The Dark Energy Crisis in the Longer Term
and the Prospect of Intellectual Stagnation

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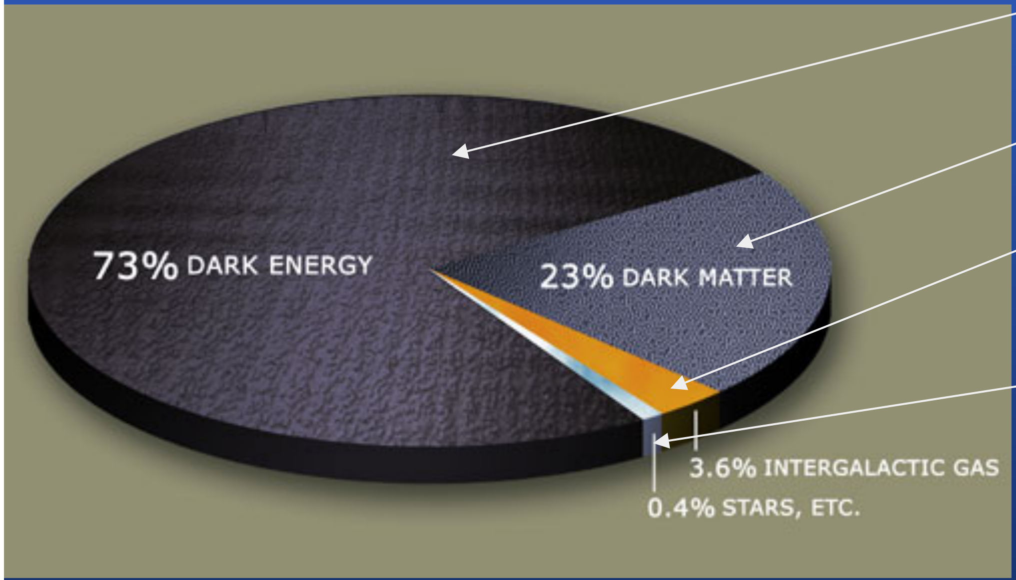
preposterous!

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 notation….

There is a "critical density" that would eventually halt the current expansion, let's call it ρ_{crit}. This quantity varies over cosmic time.

$$\rho_{crit} = \frac{3H^2}{8\pi G}, \text{ where } H_o = 75 \text{ km/sec per Mpc}$$

Measure all densities in units of ρ_{crit} ~ 5 H atoms/m^3

$$\Omega_i = \rho_i / \rho_{crit}$$

A cosmic sum rule…

General Relativity and isotropy imply

$$\Omega_b + \Omega_{dm} + \Omega_{curvature} + \Omega_\Lambda = 1$$

Baryons Dark matter Curvature Dark energy

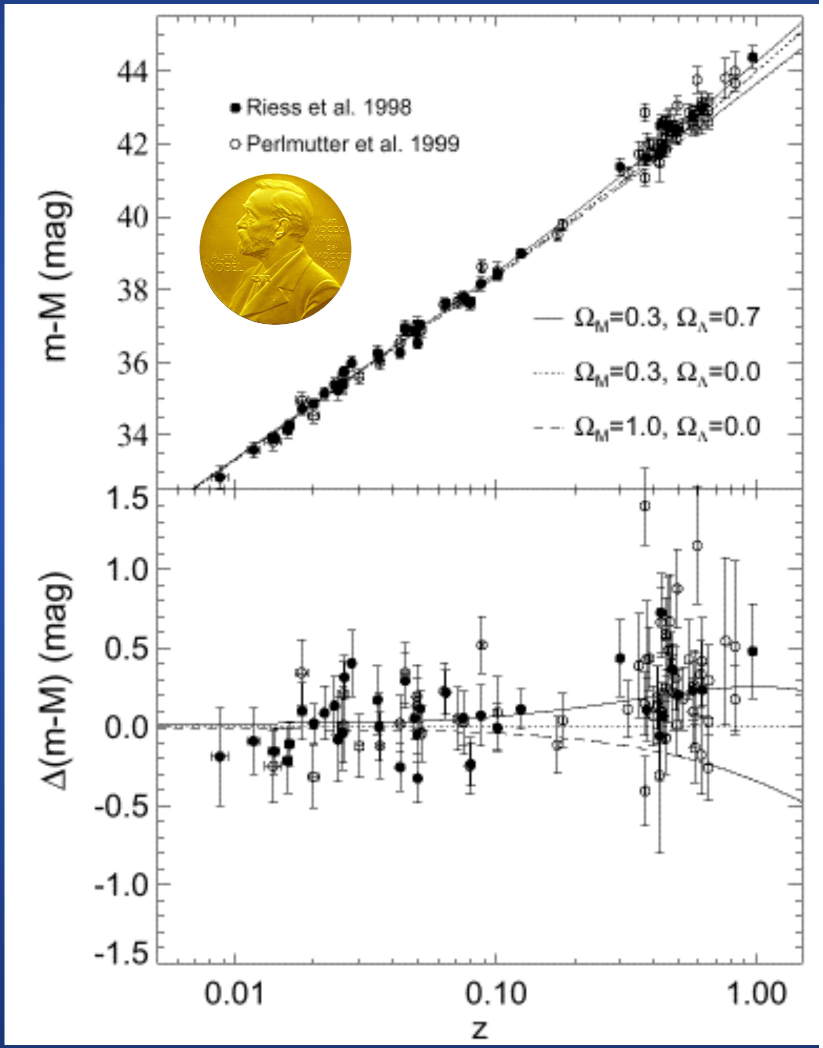
But the relative proportions of these vary over cosmic time.

Supernovae and Dark Energy- a strong heritage

Initial discovery of accelerating expansion came from type Ia supernovae at redshift z~0.6 being ~20% fainter than expected (Perlmutter et al, 1999, Riess et al 1998).

Measurements of SN luminosity distances and redshifts are a *direct* measurement of the history of cosmic expansion.

For the future, supernovae will remain a valuable probe for characterizing of the nature of dark energy



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

Lower bound on age of Universe, from stars

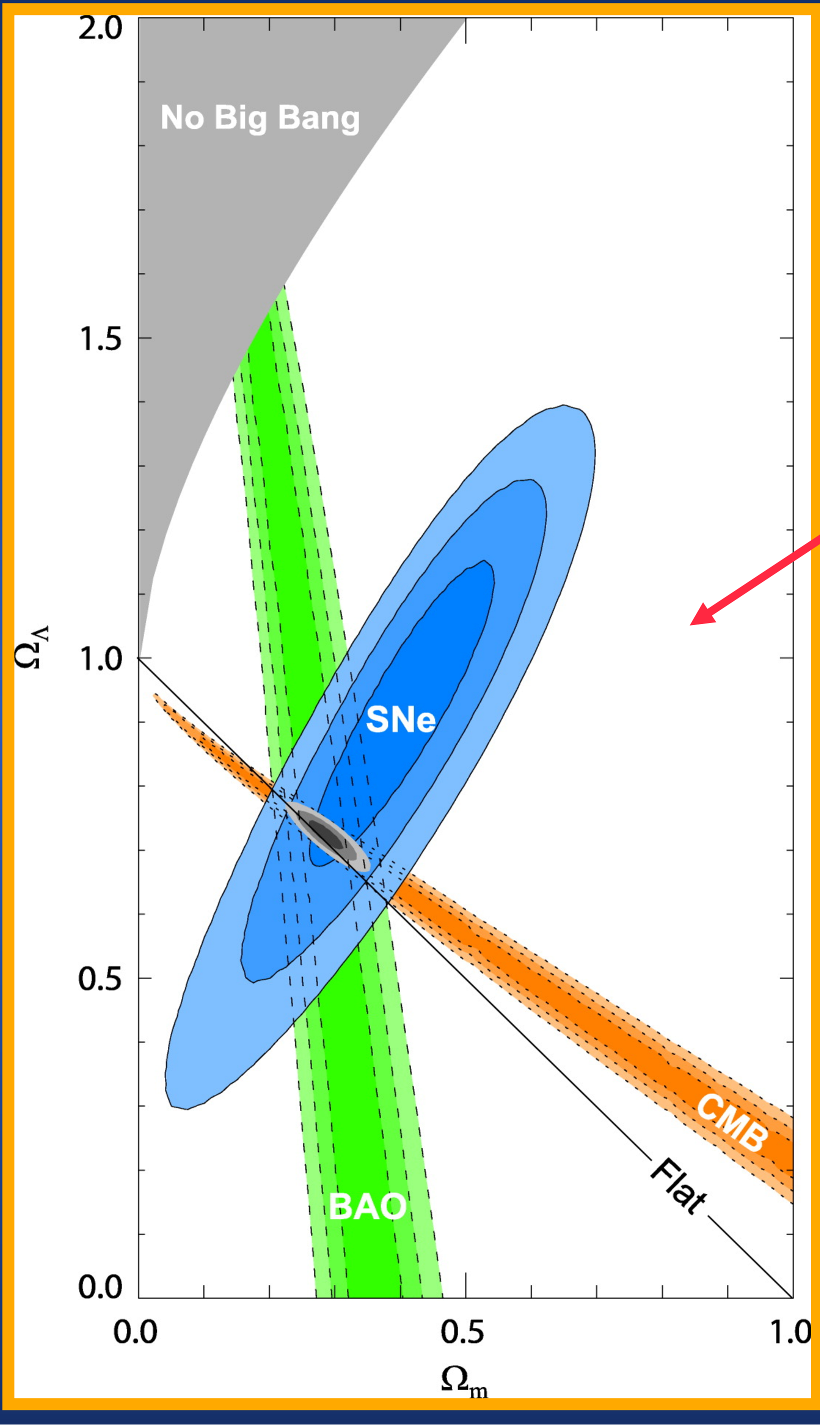
Inventories of cosmic matter content

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

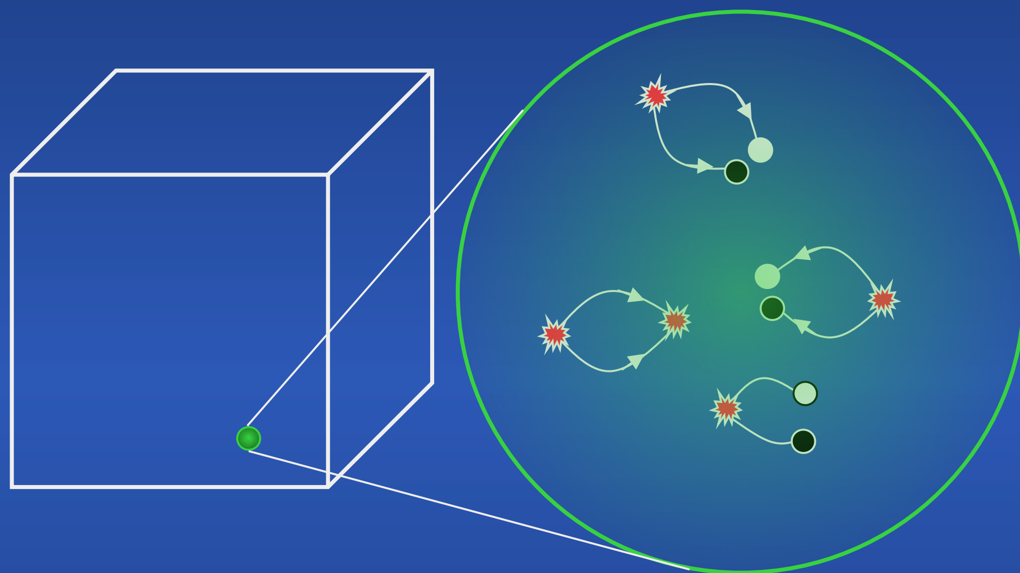


The data drive us to non-zero Ω_Λ

Why is this a crisis in fundamental physics?

Kowalski et al, ApJ ***686****, 749 (2008)*

The quantum mechanical vacuum is a seething turmoil…



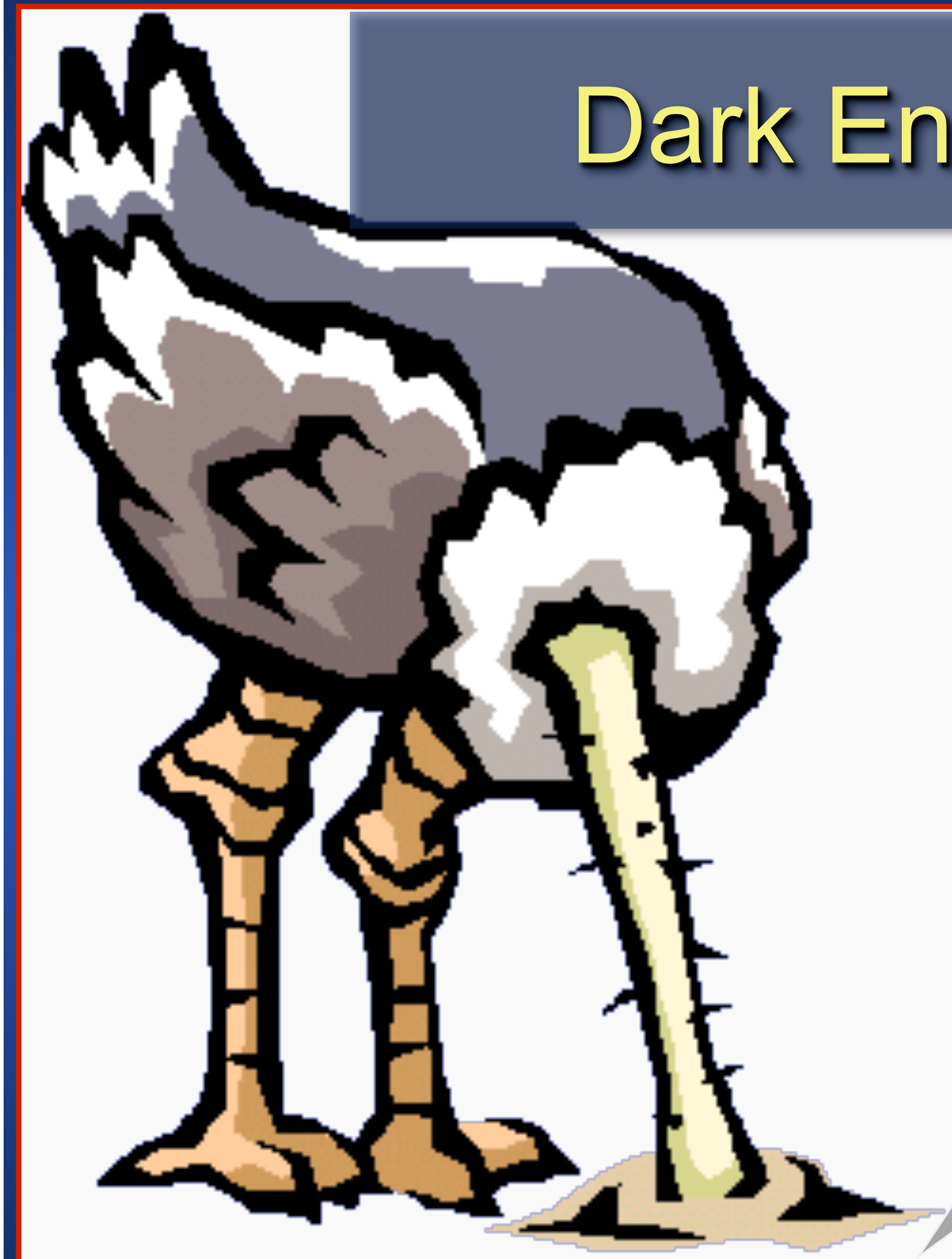
Lamb shift in Hydrogen (virtual QED process)

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 $\Omega_\Lambda \sim 10^{120}$

Cancellation via tooth fairy:

$$\Omega_\Lambda = 0.000000000000000000000000000000....$$

But it’s measured to be around 0.7!

Why Dark Energy Constitutes A Crisis in Fundamental Physics

Puzzle #1: why is Ω_Λ so *small*?

Puzzle #2: why is Ω_Λ so *large*?

Puzzle #3: 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?

But that's not all…

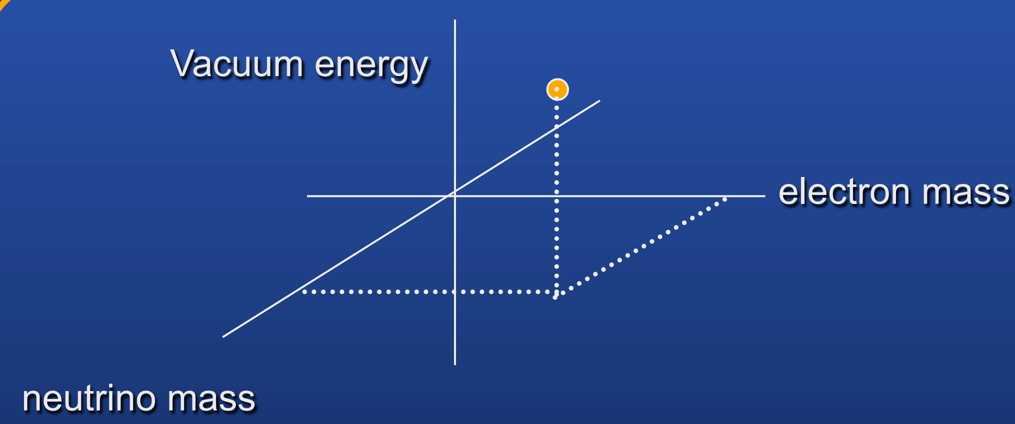
The challenge posed by the dark energy has shaken the reductionist philosophy that has served us so well….

Physics has tried to determine a simple set of rules that govern the Universe, with the expectation that these rules *and* their associated parameters are *both* uniquely determined by some profound underlying (symmetry) principles.

$$\boxed{\mathcal{L}=0}$$

The elegant theory of everything (ETOE)

The parameters of the ETOE



The Anthropic Alternative

An alternative to "unique fundamentalism" is the claim that the most basic scientific observable is that we're here, and that simple fact restricts the possible values of physical parameters.

Proponents of the anthropic approach contend that the dark energy saturates the allowed upper bound that could give rise to life as we know it. (The value of Ω_Λ was in fact *predicted* by Steven Weinberg in 1987.)

All physical parameters (masses, charges, interaction strengths…) are essentially accidental, apart from the constraint imposed by an anthropic selection effect.

This is a vibrant ongoing debate

Skeptics debate whether the anthropic approach is actually science, as opposed to philosophy.

Is it falsifiable?

I don’t know.

So let’s return our attention to measurements we can make to better understand the dark energy.

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 $w = -1$.

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

Current State of SN Cosmology

Supernovae establish stringent constraints on equation of state parameter (Conley et al 2011).

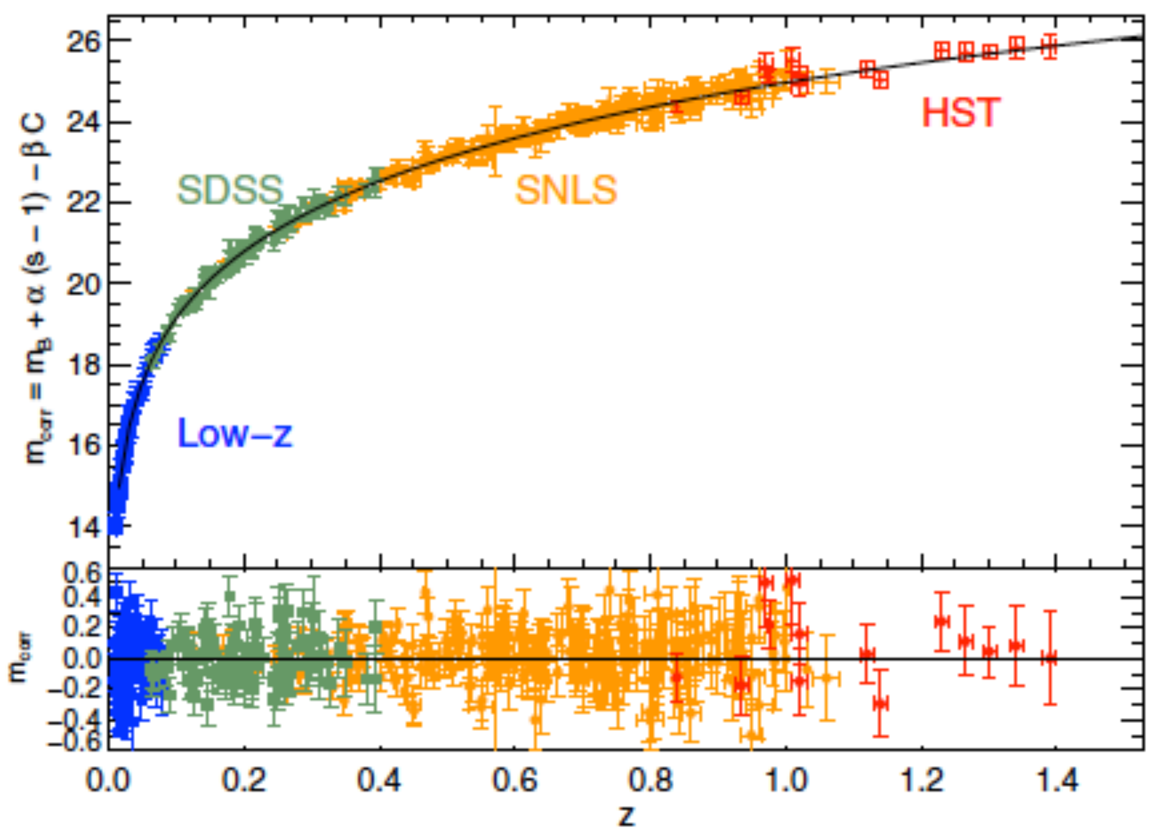


Figure 5. Hubble diagram of the combined sample. The residuals from the best fit are shown in the bottom panel.

Snapshot of our understanding today:

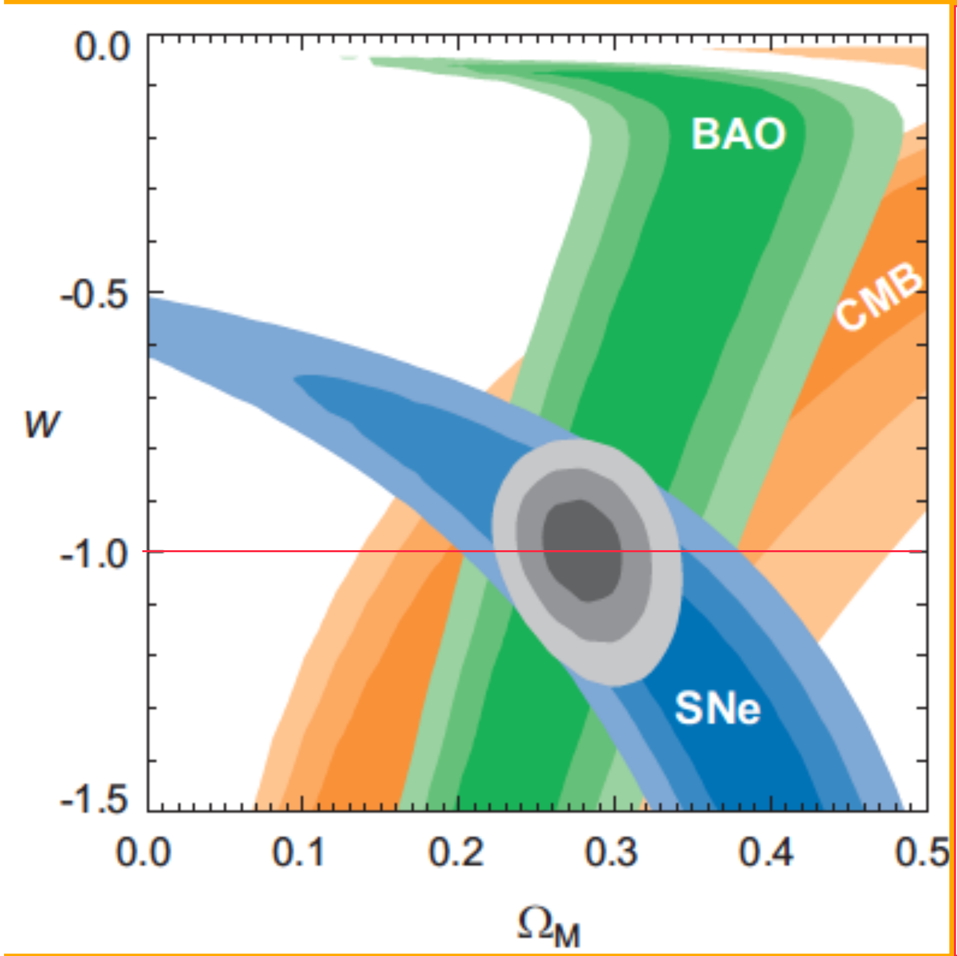
- Evidence for accelerating expansion seems robust.
- All data are thus far consistent with

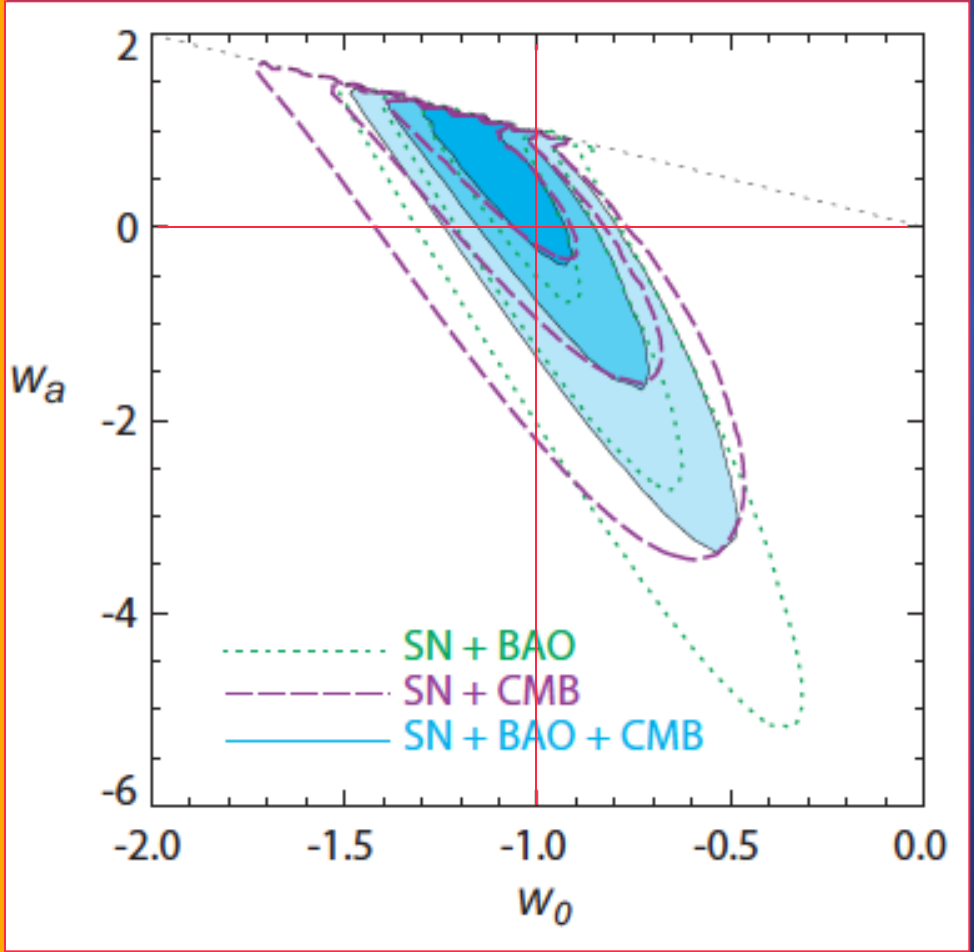
$$w_0 = -1$$
$$w_a = \ \ 0$$

- 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.

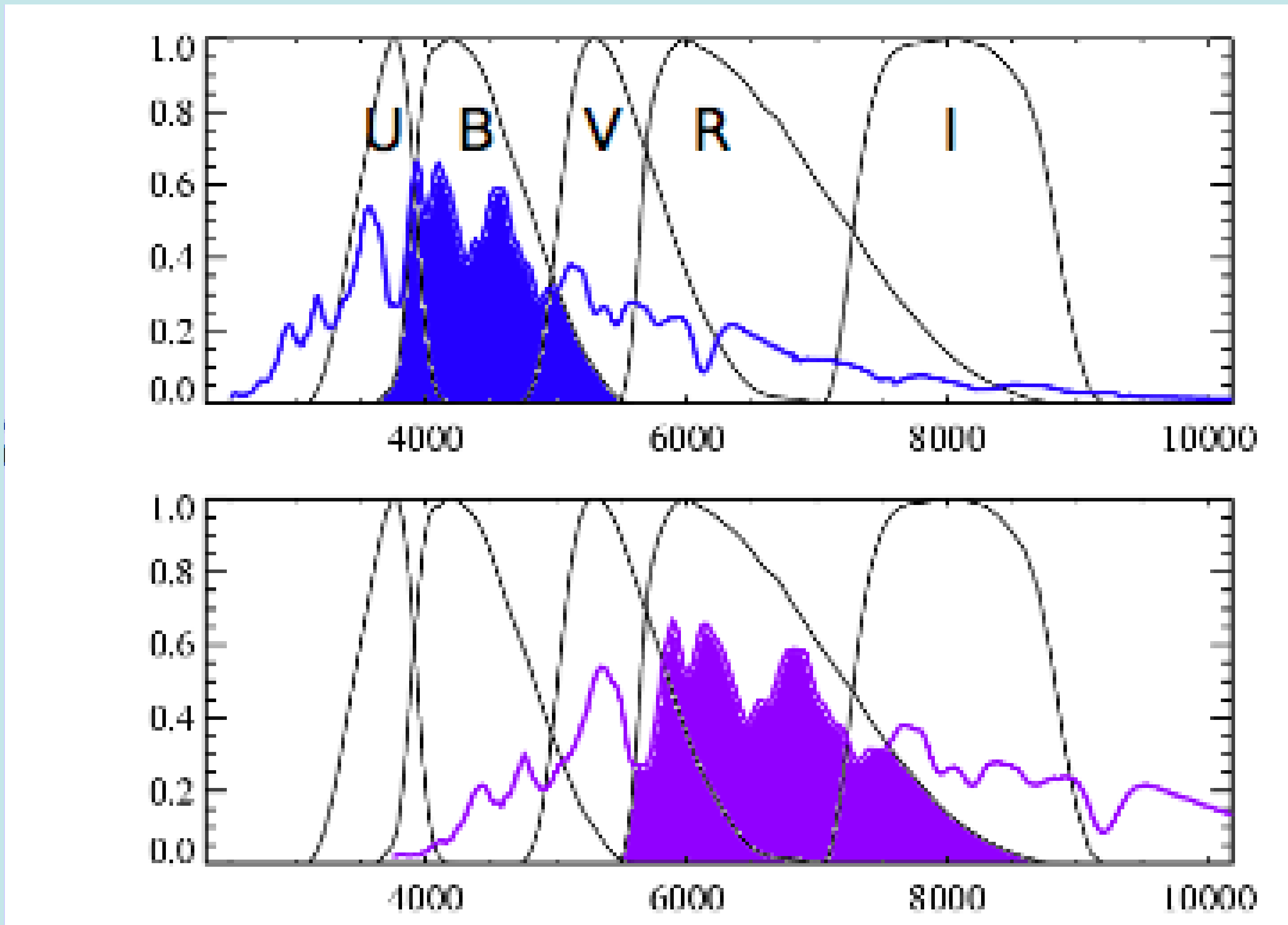
Current limits on w, w_a.

From Kowalski et al, 2008.

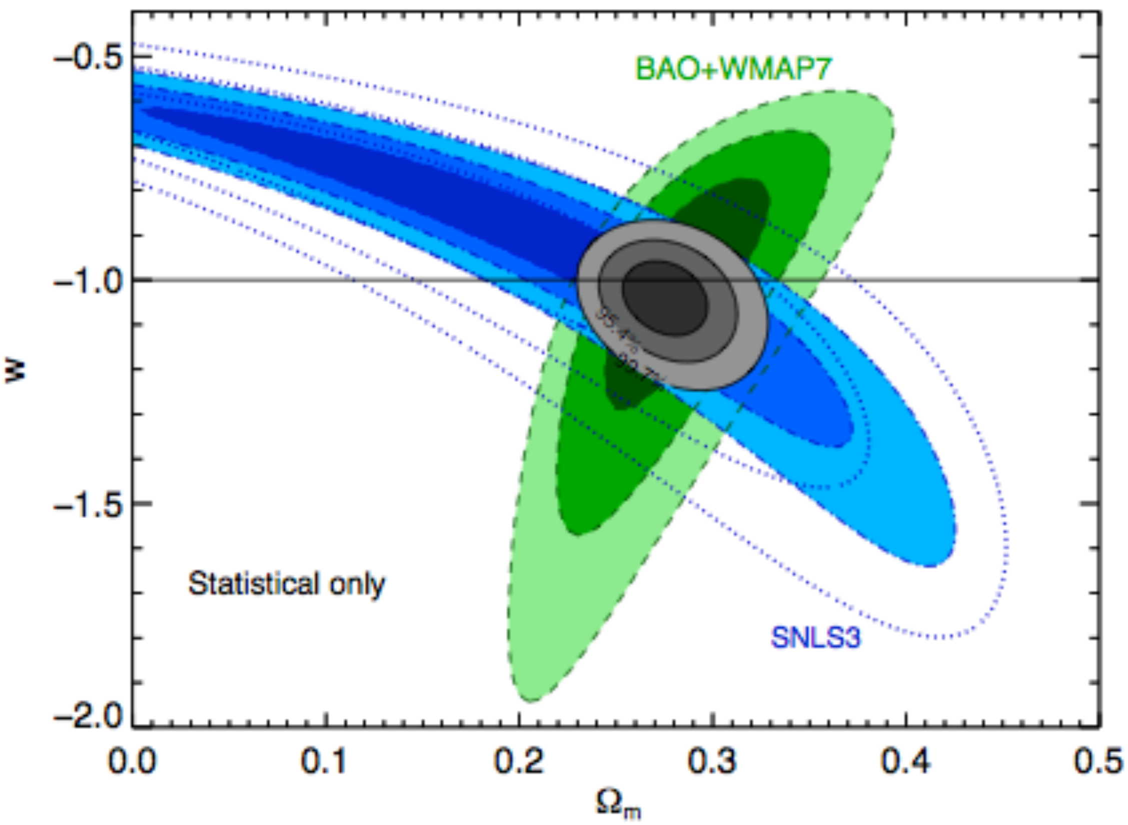




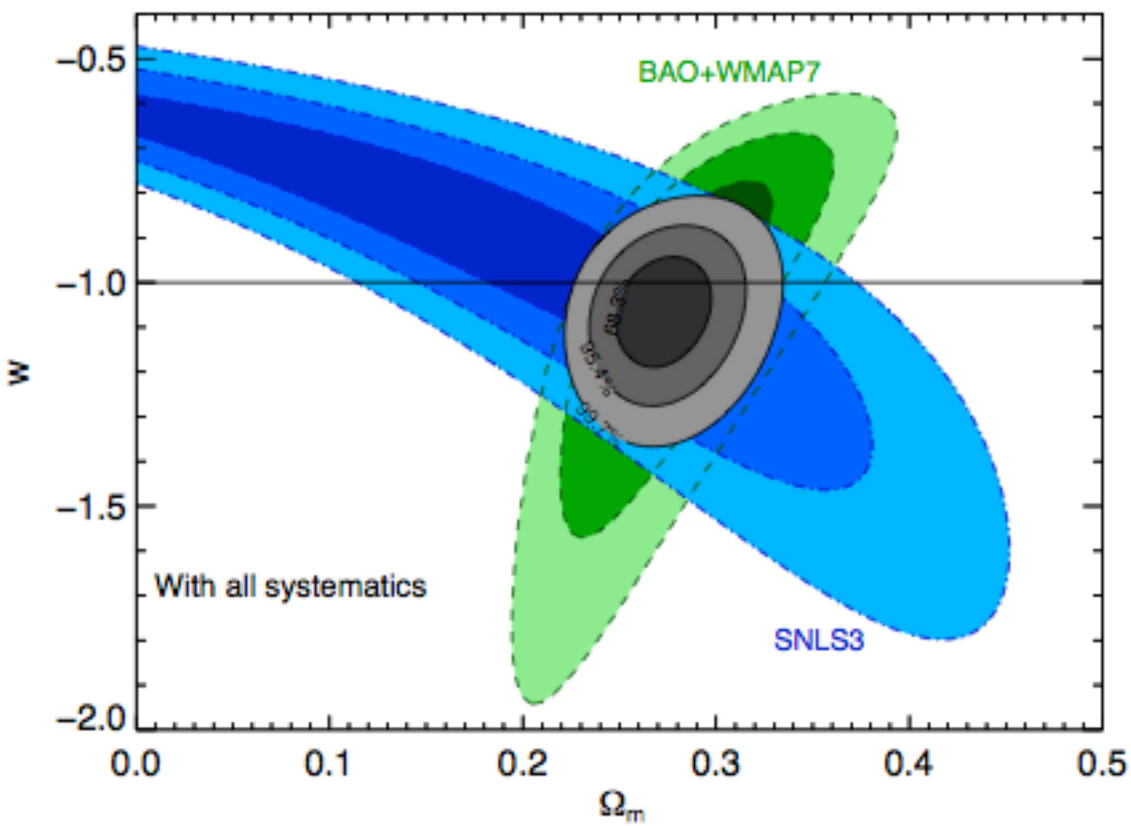
Passbands and System Sensitivity



Current State of SN Cosmology



Current State of SN Cosmology



Current State of SN Cosmology

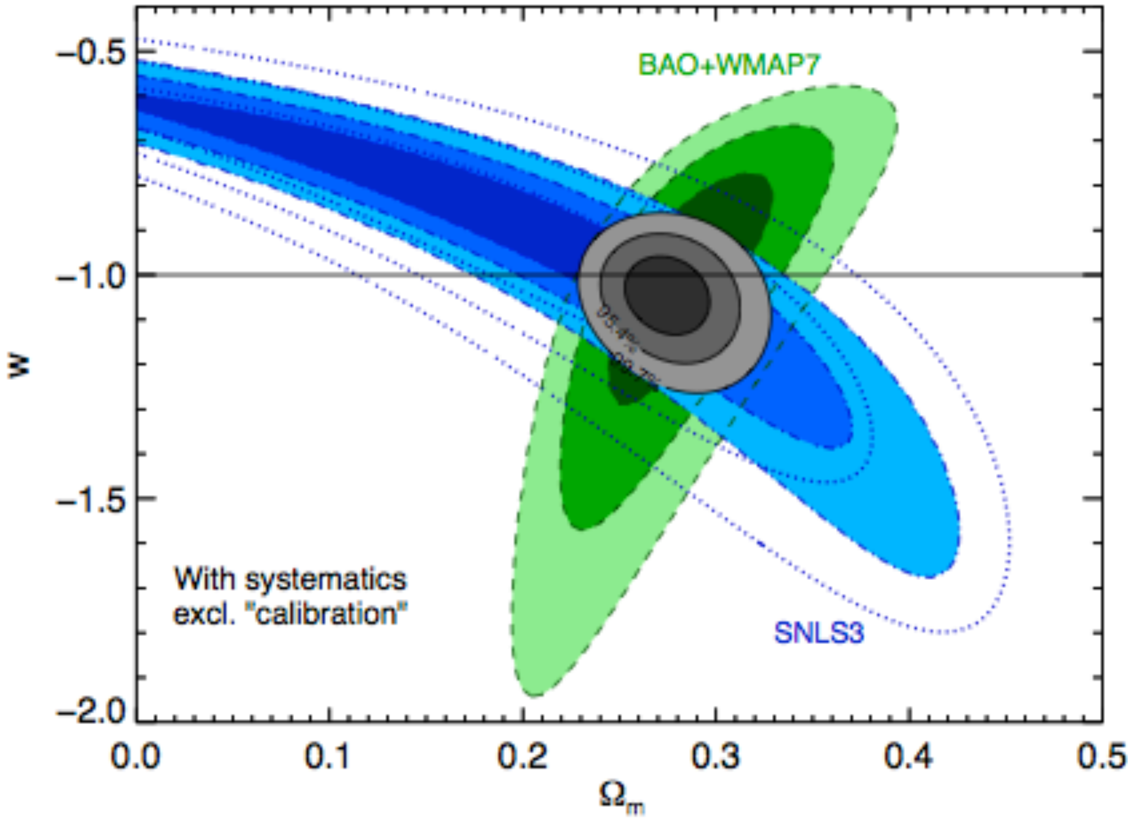


Table 3. Detailed summary of systematic uncertainties

Source	Ω_m	w	Relative area[a]
Statistical only	$0.2763^{+0.0163}_{-0.0132}$	$-1.0430^{+0.0543}_{-0.0546}$	1.0
All systematics	$0.2736^{+0.0186}_{-0.0145}$	$-1.0676^{+0.0799}_{-0.0821}$	1.693
All systematics, except calibration	$0.2756^{+0.0164}_{-0.0133}$	$-1.0481^{+0.0573}_{-0.0580}$	1.068
All systematics, except host term	$0.2738^{+0.0186}_{-0.0145}$	$-1.0644^{+0.0790}_{-0.0809}$	1.677
All systematics, fixing α, β[b]	$0.2656^{+0.0179}_{-0.0144}$	$-1.1168^{+0.0807}_{-0.0824}$	1.641
Contribution of different systematics:			
Calibration	$0.2750^{+0.0185}_{-0.0150}$	$-1.0581^{+0.0774}_{-0.0791}$	1.614
SN Ia model	$0.2767^{+0.0163}_{-0.0132}$	$-1.0403^{+0.0543}_{-0.0547}$	1.013
Peculiar velocities	$0.2761^{+0.0163}_{-0.0132}$	$-1.0452^{+0.0544}_{-0.0548}$	1.002
Malmquist bias	$0.2758^{+0.0163}_{-0.0132}$	$-1.0474^{+0.0548}_{-0.0553}$	1.014
Non SN Ia contamination	$0.2763^{+0.0163}_{-0.0132}$	$-1.0430^{+0.0543}_{-0.0546}$	1.000
Milky Way extinction	$0.2762^{+0.0164}_{-0.0133}$	$-1.0441^{+0.0553}_{-0.0557}$	1.023
SN redshift evolution	$0.2763^{+0.0163}_{-0.0132}$	$-1.0408^{+0.0544}_{-0.0547}$	1.017
Host galaxy term	$0.2762^{+0.0163}_{-0.0132}$	$-1.0453^{+0.0556}_{-0.0562}$	1.029
Calibration:			
Colors of BD 17° 4708	$0.2719^{+0.0170}_{-0.0137}$	$-1.0720^{+0.0639}_{-0.0639}$	1.239
SED of BD 17° 4708	$0.2771^{+0.0170}_{-0.0138}$	$-1.0390^{+0.0623}_{-0.0630}$	1.205
SNLS zeropoints	$0.2767^{+0.0168}_{-0.0136}$	$-1.0421^{+0.0603}_{-0.0609}$	1.166
Low-z zeropoints	$0.2753^{+0.0164}_{-0.0133}$	$-1.0527^{+0.0578}_{-0.0586}$	1.078
SDSS zeropoints	$0.2767^{+0.0164}_{-0.0133}$	$-1.0411^{+0.0544}_{-0.0548}$	1.015
SNLS filters	$0.2789^{+0.0170}_{-0.0138}$	$-1.0330^{+0.0585}_{-0.0586}$	1.136
Lowz filters	$0.2766^{+0.0163}_{-0.0132}$	$-1.0402^{+0.0547}_{-0.0550}$	1.010
SDSS filters	$0.2770^{+0.0164}_{-0.0133}$	$-1.0396^{+0.0544}_{-0.0548}$	1.007
HST zeropoints	$0.2769^{+0.0164}_{-0.0133}$	$-1.0412^{+0.0544}_{-0.0548}$	1.007
NICMOS nonlinearity	$0.2767^{+0.0164}_{-0.0133}$	$-1.0418^{+0.0545}_{-0.0548}$	1.009

From Sullivan et al. 2011

Current State of SN Systematics

Calibration uncertainties dominate!

Next Steps on Dark Energy: Bigger Astronomical Surveys, Better Precision

1) Re-instrumenting existing telescopes

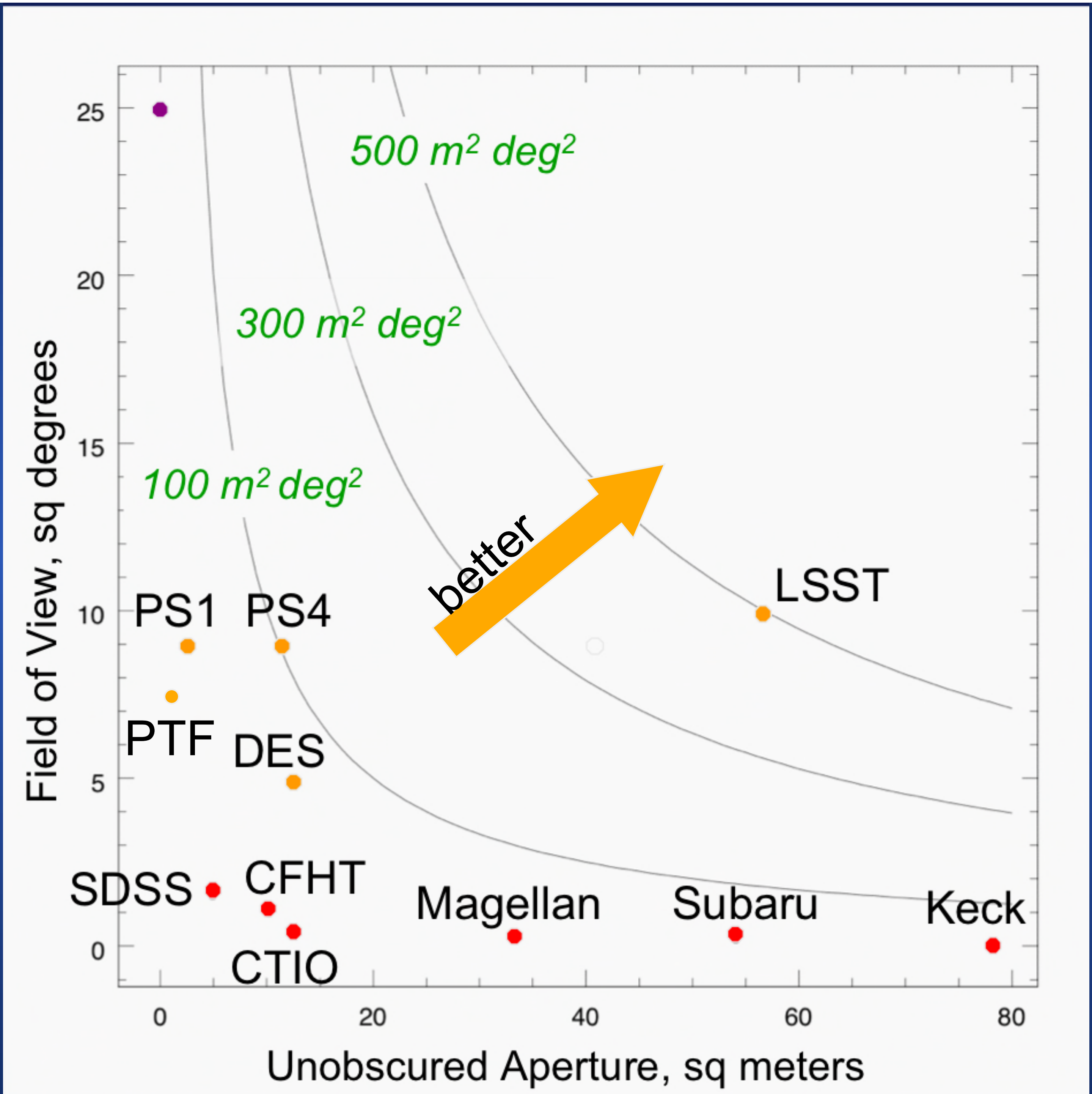
- Sloan Digital Sky Survey-III
- Dark Energy Camera on 4 meter Blanco telescope
- BOSS – updated spectrographs on SDSS telescope
- Big BOSS – updated spectrograph on Kitt Peak 4 meter

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
- …

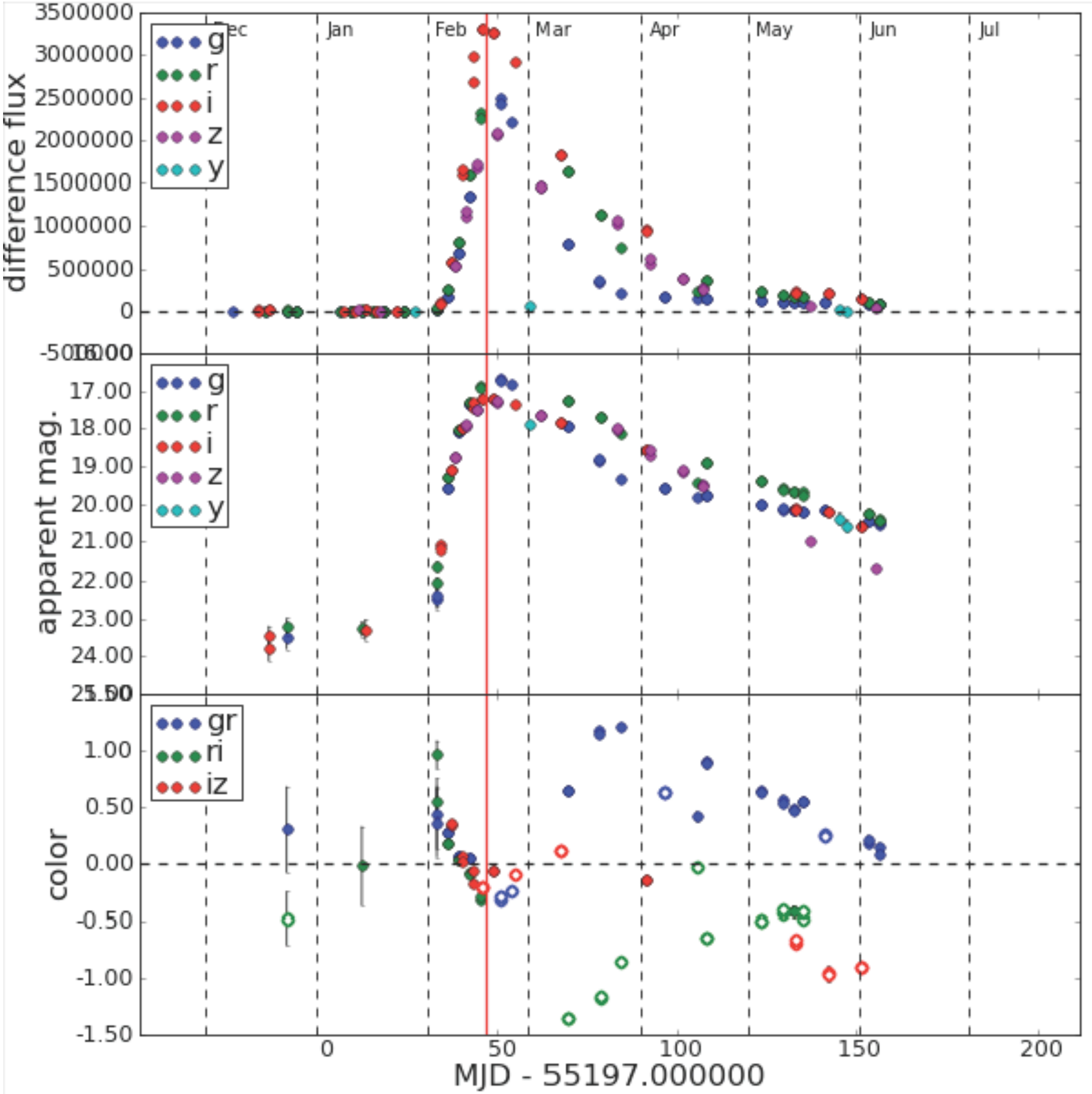


500 m² deg²
300 m² deg²
100 m² deg²
better
LSST
PS1
PS4
PTF
DES
SDSS
CFHT
CTIO
Magellan
Subaru
Keck
Field of View, sq degrees
Unobscured Aperture, sq meters
0
20
40
60
80
0
5
10
15
20
25

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%

The PanSTARRS Survey



PanSTARRS 5 band light curves

Supernova

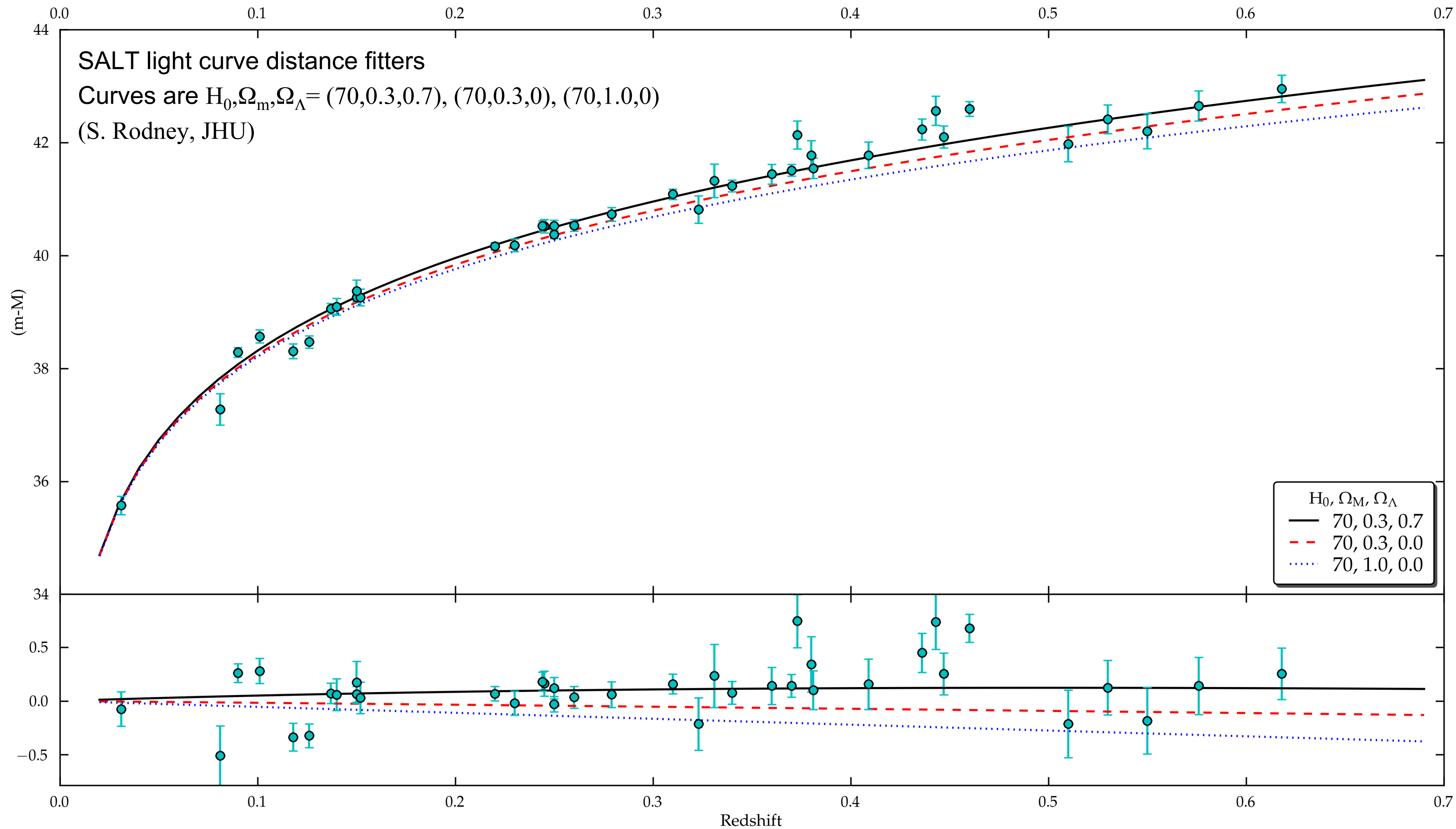
PS1-1000023

AKA

2010-B010026

redshift 0.031

A Preliminary PS-1 SN Hubble Diagram



Broadband photometry: “Metrology and Meteorology”

Galactic scattering

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

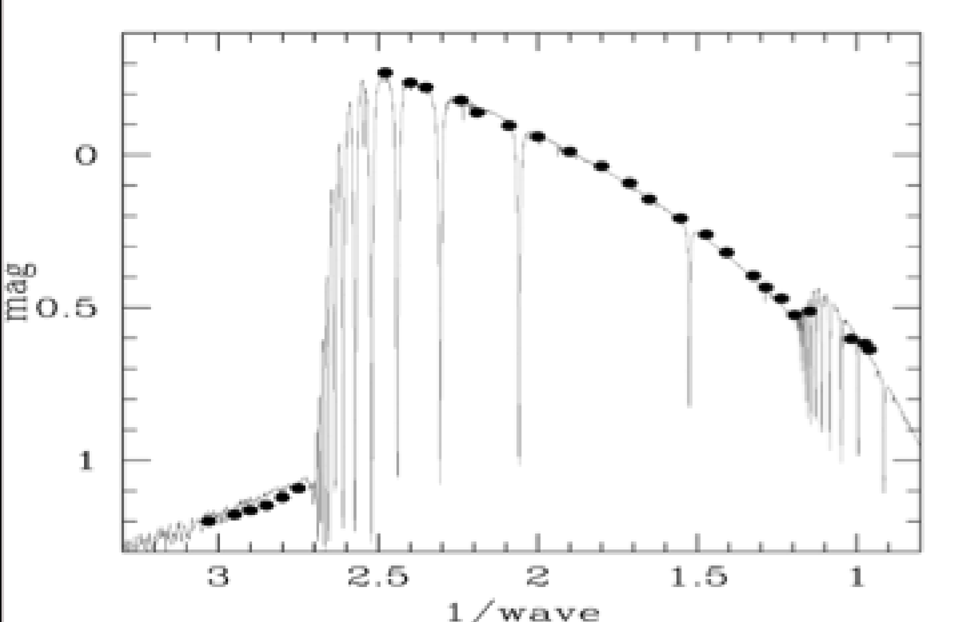
Source Atmosphere Instrumental transmission

Four aspects to the photometry calibration challenge:

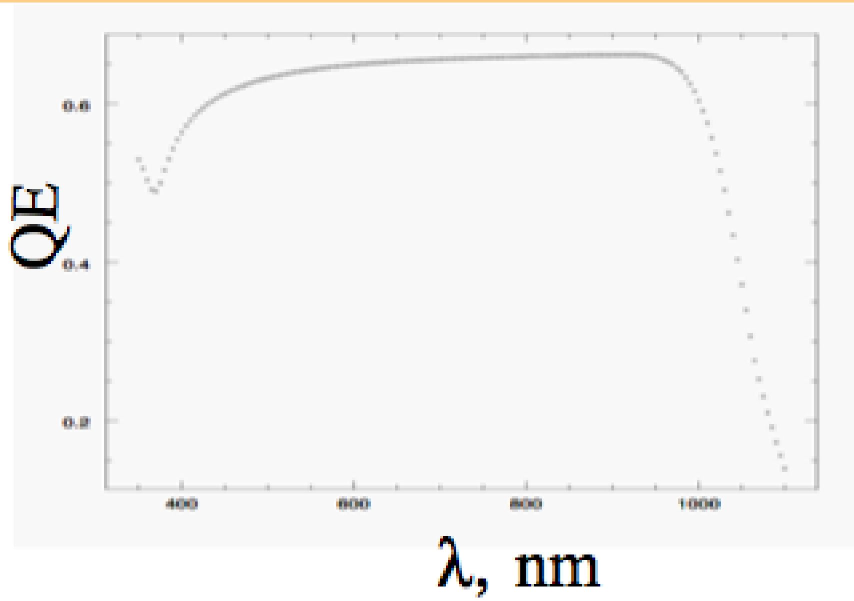
1. *Relative instrumental throughput calibration*
2. *Absolute instrumental calibration (I claim this this is far less important)*
3. *Determination of atmospheric transmission*
4. *Determination of Galactic extinction (most stars lie behind the extinction layers).*

Historical approach has been to use spectrophotometric sources (known S(λ)) 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

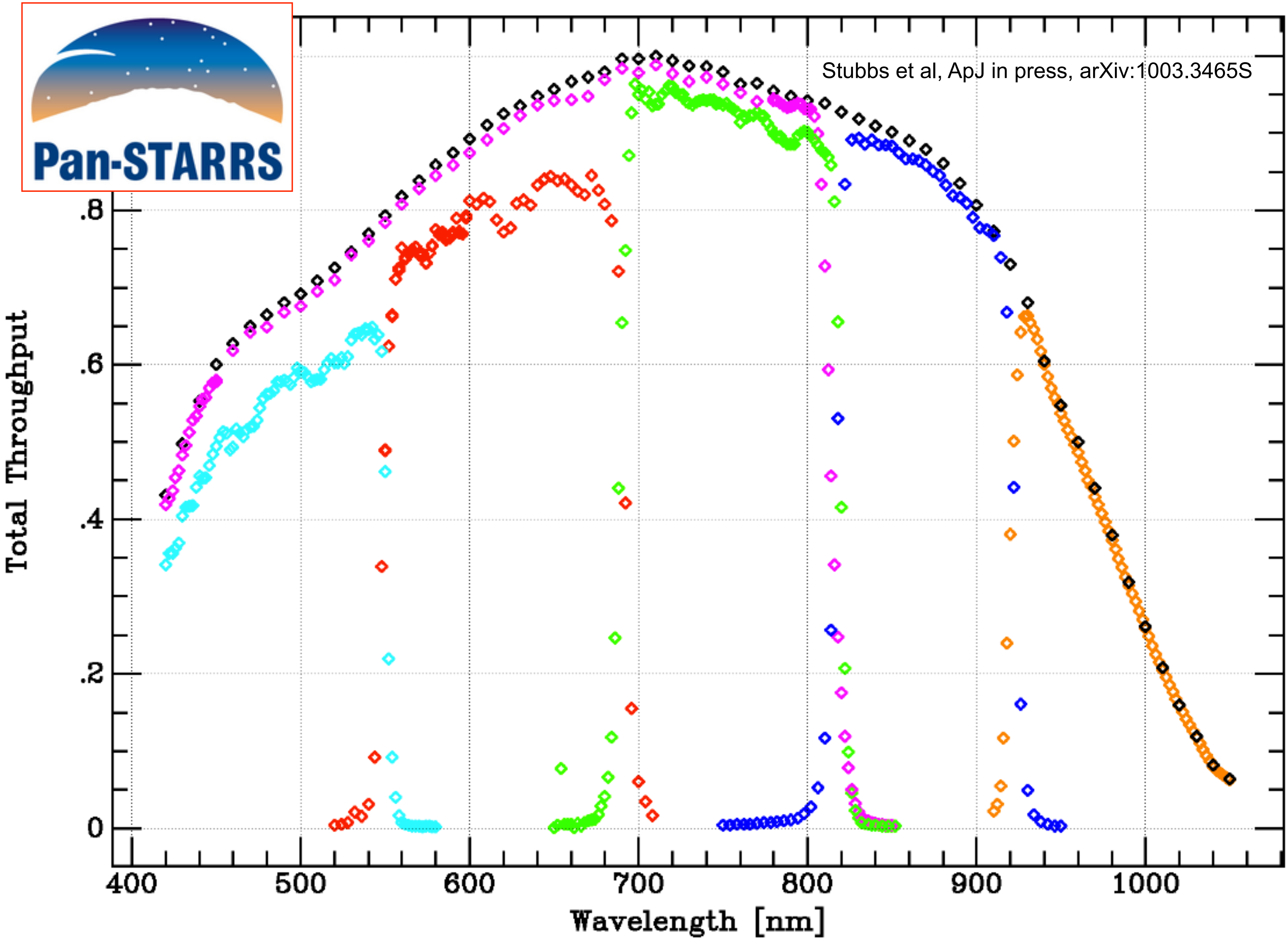


Spectrum of Vega

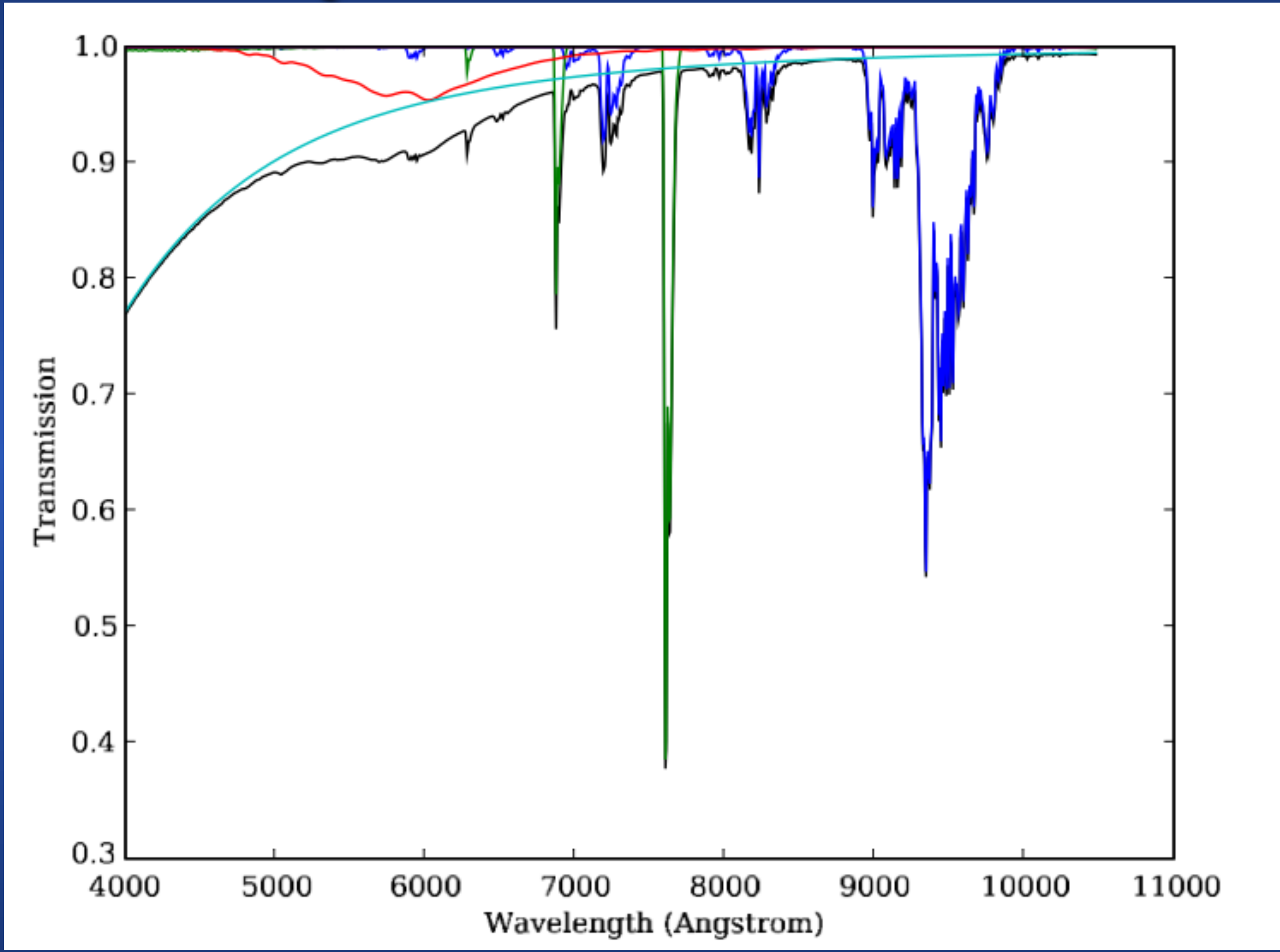


NIST photodiode QE

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

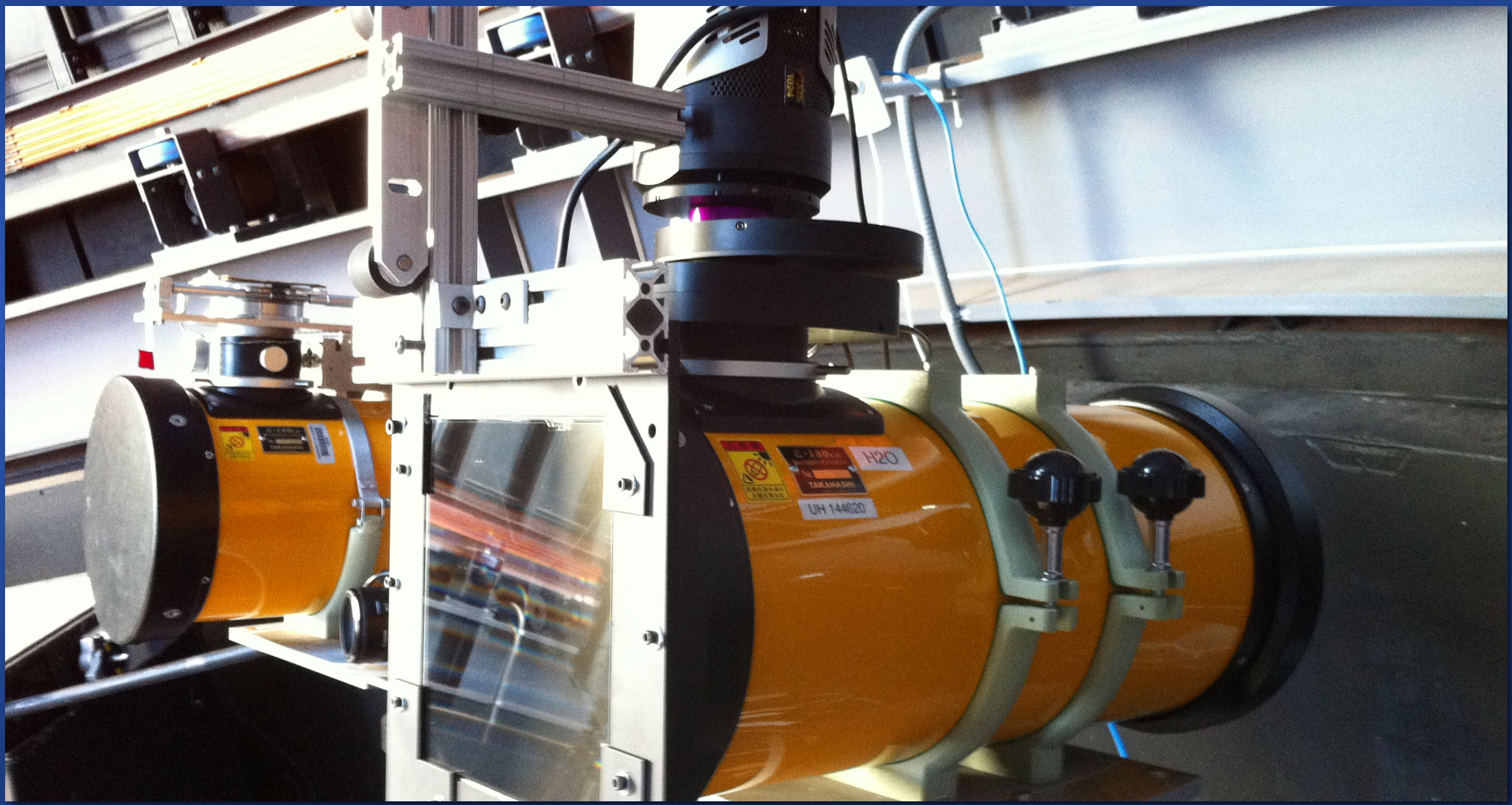

Stubbs et al, ApJ in press, arXiv:1003.3465S
Total Throughput
Wavelength [nm]
0
.2
.4
.6
.8
400
500
600
700
800
900
1000

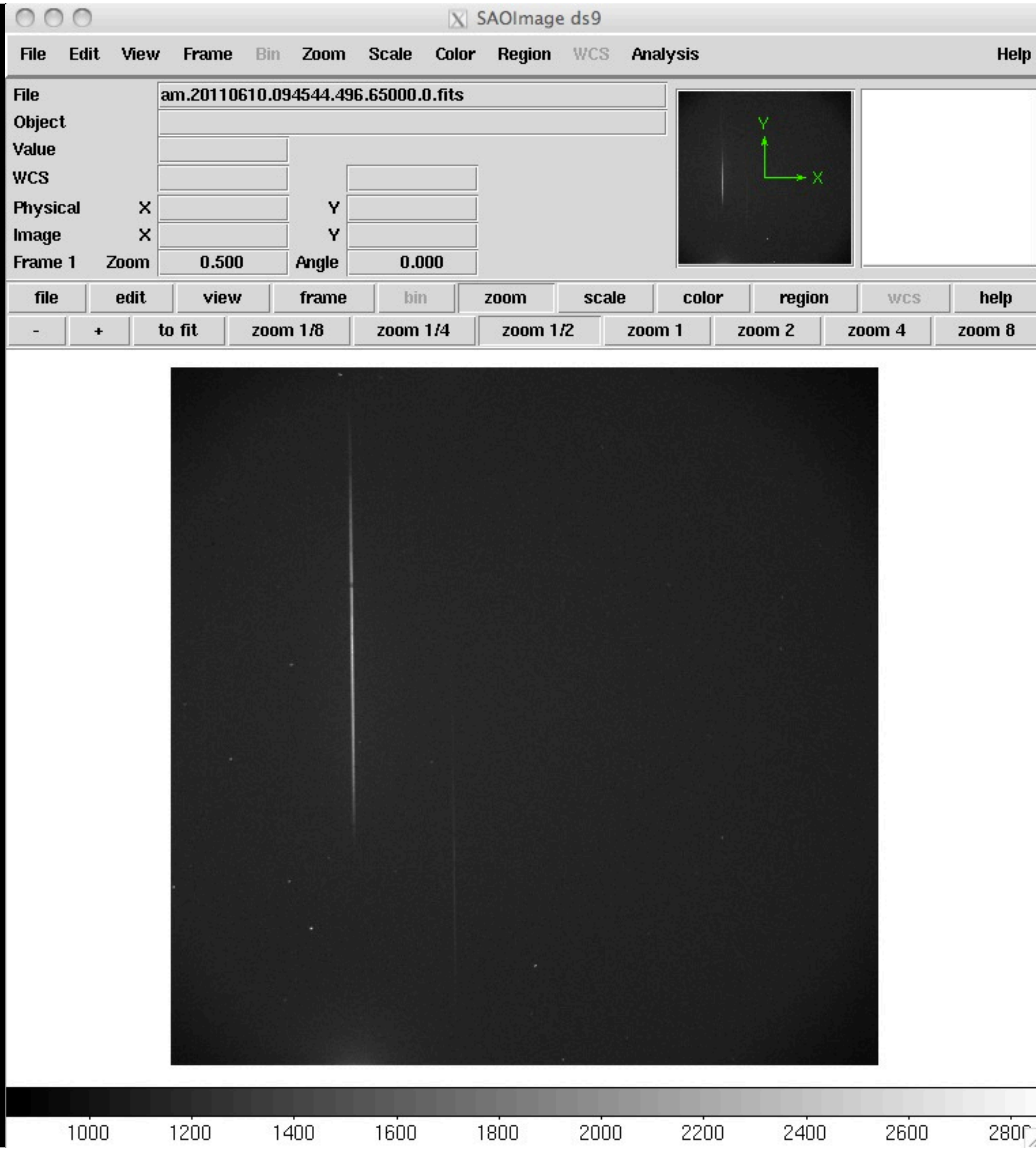
Atmospheric Transmission



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

Objective grating atmospheric monitor (Isaac Shivvers)




SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File am.20110610.094544.496.65000.0.fits
Object
Value
WCS
Physical X Y
Image X Y
Frame 1 Zoom 0.500 Angle 0.000
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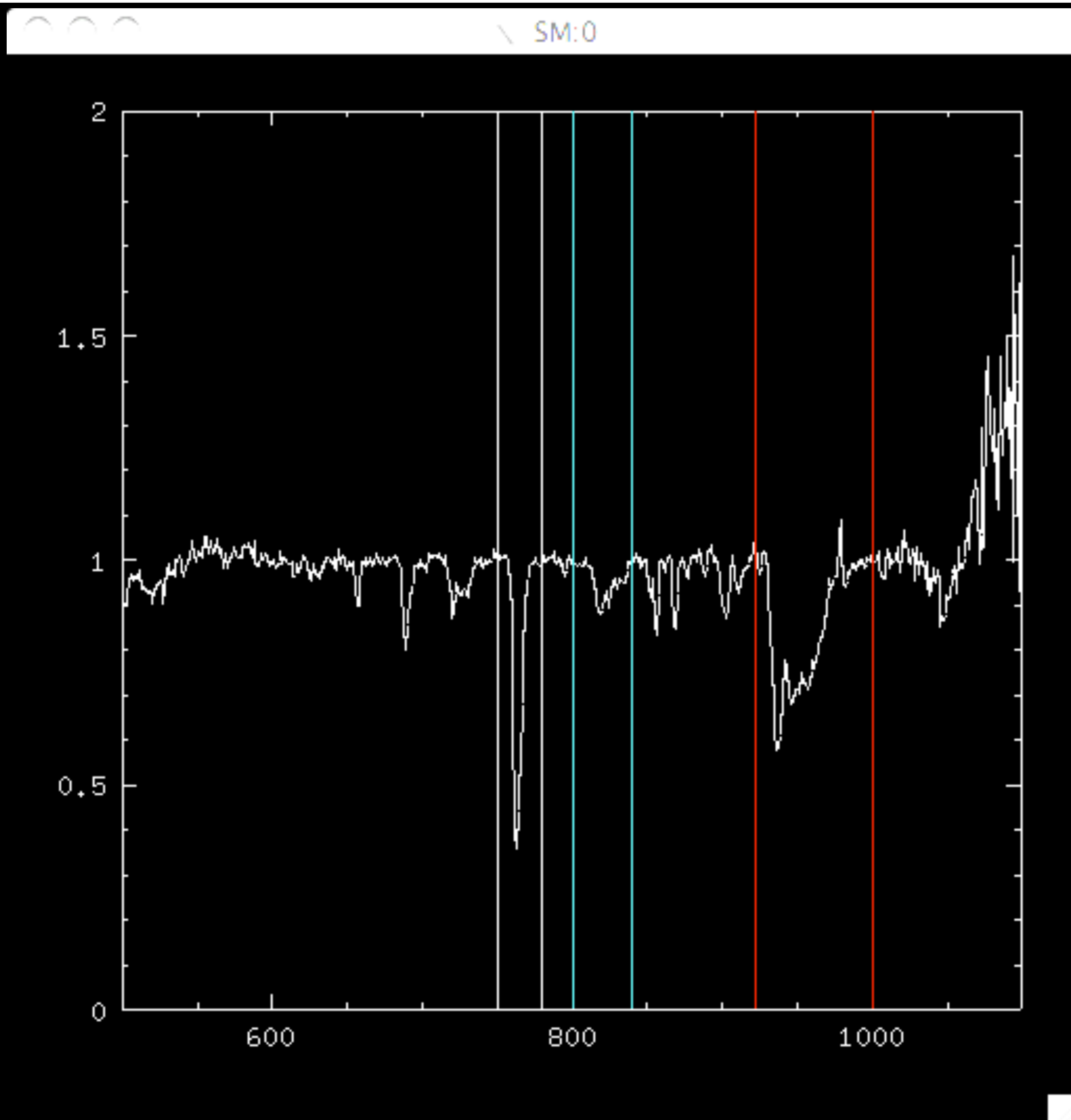
1000 1200 1400 1600 1800 2000 2200 2400 2600 2800



SM:0
2
1.5
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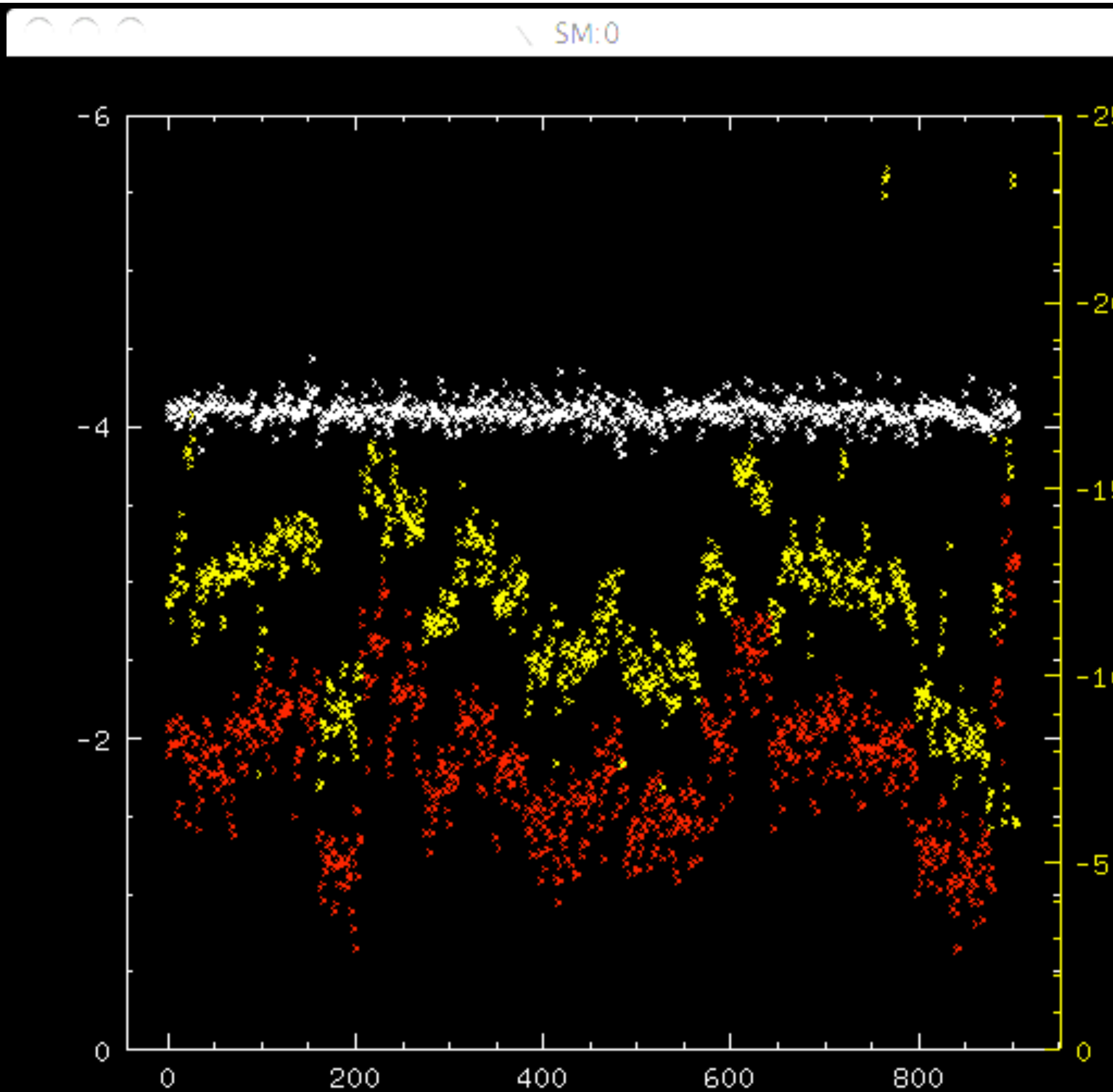
SM:0
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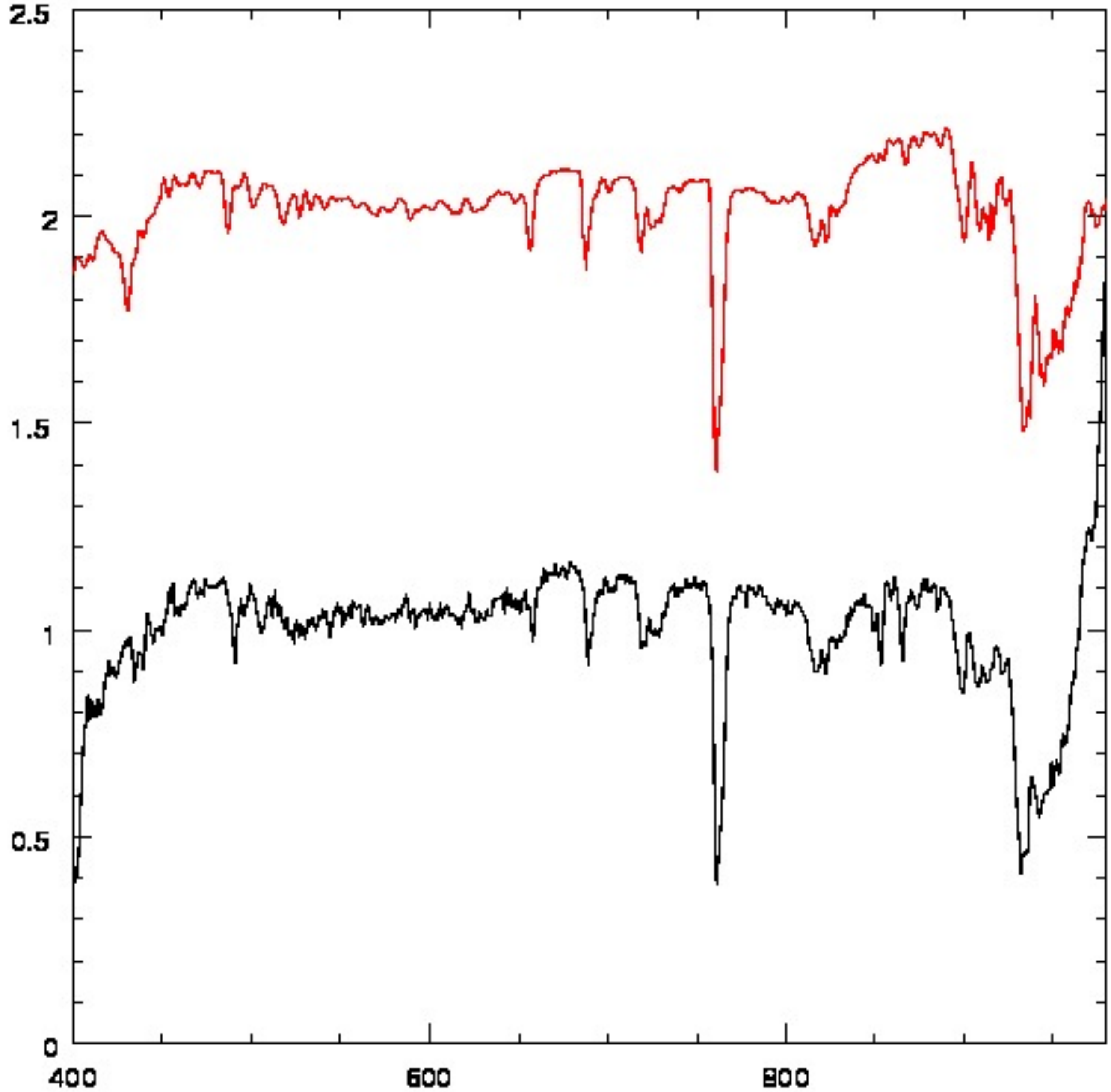
2.5
2
1.5
1
0.5
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400
600
800

PanSTARRS-1 throughput

Tonry et al
arXiv:1203.0297

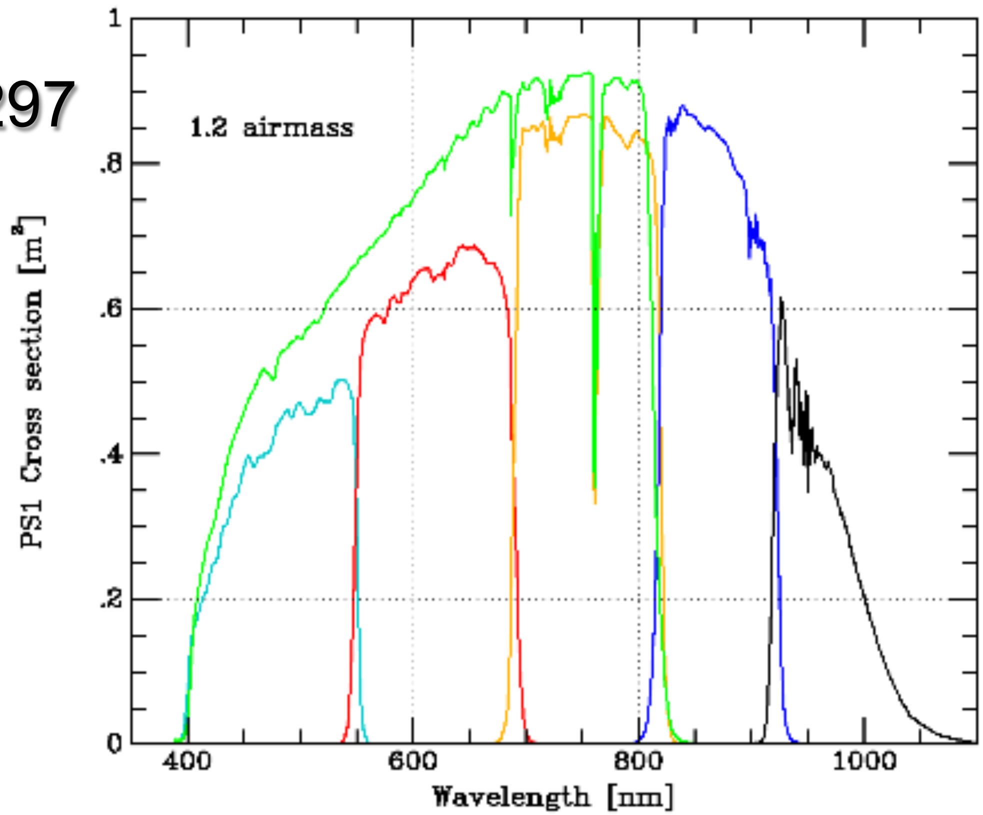


Fig. 4.— The Pan-STARRS1 capture cross section $A(\nu)$ in m^2-e^-/photon to produce a detected e^- for an incident photon for the six Pan-STARRS1 bandpasses. This is at the standard airmass of 1.2, with standard PWV of 0.65 cm and aerosol exponent 0.7. Summary properties of each bandpass are found in Table 4.

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

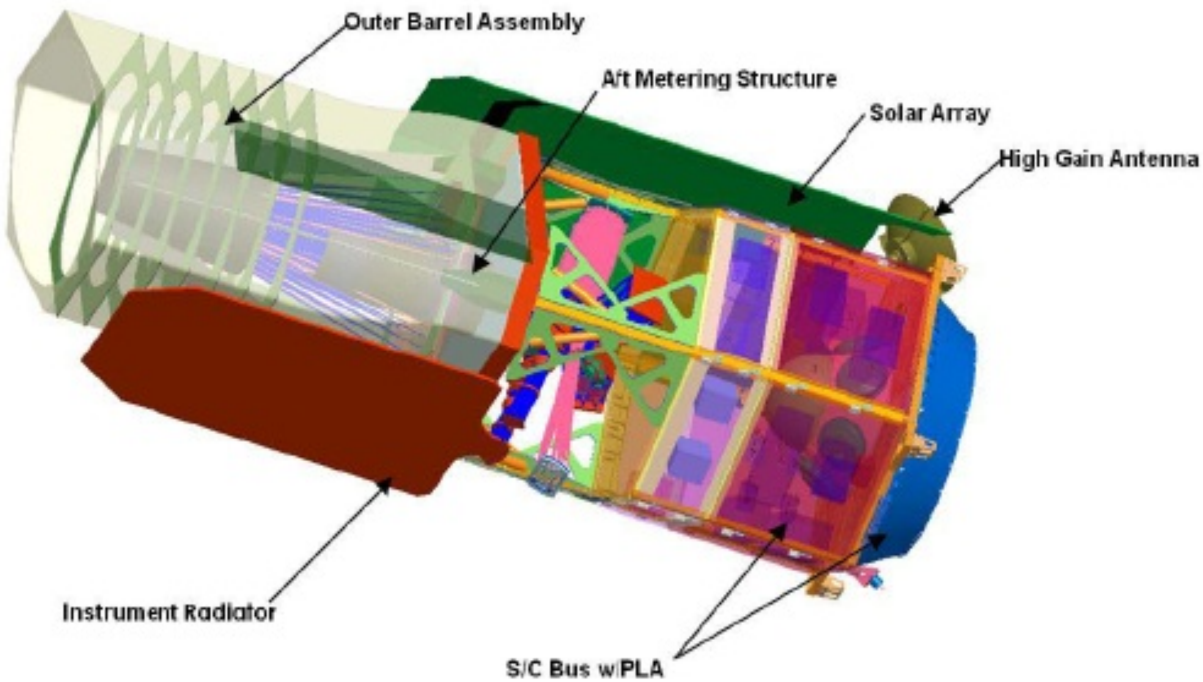


FIGURE 7.3 WFIRST is an infrared telescope with a three-mirror design. It will have HgCdTe detectors with 144 megapixels in total and angular resolution of 200 milliarcseconds. The sensitivity should be about 200 nJy or 26th magnitude, enabling shape measurements and photometric redshifts to a depth 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

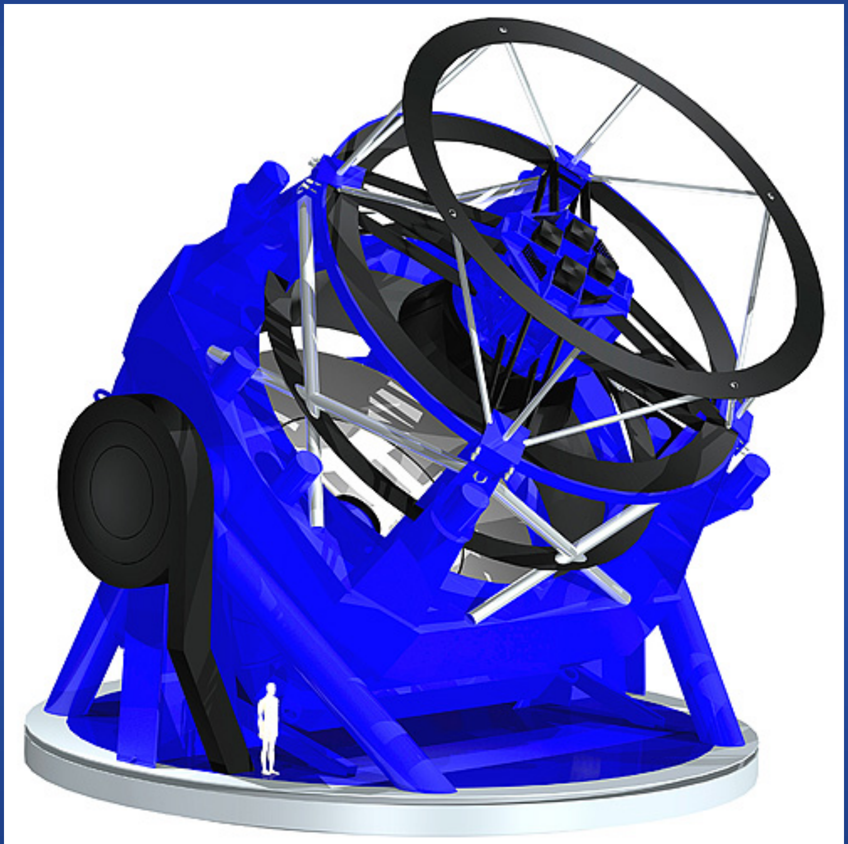
10 square degree field

6.5m effective aperture

24th mag in 20 sec

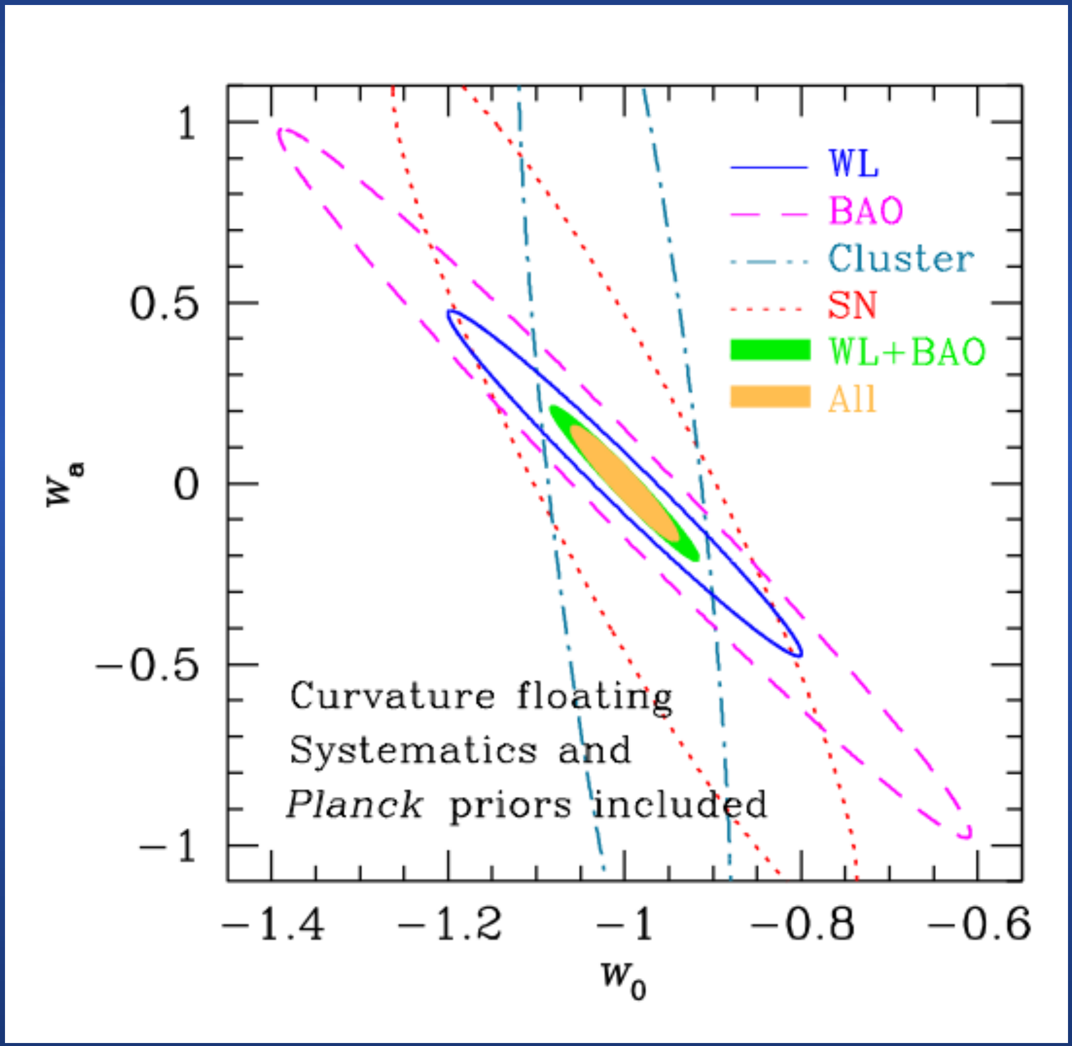
>20 Tbyte/night

Real-time analysis



Simultaneous multiple science goals

LSST is engineered to study DE

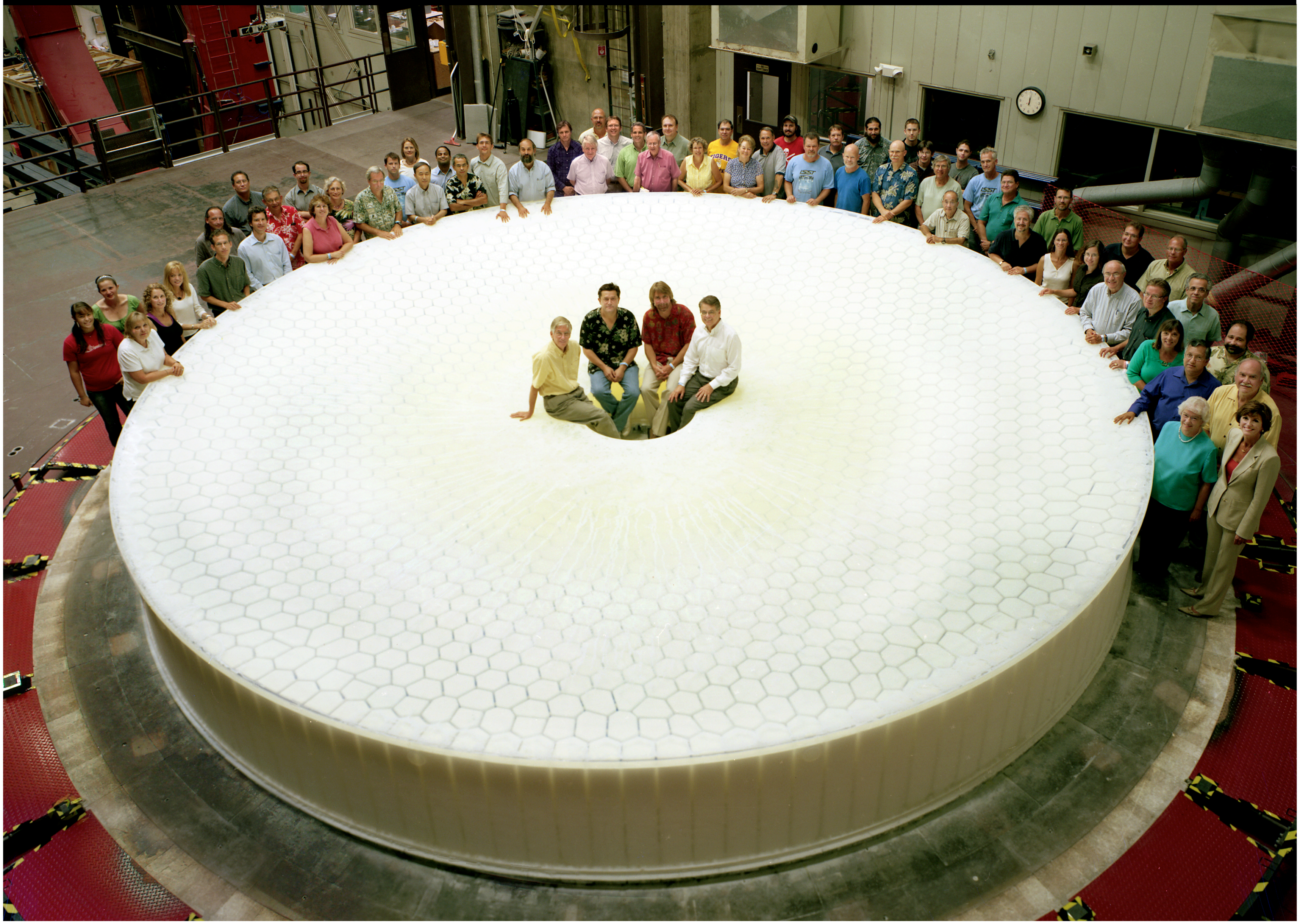


http://www.lsst.org/files/docs/sciencebook/SB_15.pdf

Also very effective for:

Neutrino mass scale
Killer asteroids
Galactic structure
Transient sources
…

Large Synoptic Survey Telescope



LSST Primary/Tertiary Mirror Blank

August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

The University of Arizona
Tucson Arizona

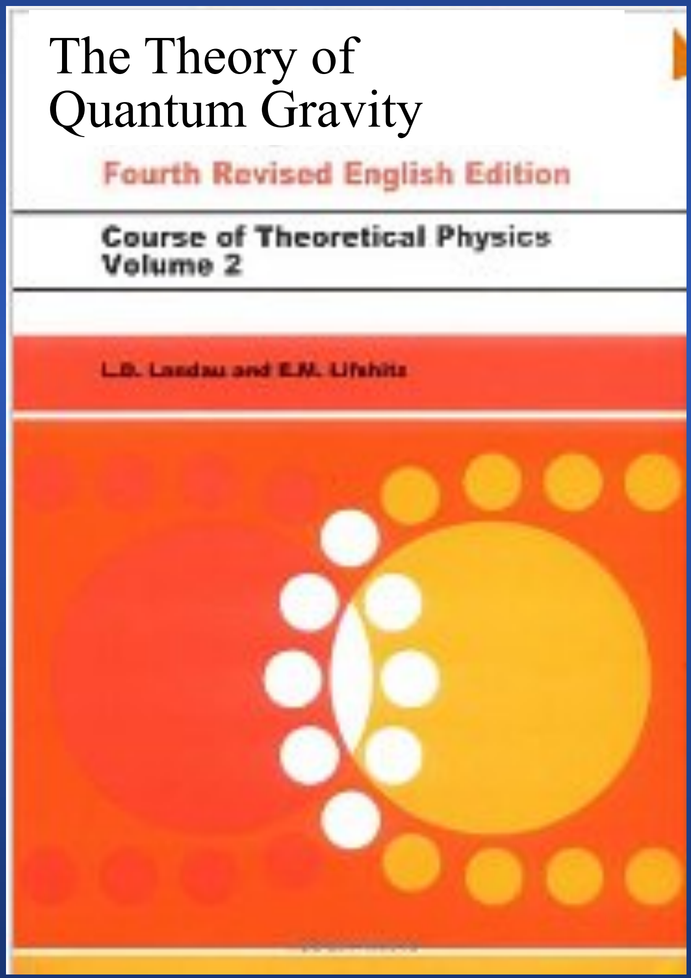
Large Synoptic Survey Telescope

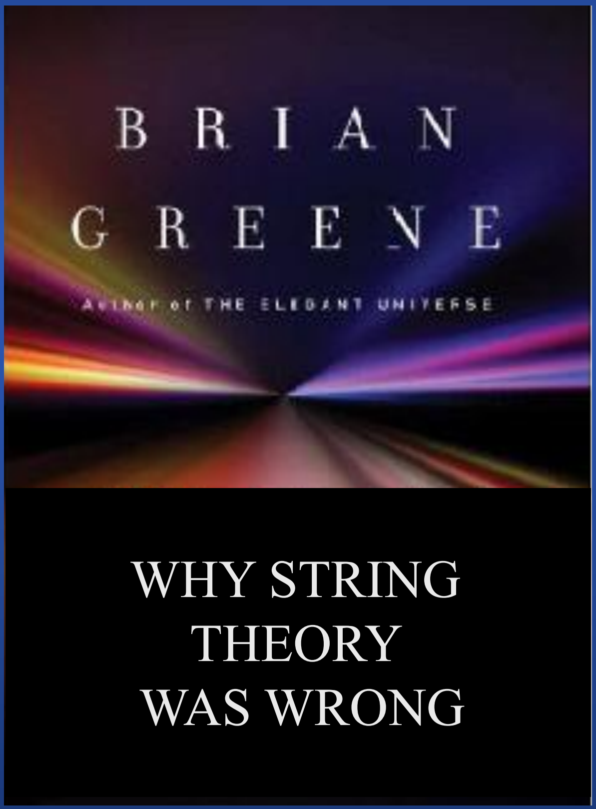
A look ahead to Dark Energy in 2028, 3 decades after its discovery

- 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(s)





The Dark Ages- scenario 2: Observational or Experimental breakthrough

"All the News That's Fit to Print"

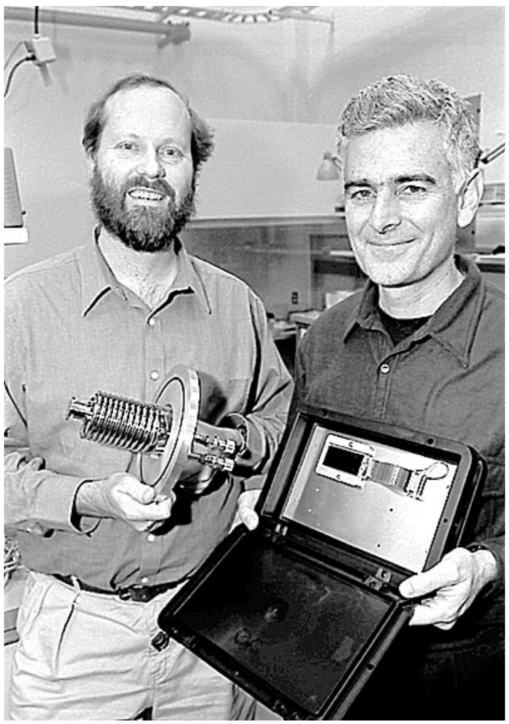
The New York Times

Late Edition

Today, sunny with a cold start, then milder, high 58. **Tonight,** thickening clouds and rain late, low 39. **Tomorrow,** cooler with some rain, high 51. Weather map appears on Page B8.

VOL. CLVIII . . No. 54,644 © 2009 The New York Times 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

PHYSICAL REVIEW LETTERS

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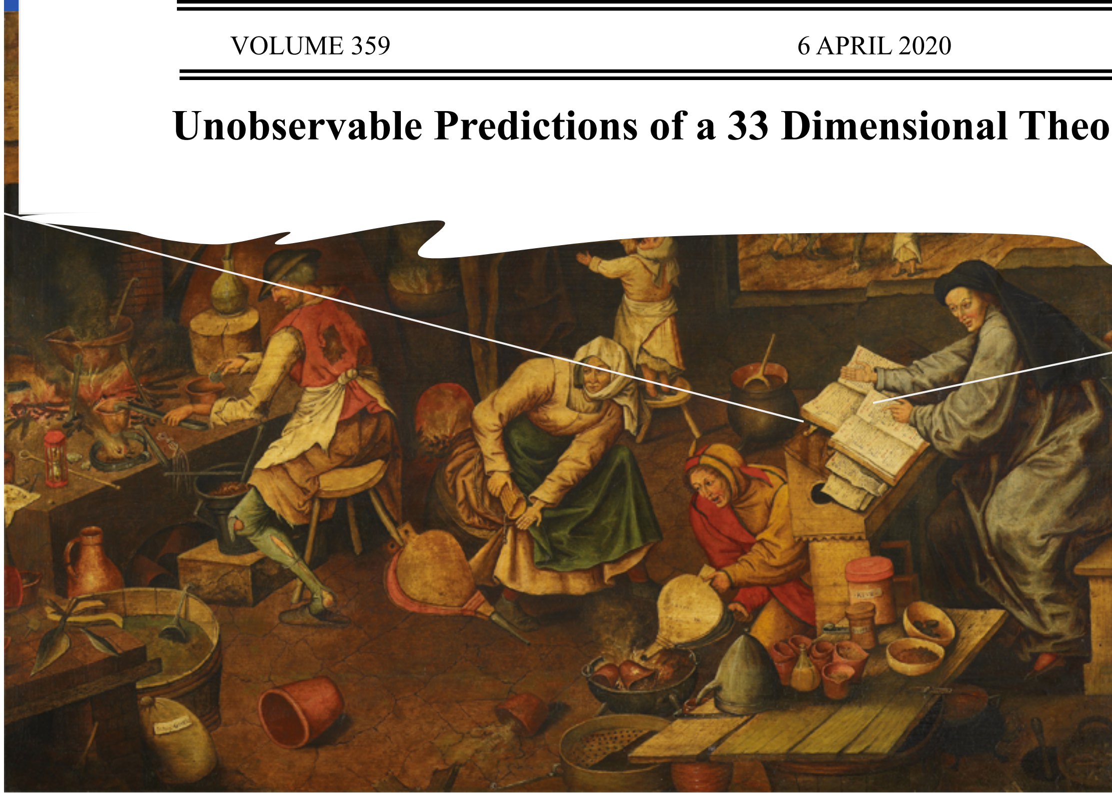
Unobservable Predictions of a 33 Dimensional Theory of Emergent Vacuum Energy



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

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?

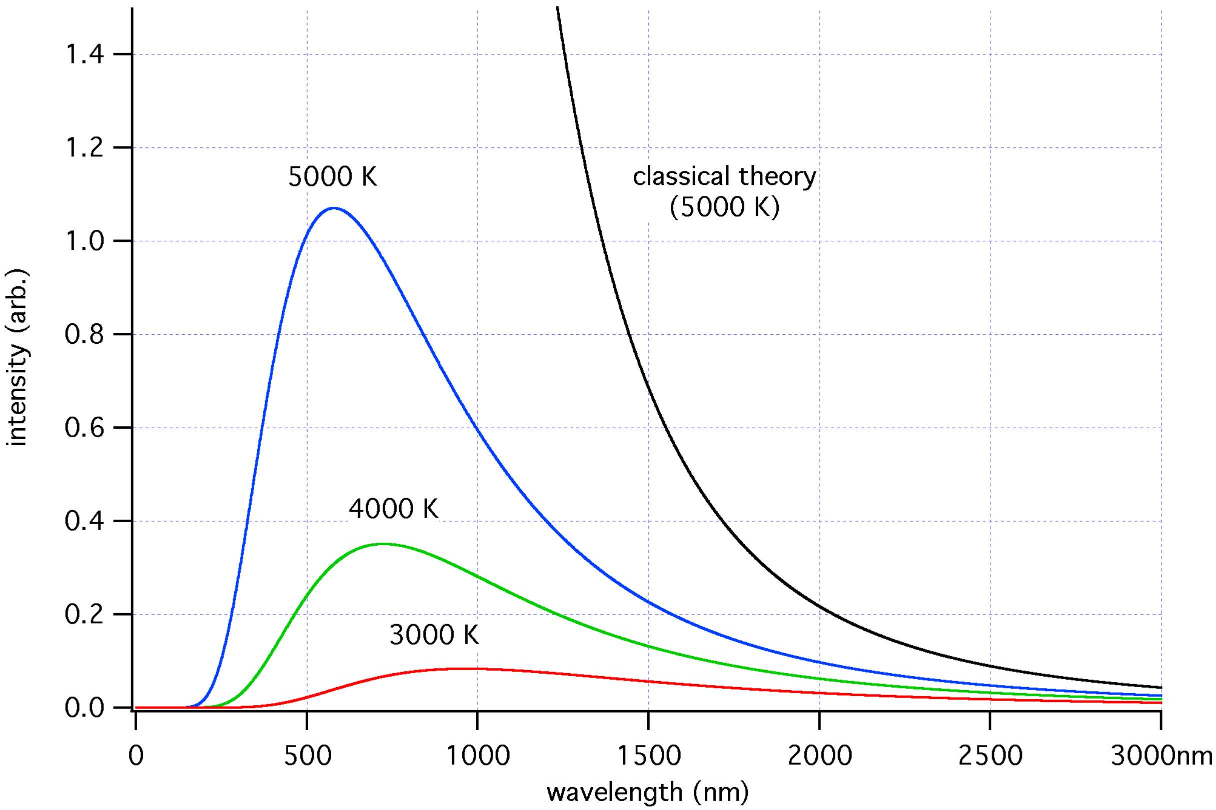
Detection of dark matter? (will eliminate prospect of MOND-like scenarios)

An analogy from the past…

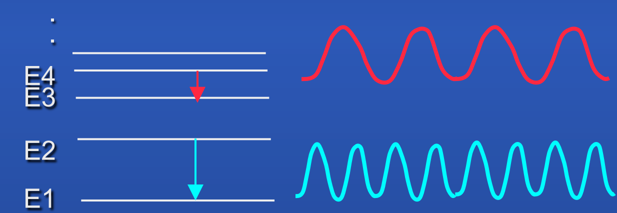
We've seen something like this before:

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

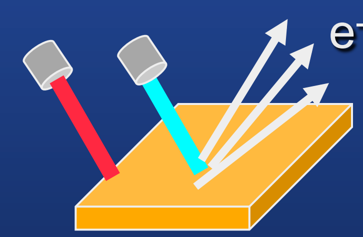
1.blackbody spectrum



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

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

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

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

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

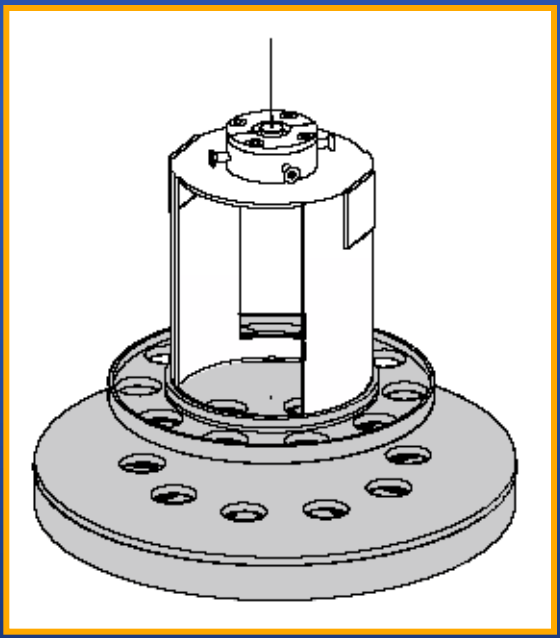
Dark Energy Length Scales

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

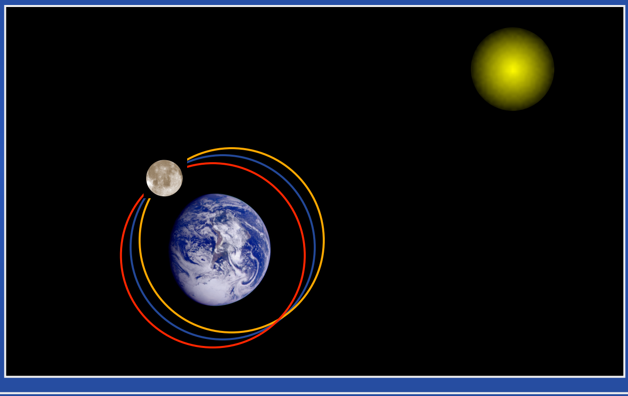
$$\ell_{QM} \sim \sqrt[4]{\hbar / \rho_{DE} c} = \sqrt{\ell_{grav} \ell_{Planck}} \sim 100 \; \mu\text{m}$$

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

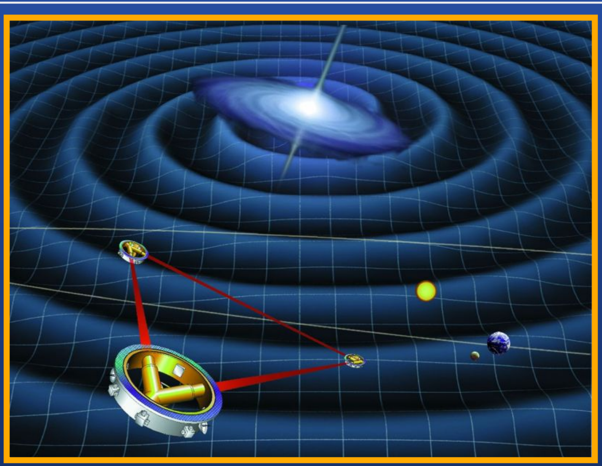


e.g. Eot-Wash group



Lunar Laser Ranging: APOLLO project

Strong gravity: LIGO & LISA



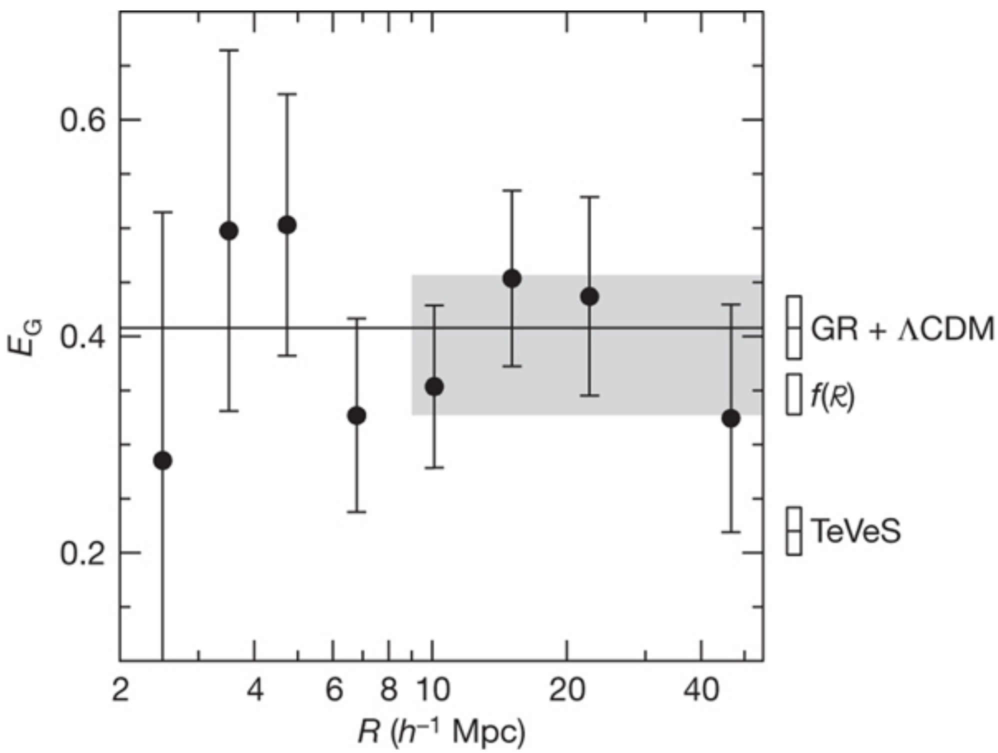
An example of testing the framework

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

Galaxy-galaxy lensing
Galaxy velocity field
Large scale structure

SDSS LRG's to z=0.3

E_G is consistency parameter



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

nature

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?


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.