Supernova Cosmology

Robert P. Kirshner

Entering 7th decade


EXIT
Bobfest
2007

Thank you!

PH.D. STUDENTS

Peter N. Kupferman I've lost track-- he was at JPL. The Aerospace Corporation.
William P. Blair, Astrophysicist and Research Professor, Johns Hopkins University
Bradley C. Whitmore, Astronomer, Space Telescope Science Institute
Robert A. Fesen, Professor of Astronomy, Dartmouth College
Eliot Malumuth, Research Scientist, Goddard Space Flight Center
J. Ward Moody, Professor of Astronomy, Brigham Young University
Michael V. Newberry, software entrepreneur, Tucson, Arizona
Ronald Eastman, Lawrence Livermore National Laboratory (retired)
R. Chris Smith, Director, Cerro Tololo Inter-American Observatory
Brian P. Schmidt, Professorial Fellow, Australian National University
Jason Pun, Assistant Professor, Hong Kong Institute of Science and Technology
Adam G. Riess, Professor, Johns Hopkins & Space Telescope Science Institute
Huan Lin, Scientist, Experimental Astrophysics, Fermi National Accelerator Lab
Saurabh Jha, Assistant Professor, Rutgers University
Maryam Modjaz, Miller Fellow, University of California, Berkeley
Malcolm Hicken, McKinsey, Houston
Ashley Ruiter SAO Predoc Munich
Andy Friedman 2010
Kaisey Mandel 2010

More!

UNDERGRADUATES

Alicia Soderberg, Clay Fellow, CfA

Patrick Kelly grad student at Stanford Quincy House

Matt George Berkeley grad student Quincy House

Peter Williams Berkeley grad student Quincy House

Jenny Graves finishing Ph.D. at Santa Cruz Senior thesis

Kuenley Chu postdoc with Richard Ellis at Caltech A-35 Head TF

Nancy Levenson Associate Director, Gemini Observatory,Senior Thesis A-35

Jon Morse NASA Headquarters Senior thesis

Marc Kuchner NASA Goddard Senior thesis

OWN CATEGORY: Peter Challis, staff member HCO

POSTDOCS

Ian Wilson (lives in Australia-- I think he may teach at a high school)

Stuart Schurmann, (I have no idea where he is!)

Alan Uomoto (Carnegie)

Eric Schlegel (UT San Antonio),

Bruno Leibundgut (ESO),

David Jeffery (UNLV),

Pilar Ruiz-Lapuente (Barcelona),

Peter Hoelfich (Florida)

Peter Garnavich (Notre Dame)

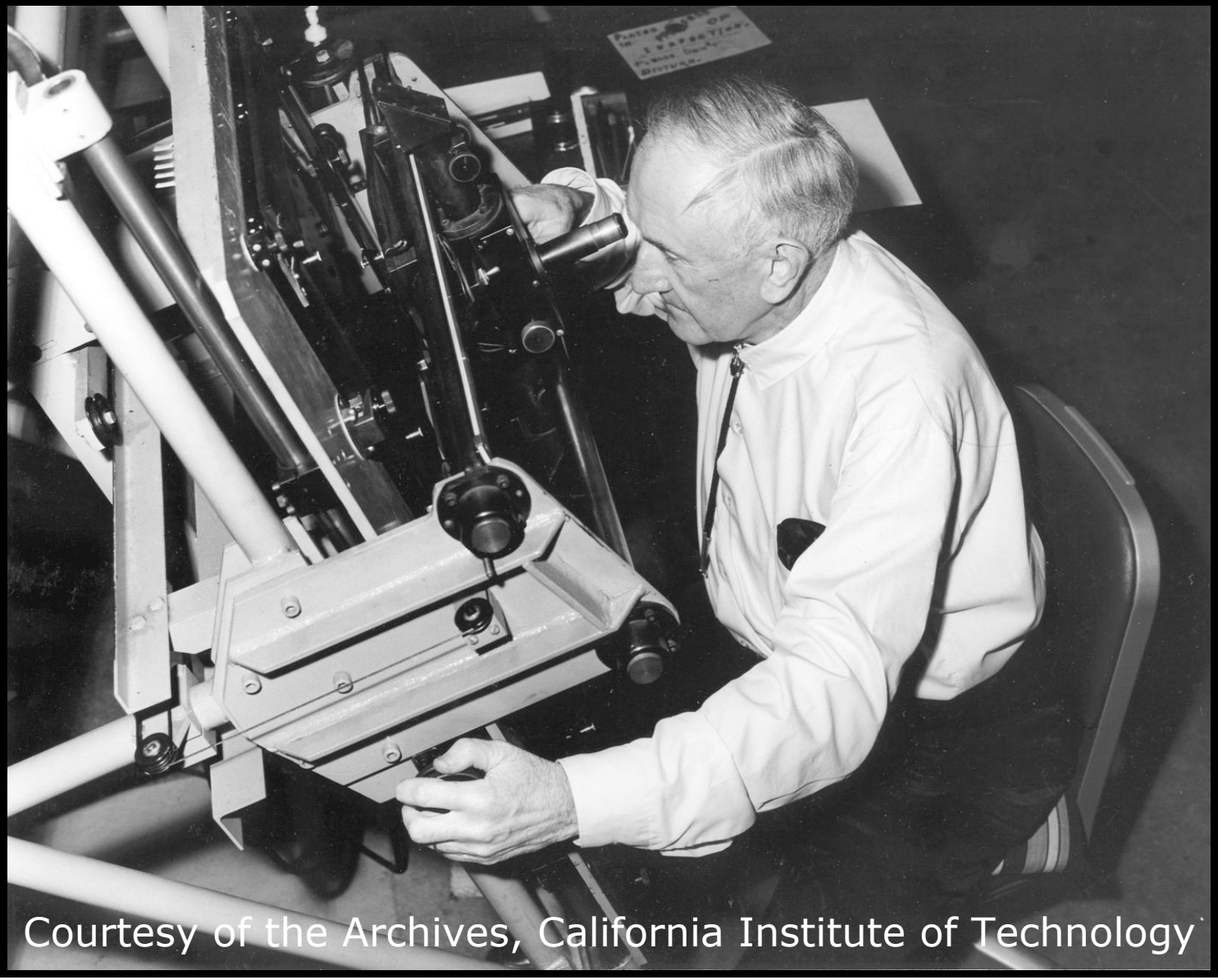
Tom Matheson (NOAO)

Stephane Blondin (ESO)

Michael Wood-Vasey (Pittsburgh)

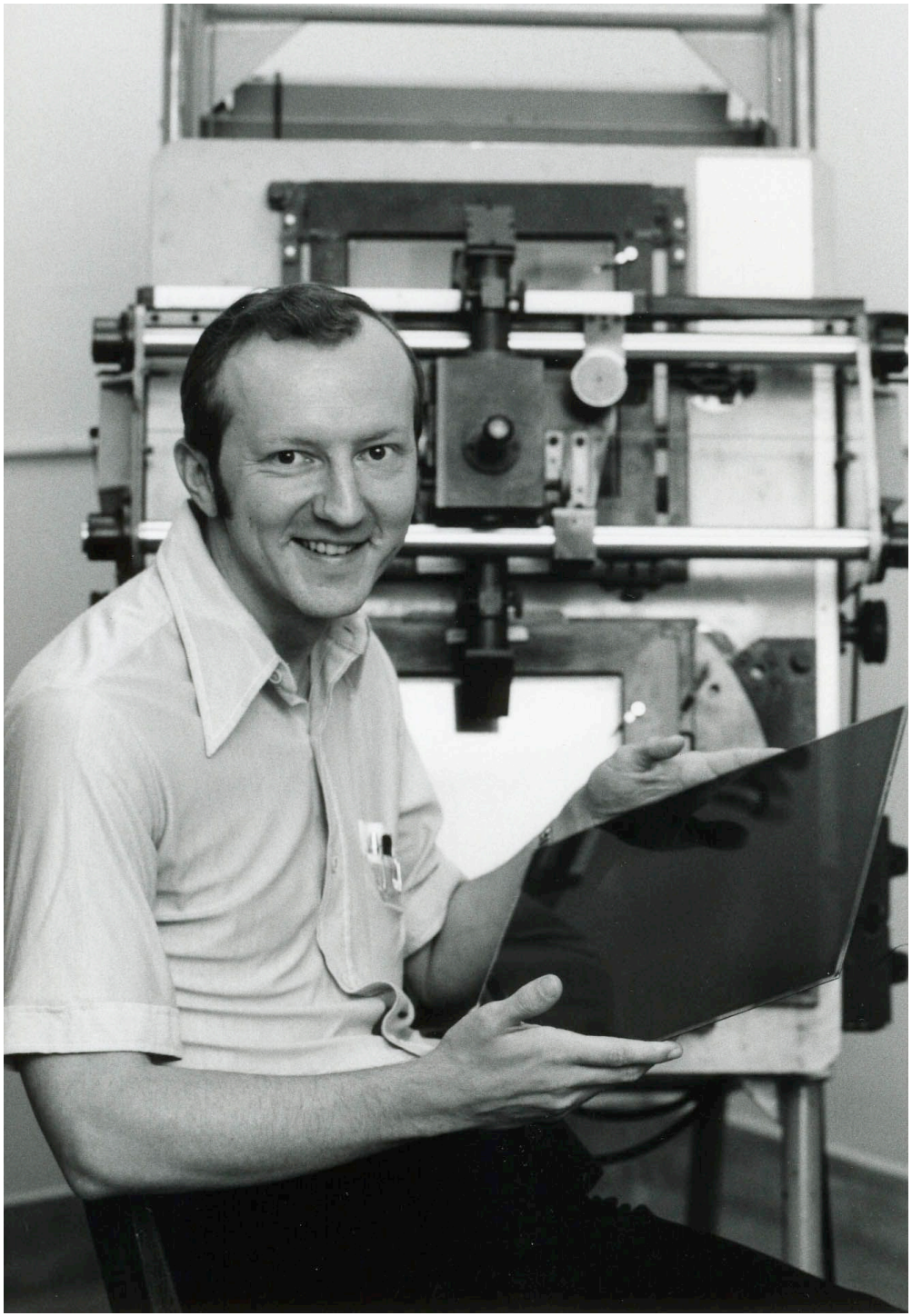
Ryan Foley, Clay Fellow (CfA)

Fritz Zwicky at work



Courtesy of the Archives, California Institute of Technology


Courtesy of the Archives,
California Institute of Technology



Charlie Kowal

At work in the engine room

Note the imaging technology of 1968!

Photo courtesy Caltech Public Relations Archives

Kowal (1968)

✓ Had distances good to ~30% from SN I

Speculated that individual measurements might be good to 5-10%

"It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become available for very distant supernovae."

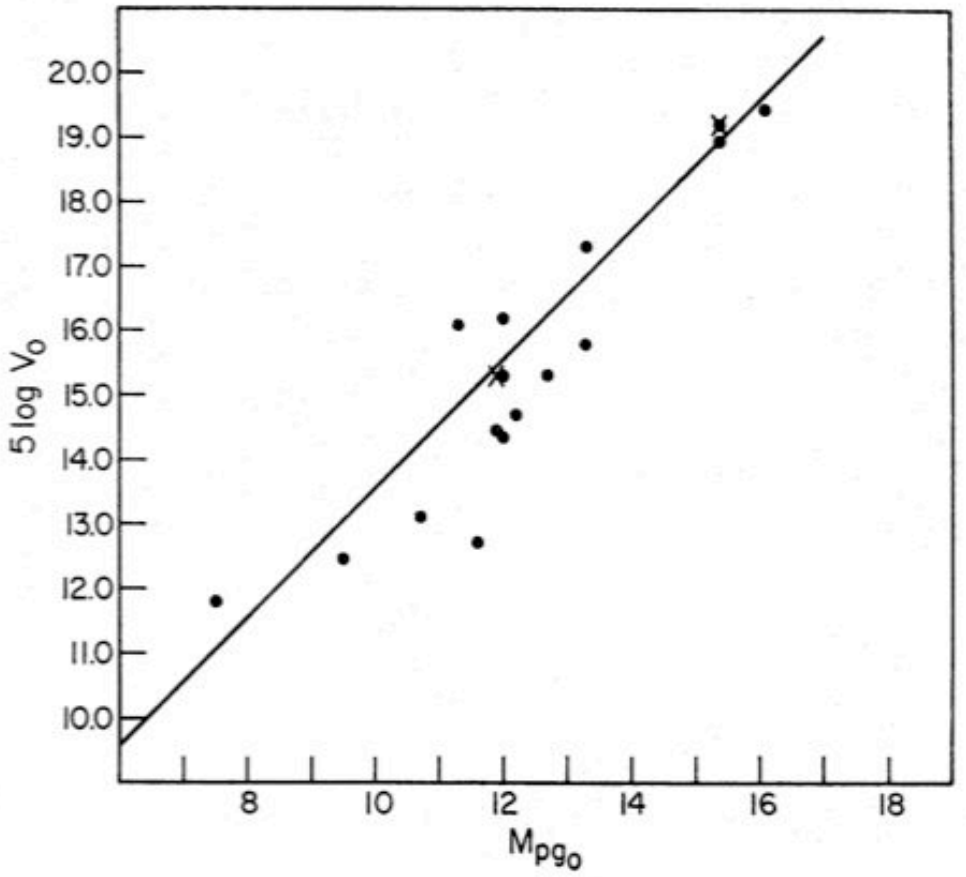


FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

Bev Oke

1928-2004

Photo courtesy
Caltech Public
Relations Archives

Giant Electronic Cameras

100’s =>1000 Megapixels

Palomar Transit Factory

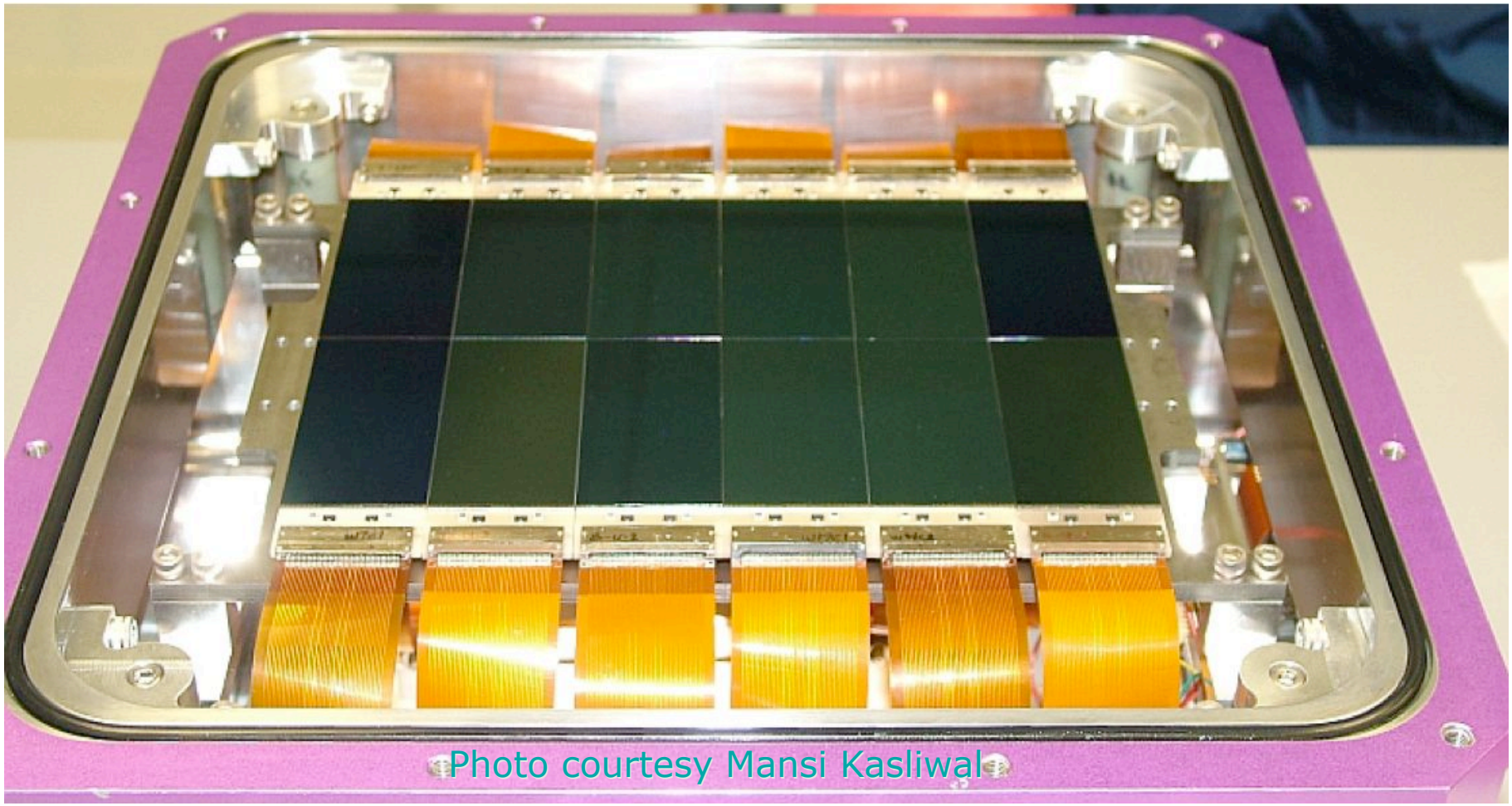
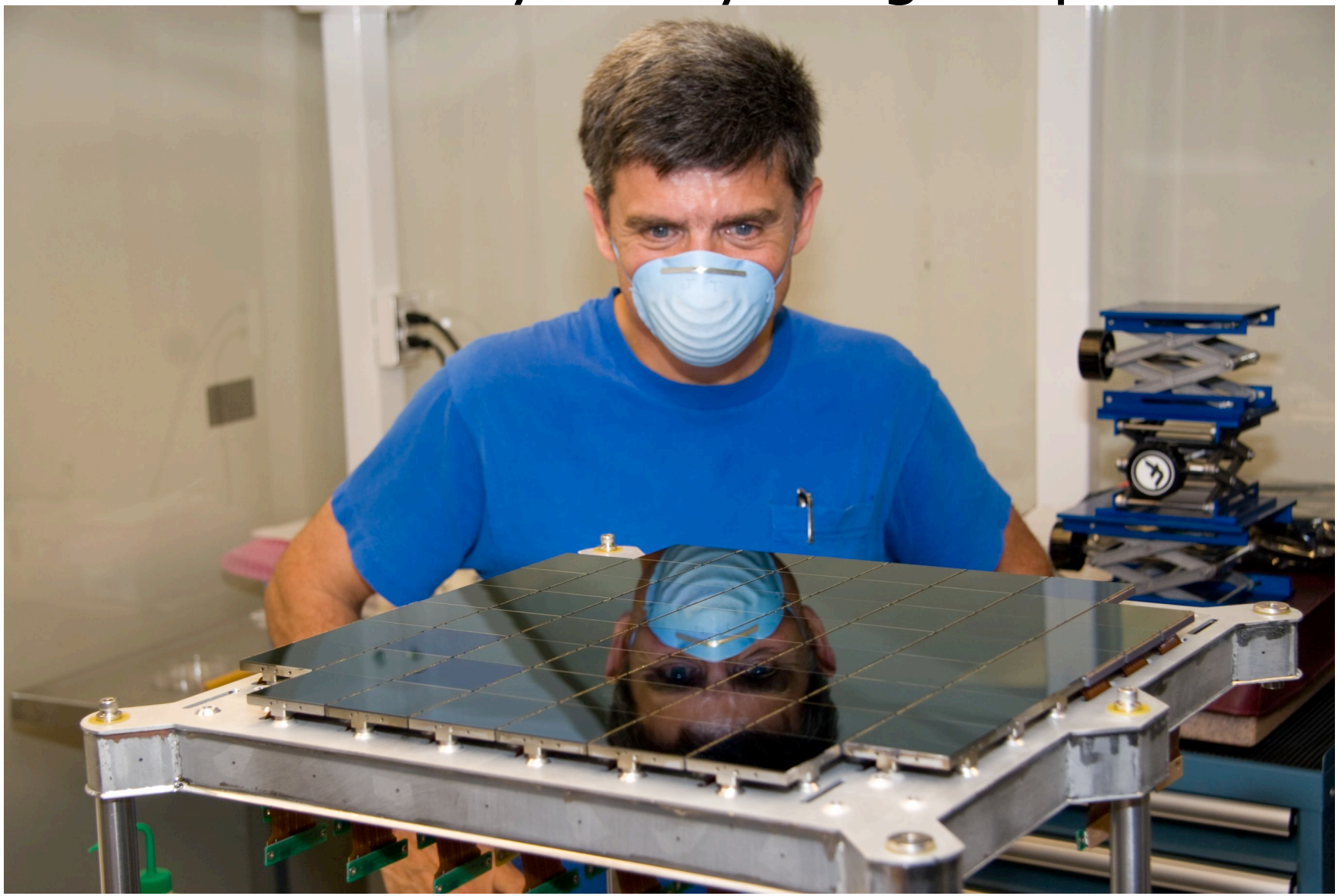


Photo courtesy Mansi Kasliwal

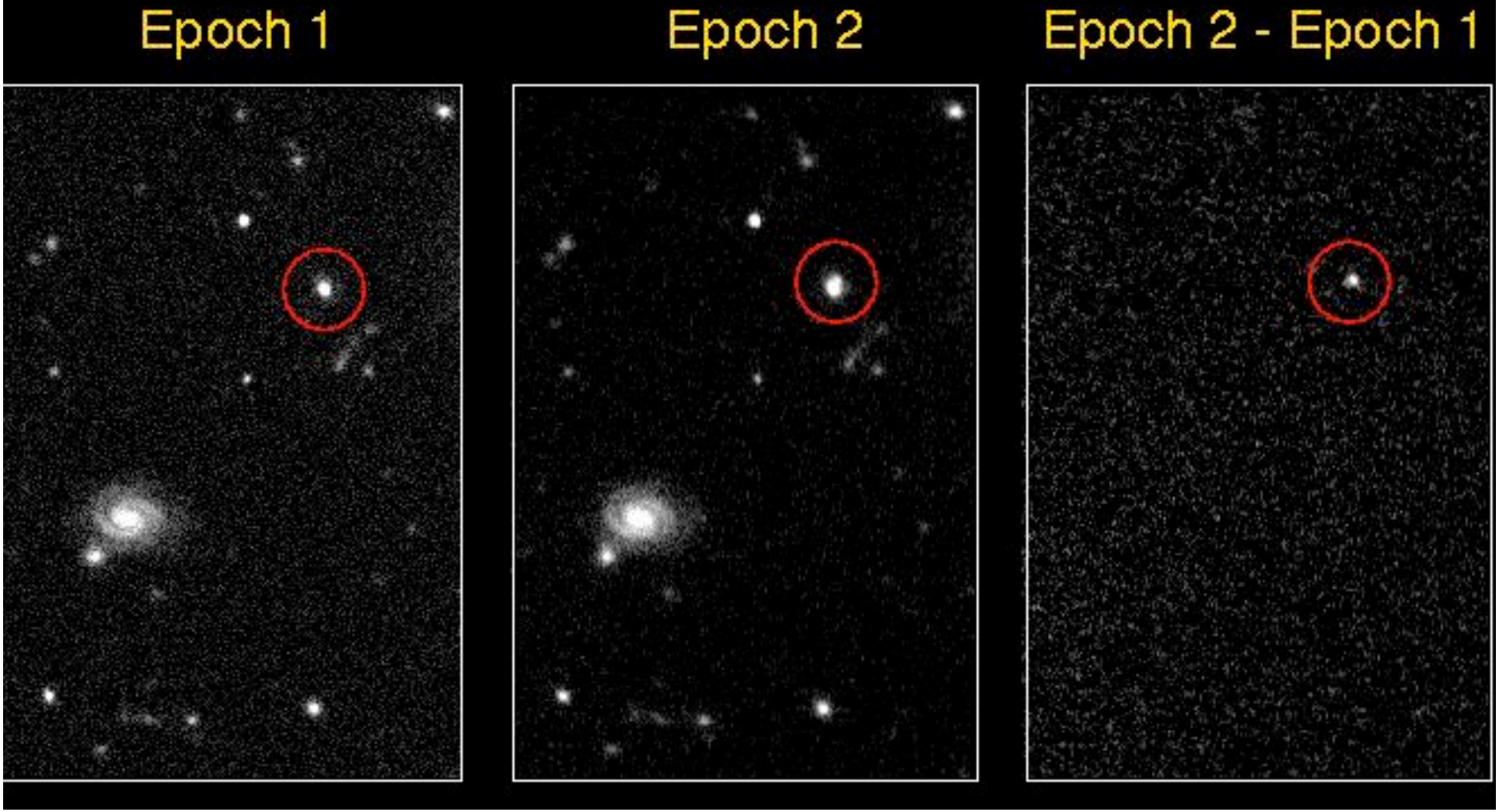
A gigapixel camera
to make your eyes light up!



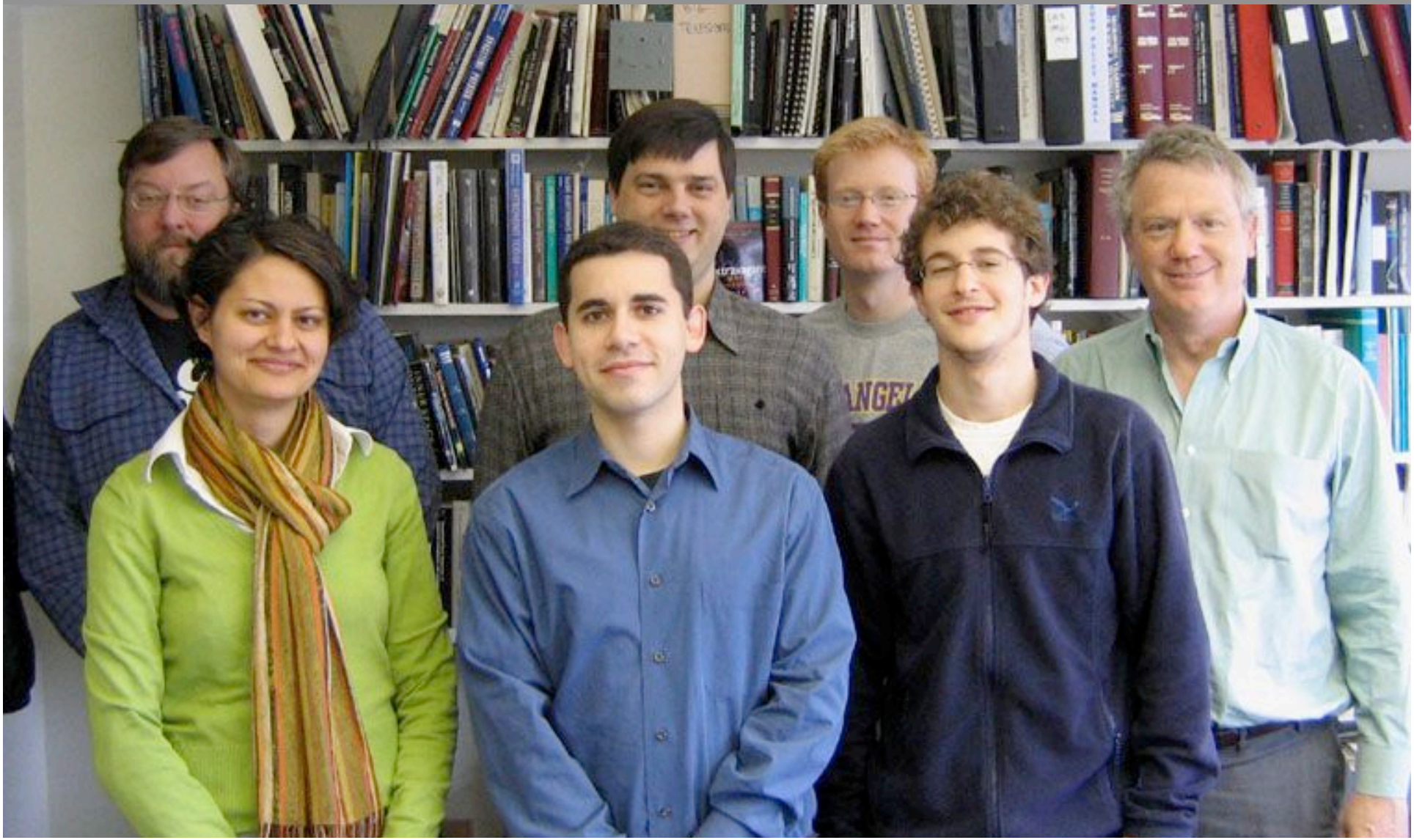
Brian Schmidt explains to his thesis advisor how easy it is to subtract images

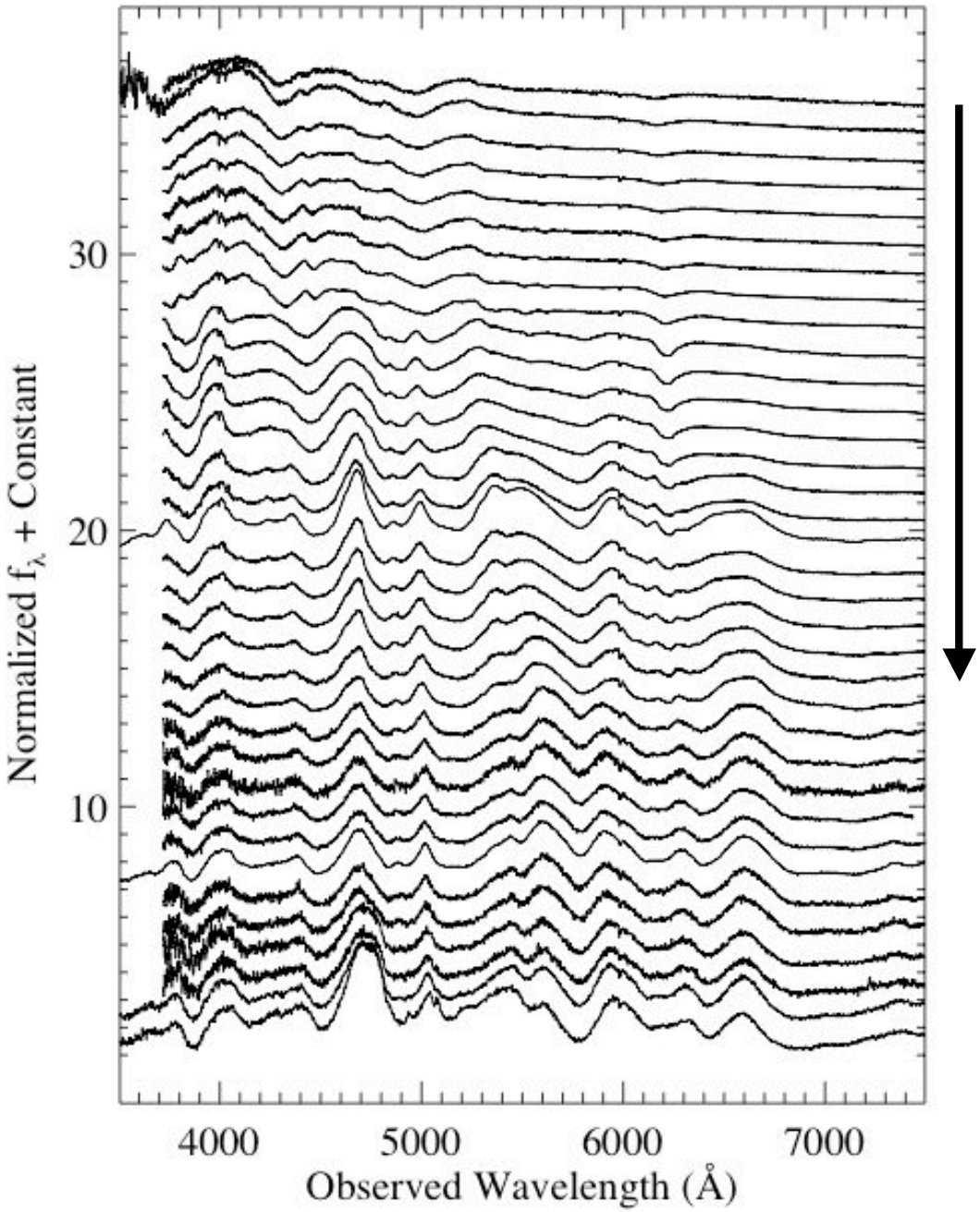
Searching by Subtraction

unskilled and therefore inexpensive labor
under careful supervision--computers!

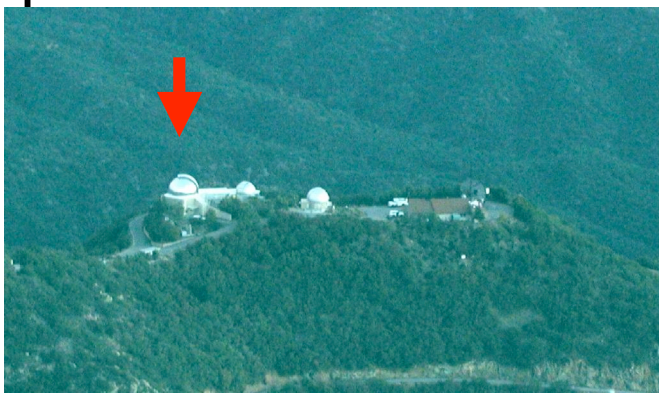


CfA Supernova Group (Also manufactured in supernovae)





Spectra



Similar at a given age, but not identical

SNID: Blondin & Tonry (2007)

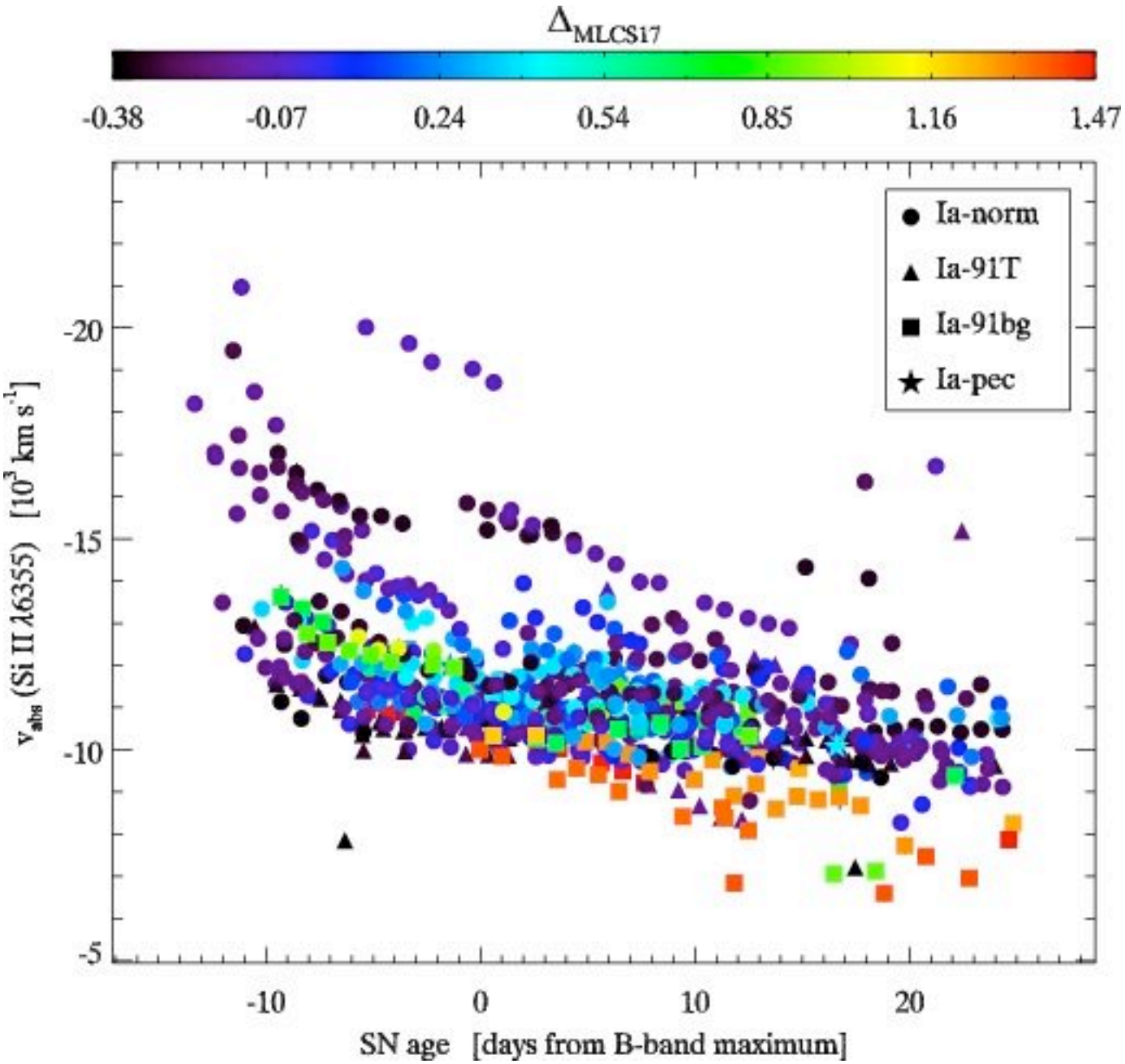
Fe seen at late times

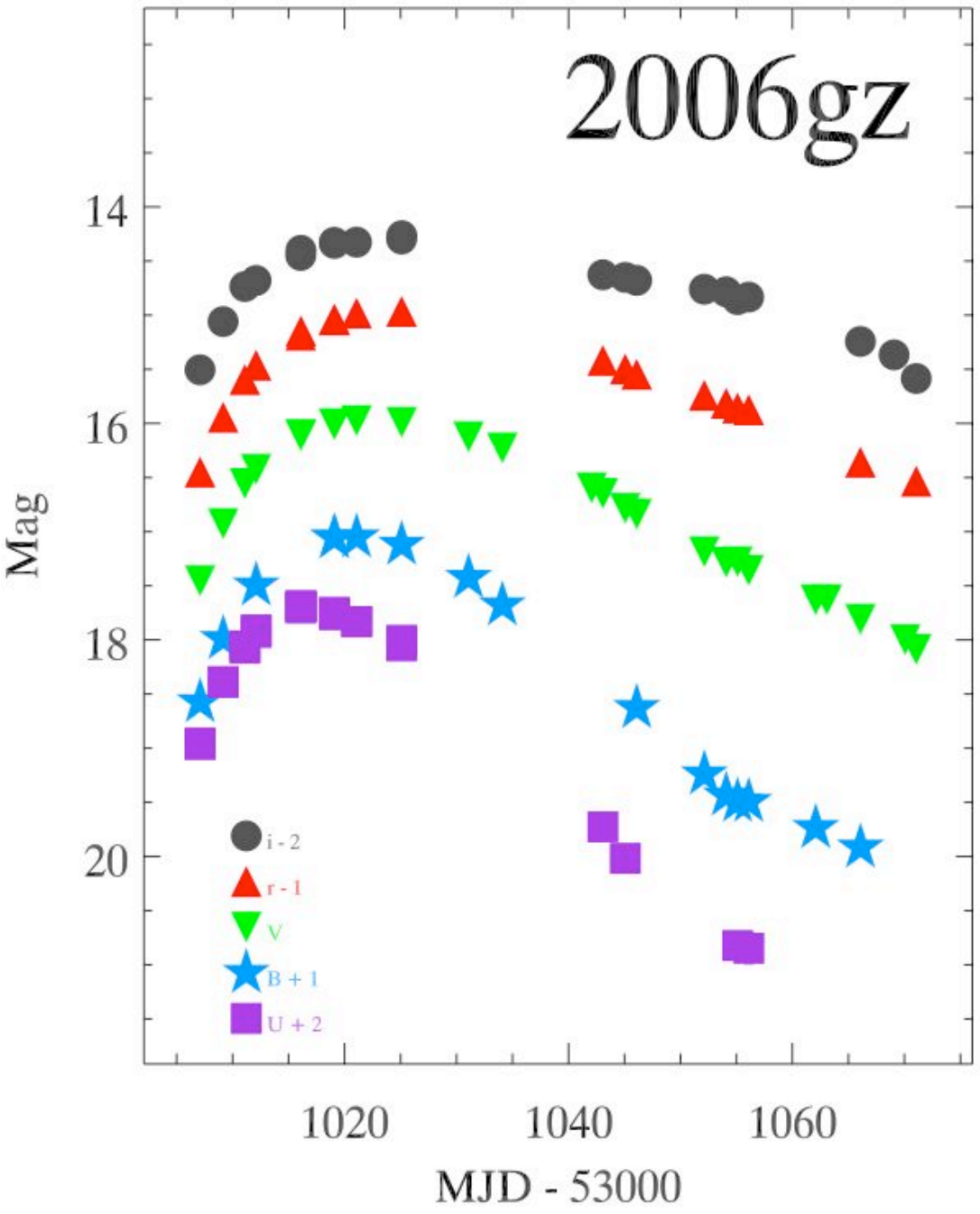
Matheson et al. (2008)

787 spectra of 55 SN Ia in

http://www.cfa.harvard.edu/supernova/SNarchive.html

2211 spectra of 413 SN Ia -- Blondin


Δ_{MLCS17}
-0.38
-0.07
0.24
0.54
0.85
1.16
1.47
Ia-norm
Ia-91T
Ia-91bg
Ia-pec
-20
-15
-10
-5
v_{abs} (Si II λ6355) [10^3 km s^{-1}]
-10
0
10
20
SN age [days from B-band maximum]



Multiband Light Curves for bright supernovae

CfA1 Riess (22)
CfA2 Jha (44)
CfA3 Hicken (185)
each ~world's total at the time

Curiously, in 2008, the biggest statistical error in SN cosmology was due to the small size of the low-z sample!

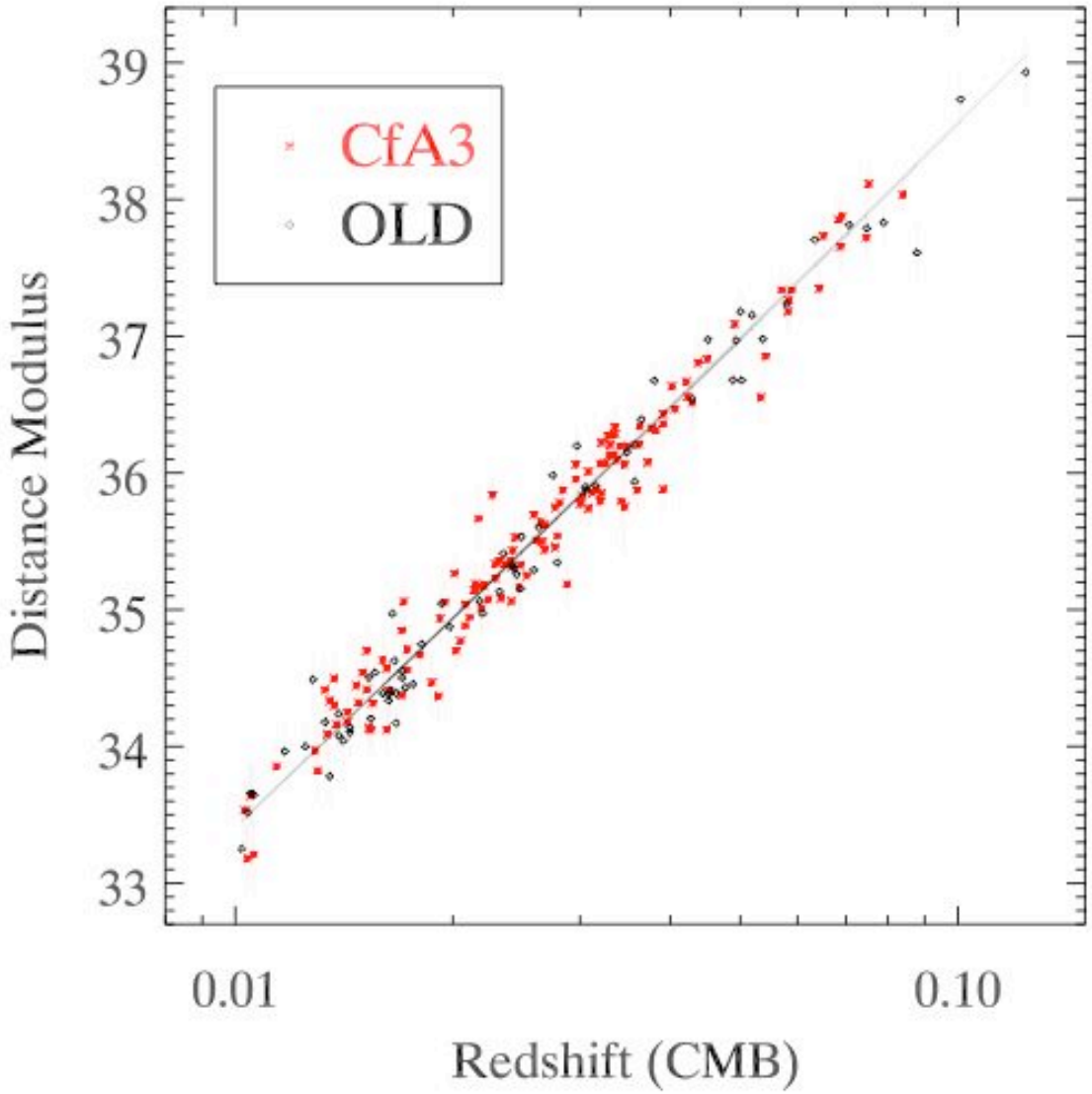
This has now been remedied by the CfA3 sample

Hicken et al. ApJ 700, 331 (2009) July 20

185 Type I Light Curves

Hicken et al. ApJ 700, 1097 (2009) August 1

Improved Dark Energy Constraints

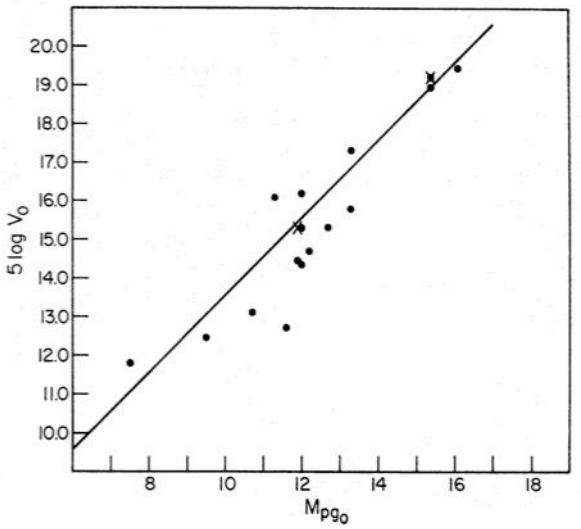


Kowal (1968)

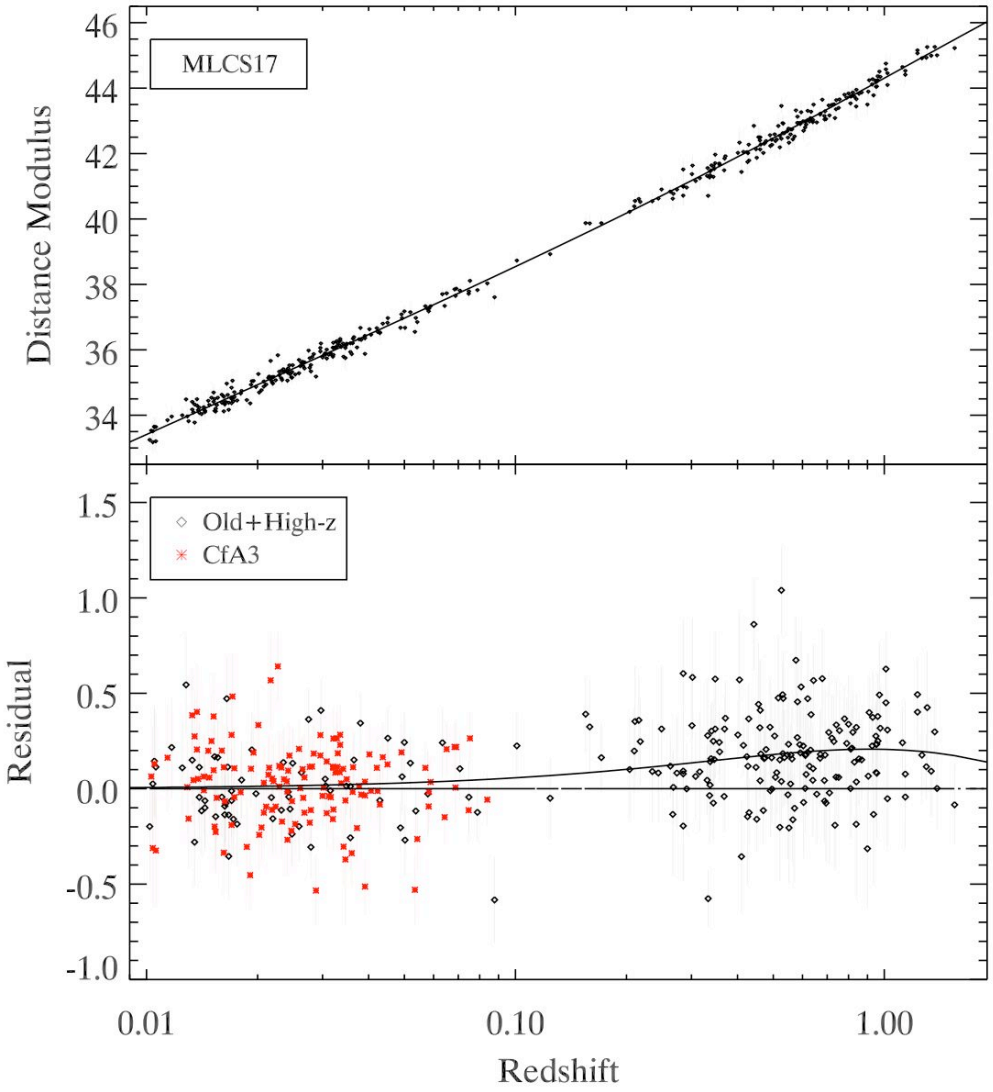
✓ Had distances good to ~30% from SN I

✓Speculated that individual measurements might be good to 5-10%

"It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become available for very distant supernovae."



Low Redshift and High



Low:

CfA3 (Hicken) +
CfA2 (Jha) +
CfA1 (Riess) +
Calan-Tololo

High:

ESSENCE

SNLS

Higher-Z

From the Union data set (Kowalski 2008)

To the Constitution (a more perfect Union!)

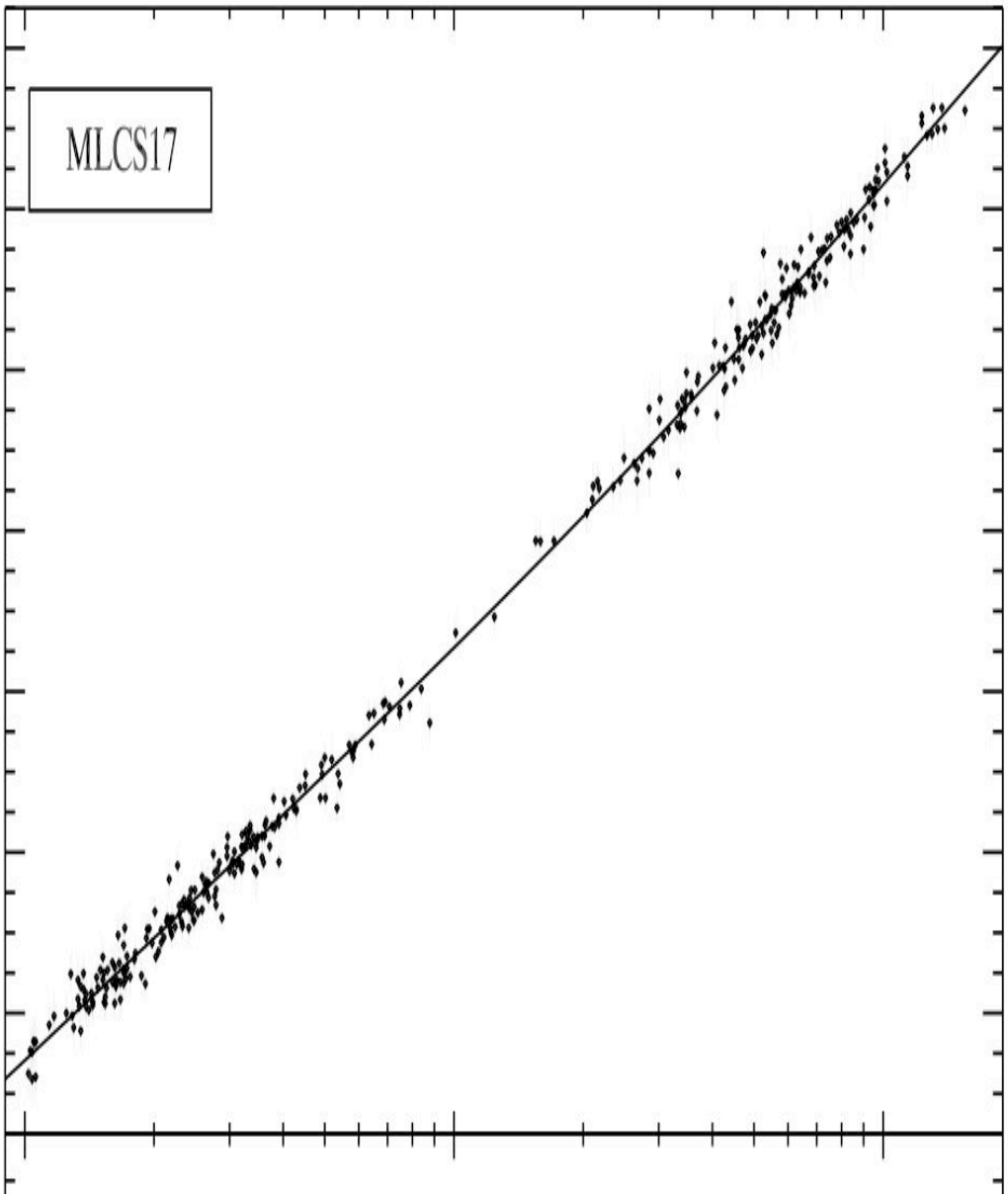
Hicken (2009)

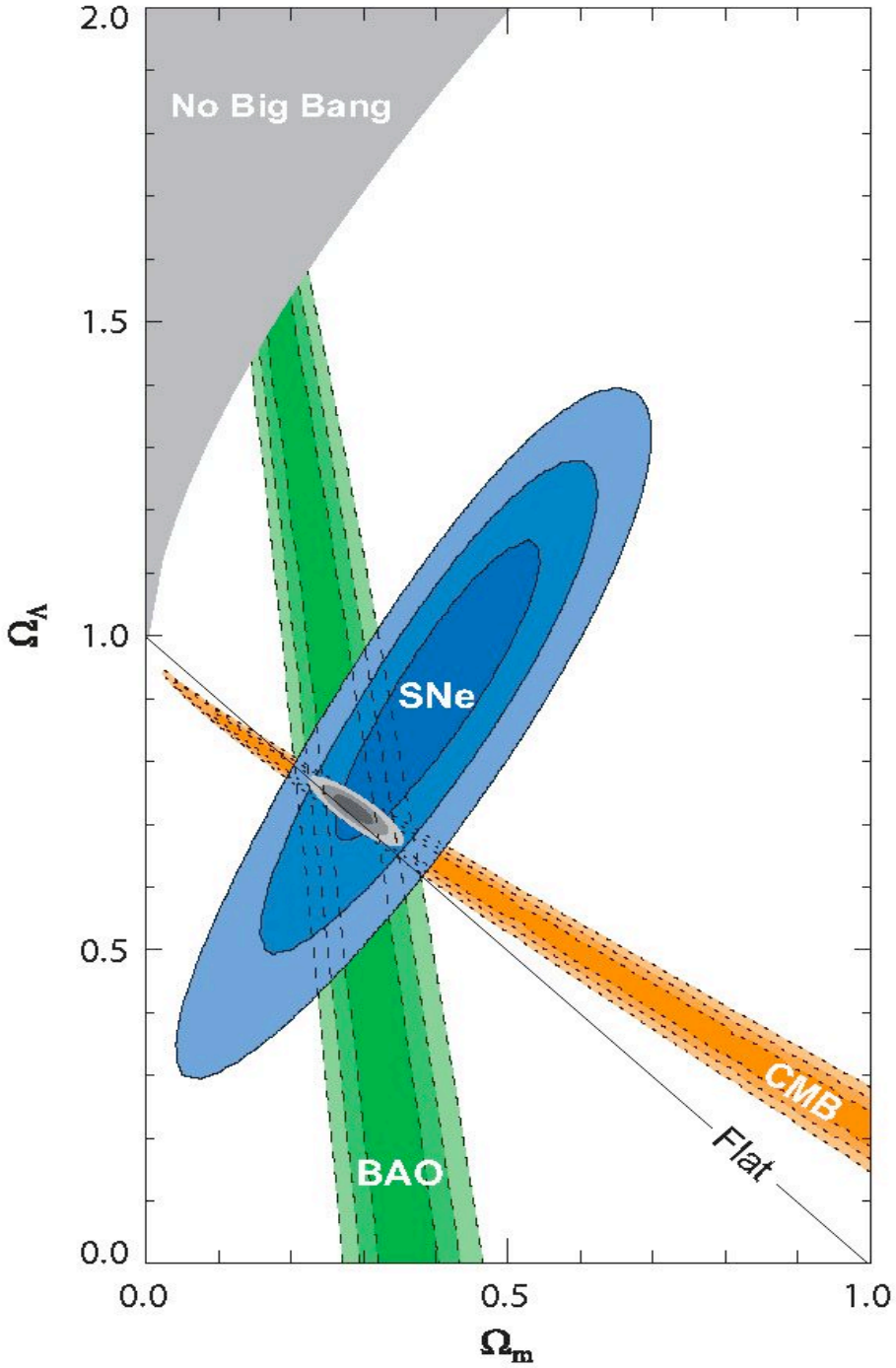
Kowal (1968)

✓ Had distances good to ~30% from SN I

✓Speculated that individual measurements might be good to 5-10%

✓"It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become available for very distant supernovae."

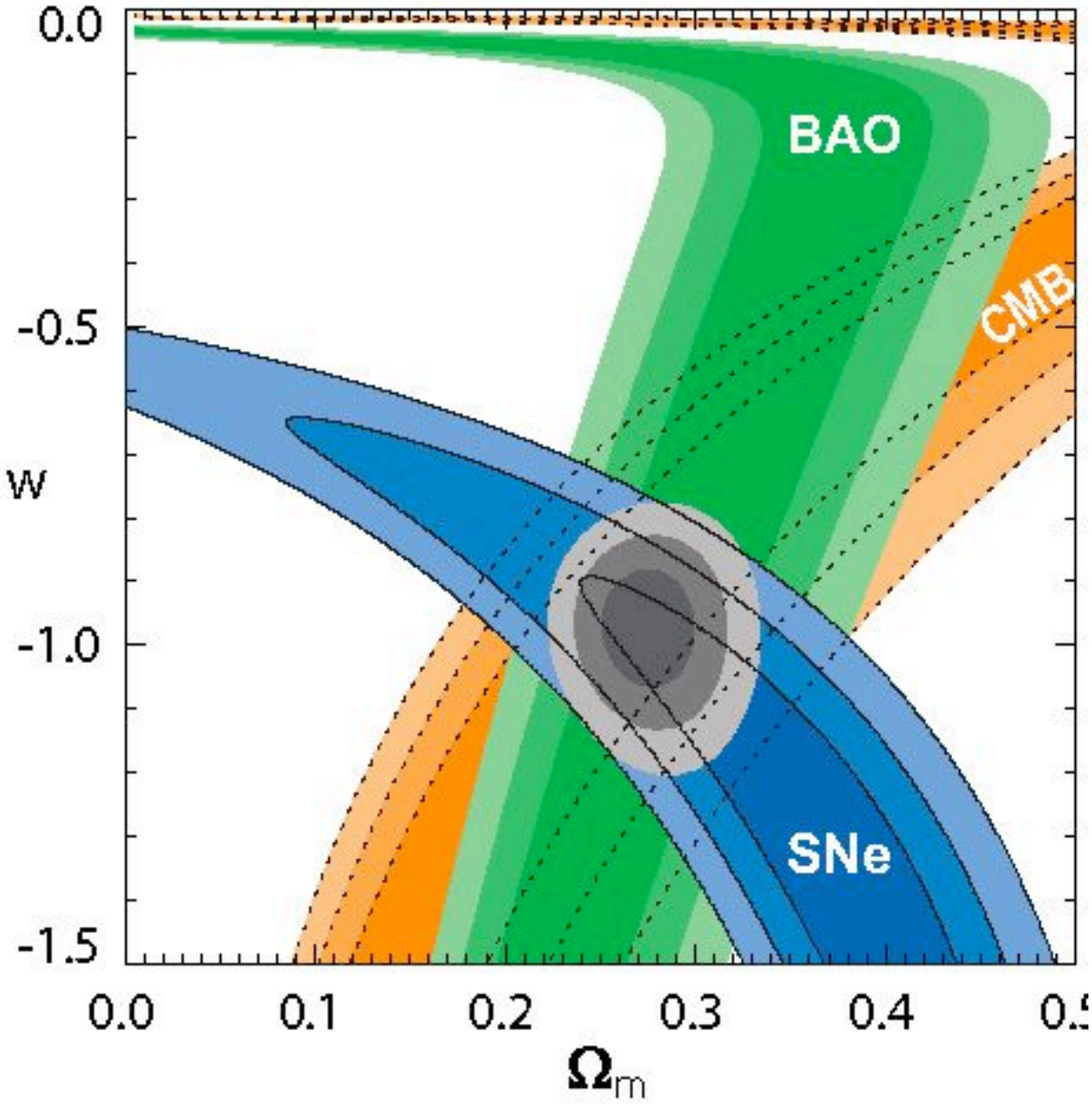




Pretty good concordance

SN orthogonal to CMB, good fit with baryon oscillation constraints

$\Omega_{DE} = 0.72 +/- 0.02$



From Kowalski astro-ph 0804.4142

Based on Low z: Calan-Tololo + CfA 1 +CfA2 + SCP

ESSENCE + SNLS + Higher-Z

w = -0.94 +/-0.1 +/- 0.1 (sys)

Does not include CfA3 (150 @ 0) Sloan (300+ @ z= 0.1)

Malcolm Hicken: squeezer of contours!

Where do we go from here?

Not much to be gained just from larger samples--need more precisely measured ones, better selected samples, and SN that are not affected by dust! (Bigger samples to be sliced more finely!)

Sloan-immanent

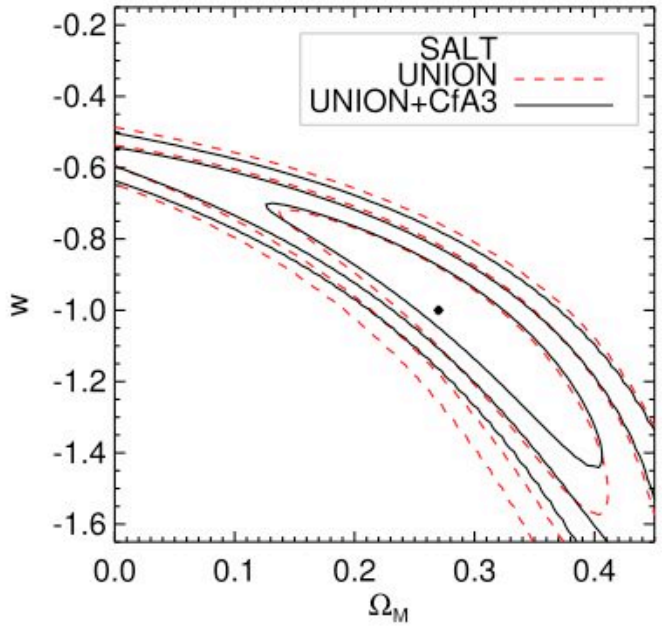
SNF

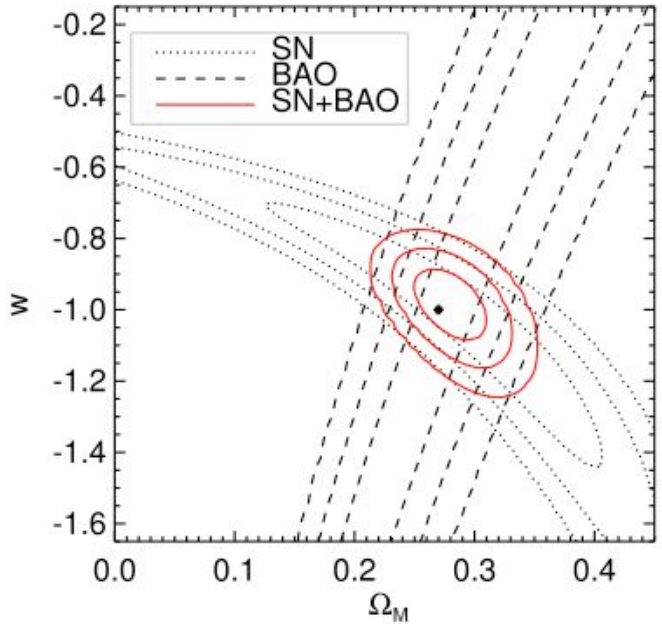
Carnegie- See Folatelli poster

PTF

Pan-STARRS

Also, need results that depend less on the light curve fitter!





INTERNATIONAL BROTHERHOOD OF THEORISTS

LOCAL 137

cogito ergo sum

UNION CARD

Robert Kirshner

MEMBER IN GOOD STANDING

UC CHAPTER

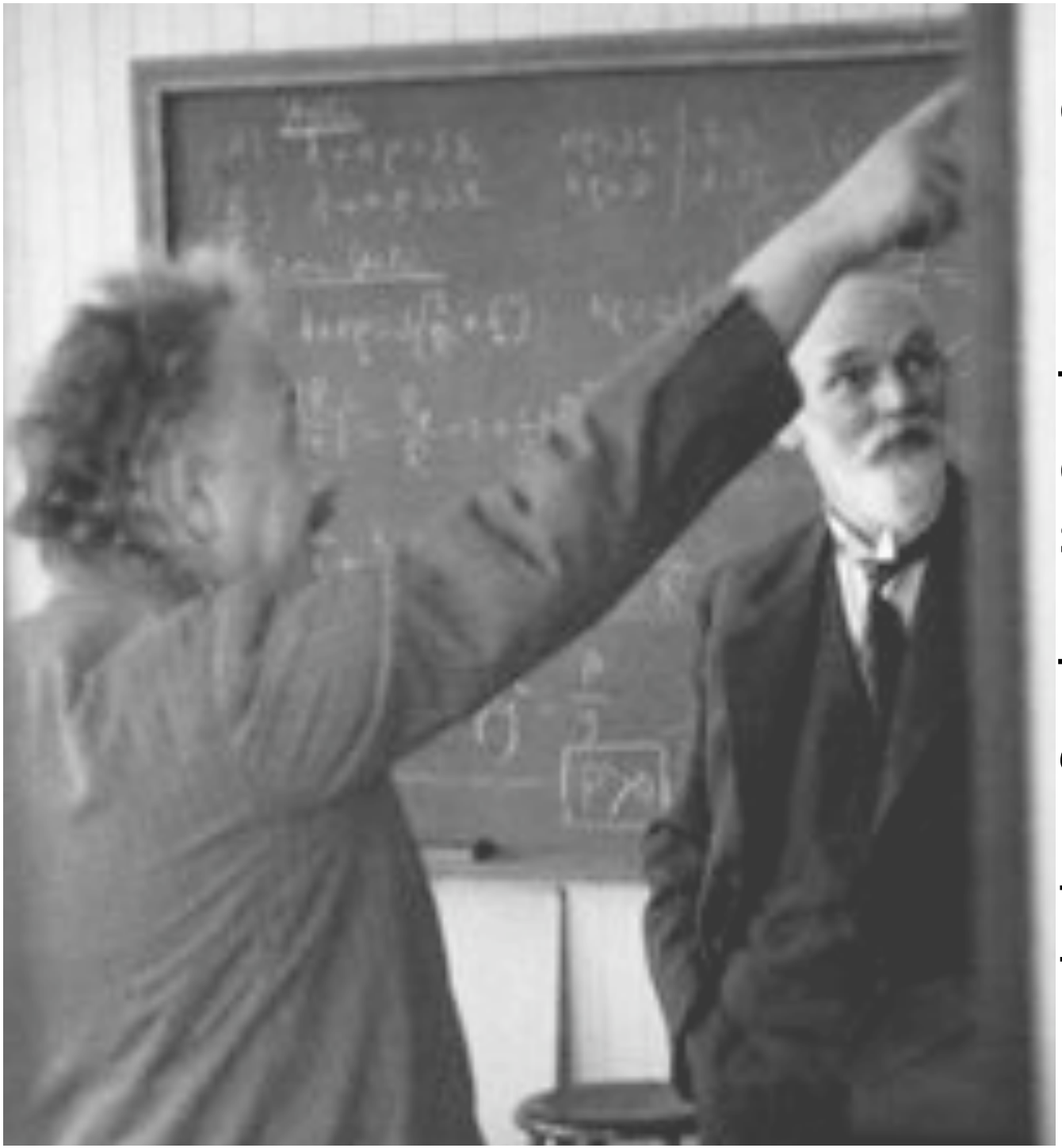
valid to ∞

David Gross

President

Lars Bildsten

Shop Steward



Einstein & de Sitter banish Λ in 1931

They didn't just set $\Lambda=0$

They ***excluded*** it from their formalism!

High-Z Team:

Riess et al. (1998)

Supernova Cosmology Project:

Perlmutter et al. (1999)

Einstein astonished!

But Lemaitre would not have been. He thought Λ might drive the expansion Hubble observed. His 1934 paper treats the cosmological constant as vacuum energy!

Georges Lemaitre

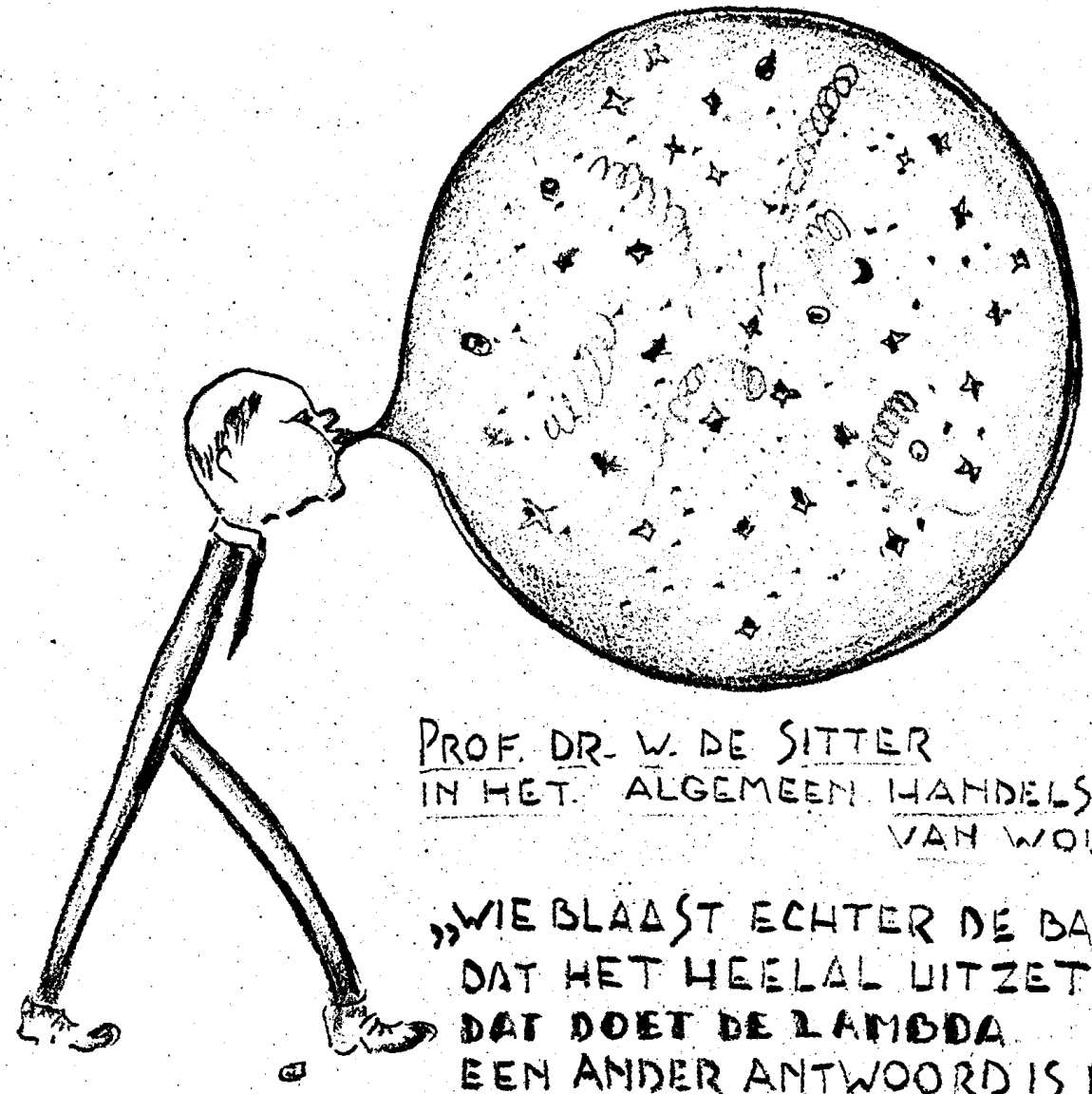
"The evolution of the world can be compared to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a well-chilled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds."

Georges Lemaitre

"Everything happens as though the energy *in vacuo* would be different from zero…we associate a pressure $p = -\rho c^2$ to the density of energy ρc^2 of vacuum. This is essentially the meaning of the cosmological constant λ."

PNAS 20, 12 (1934)

Λ as the source of cosmic expansion: DeSitter in 1930



PROF. DR. W. DE SITTER
IN HET ALGEMEEN HANDELSBLAD*
VAN WOENSDAG 9 JULI 1930

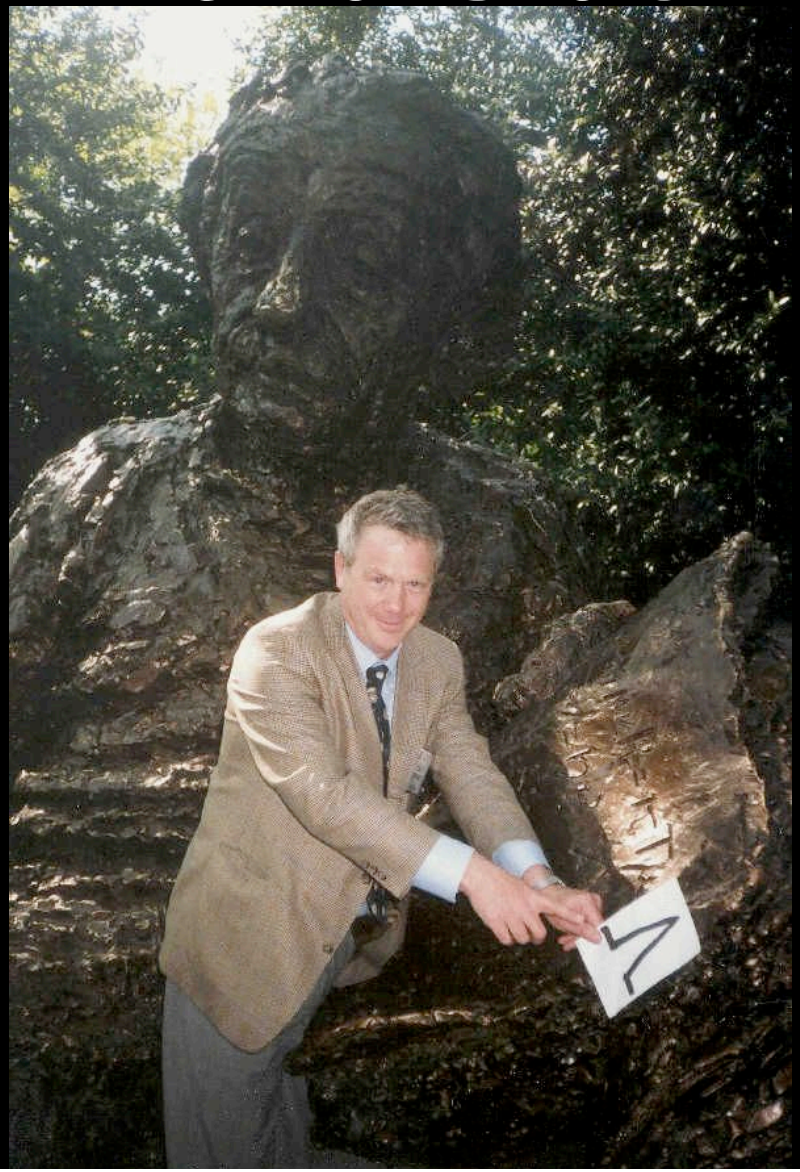
„WIE BLAAST ECHTER DE BAL OP? WAT MAAKT
DAT HET HEELAL UITZET, OF OPZWELT?
DAT DOET DE LAMBDA
EEN ANDER ANTWOORD IS NIET TE GEVEN"

"Who however blows up the ball? What makes the Universe expand: or swell up?
That is done by the Lambda.
An other answer cannot be given."

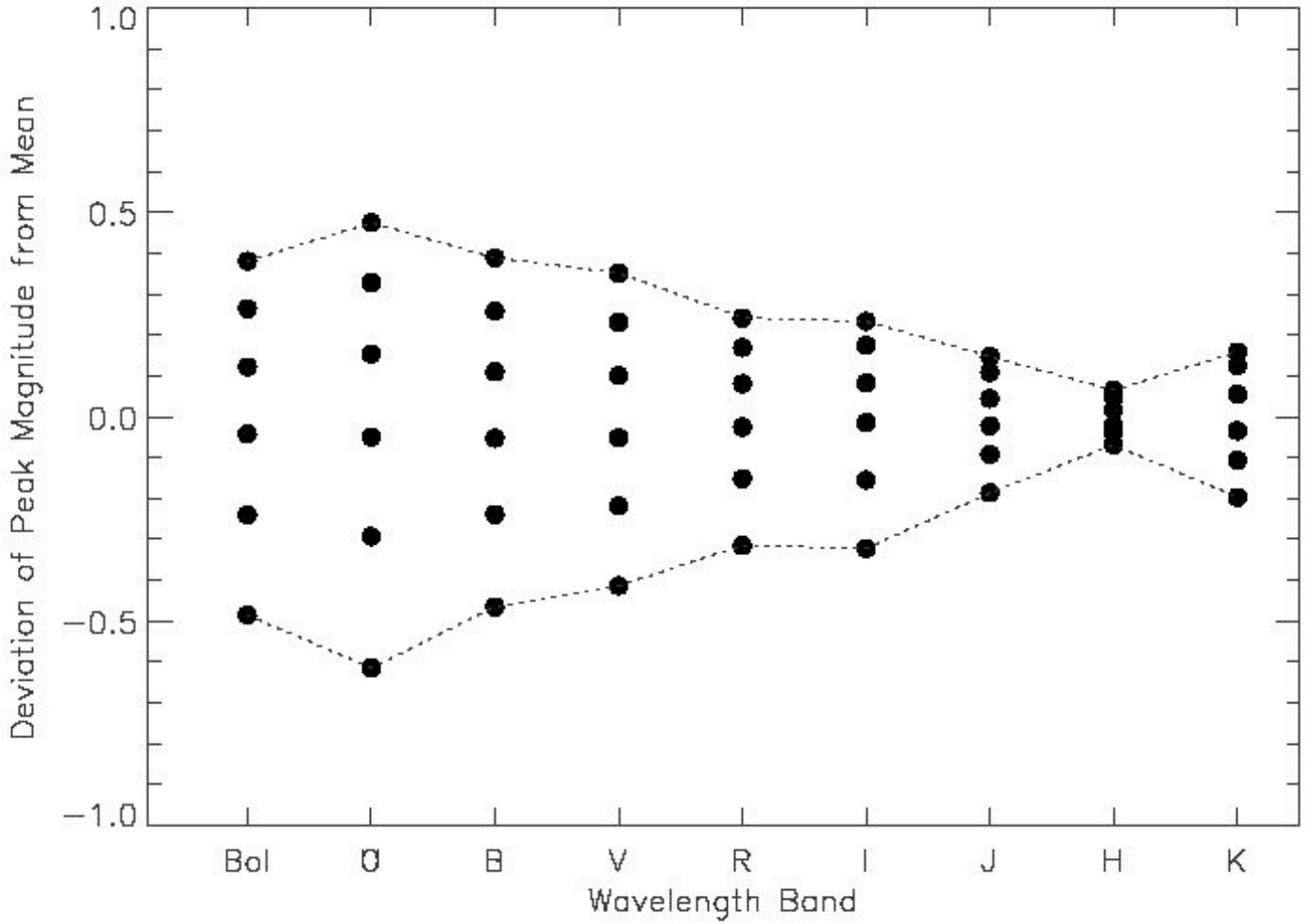
* A well known dutch daily newspaper

Thanks to Jim Peebles

Putting Λ on the Right Hand Side

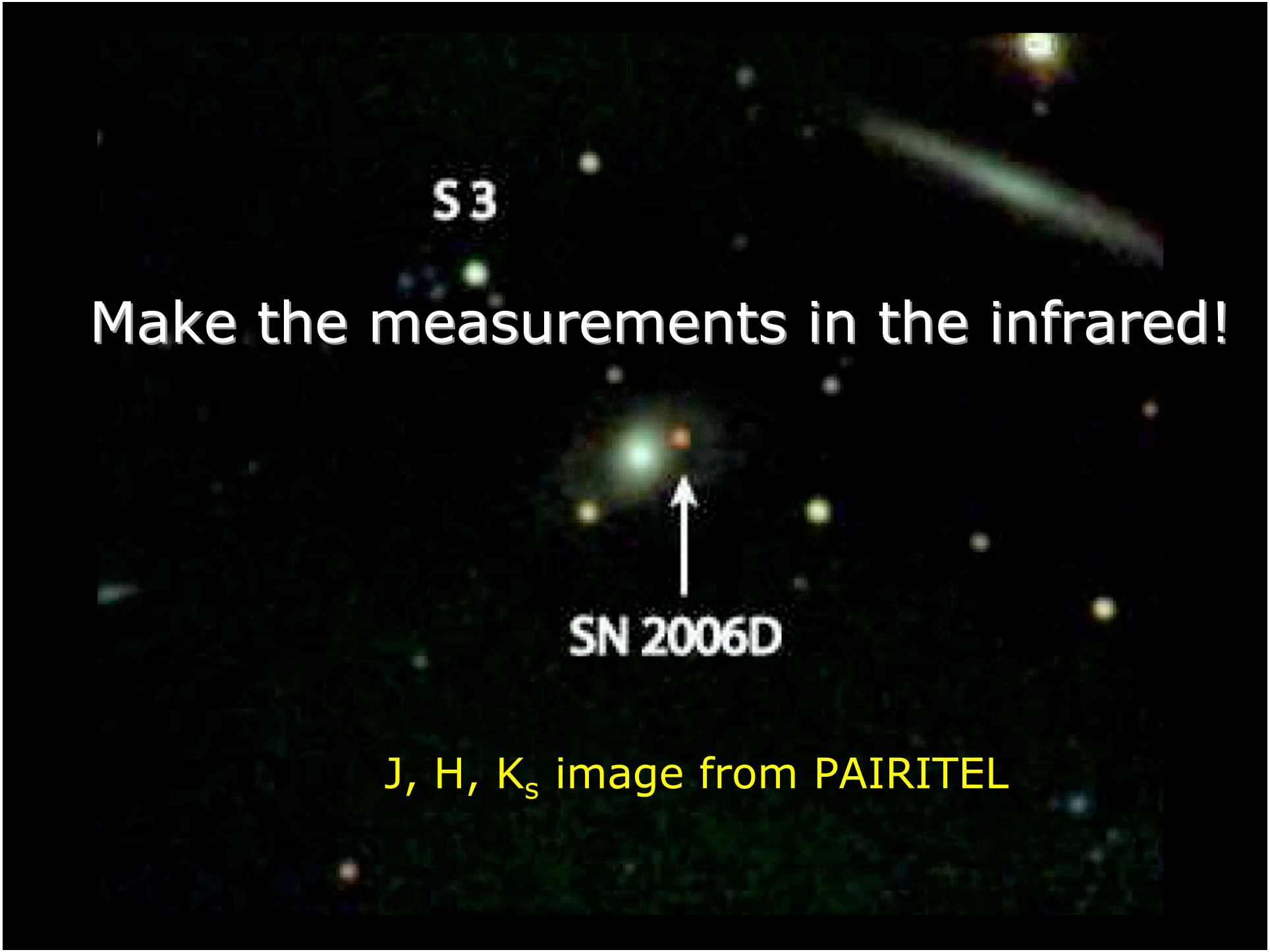


The biggest uncertainties now are **systematic errors** and the worst of these come from dust (Conley et al. 2007; Sullivan talk)



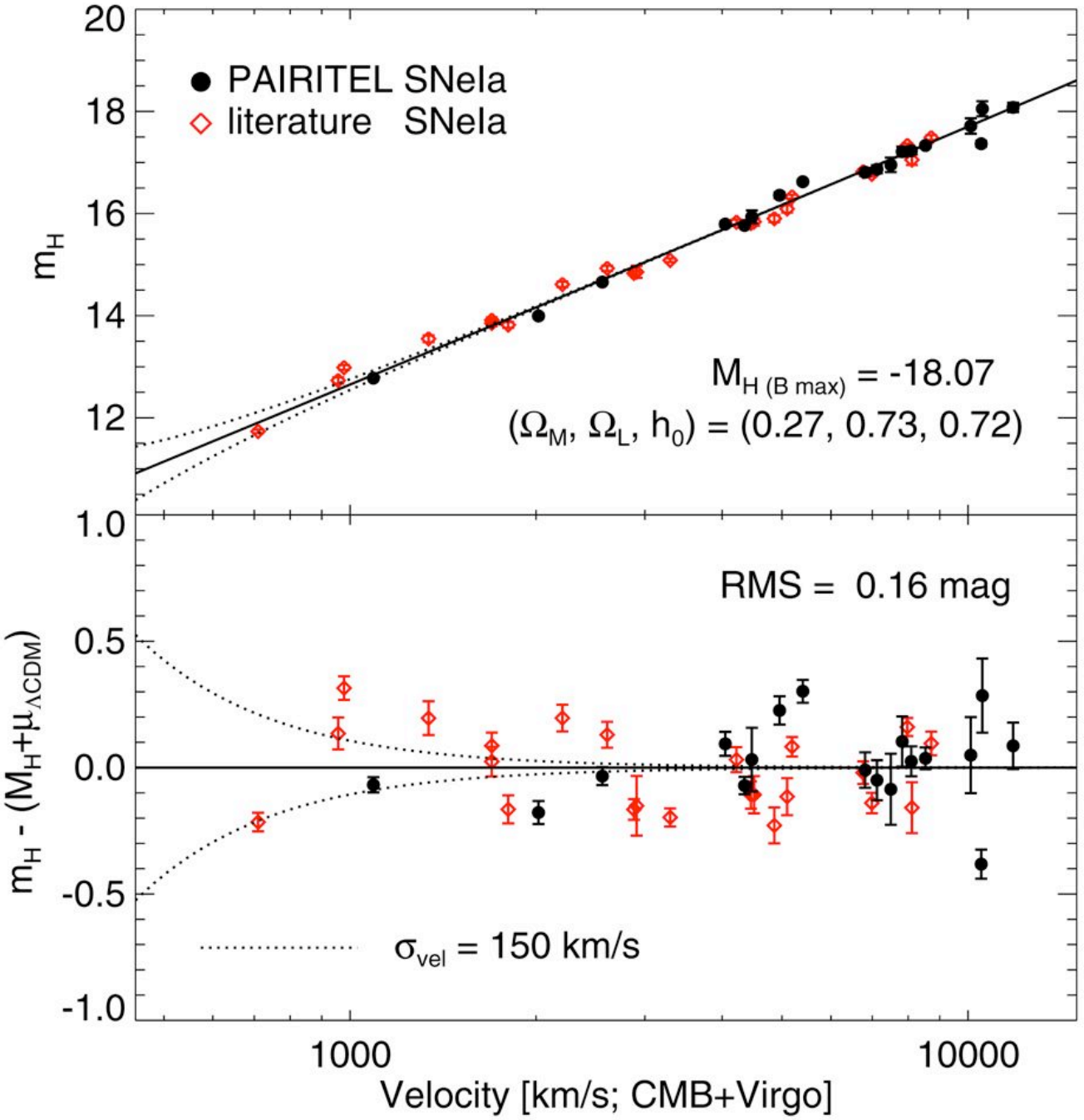
Theory by Dan Kasen (2006)- expect smallest variance in the IR: Pioneering work by Krisciunas & CTIO group shows this is actually true!

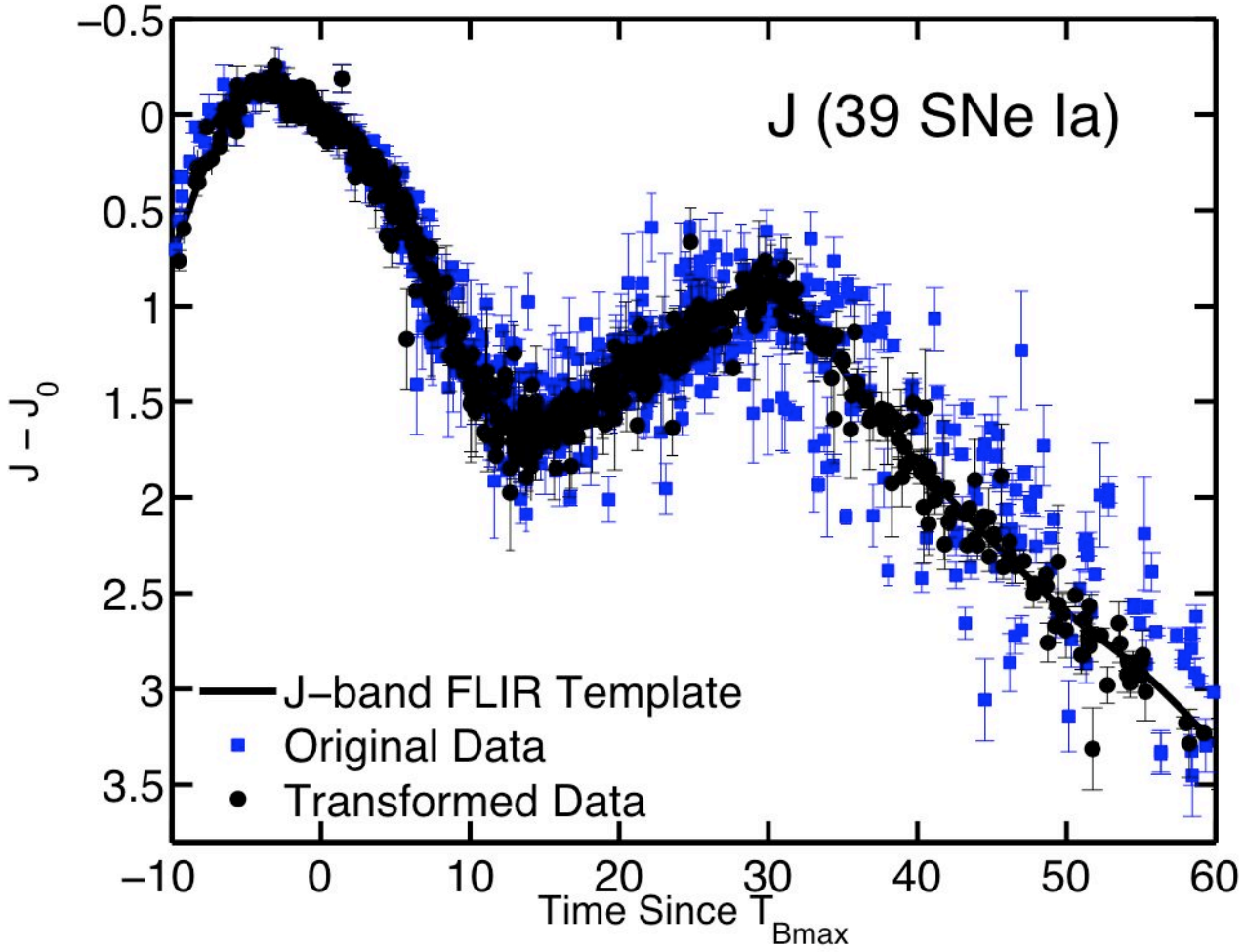
PAIRITEL (former 2MASS) revived by Josh Bloom (See Andy Friedman's poster)


S3
Make the measurements in the infrared!
SN 2006D
J, H, K_s image from PAIRITEL

Wood-Vasey et al. ApJ 689, 377 (2008)

NIR data only

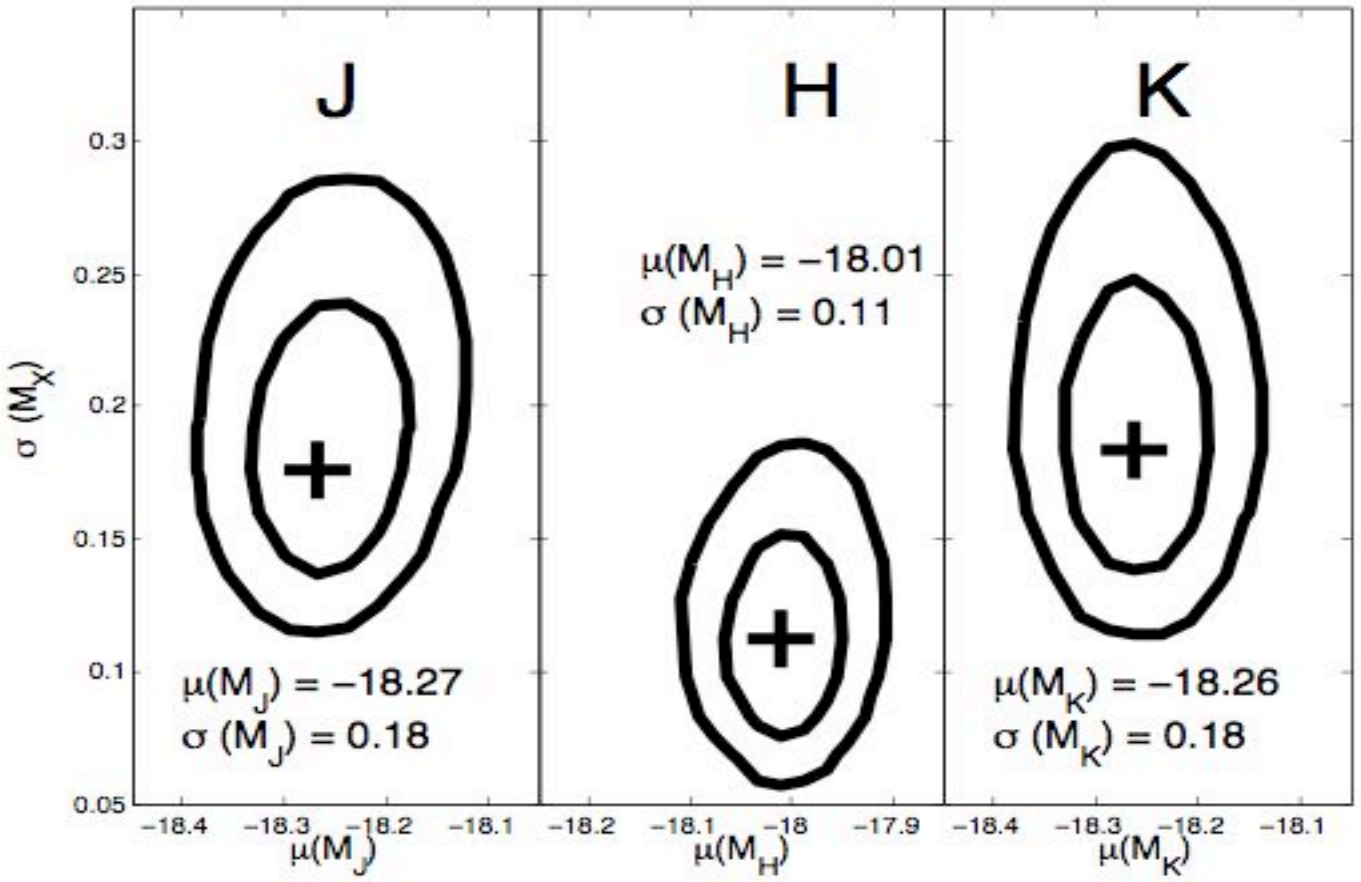




Next Step:

Better templates and BayeSN inference : Kaisey Mandel

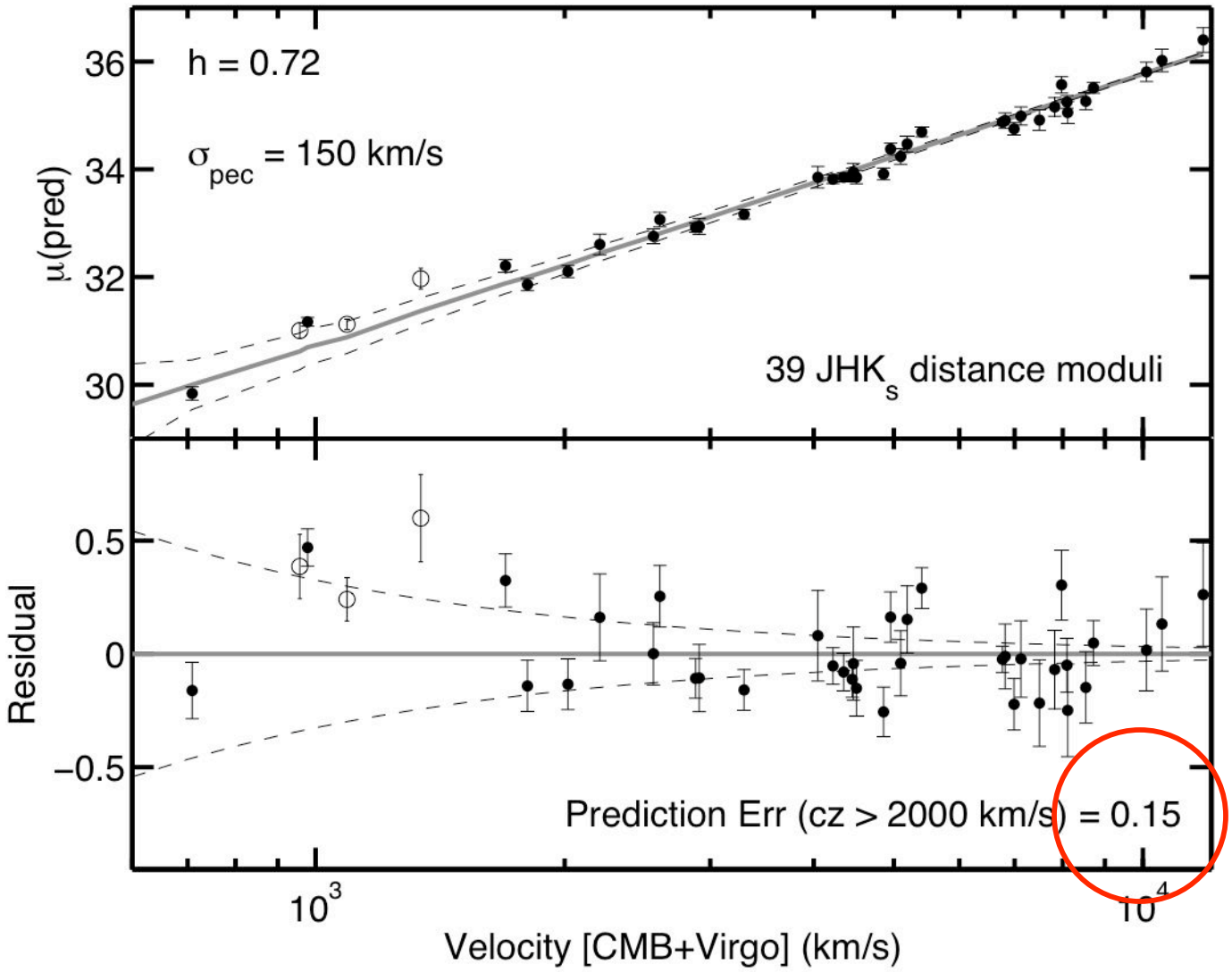
ApJ (accepted) arxiv:0908.0536



Life imitates art: facts mirror theory

H-band (1.6 microns) works best

Training and Prediction

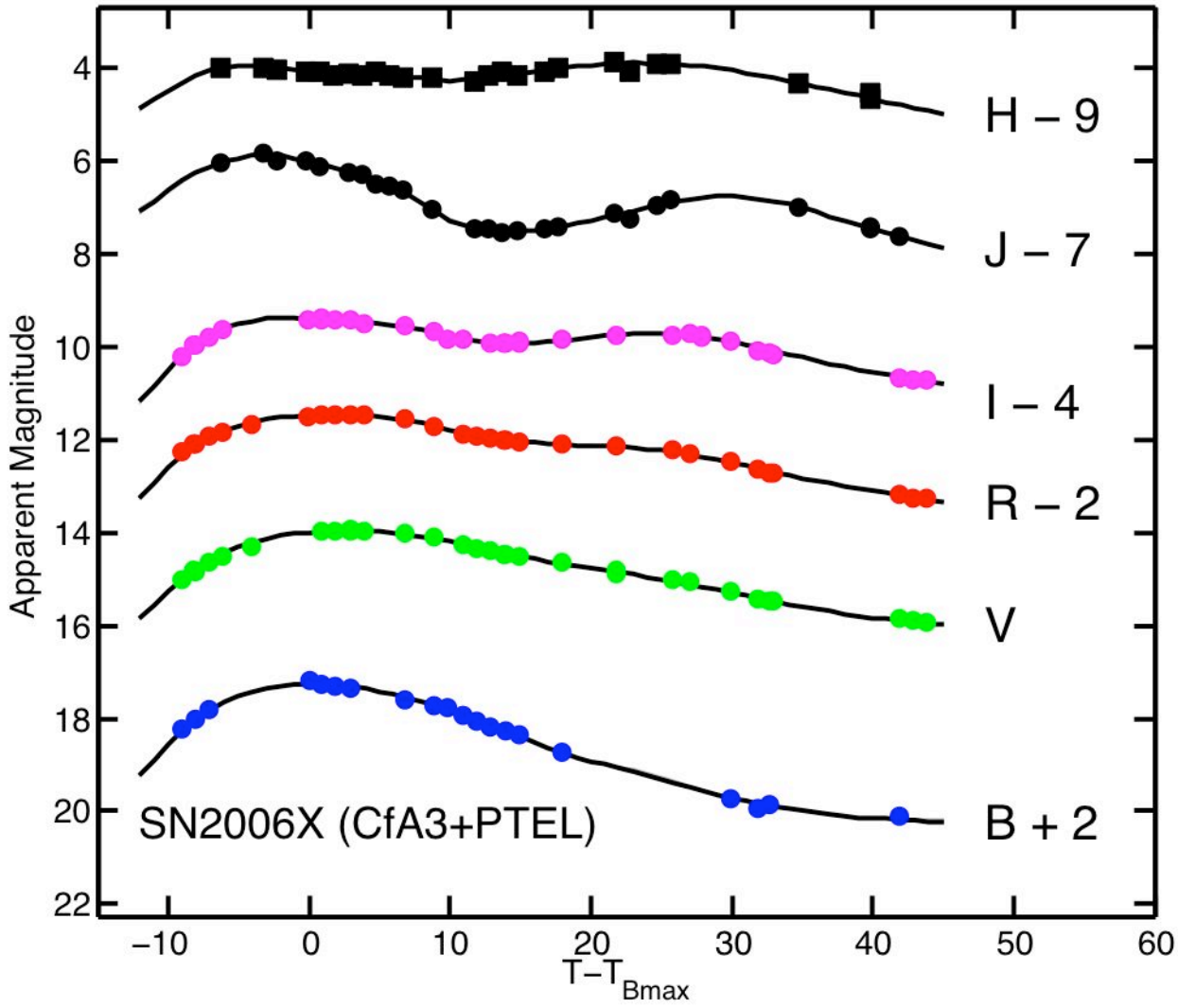


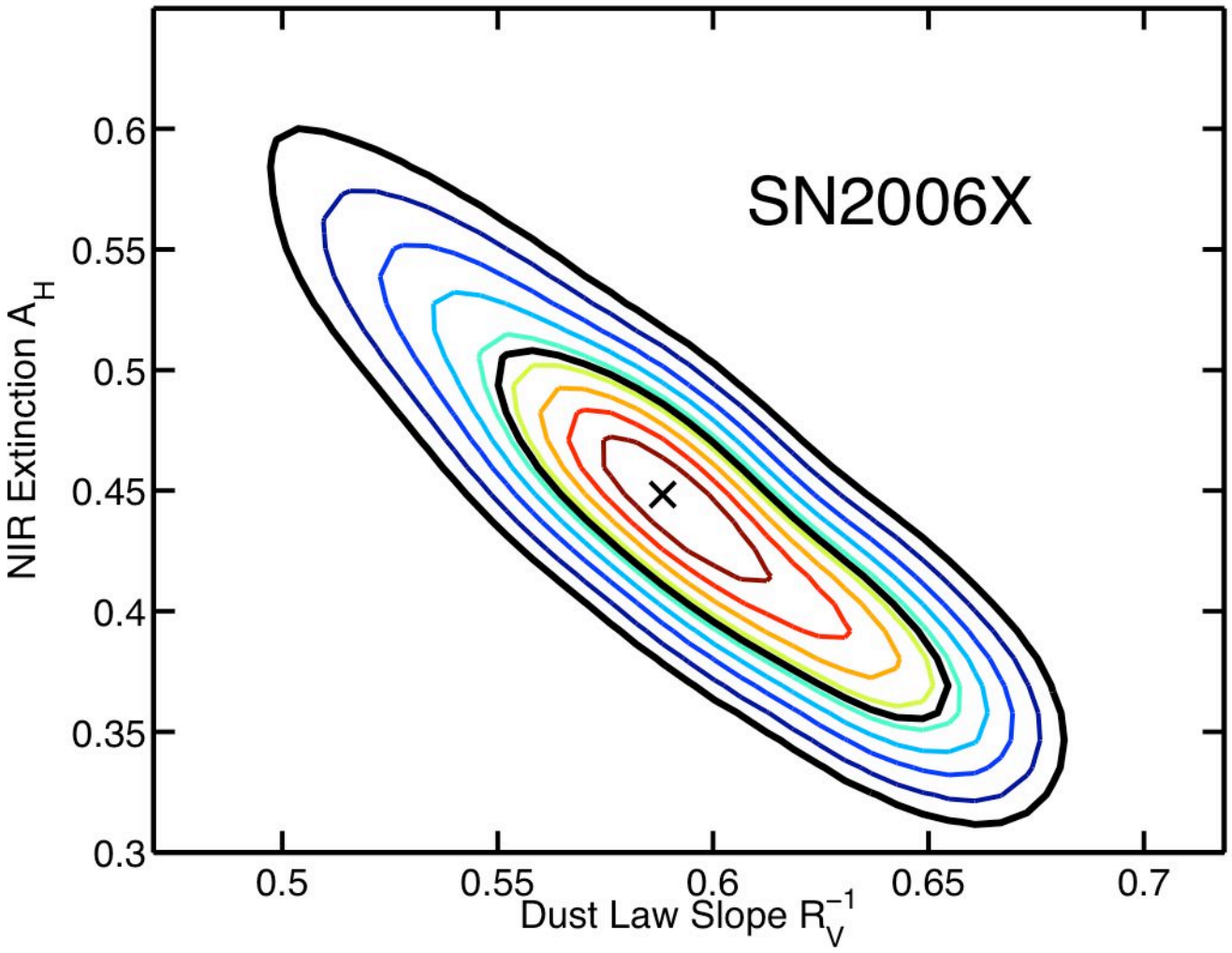
Why not include IR + Optical?

Get better distances & learn about properties of the dust by using observations over the range from B (0.4 μ) to K (2.2μ)

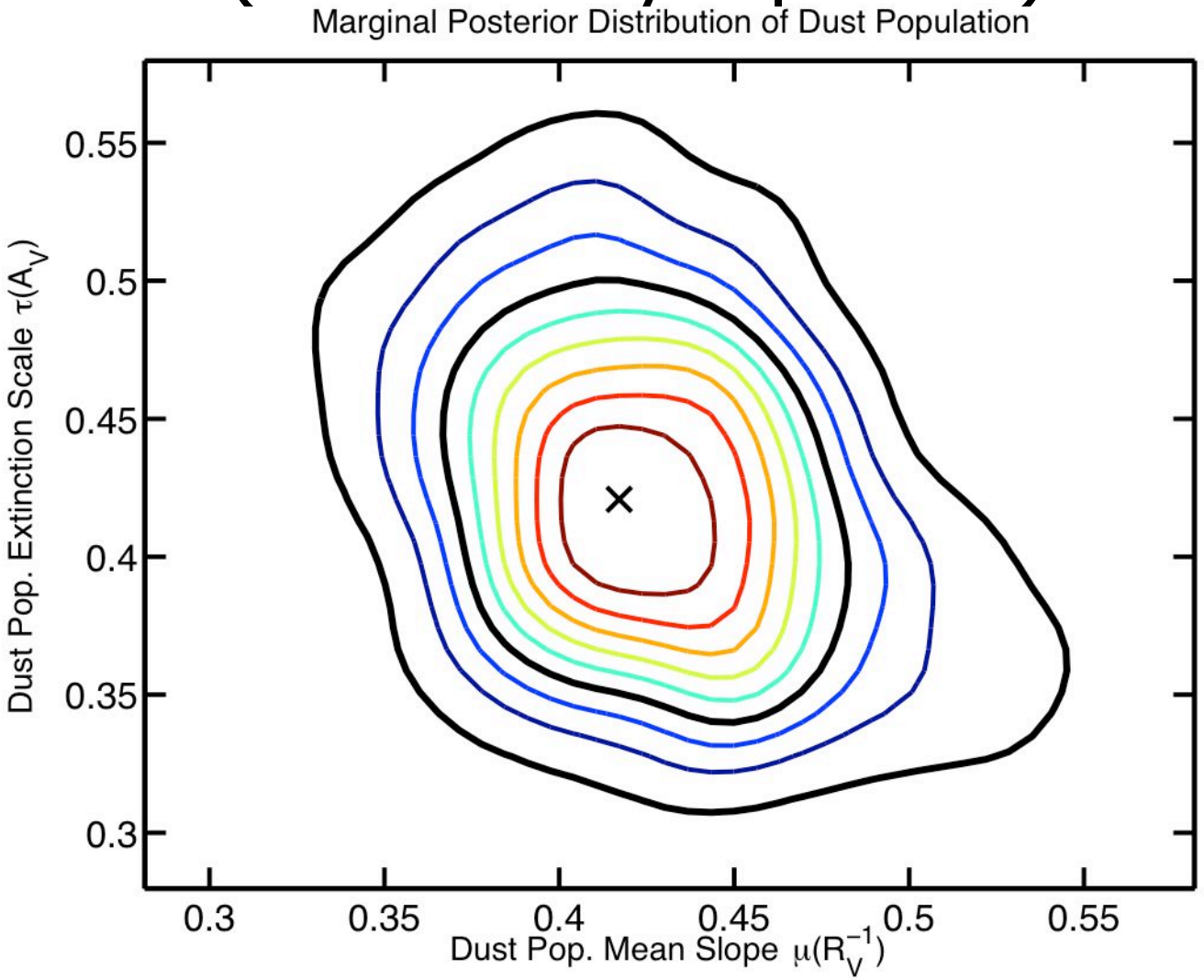
We want to know the ratio of absorption to color change (we measure colors but want to know absorption)

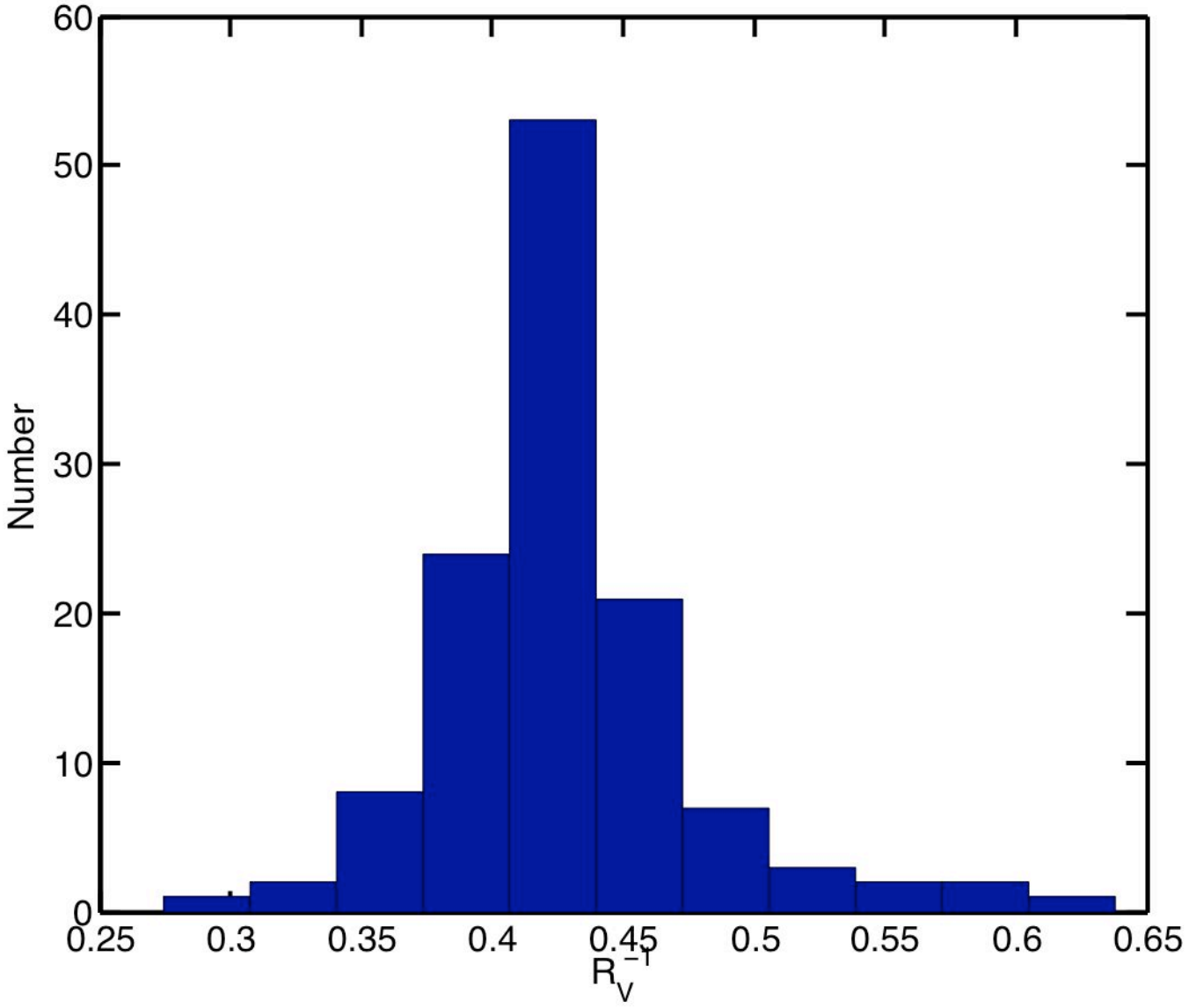
Milky Way dust R_v = 3.1 =A_v/ E(B-V), but the hints are that SN dust is not the same (R_v = 1.7 !)

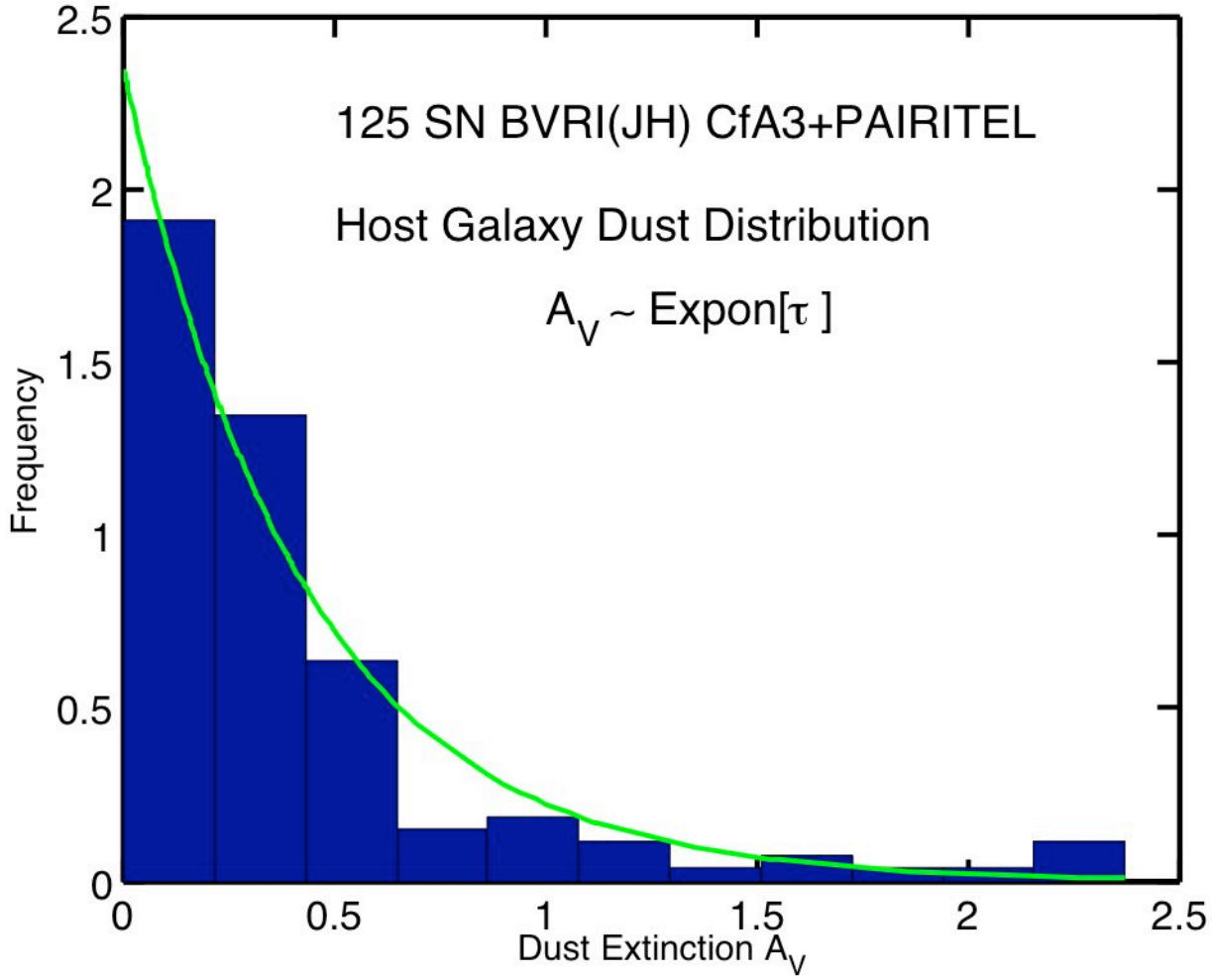

Apparent Magnitude
4
6
8
10
12
14
16
18
20
22
−10
0
10
20
30
40
50
60
T−T_Bmax
H − 9
J − 7
I − 4
R − 2
V
B + 2
SN2006X (CfA3+PTEL)


SN2006X
NIR Extinction A_H
Dust Law Slope R_V^{-1}
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.5
0.55
0.6
0.65
0.7

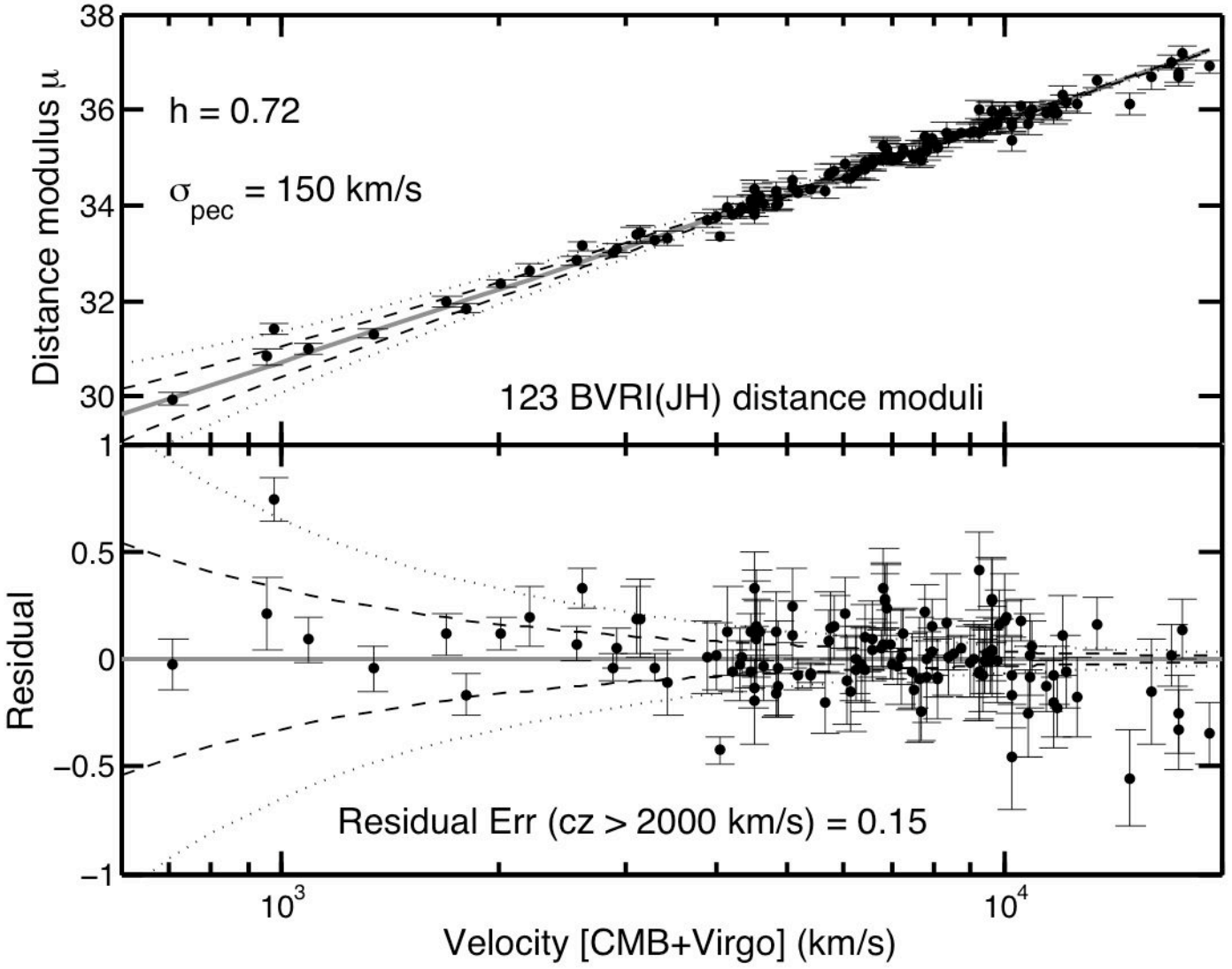
Dust properties for CfA3 (see Kaisey's poster)



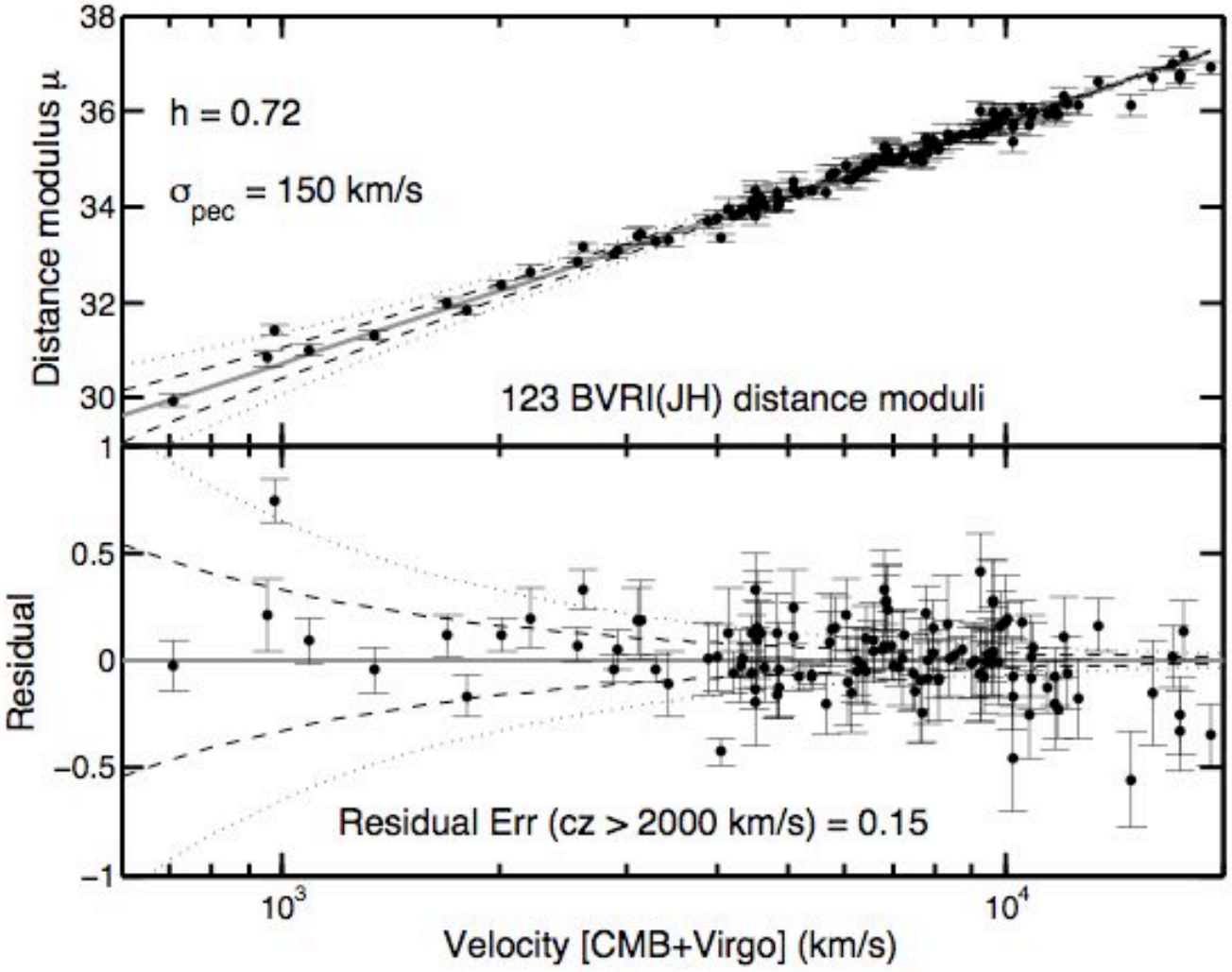

60
50
40
30
20
10
0
Number
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
R_V^{-1}


125 SN BVRI(JH) CfA3+PAIRITEL
Host Galaxy Dust Distribution
$A_V \sim \text{Expon}[\tau]$
Frequency
Dust Extinction A_V
0
0.5
1
1.5
2
2.5

The Payoff


Distance modulus μ
h = 0.72
σpec = 150 km/s
123 BVRI(JH) distance moduli
Residual
Residual Err (cz > 2000 km/s) = 0.15
Velocity [CMB+Virgo] (km/s)

The Payoff


Distance modulus μ
38
36
34
32
30
h = 0.72
σpec = 150 km/s
123 BVRI(JH) distance moduli
1
0.5
0
−0.5
−1
Residual
Residual Err (cz > 2000 km/s) = 0.15
10^3
10^4
Velocity [CMB+Virgo] (km/s)

PA**IR**ITEL
Current sample ~40
Andy's Thesis ~80-100
(See Andy's poster)

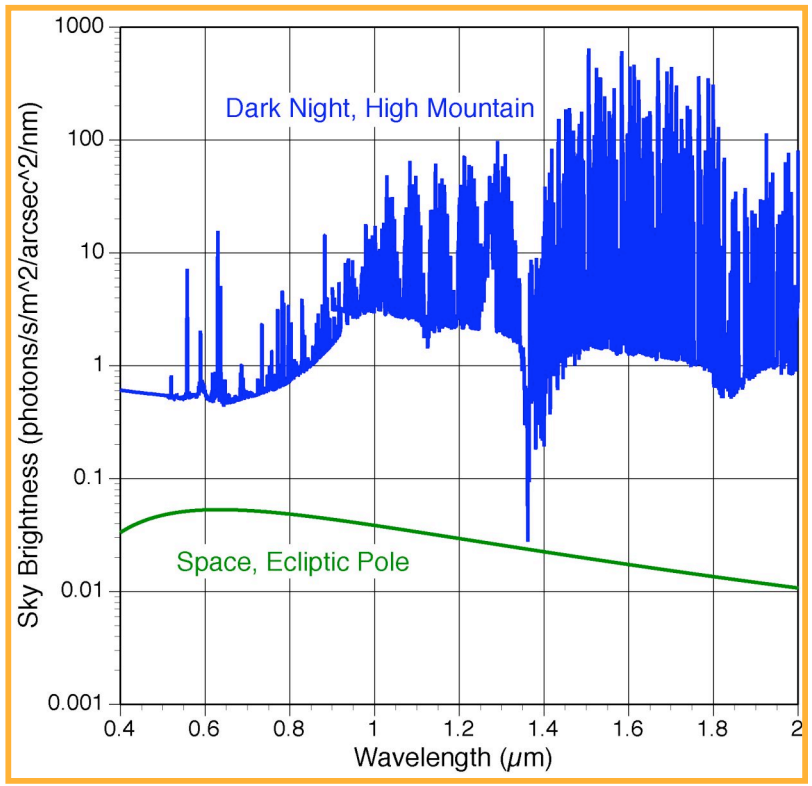
Only in space!

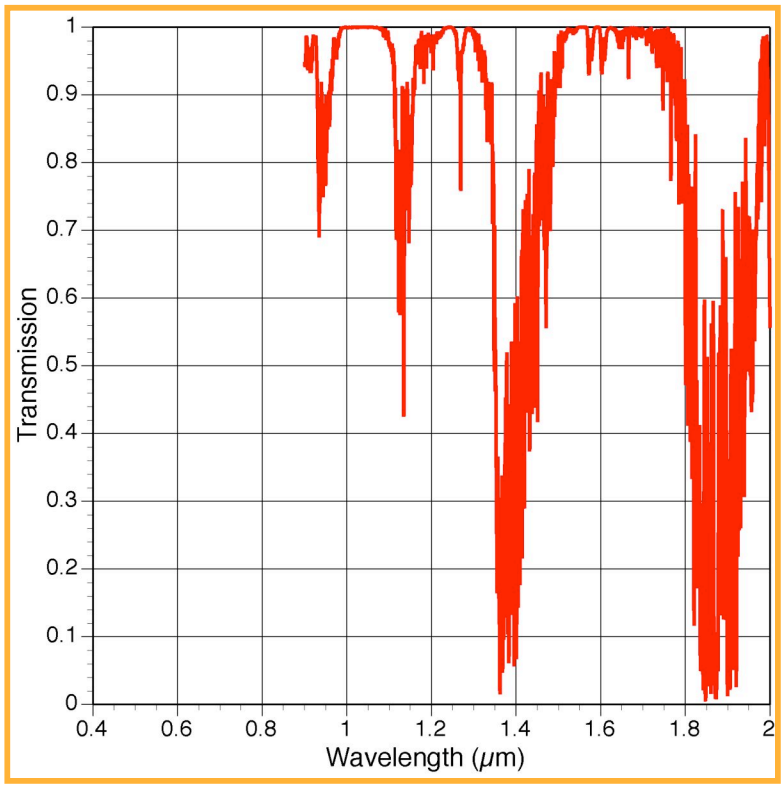
Rest frame IR measurements of z~1 supernovae are not possible from the ground (CSP was aiming at I-band, and this was very difficult)

Go as far into the IR as technically feasible!

Sky is very bright in NIR: >100x brighter than in space

Sky is not transparent in NIR: absorption due to water is very strong and extremely variable

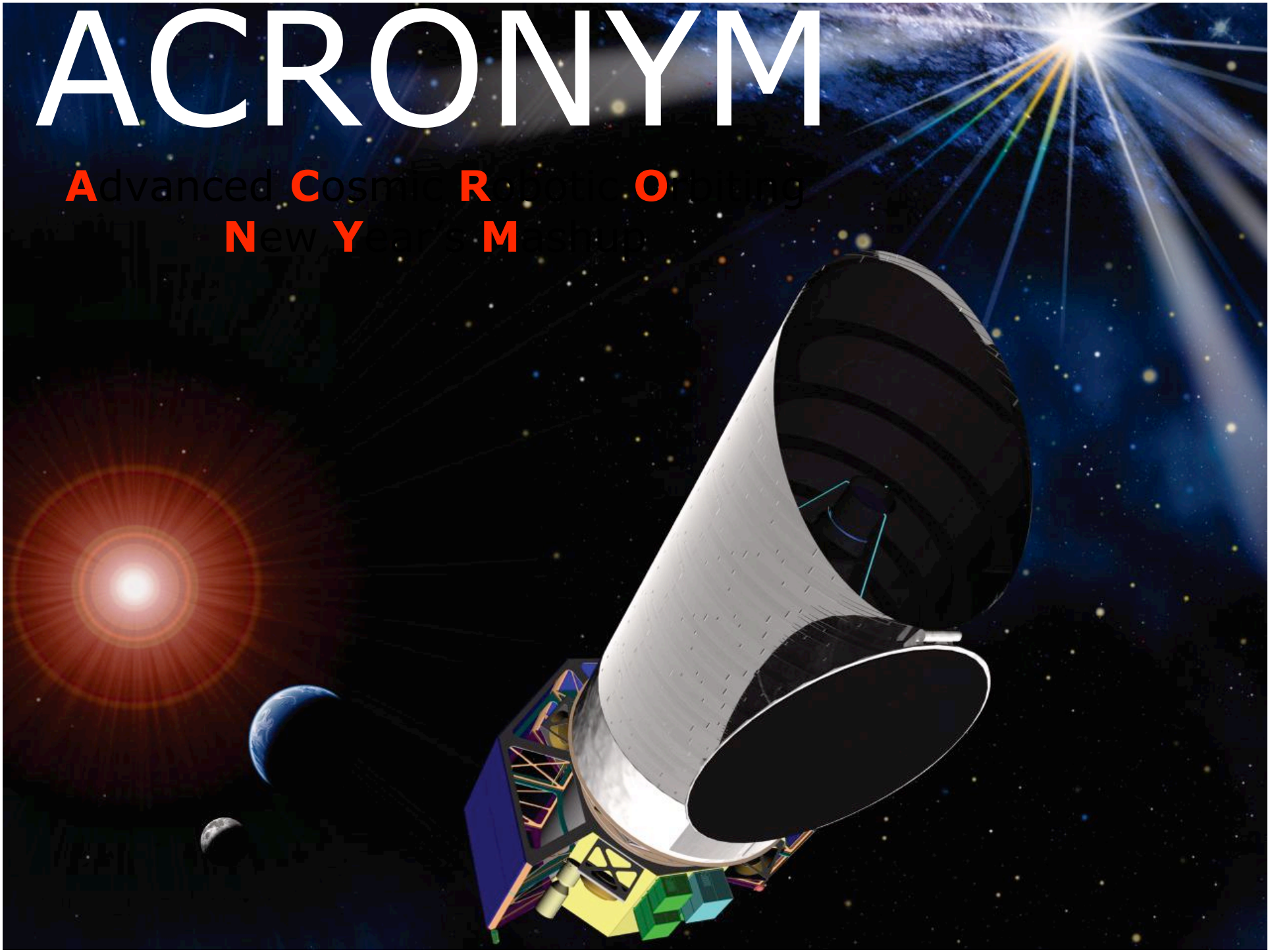





JDEM
Joint Dark
Energy Mission

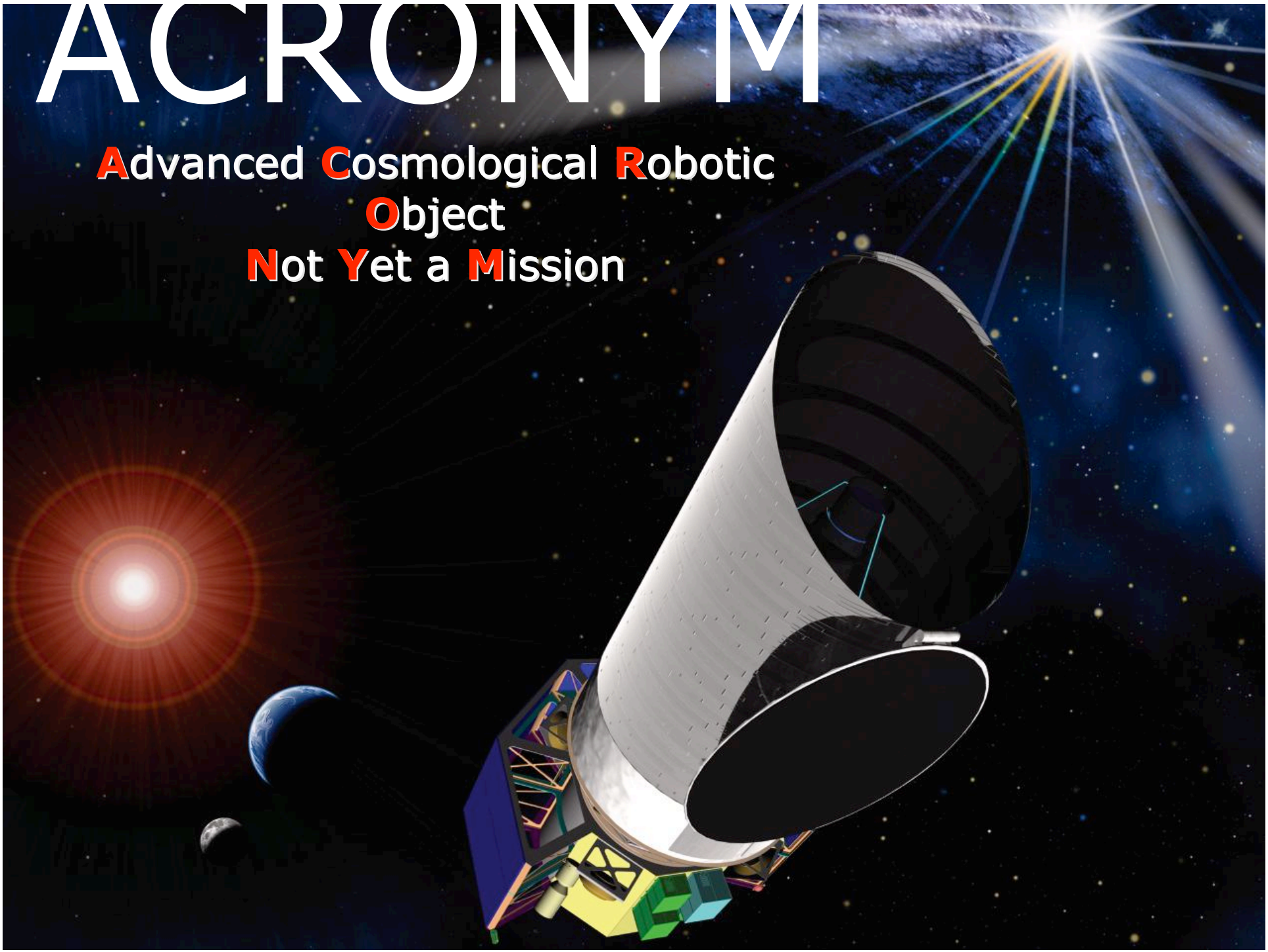
ACRONYM

Advanced **C**osmic **R**ay **O**bserving
New **Y**ork **M**ission

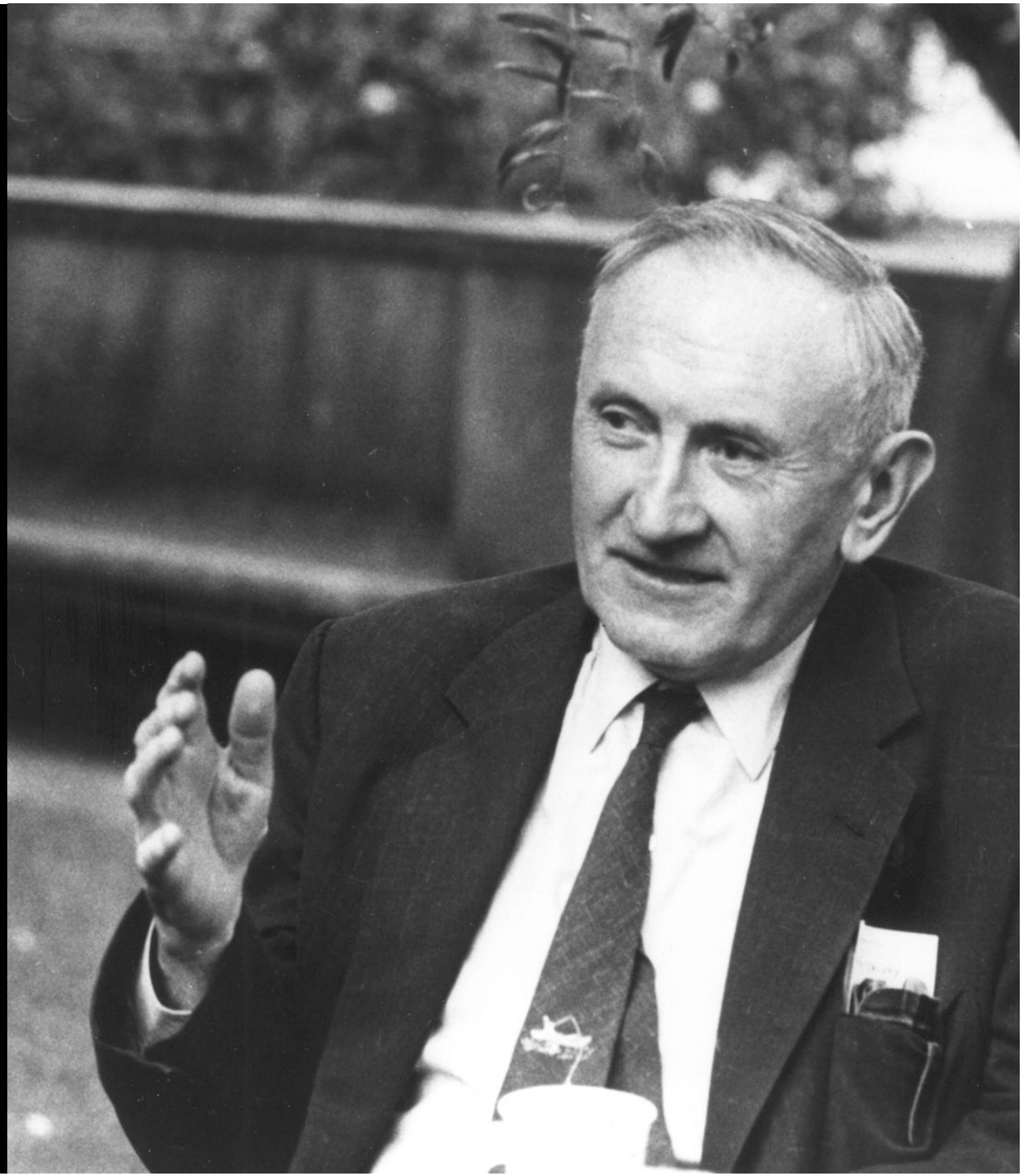


ACRONYM

Advanced **C**osmological **R**obotic
Object
Not **Y**et a **M**ission



Z
W




MAINE
AUG
0233161
XLR8N U
Vacationland
MAINE
08
6728349