Stellar Afterlife

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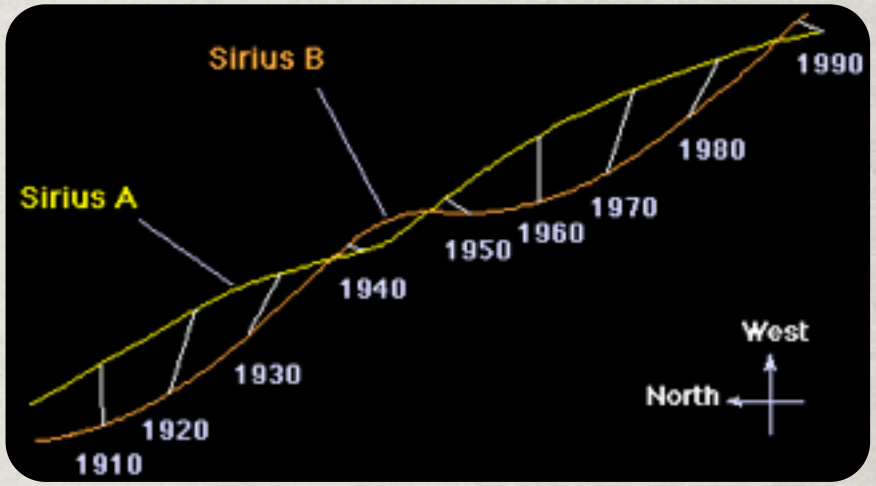
Sirius



One of the most famous and influential binary star systems is Sirius A & B.

As the brightest star in the sky, Sirius A has been known since antiquity. The gravitational effect of Sirius B on Sirius A was noted by Bessel in 1844, and Sirius B was observed in 1862 by Clark.

With a much smaller luminosity ($L_B = 0.024\ L_\odot$) than Sirius A ($L_A = 26\ L_\odot$), it was very surprising when a spectrum of Sirius B taken in 1915, revealed a color similar to Sirius A. Sirius B was the 2nd white dwarf identified.

Using modern $T_A = 9900$ K & $T_B = 24800$ K.

$$\frac{R_B}{R_A} = \left(\frac{L_B}{L_A}\right)^{\frac{1}{2}} \left(\frac{T_A}{T_B}\right)^2 = 0.005$$

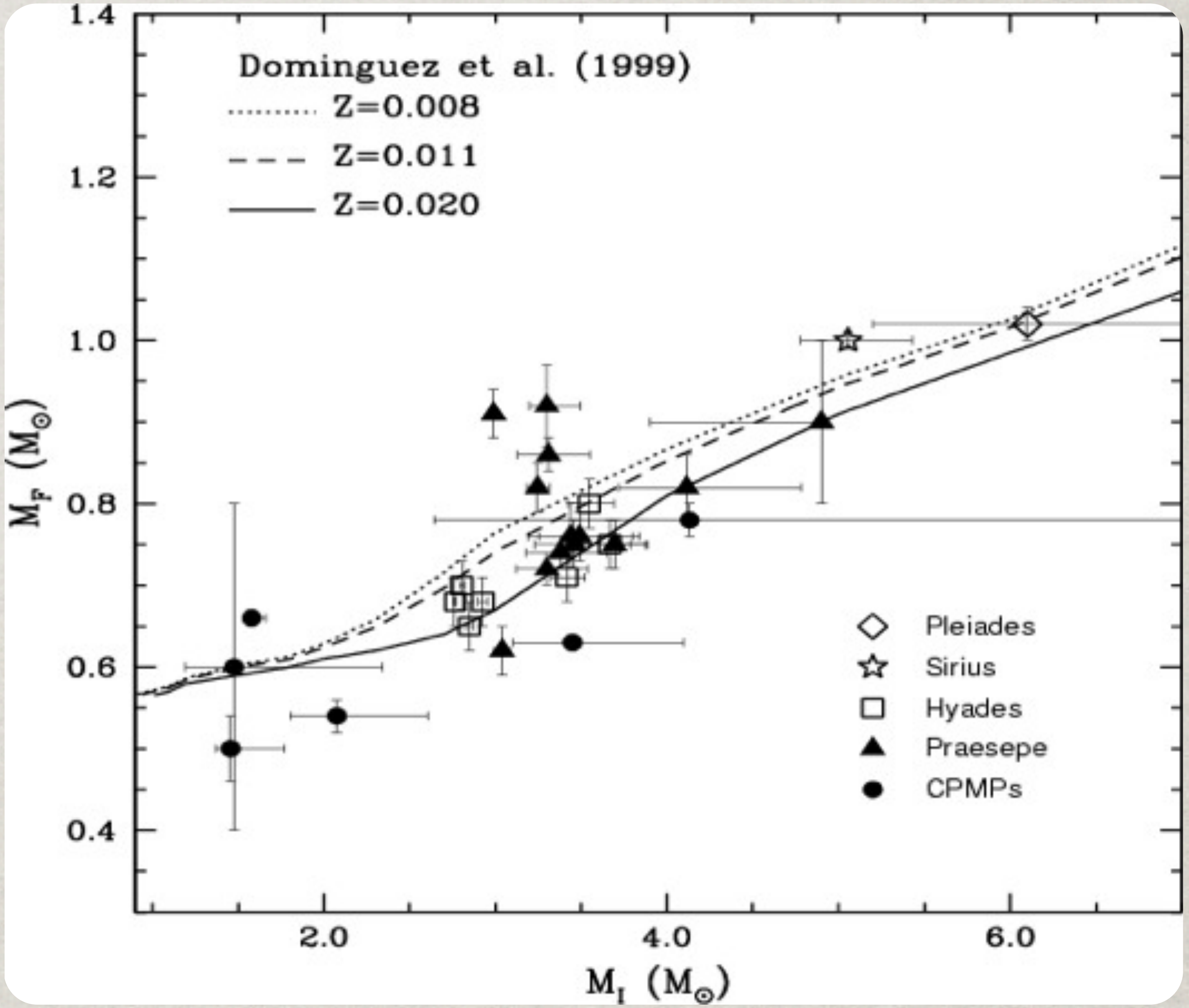
For $R_A = 1.71\ R_\odot$

$R_B = 0.008\ R_\odot = 0.9\ R_\oplus$

Making White Dwarves

The final white dwarf product of a star's evolution depends on the star's mass, as well as its metallicity and solitude.

In general, more massive stars are less efficient at growing white dwarves.



A star of 7-8 $M_\odot$ leaves a C-O white dwarf ~ 1.1 $M_\odot$.

Any larger white dwarf is either composed of O-Ne or gained more mass after it formed.

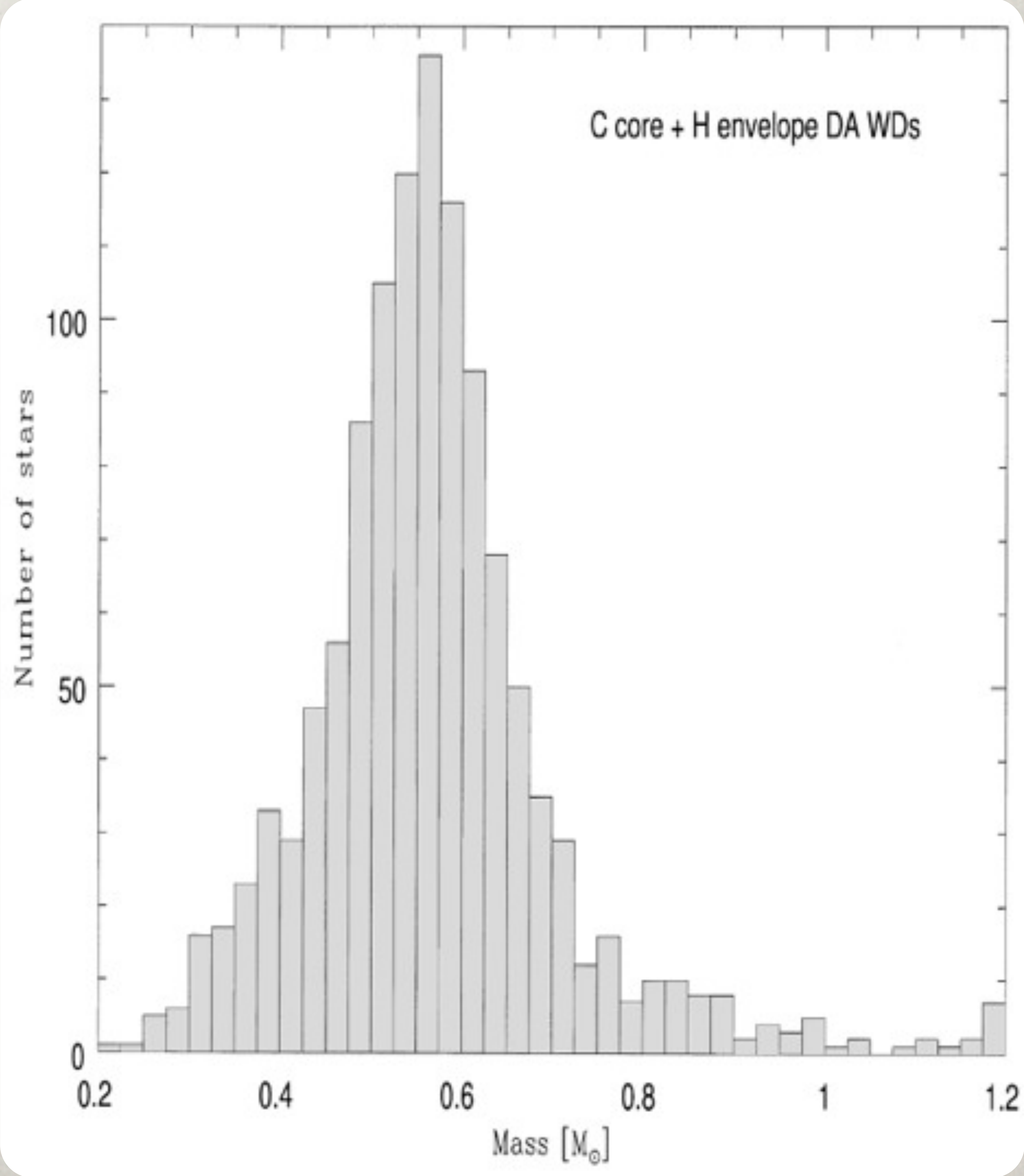
WHITE DWARF ACCOUNTING

Stellar censuses which account for the dimness of white dwarves find that typically 10% of all stars are white dwarves.

The current distribution of white dwarf masses involves a competition between the higher frequency and longer lifetimes of lower mass main sequence stars.

It also depends on changes due to binary evolution.

The observed distribution shows a peak around 0.6 $M_\odot$.



DEGENERACY PRESSURE

Thermal electrons exert a pressure

$$P_{th} = n_e kT \sim n_e m_e \upsilon_{th}^2$$

A similar pressure can be computed from the "Heisenberg speed"

$$P_{deg} \sim n_e m_e \upsilon_H^2 \sim n_e m_e \left(\frac{\hbar n_e^{1/3}}{m_e} \right)^2 \sim \hbar^2 \frac{n_e^{5/3}}{m_e}$$

It is instructive to rewrite this degeneracy pressure by separating out a proportionality to the number of electrons contributing, as is clearly present in the thermal pressure.

$$P_{deg} \sim n_e \frac{\hbar^2}{m_e} n_e^{2/3} \sim n_e E_f$$

Thus $P_{deg} > P_{th}$ as long as the gas is degenerate ($E_f > kT$).

MASS-RADIUS

Degeneracy pressure leads to an unusual relation between mass and radius.

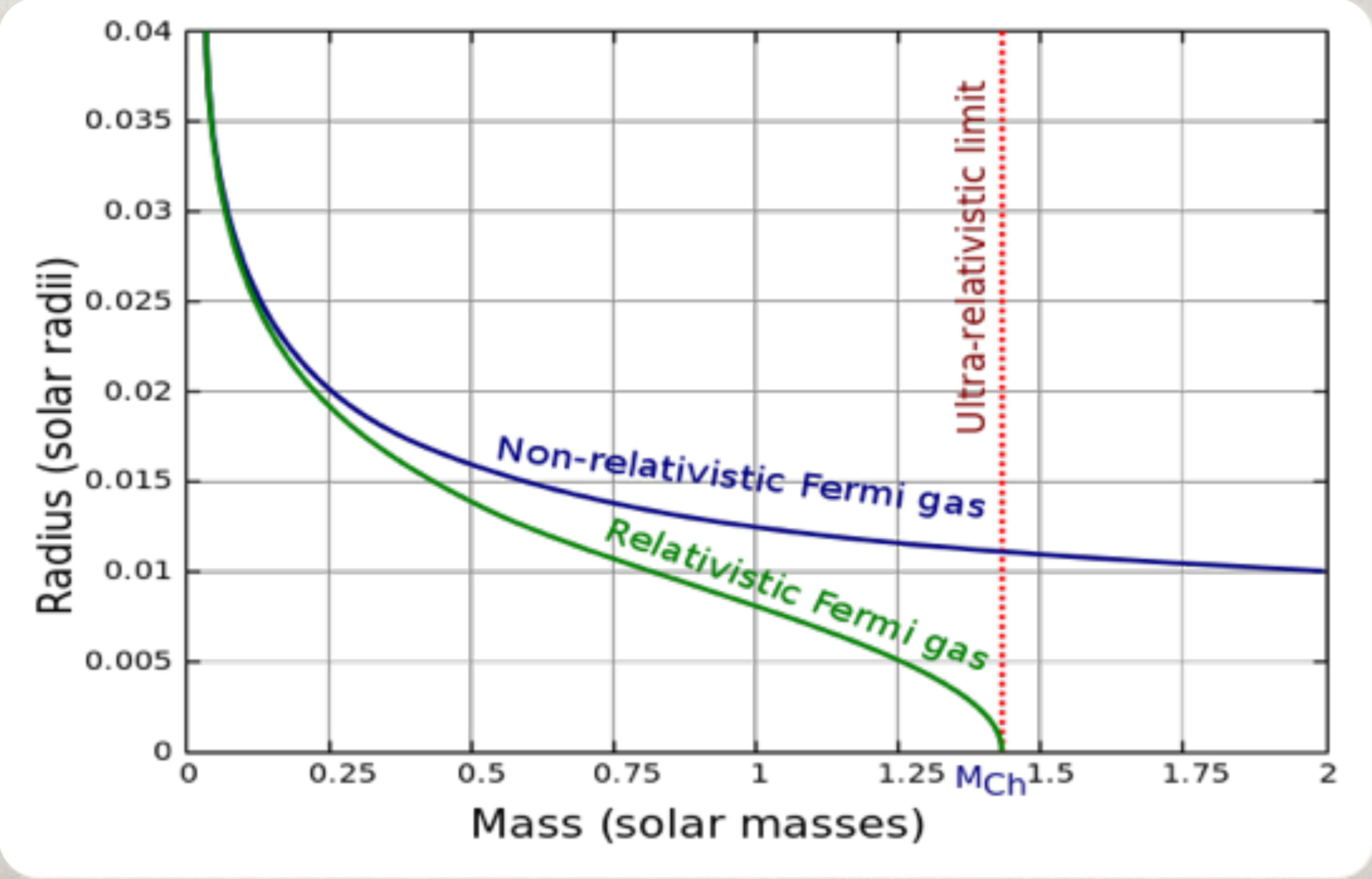
$$R \sim \frac{\hbar^2}{G m_e m_p^{5/3}} M^{-\frac{1}{3}} \approx 0.01 R_\odot \left(\frac{M}{0.7 M_\odot} \right)^{-\frac{1}{3}}$$

Subrahmanyan Chandrasekhar derived this relation in 1931 for the more general case of special relativity and a star whose density varies with radius, finding the star's radius goes to zero at a limiting mass of $M_{Ch} = 5.76\, Y_e^{\,2}\, M_\odot$.

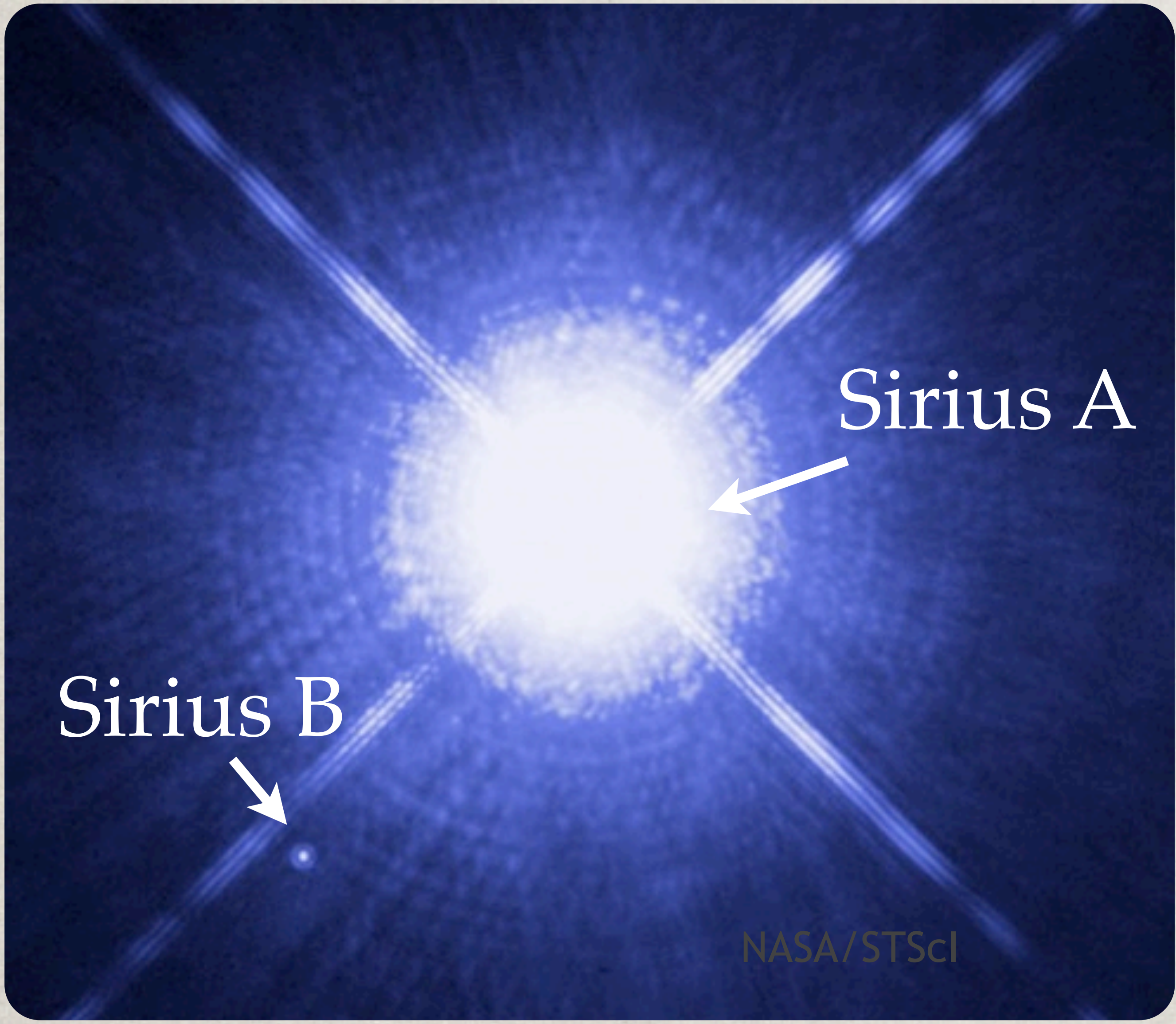
Y_e is the electron fraction, the number of electrons per nucleon, $Y_e = \langle Z/A \rangle$.

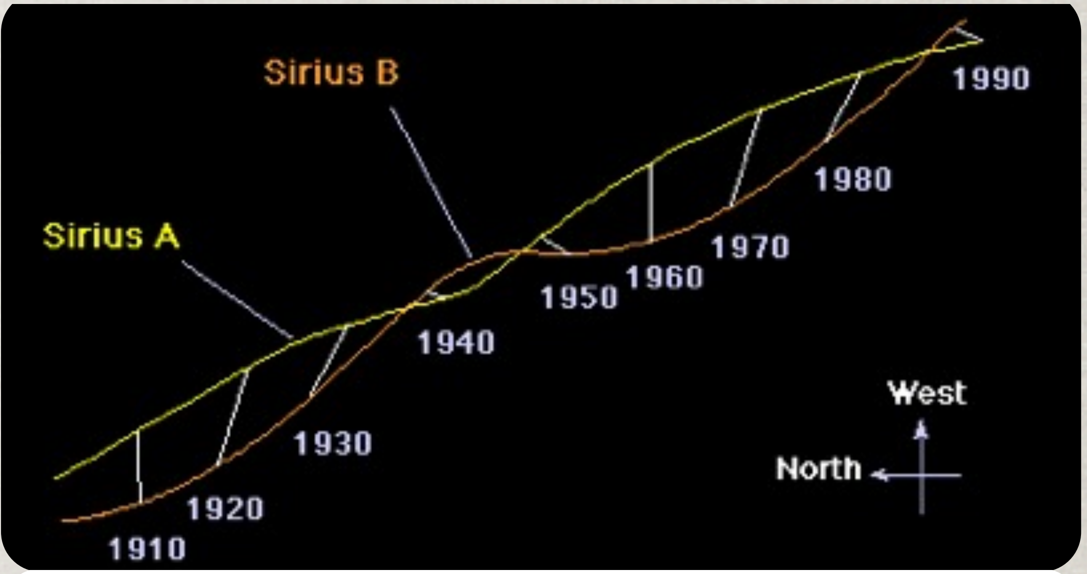
For pure C+O, $Y_e = .5$.

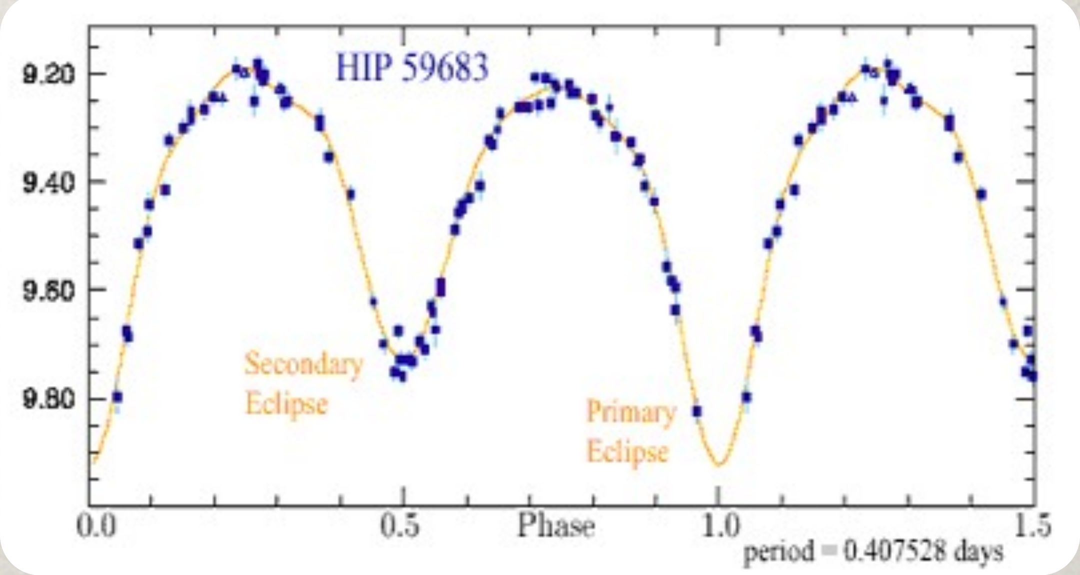
A small amount of ^{22}Ne present makes $Y_e = .498$.



STARS DON'T ALWAYS LIVE ALONE







Many (most?) stars are members of binary systems.

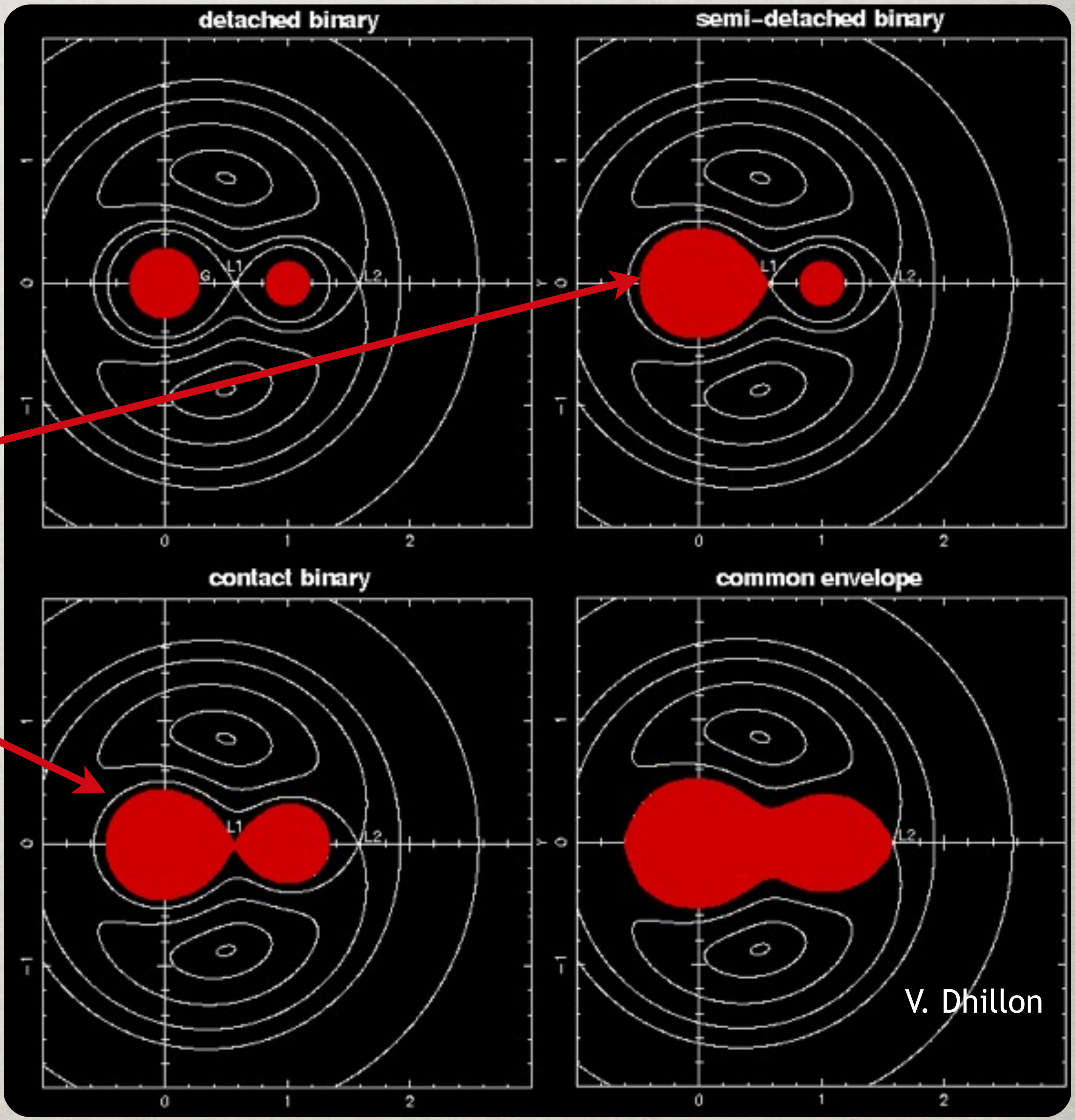
Binaries can be identified by their orbits effect on the position (astrometric), light curve (eclipsing) or spectra (spectroscopic) of the stars.

Equipotentials

Presence of companion star results in non-spherical equipotential surfaces.

When a giant star expands, it can fill its Roche Lobe and preferentially lose mass to the companion.

This mass, with significant angular momentum, accretes on to the companion.



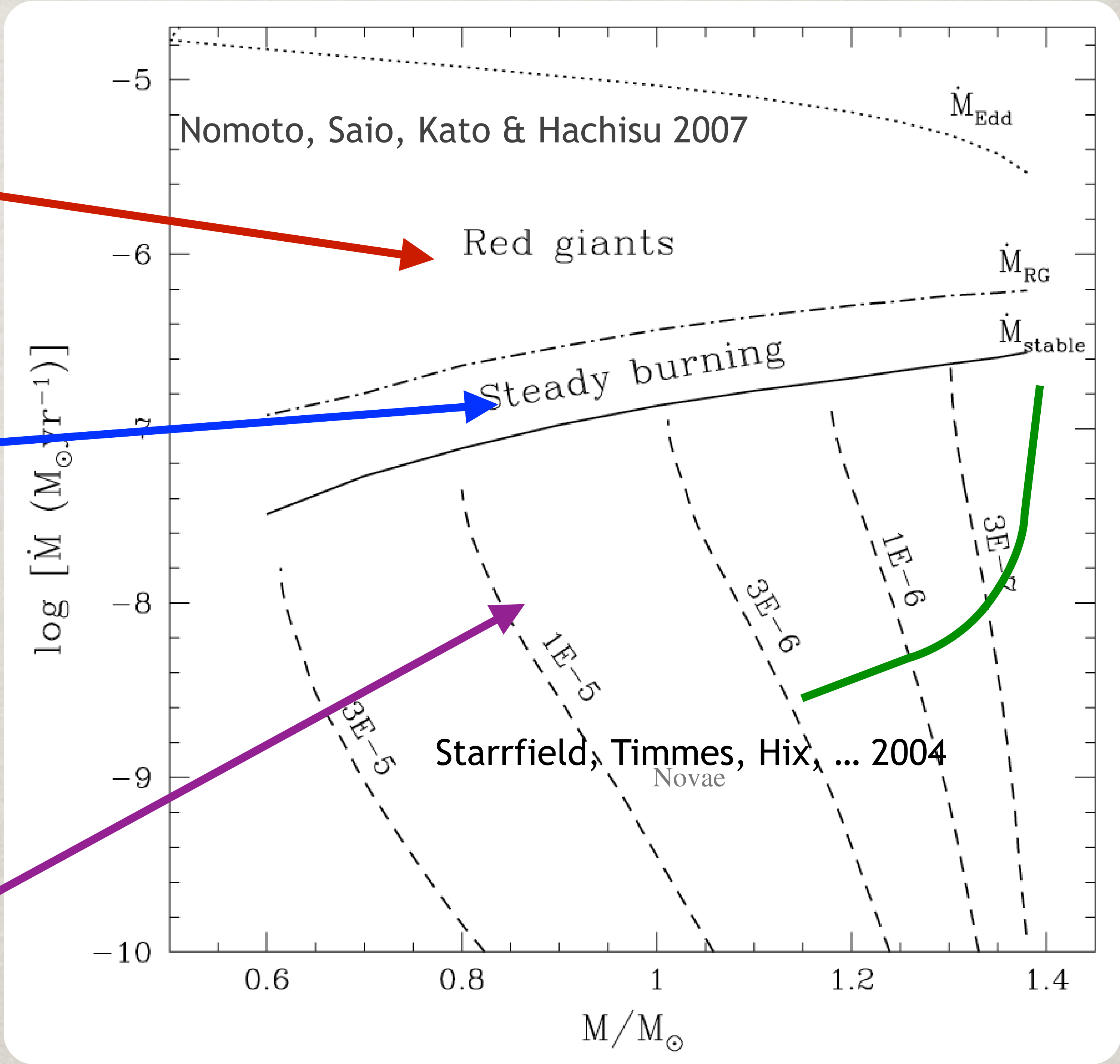
V. Dhillon

LOADING A WHITE DWARF

For high acretion rates, a Red Giant-like envelope re-forms.

For the right accretion rate, H and He burn steadily to C & O as they fall onto the white dwarf, causing it to grow.

For lesser accretion rates, a layer of H builds on the surface.


Nomoto, Saio, Kato & Hachisu 2007

Starrfield, Timmes, Hix, … 2004

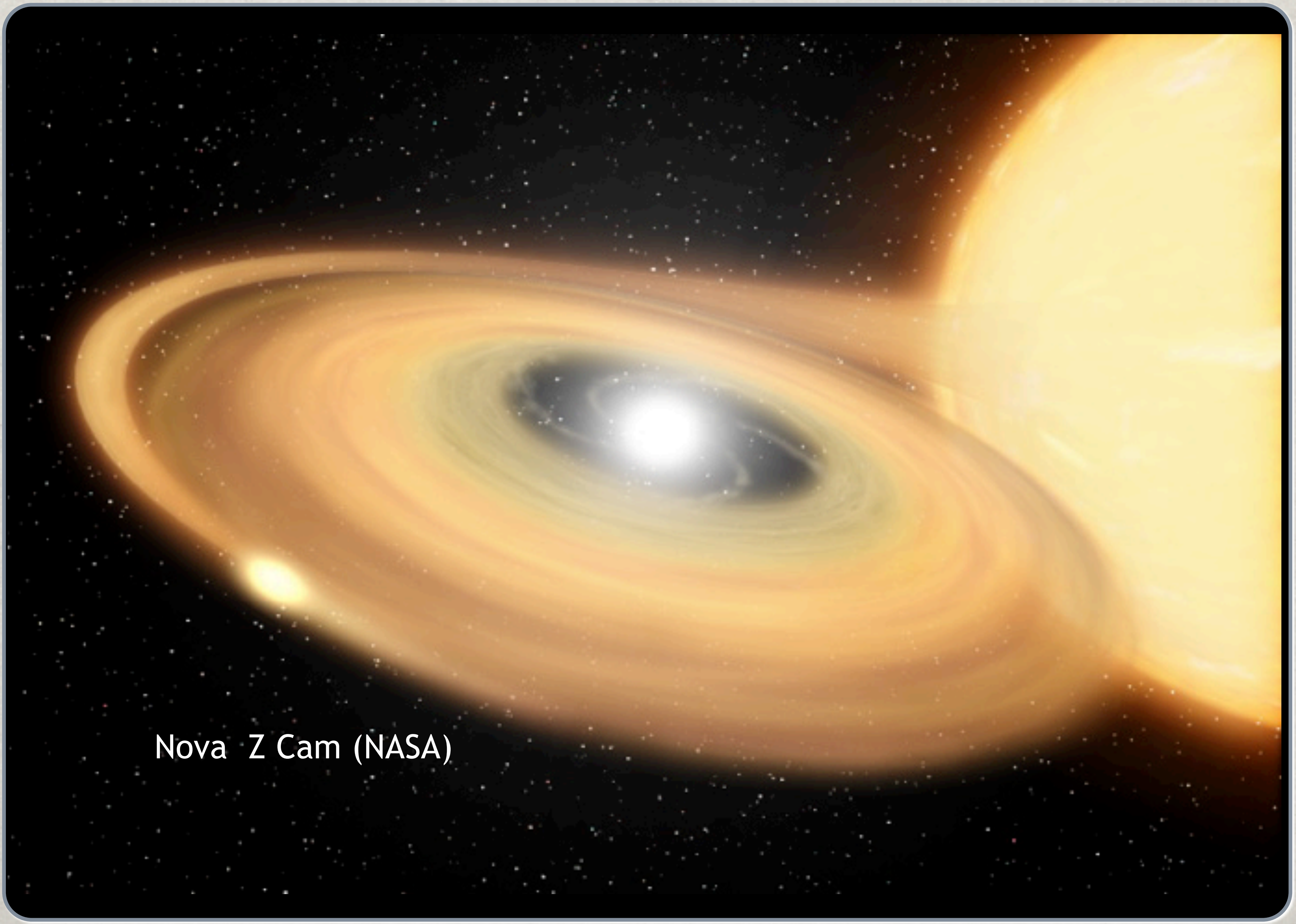
Accreting on a hot white dwarf may broaden range of accretion where the accreted matter burns to CO.

TYPES OF NOVAE

Observational Novae are categorized into 3 types based on recurrence timescale; dwarf, recurrent & classical.

Dwarf and some recurrent seem to be due to an accretion disk instability.

Others are thermo-nuclear explosion with recurrence time related to WD mass and accretion rate.



Nova Z Cam (NASA)

CLASSICAL NOVAE

T. Credner 12/99

Star Brightens a million-fold.

10^{38} J (10^{22} Megaton) Hydrogen bomb!

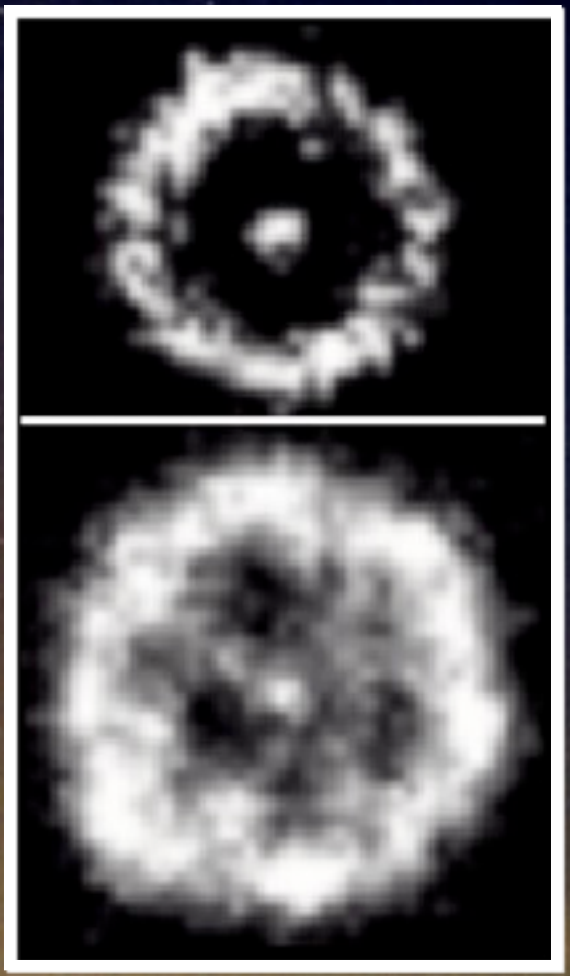
About 40 novae each year in our galaxy.

Frequently discovered by amateurs.

The binary systems that make up these cataclysmic variables are typically very tight ($a \sim R_\odot$) with periods of < 1 day.

Eject dust grains of material into space.

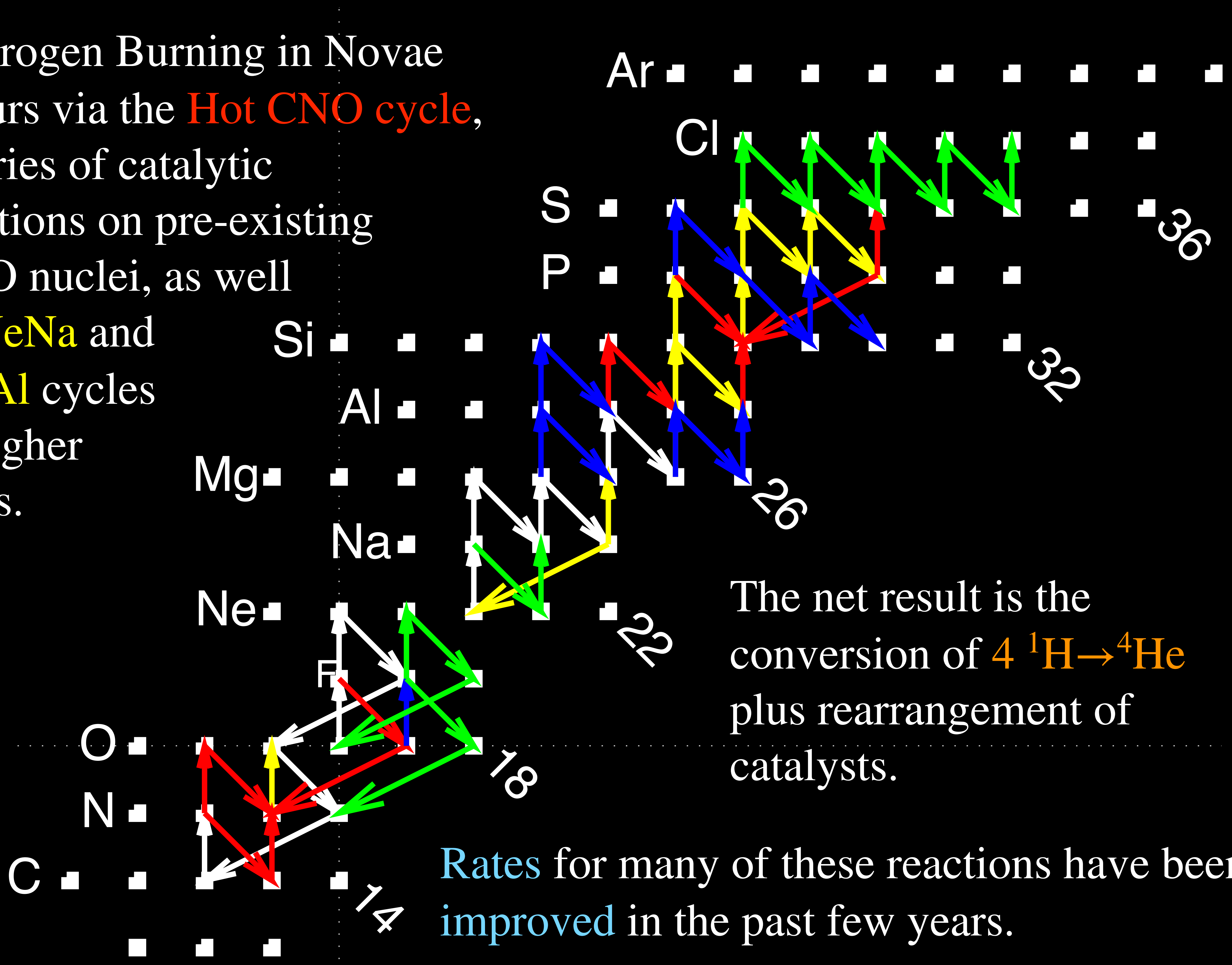
Ejecta includes White Dwarf material




Nova T Pyxdis (HST/NASA)

NUCLEAR REACTIONS IN NOVAE

Hydrogen Burning in Novae occurs via the Hot CNO cycle, a series of catalytic reactions on pre-existing CNO nuclei, as well as NeNa and MgAl cycles at higher mass.



The net result is the conversion of 4 $^{1}H \rightarrow {}^{4}He$ plus rearrangement of catalysts.

Rates for many of these reactions have been improved in the past few years.

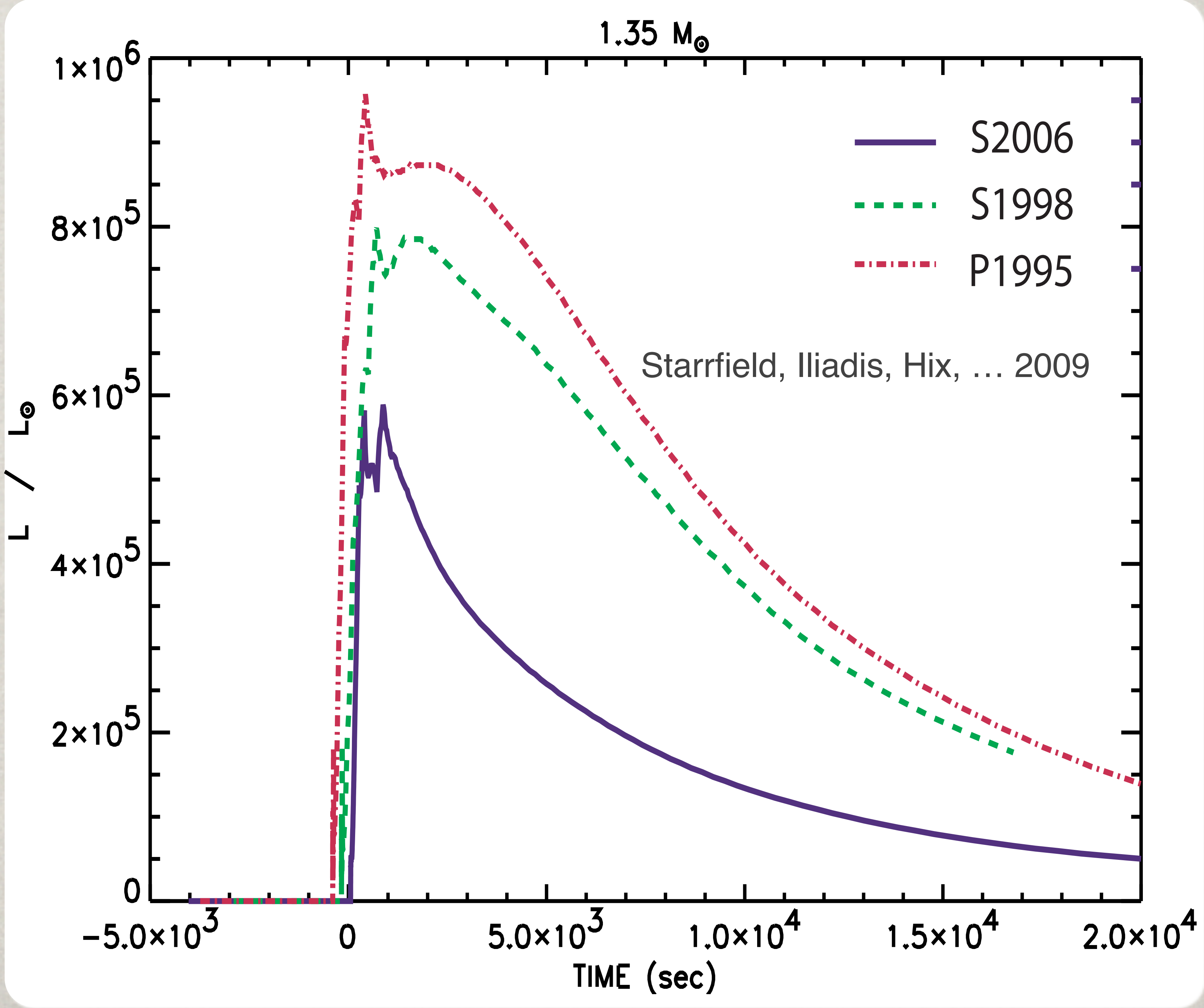
UPDATING NUCLEAR DATA

Models using newer rates show significant variations in bulk properties, like luminosity.

Nucleosynthesis products change by factors of two or more.

For example,

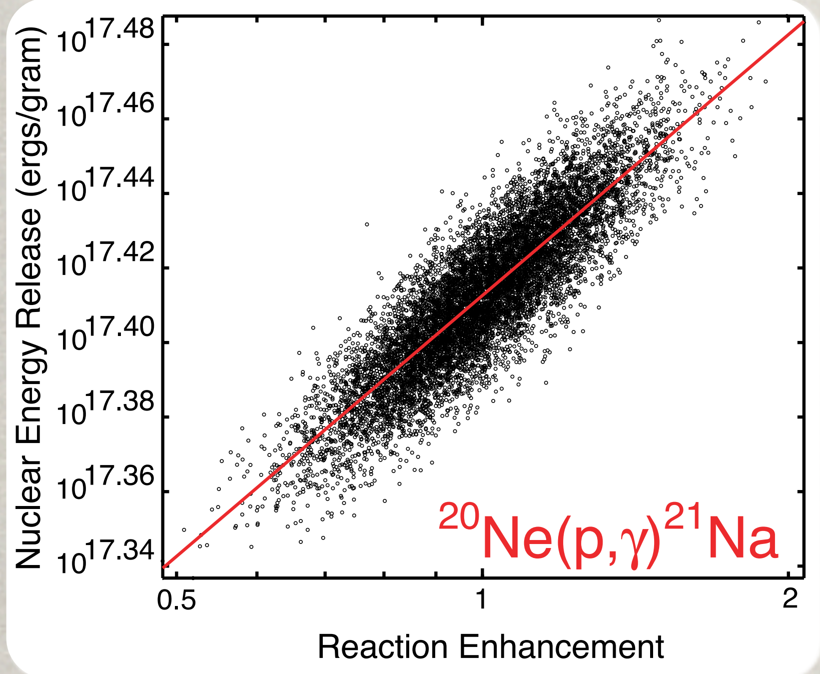
^{13}C(-17%)
^{15}N(-83%)
^{17}O(-64%)
^{22}Na(-52%)
^{26}Al(+7%)

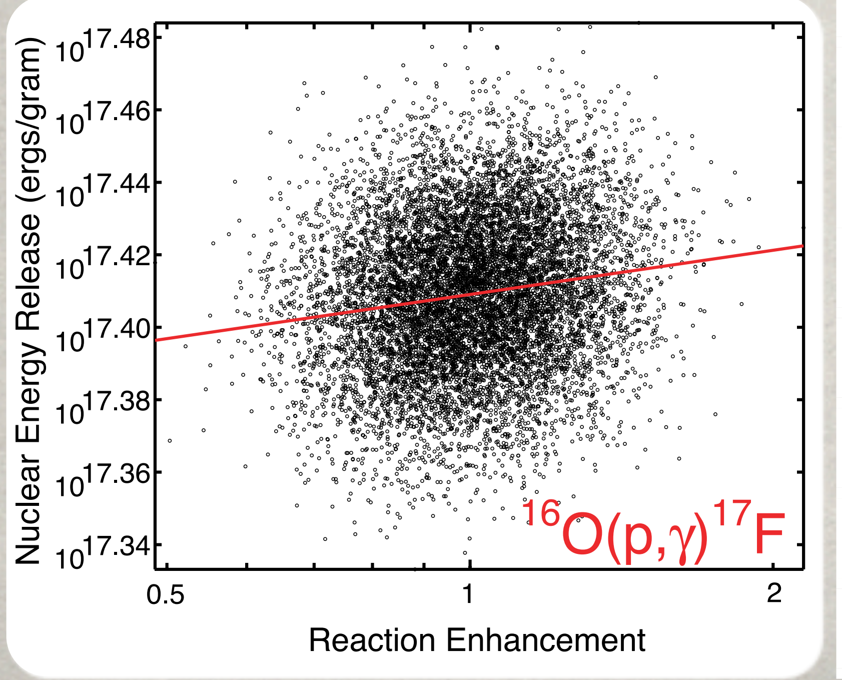


Starrfield, Iliadis, Hix, … 2009

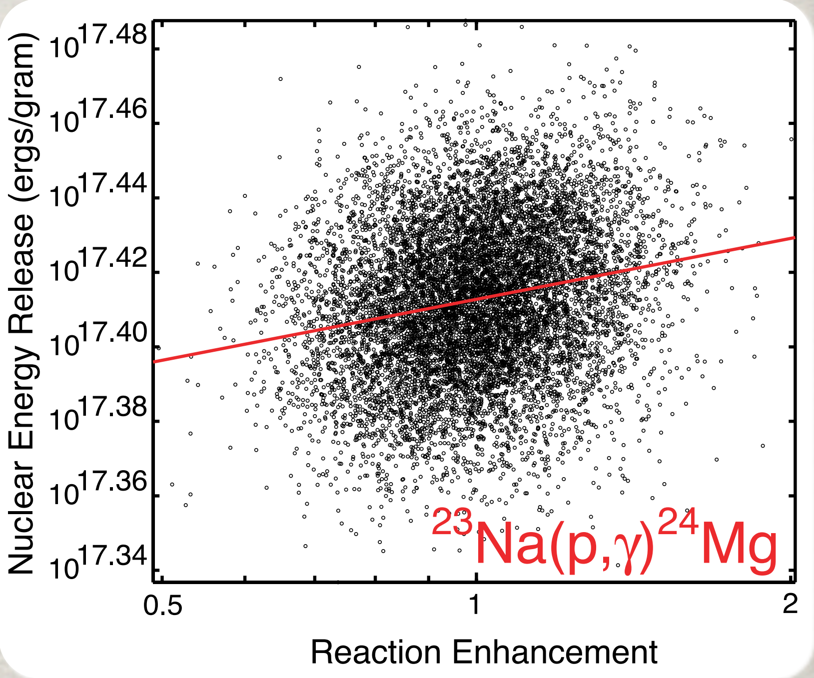
FINDING SENSITIVITIES

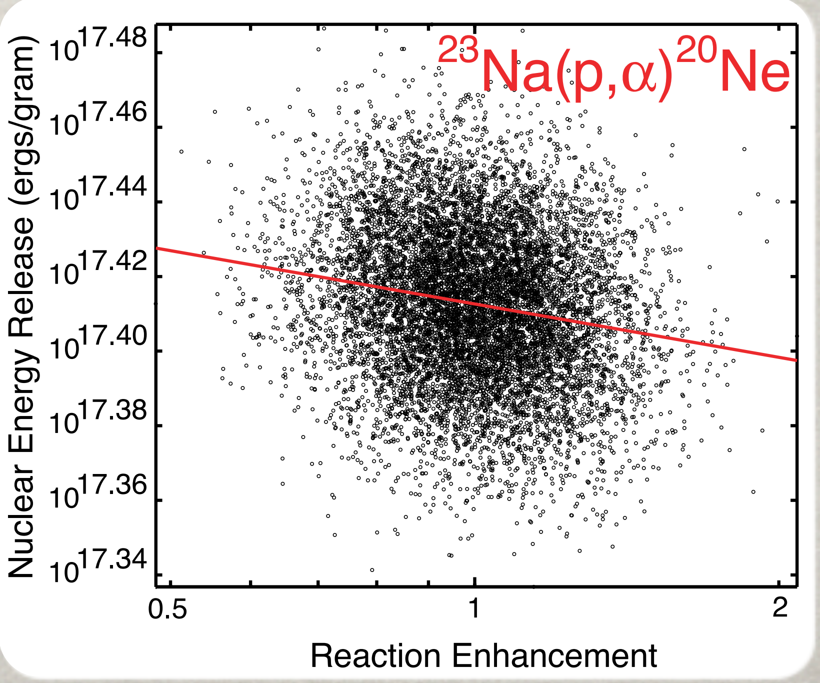
For a nova on a 1.25 solar mass WD, Monte Carlo sensitivity analysis indicates these reactions most strongly impact the energy generation.



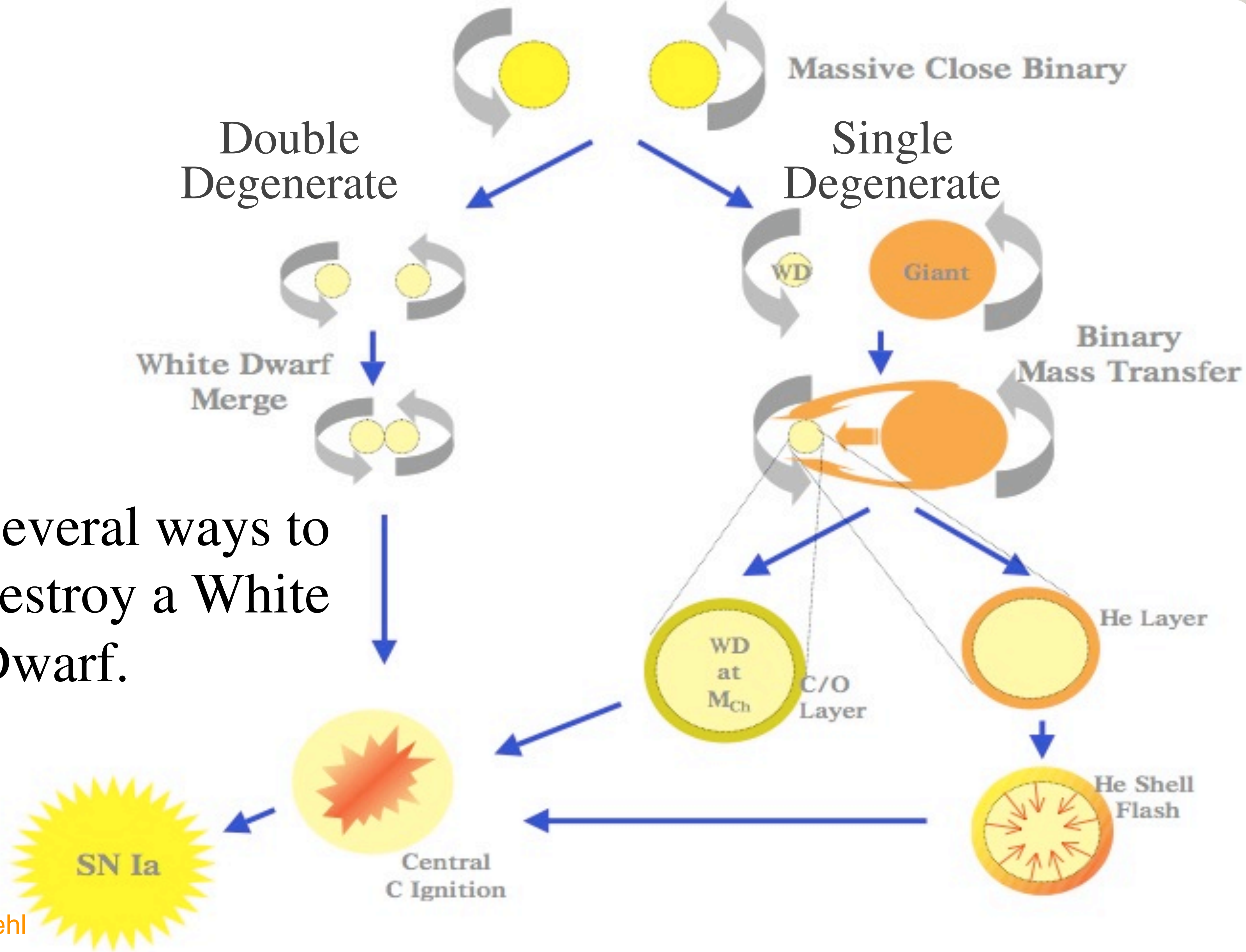


Reaction	Slope
^{20}Ne(p,γ)^{21}Na	0.233±0.001
^{23}Na(p,γ)^{24}Mg	0.054±0.003
^{23}Na(p,α)^{20}Ne	-.047±0.003
^{16}O(p,γ)^{17}F	0.041±0.003
^{28}Si(p,γ)^{29}P	0.025±0.003
^{23}Mg(p,γ)^{24}Al	0.024±0.001
^{14}N(p,γ)^{15}O	0.021±0.003
^{17}F(p,γ)^{18}Ne	0.021±0.001
^{25}Al(p,γ)^{26}Si	0.011±0.001
^{27}Si(p,γ)^{28}P	0.010±0.001
^{25}Mg(p,γ)^{26}Al	0.009±0.003
^{30}P(p,γ)^{31}S	0.009±0.001
^{26}Al(p,γ)^{27}Si	0.007±0.001
^{13}N(p,γ)^{14}O	0.004±0.001





THERMONUCLEAR SN MECHANISM



Several ways to destroy a White Dwarf.

R. Diehl

TNSN PROGENITORS

One approach to understanding the relative frequency of the different potential mechanisms is to search for the binary companions. Unfortunately, the results have been mixed.

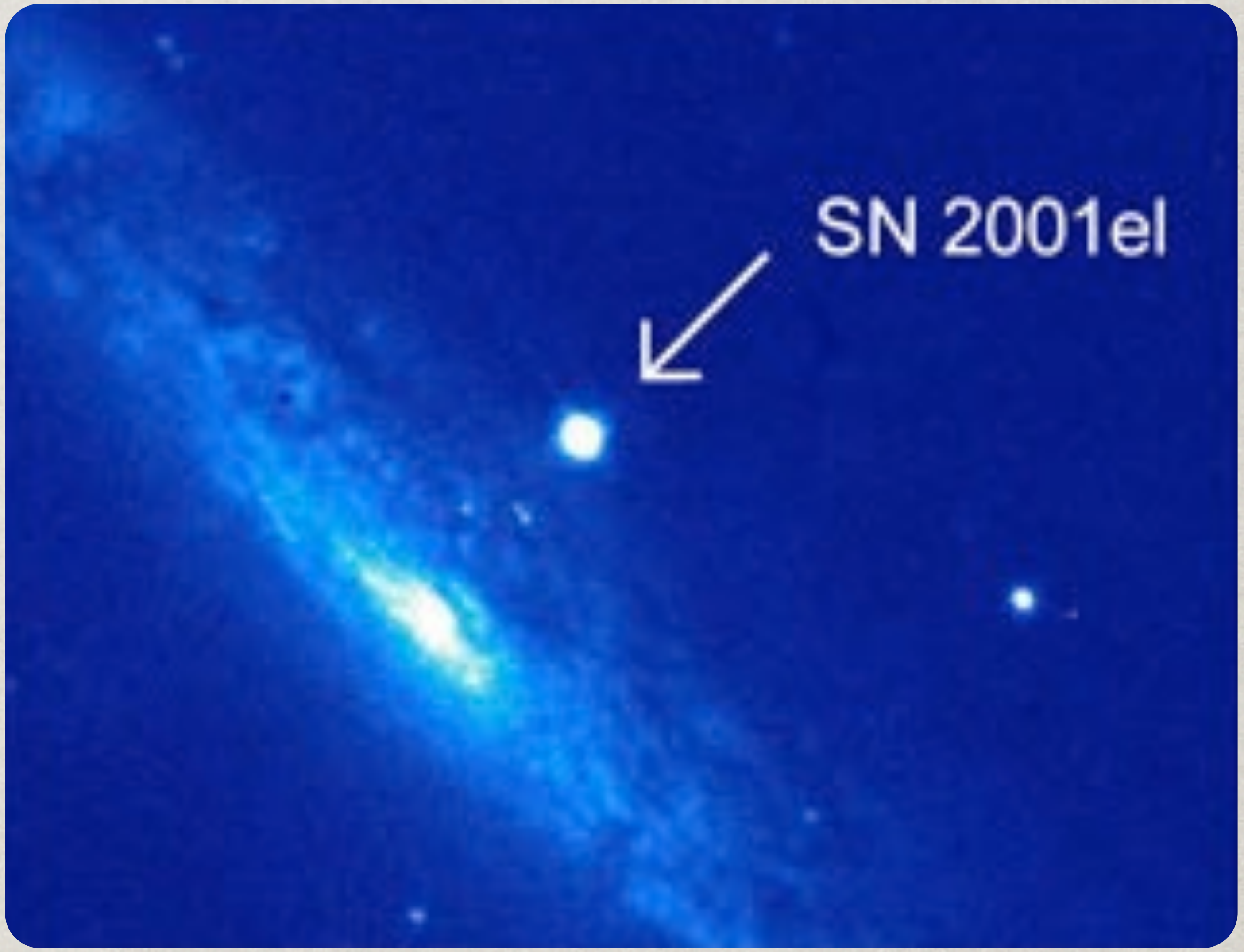
Supernova PTF 11kx, discovered 1/16/11, showed evidence of interaction between the supernova ejecta and nova ejecta, suggesting that the WD had previously experienced a nova outburst. This supports the single degenerate scenario, since novae have hydrogen-rich companions.

Observations of Supernova 2011fe, discovered 8/24/11 in nearby M101, lack features expected for a red giant or white dwarf companion, favoring a main sequence star.

Deep observations of SNR 0509−67.5 find no suitable ex-companion star, supporting the double degenerate scenario.

VISIBLE AT GREAT DISTANCE

Because of their tremendous brightness, supernovae are very useful for determining distances.



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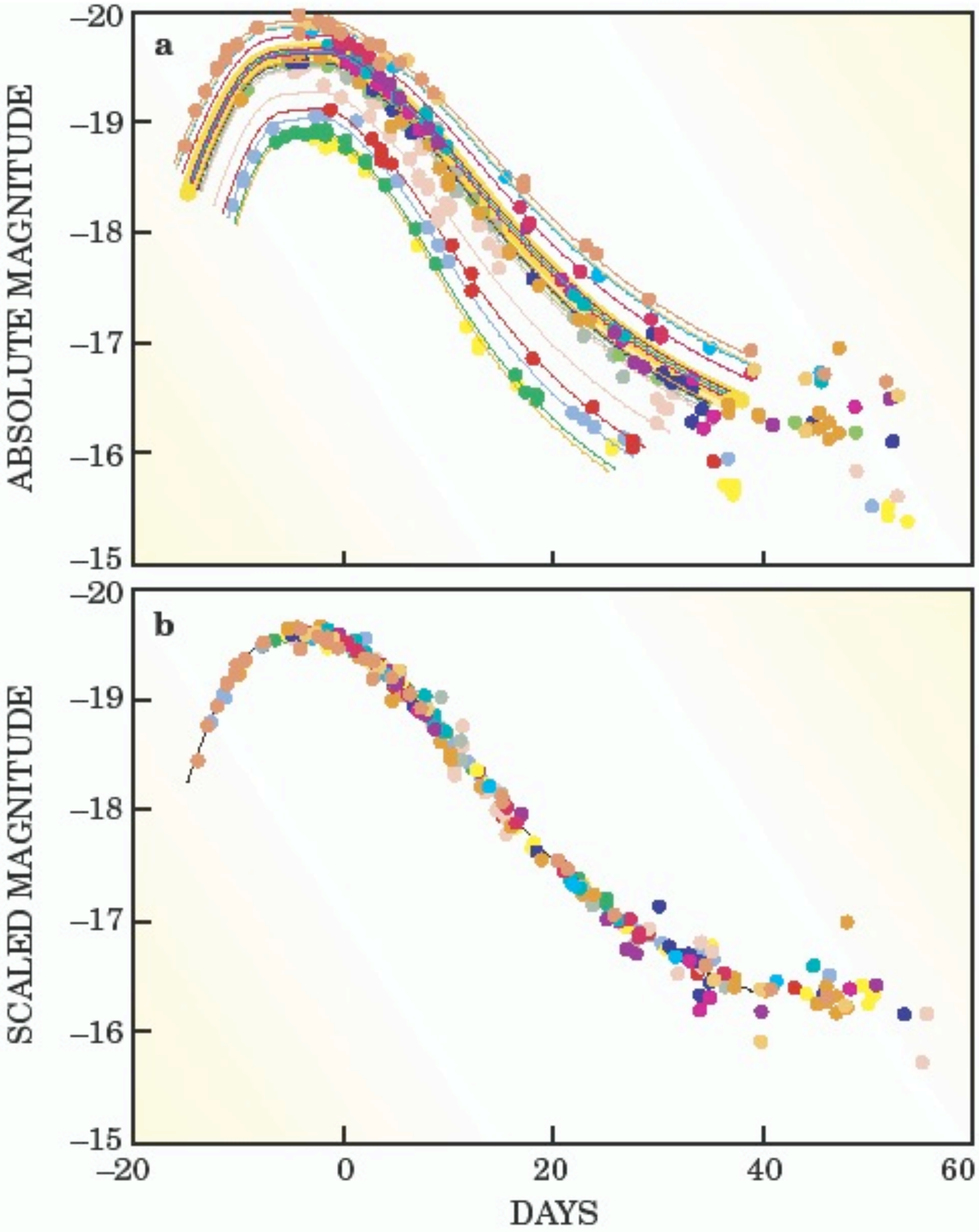
This is particularly true for Type Ia SN, whose luminosity can be calibrated from their light curve.



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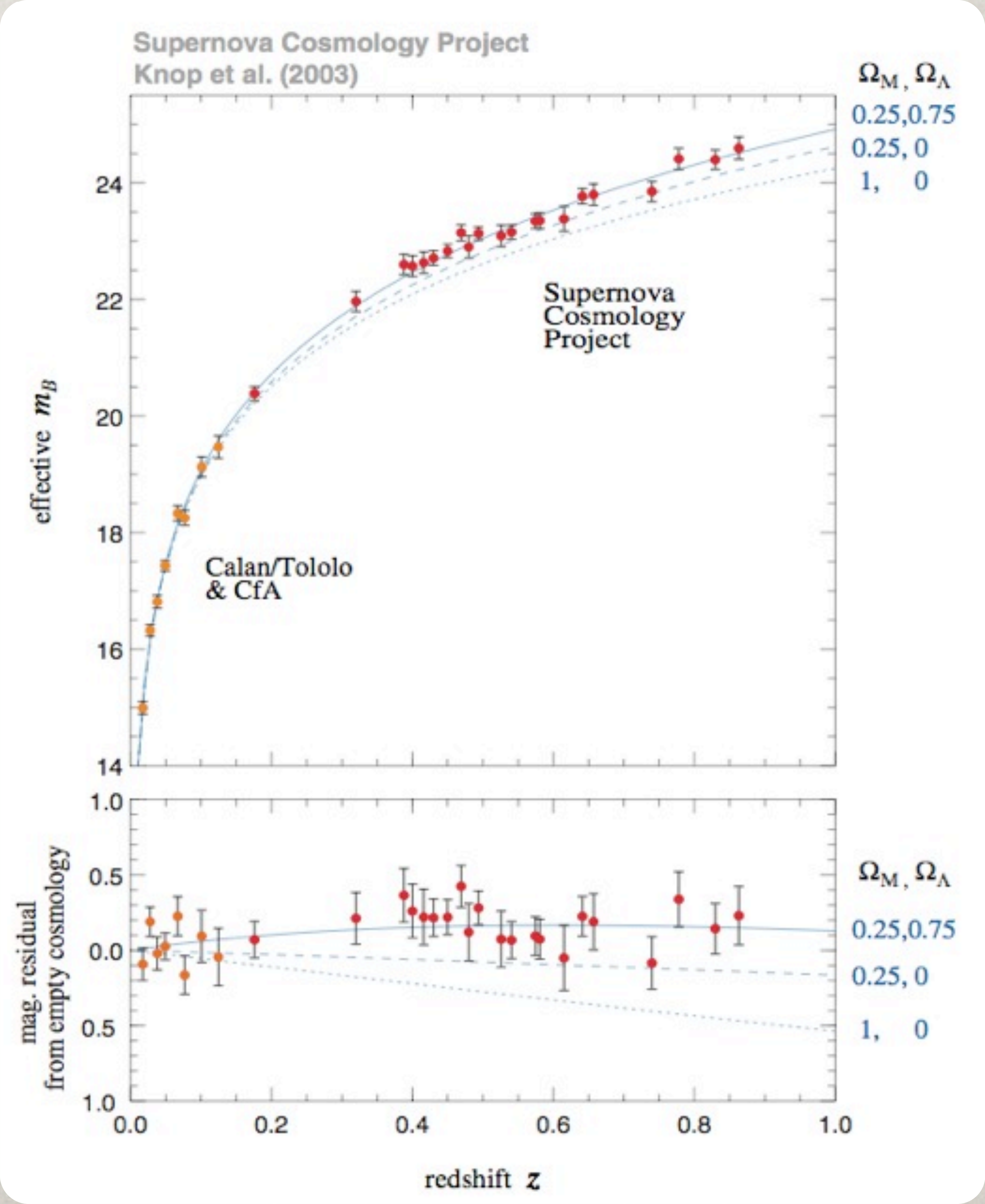
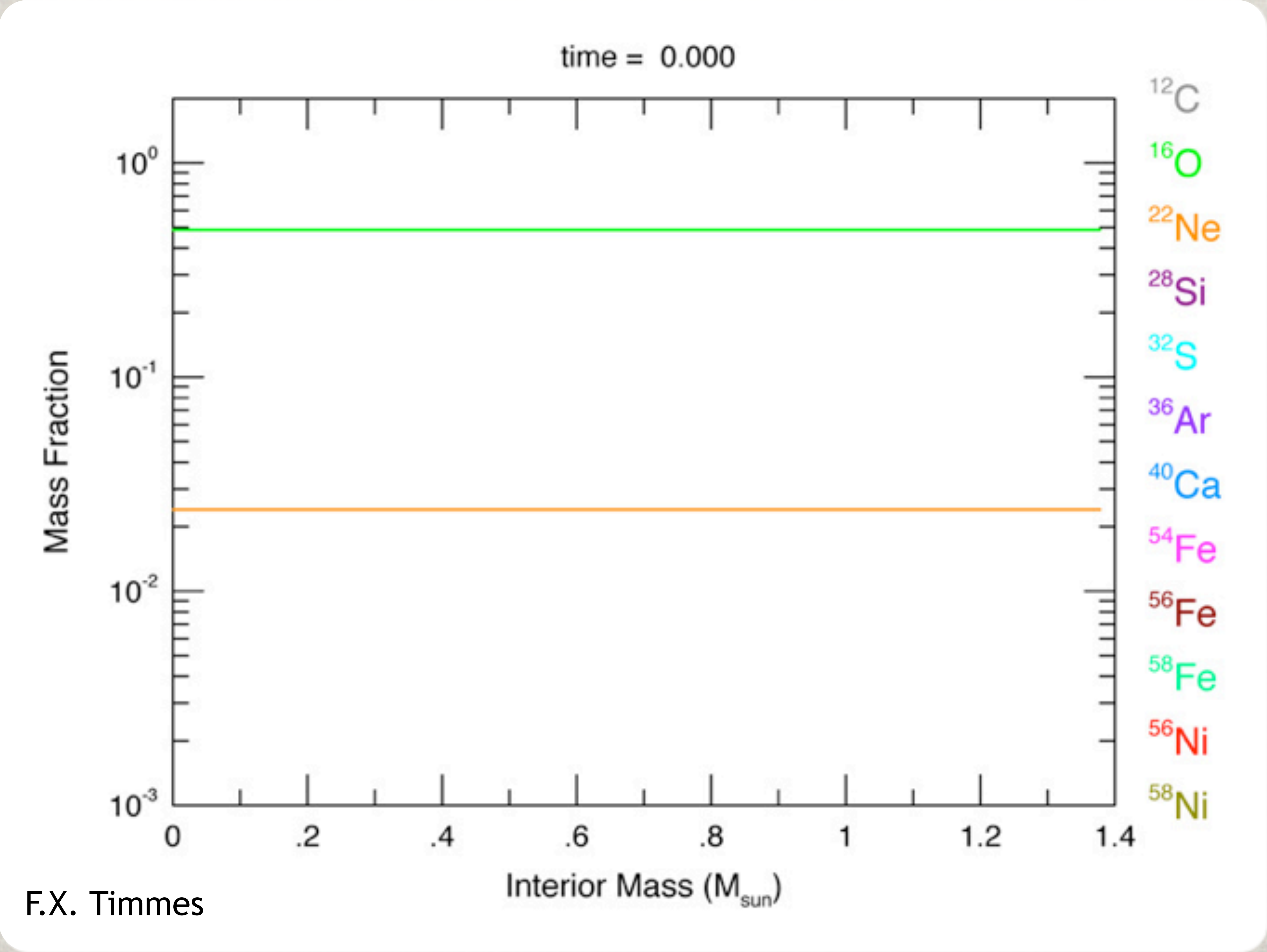
This led to the discovery that the expansion of our universe is accelerating.



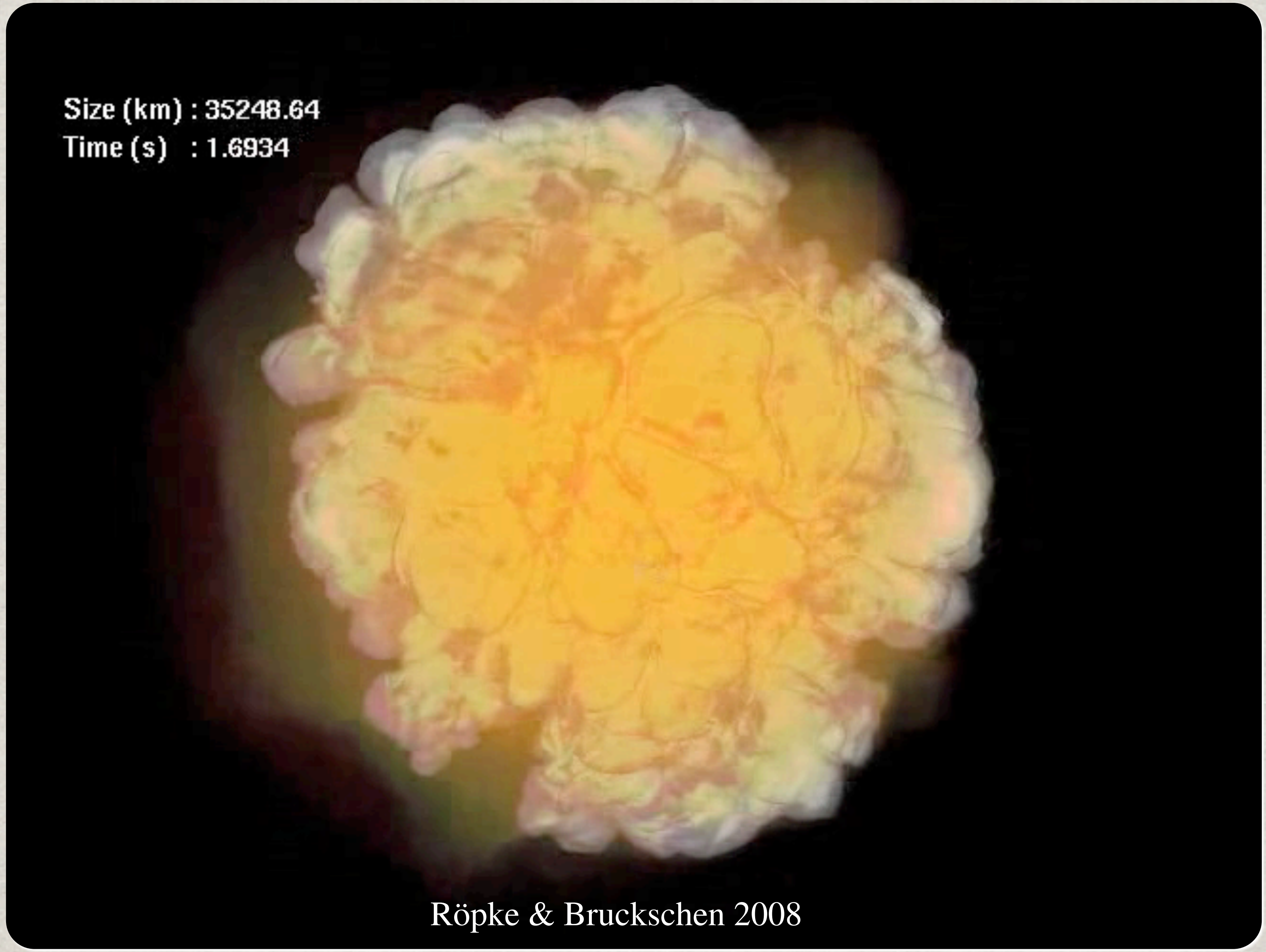
NUCLEOSYNTHESIS IN THERMONUCLEAR SN



F.X. Timmes

As the central density rises, a thermonuclear flame is ignited which eventually propagates throughout the star.

THE MULTI-D VIEW



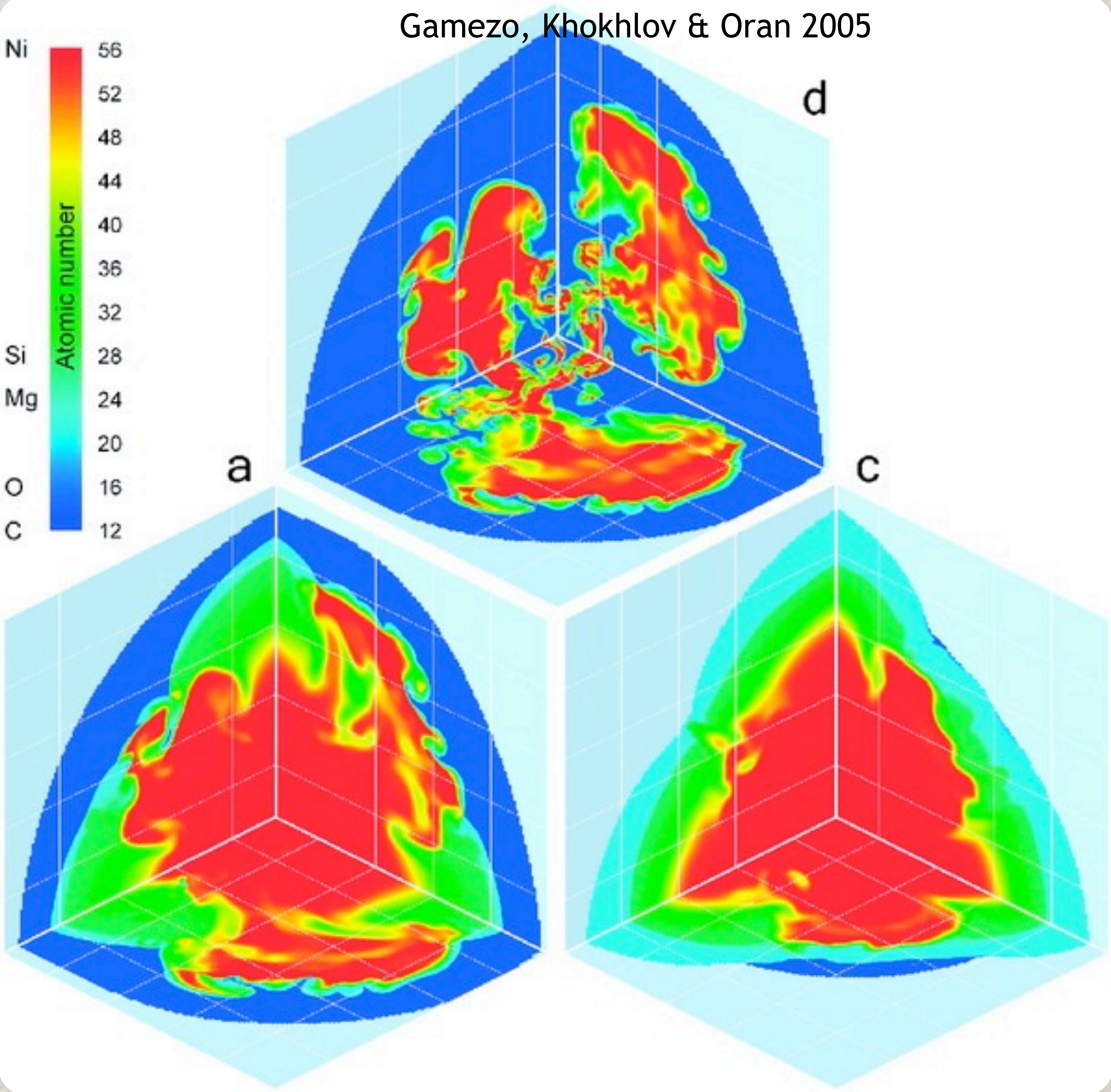
Röpke & Bruckschen 2008

In reality, the flame propagation is much more complex than 1D implies, with turbulence and other hydrodynamic instabilities shaping the flame.

DEFLAGRATION/DETONATION

Multi-D deflagrations leave pockets of unburned material behind, but observations do not show this.

A Deflagration to Detonation transition (DDT) must occur to burn these pockets.


Gamezo, Khokhlov & Oran 2005

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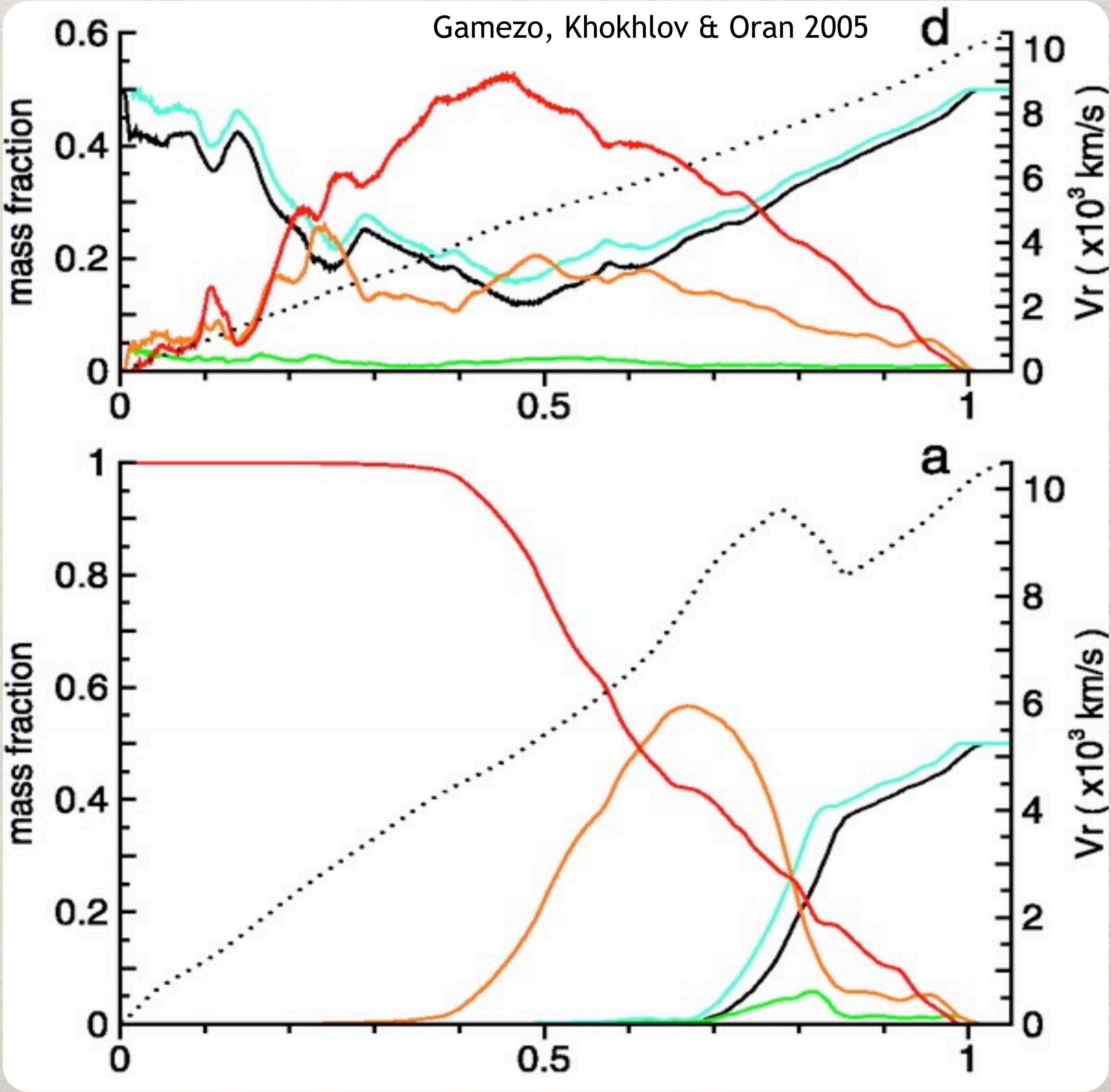
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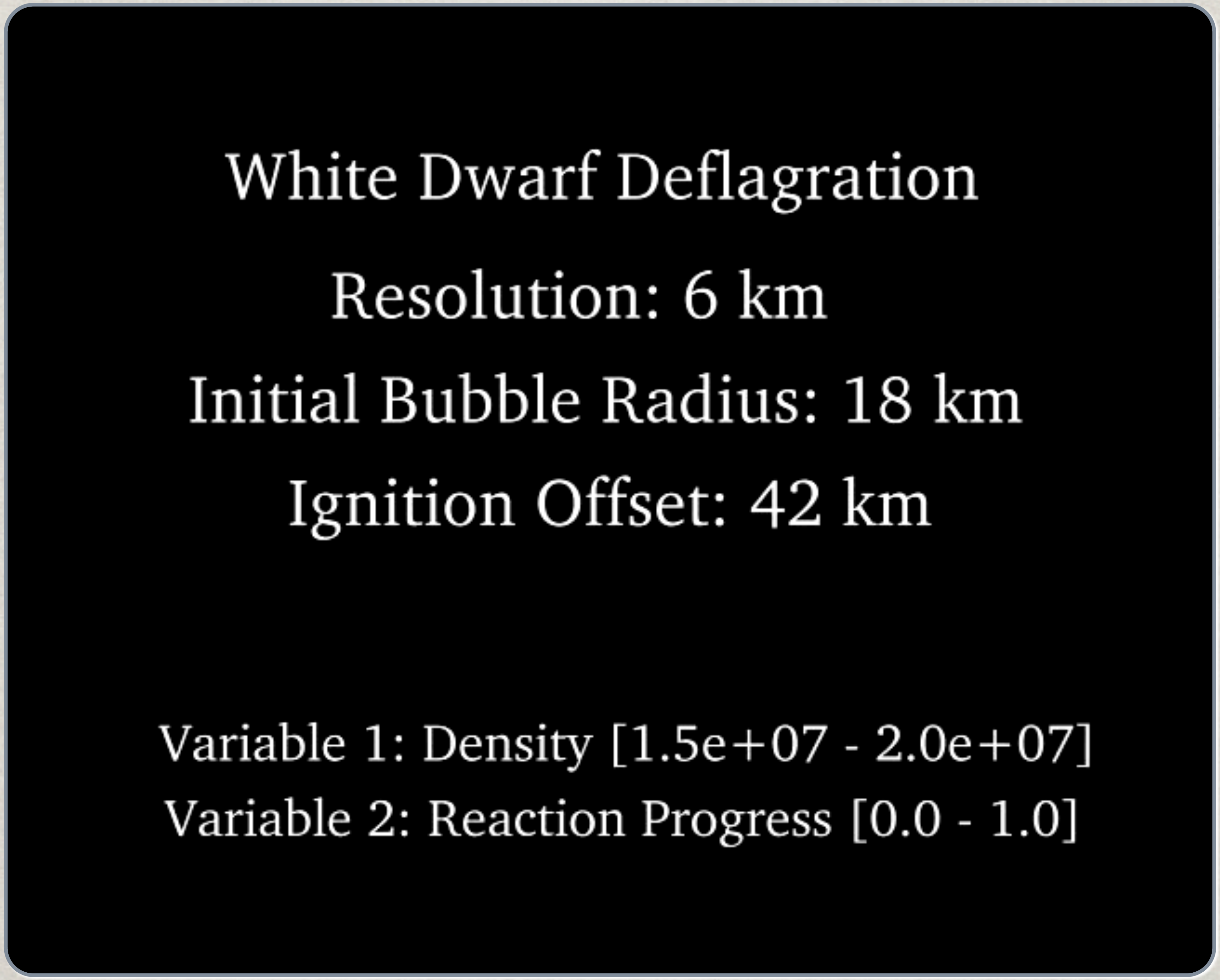
ONE WAY TO DDT?



White Dwarf Deflagration

Resolution: 6 km

Initial Bubble Radius: 18 km

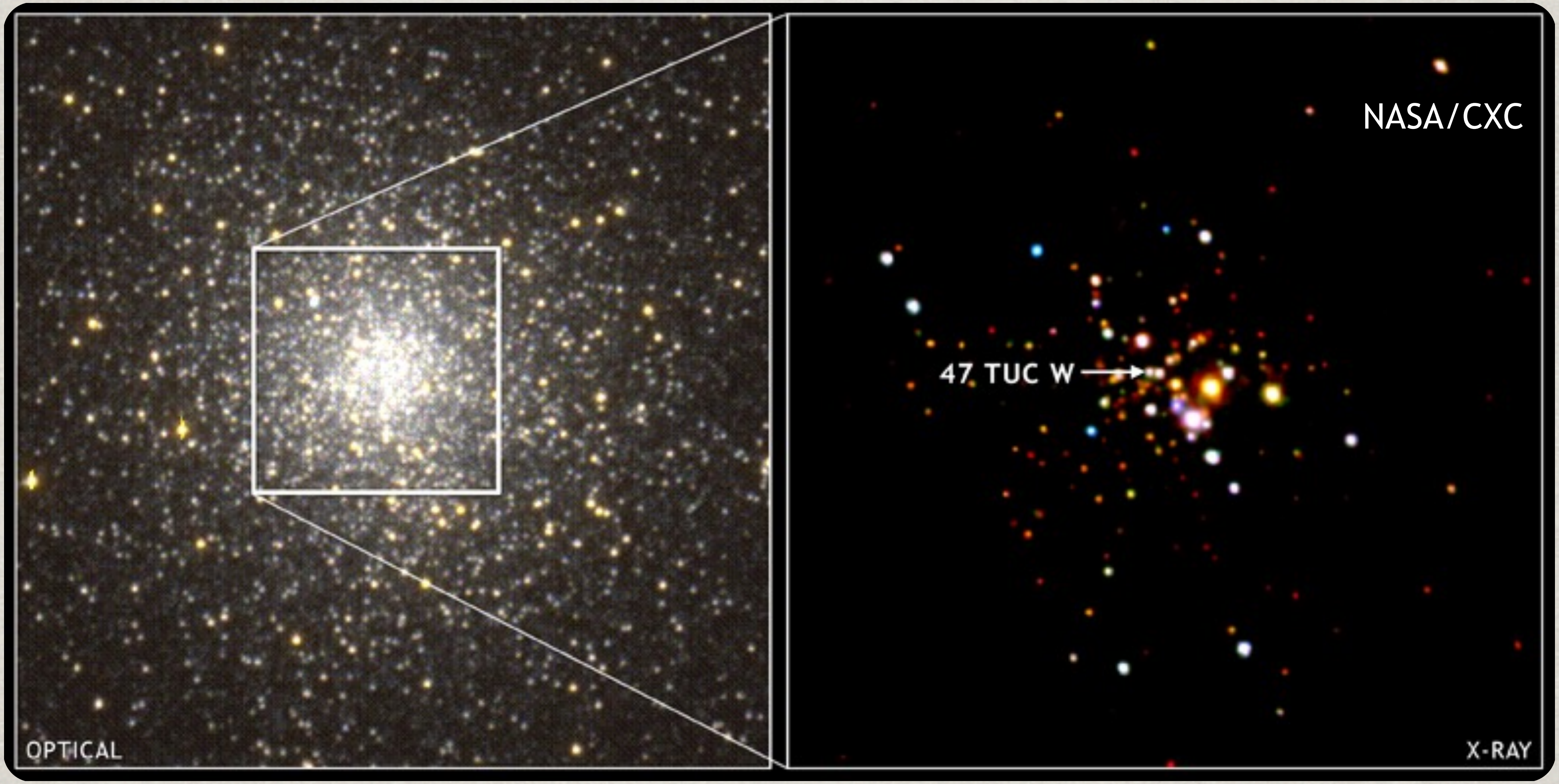
Ignition Offset: 42 km

Variable 1: Density [1.5e+07 - 2.0e+07]

Variable 2: Reaction Progress [0.0 - 1.0]

In terrestrial conditions, like a back-firing engine, DDT is often due to geometry/confinement. Perhaps this is also true for Thermonuclear SN.

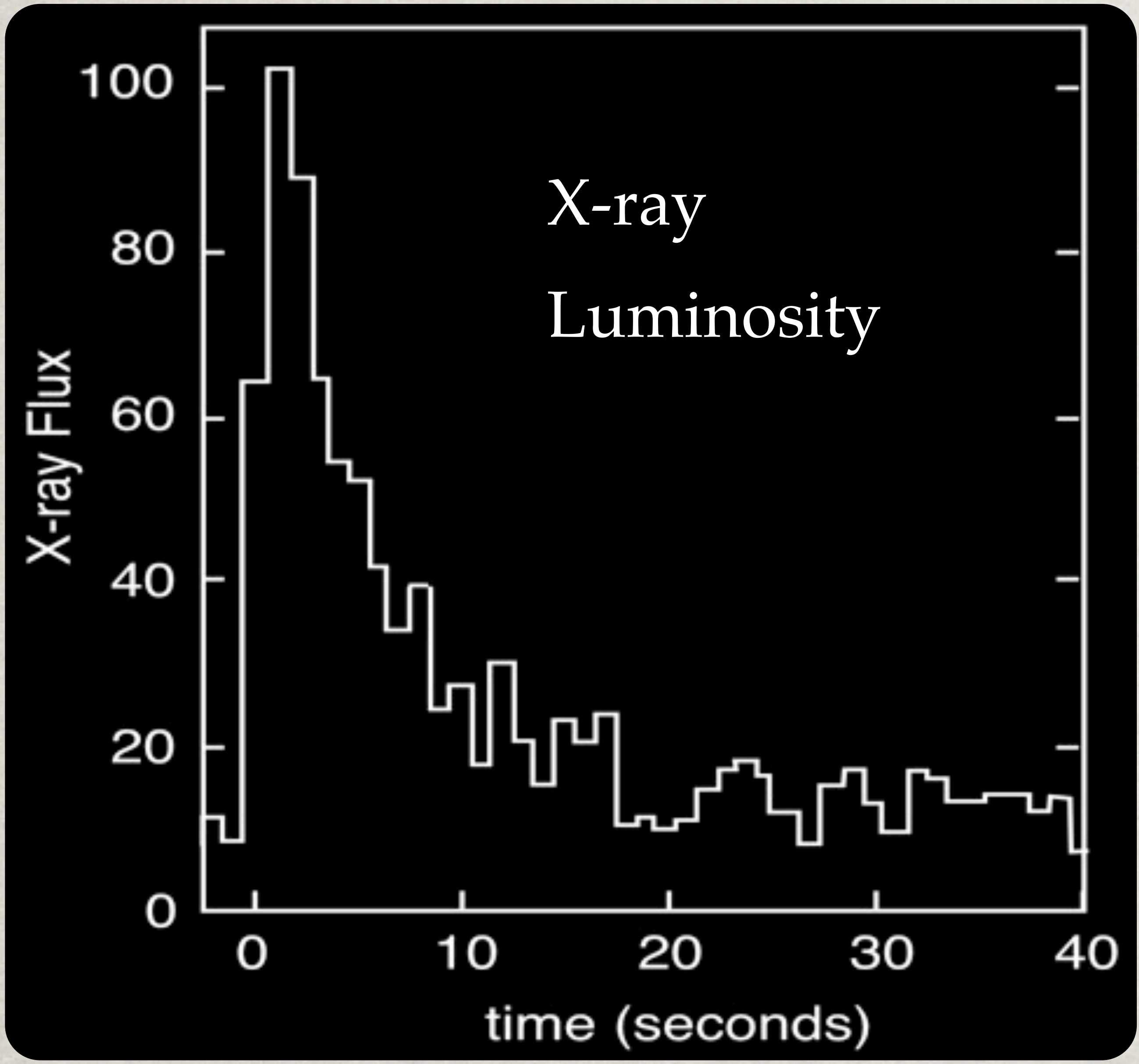
ACCRETION ONTO NEUTRON STARS

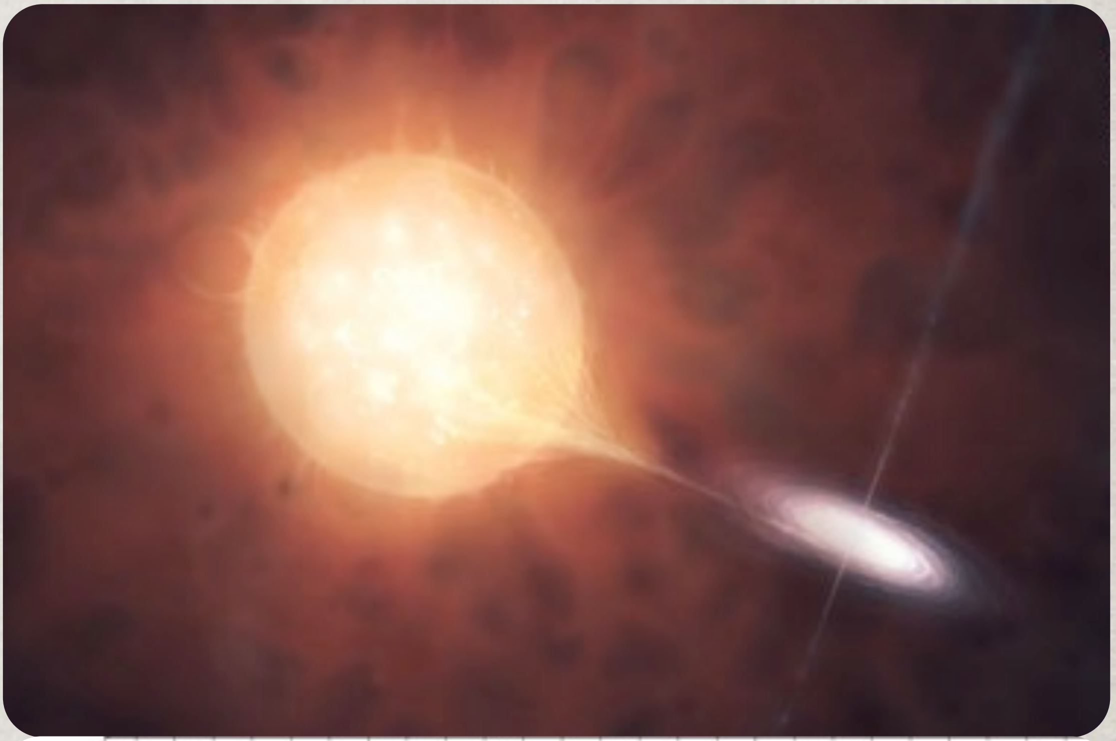


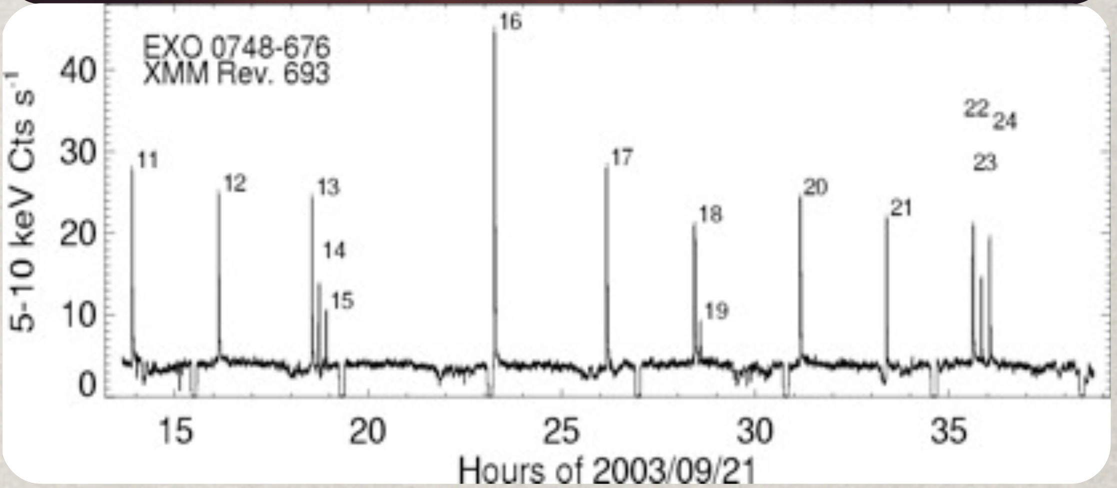
Accretion from a companion can also occur onto a neutron star. Such accreting neutron stars account for many observed X-ray sources.

Unlike for a white dwarf, nuclear energy release (~ 0.01 mc^2) is insignificant compared to the gravitational energy (~ 0.1 mc^2) release, unless it is intermittent.

X-RAY BURSTS







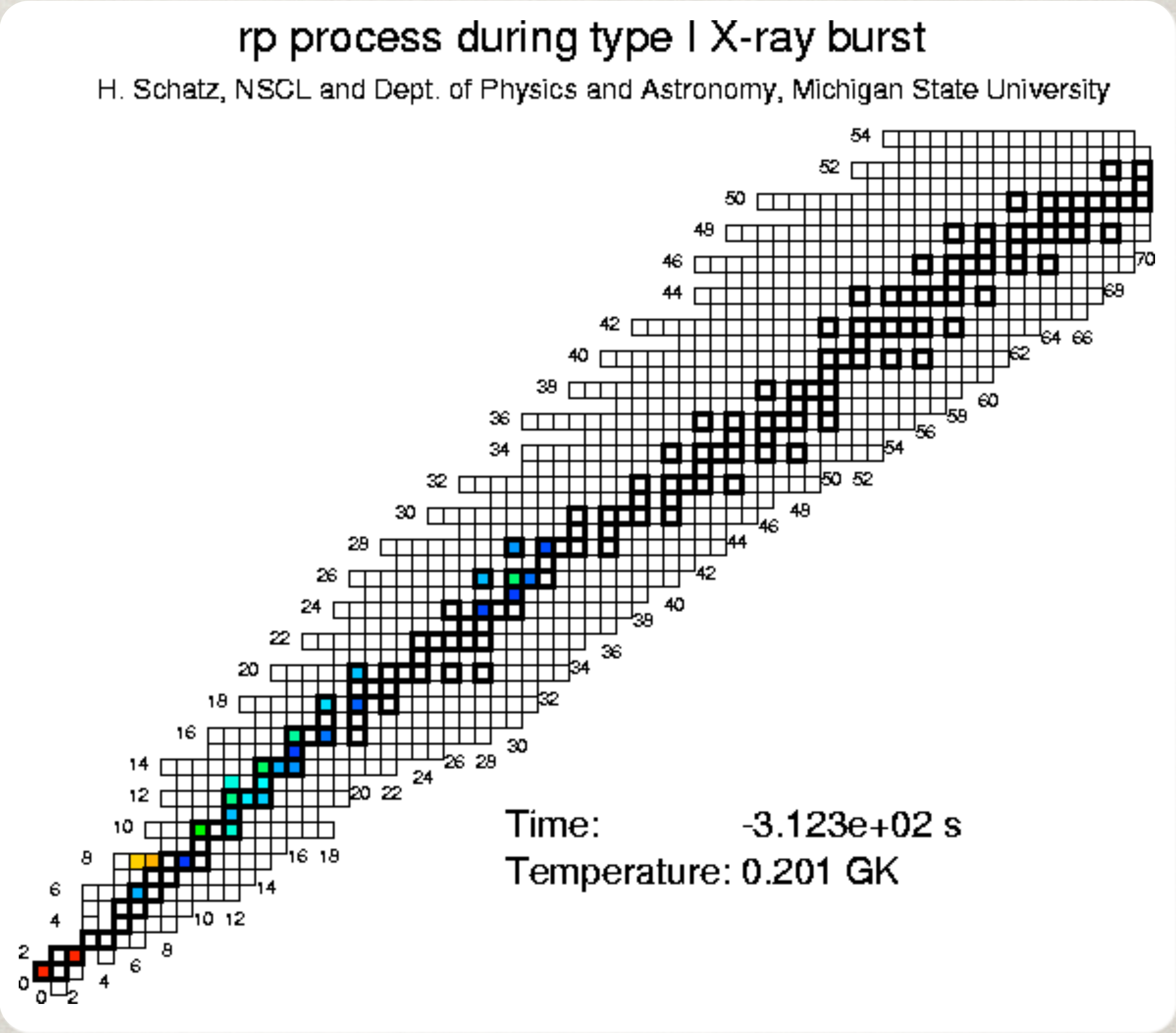
Some X-ray binaries periodically produce seconds-long bursts of X-rays (~10^{38} ergs s^{-1}) can recur hourly or daily.

These Type 1 X-ray bursts are due unstable H-He burning on the neutron star surface.

The rp-process

Initial CNO cycle burning leads to breakout and the rp-process reaching as high as Sn-Sb-Te.

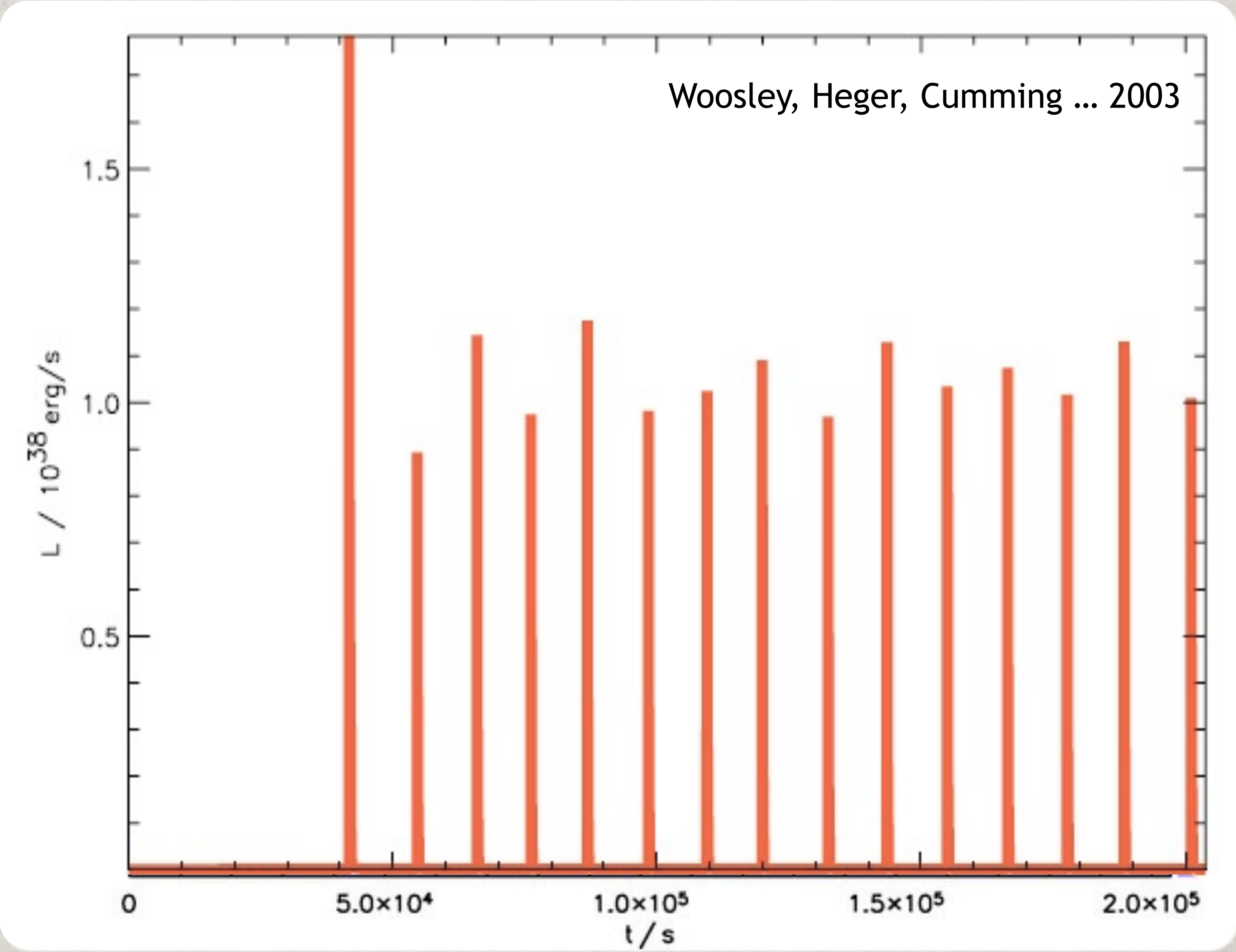
He burning via triple-α builds additional seeds for the rp-process.



Several waiting points control the reaction flow, mostly β decays, but also equilibrated (p,γ) (γ,p) reaction pairs.

BETTER MODELING FOR XRB

Single zone models have been replaced by true 1D hydrodynamic models which include large networks and General Relativity.



These improved models have taught us the importance of the ash to subsequent bursts, as the heavy element ash "dilutes" the accreted matter, weakening the burst.

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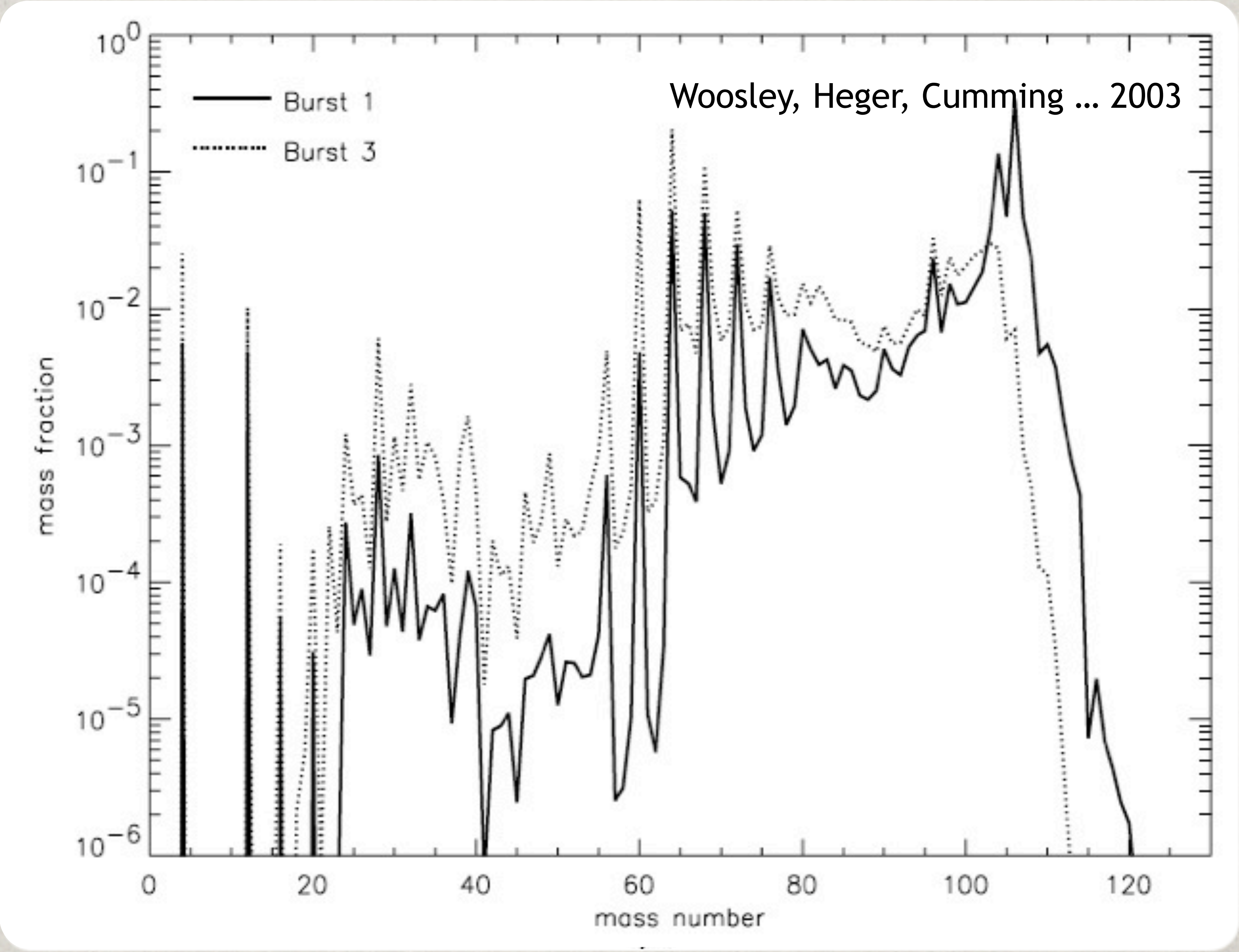

Woosley, Heger, Cumming … 2003

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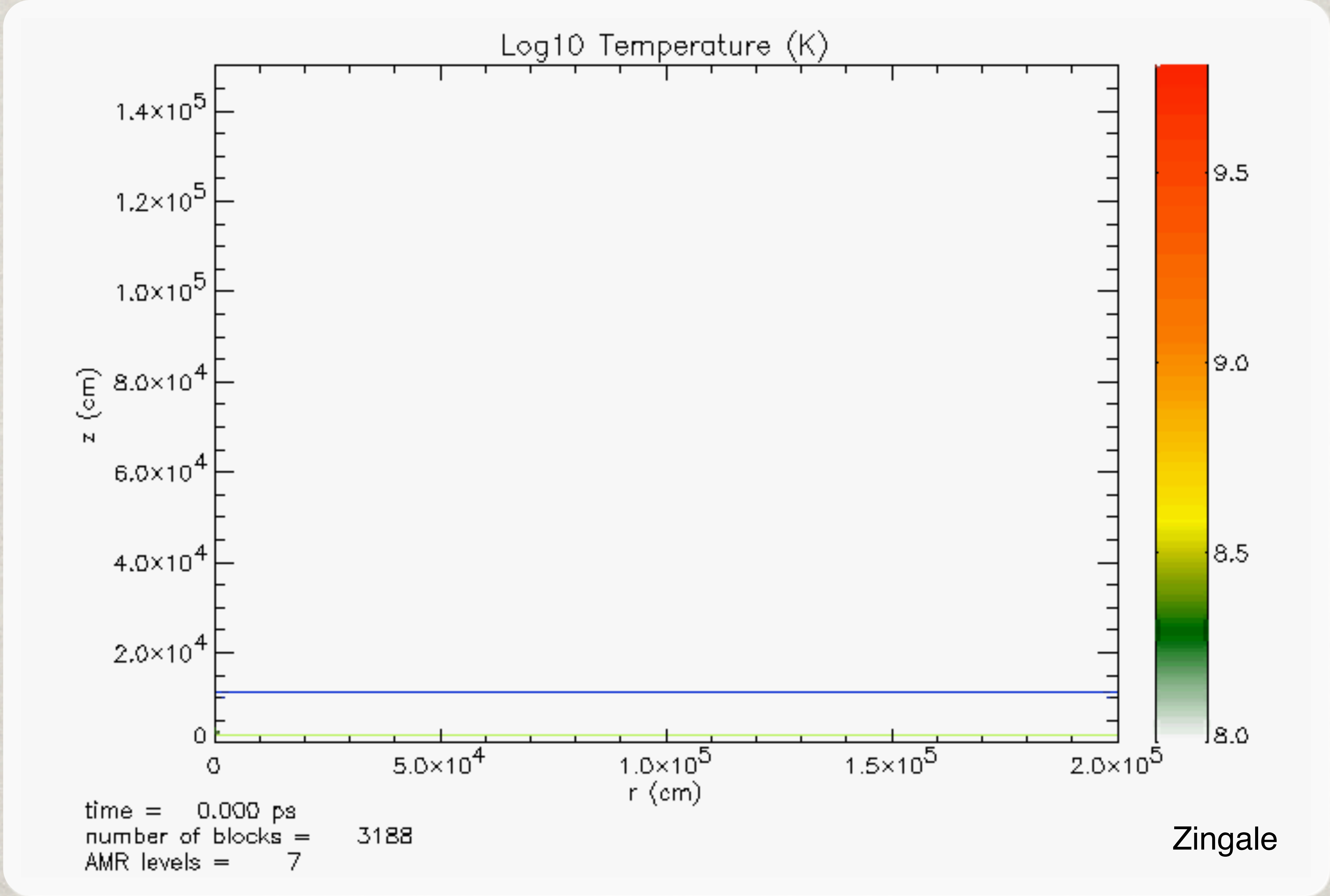
XRB IN MULTI-D

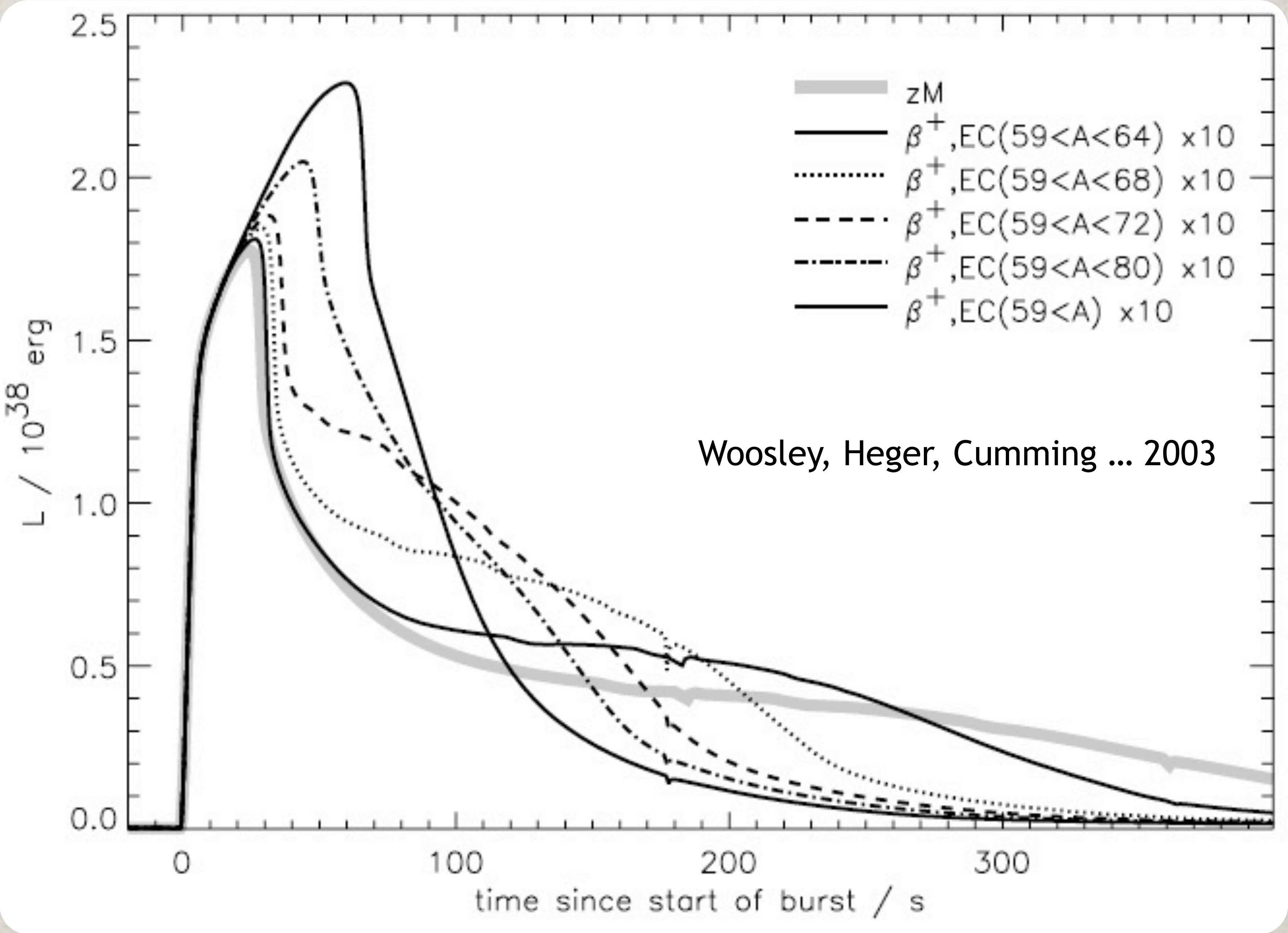


While 1D models (by design) assume simultaneous ignition over the entire surface, ignition of the XRB takes several hundred μs to circle the neutron star.

Nuclear Physics influence on X-Ray Bursts

Many of the rp-process waiting points are β^+ decays.

Variations of β^+ decays produce noticeable effects on XRB luminosity.



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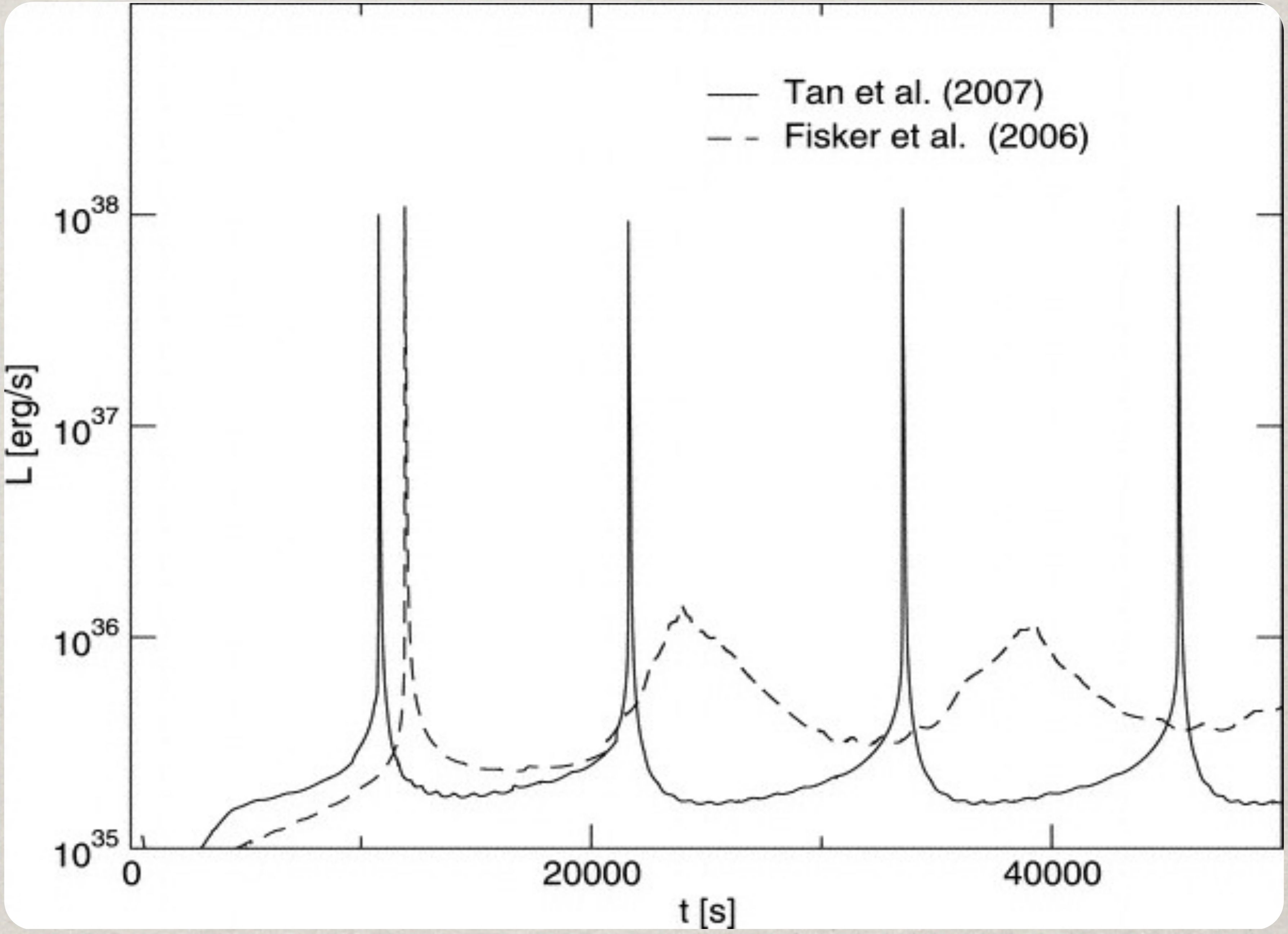
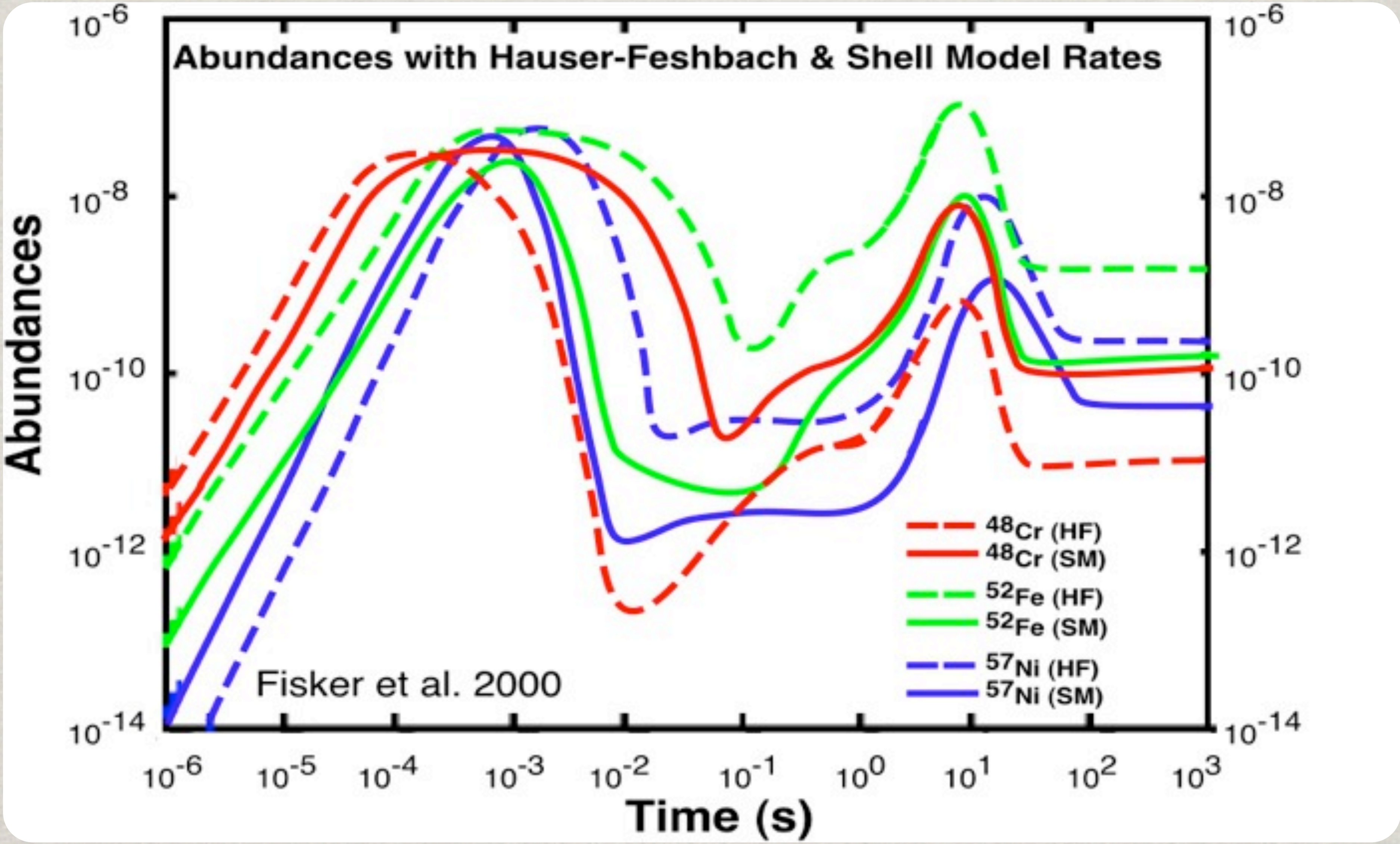


XRB luminosity has also shown significant sensitivities to $^{15}O(\alpha,\gamma)^{19}Ne$ (Fisker, Tan , Görres & Wiescher 2007)

NUCLEAR PHYSICS INFLUENCE ON X-RAY BURSTS



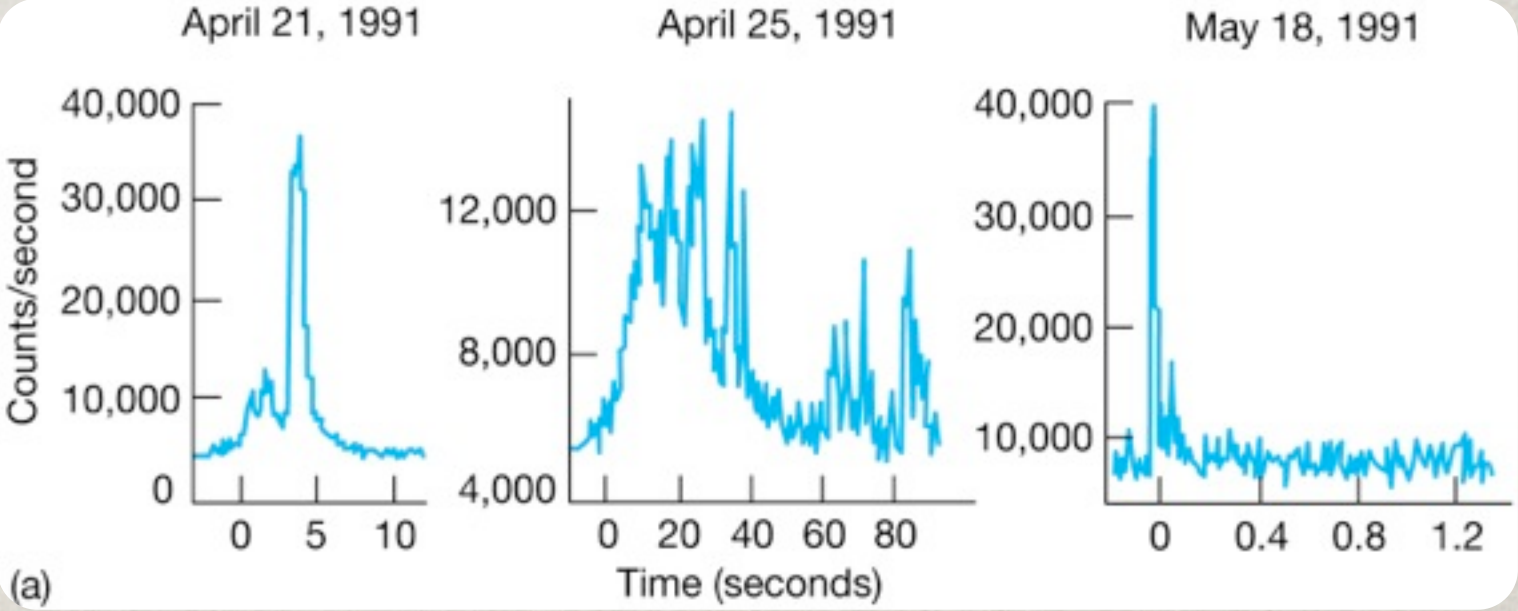
Nucleosynthesis in XRBs is also sensitive to nuclear reaction rates.

Improved shell model calculations for new rates change predictions of synthesized abundances ~10x.

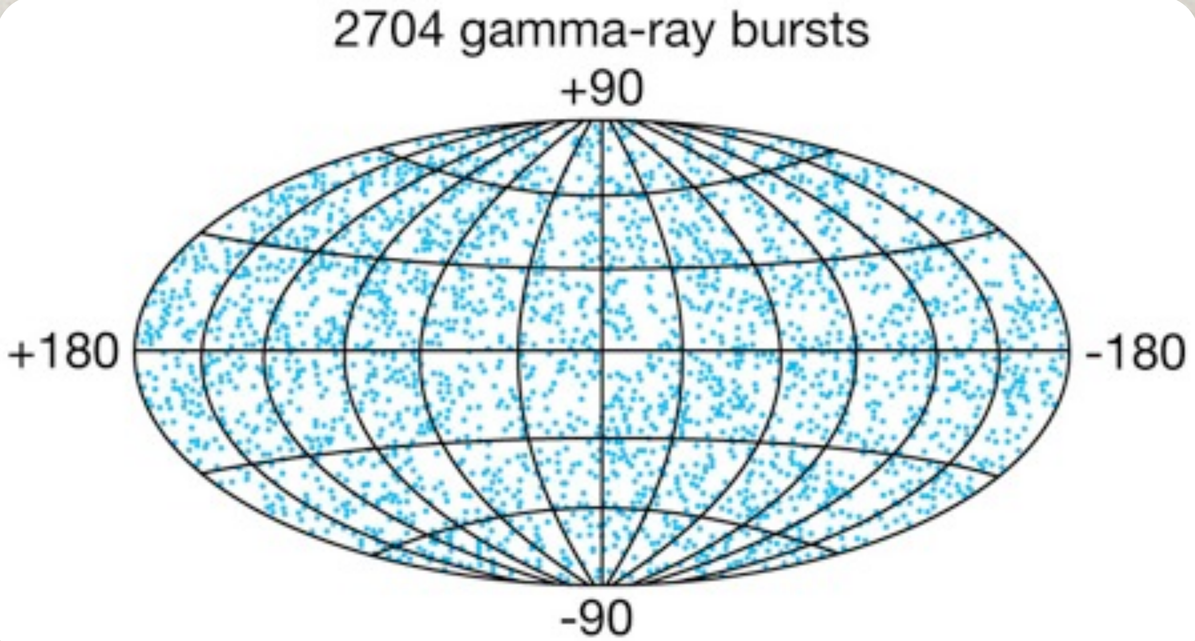
GAMMA-RAY BURSTS

Intense bursts of gamma-rays are also observed lasting seconds and occurring roughly once per day.

The bursts can be divided into short and long duration bursts ($t \sim 0.3$ s and ~ 30 s, respectively).

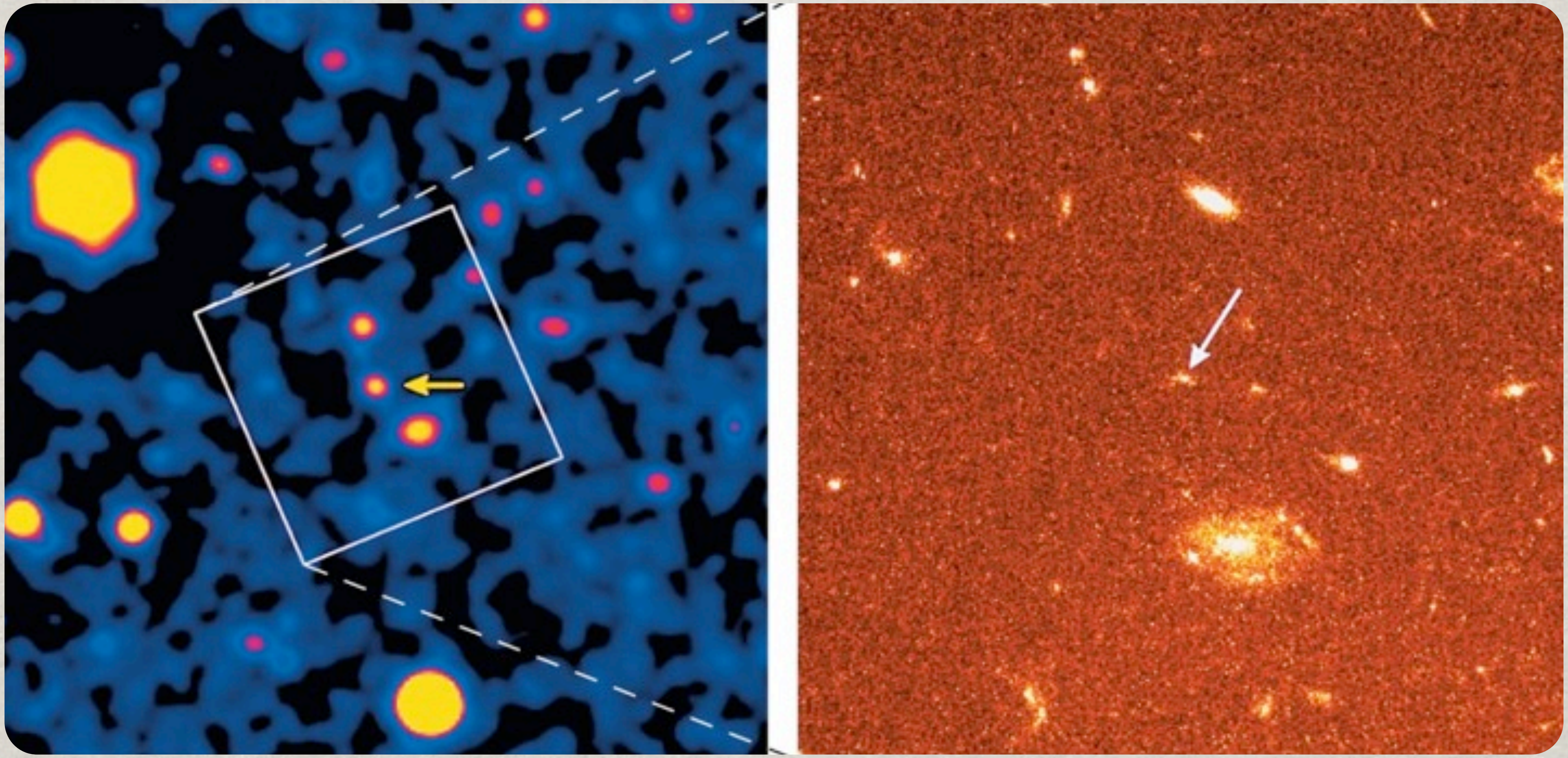


Maps of the burst's distribution on the sky show no "clumping" of bursts anywhere, particularly not within the Milky Way. Therefore, the bursts must originate from outside our Galaxy.



EXTRA-GALACTIC BURSTS

Distance measurements of optical counterparts of some gamma bursts have revealed coincidence with distant galaxies billions of light years away. Occasional spectral lines in the burst confirm the large redshift.

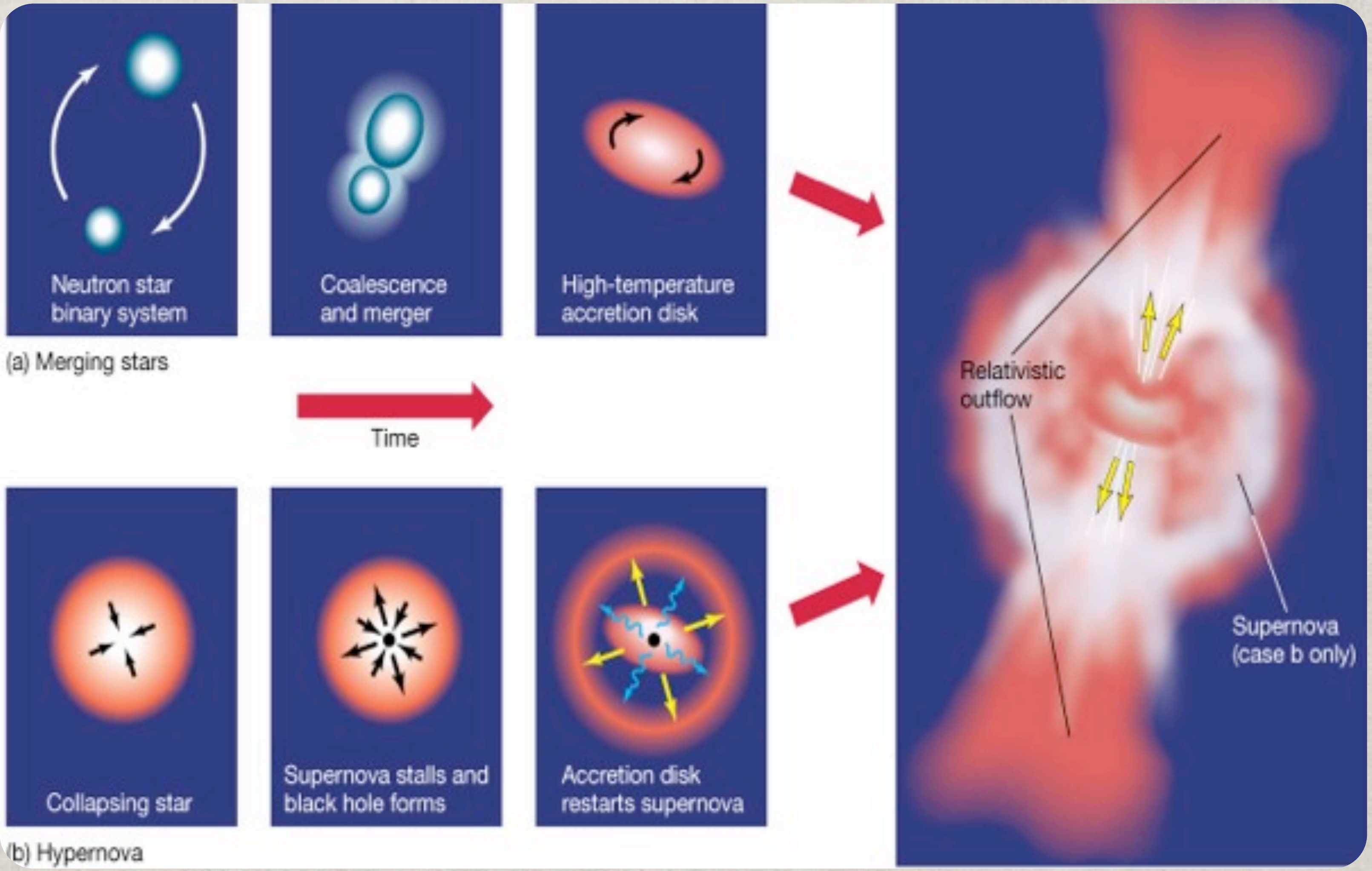


This requires tremendous luminosity, 10^{44} J, but confined to a narrow beam a few degrees wide.

GAMMA-RAY JETS

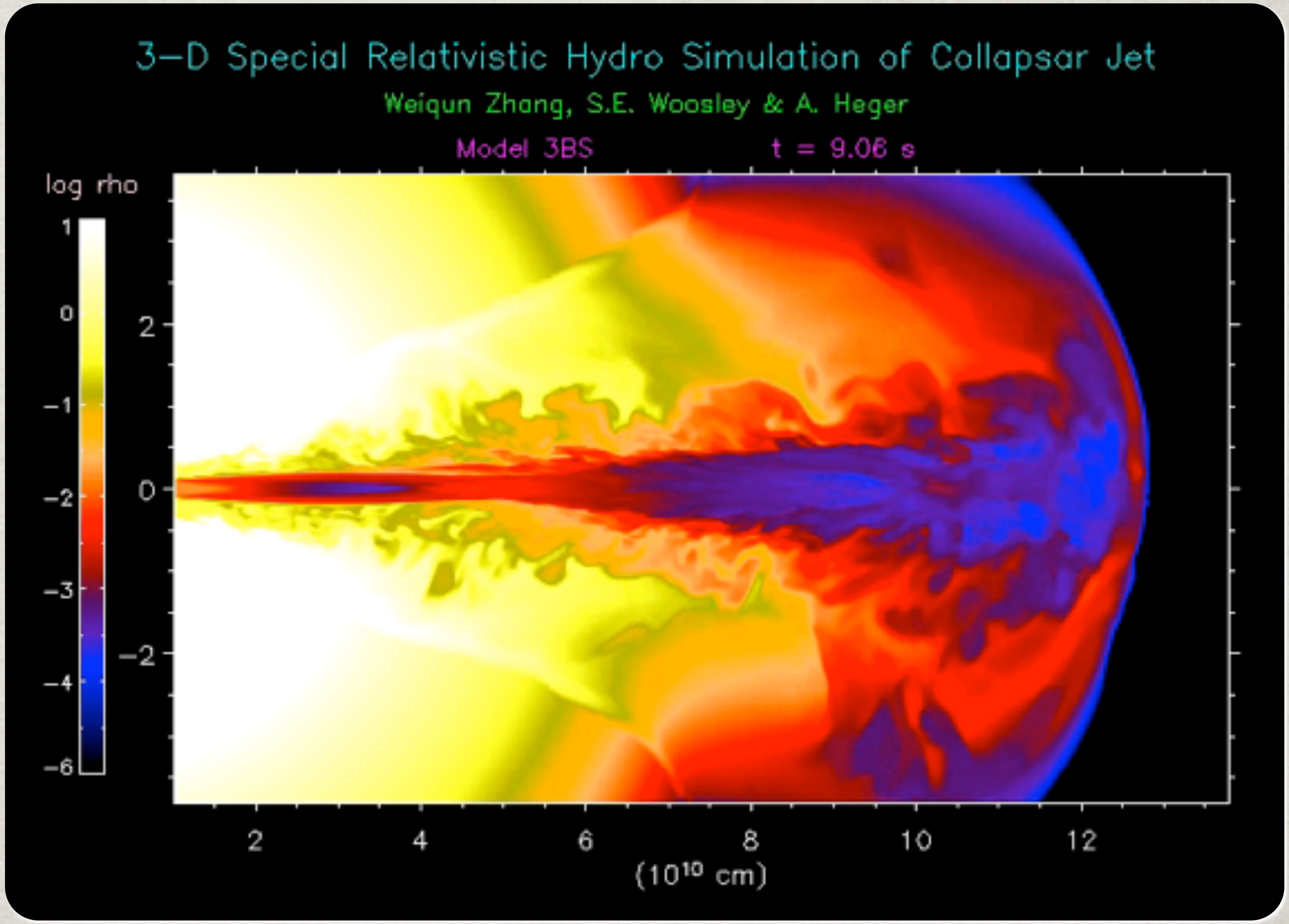
In both cases, the γ rays originate as relativistic jets created by accretion disks around newly formed black holes.

For the short bursts, binary neutron stars merge as a result of gravitational radiation, producing a black hole and jet.



Long bursts result when the black hole is the result of a failed supernova. The jets punch through the envelope of the star, later a disk wind drives of the envelope, causing a very bright supernova.

COLLAPSAR OR MAGNETAR



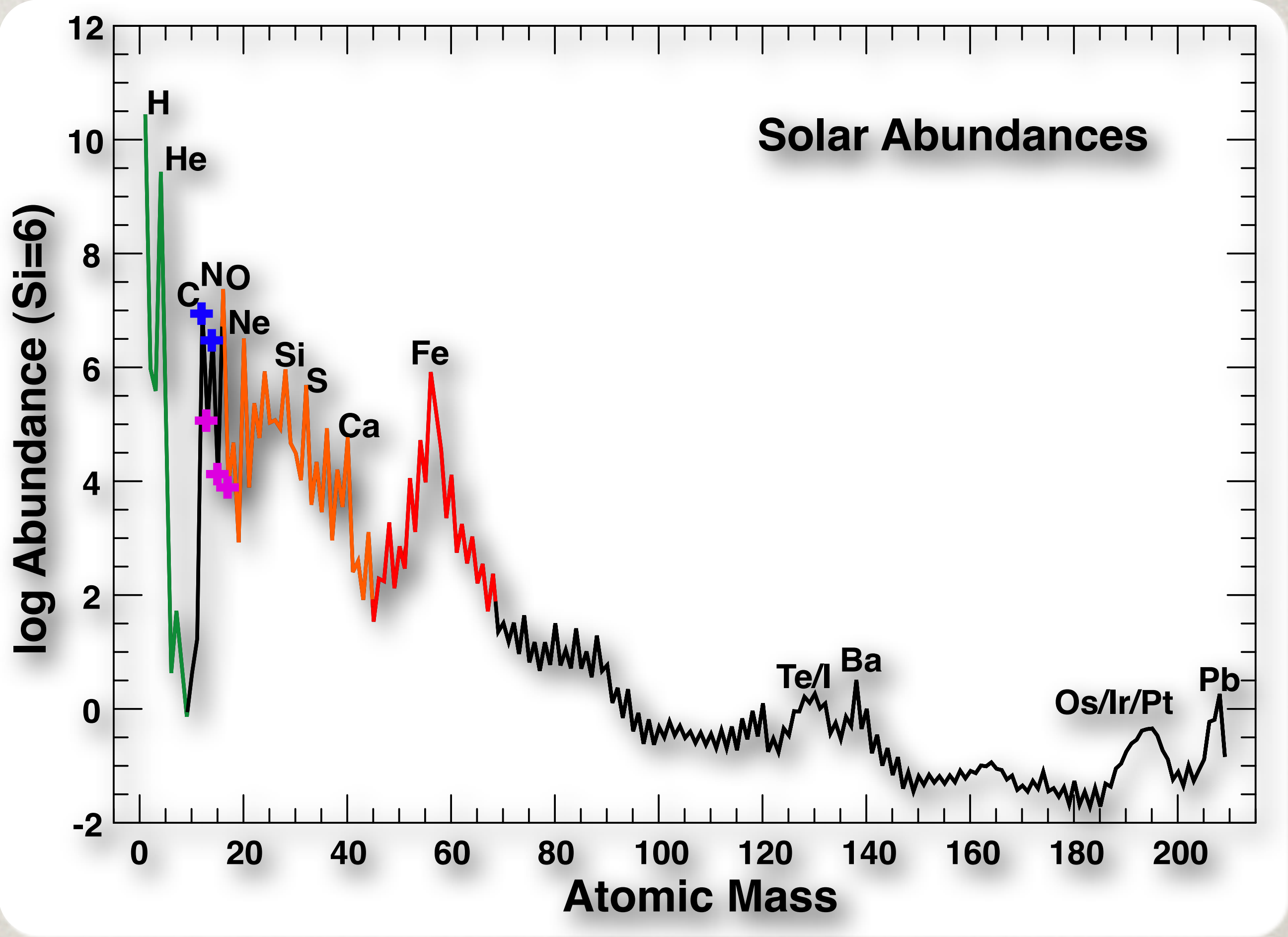
Observations have tied some of these long GRBs to peculiar, hyper-energetic SN Ic.

One model is a collapsar, where an accretion disk forms around a newly-formed black hole in a failed supernova ($M > 30\ M_\odot$), producing a jet which we see as the GRB.

Another model concerns the formation of a magnetar, an extremely magnetized neutron star.

SUMMARY

What role do star, supernovae, novae & X-ray bursts play in cosmic nuclear evolution?



- ✶Core Collapse SN produce the intermediate mass elements, O - Si- Ca, and ~½ of Iron Peak species.
- ✶Thermonuclear SN produce ~½ of the Iron peak isotopes.
- ✶Stars produce C, N & s-process.
- ✶Novae are likely responsible for odd mass isotopes of light elements like C, N, O.

Nuclear physics drives all of these events and their resulting nucleosynthesis.