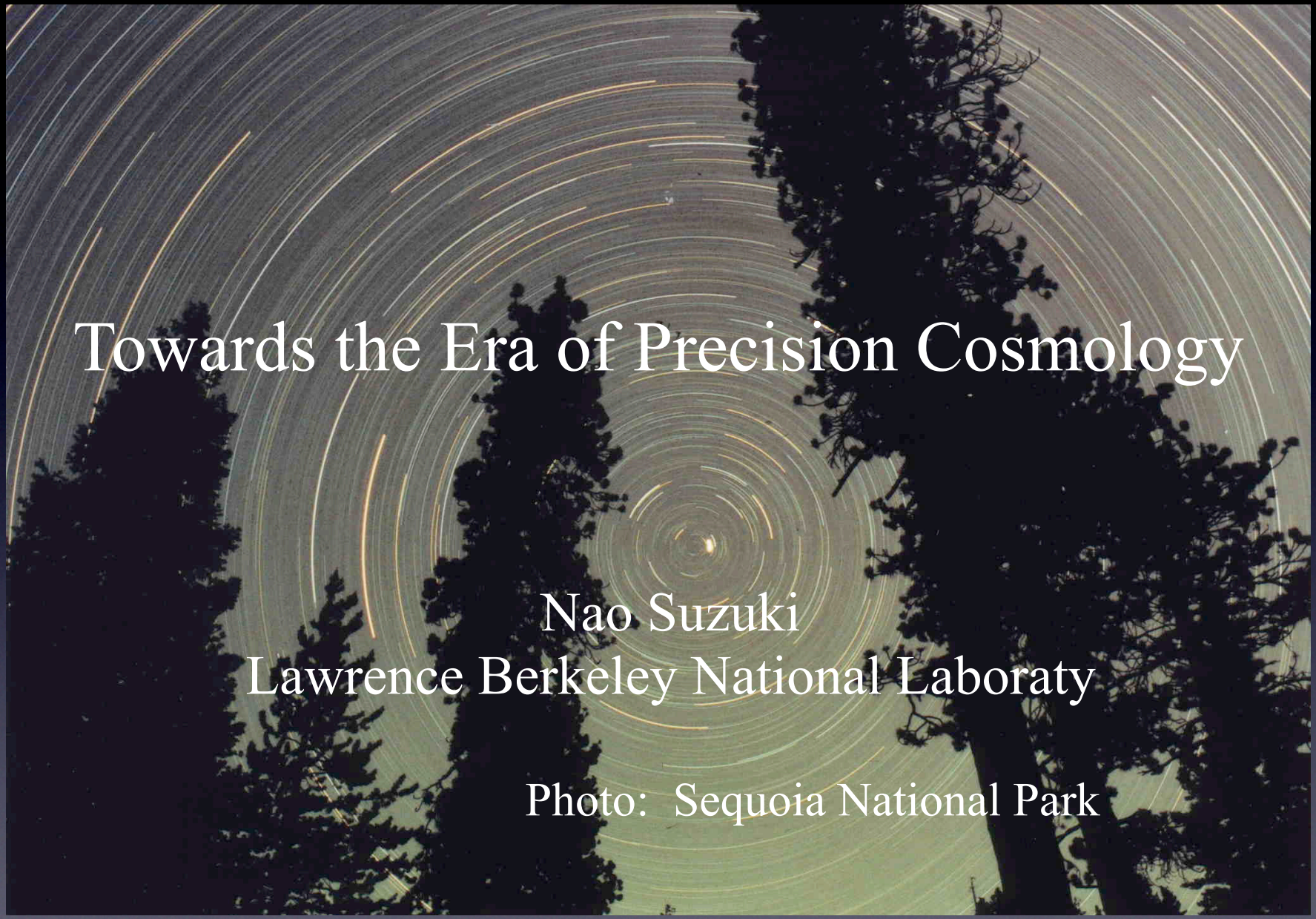


Towards the Era of Precision Cosmology

Nao Suzuki
Lawrence Berkeley National Laboraty

Photo: Sequoia National Park

Part I : Baryon Asymmetry

- Big Bang Nucleosynthesis (BBN)
  - A Brief History of BBN
  - Light Element & Deuterium
  - Quasar Absorption Line
  - Key Issues for Precise Measurement
  - Results & Implications for Dark Energy

Part II : Supernova Cosmology

- Dark Energy
  - A Brief History of Dark Energy
  - Phillips Relation & Type Ia Supernova
  - Supernova Cosmology Today
  - Ongoing HST/ACS cluster survey
  - Key Issues for Precise Measurement
  - PCA application to SNIa Spectra & SNAP

A Brief History of BBN

- Wolfgang Pauli wrote a letter to Hiesenberg right after the discovery of postitron (1933)

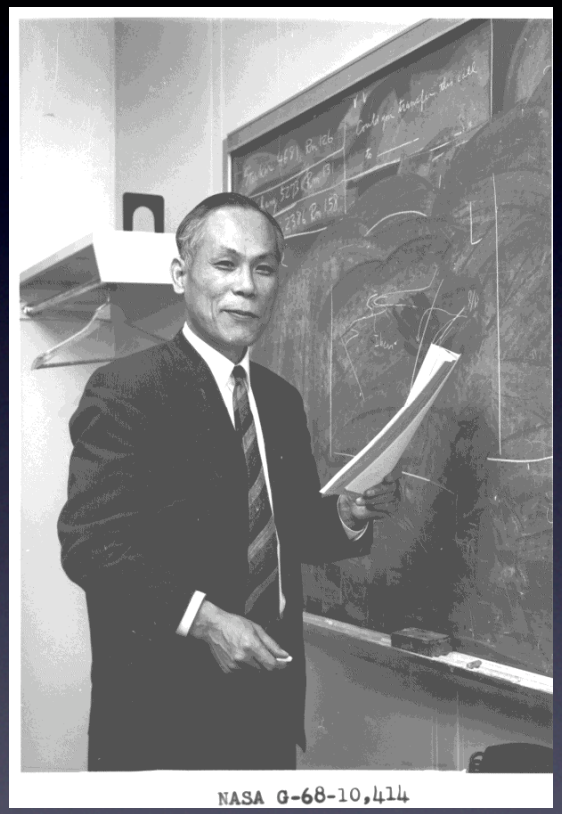
  "I do not believe in the (Dirac's) theory since I would like to have the asymmetry between particle and negative electricity in nature"

- Baryon Asymmetry =

  = (particle-antiparticle) / (particle+antiparticle)

  = baryon / photon

A Brief History of Deuterium



Chushiro Hayashi (1920-)

Beatrice Tinsley (1941-1981)

The First 3 minutes

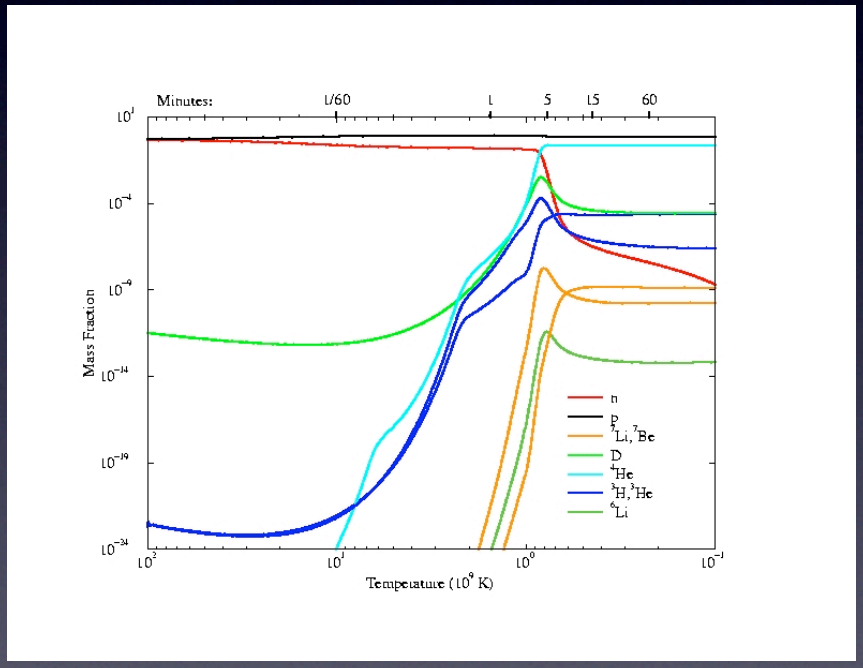
- 1948 Alpher, Bethe, Gamow

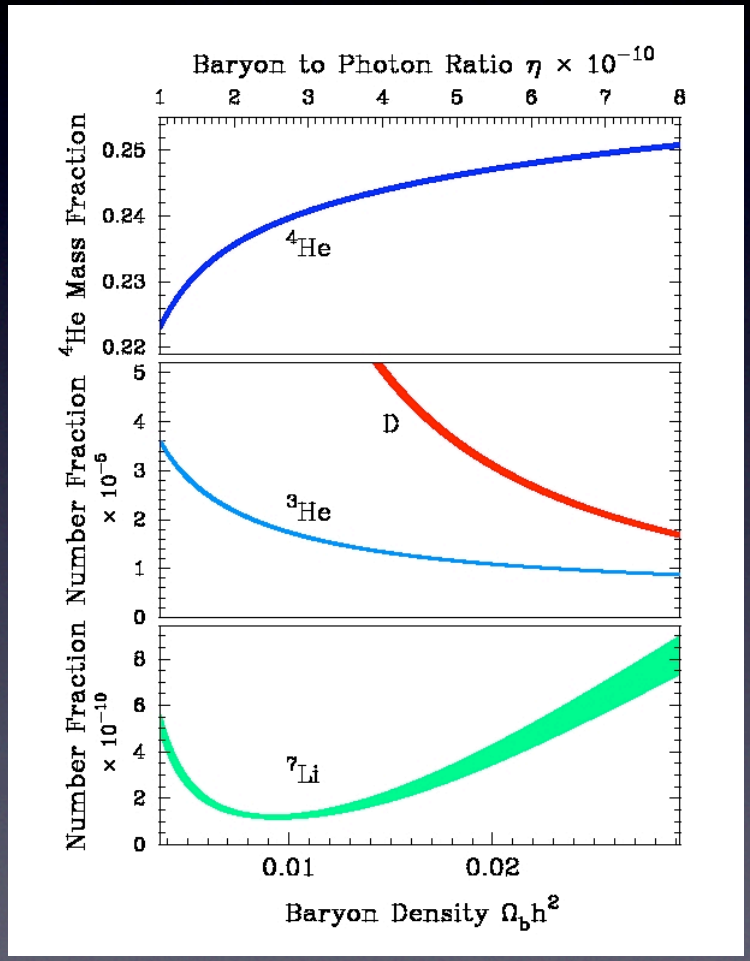
(Physical Review, volume 73, 7, April 1st)
"we must imagine the early stage of matter as a highly compressed neutron gas"

1950 Hayashi : n-p Equilibrium

"Once Hayashi recognized the role of n-p equilibration, the frame work of big bang nucleosynthesis calculation has not varied significantly. "

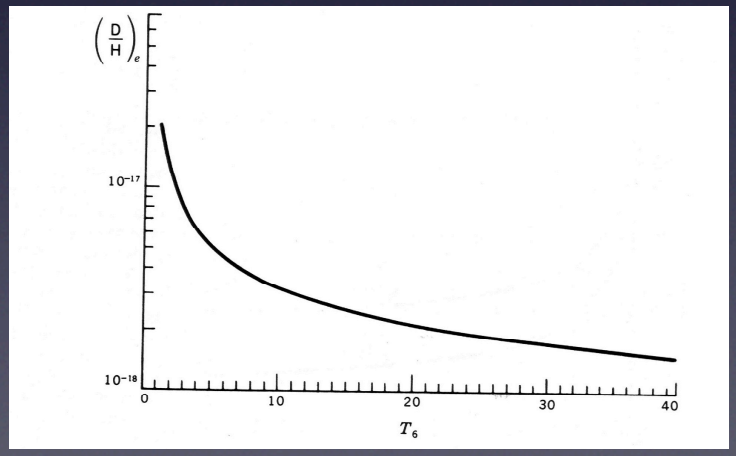
The First 3 Minutes: Big Bang Nucleosynthesis

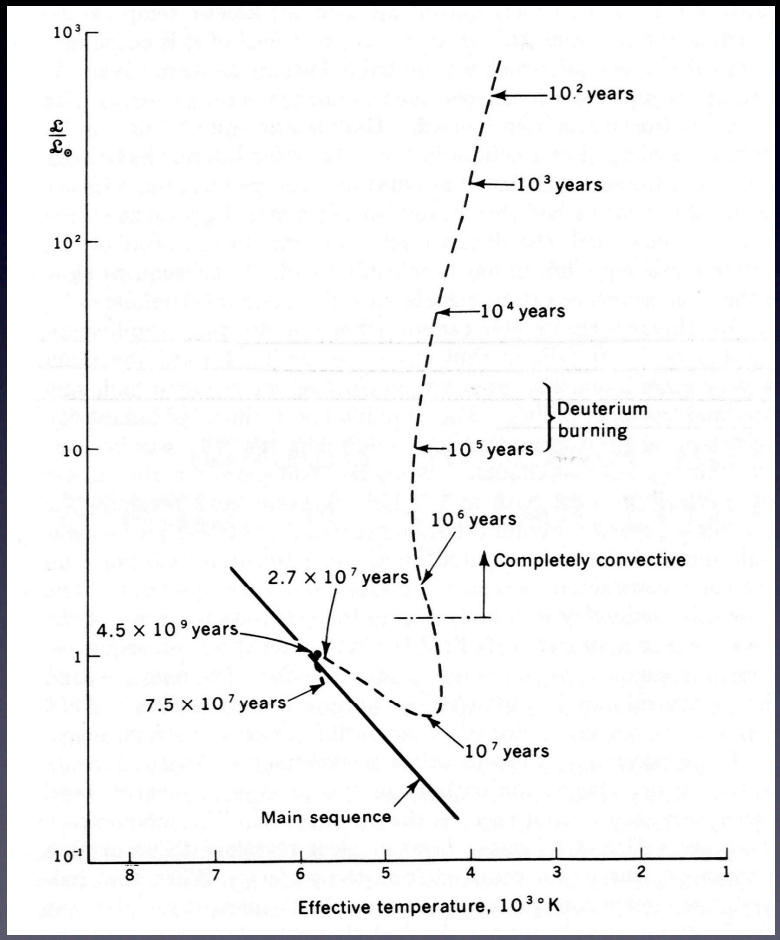




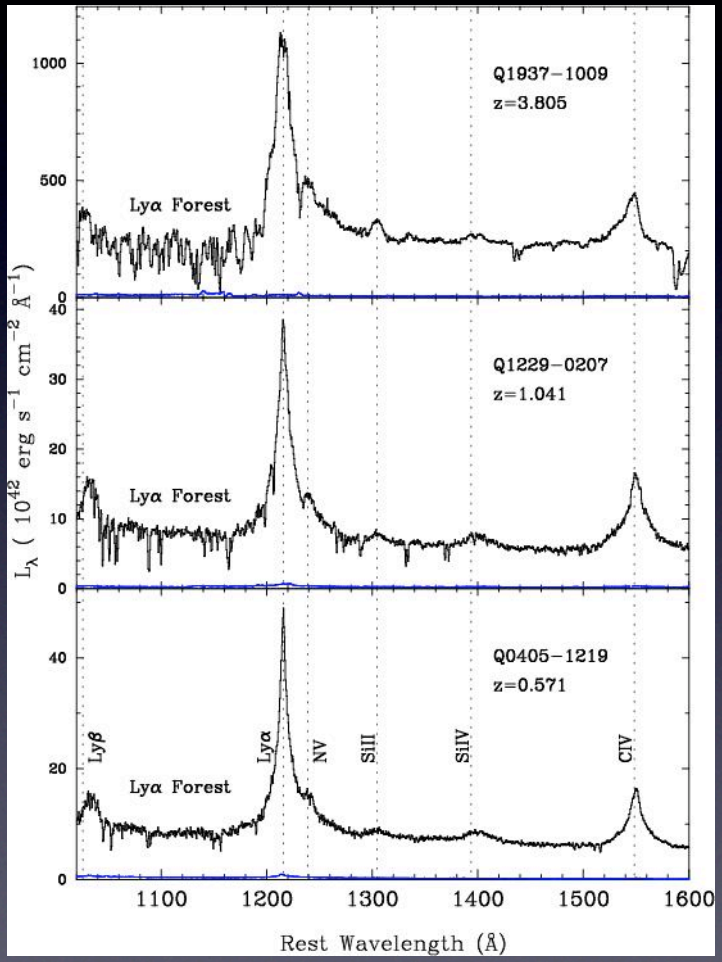
Why D/H? :Hayashi Track

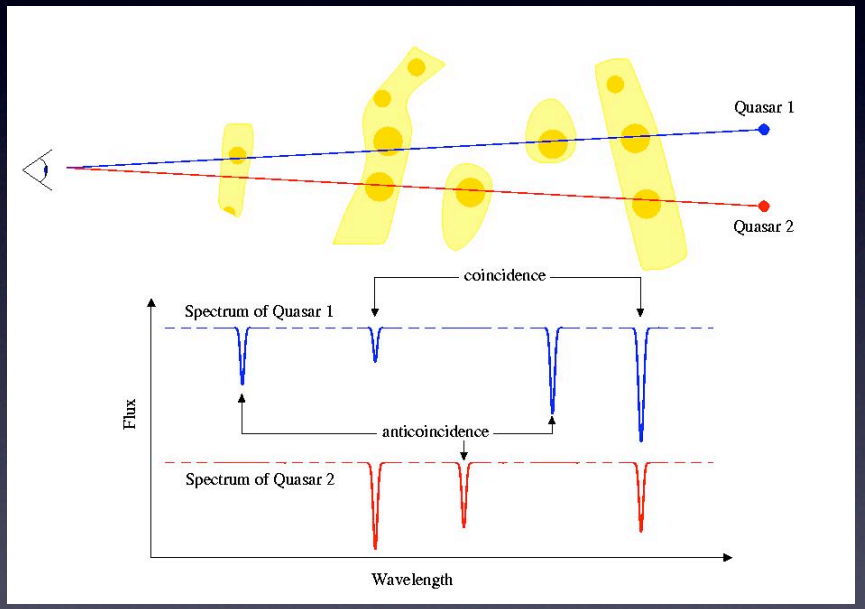
- Destruction of D
- Evolution of Pre-Main Sequence Star
- Hayashi Track





Quasar Absorption Lines: Lyα Forest

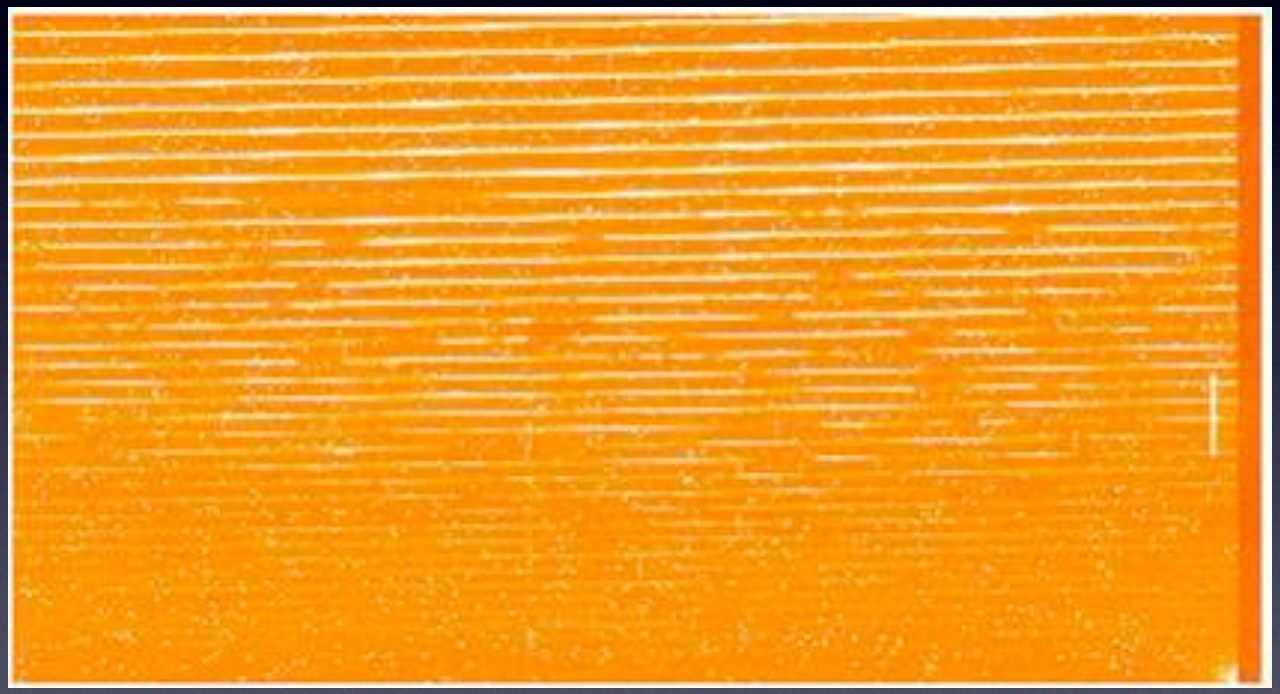




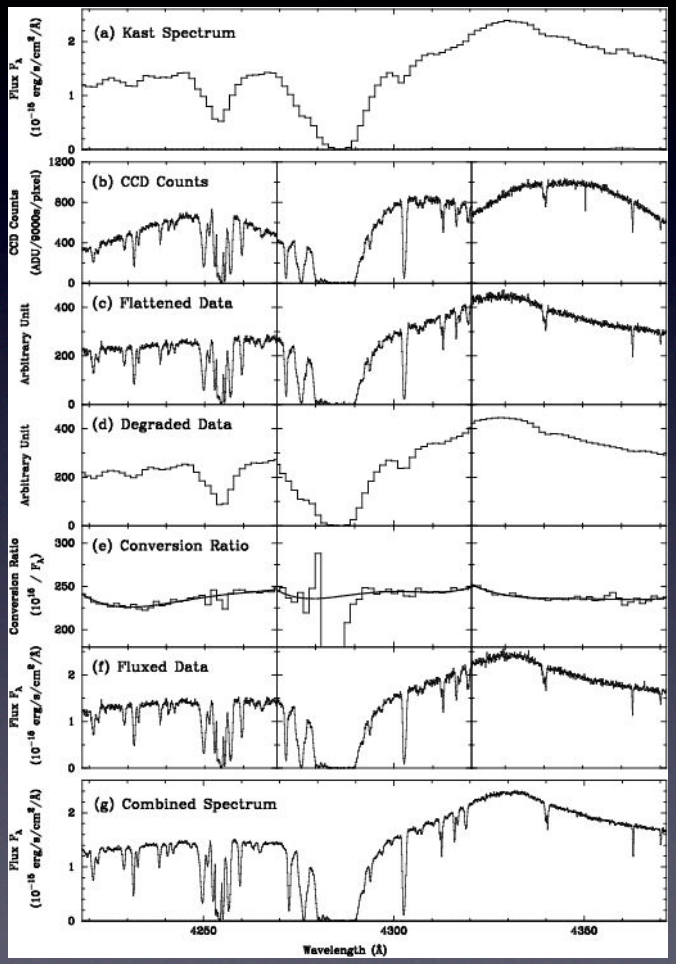
10m Keck Telescope (Hawaii)

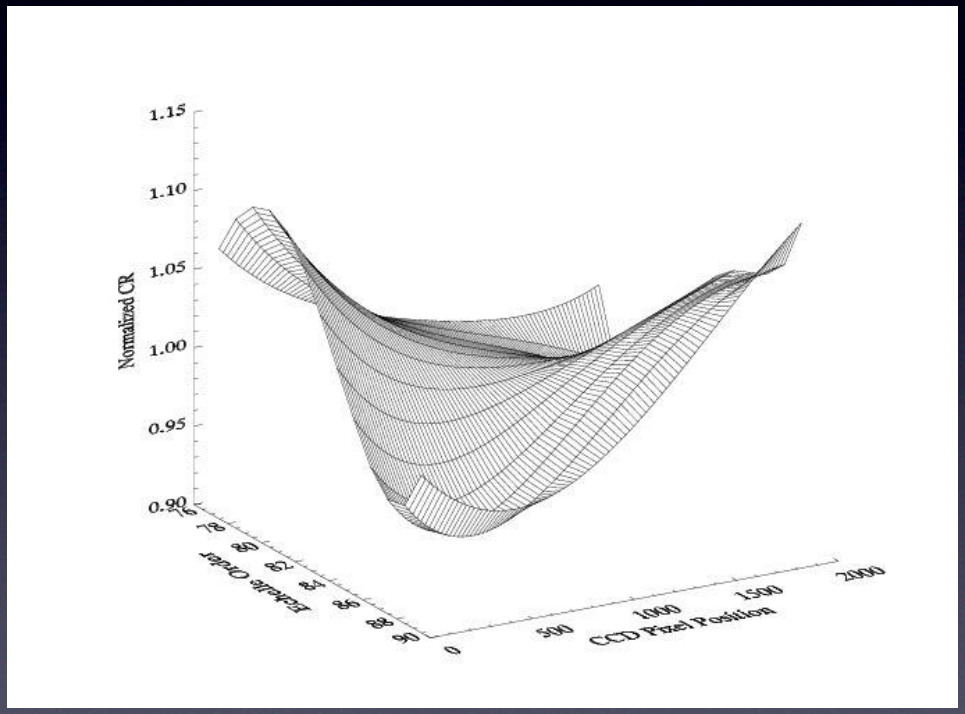
3m Lick (San Jose)

CCD image to Spectrum: Flux Calibration

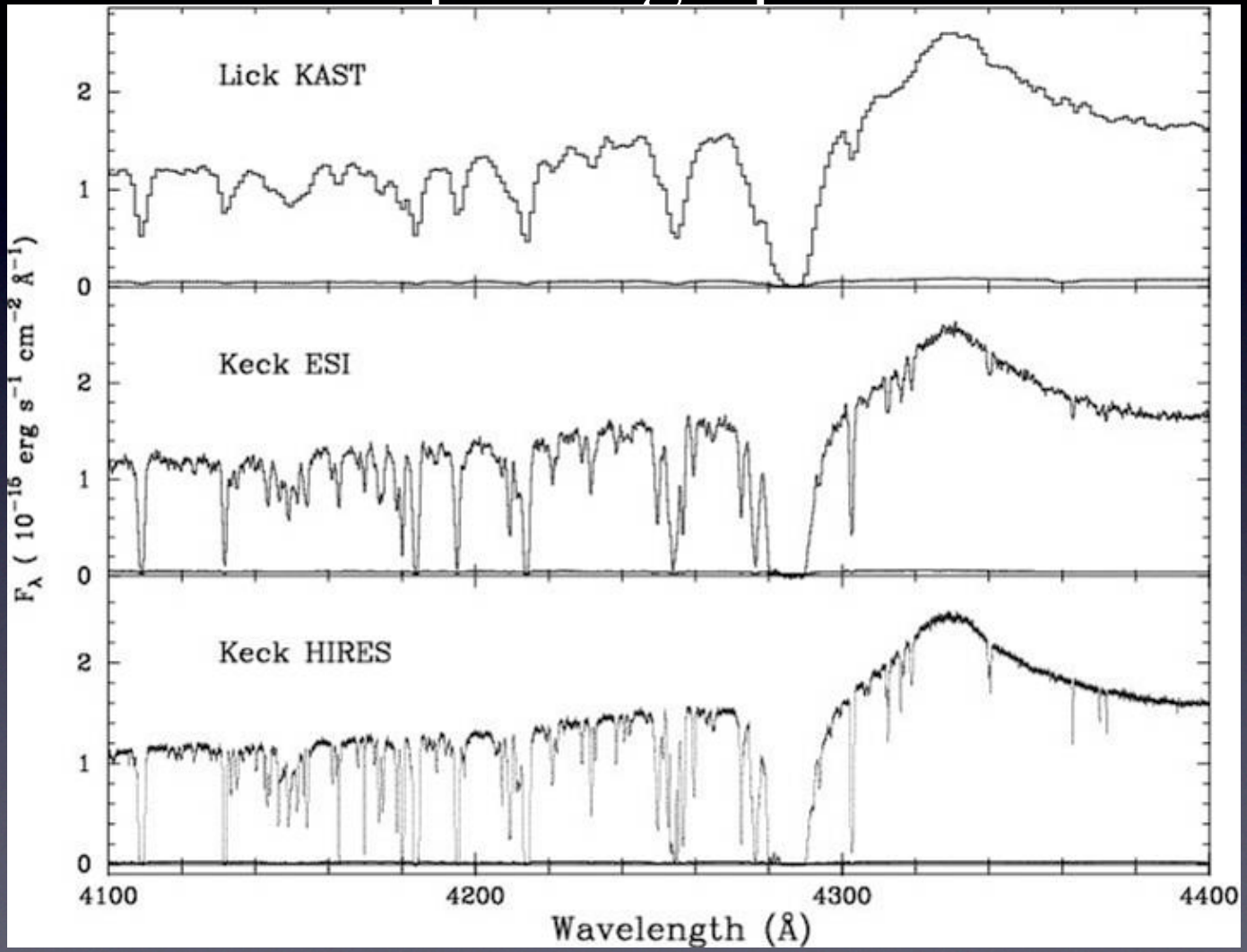


Flux Calibration
from the same Quasar Spectrum



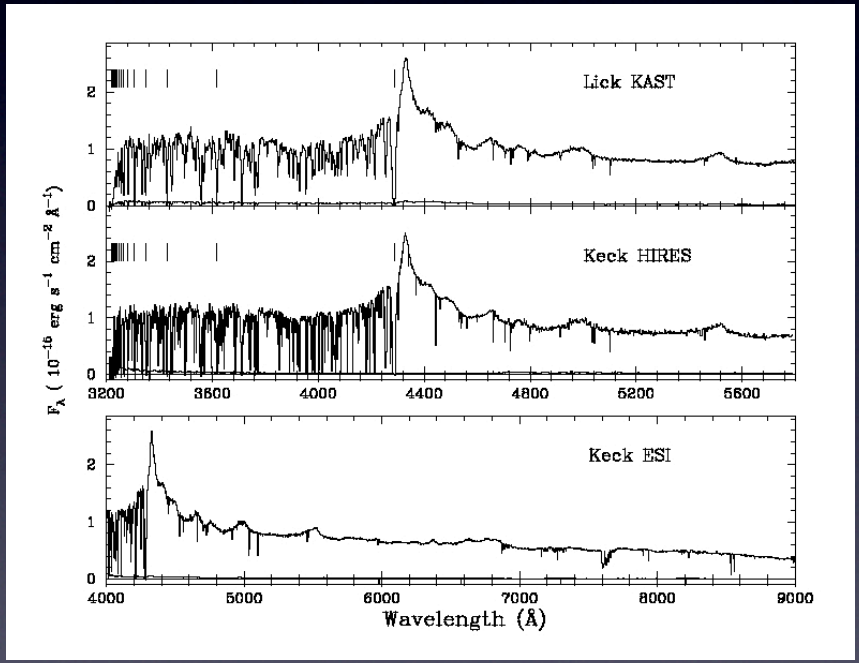


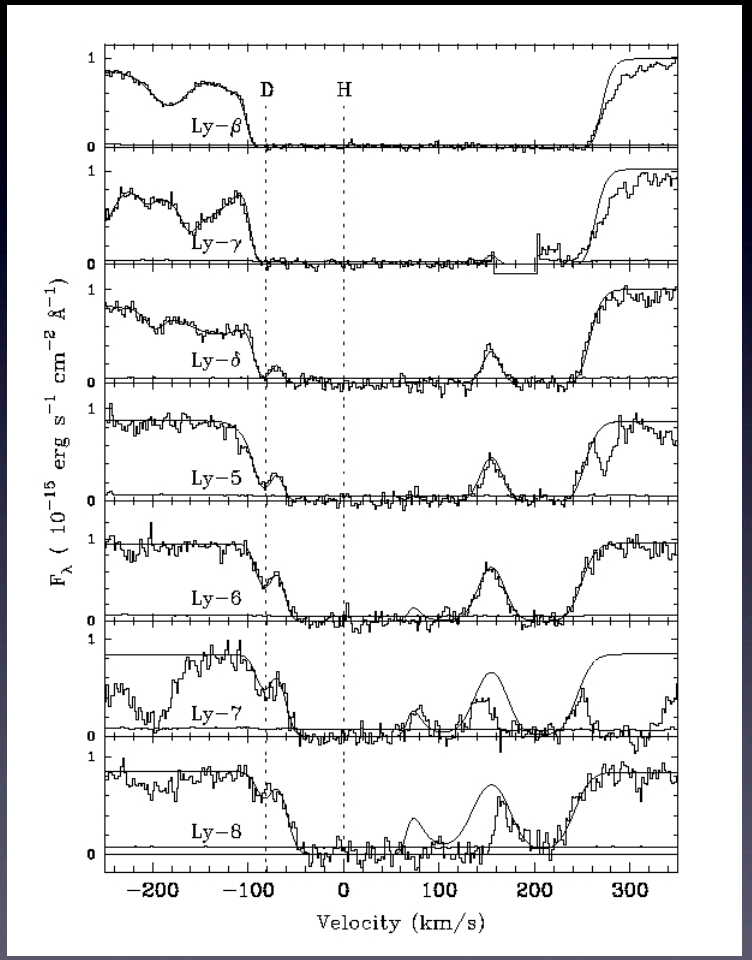
Take Advantage of Other Spectrographs



Quasar Absorption Line System

Quantum Mechanics

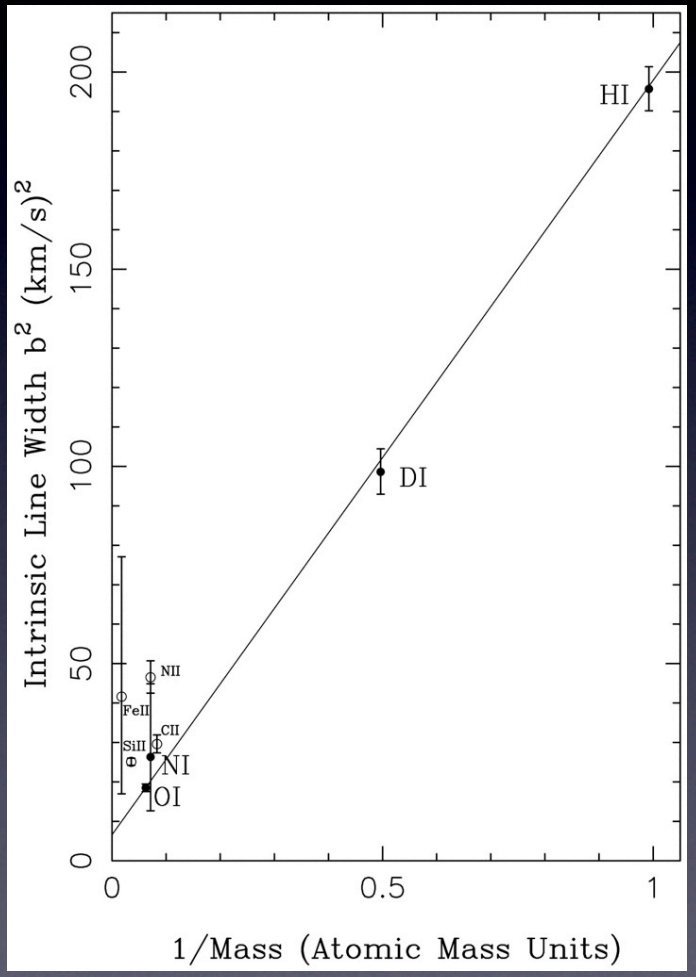




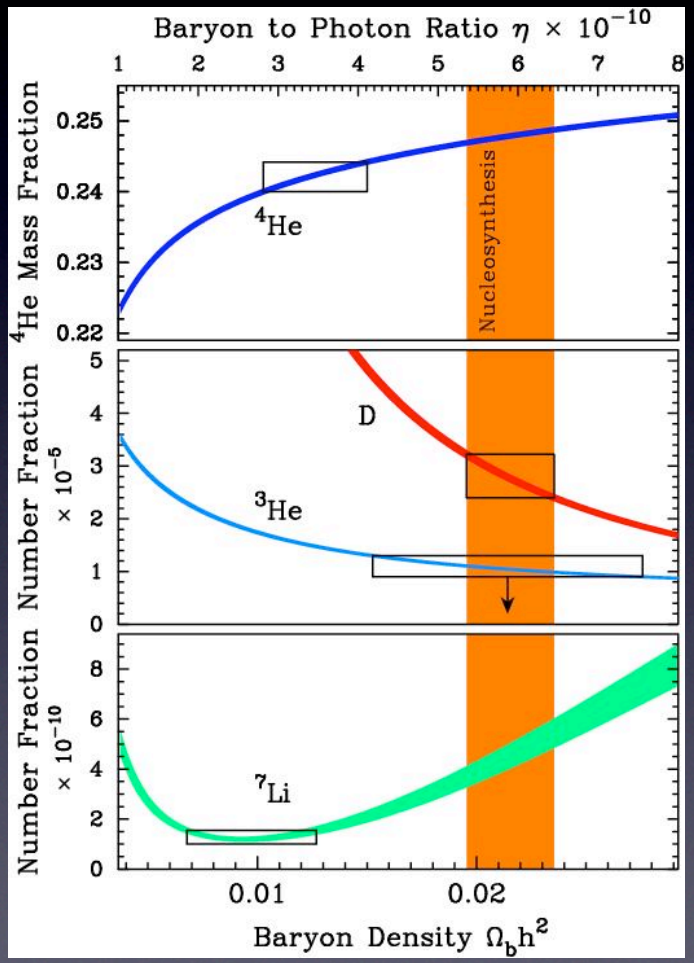
Themodynamics

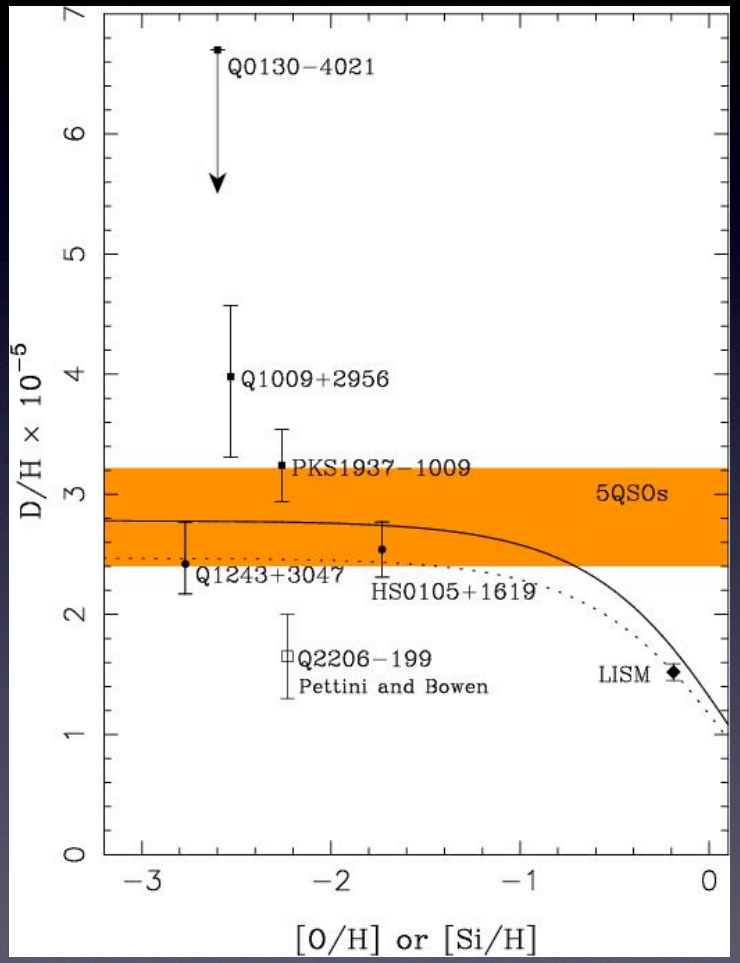
$$E = \frac{1}{2}mv^2$$

$$v^2 \propto \frac{1}{m}$$

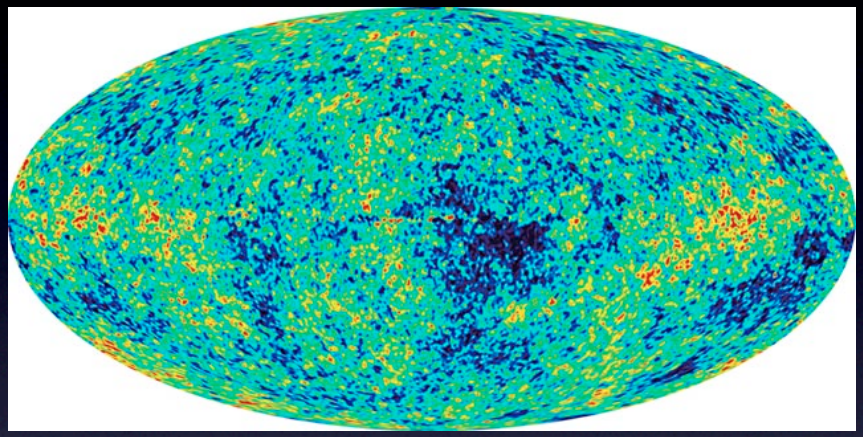


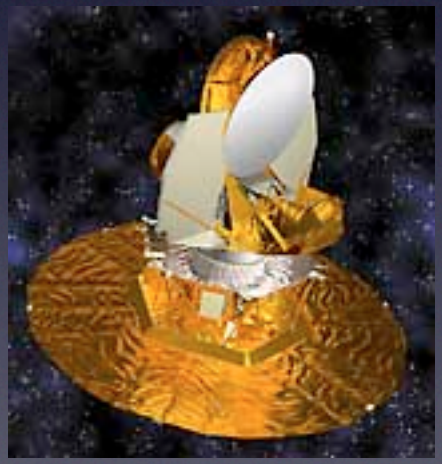
D/H : Ω_b Baryon Density Measurements

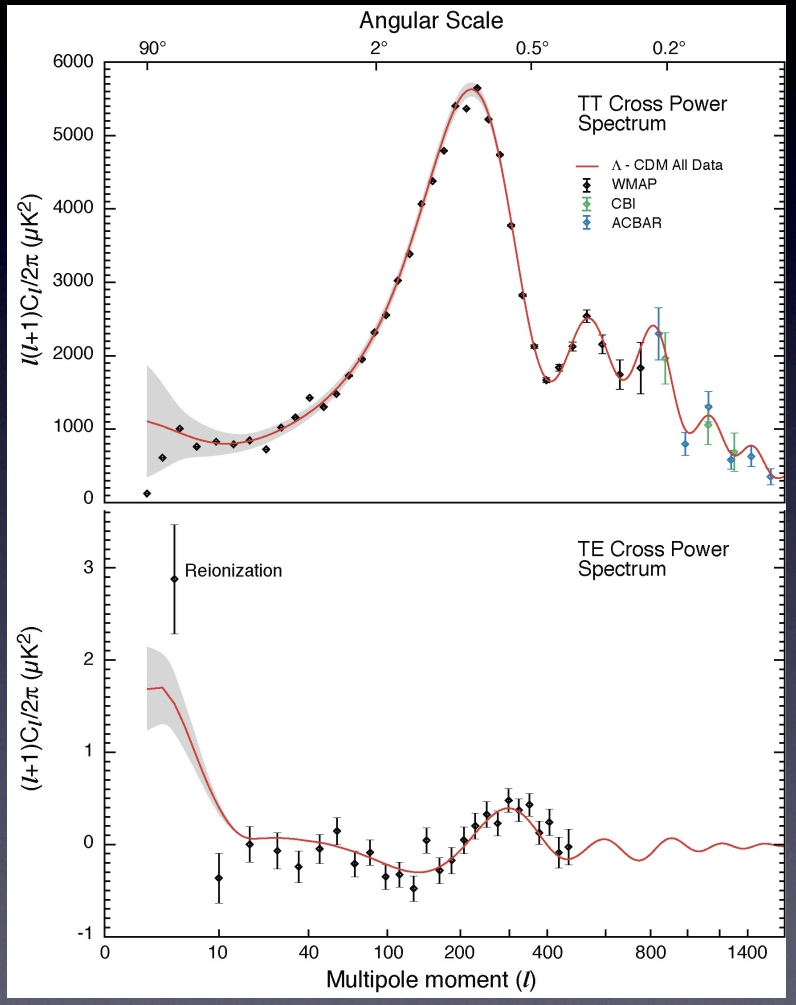




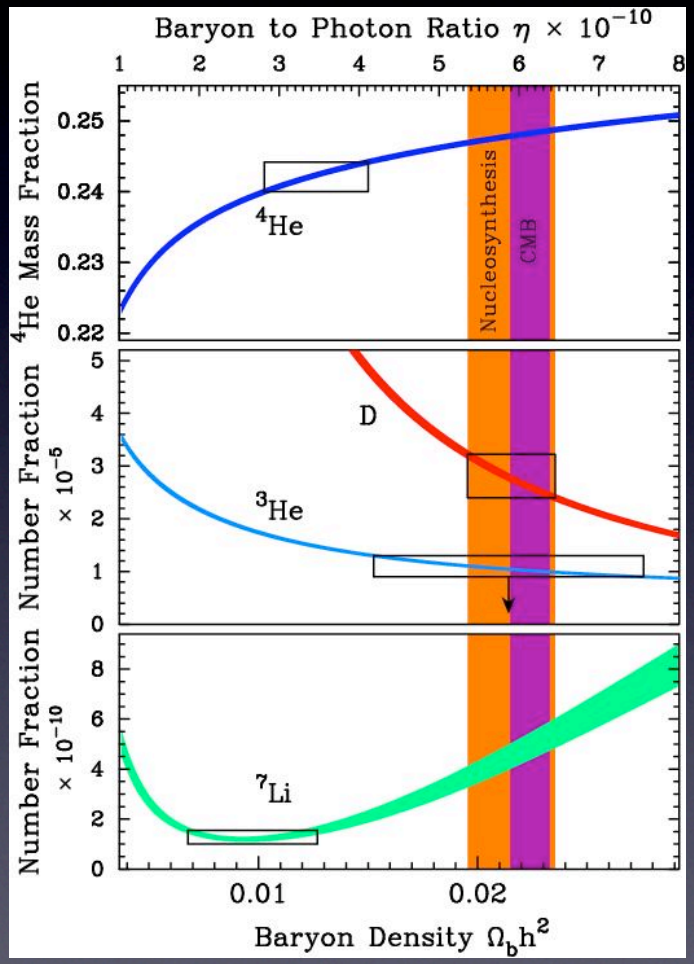
WMAP
(Cosmic Microwave Background)

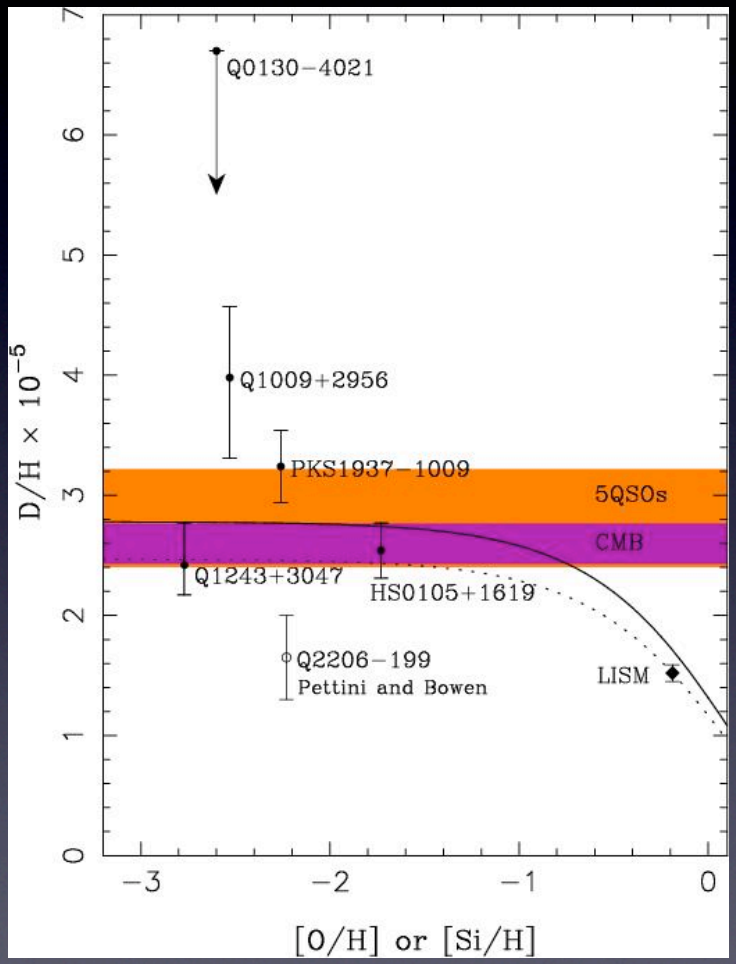






Big Bang Nucleosynthesis vs. CMB

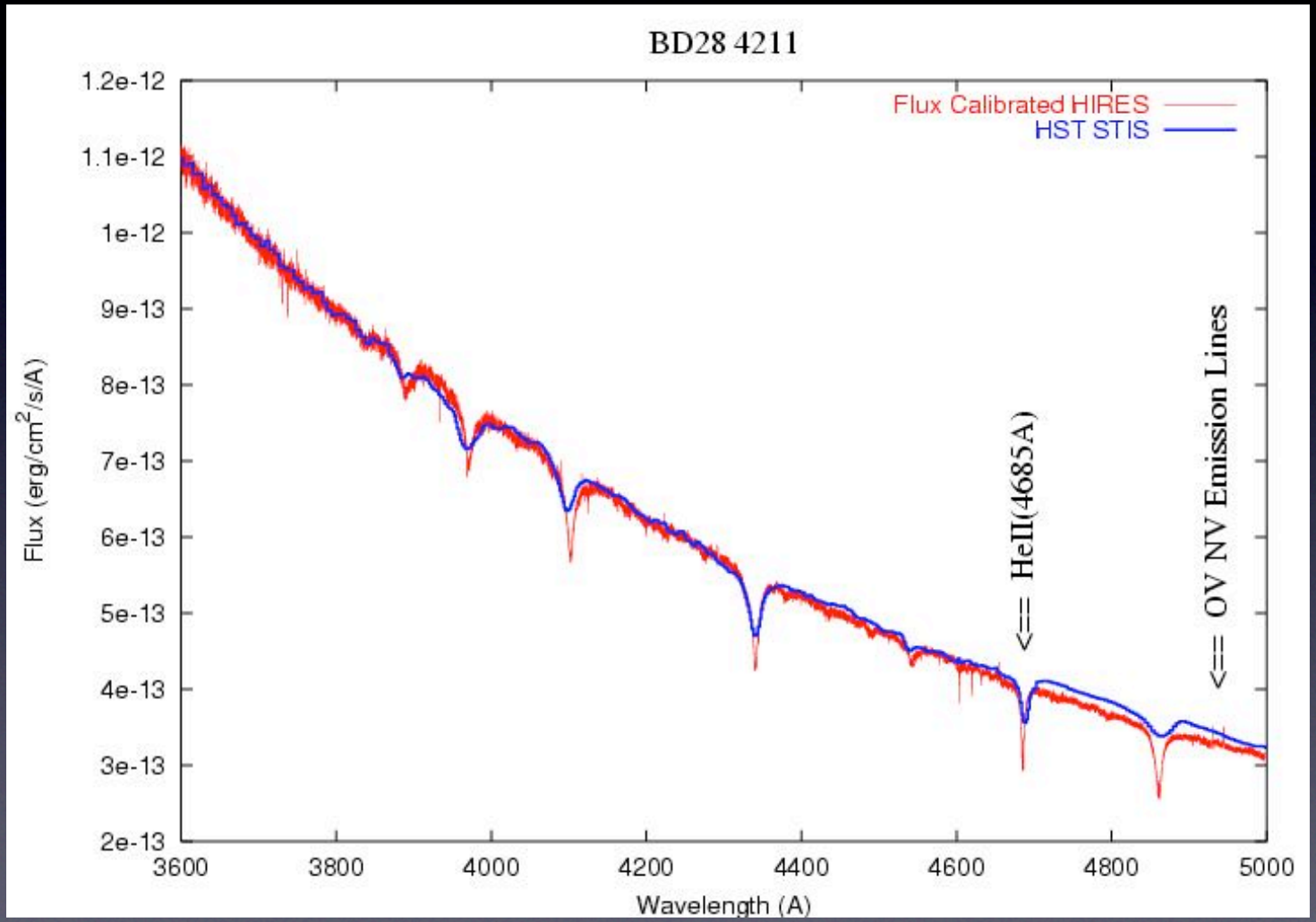




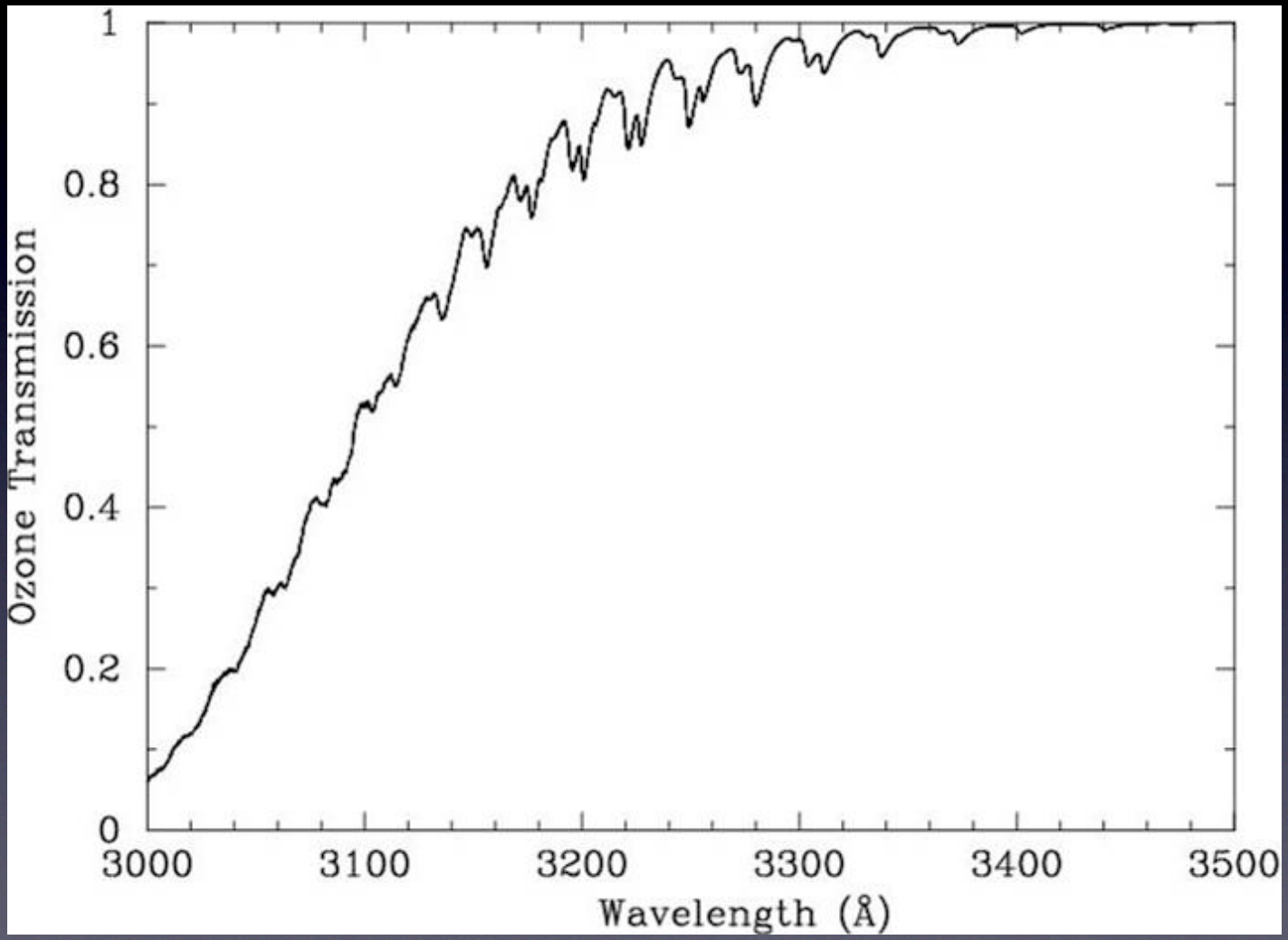
Key Issues for precision Baryon Asymmetry Measurement

1. Standard Star Accuracy (1-2%)
2. UV Ozone lines (2-5%)
3. Intrinsic Quasar Spectrum diversity (PCA diversity study)

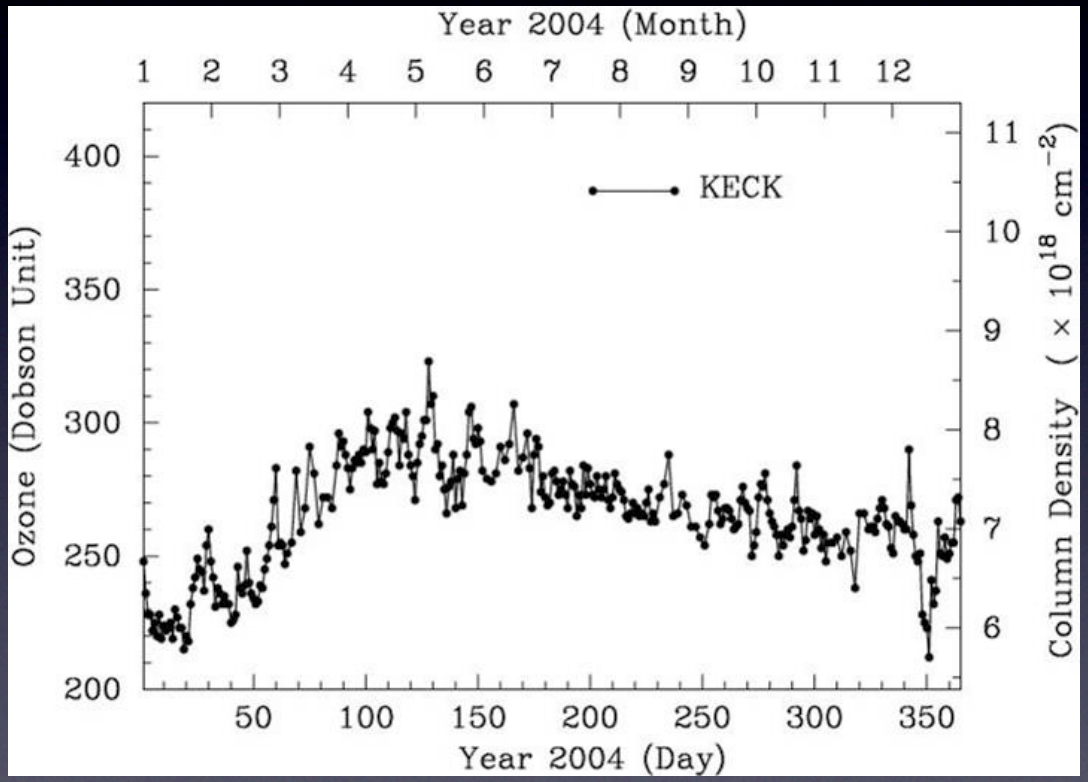
1. Standard Star Spectrum

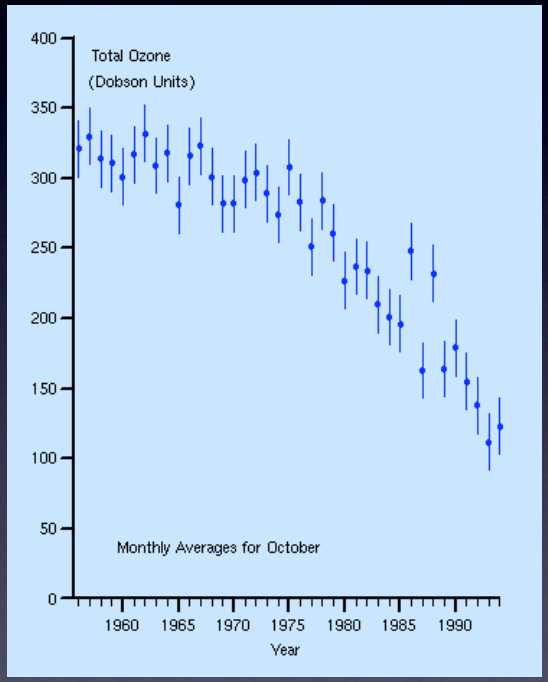


2. Ozone Lines in UV

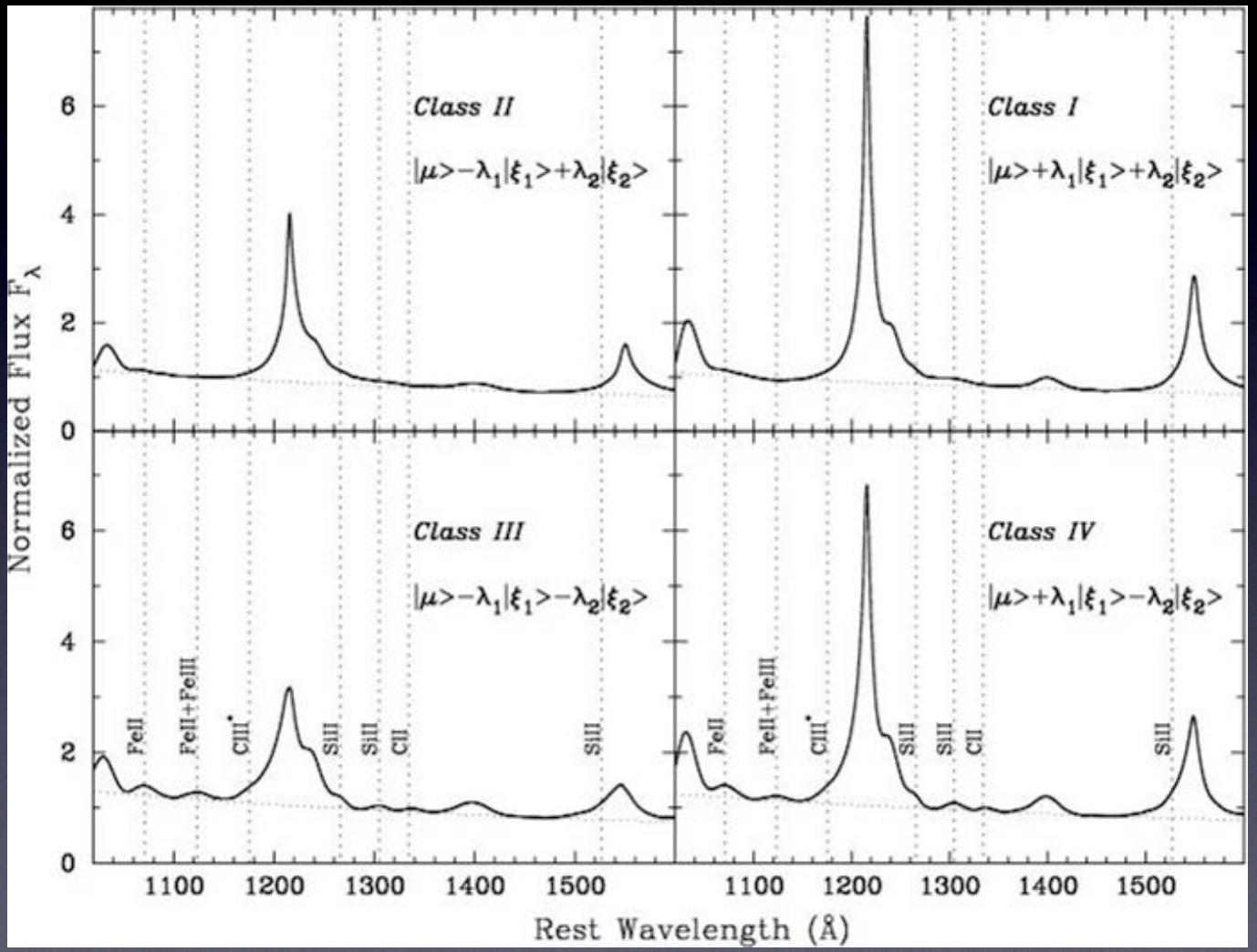


Variations of Ozone

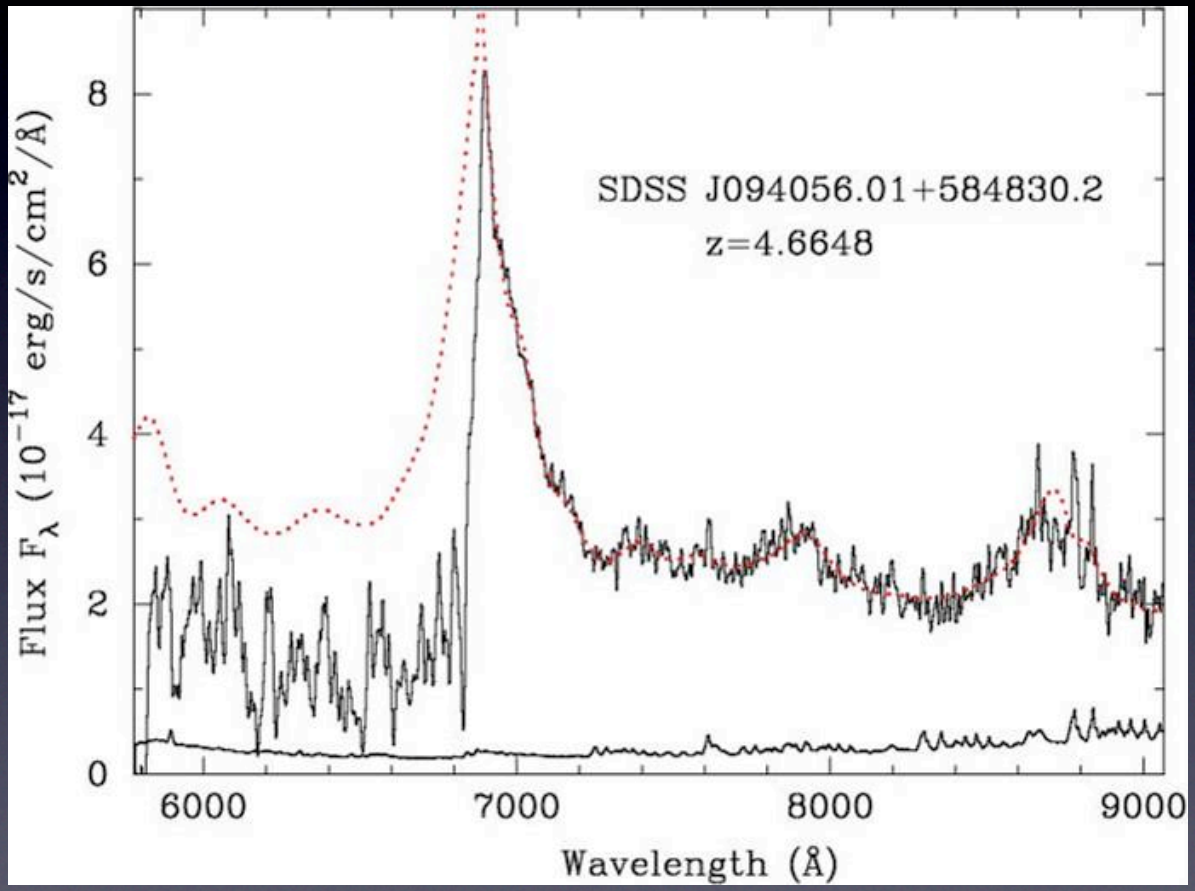




3. Quasar Spectral Diversity



Quasar Continuum Prediction



Baryon Asymmetry, Why?

- P.J.E. Peebles: "I'm expecting someday, someone like you will tell me why"
- Paul Steinhardt: "It is still far, but maybe we can explain that"
- Sir Martin Rees: "We don't have a good theory, today"
- Stephen Hawking:

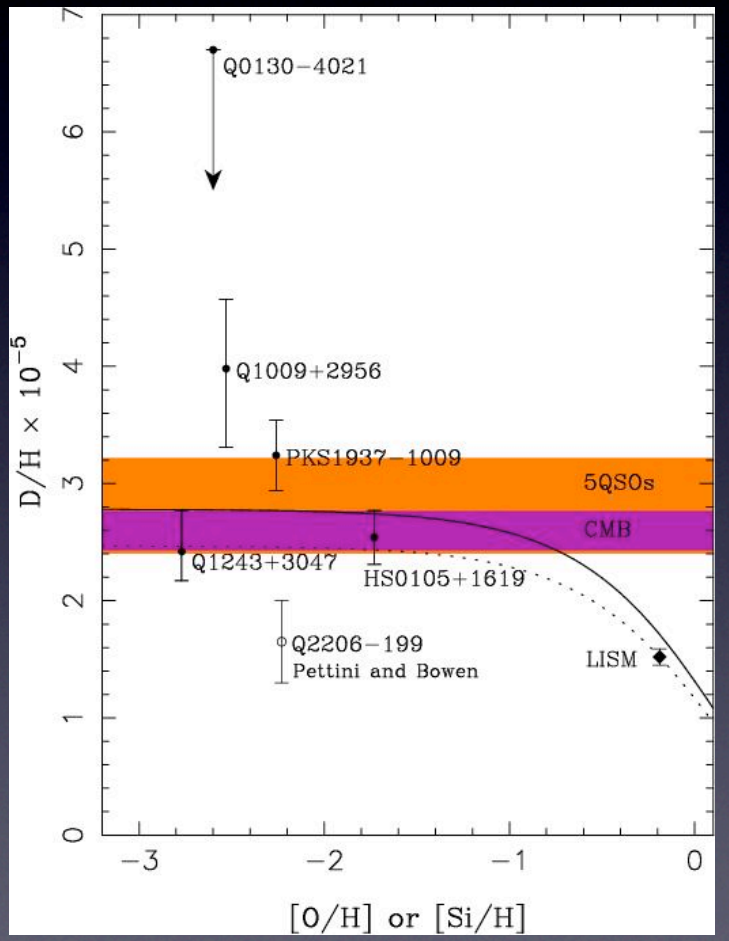
"We may need to realize that the universe is not unique"

Beatrice Tinsley

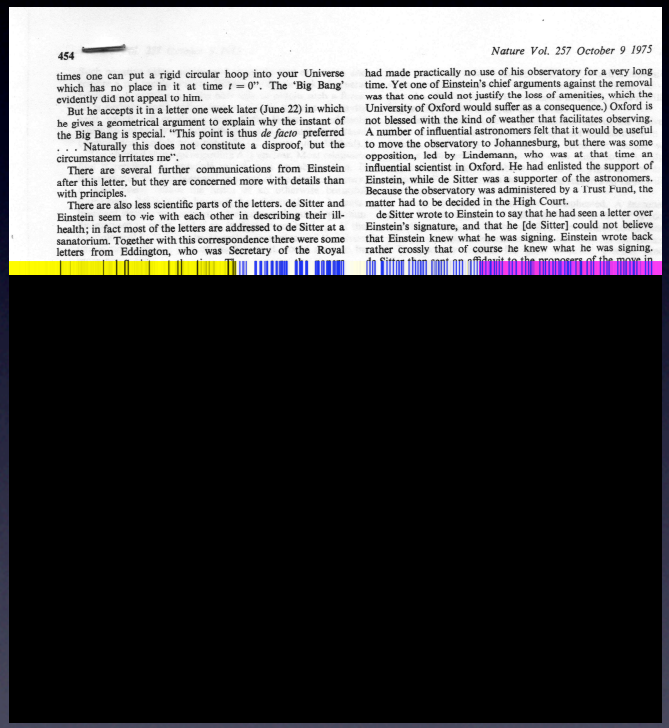
- Chemical Evolution

Univ of Canterbury ’63 MS
Univ of Texas in Austin ’67 phD
’68-’74 adopted son & daughter
Hale Observatory, Lick Observatory, Caltech, Univ of Maryland, Univ of Texas
’75 Associate Prof. at Yale, ’78 Full Prof.
’81 3/23

•D/H=(D/H)p x exp(z/y R/1-R)



Tinsley predicted Λ universe in 1975



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times one can put a rigid circular hoop into your Universe which has no place in it at time $t = 0$". The 'Big Bang' evidently did not appeal to him.

But he accepts it in a letter one week later (June 22) in which he gives a geometrical argument to explain why the instant of the Big Bang is special. "This point is thus *de facto* preferred . . . Naturally this does not constitute a disproof, but the circumstance irritates me".

There are several further communications from Einstein after this letter, but they are concerned more with details than with principles.

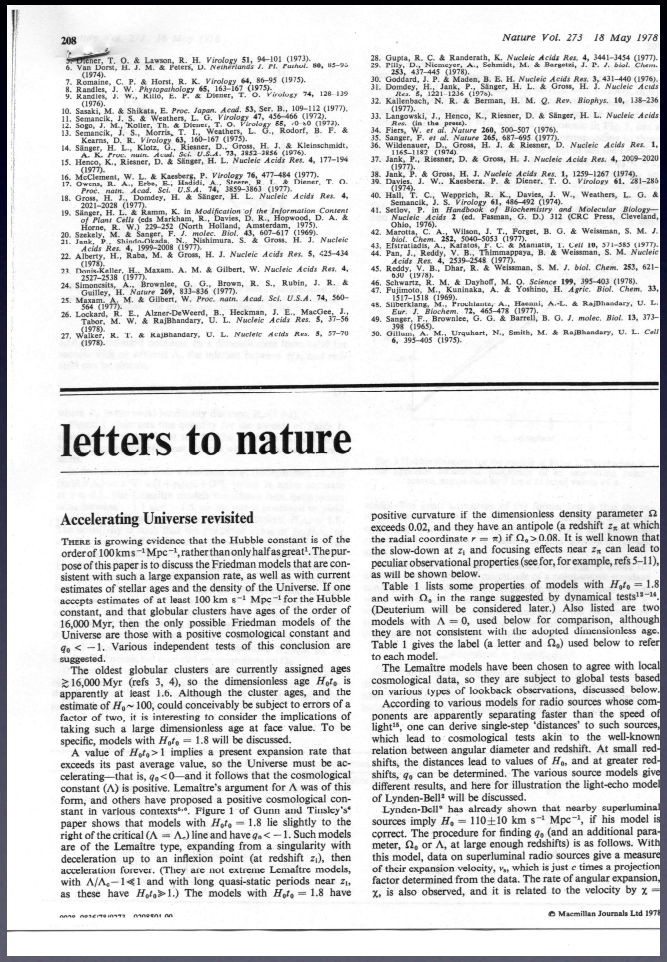
There are also less scientific parts of the letters. de Sitter and Einstein seem to vie with each other in describing their ill-health; in fact most of the letters are addressed to de Sitter at a sanatorium. Together with this correspondence there were some letters from Eddington, who was Secretary of the Royal

had made practically no use of his observatory for a very long time. Yet one of Einstein's chief arguments against the removal was that one could not justify the loss of amenities, which the University of Oxford would suffer as a consequence.) Oxford is not blessed with the kind of weather that facilitates observing. A number of influential astronomers felt that it would be useful to move the observatory to Johannesburg, but there was some opposition, led by Lindemann, who was at that time an influential scientist in Oxford. He had enlisted the support of Einstein, while de Sitter was a supporter of the astronomers. Because the observatory was administered by a Trust Fund, the matter had to be decided in the High Court.

de Sitter wrote to Einstein to say that he had seen a letter over Einstein's signature, and that he [de Sitter] could not believe that Einstein knew what he was signing. Einstein wrote back rather crossly that of course he knew what he was signing.

de Sitter then sent an affidavit to the proposers of the move in

Tinsley insisted Λ universe in 1978



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letters to nature

Accelerating Universe revisited

THERE is growing evidence that the Hubble constant is of the order of 100 km s^{-1} Mpc^{-1}, rather than only half as great[1]. The purpose of this paper is to discuss the Friedman models that are consistent with such a large expansion rate, as well as with current estimates of stellar ages and the density of the Universe. If one accepts estimates of at least 100 km s^{-1} Mpc^{-1} for the Hubble constant, and that globular clusters have ages of the order of 16,000 Myr, then the only possible Friedman models of the Universe are those with a positive cosmological constant and $q_0 < -1$. Various independent tests of this conclusion are suggested.

The oldest globular clusters are currently assigned ages $\gtrsim$16,000 Myr (refs 3, 4), so the dimensionless age $H_0 t_0$ is apparently at least 1.6. Although the cluster ages, and the estimate of $H_0 \sim 100$, could conceivably be subject to errors of a factor of two, it is interesting to consider the implications of taking such a large dimensionless age at face value. To be specific, models with $H_0 t_0 = 1.8$ will be discussed.

A value of $H_0 t_0 > 1$ implies a present expansion rate that exceeds its past average value, so the Universe must be accelerating—that is, $q_0 < 0$—and it follows that the cosmological constant (Λ) is positive. Lemaître's argument for Λ was of this form, and others have proposed a positive cosmological constant in various contexts[5,6]. Figure 1 of Gunn and Tinsley's[5] paper shows that models with $H_0 t_0 = 1.8$ lie slightly to the right of the critical ($\Lambda = \Lambda_c$) line and have $q_0 < -1$. Such models are of the Lemaître type, expanding from a singularity with deceleration up to an inflexion point (at redshift z_i), then acceleration forever. (They are not extreme Lemaître models, with $\Lambda/\Lambda_c - 1 \ll 1$ and with long quasi-static periods near z_i, as these have $H_0 t_0 \gg 1$.) The models with $H_0 t_0 = 1.8$ have positive curvature if the dimensionless density parameter Ω exceeds 0.02, and they have an antipole (a redshift z_π at which the radial coordinate $r = \pi$) if $\Omega_0 > 0.08$. It is well known that the slow-down at z_i and focusing effects near z_π can lead to peculiar observational properties (see for, for example, refs 5–11), as will be shown below.

Table 1 lists some properties of models with $H_0 t_0 = 1.8$ and with Ω_0 in the range suggested by dynamical tests[12–14]. (Deuterium will be considered later.) Also listed are two models with $\Lambda = 0$, used below for comparison, although they are not consistent with the adopted dimensionless age. Table 1 gives the label (a letter and Ω_0) used below to refer to each model.

The Lemaître models have been chosen to agree with local cosmological data, so they are subject to global tests based on various types of lookback observations, discussed below.

According to various models for radio sources whose components are apparently separating faster than the speed of light[18], one can derive single-step 'distances' to such sources, which lead to cosmological tests akin to the well-known relation between angular diameter and redshift. At small redshifts, the distances lead to values of H_0, and at greater redshifts, q_0 can be determined. The various source models give different results, and here for illustration the light-echo model of Lynden-Bell[2] will be discussed.

Lynden-Bell[2] has already shown that nearby superluminal sources imply $H_0 = 110 \pm 10$ km s^{-1} Mpc^{-1}, if his model is correct. The procedure for finding q_0 (and an additional parameter, Ω_0 or Λ, at large enough redshifts) is as follows. With this model, data on superluminal radio sources give a measure of their expansion velocity, v_s, which is just c times a projection factor determined from the data. The rate of angular expansion, $\dot{\chi}_s$, is also observed, and it is related to the velocity by $\chi =$

Part II : Supernova Cosmology

- Dark Energy
  - A Brief History of Dark Energy
  - Phillips Relation & Type Ia Supernova
  - Supernova Cosmology Today
  - Ongoing HST/ACS cluster survey
  - Key Issues for Precise Measurement
  - PCA application to SNIa Spectra & SNAP

Einstein's Λ

Kosmologische Betrachtungen zur allgemeinen Relativätstheorie (1917)

- Poisson's Equation

$$\nabla^2\phi = 4\pi\kappa\rho$$

- Rewriting a Poisson's Equation with λ

$$\nabla^2\phi - \lambda\phi = 4\pi\kappa\rho$$

- where λ denotes the universal constant. If ρ be the uniform density of distribution of mass, then

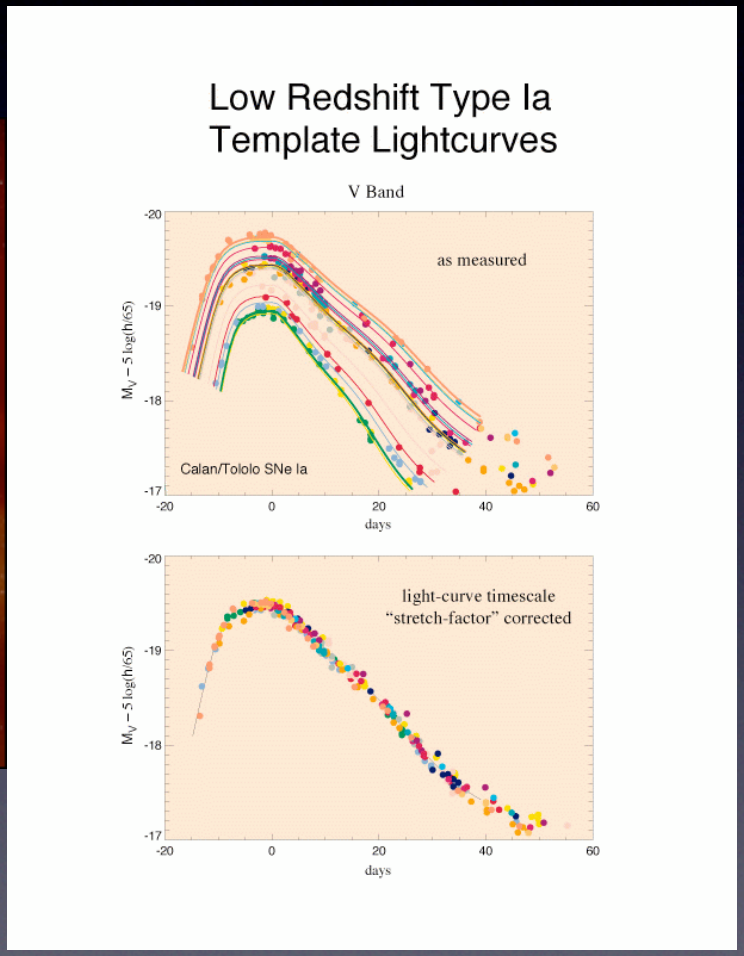
$$\phi = -\frac{4\pi\kappa}{\lambda}\rho_0$$

A Brief History of Dark Energy
Hints of Dark Energy

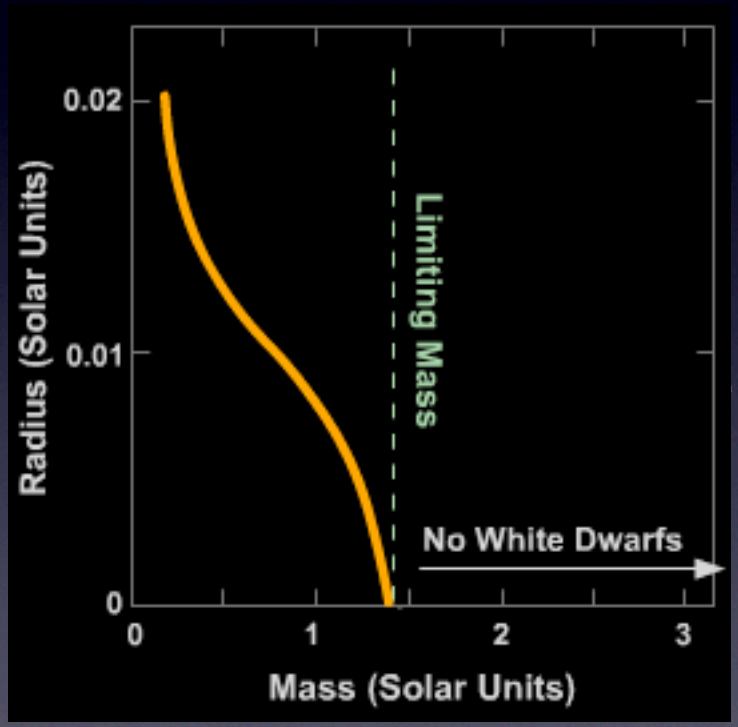
- Zeldovich 1967

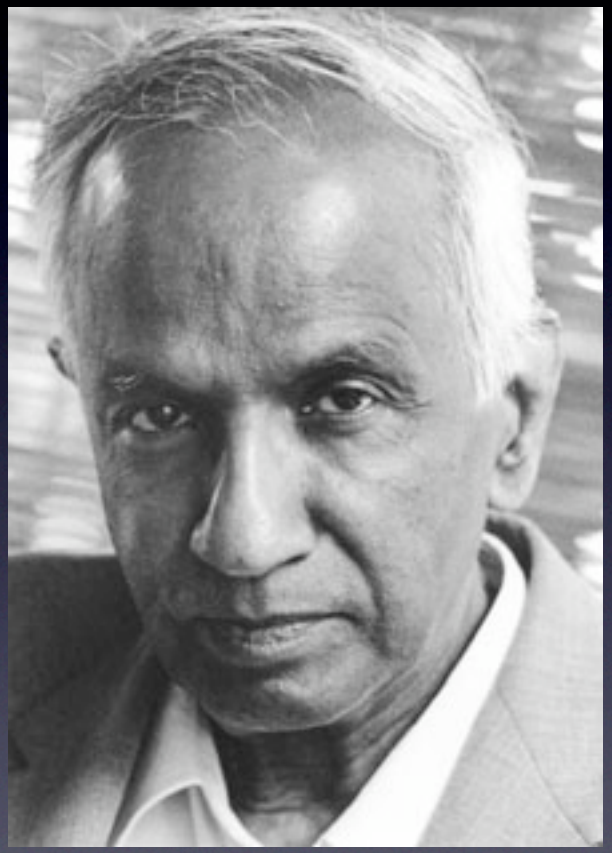
  Vacuum Energy could be responsible for cosmological constant
- Tinseley (1975-1978)
- Alcock Paczynski Test (1979)
- Galaxy Number Counts (1985-95)
- Globular Cluster Age, Galaxy Chemical Evolution
- Concordance Model (‘90s)

Supernova Type Ia Phillips Relation



Chandrasekhar Limit
1.4 Solar Mass

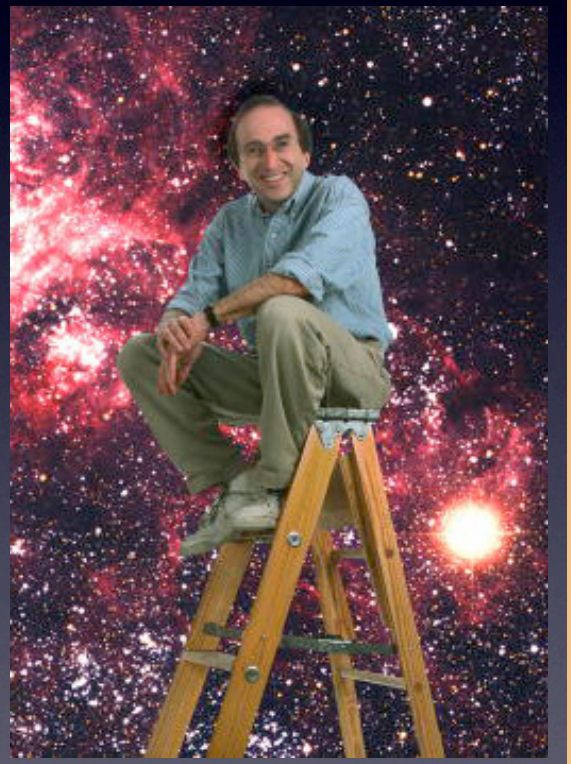


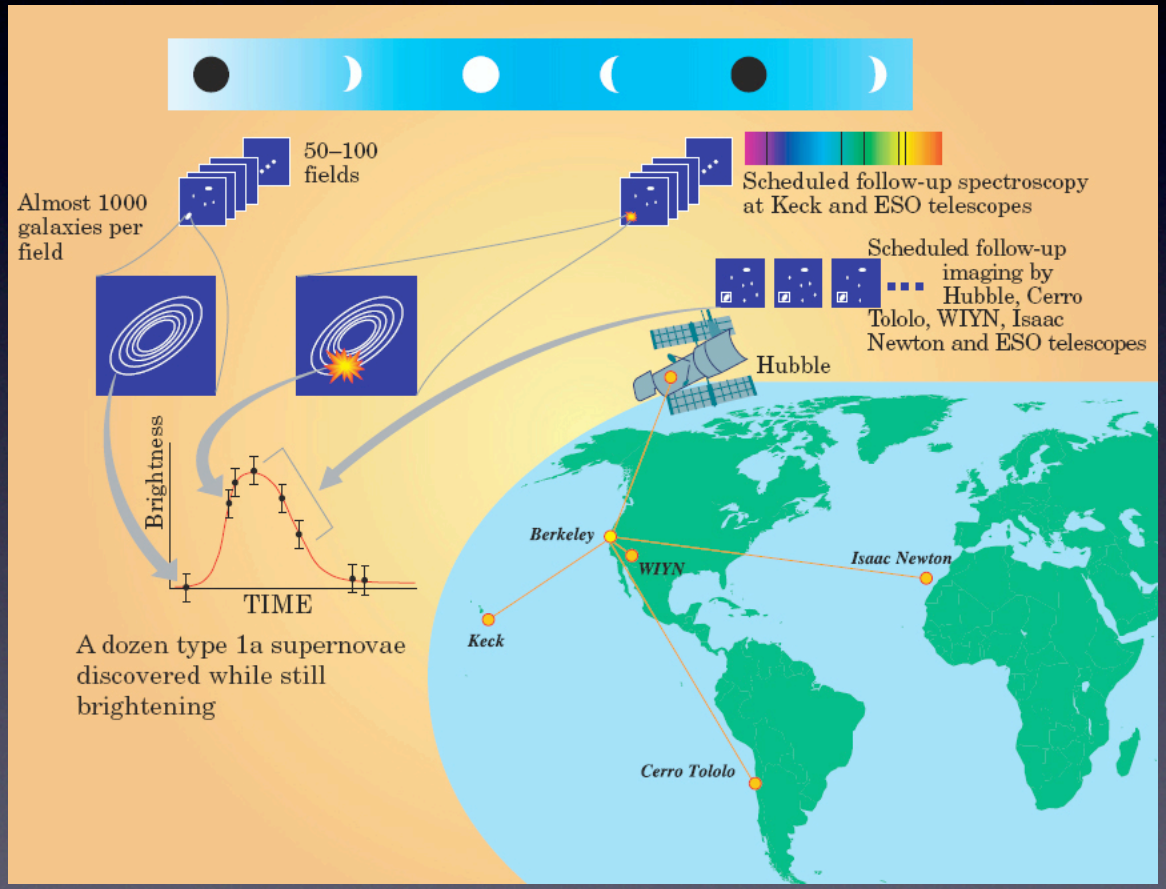


1910-1995

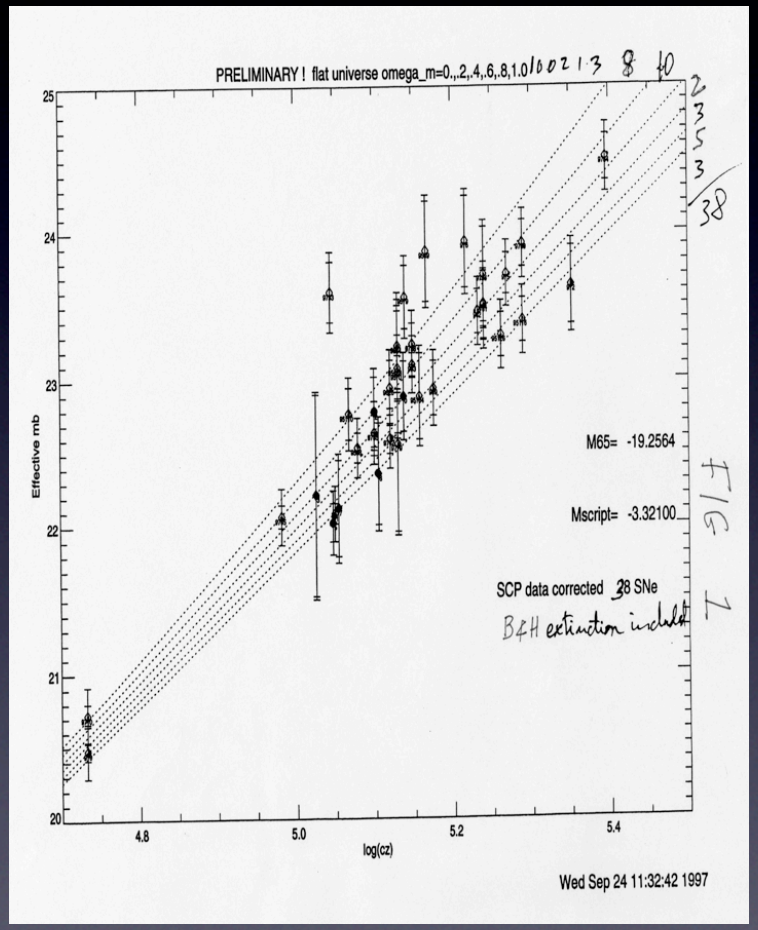
Supernova Cosmology Project:
SNIa+HST+Large Telescopes (CCDs)

Saul Perlmutter

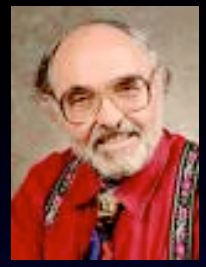


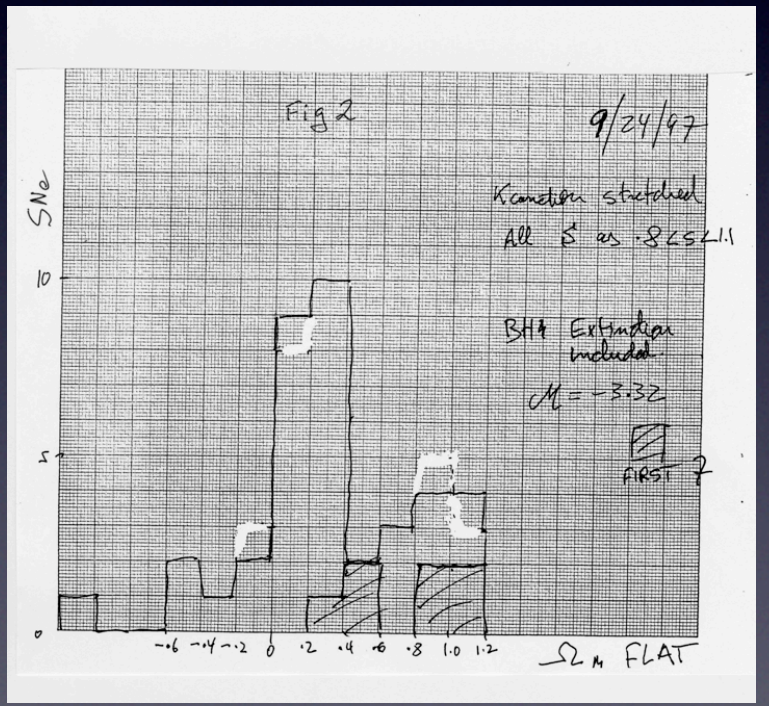


Discovery of Dark Energy (SCP 1997)

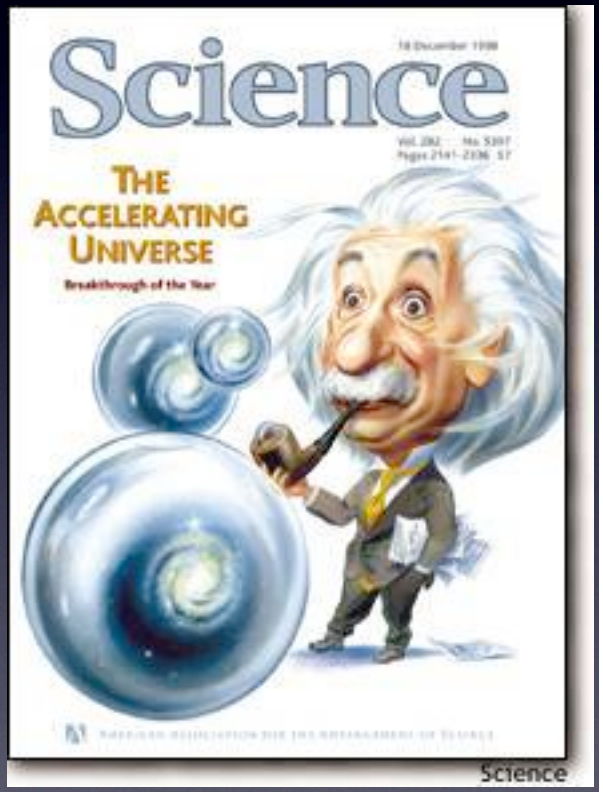


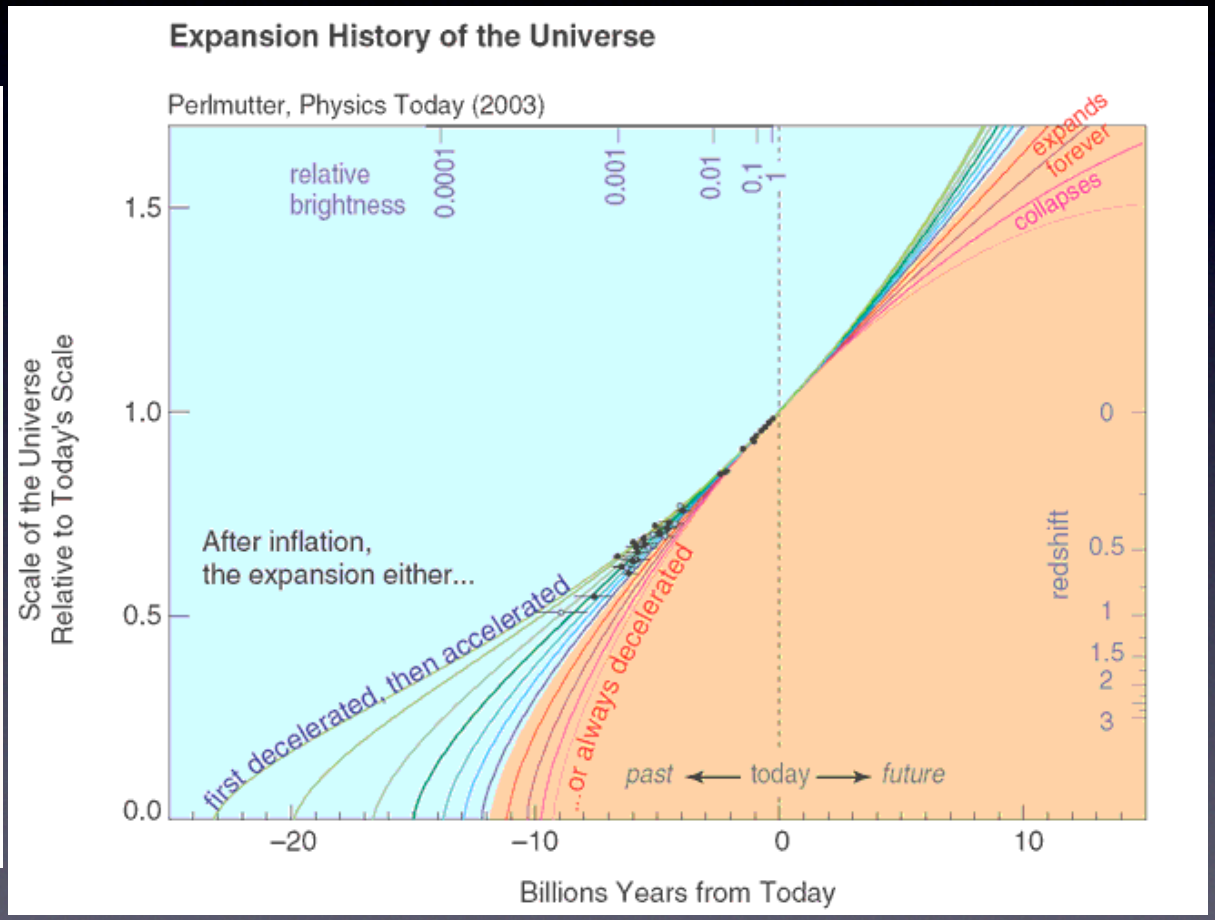
Gerson Goldhaber reported non-zero Λ in Sep ’97





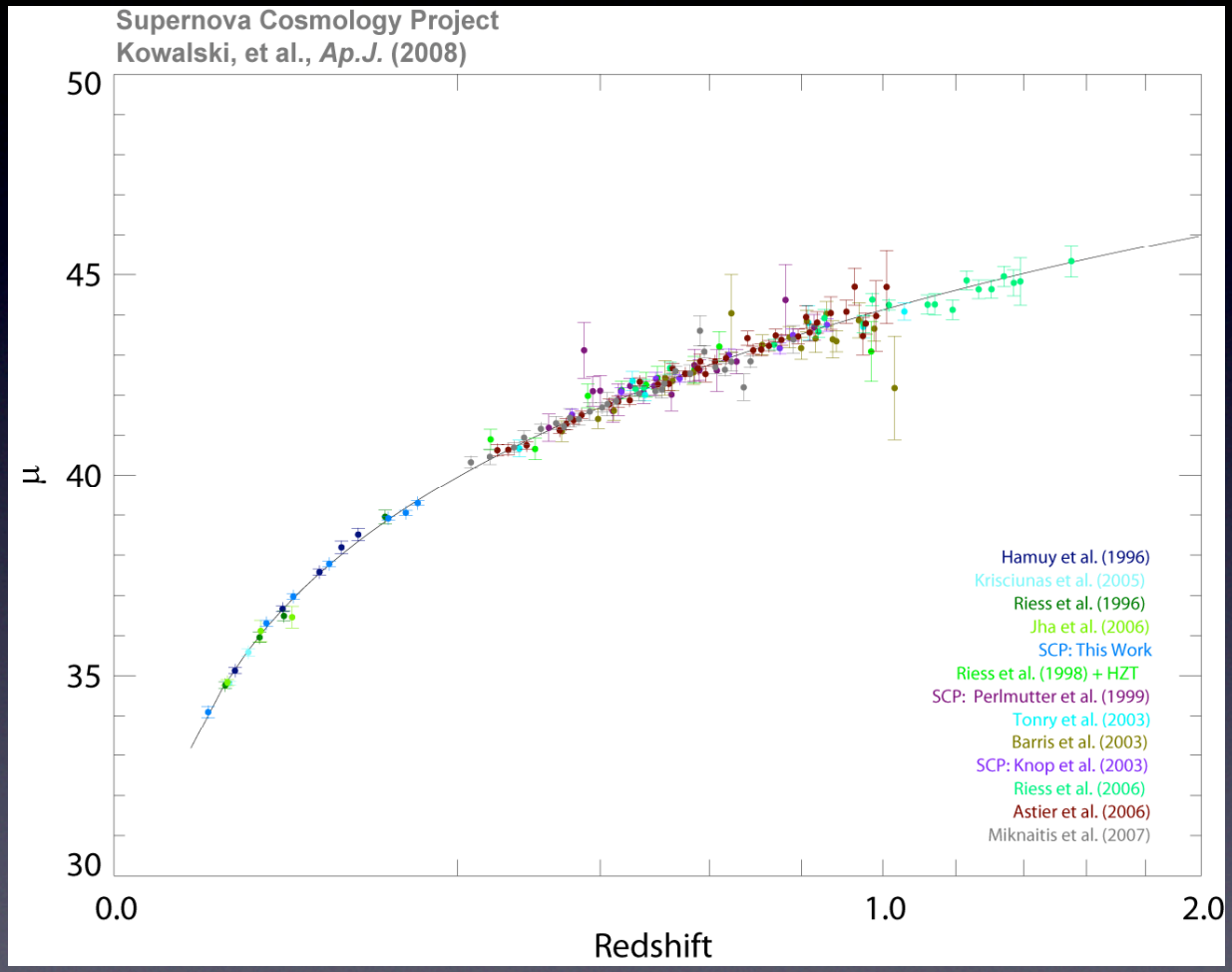
Acceralating Universe





Supernova Cosmology Project 2008

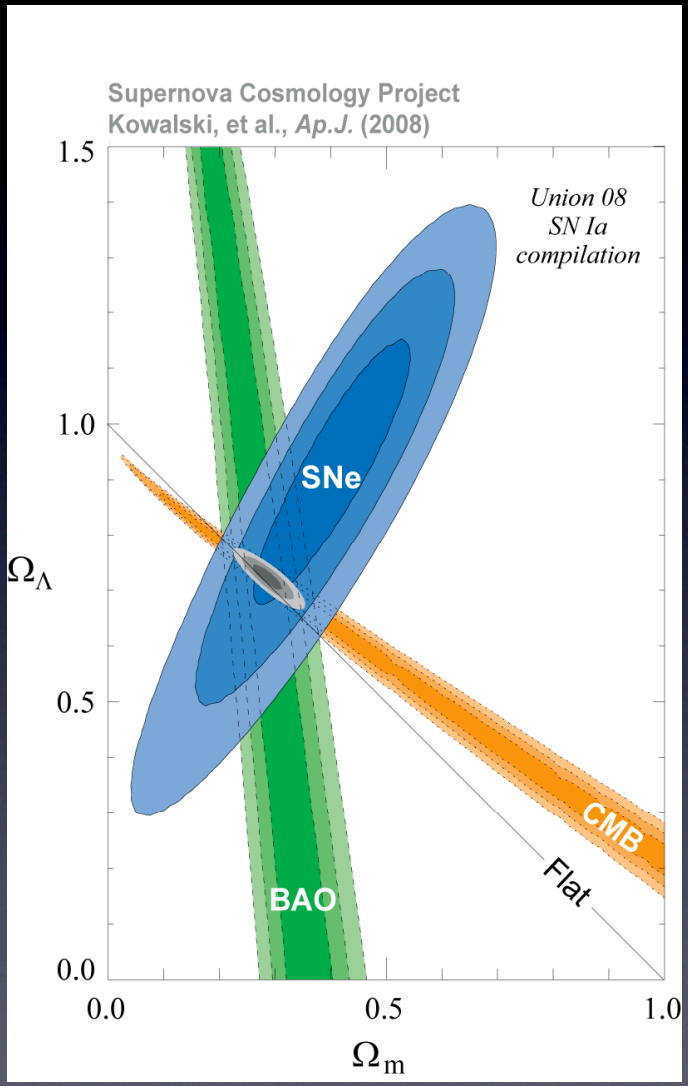
SNIa Cosmology Today (2008)



Λ Today

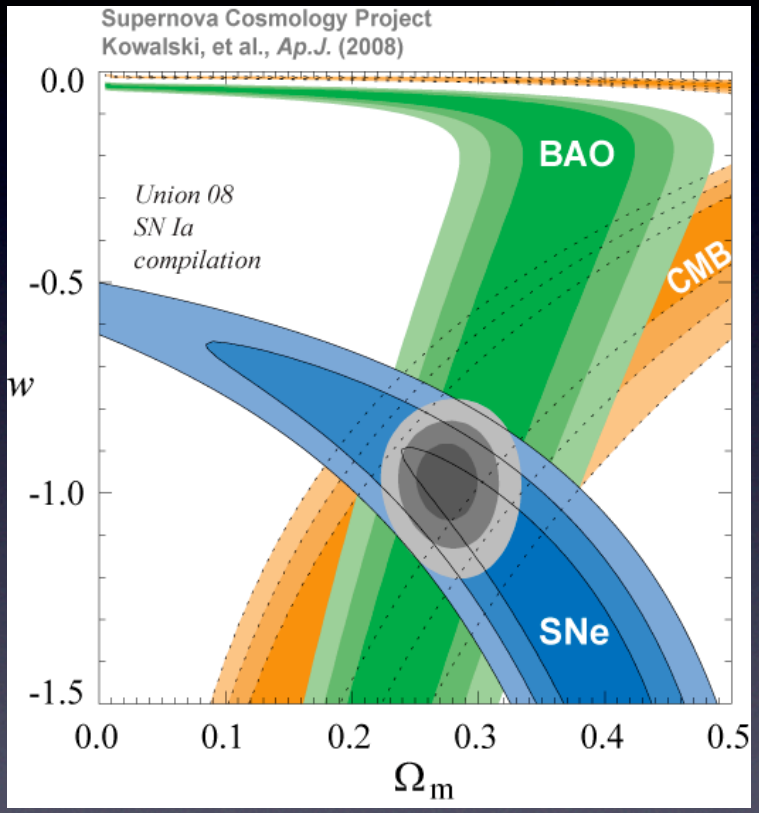
Combination of SNe with:
BAO (Eisenstein et. al., 2005)
CMB (WMAP-5 year data, 2008)
For a flat Universe:
… and with curvature:

$\Omega_m = 0.274 \pm 0.016(\text{stat}) \pm 0.012(\text{sys})$
$\Omega_m = 0.285 \pm 0.020(\text{stat}) \pm 0.010(\text{sys})$
$\Omega_k = -0.001 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$



w=P/ρ : equation of state
(stat err < sys err)

w = −0.969 ± 0.061(stat) ± 0.065(sys)
SNe + BAO + CMB
... and allowing for curvature:
w = −1.001 ± 0.071(stat) ± 0.081(sys)
with systematics



- w=-1 : cosmological constant
- w=0 : matter
- w=1/3: radiation

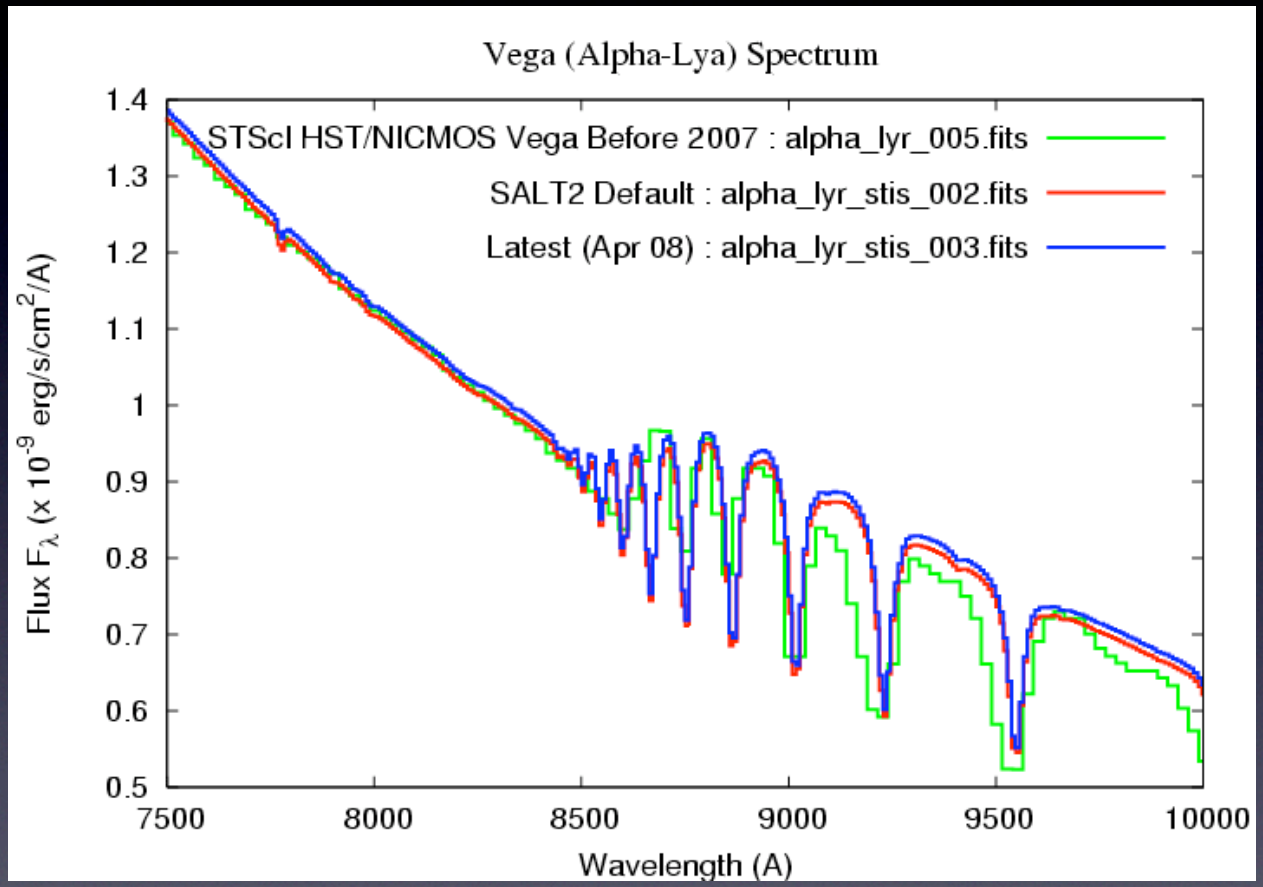
$$E \propto a^{-3(1+w)}$$

Key Issues for precision SN cosmology

1. Vega Spectrum & its magnitude (1-2%)
2. Filter Response (2-5%)
3. Dust Extinction (HST/ACS cluster survey)
4. Intrinsic SNIa diversity

(PCA diversity study)

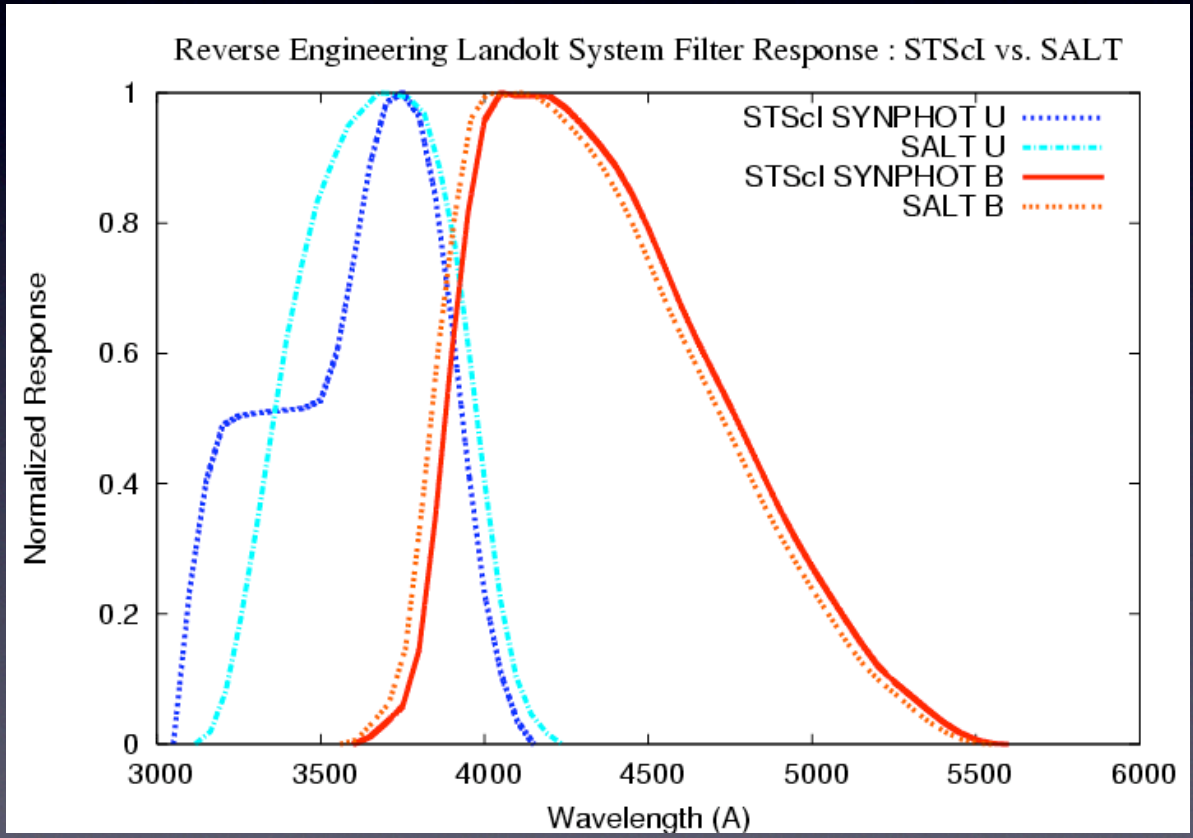
1 : Vega Spectrum



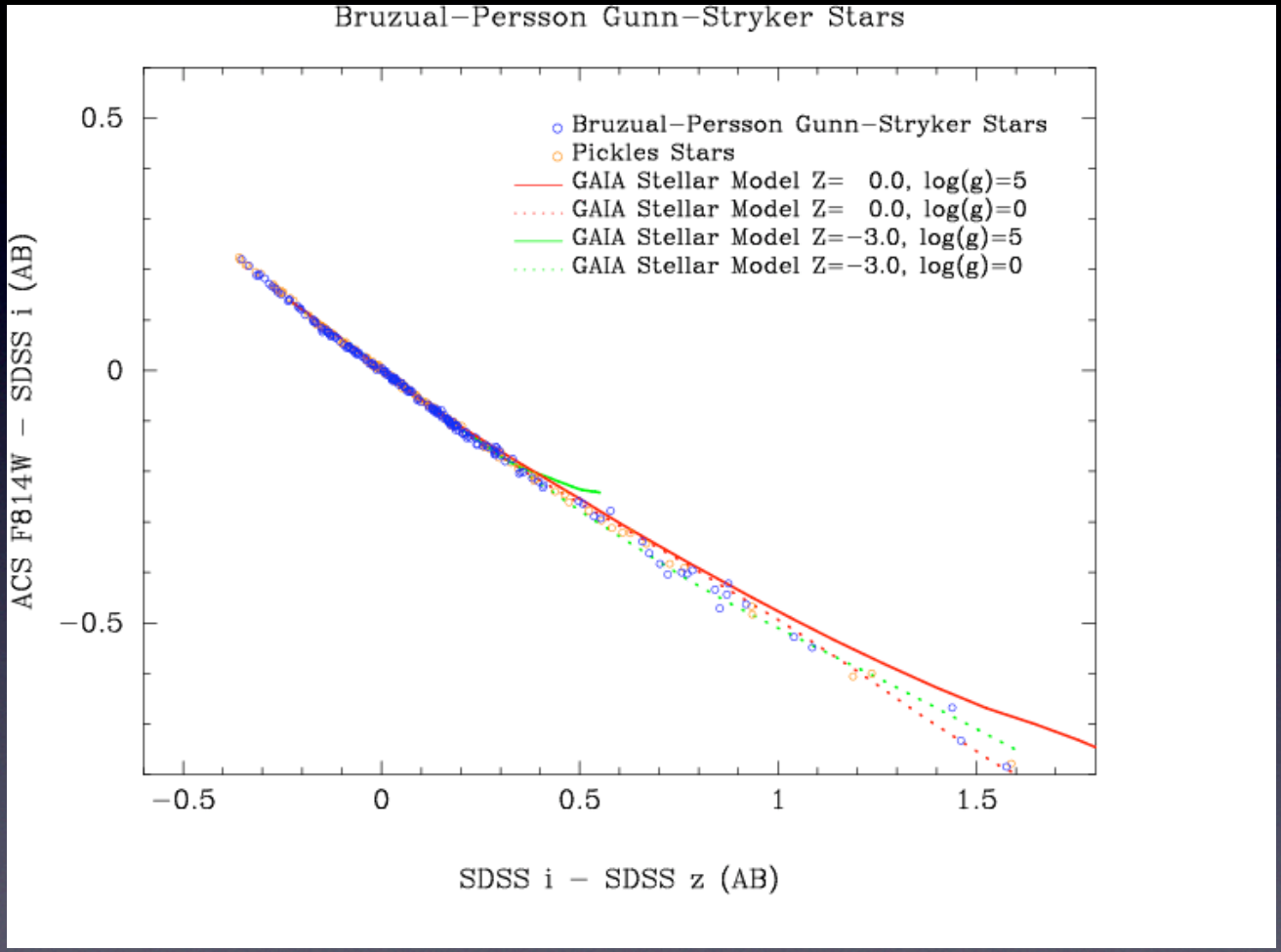
- Hayes 1985 : $3.44 \pm 0.05 \times 10^{-9}$ @ 5556Å

Problem 2a : Landolt Response Reverse Engineering Maiz-Appelleraiz (2006) vs. SALT

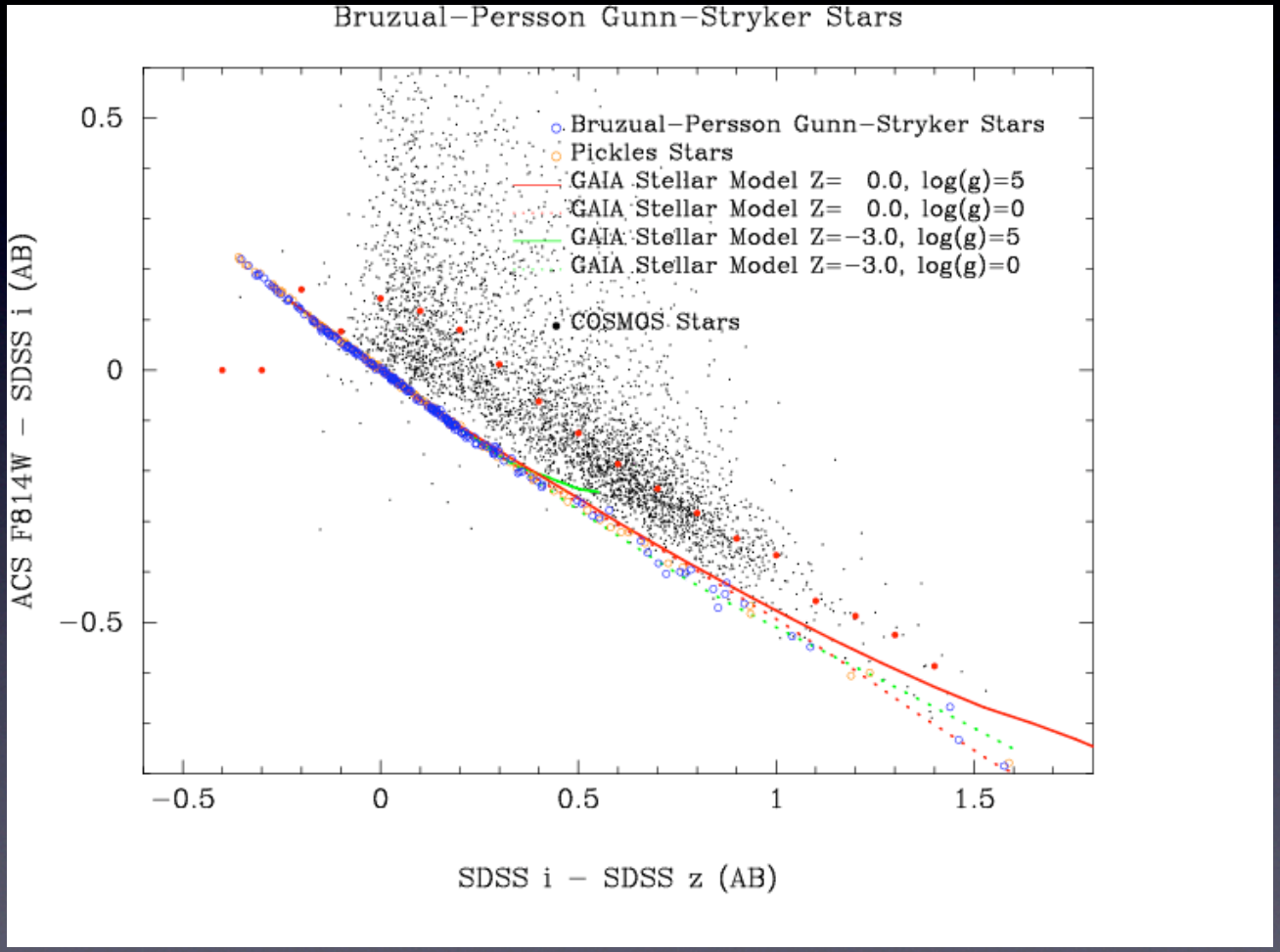
U



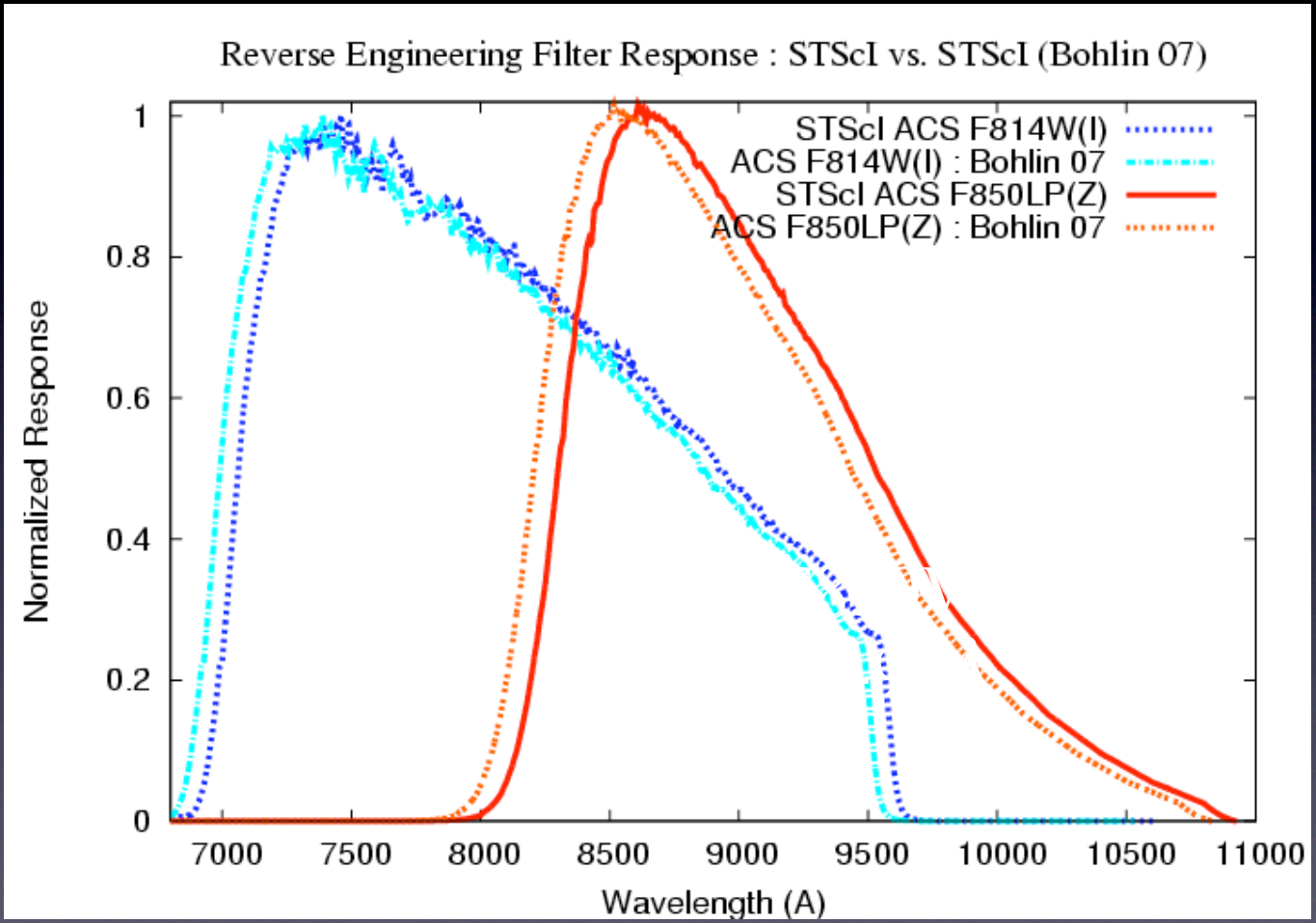
Problem 2b: HST/ACS Response



Problem 2b: HST/ACS Response

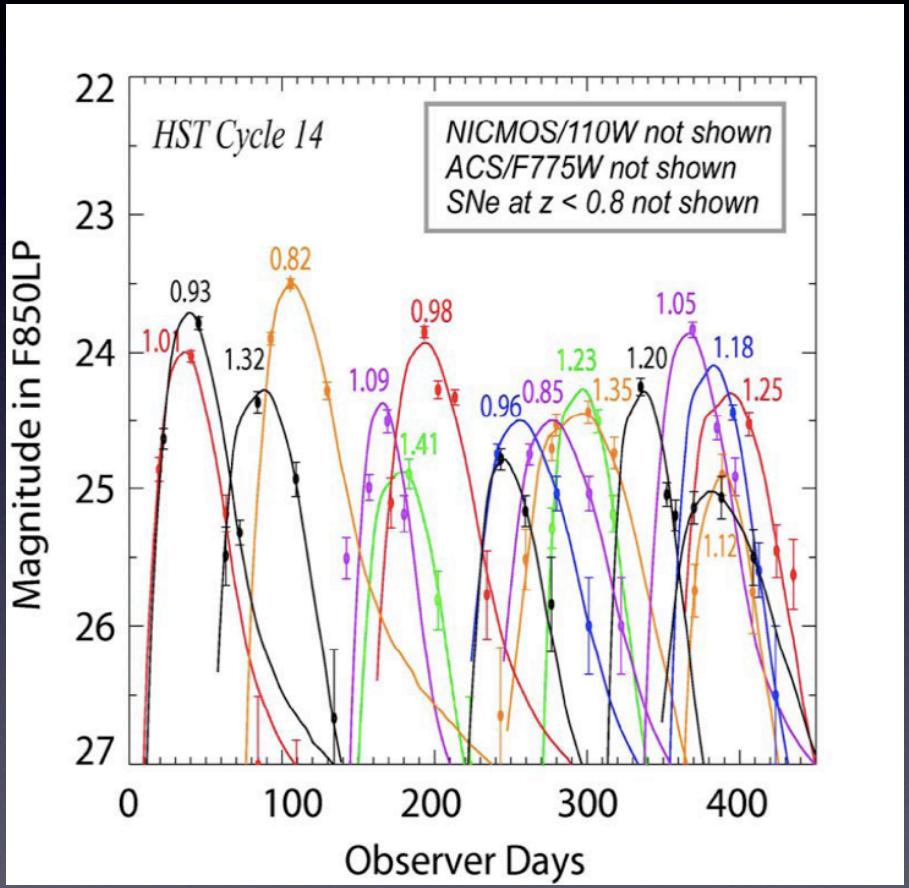


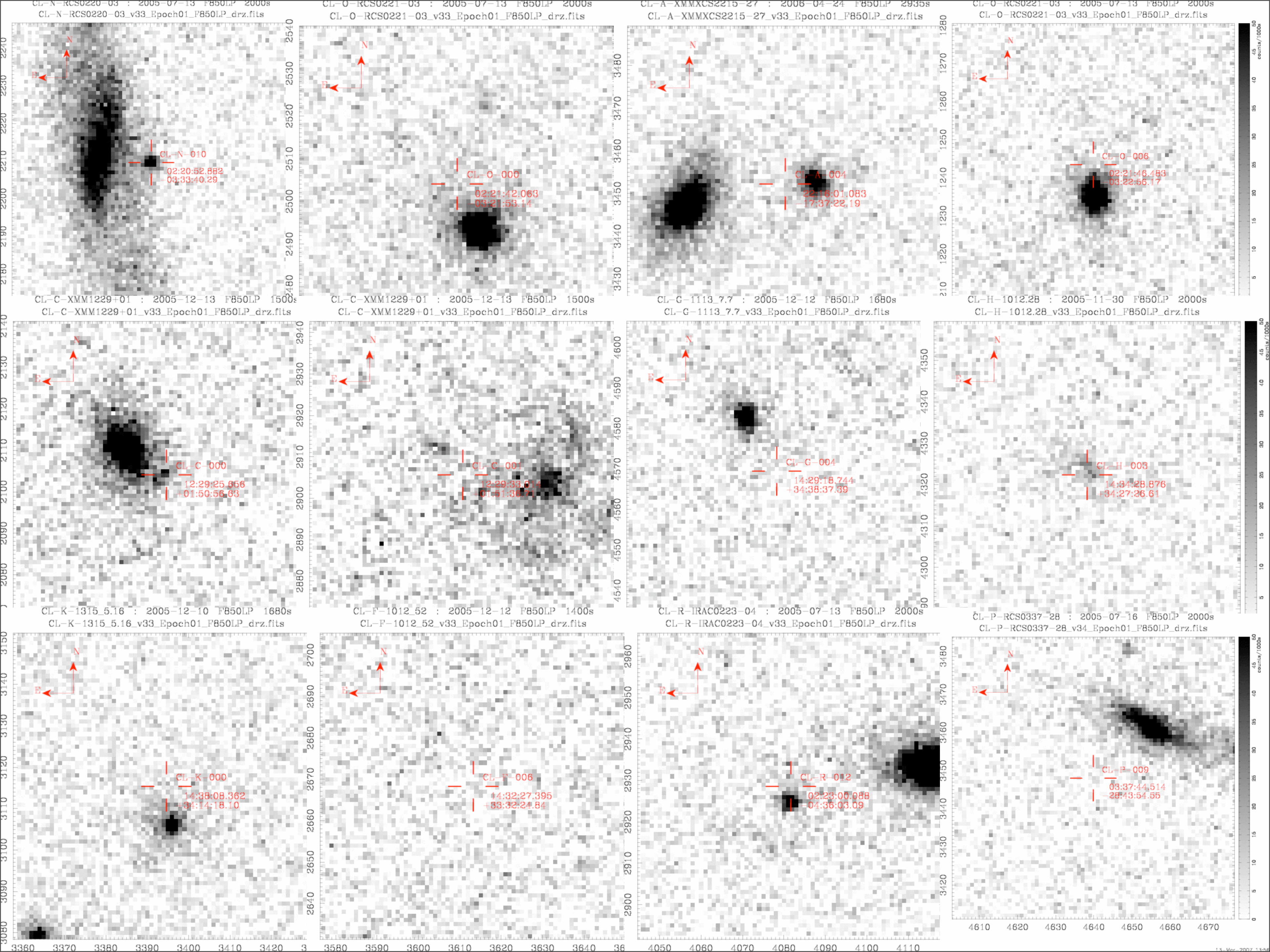
Problem 2c : HST/ACS Response



3. Dust Free SNIa
HST/ACS Cluster Suervey

- 219 HST orbits
- 25 clusters
- $0.9 < z < 1.4$
- ACS i, z band
- NICMOS J

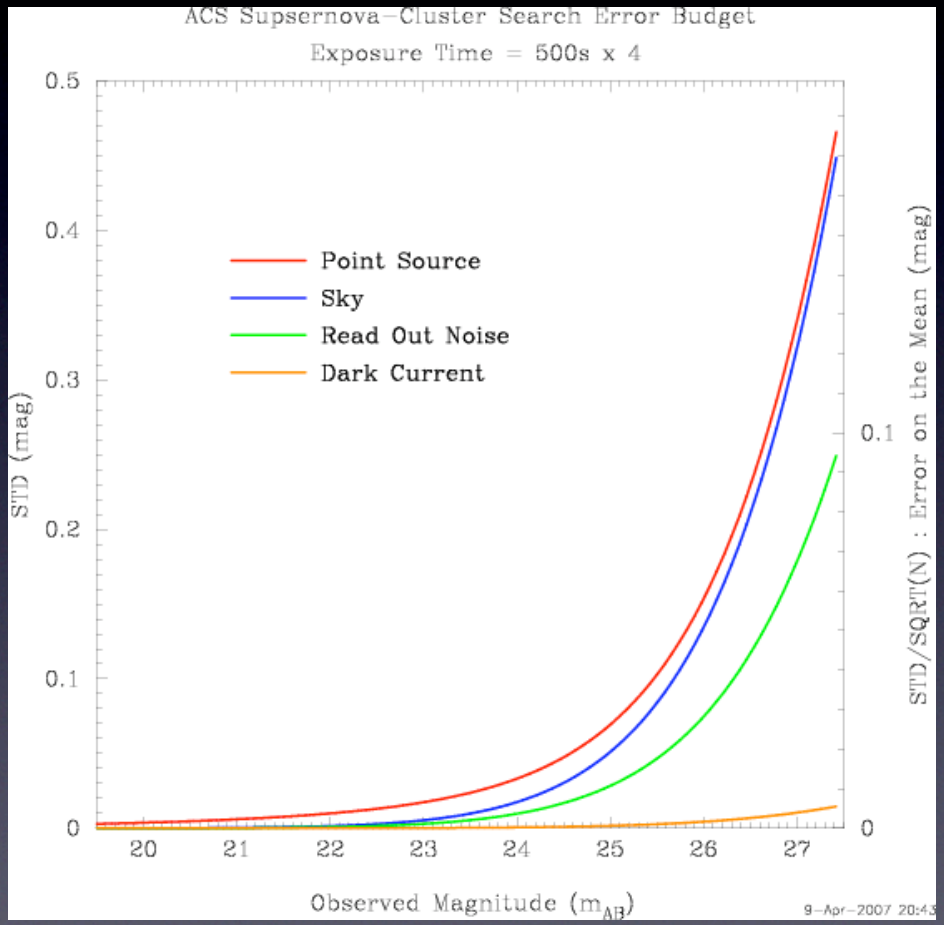




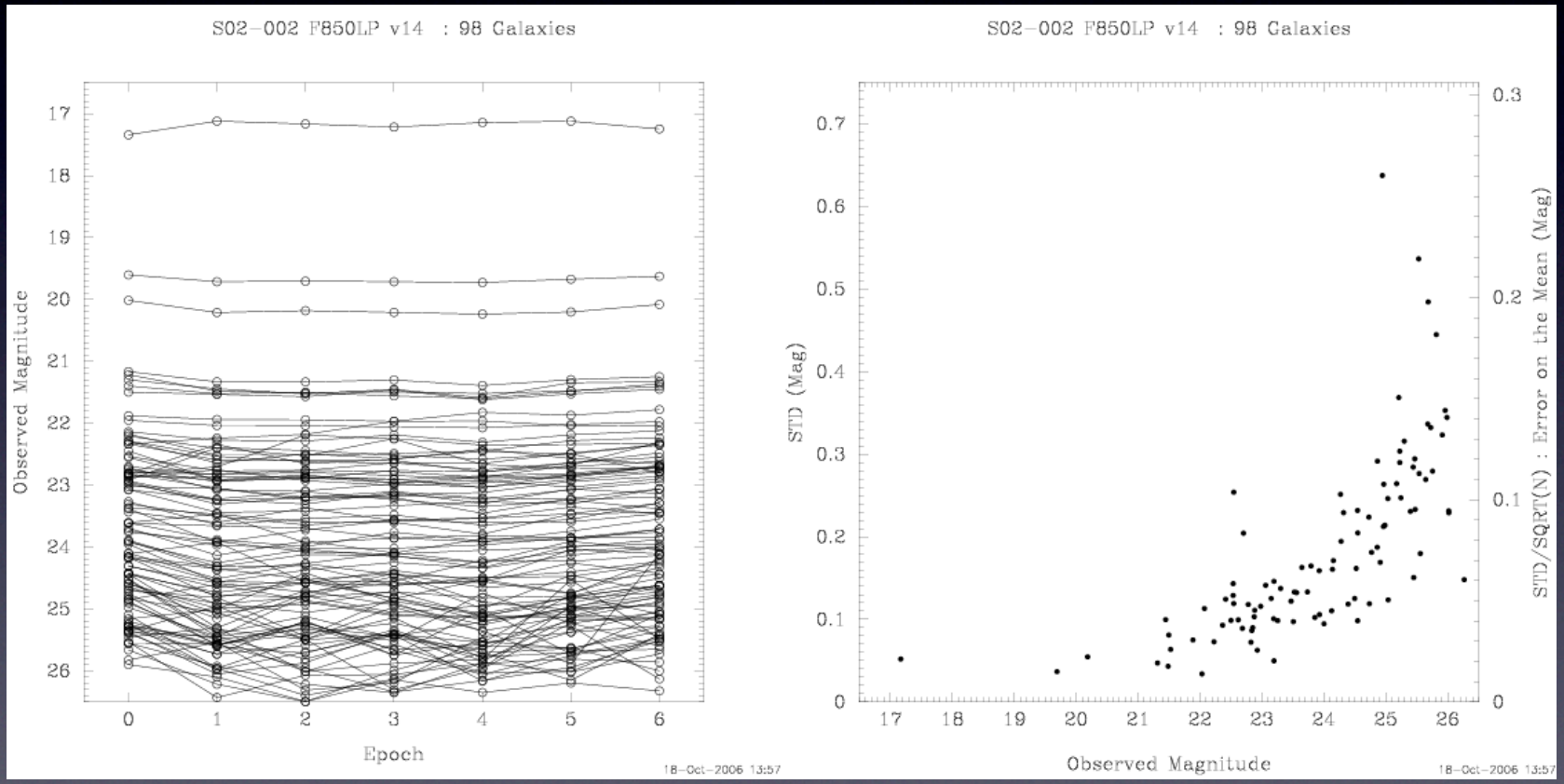
CL-N-RCS0220-03 : 2005-07-13 F850LP 2000s
CL-N-RCS0220-03_v33_Epoch01_F850LP_drz.fits
CL-O-RCS0221-03 : 2005-07-13 F850LP 2000s
CL-O-RCS0221-03_v33_Epoch01_F850LP_drz.fits
CL-A-XMMXCS2215-27 : 2006-04-24 F850LP 2935s
CL-A-XMMXCS2215-27_v33_Epoch01_F850LP_drz.fits
CL-O-RCS0221-03 : 2005-07-13 F850LP 2000s
CL-O-RCS0221-03_v33_Epoch01_F850LP_drz.fits
CL-C-XMM1229+01 : 2005-12-13 F850LP 1500s
CL-C-XMM1229+01_v33_Epoch01_F850LP_drz.fits
CL-C-XMM1229+01 : 2005-12-13 F850LP 1500s
CL-C-XMM1229+01_v33_Epoch01_F850LP_drz.fits
CL-G-1113_7.7 : 2005-12-12 F850LP 1680s
CL-G-1113_7.7_v33_Epoch01_F850LP_drz.fits
CL-H-1012.28 : 2005-11-30 F850LP 2000s
CL-H-1012.28_v33_Epoch01_F850LP_drz.fits
CL-K-1315_5.16 : 2005-12-10 F850LP 1680s
CL-K-1315_5.16_v33_Epoch01_F850LP_drz.fits
CL-F-1012_52 : 2005-12-12 F850LP 1400s
CL-F-1012_52_v33_Epoch01_F850LP_drz.fits
CL-R-IRAC0223-04 : 2005-07-13 F850LP 2000s
CL-R-IRAC0223-04_v33_Epoch01_F850LP_drz.fits
CL-P-RCS0337-28 : 2005-07-16 F850LP 2000s
CL-P-RCS0337-28_v34_Epoch01_F850LP_drz.fits

HST/ACS Detector Limit

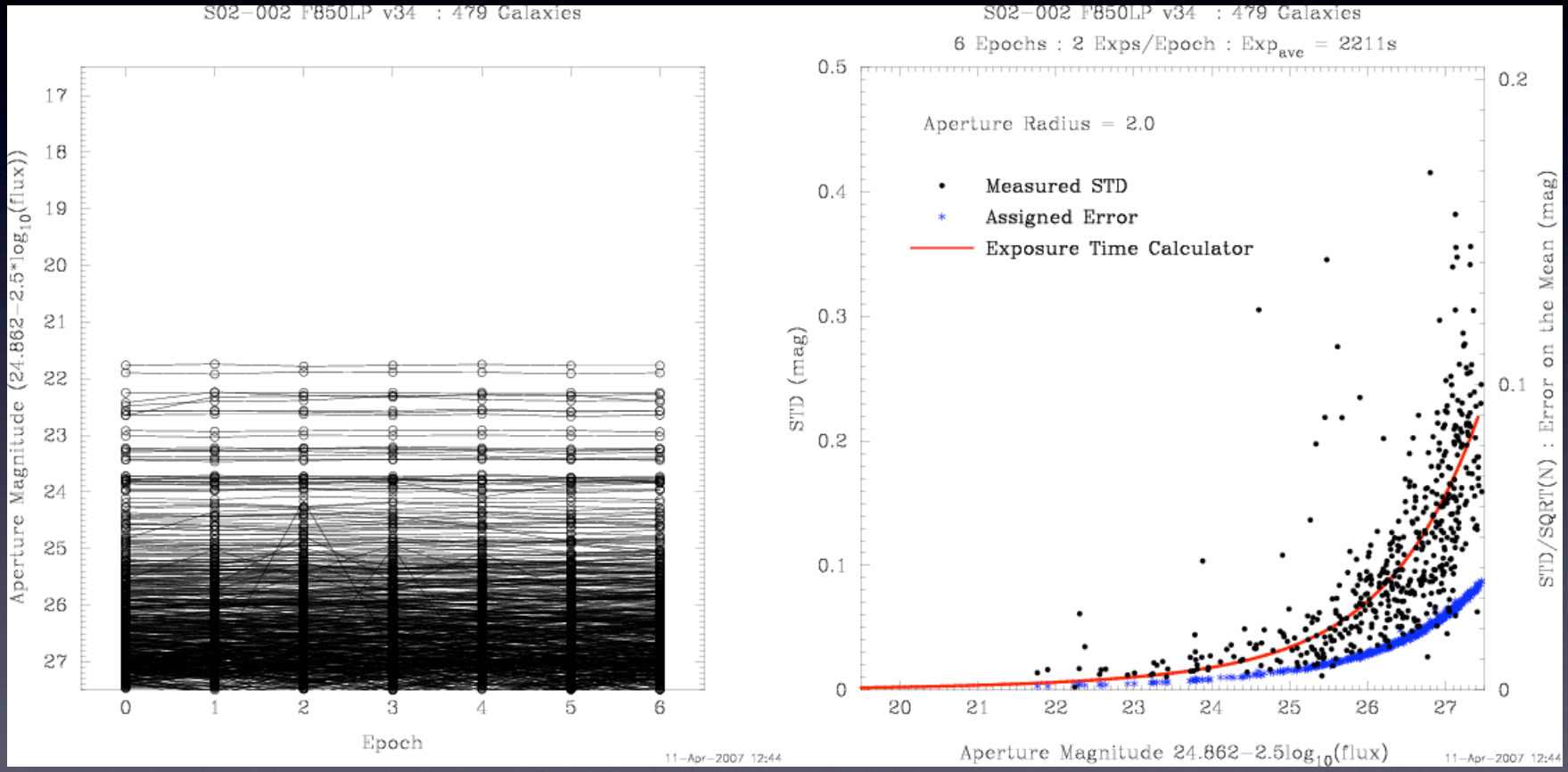
- Theory



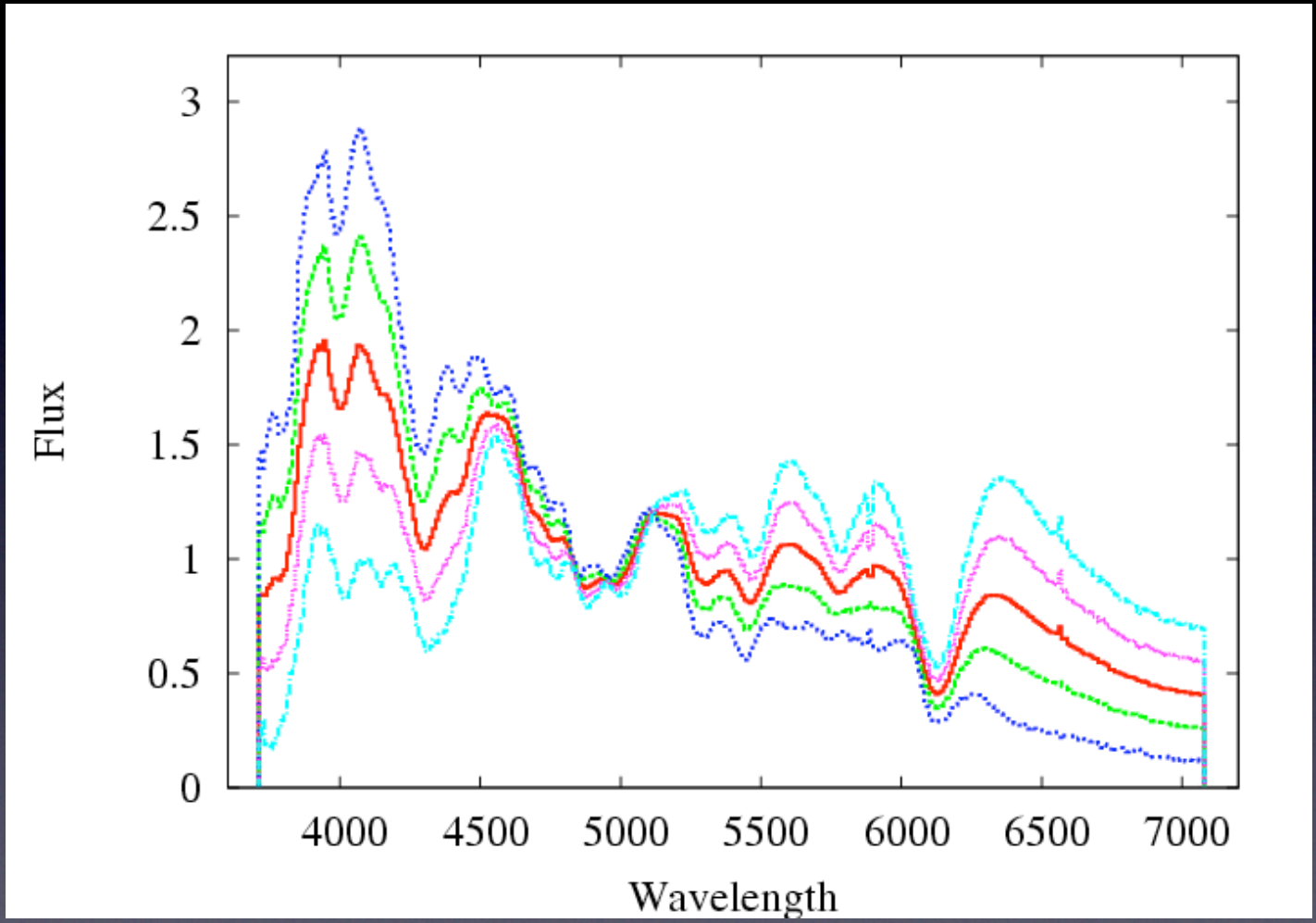
Before Calibration



After Calibration:
Detection Limit is achieved



4. SNIa Diversity



PCA application to SNIa Spectra
Studies of SNIa Diversity

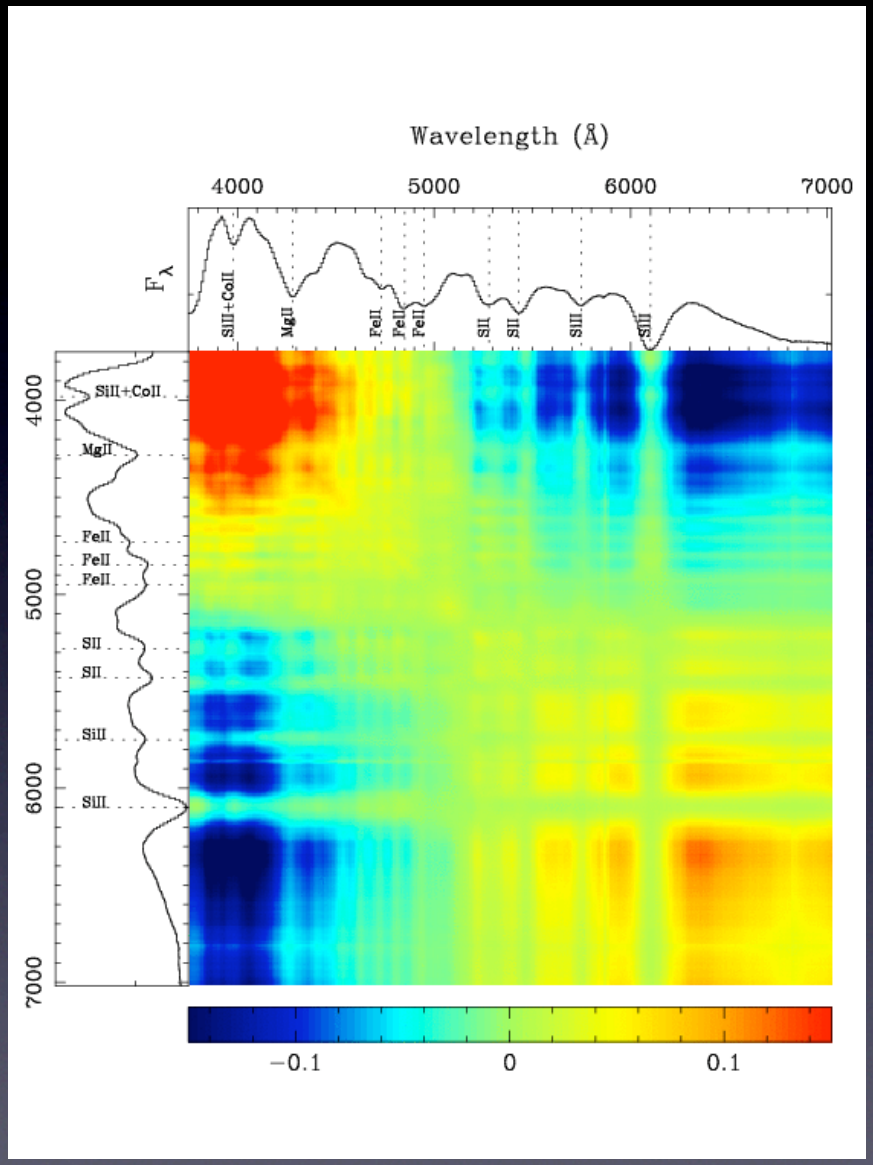
- SNIa diversity studies (Dust or Intrinsic)

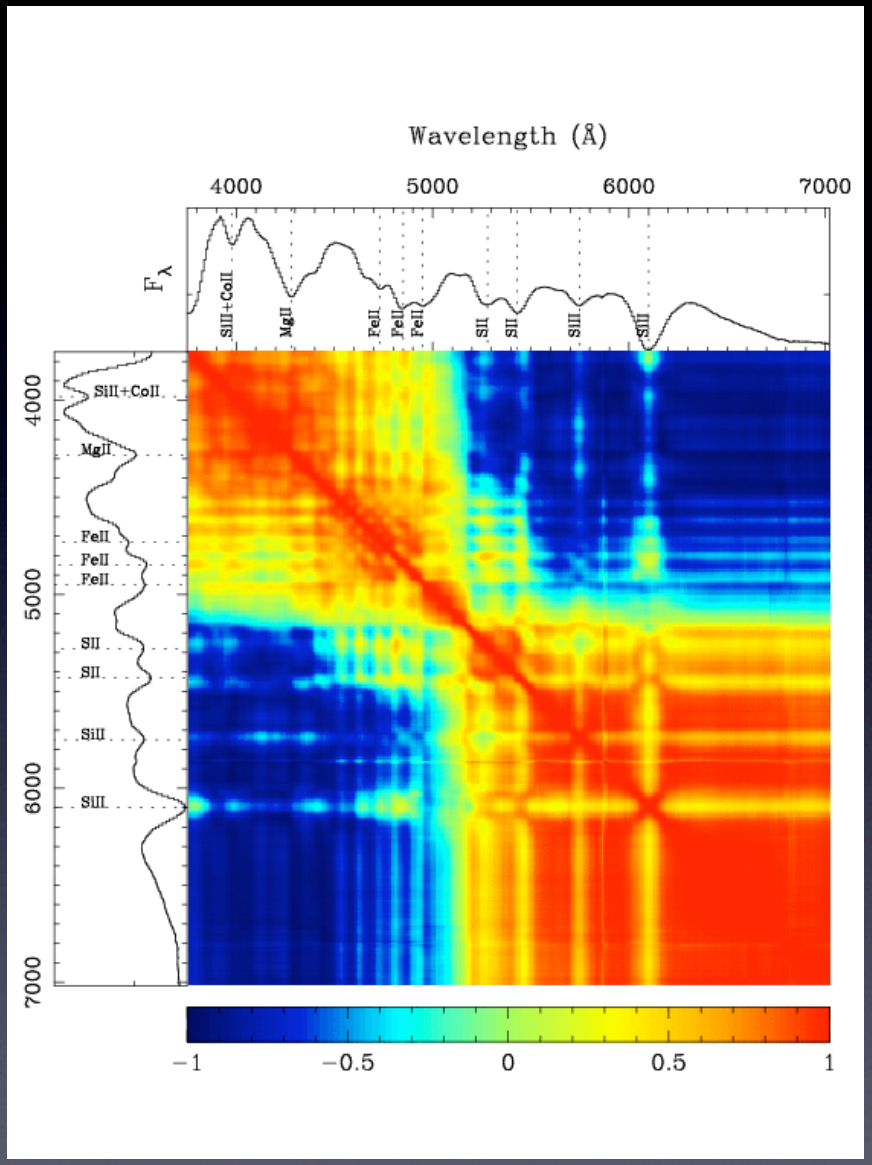
  T. Matheson et al (2008) + Literature Spectra

  20 SNIa spectra + 60 SNIa more (ongoing)

- $$\vec{S} = \vec{\mu} + \sum_{j=1}^{n} c_j \vec{\xi_j}$$

$$\vec{\xi_i} \cdot \vec{\xi_j} = \delta_{ij}$$


Wavelength (Å)
4000
5000
6000
7000
F_λ
SiII+CoII
MgII
FeII
FeII
FeII
SII
SII
SiII
SiII
−0.1
0
0.1

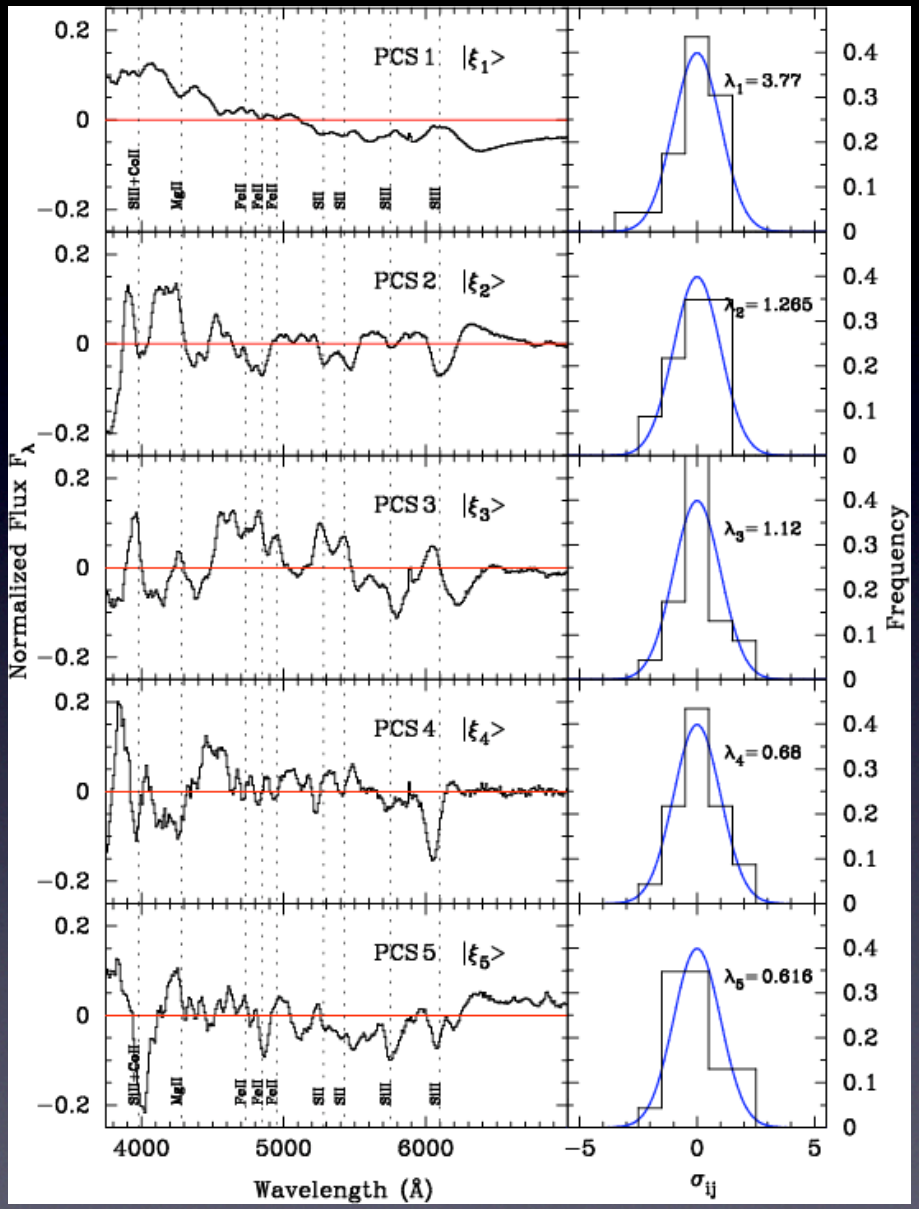

Wavelength (Å)
4000
5000
6000
7000
F_λ
SiII+CoII
MgII
FeII
FeII
FeII
SII
SII
SiII
SiII
−1
−0.5
0
0.5
1

Eigenspectra

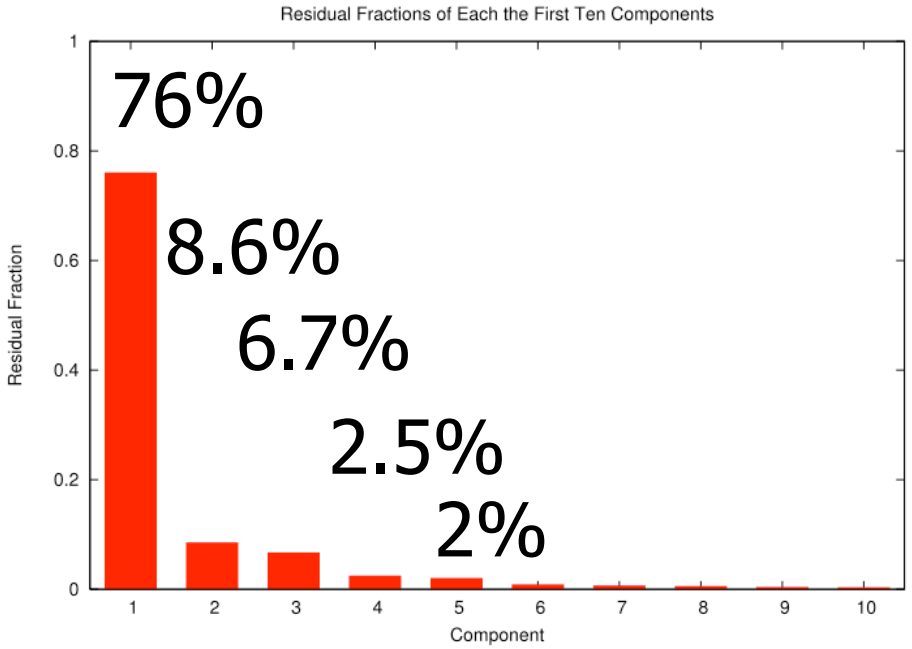
- 1st Eigenspectrum

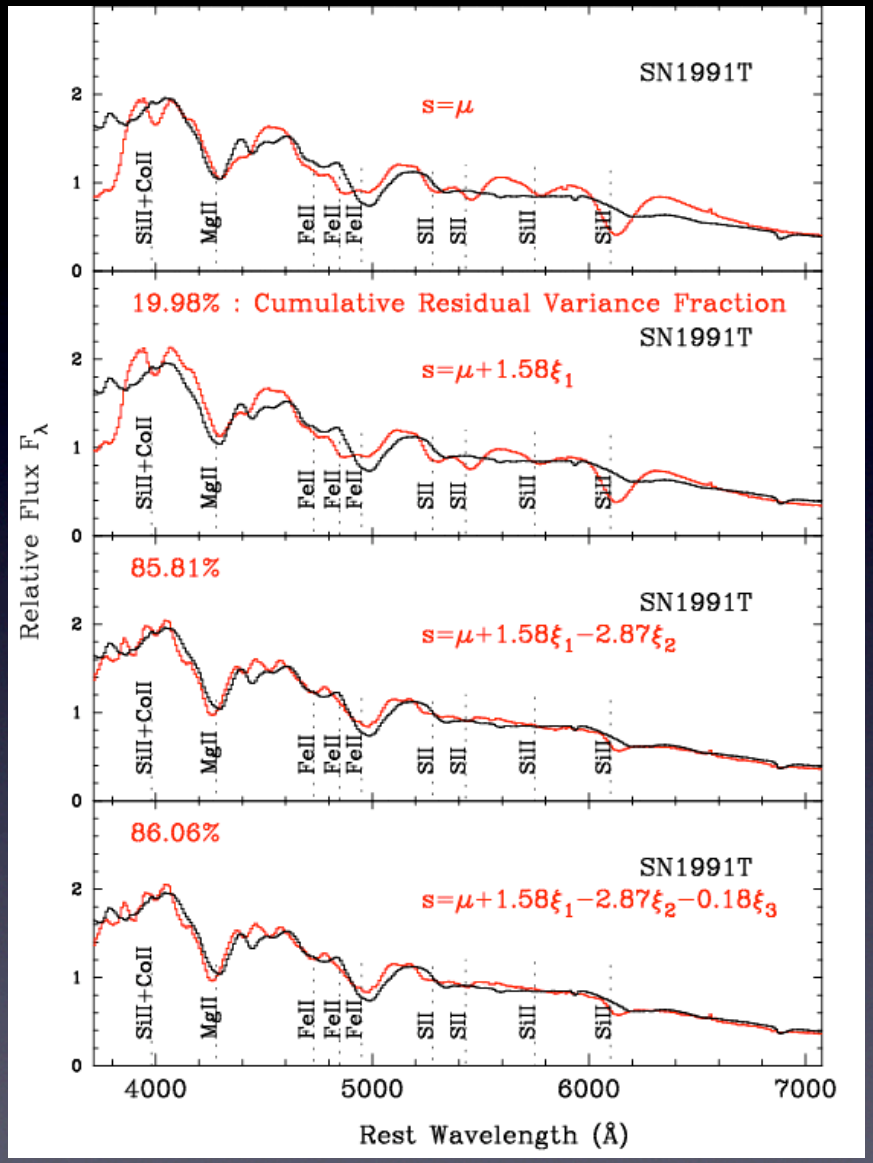
=> color but slope is different from extinction law

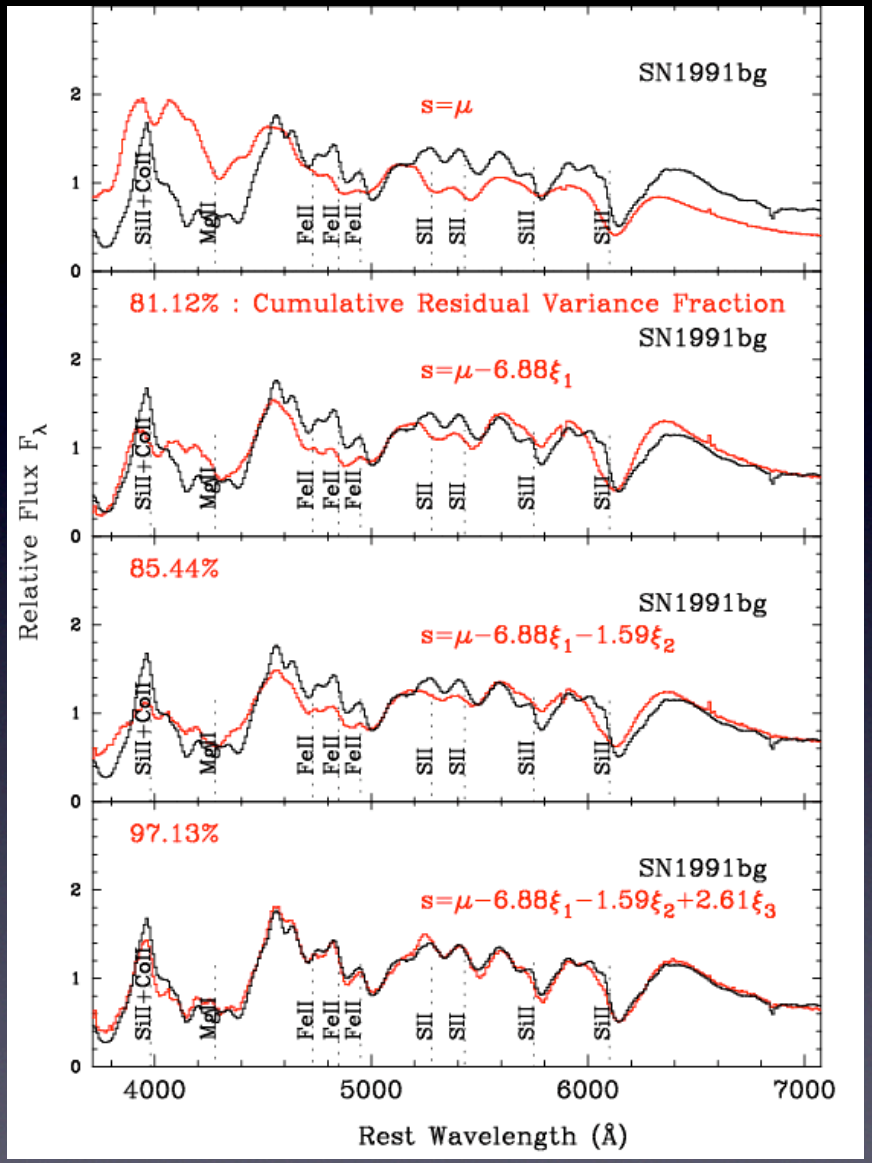
- ~ 90% of residual goes to first 3 components
- 1st+2nd distinguishes dust or intrinsic color

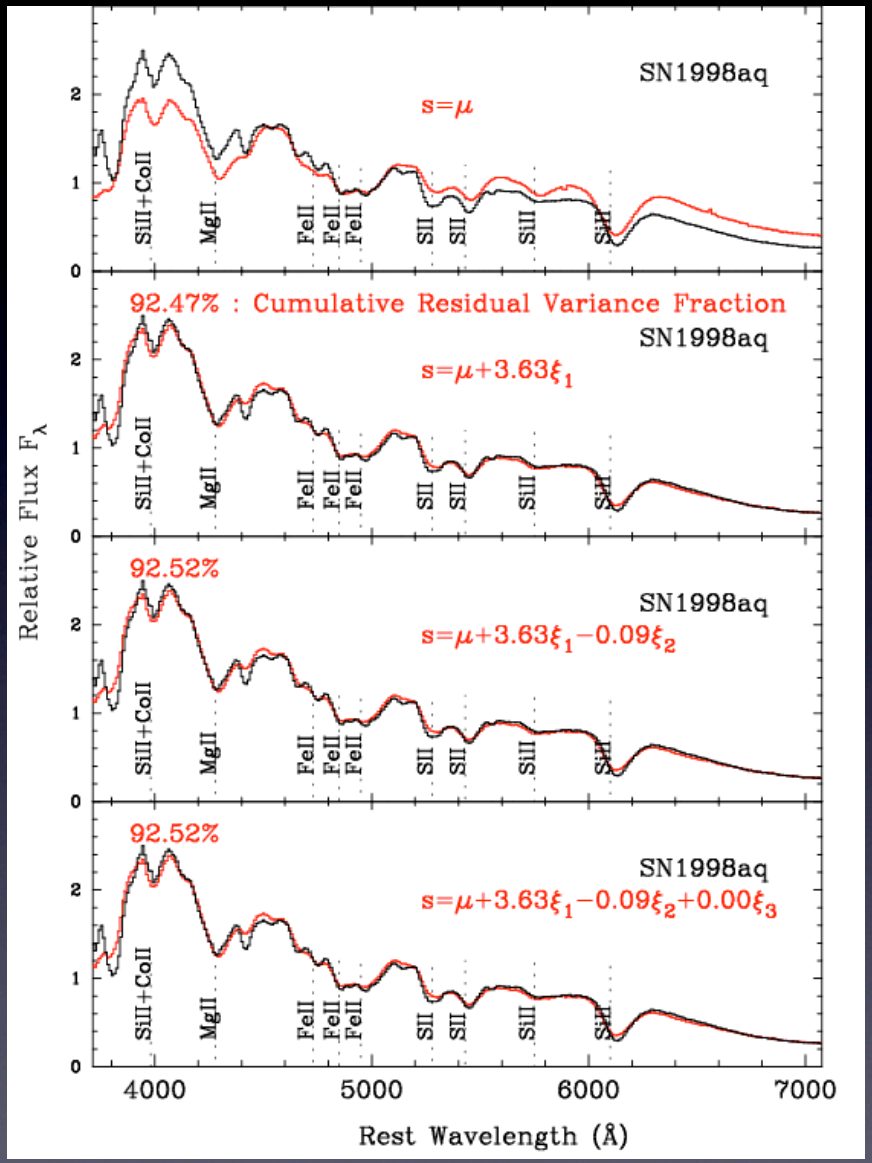


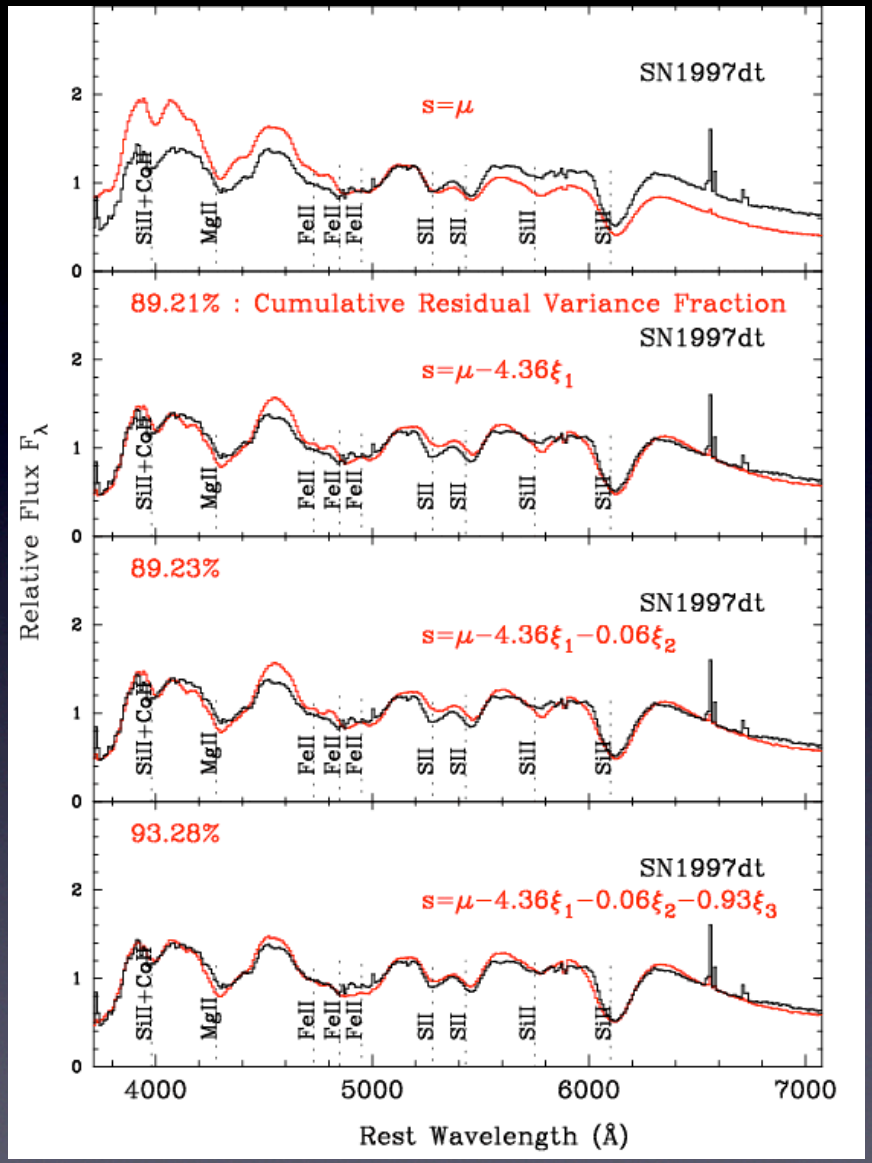
PCA: Components vs Residual

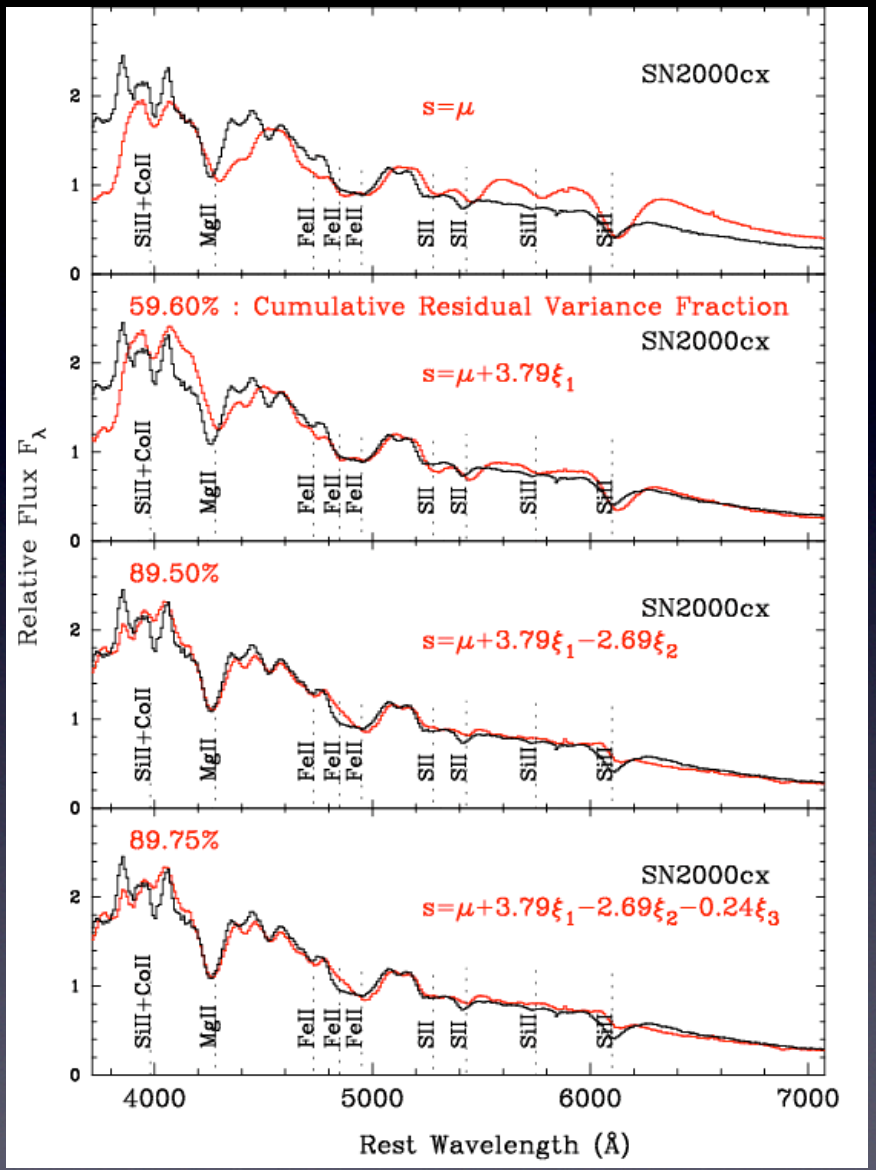


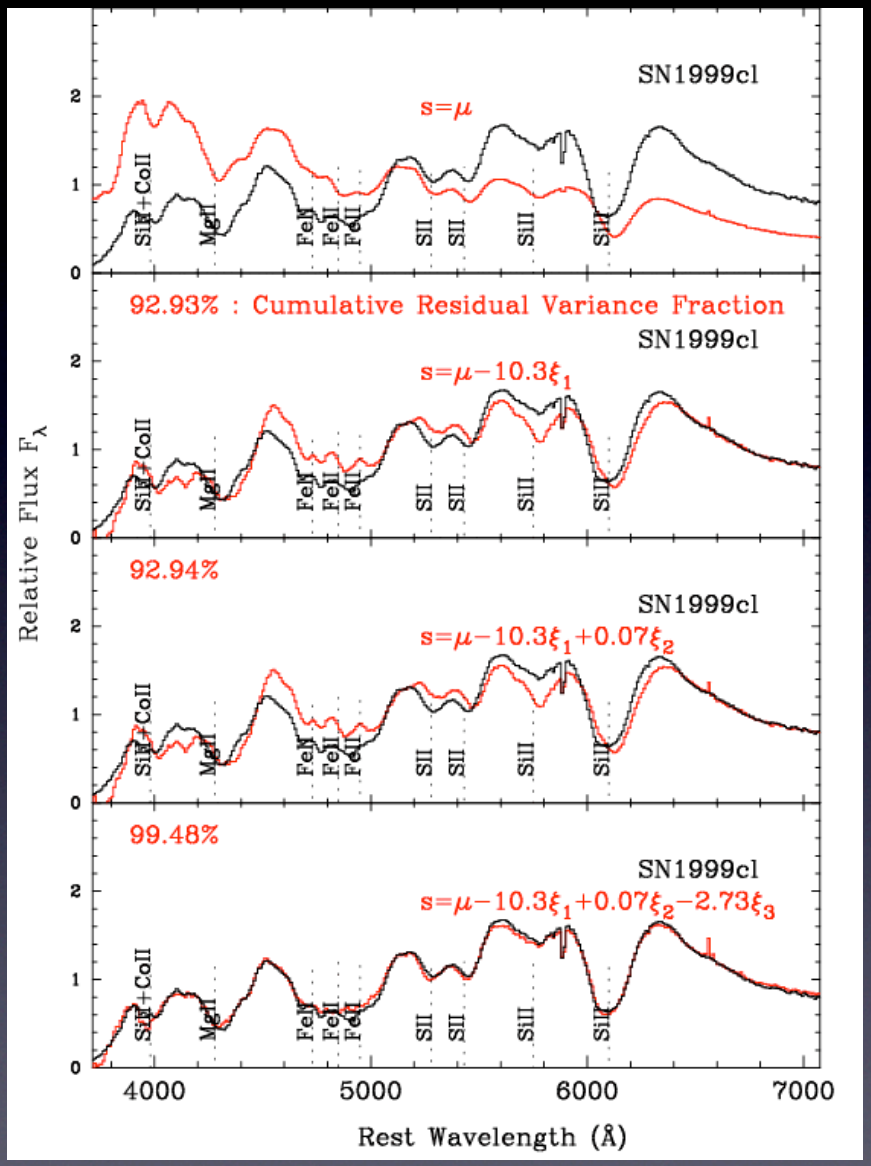

SN1991T
s=μ
19.98% : Cumulative Residual Variance Fraction
SN1991T
s=μ+1.58ξ1
85.81%
SN1991T
s=μ+1.58ξ1−2.87ξ2
86.06%
SN1991T
s=μ+1.58ξ1−2.87ξ2−0.18ξ3
SiII+CoII
MgII
FeII
SII
SiII
Relative Flux Fλ
Rest Wavelength (Å)
4000
5000
6000
7000


SN1991bg
s=μ
81.12% : Cumulative Residual Variance Fraction
SN1991bg
s=μ−6.88ξ1
85.44%
SN1991bg
s=μ−6.88ξ1−1.59ξ2
97.13%
SN1991bg
s=μ−6.88ξ1−1.59ξ2+2.61ξ3
SiII+CoII
MgII
FeII
SII
SiII
Relative Flux Fλ
Rest Wavelength (Å)
4000
5000
6000
7000

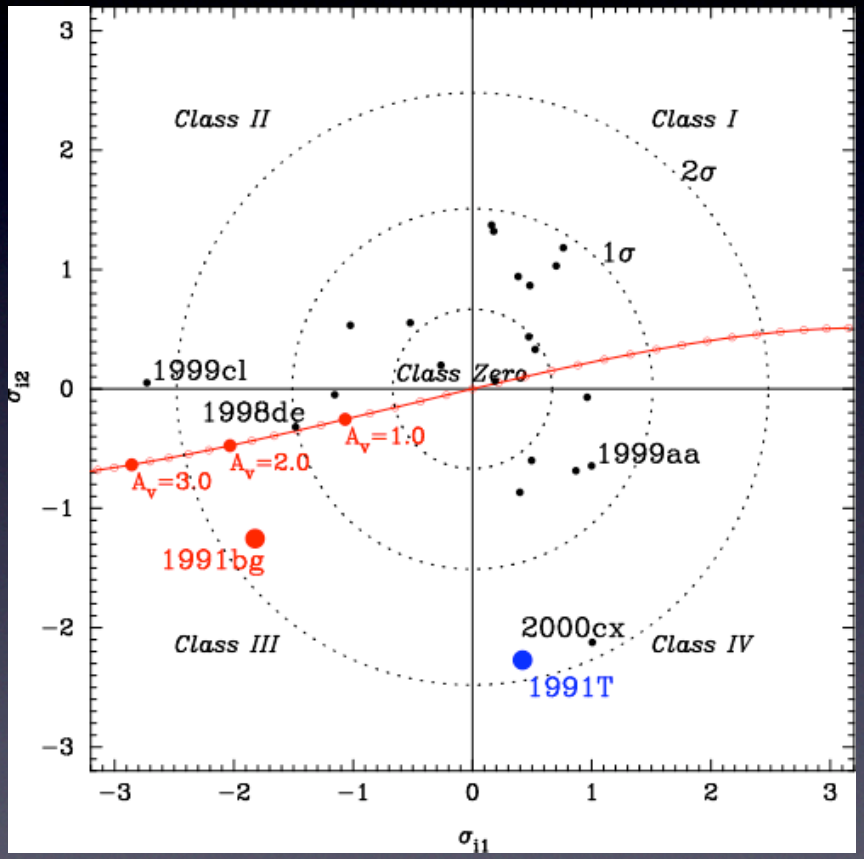

SN1998aq
s=μ
92.47% : Cumulative Residual Variance Fraction
SN1998aq
s=μ+3.63ξ1
92.52%
SN1998aq
s=μ+3.63ξ1−0.09ξ2
92.52%
SN1998aq
s=μ+3.63ξ1−0.09ξ2+0.00ξ3
SiII+CoII
MgII
FeII
SII
SiII
SiII
Relative Flux Fλ
Rest Wavelength (Å)
4000
5000
6000
7000

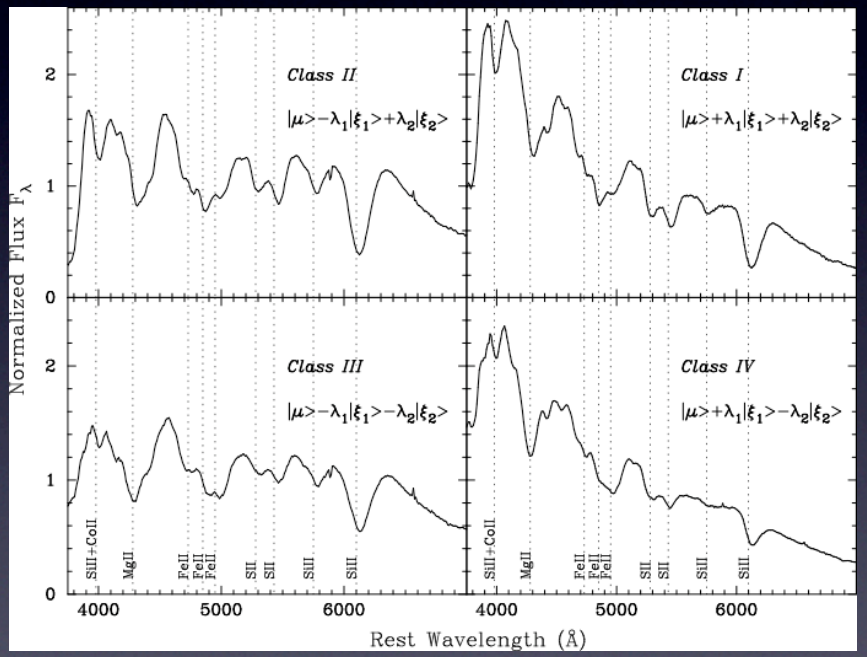

SN1997dt
s=μ
89.21% : Cumulative Residual Variance Fraction
SN1997dt
s=μ−4.36ξ1
89.23%
SN1997dt
s=μ−4.36ξ1−0.06ξ2
93.28%
SN1997dt
s=μ−4.36ξ1−0.06ξ2−0.93ξ3
SiII+CoII
MgII
FeII
SII
SiII
SiII
Relative Flux Fλ
Rest Wavelength (Å)
4000
5000
6000
7000


SN2000cx
s=μ
59.60% : Cumulative Residual Variance Fraction
SN2000cx
s=μ+3.79ξ1
89.50%
SN2000cx
s=μ+3.79ξ1−2.69ξ2
89.75%
SN2000cx
s=μ+3.79ξ1−2.69ξ2−0.24ξ3
SiII+CoII
MgII
FeII
SII
SiII
Relative Flux Fλ
Rest Wavelength (Å)
4000
5000
6000
7000

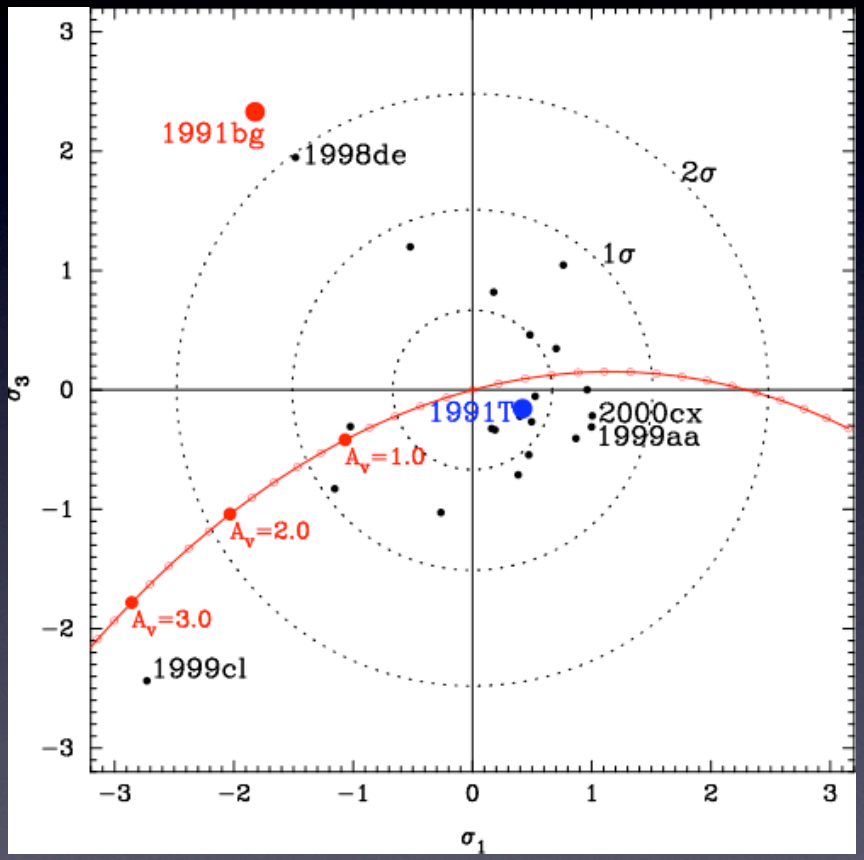

SN1999cl
s=μ
92.93% : Cumulative Residual Variance Fraction
SN1999cl
s=μ−10.3ξ1
92.94%
SN1999cl
s=μ−10.3ξ1+0.07ξ2
99.48%
SN1999cl
s=μ−10.3ξ1+0.07ξ2−2.73ξ3
SiII+CoII
MgII
FeII
SII
SiII
Relative Flux Fλ
Rest Wavelength (Å)
4000
5000
6000
7000

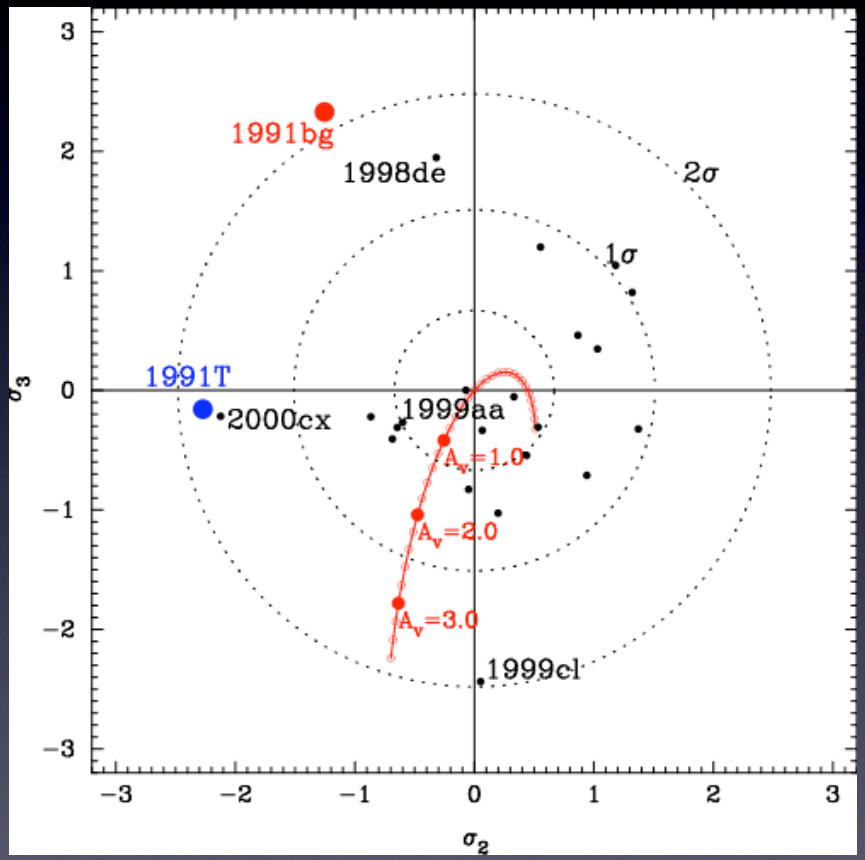
Cardelli's Law on PCA diagram
c1 vs. c2



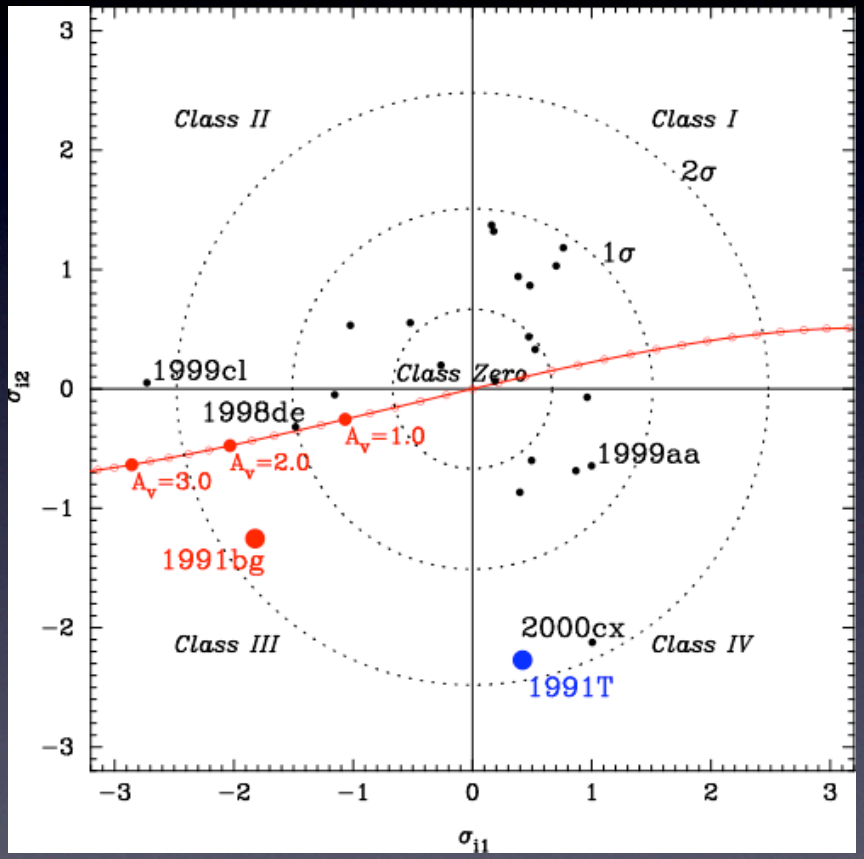


Cardelli's Law on PCA Diagram
c1 vs. c3 & c2 vs. c3



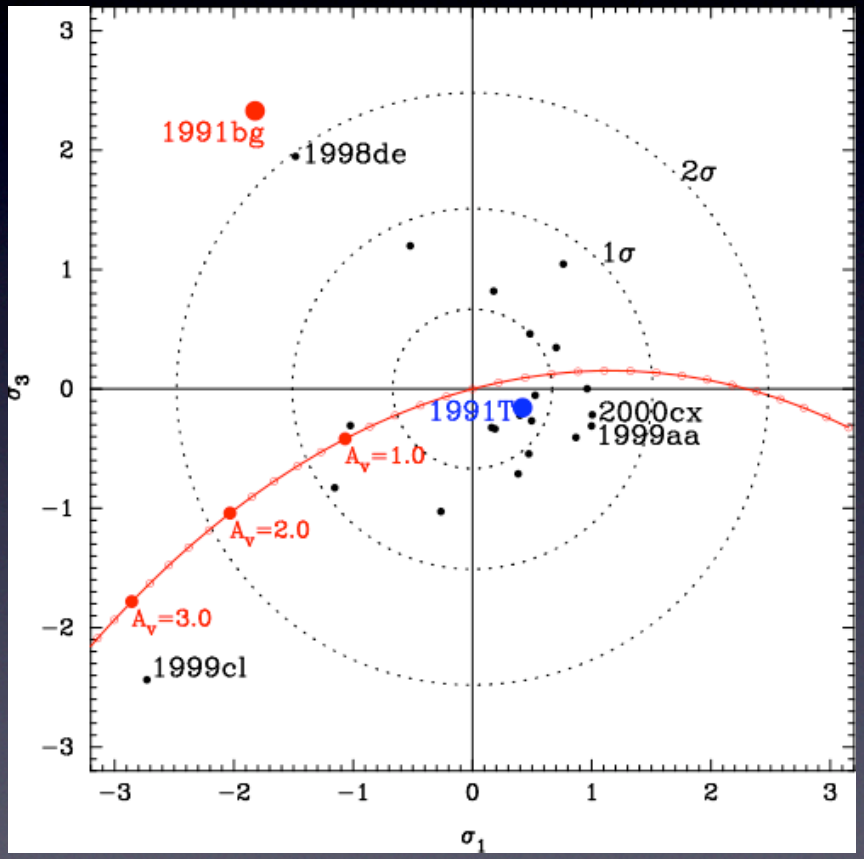


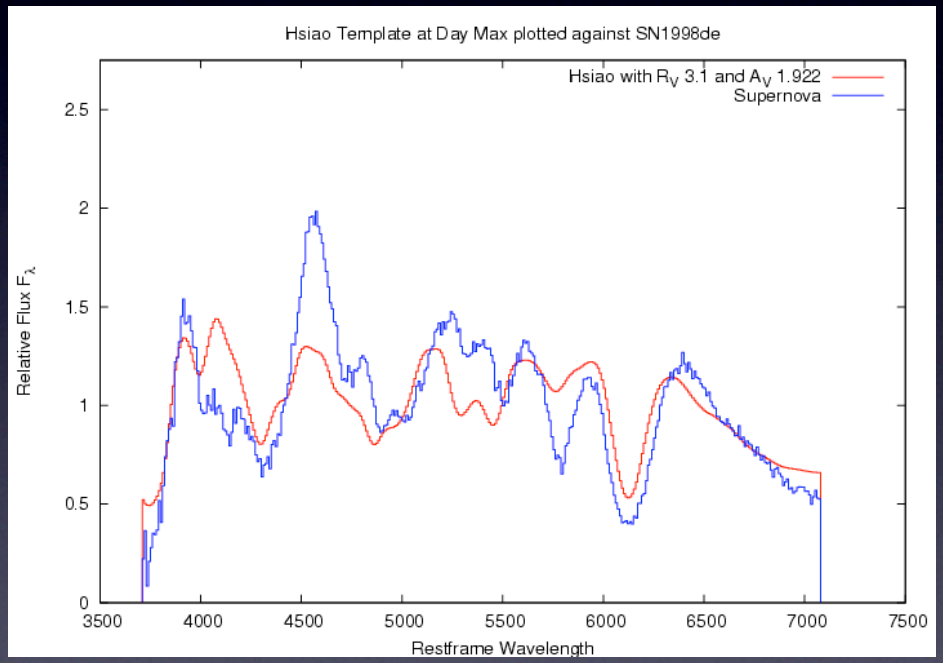
Case1 :
Cardelli's Law is working



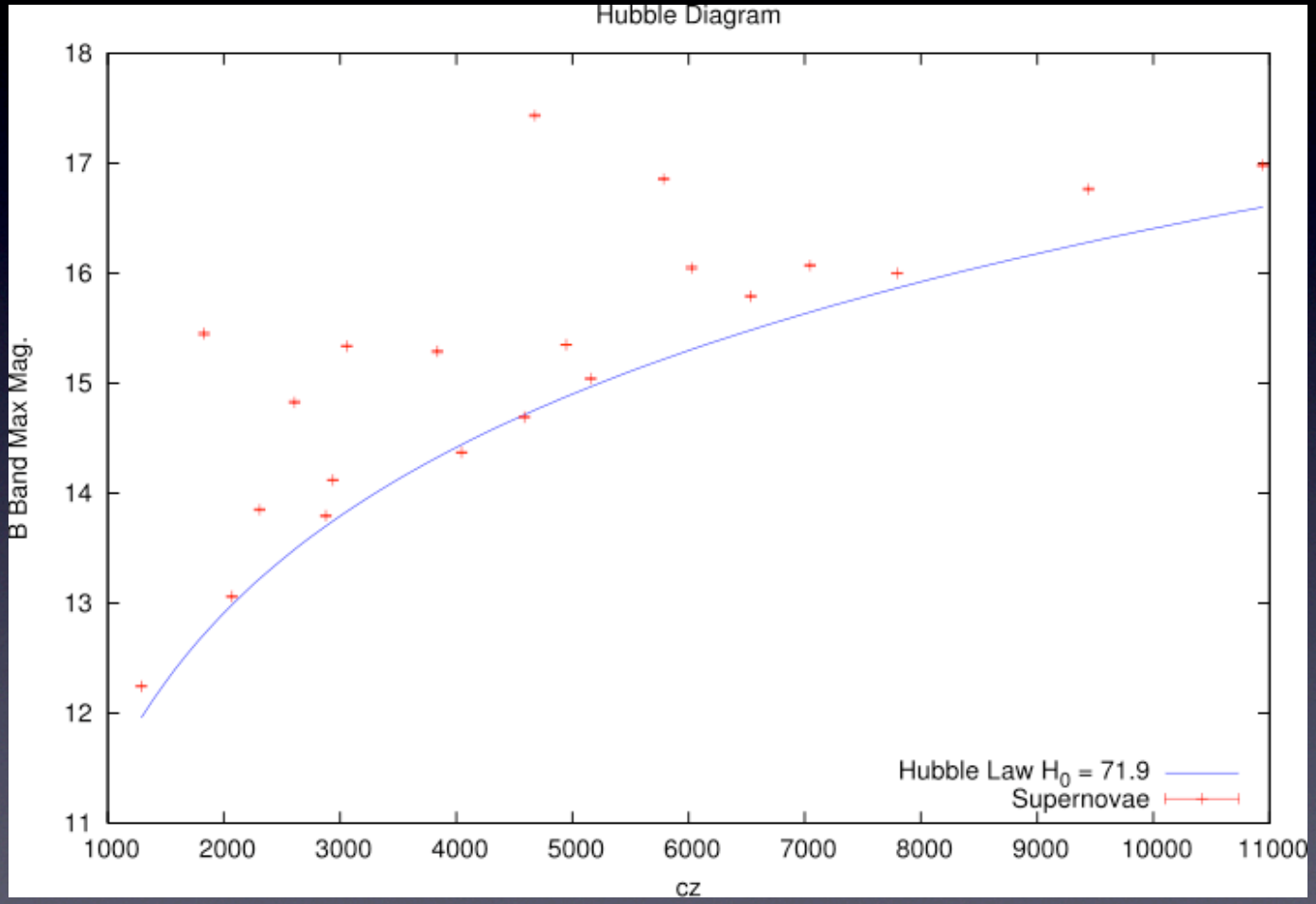
Case2 :

Cardelli's Law is NOT working

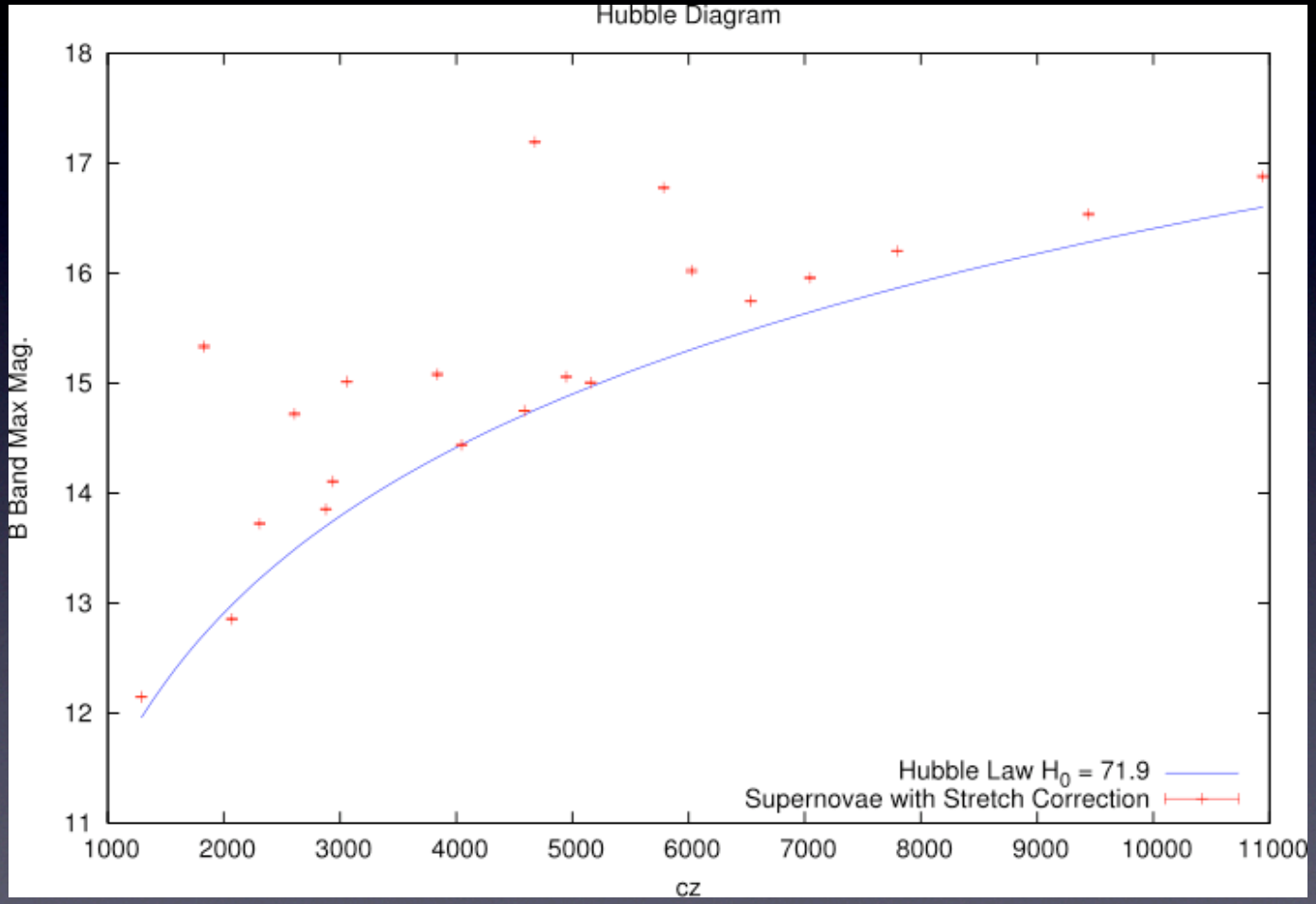




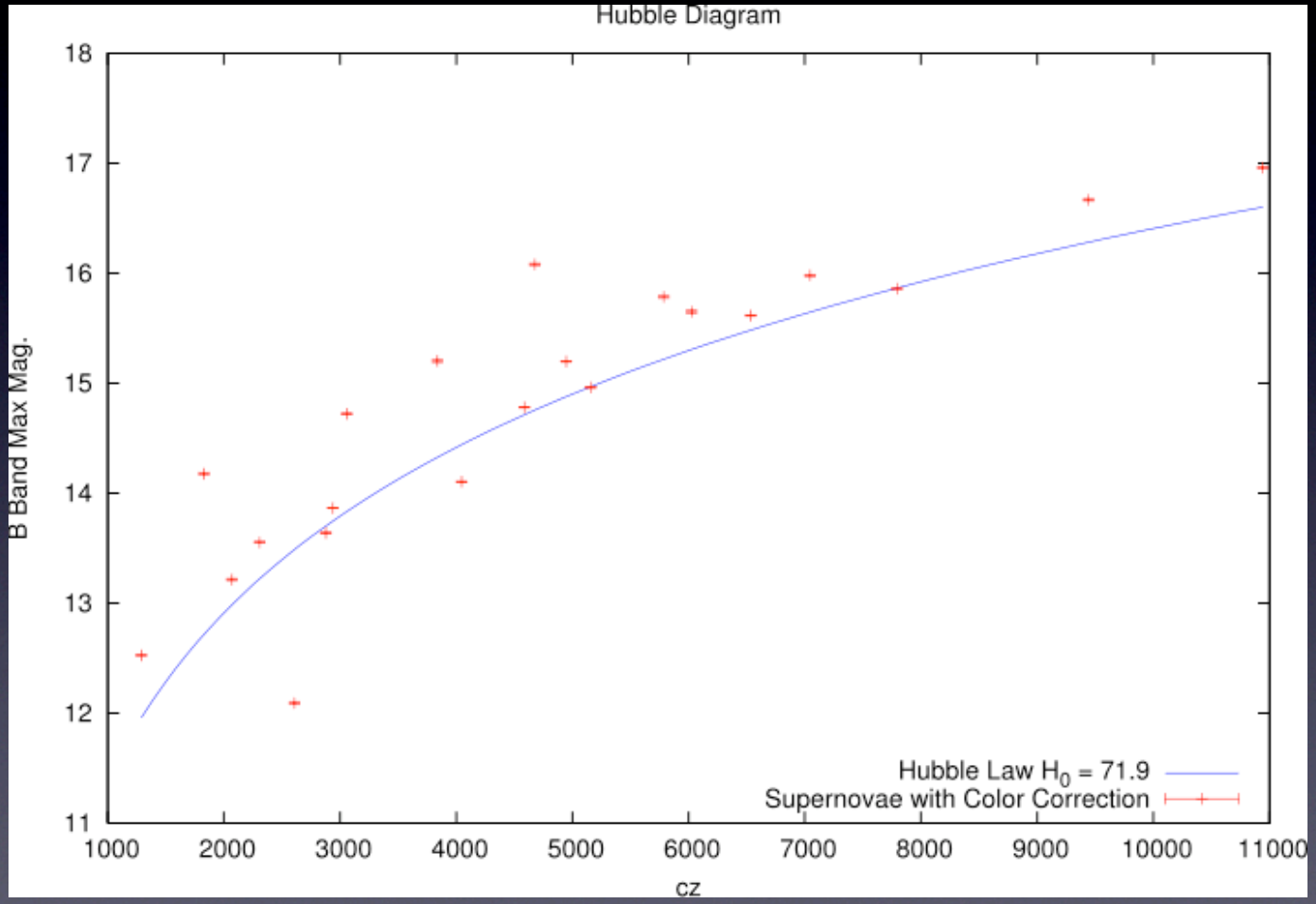
Cosmology: Raw Data



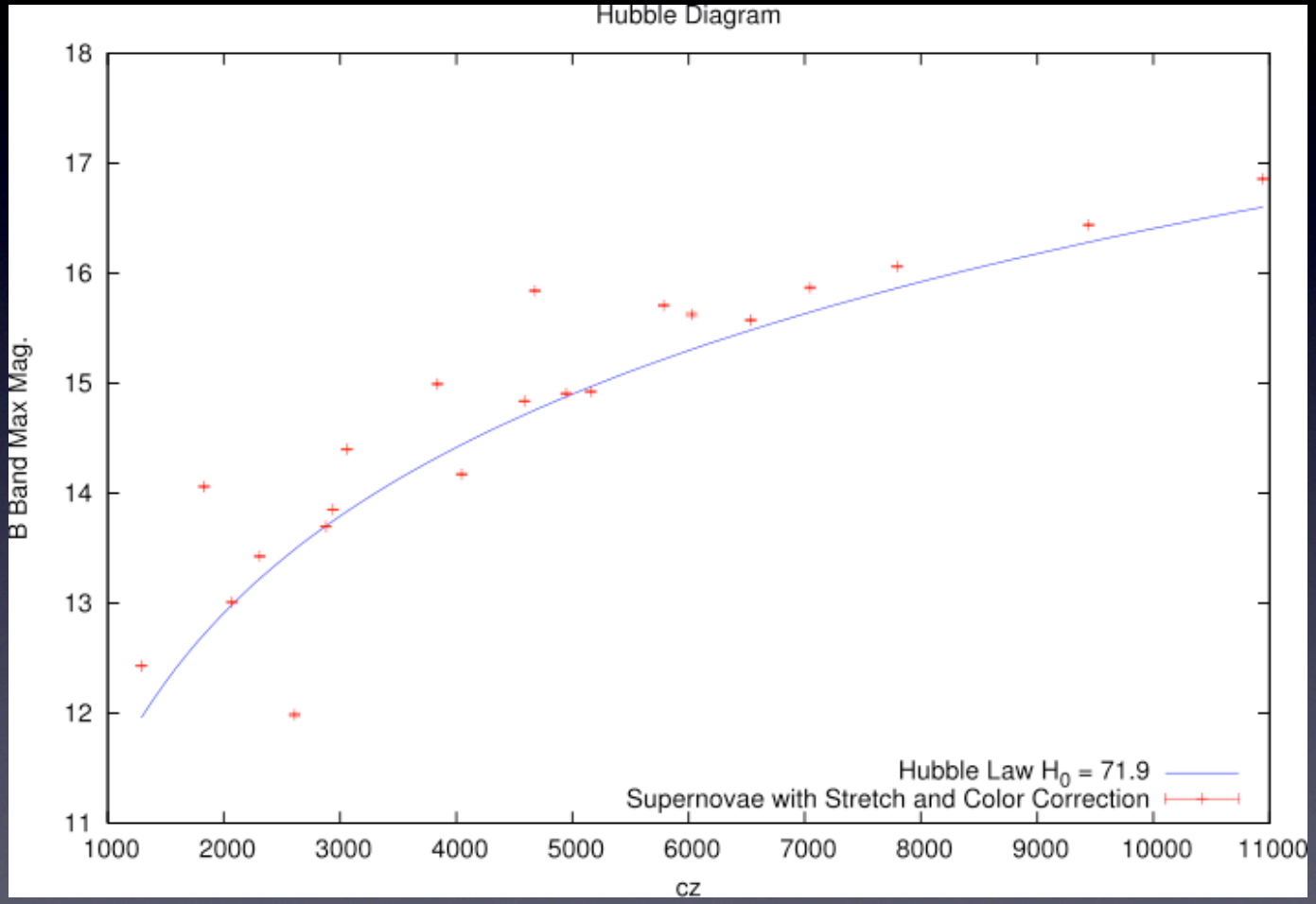
Cosmology: Stretch Corrected



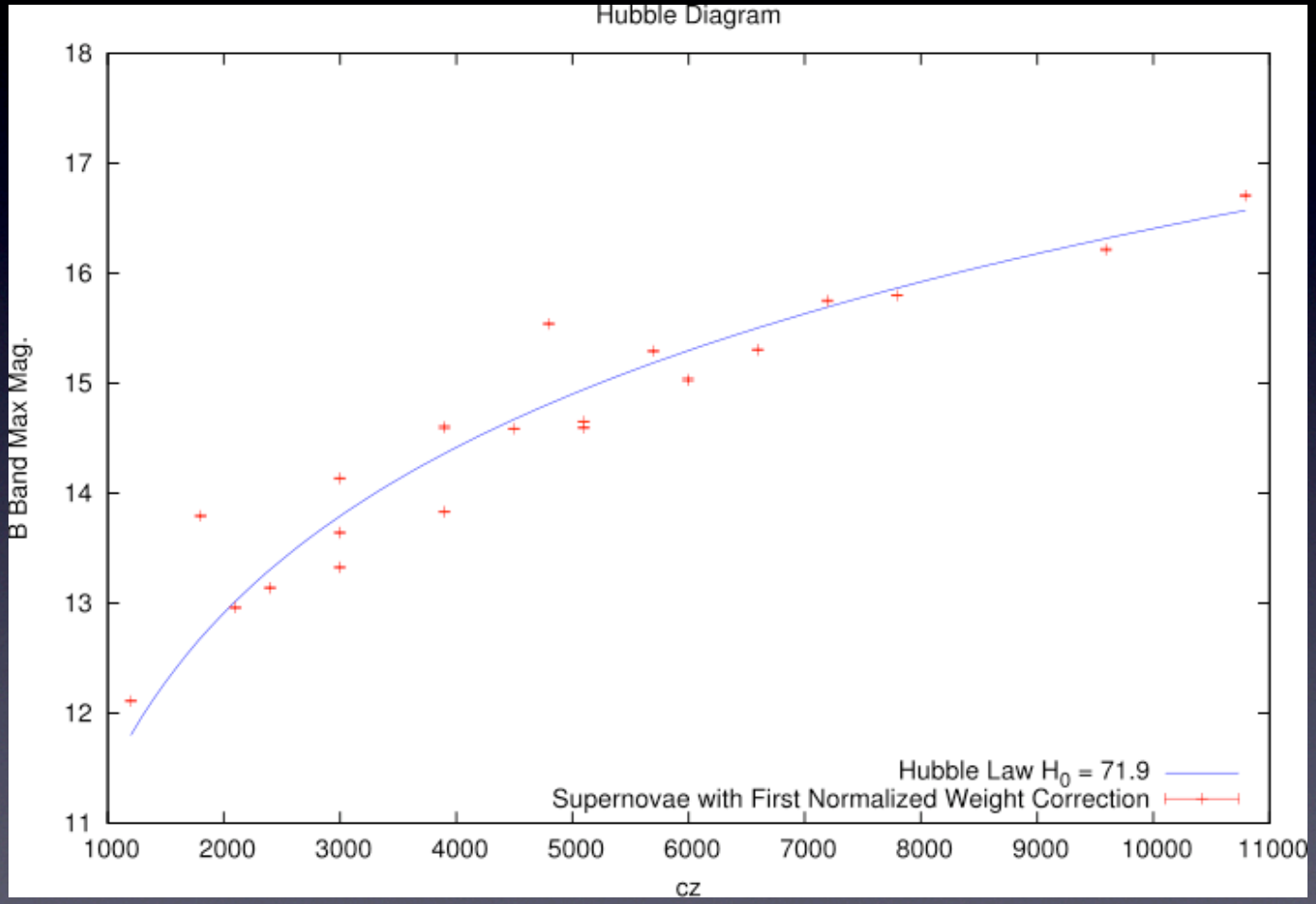
Cosmology: Color Corrected



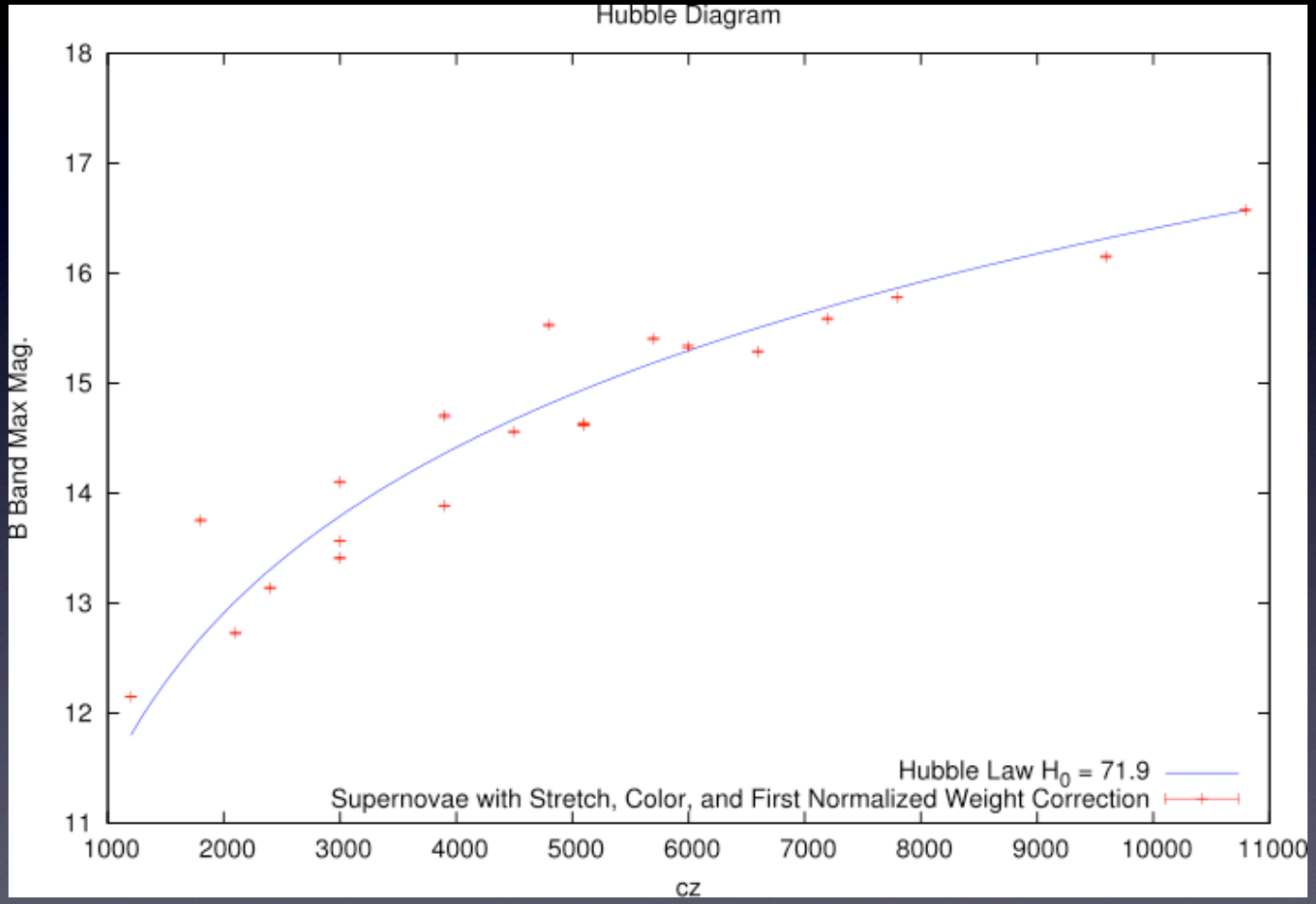
Cosmology: Stretch and Color Corrected

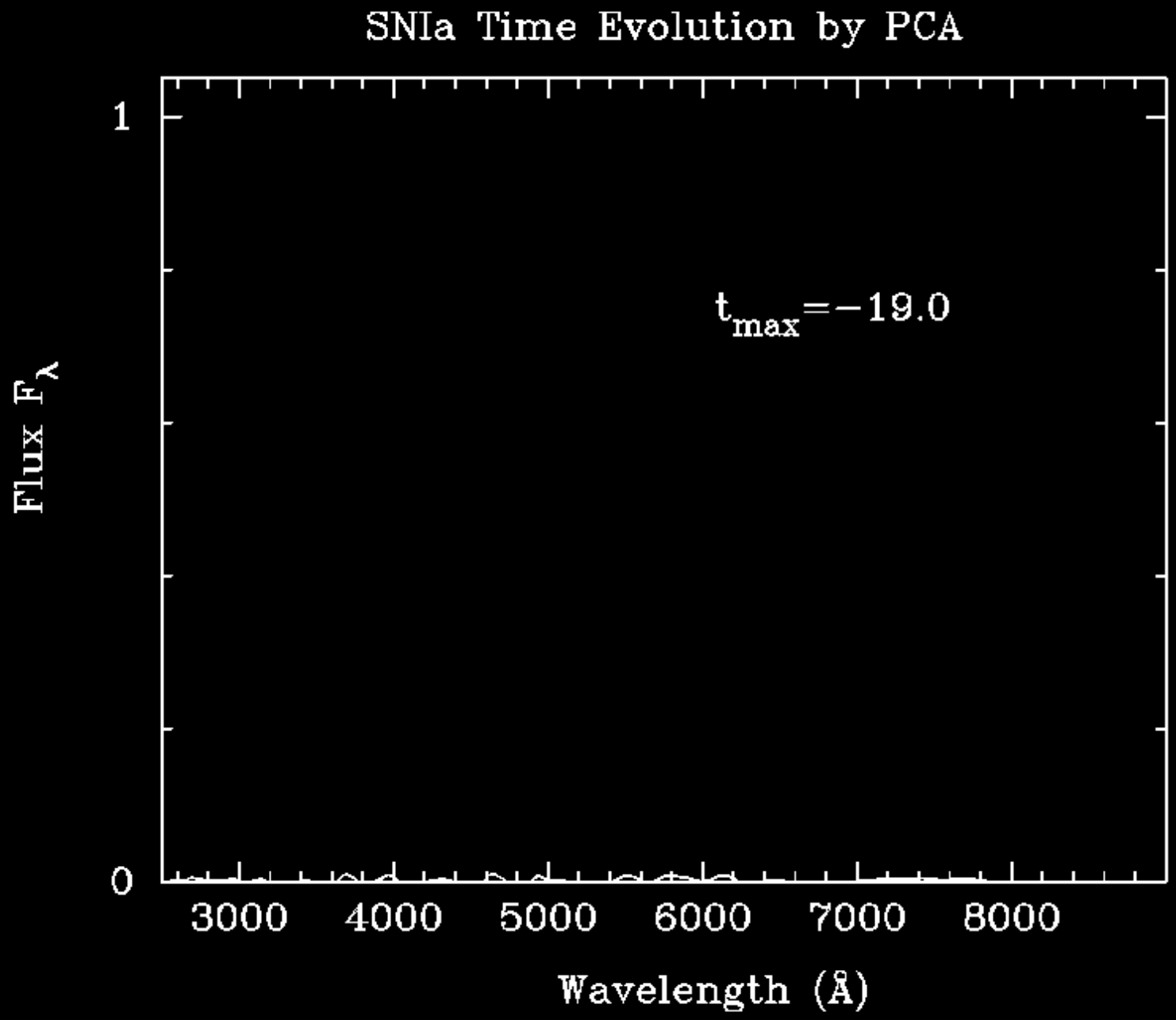


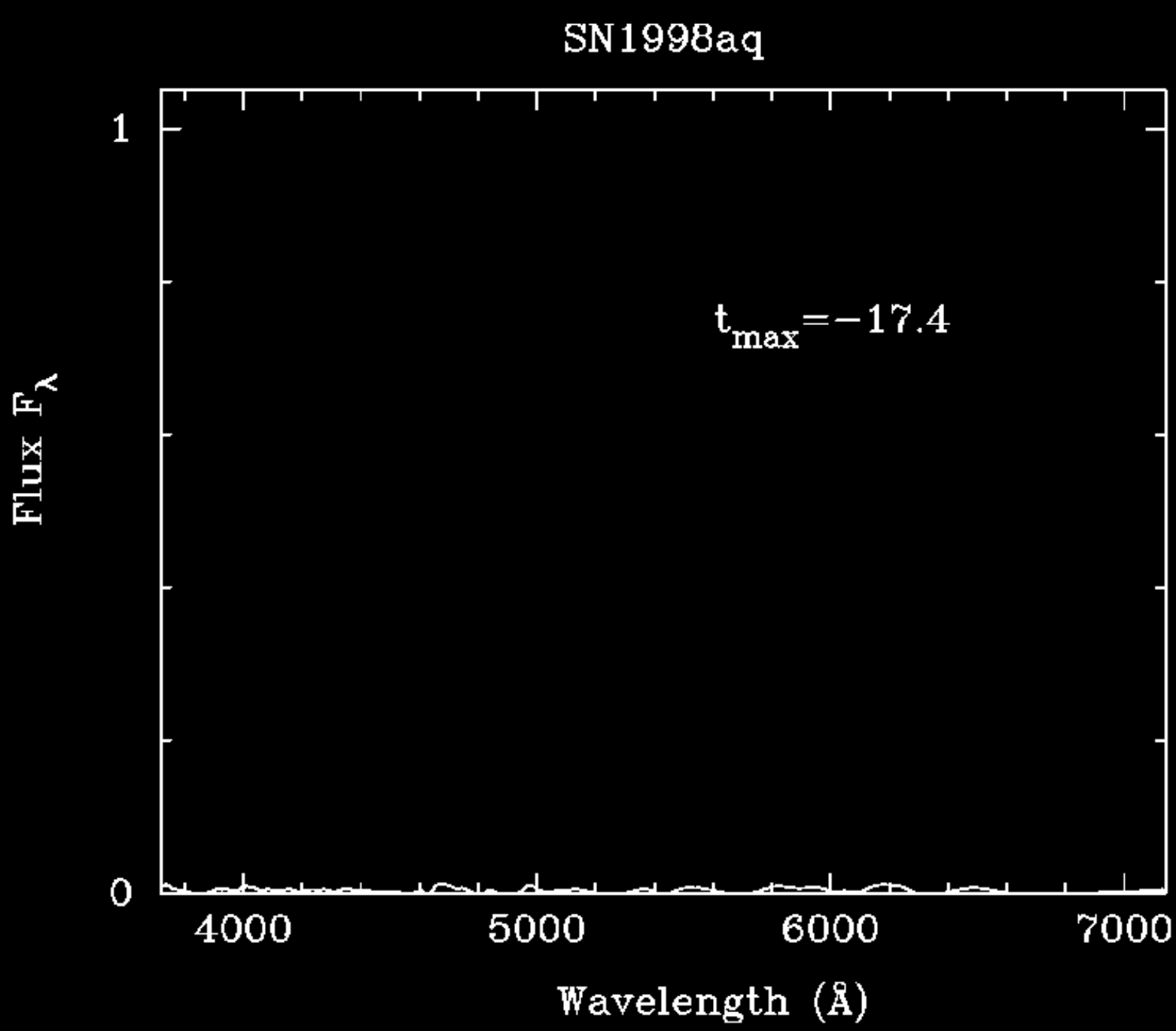
Cosmology: PCA Weight 1 Corrected



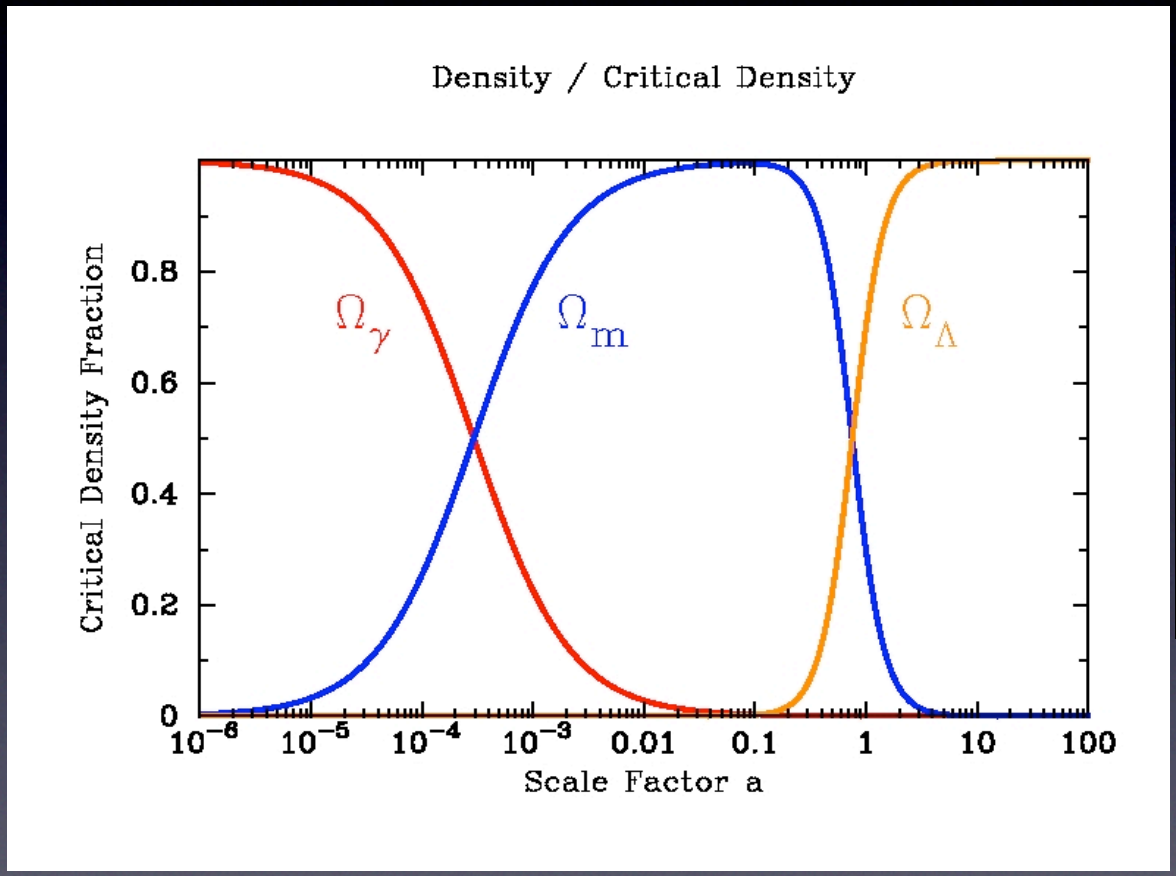
Cosmology: Color, Stretch, and PCA Weight1 Corrected

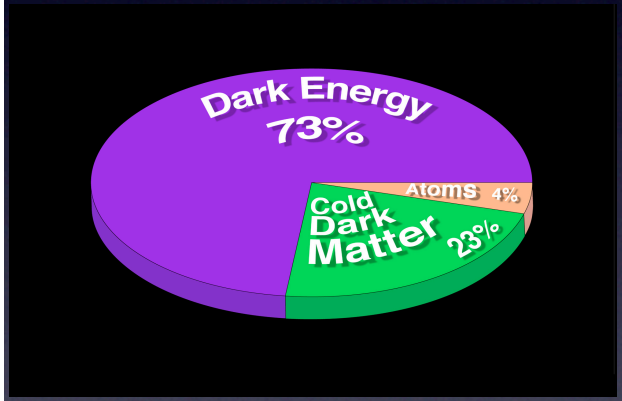



SNIa Time Evolution by PCA
1
0
Flux F_λ
t_{max}=−19.0
3000
4000
5000
6000
7000
8000
Wavelength (Å)

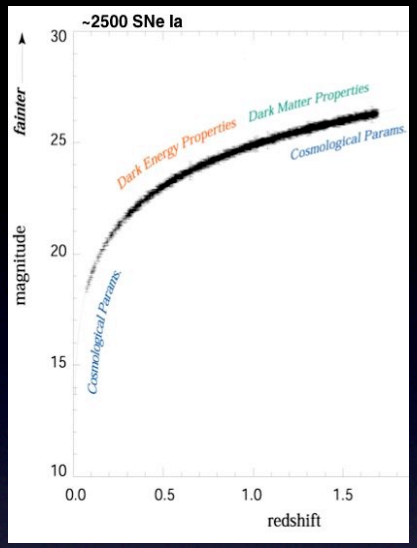

SN1998aq
1
0
Flux F_λ
$t_{max}=-17.4$
4000
5000
6000
7000
Wavelength (Å)

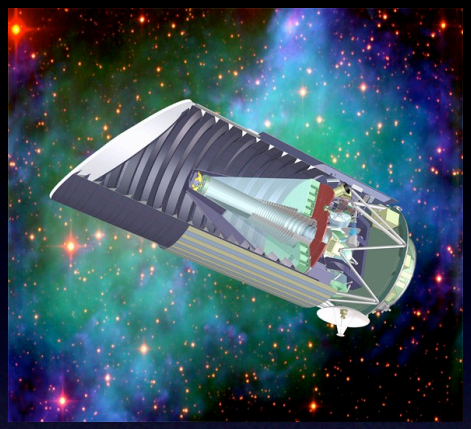
ΛCDM works for 13.7 Gyrs





Summary





- For JDEM era, we need to reduce systematic errors: 1.Vega Spectrum, 2. Filter Response, 3. SNIa diversity and expect for unexpected.
- We don't know what we are doing, that's why it is called research. (A. Einstein)

PCA application to Galaxy Spectra

- 1. Galaxy Spectral Classification
- SDSS 12,000 Spectra

Nao Suzuki

$$\vec{S} = \vec{\mu} + \sum_{j=1}^{n} c_j \vec{\xi}_j$$

$$\vec{\xi}_i \cdot \vec{\xi}_j = \delta_{ij}$$

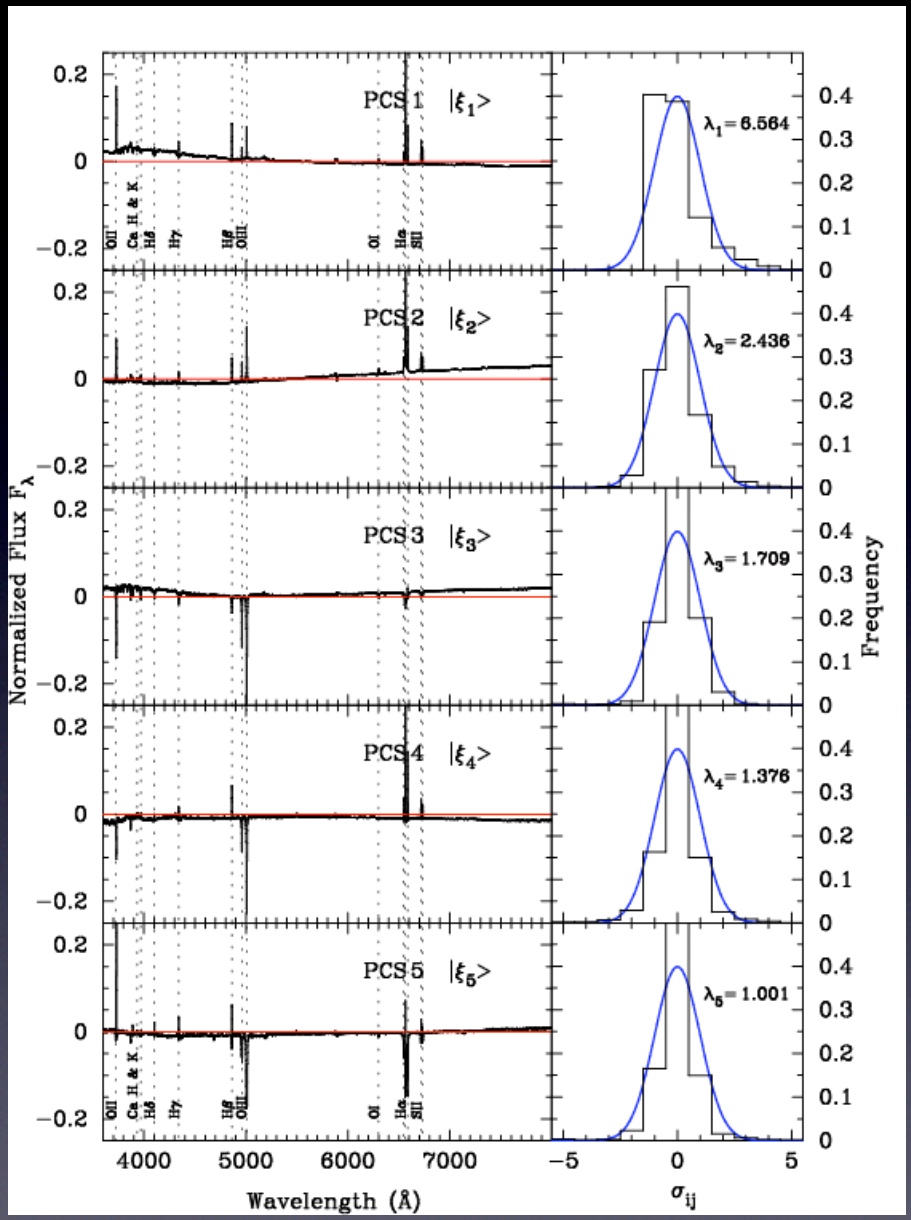
Eigenspectr

- 1st Eigenspectrum

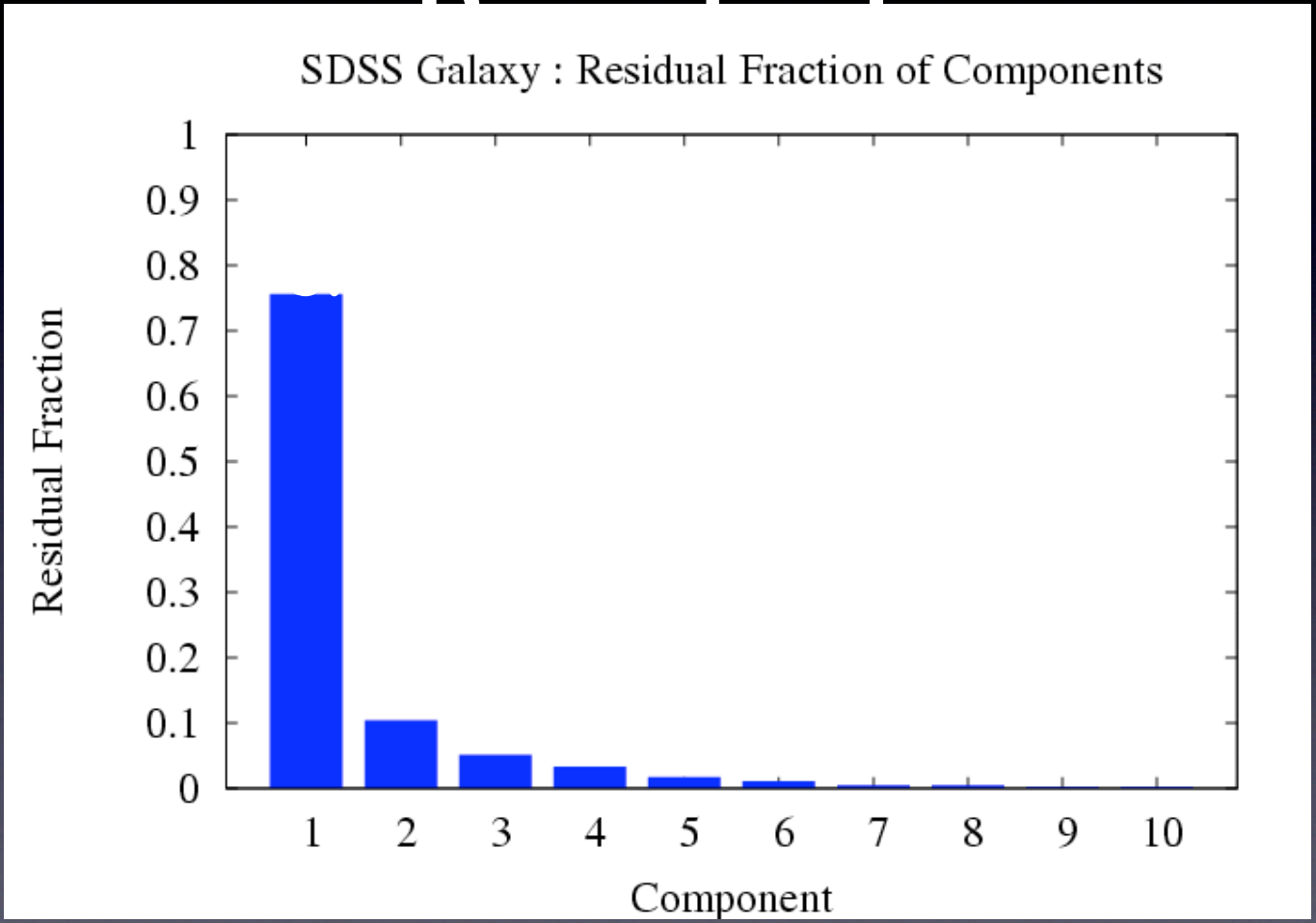
  => color with emission lines

- ~ 90% of residual goes to first 3 components

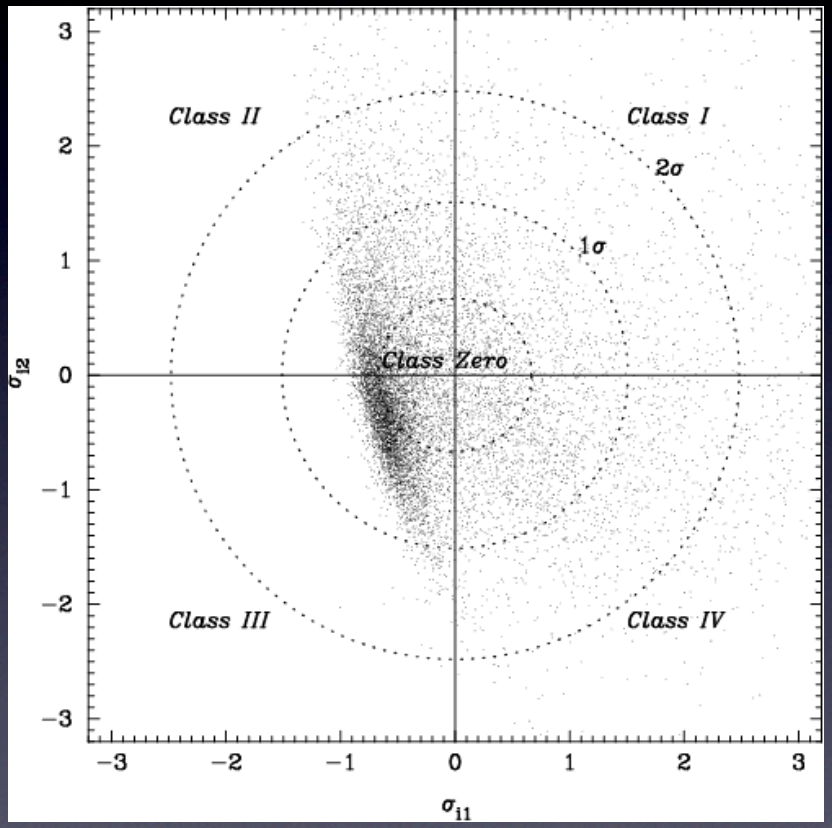
- Coefficient distribution is not gaussian

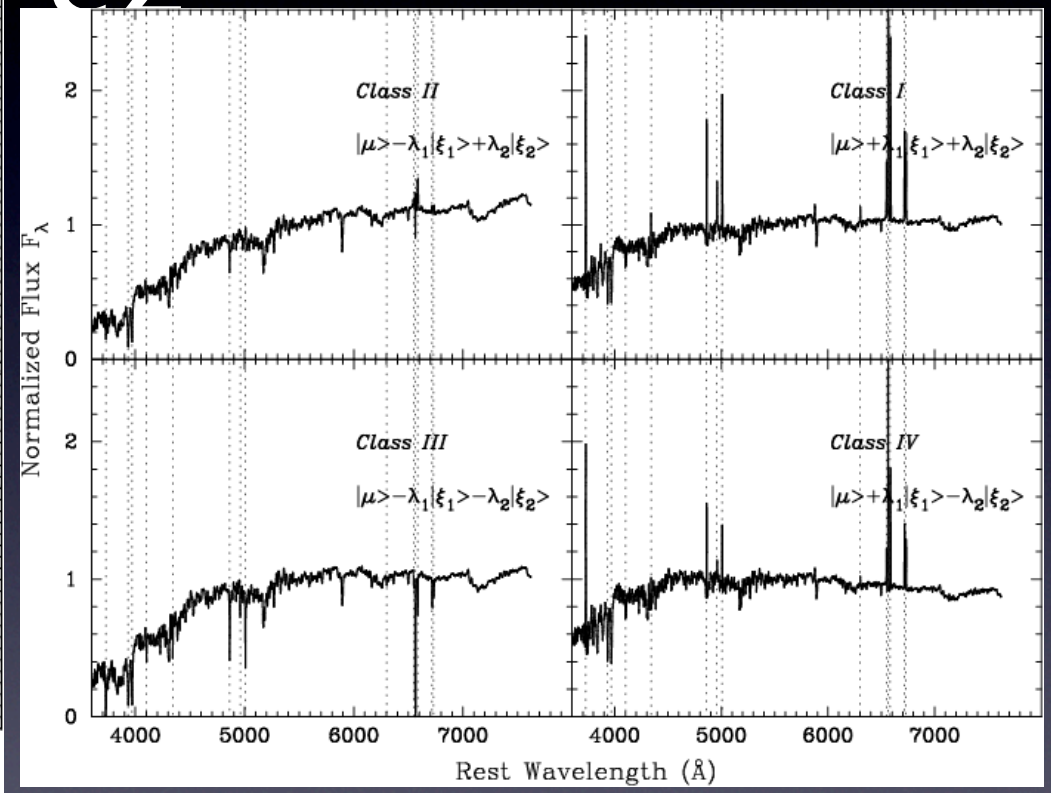


PCA: Components vs

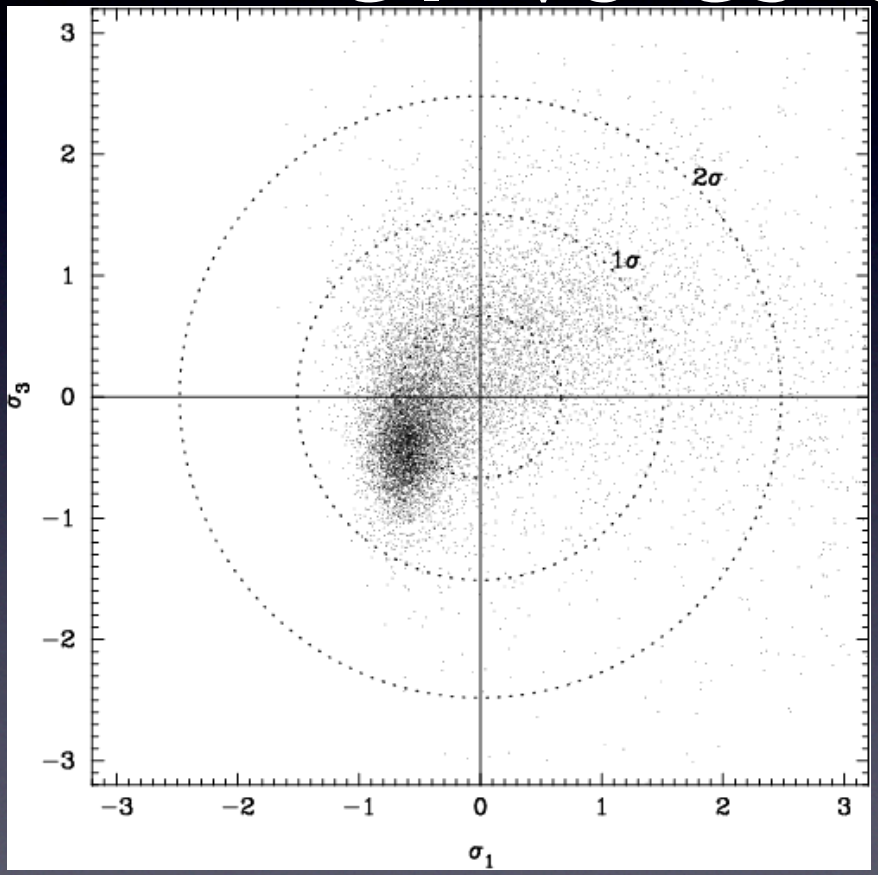


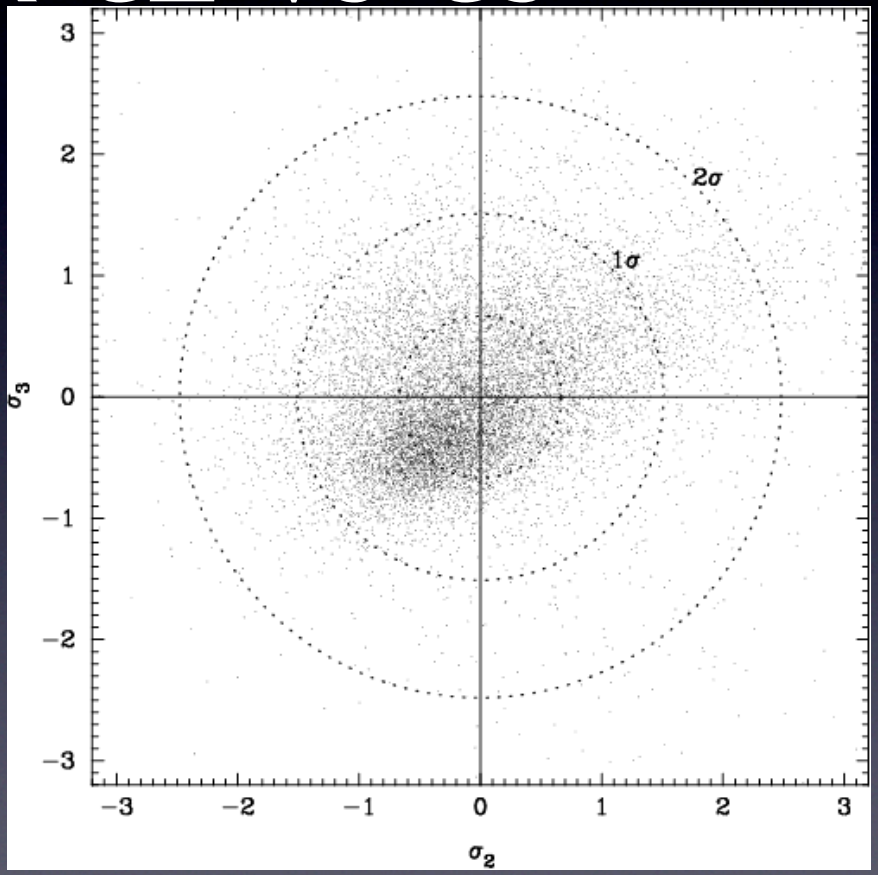
Spectral Diversity : c1 vs. c2





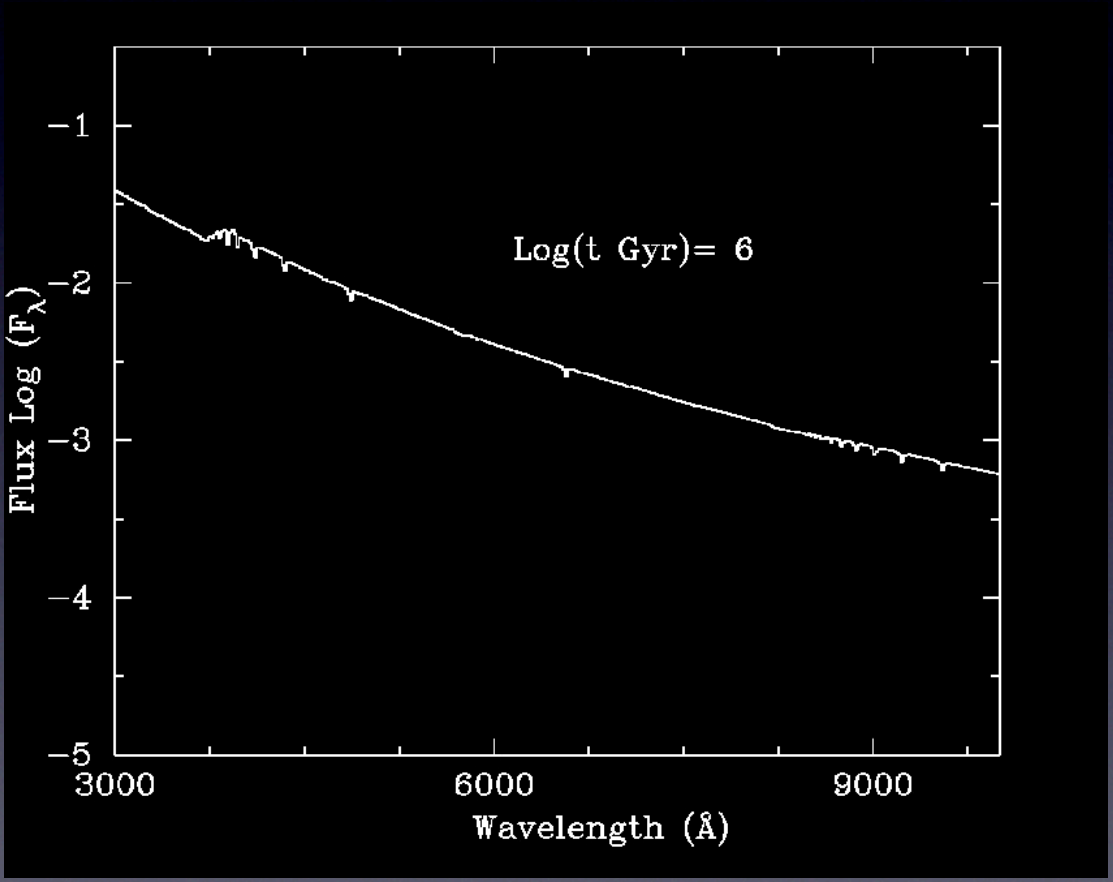
Spectral Diversity : c1 vs c3 & c2 vs c3





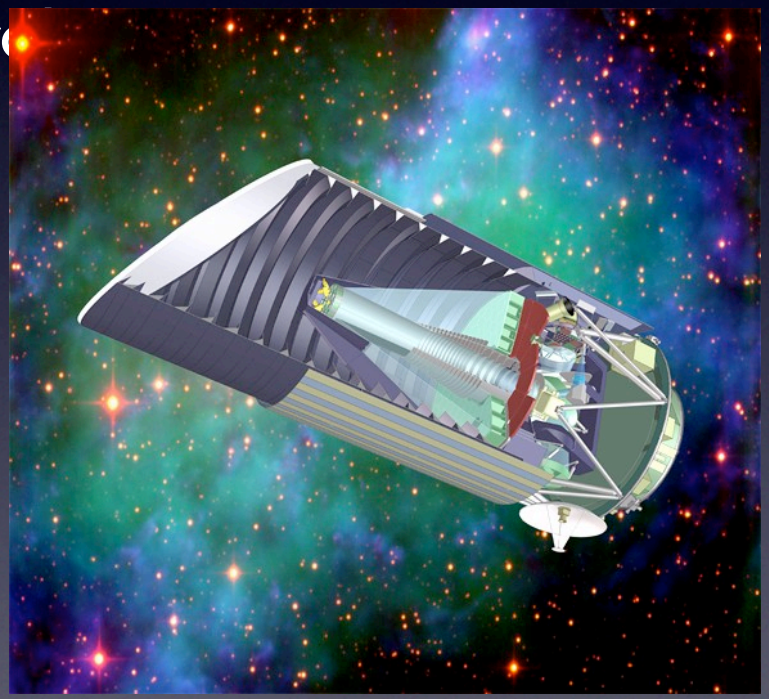
PCA application to Galaxy

PCA application to Galaxy



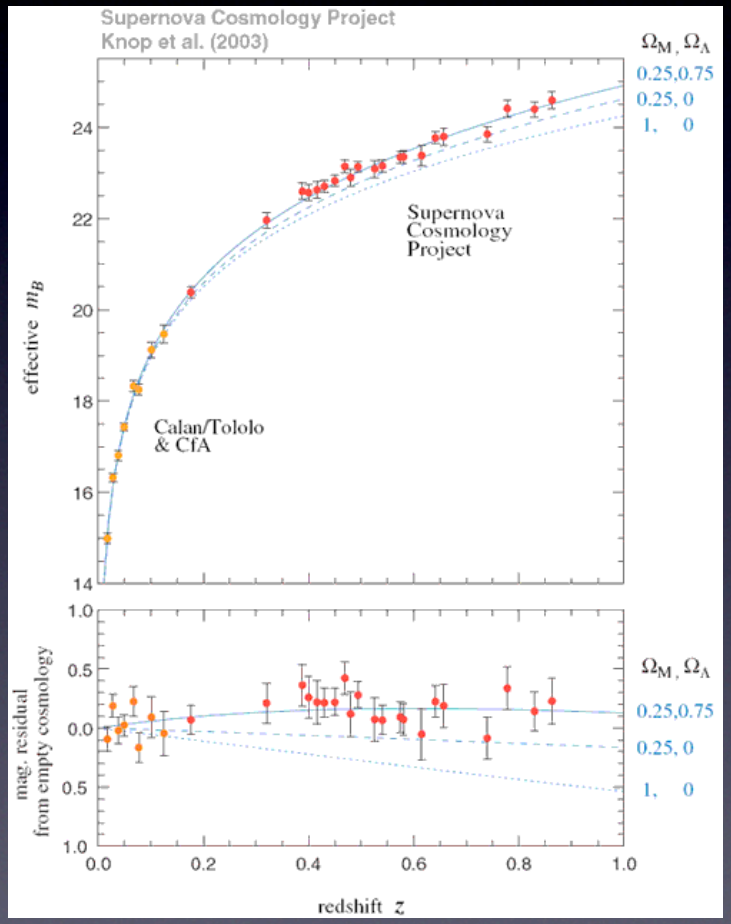
Future Plans I : SNAP

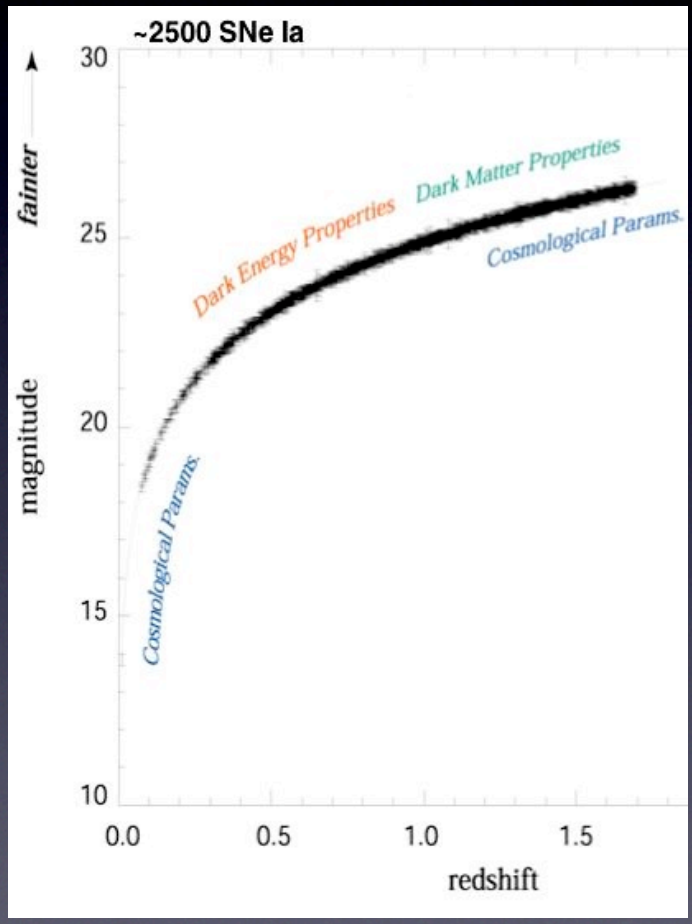
S SNAP n Pr



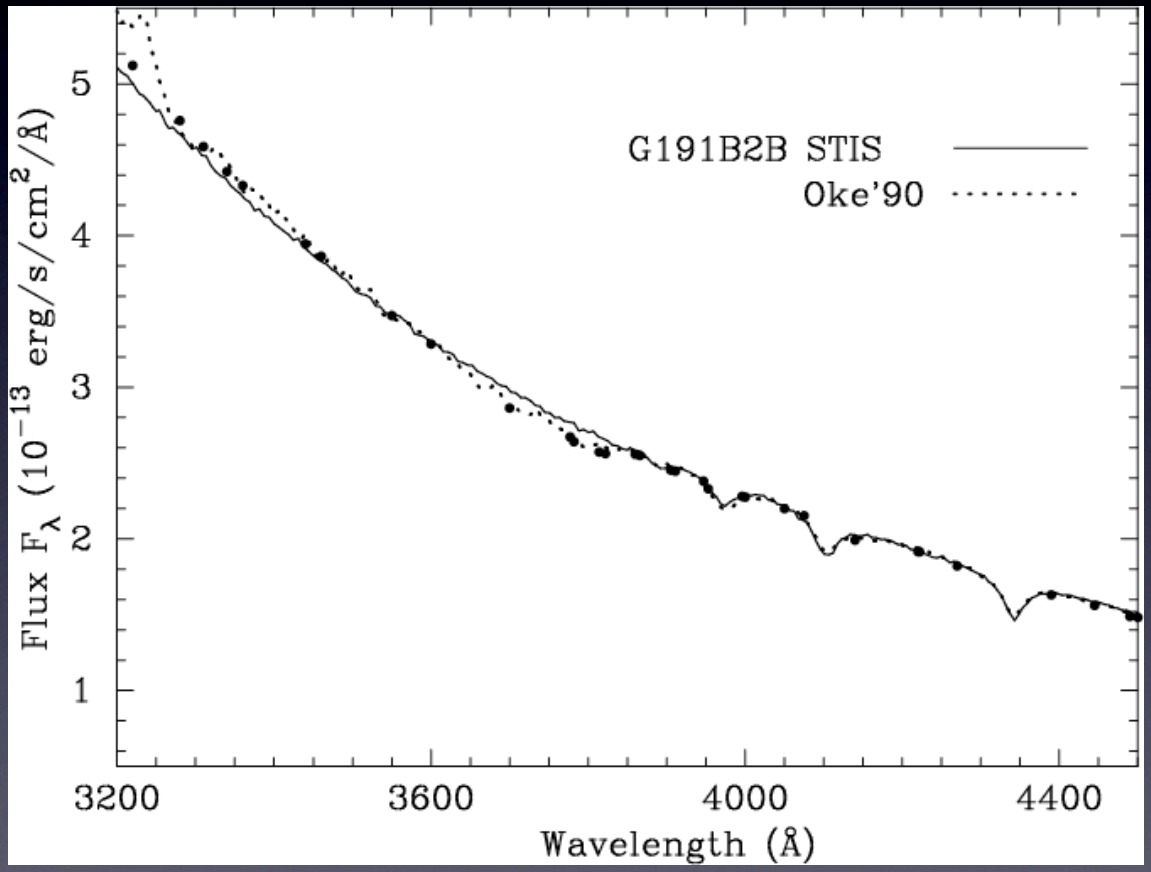
- Dark Energy Probe
- Supernovae
- Weak Lensing

Precision Cosmology

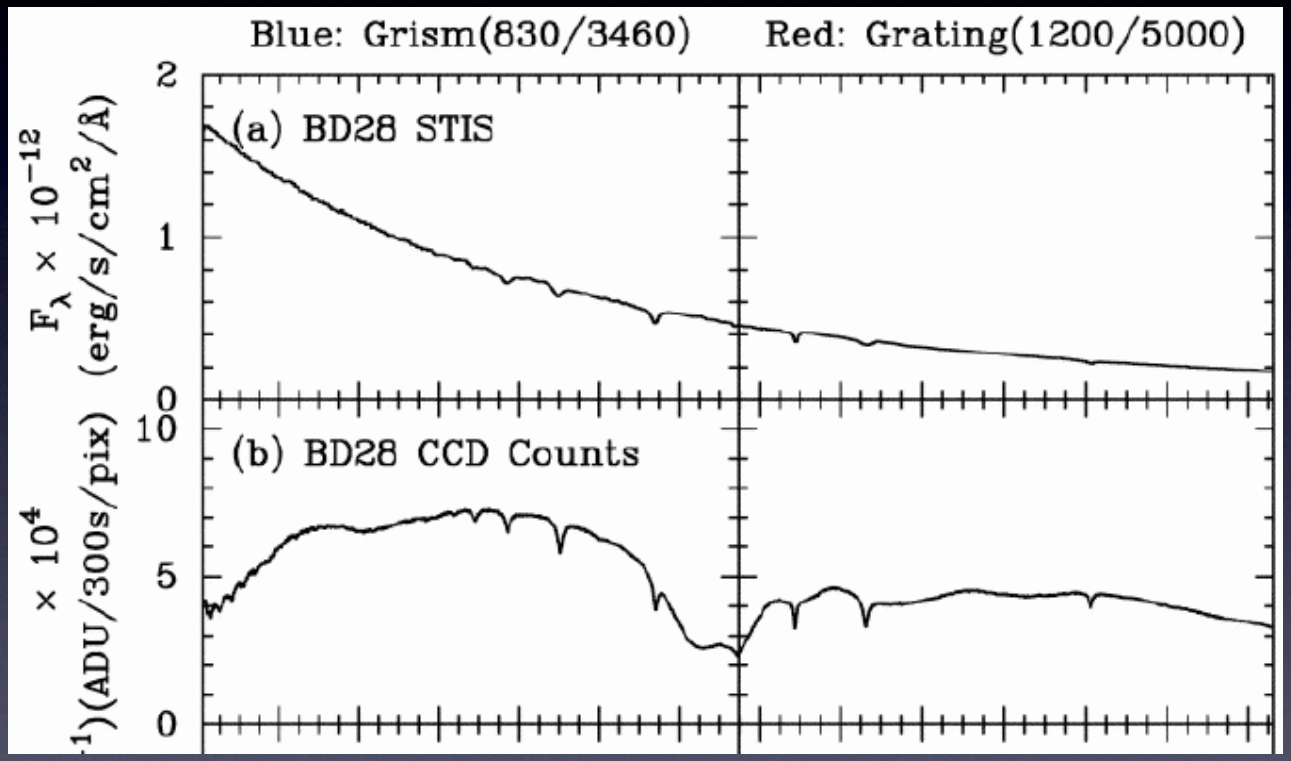




Problem 4: UV Spectrum

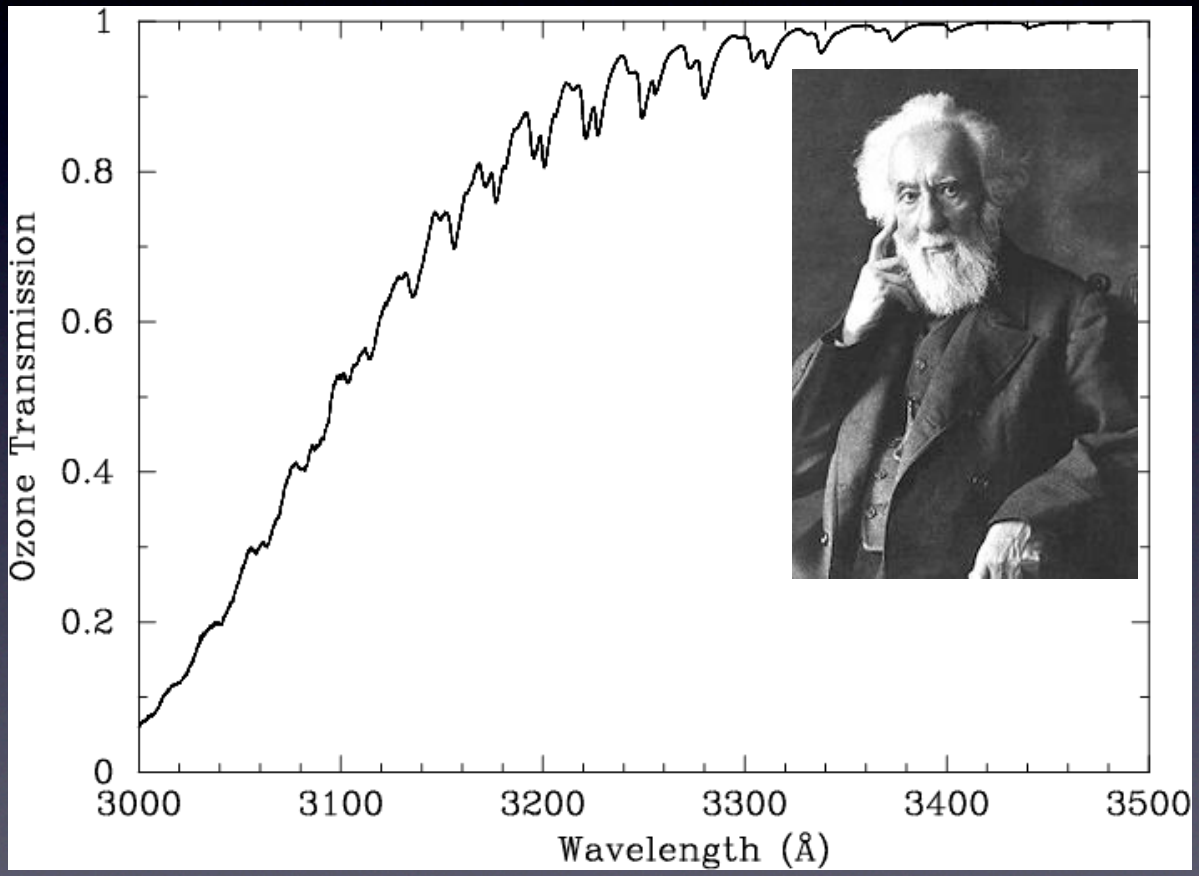


Observed UV Feature

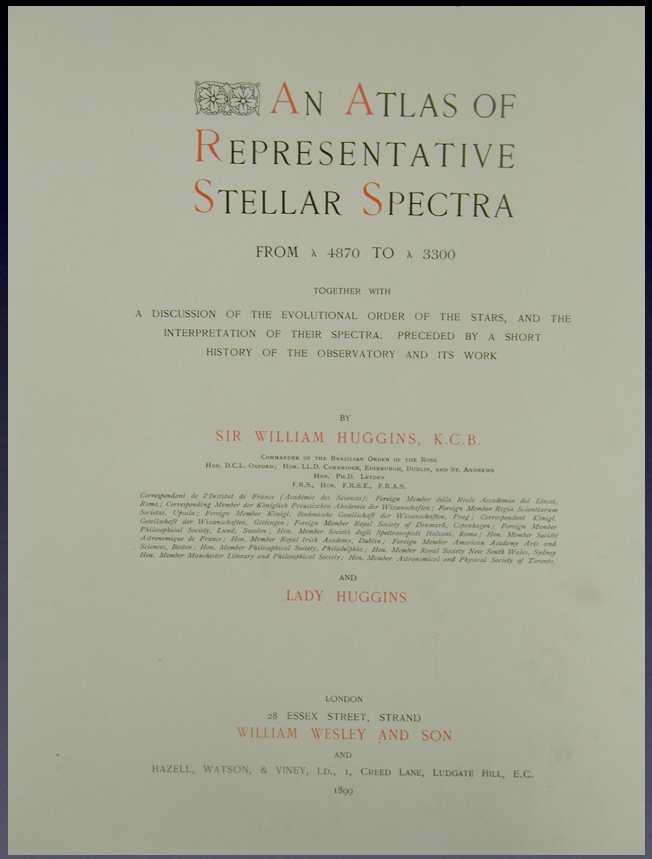


Suzuki et al. 2003

Ozone Transmission



Atlas of Representative Stellar Spectra (1899)



AN ATLAS OF REPRESENTATIVE STELLAR SPECTRA

FROM λ 4870 TO λ 3300

TOGETHER WITH

A DISCUSSION OF THE EVOLUTIONAL ORDER OF THE STARS, AND THE INTERPRETATION OF THEIR SPECTRA. PRECEDED BY A SHORT HISTORY OF THE OBSERVATORY AND ITS WORK

BY

SIR WILLIAM HUGGINS, K.C.B.

COMMANDER OF THE BRAZILIAN ORDER OF THE ROSE

HON. D.C.L. OXFORD; HON. LL.D. CAMBRIDGE, EDINBURGH, DUBLIN, AND ST. ANDREWS

HON. PH.D. LEYDEN

F.R.S., HON. F.R.S.E., F.R.A.S.

Correspondant de l'Institut de France (Académie des Sciences); Foreign Member della Reale Accademia dei Lincei, Roma; Corresponding Member der Königlich Preussischen Akademie der Wissenschaften; Foreign Member Regia Scientiarum Societas, Upsala; Foreign Member Königl. Bohmische Gesellschaft der Wissenschaften, Prag; Correspondent Königl. Gesellschaft der Wissenschaften, Göttingen; Foreign Member Royal Society of Denmark, Copenhagen; Foreign Member Philosophical Society, Lund, Sweden; Hon. Member Società degli Spettroscopisti Italiani, Roma; Hon. Member Société Astronomique de France; Hon. Member Royal Irish Academy, Dublin; Foreign Member American Academy Arts and Sciences, Boston; Hon. Member Philosophical Society, Philadelphia; Hon. Member Royal Society New South Wales, Sydney Hon. Member Manchester Literary and Philosophical Society; Hon. Member Astronomical and Physical Society of Toronto.

AND

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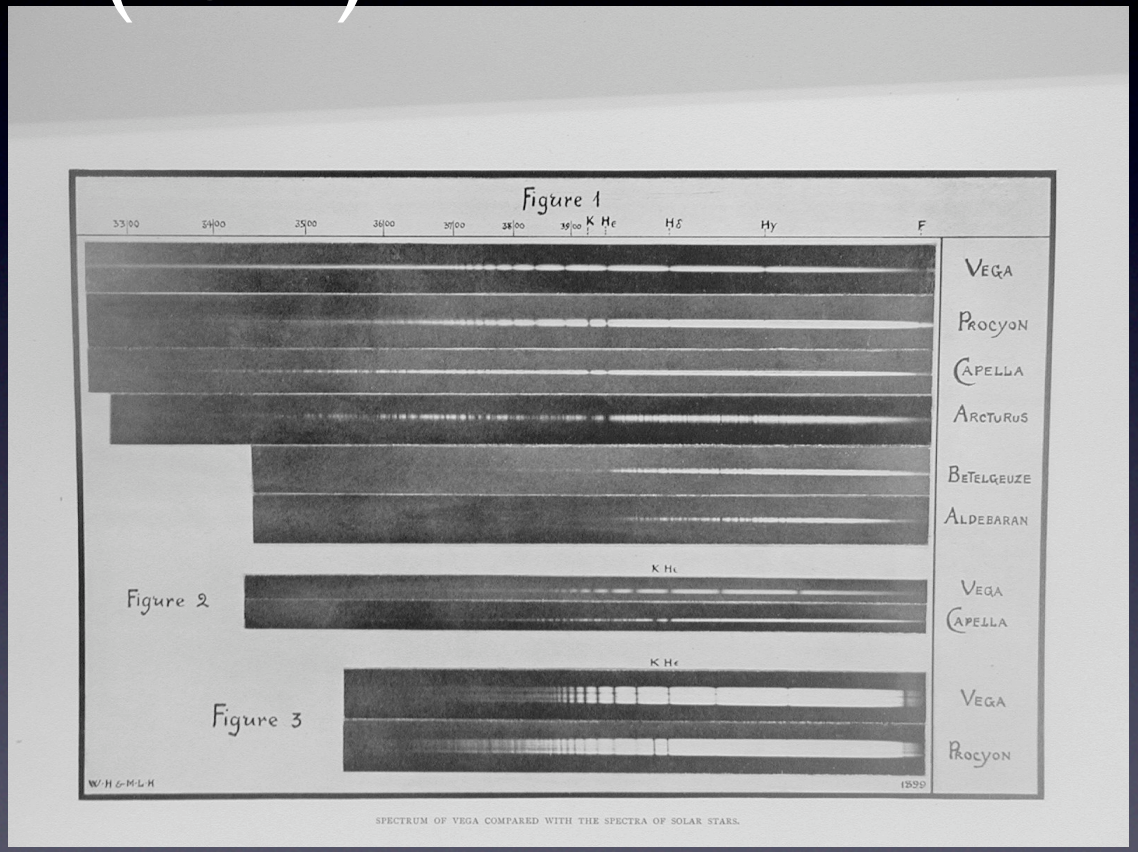
WILLIAM WESLEY AND SON

AND

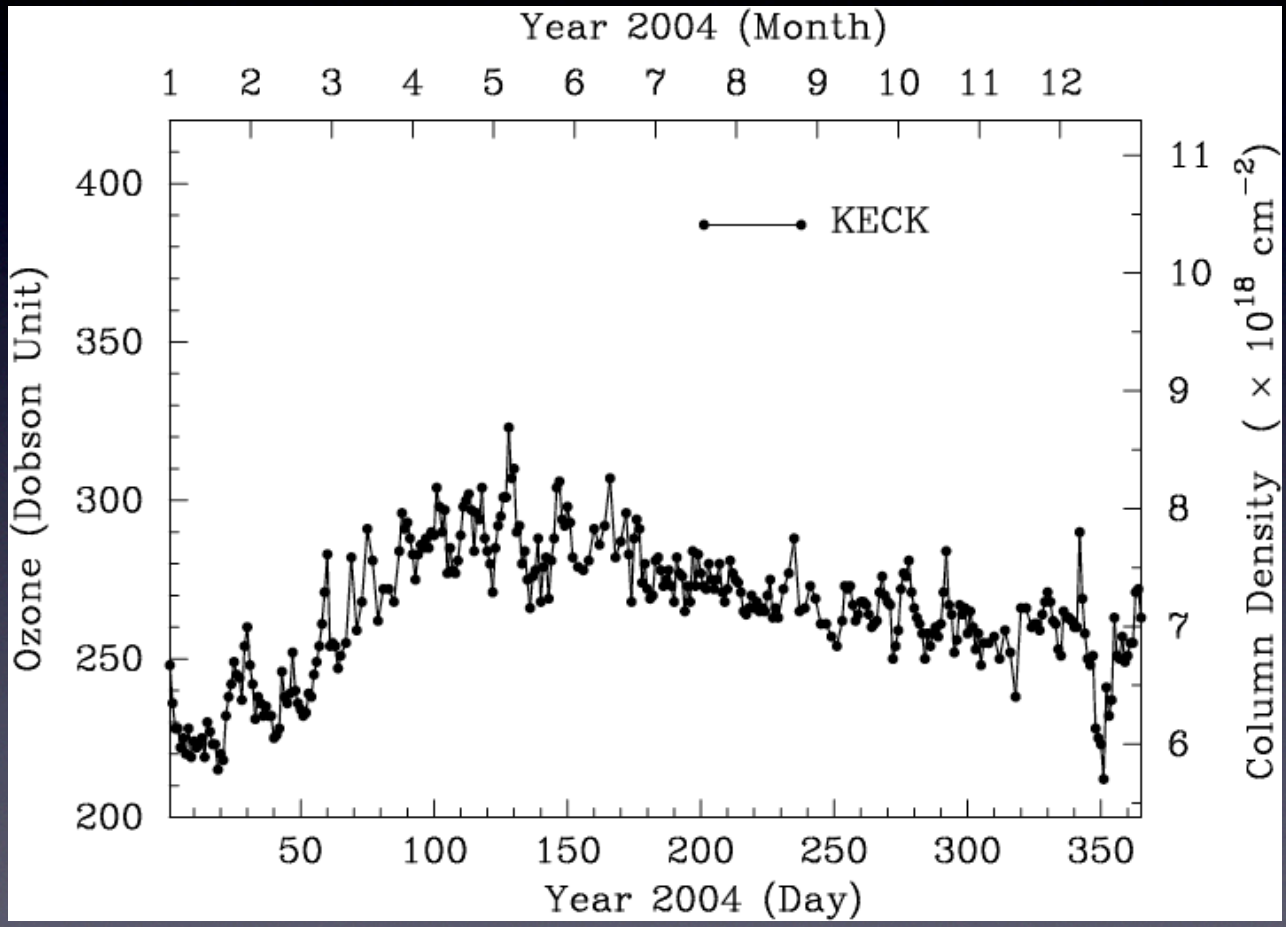
HAZELL, WATSON, & VINEY, LD., 1, CREED LANE, LUDGATE HILL, E.C.

1899

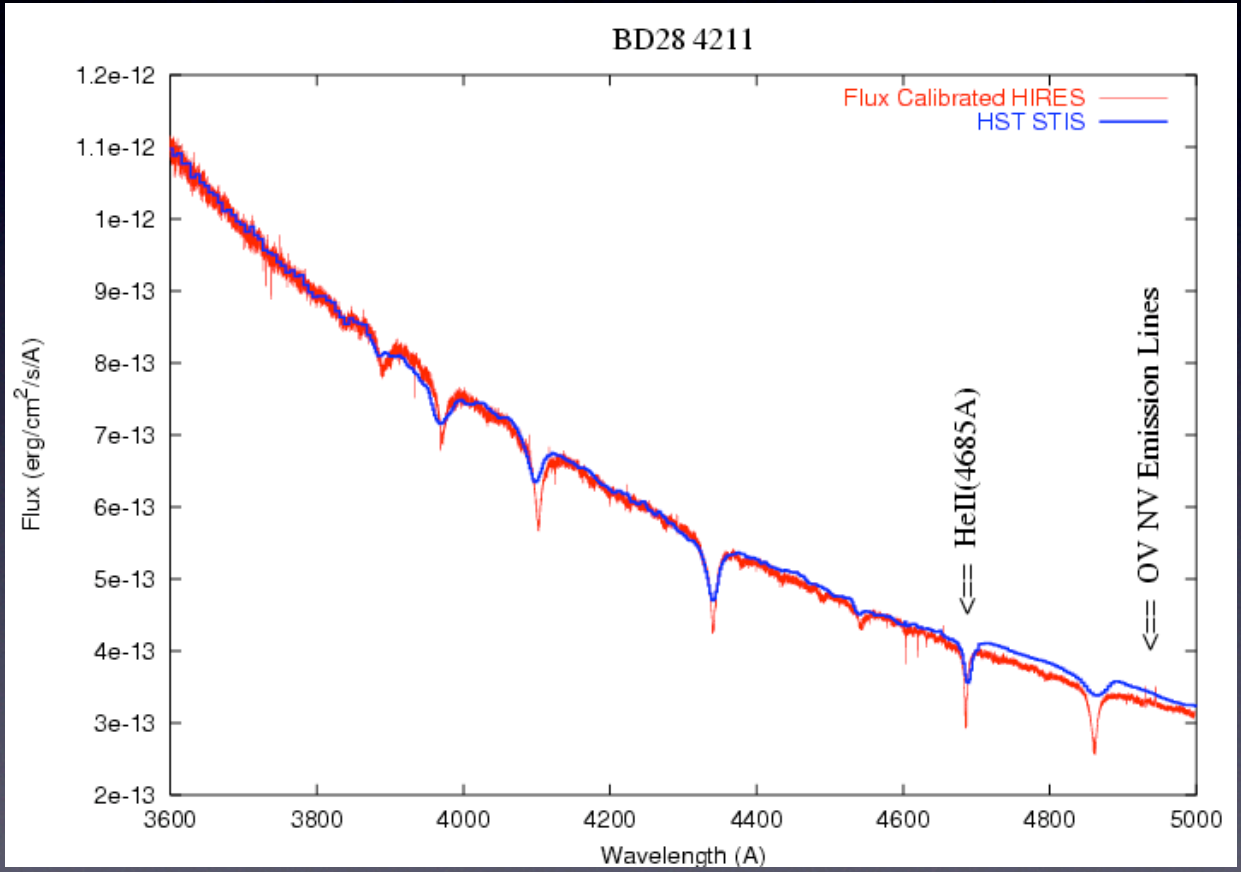


SPECTRUM OF VEGA COMPARED WITH THE SPECTRA OF SOLAR STARS.

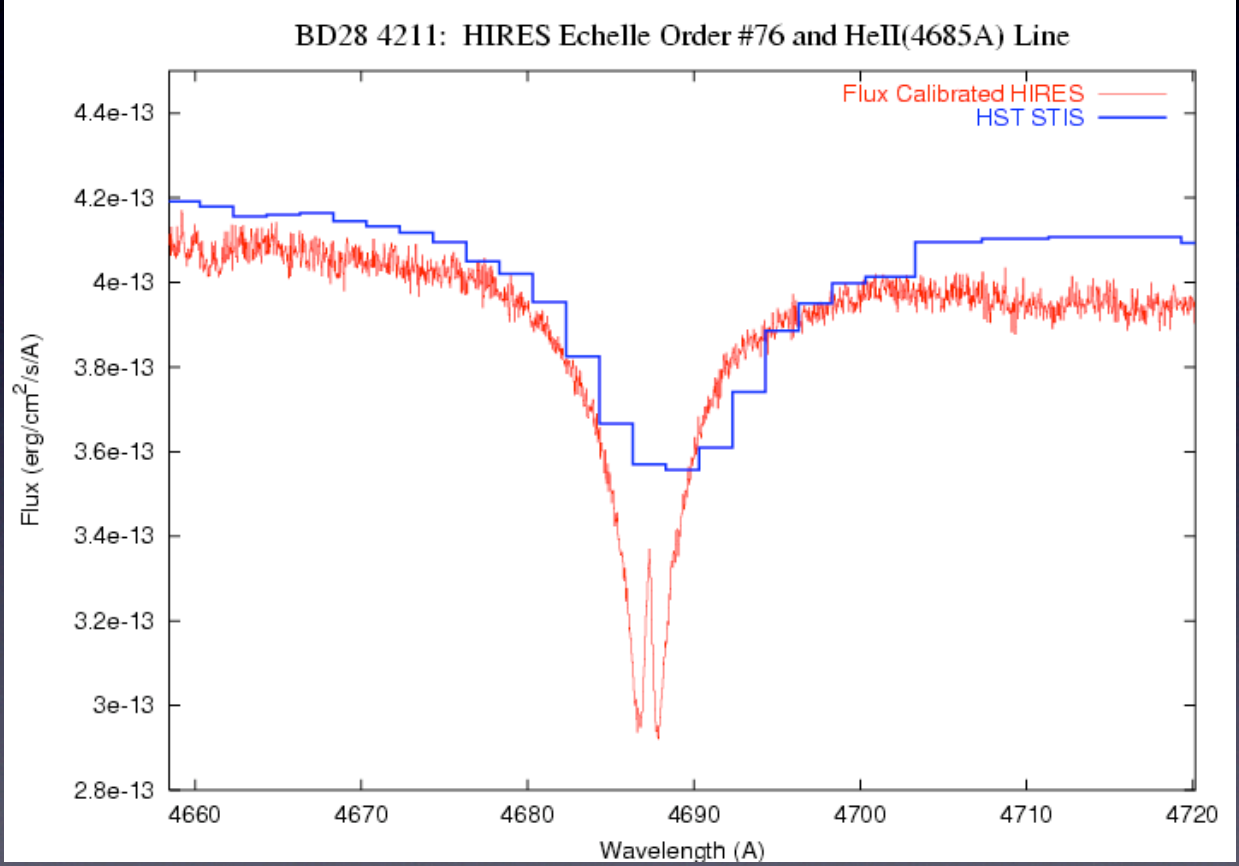
Annual Change of Ozone



Keck/HIRES vs. HST/STIS



HeII Line


BD28 4211: HIRES Echelle Order #76 and HeII(4685A) Line
Flux Calibrated HIRES
HST STIS
4.4e-13
4.2e-13
4e-13
3.8e-13
3.6e-13
3.4e-13
3.2e-13
3e-13
2.8e-13
Flux (erg/cm2/s/A)
4660
4670
4680
4690
4700
4710
4720
Wavelength (A)