The Large Synoptic Survey Telescope

A Proposed Facility for Pursuing New Fundamental Physics

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Astrophysical Evidence
for New Physics

- ➢ Matter-antimatter asymmetry
  - Baryon number & CP violation in early universe?
- ➢ Non-baryonic Dark Matter
  - New particle physics sector?
- ➢ Neutrino oscillations, mass constraints
  - Non-zero masses, mixing/oscillations
- ➢ Non-zero Cosmological Constant, Λ
  - Evidence for weirdness in the vacuum
  - Puzzle #1: why is Λ so small?
  - Puzzle #2: why is Λ so large?
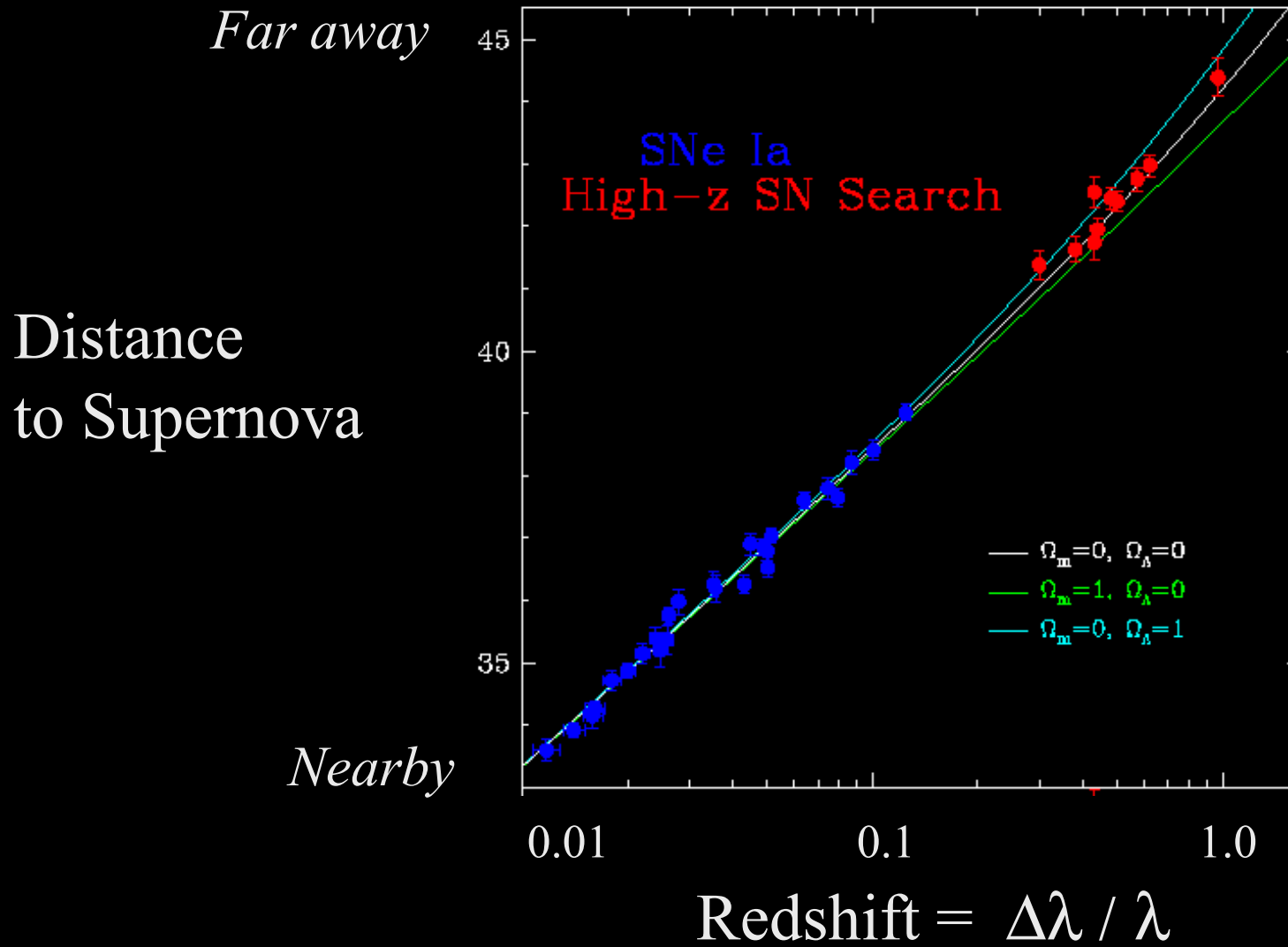
(Susskind, hep-th/0204027)

Supernovae are powerful
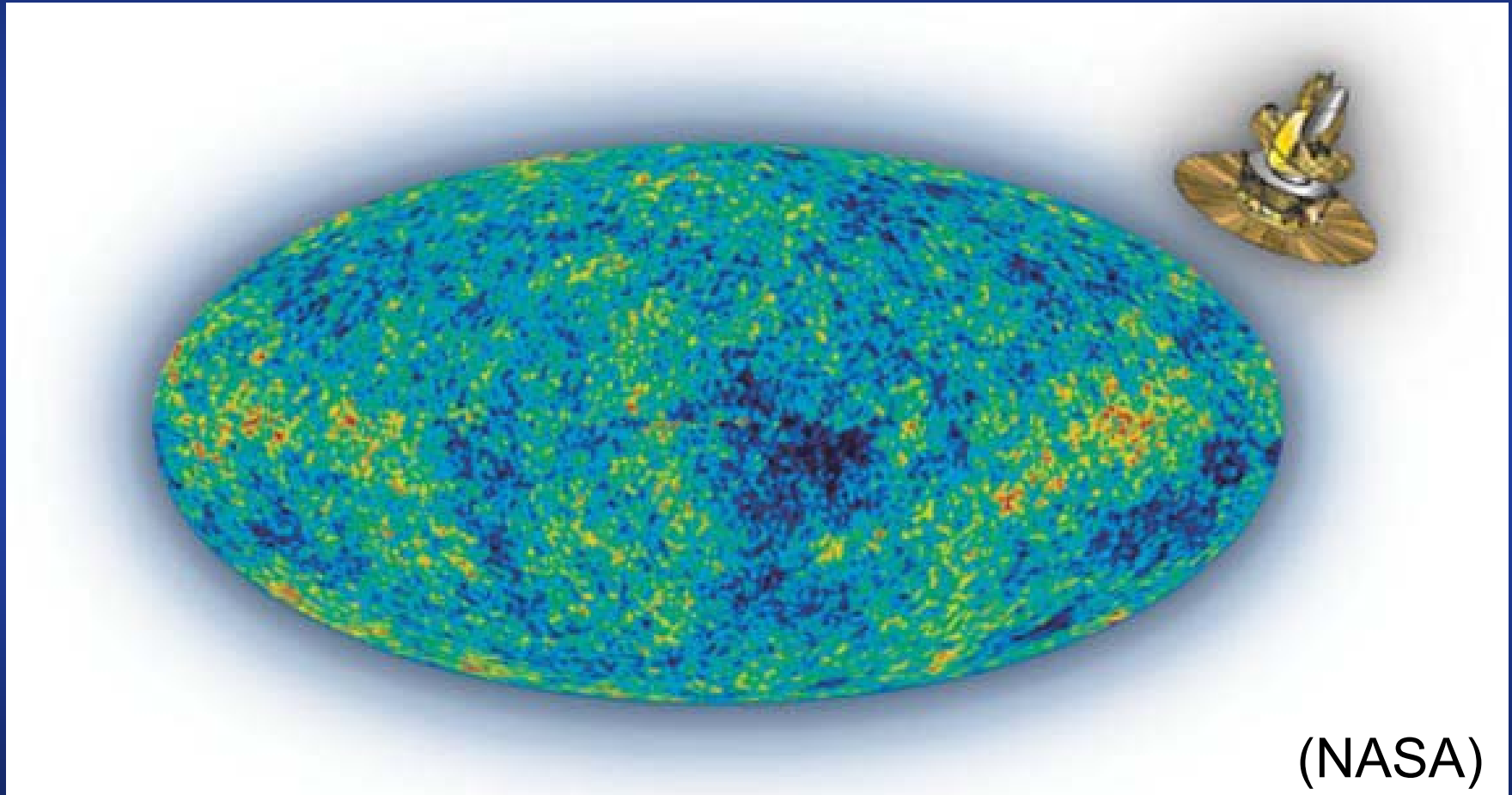cosmological probes
  Distances to ~6% from brightness
  Redshifts from features in spectra

(Hubble Space Telescope, NASA)

Schmidt et al, High-z SN Team

Far away

Distance
to Supernova

Nearby

SNe Ia
High−z SN Search

$\Omega_m=0$, $\Omega_\Lambda=0$
$\Omega_m=1$, $\Omega_\Lambda=0$
$\Omega_m=0$, $\Omega_\Lambda=1$

0.01   0.1   1.0

Redshift = $\Delta\lambda / \lambda$

WMAP- The Relic Hiss of the Big Bang


(NASA)

Emergence of a Standard Cosmology

Our geometrically flat Universe started in a hot big bang 13.7 Gyrs ago.
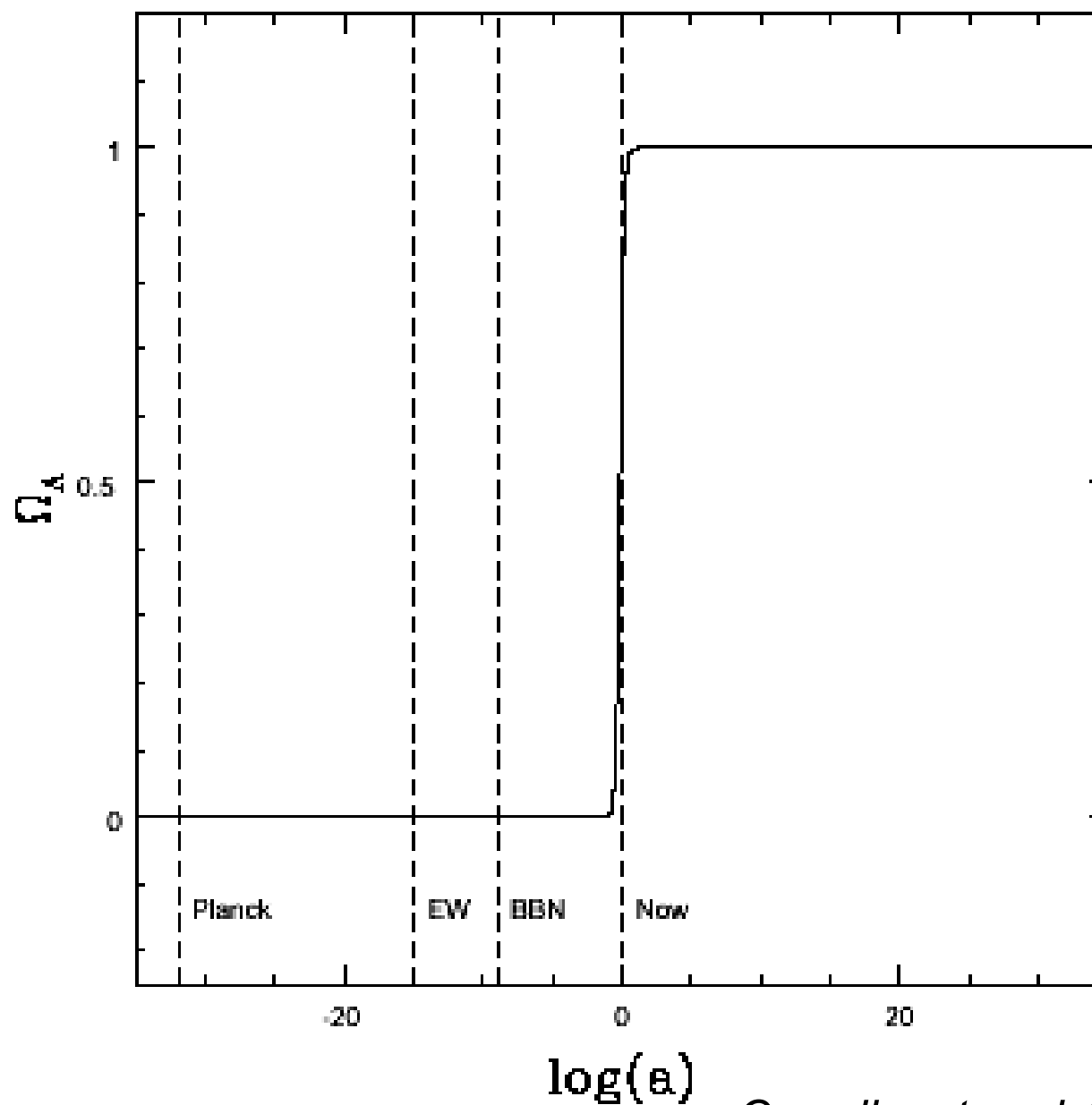
The evolution of the Universe is increasingly dominated by the phenomenology of the vacuum.

Matter, mostly non-baryonic, is a minor component.

Luminous matter comprises a preposterously low fraction of the mass of the Universe.

- lambda
- non-baryonic
- baryonic
- luminous

A Repulsive Result!

Carroll, astro-ph/0004075
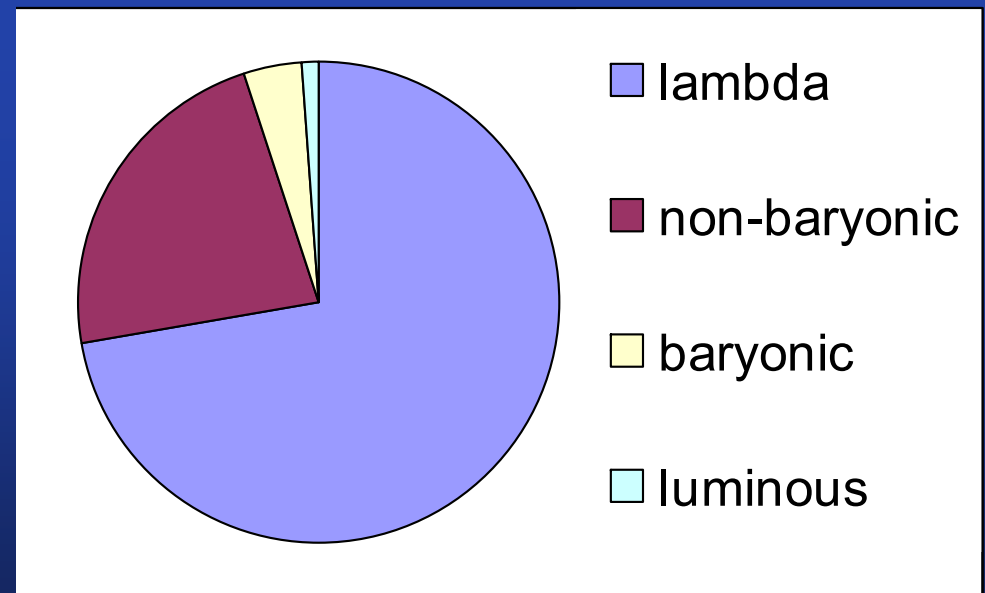
Two philosophically distinct possibilities…

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

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

In either case, it's new fundamental physics!

A Roadmap for Probing New Physics

- Existing facilities have shown us new mysteries

- We should pursue the signal!

- Evolving facilities

    - New instruments for existing telescopes

    - Dedicated ground-based facilities with control of systematics

    - Space-based initiatives

    - ...

What would an optimized ground-based facility look like?

- Large collecting area
- Wide field of view
- Real-time analysis of data
- Significant leap in figure-of-merit

    Area x Field of View

Large Synoptic Survey Telescope

Highly ranked in Decadal Survey

Optimized for time domain
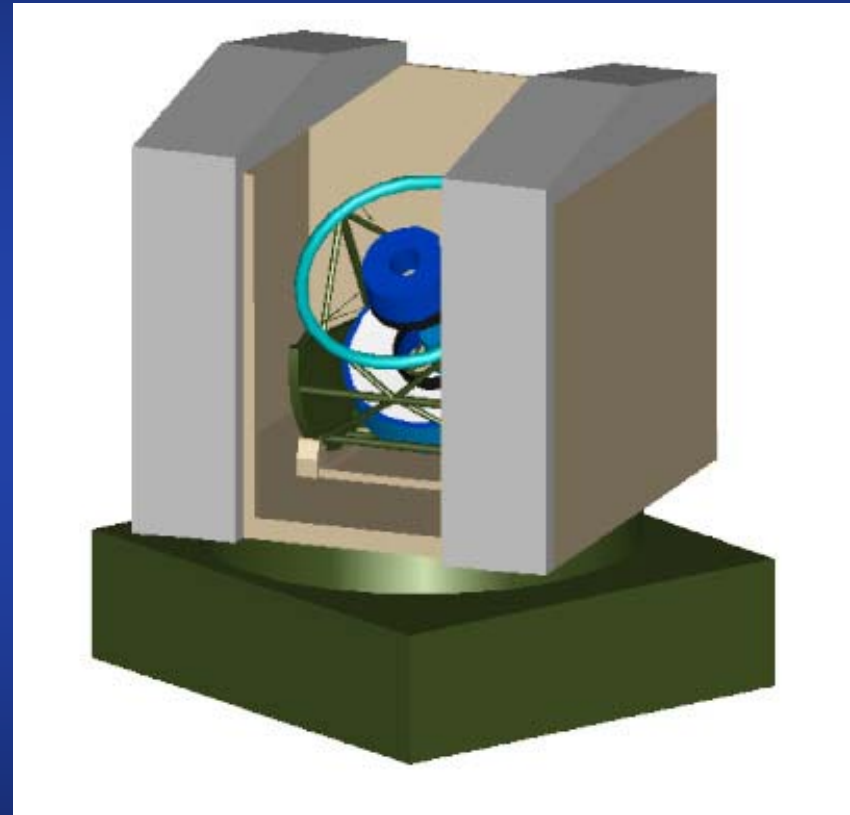
scan mode

deep mode

9.6 square degree field

6.5m effective aperture

24th mag in 20 sec

> 20 Tbyte/night
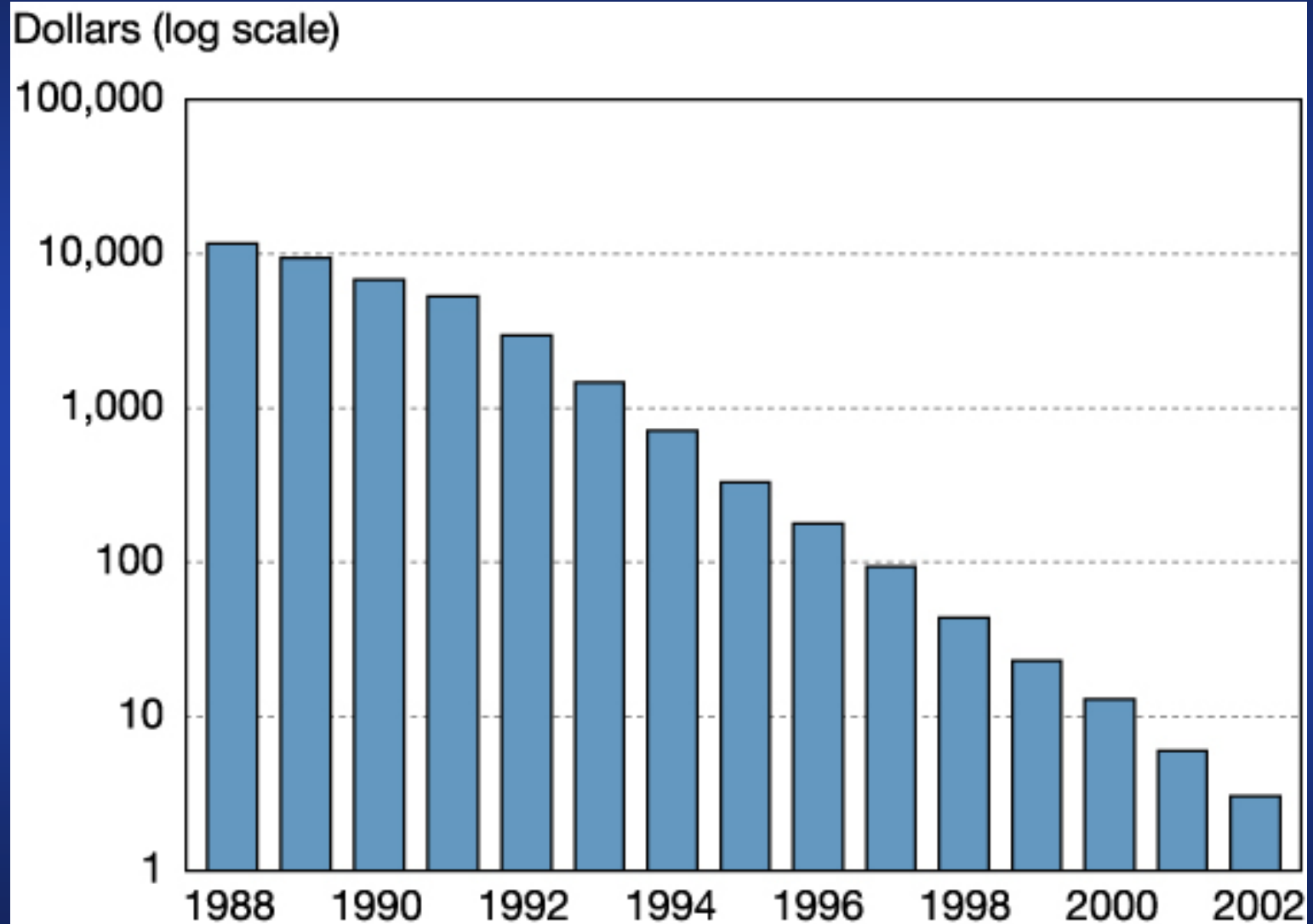
Real-time analysis

Simultaneous multiple science goals

Large Mirror Fabrication
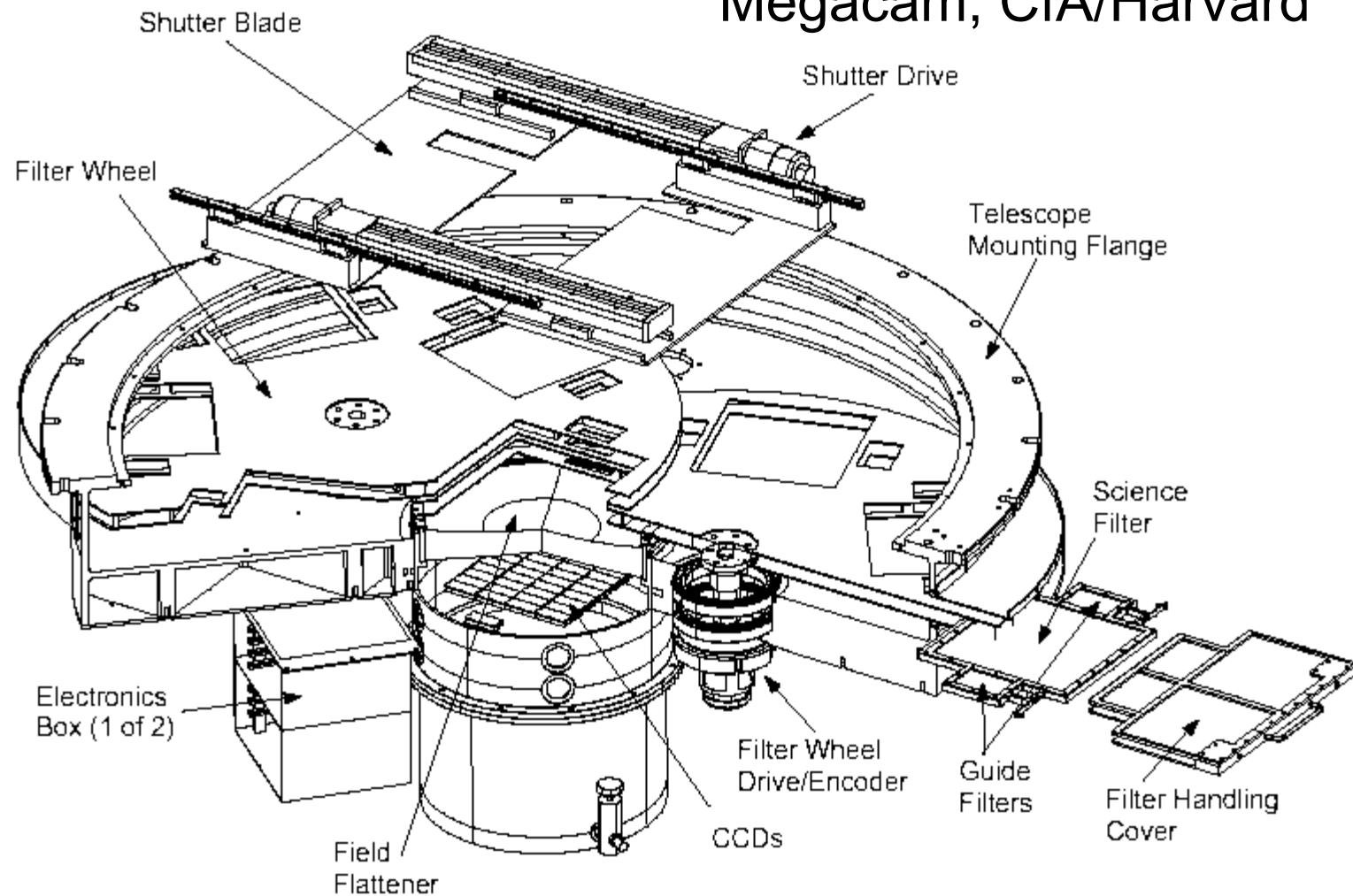

University of Arizona

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Cost per Gigabyte
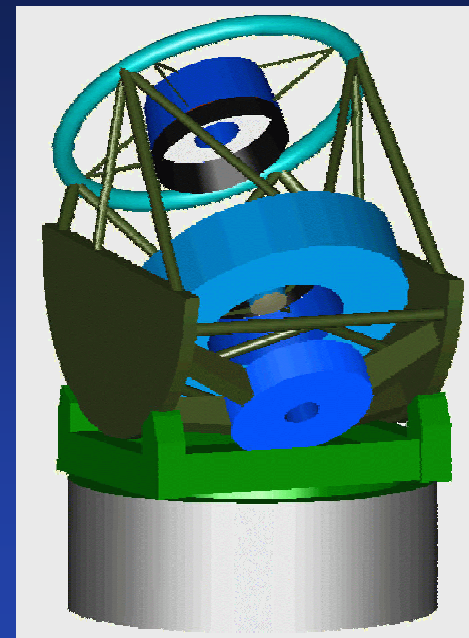

Dollars (log scale)

NOTES: 2001 and 2002 data are projected.

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Large Format CCD Mosaics

Megacam, CfA/Harvard

So Why Should <u>Physicists</u> Care About the Large Synoptic Survey Telescope?



Fundamental Physics via Astrophysics
- Nature of Dark Matter (strong, weak and μlensing)
- Dark Energy (SNe, lensing, Large Scale Structure)
- Extreme Systems (linkages with LISA, EXIST…)

Qualitative leap in capabilities (AΩ product)

Some Examples

- **Thousands of type Ia supernovae**
  - ➤ Detailed study of Λ physics
  - ➤ Isotropy of Hubble diagram
  - ➤ Subdivide data set
    - Host galaxy type
    - Redshift shells
    - SN color/decline parameter

- **Time delays from strongly lensed SNe**
  - ➤ Constrains nature of dark matter

- **Weak Lensing of galaxies as a probe of evolution of structure**

- **Optical counterparts to gravity wave sources**
  - ➤ Break degeneracy in $(1+z)M_{chirp}$

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Cosmic shear vs redshift

PATH OF LIGHT
AROUND
DARK MATTER

DISTANT
UNIVERSE

OBSERVED SKY
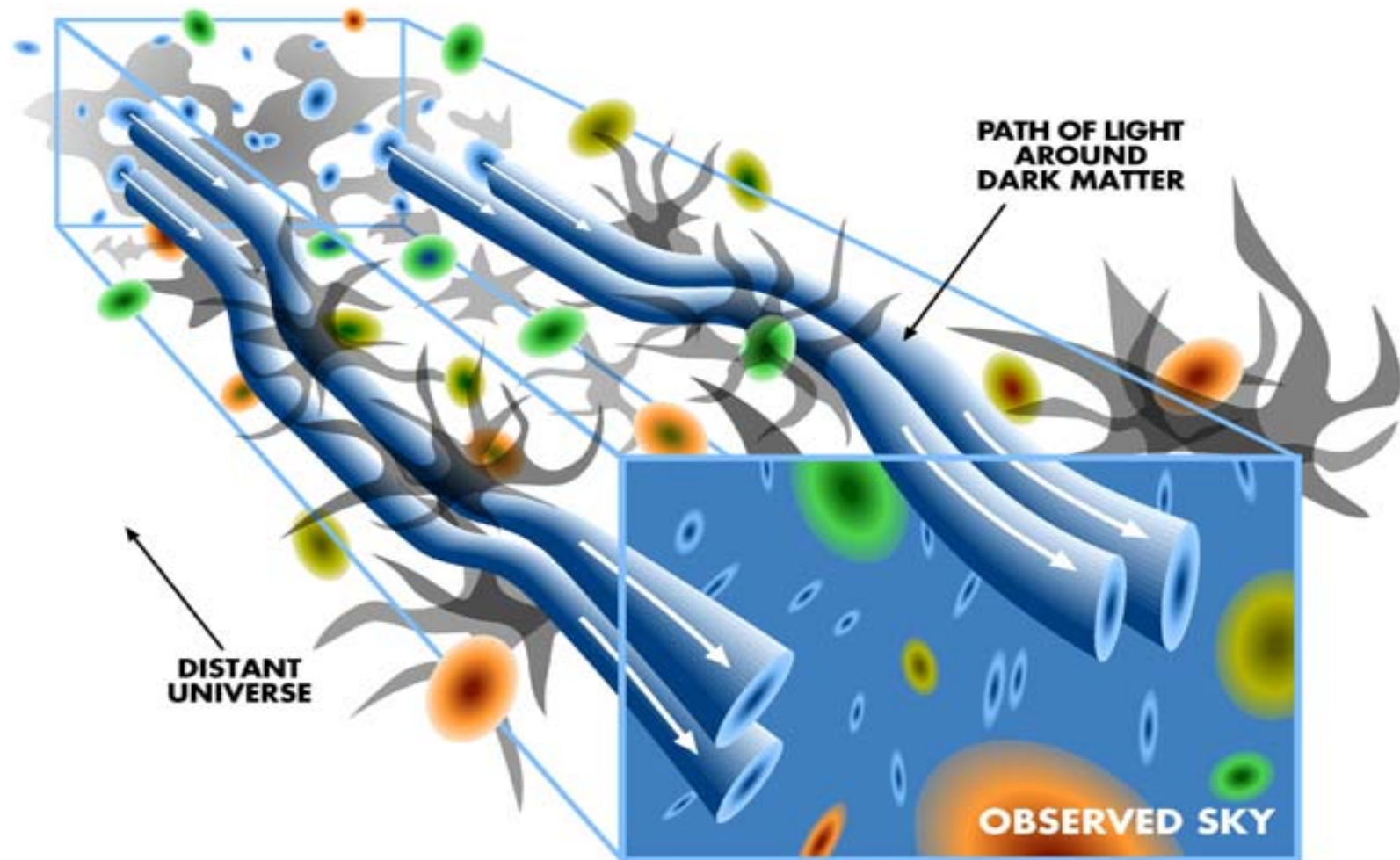
Near Earth Asteroids

- Inventory of solar system is incomplete
- R=1 km asteroids are dinosaur killers
- R=300m asteroids in ocean wipe out a coastline
- Demanding project: requires mapping the sky down to 24th every few days, individual exposures not to exceed ~20 sec.
- LSST will detect NEAs to 300m

LSST Challenges

- Large effective aperture wide field telescope

- 2.8 Gpix focal plane

- Analysis pipeline, realtime.

- Automated Variability Classification
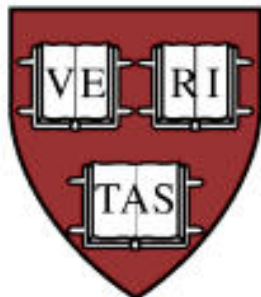
- Database schema/structure and indexing

LSST Optics
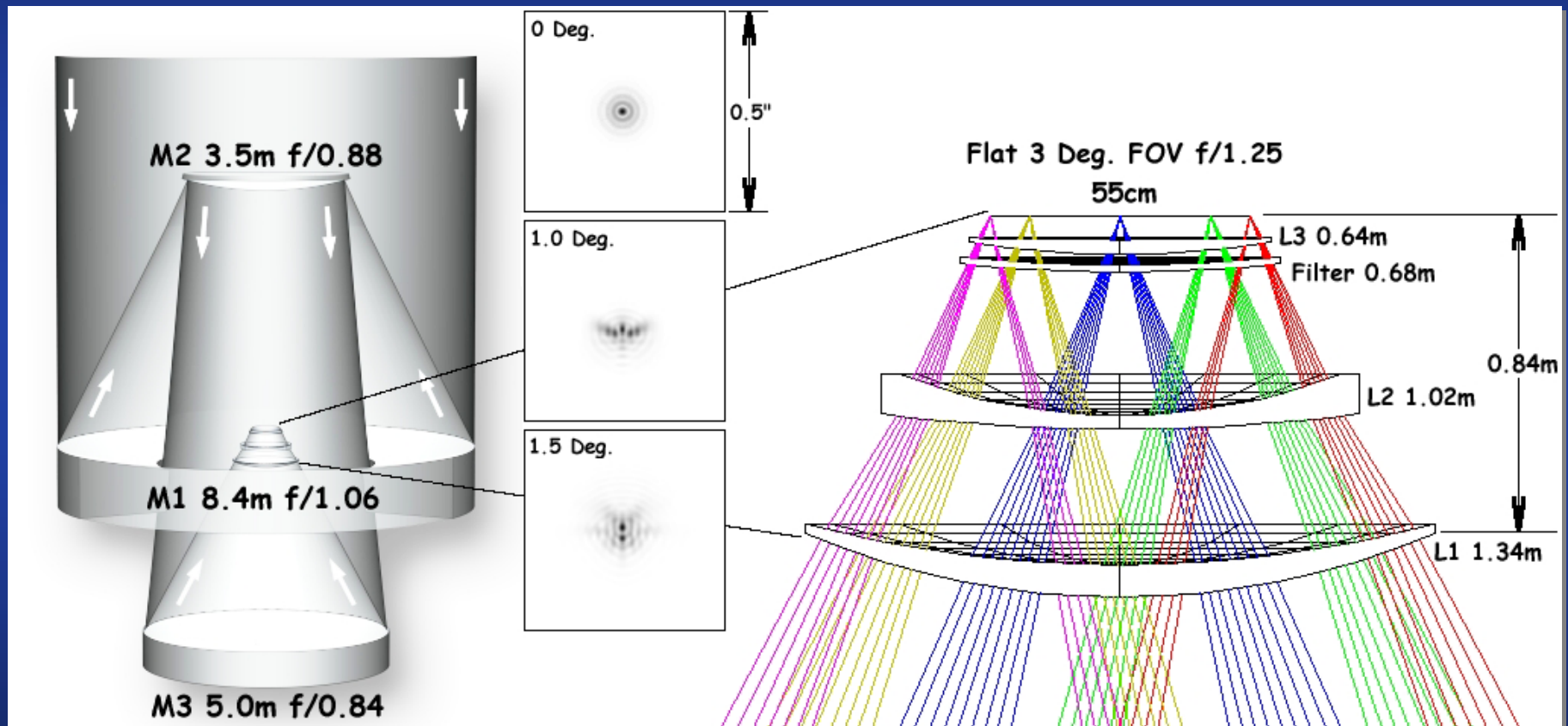
The Flavor of Astronomical Data

Sources at r = infinity

Wavefront distortion due to atmospheric structure – "seeing"

2-d Gaussian distribution of flux from point source, "Point Spread Function"

Optical system maps angles to focal plane position

2-d array of 16 bit integers
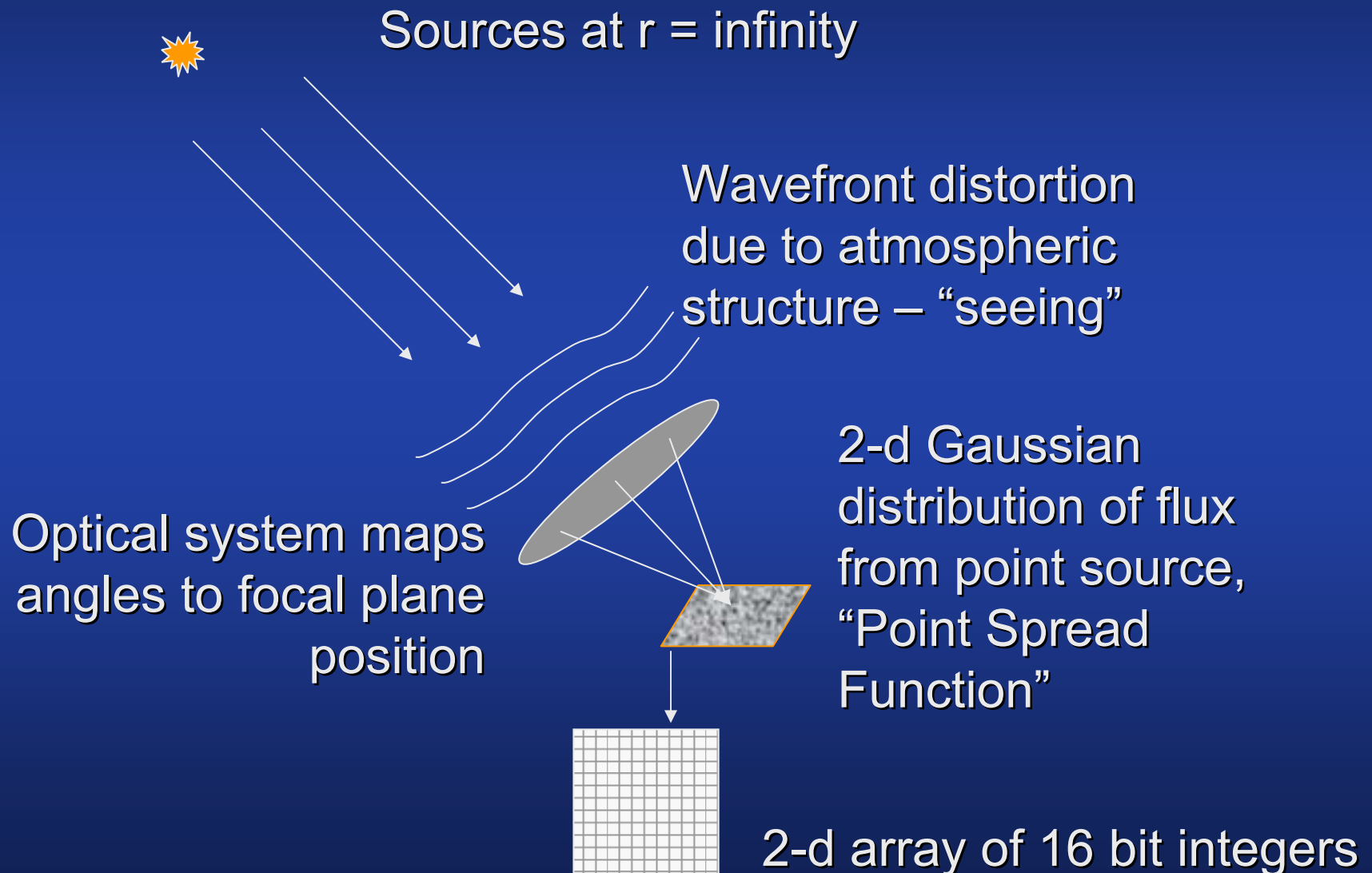
Point Sources
Appear as 2-d Gaussians
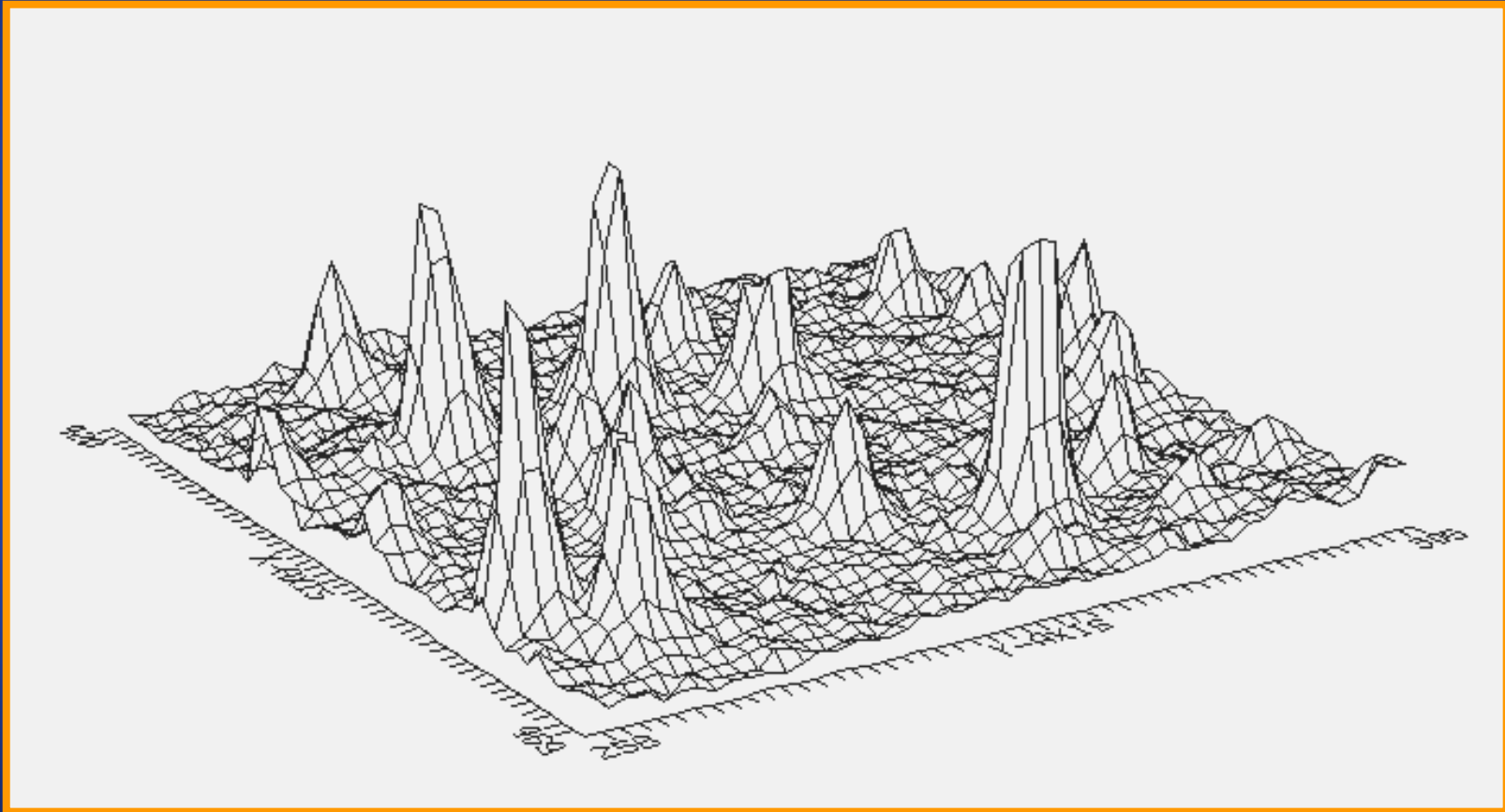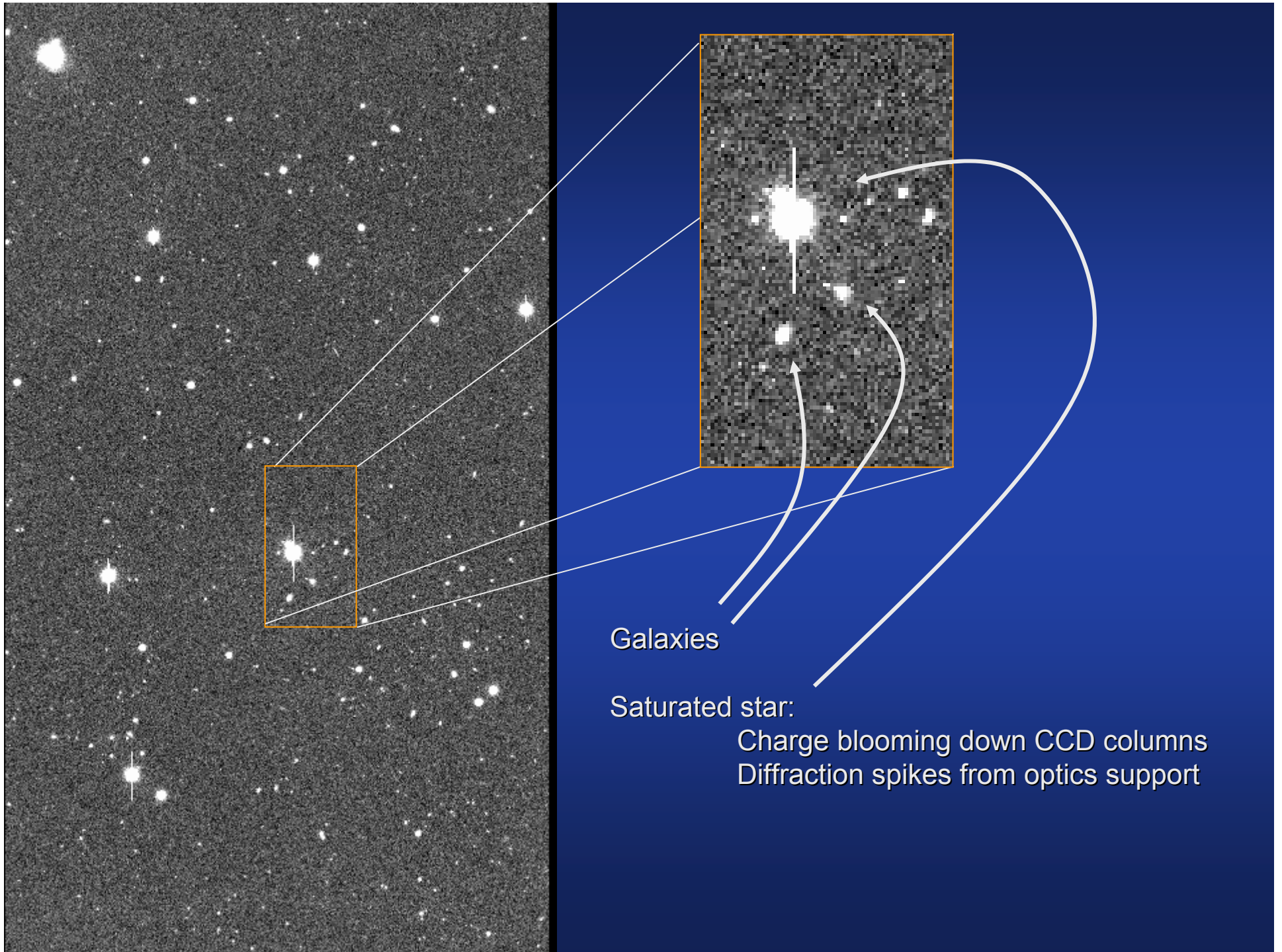
Galaxies

Saturated star:

Charge blooming down CCD columns
Diffraction spikes from optics support

Typical Image Processing Stages

Pre-processing:
Crosstalk removal

Cleanup and source detection:
Subtract bias structure
Divide by QE frame
Artifact removal
Optimal spatial filtering
Threshold detection
Object Characterization

Catalog insertion:
Classification tags
Index update
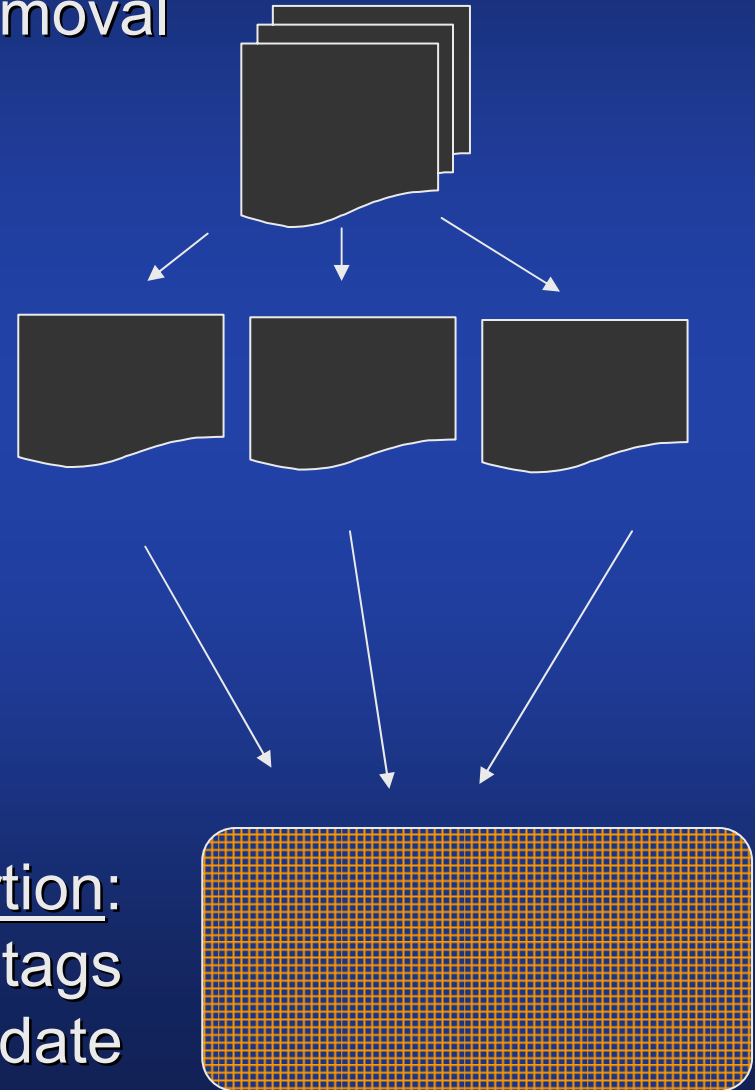
Optimal Image Arithmetic

- To identify variability, can subtract a "template" image constructed from prior images.

- In trying to go as deep as possible, can co-add frames together.

- In both cases, algorithmic work needed.

Frame Subtraction

Epoch 1   Epoch 2 (3 weeks later)   Epoch 2 - Epoch 1

(High-z Supernova Team)

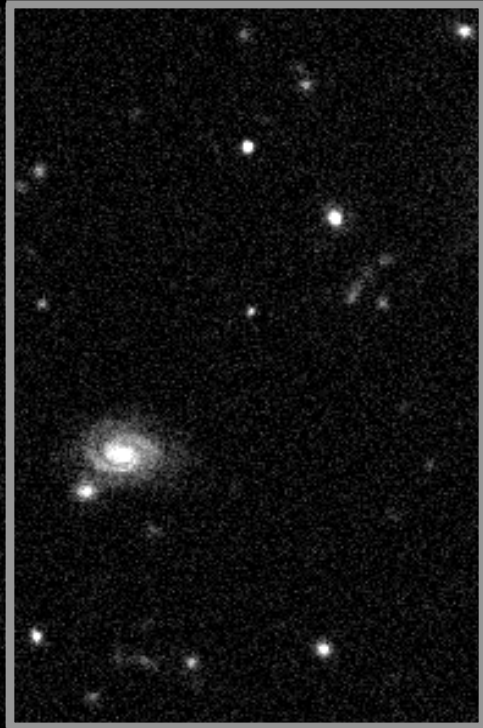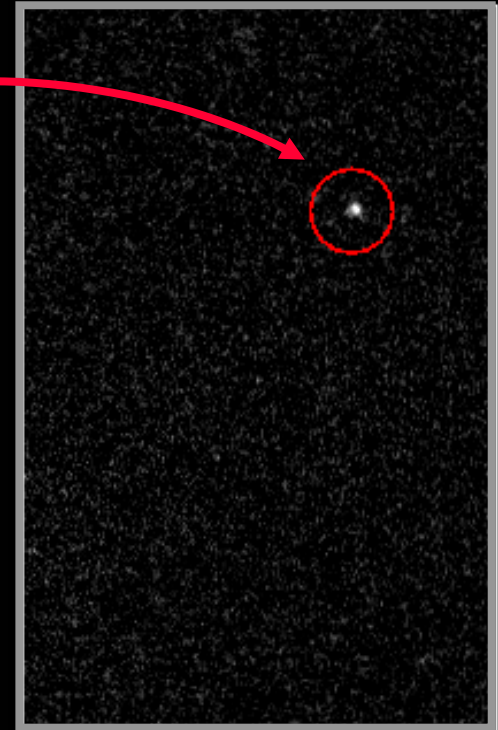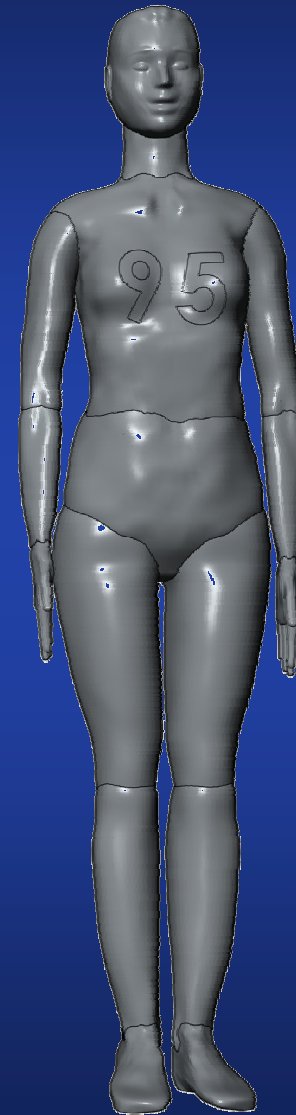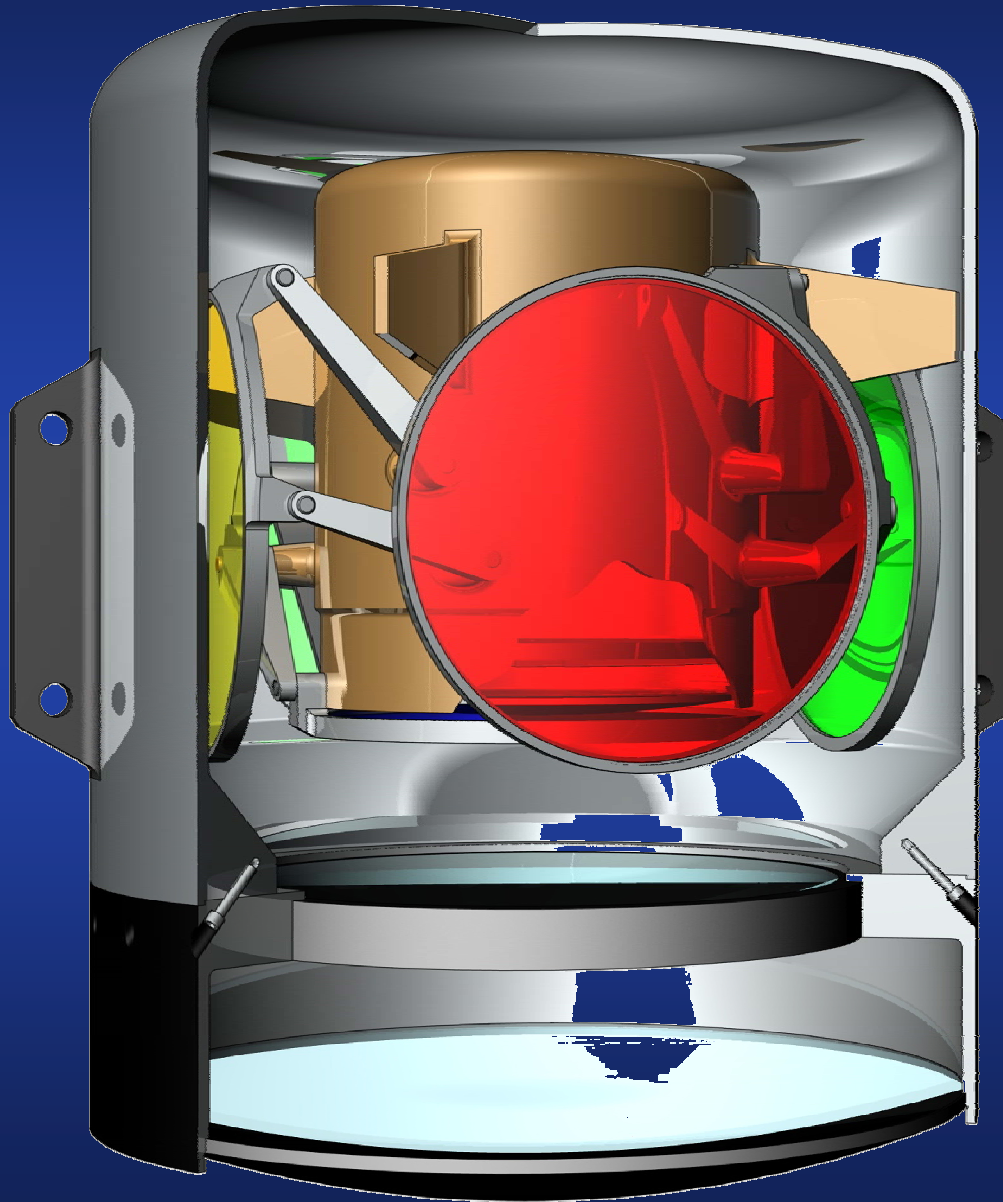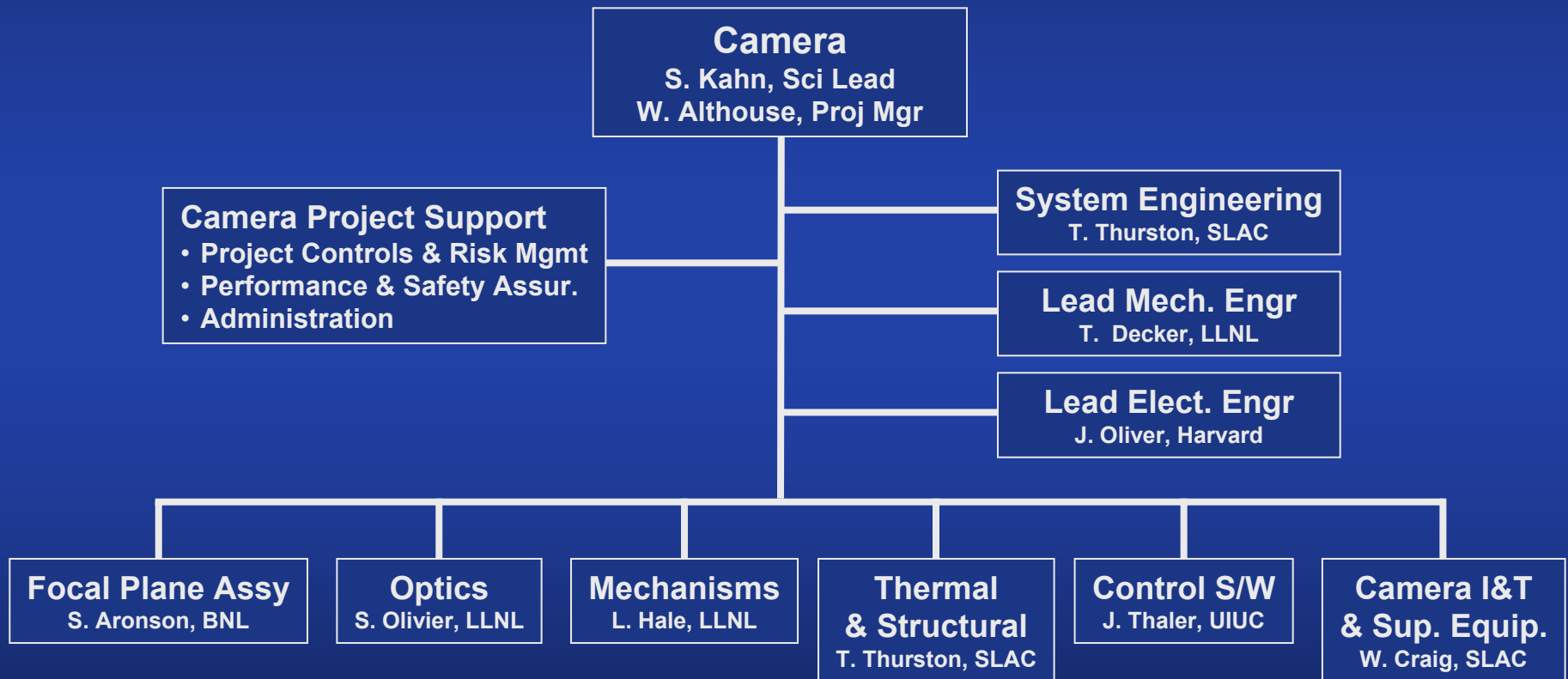|	Astronomy					High Energy Physics		
	LSST	SDSS	2MASS	MACHO	DLS	BaBar	Atlas	RHIC
First year of operation	2011	1998	2001	1992	1999	1998	2007	1999
Run-time date rate to storage (MB/sec)	5000 Peak 500 Av	8.3	1	1	2.7	60 (zero-suppressd) 6*	540*	120* ('03) 250* ('04)
Daily average data rate (TB/day)	20	0.02	0.016	0.008	0.012	0.6	60.0	3 ('03) 10 ('04)
Annual data store (TB)	2000	3.6	6	1	0.25	300	7000	200 ('03) 500 ('04)
Total data store capacity (TB)	20,000 (10 yrs)	20.0	24.5	8	2	10,000	100,000 (10 yrs)	10,000 (10 yrs)
Peak computational load (GFLOPS)	140,000	100	11	1.00	0.600	2,000	100,000	3,000
Average computational load (GFLOPS)	140,000	10	2	0.700	0.030	2,000	100,000	3,000
Data release delay acceptable	1 day moving 3 months static	2 months	6 months	1 year	6 hrs (trans) 1 yr (static)	1 day (max) <1 hr (typ)	Few days	100 days
Real-time alert of event	30 sec	none	none	<1 hour	1 hr	none	none	none
Type/number of processors	TBD	1GHz Xeon 18	450MHz Sparc 28	60-70MHz Sparc 10	500MHz Pentium 5	Mixed/ 5000	20GHz/ 10,000	Pentium/ 2500

LSST Camera

LSST Camera Project Organization

Camera
S. Kahn, Sci Lead
W. Althouse, Proj Mgr

Camera Project Support
- Project Controls & Risk Mgmt
- Performance & Safety Assur.
- Administration

System Engineering
T. Thurston, SLAC

Lead Mech. Engr
T. Decker, LLNL

Lead Elect. Engr
J. Oliver, Harvard

Focal Plane Assy
S. Aronson, BNL

Optics
S. Olivier, LLNL

Mechanisms
L. Hale, LLNL

Thermal & Structural
T. Thurston, SLAC

Control S/W
J. Thaler, UIUC

Camera I&T & Sup. Equip.
W. Craig, SLAC

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2.8 billion pixels

Camera Challenges

- Detector requirements:
  - 10 μm pixel size
  - Pixel full-well > 90,000 e$^-$
  - Low noise (< 5 e$^-$ rms), fast (< 2 sec) readout ($\rightarrow$ < –30 C)
  - High QE 400 – 1000 nm
  - All of above exist, but not simultaneously in one detector
- Focal plane position precision of order 3 μm
- Package large number of detectors, with integrated readout electronics, with high fill factor and serviceable design
- Large diameter filter coatings
- Constrained volume (camera in beam)
  - Makes shutter, filter exchange mechanisms challenging
- Constrained power dissipation to ambient
  - To limit thermal gradients in optical beam
  - Requires conductive cooling with low vibration

Focal Plane Implementation

Detector + ASIC Module

Hermetic Seal

Multiplexer Hardware

Fiber Optic output
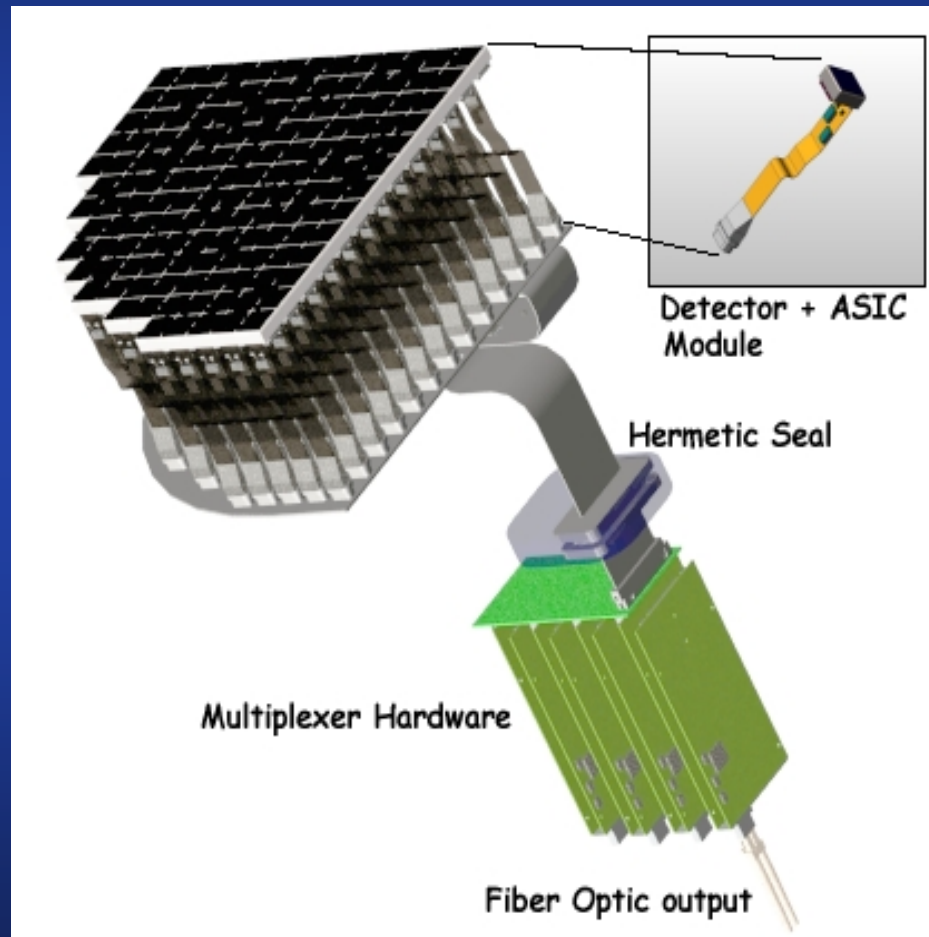
LSST Detector Challenge

- The focal plane array will have about *an order of magnitude larger number of pixels* (~2.8 gigapixels) than the largest arrays realized so far or being built.

- The effective aggregate pixel readout speed will have to be about *two orders of magnitude higher* than in previous telescopes in order to achieve a readout time for the telescope of ~ 2 seconds.

- The silicon detectors will have to have an *active region ~100 μm thick* to provide sufficiently high quantum efficiency at ~1000 nm, and they will have to be fully depleted so that the signal charge is collected with minimum diffusion as needed to achieve a narrow point spread function.

CCDs vs. Hybrid CMOS?

- CCD technology is very mature and has been proven in many scientific high performance applications. All the technological ingredients necessary to design an advanced device appropriate for the LSST exist. This could be accomplished on a time scale consistent with the proposed LSST schedule.

- Some of the essential technology ingredients are:

  a) back illuminated, fully depleted device (~100 μm thick);

  b) segmented readout structure with multiple ports to achieve the required readout time of ~2 s for ~2.8 Gpixels, and to restrict the effects of blooming to a small area;

  c) extensive use of ASICs to make the readout of a large number of channels practical, and to reduce the number of output links and penetrations of the dewar. This makes possible a low CCD clock frequency (in the 200-400 kHz range), to minimize the read noise and electronic crosstalk.

A CCD Strawman Design

Desired features:

- 2 sec readout @ 250 kHz implies no more than ca. 512K pixels per output.

- Fill factor must approach unity (which argues for a fairly large- area footprint).

- Flatness requirements argue for bond pads only on periphery.

- Segmentation for blooming control of bright stars – no more than ca. 512 pixels in the parallel direction per segment.

- Contiguous imaging area should be at least 512 pixels in the parallel direction.
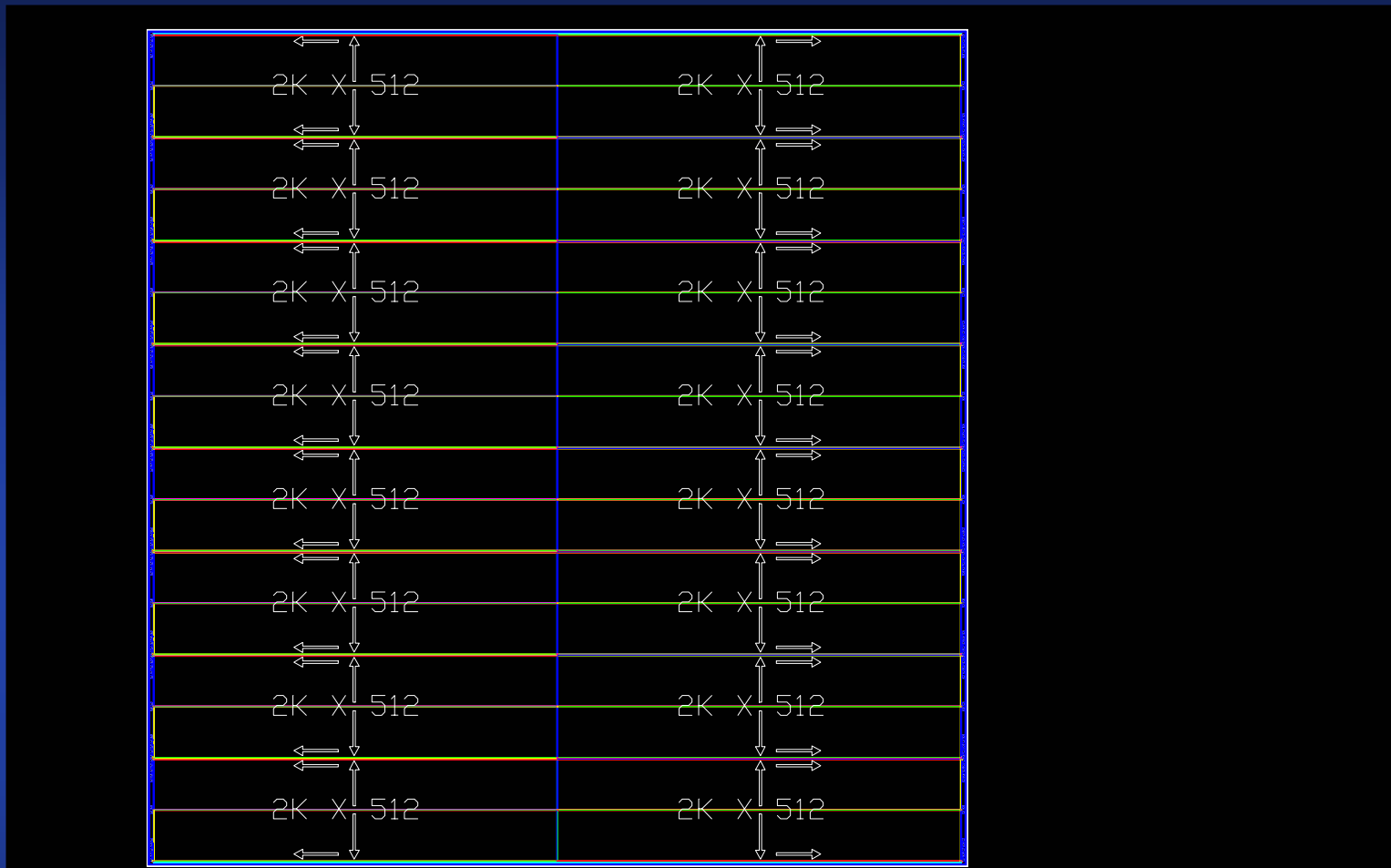
4K X 4K strawman CCD design, with 16 sections of 2K X 512 format and two serial register outputs each. All pinout pads are along the left and right edges. Physical size is 41.7mm X 42.1mm (100 micron guard ring). Fill factor is 95.5%.

FPA

FEE

Data cards

Timing/control crate

External services
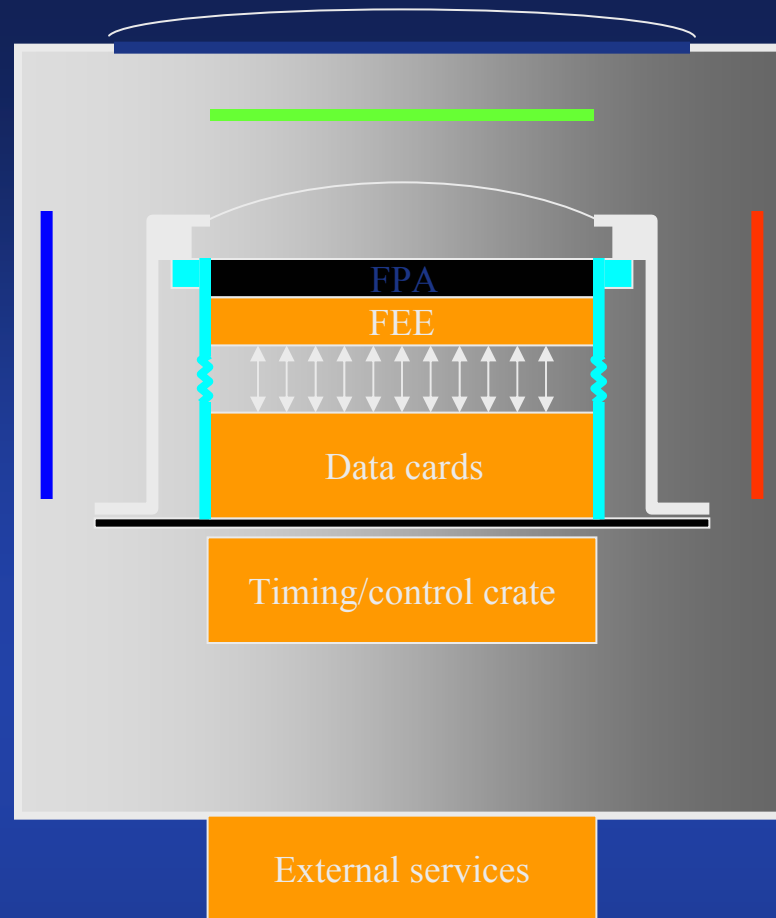
Secondary mirror

Summary

- The Large Synoptic Survey Telescope is a proposed facility that will probe fundamental physics

- Design work under way, drawing heavily on existing precursor projects
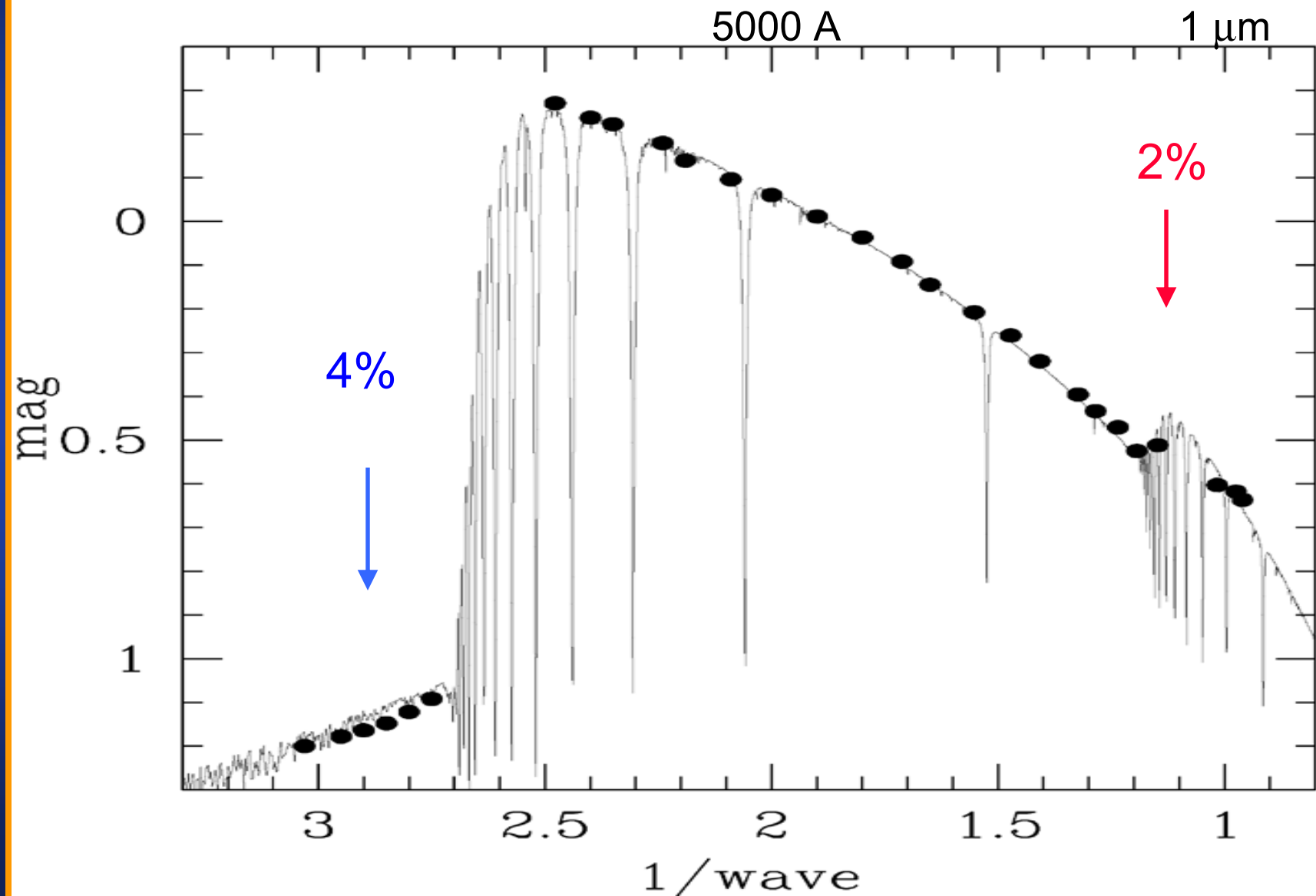
- Goal is first light in 2011.

Backup slides

Current Metrology Chain for Ground-based Astronomical Flux Measurements.

Black Body Calibrator ⟷ Celestial Calibrator, Vega ⟷ Celestial Sources

Supernova measurements require knowing relative instrumental sensitivity vs. λ

Vega is primary celestial calibrator

Detector-based Radiometry

Liquid Helium Reservoir
Liquid Nitrogen Reservoir
Germanium Resistance Thermometer
5 K Reference Block
50 K Radiation Shield
Thin Film Heater 10 K
77 K Radiation Shield
Absorbing Cavity (specular black paint)
Radiation Trap (4.2 K)
Alignment Photodiodes
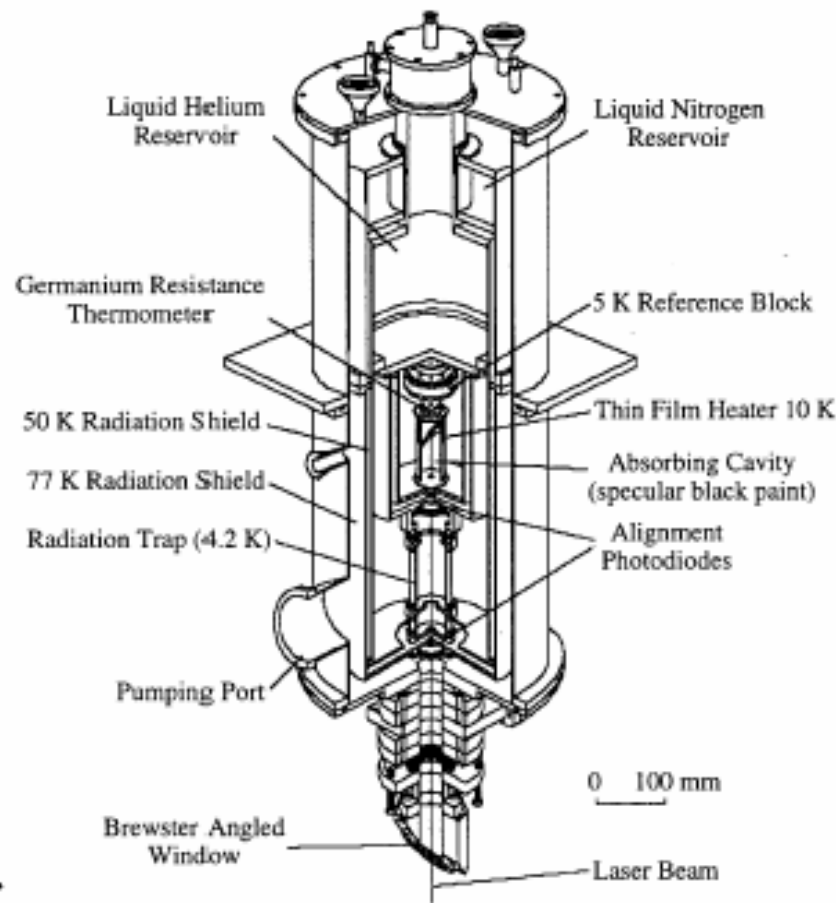Pumping Port
0   100 mm
Brewster Angled Window
Laser Beam

Figure 5.1. NIST High Accuracy Cryogenic Radiometer (HACR).

Modern metrology for radiometric measurements is based on detectors, not sources.

Larson, Bruce and Parr, NIST special publication 250-41

Transferring flux standard to photodiodes

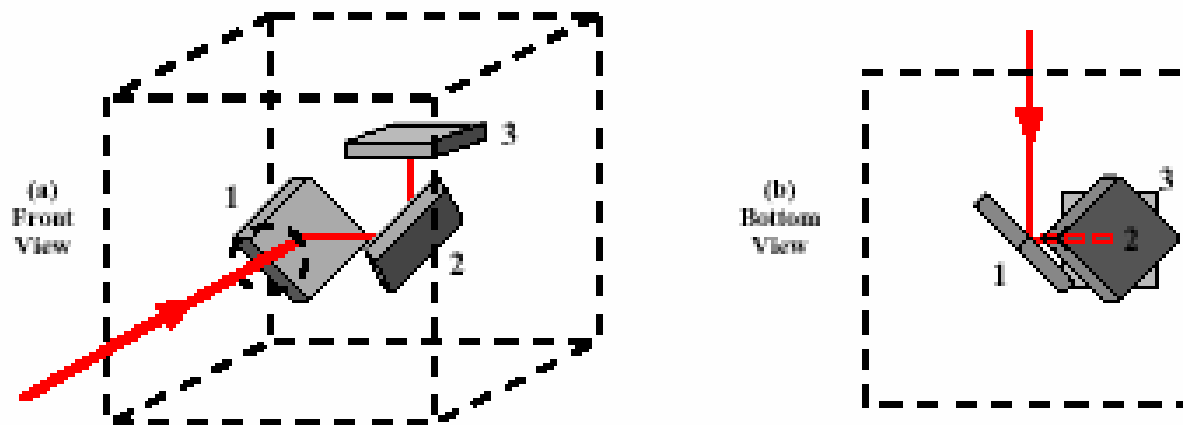Through 1 intermediate step, this calibration is transferred to Si photodiodes
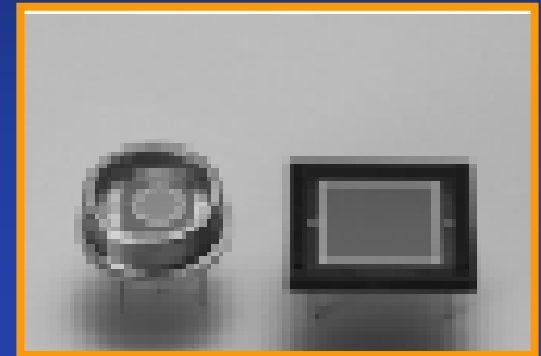

Figure 5.2. Trap detector arrangement of photodiodes minimizes light lost to reflections.

An alternative calibration approach

Calibrate relative system response
    primary
    corrector optics
    filter
    detector
relative to Si photodiode.

Measure transfer function of atmosphere with dedicated spectrograph

LSST Data Rates

- 2.8 billion pixels read out in less than 2 sec, every 12 sec

- 1 pixel = 2 Bytes (raw)

- Over 3 GBytes/sec peak raw data from camera

- Real-time processing and transient detection: < 10 sec

- Dynamic range: 4 Bytes / pixel

- > 0.6 GB/sec average in pipeline

- Real-time reduction requires ~ 140 Tflops peak

- Data rate is comparable to ATLAS on LHC.

Software

Rate limiting aspect of many past projects

Budget-busting potential

Has traditionally been written by practicing scientists
> Management challenge is to capture best of this
> Optimize interaction between astron. & s/w professionals
> Need informed choices as project scope evolves

Typically evolves over the project
> Results change with re-processing
> The developers are best able to maintain the code

Goal: Identify and classify variability in real time

1. Remove instrumental artifacts
2. Frame subtraction
   - Geometrical registration
   - Convolution with varying kernel
   - Subtraction
   - Object identification on difference image
3. Classification (SN, asteroid, etc.)
4. Ingest into Postgres database structure