HYDROGEN-Deficient Explosions and their Environments

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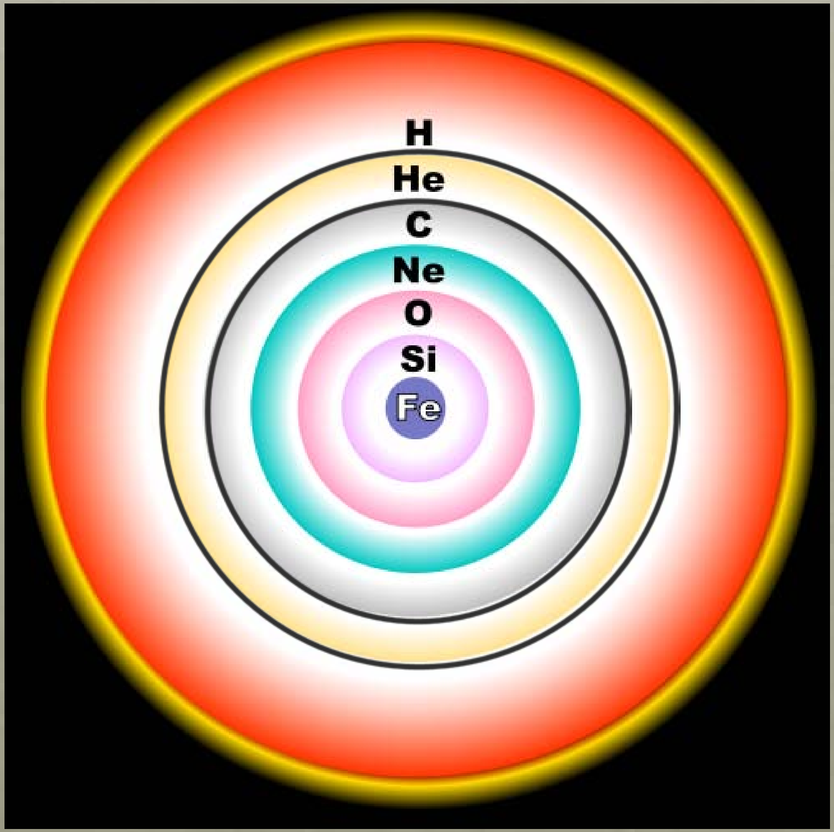
Outline

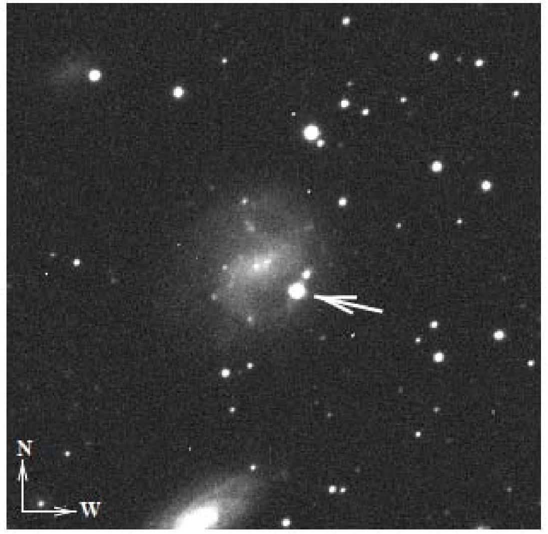
- PART I
  - Locations of WR stars, SNe Ib/c and GRBs (Leloudas+ 2010)
  - Environmental metallicities and stellar ages (Leloudas+ 2011)
- PART II
  - SN 2006oz: the rise of a super-luminous SN (Leloudas+ 2012)

Stripped SNE: the questions

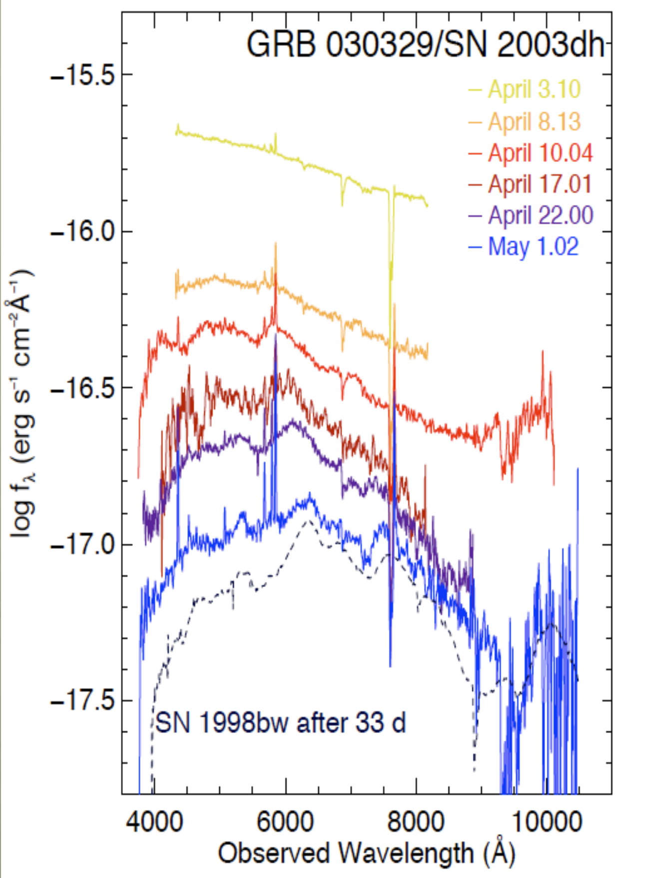


- No progenitor detection
  - Should be WR stars
- How is the H envelope lost?
  - Strong winds
  - Binary interactions
- What gives a GRB?
  - Low metallicity? (or observational bias?)

SN - GRB connection



SN 1998bw
Galama+ 1998

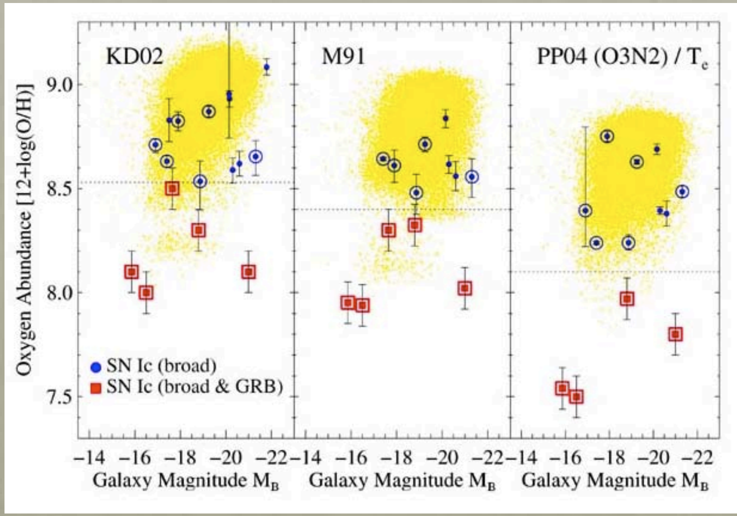


Hjorth+ 2003

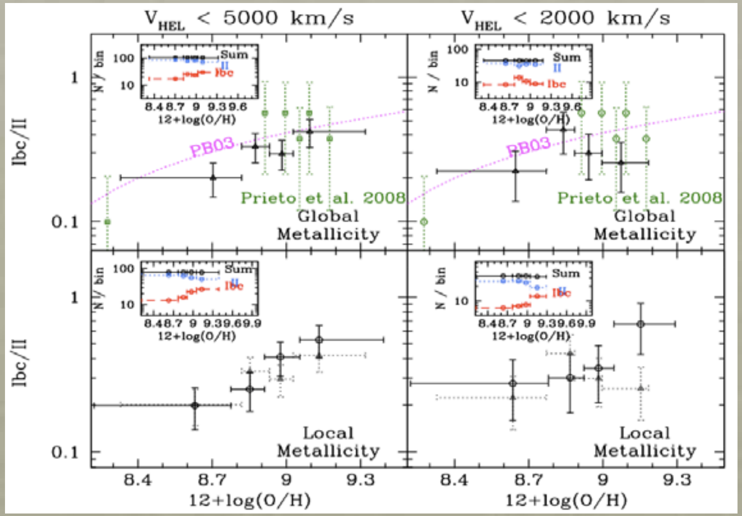
Stripped SNe: the diagnostics

- Single progenitors: the envelope is stripped by stellar winds.
  - Wind strength depends on metallicity (Vink & De Koter 2005)
- *Prediction*: in the single progenitor scenario, SNe Ic expected to occur in more metal- rich environments than SNe Ib
- Massive stars are like *Rock N' Roll stars*: live fast and die young!
  - Proximity to recent star formation.

Explosion birthplace studies



Modjaz+ 2008



Boissier & Prantzos 2009

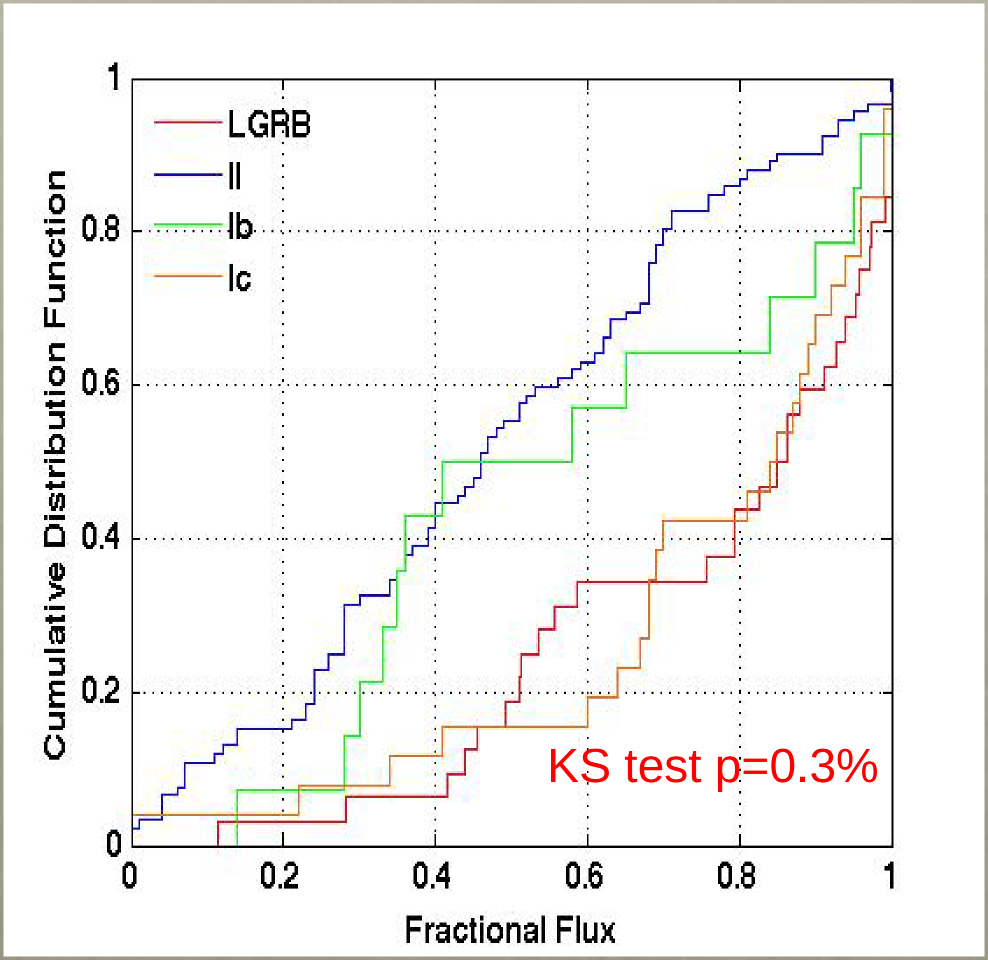
- Detailed studies of special events (e.g. Sollerman+ 2005, Modjaz+ 2008)
- Larger statistical studies of regular events but with:
  - global properties (Prantzos & Boissier 2003, Prieto+ 2008)
  - local proxies (Anderson 2009, Boissier & Prantzos 2009)

Location with respect to galaxy light

- GRBs tend to occur in the brightest locations of their hosts (Fruchter+ 2006)
- SNe Ic in brighter pixels than Ib, and Ib in brighter than II (Kelly+ 2008)
- This statistic also used in theoretical studies with predictive power (Larsson+ 2007, Raskin+ 2008)

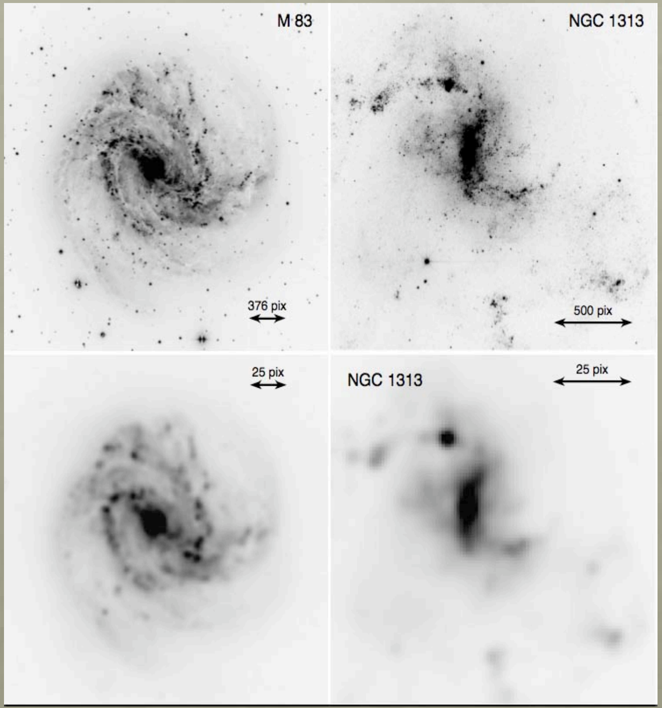
$$FF_{\text{i-th pixel}} \; \frac{\sum_{\text{pixels with counts} < \text{i-th pixel}} \text{counts}}{\sum_{\text{all galaxy pixels}} \text{counts}}$$

See also Anderson+ 2008



The next obvious step

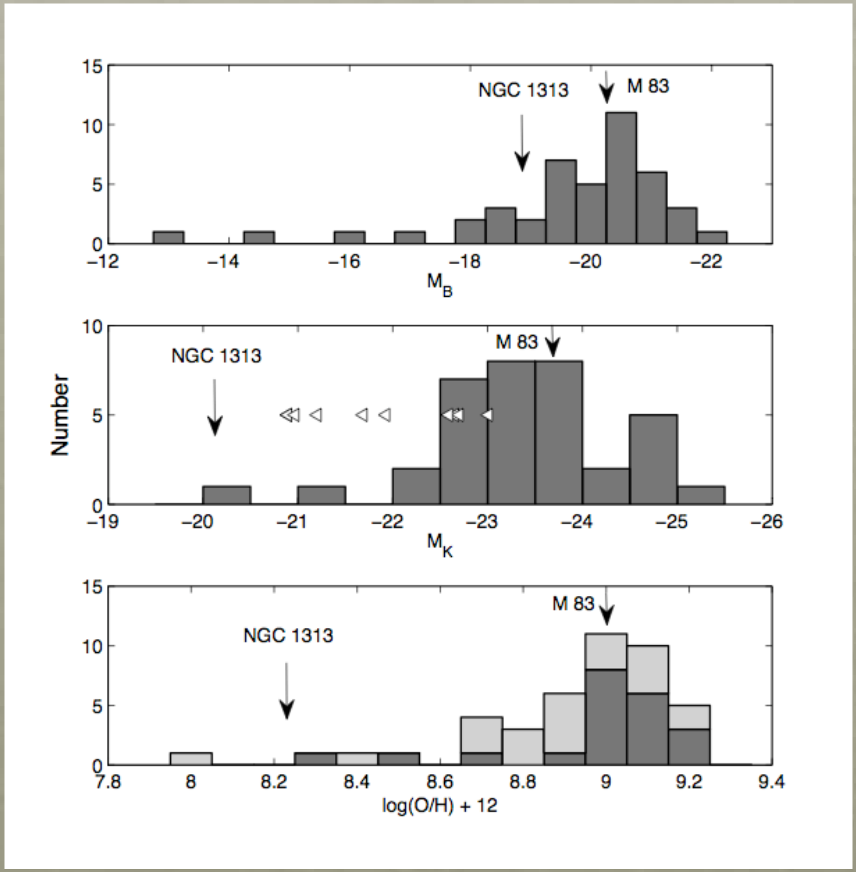
- *If they have WR progenitors, their locations within their hosts should be similar*
- Theoretically:
  - WN → SN Ib
  - WC → SN Ic
- Used work of Crowther & collaborators
- *Completeness* is crucial
  - M 83 (Hadfield+ 2005)
  - NGC 1313 (Hadfield & Crowther 2007)
- Removed foreground stars & resampled



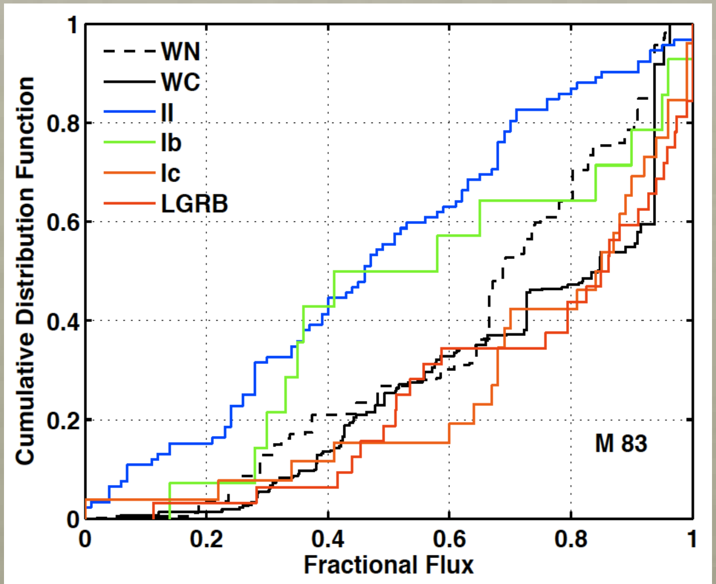
Leloudas+ 2010

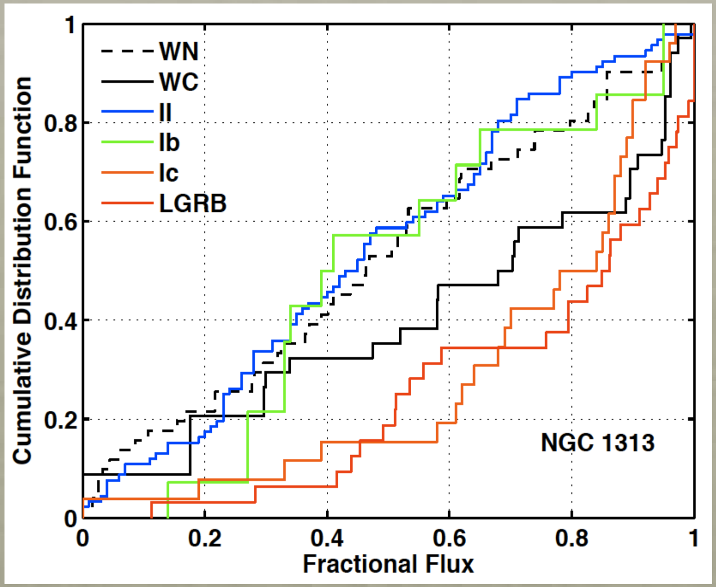
On the statistics

- 2 galaxies but > 1000 WR stars.
- N_{SN}=44, N_{GRB}=32
- Galaxies are not special, so results can be generalized.
- Metallicity is important
- Now data available for 2 more galaxies (Bibby+ 2010, 2012)



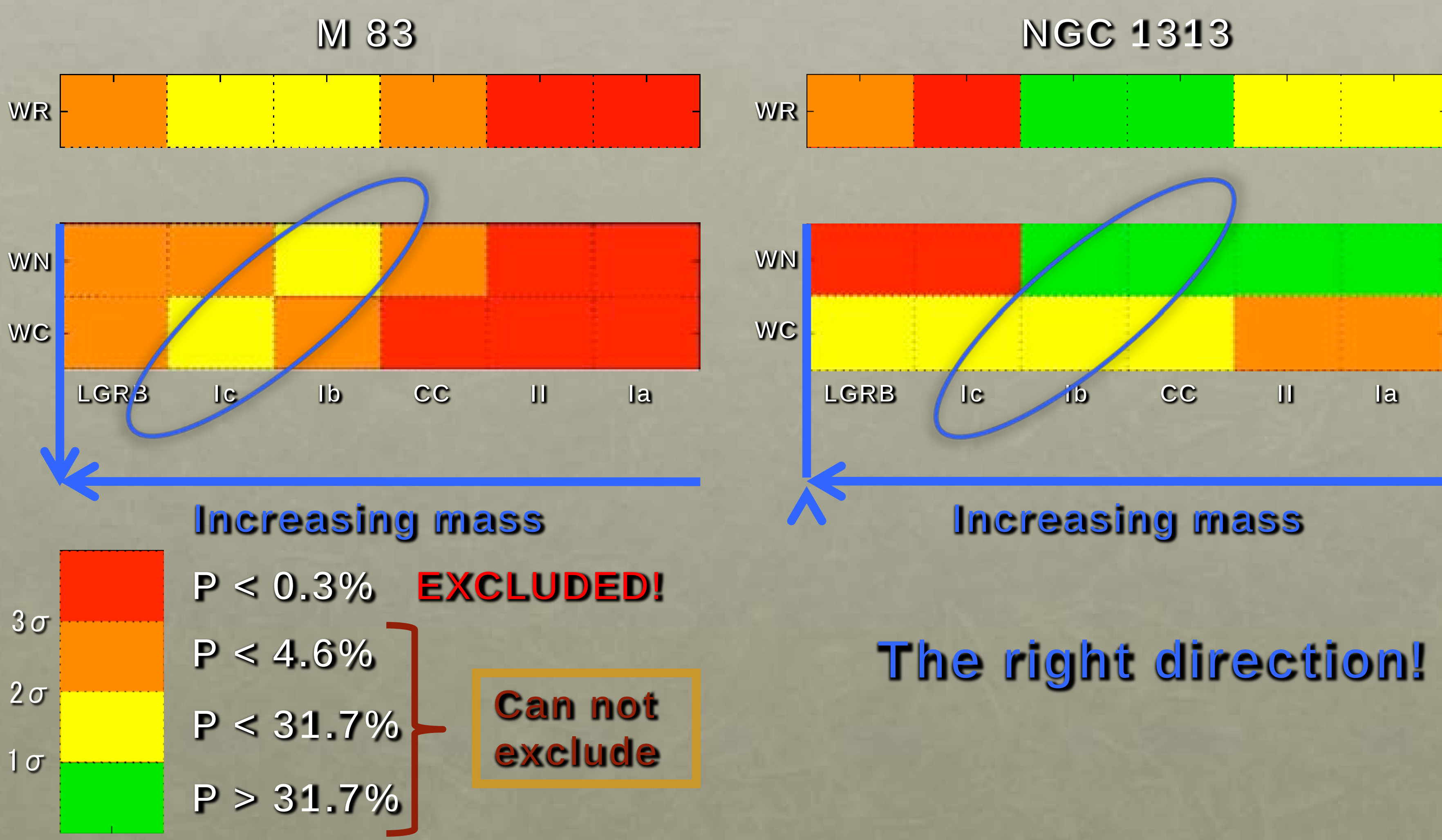
Results





- WC in brighter locations than WN
- Differences with metallicity exist. E.g. SNe II and WN stars compatible at low Z. Expected to some degree (e.g. Georgy+ 2009)

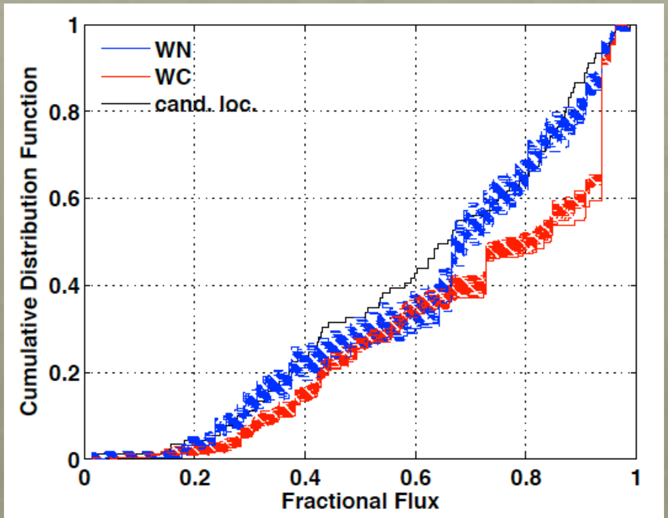
A poor man's contour plot



The right direction!

Discussion

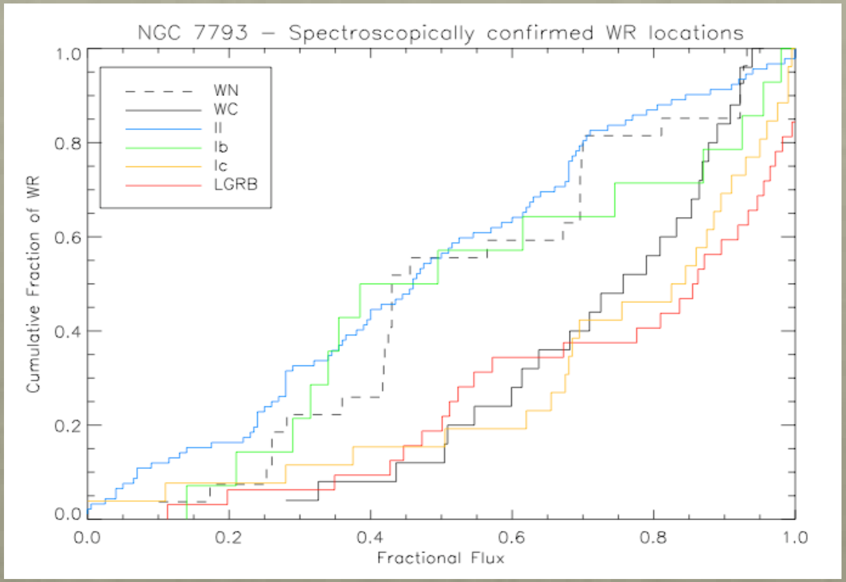
- WR viable progenitors of SNe Ib/c and GRBs
- WC distribution at brighter locations than WN
  - WC probabilistically more associated with SNe Ic and WN with SNe Ib
- SNe II compatible with WR (esp. WN) at low Z
- Monte Carlo simulations for:
  - Candidate WR stars
  - Number errors
  - Foreground stars
  - WN to WC transition



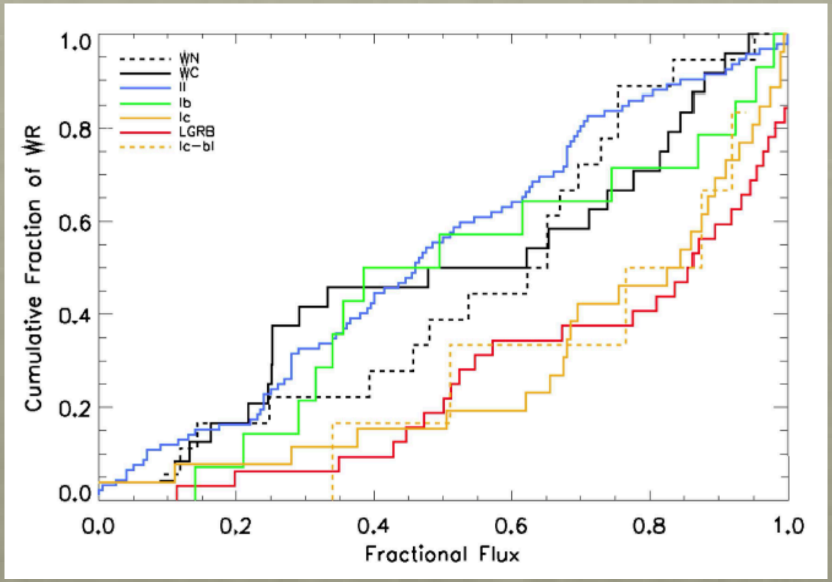
The SAMPLE is INCREASING

- NGC 7793
- 12 + log(O/H) = 8.44

- NGC 5068
- 12 + log(O/H) = 8.73 with steep gradient



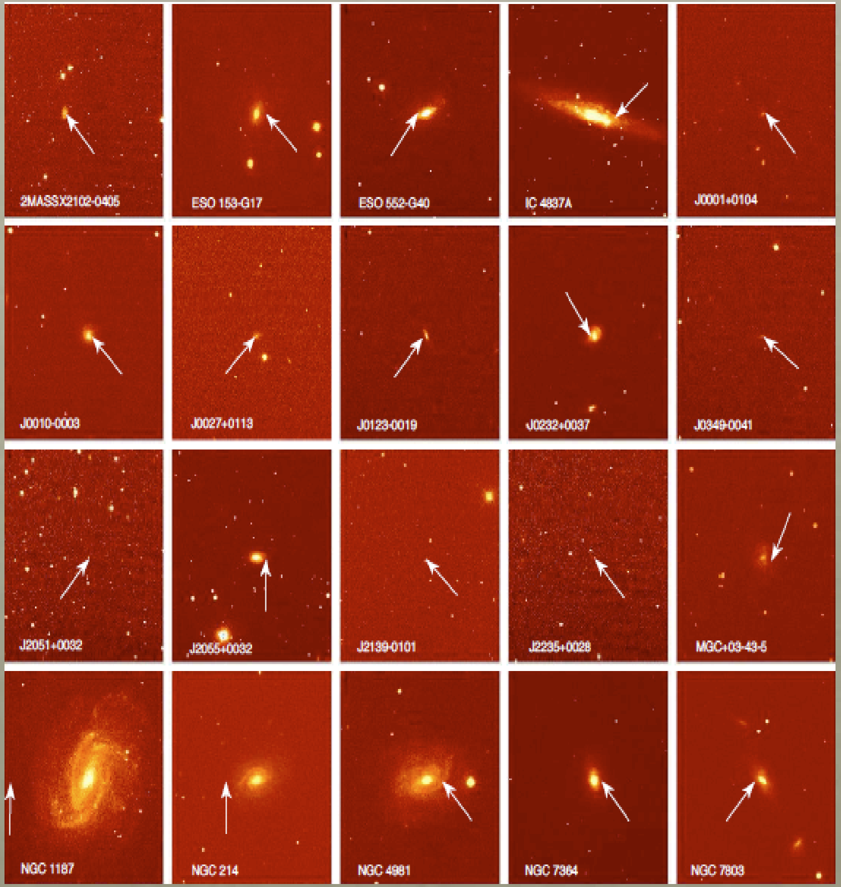
Credit: Joanne Bibby



Bibby & Crowther (2012)

Birthplaces of normal SNe Ib/c

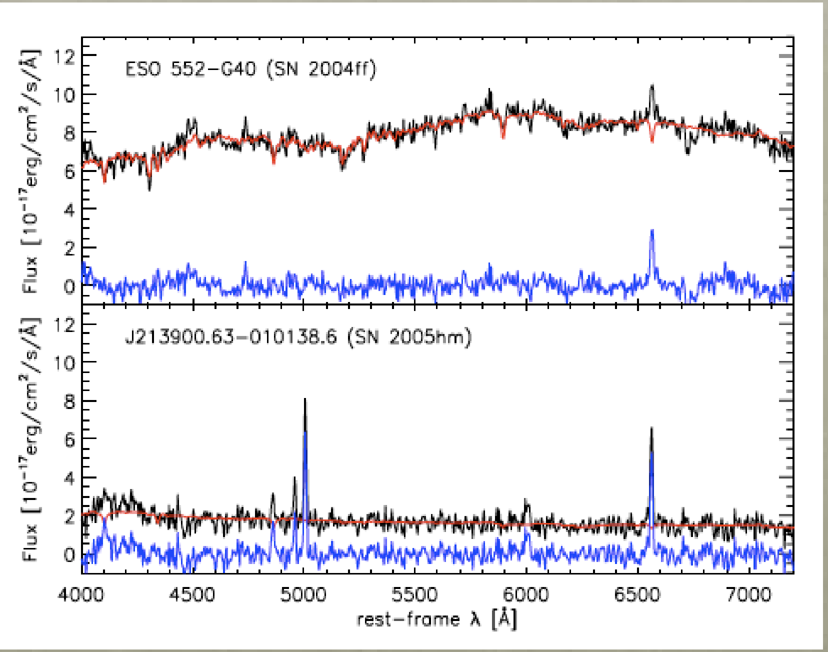
- NTT + EFOSC2
- 20 host galaxies of normal SNe Ib/c
  - Some re-classified !
- Selected to have good SN data
- Both 'bright' CSP and SDSS galaxies
- Targeted and non-targeted surveys
- Slit through exact site and galaxy nucleus



Leloudas+ 2011

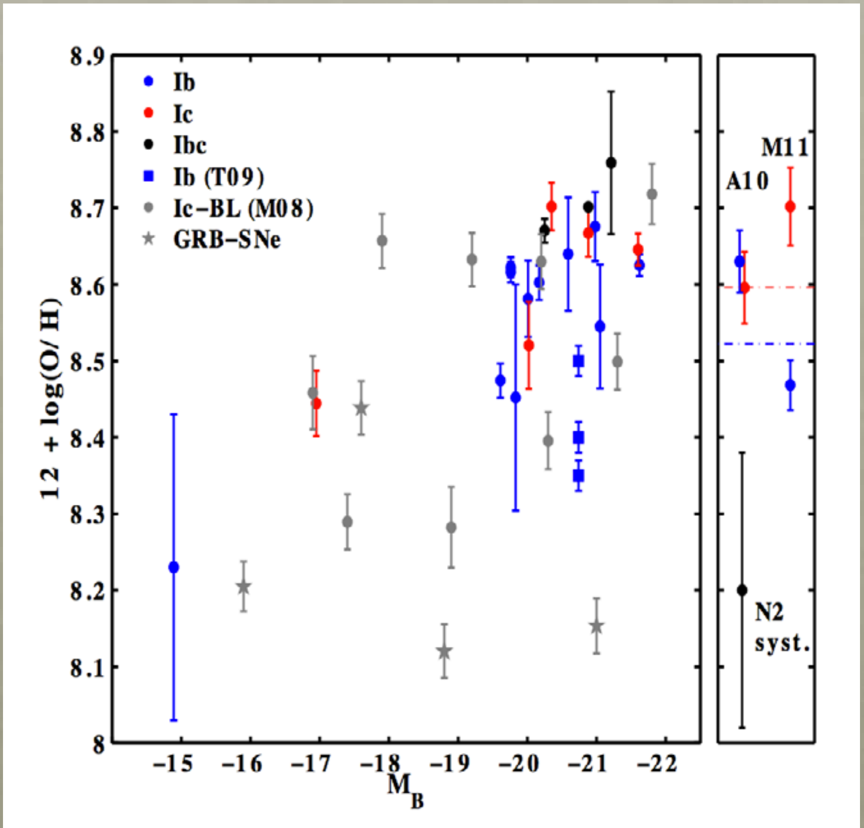
Metallicities

- SN Ib location avg. metallicity: 8.52 ± 0.05.
- SNe Ic: 8.60 ± 0.08.
- So maybe a tentative trend that $Z_{Ic} > Z_{Ib}$ but low significance.
- KS test: no significant evidence for Ib and Ic locations being different. p-val. = 17%.



- Stellar continuum removal to obtain emission line spectrum
- BC03 stellar population synthesis models

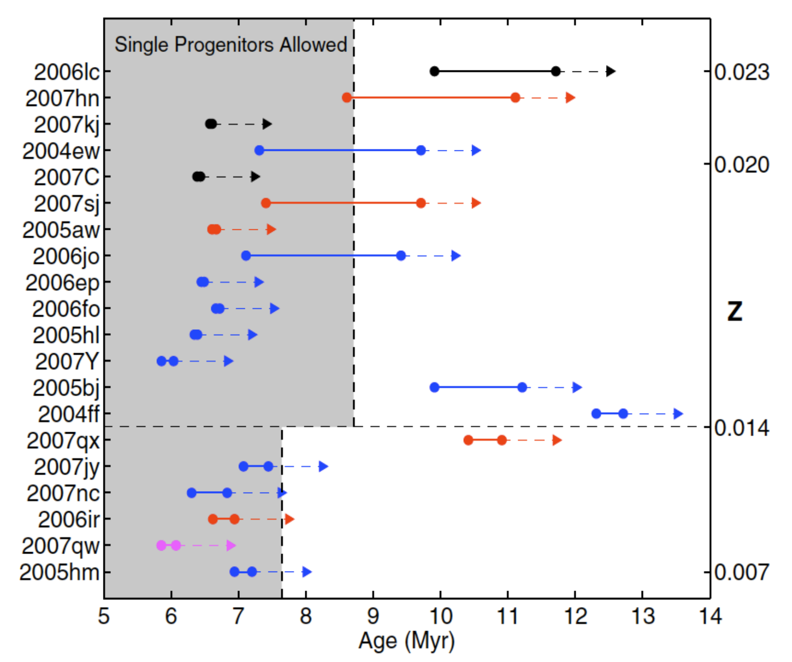
More metallicities



- I. Anderson+ 2010: 27 hosts
  - $Z_{Ib} \sim Z_{Ic}$
- II. Modjaz+ 2011: 35 hosts
  - Report significant difference: 0.2 dex, p = 1%
- Our result is in the middle:
  - Different biases can play a role
  - Important to treat systematic errors properly
- Targeted: 8.67±0.06 (σ=0.06); Non-targeted: 8.55 ±0.06 (σ=0.19); p = 8% (see also Arcavi+ 2010)
- Inconclusive on binarity issue ?

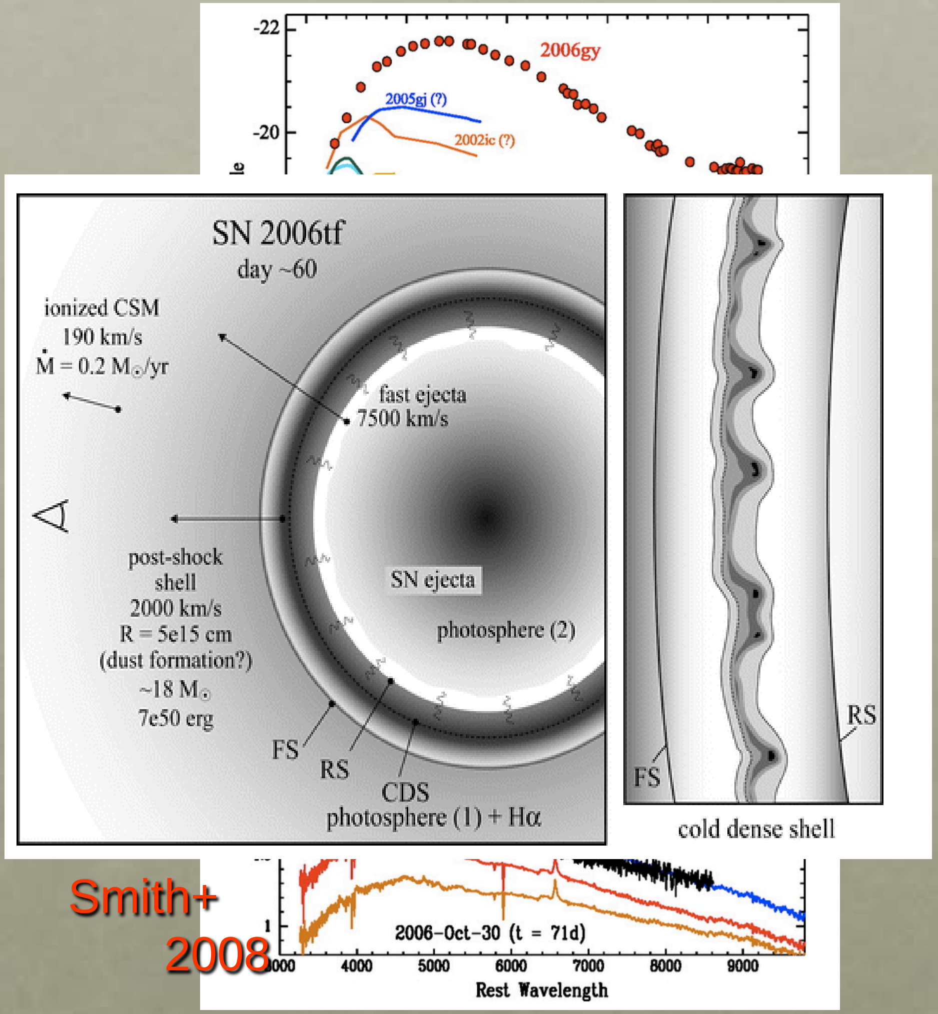
Stellar lifetimes comparison

- Take youngest stellar population by Hα EW as *lower age limit* of SN region.
    - Starburst99 and *assumption of instantaneous SF episode*.
- Compare to lifetimes of single stars: *upper limits*.
    - Geneva models (Meynet & Maeder 2003, 2005, Georgy+ 2009)
- These are conservative limits
- 20-35% of regions examined too old to give SNe Ib/c from single progenitors.
    - But conclusion limited by assumption



Part II: Super-luminous SNe

- Discovered recently
- Found only in blind, unbiased searches (e.g. Texas SN Search)
- M < -21.5
- Famous example: SN 2006gy
  - SNe 2006tf, 2008es (II-L), …
- H-rich: CSM interaction
  - See Moriya & Tominaga 2011 for diversity due to density structure

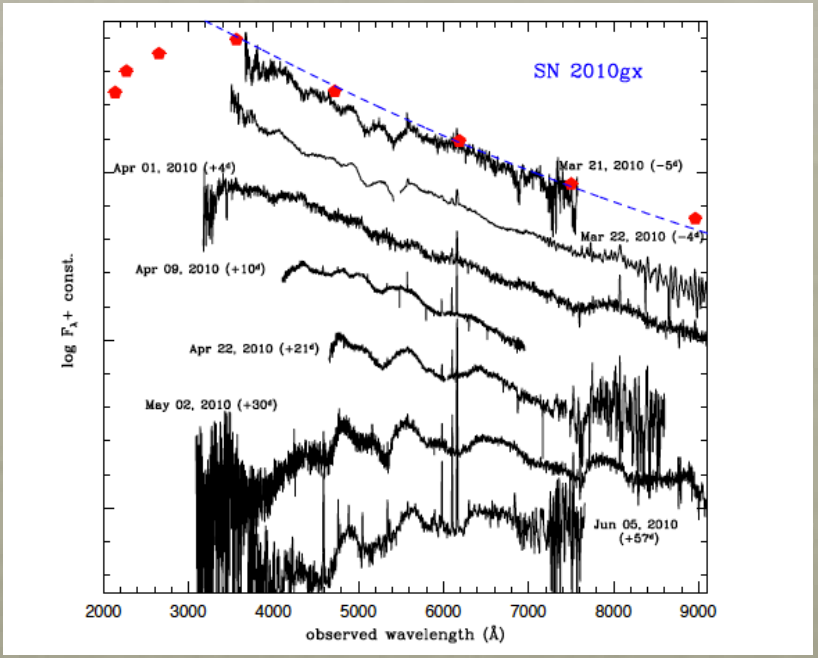


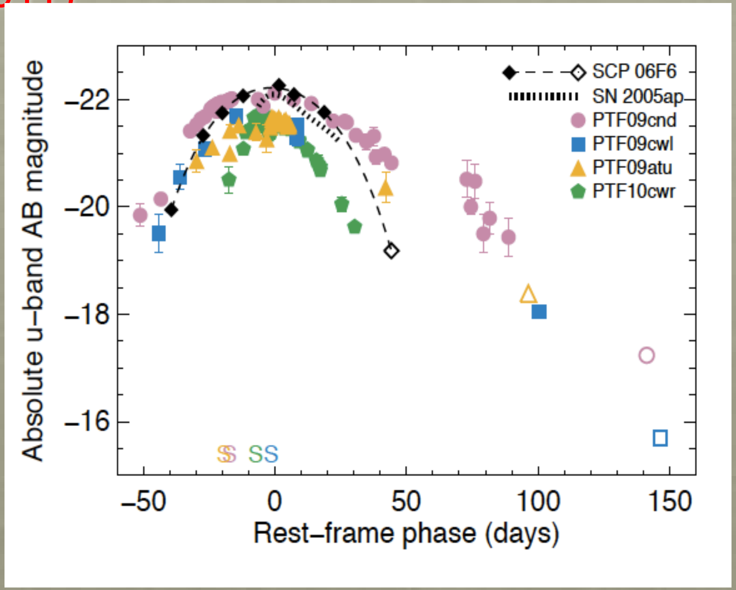
Smith+ 2008

Smith+ 2007

H-poor events

- SN 2005ap (Quimby+ 2007)
- Mysterious SCP06F6 (Barbary+ 2007)
- 4 objects by PTF (Quimby+ 2011)
- 2 more by PS1 at z ≈ 0.9 (Chomiuk+ 2011)

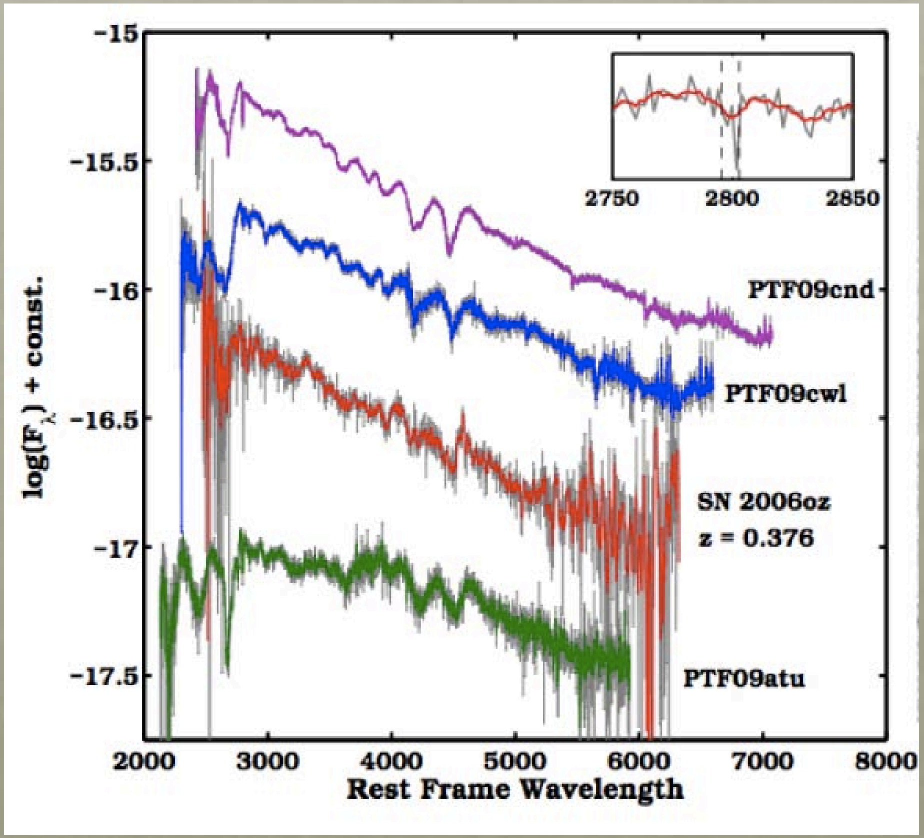




- Not radioactive decay
- Magnetar? CSM? PPI ?
- Some connection with SN Ic (Pastorello+ 2010)

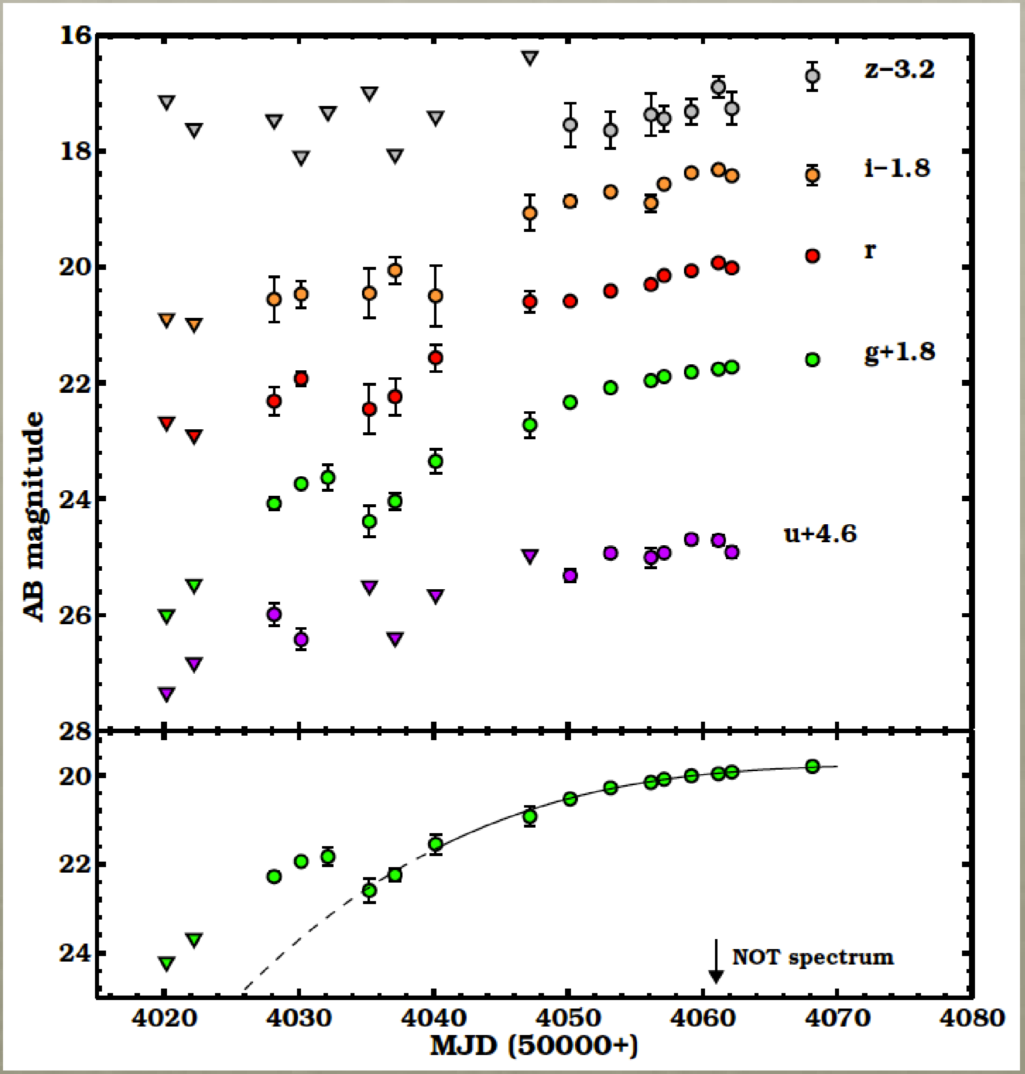
SN 2006oz

- SDSS-II SN Survey
  - Important contribution from Texas group
- Spectrum obtained at the NOT
- Misclassified as possible Ib. Hostless.
- z ≈ 0.376 by SN
  - No obvious Mg II (2.7σ) or other galaxy emission lines

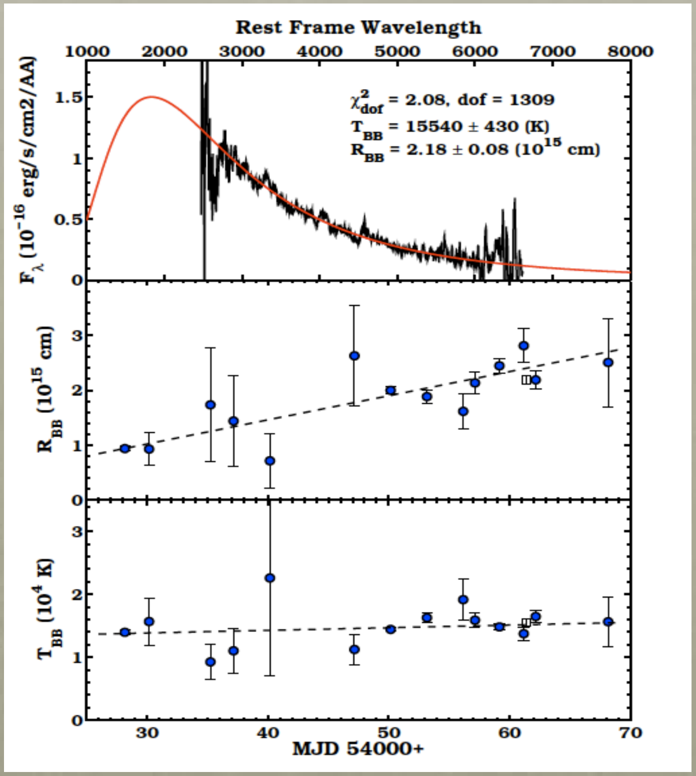


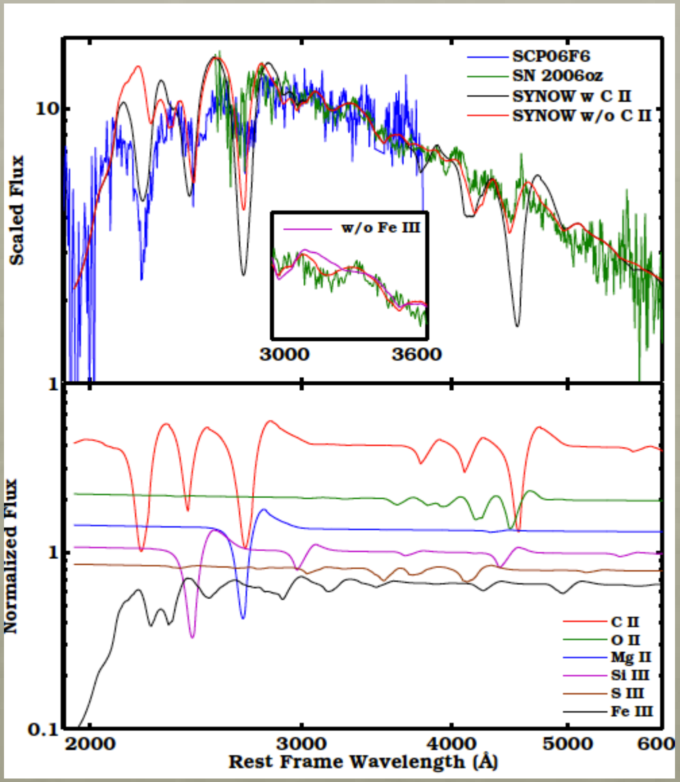
Light Curve

- No post-maximum ☹
- Caught early ☺
- Multi-color ☺
- $M_u < -21.5$ mag
- *Unusual early evolution*:
  - Dip in g, r bands
  - Possible fading in u



Black Body & SYNOW fits



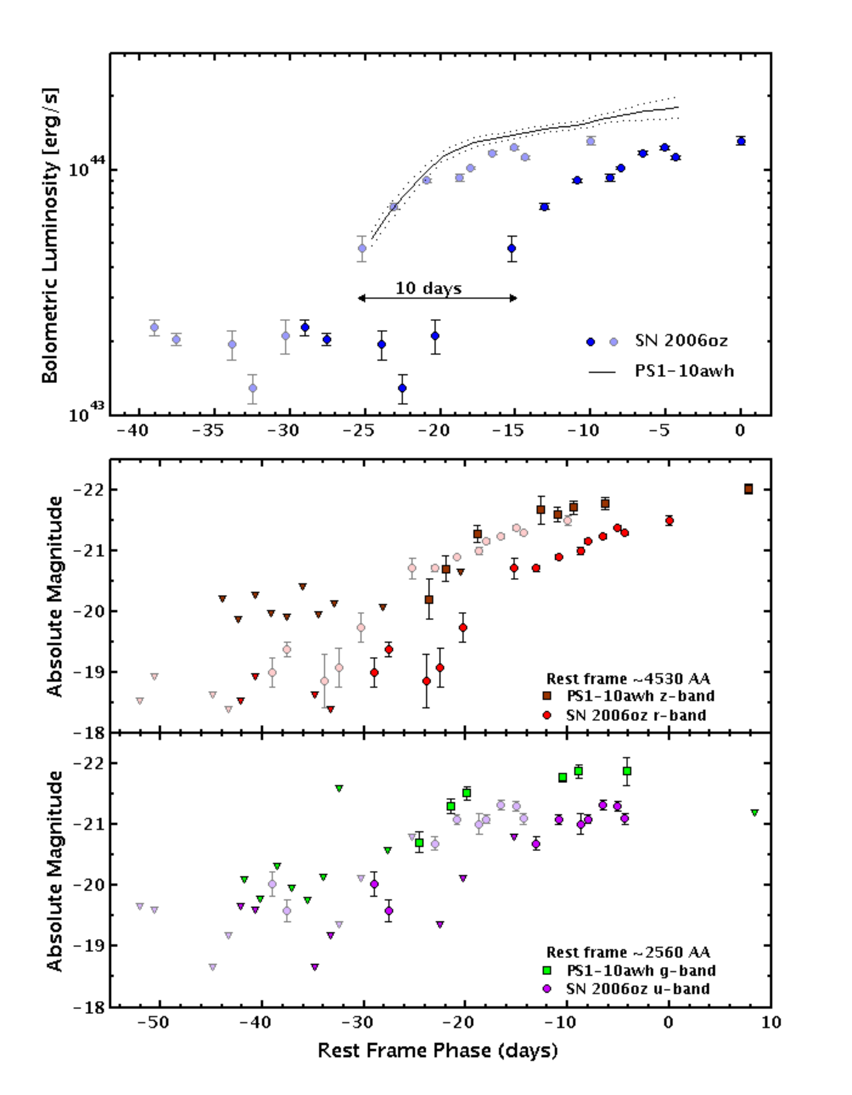


- T ≈ 15000 K
- R increases from ≈ 1 to 2 x 10^{15} cm

- OII, Mg II
- C II ? Tentative Fe III ?
- Consistent with carbon-burned atmosphere

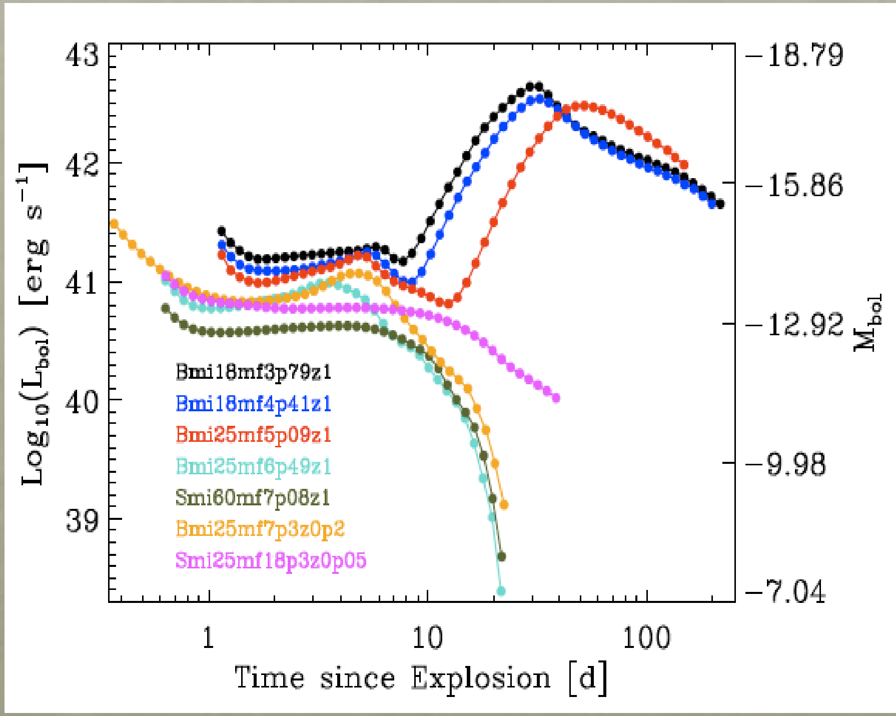
Bolometric light curve

- Covers rest frame 2350 -7000 Å
- *We see an initial "precursor" plateau !*
- Is this evolution intrinsic to all similar events?
  - Observations of other events not blue or deep enough to probe it
- Uncertainty in t_{max}
- Can be an important hint for nature of explosion



Origin of plateau?

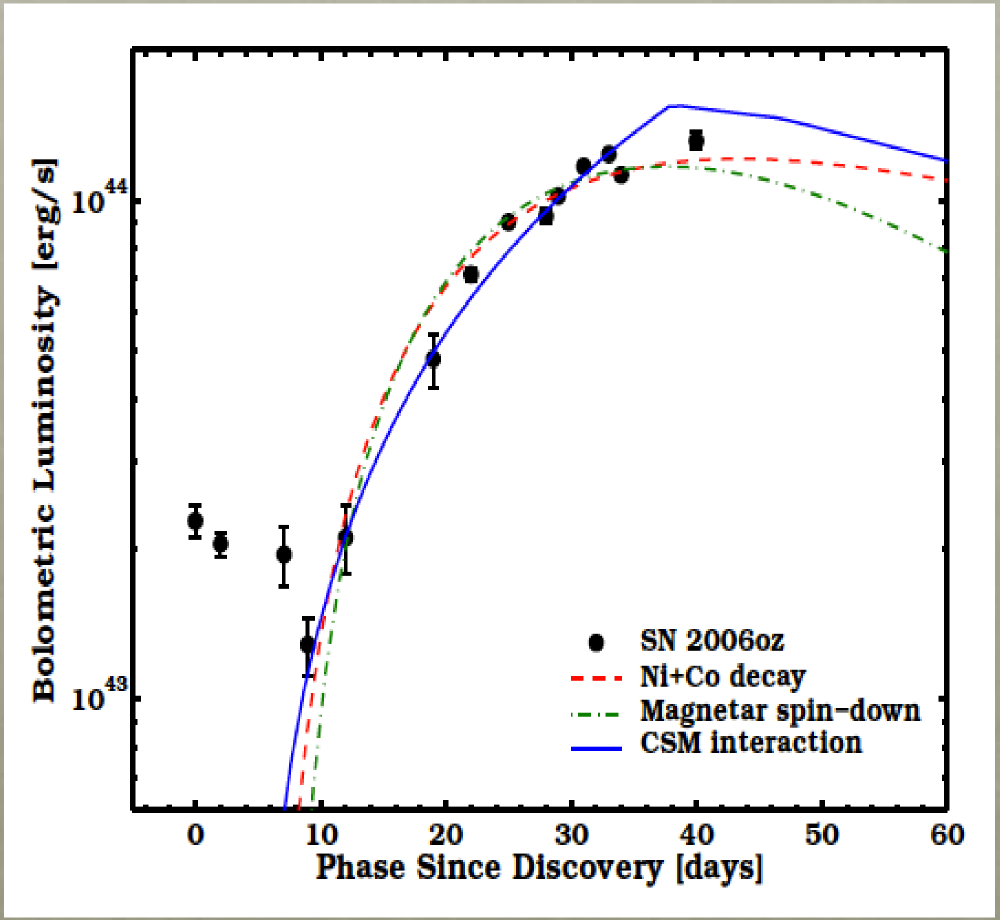
- Similar plateaus seen in NLTE simulations of SNe Ib/c (Dessart+ 2010)
- Recombination wave after shock-breakout. In this case He.
  - H in Type II-P
- If physics of SN 2006oz similar, then larger radius shows CSM
- Composition? O- rich? Could fit with temperature and spectrum



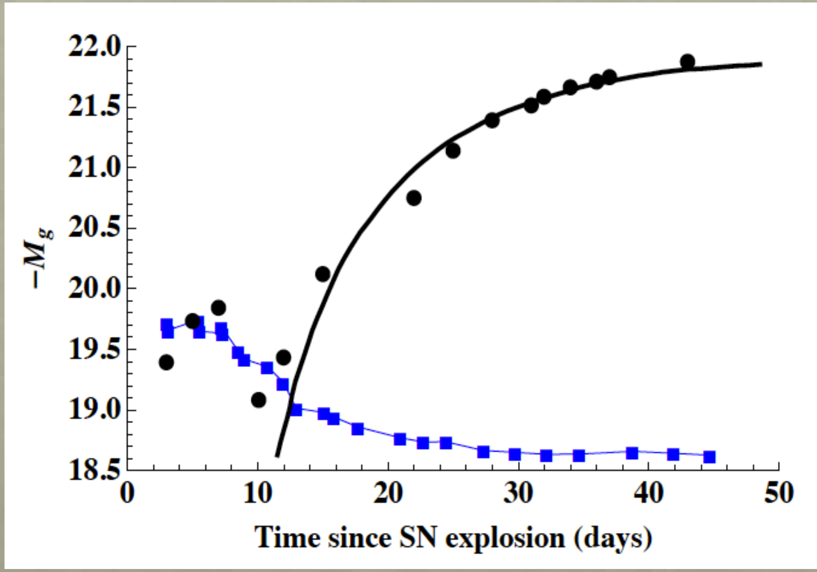
Dessart+ 2011

Origin of rise to maximum

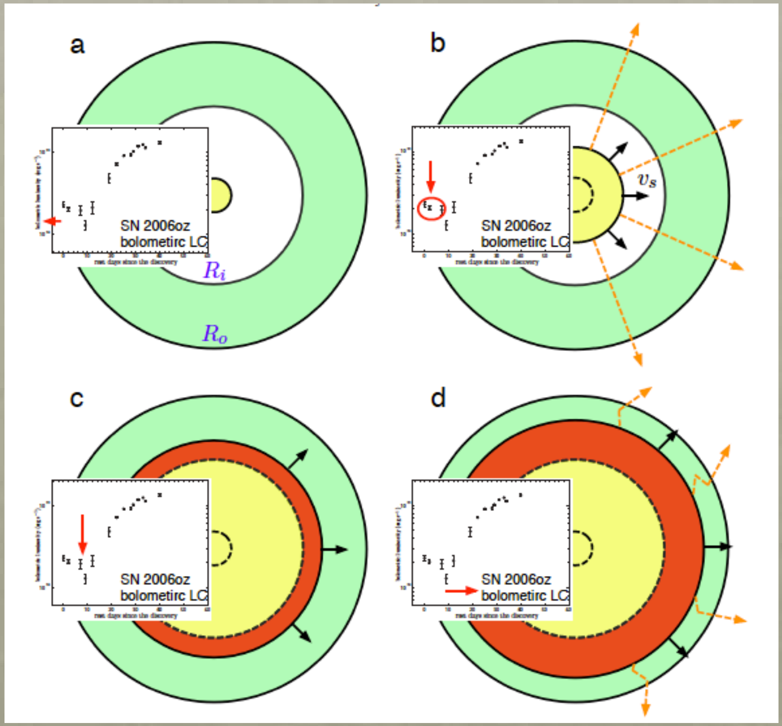
- Models by Chatzopoulos, Wheeler & Vinko (2011)
- Radioactive Decay?
  - Unlikely: M_{Ni}= 11 $M_{\odot}$, M_{ej}= 14 $M_{\odot}$
  - Also ruled out by others
- Magnetar
- CSM
  - But self-consistent?
  - Hybrid model?!
- M_{ej}= 14 $M_{\odot}$, M_{csm}= 6.5 $M_{\odot}$
- Very massive progenitor
  - Mass loss ?



Alternatives



Quark Nova: Ouyed & Leahy 2012

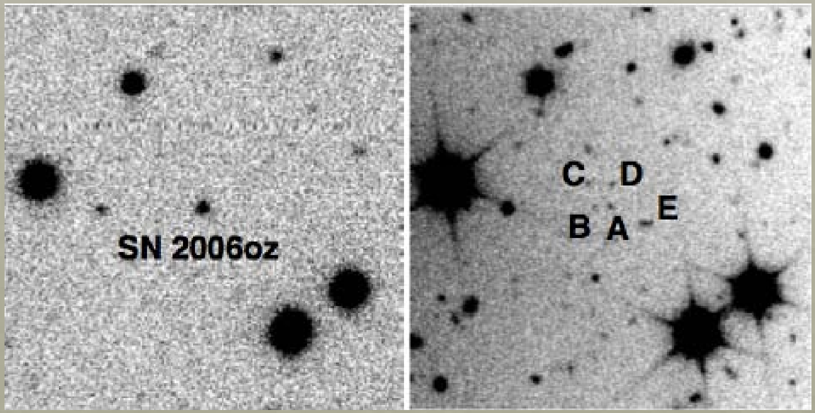


Moriya & Maeda 2012

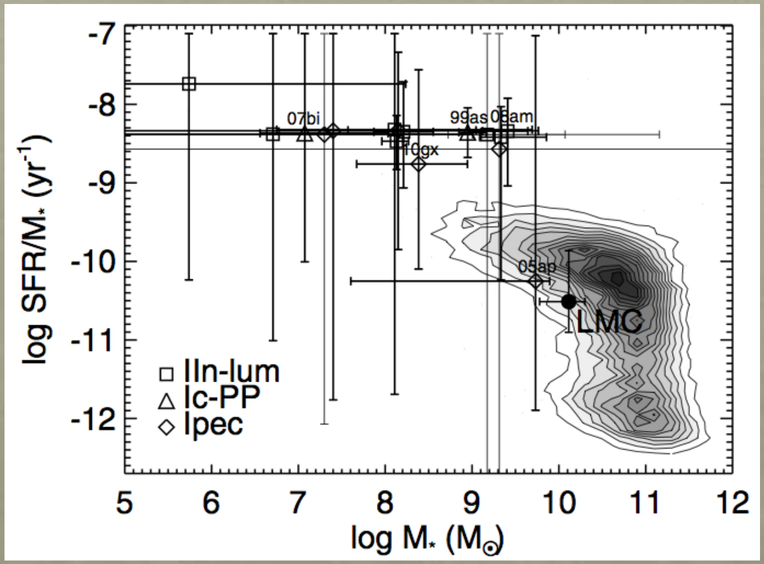
Today !!!

Host galaxy

- GTC/OSIRIS detection
- Not many hosts detected so far (and most are in 1 filter)
- Photo-z = 0.37 (-0.04 +3.72)



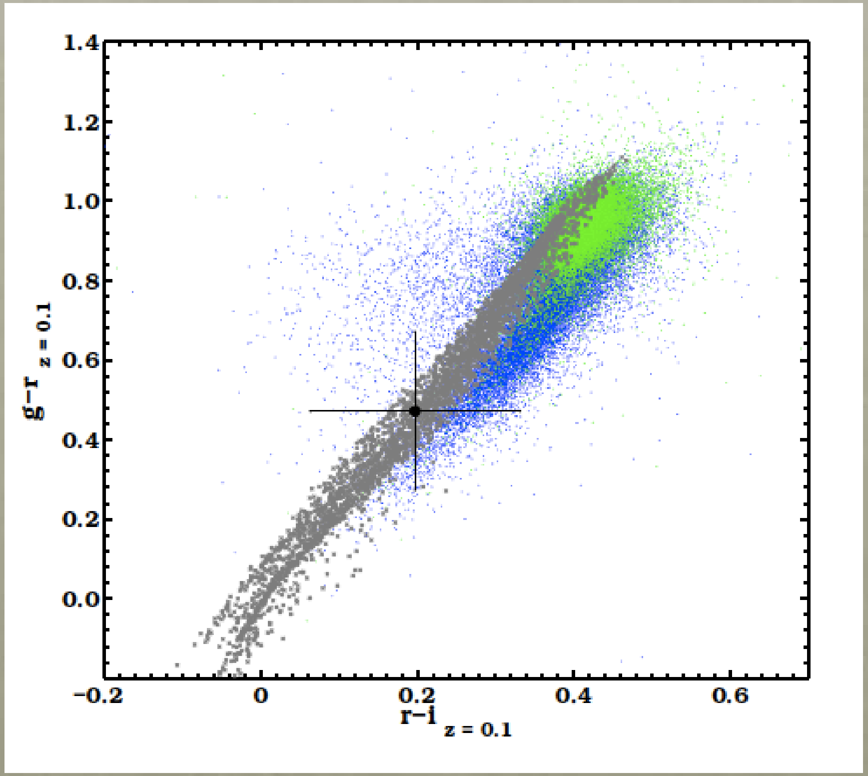
id	g (mag)	r (mag)	i (mag)	dist. (arcsec)
A	25.74 ± 0.19	24.43 ± 0.06	24.14 ± 0.12	$0.47''$
B	>26.47	25.62 ± 0.16	25.02 ± 0.25	$2.97''$
C	>26.47	25.81 ± 0.19	24.65 ± 0.18	$6.26''$
D	25.18 ± 0.11	24.70 ± 0.07	24.32 ± 0.12	$4.56''$
E	25.28 ± 0.15	23.71 ± 0.03	23.21 ± 0.06	$6.56''$



Neill+ 2011

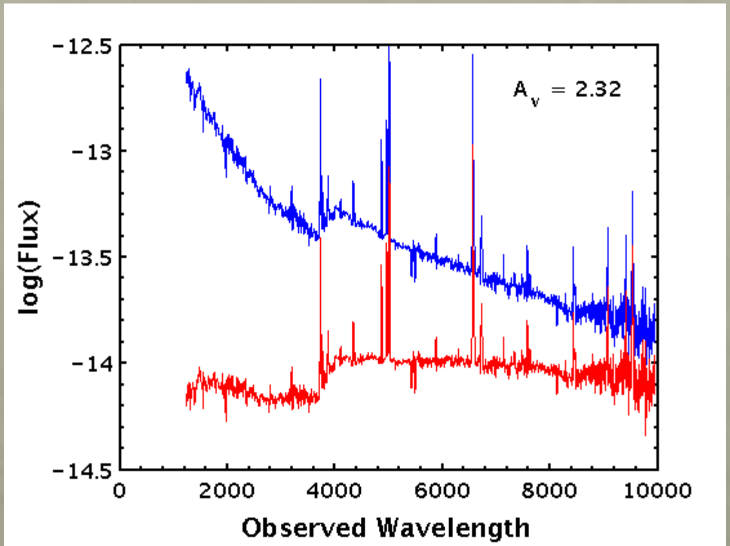
Host properties

- M_g = -16.9
- Significant 4000 Å break: contribution by an older population
- $\log(M/M_\odot)$= 8.7 ± 0.23
- SFR = $0.17^{+0.18}_{-0.07}$ $M_\odot$/yr
- $\log(SFR/M_\star)$ = - 9.47 /yr
- Metal-poor? 0.45 $Z_\odot$ (Tremonti+ 2004)
- Low mass, SF dwarf galaxy
- But *not* starburst!



What MORE CAN THE ENVIRONMENT TELL US?

- Are host galaxy properties consistent with the presence of a very massive star?
- Can the host colors be due to extinction? (no)
- But is there any extinction anyway?
  - Supposed 0 but even if moderate it will affect colors, temperature, bolometric LC, model fits, PHYSICS
- What is the true gas metallicity?
- Understanding environment is key for understanding stellar evolution & mass loss
- Accepted VLT proposal to observe 3 hosts in detail:
  - Deep imaging (FORS, HAWK-I)
  - Spectroscopy (X-shooter)



The End

Thank you!