Supernovae

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Outline

- Introduction
- SN classification
- Thermonuclear SNe
- Core-collapse SNe
- Transient surveys

Our Universe is not static at all. It is actually extremely dynamical and changing all the time.

credit: HST

credit: ESA/Hubble

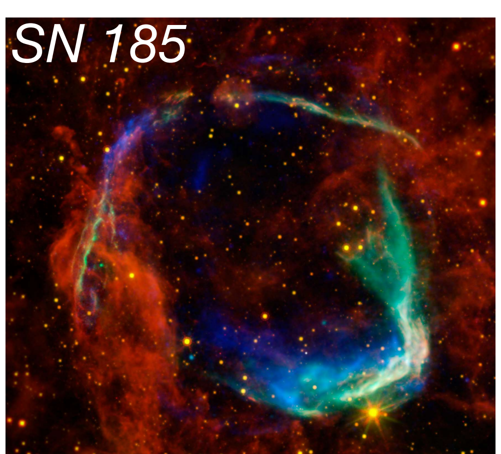
Historical supernovae

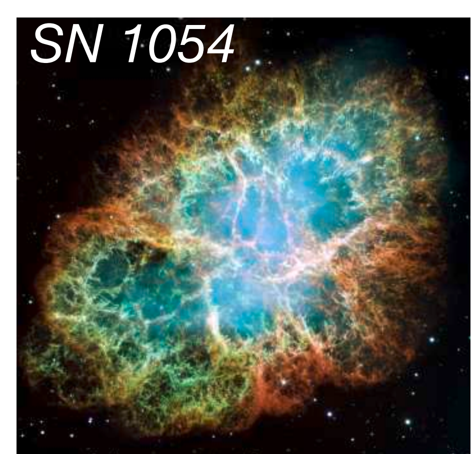
- **SN 185** - The first recorded supernova in human history by Chinese astronomers. 《後漢書・卷十二・天文下》：中平二年十月癸亥，客星出南門中，大如半筵，五色喜怒稍小，至後年六月消。

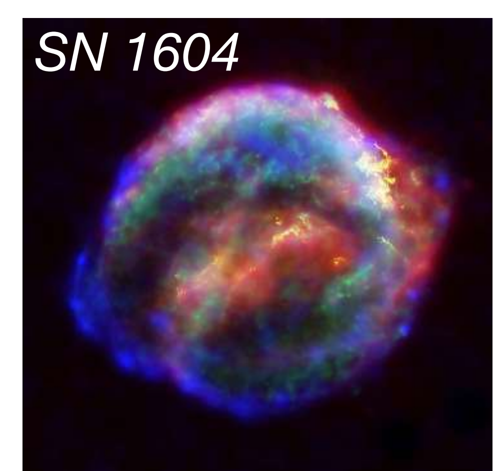
- **SN 1006** - Might be the brightest SN in recorded history ($m\approx-7.5$ mag).

- **SN 1054** - The remnant is called “Crab Nebula”

- **SN 1604** - Also knows as Kelper’s SN. The most recent SN discovered in our own Milky Way



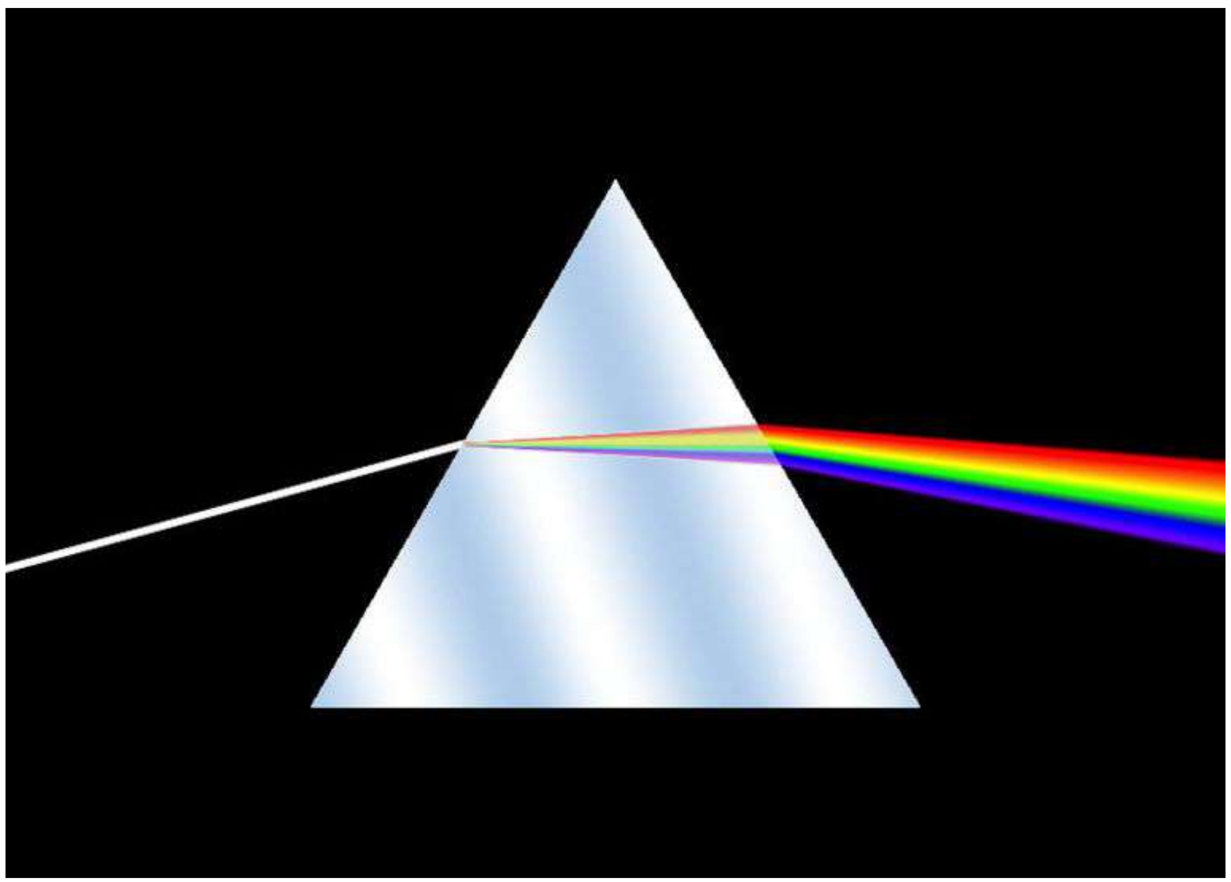




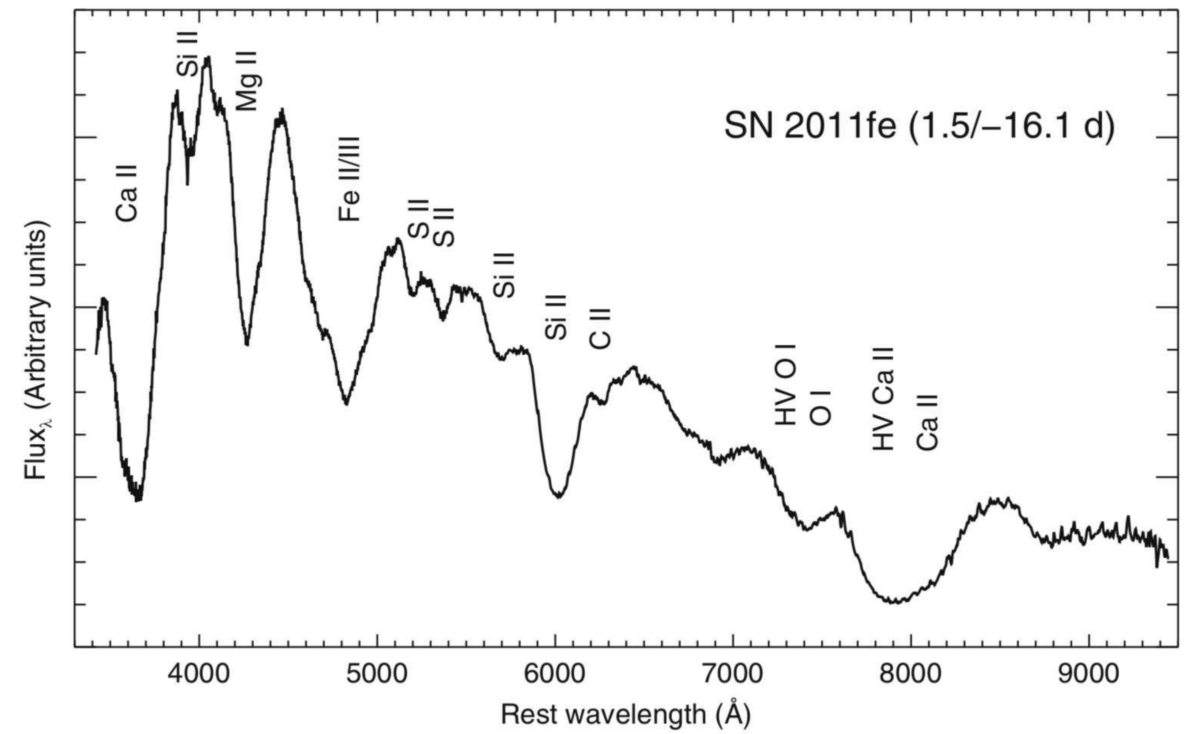
credit: NASA

How do we distinguish between different kinds of supernovae?

Spectroscopic observations



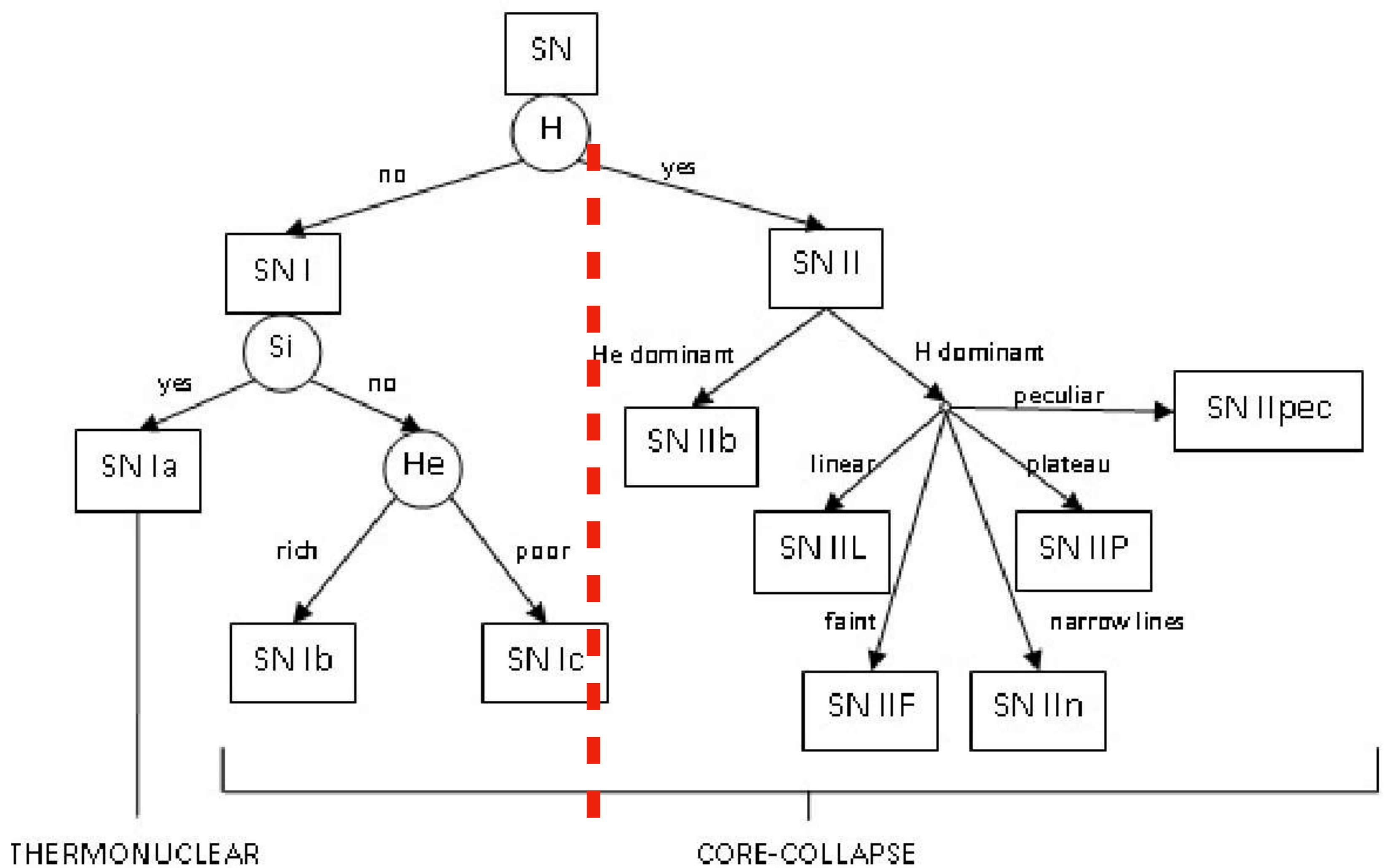
SN Ia spectrum



credit: Handbook of Supernovae

SN classification

- The first supernova classification was introduced by Rudolph Minkowski in 1941. He created sub-groups called Type-I and Type-II based on the presence of hydrogen feature in the spectra.

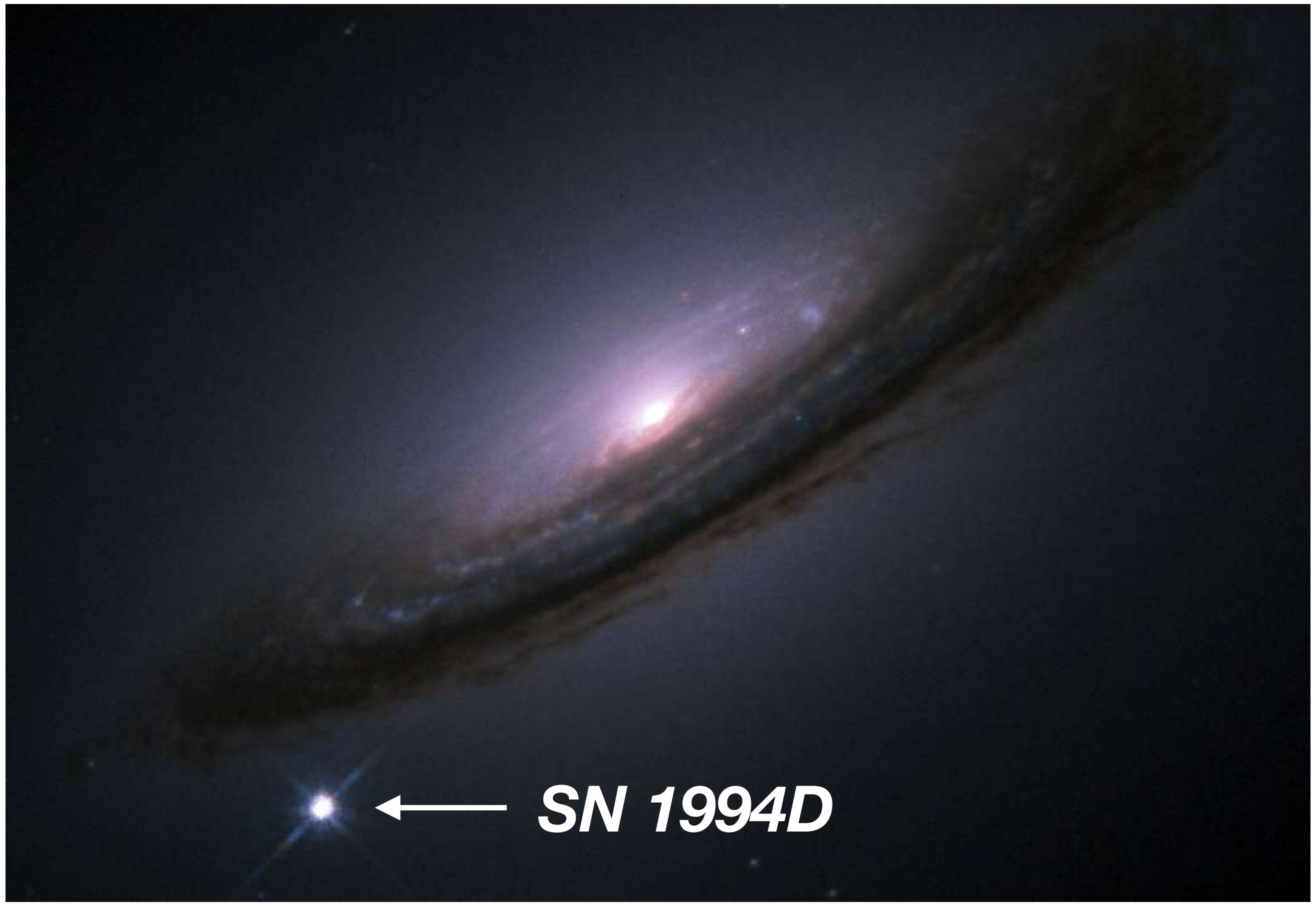


Modolo+ 2016

What is thermonuclear supernova (or Type Ia supernova)?

Thermonuclear supernovae

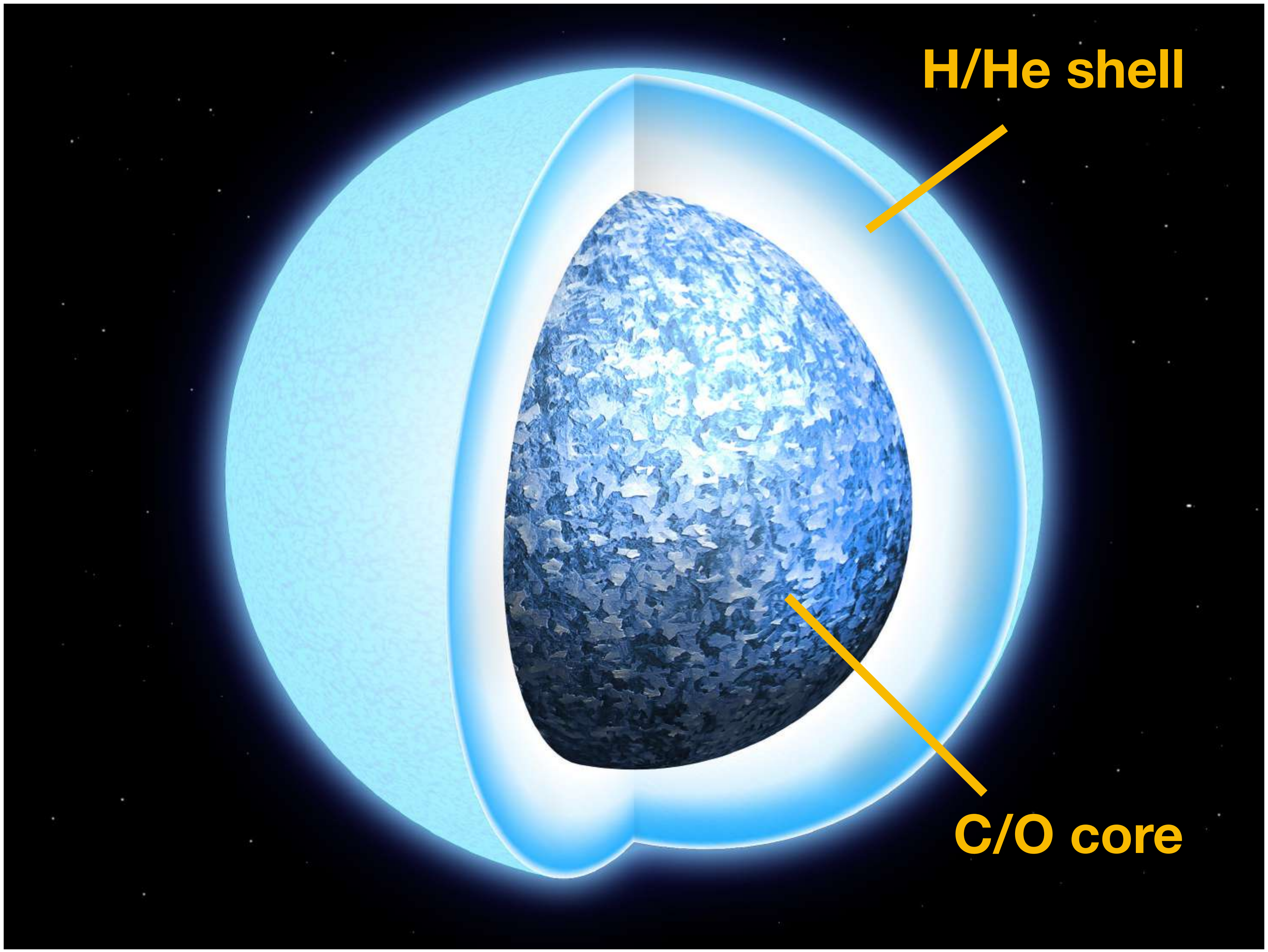
- Also called *white dwarf* supernovae, where the energy released in the explosion is mainly the result of thermonuclear burning (e.g., Type Ia supernovae)



credit: HST

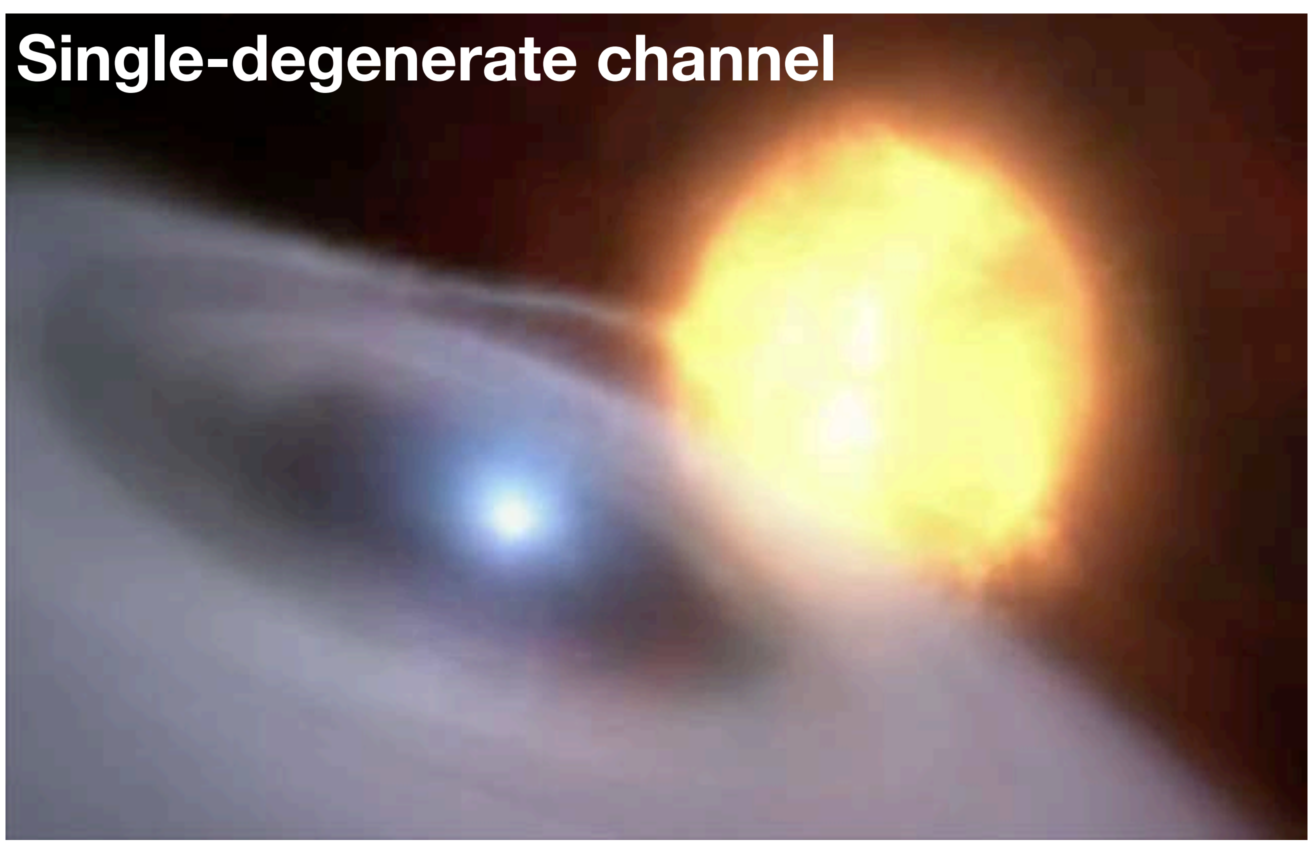
How to make a white dwarf to explode?

White dwarf explosion



White dwarf explosion

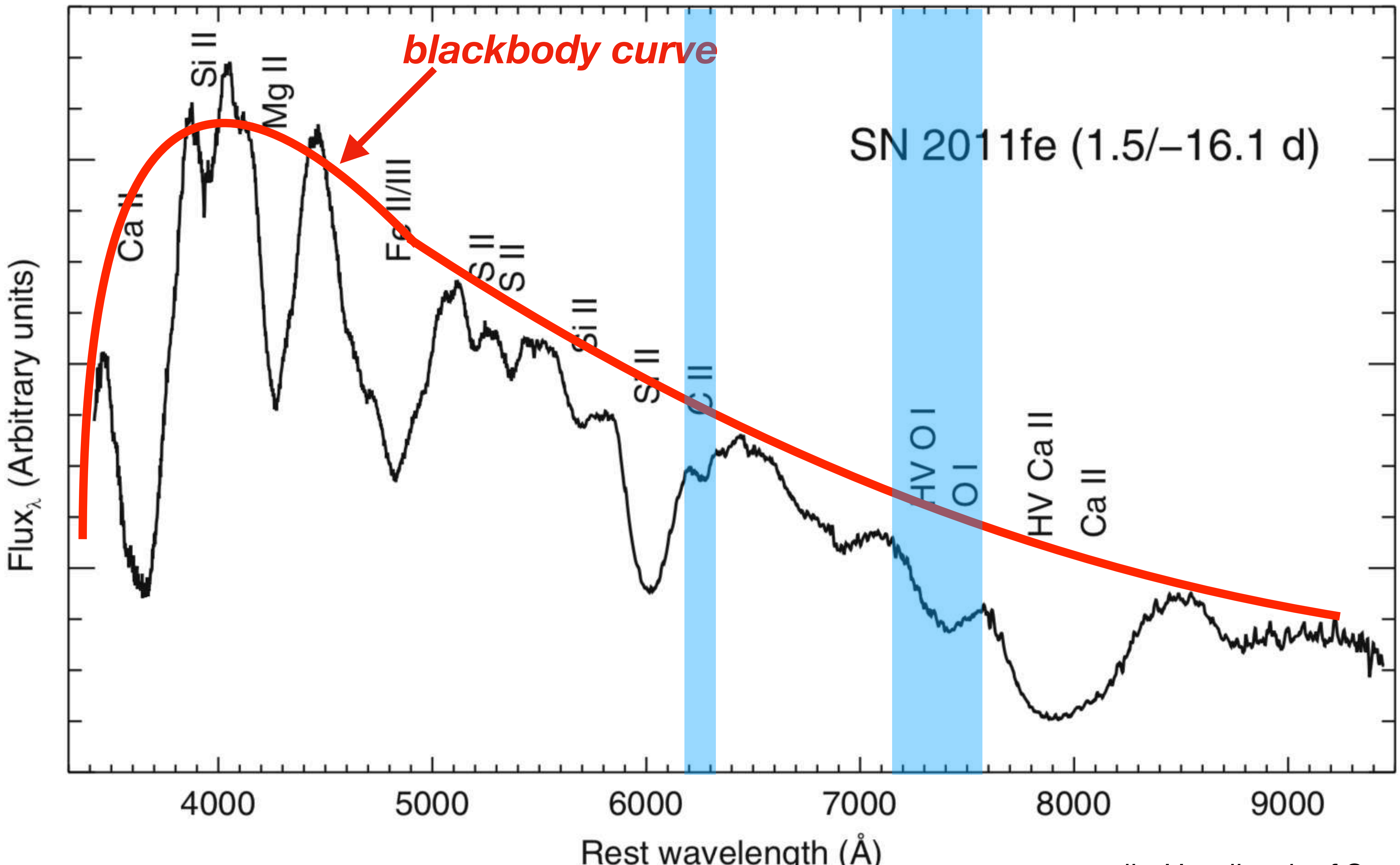
- White dwarf has an averaged mass of $\sim 0.6\,M_{\odot}$. To ignite a white dwarf, there must be a channel through which the white dwarf can gain the mass until it approaches the *Chandrasekhar* limit (~1.4 $M_{\odot}$) and trigger the carbon detonation in the center of the star. This can be done via either **accretion** or **merger** in a close binary system.



credit: ESO

How do we know that the thermonuclear supernovae are white dwarf explosions?

Evidence of unburned carbon and oxygen and lack of hydrogen



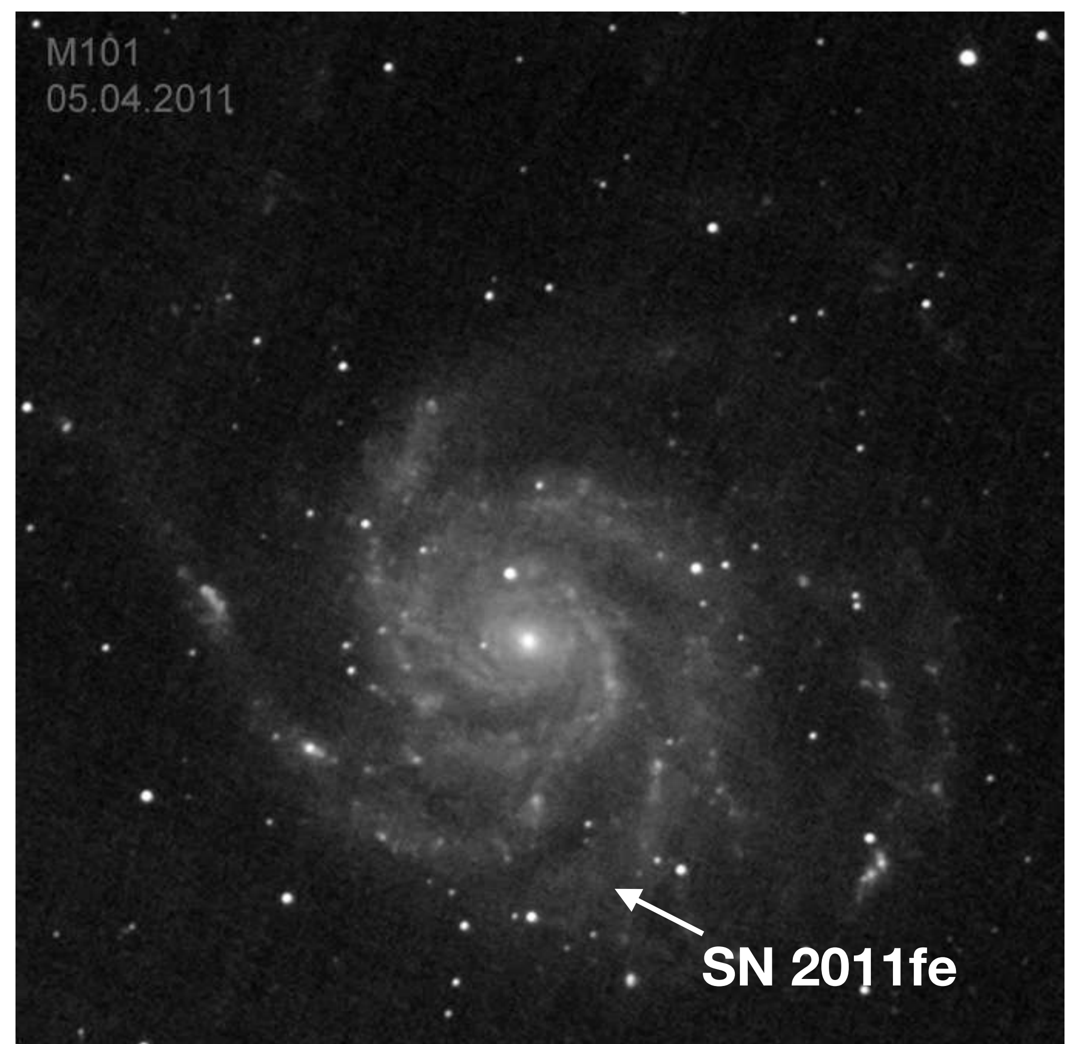
credit: Handbook of Supernovae

Can be found in all kinds of galaxies

credit: SDSS-II SN Survey

Deep imaging on nearby SNe

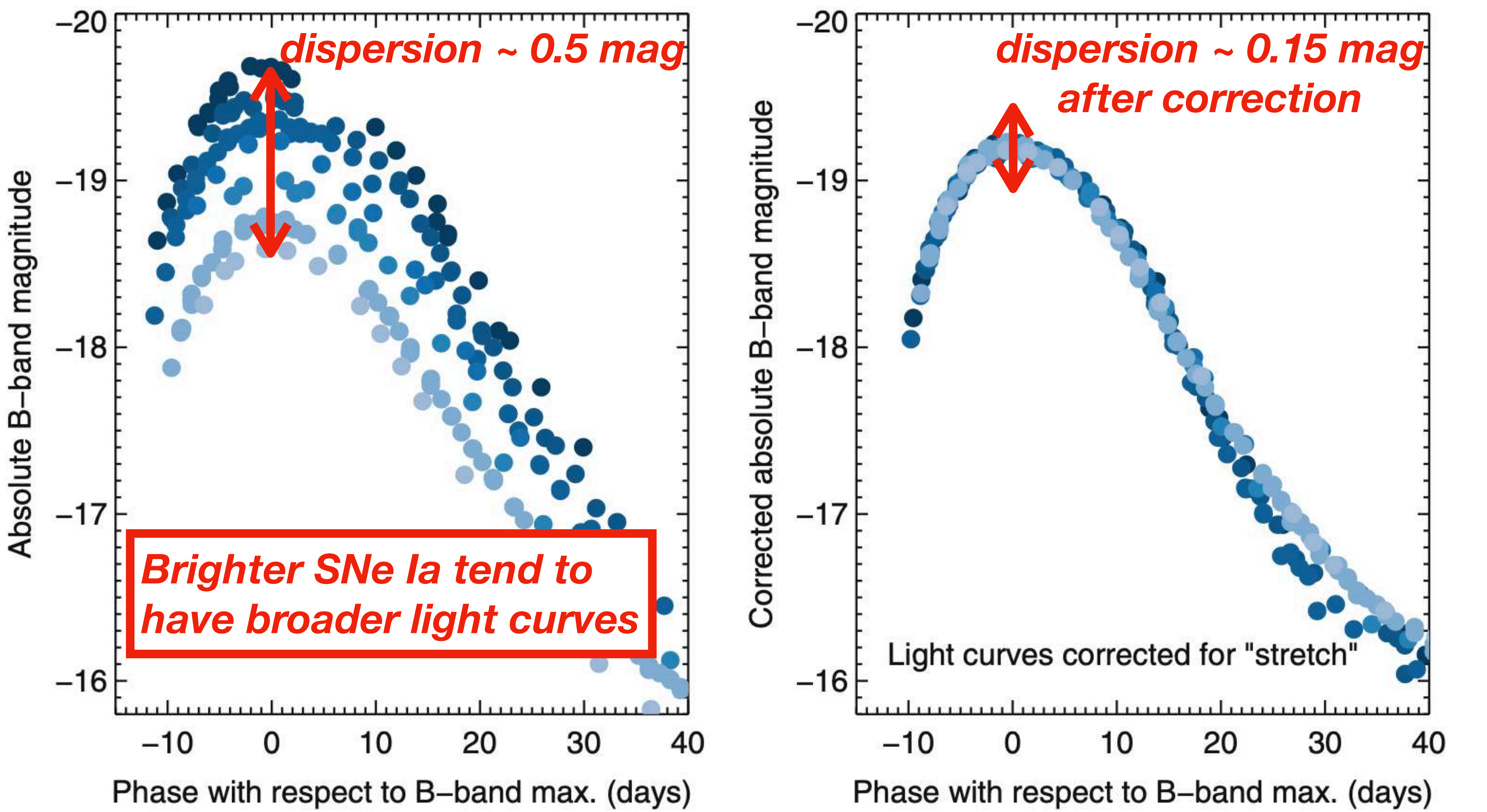
- By looking into the early non-detections in deep images of nearby SNe Ia, we can constrain the progenitors to be likely compact objects (i.e., $R < 0.02R_{\odot}$).



credit: Nugent+ 2011

Uniform luminosities of SNe Ia

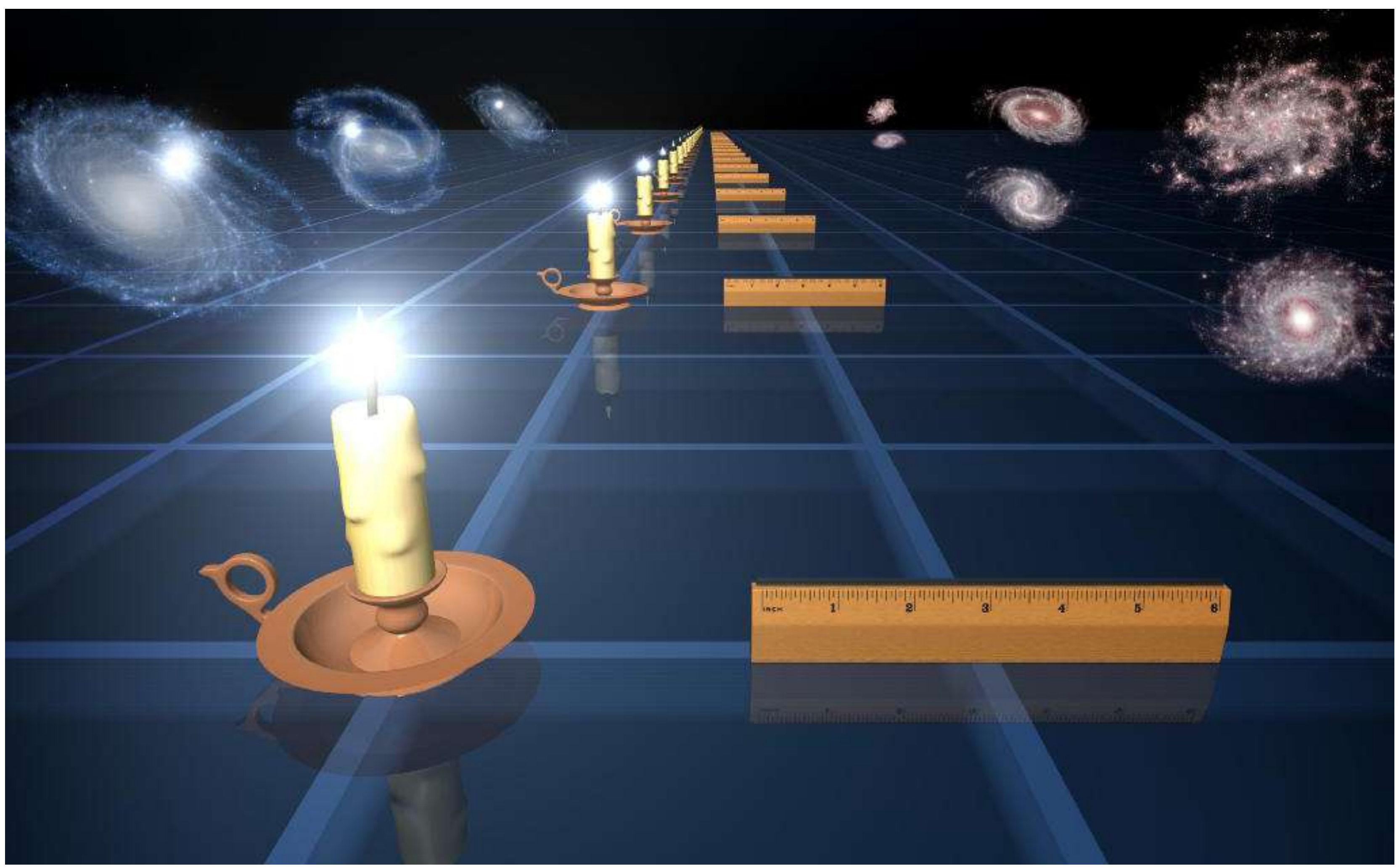
The light curve is powered by the radioactive decay of $^{56}Ni -> ^{56}Co -> ^{56}Fe$



credit: Handbook of Supernovae

Uniform luminosities of SNe Ia

- The uniform luminosities of SNe Ia make them superb standard candles in measuring the distances, and further revealed that our Universe is undergoing the accelerated expansion.



credit: NASA

What are the progenitors of Type Ia supernovae?

Single v.s. Double degenerate scenarios

<u>Strength or evidence of single degenerate:</u>

1. Naturally explains the uniform luminosity of SN Ia
2. Early excess in light curves indicates possible companion interaction
3. Lack of polarization indicates a symmetrical explosion

<u>Weakness of single degenerate:</u>

1. No evident companion stars found in the supernova remnants
2. No hydrogen found in the late-time spectra
3. Only a small range of accretion rate can produce stable mass accretion

credit: Kuo-Chuan Pan

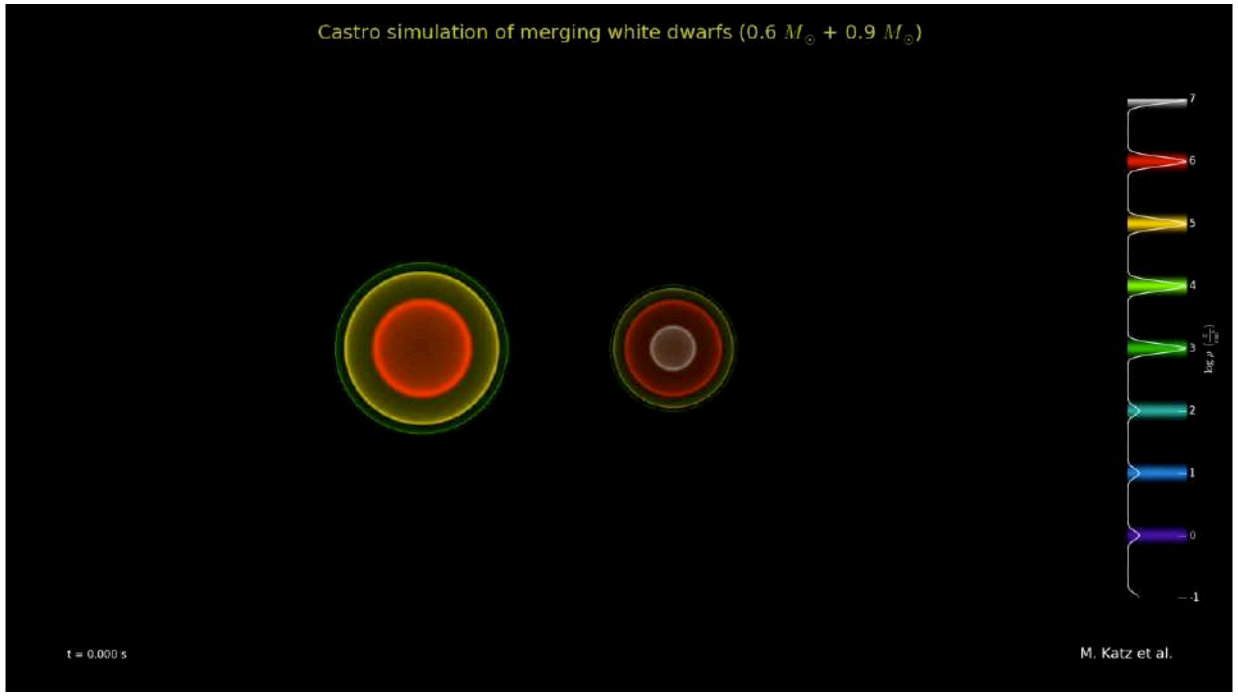
Single v.s. Double degenerate scenarios

<u>Strength or evidence of double degenerate:</u>

1. Natural to explain the lack of hydrogen
2. Easy to produce explosions (although may not be M_{ch} explosions)

<u>Weakness of double degenerate:</u>

1. Some simulations produce accretion-induced collapse instead of SN
2. Hard to explain the uniform luminosities with some DD channels
3. Difficult to explain the lack of polarization

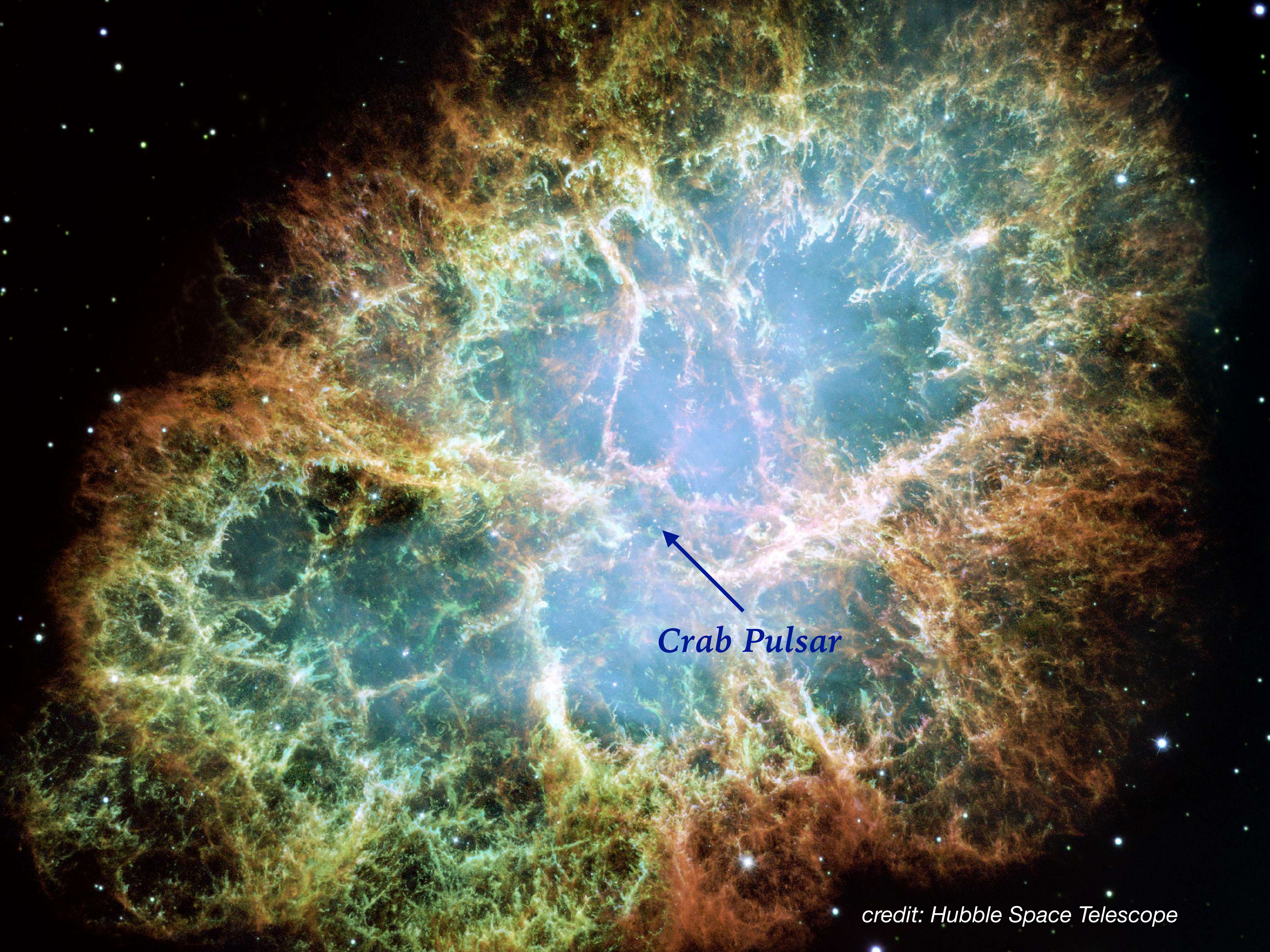


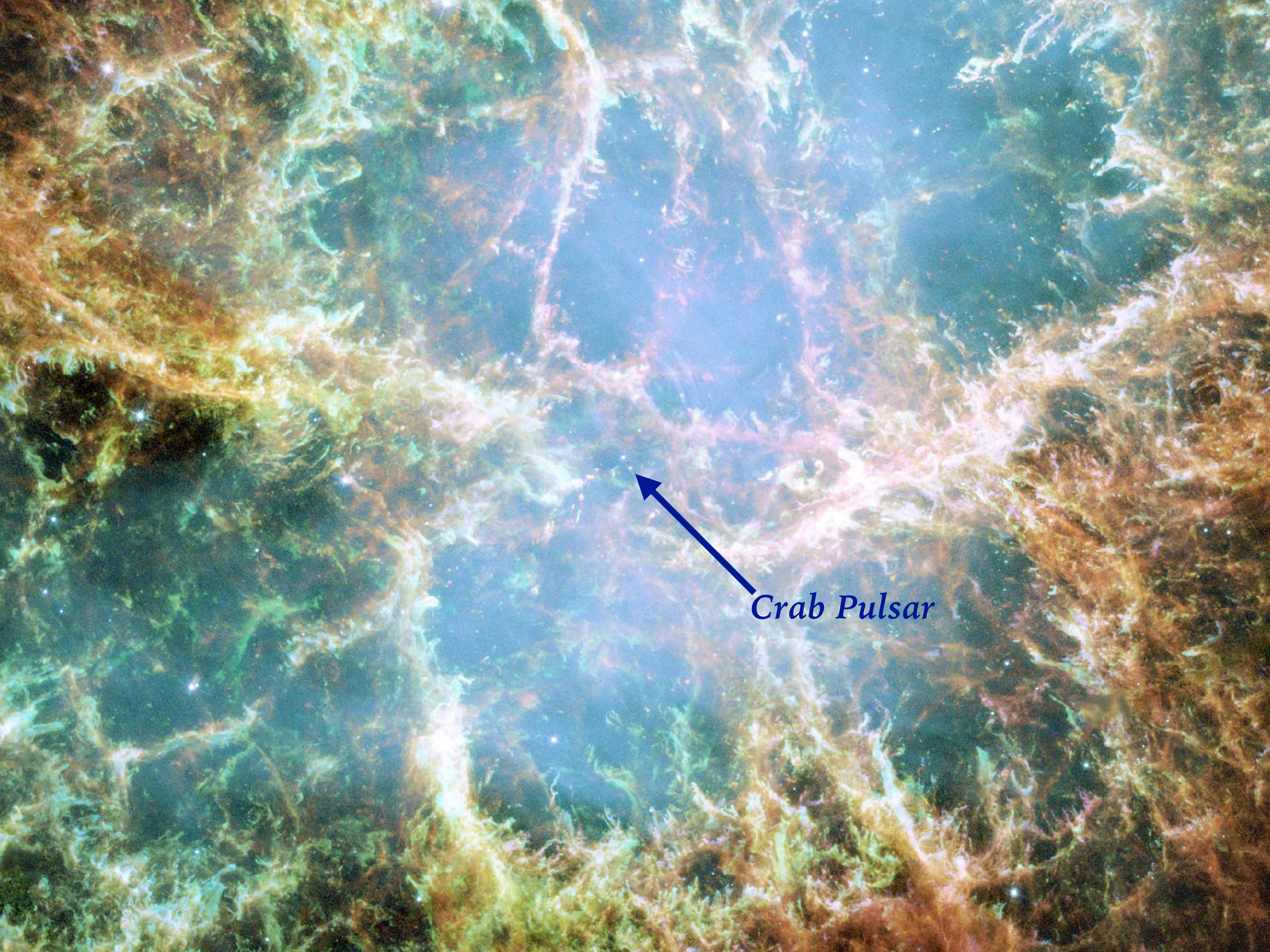
credit: M. Katz

Single v.s. Double degenerate scenarios

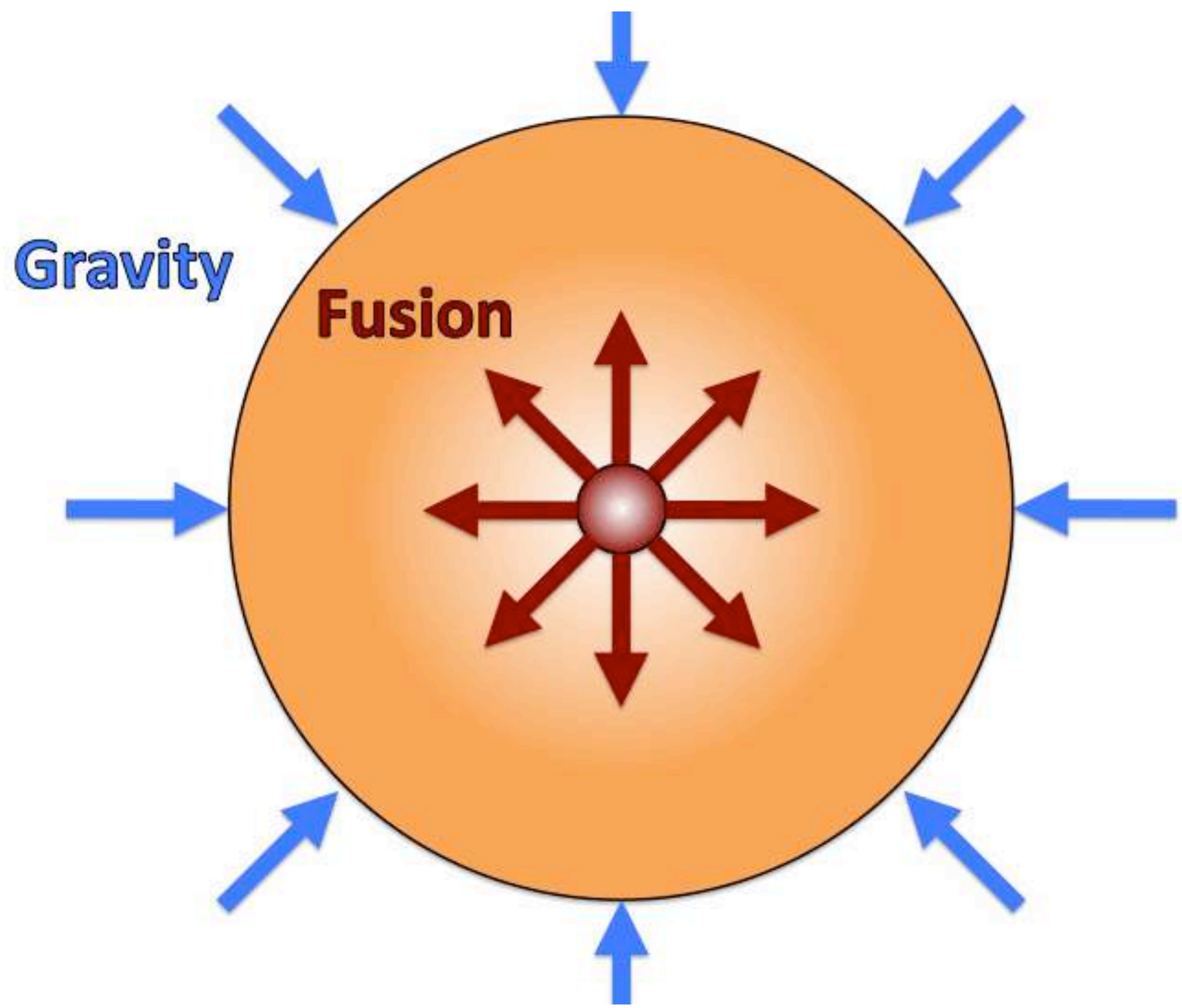
- Ironically, SNe Ia have been widely used as standard candles even though we do not really know their progenitors systems. Understanding the progenitor is critical to evaluate their evolution with redshift (if any) and improve the cosmology.
- Also, it is evident that SNe Ia are produced via more than one channel. Understanding the channel which produced the majority of the normal SNe Ia will be important to reduce the cosmological uncertainties.

What is core-collapse supernova?


Crab Pulsar
credit: Hubble Space Telescope

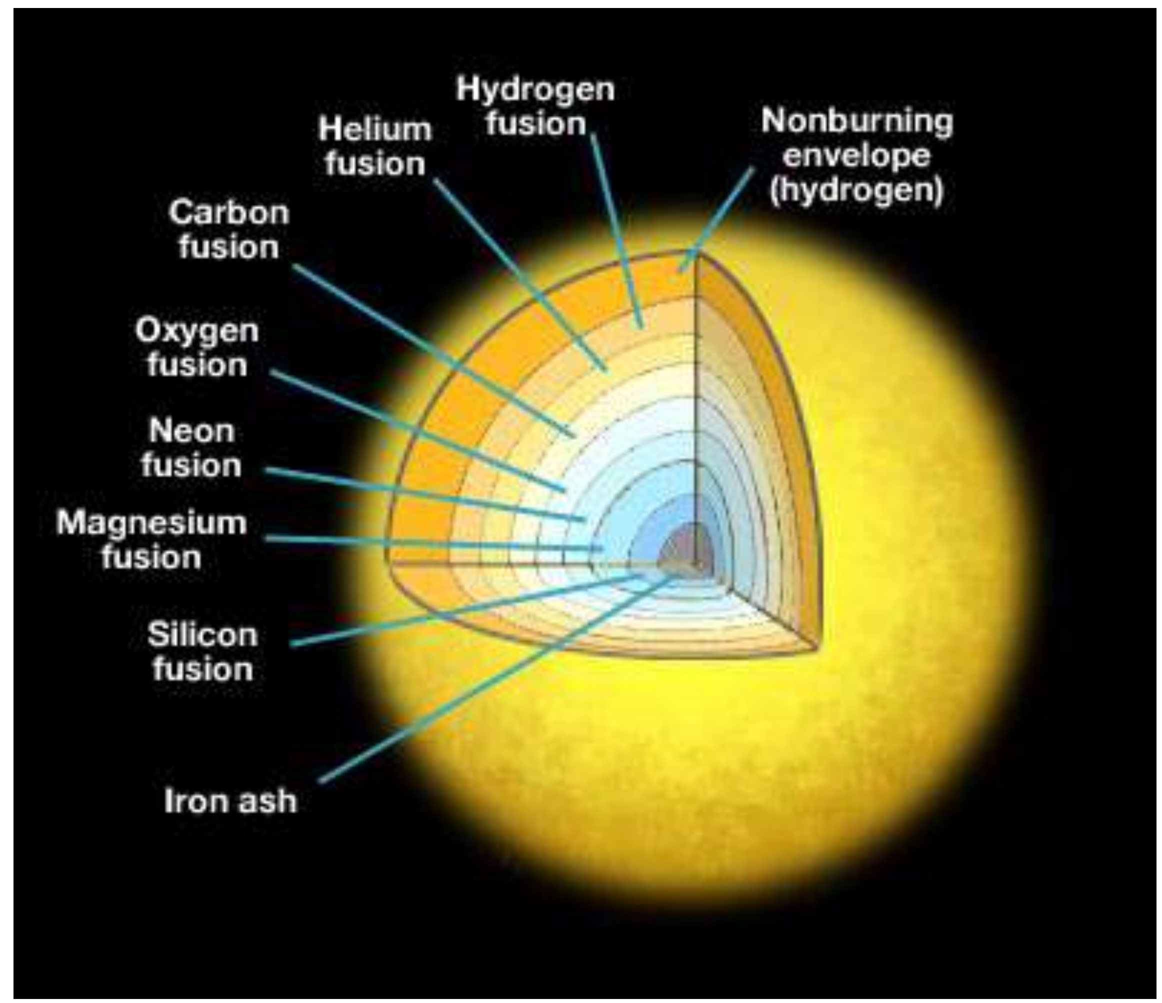

Crab Pulsar

Core collapse of massive stars



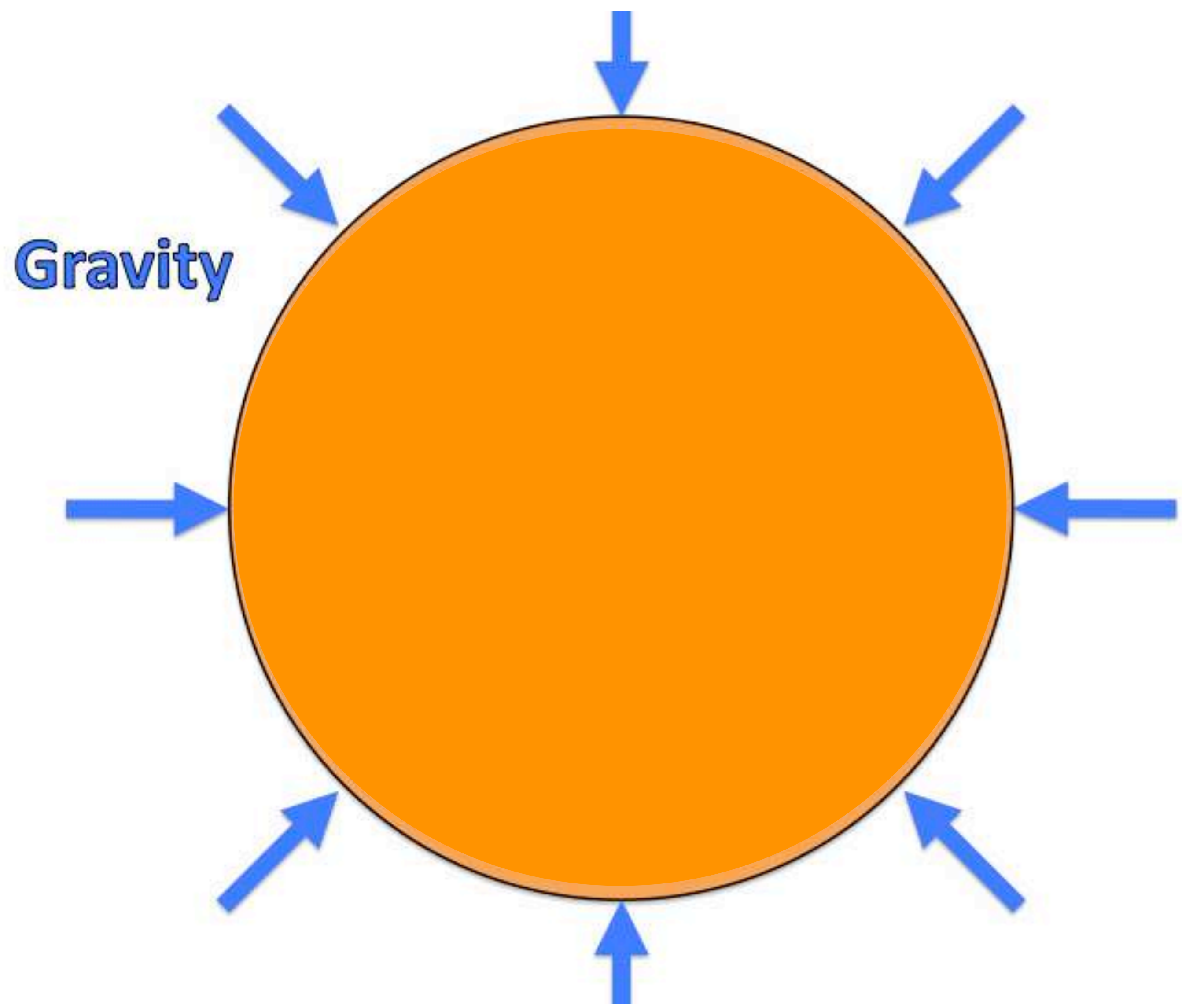
Core collapse of massive stars

- Iron core is formed when a massive star comes to the end of its life.
- No more energy can be extracted to resist the gravity by fusing the iron into heavier elements.



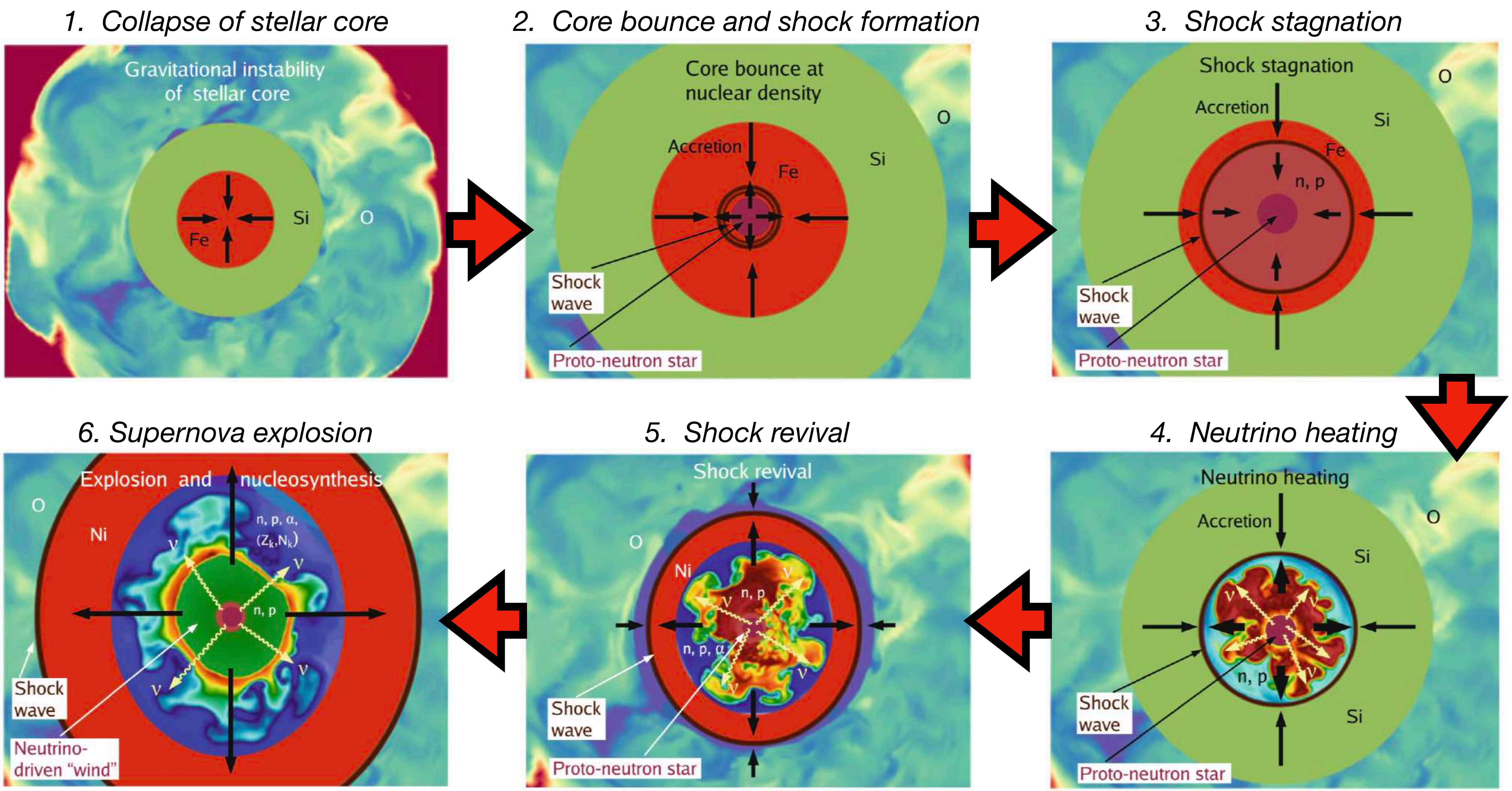
credit: Penn State Astronomy & Astrophysics

Core collapse of massive stars



How does this core-collapse produce a supernova?

Steps to produce a CCSN

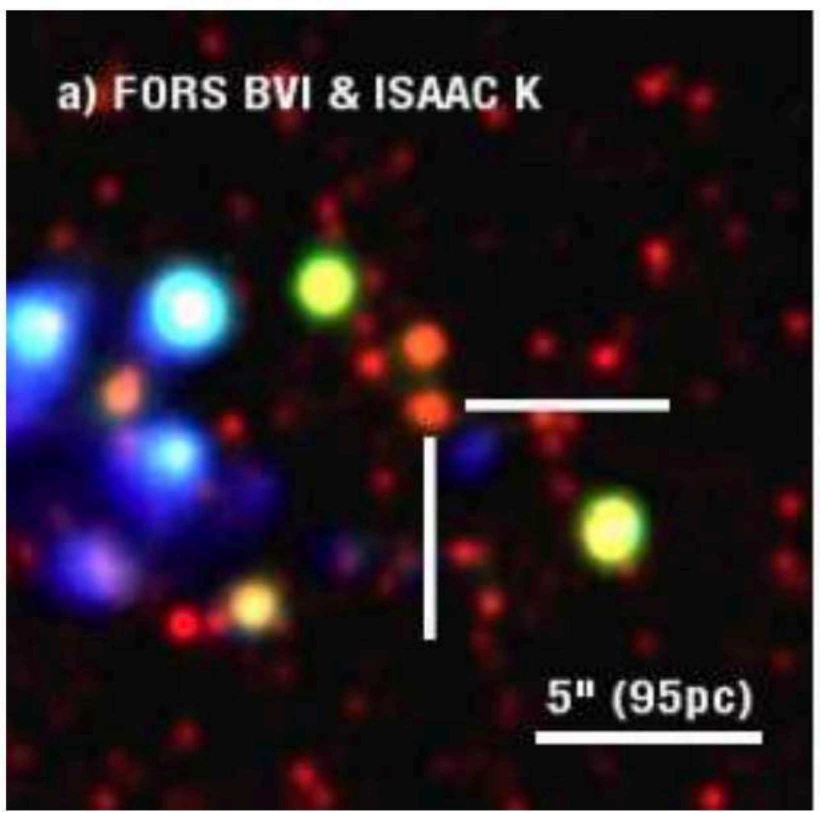


credit: Handbook of Supernovae

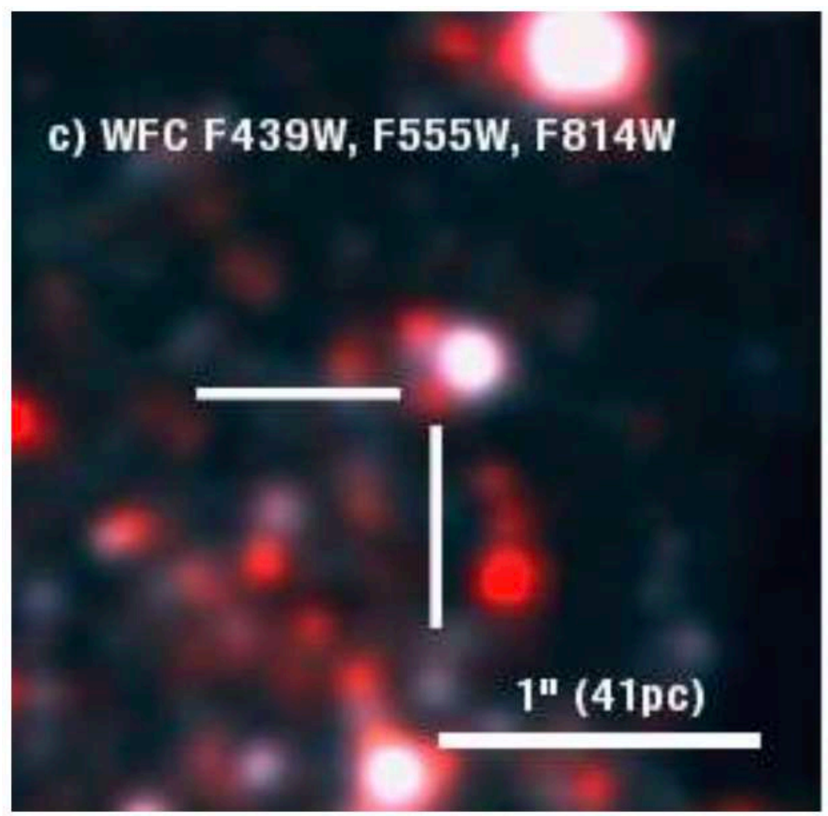
Progenitors of CCSNe are massive stars

- It is evident that the progenitors of CCSNe are likely massive stars based on the pre-explosion images (e.g., SNe II-P are associated with the red supergiant stars).

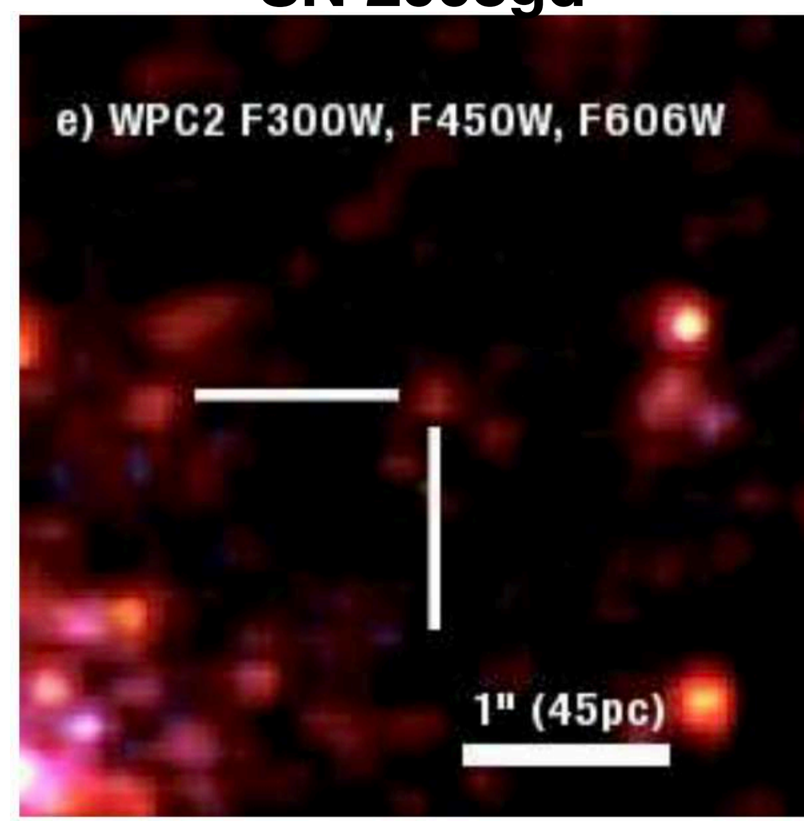
SN 2008bk



SN 2005cs



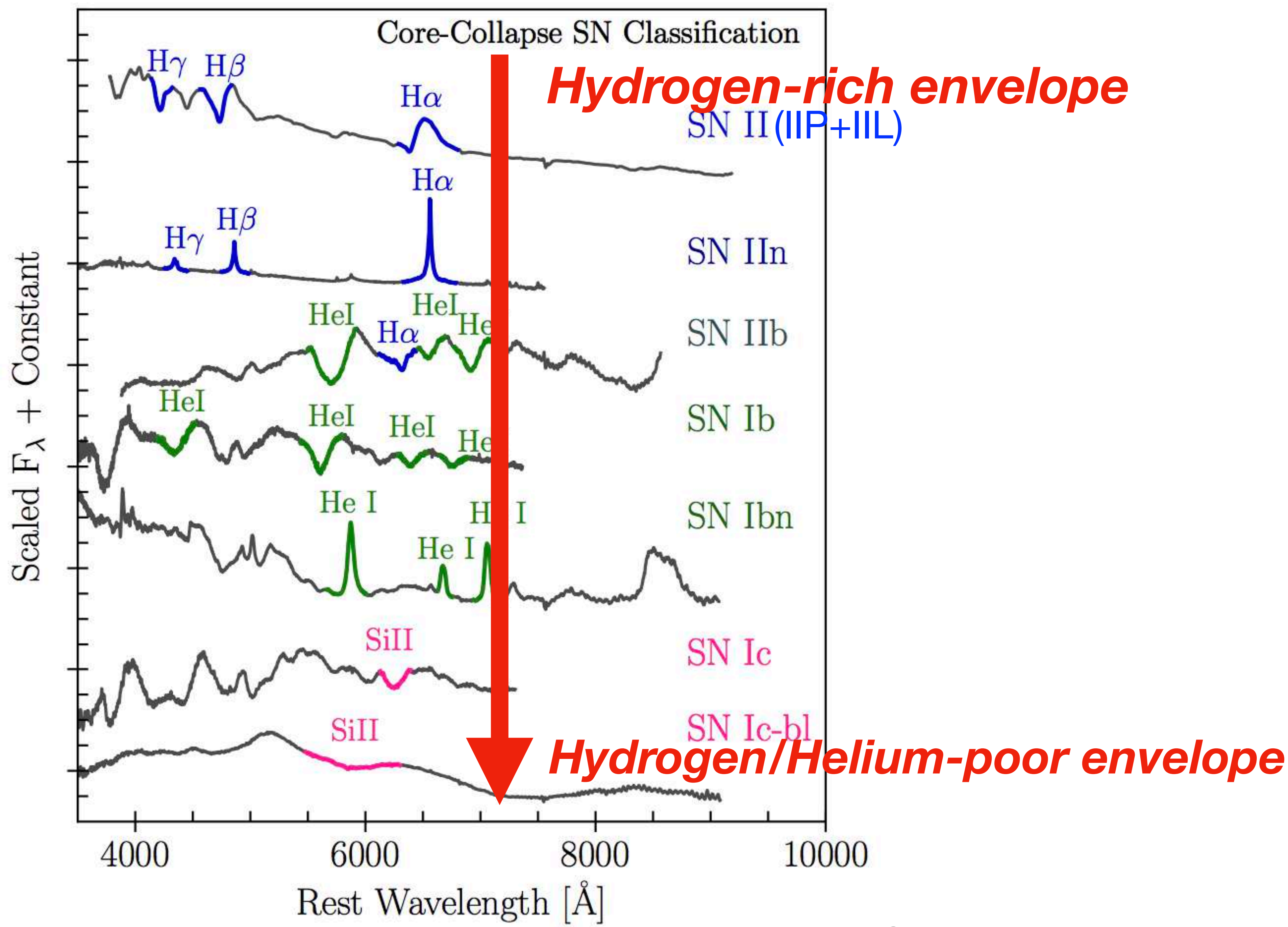
SN 2003gd



Smartt+ 2009

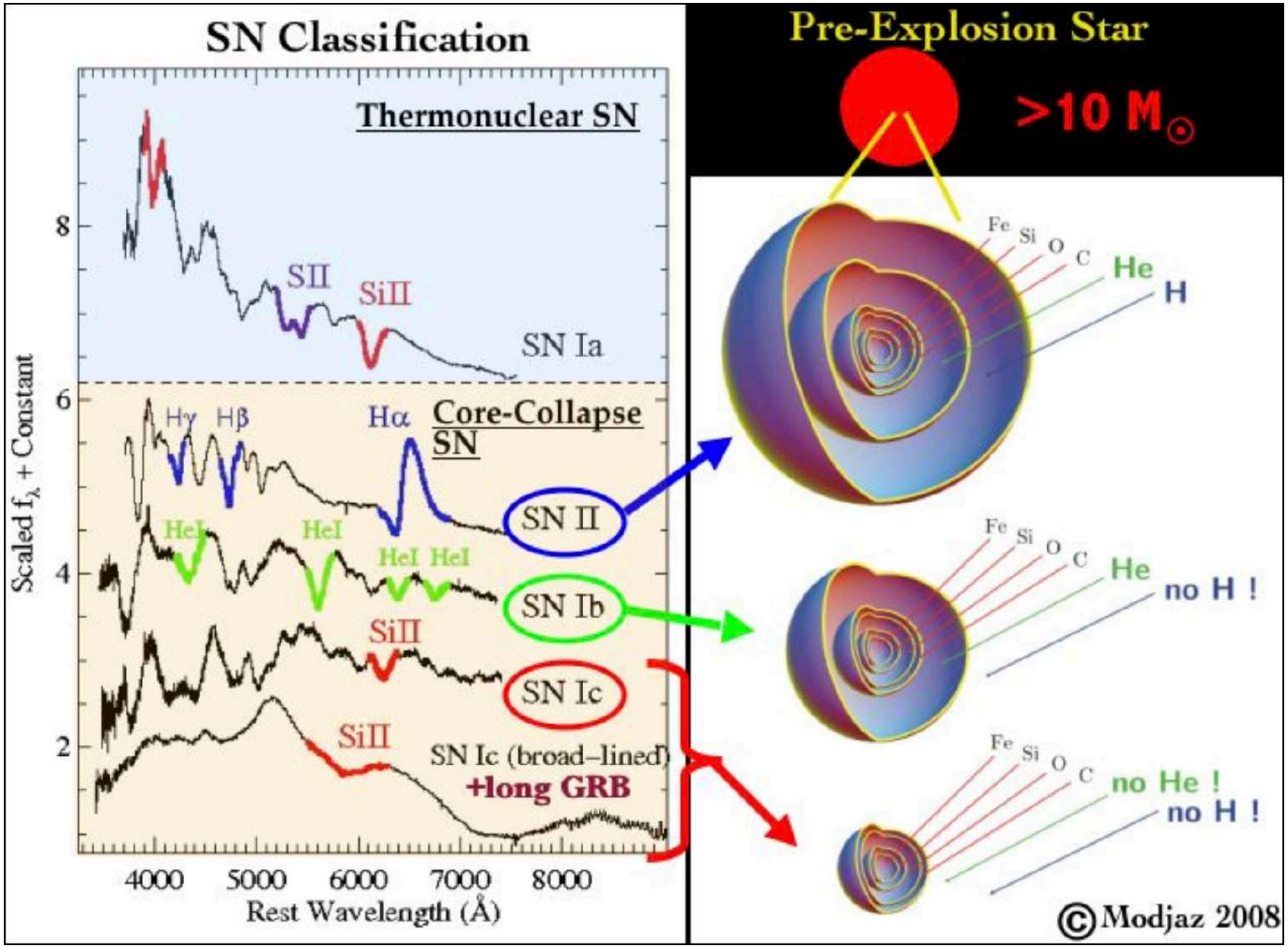
The diversity of core-collapse SNe

The diversity of core-collapse supernovae

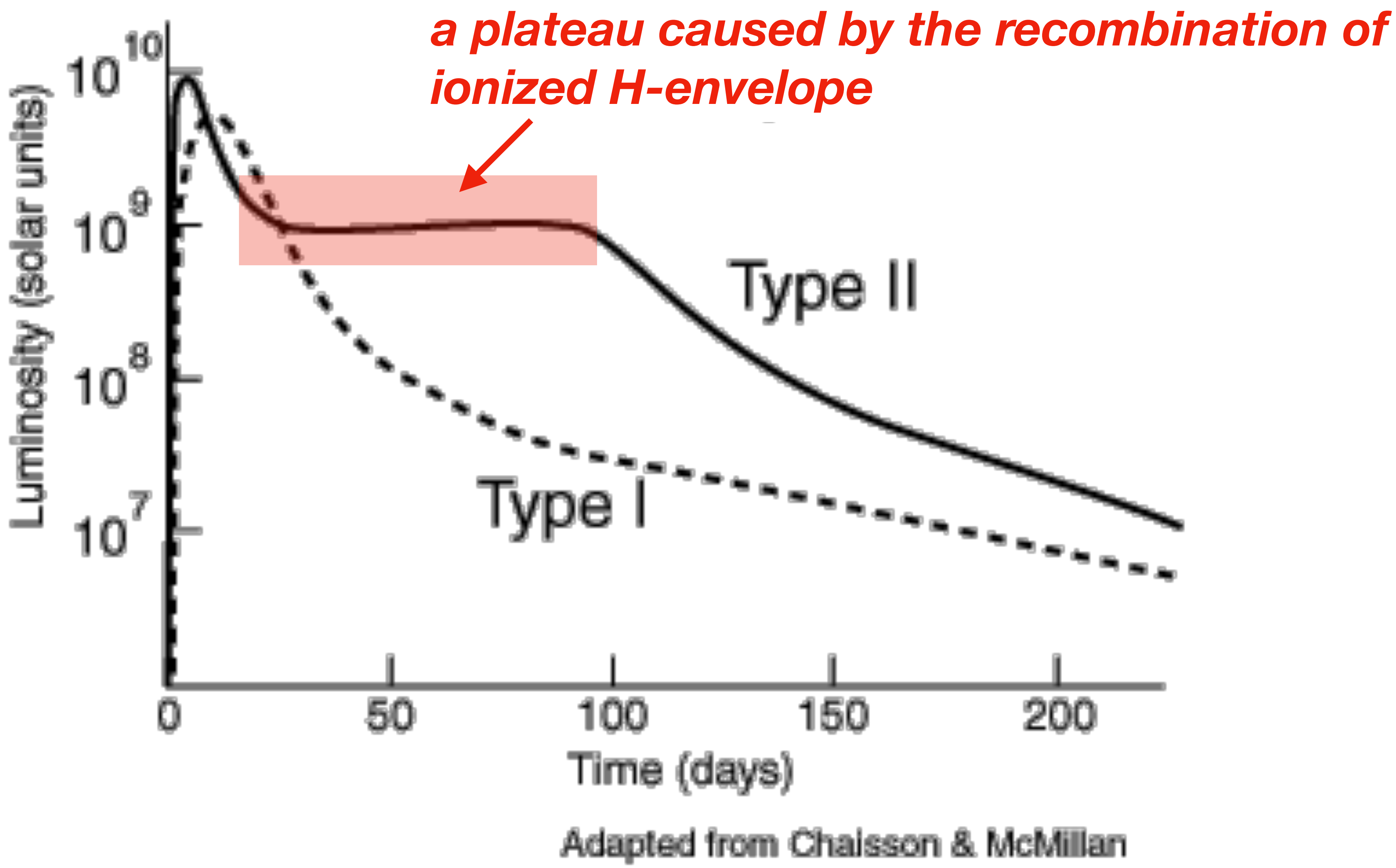


Modjaz, Gutierrez & Arcavi 2019

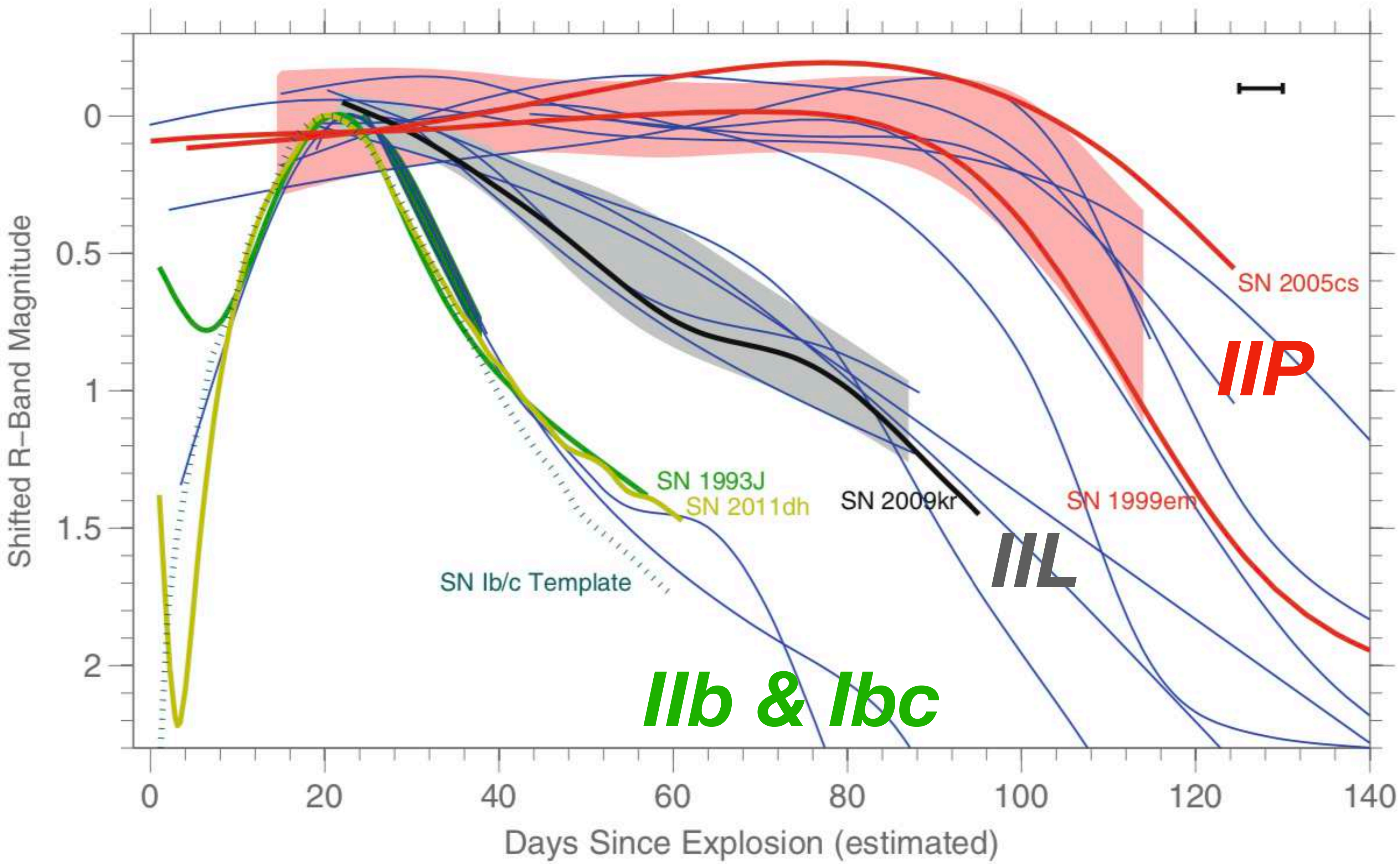
The diversity of core-collapse supernovae



The diversity of core-collapse supernovae

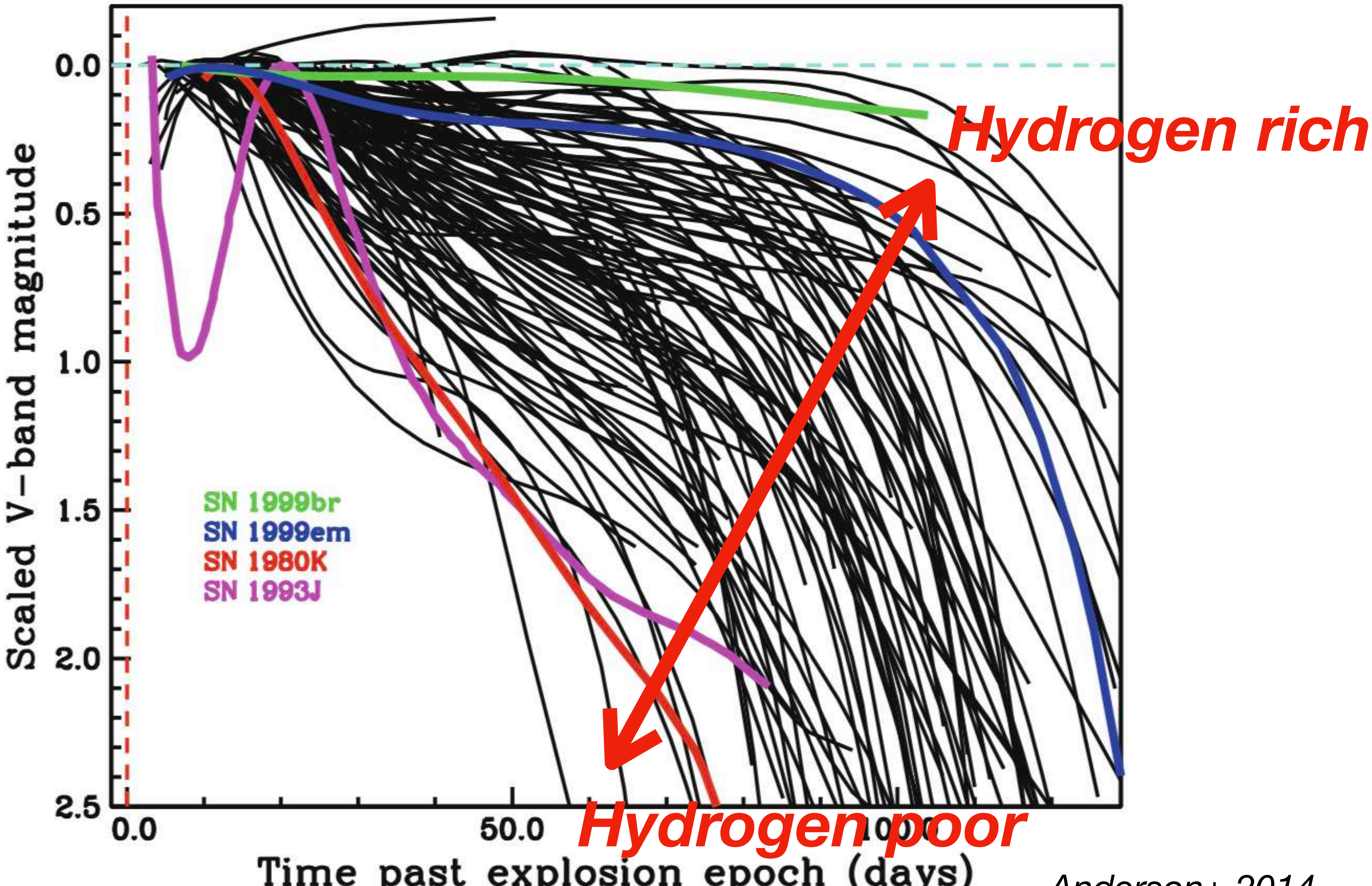


The diversity of core-collapse supernovae



Arcavi+ 2012

The diversity of core-collapse supernovae



Anderson+ 2014

The origin of CCSN diversity

- The mass of hydrogen (and helium) in the envelope is likely an important factor in altering the observed diversity of CCSNe.

- The more important question to ask is what makes the hydrogen/helium envelope of different types of CCSNe so different?

- Several possibilities including 1) different masses of stars will have different levels of mass loss during the stellar evolution. 2) a binary evolution could also be important in removing the hydrogen or helium envelopes of stars. This is still a very active area to study!

Why do we study supernovae?

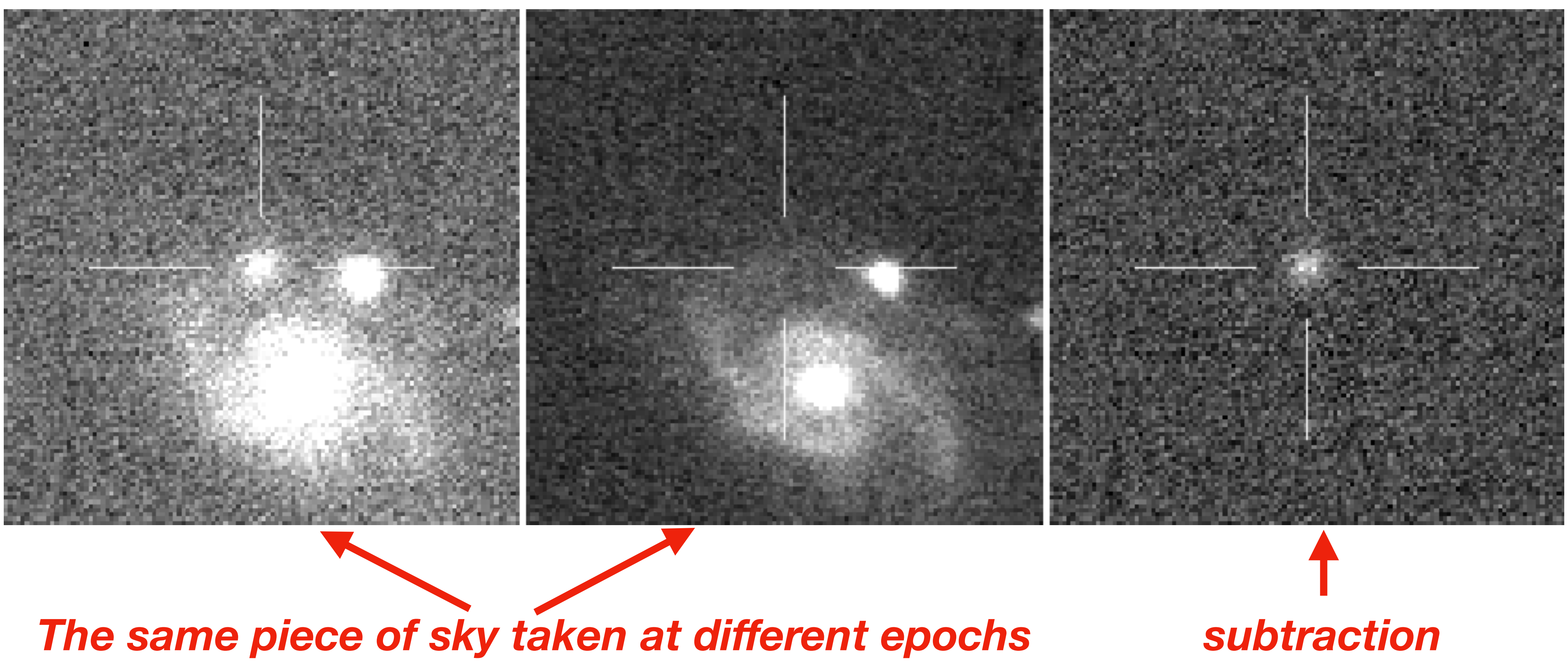
Applications of SN studies

- Stellar evolution
- Chemical enrichment
- Galaxy evolution
- Cosmology

How do we hunt for these supernovae?

Searching for the astrophysical transients

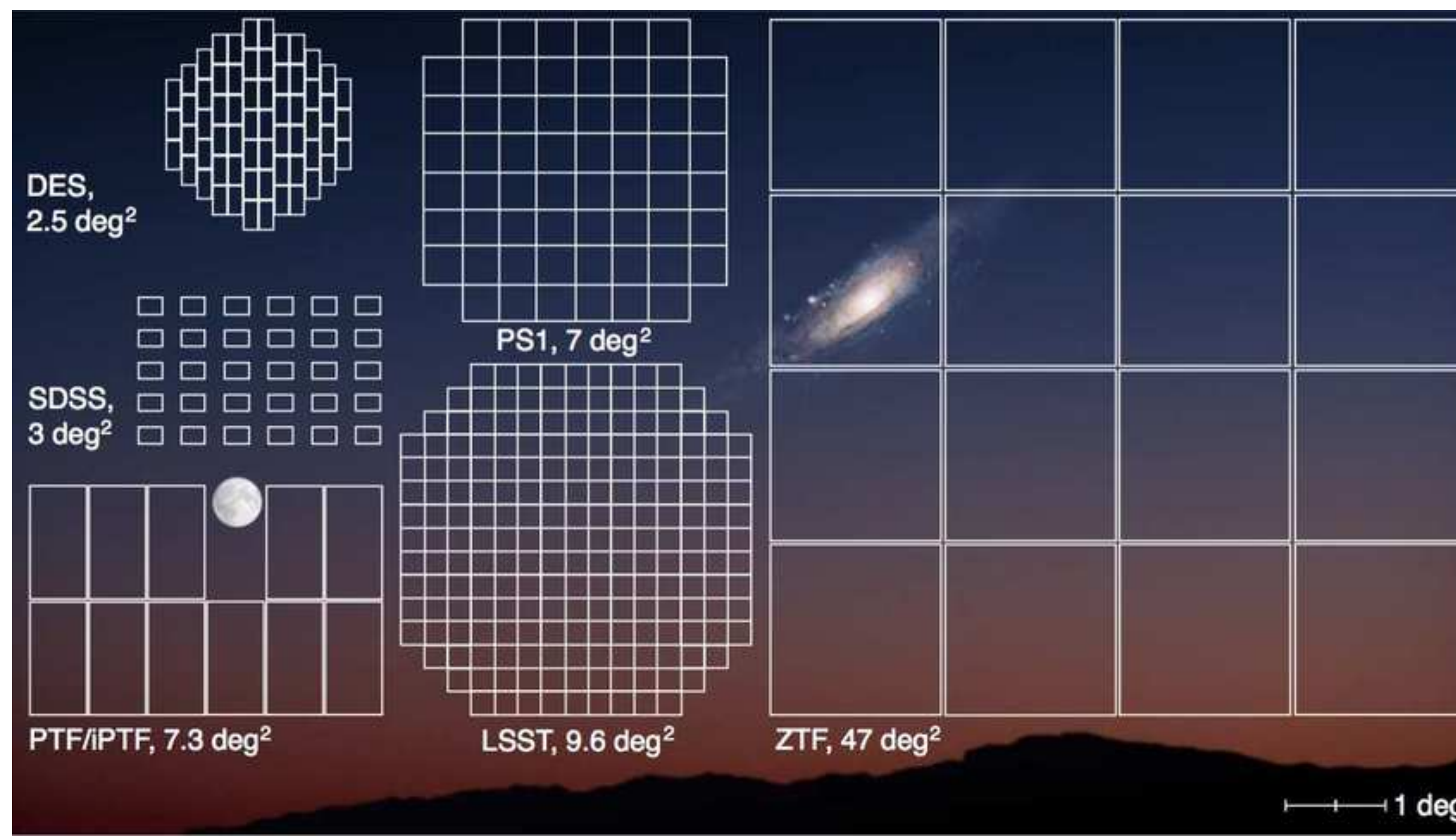
- Map a piece of sky with a certain cadence to detect the variability



Transient surveys

A transient survey can be defined by the following three parameters:

- ✓ Field of view
- ✓ Telescope aperture size
- ✓ Survey cadence/strategy



credit: ZTF