Astier et al (2006)

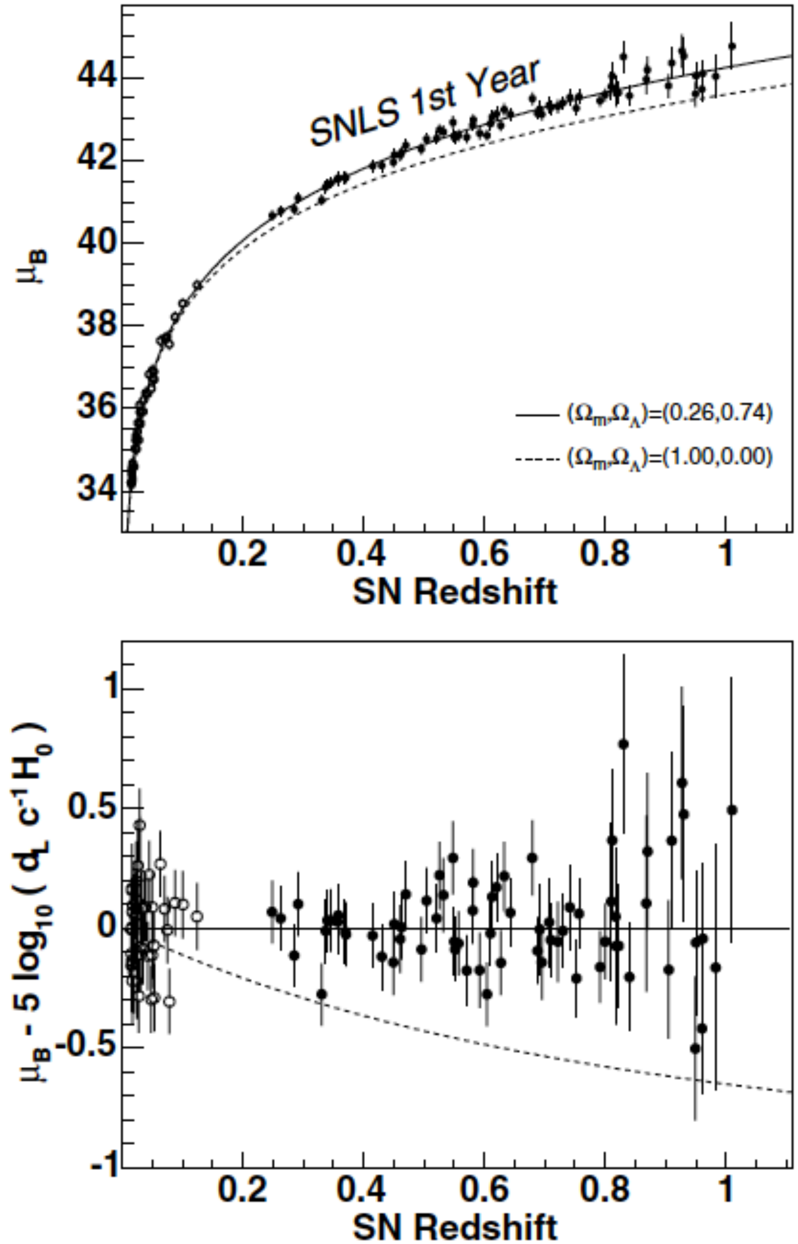


Fig. 4. Hubble diagram of SNLS and nearby SNe Ia, with various cosmologies superimposed. The bottom plot shows the residuals for the best fit to a flat Λ cosmology.

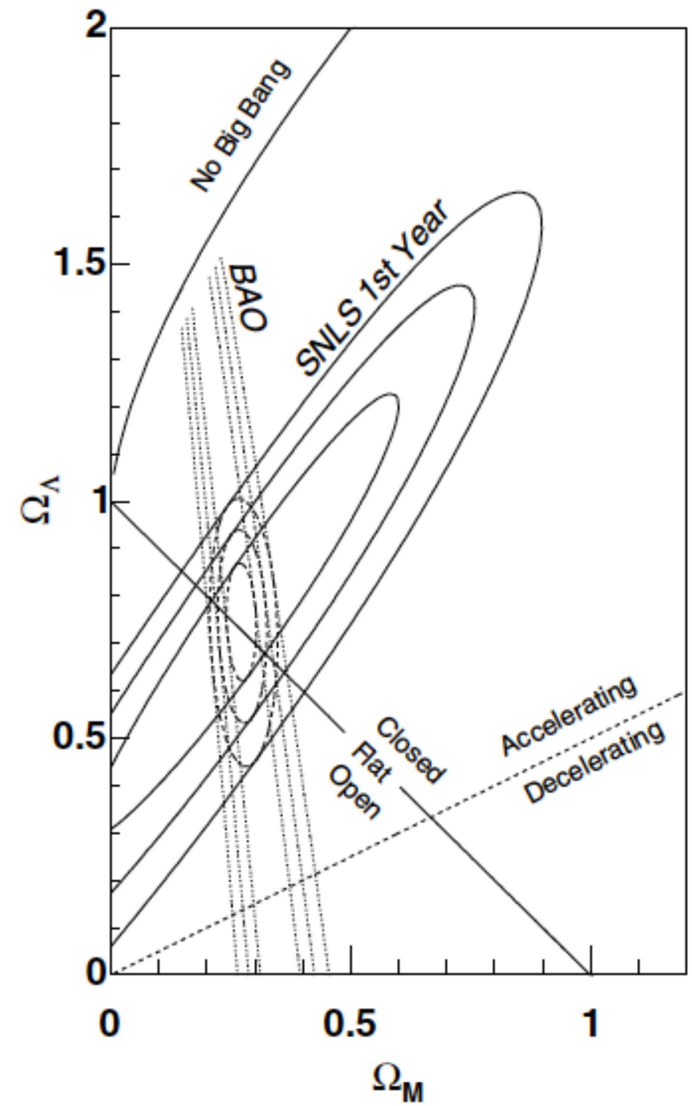


Fig. 5. Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to an $(\Omega_M, \Omega_\Lambda)$ cosmology from the SNLS Hubble diagram (solid contours), the SDSS baryon acoustic oscillations (Eisenstein et al. 2005, dotted lines), and the joint confidence contours (dashed lines).

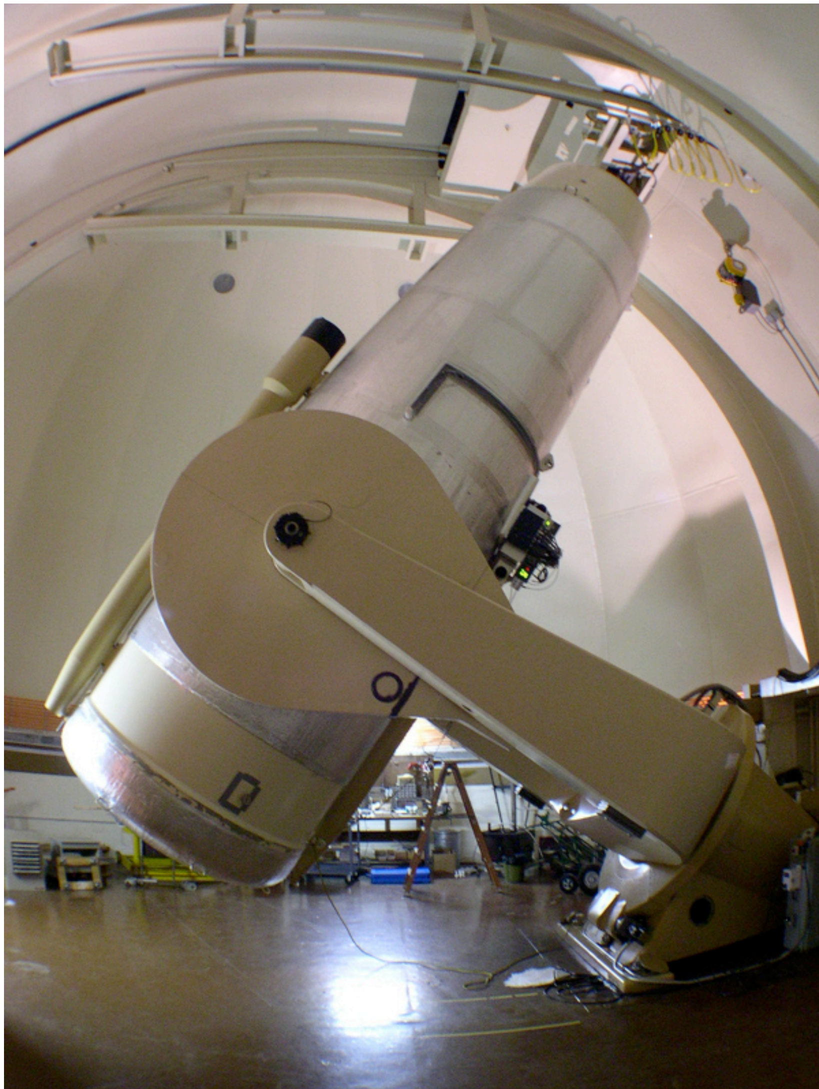
White Dwarf Explosions

- We already showed that the nuclear energy exceeds the gravitational binding energy…
- So, if all the nuclear energy release goes into kinetic energy, how fast is the material moving?

Surveys, Surveys, Surveys!

Completed survey (V=22.5, 260 deg^2)

Medium deep survey (V=24, 50 deg^2)

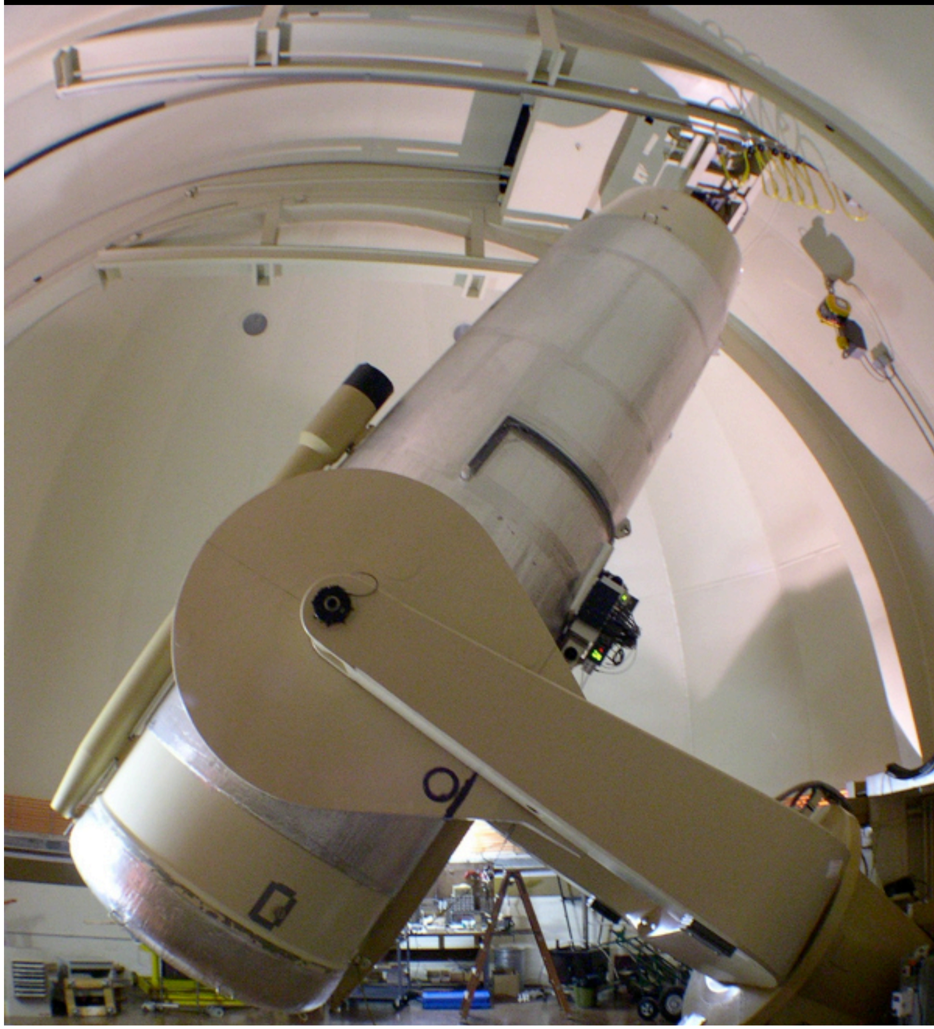


ROTSE (V=18, 200 deg^2)

SkyMapper ('10; V=19, 1000 deg^2 every 3-4 d)

Palomar Transient Factory ('09; R=21, 3000 deg^2, 5d)

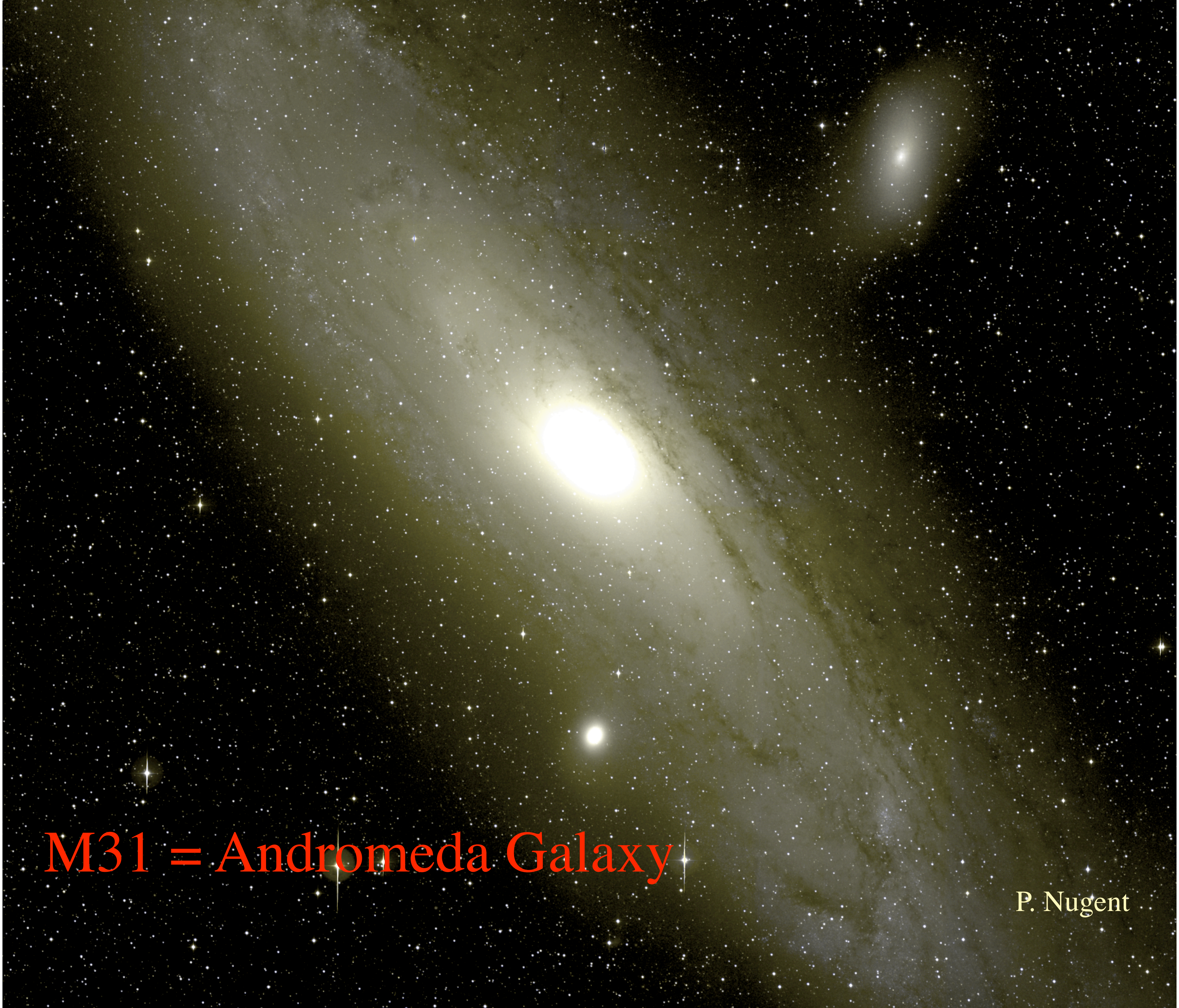
Palomar Transient Factory



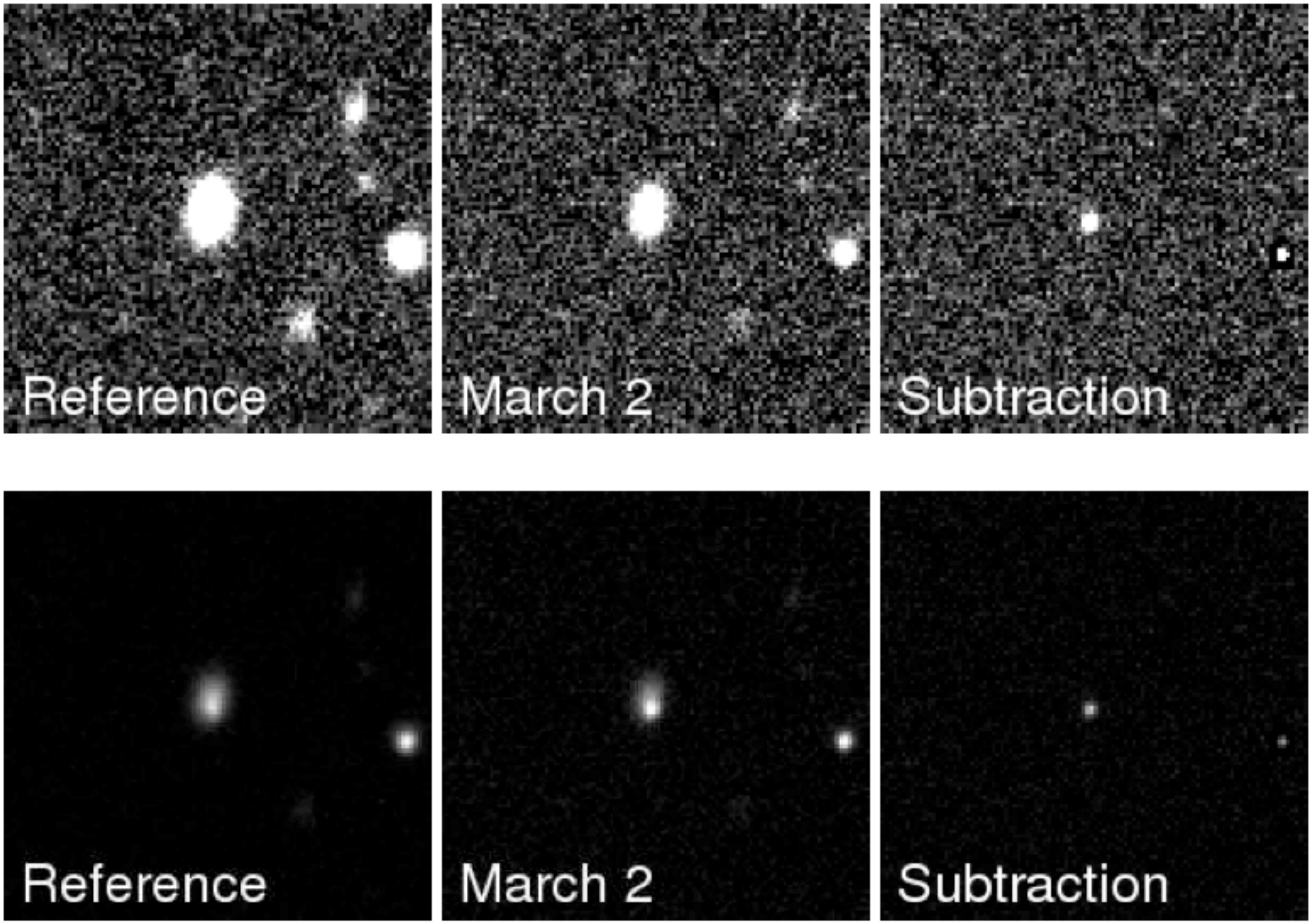
- A 100 Mega-Pixel CCD camera (CFH12K from CFHT) on the 48 inch Schmidt Telescope at Palomar (near San Diego)

- We now scan 10% of the sky every 5 nights, finding a supernova every 10 minutes.

- We find ~1000 supernovae per year that are tracked by a network of telescopes for photometry and spectroscopy… typing..

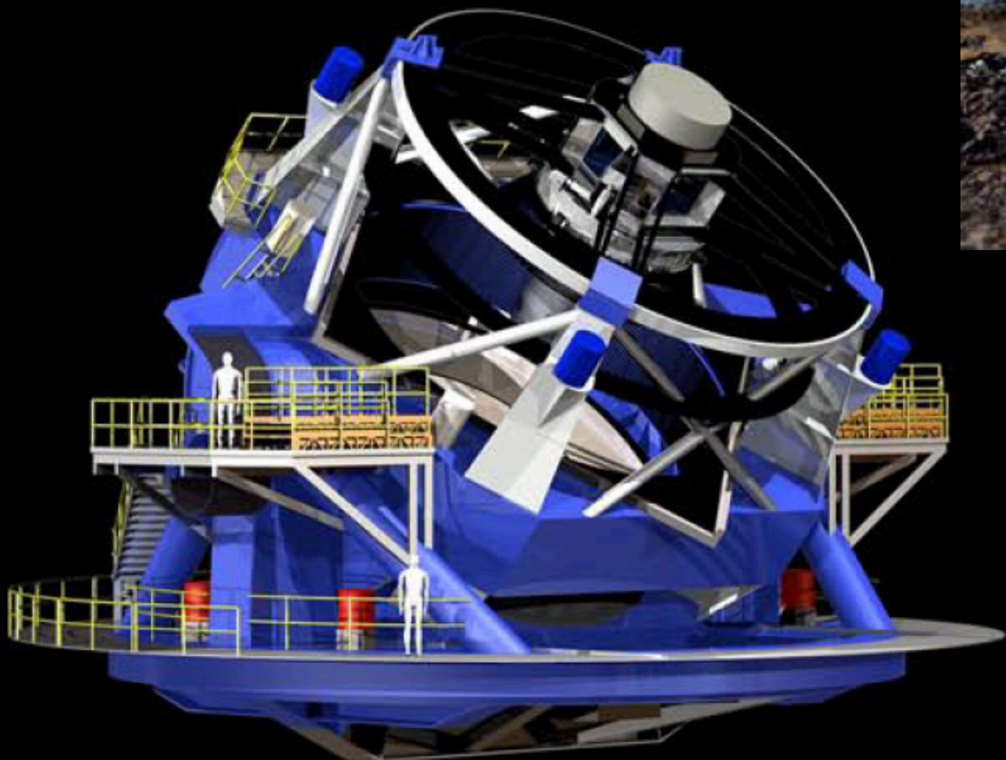

M31 = Andromeda Galaxy
P. Nugent

SN2009av – The First PTF Transient Discovery

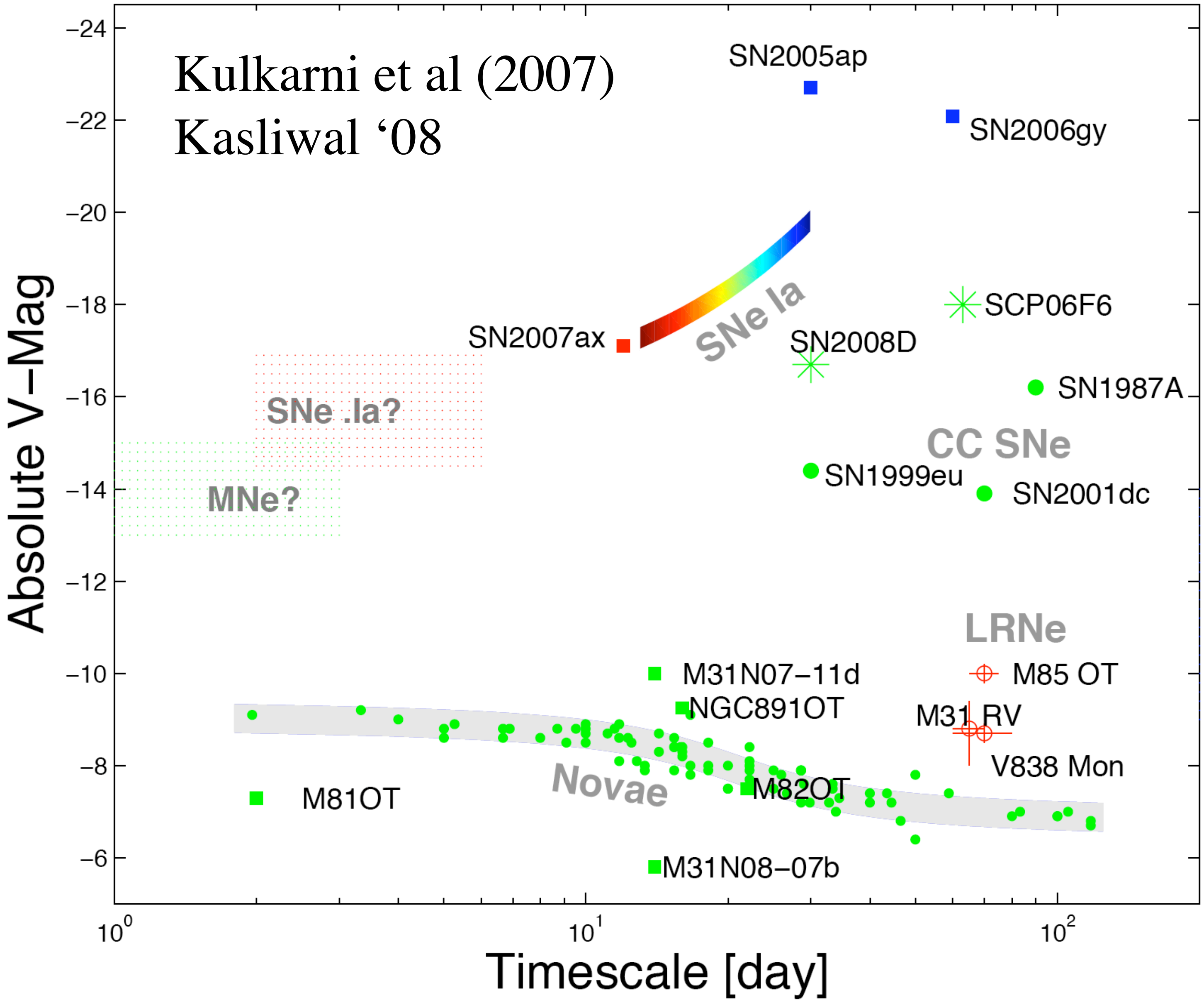


A type Ia supernova caught 8 days before maximum light in a redshift z=0.055 host galaxy

Large Synoptic Survey Telescope (LSST) is a proposed 8.4-meter, 10 deg^2 telescope that will provide V=24 imaging across the entire visible sky over a few nights.



Supernovae and Transients



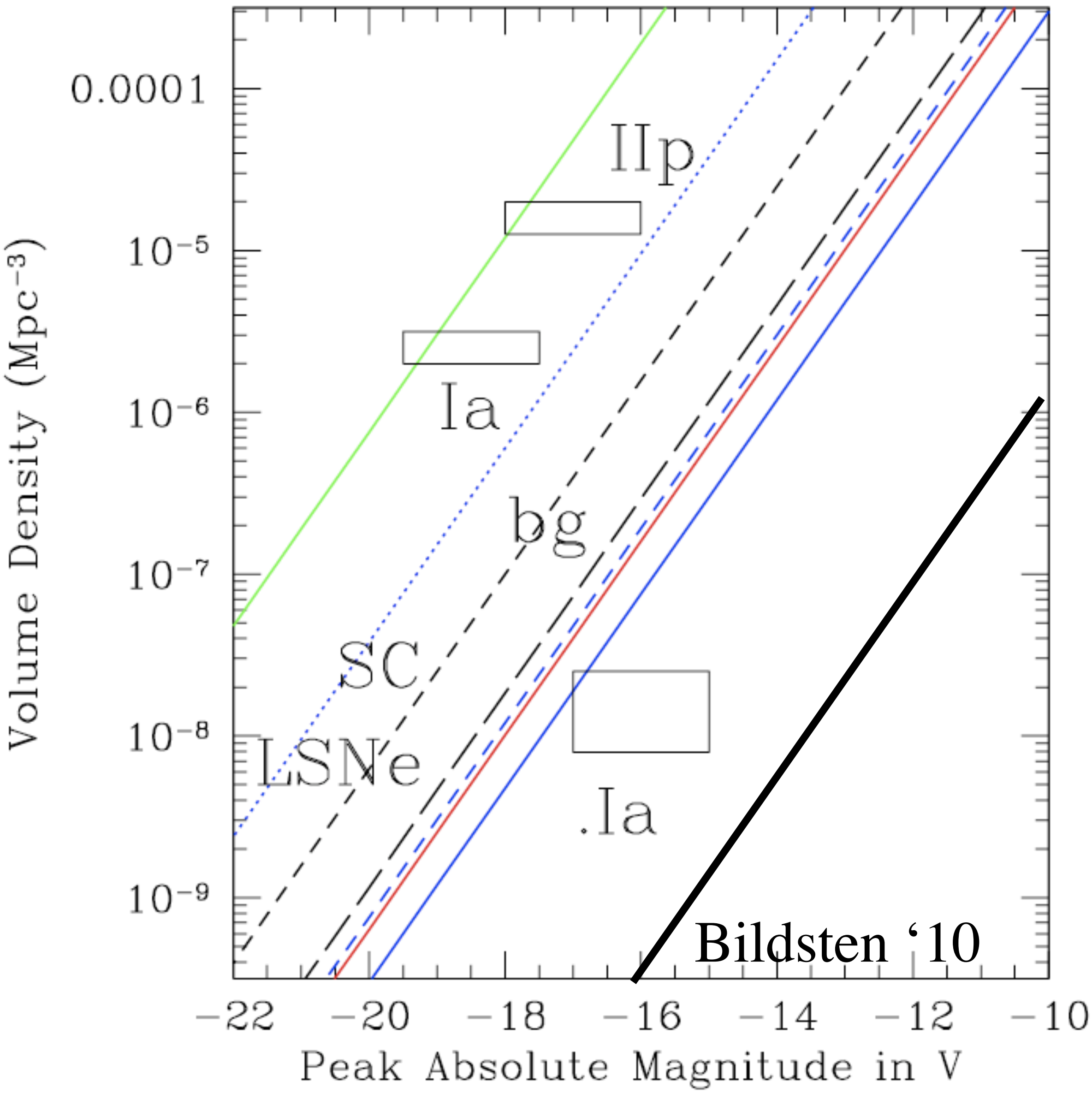
Three Metrics for Surveys

- Fraction of the sky that is ‘monitored’
  - All sky is 40,000 deg^2, but, of course, not all of the sky is available every night..
- “Depth” of survey.
  - One magnitude is a factor of 2 in brightness, $2^{1/2}$ in distance, $2^{3/2}$ in volume.
- Cadence (frequency of looks) helps to find and followup on ‘fast’ trending objects, but many last longer than the cadence and are not missed!

Rough Survey Parameters

Survey	SNLS	SDSS	TSS	SKY	PTF	PS1	DE S	LSST
Depth	24.3	22.5	18	19	20.5 R	24	25R	24
Omega	4	260	200	1000	2700	50	15	30000
Cad (d)	3	2	1	3-4	5	4	5	3-4
Year	03-08	05-08	now	10-?	now	now	11-	?
z at -18	0.7	0.3	0.04	0.06	0.15	0.6	0.6	0.6

Survey Volumes and Expectations



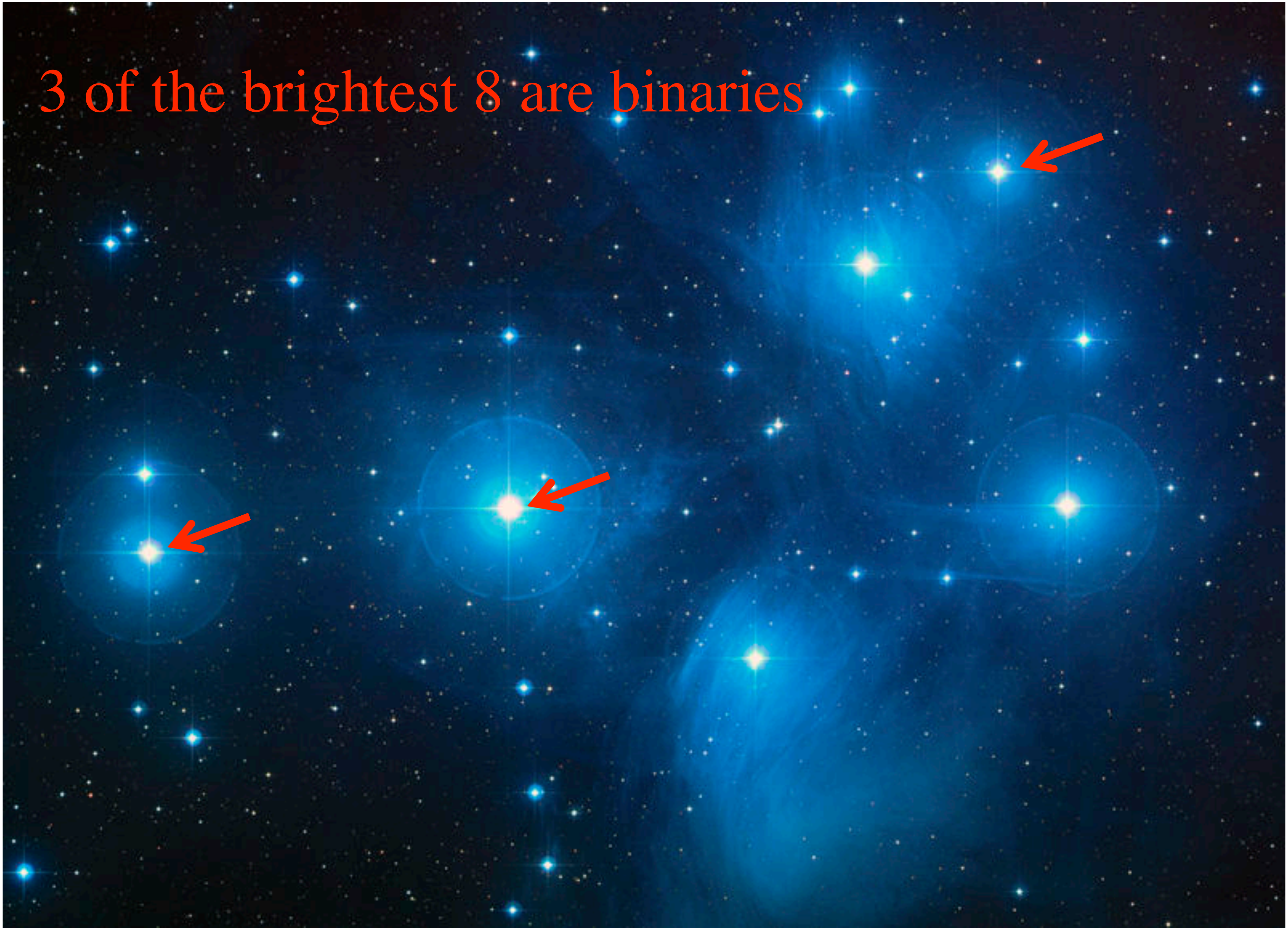
- The boxes plot the volume rate * duration for Type Ia (30 d), Type IIp (100 d) and .Ia (5 d)
- Densities rough for LSNe, 'Super-Chandra' and Faint Ia (bg)
- Lines show the 1 event per "exposure" line for
  - ROTSE (green)
  - SKYM (blue-dotted)
  - SNLS (dashed)
  - SDSS (long-dashed)
  - PS1 (blue-dashed)
  - PTF (blue-solid)
  - DES (red)
  - LSST (heavy-black)

What to do with 1000 Supernovae??

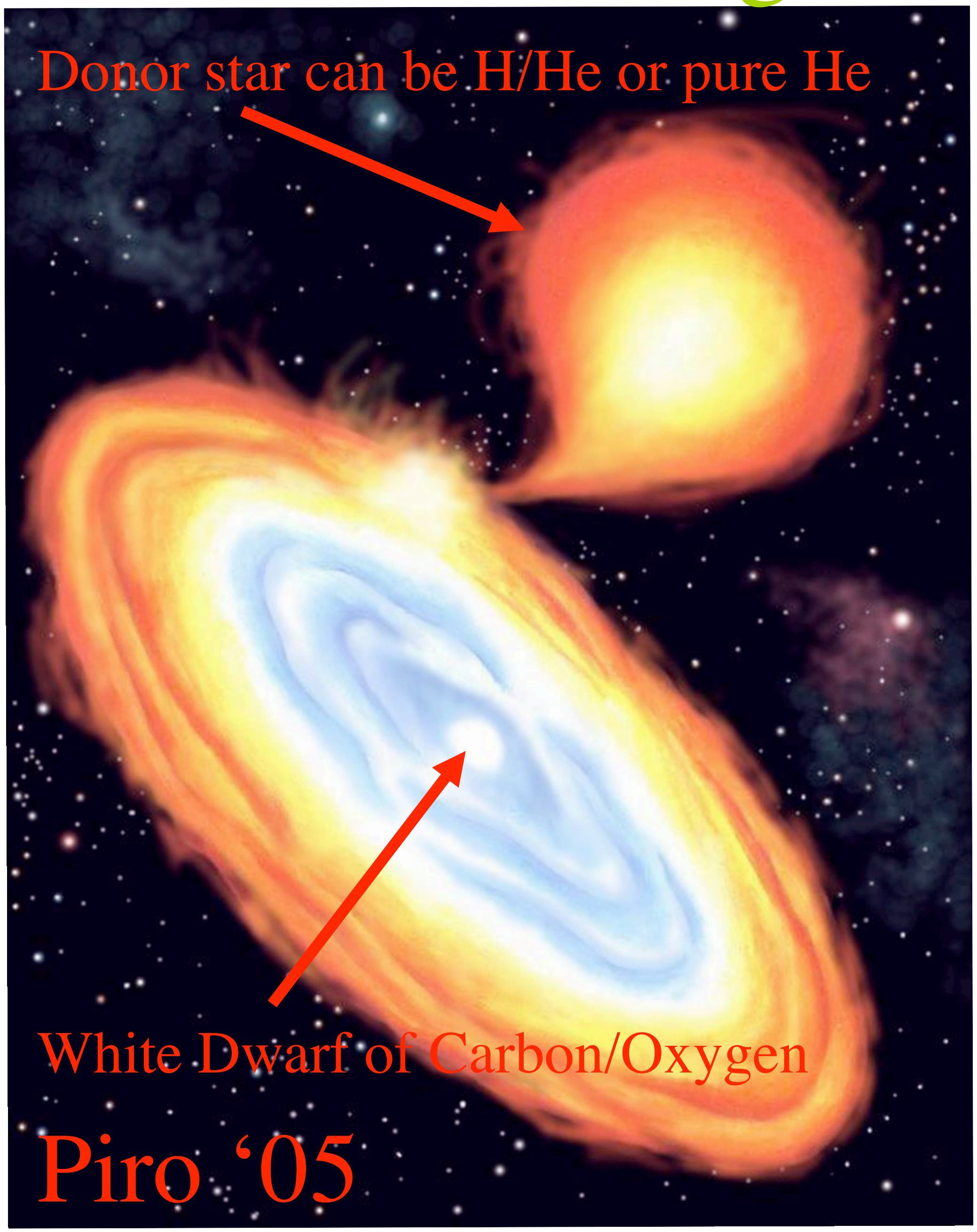
- Value of luminosity functions for all Sne
    - Nickel mass and total mass distributions for Ia
    - Energies and ejected masses for IIp
    - Faint and Bright Fractions of each/every class
- Probe the Physics of rise times
- Find a few VERY NEARBY events.
- Rates as a function of each galaxy type (delay time distributions)
- Find a FEW of the new ‘odd’ ones.. Something I will emphasize in the next two lectures

HW Problem

- Imagine a cloud of uniform density contracting by a factor of 1000 in radius. If it is slowly rotating initially at Omega, how fast will it rotate after contraction?
- What’s the fastest rotation possible for an object of mass M and radius R?


3 of the brightest 8 are binaries

Accreting White Dwarfs



<1% of white dwarfs are in binaries where accretion occurs, releasing gravitational energy

$$\frac{GM}{R} \approx 100 - 300 \ \frac{\mathrm{keV}}{\mathrm{nucleon}}$$

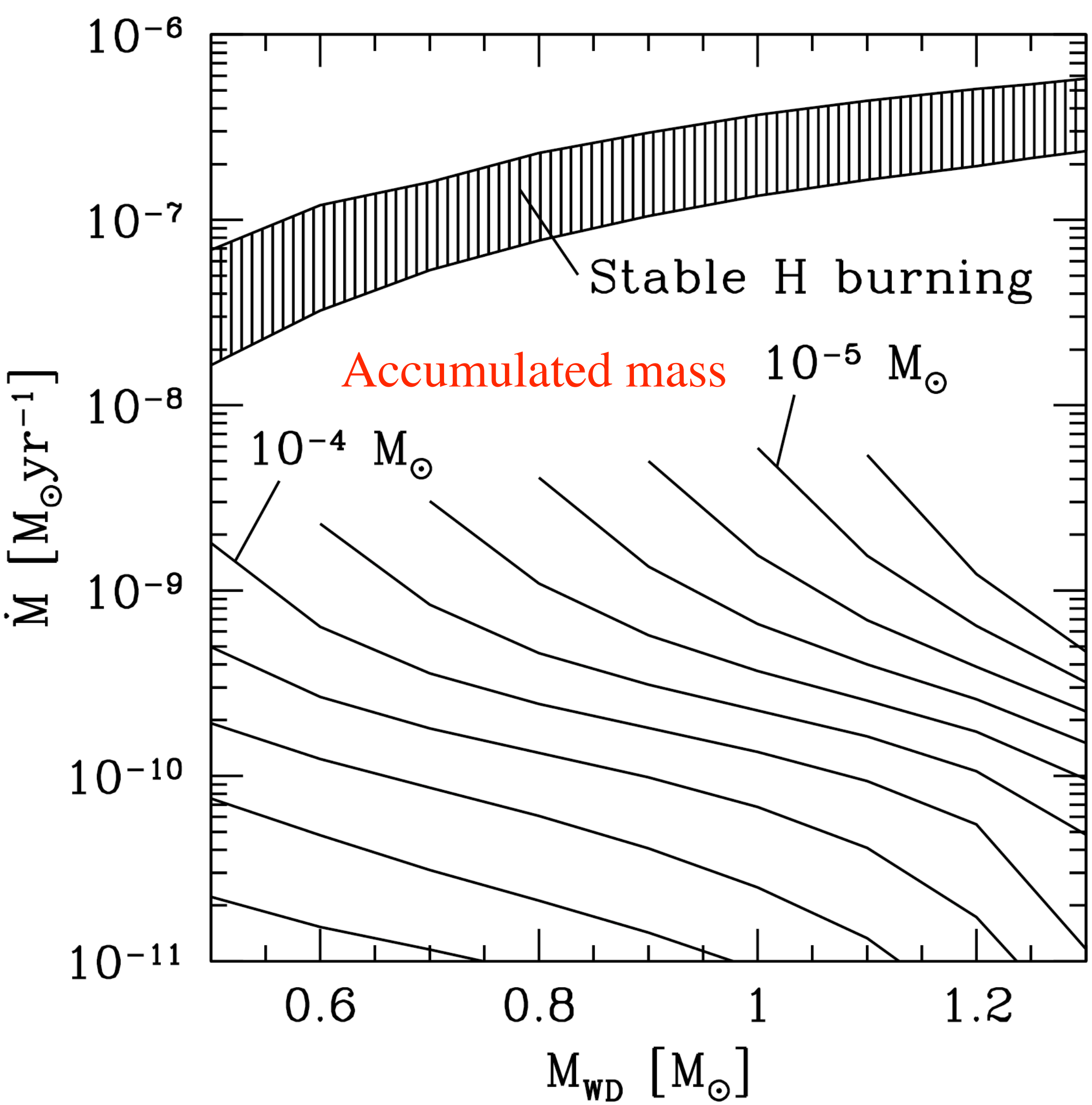
Whereas nuclear fusion of H→He or He→C releases

$$1 - 5 \frac{\mathrm{MeV}}{\mathrm{nucleon}}$$

This contrast is further enhanced when the white dwarf stores fuel for > 1000 years and burns it rapidly, making these binaries detectable in distant galaxies during thermonuclear events.

Hydrogen Burning is Usually Unstable

Townsley & Bildsten 2005



Supersoft Sources: Burn H Stably (van den Heuvel et al 1992), or weakly unstable. Accretion phase ~100 Myrs

Cataclysmic Variables: unstable burning leads to Classical Novae. Whether the mass stays or goes is uncertain, but WDs are not massive enough!

Some numbers:

M87 in Virgo

Two WDs are made per year in a 10^{11} $M_\odot$ elliptical galaxy. The observed rates for thermonuclear events are:

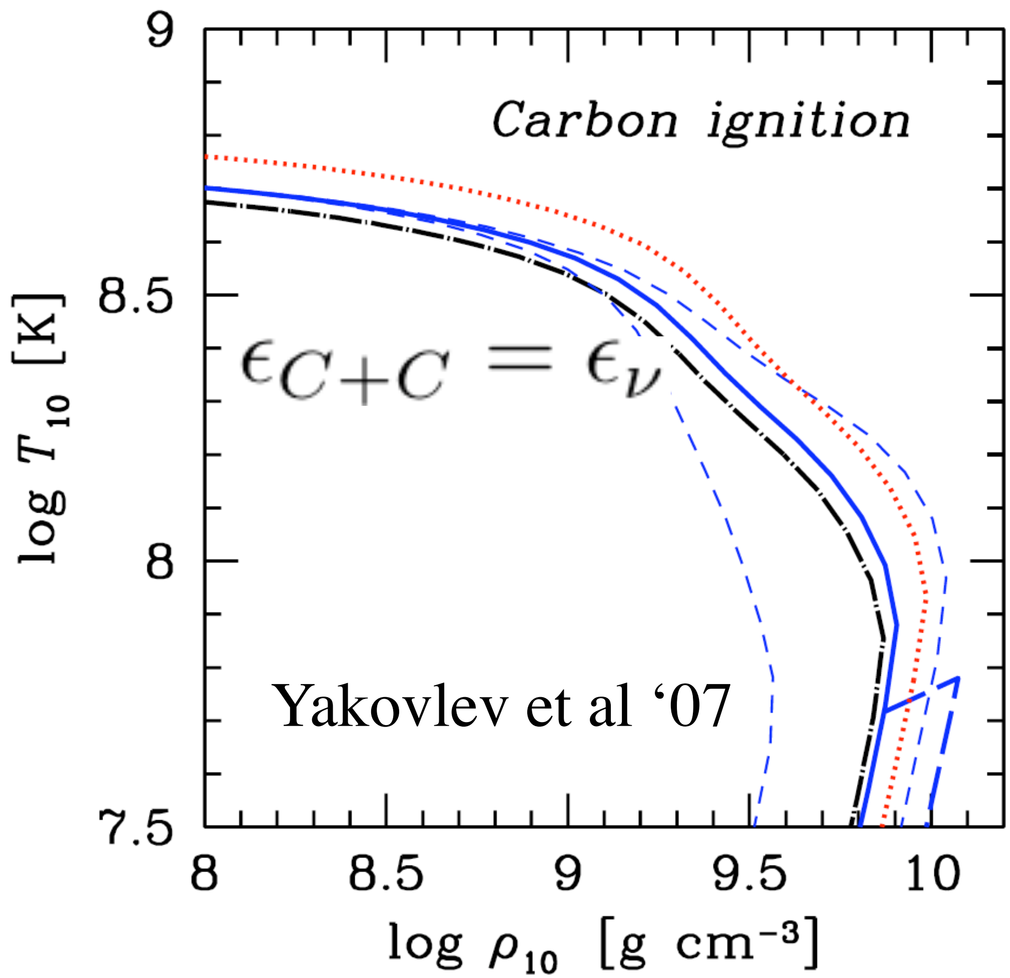
- 20 Classical Novae (Hydrogen fuel) per year, implying a white dwarf/main sequence contact binary birthrate (Townsley & LB 2005) of one every 400 years.
- One Type Ia Supernovae every 250 years, or one in 500 WDs explode!

Predicted rates are:

Helium novae (Eddington-limited) every ~250 years, one large He explosion every ~5,000 years, and WD-WD mergers every 200 years

Carbon Ignition

If cold (T<3x10^8 K or so), then ignition is from high densities.. which only occur for massive white dwarfs, requiring accretion!



$$C_P \frac{dT}{dt} = \epsilon_{C+C} - \epsilon_\nu$$

$$\rho_c = 3\times 10^8 \mathrm{g\ cm}^{-3} \rightarrow M = 1.25 M_\odot$$
$$\rho_c = 10^9 \mathrm{g\ cm}^{-3} \rightarrow M = 1.33 M_\odot$$
$$\rho_c = 2\times 10^9 \mathrm{g\ cm}^{-3} \rightarrow M = 1.36 M_\odot$$
$$\rho_c = 3\times 10^9 \mathrm{g\ cm}^{-3} \rightarrow M = 1.37 M_\odot$$

FIG. 5: (color online) Carbon ignition curves in ^{12}C^{16}O matter. The dot-and-dashed line is the optimal model for carbon

Heat Transport in the White Dwarf Core

Townsley & LB 2004

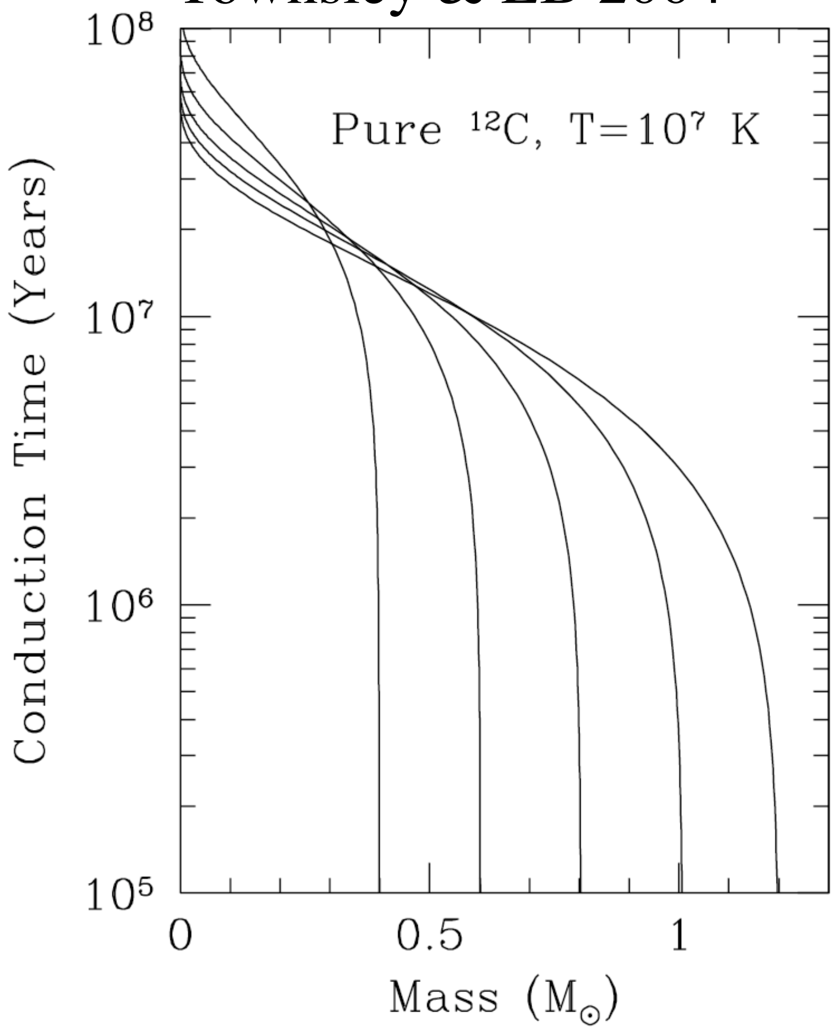


FIG. 11.—Thermal conduction time (t_{cond} in eq. [A2]) from the exterior of a pure carbon WD to an interior mass point. The curves are for isothermal WDs ($T = 10^7$ K) with masses $M = 0.4, 0.6, 0.8, 1.0$, and $1.2\ M_\odot$.

There are no heat sources deep in the white dwarf prior to the explosion, so to increase the core temperature for C ignition, must either:

- Compress the matter adiabatically
- Allow heat to flow in from a hotter surface set by the temperature from H or He Burning:

$$\tau_{\rm th} \approx \frac{C_P R^2}{K}$$

where K is the conductivity and C_P the heat capacity of the WD.

Type Ia Supernovae

Type Ia events are associated with burning of a $M_\odot$ to ^{56}Ni. How does this happen? Standard story is unstable C ignition followed by 1000 years of simmering (Woosley et al '04; Piro & LB '08) and explosion.

- The density must $>10^9$ gr/cm^3 in the cold ($\sim 10^8$ K) core to trigger C burning. This requires $M>1.33M_\odot$ and accumulation of mass during accretion. . .

- Challenge is the outcome of H and He burning, and how mass accumulates to trigger C ignition in the core, leading to MANY progenitor scenarios.

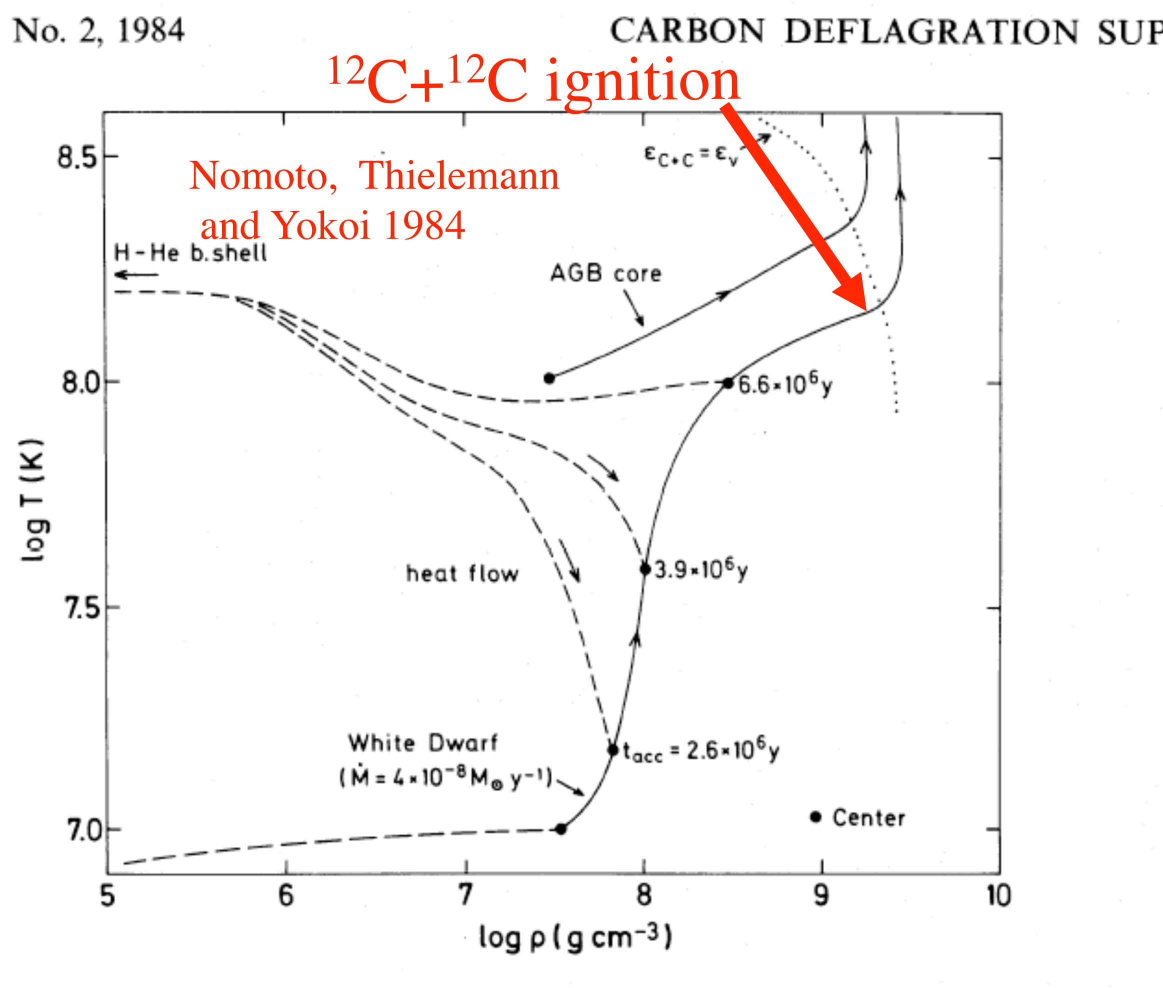
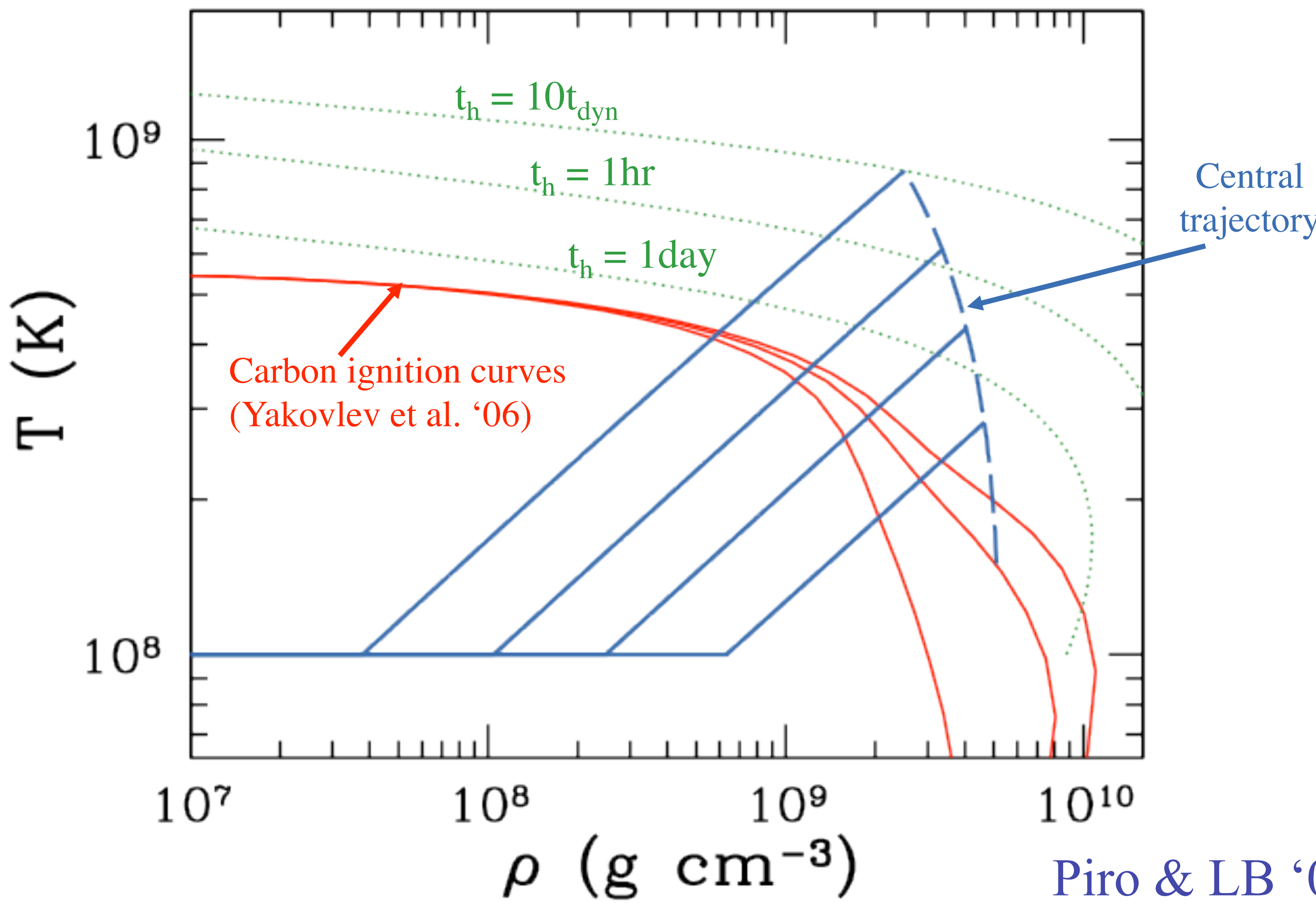


FIG. 2a

FIG. 2—(a) Accretion onto the white dwarf ($\dot{M} = 4 \times 10^{-8}\ M_\odot$ yr^{-1}) and growth of the core i

When carbon first ignites, it undergoes ~1000 years of Simmering

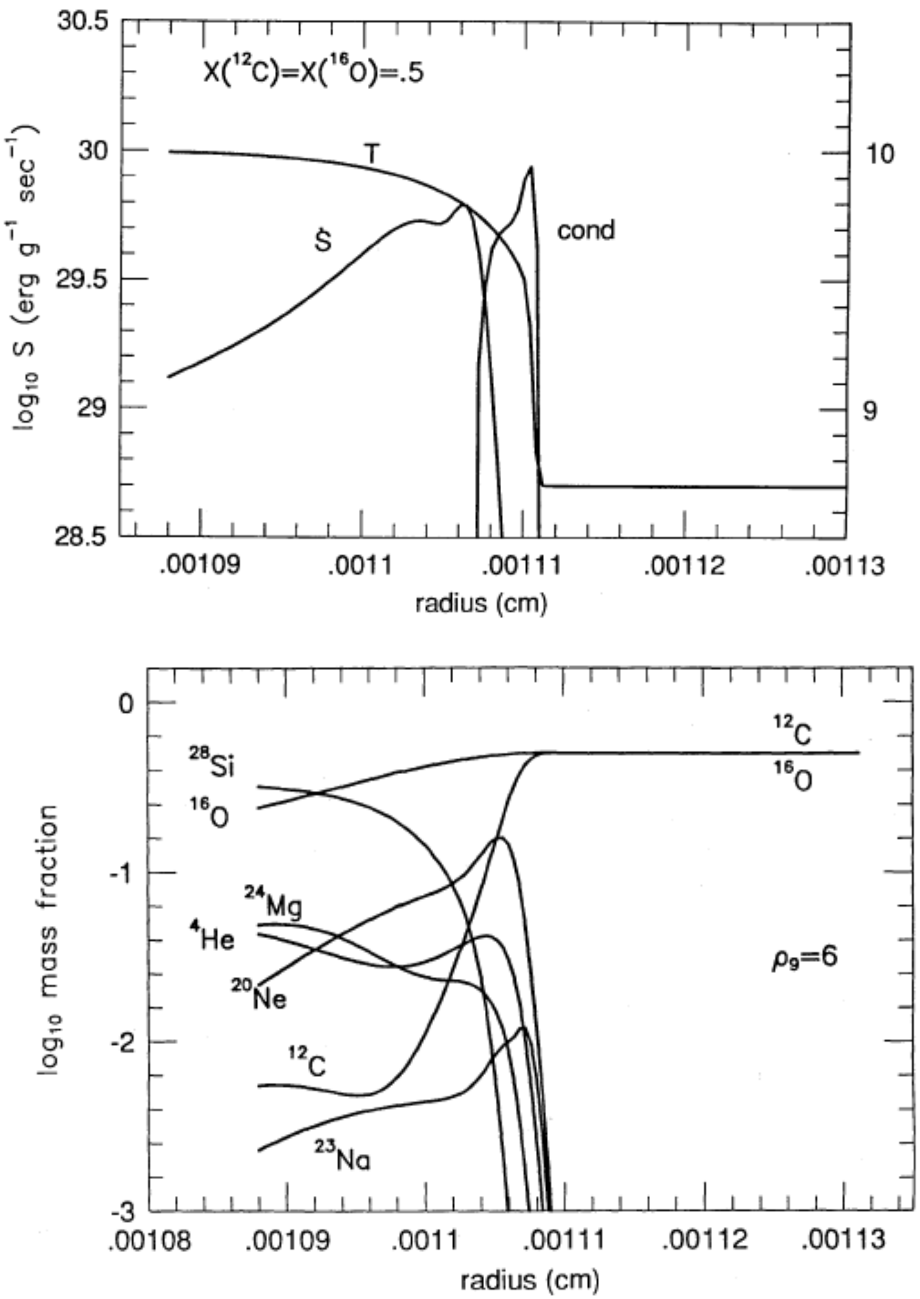
Nomoto et al. 1984; Woosley & Weaver 1986



Piro & LB '08

Combustion!

Jesusita Fire, May 2009
Photo: K. Paxton



Timmes and Woosley 1992

Burning Modes: Deflagration

5-100 km/s

HW: Instabilities

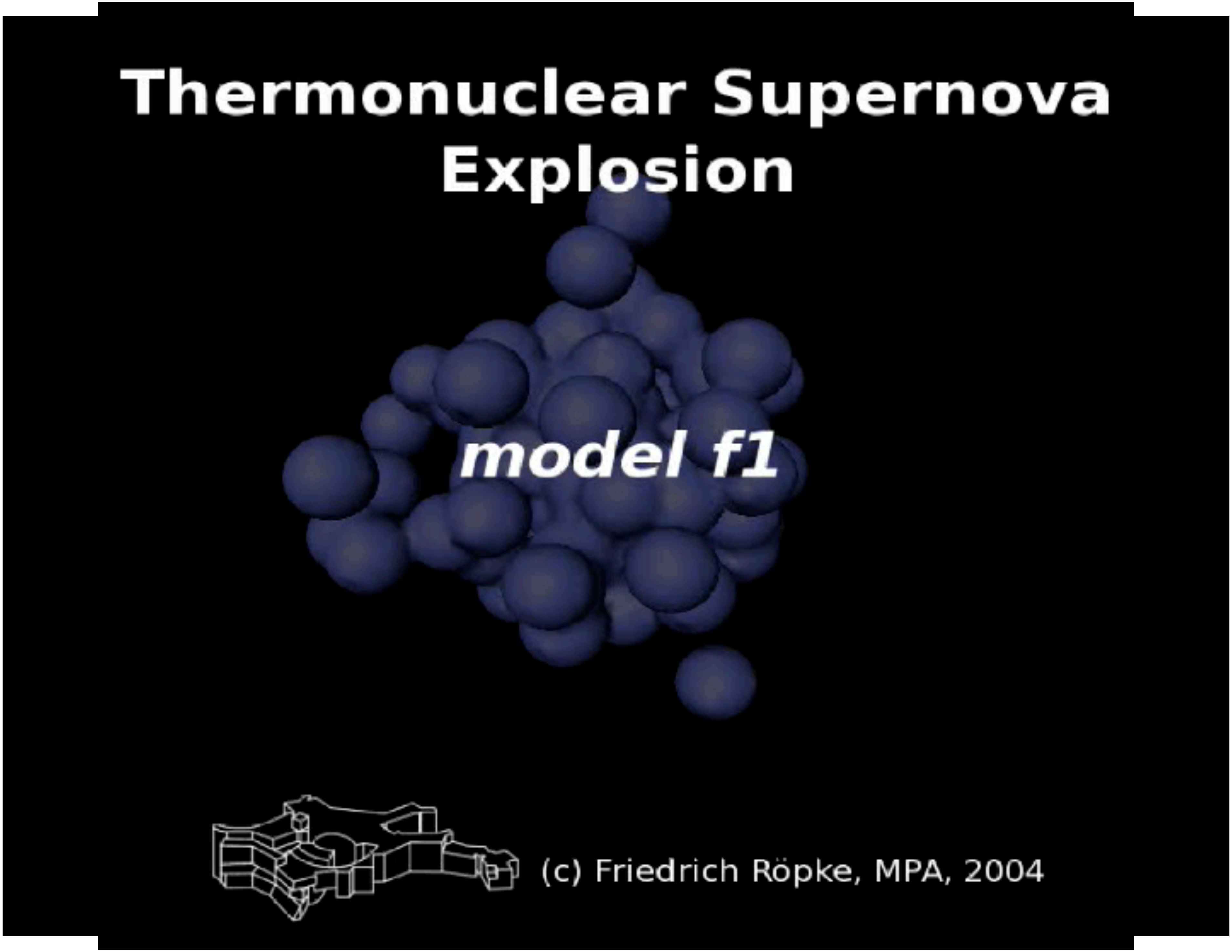
The ashes from the burning are less dense than the cold fuel.

What instability can therefore arise??

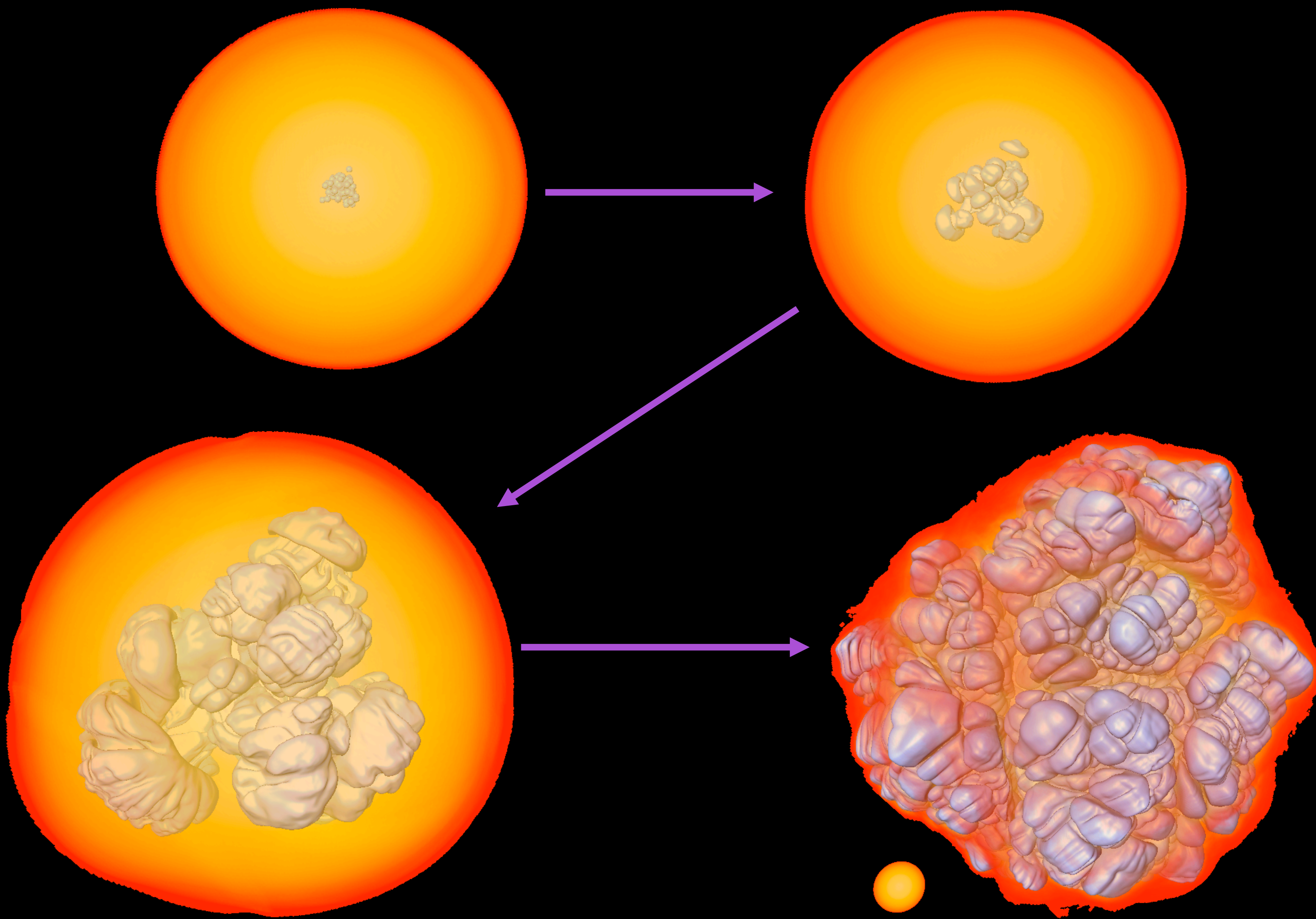
TABLE 3

CARBON-OXYGEN CONDUCTIVE WAVE PROPERTIES[a]

Composition	ρ_9	v_{cond}	Width	$\Delta\rho/\rho$	t_{recov}	λ_{max}	λ_{min}
$X(^{12}C) = 0.2$, $X(^{16}O) = 8.0$	10.0	187	1.27 (−5)	0.085	6.78 (−2)	12.7	18.5
	8.0	152	1.65 (−5)	0.090	1.26 (−1)	19.2	14.4
	6.0	115	2.50 (−5)	0.098	2.94 (−1)	33.8	10.1
	4.0	76.3	4.96 (−5)	0.111	1.14 (+0)	87.0	5.92
	2.0	35.3	1.85 (−4)	0.139	1.47 (+1)	519	2.01
	1.0	15.1	7.28 (−4)	0.205	5.78 (+2)	8.73 (+3)	0.500
	0.5	5.46	2.79 (−3)	0.222	1.75 (+3)	9.56 (+3)	0.121
	0.2	1.09	2.03 (−2)	0.398	8.99 (+3)	9.80 (+3)	8.96 (−3)

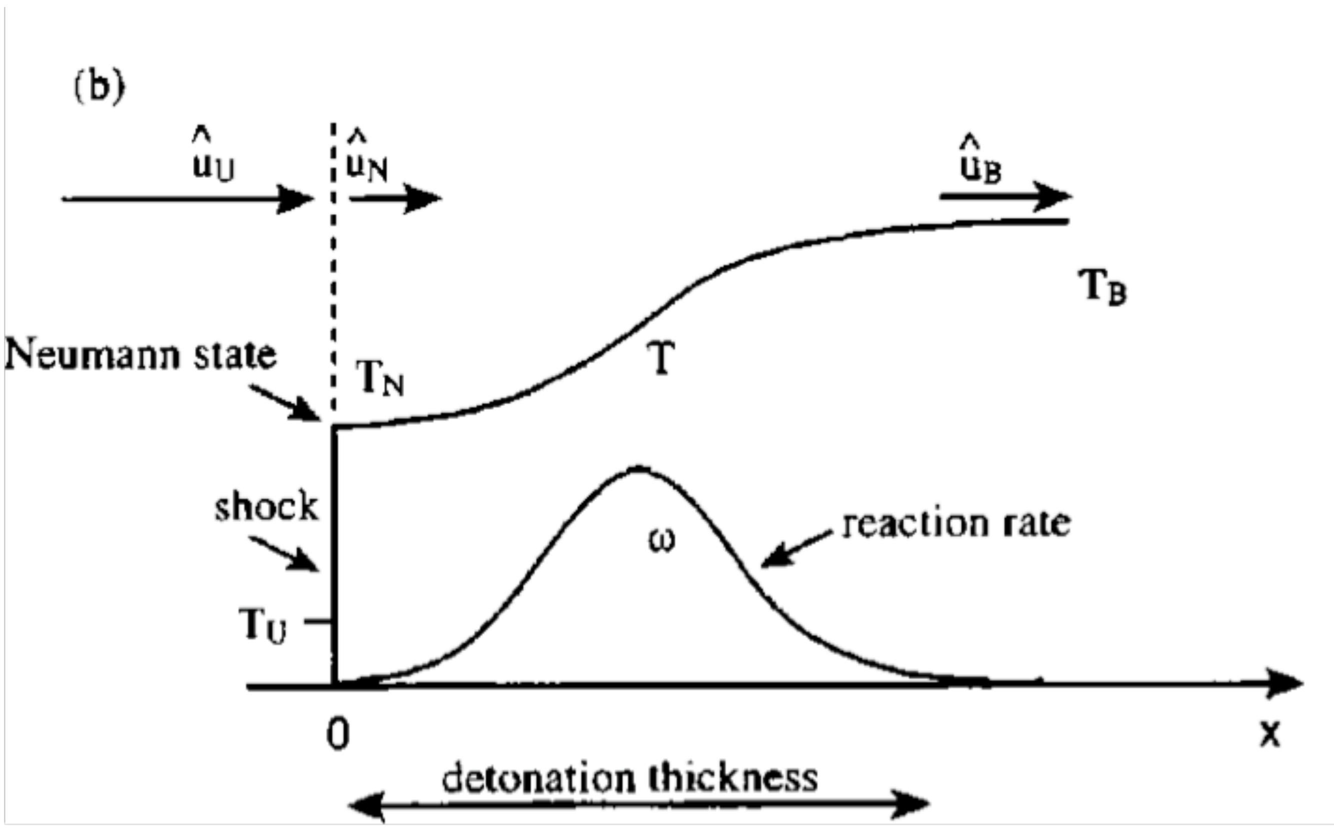

Thermonuclear Supernova
Explosion
model f1
(c) Friedrich Röpke, MPA, 2004

Numerical Simulations of Explosions



Röpke et al. (2005)

Detonation



(b)
$\hat{u}_U$
$\hat{u}_N$
$\hat{u}_B$
T_B
Neumann state
T_N
T
shock
ω
reaction rate
T_U
0
x
detonation thickness

Kasen et al ‘09

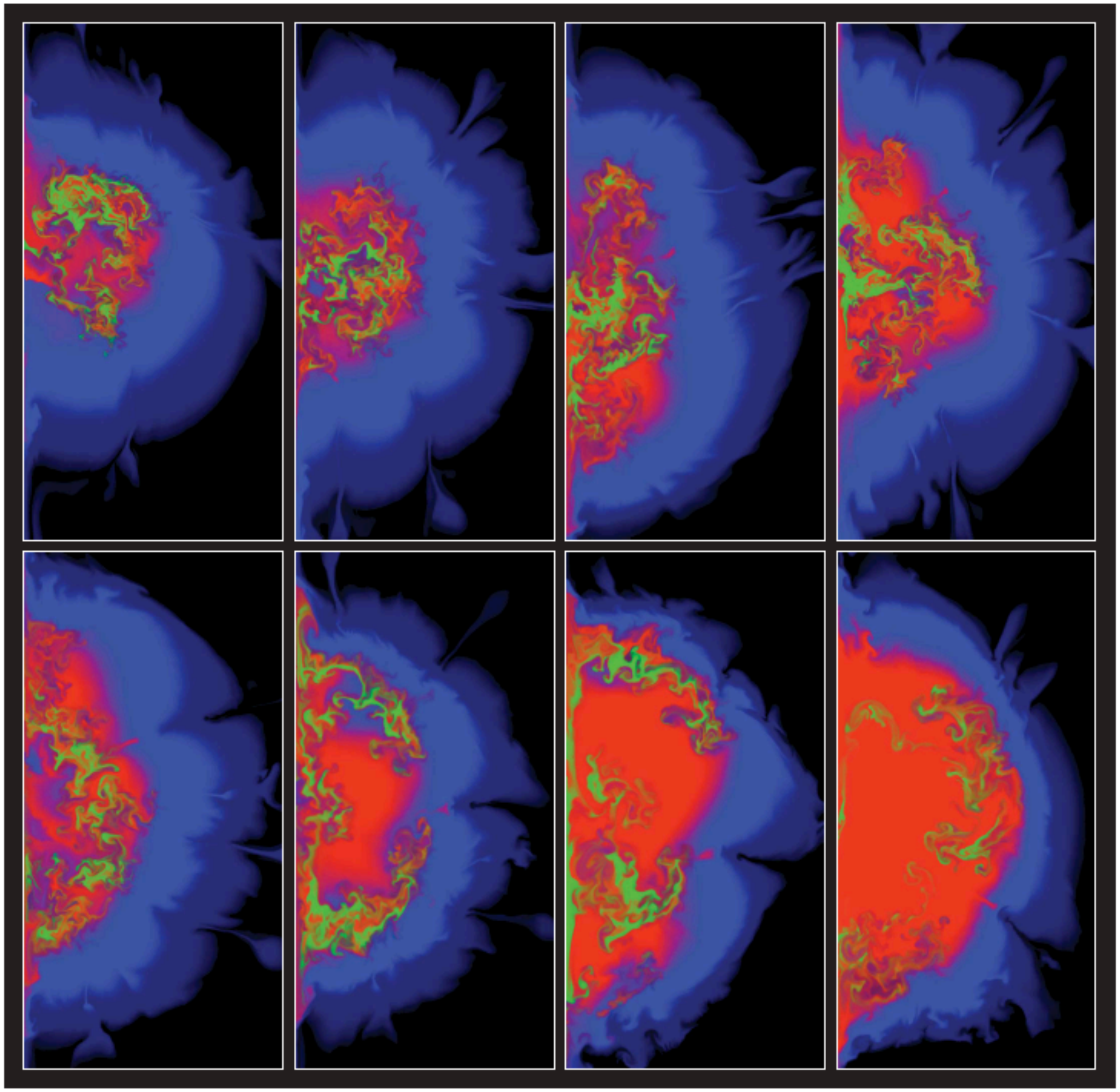


Figure 1 | Chemical structure of the ejected debris 100 s after ignition for a subset of the explosion models with different ignition and detonation conditions. Blue, intermediate-mass elements (that is, silicon, sulphur, calcium); green, stable iron-group elements produced by electron capture; and red, ^{56}Ni. The ^{56}Ni production increases (left to right) for models which undergo relatively more burning in the detonation as compared to the deflagration phase of the explosion. The turbulent inner regions reflect Rayleigh–Taylor and other instabilities that develop during the initial deflagration phase of burning. The subsequent detonation wave enhances the ^{56}Ni production in the centre by burning remaining pockets of fuel. The lower-density outer layers of debris, processed only by the detonation, consist of smoothly distributed intermediate-mass elements.

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LETTERS

The diversity of type Ia supernovae from broken symmetries

D. Kasen[1], F. K. Röpke[2] & S. E. Woosley[1]

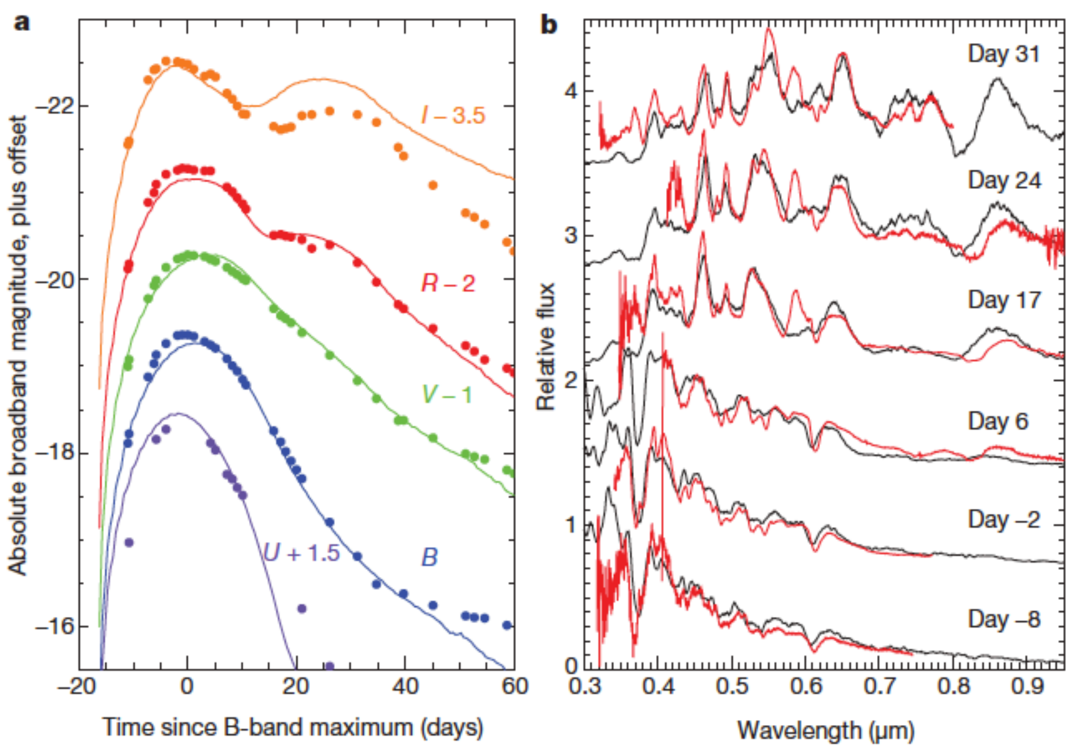
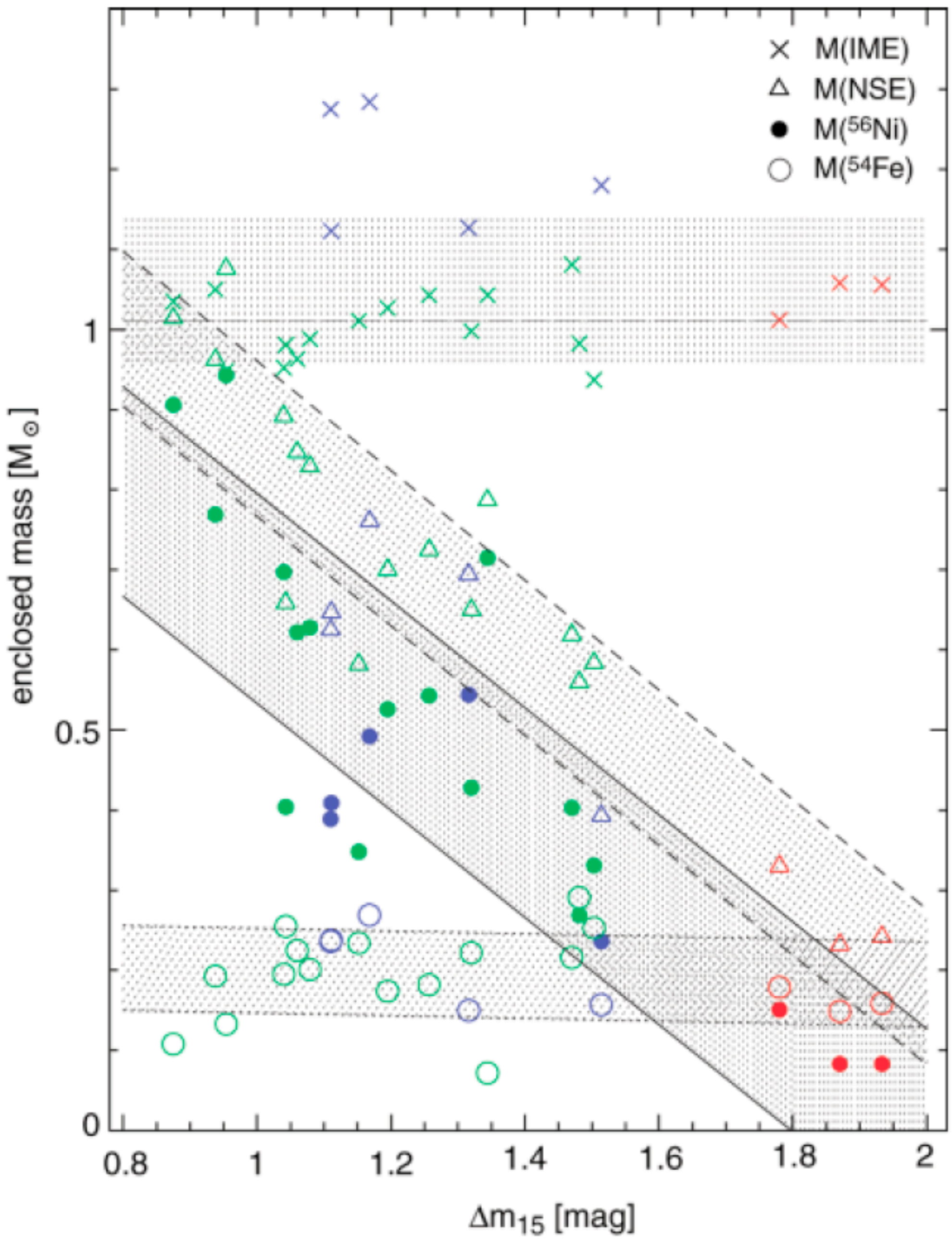


Figure 2 | Synthetic multi-colour light curves and spectra of a representative explosion model compared to observations of a normal type Ia supernova. a, The angle-averaged light curves of model DFD_iso_06_dc2 (solid lines) show good agreement with filtered observations of SN 20003du[24] (filled circles) in wavelength bands corresponding to the ultraviolet (U), optical (B, V, R) and near-infrared (I). **b**, The synthetic spectra of the model (black lines) compare well to observations of SN2003du (red lines) taken at times marked in days relative to B-band light-curve maximum. Over time, as the remnant expands and thins, the spectral absorption features reflect the chemical composition of progressively deeper layers of debris, providing a strong test of the predicted compositional stratification of the model.

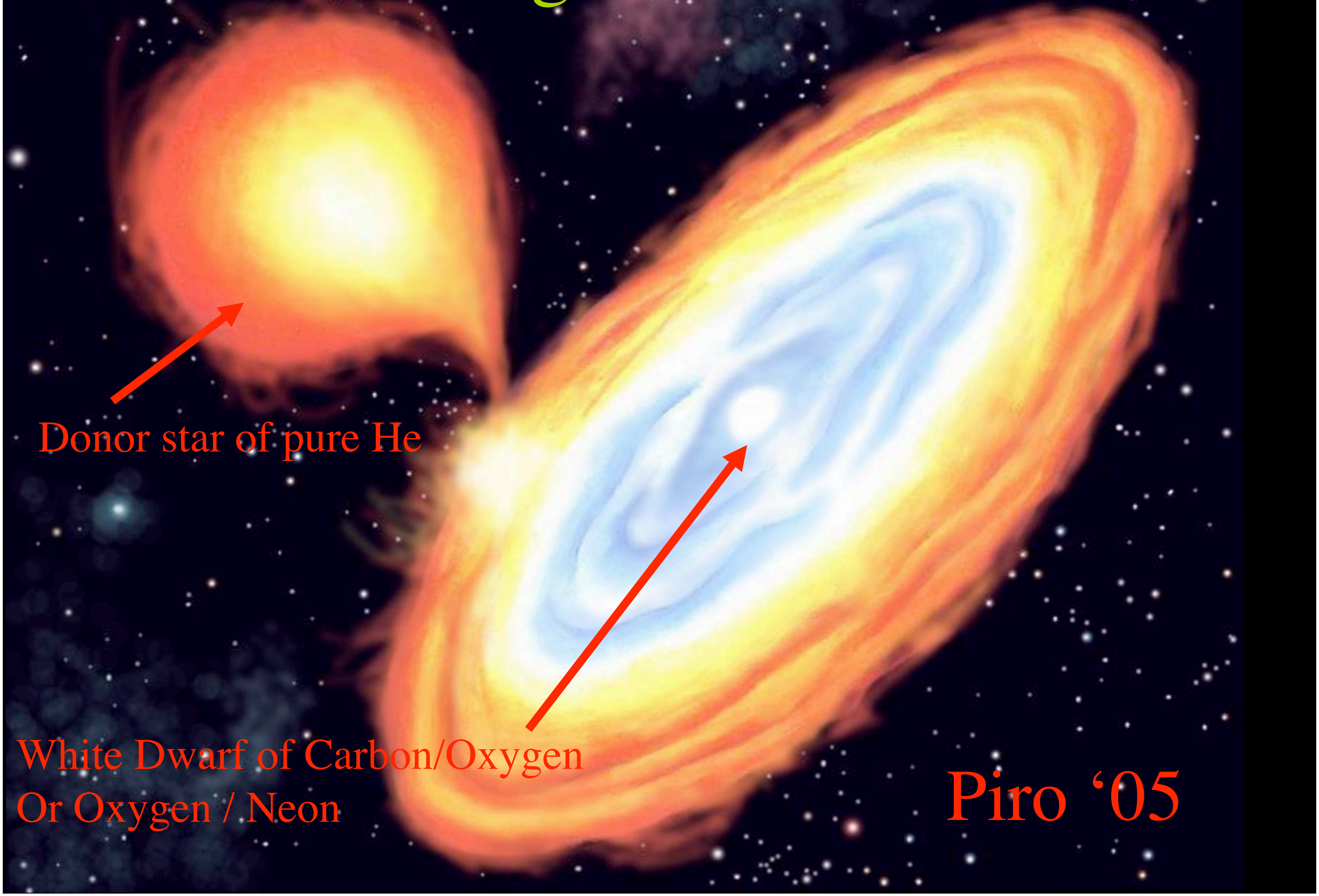
Mazzali et al 2007



Light Curve Fitting Results

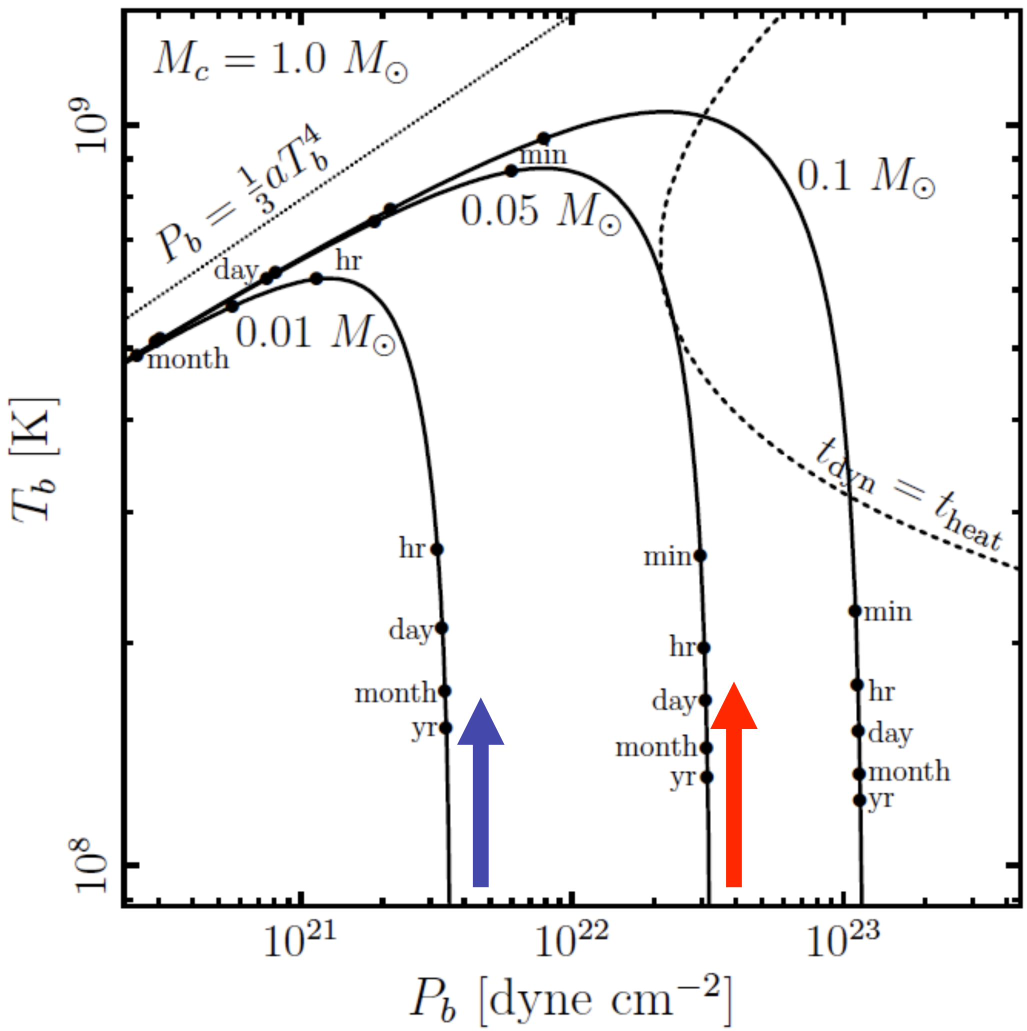
- Typical' Ia's imply a total mass of 1.1-1.3 $M_\odot$ ejected (Mazzali et al 2007)
- Light curve fitting (see Kasen & Woosley 2007; Woosley et al. 2007) has shown that the Phillips relation can be found.

Accreting White Dwarfs



Path to Dynamical Helium Shells

The radial expansion of the convective region allows the pressure at the base to drop. For low shell masses, this quenches burning. For a massive shell, however, the heating timescale set by nuclear reactions:



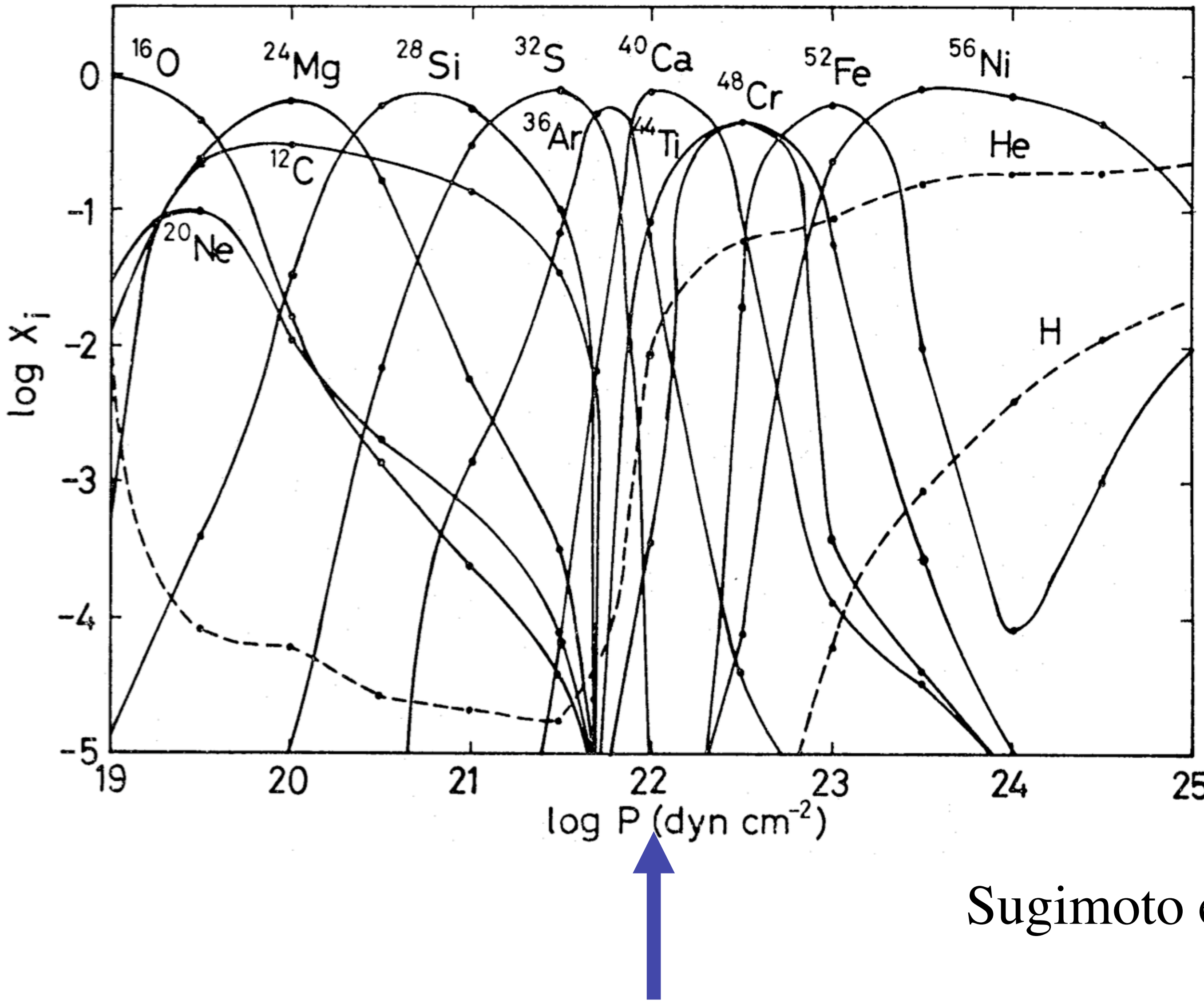
$$t_{\rm nuc} = \frac{C_P T}{\epsilon_{\rm nuc}}$$

will become less than the dynamical time,

$$t_{\rm dyn} = \frac{H}{c_s} = \frac{P}{\rho g c_s}$$

So that the heat cannot escape during the burn, potentially triggering a detonation of the helium shell. This condition sets a minimum shell mass.

Nucleosynthesis



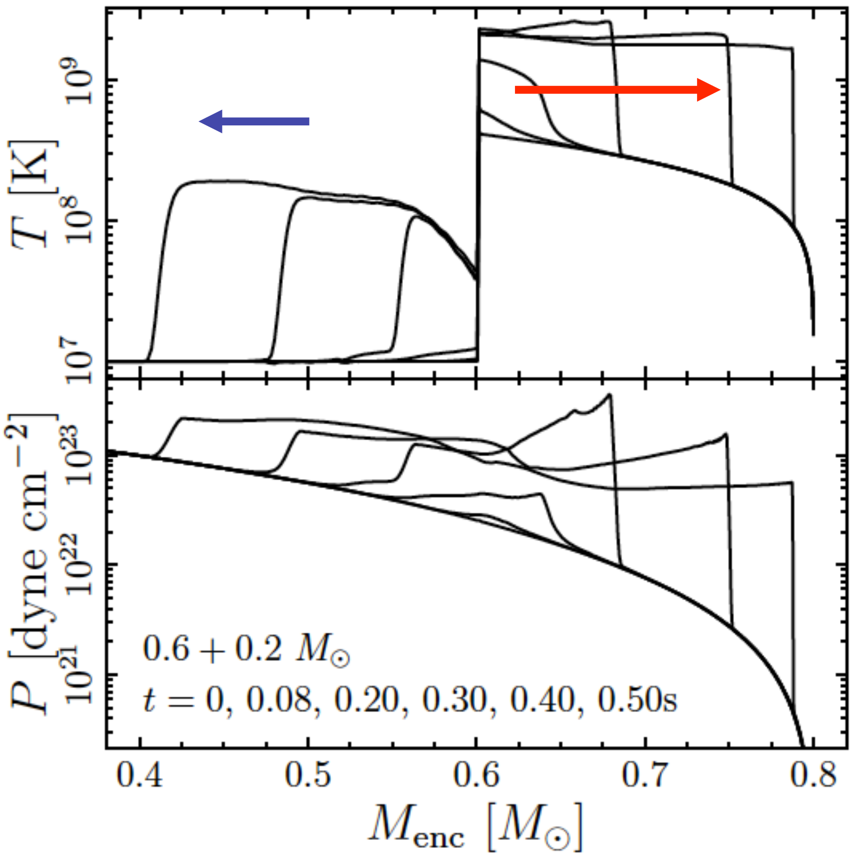
Sugimoto et al (1983)

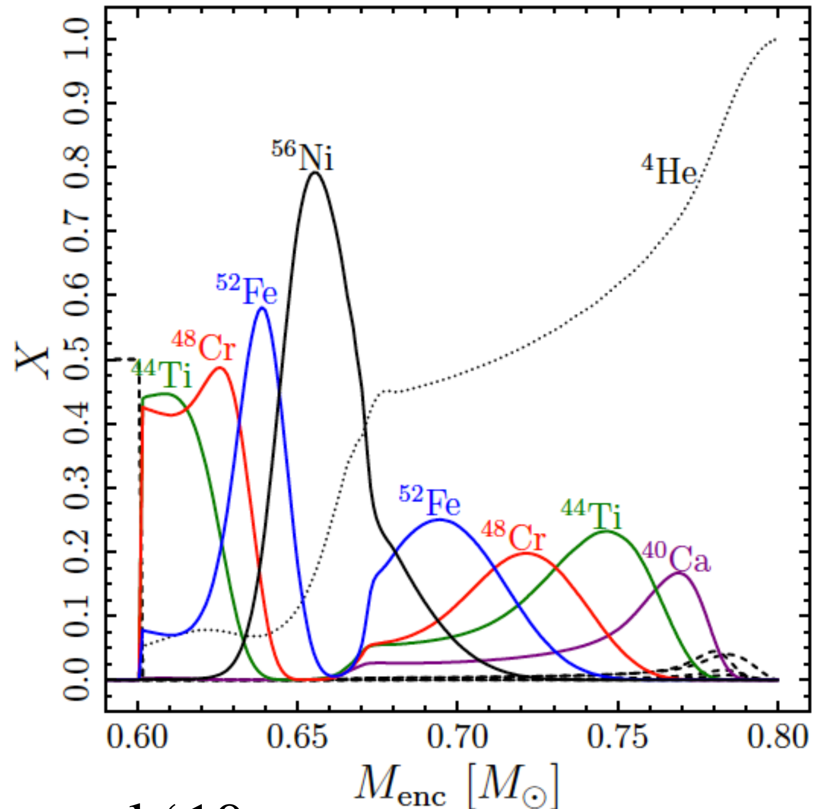
Radioactive Decay Chains

$$^{52}\mathrm{Fe}\ (8.2\mathrm{hr}) \rightarrow^{52} \mathrm{Mn}\ (21\mathrm{min}) \rightarrow^{52} \mathrm{Cr}$$

$$^{48}\mathrm{Cr}\ (21\ \mathrm{hr}) \rightarrow^{48} \mathrm{V}\ (16\ \mathrm{d}) \rightarrow^{48} \mathrm{Ti}$$

Sample Detonation



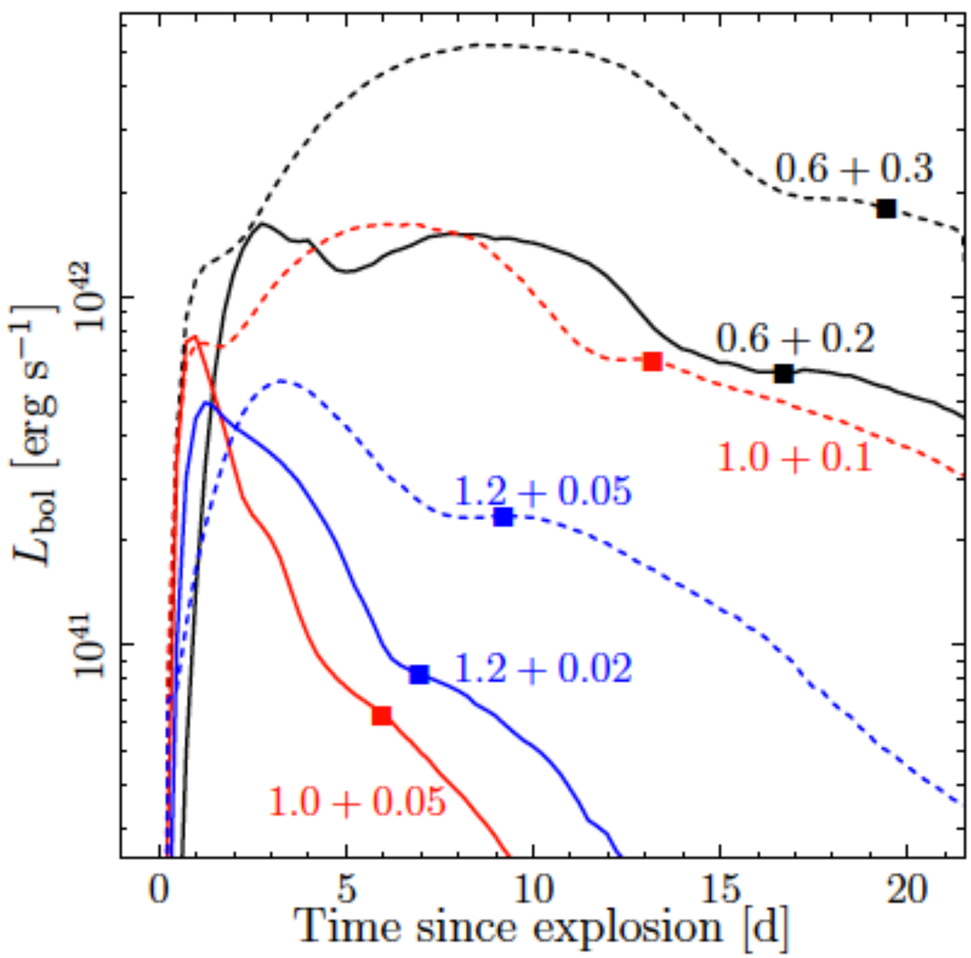


Shen et al '10

Shock (blue arrow) goes into the C/O and a He detonation (red arrow) moves outward. The shocked C/O under the layer is not ignited. Underlying WD remains unless converging shocks detonate it (see Livne & Glasner; Fink, Roepke & Hillebrandt '07)

.Ia Supernovae*

L. B., Shen, Weinberg & Nelemans '07
Shen et al 2010



1

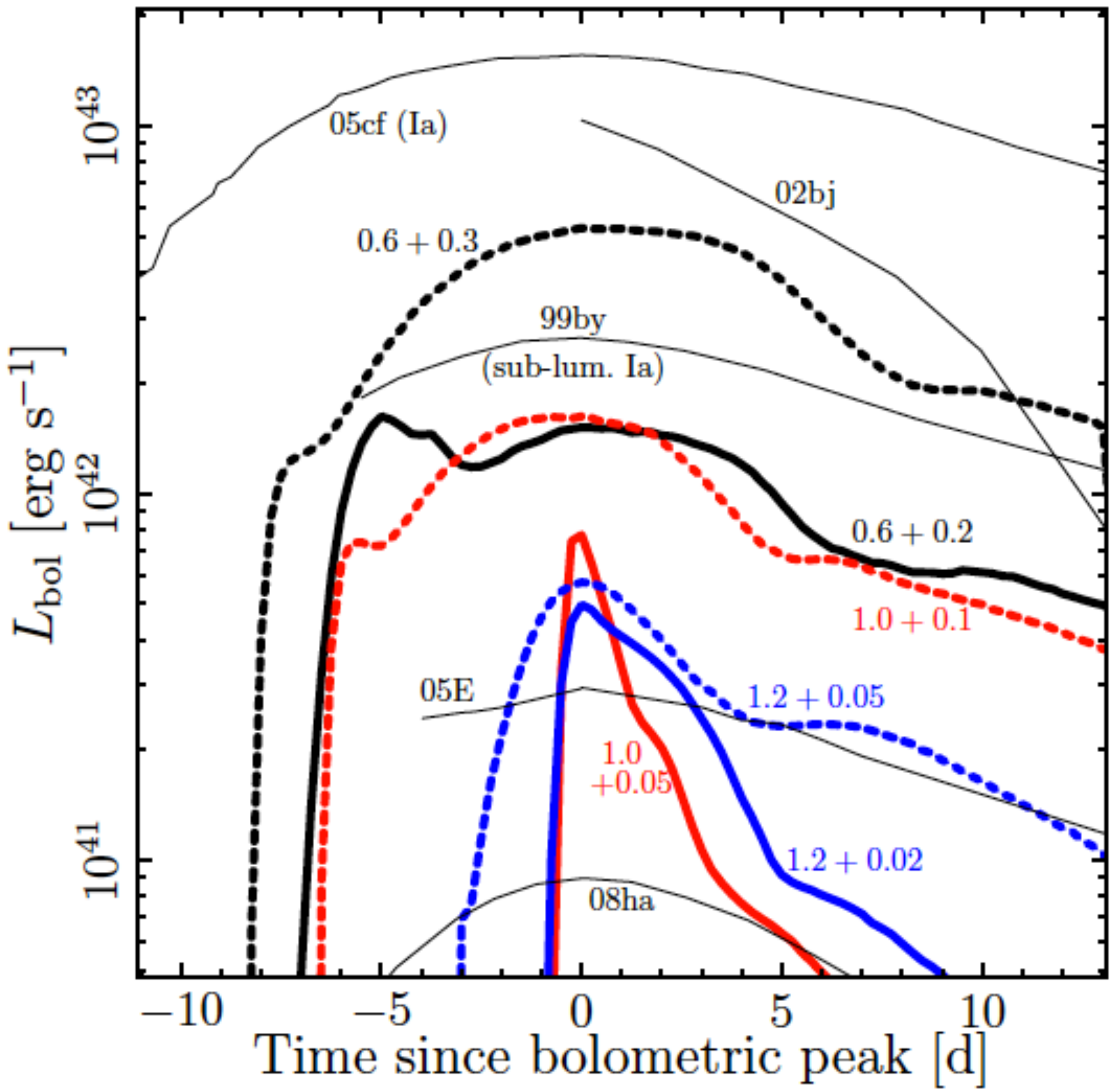
*Thanks to Chris Stubbs for the name

- The 0.02-0.1$M_\odot$ ignition masses only burns the helium, which leaves the WD at 10,000 km/sec, leading to brief events

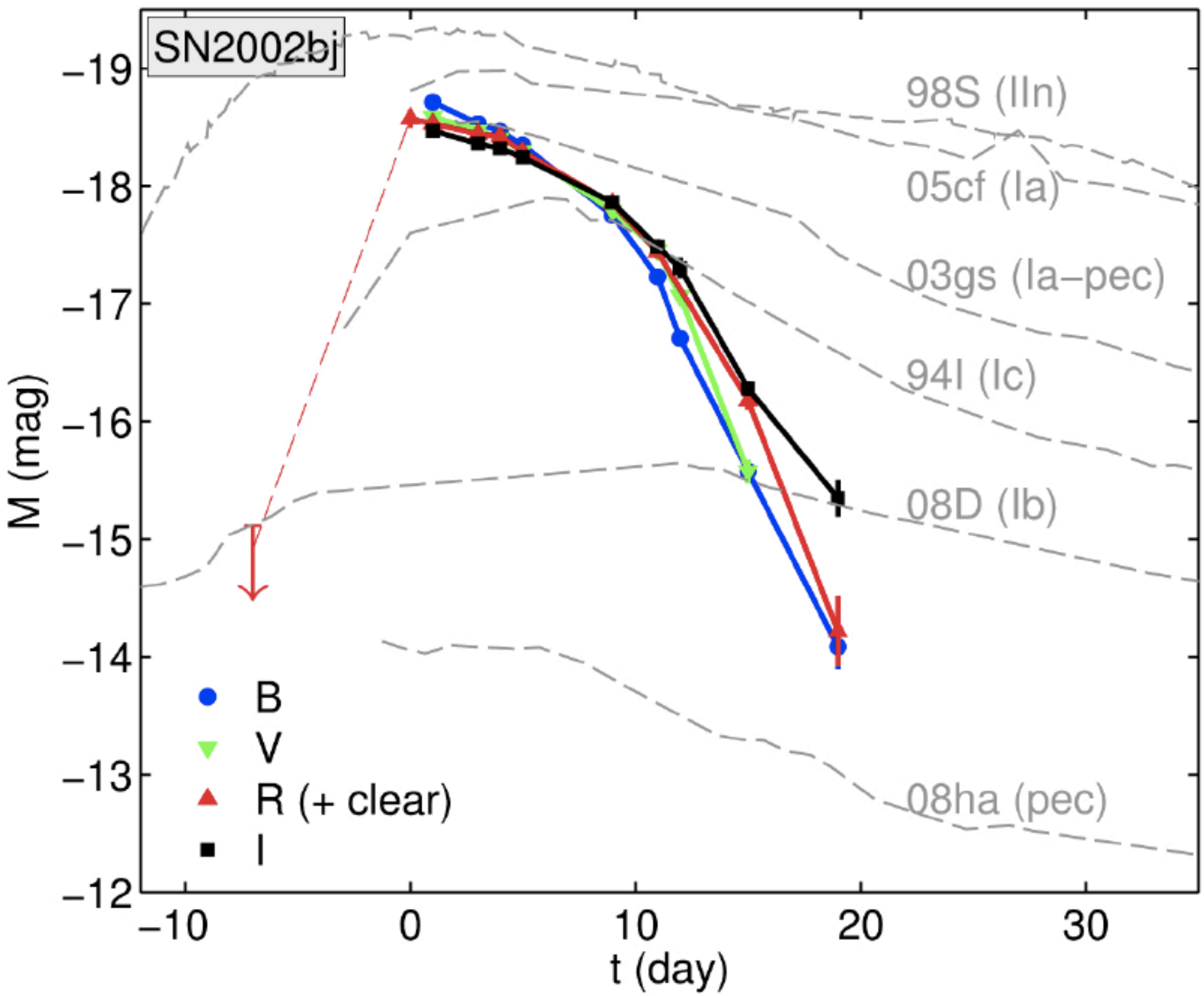
$$\tau_m = \left(\frac{\kappa M_e}{7cv}\right)^{1/2} \approx 3-5 \text{ d}$$

- The radioactive decays of the freshly synthesized ^{48}Cr (1.3 d), ^{52}Fe (0.5 d) and ^{56}Ni (8.8 d) will provide power on this short timescale!!

Faint and Fast Events!!!

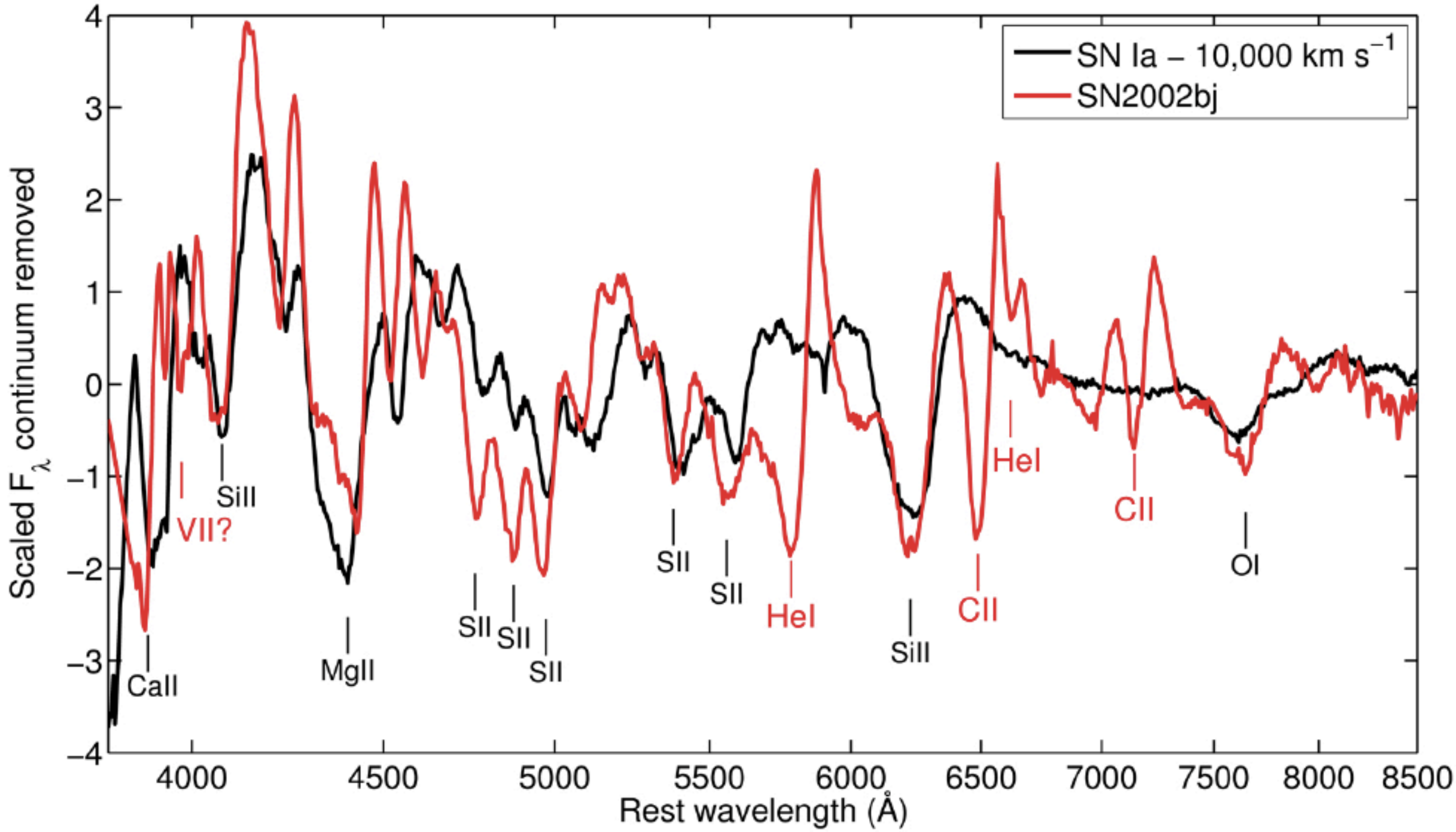


2002bj: Poznanski et al. ‘09

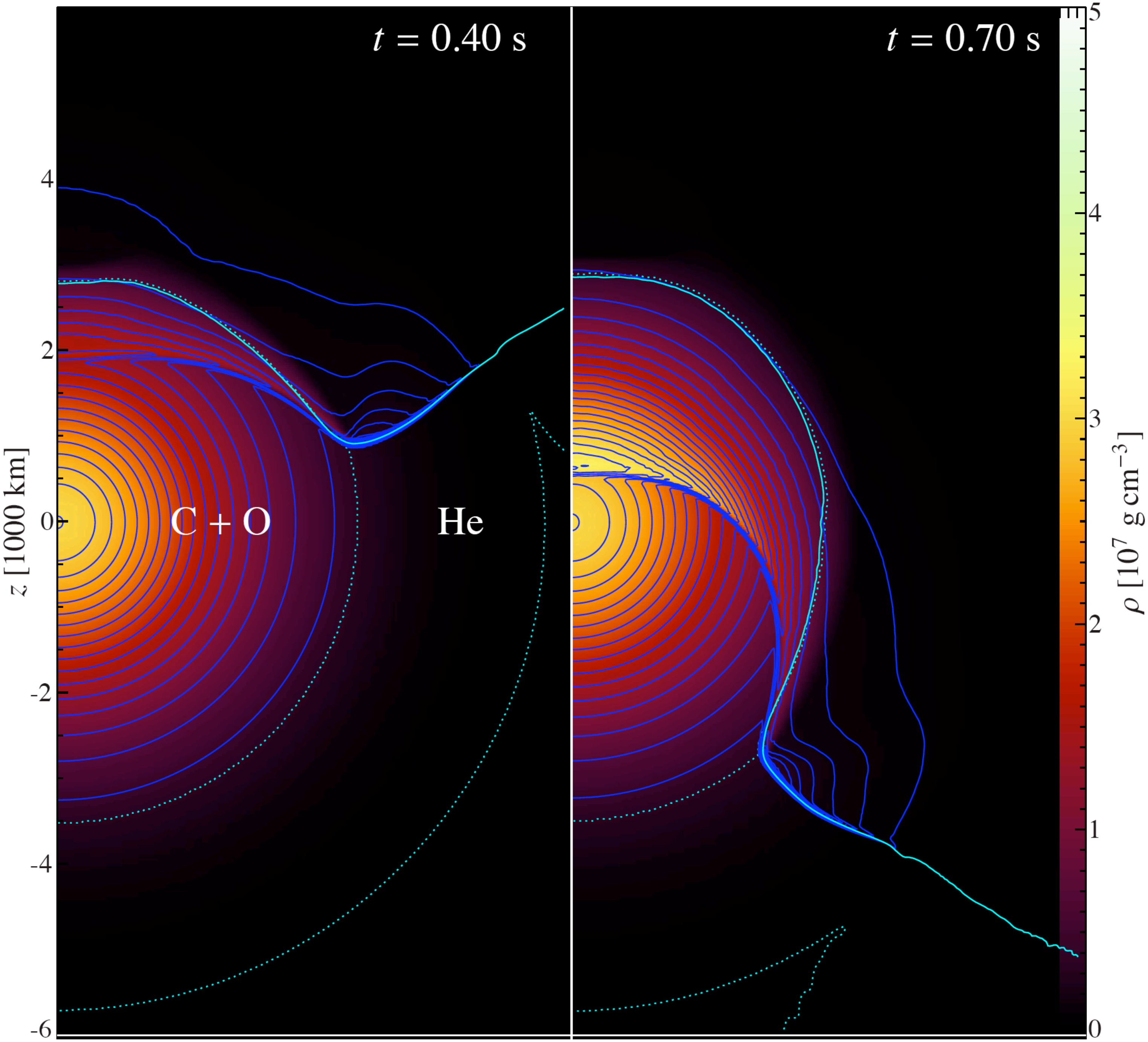


Helium, Carbon and maybe V!

$$^{48}\mathrm{Cr}\ (21\ \mathrm{hr}) \rightarrow {}^{48}\ \mathrm{V}\ (16\ \mathrm{d}) \rightarrow {}^{48}\ \mathrm{Ti}$$



Fink, Hillebrandt and Ropke 2007



Fink, Hillebrandt and Ropke 2007