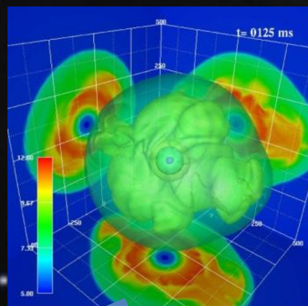
YITP NS-NS WS, 12 February 2015

?



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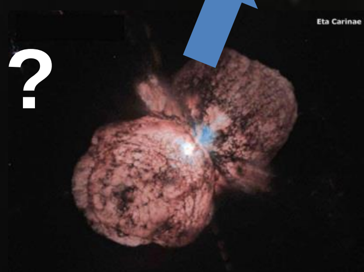
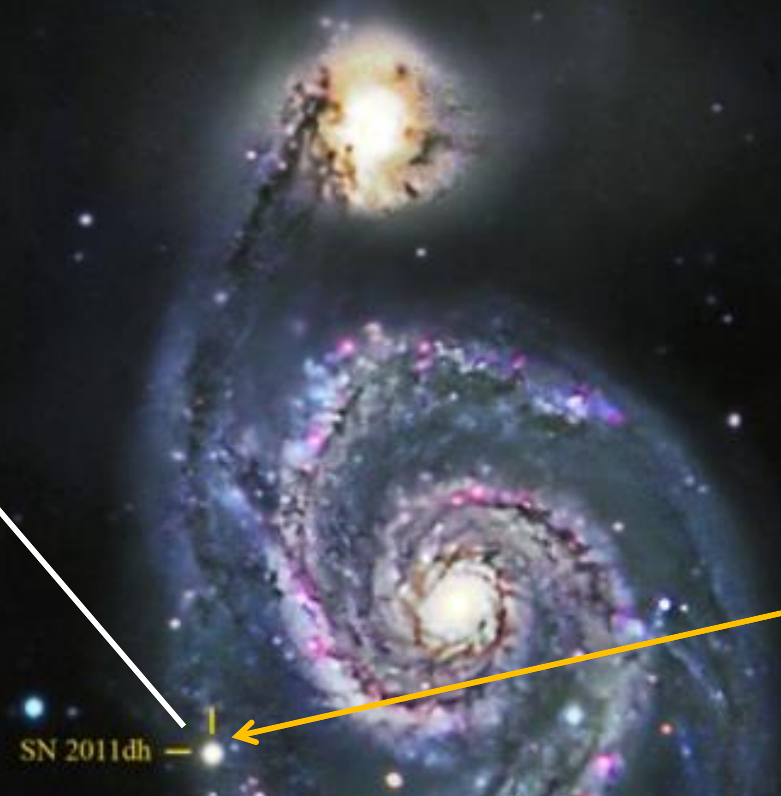




Supernovae

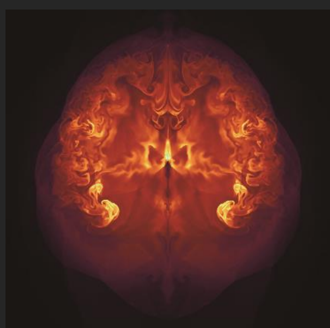
Keiichi Maeda
Dept. Astron., Kyoto University

Contents

- **Introduction to supernovae (SNe).**
  - Key questions, observational basics.
- **Type Ia Supernovae.**
- **Core-Collapse Supernovae.**
  - Progenitor.
  - Companion.
  - CSM environment.
  - Explosion mechanism.

Type Ia Supernovae (SNe Ia)

- Thermonuclear explosions of a (near Chandrasekhar) white dwarf (WD).
- **But we do not yet know what make them.**

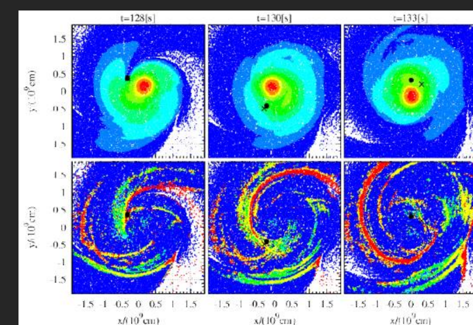


KM+ 2010

?

Accreting WD?

Sato+ (w/ KM) submitted
Tanigawa+ (w/ KM) submitted



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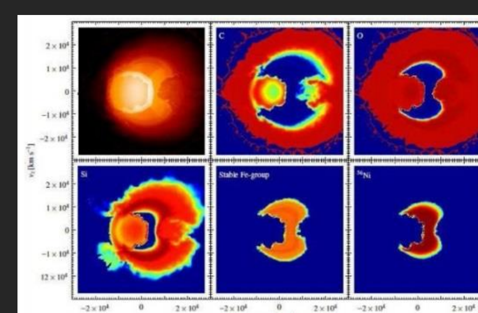
Merging WDs?

?

Roepke+ 2012



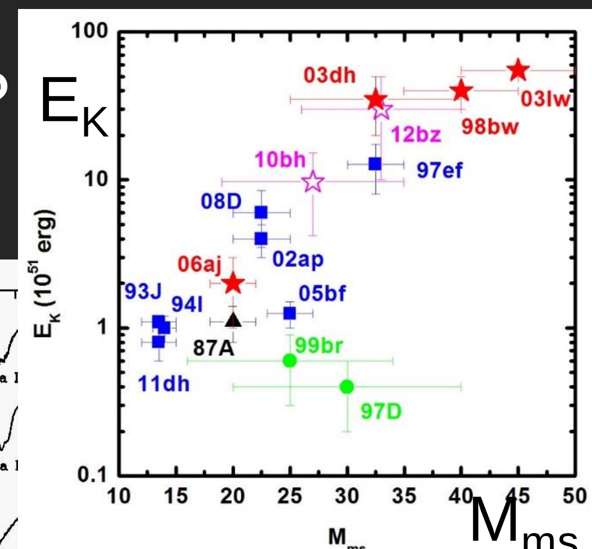
Progenitor?
Explosion Mechanism?
Multiple populations?
Diversity and origins?

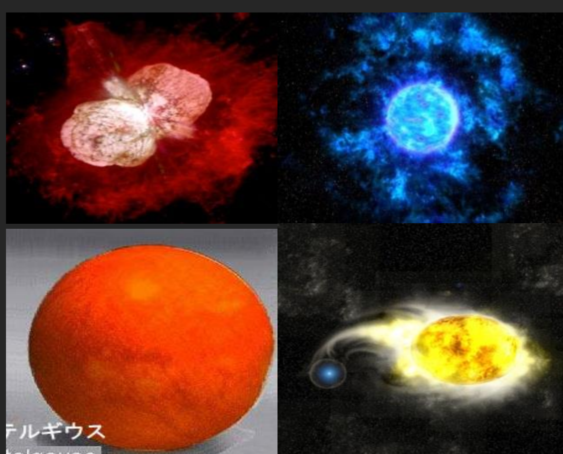
Core-Collapse SNe

- Gravitational collapse of a massive star.
- **But we do not yet know what make them.**

Progenitor mass/rotation/metallicity?
Single/binary evolutions? Mass loss?
Explosion Mechanisms?
Gamma-Ray Bursts?

Mass-energy





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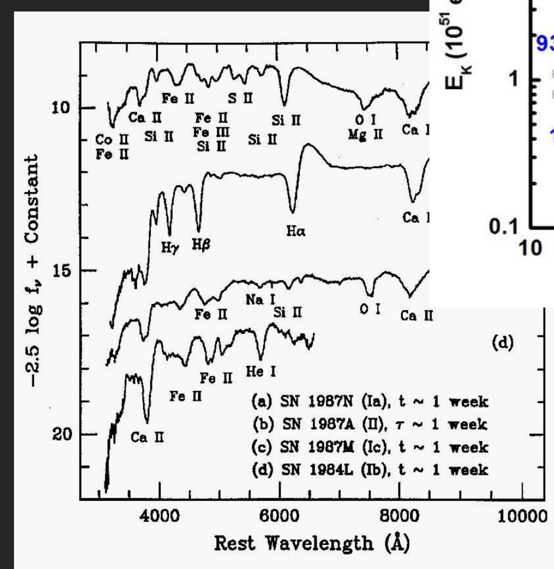


Possible Progenitors

Spectral classes

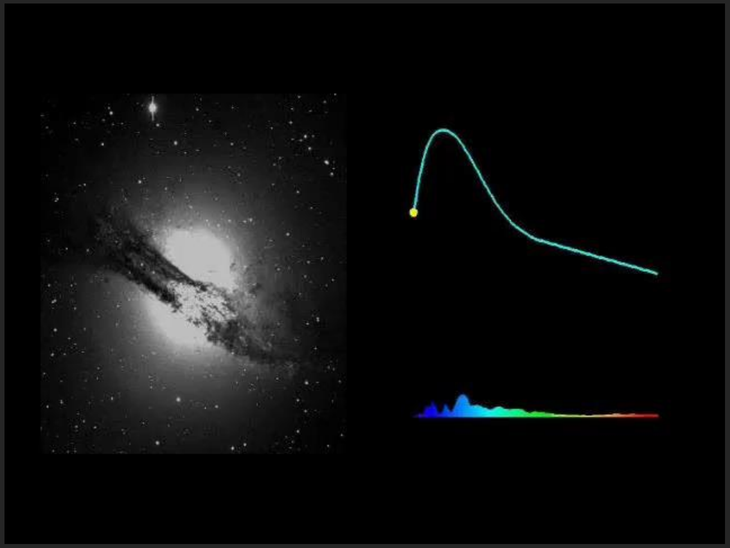
So, we know down to nothing

Observational Characteristics of Supernovae

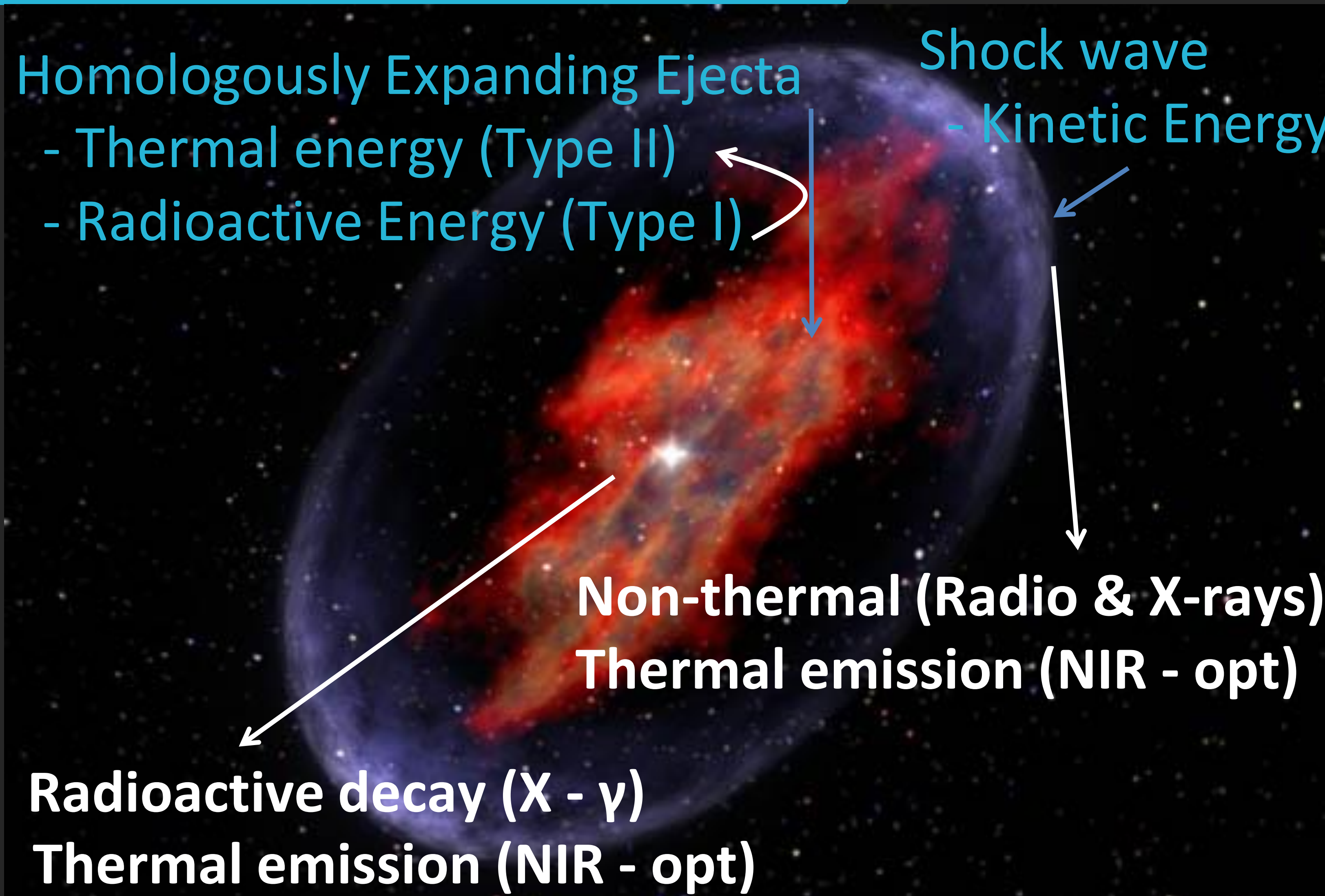
- > 1000 discoveries per year.
  - **Only a part** (nearby) observed in detail.
- Distance > ~ 10 Mpc (extragalactic).
  - **Point sources** (except for a few by HST/AO/VLBI).
  - Typical maximum mag. V > ~ 16 mag（roughly）.
- Most of obs. = Optical.
  - Imaging + spectra (time-dep.)

⬇ Interpretation

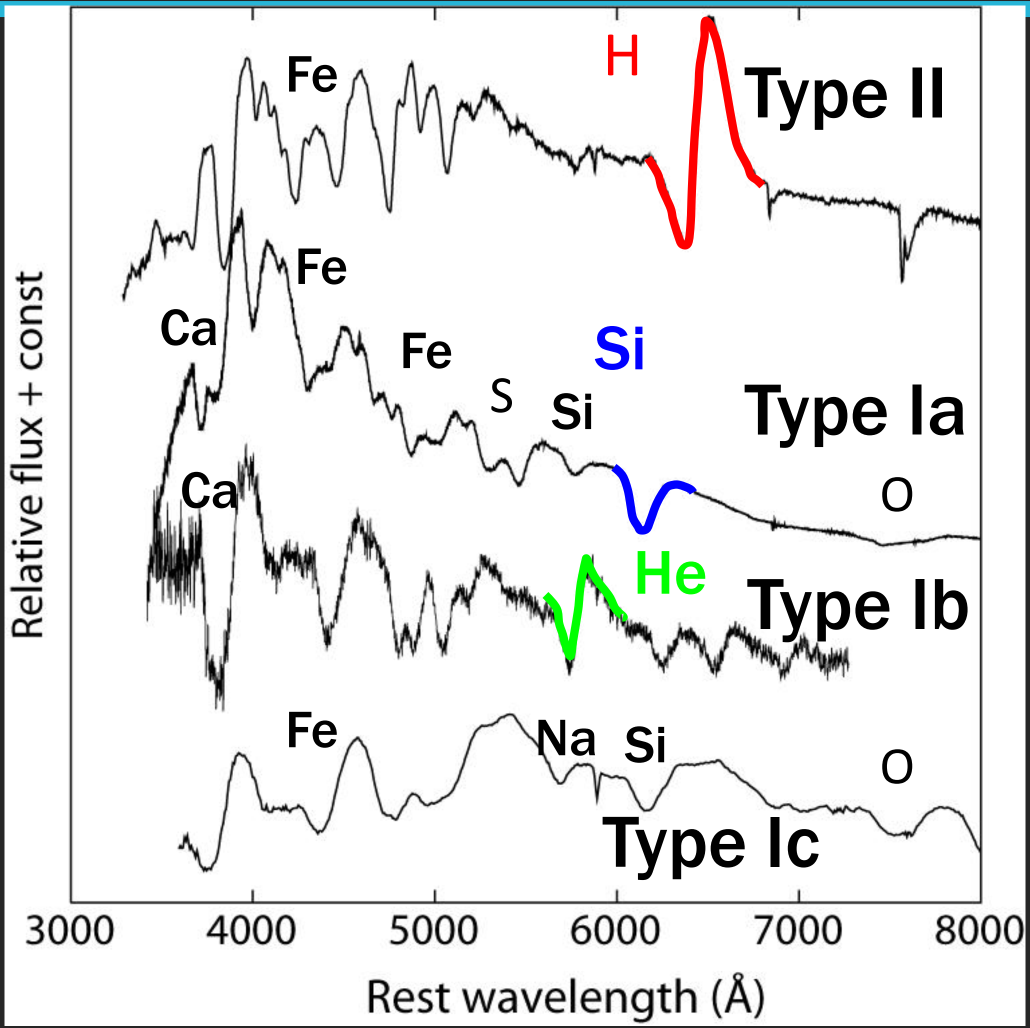
Supernova Physics
（e.g., exp. mech.）



Energy Budget in SNe ⇒ Emission



Supernova Classification

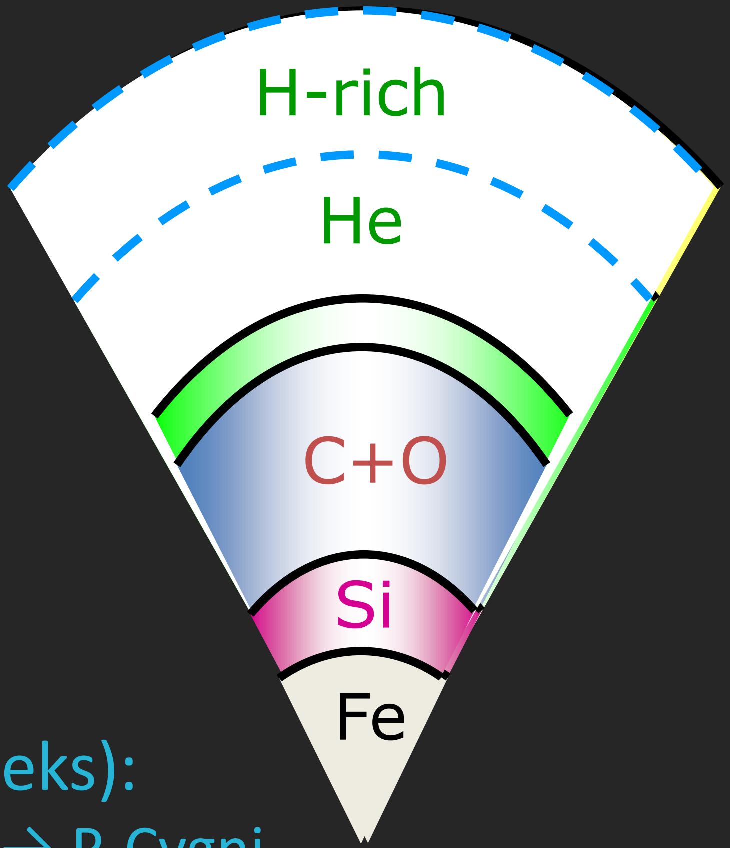


Ia

Thermonuclear exp. of white dwarf

II/Ib/Ic

Core-Collapse (CC) of massive stars

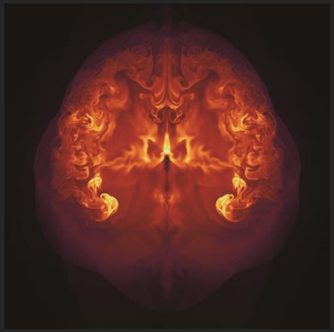


@ maximum brightness (~ a few weeks):

– Expanding optically thick medium → P-Cygni.

Type Ia Supernovae (SNe Ia)

- Thermonuclear explosions of a (near Chandrasekhar) white dwarf (WD).
- **But we do not yet know what make them.**



KM+ 2010

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?

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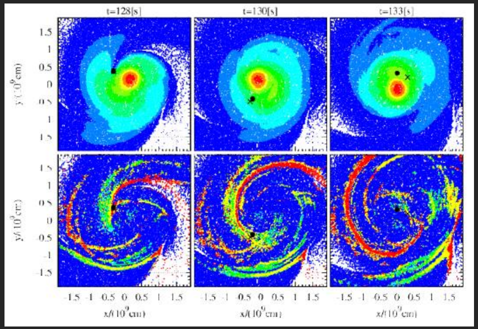
Tanikawa+ (w/ KM) submitted

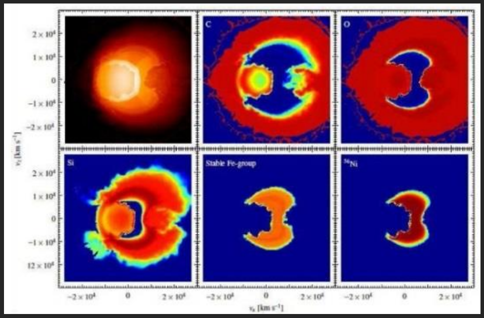


?

Merging WDs?

?

Roepke+ 2012



Progenitor?
Explosion Mechanism?
Multiple populations?
Diversity and origins?

Extremely nearby SNe Ia in this decade

SN 2011fe in M101

~6.4 Mpc

Normal (low-velocity)

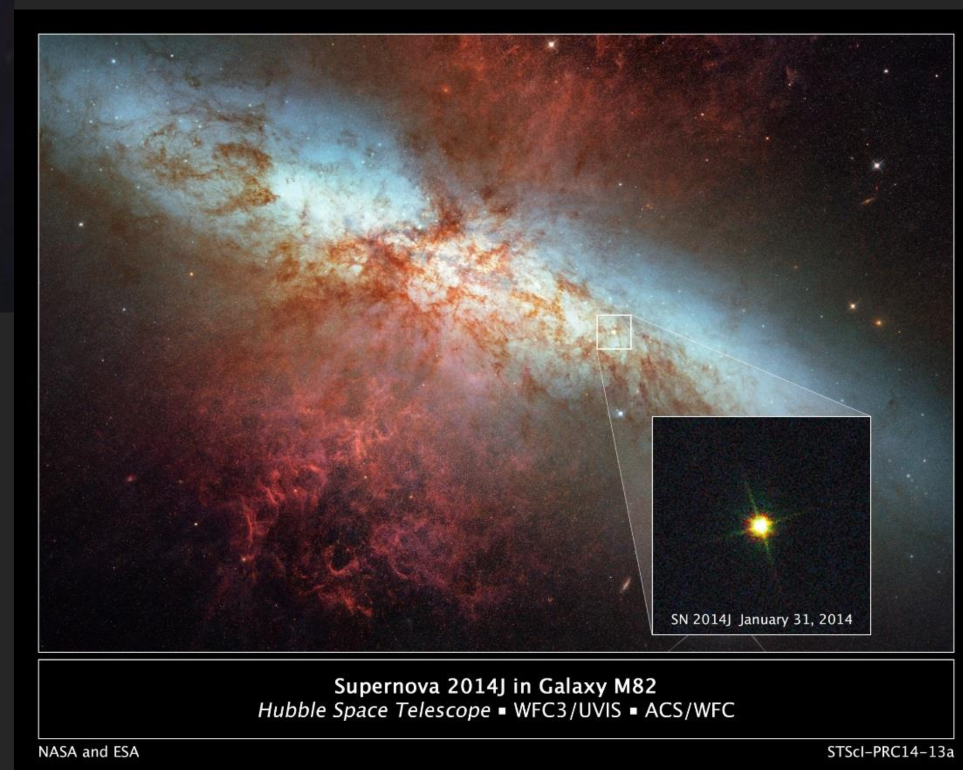
“clean” (little extinction)

SN 2014J in M82

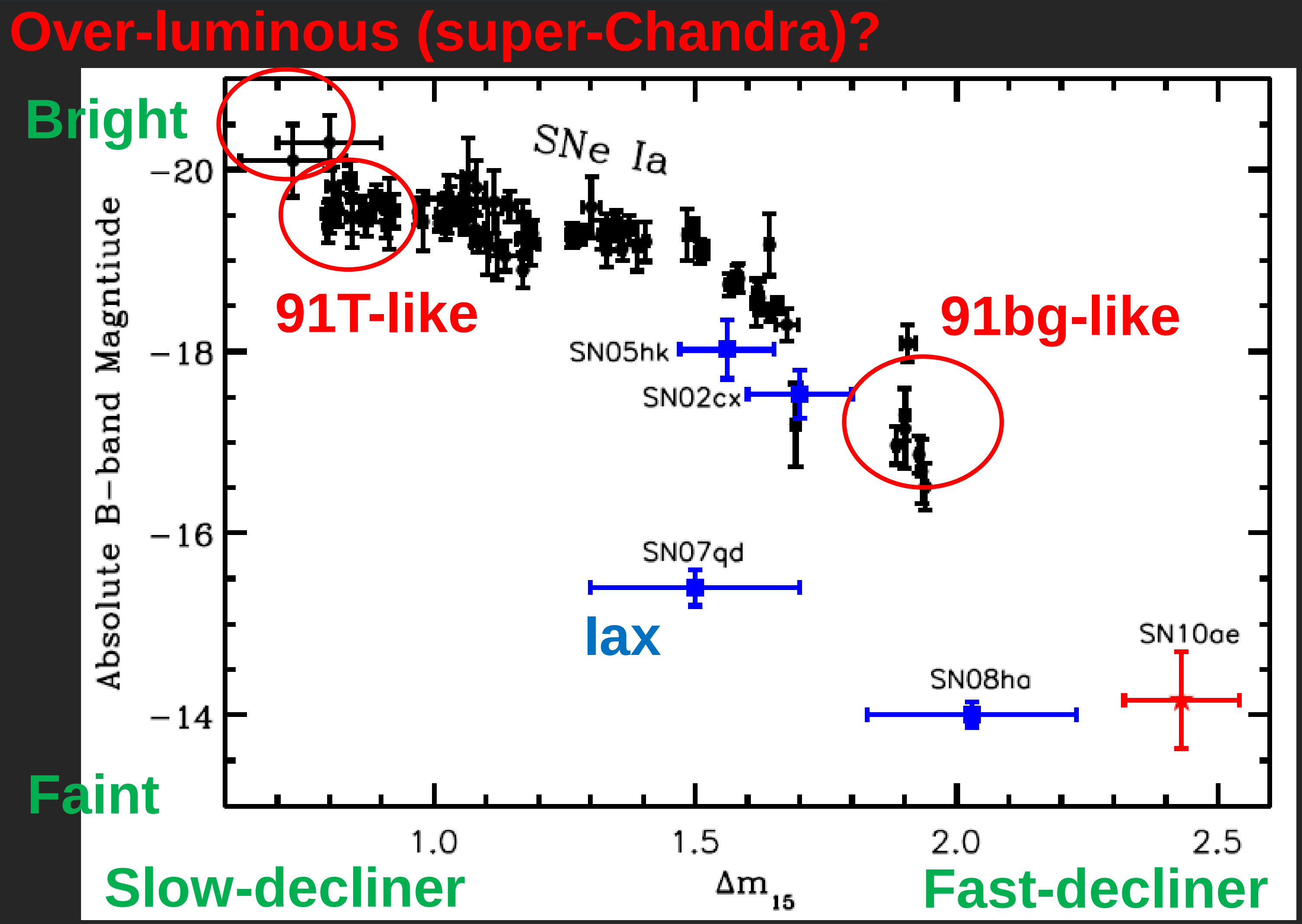
~3.8 Mpc

Normal (high-velocity)

“dirty” (substantial extinction)

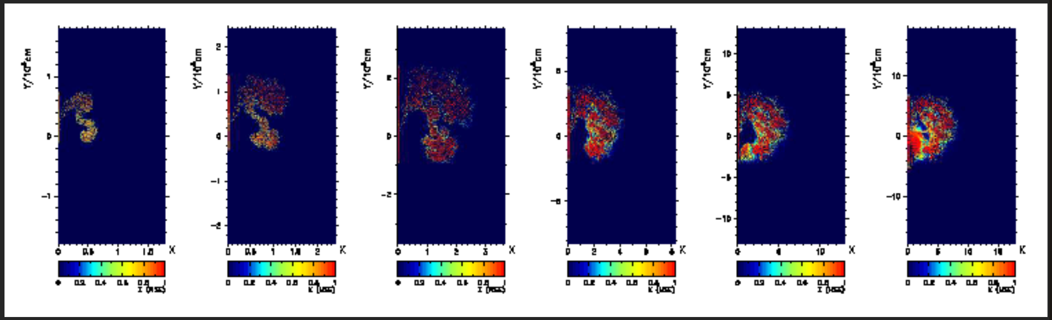


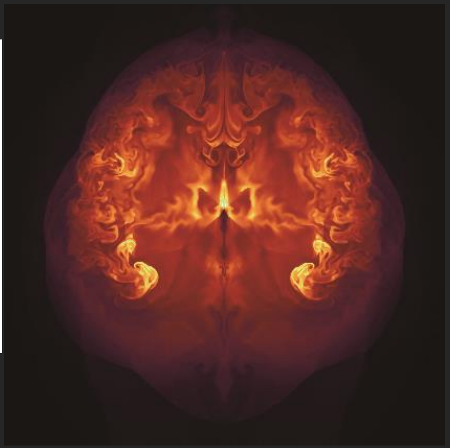
Normal vs. peculiar SNe Ia



Stritzinger+ (w/KM) 2014

Examples of explosion models



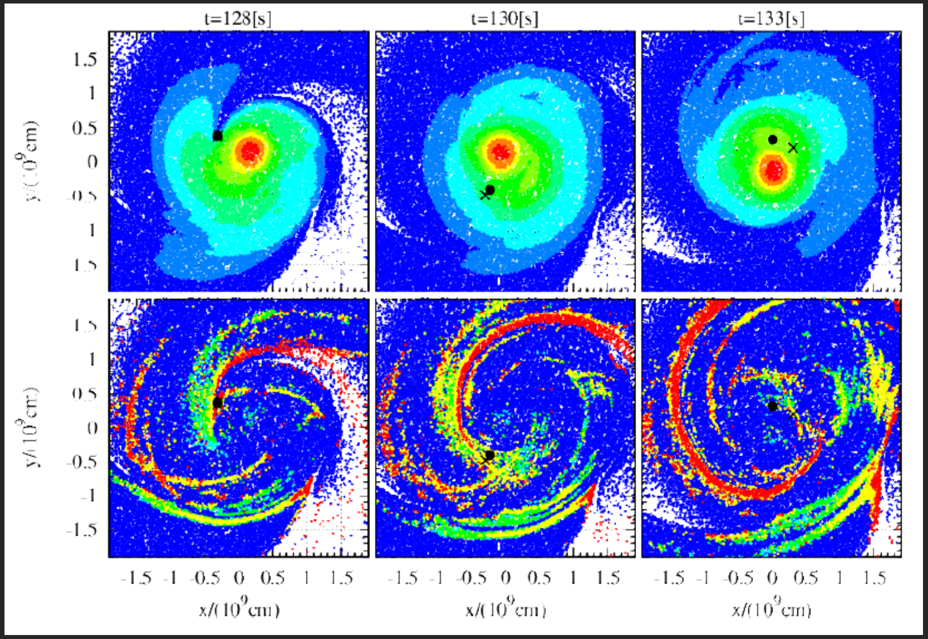


Single Degenerate

Chandrasekhar WD

Central (off-center) ignition

KM, Roepke+ 2010



Double Degenerate

Various WD+WD masses

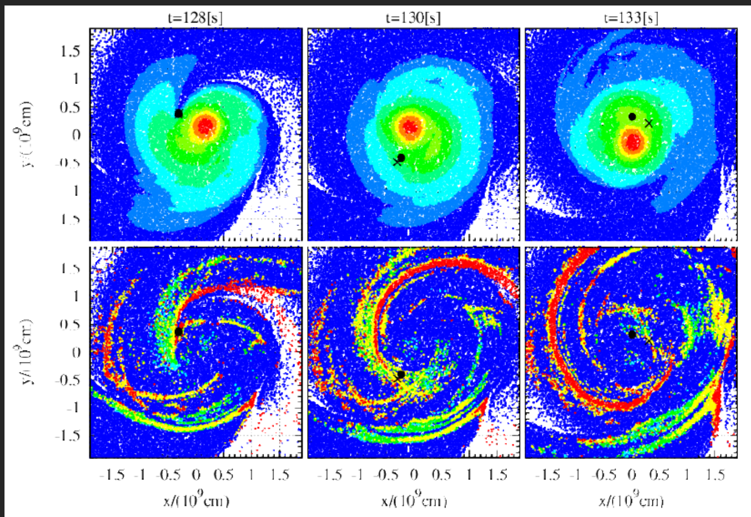
Explosion not yet

Tanikawa+ (w/ KM) submitted

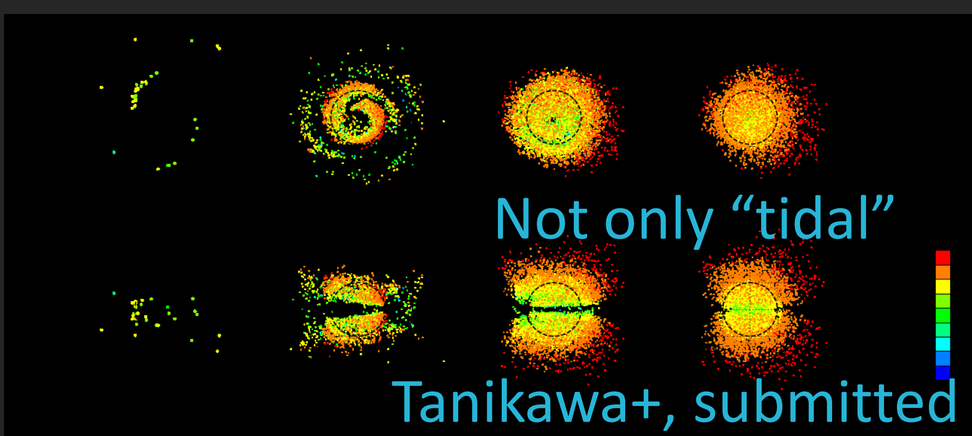
Sato+ (w/ KM) submitted

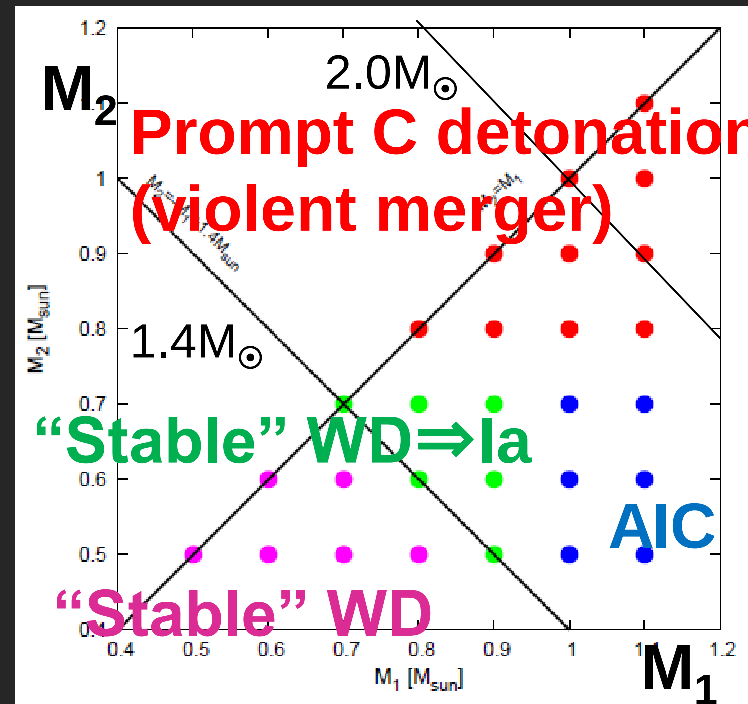
Increasing Attentions to Merging WDs

Sato+, submitted



Mass Ejection (1.1 COWD + 1.0 COWD)



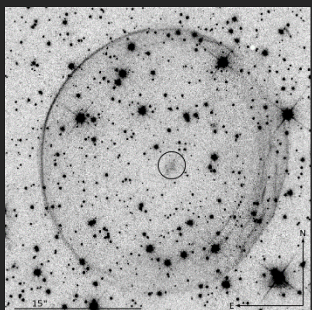


Prompt only for super-Ch.

“Delayed” Ch. WD explosion

Tanikawa, Sato, Nakasato, Nomoto, Hachisu, KM

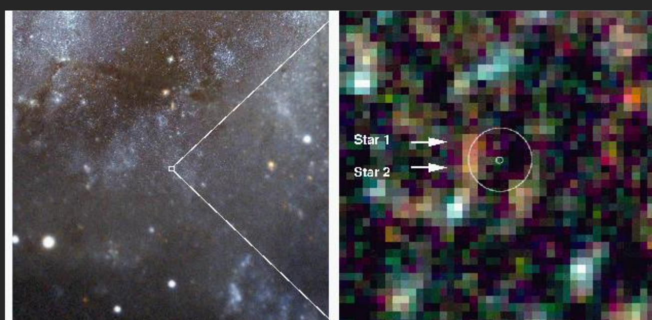
Companions in pre-SN/SNRs



LMC SNR 0509-67.5: Against RG/MS
Schafer & Pagnotta 2010

SN 1006: Against RG González Hernández+ 2012

Tycho: Controversial Ruiz-Lapuente+ 2004, …

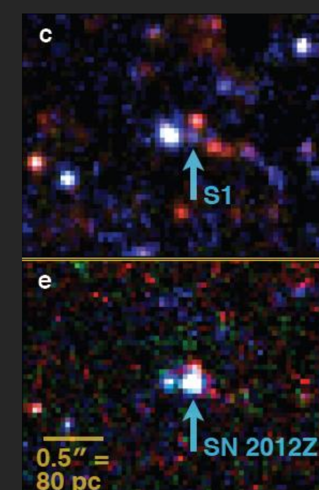


Li+ 2011

SN 2011fe: Against RG down to ~ 1 $M_\odot$

SN 2014J: Against RG down to ~ 1 $M_\odot$

Kelly+ 2014 and some He donor



So far, seems to disfavor SD for normal’s.

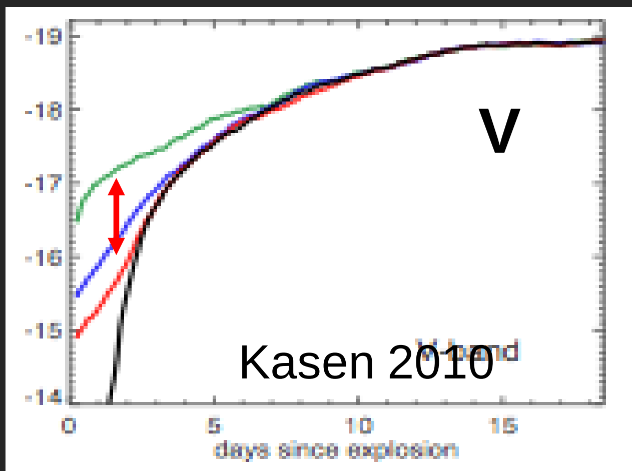
McCully+ 2014

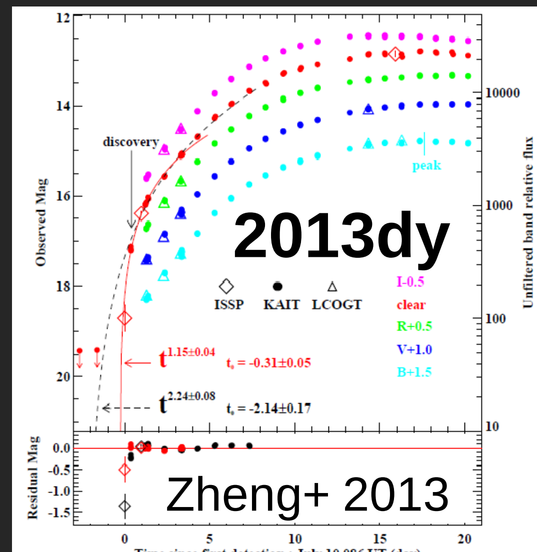
SN “Iax” 2012Z: He donor? He star progenitor?

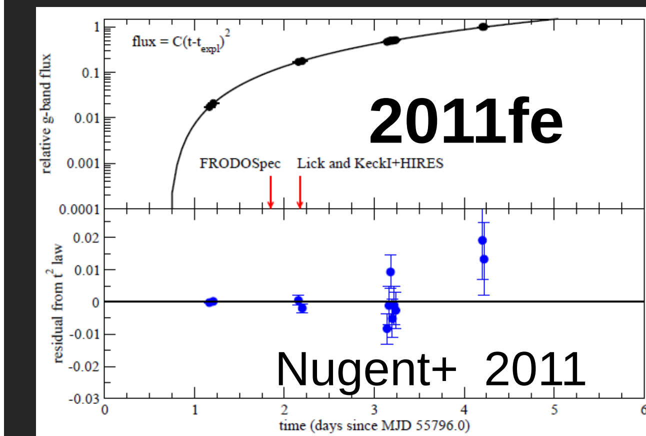
SN “Iax” 2008ha: Red source (post-SN). Foley+ 2014

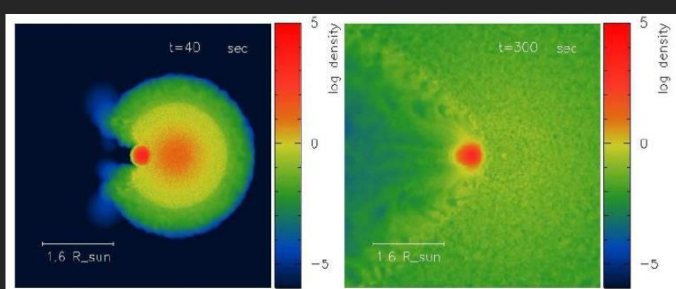
So far, seems to favor SD for peculiars.

Shock-deposited emission

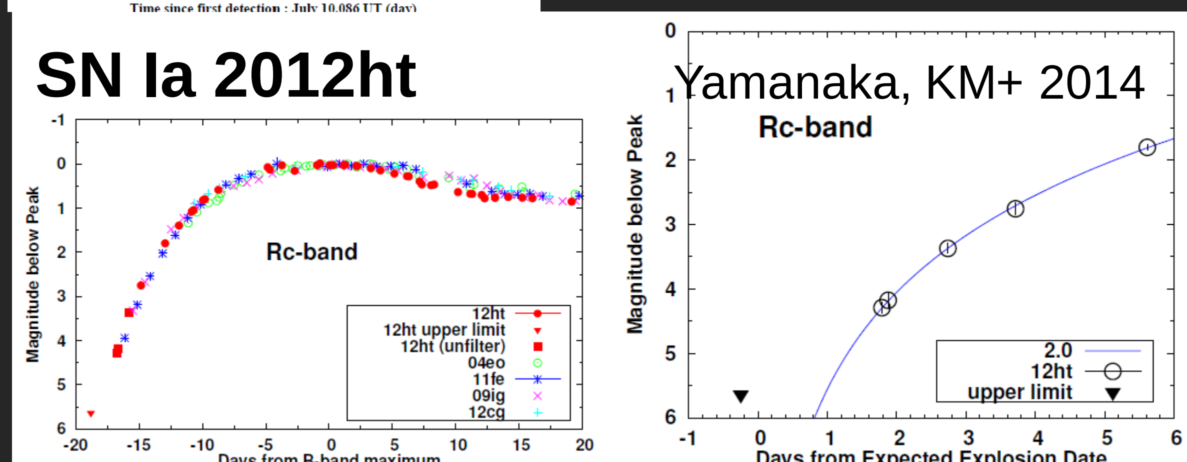








Liu+ (w/ KM), 2013

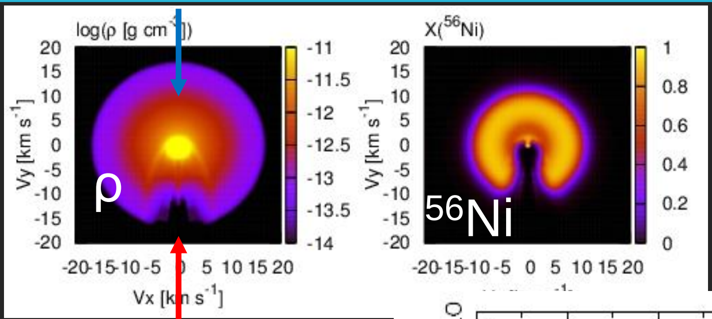


So far, no signature detected?

#possible – SNe 2011de (Brown 2014), 2014J (Goobar+ 2014)

KM, Kutsuna, Shigeyama, 2014, ApJ

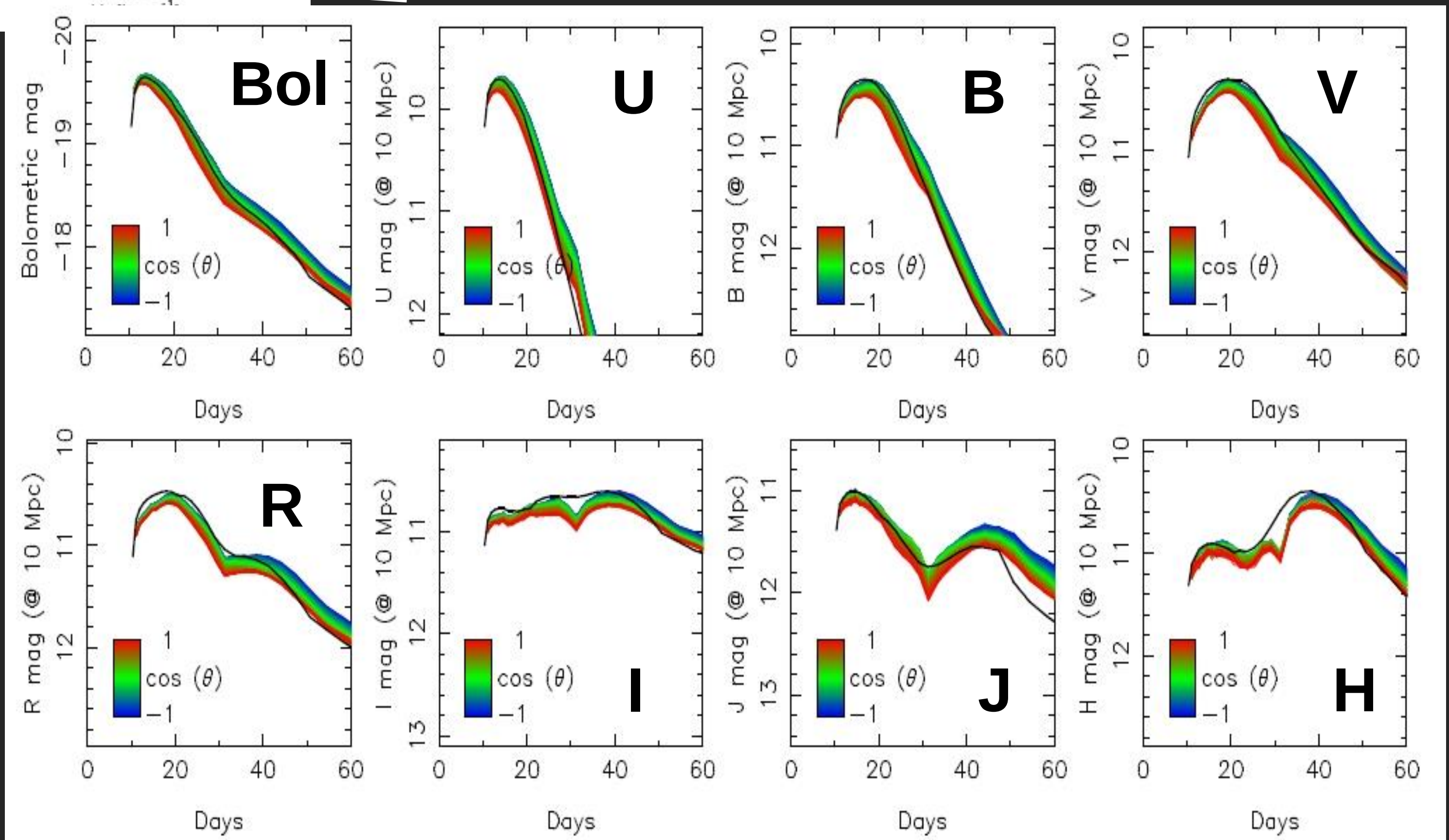
Signatures of a companion at max/post-max?



Radiation Hydro (w/ simplified transfer)

Detailed multi-D transfer (frequency-dependent w/ 0.5M transitions)

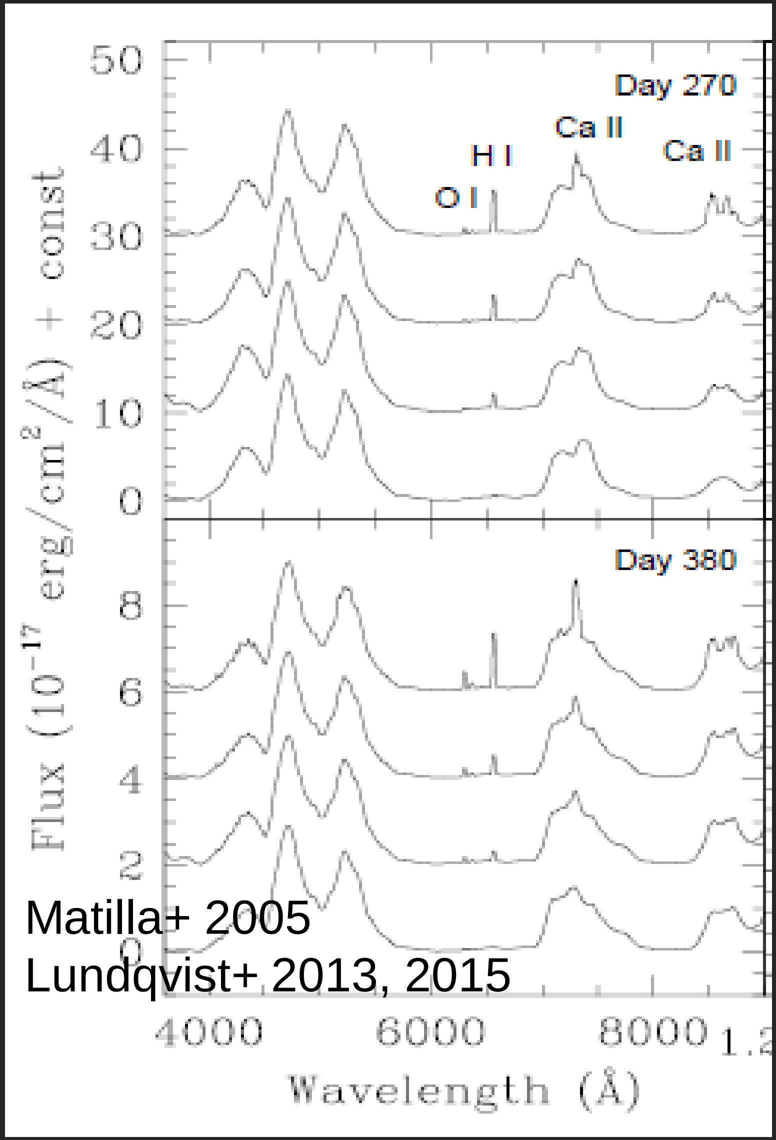
Companion
No companion
Opposite

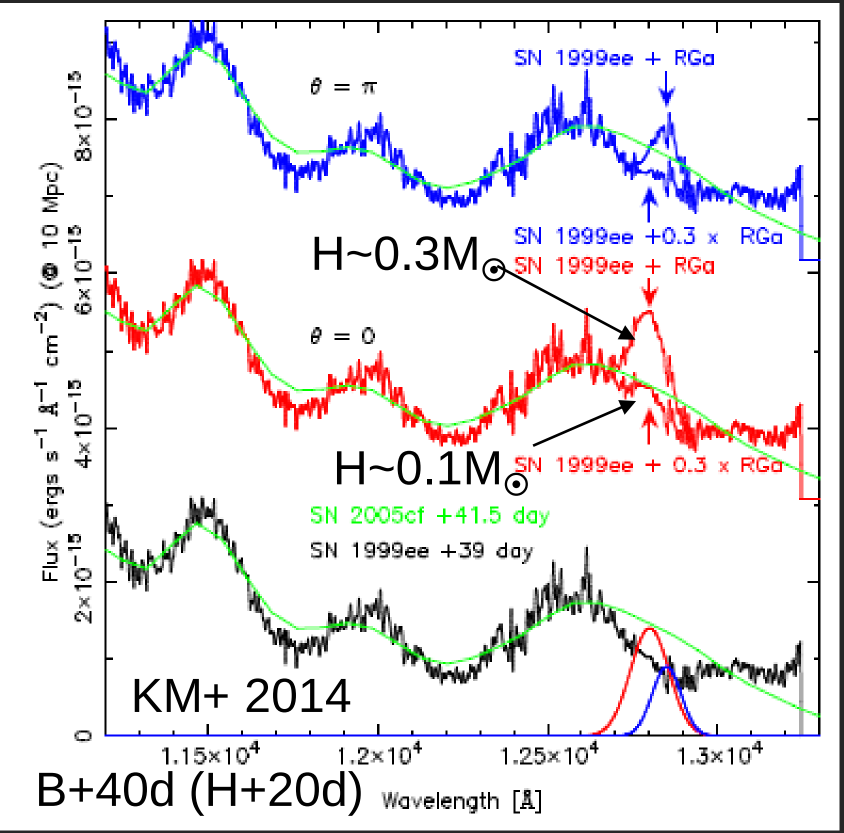


~0.1 mag level (statistically detectable)

Companion **not** rejected (≠ Kasen+ 2004)

No hydrogen in mid/late-phases





No signature of contaminated H-envelope so far
(but the observation is tough)

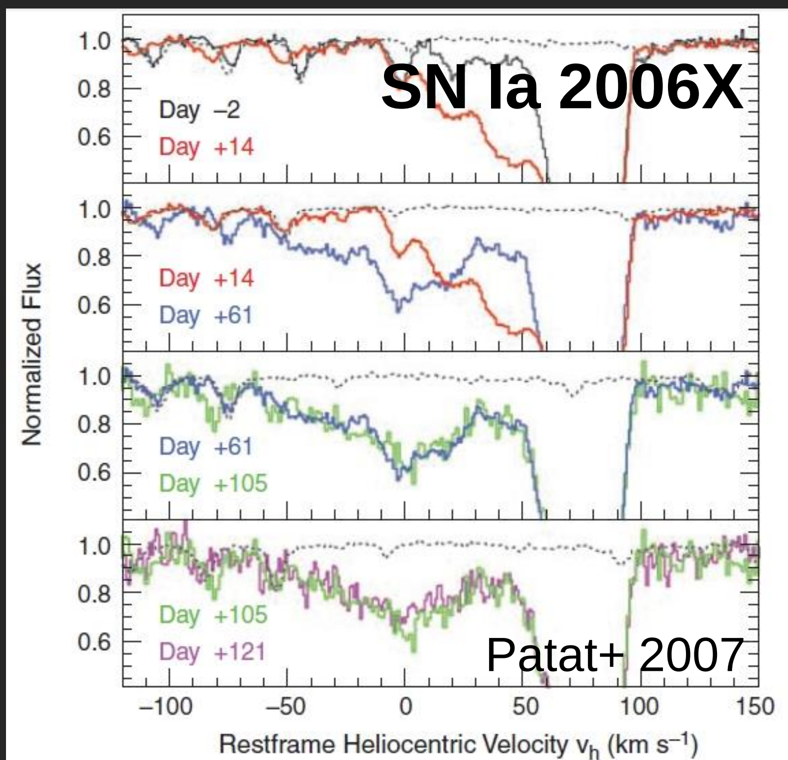
CSM – another key

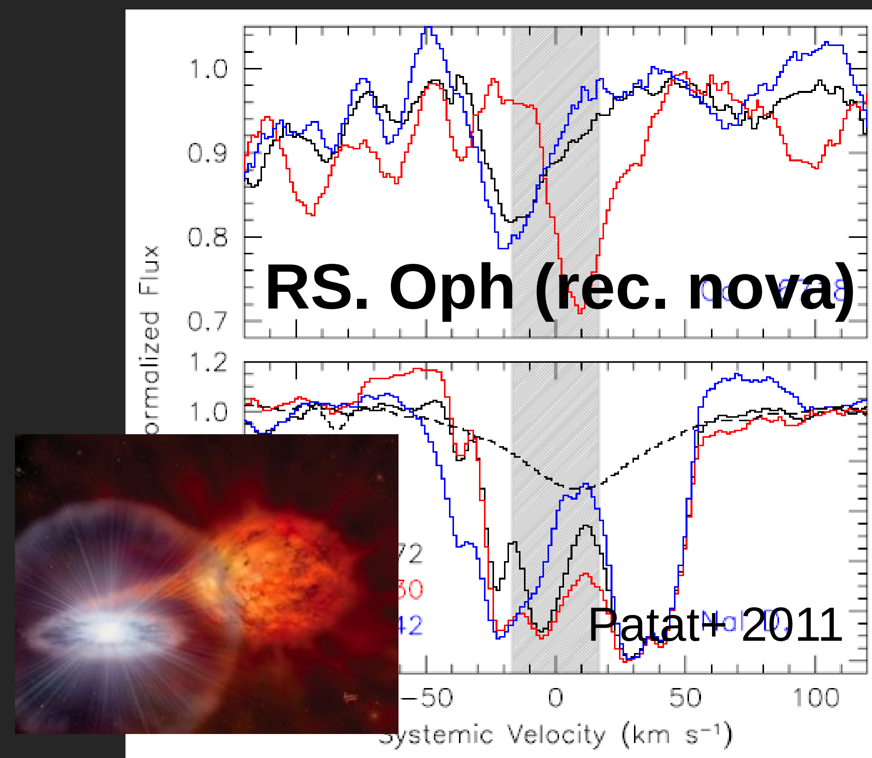
SN Background

CSM Abs.

ISM Abs.

Time variability = CSM
(Generally) Need high-res.





No Variation for SN 2014J?

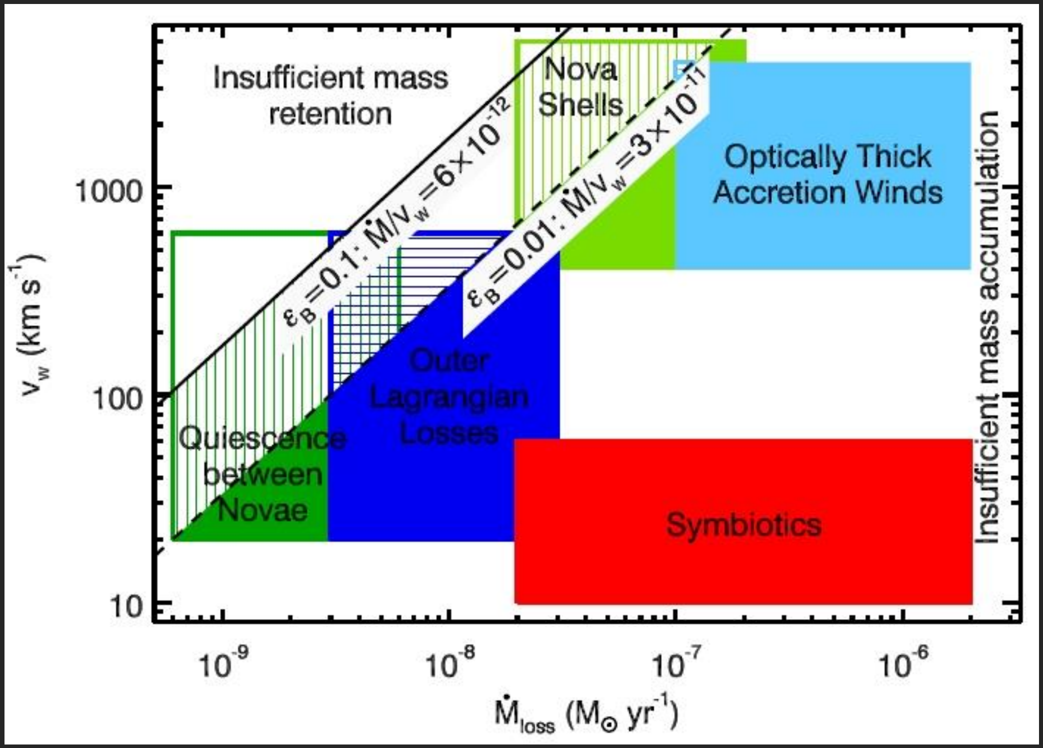
(but possible KI variation; Graham+ 2014)

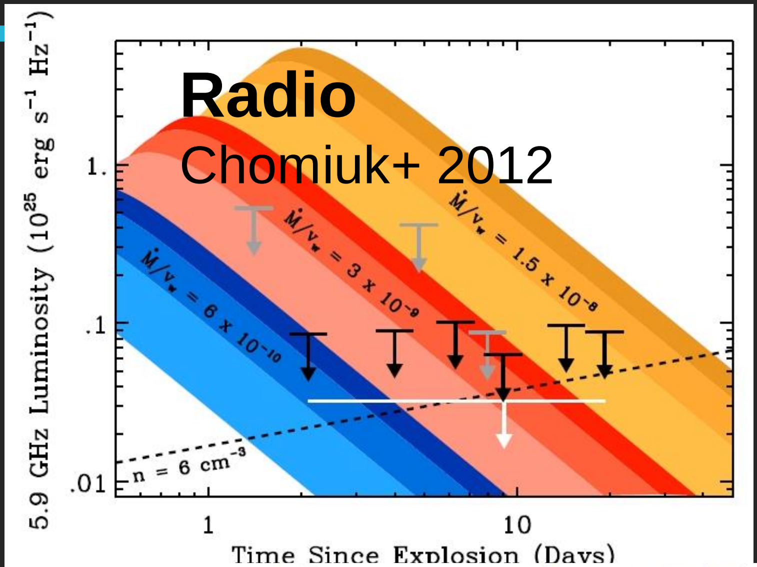
Subaru (HDS) ongoing: KM+

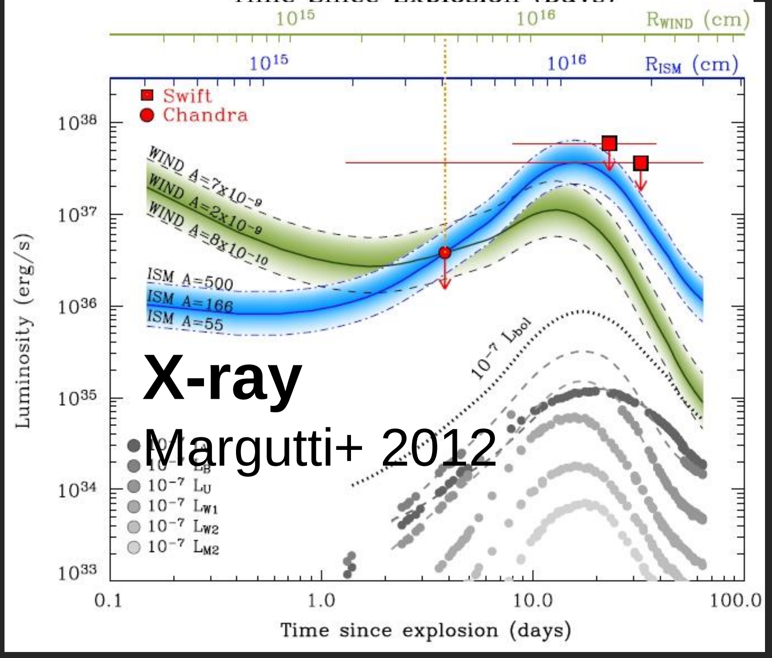
Back in the history of ~ 100 day x ($V_{SN}/V_{mass\text{-}loss}$) ~ 30 yrs (~ 0.01 pc)

CSM around "normal" SNe Ia

Tight limit for SN 2011fe (<0.01pc):
M_{dot}/v_w < ~$10^{-8} M_\odot yr^{-1}/100 km\ s^{-1}$





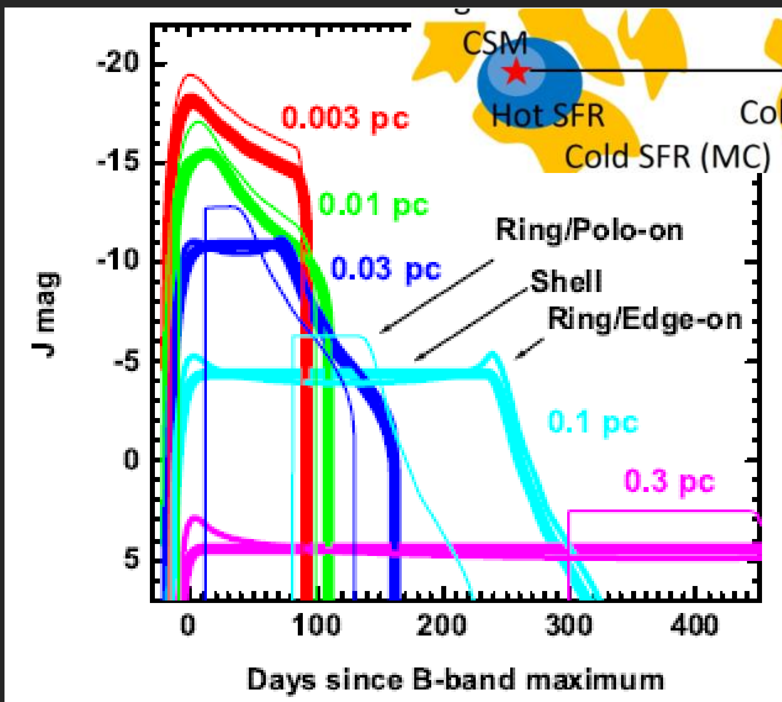


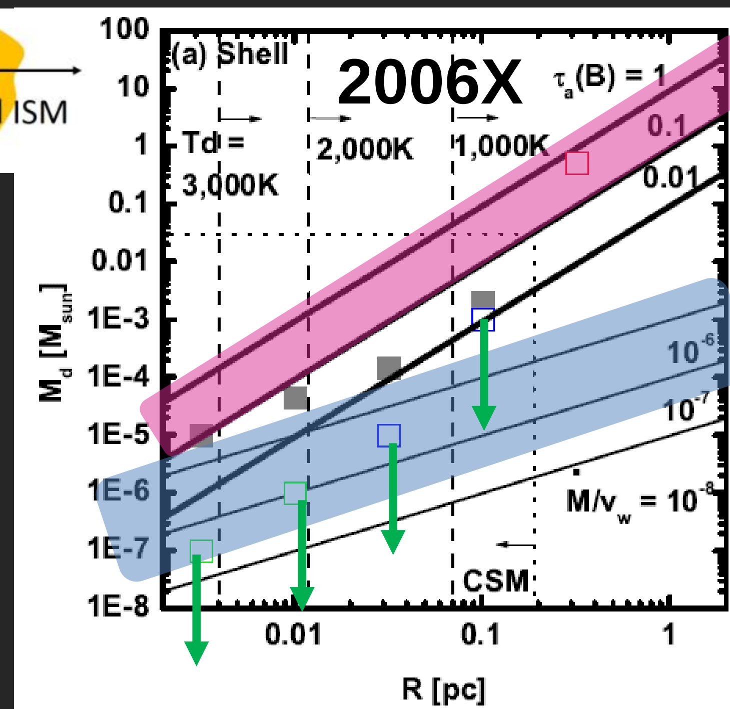
Radio: Synchrotron

X-Ray: Inverse Compton (+ thermal)

Back in the history of ~ 100 day x ($C/V_{mass-loss}$) ~ 300 yrs (~ 0.1 pc)

CSM around "normal" SNe Ia





CSM extinction

Symbiotic Model (SD)

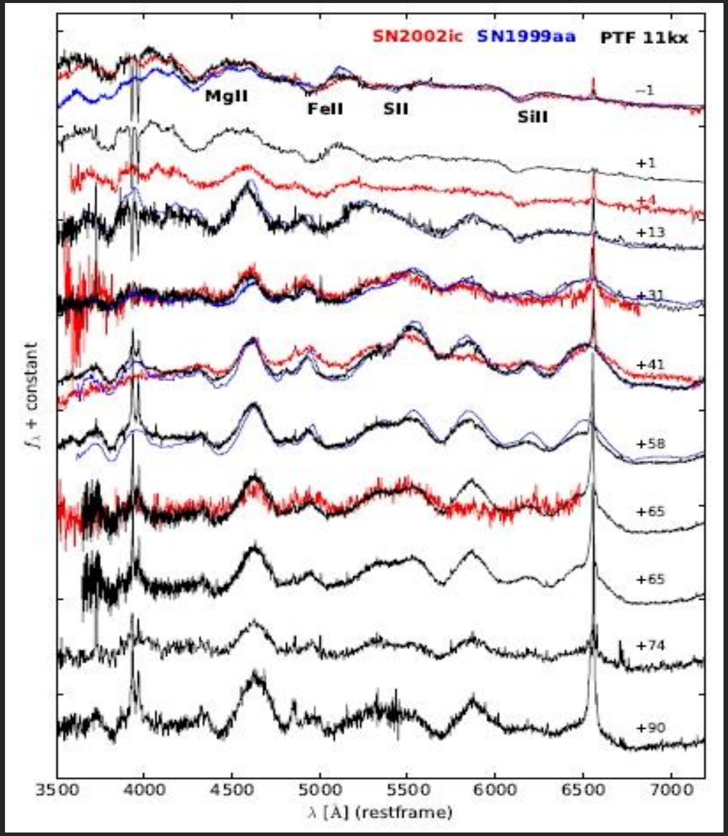
No CS-dust echo seen in (normal) SNe Ia.
There is little CSM (dust) at R < 0.5pc.

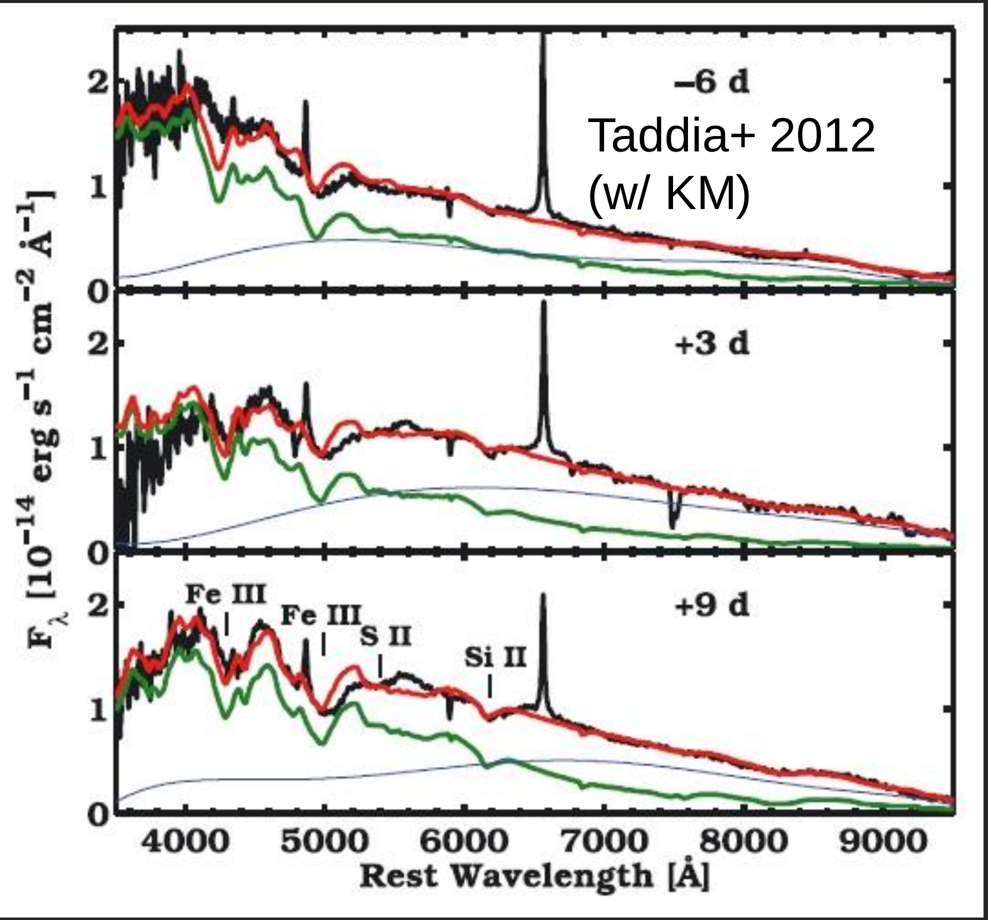
 # SNe Ia's extinction law suggested to originate in CSM (Goobar 2008), but it is generally not the case.

KM, Nozawa, Motohara, submitted.

SNe Ia within dense CSM?

Dilday+ 2012



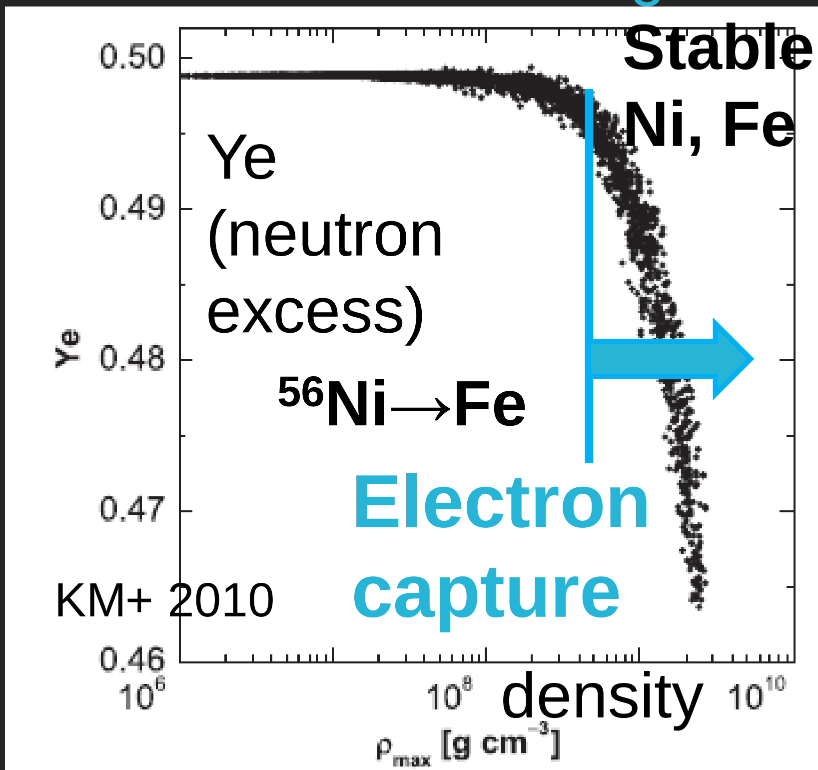


SNe Ia colliding with Nova shells? (← Single degenerate)
Associated SNe are SN 1991T-like (normal but bright-end)

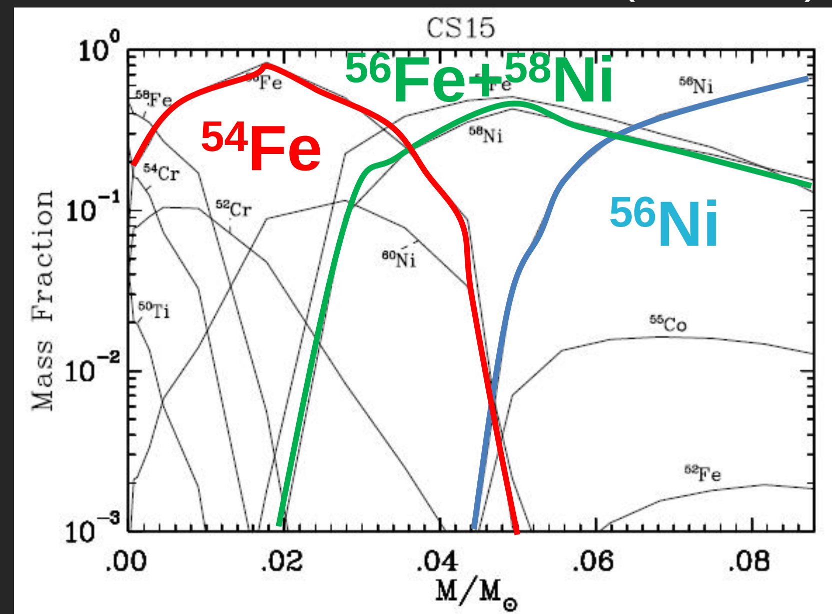
Leloudas+ 2015 (w/ KM)

Chandrasekhar or sub-Ch WD?

A few 10^8 g cm^{-3}



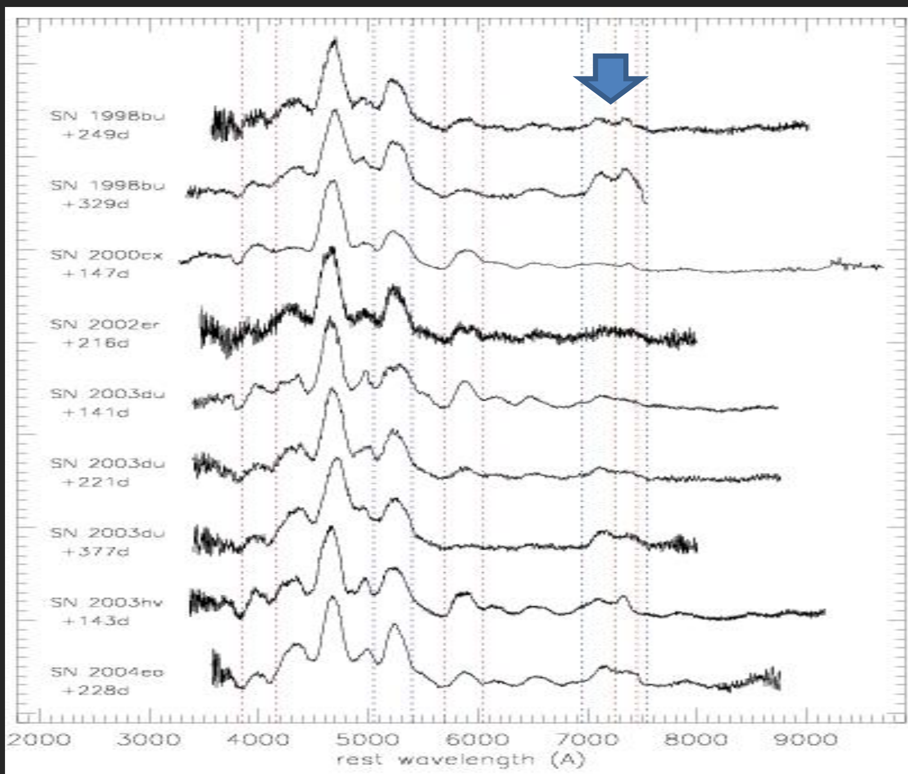
W7 model (Nomoto)



after a few hundred days). We emphasize that the late-time spectroscopy is currently the most effective way to hunt for the signature of the DDT model in the innermost region. See also Maeda et al. (2010) who discussed the following points in details.

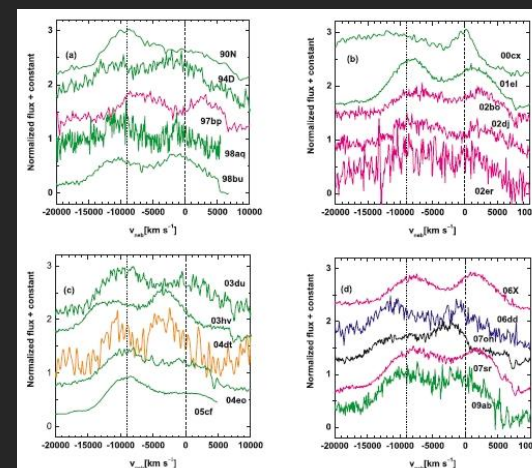
electron capture

"Stable" Fe-peaks: Smoking gun?



Stable Fe/Ni is there.

Motohara, KM+ 2006
Mazzali+ 2008, Science
KM+ 2010, ApJ; KM+ 2010 Nature



Chandrasekhar favored

after a few hundred days). We emphasize that the late-time spectroscopy is currently the most effective way to hunt for the signature of the DDT model in the innermost region. See also Maeda et al. (2010) who discussed the following points in details.

electron capture

Yamaguchi+ (w/ KM), submitted

Stable Ni in Galactic SN remnant(s)

The strongest Ni so far,
requiring Mch WD.

Variations – Ni weaker in Tycho, Kepler, etc.

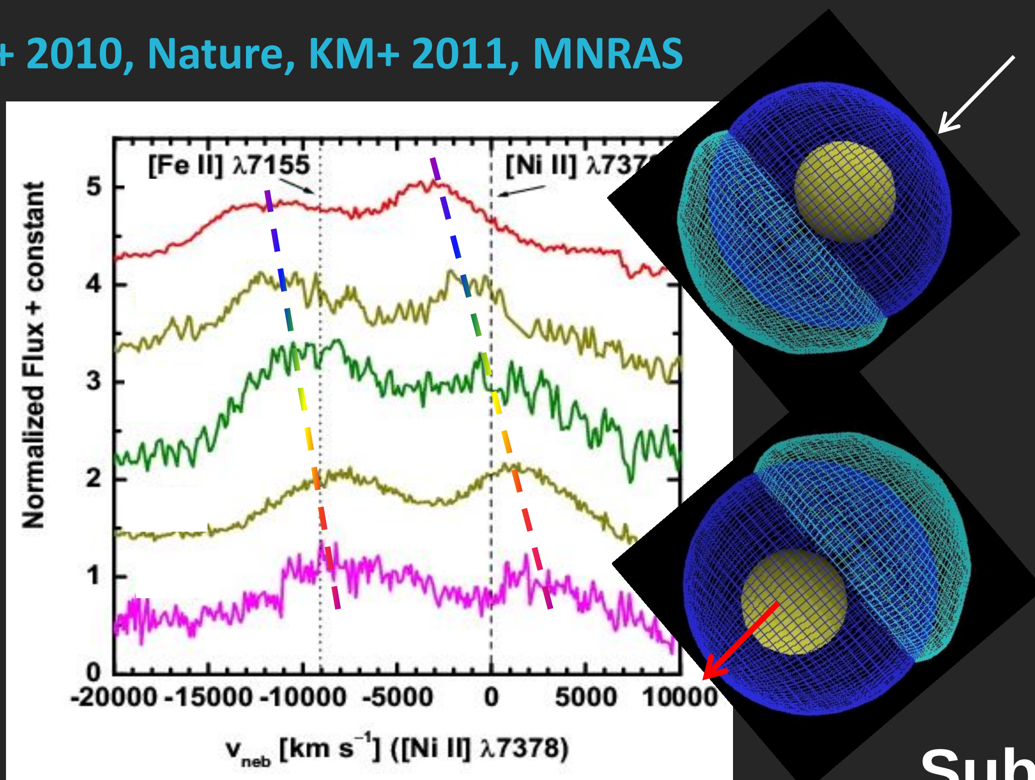
(e.g., Park+2013, Yamaguchi+ 2014)

Type Ia Supernovae are not spherical

Some SNe showing blueshift in the “stable-Ni” core, while others showing redshift.

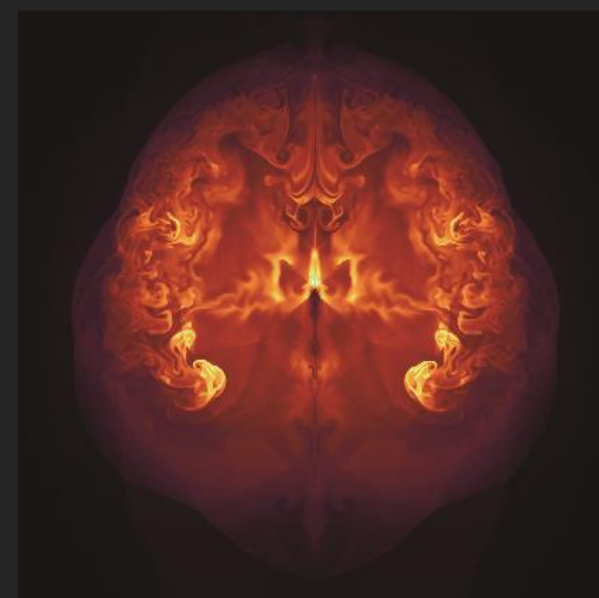
⇒ “Offset” in kinematics + viewing angle.

KM+ 2010, Nature, KM+ 2011, MNRAS



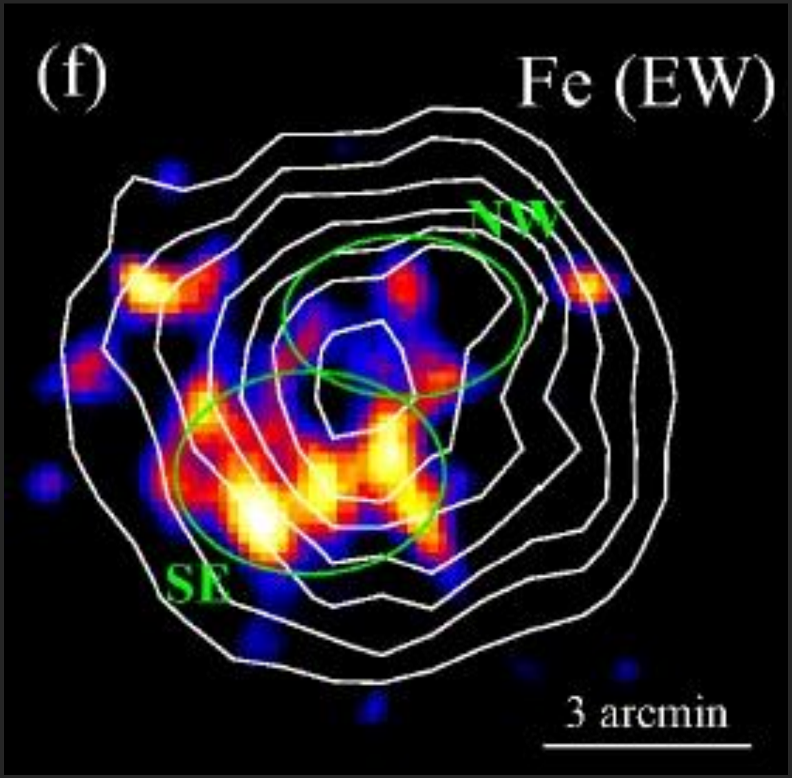
Blueshift ←

Redshift →



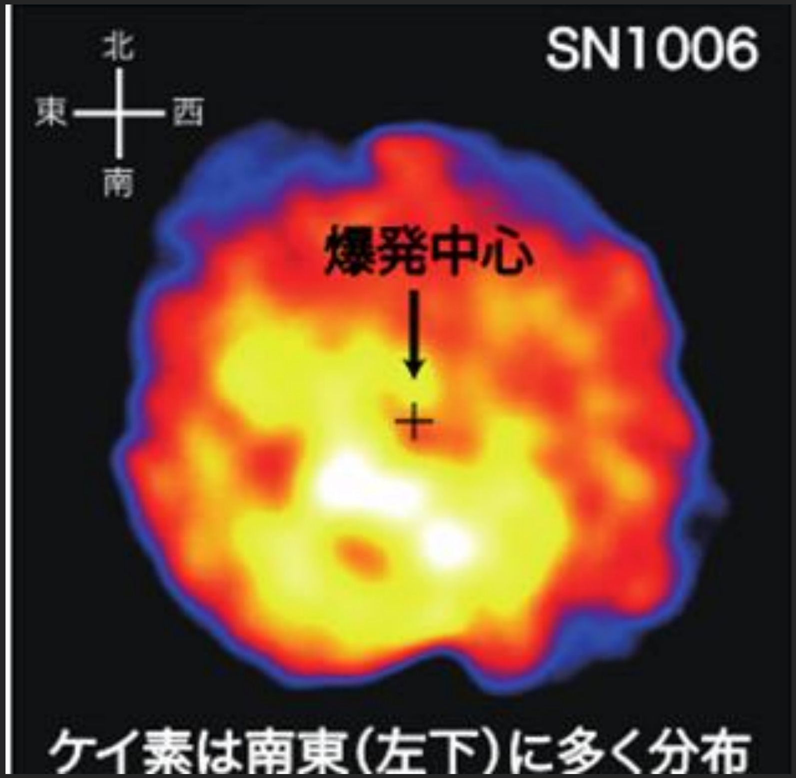
Subaru ongoing: KM+
Optical FOCAS / NIR IRCS

Asymmetry in SN Ia Remnant?



G344.7-0.1 (Suzaku)

Yamaguchi, Tanaka, KM+ 2012

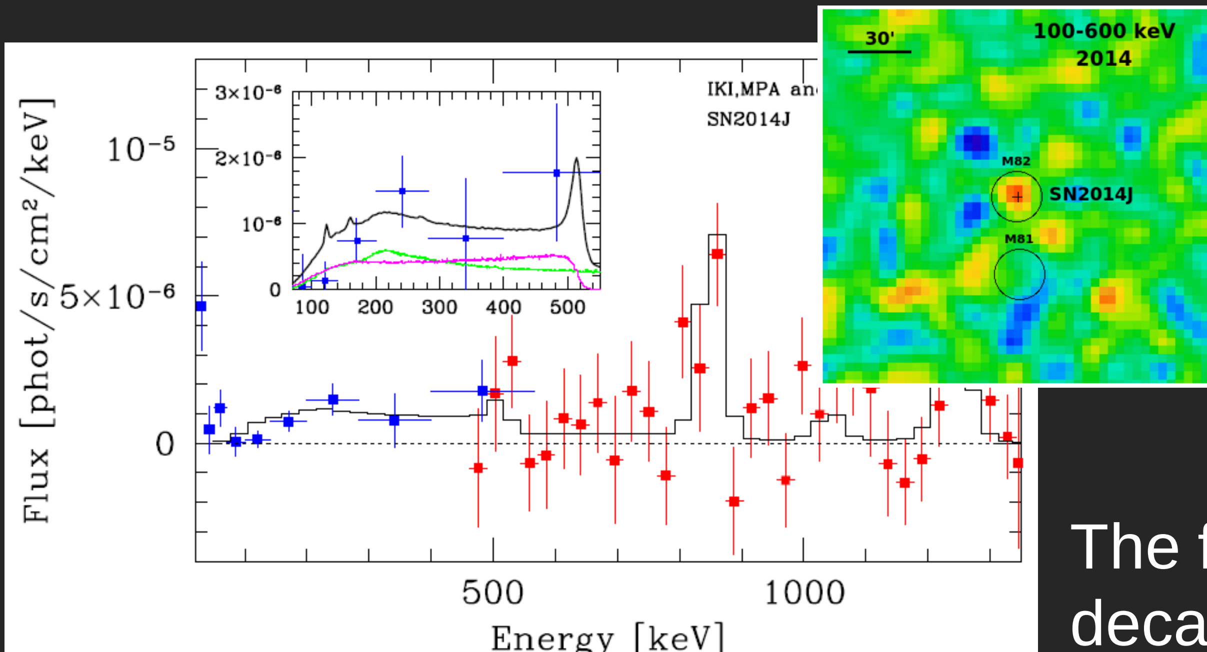


SN1006 (Suzaku)

Uchida+ 2013

INTEGRAL detection of MeV γ from SN Ia 2014J (~ 6 Ms in total)

Solid confirmation of thermonuclear nature



日経(8/1)


超新星爆発、仕組み解明

京大など 星の表面でも核反応

巨大な星が最期を迎えた時に起きる超新星爆発の詳しい仕組みを京都大の前田啓一准教授らが解明した。従来は星の中心部で核反応による爆発が起きると考えられていたが、表面近くでも起きていた。星が消滅するメカニズムを解明する手掛かりになる。独マックスプランク研究所との共同研究成果で、米科学誌サイエンス（電子版）に8月1日掲載された。

前田准教授らは宇宙空間に浮かぶ「インテグラル」という欧州の望遠鏡を使って、爆発時の核反応で出るガンマ線をとらえた。地球から約1千万光年離れた恒星が燃え尽きてできる「白色わい星」を観測した。

これまでは星の中心部で核反応が起きるため、ガンマ線の観測は爆発から数カ月後と考えられていたが、わずか18日後に検出した。これは星の表面近くで核反応が起きたためとみられる。研究チームは白色わい星の近くにある「連星」と呼ぶ別の天体から核反応を引き起こすヘリウムが流れ込み、表面で爆発が起きたとみている。

SN Ia 2014J
@M82
Most nearby
SN Ia
since 1986

The first detection of ^{56}Ni/Co decays from SNe Ia.

Diehl+ 2014 (w/ KM), Science
Churazov+ 2014, Nature
Diehl+ (w/ KM) 2015, A&A
Churazov+ 2015, ApJ (submitted)

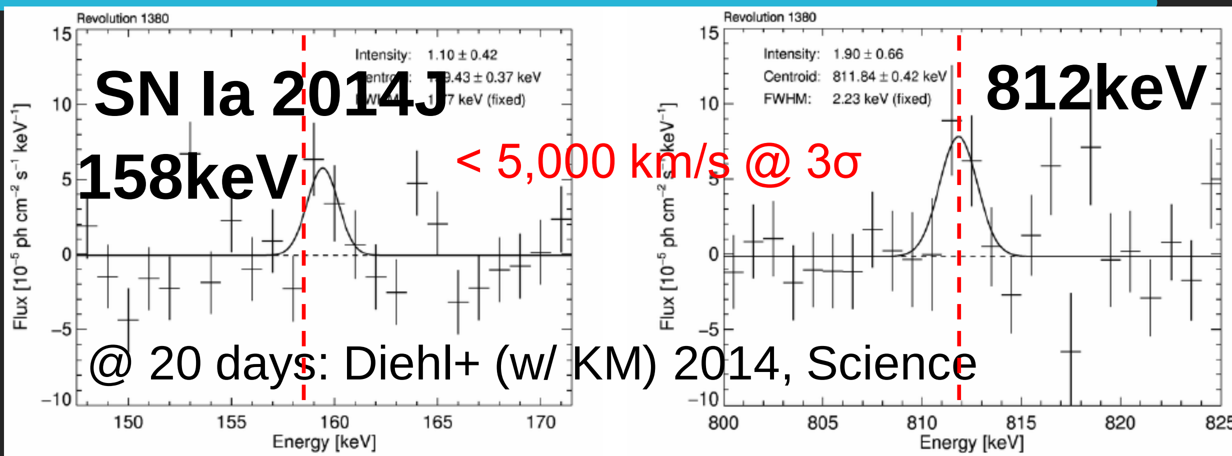
Confirmation of basic concept of thermonuclear explosion,

but…

Suzaku hard-X data to come (DDT by Terada, KM+)
For “next” nearby SNe Ia:
INTEGRAL ToO Ongoing (Diehl w/ KM) ⇒ Future Astro-H?

Seen both in IBIS and SPI
SPI analyzed by two independent groups

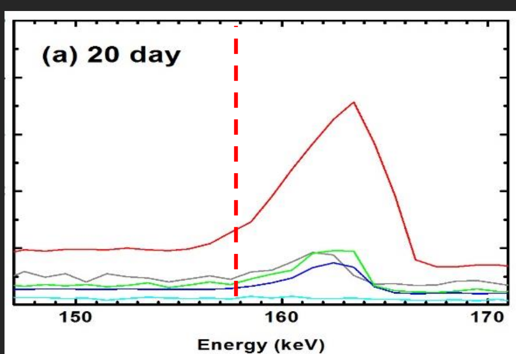
MeV Diagnostic Power: SN explosion physics



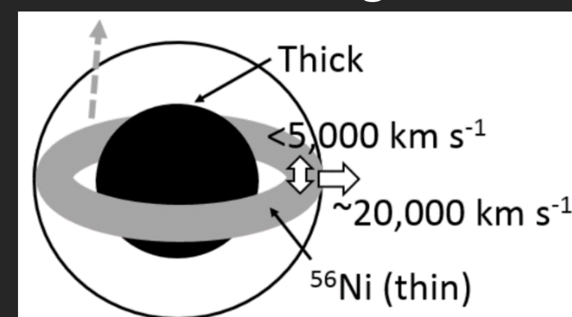
Challenge to theories
Early emergence
Small Doppler shift

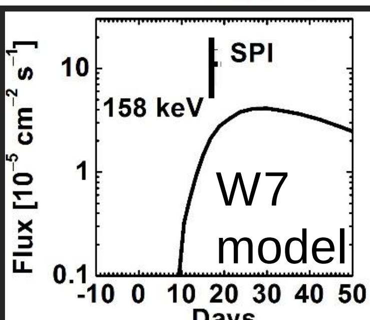
⇒ Suggested scenario
WD + He donor
Surface He ignition

(**not** a leading model!)



Model Prediction
KM, Terada+ 2012





SN 2014J looks like quite normal in optical.

- The model applies to SNe Ia in general?
- Variations even if optical is identical?

⇒ Need at least another few SNe detected.

Summary

- **Lots of progress, but still many unresolved problems in progenitors and explosions.**
- **Type Ia Supernovae.**
  - **Progenitor issue:** DD generally favored, but some supports for SD.
    - SD especially supported for outliers.
    - DD supported by "no-evidence for SD". Need more work.
  - **Explosion issue:** Delayed-detonation (SD w/ Chandrasekhar WD) is the best.
    - Nucleosynthesis & asymmetry.
    - Need more work especially for DD.
  - **Problem: So far mush less predicting power in DD than SD.**