The differences and similarities between supernovae and kilonovae, and their impact on galaxy evolution

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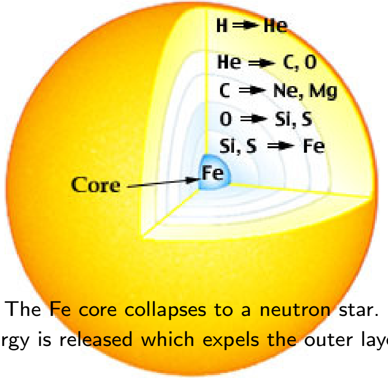
Learning goals of this lecture

- Be able to state **basic properties of SNe and KNe**, with emphasis on similarities and differences.
- Be able to derive and explain the rough impact of SNe and KNe on galaxies both **dynamically** and **chemically**.
- Be able to describe **which elements SNe and KNe produce**, with arguments from theory and observations, and from this be able to **discuss and interpret observed Galactic Chemical Evolution patterns** (in particular for O, Fe, and Eu).

Supernovae - the deaths of stars

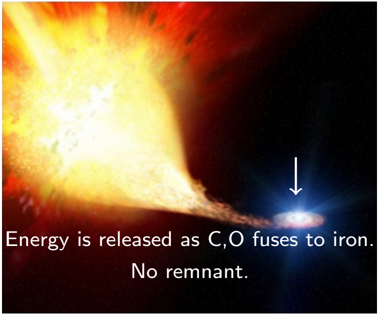
Two fundamentally different types

1 Core-collapse of a **massive star** ($M_{ZAMS} \gtrsim 8\ M_{\odot}$) as it runs out of fuel at the end of its life. CCSN



The Fe core collapses to a neutron star.
Energy is released which expels the outer layers.

2 Thermonuclear explosion of a **white dwarf** exceeding the Chandrasekhar limit (1.4 $M_{\odot}$). The WDs are the end-products of $M_{ZAMS} \approx 3 - 8\ M_{\odot}$ stars. TNSN



Energy is released as C,O fuses to iron.
No remnant.

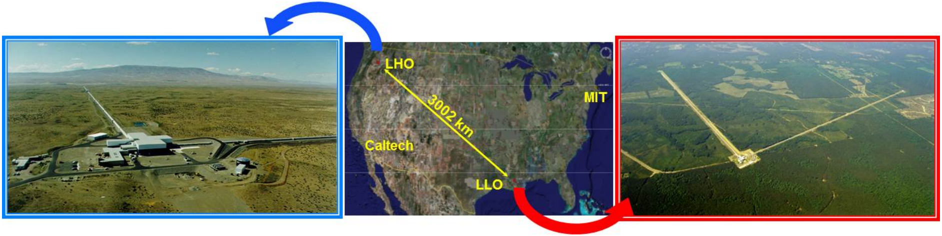
What are kilonovae? KN

Kilonovae are ejecta thrown out as **two neutron stars in a binary merge**.

The merger occurs because all binary orbits decay by **gravitational wave radiation**.

The merger leaves a black hole remnant - only **about 1% of the total mass is ejected**.

LIGO has opened up window on merging compact objects



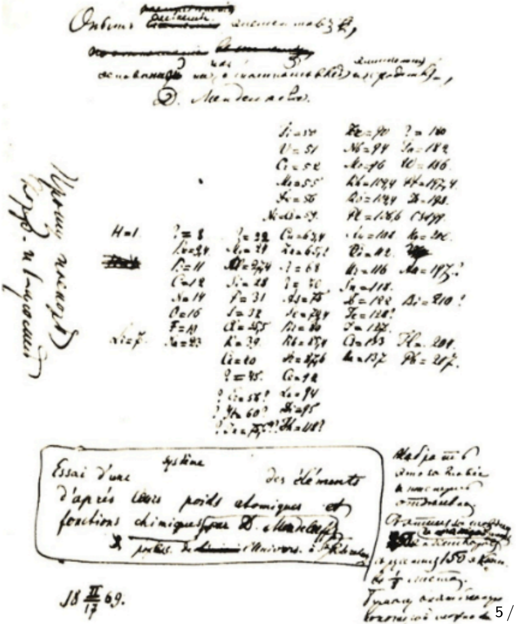
First detection of Gravitational Waves in 2015 (from merging black holes).

 in 2017.

First detection of GW from merging NS in August 2017 (more later).

The origin of elements

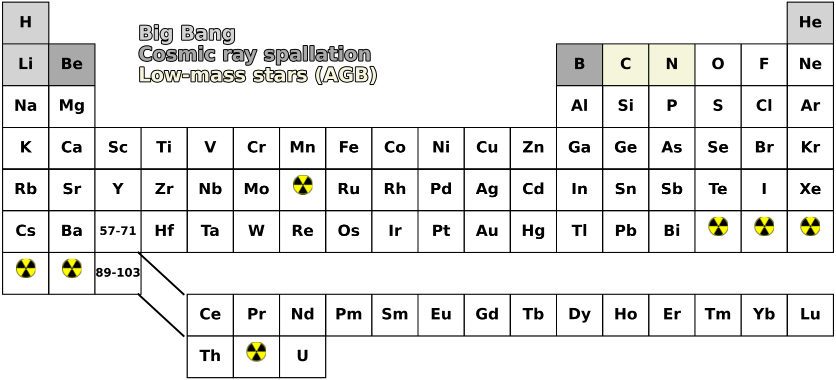
1869 : Dimitri Mendeleev makes the periodic table



The origin of elements

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	☢	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	☢	☢	☢
☢	☢	89-103															
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
				Th	☢	U											

The origin of elements



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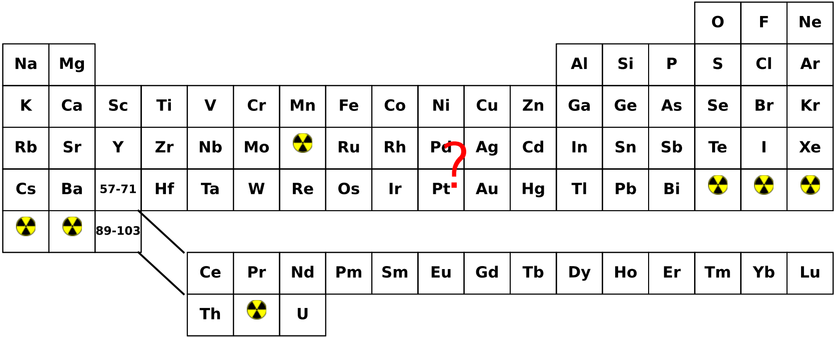


Energy, mass and momentum injection to the galaxy

Energy, mass and momentum injection to the galaxy

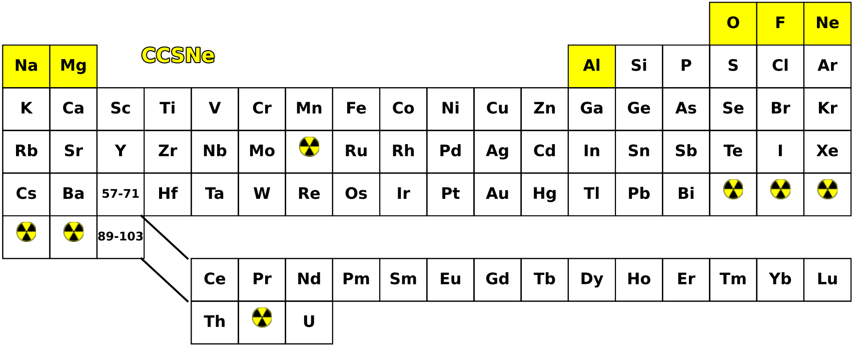
Take-home exercise:

1. The stars in the galaxy radiate about 10^{54} erg in light per century ($\approx 10^{11}\ L_{\odot}$). What role do SNe play compared to stellar radiation for input of energy and momentum to the galaxy?
2. Stars inject energy and momentum also by stellar winds. Given what you know about wind mass loss, estimate the role of winds compared to SNe.

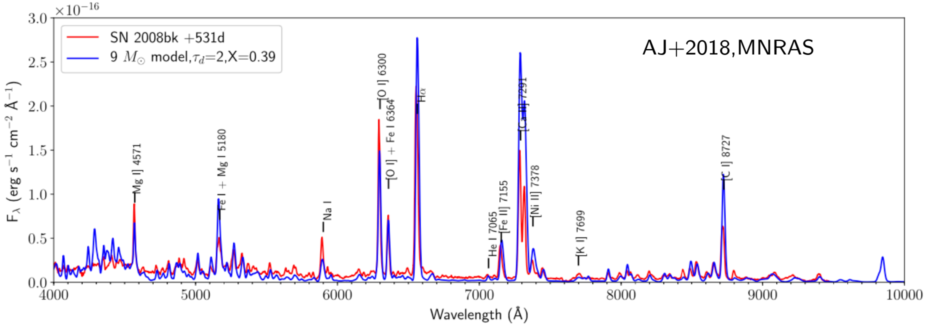
You will find that stellar light, winds, and explosions can all play dynamic roles, with relative importance depending on galaxy type and epoch. Supernovae are often dominant.

CCSNe enrich galaxies in O-Al

- Almost all of the CCSN mass is He,C,O,Ne,Mg. They win hands-down for production of light elements, O-Al.



Direct observational evidence of CCSN nucleosynthesis



- Good overall agreement with predicted yields : Of light elements C,N,O,Na,Mg directly diagnosable.

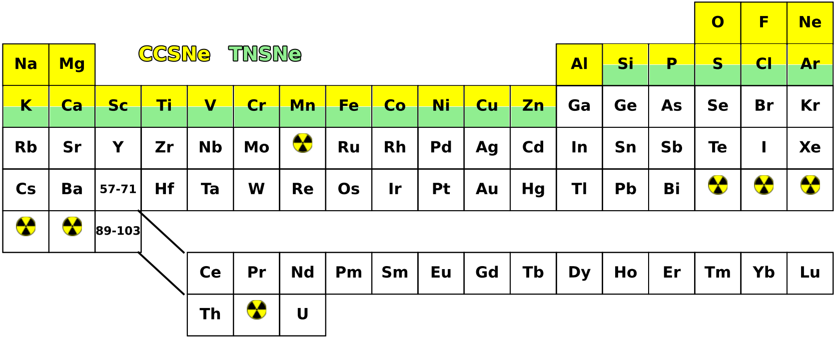
Explosive nucleosynthesis in CCSNe and TNSNe

- 10^{51} erg released in a small region ($R \lesssim R_{\oplus}$). What happens?

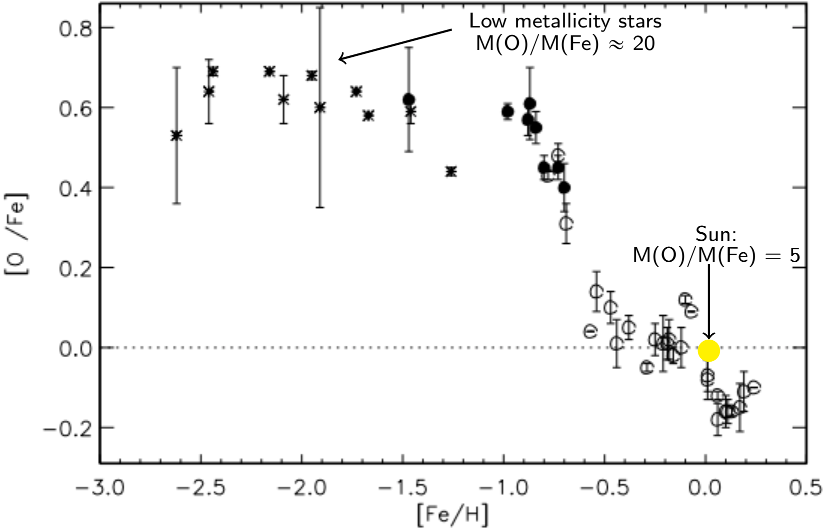
Explosive nucleosynthesis in CCSNe and TNSNe

- 10^{51} erg released in a small region ($R \lesssim R_\oplus$). What happens?
- CCSNe eject $\sim$ 0.1 $M_\odot$ of Fe-group material, TNSN ~ 0.6 $M_\odot$.
- Explosive burning at lower temperatures creates a similar amount of Si-Ca elements.

CCSNe and TNSNe enrich galaxies in Si-Zn in roughly equal amounts

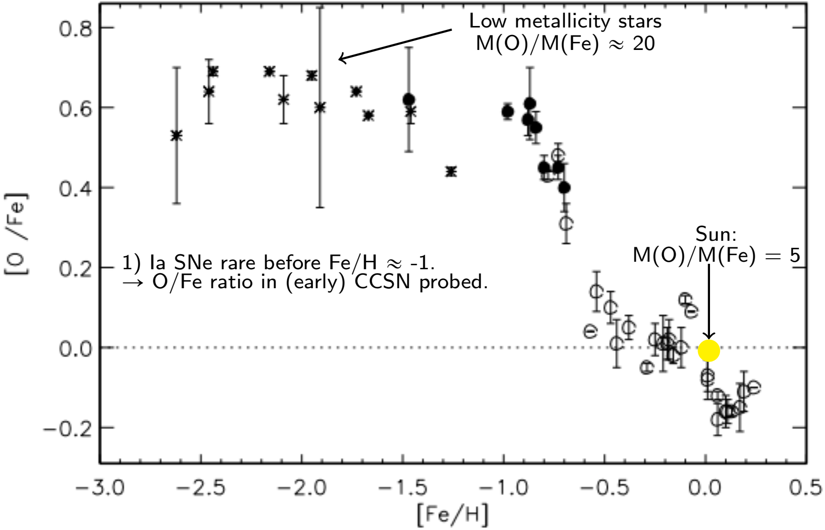


Galactic evolution, O/Fe



Galactic time ⟶

Galactic evolution, O/Fe



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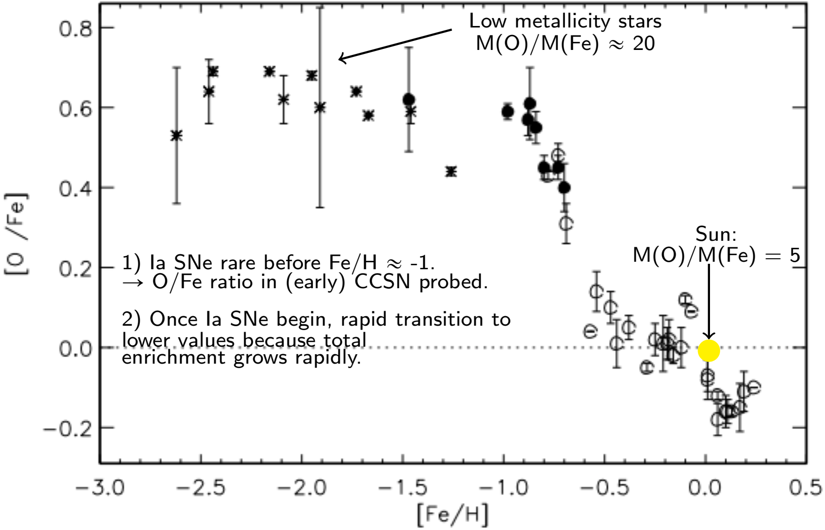

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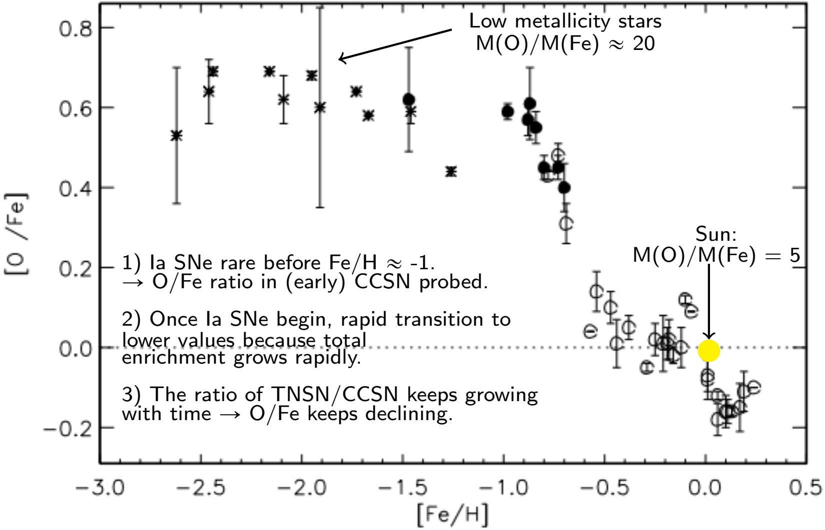


Galactic time ⟶

Neutron capture

- Fusion to heavier nuclei than iron-group is **endothermic**: it costs energy.

- The **Coulomb barrier** gets prohibitively high charged projectiles.

Z>30 nucleosynthesis occurs by **neutron capture**.

s-process

r-process

AGB stars + some in massive stars

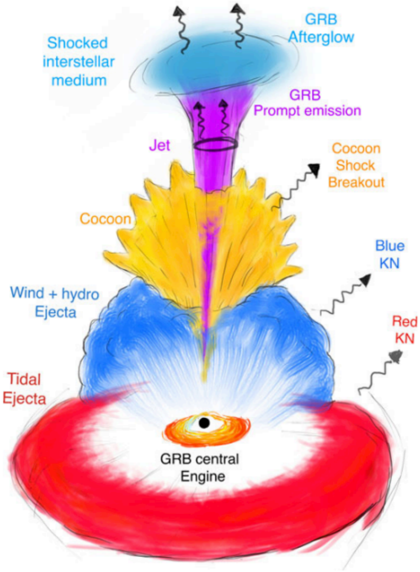
Explosions

Isotopic information for solar system allows disentanglement.

Panning for gold

- Neither CCSNe or TNSNe appear to give the right conditions to burn material much beyond iron-group. The neutron densities are too low to make an r-process because
  1. The progenitor stars have $Y_e = \frac{N_p}{N_n + N_p} \approx 0.5$, consisting of fuel layers produced by successive α-captures (which have $Y_e = 0.5$).
  2. The entropies are not high enough (for those Y_e values).
- In neutron star mergers, on the other hand
  1. The fuel is neutron rich (neutron star material, $Y_e \approx 0.05$)
  2. The entropy is sufficient.

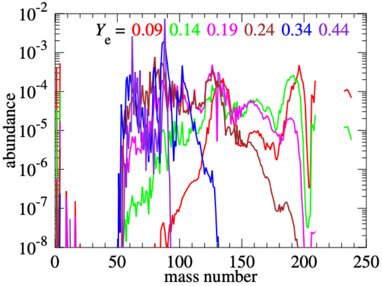
Kilonova nucleosynthesis



The big difference to SNe: start explosion with neutron-rich fuel ($Y_e \approx 0.05$ in a NS).

- Several different components.

Kilonova nucleosynthesis



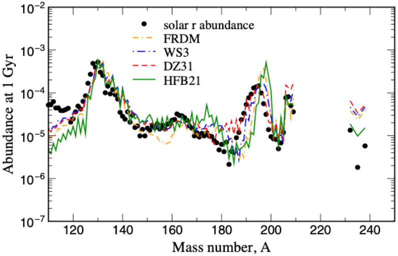
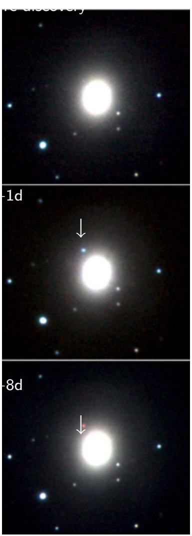


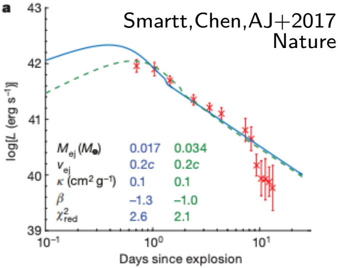
FIG. 23. Final mass-integrated *r*-process abundances obtained in a neutron-star merger simulation using four different mass models. Adapted from Mendoza-Temis *et al.*, 2015.

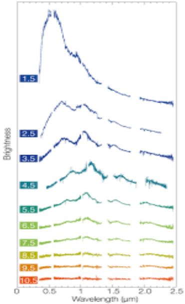
The big difference to SNe: start explosion with neutron-rich fuel ($Y_e \approx 0.05$ in a NS).

- Y_e is the most critical parameter.
  - **If it stays low ($\lesssim 0.25$):** heavy r-process elements made : 2nd and 3d peaks ($A \approx 130$, $A \approx 190$).
  - **If it is raised (by neutrino illumination) ($\gtrsim 0.25$)**: light r-process elements made (1st peak, $A \approx 80$).

AT2017gfo - the first kilonova



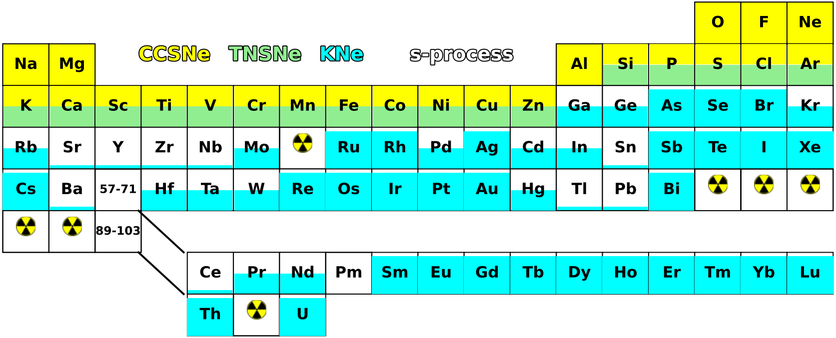




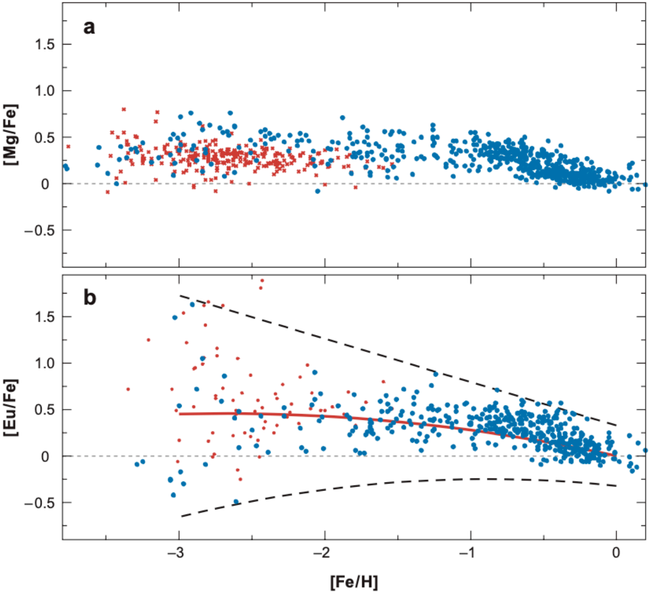
- Light curve consistent with r-process radioactivity ($t^{-1.3}$).
- Colour evolution consistent with expected r-process opacities.
- Direct spectral identification of at least one r-process element (strontium, Watson+2019).

First direct detection of an r-process production site.

The origin of elements



GCE of Europium



Open questions

1. **Are KNe the only r-process sources?**
   - No LIGO dections in O4 so far.
   - Some issues to understand observed early galactic r-process enrichment (as the mergers take a long time to happen).
   - Alternatives : Magnetorotational SNe, neutrino-driven winds in some CCSNe, collapsars : Active research area.

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3. How do **stellar evolution, explosion physics, and galactic chemo-dynamic evolution** combine to explain the structure and history of our galaxy, and others?

Summary, similarities and differences between SNe and KNe

Similarities

- Involve formation or destruction of compact objects (WD,NS,BH).
- Explosive nucleosynthesis, ejecta expanding as several percent speed of light.
- Light displays powered by radioactive decay : all classes now observed.

Differences

- KNe are much more rare, and much harder to observe.
- SNe inject mass and energy to galaxy (with CCSN dominating over TNSNe).
- SNe produce light and intermediate elements, KNe produce heavier elements. This is because SNe explode and eject matter with $N_n \approx N_p$, whereas KNe eject (neutron star) matter with $N_n \gg N_p$ which allows an r-process.