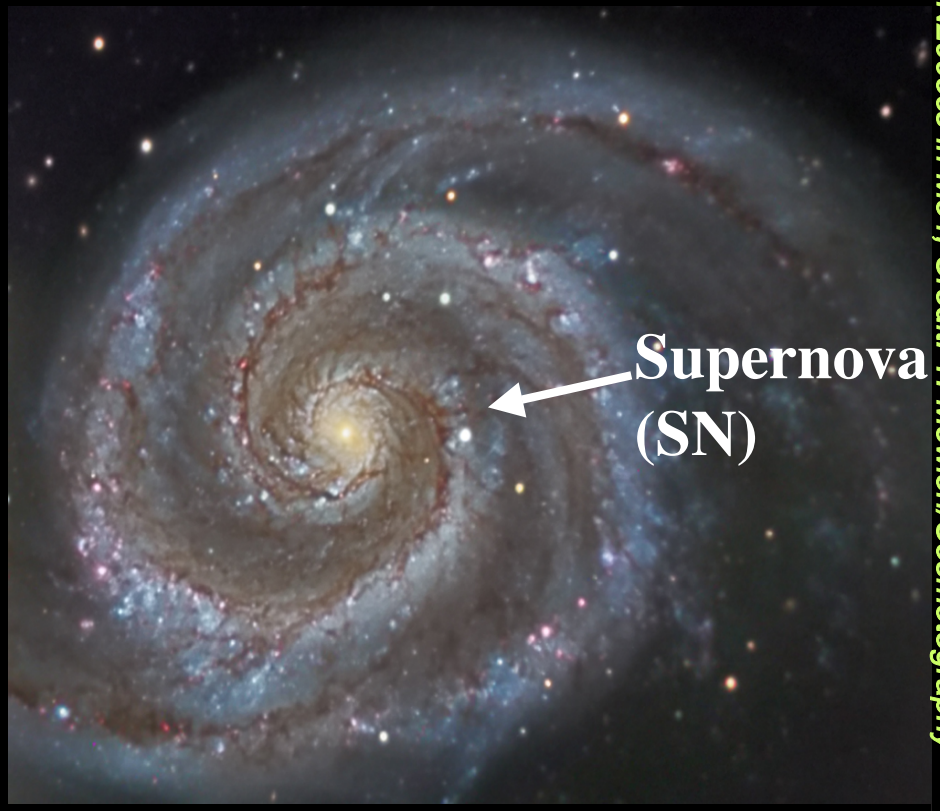
SNe Ib/c with and without GRBs



SN2005cs in M51, Credit: T. Mewlon/Cosmotography

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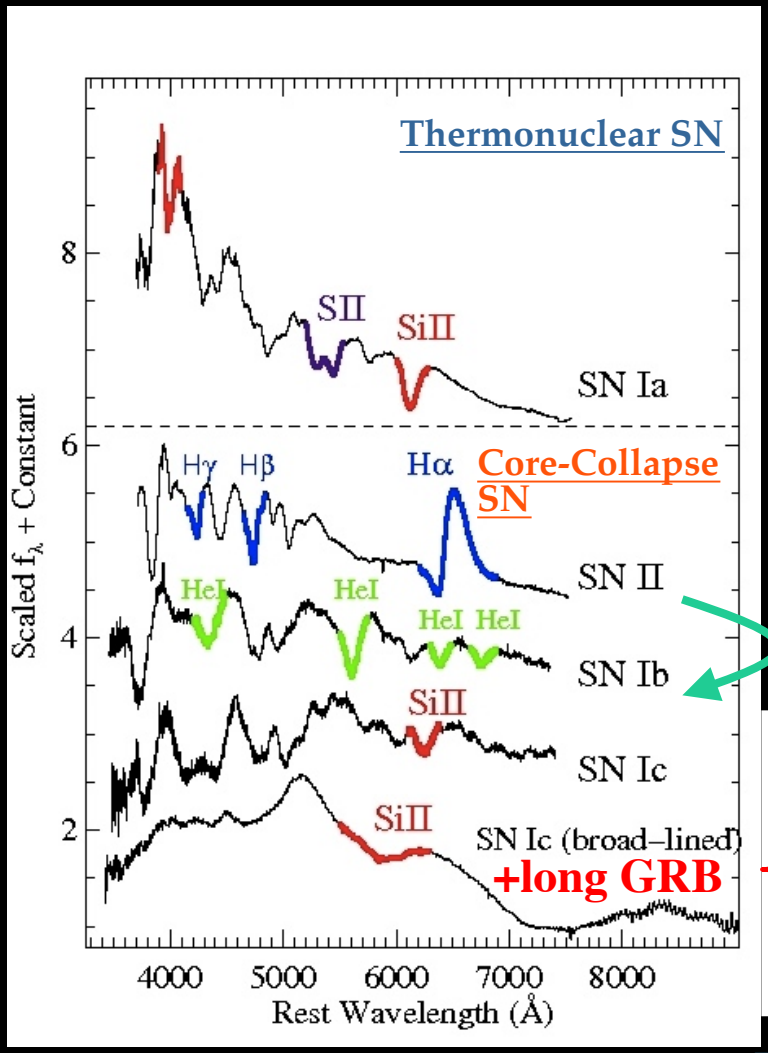
SN ZOO

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



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

+ Exploding Zoo: Ca-rich Transients, Overluminous SNe, …

SN IIb

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

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

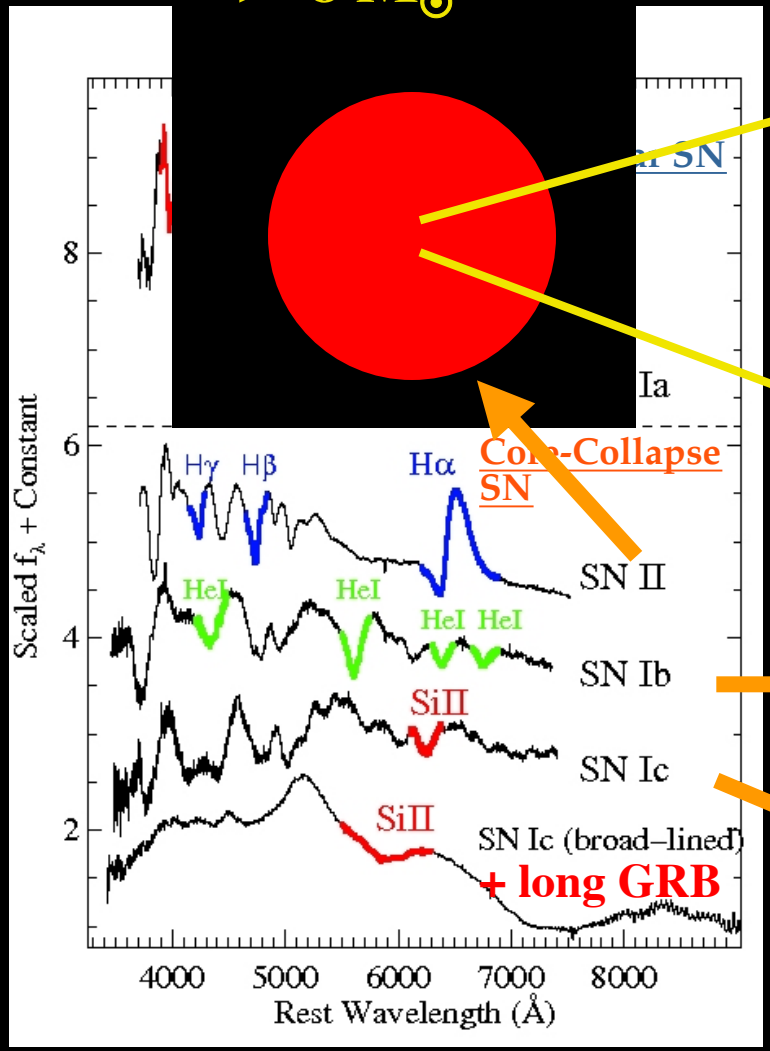
Stripped-Envelope SN

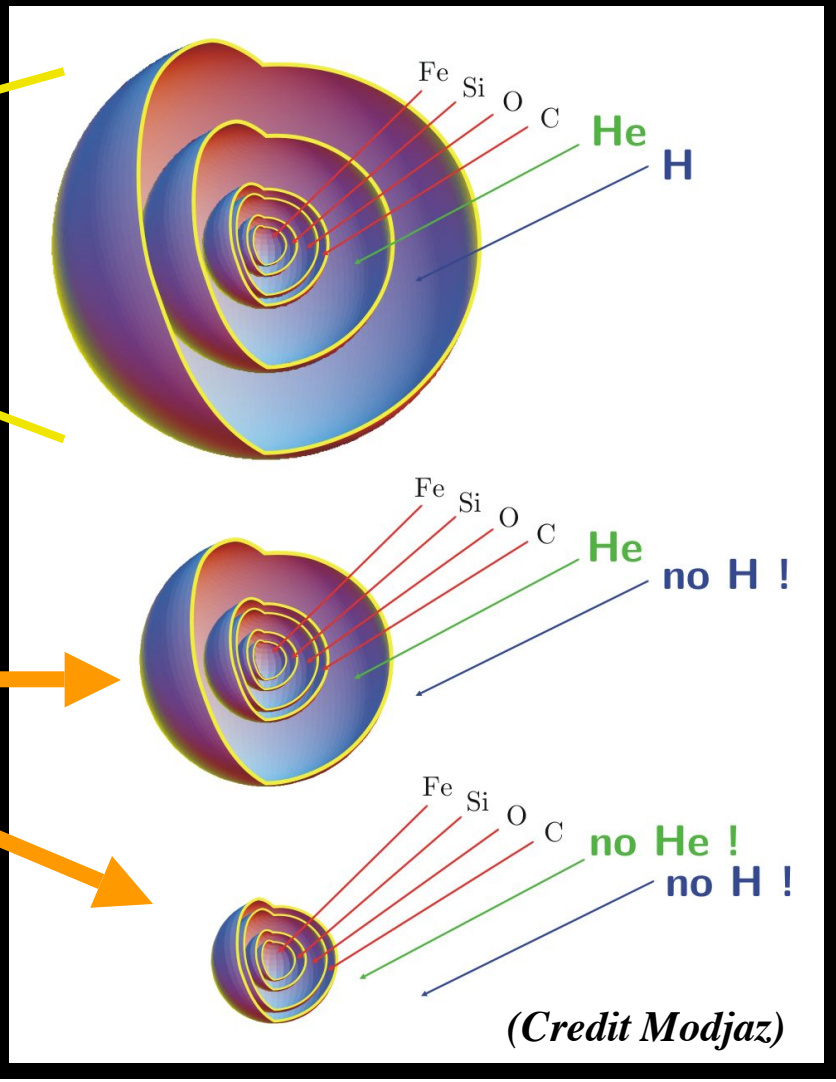
Maryam Modjaz

SN Classification

- **Spectra:** Type I (without H) and Type II (with H)

>~8 $M_\odot$





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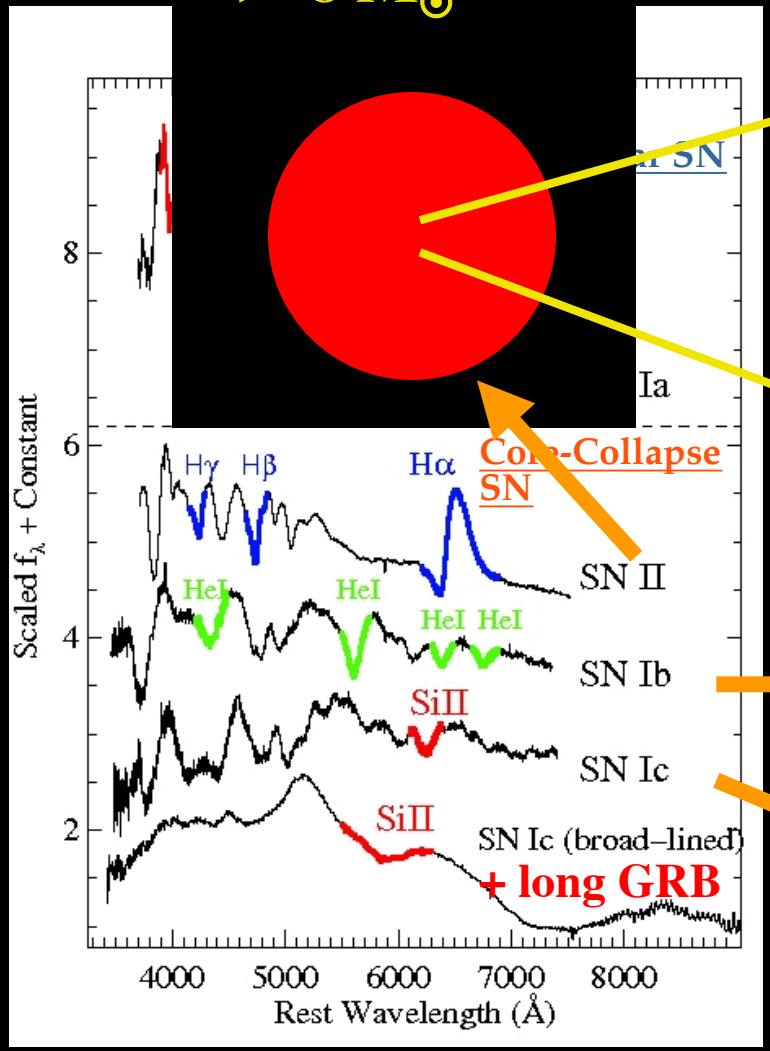
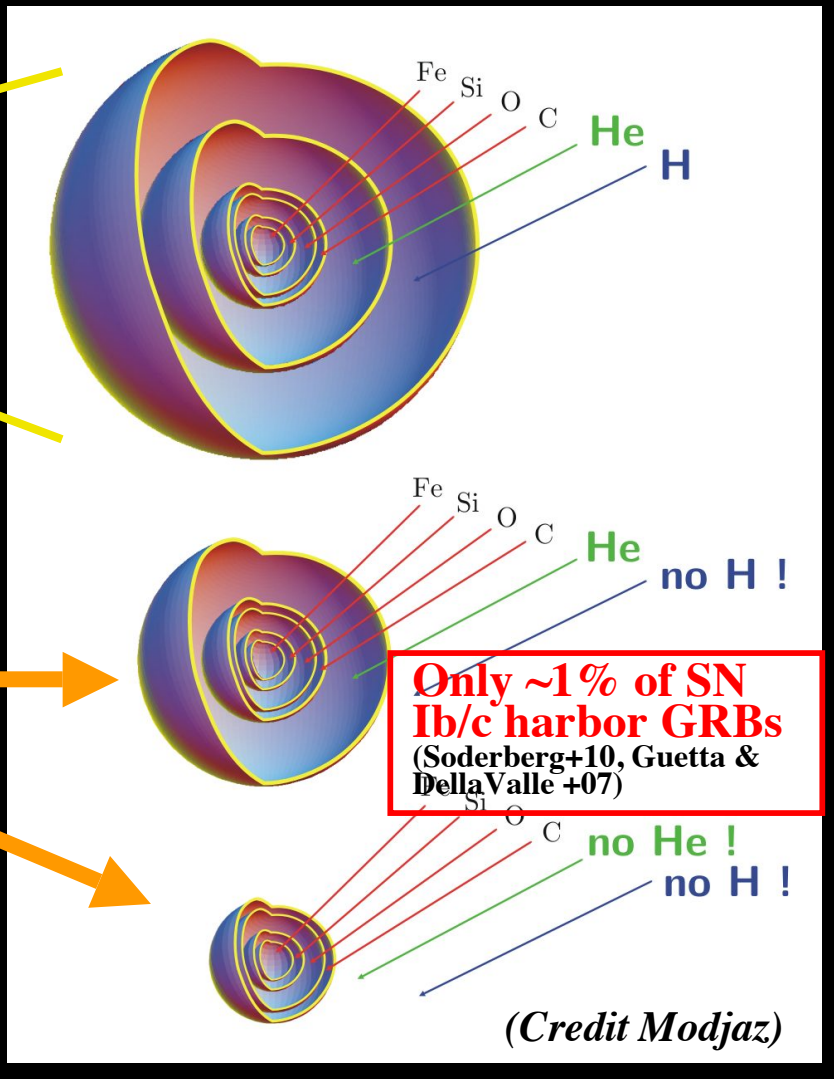


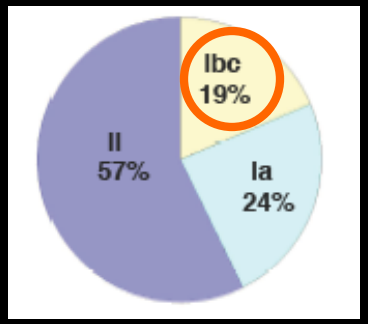


UNDERSTANDING SNE IB/C WITH AND WITHOUT GRBS

- Focus on Stripped SNe **with and without** GRBs to elucidate conditions and progenitors of different types of explosions
- 2-thronged approach:
  1) **(Early-time) Spectra:** b/c classifying feature
  2) **Measured Metallicities at SN sites:** b/c impact of Z expected from stellar evolution

"Large" data-sets: **robust statistical analysis**

Need For Studying 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 SNe Ic
  (Clocchiatti et al. 2000, Homeier 2005)
- Identify & compare to "new" classes of transients/SNe (e.g., Overluminous SNe Ic, Ca-rich transients)

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

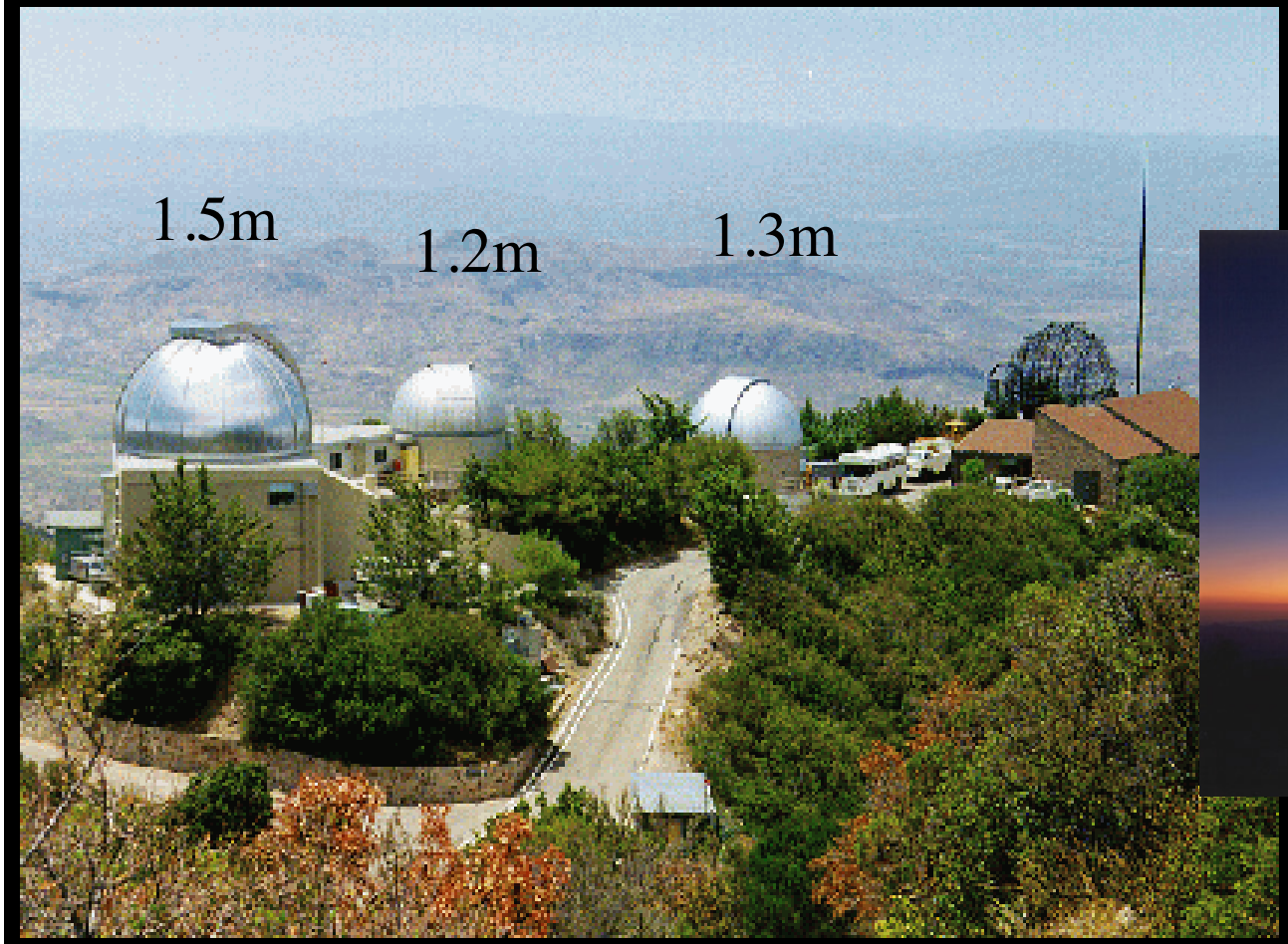
- 93J, 94I, 99ex, **05bf**, 07gr, 07Y, **08D, 08ax**, 09jf, 11dh, & SN-GRBs
- **Larger SN samples:**
  - **Matheson et al (2001):** mostly spectra, very little photometry
  - **Richardson et al. (2006):** only published LC, pre-CCD SNe
  - **Drout et al (2011):** large dataset, but only V&R photometry

NEARBY SN CFA FOLLOW-UP (SINCE 1994, ESP. >2003)

- 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

(see also Modjaz et al. 2008)

NEARBY SN CFA FOLLOW-UP
(SINCE 1994, ESP. >2003)



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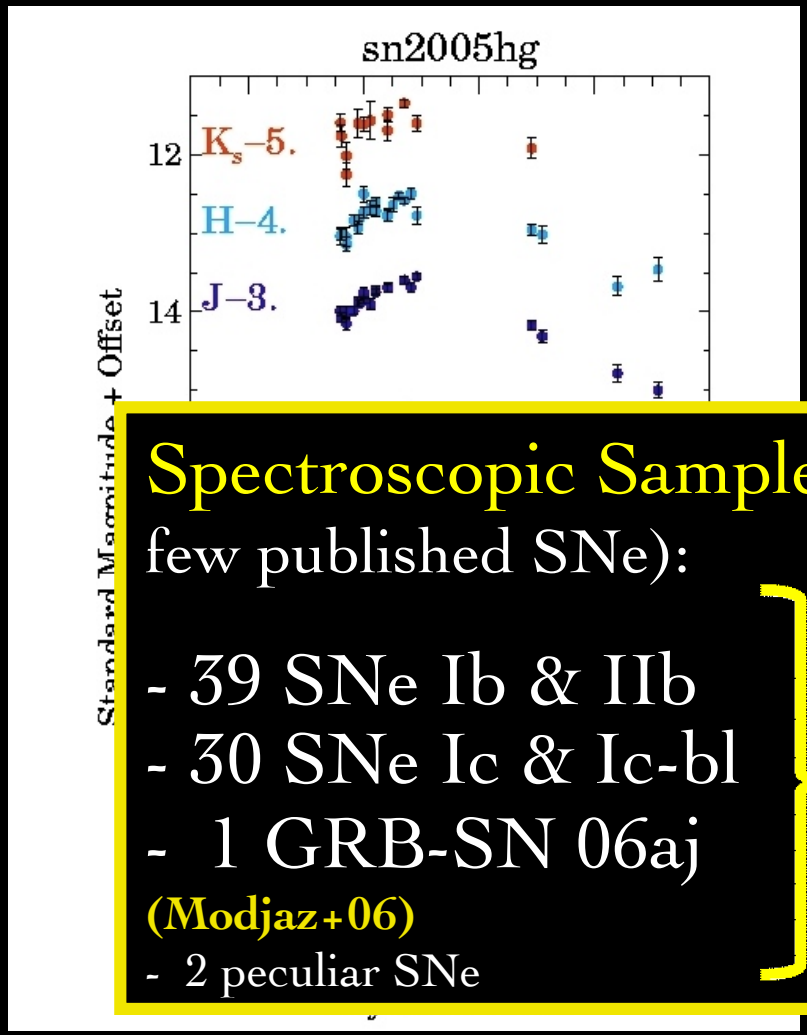
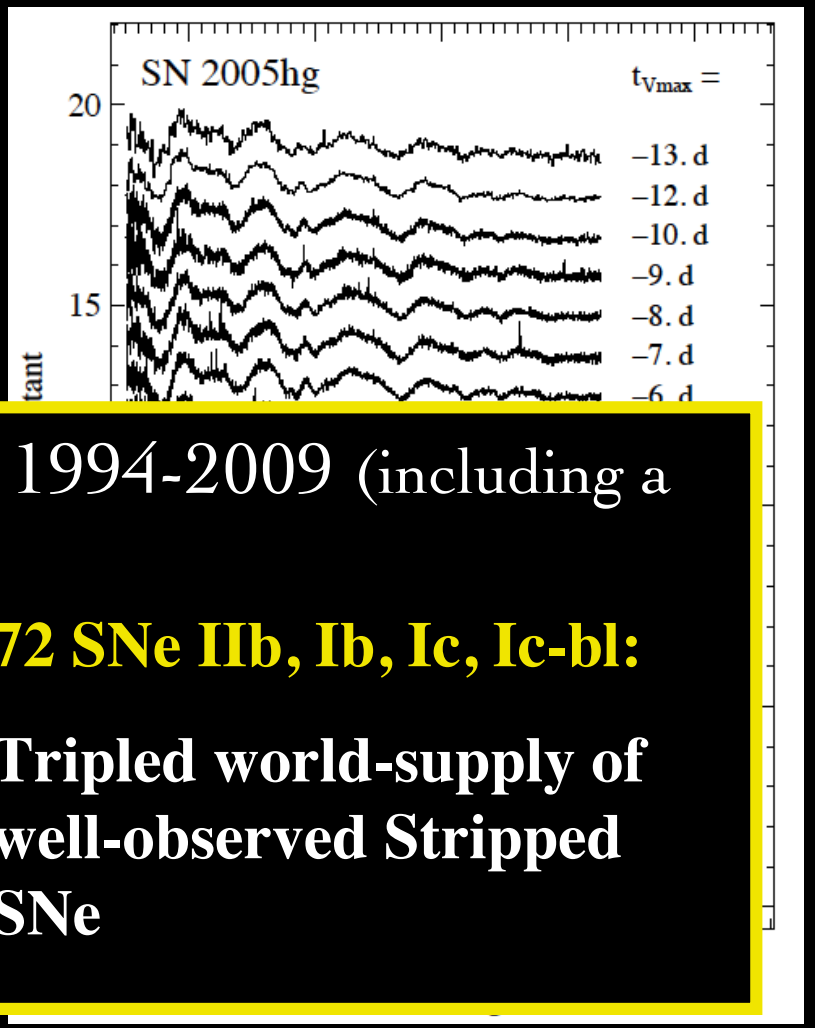
Example: Extensive LC & Spectra of CfA SNe





t

Spectroscopic Sample: 1994-2009 (including a few published SNe):

- 39 SNe Ib & IIb
- 30 SNe Ic & Ic-bl
- 1 GRB-SN 06aj (Modjaz+06)
- 2 peculiar SNe

72 SNe IIb, Ib, Ic, Ic-bl:

Tripled world-supply of well-observed Stripped SNe

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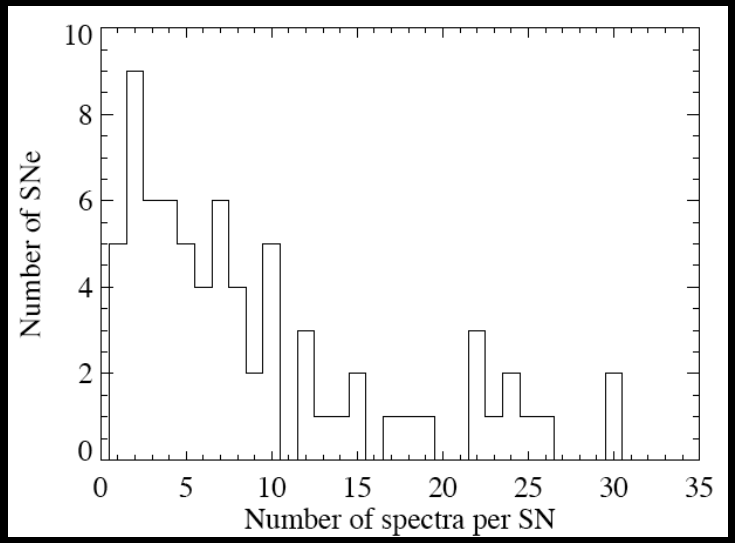
Paper I: release of extensive Spectroscopic Data

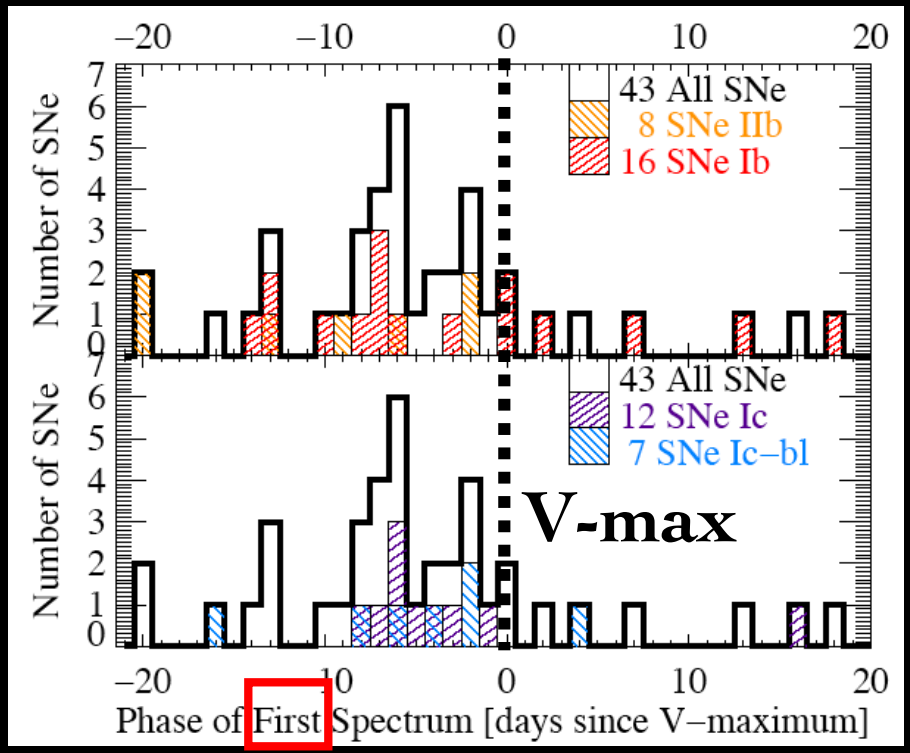
- SN relatively nearby (<cz>~ 4100 km/s)
- 43 of 72 SNe have measured date of max

Many Spectra: Total of 651, $<N_{spec}>$= 10 spec/SN -> time-evolution: important for SN classification & progenitor nature



Modjaz et al. (2012)

Many Early Spectra (before max)



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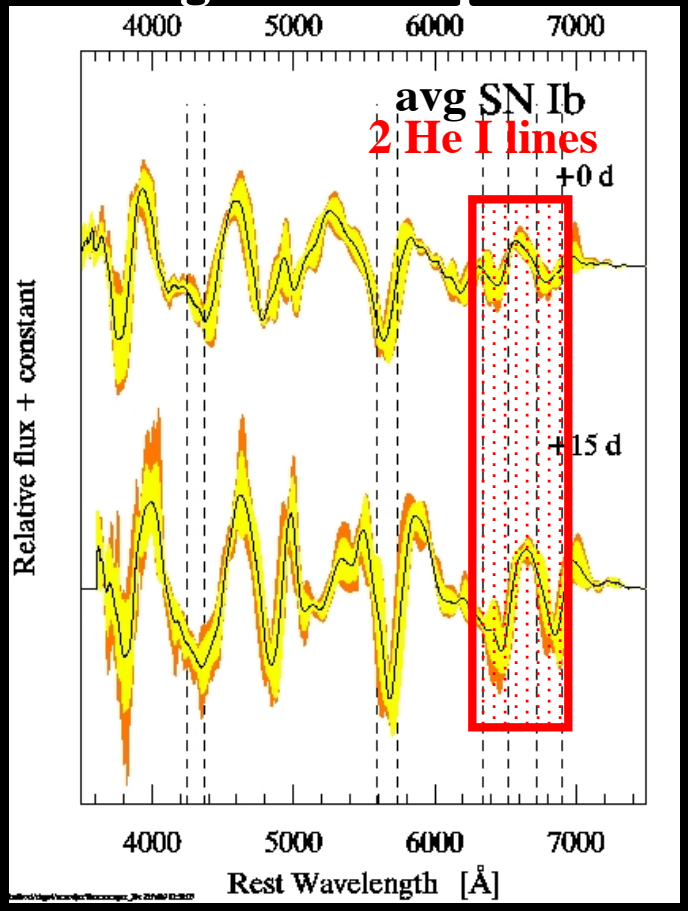
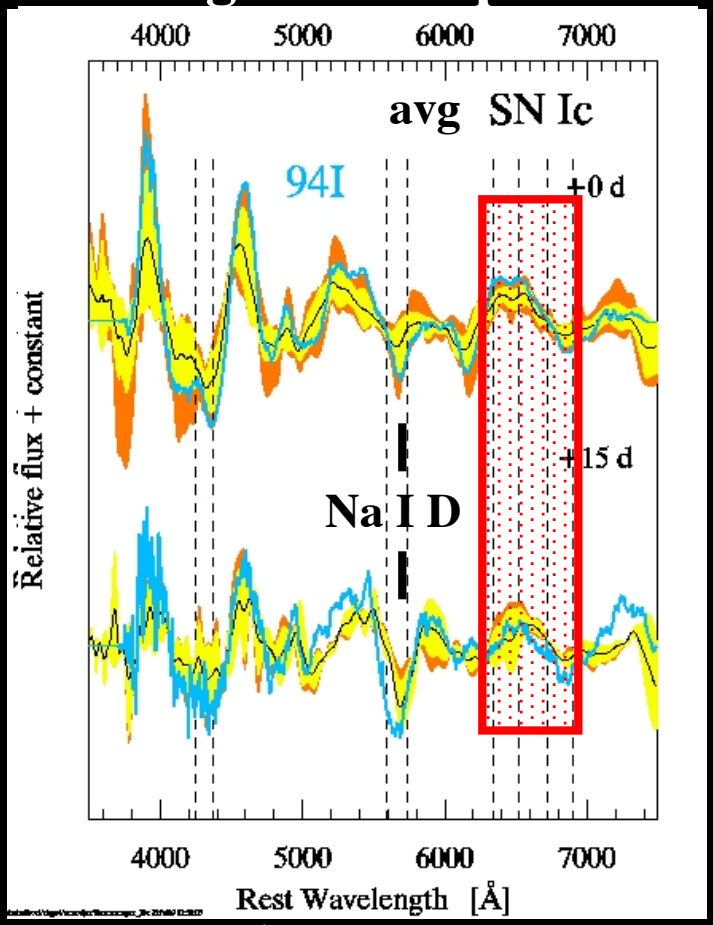
Paper II: "Typical" SN in SN Zoo?

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 λ6678 & 7065 emerge (as early as -10d)

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

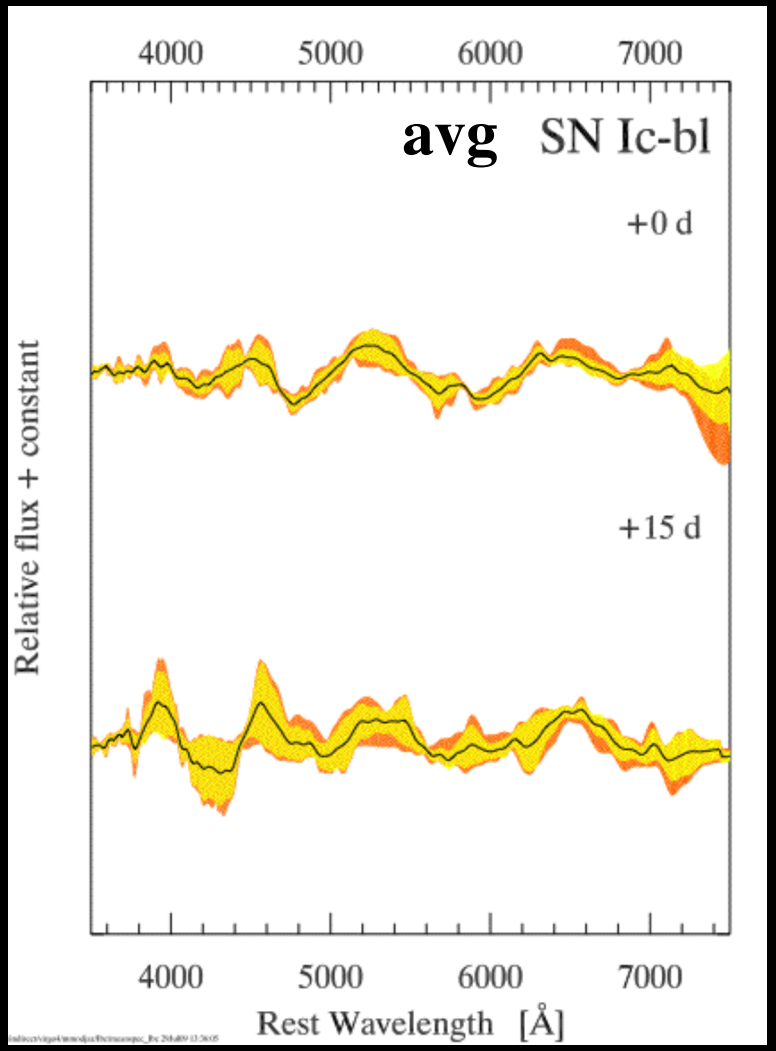
94I is not typical! 1 std dev away from average SN Ic

Typical Sn Ic vs SN Ic-bl

Line widths:

SN Ic @ +0d: ~7000-15,000 km/s

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



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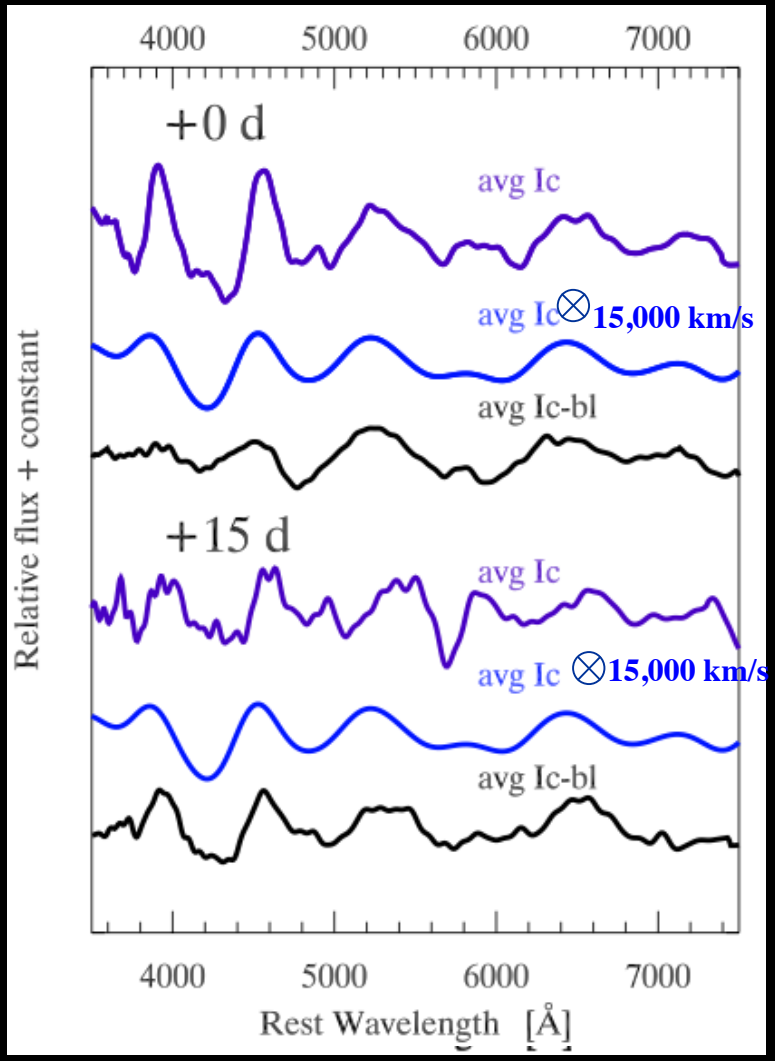
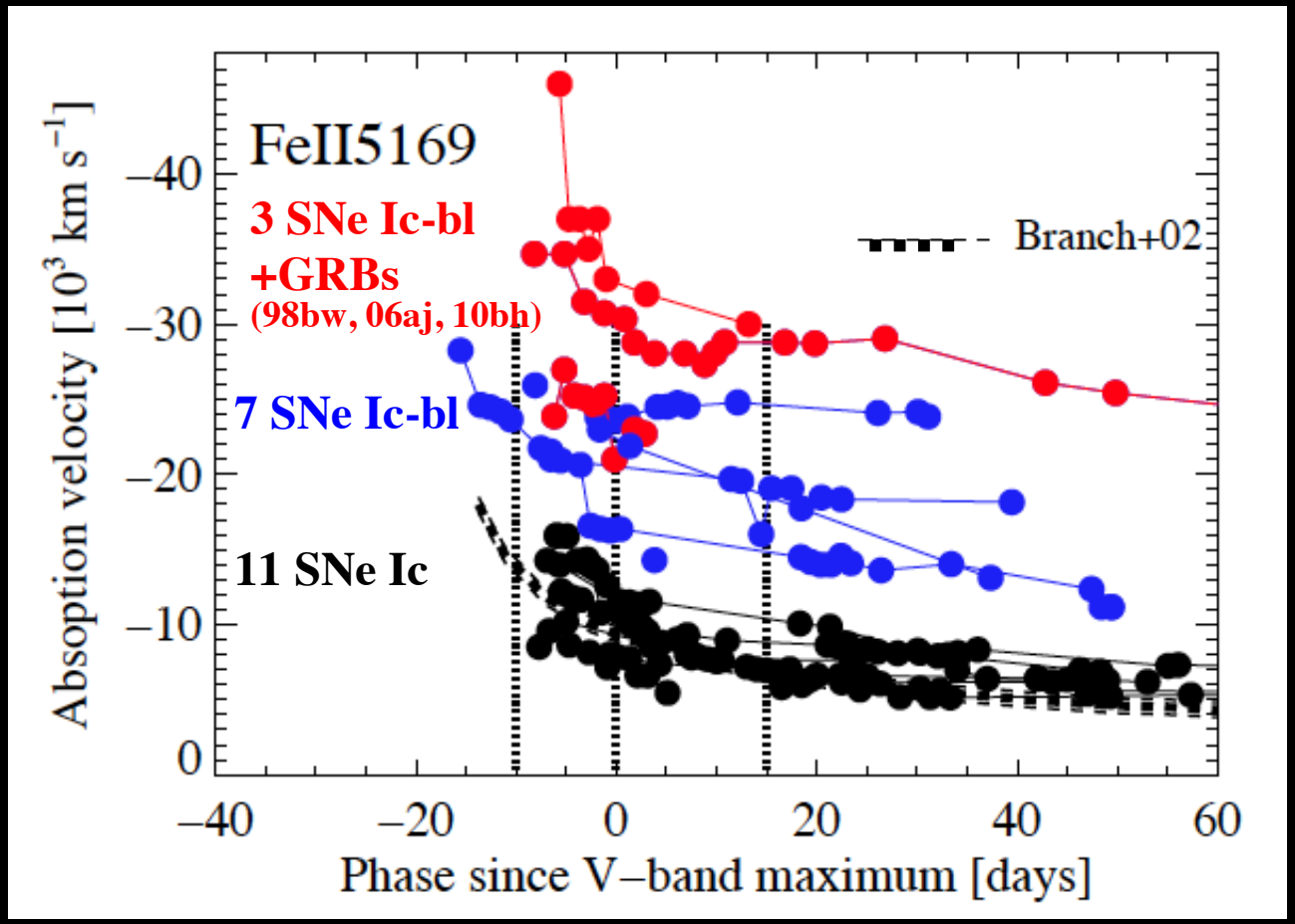
Typical Sn Ic vs SN Ic-bl

Average Spectra

SN Ic convolved with ~15,000 km/s Gaussian + blueshifted by 3000 km/s =~ SN Ic-bl



Systematic Analysis: e.g., Absorption Vel

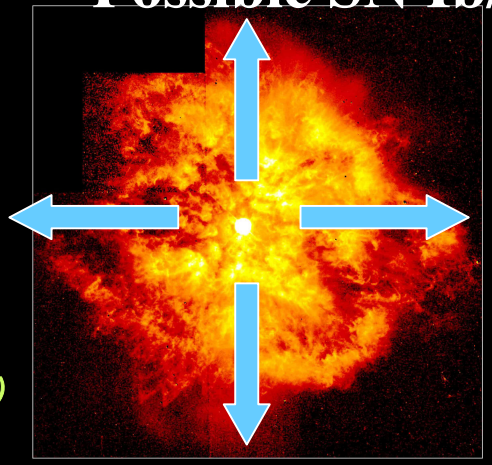


SNe Ic-bl/GRBs: largest velocities, followed by SNe Ic-bl and then SNe Ic (see also Mazzali+06, Pian+06, Mazzali's talk, Chornock+10)

Caveat: blending for SNe Ic-bl!

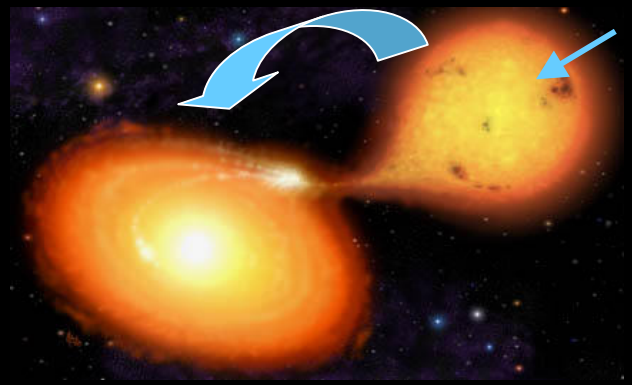
Hunt For Progenitors

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, runaway binaries (e.g., Podsiadlowski et al. 2004)

Direct Study (but either not conclusive & or few SNe):

- Pre-Explosion images: no progenitor detections (Smartt09, Van Dyk talk)
- Shock-breakout for a few SNe (Soderberg +08, Modjaz+09, Arcavi+11, Corsi+11) and 1 SN-GRB (Campana et al 2006)

Statistical Study:

Differentiate between GRB, SN Ib and SN Ic progenitor models via
- Environments & their Metallicities

[- SN Rates (Smartt+, Smith+)]

Definition of "Metallicity"

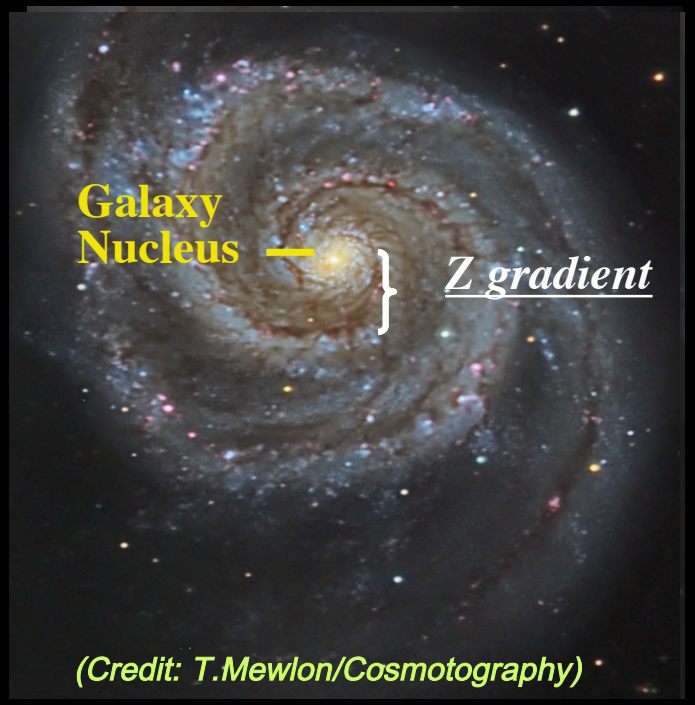
- Metallicity = Oxygen abundance in HII regions from emission lines [$12+\log_{10}(O/H)$]
- Why Oxygen?
  - Most abundant metal in the universe
  - Weakly depleted onto grains
  - Dominant coolant (besides H): strong nebular lines in optical
  - Well-established diagnostics, e.g., Kewley & Dopita (2002, KD02), Pettini & Pagel (2004,PP04), McGaugh 1991 (M91)
- From HII regions at SN site by massive young stars

  = natal metallicity of core-collapse SN progenitor

Recipe for measuring "Z": State of the Art

- Spectra at position of SN or GRB (b/c of Z gradients): probe natal Z
- SNe with secure ID (many spectra)
- Large λ range: robust & uniform Z estimate, correct for reddening
- Remove stellar absorption in spectrum when necessary
- Uncertainty budget
- In different and independent oxygen abundance diagnostics (e.g., Kewley & Ellison 2008)

A large-aperture telescope (Keck, VLT, Gemini …)



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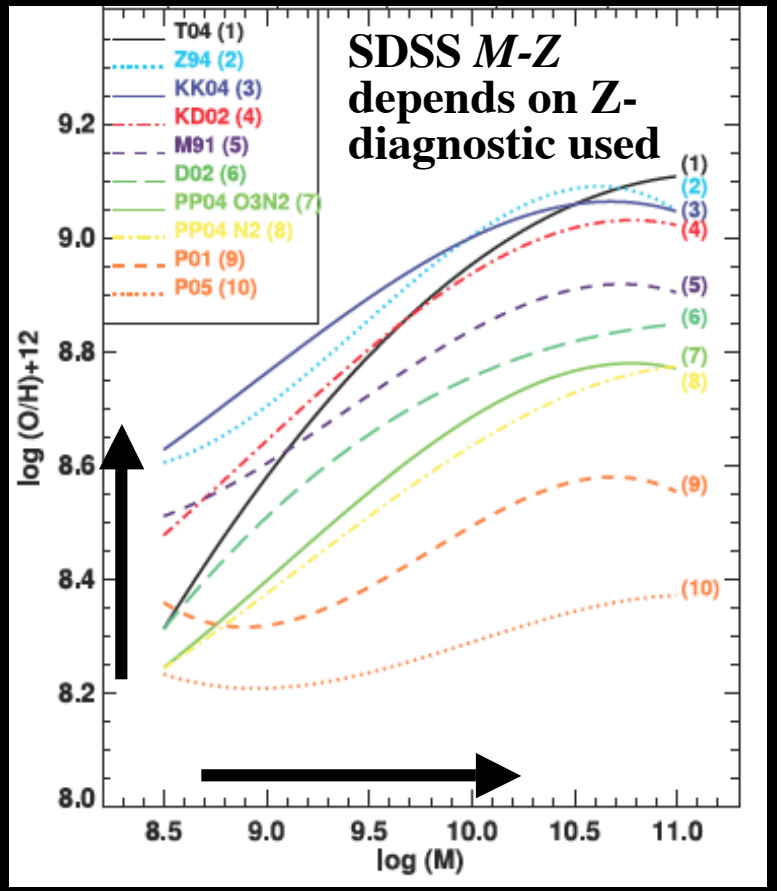
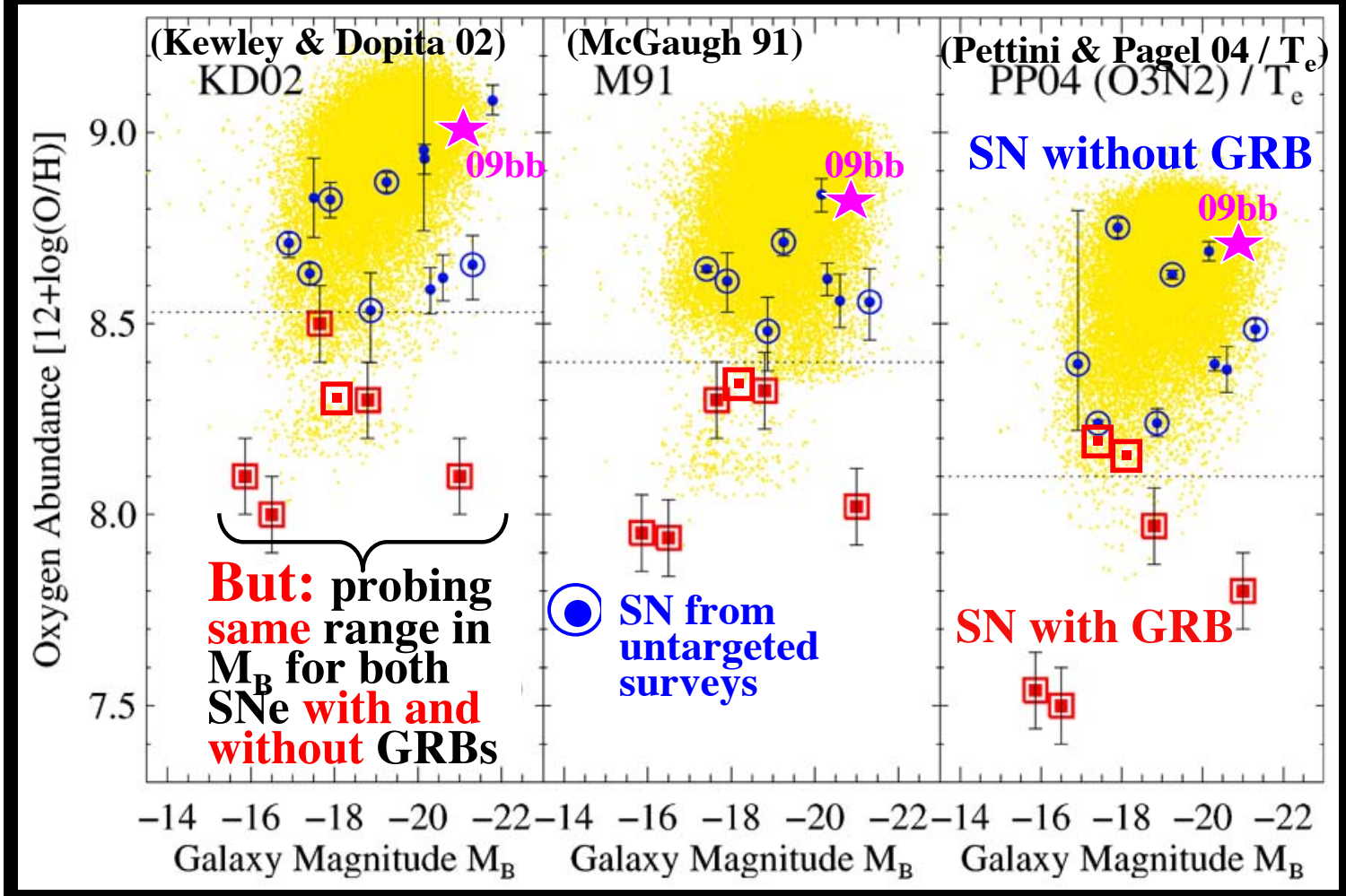
- Uncertainty budget
- In different and independent oxygen abundance diagnostics (e.g., Kewley & Ellison 2008)
- Also include SNe from galaxy-unbiased surveys: mitigate selection effects (e.g., Modjaz et al. 2008, Young et al. 2008)



Kewley & Ellison (2008)

Metallicities at the Sites of SN Ic-bl with and without GRBs



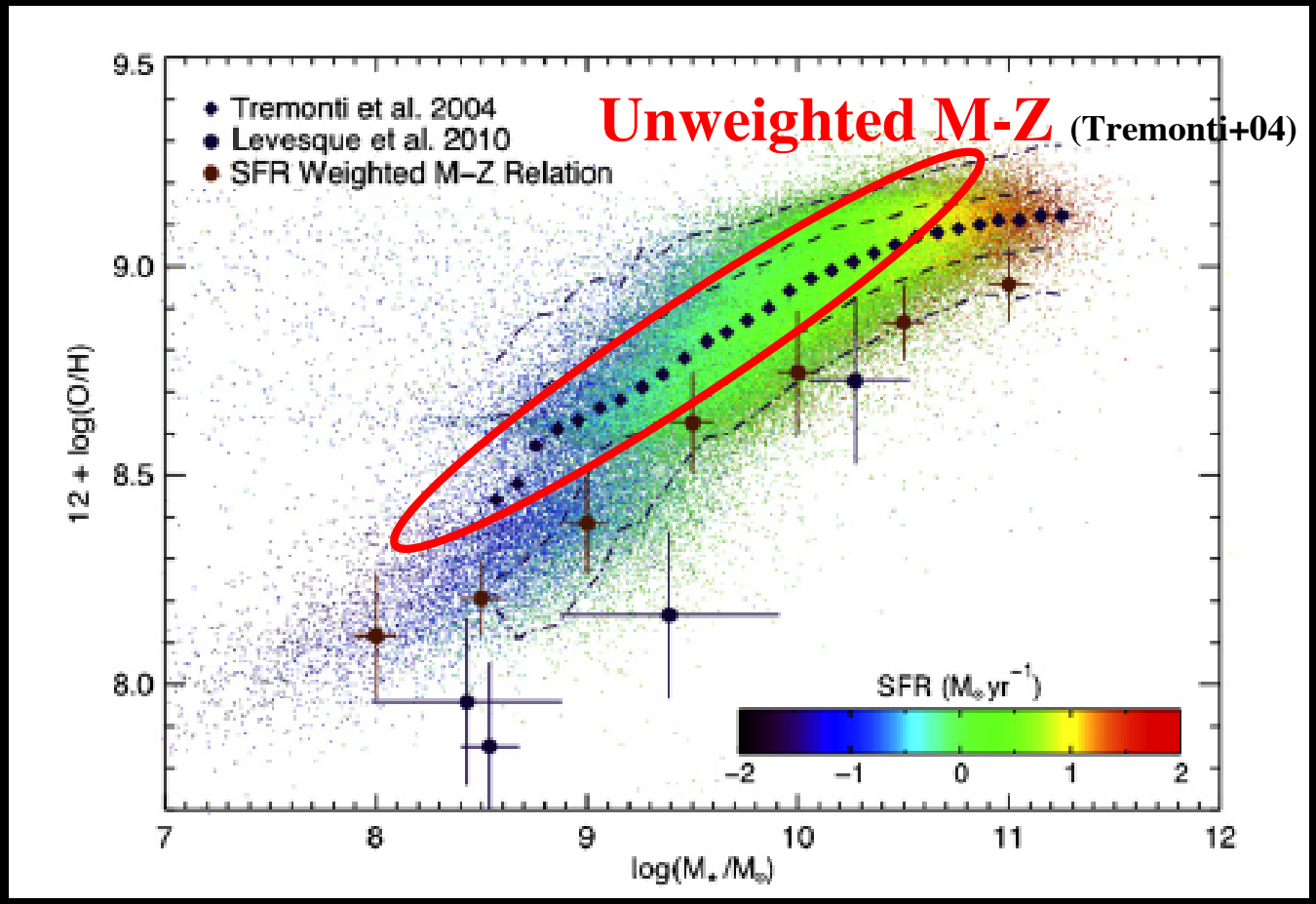
Updated Modjaz et al (2008): For 10bh/100316D: Chornock +11, Starling+ 11, Levesque+11; for 98bw's PP04: Christensen+08 SN2009bb: Levesque+10

Reason(s):

- Low Z GRB progenitor? (Yoon & Langer 05, Woosley & Heger 06)
- Dust? (Fynbo +10, Perley+10)
- M-Z-SSFR? (Mannucci +10, Koveski & West 11)

Test with SN crop from **new surveys** (PTF, LSST)

Do GRBs trace star formation?



Kocevski & West (2011): SFR weighting **not enough** to explain GRB host M-Z's offset to low Z - **(see also John Graham's talk)**

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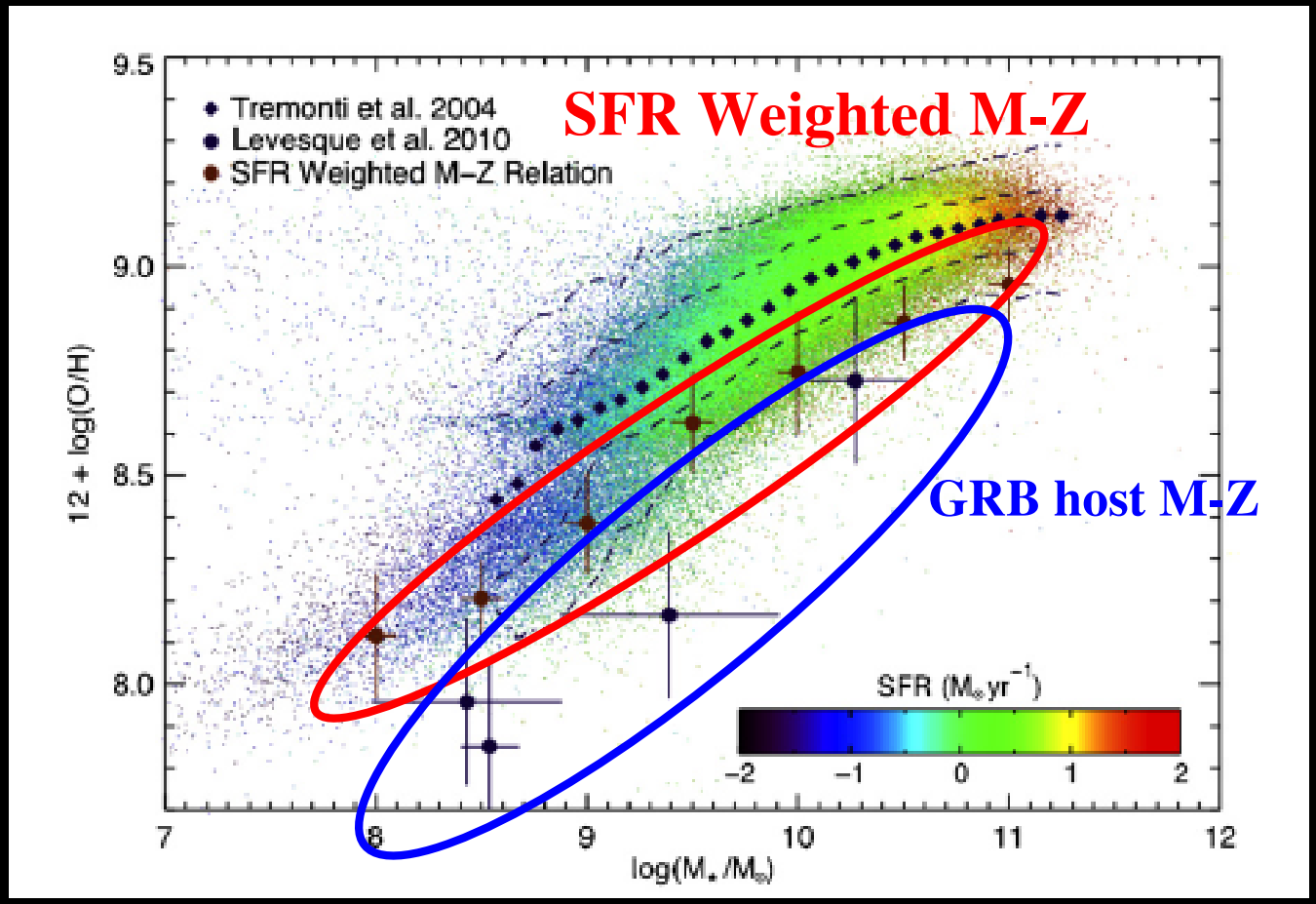

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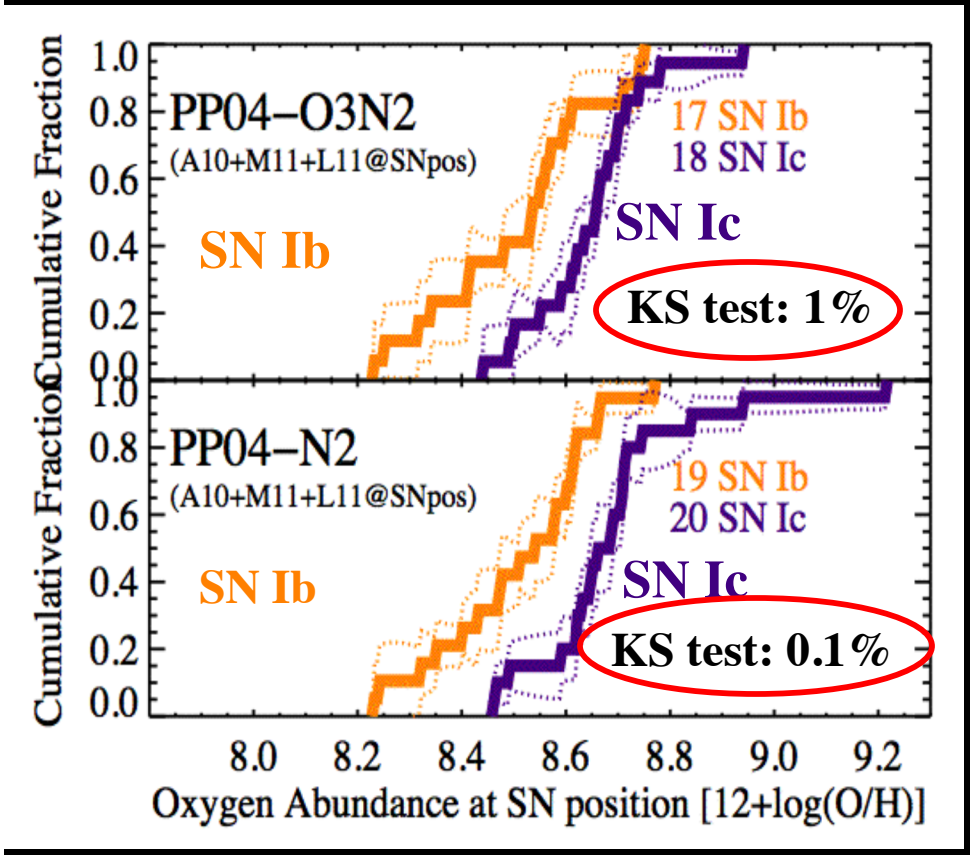
Hunt For SN Ib/c Progenitors: Sites of SN Ic are more metal-rich than those of SN Ib



more metal-rich

Meta-Analysis:

Modjaz+ 11 & Anderson +10 & Leloudas +11 @SN position:

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

(see also Arcavi et al. 2010, Kelly & Kirshner 2011, astro-ph)

Implications:

- consistent with WR scenario

-Locally measured Z different from SDSS prediction & nuclear values

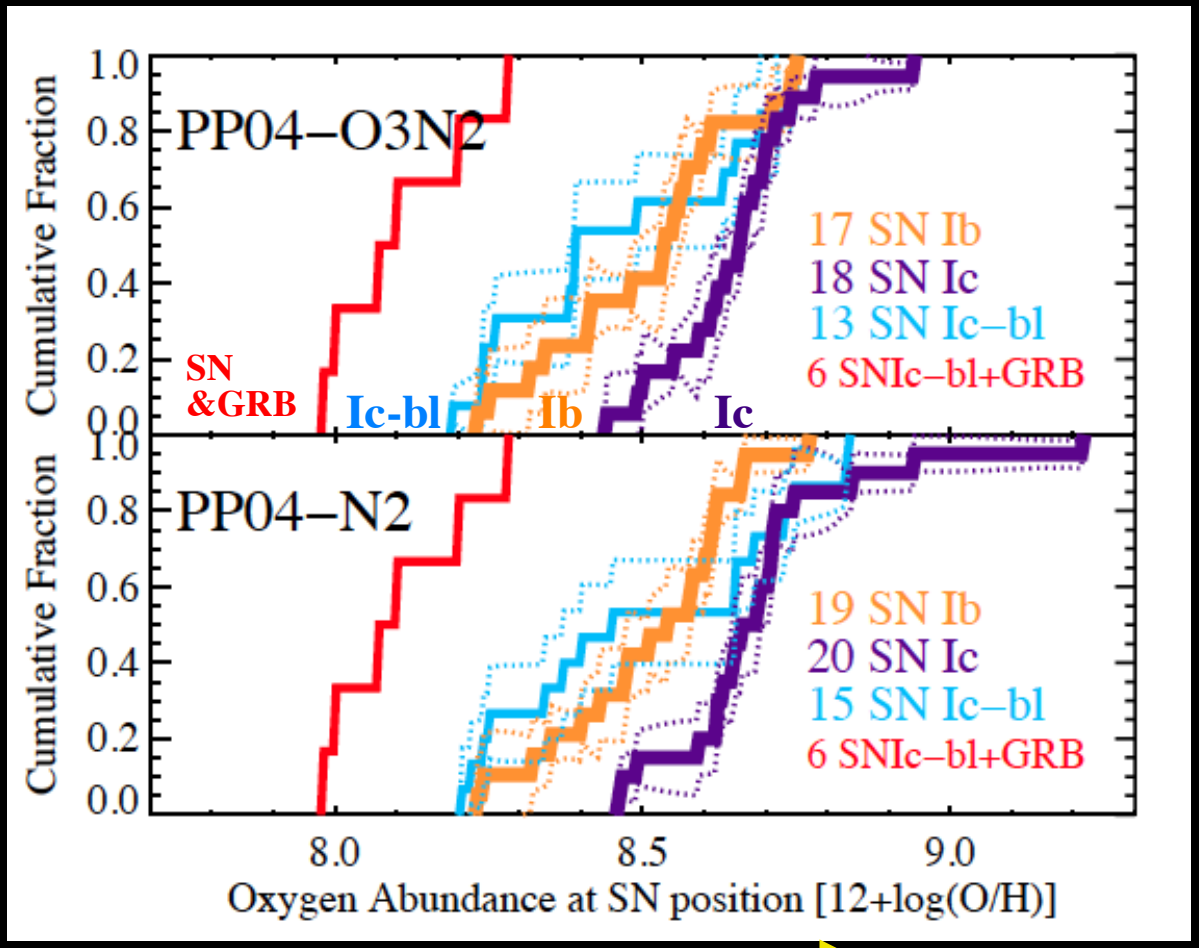
- SN sub-types are physically motivated: different progenitors for different SN types - not just viewing effects or mixing

Maryam Modjaz

Oxygen abundance @ SN Sites

$$Z_{\text{Ic-bl\&GRB}} < Z_{\text{Ic-bl}} \lesssim Z_{\text{Ib}} < Z_{\text{Ic}}$$

more metal-rich



more metal-rich

(Modjaz+ 08 &11 & Anderson +10 & Leloudas +11 @SN position)

Consistent with Arcavi+10, in prep

What about Z_{IIb}?

->Kelly & Modjaz (in prep)

Conclusions: SNe Ib/c with and without GRBs

- Growing amount of comprehensive data -> quantify diversity & systematic study
- CfA Spectroscopic (& photometric) dataset for 72 Stripped SNe is densely time-sampled, homogeneous & extensive
  - Average spectra: SNe Ic and SNe Ic-bl different
  - SN1994I (classical SN Ic) is not typical for a SN Ic
  - Velocities: $v_{SN\text{-}GRB} > v_{SNIc\text{-}bl} > v_{SNIc}$
- Environmental & metallicity studies are a rapidly developing field
  - Meta-analysis: $Z_{SNIc} > Z_{SNIb}$ is robust, also
  - $Z_{Ic\text{-}bl\&GRB} < Z_{Ic\text{-}bl} \sim< Z_{Ib} < Z_{Ic}$ (though interpretation debated for GRB-SN)
  - Need local Z measurements vs. nuclear measurements