# Ay 20 - Fall 2004

## Lecture 12:

# Supernovae
# and
# Gamma-Ray Bursts
## and some of their uses

# Supernovae (SNe): Exploding Stars

- Two basic types and several sub-types, which differ in spectroscopic properties, light curves, locations, progenitors, etc.
- Previously normal star suddenly (~few days to weeks) becomes *much* more luminous (up to $\sim 10^{10}$ $L_\odot$), rivals entire galaxy in brightness for a few weeks! Fades over months to years
- Most energy (~ 99%, up to $\sim 10^{54}$ erg) in neutrinos; kinetic energy ~ 1% (typically $\sim 10^{51}$ erg); visible light only ~ 0.1% of the total
- Gas expands at $v \geq 10{,}000$ km/s!
- Leave a nebular remnant, and a compact remnant (neutron star or a black hole)

# Supernova Classification

**Type I:** no lines of hydrogen in the spectrum
Occur in all types of galaxies

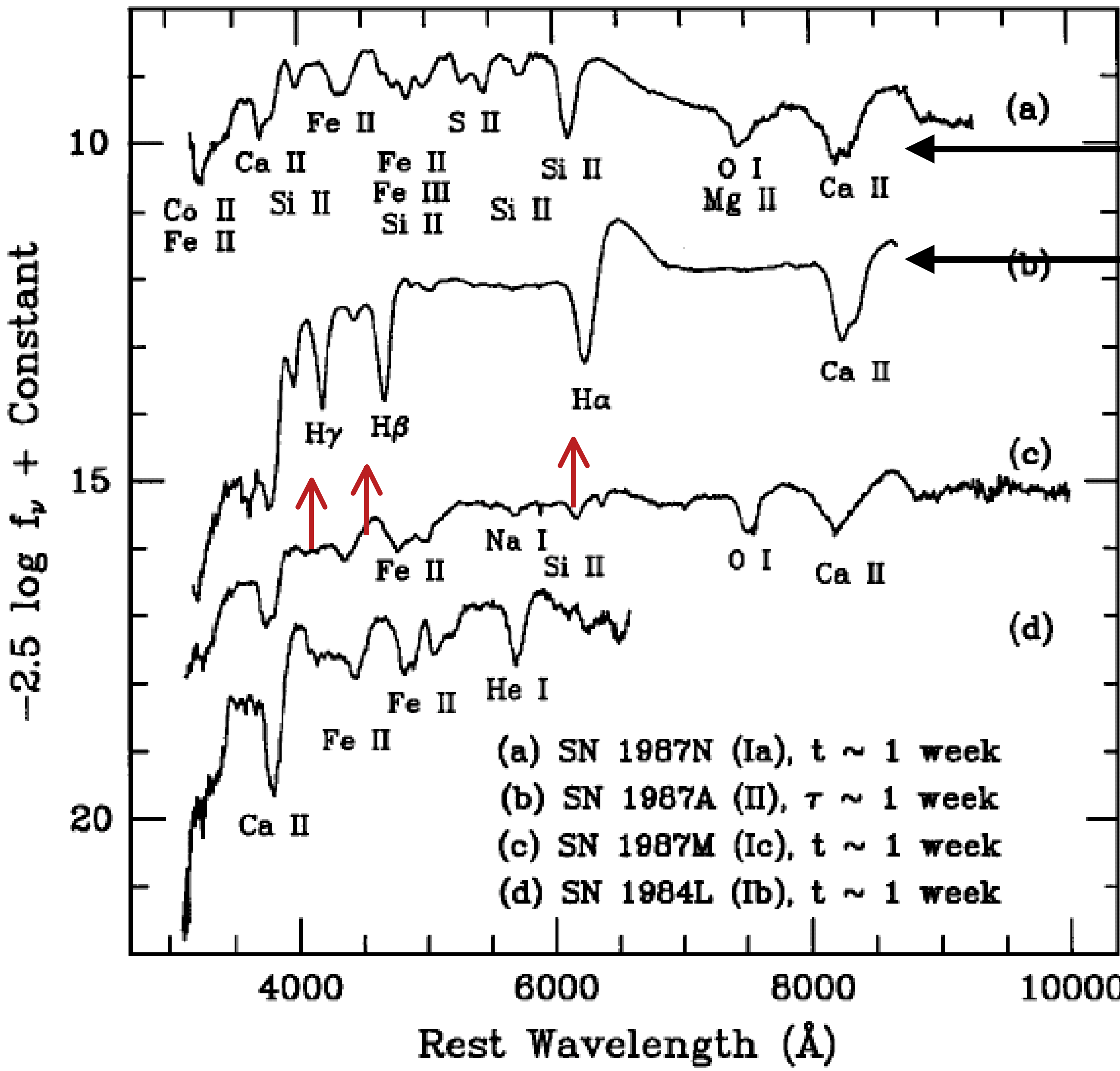
**Type II:** lines of hydrogen seen in spectrum
Occur in star-forming galaxies only

Type I's are further divided into subclasses (Ia, Ib, Ic) again based on their spectral properties. There are also "peculiar" cases.

Type Ia SNe are believed to result from explosions of Chandrasekar mass white dwarfs. All other types are thought to result from the collapse of massive stars.

Note: this empirical classification predates any physical understanding, and so is potentially confusing!

# SN Spectra Comparison

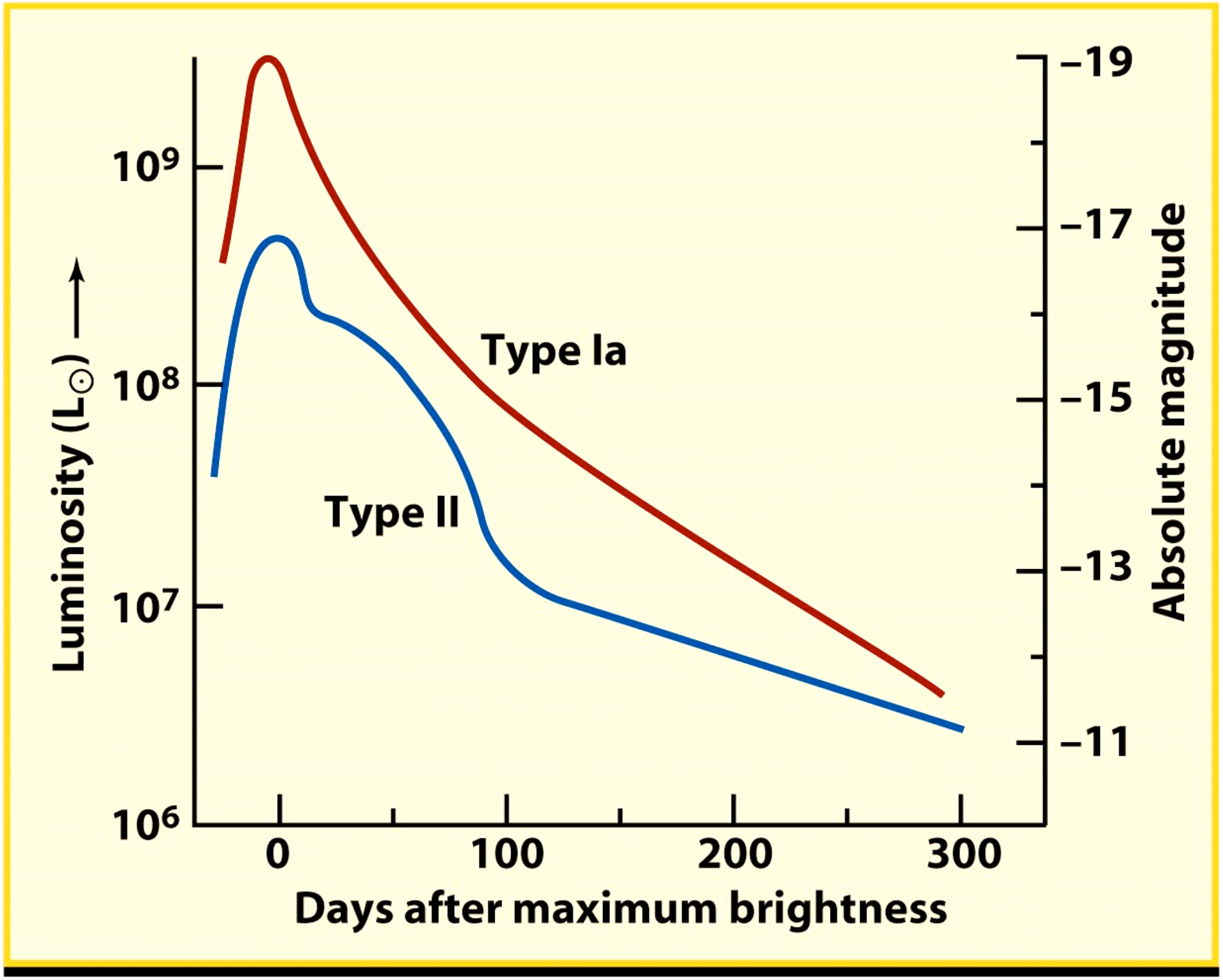



Type Ia

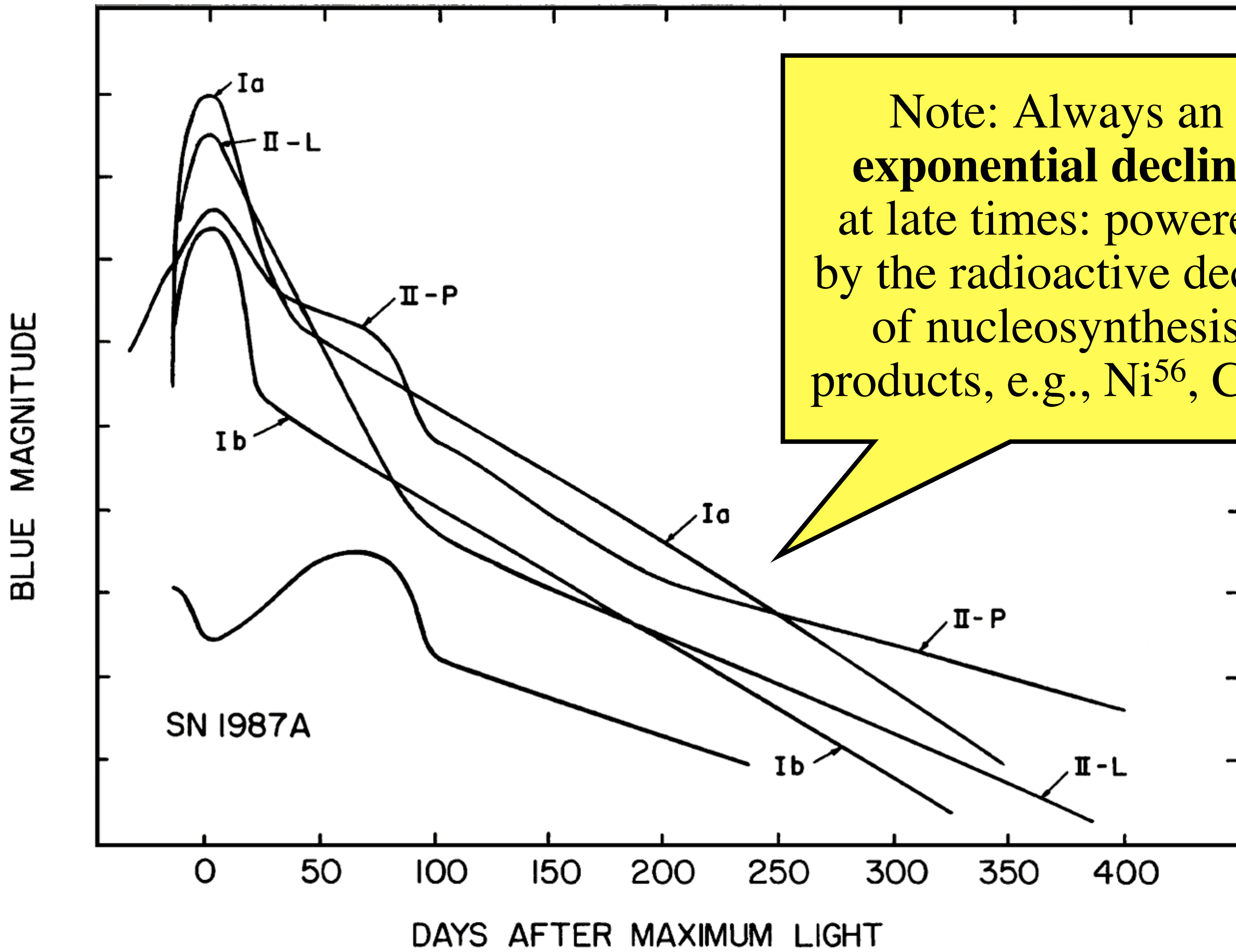
Type II

Clear lines of hydrogen in spectrum

# SN Types: Light Curve Differences

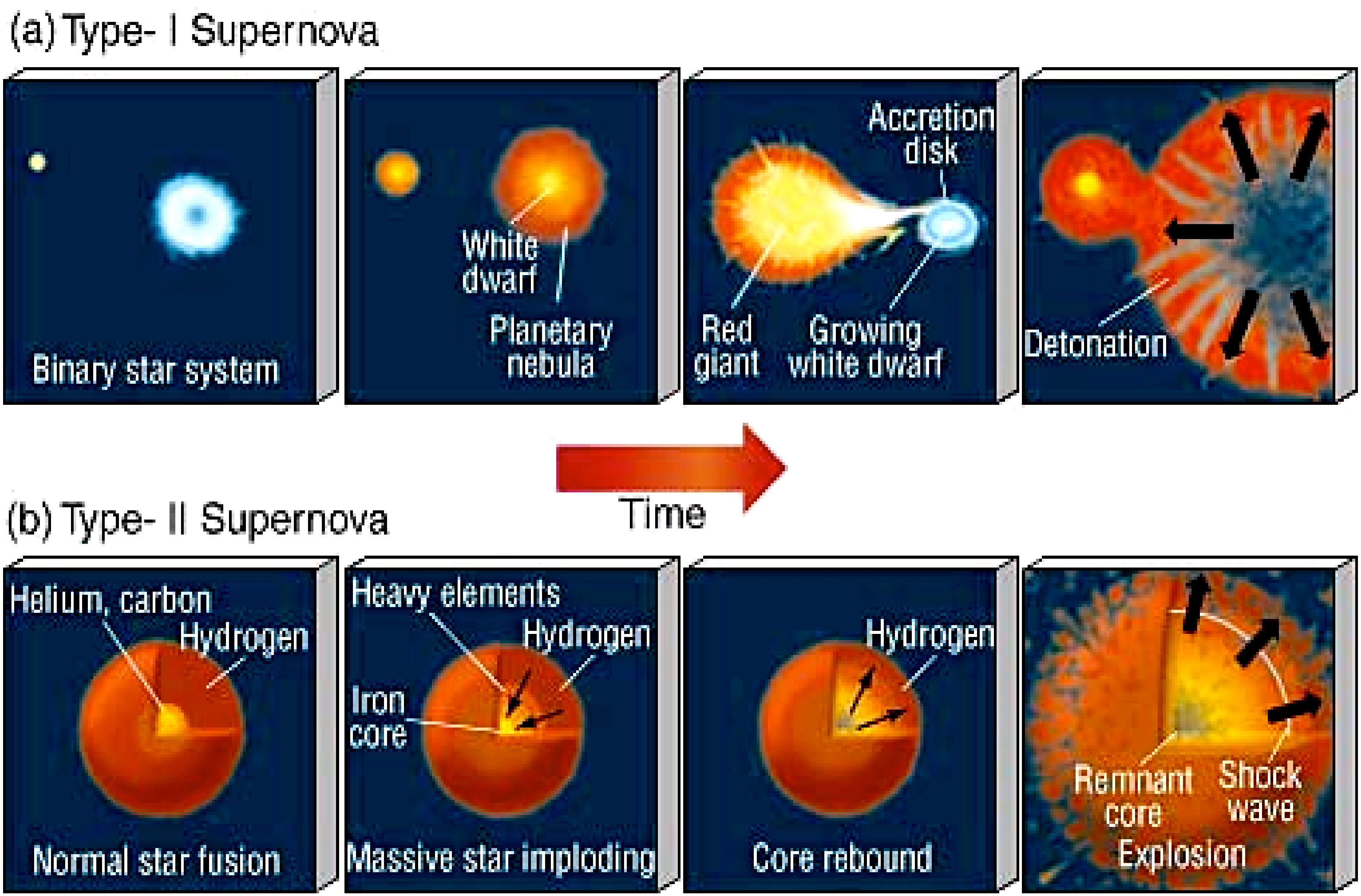


# A Considerable Variety of Light Curves




Note: Always an **exponential decline** at late times: powered by the radioactive decay of nucleosynthesis products, e.g., $Ni^{56}$, $Co^{56}$

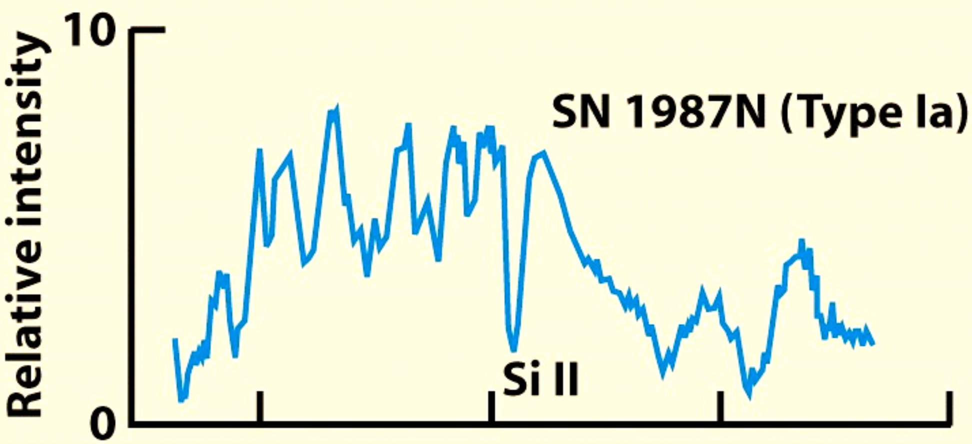
# SN Types: Physical Mechanisms

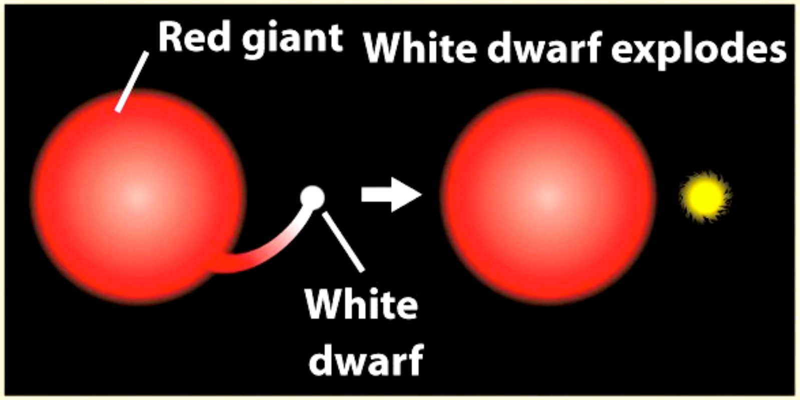


# Type Ia SNe: produced by accreting white dwarfs in close binaries

**(a) Type Ia supernova**

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).

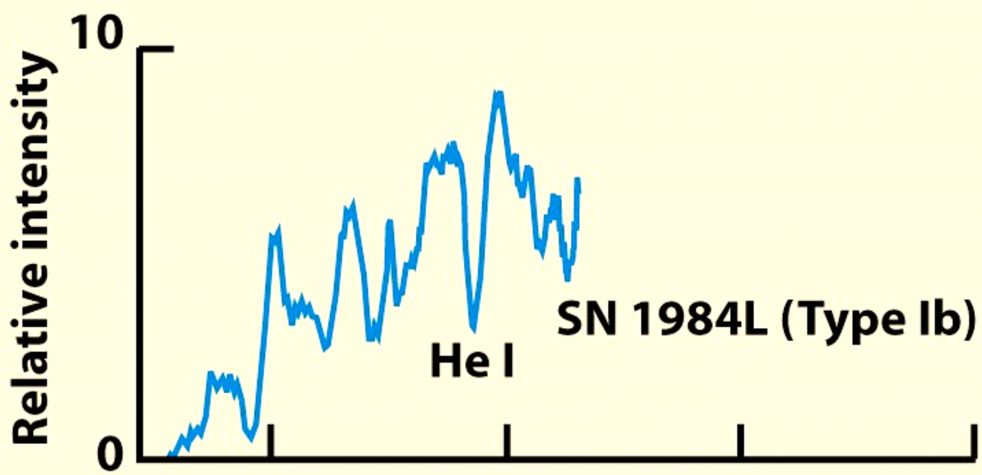


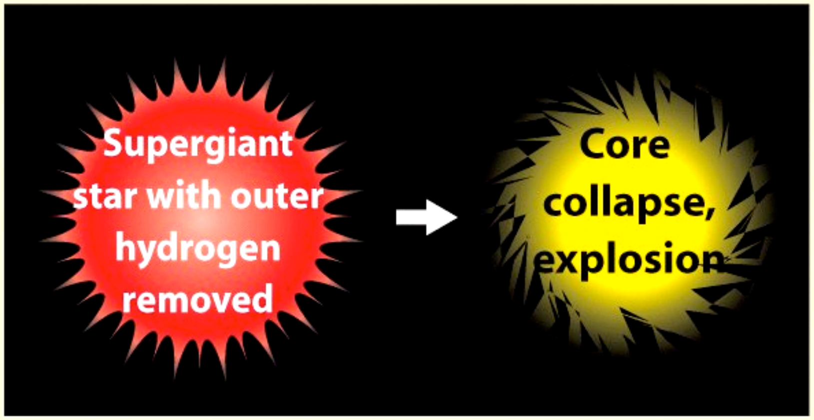



# Type Ib SNe occur when the star has lost a substantial part of its outer layers (the H envelope) before exploding

**(b) Type Ib supernova**

- The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).
- Produced by core collapse in a massive star that lost the hydrogen from its outer layers.

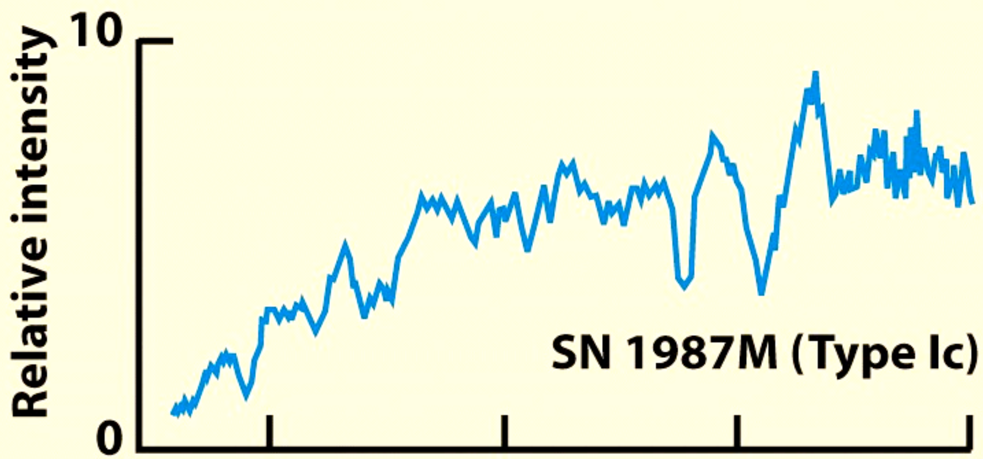


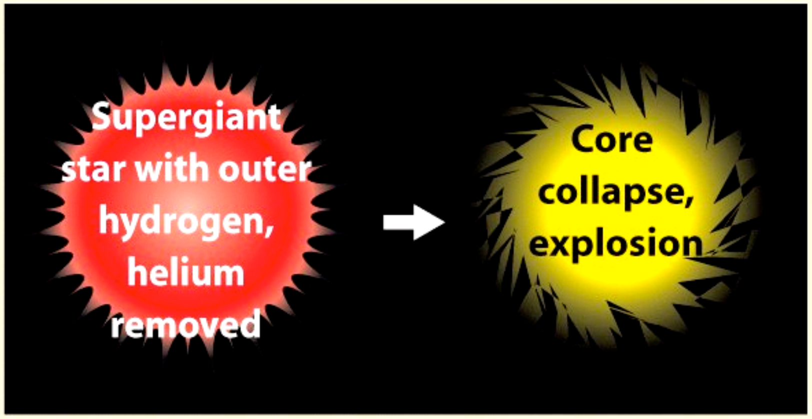



# Type Ic SNe: both H and He envelopes lost before exploding

**(c) Type Ic supernova**

- **The spectrum has no hydrogen lines or helium lines.**
- **Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.**

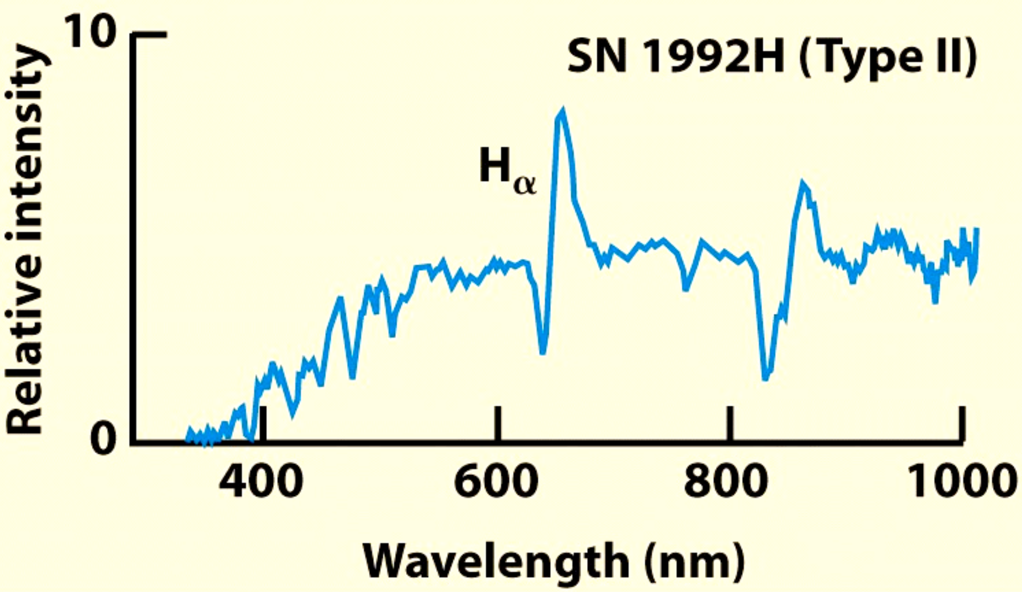


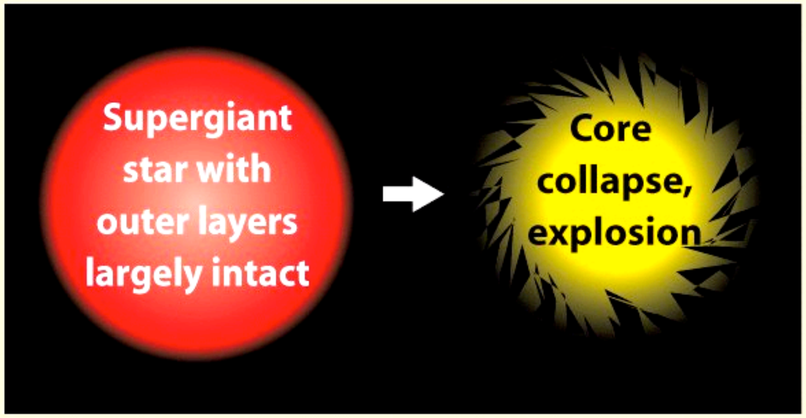



# Type II supernovae are created by the deaths of massive stars at the end of their thermonuclear evolution

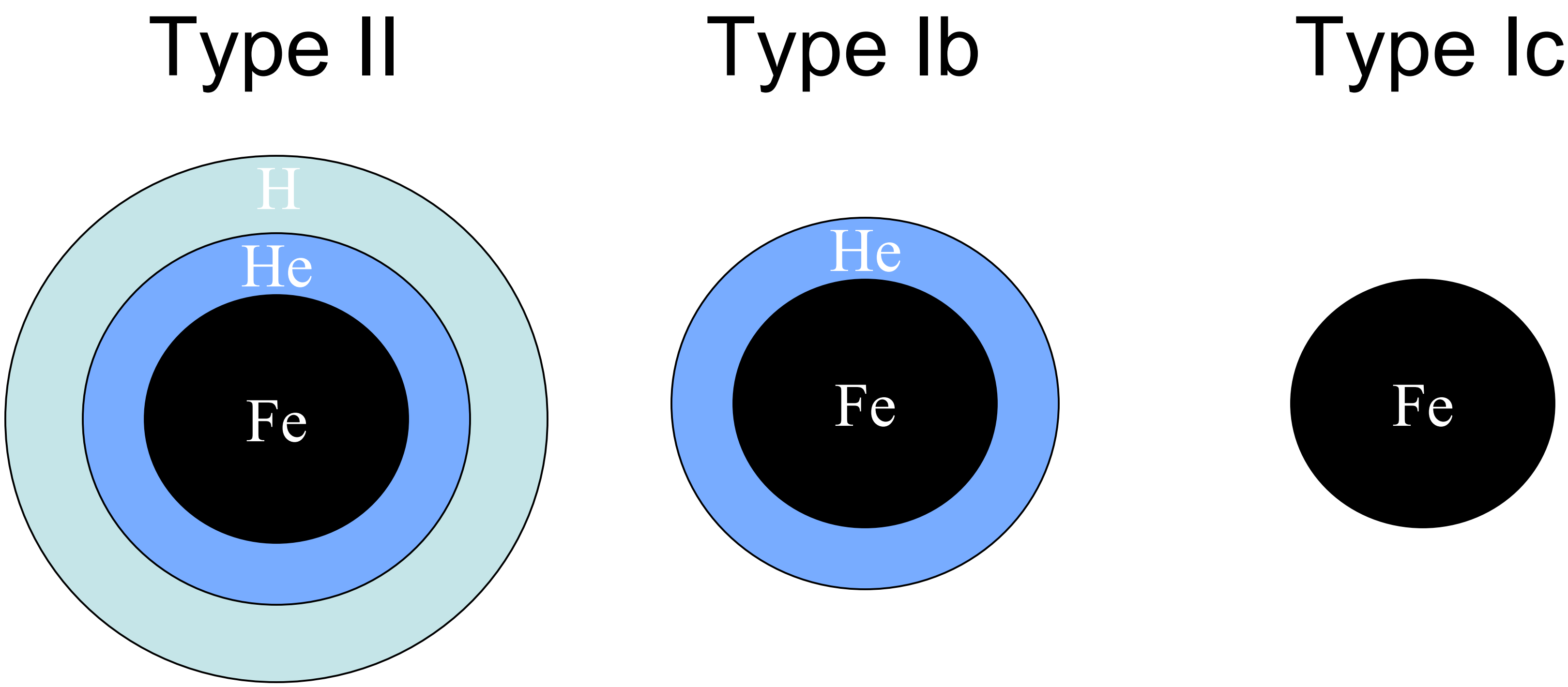
**(d) Type II supernova**

- **The spectrum has prominent hydrogen lines such as $H_\alpha$.**
- **Produced by core collapse in a massive star whose outer layers were largely intact.**



# Core Collapse (Type II, Ib, Ic) SNe




Progenitors: $>8M_{\odot}$ Red giant
Leave: Neutron star or black hole

# Endpoints of Stellar Evolution

**1) Stars with $M < 8\ M_{sun}$:**

These stars never develop a degenerate core more massive than the Chandrasekhar limit (for the more massive stars, this requires a lot of mass loss).

Endpoint is a white dwarf with a mass smaller than $M_{Ch}$, in which the pressure is provided by non-relativistic degenerate electrons.

An isolated white dwarf simply cools off and becomes dimmer and dimmer for all time.

**2) Stars with $M > 8\ M_{sun}$:**

Nuclear reactions in these stars cease once an iron core has developed. Core is too massive to be supported by electron degeneracy, leading to **core collapse**.

## Type II Supernovae

Overwhelming observational evidence that Type II supernovae are associated with the endpoints of massive stars:

Association with spiral arms in spiral galaxies

## Type II Supernovae

Overwhelming observational evidence that Type II supernovae are associated with the endpoints of massive stars:

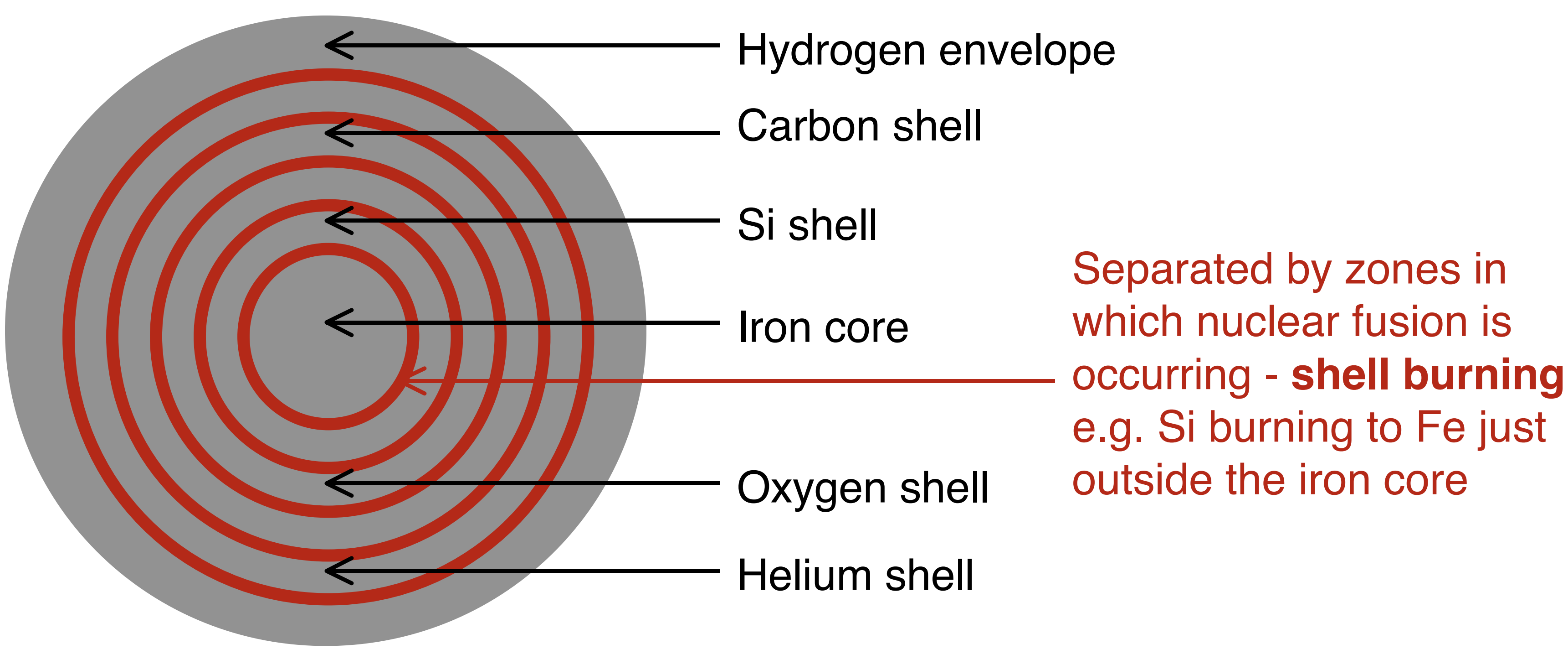
Identification of the progenitors of some core collapse SN

Thought to represent core collapse of massive stars with $M > 8\ M_{sun}$. Type Ib and Type Ic are thought to be similar events in stars that have lost their outer hydrogen envelopes prior to the explosion.

## Core collapse in massive stars

In a massive star, core temperature can be high enough that nuclear burning of Si to Fe can occur. Beyond Fe, further fusion is *endothermic*, and will not occur *under equilibrium conditions*. As an iron core develops, other reactions still proceed at larger radii:

`Onion shell' structure



Eventually iron core becomes too massive to be supported by electron degeneracy pressure:

- Can't explode like a white dwarf (Type I SN) - the core is *already* made of iron so no more exothermic nuclear reactions possible
- **Core collapses**

Once collapse starts, it proceeds very rapidly:

Photodisintegration

$$^{56}\mathrm{Fe} + \gamma \rightarrow \text{lighter elements}$$

Needs high energy gamma rays

Inverse beta decay

$$e^{-} + p \rightarrow n + \nu_e$$

Needs $e^-$ and p to have enough energy to overcome mass difference between neutron and proton

These processes rob the core of pressure support, accelerate the collapse, and drive the composition toward neutron rich matter.

Once the core reaches nuclear densities - $\rho \sim 10^{15}$ g cm$^{-3}$, nuclear forces provide a new source of pressure support.

Scale is now: $M = \frac{4}{3}\pi R^3 \rho_{nuc}$

$$R \approx \sqrt[3]{\frac{3M}{4\pi\rho_{nuc}}} \sim 10 \text{ km}$$

Formation of a proto-neutron star stops the collapse, and produces a bounce which sends a shock wave back out into the star.

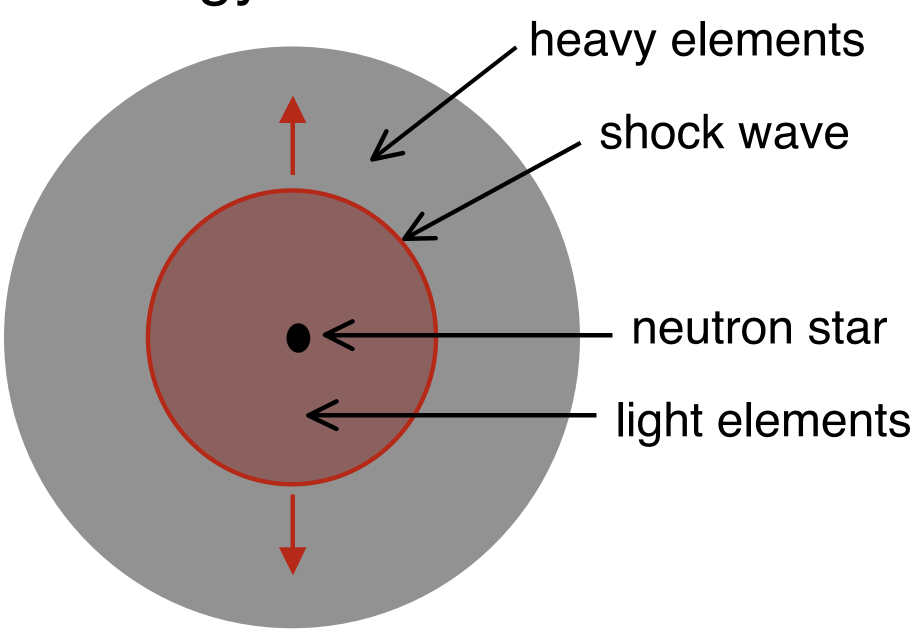
Shock wave can explode the star, *if it can propagate out through the infalling matter*.

Core may leave a **neutron star**, or if it is too massive, collapse further to form a **black hole**.

Proven very difficult to ascertain the exact mechanism of Type II supernova explosions:

**Problem**: the bounce launches a shock wave with an energy that is a fraction of the binding energy of the neutron star - typically ~$10^{52}$ erg.

As the shock propagates through the star, high temperatures break up heavy elements into lighter ones, which absorbs some of the energy:




Energy needed to completely break up heavy elements is about 8 MeV per nucleon:

$$1.6\times10^{52}\ \mathrm{erg}\ M_{sun}^{-1}$$

`Prompt' mechanism for Type II SN fails…

## Neutrino-driven explosions

Neutronization reaction in the core: $e^{-} + p \rightarrow n + \nu_e$
yields a very large flux of neutrinos, with total energy of a few x $10^{52}$ erg.

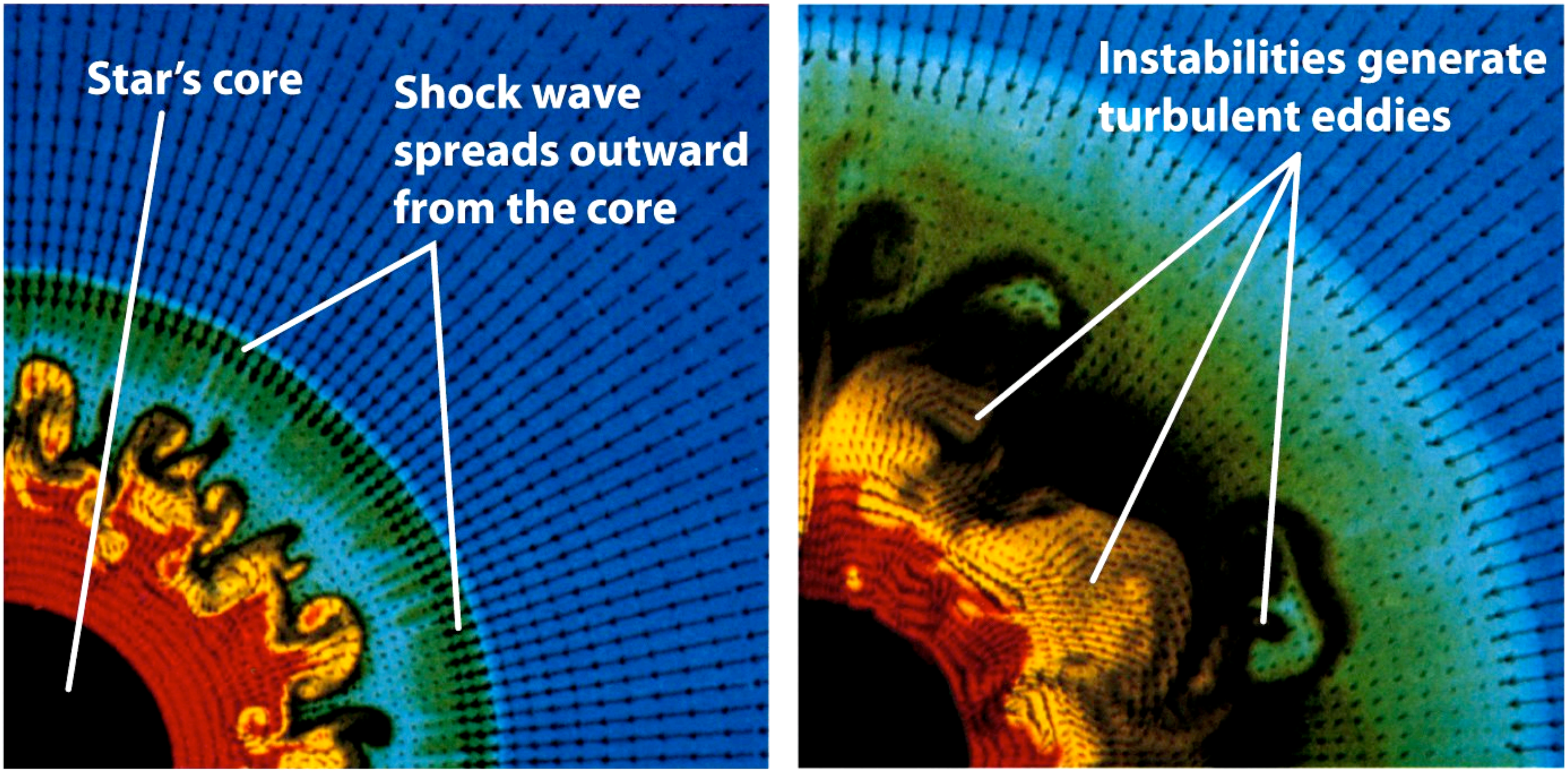
For an interaction cross-section of $\sigma \sim 10^{-44}$ cm$^2$, mean free path near the neutron star is:

$$l = \frac{1}{\sigma n} \approx 2 \text{ km}$$

(for scattering off nucleons at $\rho = 10^{15}$ g cm$^{-3}$)

i.e. smaller than the size of a neutron star. Most neutrinos will interact with matter as they escape, on a time scale much longer than the free fall time of the core (several seconds).

A fraction of the neutrinos will be absorbed by the post-shock matter, heating it and reviving the shock.




**(a)** 10 milliseconds after the core "bounce"

**(b)** 20 milliseconds after the core "bounce"

# Detonation or Deflagration

- Modeling SN explosions is a tricky business; only recently we have developed reliable models, as a combination of numerical and analytical
- If flame travels supersonically (***detonation***), then entire star burned at high density, all the way to Ni
- We don't see entirely Ni supernovae, so star must pre-expand
- If flame travels subsonically (***deflagration***), then the star can pre-expand and burn at lower densities
- But deflagrations cannot produce fastest elements; both probably occur

# A nearby supernova 1987A in LMC gave us the forst and only modern close-up look at the death of a massive star …

… Including the first detection of extra-Solar neutrinos, thus confirming our basic model for core-collapse SNe:

***> 99% of the total SN energy emerges in neutrinos!***

# Type I SNe: Accreting White Dwarfs in Close Binary Systems

- An accreting white dwarf in a close binary system can also become a supernova when carbon fusion ignites explosively throughout such a degenerate star

## Type I SNe: Going Over the Chandrasekhar Limit

We showed that there is a maximum mass for a star held up by the pressure of degenerate material (e.g. a white dwarf):

$$M_{Ch} \approx 1.4 M_{sun}$$

This mass corresponds to the mass at which electrons in the degenerate matter first become relativistic.

Observationally, no white dwarfs are known with masses exceeding this limit (most are well below ~ 0.6 $M_{sun}$).

Properties of **Type Ia** supernovae, especially the lack of hydrogen in their spectra and their existence in old stellar populations, are consistent with explosions of carbon / oxygen white dwarfs near the Chandrasekhar limit.

How can a white dwarf gain mass and thereby reach the Chandrasekhar limit?

## Exceeding the Chandrasekhar limiting mass

Suppose we add mass to a white dwarf, for example in a mass transfer binary system, to bring it up to the Chandrasekhar limit. What happens?

Possibility 1

Once $M_{Ch}$ is reached, the pressure of degenerate electrons can no longer hold the star up:

collapse

If this *accretion-induced collapse* occurs, the end state would be a neutron star. The collapse would produce very little in the way of observable phenomenon.

Possibility 2

As M approaches $M_{Ch}$, the temperature and density in the core ignite fresh nuclear reactions.

Unlike in the case of ordinary stellar nuclear reactions, this is devastating to the star. Recall:

$$P = K\rho^{5/3}$$ …with no temperature dependence

Hence, large energy release from nuclear reactions heats the material up without changing the pressure or density.

Reactions runaway, eventually lifting the degeneracy but not before all the star has been burned:

Supernova explosion, production of ~1 $M_{sun}$ of radioactive nickel.

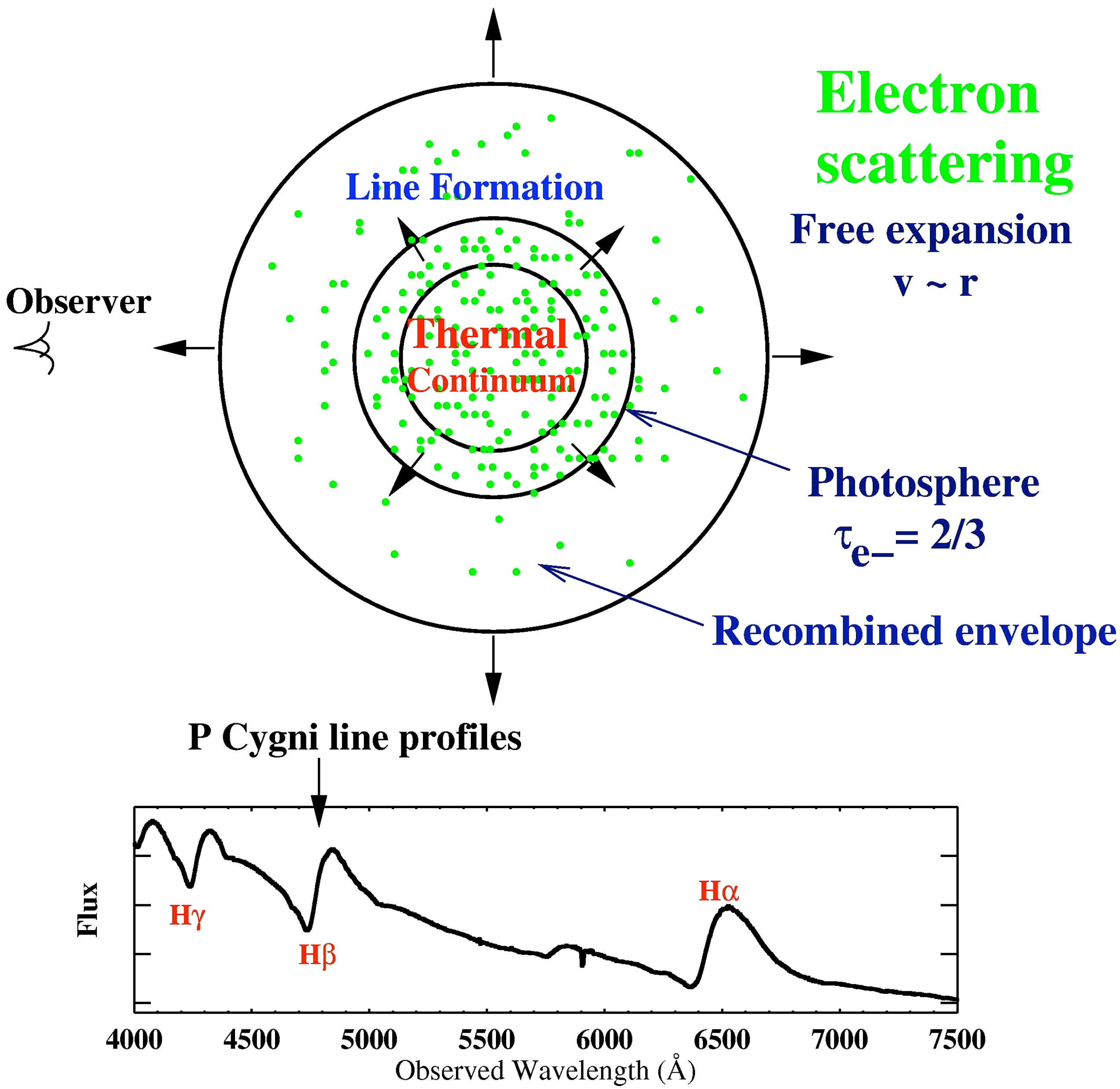
# Type Ia Supernovae

Identification of Type Ia supernovae with exploding white dwarfs is circumstantial but strong. Main clues are:

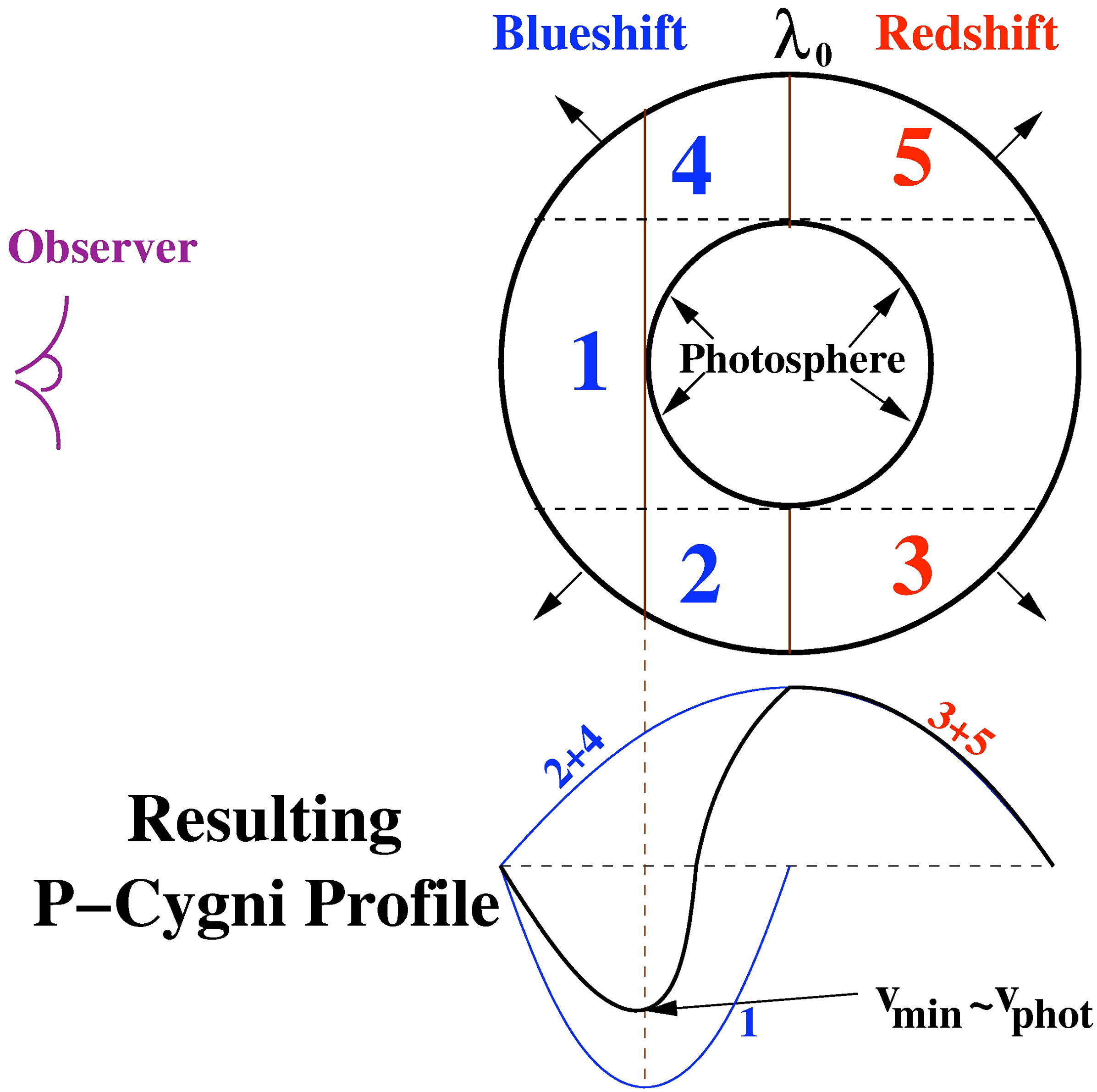
- No H lines but presence of Si lines in absorption
  At most ~ 0.1 Solar masses of H in vicinity
  Nuclear burning all the way to Si must occur
- Observed in elliptical galaxies as well as spirals
  Old stellar population - not massive stars
- Remarkably homogenous properties
  `Same object' exploding in each case
- Lightcurve fit by radioactive decay of about a Solar mass of $^{56}$Ni

Does **not** mean that accretion-induced collapse does not occur in some circumstances as well…

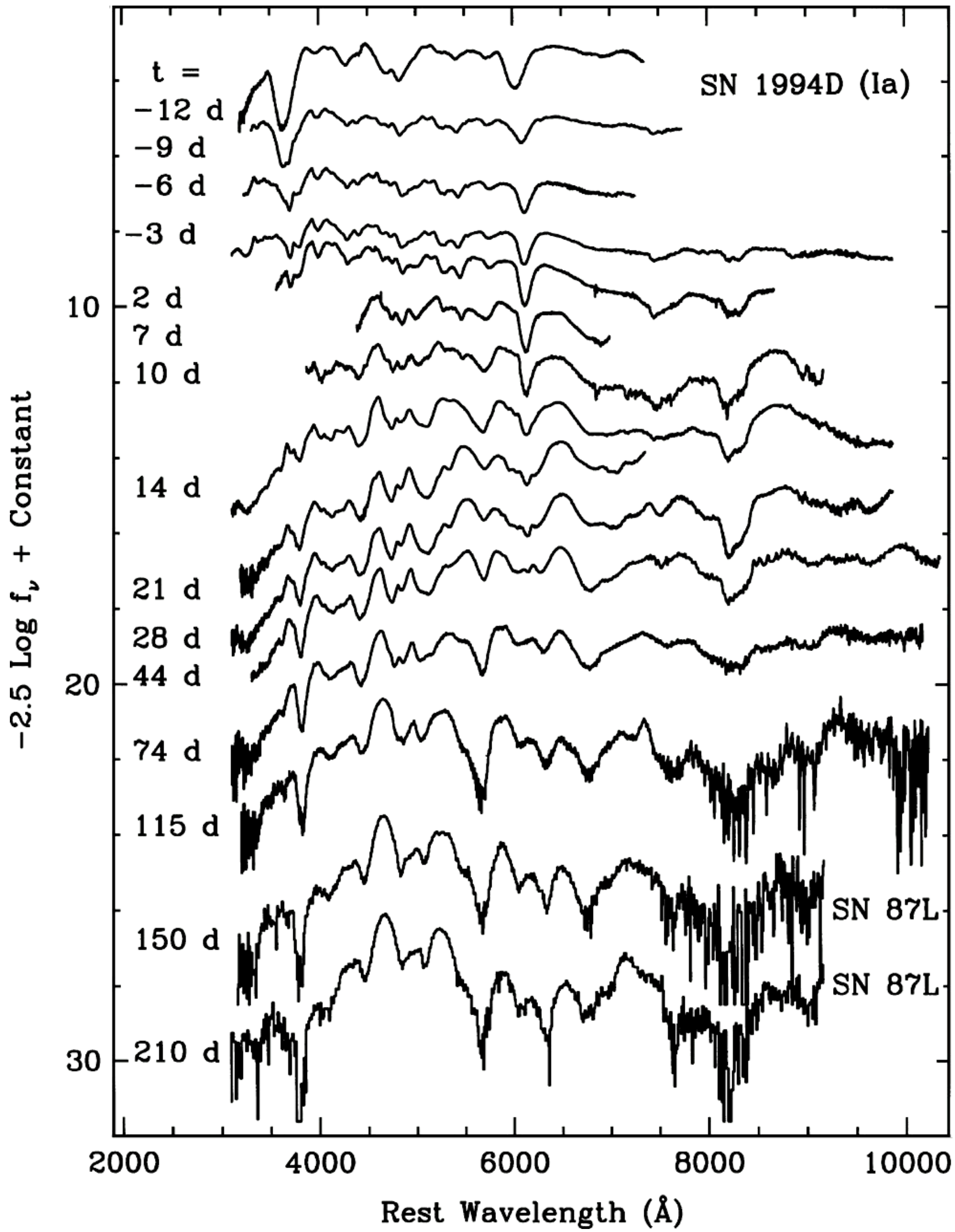
# SN Spectrum Formation



# P–Cygni Line Formation

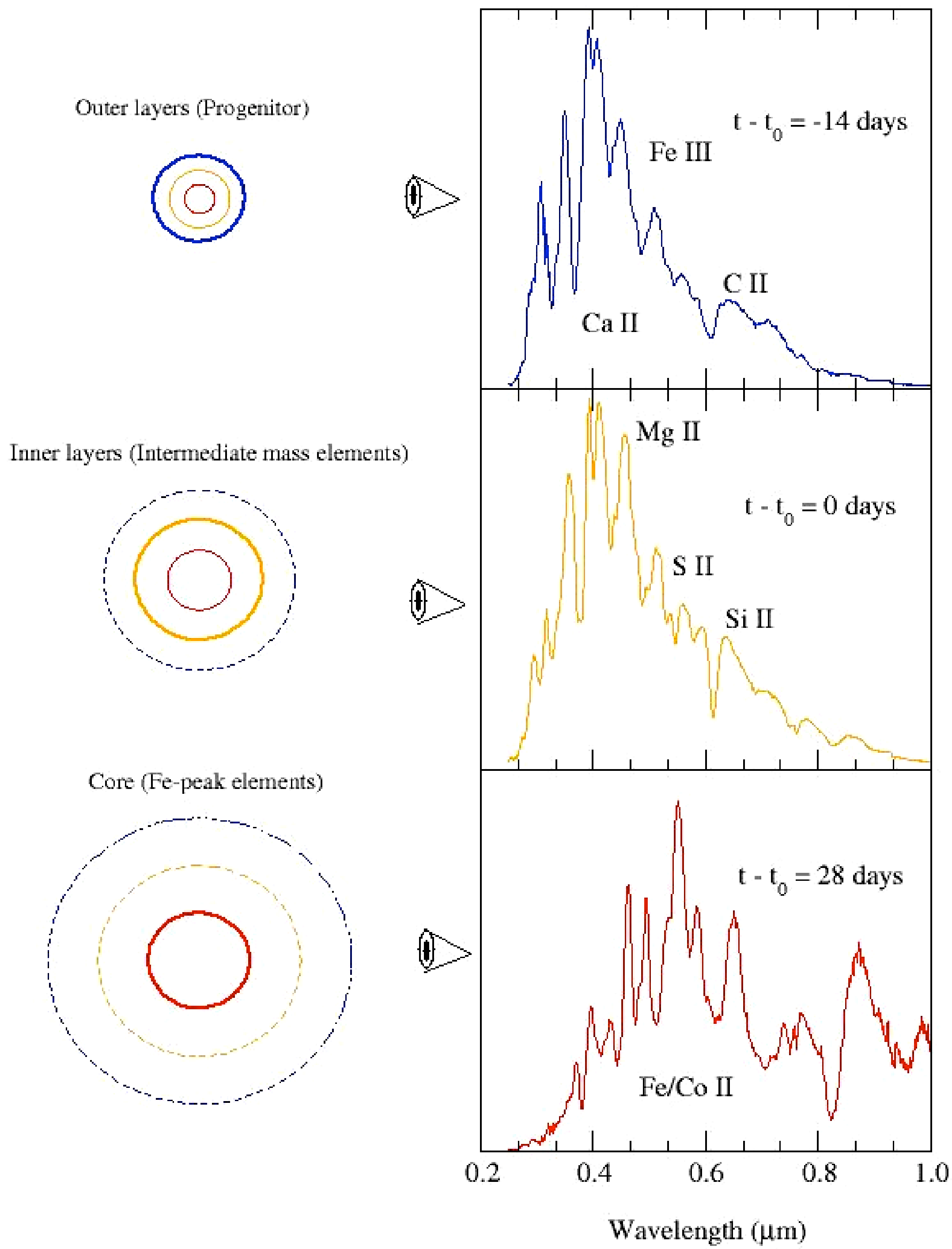


# Spectral Evolution of a SN Ia



# Time Resolved SN Spectra as a “CAT Scan”

- *See to deeper layers with time, as the optical depth changes with the expansion*



# Supernova Remnants

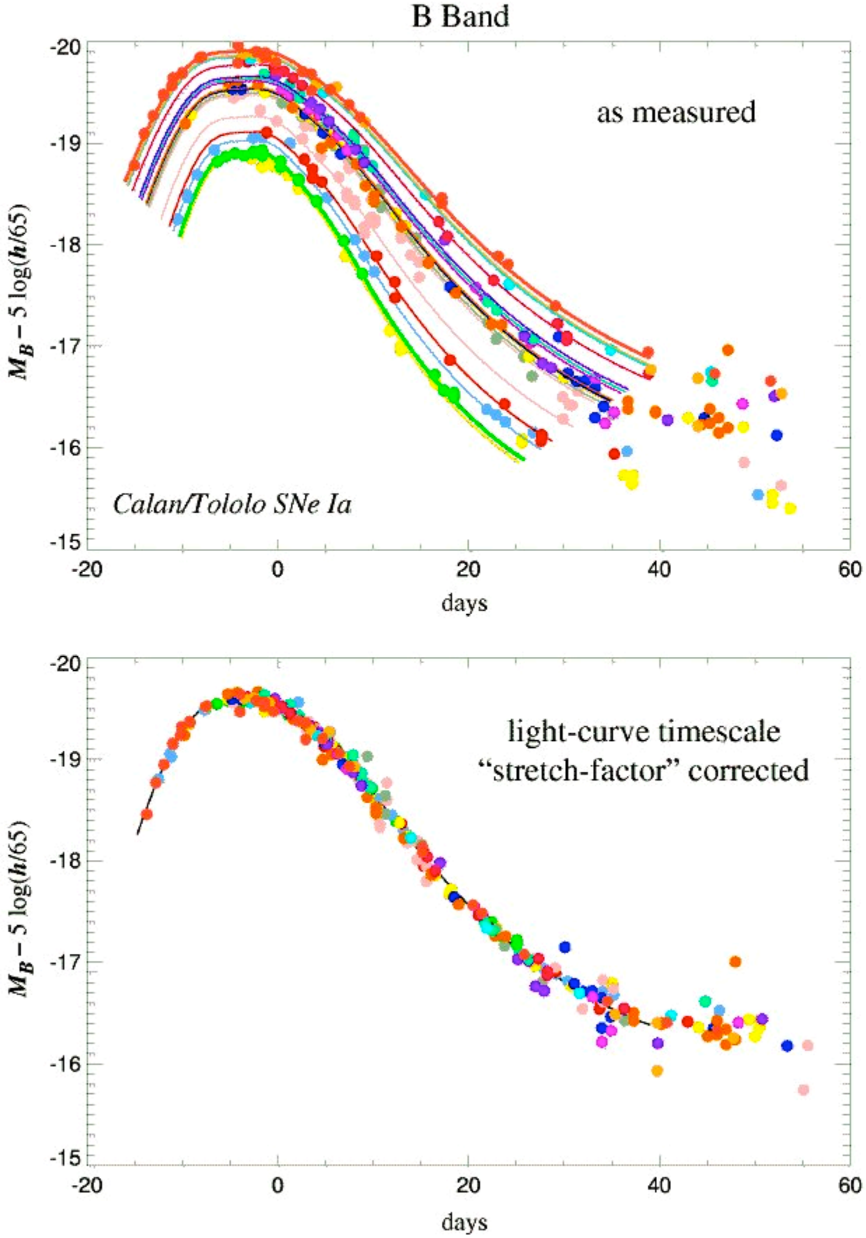
- The gaseous shell ejected by a supernova plows into the surrounding interstellar medium at $V > 10^4$ km/s, compresses it, intermingles with it, enriches it with freshly synthesized heavy elements, and forms what is called a supernova remnant
- Supernova remnants may be observed for hundreds of thousands of years as often beautiful, visual objects, but also as emitters of radio waves and X-rays
- Close to 150 supernova remnants have been detected in the Milky Way and more than a hundred are being discovered every year in distant galaxies

# The Crab Nebula

- The result of a supernova that, according to Chinese and Japanese chronicles, exploded in 1054. Despite a distance of about 7,000 light-years, the supernova was brighter than Venus for weeks before fading from view after nearly two years. Interestingly, no European records of the event have been found ("The Dark Ages are called that not because the light fails to shine, but because people refuse to see it")
- The nebula is still expanding at V > 1300 km/s and emits synchotron radiation in all wavelengths, from gamma rays to radio waves
- And of course, it is the home of the Crab Pulsar

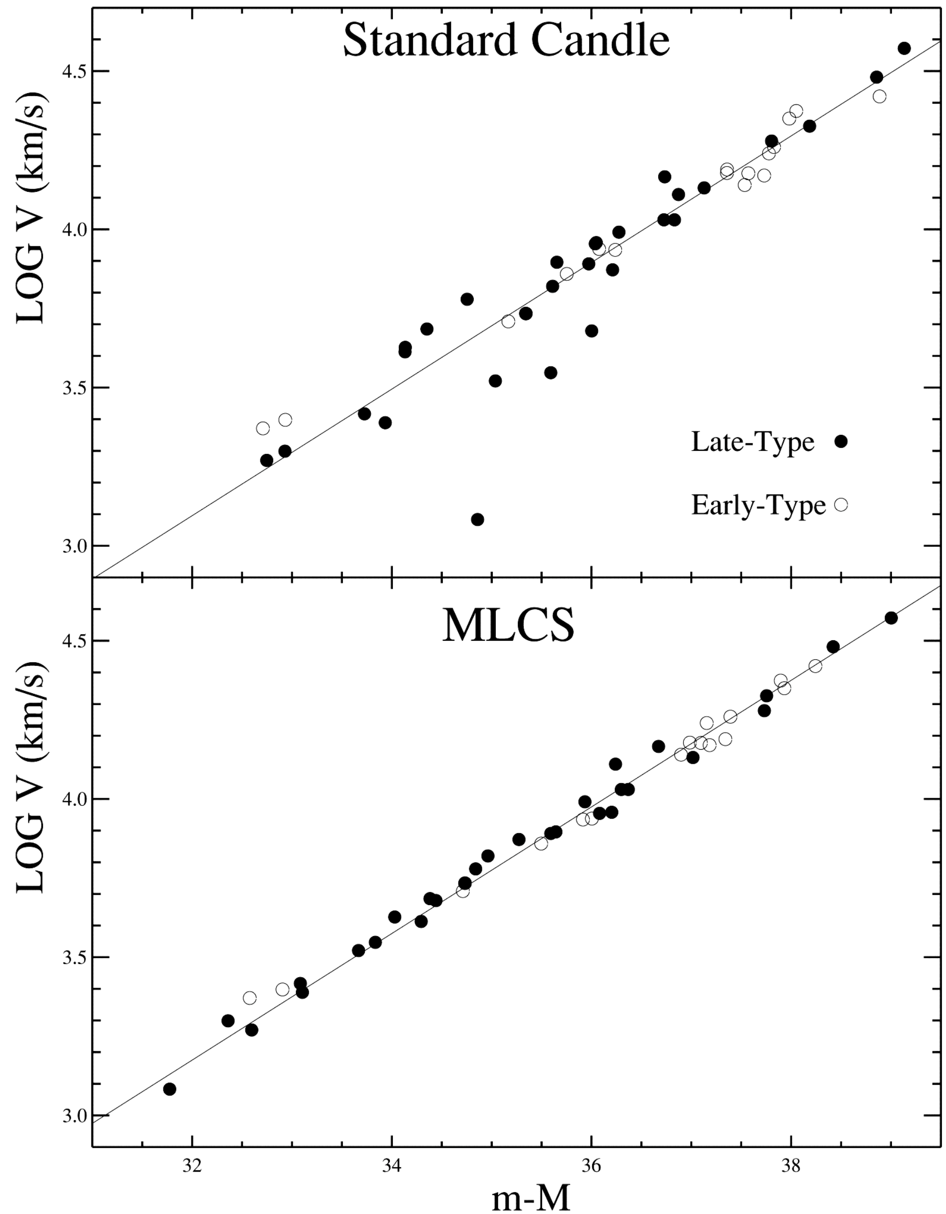
# SNe Ia as Standard Candles

- The peak brightness of a SN Ia correlates with the shape of its light curve
- Correcting for this effect standardizes the peak luminosity to ~10% or better
- However, the absolute zero-point of the SN Ia distance scale has to be calibrated externally, e.g., with Cepheids

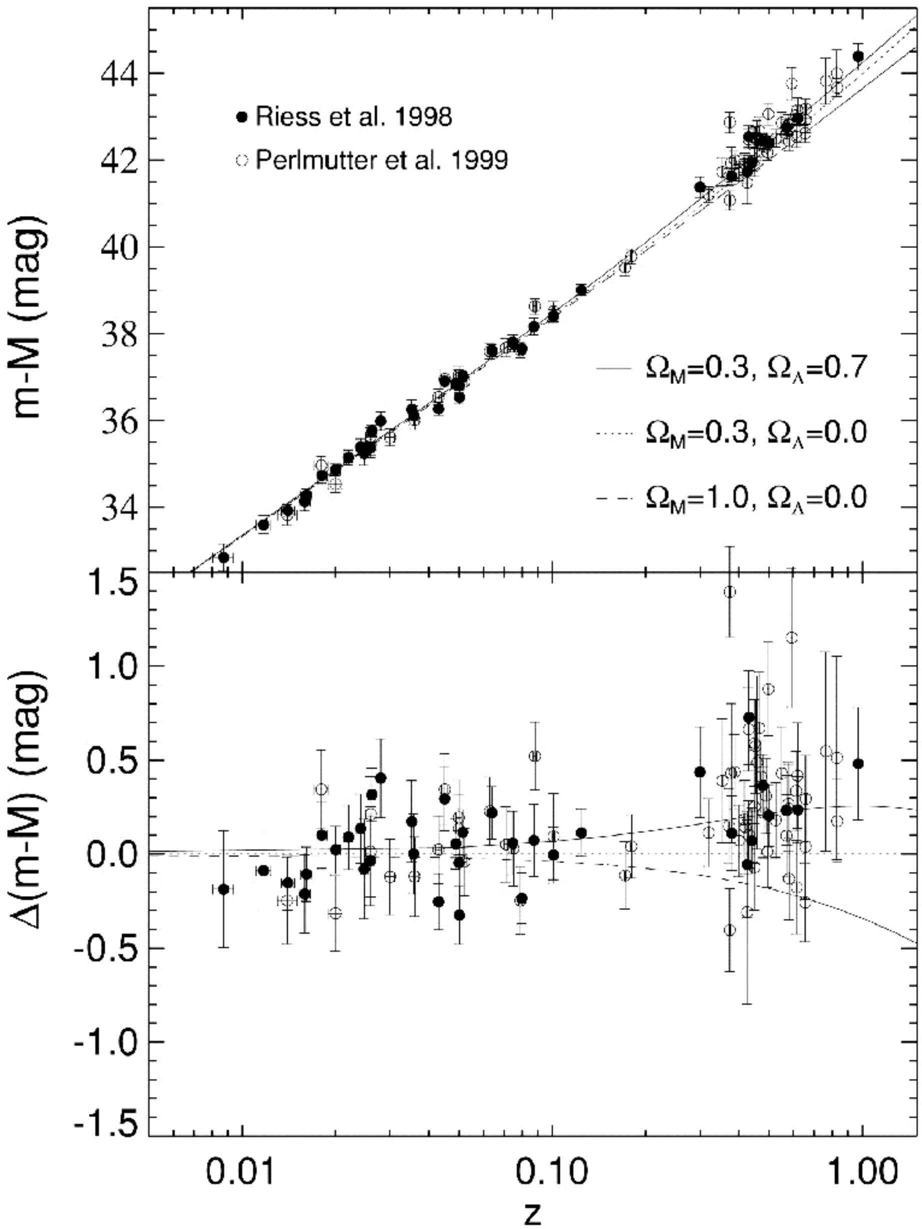


# SNe Ia as Standard Candles

- A comparable or better correction also uses the color information (the Multicolor Light Curve method)
- This makes SNe Ia a superb cosmological tool (note: you only need relative distances to test cosmological models; absolute distances are only needed for the $H_0$)



# Supernova Cosmology




Evidence for the accelerating universe, or "dark energy" (cosmological constant is a special case) …

*(Perlmutter et al., Riess et al., Schmidt et al.)*

… Especially in conjunction with CMBR and other data

# The Expanding Photosphere Method (EPM)

- One of few methods for a direct determination of distances; unfortunately, it is somewhat model-dependent
- Uses Type II SNe - could cross-check with Cepheids
- Based on the Stefan-Boltzmann law, $L \sim 4\pi R^2 T^4$

If you can measure T (distance-independent), understand the deviations from the perfect blackbody, and could determine R, then from the observed flux F and the inferred luminosity L you can get the distance D

EPM assumes that SNII radiate as dilute blackbodies

Apparent Diameter

$$\theta_{ph} = \frac{R_{ph}}{D} = \sqrt{\frac{F_\lambda}{\zeta^2 \pi B_\lambda(T)}},$$

Fudge factor to account for the deviations from blackbody, from spectra models

Determine the radius by monitoring the expansion velocity

$$R_{ph} = v_{ph}(t - t_0) + R_0,$$

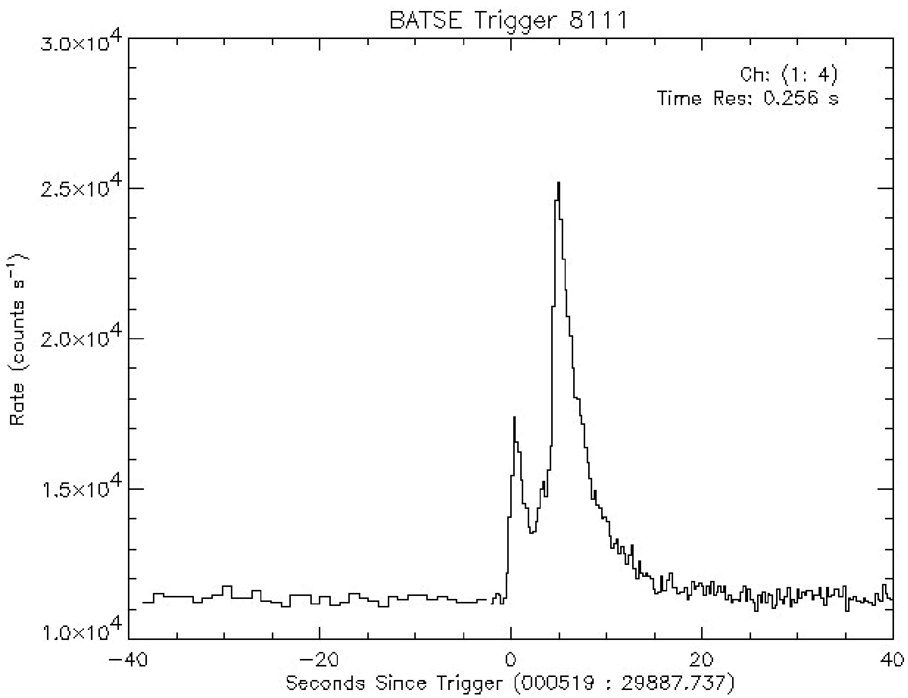
And solve for the distance!

$$t = D\left(\frac{\theta_{ph}}{v_{ph}}\right) + t_0$$

# Gamma-Ray Bursts:

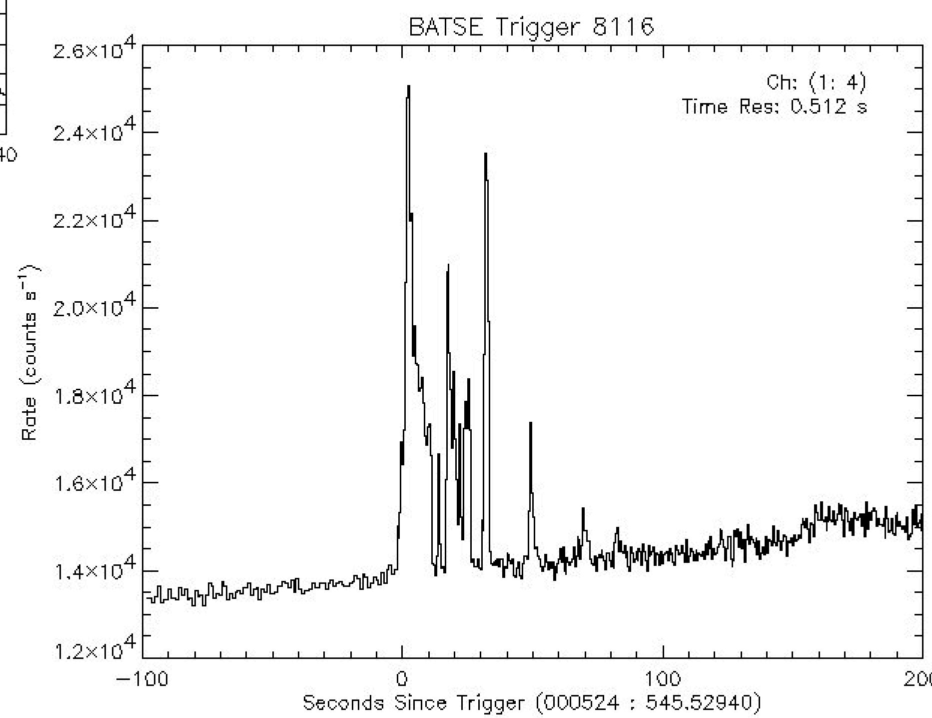
**Supernovae**
**De Luxe ?**

# Typical GRB Light Curves




Typical detected fluences are ~ $10^{-5}$ - $10^{-6}$ erg/cm$^2$ So, if GRBs are at cosmological distances, ~ $10^{29}$ cm, then the energies are ~ $10^{52}$ - $10^{54}$ erg !

Rapid (~ ms) variability time scales imply small sizes, ~ 100 km. Thus, the source of the emisison must be nonthermal



# Isotropic Distribution on the Sky

Observed rate ~ 1/day

Until 1997, one of the greatest mysteries of astrophysics …

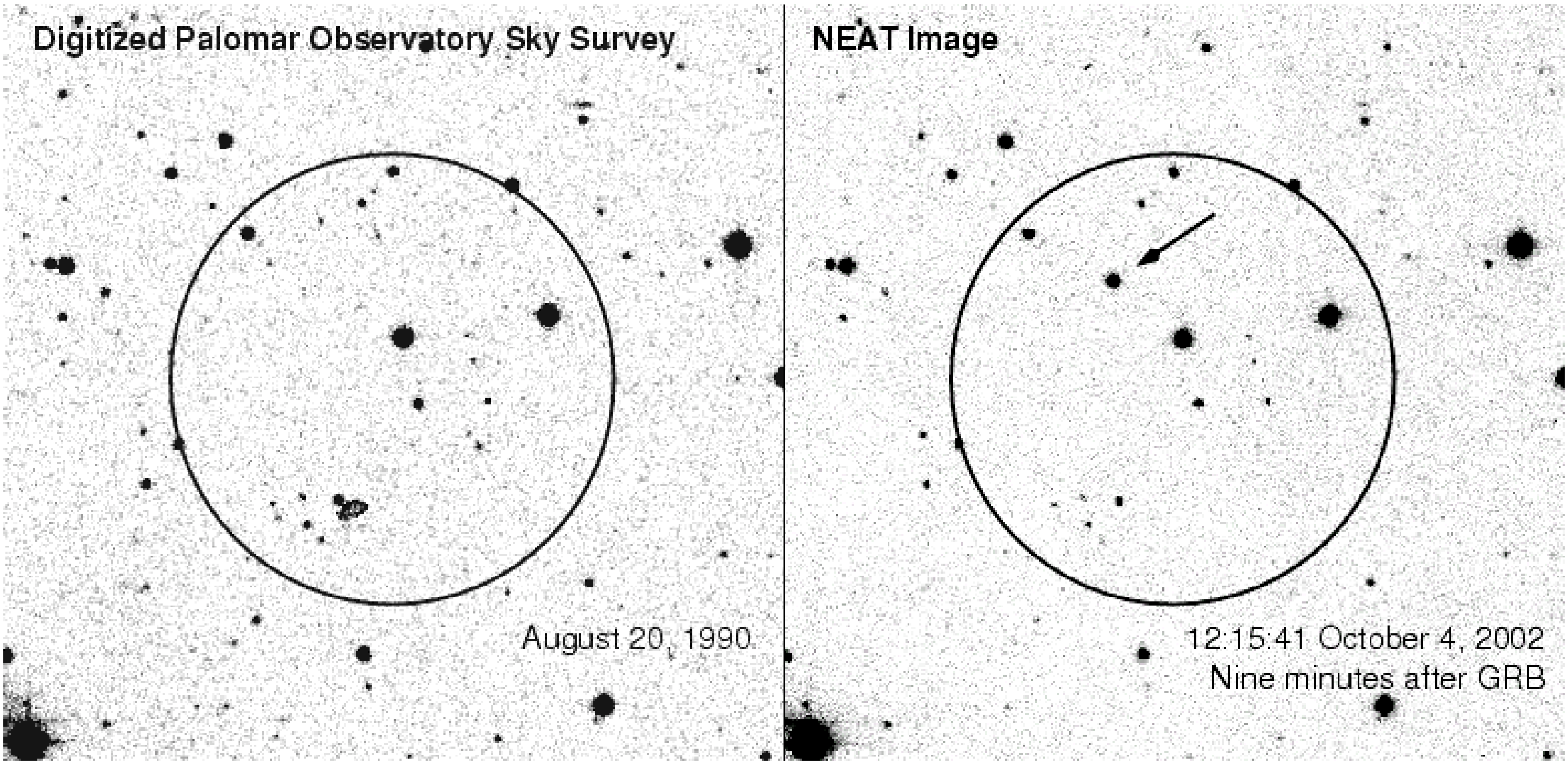
… With > 150 published theoretical models!

The key obstacle: precise, rapid localization and follow-up on other wavelengths

It all changed with the precise (~ arcmin) X-ray localizations of GRB afterglows by the BeppoSAX satellite …

… which led to optical IDs, and then redshifts

# Optical Transients Associated With GRBs

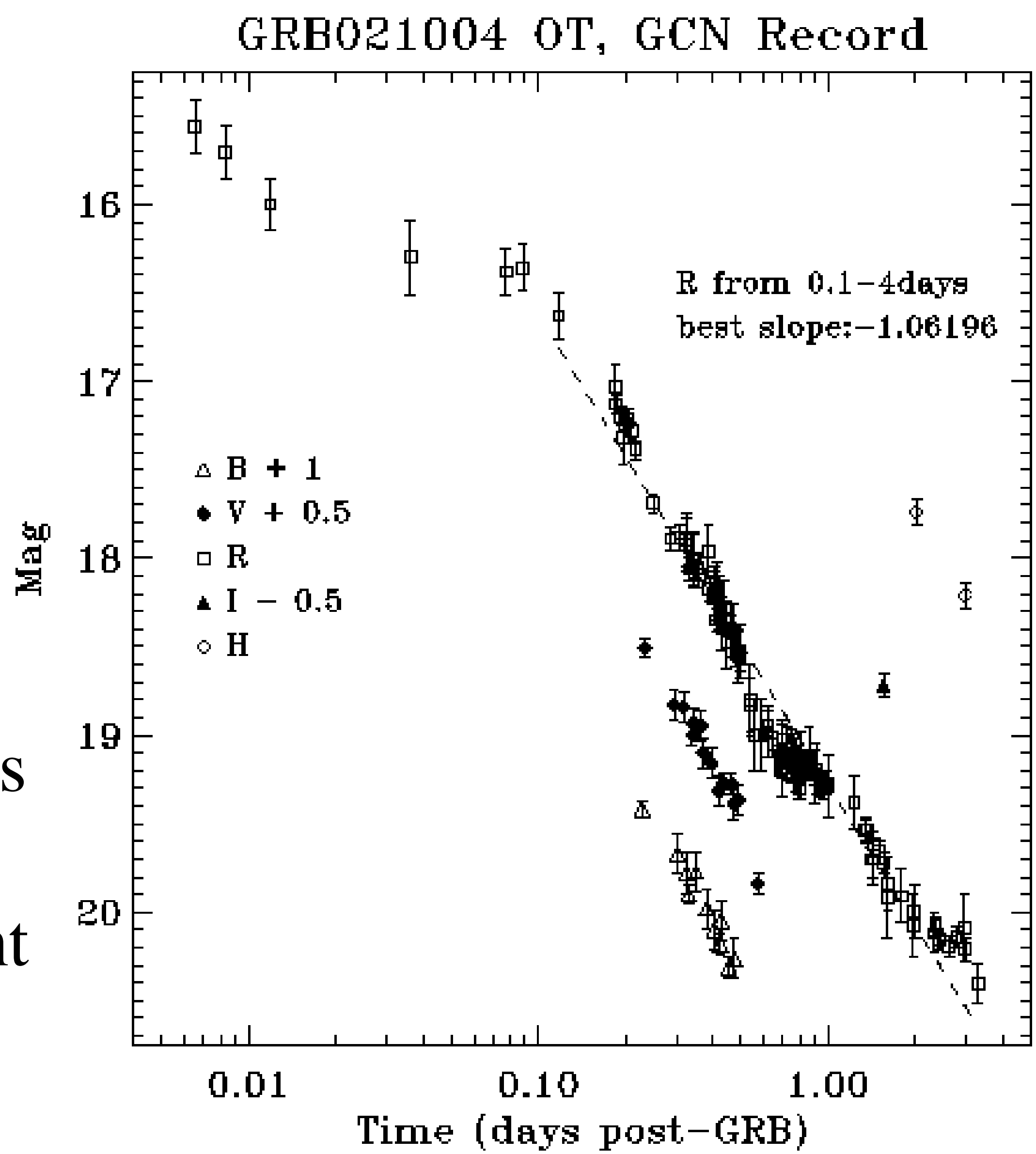



Typically fade as ~ $t^{-1}$

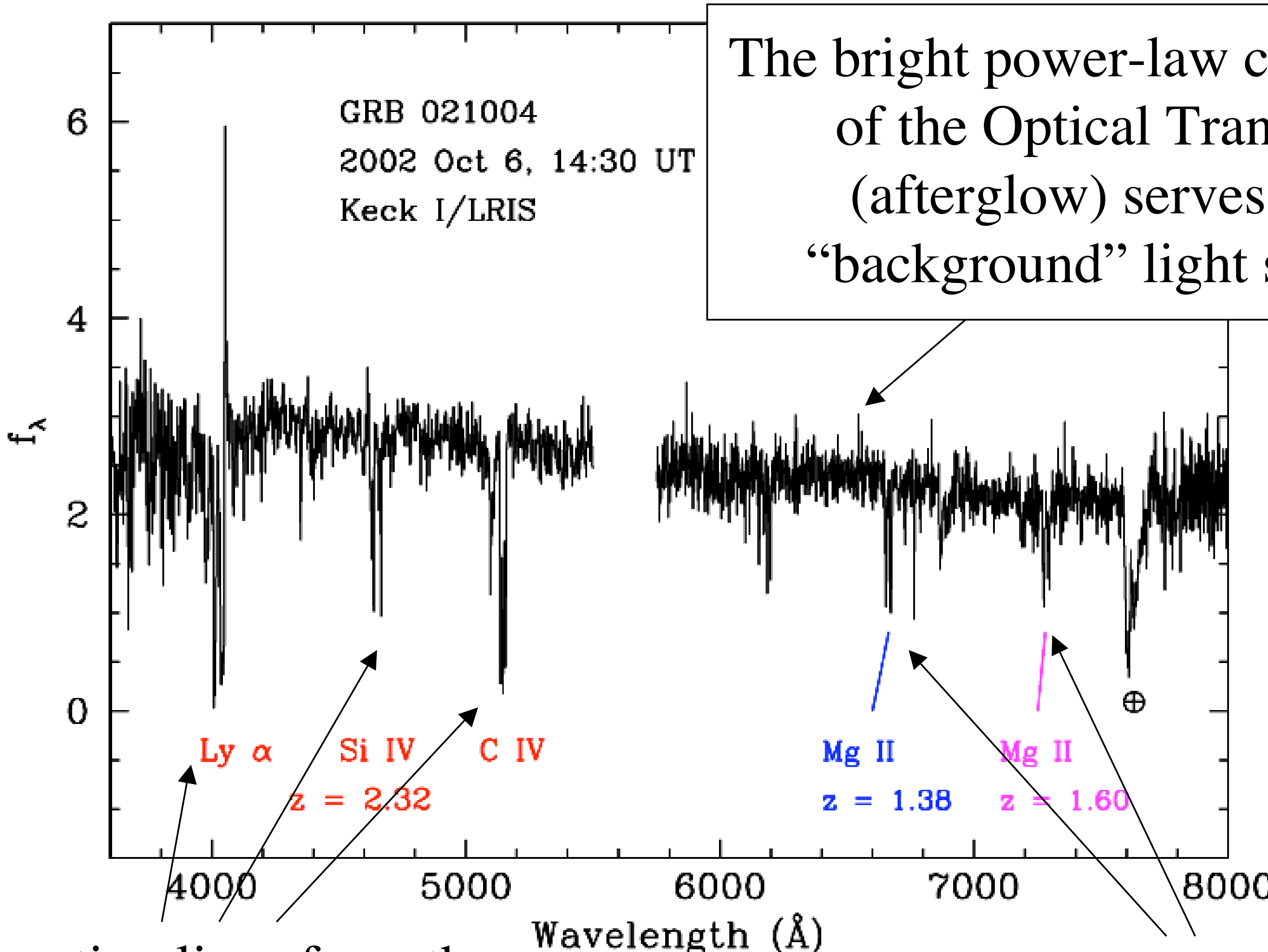
Explained (and predicted) as afterglows of GRBs

# Typical GRB Afterglow Light Curves

Detected and monitored from X-rays to radio. Observed changes in an excellent agreement with theoretical models.



# GRB Host Galaxy + Opt. Transient Spectrum

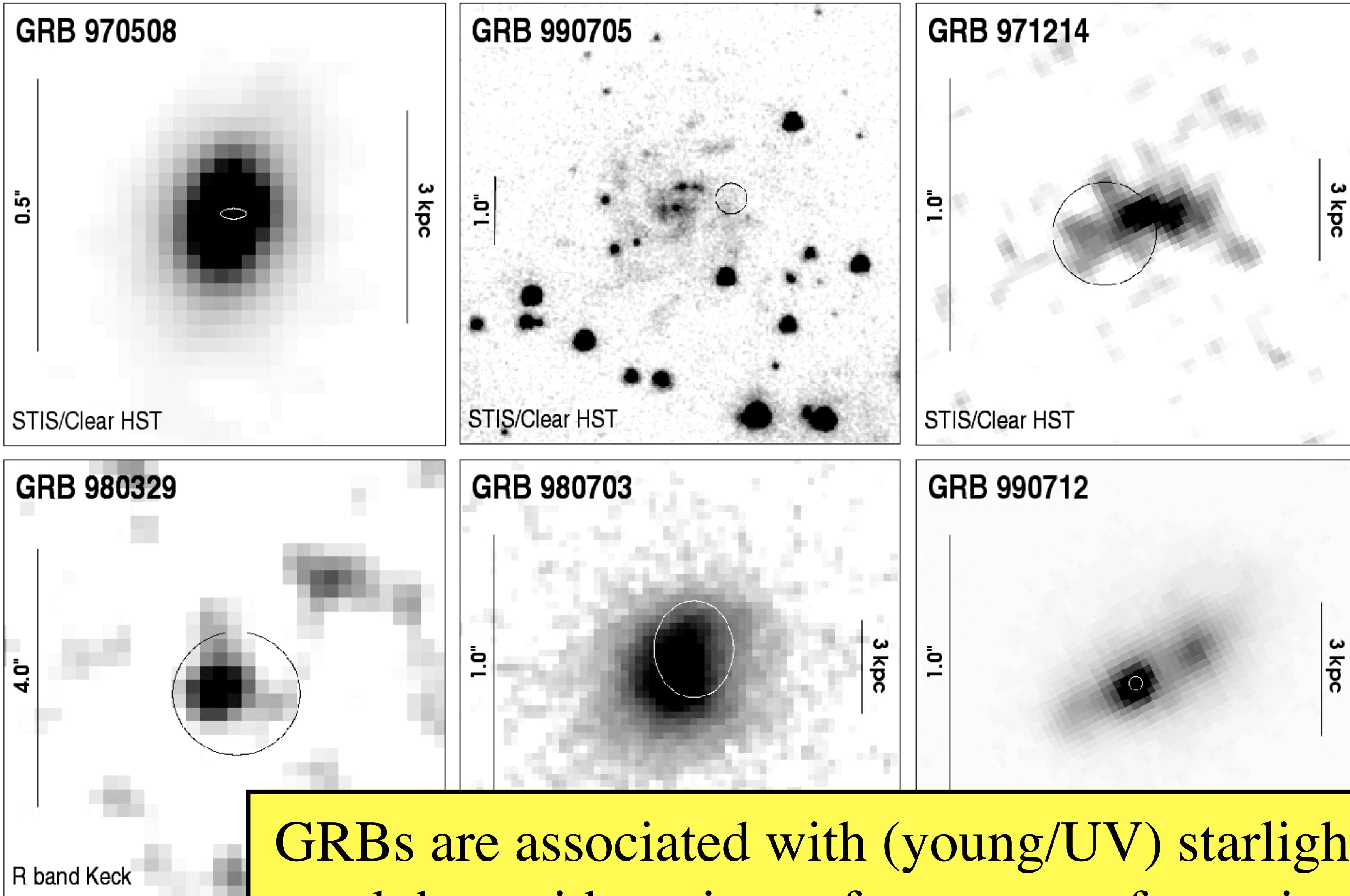



The bright power-law continuum of the Optical Transient (afterglow) serves as a "background" light source

Absorption lines from the ISM in the host galaxy

… and from intervening galaxies along the line of sight

# Location of GRBs Within Their Host Galaxies



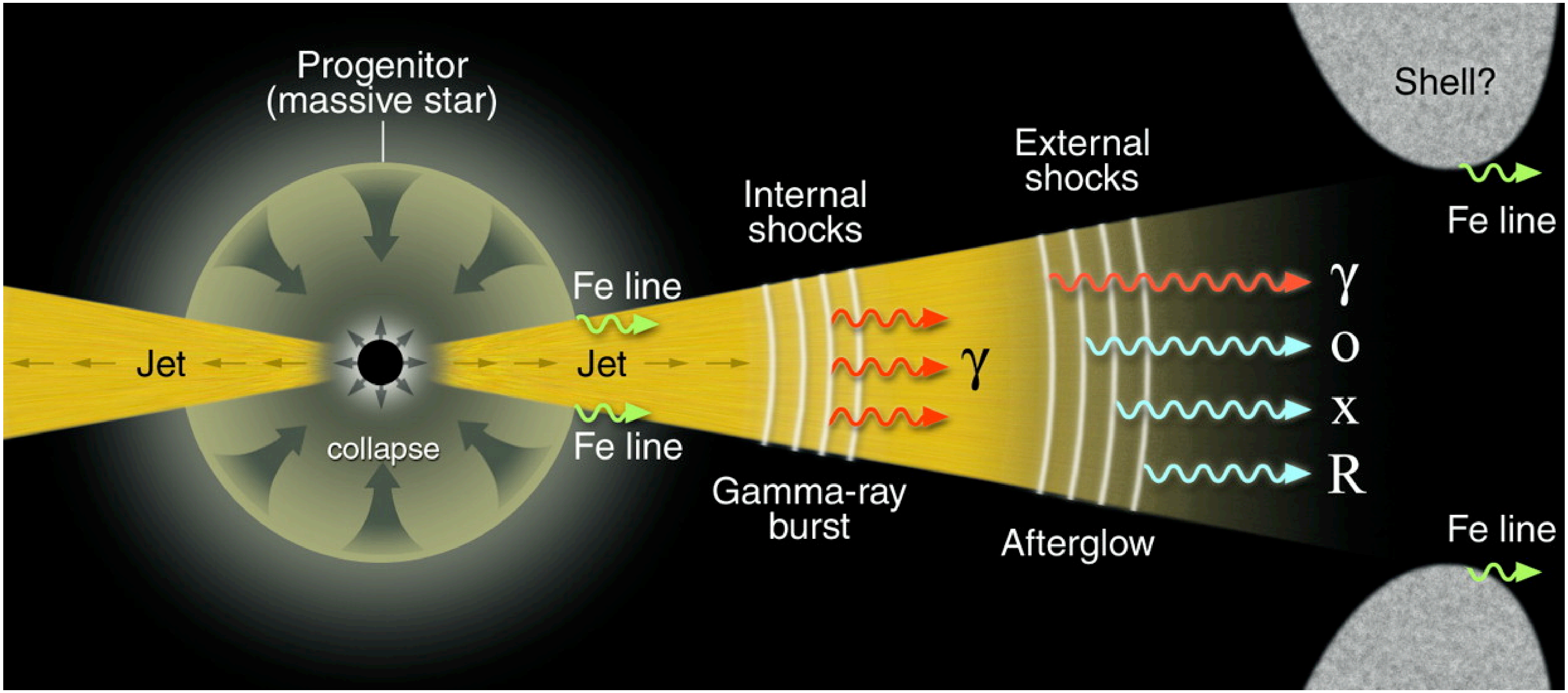

GRBs are associated with (young/UV) starlight, and thus with regions of recent star formation

# Popular Models for GRB Origins

Merging Neutron Stars

Hypernova Explosions

# The Collapsar Model for GRBs



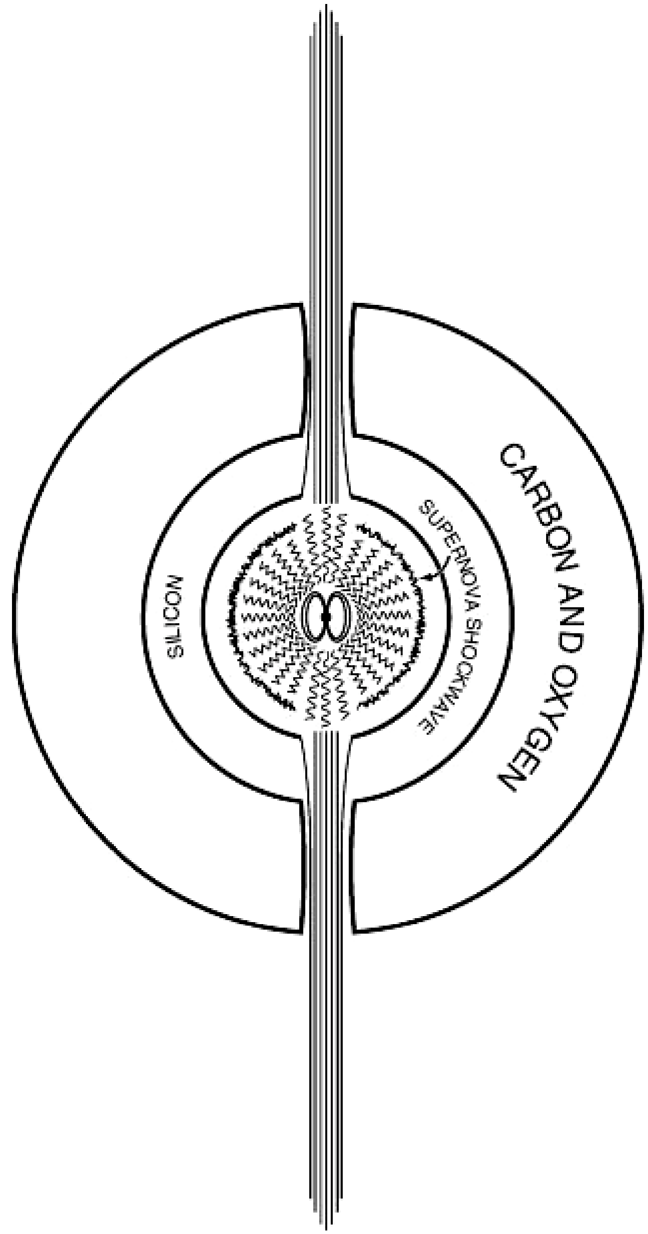

- rotating massive star
- core collapses to BH
- forms accretion disk
- drives collimated outflow

| |
|---|
| $\Gamma \sim 100$ |
| $r \sim 10^{15}$ cm |
| $E_{\gamma} \sim 10^{51}$ erg |

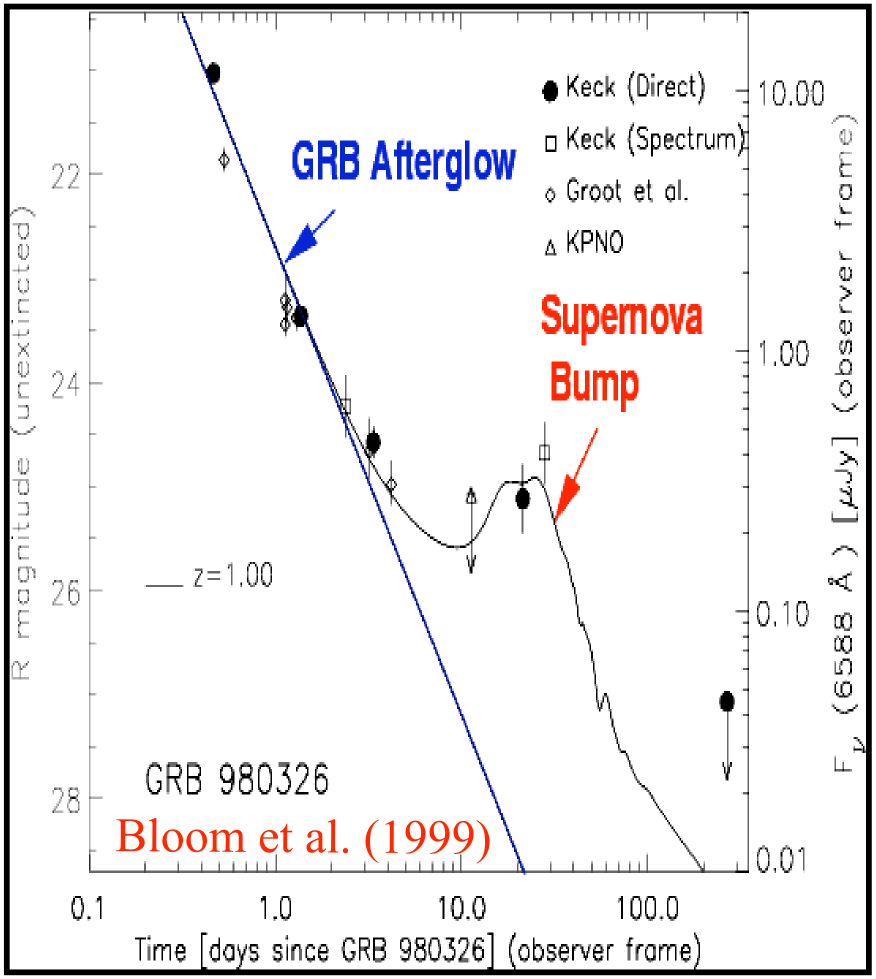
| |
|---|
| $\Gamma \sim 10 \rightarrow 1$ |
| $r \sim 10^{17}$ cm |
| $E_k \sim 10^{51}$ erg |

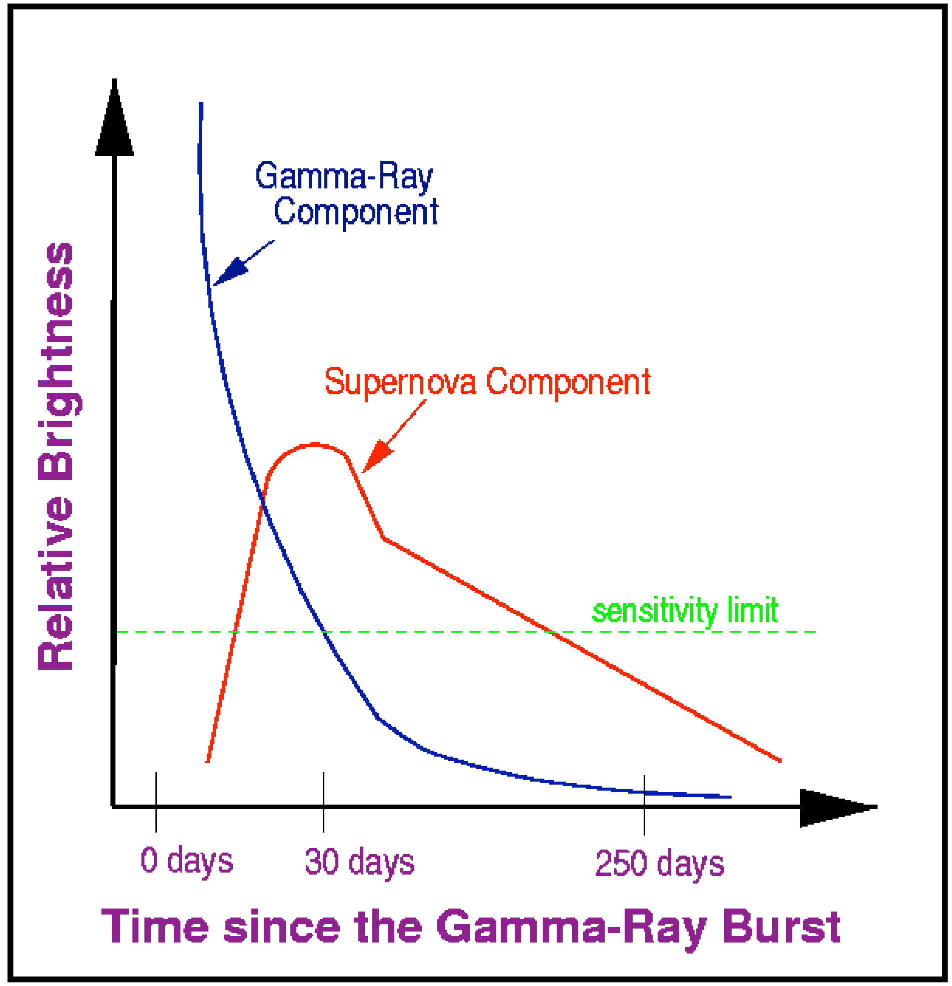
# Hypernovae or Collapsars

- For these most massive stars, the supernova explosion can be smothered by the massive outer layers of the star
- The star may collapse directly into a black hole: these are called hypernovae or collapsars
- Hypernova may or may not produce a supernova explosion, it can emit jets of gamma rays
- Mergers of neutron stars should occur occassionally but not enough to produce the number of GRBs we observe



# Direct Clues to the SNe/GRB Link:
## "Bumps" in the Afterglow Lightcurves

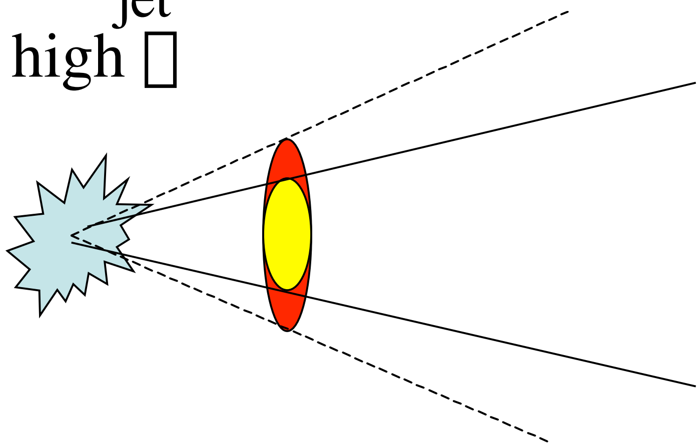


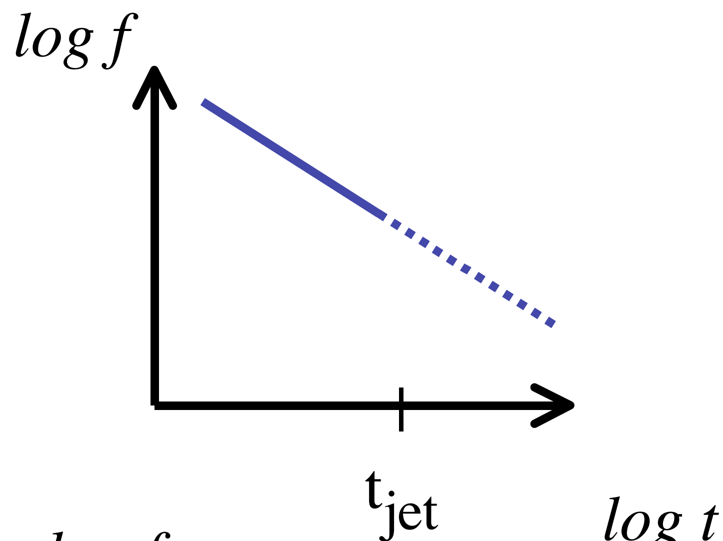




Some have been also confirmed spectroscopically

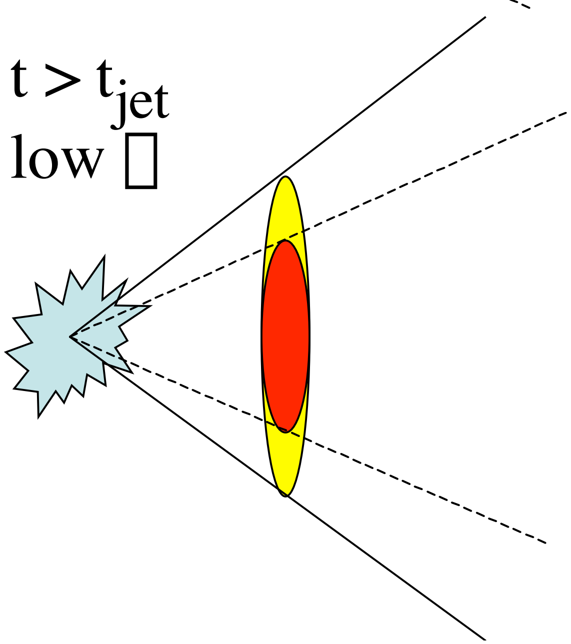
# The Solution of the GRB Energy Problem:  Relativistic Beaming

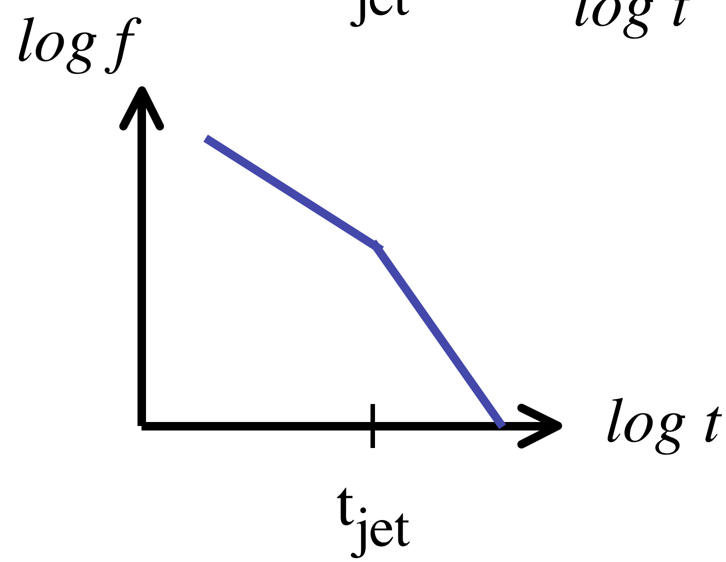
$t < t_{jet}$
high □



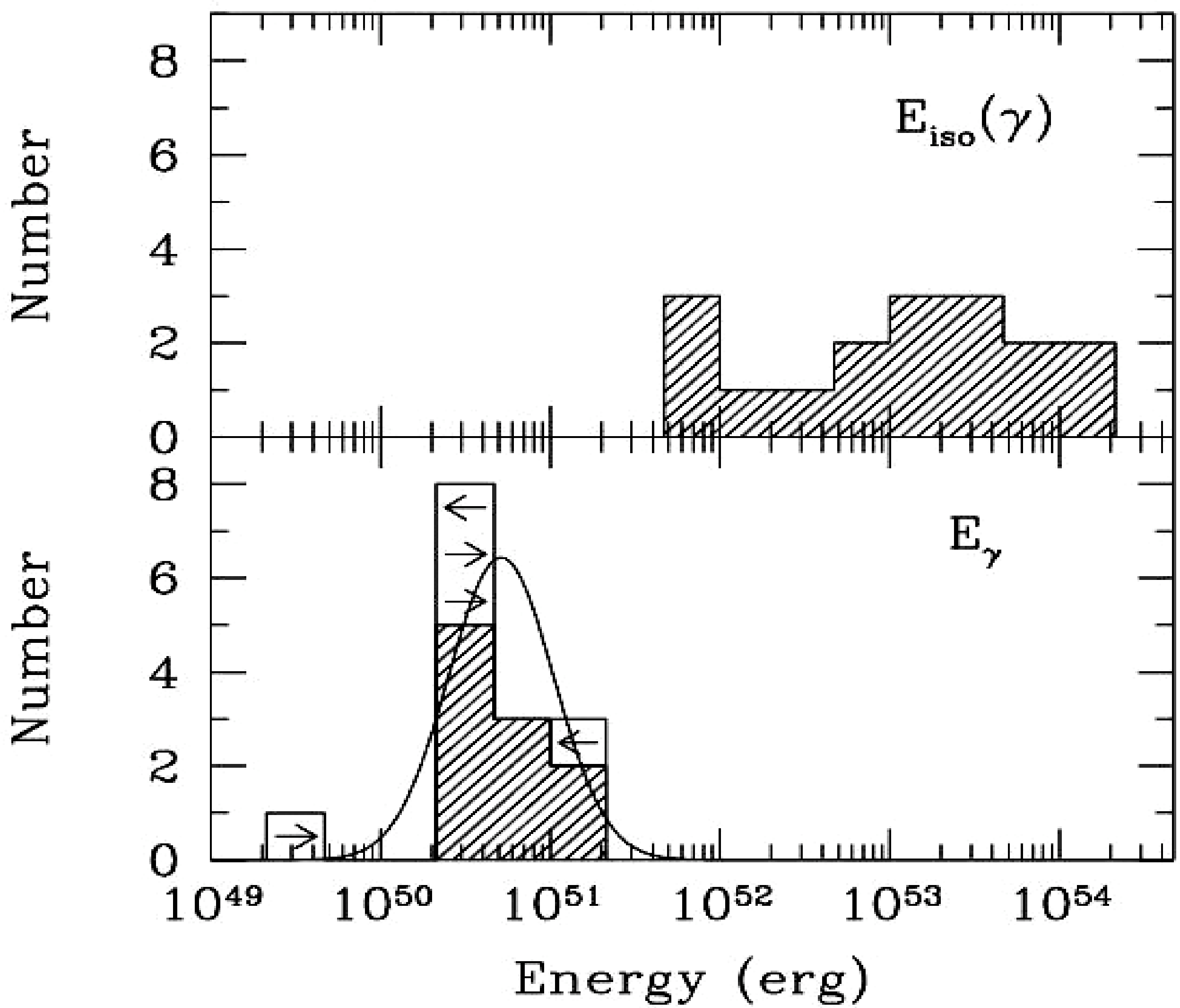



$t > t_{jet}$
low □





# GRB Energetics: Jets and Beaming




**Before** the beaming correction (isotropic)

**After** the beaming correction

*(Frail et al.)*

# Astrophysical Uses of GRBs

- Probes of the death of very massive stars, and the birth of stellar mass black holes (seeds of supermassive BH?)
- A new probe of extreme relativistic astrophysics
- A new way of mapping the star formation history in the universe, and its obscured fraction (from "dark bursts")
- Probe the Intergalactic Medium
- Probe the Interstellar Medium, its chemical enrichment in the disk of distant galaxies, in a complementary way to QSO absorbers
- Potentially probe the epoch of reionization, the formation of first stars (Population III), and the early chemical enrichment

# A Prototype Dark Burst: GRB 970828

We know that *some* GRBs originate in dusty starburst galaxies, and can thus be used as probes of obscured star formation in the universe

Also: sub-mm/cm detections of dusty GRB host galaxies

## GRBs vs. QSO Absorbers: A Complementary Picture?

GRBs show higher gas densities and metallicities, and have significantly lower [(Si,Fe,Cr)/Zn] ratios, implying a higher dust content → **SF regions?**

# Probing the First Stars

A generic expectation in all modern models of primordial star formation is that such stars (Population III) would have high masses, $M_\star \sim 100 - 1000\ M_\odot$ .

Their explosions may produce detectable GRBs, and enrich the primordial intergalactic medium (IGM).

Their afterglows would be powerful probes of the primordial star formation and early chemical enrichment.

# High-$z$ GRBs as Probes of the Reionization

GRBs vs. Quasars:

- May exist at high redshifts when there are no bright AGN
- No Ly□ line - easier interpretation of the Gunn-Peterson damping wing
- Different Strömgren spheres - more representative of the primordial IGM?