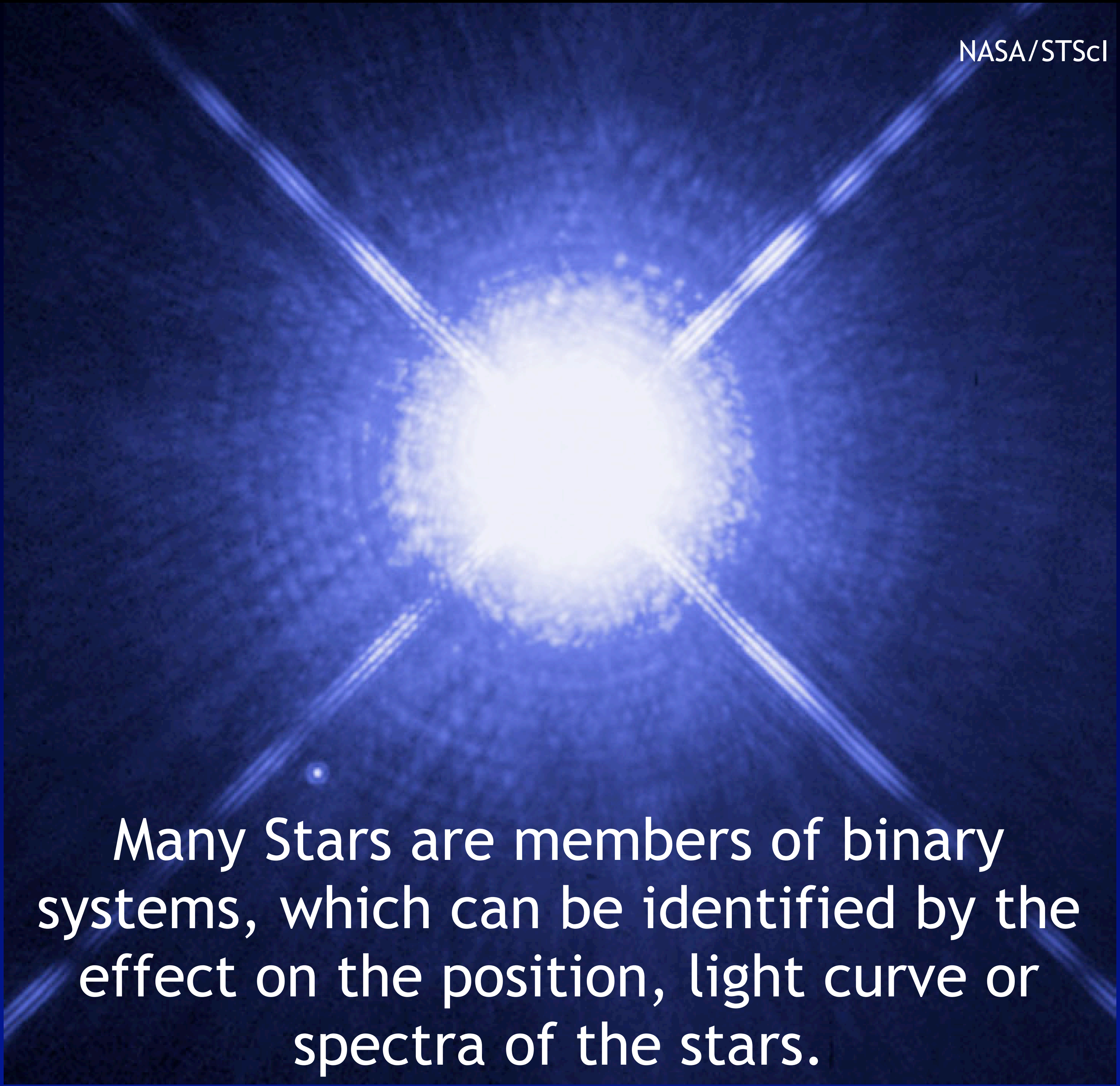
Stellar Afterlife

W.R. Hix (ORNL/UTK), CNS Summer School

Lecture Schedule

1. Nuclear Physics for Astrophysics
2. Lives of Stars
3. Core Collapse Supernovae
4. Stellar Afterlife
    a) What role do novae, X-ray bursts and thermonuclear supernovae play in cosmic nuclear evolution?
    b) How does nuclear physics affect these explosive events and the resulting nucleosynthesis?

Stars don’t always live alone



NASA/STScI

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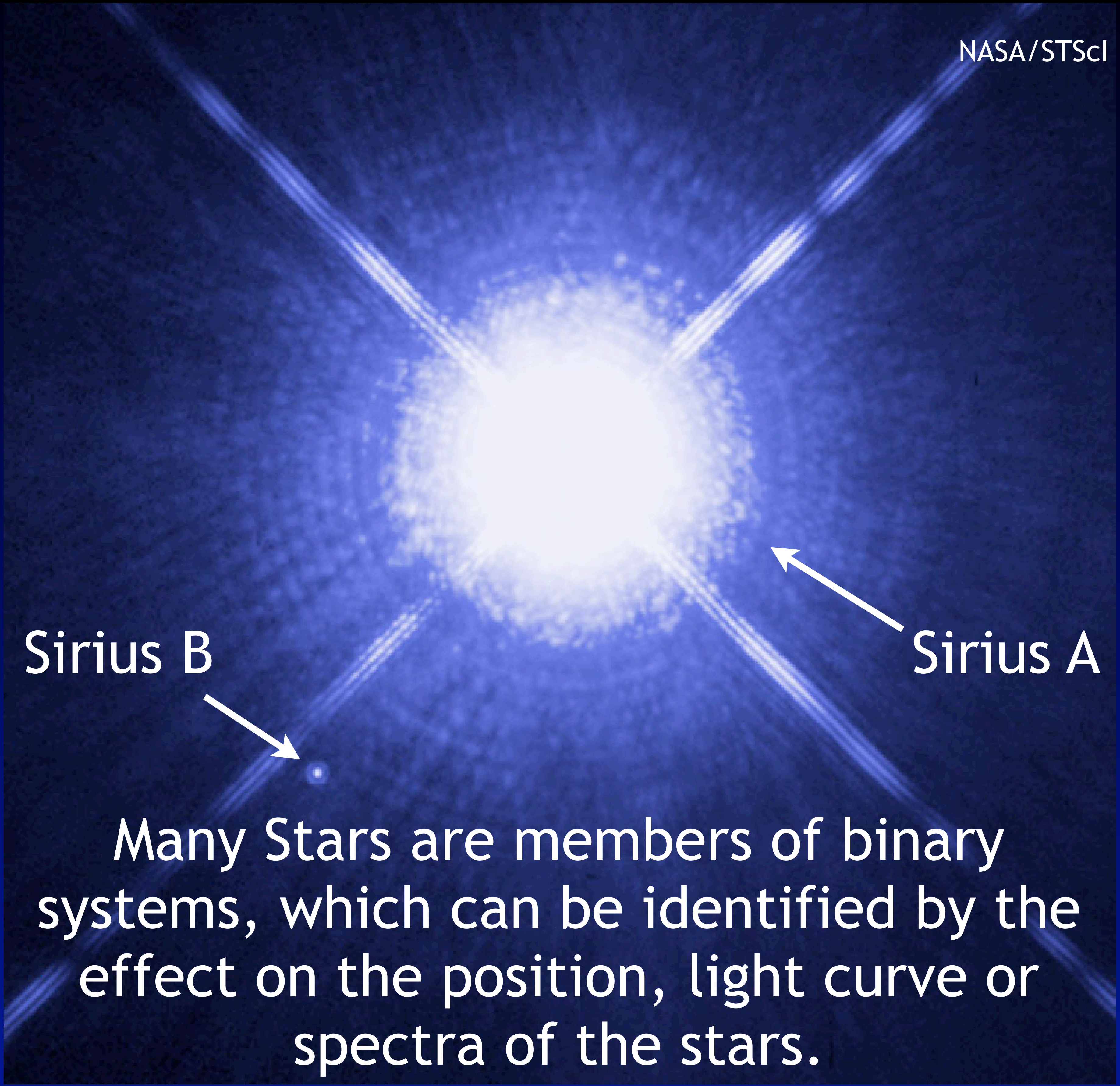

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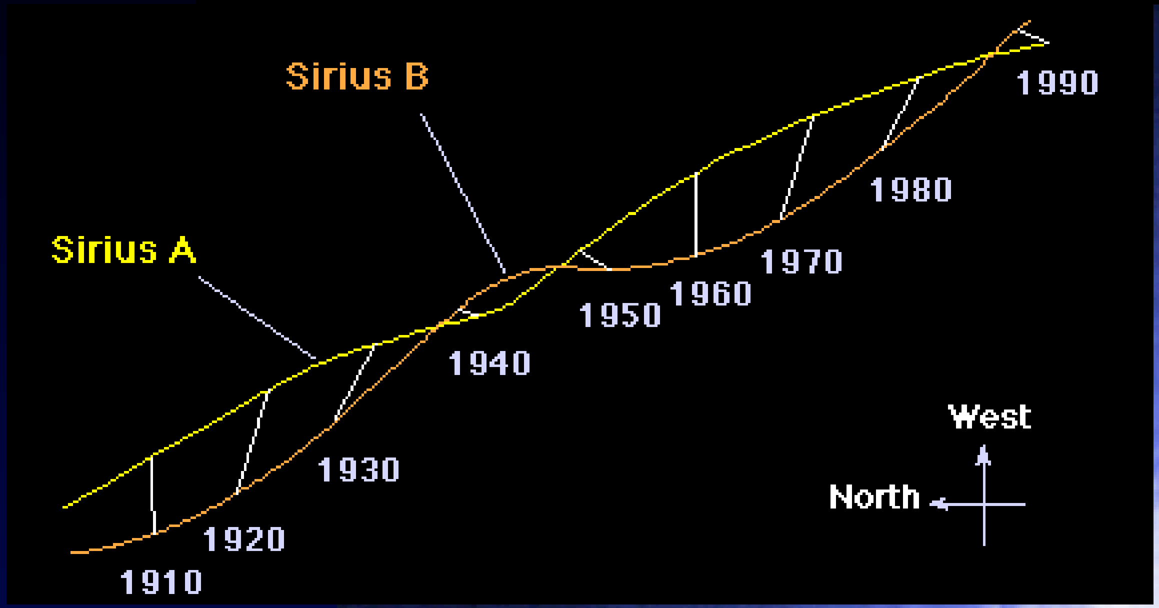
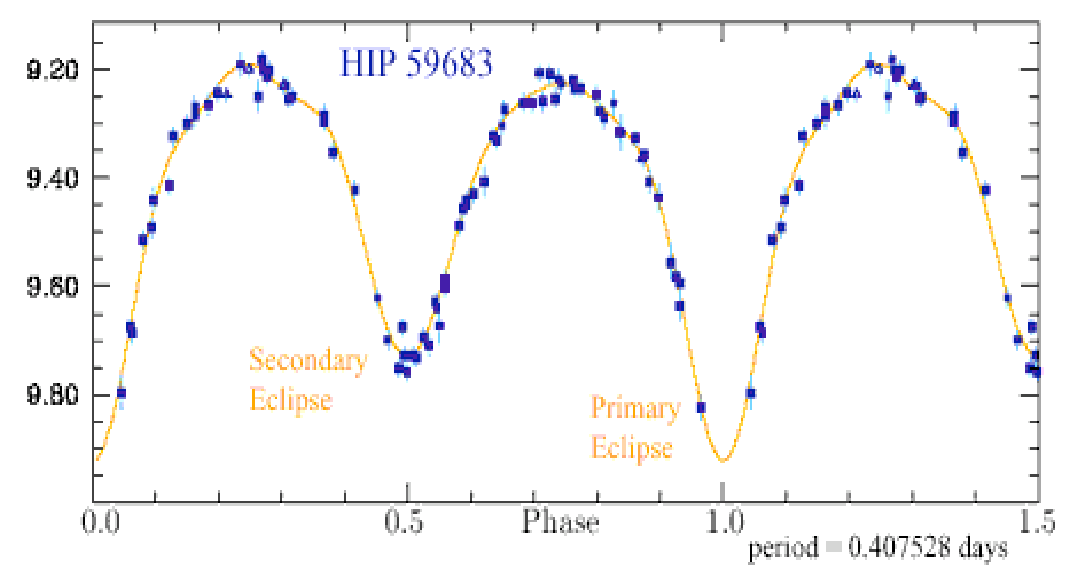
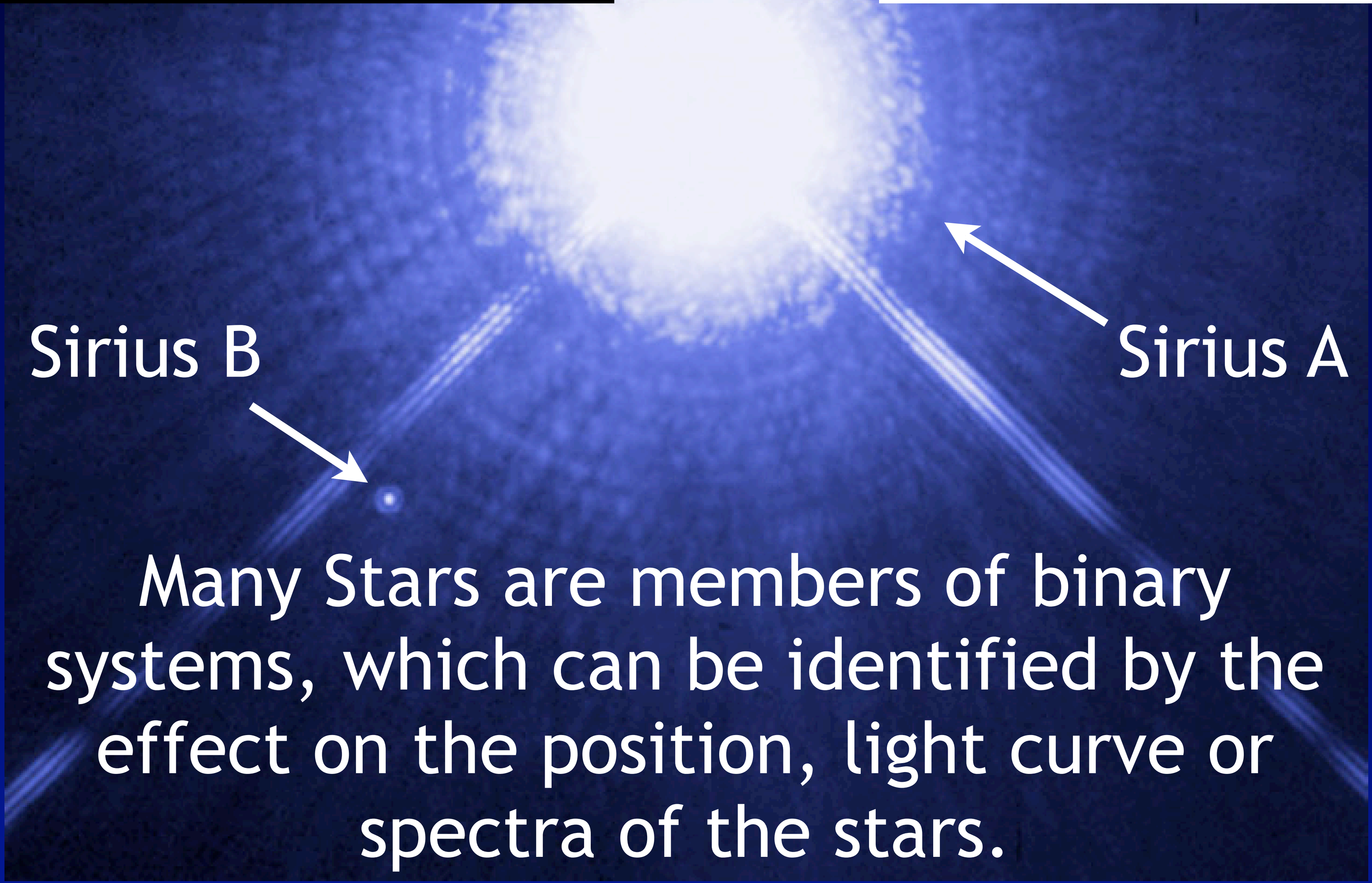






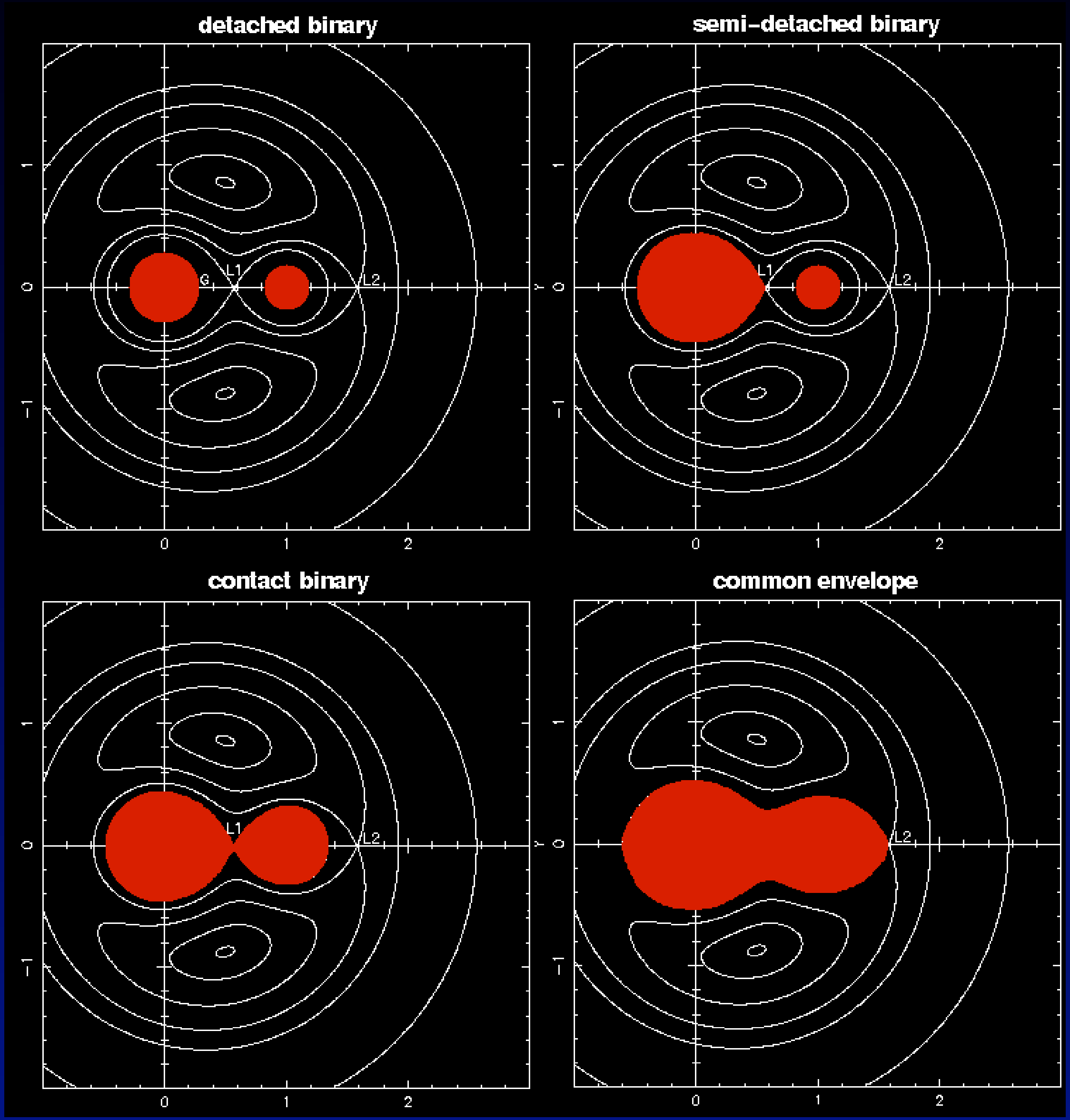
Many Stars are members of binary systems, which can be identified by the effect on the position, light curve or spectra of the stars.

Mass loss and Equipotentials

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

When a giant star expands, it can fill it’s Roche Lobe and preferentially loses mass to the companion.

This mass, with significant angular momentum, accretes unto the companion.



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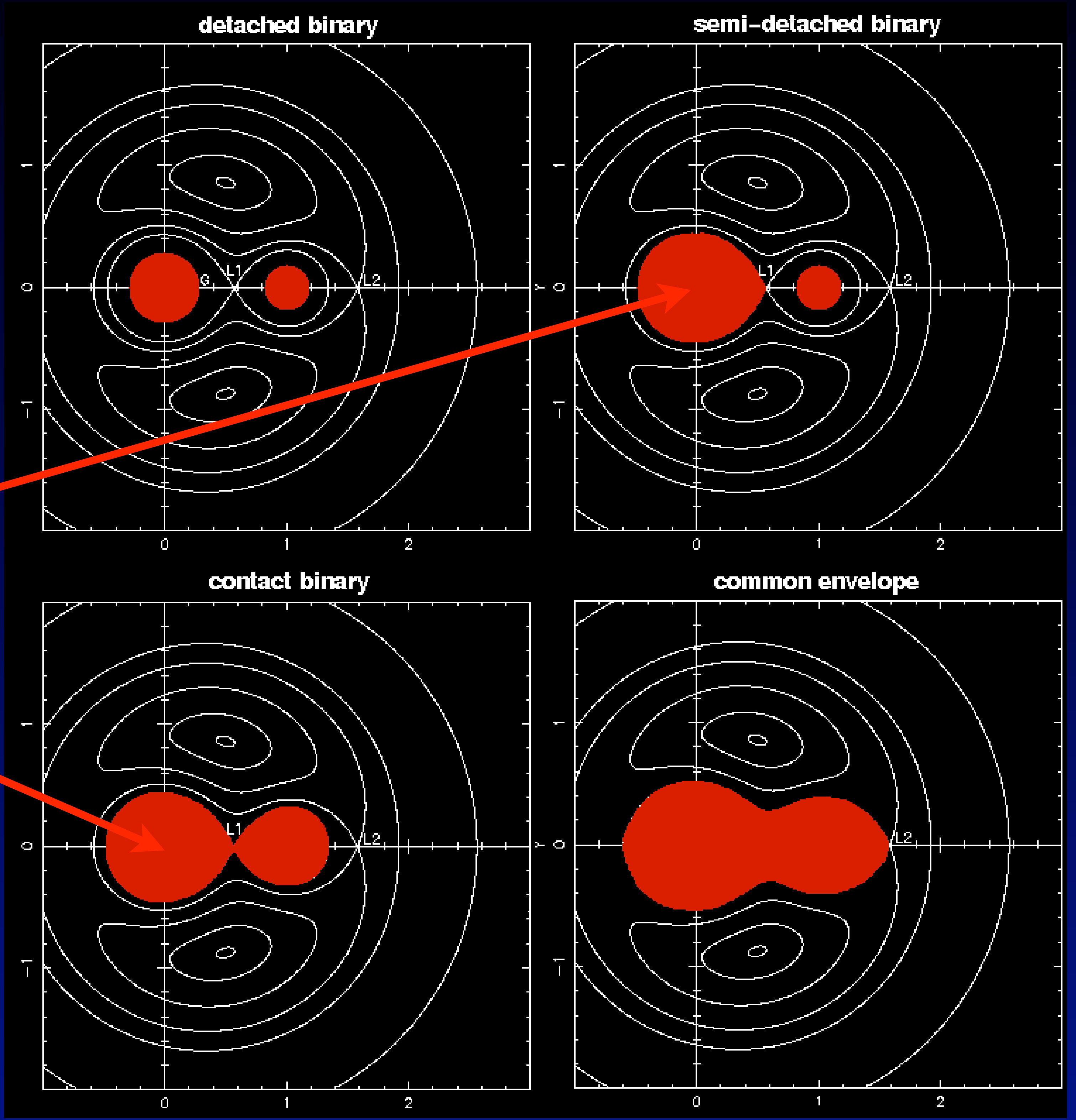
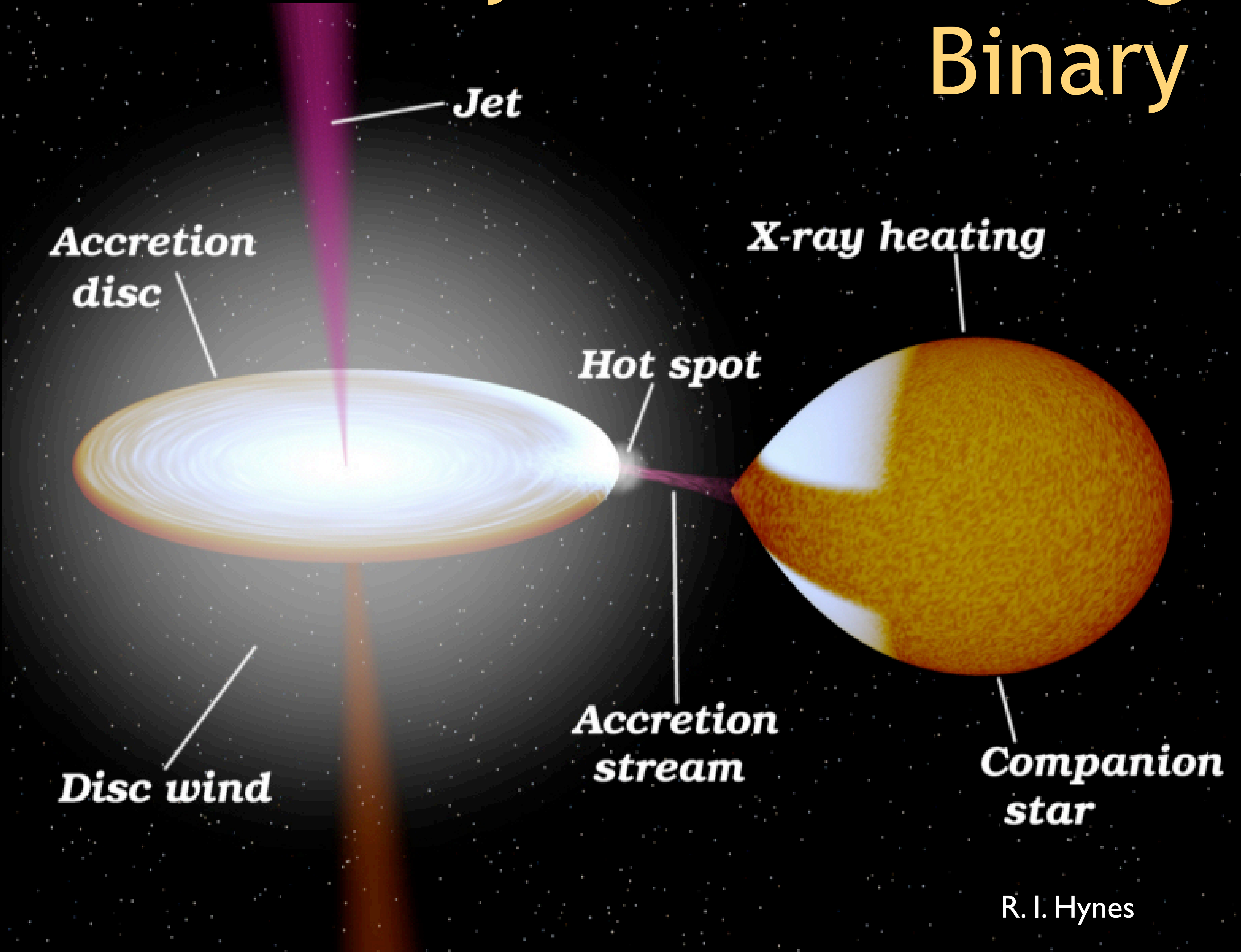


Anatomy of an accreting Binary



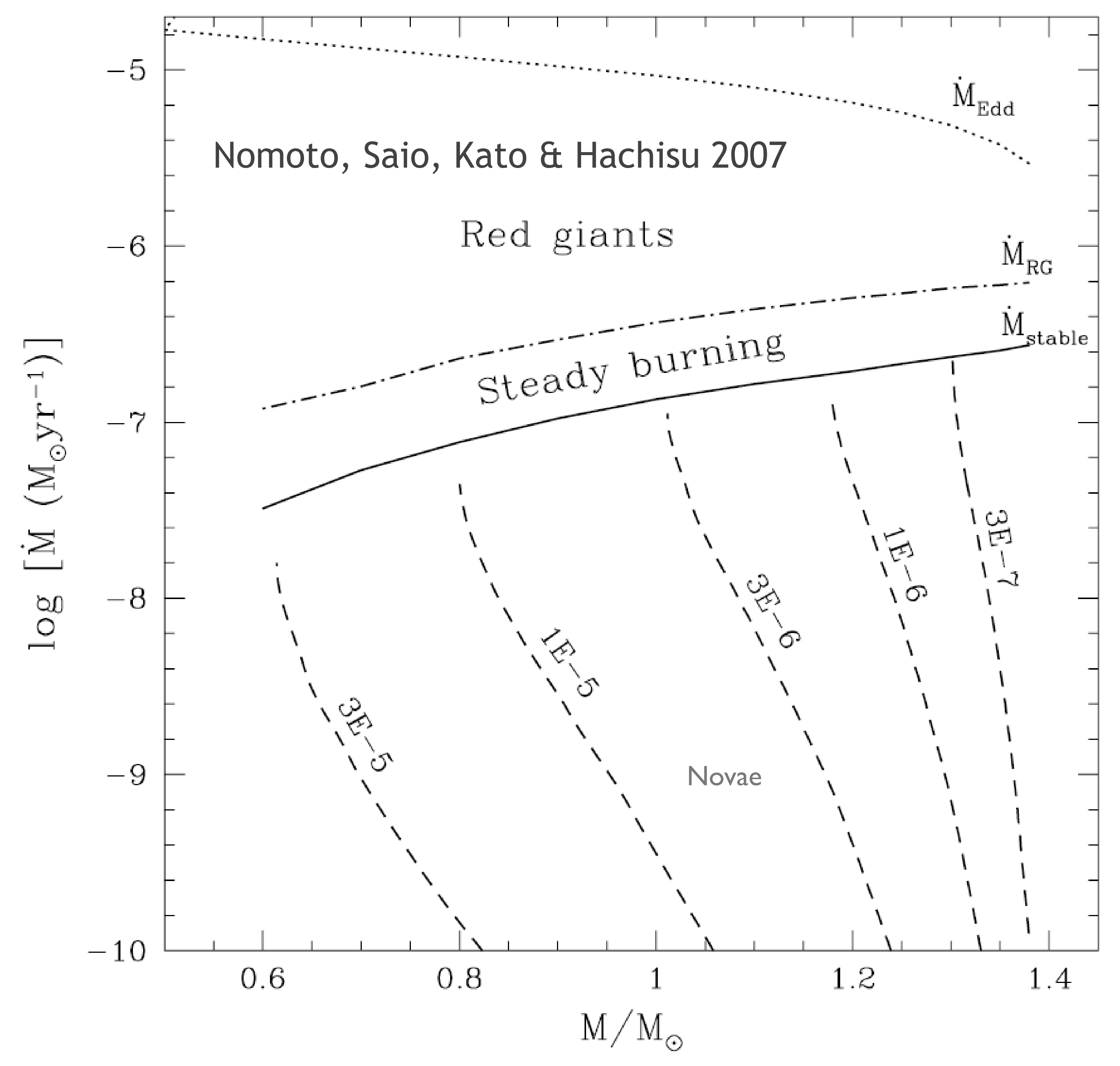
R. I. Hynes

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

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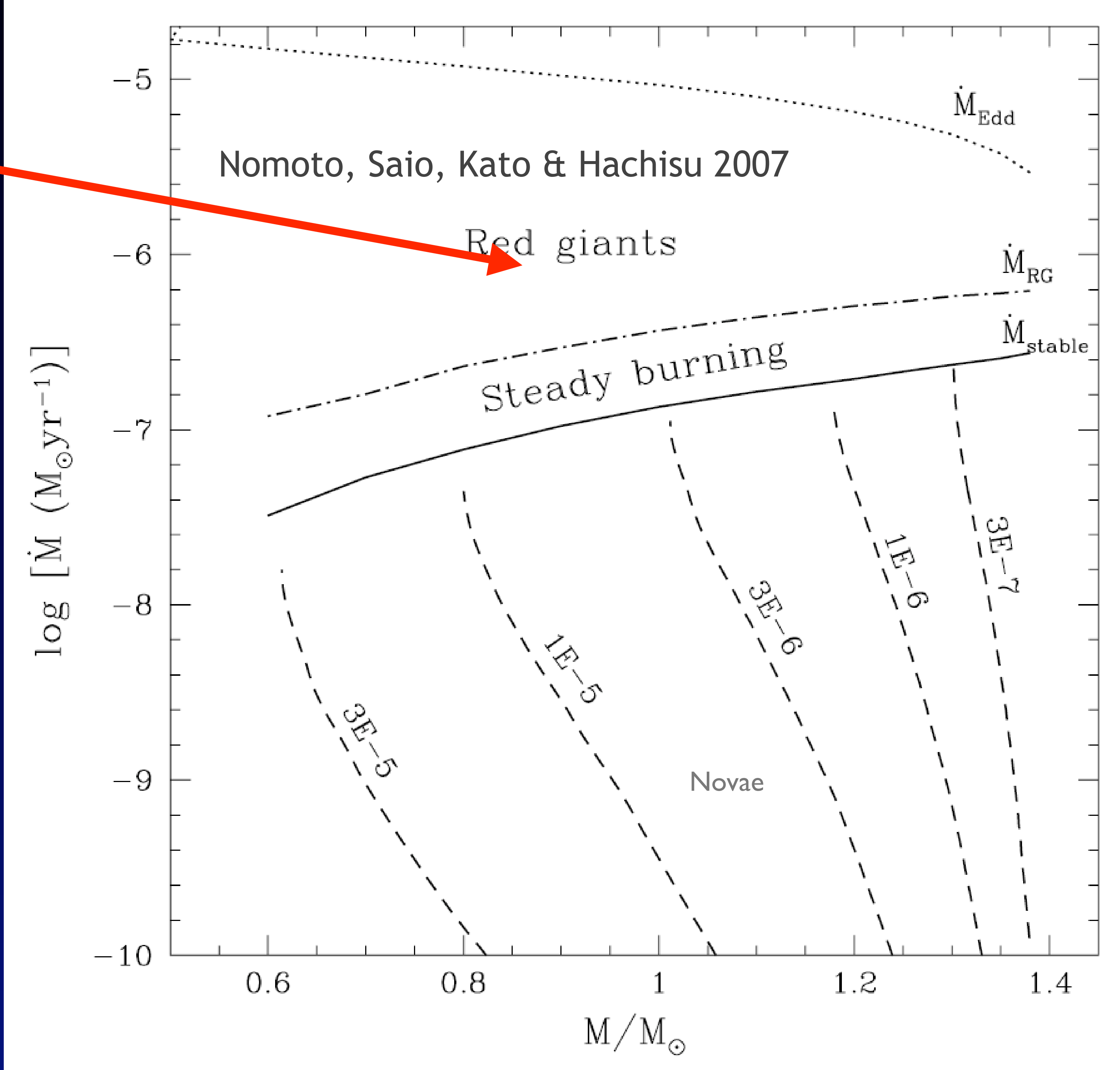

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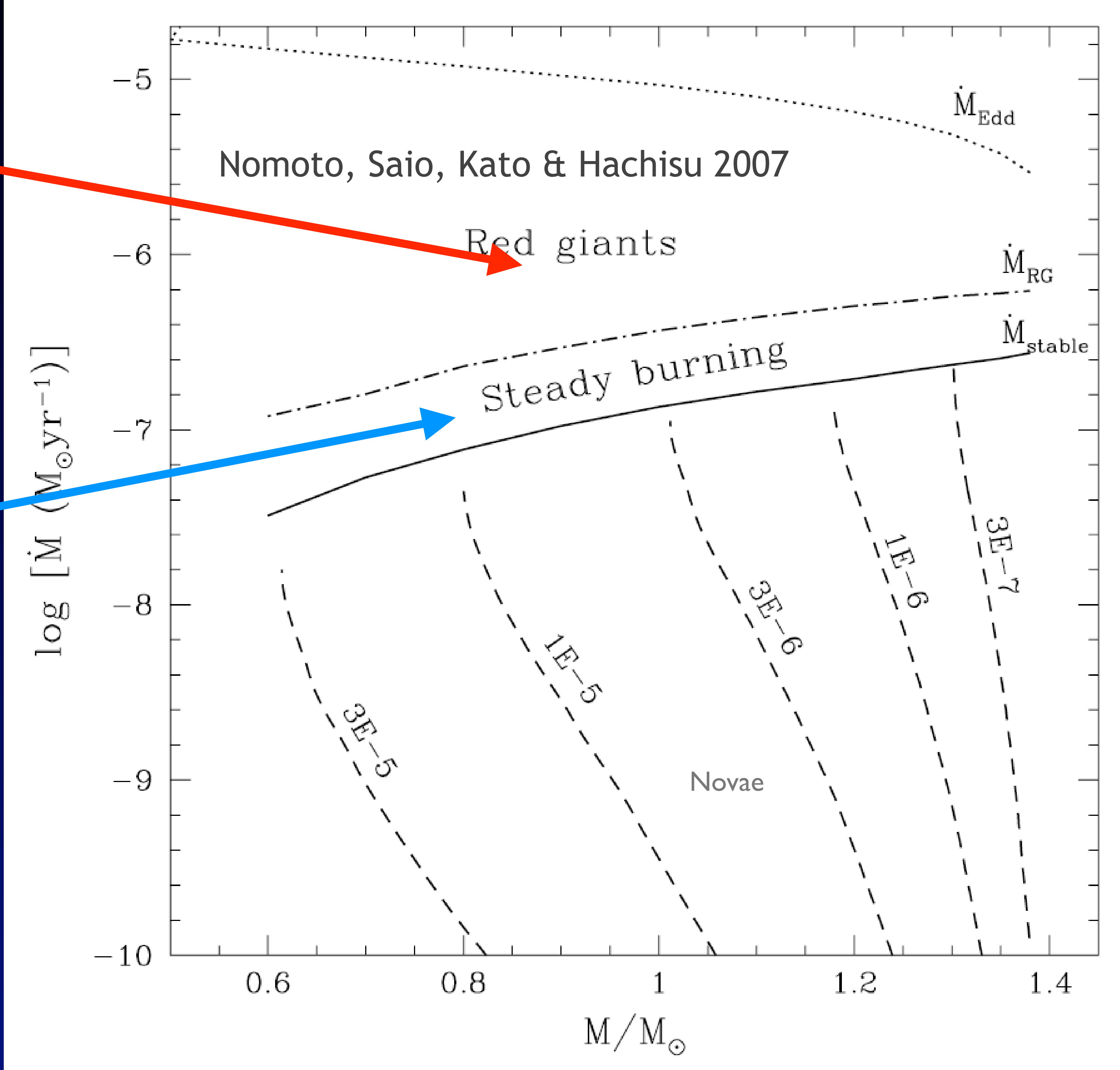

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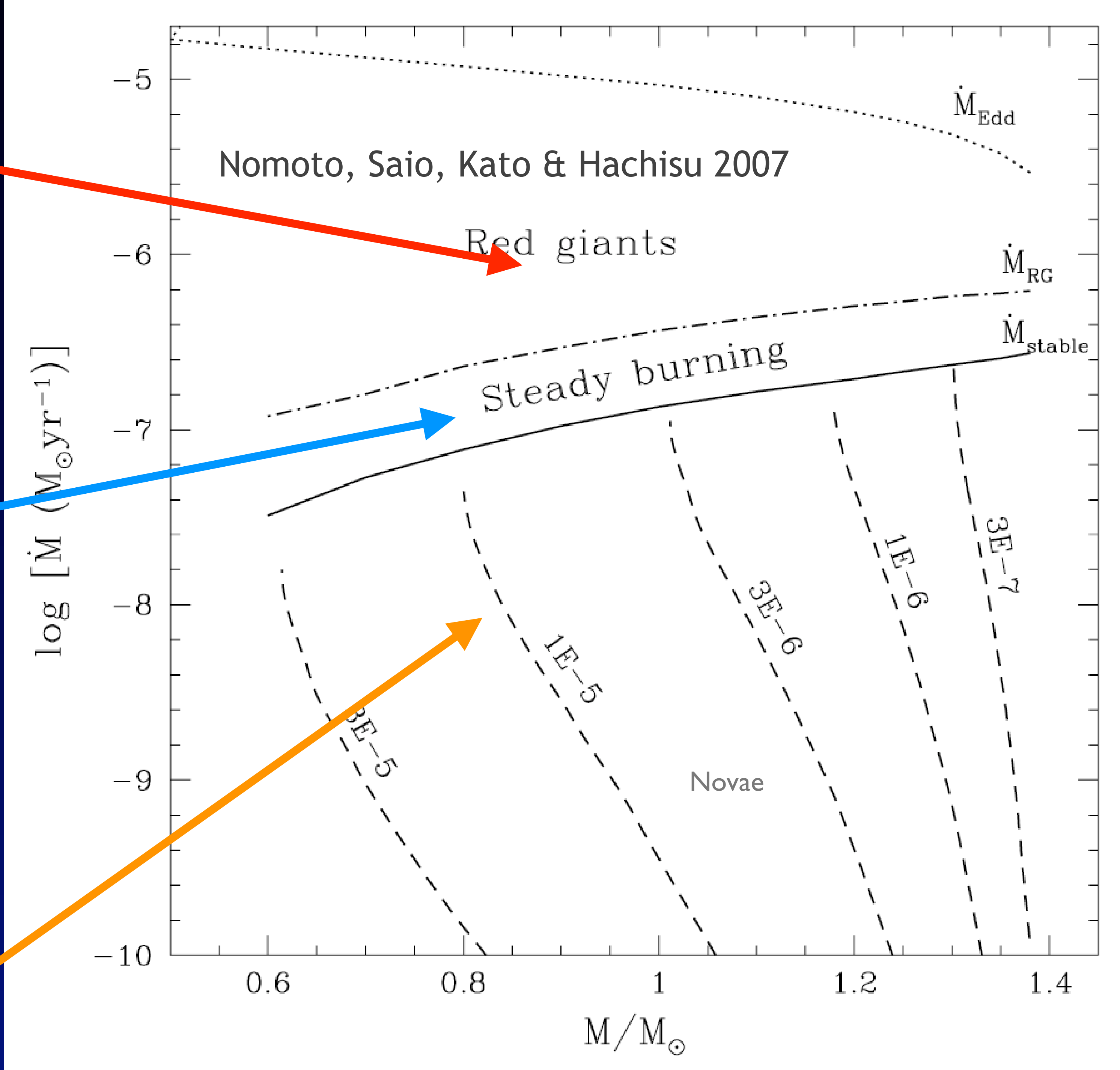

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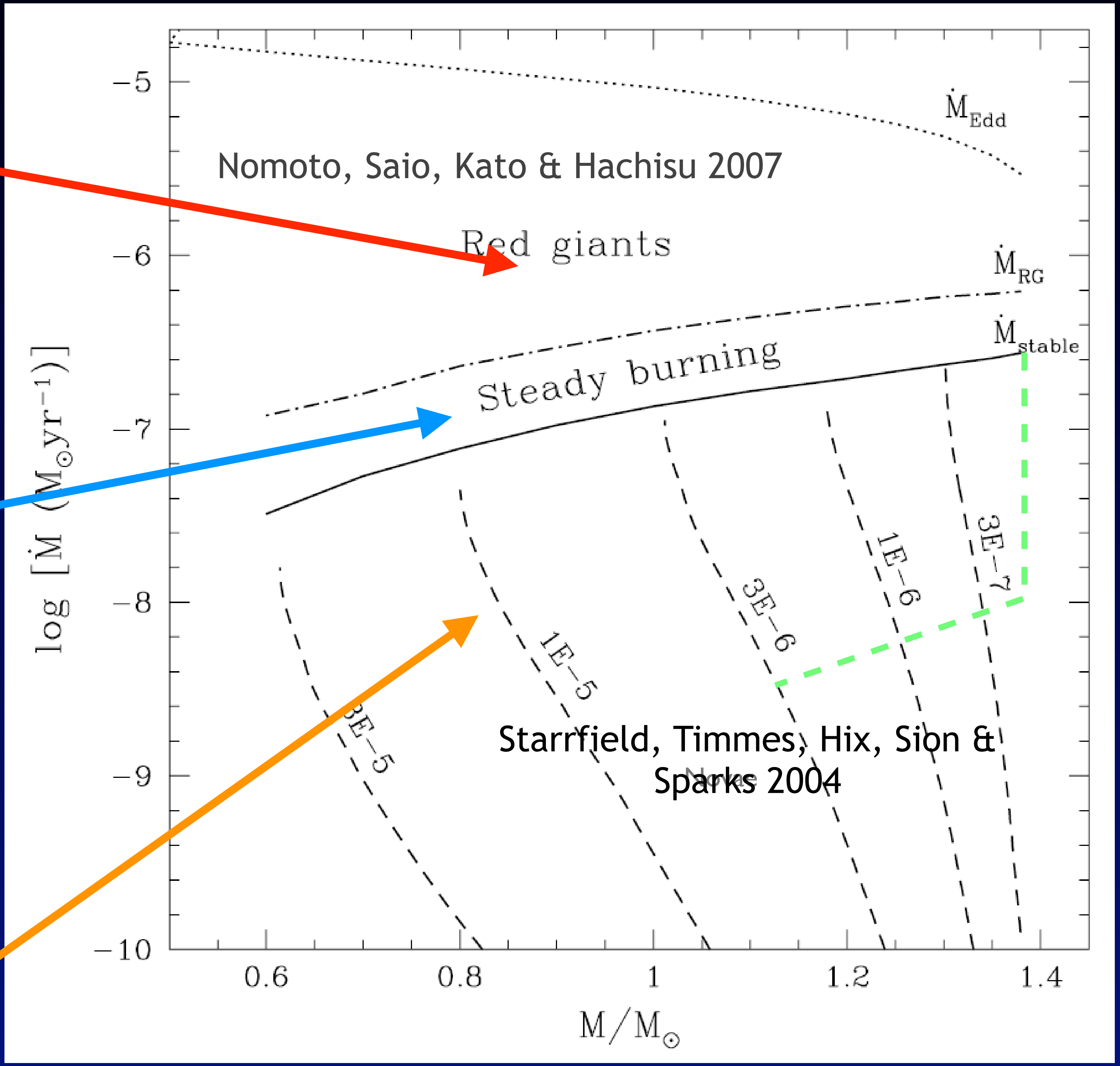


Nomoto, Saio, Kato & Hachisu 2007

Starrfield, Timmes, Hix, Sion & Sparks 2004

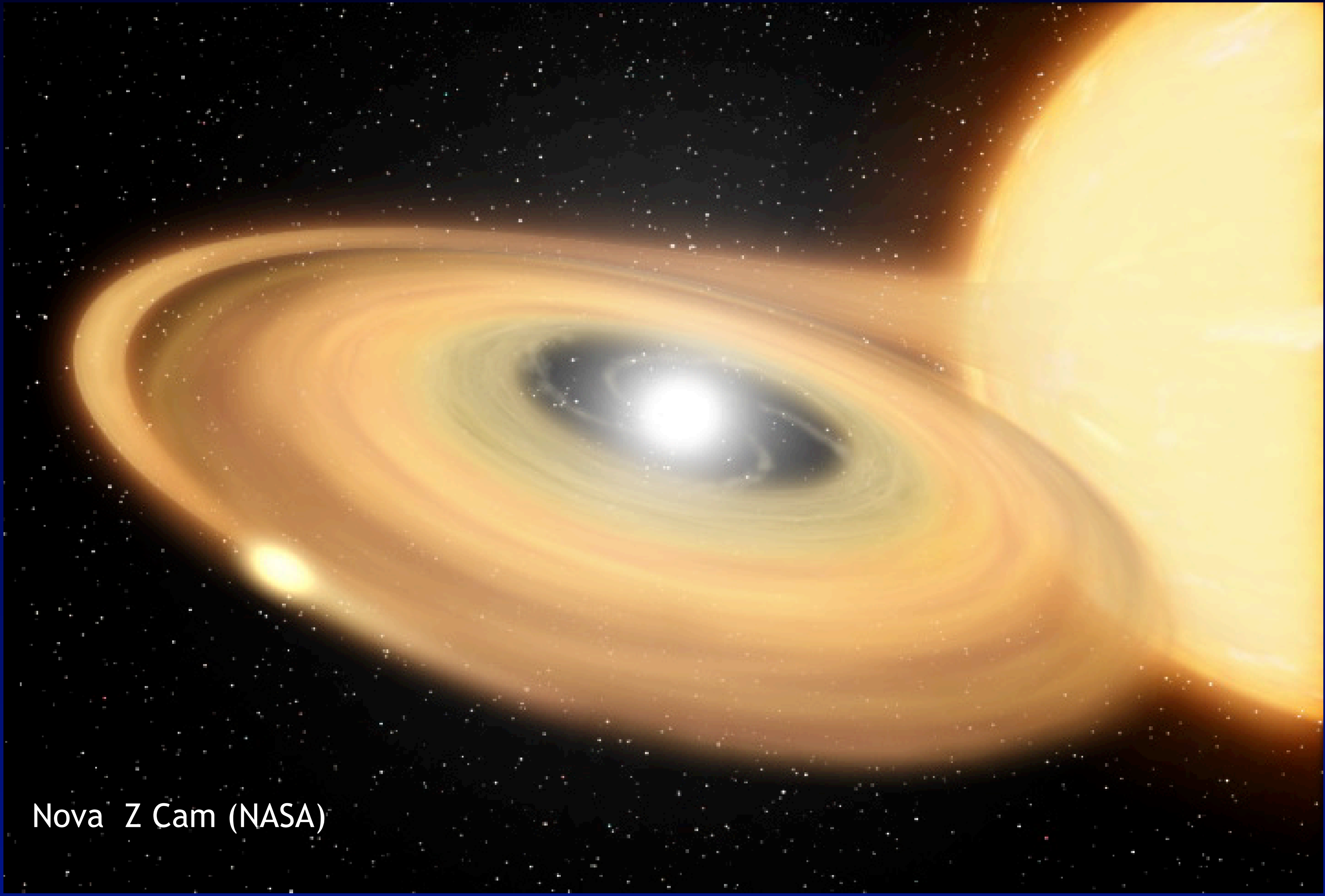
Accreting on a hot white dwarf, may broaden range of CO accretion.

Types of Novae

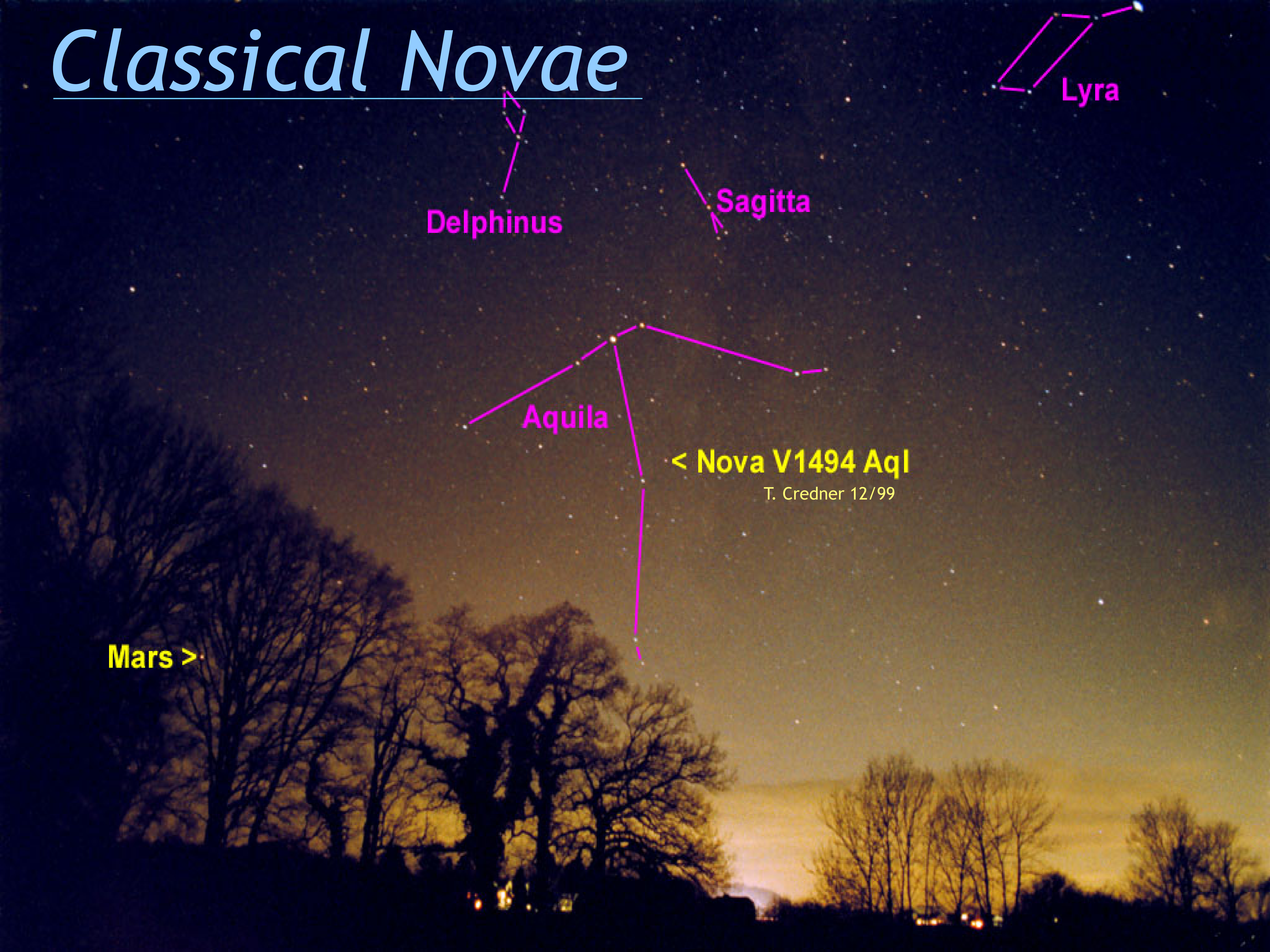
Observational Novae are categorized into 3 types based on recurrence timescale; dwarf, recurrent & classical.

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

Others are thermonuclear explosion with recurrence time related to WD mass and accretion rate.


Nova Z Cam (NASA)

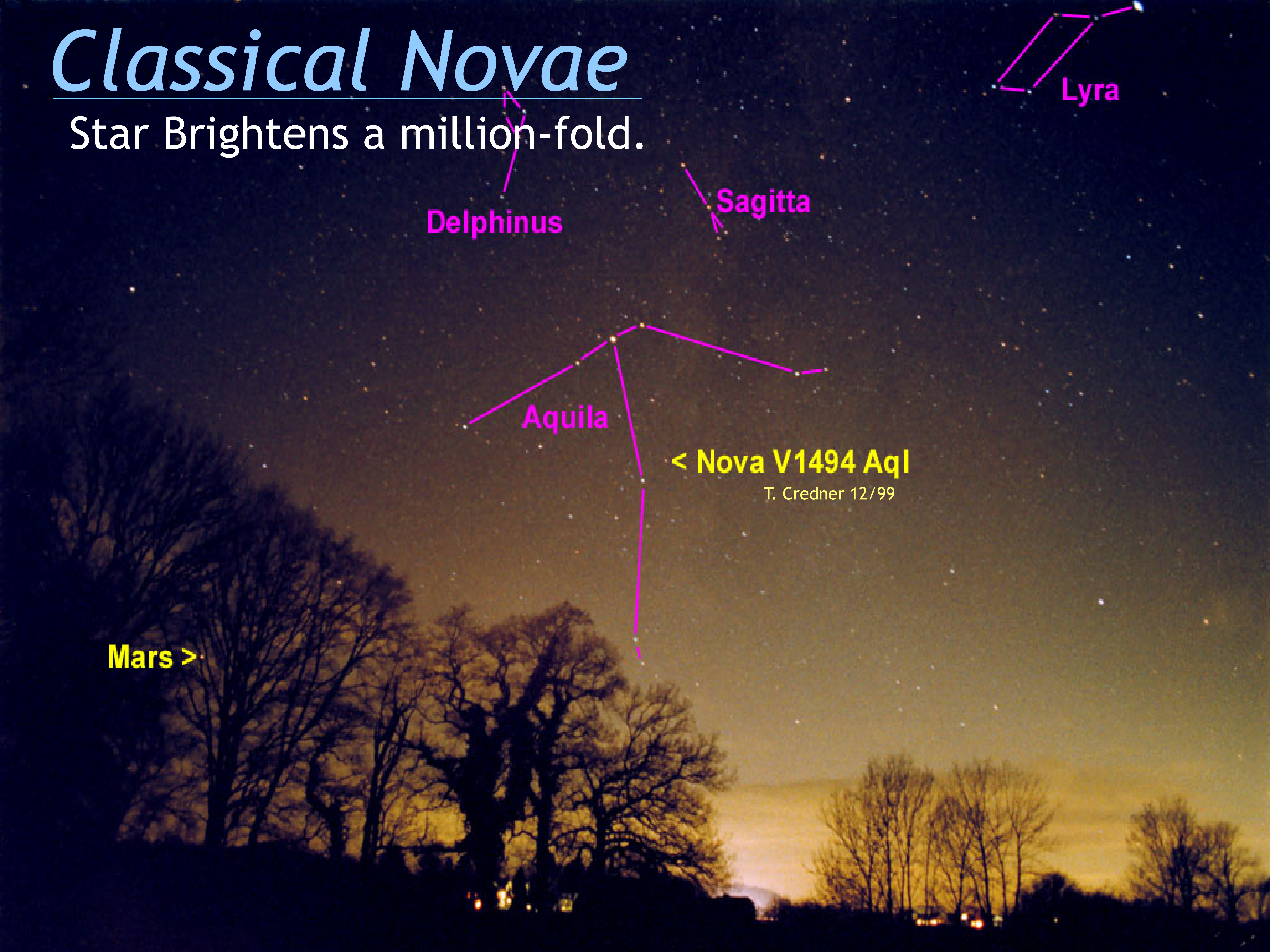
Classical Novae



T. Credner 12/99

Classical Novae

Star Brightens a million-fold.



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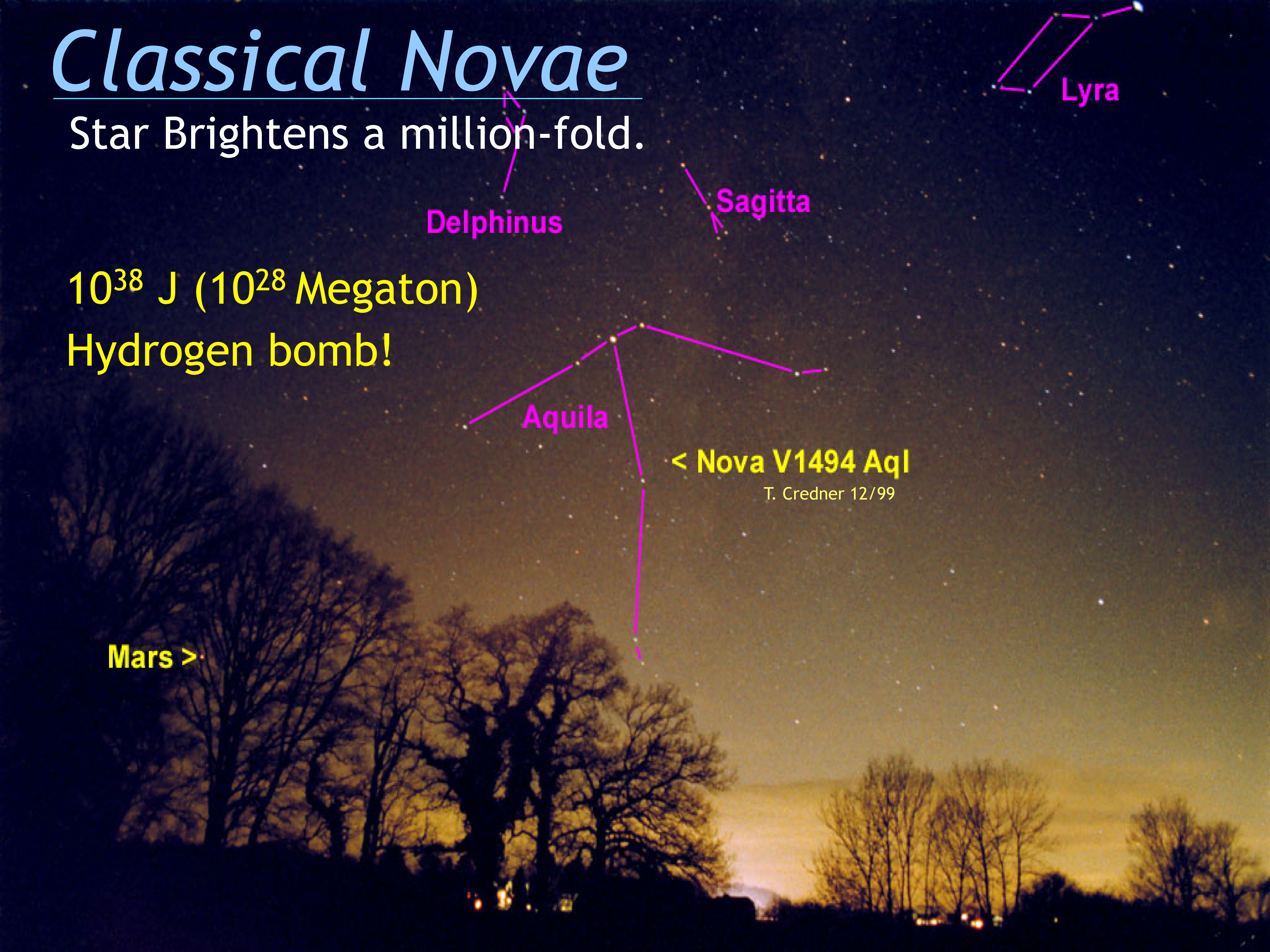
Classical Novae

Star Brightens a million-fold.

10^{38} J (10^{28} Megaton)

Hydrogen bomb!



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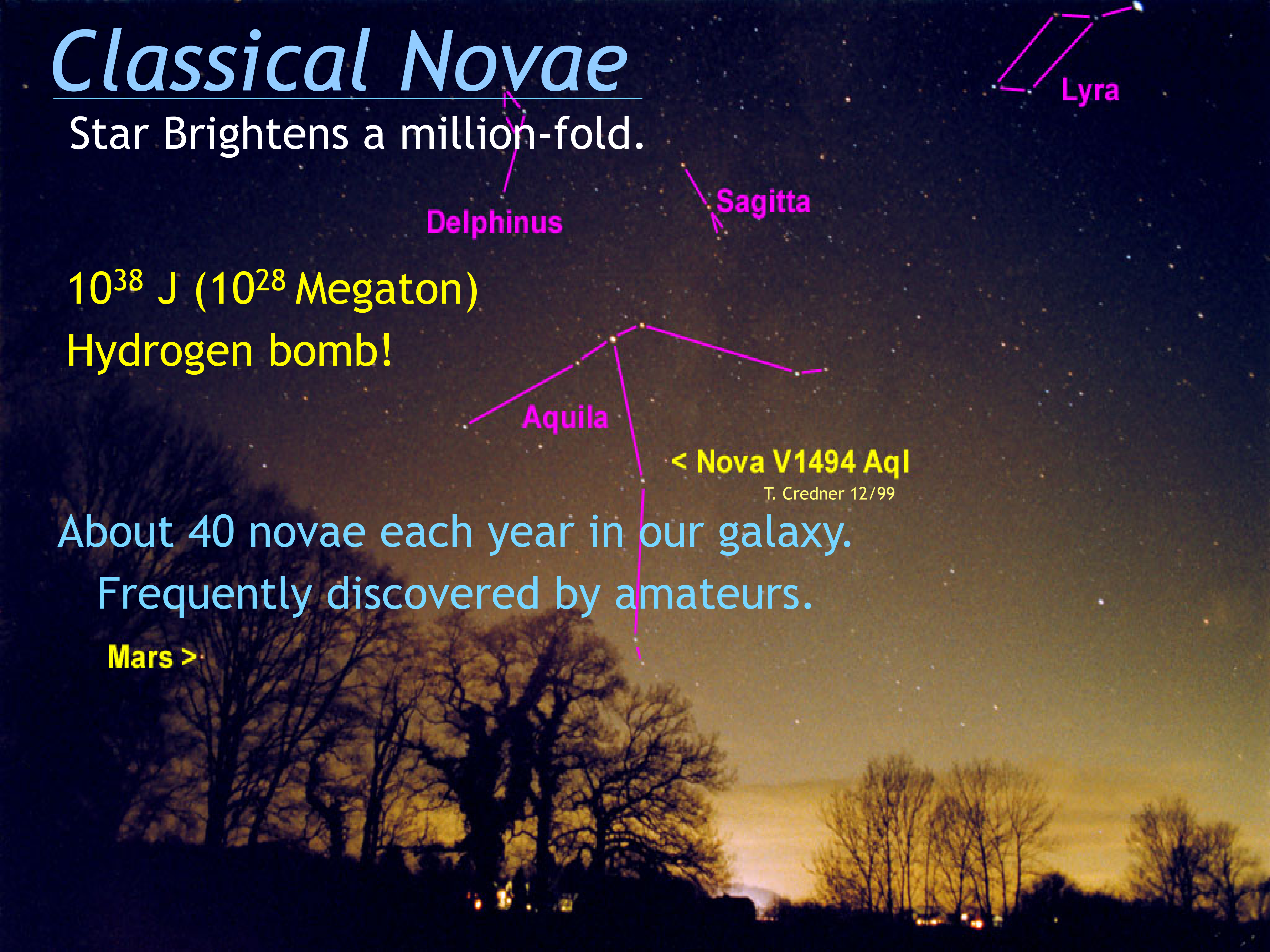

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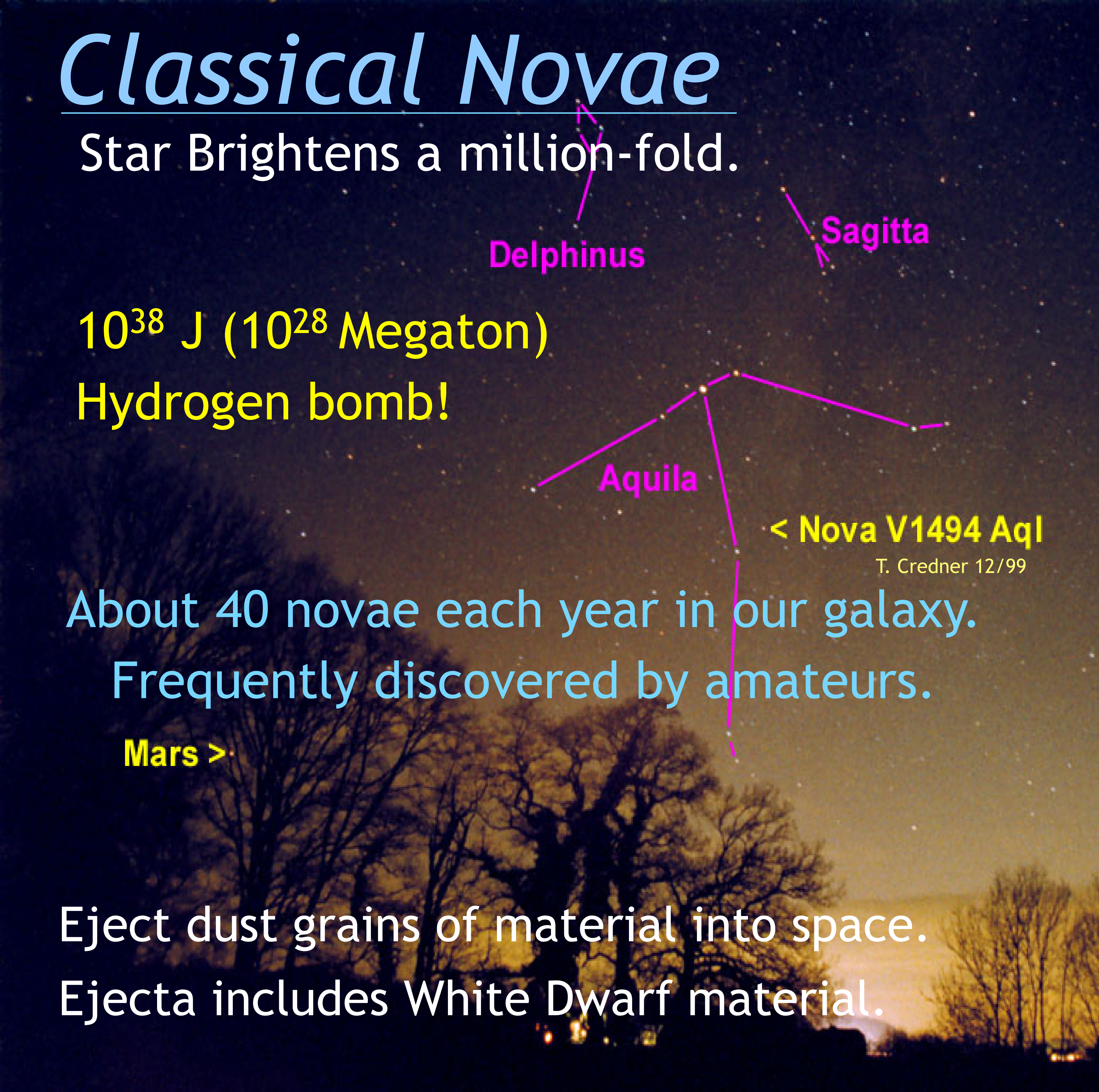
Eject dust grains of material into space.

Ejecta includes White Dwarf material.



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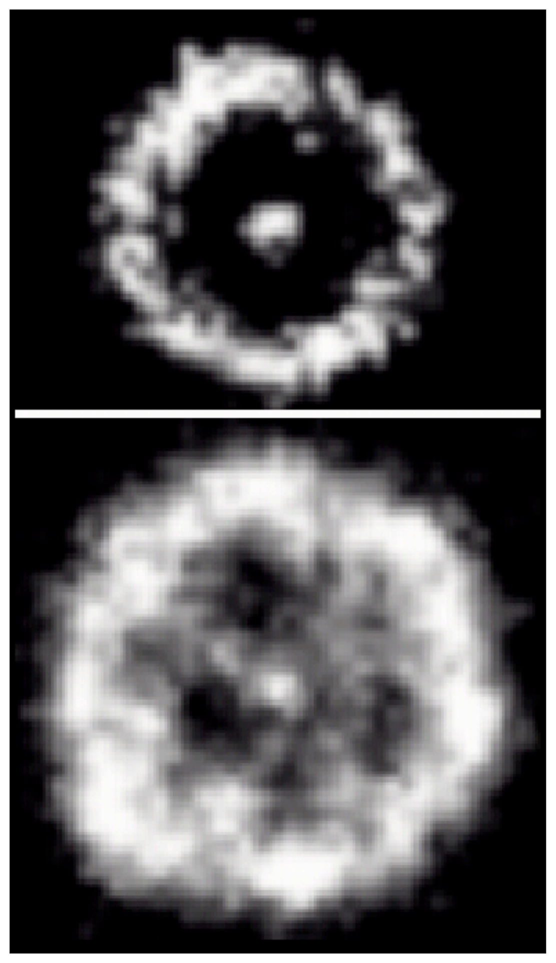

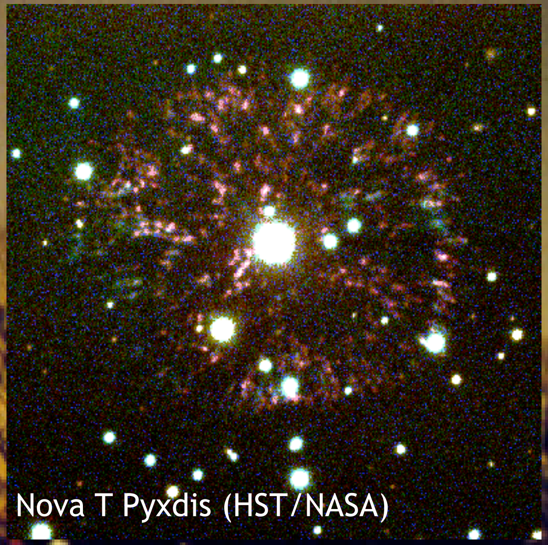

Nova T Pyxdis (HST/NASA)

Nova QUVul 1999 from Hubble Space Telescope

NASA/STSCI

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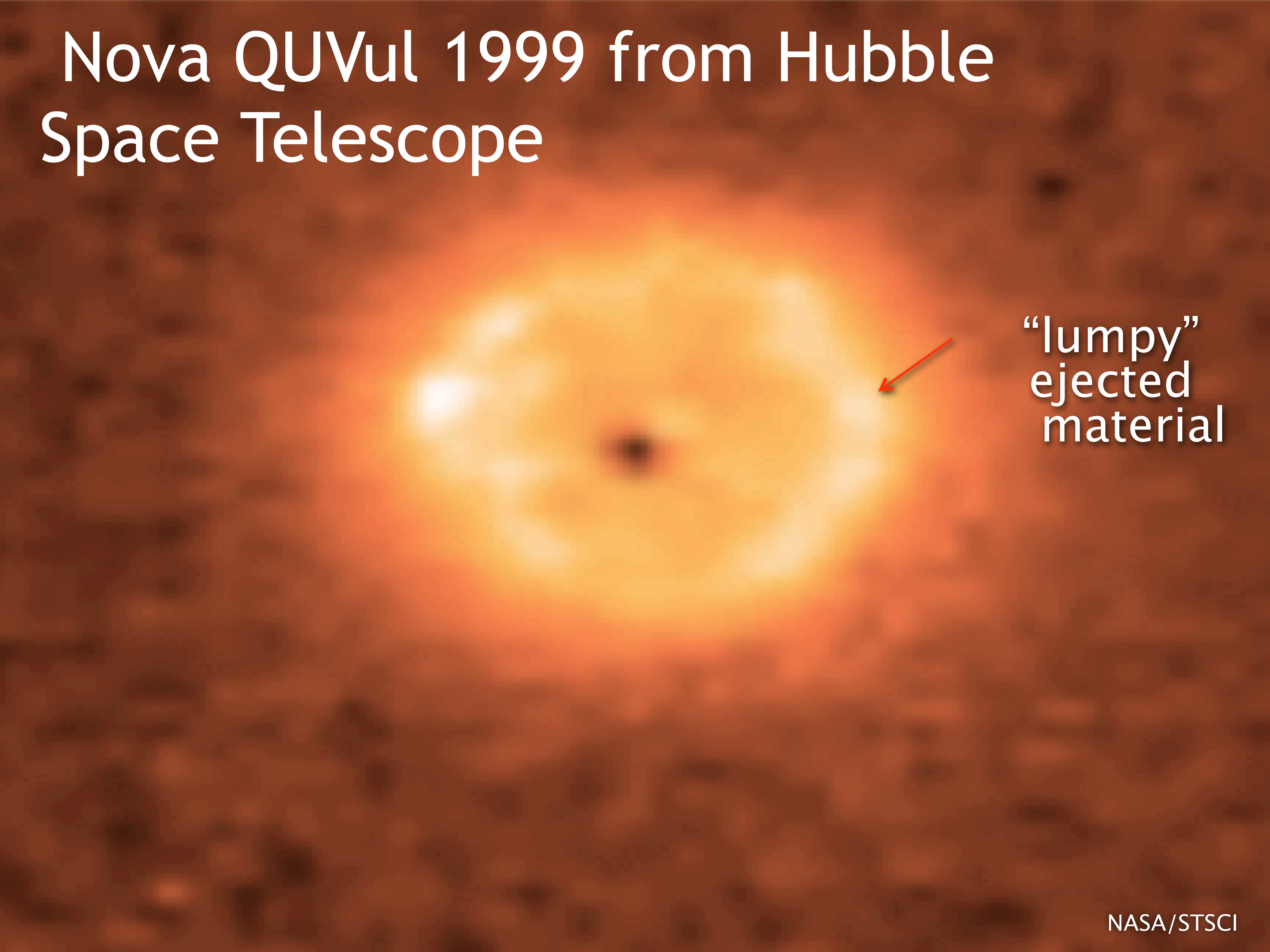
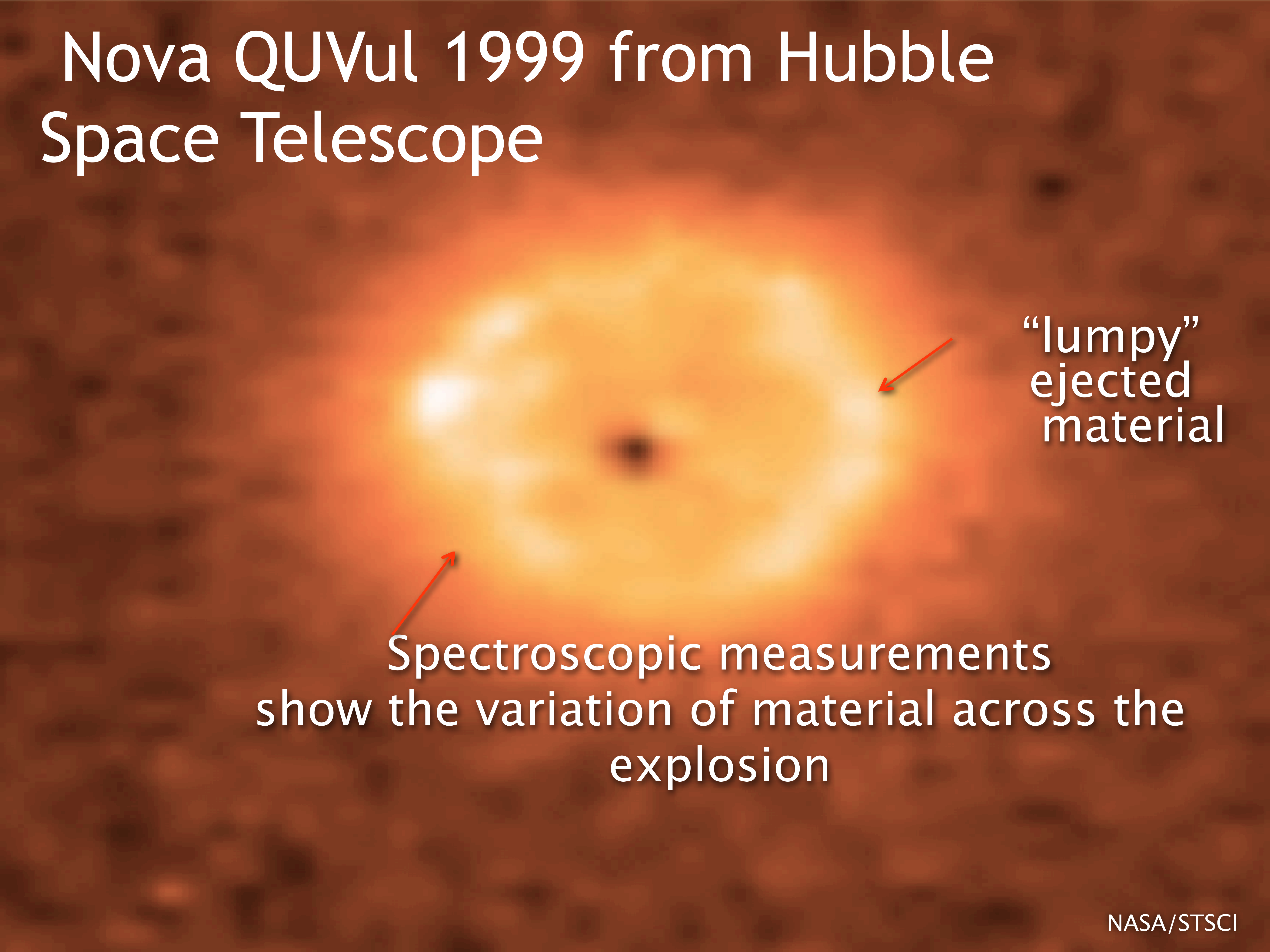


“lumpy” ejected material

NASA/STSCI

Nova QUVul 1999 from Hubble Space Telescope



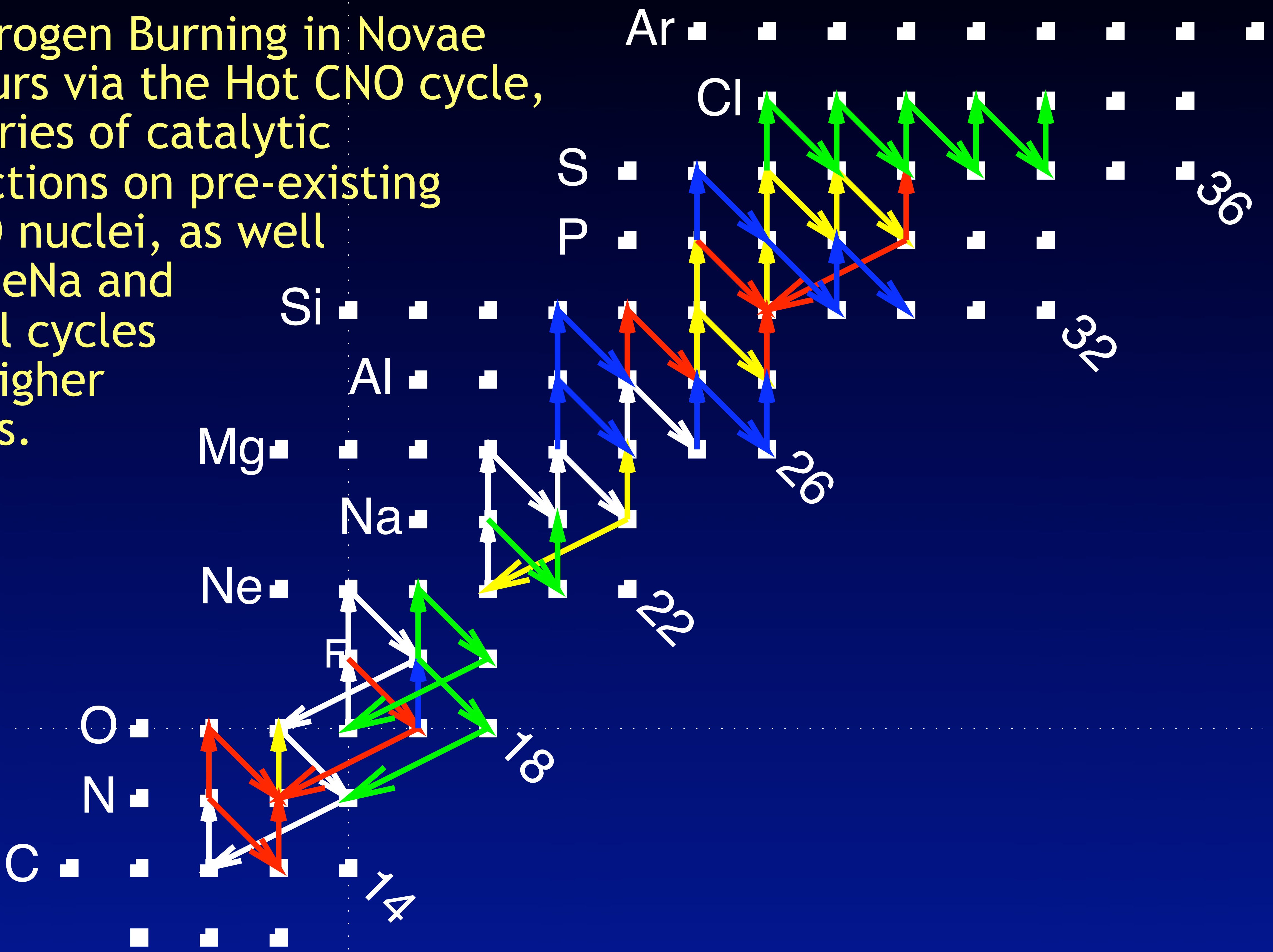
"lumpy" ejected material

Spectroscopic measurements show the variation of material across the explosion

NASA/STSCI

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.



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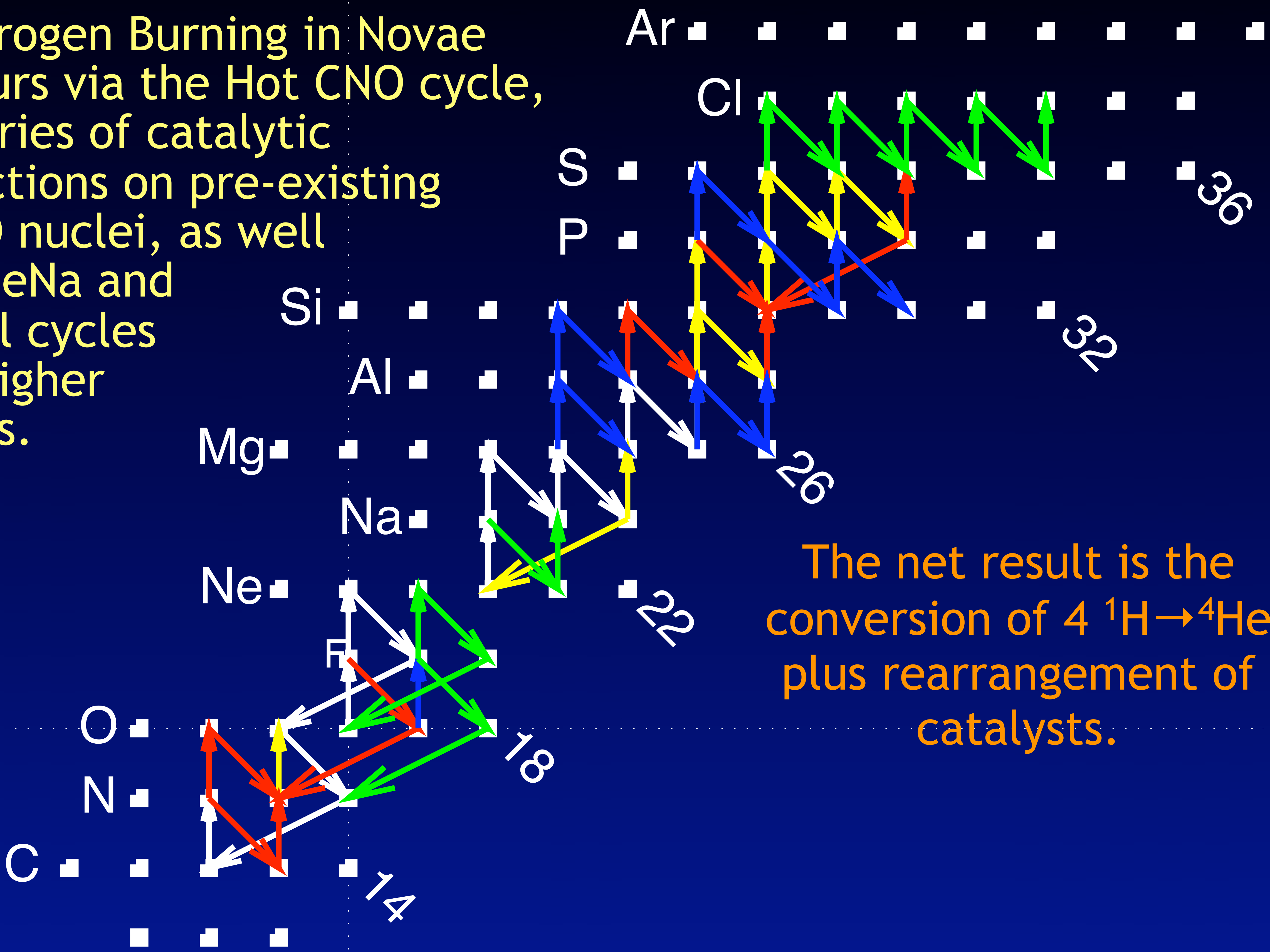

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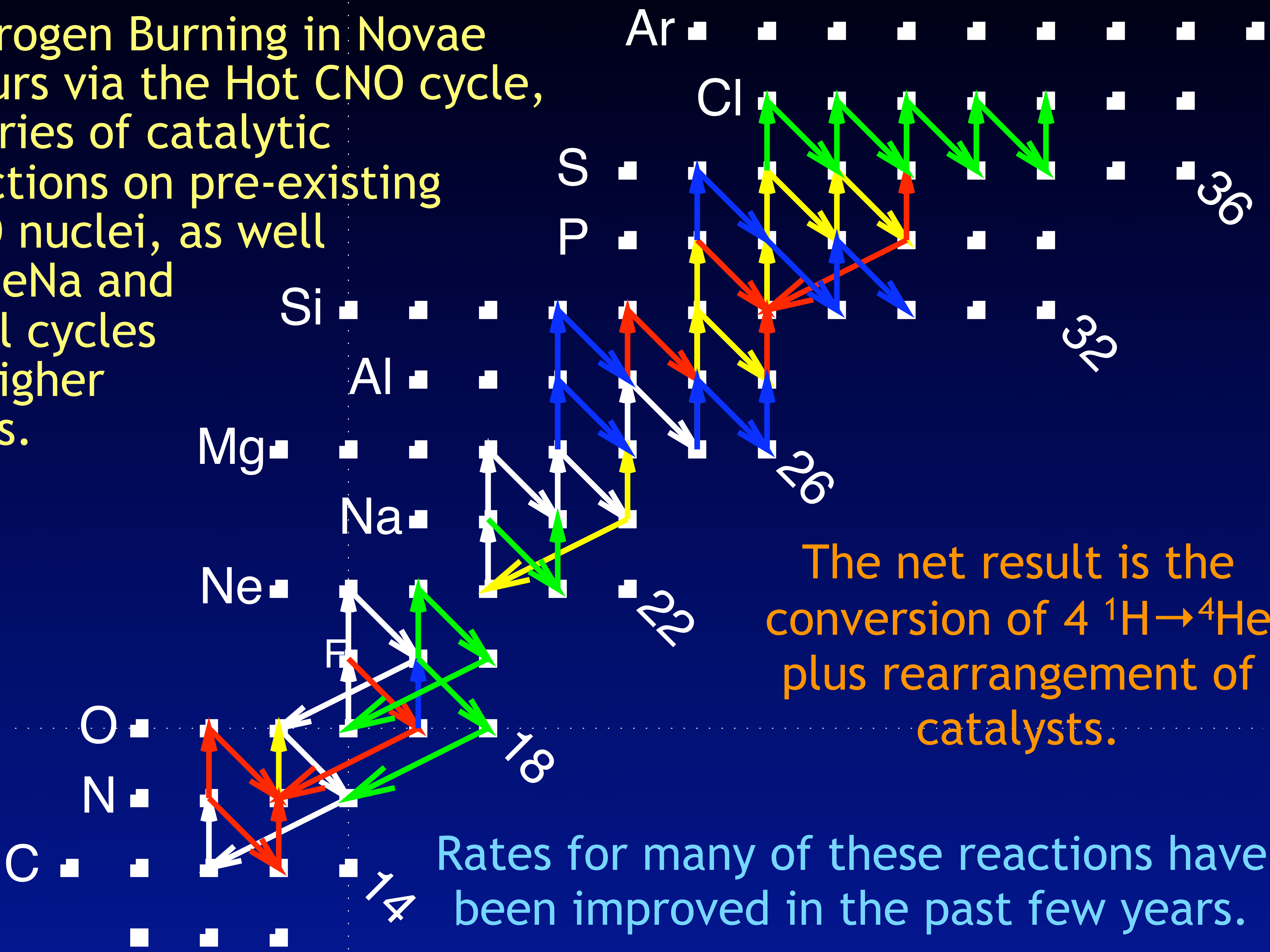

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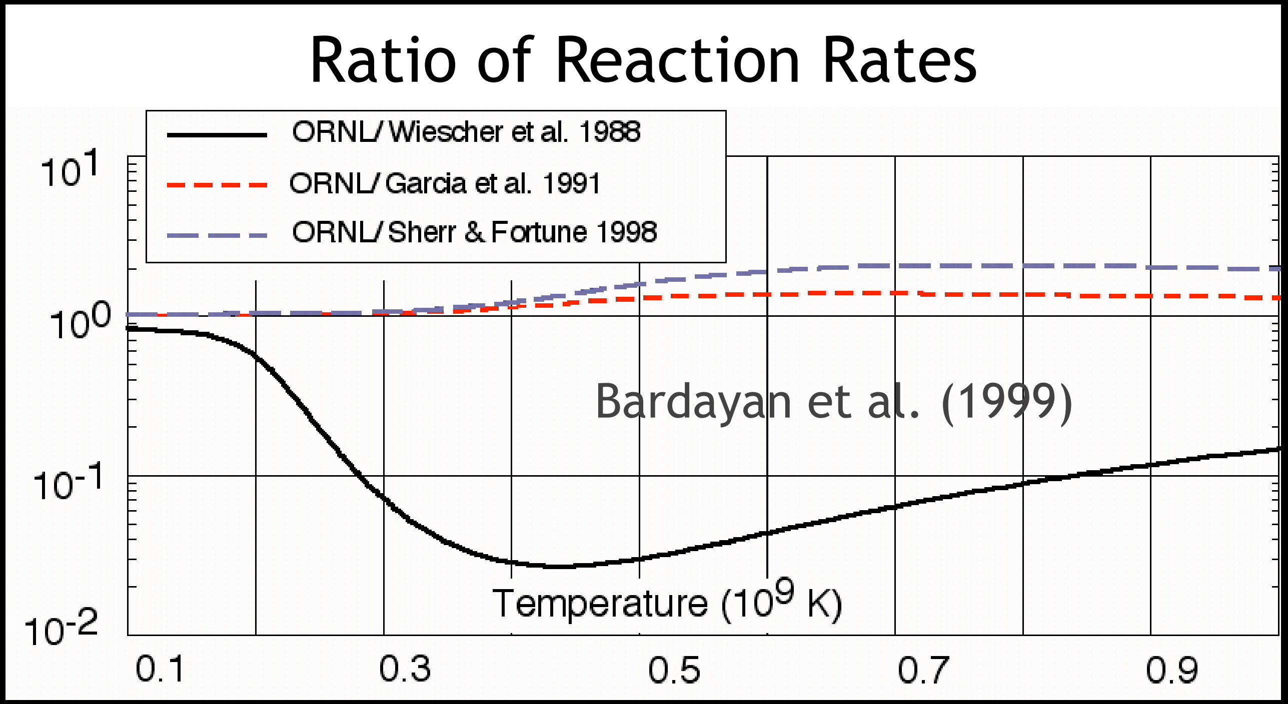
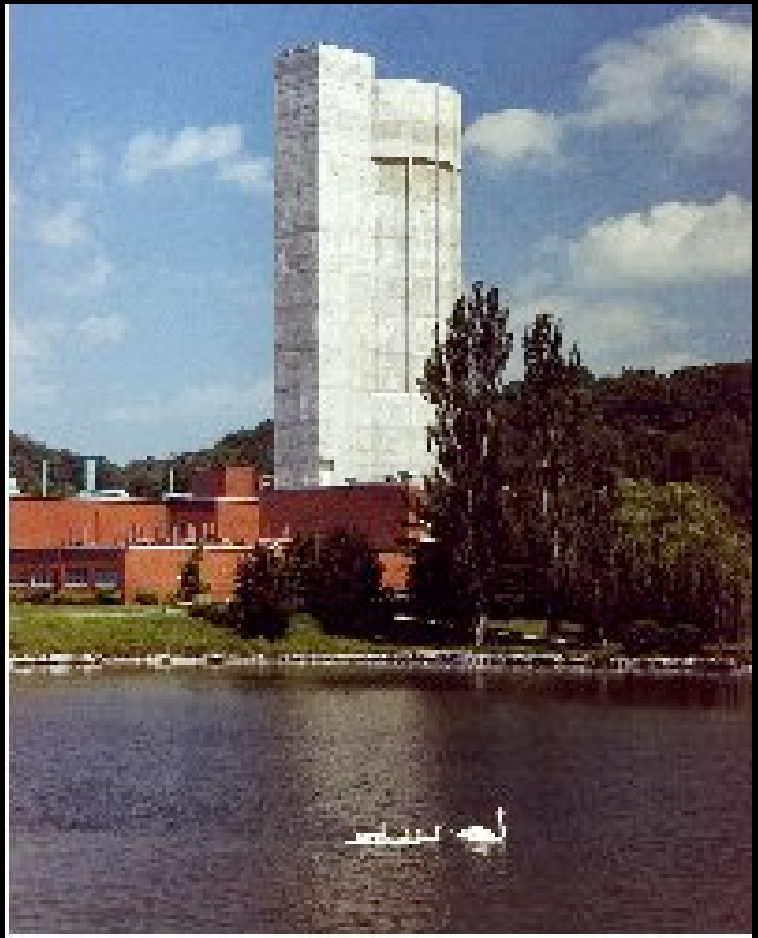
Rates for many of these reactions have been improved in the past few years.

Analyzing a new Reaction Rate

ORNL measurements produced a new $^{17}F(p,\gamma)^{18}Ne$ Reaction Rate that differed by up to factor of 30 from standard rate.





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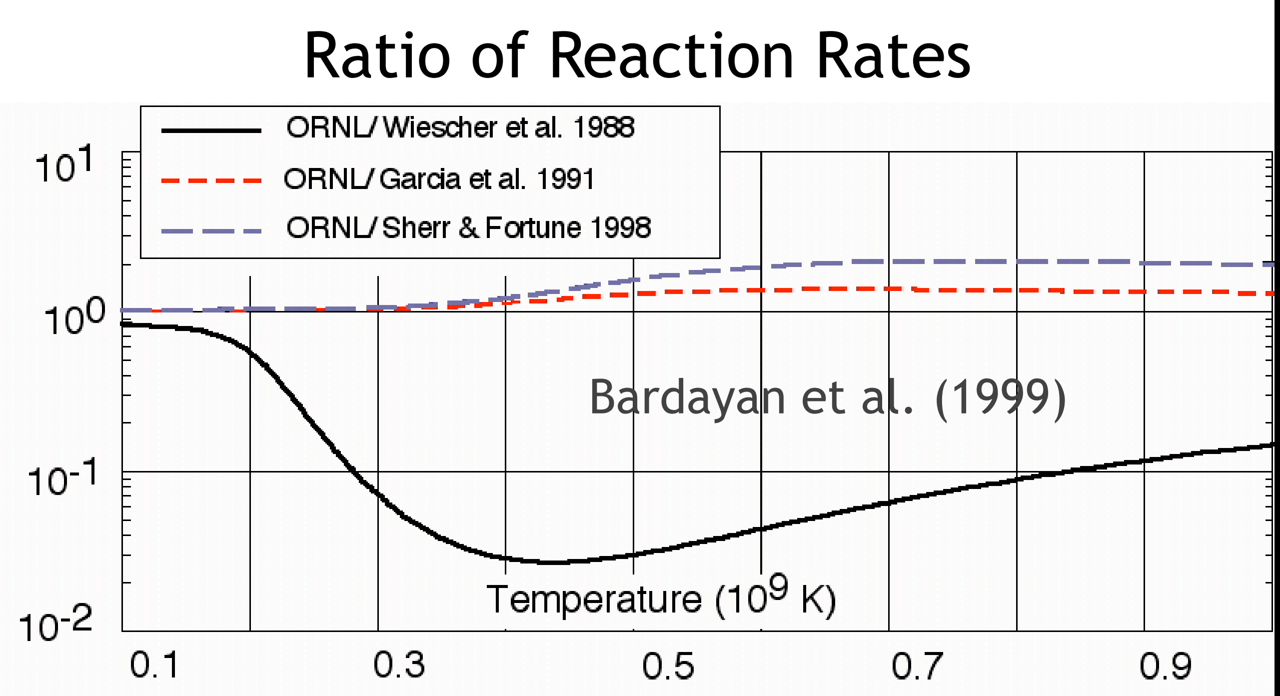
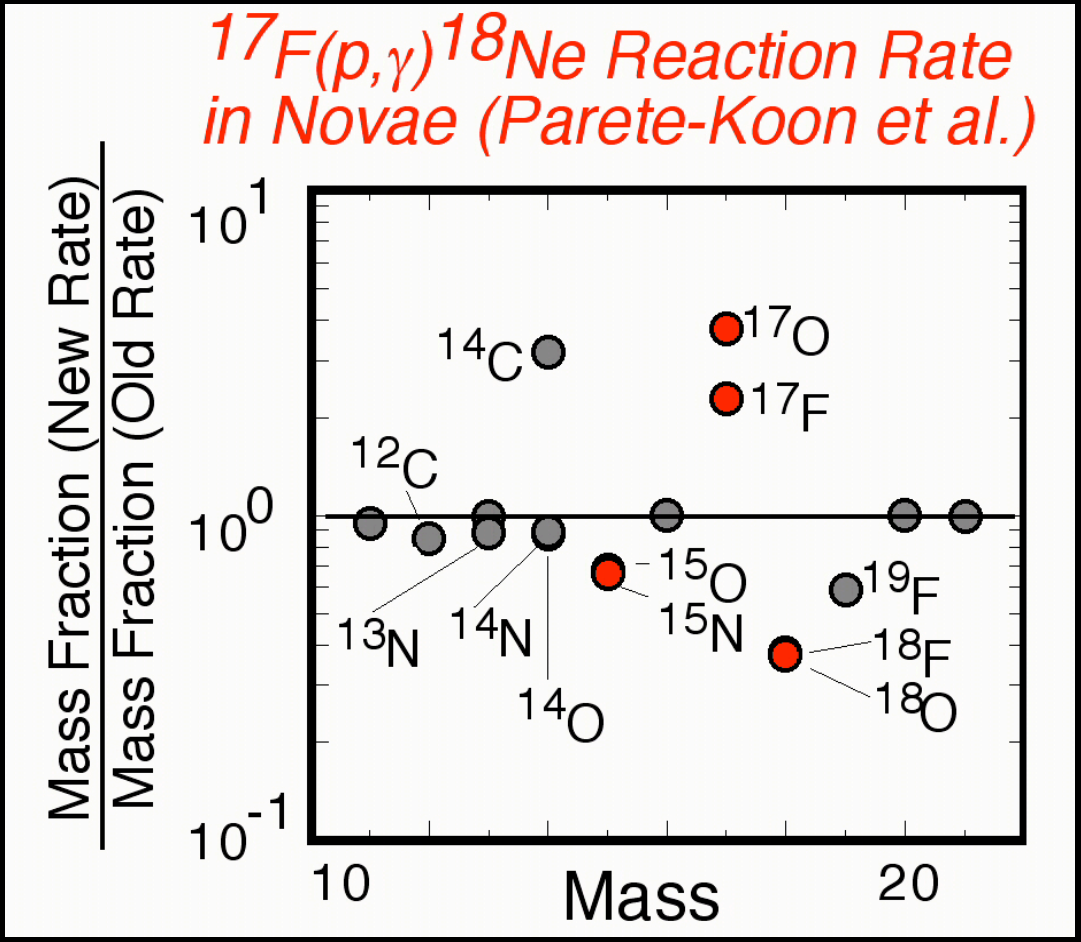


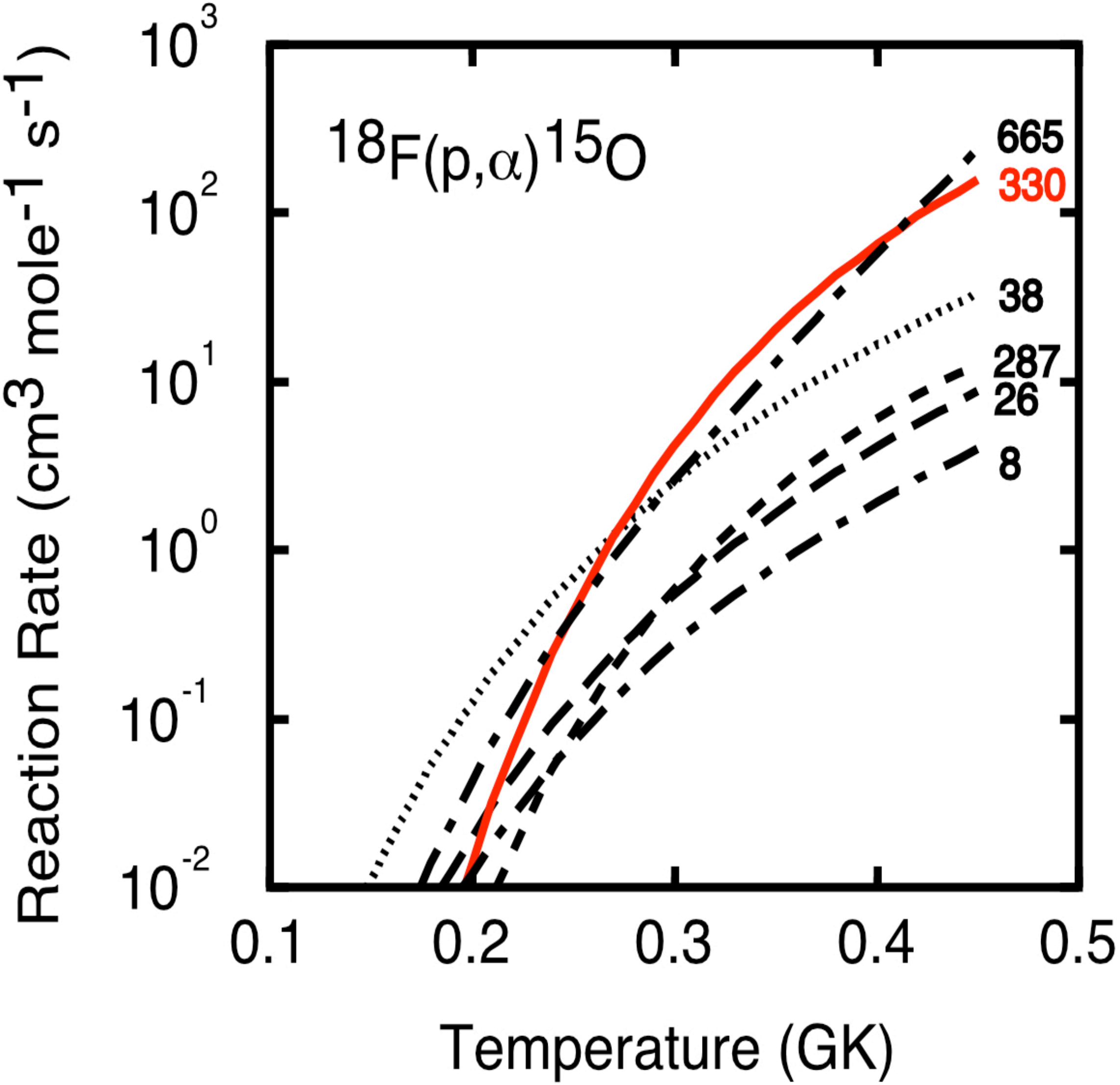


Changes predictions of synthesis of some isotopes for which novae are thought responsible, such as ^{17}O, by

- up to a factor of 15,000 in the innermost ejecta
- up to a factor of 3 averaged over entire ejecta

(Parete-Koon, Hix, … 2003, ApJ, 598, 1239)

Impact of a New $^{18}F(p,\alpha)^{15}O$ Reaction Rate



Bardayan et al. (2002) measured strength of dominant 330-keV ^{18}F+p resonance in ^{19}Ne using unstable ^{18}F beam, affecting $^{18}F(p,\alpha)^{15}O$ and $^{18}F(p,\gamma)^{19}Ne$.

Recent $^{18}F(p,p)$ (Bardayan et al. 2005) and $^{18}F(d,p)$ (Kozub et al. 2005) measurements have refined these rates.

New $^{18}F(p,\alpha)^{15}O$ and $^{18}F(p,\gamma)^{19}Ne$ Reaction Rates factor of 2 - 3 lower than rate in REACLIB library.

Changes predictions of synthesis of long-lived radioisotope ^{18}F by up to

1.6x(2x) for entire ejecta

6x(10x) in innermost ejecta

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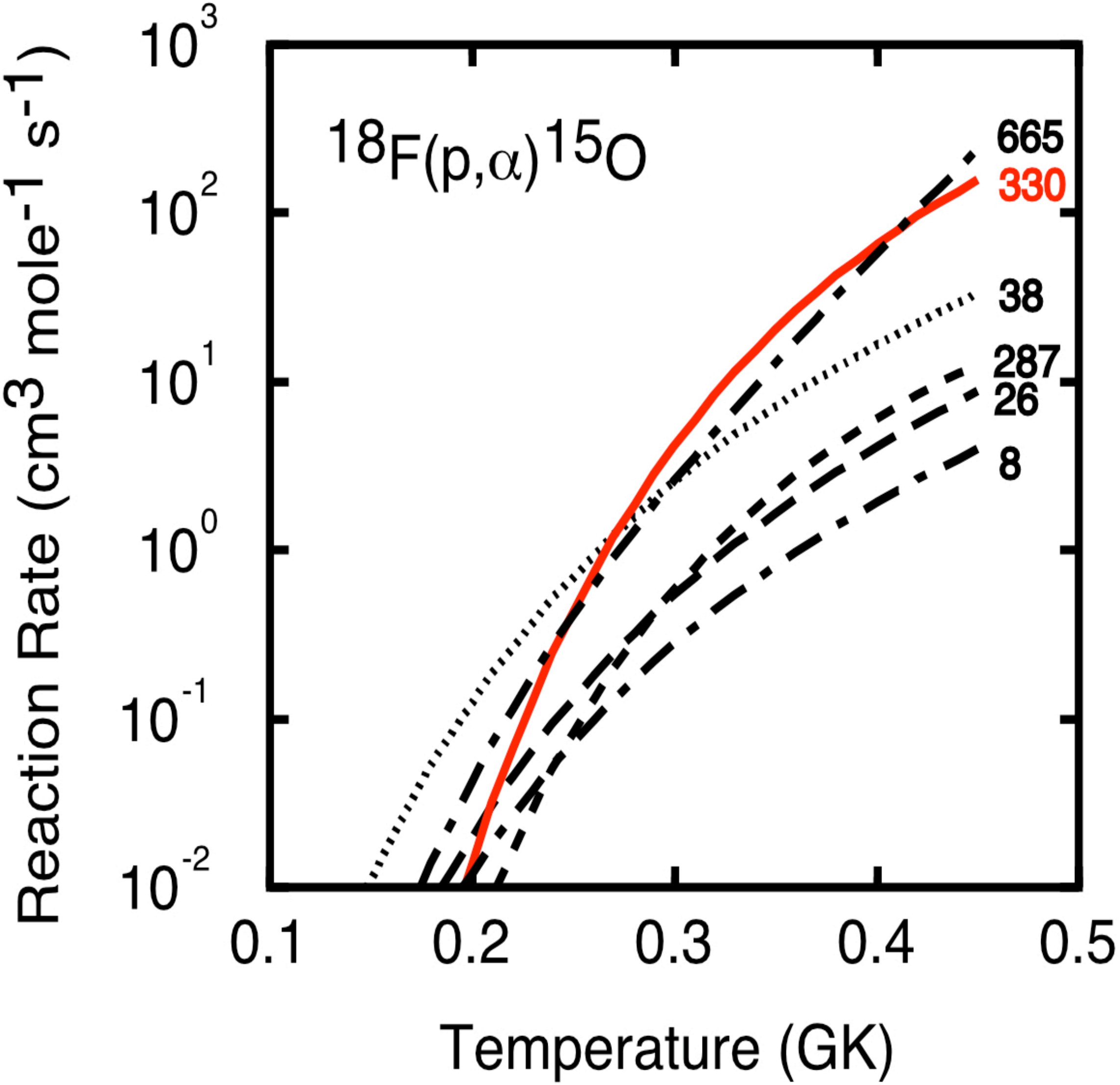

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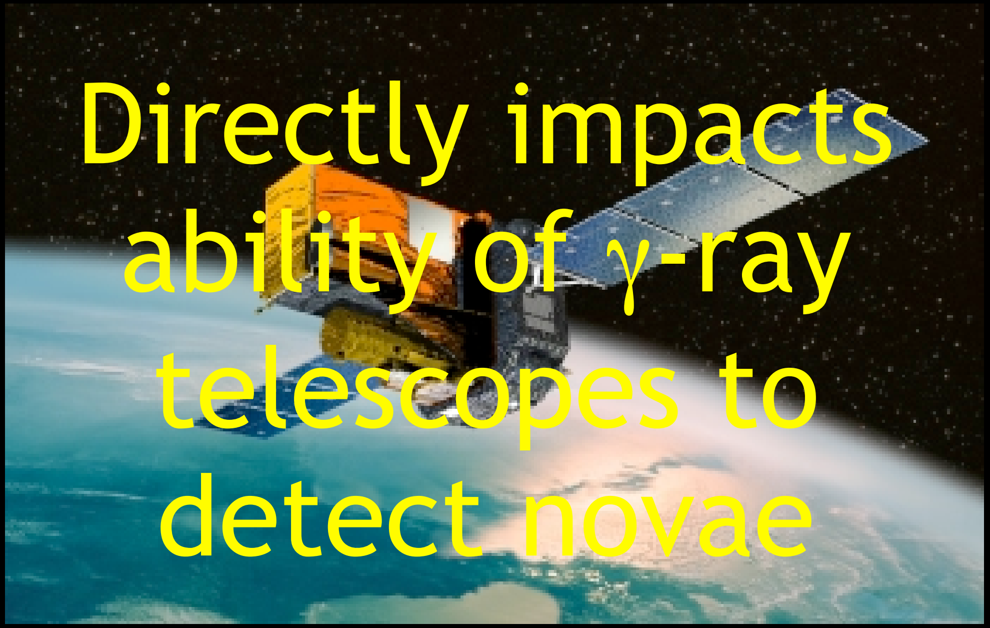


Directly impacts ability of γ-ray telescopes to detect novae

Changes predictions of synthesis of long-lived radioisotope ^{18}F by up to

1.6x(2x) for entire ejecta

6x(10x) in innermost ejecta

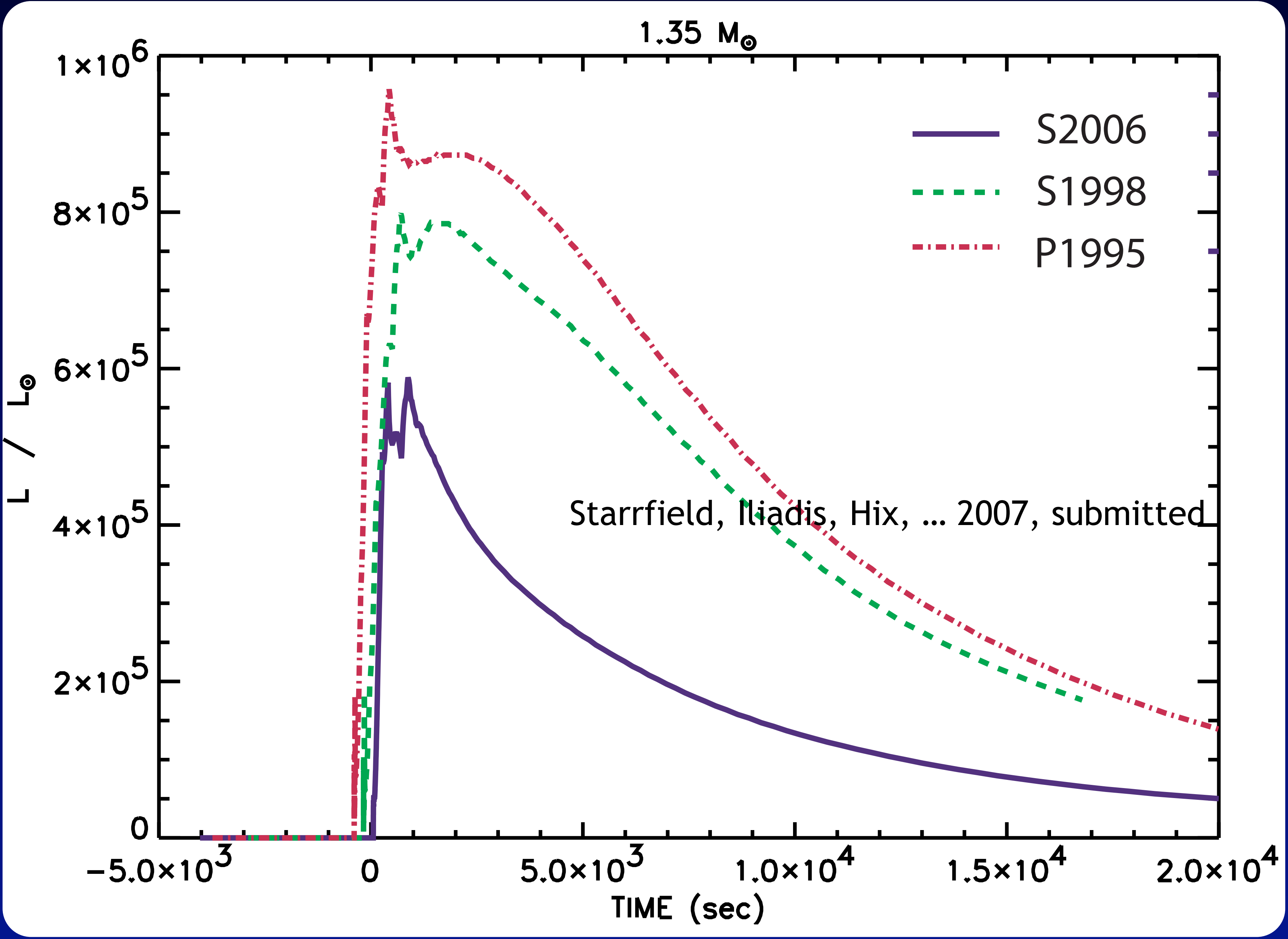
Global Impact of Nuclear Reaction

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

Nucleosynthesis products change by factors of two or more.

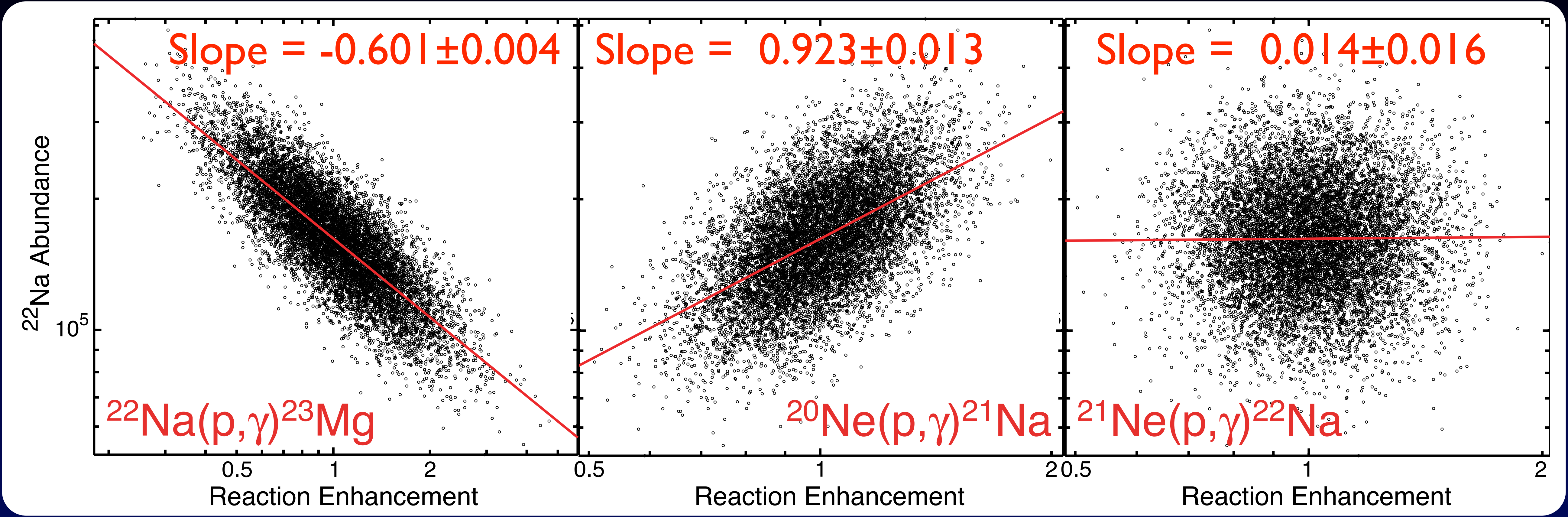
For example,

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



Starrfield, Iliadis, Hix, ... 2007, submitted

Helping to Choose Future Measurements



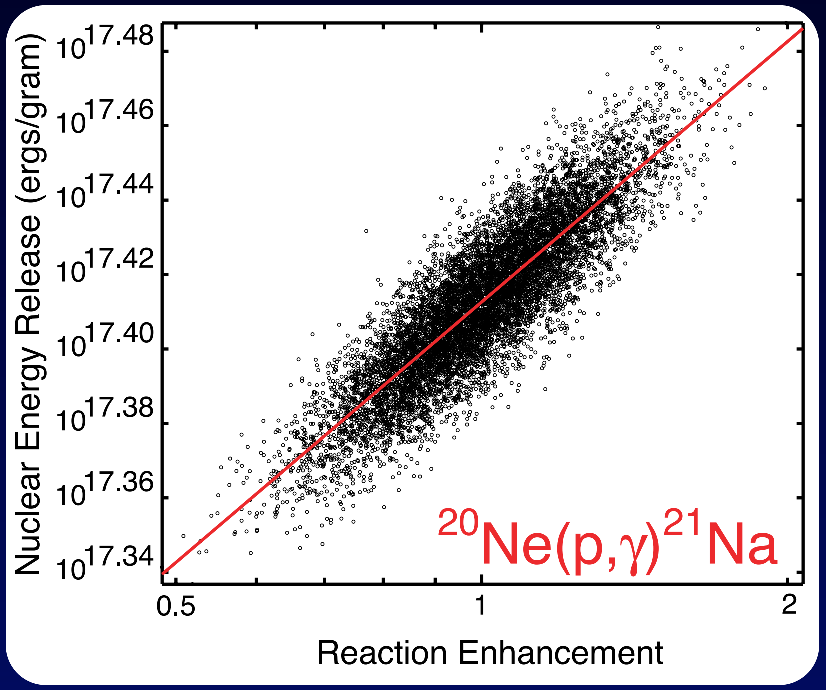
List of most important reactions for producing ^{22}Na:
^{20}Ne(p,γ)^{21}Na, ^{22}Na(p,γ)^{23}Mg, ^{21}Na(p,γ)^{22}Mg.

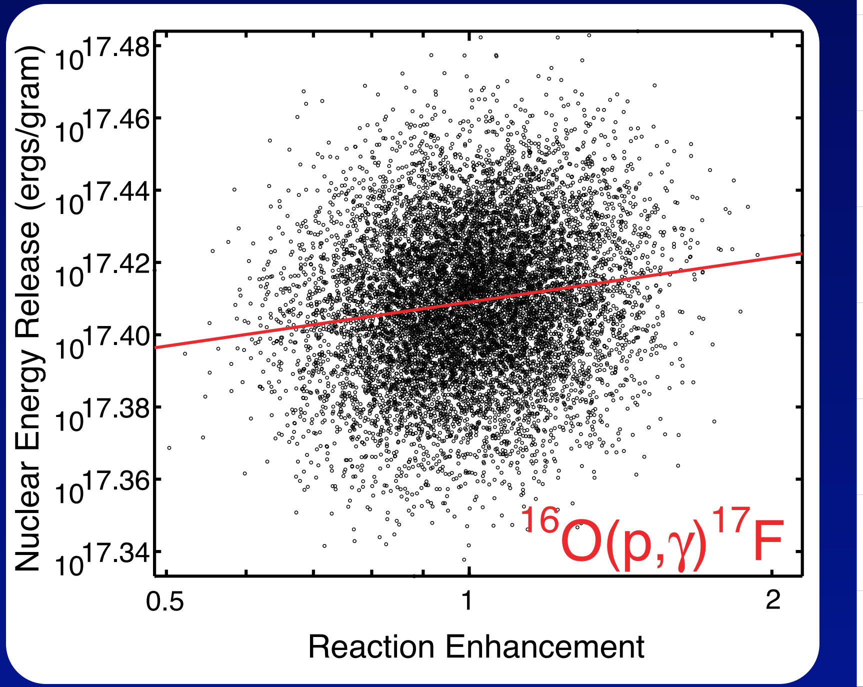
Noteworthy that the production of ^{22}Na is insensitive to the rate of ^{21}Ne(p,γ)^{22}Na and ^{23}Na(p,γ)^{24}Mg.

(see José, Coc & Hernanz 1999).

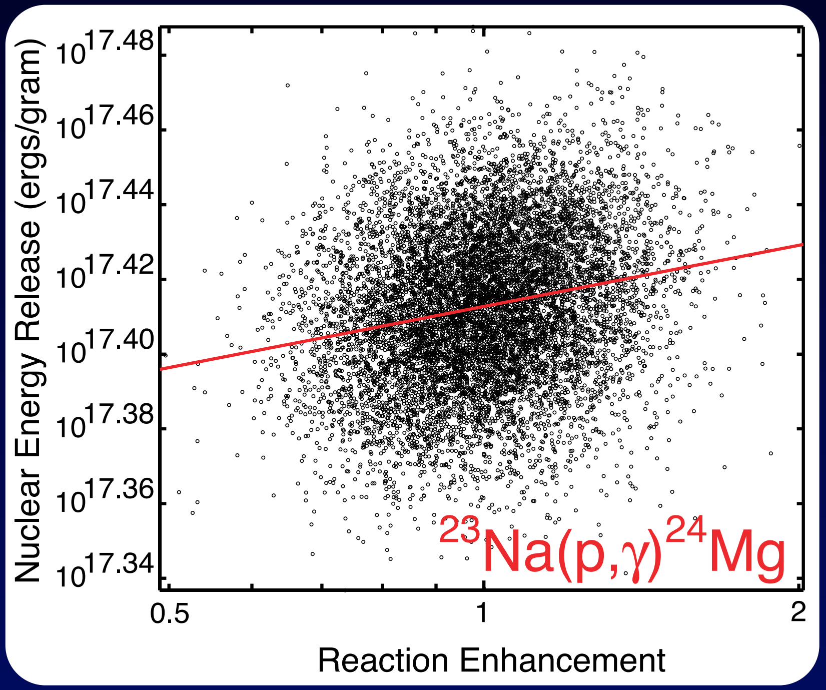
Which Reactions affect Luminosity?

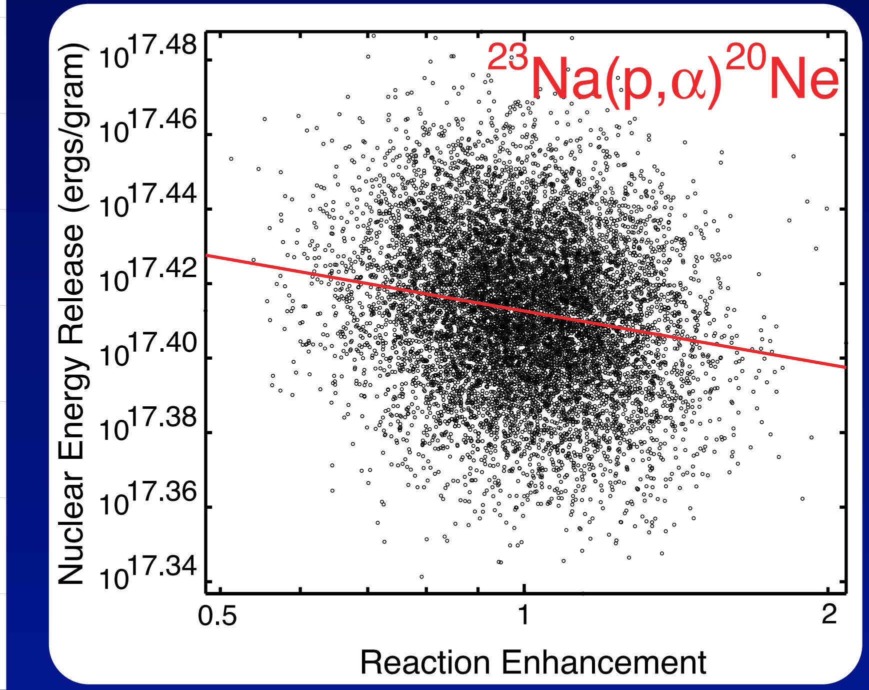
For 1.25 solar mass WD, MC indicates these reactions impact the energy generation.



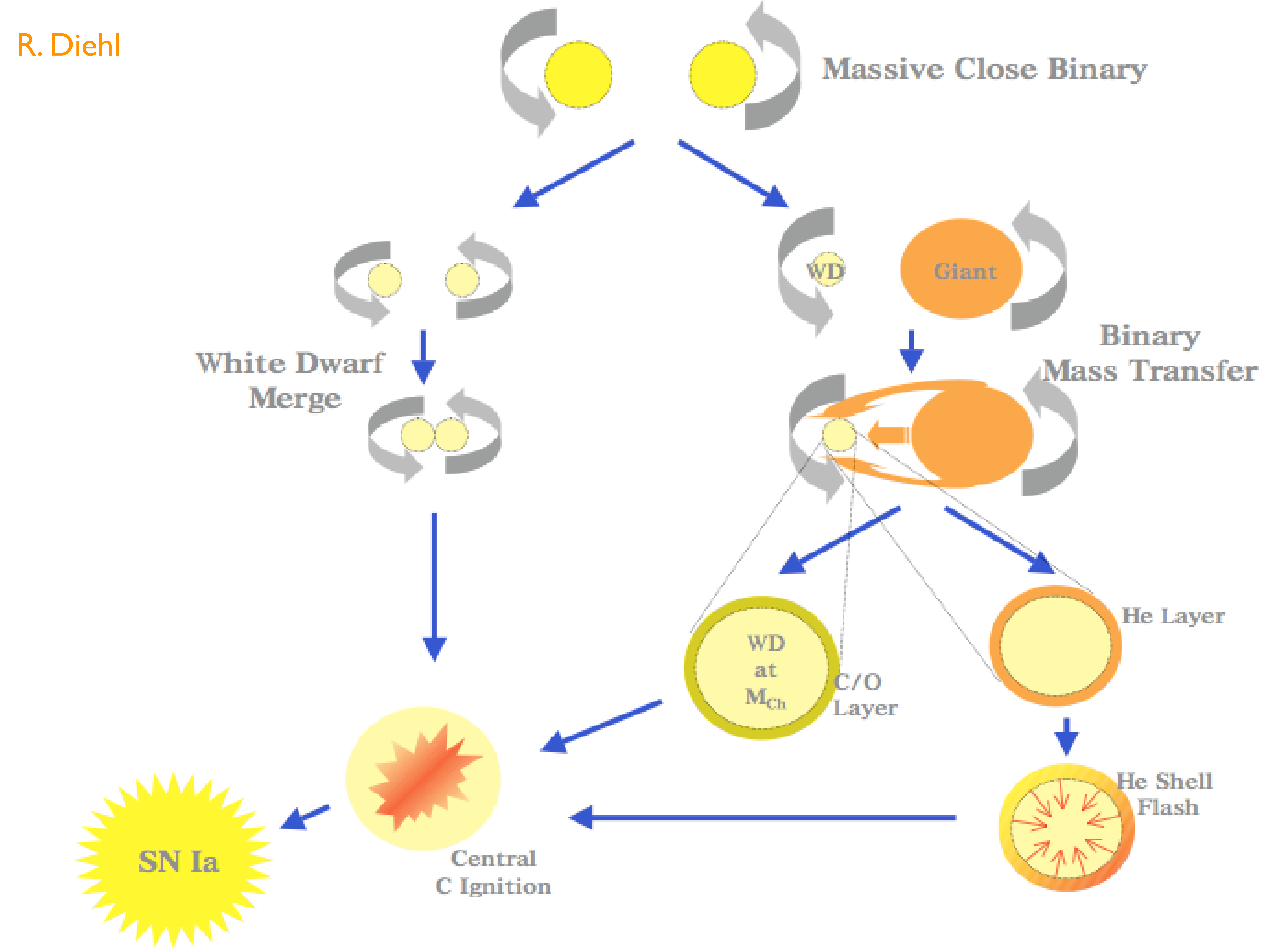


Reaction	Slope
$^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}$	0.233±0.001
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$	0.054±0.003
$^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$	-.047±0.003
$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$	0.041±0.003
$^{28}\mathrm{Si}(p,\gamma)^{29}\mathrm{P}$	0.025±0.003
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$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





Thermonuclear SN Mechanism



Several ways to destroy a White Dwarf.

Chandrasekhar Limit

Pressure in a white dwarf results from degenerate electrons.

As WD mass increases, electron velocities approach the speed of light and provide decreasing pressure.

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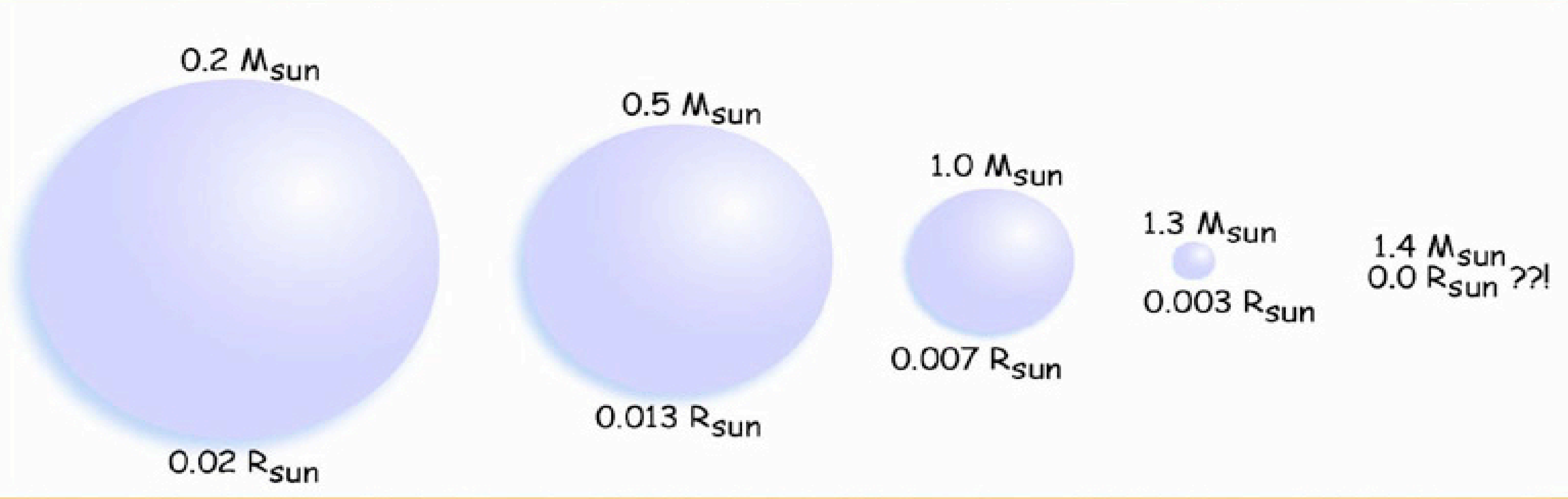
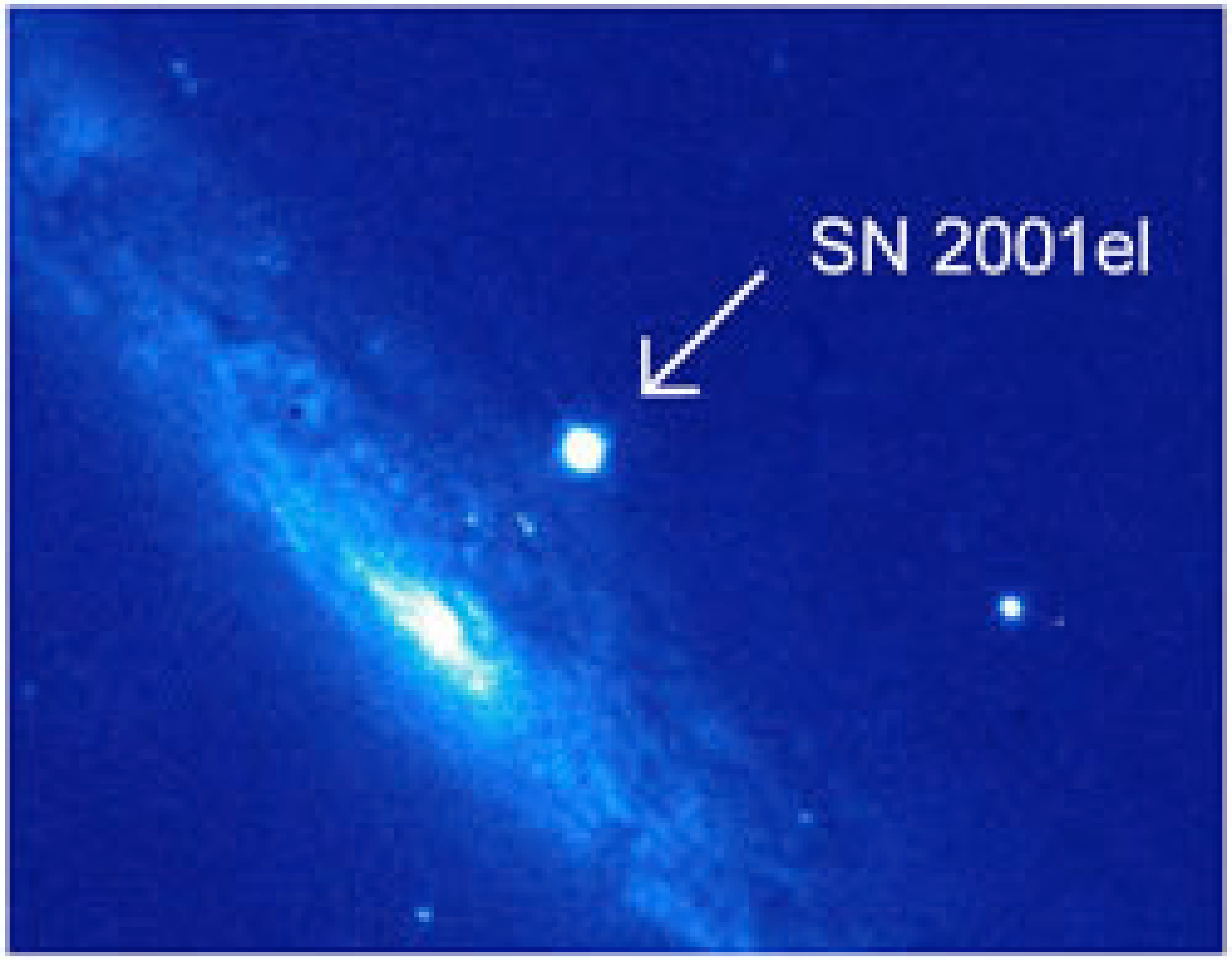
As a result, there is a limit to the pressure provided. This results in a maximum mass for a white dwarf, the Chandrasekhar mass.

~ 1.4 solar masses



Visible at great distance

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



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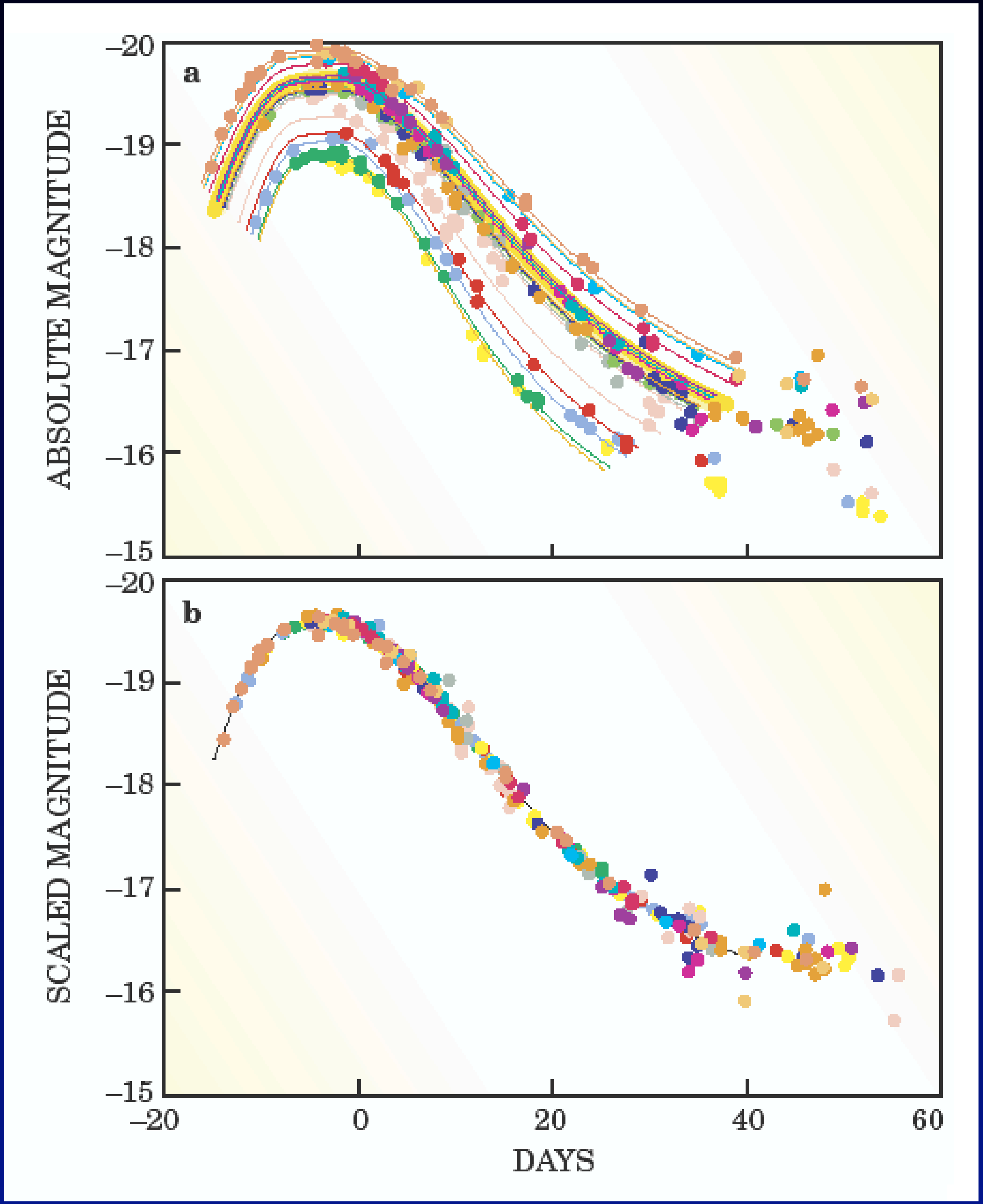

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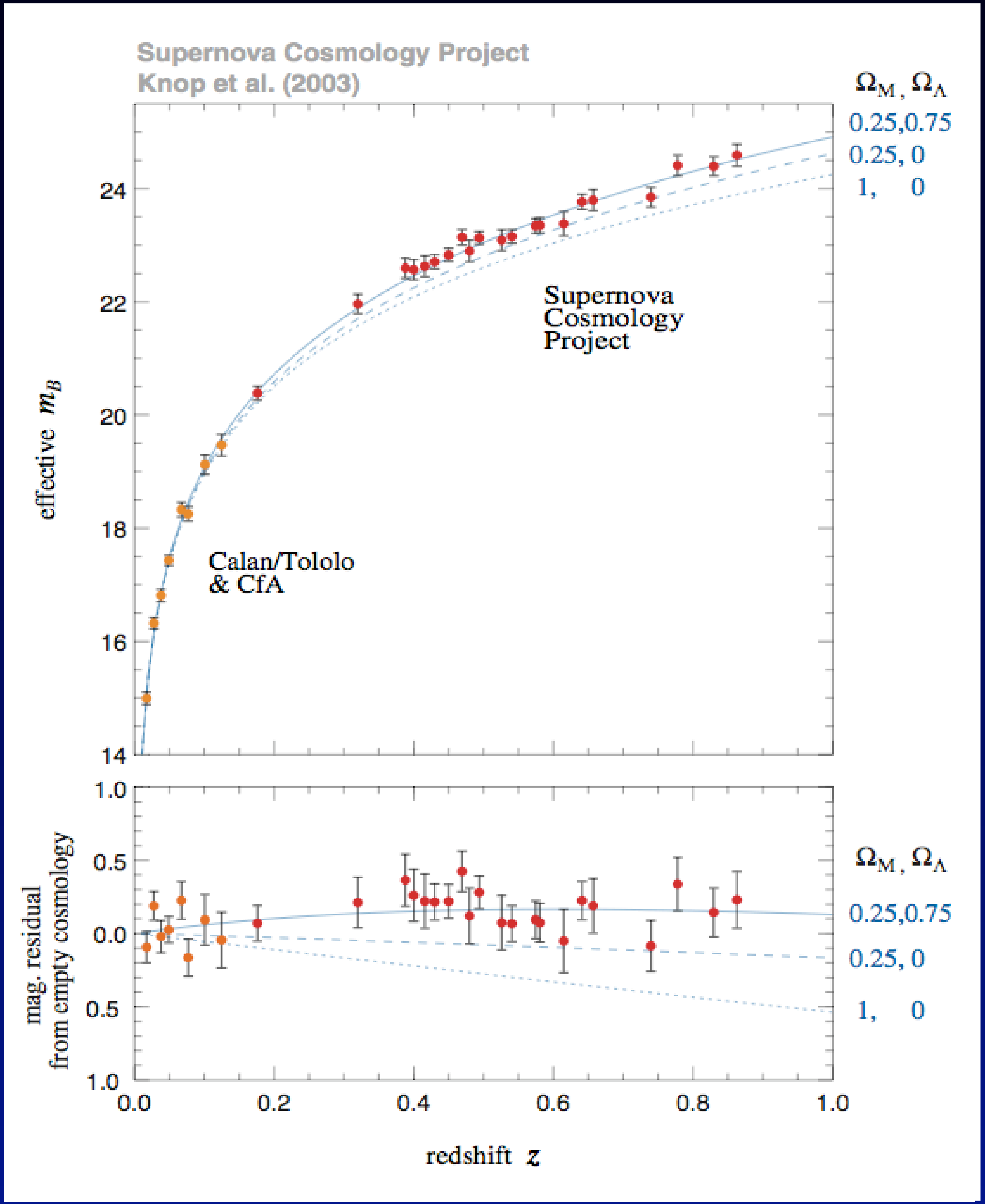
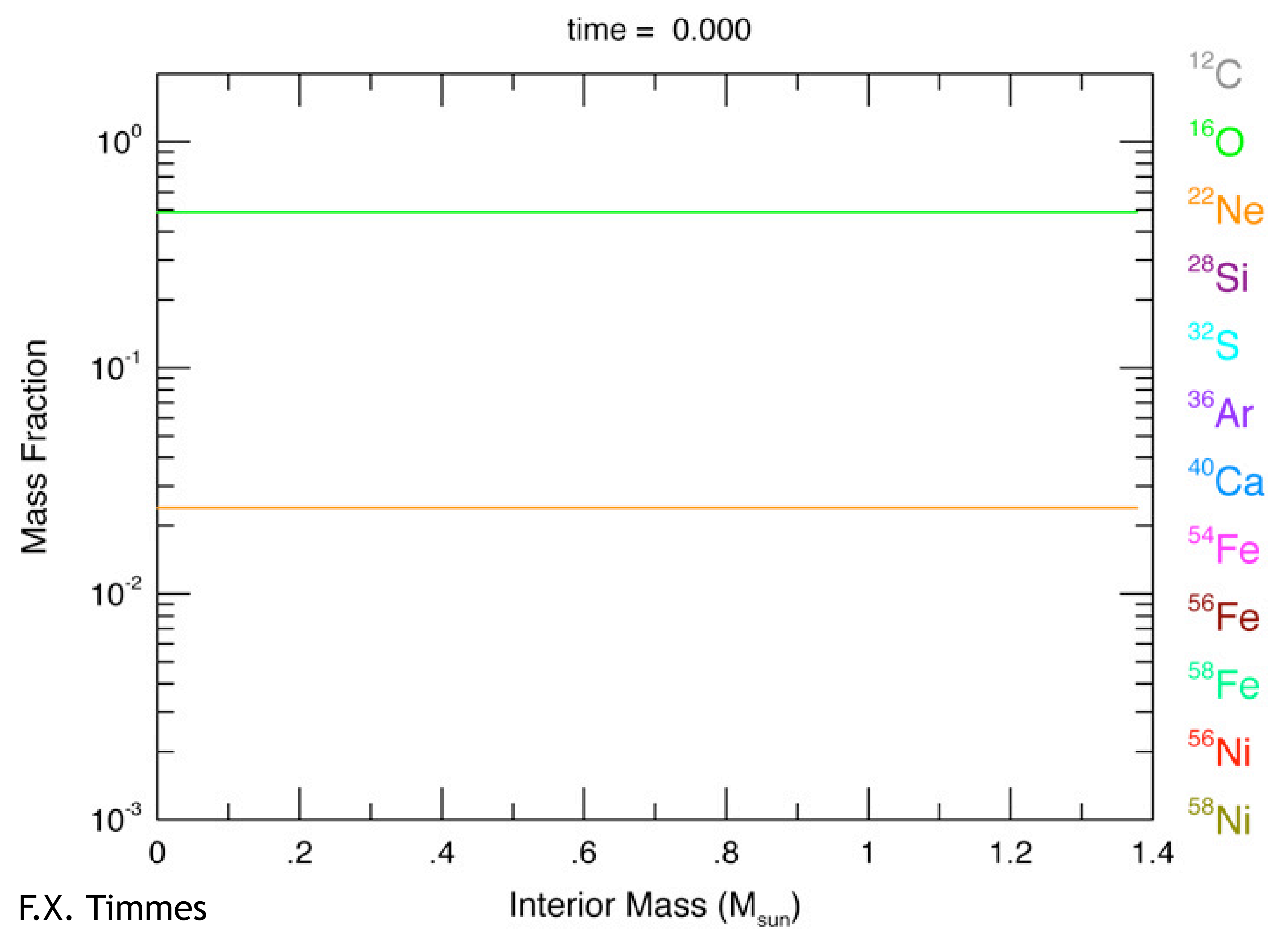
This led to the discovery that the expansion of our universe is accelerating.



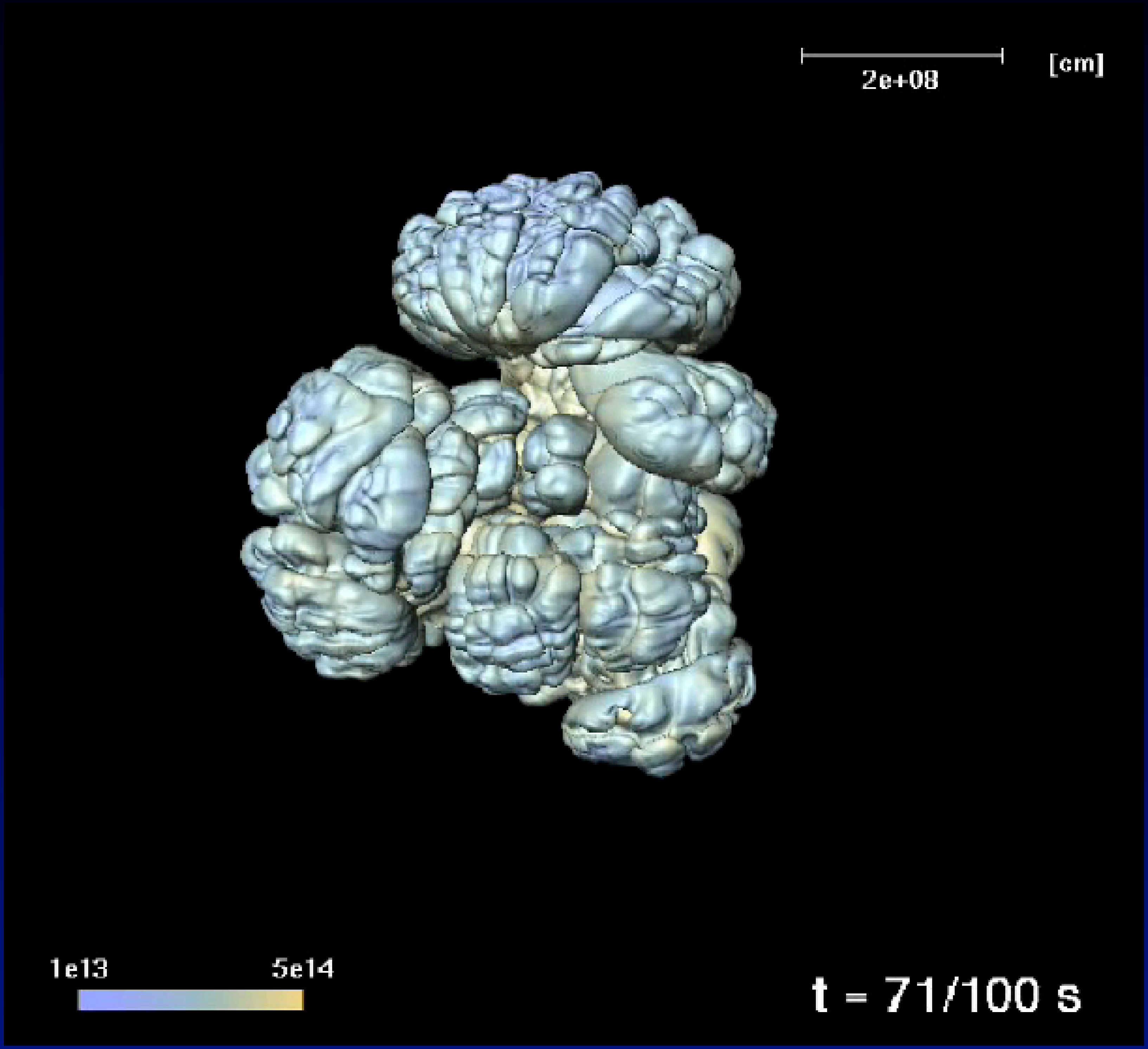
Nucleosynthesis in Thermonuclear SN



F.X. Timmes

Density rise as WD nears Chandrasekhar limit ignited thermonuclear flame which propogates out through the star.

The Multi-D view



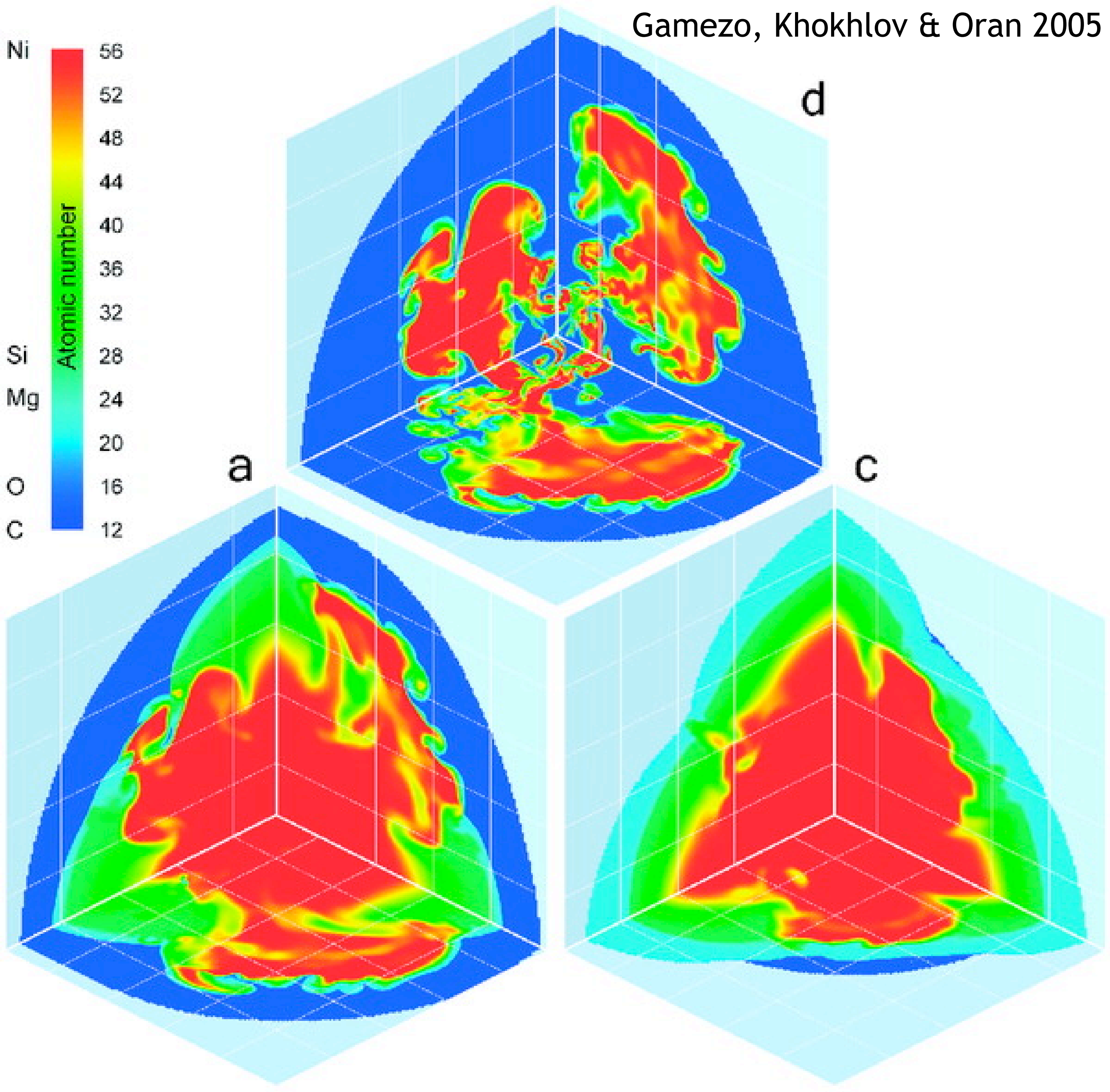
Röpke &
Hillebrandt 2005

In reality the flame propagation is much more complex than 1D implies.

Deflagration/Detonation

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

A Deflagration/ Detonation transition (DDT) must occur.

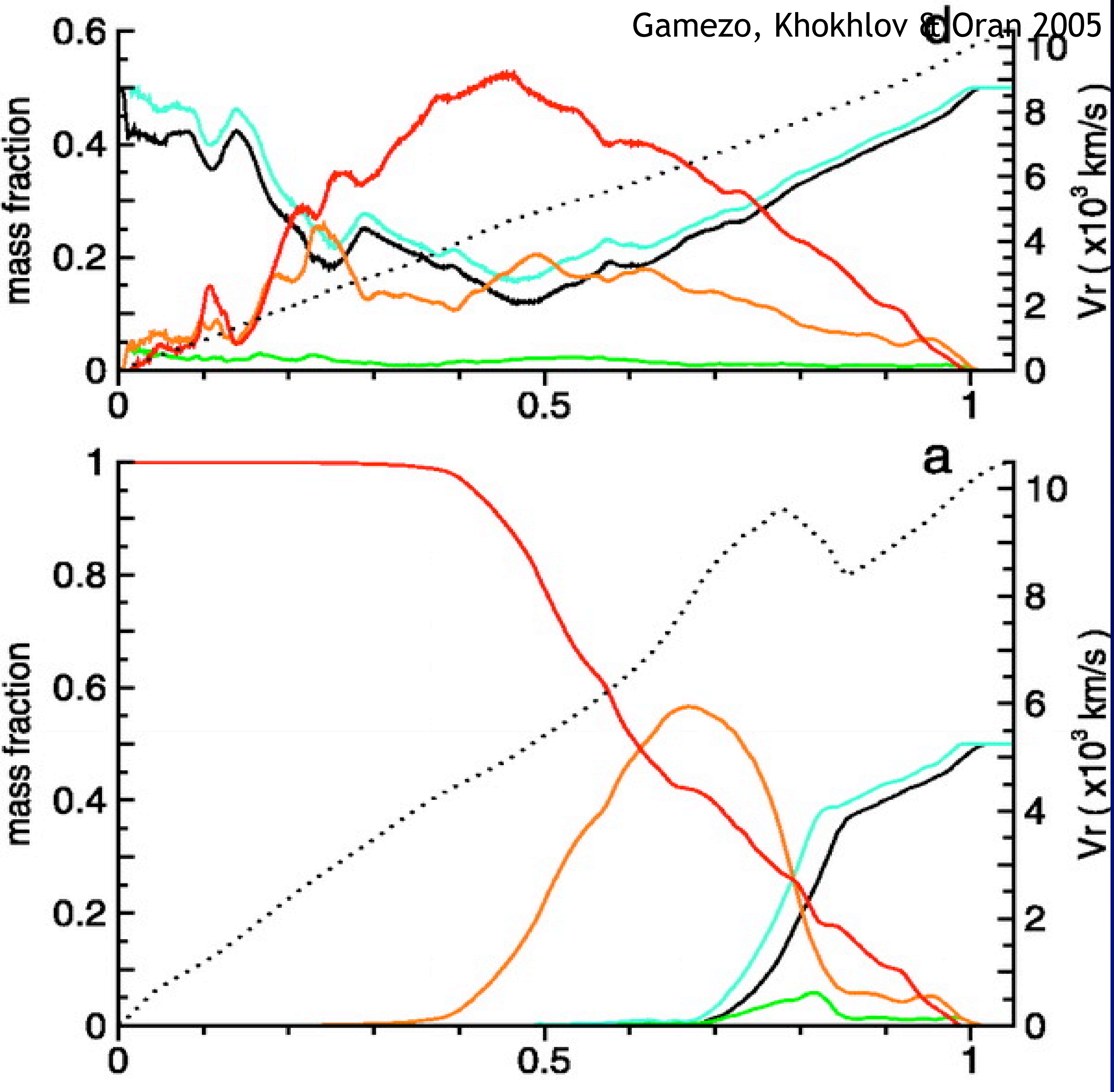


Gamezo, Khokhlov & Oran 2005

Deflagration/Detonation

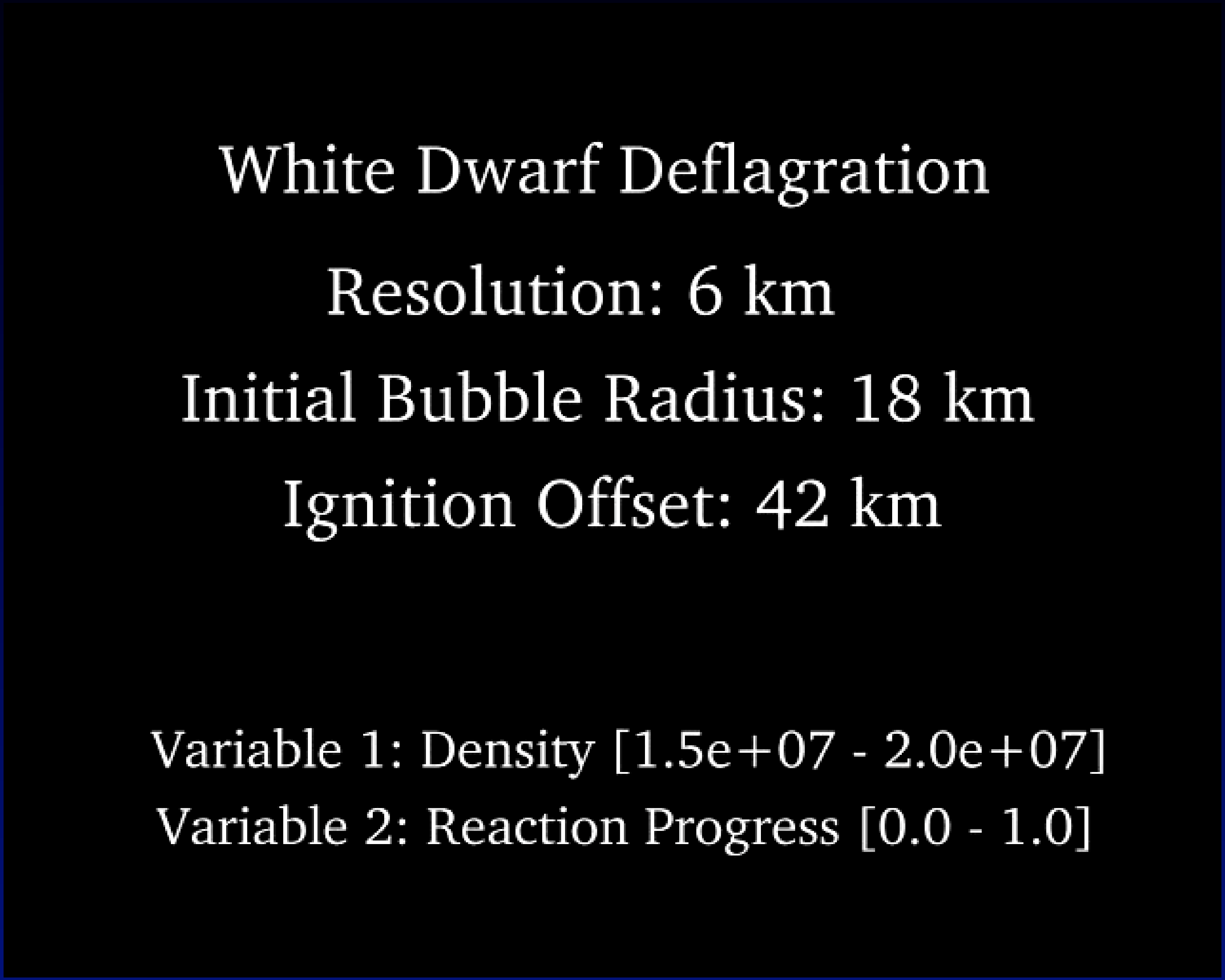
Multi-D deflagrations leave pockets of unburned material behind, but observations do not show this.

A Deflagration/ Detonation transition (DDT) must occur.



Gamezo, Khokhlov & Oran 2005

How 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]

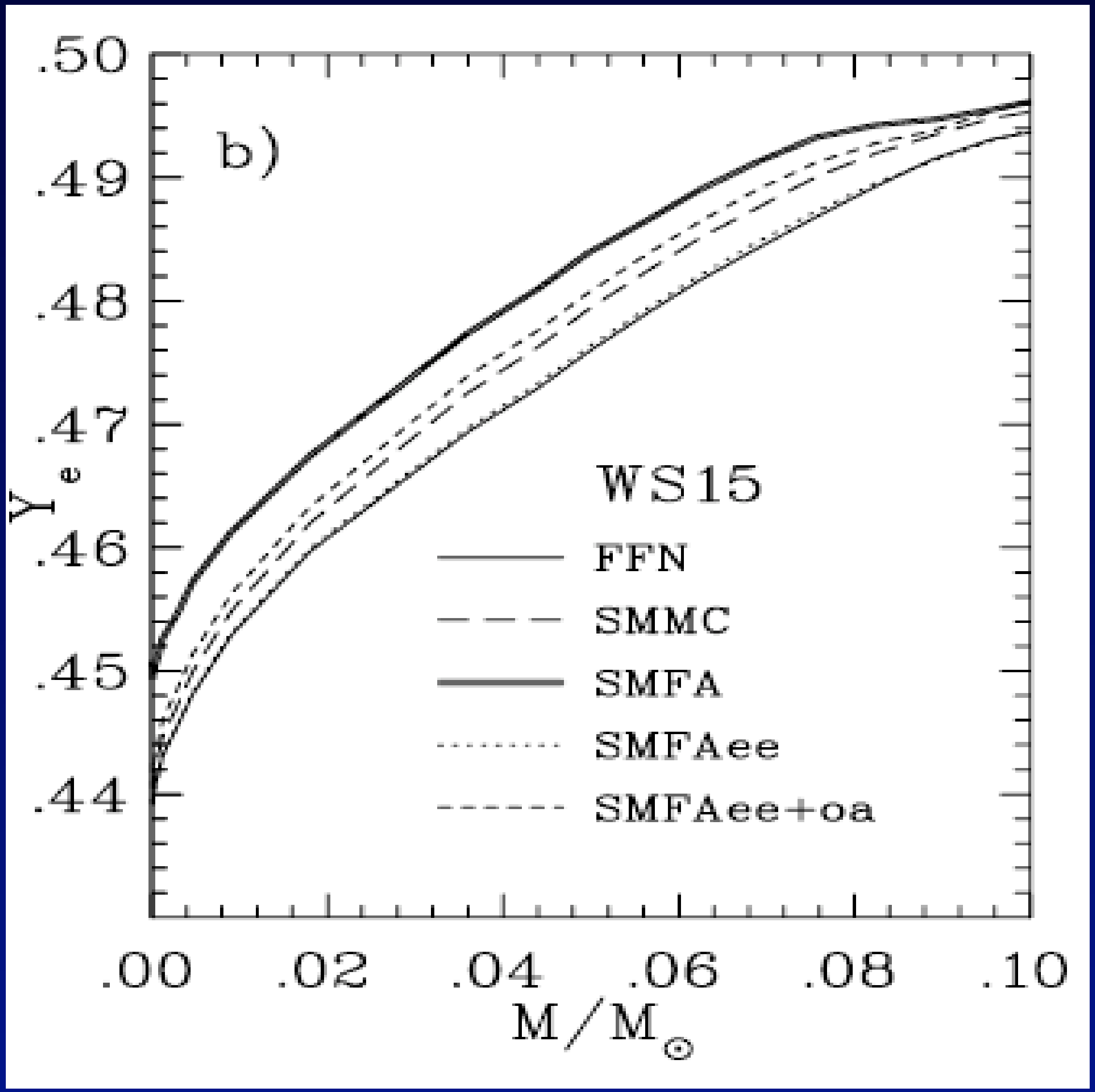
In terrestrial conditions, DDT is often due to geometry/confinement. Perhaps this is also true for Thermonuclear SN.

Nuclear Physics of Thermonuclear SN

Initial composition, and global energetics, are determined by $^{12}C(\alpha,\gamma)^{16}O$ during stellar evolution.

Weak nuclear reactions on iron peak nuclei determine the amount of neutron-rich matter which is ejected, providing a limit on the ignition density.

With better electron capture rates, this limit changes by 25%



Brachwitz, Dean, Hix …2001

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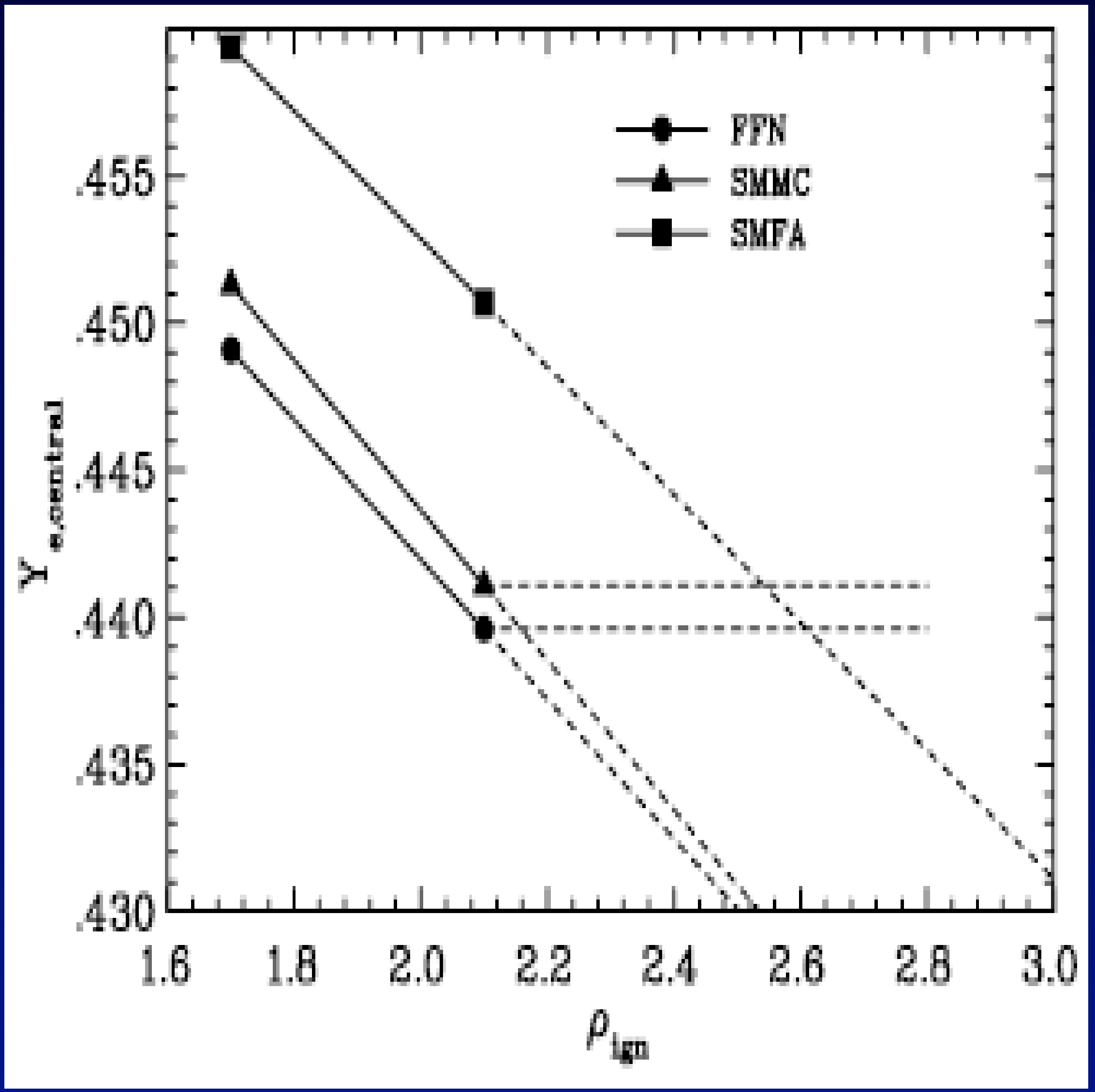
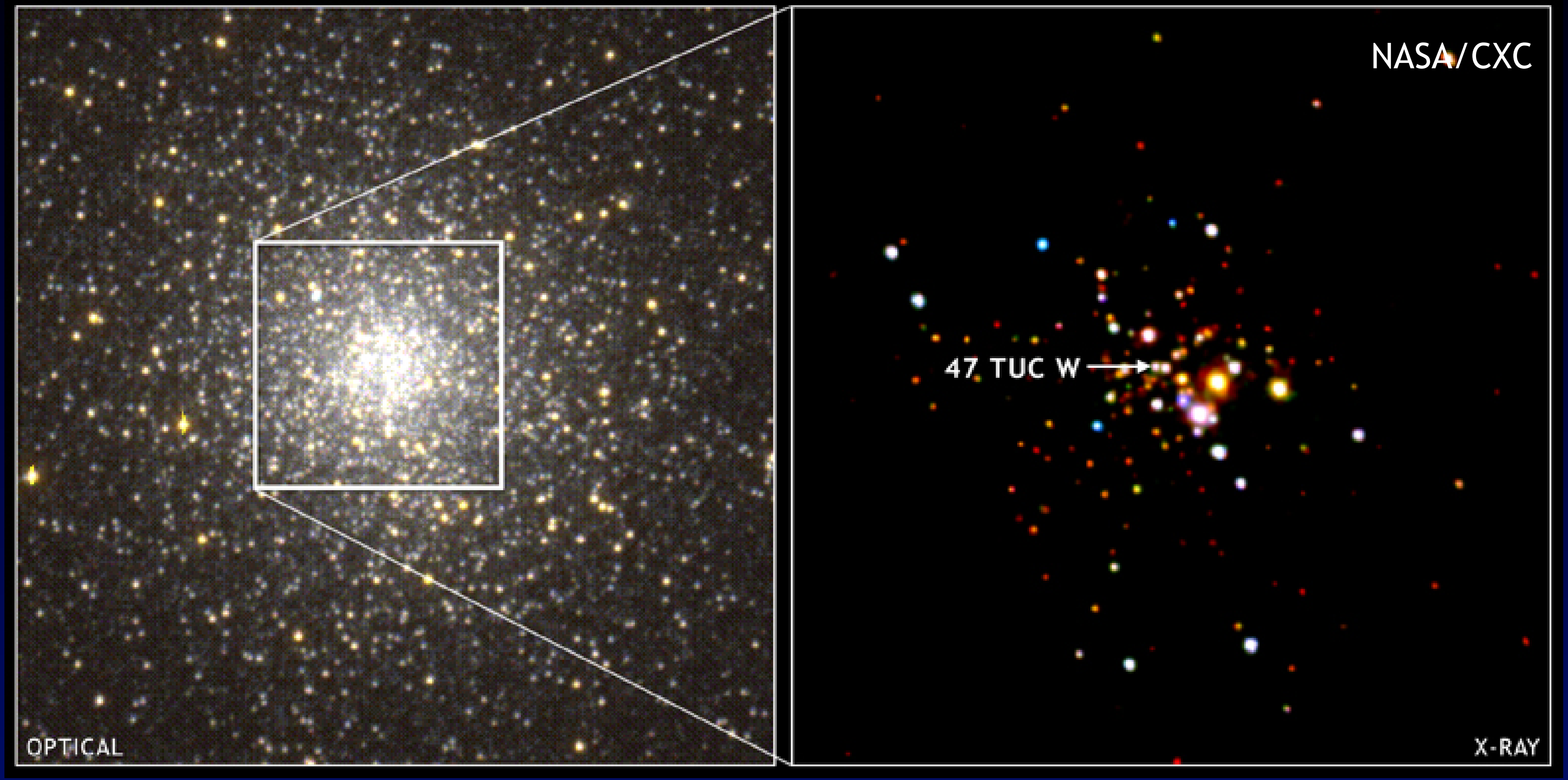


Brachwitz, Dean, Hix …2001

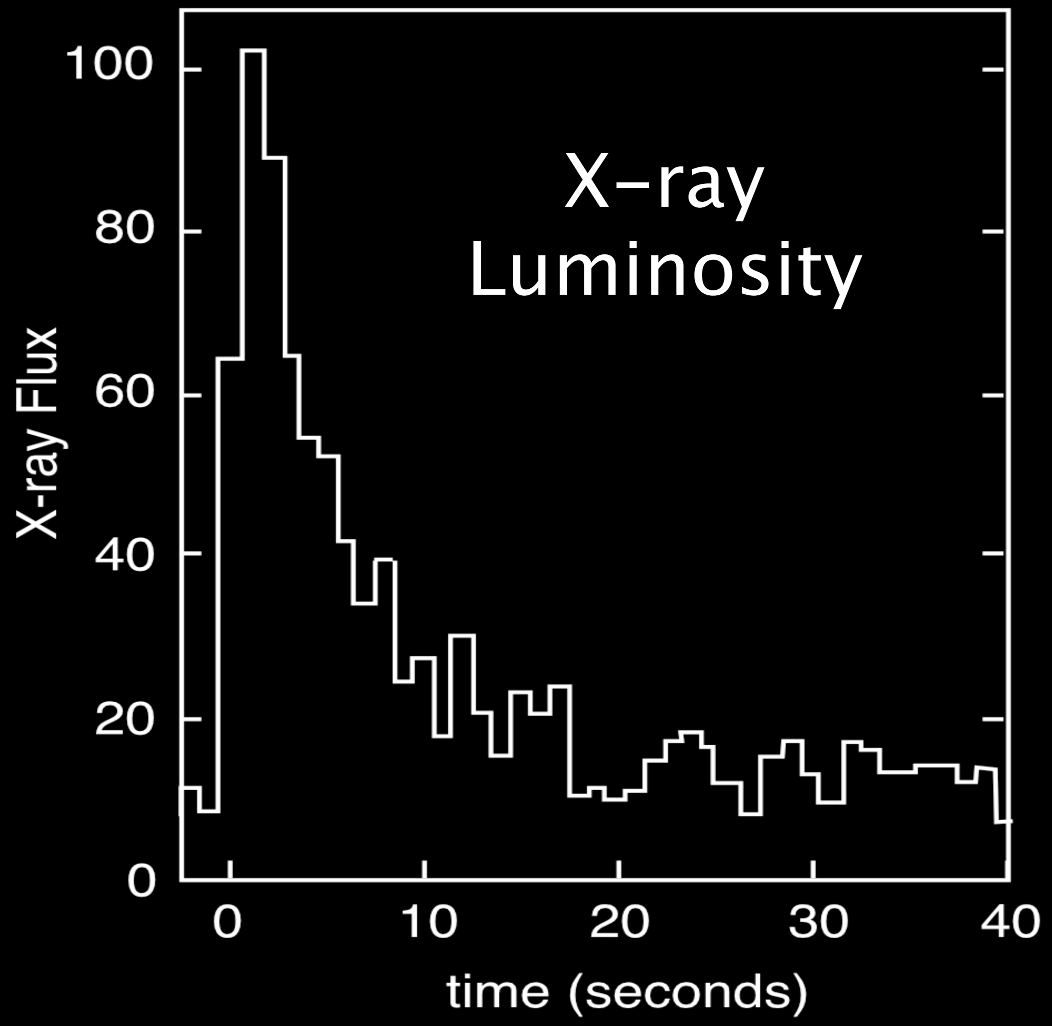
Accretion onto Neutron Stars

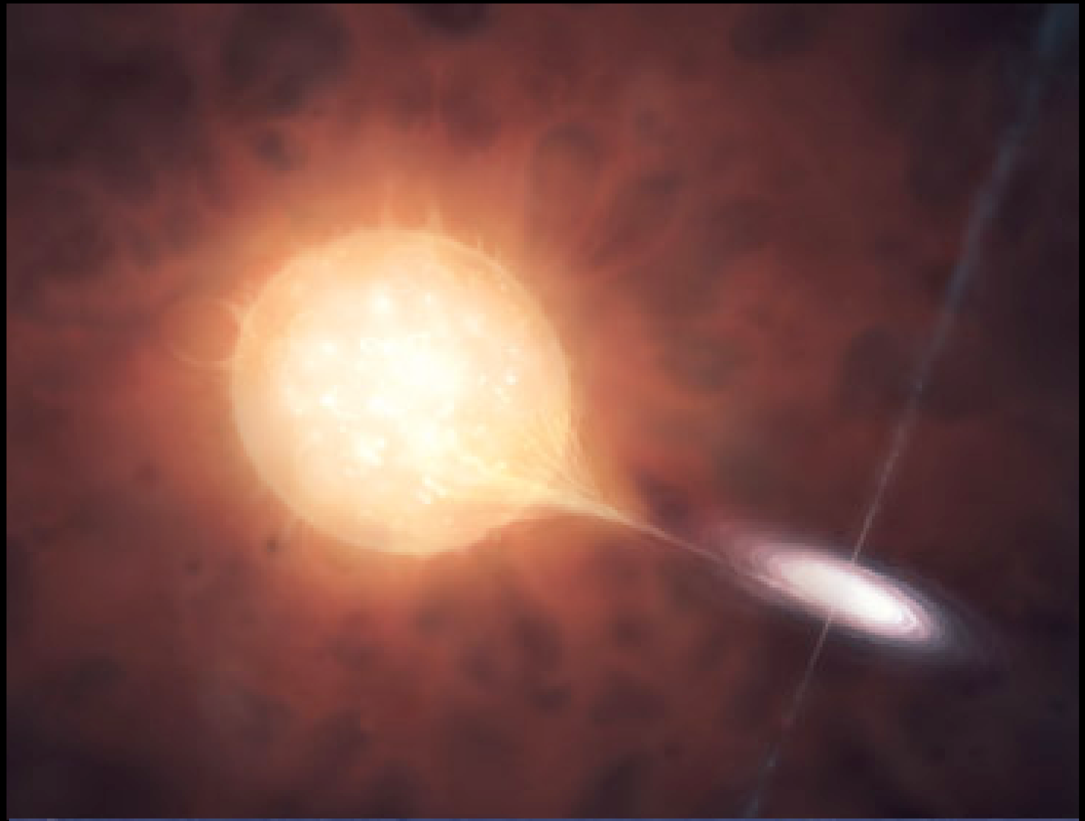


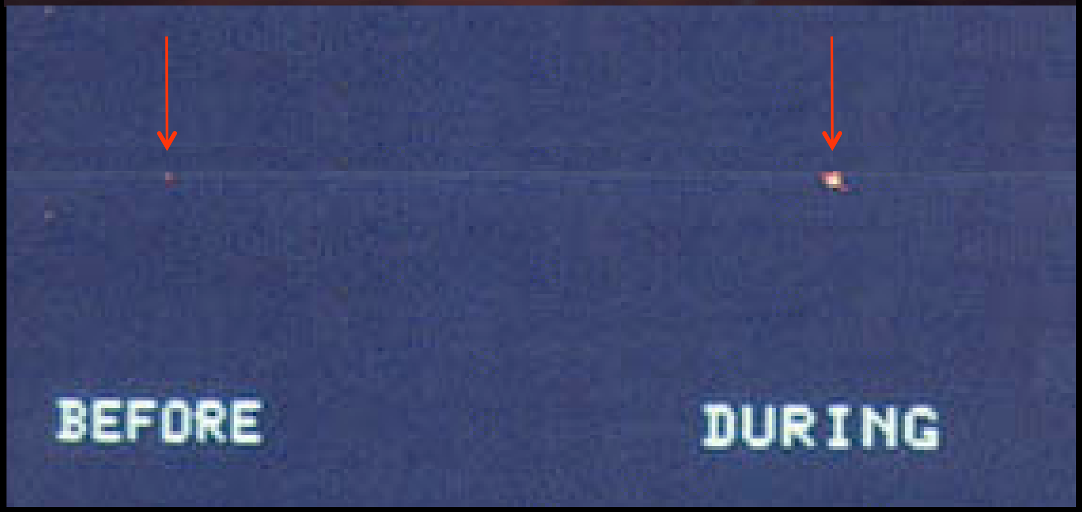
Accretion from a companion can also occur on a neutron star. Such accreting neutron stars account for many observed X-ray sources.

Unlike for a white dwarf, nuclear energy release is insignificant compared to the gravitational energy release, unless it is intermittent.

X-ray Bursts







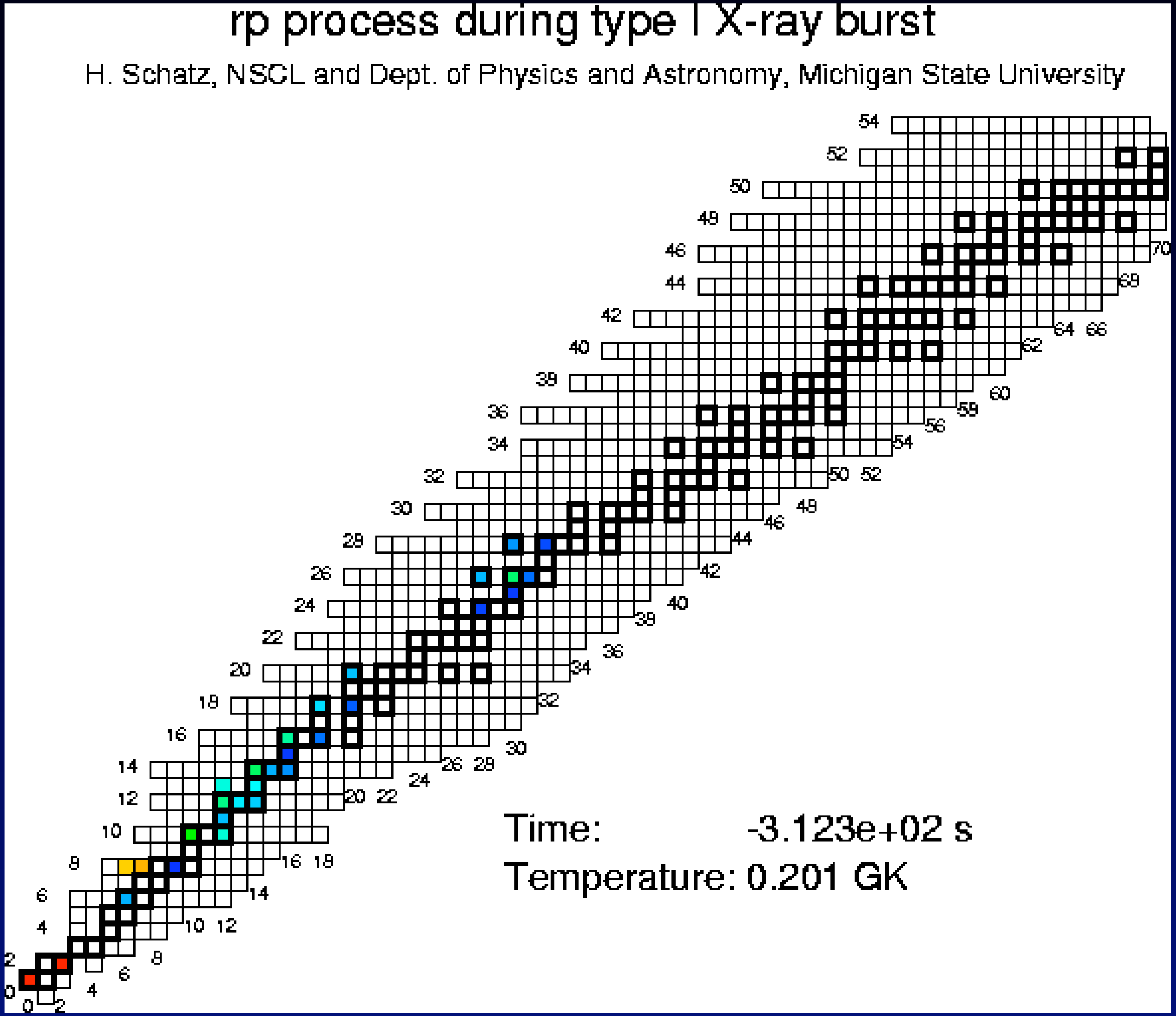
Some X-ray binaries periodically produce bursts of X-rays (~10^{38} ergs s^{-1}) can recur hourly or daily.

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 more seeds for the rp–process.



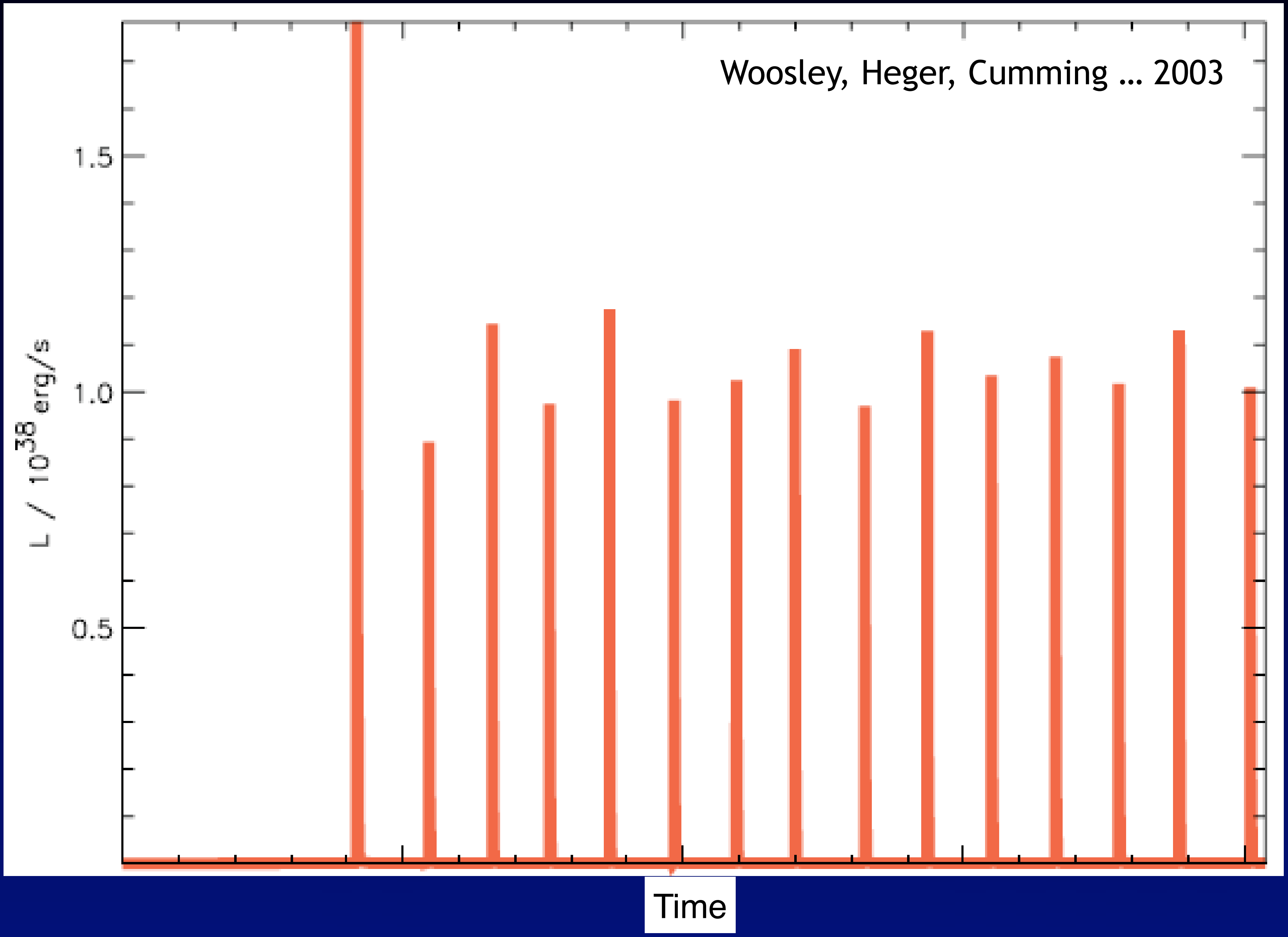
rp process during type I X-ray burst

H. Schatz, NSCL and Dept. of Physics and Astronomy, Michigan State University

Several waiting points control the reaction flow.

Better Modeling for XRB

Recent years have seen the replacement of single zone models with true 1D hydrodynamics models including large networks and GR.



These models have taught us the importance of the ash to subsequent bursts.

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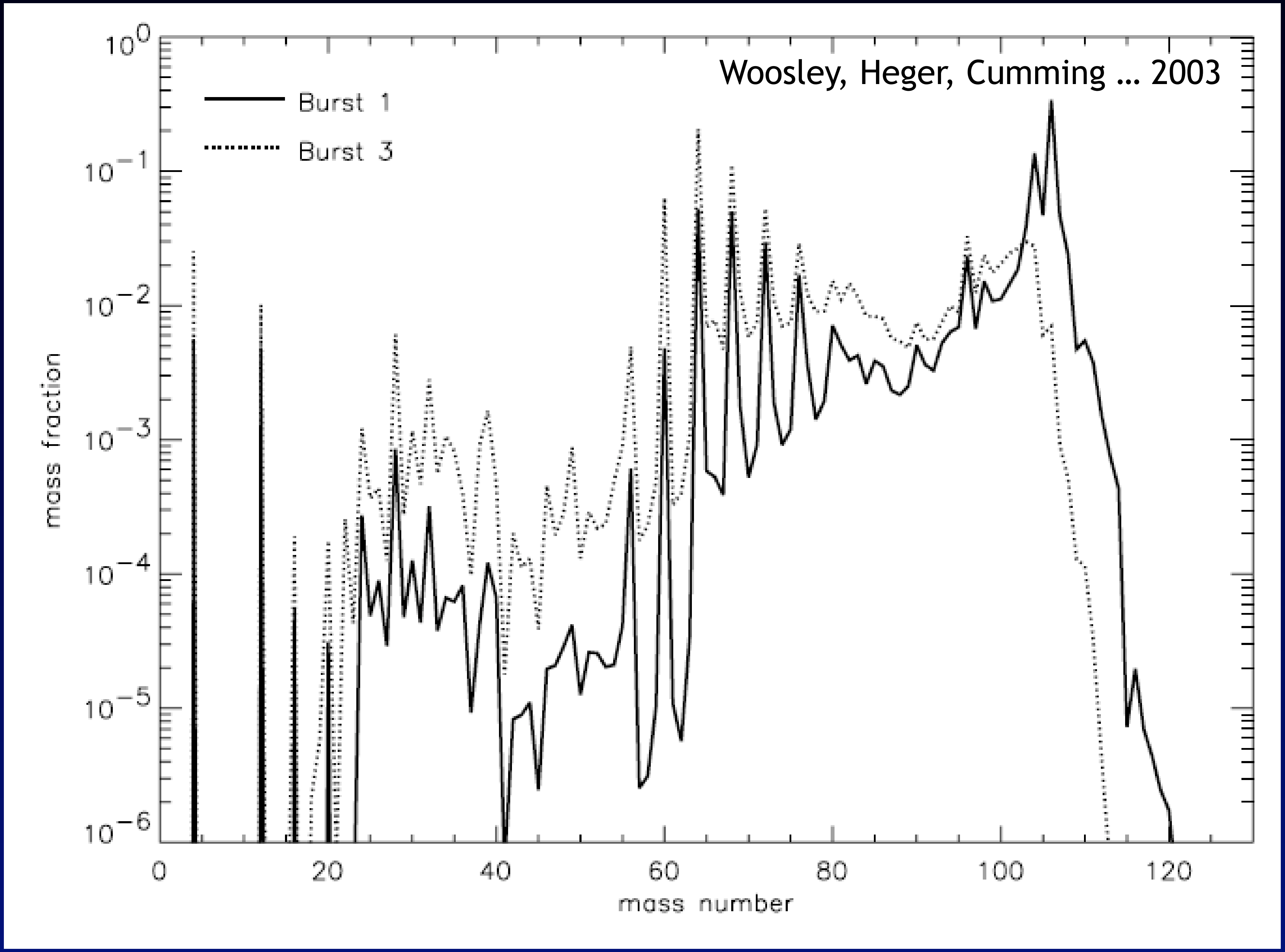

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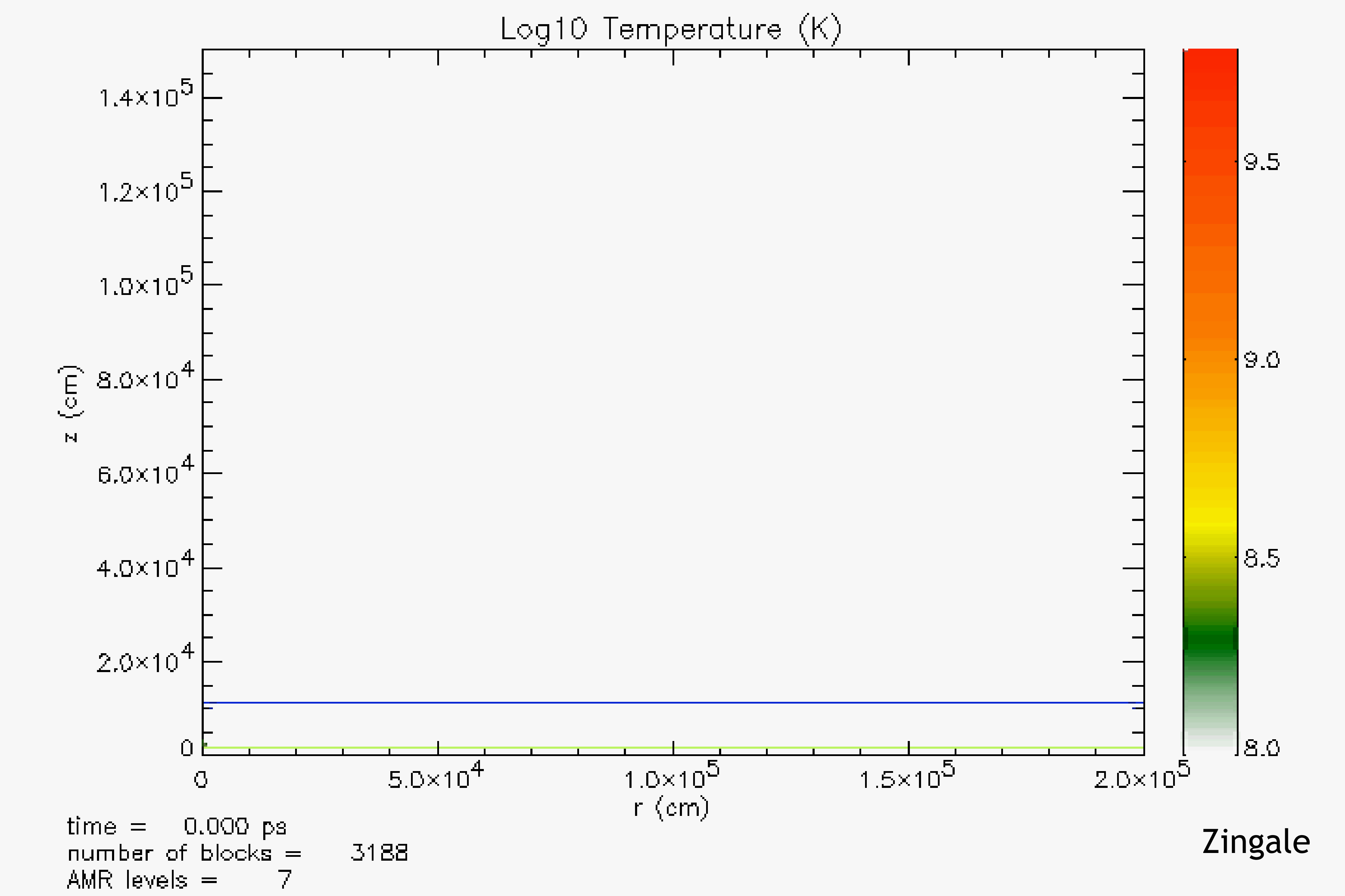
XRB in Multi-D

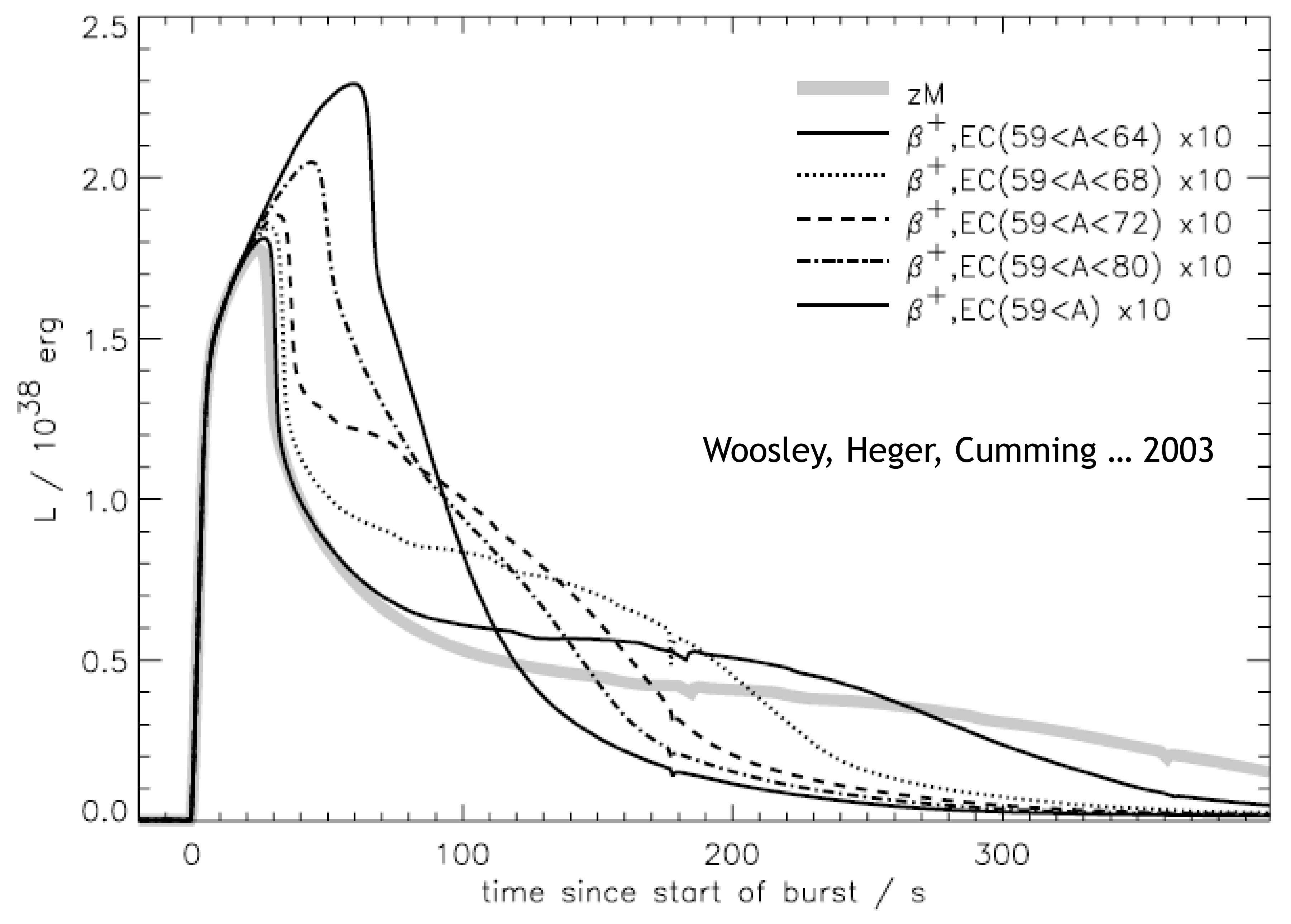


Unlike 1D models, ignition of the XRB takes several hundred μs to circle the neutron star.

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.



Woosley, Heger, Cumming … 2003

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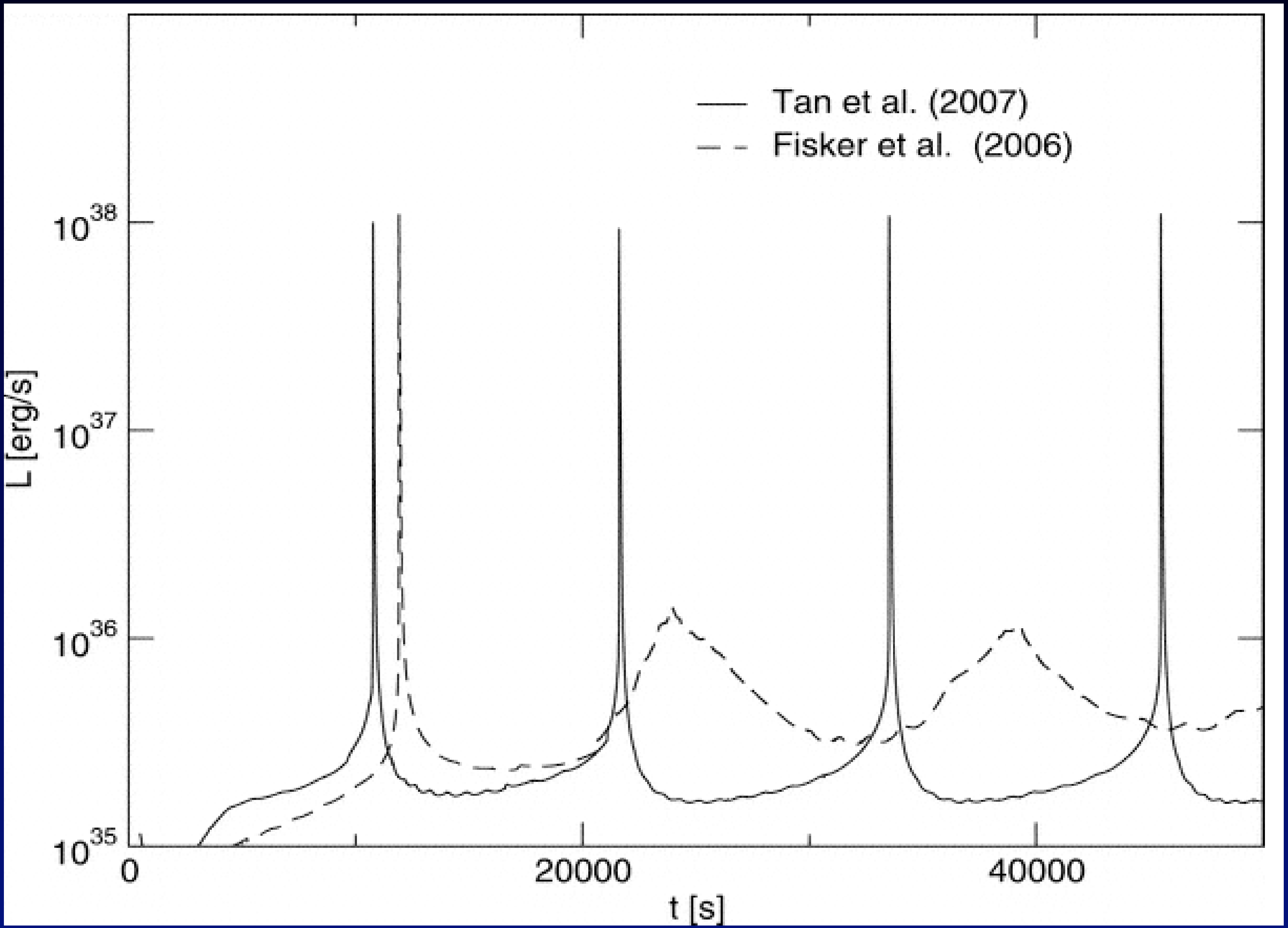
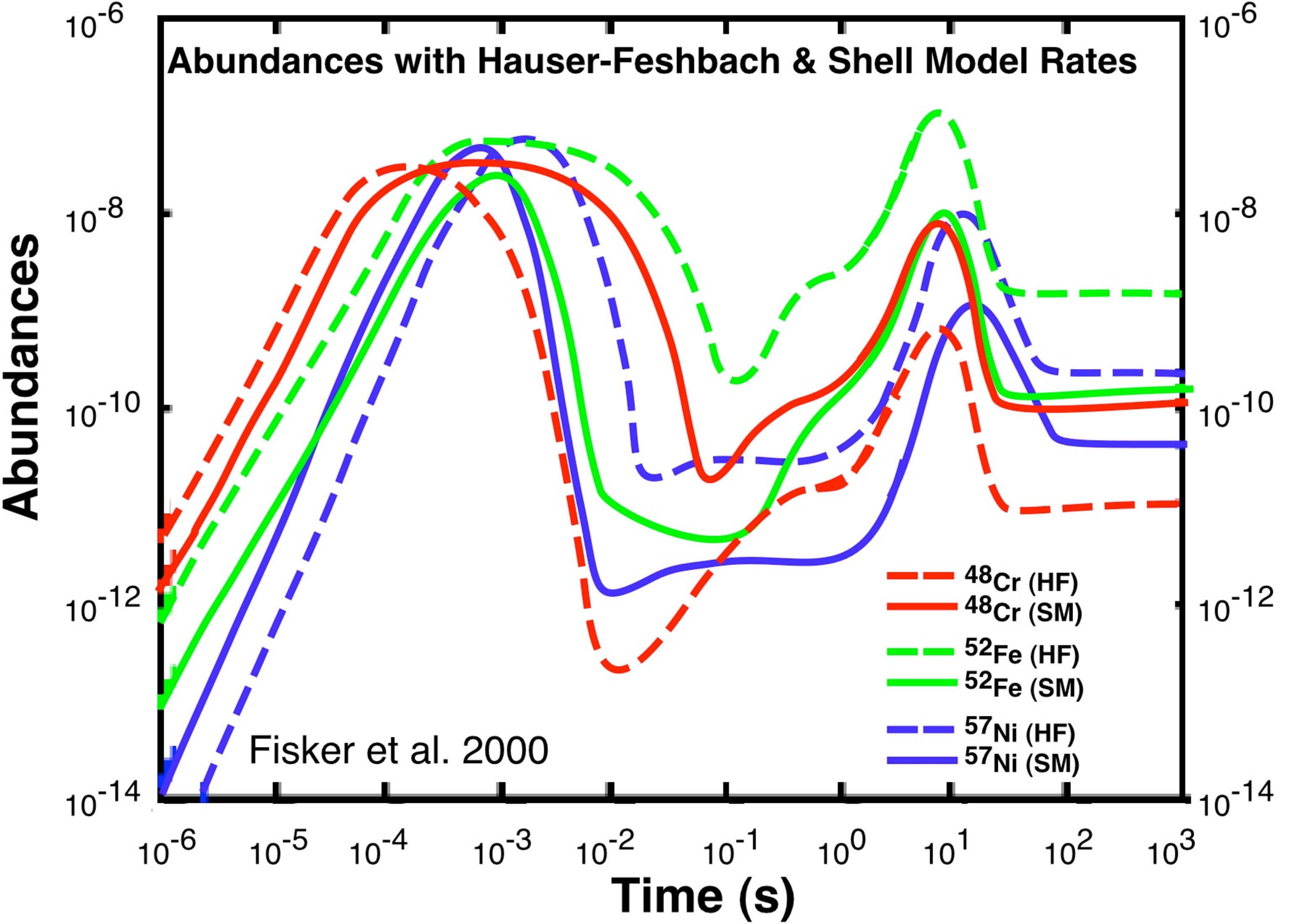


XRB luminosity has also shown significant sensitivities to $^{15}O(\alpha,\gamma)^{19}Ne$ (Fisker, Tan , Görres & Wiescher 2007)

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.

Summary

1) What role do novae, X-ray bursts and thermonuclear supernovae play in cosmic nuclear evolution?
   a) Thermonuclear supernovae produce perhaps half of the iron peak isotopes.
   b) Novae are likely responsible for odd mass isotopes of light elements like C, N, O.
2) How does nuclear physics affect these explosive events and the resulting nucleosynthesis?
   a) Proton Captures and beta decays on proton-rich nuclei drive novae and X-ray bursts.
   b) The initial C/O ratio of the White Dwarf and the neutronization of the ejecta in a thermonuclear depend on nuclear physics.

Lectures Completed

1. Nuclear Physics for Astrophysics
2. Lives of Stars
3. Core Collapse Supernovae
4. Stellar Afterlife

Hopefully, these 4 lectures have provided a brief introduction into the many nuclear processes and astrophysical sites that contribute to our cosmic origins and the many ways in which nuclear physics influences astrophysics.