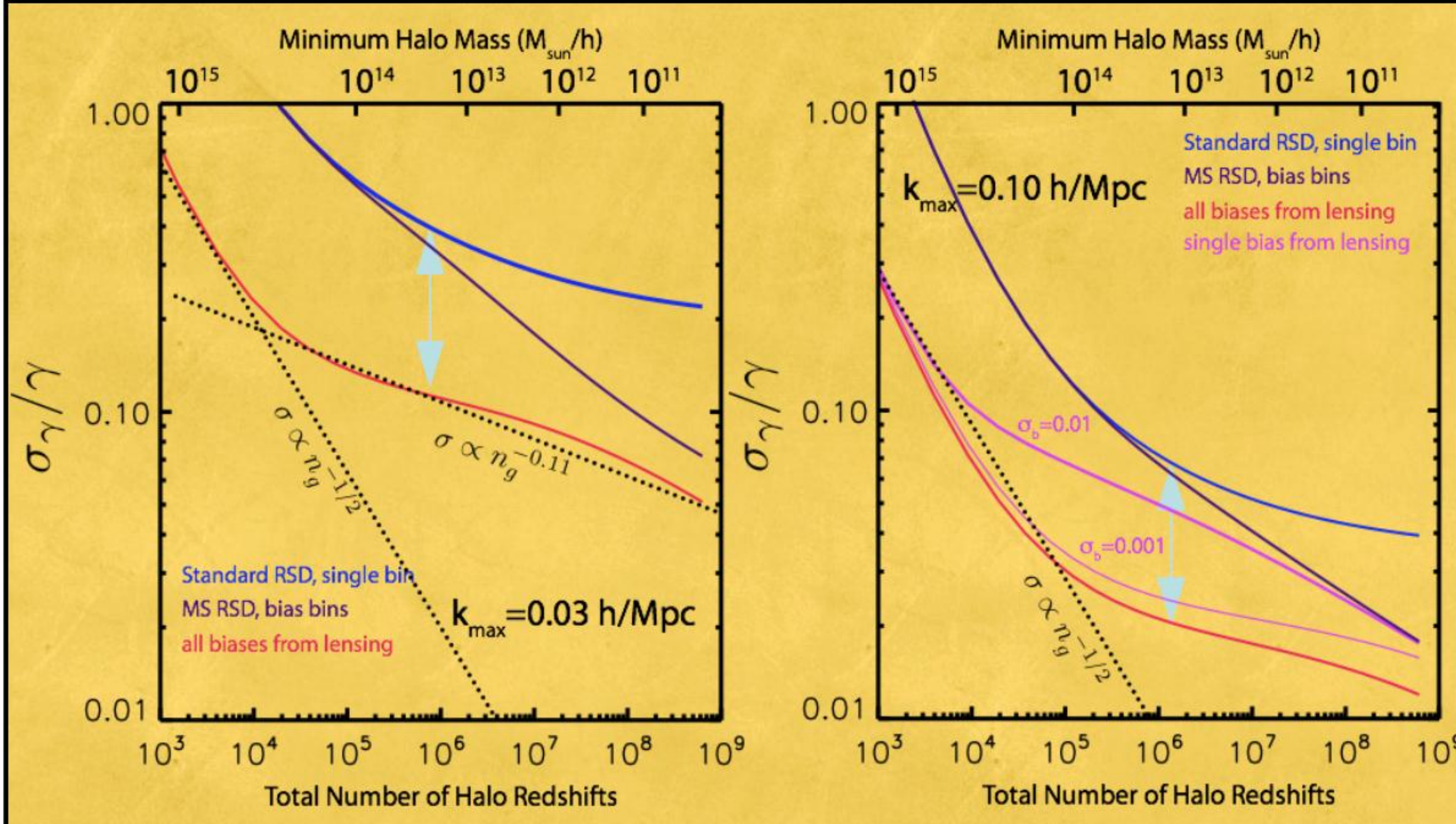
- 4m AAT/AAOmega (OZDES Collaboration), Keck, VLT LBT, + others.

DES SN Community Meeting, Oct. 12-13,
U. Pennsylvania. Contact: Bob Nichol (Portsmouth)

DES Spectroscopic Follow-up

- Massive Redshift Survey(s) of DES targets could provide:
  - Cluster velocity dispersions (dynamical mass estimates)
  - Radial Baryon Acoustic Oscillation measurements: $H(z)$
  - Redshift Space Distortion (RSD) measurements: $\delta(z)$
  - Combination of RSD with DES WL: powerful test of gravity
  - Improved Photo-z Calibration
- Enhance Dark Energy science reach of DES by factor of several
- Redshift survey of ~5-10 M galaxies over ~5000 sq deg could be done with 4-m class wide-field telescope(s)
- Preliminary science studies (and discussions with BigBOSS) underway

WL data increases effective volume of RSD 10-fold



Assuming 1/2-sky survey of z=0.5±0.05

Bernstein & Cai 2011

Conclusion

•DES poised to take the next step in understanding the nature of dark energy, with survey operations starting next year.

•DES data processed through DES Data Management system will be available to the public 12 months after it's taken (raw and processed images), with periodic releases of co-added images and catalogs.

•DECam, with its associated Community Pipeline, will be a powerful imaging instrument for community use: I look forward to hearing how you plan to use it.

•There are opportunities for synergistic observations with community participation (e.g., extension of time domain observations throughout the year).