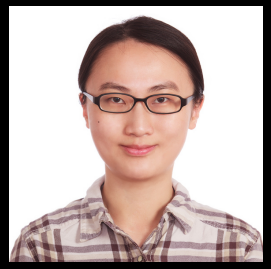
Statistical Studies of Stripped-Envelope SNe

Maryam Modjaz

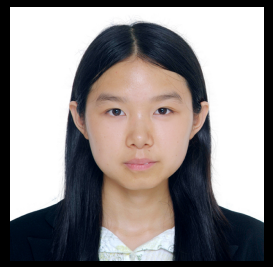
Fed Bianco (LSST Co-Chair for Transients)



Shan Huang

Or Graur (NSF fellow @Harvard)

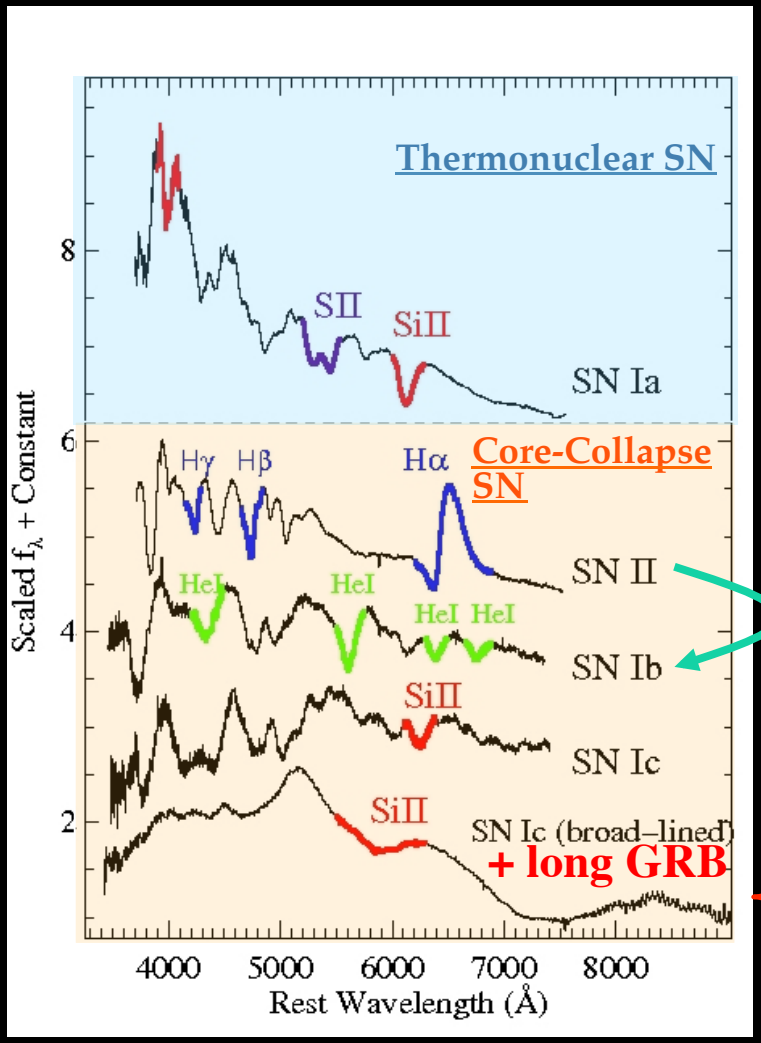
Kieran Finn



Yuqian Liu (Dean's Dissertation fellow)

SN Zoo

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



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

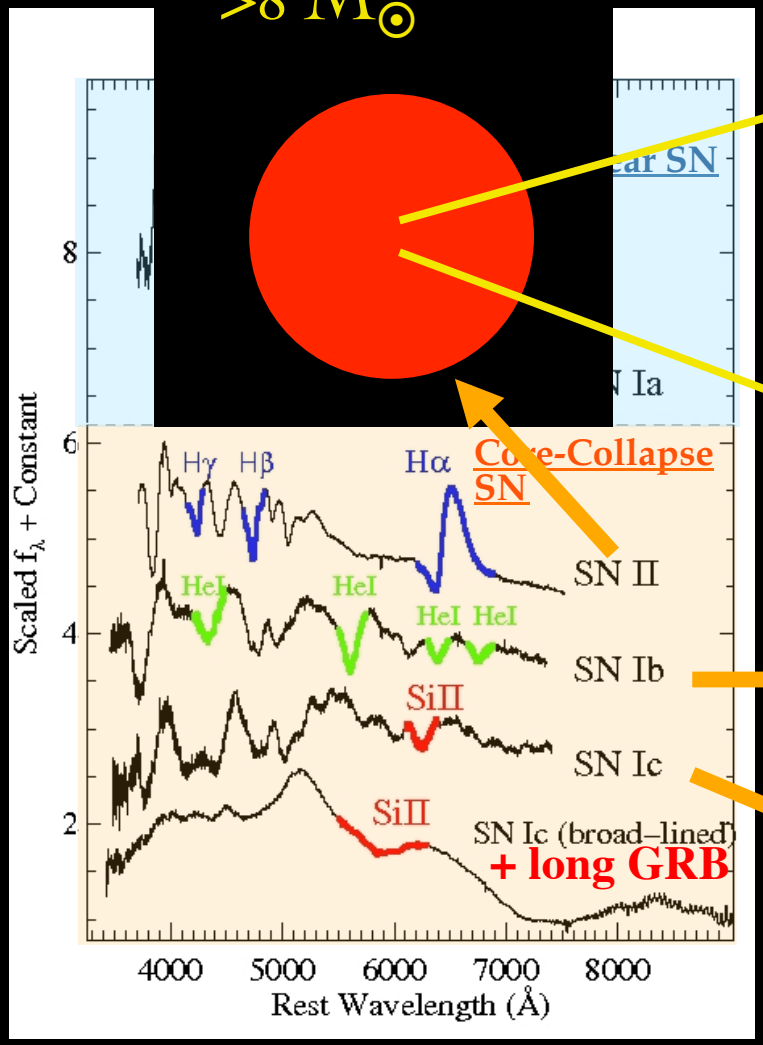
SN IIb

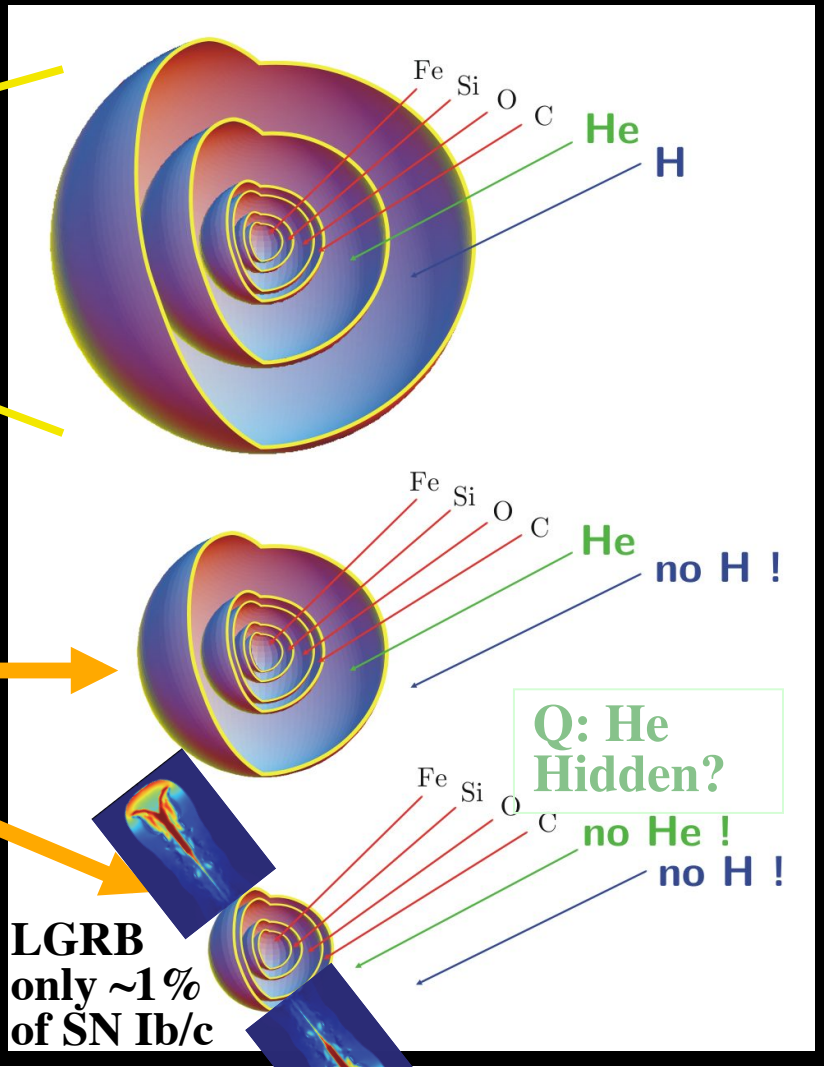
Broad lines -> large expansion velocities (~20,000 kms^{-1})

large $E_{kinetic}$(0.X -Y x10^{52} erg)

SN Zoo

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



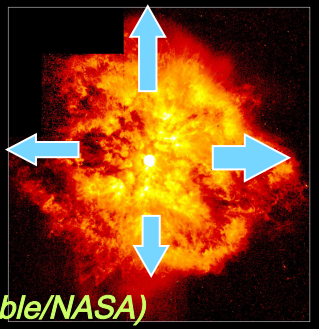


Importance of Stripped SN & GRB progenitors

- **Stellar & High-Energy Astrophysics:**
  - SN Remnants are Black Holes, Neutron Stars, Magnetars
  - Sources for Gravitational Wave & Neutrino Emission, Candidates for High-Energy Cosmic Ray Acceleration
- **Chemical Enrichment History of Universe:**
  - Nucleosynthesis (r-process elements, Zn/Fe)
- **Cosmology:**
  - Illuminate early Universe: GRBs detected up to z~8.2 and z~10 (Tanvir et al. 2009, Salvaterra et al 2009, Cucchiara, et al. 2011)
  - Tool: star formation probes over cosmological distances (e.g.,Chen et al 2009)

Stellar Forensics: Hunt For Progenitors

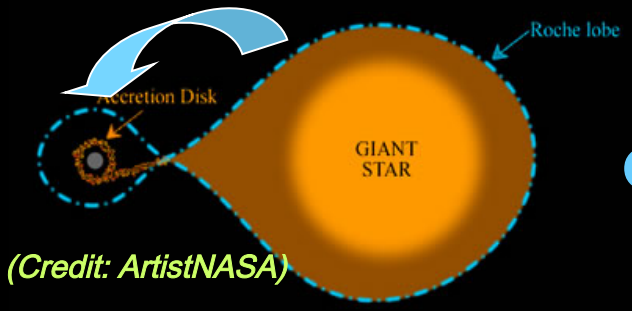
Stripped SN & SN-GRB progenitors:



(Hubble/NASA)

Single massive (> 30 $M_\odot$) with metallicity-dependent winds

or



(Credit: ArtistNASA)

SN progenitor

Stars (8-40 $M_\odot$) in binaries, can remove H & He even at low Z

or

(Credit: ArtistESO)

?

Single massive highly rotating star, "homogeneous evolution"

- Direct Study: not possible/successful
- -> Need for indirect, statistical studies for Stellar Forensics

1) SN & GRB explosion properties (Modjaz+14&16, Liu+16, Finn+16, Modjaz & Liu 17)

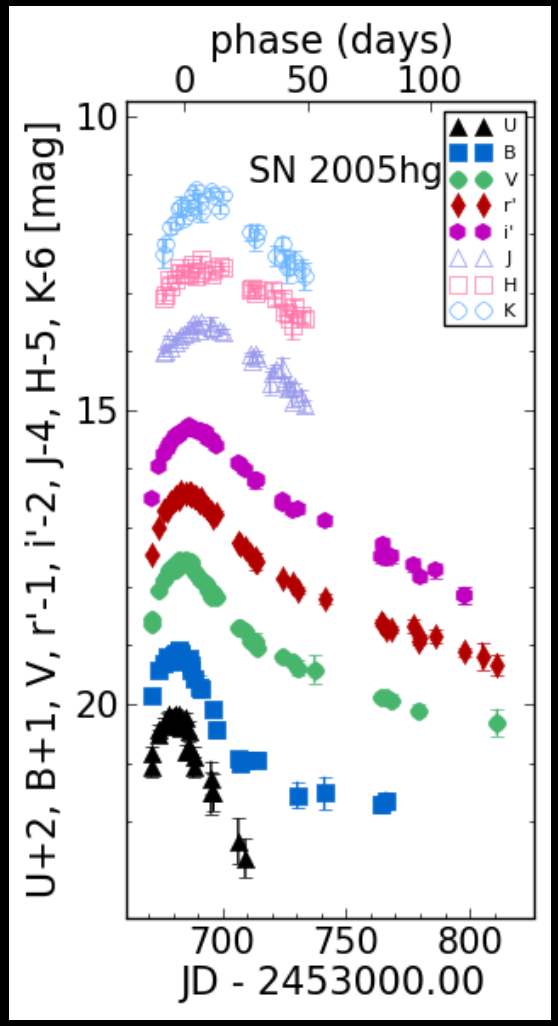
2) SN rates & Host galaxy/environments (Modjaz+11&12,Kelly+14,Graur+15, Bianco+15, Graur16a&16b, Huang+in prep)

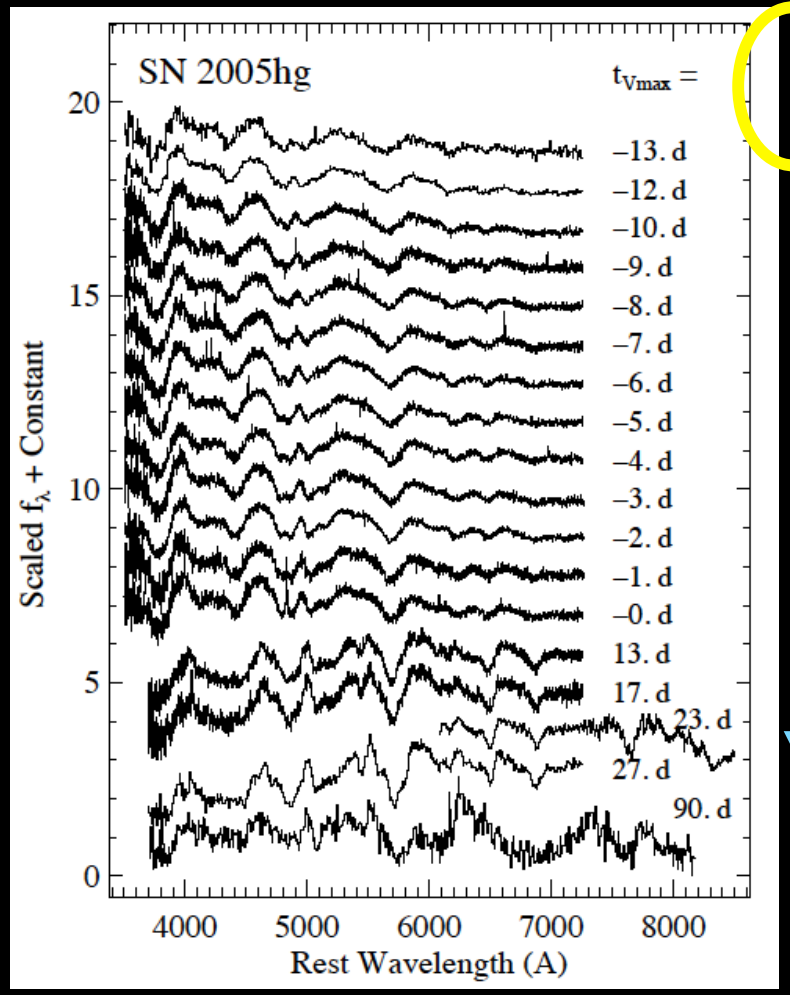
"Big" Data

- SN Ib/c
  - **datasets** (Matheson+01, Drout+11, Modjaz+14, Bianco+16, Taddia+15)
  - **analysis** (Richardson+14, Lyman+14, Modjaz+16, Liu+16,, Parrent+16, Prentice+16)
- SN II datasets & analysis (Arcavi+12, Anderson+14, Faran14a&14b, Poznanski+15, Sanders+15, Valenti+15,16, Gall+15, Rubin & Gal-Yam 16)
- Freely available after published:
  - **CfA SN Archive, Berkeley SNDB, SNYU, SUSPECT, WISeREP, Open SN catalog** (Guillochon, Parrent, Margutti+16)

CfA Stripped Sample: Extensive photometry & Spectra

Fed Bianco et al. 14





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Modjaz et al. 14

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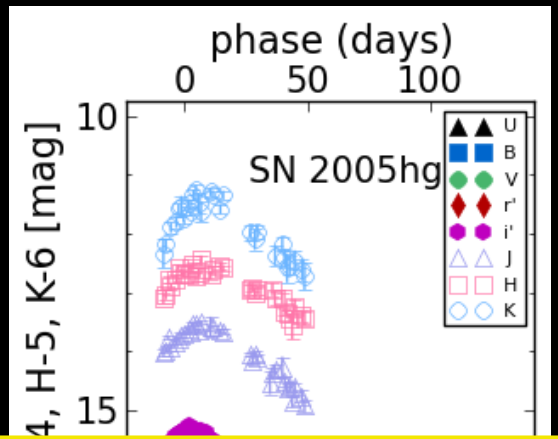

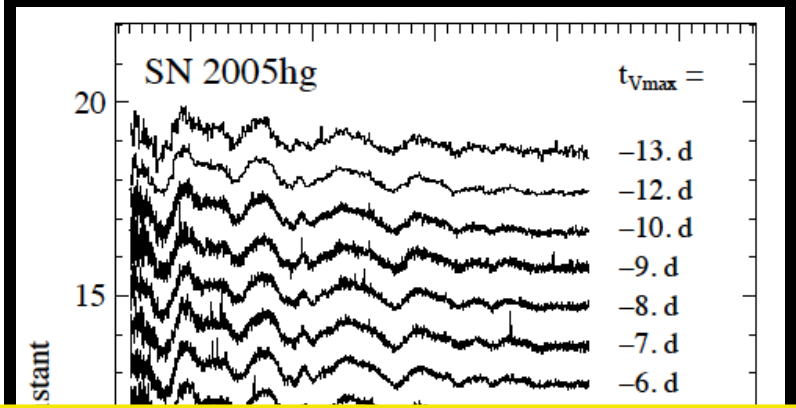

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Modjaz et al. 14

CfA sample: 1994-2009 (including published SNe):

Spectroscopic: Modjaz et al (2014): **73 Stripped SNe**

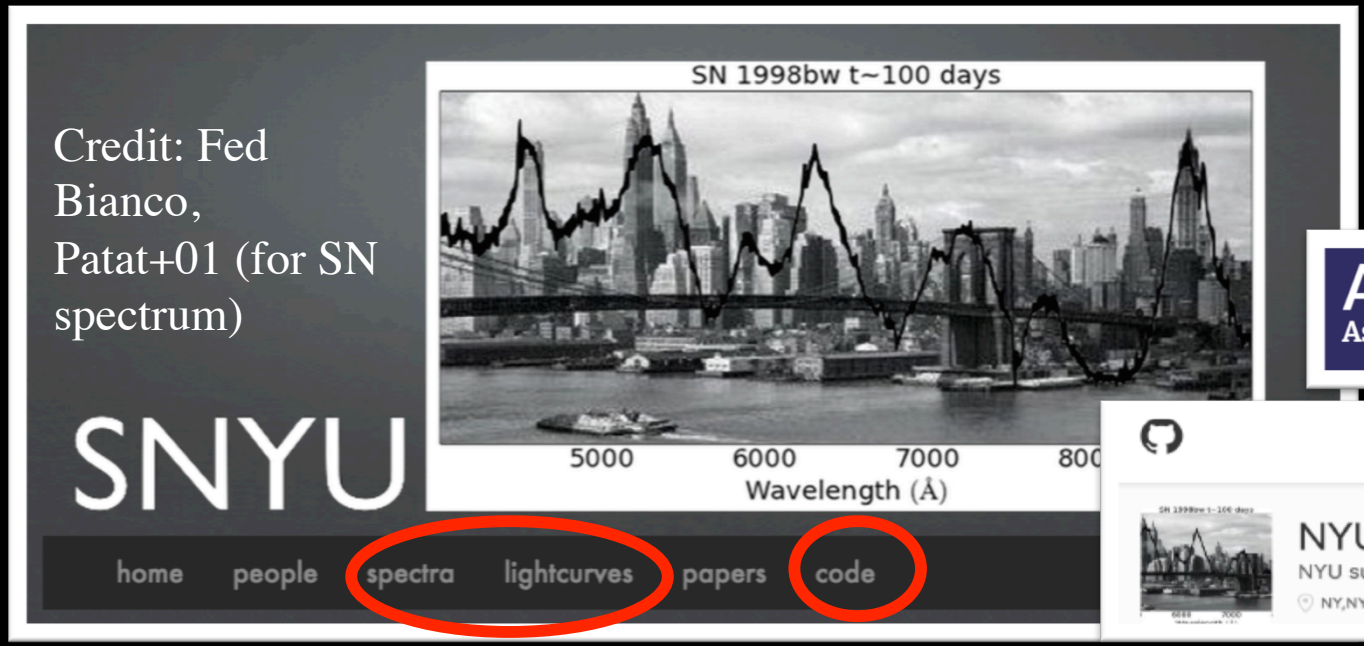
Photometric: Bianco, Modjaz et al. (2014): **64 Stripped SNe**

Doubles world-supply of well-observed Stripped SNe

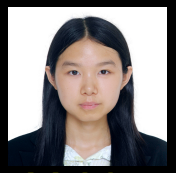
JD - 2453000.00

Rest Wavelength (A)

Software infrastructure



- Data & Data products & Code are freely available
  (Modjaz+14, Bianco, Modjaz+14, Modjaz+16, Liu, Modjaz+16, Bianco+16)
- New & modified templates for SNID library Liu,
  (Liu & Modjaz 14, Modjaz+16, Liu, Modjaz+16)



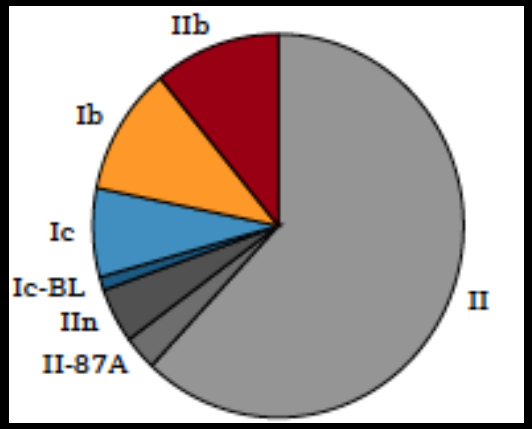
Y. Liu

BIG IMPACT:

- correct fingerprinting (e.g, GRB-SNe, SN Ia for cosmology)
- developed new tools & solid statistical framework

Fingerprinting Stripped Sn & implications:

- Modjaz+14: Many SN Ic are actually SN Ib (SNID templates, telluric absorption, time coverage, Ic: "rejects")
- SN rates: Is ratio of Ic/Ib=2.6 ± 1.1 correct? (LOSS: Li+11, Smith+11) ?
- LOSS volume-limited sample revisited (Shivvers, Modjaz+17, Graur+17a, Graur+17b)



Shivvers, Modjaz+17

Shivvers, Modjaz+ 17:
No! SN Ib are more common:
Ib/Ic = 1.7 ± 0.9

Fingerprinting Stripped Sn & implications:

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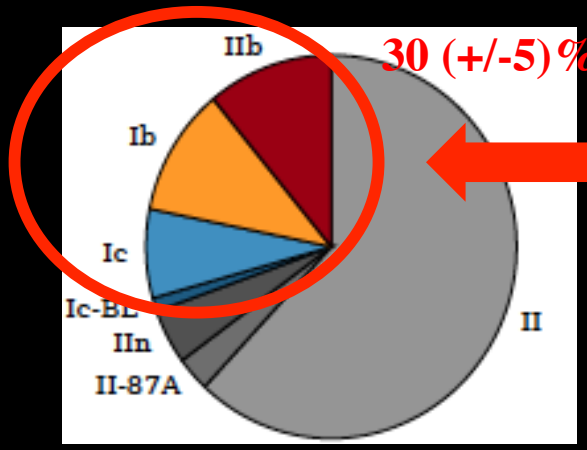
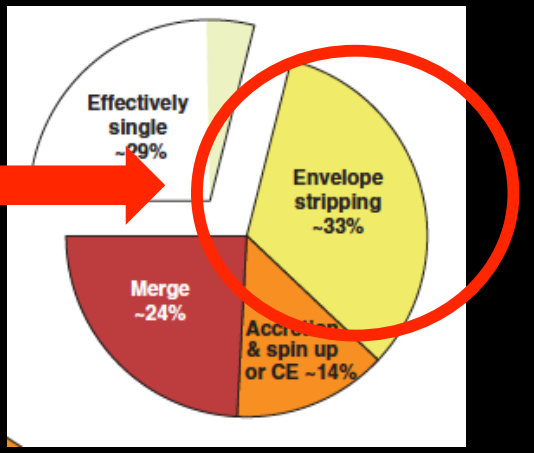


Shivvers, Modjaz+17

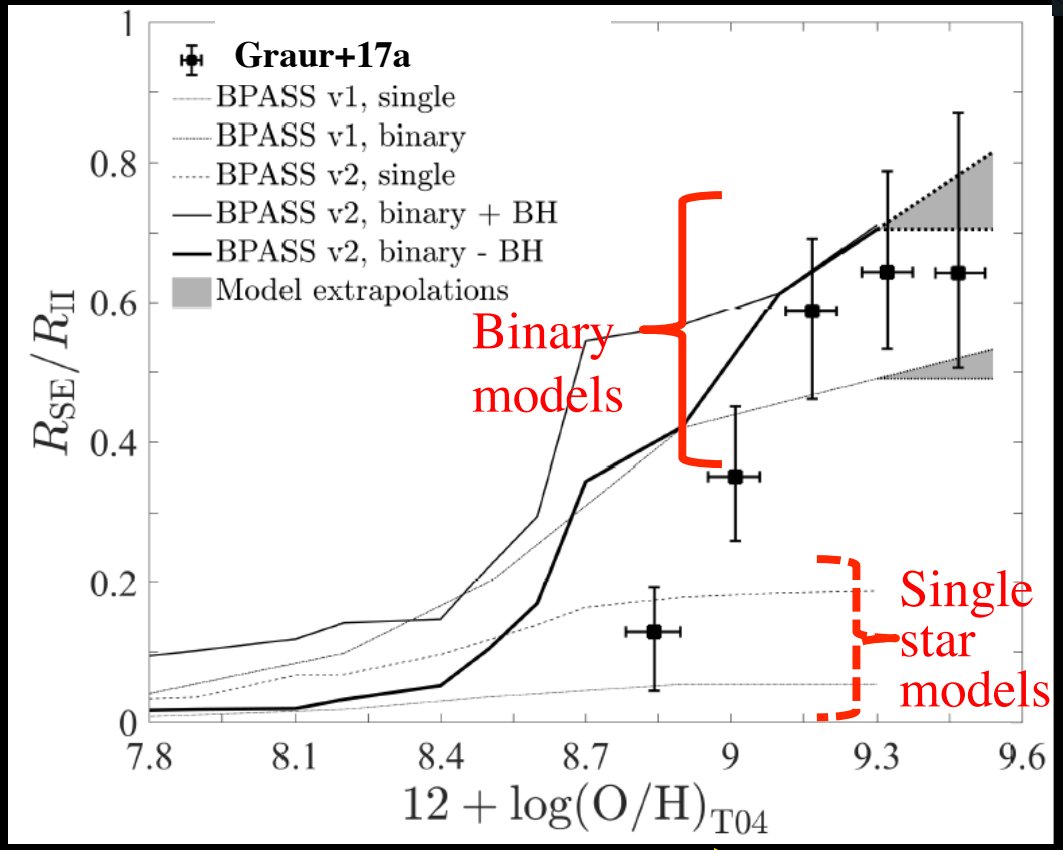
SESN: still 30% of all CCSNe



Sana, de Mink+12

Binaries are Common

- Stripped SNe



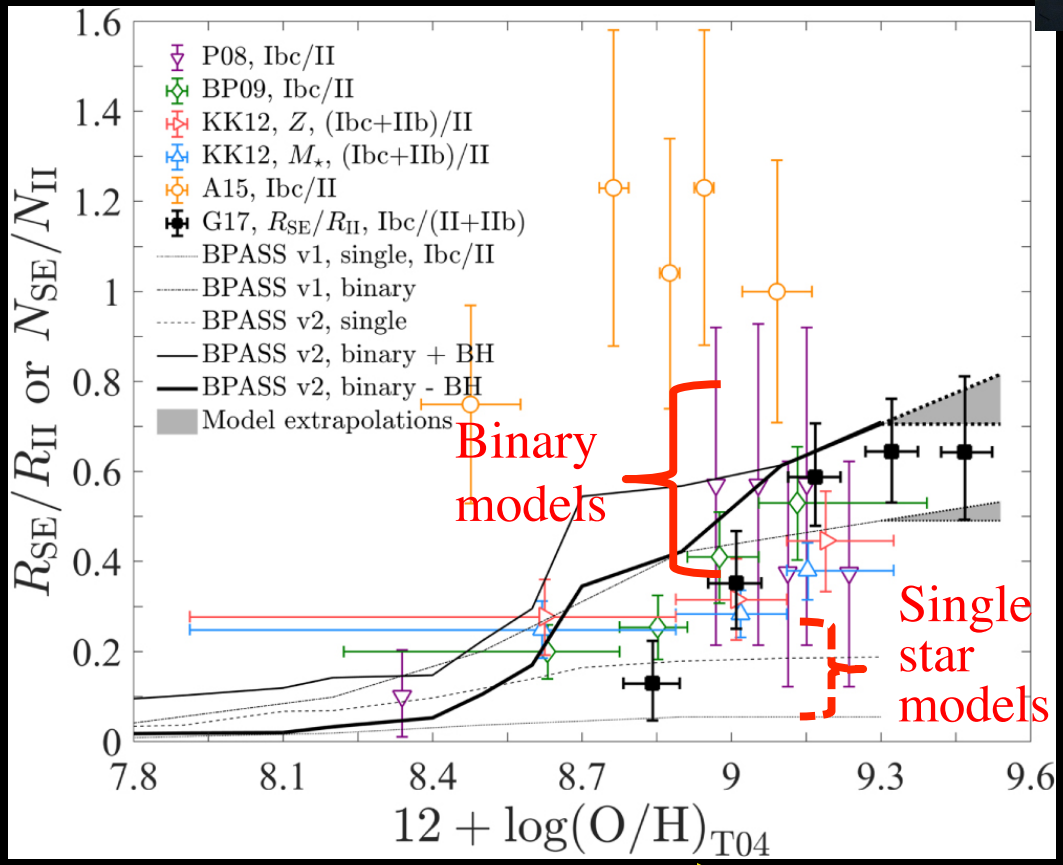
more metal-rich

Graur, Bianco, Huang, Modjaz+17a

- Lick Observatory Supernova Search: 10 years & 1000 SNe
- Correct SN IDs
- High rate of Stripped SNe only reproduced by binaries, not single stars (e.g. Smith+11)

Binaries are Common

- Stripped SNe



more metal-rich

Consistent with Stephen Smartt's talk

Graur, Bianco, Huang, Modjaz+17a

- Lick Observatory Supernova Search: 10 years & 1000 SNe
- Correct SN IDs
- High rate of Stripped SNe only reproduced by binaries, not single stars
- Absolute rates & smallest error bars wrt prior works
- Caveats: galaxy-targetted survey, model uncertainties

Binaries are Common

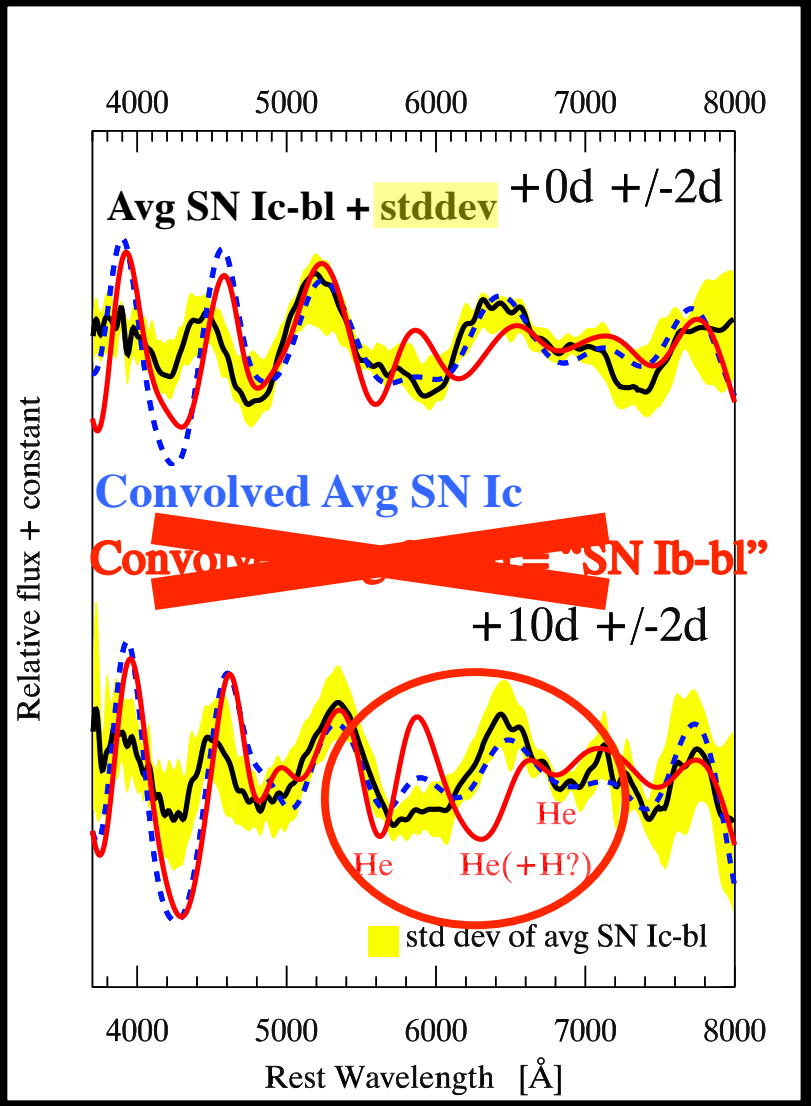
- SNe Ic-bl & SN-GRBs

  He problem for SN-GRBs

- Avg SN Ic-bl reproduced by normal avg SN Ic convolved with Gaussian (μ=-3000 km/s,σ=6000 km/s)

- BUT: not by convolved avg SN Ib

-> SN Ic-bl spectra: most likely no smeared-out Helium layer!
-> binaries (hard to make by single & chem. hom. Stars @observed low Z)



Modjaz+ 16

Caveat: non-thermal excitation

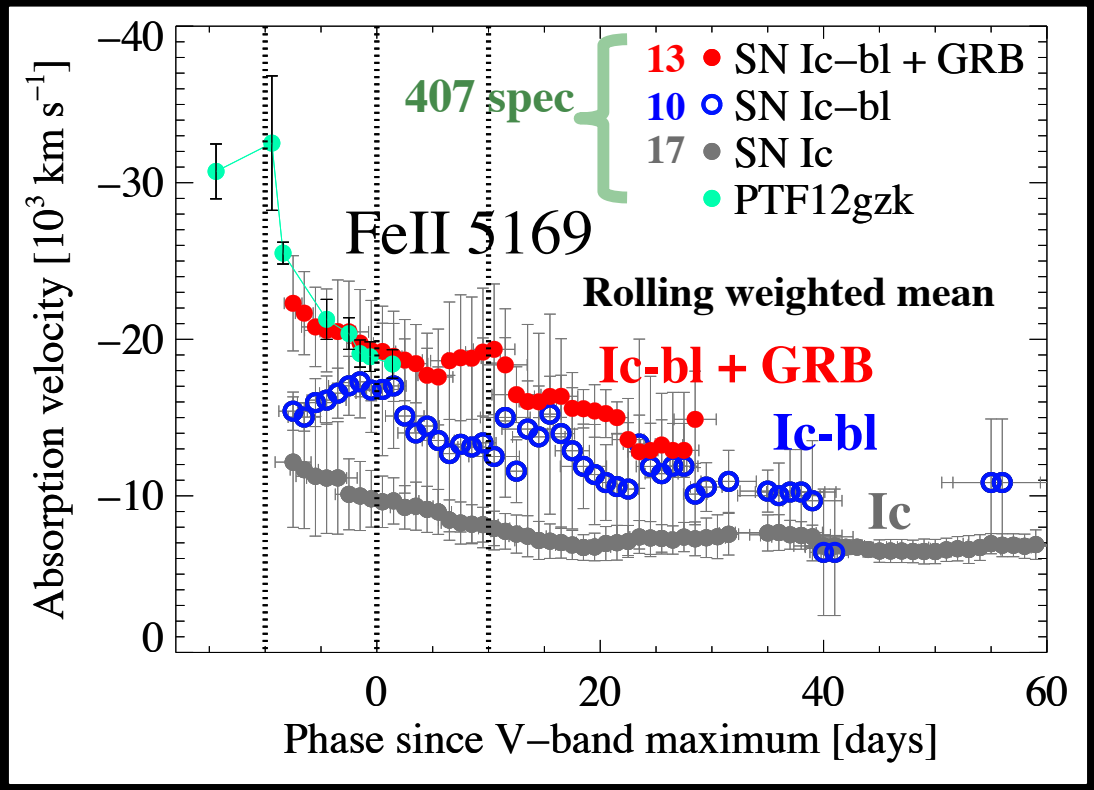
SN Ic-bl with and without GRBs

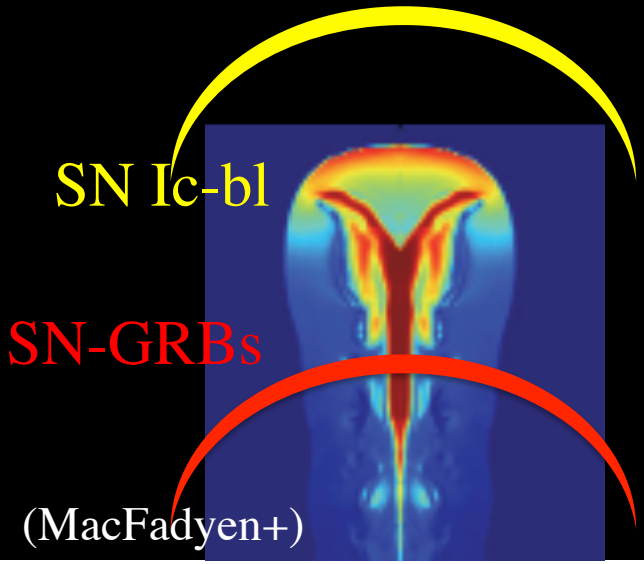
- **Largest datasets**
- **Novel** MCMC method for measuring vel's for SN Ic-bl

emcee The MCMC Hammer

Modjaz+16

$v_{SNIc\text{-}bl\ GRB} > v_{Ic\text{-}bl}$ (by ~6,000 km/s)



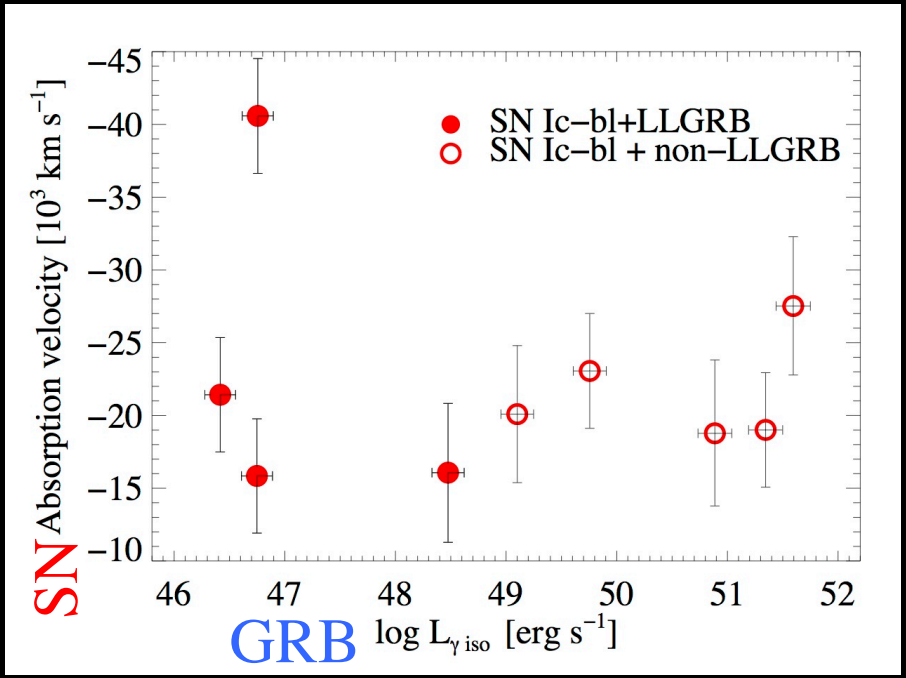


-> **choked, lower energy** jet in SN Ic-bl without GRBs

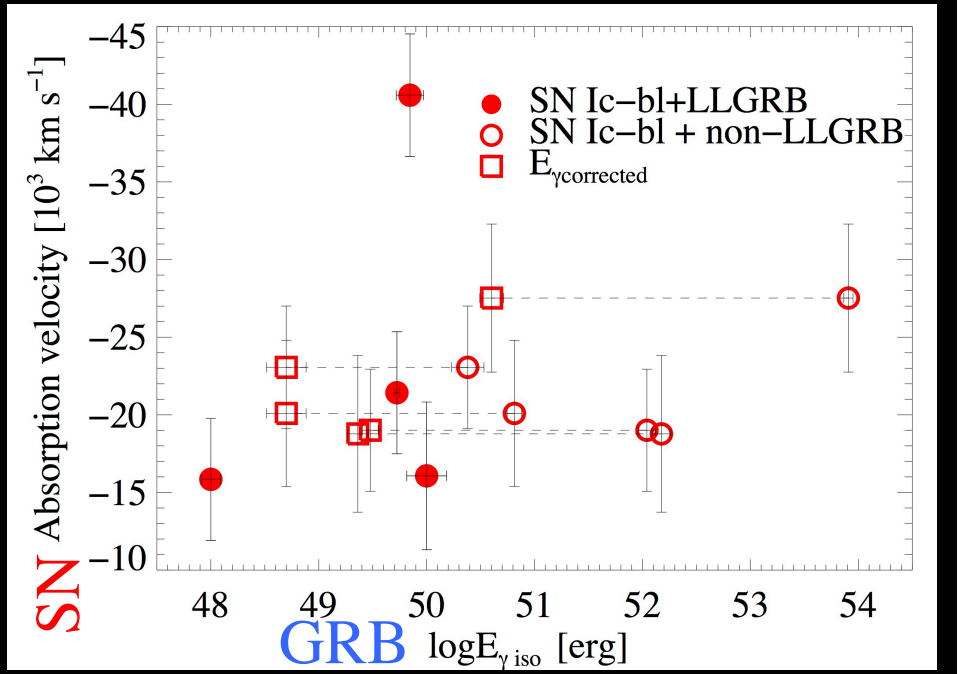
- viewing angle effects? NO, b/c SN-GRB have different environs than SN Ic-bl (Shan, Modjaz+ in prep)

SN knows about GRB, but doesn't care about its observed Strength

GRB Luminosity



GRB Energy

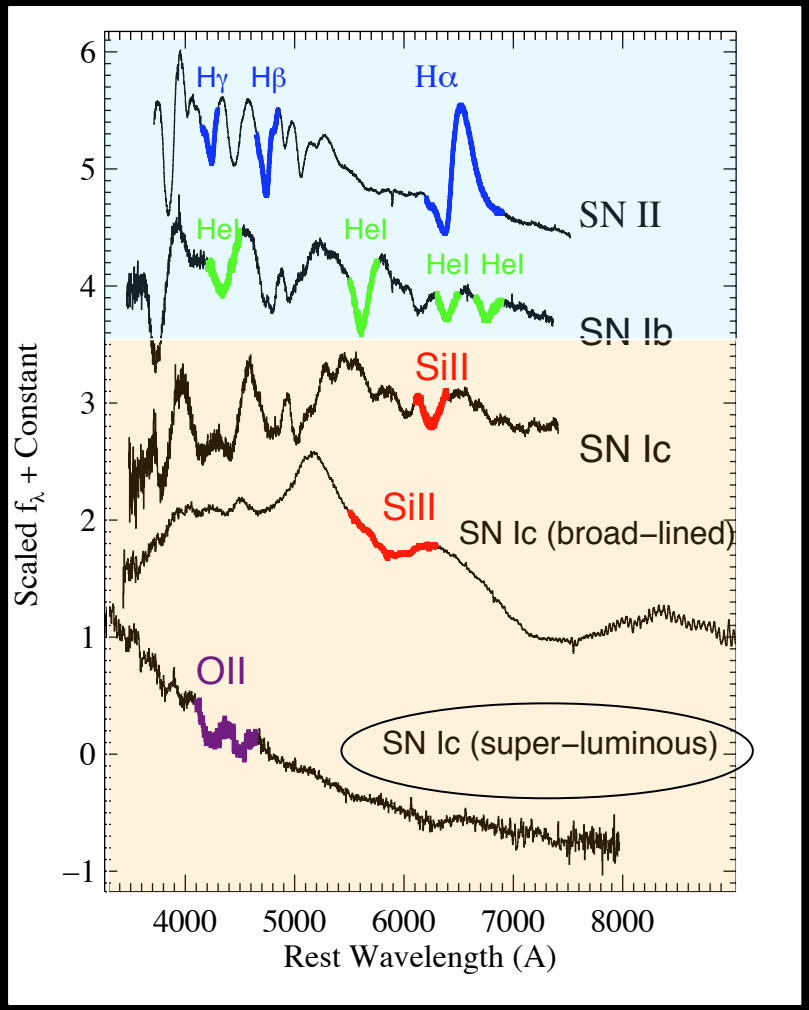


Modjaz+ 16

-No obvious correlation b/w GRB luminosity/energy and SN-GRB spectral velocity

- neither with Ic-bl's L (Hjorth+13) nor Ic-bl's Z (Levesque+11)

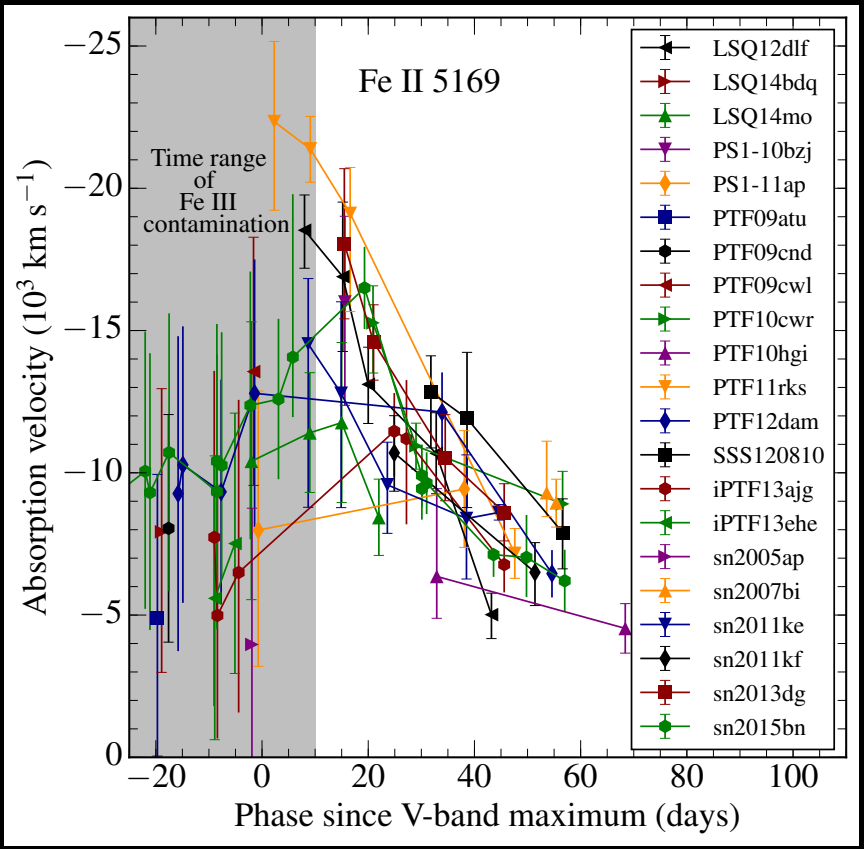
Recent SN Ic Family Member: SLSNe Ic

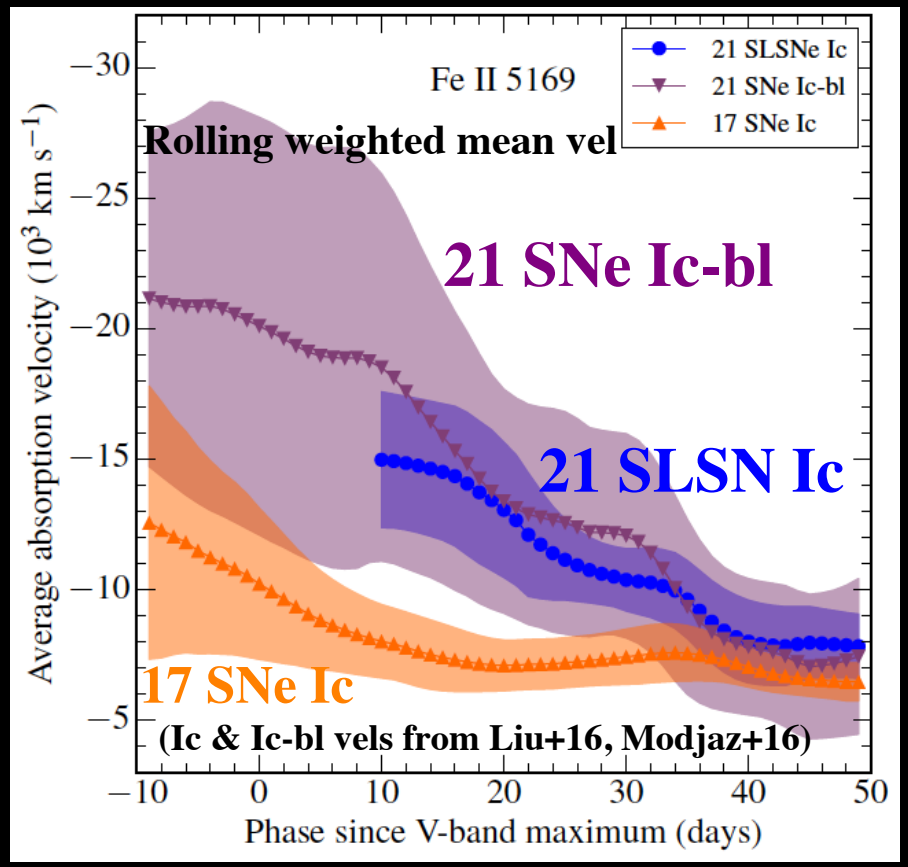


- More luminous than -21 mag -> $L_{SLSN} > 10^2 L_{CCSN}$
- Outstanding Q:
  - **What powers their brilliance?**
  - **What are their progenitors?**
- Liu & Modjaz 17
  - **First systematic investigation of spectral properties**
  - **Velocities: dynamics**
  - **Largest spec. datasets**

	No. of SN	No. of Spectrum
Normal SN Ic	17	200
Ic-bl	23	200
SLSNe Ic	33	170

SLSN-GRB CONNECTION



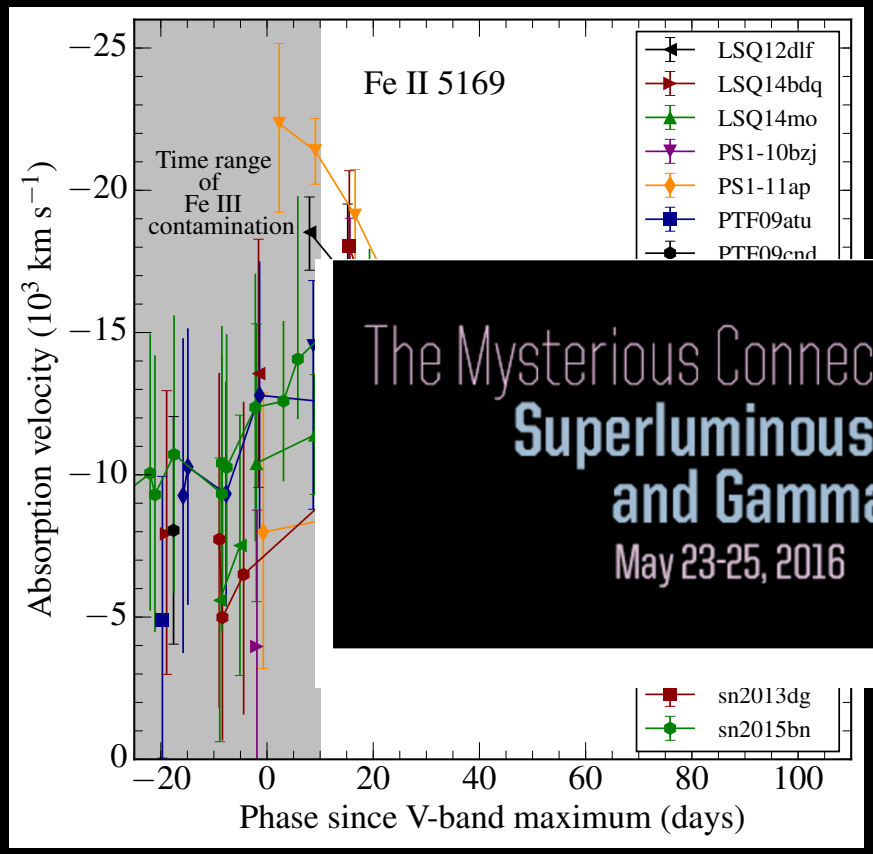


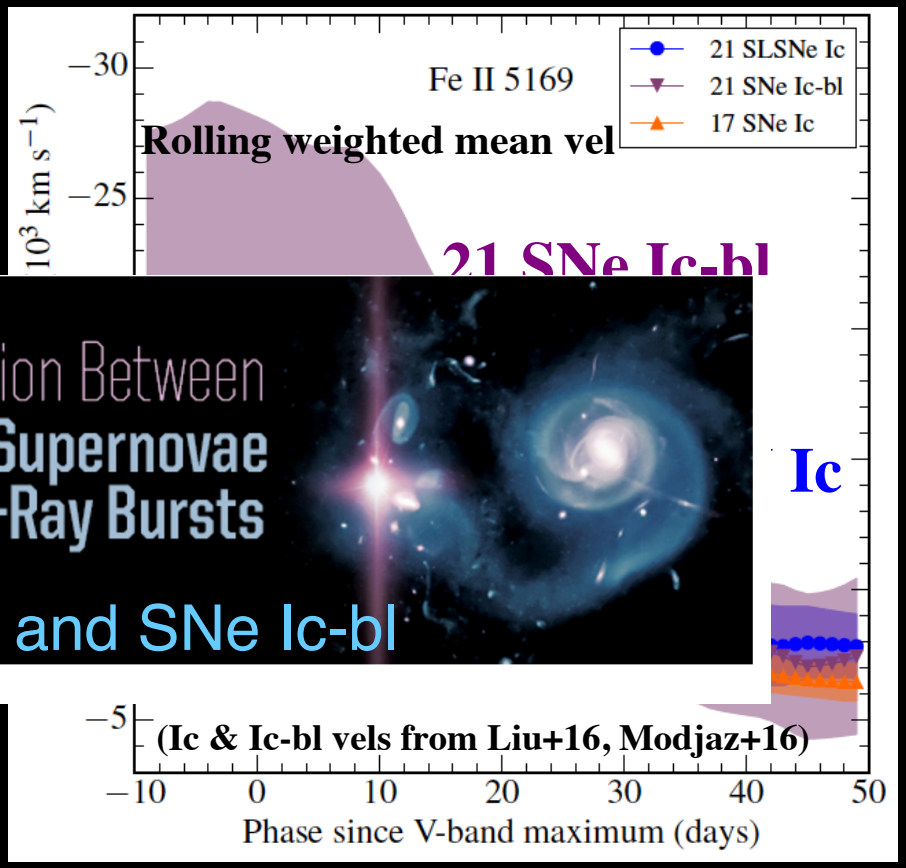
Liu & Modjaz 2017 (arXiv:161207321)

- SLSN-SN Ic-bl: SLSN Ic have higher vels (and broader lines) than SNe Ic, similar to SN Ic-bl*
- Caveats: 1) He? 2) as a population

(*=but different continuum)

SLSN-GRB CONNECTION





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SLSN-GRB CONNECTION

SLSNe Ic have higher vels (and broader lines) than SNe Ic, similar to SNe 1c-bl

Tension with current models for powering mechanisms:

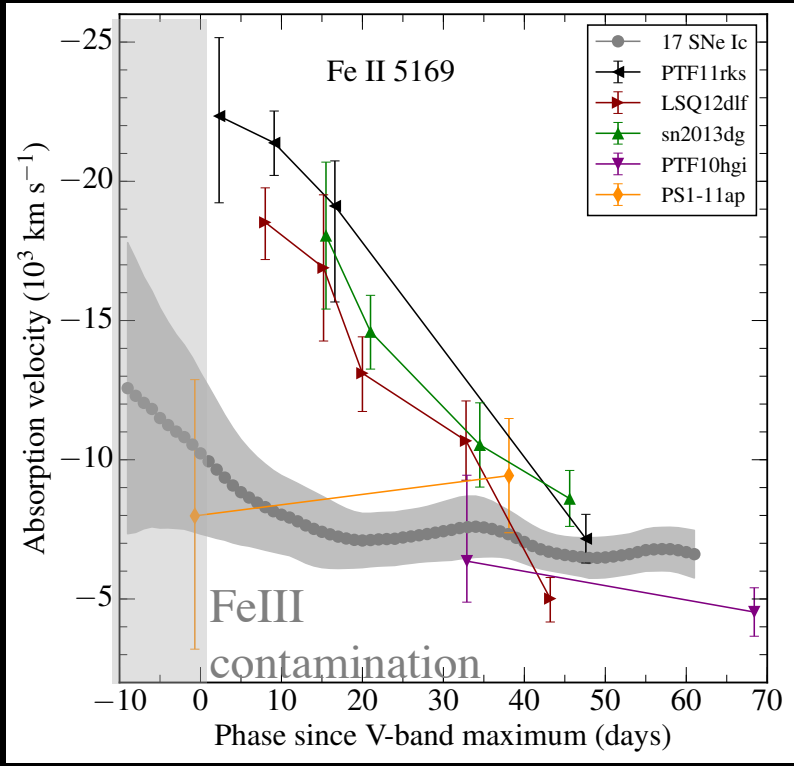
a) Interaction (e.g, Sokorina+16): hard to produce high vels , but need hydro models & synthesize spectra

b) 1D magnetar (e.g., Kasen& Bildsten 10, Woosley10, Metzger+14)

- Predicts velocity plateau
- Predicts narrow lines

-> not observed (for this line)!

-> Need 2D models (e.g, Chen+16, Suzuki&Madea 16)



Liu & Modjaz 2017

SLSN-GRB connection

SLSNe Ic have higher vels (and broader lines) than SNe Ic, similar to SNe 1c-bl

Table 3
Weighted mean absorption velocity and convolution FWHM, i.e., width, of Fe II λ5169 at $t_{max} \simeq 10$ day

SN type	$V_{absorption}$ ($10^3 kms^{-1}$)	$V_{convFWHM}$[a] ($10^3 kms^{-1}$)
SNe Ic	-8.0 ± 1.4	benchmark ($= 0$)
SNe Ic-bl	-18.5 ± 7.4	8.9 ± 2.1
SLSNe Ic	-15.0 ± 2.6	11.3 ± 3.6

Note. — The errors are the weighted standard deviations of data that contribute to the weighted average value, which are indicated as the error bars in the figure that shows the weighted average values.

[a] The convolution FWHM is with respect to the width of the feature in the SN Ic average spectrum at the corresponding phase.

Liu & Modjaz 2017

Where are the Off-axis GRBs ?

- Exist but not observed (yet)
  - PTF11agg, iPTF14yb? Both untriggered on-axis GRBs? (Cenko+13,15)
  - Candidates: SNe Ic-bl @low Z & @high v (e.g., SN2010ay)
  - **Hope: New radio surveys**
- Do not exist (as many)
  - nearby GRBs are ~spherical

Conclusions: Observations of Stripped CCSN

- Era of statistical analysis of "normal" & exotic Stripped SNe
- Get SN IDs right –> Ib/Ic rate: 2:1! !
- Statistical analysis:
  - **No hidden He layer in SN Ic-bl –> progenitors hard to produce!**
  - **SN Ic-bl knows about GRB, but SN-GRB does not care about its GRB strength**
  - **SLSN-GRB connection for SLSNe as a population: SLSNe Ic have high velocities & broad lines - > challenge for models**