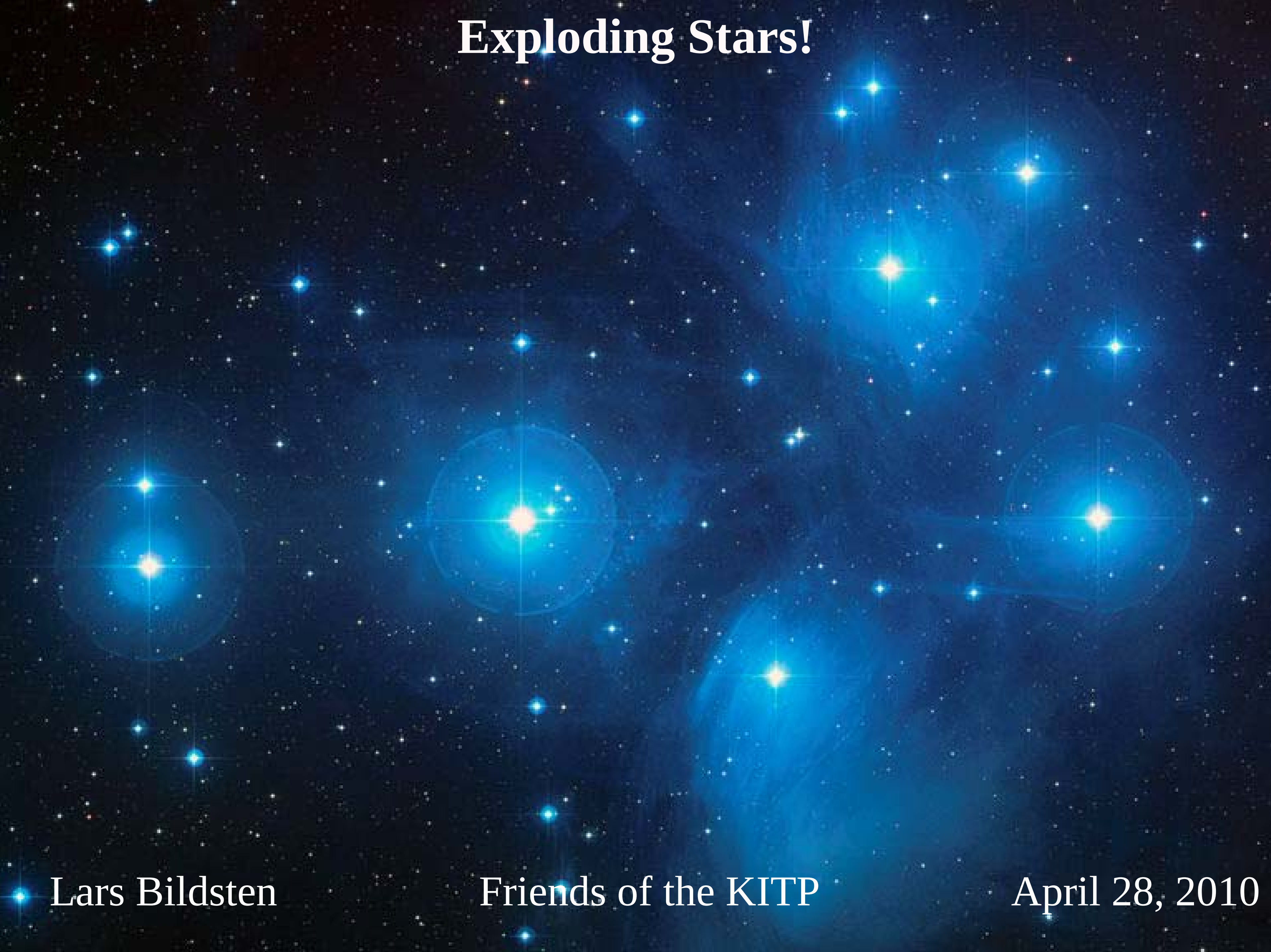
Exploding Stars!



Lars Bildsten Friends of the KITP April 28, 2010

Exploding Stars!

Stars explode once every second in the Universe, often becoming brighter than their home galaxies. Enhanced capabilities to scan the skies now detect about 10 per day, revealing some remarkable new phenomena!

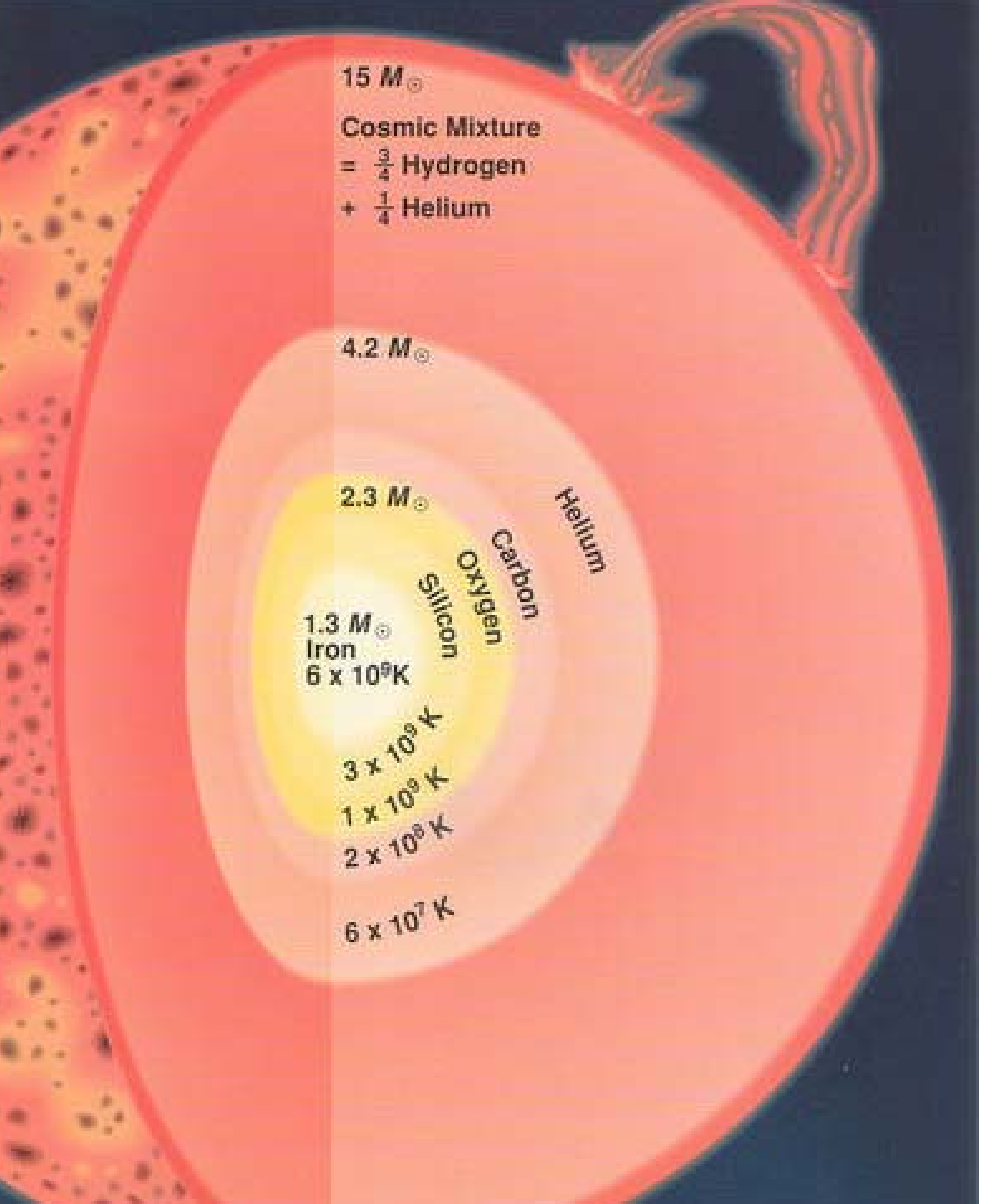
Dan Kasen (UCSC), Kevin Moore (UCSB), Gijs Nelemans (U. Nijmegen), Evan Scannapieco (KITP=>ASU), Ken Shen (UCSB), and Nevin Weinberg (KITP=>UCB)

It's all about Energy!

- Gravity . . . The release of energy as the star contracts onto itself
- Nuclear . . . The release of energy from fusing the Hydrogen and Helium made in the big bang to heavier elements like Carbon, Oxygen, . . Iron. .

Stars tap into both of these energy sources, but only at the rate needed to match that lost from the surface.

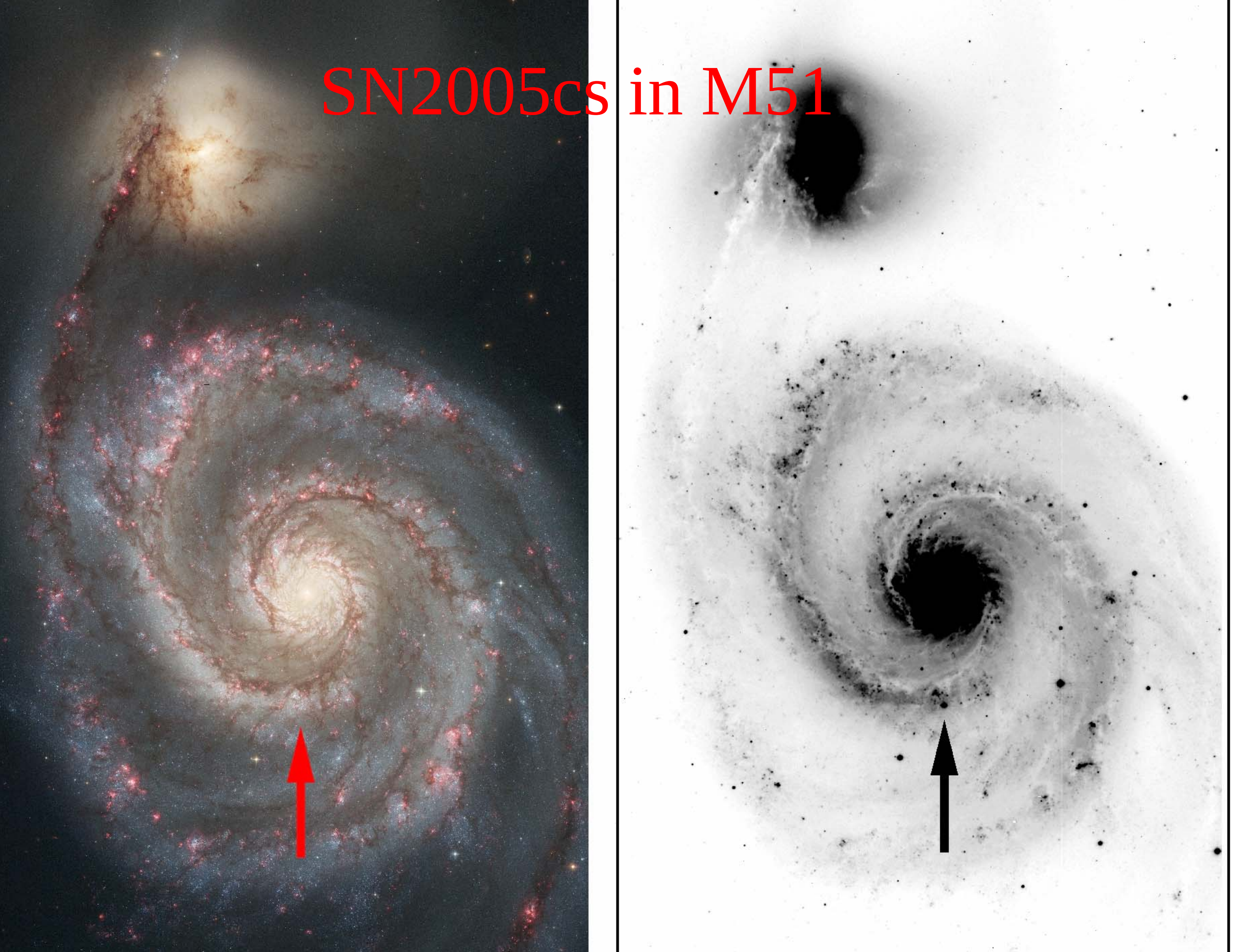
Supernovae do the opposite. They release the energy so rapidly that the object explodes, completely disintegrating.

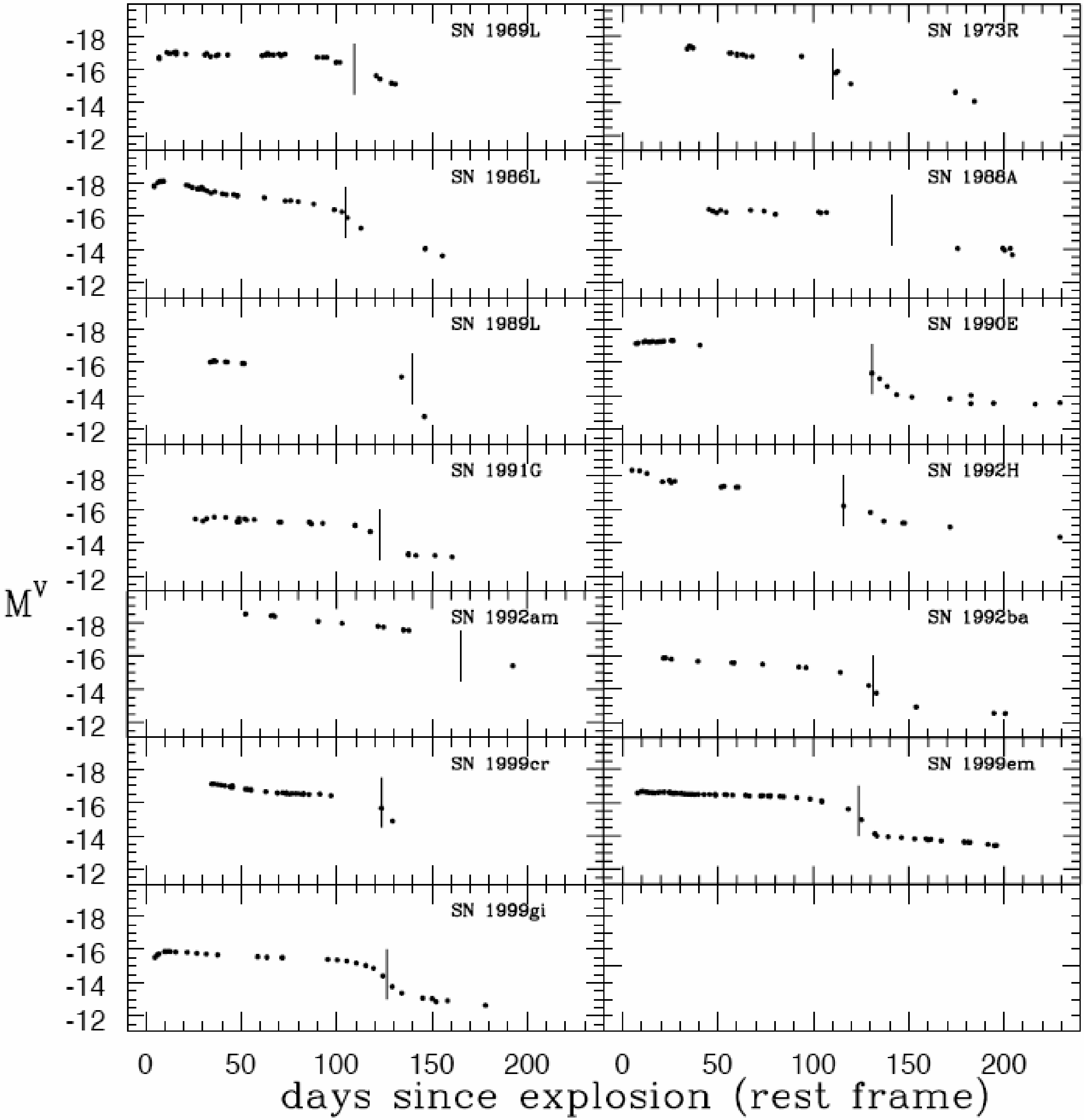


- The outer shells of matter get ejected, enriching the matter between stars with freshly made Helium, Carbon, Oxygen, Silicon. . . and some Iron.

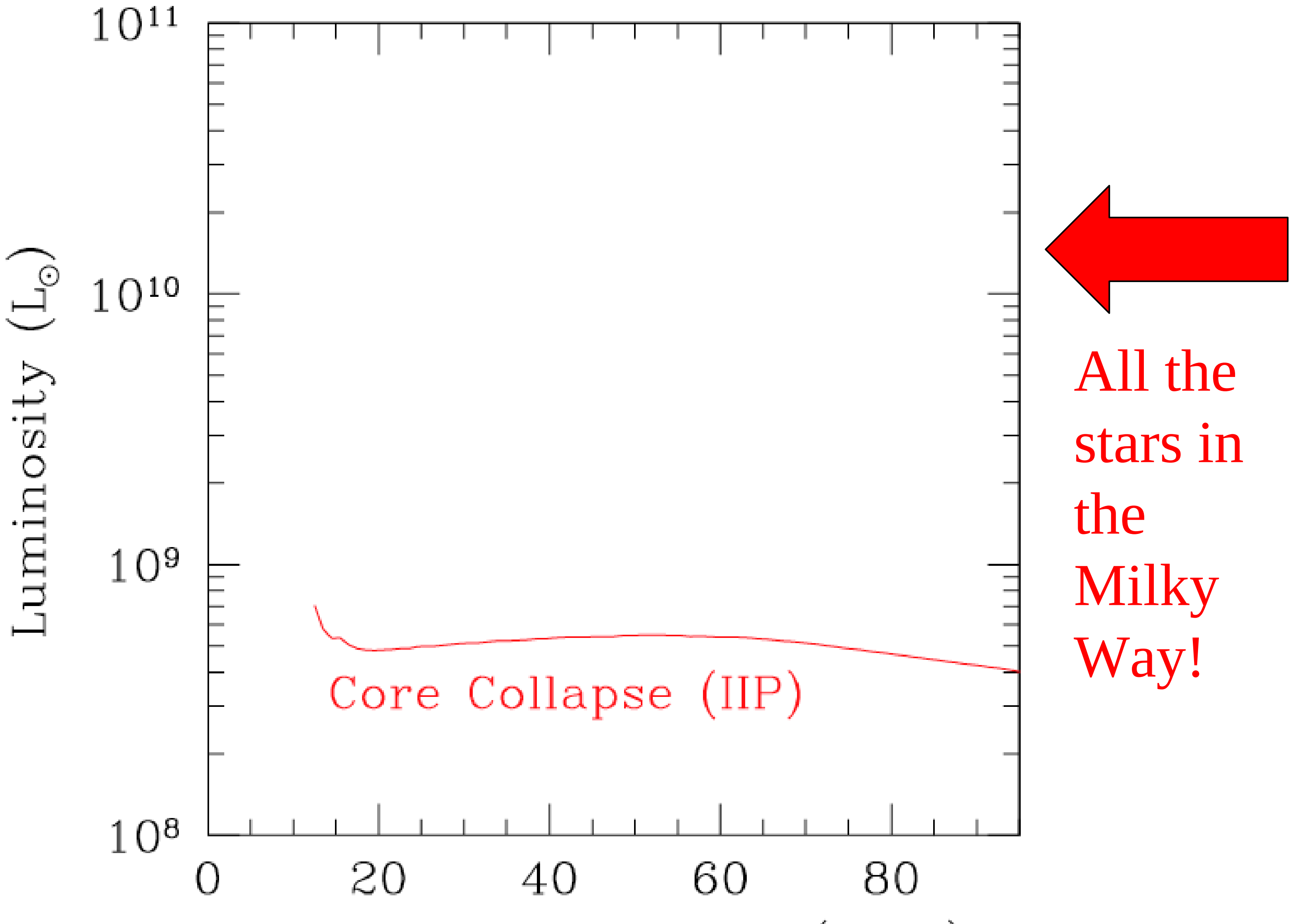
- The dense remnant left from the collapse is either a Neutron Star or a Black Hole.

SN2005cs in M51



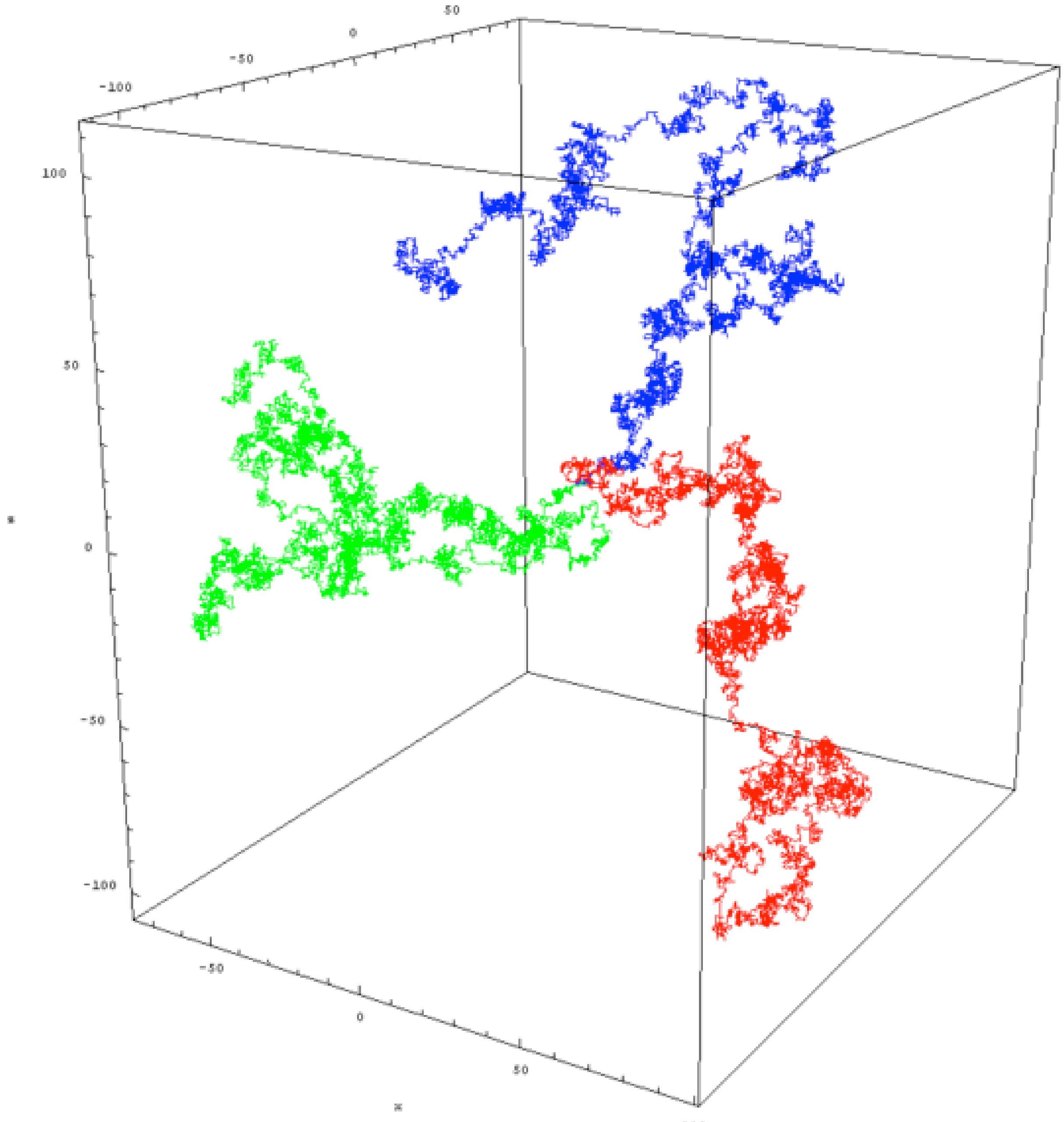

SN 1969L
SN 1973R
SN 1986L
SN 1988A
SN 1989L
SN 1990E
SN 1991G
SN 1992H
SN 1992am
SN 1992ba
SN 1999cr
SN 1999em
SN 1999gi
-18
-16
-14
-12
M^V
0
50
100
150
200
days since explosion (rest frame)

Theorist Version!



All the stars in the Milky Way!

Random Walks: Chalk!



Simple Lightcurves

- Consider an ejected mass M that is expanding at v, so R=vt, and has opacity Kappa

$$t_{\rm diff} \sim \frac{N\lambda}{c} \sim \frac{R^2}{\lambda c} \sim \frac{\kappa M}{Rc}$$

- Radiation diffusion time is >R/v=age until a time

$$t_d \approx \left(\frac{\kappa M}{vc}\right)^{1/2} \approx (10-20) \text{ days}$$

- But before then the expansion is adiabatic and since it is radiation-dominated=> $T \approx T_o \left(\frac{R_o}{R}\right)$

Luminosity Estimate

- The luminosity is

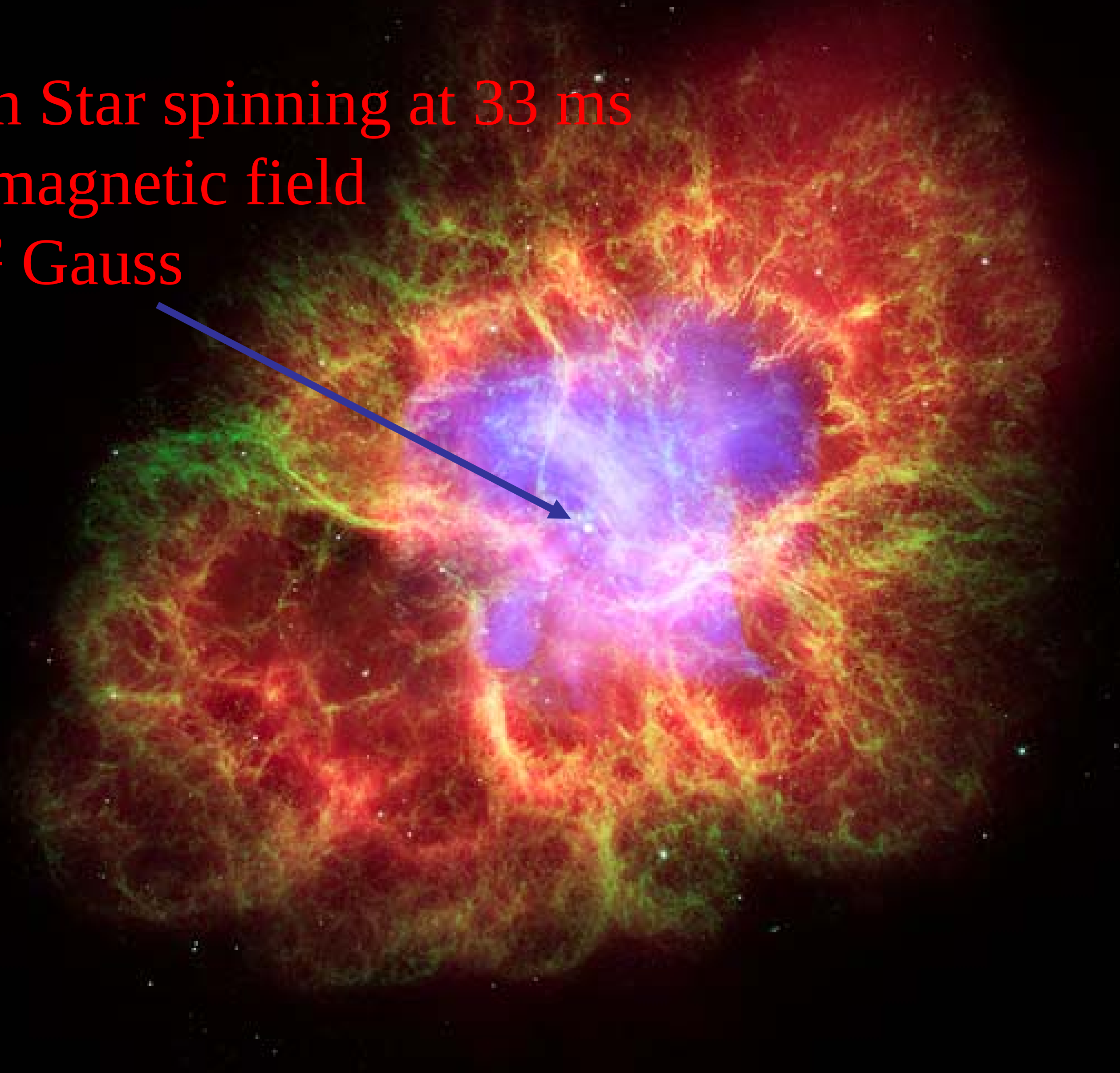
$$L \sim R^2 \frac{c}{\kappa\rho} \frac{d}{dr} aT^4 \sim \frac{R^3 E_{\rm rad}}{t_{\rm diff}}$$

- During the adiabatic phase, T goes like 1/R, giving

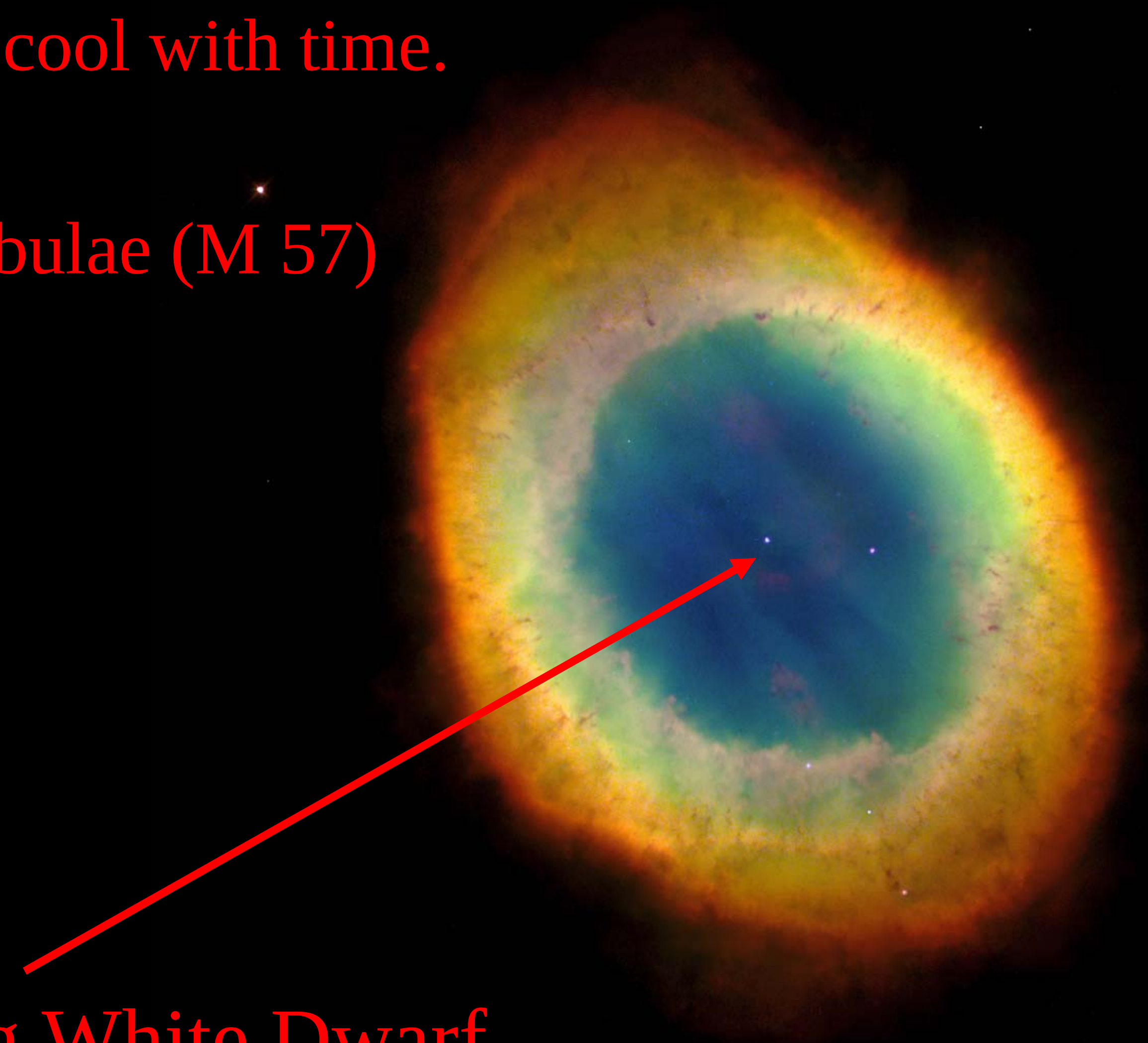
$$L \sim \frac{R_o^4 ac T_o^4}{\kappa M} \sim \frac{E_{\rm sn} c R_o}{\kappa M}$$

- An excellent estimate for the peak luminosity of Type IIP SNe ($\sim 10^9\ L_\odot$) where R_o is comparable to distance from Earth to Sun for red giants.

Crab Nebula from the supernova of 1054 AD

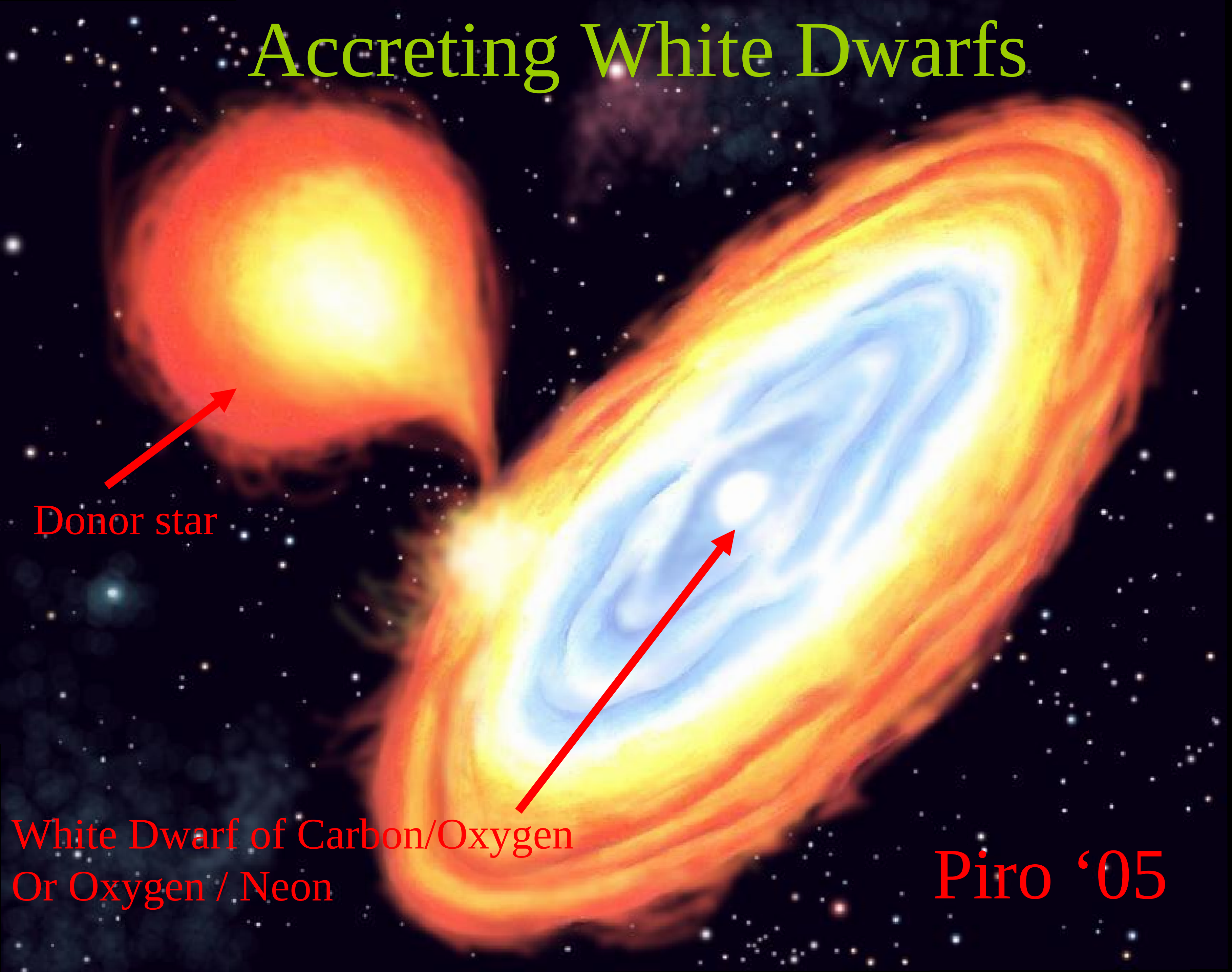


Stars with < 6-8 $M_\odot$ make 0.5-1.0 $M_\odot$ Carbon/Oxygen white dwarfs with radius ~ Earth and central densities $>10^6$ gr/cm^3 that cool with time.




3 of the brightest 8 are binaries

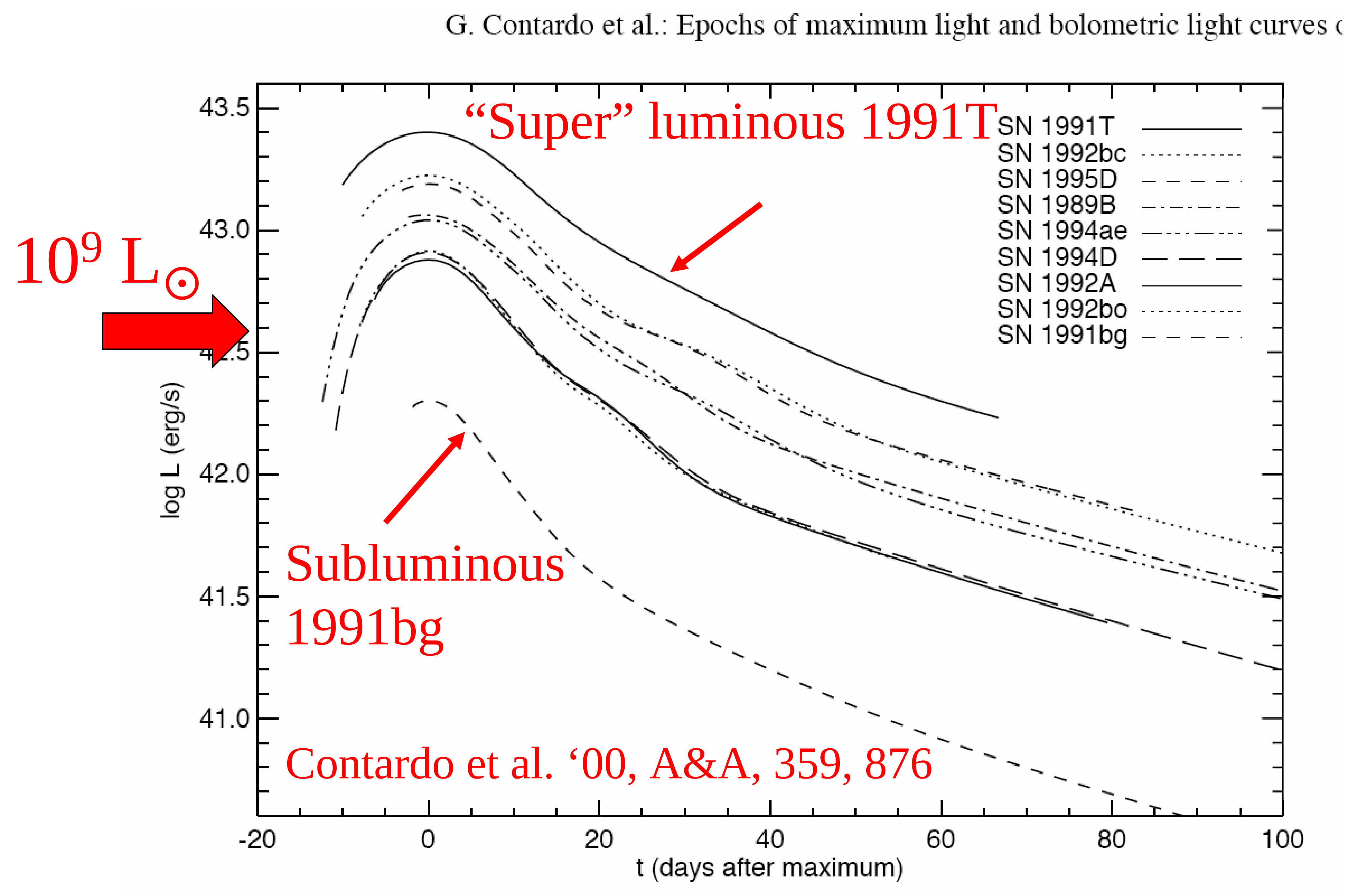
Accreting White Dwarfs



Type Ia Supernovae: Thermonuclear!

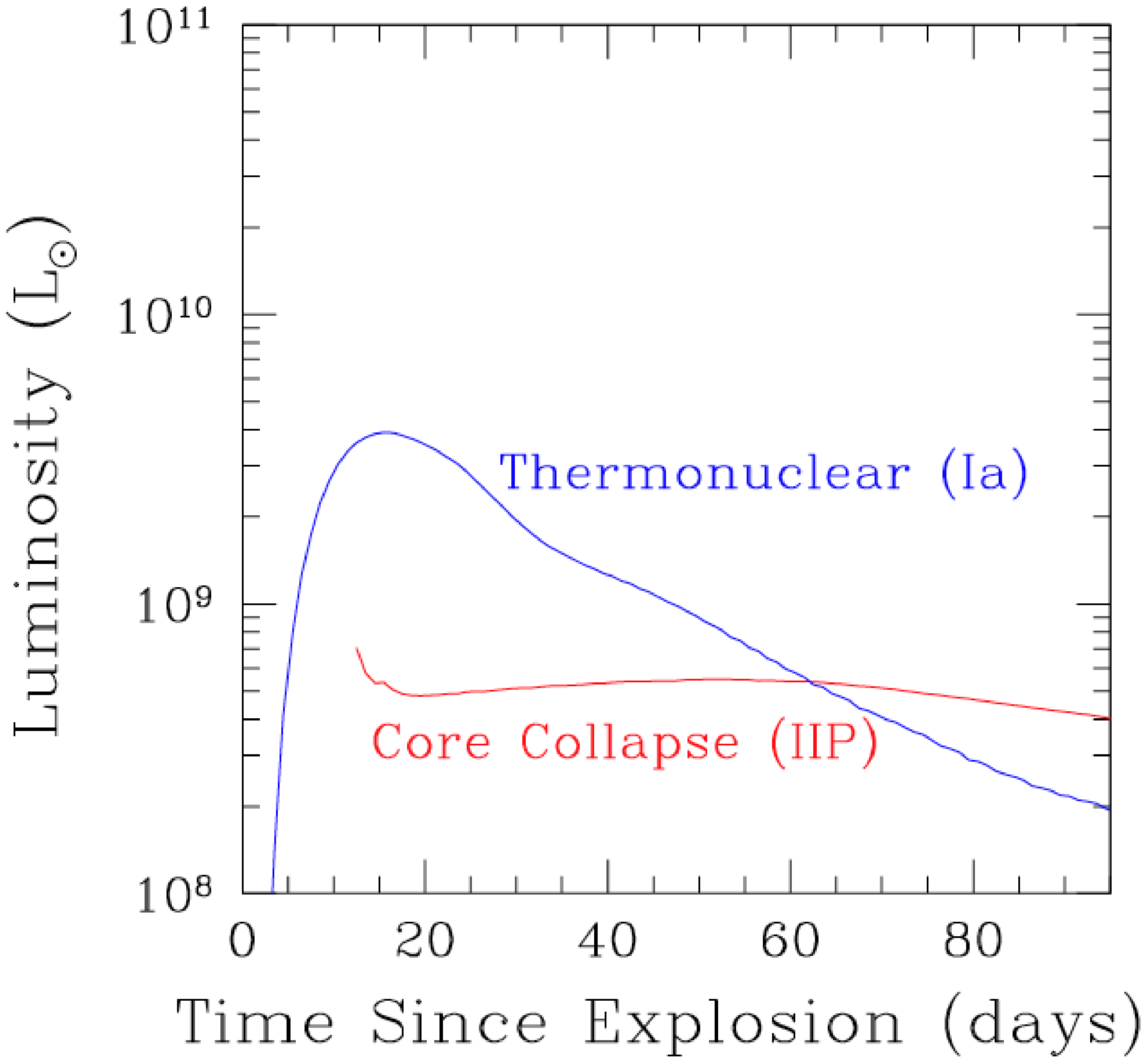
- Runaway carbon fusion is triggered by new material compressing and heating the core, burning much of the material to ^{56}Ni in ~10 seconds
- About 1 in 500 white dwarfs eventually have this fate.
- Over 2/3 of the Iron in your body was made this way!


Bright as a galaxy for a month!
Supernova 1994D



G. Contardo et al.: Epochs of maximum light and bolometric light curves o
"Super" luminous 1991T
10^9 L☉
Subluminous
1991bg
Contardo et al. '00, A&A, 359, 876
SN 1991T
SN 1992bc
SN 1995D
SN 1989B
SN 1994ae
SN 1994D
SN 1992A
SN 1992bo
SN 1991bg
log L (erg/s)
t (days after maximum)
43.5
43.0
42.0
41.5
41.0
-20
0
20
40
60
80
100

Brighter than Core Collapse



Thermonuclear Supernova Lightcurves

Since R_o is smaller than core collapse by 10^5 these would be very faint events, however… the remnant is heated by the radioactive decay: ^{56}Ni (6.1 d) ⇒ ^{56}Co (78 d) ⇒ ^{56}Fe

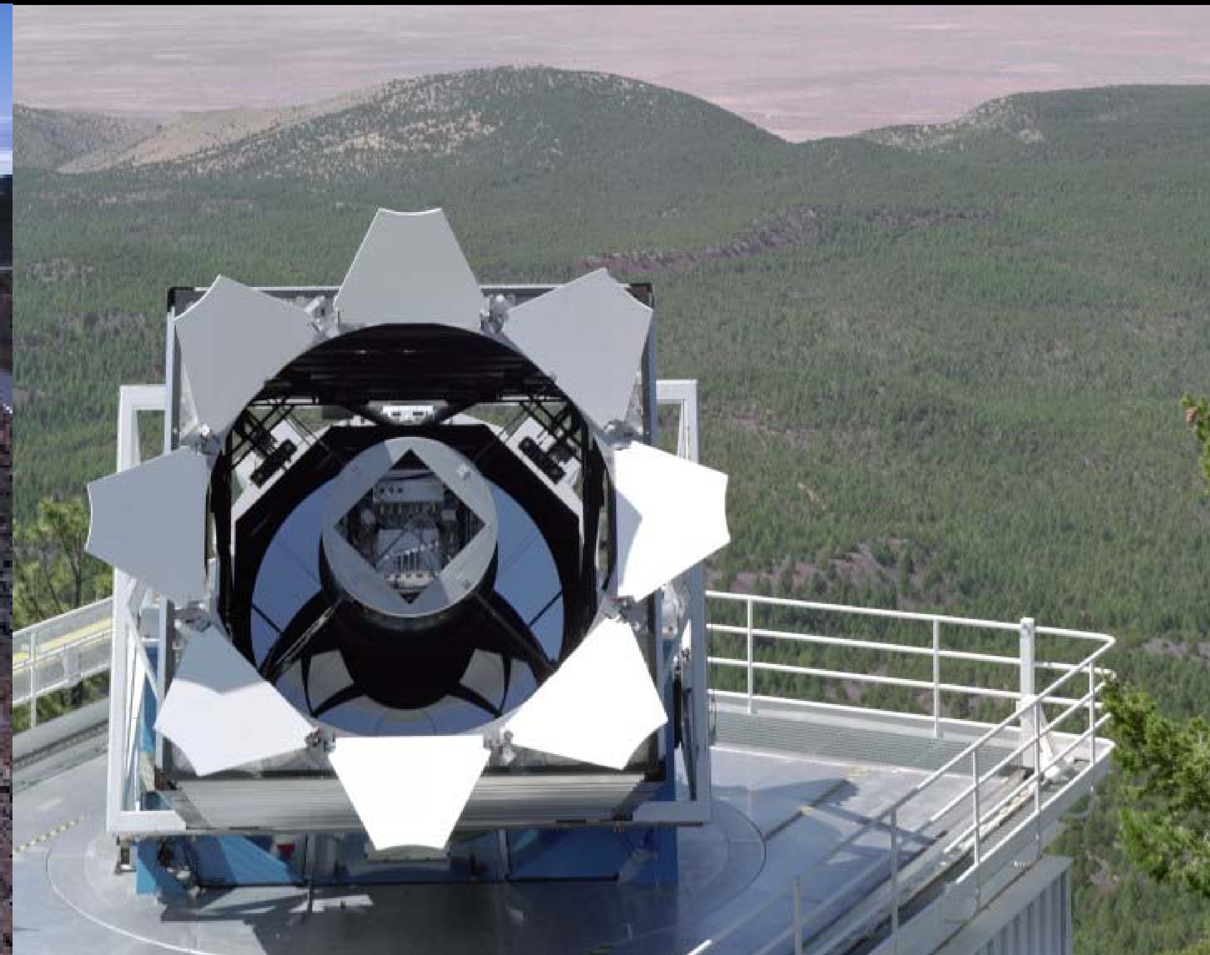
• The peak in the light-curve occurs when the radiation diffusion time through the envelope equals the time since explosion. . .

$$\tau_m = \left(\frac{\kappa M_e}{7cv}\right)^{1/2} \approx 20 \text{ days}$$

• The luminosity after peak is set by the radioactive decay heating rate ⇒ can measure the ^{56}Ni mass via the peak luminosity, yielding 0.10-1.3 $M_\odot$

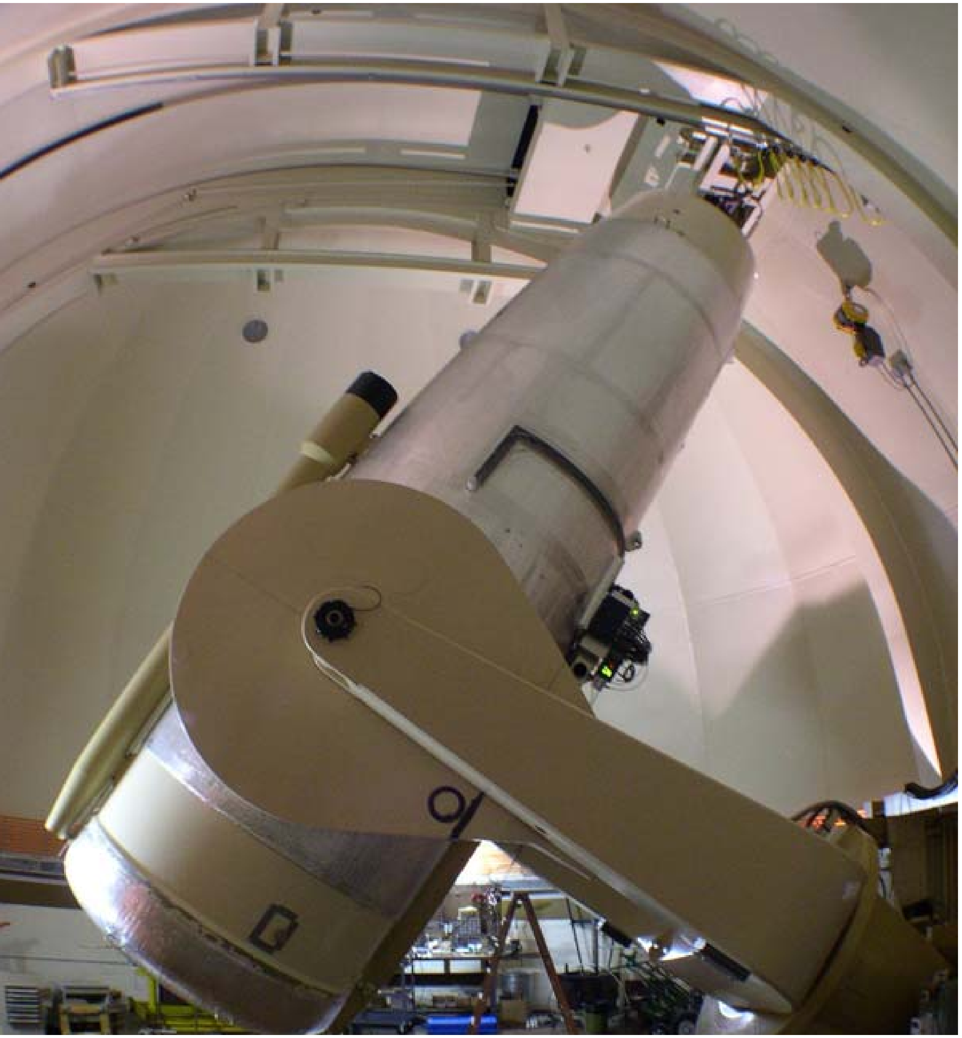
Surveys, Surveys, Surveys!

Pan-Starrs1 (‘10)



Sloan Digital Sky Survey (‘05-’08)

Palomar Transient Factory



- A 100 Mega-pixel CCD camera on the 48 inch Schmidt Telescope at Palomar (near San Diego) that:
  - -- scans 10% of the sky every week
  - -- finds 100’s of transient per year that are tracked by small telescopes

- I am most interested in rare explosions revealed by intense monitoring:
  - - Bright events associated with the rare birth of a highly magnetized neutron star
  - - Faint events from incomplete detonations of stars; fizzles.

The Astrophysical Journal, 668: L99–L102, 2007 October 20

SN 2005ap: A MOST BRILLIANT EXPLOSION

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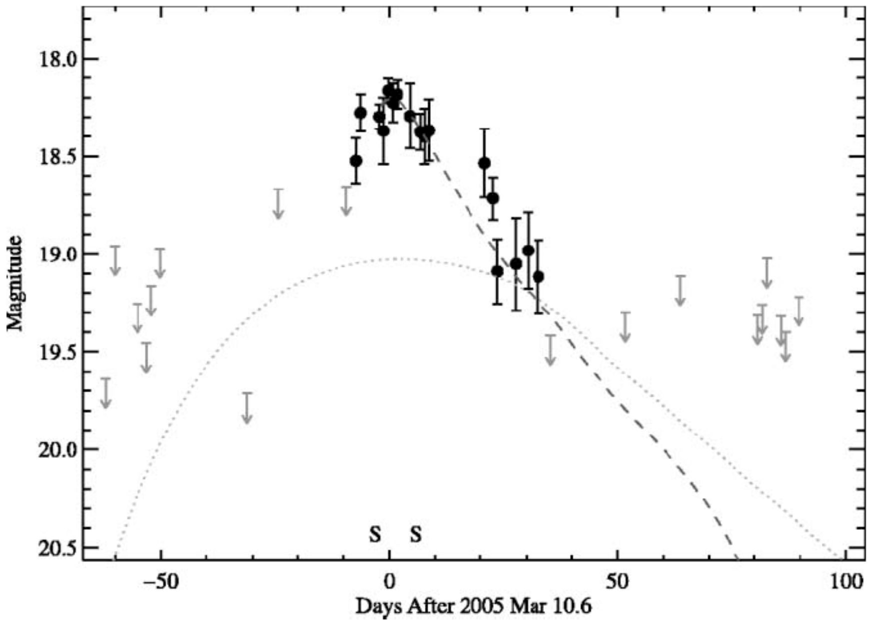
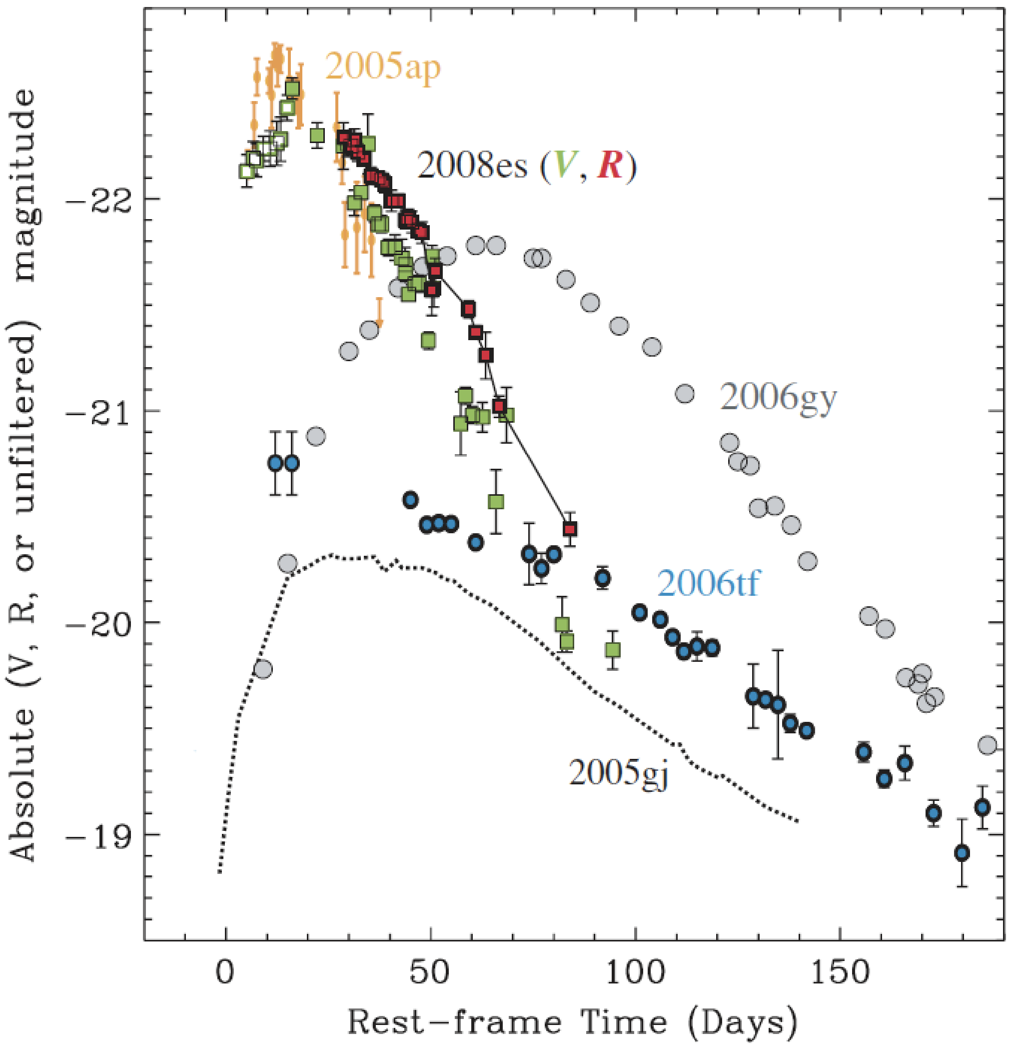
ABSTRACT

We present unfiltered photometric observations with ROTSE-III and optical spectroscopic follow-up with HET and the Keck telescope of the most luminous supernova yet identified, SN 2005ap. The spectra taken about 3 days before and 6 days after maximum light show narrow emission lines (likely originating in the dwarf host) and absorption lines at a redshift of $z = 0.2832$, which puts the peak unfiltered magnitude at -22.7 ± 0.1 absolute. Broad P Cygni features corresponding to Hα, C III, N III, and O III are further detected with a photospheric velocity of ~20,000 km s^{-1}. Unlike other highly luminous supernovae such as 2006gy and 2006tf that show slow photometric evolution, the light curve of SN 2005ap indicates a 1–3 week rise to peak followed by a relatively rapid decay. The spectra also lack the distinct emission peaks from moderately broadened (FWHM ~2000 km s^{-1}) Balmer lines seen in SN 2006gy and SN 2006tf. We briefly discuss the origin of the extraordinary luminosity from a strong interaction as may be expected from a pair instability eruption or a GRB-like engine encased in a H/He envelope.

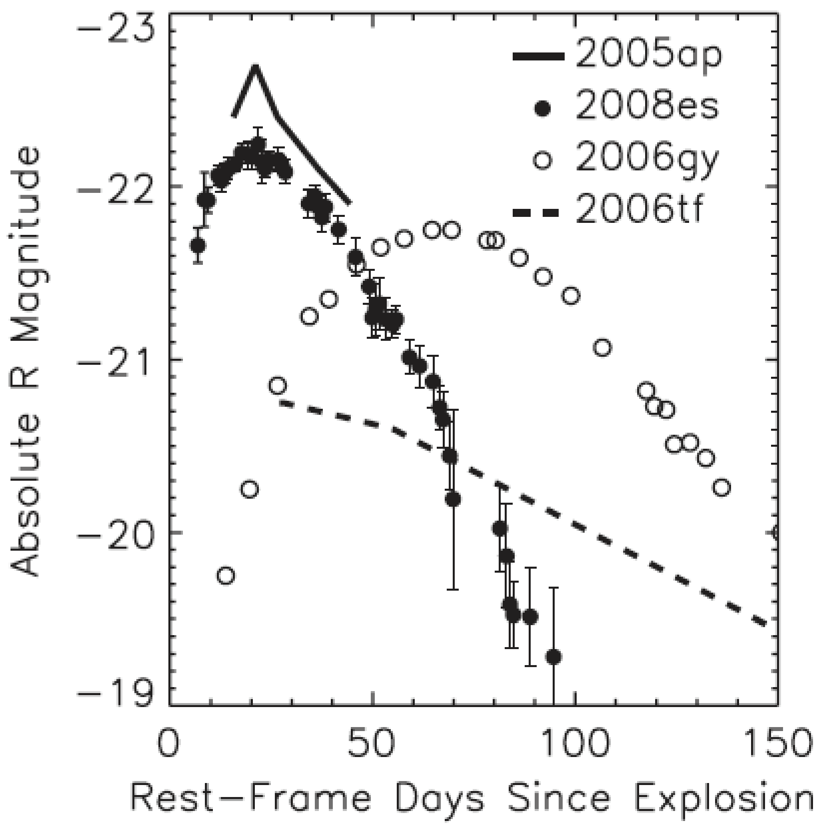


ROTSE (18 inches!)

2008es: L_{peak}=8x10^{10} $L_{\odot}$

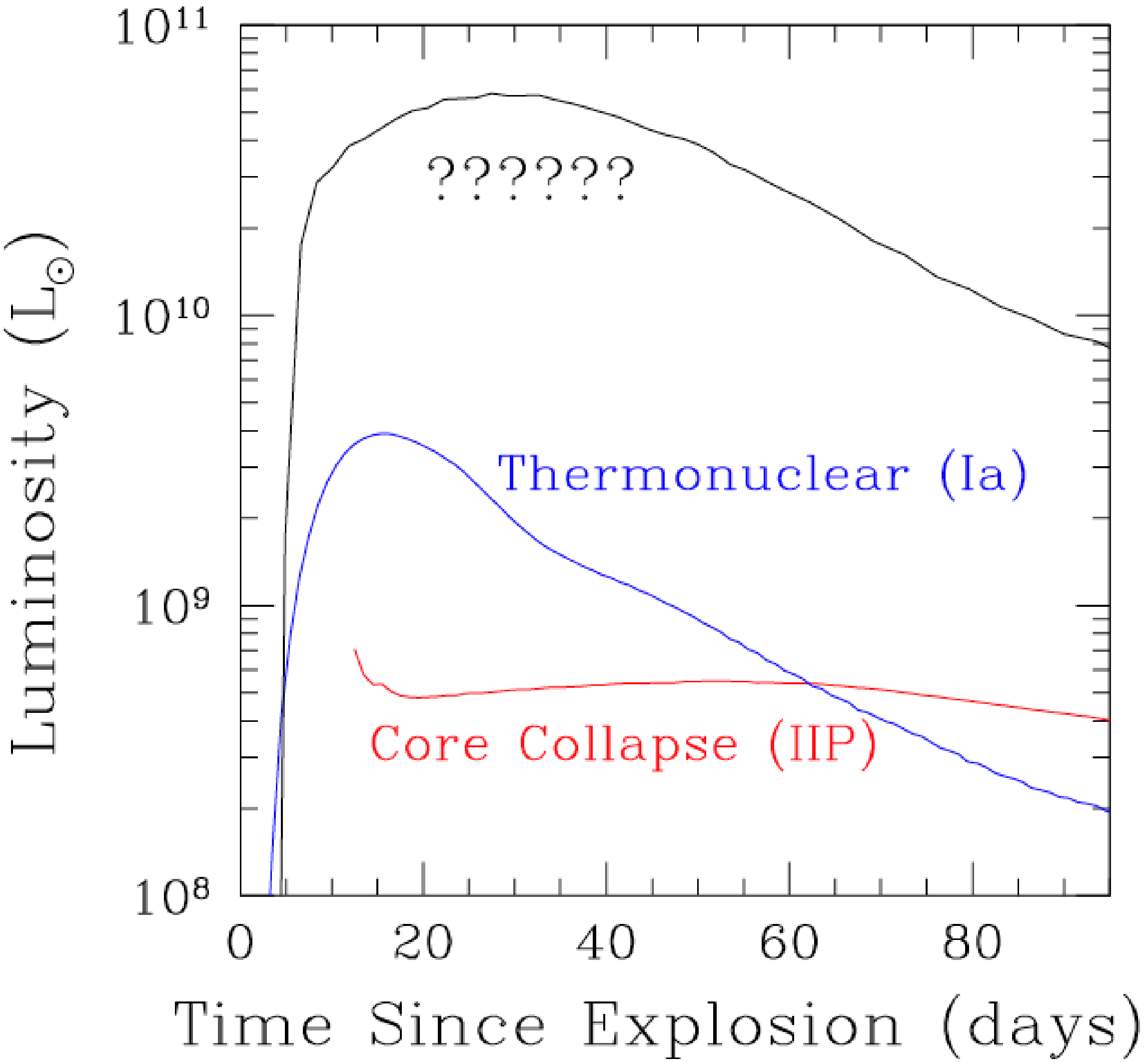


Miller et al. 2009



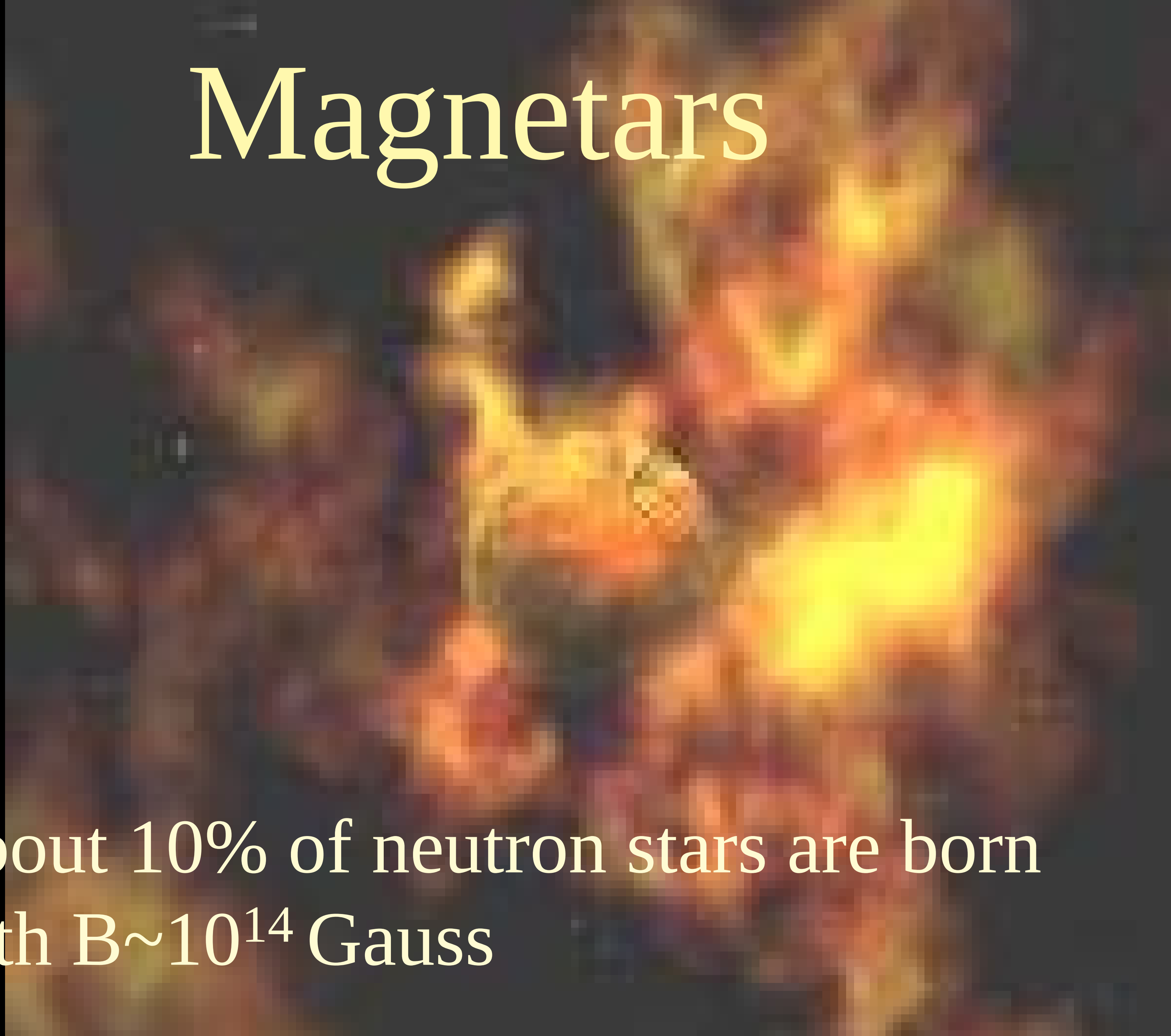
Gezari et al. 2009

Who Ordered This???



- Associated with actively star forming galaxies => massive stars..
- 100 times brighter than typical core collapse supernovae
- Likely < 1% of all core collapse events

Magnetars



About 10% of neutron stars are born with B~10^{14} Gauss

Births of Magnetars!

- If magnetars are born spinning at P=2-20 ms, then spin-down and deposition of the rotational energy will occur in days-months-years

- To substantially impact the lightcurve, want this to occur before diffusion occurs, requiring a magnetic field $>10^{14}$ Gauss (Kasen & L.B. ‘10; Woosley ’10) !!

Resetting the Internal Energy

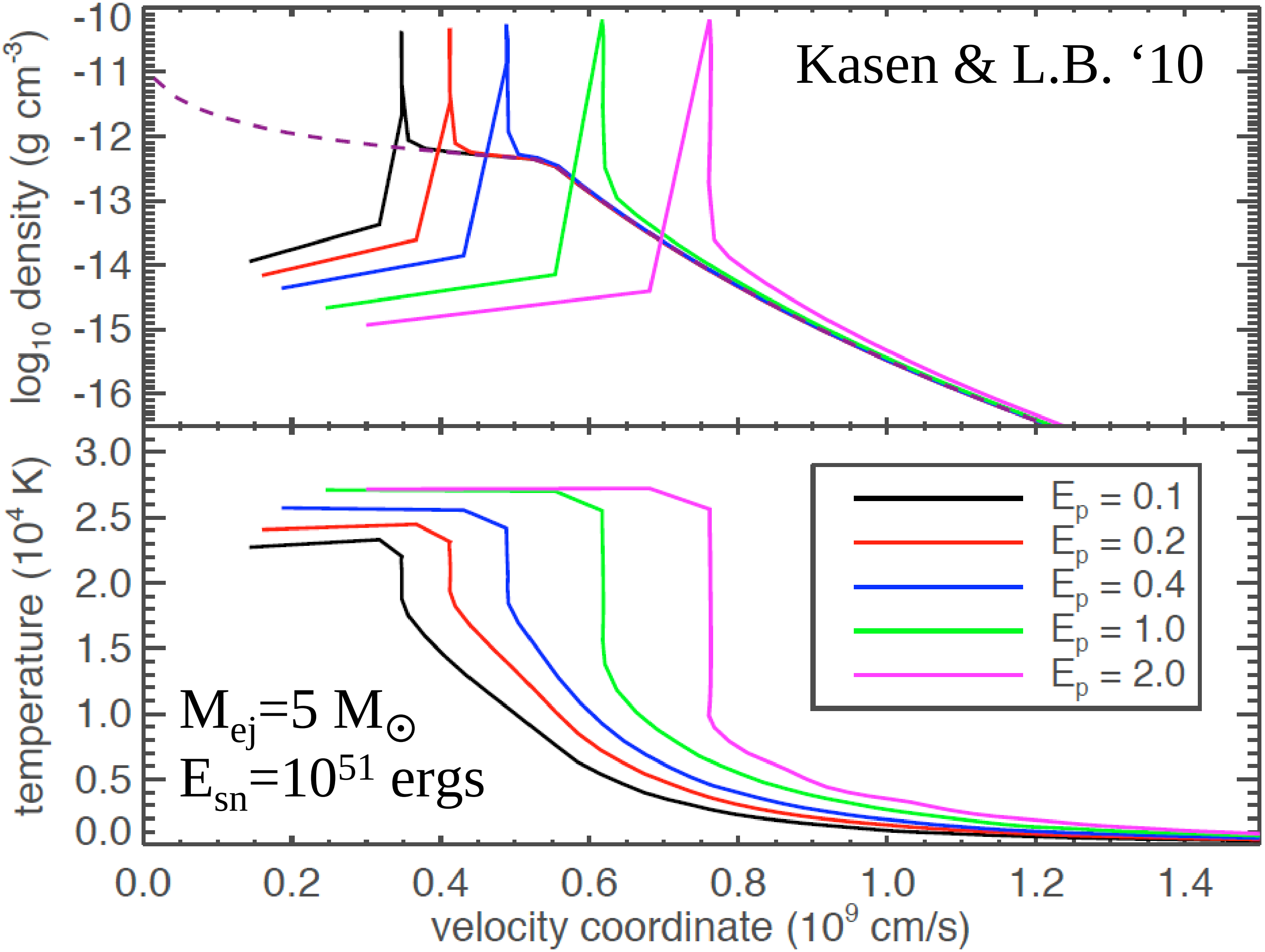
- The deposition of the NSs rotational energy resets the internal energy of the expanding envelope

$$L \sim \frac{E_{\rm sn} c R_o}{\kappa M} \rightarrow \frac{E_p c (v t_p)}{\kappa M}$$

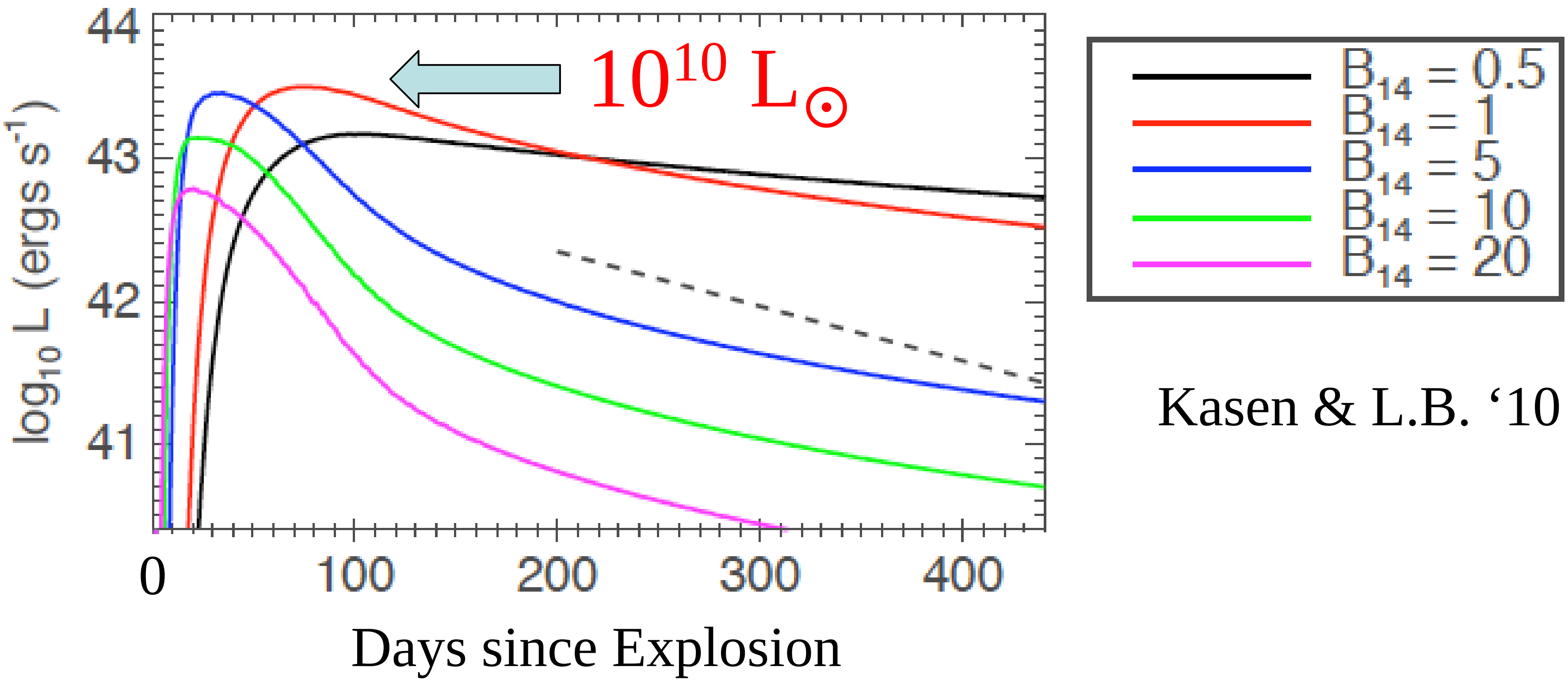
- As long as $E_p > E_{sn}(R_o/vt_p)$, the energy is reset, so can brighten the supernovae even when $E_p < E_{sn}$
- Can 'naturally' reach the high observed luminosities of a few $10^{10}\, L_\odot$

Hot Bubble Formation at One Month

Magnetar spin-down time = 1 day



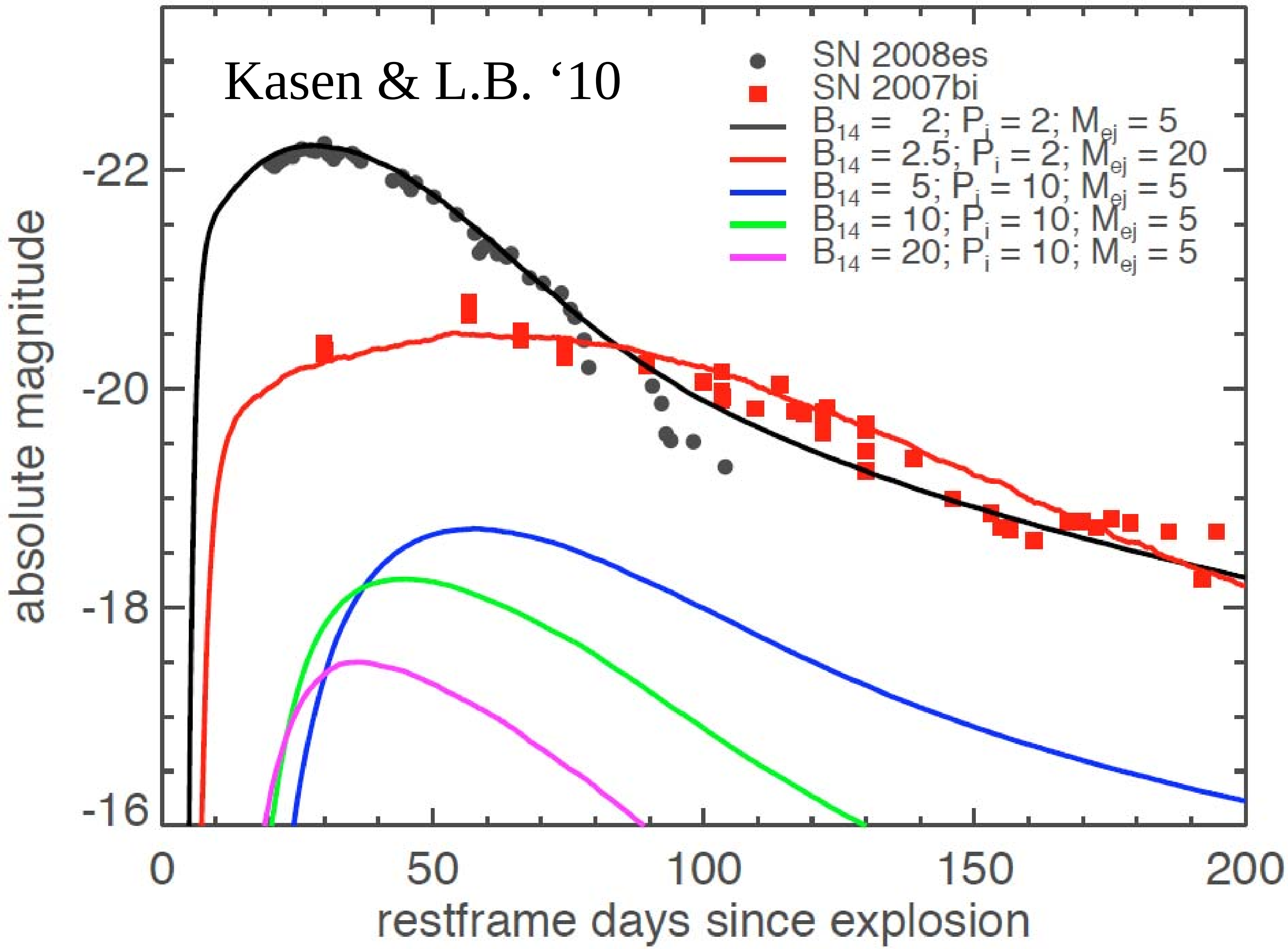
It Really Works!



Kasen & L.B. '10

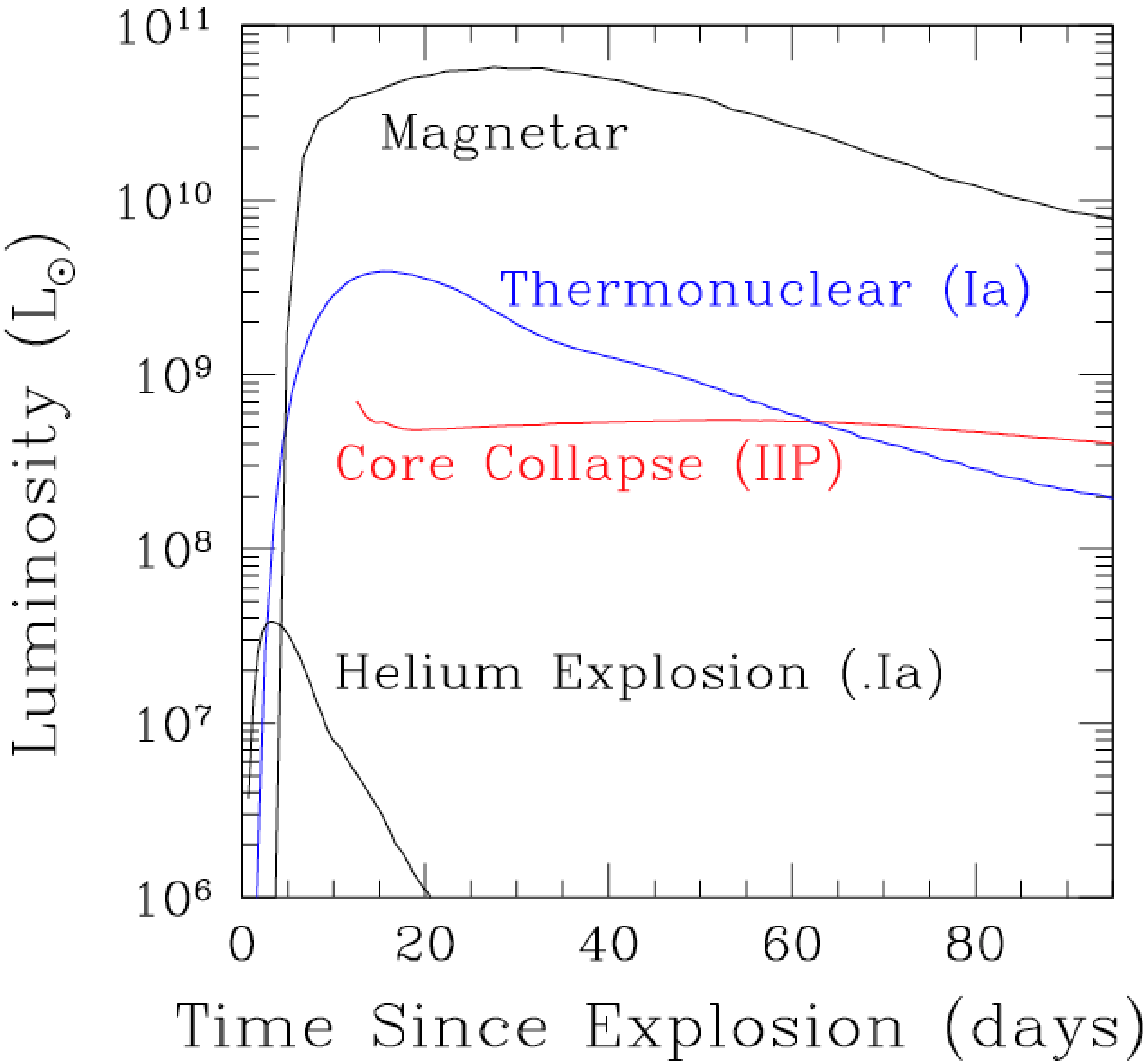
- M_{ej}=5 $M_\odot$, E_{sn}=10^{51} erg, P_i=5 ms
- Dashed line is 1 $M_\odot$ of ^{56}Ni

Radiation Hydrodynamics Examples



.Ia Supernovae

L. B., Shen, Weinberg & Nelemans '07
Shen et al '10



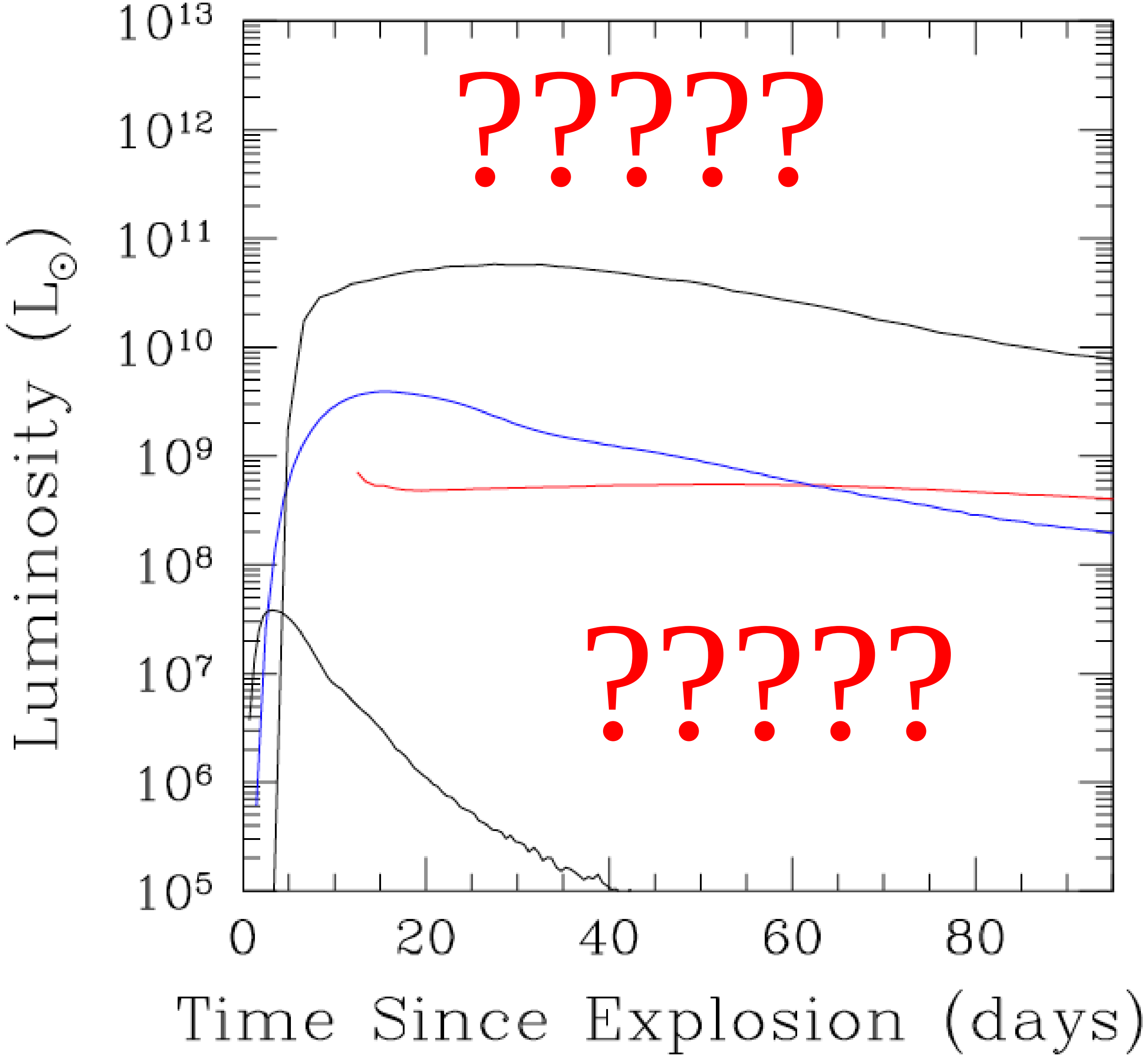
- The He shell leaves the the WD at 10,000 km/sec, leading to brief events

$$\tau_m = \left(\frac{\kappa M_e}{7cv}\right)^{1/2} \approx 3-5\ \mathrm{d}$$

- The radioactive decays of the freshly synthesized ^{48}Cr (21 hr), ^{52}Fe (8.3 hr) and ^{56}Ni (6.1 d) will provide power on this short timescale!!

- In 2007, no observed events looked like this!

What's Next????


?????
?????
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
Luminosity ($L_\odot$)
0
20
40
60
80
Time Since Explosion (days)