Title: The Dark Energy Crisis, and the Prospect of Intellectual Stagnation

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Abstract: I will describe the current state of our attempts to characterize the nature of the Dark Energy, the name given to the unknown phenomenology that is driving the observed accelerating cosmic expansion. There is a historical analogy between our current situation and the days of

confusion before the advent of quantum mechanics. But while quantum physics emerged in a single academic generation, I fear that our attaining a deeper understanding of Dark Energy may not be as rapid. I will outline some steps we can take to try to avoid an extended period of sophisticated confusion and intellectual stagnation.

The Dark Energy Crisis, and the Prospect of Intellectual Stagnation

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Outline -
(the good news and the bad news…)

Why Dark Energy has precipitated a crisis in fundamental physics

A snapshot of our current state of confusion

The near term future

Next-generation projects: WFIRST and LSST

An analogy with the past- the development of QM

The longer term future: 3 scenarios (one is to be avoided!)

Some references

Freiman, Turner and Huterer, *Dark Energy and the Accelerating Universe*, Annual Reviews of Astronomy and Astrophysics, 46, 2008.

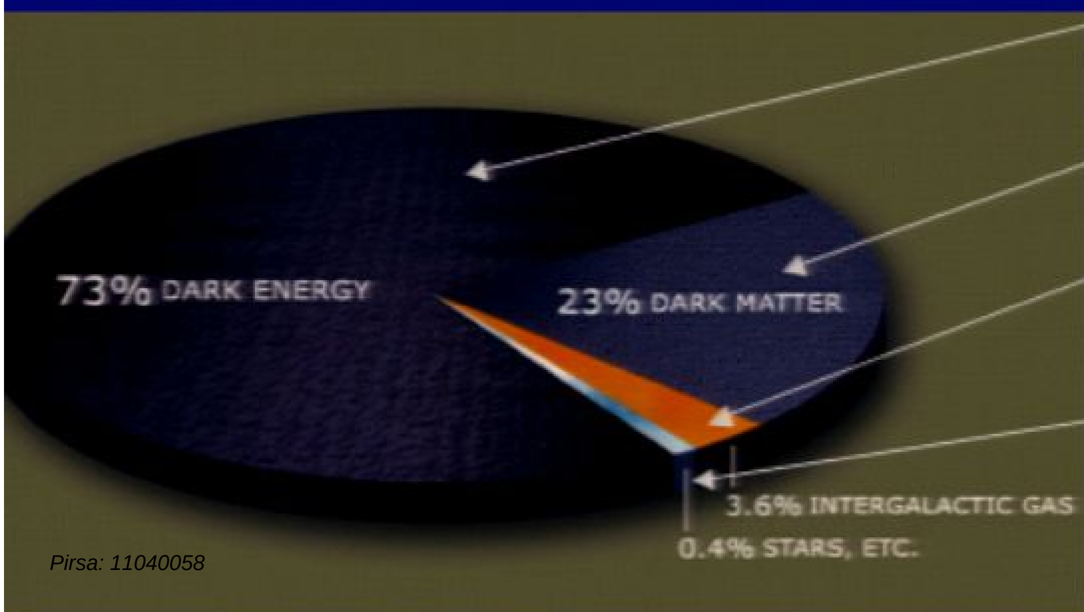
Cahn et al, *Dark Energy Task Force Report*, IJMPD 16, 2551 (2007)

Perl, *Can the Existence of Dark Energy be Directly Detected?* arXiv:0809.5083v2

Emergence of a Standard Cosmology

Our geometrically flat Universe started in a hot big bang 13.7 billion yrs ago. It has been expanding ever since.

The evolution of the Universe is increasingly dominated by the phenomenology of the vacuum, the "Dark Energy".



"Dark matter": what is it?

Ordinary matter is a minor component.

Luminous matter comprises a *very* small fraction of the mass of the Universe.

Some astrophysical observables that exhibit dark energy dependence

$H(z)$: cosmic history of the expansion rate

- tough to measure directly
- we typically observe quantities that incorporate it

$D_L(z)$: luminosity distance vs. redshift-

- standard candles, e.g. type Ia supernovae

$D_A(z)$: angular diameter distance vs. redshift

- standard rulers, e.g. baryon acoustic oscillations
- gravitational lensing
- CMB

$G(\rho,z)$: evolution of density fluctuations, aka growth function

- large scale structure
- galaxy cluster abundances

Ω_m: cosmic matter density

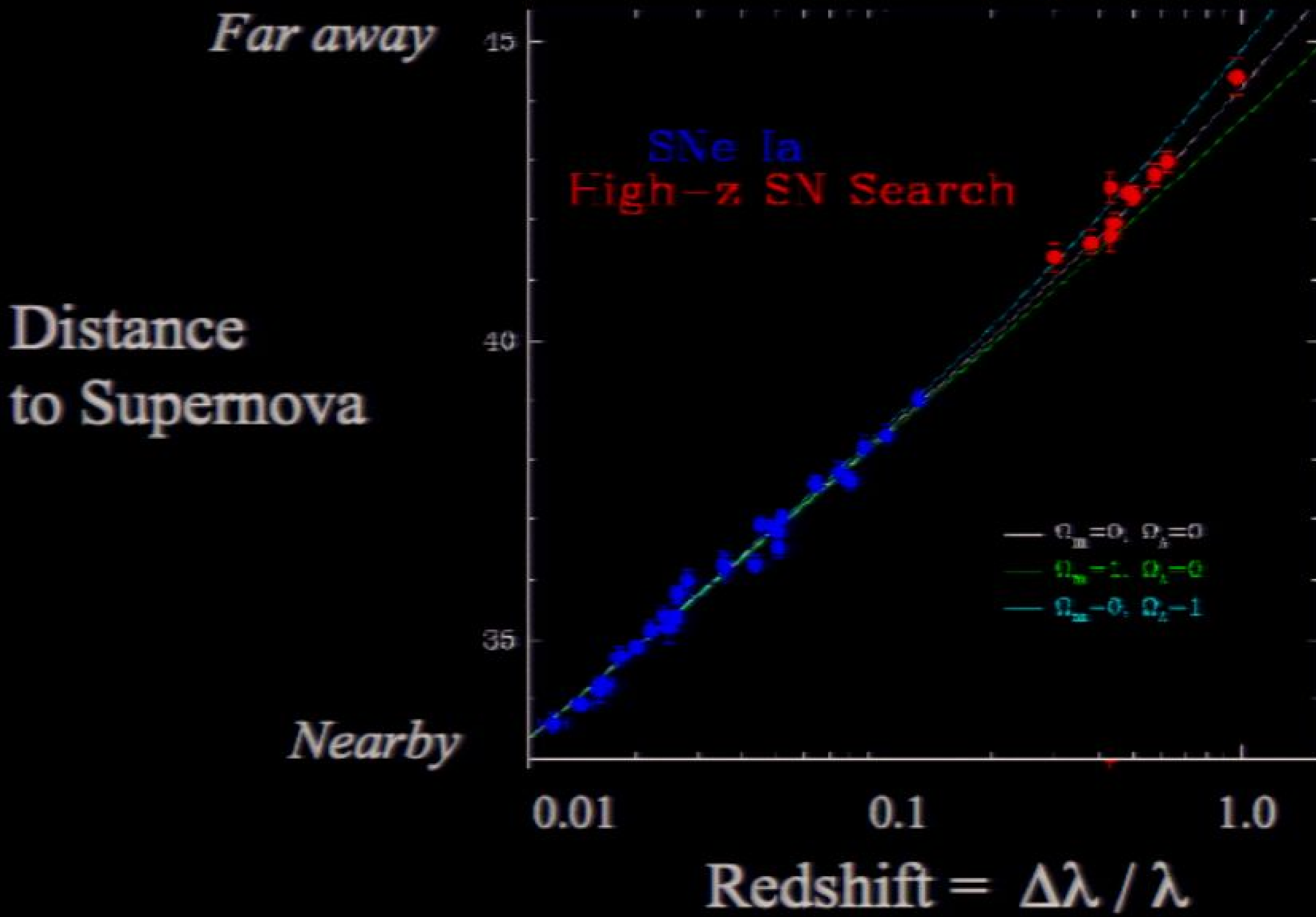
- CMB

Ω_K : geometrical curvature

- CMB

Some of The Original Evidence for Accelerating Expansion, 1998

Schmidt et al, High-z SN Team



The accelerating Universe scenario is supported by multiple independent lines of evidence

Lower bound on age of Universe, from stars

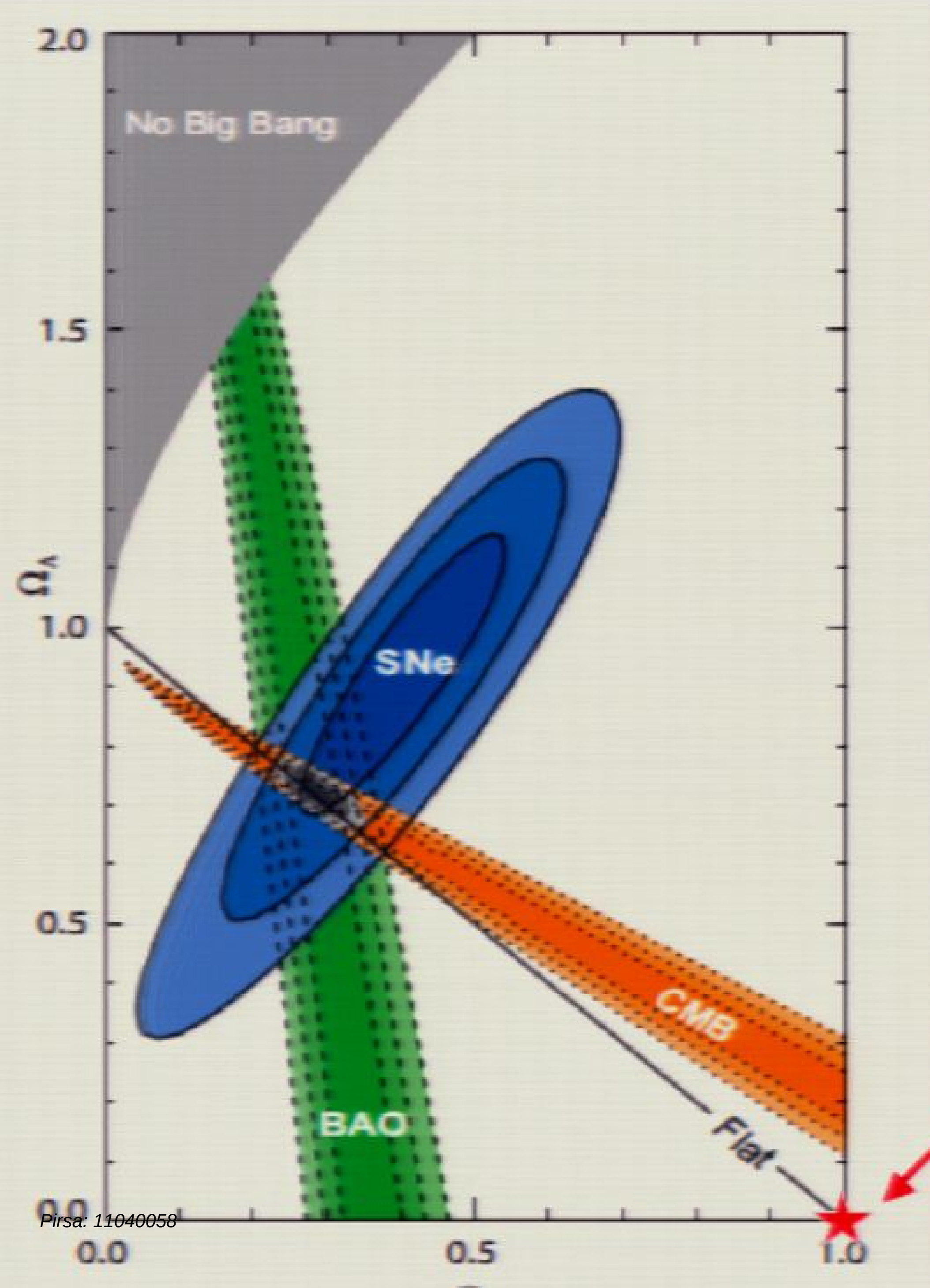
Inventories of cosmic matter content

Measurements of expansion history using supernovae

“Baryon acoustic oscillations”: large scale galaxy distribution

Abundance of galaxy clusters vs. mass and redshift

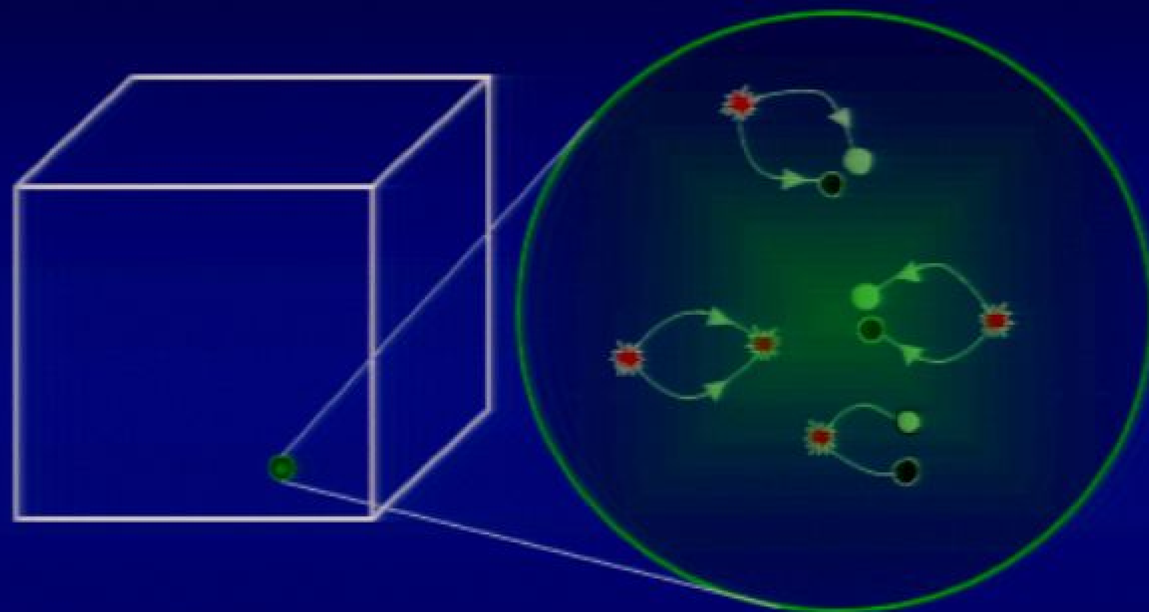
Cosmic Microwave Background provides strong confirmation



An earlier prediction from our theoretical friends….circa 1990

From Kowalski et al, 2008

The quantum mechanical vacuum is a seething turmoil…



Lamb shift in Hydrogen (virtual QED process)

Electron (g-2) (Hanneke et al, PRL 100, 1120801 (2008))

Casimir-Polder forces… (Lamoreaux, PRL 78, 5L (1997) & …)

It's confusing…. So let's ask the theorists!

Dark Energy Theory

$\Omega_\Lambda = 10^{120}$. Well, that can't be right…

$\Omega_\Lambda = 0$. Through some profound but not yet understood mechanism, the vacuum energy must be cancelled to arrive at value of identically zero

ummm... Supersymmetry

uhhh ...Planck Mass

$\Omega_\Lambda = 0.7$, you say??

String landscapes….uhhhh

No, wait! IT'S ANTHROPIC!

Two possible "natural" values

Vacuum energy integrated up to Planck scale $\Omega_\Lambda \quad 10^{120}$

Cancellation via tooth fairy:

$$\Omega_\Lambda = 0.0000000000000000000000000000....$$

But it's measured to be around 0.7!

Why Dark Energy Constitutes A Crisis in Fundamental Physics

<u>Puzzle #1</u>: why is Ω_Λ so *small*?

<u>Puzzle #2</u>: why is Ω_Λ so *large*?

<u>Puzzle #3:</u> what's the underlying physics?

Understanding the nature of the Dark Energy is arguably the most profound outstanding problem in fundamental physics.

Are the properties of the Universe we see the result of some beautiful (but as yet not understood) underlying symmetry principle, or just an anthropic selection effect?

Four philosophically distinct possibilities…

1) A "classical" cosmological constant, as envisioned by Einstein, residing in the gravitational sector.

2) A "Vacuum energy" effect, arising from quantum fluctuations in the vacuum, acting as a "source" term.

3) Departure from GR on cosmological length scales.

4) "Other"

Regardless, it's evidence of new fundamental physics!

Characterization: Dark Energy's Equation of State

$$P = w\rho \qquad \begin{cases} w = 0, \text{ matter} \\ w = 1/3, \text{ radiation} \\ w = -1, \ \Lambda \\ w = -N/3, \text{ topological defects} \end{cases}$$

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \sqrt{(1-\Omega_\Lambda)(1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}}\ dz'$$

- For a flat Universe, luminosity distance D_L depends z, Ω_Λ, w.
- Evolution of Dark Energy density depends on w.
- Any value of w other than -1 excludes cosmological constant
- Any evolution in w excludes cosmological constant

Parameterization of ignorance

A cosmological constant has $w = -1$

So do numerous other scenarios

Current projects are capable of determination of w to 10%, assuming constant value.

Next step is to allow for w to vary, a common approach is

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

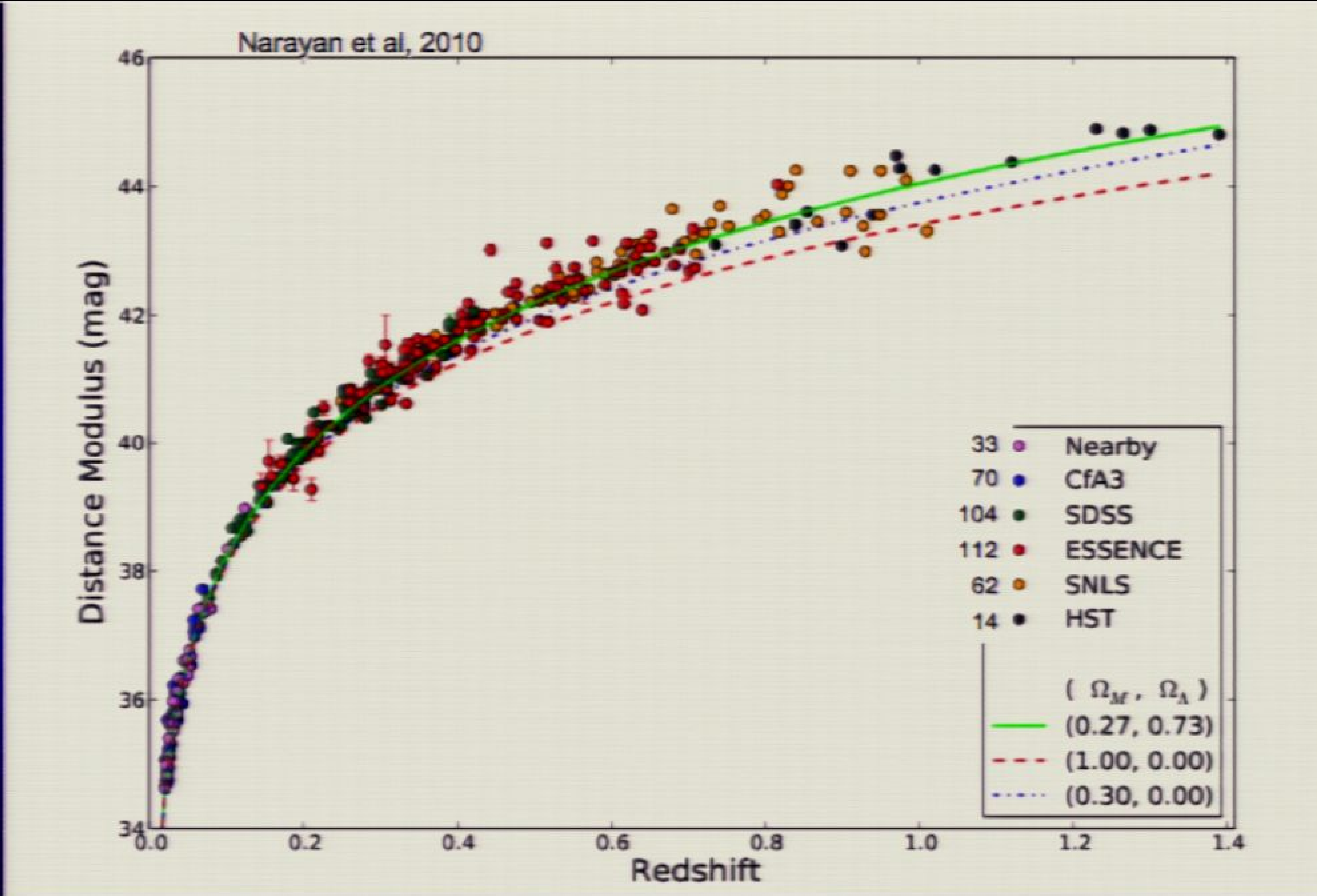
Why the characterization of dark energy is hard

Signature of non-zero Dark Energy is 20% reduction in apparent brightness of type Ia supernovae.

Determination of w at 10% level requires 1% measurements.
Both random and systematic errors are a challenge.

Trying to characterize a “cosmic fluid” from within local structure and mass inhomogeneities; gravitational lensing is both a tool and a complication.

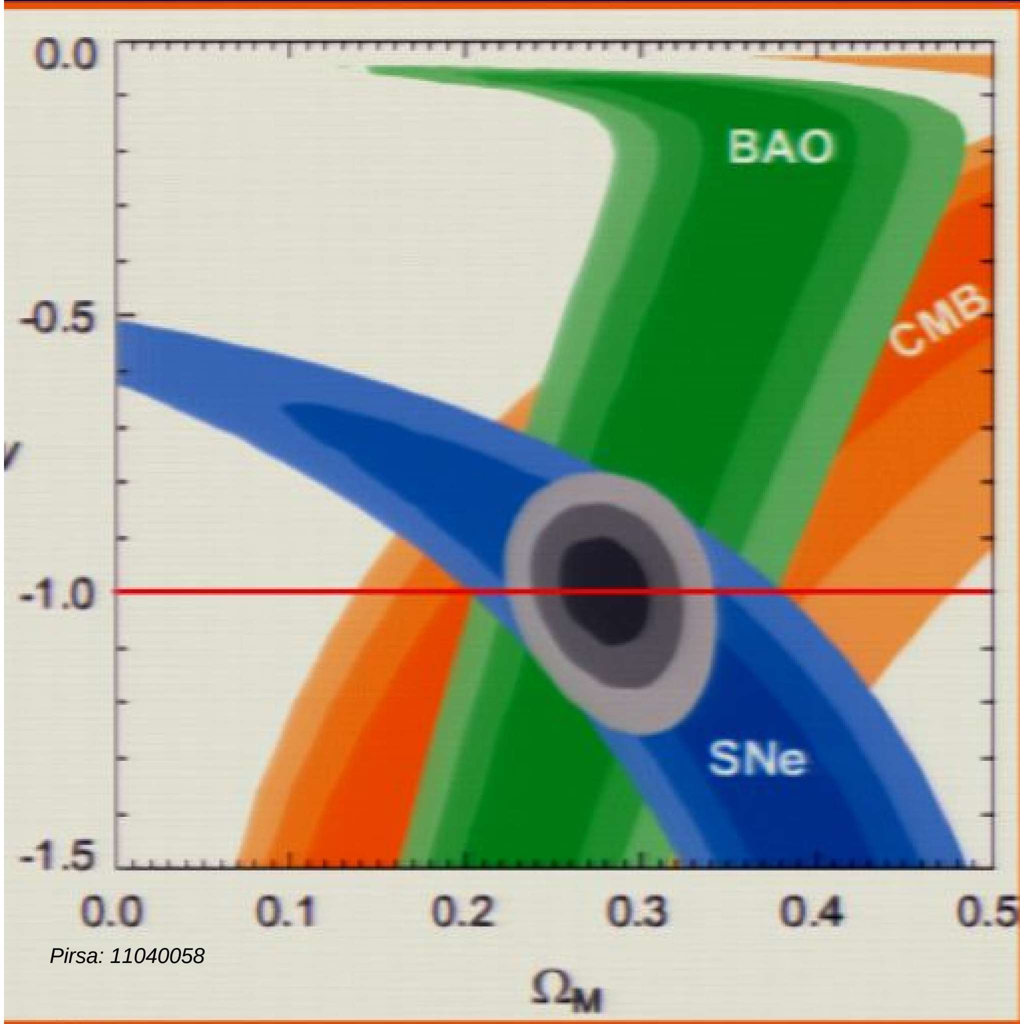
While we have numerous theoretical “scenarios”, very few concrete falsifiable predictions. A constant Ω_Λ is an exception, it requires $w = -1$.

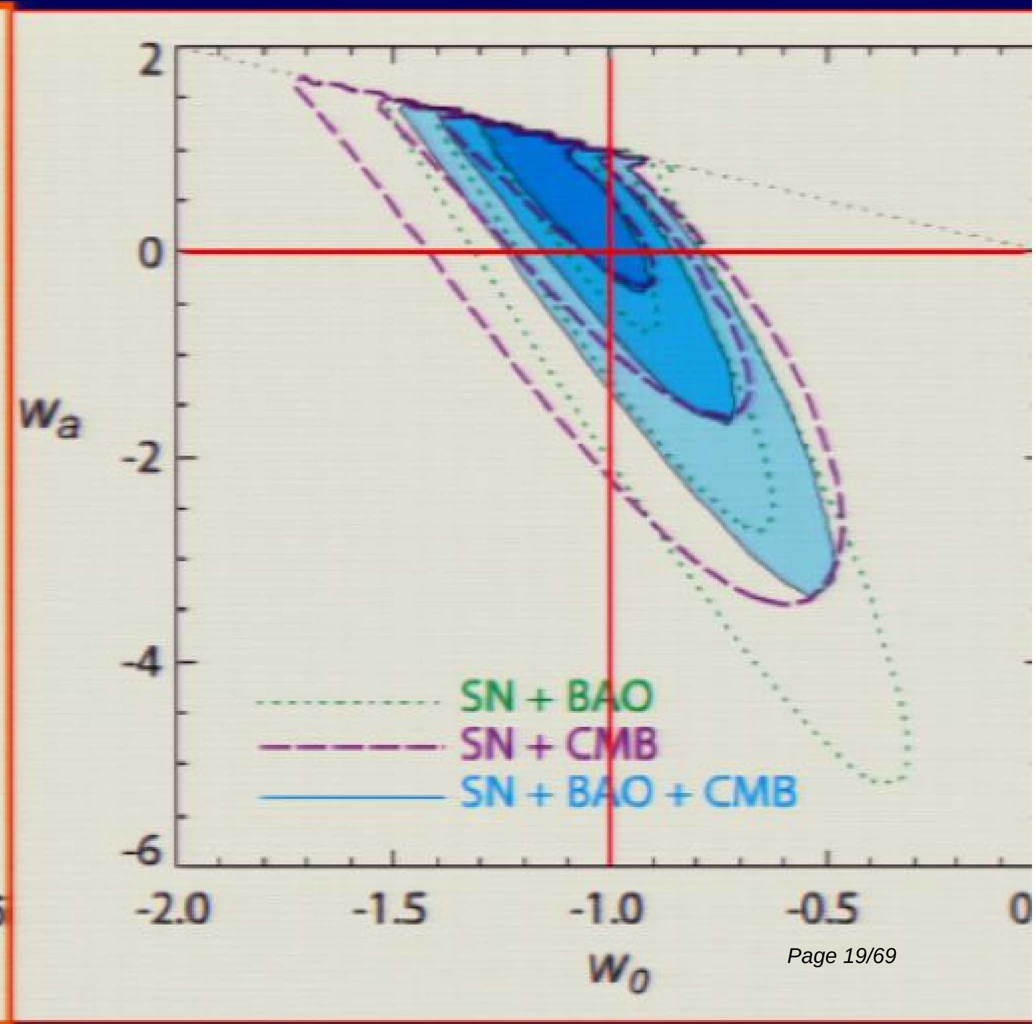


$$(1+w) = 0.008 \pm 0.07(stat) \pm 0.13(syst)$$

Current limits on w, w_a.

From Kowalski et al, 2008





Snapshot of our understanding today:

- Evidence for accelerating expansion seems robust.
- All data are thus far consistent with

$$w_0 = -1$$
$$w_a = 0$$

- This matches expectations for a vacuum energy or Λ phenomenology, but does not exclude other possibilities.
- We have no idea what's really going on here.

Next Steps on Dark Energy: Bigger Astronomical Surveys

1) Re-instrumenting existing telescopes

- Sloan Digital Sky Survey-III
- Dark Energy Camera on 4 meter Blanco telescope
- ...

2) Construction of new optical and infrared survey instruments

- PanSTARRS survey
- Space-based observations with optimized apparatus
- Large Synoptic Survey Telescope (LSST)
- ...

3) Other methods

- Galaxy cluster abundances, using microwave background distortion
- 21 cm 3-d surveys
- ...

Survey Figure of Merit

$$FOM = N/t = \left[\frac{\phi}{SNR}\right]^2 \frac{A\Omega\varepsilon}{\phi_{sky}(\delta\Omega)}$$

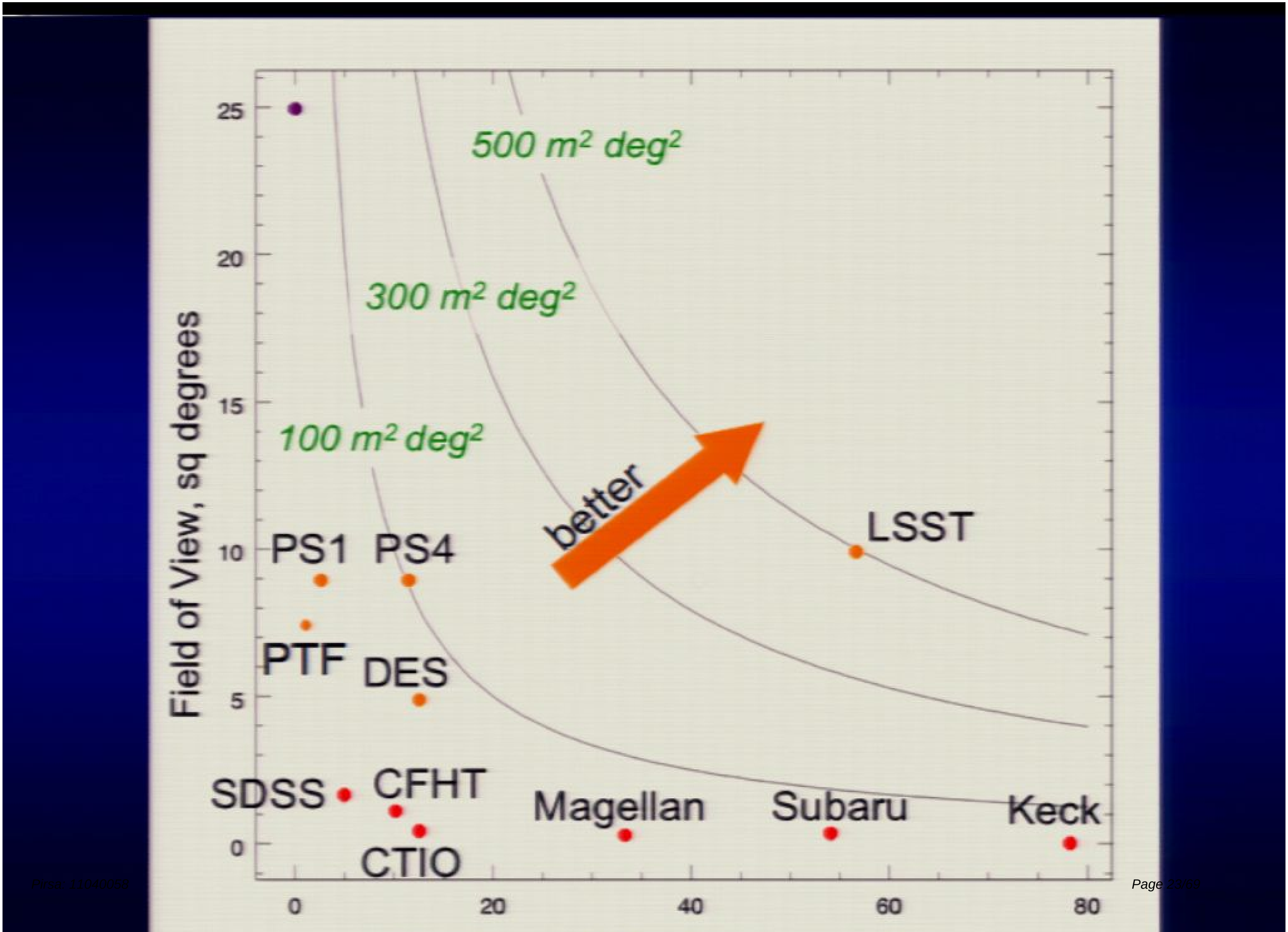
System:
Collecting Are[a]
Field of View
Efficiency

Source flux,
signal to noise

Site: sky brightness,
seeing

Each generation of astronomical survey hardware is providing a substantial increase in $A\Omega\varepsilon$ product.

Still on steep part of FOM vs. cost curve.


Field of View, sq degrees
500 m² deg²
300 m² deg²
100 m² deg²
better
LSST
PS1
PS4
PTF
DES
SDSS
CFHT
CTIO
Magellan
Subaru
Keck
25
20
15
10
5
0
0
20
40
60
80

Some of the bigger and better surveys, current and planned…

PanSTARRS, multiband optical survey in Northern hemisphere, now coming into full operation

Large Synoptic Survey Telescope (LSST), wide-field optical survey system planned for Southern hemisphere

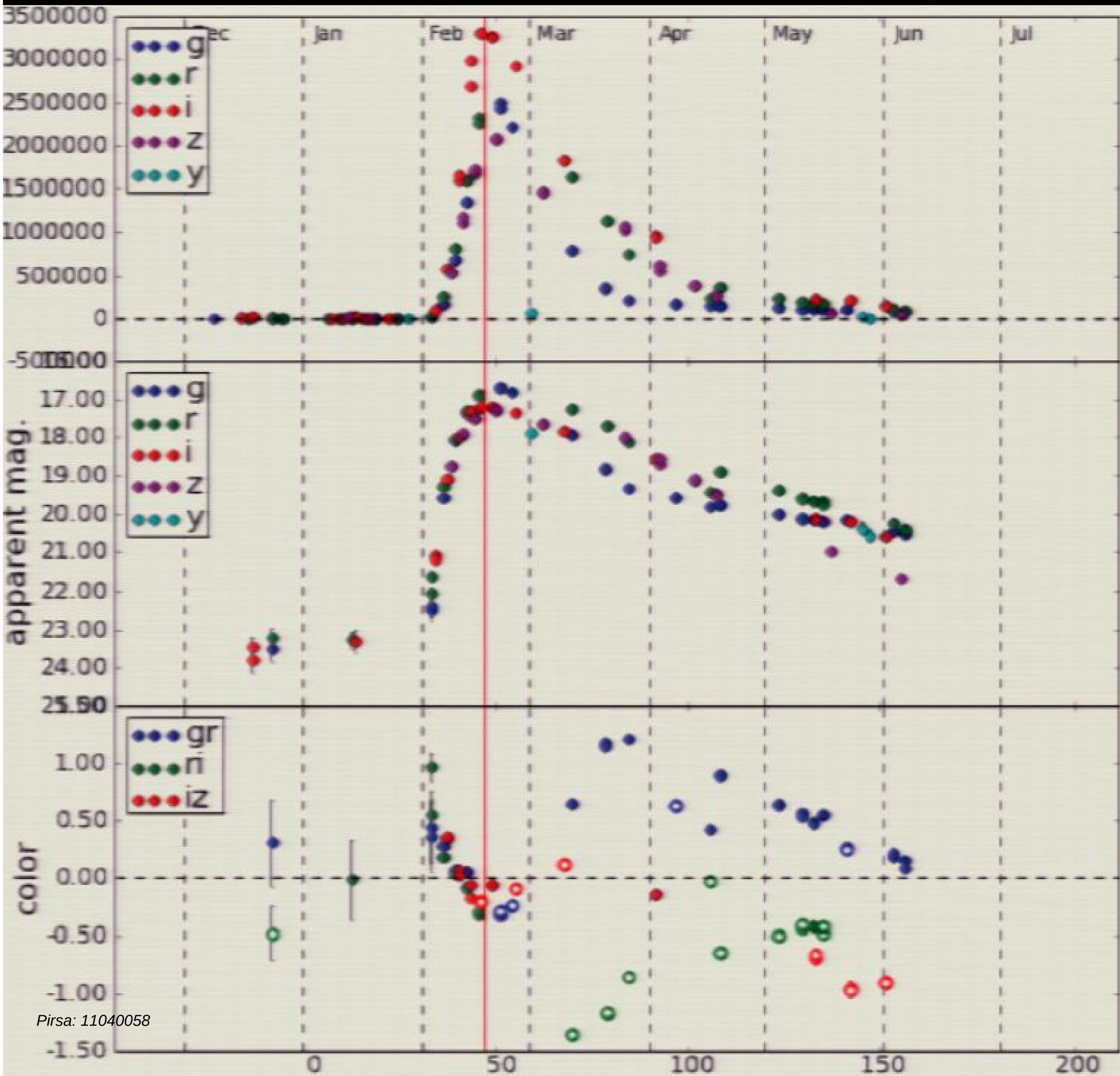
WFIRST, a proposed 1.5m infrared space telescope

The South Pole Telescope, mapping the evolution of the most massive galaxy clusters in the Universe.

Next Steps on Dark Energy: Better Imaging Surveys

Discovery data 1998	20 distant SNe	10% precision
ESSENCE, SNLS ... 2009	200 distant SNe	3 % precision
PanStarrs 2011	2000 SNe	1% precision
LSST 2018	20,000 SNe	< 1%


.4 Gpix camera
.3 degree FOV
The PanSTARRS Survey
1.8 meter telescope

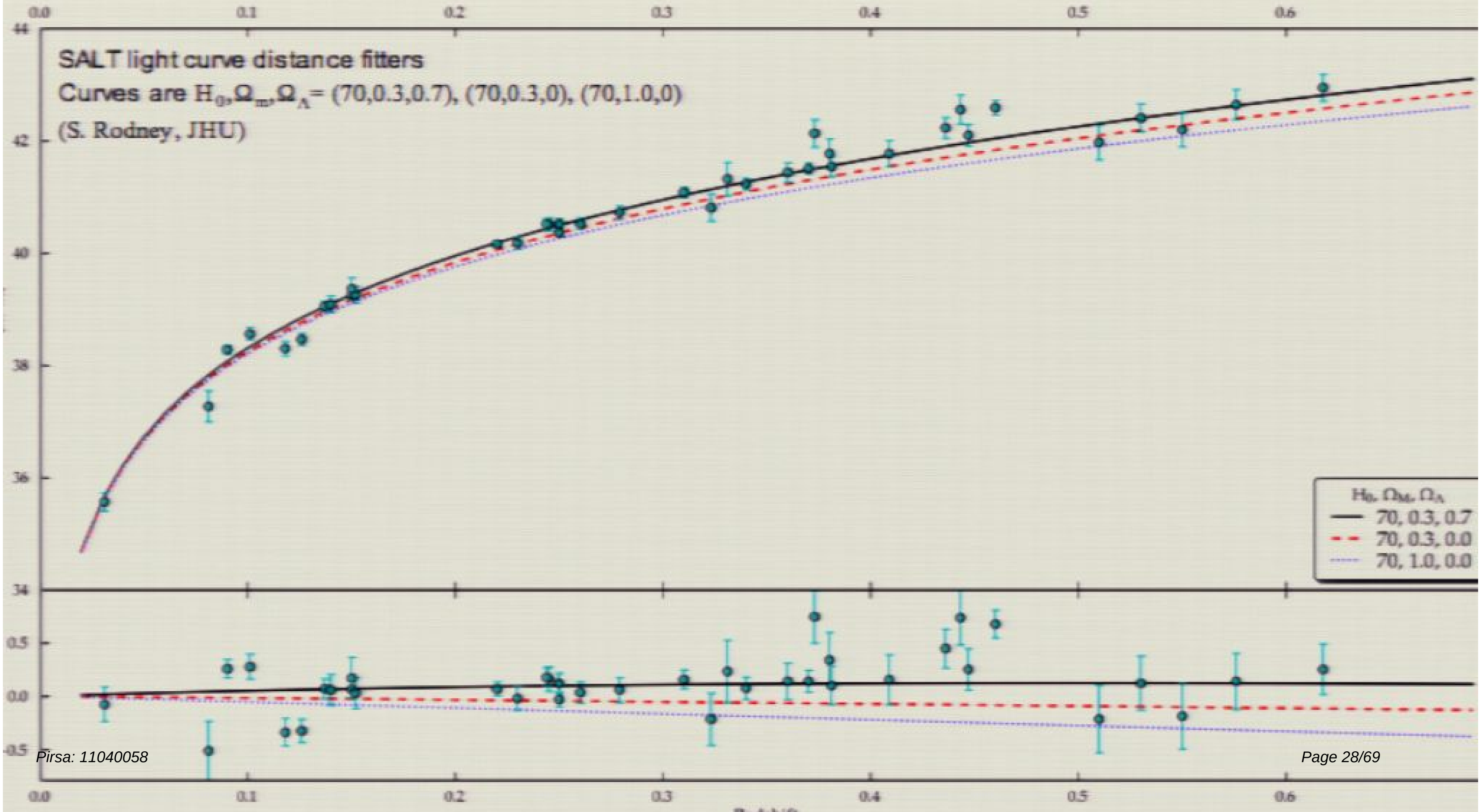


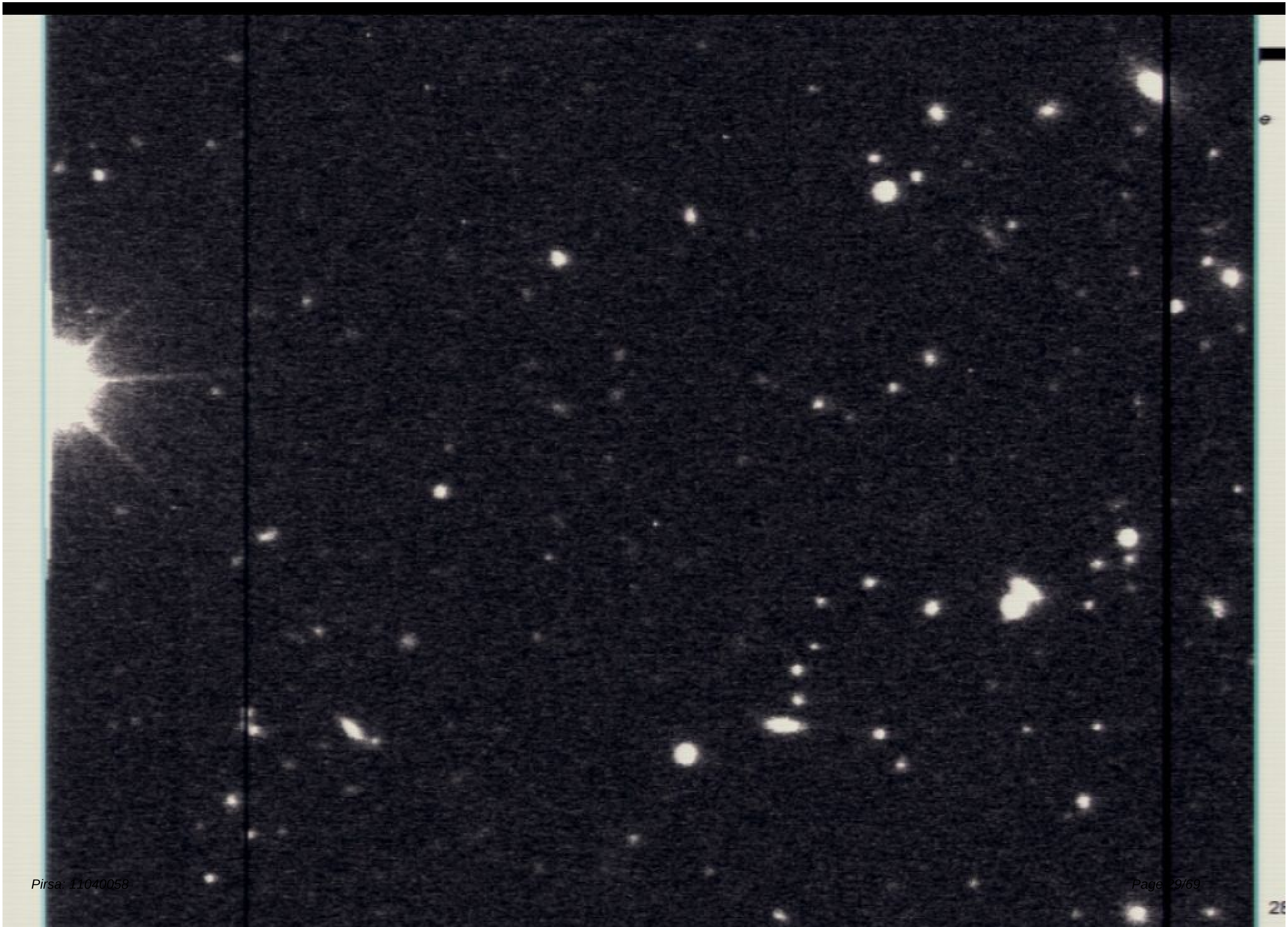
PanSTARRS 5 band light curves

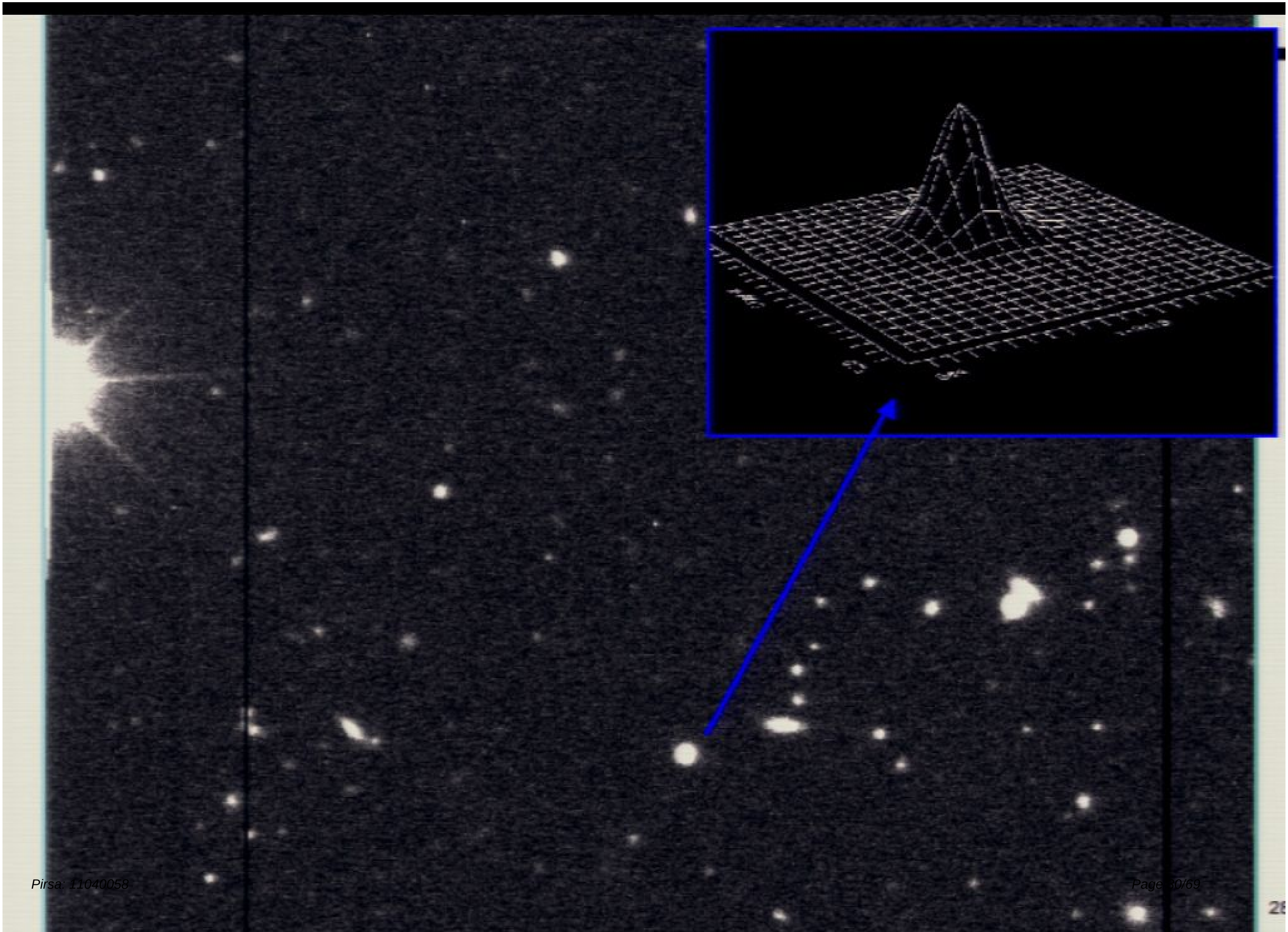
Supernova PS1-1000023 AKA 2010-B010026

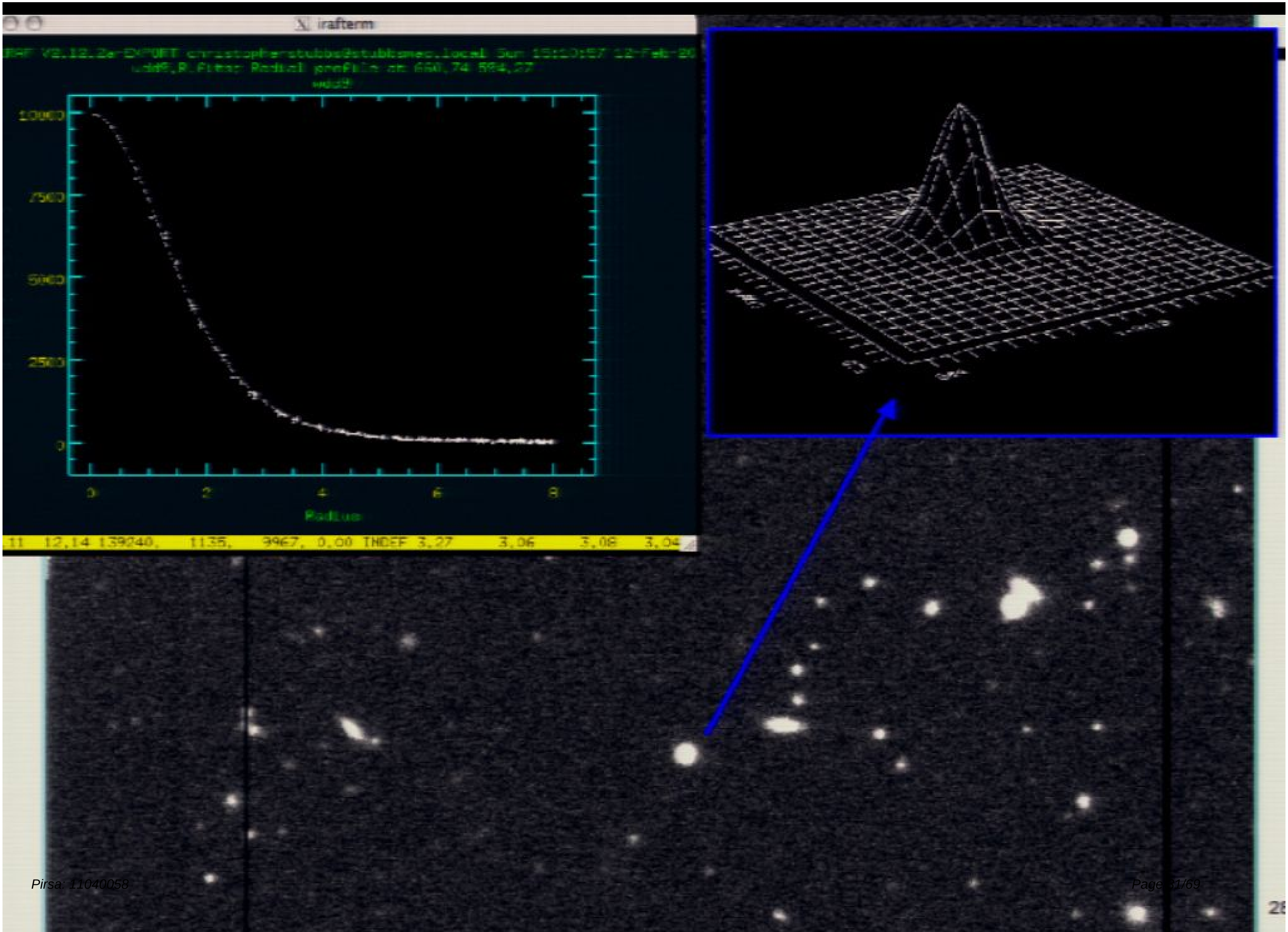
redshift 0.031

A Preliminary PS-1 SN Hubble Diagram



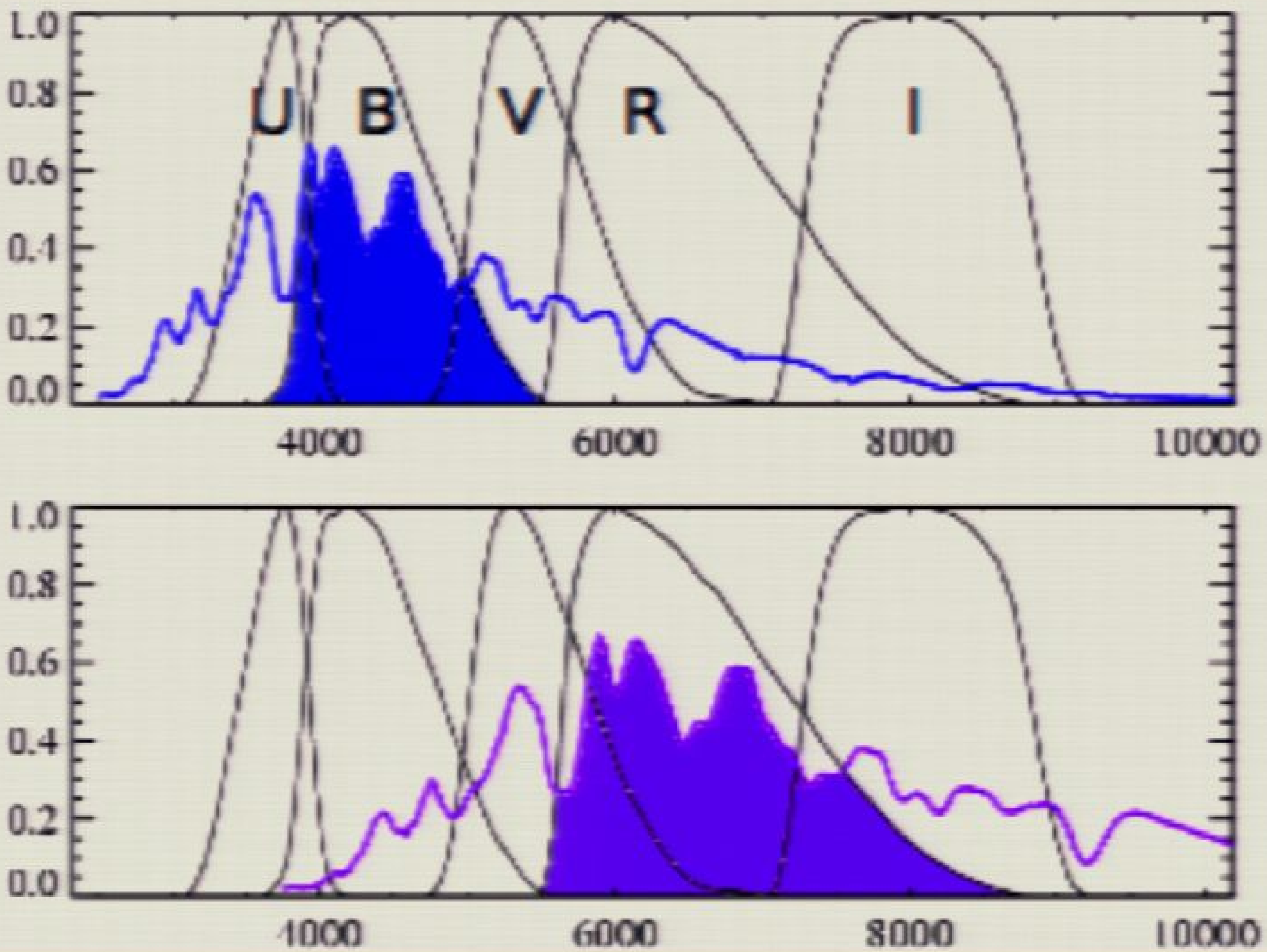





irafterm
10000
7500
5000
2500
0
0
2
4
6
8
Radius

Passbands and System Sensitivity

LSST
Large Synoptic Survey Telescope



Broadband photometry: "Metrology and Meteorology"

Galactic scattering

$$\phi(i,j) = \sum_{sources} \int S(\lambda)A(\lambda)G(\lambda)T(\lambda)\, d\lambda$$

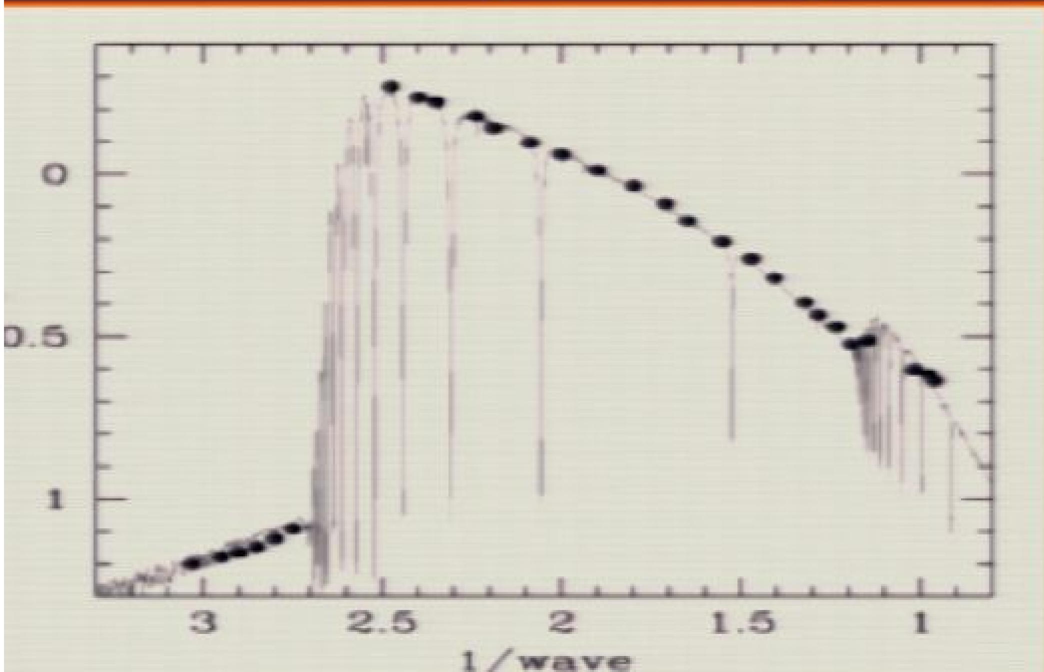
Source — Atmosphere — Instrumental transmission

Four aspects to the photometry calibration challenge:

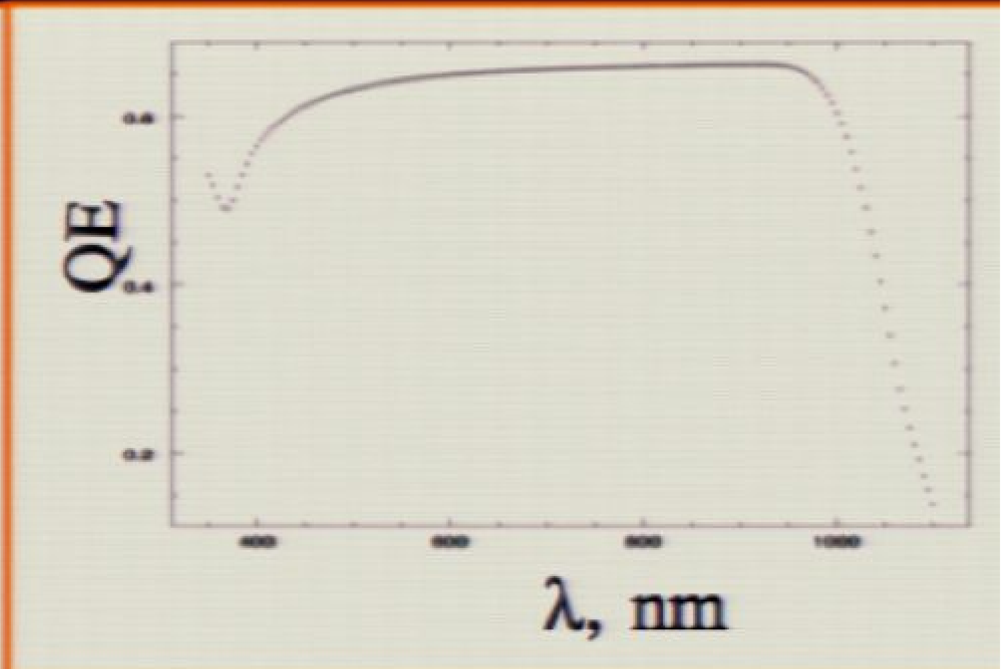
1. *Relative instrumental throughput calibration*
2. *Absolute instrumental calibration (I claim this this is far less important)*
3. *Determination of atmospheric transmission*
4. *Determination of Galactic extinction (most stars lie behind the extinction layers).*

Historical approach has been to use spectrophotometric sources (known $S(\lambda)$) to deduce the instrumental and atmospheric transmission, but this (on its own) is problematic: integral constraints are inadequate, plus we don't know the source spectra to the requisite precision.

Detectors are better characterized than *any* celestial spectrophotmetric source

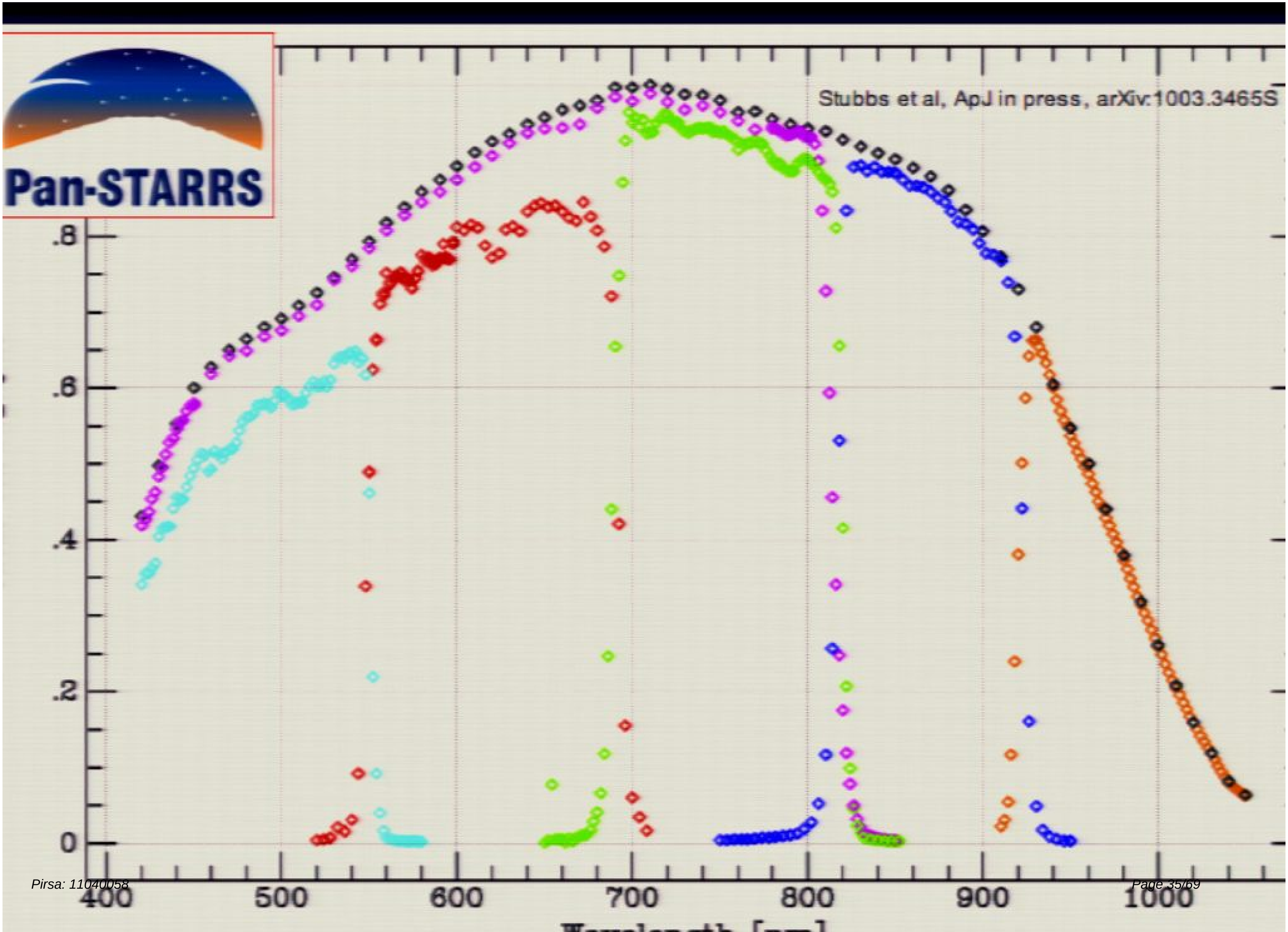


Spectrum of Vega



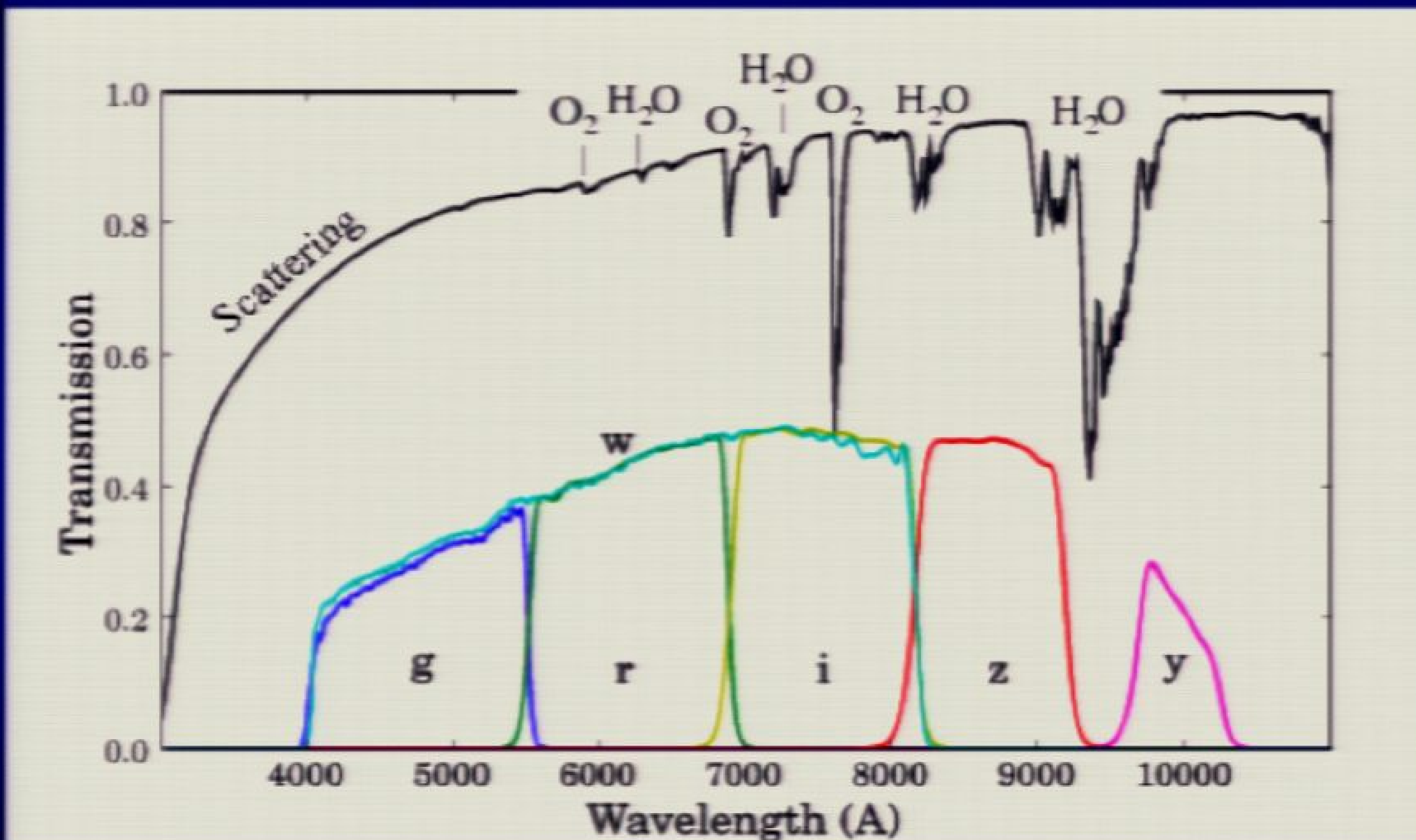
NIST photodiode QE

Measuring instrumental throughput relative to photodiode establishes zeropoints across filters. Leaves a single overall unknown (~ effective aperture), which is of less interest.



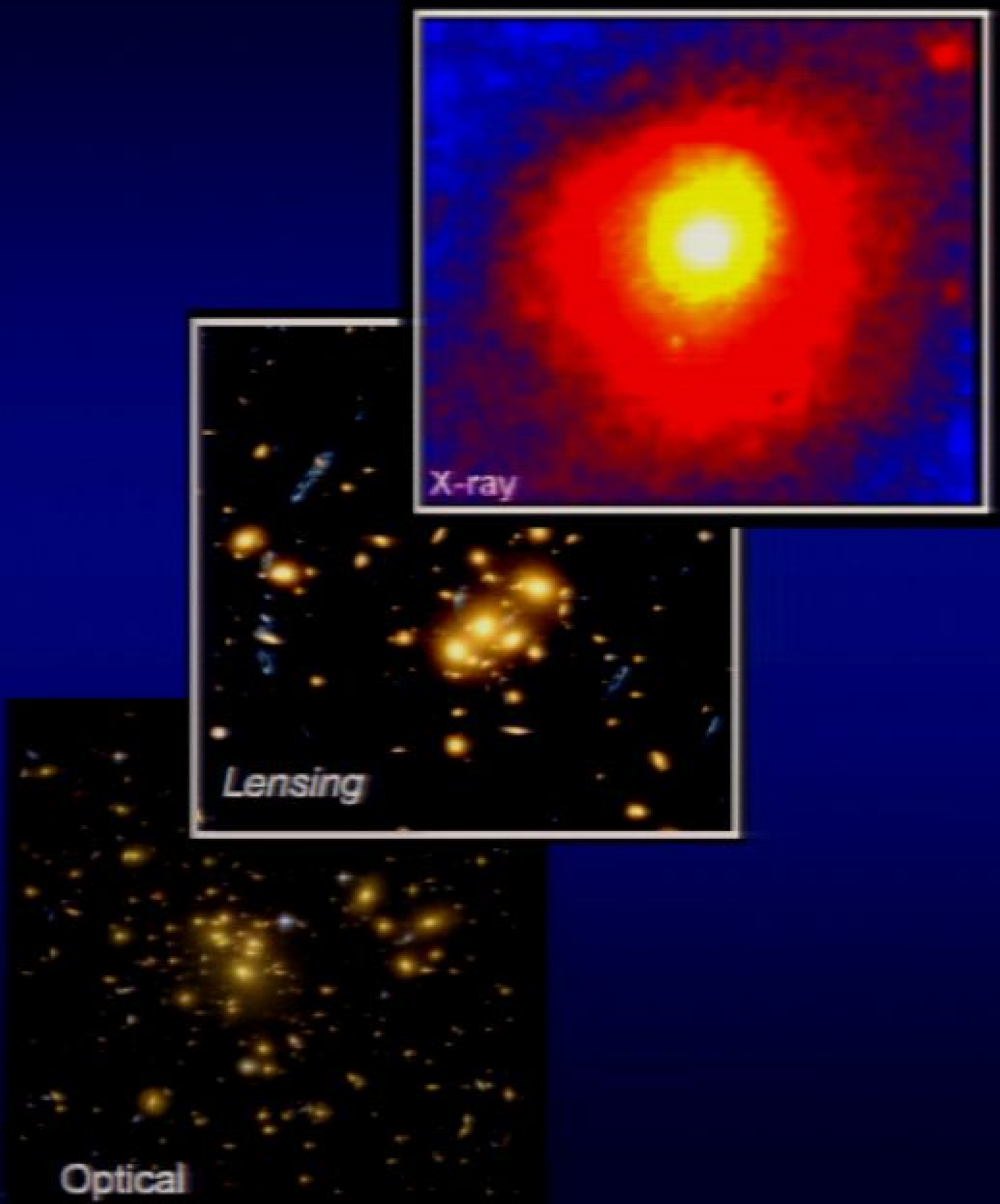
Pan-STARRS
Stubbs et al, ApJ in press, arXiv:1003.3465S
.8
.6
.4
.2
0
400
500
600
700
800
900
1000

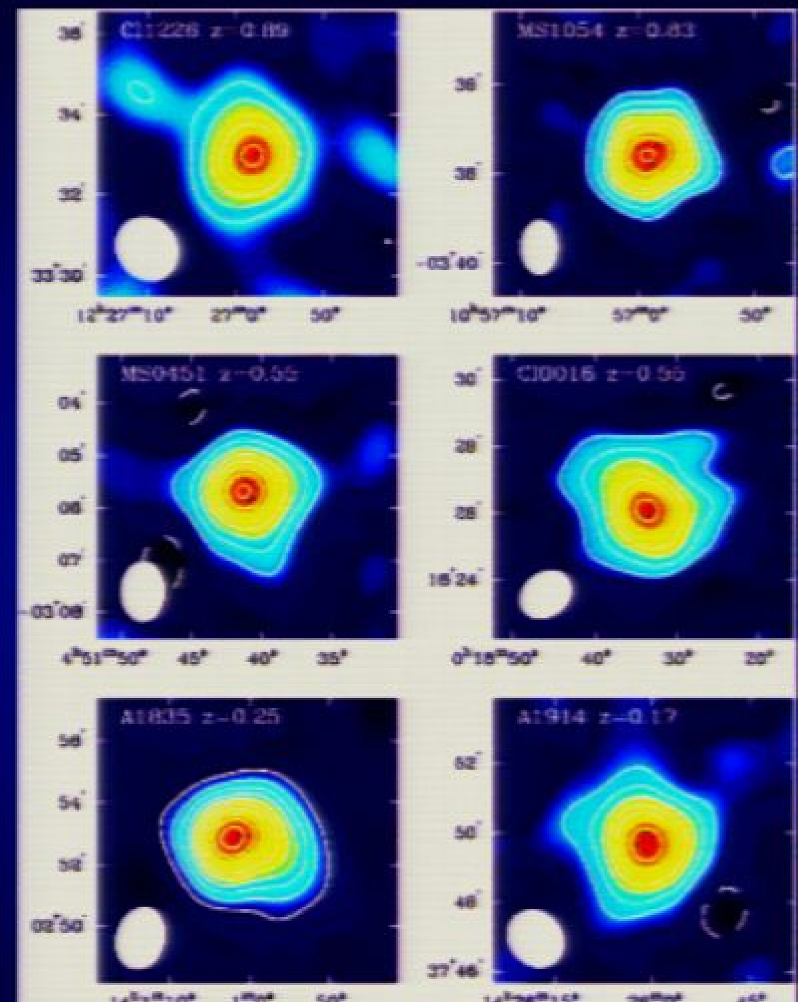
Atmospheric Transmission



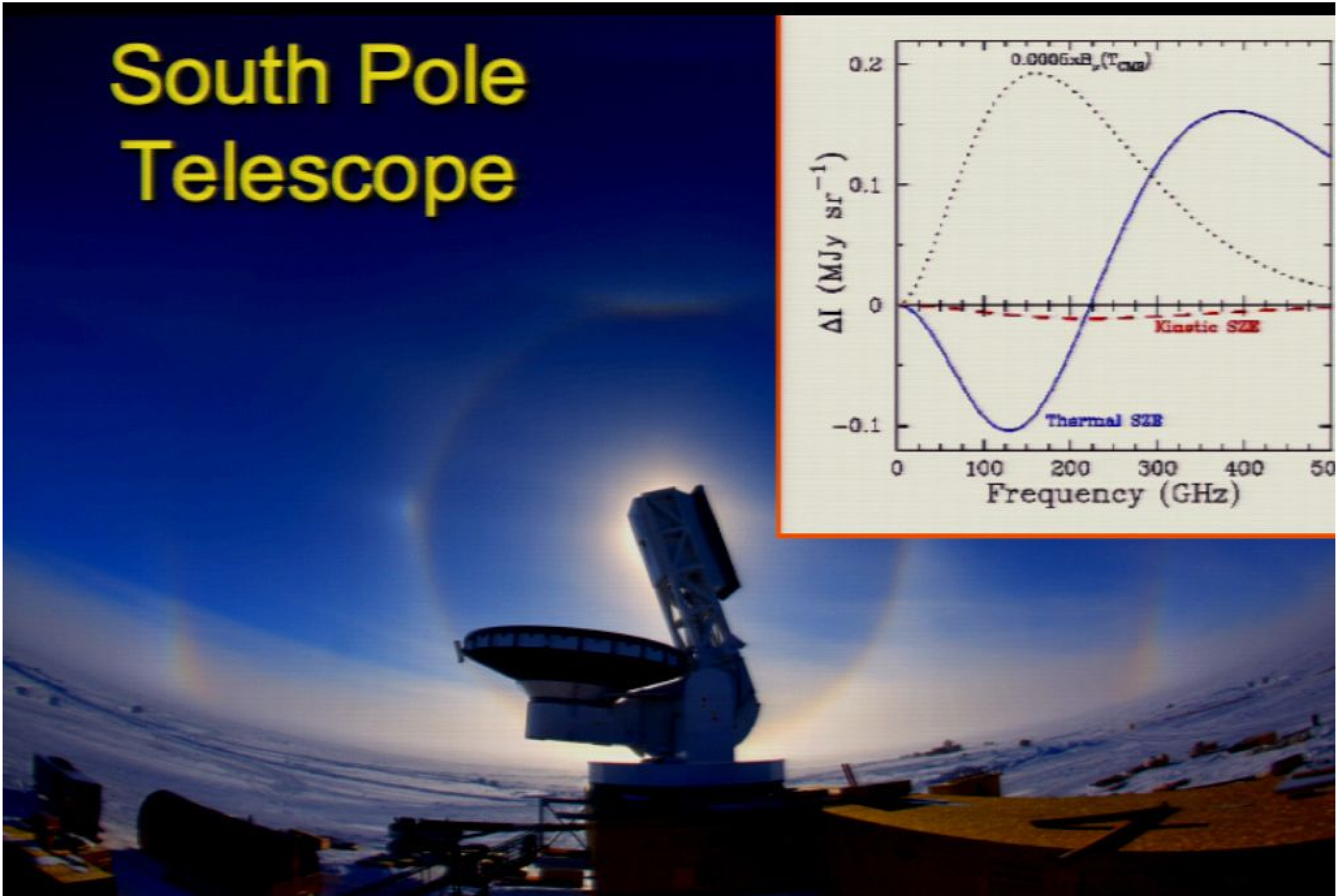
Burke et al, ApJ 720, 811B (2010)

Galaxy Clusters

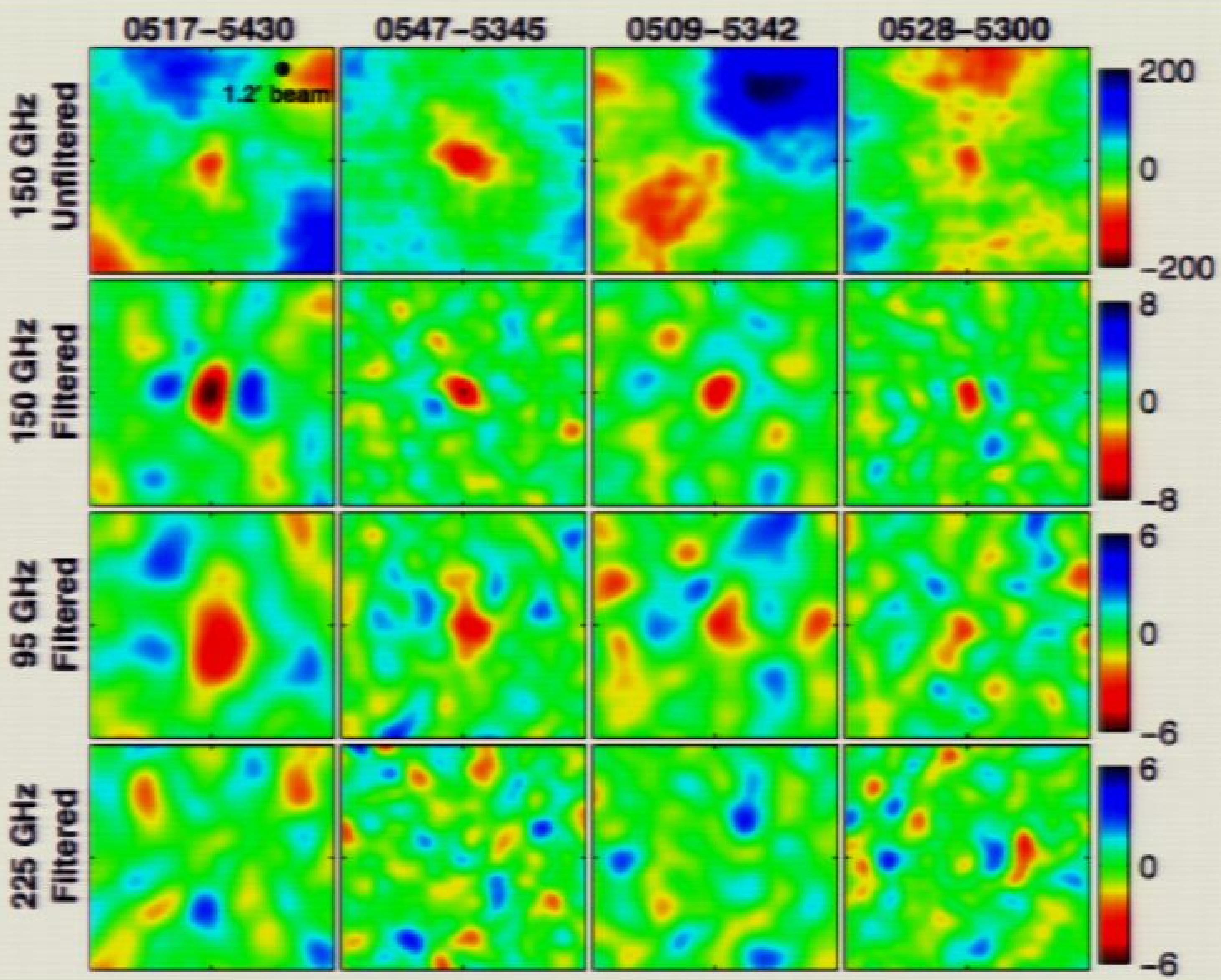




Sunyaev-Zeldovich CMB distortion


South Pole
Telescope
0.2
0.1
0
−0.1
ΔI (MJy sr⁻¹)
0.0005xBν(TCMB)
Kinetic SZE
Thermal SZE
0
100
200
300
400
Frequency (GHz)

First “blind” SZ detection of clusters



Staniszewski et al, arXiv 0810.1578

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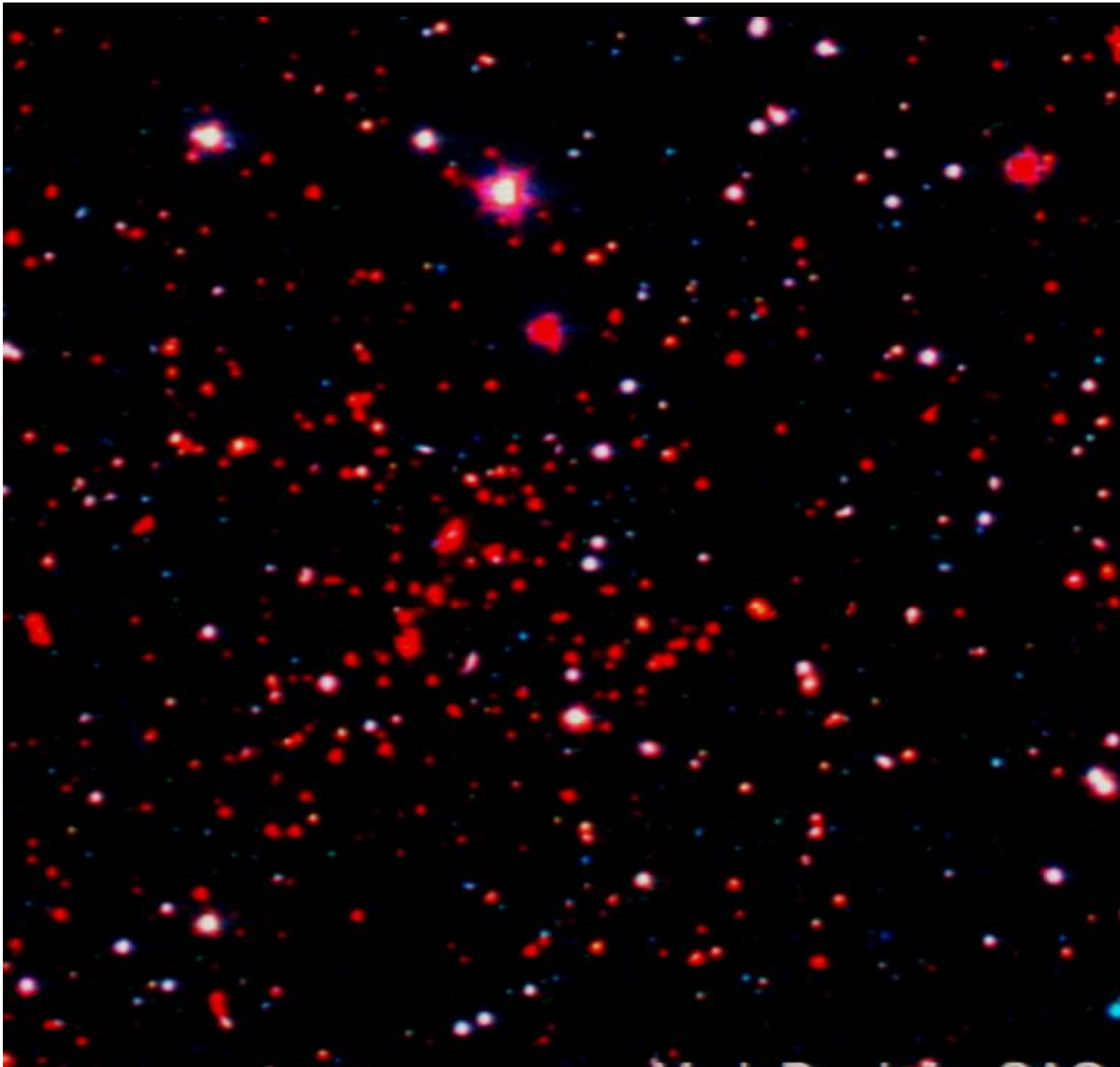
Magellan
telescope
images
400 nm to 900 nm



Spitzer, IR
Space Telescope

3.6 micron
image in red

High redshift
cluster
galaxies
stand out

South Pole Telescope Clusters- Status

SPT works, and works well: See High et al (2010) Valderlinde et al (2010), Williamson et al (2011), Foley et al (2011), and Brodwin et al (2011).

Cluster detection algorithms have yielded ~300 of candidates at > 5 s .

We have photometric redshift estimates 67 clusters

spectroscopic redshifts to ~50 clusters

velocity dispersions on 36 high-mass clusters

Xray data on 60

HST lensing scheduled for 8 clusters

This is a unique data set, and even 20 clusters provide constraints on cosmological parameters, with a different set of systematic uncertainties.

A major priority is to obtain multiband mass estimators.

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Shifting to future projects….

In the recent US Decadal Survey for Astronomy and Astrophysics, first-ranked projects on ground and in space were Dark Energy related:

Wide Field InfraRed Space Telescope

Large Synoptic Survey Telescope

WFIRST: 1.5 meter aperture IR telescope

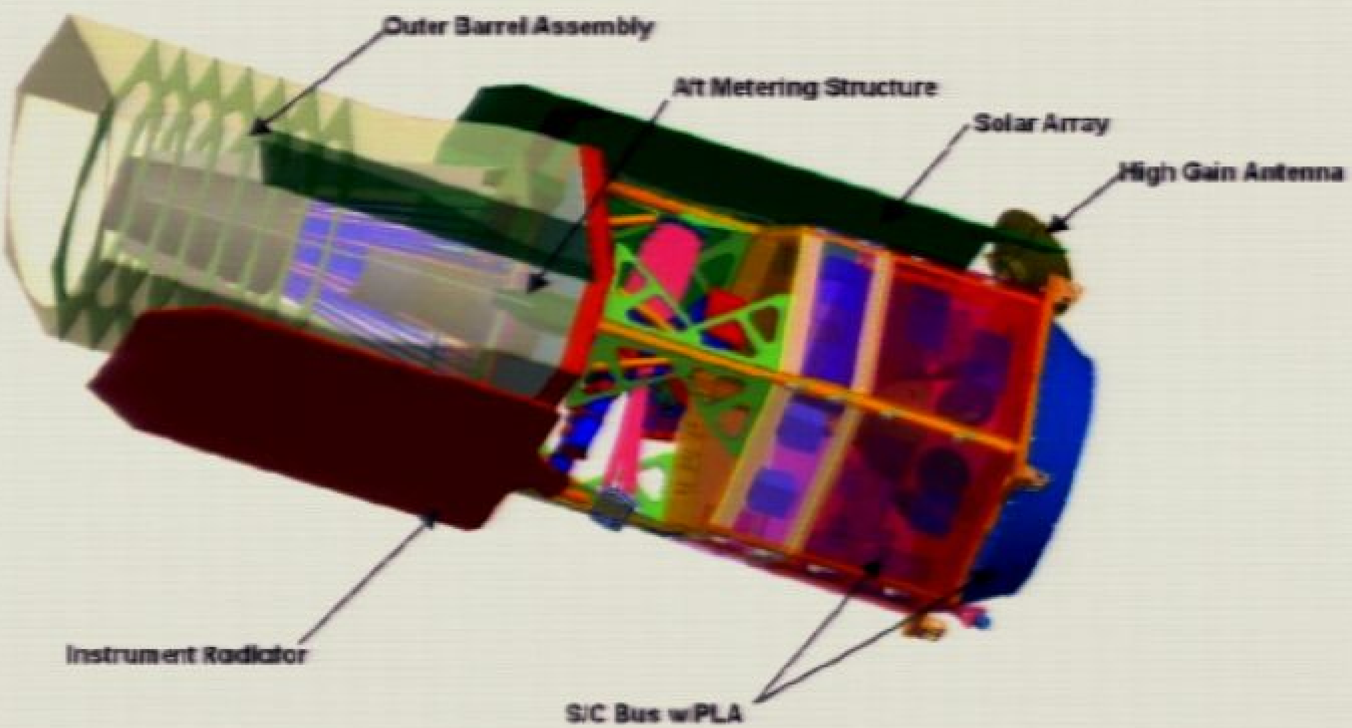


FIGURE 7.3 WFIRST is an infrared telescope with a three-mirror design. It will have HgCdTe detectors with 144 megapixels in total and angular resolution of 200 milliarcseconds. The sensitivity should be about 200 nJy or 26th magnitude, enabling shape measurements and photometric redshifts to a depth of 100,000 galaxies per square degree over half the sky. Spectroscopy will be achieved with a grism or prism and will rely mainly on measurement of H alpha out to a redshift of about 1.8 Credit: JDEM Project, NASA-GSFC.

WFIRST

"It seems that there was no need for NASA to participate in the decadal, as there are unlikely to be any funds available before 2020 to start anything big and new," says Alan Boss, chair of the NASA advisory council astrophysics subcommittee and an astrophysicist at the Carnegie Institution for Science in Washington DC. Particularly vulnerable, says Stern, is the Wide-Field Infrared Survey Telescope (WFIRST), the decadal survey's top large-scale, space-based project. The mission, intended to study the 'dark energy' driving the acceleration of the Universe's expansion, is estimated to cost $1.6 billion.

- Nature News online, posted Nov 16 2010.

Large Synoptic Survey Telescope

Top National ground-based priority in 2010 Decadal Survey

Optimized for time domain

scan mode

deep mode

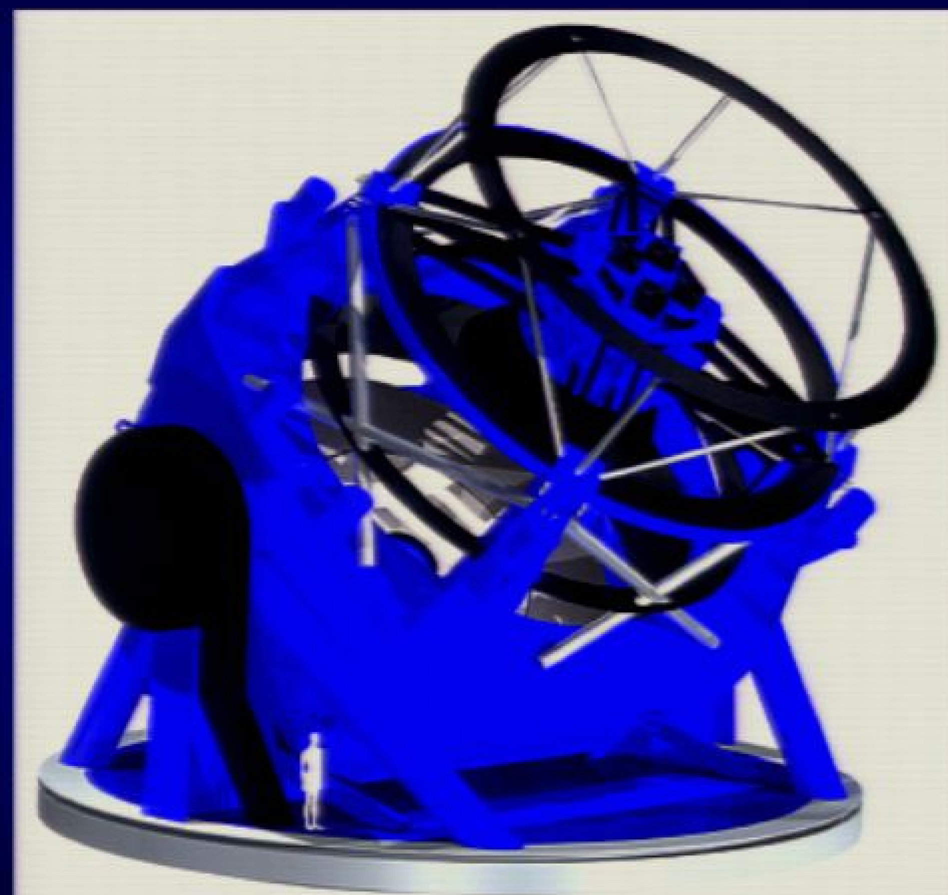
10 square degree field

6.5m effective aperture

24th mag in 20 sec

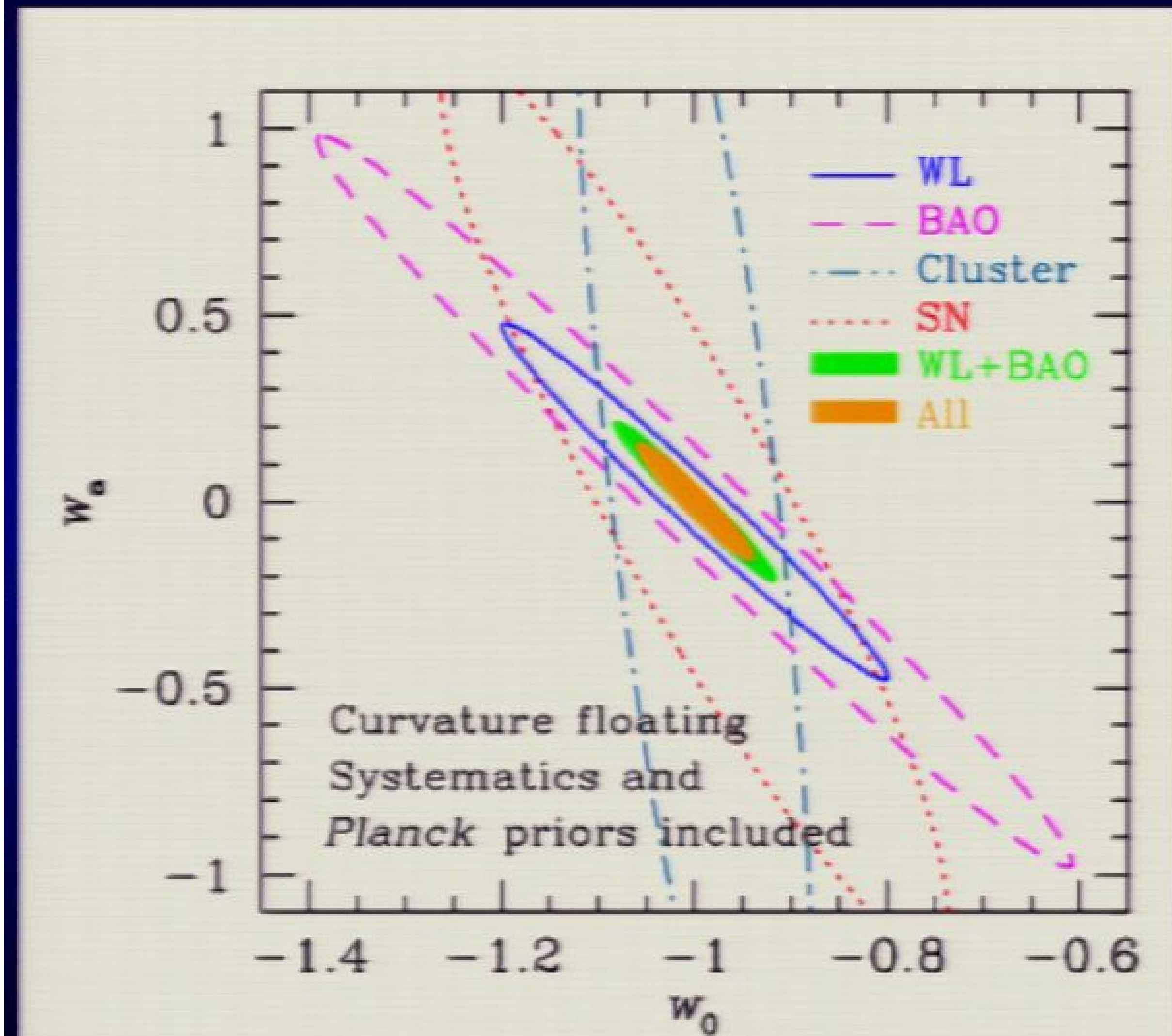
>20 Tbyte/night

Real-time analysis



Simultaneous multiple science goals

LSST is engineered to study DE

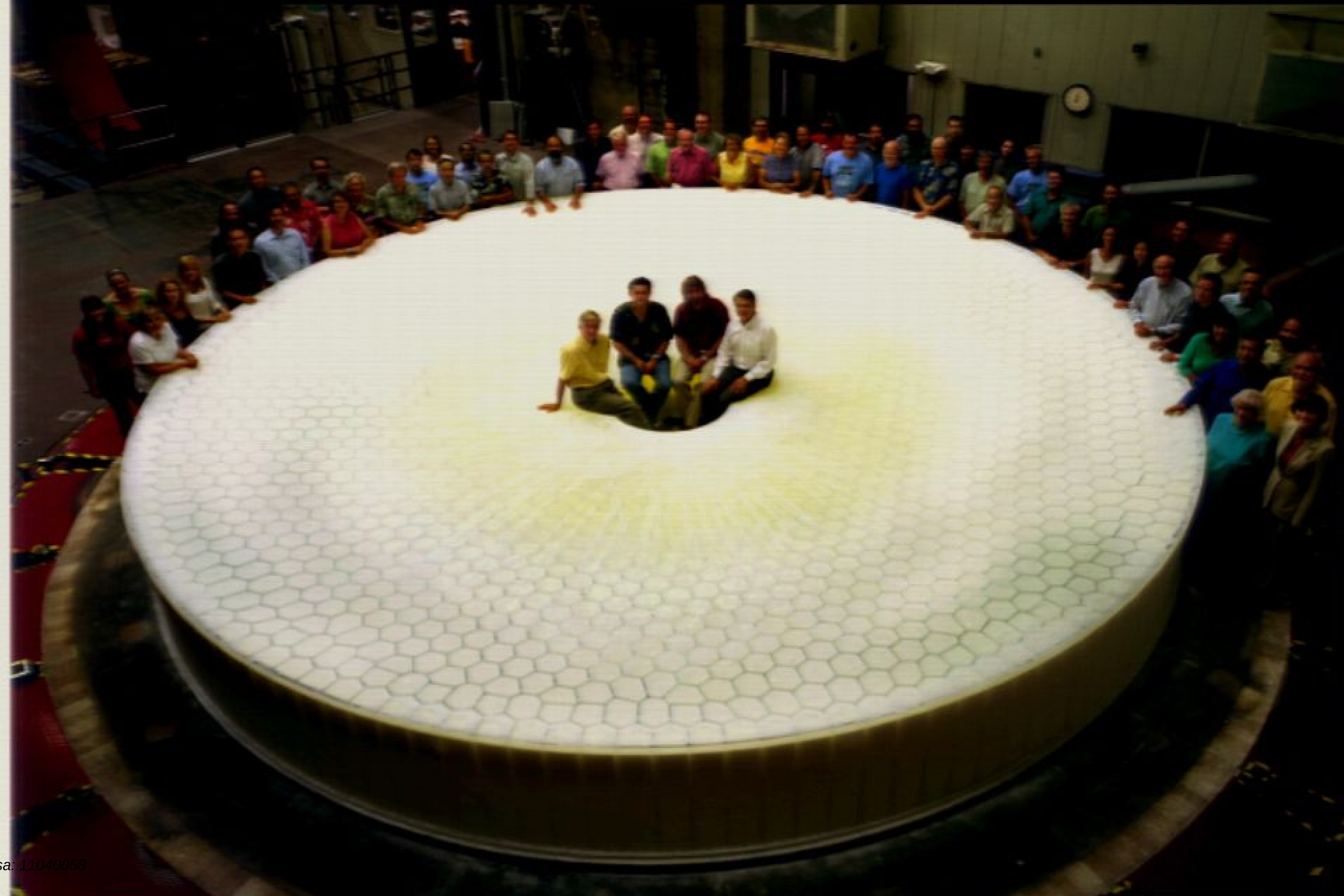


Also very effective for:

Neutrino mass scale
Killer asteroids
Galactic structure
Transient sources
...

http://www.lsst.org/files/docs/sciencebook/SB_15.pdf

Large Synoptic Survey Telescope

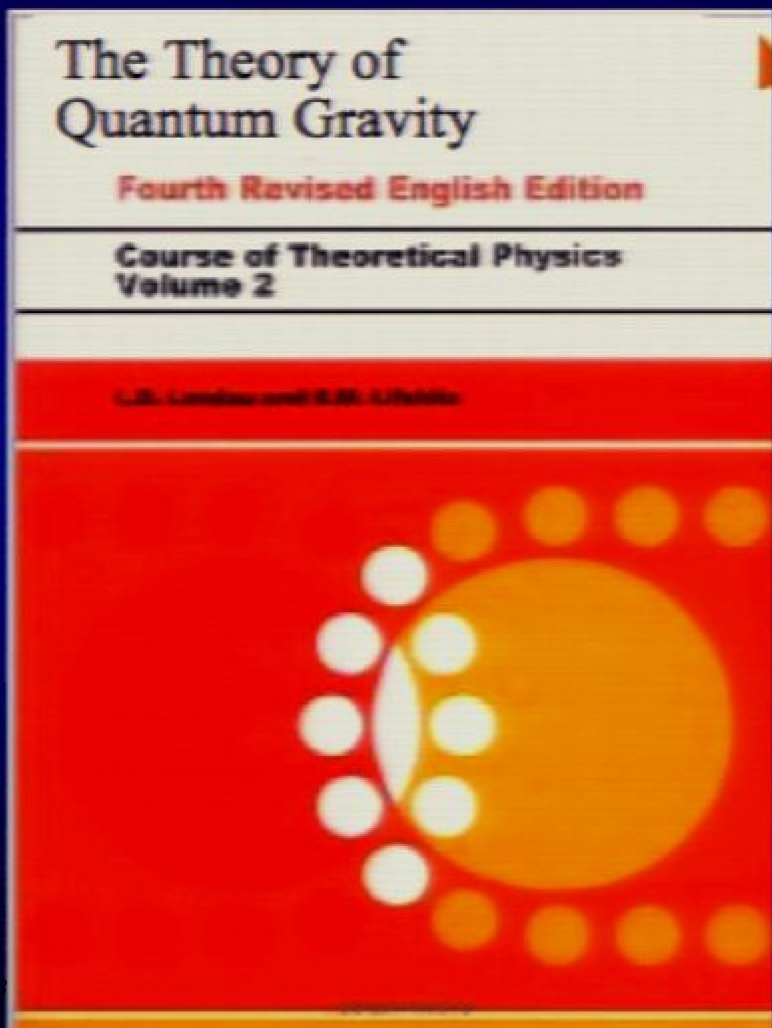


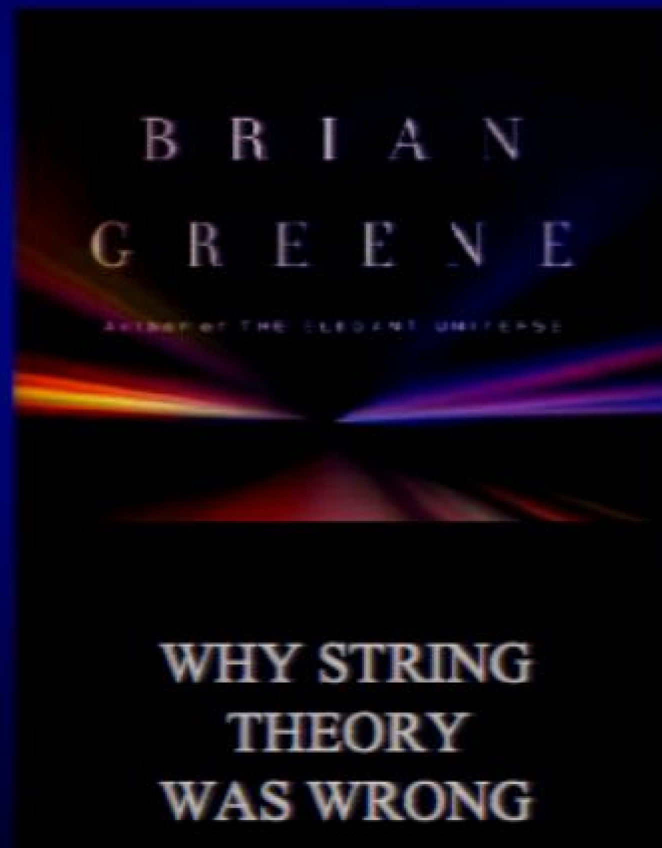
A look ahead to Dark Energy in 2028, 3 decades after its discovery

- Results from LSST, WFIRST, or other Stage IV dark energy projects.
- Measurements of $\Omega_\Lambda(\alpha,\delta,\rho_m,z)$
- LHC results in hand
- Numerous “consistency tests” of gravity

Ok, then what? Let’s consider 3 scenarios in the Dark Ages ahead…

The Dark Ages- scenario 1: Theoretical breakthrough





The Dark Ages- scenario 2: Observational or Experimental breakthrough

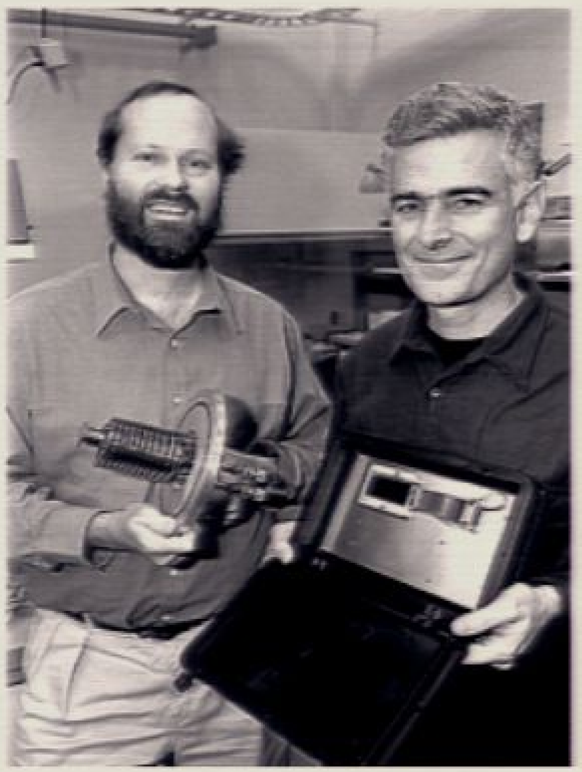
"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLVIII . . No. 54,644 — NEW YORK, MONDAY, APRIL 13, 2018 — $1.50

Scientists Discover Nature of Dark Energy



By JAMES JONES

Scientists announced today that they now understand the Dark Energy that has long mystified physicists and astronomers. In a surprising observation that was totally unexpected,

But…

What if:

- Measurements continue to favor $w = -1$
- No deeper theoretical ideas emerge
- LHC gives vanilla Higgs and little else
- …

Then, things look bleak. It will be difficult to extend existing techniques to the milli-w level.

The Dark Ages- scenario 3: intellectual stagnation

"Dark Ages" is a term referring to the …period marked by cultural, intellectual, and economic deterioration followed by intellectual and religious intolerance, stagnation and poverty...

- Wikipedia

The Alchemist, Peter Brughel the elder 1558
http://www.lempertz.eu/125+M54915cadc72.ht

The Dark Ages- scenario 3: intellectual stagnation

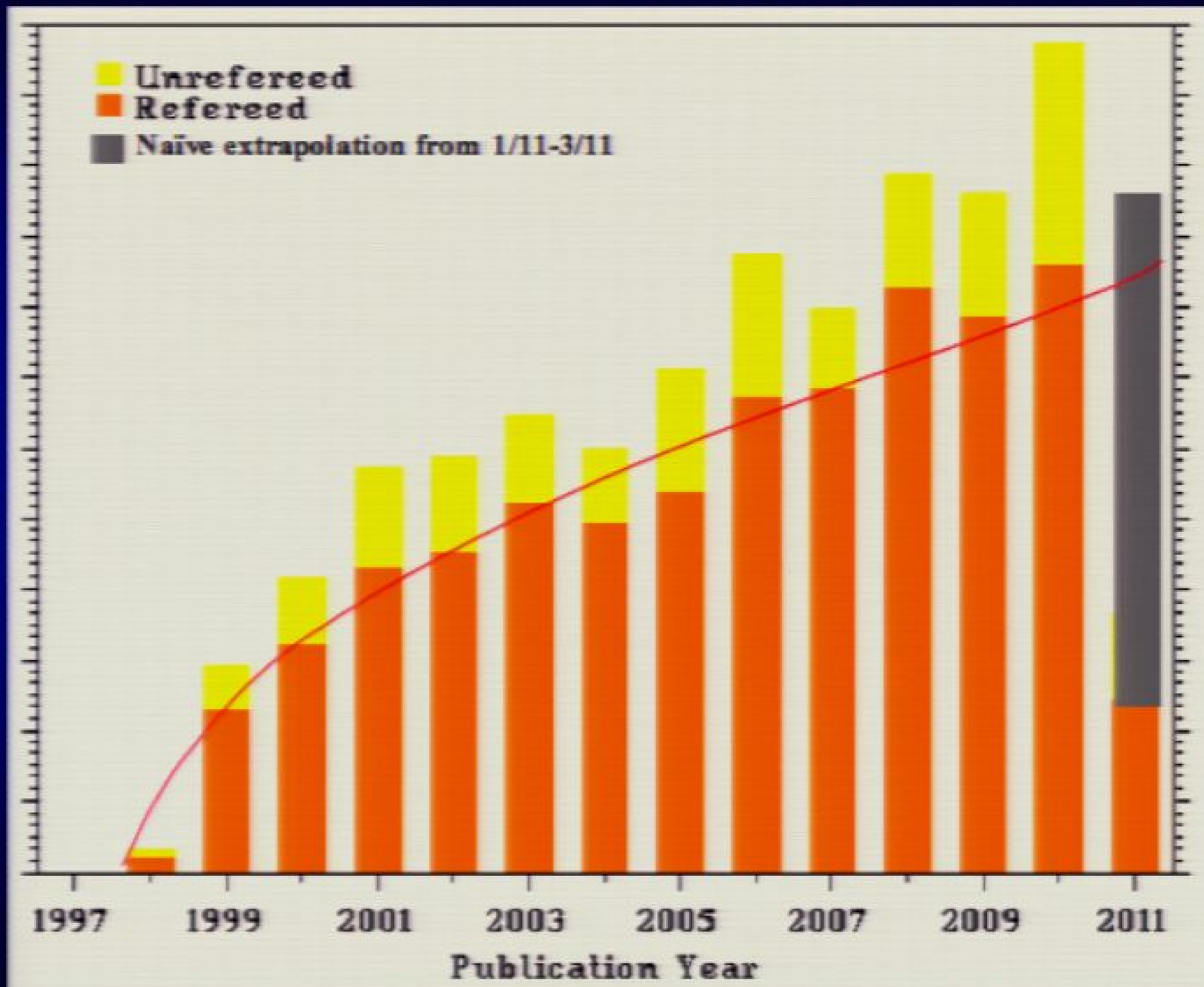
PHYSICAL REVIEW LETTERS

VOLUME 359	6 APRIL 2020	NUMBER 5

Unobservable Predictions of a 33 Dimensional Theory of Emergent Vacuum Energy

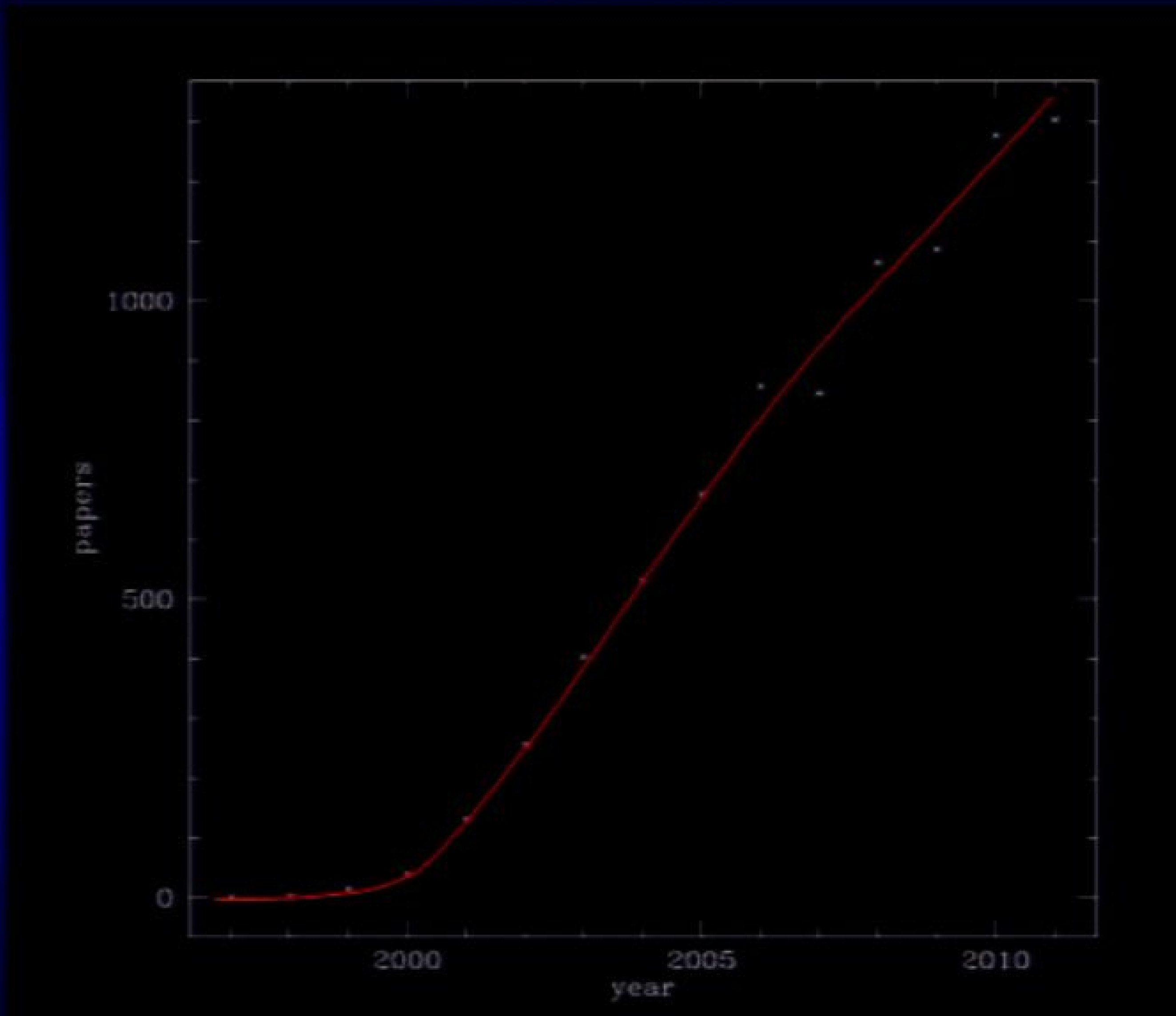
The Alchemist, Peter Brughel the elder
1558
http://www.lempertz.eu/125+M54915cadc72.ht

Citations to one of the discovery papers



Citation history for one of the Dark Energy discovery papers (ADS)

$N_{papers}(t)$



ADS search for papers with “dark energy” in abstract

We should strive to avoid the stagnation scenario

Imagine we measure $w = -1.00$, no evidence for variation

Optical and infrared surveys after LSST/WFIRST generation will become more difficult.

21 cm surveys?

Relevant results from LHC?

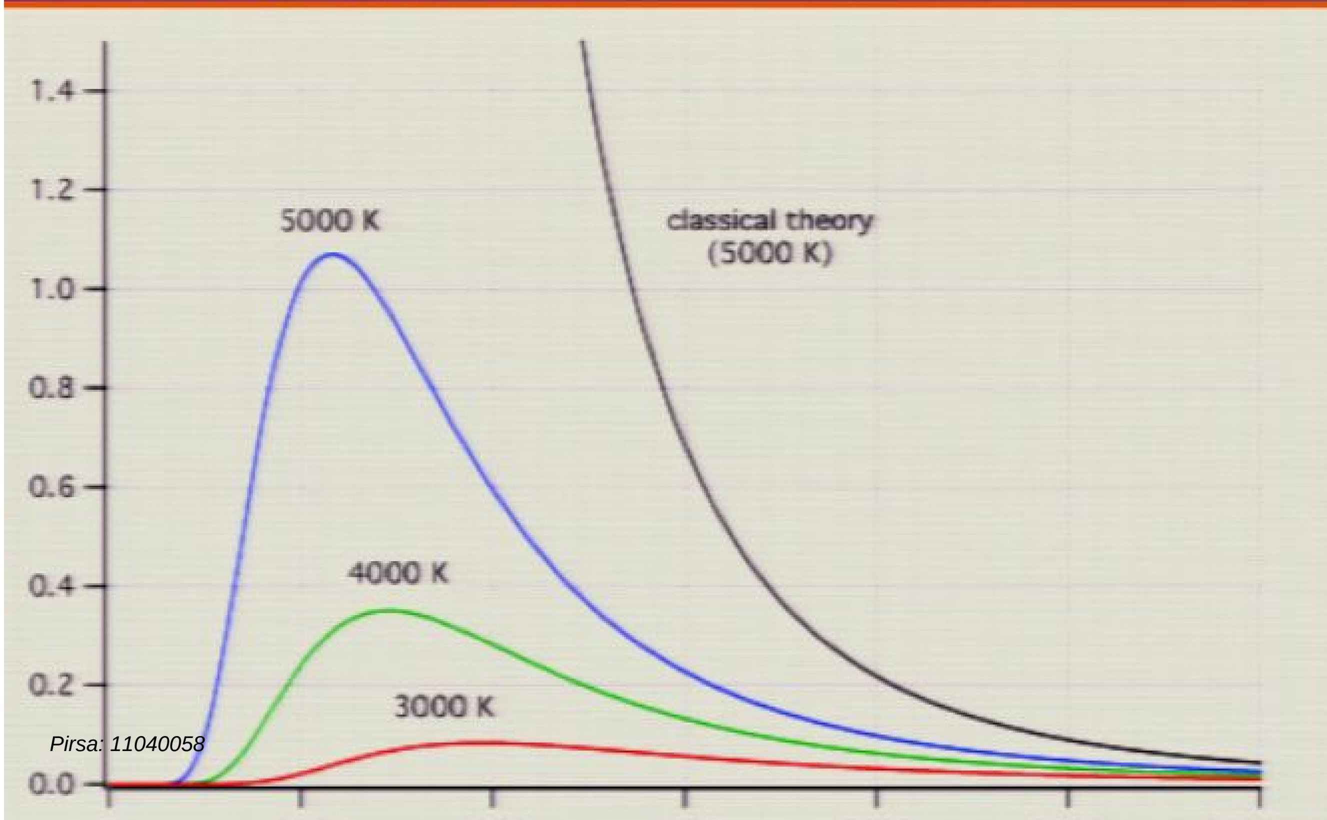
Detection of dark matter? (will eliminate prospect of MOND-like scenarios)

An analogy from the past…

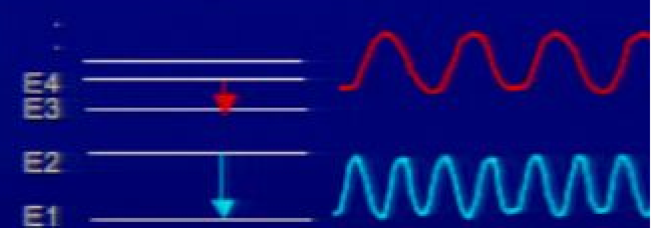
Ve've seen something like this before:

- 1880's - early 1900's physics faced three profound experimental puzzles:

.blackbody spectrum



2. discrete atomic spectra



3. Photoelectric effect

Fishing for Another Anomaly

- At present, dark energy theory and experiment are out of balance (like string theory, but opposite sign).
- If data continue to support constant w = −1, cosmology will have little else to contribute to a deeper understanding of dark energy.
- In my opinion we will likely require some new anomaly, another piece of the puzzle.

Dark Energy Scales

$\rho_{DE} \sim 3\ keV/cm^3 \sim 10^{-29}\ gm/cc \sim \bar{\rho}_{DM}$

$\rho_{DM}(here) \sim 0.3GeV/cc \sim 100\ X$ higher

$\rho_{apparatus} \sim 1\ gm/cc$

$\rho_{DE} \sim \int_0^{few\ meV} (QM\ fluctuations)\ dE$

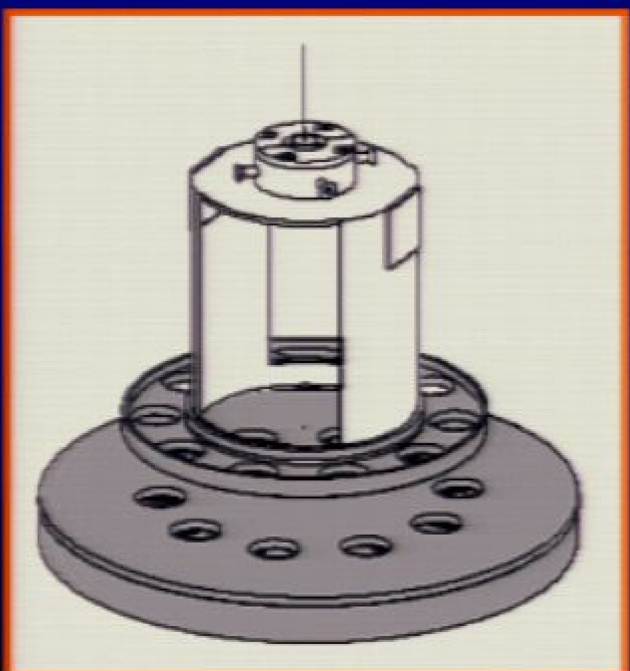
Dark Energy Length Scales

$$\ell_{grav} \sim \sqrt{\frac{c^2}{\rho_{DE} G}} \sim 10^{27}\,cm \sim 10^{10}\ \text{lightyears}$$

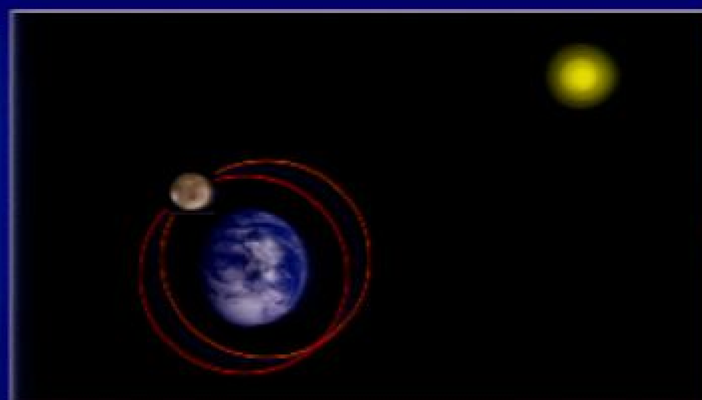
$$\ell_{QM} \sim \sqrt[4]{\hbar / \rho_{DE} c} = \sqrt{\ell_{grav} \ell_{Planck}} \sim 100\ \mu\text{m}$$

Next Steps on Dark Energy: Probing the Foundations of Gravitation

- Seek any evidence for other anomalies, especially in the gravitational sector
- Test our understanding of gravity on all accessible length and energy scales

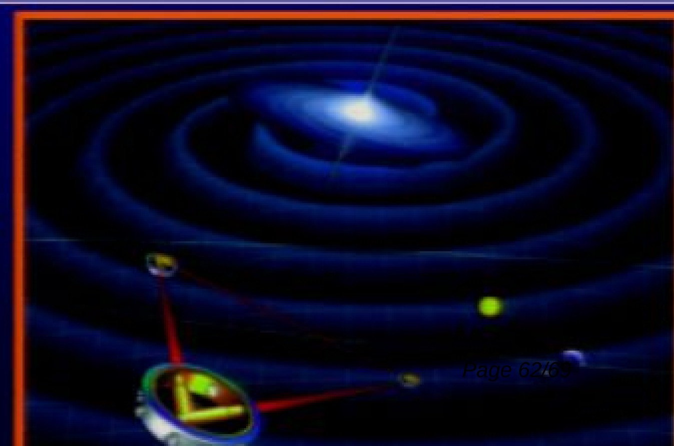


e.g. Eot-Wash group



Lunar Laser Ranging: APOLLO project

Strong gravity: LIGO & LISA



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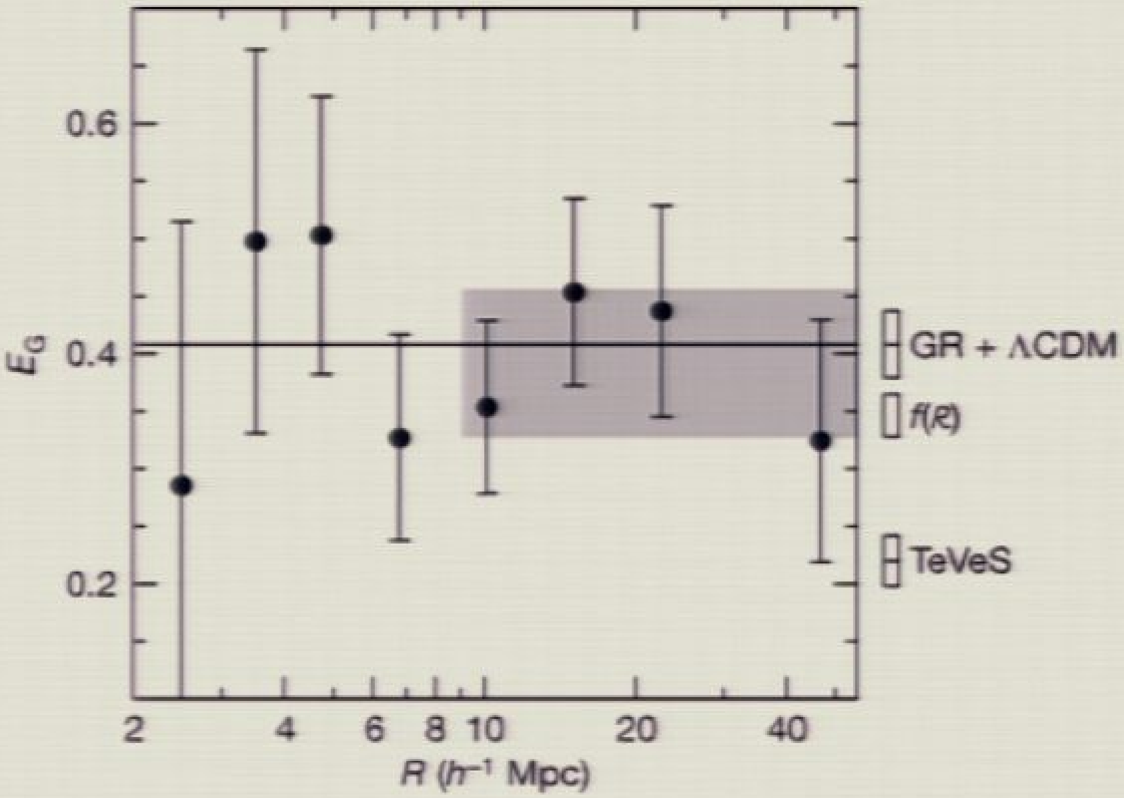
An example of testing the framework

Comparison of observational constraints with predictions from general relativity and viable modified theories of gravity.

- alaxy-galaxy lensing
- alaxy velocity field
- arge scale structure

DSS LRG's to z=0.3

$_G$ is consistency arameter



R Reyes *et al.* *Nature* **464**, 256-258 (2010) doi:10.1038/nature08857

nature

An example of testing ΛCDM

Foley et al, arXiv:1101.1286v1

SPT - CL J2106 - 5844

$z = 1.132 \pm 0.003$

$M_{200} = 1.3 \pm 0.2 \times 10^{15}\ h_{70}^{-1}\ M_{solar}$

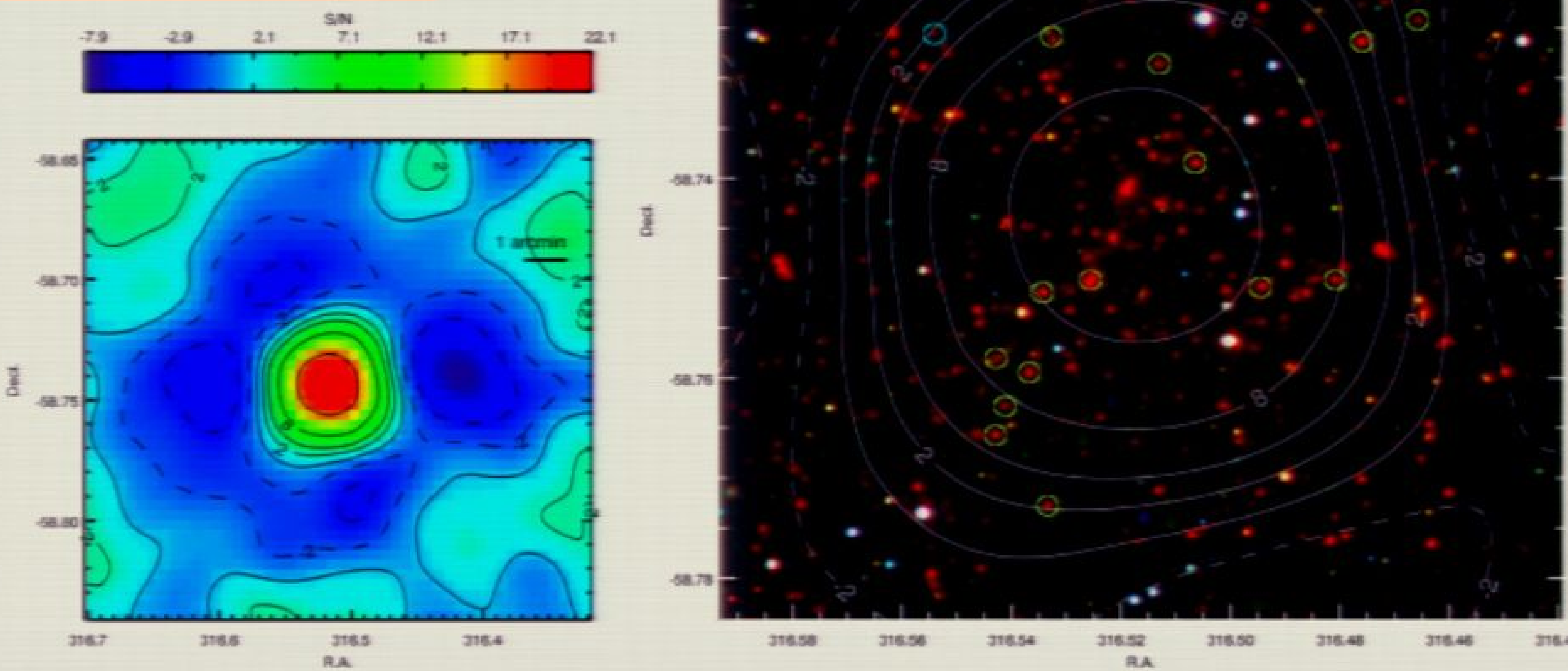
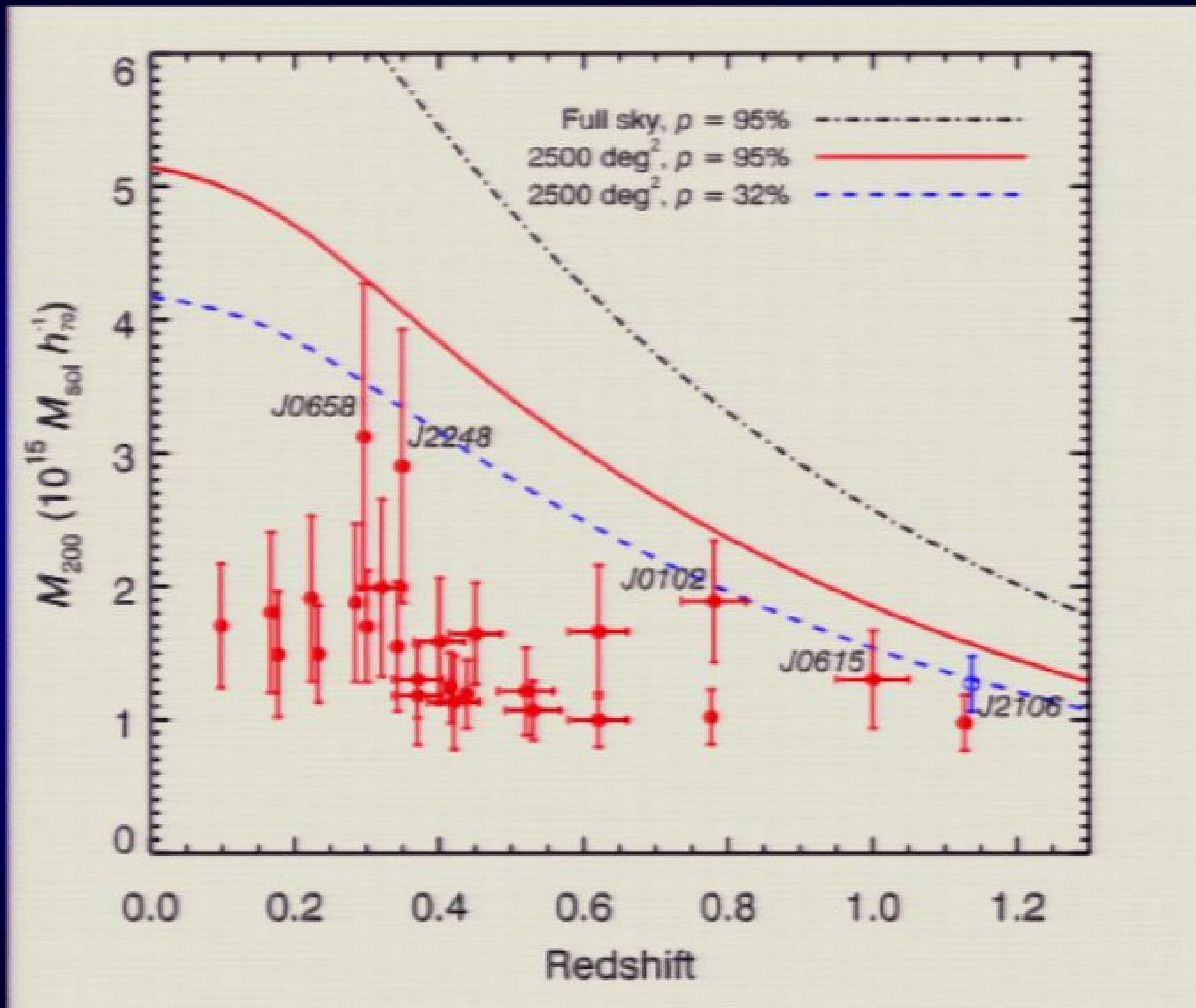


FIG. 1.— SPT-CL J2106-5844 at millimeter, optical, and infrared wavelengths. *Left:* The filtered SZ significance map derived from multi-band SPT data. The frame subtends 12′ × 12′. The negative trough surrounding the cluster is a result of the filtering of the time ordered data and maps. *Right:* LDSS3 optical and Spitzer/IRAC mid-infrared *gi*[3.6] (corresponding to BGR channels) images. The frame subtends 4.′8 × 4.′8. The white contours correspond to the SZ significance from the left-hand panel. The circles mark spectroscopically

An example of testing ΛCDM



Williamson et al, SPT team, arXiv:1101.1290,

An assessment, and 3 questions

Measurements regarding the Dark Energy are "out of pace" with theoretical understanding. This is a Bad Thing. (Same as string theory, but with opposite sign.)

Current data favor $w = -1$, with no evidence for any cosmic evolution.

1. What if this is the real answer (i.e. $w = -1.0000\ldots$)? When do we quit the astrophysical characterization efforts, absent guidance from theory?

2. If cosmology has thrown down this challenge to our understanding of fundamental physics, how long must we wait until it's resolved?

3. What other experimental anomalies might shed light on the Dark Energy? What's the best strategy for finding the next clue?

Group members

SN cosmology

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Precision calibration

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Galaxy Clusters

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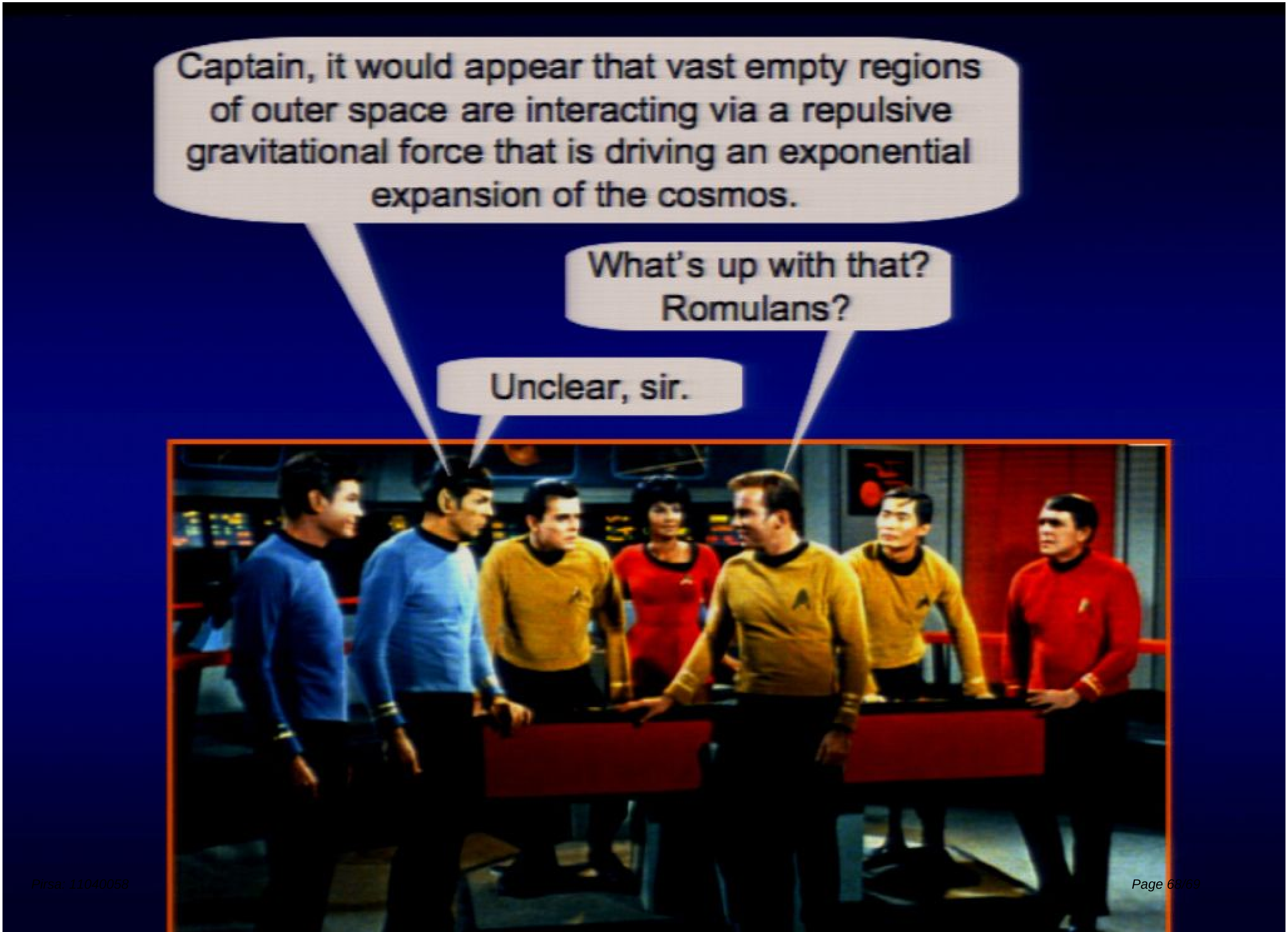
Captain, it would appear that vast empty regions of outer space are interacting via a repulsive gravitational force that is driving an exponential expansion of the cosmos.
What's up with that? Romulans?
Unclear, sir.

[redacted]