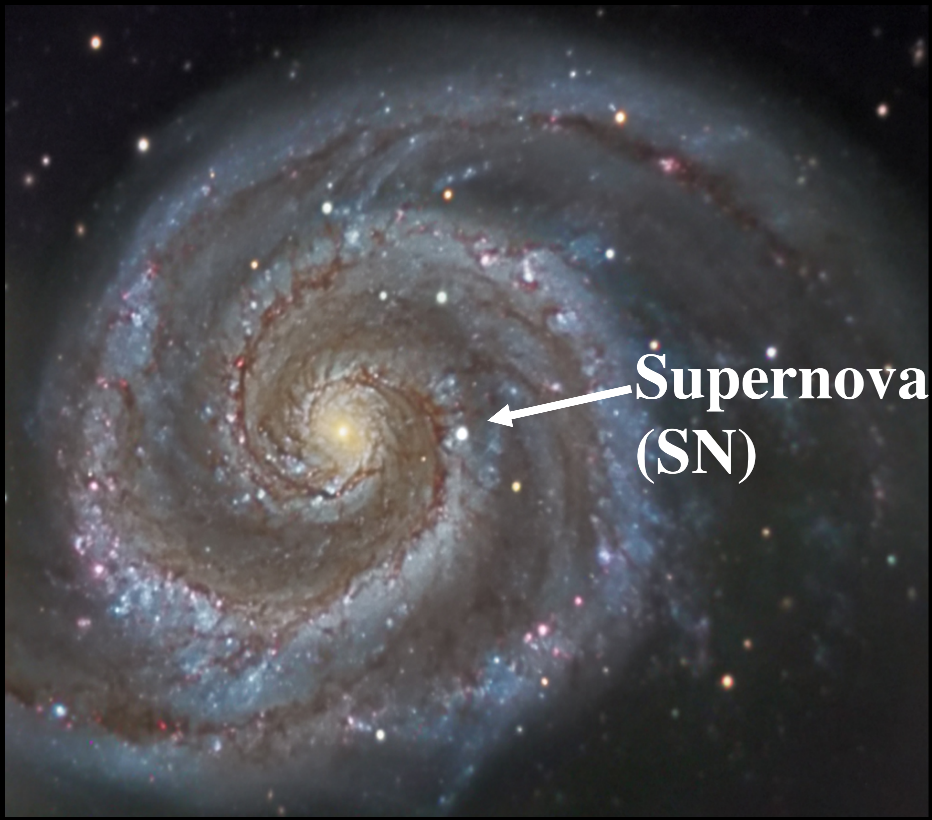
# Stellar Forensics from Environments of Stripped SN and GRBs + *SN explosion properties*




SN2005cs in M51, Credit: T. Mewlon/Cosmotography

*Maryam Modjaz*
*(New York University)*

# Fellow Stellar Death Detectives

t

- **<u>Harvard-CfA:</u> Bob Kirshner**

  H. Marion, M. Hicken, S. Blondin, P. Challis, M. Wood-Vasey, A. Friedman
- K. Z. Stanek (Ohio State), J. L. Prieto (Carnegie-Princeton), T. Matheson (NOAO), L. Kewley (Hawaii), P. Garnavich (Notre Dame), J. Greene (Princeton)
- **<u>UC Berkeley:</u> Alex Filippenko, Josh Bloom**, N. Butler, R. Chornock, R. Foley, A. West, D. Kocevski, W. Li, A. Miller, M. Ganeshalingam, D. Perley, D. Poznanski, J. Silvermann, N. Smith, D. Starr, P. Kelly
- **<u>PTF:</u>** Avishay Gal-Yam, Iair Arcavi, +PTF team
- **<u>NYU:</u>**

**Federica Bianco**

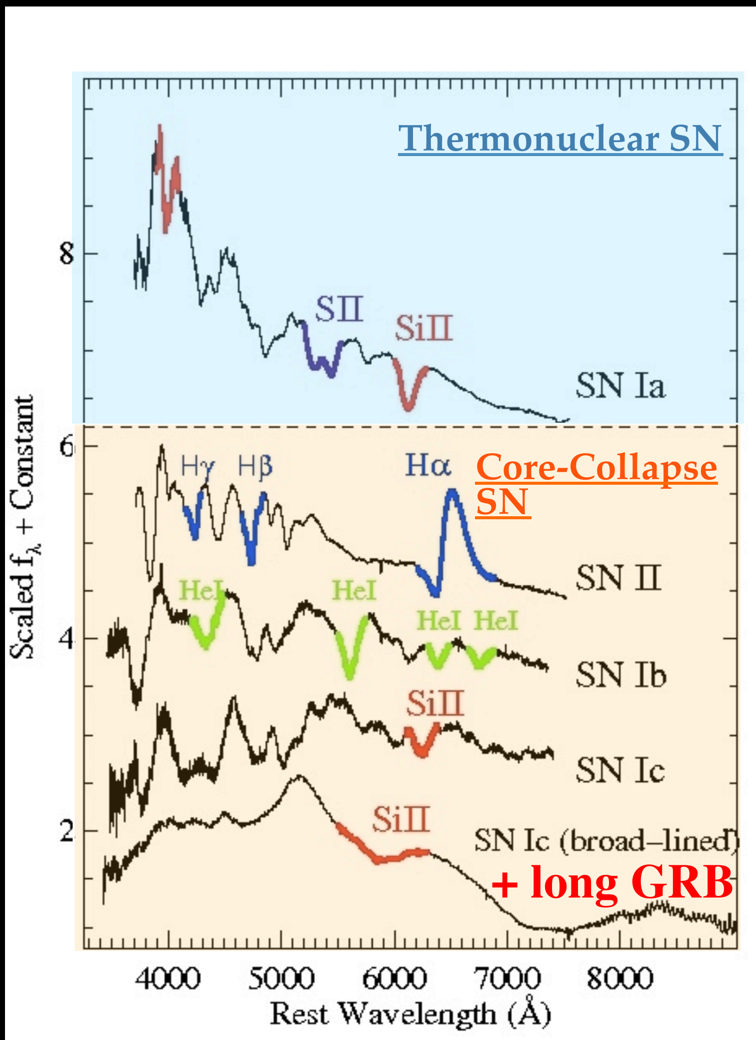
**Yuqian Liu**

**David Fierroz**

**Or Graur**

# SN ZOO

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




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

+ Exploding Zoo:
Superluminous SNe (SLSN), …

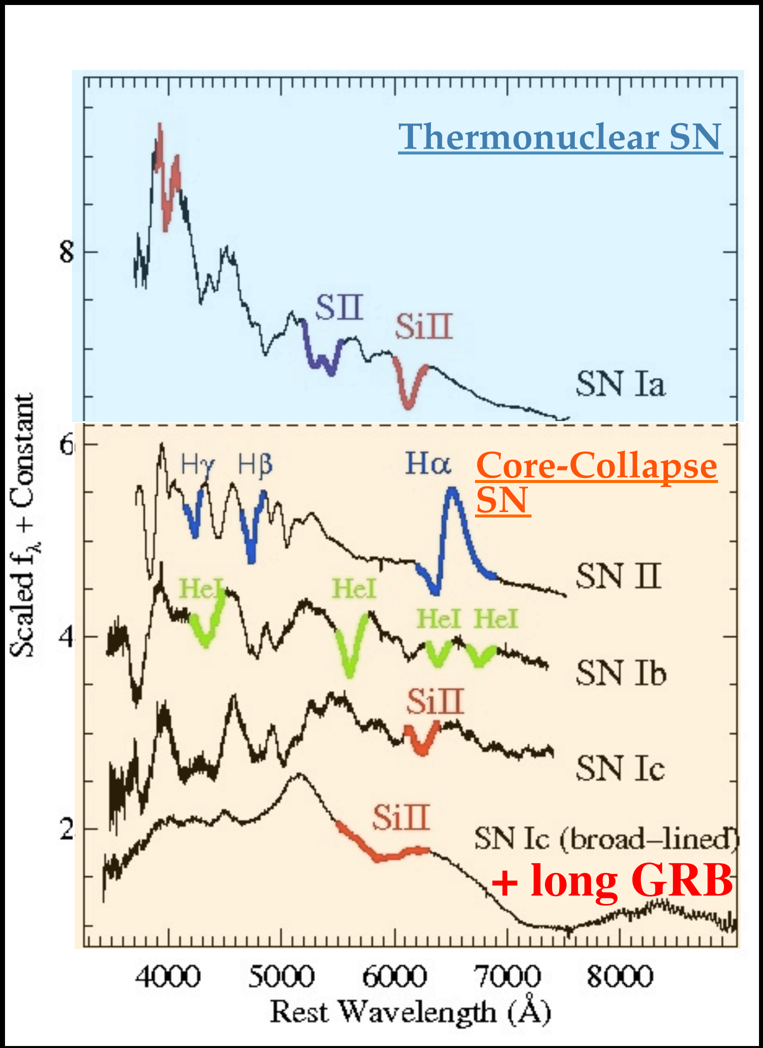
**Broad lines:large expansion velocities (~30,000 kms$^{-1}$ )**

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

Maryam Modjaz

# SN ZOO

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




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

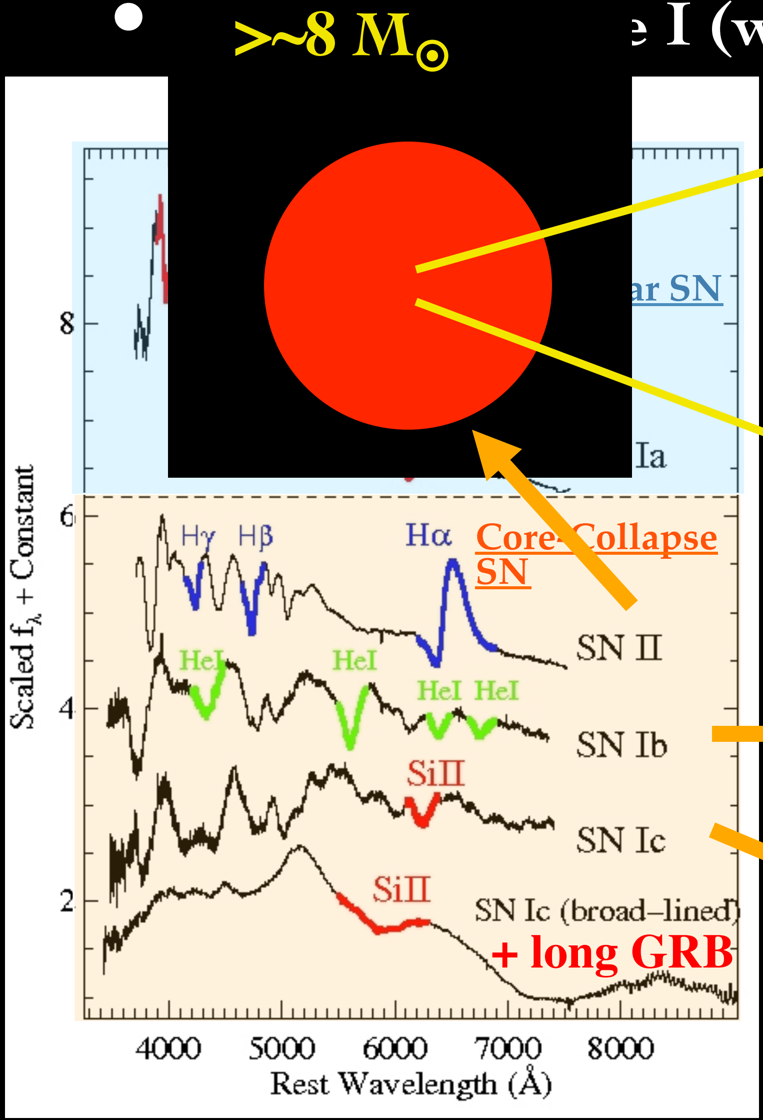
+ Exploding Zoo:
Superluminous SNe (SLSN), …

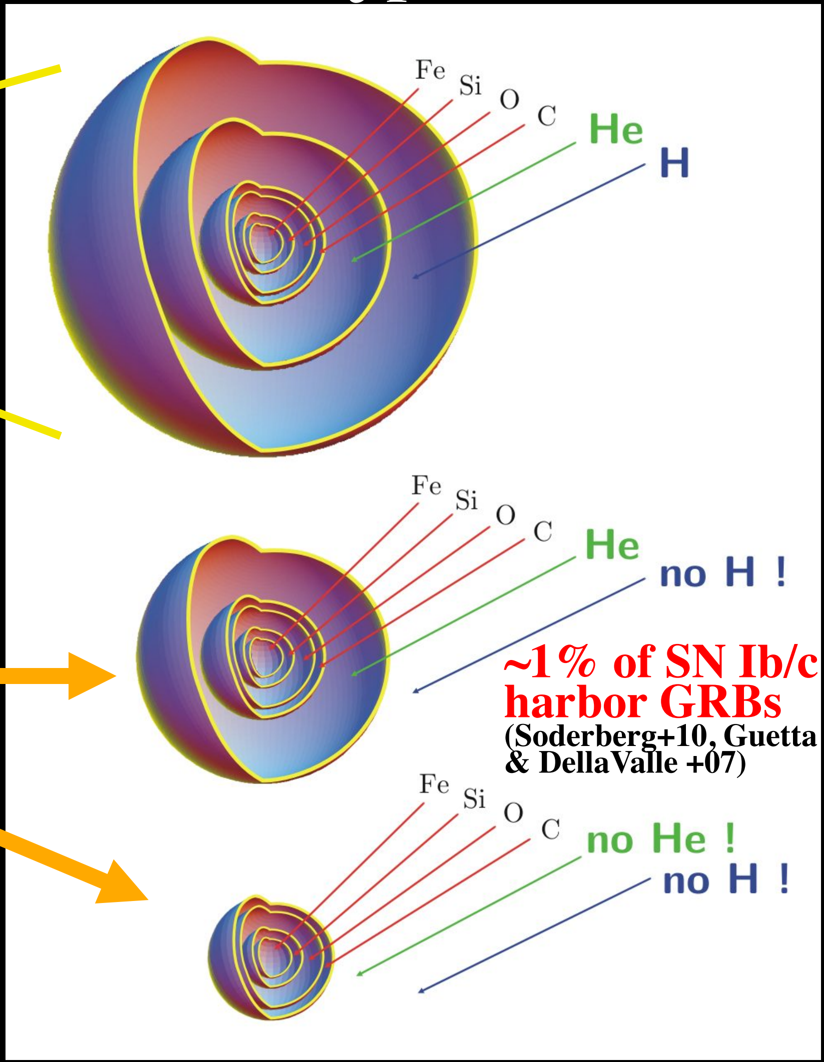
**Stripped-Envelope SN**

Maryam Modjaz

# SN ZOO

- e I (without H) and Type II (with H)



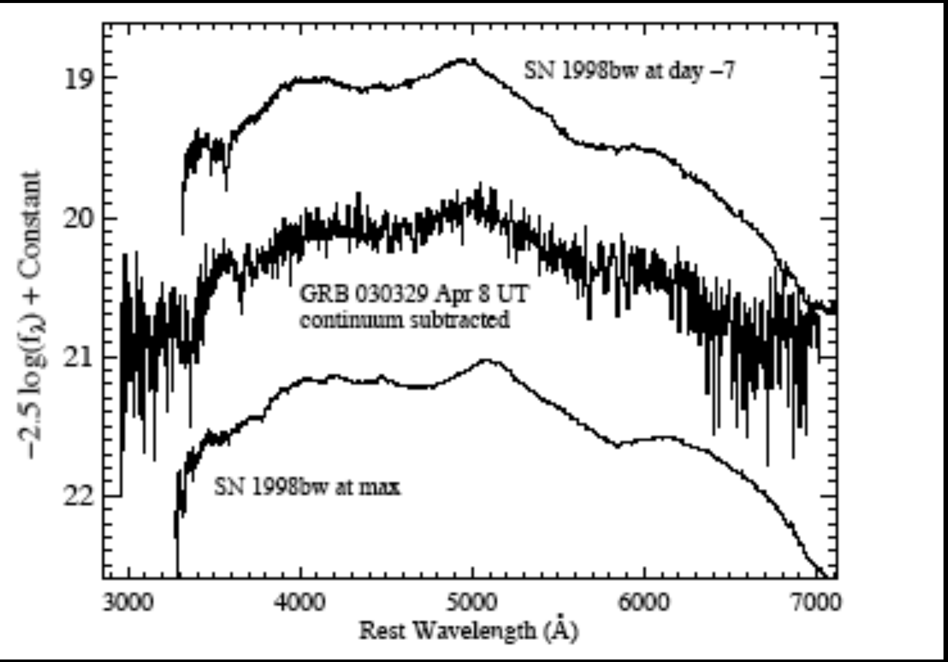




Maryam Modjaz

# SN-GRB Connection

**1998-2013:** 10 solid SN-GRBs
with Spectroscopic IDs:
broad-lined SN Ic
(0.0085 < z < 0.5)

Most recent SN-GRB
(SN13cq/GRB130427A
SN13dx/GRB130702A)




Stanek et al. (2003), Matheson et al. (2003), see also Hjorth et al. (2003)

**see Reviews: Woosley & Bloom (2006), Hjoerth & Bloom (2011), Modjaz (2011)**

- Many (~80/90) broad-lined SN Ic have NO observed GRB
- Probably not off-axis GRBs (e.g., Soderberg et al. 2006)

-> GRBs need special conditions

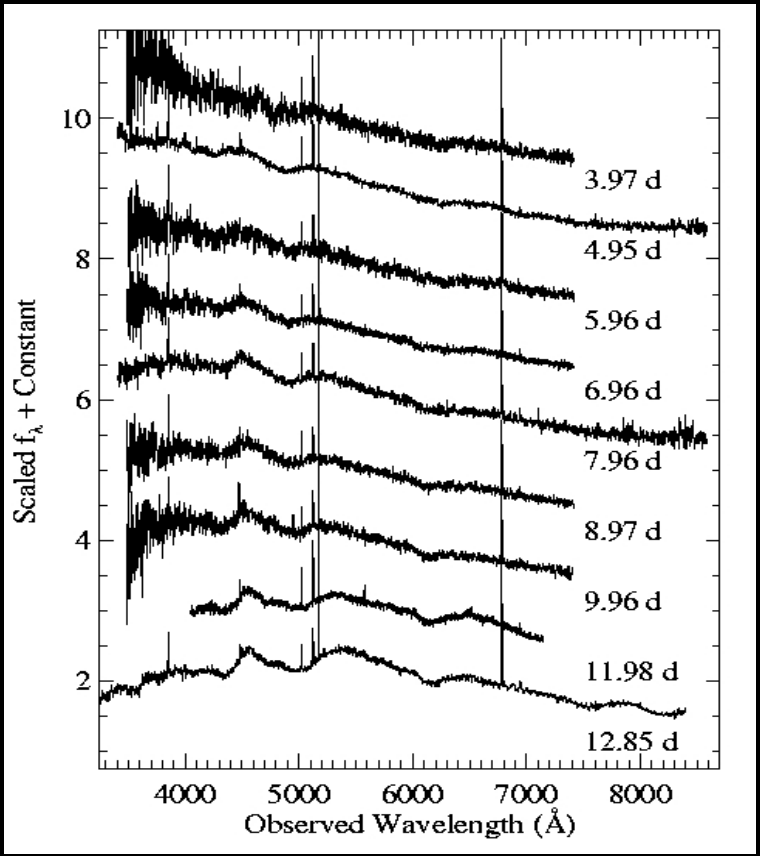
Maryam Modjaz

# SN-GRB Connection

**1998-2013:** 10 solid SN-GRBs with Spectroscopic IDs: <u>broad-lined SN Ic</u>

(0.0085 < z < 0.5)

Most recent SN-GRB (SN13cq/GRB130427A SN13dx/GRB130702A)



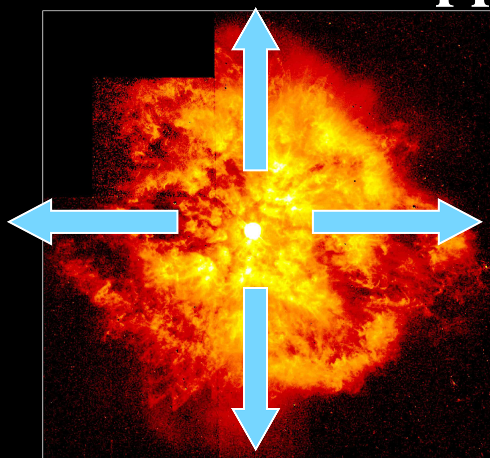

Modjaz et al. (2006)

- Many (~80/90) broad-lined SN Ic have NO observed GRB
- Probably not off-axis GRBs (e.g., Soderberg et al. 2006)

-> GRBs need special conditions

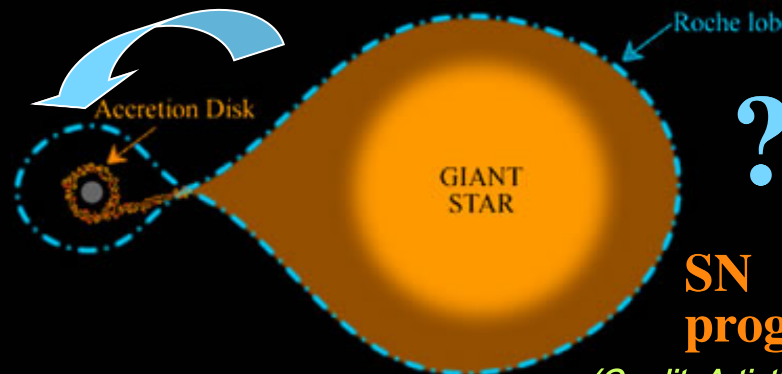
# Stellar Forensics: Hunt For Progenitors

## Stripped SN & SN-GRB progenitors:



(Credit: Hubble/ NASA)

or




?

SN progenitor

(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 +04)

-> Binaries are common: ~70% interacting! (Sana, deMink et al. 2012)

## Importance of Stripped SN & GRB progenitor:

- Stellar & High-Energy Astrophysics
- Chemical Enrichment History of Universe
- Cosmology: Light houses illuminating early universe

Maryam Modjaz

# Stellar Forensics: Environmental Clues

## Direct Study:

**NO progenitor detections** for ~10 SN Ib, Ic, Ic-bl (e.g. Smartt09)

->not conclusive (Bibby+12, Yoon+12)

## Statistical Study:

Differentiate between GRB, and Stripped SN progenitor models via observations of environments & host galaxies

## 3 Methods:

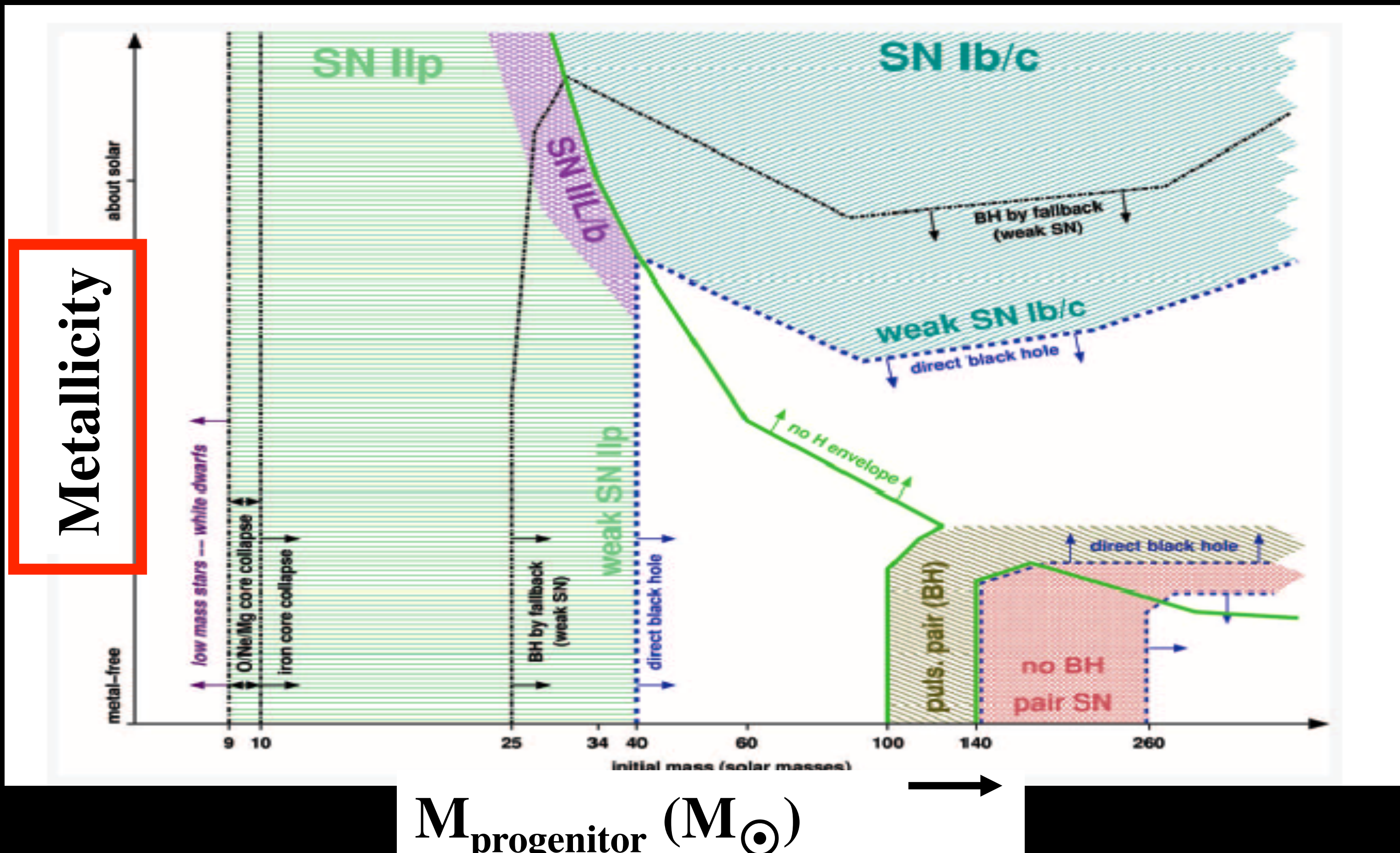
- **Proximity to HII regions** (Van Dyk 1992, 1996, Anderson+10, +12)
- **Brightest Blue regions** (Fruchter+06, Kelly+08, Anderson+09, Svensson+10, Leloudas10, Kelly & Kirshner12)
- **Metallicity:** indirectly via proxy (Prieto+08, Arcavi+10) or directly at explosion sites (Modjaz+08, Anderson+10, Modjaz+11, Leloudas+11, Sanders+12, Kuncarayakti+13, Levesque+10,12 for GRB samples)

# Star's Mass & Metallicity is important

- Massive stars at different Z: different amount of
  - mass loss
  - core angular momentum (e.g. for both GRB collapsar and magnetar model **[Woosley (1993), MacFadyen & Woosley (1999), Yoon & Langer (2005)]**)

# Star's Mass & Metallicity is important

•

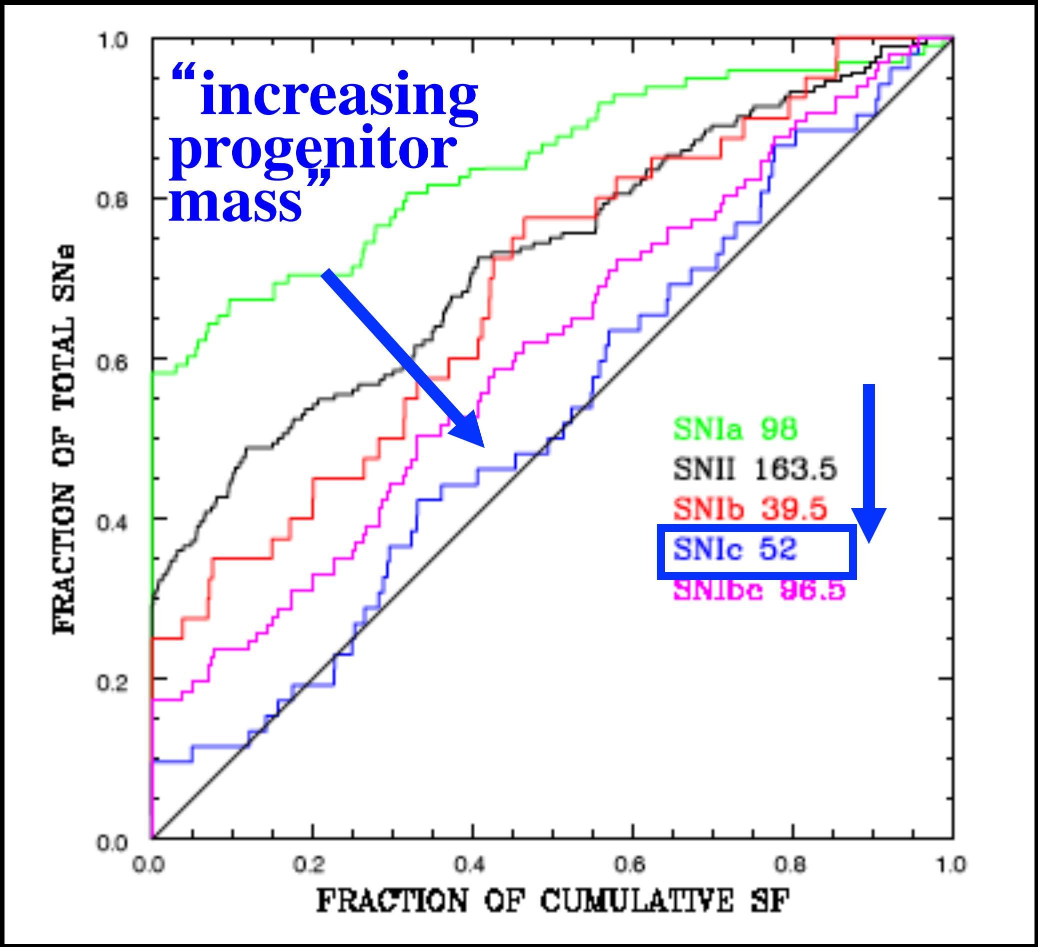



**THEORY: Heger et al (2003)**

[also **O' Connor & Ott (2011), Dessart, O' Connor & Ott +12**]

Maryam Modjaz

# I. Association with HII regions (on-going SF)




But: need to consider duty cycles of HII regions! (Crowther 13)

But: need to consider binaries & runaways! (Eldridge in prep)

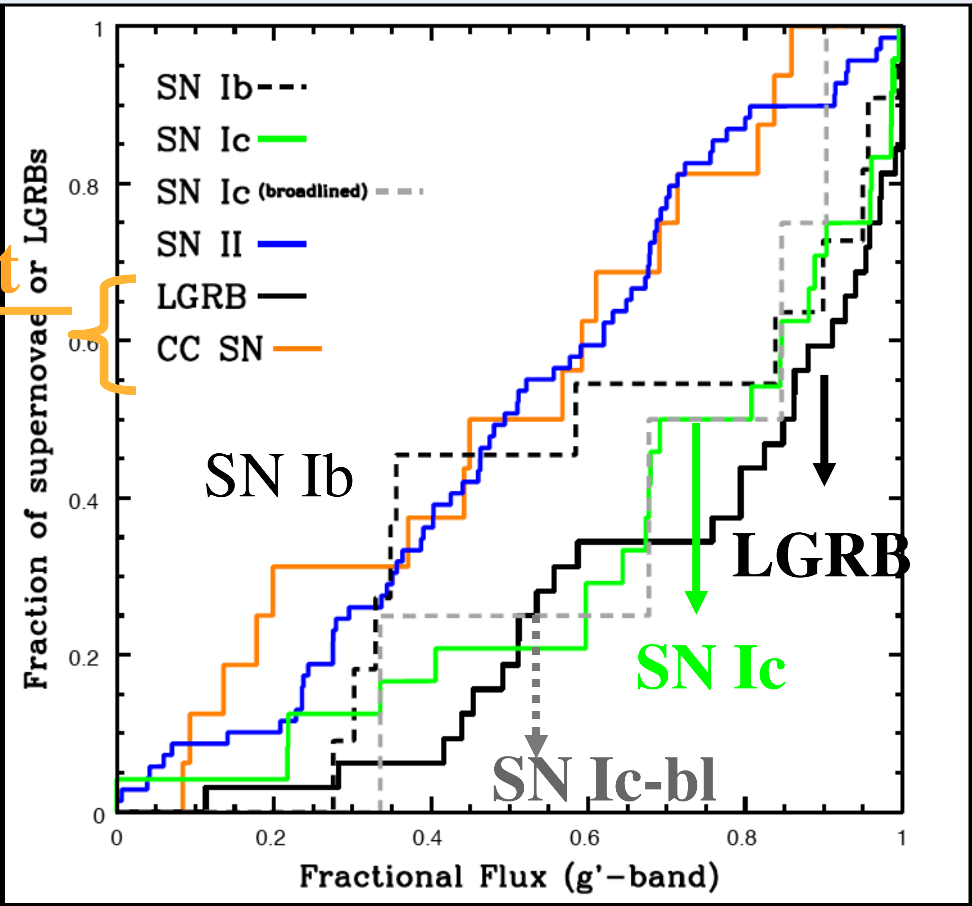
Anderson et al (2012) - consistent with Kelly et al. (2008, 2012)

Maryam Modjaz

# II. Brightest Blue Regions

**Local SN Ic and GRB have similar locations compared to blue host galaxy light**

Fruchter et al (2006)




Kelly, Kirshner, & Pahre (2008)

- Similar (large) progenitor masses for SN Ic and GRBs
[see also Anderson & James (2009)]

- Additional ingredient needed for GRB production: metallicity?

# III. 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 <u>at SN site</u> by massive young stars

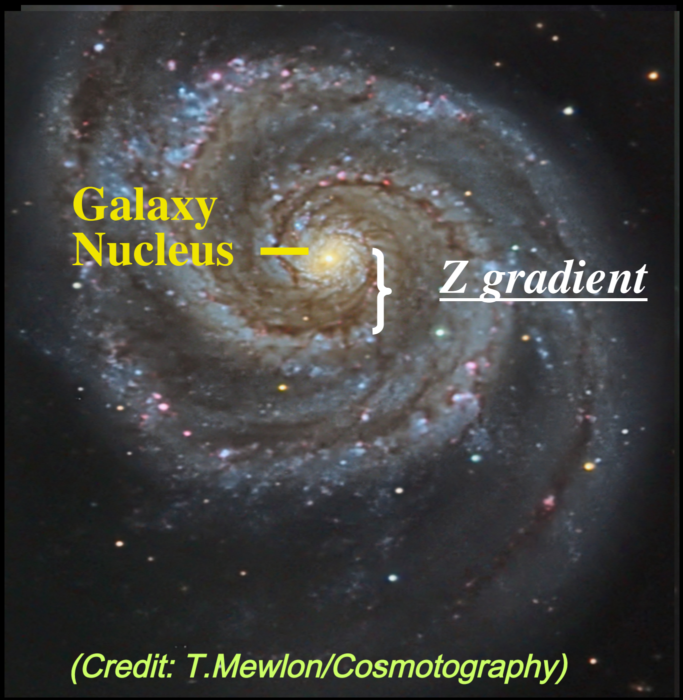
~ natal metallicity of core-collapse SN progenitor

- At low oxygen abundance: <u>upper limit</u> to Fe/H (e.g., Stoll et al. 2012)

# Recipe for measuring "Z": State of the Art

- Spectra at position of SN or GRB (b/c of Z gradients): probe natal Z [future: IFUs (e.g. Selsing talk)]
- SNe with secure ID
- Large λ range: robust & uniform Z estimate, correct for reddening
- Uncertainty budget
- In different and independent oxygen abundance diagnostics – PP04 not enough! (e.g., Kewley & Ellison 2008)

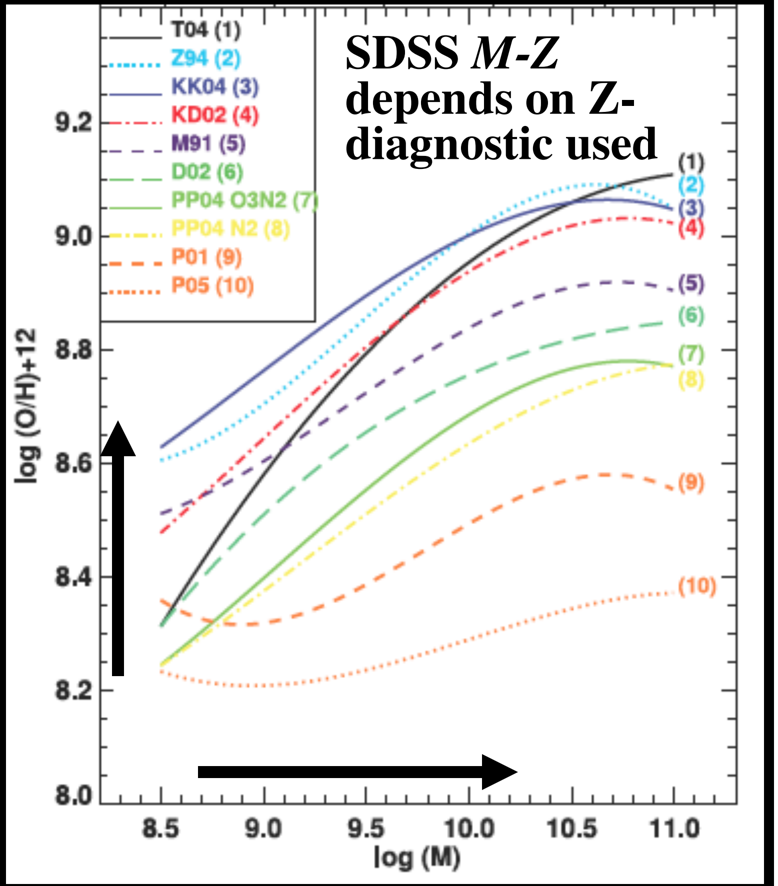

A large-aperture telescope (Keck, VLT, Gemini …)




Maryam Modjaz

# Recipe for measuring "Z": State of the Art

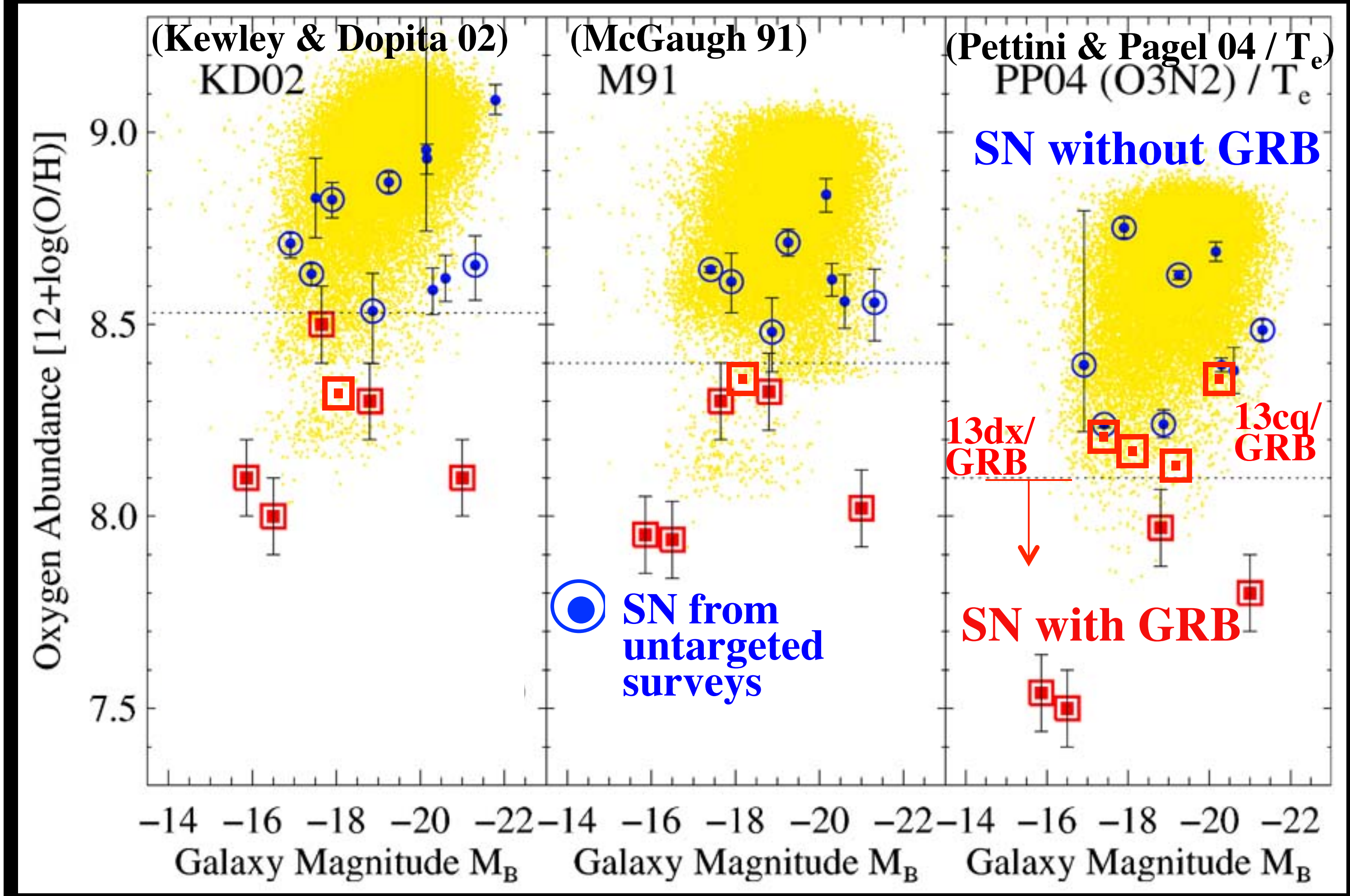
- Spectra at position of SN or GRB (b/c of Z gradients): probe natal Z [future: IFUs (e.g. Selsing talk)]
- SNe with secure ID
- Large λ range: robust & uniform Z estimate, correct for reddening
- Uncertainty budget
- In different and independent oxygen abundance diagnostics – PP04 not enough! (e.g., Kewley & Ellison 2008)
- Also include SNe from galaxy-unbiased surveys: mitigate selection effects (e.g., Modjaz et al. 2008, Young et al. 2008, Sanders et a. 2012)




Kewley & Ellison (2008)

Maryam Modjaz

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

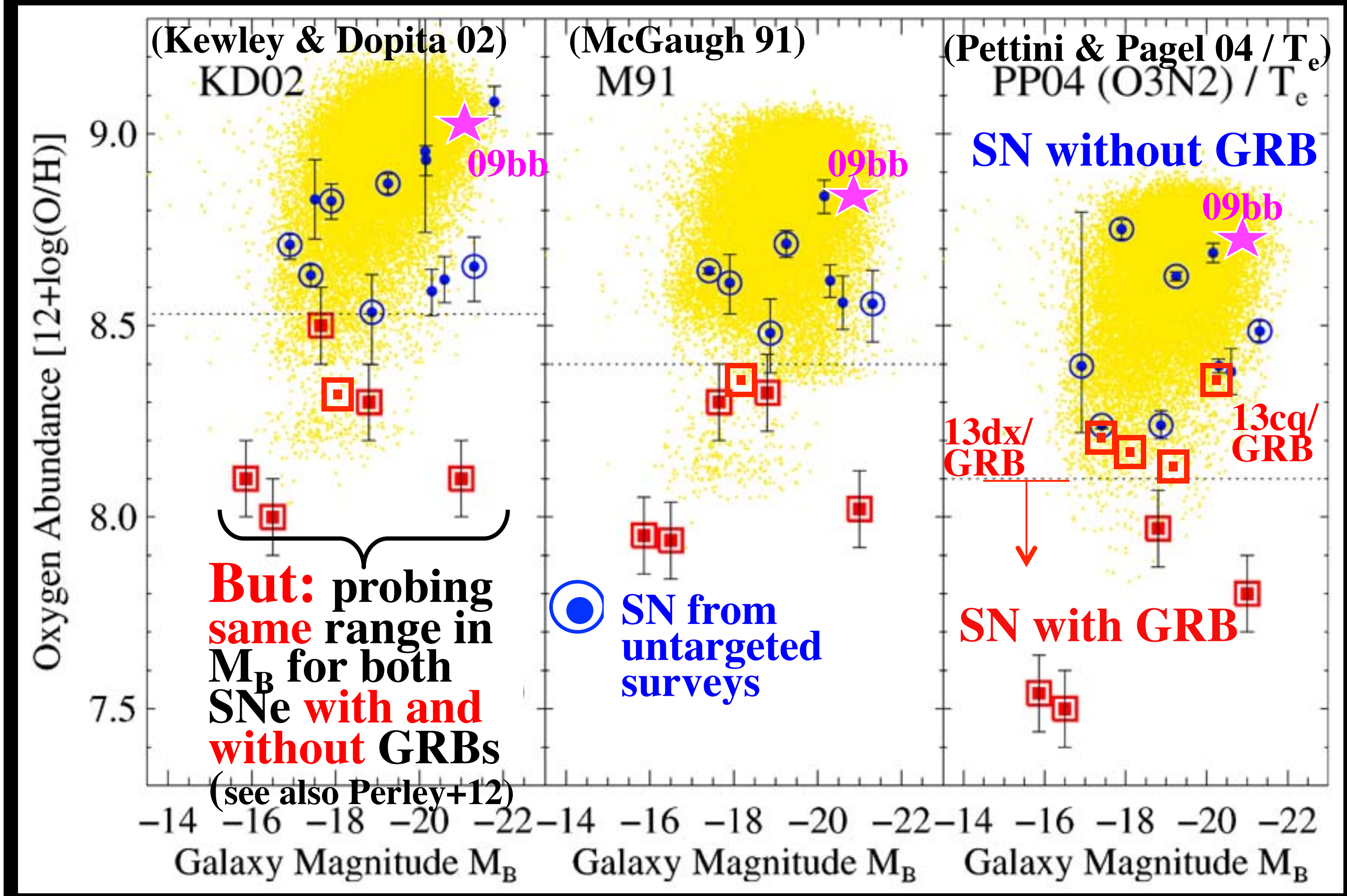



***Reason(s):***

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

**Updated Modjaz et al (2008):** For 10bh/100316D: Chornock +11, Starling+ 11, Levesque+11; for 98bw's PP04: Christensen+08, 12bz: Levesque+12, 13cq: Xu+13, 13dx: Kelly+13

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

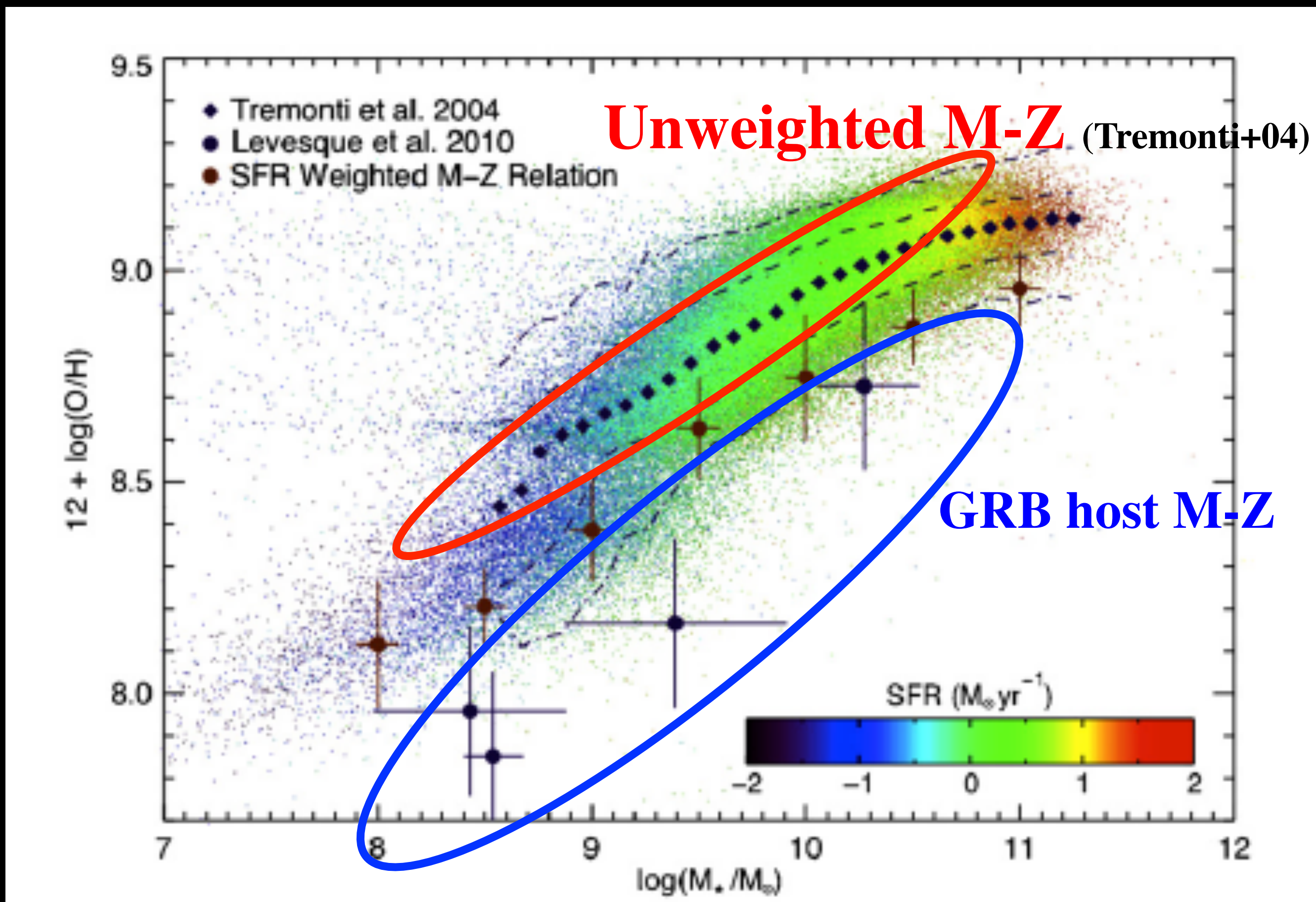



## *Reason(s):*

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

**Updated Modjaz et al (2008):** For 10bh/100316D: Chornock +11, Starling+ 11, Levesque+11; for 98bw's PP04: Christensen+08, 12bz: Levesque+12, 13cq: Xu+13, 13dx: Kelly+13 SN2009bb: Levesque+10

# Metallicity: Causation or Correlation?




***Reason(s):***

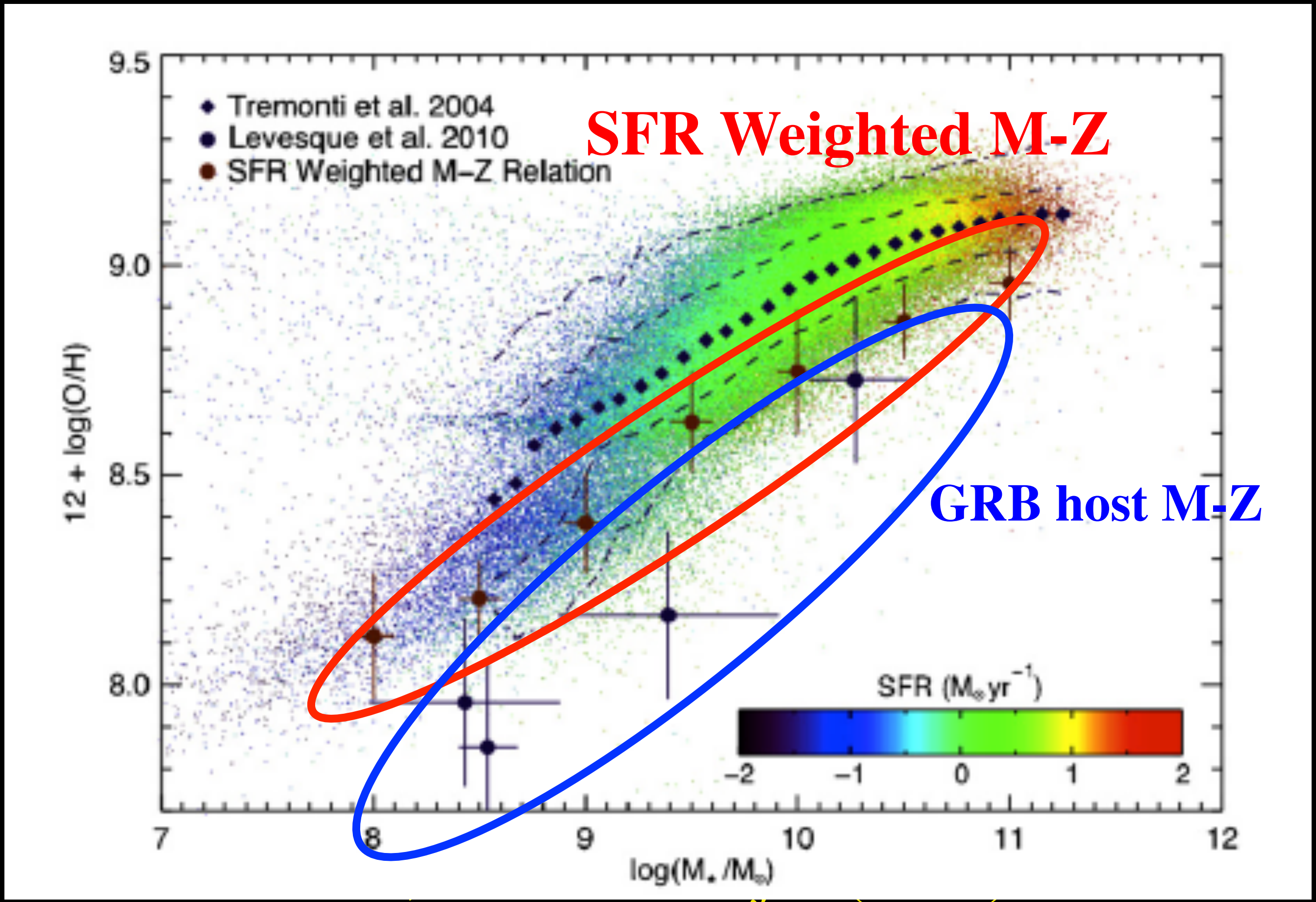
- Low Z GRB progenitor? (Yoon & Langer 05, Woosley & Heger 06)

- Dust? (Fynbo +10, Perley+10, ..)

- Star formation effect? (Mannucci +10, Koveski & West 11,)

Kocevski & West (2011): SFR weighting not enough to explain GRB host M-Z's offset to low Z (see also Kocevski, West & Modjaz 2009)

# Metallicity: Causation or Correlation?

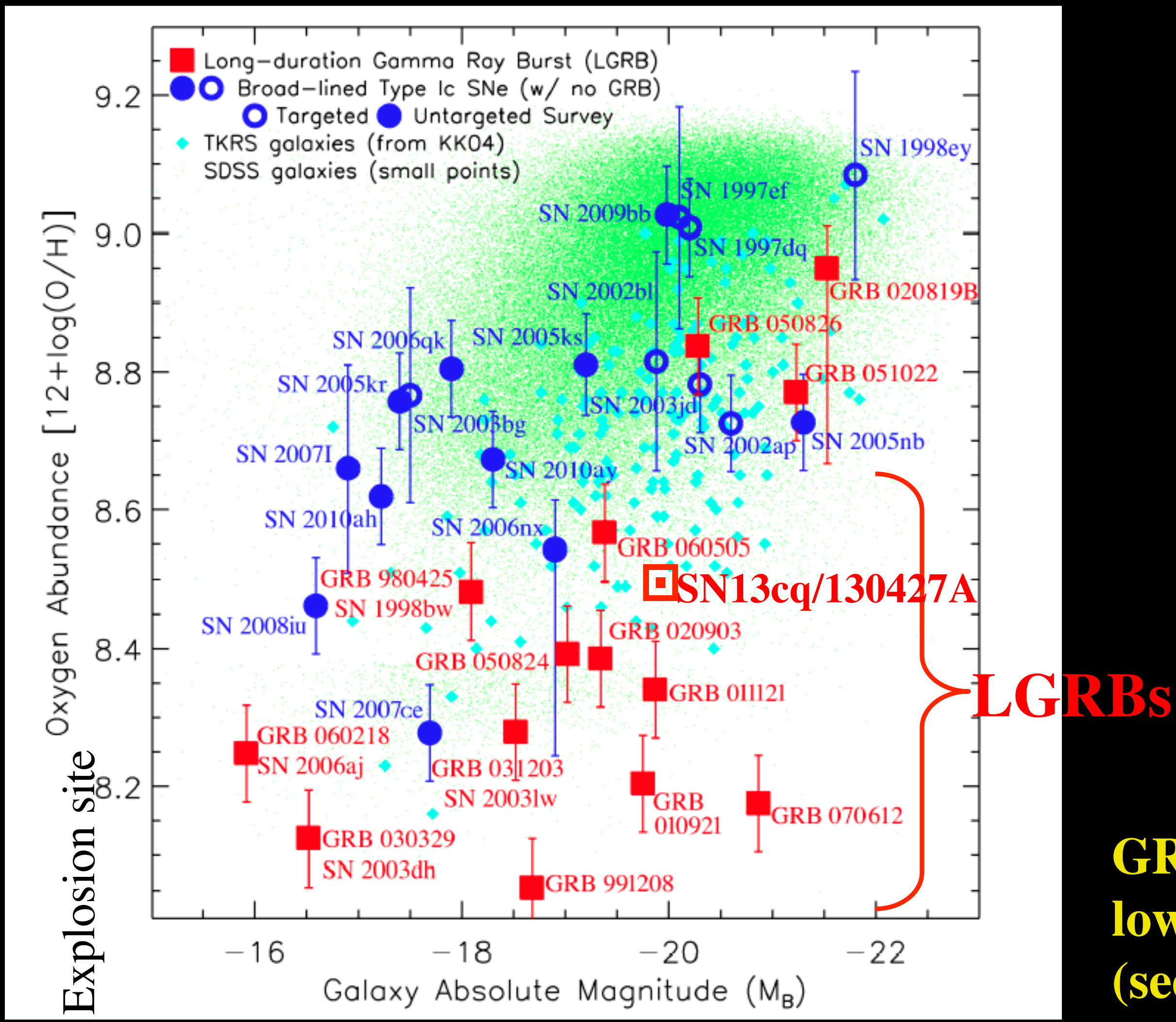



***Reason(s):***

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

**Kocevski & West (2011): SFR weighting not enough to explain GRB host M-Z's offset to low Z** (see also Kocevski, West & Modjaz 2009)

# Metallicity: Causation or Correlation?




Graham & Fruchter 13 -> John Graham's talk

Xu+13 (for 13cq/GRB130427A)

***Reason(s):***

- **Low Z GRB progenitor?** (Yoon & Langer 05, Woosley & Heger 06)
- **Dust?** (Fynbo +10, Perley+10, ..)
- ~~**Star formation effect?** (Mannucci +10, Koveski & West 11,)~~

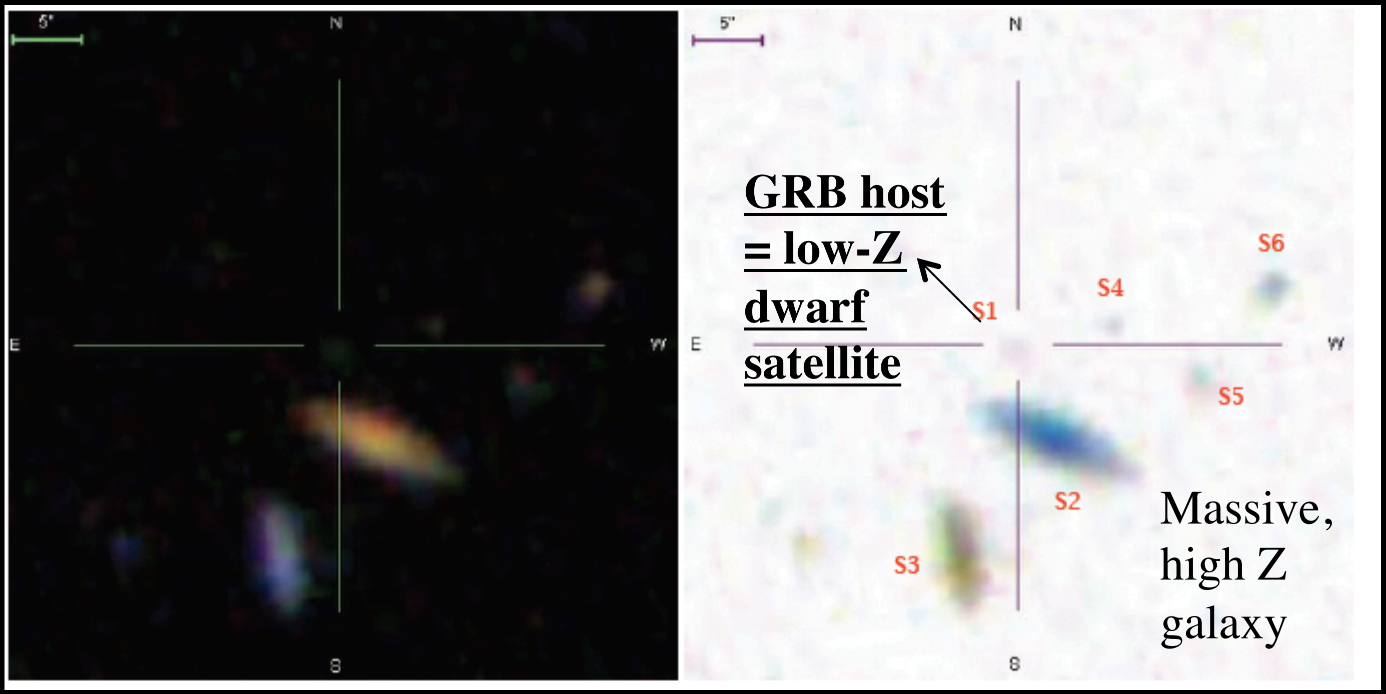
**GRB are systematically at low Z, but not exclusively (see also Levesque+12)**

Maryam Modjaz

# Metallicity: Causation or Correlation?

Word of caution for high-z GRB host studies:

Host of SN13dx/GRB130704A

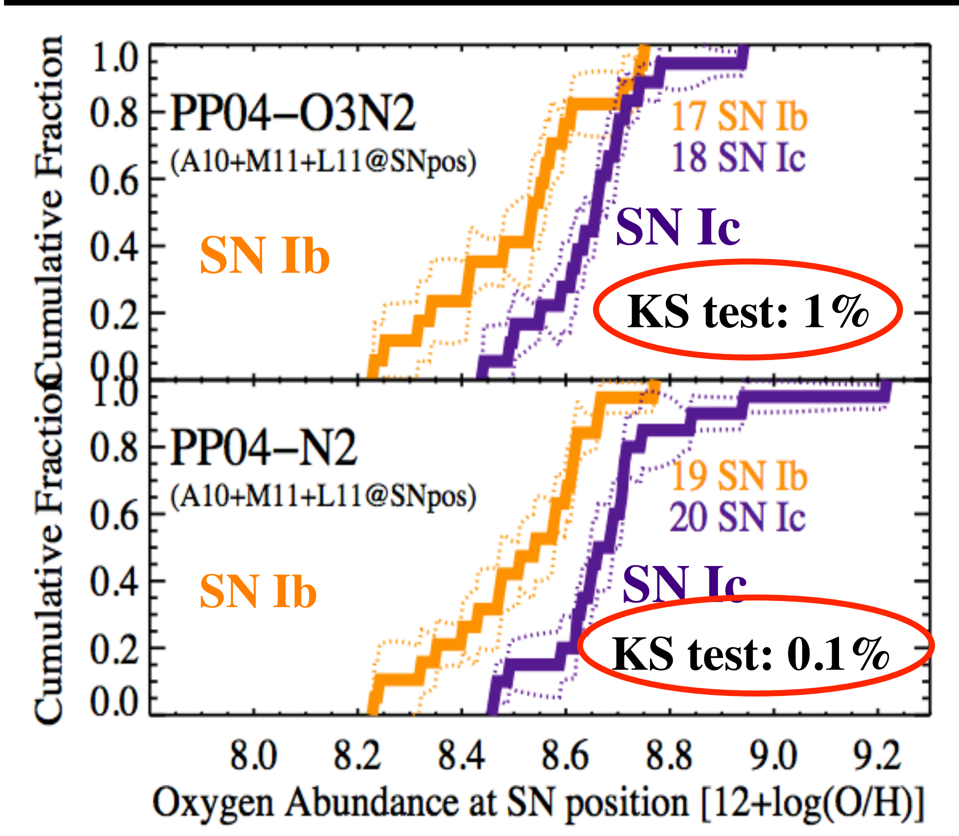



Kelly+13 -> Pat Kelly's talk on Thu

***Reason(s):***

- **Low Z GRB progenitor?** (Yoon & Langer 05, Woosley & Heger 06)
- **Dust?** (Fynbo +10, Perley+10, ..)
- ~~**Star formation effect?** (Mannucci +10, Koveski & West 11,)~~

# 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**

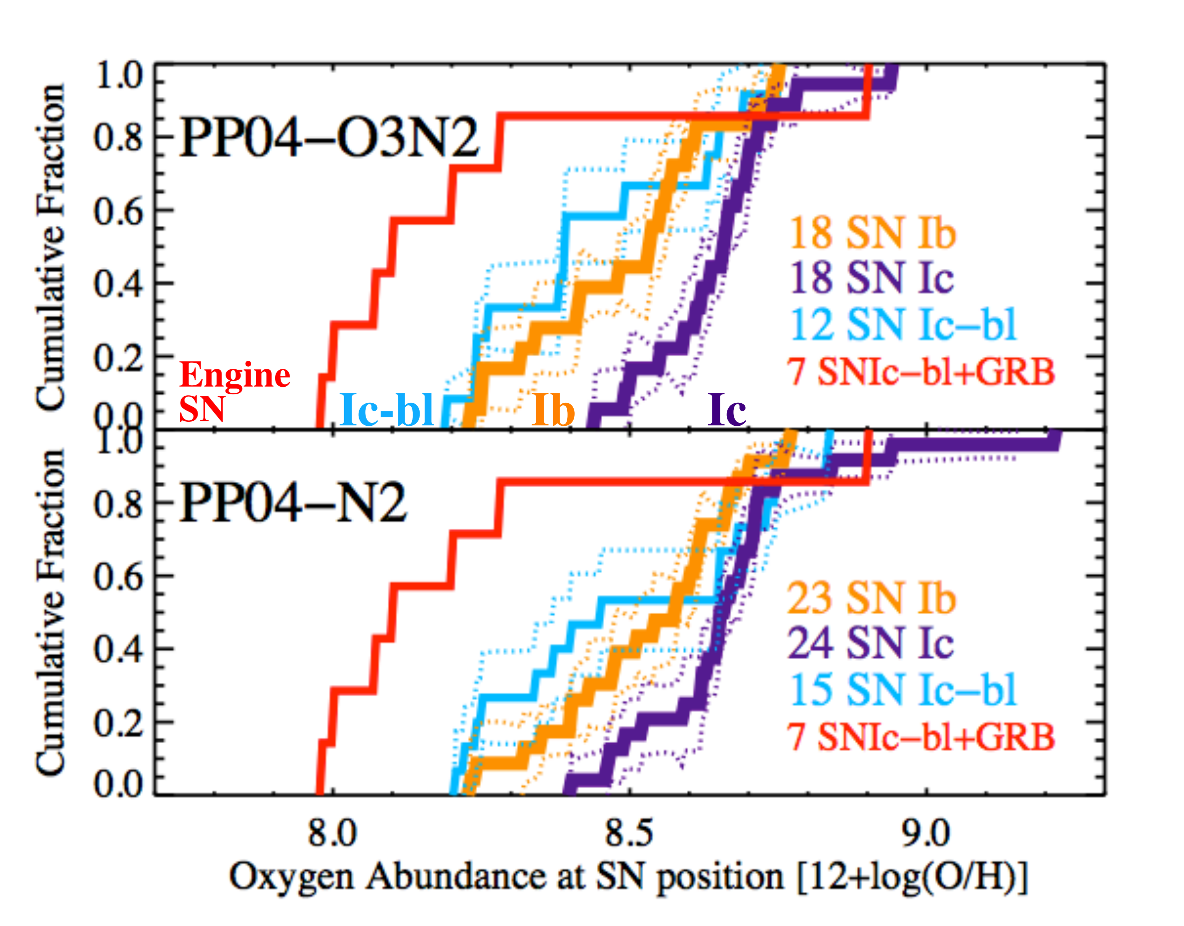
Maryam Modjaz

# Oxygen abundance @ SN Sites

**Meta-analysis:**

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

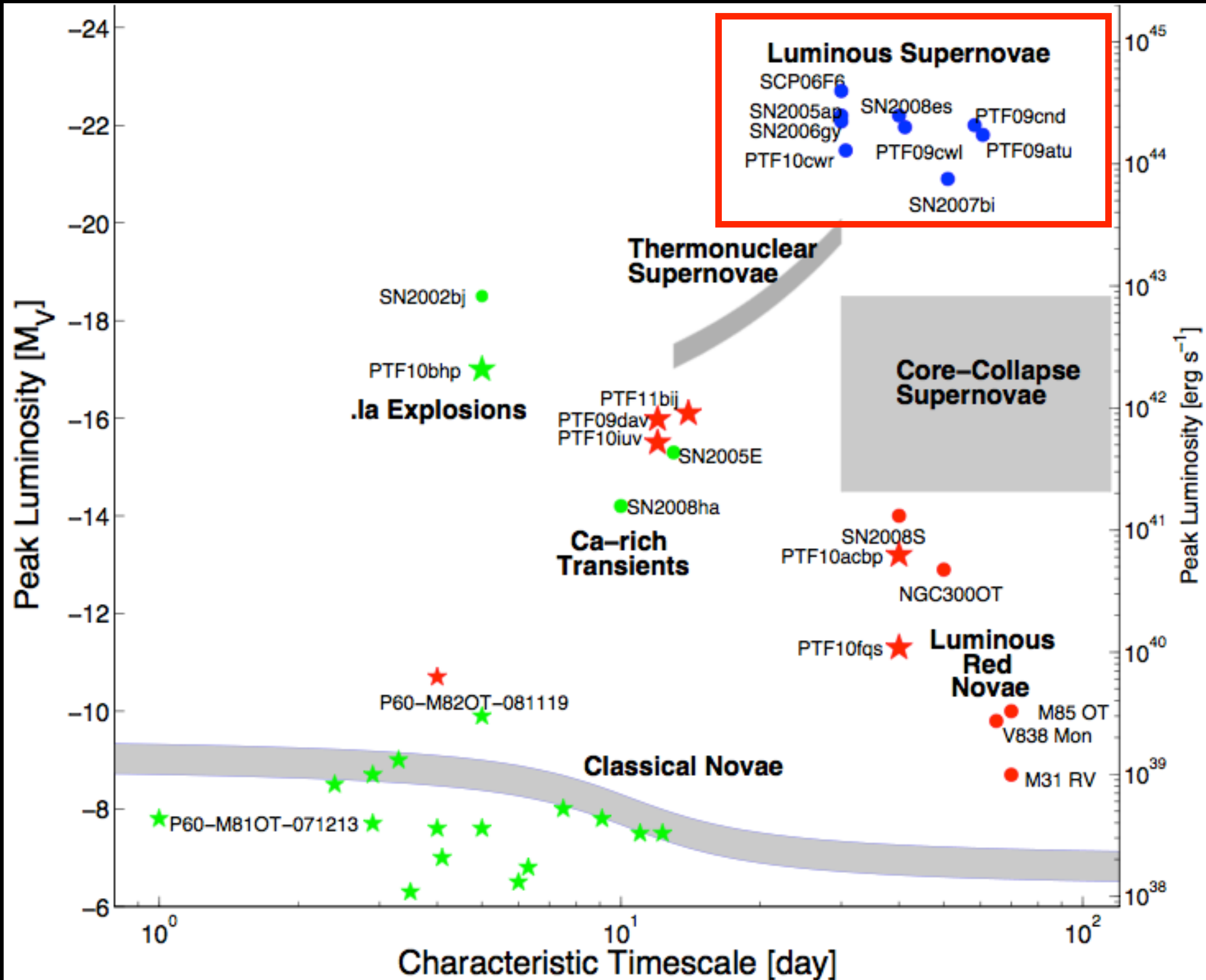
**(=Modjaz + 08 &11 & Anderson +10 & Leloudas +11 @SN position**




**more metal-rich**

**Consistent with Arcavi+10, Kelly & Kirshner 12, Kuncaravakti +13, but see Sanders et al. (2012)**

# Teeming Universe of Transients



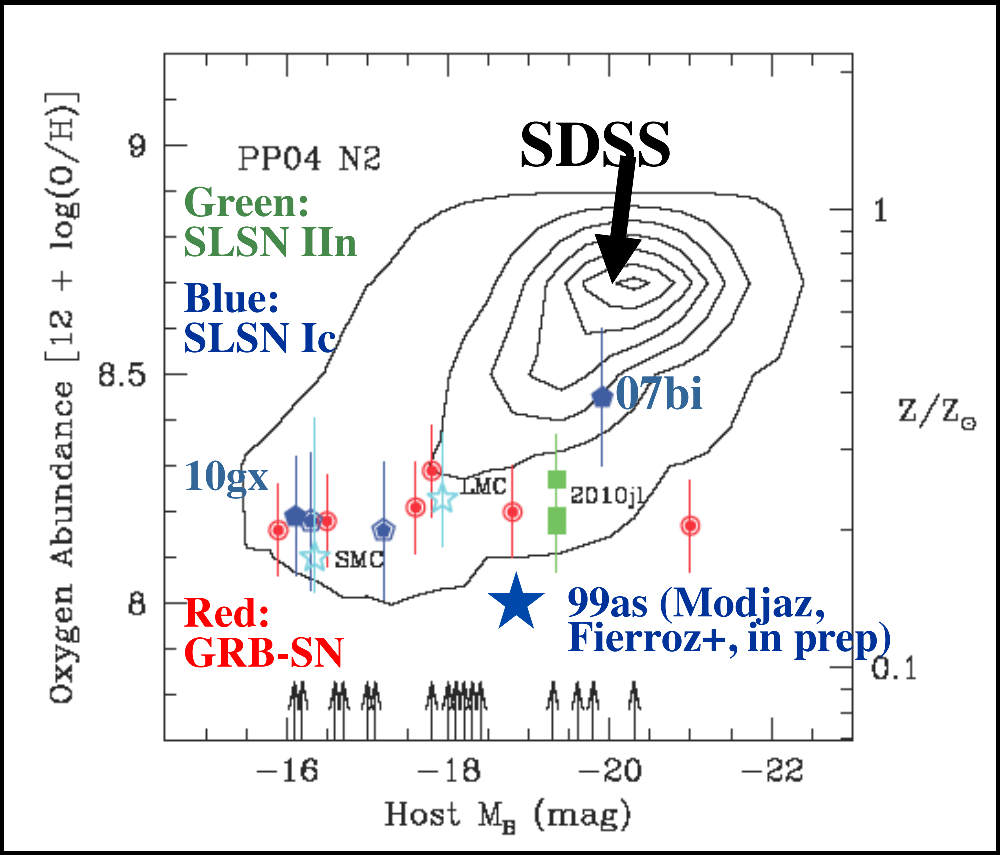

**SLSN: very rare: ~$10^{-4}$ CCSN,**

**~ GRB-rate**

(Quimby+11; Gal-Yam 12)

Shri Kulkarni, see Rau et al. (2009) Kasliwal+ 2011 (references therein)

# Superluminous SNe Ic & IIn: Low-L, low-Z, high-SFR Hosts

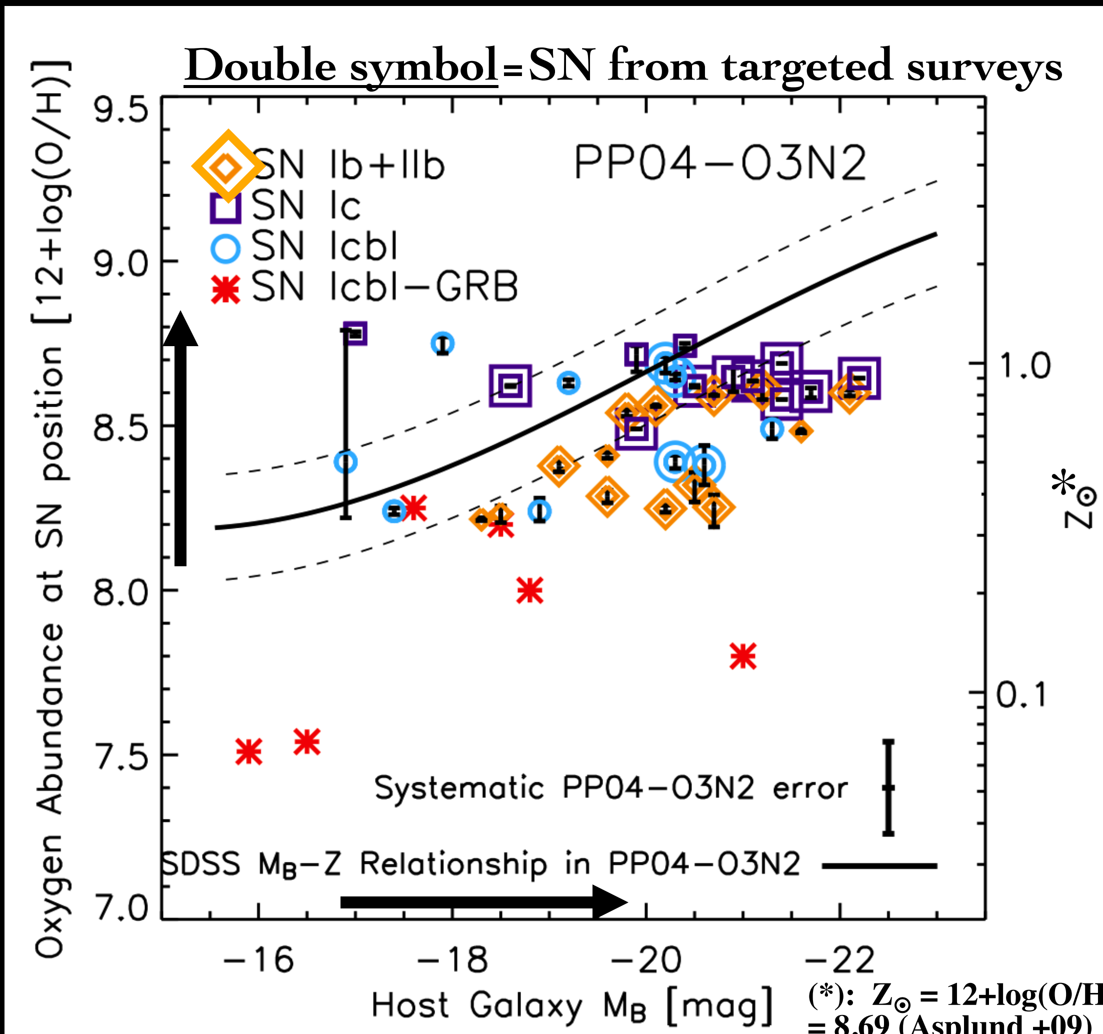



Stroll et al (2011):" Low Z, because of mass loss"

See poster by G. Leloudas!

**But:** Z-effect even for H-rich SNe (SLSN IIn)? And/or rather top-heavy IMF at lower Z?

# Need for homogeneous, Z-unbiased, Single Survey

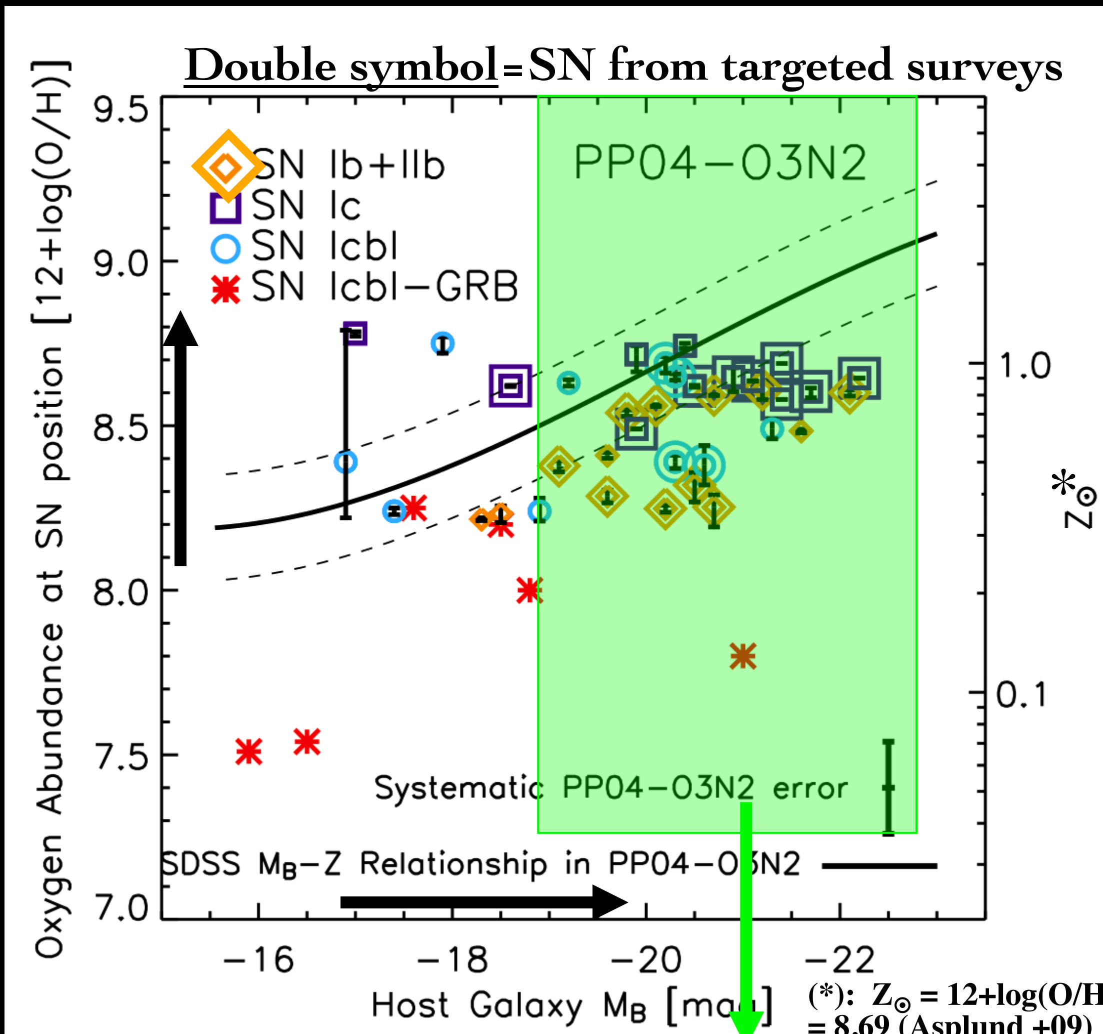



1) Almost all SN in dwarfs are from **untargeted** SN surveys

**2) Big Difference** b/w L-Z prediction, nuclear Z and locally measured Z (**-0.4 dex < Δ Z < 0.5 dex**) **-> Need locally measured abundances**

Modjaz et al (2011)

# Need for homogeneous, Z-unbiased, Single Survey



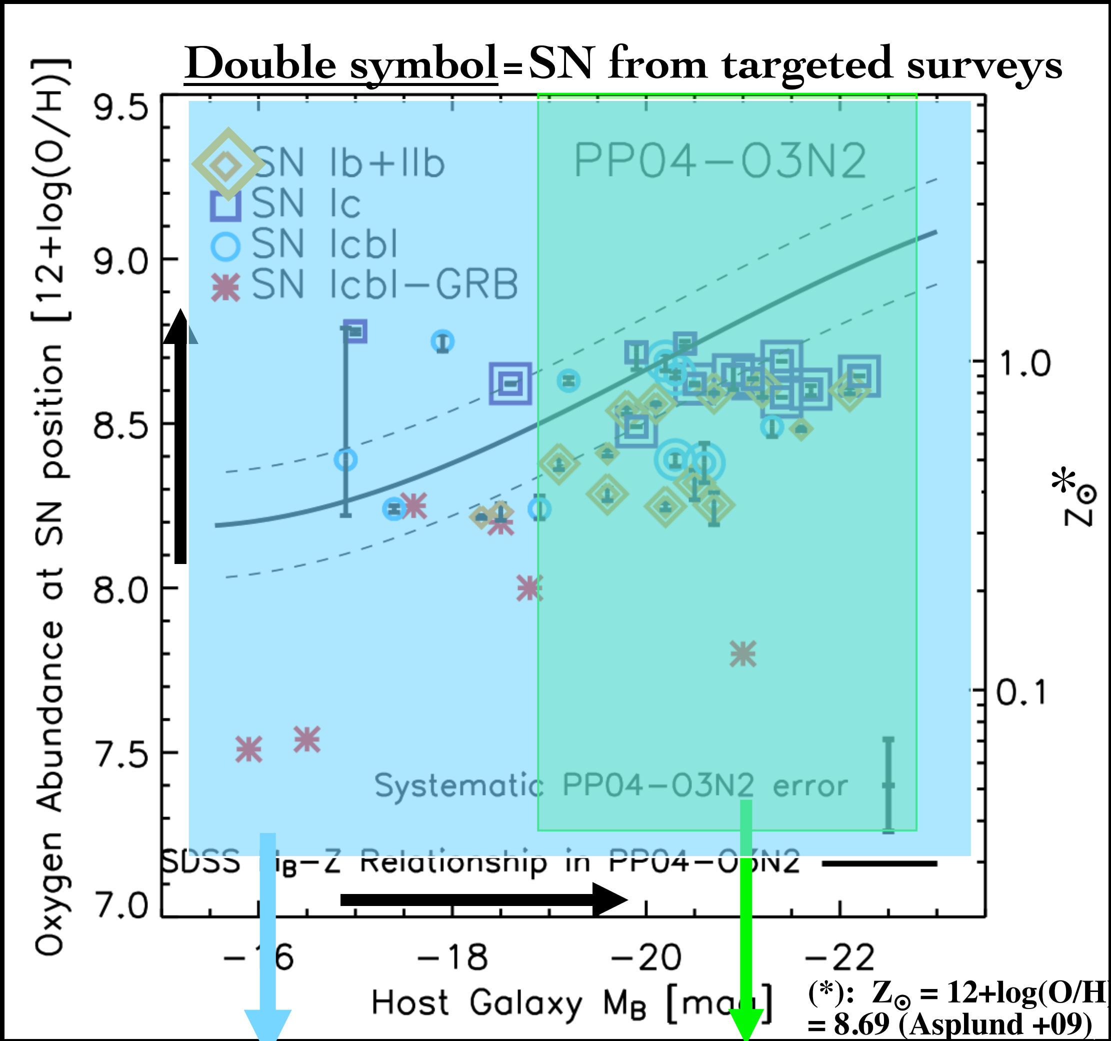

1) Almost all SN in dwarfs are from **untargeted** SN surveys

**2) Big Difference** b/w L-Z prediction, nuclear Z and locally measured Z **(-0.4 dex < Δ Z < 0.5 dex) -> Need locally measured abundances**

**e.g., Lick SN Survey (Li et al. 2011)**

**Modjaz et al (2011)**

# Need for homogeneous, Z-unbiased, Single Survey




1) Almost all SN in dwarfs are from **untargeted** SN surveys

**2) Big Difference** b/w L-Z prediction, nuclear Z and locally measured Z **(-0.4 dex < Δ Z < 0.5 dex) -> Need locally measured abundances**

**Next step: PTF or other innovative surveys, e.g., PanSTARRS, Skymapper, LSST**

**e.g., Lick SN Survey (Li et al. 2011)**

**Next step: PTF**

**Modjaz et al (2011)**

# Palomar Transient Factory (PTF)

PALOMAR TRANSIENT FACTORY

as of Dec 2012 (continues now as iPTF)

**Stripped SN host galaxy program:** ~1/2 data taken

## The Palomar Transient Factory

- Home
- AAS January 2013
- The PTF Team
- Gallery
- Public Papers / Docs
- Education and Public Outreach
- Internal Project TWiki
- Caltech Astronomy

The Palomar Transient Factory (PTF) is a fully-automated, wide-field survey aimed at a systematic exploration of the optical transient sky.

| | All SNe | SNe Ia | SNe Ibc | SNe II |
|---|---|---|---|---|
| Spectroscopically confirmed supernova discoveries (as of today) Access public spectra (WISEASS) | 1923 | 1294 | 89 | 467 |

| | |
|---|---|
| PTF papers | 57 (list of papers) |

### Recent News

February 2013: PTF discovers an outburst from a massive star 40days before a supernova explosion (Nature)

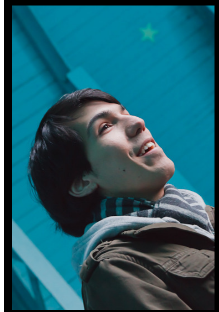
February 2013: The intermediate Palomar Transient Factory (iPTF) begins (Atel #4807)

# PTF: Different Galaxies host different CC SNe

**Future is now:** ~3x more Stripped SN than early 2010

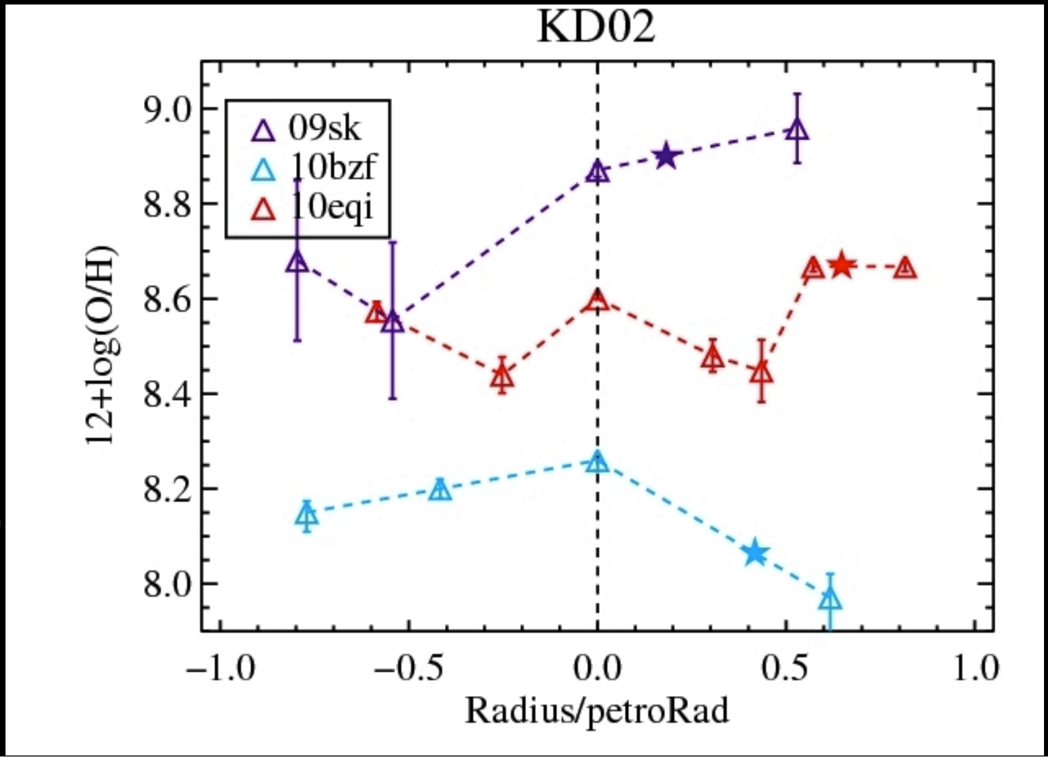
**Leading large, unprecedented host galaxy study of 89 PTF Stripped SN from single & homogeneous, galaxy-untargeted survey**

Metallicity gradients in PTF Hosts:

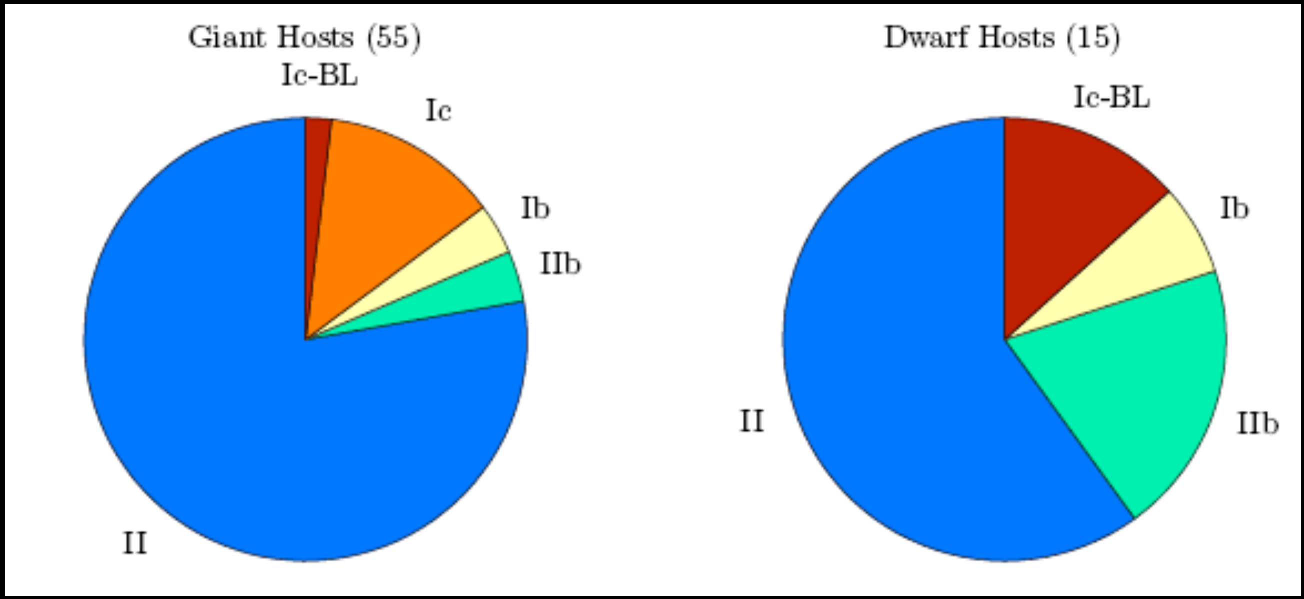


**Modjaz, Fierroz et al (in prep)**

David Fierroz



# PTF: Different Galaxies host different CC SNe




**Arcavi et al (2010) [sample as of early 2010]**

**Dwarfs galaxies (with low Z):** 1. No normal SN Ic, but SN Ic-bl

2. Excess of SNe Ib and IIb

-> Fully Consistent with Modjaz et al. (2011) and Kelly & Kirshner (2012) but need direct metallicity measurements & larger sample

**Future is now:** ~3x more Stripped SN than early 2010

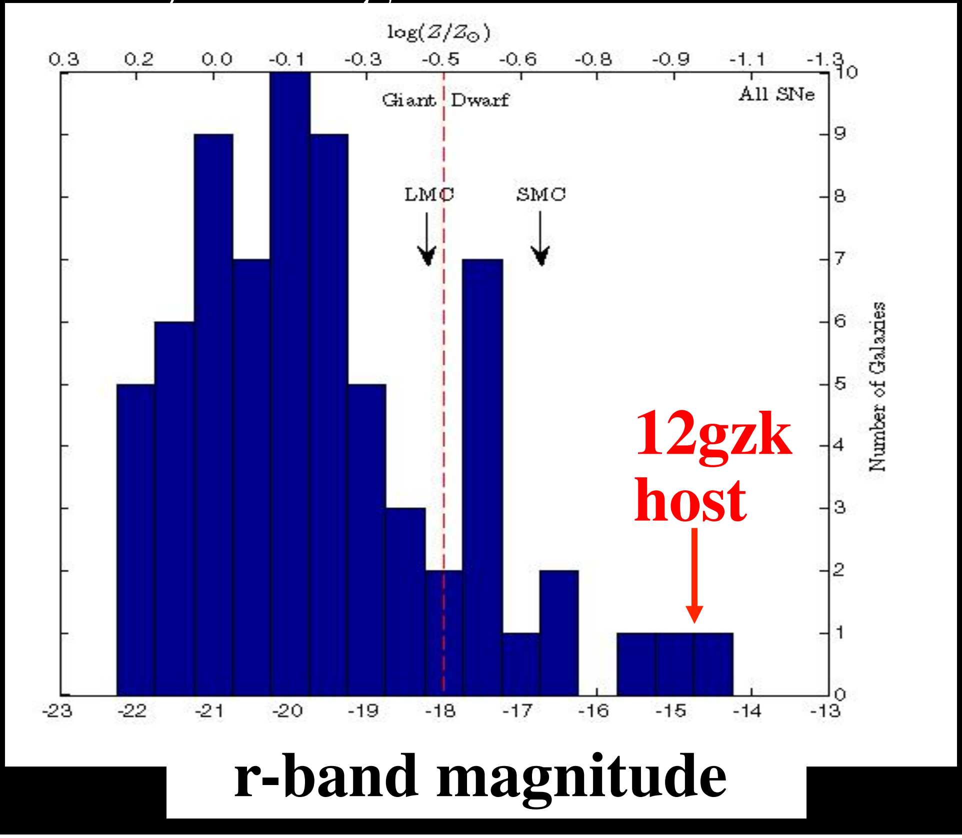
# PTF: Curious Case of PTF 12gzk (Ben-Ami, Modjaz, +12)

- SN Ic with high absorption velocities, but no broad lines

- high KE & ejecta mass, from massive star (>25-35$M_{\odot}$?)

- **Host Galaxy** : $M_r$ =-14.8 mag: amongst least luminous host of PTF-CCSN, usually hosting SN Ic-bl/SN-GRB/SLSN

**Host galaxies of PTF CCSN (Arcavi+10)**




**High L / "Metal Rich" @center**

**Low L / Metal Poor**

# PTF: Curious Case of PTF 12gzk (Ben-Ami, Modjaz, +12)

- SN Ic with high absorption velocities, but no broad lines

- high KE & ejecta mass, from massive star (>25-35$M_{\odot}$?)

**- Host Galaxy** : $M_r$ =-14.8 mag: amongst least luminous host of PTF-CCSN, usually hosting SN Ic-bl/SN-GRB/SLSN

# PTF: Curious Case of PTF 12gzk (Ben-Ami, Modjaz, +12)

- SN Ic with high absorption velocities, but no broad lines
- high KE & ejecta mass, from massive star (>25-35$M_{\odot}$?)
- **Host Galaxy** : $M_r$ =-14.8 mag: amongst least luminous host of PTF-CCSN, usually hosting SN Ic-bl/SN-GRB/SLSN

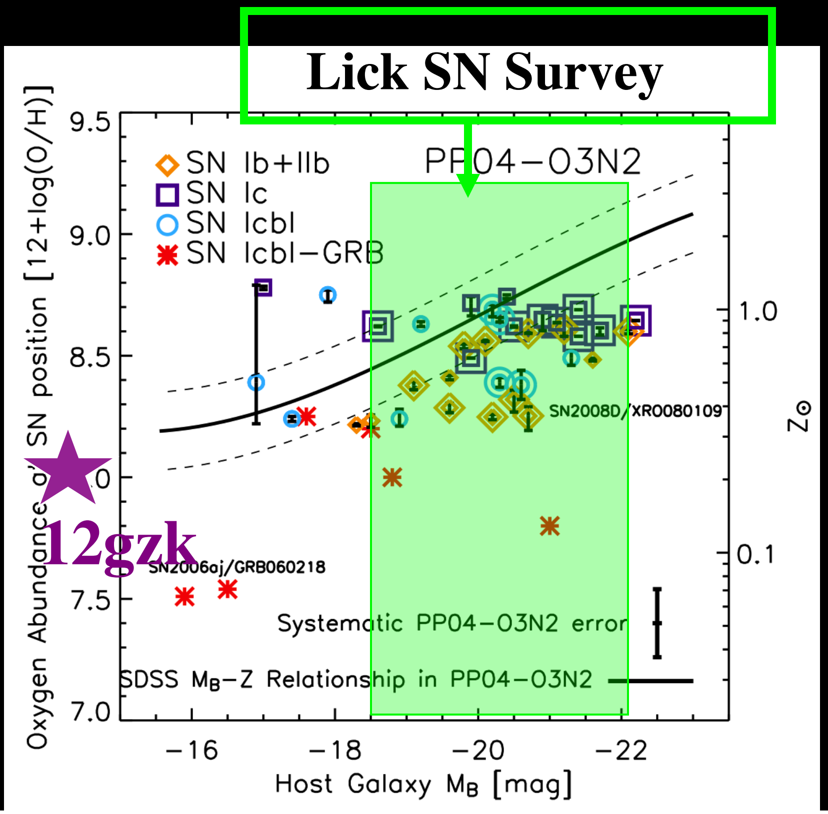
**12gzk: 12+log(O/H)$_{PP04}$=8.1 -> very low!**

**SN Ic from untargetted surveys:**

**<12+log(O/H)>= 8.7 +/- 0.1** (Modjaz+11)

**<12+log(O/H)>= 8.6 +/- 0.2** (Sanders+12)

**Modjaz+11**



# Stellar Forensics: From Explosions

## Direct Study:

NO progenitor detections for ~10 SN Ib, Ic, Ic-bl (e.g. Smartt09)
->not conclusive (Bibby+12, Yoon+12)

## From Explosion Properties:

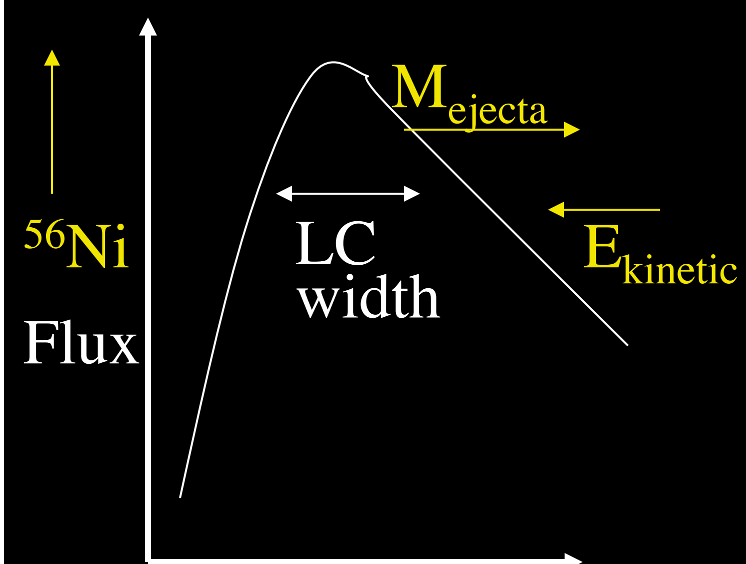
(- SN Shock breakout & Envelope-Cooling )
- Light curves & Spectra (Bianco, Modjaz in prep) ( Drout+11, Cano+13)

# Ejecta Masses From SN

## Light curves

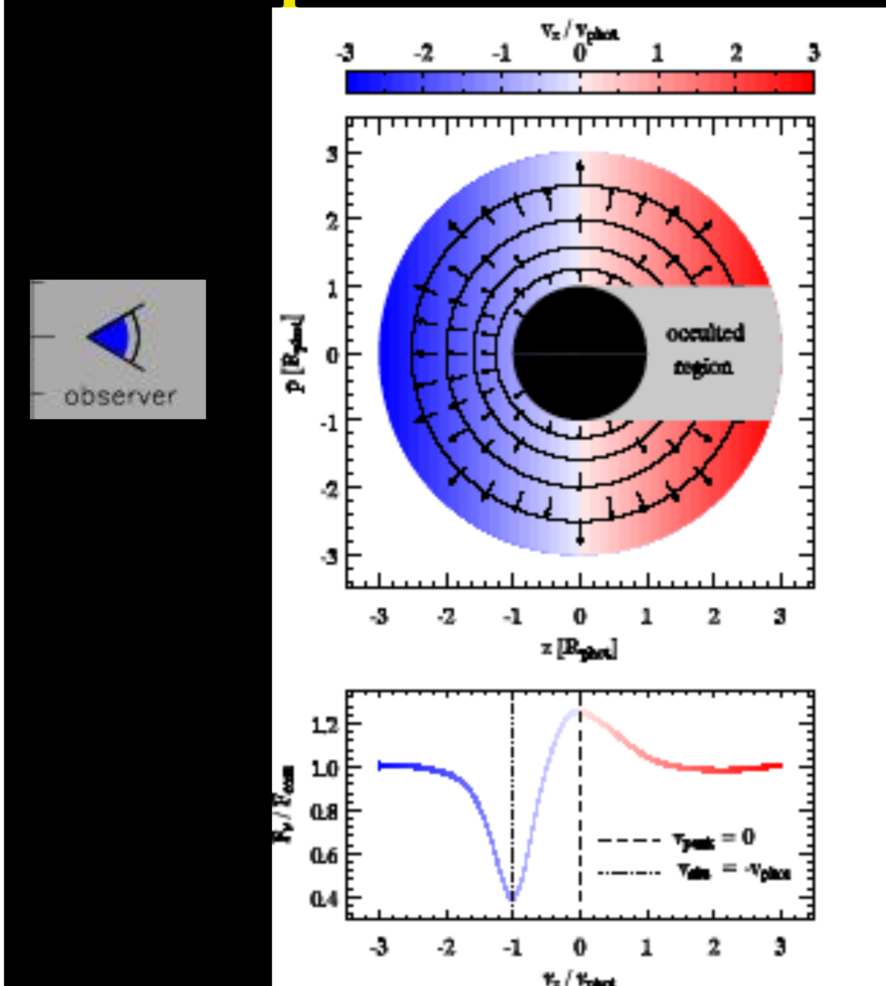
Type SN I (no H):

$$^{56}\mathrm{Ni} \xrightarrow[6.6\mathrm{d}]{\gamma} {}^{56}\mathrm{Co} \xrightarrow[78\mathrm{d}]{\gamma} {}^{56}\mathrm{Fe}$$




**LC width $\propto M_{ejecta}\, E_{kinetic}^{-3}$**

## Spectra

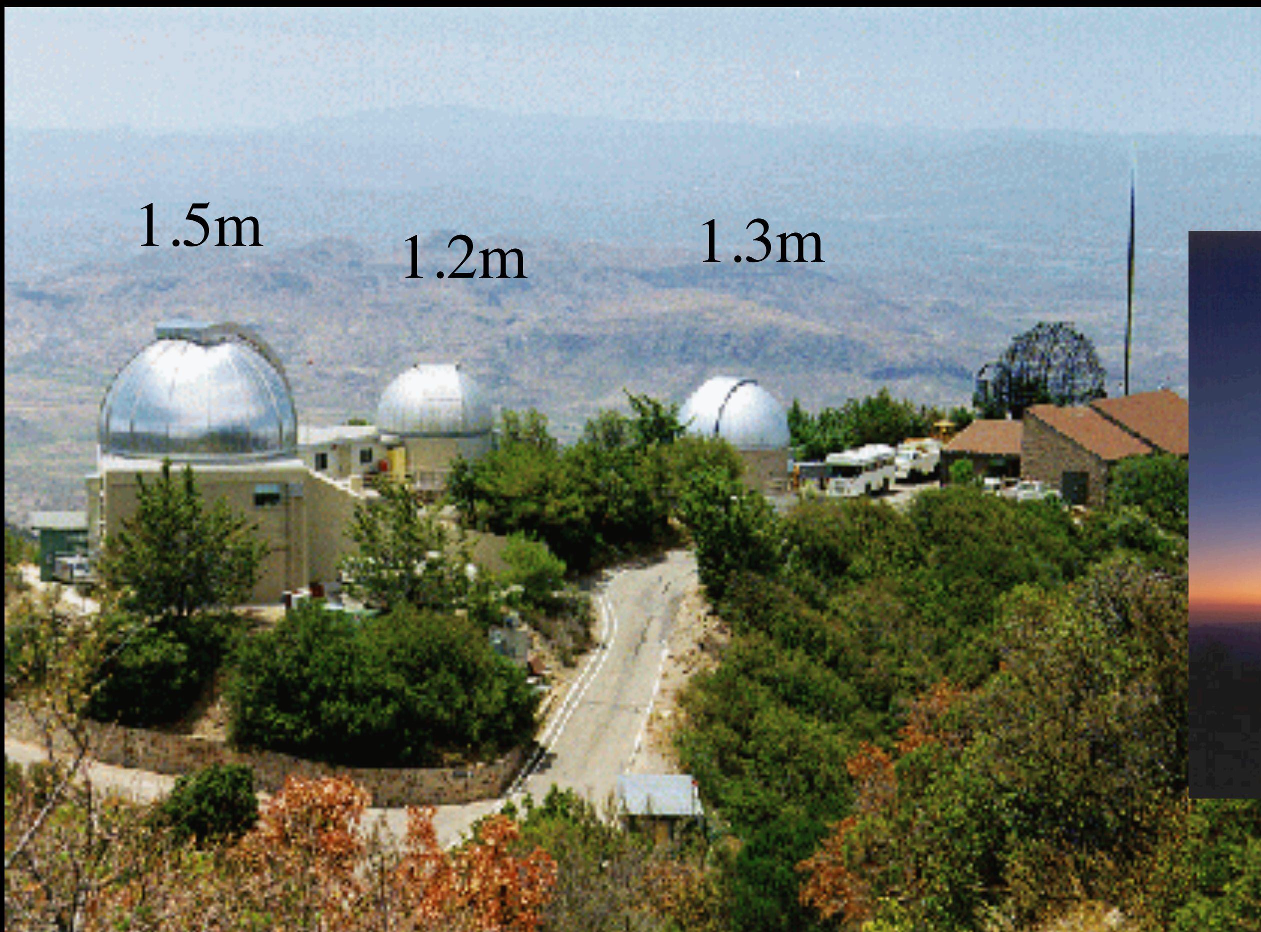



P Cygni: Blue absorption, Red emission

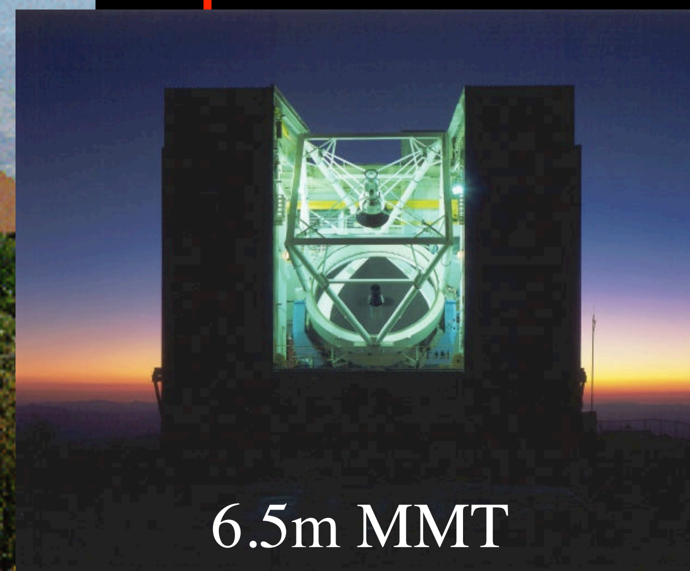
**velocity $\propto M_{ejecta}^{1/2}\, E_{kinetic}^{1/2}$**

*Credit: S. Blondin*

# NEARBY SN CFA FOLLOW-UP (SINCE 1994, ESP. >2003 -2009)




1.5m




Maryam Modjaz

# Stellar Forensics: From Explosions

**Federica Bianco**
**(NYU)**

**<u>CfA Stripped SN sample of spectra & light curves:</u>**
**2x larger than literature**

**--> Ejecta masses for SN Ib and SN Ic a) the same**
**b) low ("~2" $M_{sun}$)!**

**From literature SN-GRB:**
**higher average $M_{ej}$ (Cano+13)**

-> binaries!?

**Bianco, Modjaz et al, in prep**

# Stellar Forensics:

1) Environments: All 3 methods: SN Ib and SN Ic are different (SN Ic environs more metal-rich & more massive stars than SN Ib
2) From Explosion properties: SN Ib and SN Ic are same
3) 2x larger than literature

## Light curves & Spectra:

-Light curves of SN Ib and SN Ic are the same (see also Drout+11)

- Spectral velocities are the same (new!)

--> Ejecta masses for SN Ib and SN Ic: a) the same
b) low (~2 or 4 $M_{sun}$)!

-> binaries!?

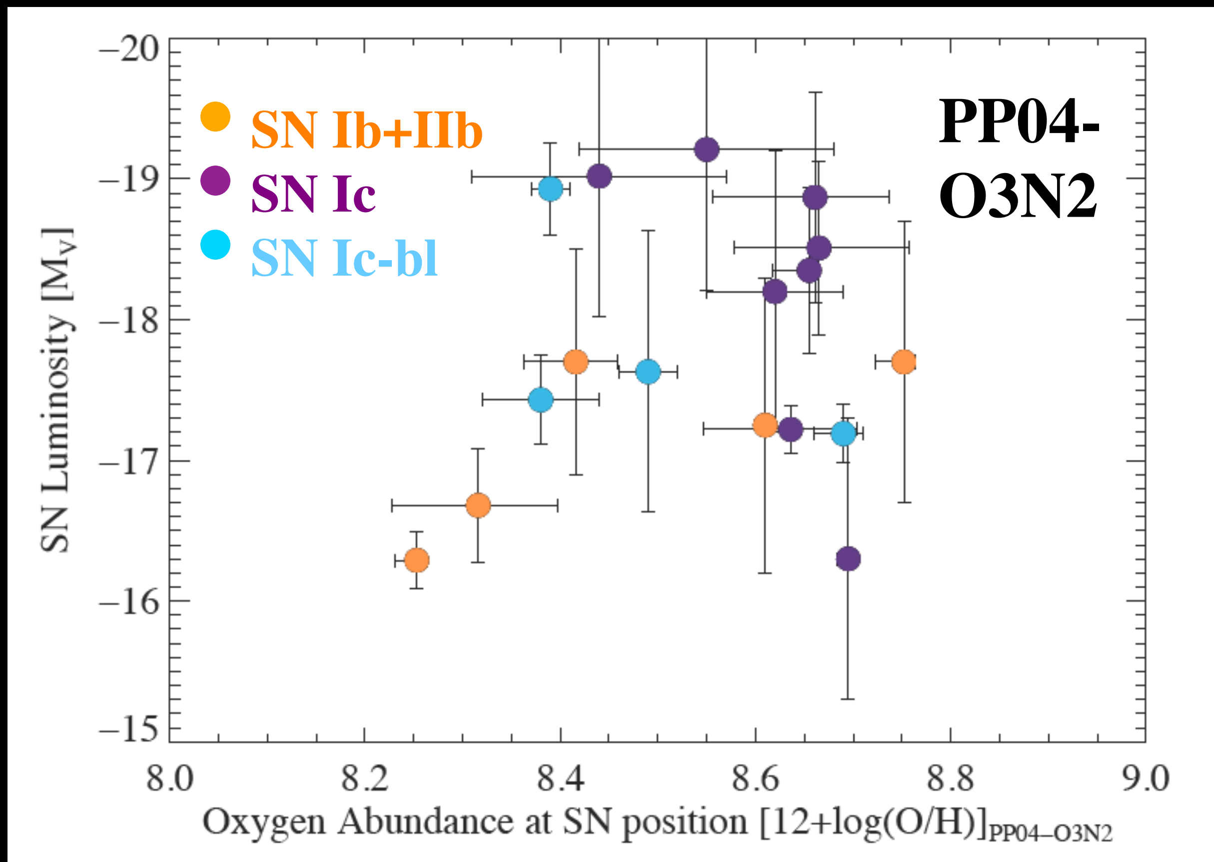
# Conclusions: Stellar Forensics with SN & GRBs

- No Progenitor detections for SN Ib, Ic, Ic-bl, SN-GRBs
  -> NEED for statistical studies of environments & explosion properties

- Environments: emerging & rapidly developing field (almost all papers in last ~5 years)
- Trends as a function of SN subtype
  - SN Icbl -GRBs are at systematically lower oxygen abundances (but NOT exclusively)
- Importance of untargetted SN searches to find explosions in low-L, low-Z environments
- SN Ib & Ic: ejecta masses: same & low -> binary channel with mass loss from winds (since Z-dependence)
- SN-GRB: large ejecta masses: massive stars @low Z

Maryam Modjaz

# SN property vs oxygen abundance




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

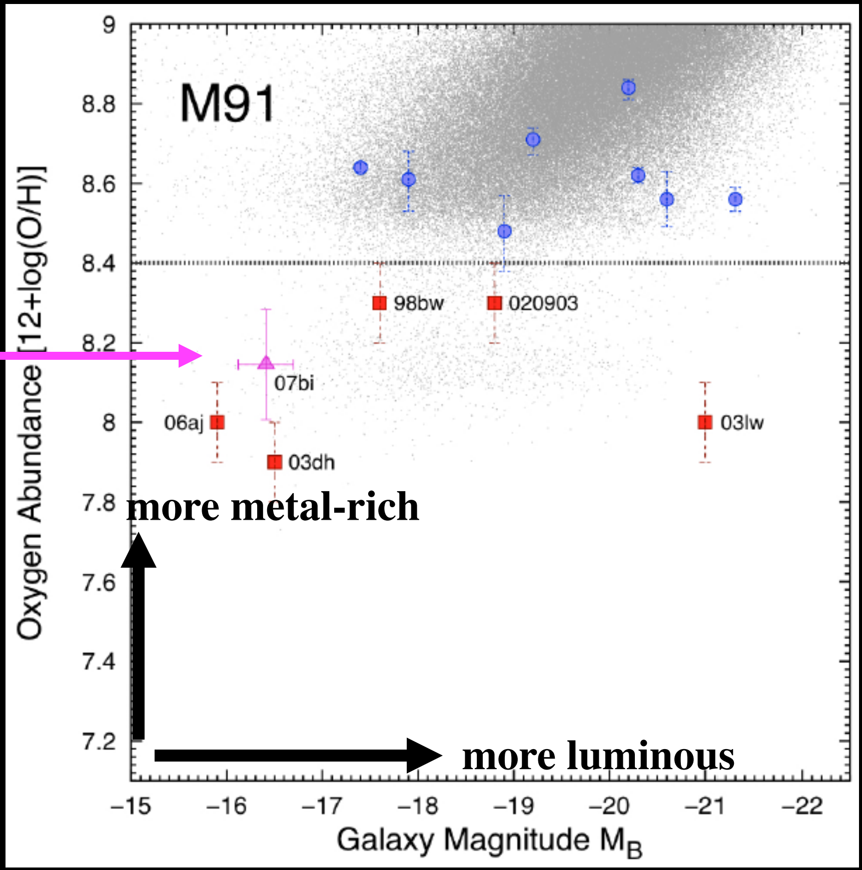
# Metallicity Studies is Rapidly developing field

**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)
- 5 Superluminous SNe (e.g., Neill et al 2010, Stroll et al. 2011, Quimby )

**Need:** -large metallicity samples from same galaxy-unbiased survey -> underway

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




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

Maryam Modjaz