# Nuclear Physics I: Nuclear Astrophysics

## PHYS 8801

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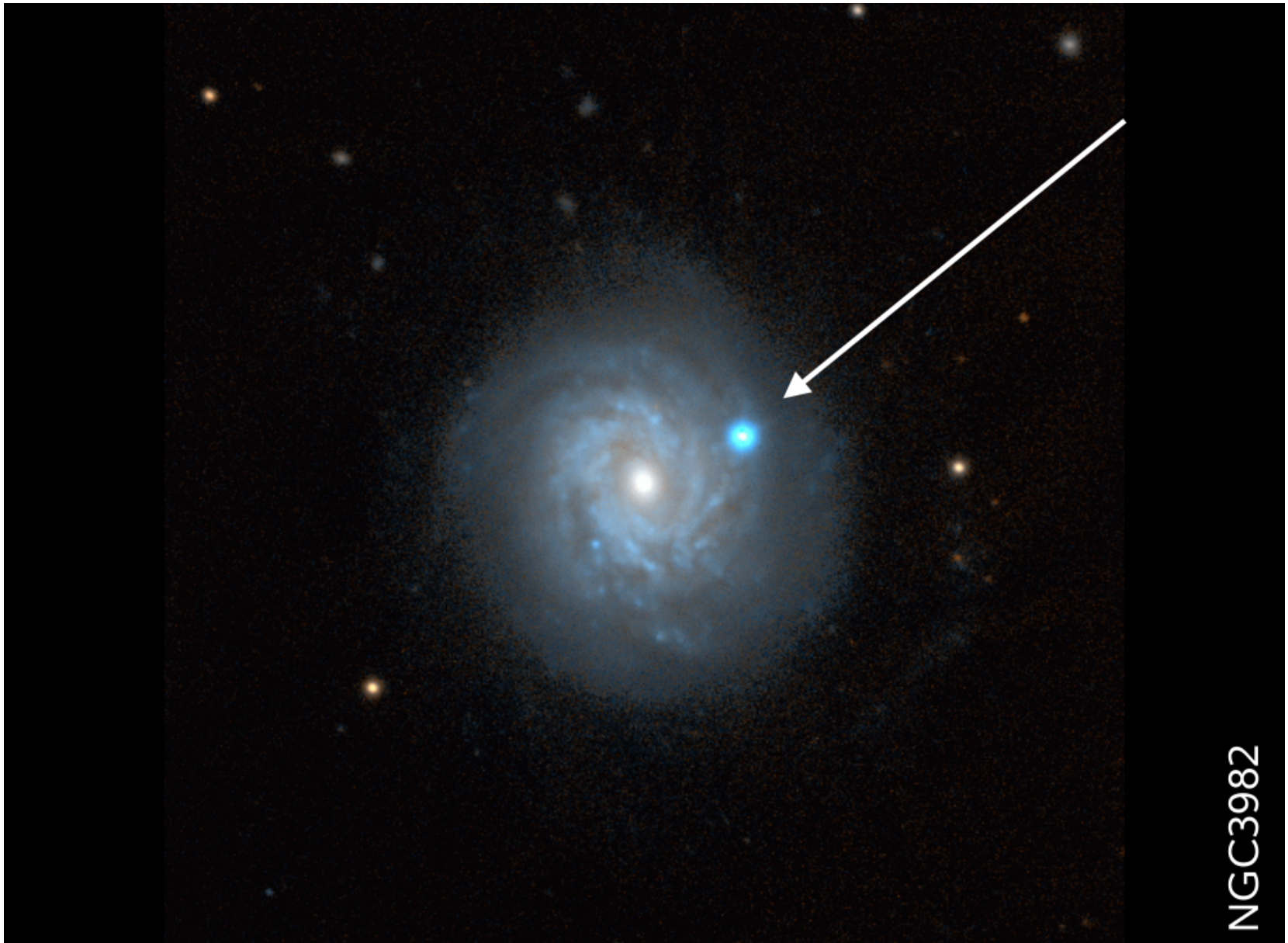
Nuclear Physics I: Nuclear Astrophysics, Spring 2012

# Agenda

1. Supernovae
   - Type Ia Supernovae
   - Accretion-Induced Collapse
   - Collapsars
   - Pair-Instability Supernovae
   - Supernova Types and Light Curves
   - Supernovae as a Function of Mass and Metallicity

# Supernovae



# Supernovae - Overview

## Things that blow up

supernovae from massive stars

1B=$10^{51}$ erg

MASS

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=$10^{51}$ erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

# Supernovae

## Things that blow up

### Neutron star-powered supernovae

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
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# Supernovae

## Things that blow up

### Thermonuclear supernovae (no *r*-process)

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
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- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=$10^{51}$ erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

## Supernovae

# Things that blow up

Black hole-powered supernovae ("Collapsars)

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- "SAGB" star (AGB, then SN) ➔ EC SN
- "normal" SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- "Collapsar", GRB ➔ broad line Ib/a SN, "hypernova"
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, $\lesssim$100B (1B=$10^{51}$ erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- Supermassive stars ➔ $\gtrsim$100000 B SN or SMBH

# Supernovae

## Things that blow up

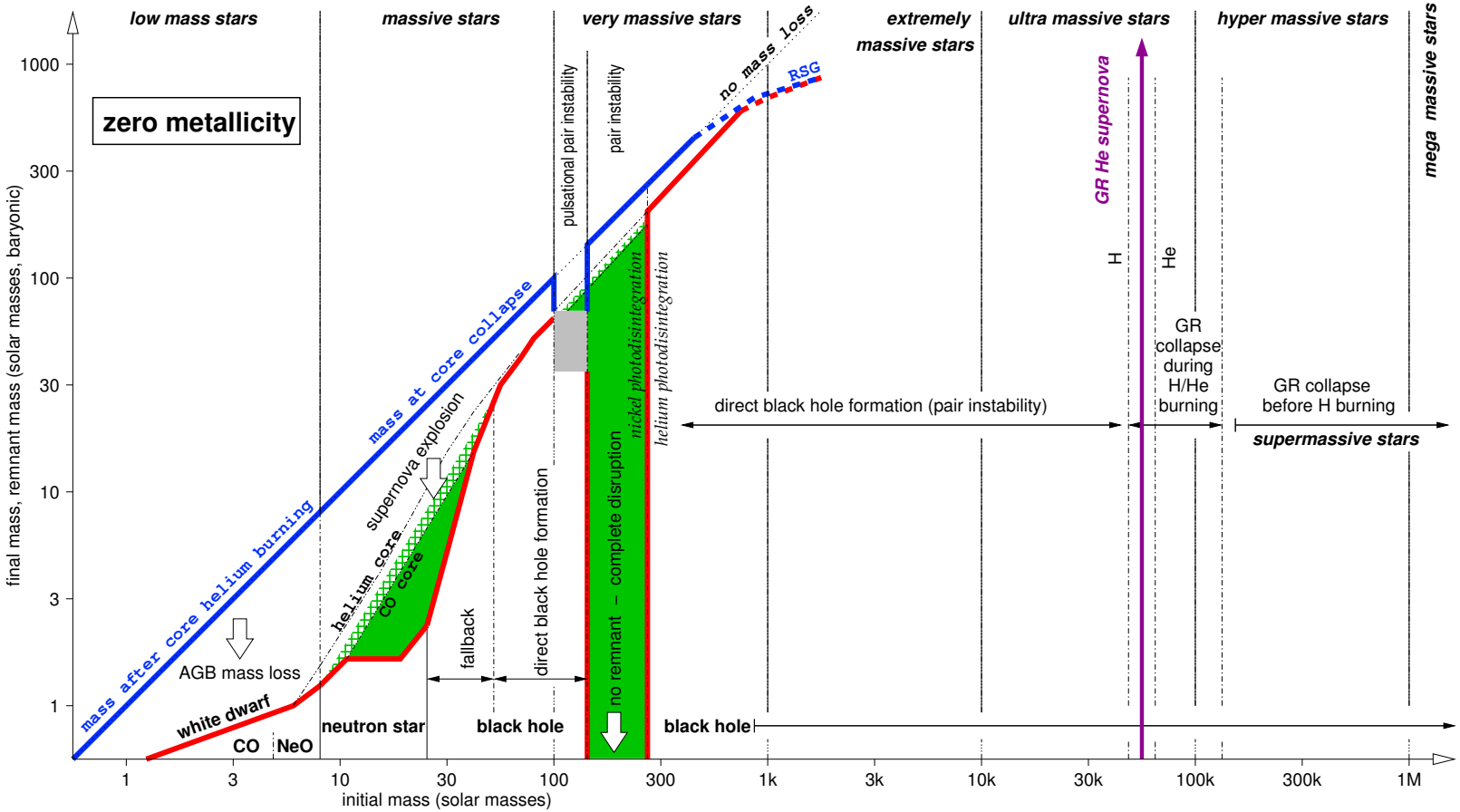
supernovae

1B=$10^{51}$ erg

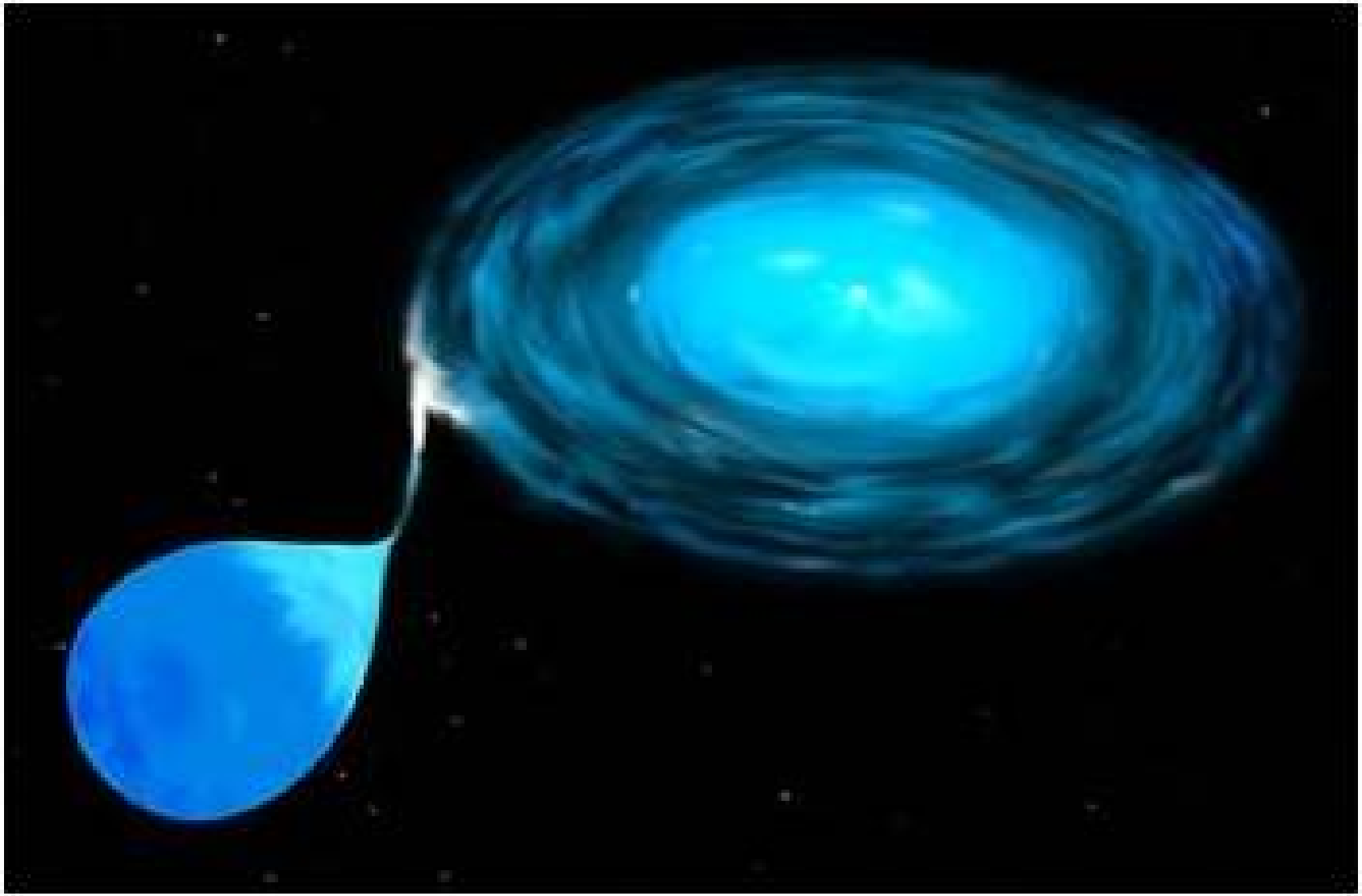
MASS

- CO white dwarf ➔ Type Ia SN, E≈1Bethe
- MgNeO WD, accretion ➔ AIC, faint SN
- “SAGB” star (AGB, then SN) ➔ EC SN
- “normal” SN (Fe core collapse) ➔ Type II SN
- WR star (Fe CC) ➔ Type Ib/c
- “Collapsar”, GRB ➔ broad line Ib/a SN, “hypernova”
- Pulsational pair SN ➔ multiple, nested Type I/II SN
- Very massive stars ➔ pair SN, ≲100B (1B=$10^{51}$ erg)
- Very massive collapsar ➔ IMBH, SN, hard transient
- GR He instability ➔ >100 B SN+SMBH, or 10,000 B
- Supermassive stars ➔ ≳100000 B SN or SMBH

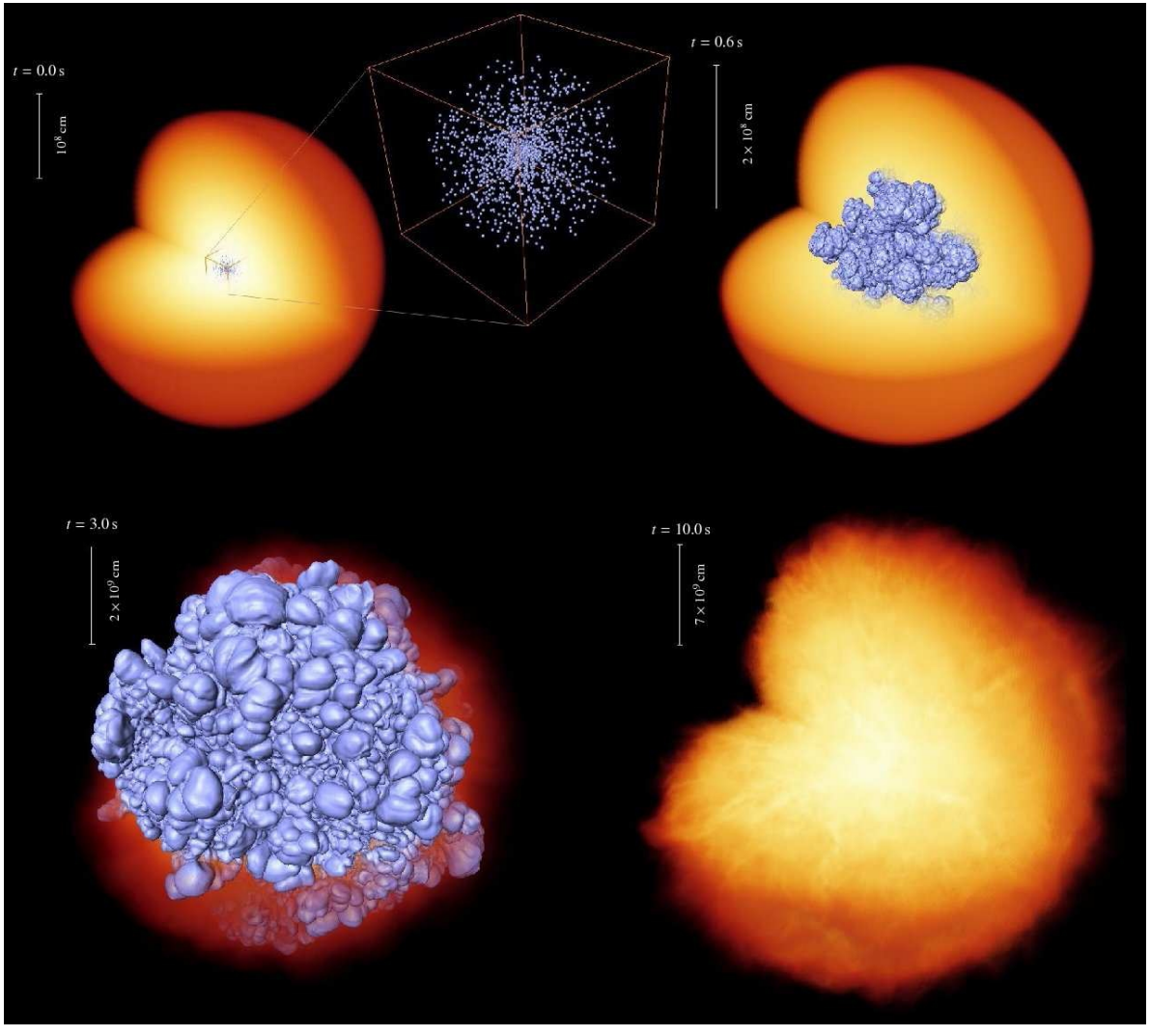
# Fates


low mass stars
massive stars
very massive stars
extremely massive stars
ultra massive stars
hyper massive stars
mega massive stars
zero metallicity
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1k
3k
10k
30k
100k
300k
1M
mass after core helium burning
mass at core collapse
no mass loss
RSG
pulsational pair instability
pair instability
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star
fallback
black hole
direct black hole formation
no remnant – complete disruption
nickel photodisintegration
helium photodisintegration
black hole
GR He supernova
H
He
direct black hole formation (pair instability)
GR collapse during H/He burning
GR collapse before H burning
supermassive stars

# Type Ia Supernova Progenitor



# Type Ia Supernova Explosion

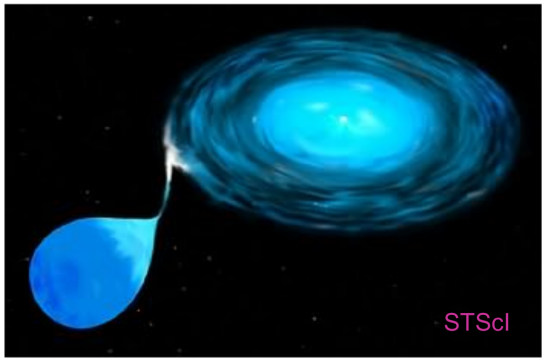



simulation of a Type Ia supernova explosion

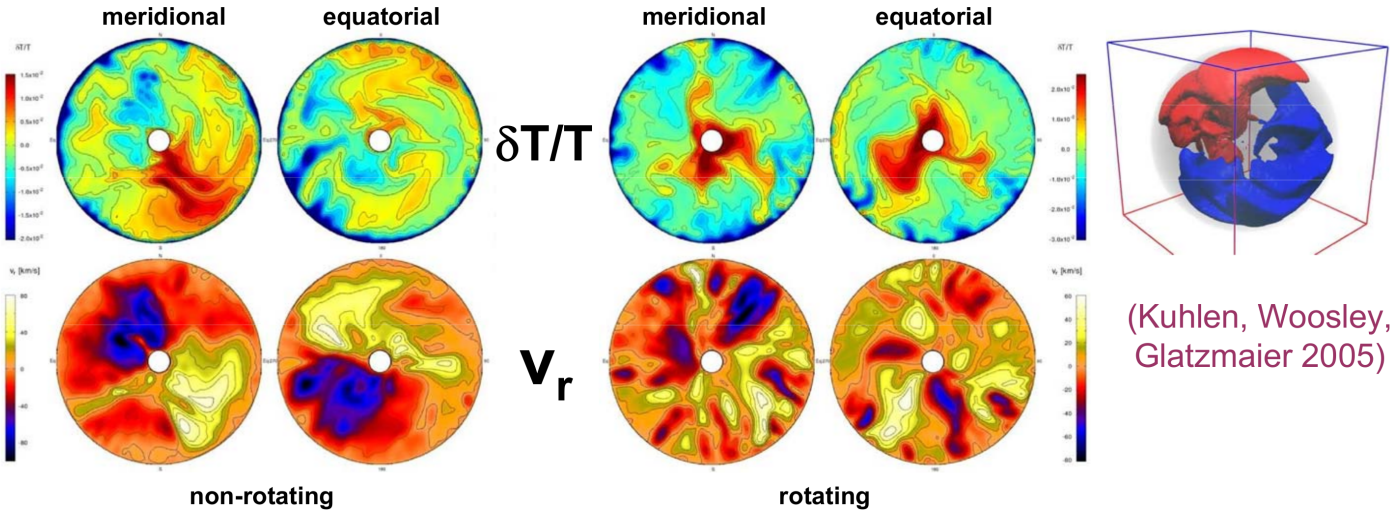
(by Fritz Röpke)

# Type Ia Supernovae

## SN Type Ia Ignition



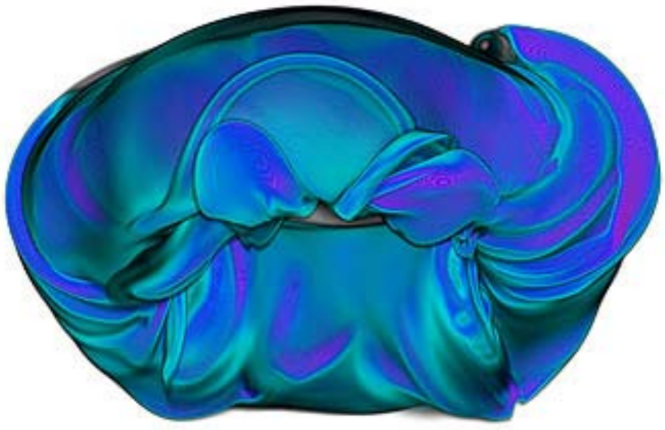

- Accreting CO white dwarf in binary star system
- ~1000 yr of convective “smoldering” carbon burning
- Quick final thermonuclear and ignition
- **How many sparks form? Where? Timescale?**




(Kuhlen, Woosley, Glatzmaier 2005)

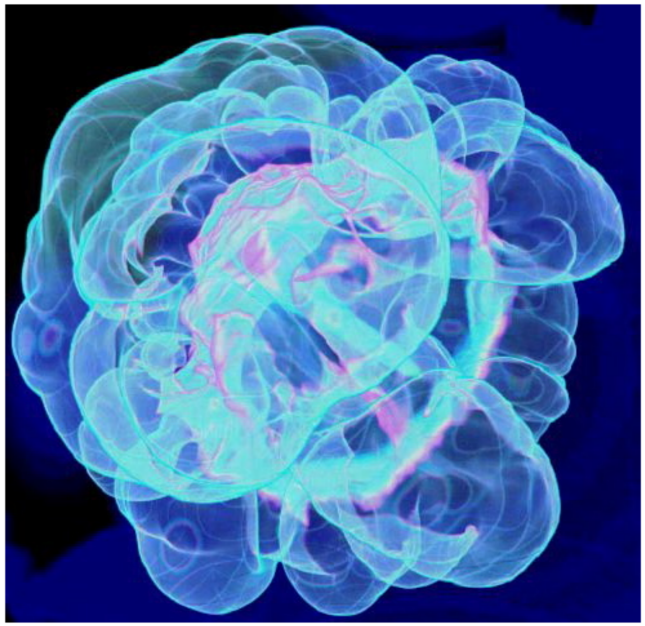
# Type Ia Supernovae

## SN Type Ia – A single Spark?



(Zingale *et al*. 2005)

Fully resolved singe ignition “spark”.



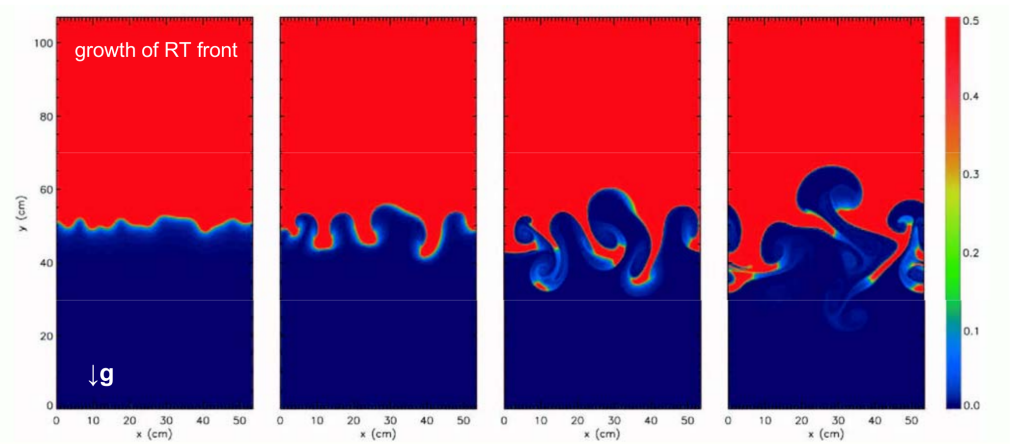
(Calder *et al*. 2004)

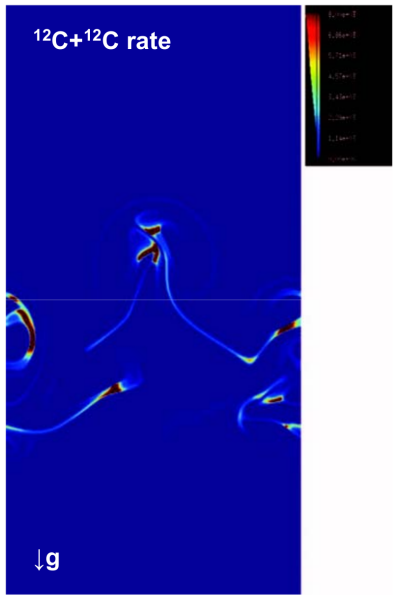
Single slightly off-center ignition spot.

Single off-center ignition gives bubble that quickly rises in one direction
➔ no successful supernova explosion.

# Type Ia Supernovae

## SN Type Ia Flames – 2D



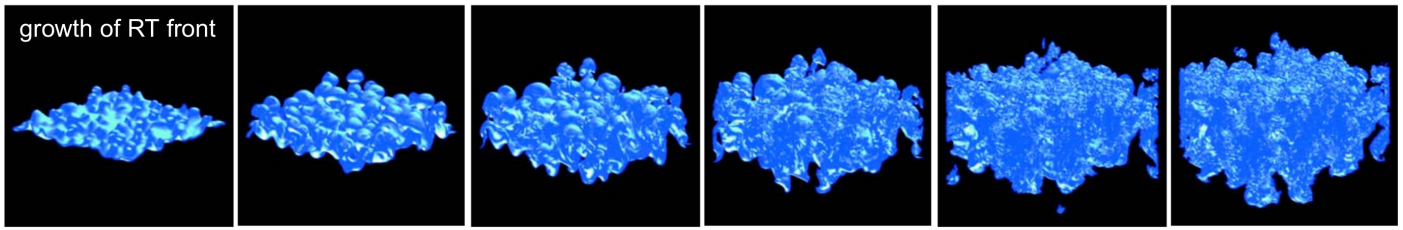



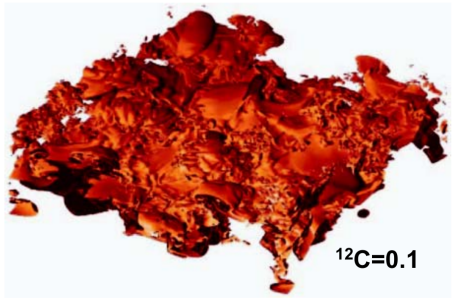

(Zingale *et al*. 2005)

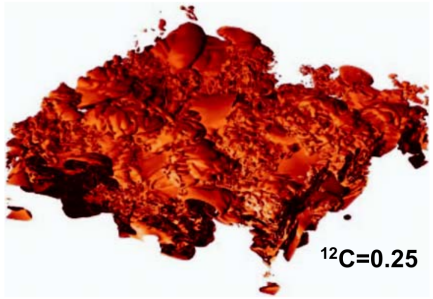
Due to 2D symmetry front has lots of power on large scales

# Type Ia Supernovae

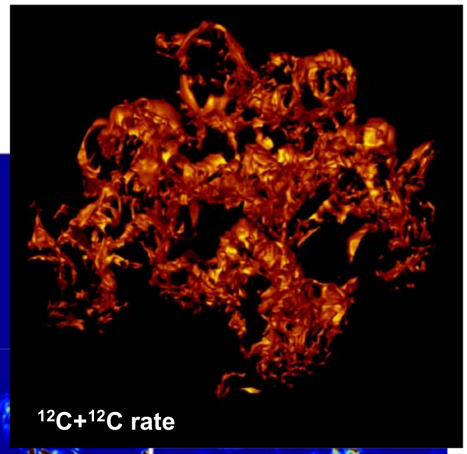
## SN Type Ia Flames – 3D



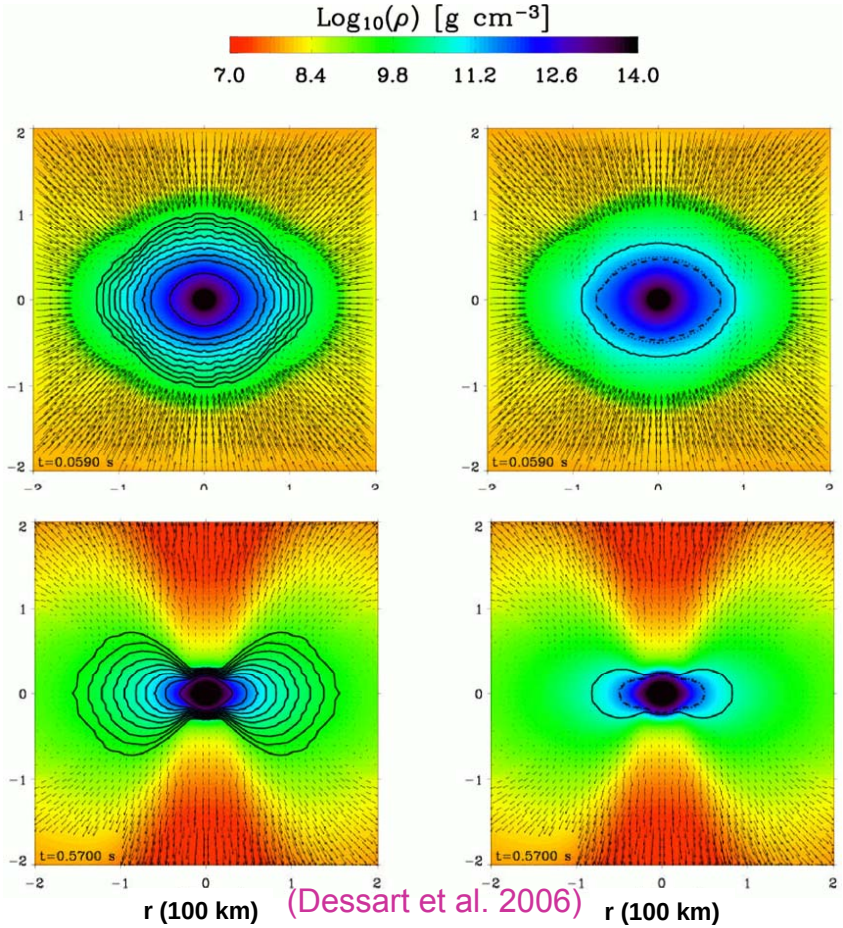




(Zingale *et al*. 2005)



# Accretion Induced Collapse

## Accretion Induced Collapse



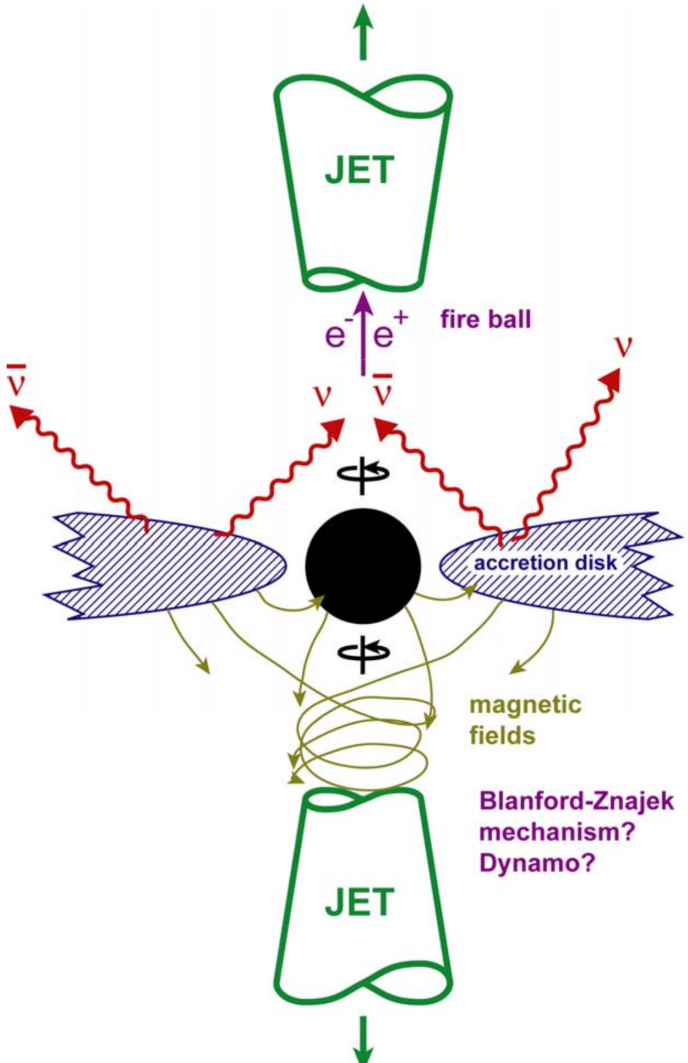

(Dessart et al. 2006)

- NeMgO WD accretes from companion star
- When Chandrasekhar mass is approached, electron captures reduce electron degeneracy pressure support

◀ Rapid collapse and bounce (faint SN)

# Supernovae

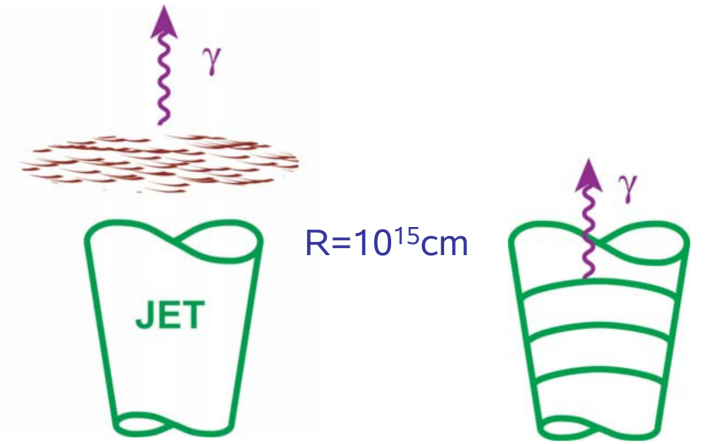
## The Collapsar Engine




Accretion disk around **black hole**
may power **jet** by **neutrino annihilation** or by **MHD process**.

Jet will explode star
("hypernova"; see talk by Andrew MacFadyen)

and may power GRB
if it can escape from the stellar interior; requires
→ relativistic jet with high $\Gamma > 100$ and low baryon loading

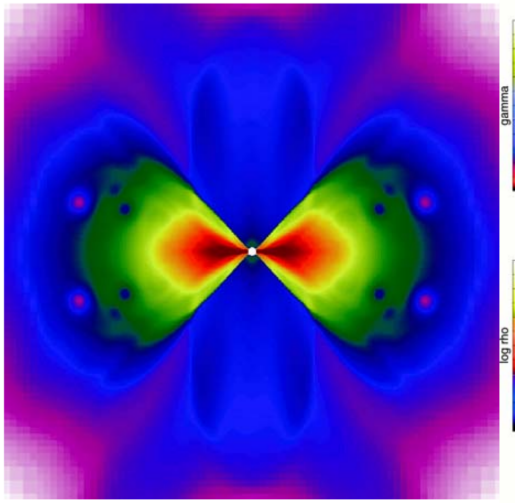



interaction with circumstellar matter

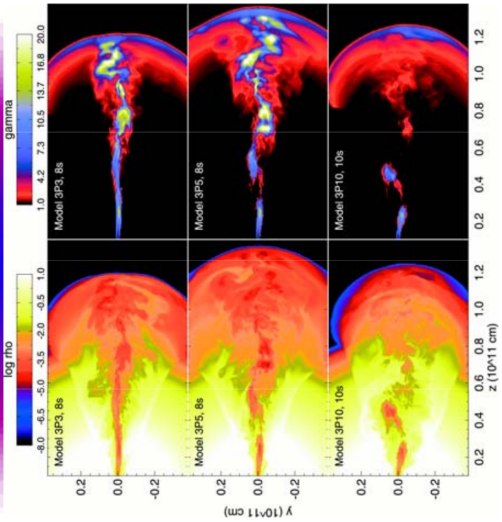
internal shocks

# Supernovae

## GRBs, Collapsar - Nucleosynthesis



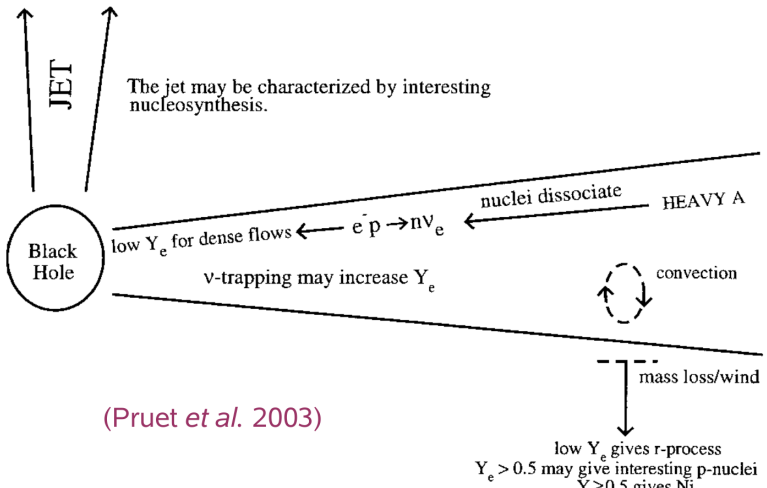
(MacFadyen, Zhang, Woosley 2005)



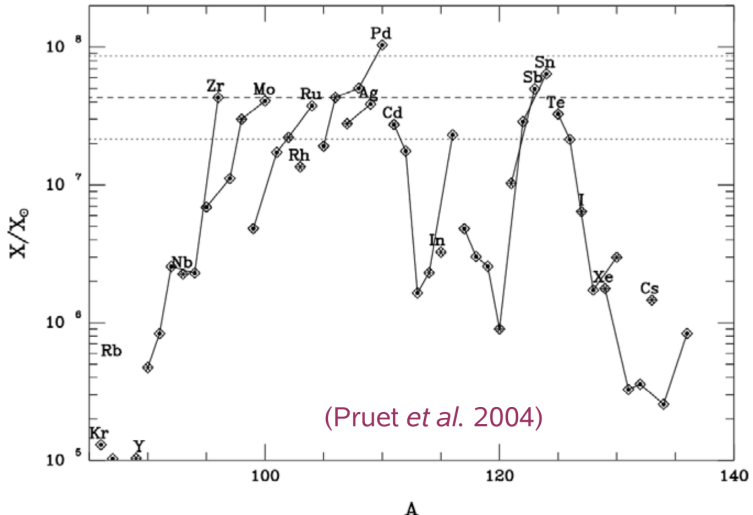

(Zhang, Woosley, Heger 2004)

←Hot accretion disk powers jet that may make GRB and explodes star

Nucleosynthesis in outflow from disk ↓

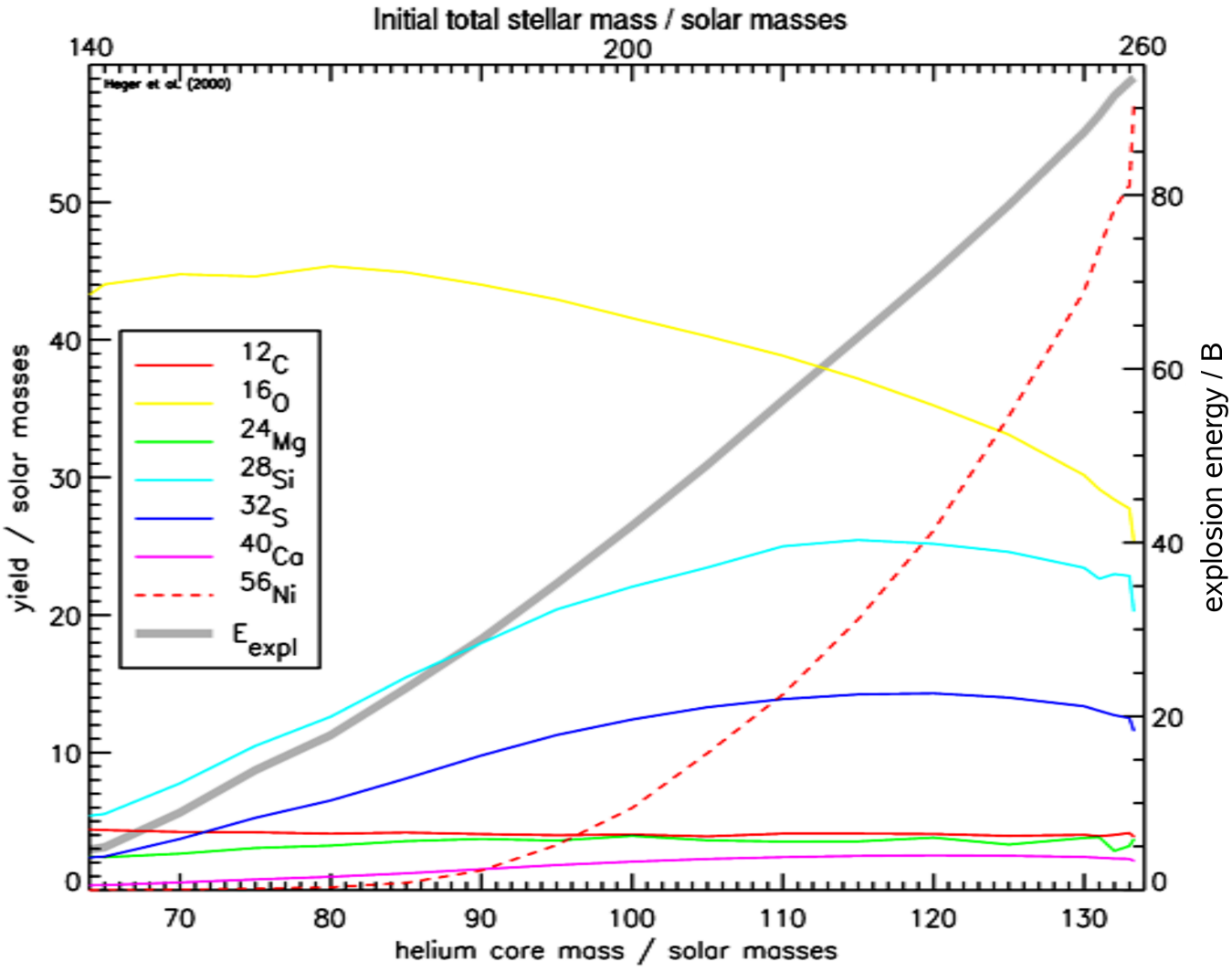



(Pruet *et al.* 2003)

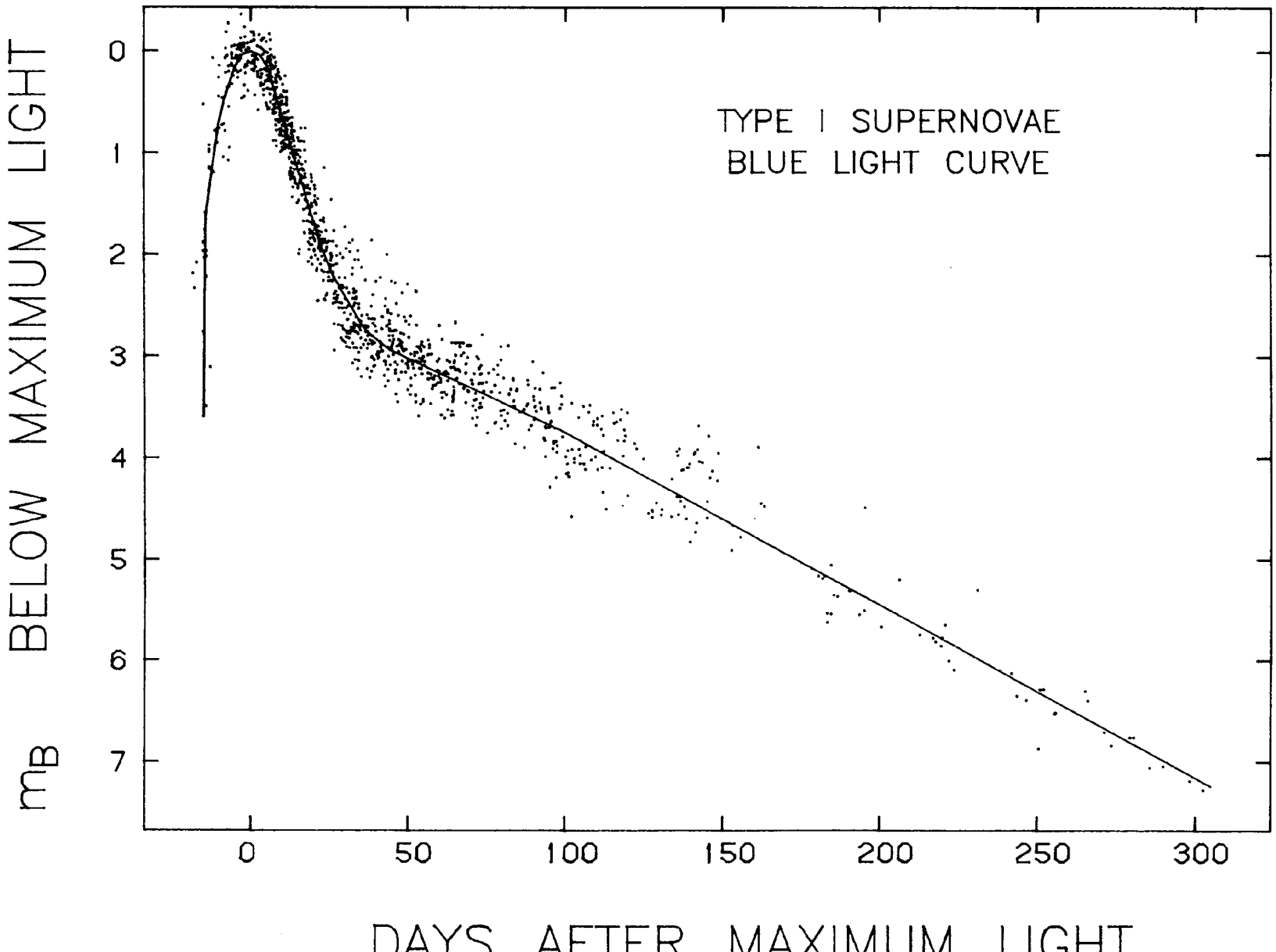



(Pruet *et al.* 2004)

# Pair-Instability Supernovae



# Supernovae Light Curve



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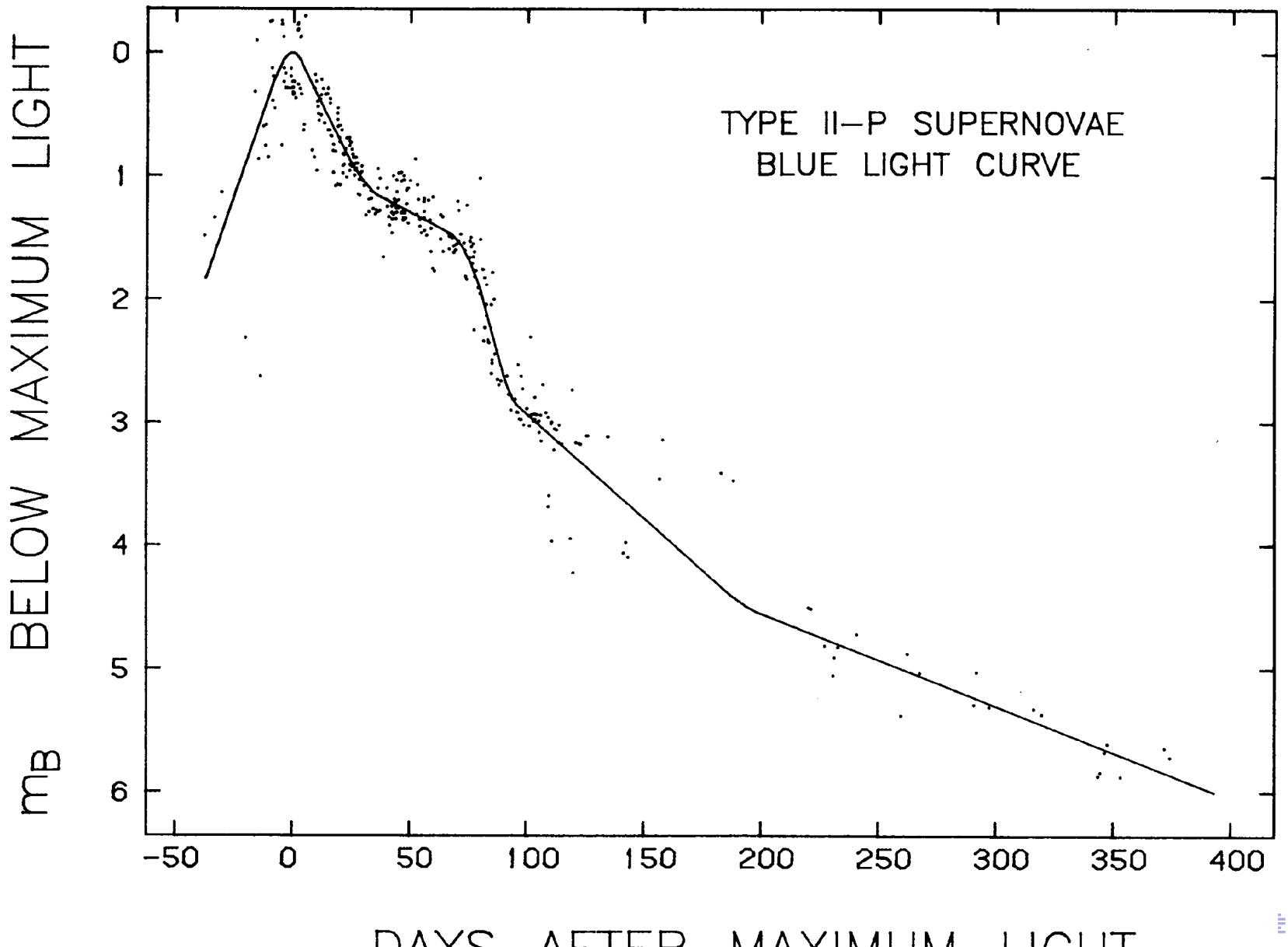

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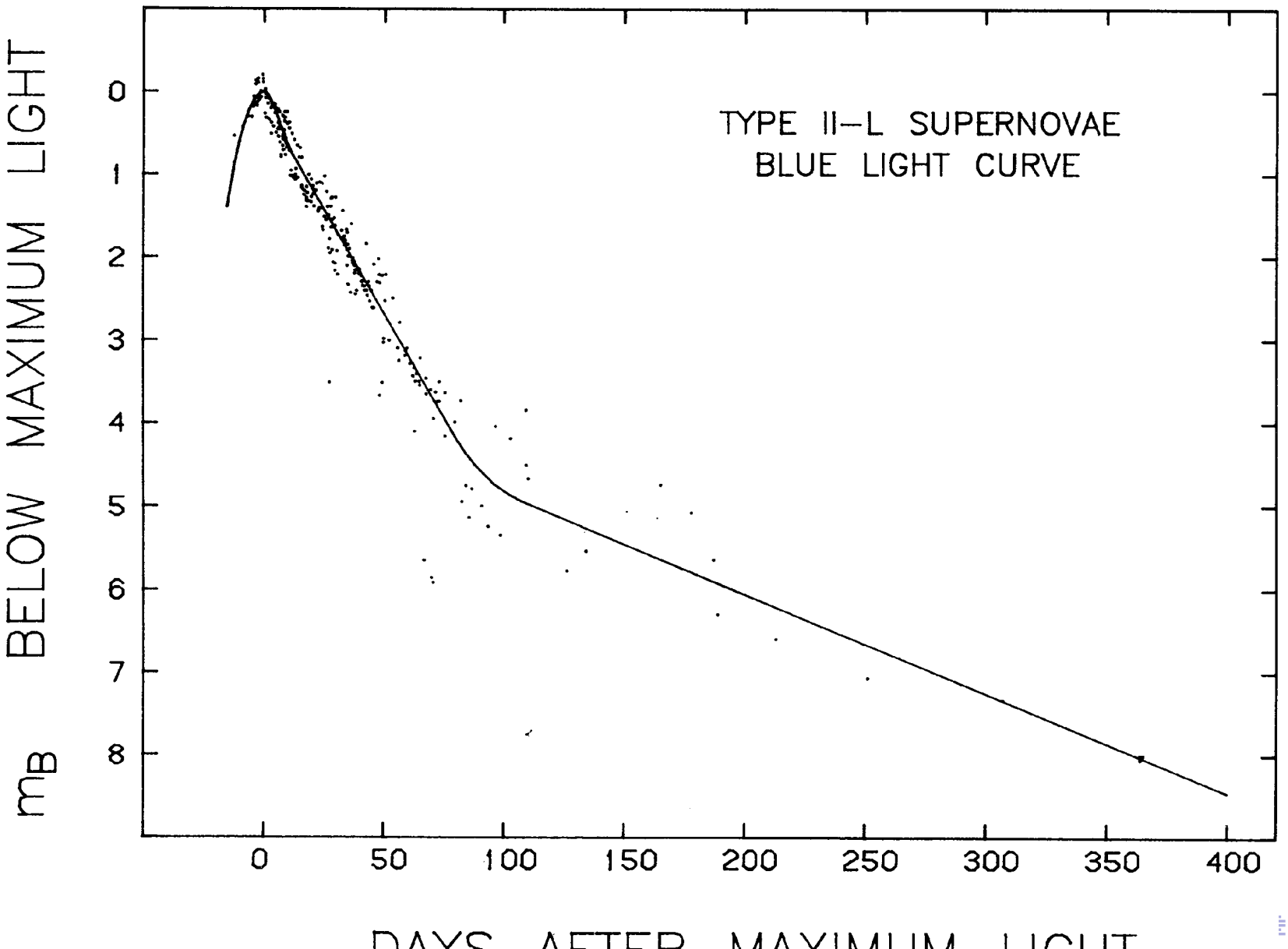
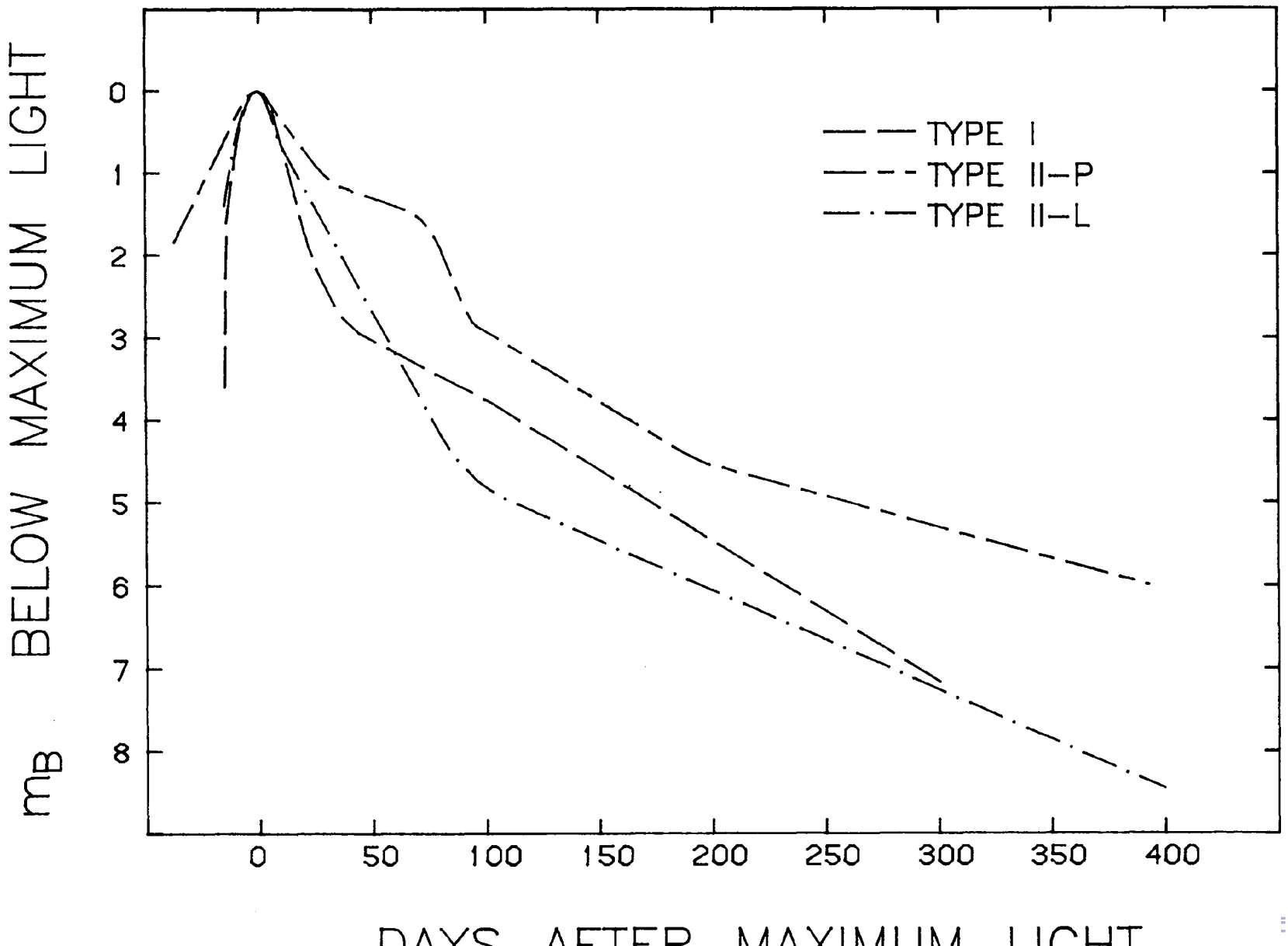


# Supernovae Light Curve



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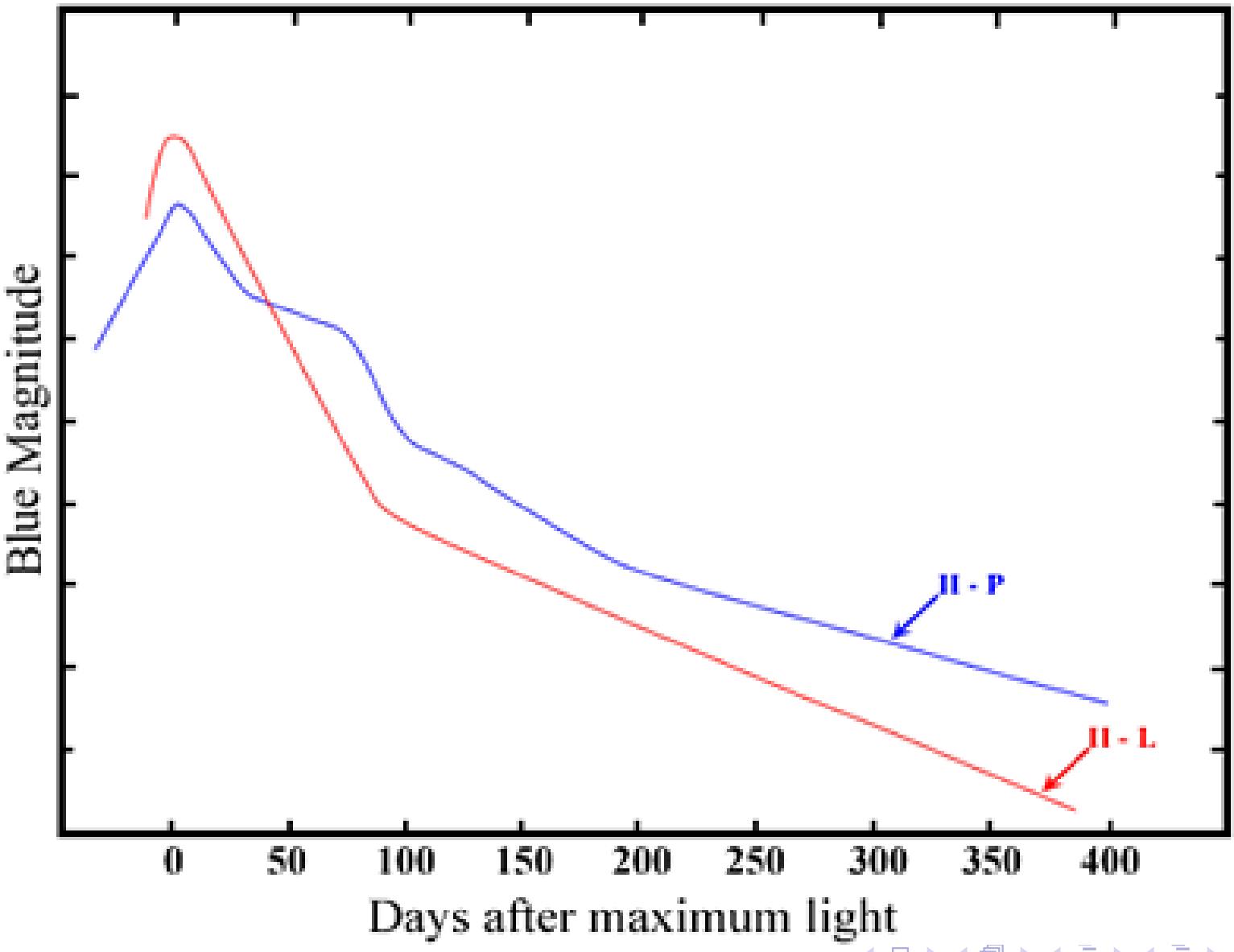
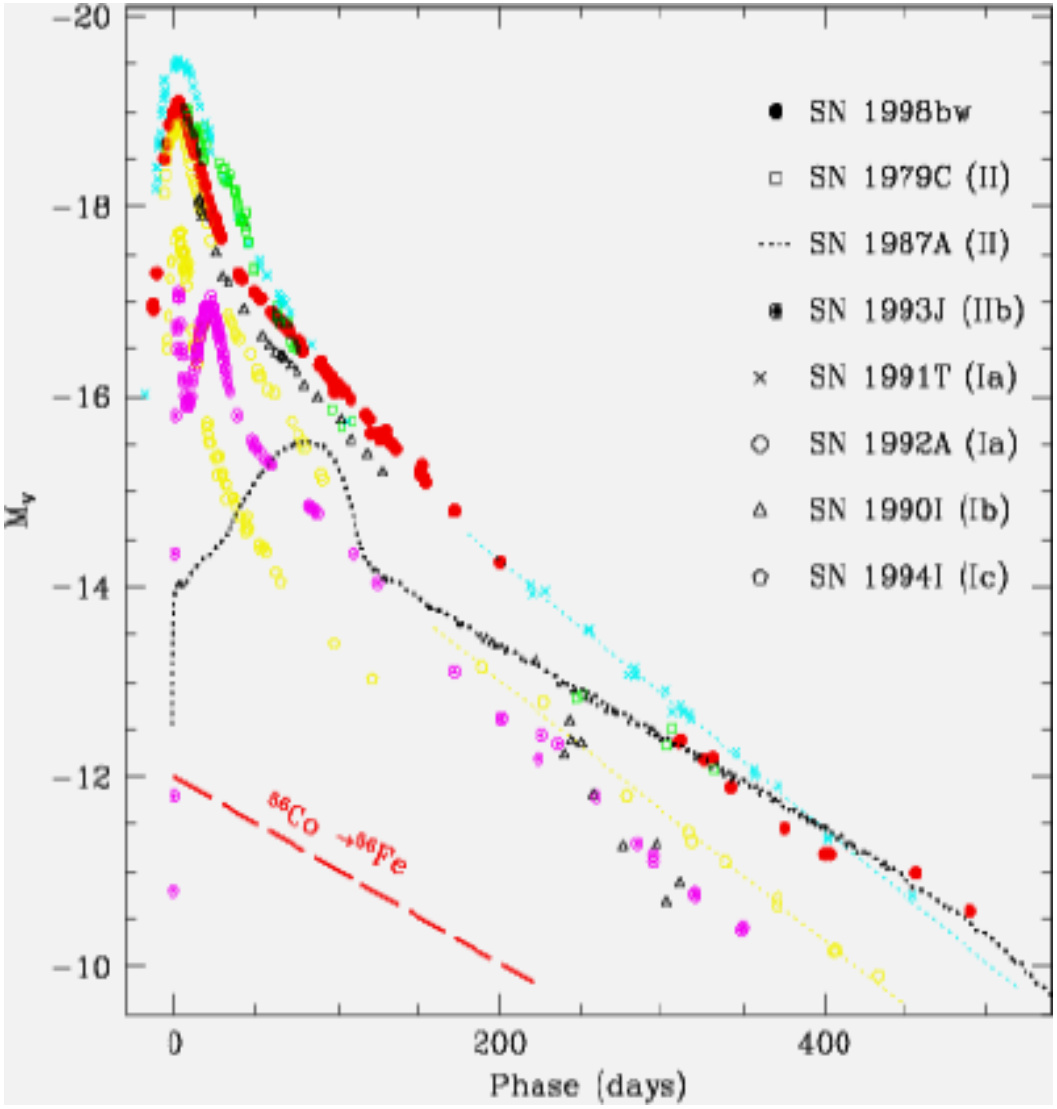
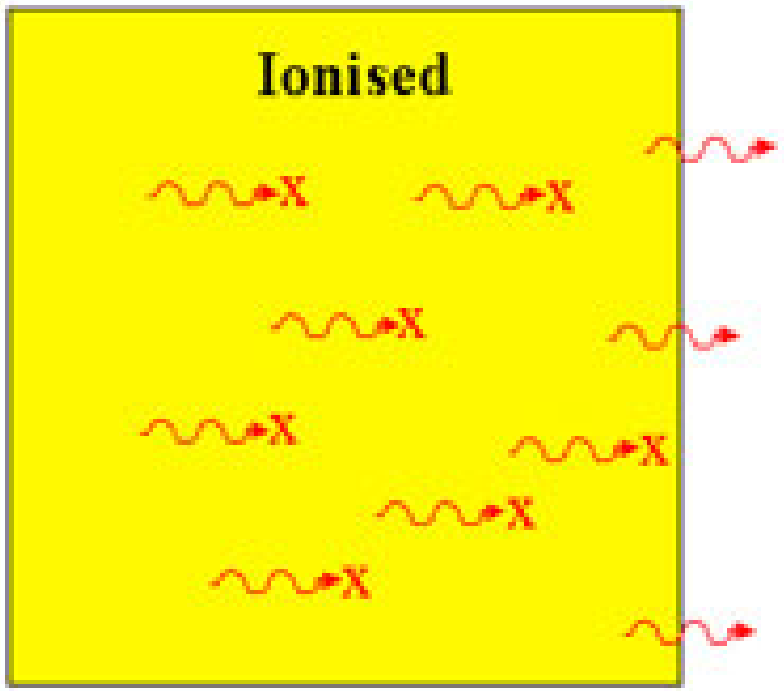
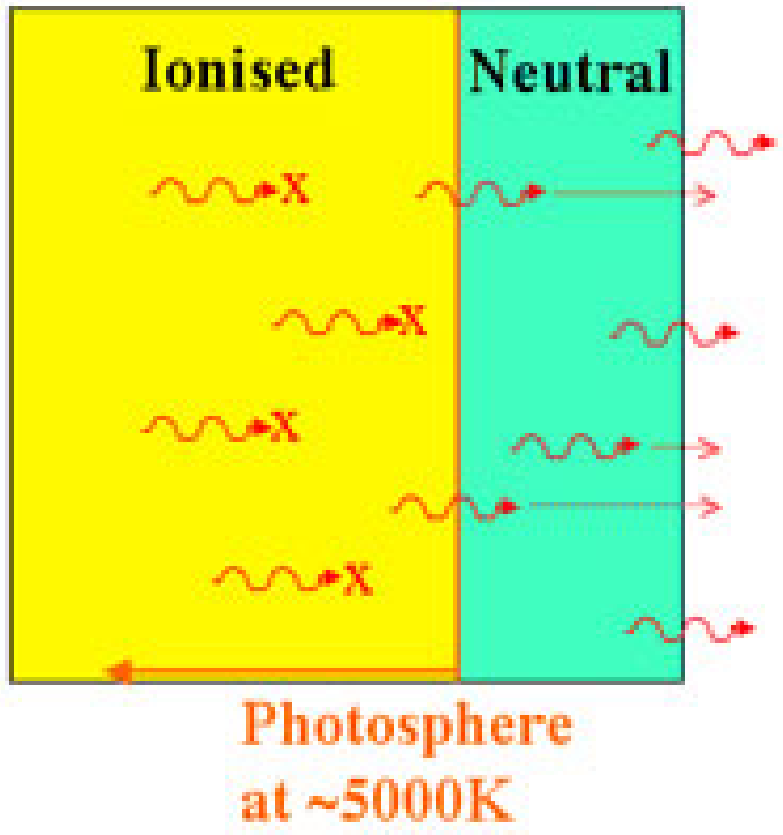


# Supernovae Light Curve

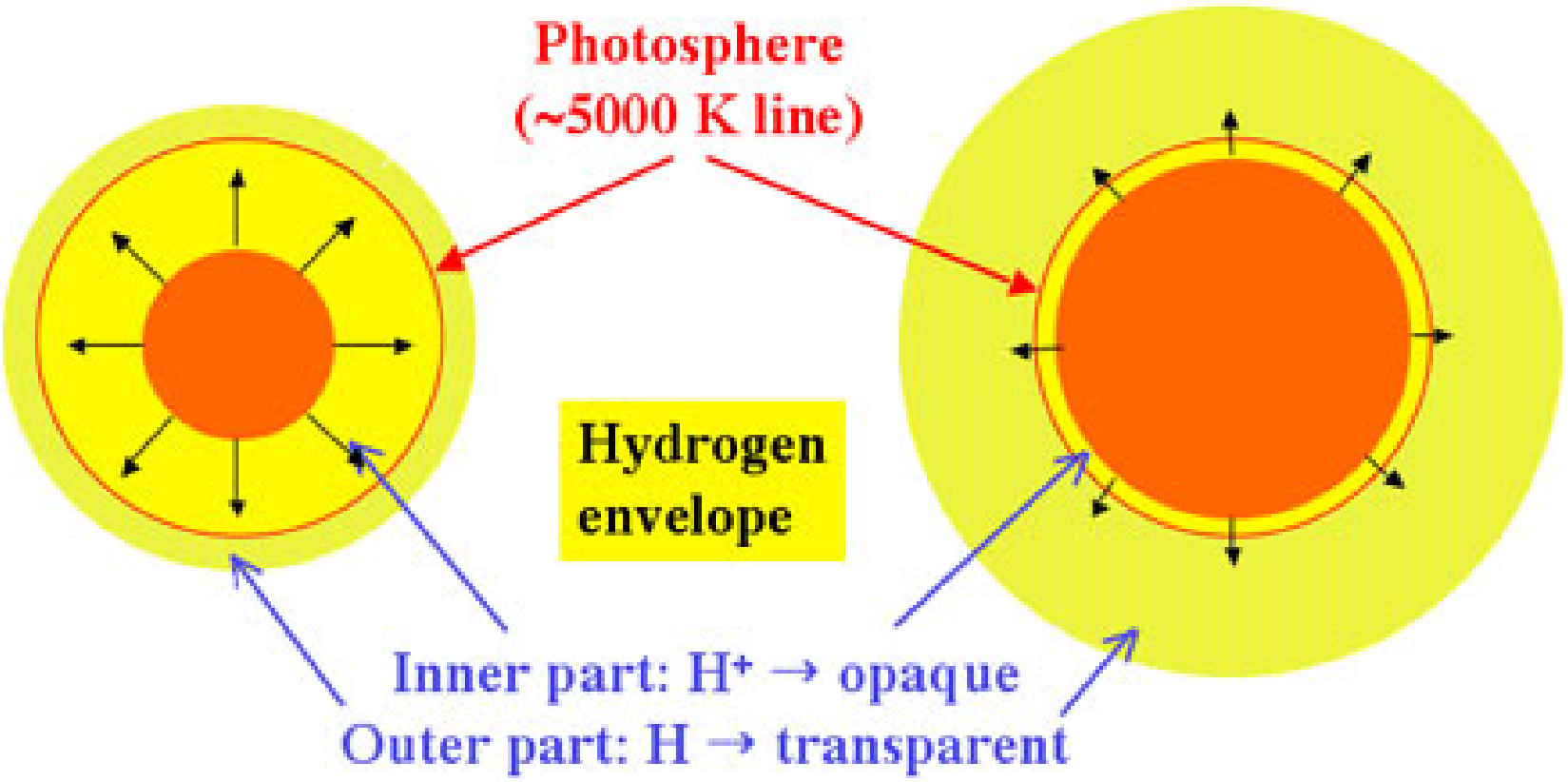


# Escape of photons from photosphere

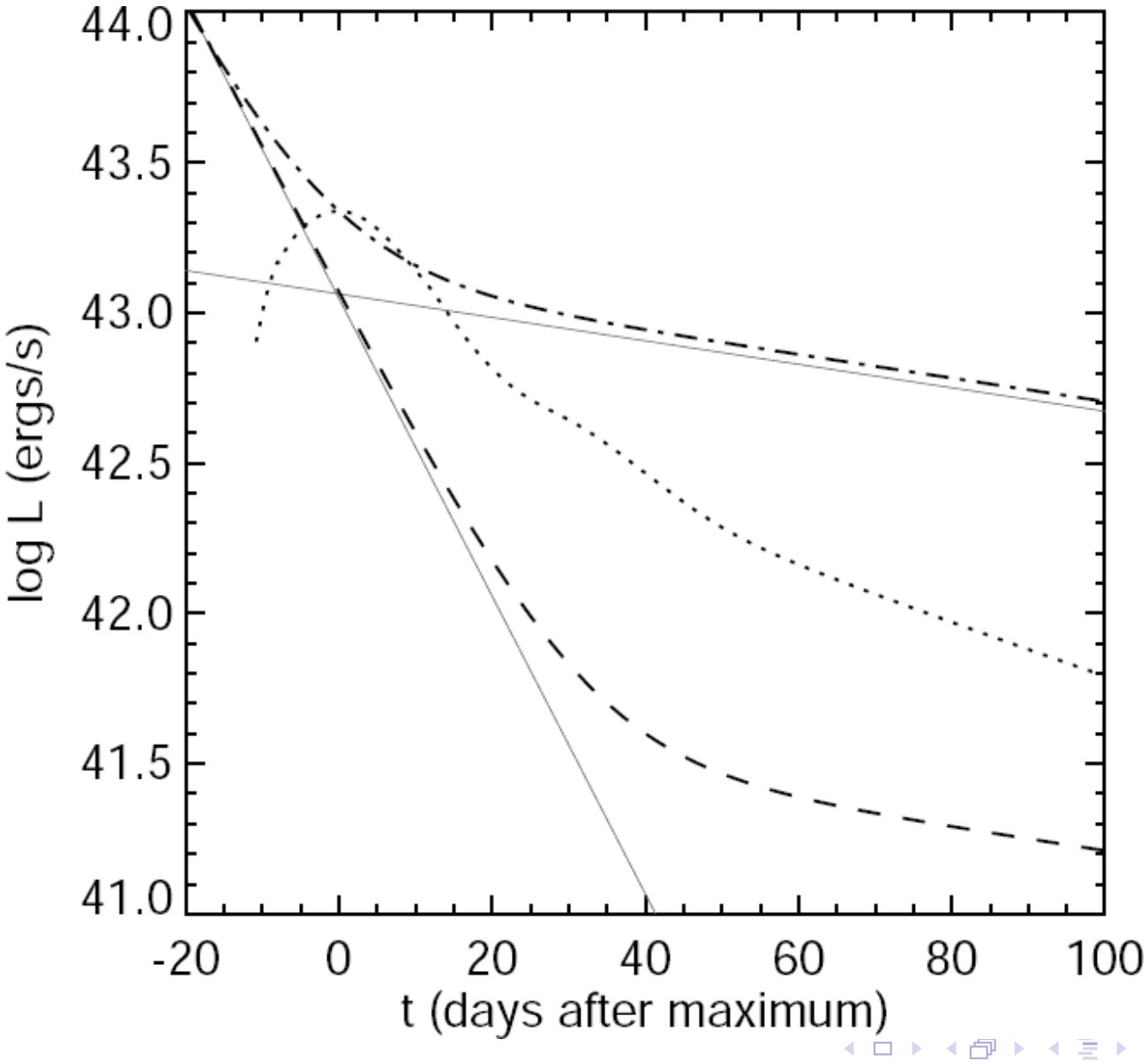


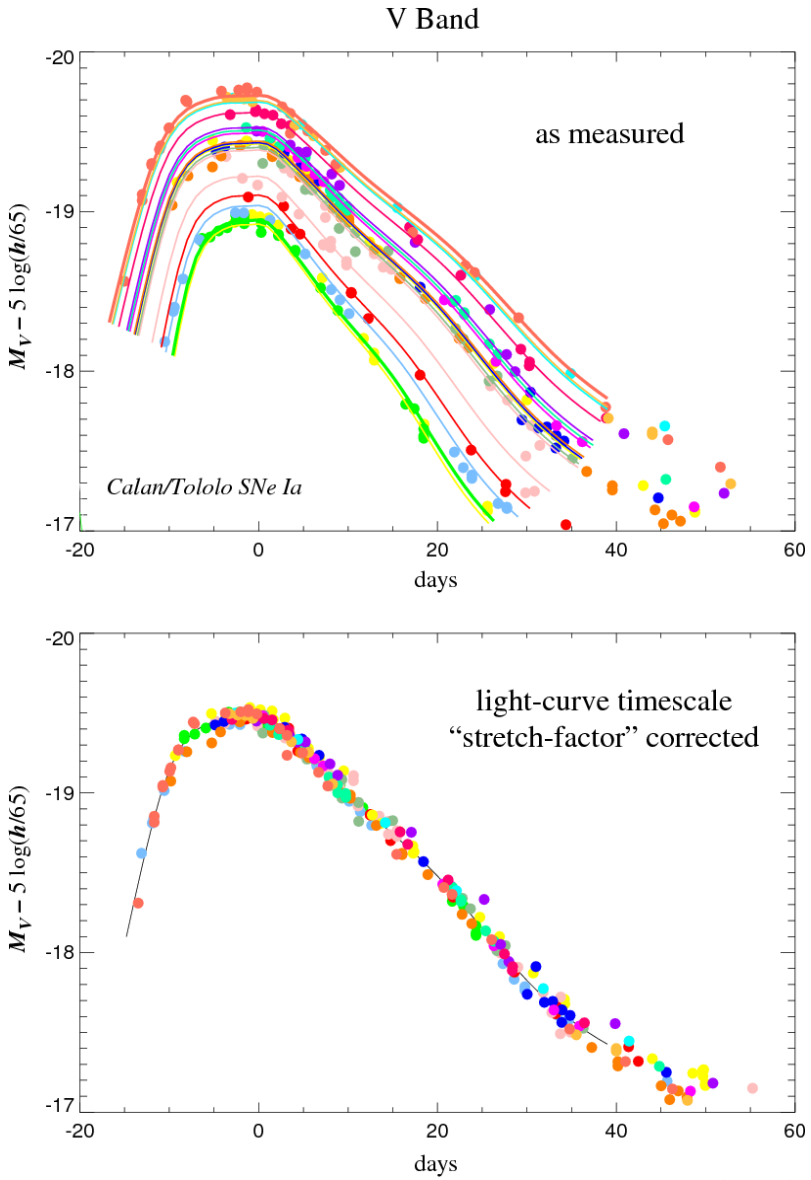
# Retreat of Photosphere during SN Expansion



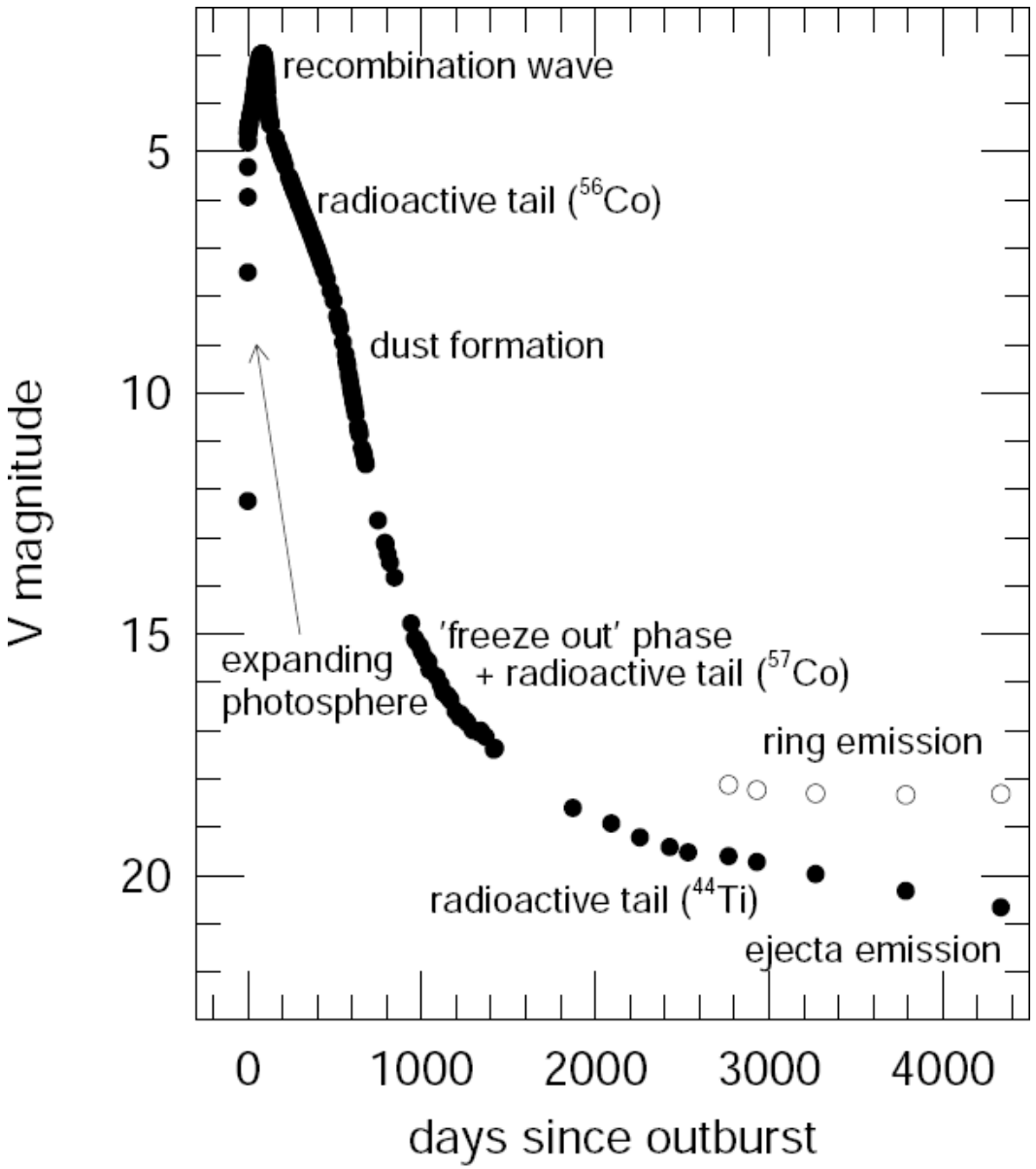
# Type Ia Supernovae and Radioactivity



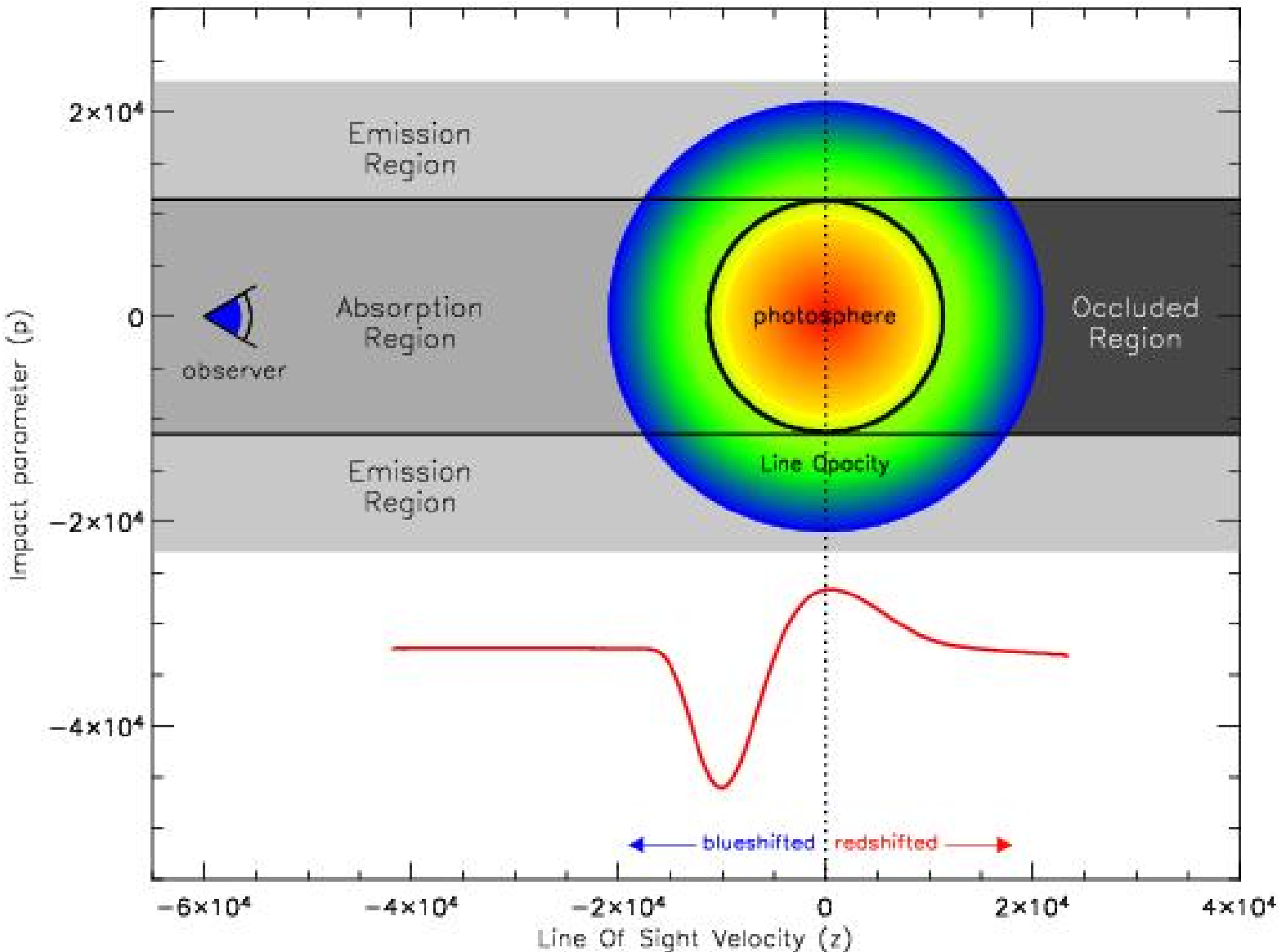
# Type Ia Supernovae Lightcurve Fitting



# Supernovae Light Curve - SN 1987A



# Supernovae Light Curve - P-Cygni Profile Formation



# Supernovae - Mass and Metallicity