LANDSCAPE OF DARK ENERGY EXPERIMENTS

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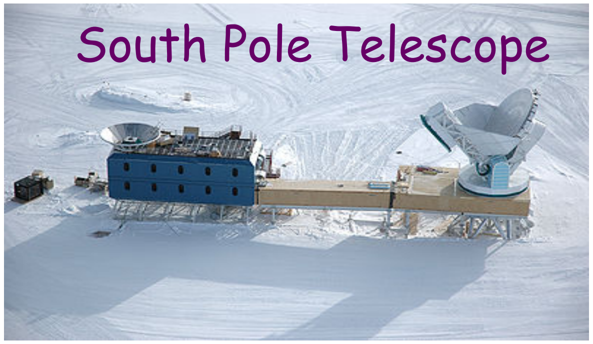
LMU Physics/Excellence Cluster/Ronin Inst
Particle Physics Seminar
University of Warsaw

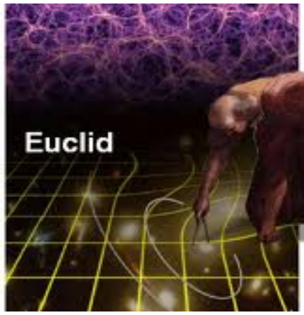
Projects I am part of (2008-present)

DARK ENERGY
SURVEY

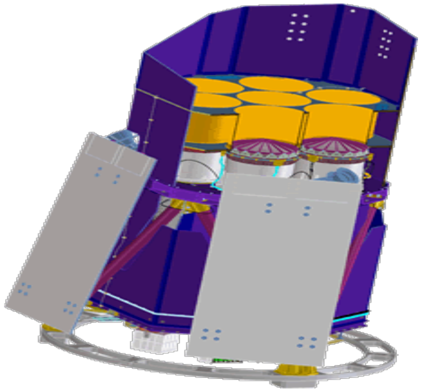

South Pole Telescope

XXL
PROJECT

Pan-STARRS



2020


EROSITA
(~2017)

Blanco Cosmology Survey

(2005-2008)

Talk Outline

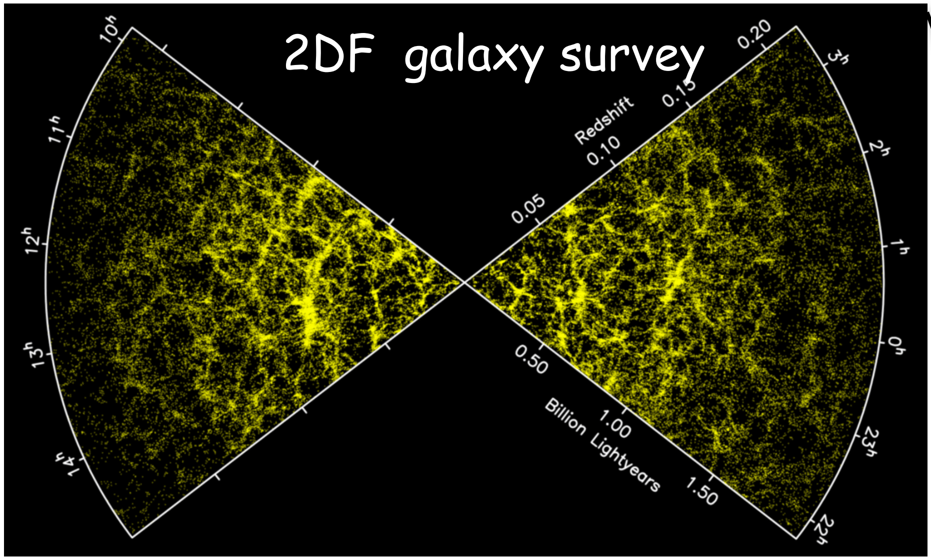
Rudiments of Cosmology

- List of unsolved problems in Cosmology requiring new Physics
- Dark Energy Discovery with Supernova leading to 2011 Nobel Prize
- South Pole Telescope (microwave) :
  - Optical follow-ups of galaxy cluster
  - Cosmology Results from galaxy cluster survey
- Dark Energy Survey (optical)
- Euclid space based mission (optical/near infrared)

Theme of any talk on Cosmology talk : Universe is full of Mystery and Surprises

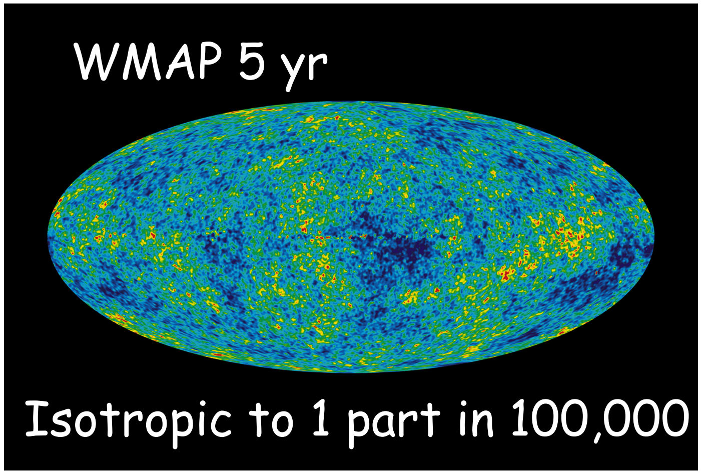
Foundations of Cosmology

- General Relativity/Metric Theory
- Universe is Homogenous & Isotropic


2DF galaxy survey

Robertson-Walker metric describes universe dynamics on large scales

Weinberg (1972)

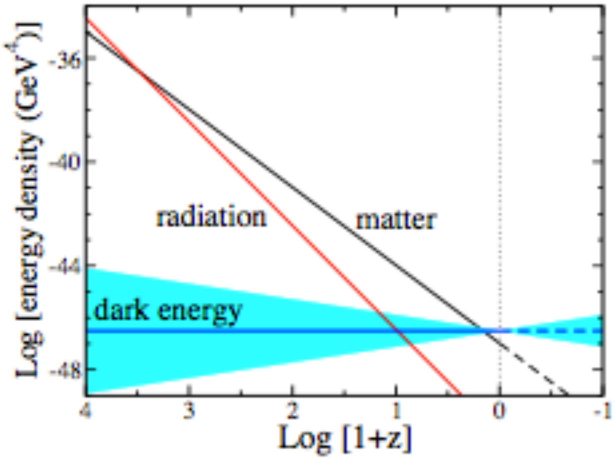

WMAP 5 yr

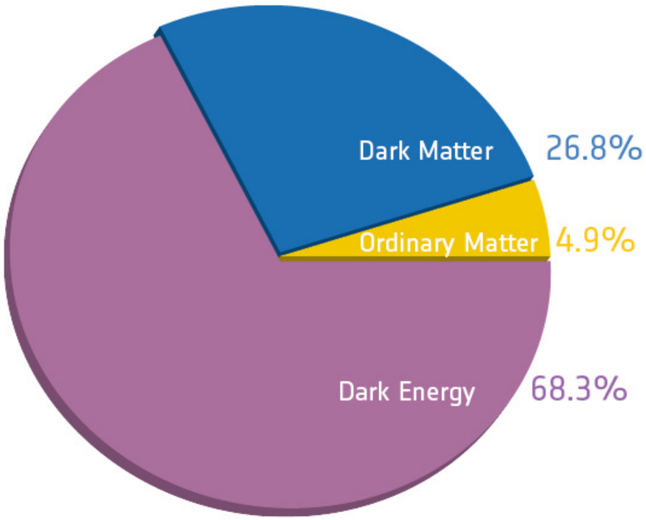
Isotropic to 1 part in 100,000

Geometry, Dynamics, Destiny of Universe is entirely determined by matter/energy content

Inventory of Universe

$$\Omega = \frac{8\pi G}{3H^2}\rho \,.$$

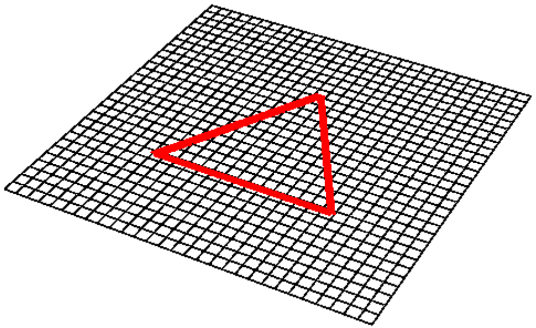




Neutrinos > 0.1%
Photons 0.01 %

Ω = 1

Dark Energy (???)
Dark Matter (???)
Matter-Antimatter Asymmetry (???)



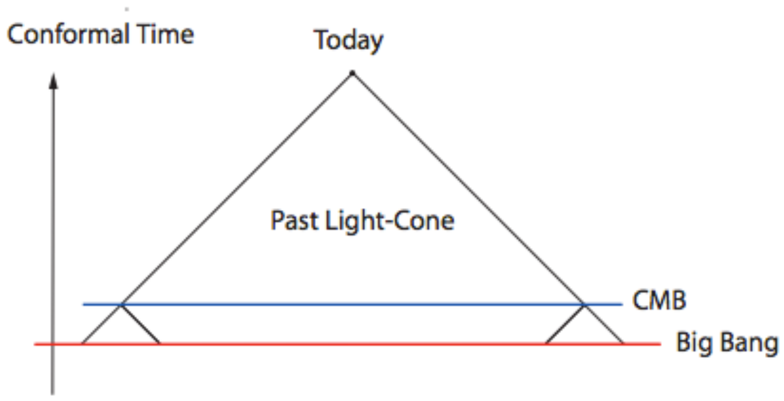
Flat Universe k = 0

Other Unsolved Problems

- Horizon and Flatness problem in Big Bang Cosmology

(Peebles & Dicke 1979)

$d\Omega/d\ln a \;\; \alpha \;\; \Omega(\Omega-1)$



Inflation

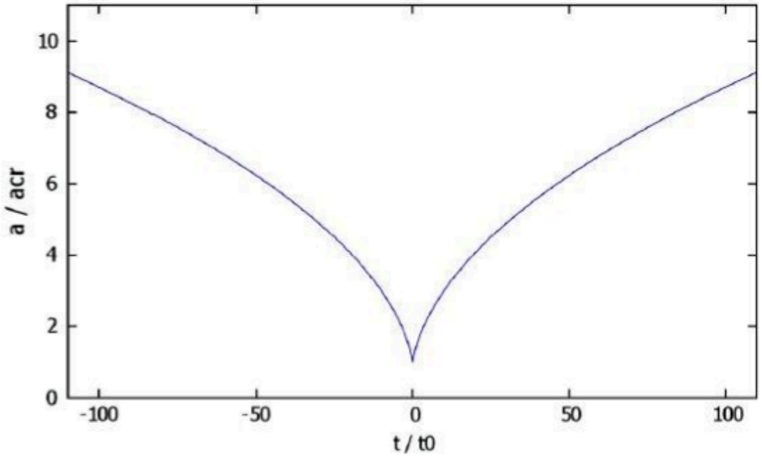
(Guth, Linde, Kazanas,Starobinsky)

- Short Period of exponential expansion with > 60 e-foldings
- Mainly based on scalar fields
- Observables include gravitational waves, spectrum of scalar perturbations, non-gaussianity of density fluctuations, scale –dependent bias

Inflation from Einstein-Cartan gravity

SD + Nikodem Poplawski (Univ. of Warsaw alumni)

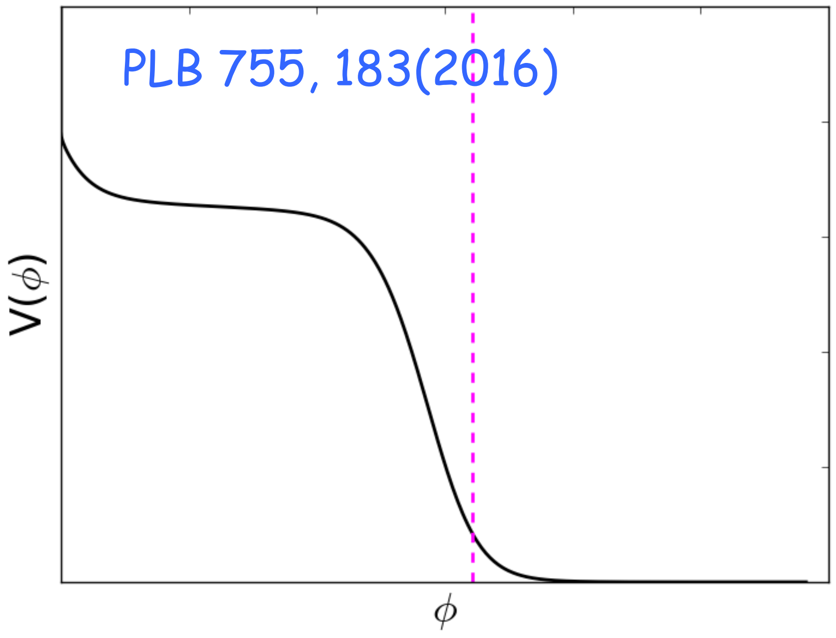
- Einstein-Cartan gravity simplest extension to GR which accounts for spin of fermions (Sciama 64, Kibble 61) (also known as ECKS theory)
- ECKS deviates from GR only at ultra-high densities (> 10^{45} kg/m$^{\hat{}3}$)
- ECKS solves Big-bang singularity and other problems of Big-bang cosmology

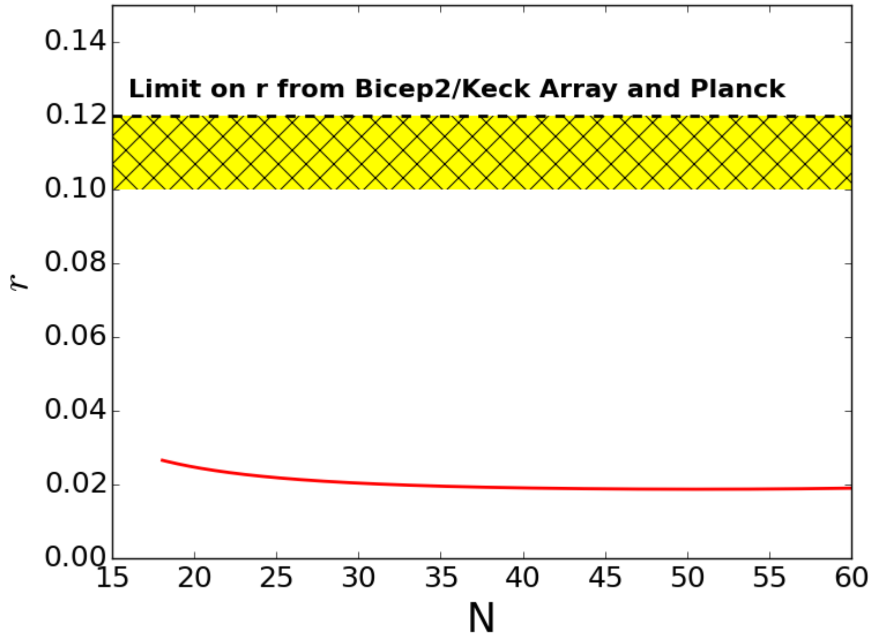


Big bounce

Poplawski 2012
PRD 85, 107502

Inflation from Einstein-Cartan gravity





- Period of inflation lasts for ~ 10^{-42} seconds with ~60-100 e-folds
- No re-heating and no fundamental scalar field

scalar spectral index, tensor-to-scalar ratio consistent with Planck 2015 data

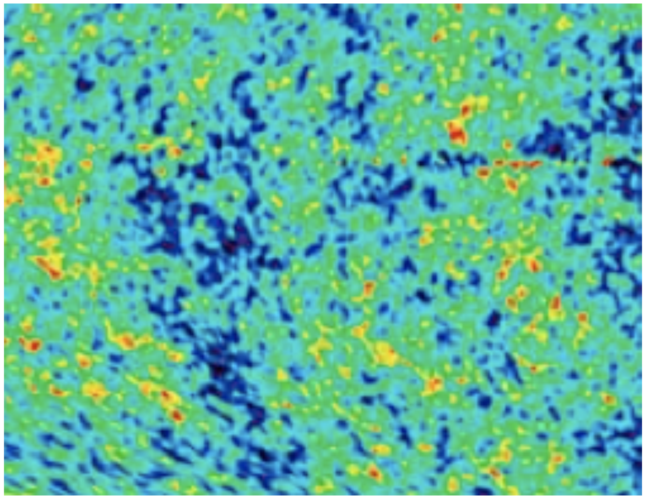
For more media coverage, check out

N. Poplawski on Polish TV https://www.youtube.com/watch?v=5cdlYU-2wR4

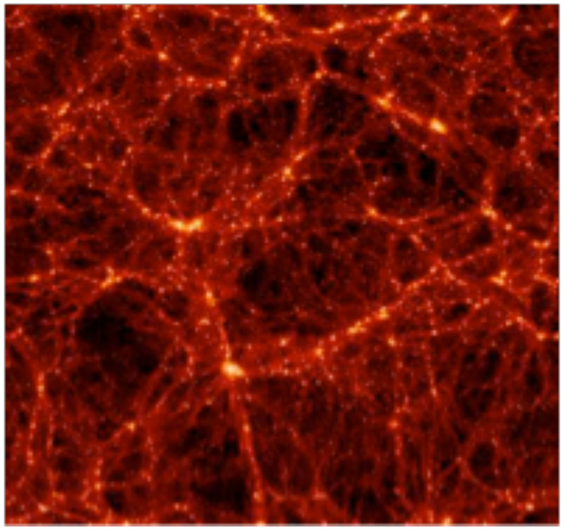
Looking through the wormhole http://topdocumentaryfilms.com/through-the-wormhole-are-there-parallel-universes/

(*hosted by Morgan Freeman around 32nd minute)

Growth of Structure in Universe



Cosmic Microwave Background

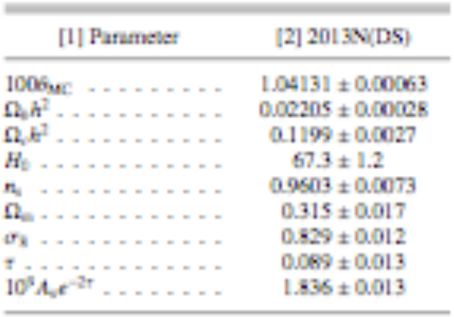


Structure Formation

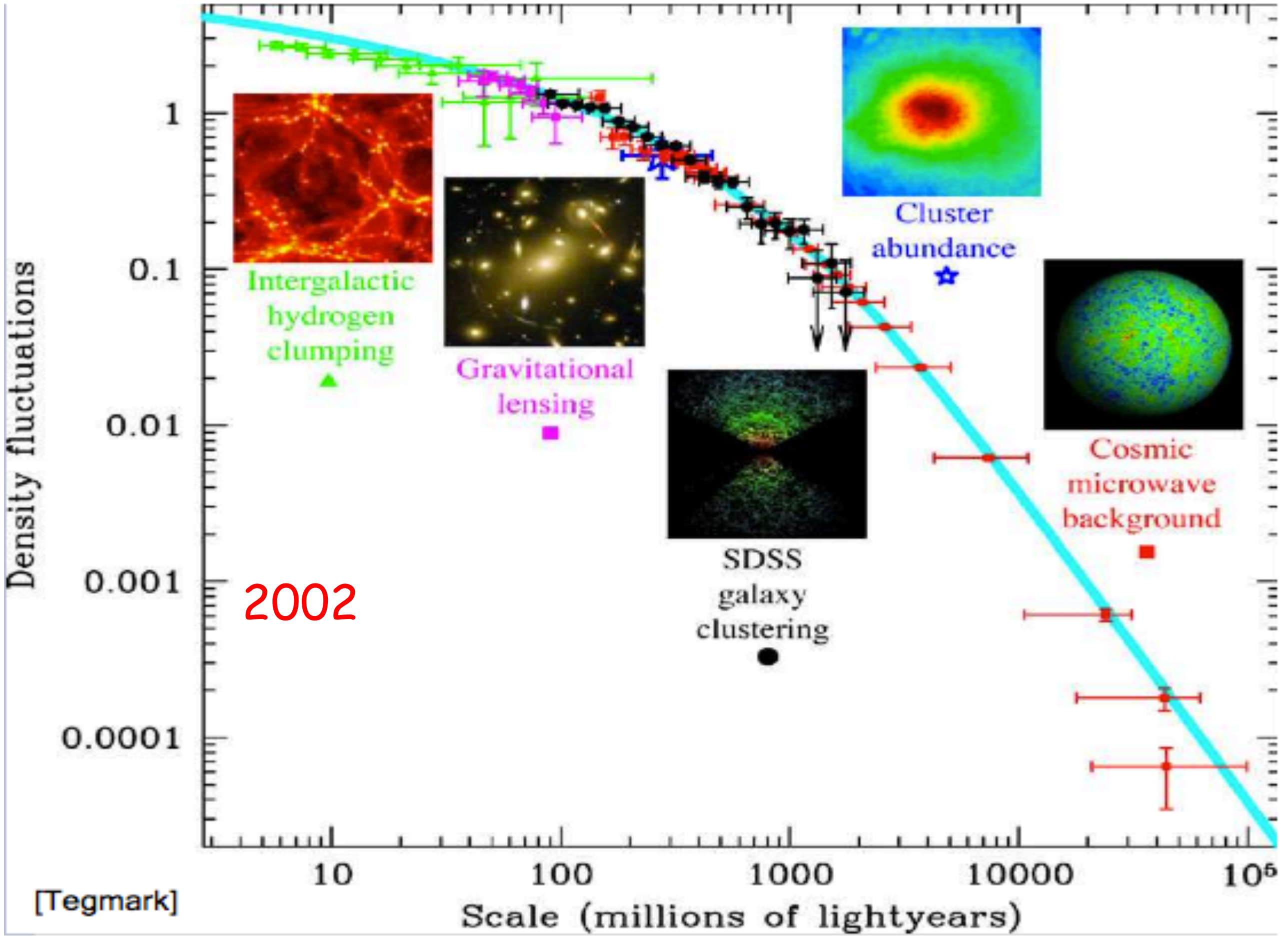
Galaxies and Clusters of Galaxies

Structure grows from amplification of density perturbations

Consistency of Lambda CDM Model



[1] Parameter	[2] 2013N(DS)
$100\theta_{MC}$	1.04131 ± 0.00063
$\Omega_b h^2$	0.02205 ± 0.00028
$\Omega_c h^2$	0.1199 ± 0.0027
H_0	67.3 ± 1.2
n_s	0.9603 ± 0.0073
Ω_m	0.315 ± 0.017
σ_8	0.829 ± 0.012
τ	0.089 ± 0.013
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013

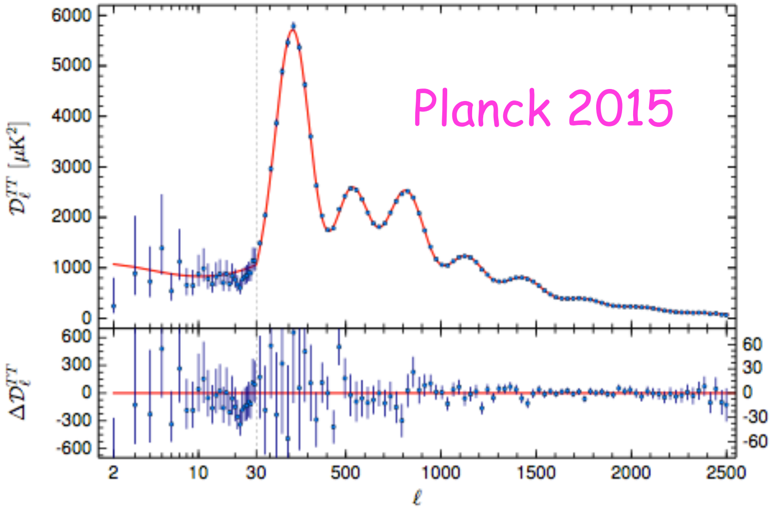


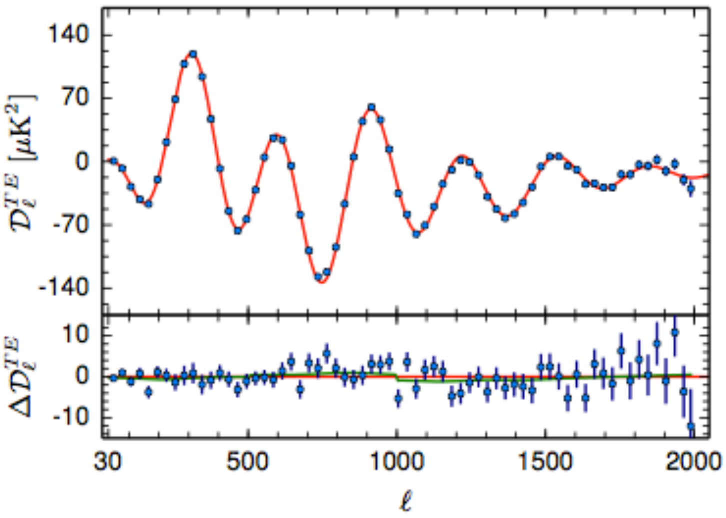
2002

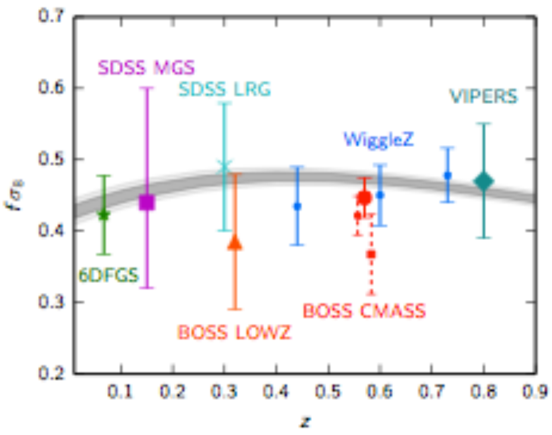
[Tegmark]

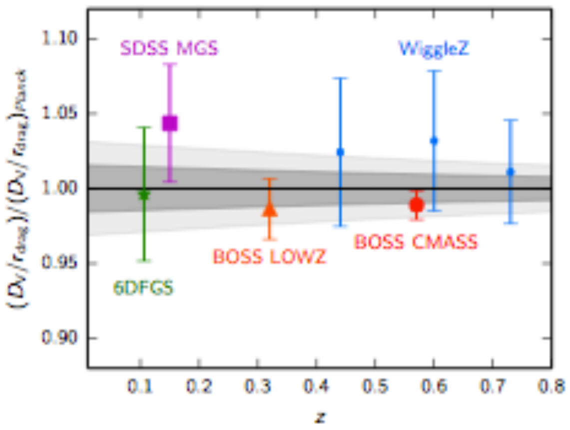
Spectrum of
density
fluctuations
consistent
at all scales
using a simple
8-parameter
model for the universe

2015 Cosmological Parameters vs Data



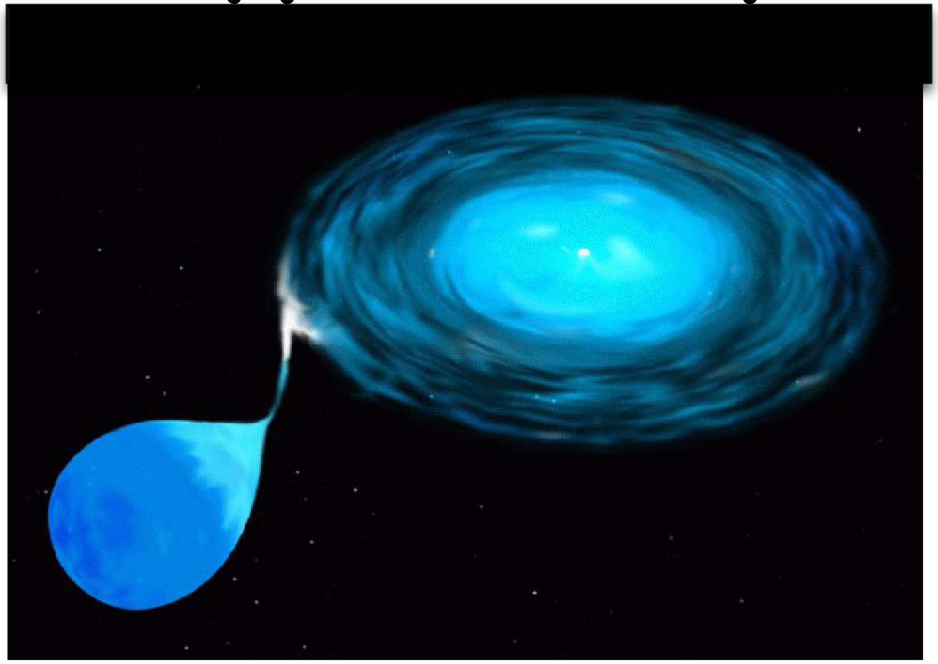




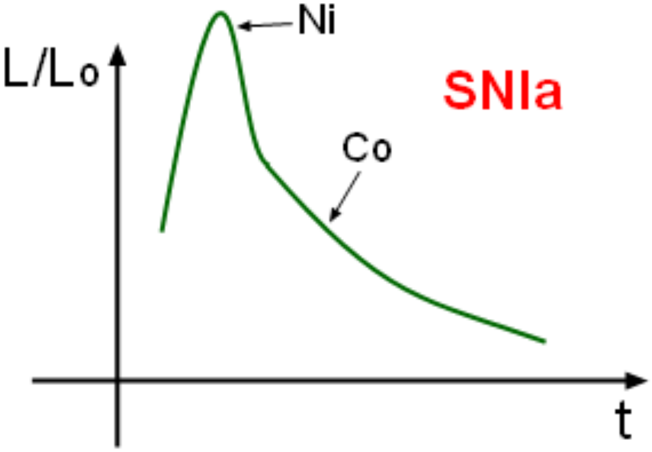


Statistical Properties of observables in universe based on growth of structure agree with ~seven parameter model

Type 1a Supernovae



- Thermonuclear Explosion of white dwarf
- $M \sim 1.35\ M_\odot$
- K.E. ~ 10^{51} ergs



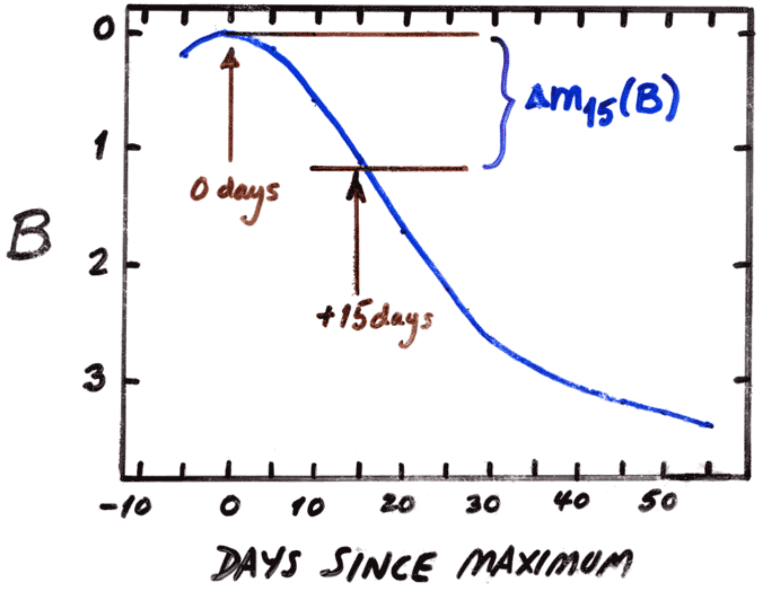
Luminous output powered by Radioactive decays

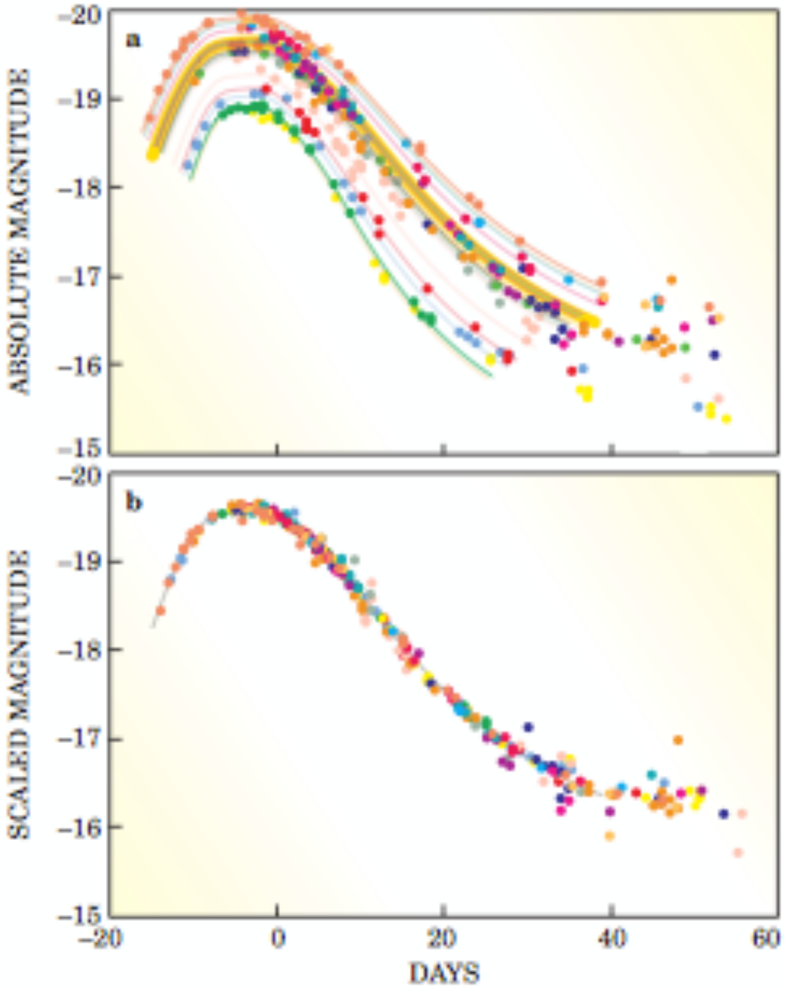
$^{56}Ni \longrightarrow {}^{56}Co \longrightarrow {}^{56}Fe$

8 days 111 days

Mark Phillips insight (1993)

Width of Light Curve
Correlated with peak
Luminosity



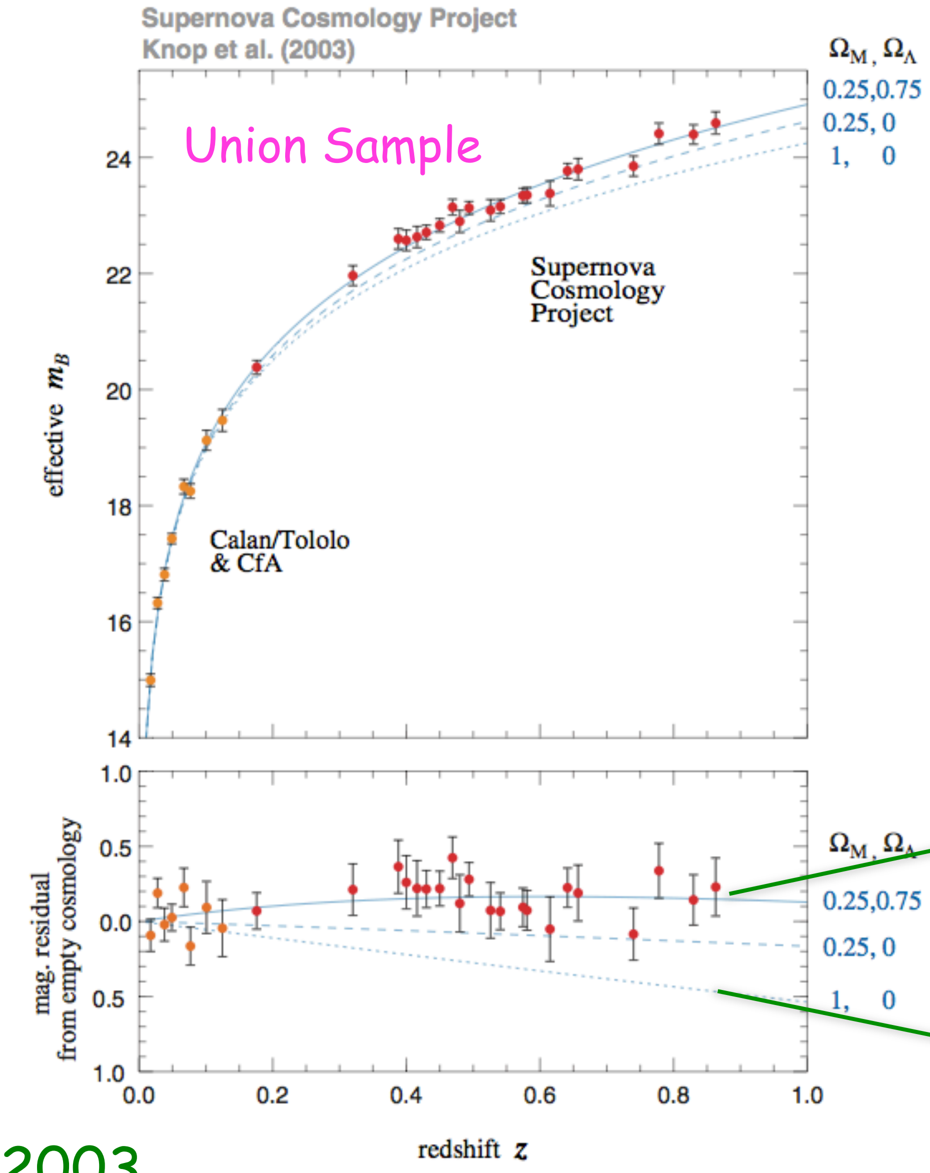


Type 1a supernova are standardizable candles and used as distance Probes and once you know redshift you can solve for cosmology

Hubble Diagram with Type 1a SN

Two groups: SCP and High-z

Extend Hubble diagram to high redshift and make precise estimates of q



Union Sample

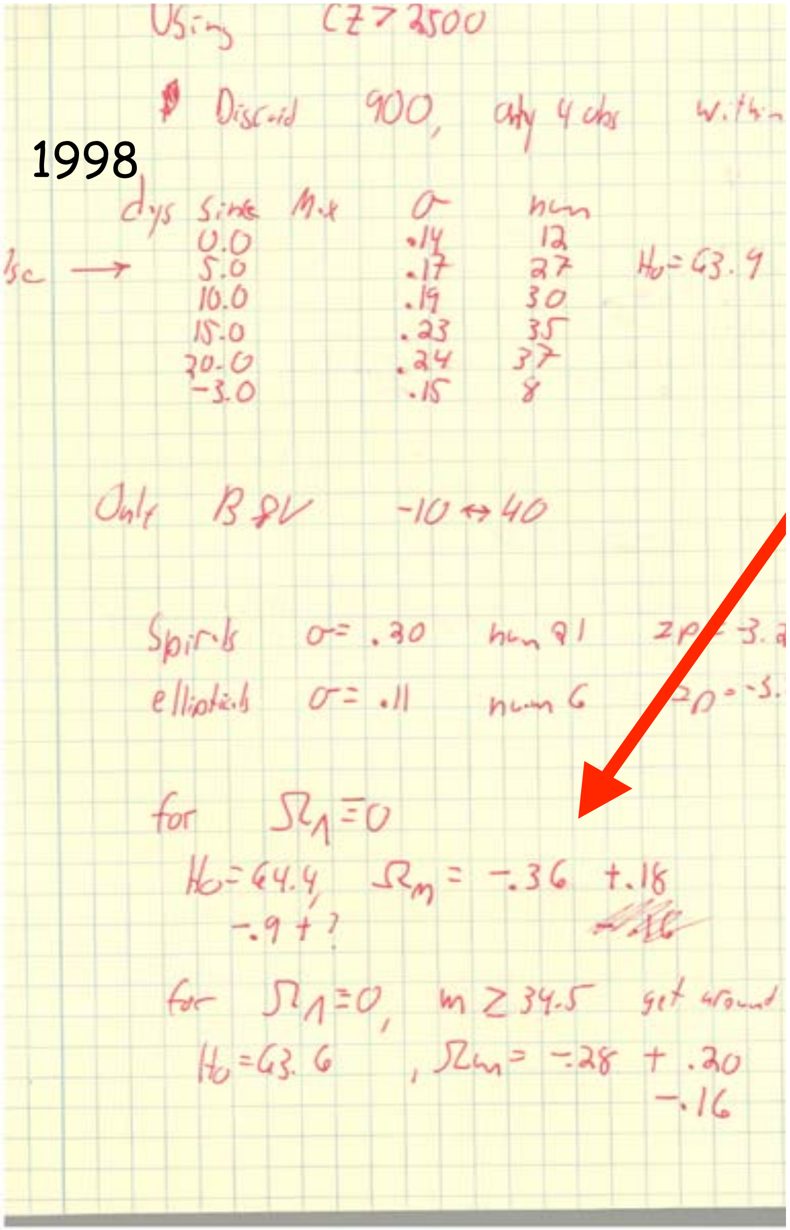
Universe was accelerating instead of decelerating!!

Accelerating

Decelerating

2003

"Eureka" moment in Adam Riess notebook



1998

Using $cz > 2500$

Discard 900, only 4 obs within

	dys since Max	σ	num	
	0.0	.14	12	
Isc →	5.0	.17	27	$H_0 = 63.9$
	10.0	.19	30	
	15.0	.23	35	
	20.0	.24	37	
	−3.0	.15	8	

Only B & V −10 ↔ 40

Spirals $\sigma = .30$ num 91 zp = −3.

ellipticals $\sigma = .11$ num 6 zp = −3.

for $\Omega_\Lambda = 0$

$H_0 = 64.4$, $\Omega_m = -.36$ $+.18$ ~~−.16~~

$-.9\ +?$

for $\Omega_\Lambda = 0$, $m \geq 34.5$ get around

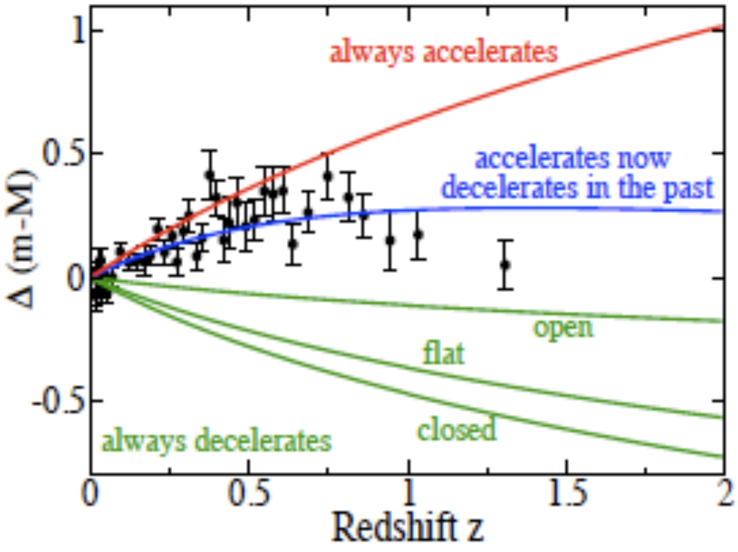
$H_0 = 63.6$, $\Omega_m = -.28\ ^{+.20}_{-.16}$

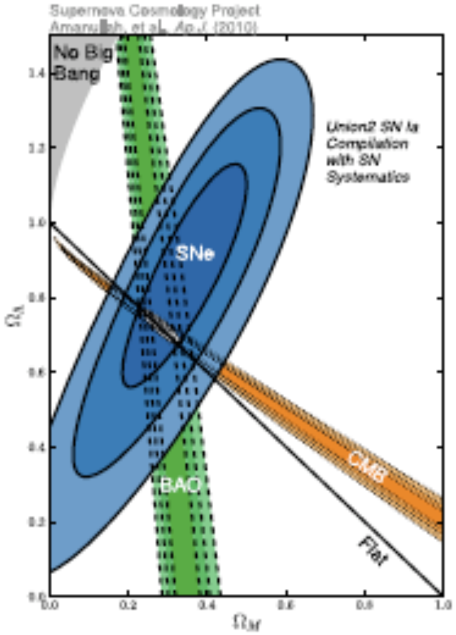
Discovery of Dark Energy

Found sum of matter to be negative

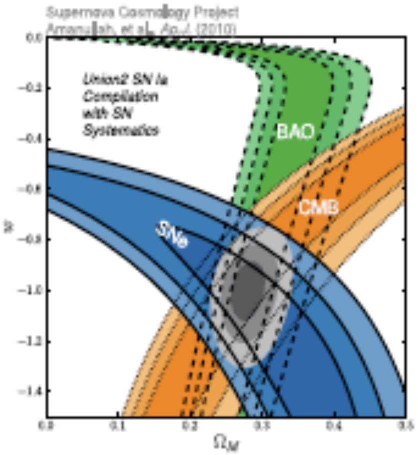
$\Omega_m < 0$

Recent Supernovae Results (2010)




Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)

2010 data


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)

Supernovae data along with other cosmological probes (CMB, baryon acoustic oscillations, Clusters, Weak lensing) consistent with universe containing 70% dark energy and about 25% dark matter

MOST RUDIMENTARY EXPLANATION

Main difference between GR and Newtonian Gravity :

GR : **Pressure gravitates**

Newtonian gravity : **Pressure counteracts gravity**

$$\rho \longrightarrow \rho + 3P$$

$$\frac{1}{a}\frac{d^2a}{dt^2} = -\frac{4\pi G}{3}\sum_i(\rho_i + 3p_i)$$

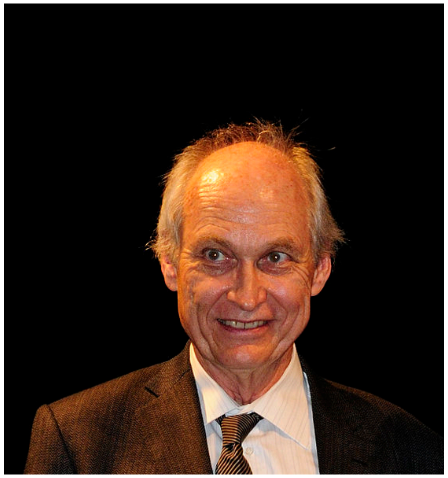
$$\ddot{a} > 0 \longrightarrow \rho + 3P < 0$$

Not predicted by General Relativity

Dark Energy coined by M. Turner (1998)

→

(Dark Pressure/Smooth Tension)
would have been more appropriate



Simplest Extension to GR

+ Cosmological constant (Λ)
= Energy Density of
Quantum Vacuum
(Zeldovich 1968)

Cosmological Constant
$P = -\rho$

Kragh 1111.4623

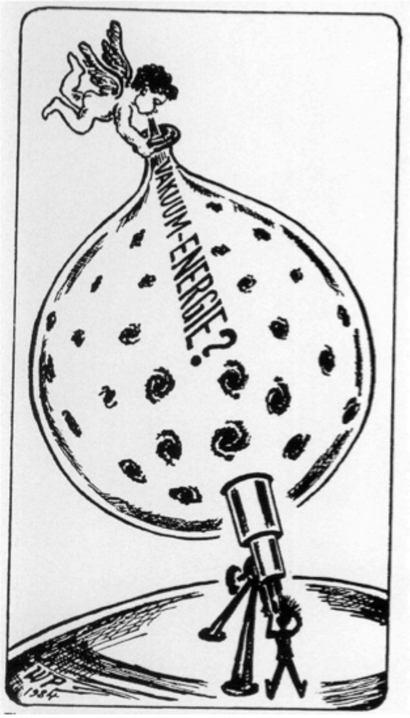
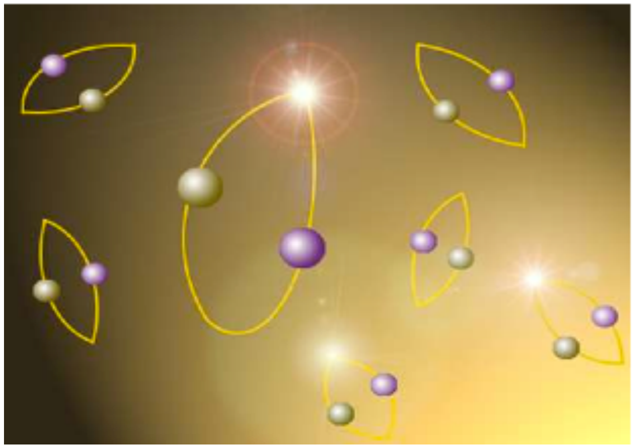


Figure 4. Wolfgang Priester's illustration of vacuum energy from 1984, as reproduced in Overduin et al. (2007, p. 419). Source: Priester (1984).

ρ_Λ (obs) ~ 10^{-12} eV^4

ρ_Λ (theor.) ~ 10^{76} GeV^4

QFT Theoretical prediction ~ 10^{120} observed



Most embarrassing example of order
of magnitude calculation wrong (F. Wilczek)

Summary of Dark Energy Theories

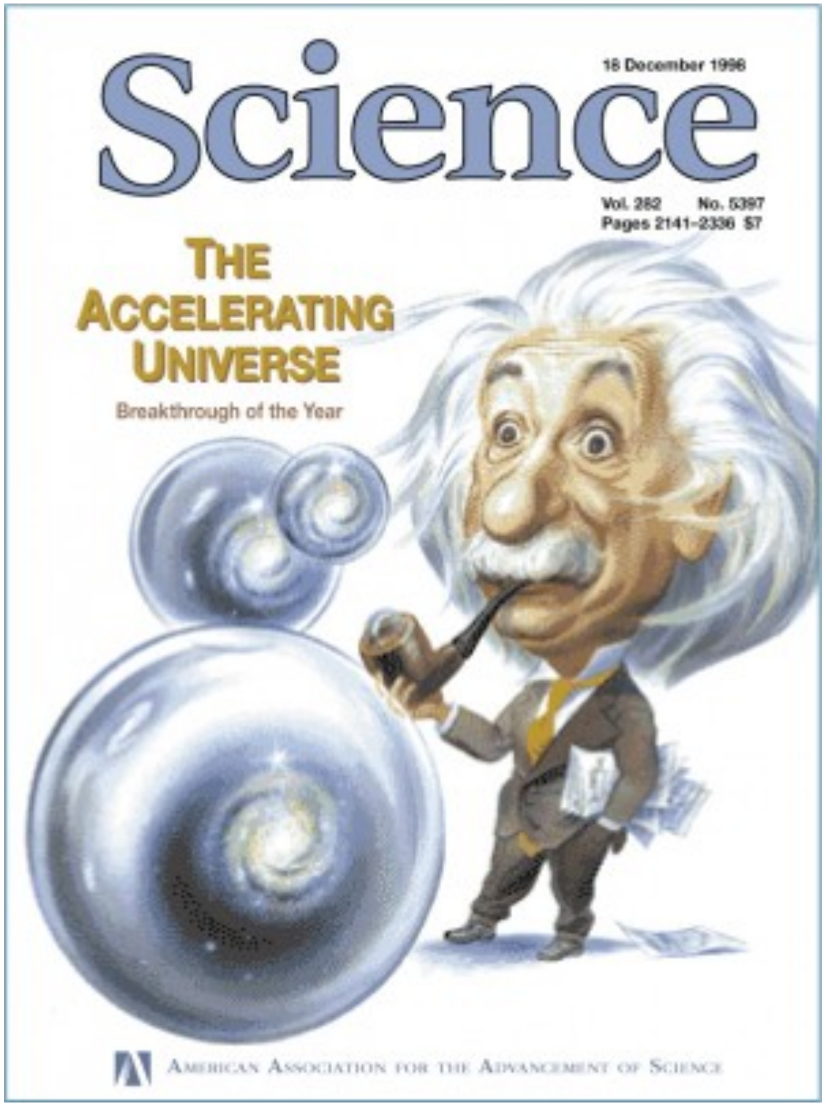
- Cosmological Constant
- Addition of exotic fields/matter
- Modification of general relativity

⇕

- Universe NOT homogenous

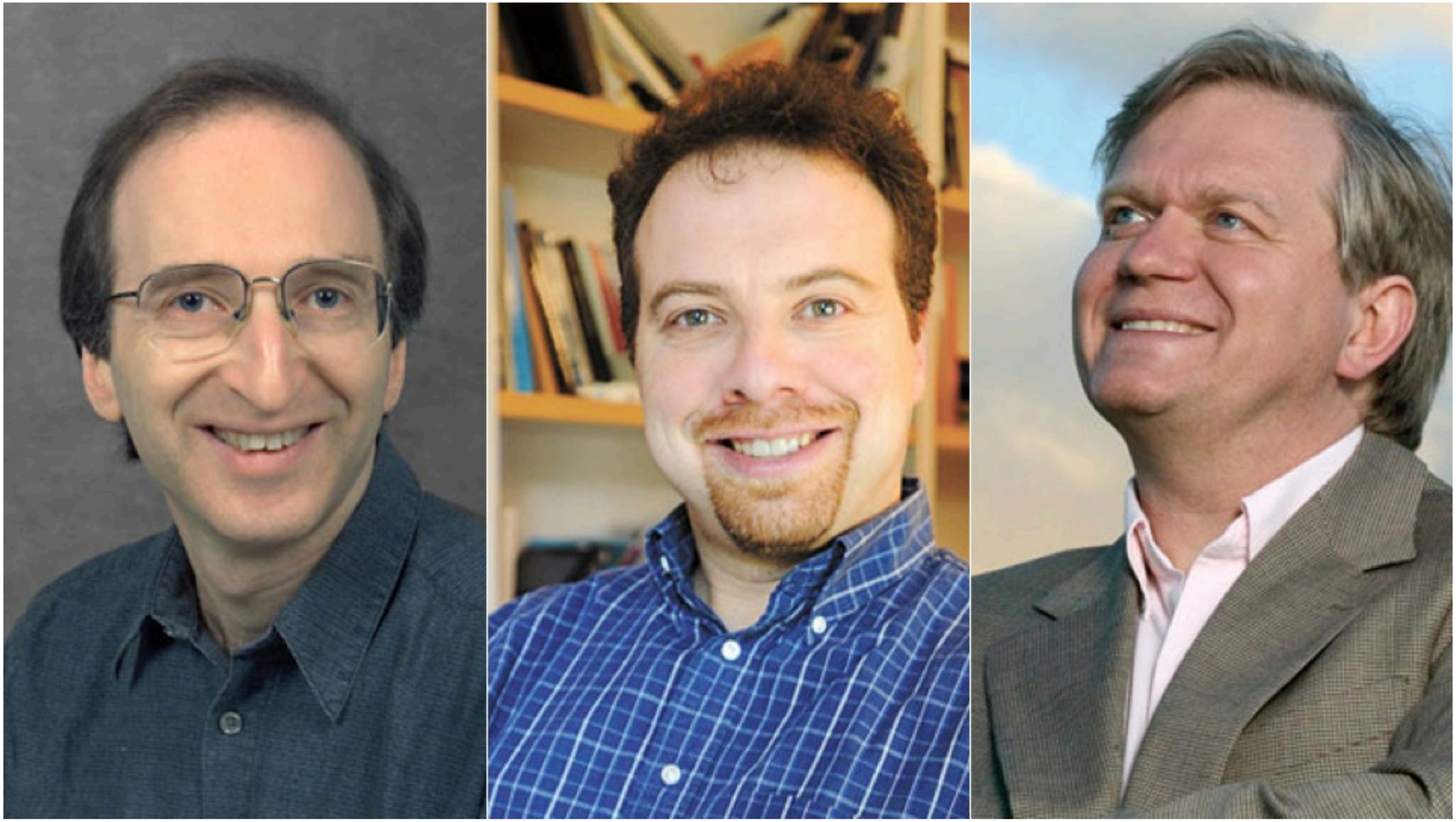
More than 10,000 papers on different explanations/models of accelerating universe

"Most profound mystery in all of science" – Mike Turner



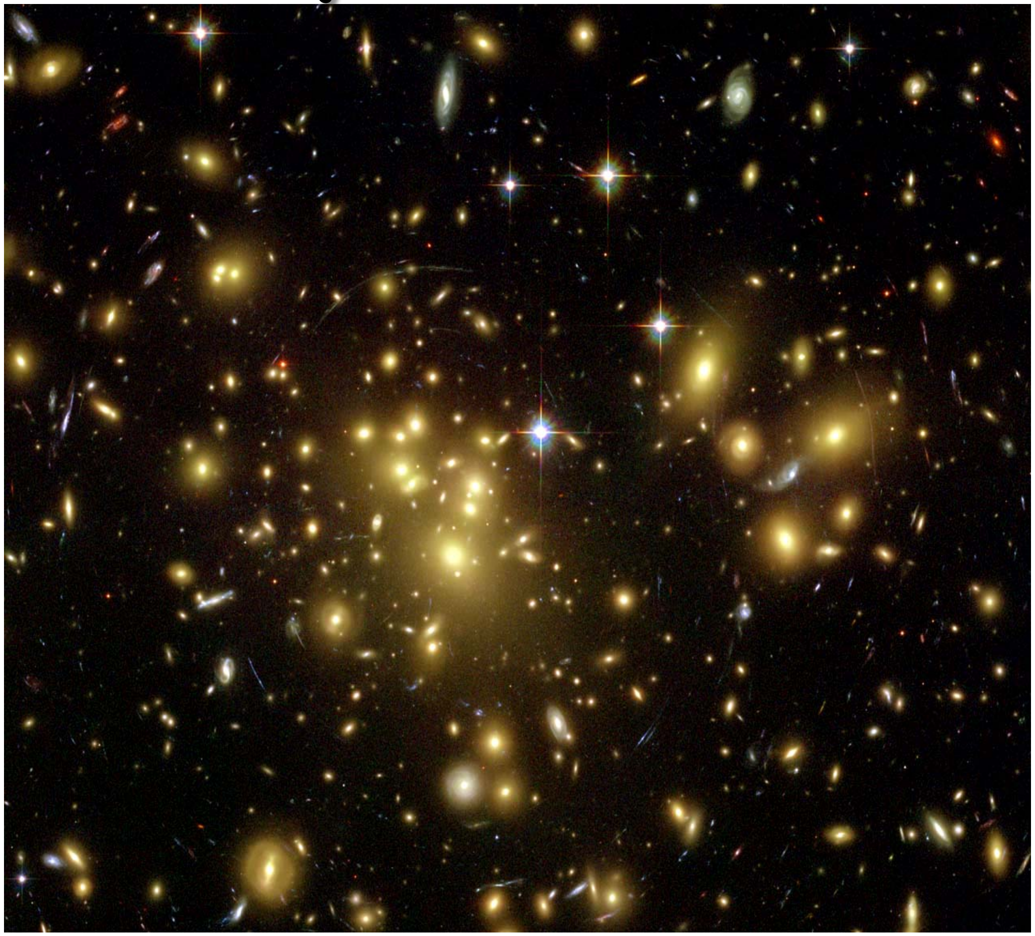
Observers parameterize dark energy by equation of state $w=P/\rho$

2011 Physics Nobel Prize



The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".

Galaxy Clusters 101



Abell 1689
Credit : N. Benitez (Hubble Space Telescope)

Most massive gravitationally collapsed objects with masses $> 10^{14}\ M_{\odot}$

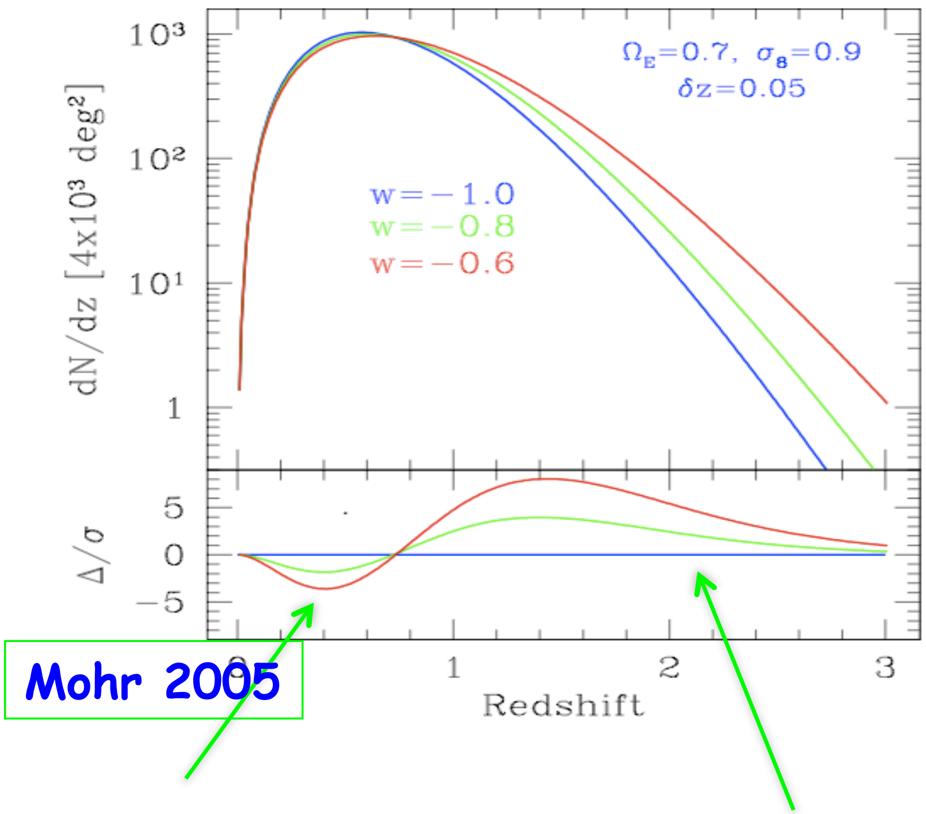
- Galaxies 2 %
- Plasma (baryons) 13 %
- Dark Matter 85 %

Typical Size 1-10 Mpc

Seen in all wavelengths from radio to X-rays

Dedicated surveys for galaxy Clusters in optical, X-ray Microwave in last 2 decades

Cosmology with Clusters



Mohr 2005

Volume Effect

Growth Effect

Cluster Abundance

- Need masses and redshifts of clusters in order to do cosmology

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

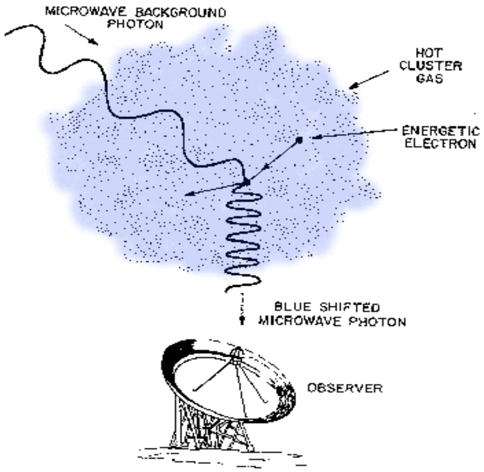
Depends on:
Rate of Expansion, *H(z)*

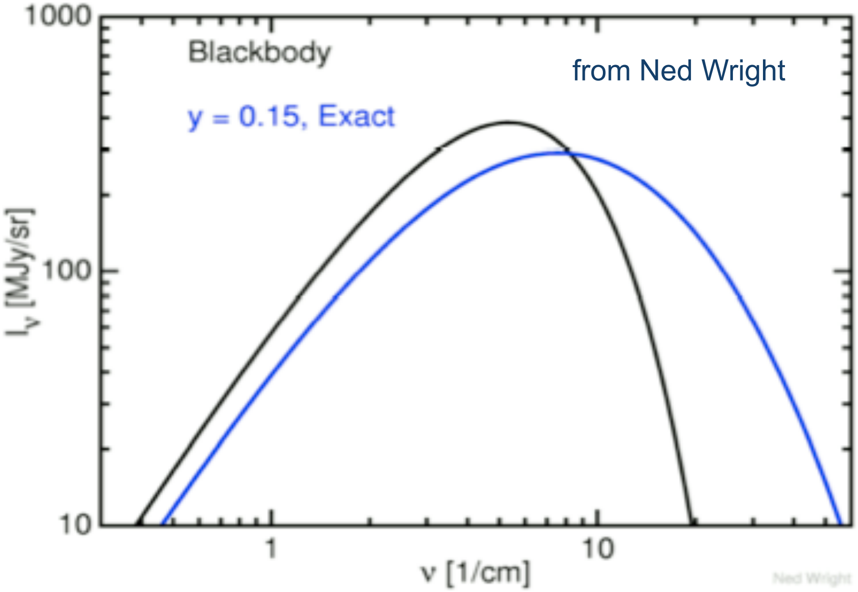
Depends on:
Matter Power Spectrum, *P(k,z)*
Growth Rate of Structure, *D(z)*

- Sensitive to both Expansion Rate of Universe & growth of density perturbations

- Also probe non-Gaussianity of density perturbations

Sunyaev-Zel'dovich Effect (1972)





Compto-ionization of CMB photons on interaction with hot electrons in cluster gas

$$\frac{\partial n}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x}\left[x^4\left(\frac{\partial n}{\partial x} + n + n^2\right)\right] \longrightarrow y = \int \left(\frac{k_B T_e}{m_e c^2}\right) n_e\,\sigma_T\,dl,$$

$x_e = h\nu / k_B T_e,$

Typically y ~ 0.001

Kompaneet's equation (1957)

South Pole Telescope (SPT)

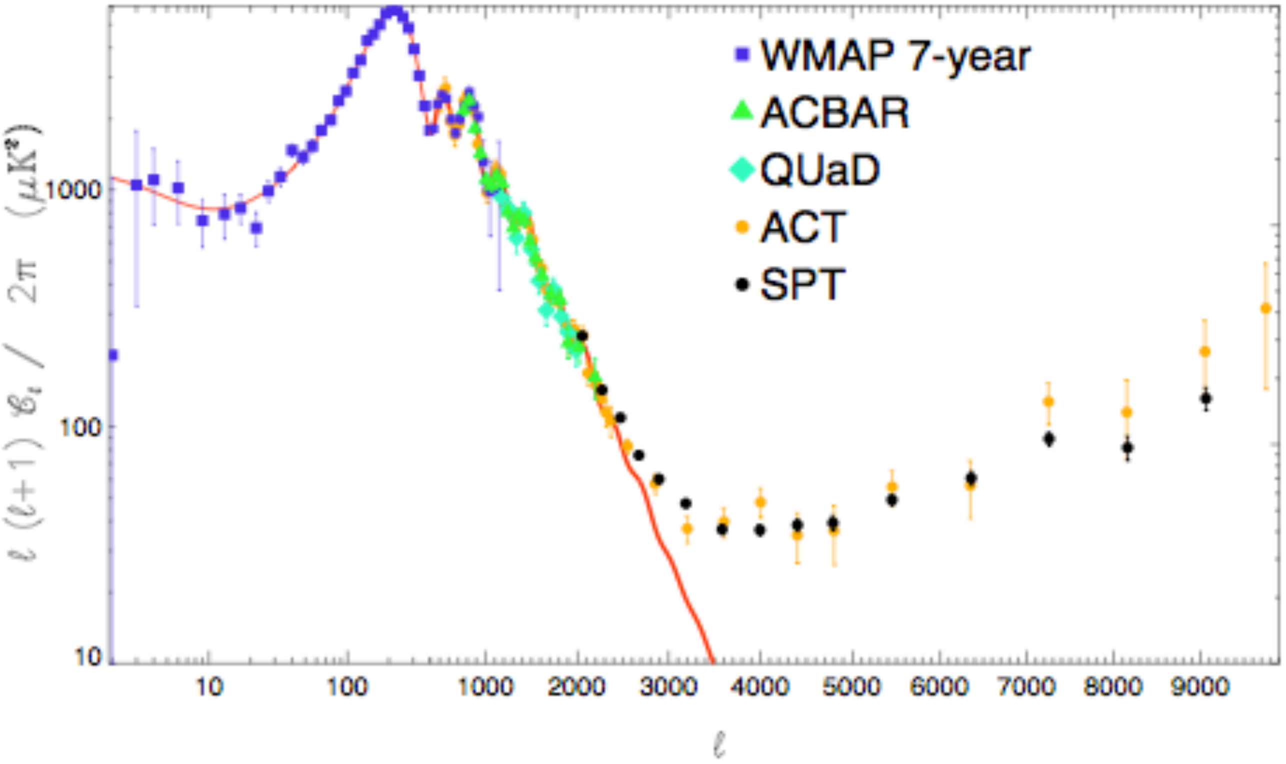
- (Sub) millimeter wavelength telescope:
  - At the South Pole
  - 10 meter aperture
  - 1′ FWHM beam at 150 GHz
  - 20 micron RMS surface accuracy
  - 1 arcmin pointing
- SZ Receiver:
  - 1 sq. deg FOV
  - Observe in 3+ bands between 95-220 GHz simultaneously
  - Sensitivity ~ 20 – 100 μK

- Measure CMB anisotropies on very small scales (~0.02 degrees)
- 2500 sq. deg. Galaxy cluster survey 2008-2011

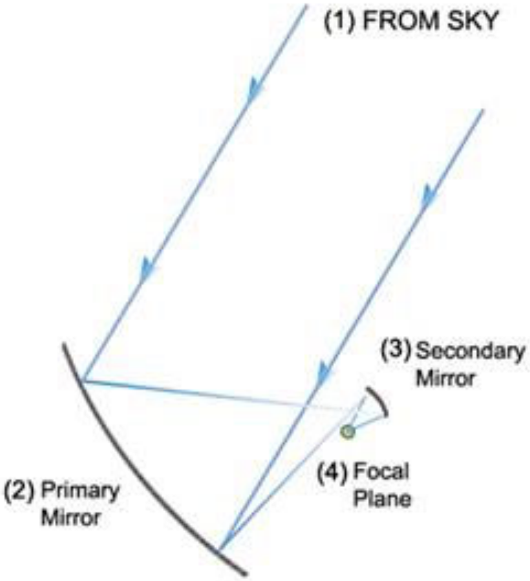
SPT Science Goals

- Measure CMB anisotropies at very small angular scales

COBE ~ 7°
WMAP ~ 0.3°
PLANCK ~ 0.1°
SPT ~ 0.02°



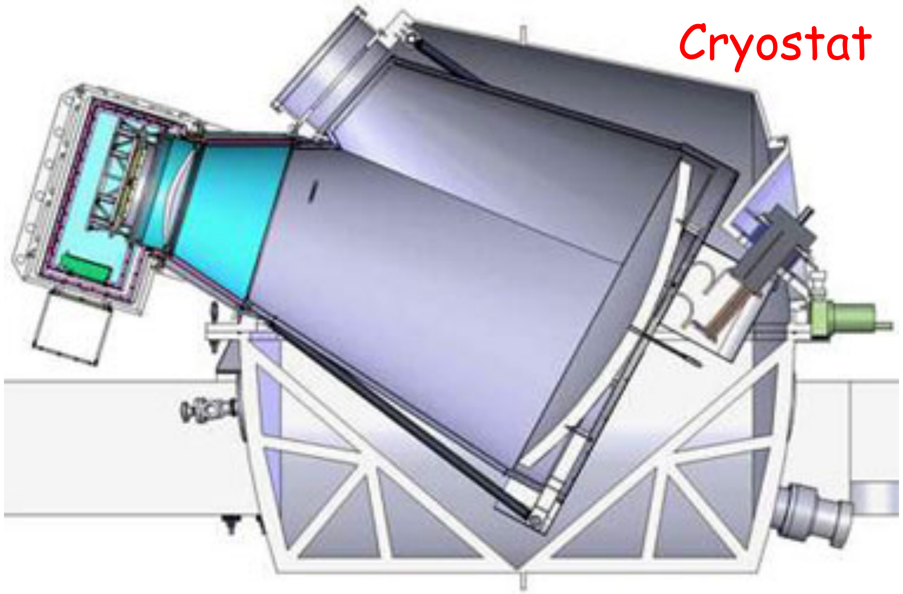
SPT Unfurled




SPT secondary mirror

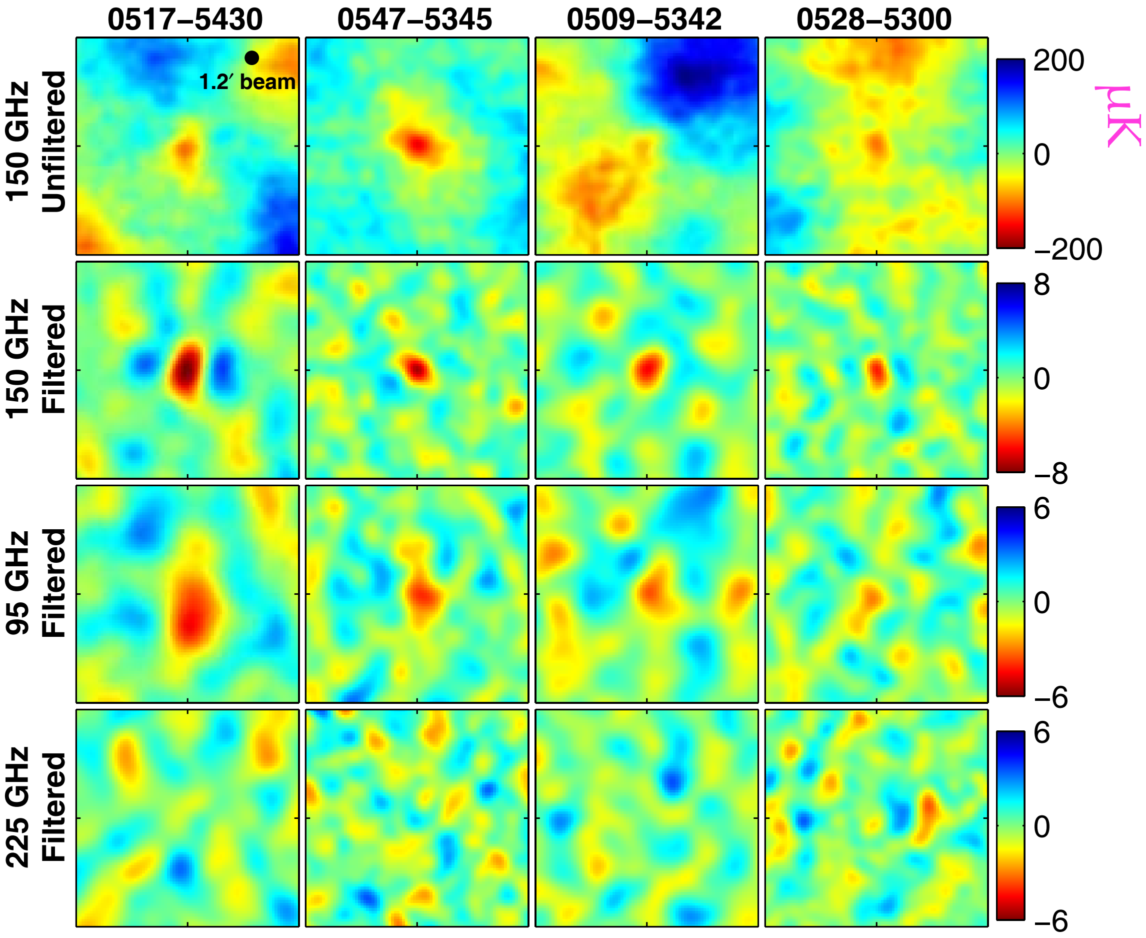

1.0 deg (on sky)

SPT Focal Plane


Cryostat

First SPT Detections

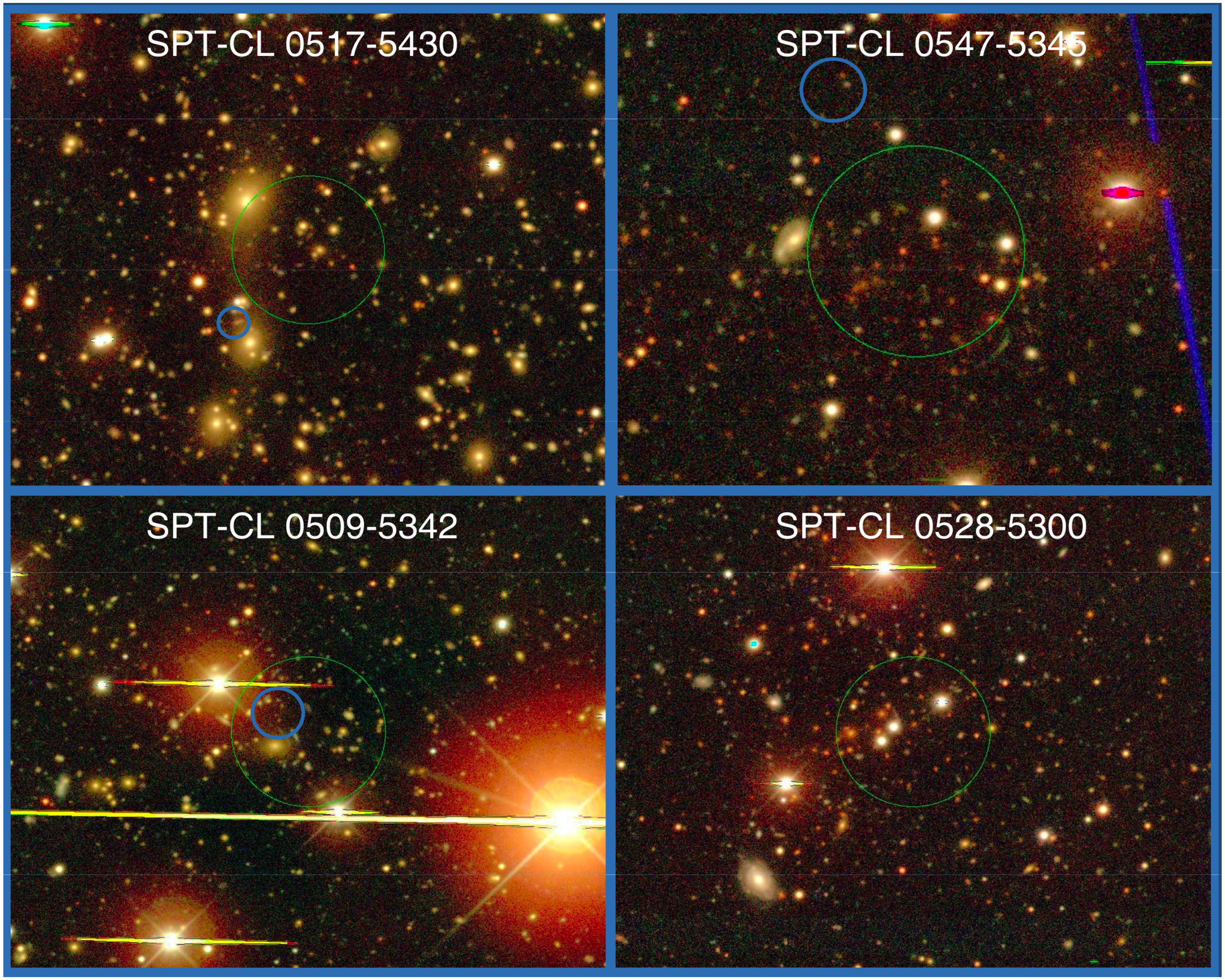
Staniszewski et al 2009



20′ x 20′

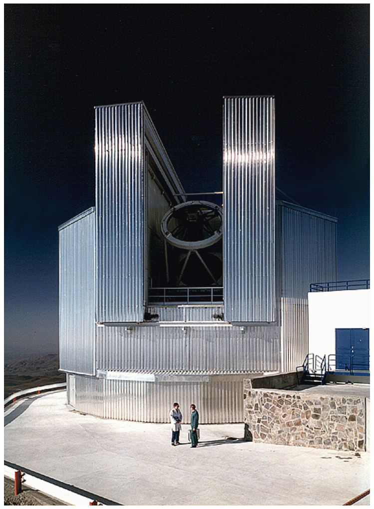
SPT observations alone do not provide red-shifts. Need multi-band data for confirmations ⟶ Optical+near IR followup

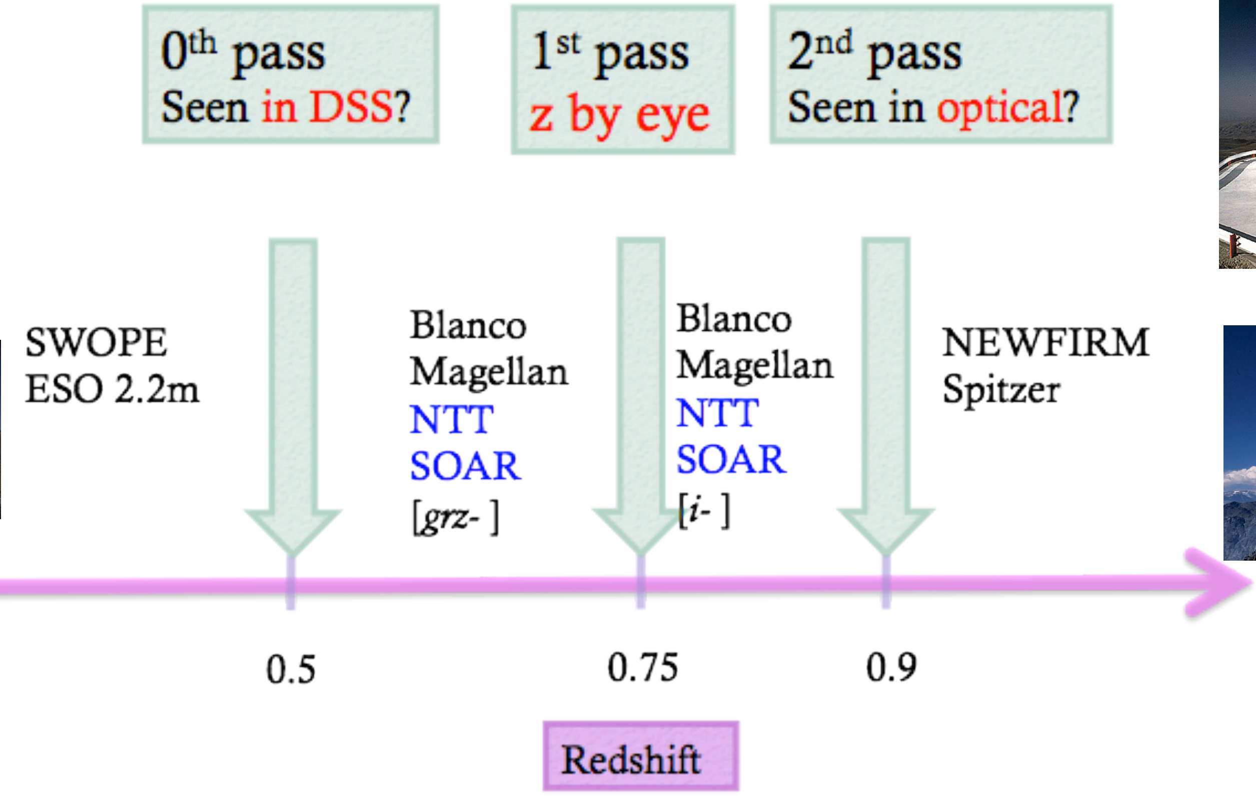
Confirmations of First 4 SPT clusters



Blanco Cosmology Survey (2005-2008) Desai et al (2012)

SPT optical follow-up strategy





0th pass
Seen in DSS?

1st pass
z by eye

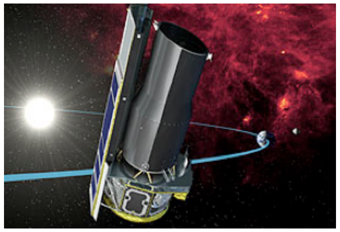
2nd pass
Seen in optical?

SWOPE
ESO 2.2m

Blanco
Magellan
NTT
SOAR
[*grz*-]

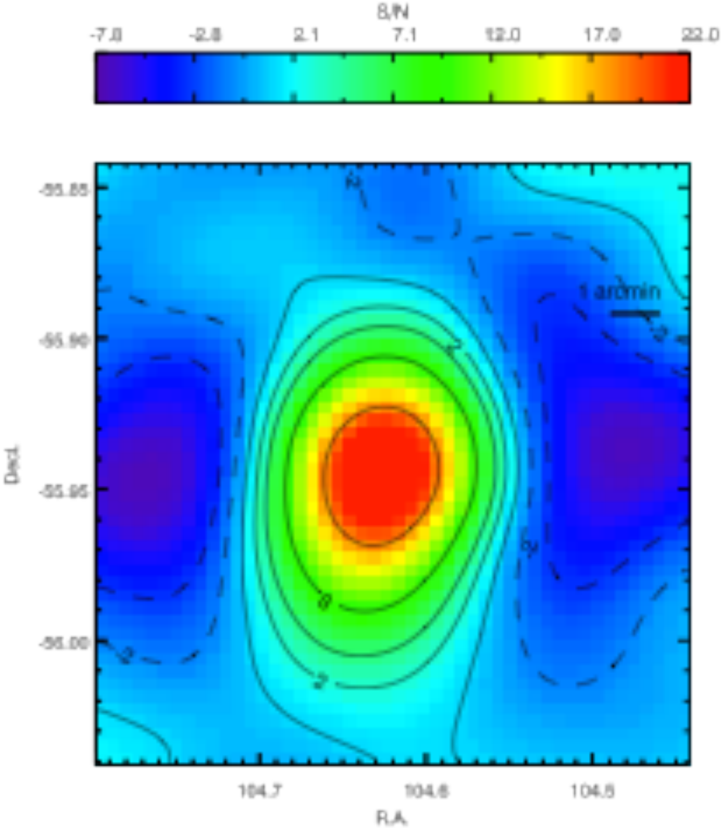
Blanco
Magellan
NTT
SOAR
[*i*-]

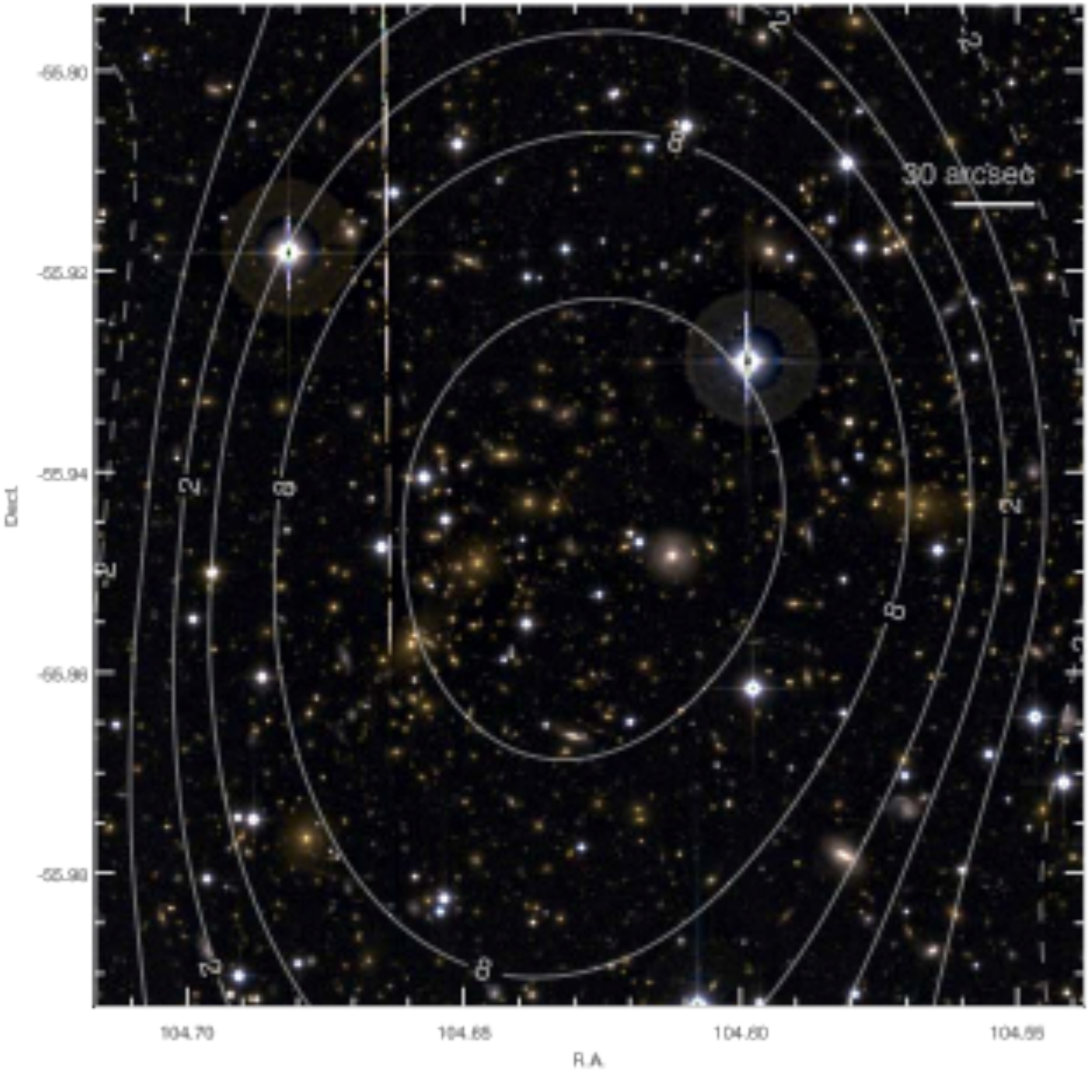
NEWFIRM
Spitzer



SPT-CLJ0658-5358 (z=0.30)

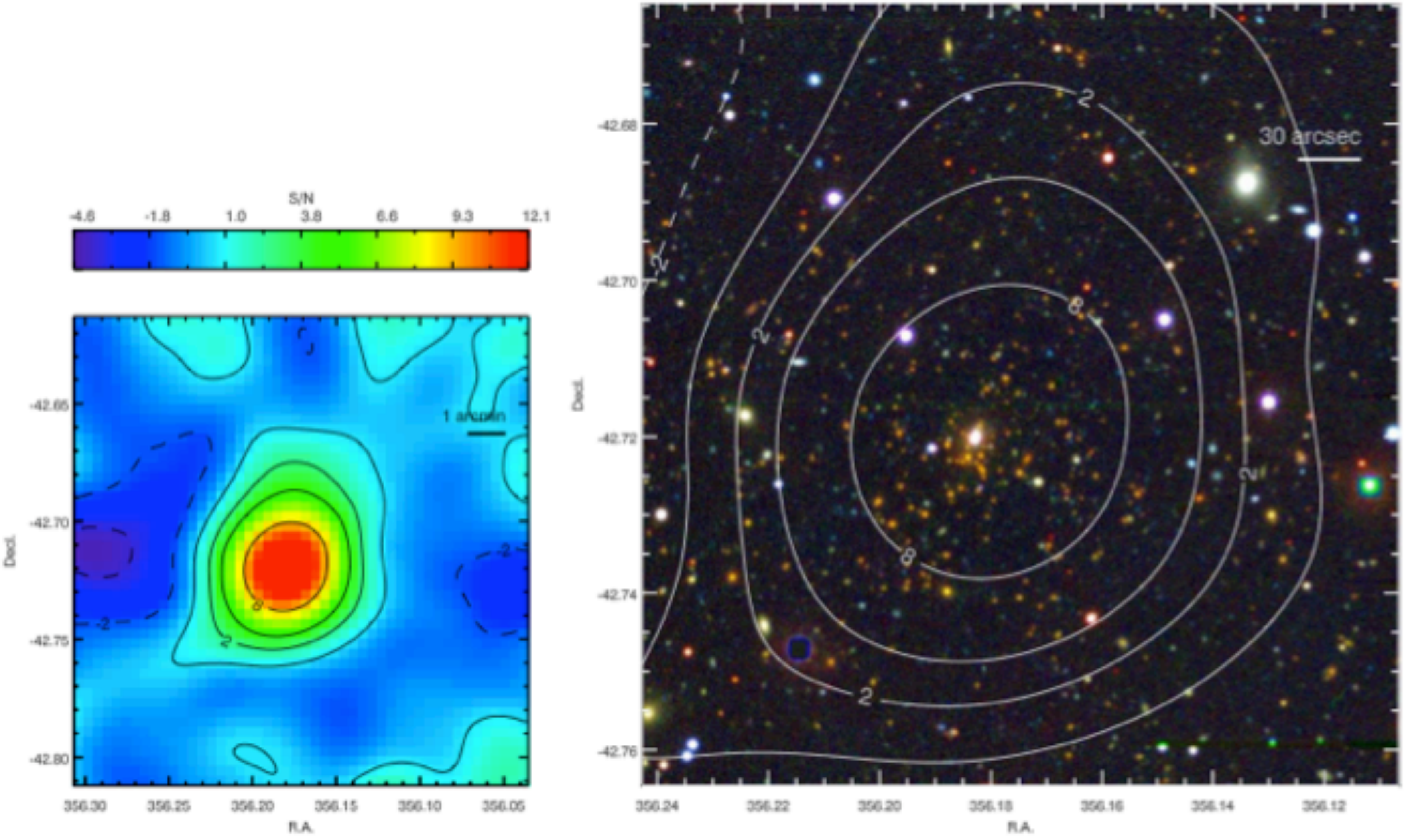
(Bullet Cluster)





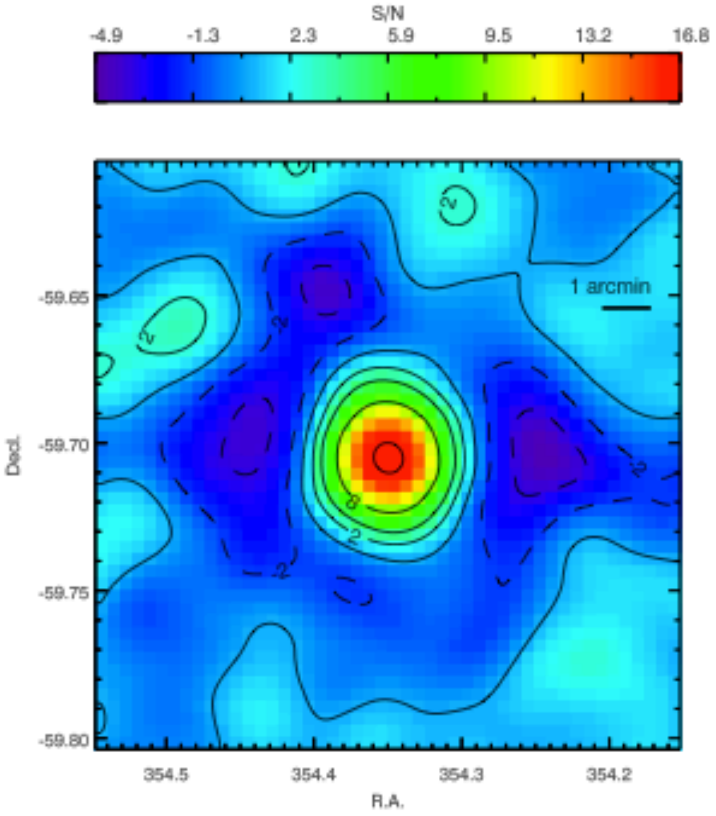
ESO/WFI R/V

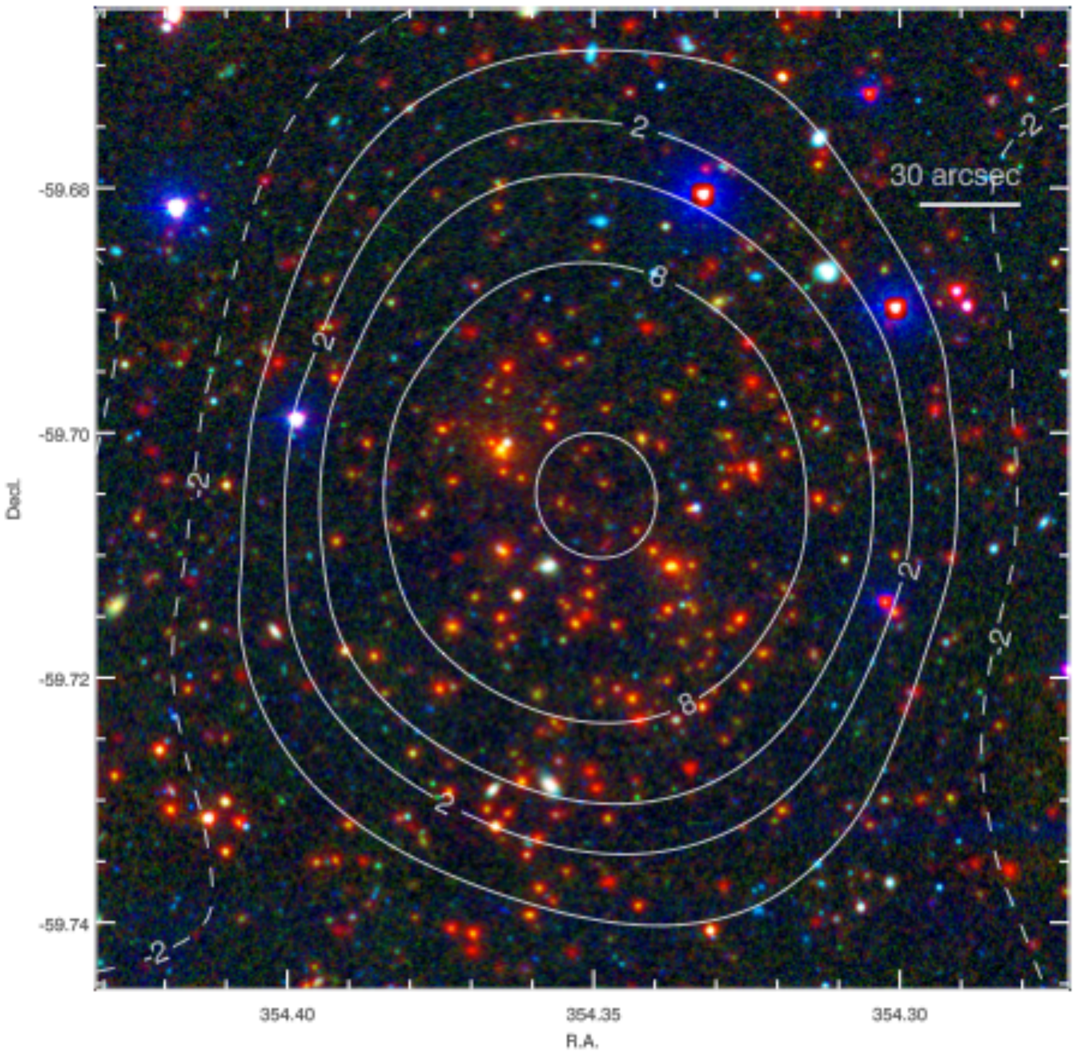
SPT-CLJ2344-4243 (z=0.62)



Blanco/Mosaic-II g/r

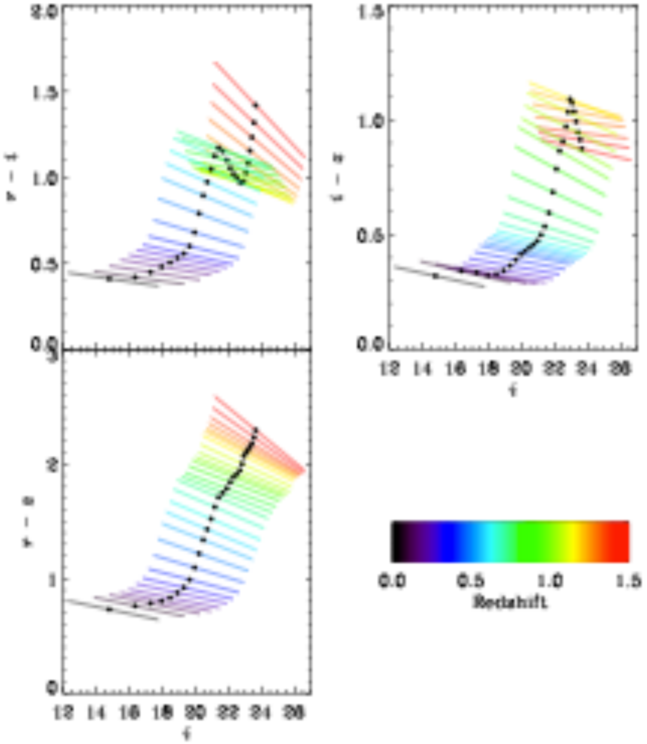
SPT-CLJ2337-5942 (z=0.78)



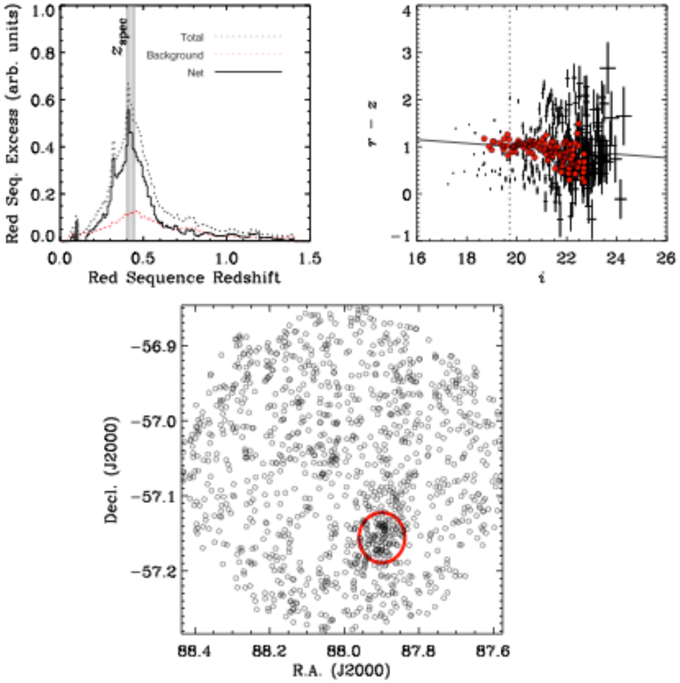


Magellan i/g and IRAC/SPITZER

Photometric Redshift Estimation



Look for excess of red galaxies around S-Z position which follow red sequence models from stellar synthesis models

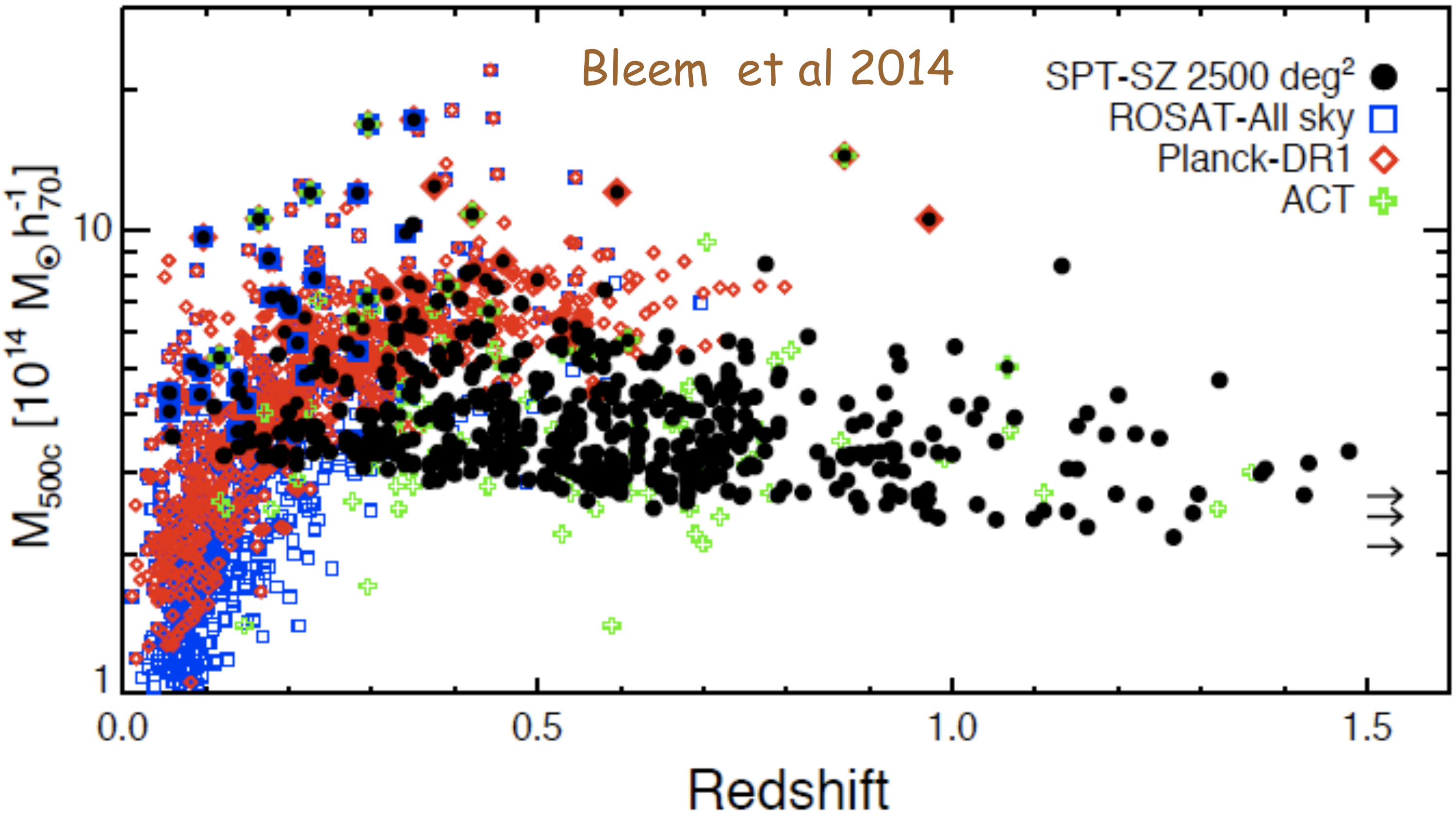


SPT-CLJ0551-5709

z ~ 0.42 and $M_{200} = 5.9 \times 10^{14} M_{\odot}$ High et al (2010) Song et al (2011)

Lots of machine learning and data mining techniques used for single galaxy photo-z

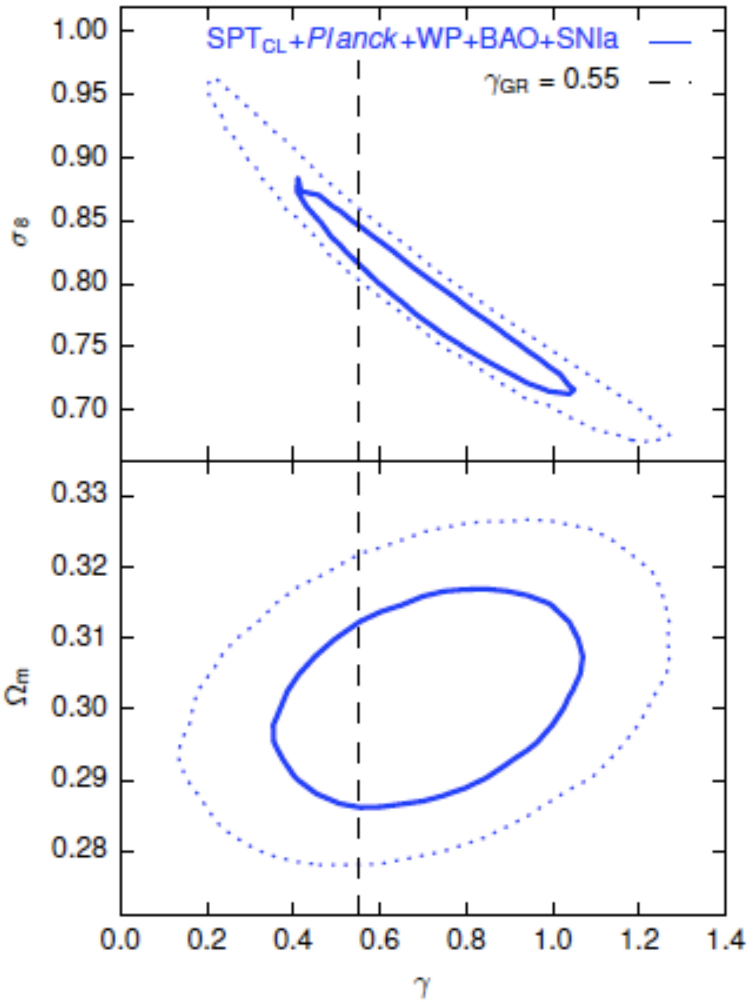
Final SPT Cluster Sample

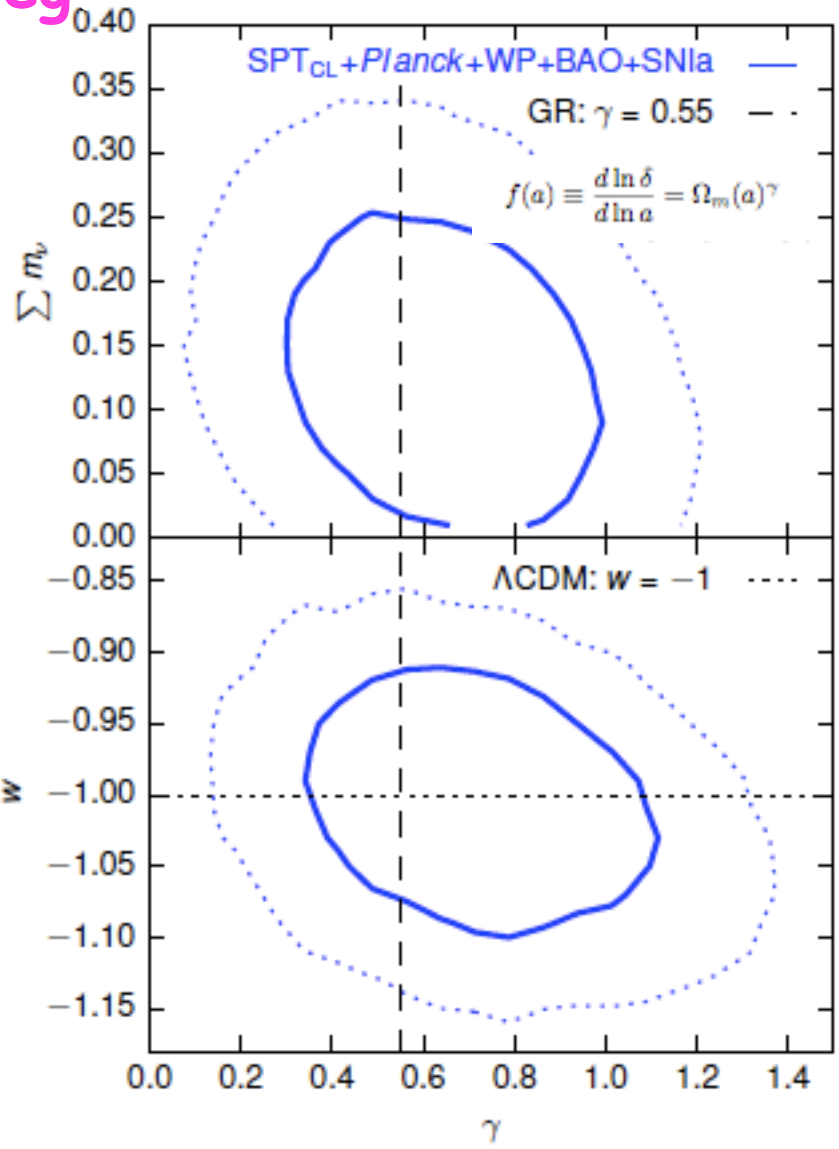


677 cluster candidates with SNR > 4.5 (400 discovered for first time)
516 optically confirmed purity ~ 95 % (SNR>5) and 75% (SNR>4.5)
Median red-shift ~ 0.55
Median mass ~ 3 x 10^{14} M_{sun}

SPT Cluster Cosmology

Results from 720 sq. deg



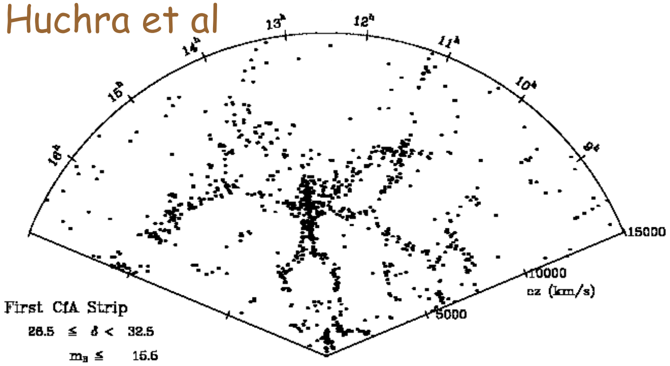


Bocquet et al 2014

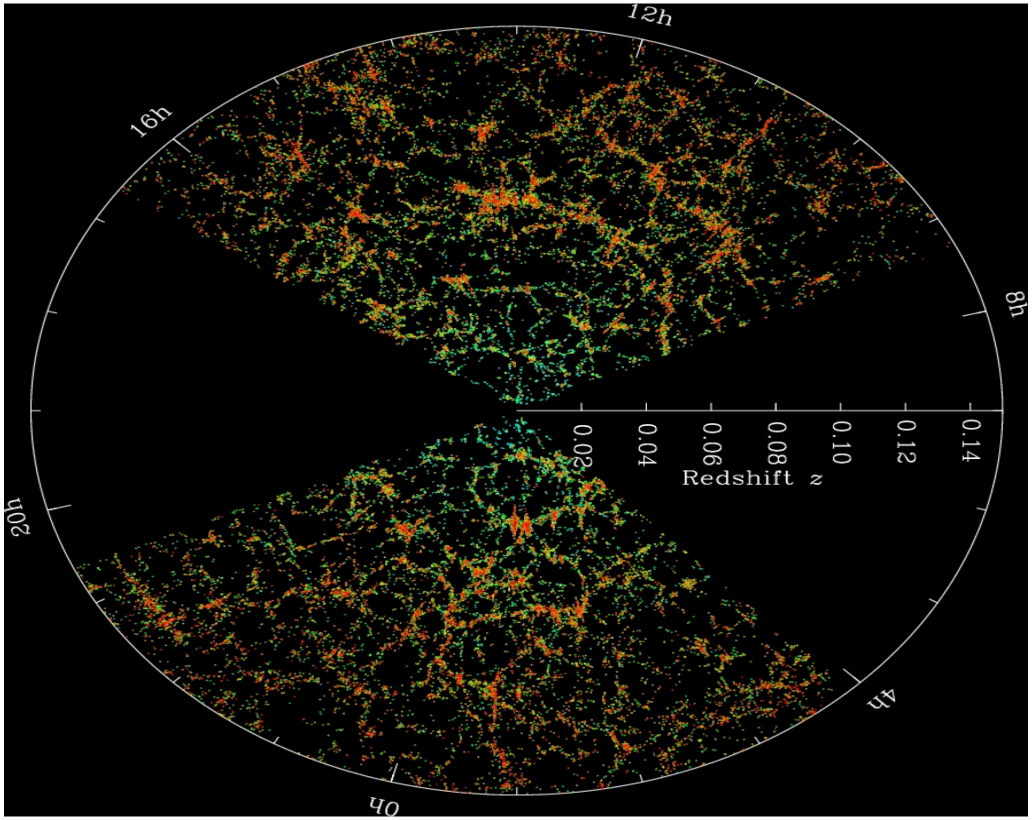
Cosmology Results from full 2500 sq. deg survey coming soon

Astronomy : Era of Optical Surveys

Smithsonian Astrophysical observatory
Huchra et al



CFA redshift survey (1982)
2500 galaxies



SDSS (2010) ~ million galaxies

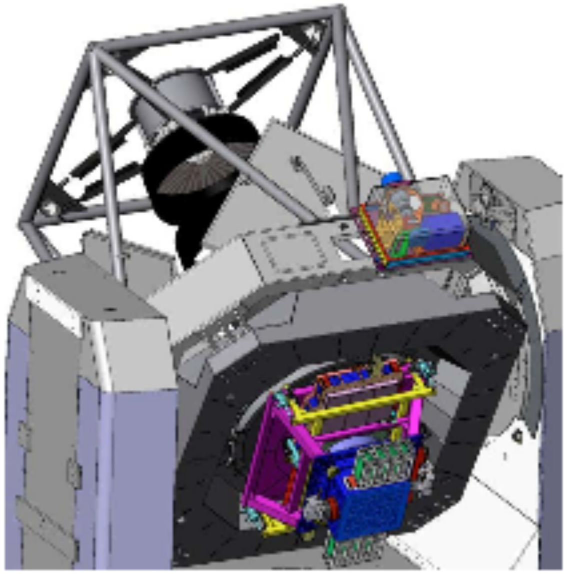
SKYMAPPER
1.4 m
268 Mpixel

(~2016)

HSC 8.2m
870 Mpixel

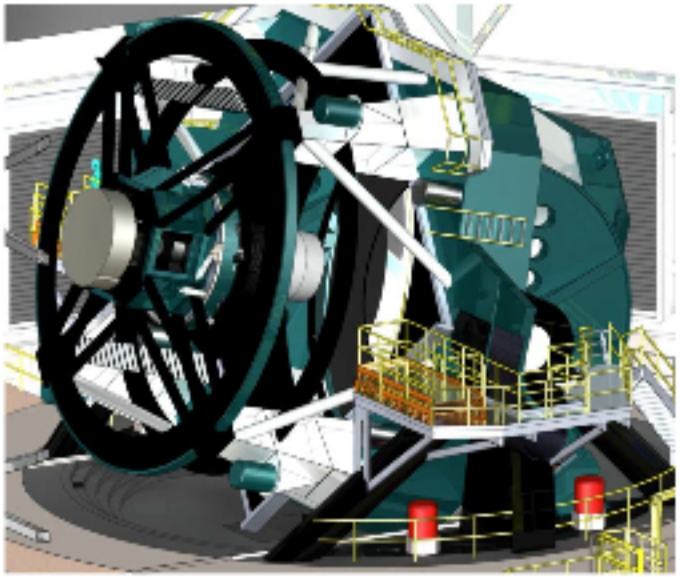
(2013-)

Pan-Starrs
1.8 m
1.4 Gpixel
(2010 -)



LSST 8.4m
3.2 Gpixel

(~ 2020)



The Dark Energy Survey

Survey project using 4 complementary techniques :

- Cluster Counts
- Weak Lensing
- Large Scale Structure
- Supernovae

Two multiband surveys :

5000 deg^2 *grizY* to 24th mag

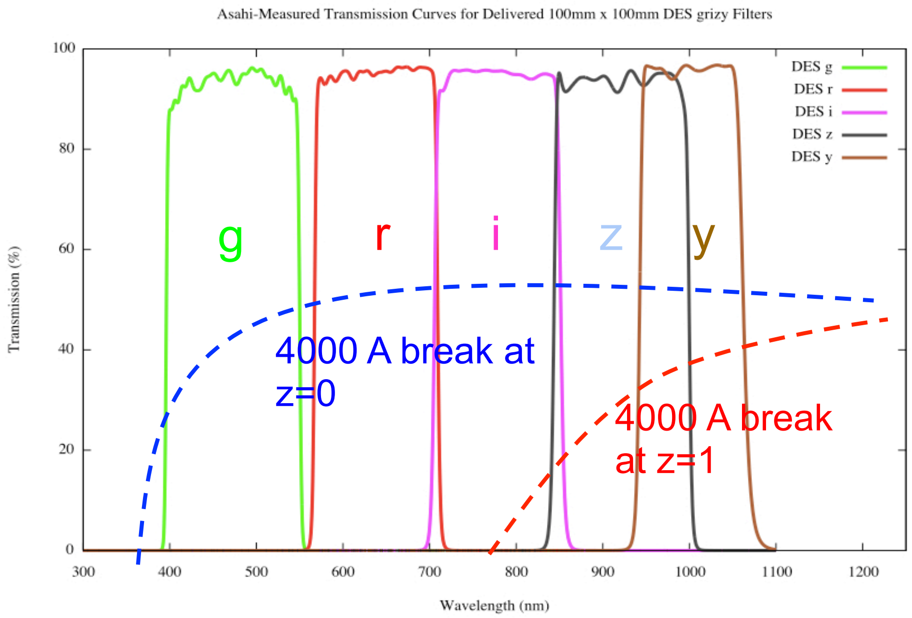
30 deg^2 repeat (SNe)
+ JHK (VHS). Also OzDES

Build new 3 deg^2 FOV camera and Data management system

Science verification phase (2012-2013)
Survey Duration (2013-2018)

Blanco 4-meter at CTIO

DES Filters



Asahi filters

World's biggest filter
i & z bands

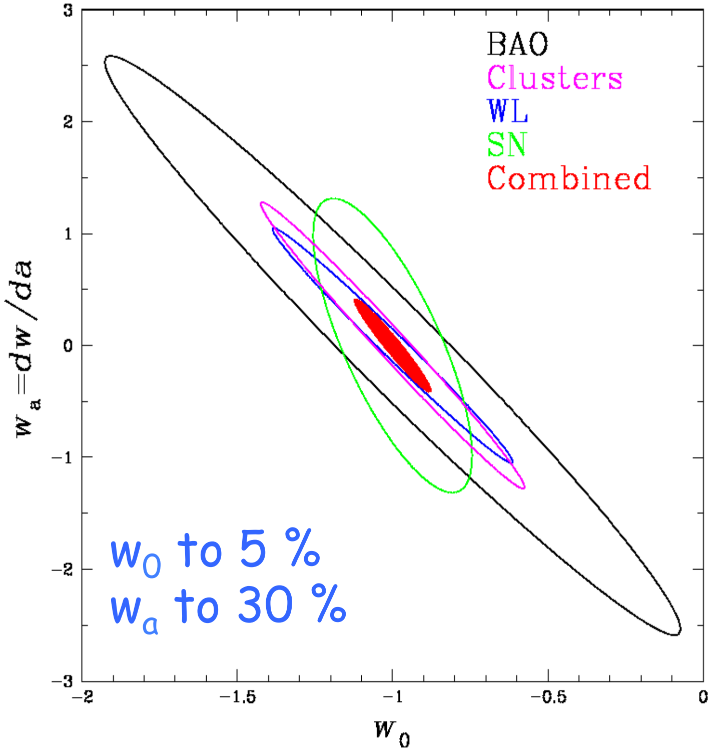
Filter Changer @ U. Michigan

DECam Shutter @ Bonn U.
(needs black anodized coating)

DES Science Summary

- Galaxy Clusters
  - ~100,000 clusters to z>1
- Weak Lensing
  - Shape measurements of 200 million galaxies
- Large-scale Structure (BAO)
  - 300 million galaxies to z = 1 and beyond
- Supernovae
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1

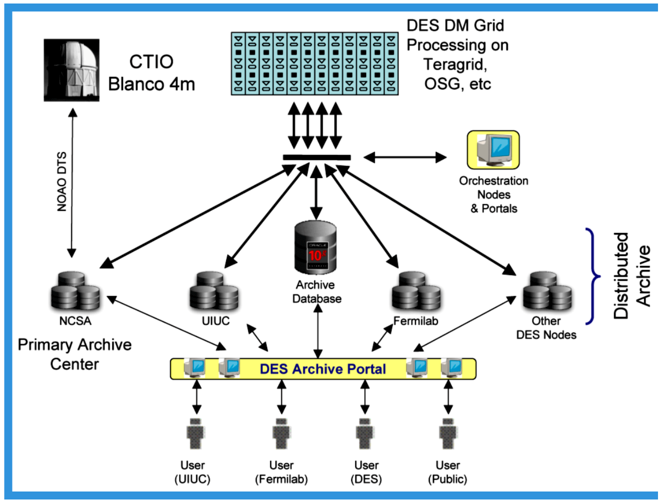
Forecast Constraints on DE Equation of State



w_0 to 5 %

w_a to 30 %

DES Data Management



- Process DES data from raw data to science ready data products (hosted at NCSA/UIUC)
- Archive DES data over the survey
  (4 PB data, 350TB database, ~150,000 exposures over 525 nights)
- Distribute data to Collaboration
- Distribute data to public

  Raw/Reduced data after 1 year
  Coadds/catalogs at midpoint and end of survey

Simulated yearly Data Challenges from 2004-2011 to vet data quality and Science codes

Image Quality of DES vs HST

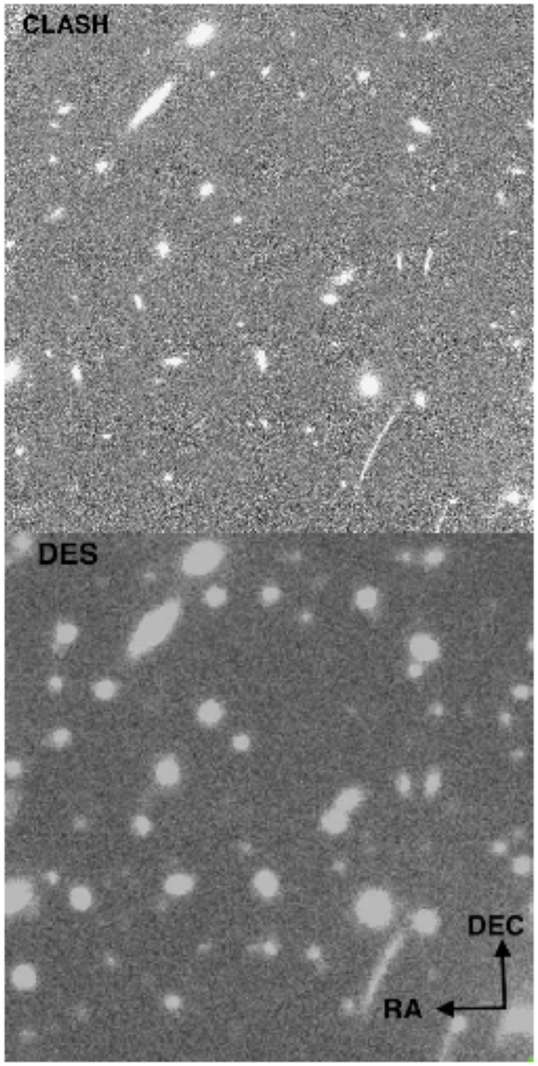


Figure 1. A portion of $1' \times 1'$ image centered in RA 22:48:48.003 and DEC -44:31:38.52 in the CLASH F625W band (top) and the DES r band (bottom).

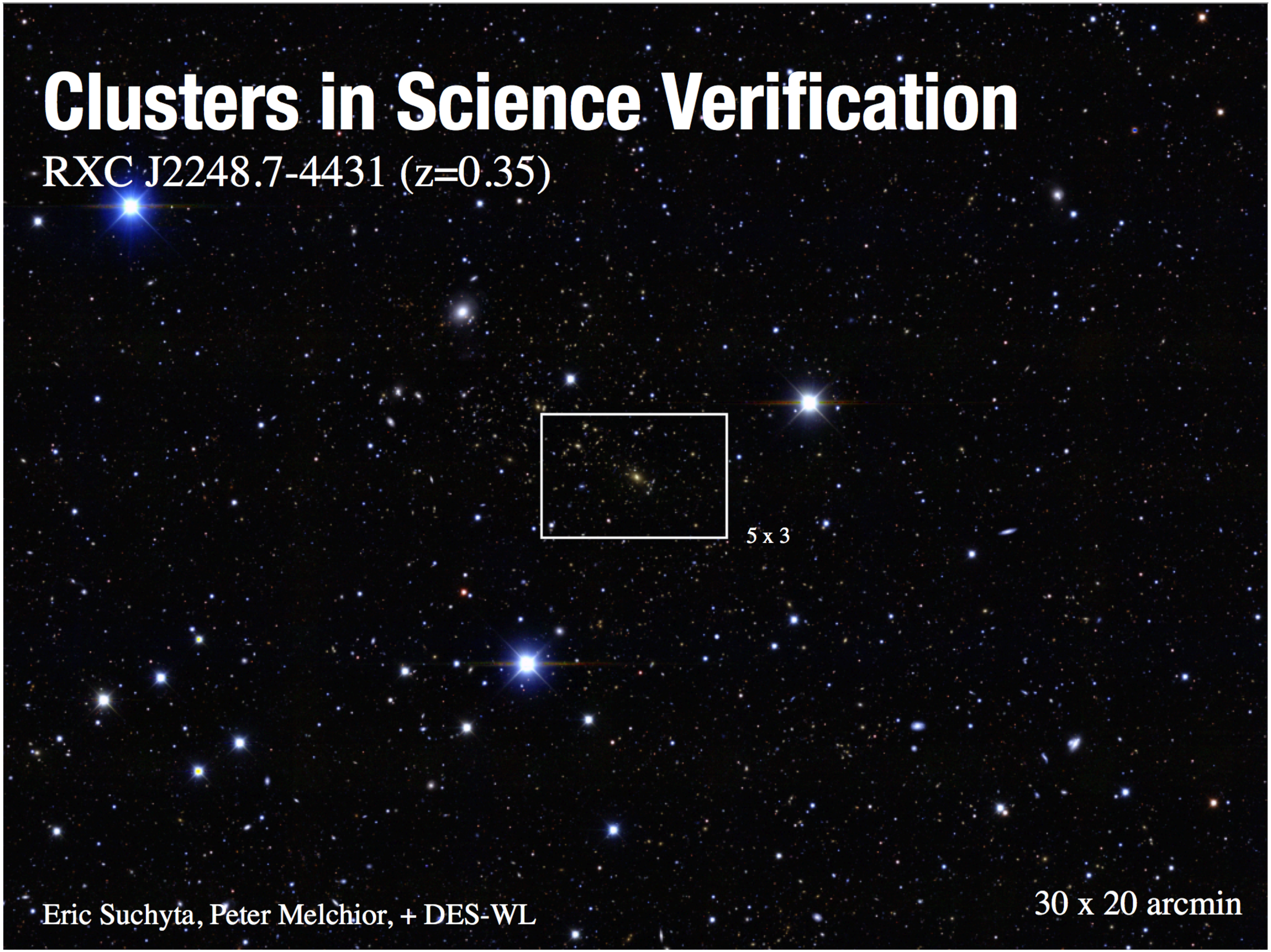
HST vs DES image of the same galaxy cluster

~ 50 papers from DES including
Discovery of new galaxy clusters,
dwarf galaxies, Trojan objects
around Neptune,
Weak Lensing mass mapping,
CMB lensing tomography,
followup of LIGO triggers,

Synergy with SPT, Fermi-LAT, LIGO, Planck, CFHT, ACT, BOSS

Clusters in Science Verification

RXC J2248.7-4431 (z=0.35)



Eric Suchyta, Peter Melchior, + DES-WL

30 x 20 arcmin

Clusters in Science Verification

RXC J2248.7-4431 (z=0.35)

Eric Suchyta, Peter Melchior, + DES-WL

Clusters in Science Verification

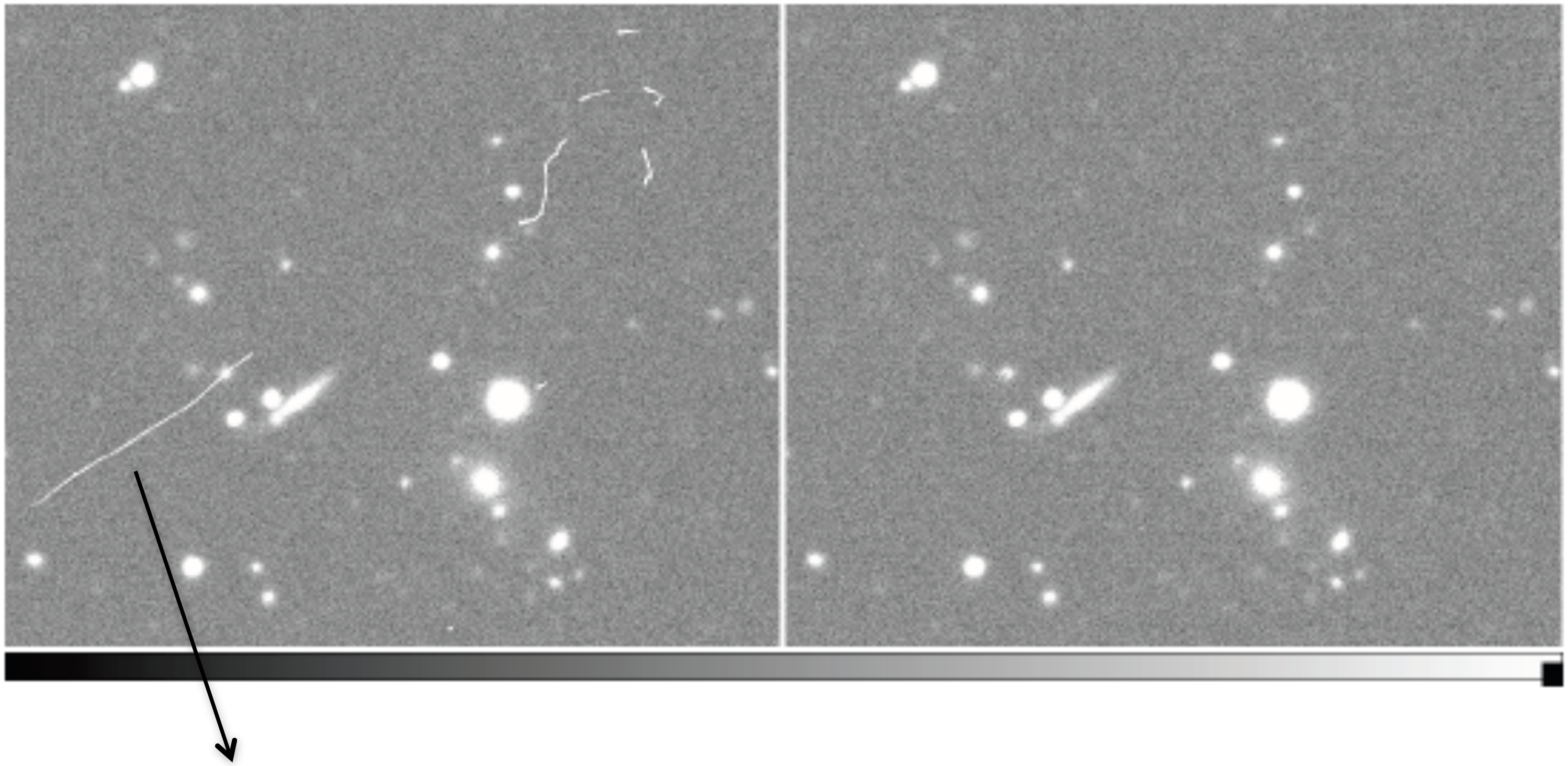
SPT-CL J2332-5358 (z=0.4)

image by Eric Suchyta

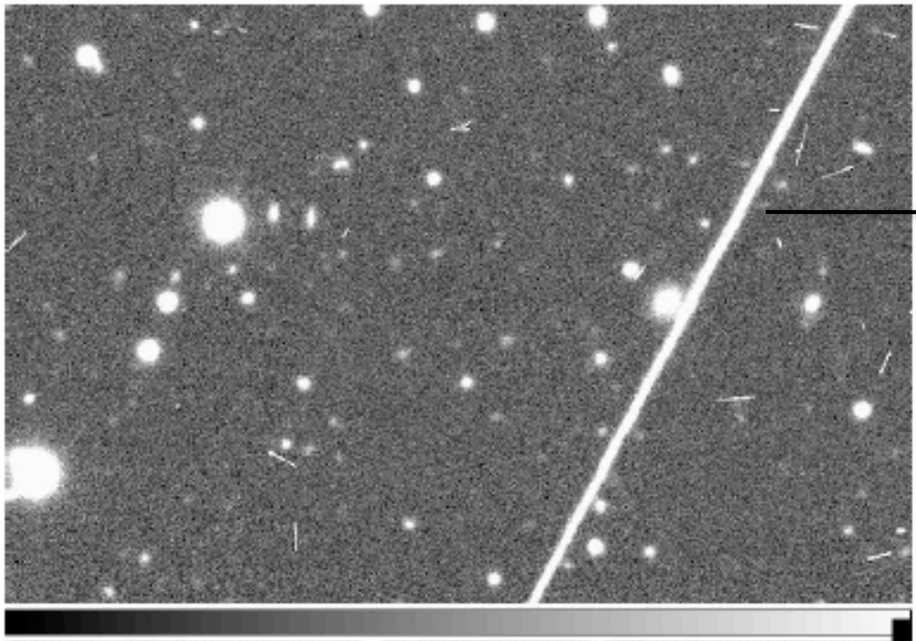
5 x 3 arcmin

My latest day-to-day work

Development of a code to remove cosmic rays and other transient defects in astronomical images

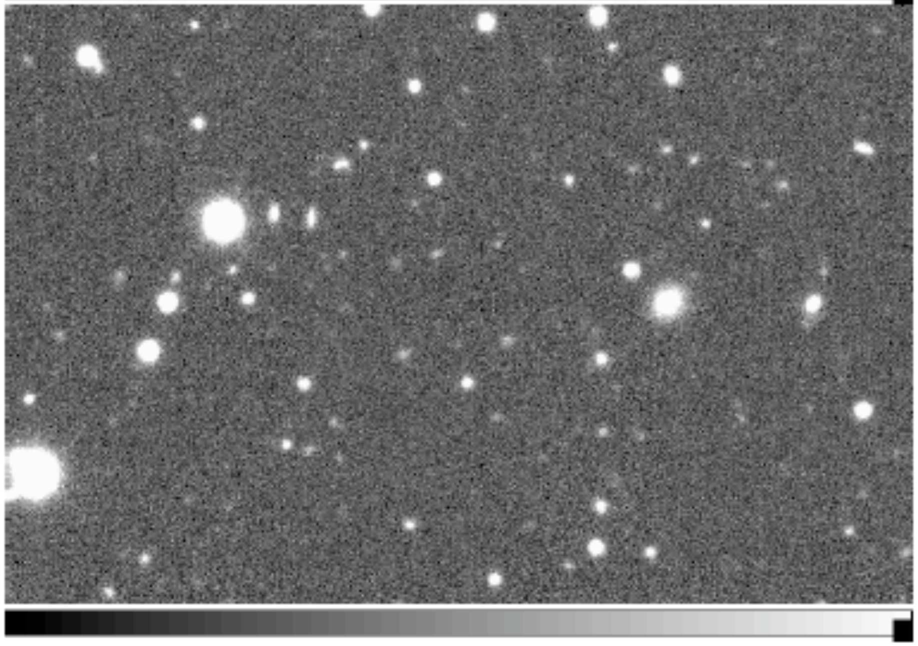


Cosmic Ray in original image



DECam coadd without masking

Satellite Trail



DECam coadd after masking

Desai et al
arxiv:1601.07182

Unsolved Problems in Cosmology

- What is Dark Energy ? (modified GR or CC or back-reaction?)
- What is Dark Matter?
- Origin of Matter- Antimatter Asymmetry ?
- Physics of Inflation ? (Alternate explanation for horizon/flatness problem in Big bang Cosmology)

All the above problems require new Physics

Conclusions

- We live in a preposterous universe with 70 % dark energy and 25% dark matter.

- Many astronomical surveys (eg. DES) with brand new state of the art Megapixel CCD imagers have started taking data to map out Dark energy equation of state to 10% accuracy.

- Lot of new galaxy clusters discovered through microwave Surveys (SPT, Planck) using Sunyaev-Zeldovich effect.

- Origin of inflation should be settled through CMB Experiments designed to detect gravitational waves and non-gaussianity of density fluctuations

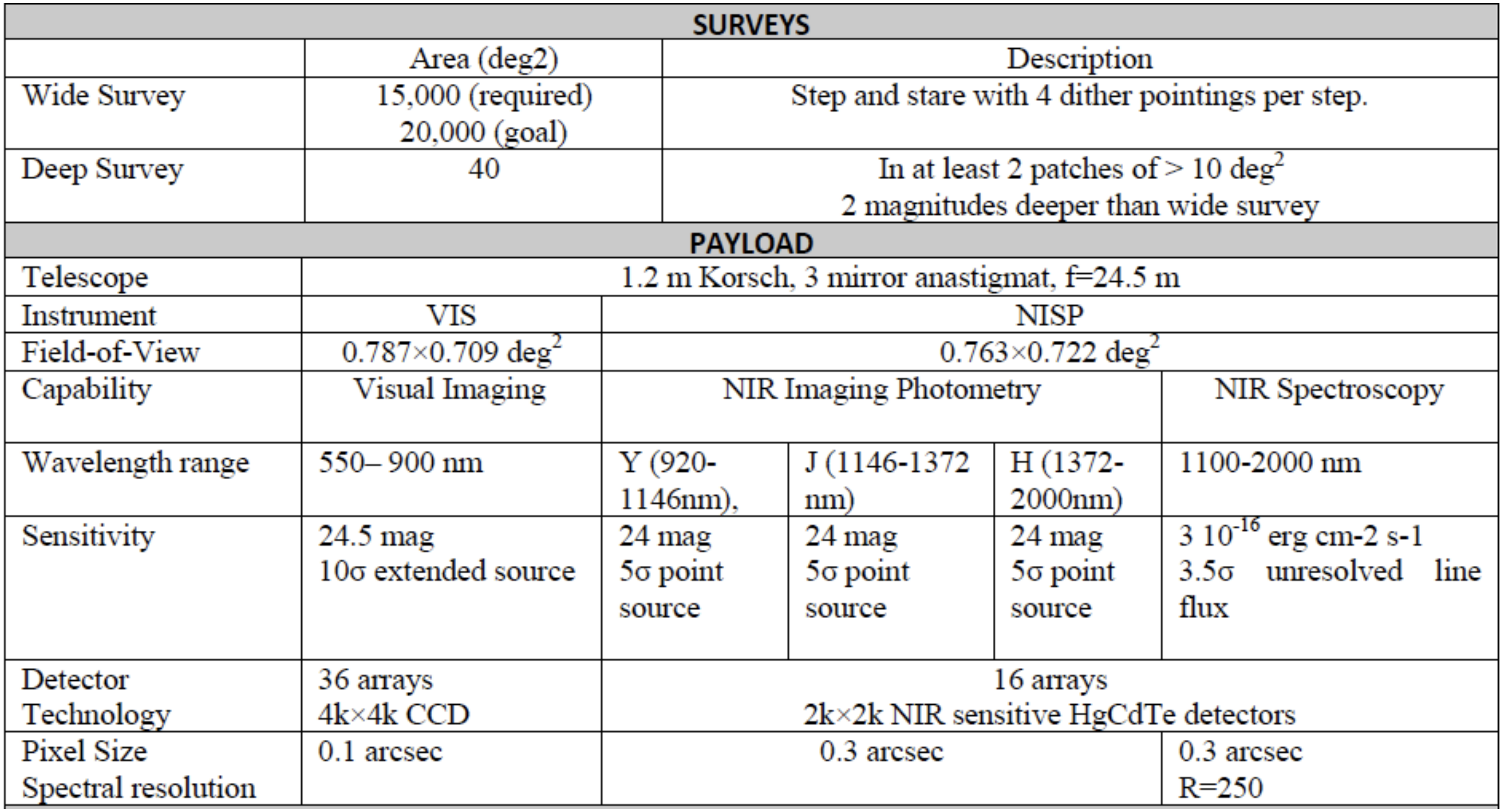
Thank you for your attention and time !!!
Hope this talk inspires students to solve these problems

Euclid Satellite Mission

(launch ~ 2020)

Consists of 1.2 m Korsch telescope . Consists of a visible imager (VIS) and a near-infrared 3 filter photometer (Y, J and H) and a slitless spectrograph

Euclid Mission Characteristics



SURVEYS		
	Area (deg2)	Description
Wide Survey	15,000 (required) 20,000 (goal)	Step and stare with 4 dither pointings per step.
Deep Survey	40	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3 10^{-16} erg cm-2 s-1 3.5σ unresolved line flux
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

Cosmological constraints from SPT Cluster

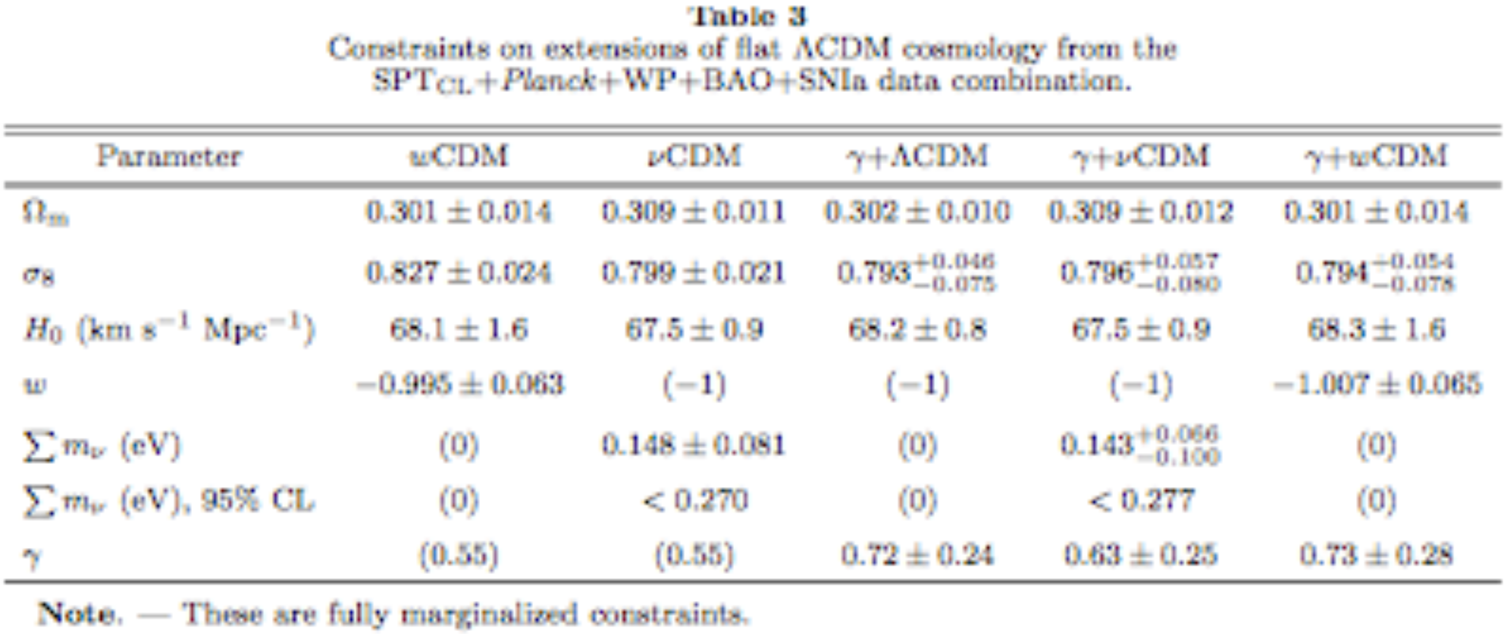


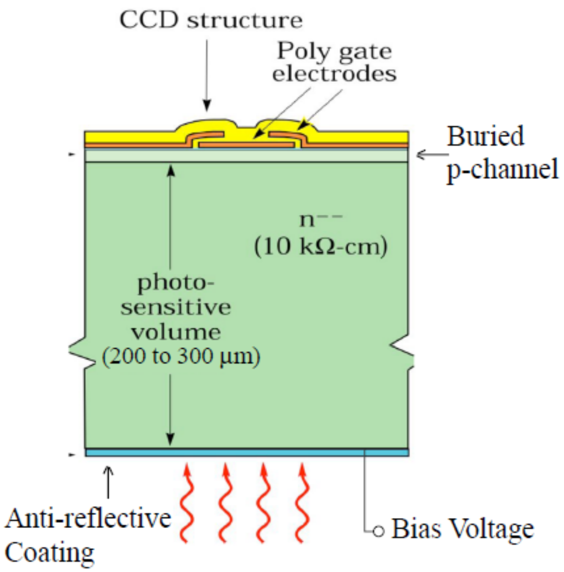
Table 3
Constraints on extensions of flat ΛCDM cosmology from the
SPT$_{\mathrm{CL}}$+*Planck*+WP+BAO+SNIa data combination.

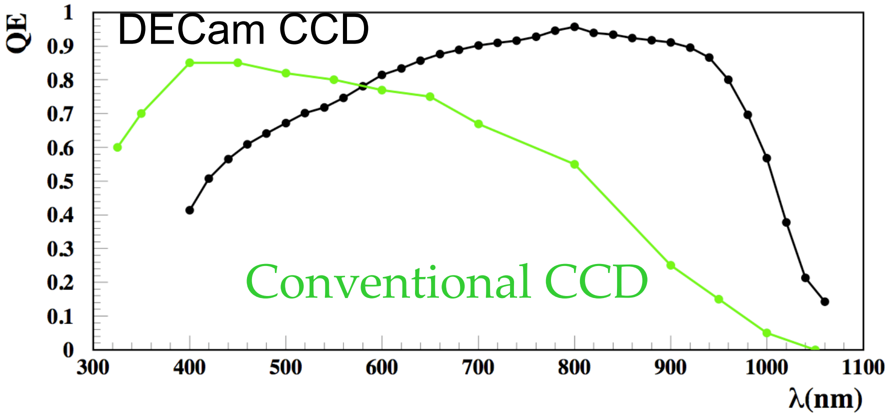
Parameter	wCDM	νCDM	γ+ΛCDM	γ+νCDM	γ+wCDM
Ω_{m}	0.301 ± 0.014	0.309 ± 0.011	0.302 ± 0.010	0.309 ± 0.012	0.301 ± 0.014
σ_8	0.827 ± 0.024	0.799 ± 0.021	$0.793^{+0.046}_{-0.075}$	$0.796^{+0.057}_{-0.080}$	$0.794^{+0.054}_{-0.078}$
H_0 (km s^{-1} Mpc^{-1})	68.1 ± 1.6	67.5 ± 0.9	68.2 ± 0.8	67.5 ± 0.9	68.3 ± 1.6
w	-0.995 ± 0.063	(-1)	(-1)	(-1)	-1.007 ± 0.065
$\sum m_\nu$ (eV)	(0)	0.148 ± 0.081	(0)	$0.143^{+0.066}_{-0.100}$	(0)
$\sum m_\nu$ (eV), 95% CL	(0)	< 0.270	(0)	< 0.277	(0)
γ	(0.55)	(0.55)	0.72 ± 0.24	0.63 ± 0.25	0.73 ± 0.28

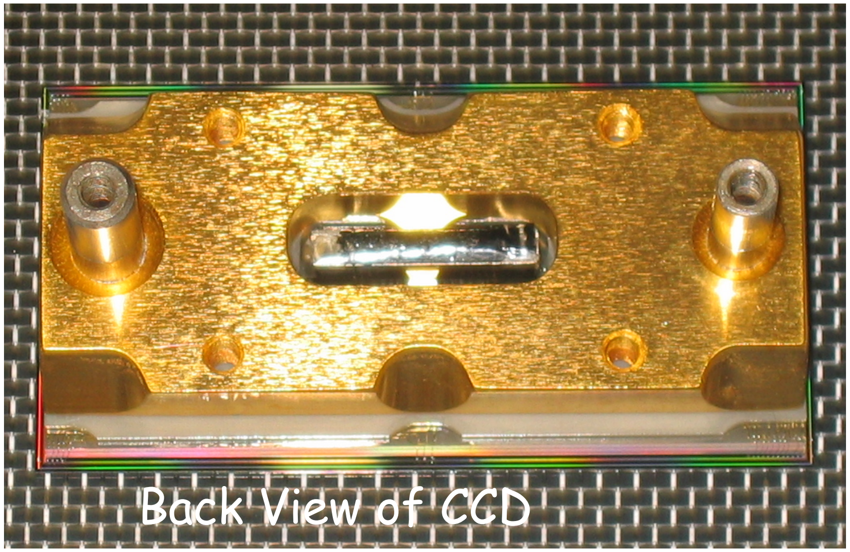
Note. — These are fully marginalized constraints.

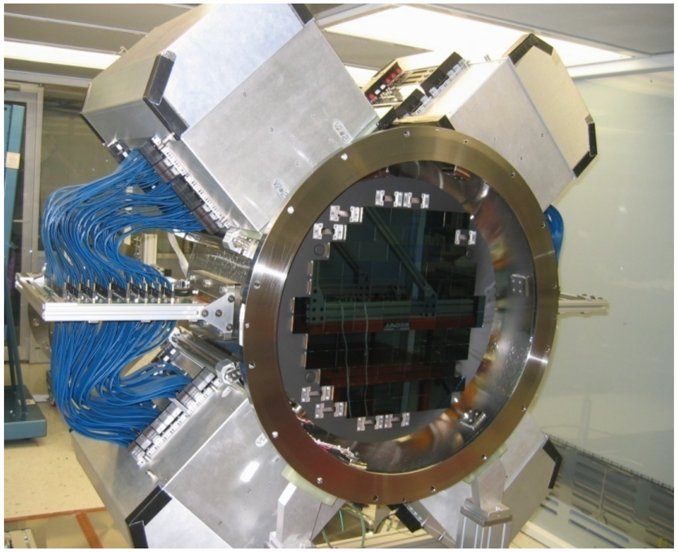
Bocquet et al (2015)

Backups

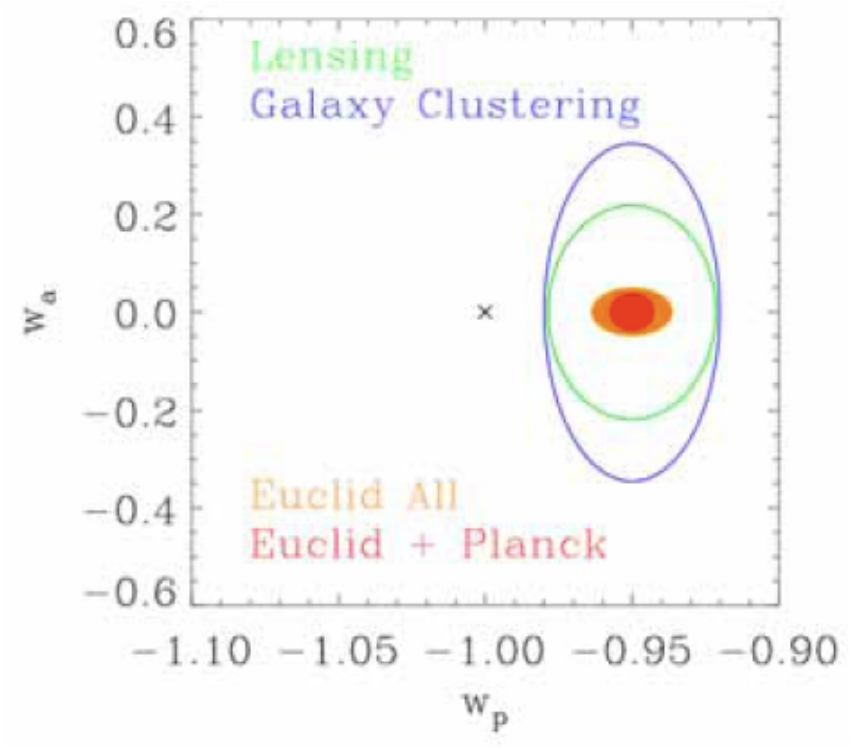

CCD structure
Poly gate electrodes
Buried p-channel
n−−
(10 kΩ-cm)
photo-sensitive volume
(200 to 300 µm)
Anti-reflective Coating
Bias Voltage

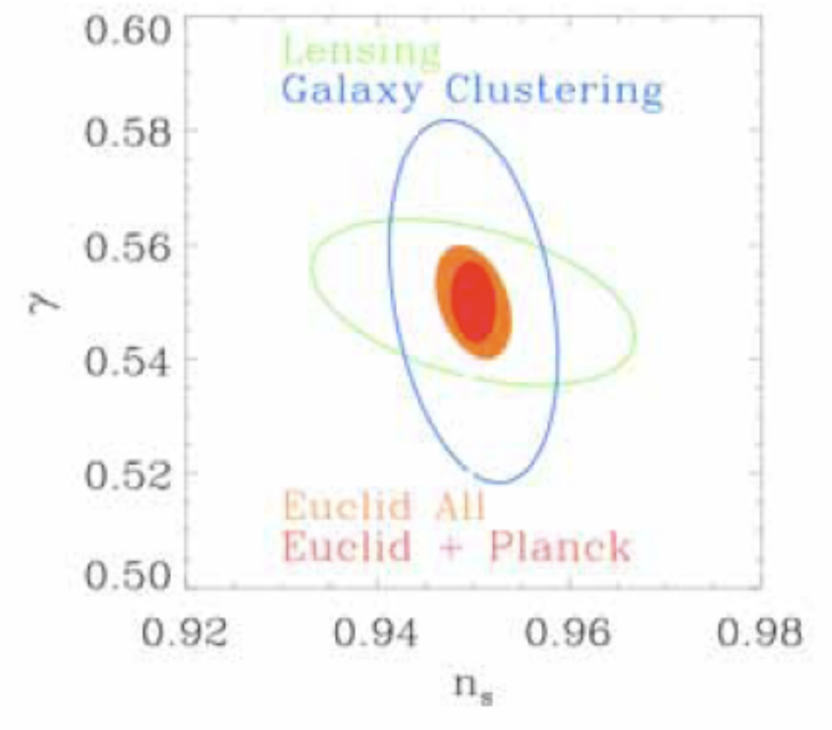

QE
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
300
400
500
600
700
800
900
1000
1100
λ(nm)
DECam CCD
Conventional CCD


Back View of CCD

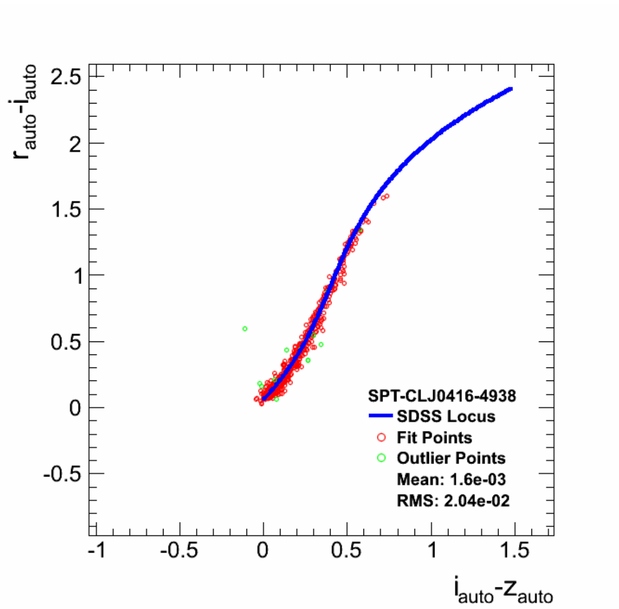


Euclid Cosmological Constraints

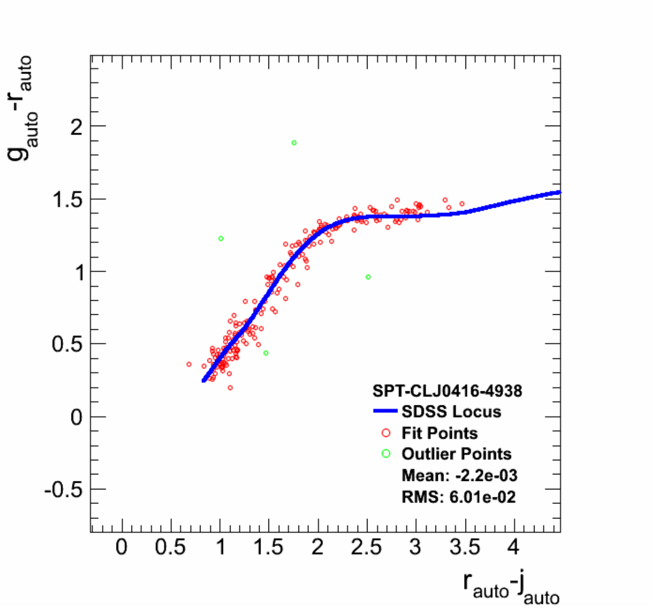


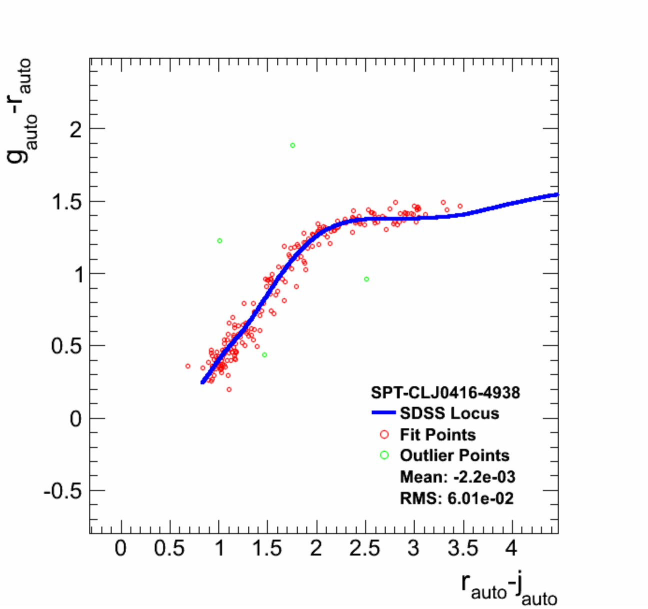


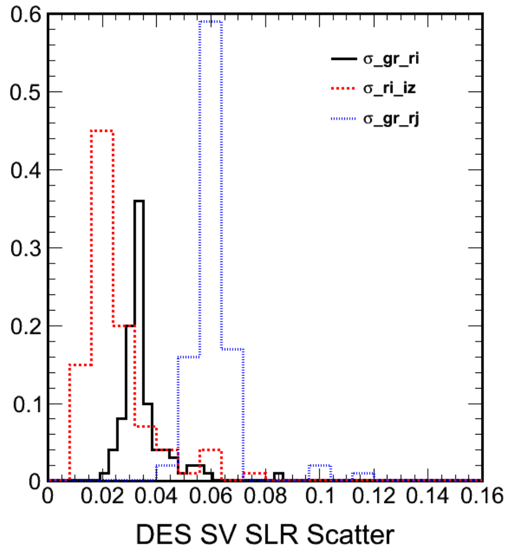
Backups



DES
gr_ri (2%)
ri_iz (3 %)



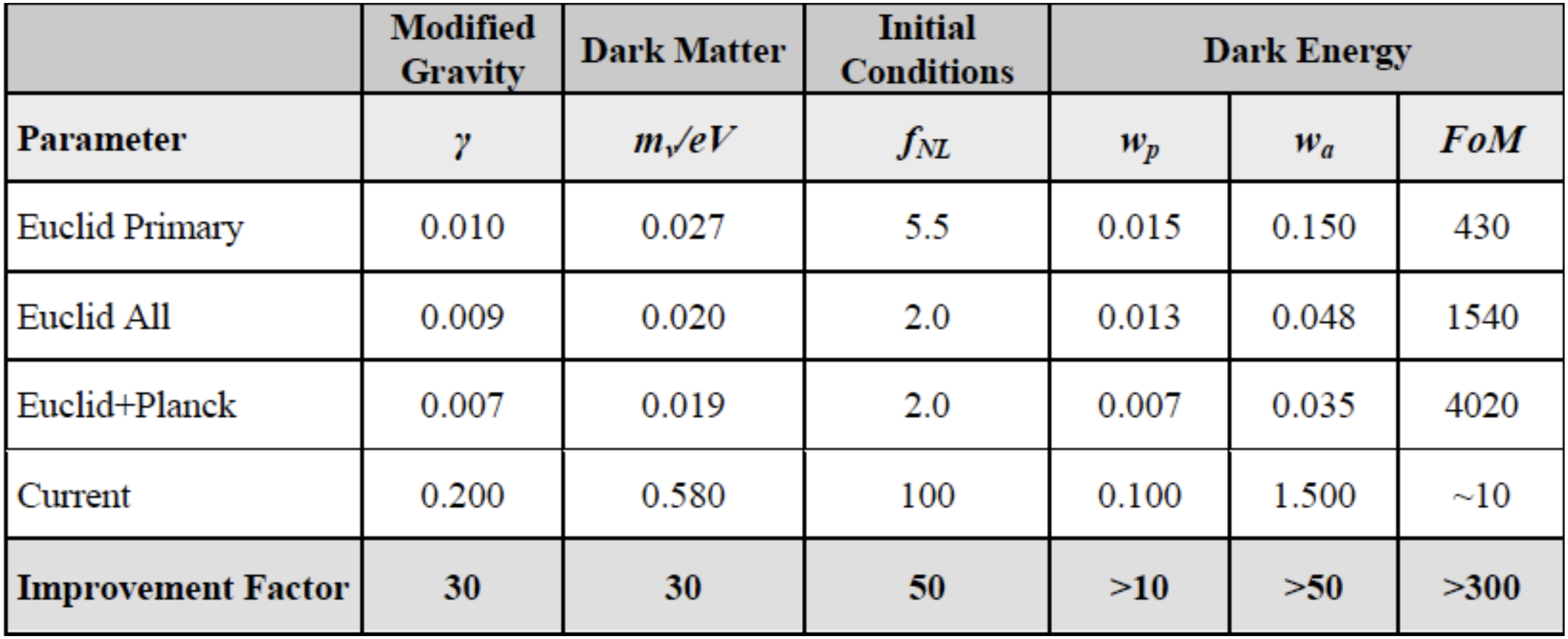




SDSS
gr_ri (4%)
ri_iz (5 %)

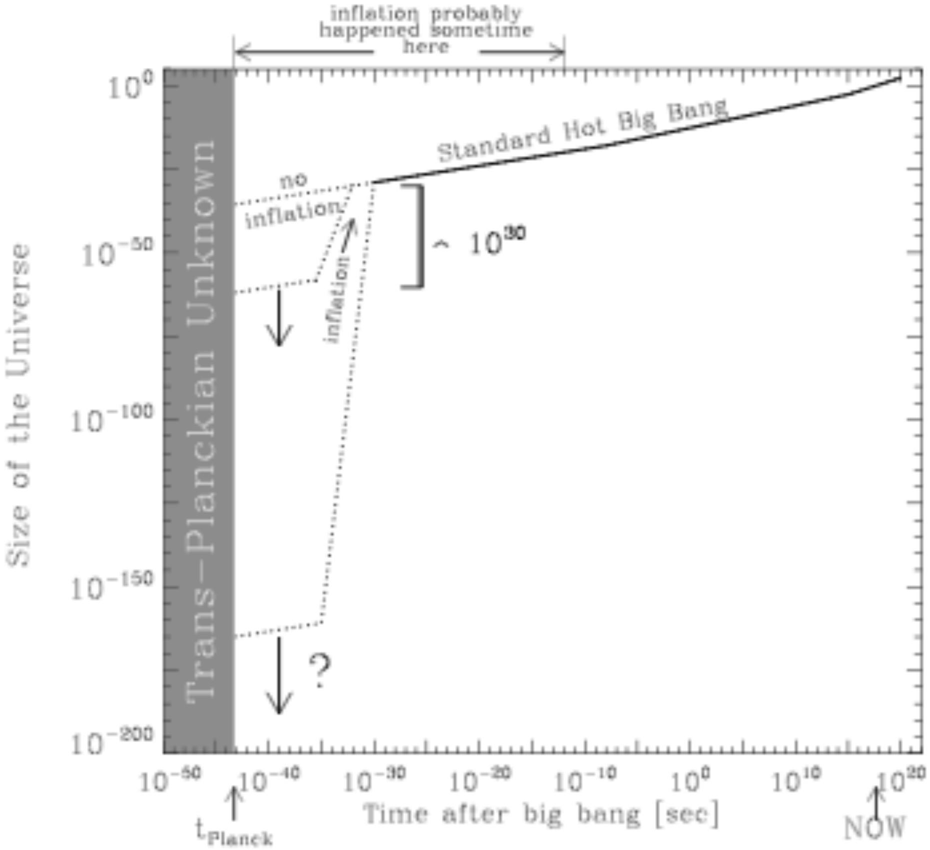
BCS
gr_ri (7%)
ri_iz (8 %)

Euclid Expected Constraints on Dark Energy

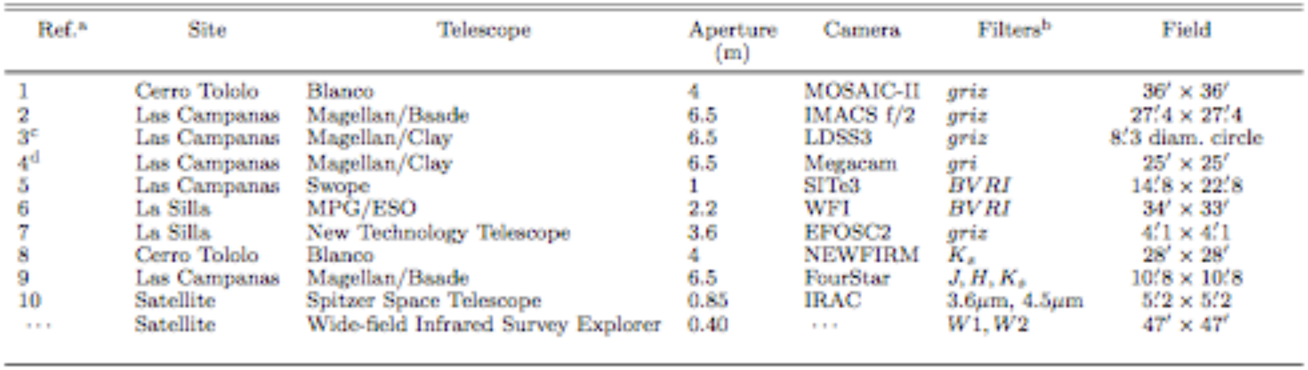


	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

Backups

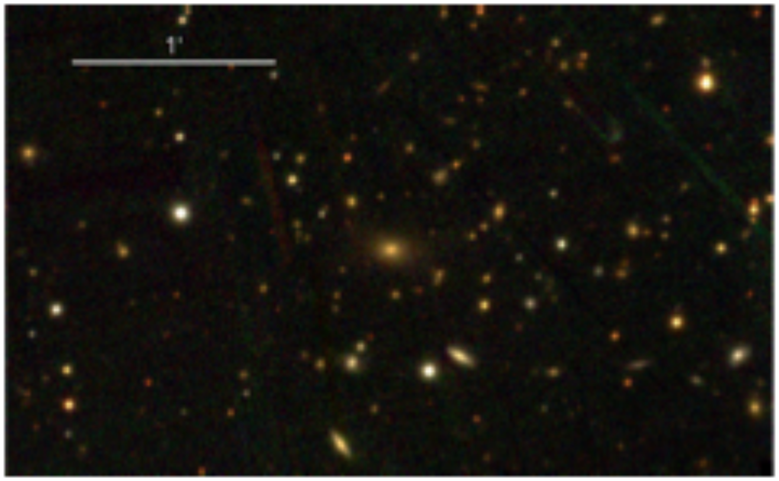

inflation probably happened sometime here
Trans–Planckian Unknown
Standard Hot Big Bang
no inflation
inflation
~ 10^{30}
?
Size of the Universe
10^{0}
10^{-50}
10^{-100}
10^{-150}
10^{-200}
10^{-50}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
Time after big bang [sec]
t_{Planck}
NOW

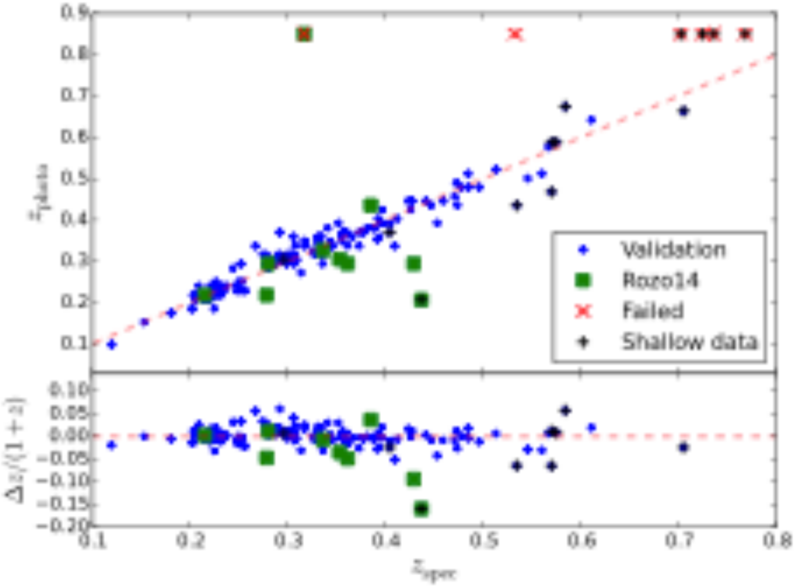
List of telescopes/satellites used



Ref.[a]	Site	Telescope	Aperture (m)	Camera	Filters[b]	Field
1	Cerro Tololo	Blanco	4	MOSAIC-II	*griz*	$36' \times 36'$
2	Las Campanas	Magellan/Baade	6.5	IMACS f/2	*griz*	$27'.4 \times 27'.4$
3[c]	Las Campanas	Magellan/Clay	6.5	LDSS3	*griz*	$8'.3$ diam. circle
4[d]	Las Campanas	Magellan/Clay	6.5	Megacam	*gri*	$25' \times 25'$
5	Las Campanas	Swope	1	SITe3	$BVRI$	$14'.8 \times 22'.8$
6	La Silla	MPG/ESO	2.2	WFI	$BVRI$	$34' \times 33'$
7	La Silla	New Technology Telescope	3.6	EFOSC2	*griz*	$4'.1 \times 4'.1$
8	Cerro Tololo	Blanco	4	NEWFIRM	K_s	$28' \times 28'$
9	Las Campanas	Magellan/Baade	6.5	FourStar	J, H, K_s	$10'.8 \times 10'.8$
10	Satellite	Spitzer Space Telescope	0.85	IRAC	3.6μm, 4.5μm	$5'.2 \times 5'.2$
···	Satellite	Wide-field Infrared Survey Explorer	0.40	···	$W1, W2$	$47' \times 47'$

Optical Confirmation of Planck SZ Clusters with Pan-Starrs





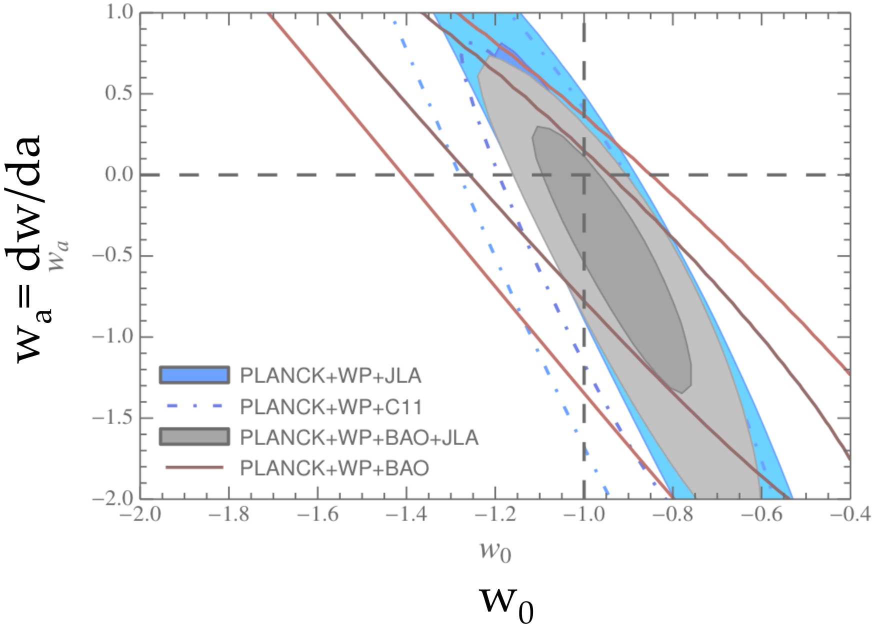
Liu, Hennig, Desai et al (2015)
Used Pan-Starrs Imaging data to confirm about ~ 200 SZ detected clusters from 2013 Planck data release.

Forecast DES Constraints on Dark Energy Equation of State

DES Goal:
Reduce area of red oval by a factor of 3-5 from previous ("Stage II") dark energy experiments

Note:
$a = R / R_0 = 1 / (1 + z)$

Betoule et al. 2014



Current Constraints