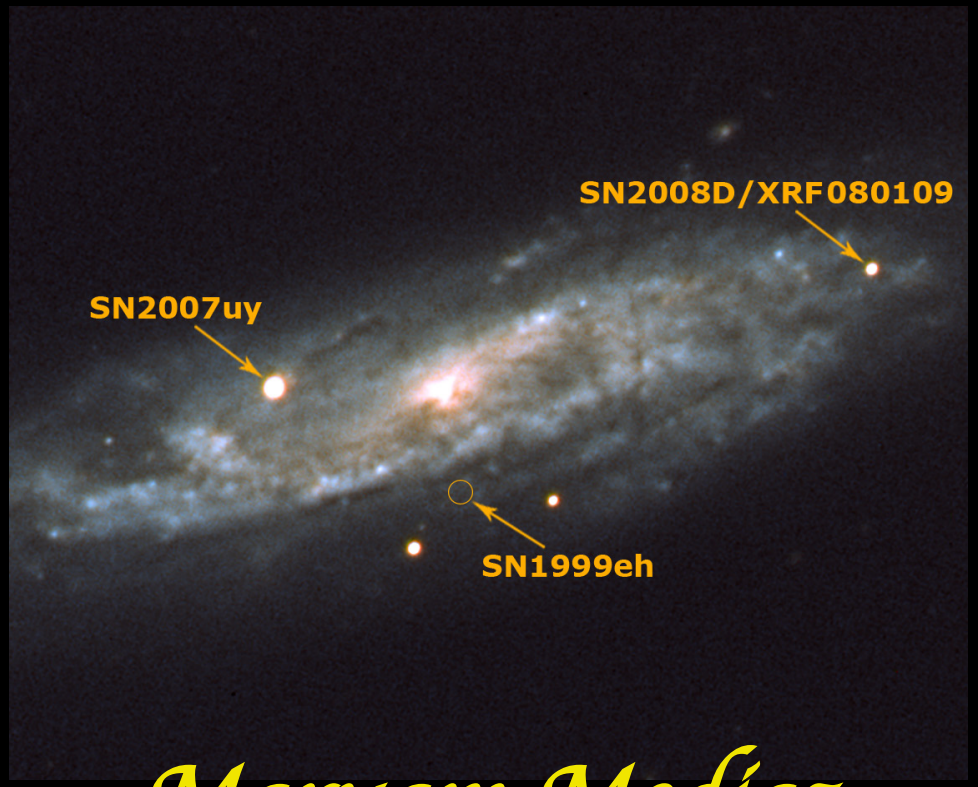
Stripped-Envelope SNe



A. de Ugarte Postigo (ESO) & Dark Cosmology Centre

Maryam Modjaz

Hubble Postdoc Fellow @ Columbia ->
Ass. Faculty @NYU

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Fellow Stellar Death Detectives

- **Harvard-CfA: Bob Kirshner**

  M. Hicken, S. Blondin, P. Challis, H. Marion, M. Wood-Vasey, A. Friedman

  Lisa Kewley (Hawaii)

- **UC Berkeley: Alex Filippenko, Josh Bloom**, N. Butler, R. Chornock, R. Foley, M. Ganeshalingam, D. Kocevski, W. Li, A. Miller, D. Perley, D. Poznanski, J. Silvermann, N. Smith, D. Starr

- **PTF:** Avishay Gal-Yam, Iair Arcavi (Weizmann Institute) & PTF collaboration

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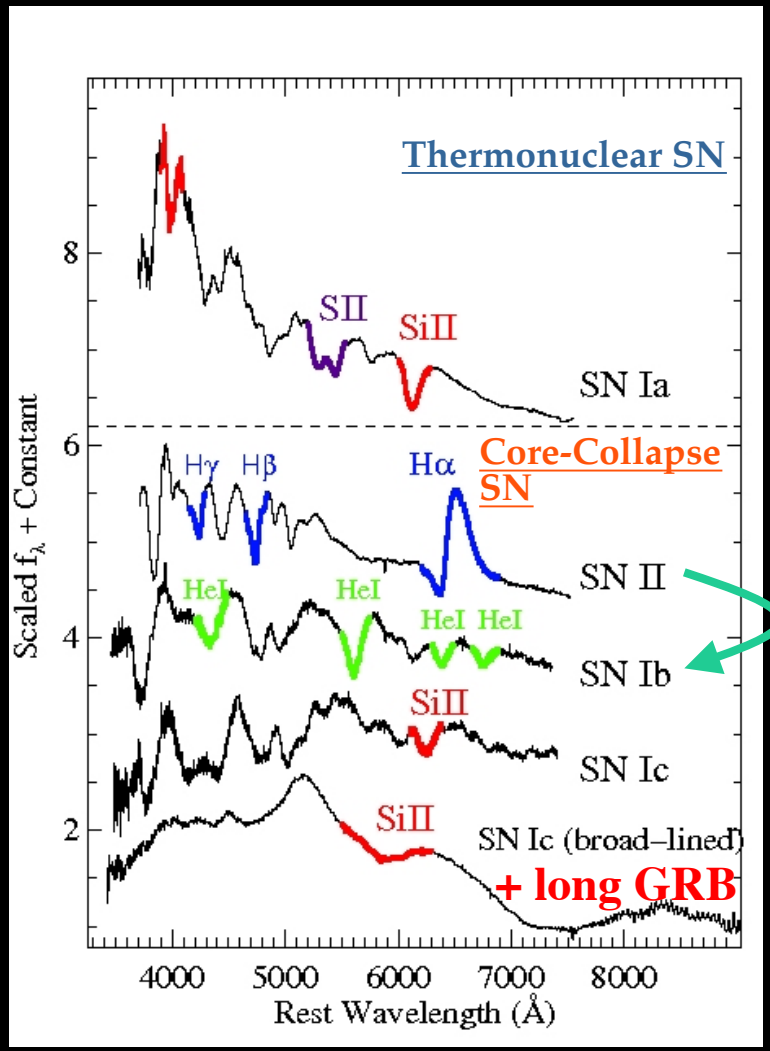
SN Zoo

- Spectra: Type I (no H) and Type II (with H)



SN IIb

+Hydrogen-rich SNe (SN IIP, IIL, IIn,.)

Broad lines:large expansion velocities (~30,000 kms^{-1})

large $E_{kinetic}$(10^{52} erg): "Hypernova"

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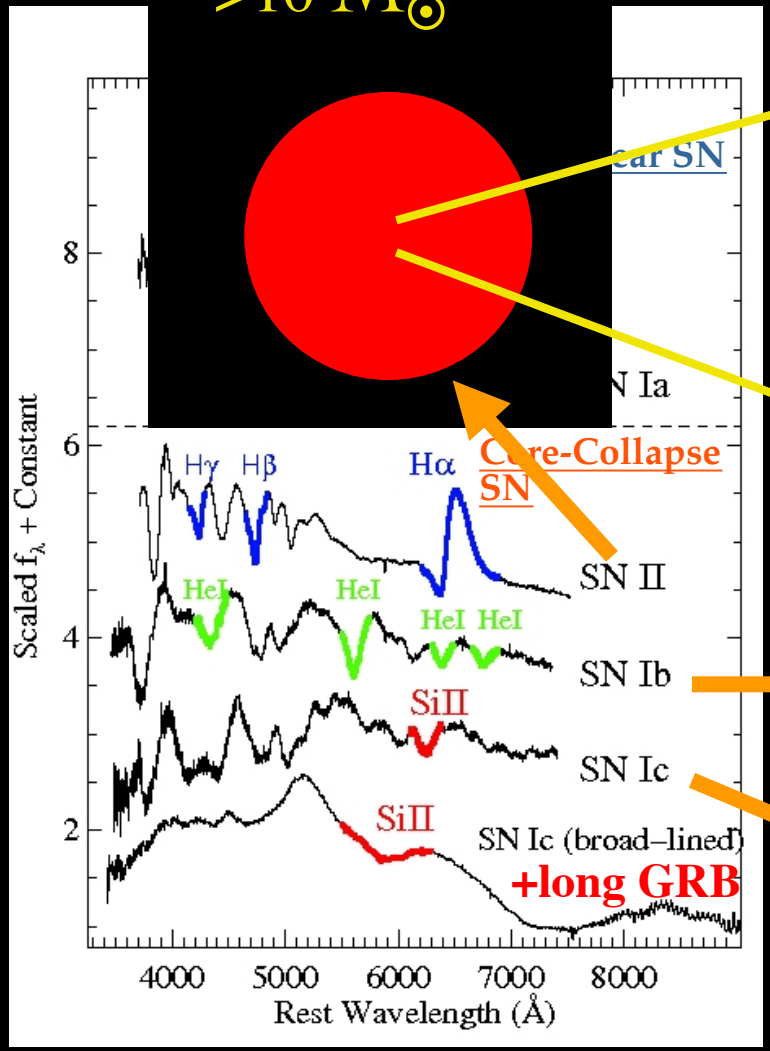
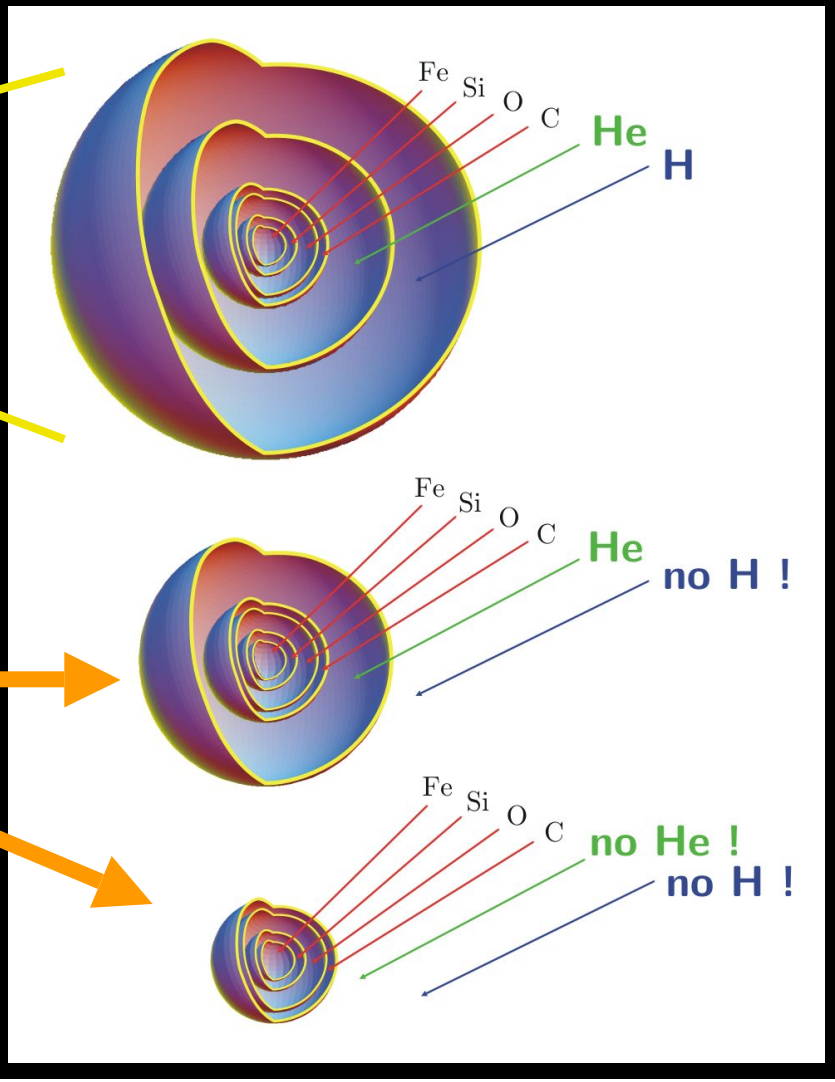
SN ZOO

- Spectra: Type I (no H) and Type II (with H)

>10 $M_\odot$





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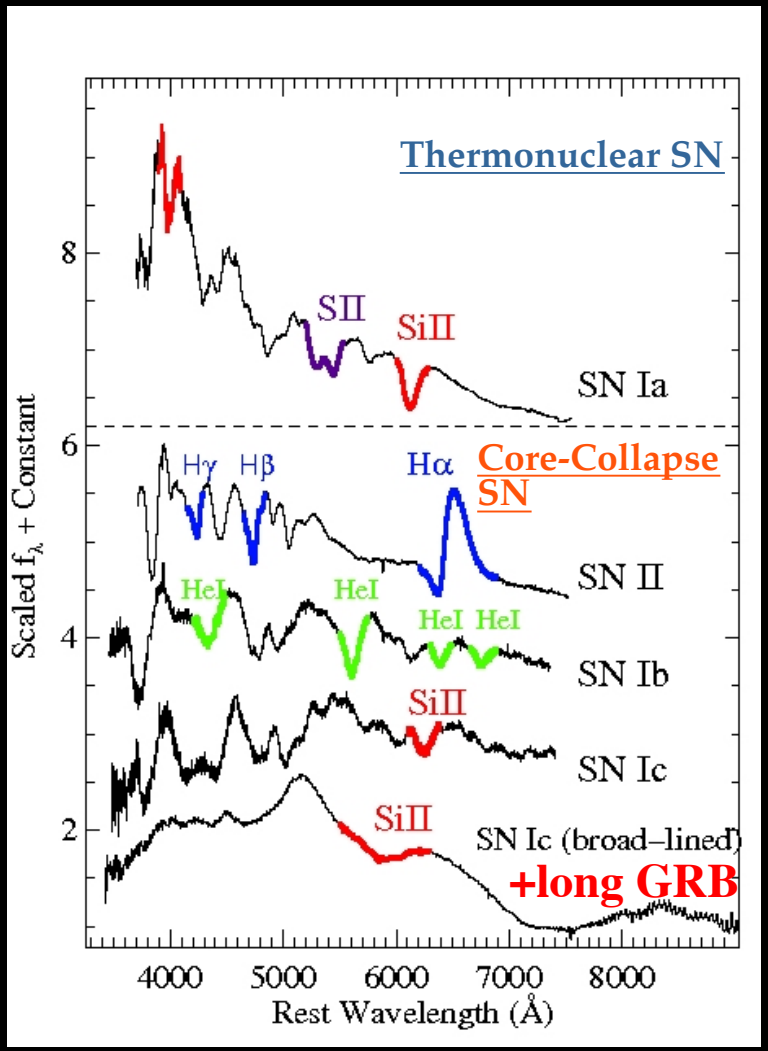
SN ZOO

- Spectra: Type I (no H) and Type II (with H)



More Zoo:

- SN Ib-n (narrow He emission)
(Matheson et al. 2001, Foley et al. 2006, Pastorello et al. 2007, Smith et al. 2007, Pastorello's Talk)

- Low-L, Calcium-rich SN Ib:
WD-WD or Core-collapse of 10 M star?
(Perets et al. 2009, 2010, Kawabata et al. 2009)

- SN2008ha + Consorts: Weak core-collapse or thermonuclear or something else? **(Valenti et al. 2009, Foley et al. 2009, Pastorello's talk)**

- Overluminous "Ic-type" SNe
(Quimby+, Pastorello's talk, Berger's talk)

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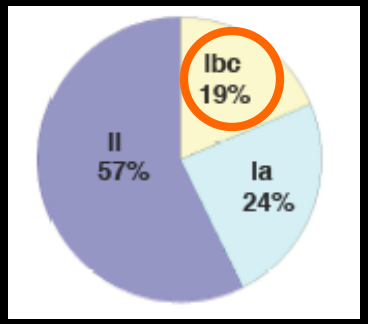
RELEVANCE OF STRIPPED SNE



SN Fractions (Volumetric, from LOSS)

(Li et al 2011, Smith et al. 2011)

- **Stellar Astrophysics**
- **Connection of SN Ic-bl to GRBs**
  - What is the range of SN Ic & SN Ic-bl properties?
  - How aspherical are (normal) SN Ib/c explosions?
- **Potential contamination** of high-z SN Ia searches by SN Ic
  (Clocchiatti et al. 2000, Homeier 2005)

- Identify & compare to "new" classes of transients/SN

However, only a **handful of well-studied** objects

- 93J, **94I**, 99ex, **05bf**, 07gr, 07Y, **08D, 08ax**, 09jf, 11dh, & SN-GRBs
- **Larger SN samples:**
  - **Matheson et al (2001):** mostly spectra, very little photometry
  - **Richardson et al. (2006):** only published LC, pre-CCD SNe
  - **Drout et al (2011):** large dataset, but only V&R photometry

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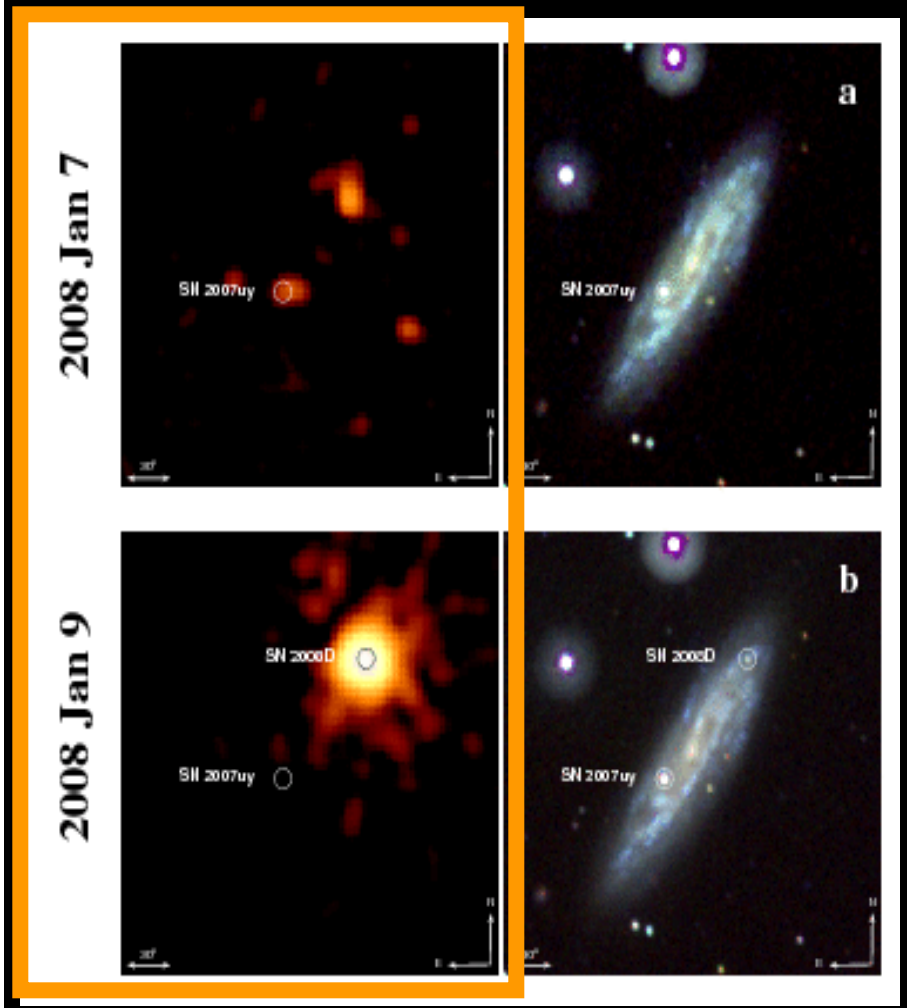
SN 2008D/XRT 080109: X-RAYS

Swift:
satellite: **Xrays** UV



Discovered by Berger & Soderberg (GCN, Jan 10, 2008)

Soderberg et al (2008)

SN2008D/XRT080109 papers:
Soderberg et al., Xi et al, Li, Malesani et al, Mazzali et al, Chevalier & Fransson, Tanaka et al, Thoene et al.

NGC 2770, D=31 Mpc

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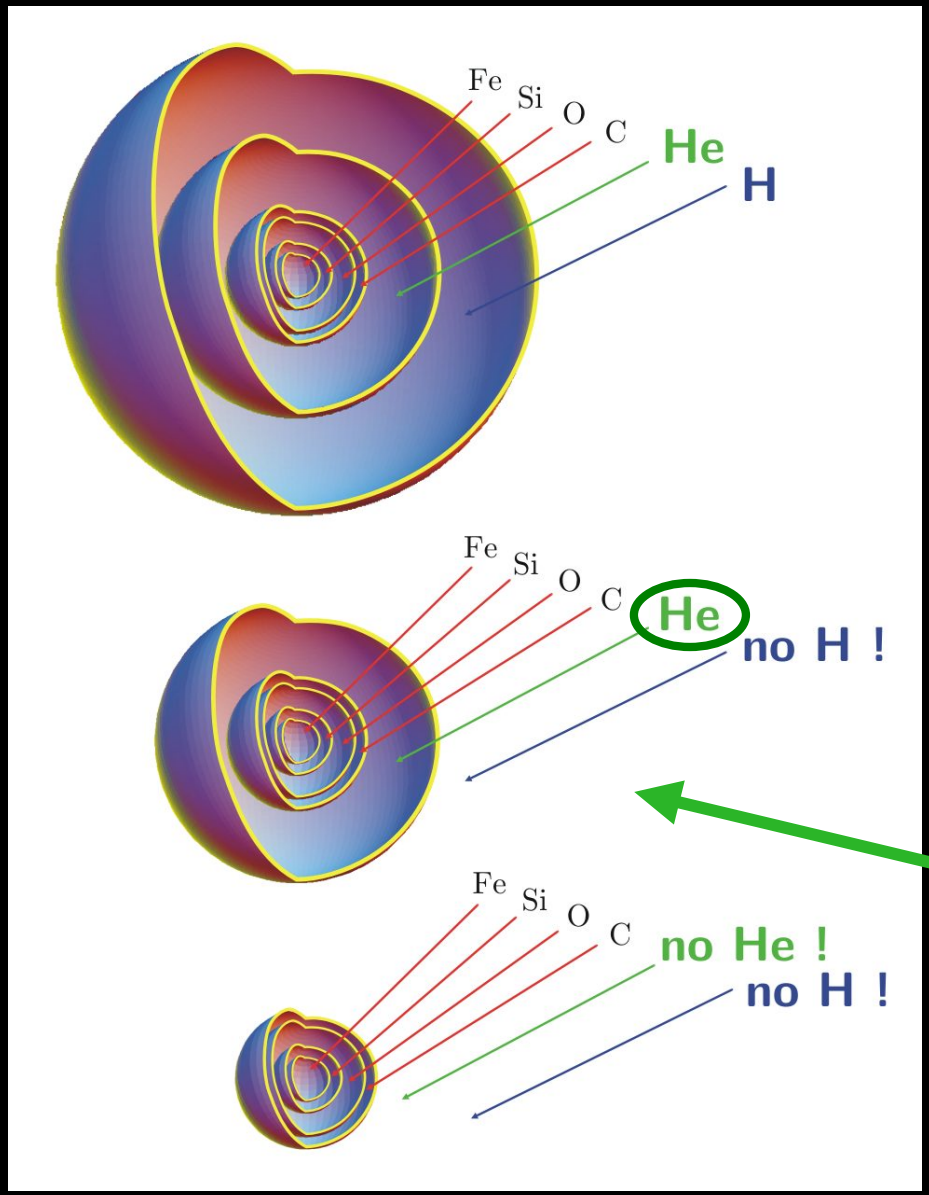
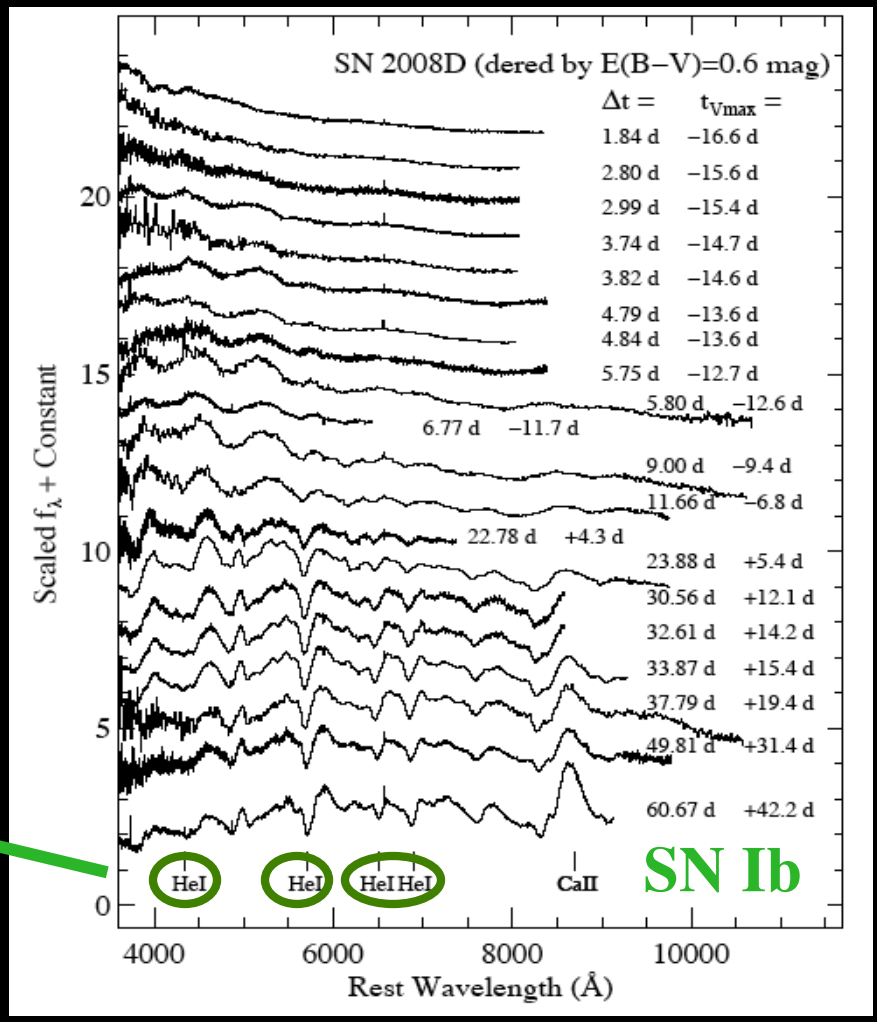
SN 2008D: SNIB (no H but He)





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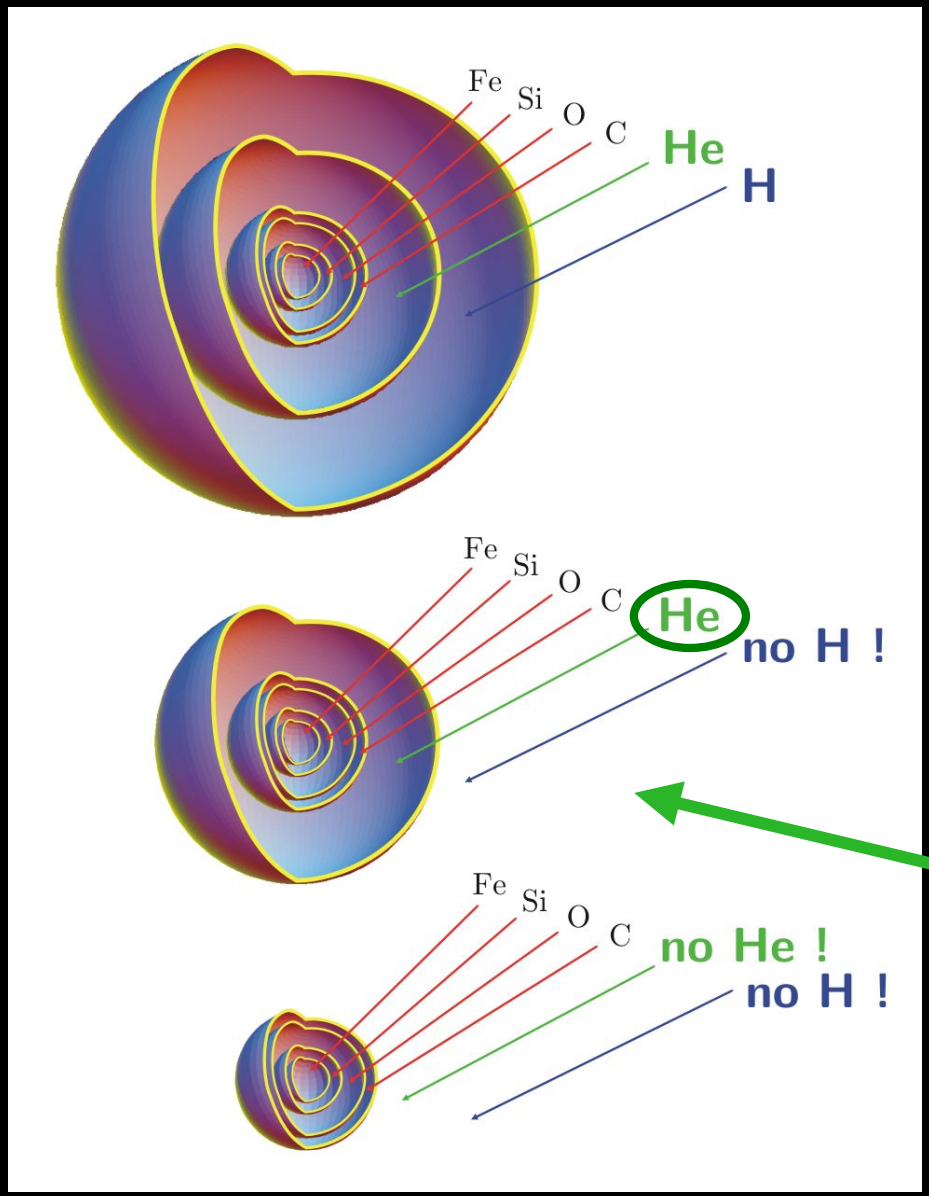
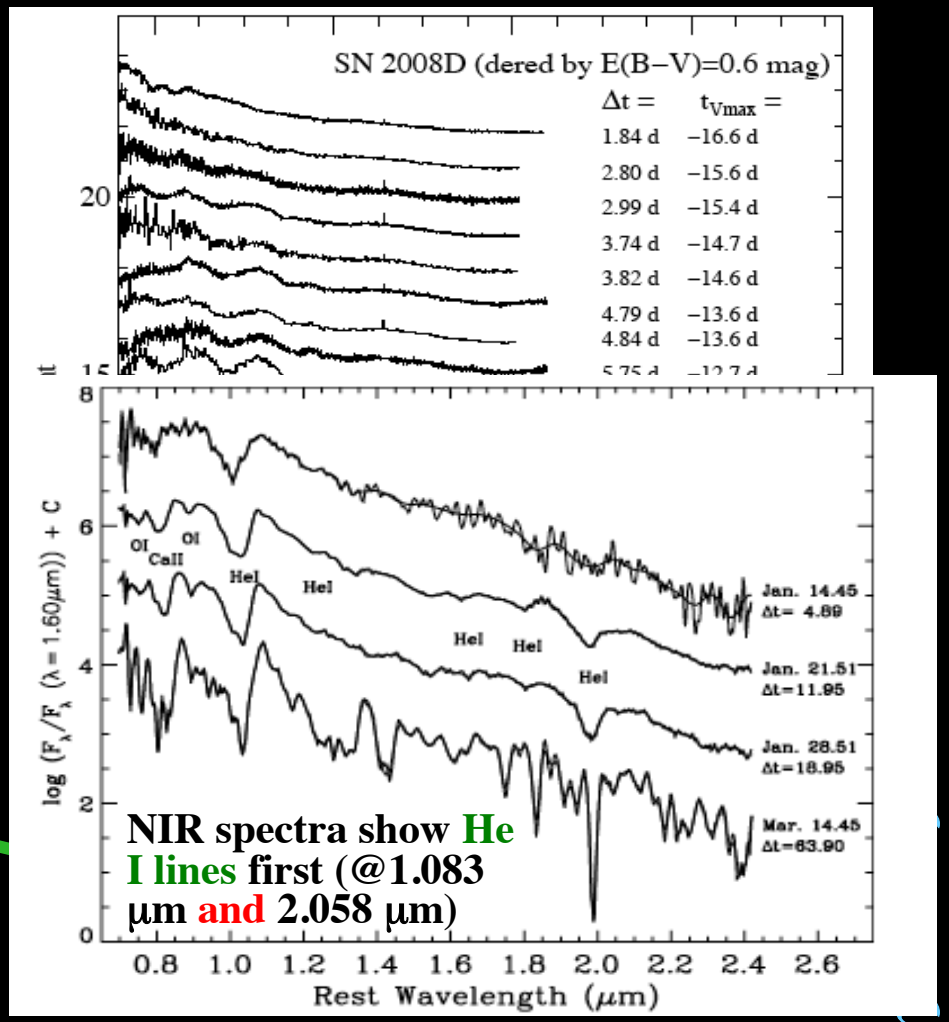
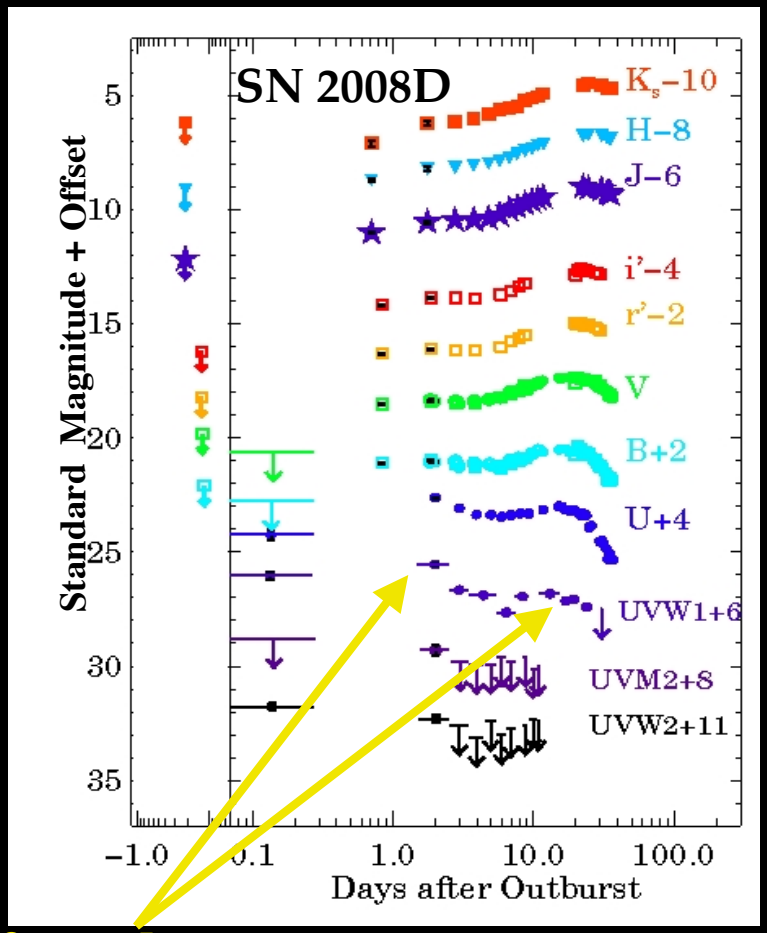
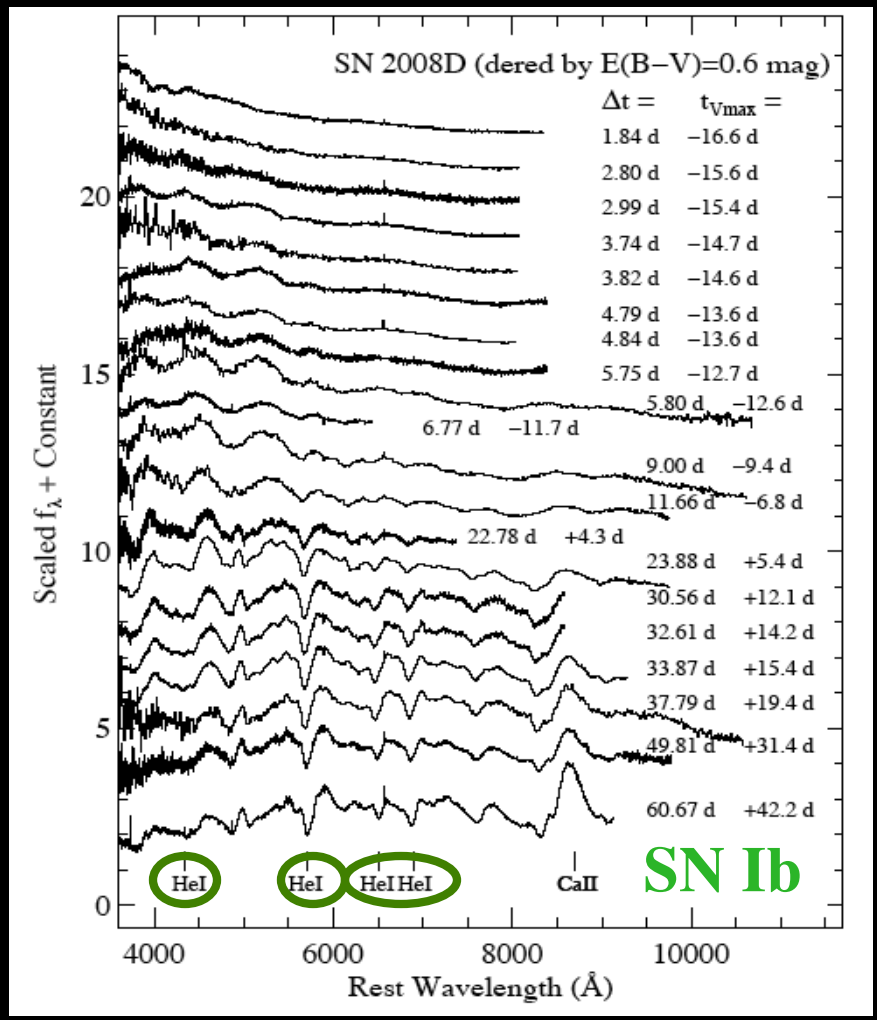
SN 2008D: SNIb (no H but He)





SN 2008D: SNIb (no H but He)





2 peaks Modjaz et al (2009)

2nd: decay of ^{56}Ni

1st : cooling stellar envelope
(e.g., Chevalier 1992, Blinnikov et al 2000)

→ **New Transient Surveys!**

Stellar Forensics:

$R_* = 1.2 +/- 0.7\ R_\odot$ (Model from Waxman et al 2006)

or $R_* = 12 +/- 7\ R_\odot$ (Model from Chevalier & Fransson 08)

(see also Rabinak & Waxman, Nakar & Sari 2010)

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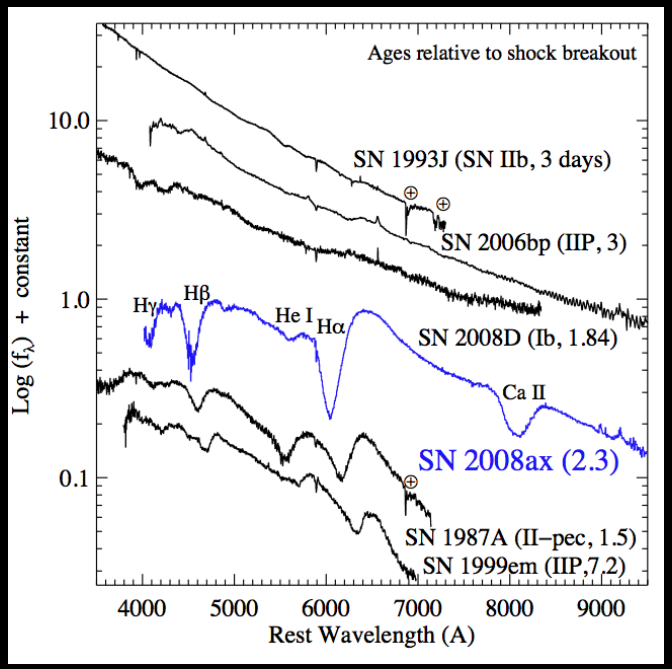
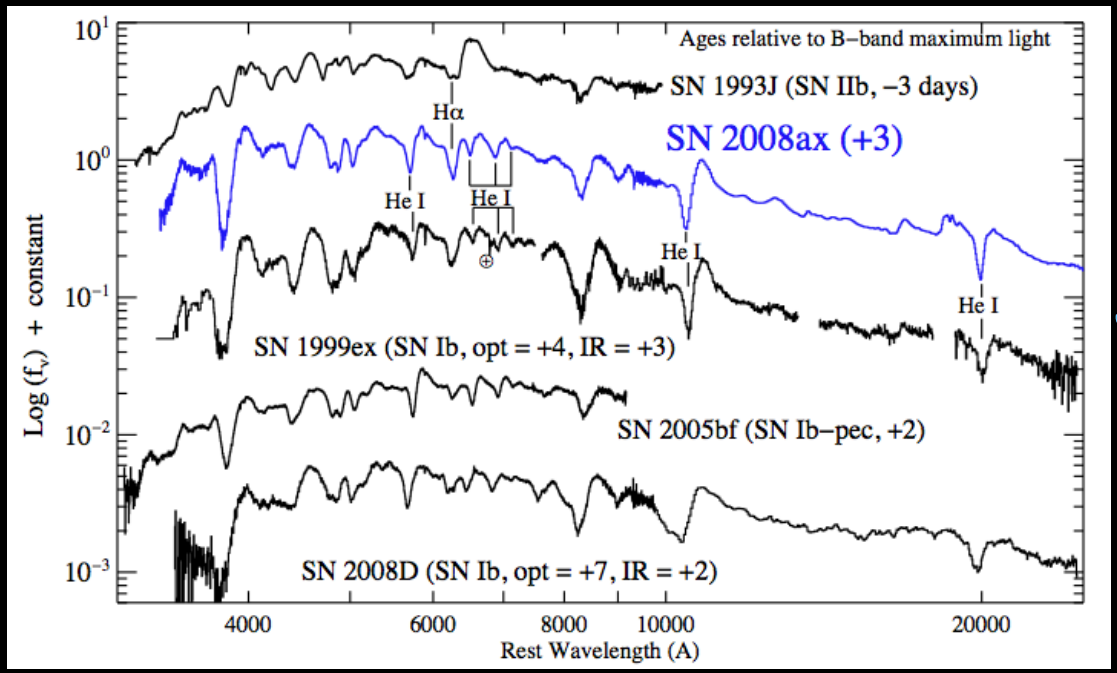
SN2008ax: Transition caught in the Act

- Discovered hours after shock breakout **(LOSS,Mostardi+08)**
- Hydrogen-dominated spectra 2 days after explosion
- Looked like normal SN Ib with strong He I lines by maximum light -> Importance of early-time, pre-max spectra !!

(See also **Pastorello+08, Crockett+08, MartÌ-Vidal+09, Roming+09, Taubenberger+11**)





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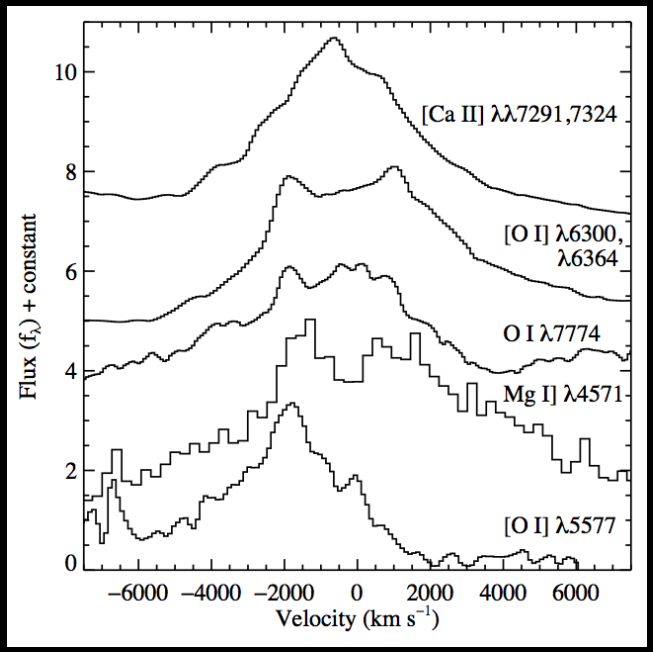
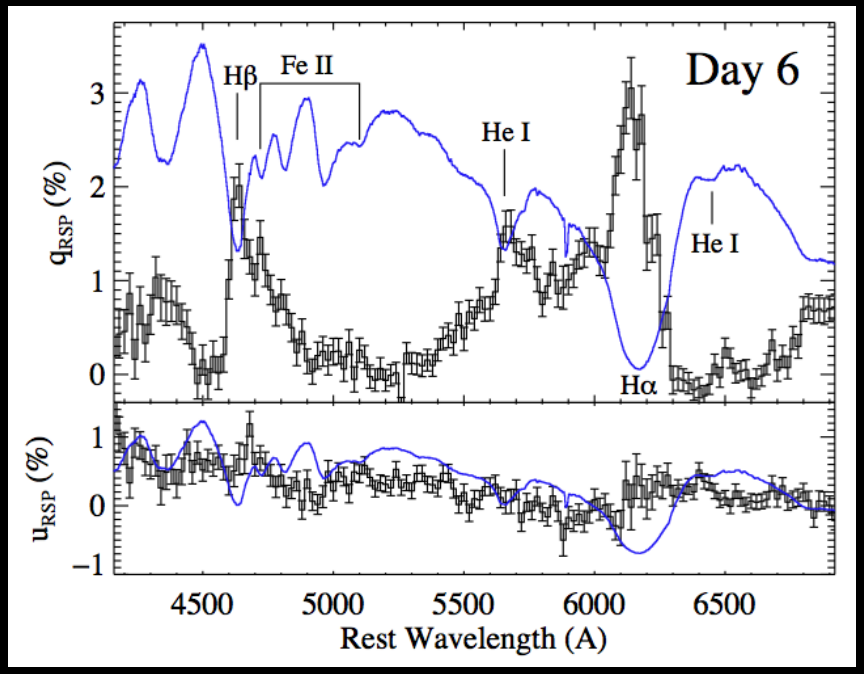
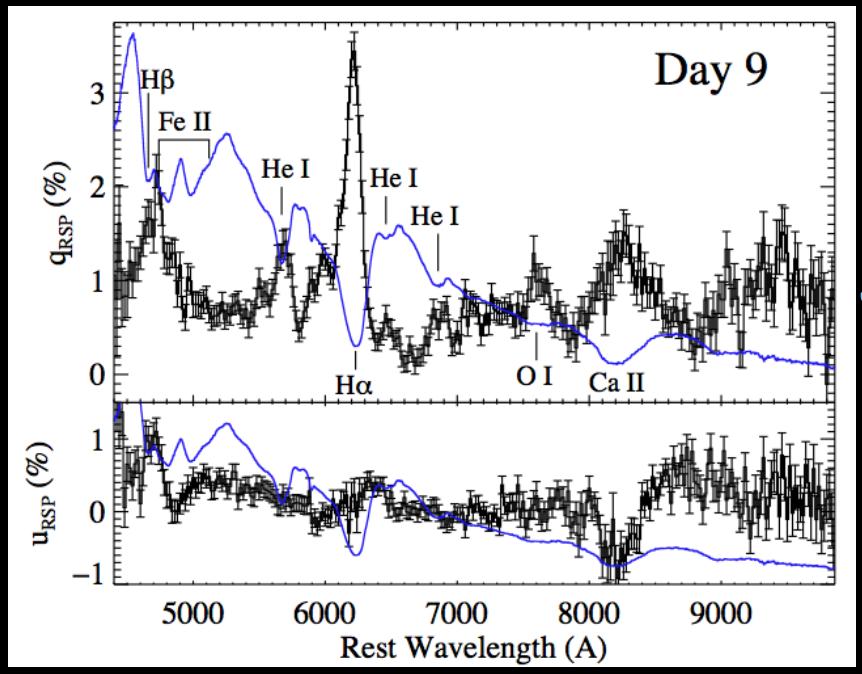
(Chornock et al. 2011, ApJ, in press)

SN2008ax: Large Asphericities

- Strong polarization (3.4% at Hα)
- H, He, and O aligned with continuum, but Fe, Ca misaligned
- Late-time line profiles







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Chornock et al. 2011, ApJ, in press

"Peculiar" or Superlative

- Titles of SN Ib/c publications:
  - "The Luminous Type IC Supernova 1992ar at z=0.145"
  - "The Peculiar Type Ib Supernova 2006jc: A WCO Wolf-Rayet Star Explosion" (Tominaga et al 2008)
  - "The Amazing Supernova 1999as"

NEXT STEP: homogeneous & densely covered data set to characterize "normal" events

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NEARBY SN CFA FOLLOW-UP

- Optical Spectroscopy: FAST on FLWO 1.5m
  - 3–4 spectra/night, ~300 spectra/year
  - Reduced in the same manner
- Optical Photometry (*UBVr'i'*): FLWO 1.2m
  - 3-4 SN/night, templates, standard star obs
- NIR Photometry (*JHK*$_s$): PAIRITEL 1.3m
  - 3-4 SN/night
- Late-time (>3 months) Spectra:
  - MMT (AZ), Magellan (Chile), Gemini-North

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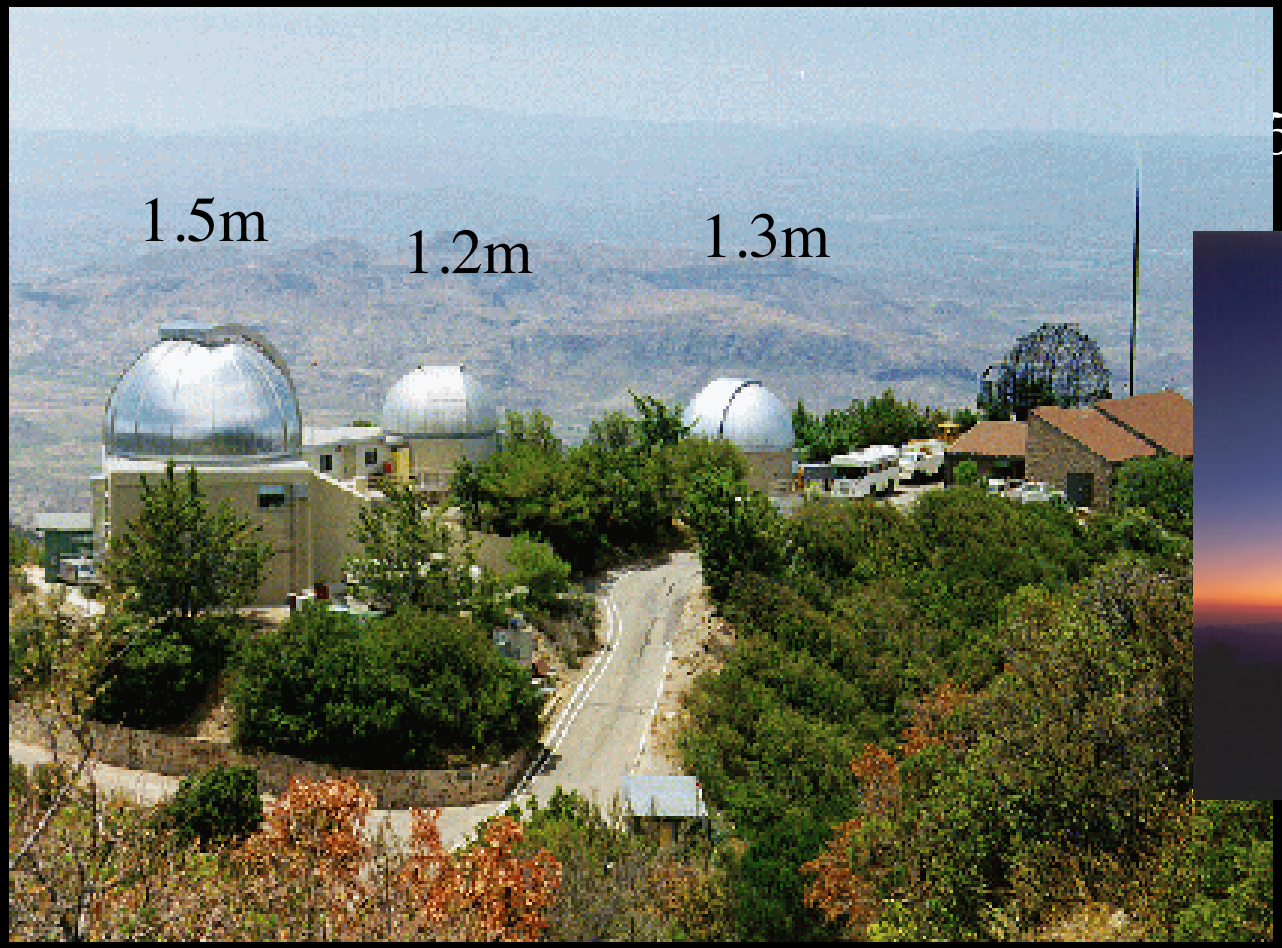
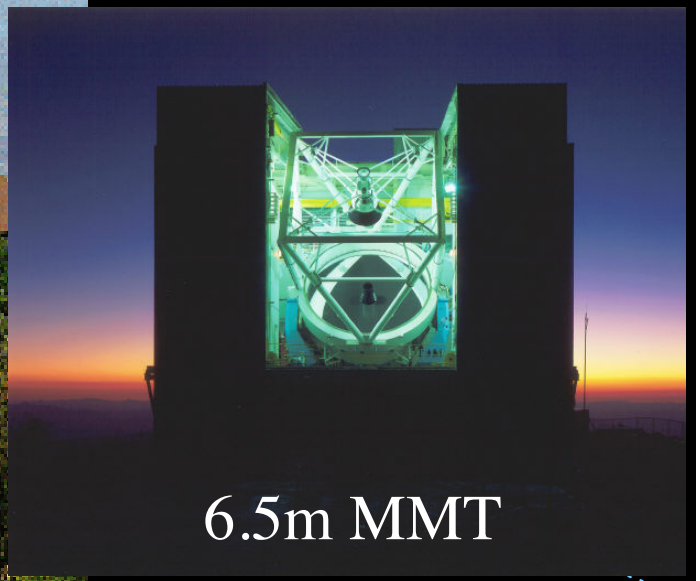
NEARBY SN CFA FOLLOW-UP

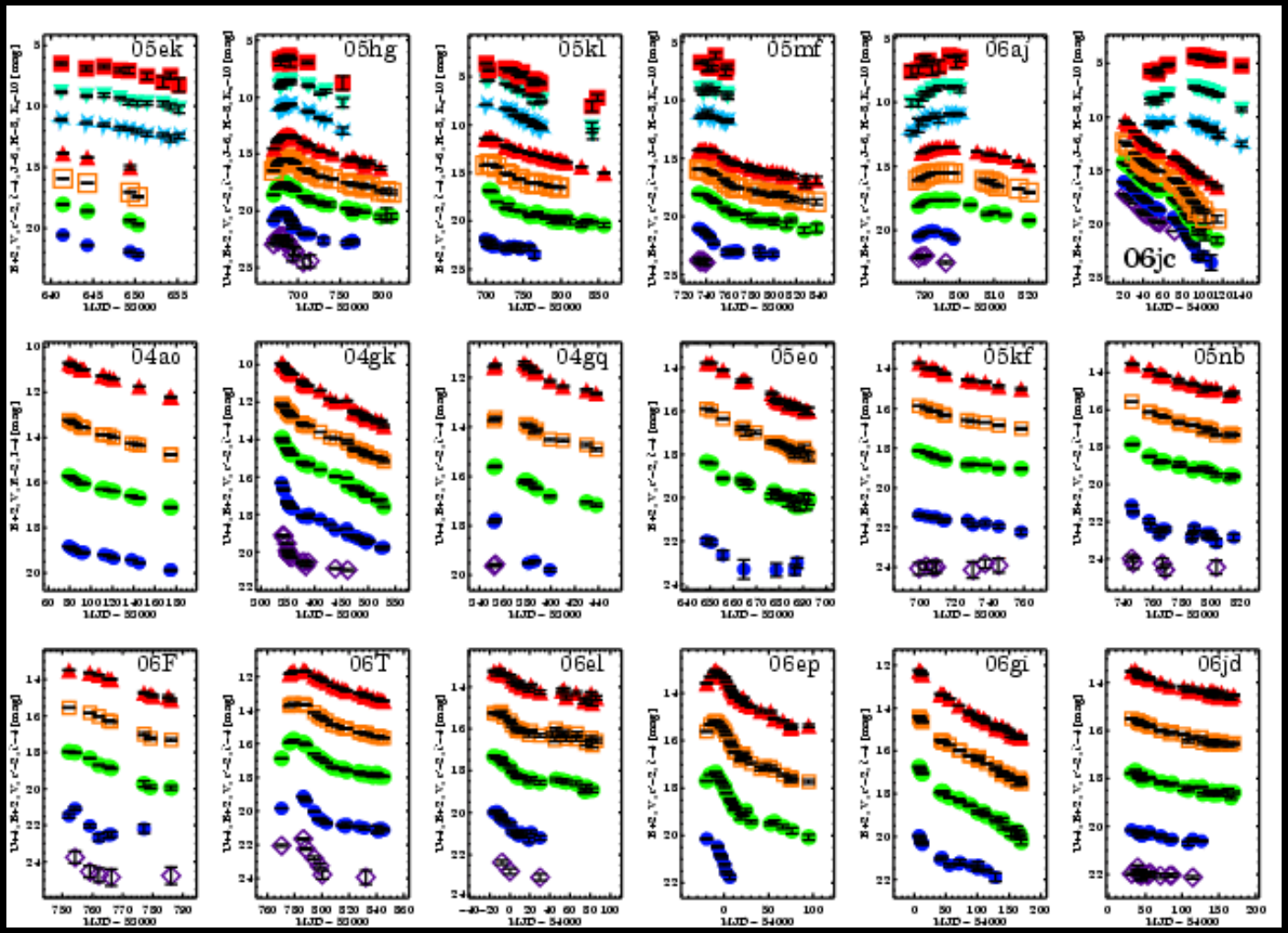


5m



Marya

Photometry: 2004-2010



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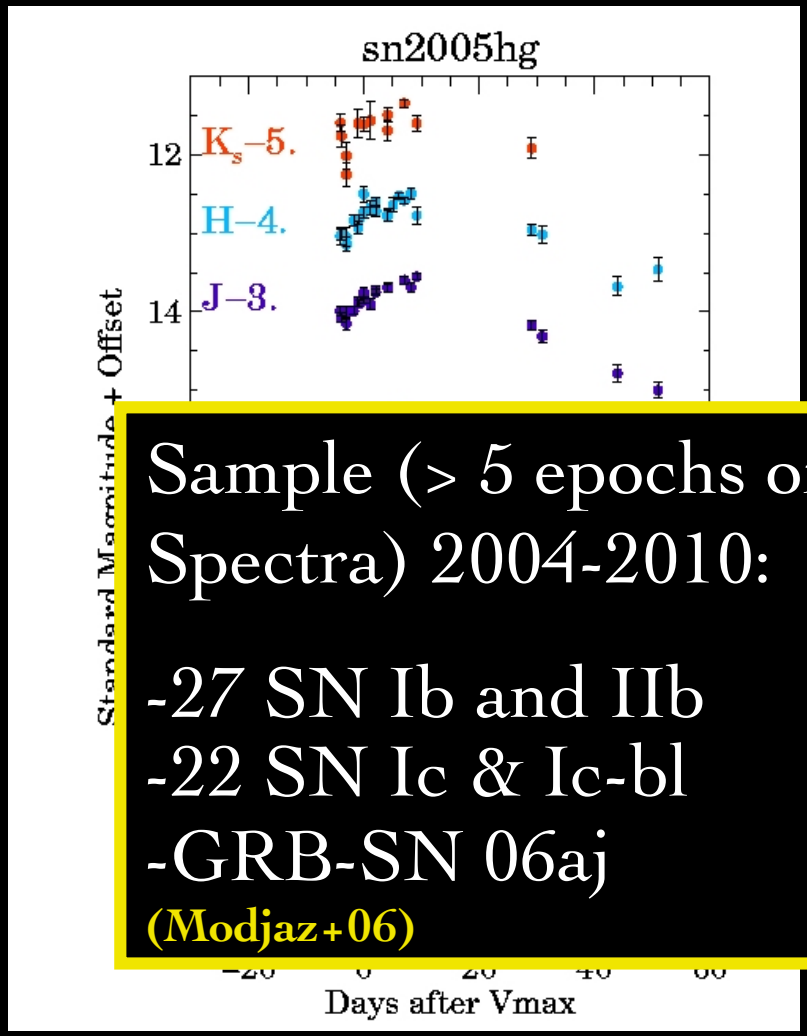
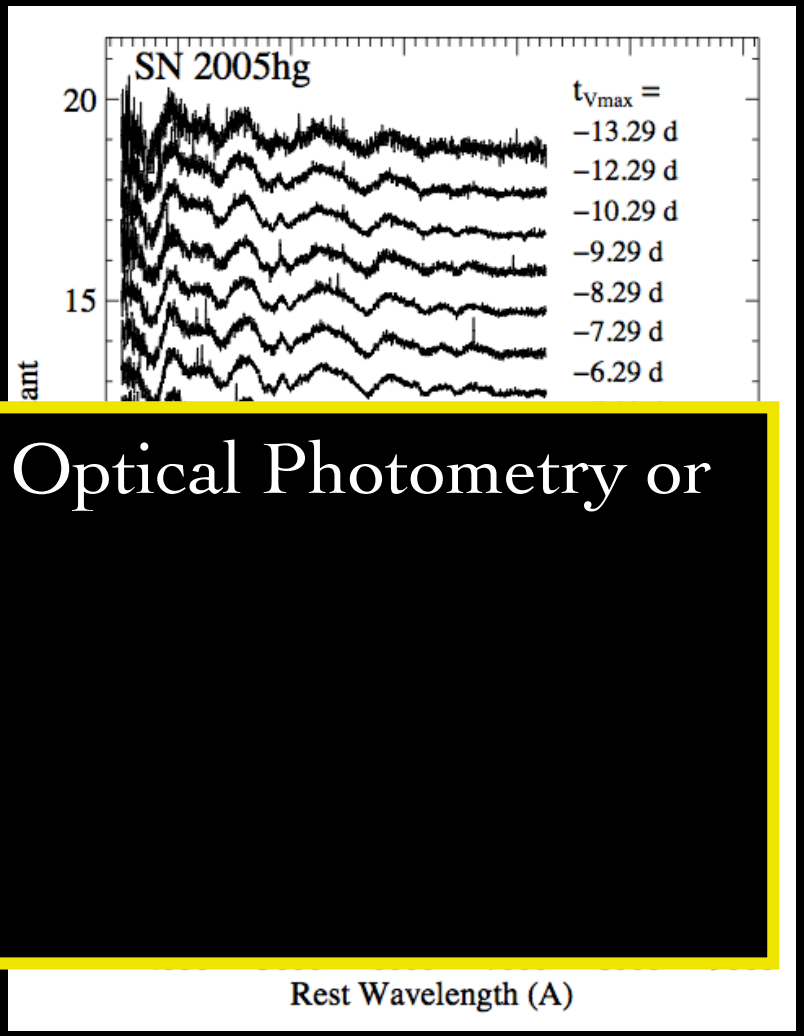
Example Data





Sample (> 5 epochs of Optical Photometry or Spectra) 2004-2010:

-27 SN Ib and IIb
-22 SN Ic & Ic-bl
-GRB-SN 06aj
(Modjaz+06)

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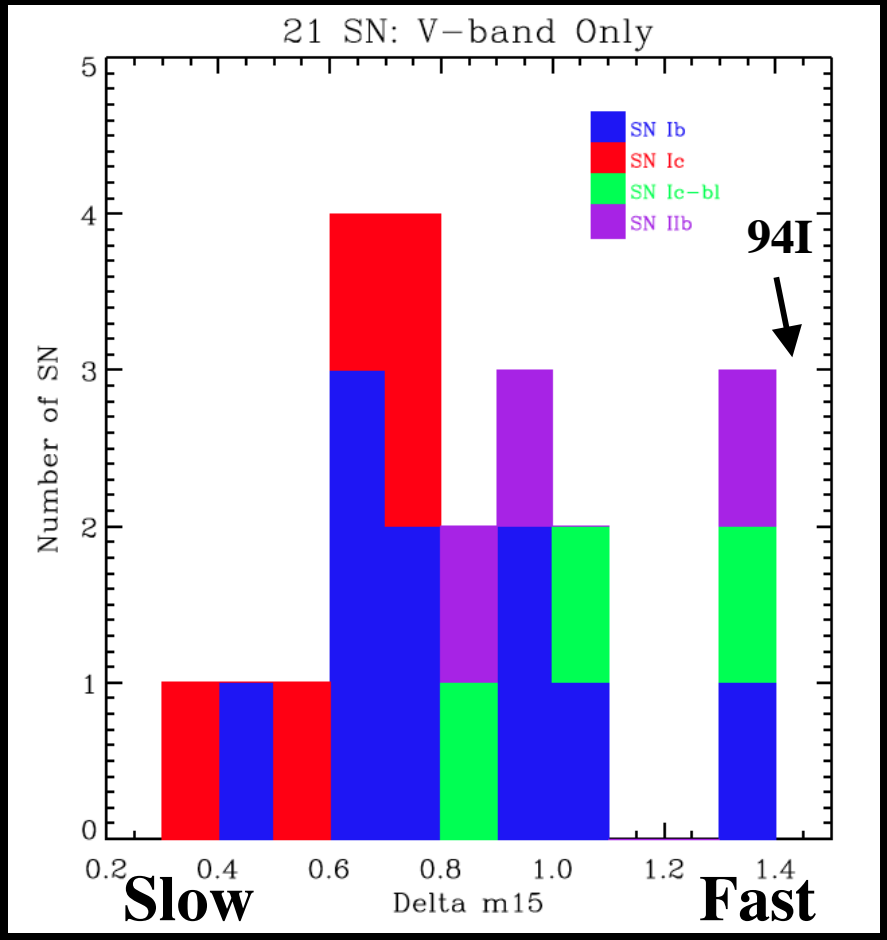
Analysis: A) Light Curve Shape



H. Marion, M. Modjaz et al (in prep): Fast and Slow LC **(see also Richardson et al. 2006, Drout et al. 2011),** but SN Ic seem to be slower (except 94I)

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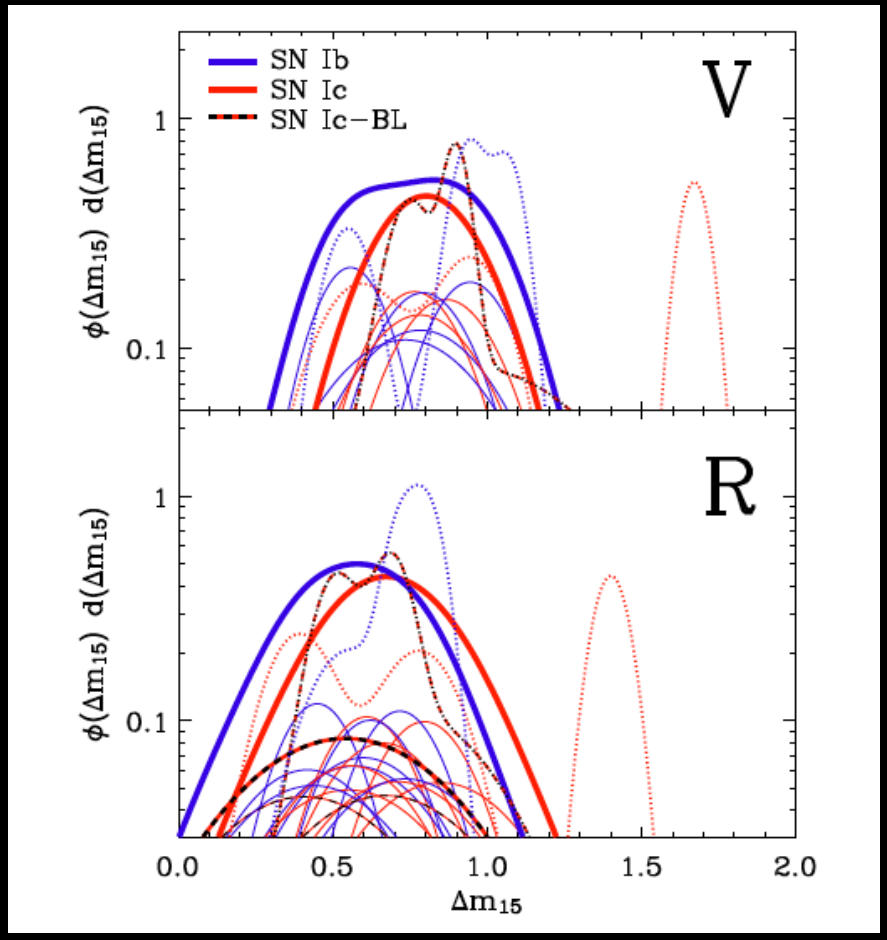
Analysis: A) Light Curve Shape

Drout et al. (2011)



H. Marion, M. Modjaz et al (in prep): Fast and Slow LC **(see also Richardson et al. 2006, Drout et al. 2011),** but SN Ic seem to be slower (except 94I)

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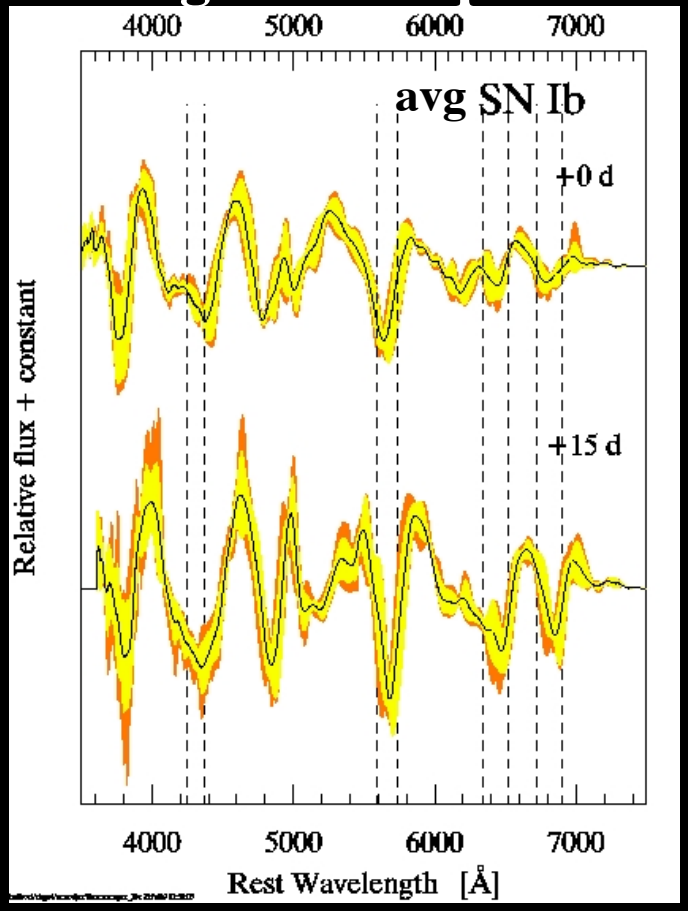
"Typical" SN in SN Zoo?

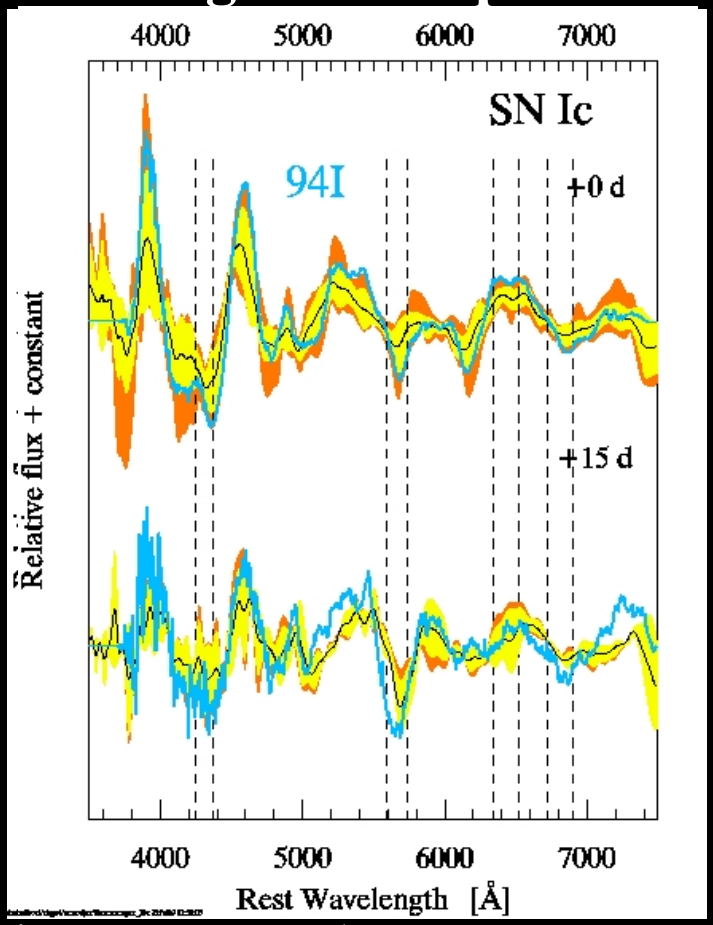
Past: "SN 1994I"-like **Present:** Quantifying diversity

std dev
max dev

average SN Ib spectrum



average SN Ic spectrum



SNIDified (S. Blondin & Tonry 2007): continuum removed

94I is not typical! More than 1 std dev away from average SN

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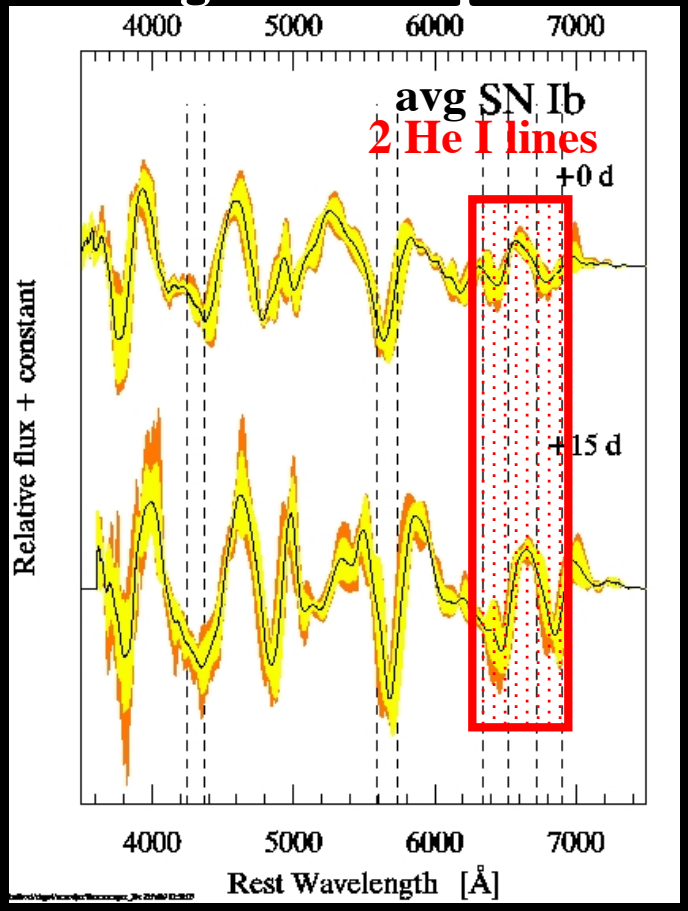
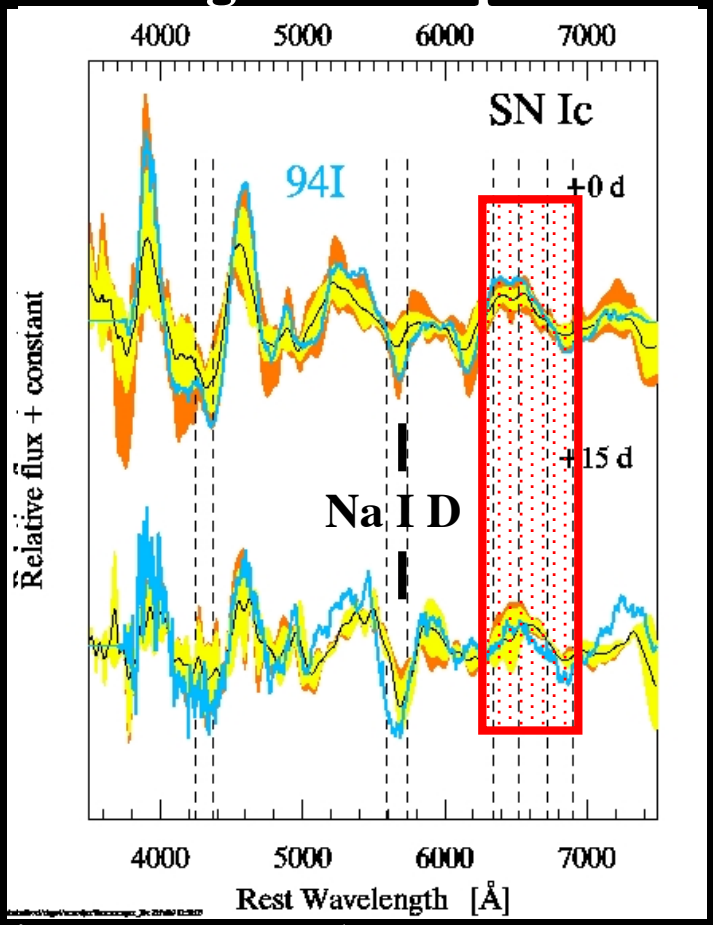
"Typical" SN in SN Zoo?

Past: "SN 1994I"-like **Present:** Quantifying diversity

average SN Ib spectrum **average SN Ic spectrum**





std dev
max dev

To classify SN as SN Ib: wait till ~Vmax to see He I 6678 & 7065 emerge (as early as -10d)

SNIDified (S. Blondin & Tonry 2007): continuum removed

94I is not typical! More than 1 std dev away from average SN Ic

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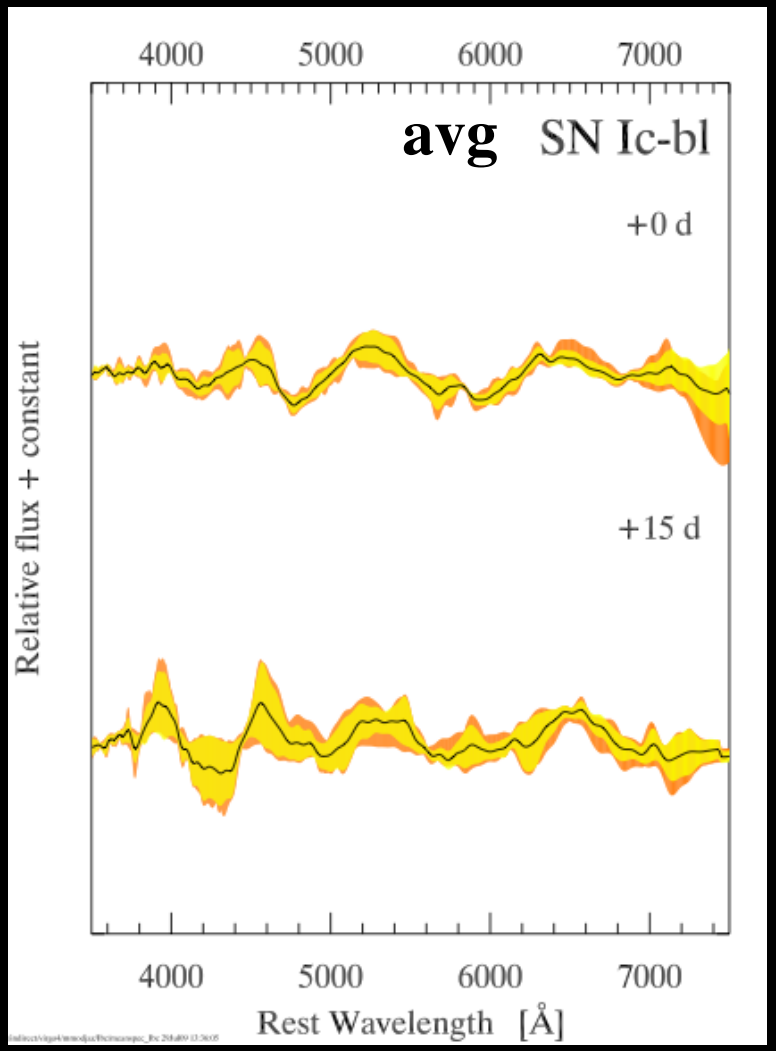
Typical Sn Ic vs SN Ic-bl

Line widths:

SN Ic @ +0d: ~7000-10,000 km/s

SN Ic-bl @+0d: 15,000-30,000 km/s (but beware blending!)

~



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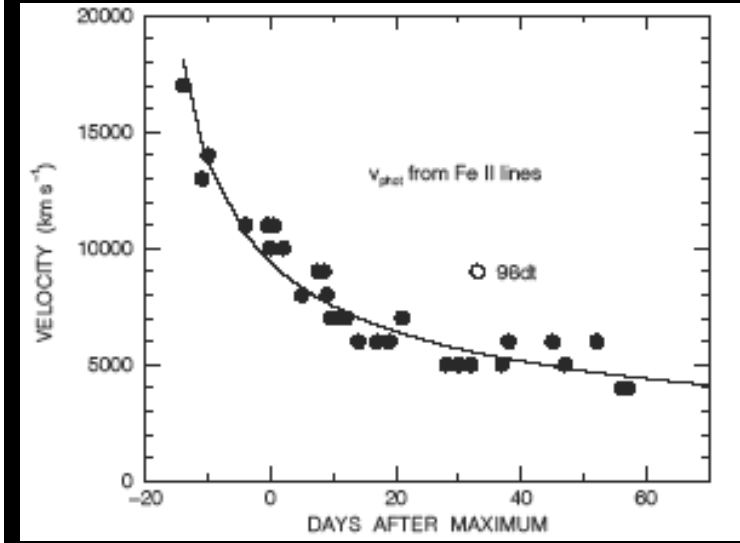
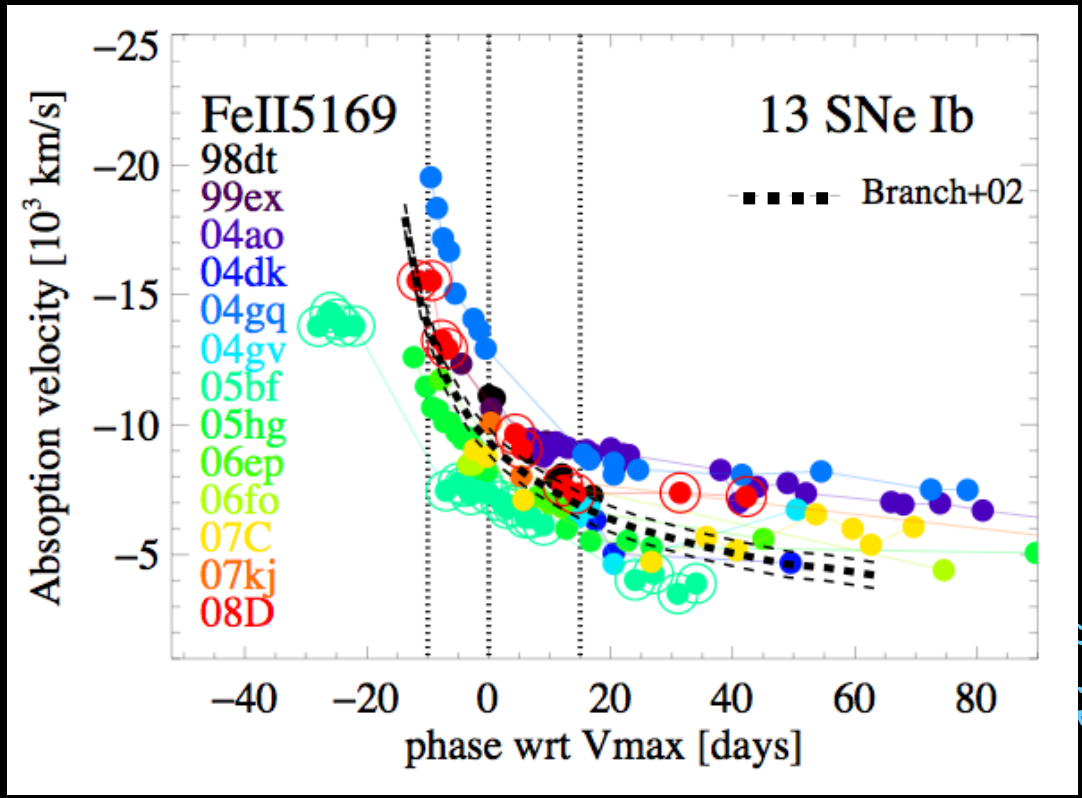
Systematic Analysis: a) Photospheric Vel

Past: Single Powerlaw **Present:** Diversity



Branch et al (2002): same photospheric vel for all 6 SNe Ib -> same KE and M_{ej} for all SNe Ib



SNe Ib @Vmax: spread of Δvel 5000km/s

-> Larger spread in photospheric velocity than previously thought

Modjaz et al. (in prep):
(Vmax from own phot & lit.)

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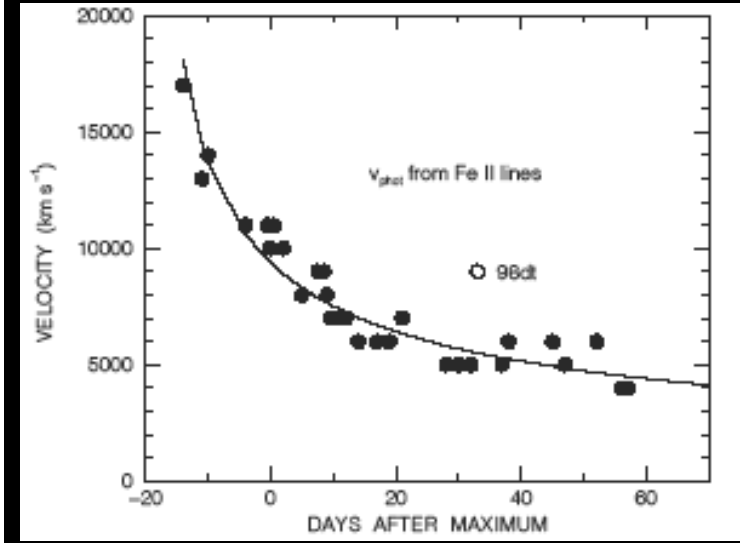
Systematic Analysis: a) Photospheric Vel

Past: Single Powerlaw **Present:** Diversity



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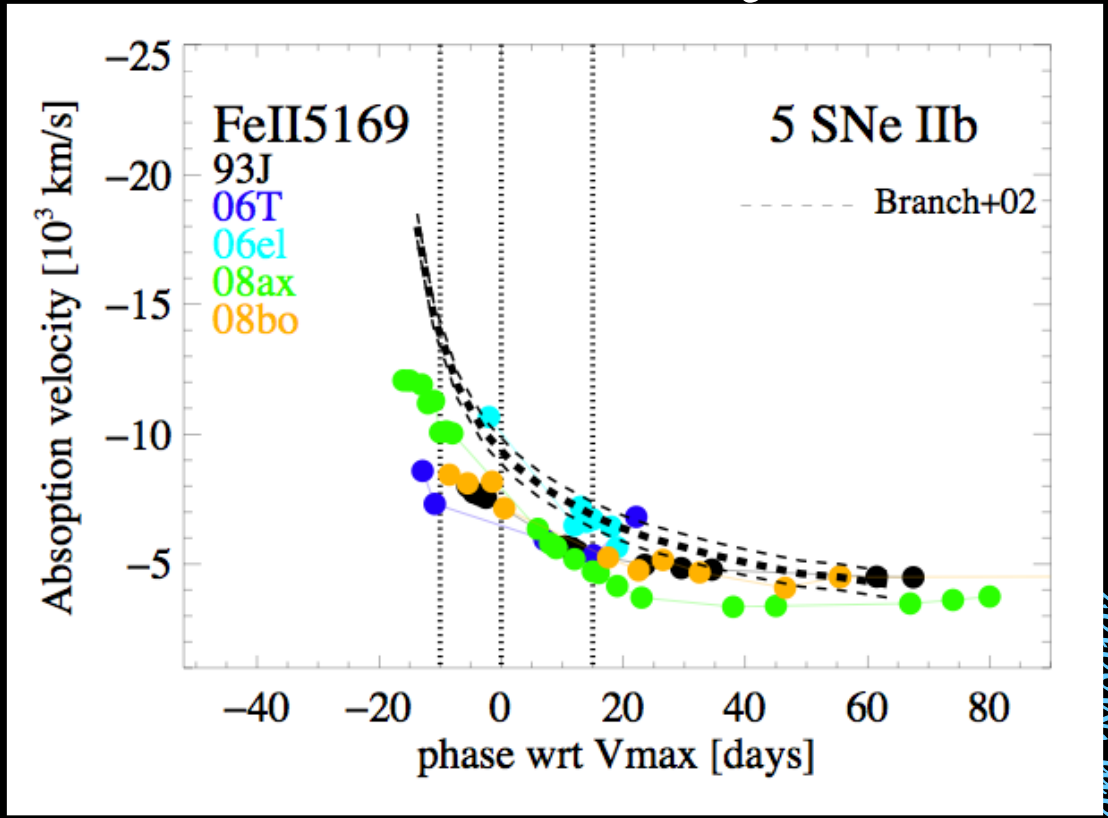

SNe Ib @Vmax: spread of Δvel 5000km/s

-> Larger spread in photospheric velocity than previously thought

Modjaz et al. (in prep):
(Vmax from own phot & lit.)

SNe IIb have lower Fe vels than SNe Ib (but more data needed!)

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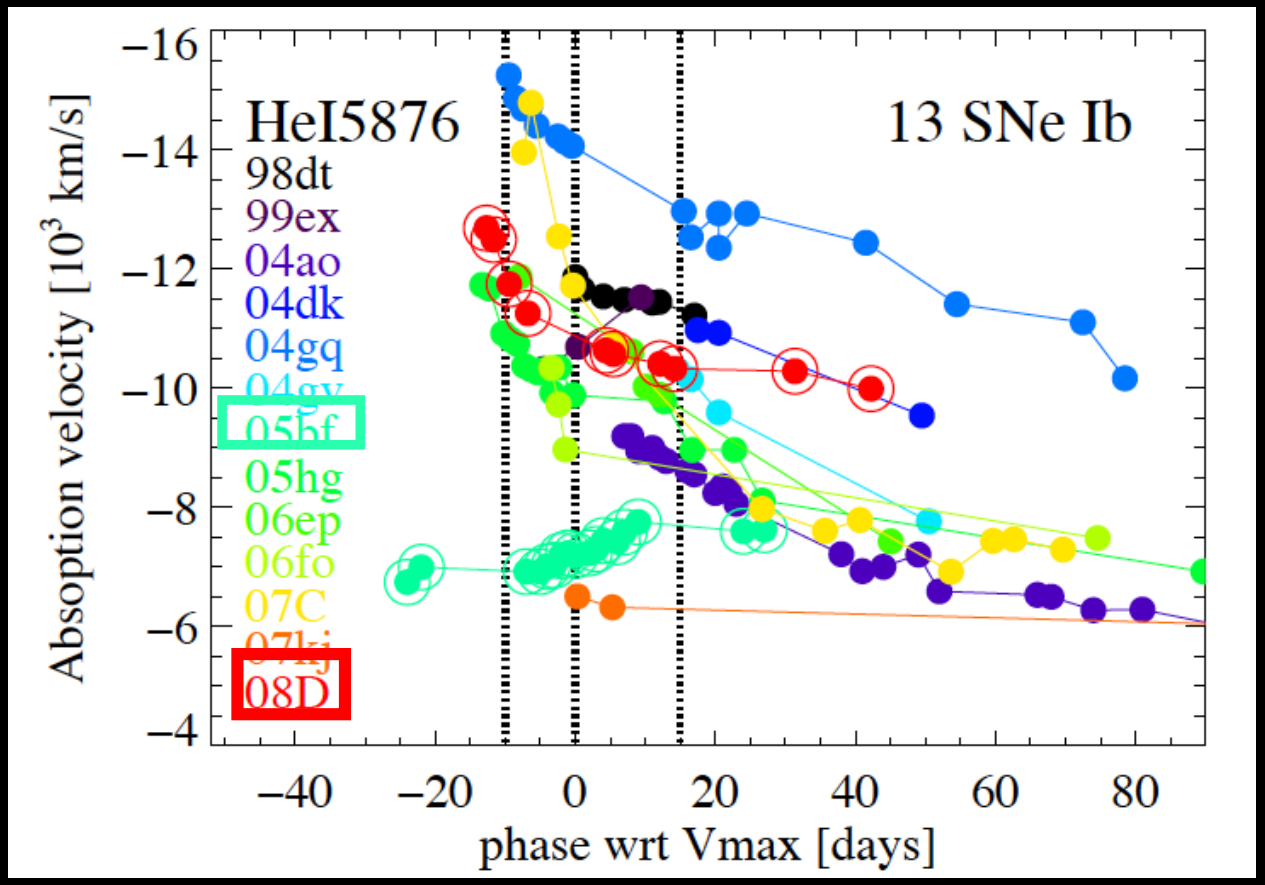
Systematic Analysis: b)He Line vels

- Large range of He I vels, eg @Vband max: Δv~7000km/s

Special SNe:

-05bf increase in He vels (seen also in Folatelli+06 data)

-08D: normal



Modjaz et al. (in prep)

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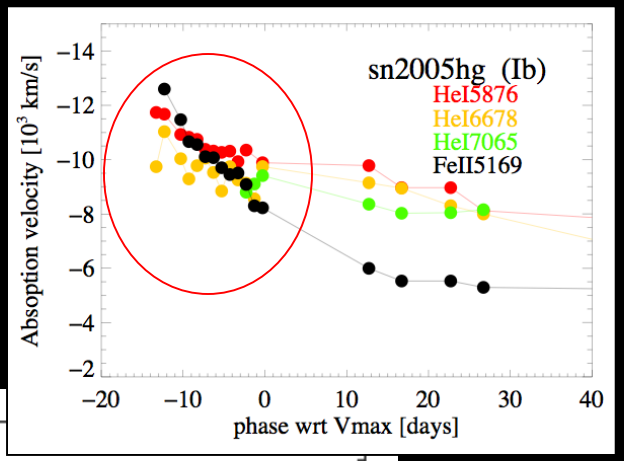
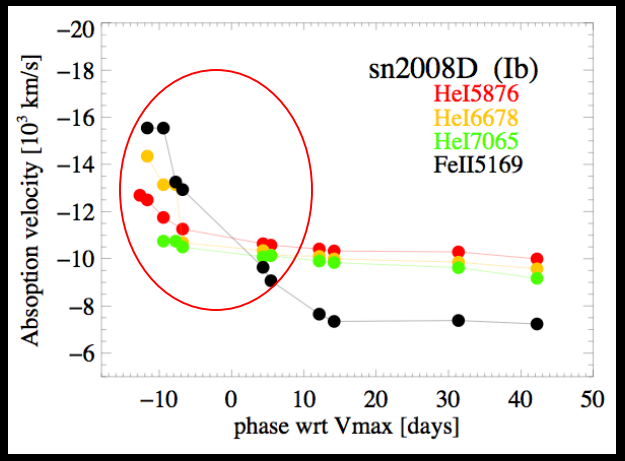
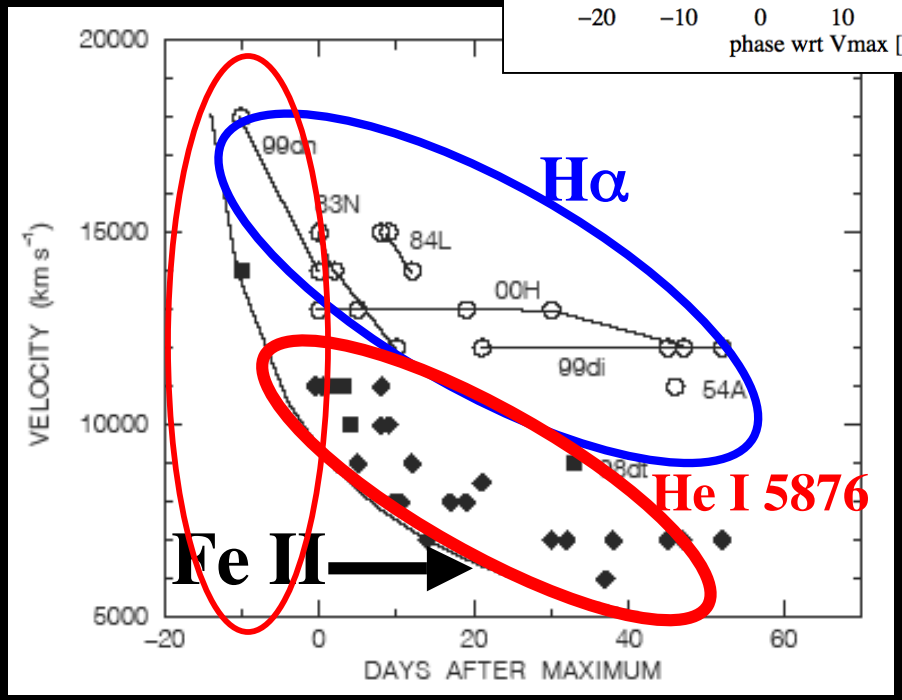
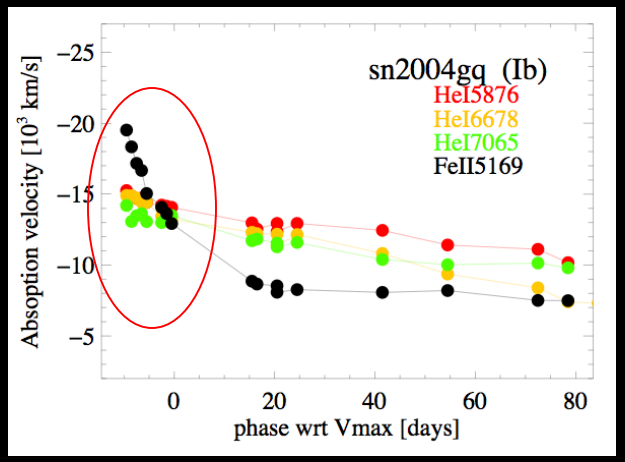
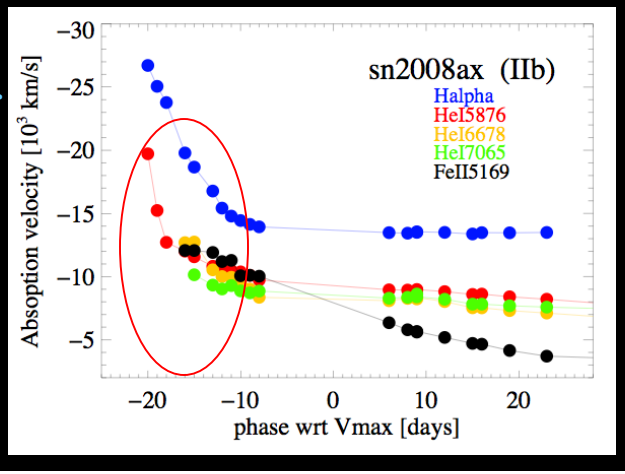








+07Y
(Stritzinger +09)



Branch+02: He vels above Fe vels, but didn't cover He line before max

Modjaz et al: Larger Sample with spectra before max: He below Fe

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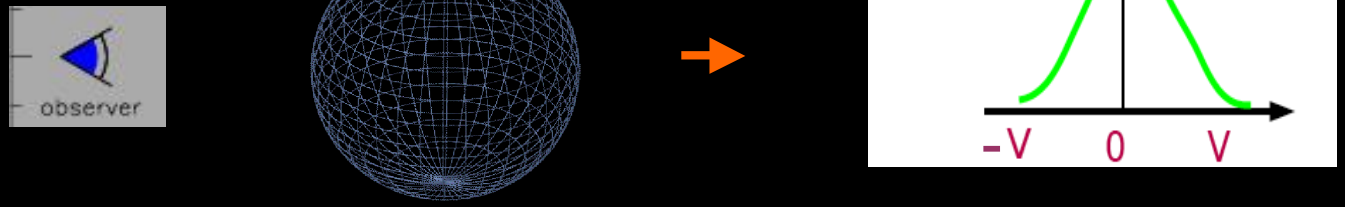
Geometry of Explosion

Late-time Spectroscopy

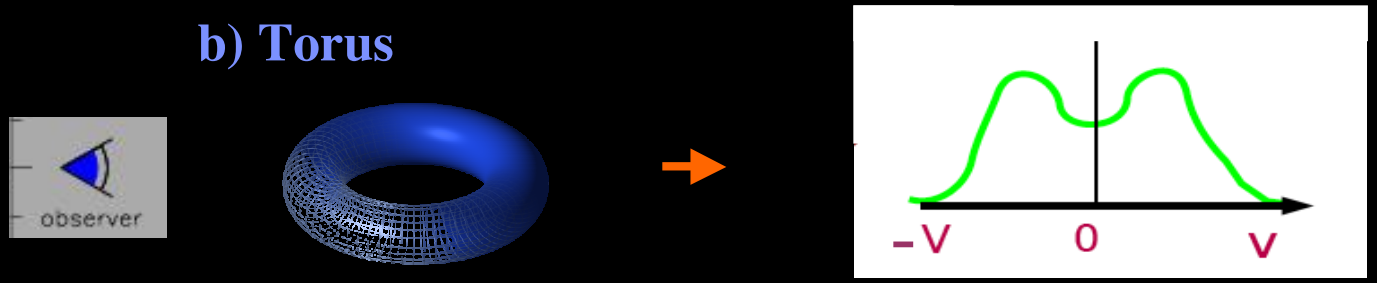
- SN ejecta is becoming optically thin (Fransson & Chevalier 1989, Spyromilio 91&94, Sollerman+98, Maeda et al. 2005, Mazzali et al. 2005, Valenti et al, 2008)
- Spectral line shape: Geometry of explosion because **v(r)∝r**

Geometry → Resulting Spectral Line Shape

a) Filled Sphere



b) Torus



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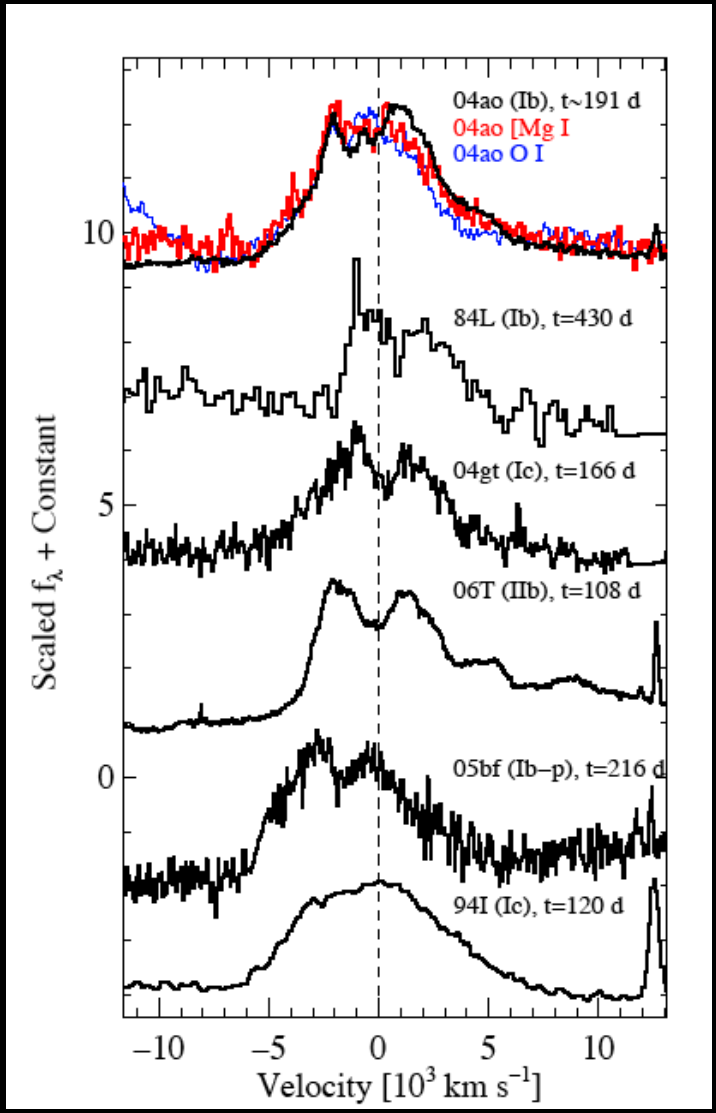
Double-peaked lines are common in SN Ib/c



Modjaz et al. (2008b)

- Asphericity is generic to normal SN process, not special to GRB-SN
  - Independent & concurrent study & conclusions by **Maeda et al (2008)**
  - Galactic SNR morphologies **(e.g, Fesen et al. 2006, Tuohy & Dopita 1983)**
  - Polarization **(e.g, Leonard et al. 2007)**
  - Neutron star kicks
  - Models of core-collapse **(e.g, Khokhlov et al. 1999, Scheck et al. 2006, Burrows et al. 2006, Dessart et al. 2008)**

Since then: 08D, 08ax, 08bo, 09jf

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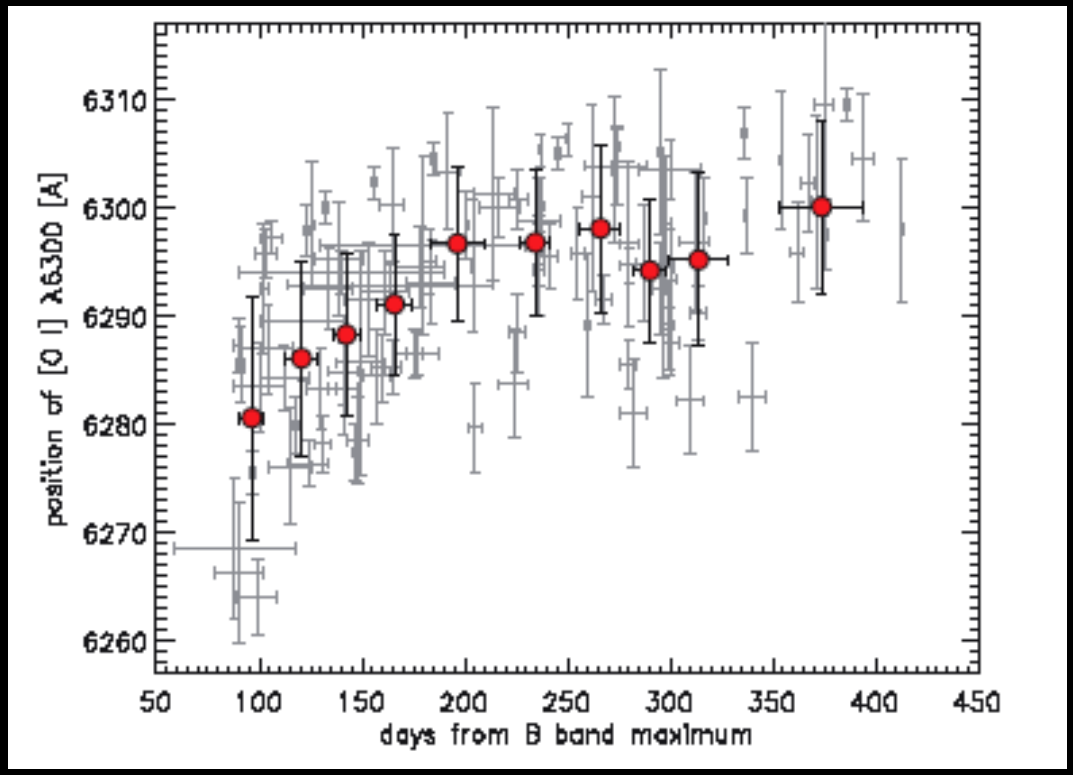
Double-peaked lines are common in SN Ib/c

…but what about **optical depth** effects ?



Blueshifts up to 200 days (Taubenberger et al. 2009)

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Double-peaked lines are common in SN Ib/c

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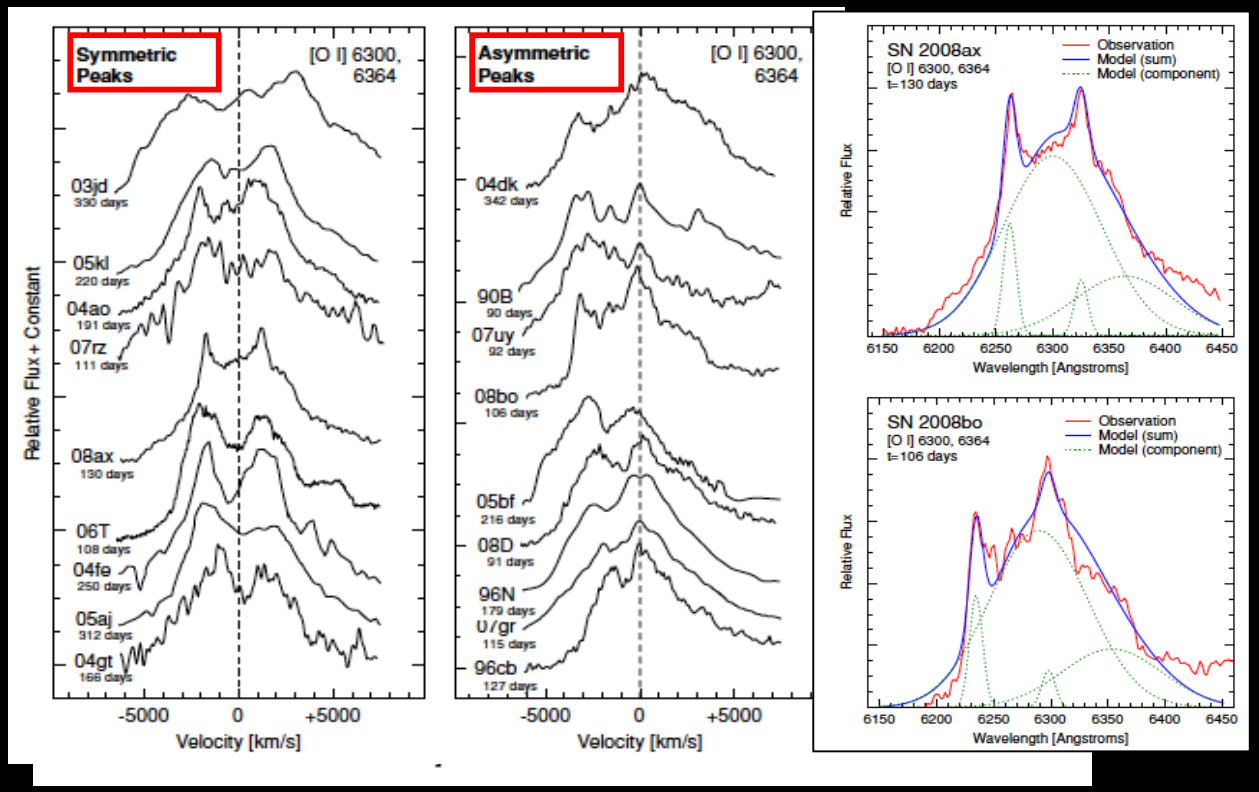

Blueshifts up to 200 days (Taubenberger et al. 2009)
Milisavljevic+ 10: 2 Types of Double Peaks & only blueshifts,

BUT: If same double-peaked line shape in other Oxygen lines (non-doublets), then geometric interpretation valid (e.g., 04ao, 06T, 08D)

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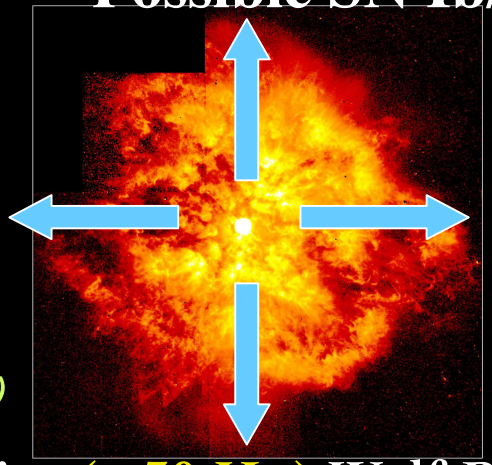
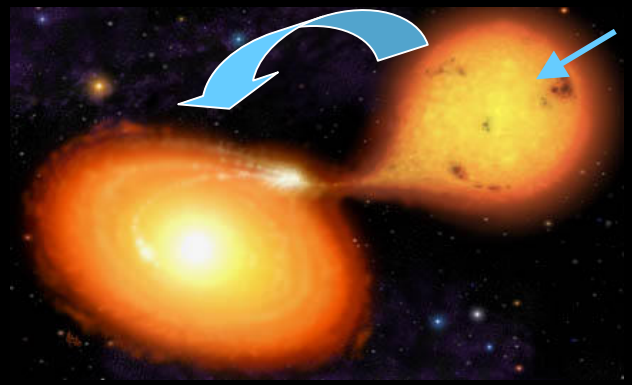
Environmental Studies

Possible SN Ib/c & SN-GRB progenitors:



(Credit: Hubble/NASA)

or



?

(Credit: ArtistNASA)

Single massive (> 30 $M_\odot$) Wolf-Rayet stars with metallicity-dependent winds (or eruptions) (e.g., Woosley et al. 1995, Maeder & Conti 2004, but see Smith & Owocki)

He stars (8-40 $M_\odot$) in binaries, (e.g., Podsiadlowski et al. 2004)

Direct Study:

- Pre-Explosion images: no progenitor detections (Smartt Review 2009)
- Shock-breakout for 1 SN Ib (Soderberg et al 2008) and 1 SN-GRB (Campana et al 2006)
- Mass loss rates from Radio & Xray SN obs (Soderberg+, Chevalier+)

Statistical Study:

Differentiate between GRB, SN Ib and SN Ic progenitor models via
- Environments & their Metallicities
- SN Rates (Smartt+09, Smith+11)

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Previous Stripped SN Metallicity studies

- Some studies in the last 3 years (e.g., Modjaz et al 2008, Prieto et al. 2008, Boissier & Prantzos 2009, Anderson et al. 2010, Leloudas et al. 2011)
- But:

  - No local Z, only nuclear proxy/measurement, beware metallicity gradients (e.g., van Zee et al. 1998)

  - No distinction b/w SN Ib- or Ic-subtype or only focused study (e.g. SN Ic-bl with and without GRBs)

  - either historical SN (subtype or offset not well known) or only from targeted surveys

  -> a variety of metallicity biases?
- First step: Keck spectra of 35 stripped SN hosts: targeted & untargeted surveys, at location of SN (Modjaz et al 2011)

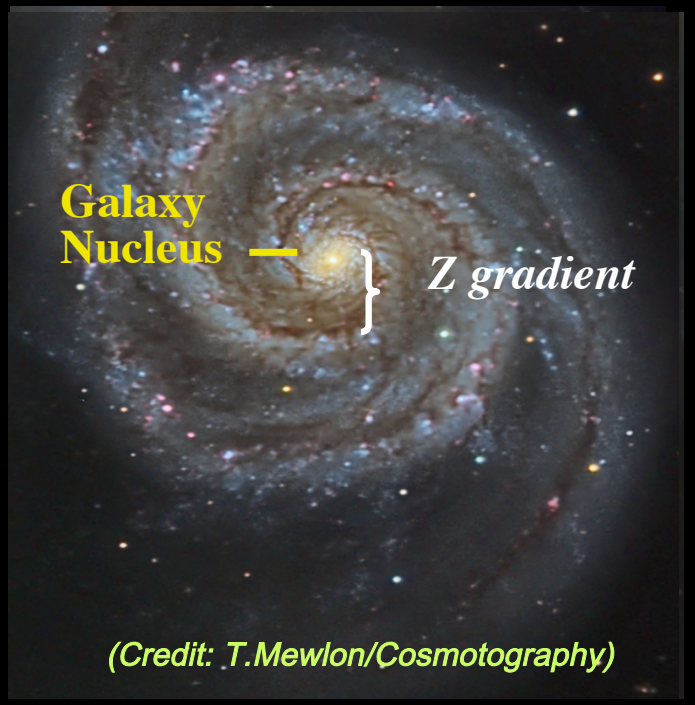
Keck Stripped SN metallicity program

50 Host Galaxy spectra of SN Ib, Ic, Ic-bl

with 10m Keck I + LRIS (+ADC)

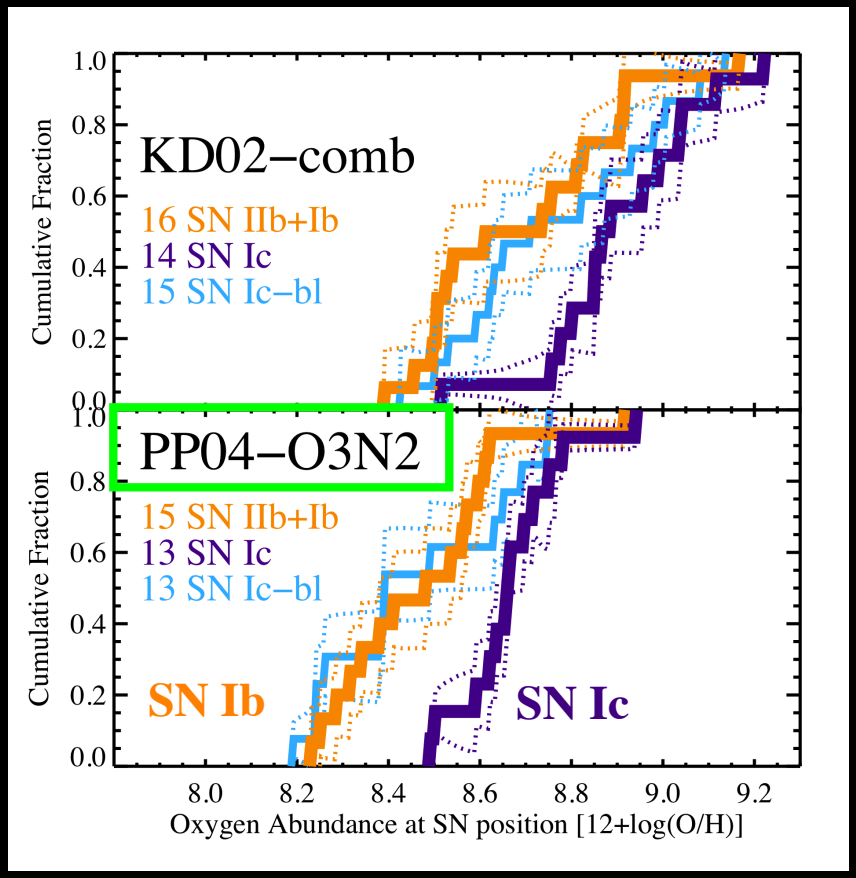
- Statistically significant sample
- 35 from targeted SN surveys, 15 from untargeted: mitigate selection effects (e.g., Modjaz et al. 2008, Young et al. 2008)
- Spectra of nucleus and at SN position (ADC!): probe natal Z
- In different & independent metallicity scales (Kewley & Ellison 2008)
- Monte-Carlo simulations for uncertainty budget

Keck



Sites of SN Ic are more metal-rich than those of SN Ib

Modjaz et al. 2011



-**Robust**: in all scales

- KS test that Z's of **SN Ib & Ic** are drawn from **same parent distribution**:

Kewley & Dopita (KD02): 7%

Pettini & Pagel (PP04-O3N2): 1 %

- Important: **SN Ic-bl** (w/o GRBs) **different** from SN Ic

Implications:

- SN Ic come from more metal-rich and more massive stars than SN Ib

- consistent with Arcavi et al (2010) & Smith et al (2011, LOSS rates)

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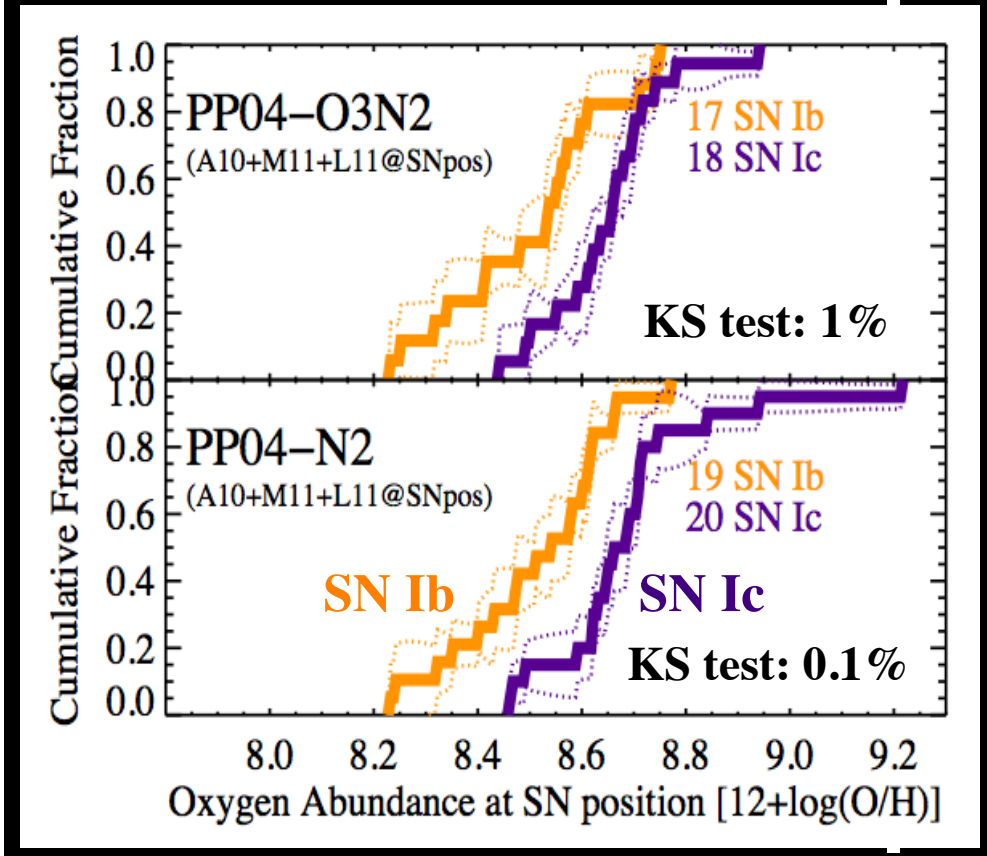
Sites of SN Ic are more metal-rich than those of SN Ib



more metal-rich

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- Important: **SN Ic-bl** (w/o GRBs) **different** from SN Ic

Meta-Analysis: Modjaz+ 11 & Anderson +10 & Leloudas +11

@SN position: SN Ic's sites are still more metal-rich than SN Ib's

(but see N. Sanders, in prep)

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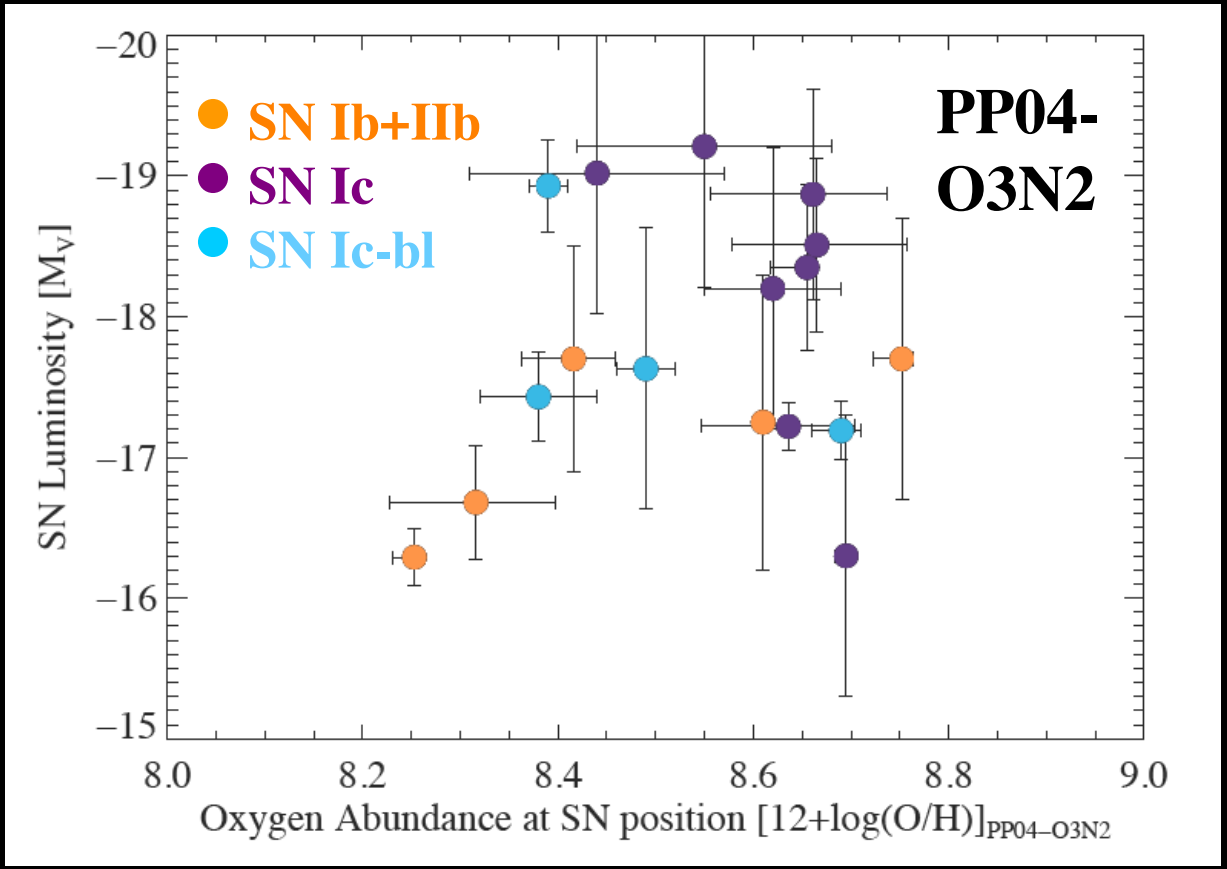
SN property vs oxygen abundance



So far, no clear correlation between SN luminosity and SN explosion site's oxygen abundance

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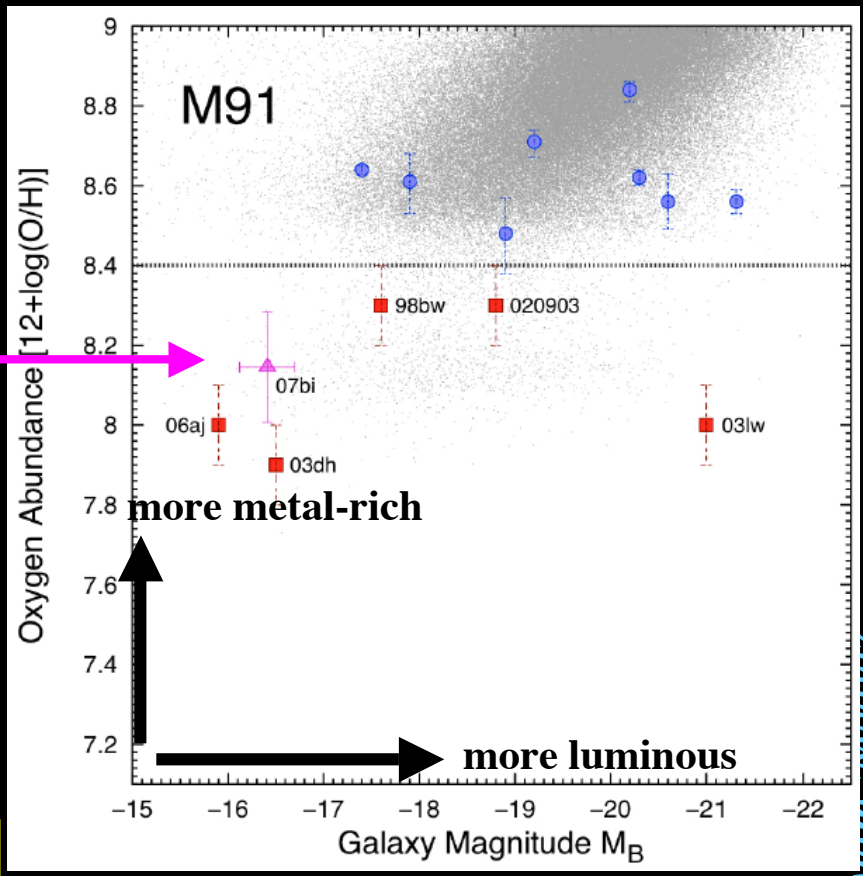
Metallicity Studies is Rapidly developing field

Individual SNe & GRBs:

- Radio-Relativistic SN at high z (Soderberg et al. 2009, Levesque et al. 2009)
- Candidate Off-axis GRB-SN & Pair-Instability SN 07bi (Gal-Yam et al. 2009, Young et al. 2009)
- 2 Dark Bursts & High-z GRBs (Graham et al. 2009, Levesque et al. 2010a, Levesque et al 2010b)
- Other Stripped SNe (Anderson et al 2010, Leloudas et al. 2011, N. Sanders in prep)
- 5 Over-luminous CCSNe (e.g., Neill et al 2010, Stroll et al. 2011)

Need: -large metallicity samples from galaxy-unbiased surveys (e.g. PTF) -> underway

-IFU metallicity maps: Christensen, Modjaz, Leloudas VLT VIMOS project



Young et al (2009), adapted from Modjaz et al. (2008a)

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Conclusions: Stripped-Envelope SNe

- Growing Zoo of SN IIb, Ib, Ic, Ic-bl, but also
- Growing amount of comprehensive data -> quantify diversity & systematic study & modeling
- SN2008D/XRT080109: best-studied SN Ib from shock breakout on & inspired a number of theorists
- SN 2008ax: early-time data! & SN1994I (classical SN Ic) is not typical for a SN Ic!
- Environmental & Metallicity Studies are a rapidly developing field
  - Largest Keck Stripped SN Metallicity Program:

    $Oxygen_{SNIc} > Oxygen_{SNIb}$: robust & uniform
  - Need local Z measurements vs. nuclear measurements
- Untargeted & wide-field SN surveys (PTF, PanSTARRS, Skymapper, LSST) : new parameter space in the SN field (& transient sky) & crucial for host galaxy studies

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