SNe Ia Progenitors and Explosion Mechanisms

NOVEMBER 5-9, 2018

THE LESS MASSIVE STARS AND THERMONUCLEAR SUPERNOVAE

1. Introduction to various progenitor and explosion scenarios.
2. Diagnostics from the data within the first few days.

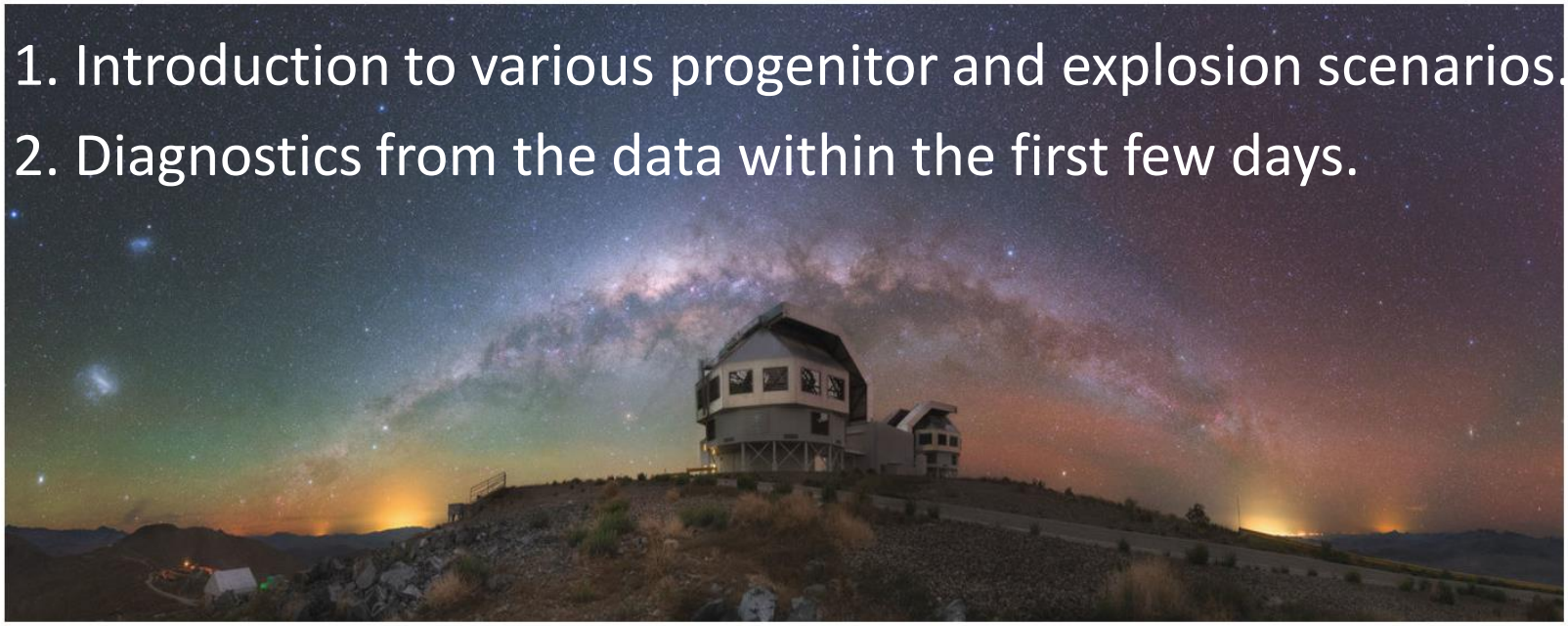

Photo by Yuri Beletsky

Keiichi Maeda, Kyoto University

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SODIUM ABSORPTION SYSTEMS TOWARD SN Ia 2014J ORIGINATE ON INTERSTELLAR SCALES*

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2	2016ApJ...816...57M Maeda, K.; Tajitsu, A.; Kawabata, K. S.; Foley, R. J.; Honda, S.; Moritani, Y.;	1.000	01/2016	Sodium Absorption Systems to

SN Ia: Thermonuclear explosion of a white dwarf

- Supported by degenerate pressure.

  → Thermonuclear runaway.

- Initiated by $^{12}C+^{12}C \rightarrow ^{24}Mg$ (carbon burning).
  - Gravitational contraction or External compression.
  - **A massive WD (near the Chandrasekhar limit?).**
- Temperature increase by runaway⇒**Fe-peak.**
  - No compact remnant (whole disruption) (in general?).
  - $2 \times ^{12}C + 2 \times ^{16}O \rightarrow ^{56}Ni$.
    - 2×10^{51}erg / Ni $1M_{\odot}$.
  - Nuclear>Gravity **⇒ Explosion energy ~ 10^{51} erg.**

Single Degenerate (SD)

C+O WD + MS/RG

C+O WD + He star

Chandrasekhar WD + MS/RG

- Delayed Detonation
(C burn deep inside WD)
- Failed/Weak Deflagration
(only deflagration, no detonation)
- etc (e.g., pulsational detonation)

Sub-Ch. WD + He star

- Double Detonation
(He flash on the surface of WD)

Ch. WD + He star

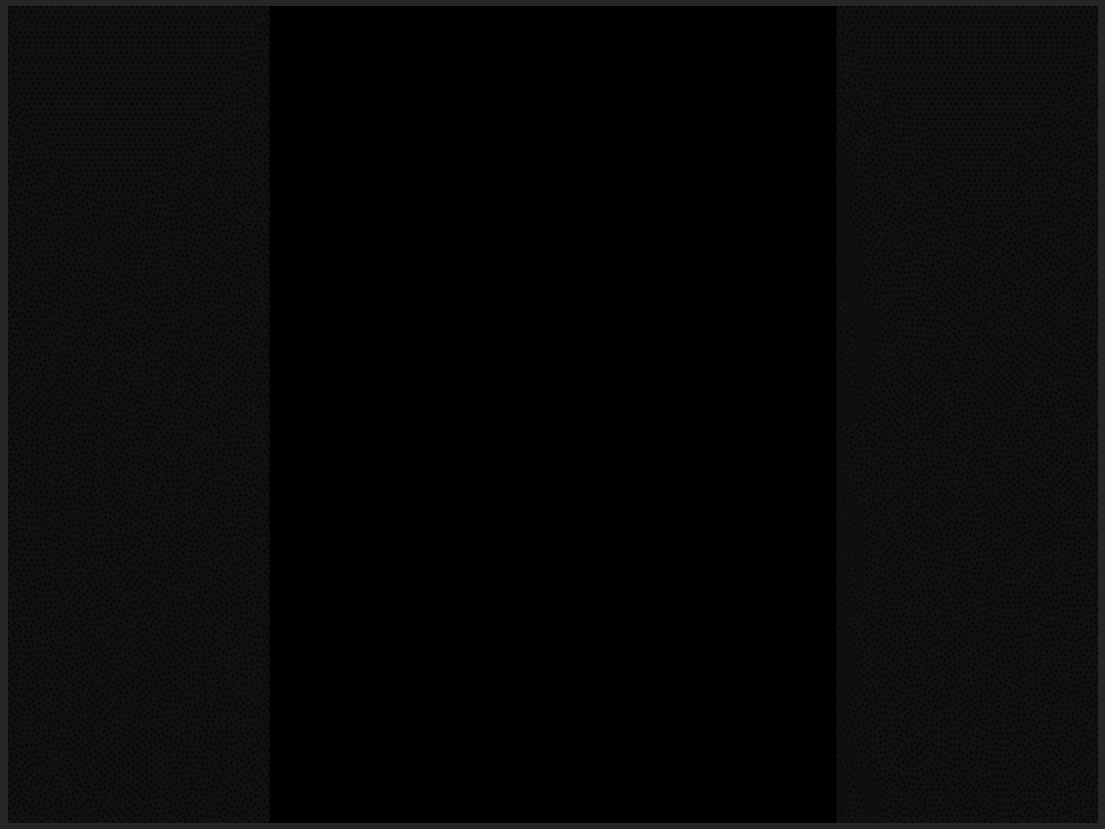
- Delayed Detonation
- Failed/Weak Deflagration

"Delayed" (e.g., spin-up/down)

Ch. WD + He WD

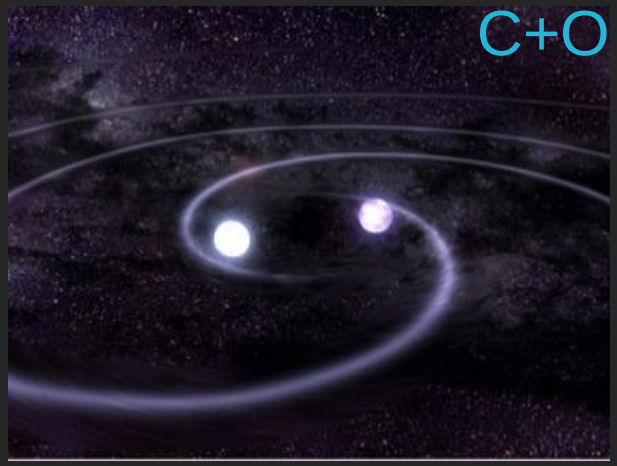
- Delayed Detonation
- Failed/Weak Deflagration
- etc.

Example of “Chandrasekhar WD” model



Ignition deep inside the Chandrasekhar mass WD (delayed detonation model: KM+ 2010).

Double Degenerate (DD)



C+O WD + C+O WD

Explosion at merging
- Violent merger
(C burn on the surface of WD)

"Survive"
Viscous/Thermal evolution
(100 secs to 1000 yrs)

C+O WD + He WD

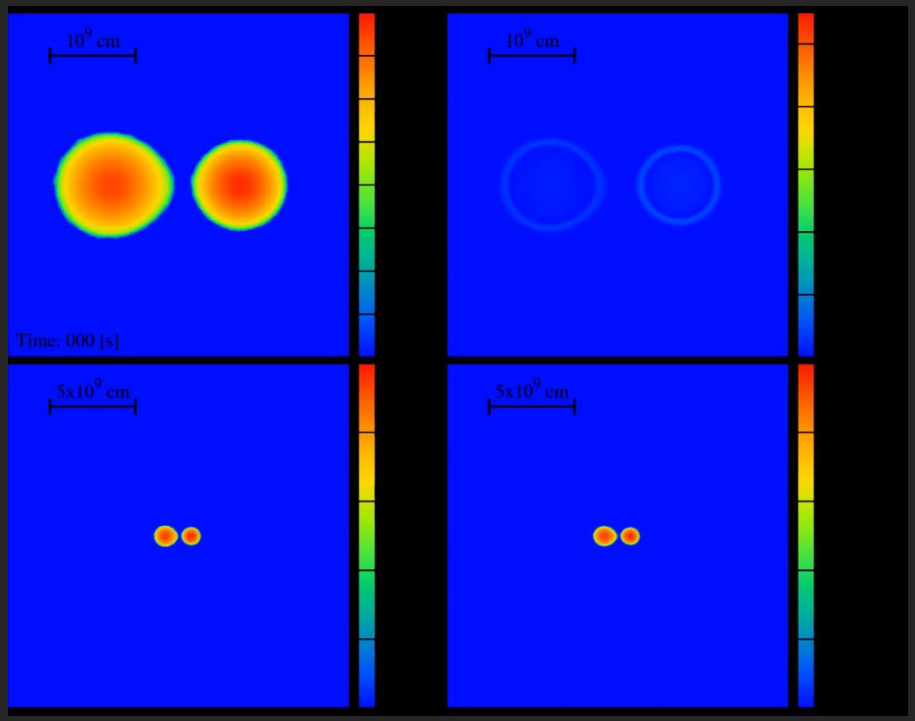
Sub-Ch. WD + He WD
- Double Detonation
(He flash on the surface of WD)

ONe WD←envelope/disk
- No SN explosion (NS formation)

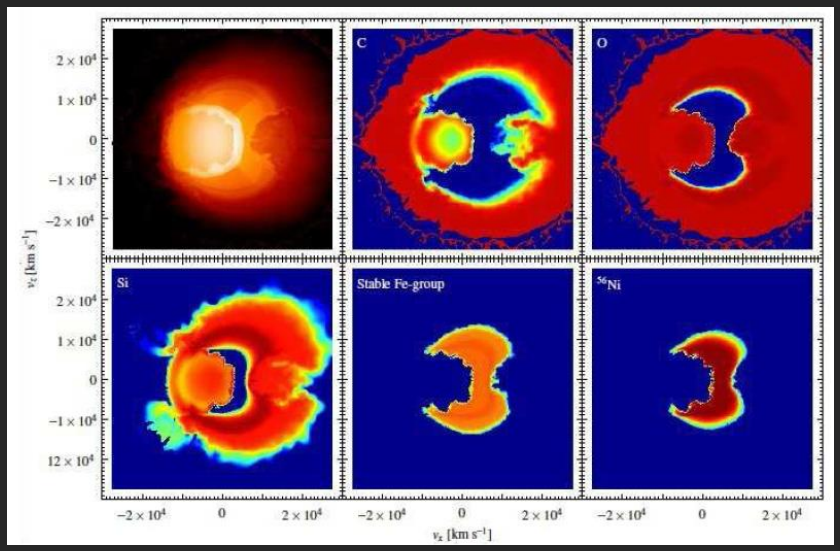
Ch. C+O WD←envelope/disk
- Delayed Detonation?
- Failed/Weak Deflagration?

(Theories predict ONe WD, not SN: Saio, Yoon, Shen, …)

Example of “External compression-driven”



Sub-Chandra WD +
Sub-Chandra WD



WD-WD merger
(Tanikawa+ 15)

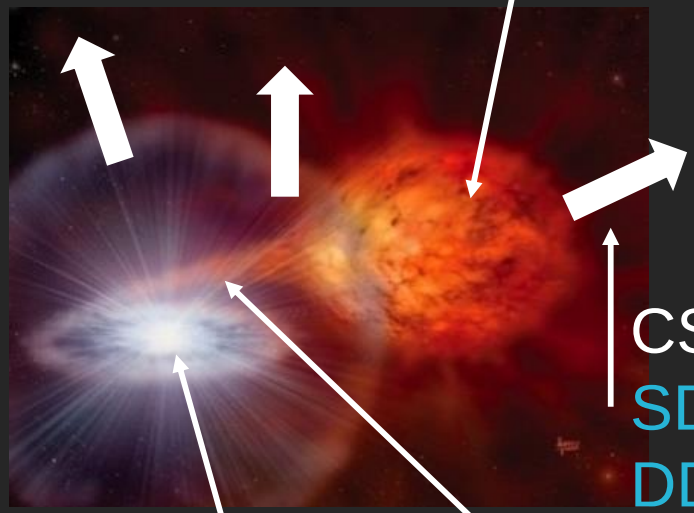
Ignition near the surface
(Roepke+ 12)

SN Ia Progenitors – which or something else?

Leftover

SD: MS/RG/He companion

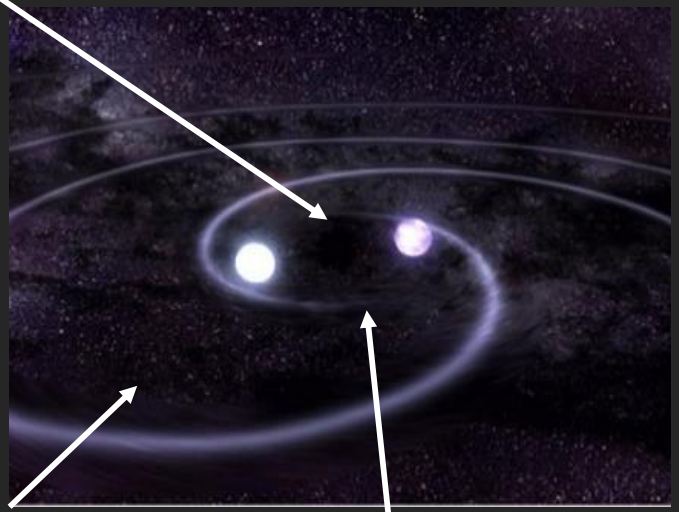
DD: nothing



CSM

SD: dirty

DD: clean



Explosion

SD: Central C-ignition, Surface He detonation

DD: (Delayed) Central C-ignition, Merger-induced C/He ignition

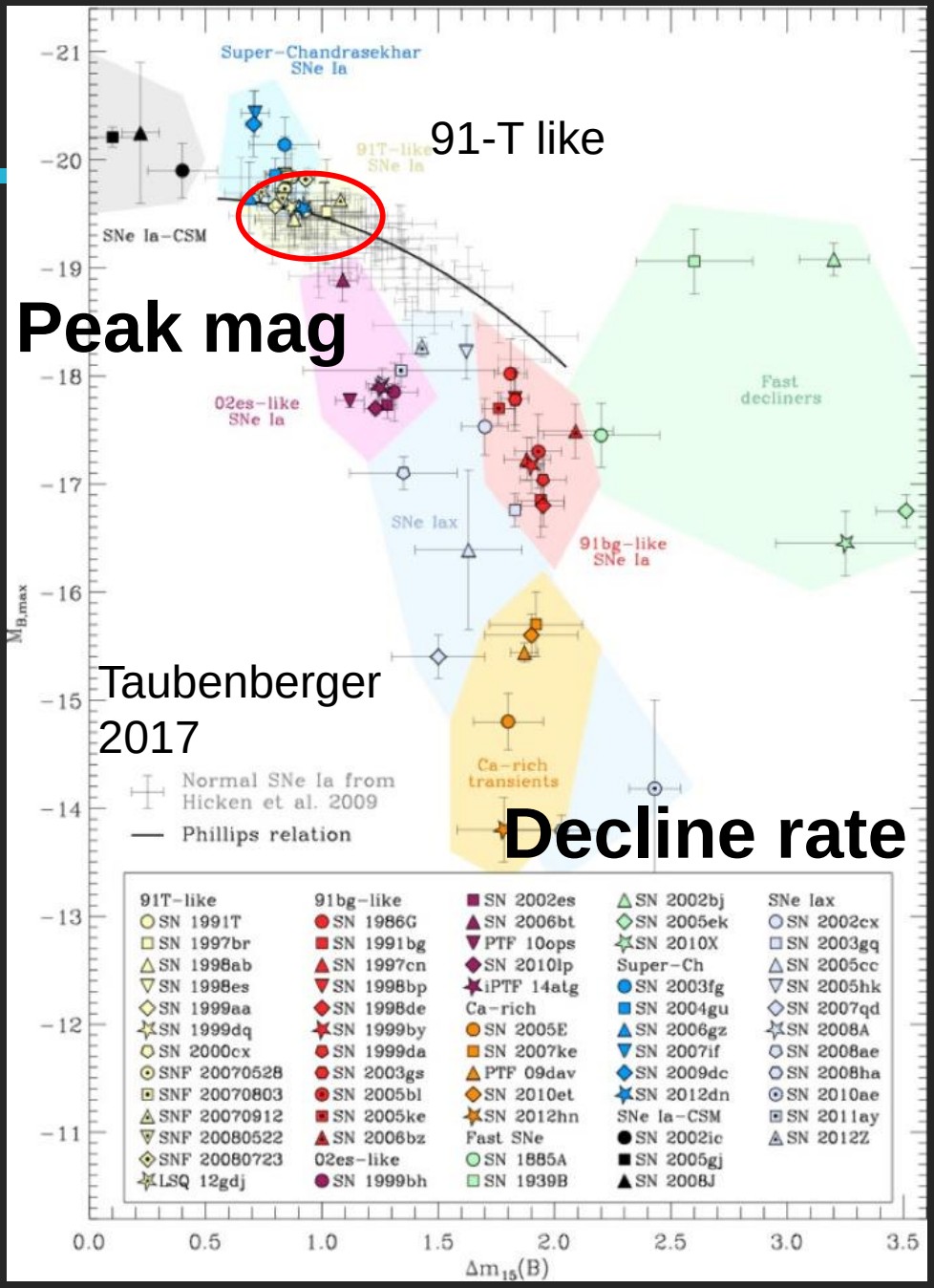
Recent reviews: KM+Terada 16, Livio+ Mazzali 18

Summary for normal SNe Ia

- **Companion: Generally against (existing) SD model.**
  - A few nearby SN (≠RG), and a few W/LMC SNR (≠MS).
- **CSM: Clean - against SD.**
  - No sign (< 10^{-8} $M_\odot$/yr) for a few nearby SNe.
- **Progenitor WD: Chandrasekhar-mass favored.**
  - Spectral evolution & characteristic n-rich isotopes.
- **Combined:**
  - **Chandrasekhar WD though DD?**
  - Cons: Theoretically NOT leading to SNe Ia (saio+nomoto).
  - Alternative? (SD w/ delay, or misinterpretation of data)

Diversity

- Too much diversity to be a single population.
- Indications for different progenitors/explosions for different classes (e.g., KM+Terada 2012 for a review).
- New paradigm: Multiple progenitors and/or explosion modes.



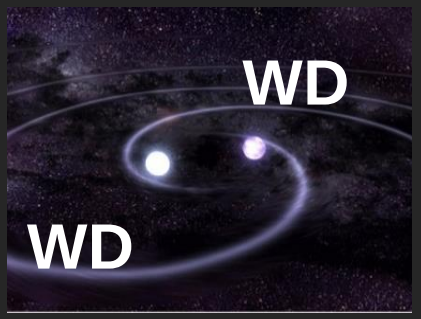
Multiple progenitors/explosions in Theory

Progenitor system(s)

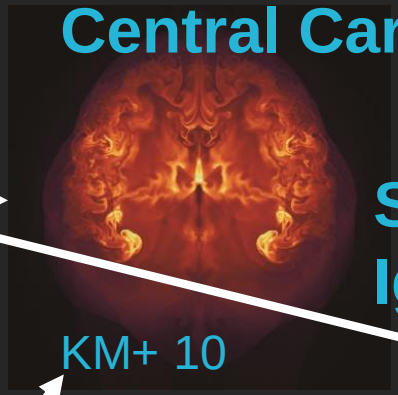
Explosion Mode(s)

Single Degenerate (SD)

Double Degenerate (DD)

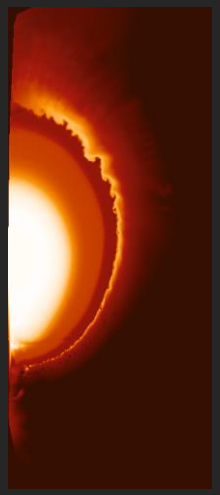


Central Carbon ignition



KM+ 10

Surface Helium Ignition



Fink+ 10

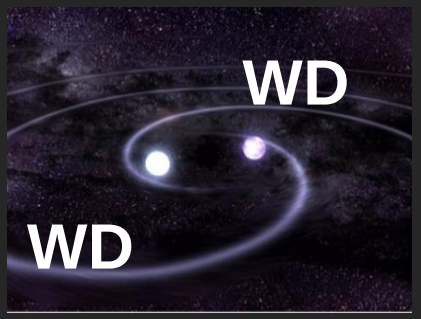
Surface Carbon Ignition

First light (within a few days)⇒Companion?

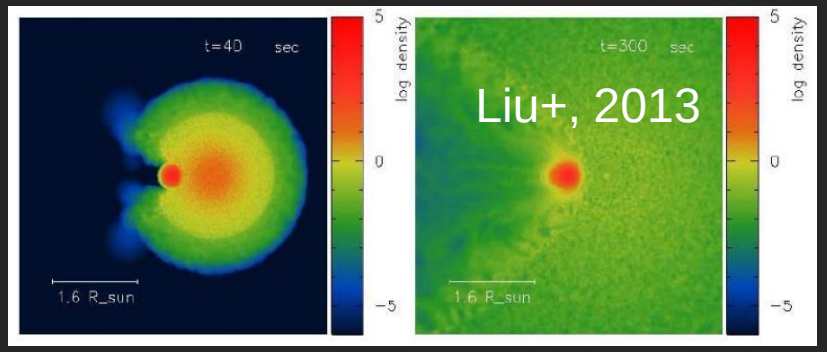
Progenitor system(s)

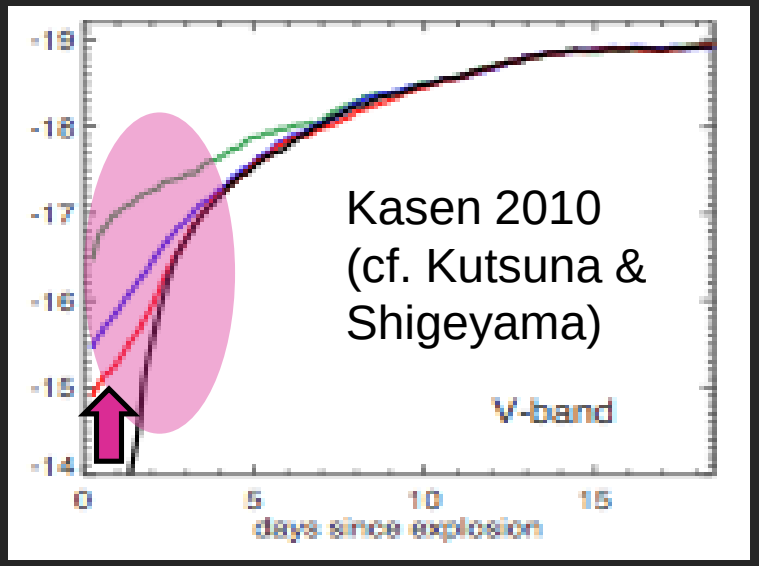
Single Degenerate (SD)

Double Degenerate (DD)

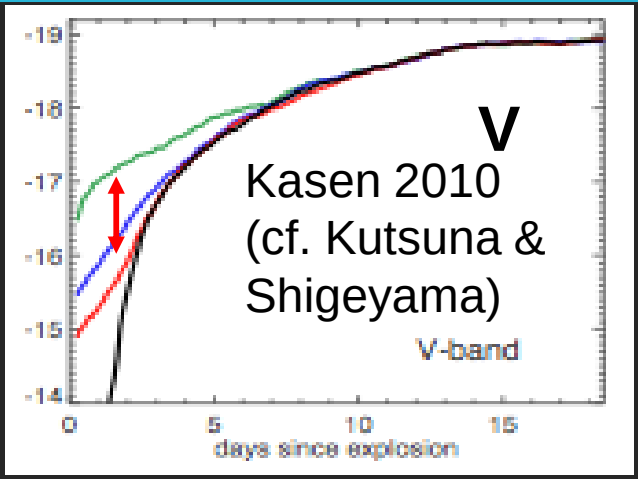


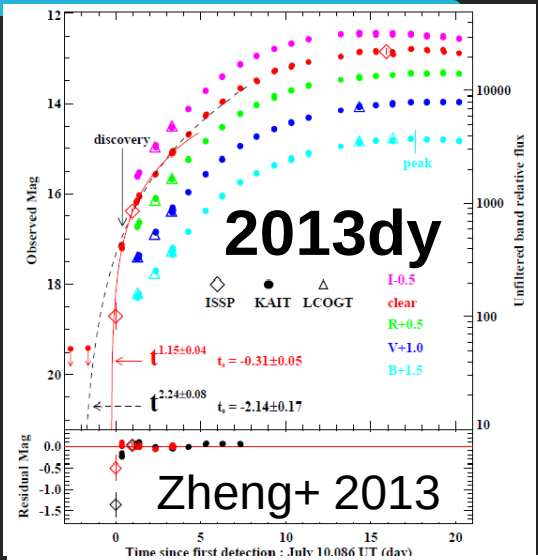
SN ejecta crashing into the companion star

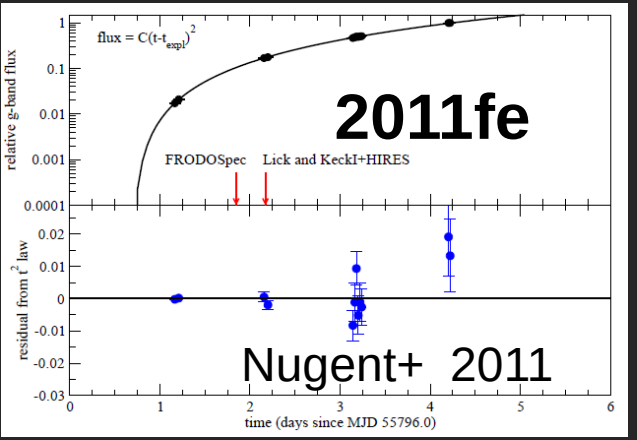


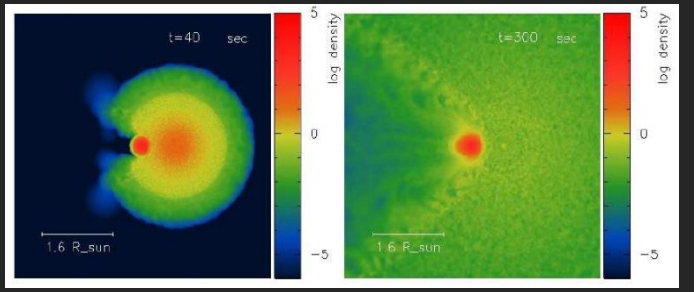


Early emission – No companion crash?

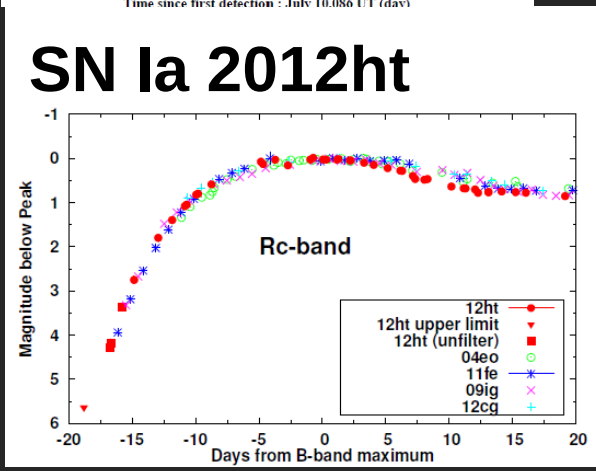


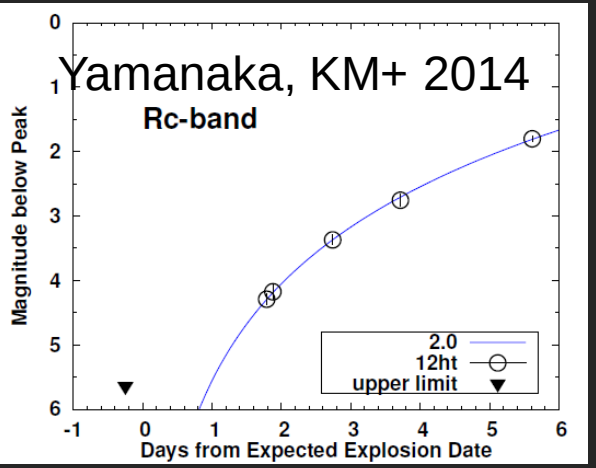






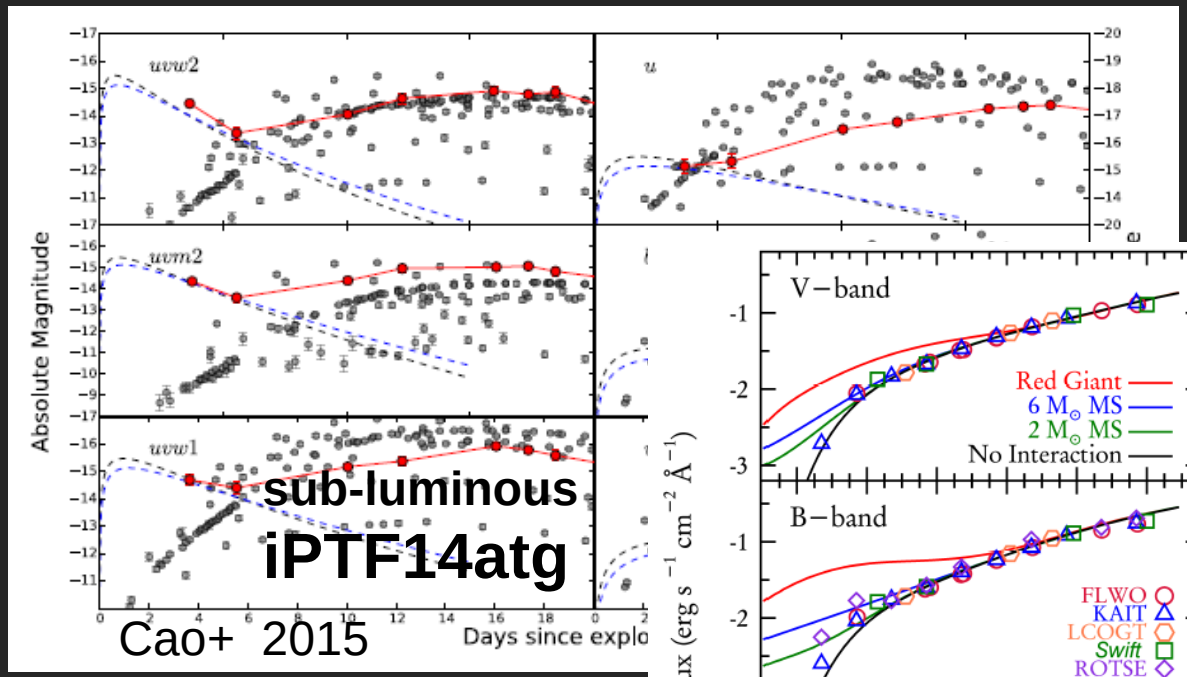
Liu+, 2013

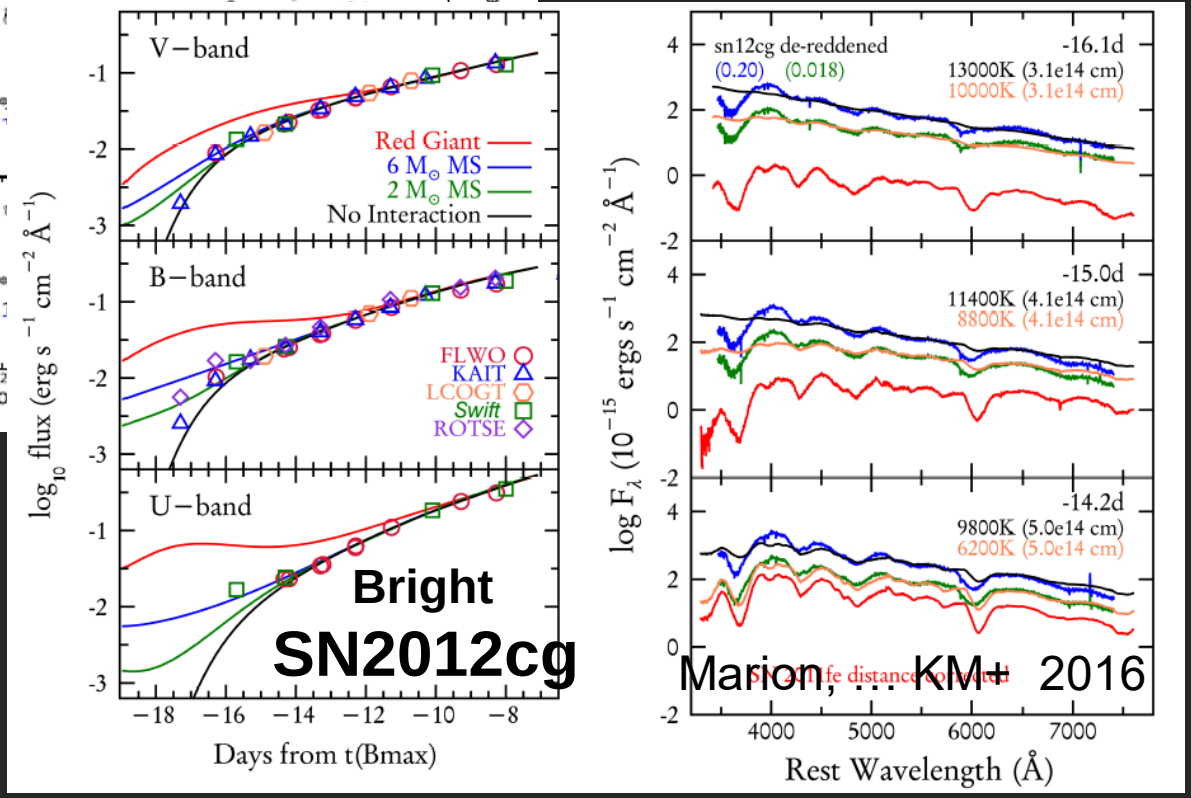




And very good limits by the Kepler (KEGS, red band: Olling+ 15)
Individual SNe and systematics search (e.g., SDSS-II: Hayden+ 10)

Early emission – Companion crash??





First detected for a faint outlier, then for a bright outlier.
Observed only for a specific direction?

Examples with possible signatures

KM+ 2018

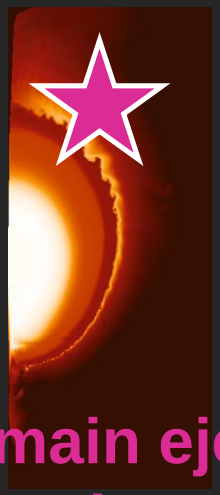
Possible mechanisms for the early “flash”

^{56}Ni mixed outward
(carbon burning product)

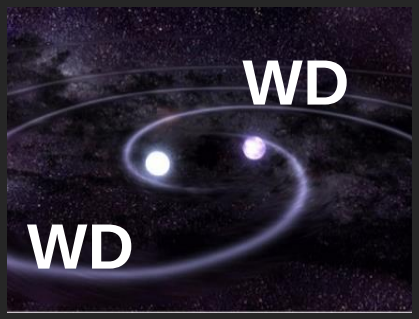
Crash to the companion
Crash to the CSM
Single Degenerate (SD)

Central Carbon ignition

Surface Helium
Ignition



Double Degenerate (DD)

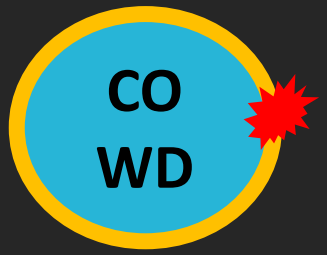


^{52}Fe & ^{48}Cr on the main ejecta
(He burning products)

Note: main source of the SN radiation = ^{56}Ni (~0.6$M_\odot$ in each SN)

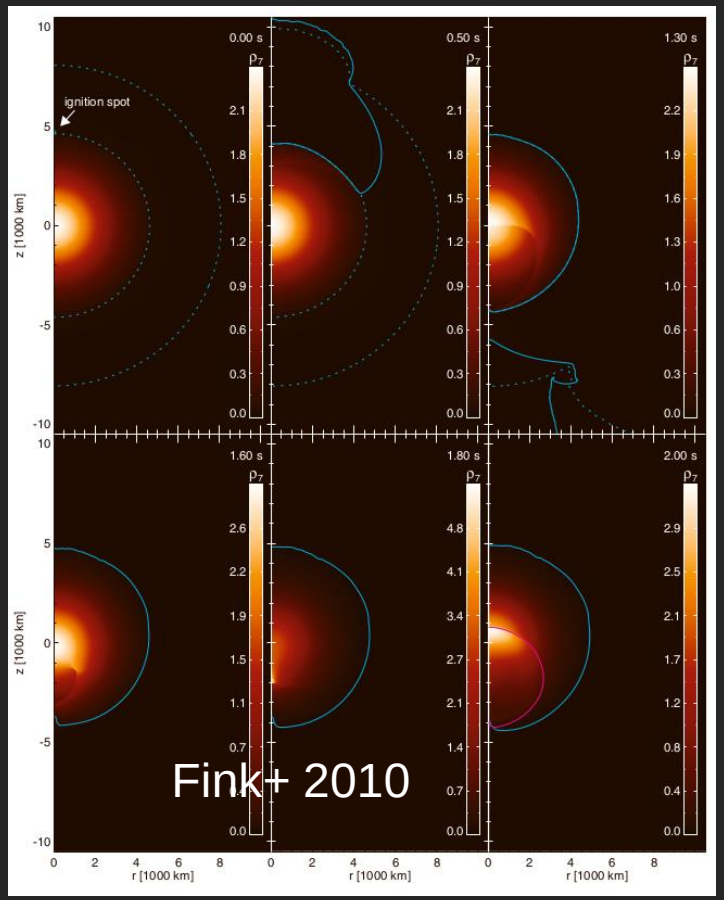
SN Ia triggered by the surface He detonation

He detonation



C detonation

SN



One of the classical models.

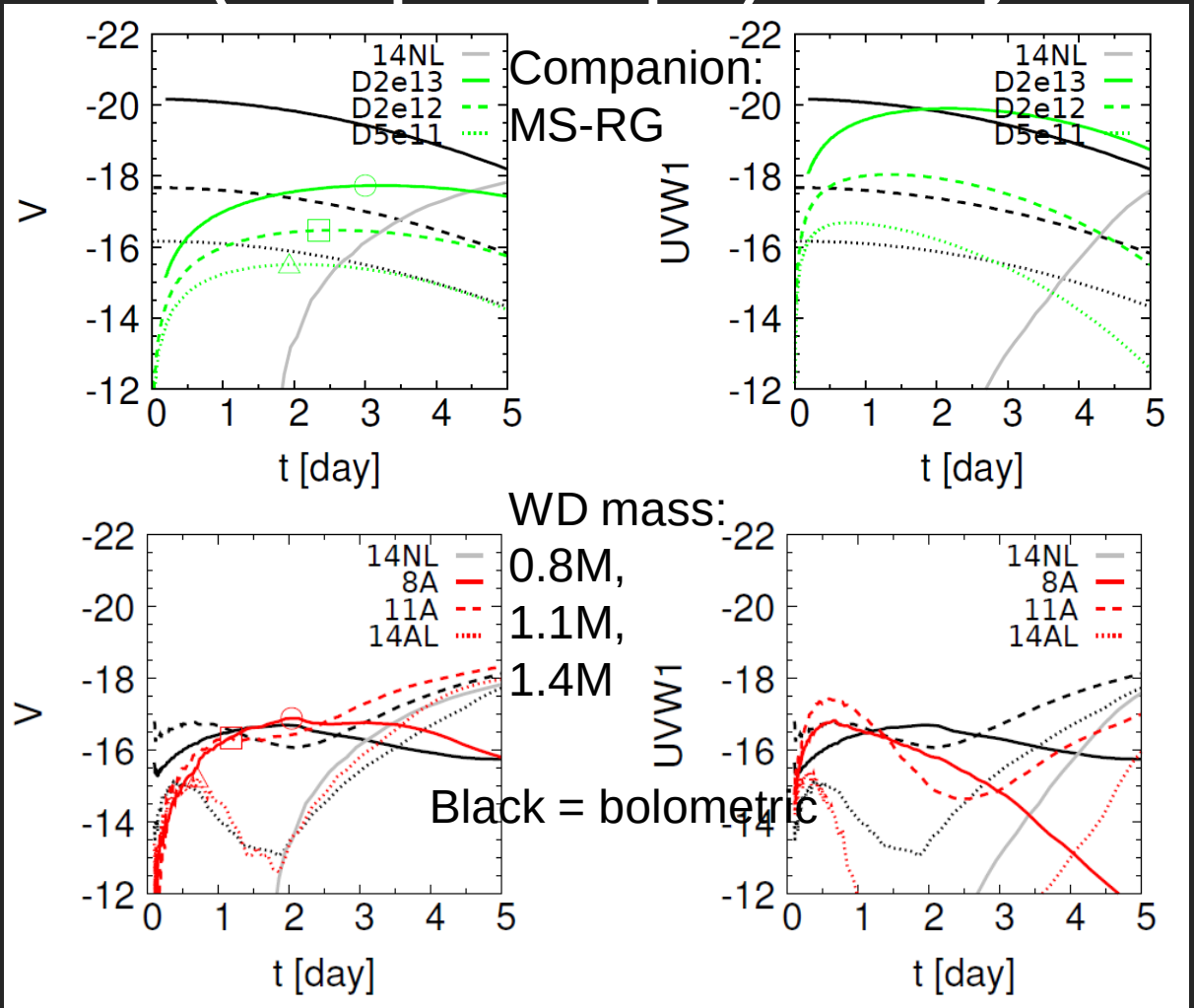
Not popular in the last decade (but now ↑).

Can happen both in SD & DD.
WD can be < $1M_{\odot}$.
He donor can be both a He star or He WD (or C+O WD w/ He env.).

Jiang, Doi, KM+, 2017, Nature, Noebauer+ 2017,
KM. Jiang, Doi, Shigeyama, 2018, ApJ

New Diagnostics (in the first few days)?

Short-lived radioactivity (^{52}Fe & ^{48}Cr) on the surface of the electa (low optical depth) ⇒ Early flash within a few days.

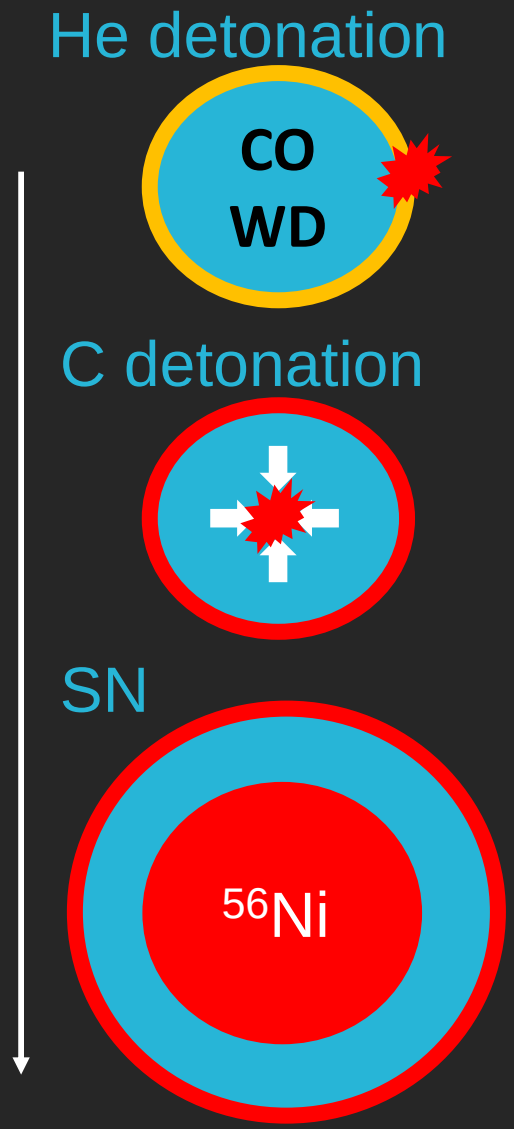


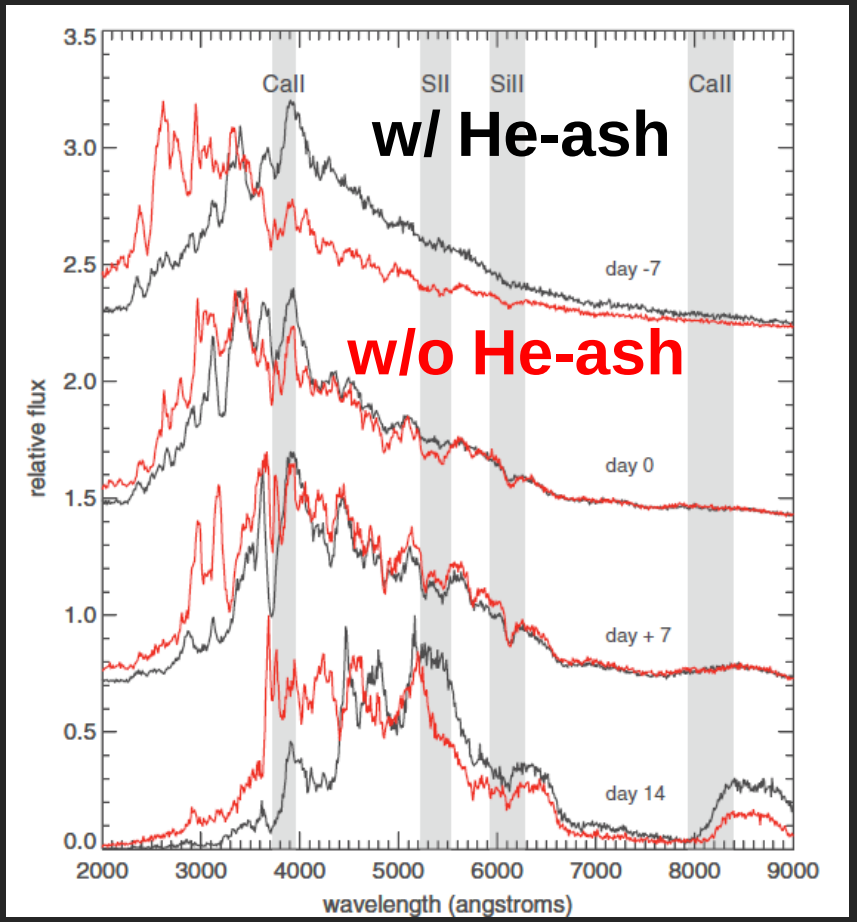
Companion Interaction:
Cooling of hot fireball
⇒ L_{bol} rapidly decreasing, Temperature high & decreasing.

He detonation:
Continuous energy injection:
⇒ L_{bol} peaks. Temperature relatively low & slowly evolving.

He detonation for outliers (around maximum)?

Woosley & Kasen 2011

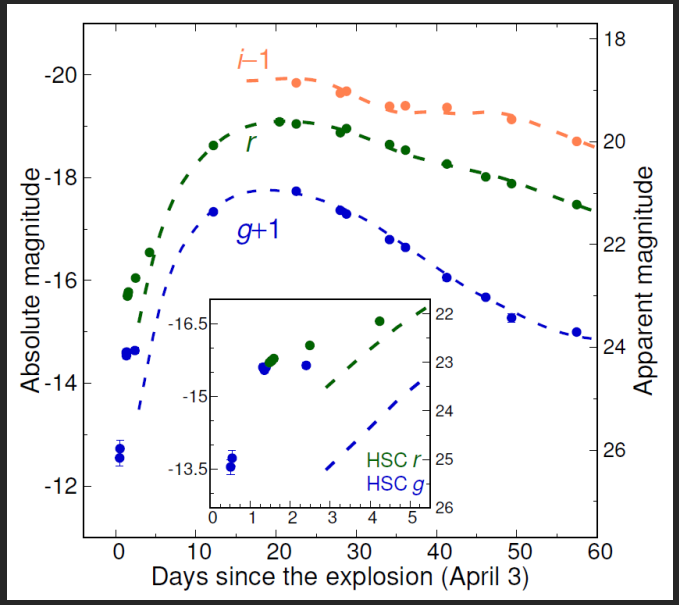




Too red to be normal, absorptions by the He detonation ash (Fe-peaks, Ca, Ti).

Subaru/HSC high cadence survey: Talk by Jian Jiang

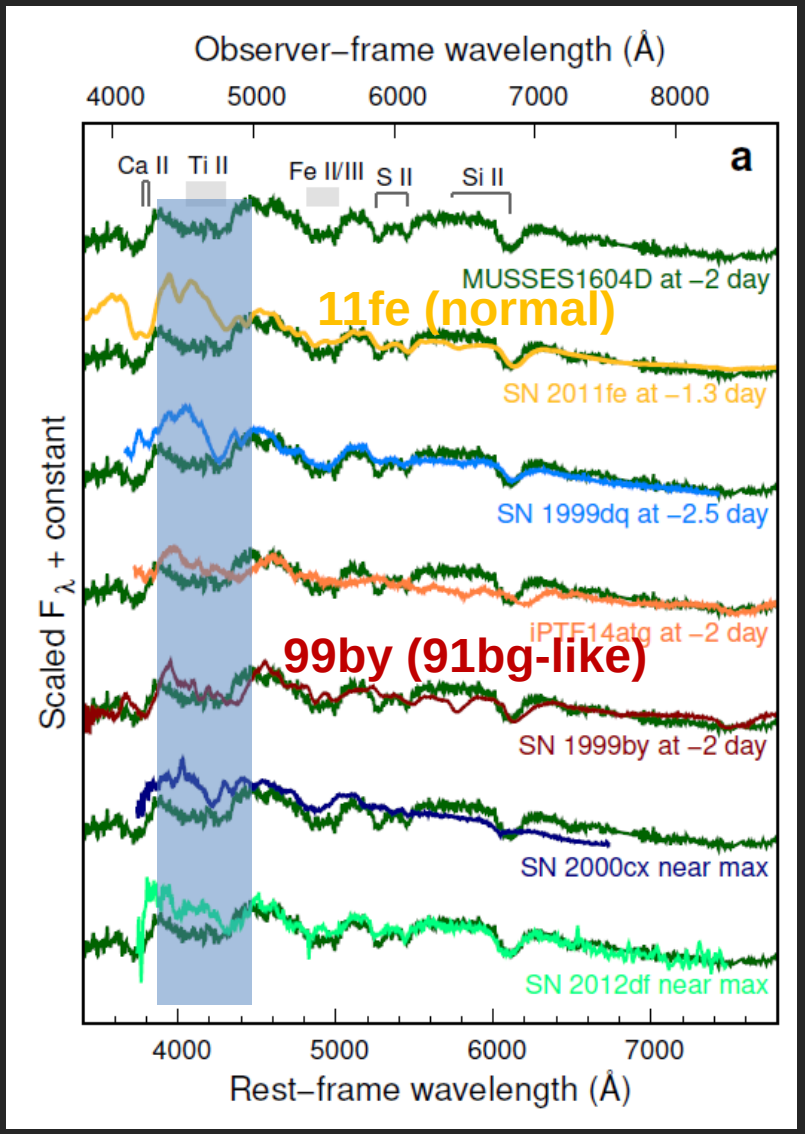
MUSSES1604D: A peculiar SN w/ early flash



"Flash" in the first few days.
Too red for the "interaction".

Spectra of normal SNe but with strong Ti II/Ca II absorptions, while the luminosity is normal.

Should have the same origin.



Jiang, Doi, KM+ 2017, Nature

"He detonation" triggers some SNe Ia

He detonation

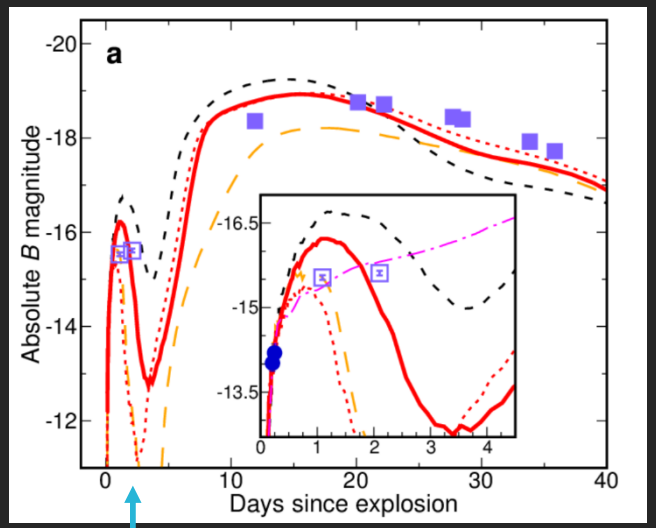
CO WD

C detonation

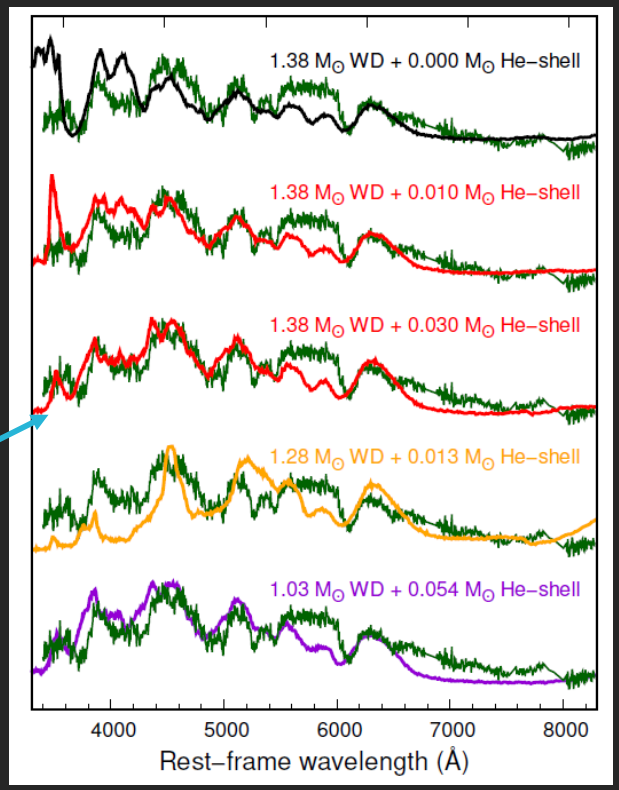
SN

^{56}Ni

He detonation-triggered SN does exist in nature (not only in theory).



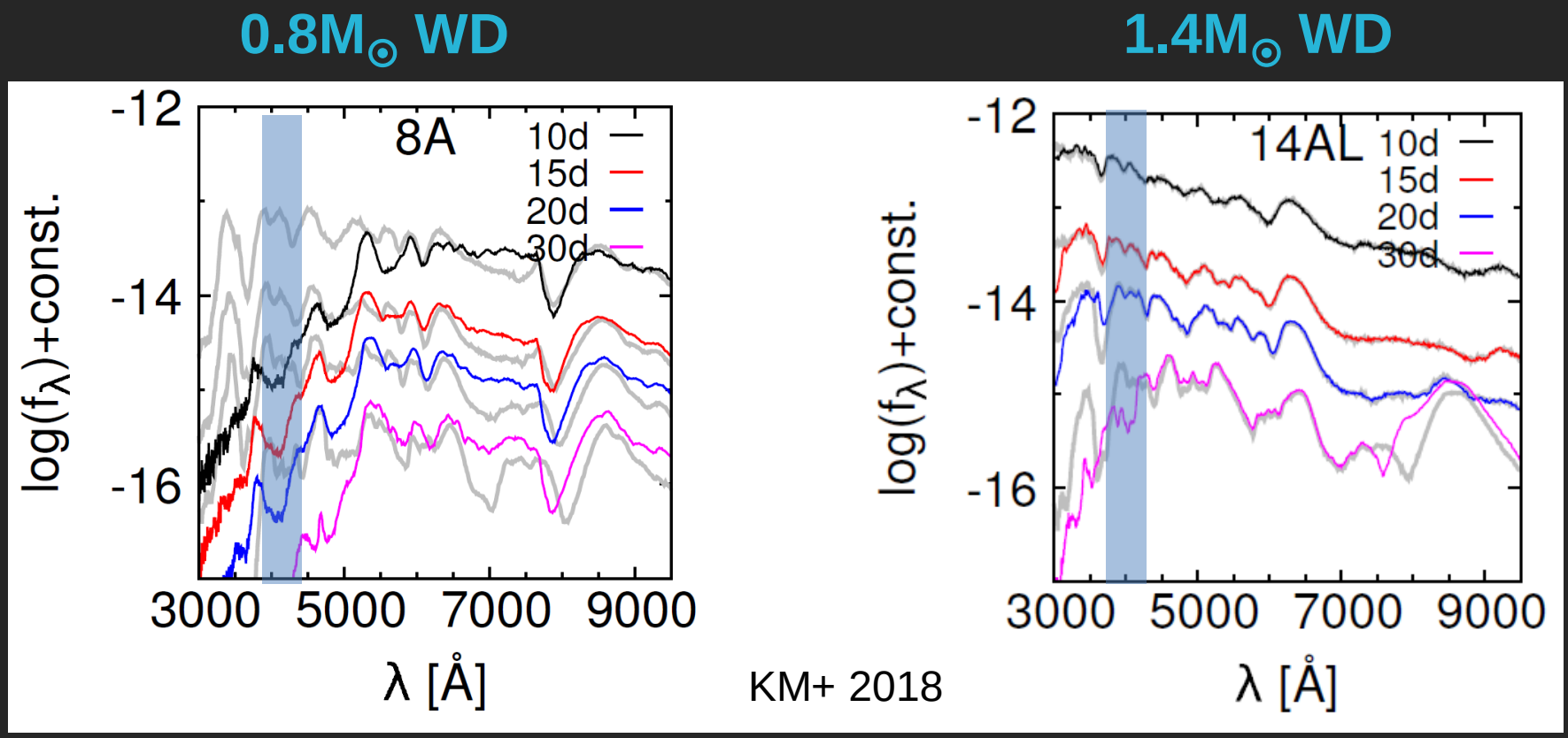
Comparison to radiation transfer models



^{52}Fe/^{48}Cr

⇒Ti, Ca-rich layer

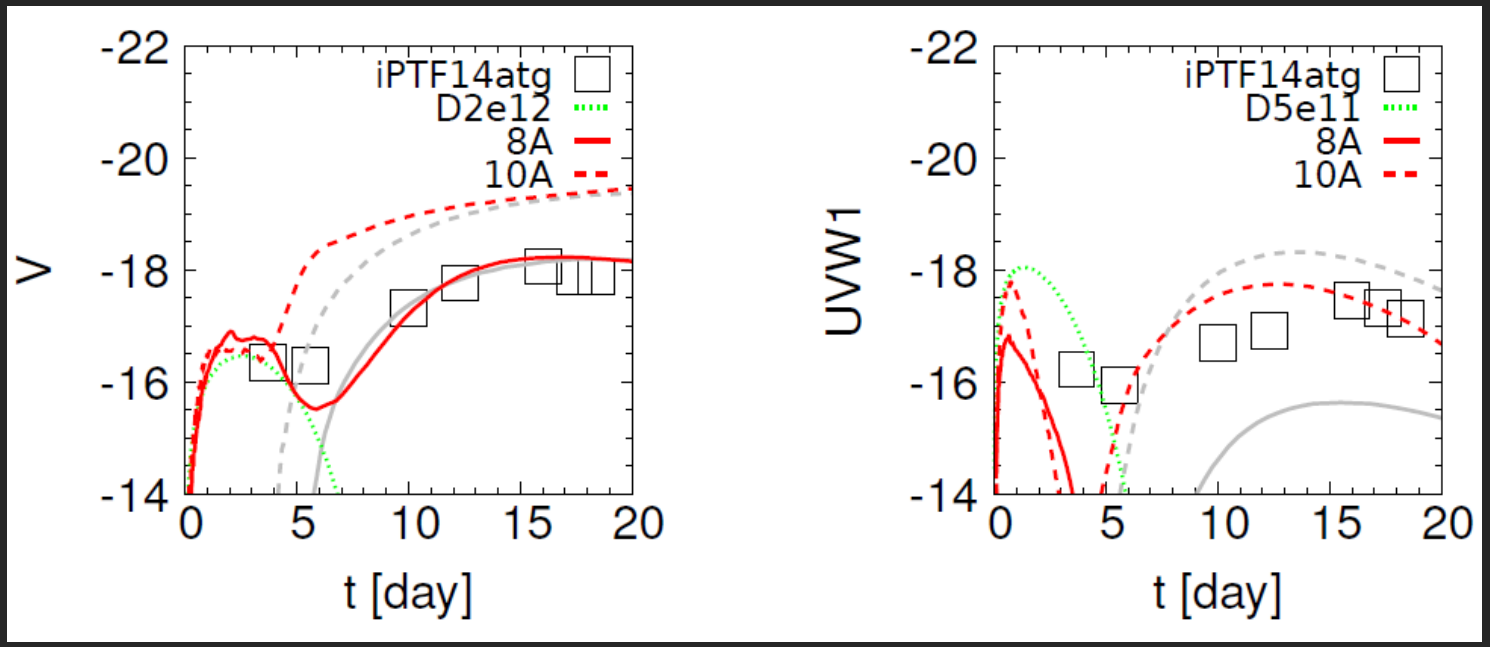
For outliers, or maybe a tip of the iceberg



The "red" spectrum around the maximum light is dependent on two functions: WD mass and the He shell mass.

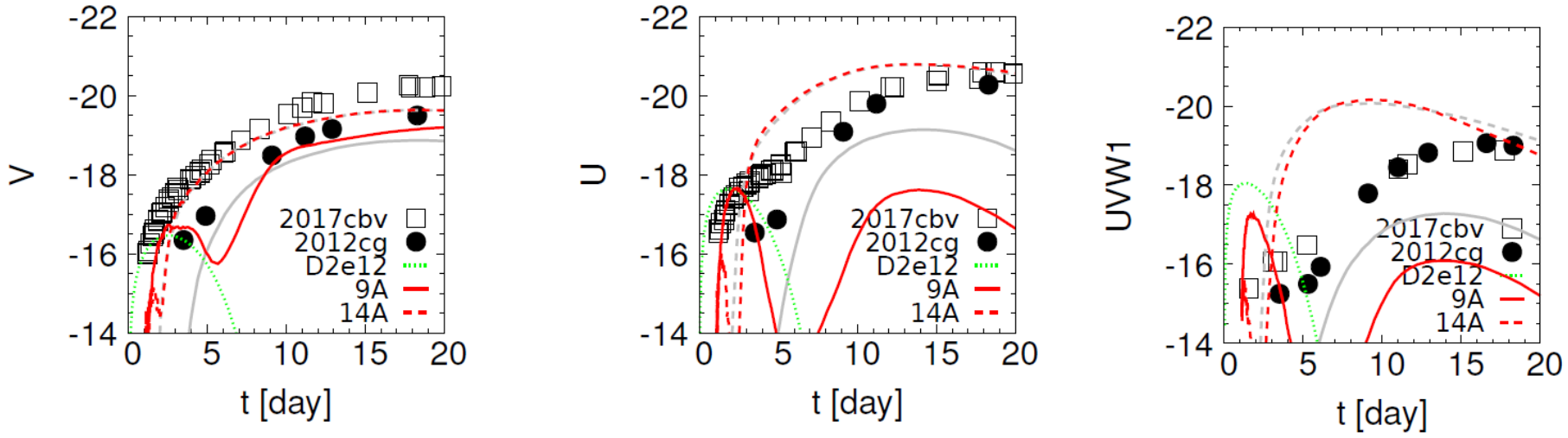
The He-detonation ash may be hidden even for (some) normal SNe Ia ("D6" model by Ken Shen).

Case Study for reported “early Flash”



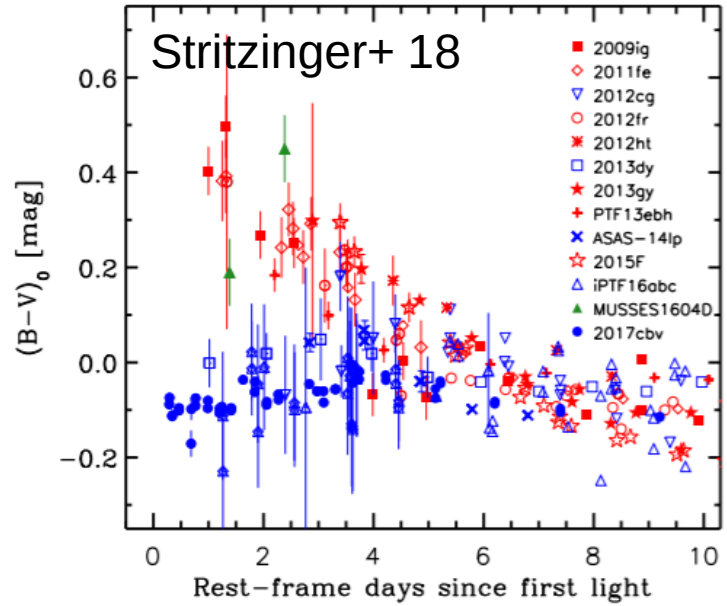
iPTF14atg: Consistent with both the companion interaction (as proposed by Cao+) and the He-detonation scenario.
The maximum phase would have tension to the He-detonation model (not that red), but the model not tuned.
Data relatively sparse – need more densly sampled points.

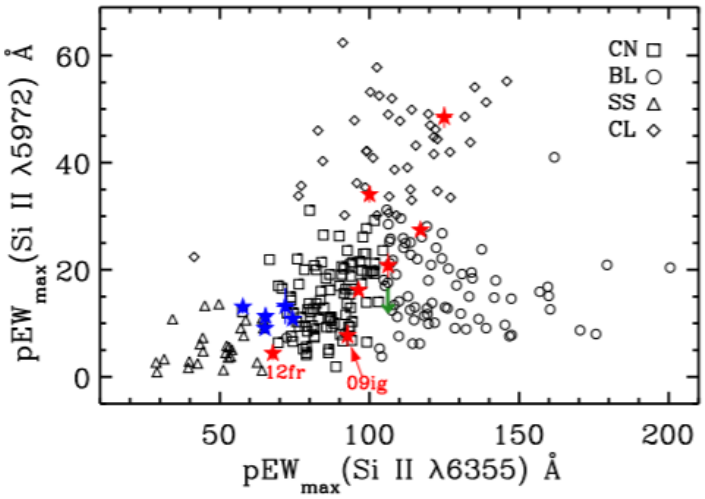
Case Study for reported “early Flash”

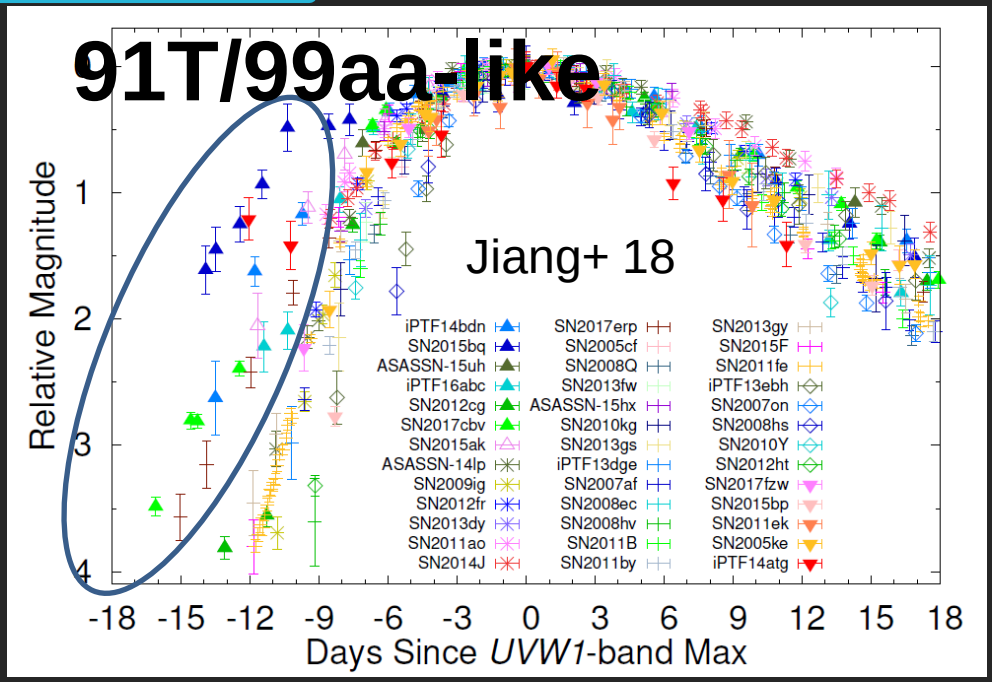


SNe 2012cg (Marion+ 2016) & 2017cbv (Hosseinzadeh+ 2017):
UV too weak to be the interaction, and no sign of “bolometric peak” in the flash. Inconsistent with the interaction.
He detonation may work, but favors more smooth distribution of the energy source – extensive ^{56}Ni mixing?
Data densely sampled for 2017cbc – that helps a lot.

“Early flash” favors a specific sub class

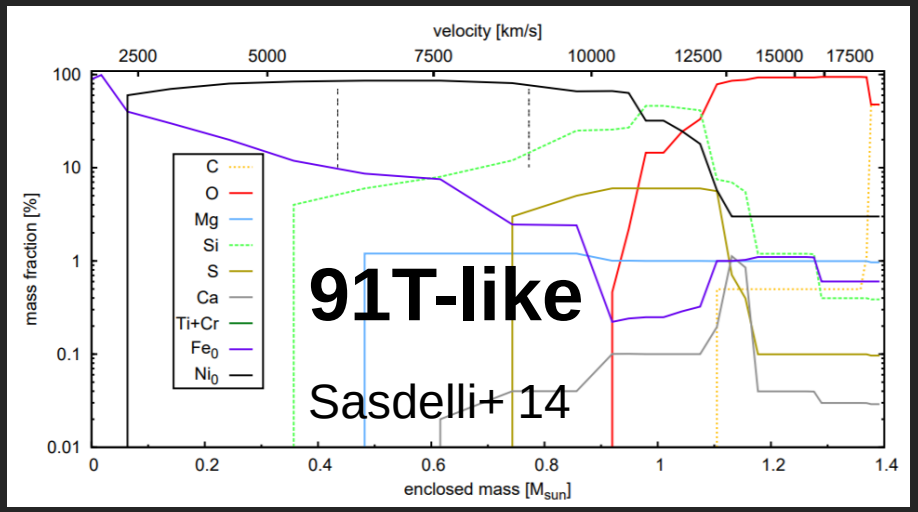


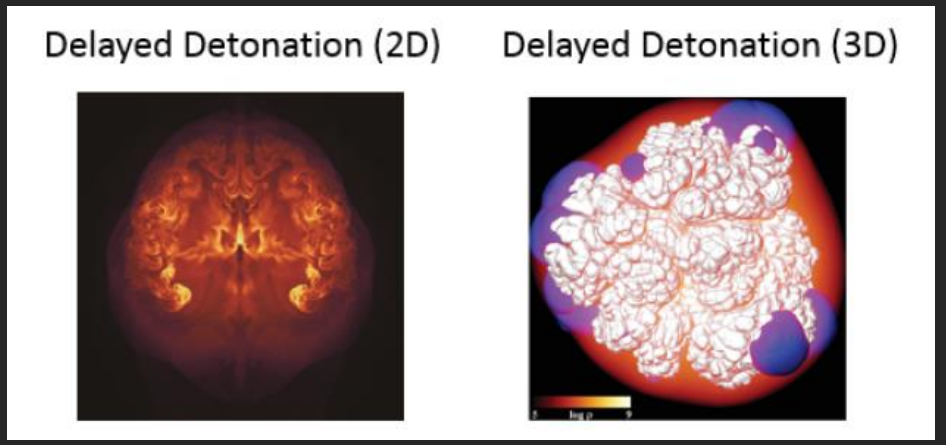




Except for iPTF14atg & MUSSES16D, they are ALL bright 91T/99aa-class.
No normal SNe with the flash.
Nearly all 91T/99a-lie shows the flash, if the early data are there.

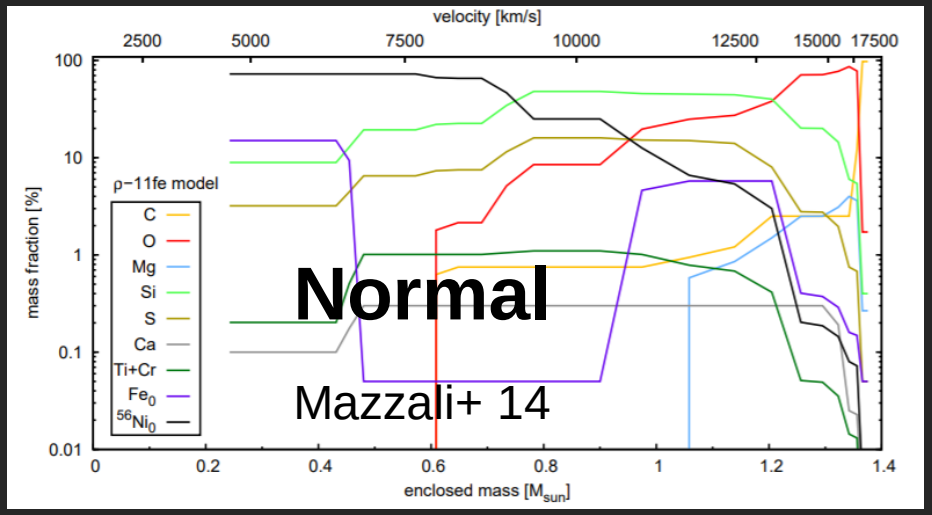
Extensive ^{56}Ni mixing at the explosion?



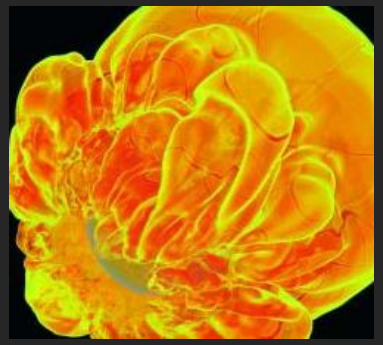


KM+ 10

Seitenzahl+ 13



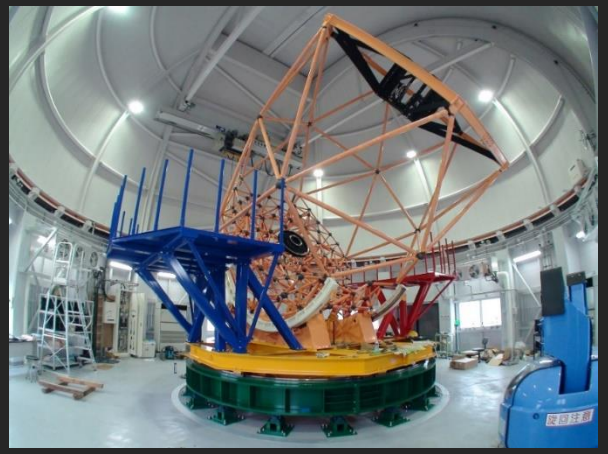
Gravitationally confined detonation



Jordan+ 12

May bring ^{56}Ni blobs up.

Conclusions



Kyoto, U New 3.8m telescope “Seimei”

- **Key: Early discovery & quick/dense follow-up: Bright future with ongoing/future facilities.**
- **SN Ia triggered by Helium detonation on the WD surface does exist. Maybe the tip of the iceberg.**
- **The early flash favors 91T-like sub class. Generally not a signature of a companion. ^{56}Ni Mixing promising.**
- **Multiple populations can be efficiently traced by the very early phase discovery and follow up.**