Hunting the Progenitors of Supernovae Type Ia

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Supernova Type Ia (SNIa) play a key role in stellar and galaxy evolution and cosmology

Distance indicators

Element factories

Cosmic-ray accelerators

Kinetic energy sources

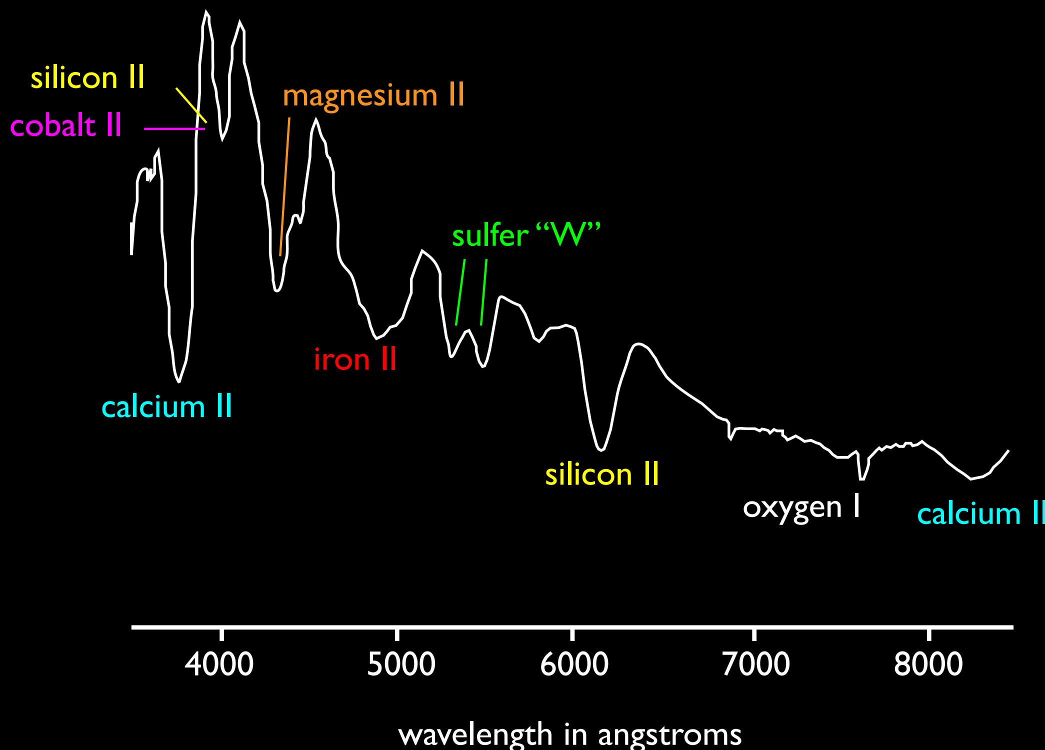
Endpoints of stellar binary evolution

SNIa occur at a rate of ~30/s in the observable universe, but identification of what is exploding remains unknown - this is the outstanding mystery in the field.

SNIa are defined by their spectra:

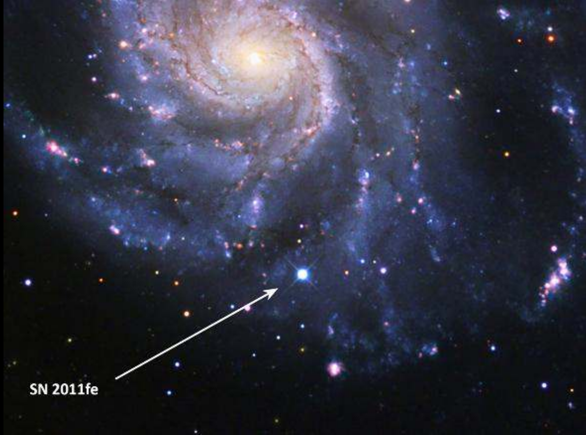
1) the lack of hydrogen lines

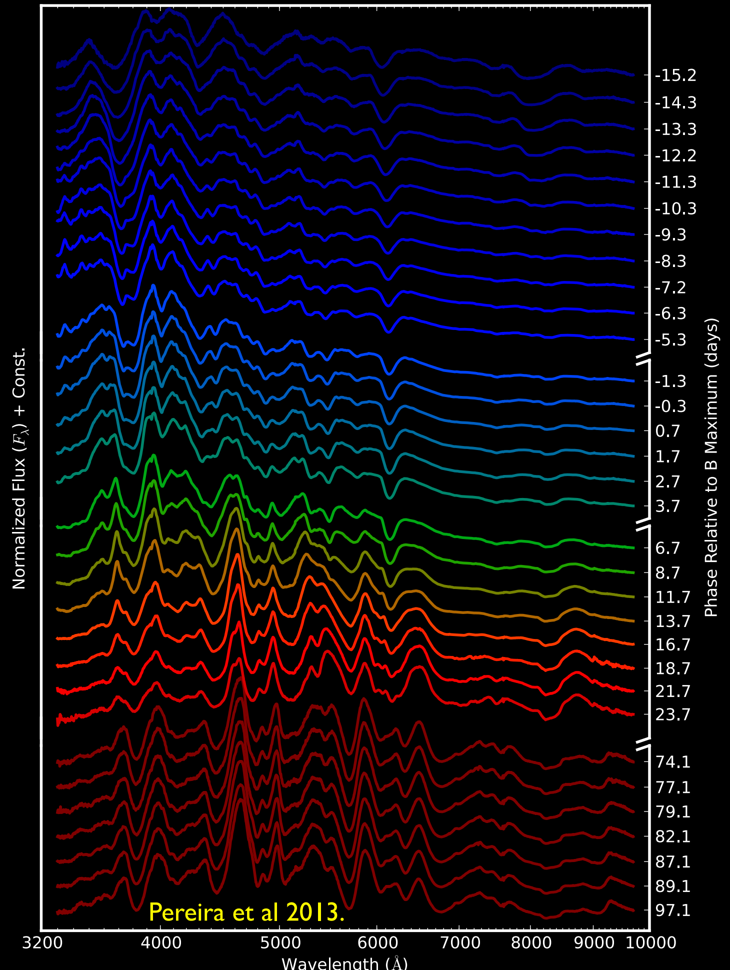
2) a strong Si II absorption feature



Once defined, here are several observational characteristics which may help in the search for progenitors:

Nearly 90% of all SNIa form a homogeneous class in terms of their spectra, light curves, and peak absolute magnitudes.

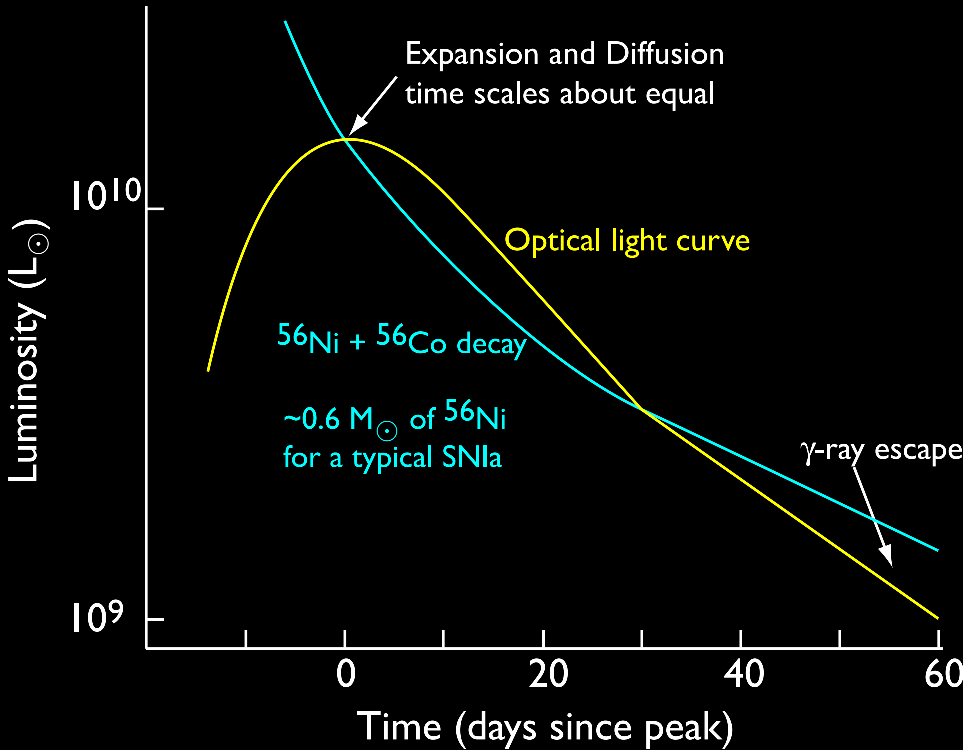




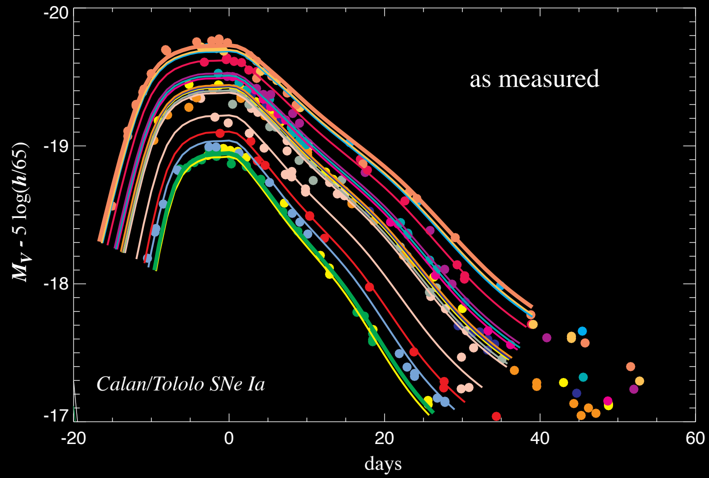
Near maximum light, spectra are characterized by O-Ca at high velocity (8k-30k km s^{-1}).

In the late, nebular phase, the spectra are dominated by lines of iron.

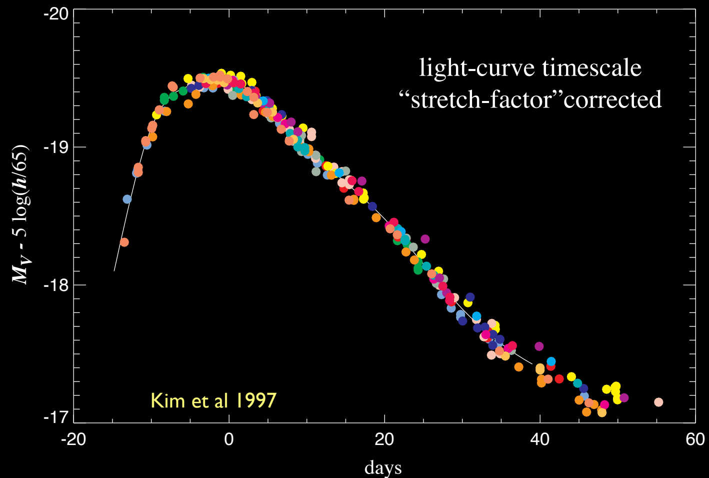
There exist a number of correlations between different pairs of observables, including one between the absolute magnitude and the shape of the light curve.



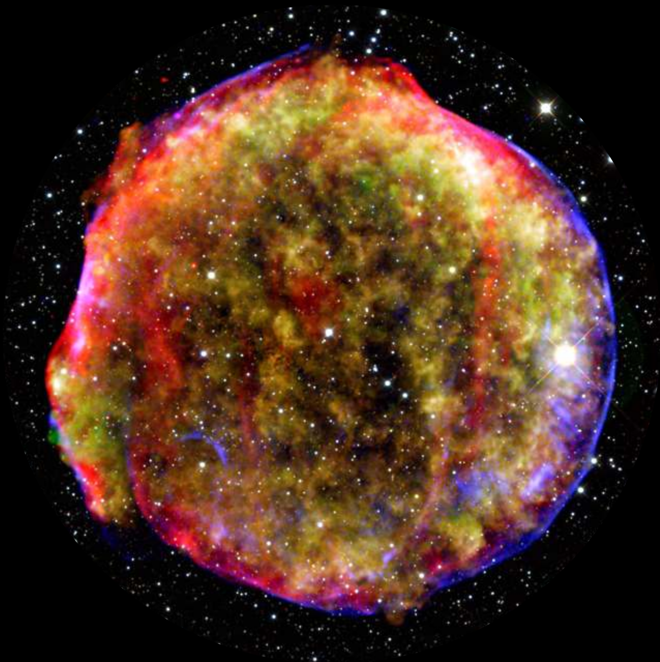
Brighter is broader.



This can be used to correct for intrinsic variations in the peak luminosity to give a standard candle.



After correction, the dispersion in luminosity distance is ≤ 7%.



Tycho Supernova Remnant:
NASA's Spitzer, Chandra, &
Spain's Calar Alto

Green & Yellow - iron and silicon

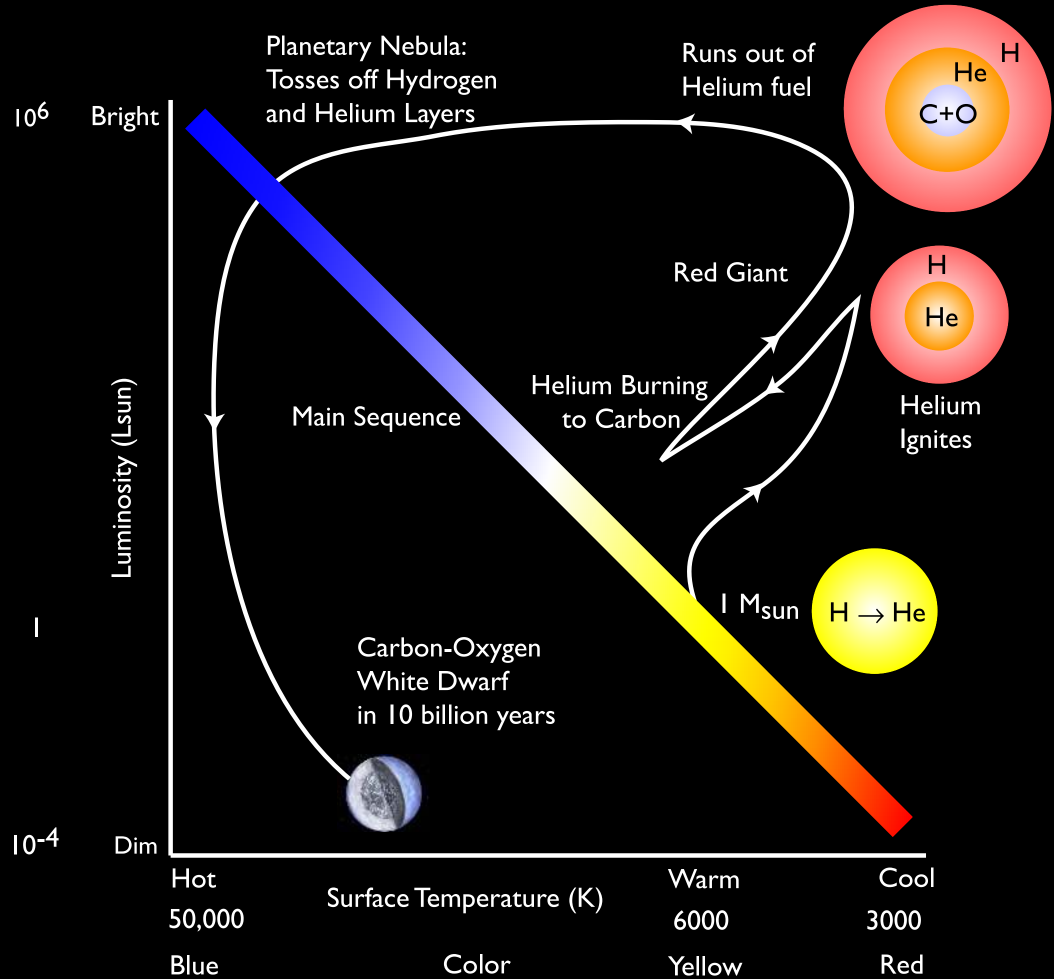
Blue - shocked electrons

Red - dust

Age: 442 years
Distance: ~ 7500 ly
Diameter: ~ 0.8' (18 ly)
Expansion: ~ 0.3''/year

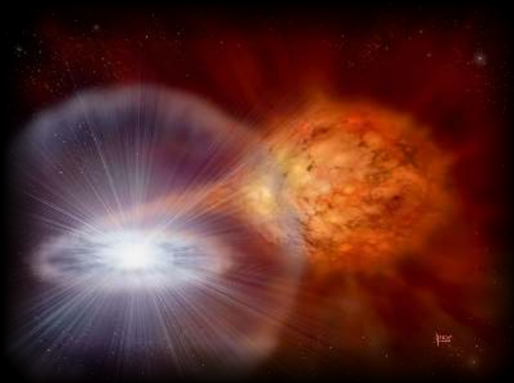
A successful model starting from a carbon+oxygen white dwarf must make

0.1 - 1.0 $M_\odot$ ^{56}Ni	for the light curve
0.2 - 0.4 $M_\odot$ Si, S, Ar, Ca	for the spectrum
< 0.1 $M_\odot$ ^{54}Fe + ^{58}Ni	for the nucleosynthesis
Not too much O close to ^{56}Ni	for the spectrum
Allow for some diversity	for fun



Planetary Nebula:
Tosses off Hydrogen
and Helium Layers
Runs out of
Helium fuel
H
He
C+O
10^6
Bright
Red Giant
H
He
Helium Burning
to Carbon
Helium
Ignites
Main Sequence
Luminosity (Lsun)
1 M_{sun}
H → He
1
Carbon-Oxygen
White Dwarf
in 10 billion years
10^{-4}
Dim
Hot
Surface Temperature (K)
Warm
Cool
50,000
6000
3000
Blue
Color
Yellow
Red

Single-Degenerate channel



The relative frequency of these channels in unknown.

Double-Degenerate channel

Mergers:

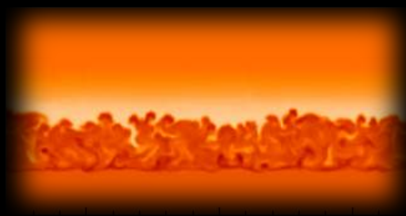
Collisions:

Standard paradigm single-degenerate pathway:

accretion

Hardy 2006

simmering

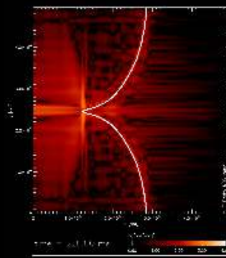


Dursi et al 2001

ignition

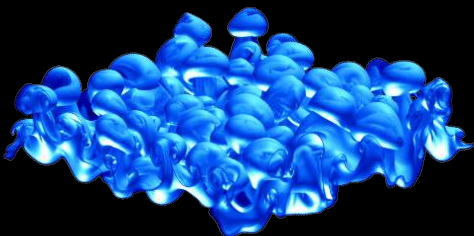
NKG 2004

subsonic flame



Röpke 2001

instabilities



Zingale et al 2006

detonation?

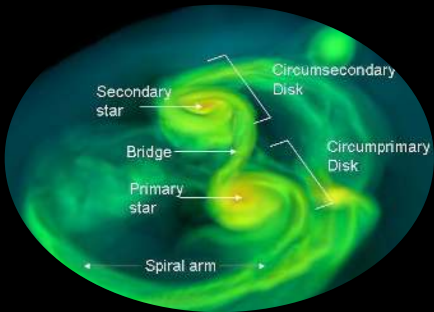
LANL 1945

supernova

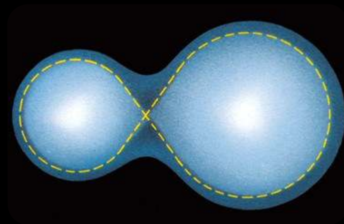
NASA

Standard double-degenerate merger pathway:

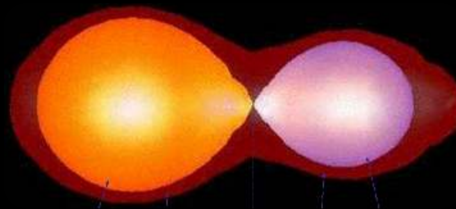
binary birth



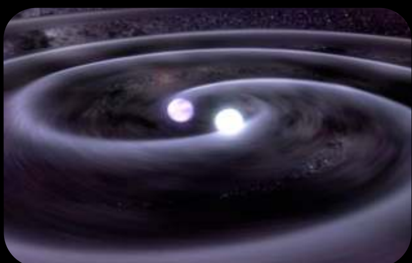
common envelope #1



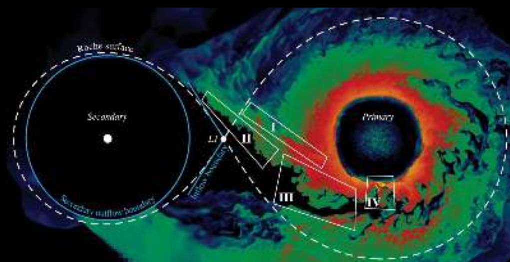
common envelope #2



angular momentum loss

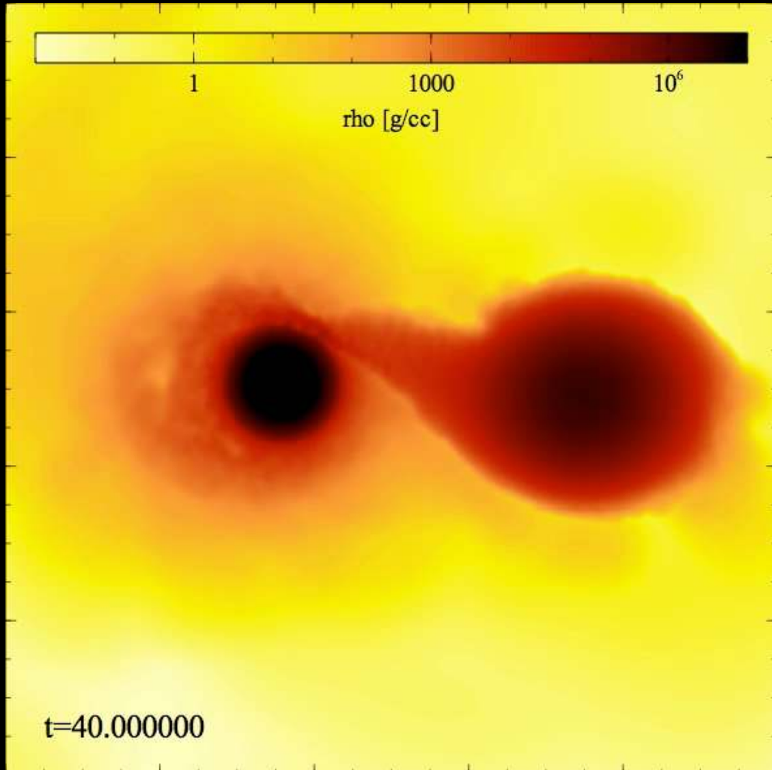


surface detonation?



Guillochon et al 2010

supernova

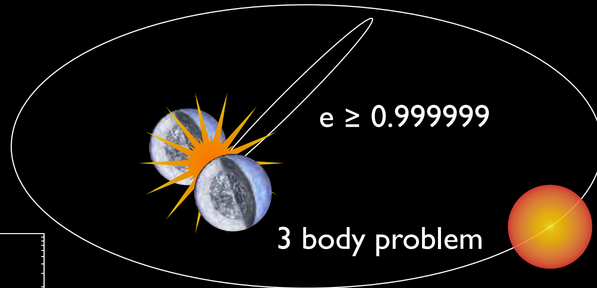


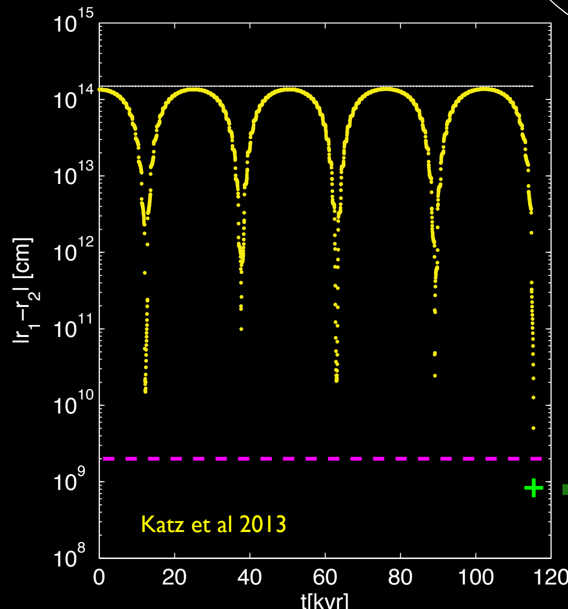
Raskin et al 2012

A double-degenerate collision pathway:

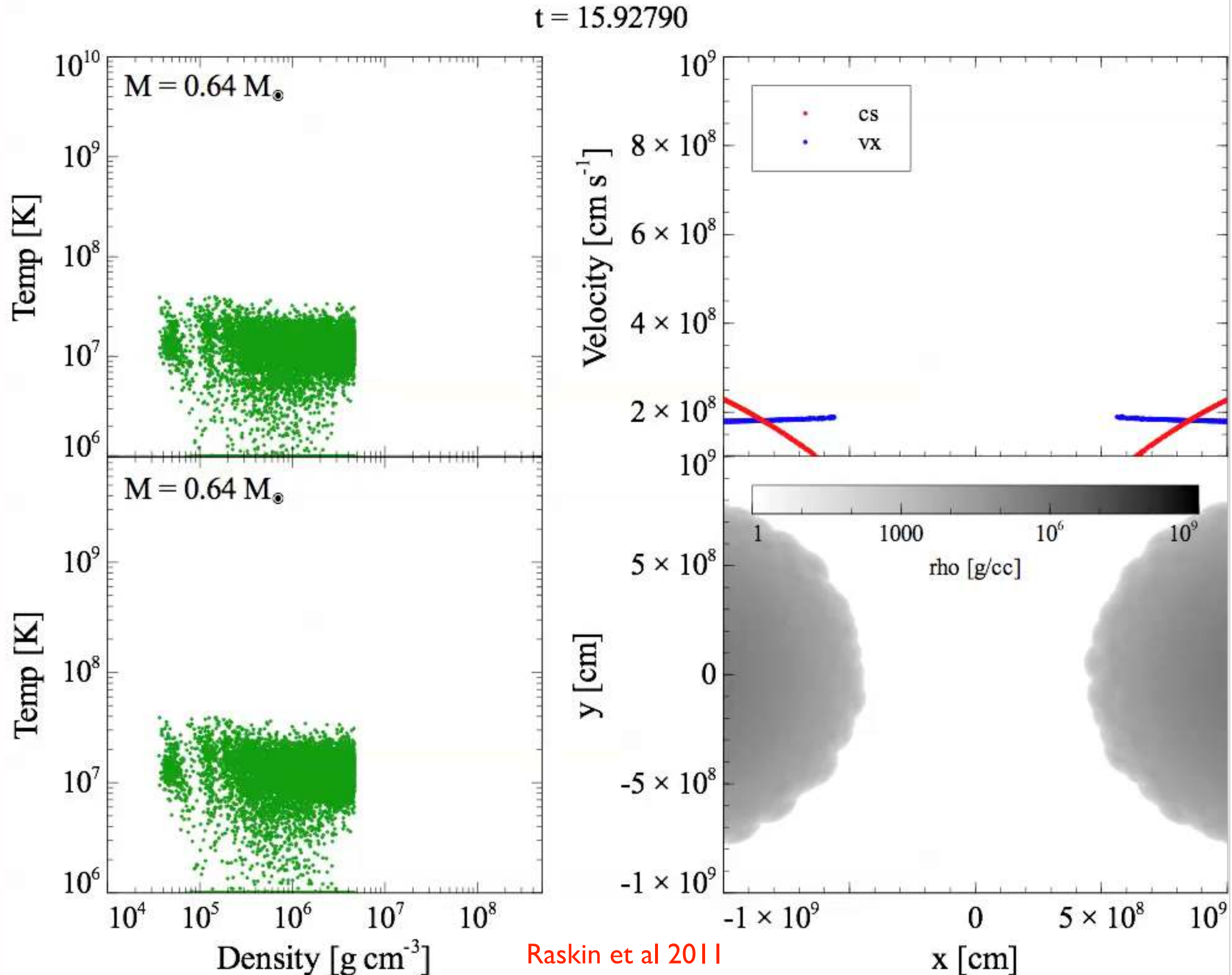
triple star system

Newtonian dynamics





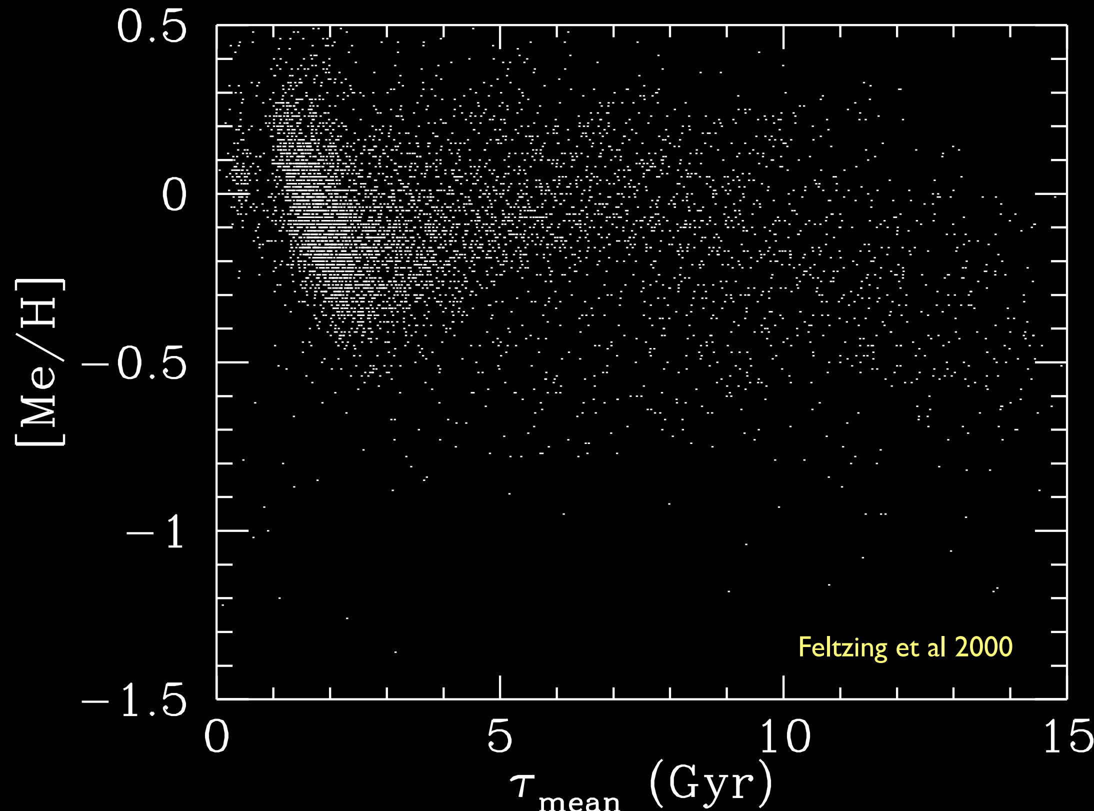
supernova



Raskin et al 2011

SNIA

Variations in the peak luminosity may originate in part from a scatter in the composition of the main-sequence stars that become white dwarfs.



A main-sequence star's initial metallicity comes from the CNO and ^{56}Fe inherited from its ambient interstellar medium.

All the CNO piles up at ^{14}N during hydrogen burning, because $^{14}N(p,g)$ is the slowest step in the CNO cycle.

During helium burning all of the ^{14}N is converted into ^{22}Ne by ^{14}N (a,g) ^{18}F (β^+,ν_e) ^{18}O (a,g) ^{22}Ne.

Pileups at ^{14}N and ^{22}Ne have been repeatedly verified for ~40 years. This is standard stellar evolution.

Mass and charge conservation set the white dwarf's neutron enrichment.

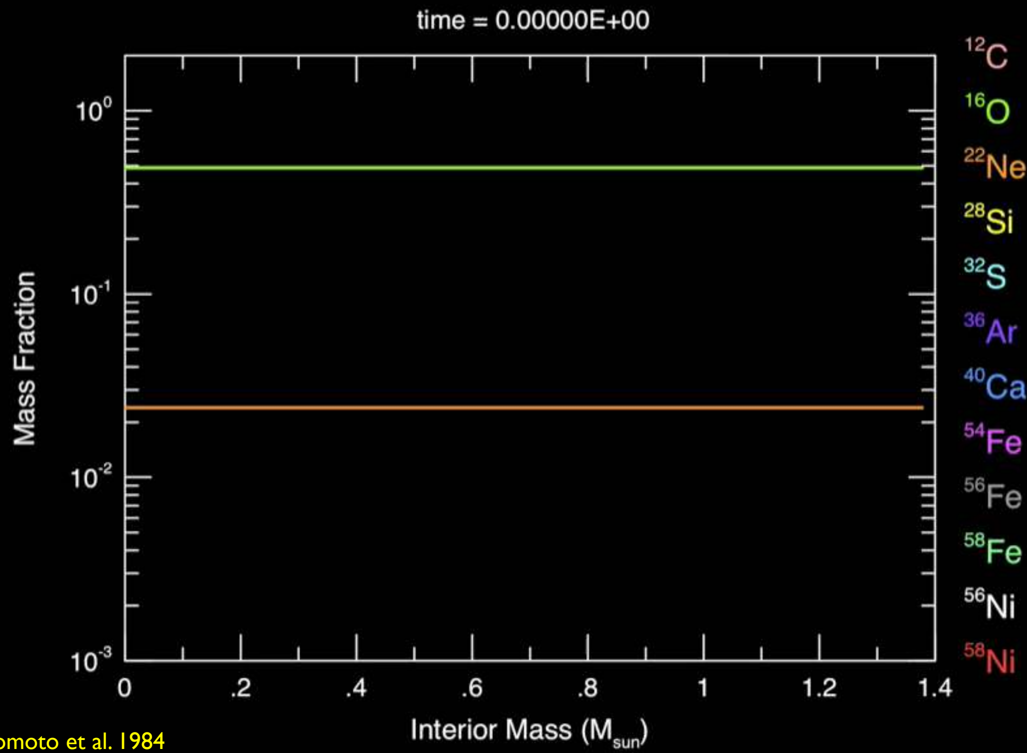
$$\sum_{i=1}^{n} \mathrm{X}_i = 1 \qquad \mathrm{Y}_e = \sum_{i=1}^{n} \frac{\mathrm{Z}_i}{\mathrm{A}_i} \mathrm{X}_i$$

$$\mathrm{X}(^{22}\mathrm{Ne}) = 22\left[\frac{\mathrm{X}(^{12}\mathrm{C})}{12} + \frac{\mathrm{X}(^{14}\mathrm{N})}{14} + \frac{\mathrm{X}(^{16}\mathrm{O})}{16}\right]$$

$$\mathrm{Y}_e = \frac{10}{22}\,\mathrm{X}(^{22}\mathrm{Ne}) + \frac{26}{56}\,\mathrm{X}(^{56}\mathrm{Fe}) + \frac{1}{2}\left[1 - \mathrm{X}(^{22}\mathrm{Ne}) - \mathrm{X}(^{56}\mathrm{Fe})\right]$$

Assuming the ^{22}Ne and ^{56}Fe are uniformly distributed.

SNIa models make most of their ^{56}Ni in nuclear statistical equilibrium between 0.2 - 0.8 M_{sun}, where weak reactions don't change the number of neutrons since they occur on time-scales longer than the explosion.



W7-like, Nomoto et al. 1984

If ^{56}Ni and ^{58}Ni are the only species in NSE, mass and charge conservation

$$\sum_{i=1}^{n} \mathrm{X}_i = 1 \qquad \mathrm{Y}_e = \sum_{i=1}^{n} \frac{\mathrm{Z}_i}{\mathrm{A}_i} \mathrm{X}_i$$

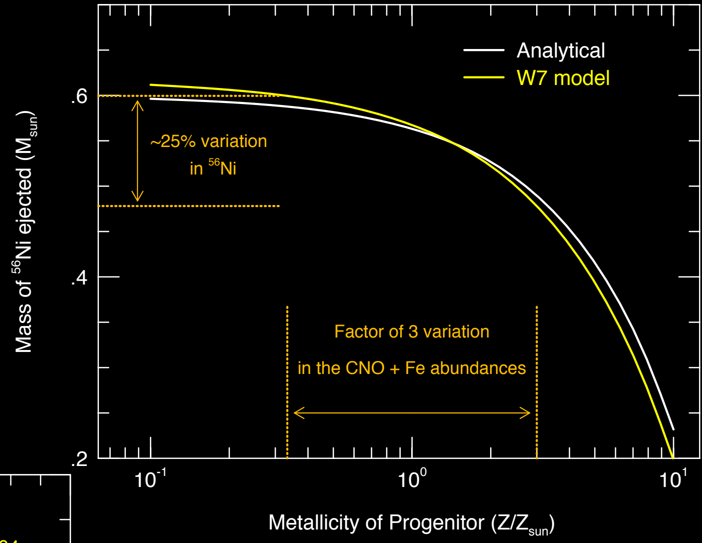
imply a linear relationship between the mass fraction of ^{56}Ni and Y_e:

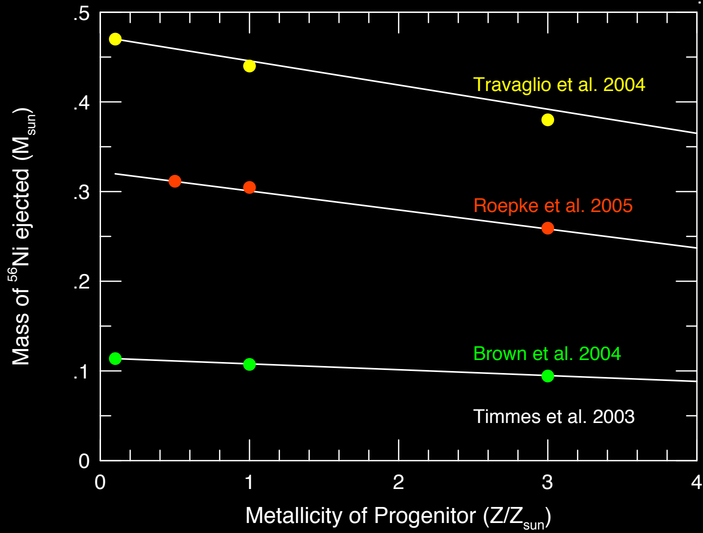
$$X(^{56}\mathrm{Ni}) = 1 - X(^{58}\mathrm{Ni}) = 58\mathrm{Y}_e - 28$$

We can set the final Y_e equal to the initial Y_e of the white dwarf since weak interactions are not dominant where most of the ^{56}Ni is made.

$$\mathrm{X}(^{56}\mathrm{Ni}) = 1 - 0.057 \frac{Z}{Z_\odot}$$

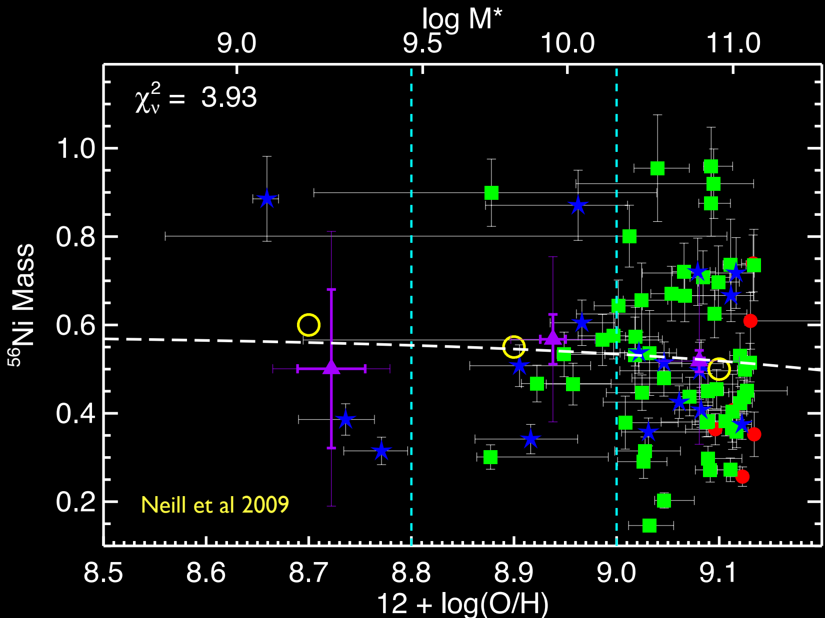
Explosion models confirm the analytical result.





$$\mathrm{M}(^{56}\mathrm{Ni}) = \mathrm{M}(^{56}\mathrm{Ni})_{Z=0} \left[1 - 0.057\frac{Z}{Z_\odot}\right] M_\odot$$

Observations find consistency with the analytical result, but the trend is smaller than predicted and there is considerable scatter.

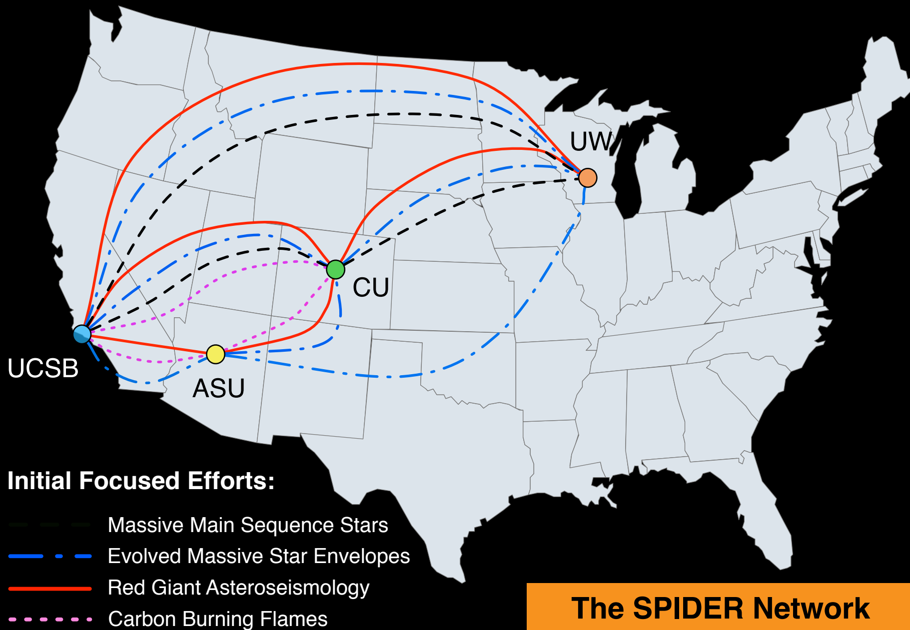


Constraining a metallicity dependence is challenging:

1) assumes galaxy metallicity = supernova metallcity

2) may be a stronger dependence on mean stellar age

SPIDER



The SPIDER Network

Node	**ASU** Arizona State University	**UW** University of Wisconsin	**CU** University of Colorado	**UCSB** University of California Santa Barbara
Fundamental Theory	Stellar Evolution, Flames, Supernovae, Nucleosynthesis	Massive Stars, Asteroseismology, Waves, MHD	Convection, Dynamos MHD, Waves, Helioseismology,	Stellar Evolution, Supernovae, Asteroseismology
Computational Tools	MESA	GYRE	ASH CSS	MESA

If the composition of the white dwarf has an observable effect on the ^{56}Ni production and thus the SNIa light curve, it could have an effect on other elements as well.

From observed Si, S, Ca, and Fe abundances, we have developed a new tool which applies the QSE relations (in reverse!) to determine all the abundances and a measure of Y_e in the silicon group regions of individual SNIa.

The method begins with mass & charge conservation, and the constraints for a two-cluster QSE:

$$Y_n + Y_p + 28Y_{28\mathrm{Si}} + 32Y_{32\mathrm{S}} + 40Y_{40\mathrm{Ca}} + 54Y_{54\mathrm{Fe}} + 58Y_{58\mathrm{Ni}} = 1$$

$$Y_p + 14Y_{28\mathrm{Si}} + 16Y_{32\mathrm{S}} + 20Y_{40\mathrm{Ca}} + 26Y_{54\mathrm{Fe}} + 28Y_{58\mathrm{Ni}} = Y_e$$

$$Y_{\mathrm{SiG}} = Y_{28\mathrm{Si}} + Y_{32\mathrm{S}} + Y_{40\mathrm{Ca}} \qquad Y_{\mathrm{FeG}} = Y_{54\mathrm{Fe}} + Y_{58\mathrm{Ni}}$$

Then, from the defining QSE relations:

$$\frac{Y_{A,Z}}{Y_{A',Z'}} = f(\rho, T) Y_p^{Z-Z'} Y_n^{A-A'-(Z-Z')}$$

$$f(\rho, T) = \frac{G_{A,Z}}{G_{A',Z'}} \left(\frac{\rho N_A}{\theta} \right)^{A-A'} \exp\left(\frac{B-B'}{kT} \right)$$

$$\theta = \left(\frac{m_{\mathrm{u}} kT}{2\pi\hbar^2} \right)^{\frac{3}{2}}$$

We derive our first (nearly trivial) result

$$\Phi(T) = \frac{Y_{28\mathrm{Si}}}{Y_{32\mathrm{S}}}\left(\frac{Y_{40\mathrm{Ca}}}{Y_{32\mathrm{S}}}\right)^{1/2} = \exp\left(\frac{-1.25}{T_9}\right)$$

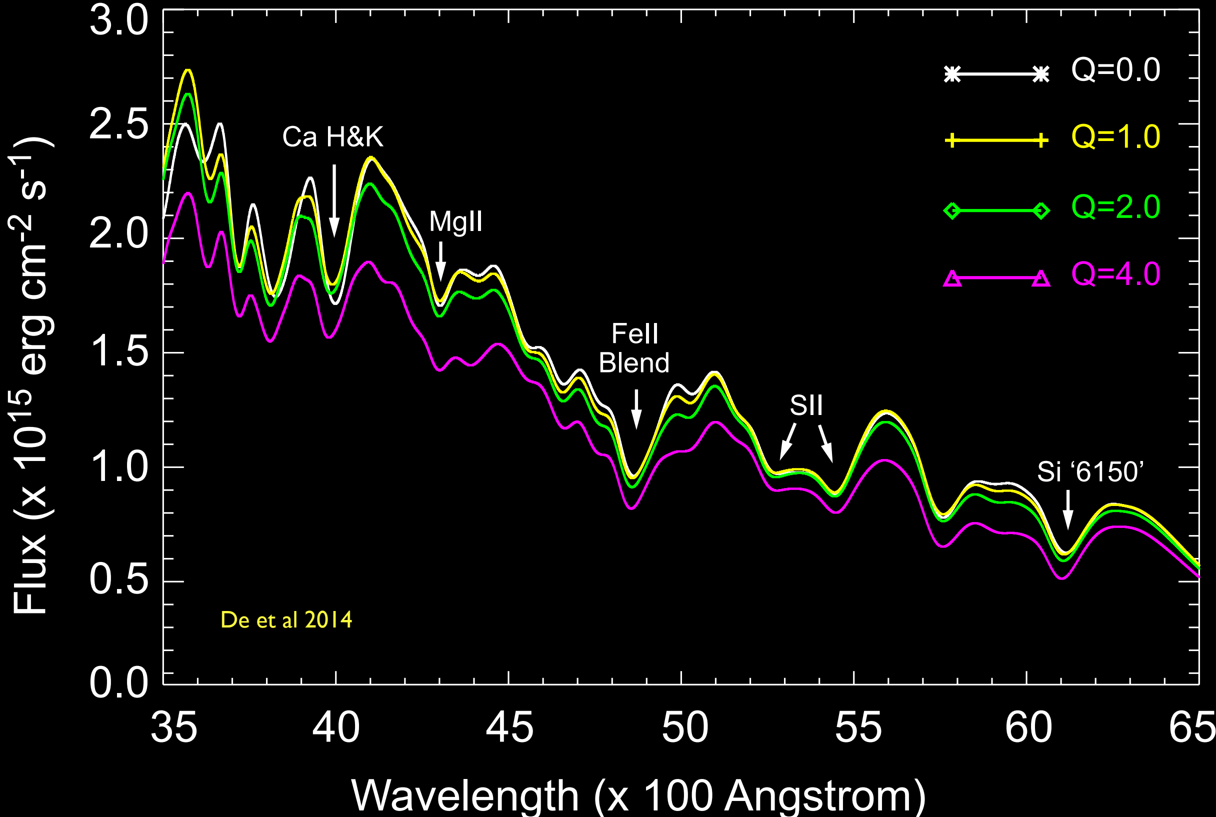
Measuring Φ at a single epoch from the abundance ratios allows a test of whether the SiG material was produced in a QSE state.

Measuring Φ at multiple epochs when silicon features dominate the spectrum allows trends in the QSE temperature to be assessed.

Measurement of four quantities Y_{28Si}, Y_{32S}/Y_{28Si}, Y_{40Ca}/Y_{32S}, Y_{54Fe}/Y_{28Si} is a sufficient basis to solve for all the abundances in the silicon-rich region of SNIa.

$$Y_e = Y_{28\mathrm{Si}} \left[14 + 16 \frac{Y_{32\mathrm{S}}}{Y_{28\mathrm{Si}}} + 20 \frac{Y_{40\mathrm{Ca}}}{Y_{32\mathrm{S}}} \frac{Y_{32\mathrm{S}}}{Y_{28\mathrm{Si}}} + 26 \frac{Y_{54\mathrm{Fe}}}{Y_{28\mathrm{Si}}} + 28 \Psi \frac{Y_{32\mathrm{S}}}{Y_{28\mathrm{Si}}} \frac{Y_{54\mathrm{Fe}}}{Y_{28\mathrm{Si}}} \right]$$

Accurate determination of Y_{28Si}, Y_{32S}/Y_{28Si}, Y_{40Ca}/Y_{32S}, and Y_{54Fe}/Y_{28Si} is sufficient to determine Y_e to ~6% because these abundances account for ~94% the QNSE composition.



Synthetic spectra for the W7-like models with 0 to 4 times solar 22Ne.

Hunting the Progenitors of Supernovae Type Ia

Advances (plus a little serendipity) over the next decade should enable us to decipher the progenitors of Supernovae Type Ia.

1) Different Si, S, Ca ratios
2) Tidal tails
3) Significant unburned carbon + oxygen
4) Early gamma-ray light curve or line profiles
5) Narrow HI in emission or absorption
6) Interaction with circumstellar medium in radio or x-rays
7) Frequency of SNIa as a function of redshift