A hypothesis or theory is clear, decisive, and positive, but it is believed by no one but the person who created it. Experimental findings, on the other hand, are messy, inexact things, which are believed by everyone except the person who did that work.

Harlow Shapley
Through Rugged Ways to the Stars
White dwarf supernova play a key role in astronomy:

Distance indicators
Element factories
Cosmic-ray accelerators
Kinetic energy sources
Binary star terminus
Identification of what is exploding is unknown - this is the outstanding mystery in the field.

Tycho Supernova Remnant:
- Age: Nov 1572
- Distance: ~ 8500 ly
- Diameter: ~ 18 ly (8 arc min)
- Expansion: ~ 0.0015 ly/yr

Blue - high energy electrons
Green & Yellow - iron and silicon
Red - dust

Constellation: Cassiopeia

NASA’s Spitzer, Chandra, & Spain’s Calar Alto
Several observational characteristics help in the hunt for the progenitors of the explosions:

1) About 90% of all white dwarf supernova form a homogeneous class in terms of their spectra and light curves.
White dwarf supernovae are defined by their spectra: no hydrogen lines and a strong silicon absorption feature. (Kasen 2008)
Near maximum light, spectra are characterized by O-Ca at high velocity (~20k km/s).

Late nebular phase spectra are dominated by iron lines.
Luminosity ($L_\odot$)

Time (days since peak)

Expansion and Diffusion time scales about equal

Optical light curve

$^{56}\text{Ni}$ ($\tau_{1/2} \sim 6 \text{ d}$) + $^{56}\text{Co}$ ($\tau_{1/2} \sim 77 \text{ d}$)

$\sim 0.6 \, M_\odot$ of $^{56}\text{Ni}$ for a typical SNIa

$\gamma$-ray escape
Several observational characteristics help in the hunt for the progenitors of the explosions:

1) About 90% of all white dwarf supernova form a homogeneous class in terms of their spectra and light curves.

2) Correlations between different observables, such as the peak luminosity and width of the light curve.
Brighter is wider.

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

After correction, distances are accurate to $\leq 7\%$!
Planetary Nebula: Tosses off Hydrogen and Helium Layers

Main Sequence

Helium Burning to Carbon

Red Giant

Runs out of Helium fuel

Helium Ignites

Helium Burning to Carbon

H → He

Carbon-Oxygen White Dwarf in 10 billion years

H → He

1 M_{sun}

50,000 6000 3000

Blue Warm Yellow Cool

Surface Temperature (K)

Luminosity (L_{sun})

Bright Dim

5 \times 10^6 10^{-4}
Different main-sequence stars make different white dwarfs.
Pluto

Radius: 1185 km

Mass: 0.18 Earth’s

White Dwarf

Radius: 1185 km

Mass: 1.37 Sun’s
A white dwarf can only have so much mass.
Single-Degenerate channel

Double-Degenerate channel

Mergers:

Collisions:

The relative frequency of these channels is unknown.
The first white dwarf smashes were calculated in 1985:

3D, 5000 particles with nuclear burning done afterwards and approximate thermodynamics.

Bottom line:
Tiny amounts of $^{56}\text{Ni}$ produced.

Message:
Nothing here, move along.
0.6 + 0.6 M☉, zero impact parameter, x-y plane, temperature.

2010: 2 million particles with inline burning and realistic thermodynamics.

Raskin et al 2010
Message in 2010: Lots of interesting possibilities!
Collisions can cover the observed range of $^{56}$Ni masses.
Exceptionally bright white dwarf supernova have been interpreted as double-degenerate events.
Observations suggest about 5 million white dwarf supernova per year within a redshift of one.
An objection to the collision scenario is the perception that such collisions are extremely rare.
Collisions have been believed to predominantly occur in dense stellar environments, such as cores of globular clusters.
Even accounting for gravitational focusing, the collision rate is \( \sim5000 \) white dwarf supernovae per year within a redshift of one.

\[
\sigma = \pi b^2 = \pi R^2 \left[ 1 + \left( \frac{v_{\text{esc}}}{v} \right)^2 \right]
\]
Wait! There is a 3rd body in this duel.
Hierarchical triple star systems with white dwarf binary orbital separations of 1-300 AU are known to exist.
The white dwarf binary’s ellipticity can be driven to large values in a triple star system because ellipticity can be traded for inclination in the conservation of angular momentum

\[ L_z = \sqrt{1 - e^2} \cos(i) \]

in Kozai-Lidov oscillations.

\( e \geq 0.9999999 \)

3 body problem
Radii of white dwarfs

Figure showing the evolution of semimajor axis and pericenter separation over time for a white dwarf binary with $m1 = m2 = 0.5 \, M\odot$ and a perturber $m3 = 0.5 \, M\odot$. The graph compares the head-on collision scenario with Katz & Dong 2013 model.
White dwarfs in a triple star system have a ~3% chance of experiencing a collision within 5 billion years.

If ~20% of white dwarfs are in triplets, the calculated supernova rate is about the same as the inferred rate.
15-20% of $1M_\odot \leq M \leq 8M_\odot$ stars with a $M > 1M_\odot$ companion makes the collision scenario dominant.

AO Measurements of A-stars, $N=121$

- All binaries
- $M_{\text{secondary}} > 1M_\odot$

RV Measurements of red giants in open clusters, $N=797$

- All Red Giants
- $0.5 < P < 5 \text{ yr}$
- $0.5 < P < 5 \text{ yr}, M_{\text{secondary}} > 1M_\odot$

Klein & Katz 2016
Prediction: GAIA will find ~10 new wide orbit double degenerates within 20 pc from the Sun.

This puts a strong constraint on the “triple-assisted” collision model for white dwarf supernovae.
Advances (plus a little serendipity) over the next decade should enable us to decipher the progenitors of white dwarf supernovae:

1) Silicon, Sulfur, Calcium ratios
2) Unburned carbon and oxygen
3) Tidal tails
4) Sufficient number of binary WDs
5) Early gamma-rays
6) Narrow hydrogen emission or absorption
7) Circumstellar interaction in radio or x-rays
8) Gravitational wave signatures
9) Frequency as a function of redshift
A successful model starting from a carbon+oxygen white dwarf must make

- $0.1 - 1.0 \, M_\odot \, ^{56}\text{Ni}$ for the light curve
- $0.2 - 0.4 \, M_\odot \, \text{Si, S, Ar, Ca}$ for the spectrum
- $< 0.1 \, M_\odot \, ^{54}\text{Fe} + \, ^{58}\text{Ni}$ for the nucleosynthesis
- Allow for some diversity for the population
$t = 15.92790$

$M = 0.64 M_\odot$

Temperature [K] vs. Density [g cm$^{-3}$]

Velocity [cm s$^{-1}$] vs. Density [g/cc]

Raskin et al 2010
0.8 + 0.6 \, M_{\odot},
zero impact parameter,
density

Raskin et al 2010

t=13.999700
0.8 + 0.6 M\odot,
zero impact parameter,
density, zoomed

Raskin et al 2010