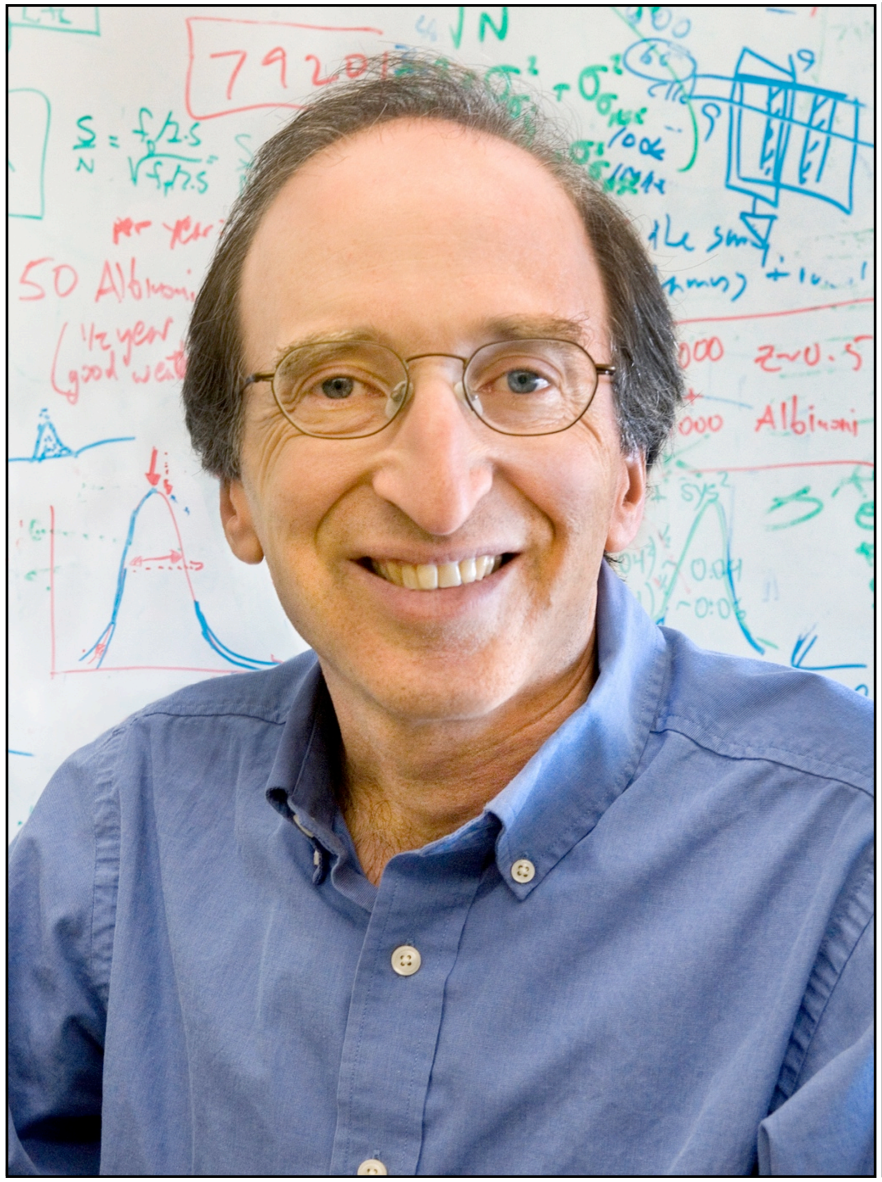
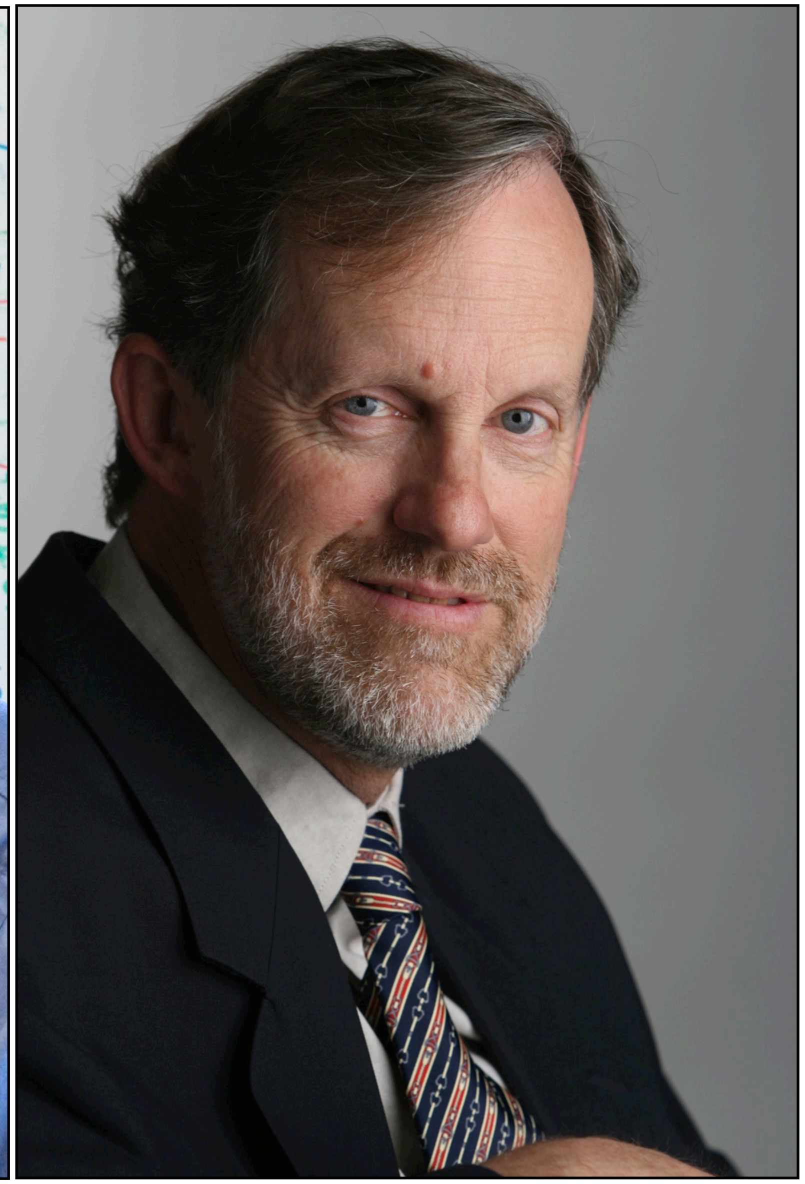
Carnegie Supernova Project

Eric Y. Hsiao
Aarhus University
Las Campanas Observatory

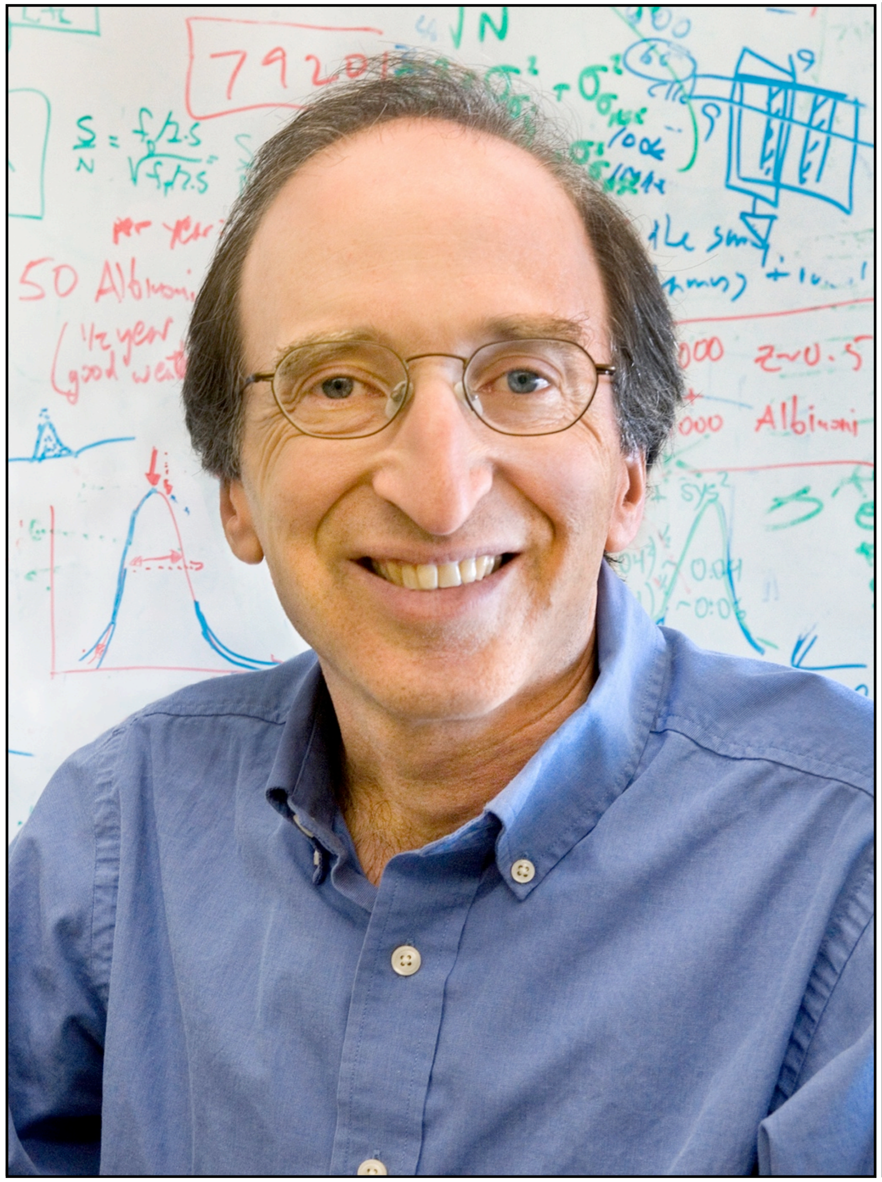


Saul Perlmutter
Lawrence Berkeley Laboratory

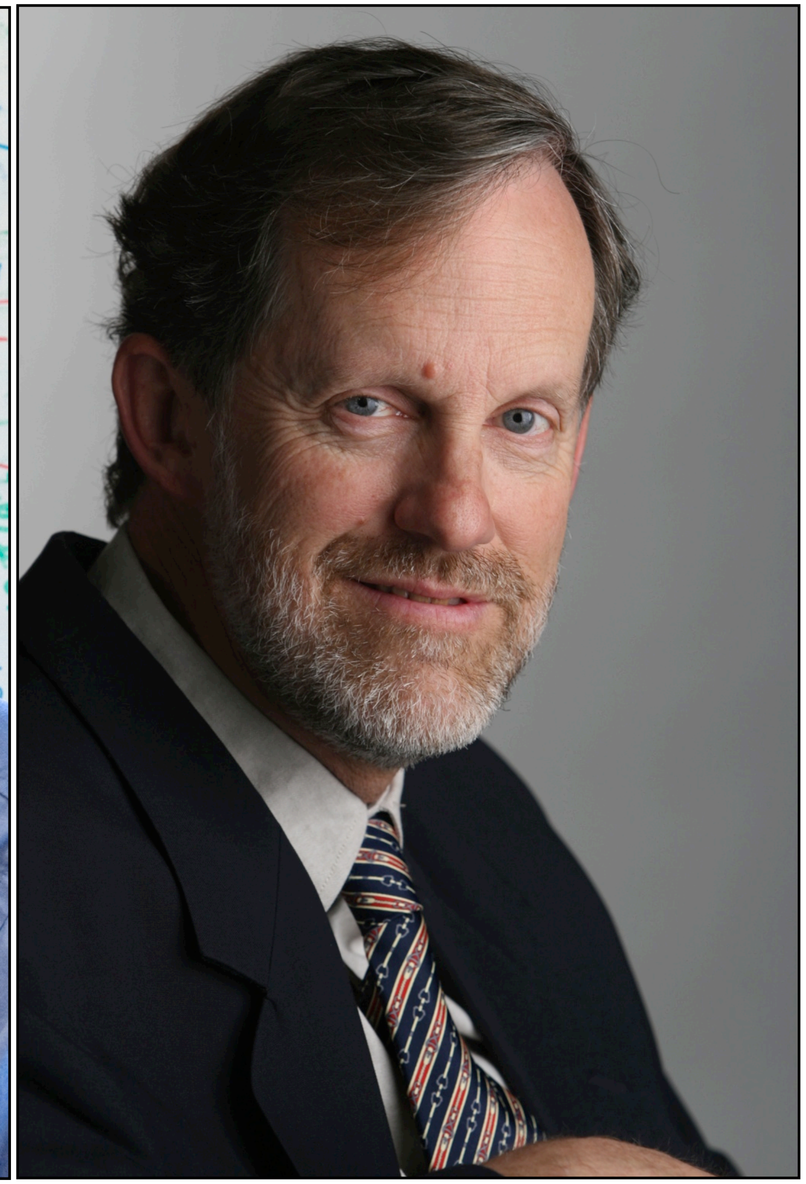


Mark Phillips
Las Campanas Observatory
Carnegie Observatories

Max Stritzinger
Aarhus University



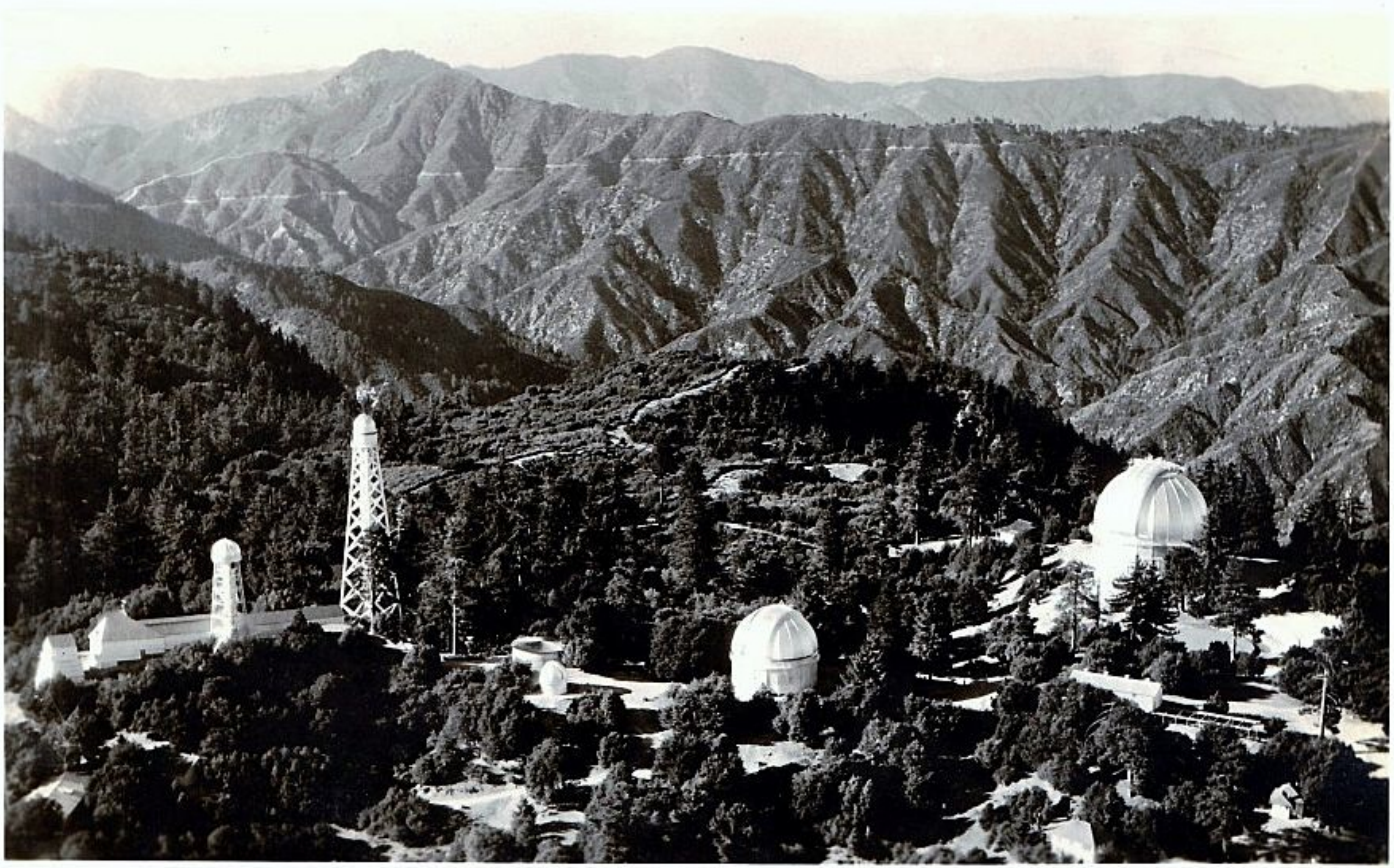
Boss #1



Boss #2

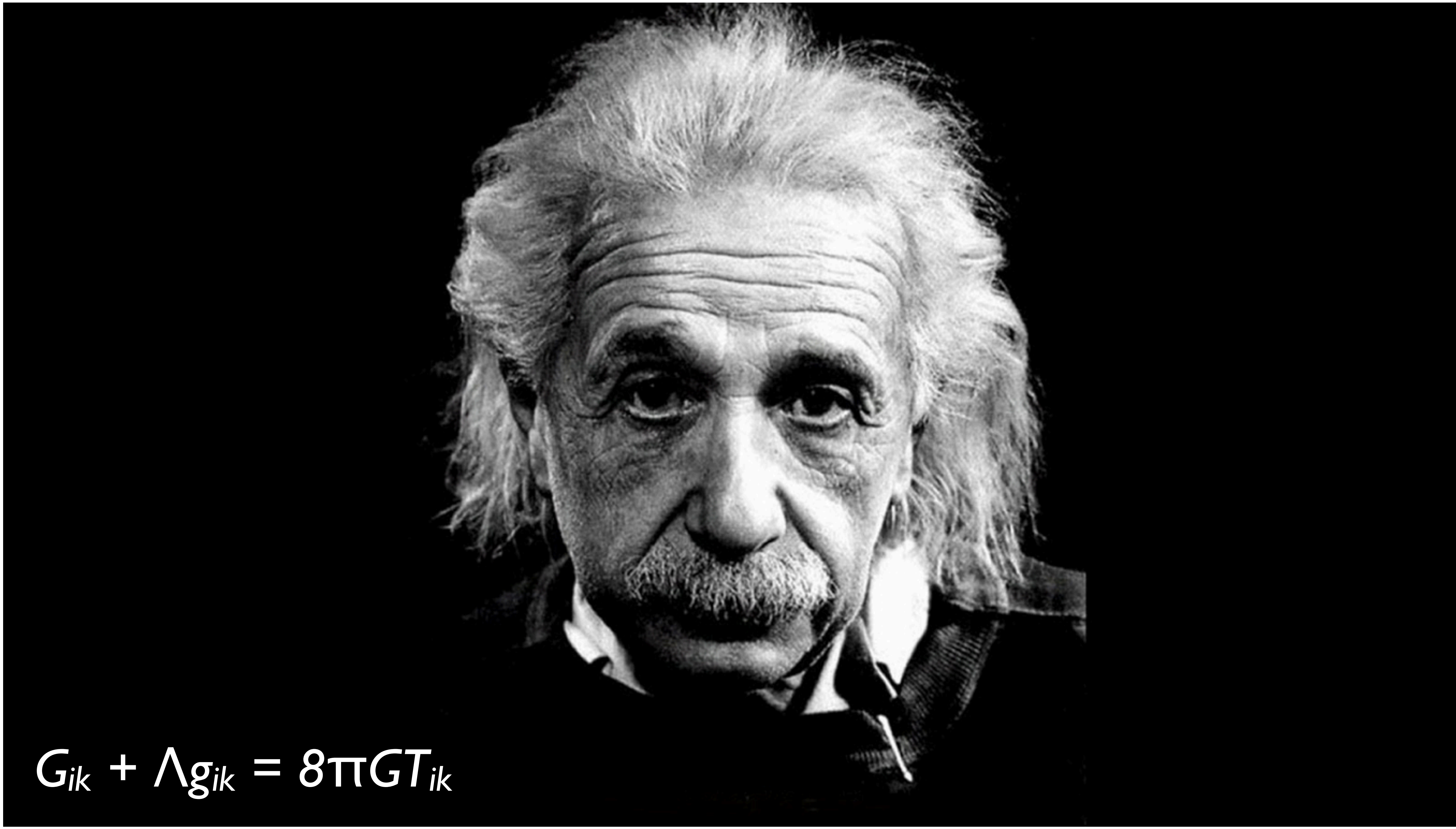
Boss #3

1904: Carnegie/Mt Wilson founded

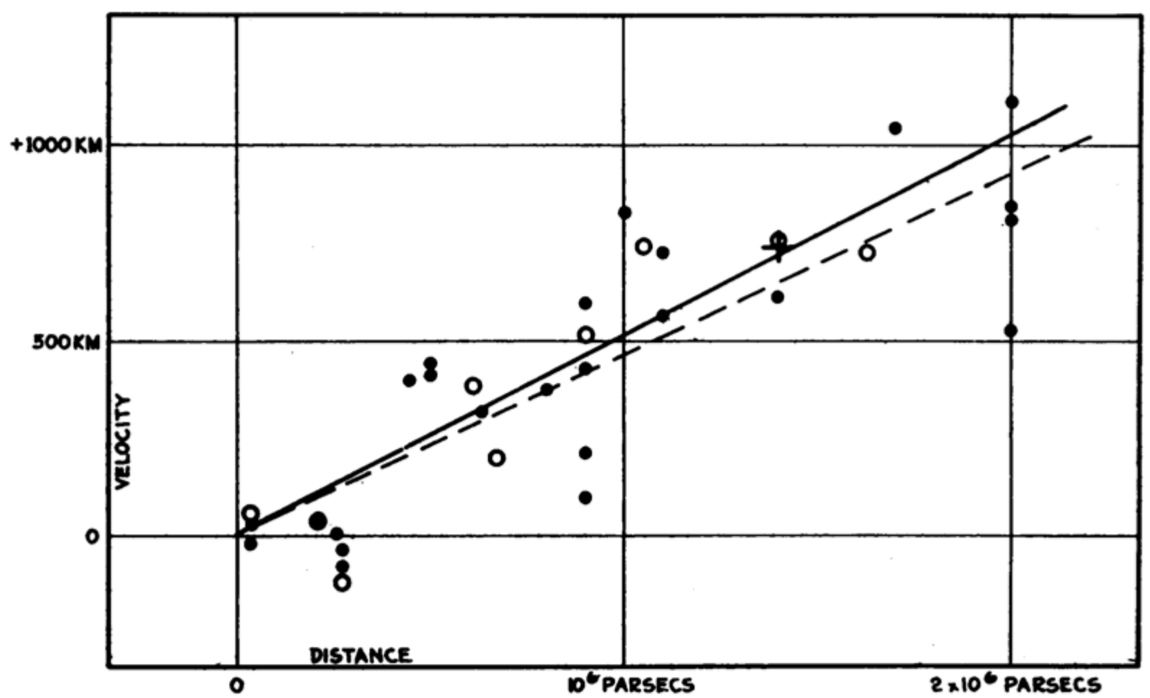


AIRVIEW MT. WILSON OBSERVATORY

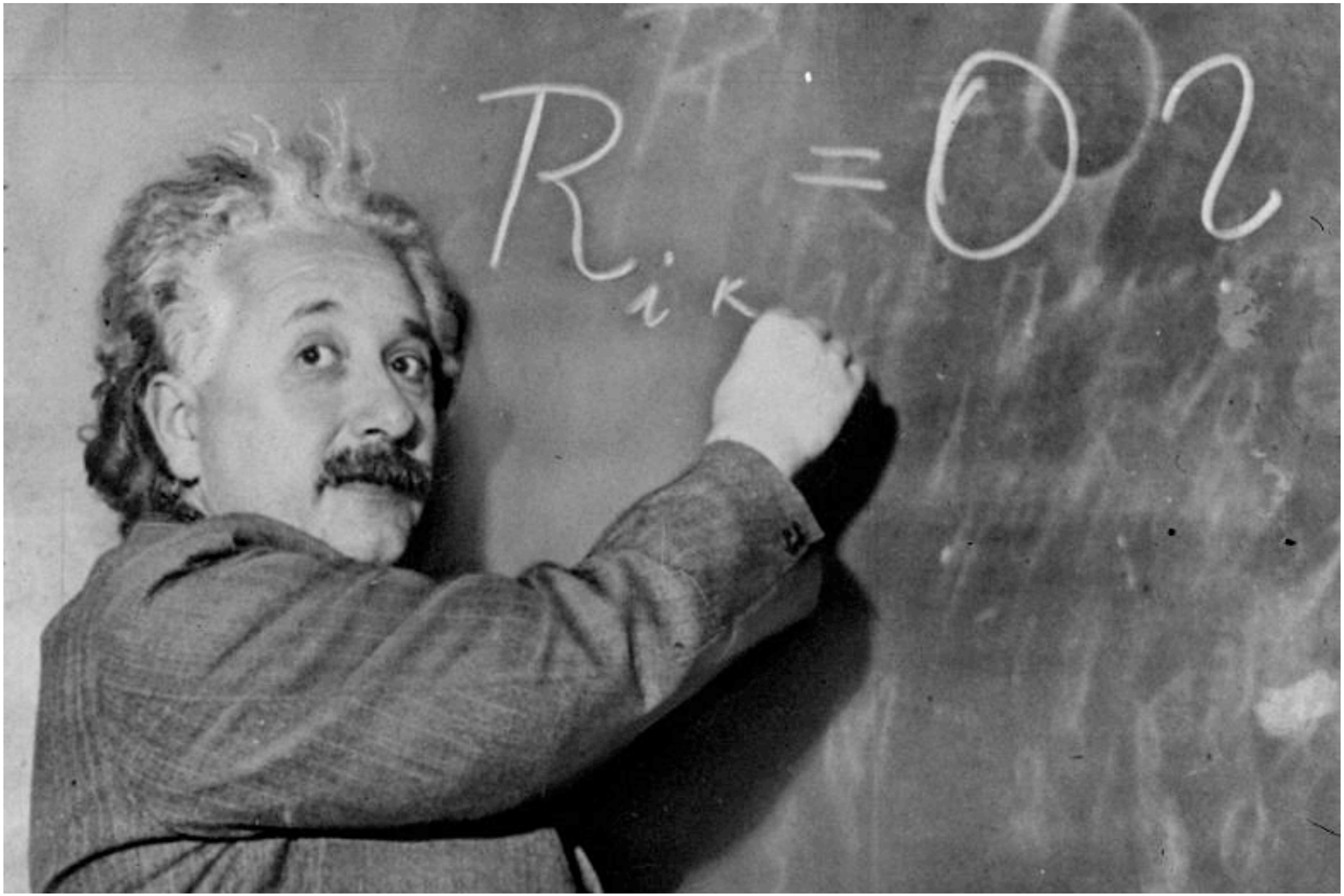
1917: General theory



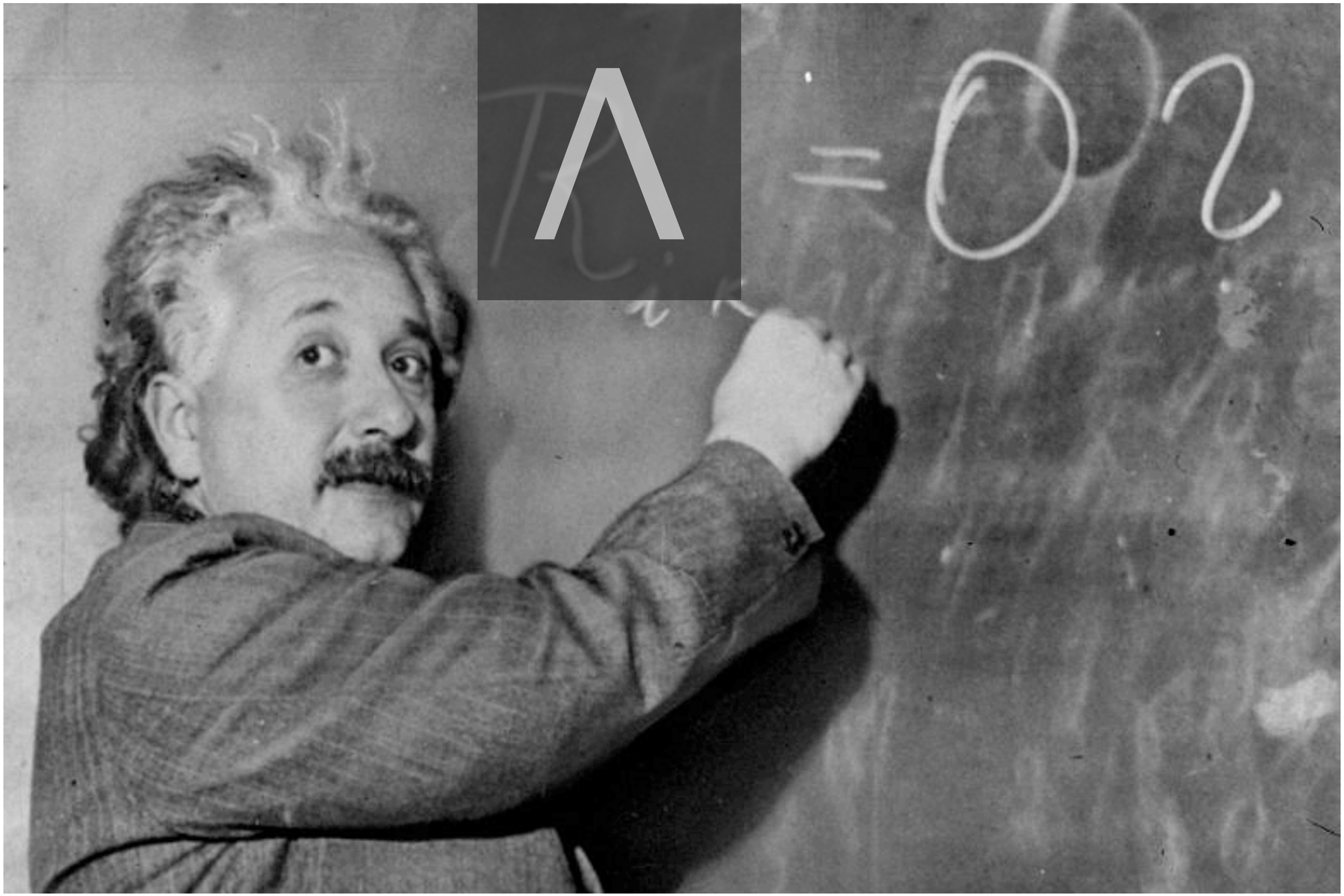
1929: Hubble law

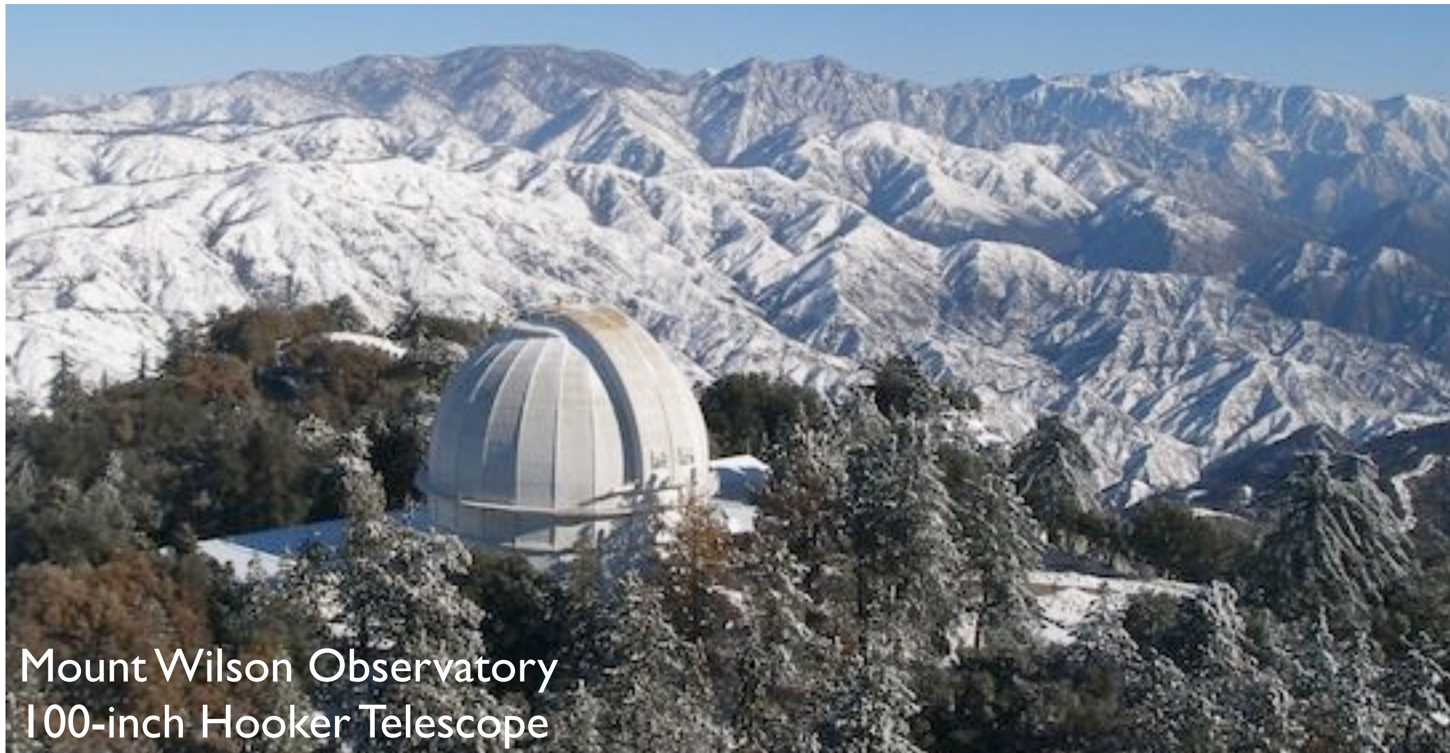


1931: Einstein's visit to Mt Wilson



1931: Einstein's visit to Mt Wilson



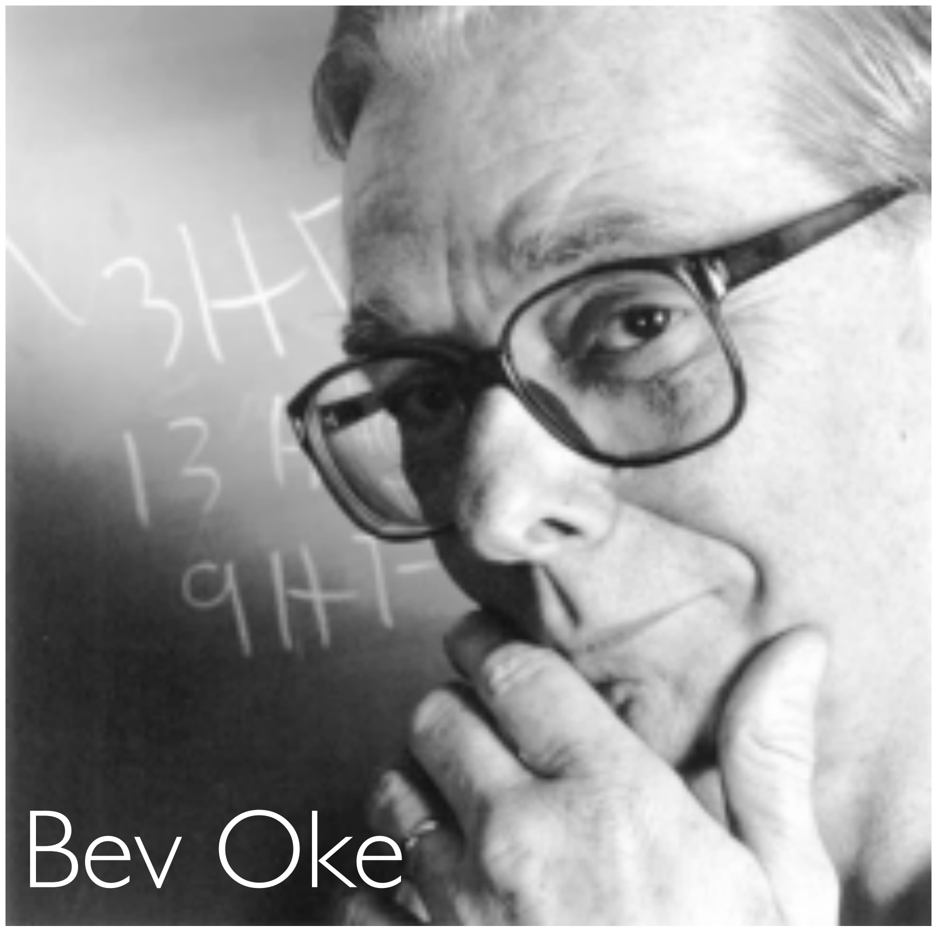


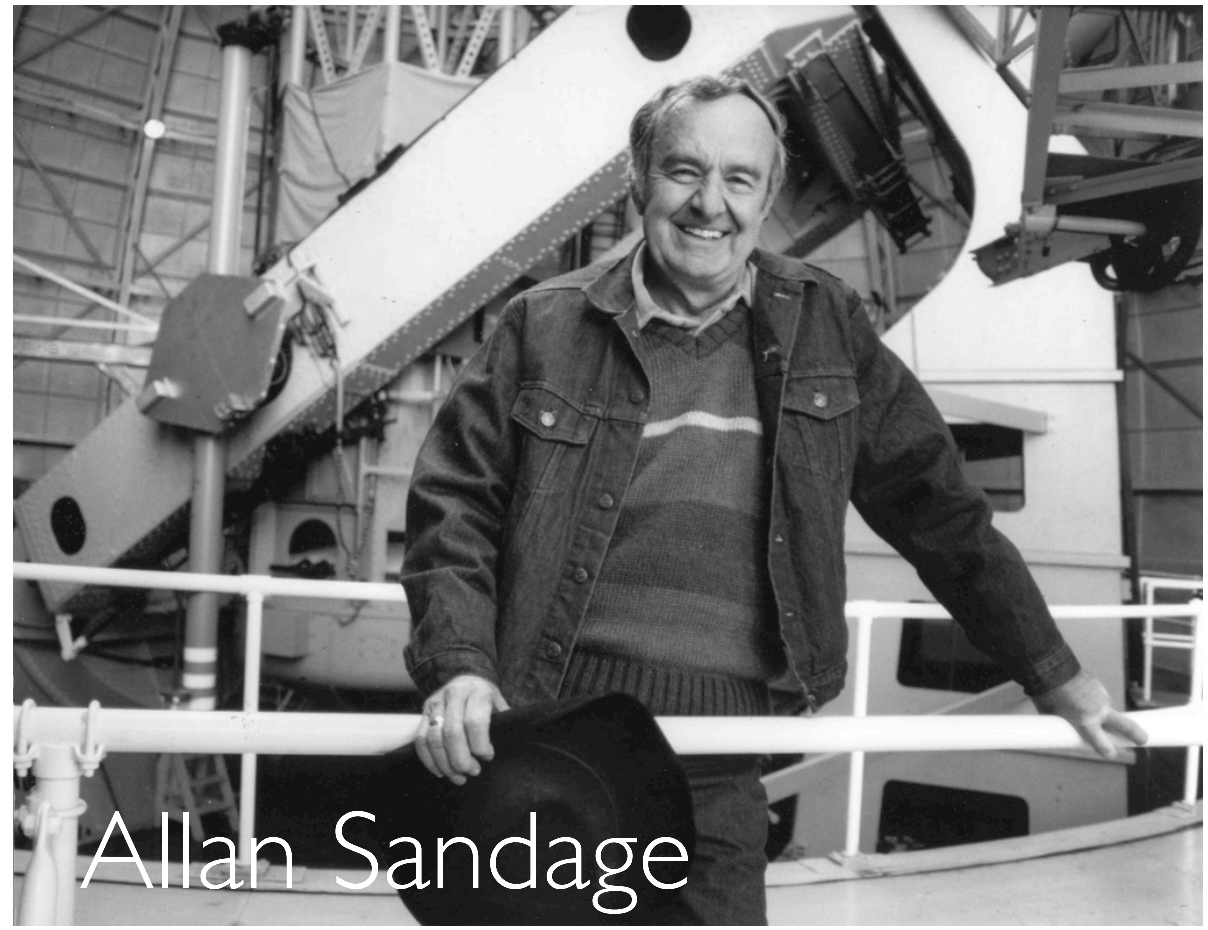
Mount Wilson Observatory
100-inch Hooker Telescope

Palomar Mountain Observatory
200-inch Hale Telescope

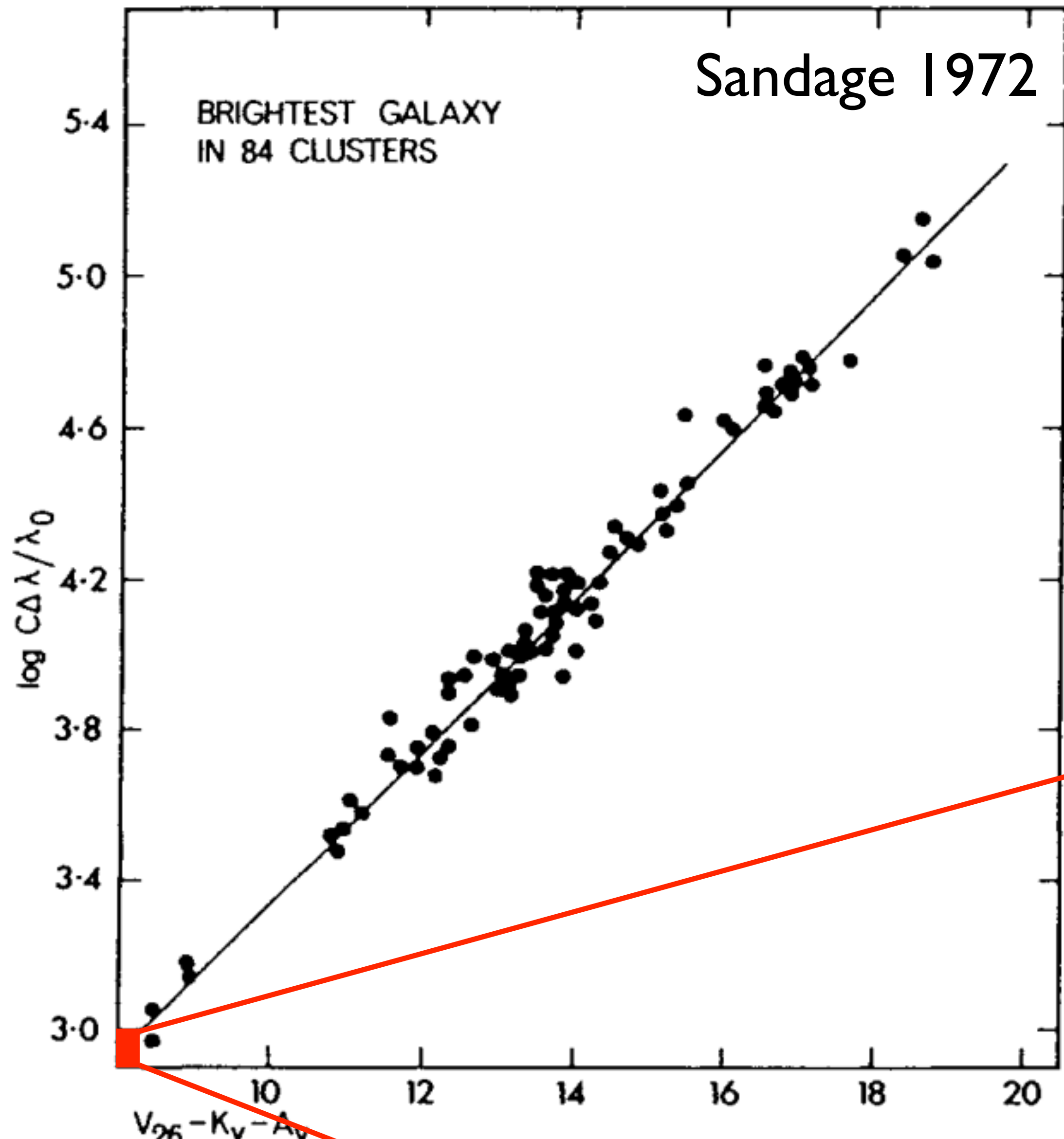
Las Campanas Observatory
6.5-m Magellan Telescopes

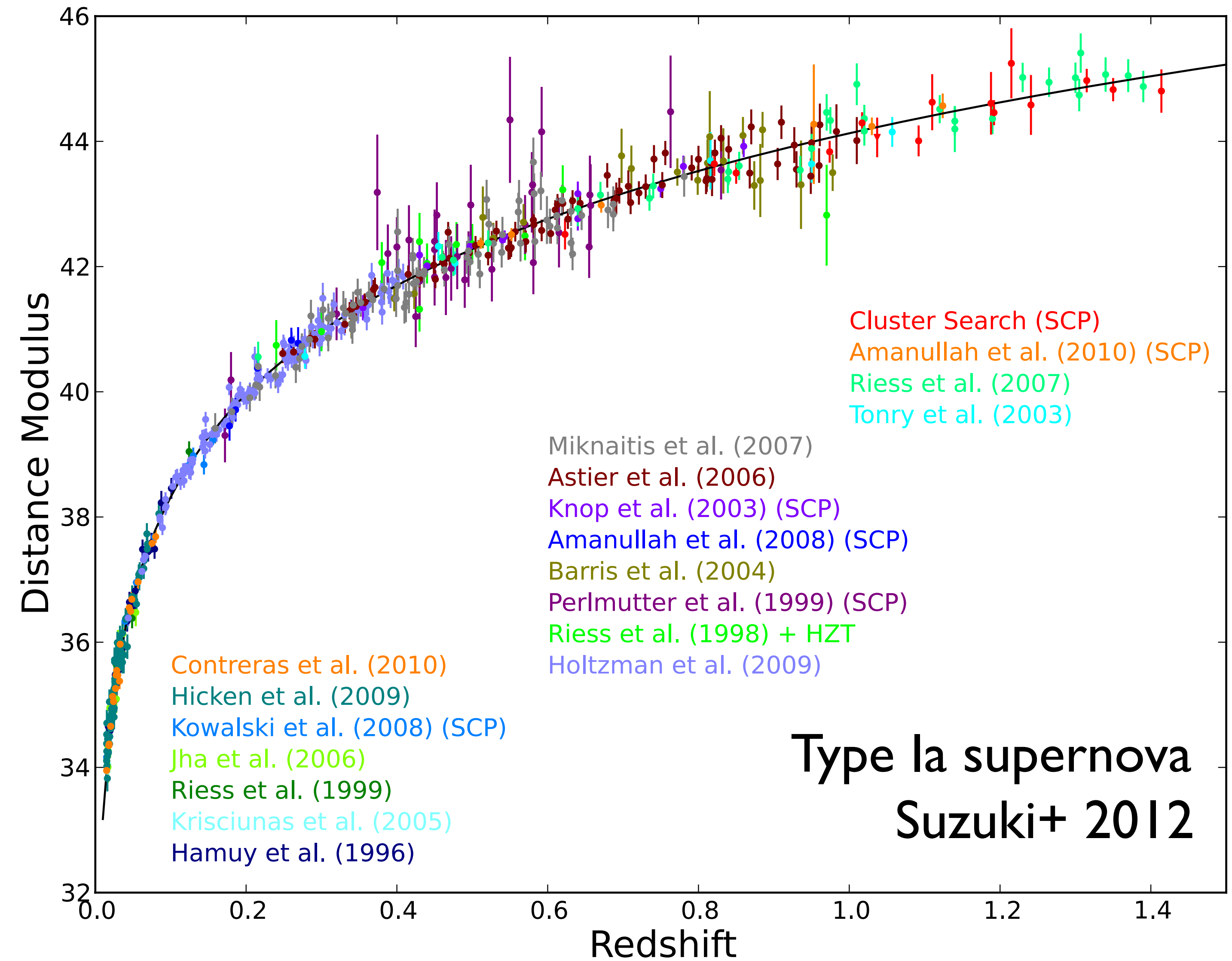
1968: k correction

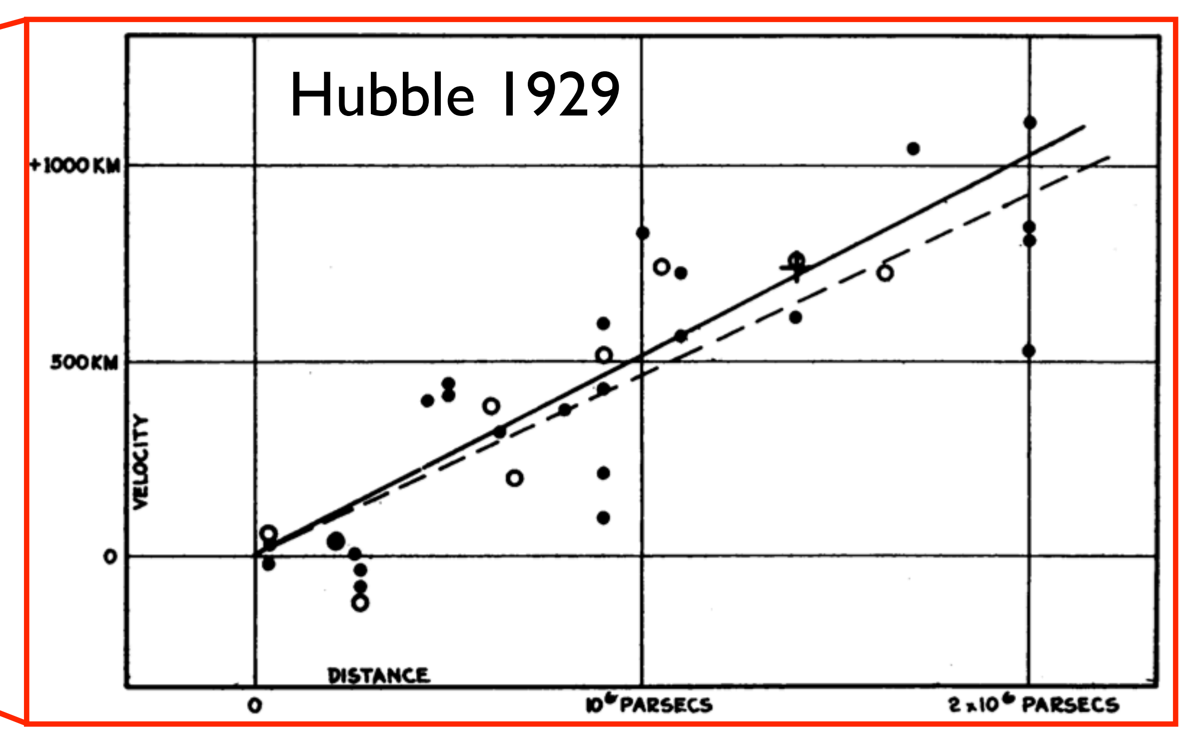


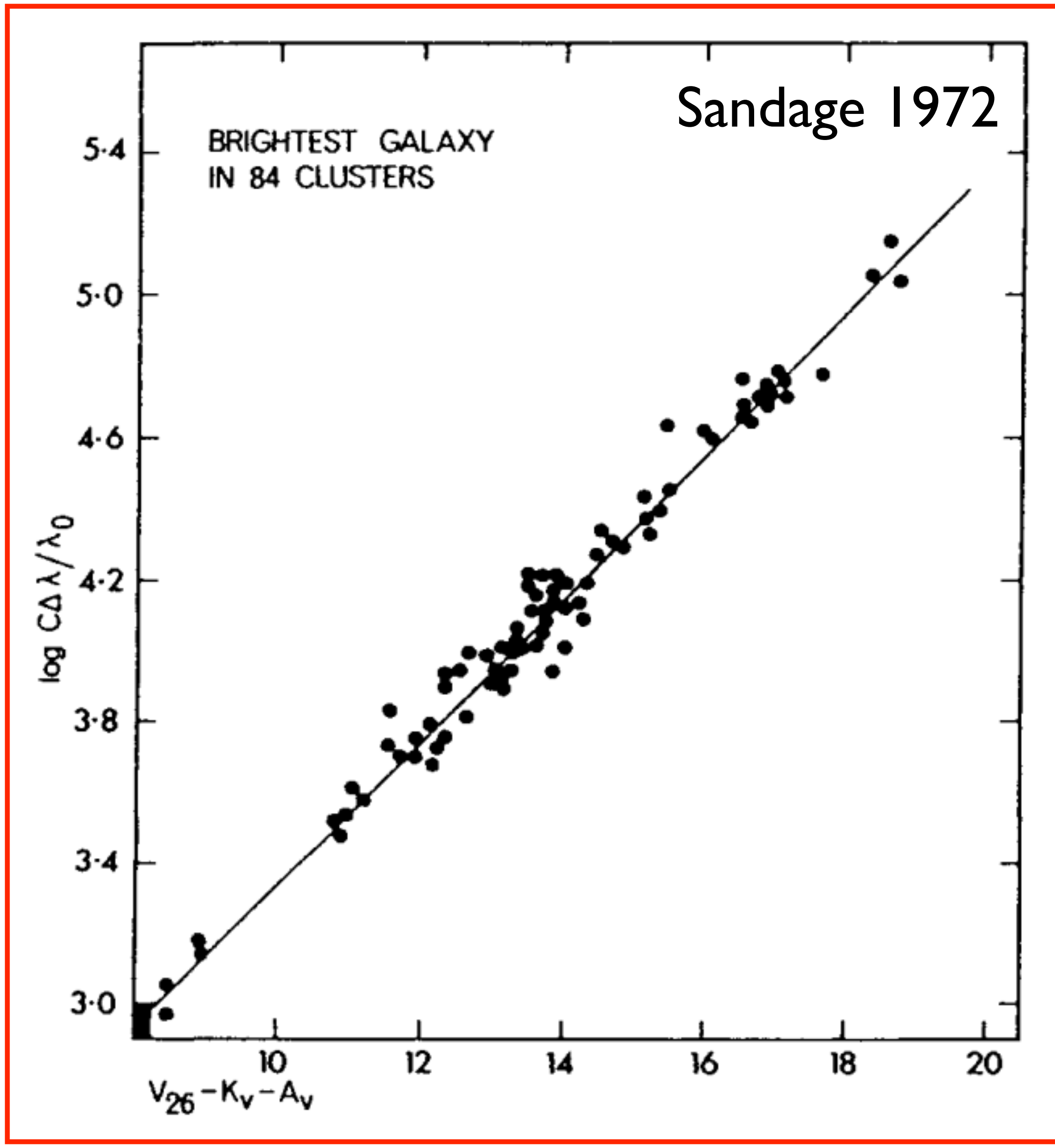


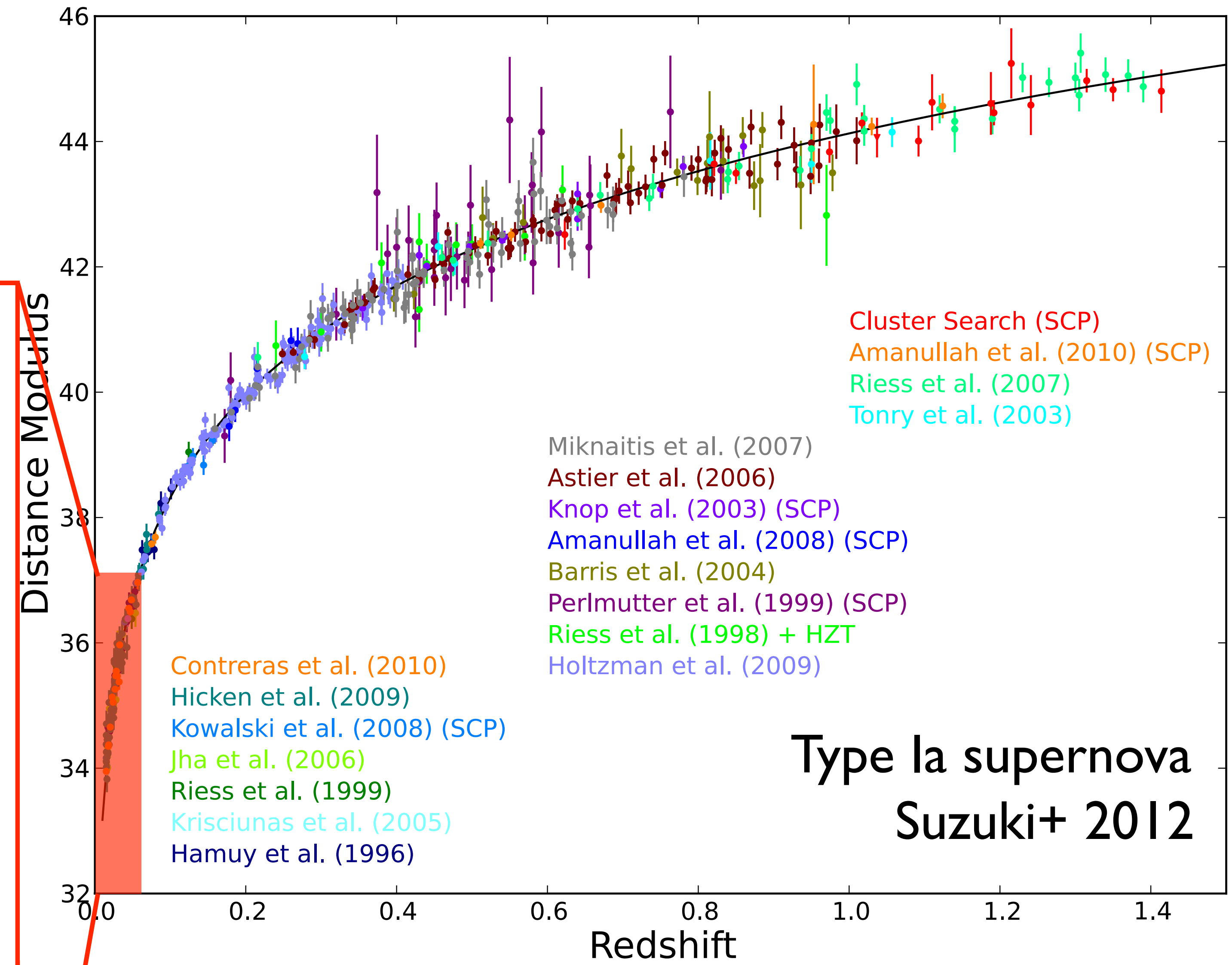
$$K_i = 2.5 \log (1 + z) + 2.5 \log \left\{ \int_0^\infty F(\lambda_0) S_i(\lambda) d\lambda \Big/ \int_0^\infty F[\lambda_0/(1+z)] S_i(\lambda) d\lambda \right\}$$


Sandage 1972
BRIGHTEST GALAXY
IN 84 CLUSTERS
log CΔλ/λ0
V26 - Kv - Av


Distance Modulus
Redshift
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)
Type Ia supernova
Suzuki+ 2012


Hubble 1929
+1000 KM
500 KM
VELOCITY
DISTANCE
10⁶ PARSECS
2×10⁶ PARSECS


Sandage 1972
BRIGHTEST GALAXY
IN 84 CLUSTERS
log CΔλ/λ0
V26 − Kv − Av
3·0
3·4
3·8
4·2
4·6
5·0
5·4
10
12
14
16
18
20


Distance Modulus
Redshift
32
34
36
38
40
42
44
46
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
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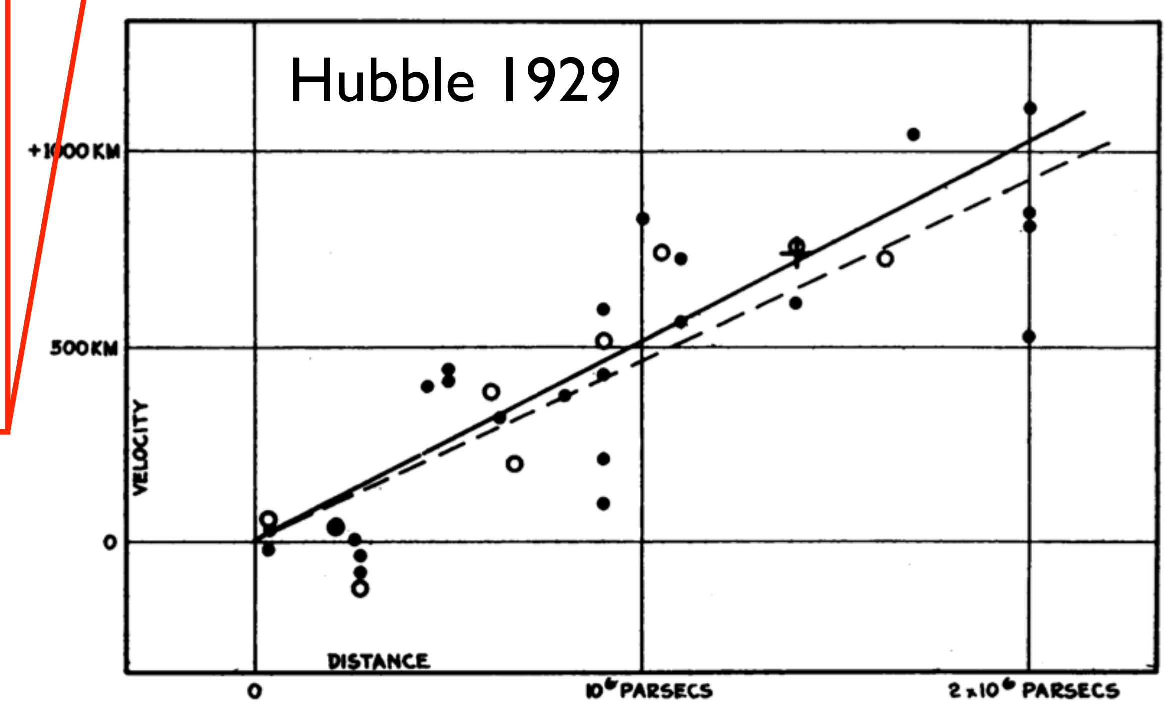

Hubble 1929
+1000KM
500KM
0
VELOCITY
DISTANCE
0
10⁶ PARSECS
2×10⁶ PARSECS

1980s: CMB and inflation

"Simple subtraction led you to conclude that... observers must be missing 80% of the universe."

Frank Wilczek

1985: Type Ia supernova

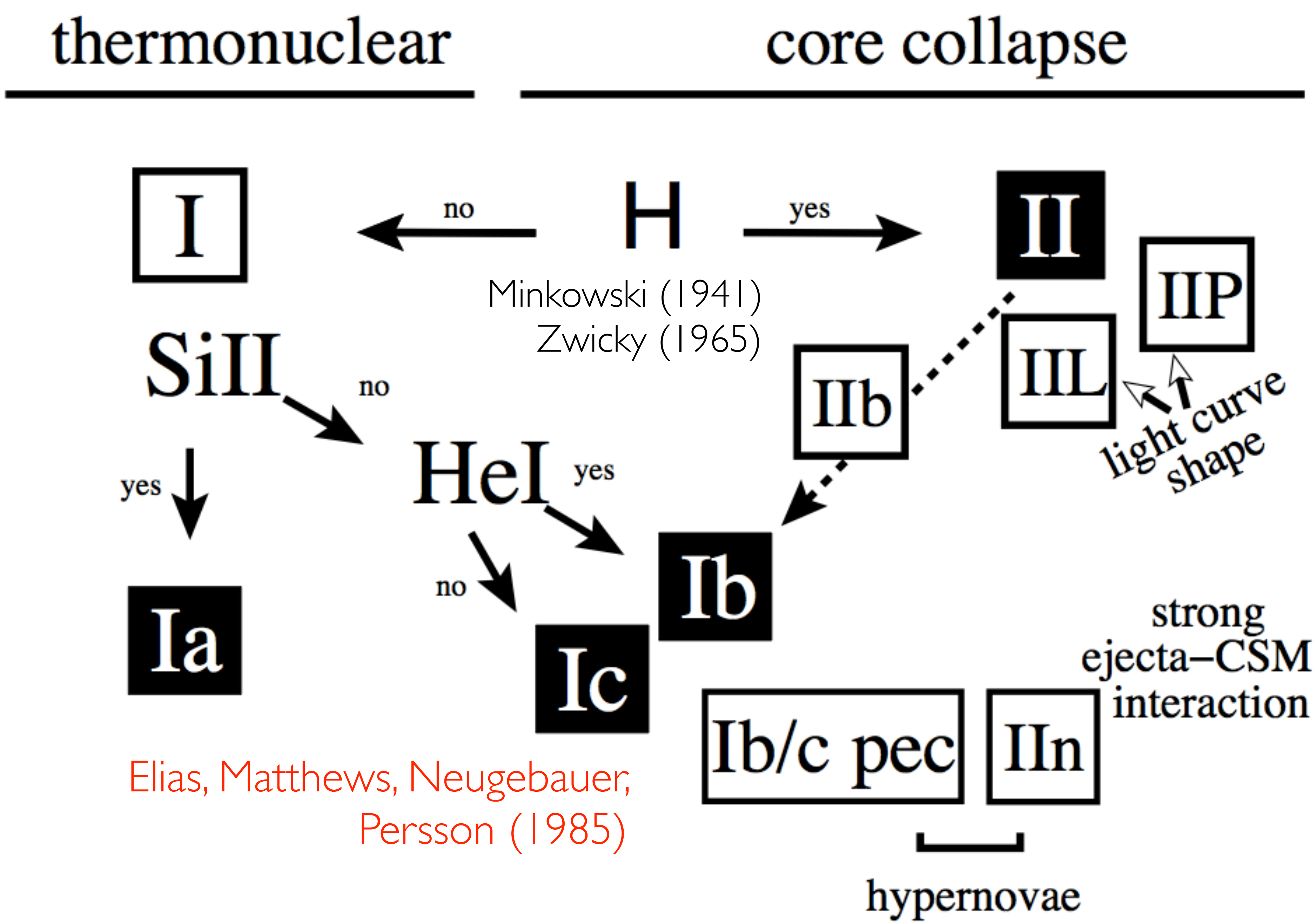
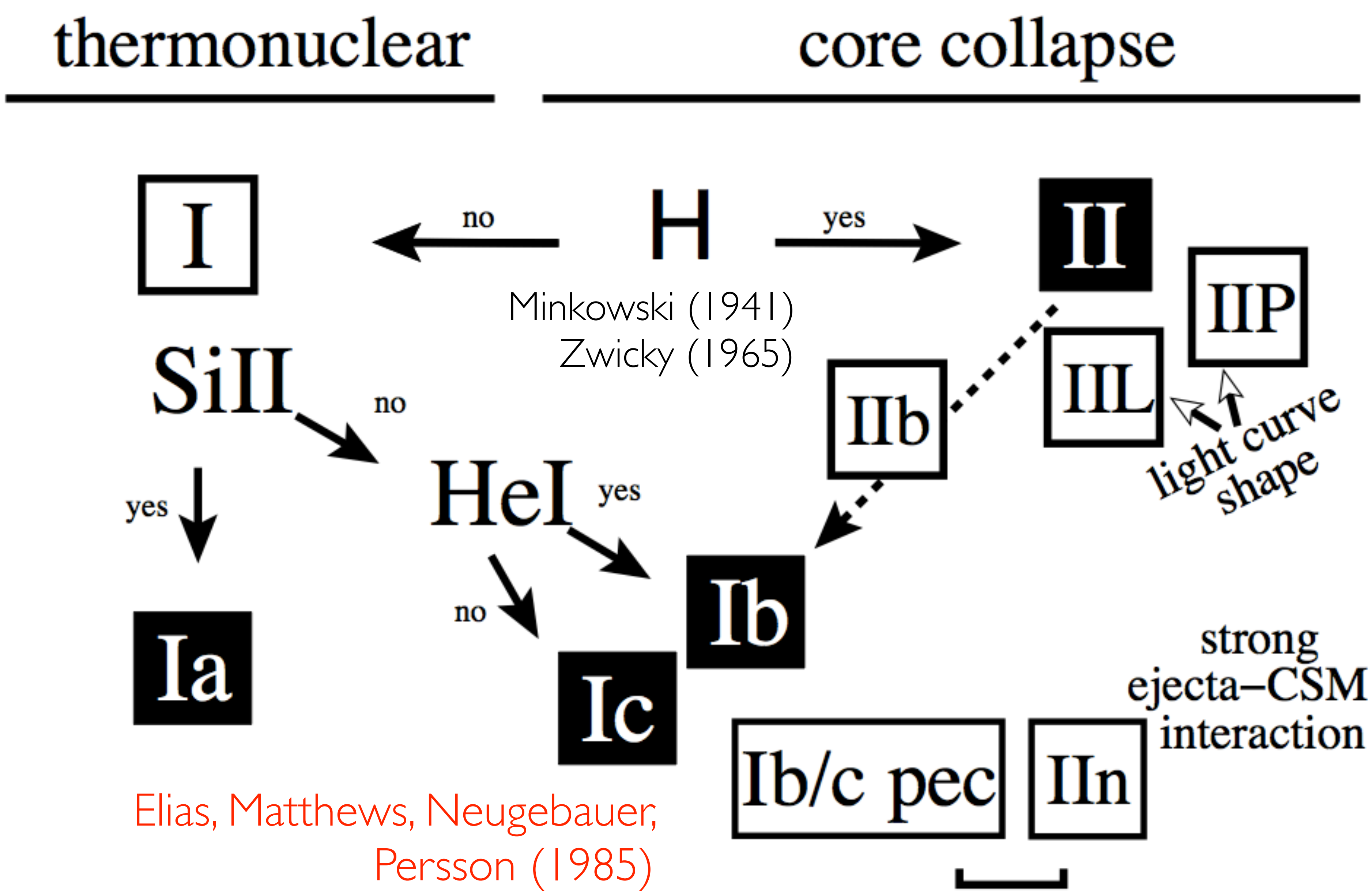


diagram taken from Turatto (2003)

1985: Type Ia supernova



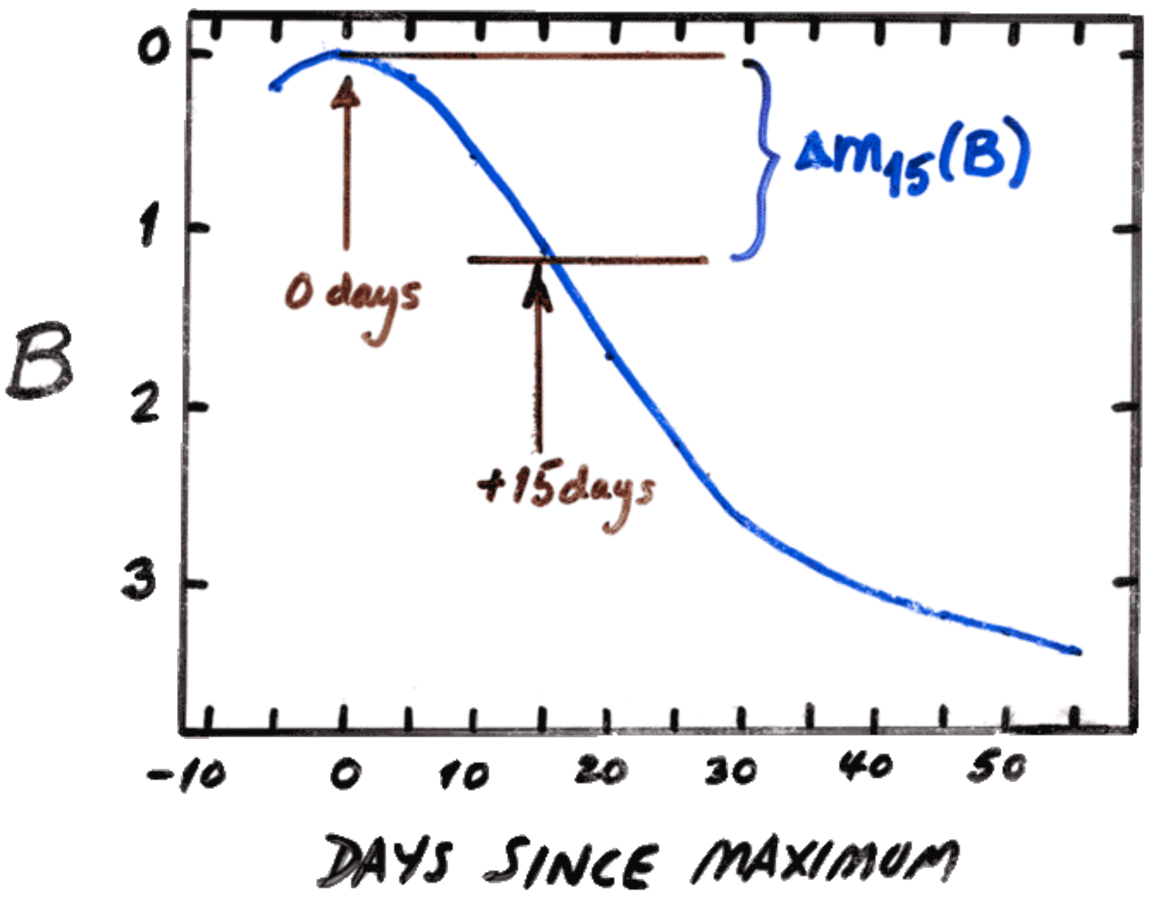
Elias, Matthews, Neugebauer, Persson (1985)

TYPE I SUPERNOVAE IN THE INFRARED AND THEIR USE AS DISTANCE INDICATORS

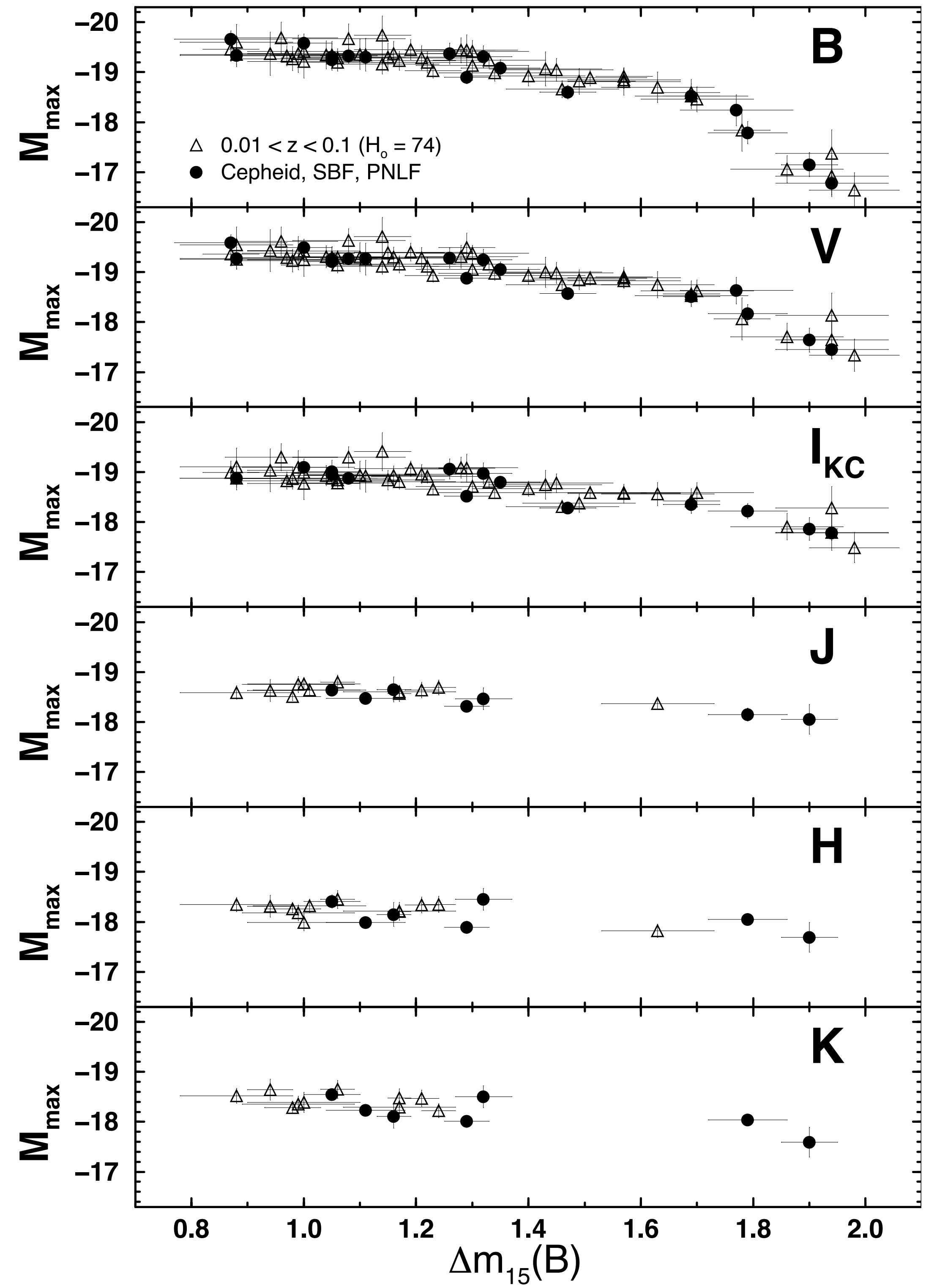
J. H. ELIAS,[1] K. MATTHEWS,[1] G. NEUGEBAUER,[1] AND S. E. PERSSON[2]

Received 1985 January 28; accepted 1985 March 22

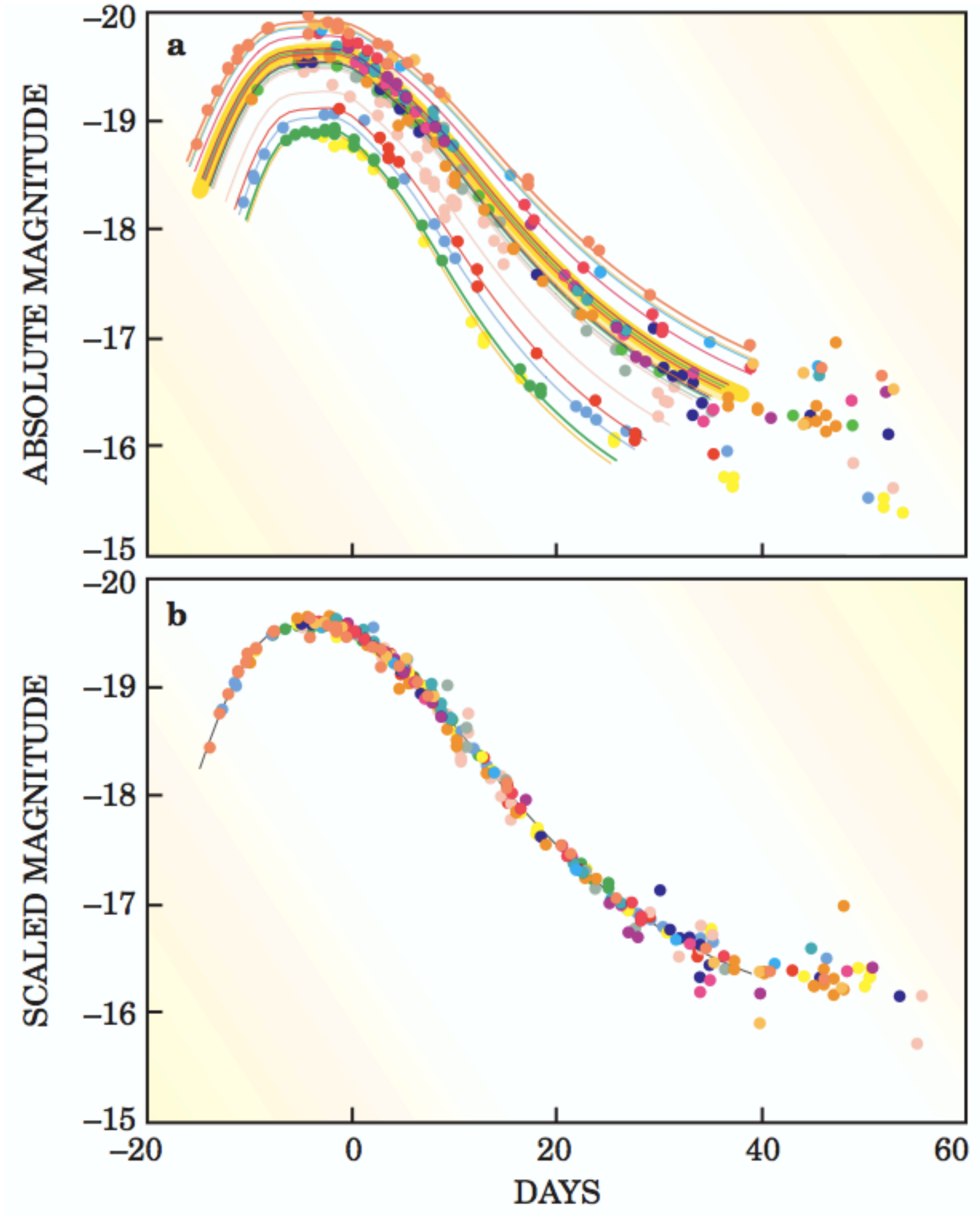
1993: Phillips relation



1993: Phillips relation

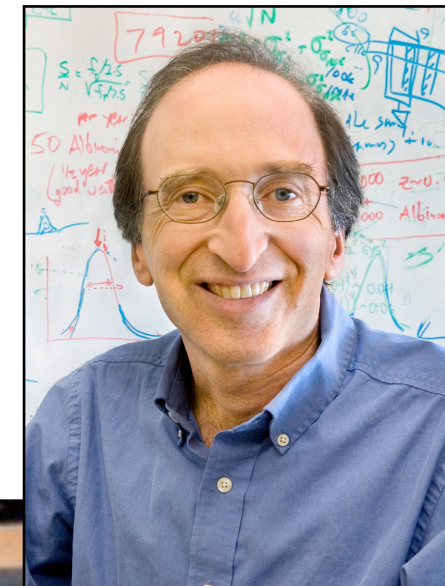


1993: Phillips relation



1990s: high-z SN race

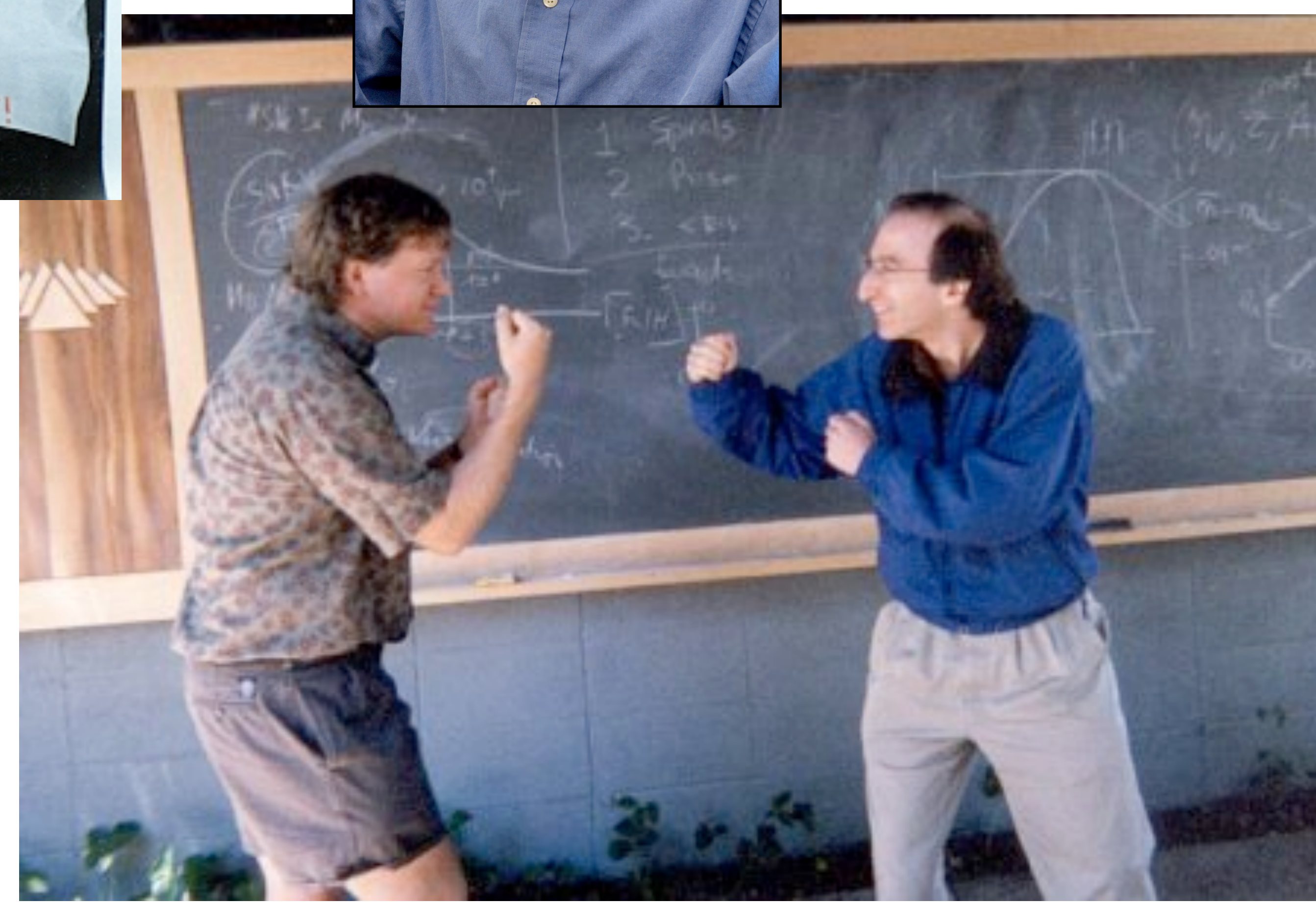
Supernova Cosmology Project (SCP)



Saul Perlmutter
Greg Aldering
Gerson Goldhaber
Peter Nugent

High-z SN Search (High-z)

Brian Schmidt
Adam Riess
Bob Kirshner
Mark Phillips
Alex Filippenko
Peter Garnavich



- **1996.08 SCP**
  Perlmutter+ 1997: 7 supernovae.
  "results inconsistent with Λ-dominated, low density, flat cosmologies."

- **1997.10 High-z**
  Garnavich+ 1998: 3 HST supernovae.
  "matter alone is insufficient to produce a flat universe."

- **1997.10 SCP**
  Perlmutter+ 1998: +1 HST supernova.
  "these new measurements <u>suggest</u> that we <u>may</u> live in a low-mass-density universe."

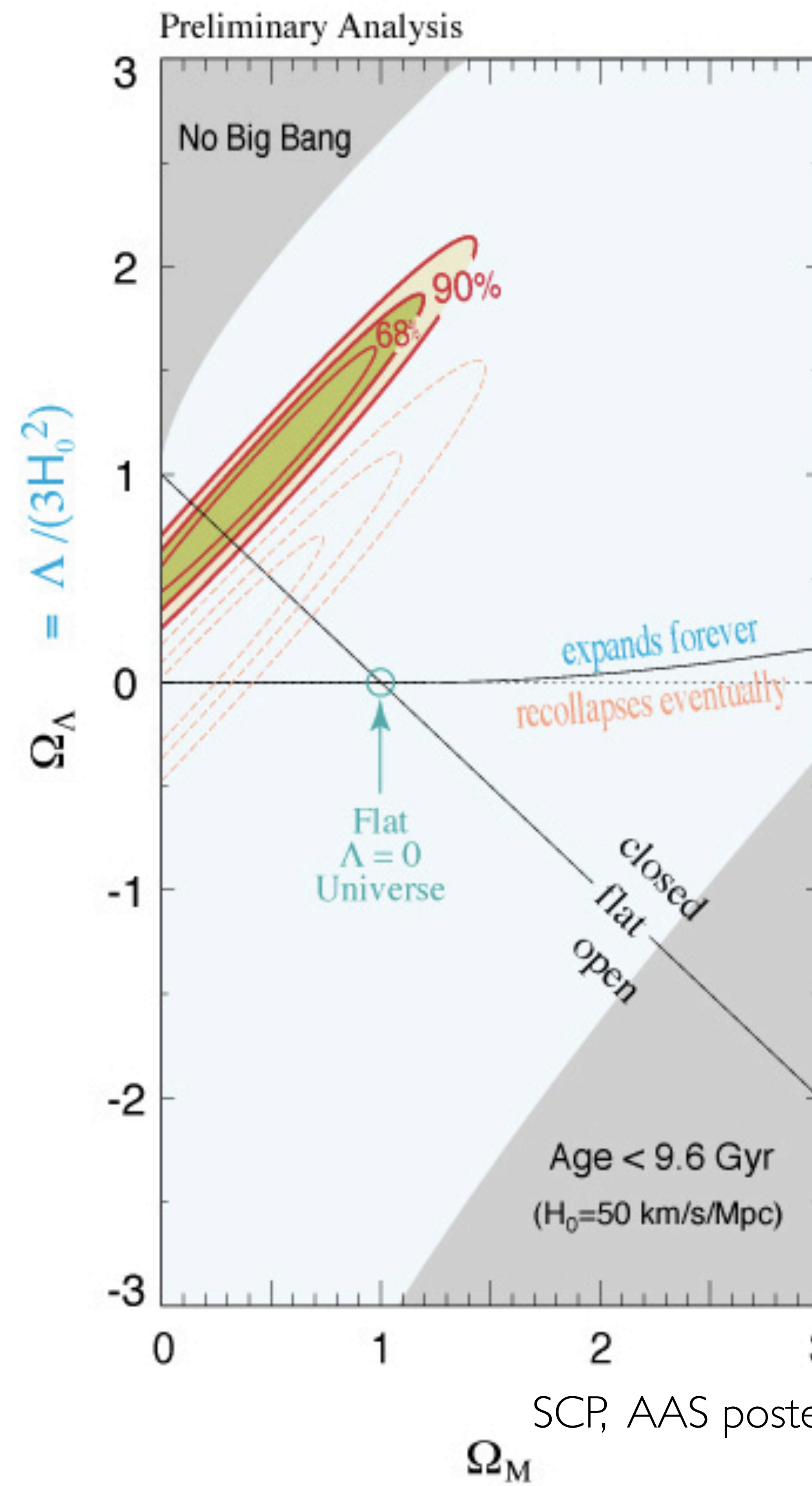
- **1998.01 AAS meeting**
  both teams showed low matter density.

- **1998.03 High-z**
  Riess+ 1998: 10 supernovae.
  titled "observational evidence from supernovae for an accelerating universe and a cosmological constant."

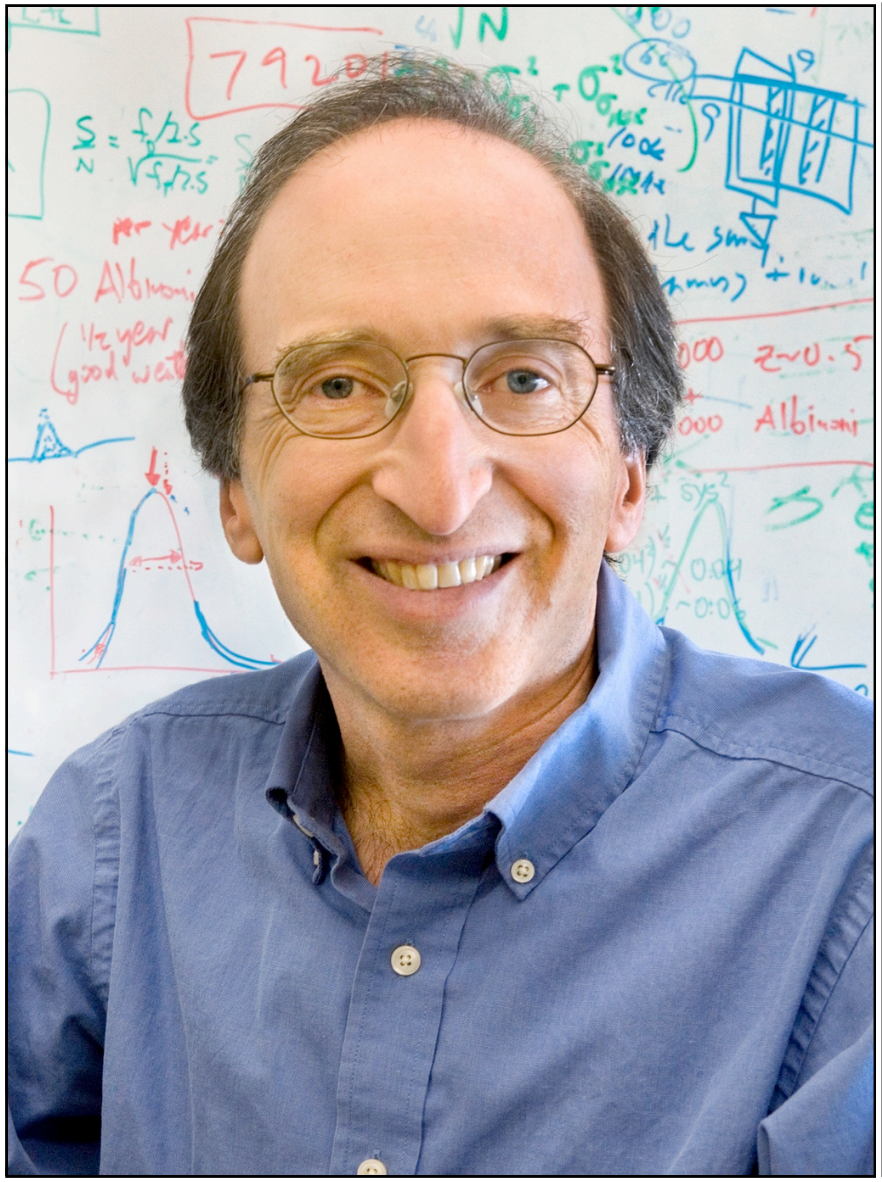
- **1998.08 SCP**
  Perlmutter+ 1998: 42 supernovae.
  "the data indicate that the cosmological constant is nonzero and positive."

Ω could be 0.2
only if accompanied by Λ

Gerson Goldhaber



SCP, AAS poster 1998



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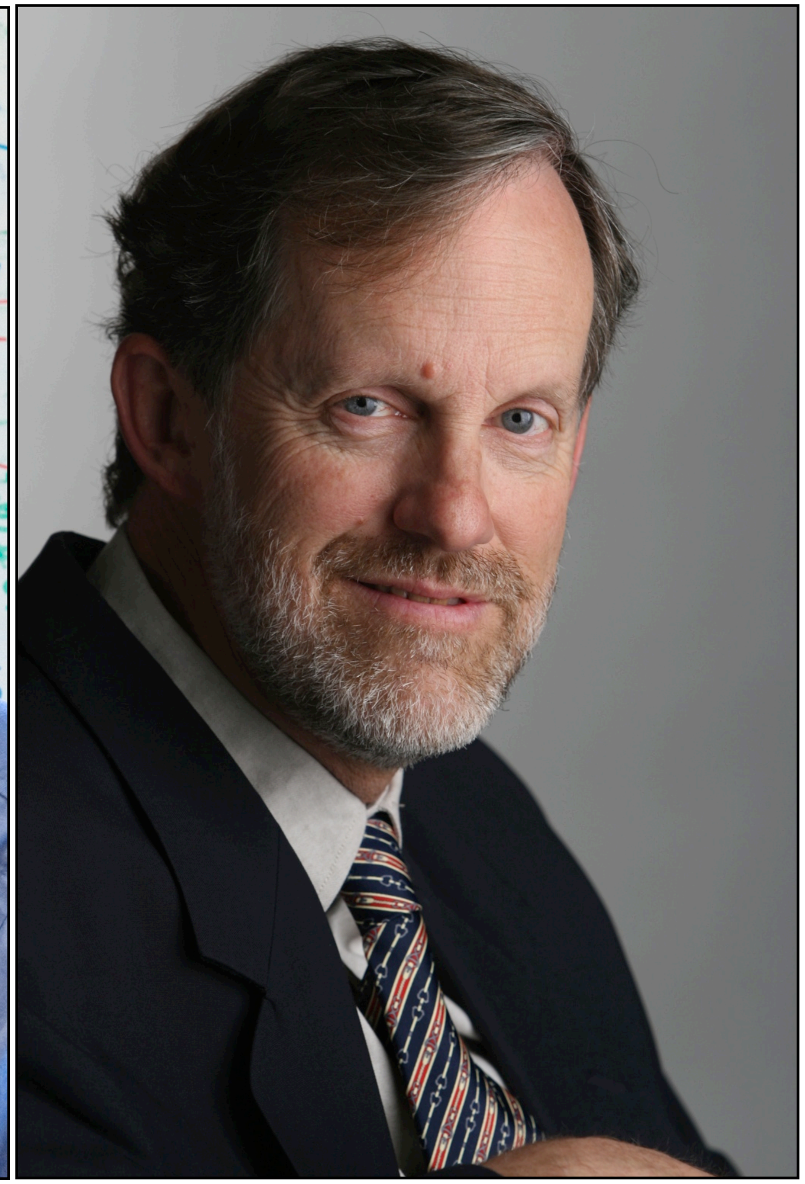
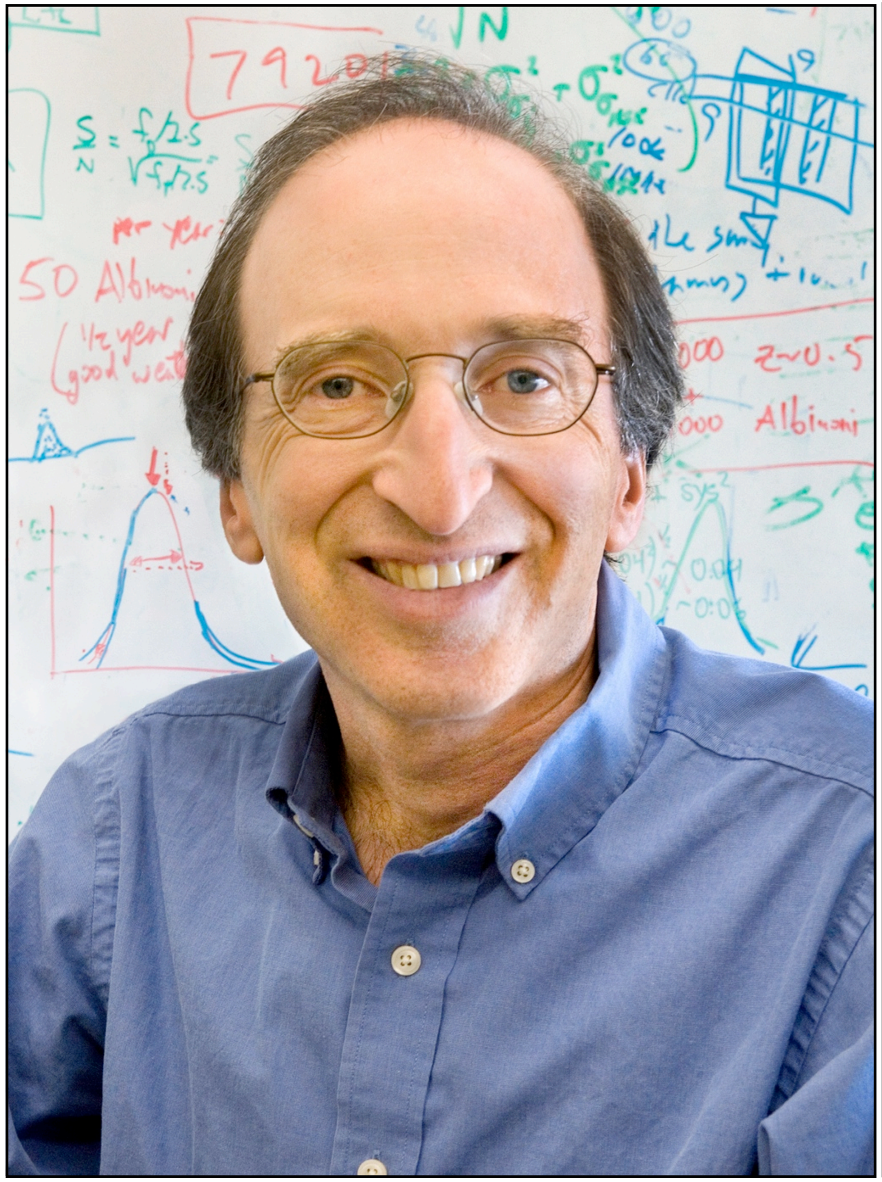
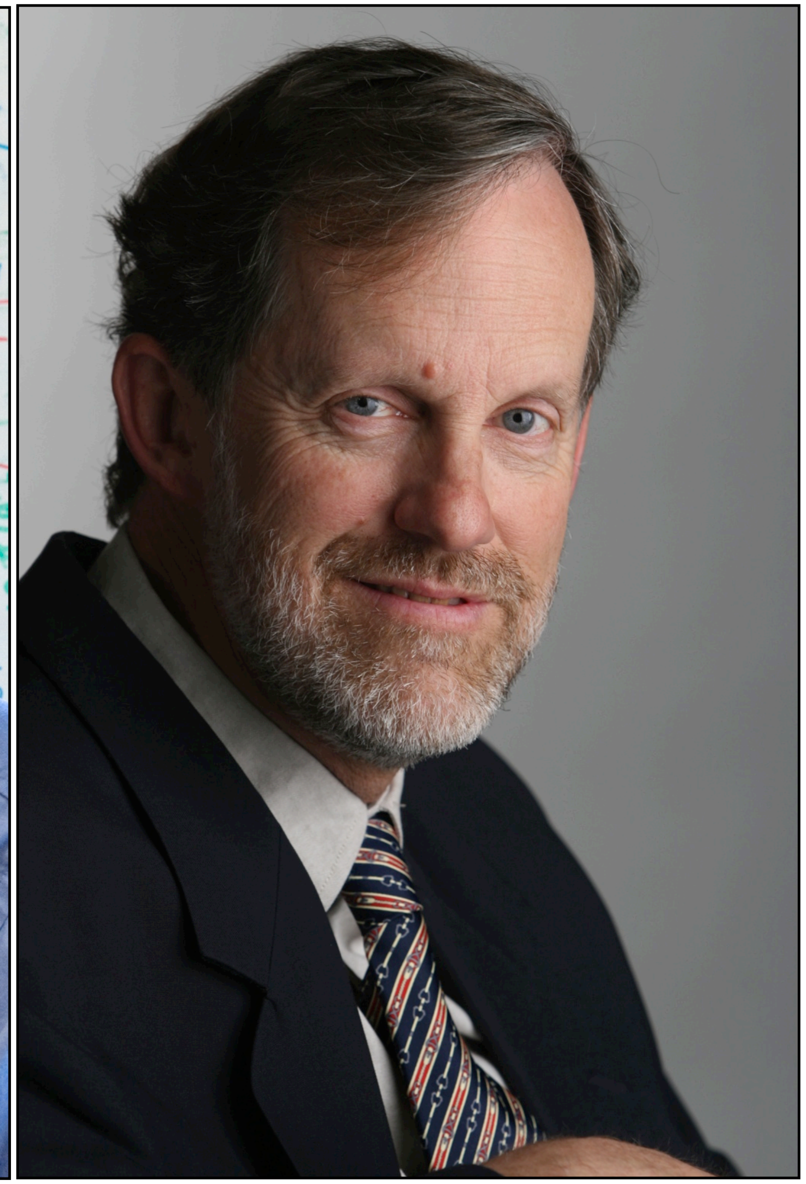


Boss #2

Boss #3



Guy who
won the Nobel Prize



Guy who should have won
the Nobel Prize

Guy who does not give a shit
who won the Nobel Prize

Cosmological constant

$$G_{ik} + \Lambda g_{ik} = 8\pi G T_{ik}$$

Einstein thought, in his heart of hearts,
the cosmological constant must be zero,
but he also knew that it has every right to be there.

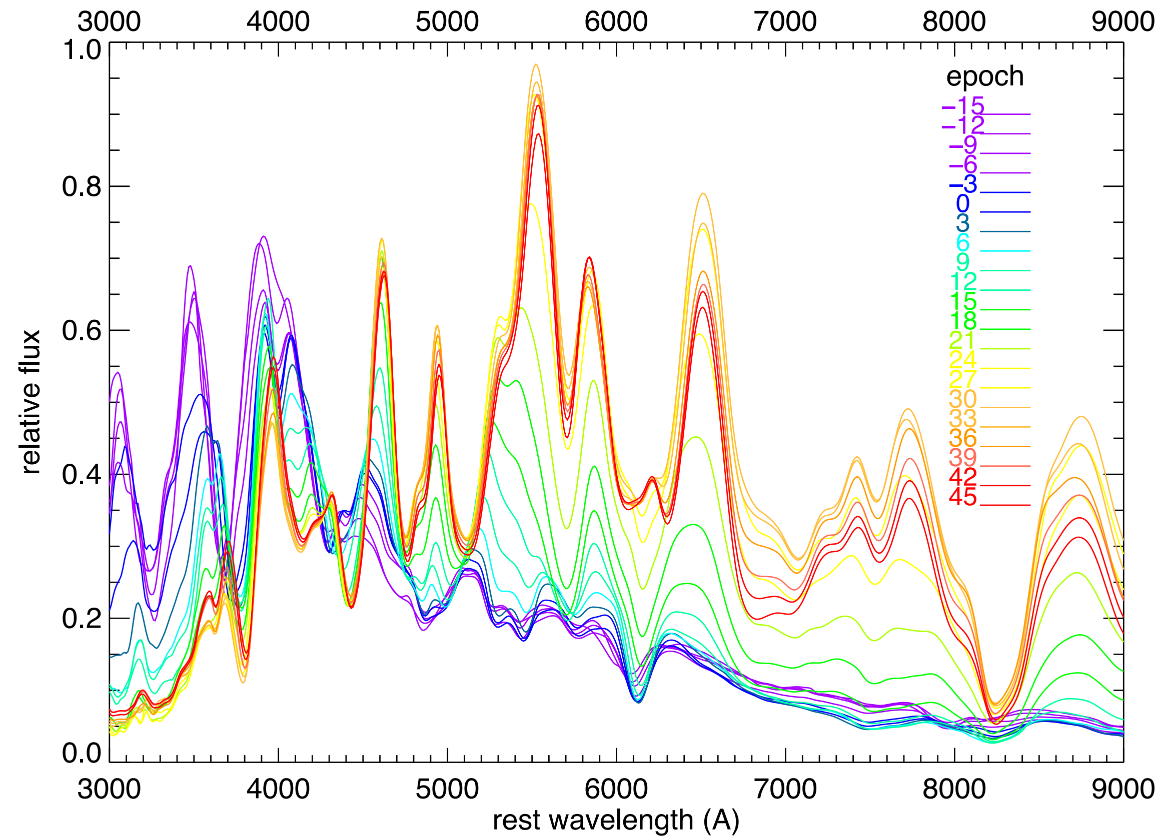
Michael Turner

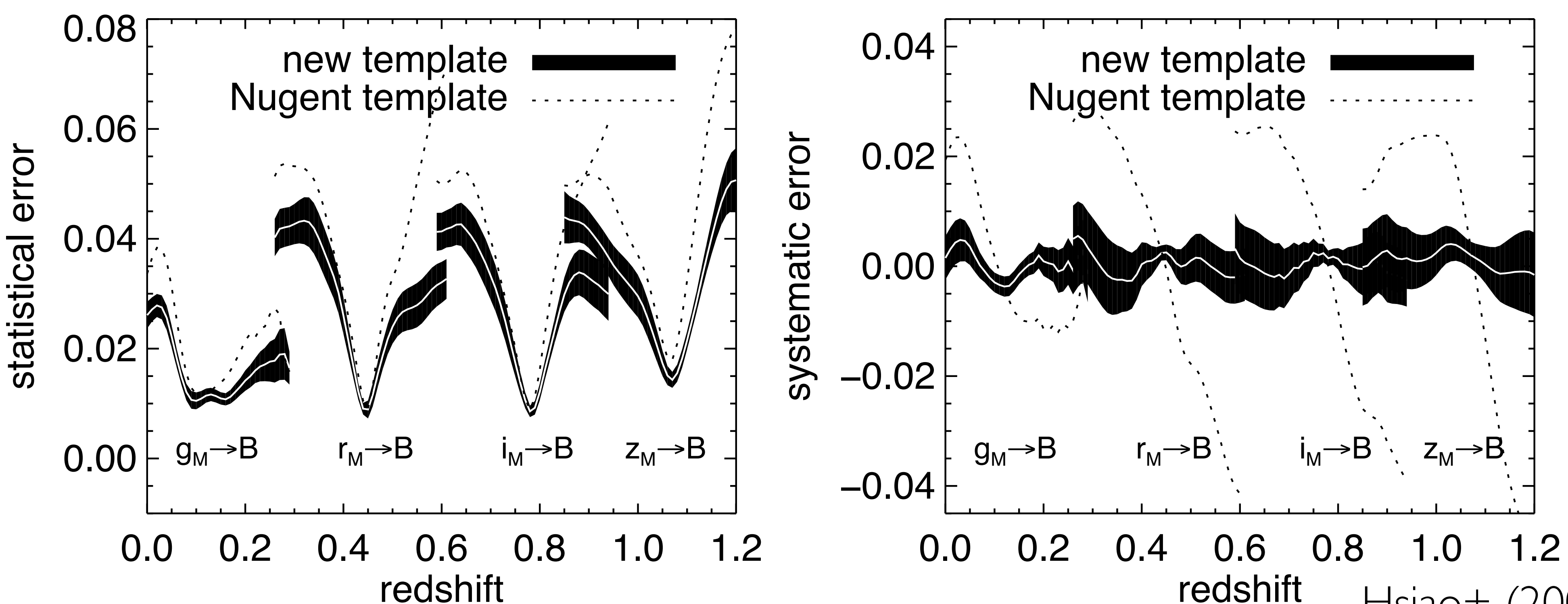
Cosmological constant

- Is it cosmological constant?

- Supernova Legacy Survey
  larger sample
- Supernova Cosmology Project
  higher redshift

k correction spectral template





Hsiao+ (2007)

Now what?

- Supernova Legacy Survey
  Sullivan+ 2011: $w = -1.069^{+0.091}_{-0.092}$

- Supernova Cosmology Project
  Suzuki+ 2012: $w = -1.013^{+0.068}_{-0.073}$

For cosmological constant, $w = -1$.

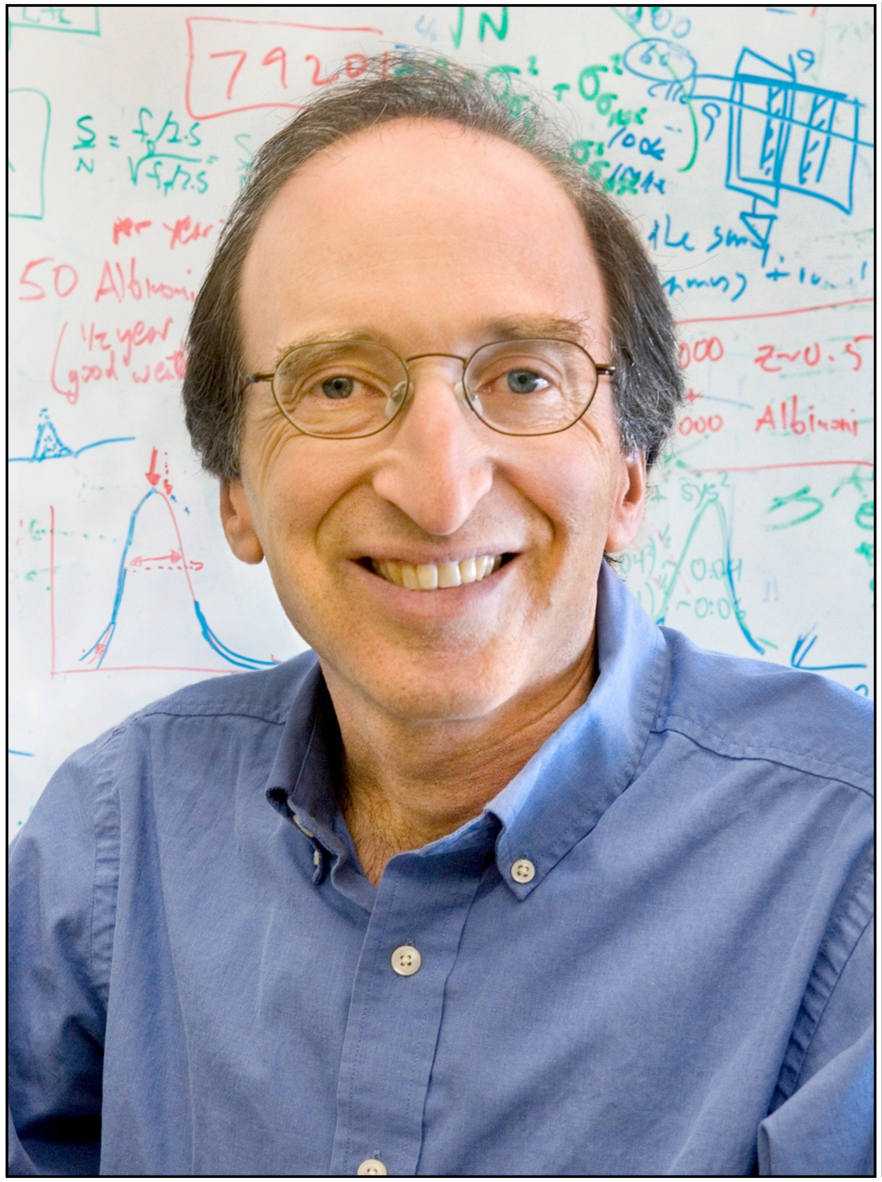
The future for SN Ia

- low redshift
- near infrared

Why low z?

- limited by systematic errors
  = we do not understand SNe Ia

- host environment dependence?
  explosion mechanism?
  progenitor system?
  reddening?



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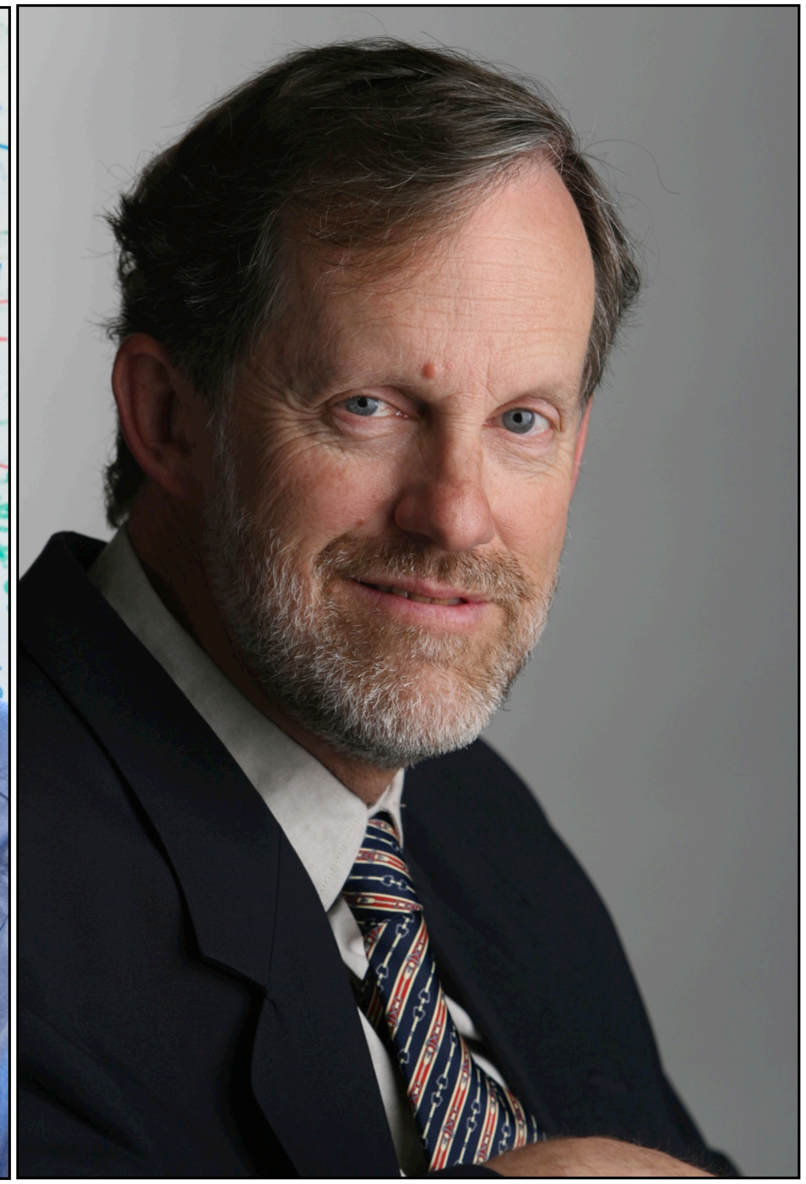
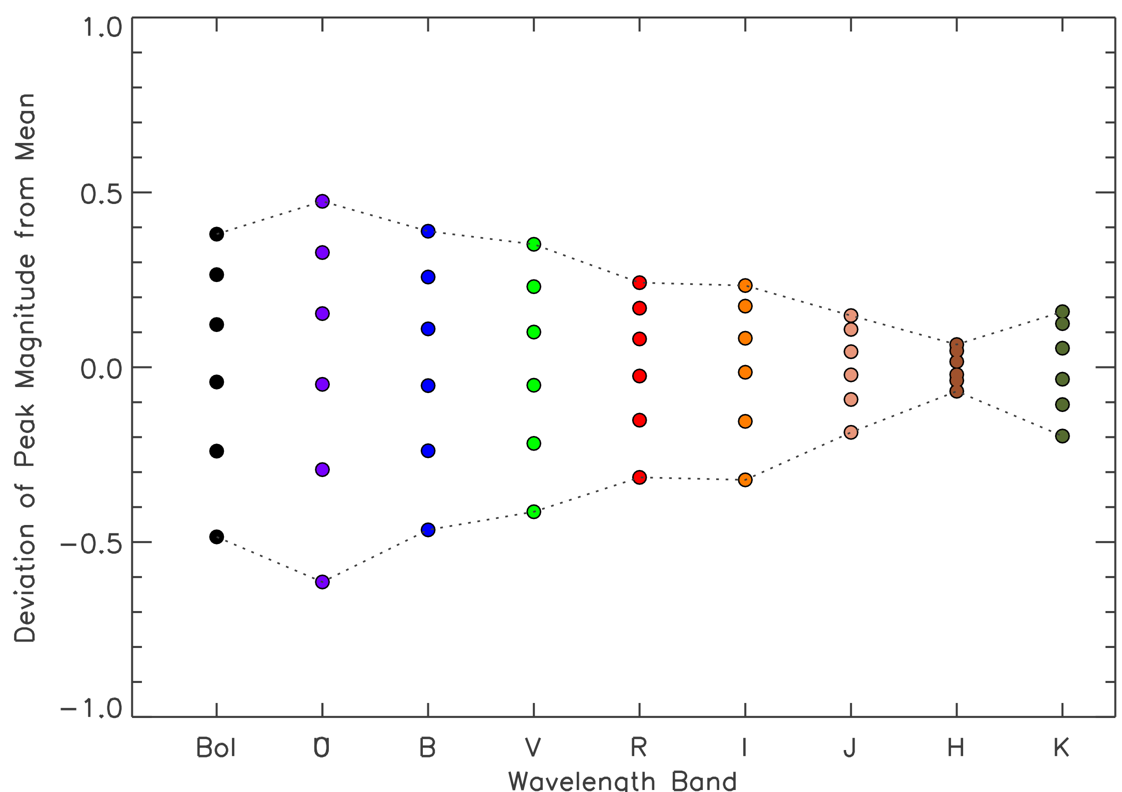


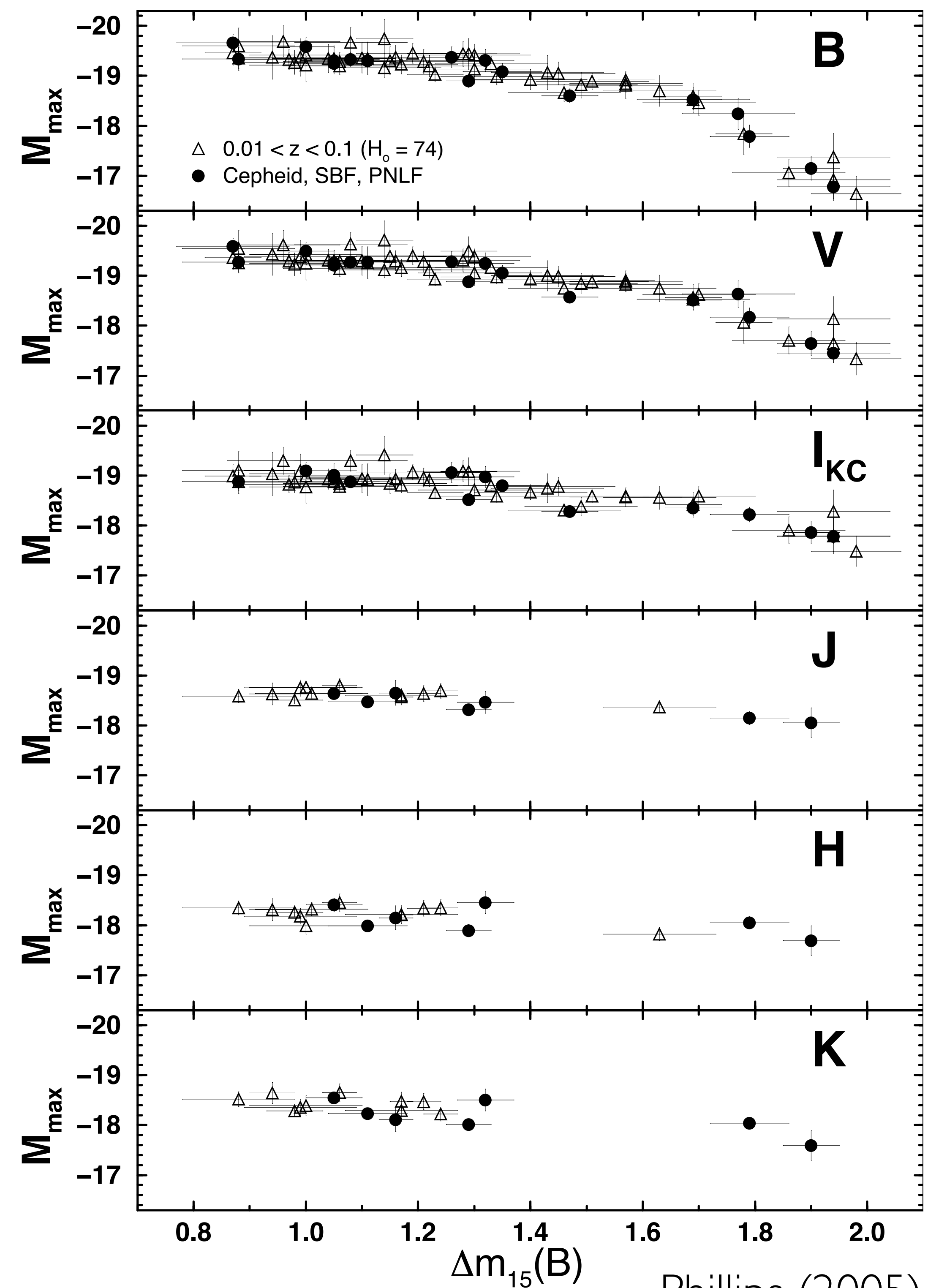
Boss #2

Boss #3

Why NIR?

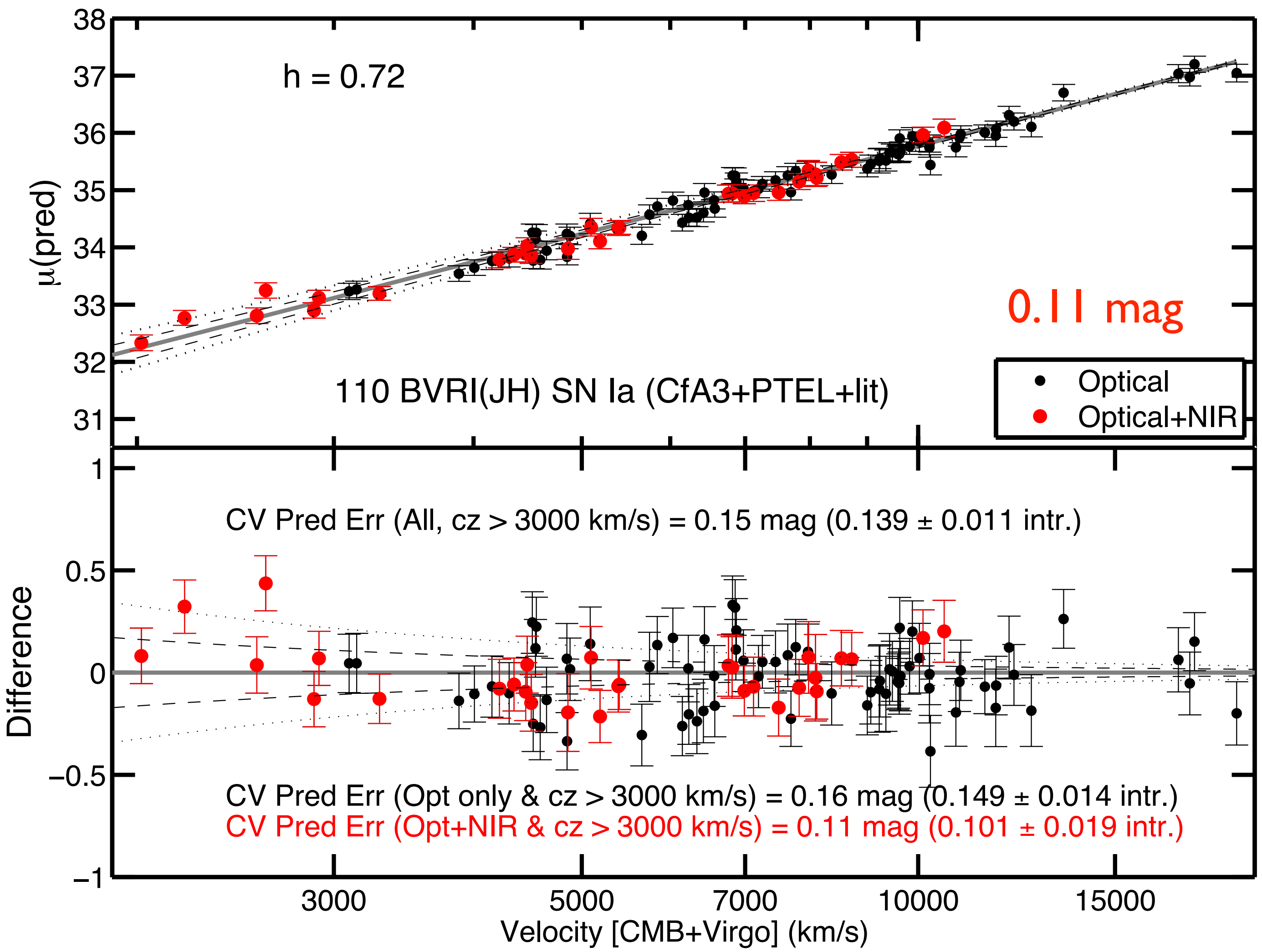


Kasen (2006)

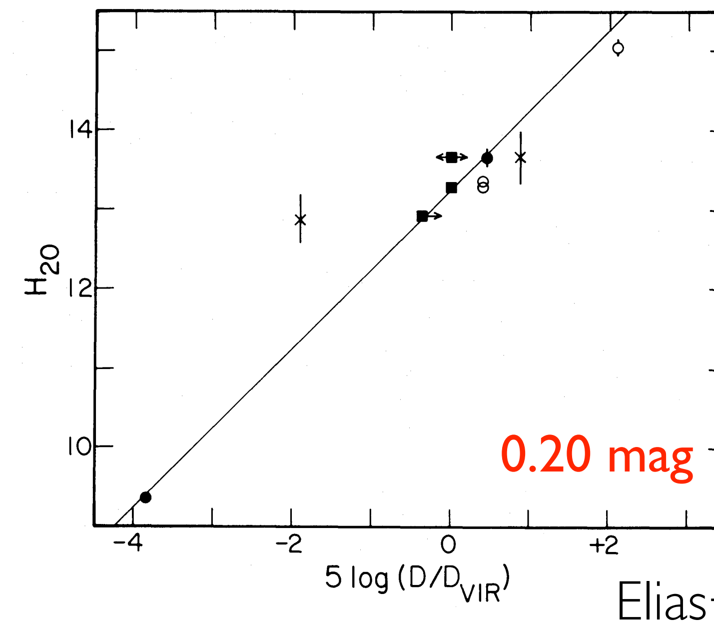


Phillips (2005)

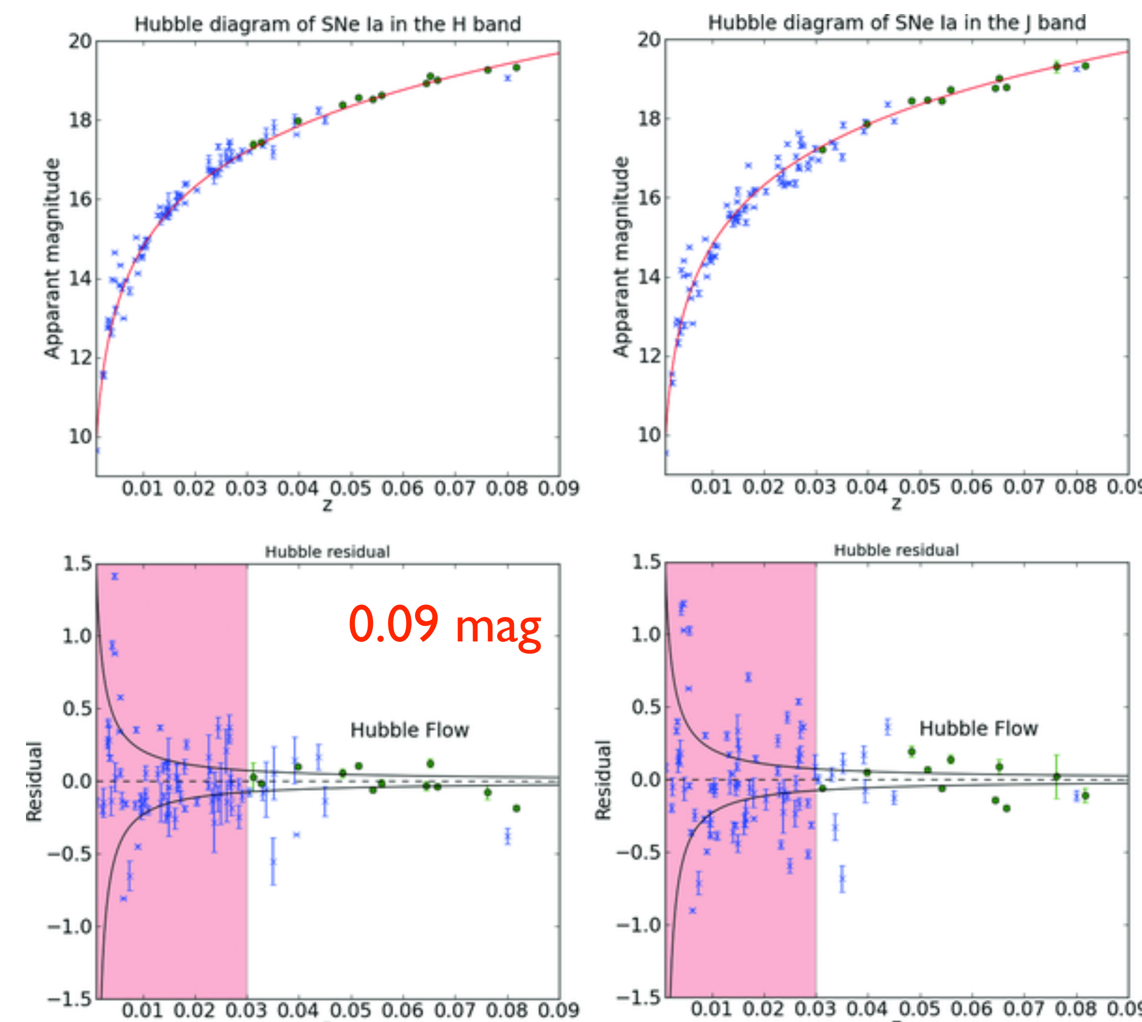
Why NIR?



Mandel+ (2011)



Elias+ (1985)



Barone-Nugent+ (2012)

Why NIR?

- lower intrinsic scatter
- lower dust/color correction
- NIR contains info independent from the optical

The future for SN Ia

- low redshift
- near infrared

Carnegie Supernova Project I

Mark Phillips

Eric Hsiao

Nidia Morrell

Chris Burns

Carlos Contreras

Carnegie Supernova Project II

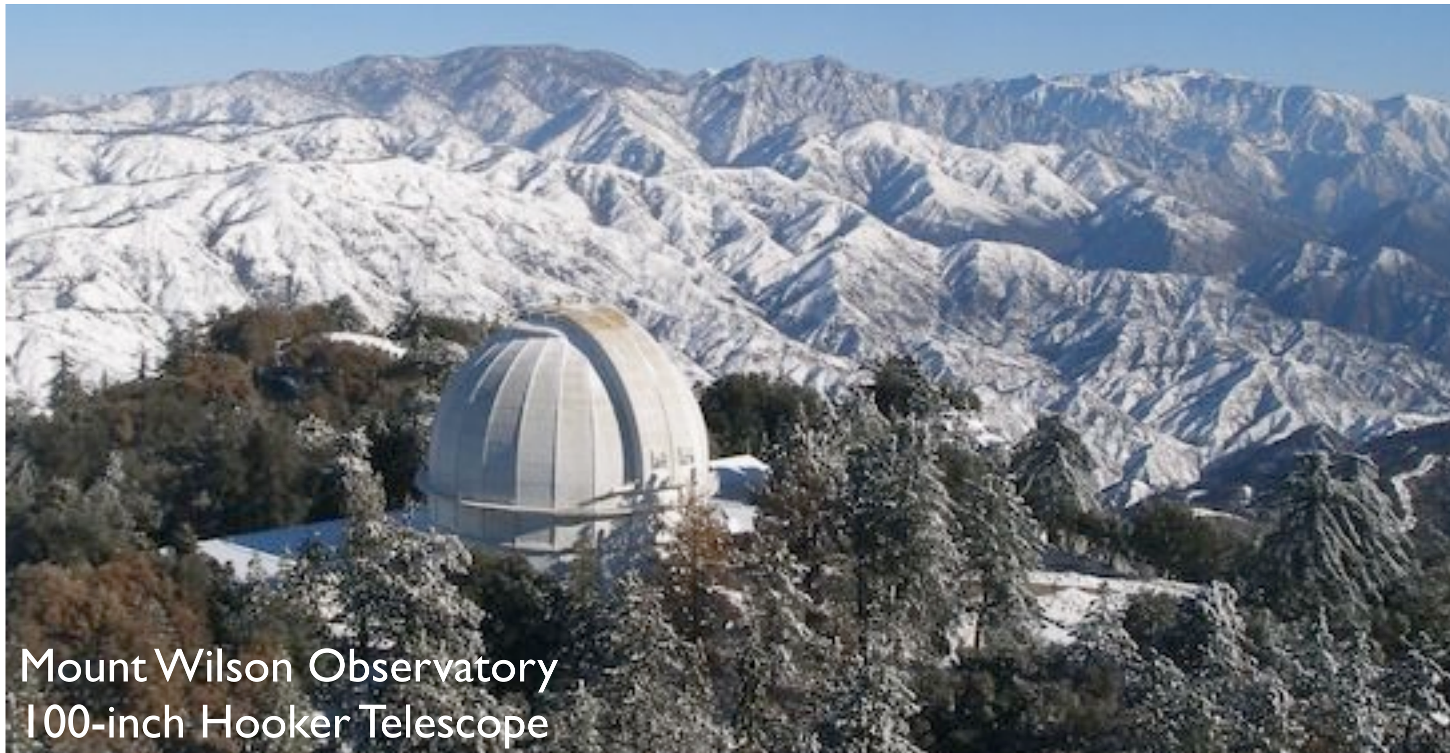
Mark Phillips | Chris Burns | Eric Hsiao | Max Stritzinger | Nidia Morrell | Carlos Contreras | Christa Gall

CSP1

- 2004-2008
- emphasis on NIR
- SNe from targeted searches
- old-school NIR k-corrections
- NIR imager on 1-m Swope
- 6.5-m Magellan time was dedicated to the high-z project

CSP2

- 2011-2015
- emphasis on NIR
- SNe from blind searches
- improved NIR k-corrections
- NIR imager on 2.5-m du Pont
- addition of FIRE/FourStar on 6.5-m Magellan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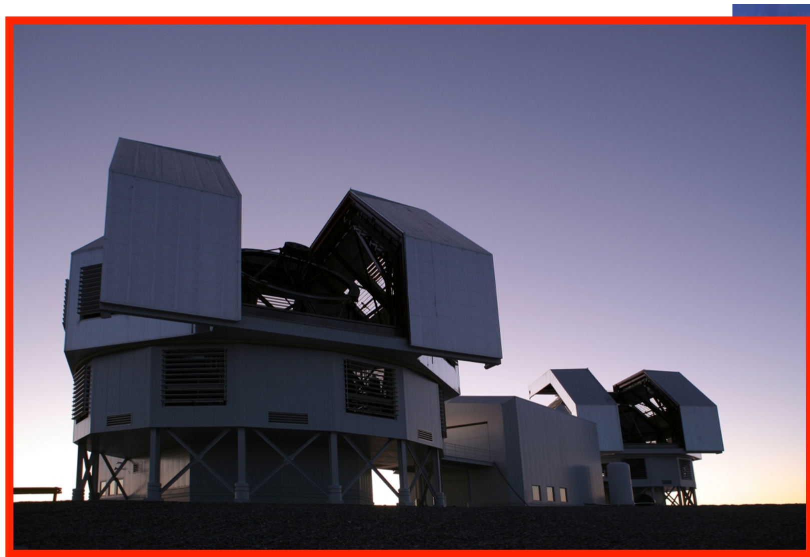
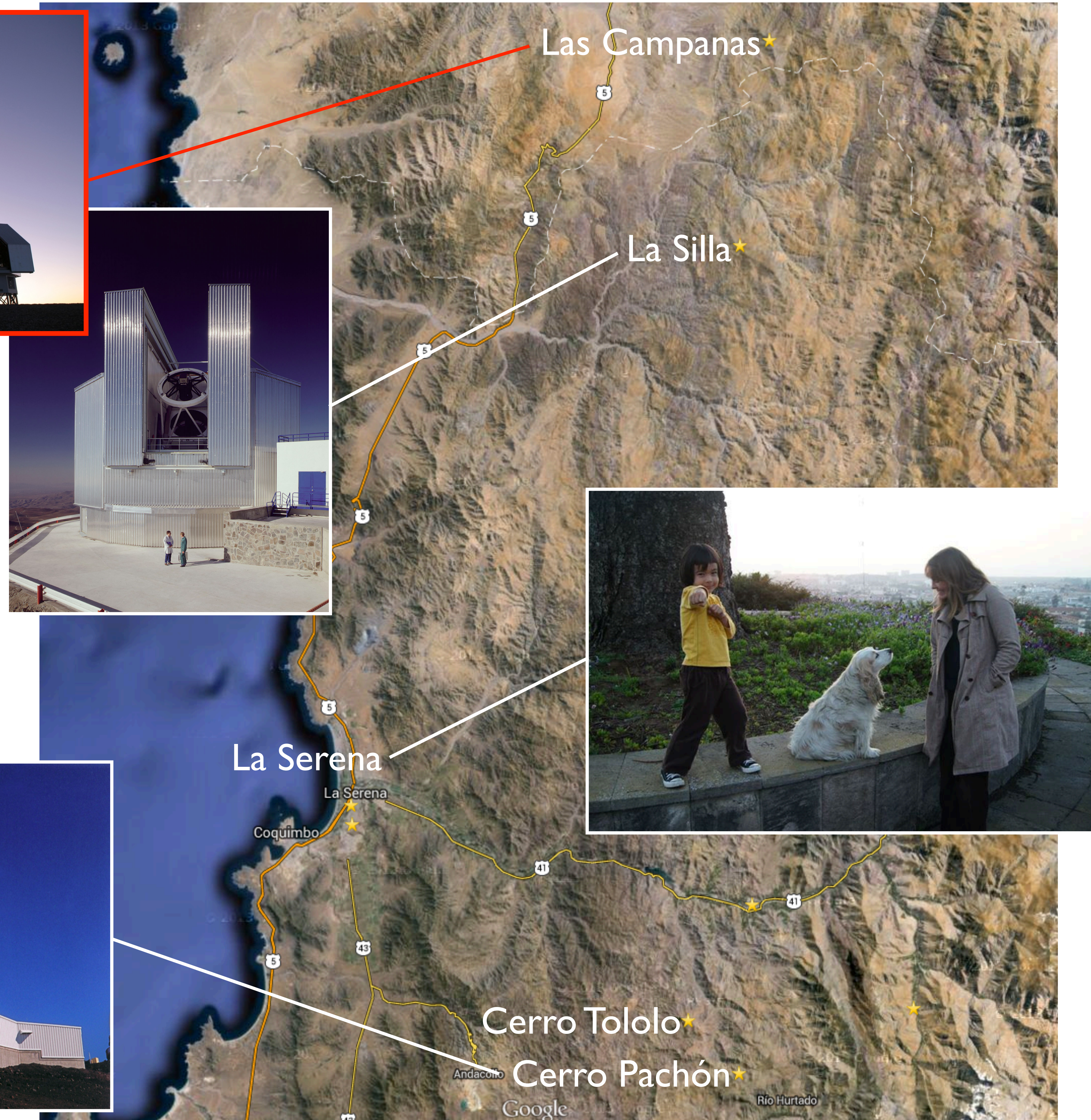


- 75% photometric nights in summer
- typical seeing 0.6-0.7



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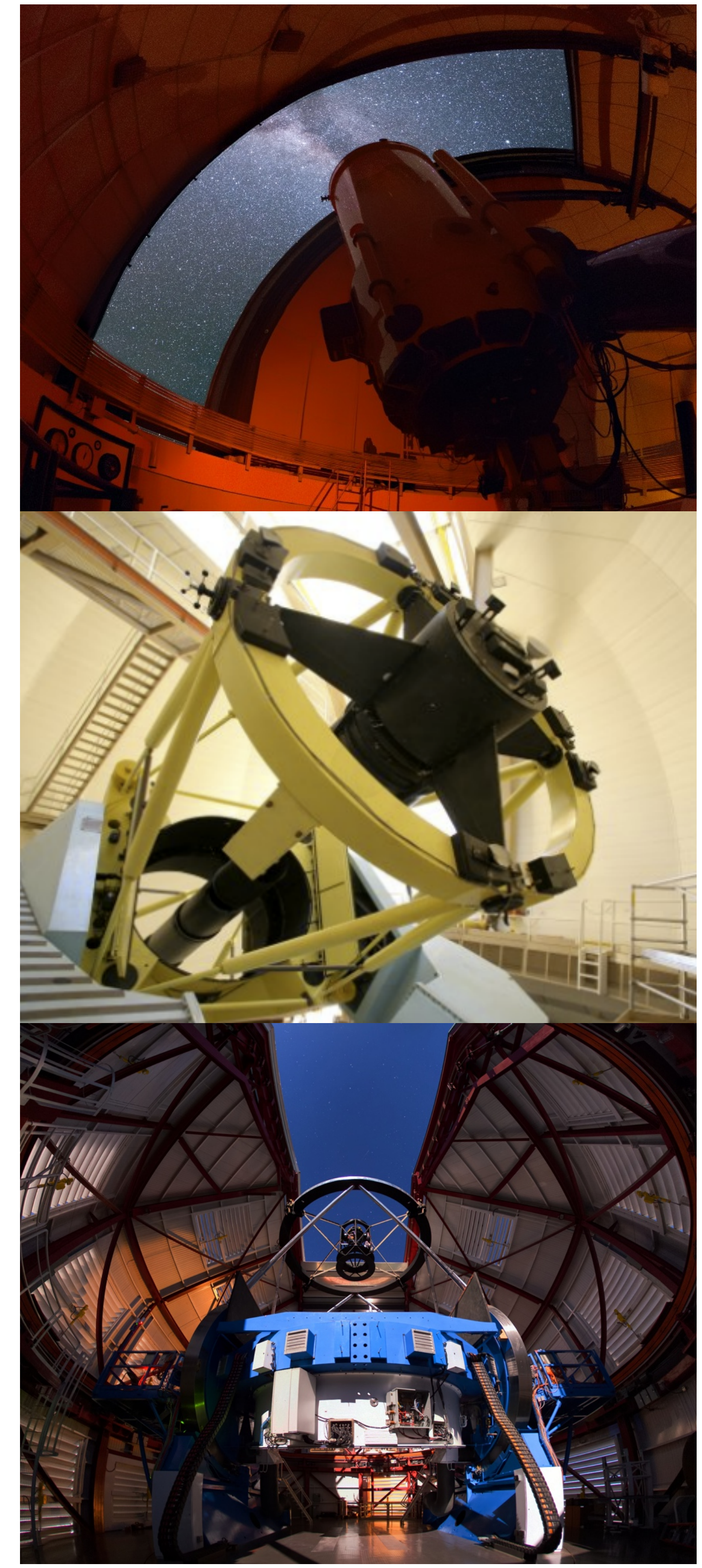
- addition of FIRE/FourStar on 6.5-m Magellan

Las Campanas Observatory

- Swope 1-m
  - e2v CCD
- du Pont 2.5-m
  - RetroCam
  - CCD, CAPSCam
  - WFCCD, B&C spectrograph, Echelle
- Magellan-I Baade 6.5-m
  - IMACS, FourStar, FIRE
- Magellan-II Clay 6.5-m
  - MIKE, MagE, LDSS3
  - MegaCam, MMIRS



Las Campanas Observatory

- Swope 1-m
  - e2v CCD
- du Pont 2.5-m
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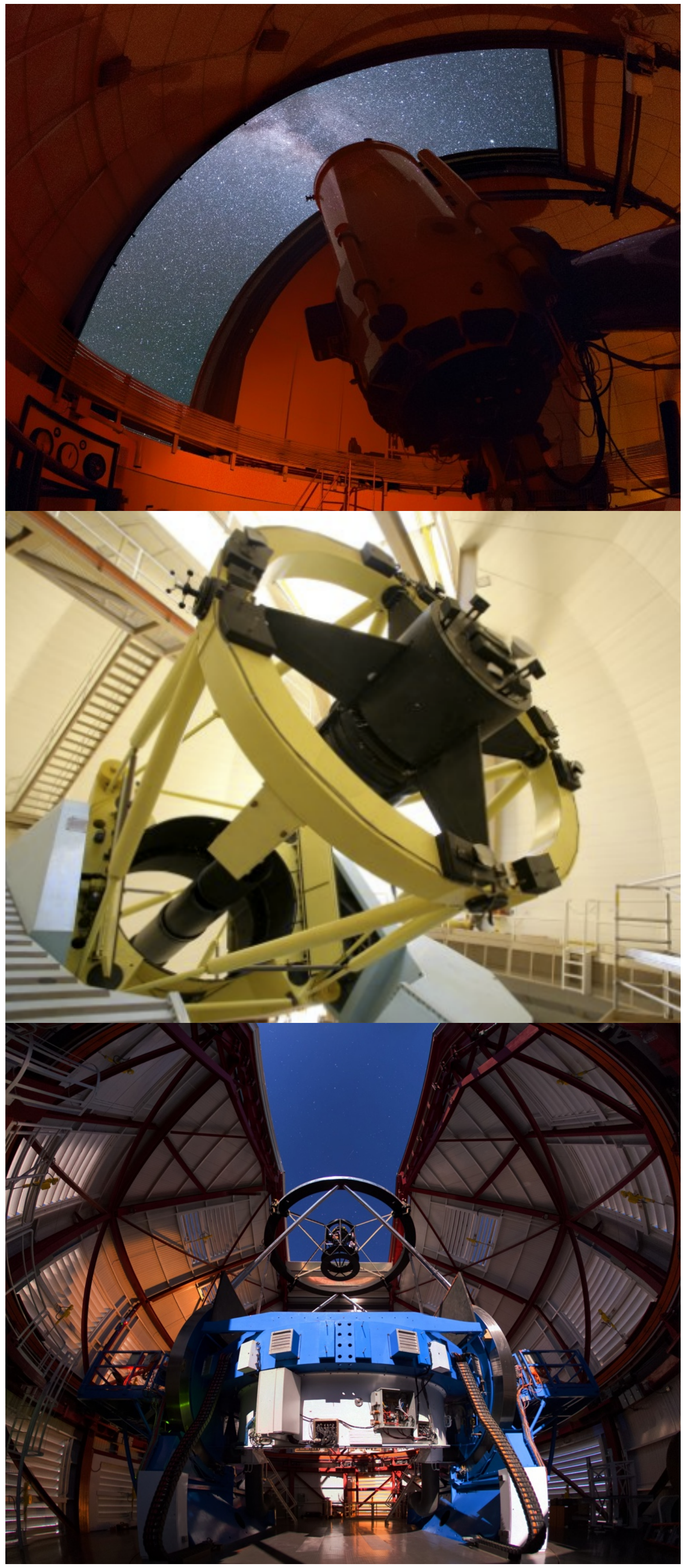

LCO instruments

- 1-m Swope
  - CCD: 8.7'x8.7' FOV, 0.435''/pixel, uBVgri
- 2.5-m du Pont
  - RetroCam: 1x1024x1024 HgCdTe, 3.4'x3.4' FOV, 0.201''/pixel, YJH
  - WFCCD: 0.38-0.92 micron, R~1000
- 6.5-m Baade
  - FourStar: 4x2048x2048 HgCdTe, 10.8'x10.8' (5.4'x5.4') FOV, 0.159''/pixel, YJHK
  - FIRE: 0.82-2.51 micron, R~6000 (echellette mode), R~500 (prism mode)
  - IMACS: 0.40-1.00 micron, R~1500
- 6.5-m Clay
  - MIKE: 0.32-1.00 micron, R~28,000 (blue), 22,000 (red)
  - MagE: 0.31-1.00 micron, R~4100
  - MMIRS: 0.94-1.51 micron, R~2400 (J+zJ); 1.25-2.45, R=1400 (HK+HK)

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CSP2

- 2011-2015
- emphasis on NIR
- SNe from blind searches
- improved NIR k-corrections
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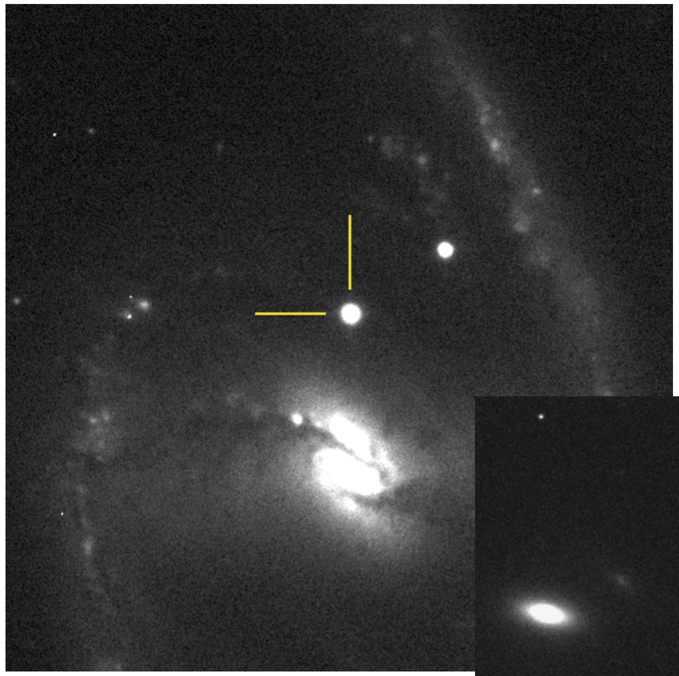
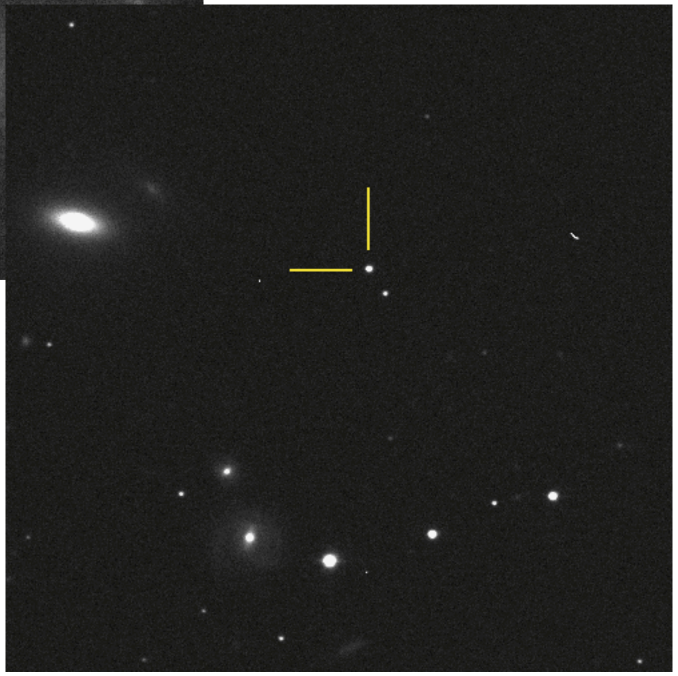
- addition of FIRE/FourStar on 6.5-m Magellan

blind searches





- SNe Ia in the Hubble flow
- SNe Ia in all host environments

- La Silla Quest Supernova Survey (LSQ)
  Palomar Transient Factory (PTF)
  Kiso Supernova Survey (KISS)
  All-Sky Automated Survey for Supernovae (ASAS-SN)
  Optical Gravitational Lensing Experiment (OGLE-IV)

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- SNe from blind searches
- improved NIR k-corrections
- NIR imager on 2.5-m du Pont
- addition of FIRE/FourStar on 6.5-m Magellan

# of SN Ia
optical spectra

10^4

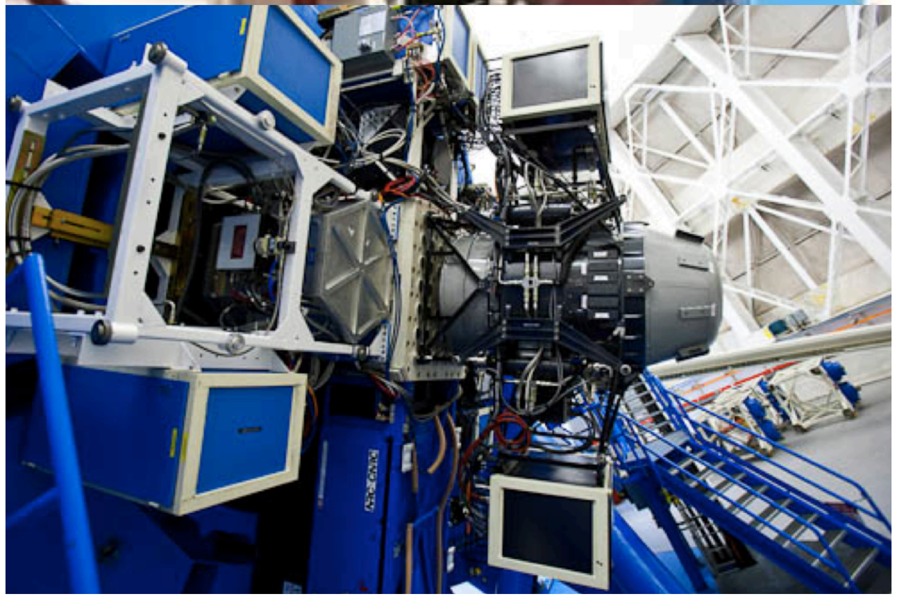
# of SN Ia
NIR spectra

10^2

41 from Marion+ (2009)
+ from individual SNe
91T, 94D, 98bu, 99by, 99ee,
02bo, 02dj, 03du, 05cf, 11fe, 14J, etc

NIR spectroscopy

- larger sample
  500 SN Ia spectra in 3 years
  700 in total
- better S/N
  Magellan+FIRE, Gemini-N+GNIRS
- time series
  scheduled FIRE nights + ToO GNIRS time
- accompanying optical+NIR LCs
- simultaneous optical spectra



NIR spectroscopy

- unburnt material (Hsiao+ 2013)
- extend of carbon burning (Wheeler+ 1998, Hsiao+ 2013)
- transition density (Wheeler+ 1998, Höflich+ 2002)
- amount/location of ^{56}Ni produced (Hsiao+ 2013)
- progenitor metallicity (Marion 2001)
- companion signature (Maeda+ 2014)
- amount of stable ^{58}Ni produced (Friesen+ 2014)
- mixing between ^{56}Ni and ^{58}Ni (Höflich+ 2004)
- asymmetric explosion (Motohara+ 2006)
- progenitor magnetic field (Penney 2011)

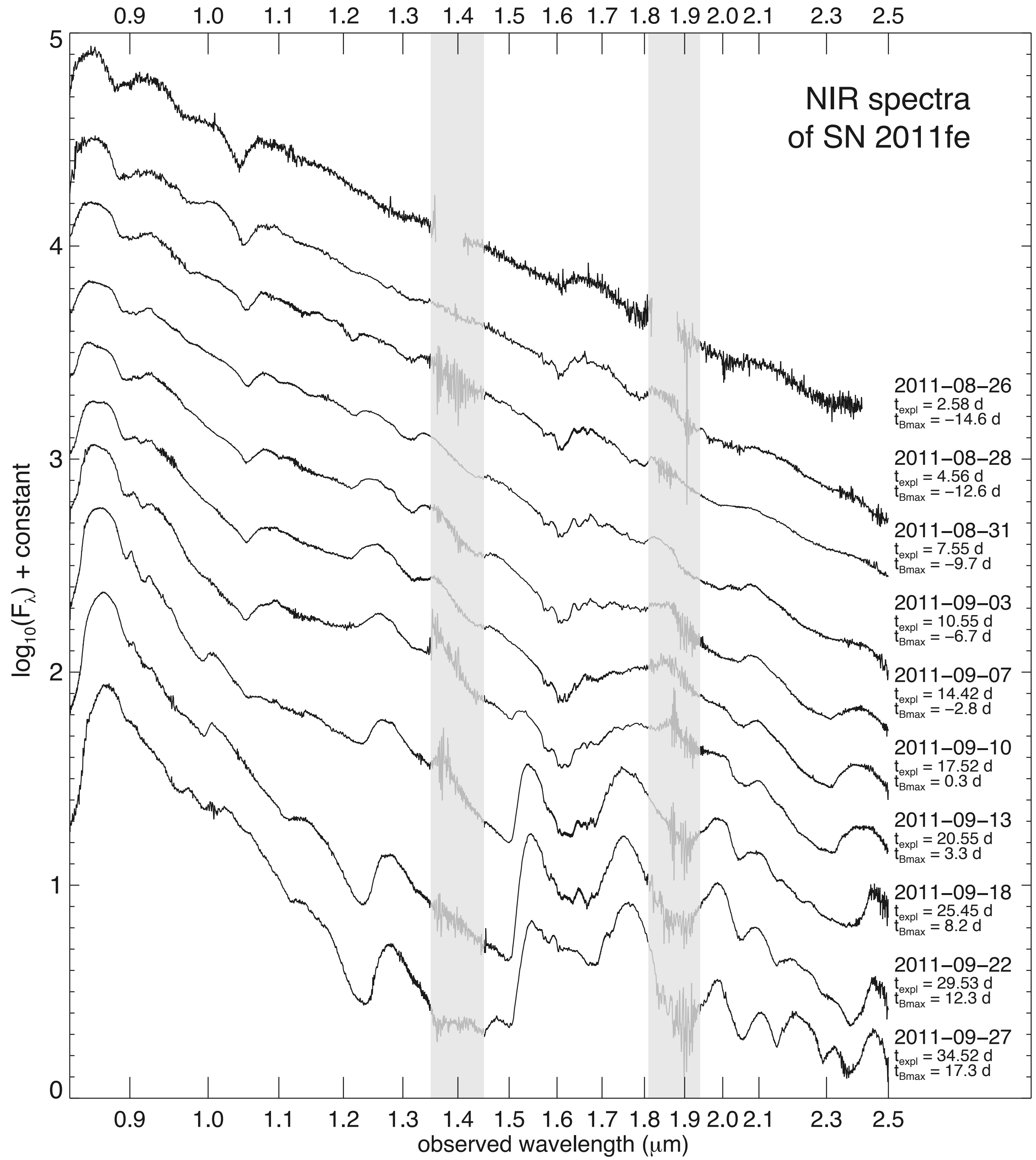
SN2011fe


SN 2011fe
Byrne Observatory at Sedgwick Reserve and the Palomar Transient Factory | LCOGT.net | BJ FULTON

SN2011fe

3 major findings

1. NIR C I
2. Flat Mg II velocity
3. Correlation between H-band break and decline rate



Hsiao+ (2013)

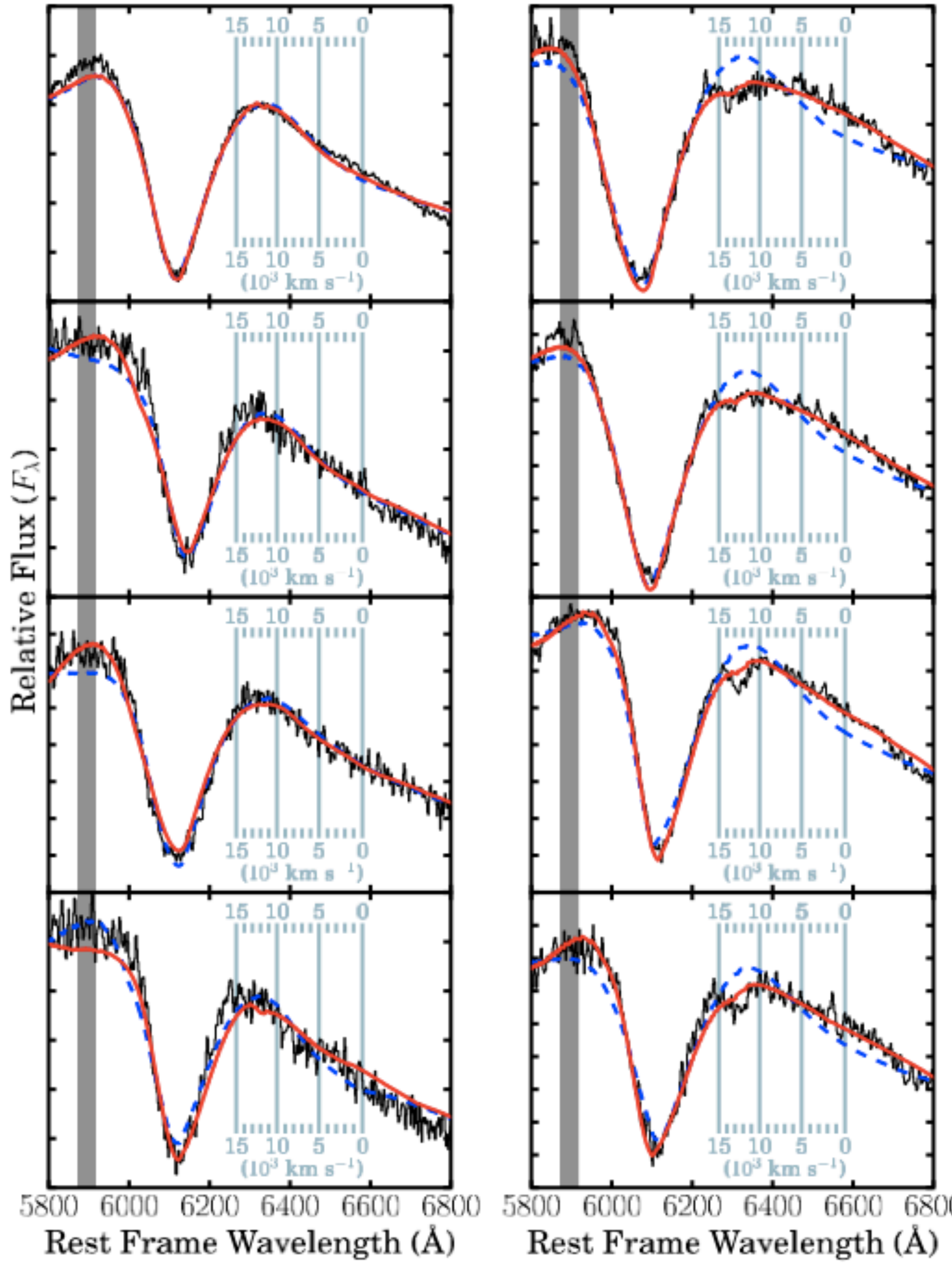
unburnt carbon

- The exploding star is a C/O white dwarf
- Oxygen can come from processed carbon
- Carbon in supernova is pristine material from the progenitor

- Amount of incomplete burning provides strong constraints for explosion models

unburnt carbon

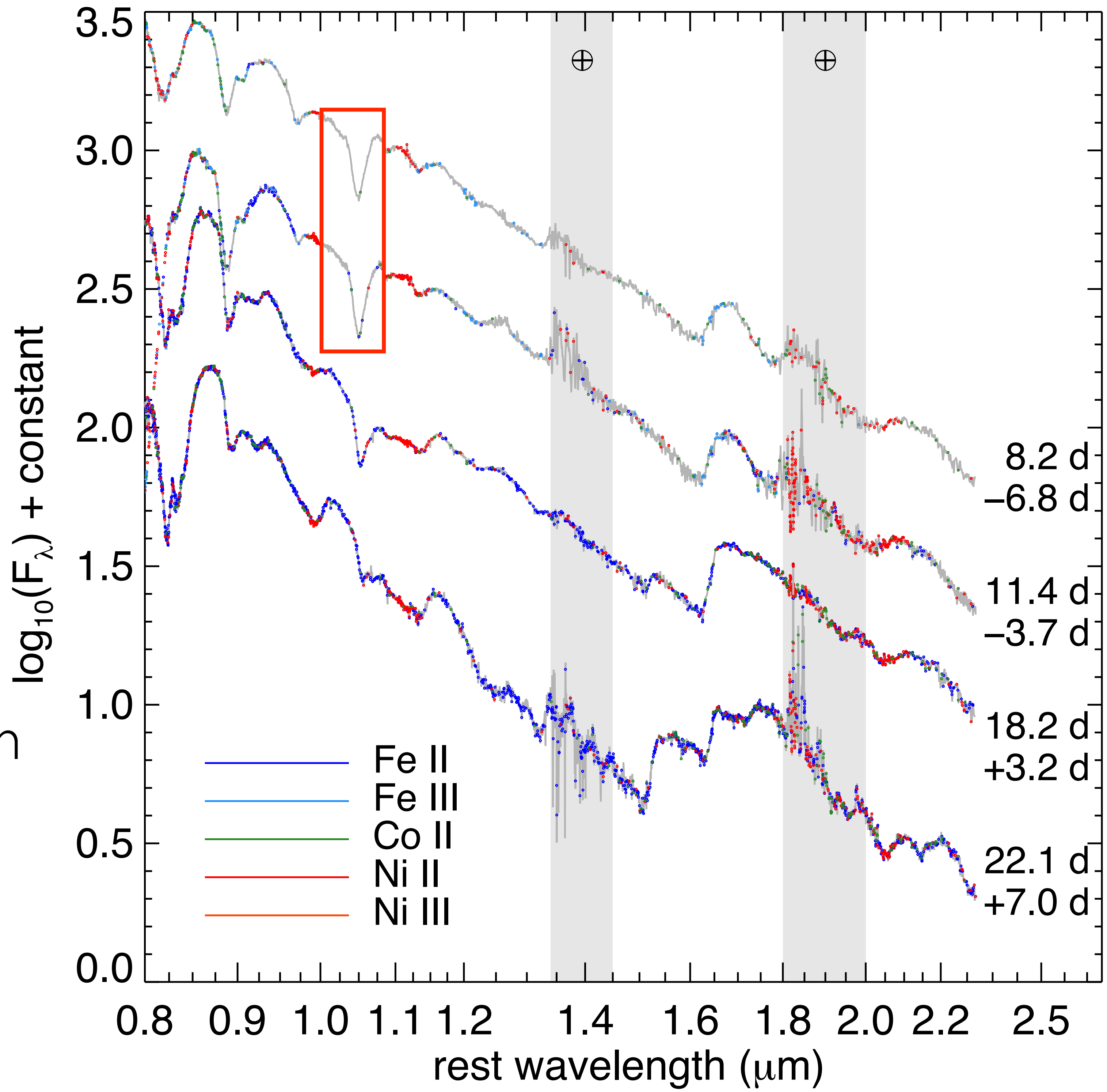
- optical C II 6580
  - only in early spectrum
  - disappears quickly
  - prefers low velocity
  - detected in 20-30% of Ia
    Thomas+ 2011
    Folatelli+ 2012
    Silverman+ 2012



Thomas+ (2011)

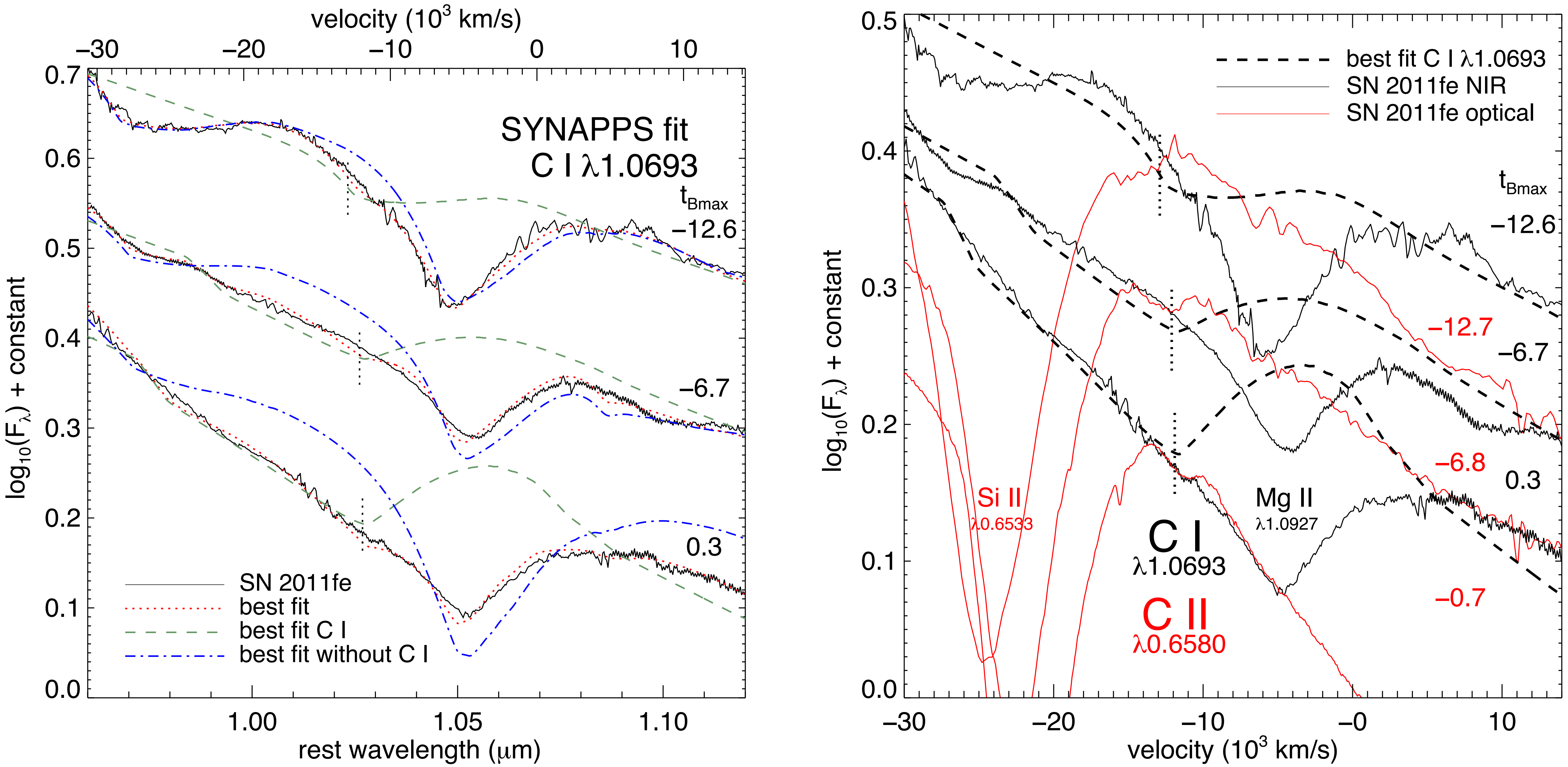
unburnt carbon

- NIR C I 10693 near Mg II 10972
- strong + isolated
- lasts until maximum



Hsiao+ (2014) in prep

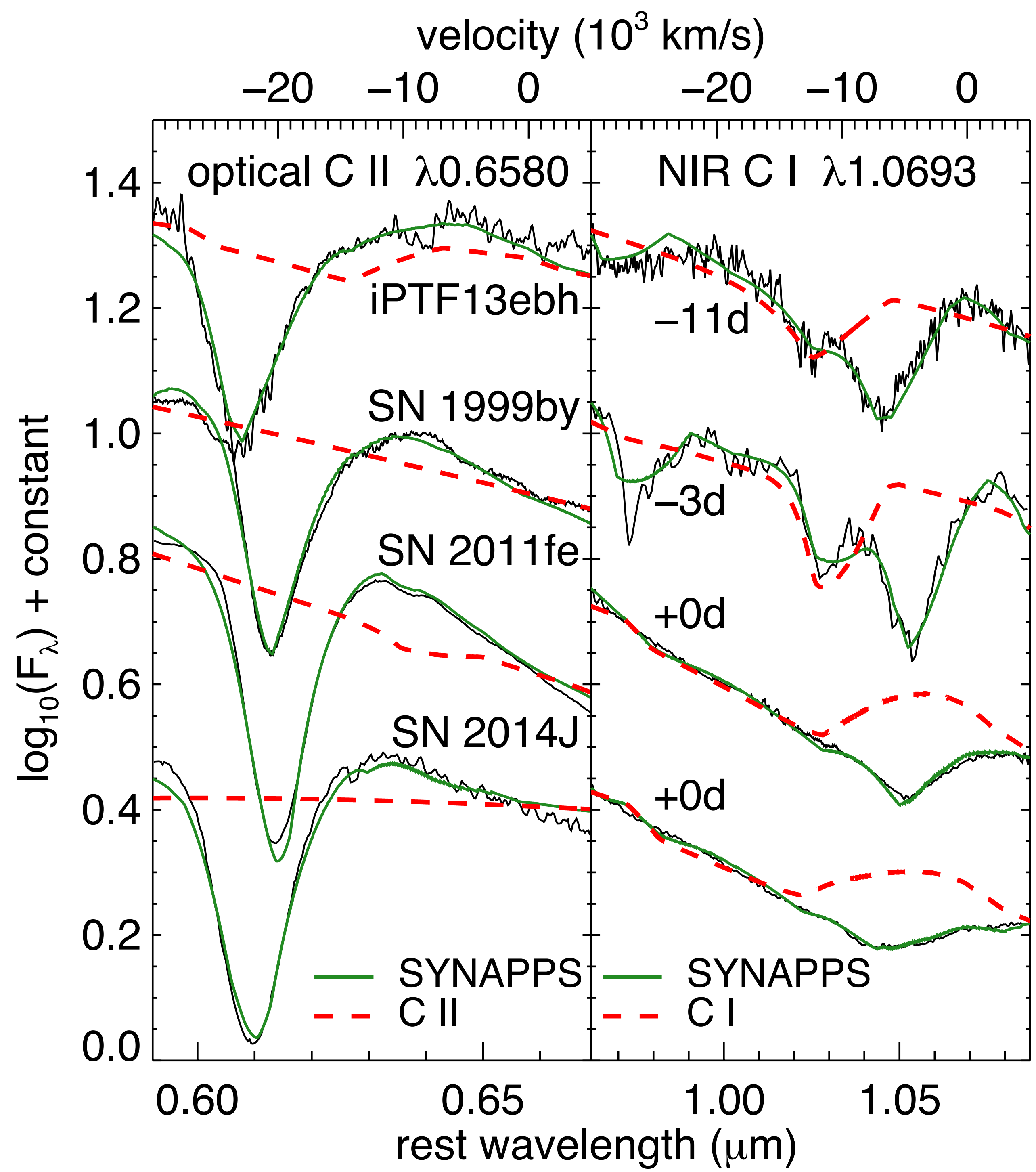
unburnt carbon



Hsiao+ (2013)

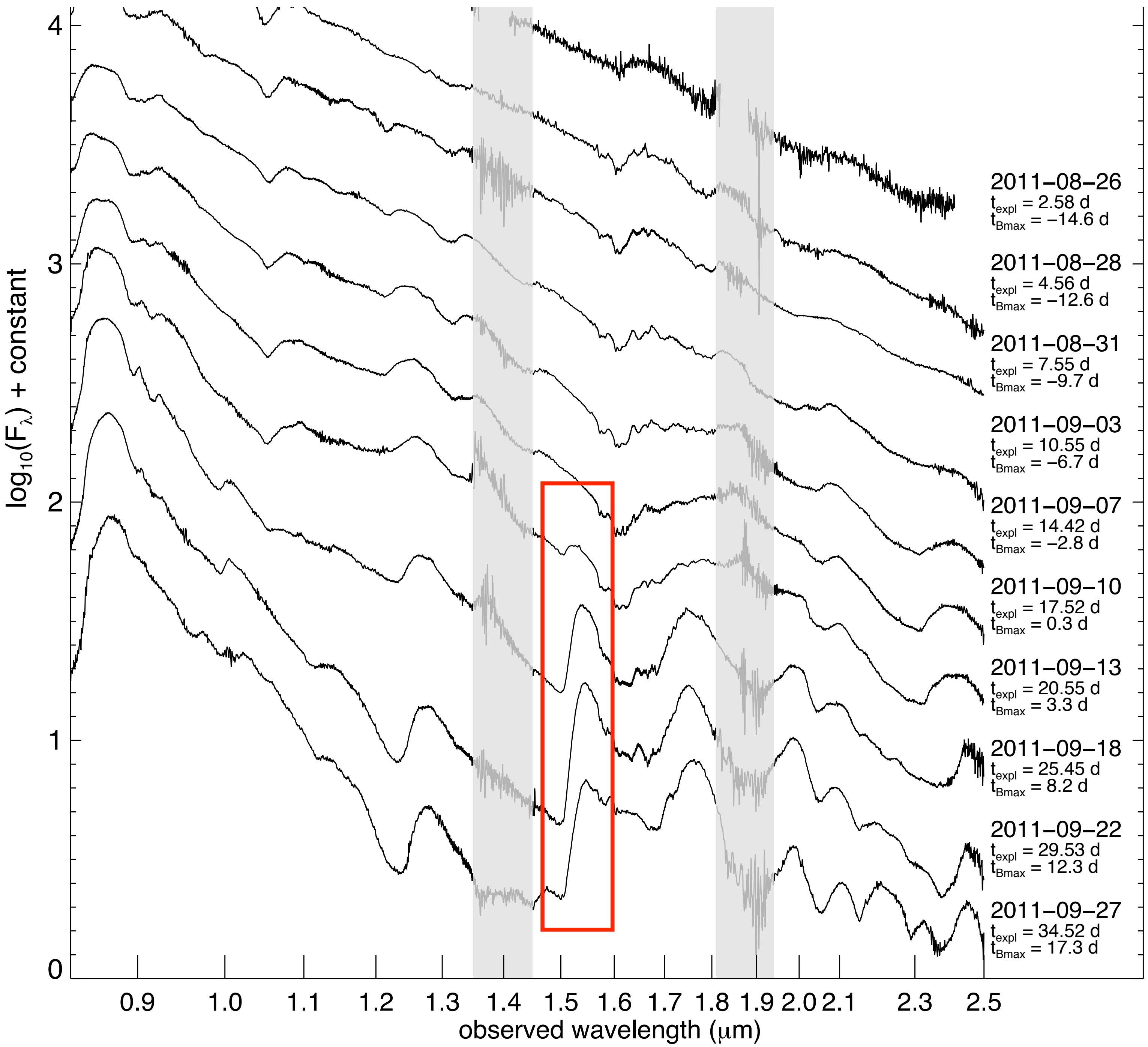
unburnt carbon

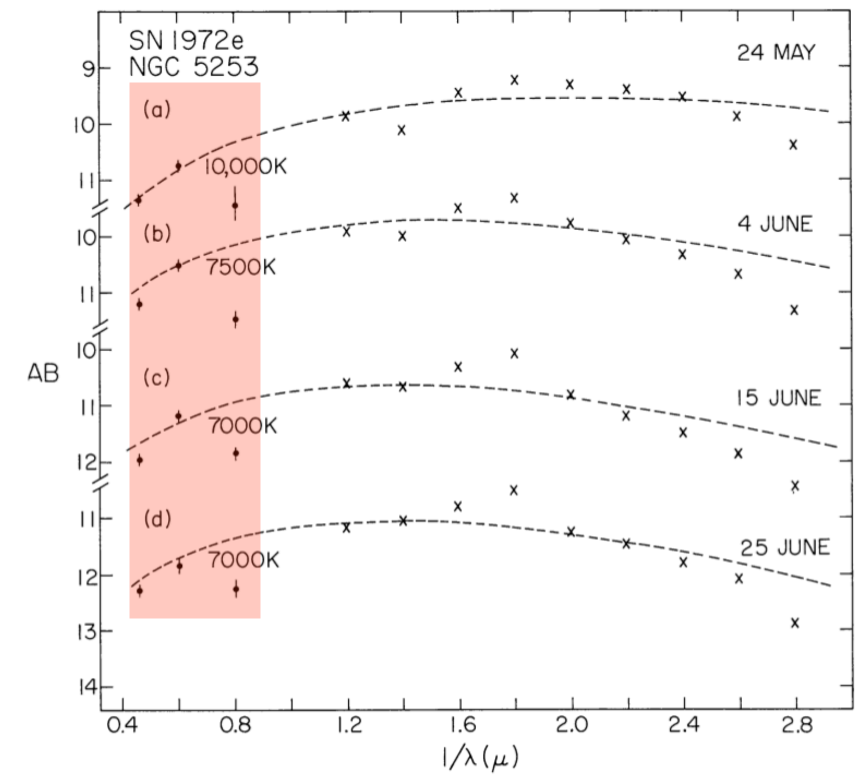
- NIR C I much stronger than optical C II
- C II to C I recombination delay in the onset of C I
- So far 4 NIR C I detections
  SN1999by (Höflich+ 2002)
  SN2011fe (Hsiao+ 2013)
  SN2014J (Marion+ 2014)
  iPTF13ebh (Hsiao+ 2014)
- Is unburnt carbon ubiquitous in SNe Ia?



Hsiao+. (2014) in prep

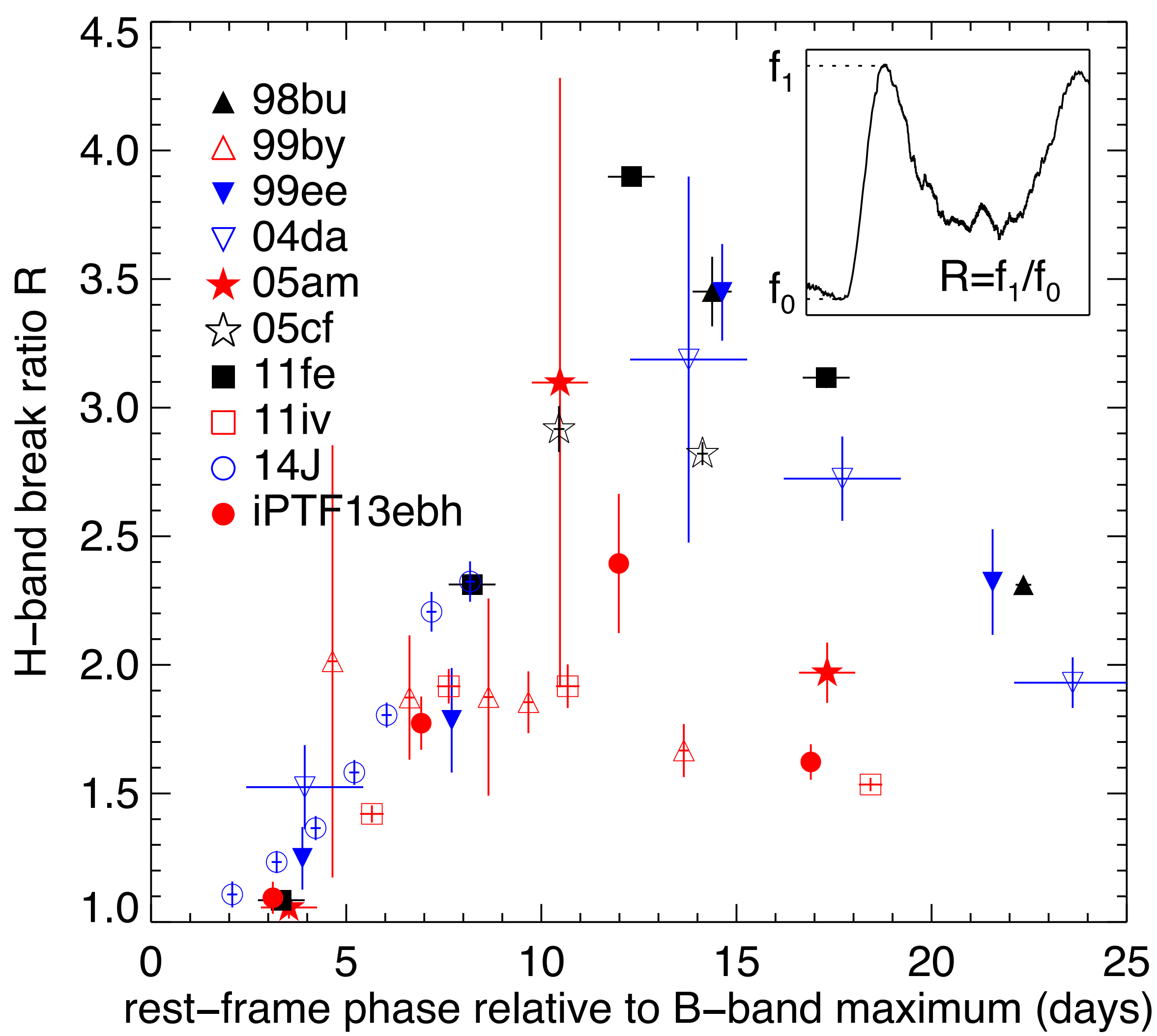
H-band break

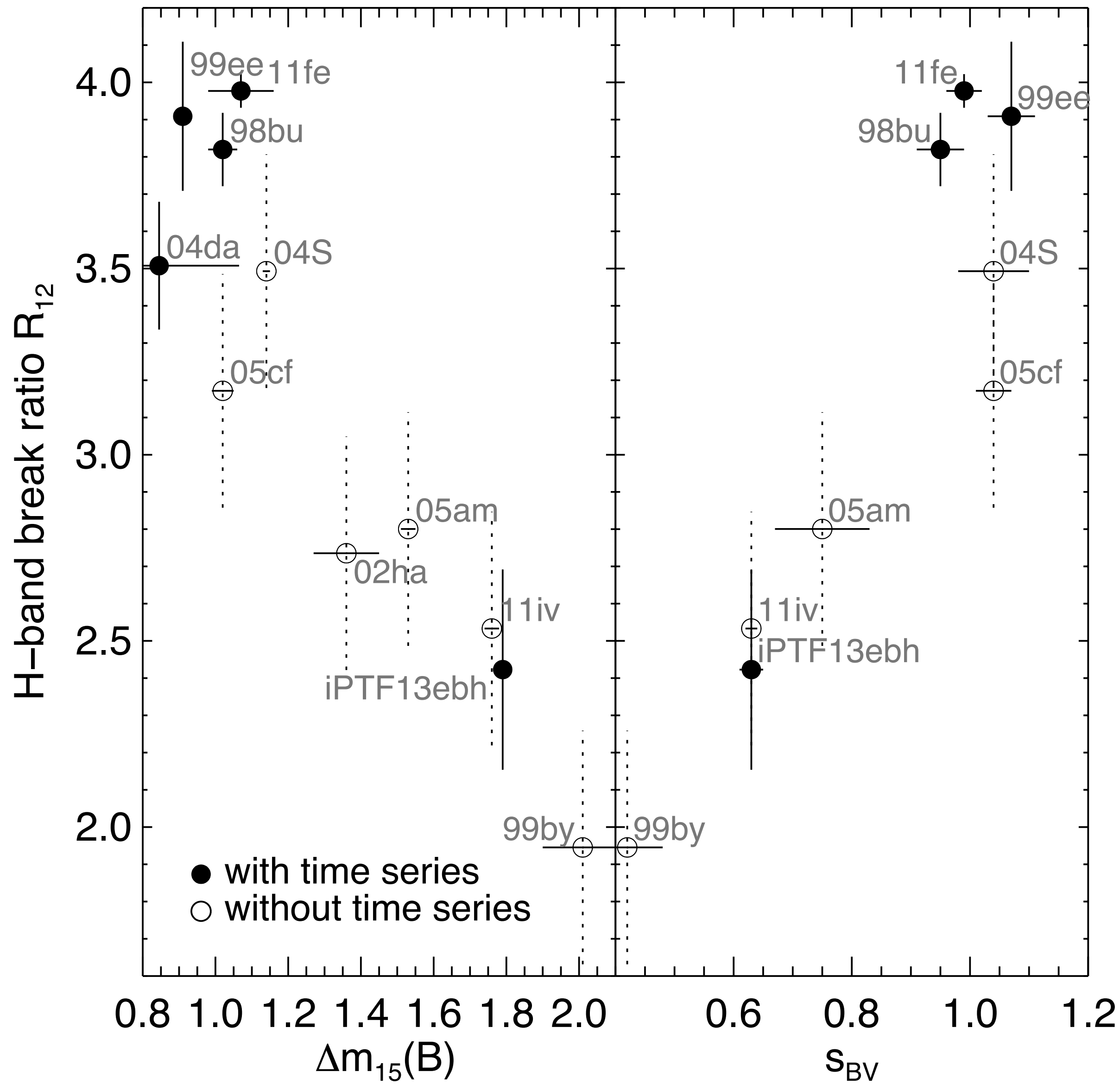




Kirshner+ (1973)
Elias+ (1985)

H-band break

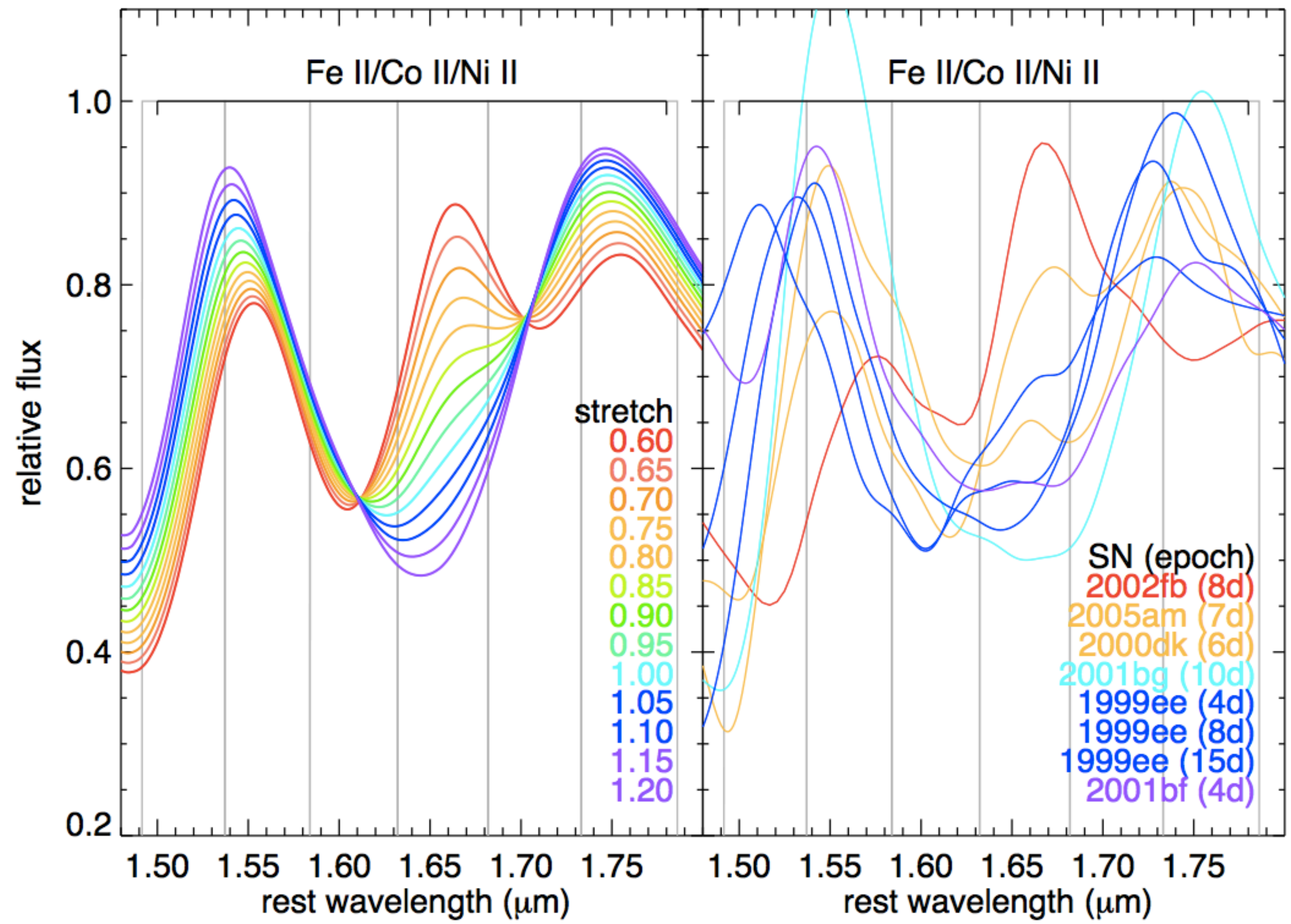




Hsiao+ (2013, 2014)

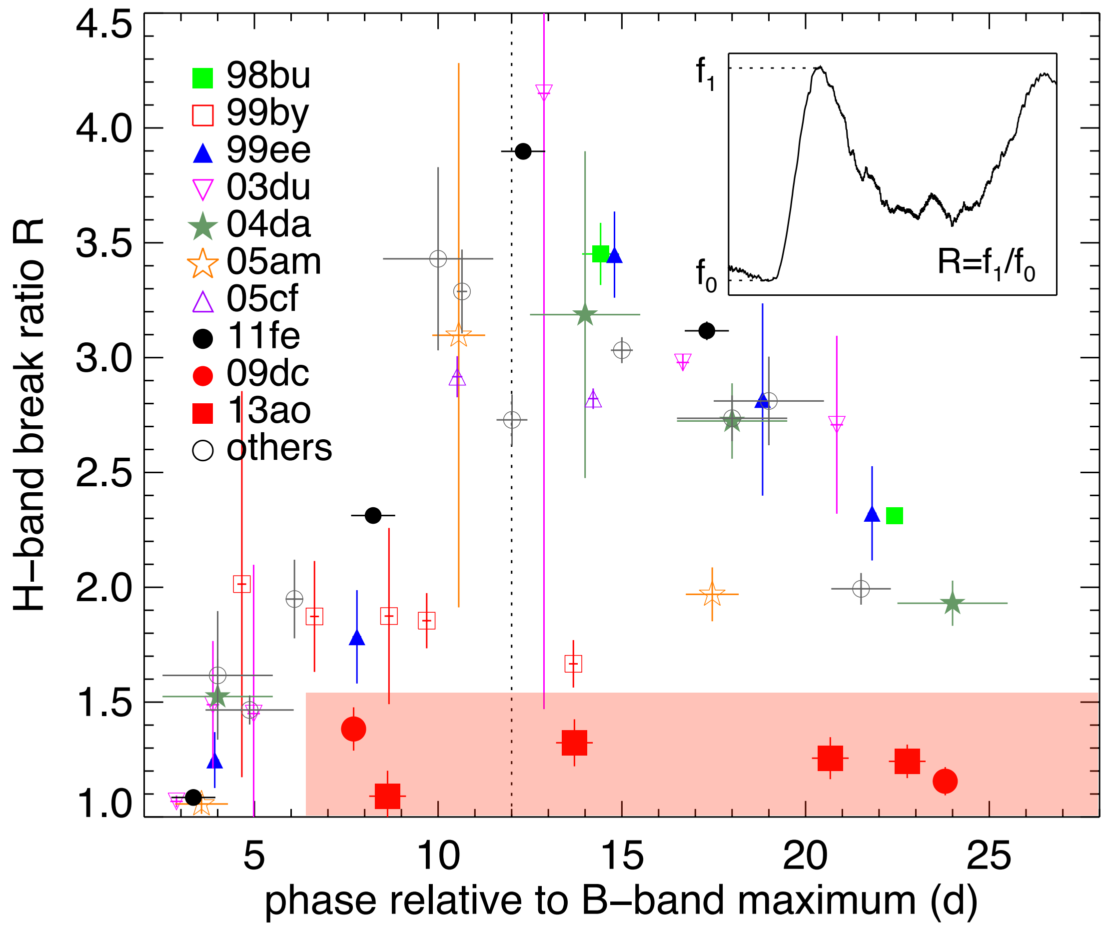
H-band break

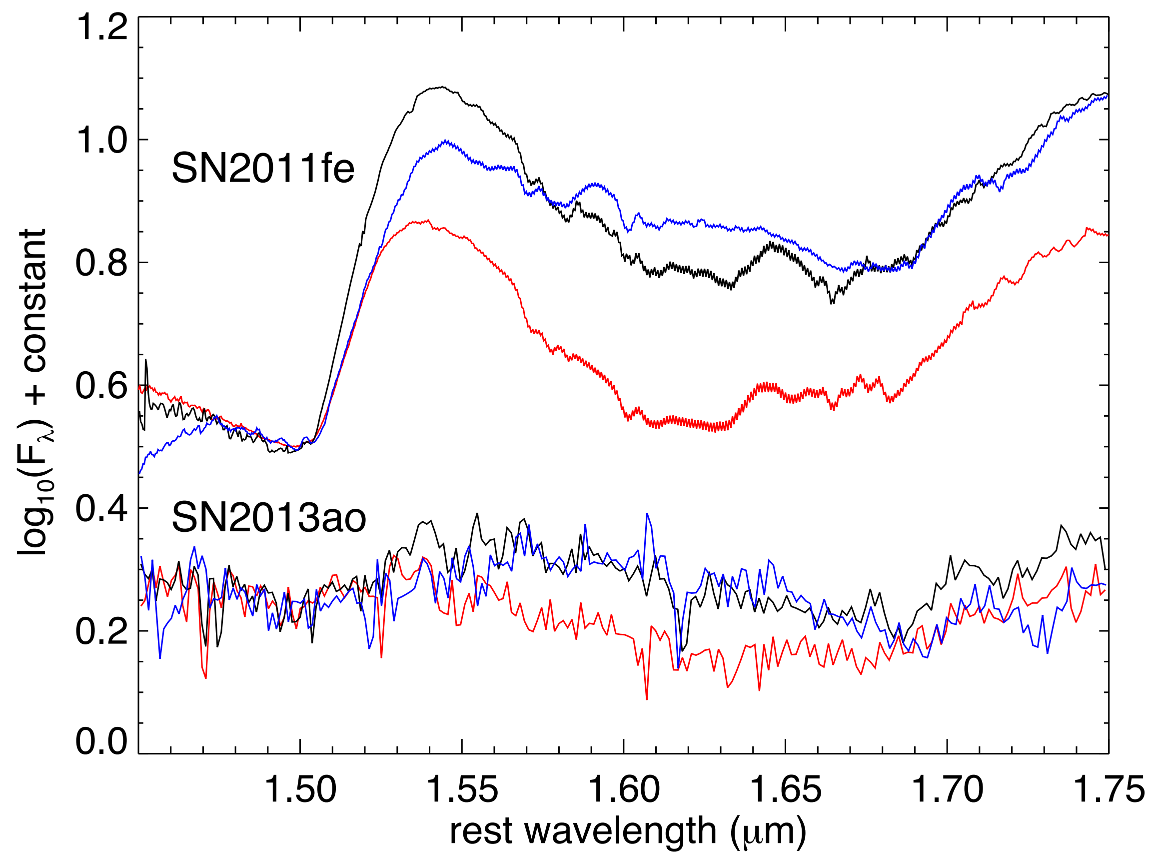
- H-band break = amount and distribution of ^{56}Ni
- There is hope of lowering k-correction errors



Hsiao (2009)

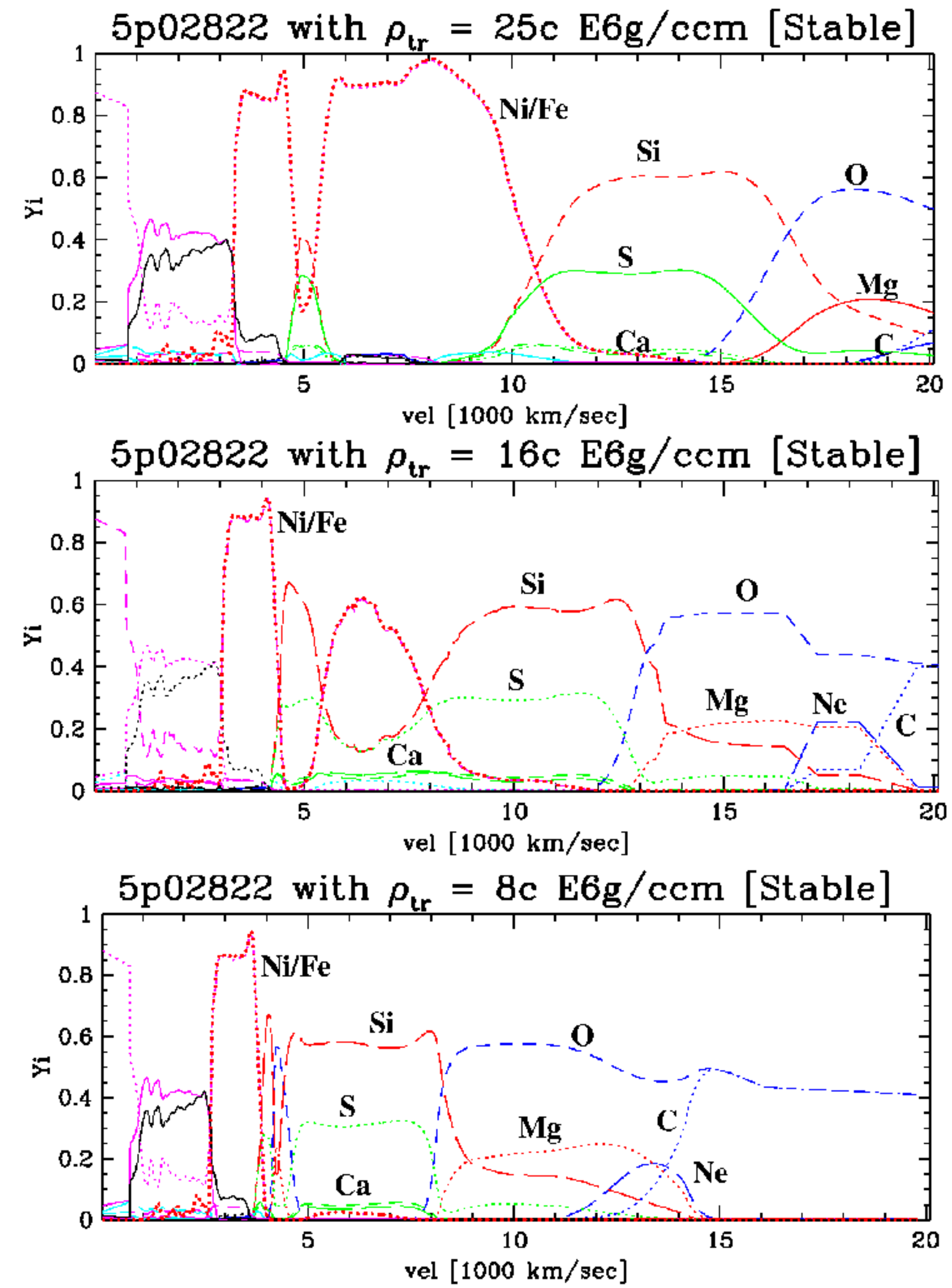
H-band break super-C





magnesium velocity

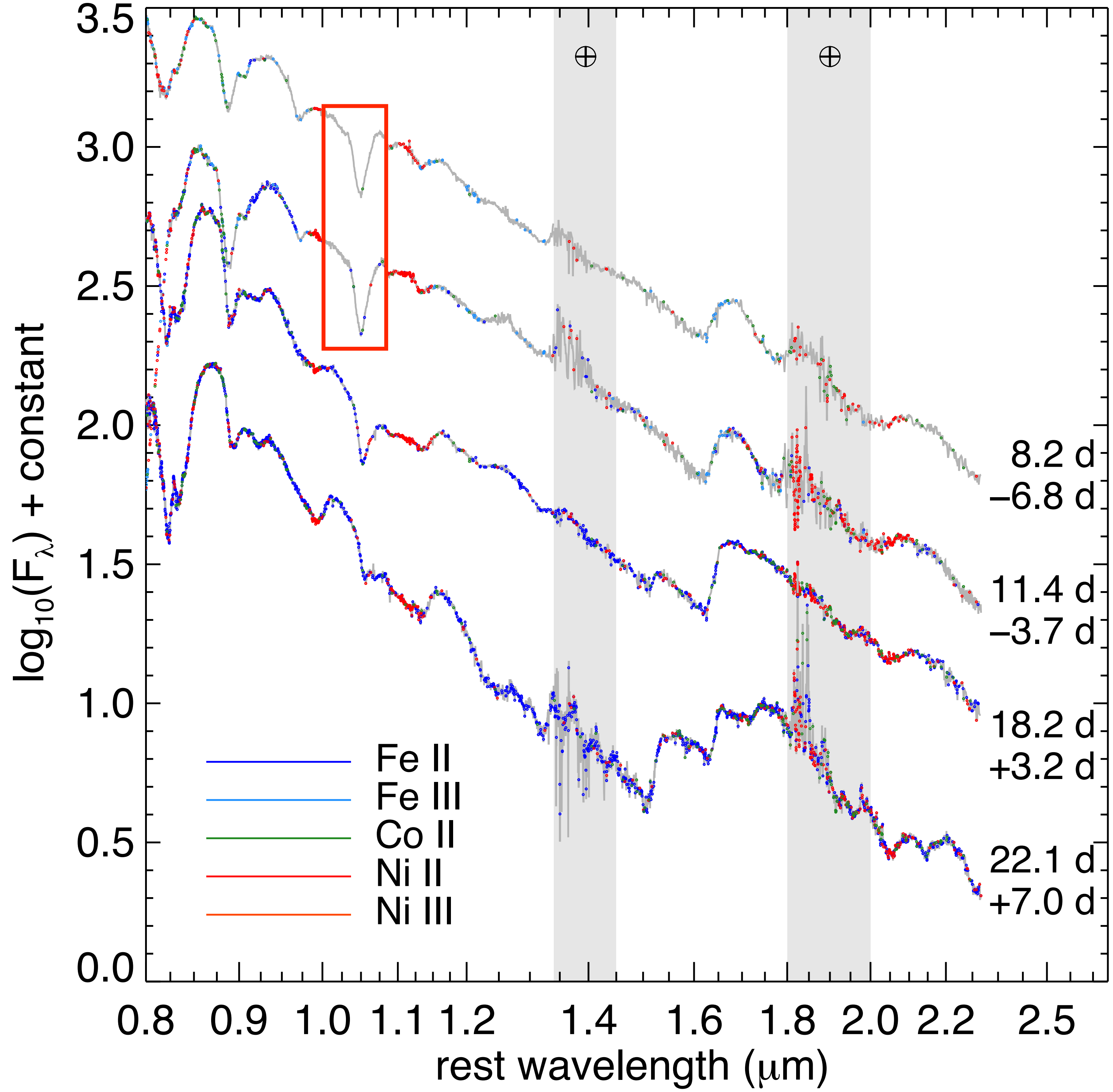
- magnesium product of carbon burning
- boundary between carbon/oxygen burning



Höflich+ 2002

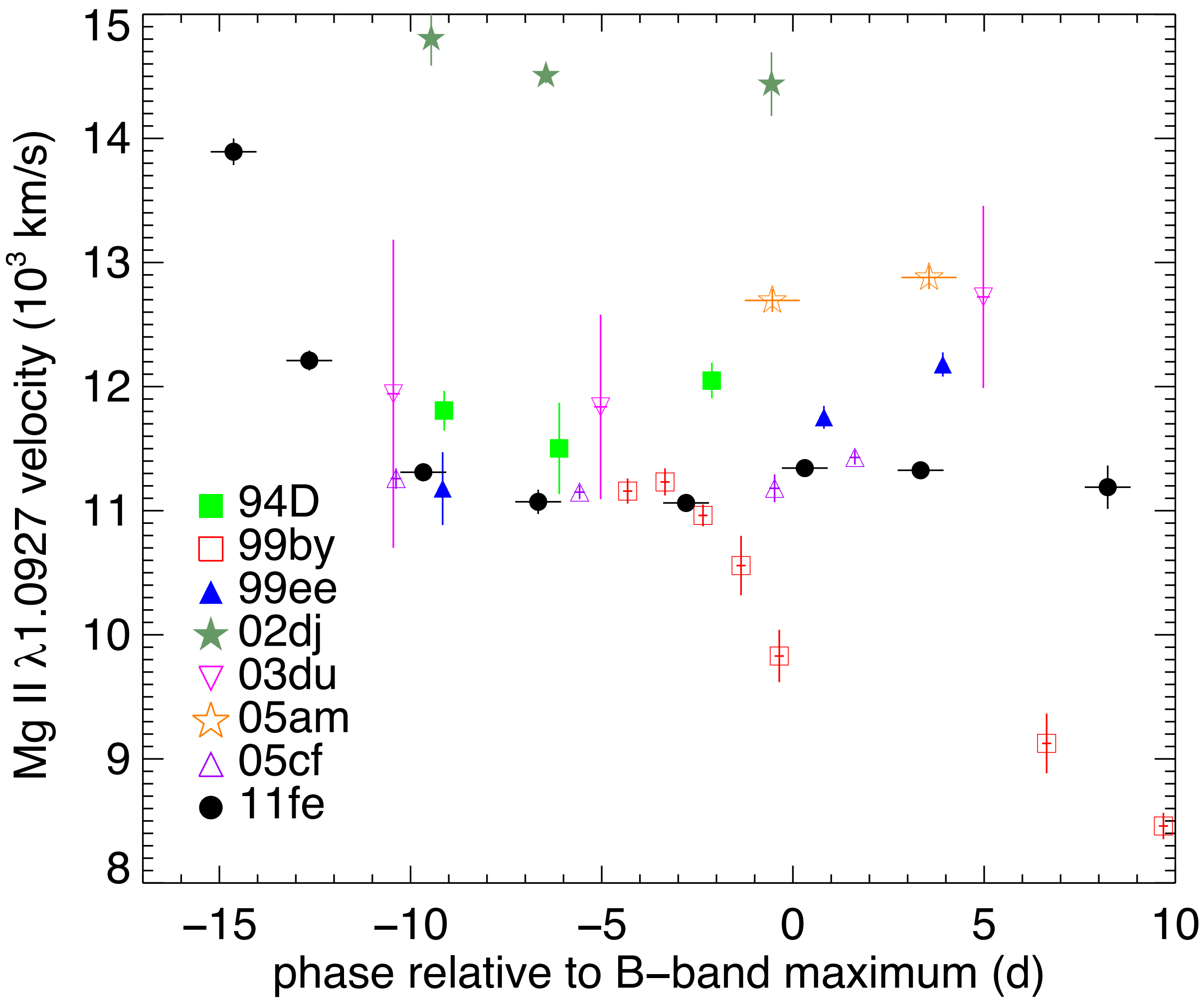
magnesium velocity

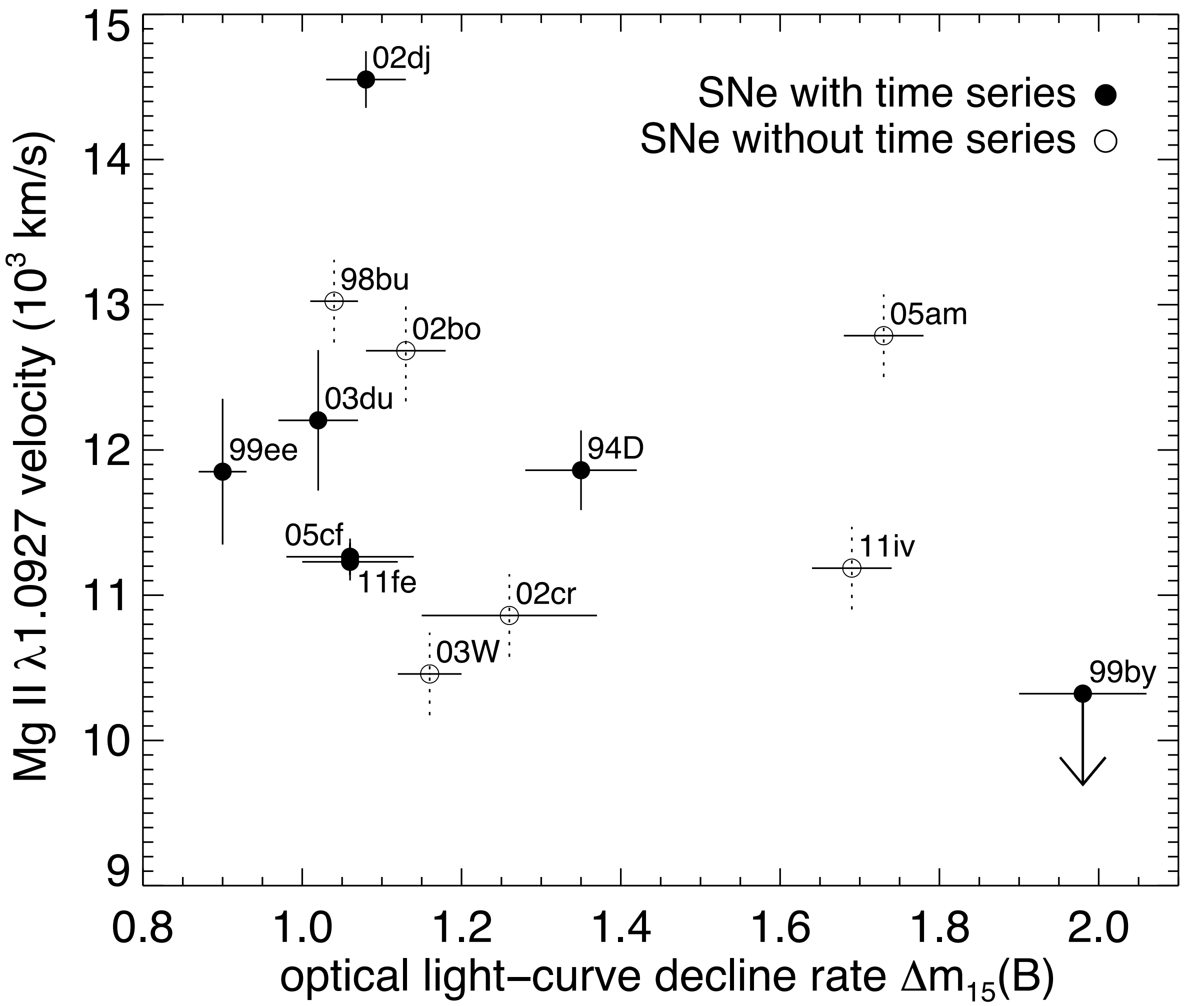
- Mg II 10972
- strong + isolated



Hsiao+ (2014) in prep

magnesium velocity

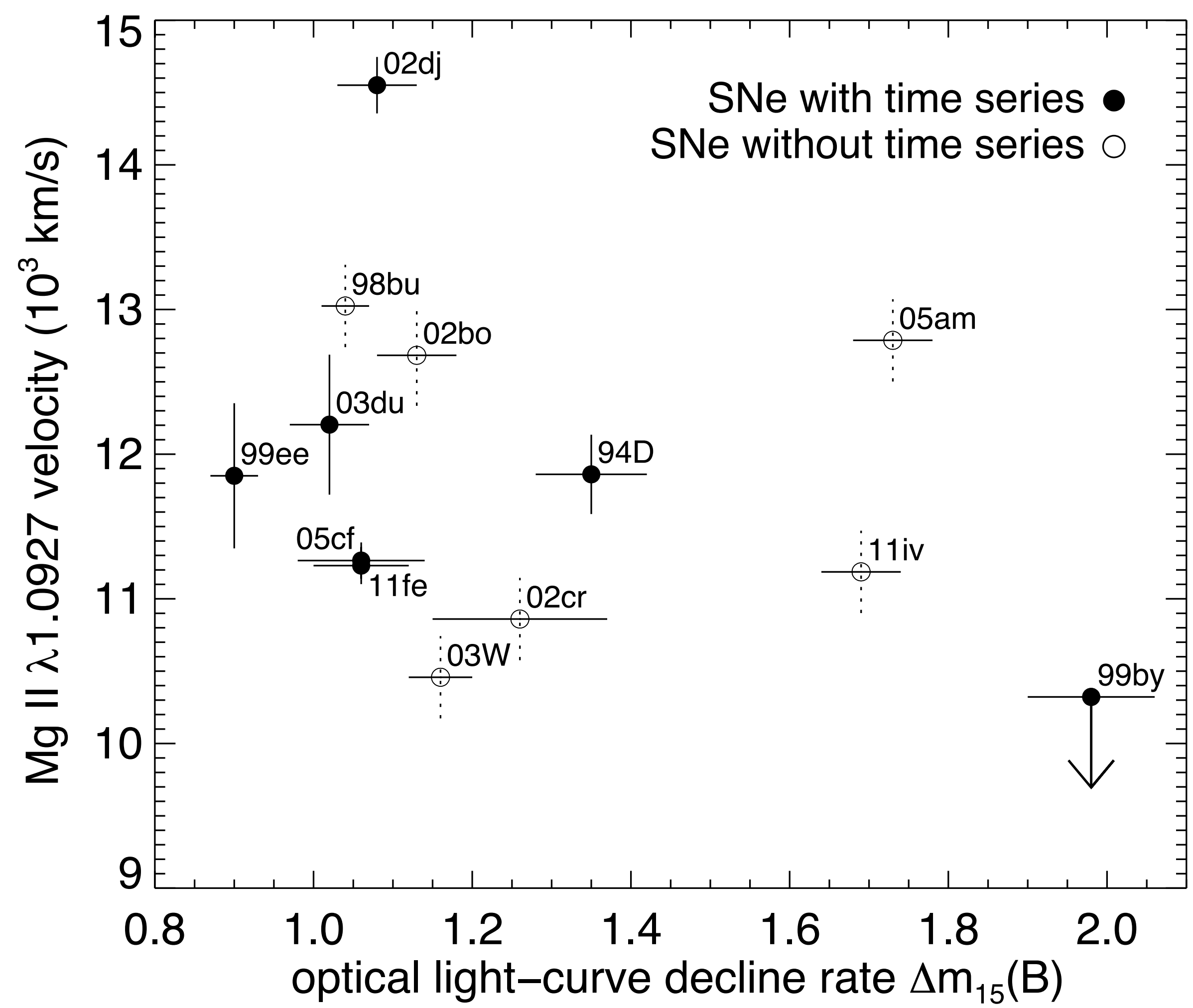




Hsiao+ 2013

magnesium velocity

- confirm Mg II is probing bottom of C burning layer
- transition density is *not* the main driver of SN brightness



Hsiao+ 2013