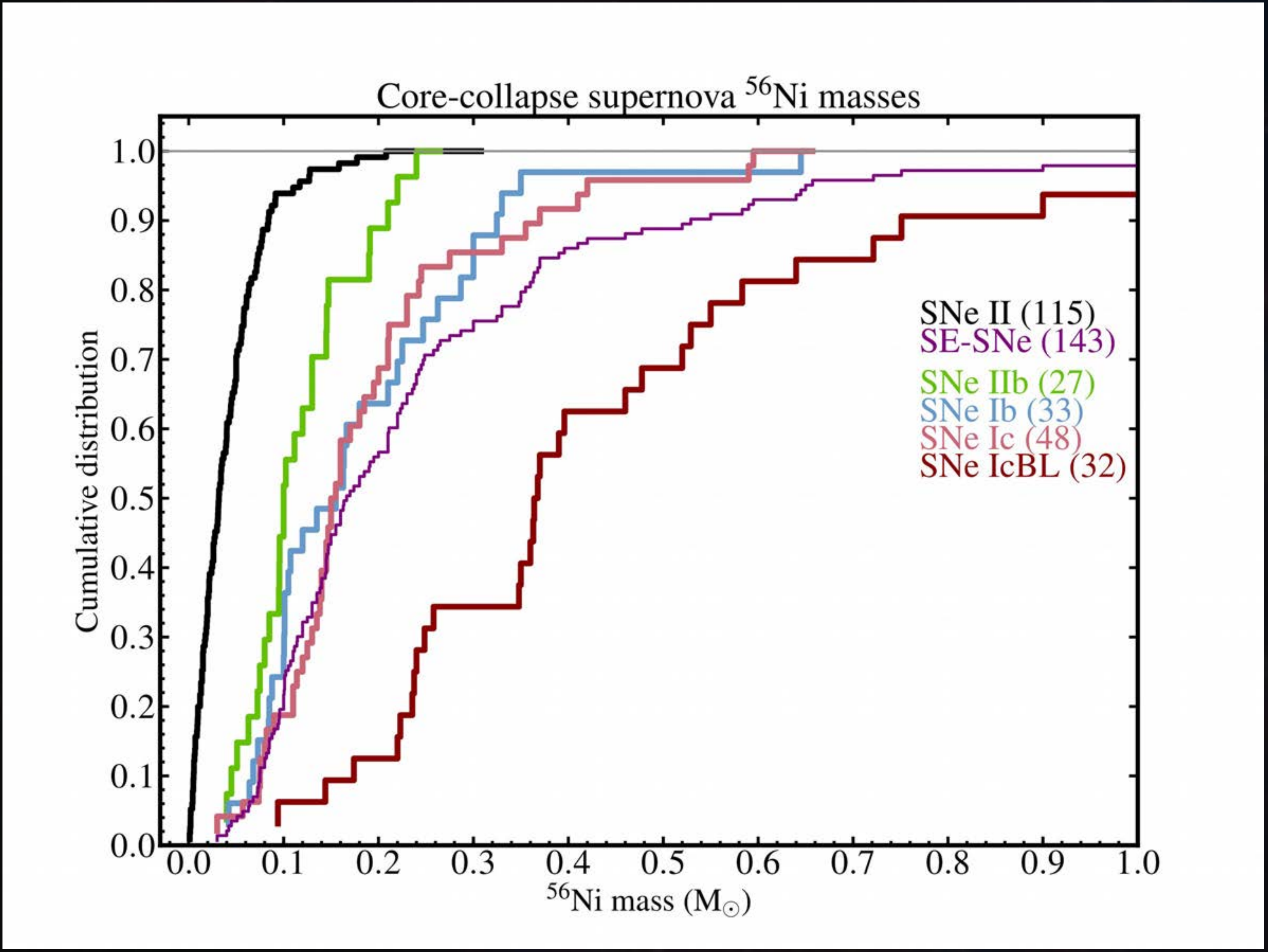
# A meta analysis of CCSN $^{56}$Ni masses

## Joe Anderson (ESO), A&A accepted




*Anderson19*

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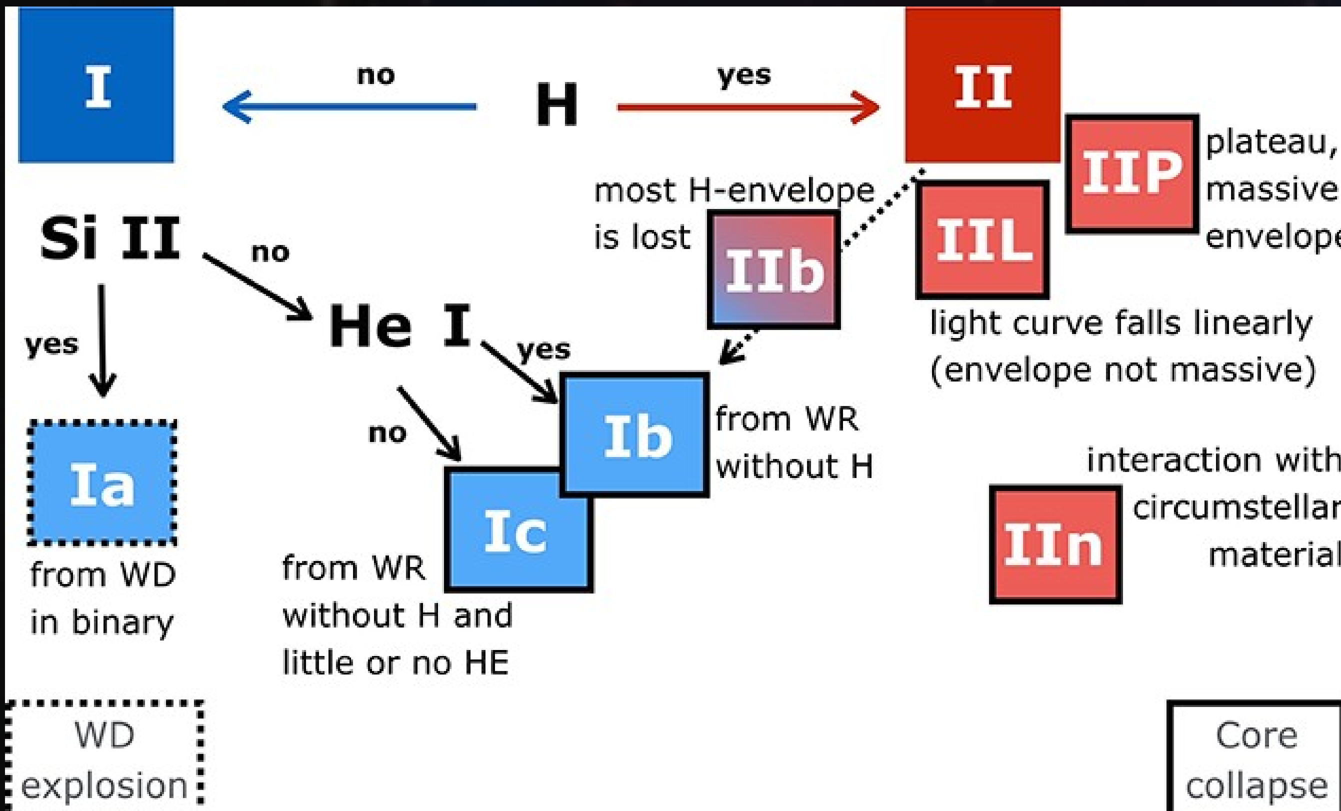
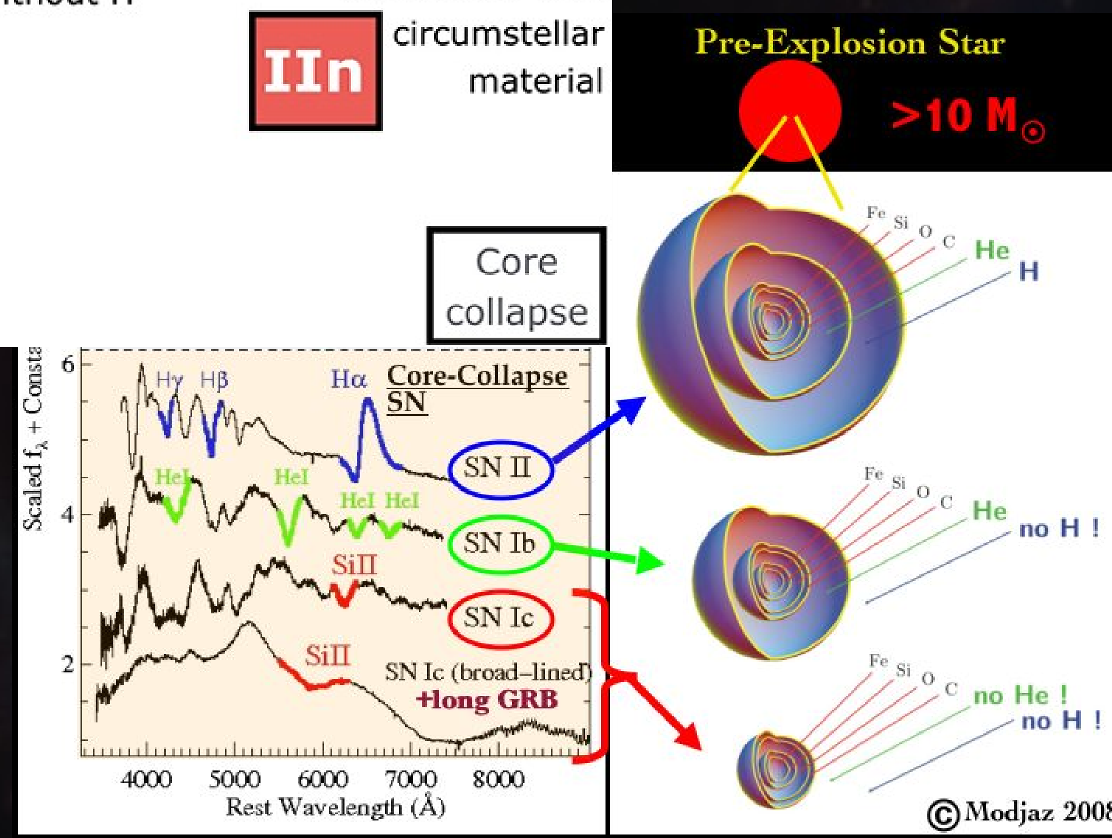
# CCSN diversity




Lamers&Levesque17



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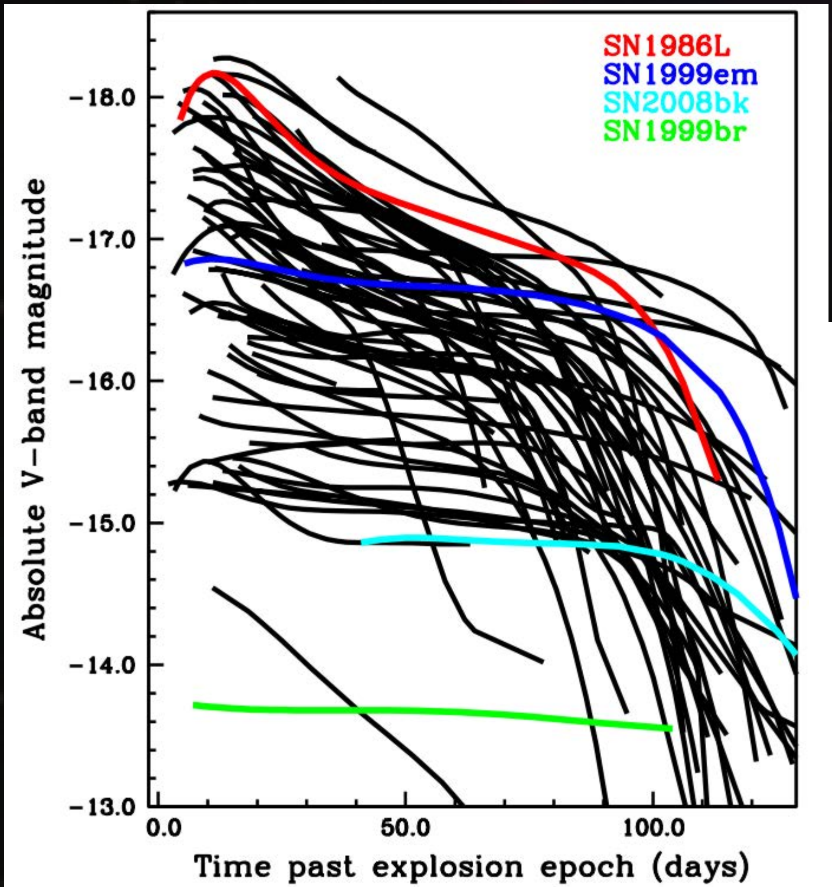
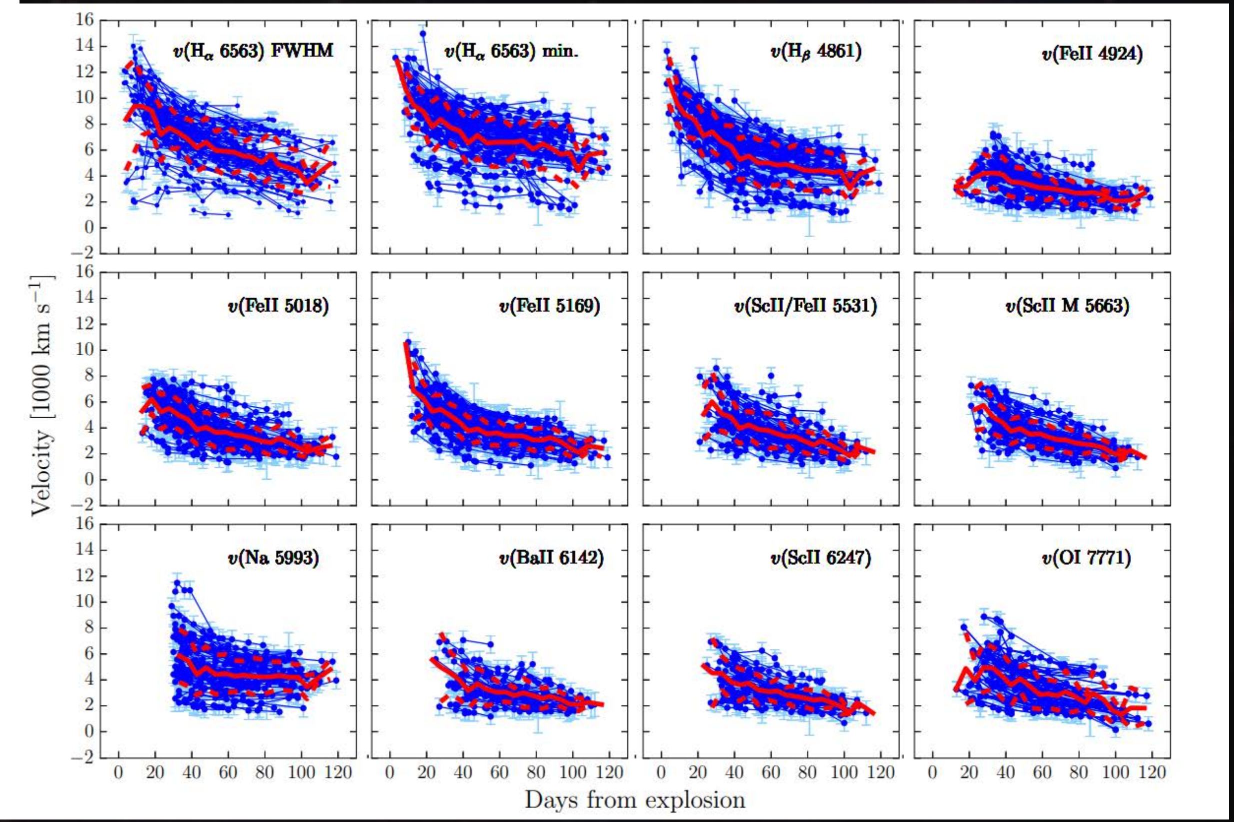
# Much diversity is observed in the core-collapse supernova family: 1) hydrogen-rich SNeII




*Anderson+14*

*Gutierrez+17*



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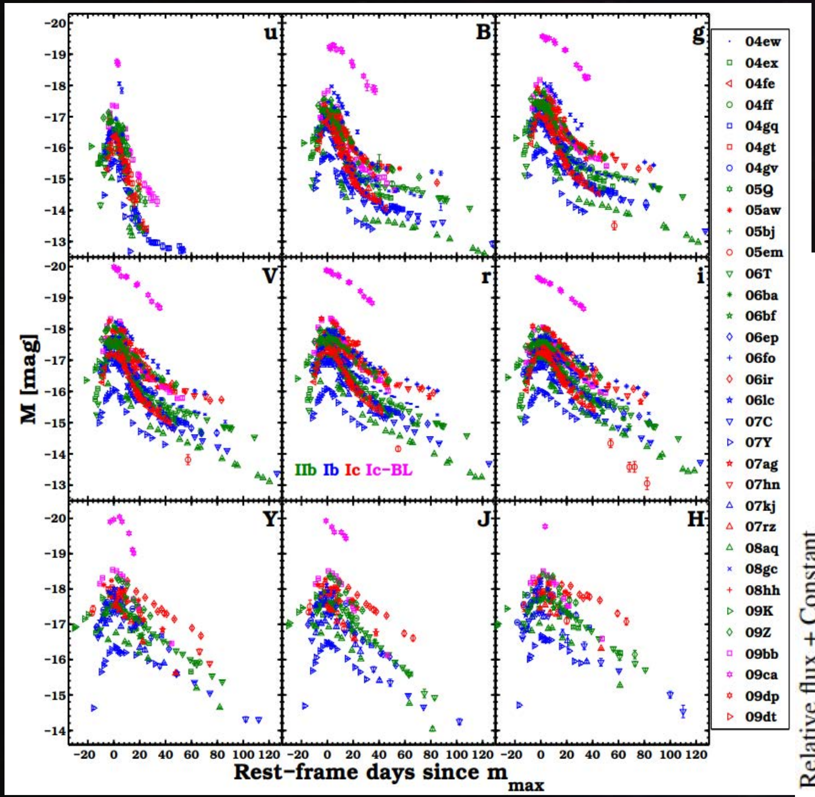
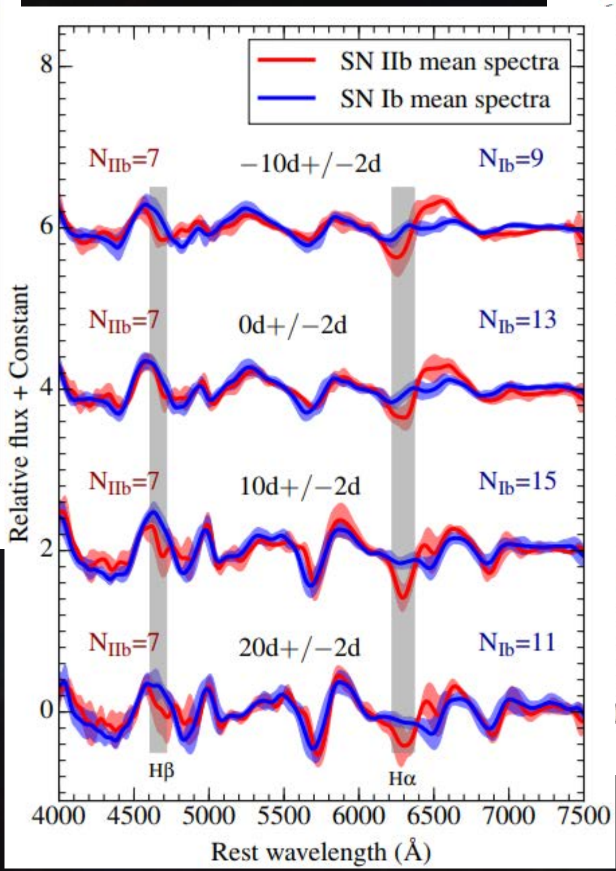
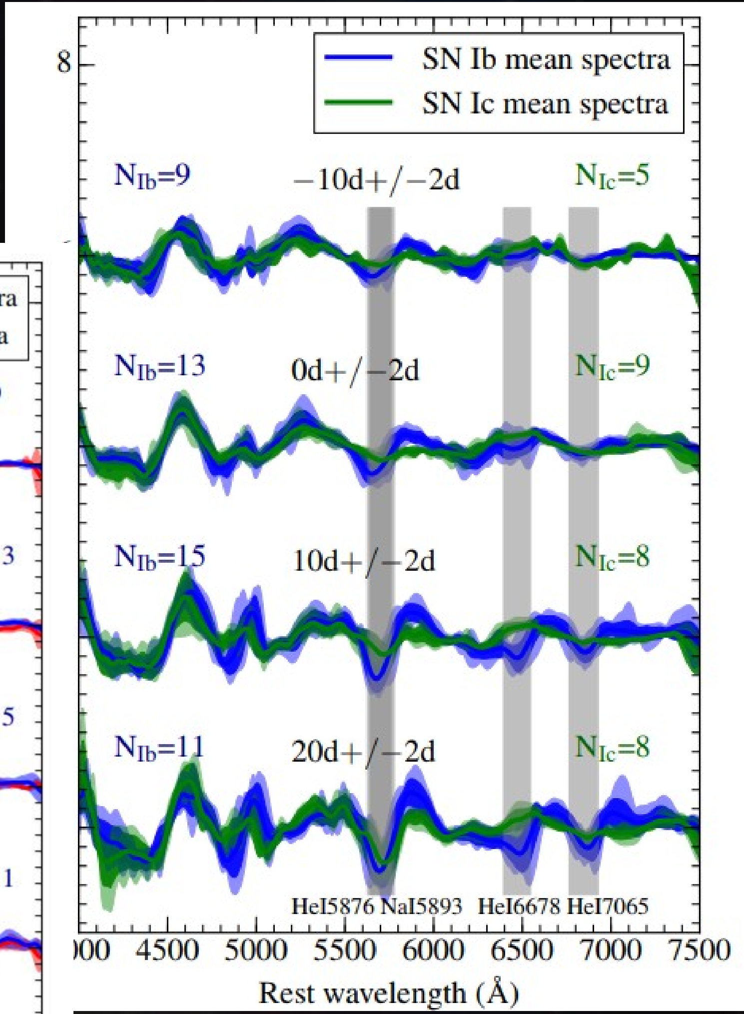
# Much diversity is observed in the core-collapse supernova family: 2) Stripped-Envelope events, SNeIIb, Ib, Ic, IcBL




Taddia+18




Liu+16

# How is this diversity is produced through different explosions of distinct progenitors following different evolutionary paths?

## Pre-SN progenitor dependent on initial conditions:

- ZAMS mass
- Presence of a close binary companion
- Progenitor metallicity
- Rotation

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- Binary mass stripping
- Steady winds
- Eruptive winds

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**Pre-SN progenitors (with some density structure) then explode:**

- Explosion energy
- $^{56}$Ni production
- Interaction with CSM

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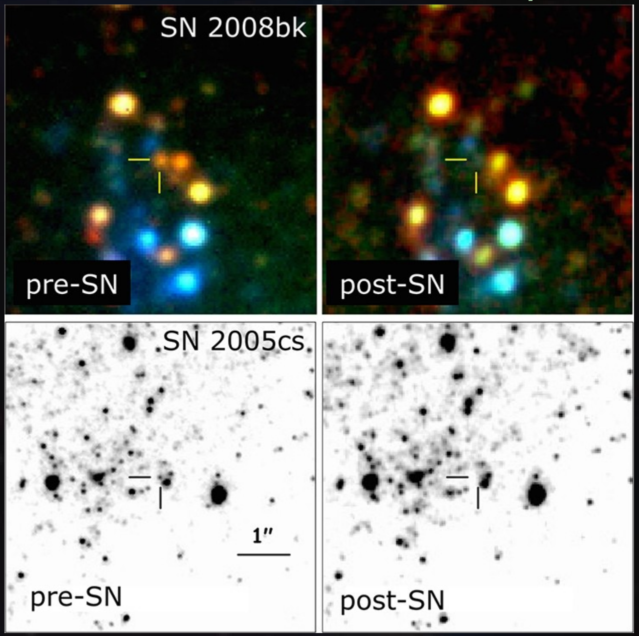
# *Our(?)* current understanding of the progenitors of CCSNe

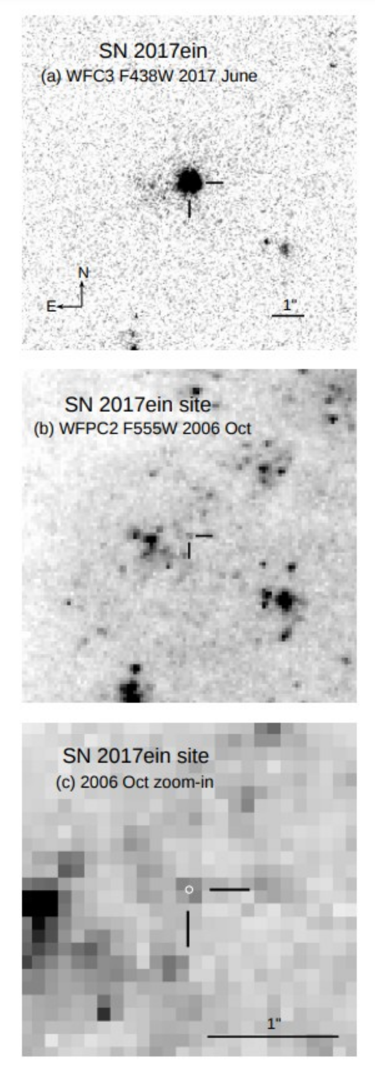
Levesque17




## Type II supernovae (SNeII)

Majority are RSGs with initial basses *between 8 and 20Msun (RSG problem?).* Evidence for dense CSM close to progenitor stars *for many (majority?)* of SNeII

van Dyk+18




## Stripped Envelope SNe (SE-SNe, IIb, Ib, Ic)

A significant fraction (if not the vast majority) arise from <20Msun binary progenitors.

*Some evidence that SNeIc arise from more massive progenitors → therefore classic WR stars.*

**Progenitor mass range very similar for SNeII and SE-SNe?**

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All literature values found through ads search:
Total of 253 CCSNe:

- 115 SNeII
- 27 SNeIIb
- 33 SNeIb
- 48 SNeIc
- 32 SNeIcBL

No preference for technique, all values complied/averaged.
Observational uncertainties:

- Bolometric corrections
- Distance
- Host Av
- Explosion epochs

**SNII = tail luminosity, SE-SNe = peak luminosity**

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# SNII $^{56}$Ni estimates

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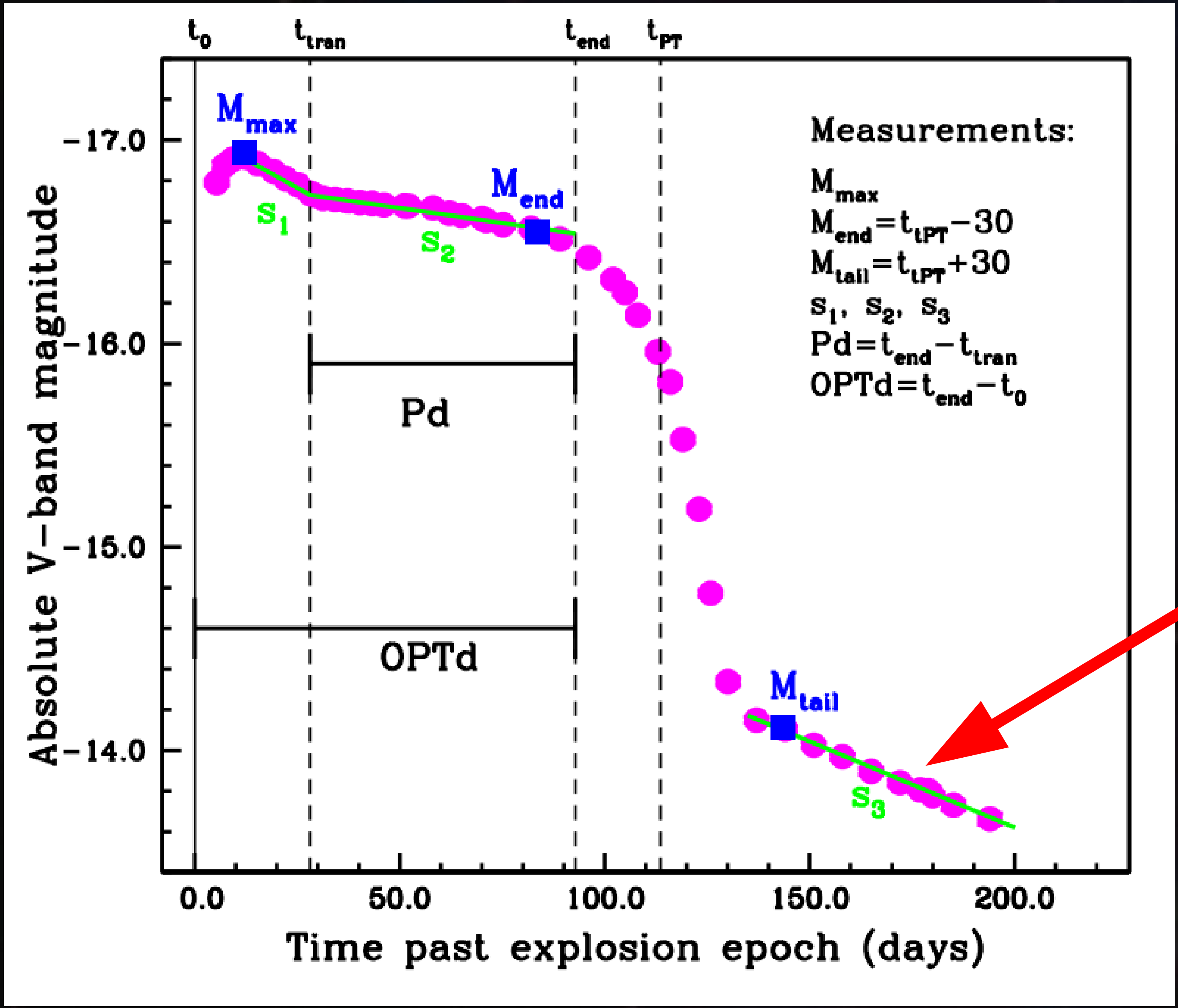


$s_3$ decline rate follows that predicted by $^{56}$Co decay in majority of SNeII → implies full trapping of gamma-rays

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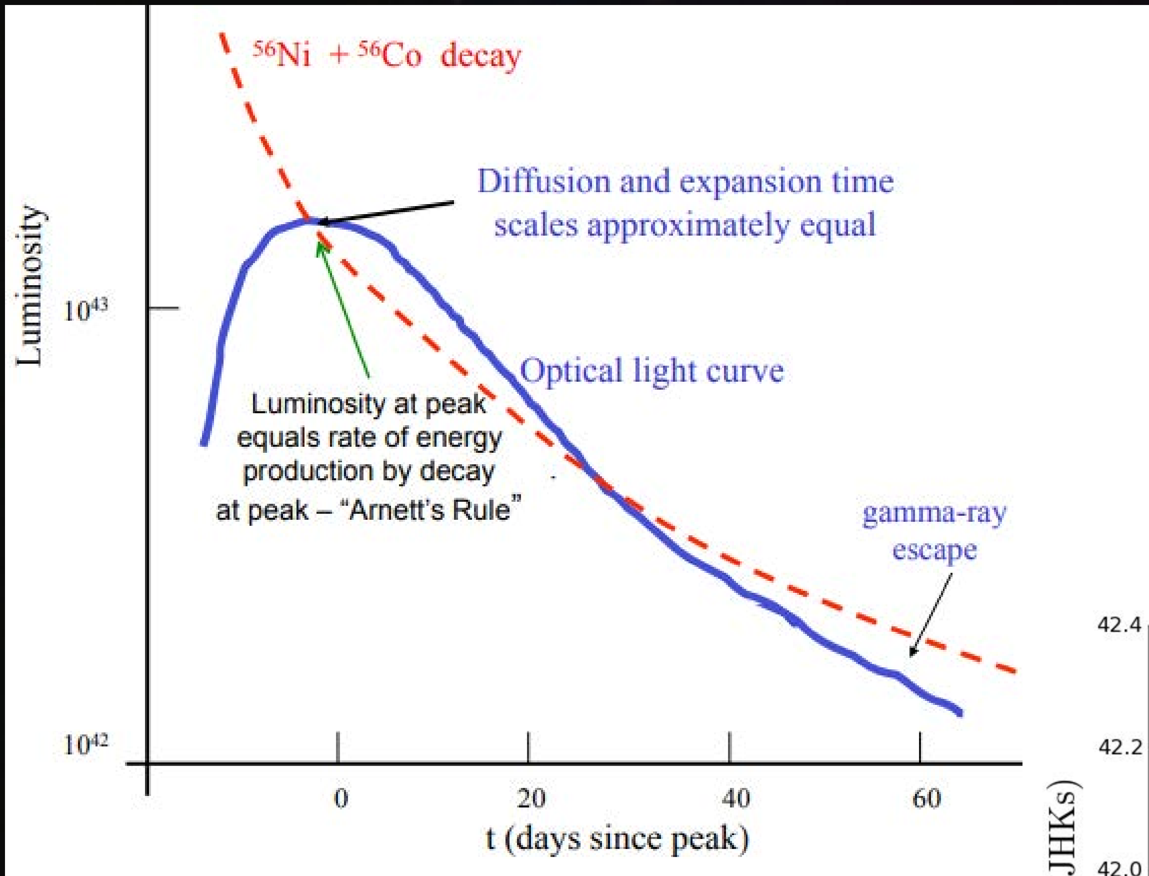
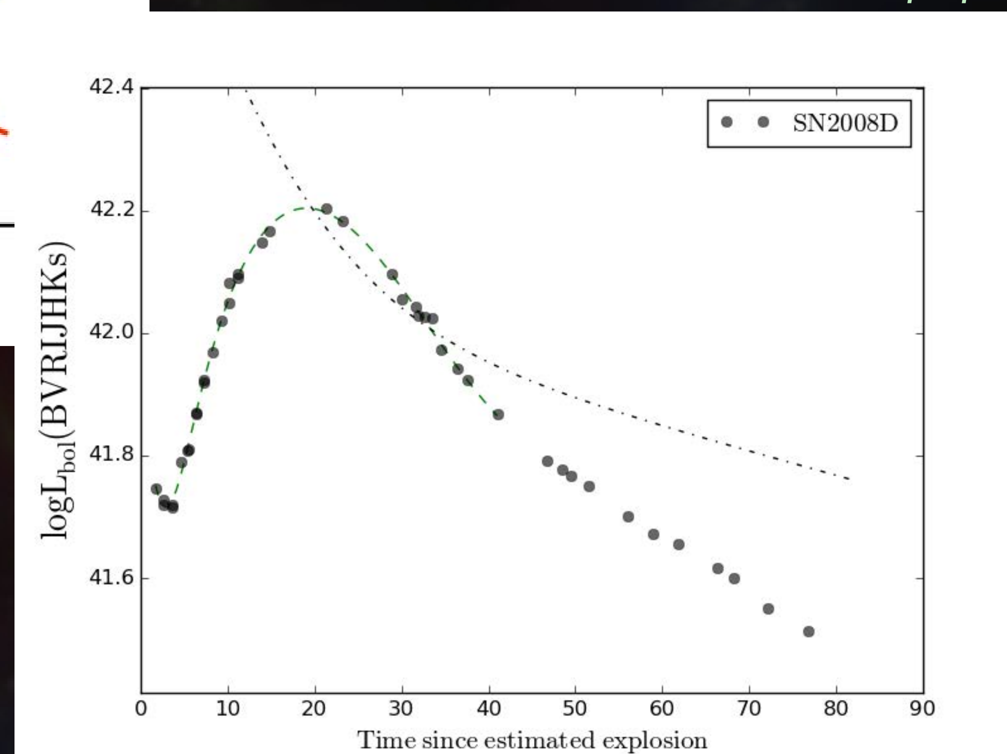
# SE-SN $^{56}$Ni estimates = **'Arnett's rule'**




*Stan Woosley*

*Meza&Anderson in prep.*



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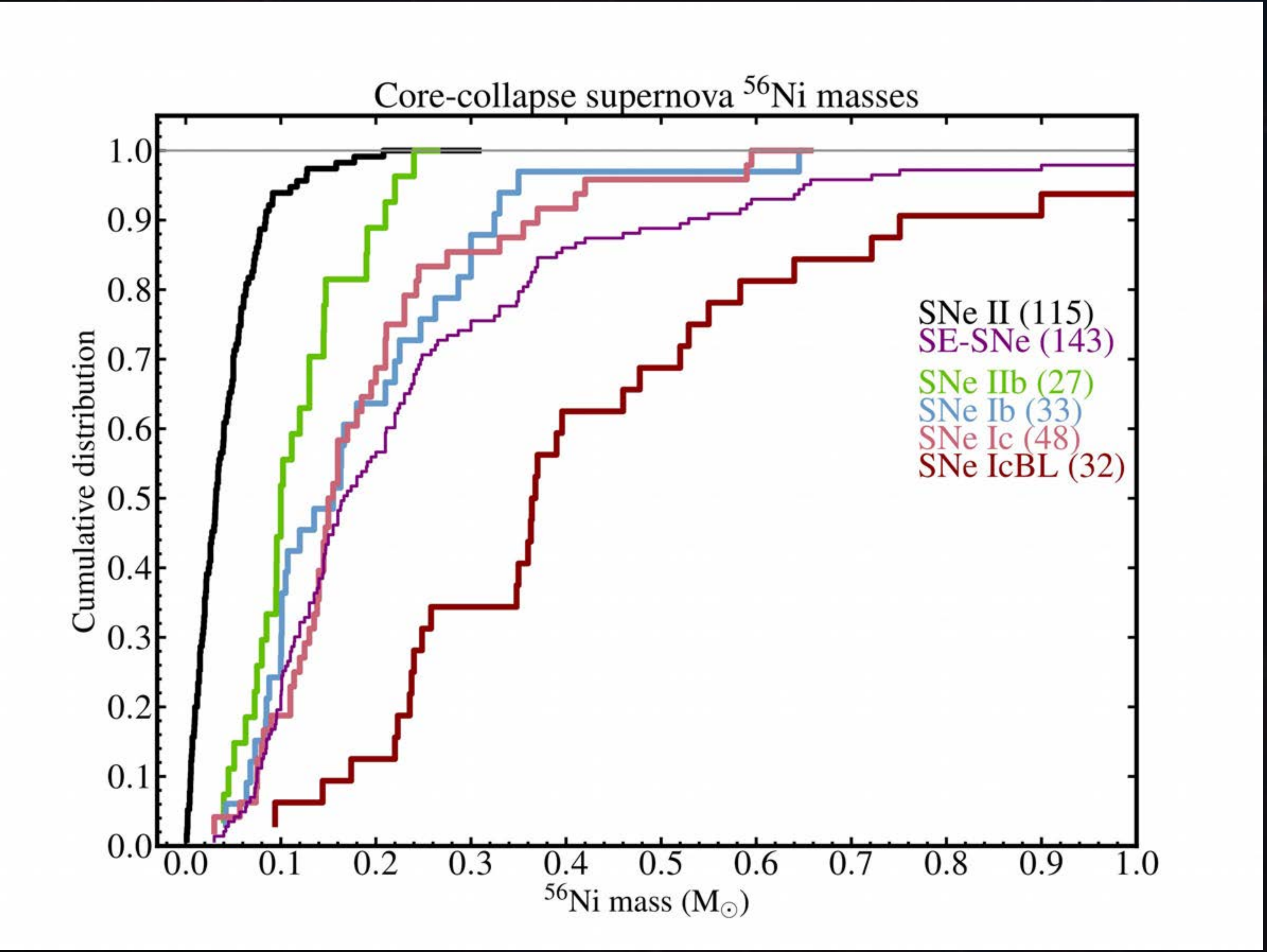
# Clear, statistically significant differences in $^{56}$Ni masses between SNeII and SE-SNe

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# Clear, statistically significant differences in $^{56}$Ni masses between SNeII and SE-SNe

- Highly significant statistical $^{56}$Ni mass differences between SNII and all other CC (SE-SN) types
- Zero SE-SN values lower than 0.03Msun, while 52 (~50%) SNII lower than such values
- SE-SNe have some very high estimated values! Highest SNII = 0.36Msun, SNIIb = 0.28Msun; **SNIb = 0.92Msun(!); SNIc = 0.84Msun; SNIcBL = 2.4Msun!!! (SNIa estimates are ~0.6Msun)**

| SN distribution (N) | Mean ($M_\odot$) | Standard deviation ($M_\odot$) | Median ($M_\odot$) | Max ($M_\odot$) | Min ($M_\odot$) |
|---|---|---|---|---|---|
| SN II (115) | 0.044 | 0.044 | 0.032 | 0.360 | 0.001 |
| SE-SN (143) | 0.293 | 0.295 | 0.184 | 2.400 | 0.030 |
| SN IIb (27) | 0.124 | 0.061 | 0.102 | 0.280 | 0.030 |
| SN Ib (33) | 0.199 | 0.146 | 0.163 | 0.920 | 0.030 |
| SN Ic (48) | 0.198 | 0.139 | 0.155 | 0.840 | 0.030 |
| SN IcBL (32) | 0.507 | 0.410 | 0.369 | 2.400 | 0.070 |

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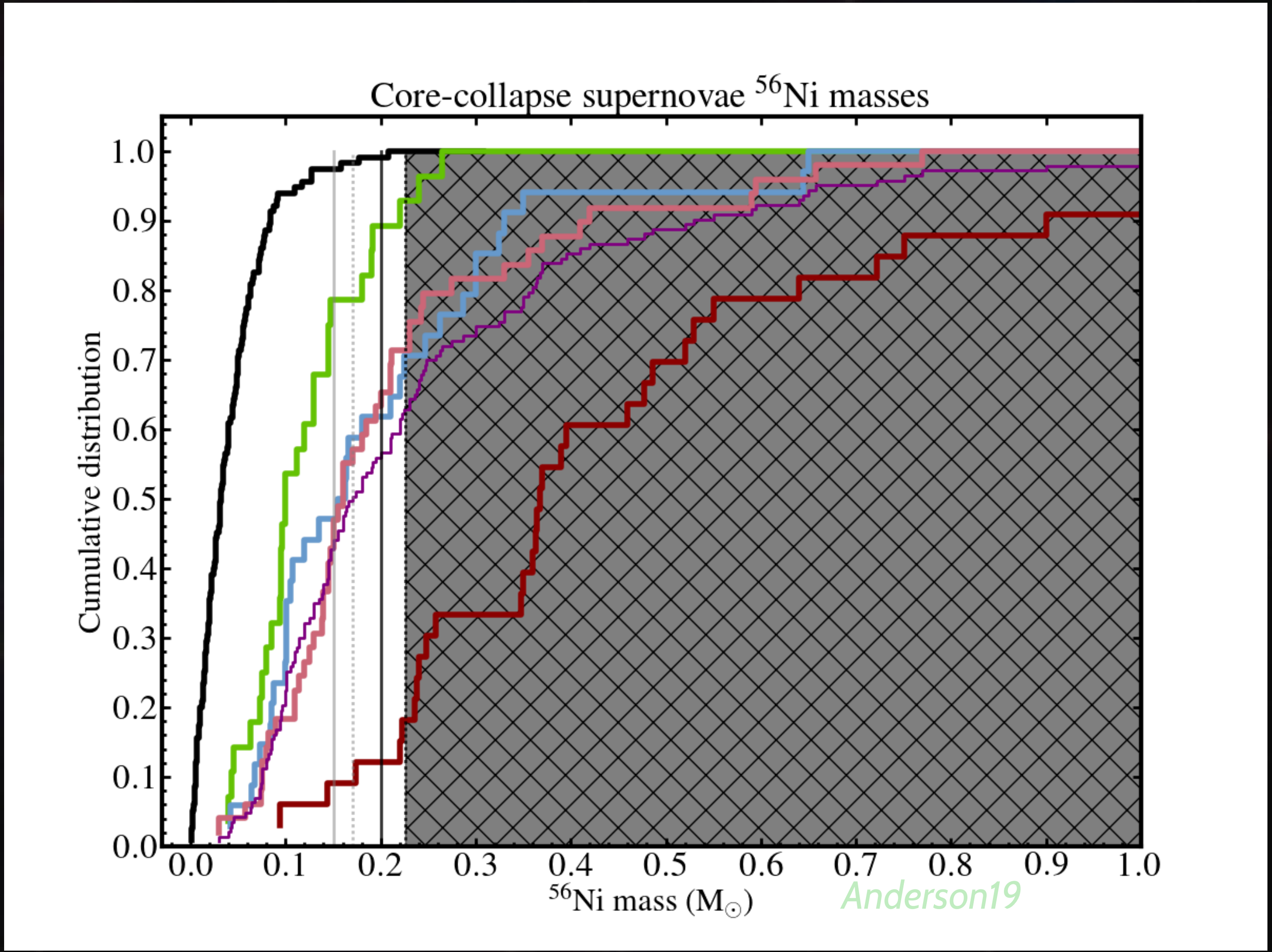
# SE-SNe have estimated $^{56}$Ni masses significantly in excess of any yields from neutrino-driven explosion models:

Ugliano+12;
Pejcha&Thompson15;
Sukhbold+16;
Suwa+19



# Differences in progenitors? Or systematic observational/modelling errors in $^{56}$Ni estimations?

If SNeII and SE-SNe arise from similar mass progenitors, then we may expect their $^{56}$Ni yields to be similar…

- $^{56}$Ni differences imply differences in core structure and explosion properties

SNII $^{56}$Ni method appears robust. Is this the case for SE-SNe?

- How accurate is Arnett's rule?
- Can observational errors explain 56Ni differences?
- Are we missing dimmest SE-SNe?

# Alternative explanations

- SE-SNe are not produced through the neutrino driven mechanism?
- $^{56}$Ni is not dominant power source at peak for SE-SNe?

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***SE-SNe do explode differently and from significantly different core structures than SNeII***

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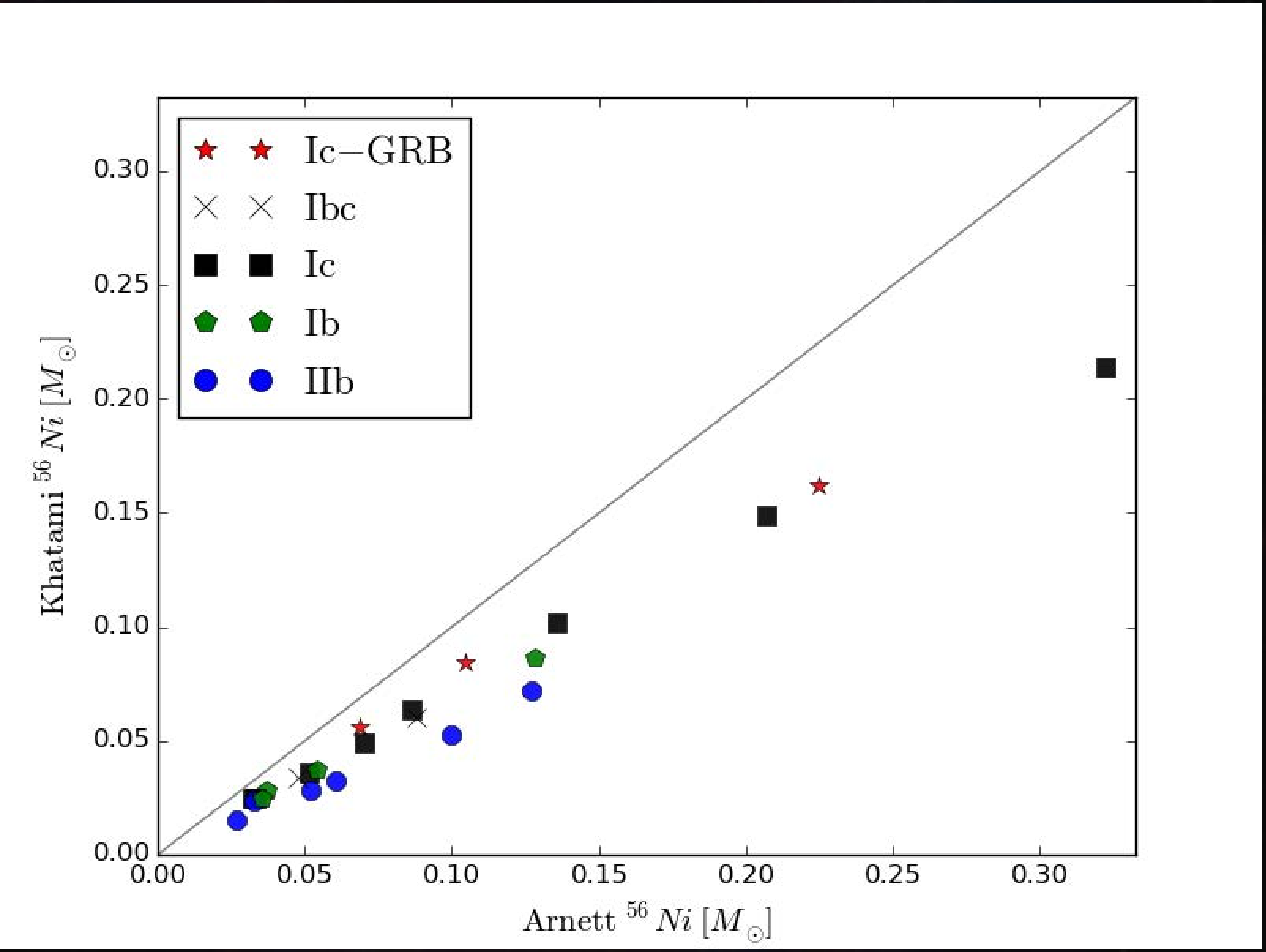
# Further analysis (Nicolas Meza)

## Khatami & Kasen (2019)




*Meza&Anderson in prep.*

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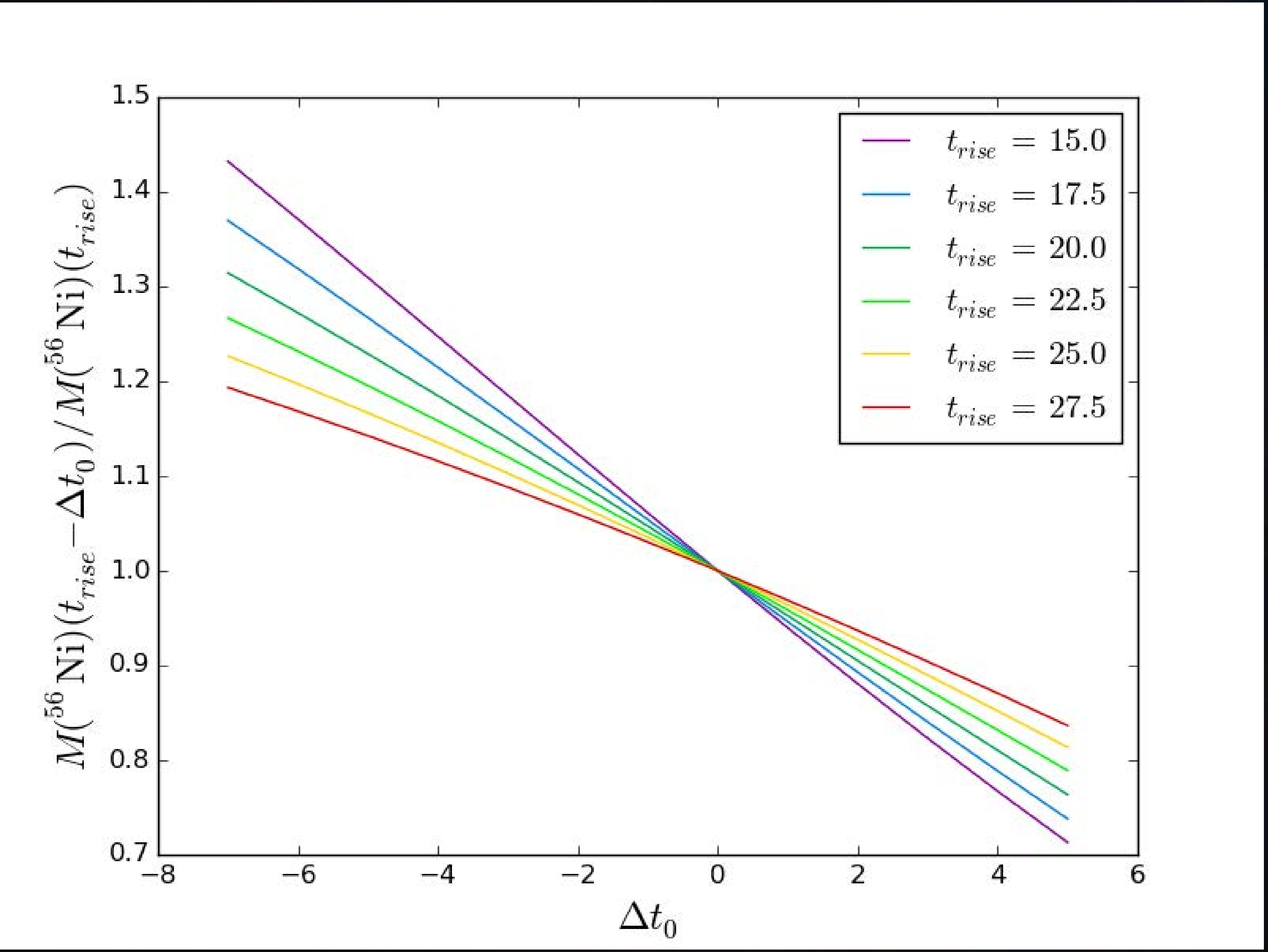
# Further analysis (Nicolas Meza)

## Dependence on rise time:

*Meza&Anderson in prep.*



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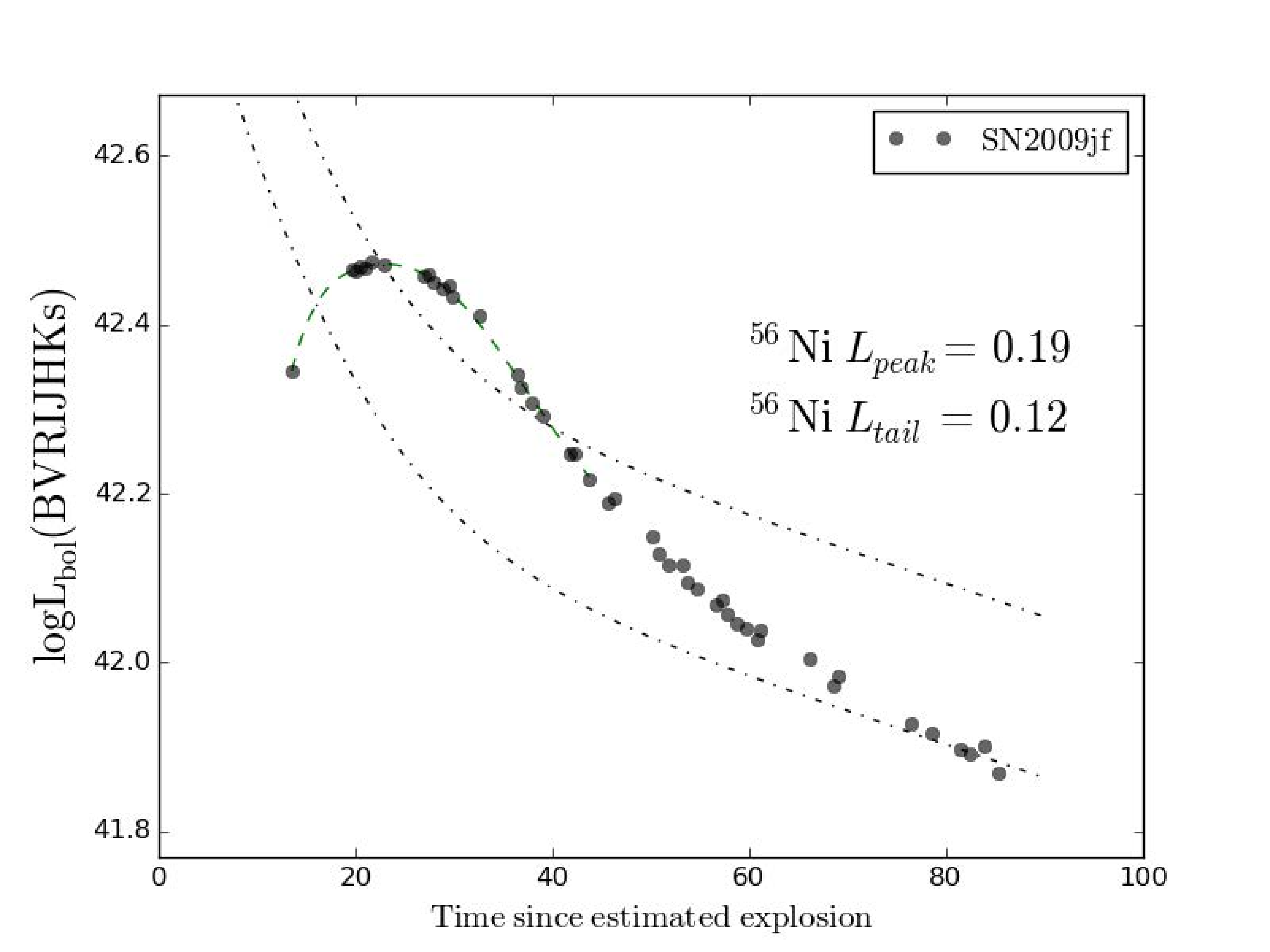
# Further analysis (Nicolas Meza)

## Difference between peak and tail




*Meza&Anderson in prep.*

# Summary

- Current consensus is that SNeII and SE-SNe arise from very similar progenitor masses
- However, clear difference between literature $^{56}$Ni masses
- SE-SN $^{56}$Ni masses much larger than those predicted by neutrino-driven explosion models

  - Progenitors and explosions of SE-SNe are significantly different from SNeII?
  - $^{56}$Ni masses for SE-SNe are significantly in error?

# Specific $^{56}$Ni values

**SN1987A = 0.072Msun** (much higher than median SNII, 87A-like all have large values).

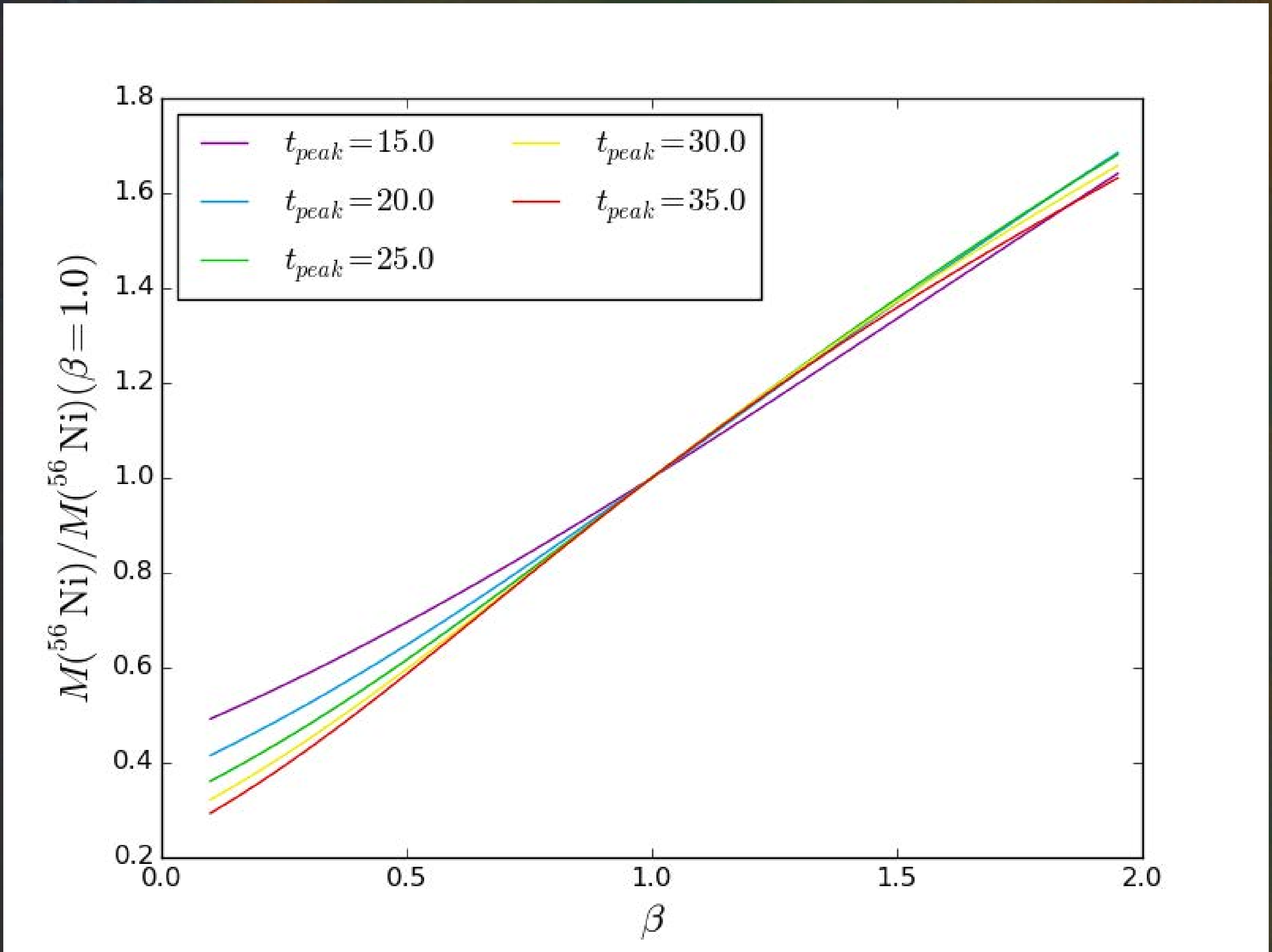
SN1999em = 0.044
SN2005cs = 0.004
SN2013ej = 0.018

SN1993J = 0.112
SN2016gkg = 0.085

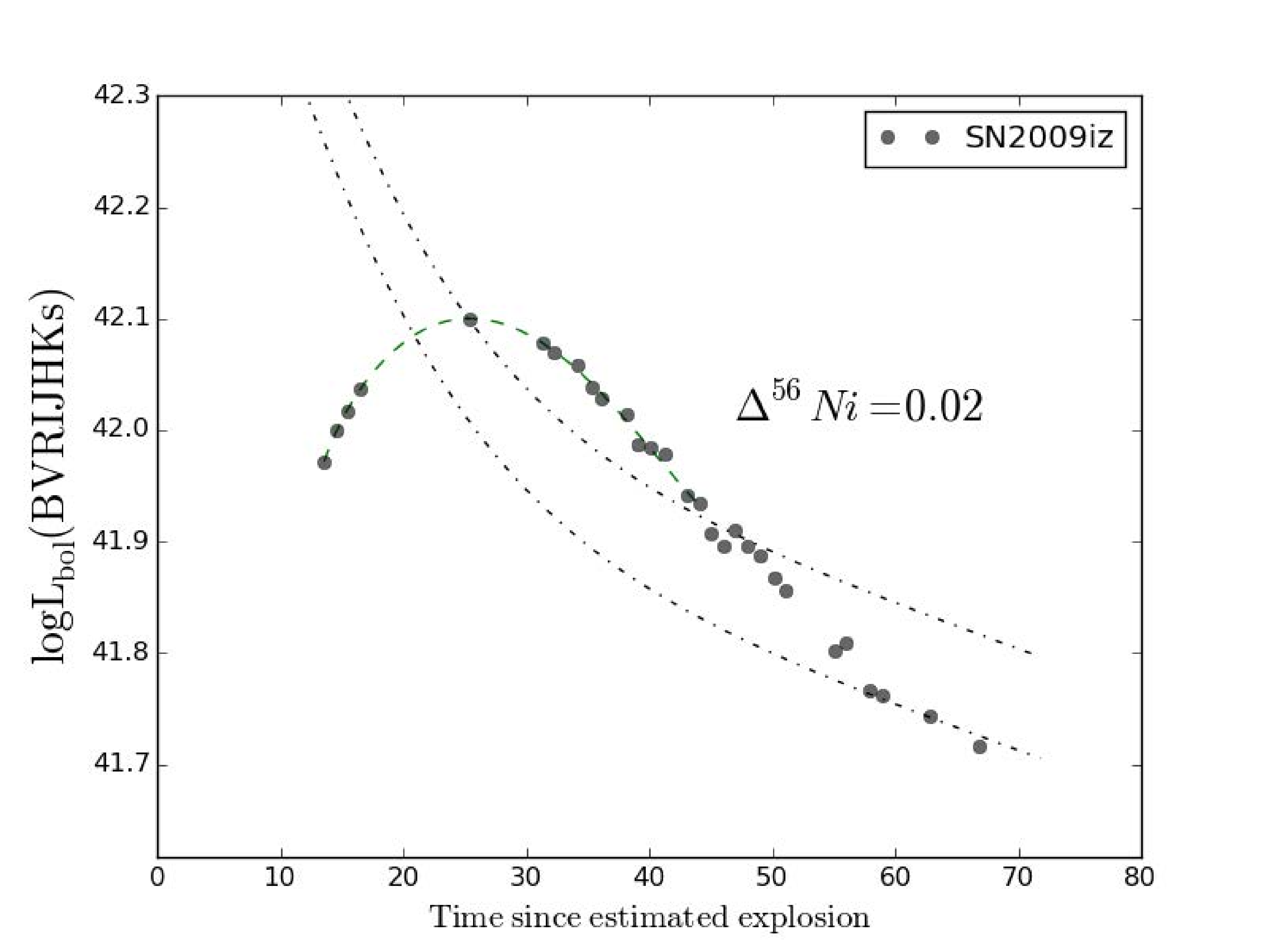
SN1984L = 0.645
SN2008D = 0.088
iPTF13bvn = 0.073

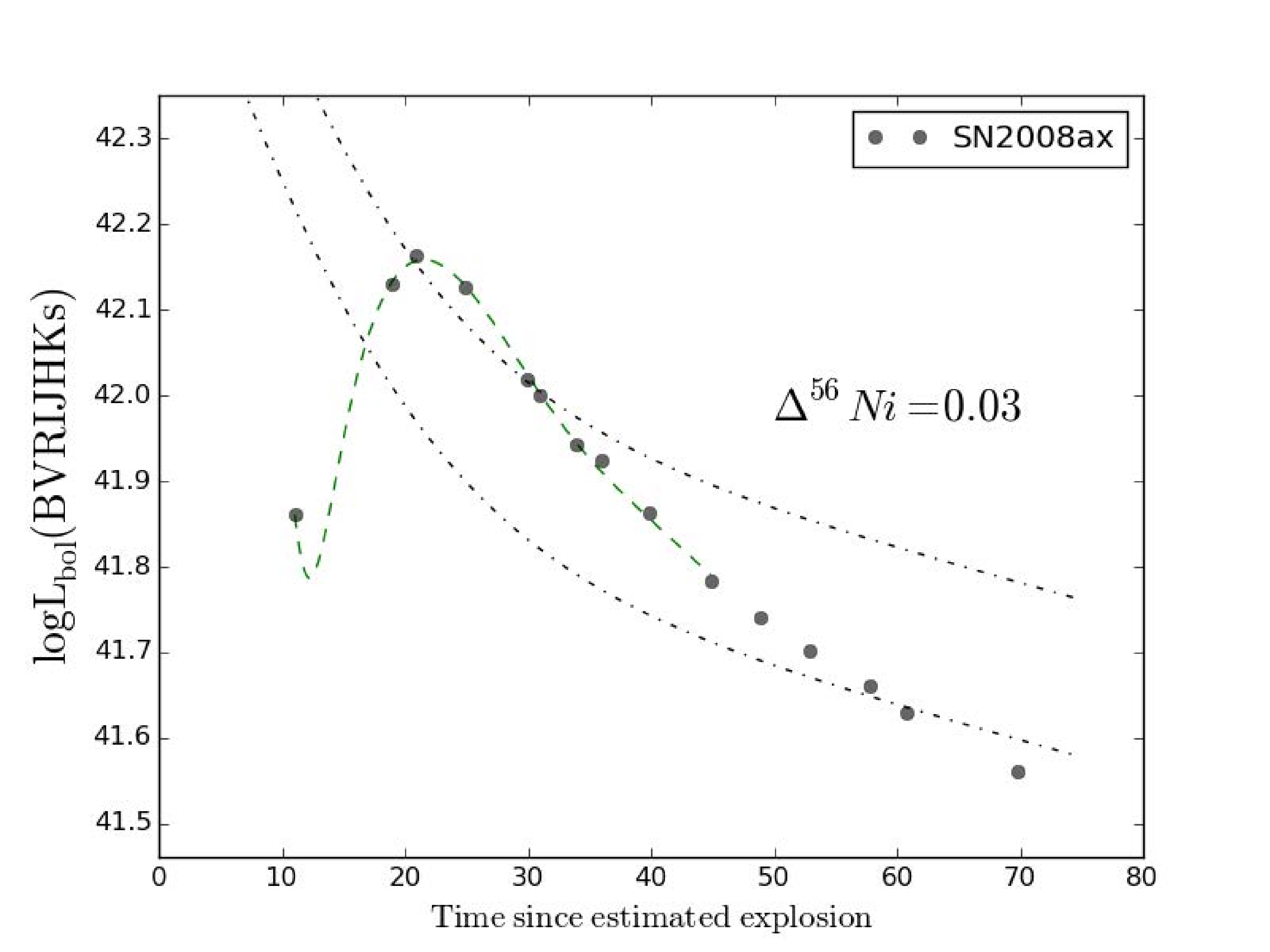
SN1994I = 0.075
SN2011bm = 0.657

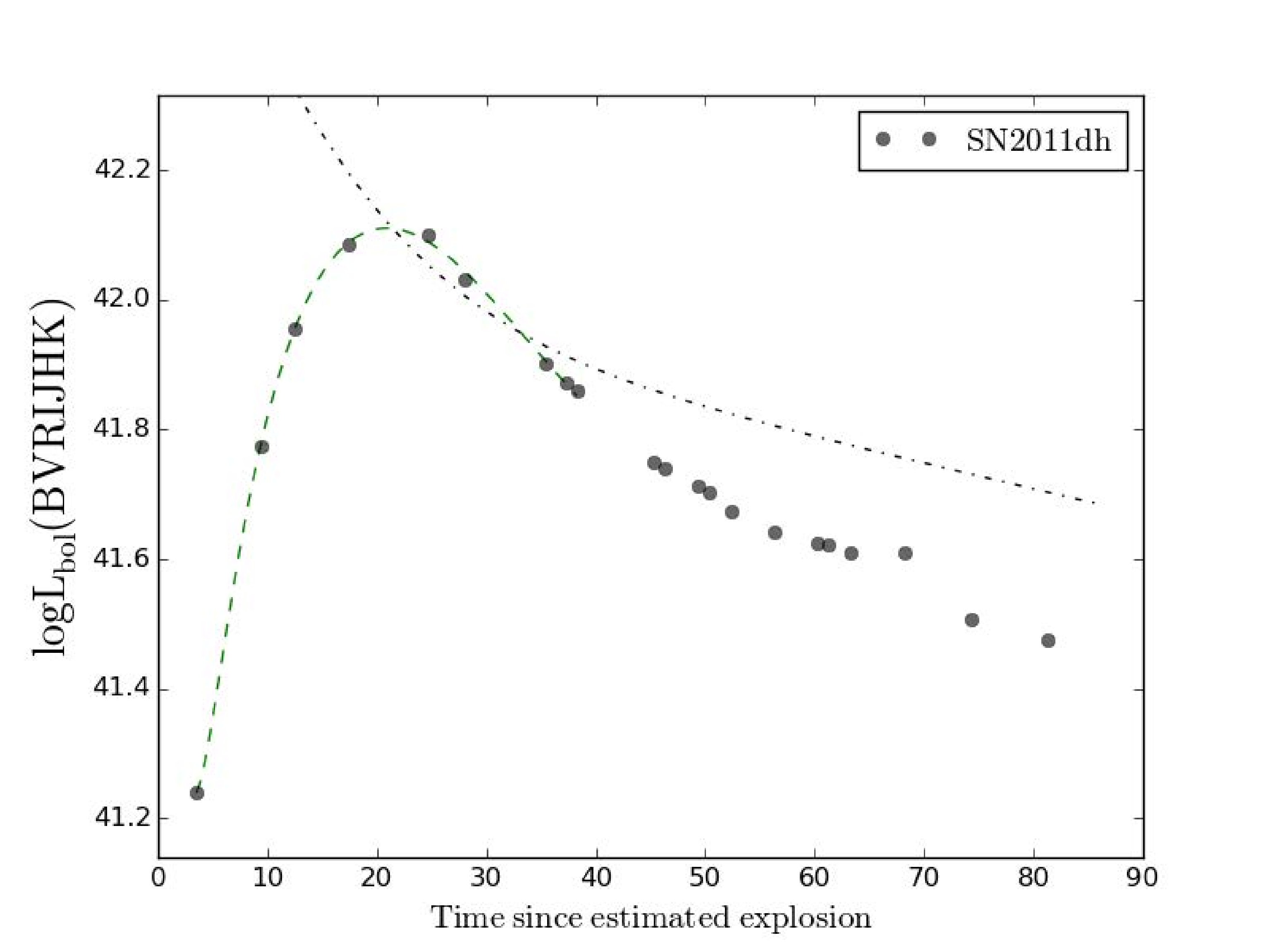
SN1998bw = 0.583

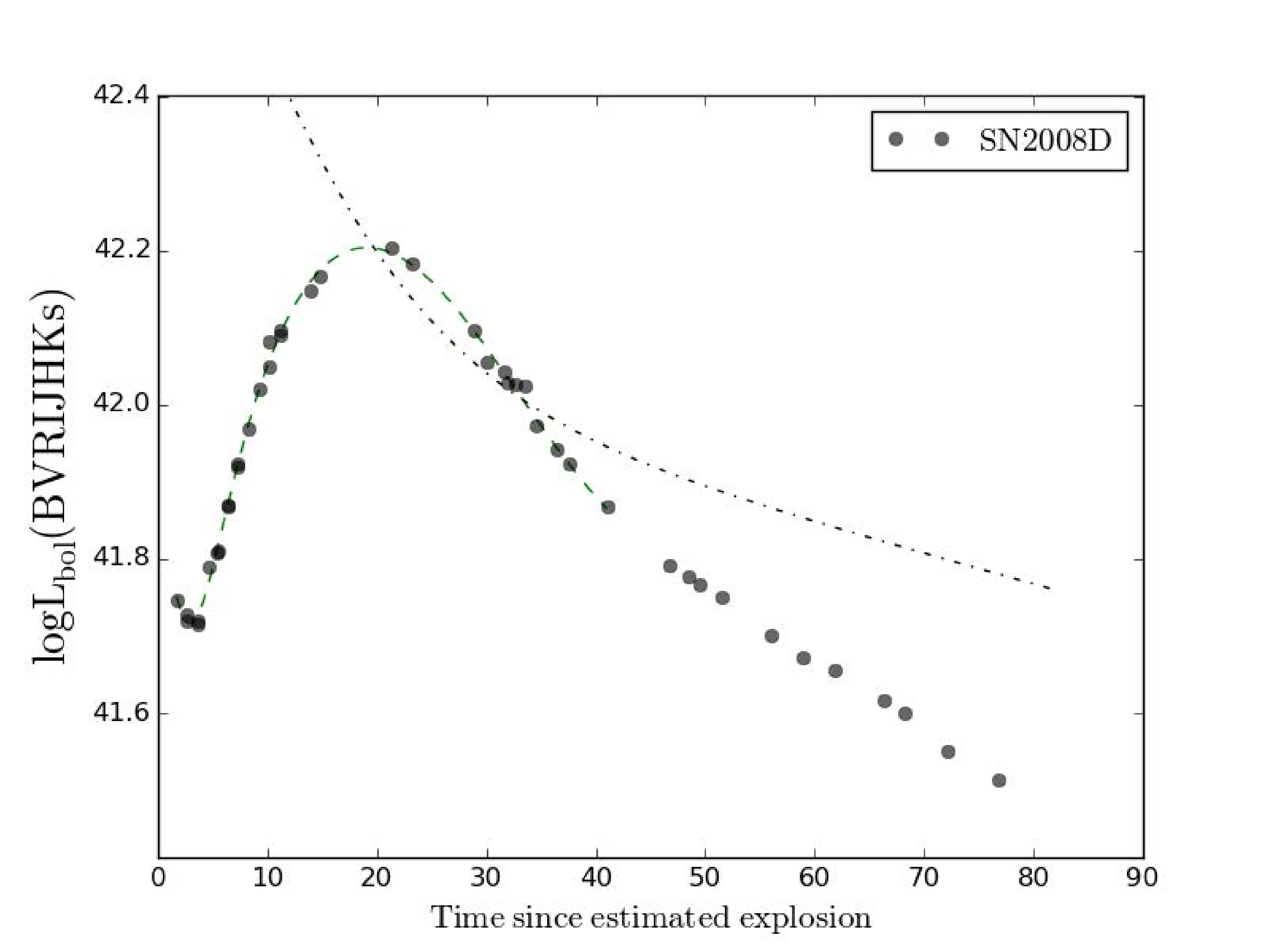


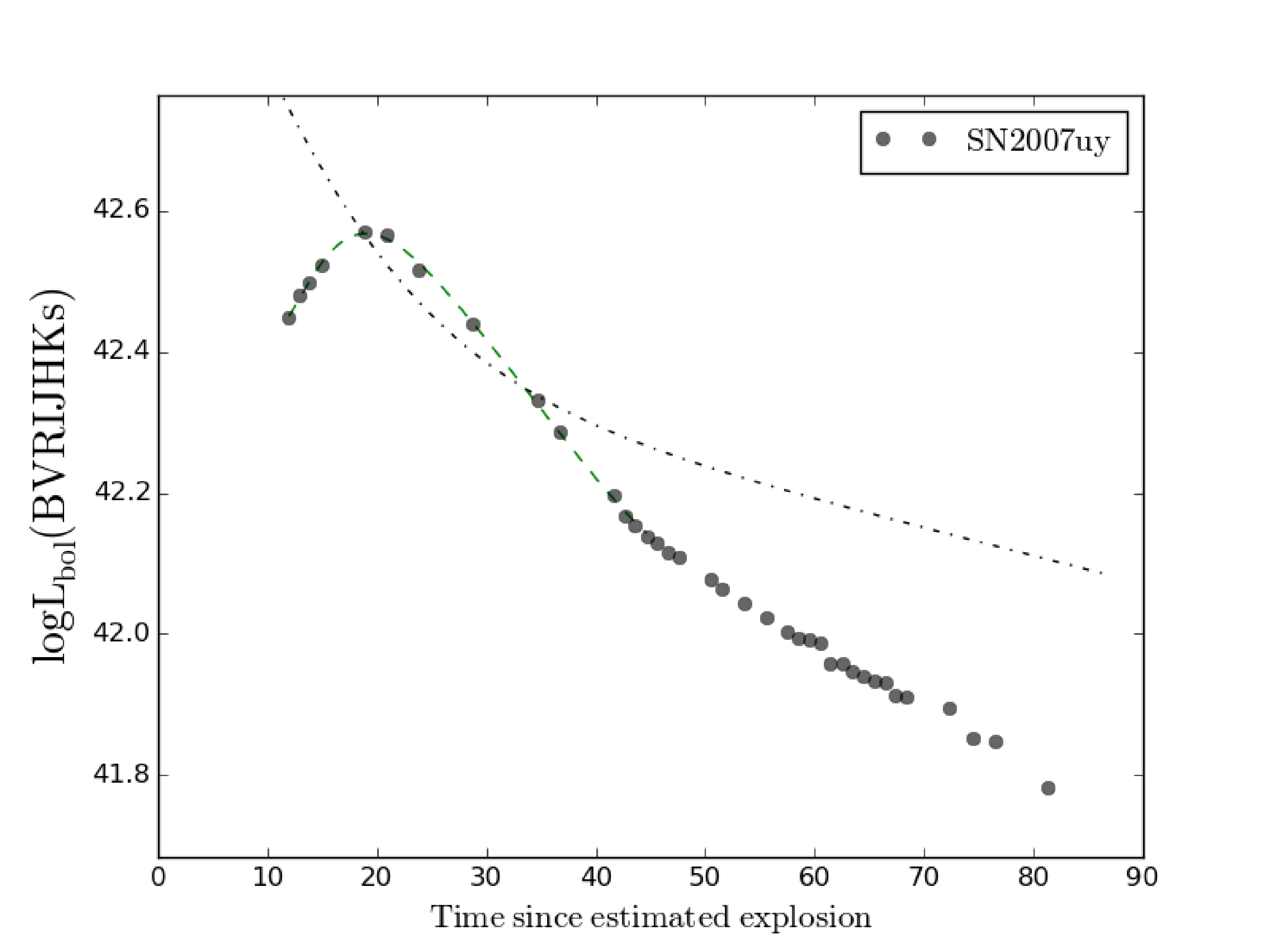
$t_{peak}=15.0$
$t_{peak}=20.0$
$t_{peak}=25.0$
$t_{peak}=30.0$
$t_{peak}=35.0$
$M(^{56}\mathrm{Ni})/M(^{56}\mathrm{Ni})(\beta=1.0)$
$\beta$
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
0.0
0.5
1.0
1.5
2.0


SN2009iz
$\Delta^{56}Ni = 0.02$
$\log L_{bol}$(BVRIJHKs)
Time since estimated explosion
42.3
42.2
42.1
42.0
41.9
41.8
41.7
0
10
20
30
40
50
60
70
80


SN2008ax
$\Delta^{56} Ni = 0.03$
$\log L_{bol}(BVRIJHKs)$
Time since estimated explosion
42.3
42.2
42.1
42.0
41.9
41.8
41.7
41.6
41.5
0
10
20
30
40
50
60
70
80


SN2011dh
$\log L_{bol}$(BVRIJHK)
Time since estimated explosion
42.2
42.0
41.8
41.6
41.4
41.2
0
10
20
30
40
50
60
70
80
90


SN2008D
42.4
42.2
42.0
41.8
41.6
$\log L_{bol}(BVRIJHKs)$
0
10
20
30
40
50
60
70
80
90
Time since estimated explosion


SN2007uy
$\log L_{bol}$(BVRIJHKs)
42.6
42.4
42.2
42.0
41.8
0
10
20
30
40
50
60
70
80
90
Time since estimated explosion