

Physics & Uses of Supernovae

Plan of talk:

- An introduction to Supernovae: Facts & Prejudices
- **Type Ia Brightness Calibration: Refinements**
- **SN Cosmology**
- **Results 1: The accelerated Universe (~1998)**
- **SN Precision Cosmology**
- **Results 2: The “Dark Energy”**

Supernovae in History

Observed since ancient times, as early as 2nd century, by
Chinese Astronomers (called “Guest Stars”)

Notable Examples in the Milky Way:

1. **185: (A.D.) The first SN on record**
2. **1006: The brightest SN ever (like a 1/4 Moon)**
3. **1054: The Crab Nebula, not recorded in Europe (?)**
4. **1572: Tycho SN**
5. **1604: Kepler SN**
6. **1665 (approx): Cassiopeia A, not seen at all (!)**

Extragalactic Supernovae

1885: S Andromedae. A peculiar SN in Andromeda Galaxy

1920-1930: Some observed in sundry galaxies

IMPORTANCE: Led to the separation of SNe from Novae

1934: Baade & Zwicky wrote a very influential paper

- **They standardized the use of the name “Supernovae”**
- **They suggested the exploding star mechanism**
- **They concluded that many more would be found with a well designed survey**

Zwicky & Baade (1934) in context

Lev Landau proposed the concept of a neutron star, an object formed of nuclear matter and supported against collapse by “degeneracy” pressure in 1932.

In 1934 this was very new. The source of power for stars was still unknown, and it was very bold to propose the connection of SNe with collapse of stellar cores to form neutron stars, still just a theoretical possibility.

Zwicky & Minkowski (1934-1944)

Zwicky secured a newly designed Schmidt telescope and started the first systematic SN search. In the first five years of the survey he found 20 SNe. Minkowsky took spectra of the SNe. For the first 12 he found:

1. **Broad wiggles resembling P Cygni profiles**
2. **A very repetitive pattern from SNe to SNe**
3. **A very regular evolution for all of them along time**
4. **A completely unknown set of lines (i.e. wiggles)**

Finally, SN # 13 showed Hydrogen lines

Type I & Type II (☺)

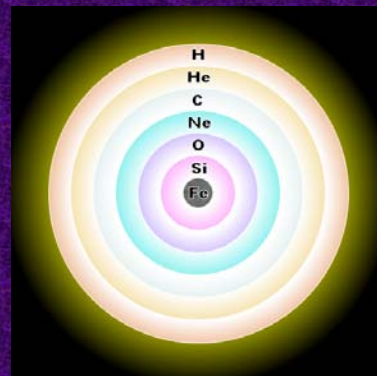
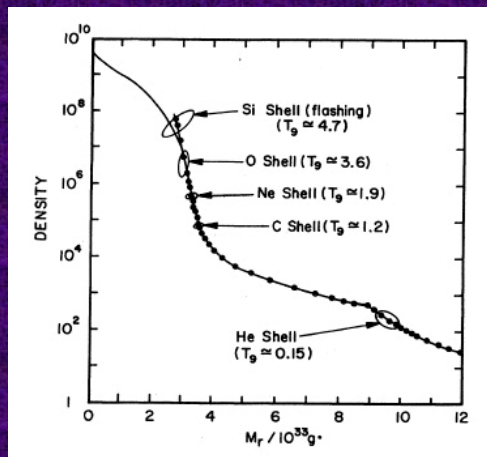
This coincidence led to:

(1) Type I (no H) & Type II (H)

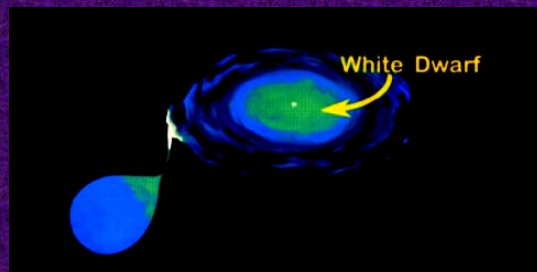
(2) The need for at least TWO explosion mechanisms

The second mechanism had to wait until 1964, when Fowler & Hoyle suggested the runaway thermonuclear reaction of degenerated C as the power source of Type Ia SNe. They also suggested the scenario: A white dwarf star near the Chandrasekhar limit accreting mass from a companion.

Cartoon Models of SNe



Cartoon Models of SNe



Type I:

Model leads naturally to “No H”

Implies association of progenitors with varied stellar populations, but none of them VERY young.

Theory of nuclear combustion is well known (microphysics).

Nuclear combustion in gravitational confinement is not (macro).

Type II:

Model requires massive stars (more than $\sim 8 M_{\text{sun}}$)

Implies association of progenitors with young stellar populations

Theory of gravitational core collapse rests on unknown physics

This is true both at the micro and macro levels.

Type I:

Model leads naturally to "No H" Implies Homogeneity !

Implies association of progenitors with varied stellar populations.

None of the VERY young. Source of inhomogeneity (?)

Theory of nuclear combustion is well known (microphysics).

Nuclear combustion in gravitational confinement is not (macro).

Type II:

Model requires massive stars (more than $\sim 8 M_{\text{sun}}$)

Implies association of progenitors with young stellar populations

Theory of gravitational core collapse rests on unknown physics

This is true both at the micro and macro levels.

Type I:

Model leads naturally to "No H"

Implies association of progenitors with varied stellar populations.

None of the V Two possible (similar) scenarios:

Theory of nuc (1) Collapse of Fe degenerate cores

Nuclear comb (2) Collapse of Ne-O cores ($\sim 8 M_{\text{sun}}$) (macro).

Type II:

Model requires massive stars (more than $\sim 8 M_{\text{sun}}$)

Implies association of progenitors with young stellar populations

Theory of gravitational core collapse rests on unknown physics

This is true both at the micro and macro levels.

Theory: Three main branches

1. Explosion (Engine): Nuclear & Particle/High Energy Physics
2. Expansion (Shock): Nucleosynthesis & Hydrodynamics
3. Atmosphere: Radiative Transfer (γ -rays, e^+ , UVOIR) in a medium moving supersonically

Some theoretic “Hits:”

Discovery of the delayed shock mechanism

Discovery of the powering chain $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$

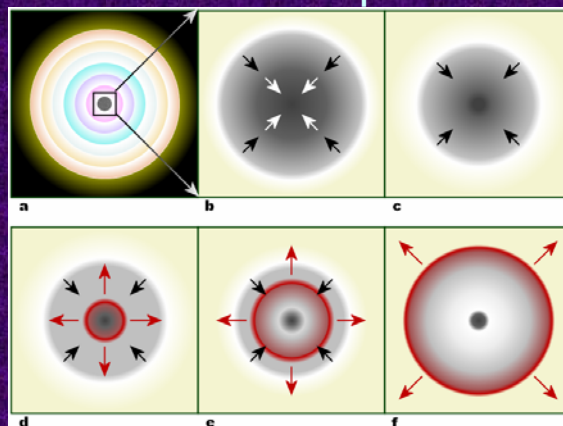
Development of the Sovolev Method

Discovery of the “W7” deflagration \rightarrow detonation model

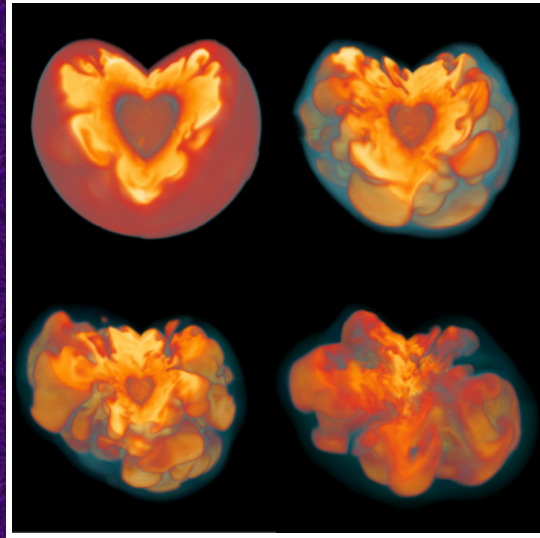
Development of interacting binary evolution

Cartoon Model of Core-Collapse

- a) Neutrino losses and photo-disintegration remove pressure support. Core, of $\sim 1.7 M_{\odot}$, starts to fall.
- b) Somewhere speed exceeds 1000 km/s. This is collapse, and it is homologous.
- c) Collapse goes on, layers close to center fall slower.
- d) Nuclear density is reached, and core of collapse stops very fast.
- e) Faster falling matter hits nuclear density core and rebounds at $\sim 0.7 M_{\odot}$.
- f) Will shock break out of collapsing core at $\sim 1.4 M_{\odot}$? (not really).

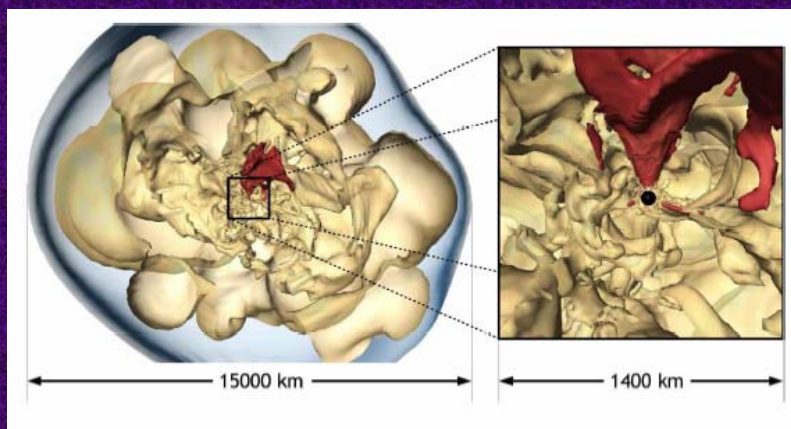


Computation of Explosion



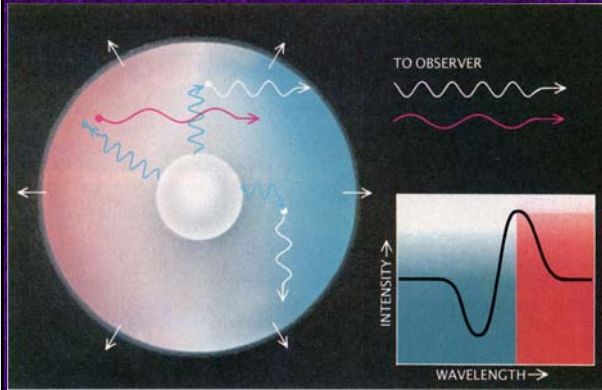
Core collapse at 0.1, 0.2, 0.3 and 0.5 seconds after implosion.
Size of square is 200, 300, 500 and 2000 km, respectively.

“Jet Engine” in Core-Collapse



Dipolar asymmetry triggered by an accreting shock instability to non-radial deformation.
Jet engine provides a kick to the neutron star.

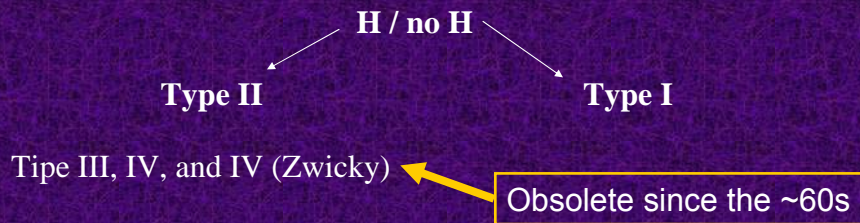
Spectral "Lines" & Classification



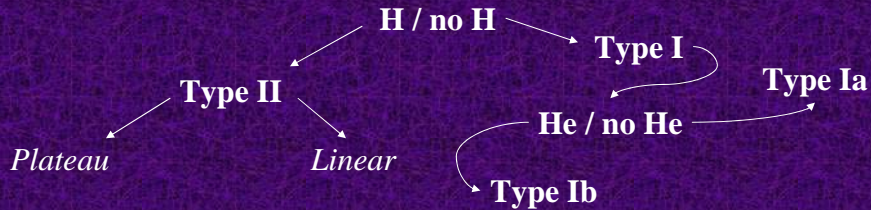
Chemical elements of the outermost layers leave the imprint of their low excitation transitions.

BUT: Due to the large expansion velocity SN lines are more complex and difficult to interpret than those of stars with a static atmosphere.

SN Classification



SN Classification



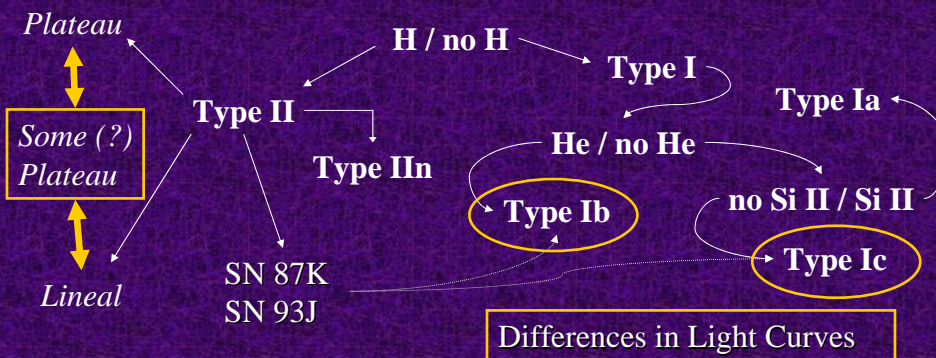
Define the *main observables* which will be used for years:

- 1.- Spectra near maximum light
- 2.- Light curve shapes

Note: Absolute brightness is not considered in classification

CRITICAL: Realization that Type Ia was not a “clean” group

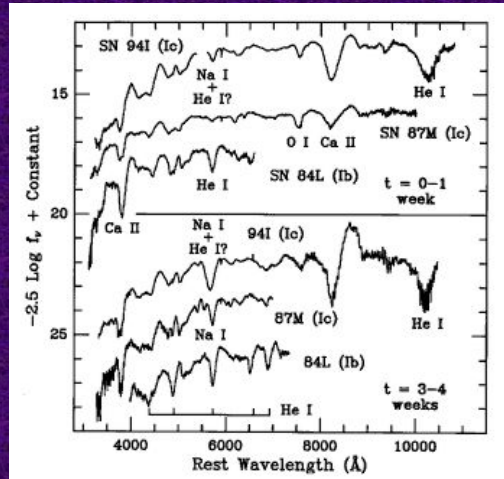
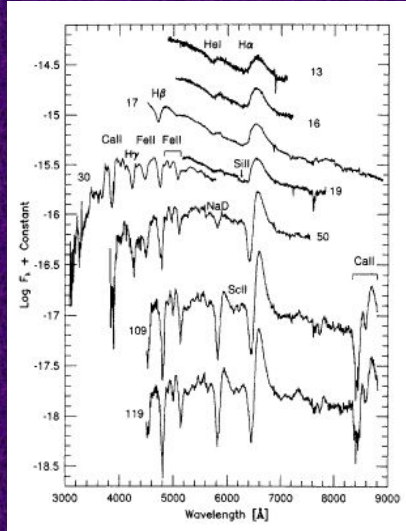
SN Classification



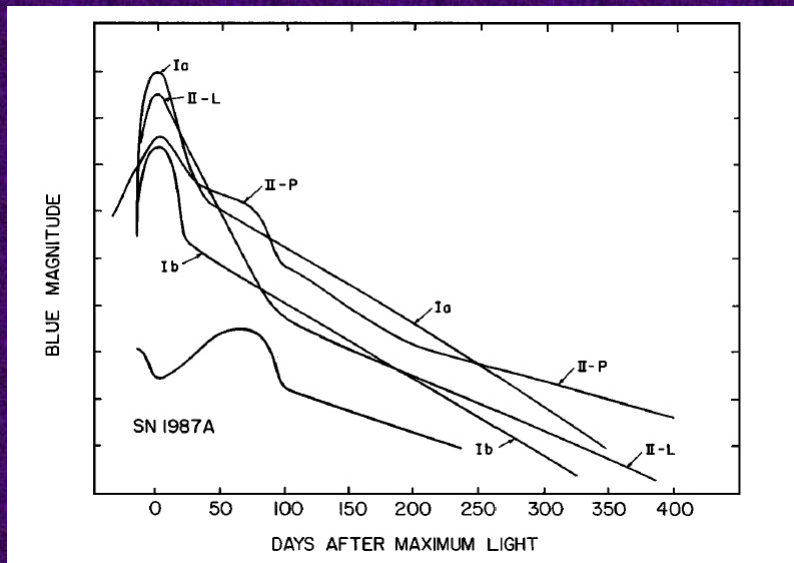
Problem: Number of core-collapse SNe imply more massive Stars than are currently available to produce progenitors.

Problem: Type Ic is just “absence of evidence” (i.e. nothing)

Prototypical Spectra



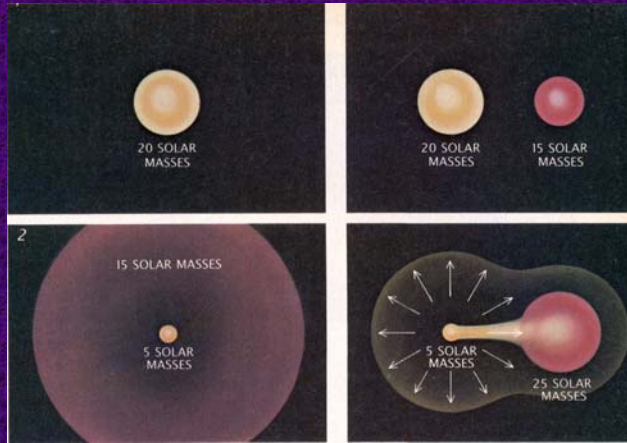
Prototypical Light Curves



Binary evolution & Transition SNe

Two different Scenarios: Single and Coupled (binary) evolution

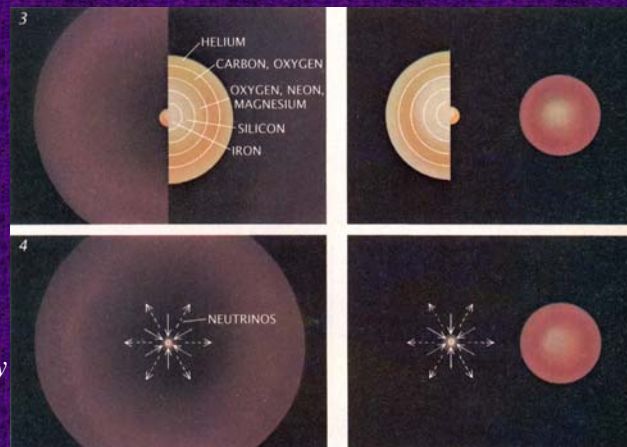
More massive star evolves.



Binary Evolution & Transition SNe

Inner structure will be similar even though outer layers will differ

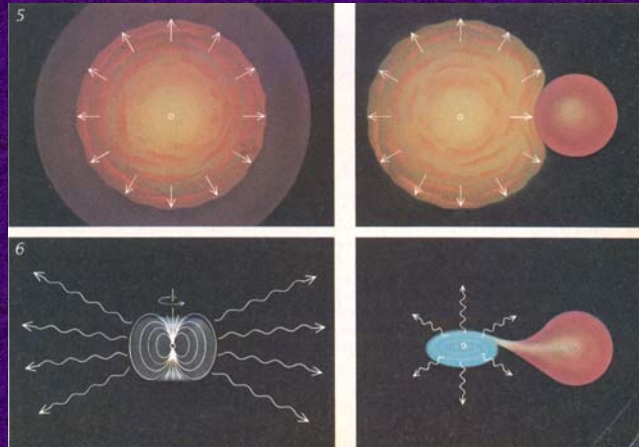
Core going to collapse is very similar, but external layers are very different



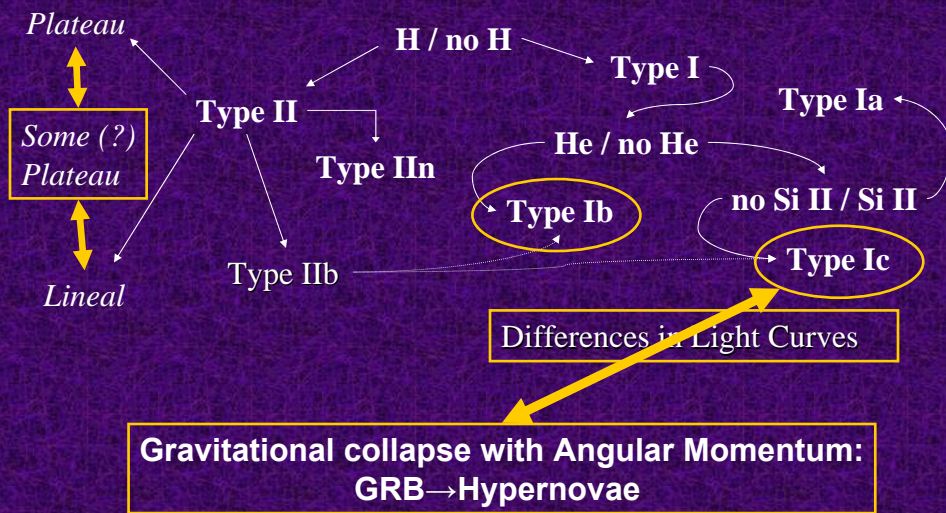
Binary Evolution & Transition SNe

Generally star 2 will survive the explosion

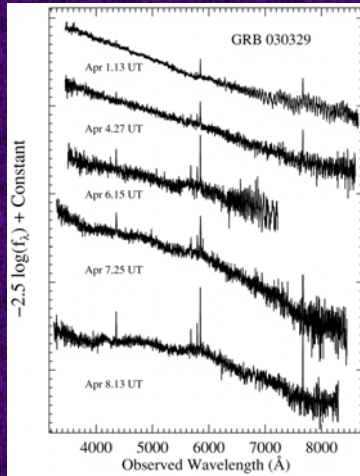
If star 2 also goes to explosion, a binary pulsar may result.



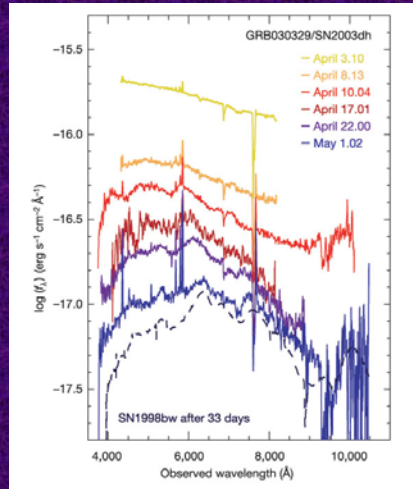
SN Classification



Spectroscopic Signs: SN 2003dh

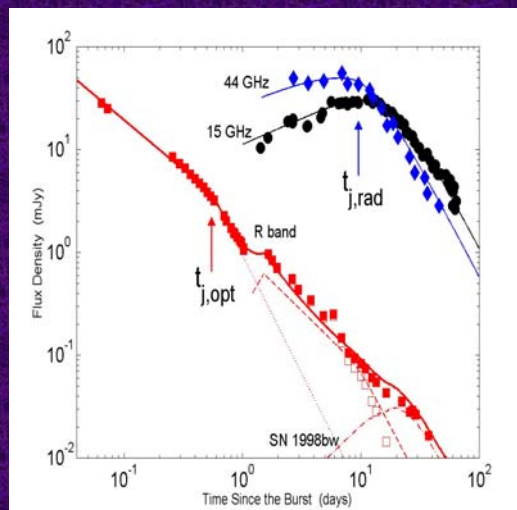


MMT (Stanek et al)

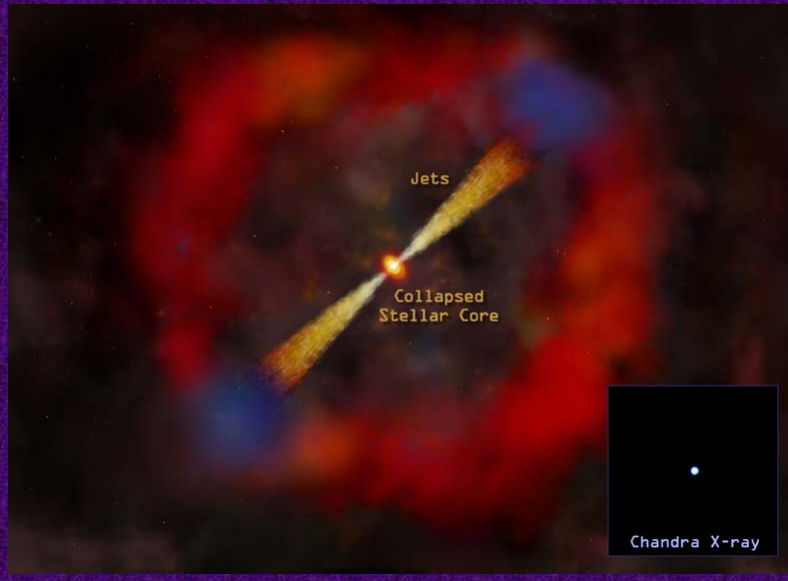


VLT (Hjorth et al)

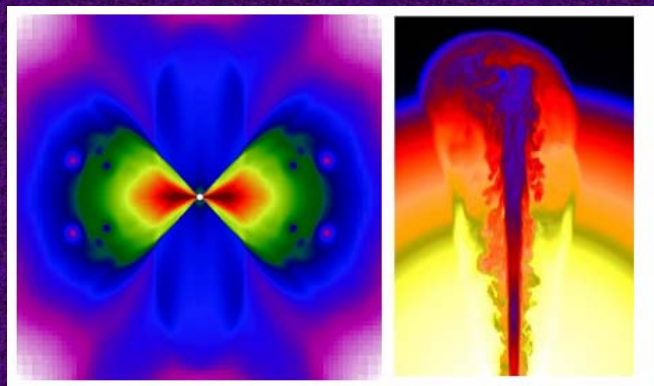
Photometric signs: SN 2003dh



A GRB/SN Cartoon Model

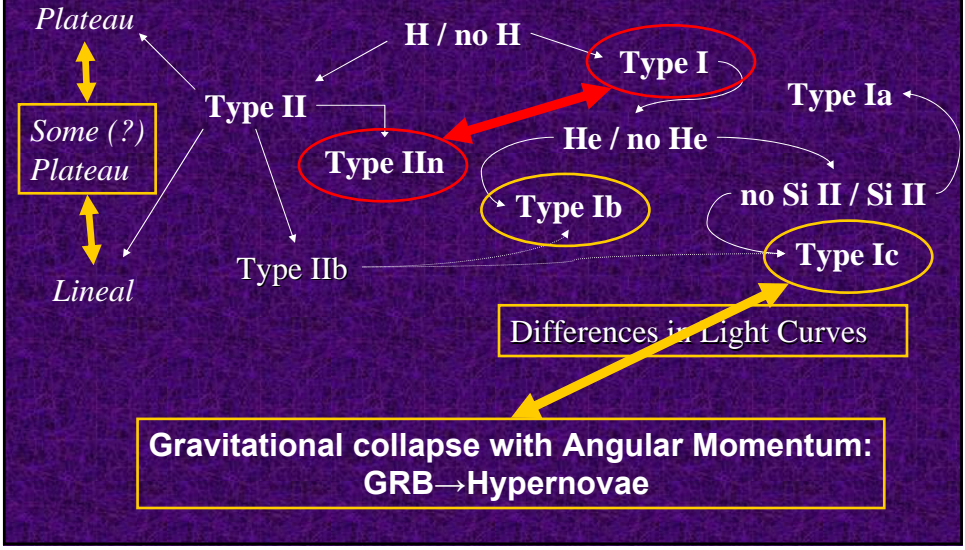


Collapsar model of GRB



Left panel: 1800 km, 20 seconds after 4.4 M_{\odot} BH formation on a rotating 14 M_{\odot} star.
Right panel: Jet emerging at $\sim 1 R_{\odot}$ 8 seconds after jet birth at center.

SN Classification



Prototypical spectra of Type IIc SNe

