The Astronomical Flux Measurement Problem: Implications for Atmospheric Monitoring

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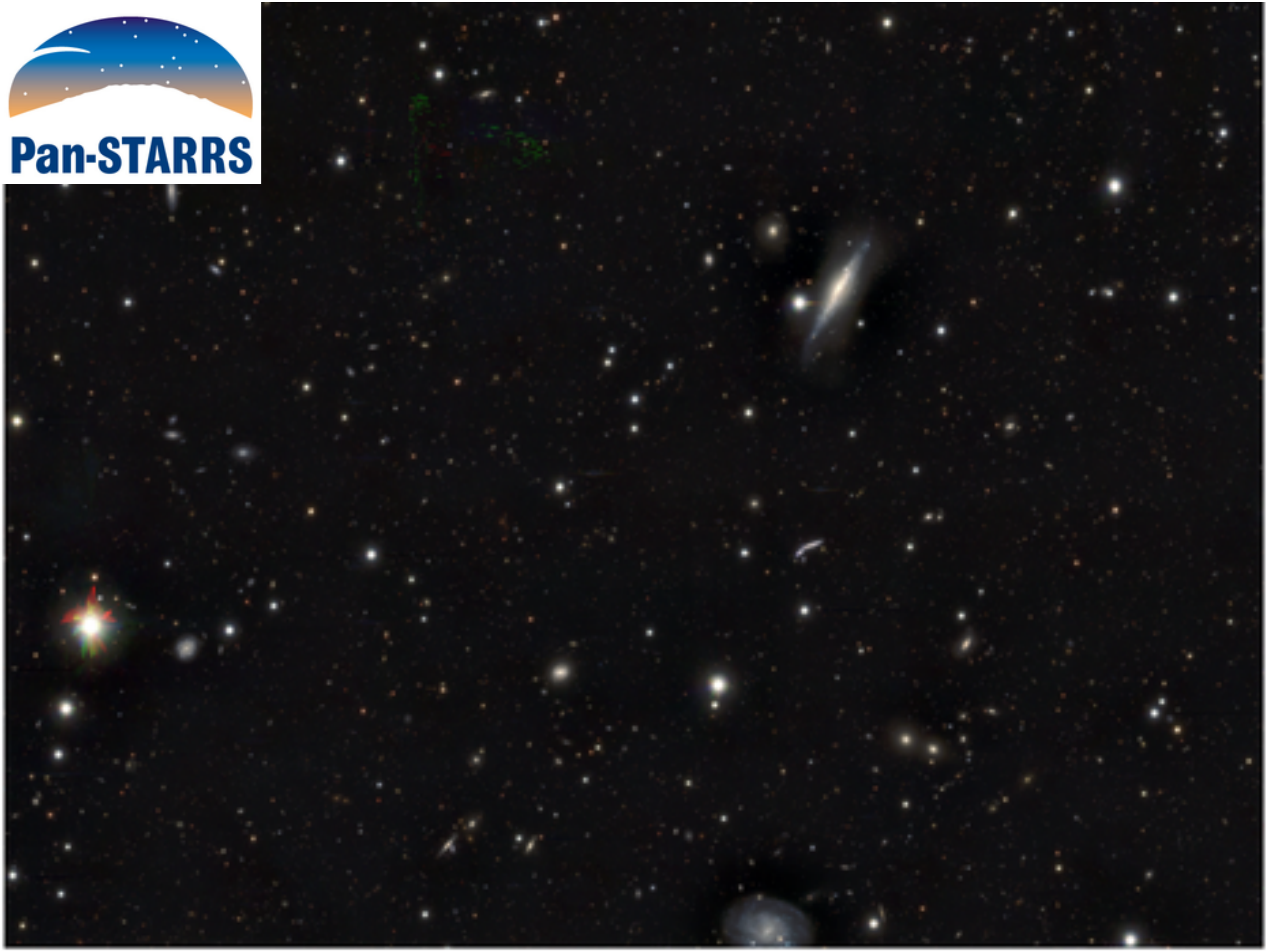
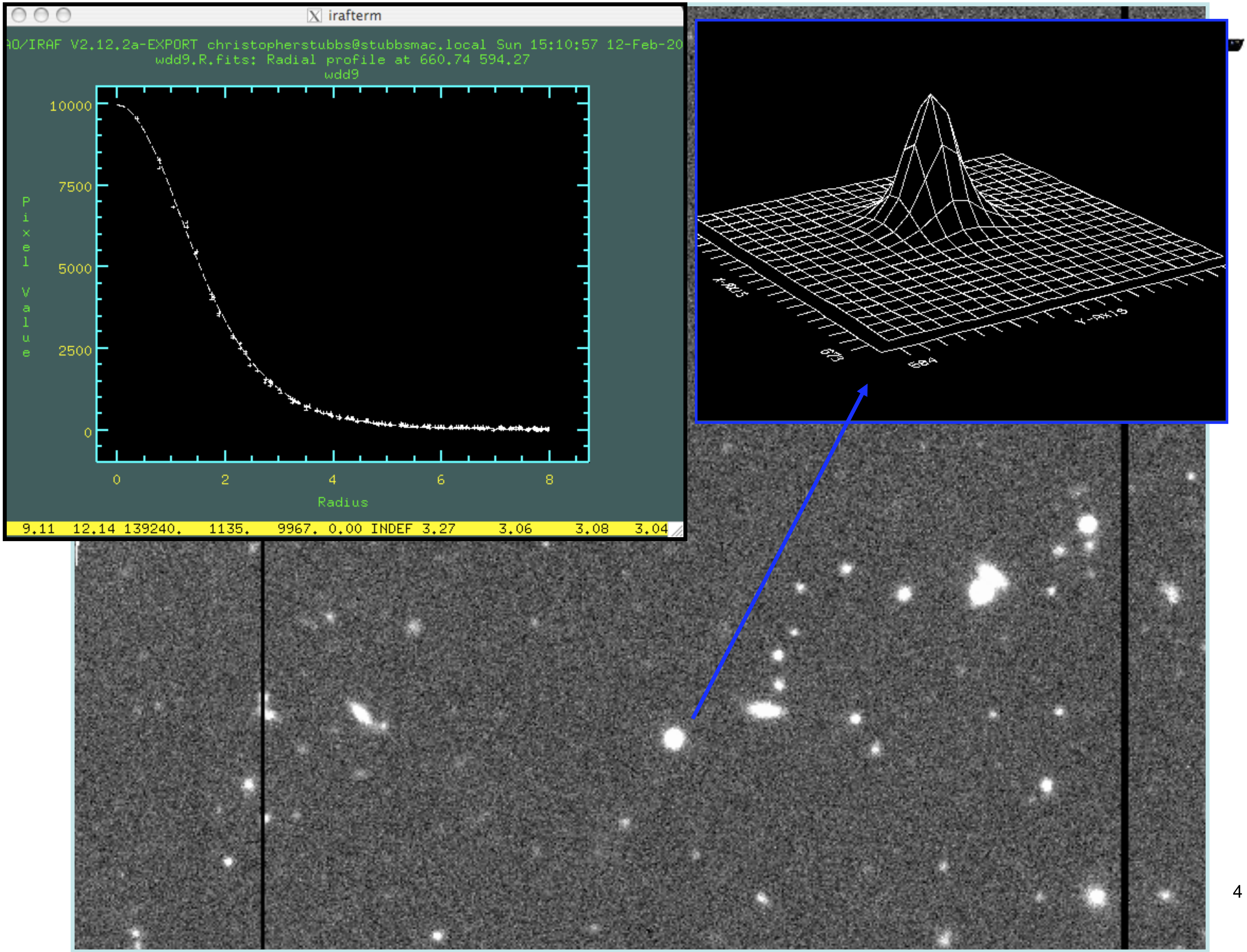
At optical & infrared wavelengths, 3 basic measurements

Photometry: Integrated detected flux collected by an imager, through a passband (filter).

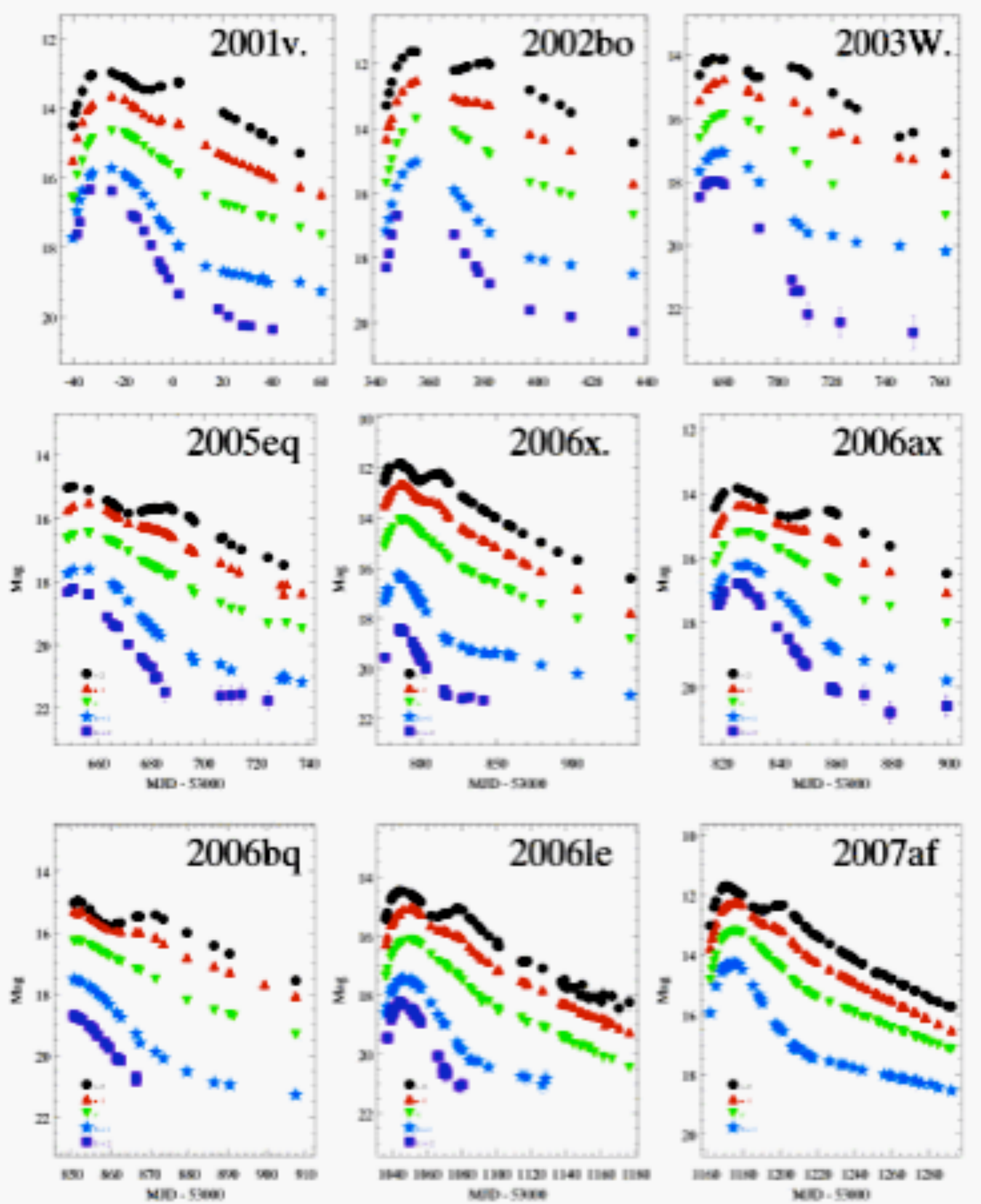
Spectroscopy: Disperse light from a slit in the focal plane, measure F(λ) with good local precision.

Spectro-photometry: Spectroscopy, but with good global flux precision and accuracy.




irafterm
AO/IRAF V2.12.2a-EXPORT christopherstubbs@stubbsmac.local Sun 15:10:57 12-Feb-20
wdd9.R.fits: Radial profile at 660.74 594.27
wdd9
10000
7500
5000
2500
0
Pixel Value
0
2
4
6
8
Radius
9.11 12.14 139240. 1135. 9967. 0.00 INDEF 3.27 3.06 3.08 3.04

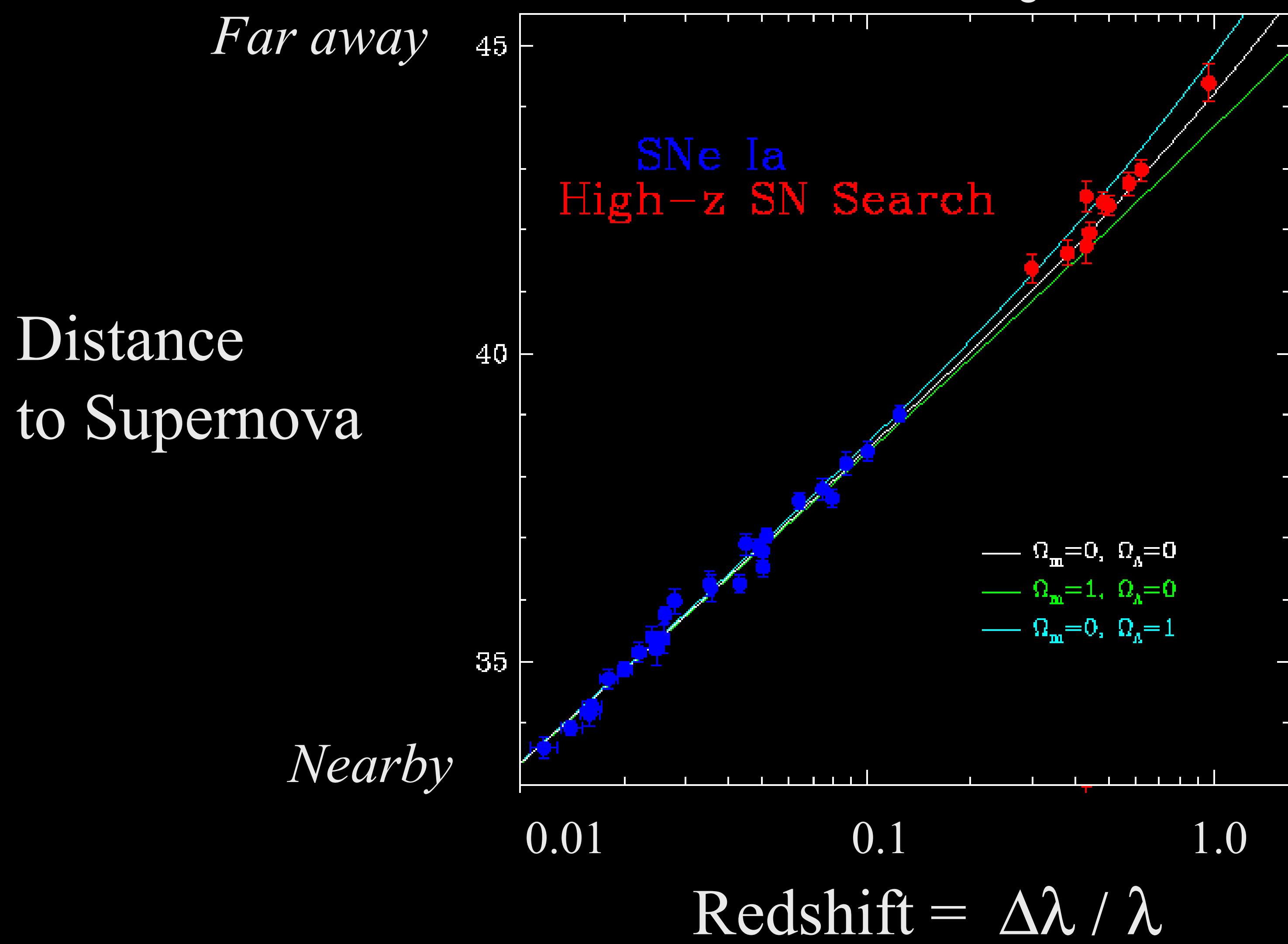
Type Ia supernova light curves

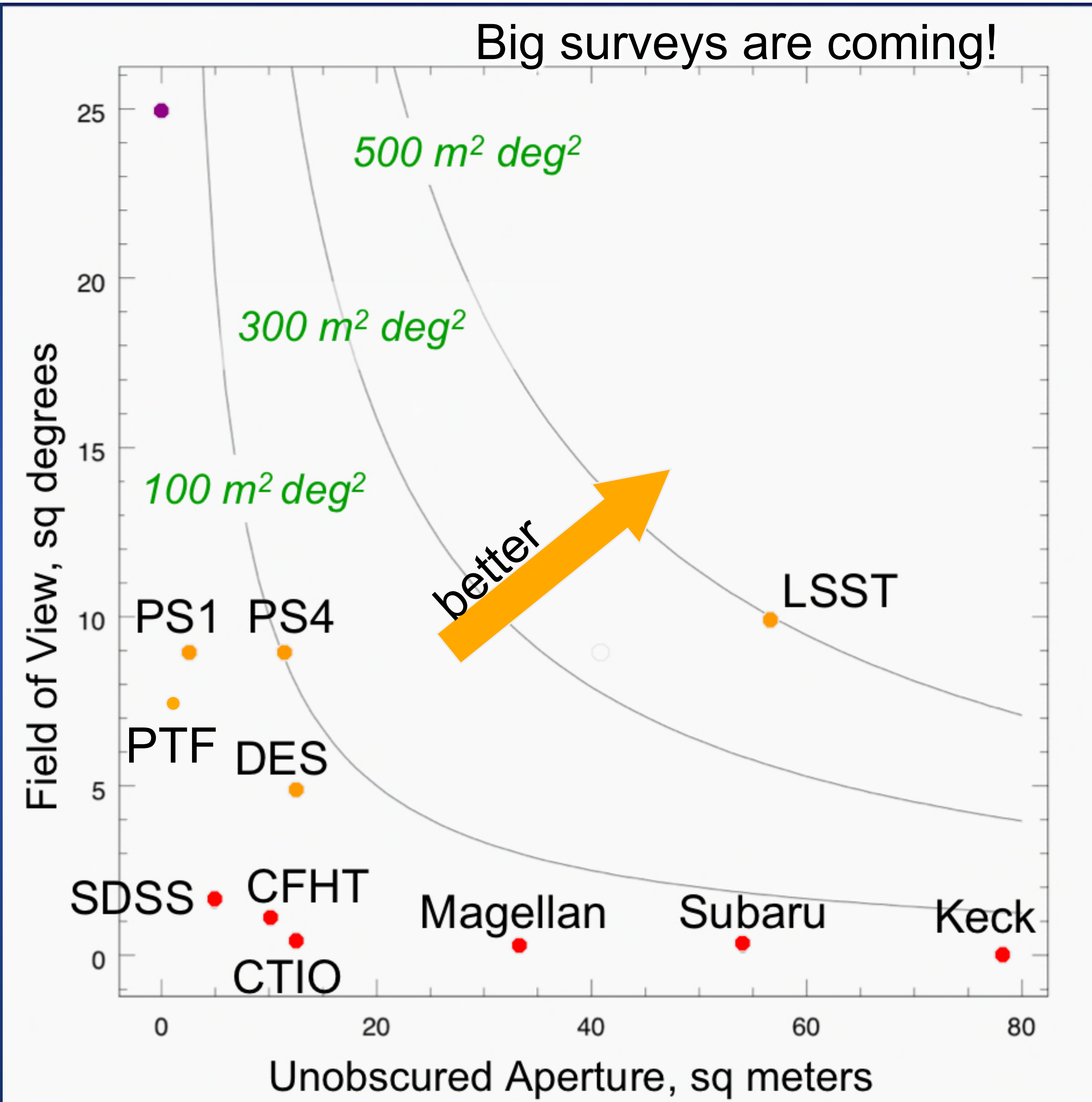


Hicken et al 2009

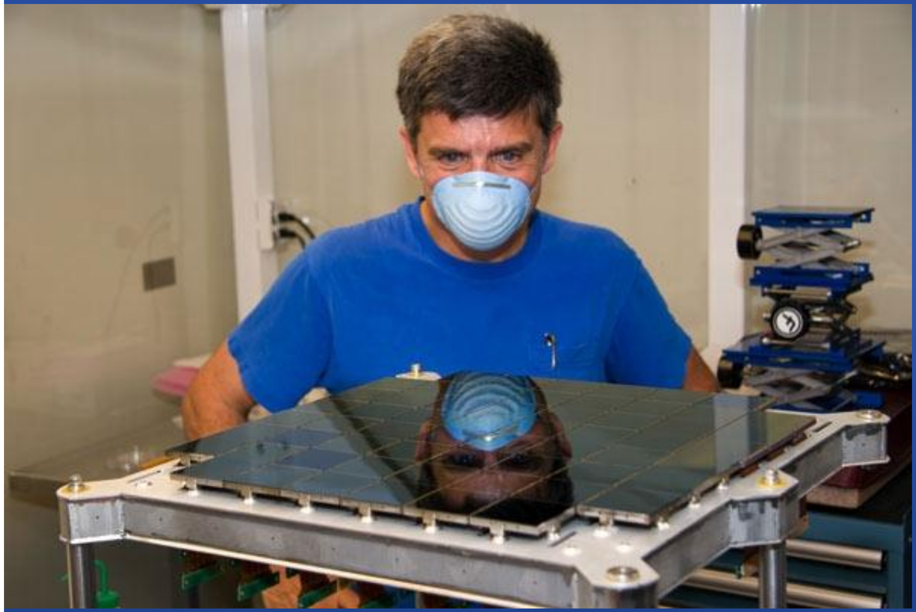
The Original Evidence for Accelerating Expansion, 1998

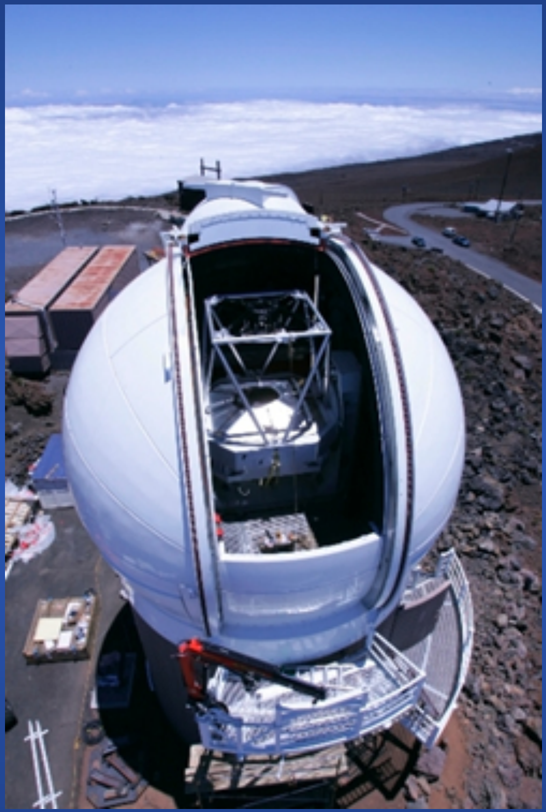
Schmidt et al, High-z SN Team




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

The PanSTARRS Survey



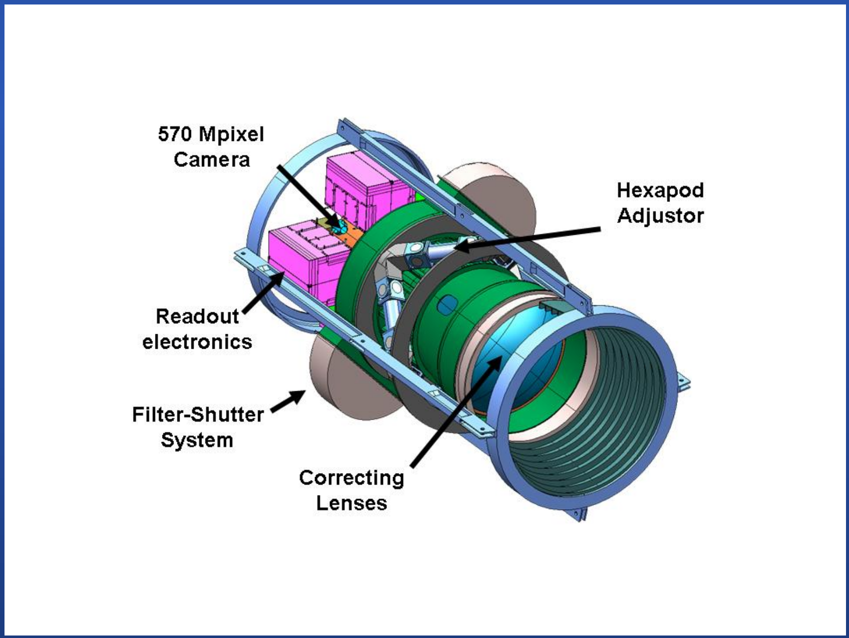


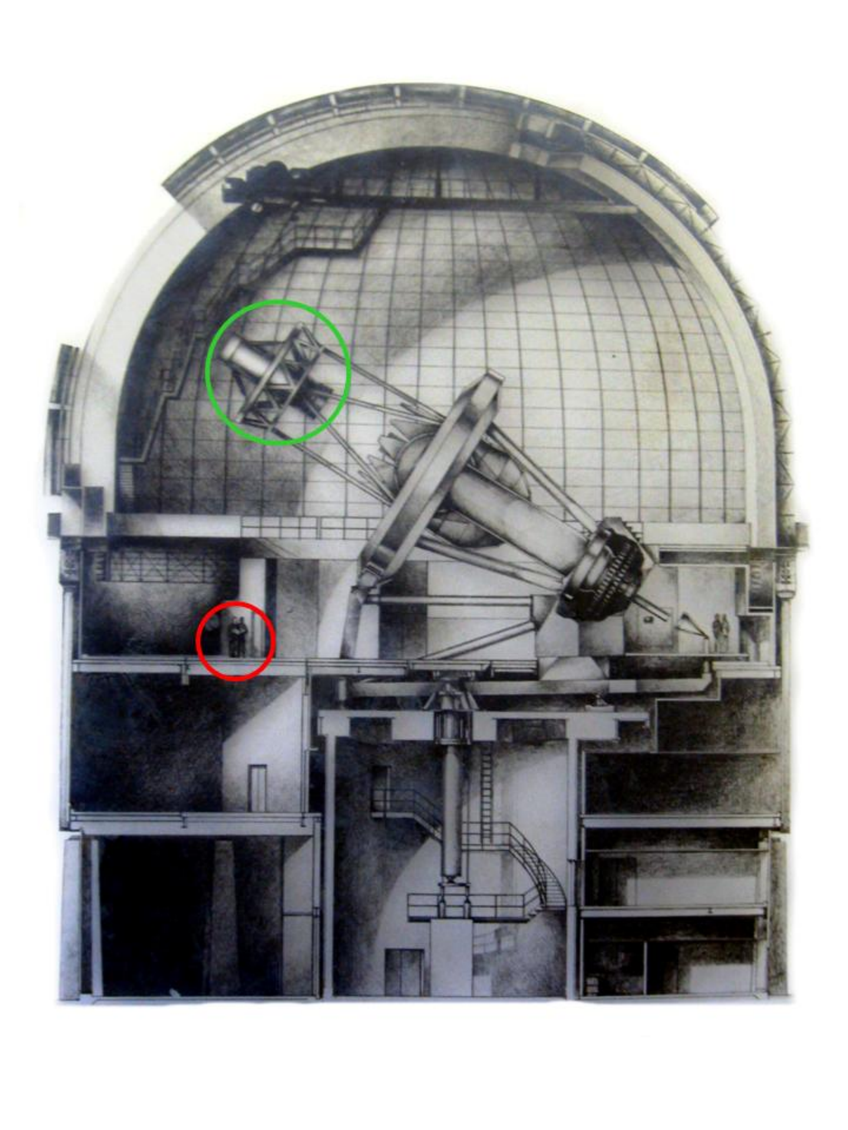
1.4 Gpix camera
3.3 degree FOV

1.8 meter telescope

The Dark Energy Survey

New wide field (2.2 deg dia) instrument on the CTIO 4 meter telescope





Large Synoptic Survey Telescope

Top ranked ground-based project in 2010 Decadal Survey

Optimized for time domain

scan mode

deep mode

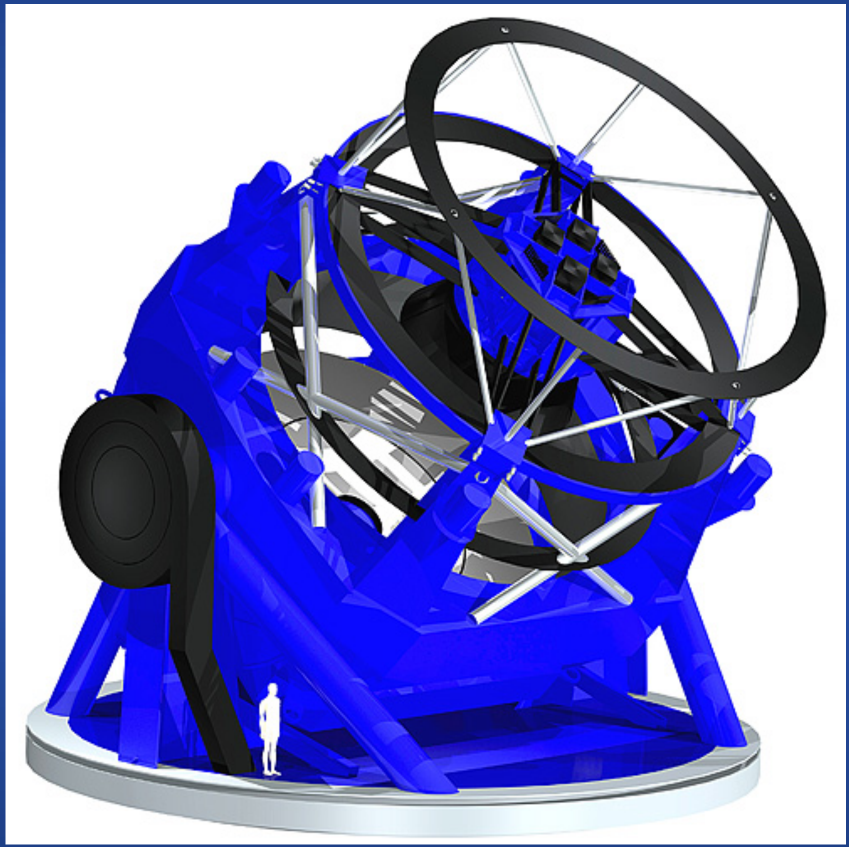
10 square degree field

6.5m effective aperture

24th mag in 20 sec

>20 Tbyte/night

Real-time analysis



Simultaneous multiple science goals

More Supernovae, Better Precision

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%

Pushing to Better Precision

Next-generation surveys promise considerable advances over current capabilities: 3 pi time domain, deep imaging…

The requisite precision for pushing to the next level of characterization of the Dark Energy is < 1%. Inadequate corrections for variable atmospheric transmission will be a leading source of systematic error in next-gen efforts.

SDSS achieved few-percent precision all-sky, while differential measurements in single frames reach millimagnitude (part per thousand) levels

We are nowhere close to the Poisson limits for objects with SNR > 100.

Why?

Broadband photometry

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:

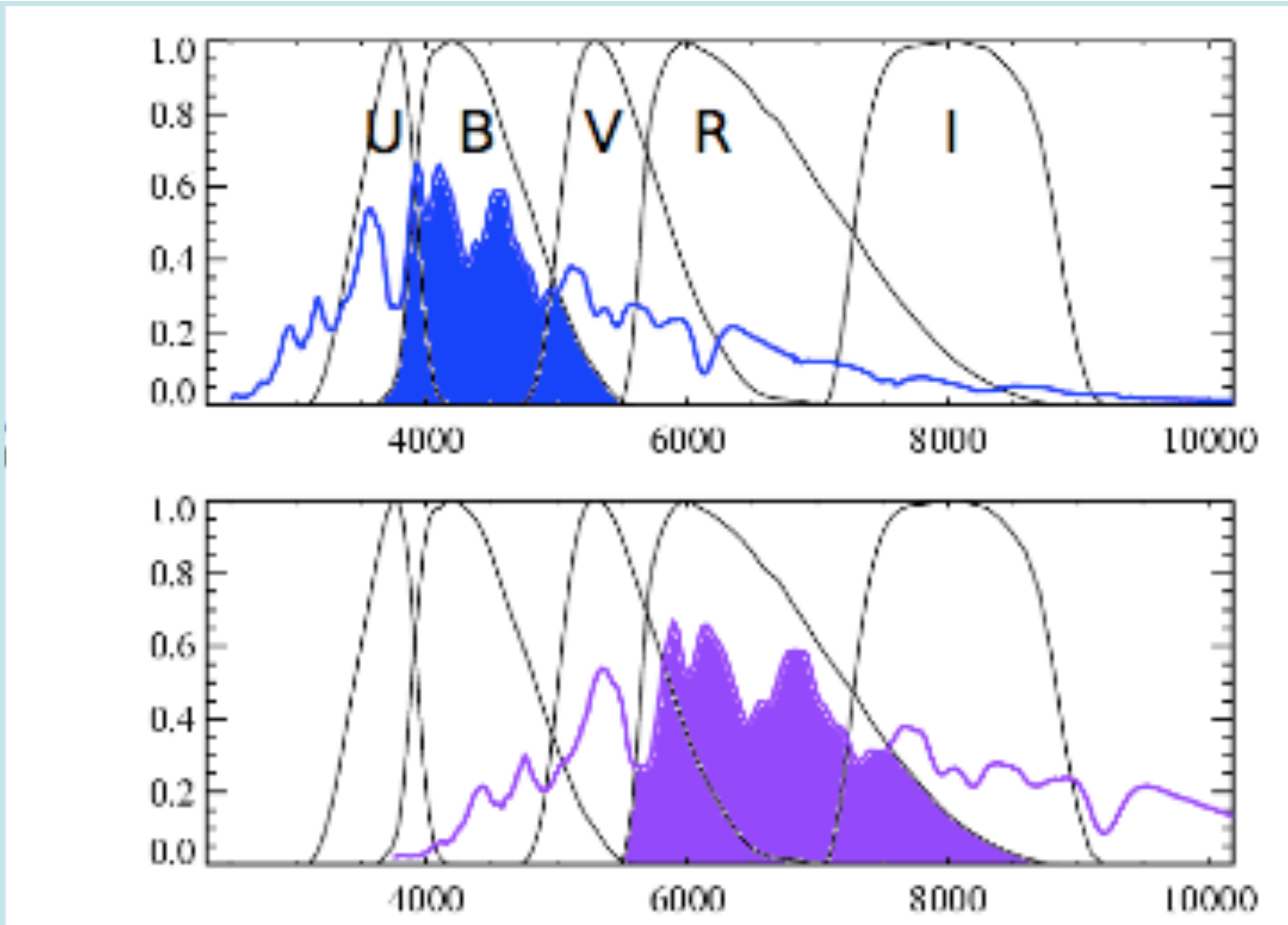
1. *Relative instrumental throughput calibration (i.e. get the colors right)*
2. *Absolute instrumental calibration (I claim this this is far less important)*
3. *Determination of atmospheric transmission*
4. *Determination of Galactic extinction (most stars lie behind the extinction layers).*

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

The Challenges

- The atmosphere is complicated…. The assumption of axisymmetric stable conditions fails, at some level.
- There aren't any sources on the sky whose photon spectrum is currently known at or below the 1% level.
- Current metrology (and meterology!) measurement chain is ill-defined.
- Must know precise instrumental sensitivity function.

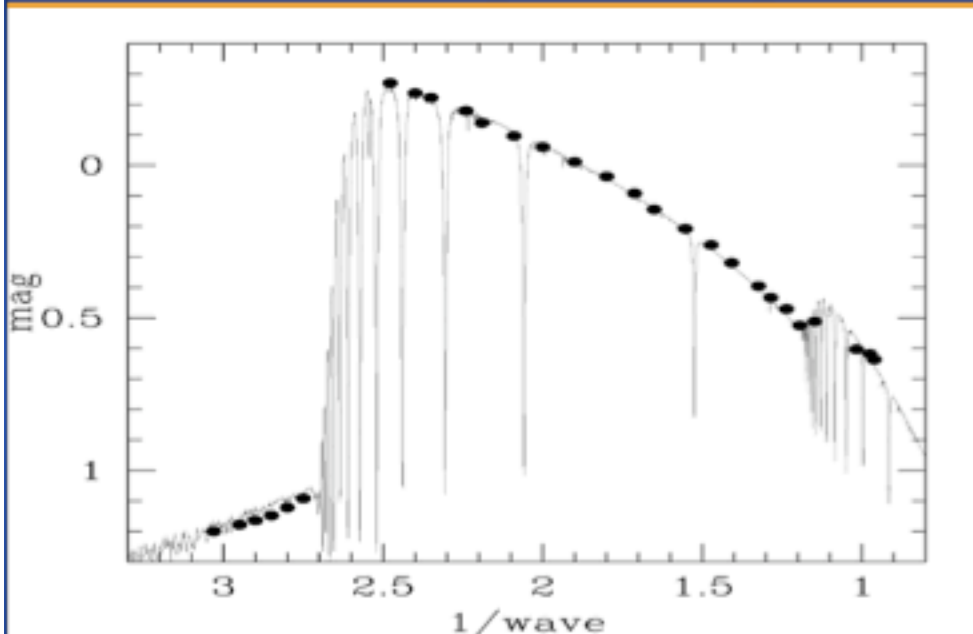
Passbands and System Sensitivity



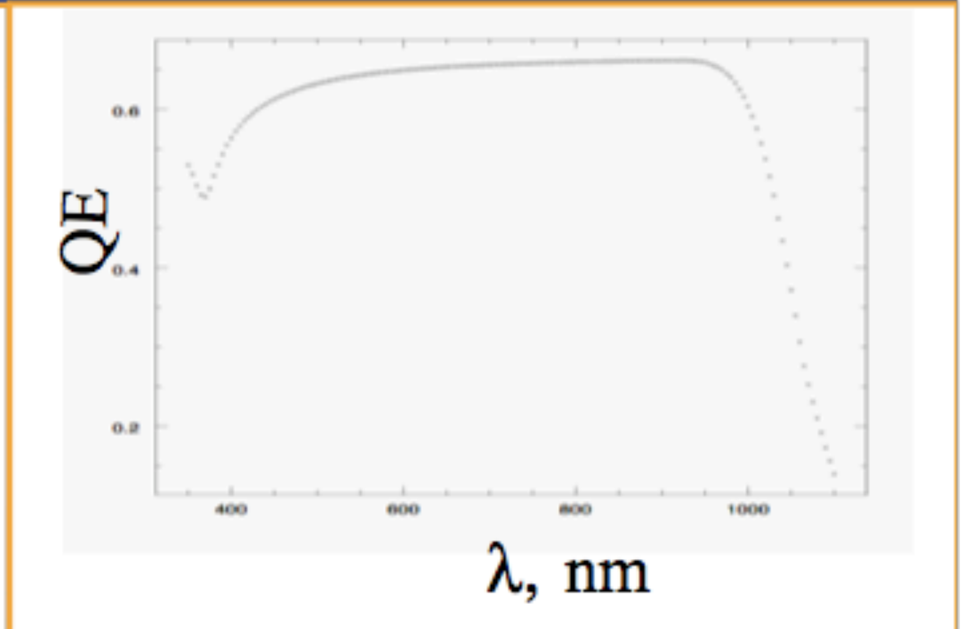
Basic Philosophy

1. *Use precisely calibrated photodiode as fundamental basis for flux measurements*
2. *Measure instrumental throughput relative to known photodiode.*
3. *Measure atmospheric transmission function directly*
4. *Determine Galactic extinction with optical/NIR data, supplemented by thermal IR emission data.*
5. *Report photometry in "natural" system of counted photoelectrons,* not *AB magnitudes. We don't measure energy! (this is a contentious and perhaps overly pedantic point….)*
6. *Deliver, for each photometric measurement, the effective passband through which it was obtained.*

Detectors are better characterized than *any* celestial spectrophotmetric source



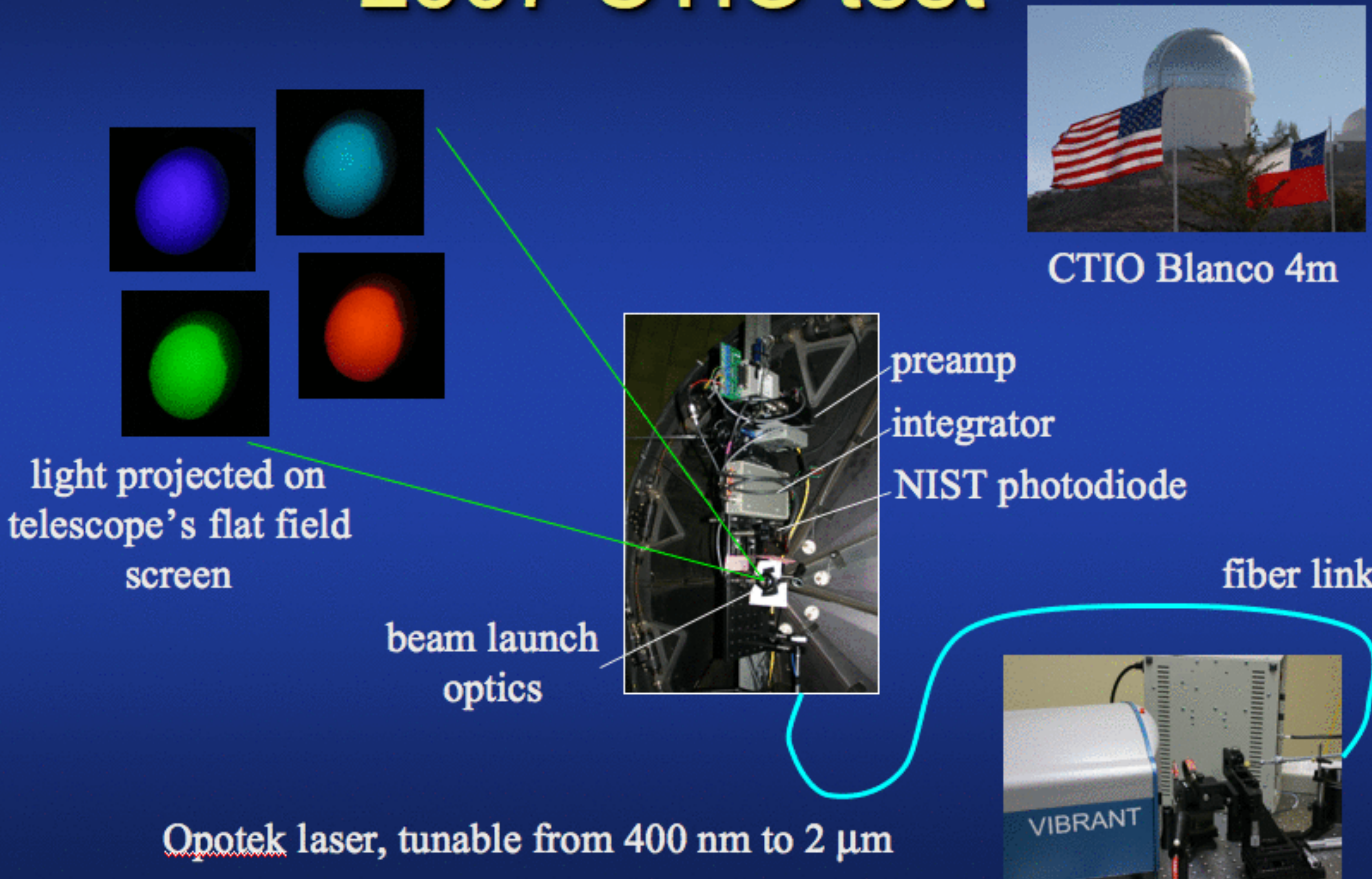
Spectrum of Vega

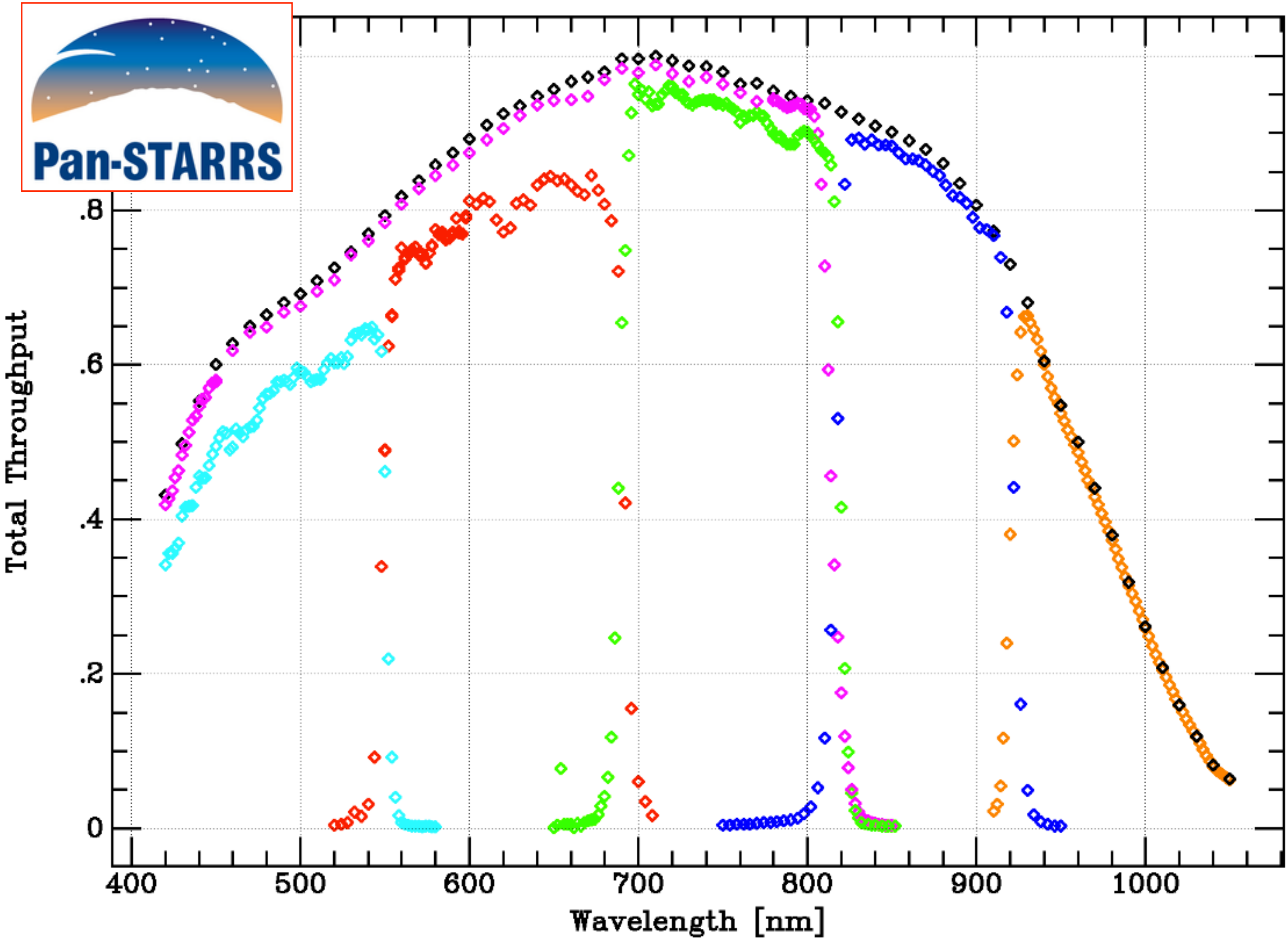


NIST photodiode QE

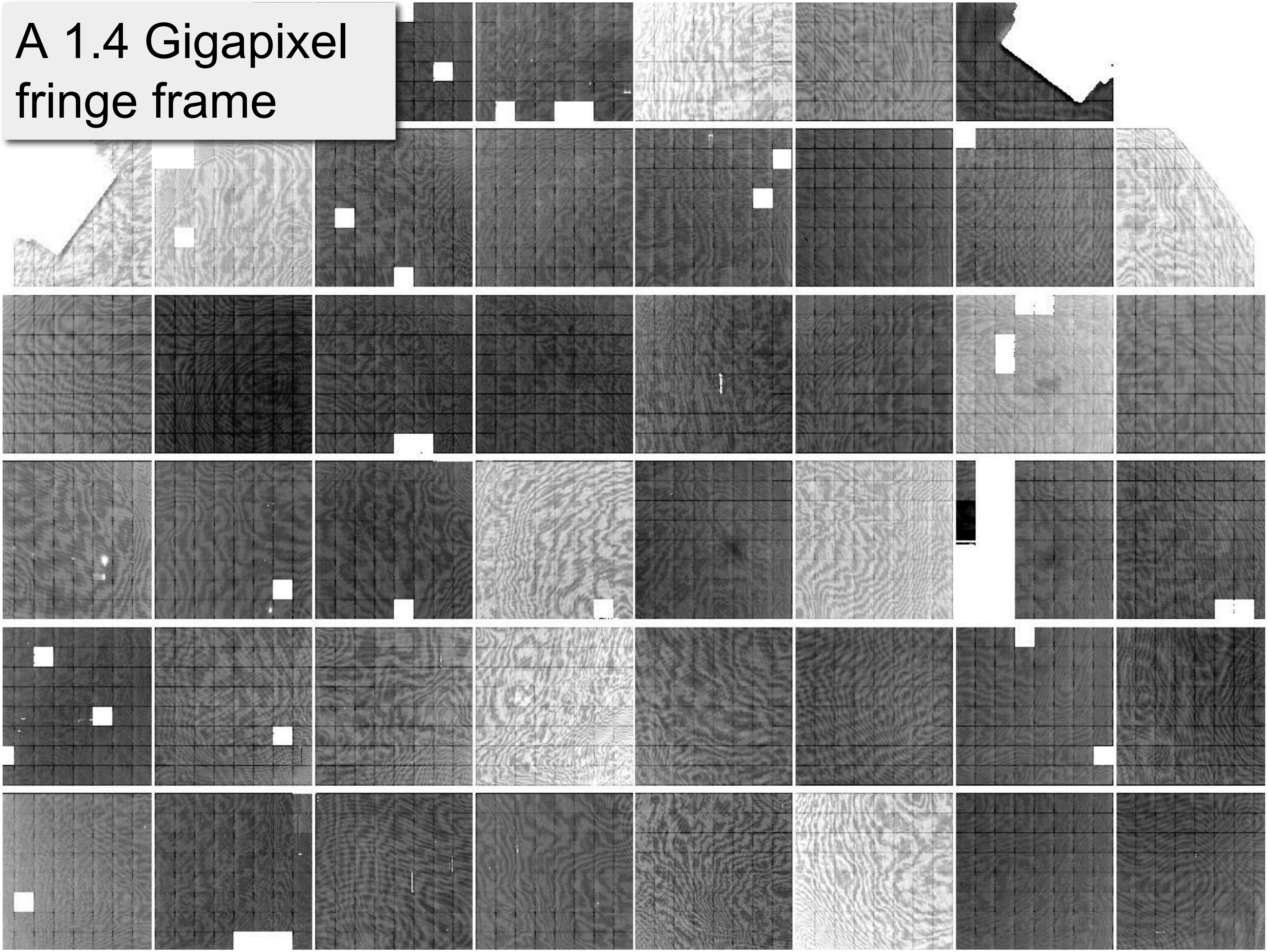
Measuring instrumental throughput relative to photodiode establishes zeropoints across filters. Leaves a single overall unknown (~ effective aperture), which is of less interest.

Proof of concept: 2007 CTIO test

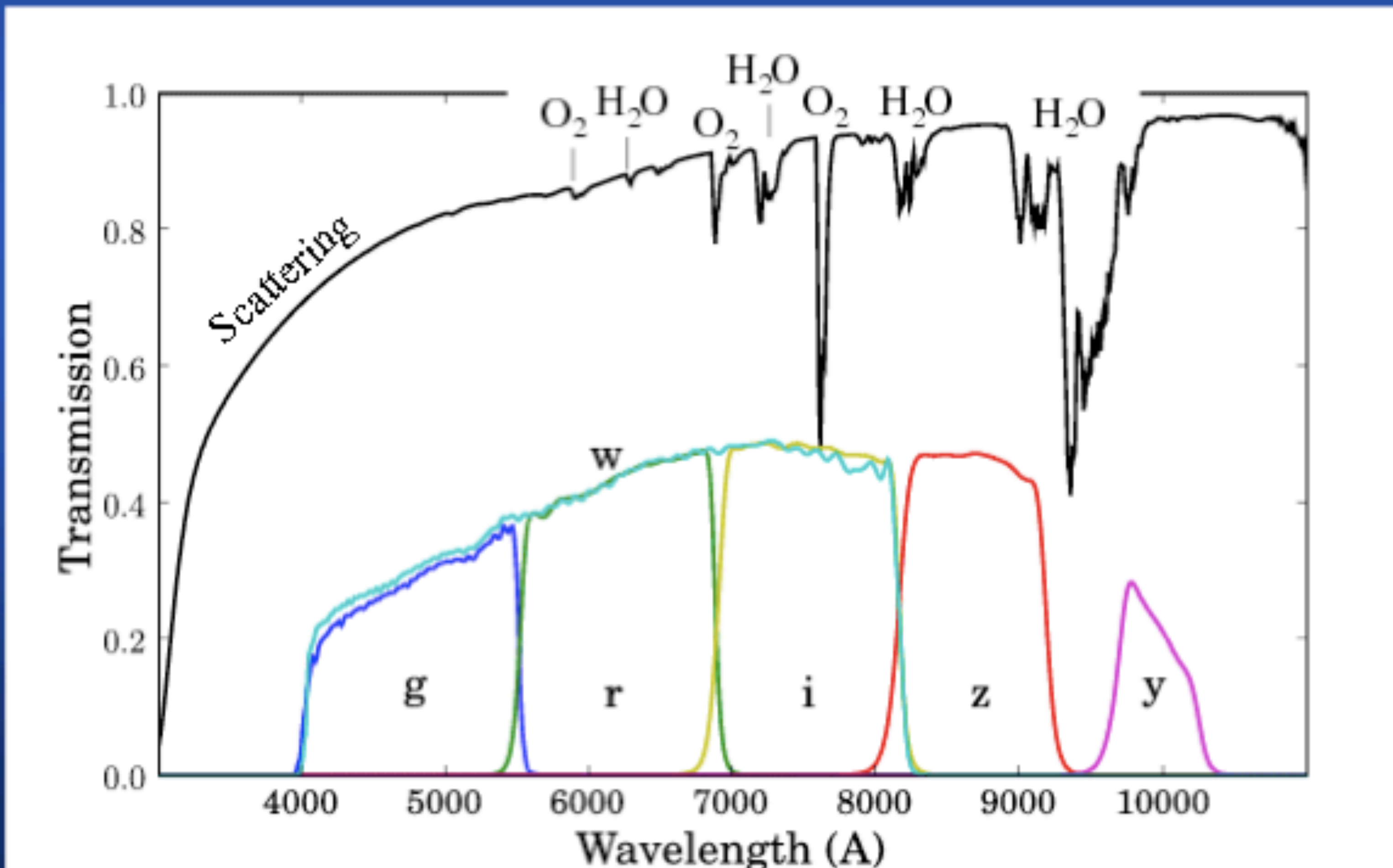



Total Throughput
Wavelength [nm]
0
.2
.4
.6
.8
400
500
600
700
800
900
1000

A 1.4 Gigapixel fringe frame



Atmospheric Transmission



The Traditional Approach

Measure “extinction coefficients” for each passband, using some combination of known stars and zenith angle variation. Regress flux data to zero atmosphere.

Use “standard stars” to determine relationship to established photometric systems.

Use thermal dust emission for Galactic extinction

Calibration observations compete with science.

From Bessell PASP (1999)

Large Corrections!

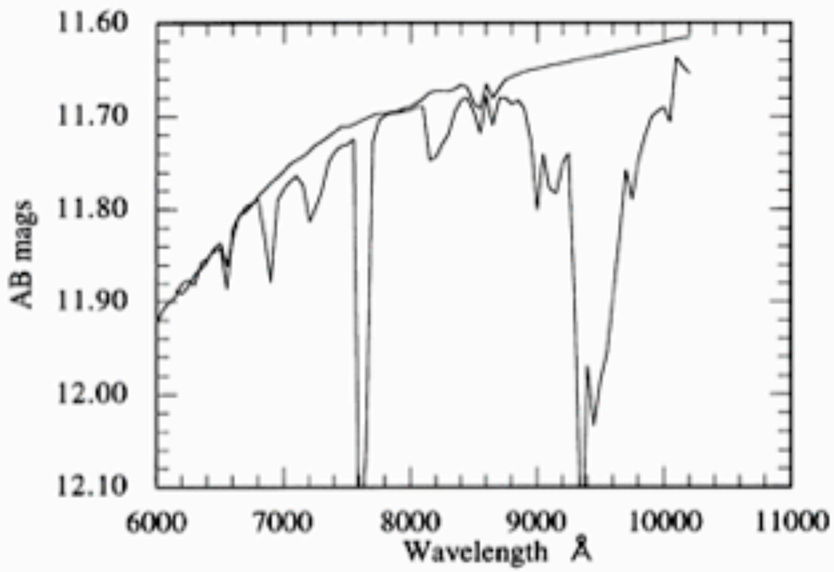


FIG. 3.—Original and revised magnitudes for LTT 9239

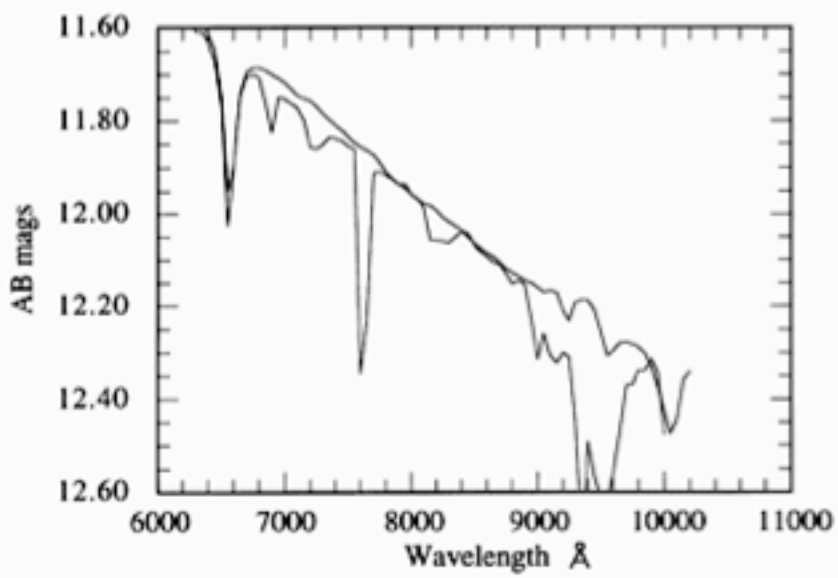


FIG. 4.—Original and revised magnitudes for EG 21

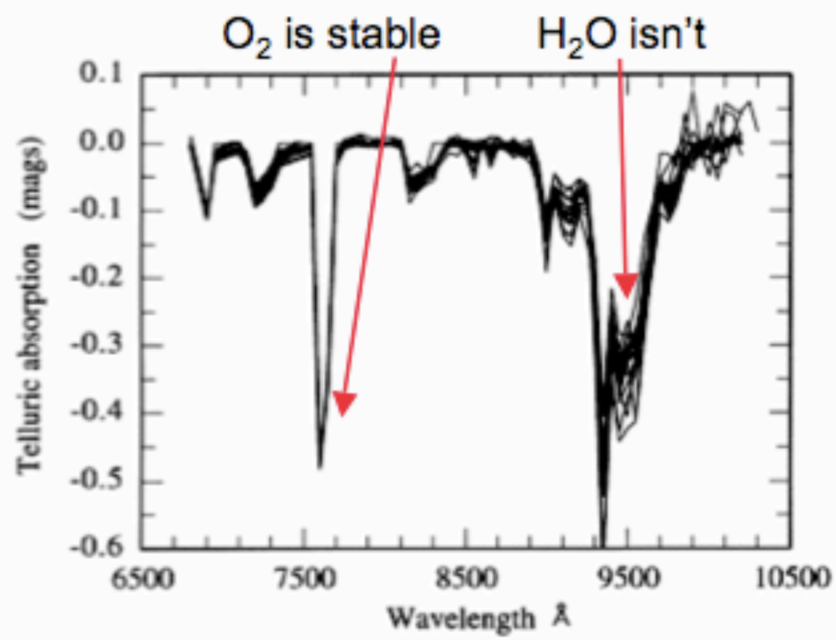


FIG. 1.—Plot of telluric absorption (revised minus original magnitudes) for the faint standards of Hamuy et al. (1994). Data are in 50 Å bins.

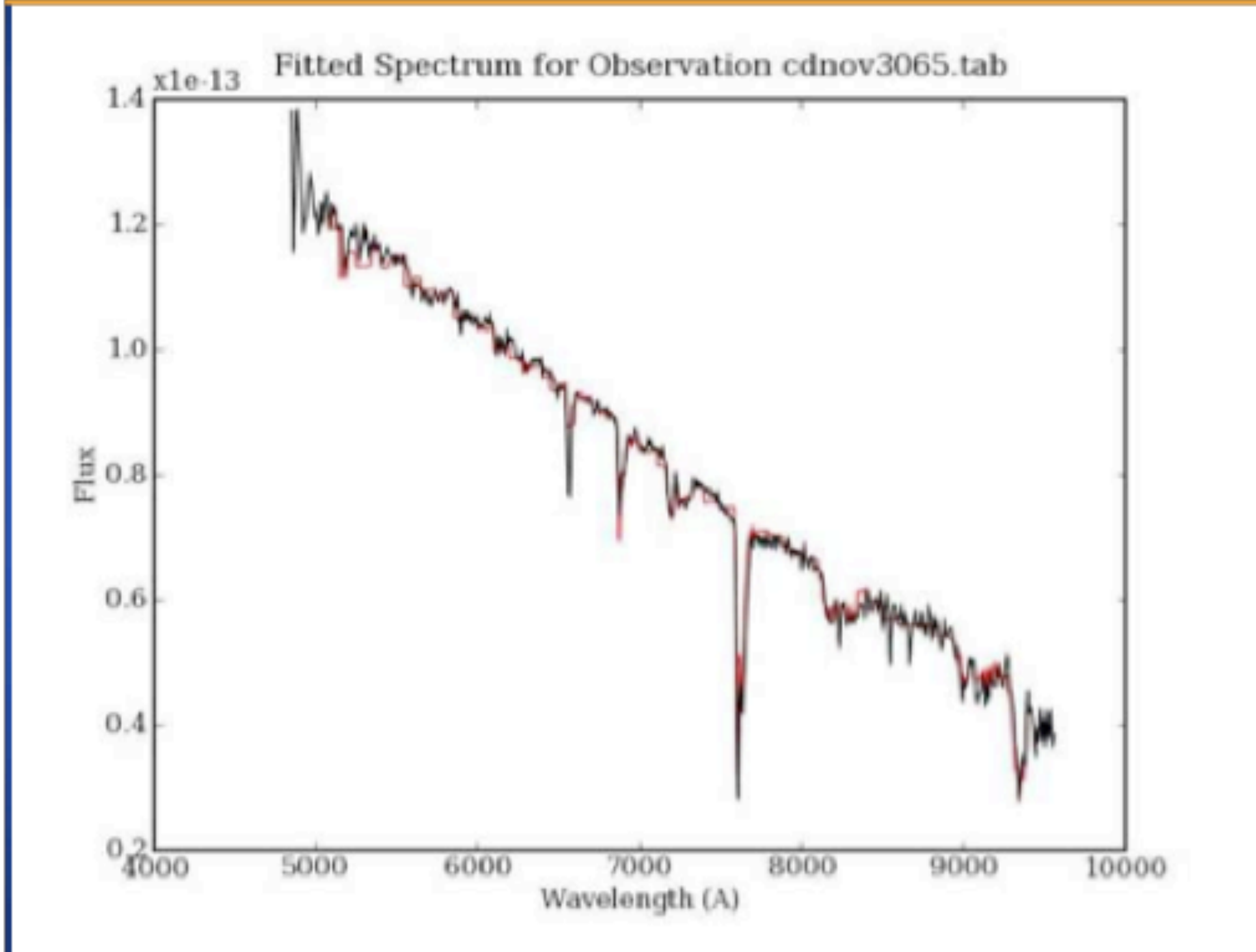
So we need to measure (or determine)

1. Extinction due to clouds, and transparency variations: This can be bootstrapped if a given field is observed many times, some in cloud-free conditions. Tougher if only a few visits per band.
2. Aerosols: LIDAR is probably best?
3. Water vapor: differential photometry or spectroscopy, or precise dual-band GPS?
4. Barometric pressure, for MODTRAN input.

Direct Measurements

- *Differential flux measurements, on and off water absorption features*
- *Differential retardance of dual band GPS signals.*
- *Infrared emission from clouds*
- *LIDAR (Rayleigh, Na, Raman…?)*
- *Differential extinction vs. wavelength*
- *Zenith dependence of extinction.*
- *….*

But we're learning how to do this…



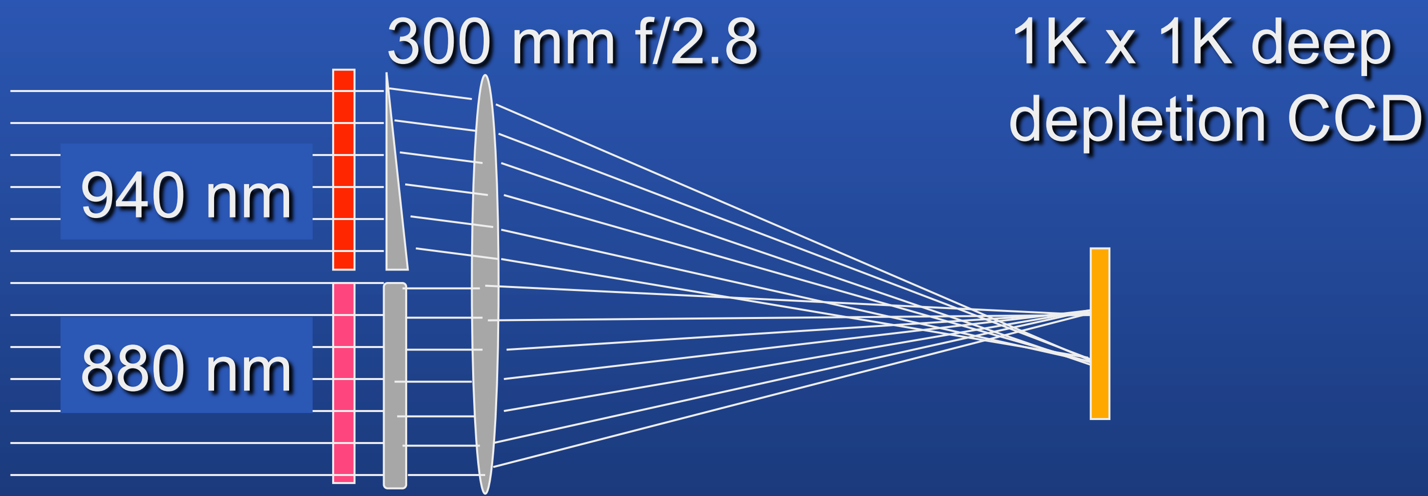
Joint fits to instrumental response, atmospheric attenuation, and source spectrum.

(D. Burke, LSST/SLAC.)

Differential Narrowband Water Monitor

Simultaneous measurements on-band (940 nm) and off-band (880 nm) using stars to back-light atmosphere.

Proof-of-principle data shows promising results



Dual-band Geodetic-Quality GPS

- Water vapor in atmosphere produces difference in arrival times for GPS signals at two different wavelengths
  (1.575 and 1.228 GHz).

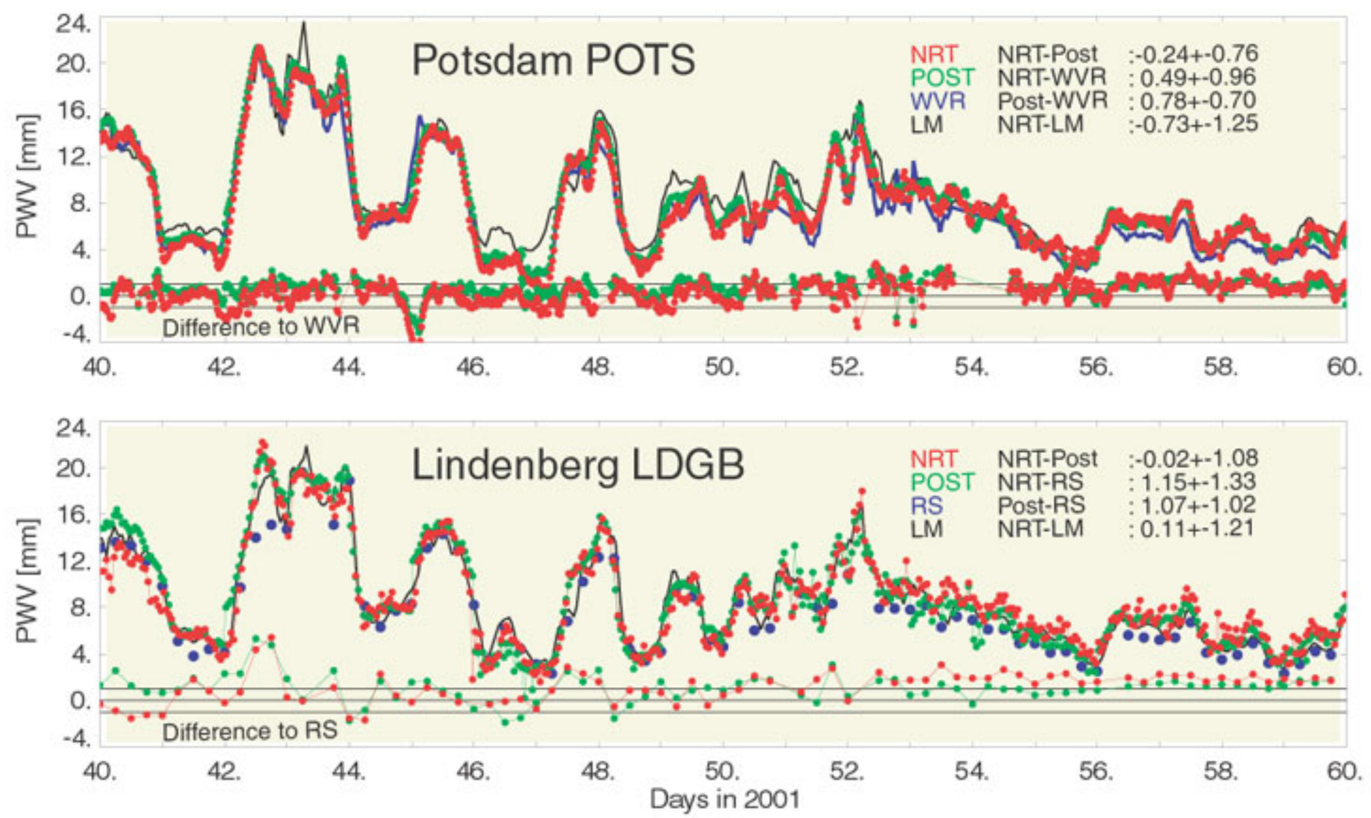


FIGURE 5 Comparison of NRT results with instrument measurements and Local Model (LM) of DWD, Potsdam and Lindenberg

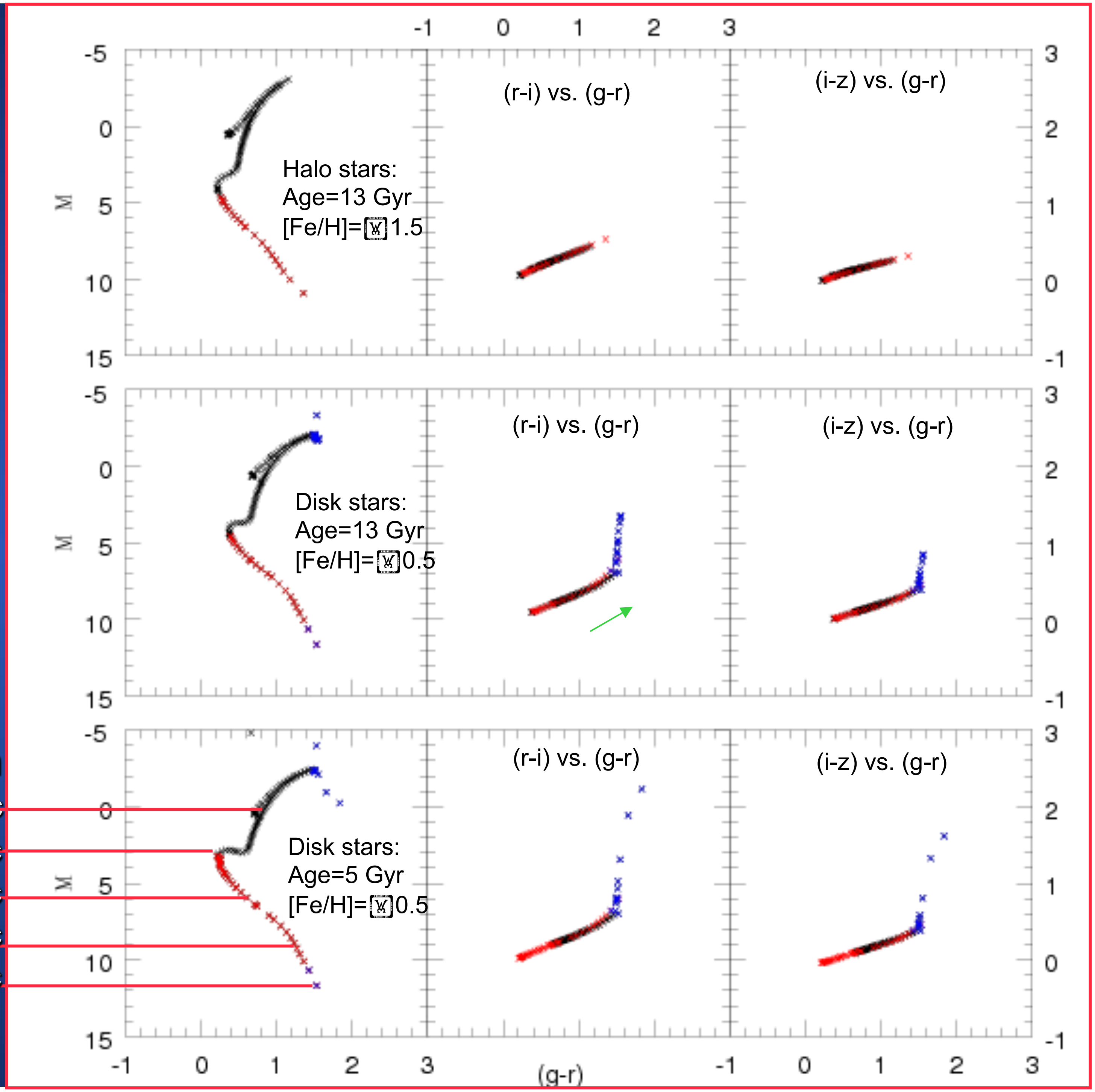
http://www.gpsworld.com/files/gpsworld/nodes/2002/721/chart3.jpg

Can we use the statistical properties of stars as a calibration tool?

Metallicity and Age Effects On Stellar Locus

Age: blue tip
Metallicity: kink

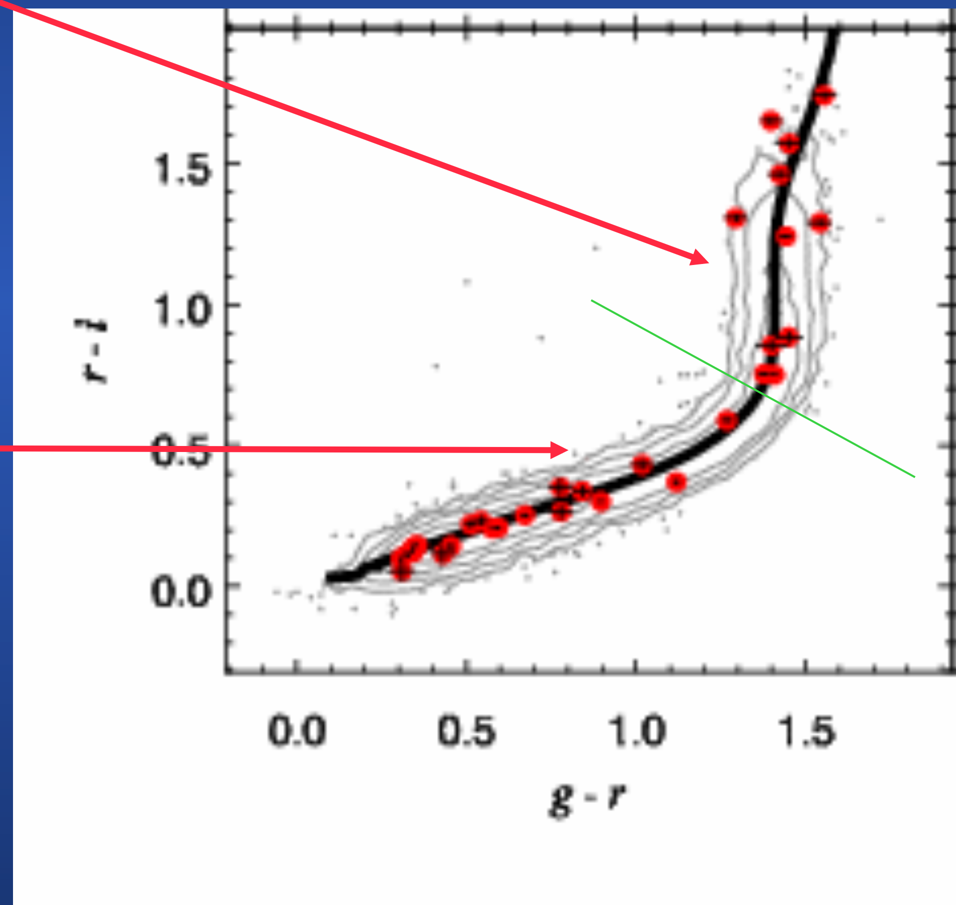
Detectable from
6 kpc to 200 kpc
1.5 kpc to 63 kpc
0.4 kpc to 16 kpc
0.1 kpc to 4 kpc
0.025 kpc to 1 kpc



A universal *observed* stellar locus

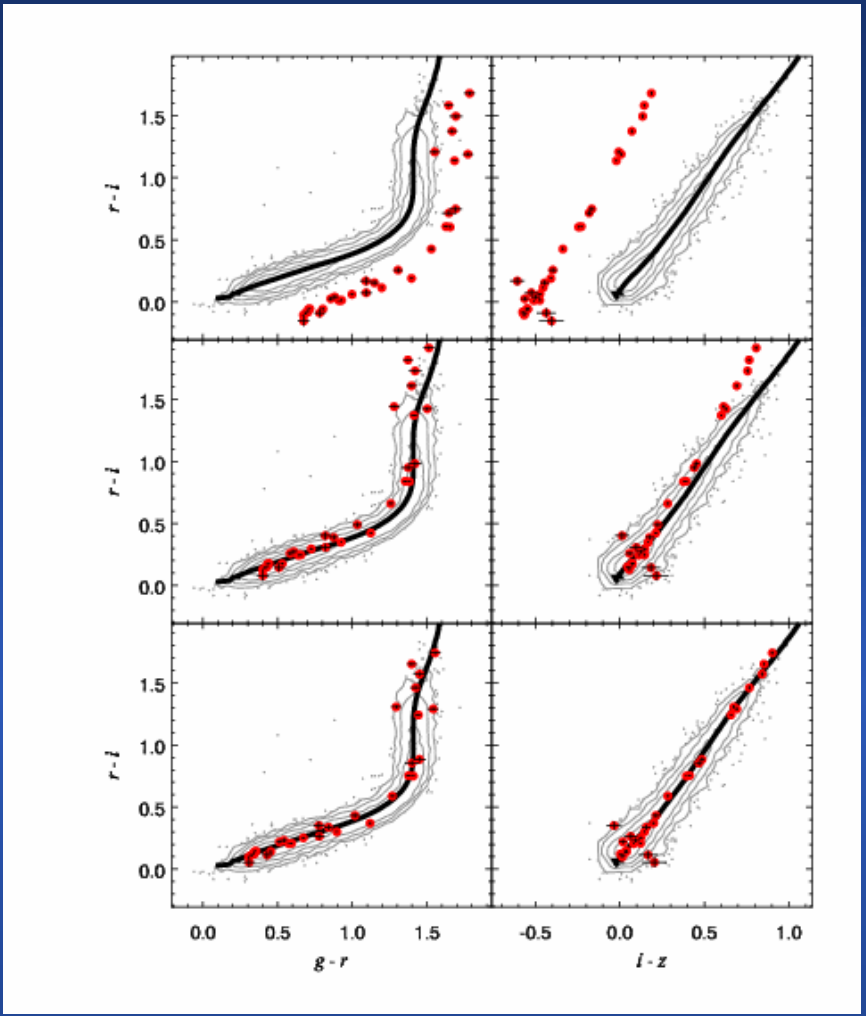
Disk M dwarfs with metallicity [Fe/H] > 0.7
all from closer than ~1 kpc
so minimal sensitivity to
MW metallicity gradients

Main sequence disk stars
and evolved halo stars



SLR- The Basic Idea

- *Take flatfielded but otherwise uncalibrated images*
- *Extract a catalog of sources*
- *Identify the stellar locus in color-color space*
- *“Snap” the observed locus into agreement with a fiducial locus*
- *Apply this color correction to all objects in the catalog*



$$\begin{bmatrix}(g-r)\\(r-i)\\(i-z)\end{bmatrix}_{instrumenal} = \begin{bmatrix}k_1\\k_2\\k_3\end{bmatrix} + \begin{pmatrix}1+M_{11} & M_{21} & M_{31}\\ M_{12} & 1+M_{22} & M_{32}\\ M_{13} & M_{23} & 1+M_{33}\end{pmatrix} * \begin{bmatrix}(g-r)\\(r-i)\\(i-z)\end{bmatrix}_{calibrated}$$

A New Network of Precise NIST-based Spectrophotometric standards?

Current spectrophotometric standards fall short in 3 ways:

1. *Too bright*

2. *Not tied to current metrology standards, they are Vega-based, or rely on white dwarf atmospheric models.*

3. *Inadequate attention paid to atmospheric attenuation.*

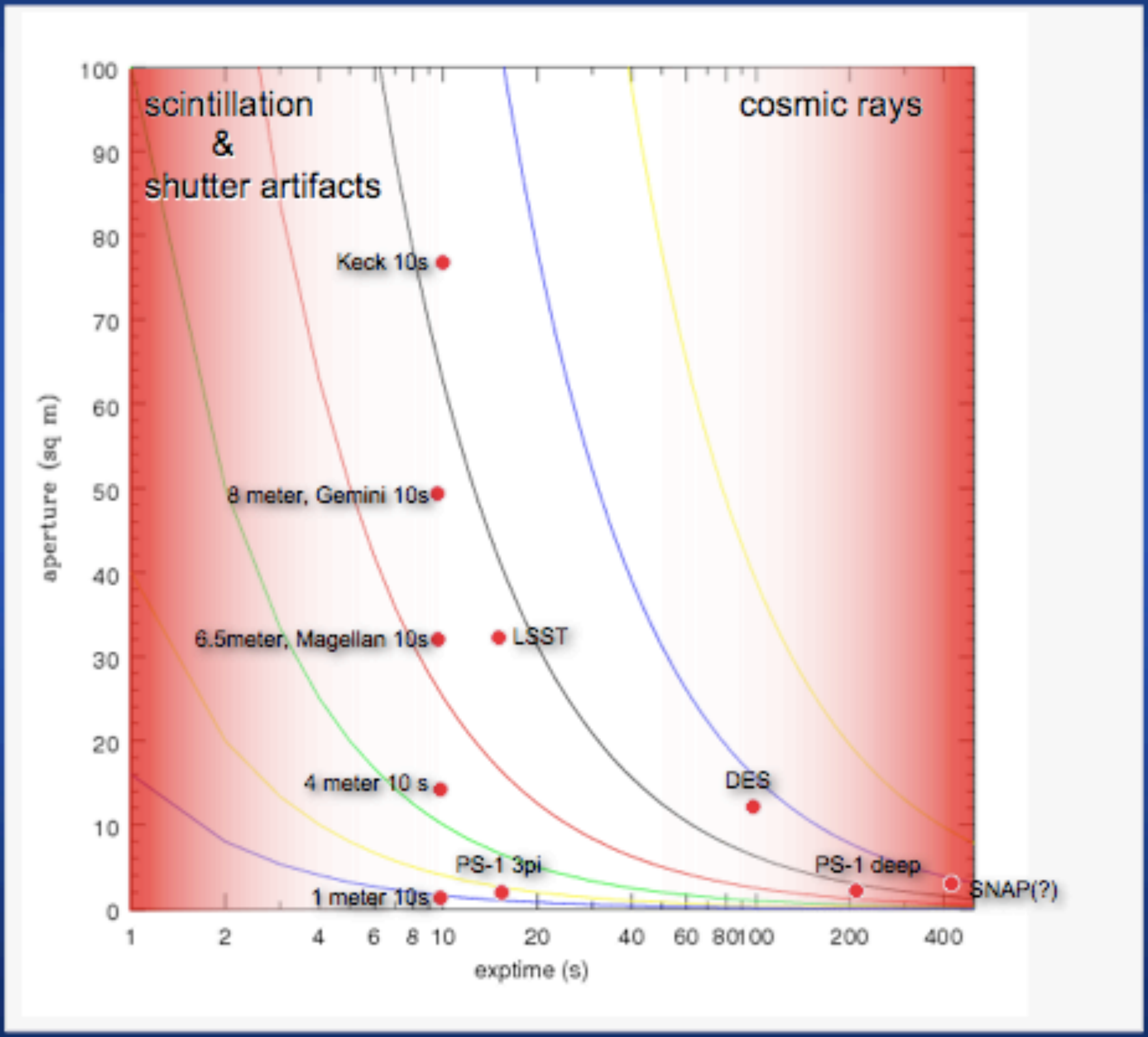
Magnitude Range per exposure

Hyperbolae are lines of constant integrated photons, separated by 1 magnitude.

Four major imaging surveys (LSST, DES, PS-1 deep fields, SNAP) all have a *common* desired photometric calibrator magnitude.

PS-1 all-sky survey is 3 magnitudes brighter

Saturation is the issue. LSST saturates at around 18th, but depends on sky brightness and clouds.

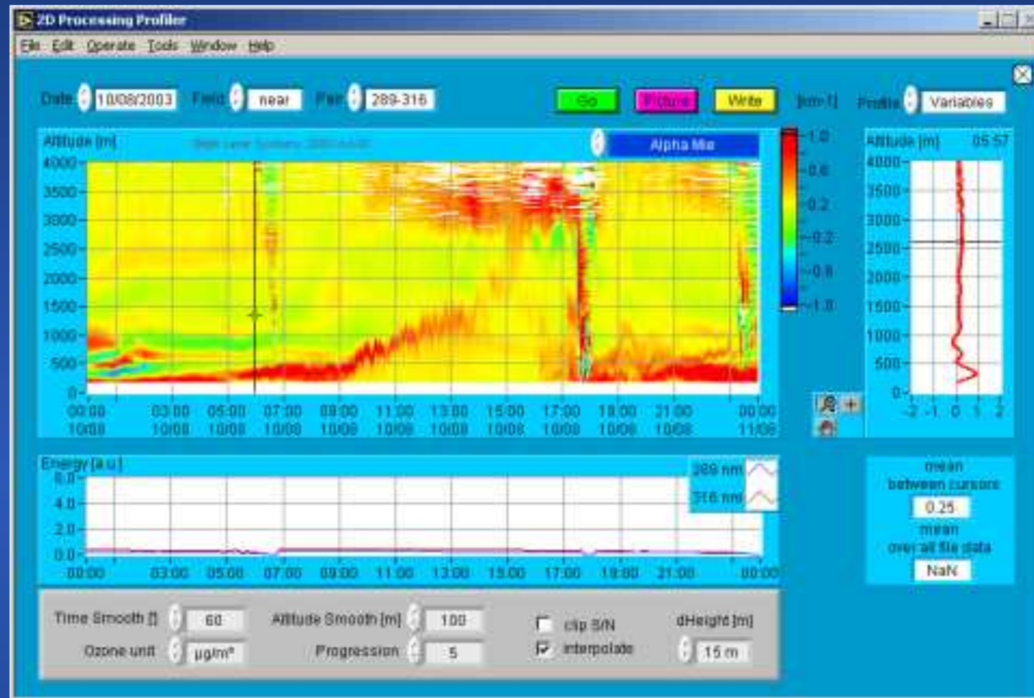


Is LIDAR the right tool for aerosols, and if so which kind of LIDAR?

Rayleigh?

Na?

RAMAN?



Astronomical observations only care about integrated line of sight attenuation.

Clouds and Grey transparency

PanSTARRS takes 30 sec images

LSST will take 15 second images.

Can do local re-normalization, over some region…"ubercal".

Over what angular scale can grey attenuation be assumed constant?

- Fast-framing imager, co-boresighted?
- Use variability of sources to deduce power spectrum of attenuation?
- Thermal imager?
- Data from geo-synch satellites?

Open Questions: Detailed

- *What is the most effective way to determine water vapor, and what is its structure function? Is GPS good enough?*
- *What is the role of artificial sources, on aircraft/balloons/satellites?*
- *What instrumentation would be optimal for establishing a new set of all-sky spectrophotometric standard stars?*
- *Can we exploit the uniformity of the stellar locus?*
- *How can we best field instruments at 3 sites of prime interest:*
    - *Mt. Hopkins, AZ*
    - *Haleakala, HI*
    - *Cerro Tololo and Cerro Pachon, Chile.*

Open Questions: High-level

- What distribution in time and pointing, will suffice to meet our goals? What are the spatio-temporal structure functions?
- How far from primary boresight can we go?
- What is the most precise atmos. transmission model available?
- What is the minimal set of observed parameters needed to adequately characterize atmospheric transmission?

How can we blend the experiences, meet common needs, and exploit the respective strengths of diverse scientific communities?

A collaborative effort…..

LSST team
PanSTARRS team
Univ of New Mexico
NIST
NOAO

Heartfelt thanks to our local organizing committee for this important workshop!

Segev BenZvi
Bianca Keilhauer
Michael Prouza
Stefan Westerhoff

Galactic Extinction

The plane of the Milky Way is laced with dust lanes. Other patches of dust may also be out there.

We currently use the thermal IR emission of dust, in conjunction with assumptions about how that relates to optical properties, to infer line of sight extinction. This is the "SFD" map.