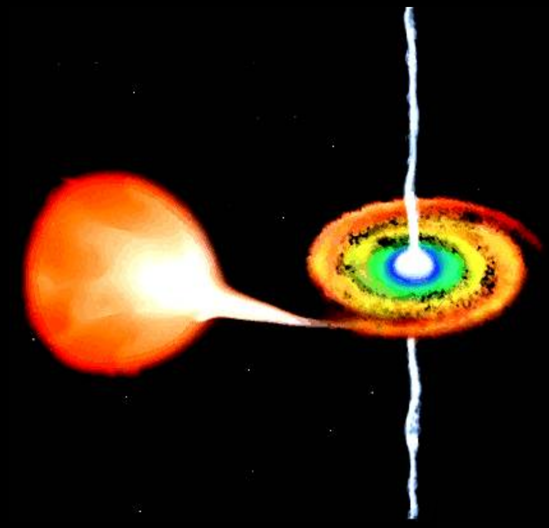
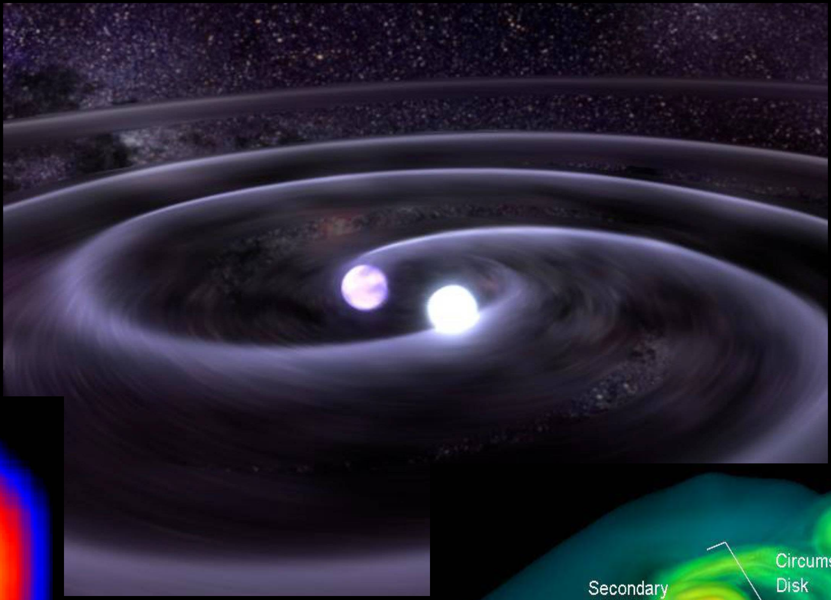
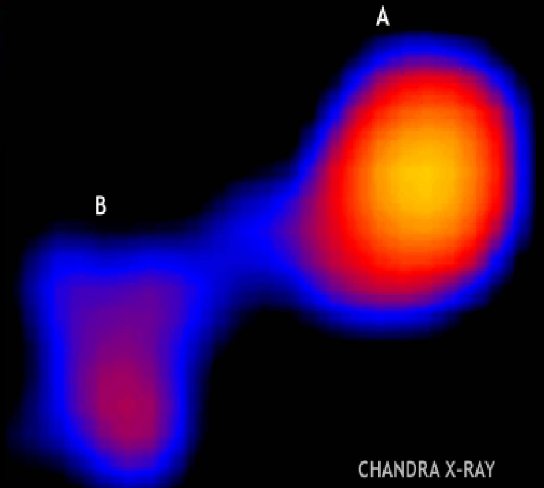
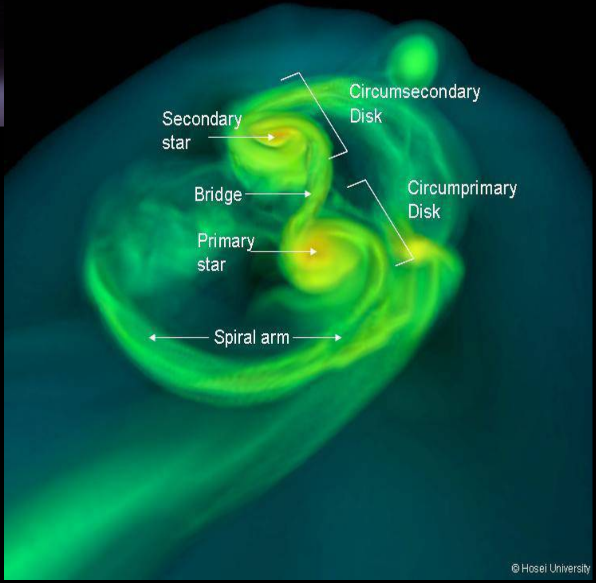
Binary Stars – Lecture 10









Astro 8501
6944

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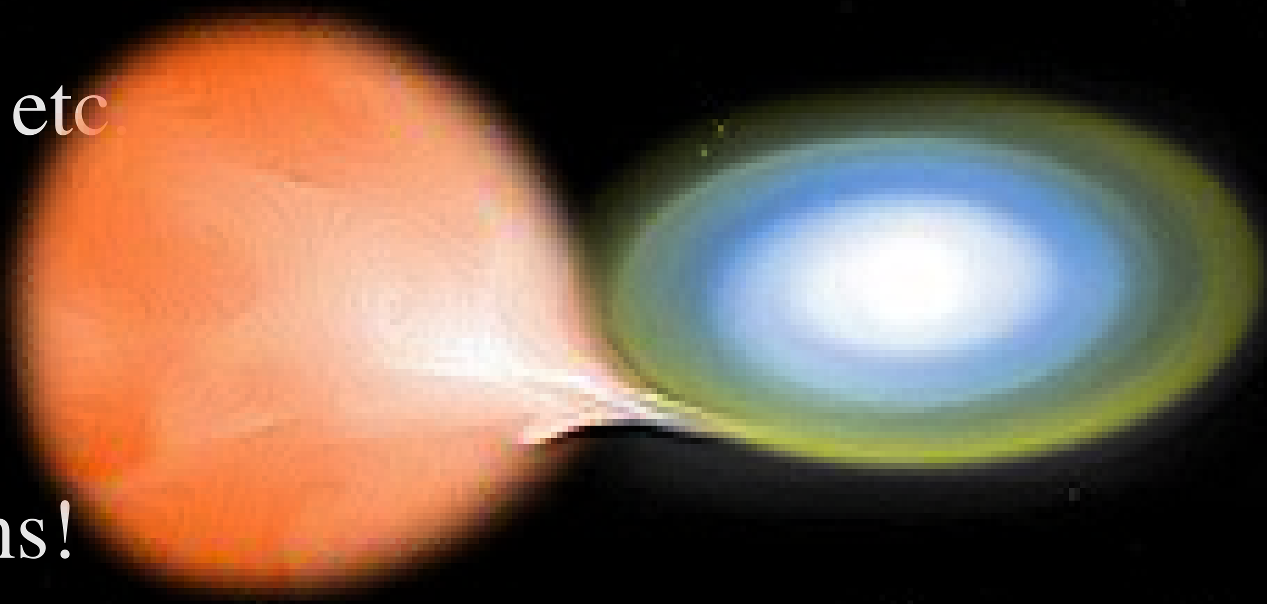
Cataclysmic Variables

- White Dwarf +
- Low mass star
- WD accreting:
- Disc, outbursts etc
- WD M ↑
- Sometimes...

  … Explosions!

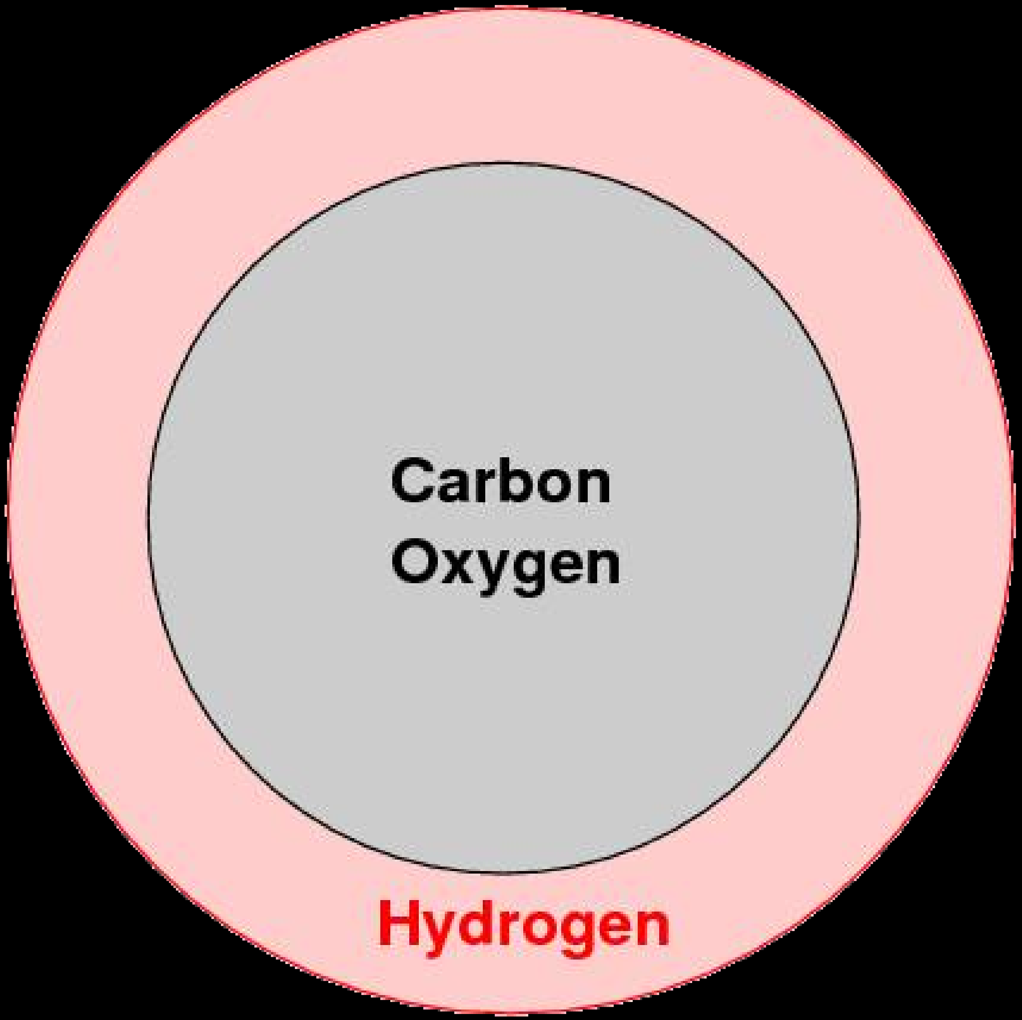


Accretion Rates onto a WD

$\dot{M} < 10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	Thermonuclear Novae
$1.03 < 10^{7}\,\dot{M} < 2.71$	Steady burning
$\dot{M} > 2.7 \times 10^{-7}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$	Giant envelope

See e.g. Warner's book (1995)
Remember the Eddington limit!

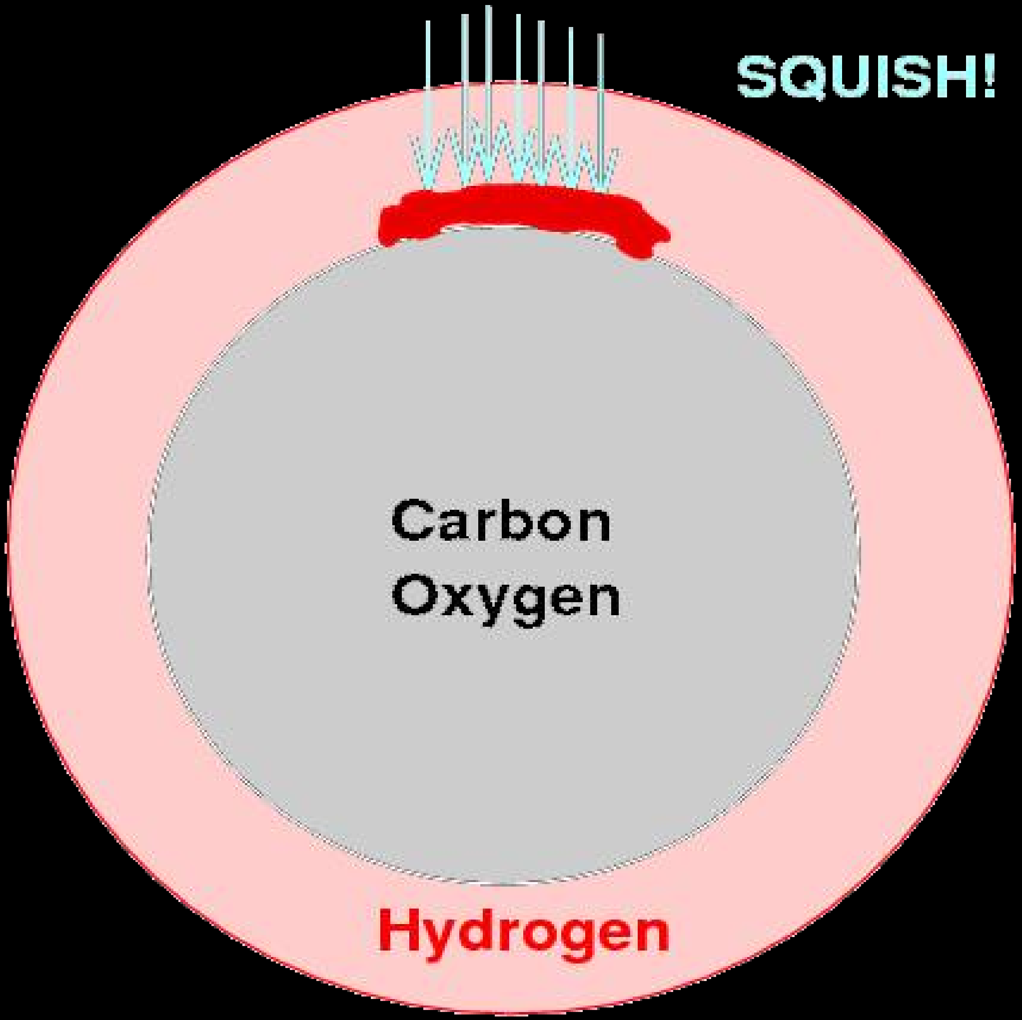
Classical Nova I



Michael Richmond

http://spiff.rit.edu/richmond/asras/sn_bh/sn_bh.html

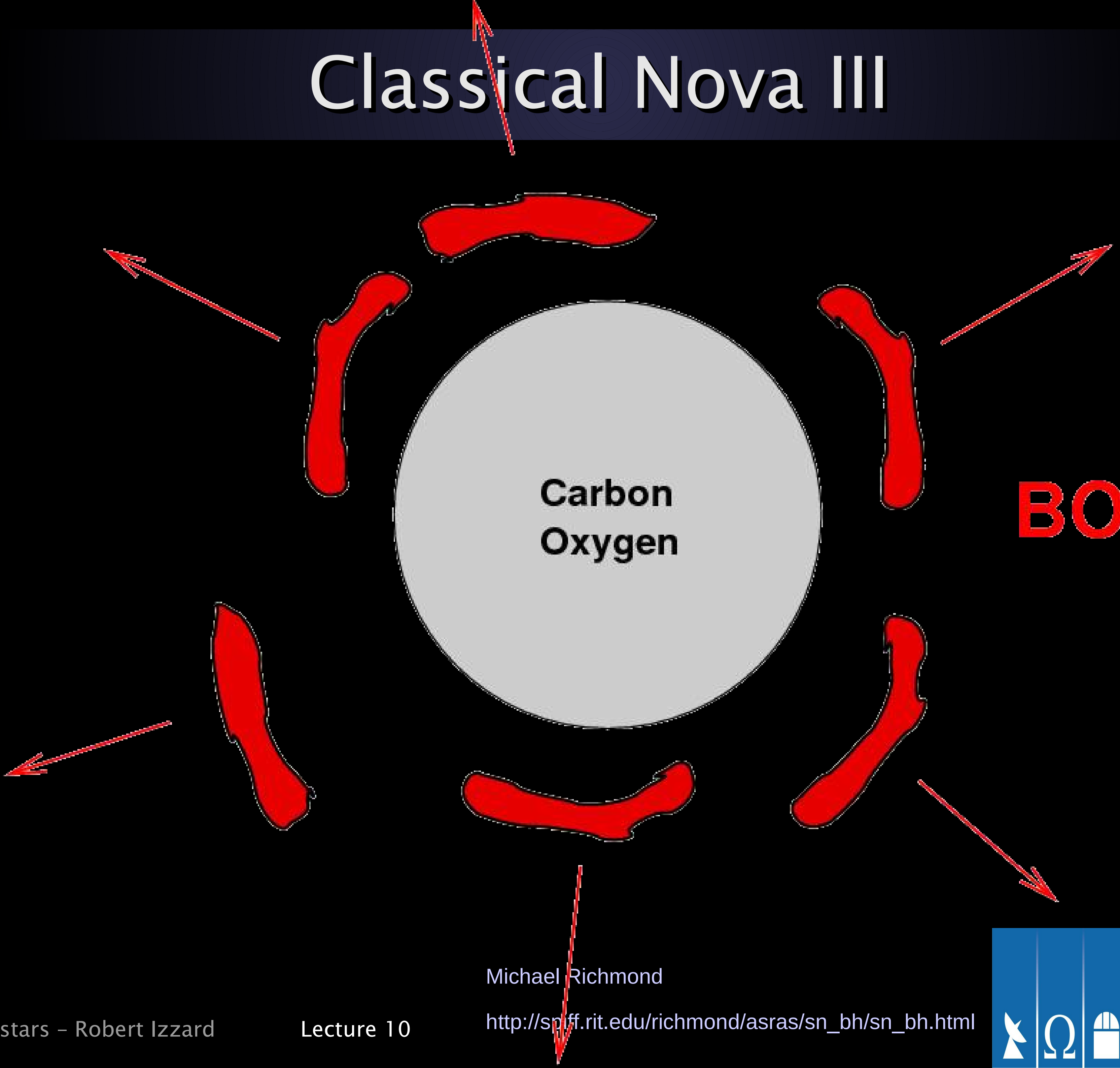
Classical Nova II



Michael Richmond

http://spiff.rit.edu/richmond/asras/sn_bh/sn_bh.html

Classical Nova III



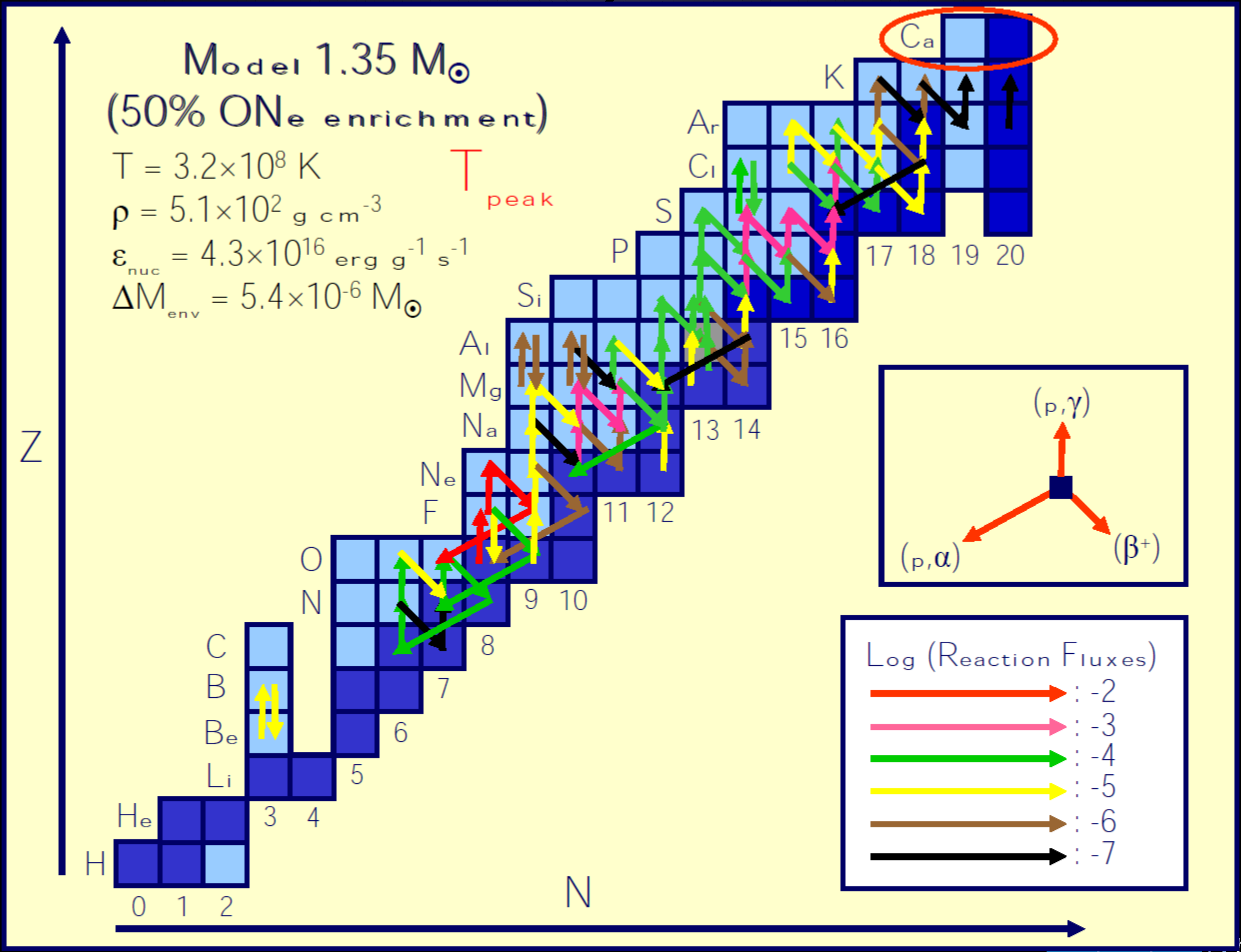
Michael Richmond

http://spiff.rit.edu/richmond/asras/sn_bh/sn_bh.html

Thermonuclear Nova Properties

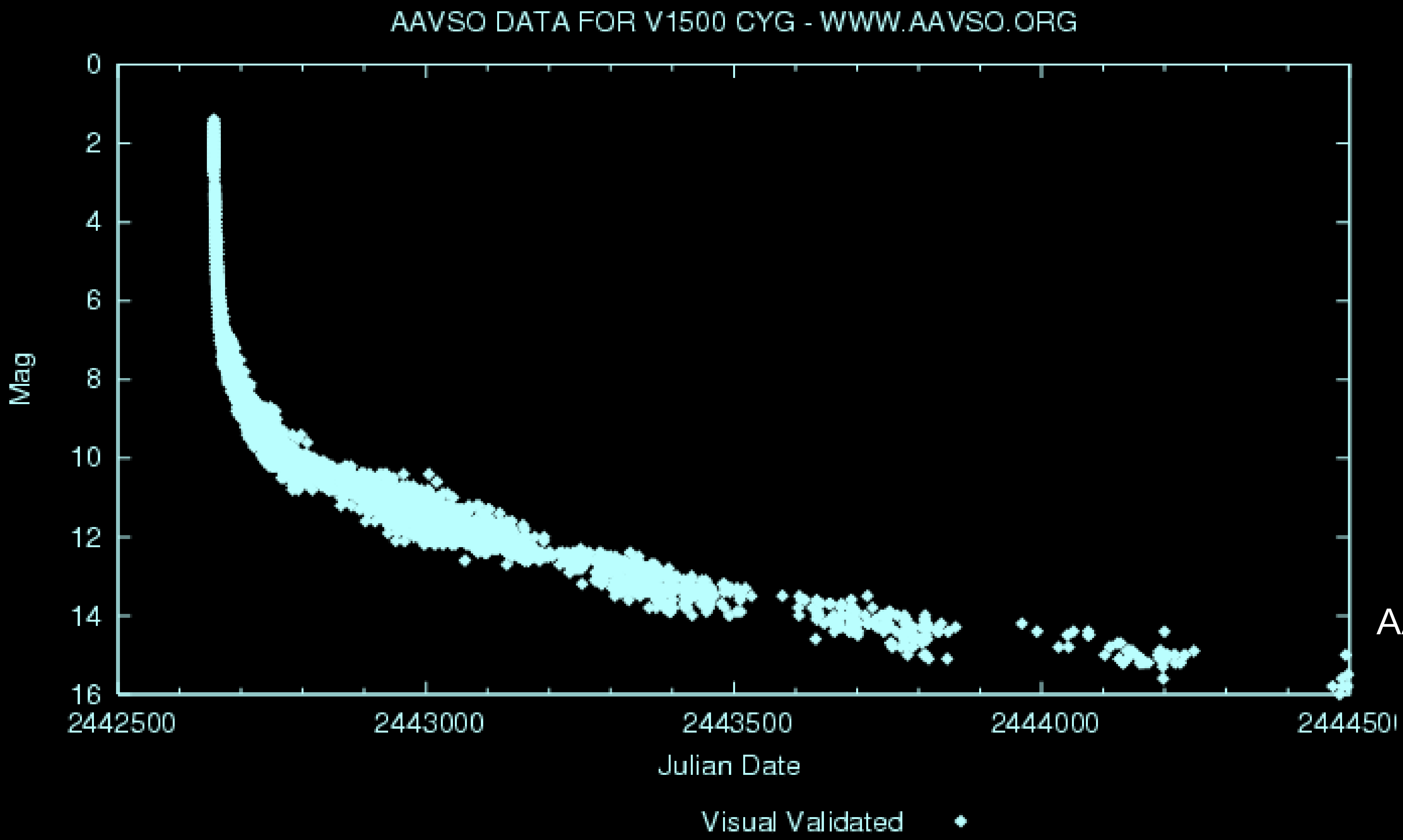
- Galactic rate $\sim 35 \pm 11\,\mathrm{yr}^{-1} (\sim 5 \text{ observed})$
- Mass return $\sim 4 \times 10^{-4}\,\mathrm{M}_{\odot}$ in $100 - 1000\,\mathrm{s}$
- Energy $E \sim 10^{45}\,\mathrm{erg}$
- Luminosity $L \sim 10^{4-5}\,\mathrm{L}_{\odot}$ (c.f.$10^{10}\,\mathrm{L}_{\odot}$ for SNe)
- Peak $T \sim 0.1 - 0.4\,\mathrm{GK}$
- Ejection velocity $\sim 10^{3}\,\mathrm{km\,s}^{-1}$ (c.f. $\sim 10^{4}$ for SNe)
- Binary progenitors $P \sim 1 - 12\,\text{hours}$
  CVs!
- Periodic: typically $10^{4} - 10^{5}$ years
- Rise time $\sim 1 - 2\,\text{days}$

Nucleosynthesis



Stolen from Jordi Jose

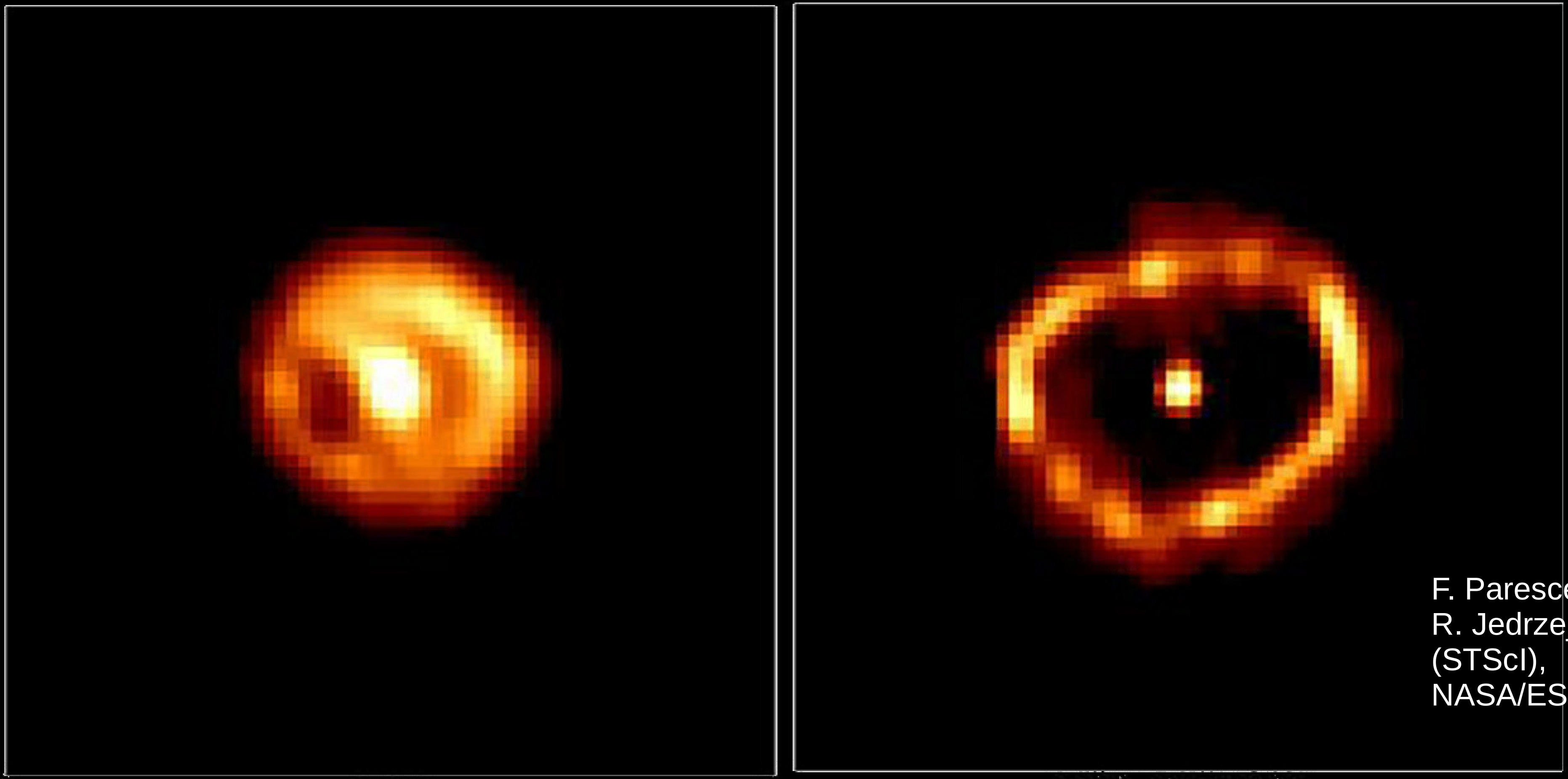
V1500 Cygni



AAVSO

Nova Cygni 1992

Hubble Space Telescope
Faint Object Camera



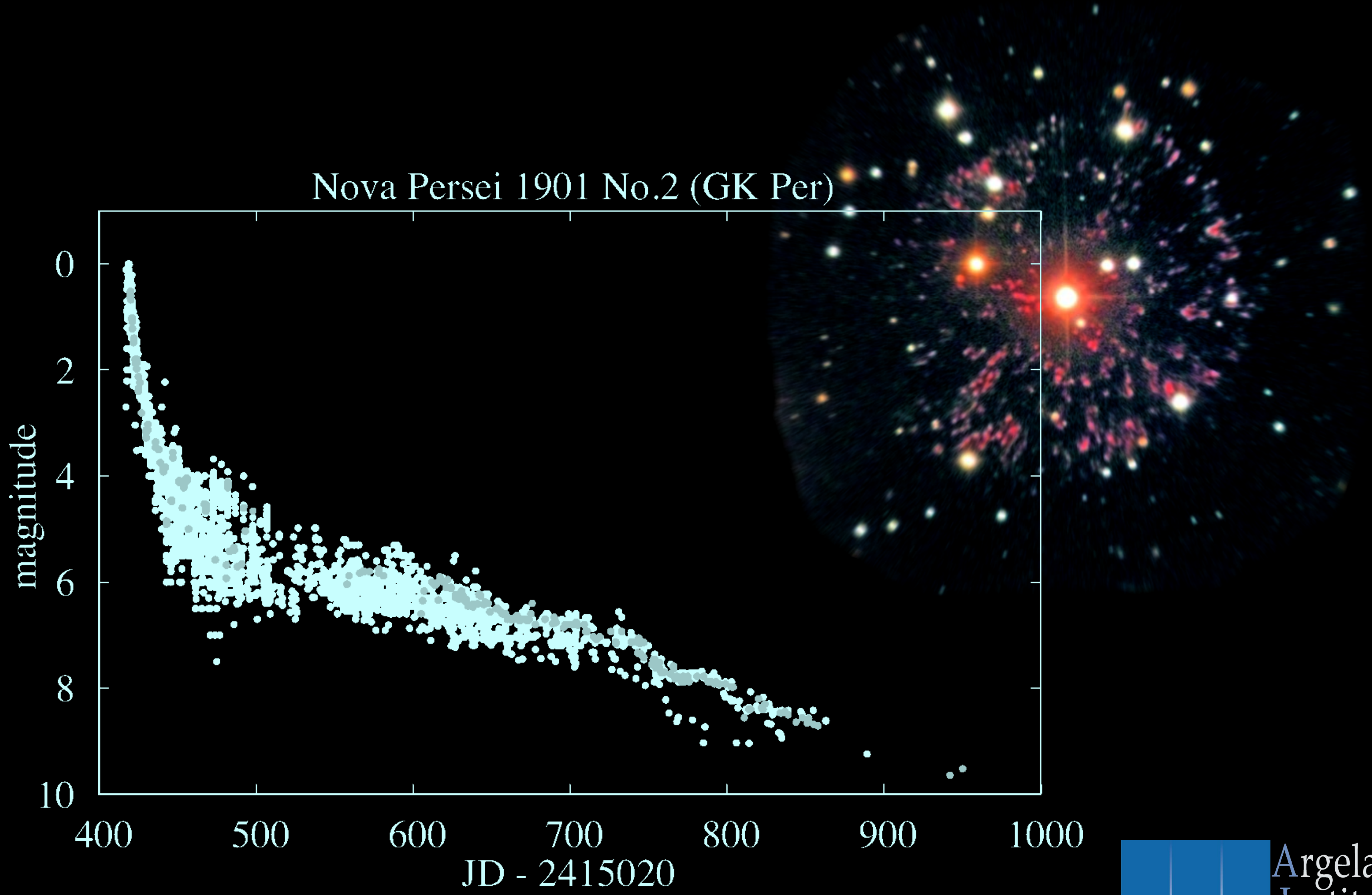
Pre-COSTAR
Raw Image

With COSTAR
Raw Image

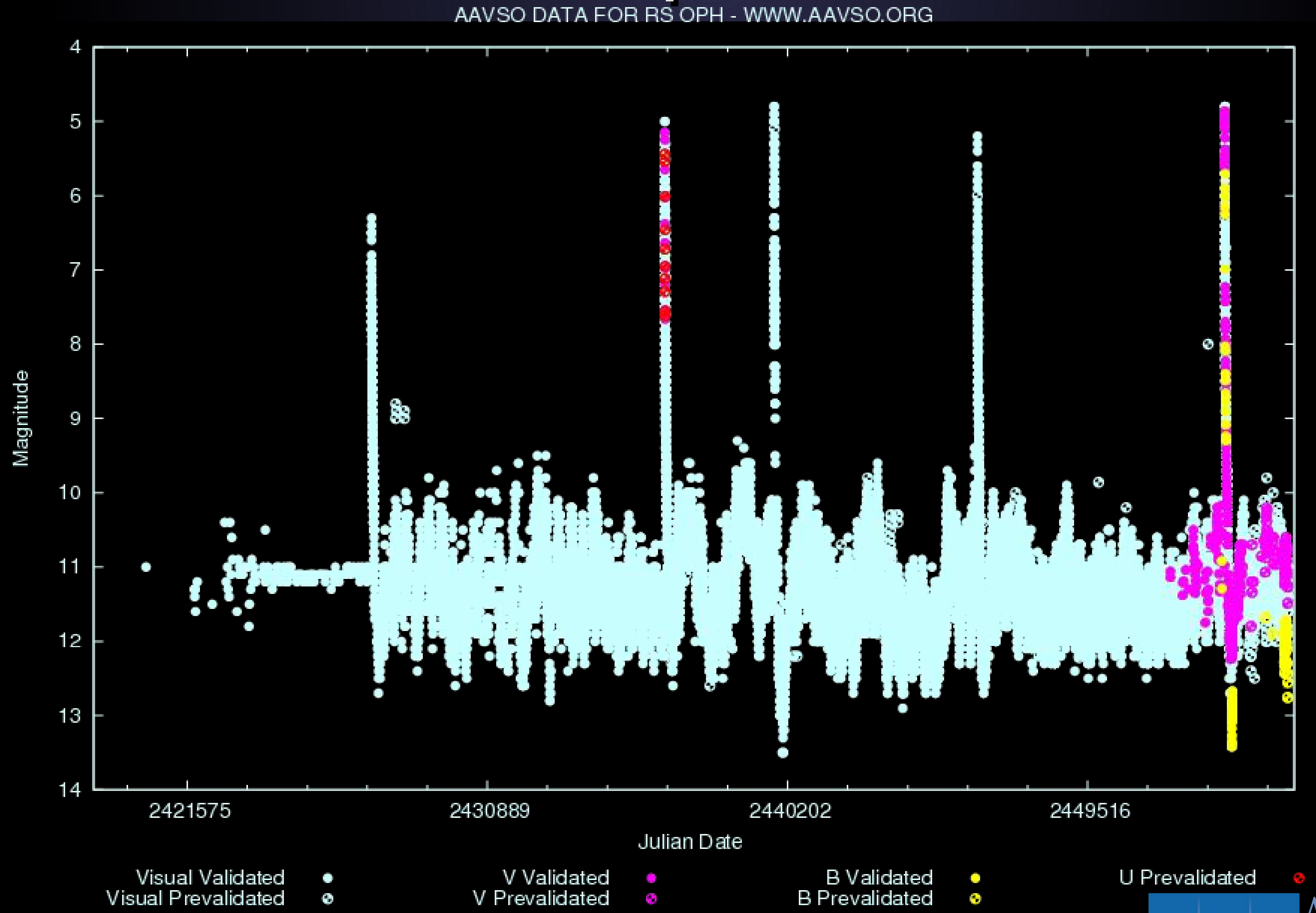
F. Paresce,
R. Jedrzejewski
(STScI),
NASA/ESA

Note the “bar” in the orbital plane

GK Per


Nova Persei 1901 No.2 (GK Per)
magnitude
0
2
4
6
8
10
400
500
600
700
800
900
1000
JD - 2415020

RS Ophiuchi



20 year period (1898, 1933, 1958, 1967, 1985, 2006)

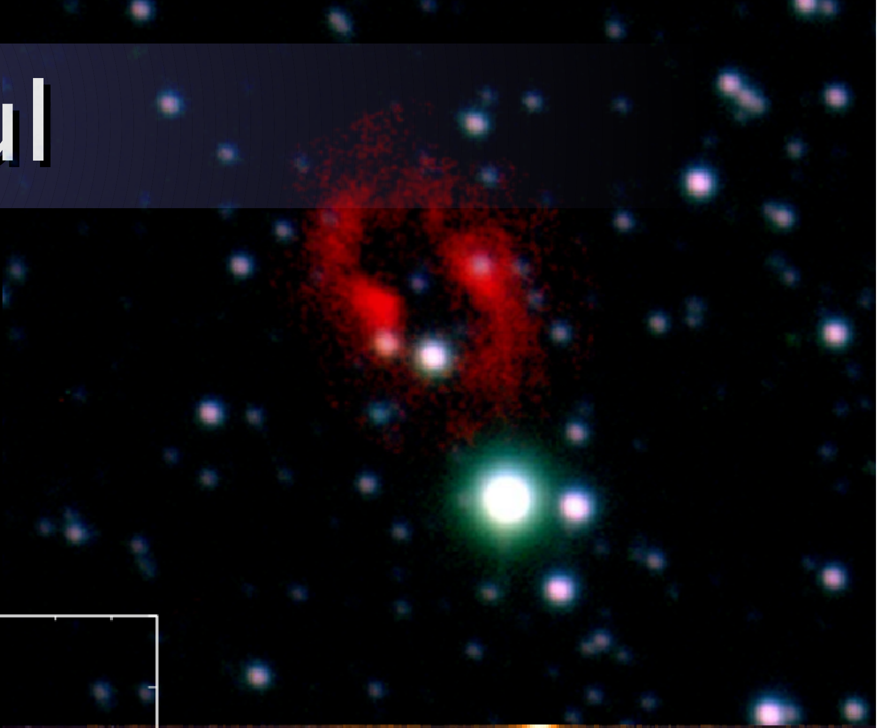
V458 Vul

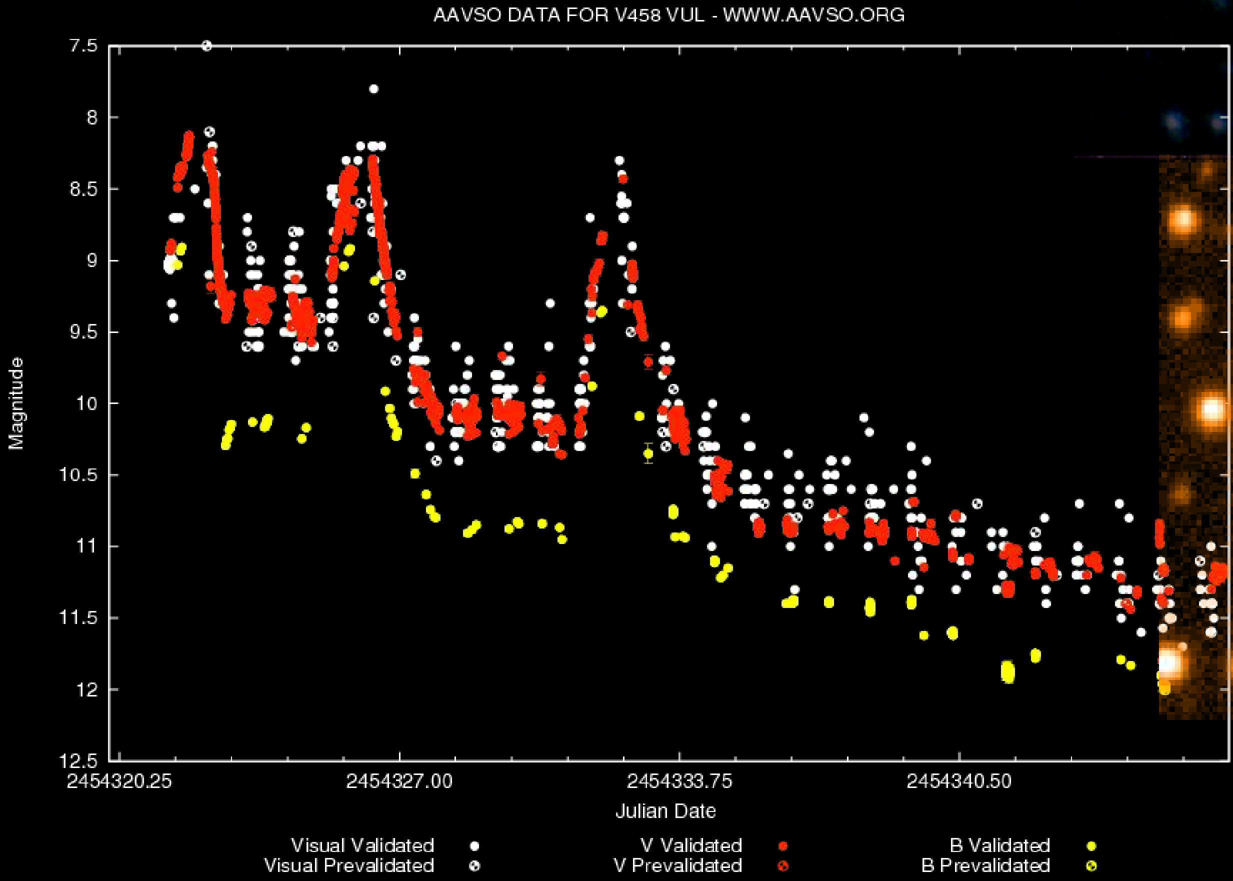
Nova inside a planetary nebula!

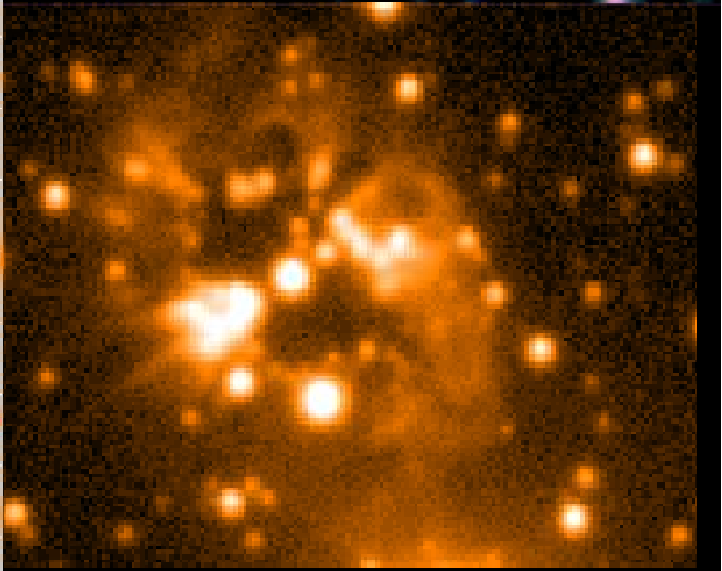
PN Estimated 14000 years old

Post common envelope

SNIa progenitor???



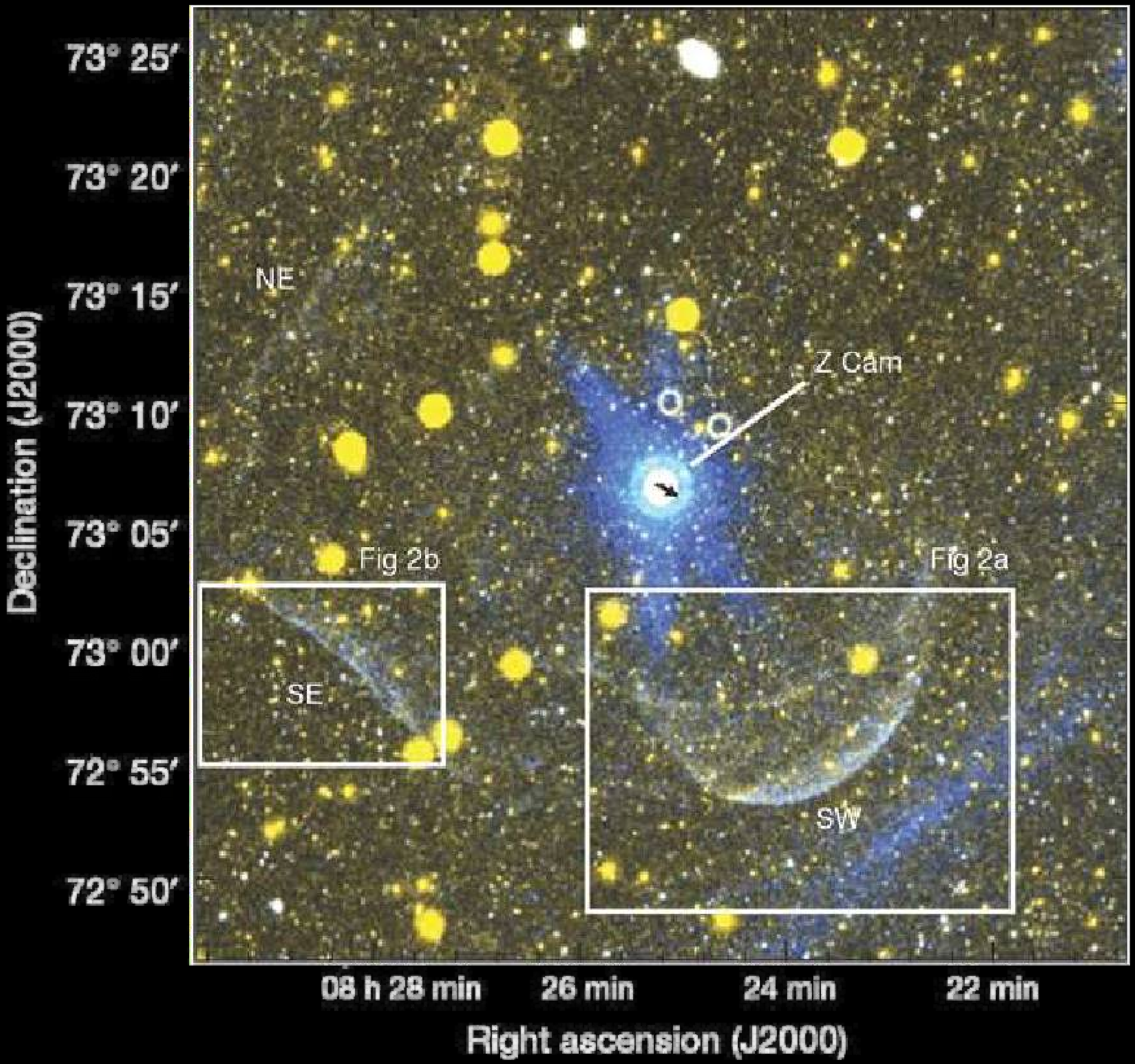




Wesson et al 2008

AAVSO

Classical – Dwarf Connection

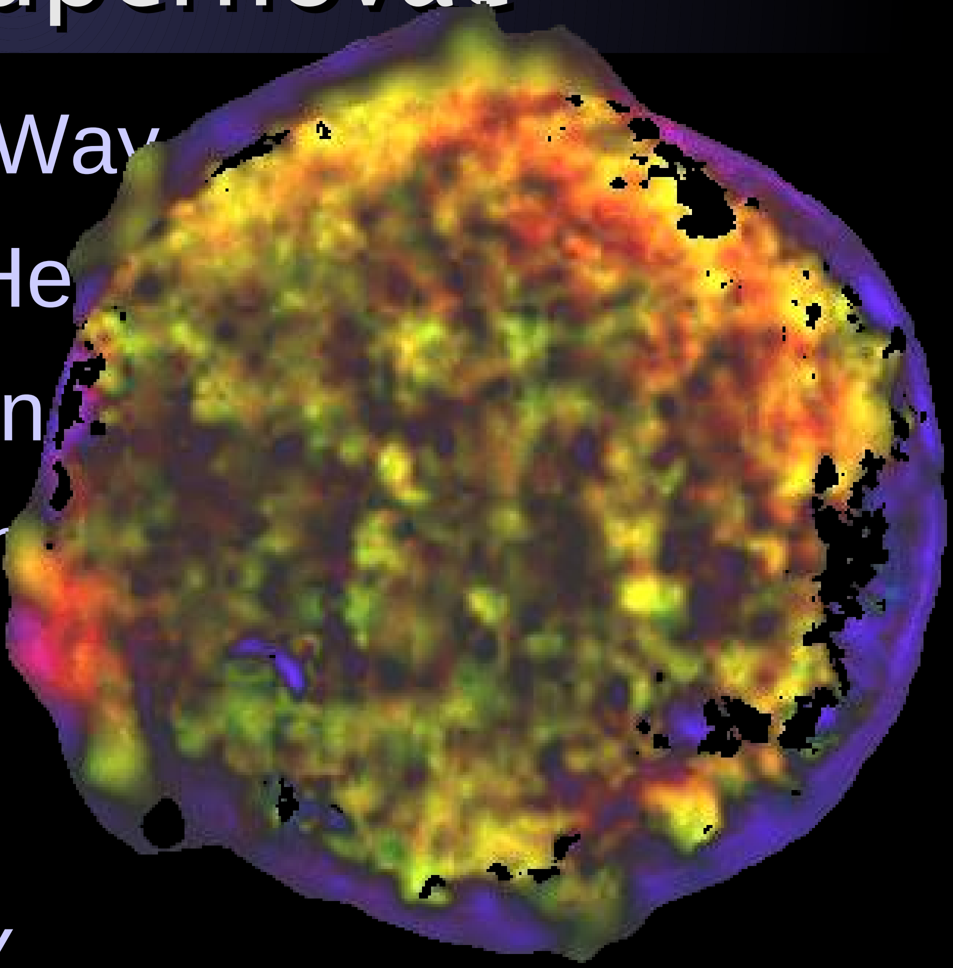


Shara et al 2007
Nature 446,159

Type Ia supernovae

- 1/250 years in Milky Way
- Spectrum: Si; No H,He
- White dwarf explosion
- Sub-MCh/MCh/>MCh
- Mag Mv=-19
- “Standard Candles”
- Useful for *cosmology*
- Iron-peak nucleosynthesis

  Fe, Ni, Co, Ti …



Tycho's SN remnant
NASA/MPIA/Calar Alto Observatory,
Oliver Krause et al.

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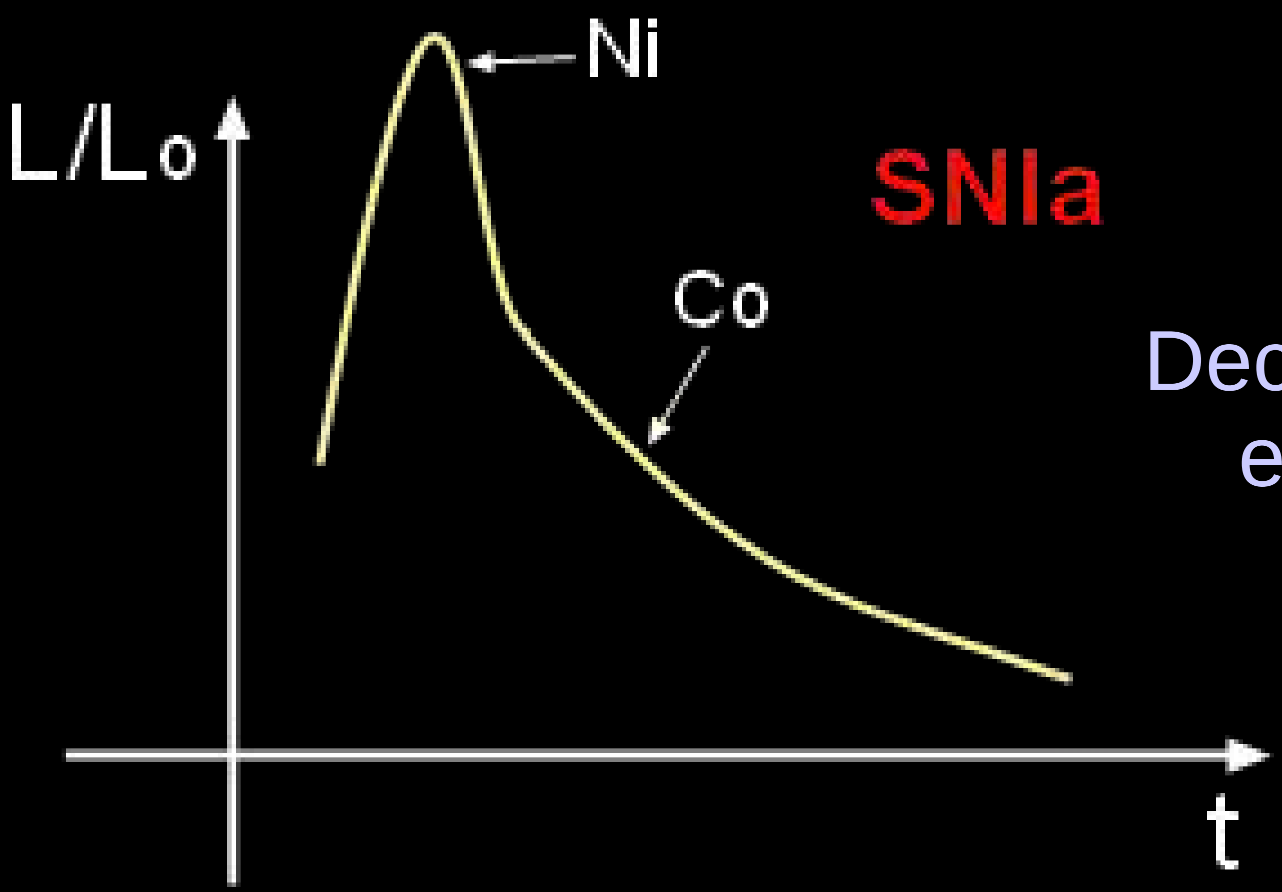
SNIa lightcurve



Decay of radioactive elements :

Nickel

Cobalt

Image from Wikipedia

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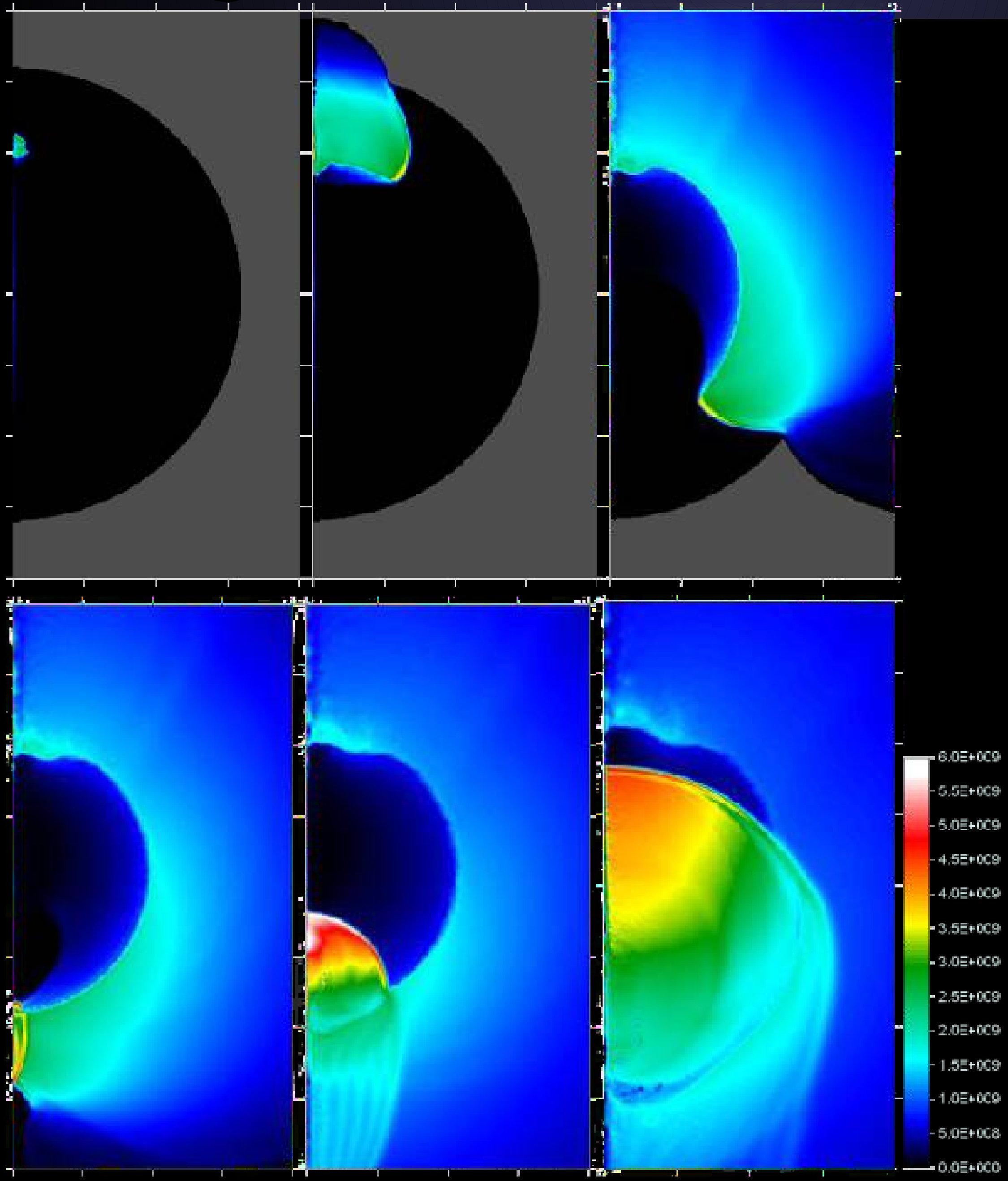
Edge-Lit Detonation (M<1.4)



colour=temperature

$$\mathrm{white} = 6 \times 10^{9}\mathrm{K}$$

$$M_{\mathrm{CO}} = 0.7\,\mathrm{M}_{\odot}$$

$$M_{\mathrm{He}} = 0.2\,\mathrm{M}_{\odot}$$

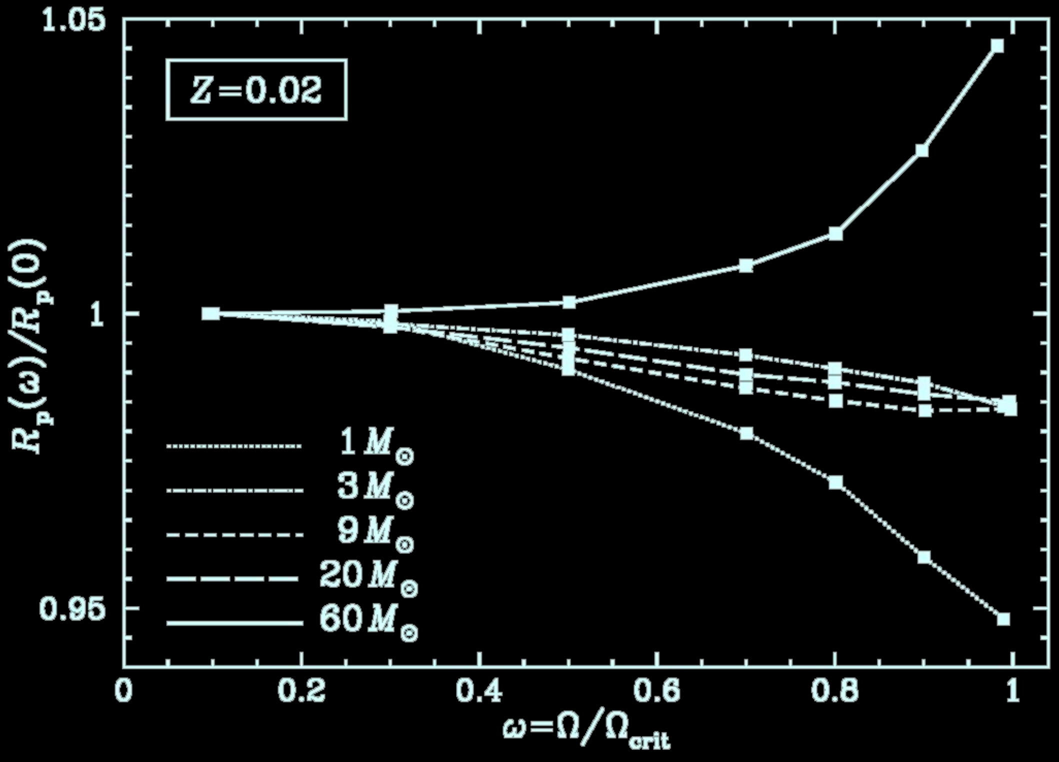
Total time < 2 seconds!

Forcada, Garcia-Senz, Jose 2007

Pause for coffee

An aside: dimensions of rotating stars

- Can we treat stars as essentially *single stars*?
- Polar radius is approx const.



Variations in the polar radius as a function of the ratio $\omega = \Omega/\Omega_{\rm crit}$, normalized to the non-rotating value, for various masses at standard metallicity.

Ekstrom et al 2008 A&A 478, 467

Rapid Stellar Models

- Creating *detailed* stellar models is slow and difficult
- Rapid or synthetic stellar models are faster
- Replace details solver with pre-solved model set:
  - Fitting formulae
  - Or lookup tables
- Sacrifice (usually unwanted) details for

  speed: up to 10,000,000 times faster.

Fitting Formulae

- Eggleton, Fitchett, Tout 1989, Hurley et al 2000,2002
- Zero-age main sequence:

$$L_0 = \begin{cases} \frac{1.107M^3+240.7M^9}{1+281.9M^4} & M \leq 1.093 \\ \frac{13990M^5}{M^4+2151M^2+3908M+9536} & M \geq 1.093 \end{cases}$$

$$R_0 = \begin{cases} \frac{0.1148M^{1.25}+0.8604M^{3.25}}{0.04651+M^2} & M \leq 1.334 \\ \frac{1.968M^{2.887}-0.7388M^{1.679}}{1.821M^{2.337}-1} & M \geq 1.334 \end{cases}$$

Fitting Formulae

- Time evolution function of $\tau = t/t_{\mathrm{MS}}$

$$t_{\mathrm{MS}} = \frac{2550 + 669M^{2.5} + M^{4.5}}{0.0327M^{1.5} + 0.346M^{4.5}} .$$

- Then

$$\begin{aligned} \log_{10} L &= \log_{10} L_0 + \alpha \tau_{\mathrm{MS}} + \beta \tau_{\mathrm{MS}}^2 \\ \log_{10} R &= \log_{10} R_0 + \alpha' \tau_{\mathrm{MS}} + \beta' \tau_{\mathrm{MS}} + \gamma' \tau_{\mathrm{MS}}^3 \end{aligned}$$

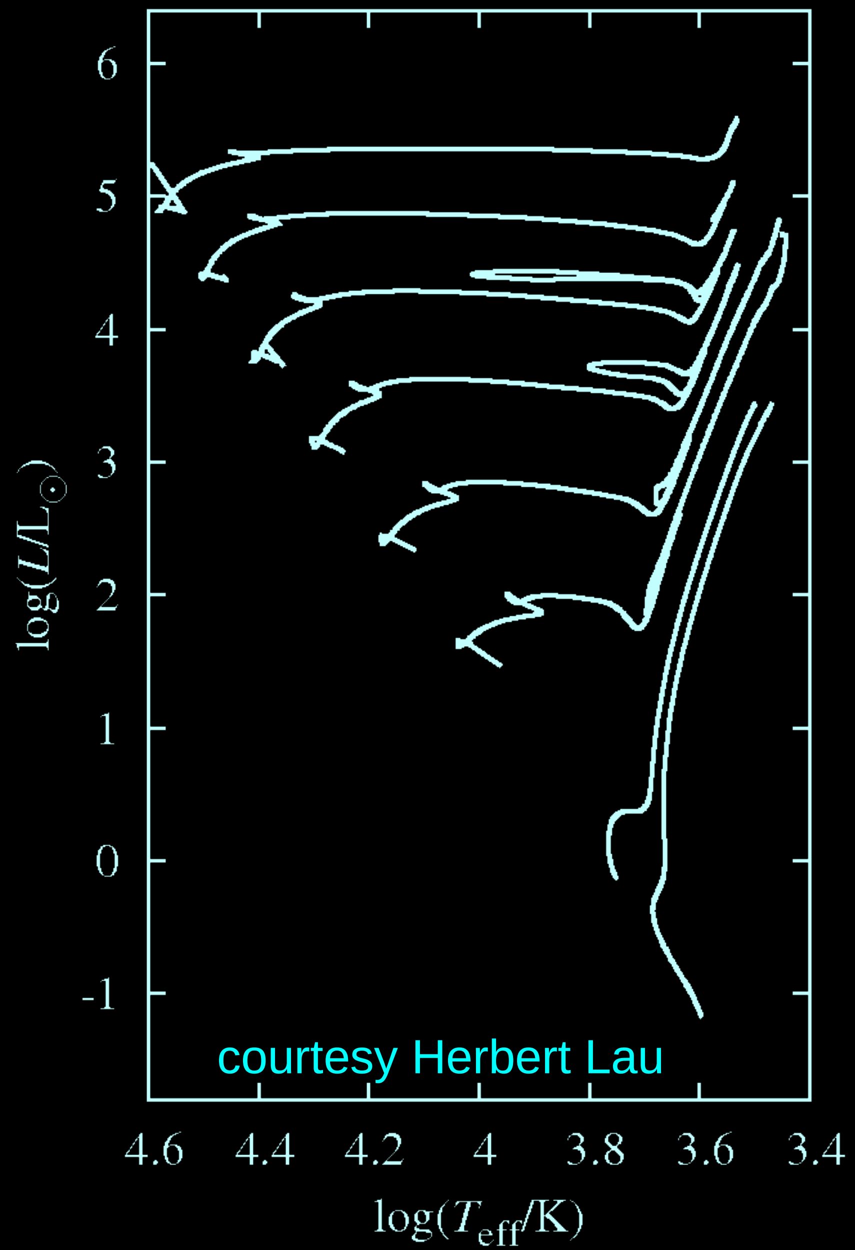
Fitting formulae

$$
\begin{aligned}
\alpha &= \begin{cases} 0.2594 + 0.1348 \log_{10} M & M \leq 1.334 \\ 0.09209 + 0.05934 \log_{10} M & M > 1.334 \end{cases} \\
\beta &= \begin{cases} 0.144 - 0.833 \log_{10} M & M \leq 1.334 \\ 0.3756 \log_{10} M - 0.1744 \left(\log_{10} M\right)^2 & M > 1.334 \end{cases}
\end{aligned}
$$

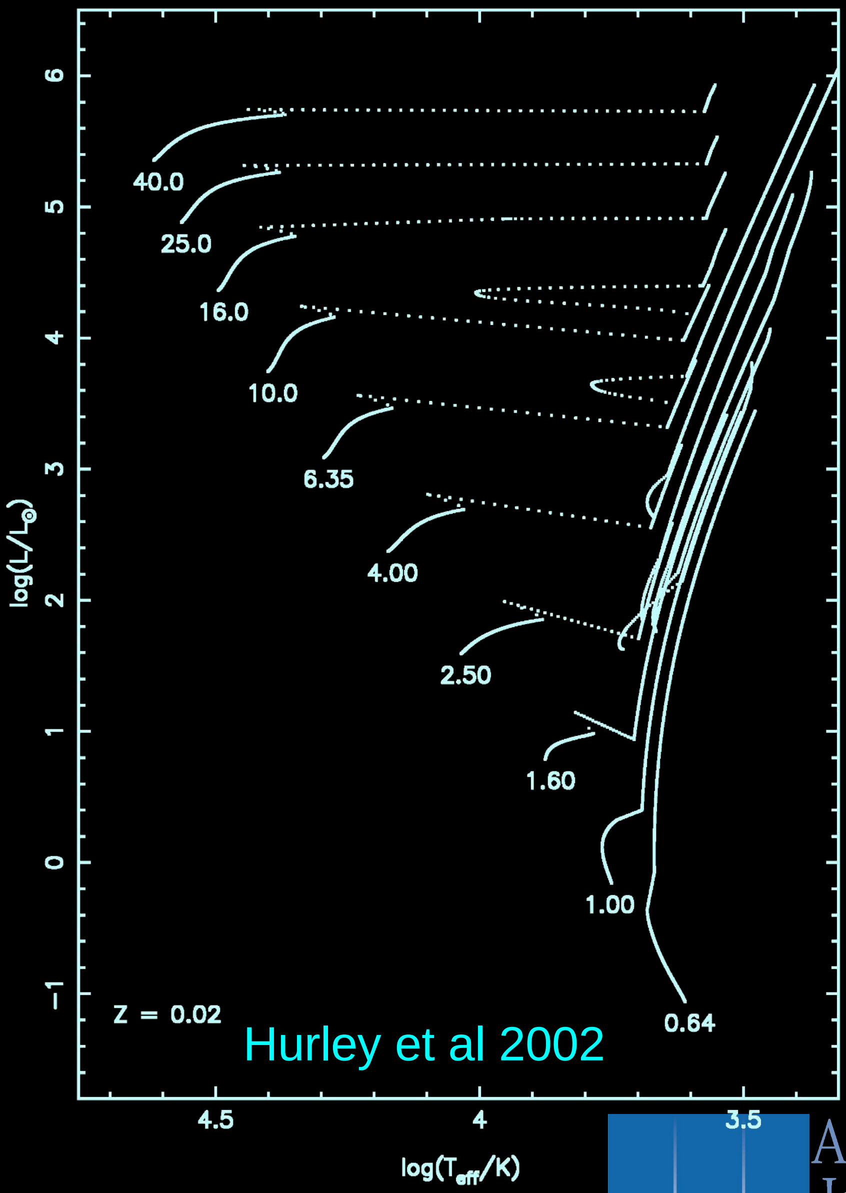
$$
\begin{aligned}
\alpha' &= \begin{cases} 0 & M \leq 1.334 \\ 0.1509 + 0.1709 \log_{10} M & M > 1.334 \end{cases} \\
\beta' &= \begin{cases} 0.2226 \log_{10} M & M \leq 1.334 \\ -0.4805 \log_{10} M & M > 1.334 \end{cases} \\
\gamma' &= \begin{cases} 0.1151 & M \leq 1.334 \\ 0.5083 \log_{10} M & M > 1.334 \end{cases} .
\end{aligned}
$$

Even more complicated formulae apply for later phases of evolution!
But computers *do not care* ...

Real vs Synthetic HRD



courtesy Herbert Lau



Hurley et al 2002

Pros and Cons

- Pros
  - Faster to compute
  - Stable

$$\begin{aligned}\log_{10} L &= \log_{10} L_0 + \alpha\tau_{\mathrm{MS}} + \beta\tau_{\mathrm{MS}}^2 \\ \log_{10} R &= \log_{10} R_0 + \alpha'\tau_{\mathrm{MS}} + \beta'\tau_{\mathrm{MS}} + \gamma'\tau_{\mathrm{MS}}^3\end{aligned}$$

- Cons
  - Fixed input physics (but could use tables!)
  - Discard of potentially useful information
  - Off-grid treatment
  - Fitting errors (<5%)

Population Synthesis

The process of combining stellar models into a stellar population upon which meaningful statistical analysis can be performed and compared to observations to better constrain the underlying physics.

1. Make your stellar models
2. Weight these according to mass, separation, time etc.
3. Extract simulated value(s)-compare
4. Determine the “real-life” distribution from obs.
5. Compare the two, see what's wrong
6. Refine your stellar models
7. Return to step 1 until you are happy

(or funding runs out)

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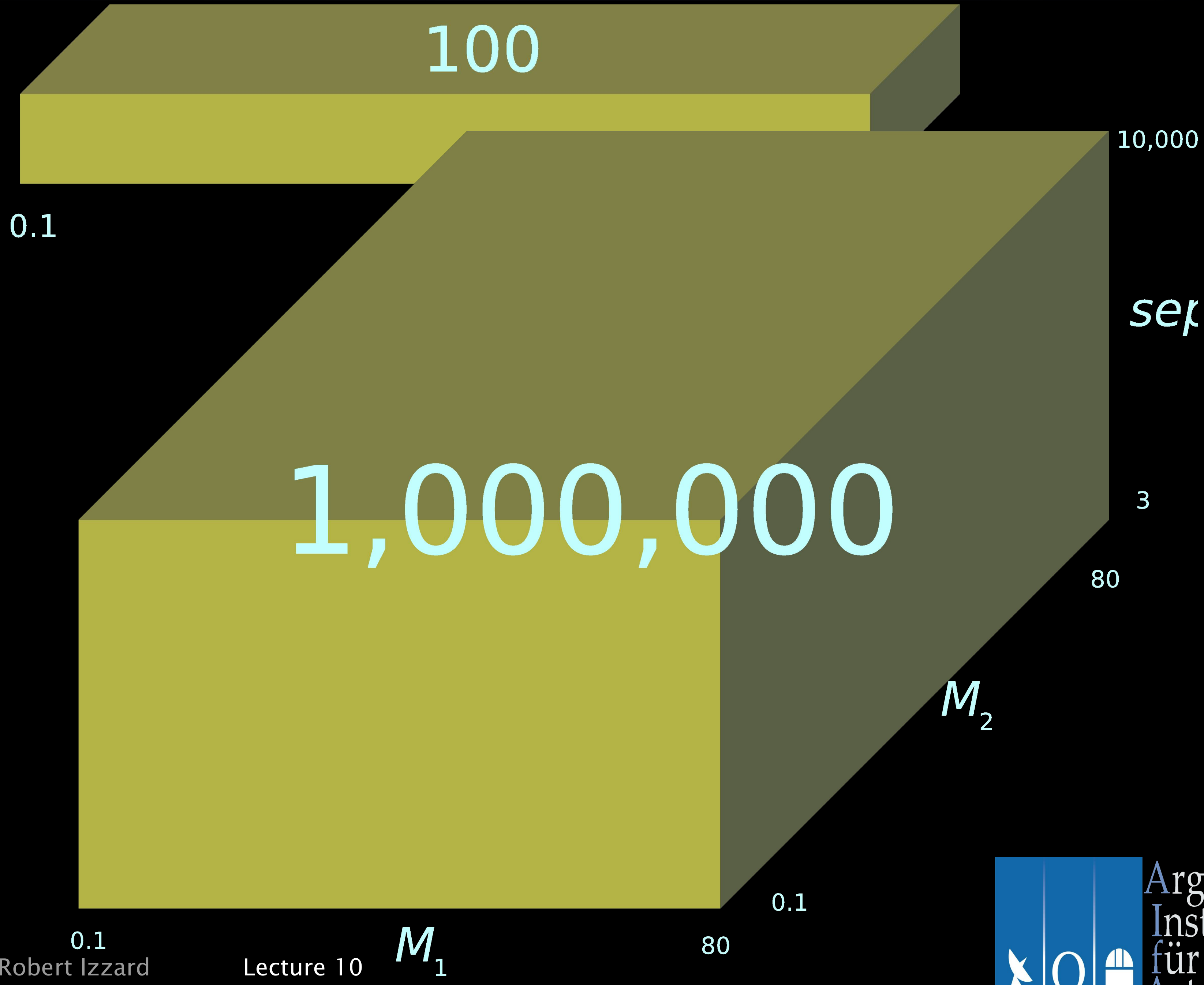
The Parameter Space Problem

- To make a single star population, one parameter
  M_1
  only: Mass
  $\sim N \times \Delta t$
- Runtime is
- Binaries many parameters :
  M_1
  - Primary mass
    M_2
  - Secondary mass
    a or P
  - Sep/Period
    e
  - Maybe more e.g.
    $\sim N^3 \times \Delta t$
- Runtime

Parameter Spaces



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Popsyn + rapid code

Discretising Parameter Space

- Single Stars

$$\delta \ln M = \frac{\ln M_{\mathrm{max}} - \ln M_{\mathrm{min}}}{n}$$

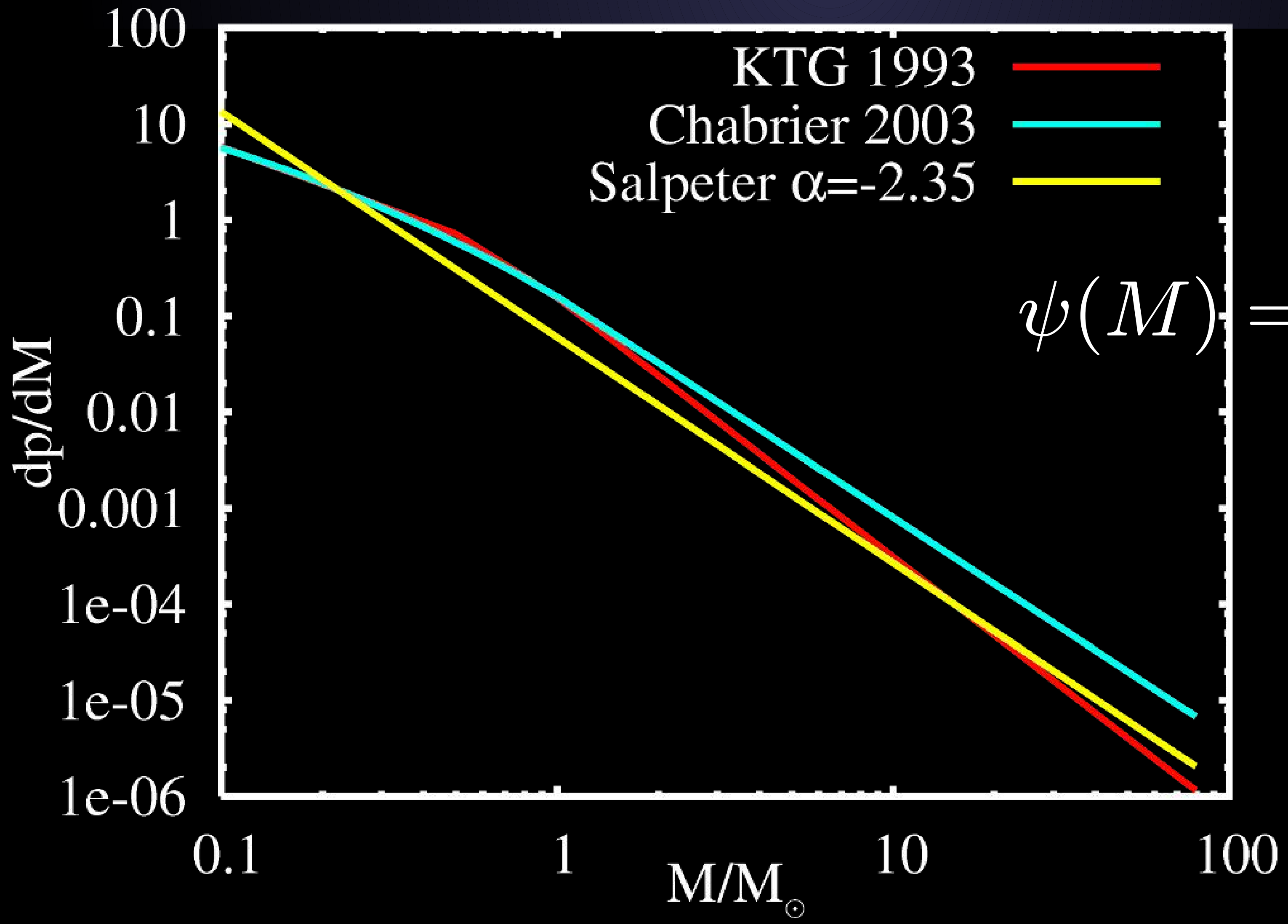
- Each star has a probability of existence

$$\delta p_i = \psi(M_i)\,\delta \ln M$$

- Where ψ is the *initial mass function*

$$\Sigma_i \delta p_i = 1$$

IMF



$$\psi(M) = \frac{dN_{stars}}{dM}$$

Salpeter IMF $\psi \propto M^{-2.35}$

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Discretising Parameter Space

- Binary Stars

$$\delta \ln x \quad = \quad \frac{\ln x_{\max} - \ln x_{\min}}{n_x}$$

where x is $M_1,\ M_2,\ a(,\ P, e\dots)$

- Each star has a probability of existence

$$\delta p_i \quad = \quad \Psi_i(M_1,\ M_2,\ a)\,\delta V$$

- Where Ψ is the *initial distribution function*

Initial Distribution Function

$$\Psi_i = \psi\left(M_{1i}\right)\phi\left(M_{2i}/M_{1i}\right)\chi\left(a_i\right)$$

$$\begin{aligned}
\psi(M_1) &= \psi(M) \\
\phi\left(q = \frac{M_1}{M_2}\right) &= \mathrm{constant} \\
\chi(a) &\propto a^{-1} \\
\chi(\ln a) &= \mathrm{constant}\,.
\end{aligned}$$

$$\delta p_i = \Psi_i \delta V_i$$

$$\delta V = \delta \ln M_1 \delta \ln M_2 \delta \ln a$$

$$\Sigma_i \delta p_i = 1$$

Stellar accounts

- Define

$$\begin{aligned}\delta(\mathrm{phase}) &= 1 \quad \text{during the phase,}\\ &= 0 \quad \text{otherwise}\,.\end{aligned}$$

- Time a star spends in a phase of interest

$$\Delta t_i = \sum_{t=t_{\mathrm{min}}}^{t_{\mathrm{max}}} \delta(\text{phase at } t)_i \, \delta t$$

Stellar accounts

- The number of stars in the phase is

$$\begin{aligned} \mathrm{count} &= \sum_i S\delta p_i \Delta t_i \\ &= \sum_i S\delta p_i \sum_{t_{\mathrm{min}}}^{t_{\mathrm{max}}} \delta(\mathrm{phase})_i \, \delta t \end{aligned}$$

where *S* is the star formation rate

- In general we have to convolve a birth function with a star formation rate function

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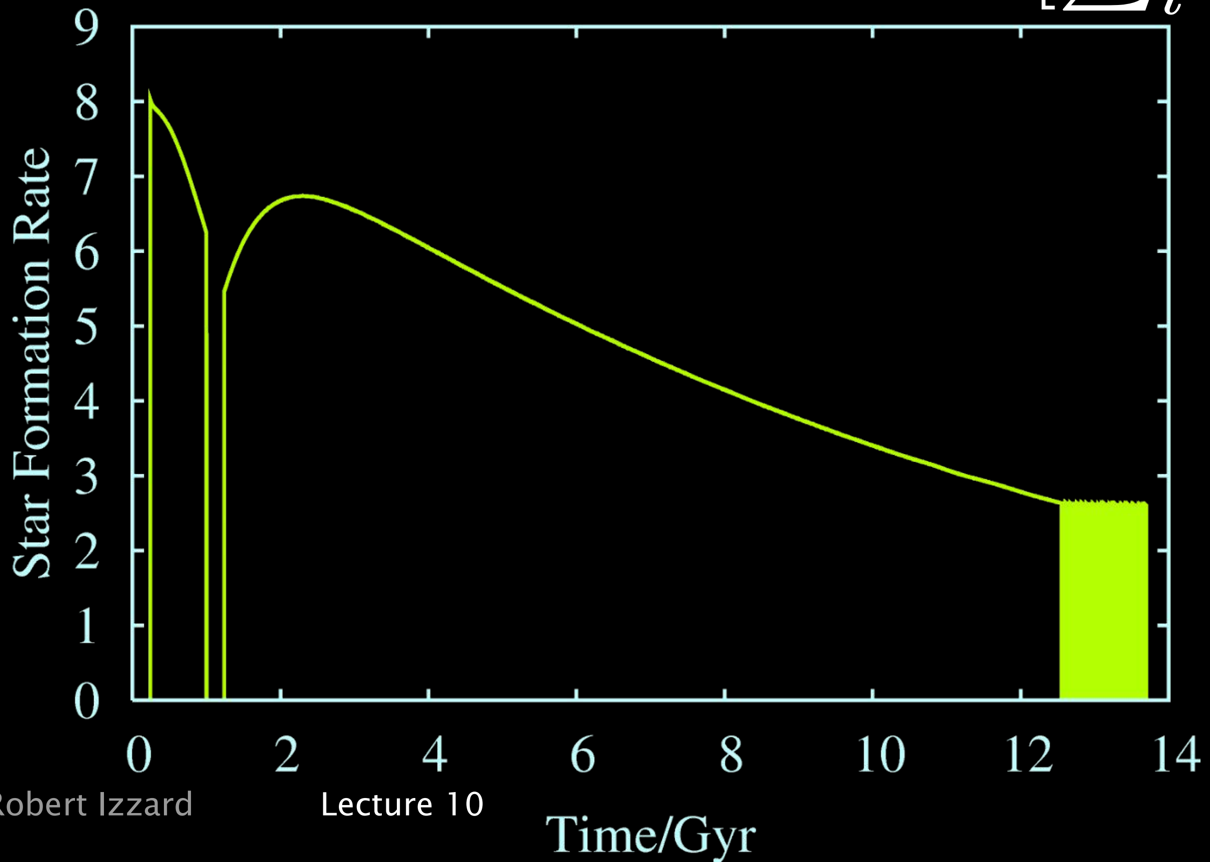
Stellar accounts

- Simple case : S = constant
- Divide counts to get ratios : S drops out

$$\mathrm{ratio} = \frac{\left[\sum_i \delta p_i \Delta t_i\right]_1}{\left[\sum_i \delta p_i \Delta t_i\right]_2}.$$



Galactic SFR
Chiappini et al 1997

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Stellar accounts

- The number of stars in the phase is

$$\Sigma_i S\delta p_i \Delta t_i$$

where S is the star formation rate

- In general we have to convolve a birth function with a star formation rate function

$$\sum_{t'_{\mathrm{min}}}^{t'_{\mathrm{max}}} \sum_i S(t)\delta p_i \delta(\mathrm{phase\ at\ } t')_i\, \delta t'$$

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Compare to Observations

- Statistics!
  - Boring (but not for everyone!)
  - Necessary e.g. χ^2 ,KS tests
  - Key to good science

- Beware observational selection effects
  - Often very hard to model
  - Data combined from multiple surveys might be impossible to model!
  - Sometimes whole papers are wrong because they neglect this! (not deliberately)

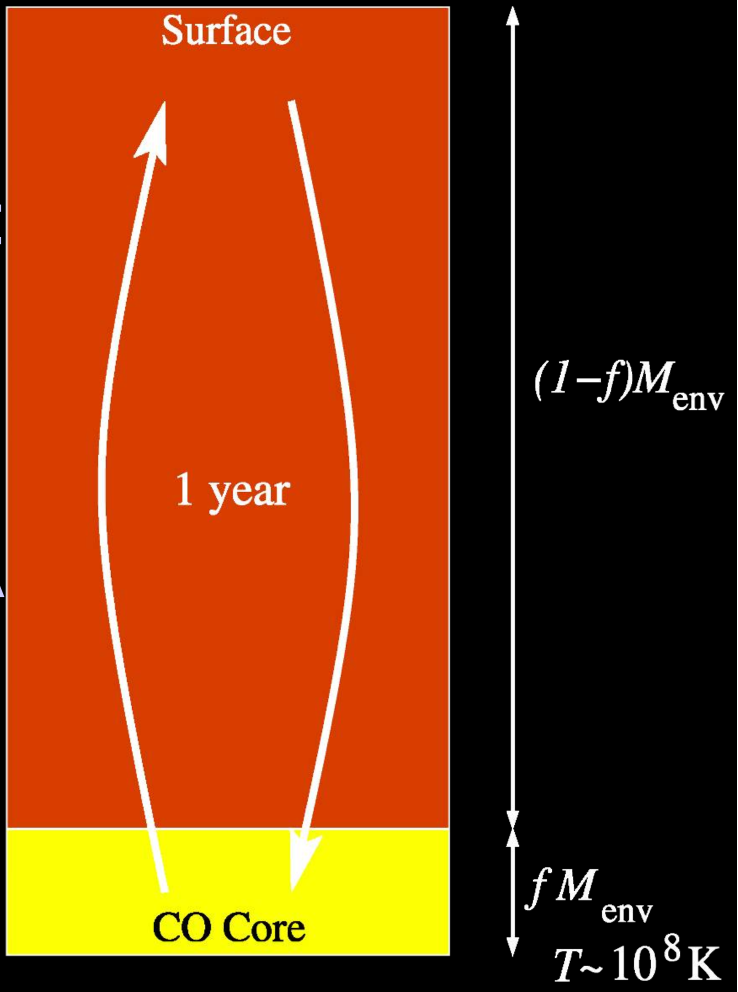
A rapid code: *binary_c*

- My code, my lectures, so …
- Based on *SSE/BSE* of EFT89, Hurley et al 2000, 2002 (e.g. see prev. eqs)
- Has fitting functions for stellar evolution
- +orbital algorithm: RLOF, Wind, Tides
- Common env., Novae, SNe Ia, Mergers etc.
- Online
- **http://www.astro.uni-bonn.de/~izzard/cgi-bin/binary3.cgi**

binary_c/nucsyn

- Added *nucleosynthesis* to *binary_c*
- First and second dredge up
- TPAGB based on Karakas' models:
  - Third dredge up
  - Hot-bottom burning

    (CNO, NeNa, MgA
  - S-process (Torino group)
- SN II/Ibc yields, novae
- Thermohaline mixing
- Physics updates over last few years



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Some examples of binary_c

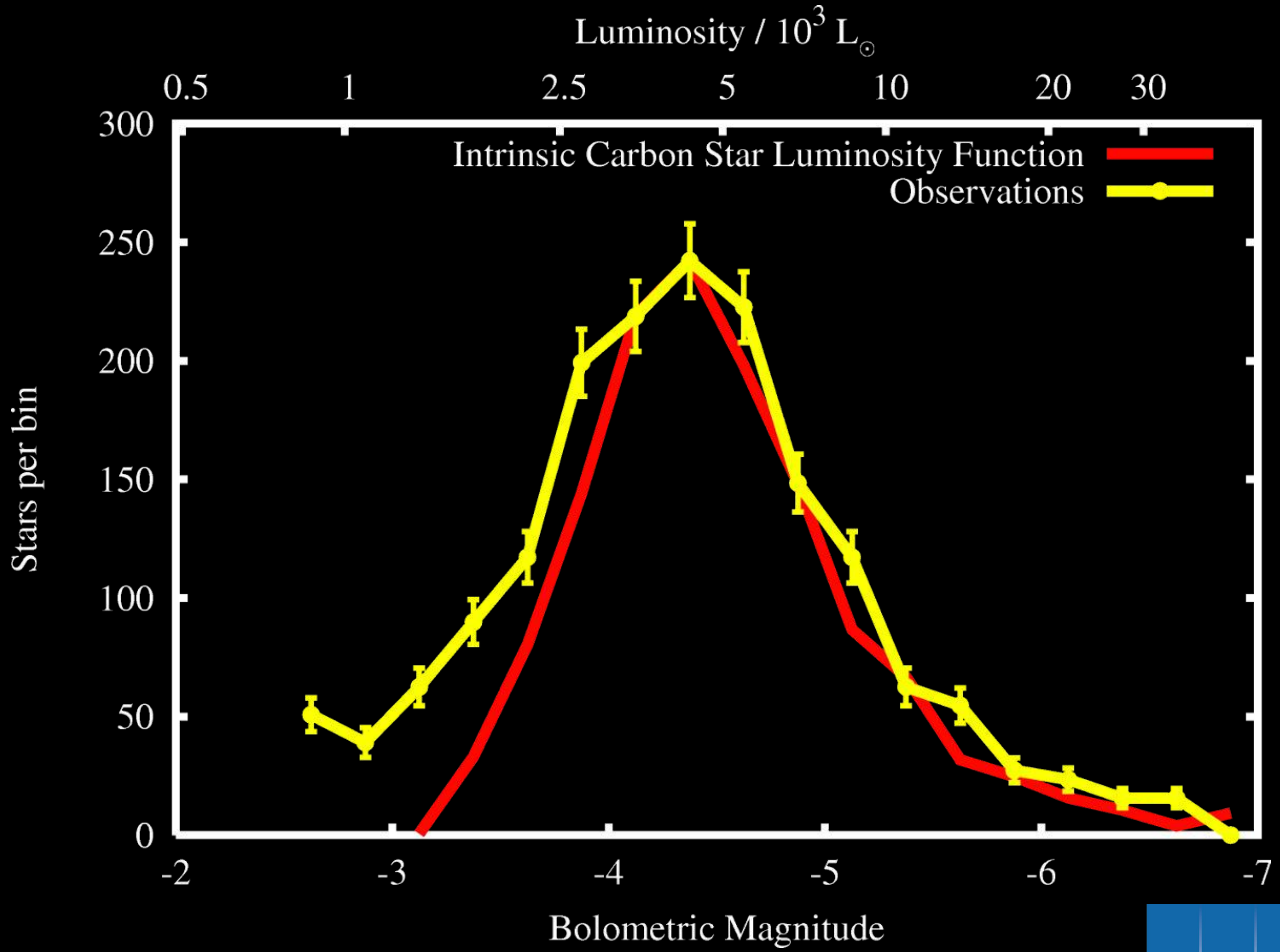
- Remember to try it yourself!
- **http://www.astro.uni-bonn.de/~izzard/cgi-bin/binary3.cg**

binary_c/nucsyn results

A frontend to the binary_c/nucsyn code

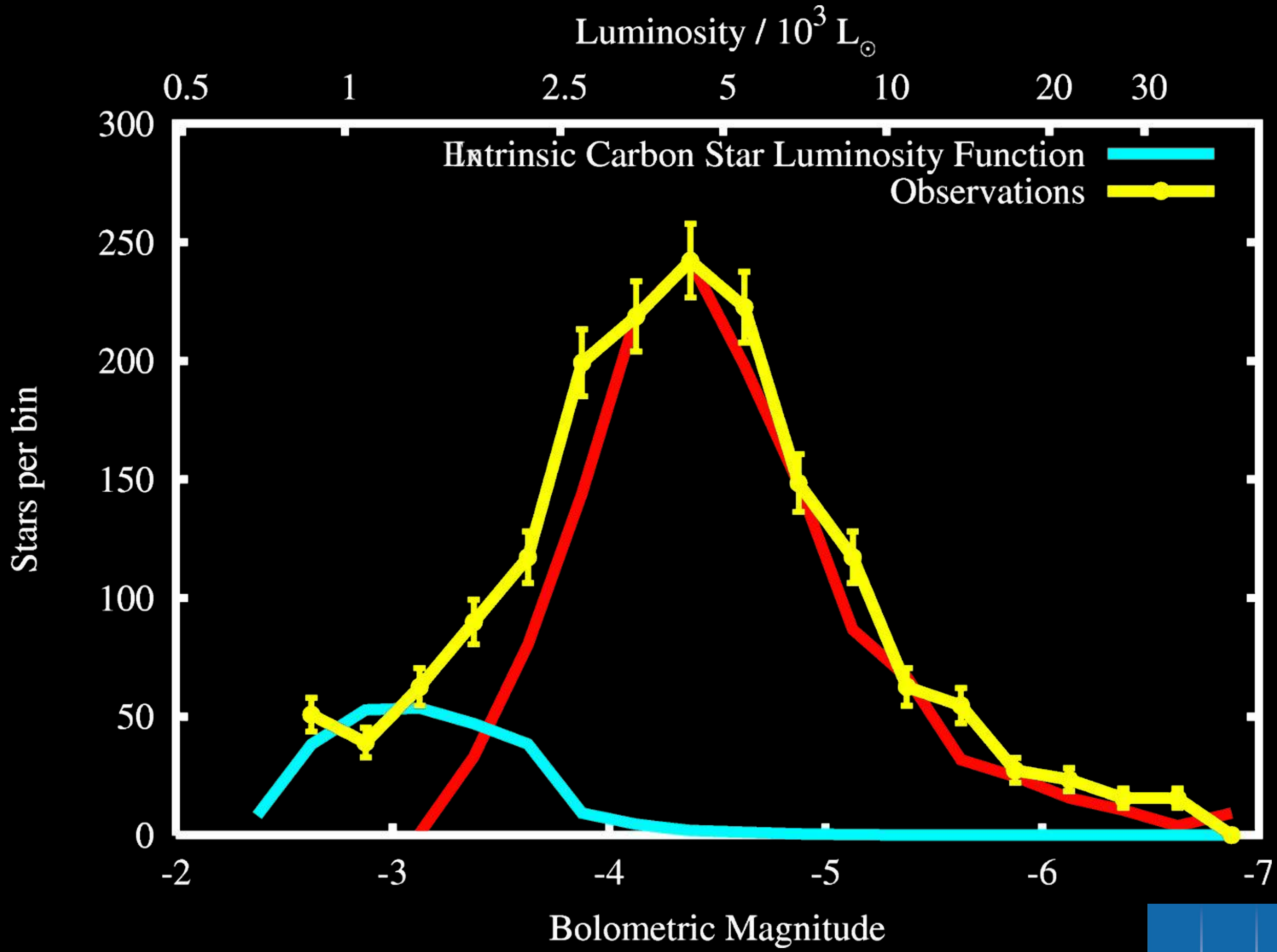
Evolution Time (MYr)	Star 1 mass (M☉)	Star 2 mass (M☉)	Star 1 type	Star 2 type	Separation (R☉)	Period	Eccentricity	Star 1 R/ROL	Star 2 R/ROL	What's happening?	
0.0000	14.000	6.000	Main Sequence	Main Sequence	100.000	25.92	0.00	0.106	0.095	In the beginning there was a star...	<—— 0.5 AU ——> 25.9 days
14.0936	13.718	6.002	Hertzsprung Gap	Main Sequence	101.340	26.63	0.00	0.256	0.103	Stellar Type Change	<—— 0.5 AU ——> 26.6 days
14.1165	13.715	6.003	Hertzsprung Gap	Main Sequence	101.384	26.64	0.00	1.000	0.103	Begin Roche Lobe Overflow	<—— 0.5 AU ——> 26.6 days
14.1165	13.715	6.003	Hertzsprung Gap	Main Sequence	101.384	26.64	0.00	1.000	0.103	Common Envelope Evolution in	<—— 0.5 AU ——> 26.6 days
14.1165	3.349	6.003	Main Sequence Naked Helium star	Main Sequence	12.748	1.72	0.00	1.000	0.103	Common Envelope Evolution	<—— 0.1 AU ——> 41.4 hours
14.1165	3.349	6.003	Main Sequence Naked Helium star	Main Sequence	12.748	1.72	0.00	0.112	0.591	End of Roche Lobe Overflow	<—— 0.1 AU ——> 41.4 hours
16.1738	3.042	6.014	Hertzsprung Gap Naked Helium star	Main Sequence	13.359	1.88	0.00	0.103	0.562	Stellar Type Change	<—— 0.1 AU ——> 45.1 hours
16.3312	2.978	6.023	Hertzsprung Gap Naked Helium star	Main Sequence	13.397	1.89	0.00	1.003	0.559	Begin Roche Lobe Overflow	<—— 0.1 AU ——> 45.5 hours

Low–L Carbon Stars



Izzard and Tout 2004

Low–L Carbon Stars



Izzard and Tout 2004

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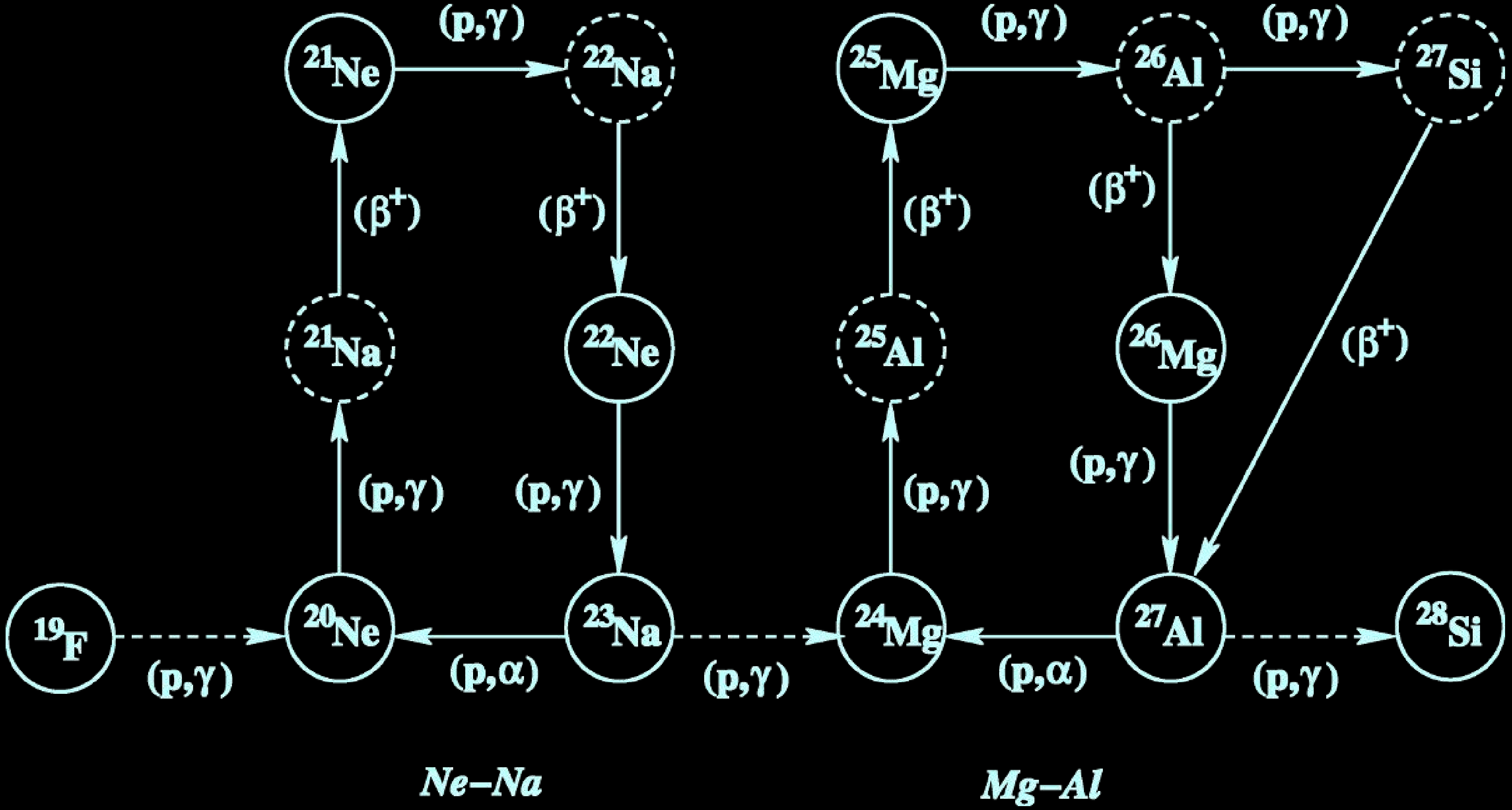
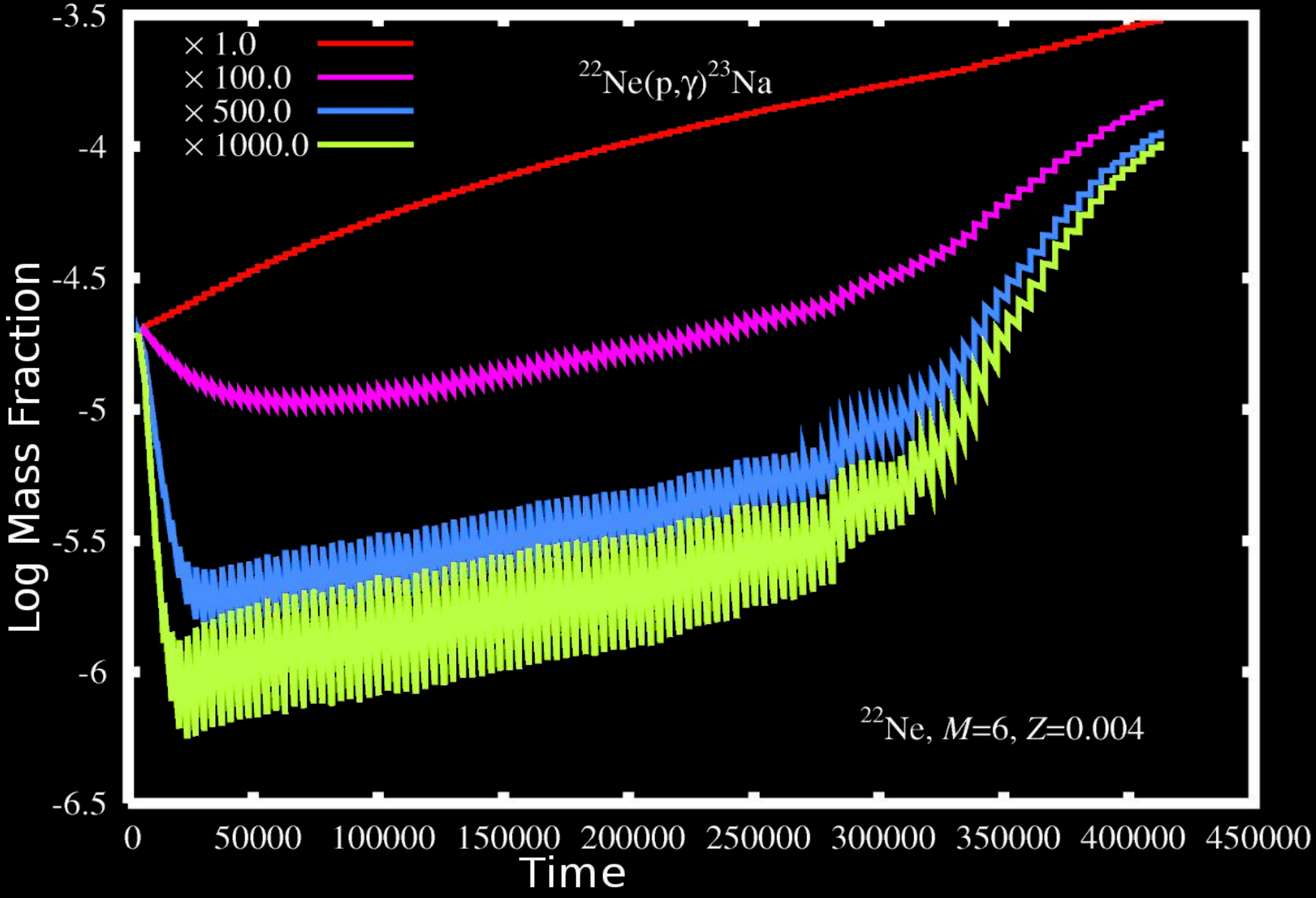
Nuclear Burning Rates



Nuclear Burning Rates

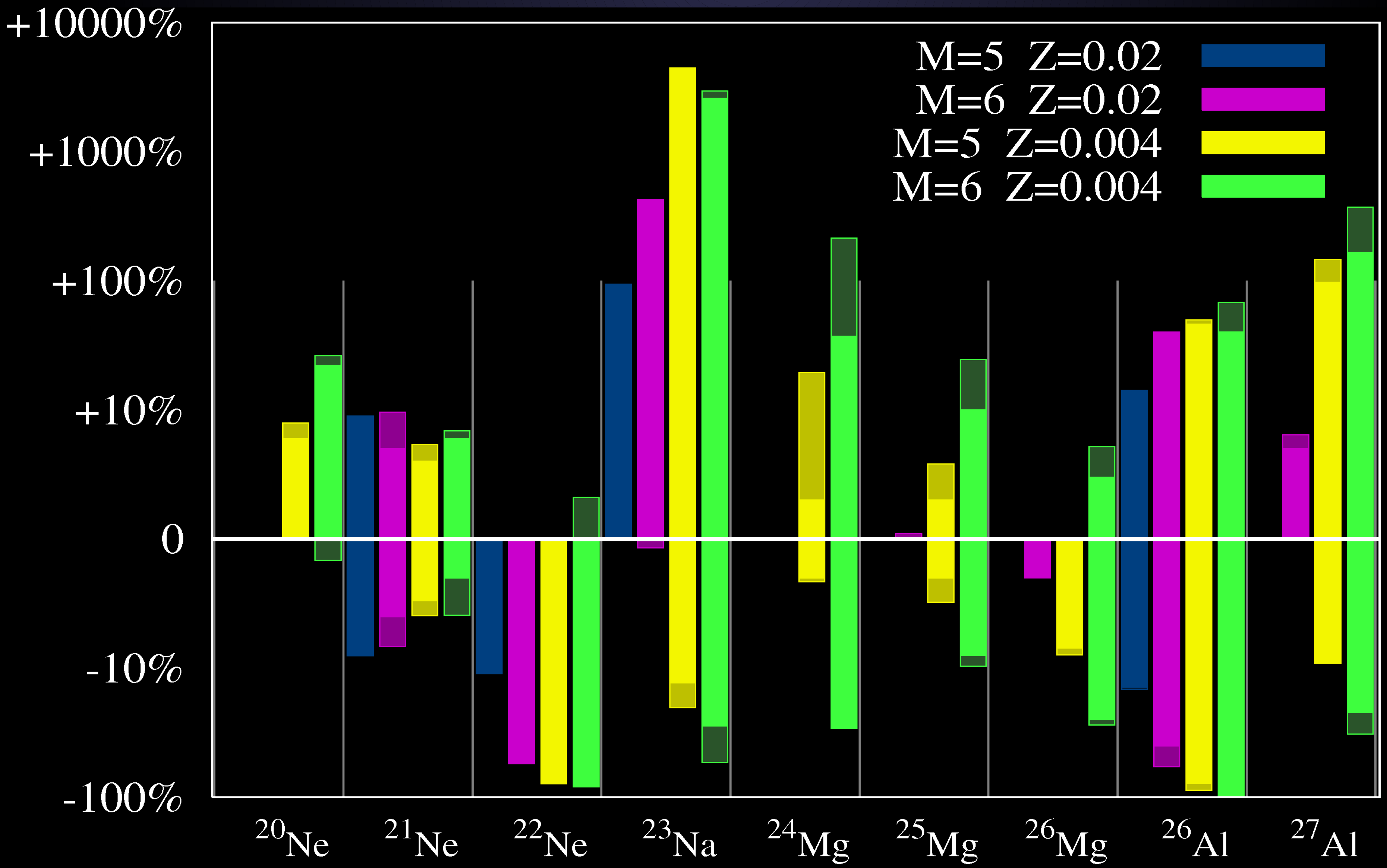
Rate			Source
$^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}(\beta^+)^{21}\mathrm{Ne}$	-50%	$+50\%$	NACRE
$^{21}\mathrm{Ne}(p,\gamma)^{22}\mathrm{Na}(\beta^+)^{22}\mathrm{Ne}$	-20%	$+20\%$	Iliadis et al. 2001
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	-50%	$\times 2000$	Hale et al. 2001
$^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$	-30%	$+30\%$	Rowland et al. 2004
$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$	$/40$	$\times 10$	Rowland et al. 2004
$^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}(\beta^+)^{25}\mathrm{Mg}$	-17%	$+20\%$	Powell et al. 1999
$^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}(\beta^+)^{26}\mathrm{Mg}$	-50%	$\times 1.5$	Iliadis et al. 2001
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	$/4$	$\times 10$	Iliadis et al. 2001
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$	-25%	$\times 3$	Iliadis et al. 2001
$^{26}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	$/2$	$\times 600$	Iliadis et al. 2001

Nuclear Burning Rates



Izzard et al. 2007

Nuclear Burning Rates



Izzard et al. 2007

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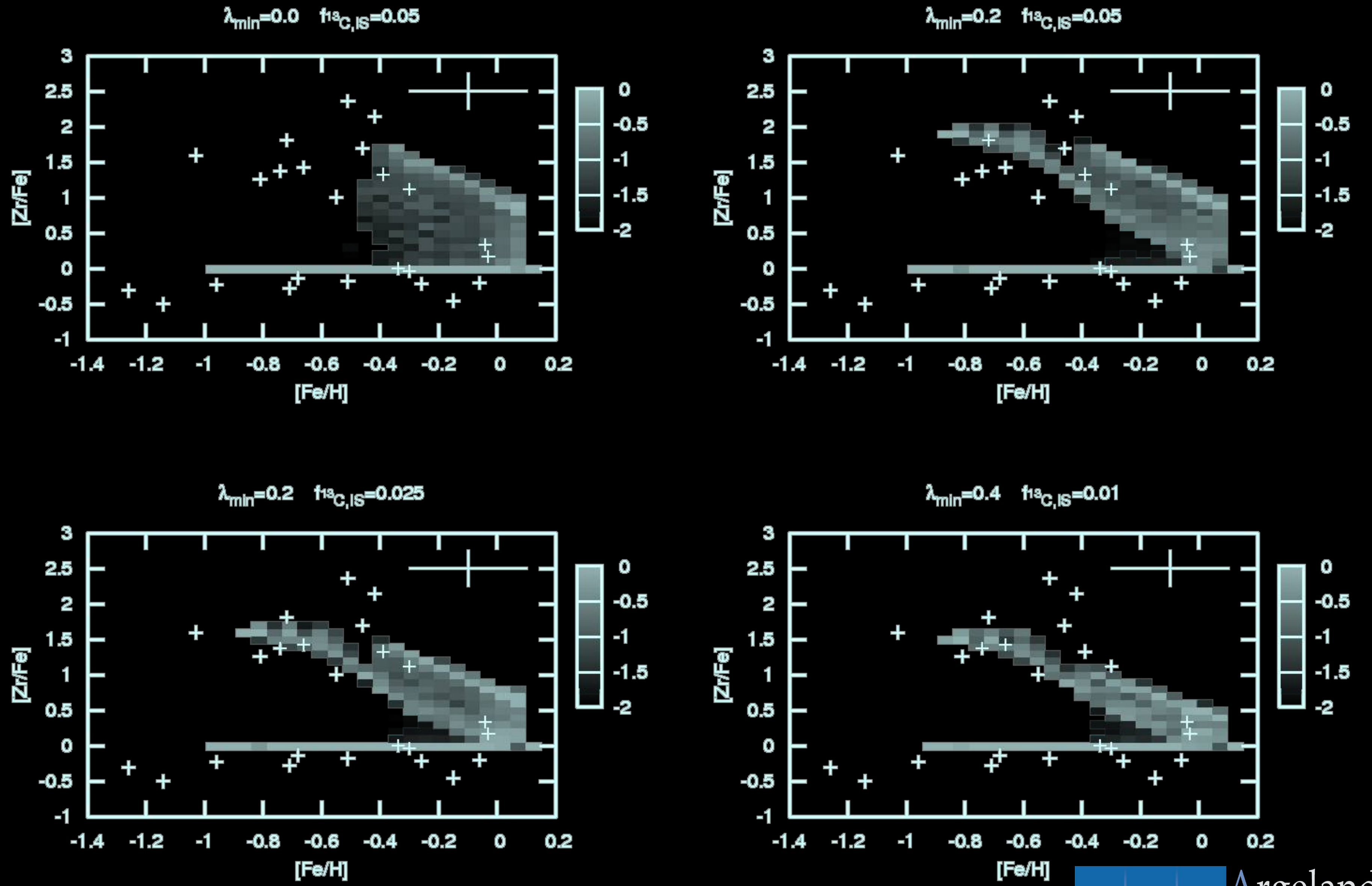
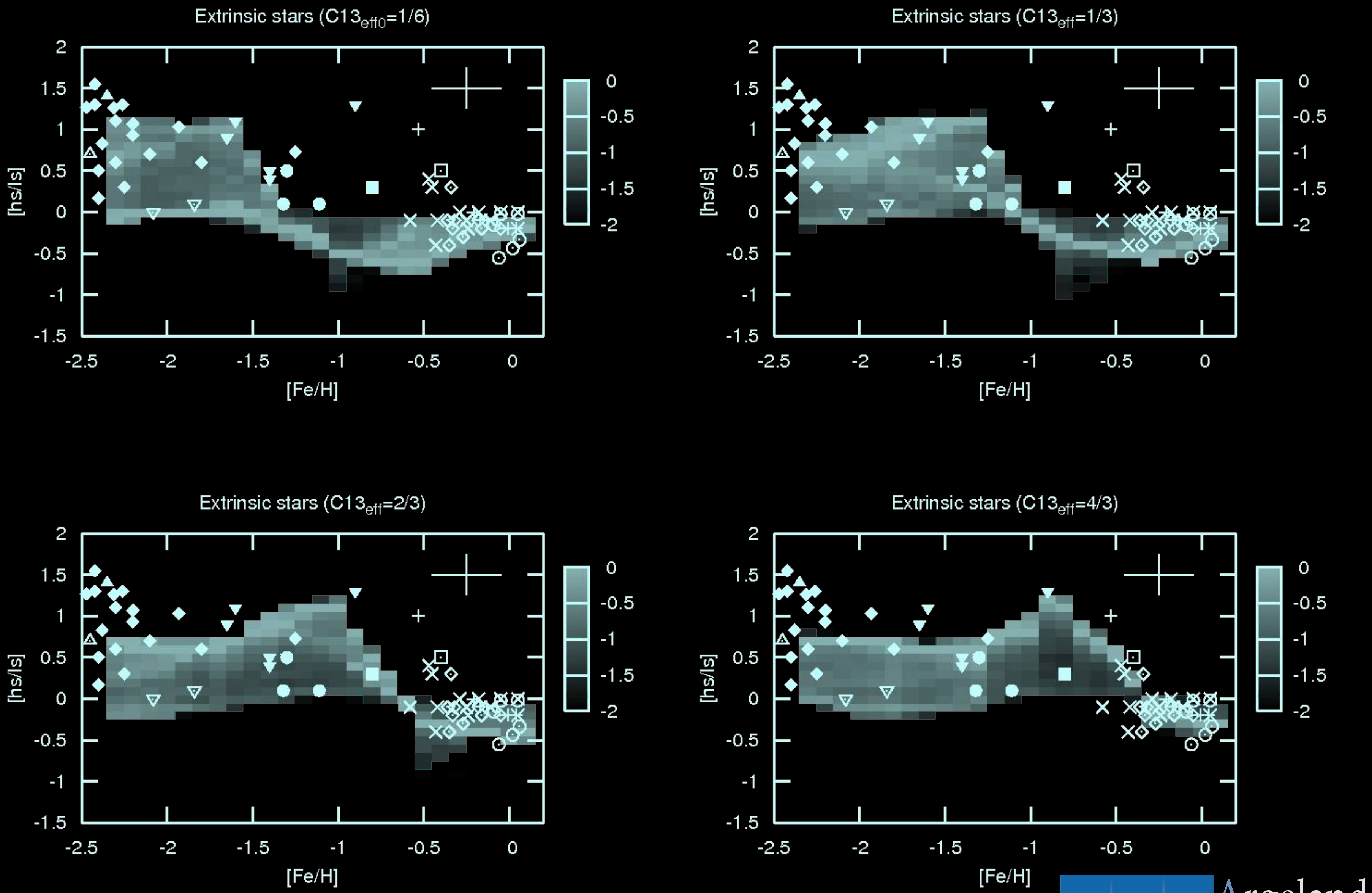
s-process in post-AGB



Bonacic et al. 2007

s–process in post–AGB


Extrinsic stars ($C13_{eff0}$=1/6)

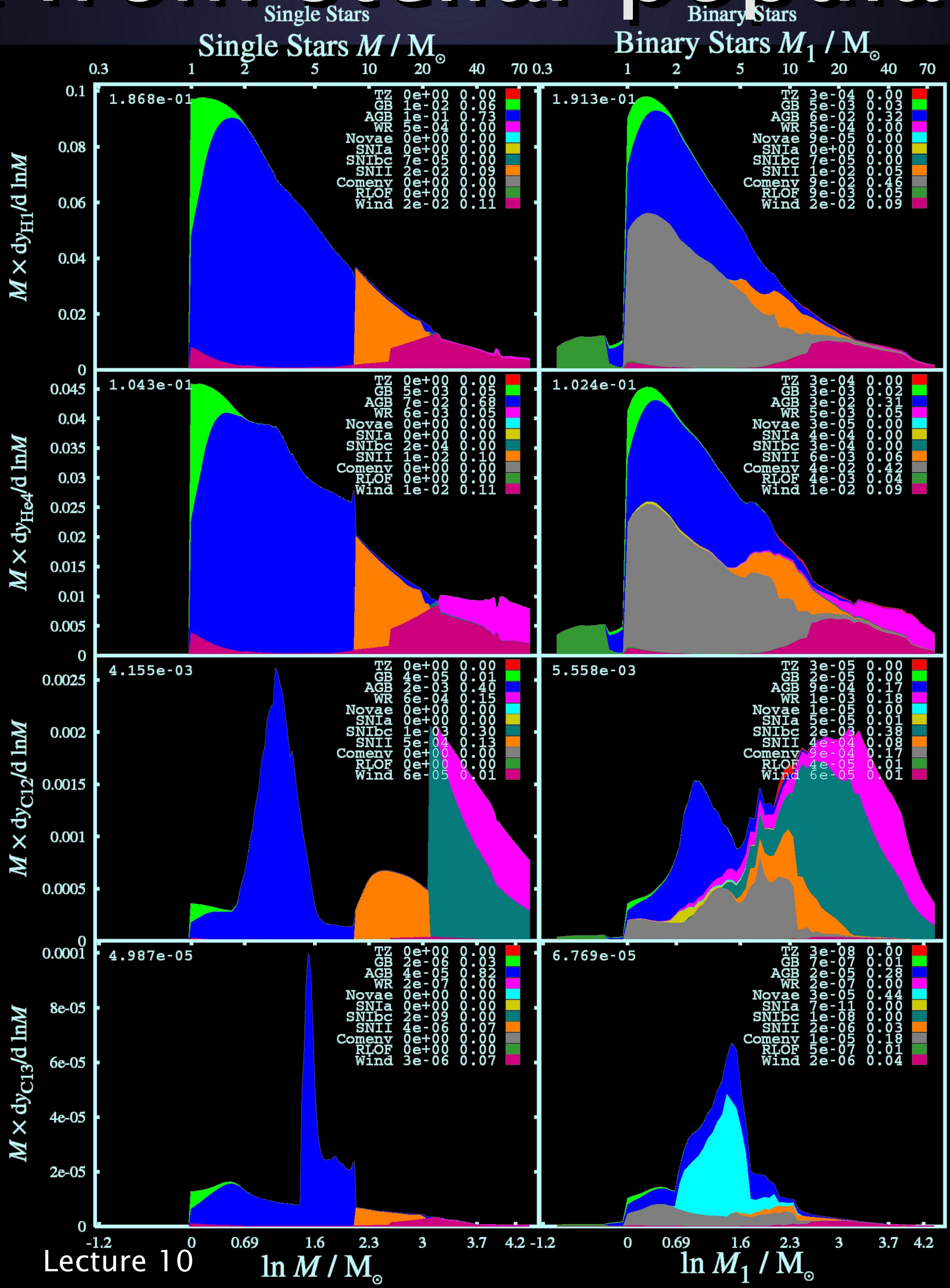
Extrinsic stars ($C13_{eff}$=1/3)

Extrinsic stars ($C13_{eff}$=2/3)

Extrinsic stars ($C13_{eff}$=4/3)

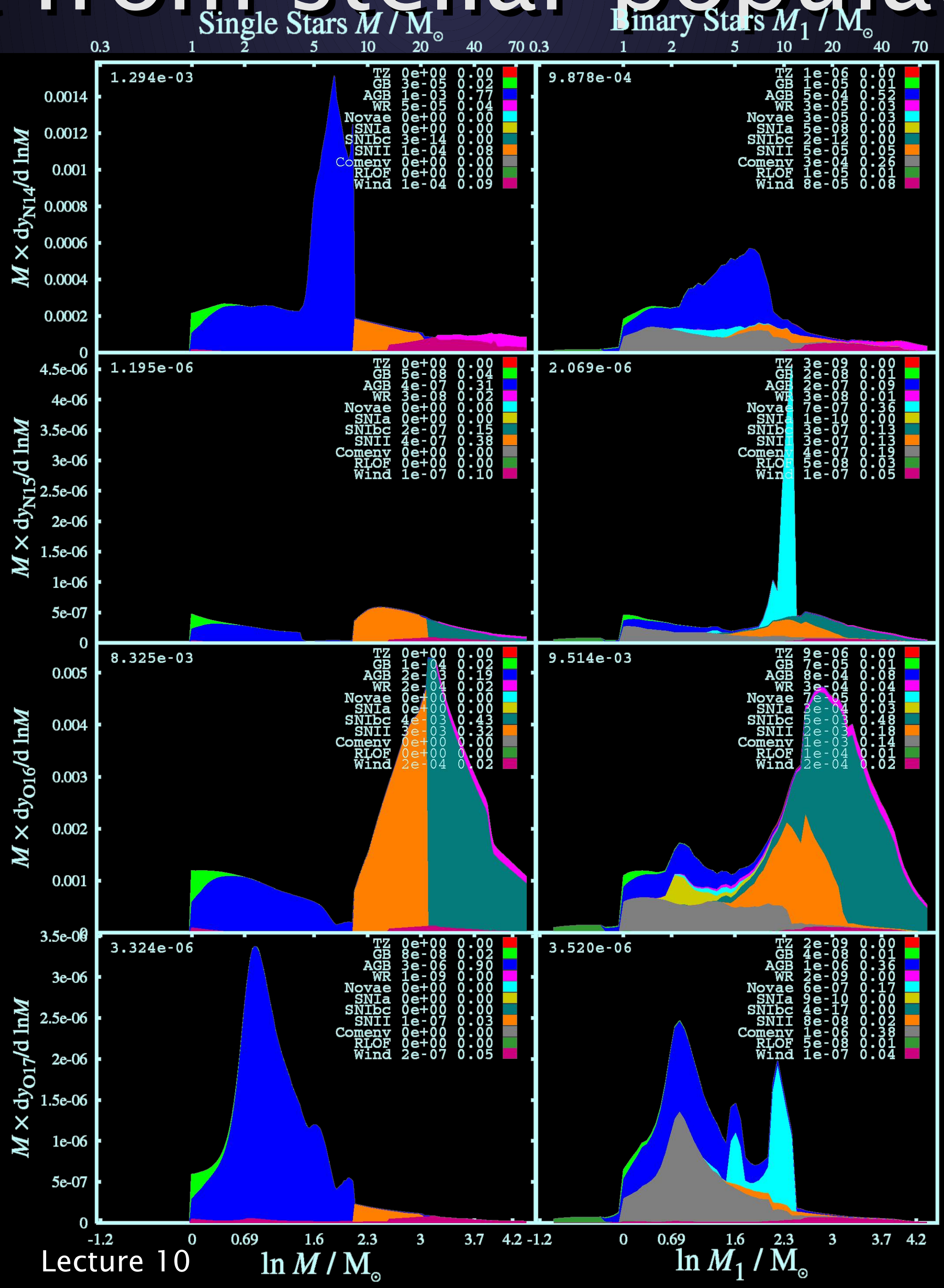
Bonacic et al. 2007

Ejecta from stellar populations



Izzard PhD!

Ejecta from stellar populations



Izzard PhD!

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