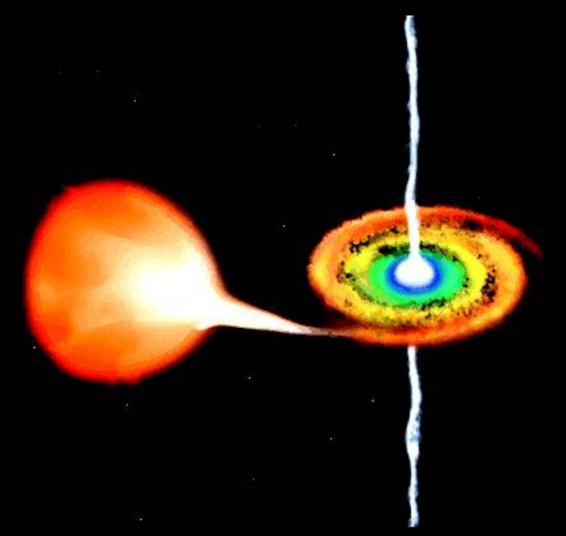
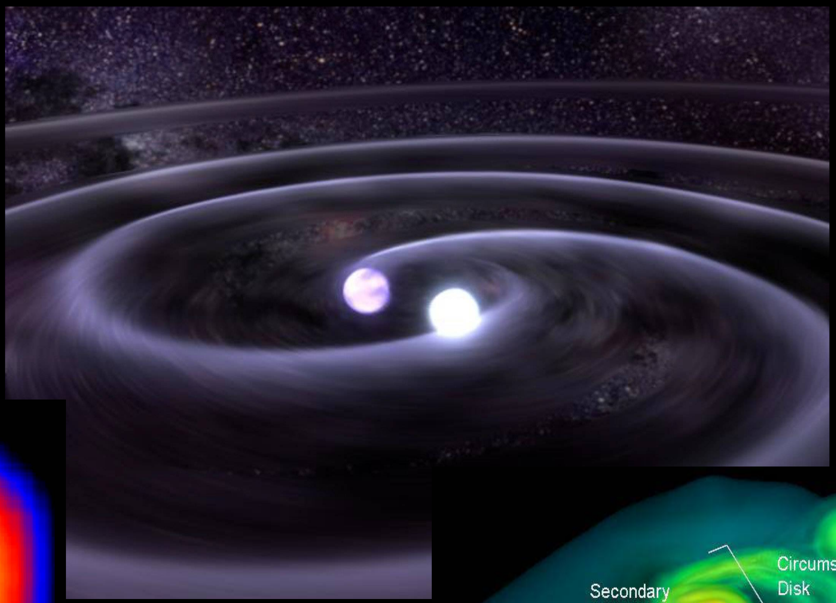
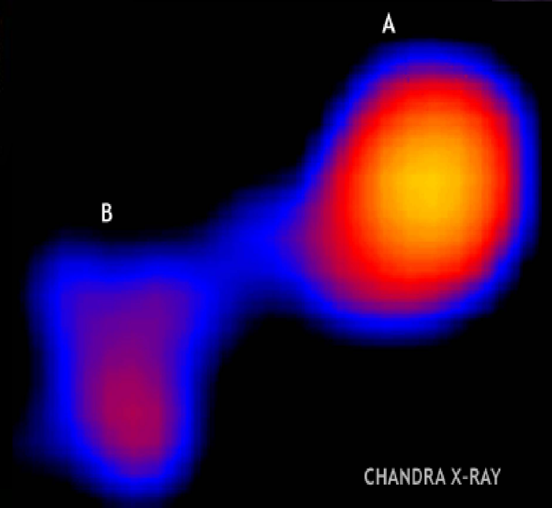
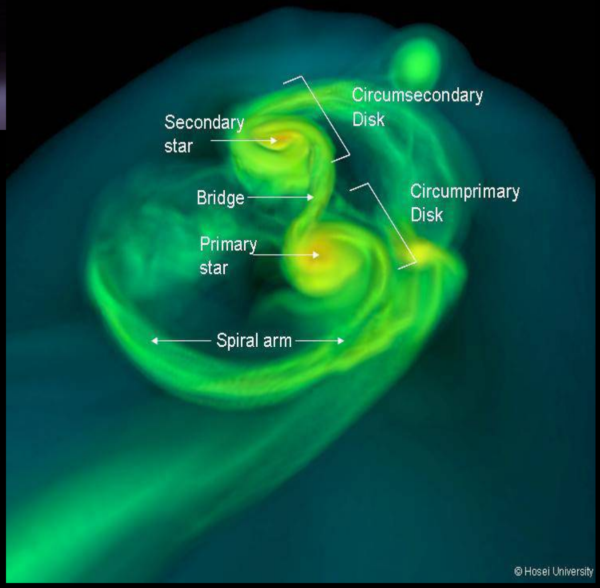
Binary Stars – Final Lecture!







Astro 8501
6944



Argelander Institut für Astronomie

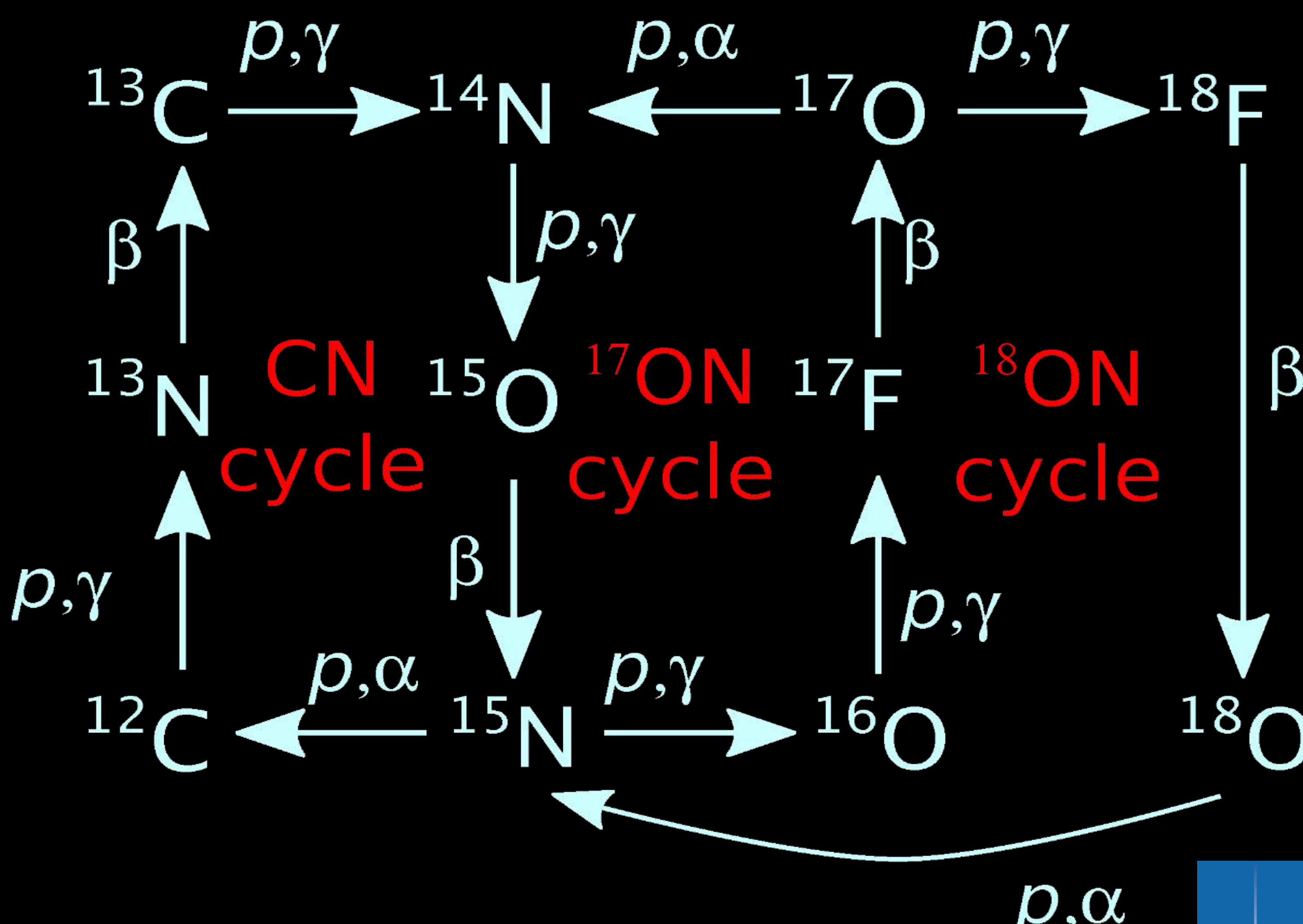
Binary-star Nucleosynthesis

- Many types of stars are only or mostly found in binaries
- The physics we have learned about in this course will help us to understand them
- Chemically peculiar binaries:
  - Algols
  - Massive stars (WR stars etc)
  - Ba/CH/CEMP stars
  - Thermohaline mixing
  - Galactic chemical evolution

Argelander Institut für Astronomie

Nuclear Burning In Stars

- All stars burn H to He, e.g. CNO cycle



Argelander Institut für Astronomie

CN cycle

$$\frac{d}{dt}\begin{bmatrix} {}^{12}\mathrm{C} \\ {}^{13}\mathrm{C} \\ {}^{14}\mathrm{N} \end{bmatrix} = \begin{bmatrix} -1/\tau_{12} & 0 & 1/\tau_{14} \\ 1/\tau_{12} & -1/\tau_{13} & 0 \\ 0 & 1/\tau_{13} & -1/\tau_{14} \end{bmatrix}\begin{bmatrix} {}^{12}\mathrm{C} \\ {}^{13}\mathrm{C} \\ {}^{14}\mathrm{N} \end{bmatrix}$$

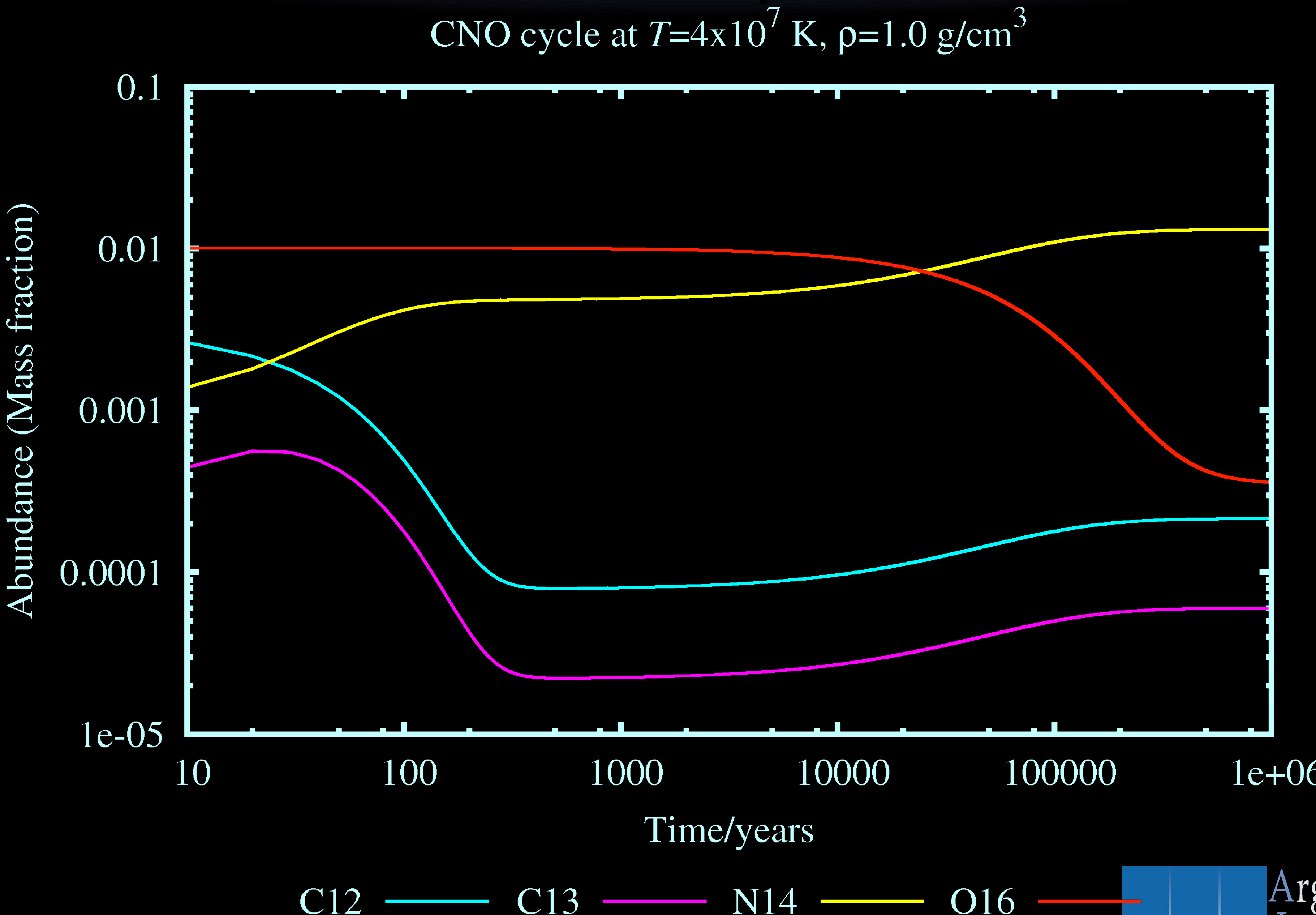
$$\frac{d}{dt}\mathsf{U} = \Lambda\mathsf{U}$$

$$\mathsf{U}\,(t) = Ae^{\lambda_1 t}\mathsf{U}_1 + Be^{\lambda_2 t}\mathsf{U}_2 + Ce^{\lambda_3 t}\mathsf{U}_3$$

And similarly for the other cycles
See e.g. Clayton's book

Argelander Institut für Astronomie

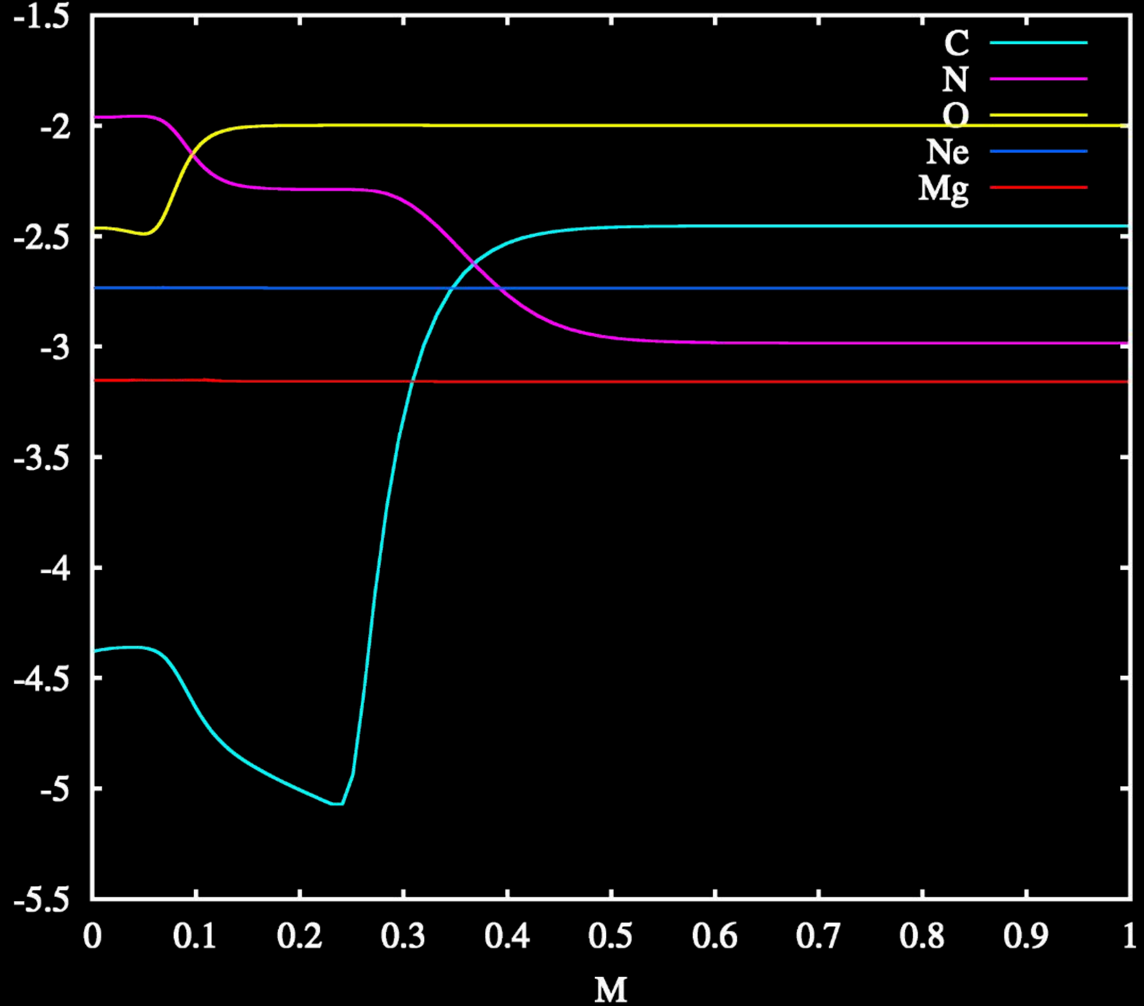
CNO cycle



CNO cycle at T=4x10^7 K, ρ=1.0 g/cm^3
0.1
0.01
0.001
0.0001
1e-05
Abundance (Mass fraction)
10
100
1000
10000
100000
1e+06
Time/years
C12
C13
N14
O16

Internal stellar evolution

- Composition changes inside a star

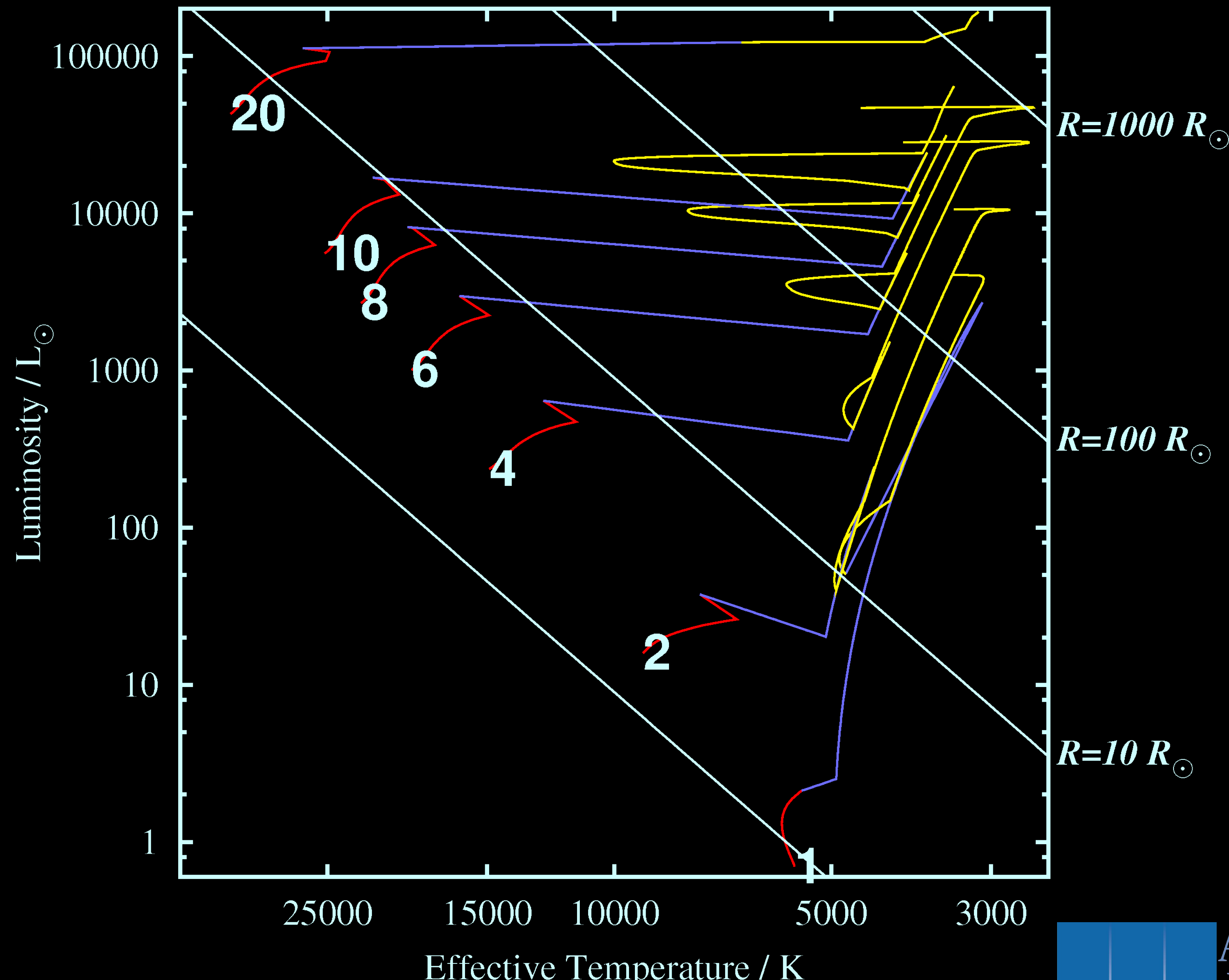


$1\,M_\odot$

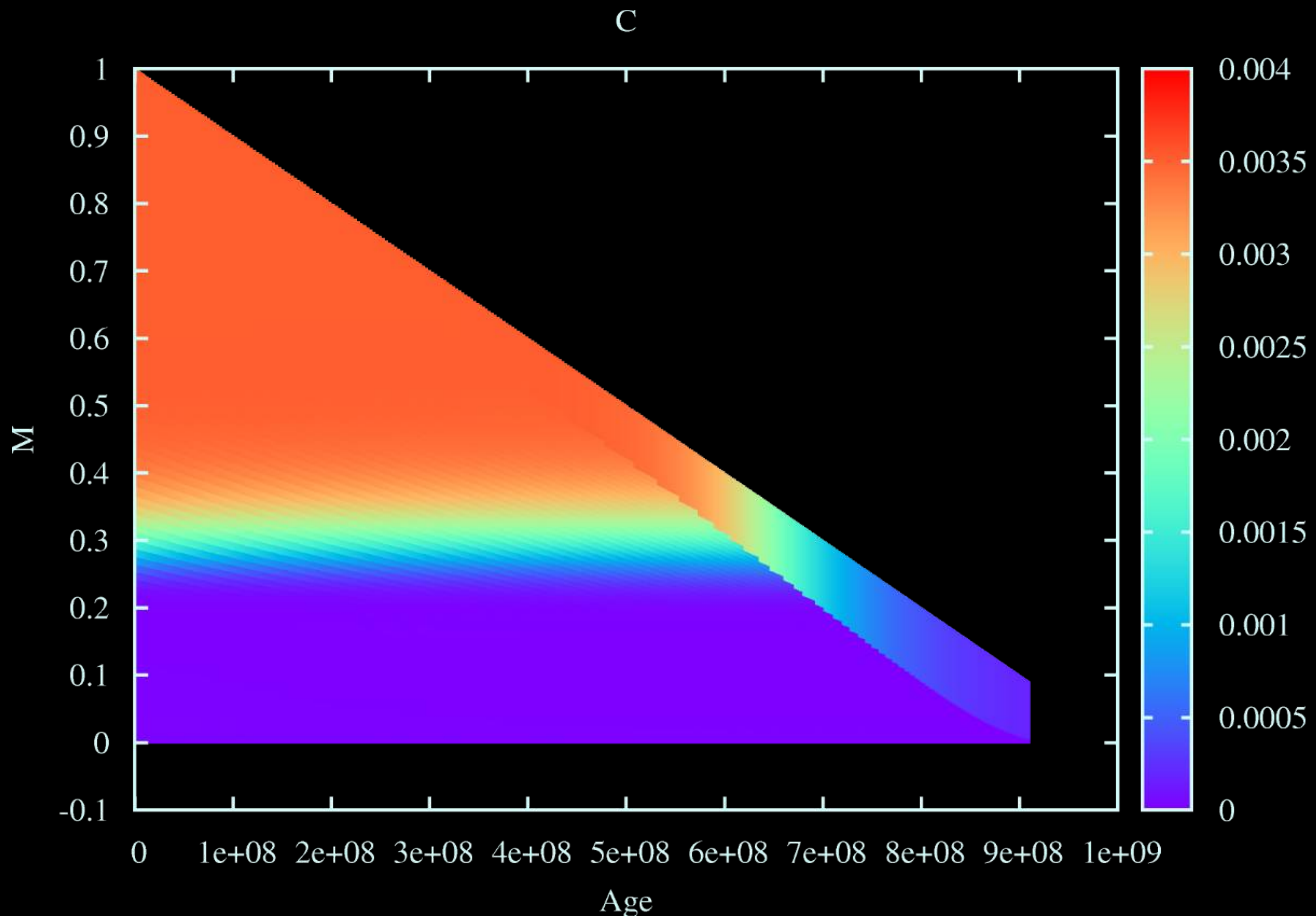
TAMS

Argelander Institut für Astronomie

Mass transfer



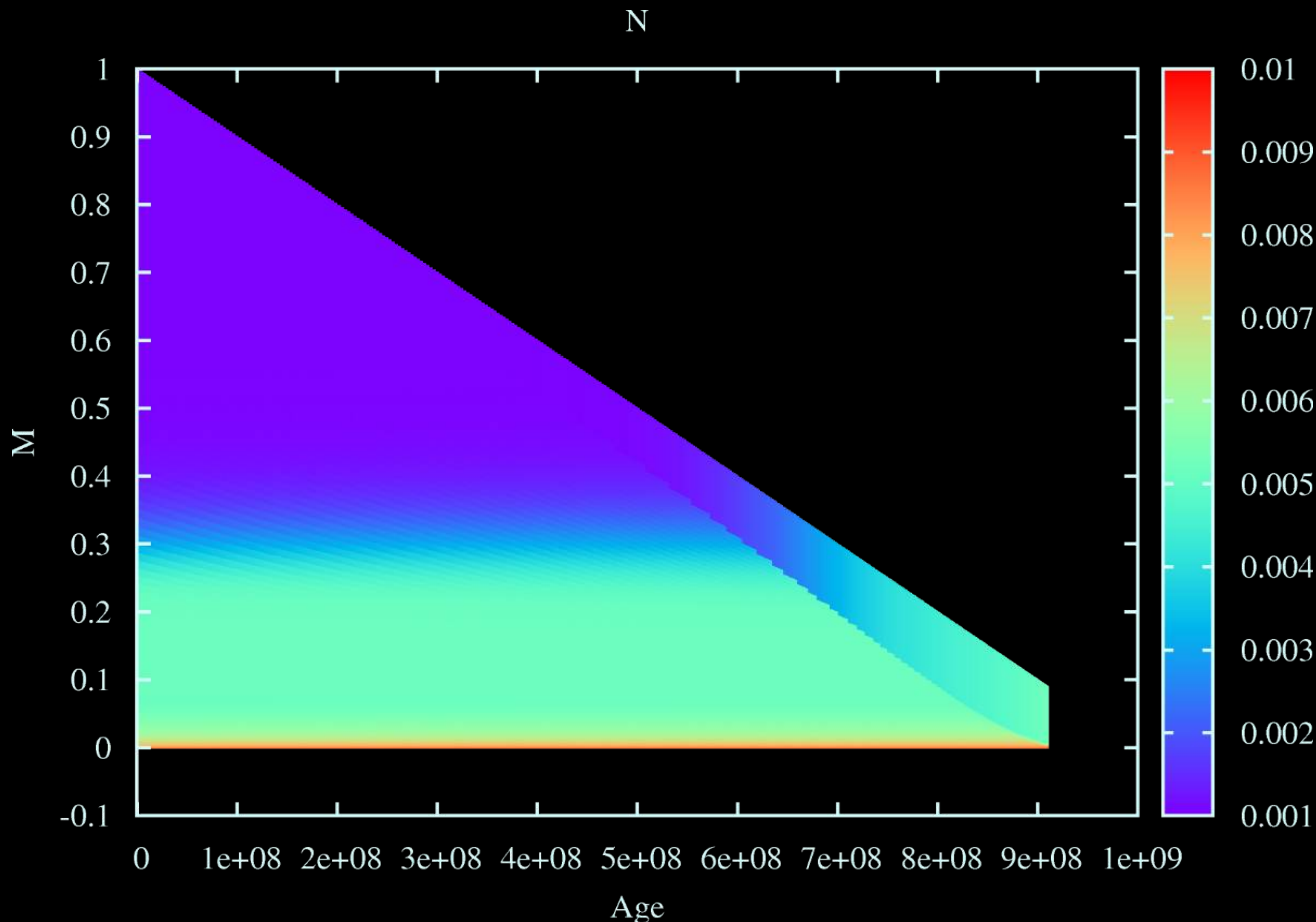
Stripping a solar-mass star



Models made with *Window To The Stars*
http://www.astro.uni-bonn.de/~izzard/window.html

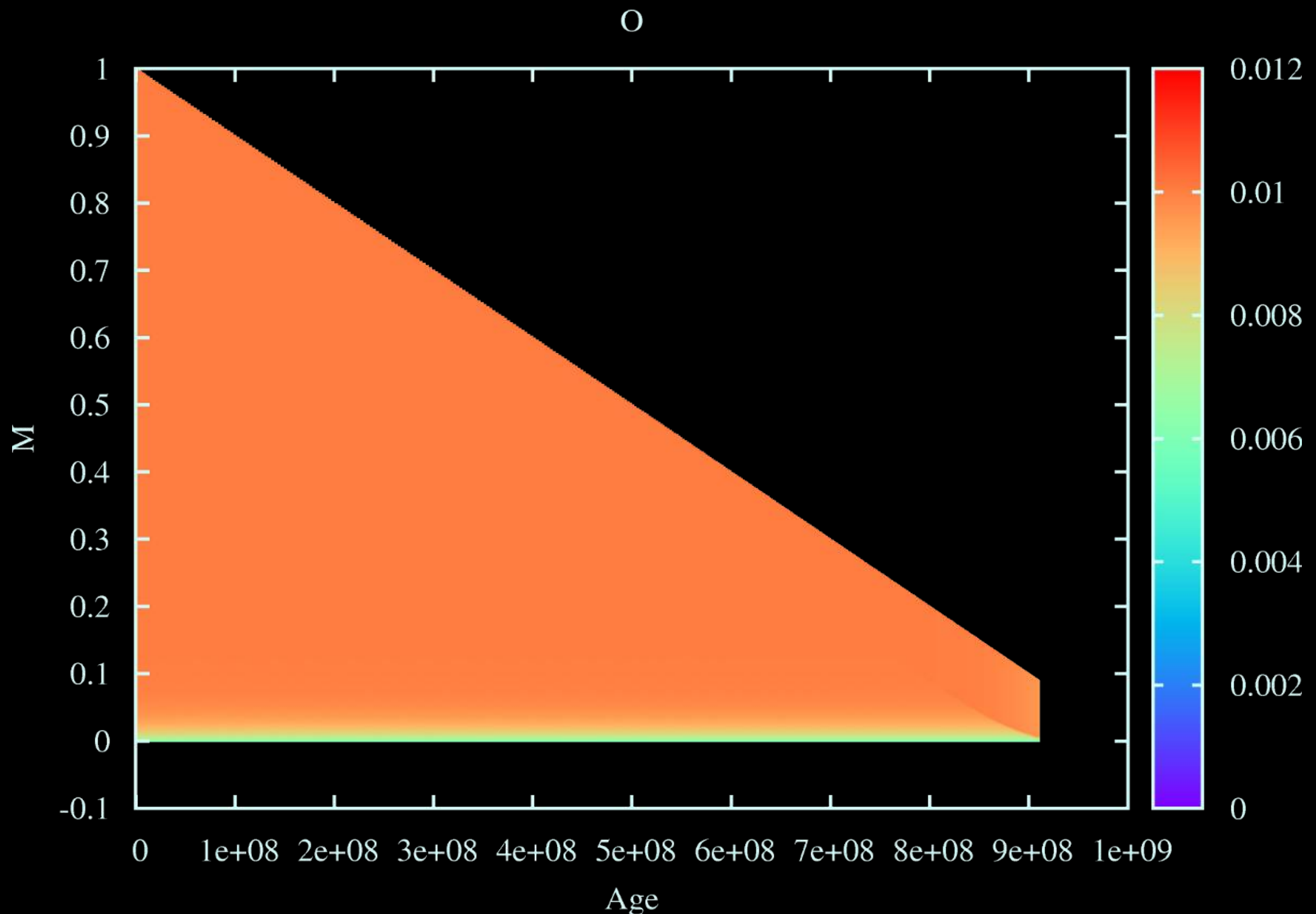
Argelander Institut für Astronomie

Stripping a solar-mass star



Models made with *Window To The Stars*
http://www.astro.uni-bonn.de/~izzard/window.html

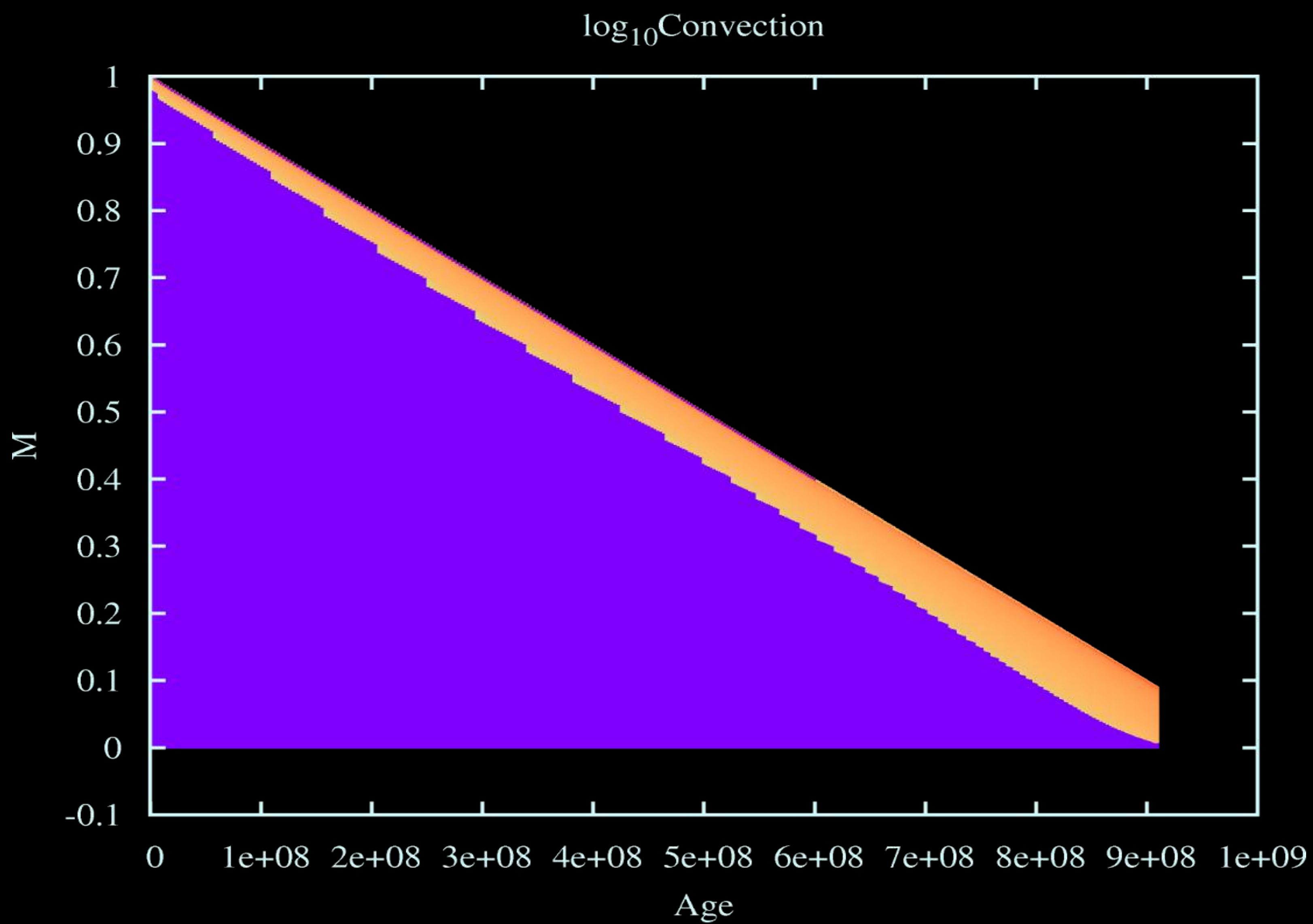
Stripping a solar-mass star



Models made with *Window To The Stars*
http://www.astro.uni-bonn.de/~izzard/window.html

Argelander Institut für Astronomie

Stripping a solar-mass star



Models made with *Window To The Stars*
http://www.astro.uni-bonn.de/~izzard/window.html

Argelander Institut für Astronomie

Algol observations

- Algols have N-enriched mass donors
- Stripping leads to exposed layers

Argelander Institut für Astronomie

Observed e.g. LZ Cep

Mahy et al 2011
ArXiv 1106.6162

Table 2. Orbital solution and stellar parameters.

	Primary	Secondary
P [d]	3.070507 (fixed)	
e	0.0 (fixed)	
T_0 [HJD – 2450000]	5032.019±0.002	
$q(M_1/M_2)$	2.53±0.05	
γ [km s^{-1}]	−11.81±0.91	−11.40±1.20
K [km s^{-1}]	88.72±1.02	224.48±2.58
$a \sin i$ [$R_\odot$]	5.38±0.06	13.61±0.16
$M \sin^3 i$ [$M_\odot$]	7.00±0.18	2.77±0.05
rms [km s^{-1}]	2.9198	
$T_{\rm eff}$ [K]	32000±1000	28000±1000
$\log \frac{L}{L_\odot}$	$5.11^{+0.19}_{-0.16}$	$4.69^{+0.19}_{-0.16}$
$\log g$	3.5±0.1	3.1±0.1
$M_{\rm spec}$ [$M_\odot$]	$15.9^{+9.8}_{-8.4}$	$4.1^{+2.4}_{-2.1}$
$M_{\rm ev}$ [$M_\odot$]	$25.3^{+8.2}_{-4.0}$	$18.0^{+2.4}_{-2.5}$
radius [$R_\odot$]	$11.7^{+3.3}_{-2.7}$	$9.4^{+2.8}_{-2.2}$
He/H	0.1±0.02	0.4±0.1
C/H [× 10^{-4}]	1.0±0.5	0.3±0.2
N/H [× 10^{-4}]	0.85±0.2	12.0±2.0
O/H [× 10^{-4}]	3.0±0.5	0.5±0.3
$V \sin i$ [km s^{-1}]	130±10	80±10
$v_{\rm mac}$ [km s^{-1}]	40±5	44±5
$\dot{M}$ [$10^{-8} M_\odot$ yr^{-1}]	1.0±0.3	–
v_∞ [km s^{-1}]	1800±100	–

Notes. The given errors correspond to 1–σ. The solar abundances for the chemical elements quoted here are He/H = 0.1, C/H = 2.45 × 10^{-4}, N/H = 0.60 × 10^{-4}, O/H = 4.57 × 10^{-4}, respectively.

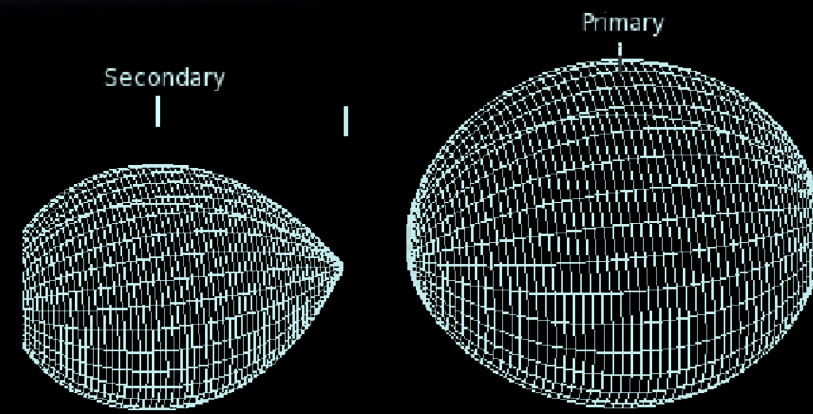


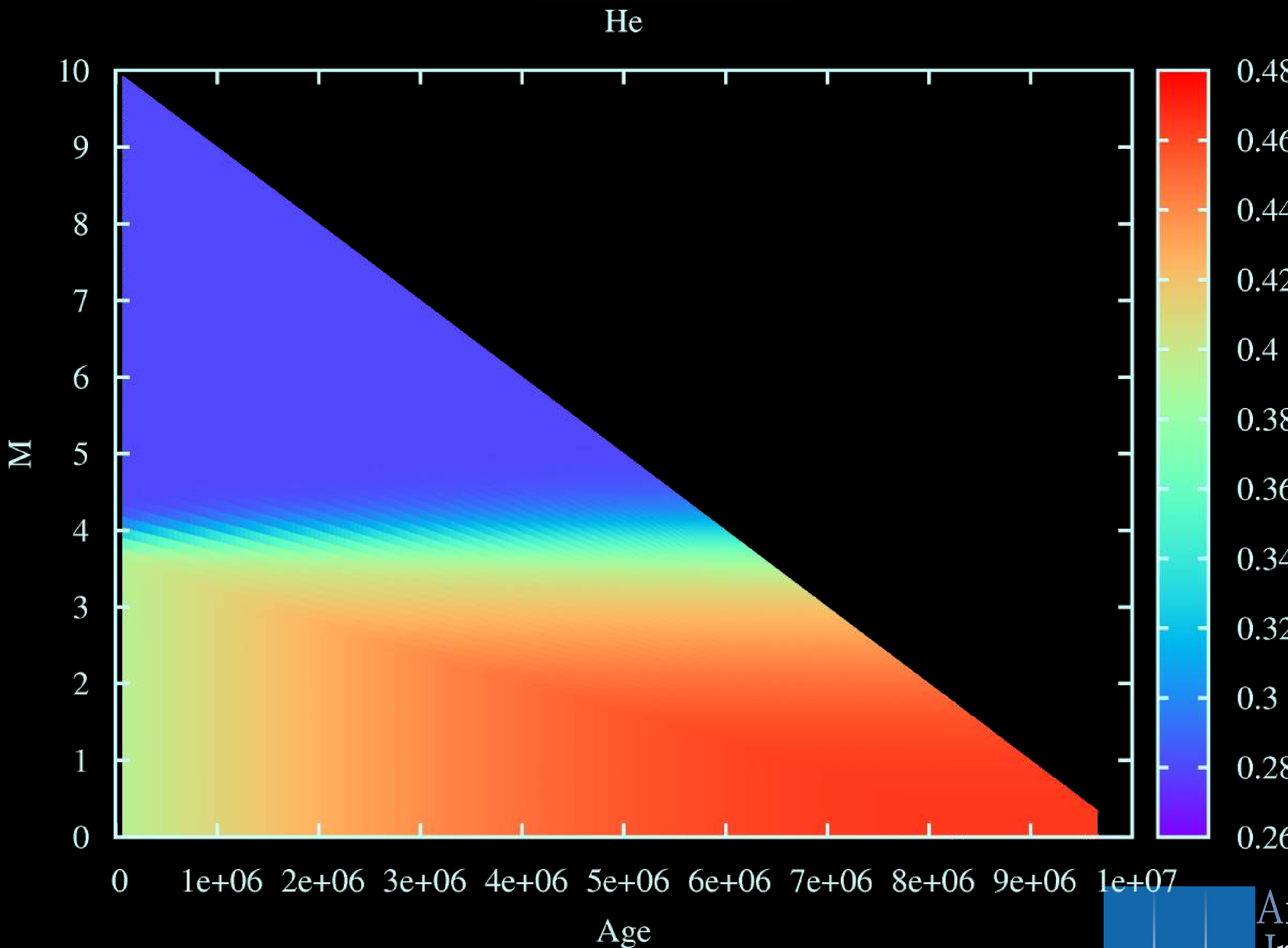
Table 3. Parameters fitted from the Hipparcos light curve.

Parameters	Sol 1	Sol 2
i [°]	$50.1^{+2.1}_{-1.5}$	$48.1^{+2.0}_{-0.7}$
q [M_1/M_2]	2.53 (fixed)	2.53 (fixed)
Filling factor primary [%]	$98.0^{+1.2}_{-1.0}$	$94.8^{+2.0}_{-3.0}$
Filling factor secondary [%]	$87.0^{+3.0}_{-5.0}$	$98.6^{+0.3}_{-1.5}$
$T_{\rm eff}$,p [K]	32000 (fixed)	32000 (fixed)
$T_{\rm eff}$,s [K]	28000 (fixed)	28000 (fixed)
$M_{\rm p}$ [$M_\odot$]	$15.5^{+1.0}_{-1.0}$	$16.9^{+1.0}_{-1.0}$
$M_{\rm s}$ [$M_\odot$]	$6.1^{+1.0}_{-1.0}$	$6.7^{+1.0}_{-1.0}$
R_{pole},p [$R_\odot$]	$10.5^{+1.2}_{-1.2}$	$10.5^{+1.2}_{-1.2}$
R_{pole},s [$R_\odot$]	$6.1^{+1.2}_{-1.2}$	$7.1^{+1.2}_{-1.2}$
R_{equ},p [$R_\odot$]	$13.1^{+1.2}_{-1.2}$	$12.4^{+1.2}_{-1.2}$
R_{equ},s [$R_\odot$]	$6.9^{+1.2}_{-1.2}$	$9.3^{+1.2}_{-1.2}$

Notes. The index 'p' ('s') refers to the primary (secondary). R_{pole} is the polar radius, and R_{equ} the equatorial radius.

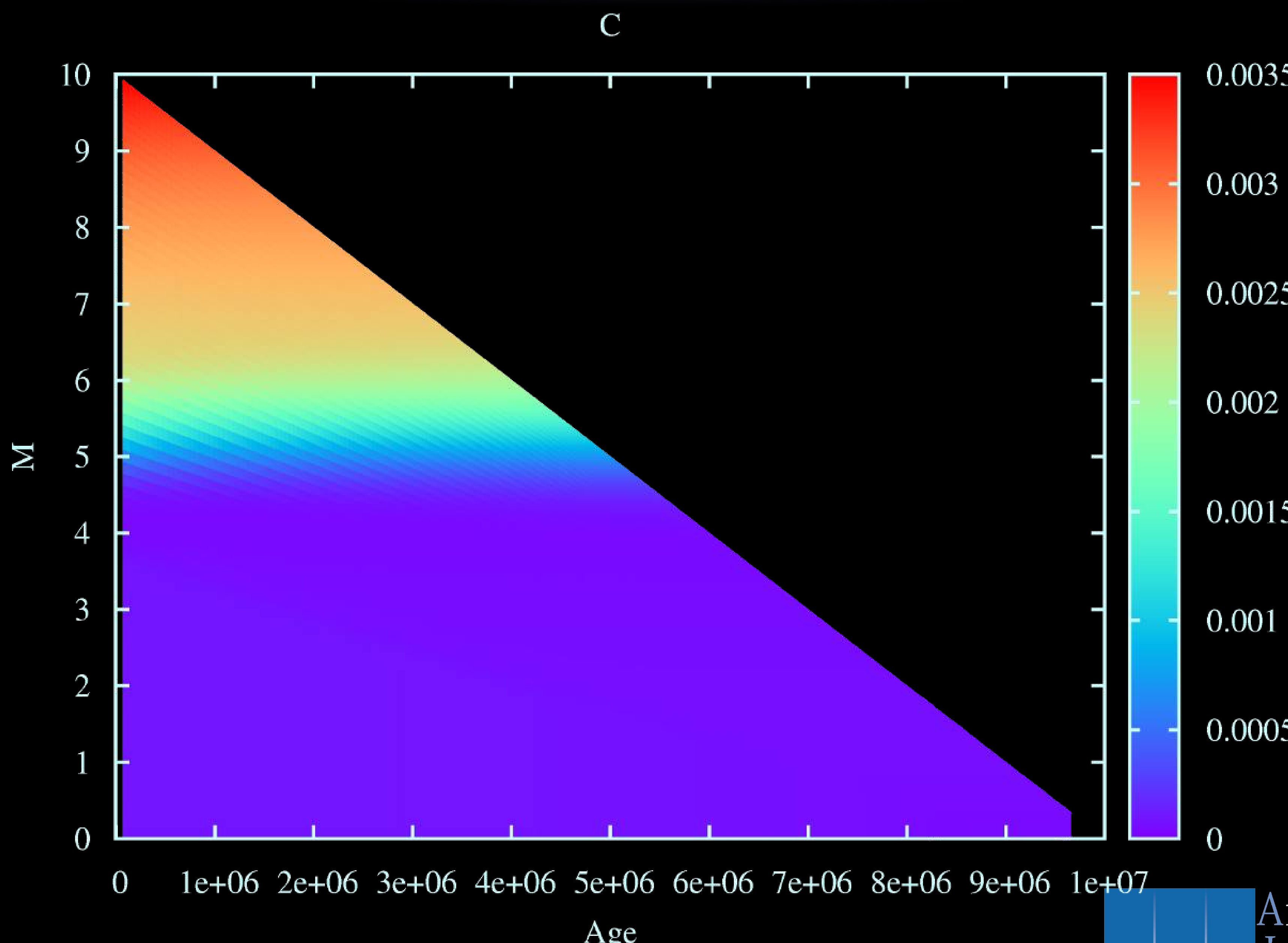
Argelander Institut für Astronomie

10Msun stripped



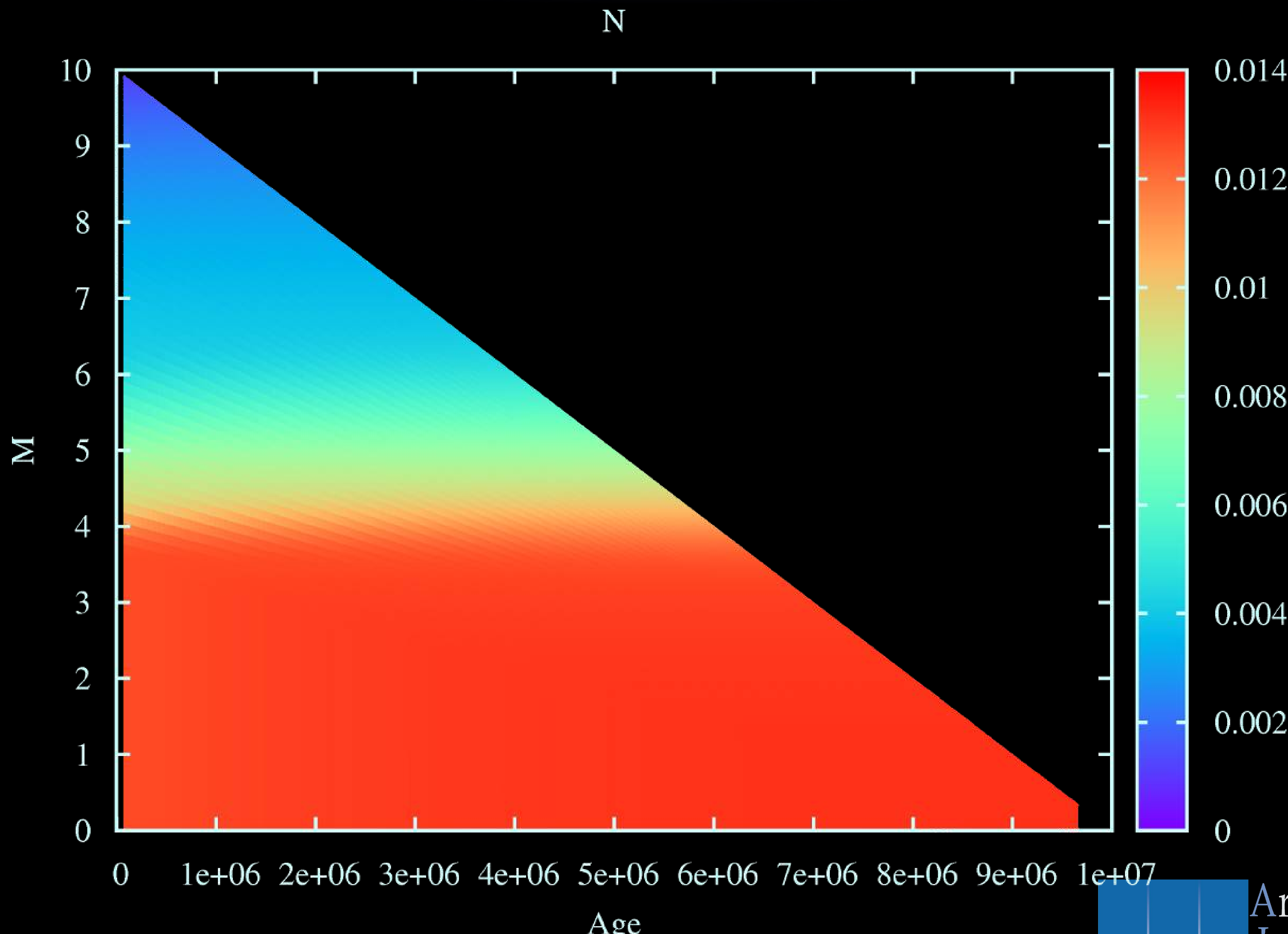
Argelander Institut für Astronomie

10Msun stripped

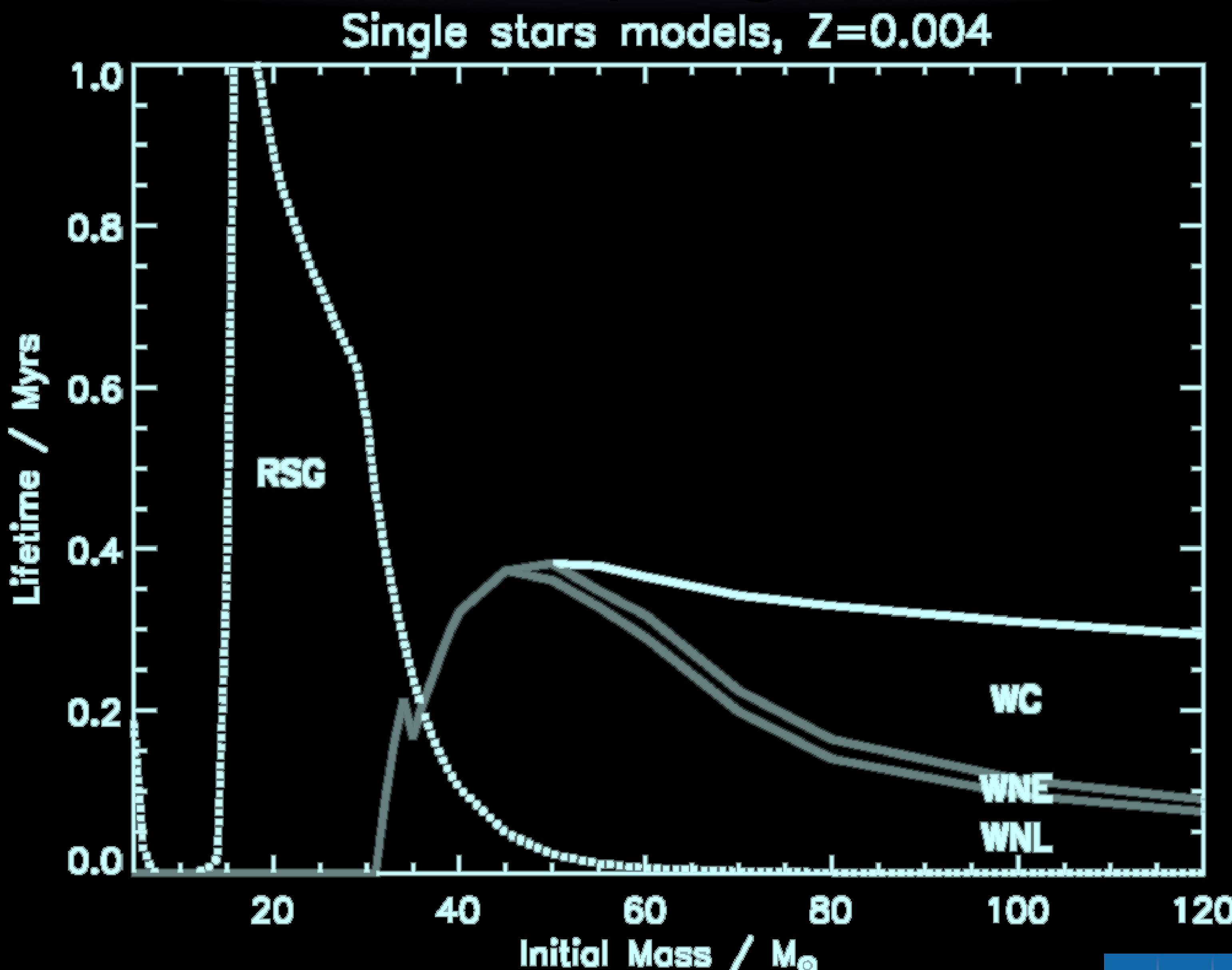


Argelander Institut für Astronomie

10Msun stripped



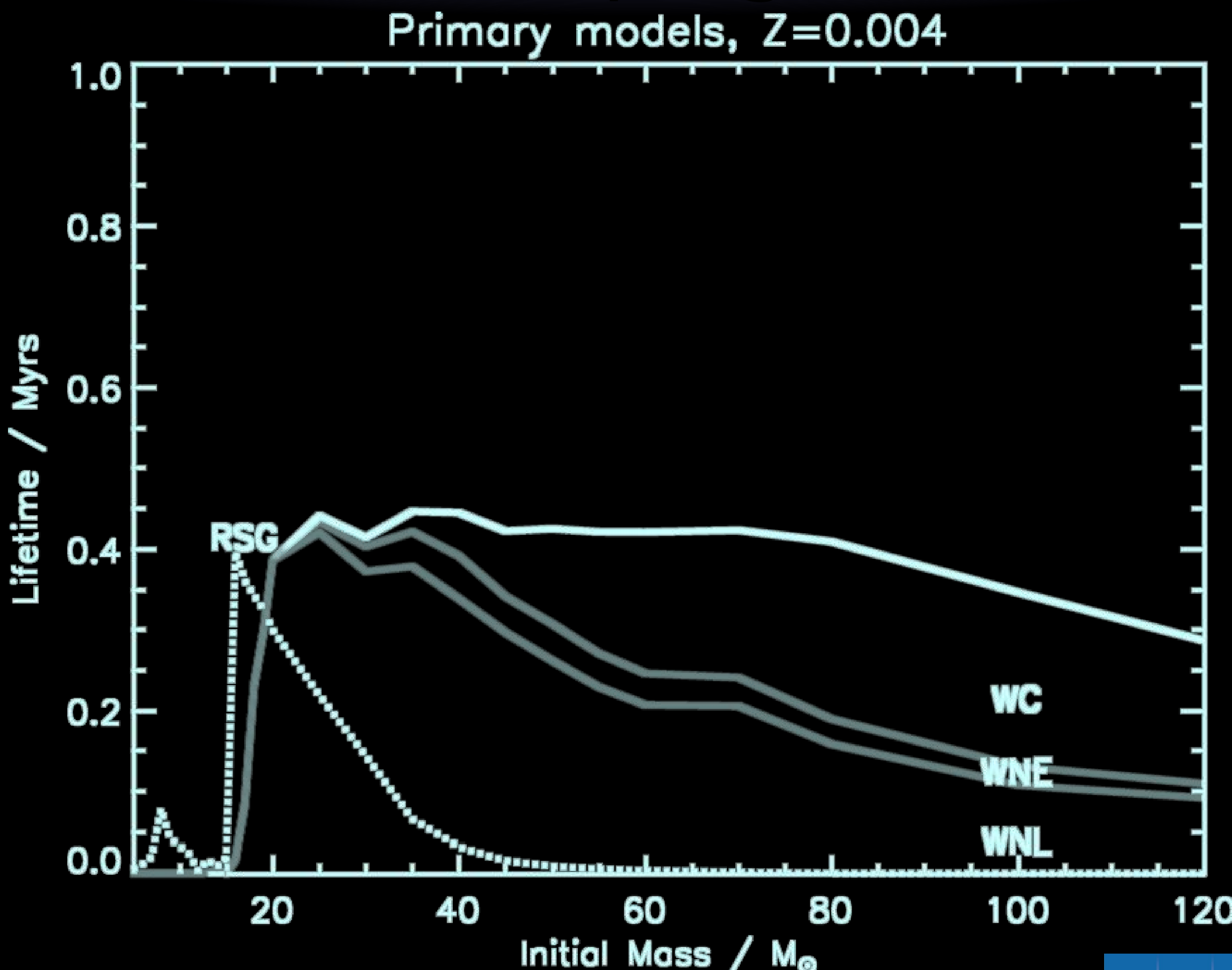
Red Supergiants



Eldridge, Izzard & Tout 2008, A&A

Argelander Institut für Astronomie

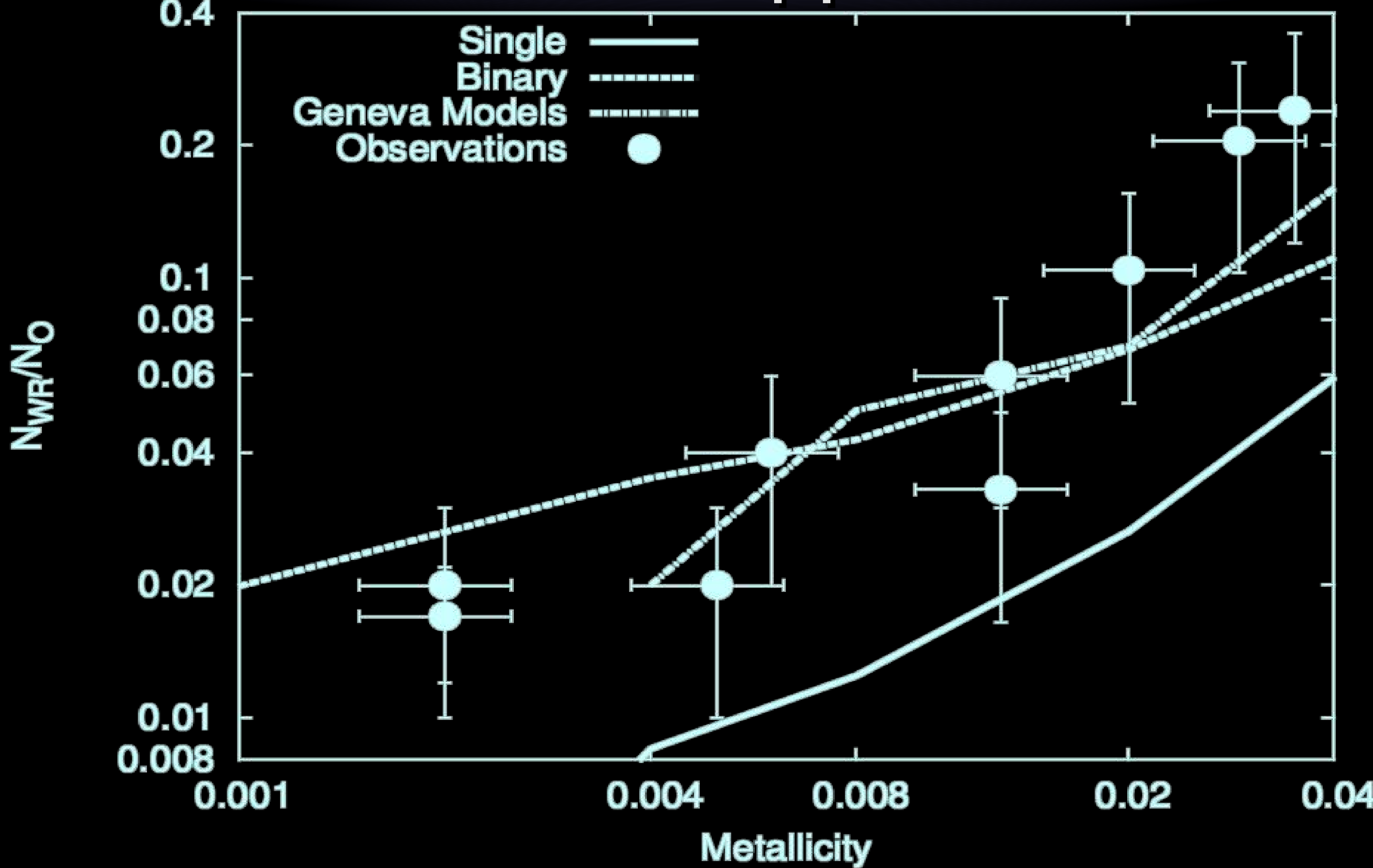
Red Supergiants



Eldridge, Izzard & Tout 2008, A&A

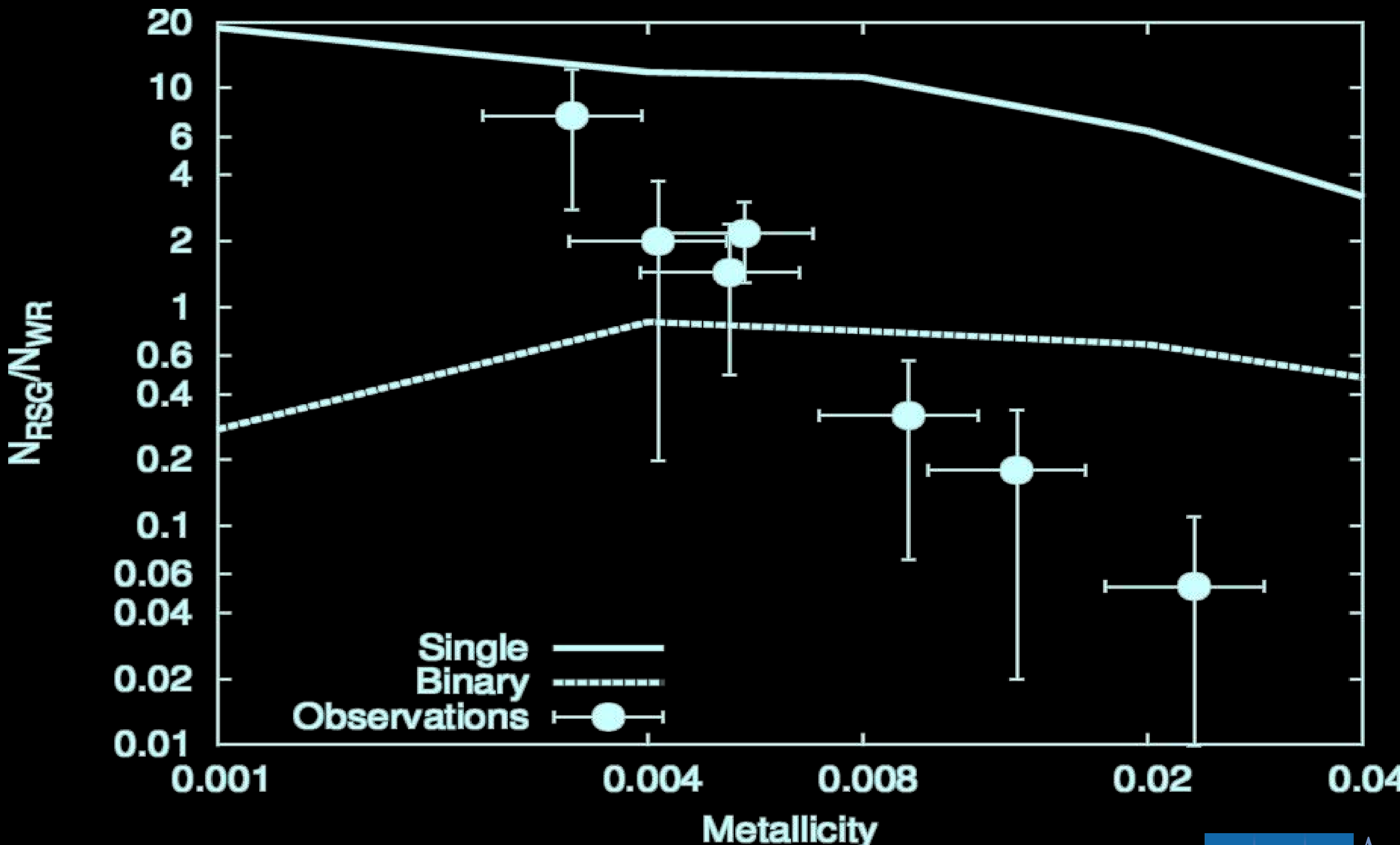
Argelander Institut für Astronomie

Num. of stripped stars



Eldridge, Izzard & Tout 2008, A&A

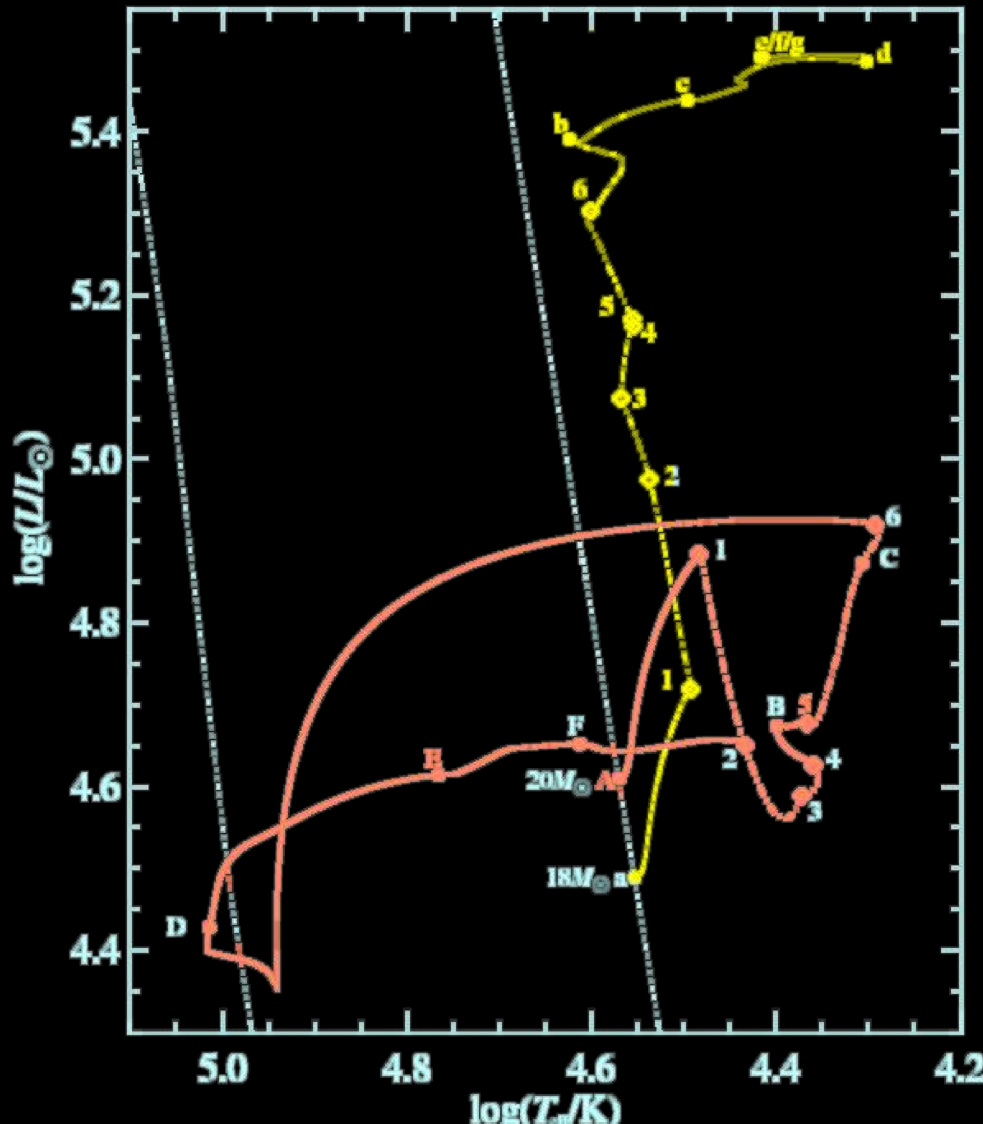
Num. of stripped stars



Eldridge, Izzard & Tout 2008, A&A

Argelander Institut für Astronomie

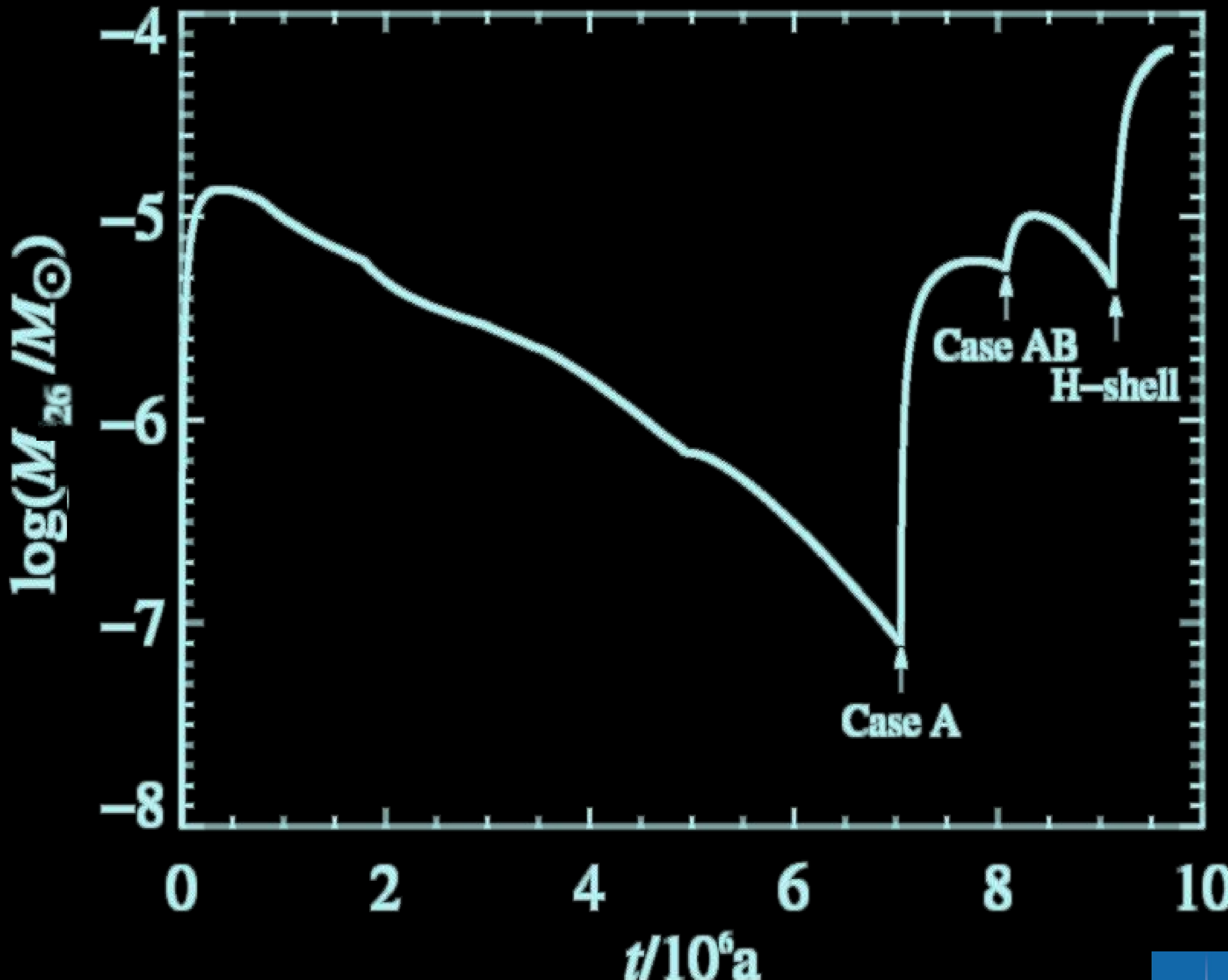
Effects of Accretion: Al26



Langer, Braun, Wellstein 1998

Figure 1: Evolutionary tracks in the HR diagram of the components of a 20+18 $M_\odot$ case A close binary system with a metallicity of $Z_\odot/4$ and an initial period of 2.5 days.

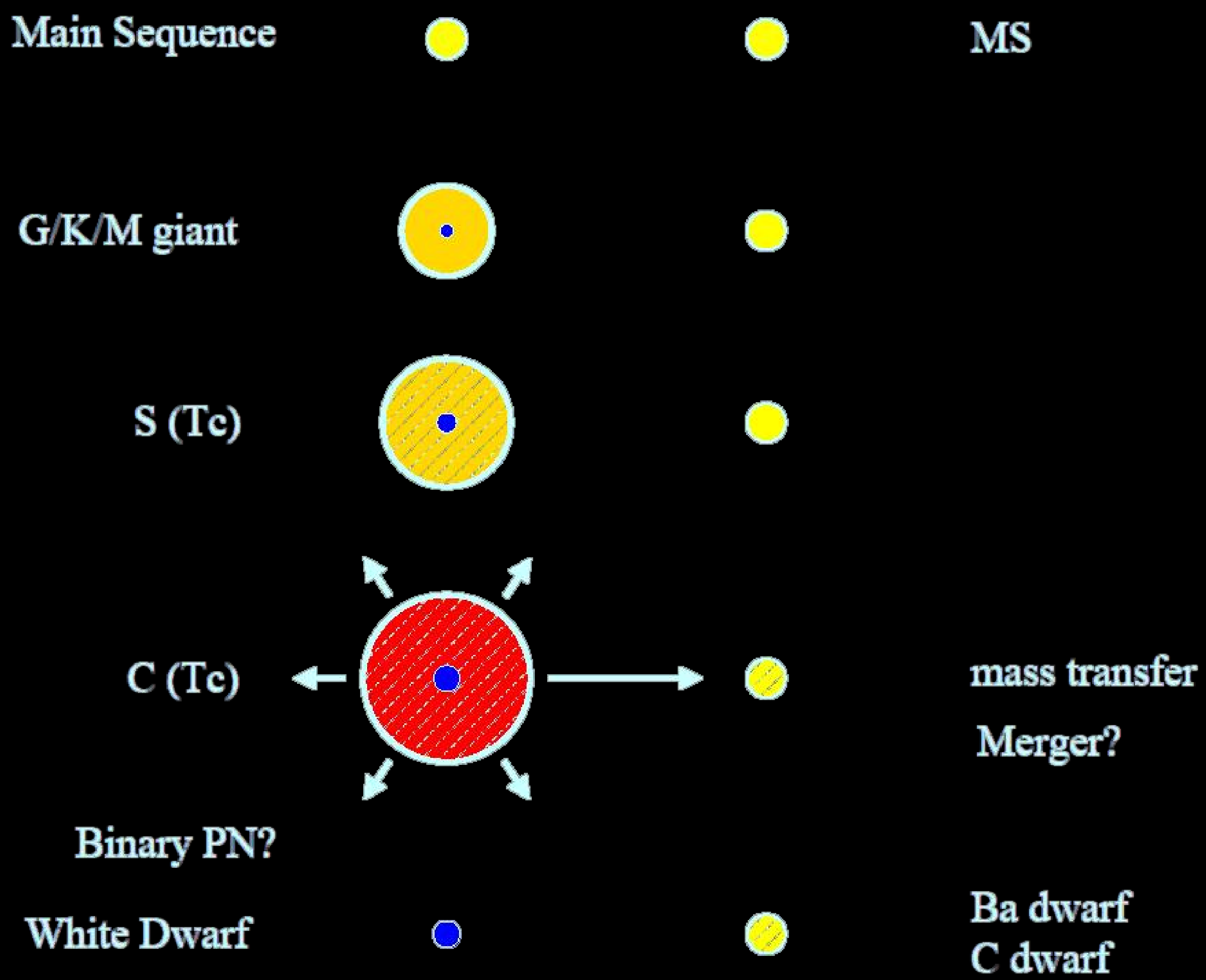
Effects of Accretion: Al26



Langer, Braun, Wellstein 1998

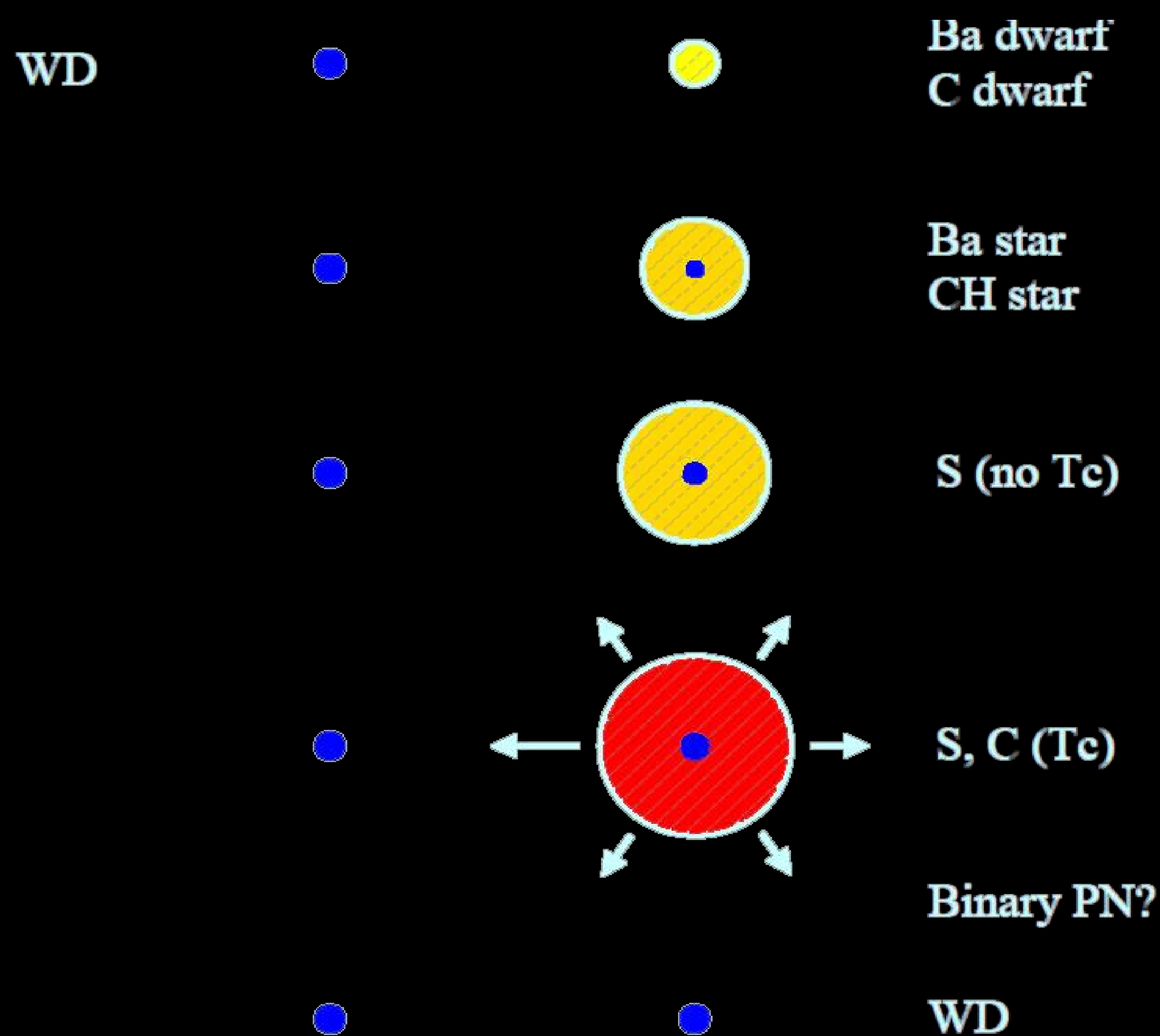
Argelander Institut für Astronomie

Wind mass transfer



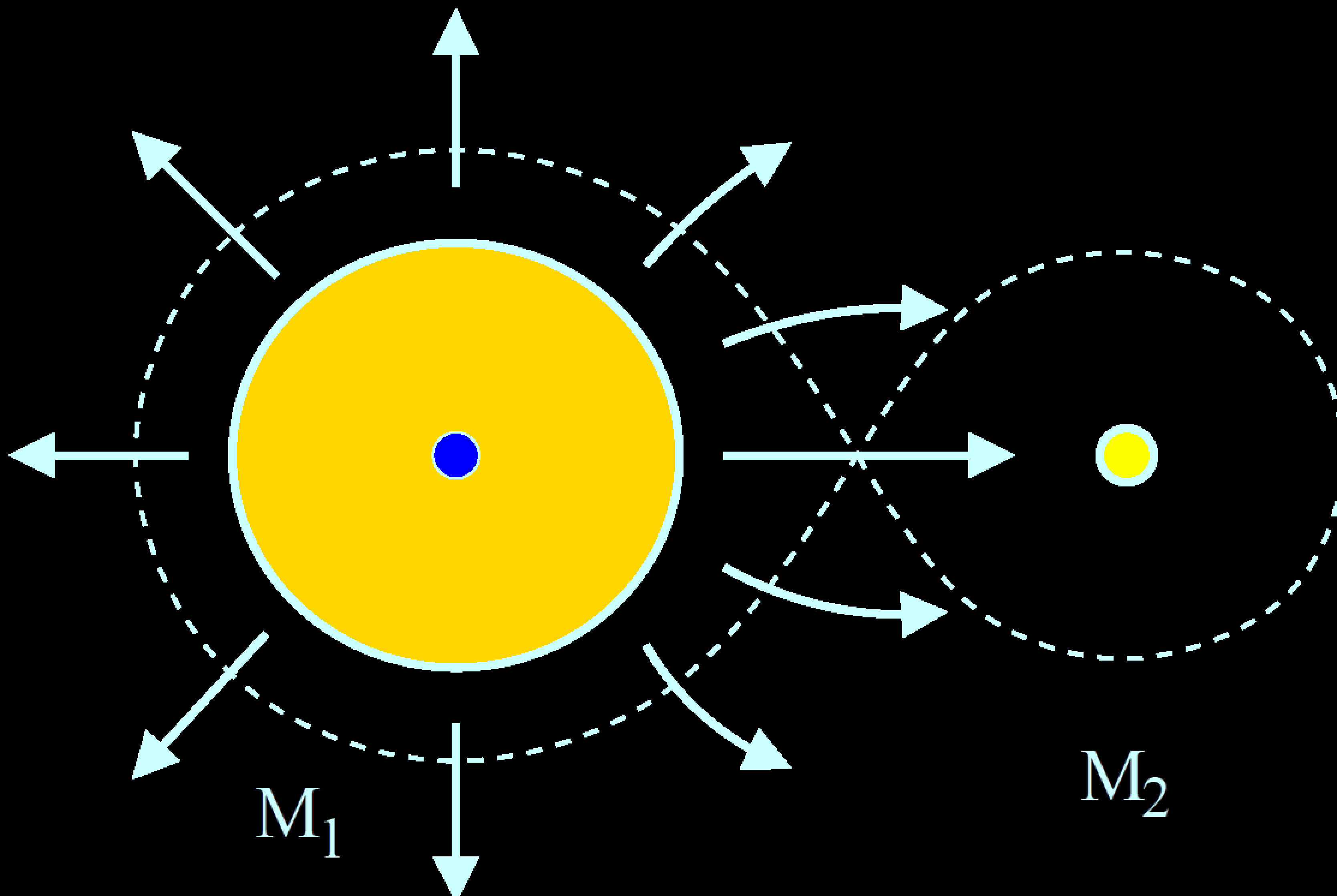
Jorissen 1999 IAUS 191,437/Pols 2005

Wind mass transfer



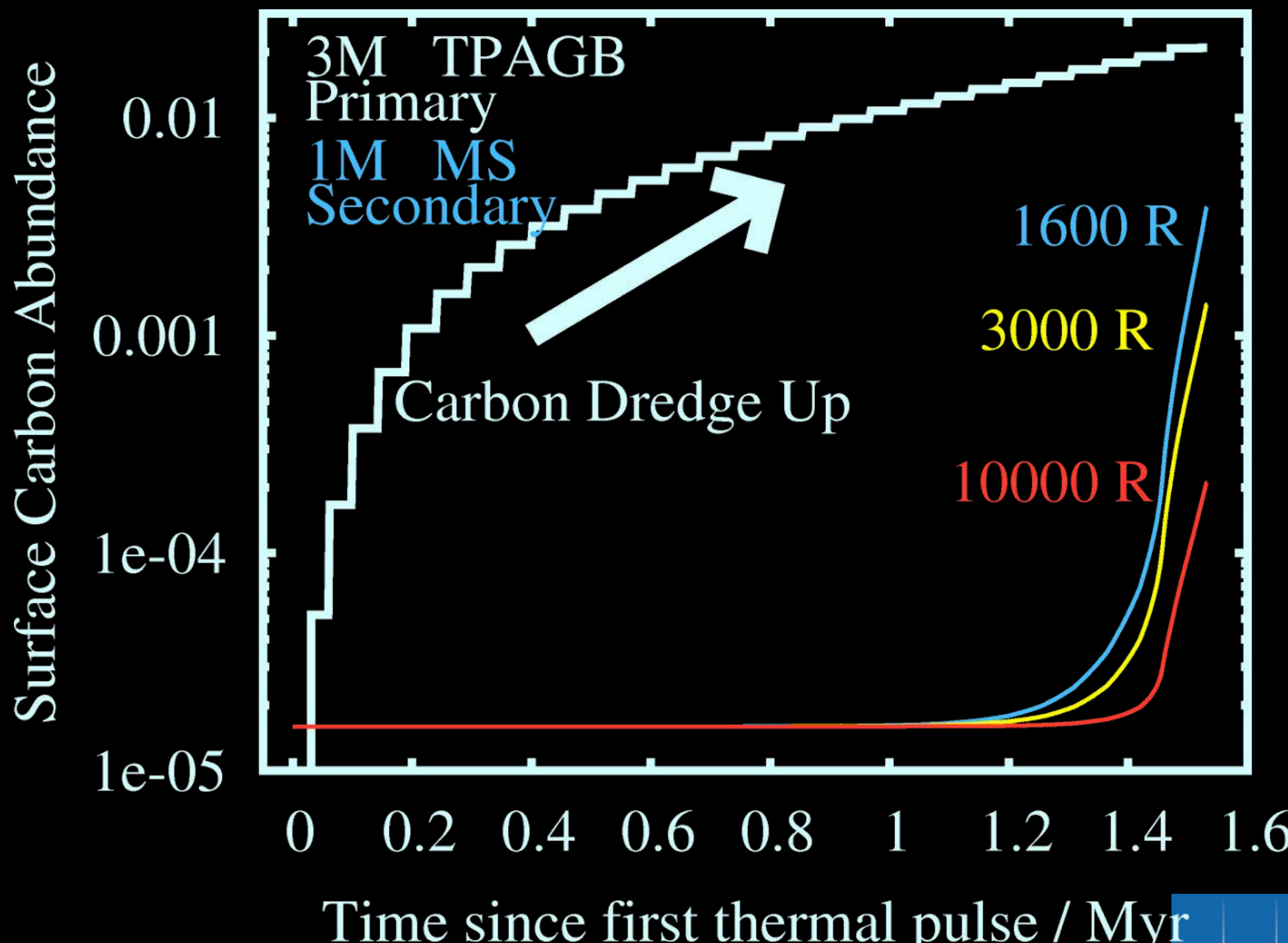
Jorissen 1999 IAUS 191,437

Wind Accretion



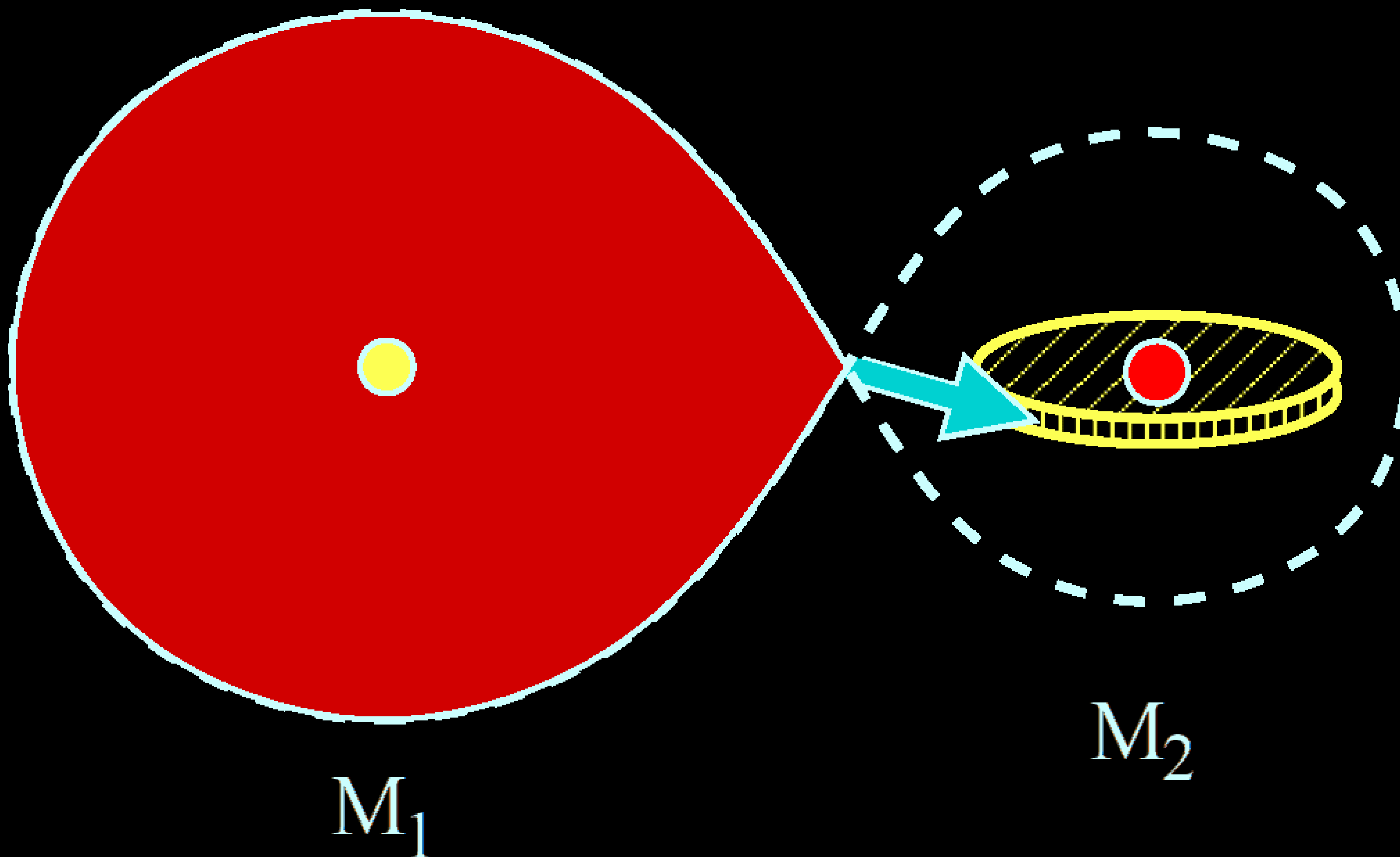
Argelander Institut für Astronomie

Wider systems: barium/CH stars



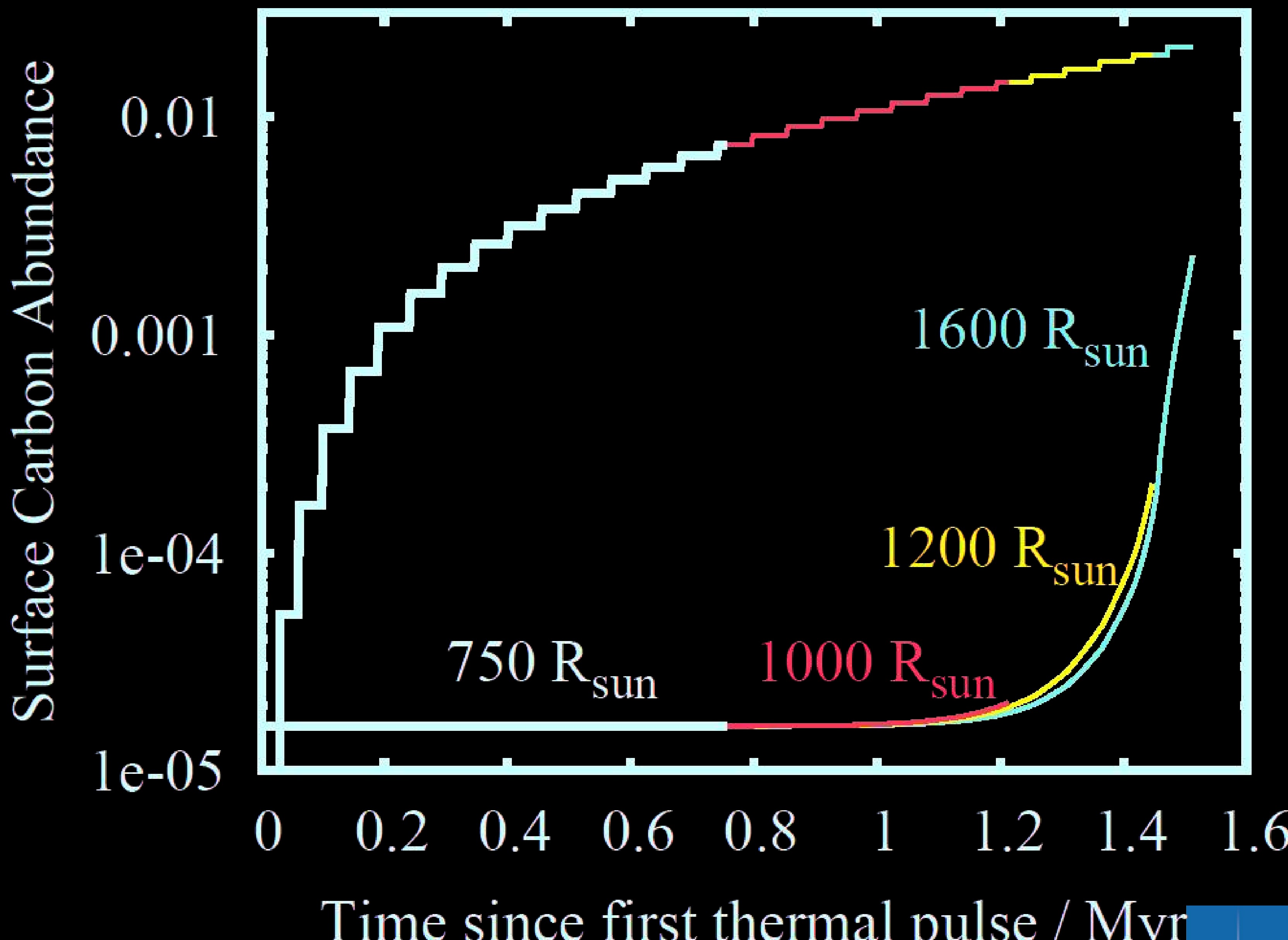
Argelander Institut für Astronomie

Also RLOF if close enough



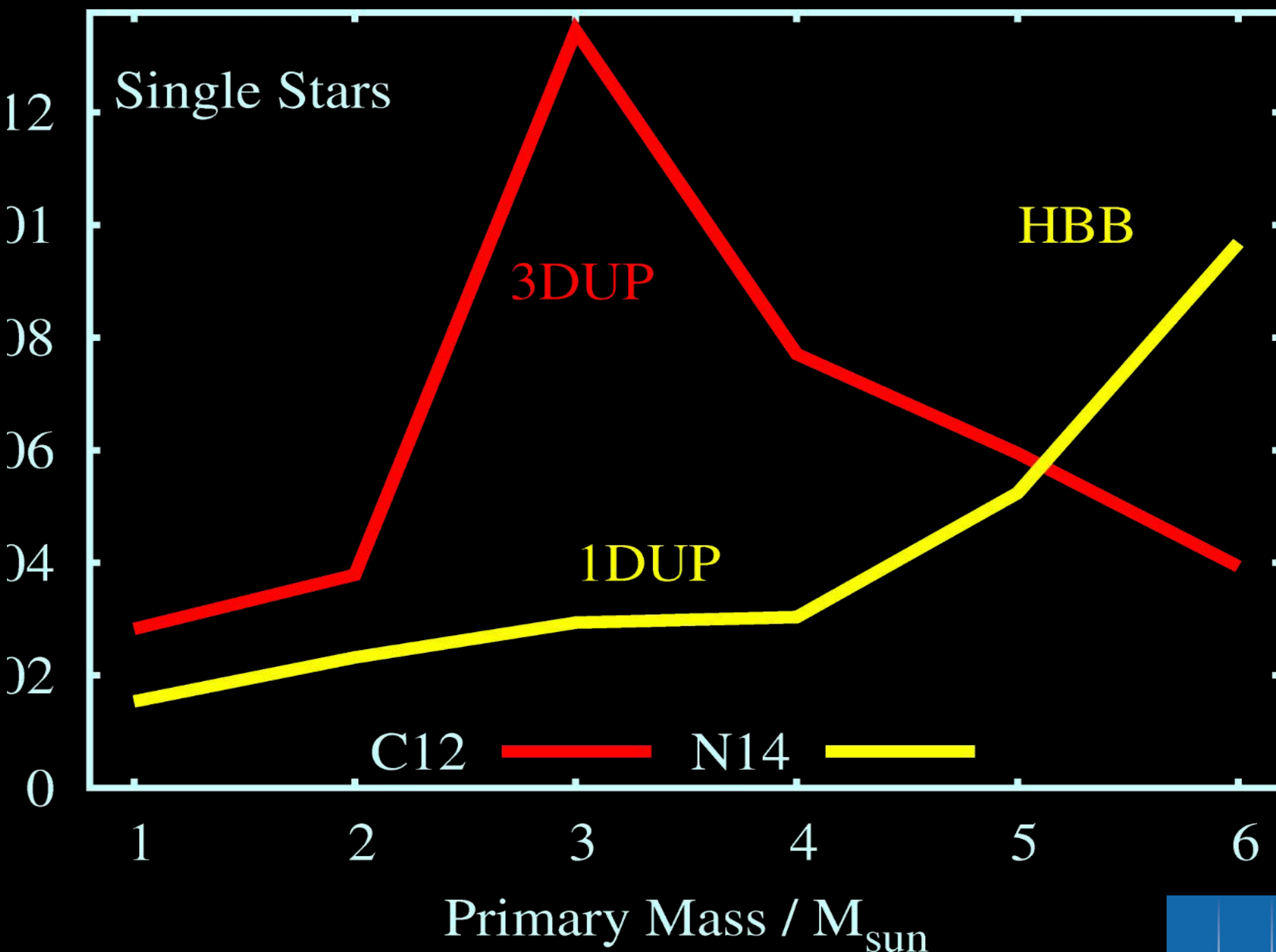
Argelander Institut für Astronomie

Also RLOF if close enough



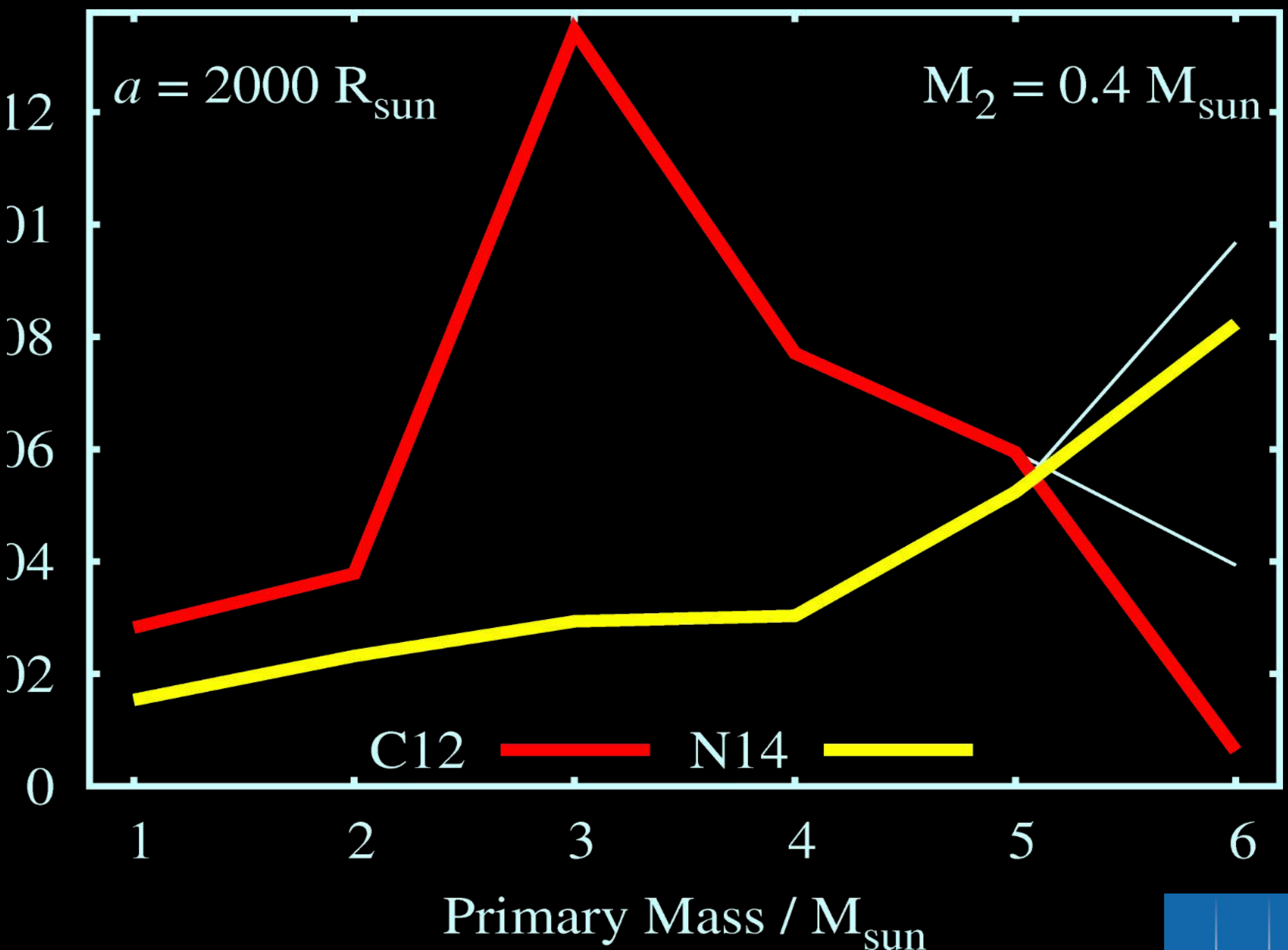
Argelander Institut für Astronomie

Wider systems: barium/CH stars



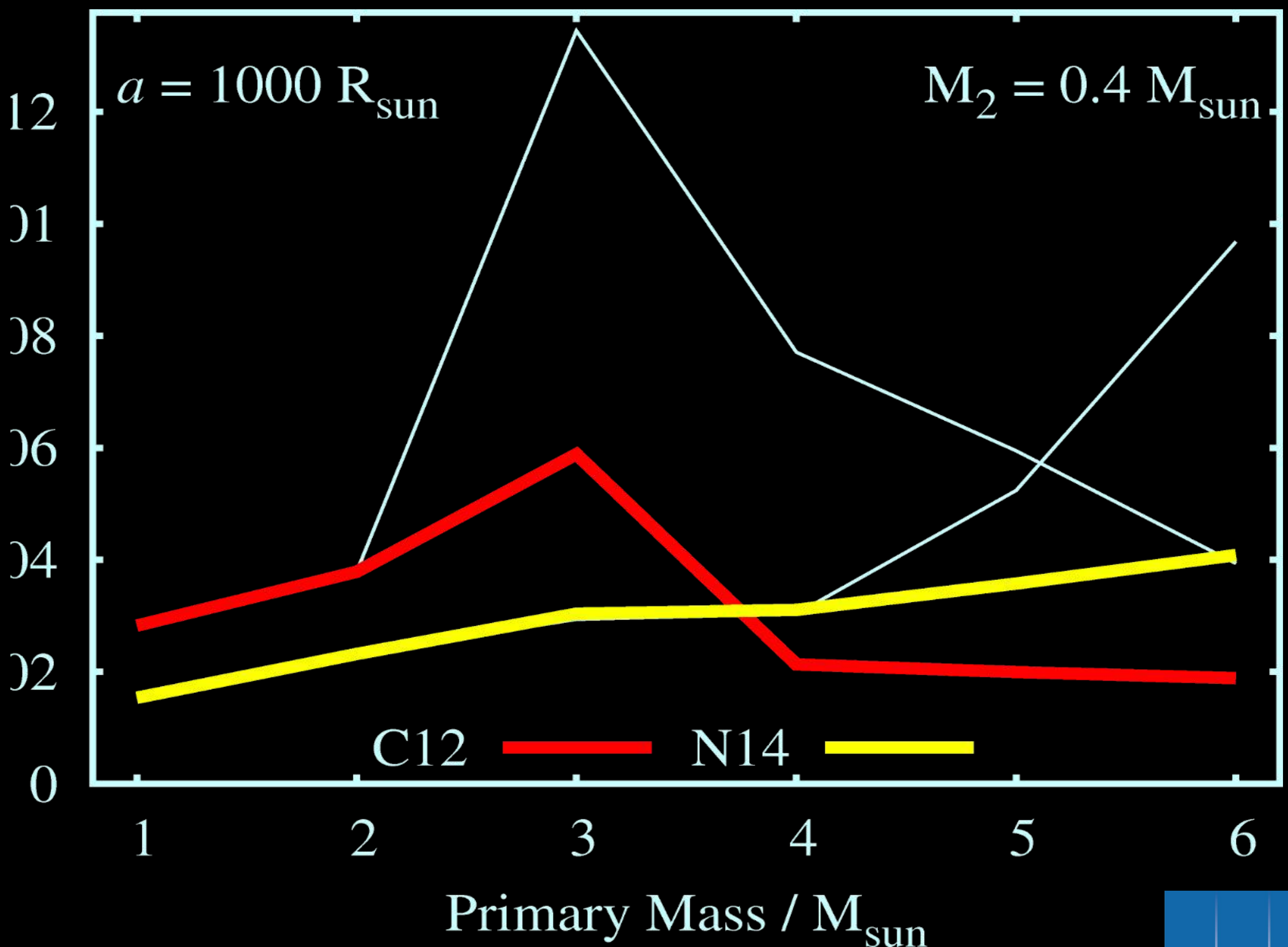
Argelander Institut für Astronomie

Wider systems: barium/CH stars



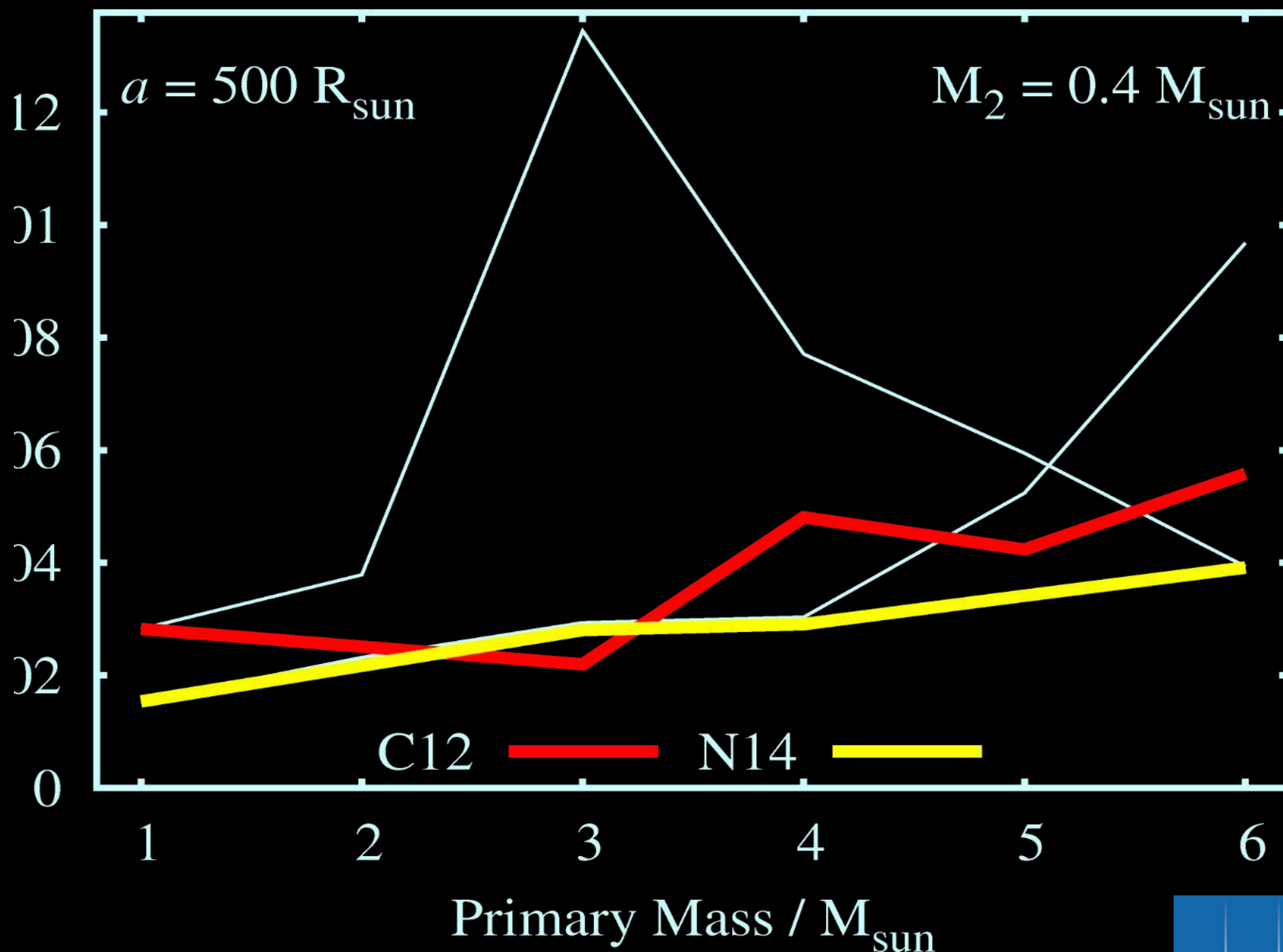
Argelander Institut für Astronomie

Wider systems: barium/CH stars



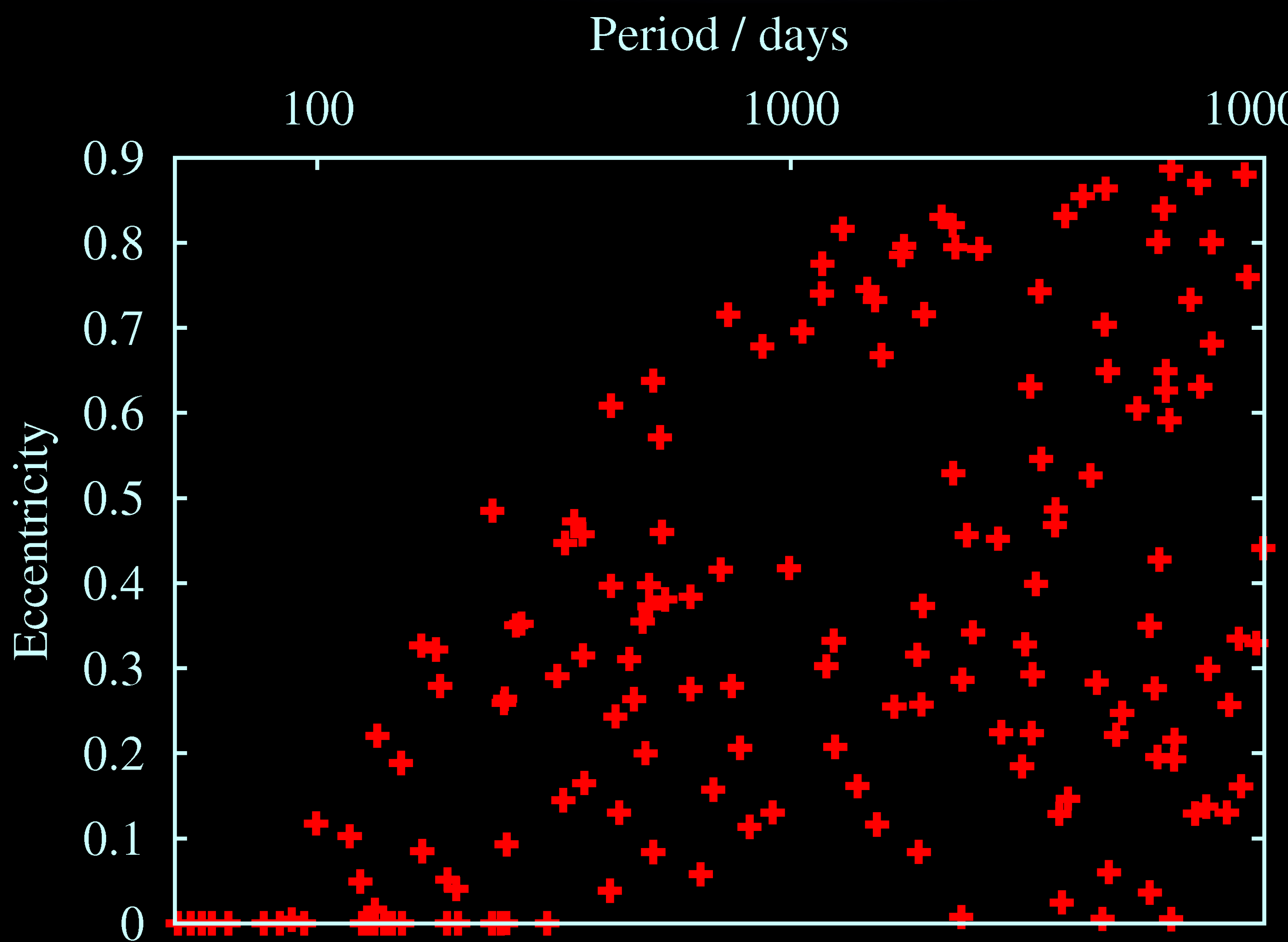
Argelander Institut für Astronomie

Wider systems: barium/CH stars



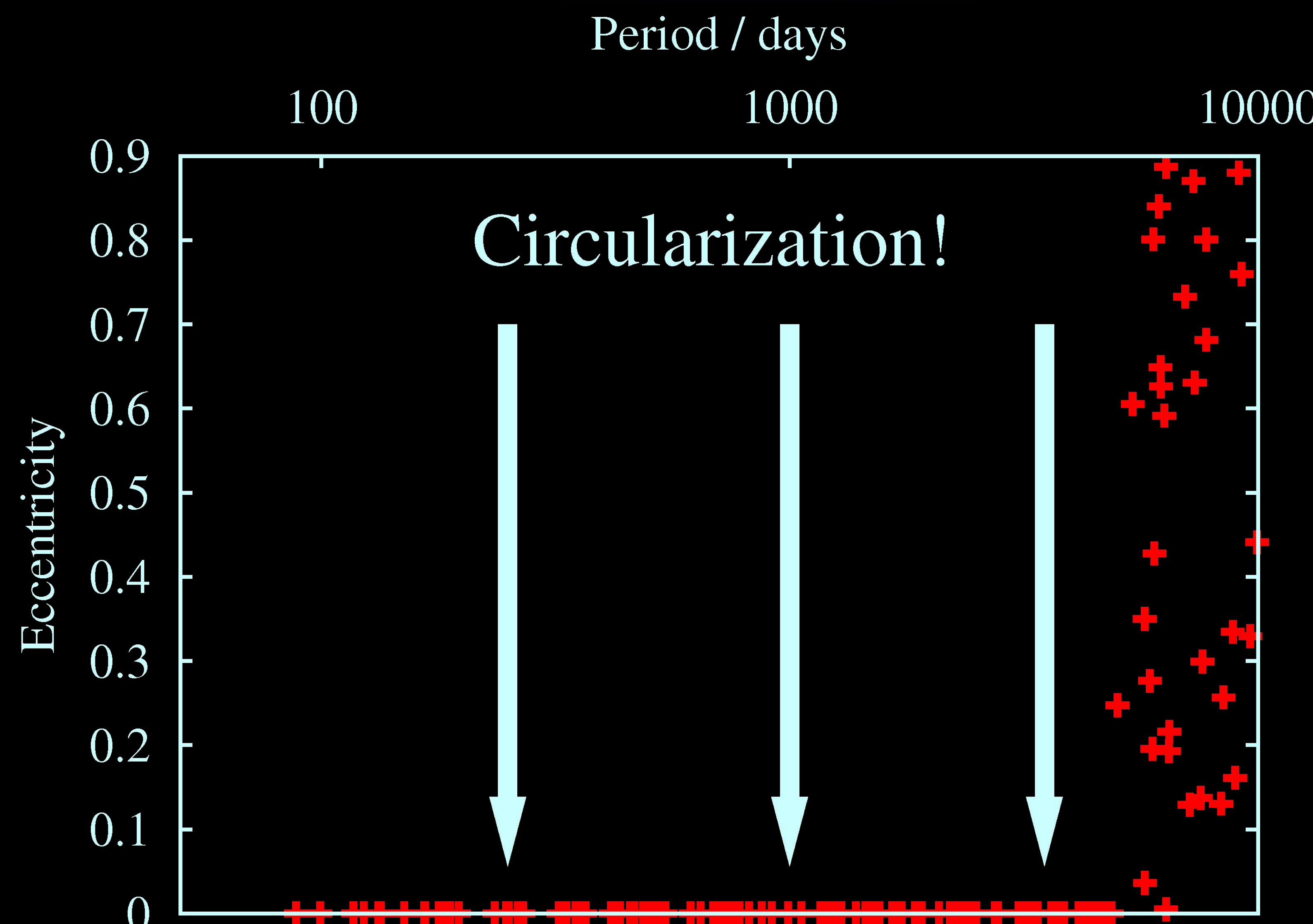
Argelander Institut für Astronomie

Barium Stars and eccentricity



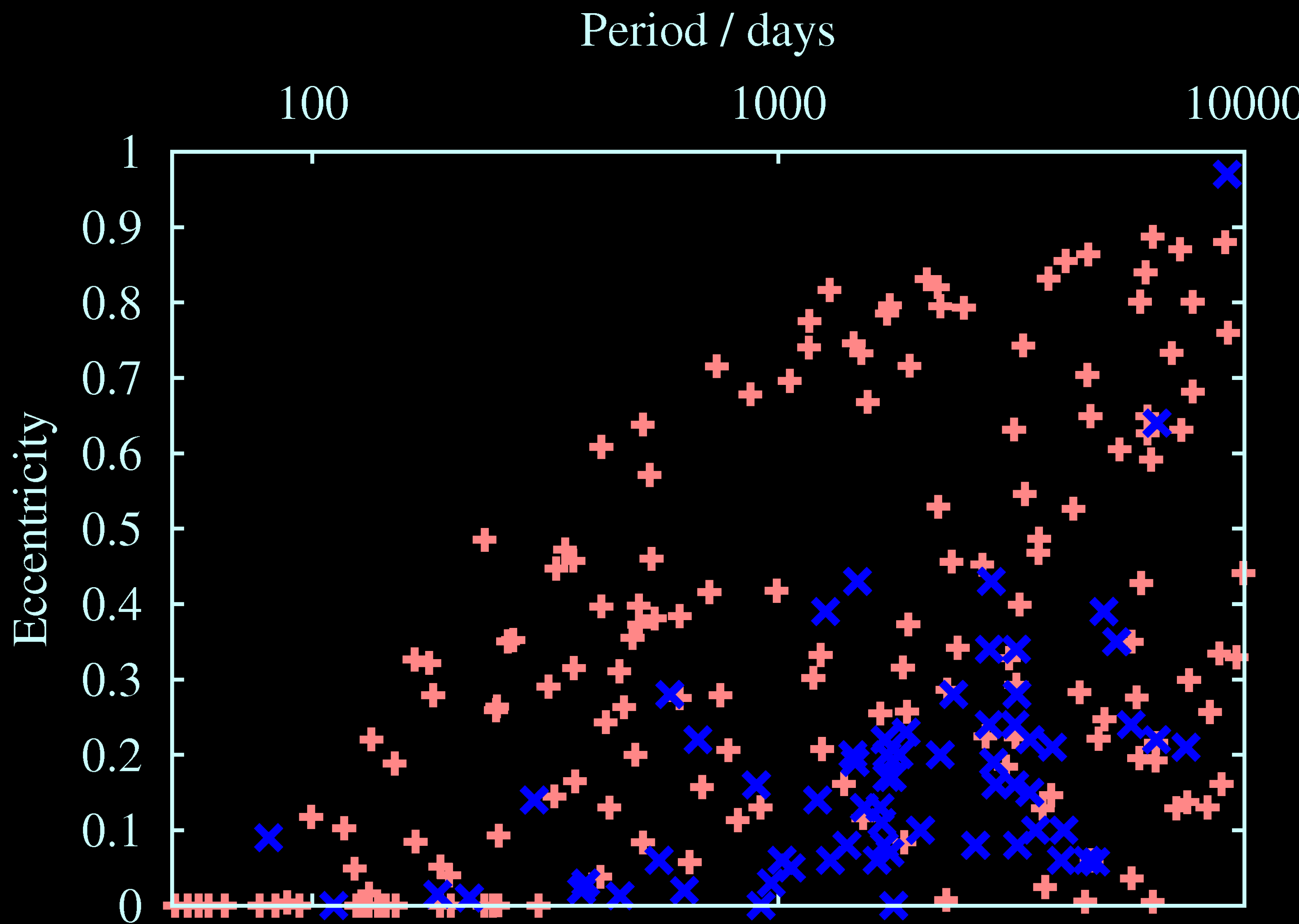
Argelander Institut für Astronomie

Barium Stars and eccentricity



Argelander Institut für Astronomie

Barium Stars and eccentricity



Argelander Institut für Astronomie

Thermohaline mixing

- *What happens to material that accretes?*
- *In general it comes from an evolved star i.e. one in which* $\mathrm{H} \to \mathrm{He}$, $\mathrm{C,N,O} \to \sim 98\%\,\mathrm{N}$ *etc.*
- *i.e. the molecular weight is larger*

$$\rho = n \times m_{\mathrm{H}} \times \mu$$

$$\mu = \frac{4}{6X + Y + 2}$$

- *Unstable to thermohaline instability*
- *See e.g.* https://secure.wikimedia.org/wikipedia/en/wiki/Thermohaline

Argelander Institut für Astronomie

Thermohaline in ink

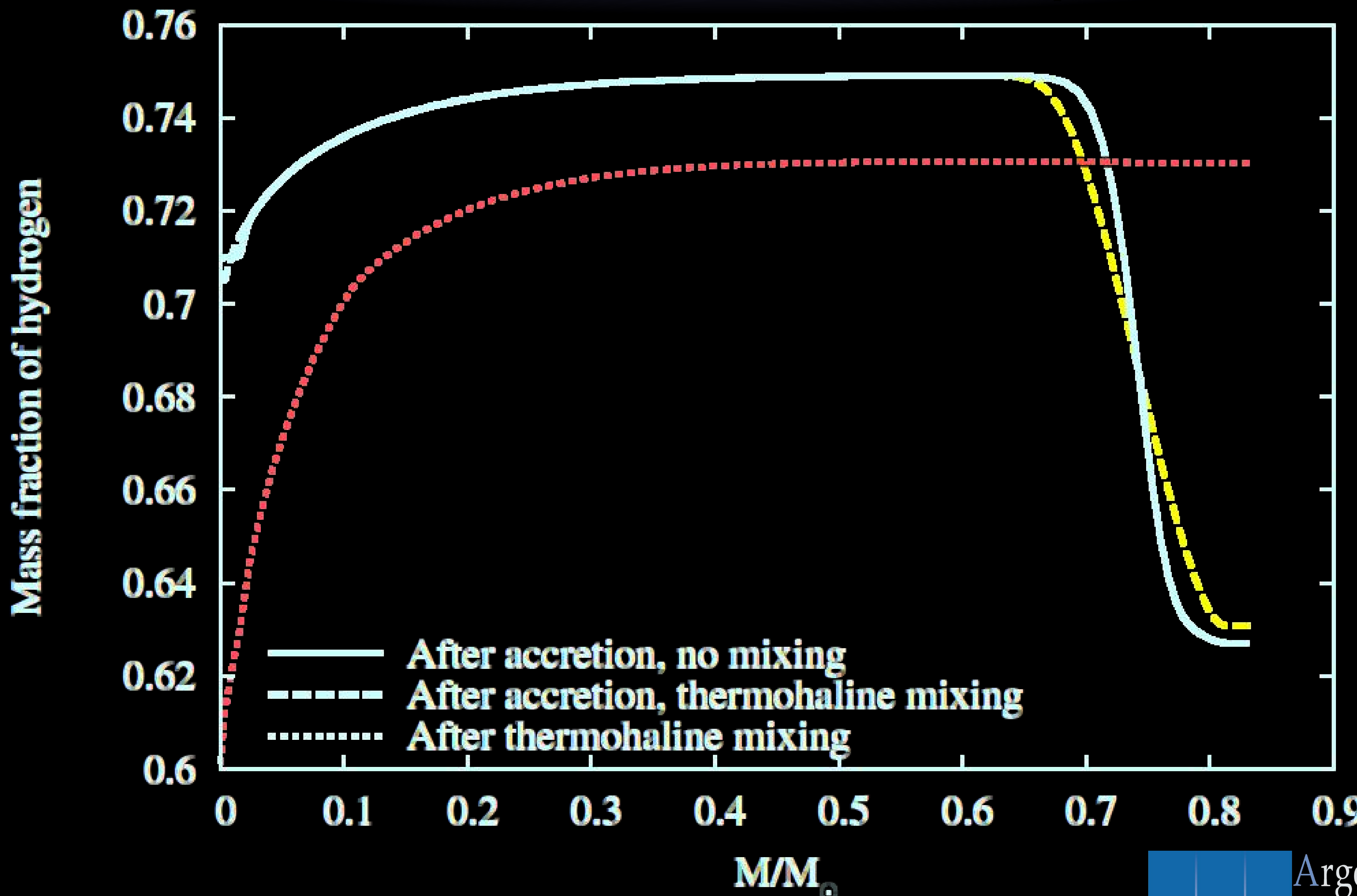
Thermohaline in stars

- Relies on thermal transport so instability occurs on thermal timescale (i.e. fast c.f. τ_{MS})
- Kippenhahn et al. 1998: diffusion model

$$D_{\mathrm{th}} = \frac{16acT^3 H_{\mathrm{P}}}{(\nabla_{\mathrm{ad}} - \nabla)c_{\mathrm{P}}\rho\kappa} \left|\frac{d\mu}{dr}\right| \frac{1}{\mu}$$

Argelander Institut für Astronomie

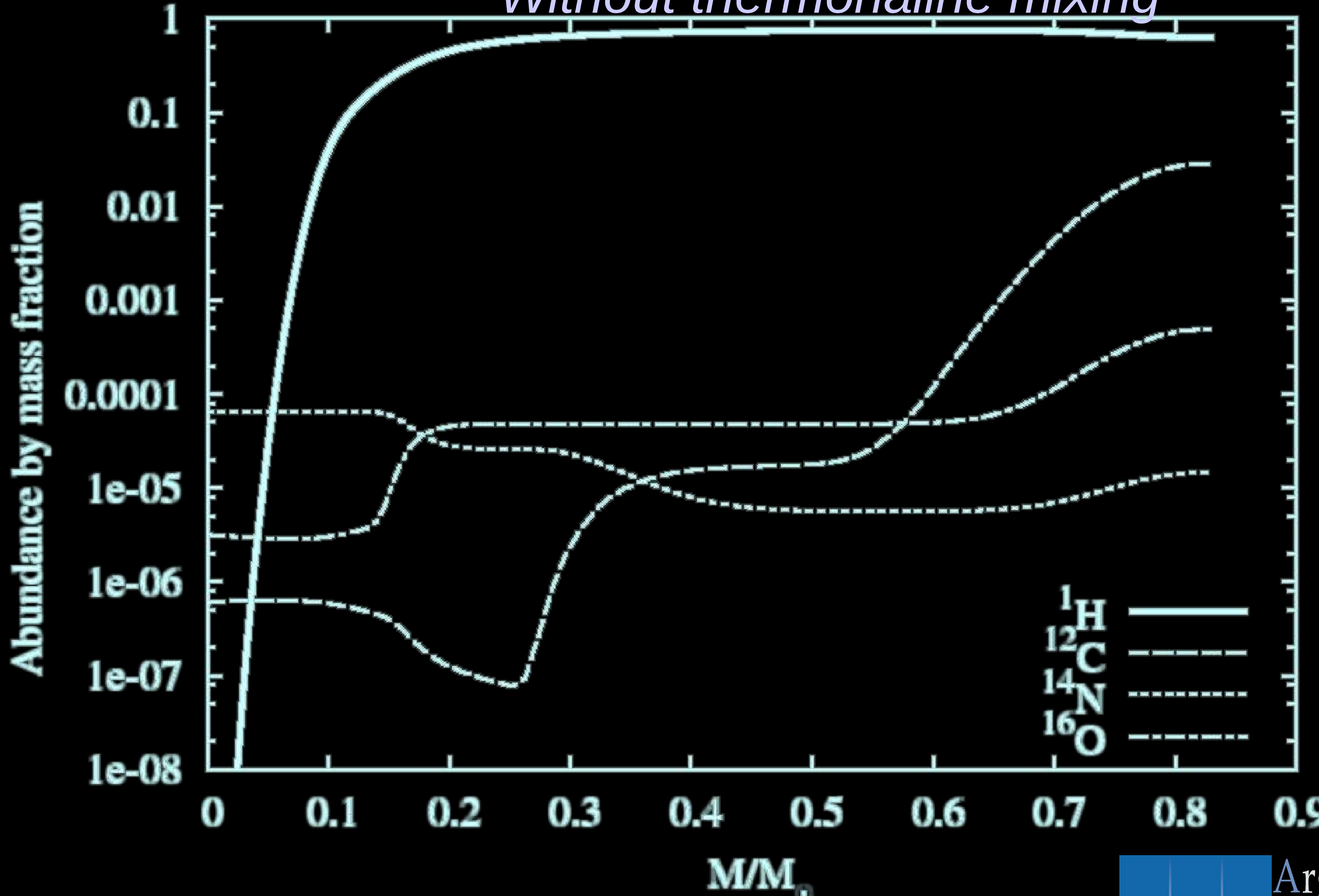
Thermohaline example



Stancliffe et al 2007 A&A 464,L57

CEMP star: [C/Fe]=3.25

Without thermohaline mixing

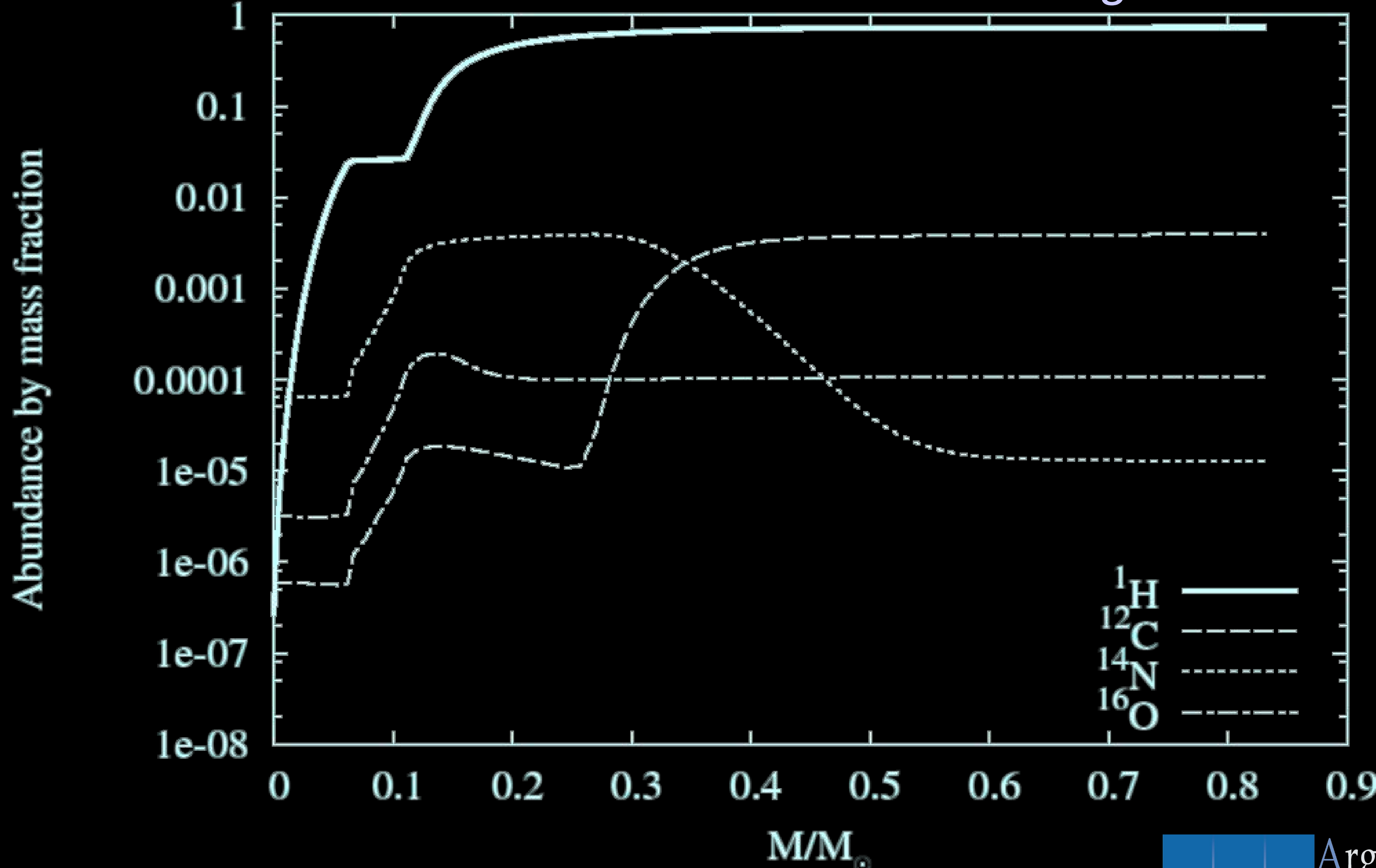


Stancliffe et al 2007 A&A 464,L57

Argelander Institut für Astronomie

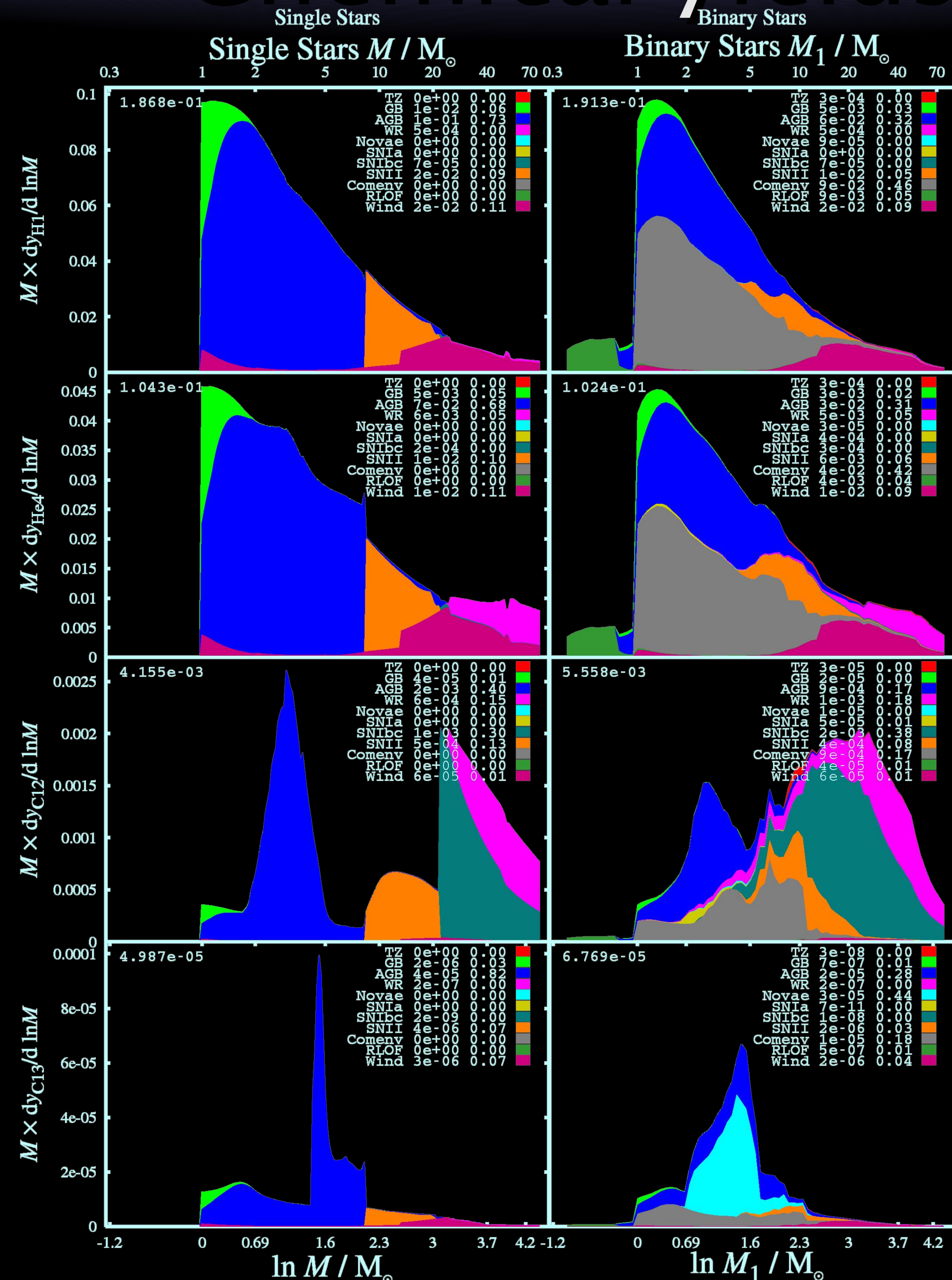
CEMP star: [C/Fe]=2.41

With thermohaline mixing



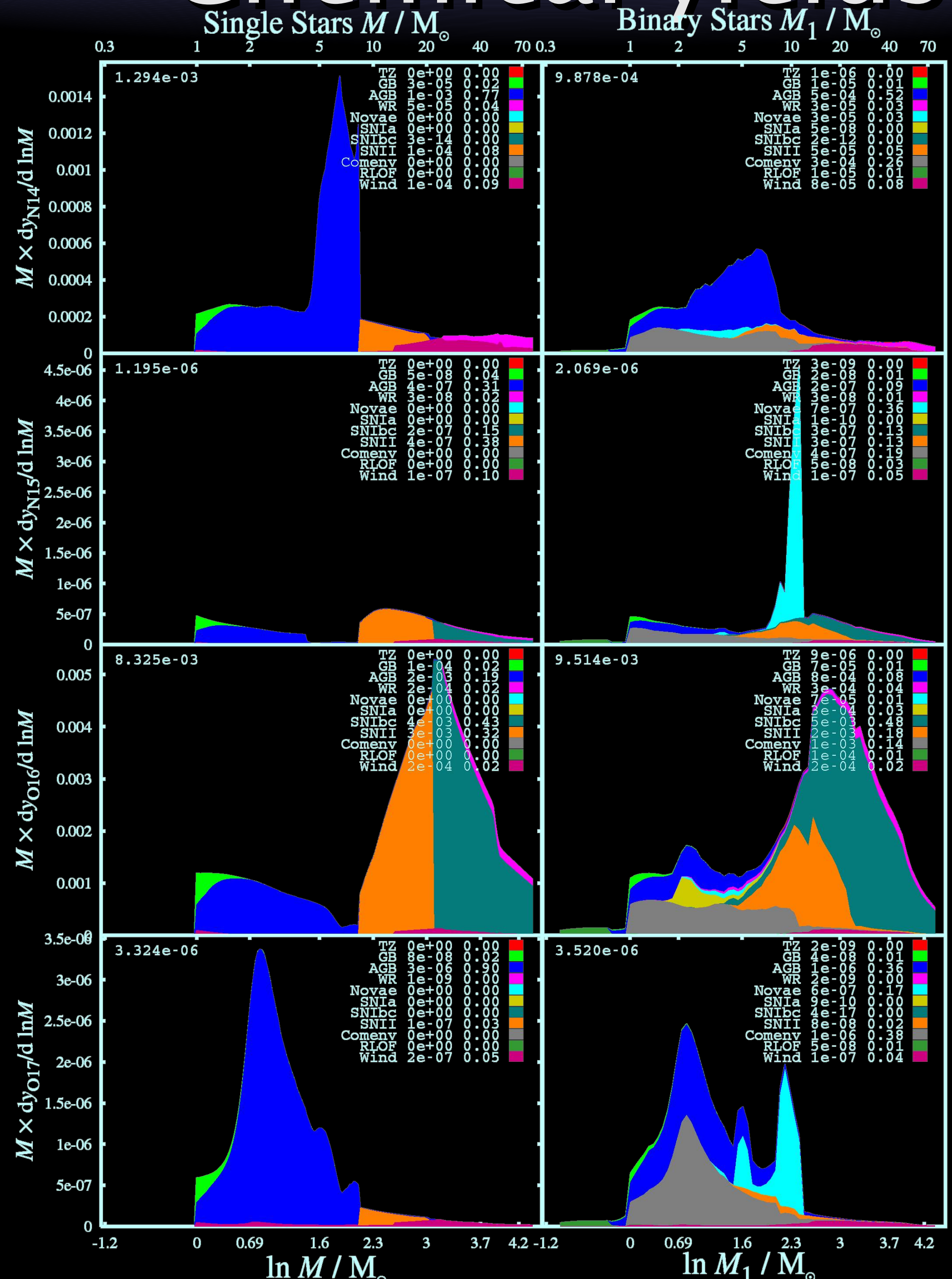
Stancliffe et al 2007 A&A 464,L57

Chemical yields



Argelander Institut für Astronomie

Chemical yields



Argelander Institut für Astronomie

Part 2: Modelling Binary Stars

- Traditional stellar models
- Rapid stellar codes
- Population synthesis
- Parameter space and initial distributions
- Stellar accountancy
- Examples of the power of population synthesis

Traditional stellar modelling

- Stellar structure equations

$$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4} \qquad \frac{dL}{dm} = \epsilon$$

$$\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho} \qquad \frac{dT}{dm} = -\frac{3}{4ac}\frac{\kappa}{T^3}\frac{F}{(4\pi r^2)^2}$$

- Stiff equations
- Solving them is CPU expensive

Discretisation

- Simplest case: mass conservation

$$dm = 4\pi\rho\, r^2 \times dr$$

- A possible discretisation:

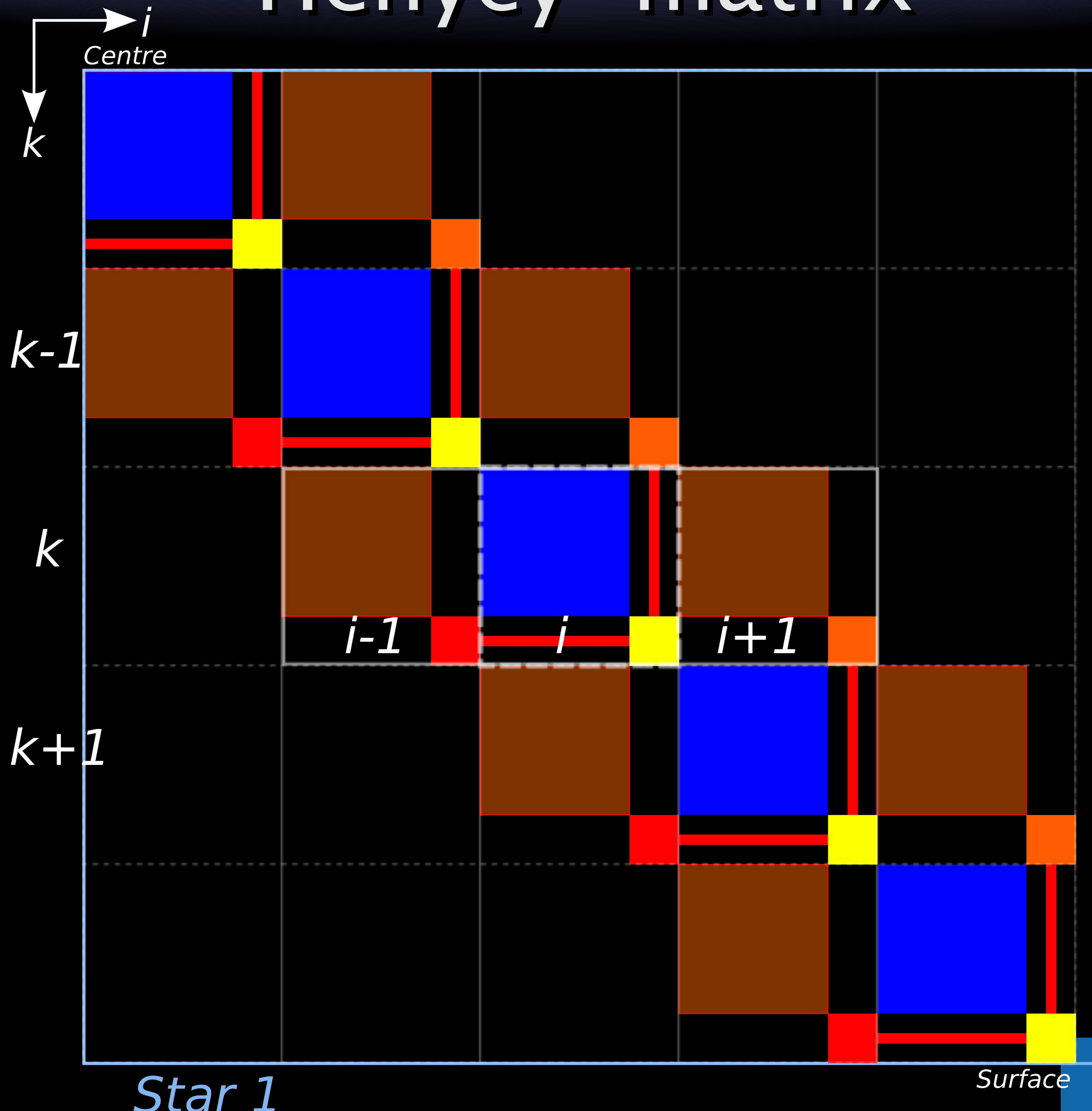
$$M_{i+1} - M_i = \frac{4\pi}{3}\rho_{i+\frac{1}{2}}\left[r_{i+1}^3 - r_i^3\right]$$

- Repeat for other equations/variables

$$T,\ P,\ r \text{ and } \ln f \text{ (degeneracy)}$$

Argelander Institut für Astronomie

"Henyey" matrix



Detailed code runtimes

- Say we want *N* timesteps
- These take Δt per timestep
- Total runtime per star
- $t_{\mathrm{CPU}} \sim N\Delta t$
- $\frac{\tau}{\delta t}\Delta t$
- Typically (for an AGB star):

$$\tau \sim 1\,\mathrm{Myr} \qquad \delta t \sim 1\,\mathrm{year} \qquad \Delta t \sim 10\,\mathrm{s}$$

$$t_{\mathrm{CPU}} \sim 10^7\,\mathrm{s}$$

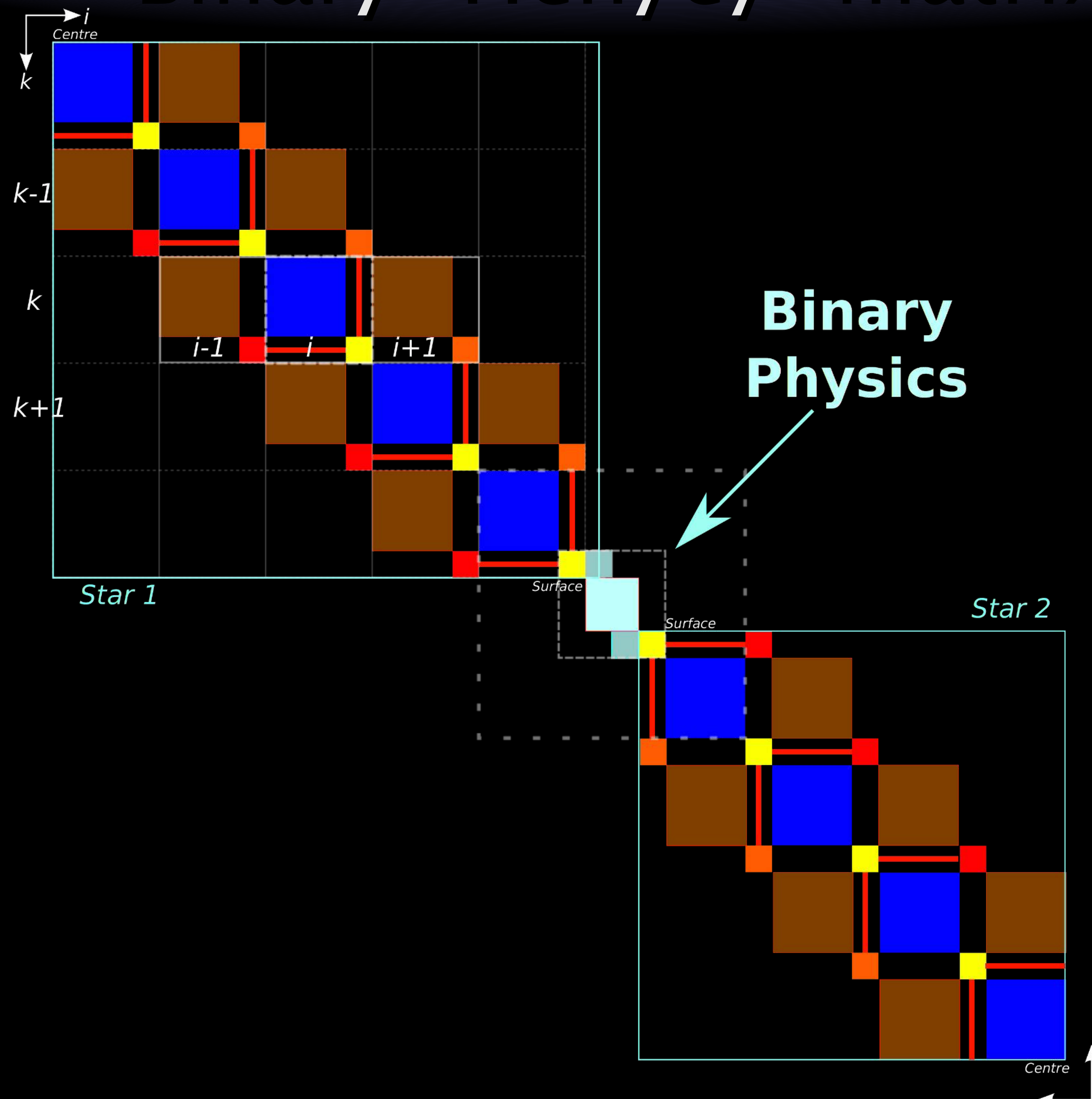
Argelander Institut für Astronomie

Binary Star Equations

- Twice everything in a single star model
- Binary interaction equations (2, 3, more?)
- Runtime *at least*
- $$t_{\mathrm{CPU}}(\mathrm{binary}) \gtrsim 2 \times t_{\mathrm{CPU}}(\mathrm{single})$$
- Will be even more in complicated mass–transfer phases
- Bigger matrix (slower to solve)

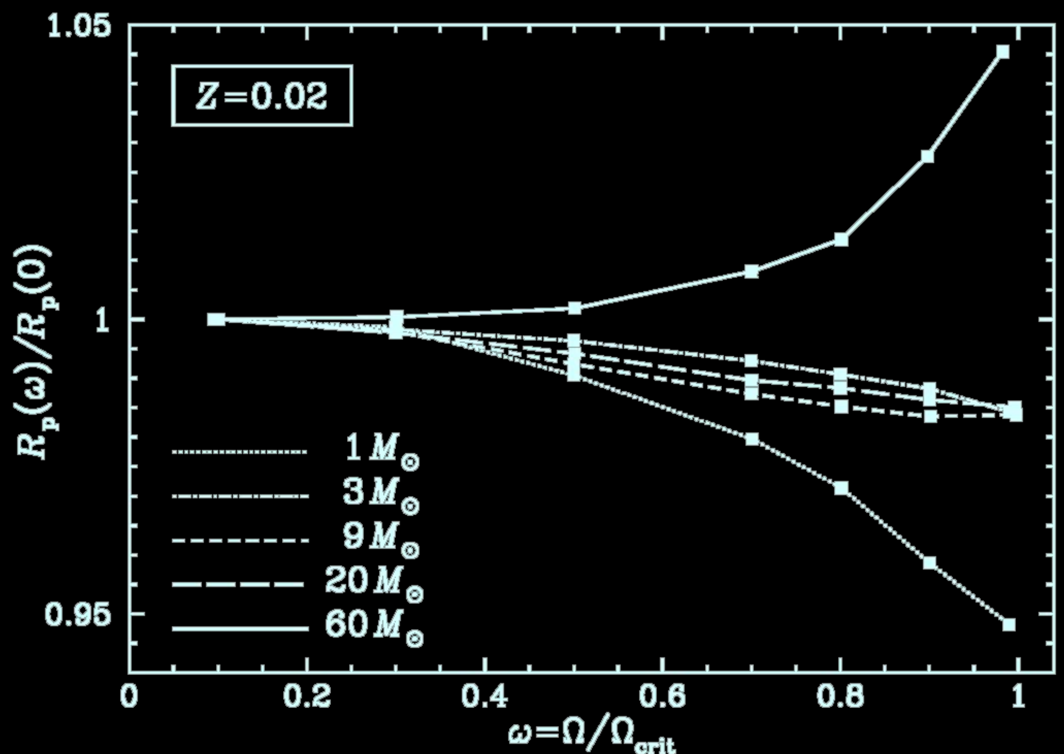
Argelander Institut für Astronomie

Binary "Henyey" matrix



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 $\omega = \Omega/\Omega_{crit}$, normalized to the non-rotating value, for various masses at standard metallicity.

Ekstrom et al 2008 A&A 478, 467

Argelander Institut für Astronomie

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.

Argelander Institut für Astronomie

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 $\tau = t/t_{\rm MS}$

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

- Then

$$\log_{10} L = \log_{10} L_0 + \alpha\tau_{\rm MS} + \beta\tau_{\rm MS}^2$$
$$\log_{10} R = \log_{10} R_0 + \alpha'\tau_{\rm MS} + \beta'\tau_{\rm MS} + \gamma'\tau_{\rm MS}^3$$

Fitting formulae

$$\alpha = \begin{cases} 0.2594 + 0.1348 \log_{10} M & M \leq 1.334 \\ 0.09209 + 0.05934 \log_{10} M & M > 1.334 \end{cases}$$

$$\beta = \begin{cases} 0.144 - 0.833 \log_{10} M & M \leq 1.334 \\ 0.3756 \log_{10} M - 0.1744 (\log_{10} M)^2 & M > 1.334 \end{cases}$$

$$\alpha' = \begin{cases} 0 & M \leq 1.334 \\ 0.1509 + 0.1709 \log_{10} M & M > 1.334 \end{cases}$$

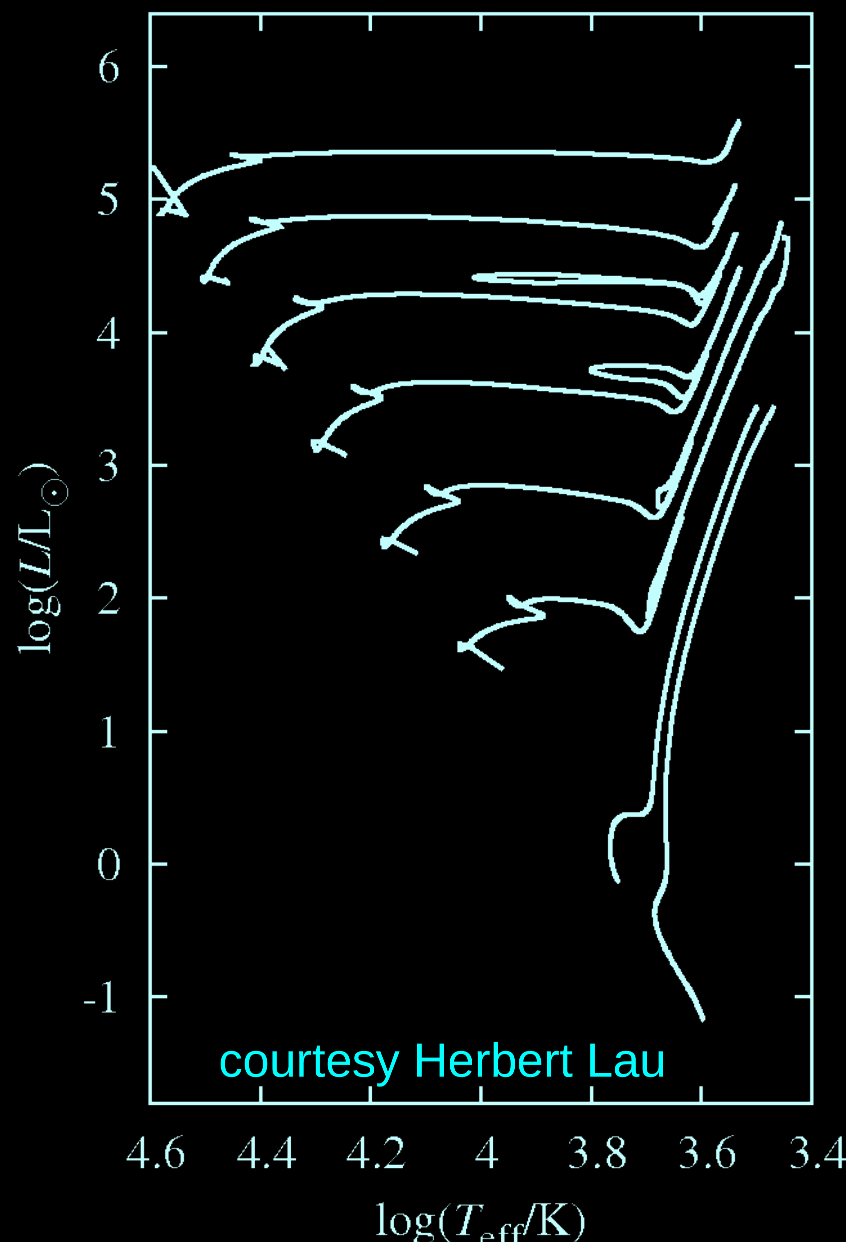
$$\beta' = \begin{cases} 0.2226 \log_{10} M & M \leq 1.334 \\ -0.4805 \log_{10} M & M > 1.334 \end{cases}$$

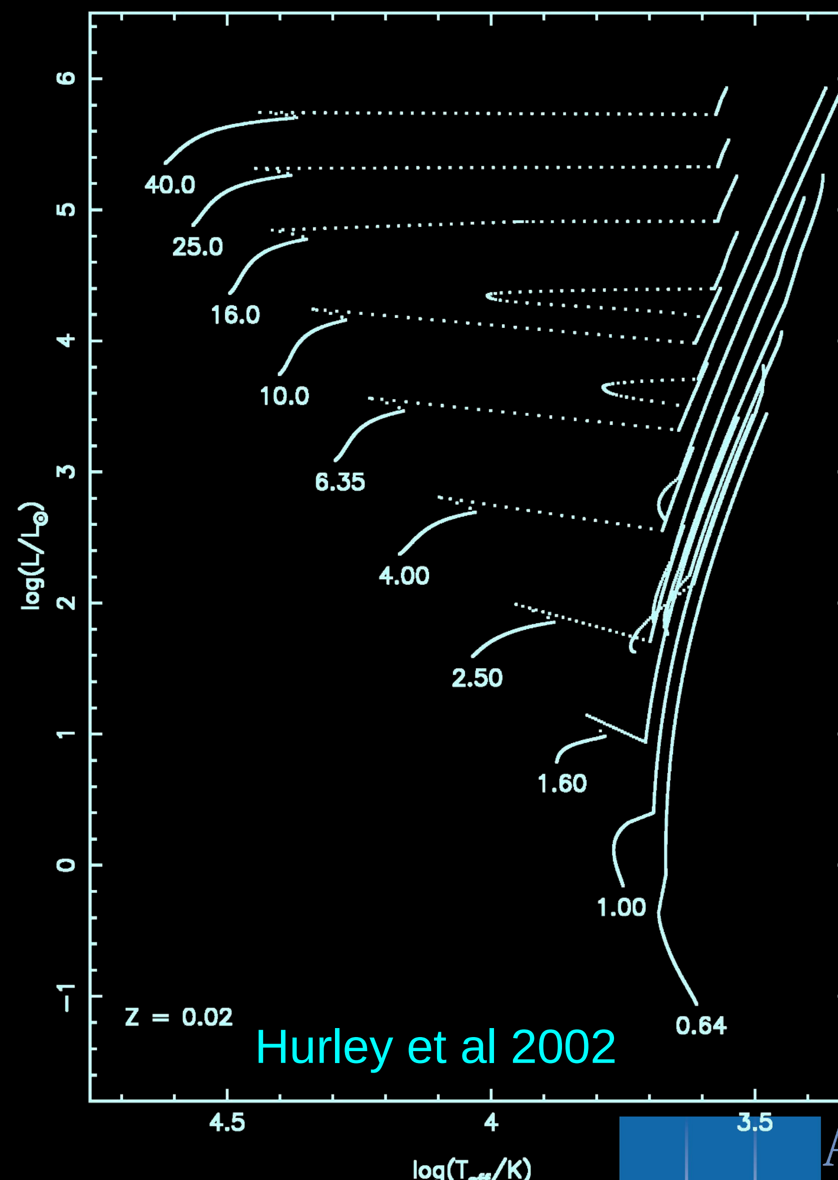
$$\gamma' = \begin{cases} 0.1151 & M \leq 1.334 \\ 0.5083 \log_{10} M & M > 1.334 \end{cases} .$$

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

Argelander Institut für Astronomie

Real vs Synthetic HRD





Pros and Cons

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

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

Argelander Institut für Astronomie

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)

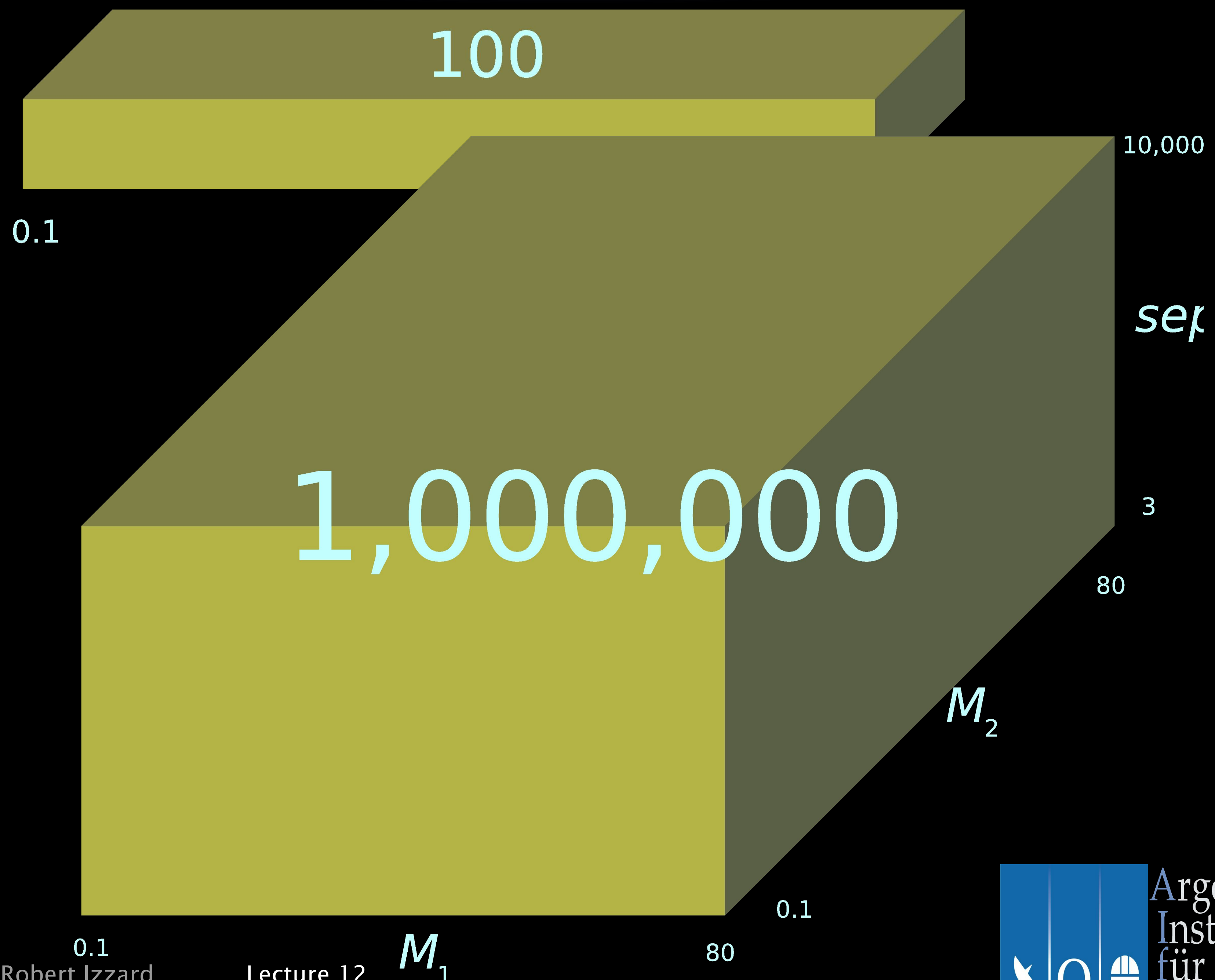
Argelander Institut für Astronomie

The Parameter Space Problem

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

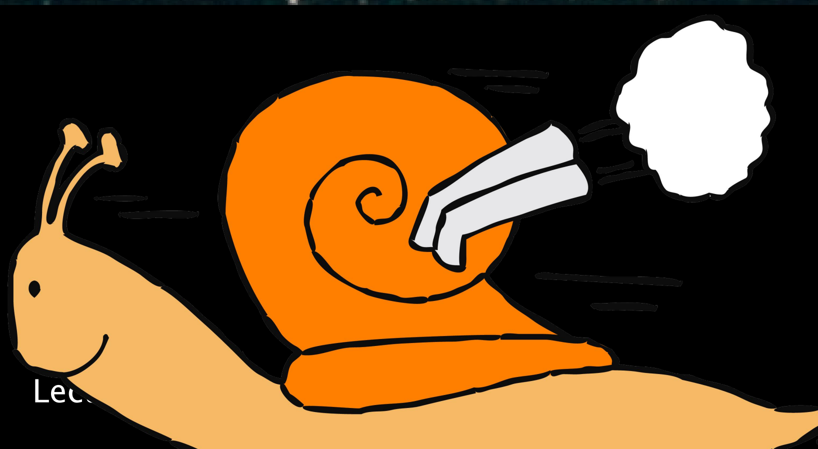
Argelander Institut für Astronomie

Parameter Spaces



Argelander Institut für Astronomie

Popsyn + rapid code



Discretising Parameter Space

- *Single Stars*

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

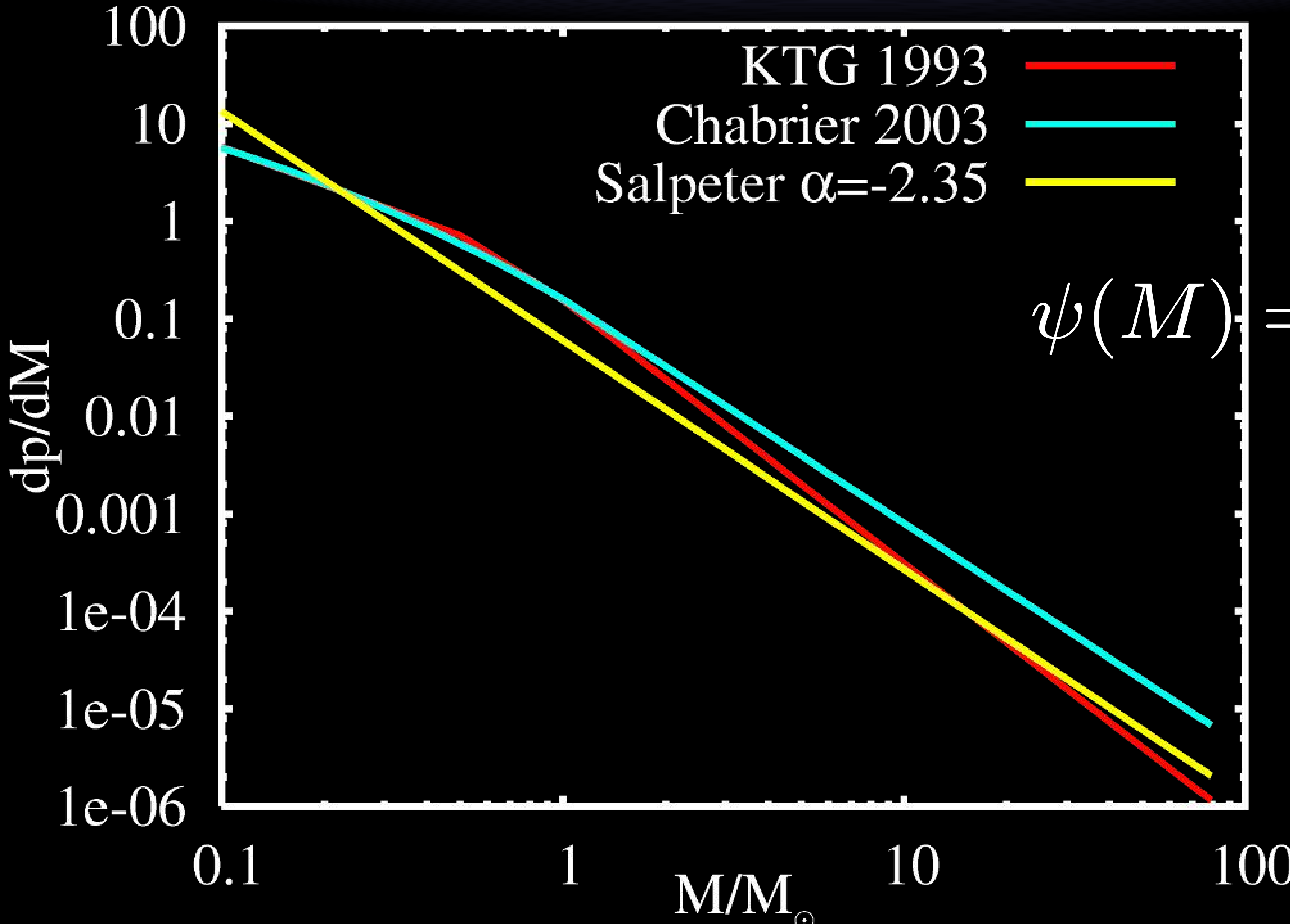
- *Each star has a probability of existence*

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

- *Where* ψ *is the initial mass function*

$$\Sigma_i \delta p_i = 1$$

IMF



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

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

Argelander Institut für Astronomie

Discretising Parameter Space

- *Binary Stars*

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

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

- *Each star has a probability of existence*

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

- *Where* Ψ *is the initial distribution function*

Argelander Institut für Astronomie

Initial Distribution Function

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

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

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

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

$$\Sigma_i \delta p_i = 1$$

Stellar accounts

- Define

$$\delta(\text{phase}) = 1 \quad \text{during the phase,}$$
$$= 0 \quad \text{otherwise}\,.$$

- Time a star spends in a phase of interest

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

Argelander Institut für Astronomie

Stellar accounts

- The number of stars in the phase is

$$\text{count} = \sum_i S\delta p_i \Delta t_i$$

$$= \sum_i S\delta p_i \sum_{t_{\min}}^{t_{\max}} \delta(\text{phase})_i \, \delta t$$

where S is the star formation rate

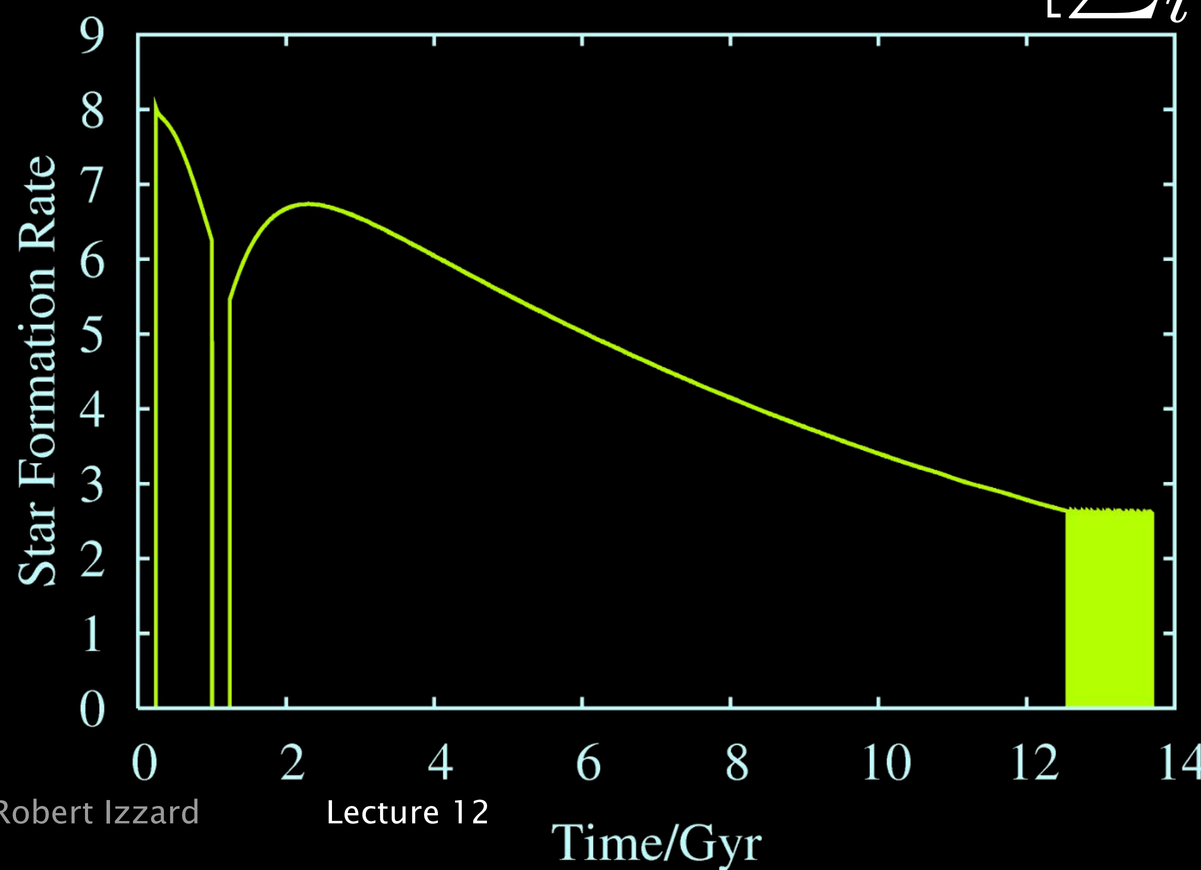
- In general we have to convolve a birth function with a star formation rate function

-

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

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

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

Argelander Institut für Astronomie

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)

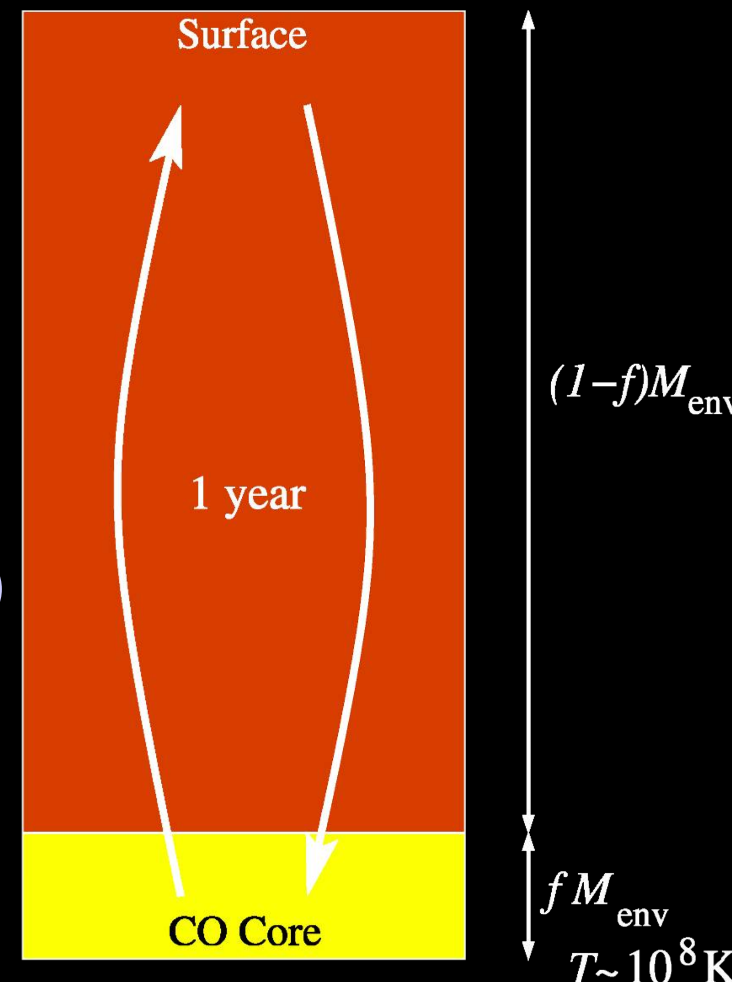
A rapid code: *binary_c*

- 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**

Argelander Institut für Astronomie

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



Argelander Institut für Astronomie

Some examples of binary_c

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

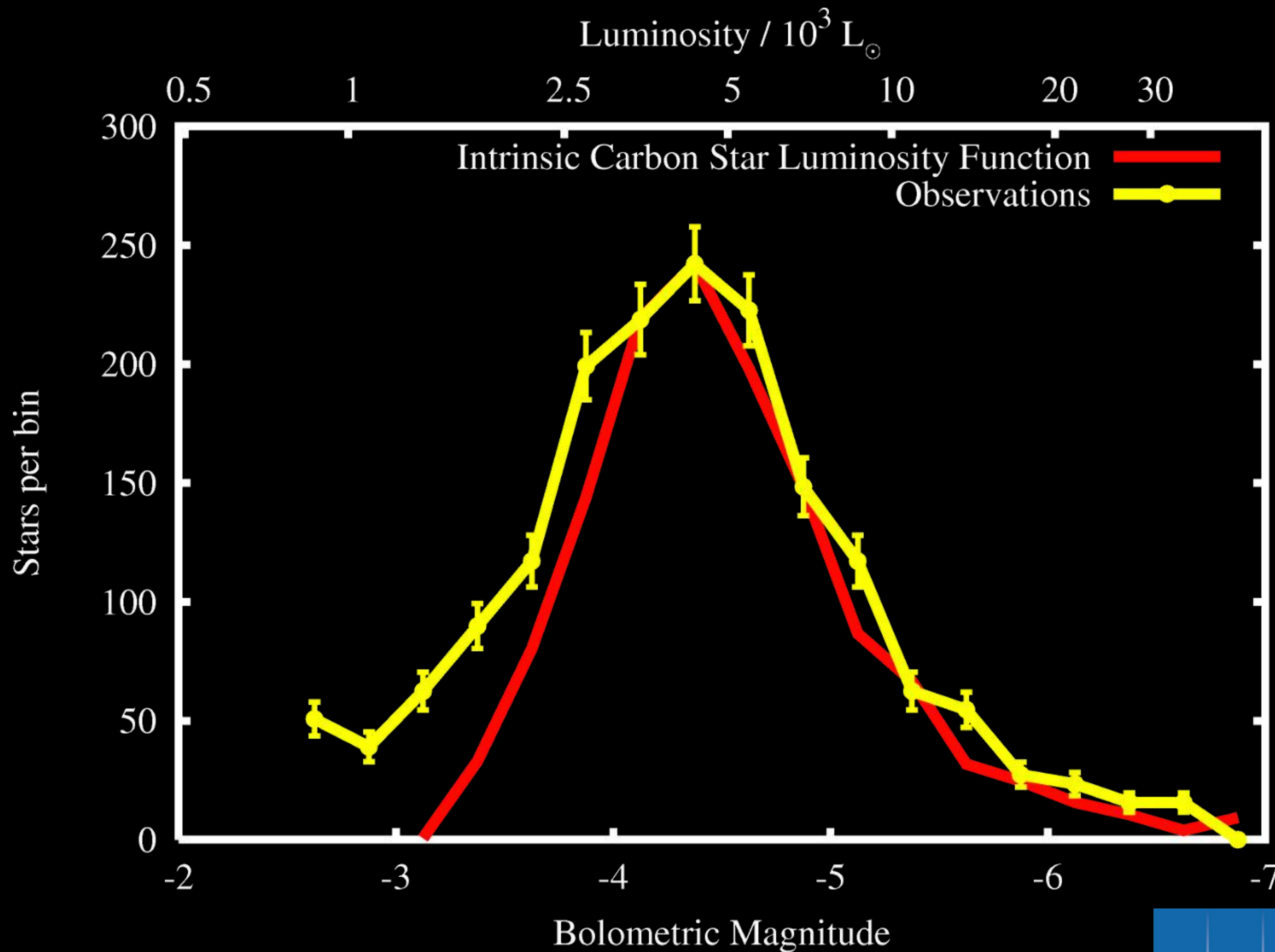
binary_c/nucsyn results

A frontend to the binary_c/nucsyn code

Evolution Time (MYr)	Star 1 mass ($M_\odot$)	Star 2 mass ($M_\odot$)	Star 1 type	Star 2 type	Separation ($R_\odot$)	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...	
14.0936	13.718	6.002	Hertzsprung Gap	Main Sequence	101.340	26.63	0.00	0.256	0.103	Stellar Type Change	
14.1165	13.715	6.003	Hertzsprung Gap	Main Sequence	101.384	26.64	0.00	1.000	0.103	Begin Roche Lobe Overflow	
14.1165	13.715	6.003	Hertzsprung Gap	Main Sequence	101.384	26.64	0.00	1.000	0.103	Common Envelope Evolution in	
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	
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	
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	
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	

Argelander Institut für Astronomie

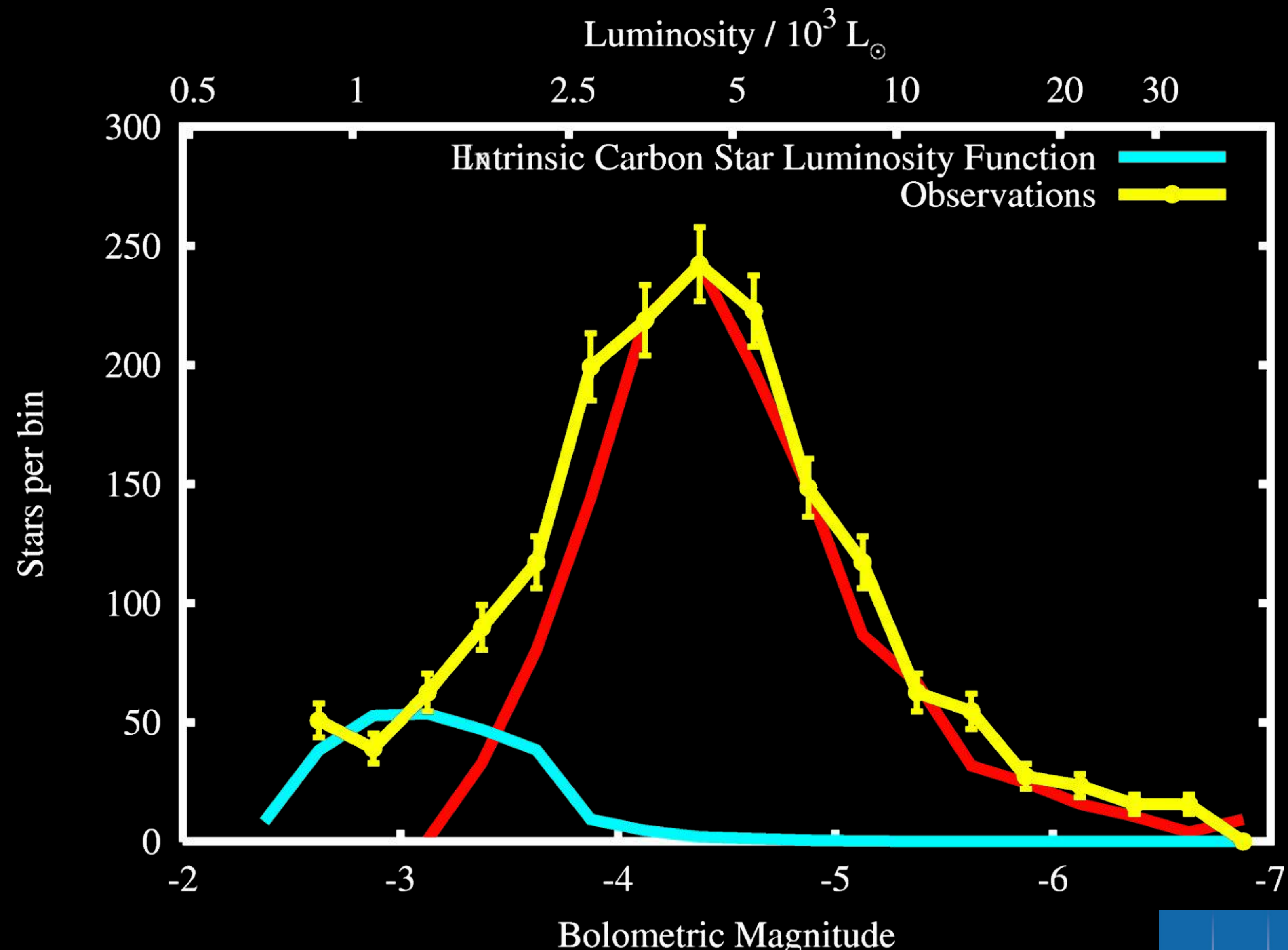
Low–L Carbon Stars



Izzard and Tout 2004

Argelander Institut für Astronomie

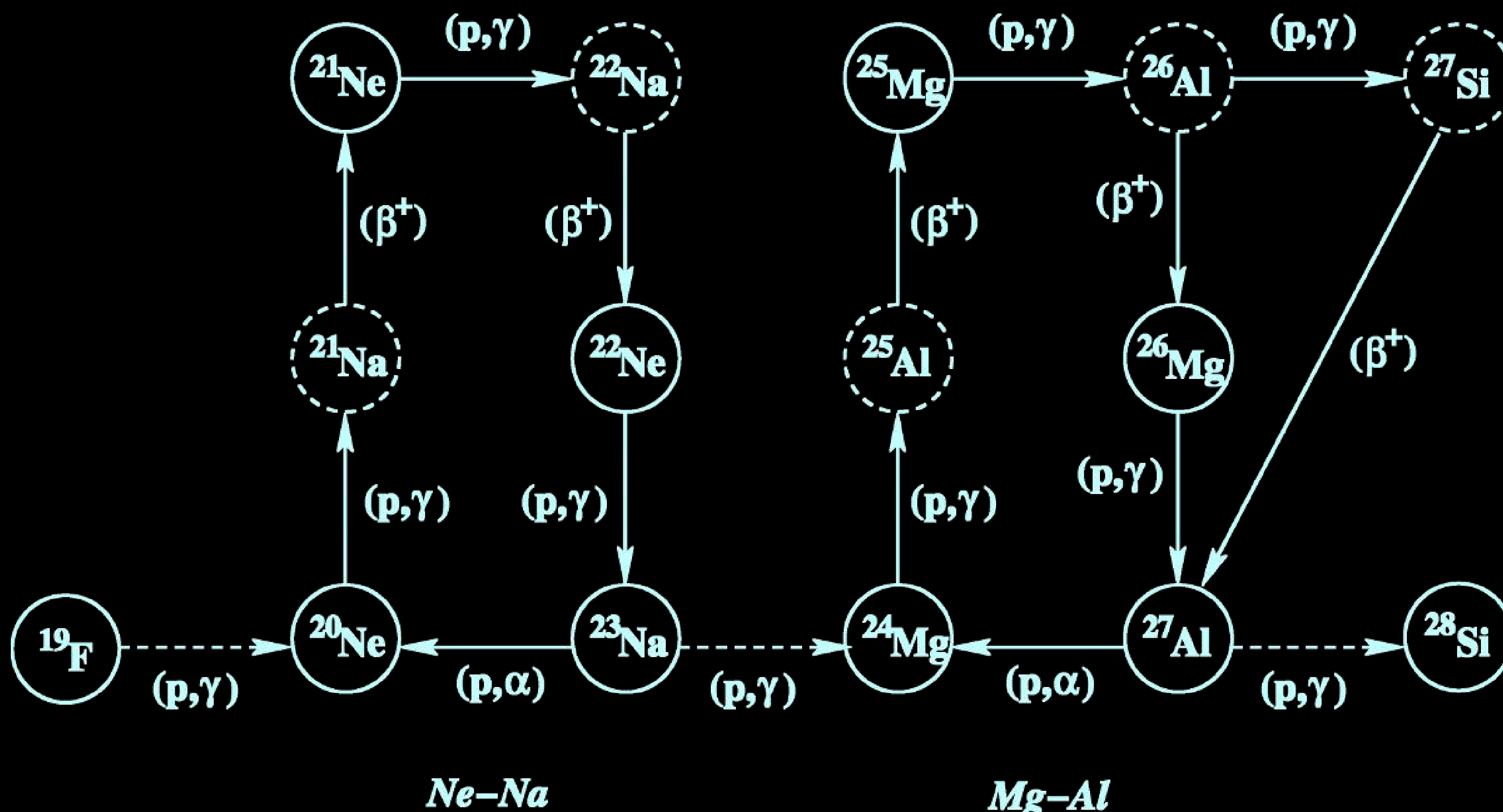
Low–L Carbon Stars



Izzard and Tout 2004

Argelander Institut für Astronomie

Nuclear Burning Rates



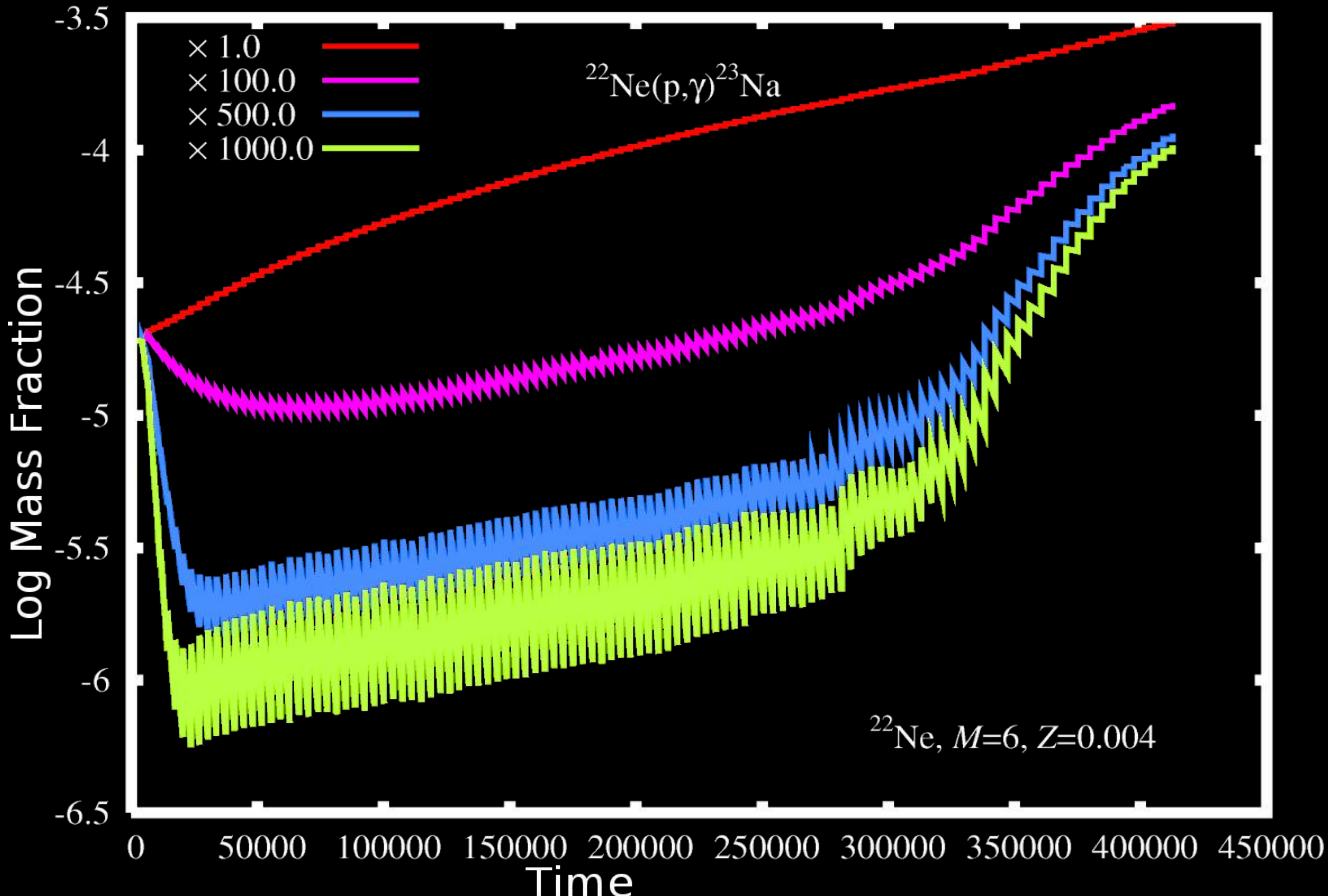
Argelander Institut für Astronomie

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

Argelander Institut für Astronomie

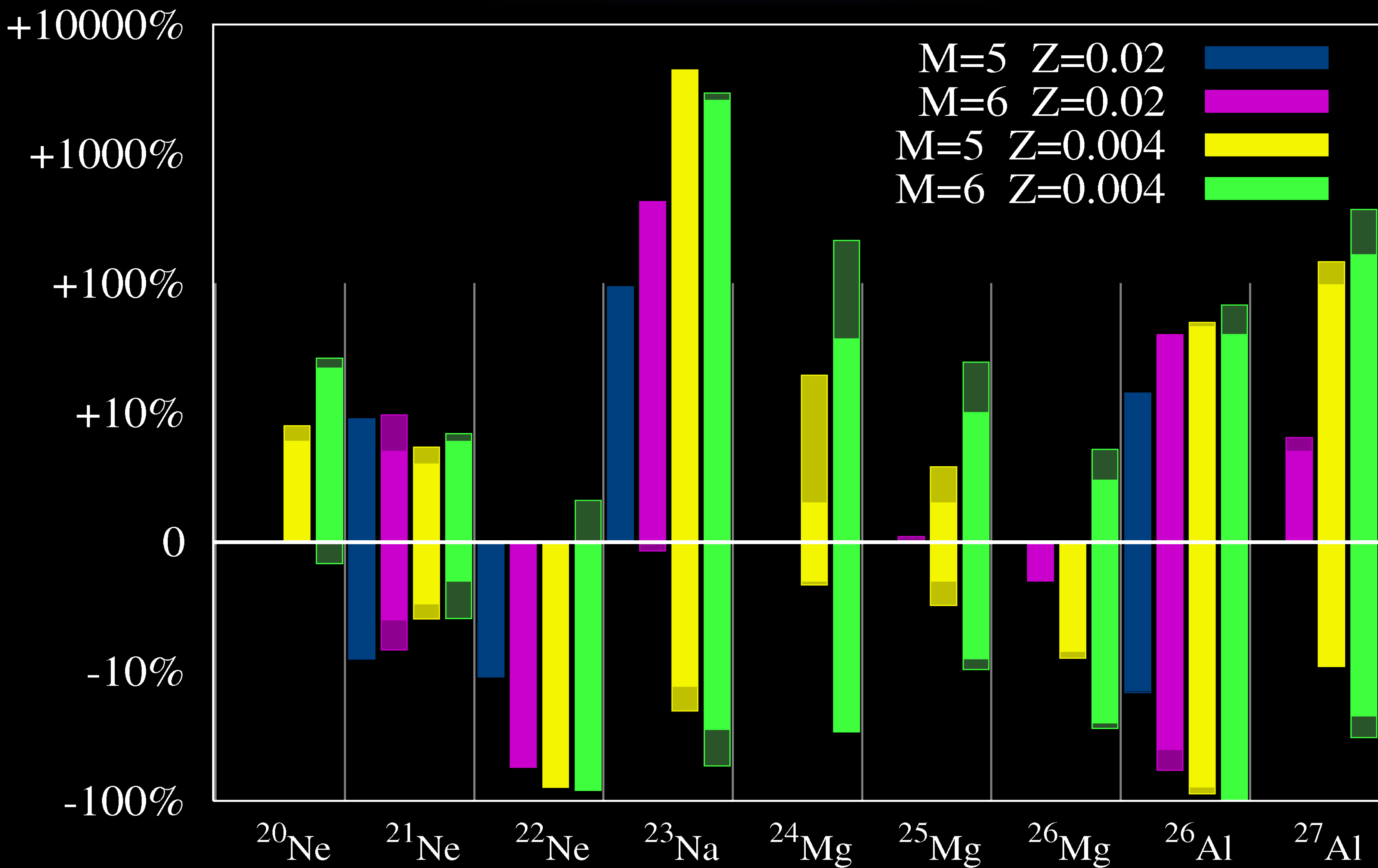
Nuclear Burning Rates



Izzard et al. 2007

Argelander Institut für Astronomie

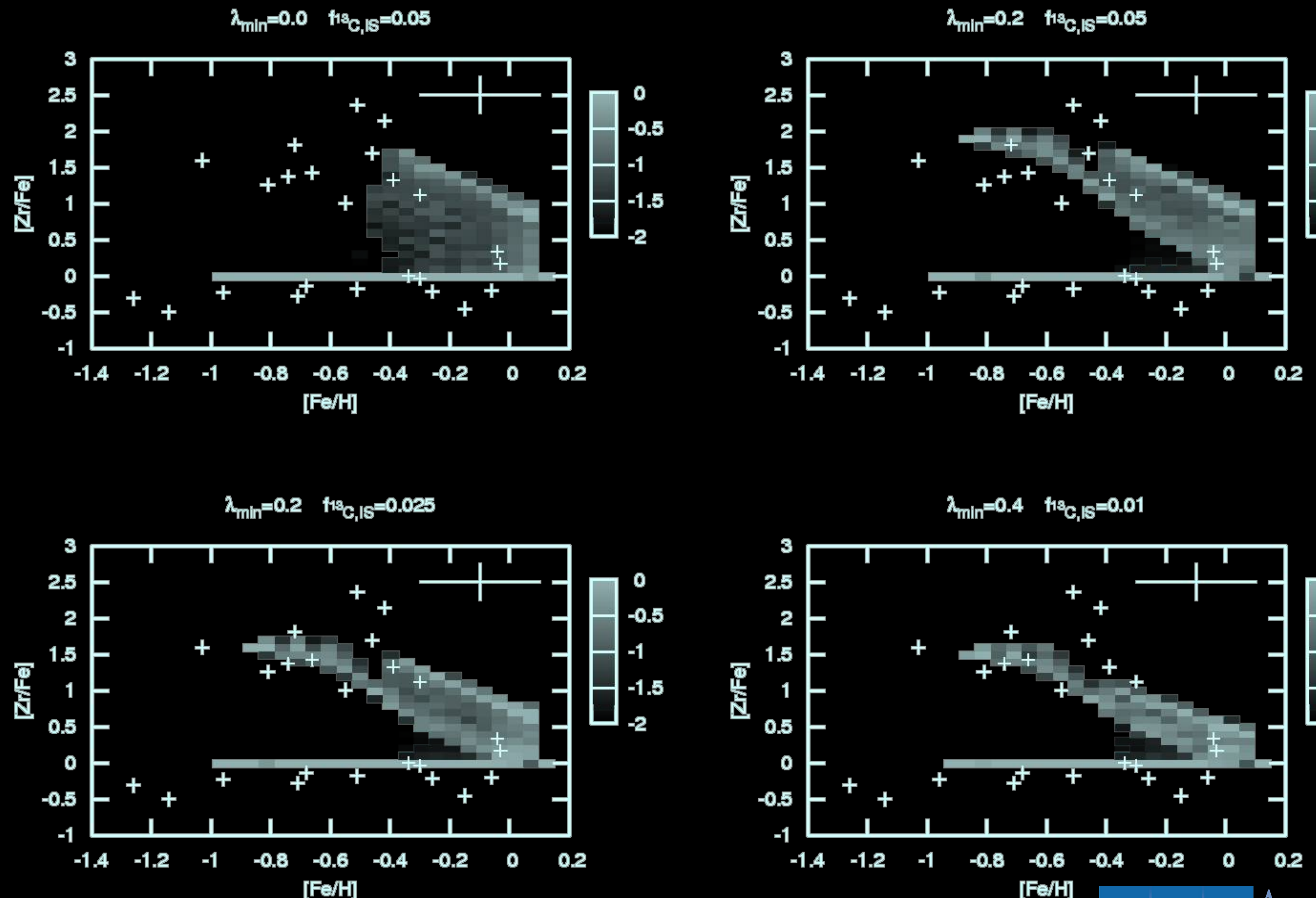
Nuclear Burning Rates



Izzard et al. 2007

Argelander Institut für Astronomie

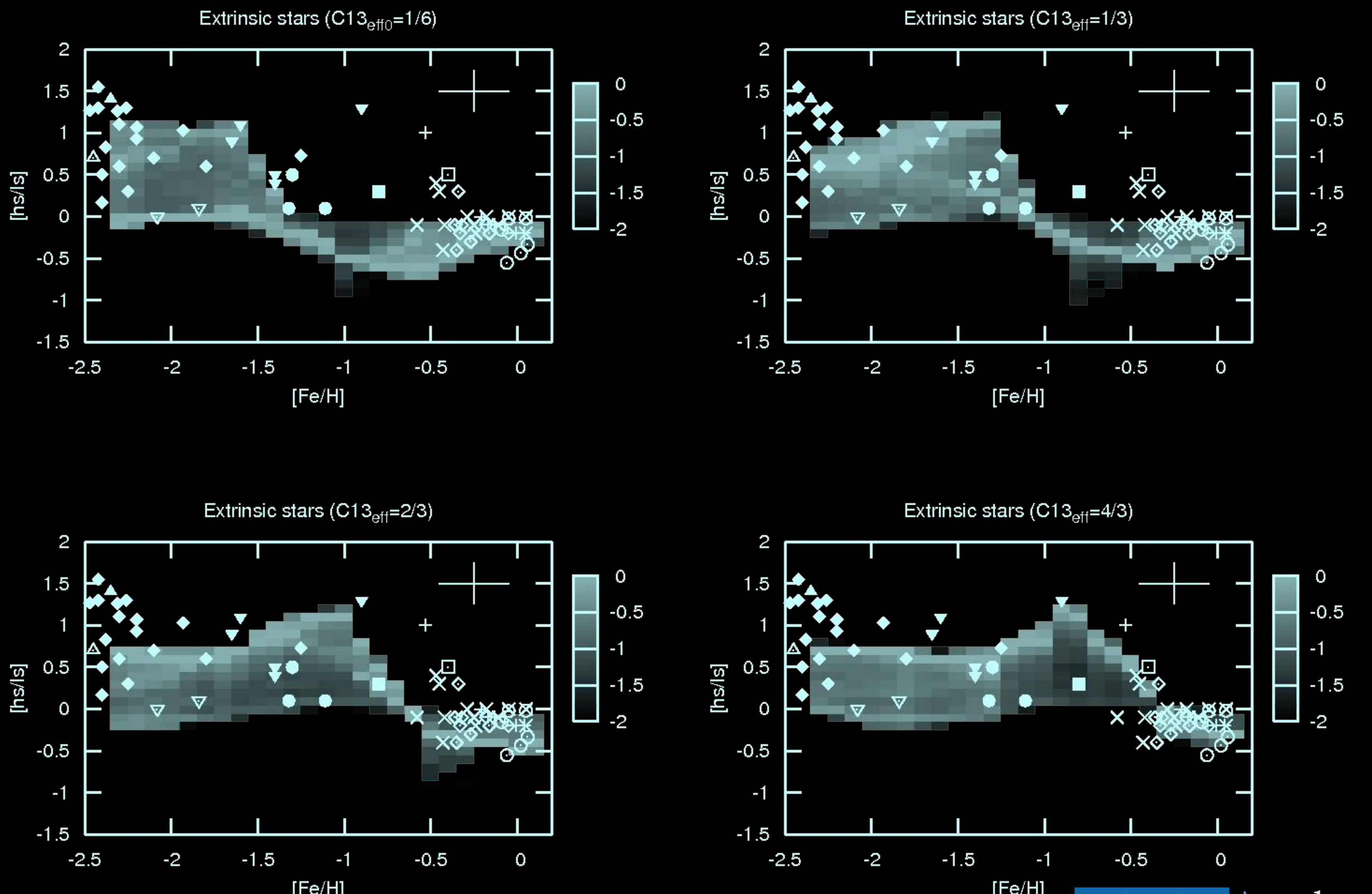
s–process in post–AGB



Bonacic et al. 2007

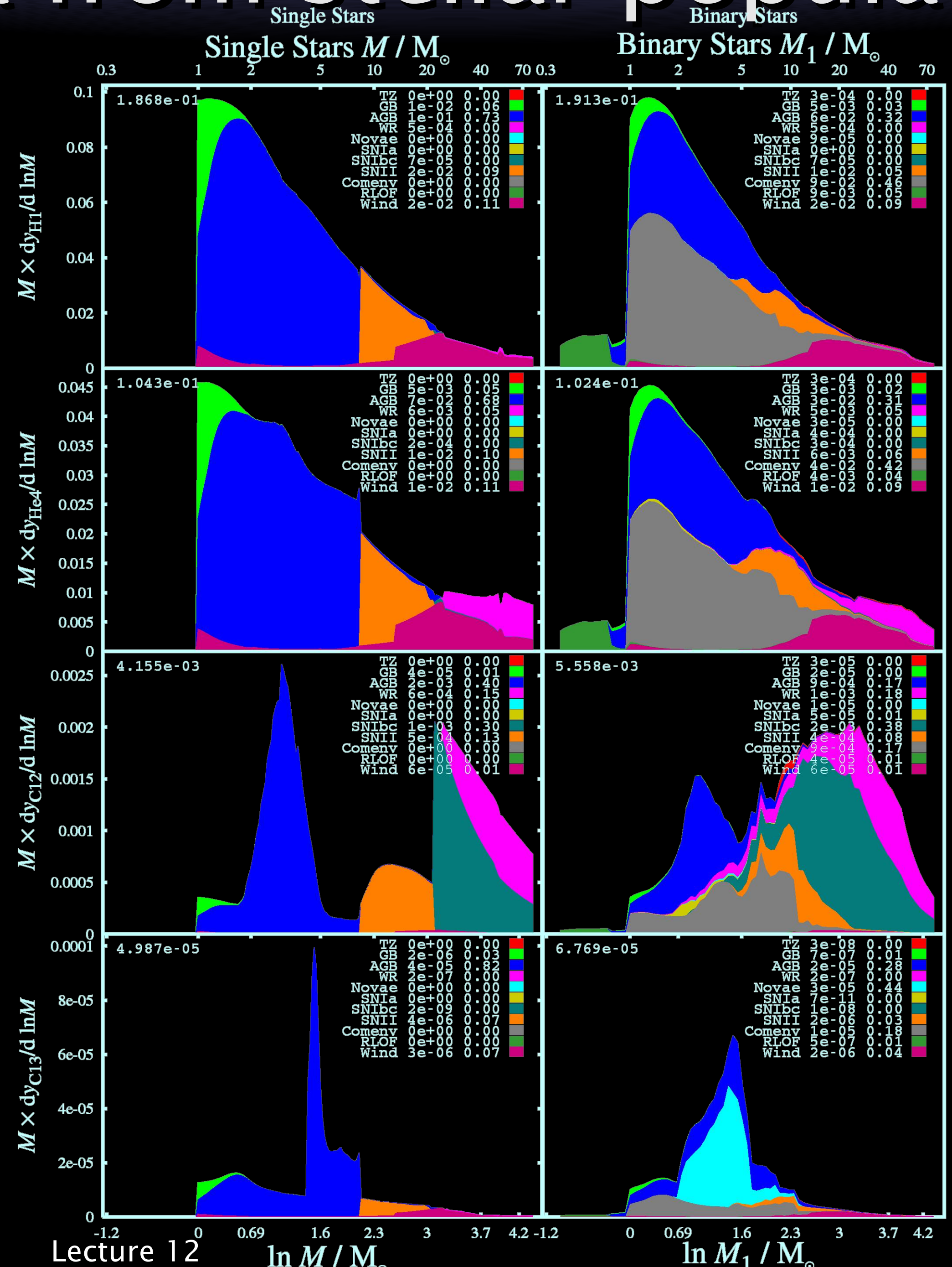
Argelander Institut für Astronomie

s-process in post-AGB



Bonacic et al. 2007

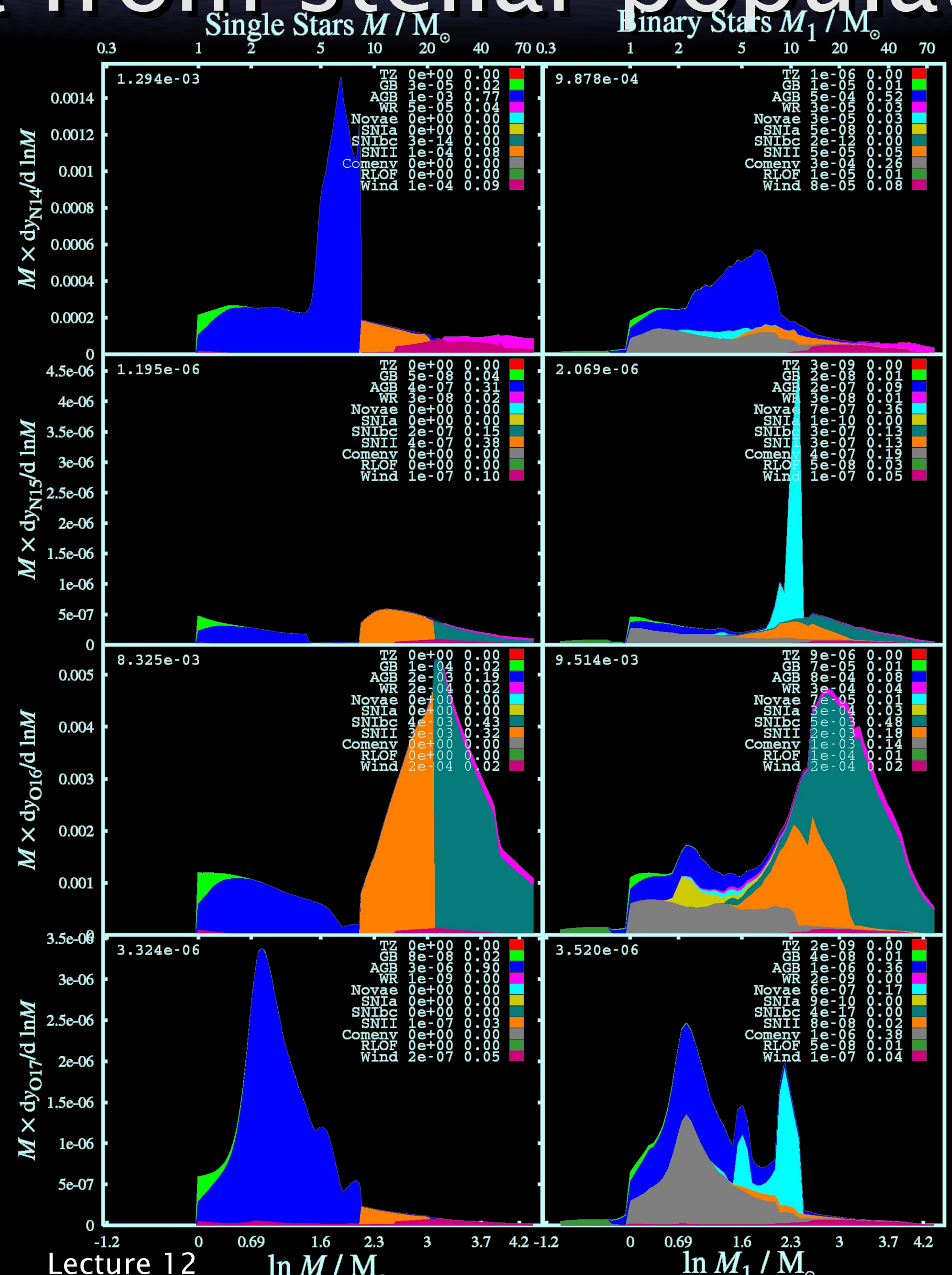
Ejecta from stellar populations



Izzard PhD!

Argelander Institut für Astronomie

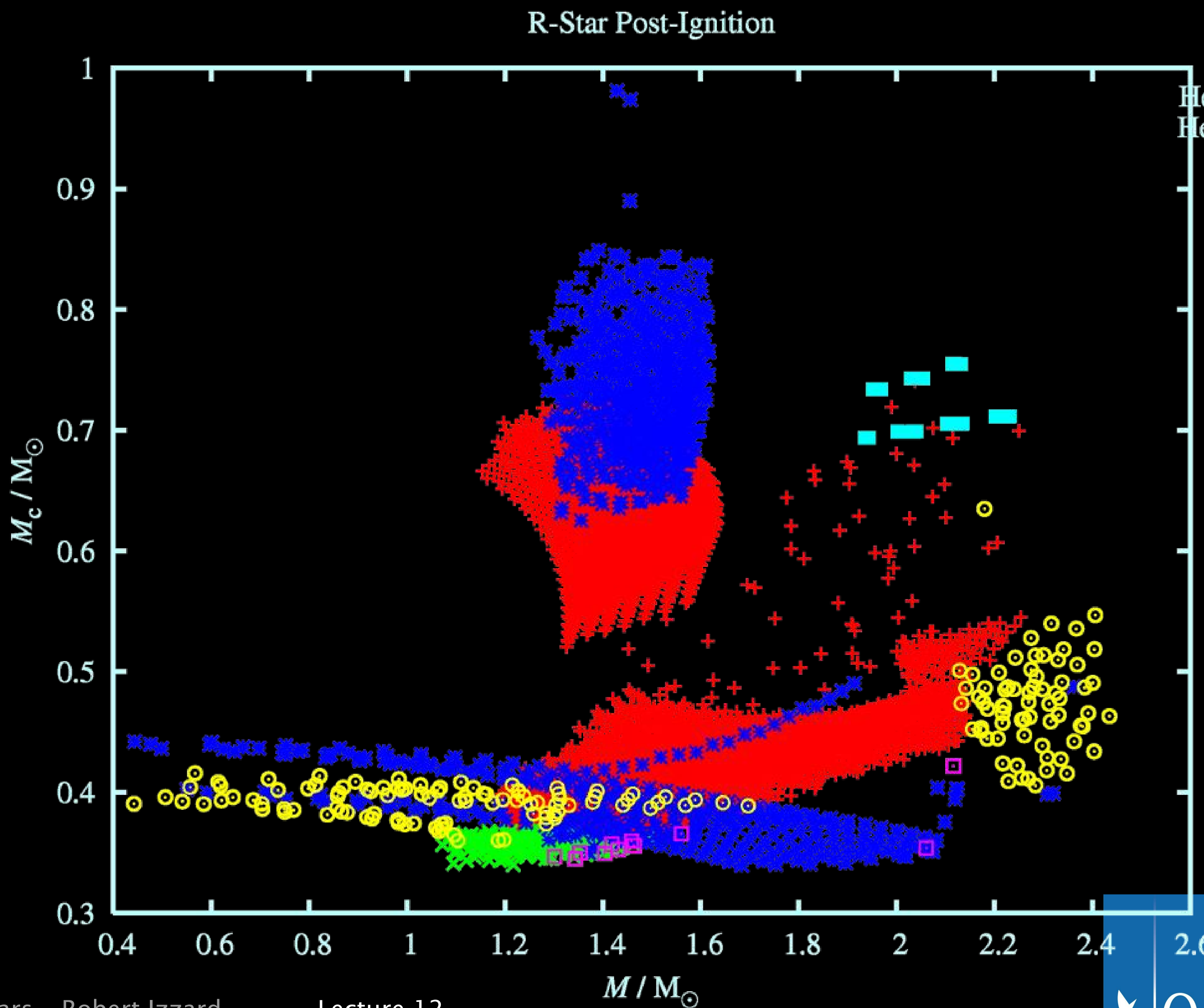
Ejecta from stellar populations



Izzard PhD!

Argelander Institut für Astronomie

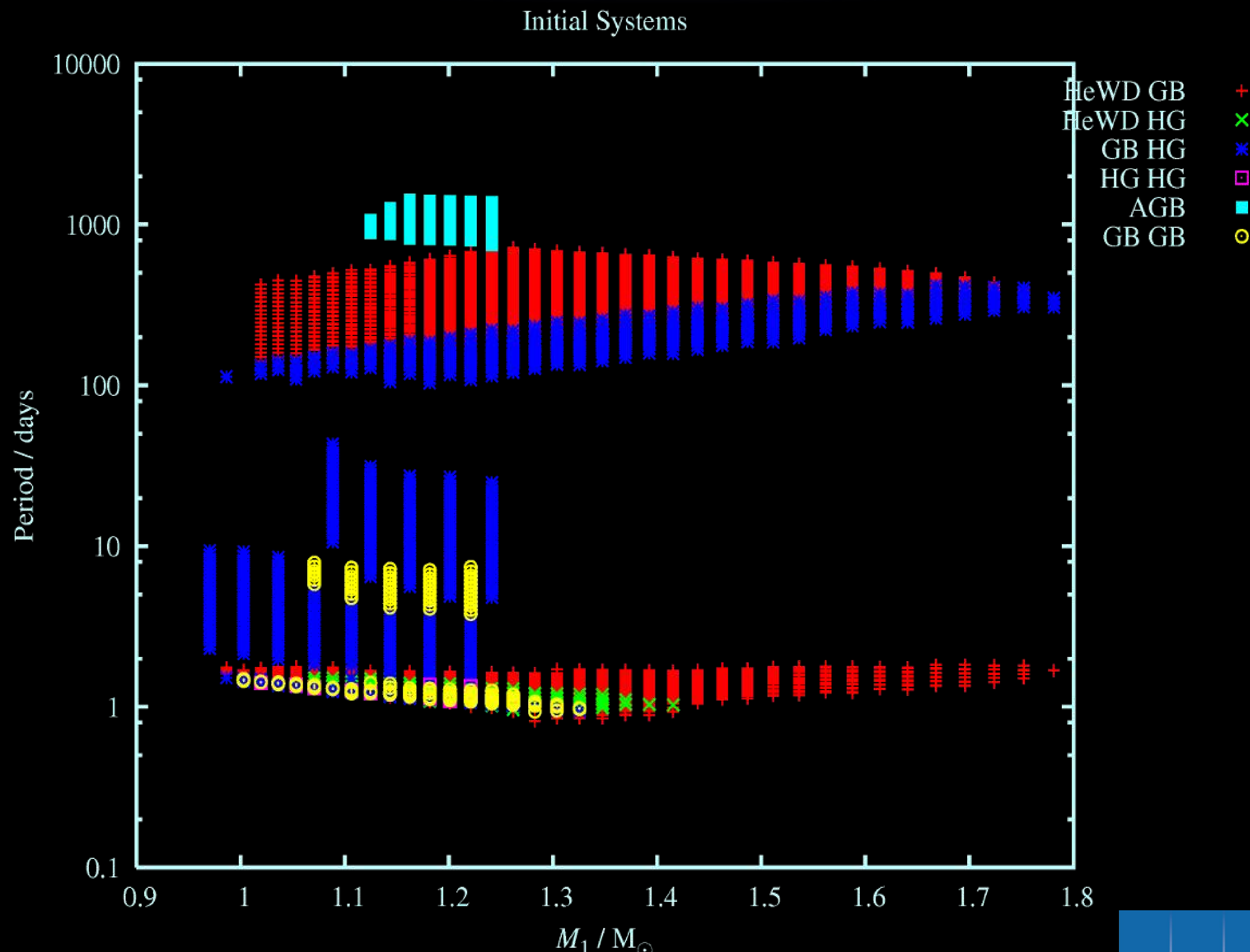
Stellar Mergers: R Stars



Izzard
Jeffery
Lattanzio
2007

Argelander Institut für Astronomie

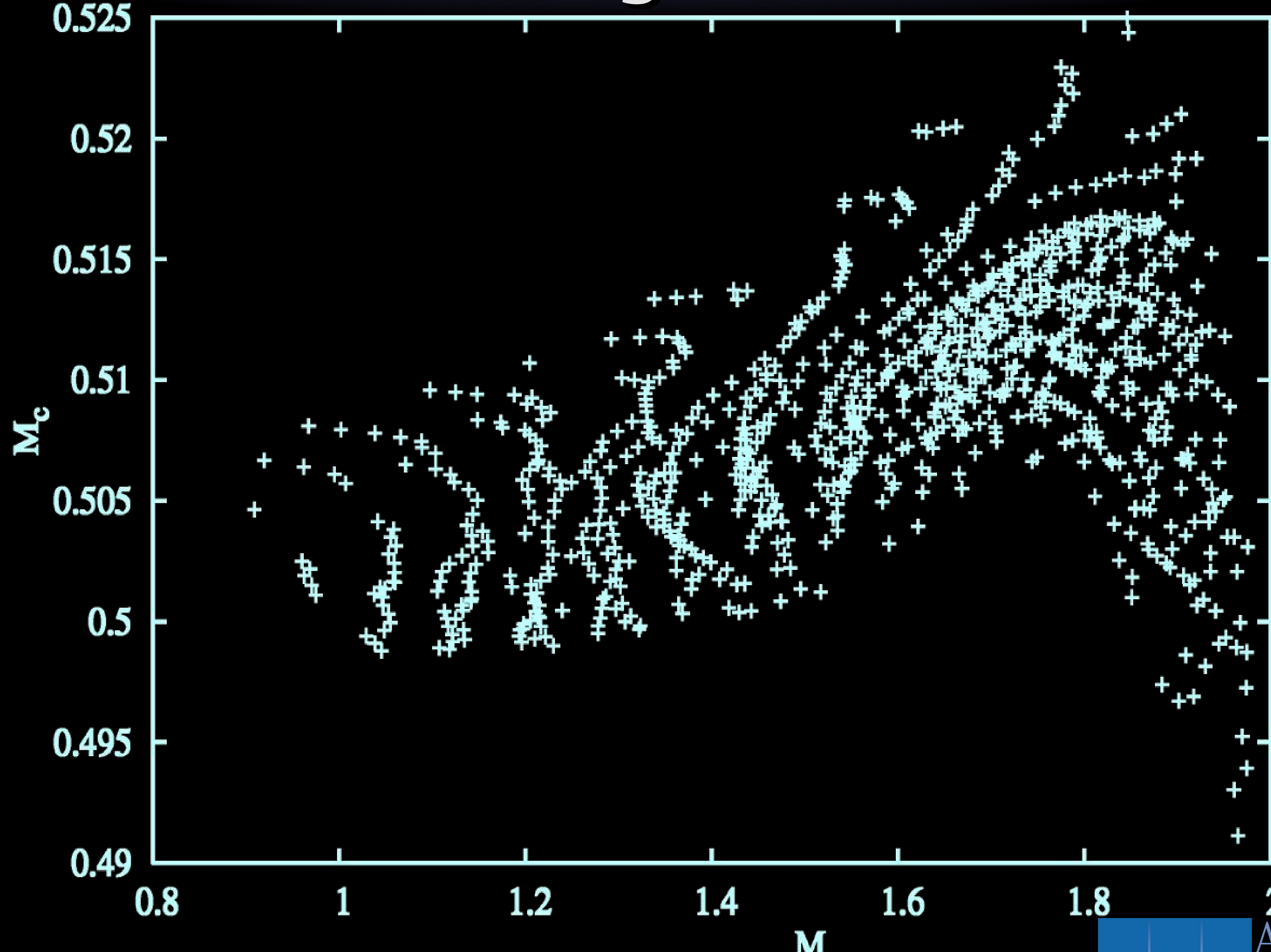
Stellar Mergers: R Stars



Izzard
Jeffery
Lattanzio
2007

Argelander Institut für Astronomie

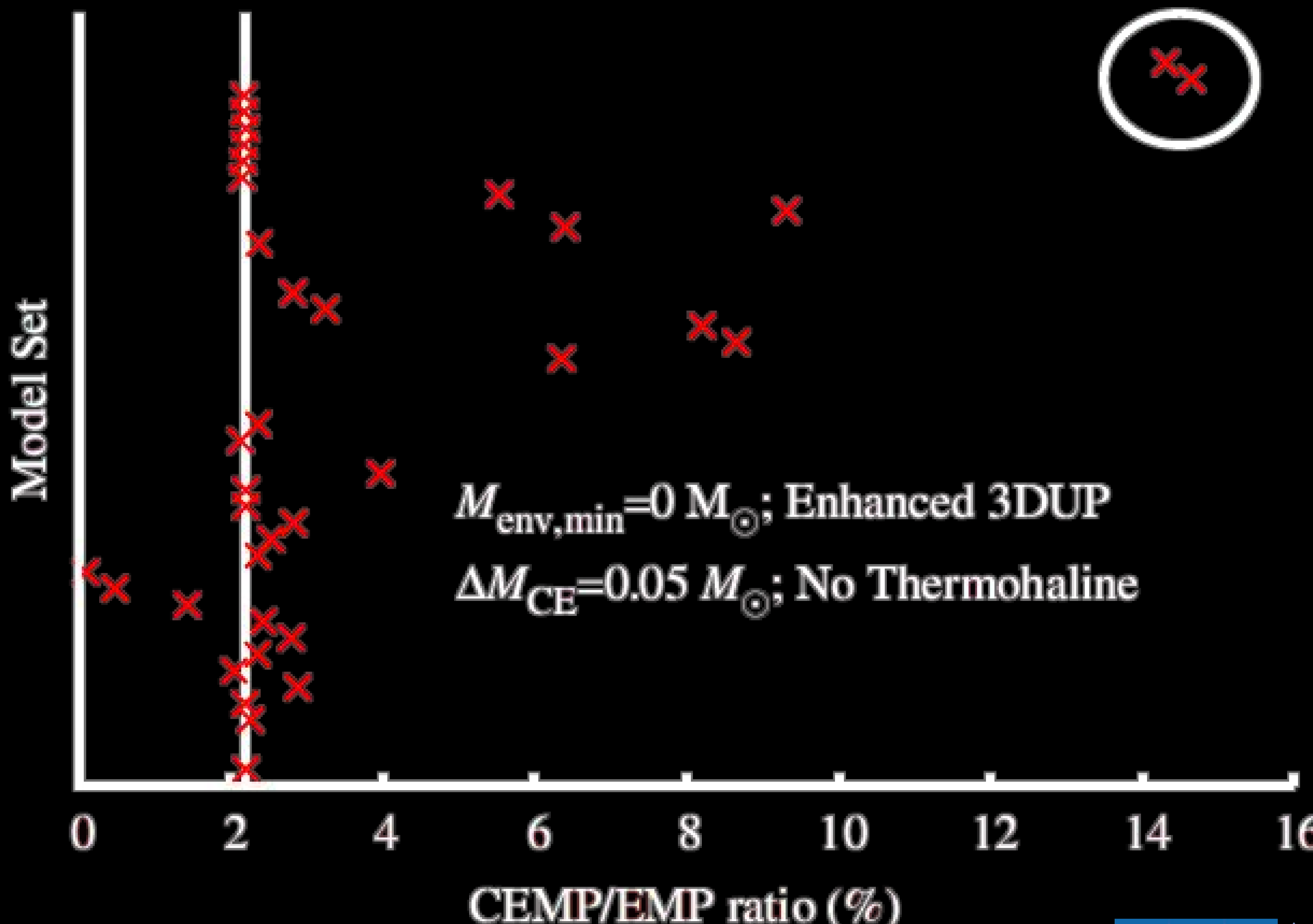
Stellar Mergers: R Stars



Izzard
Jeffery
Lattanzio
2007

Argelander Institut für Astronomie

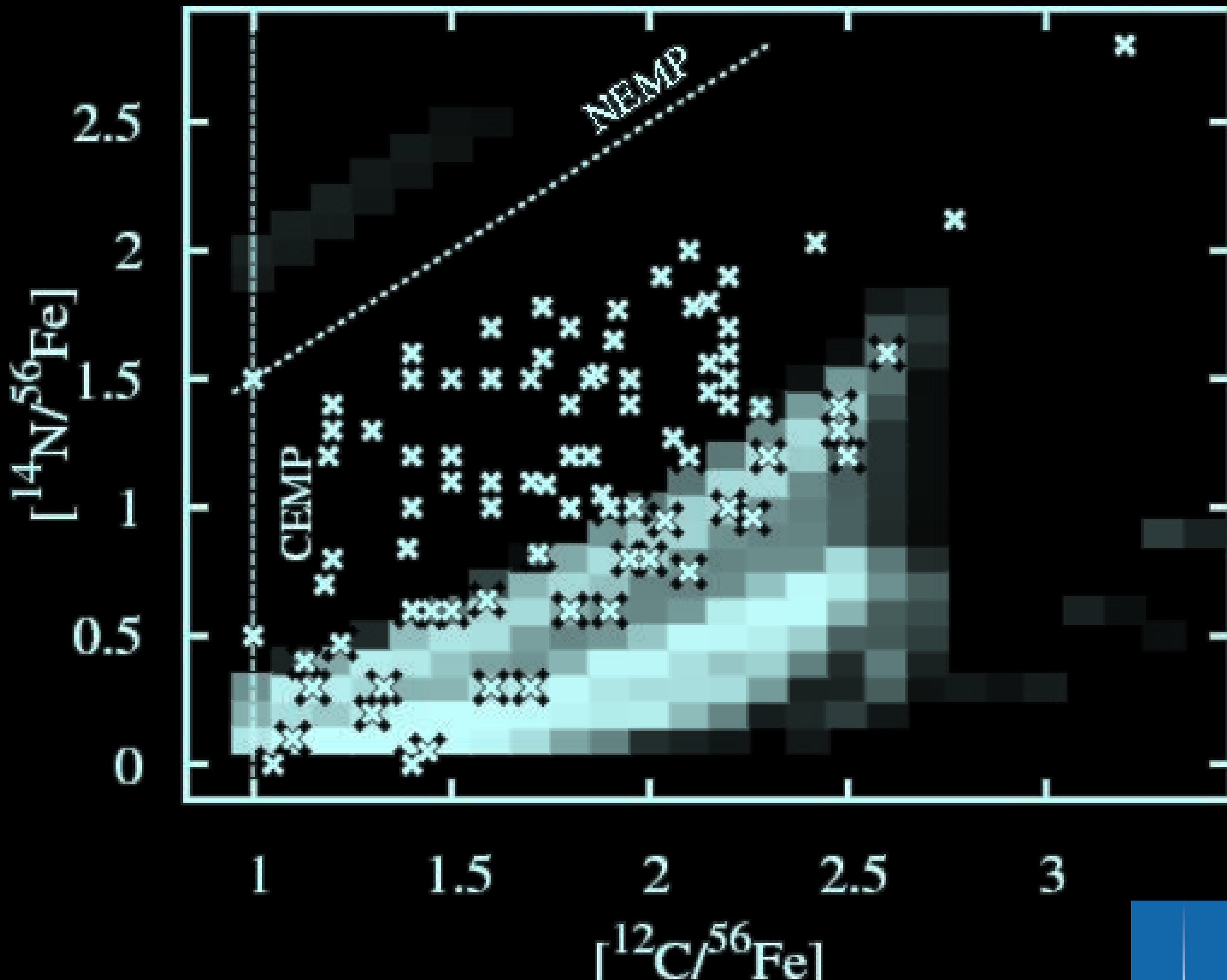
CEMP stars



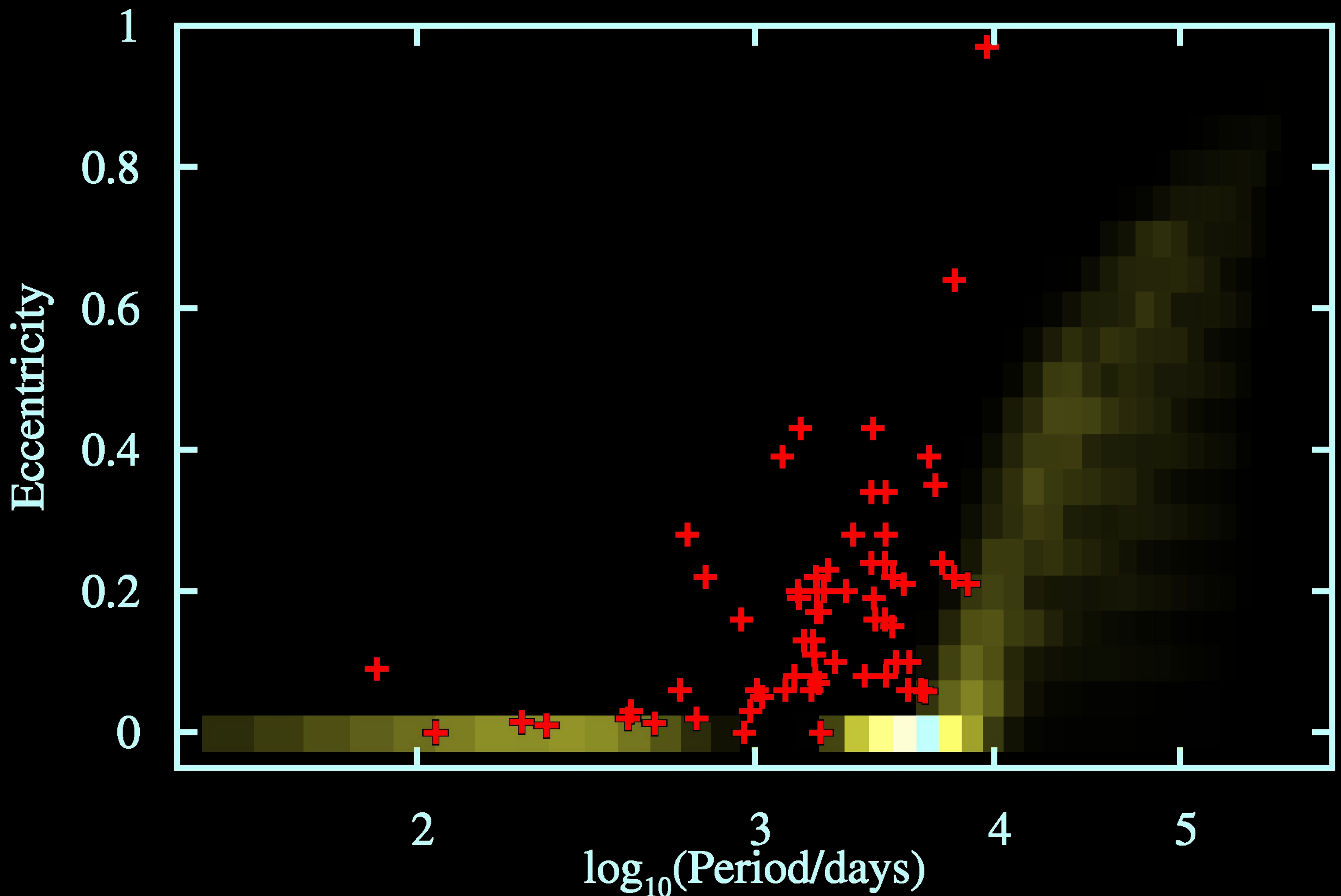
Izzard et al 2009

Argelander Institut für Astronomie

CEMP stars



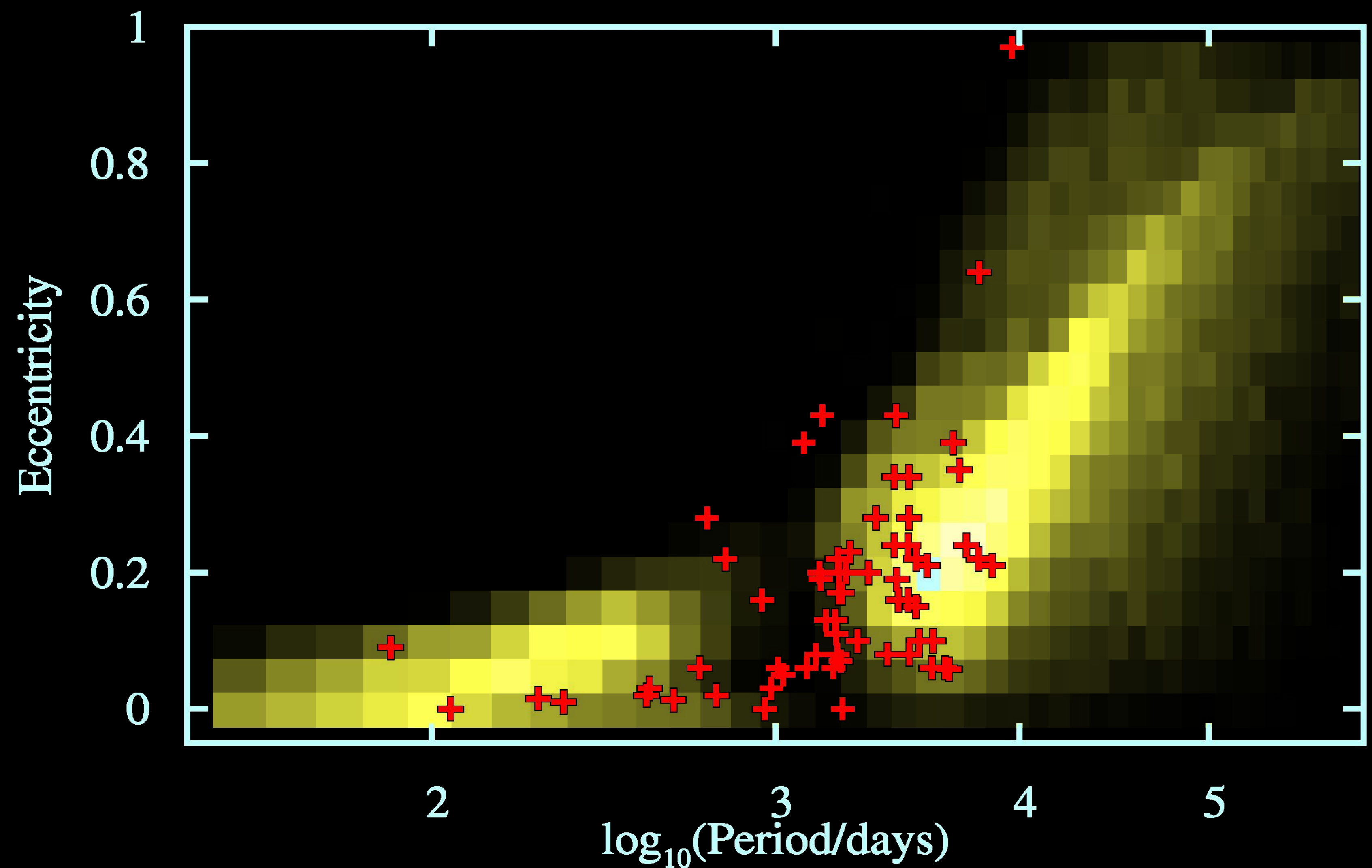
Barium Stars



Izzard et al 2009

Argelander Institut für Astronomie

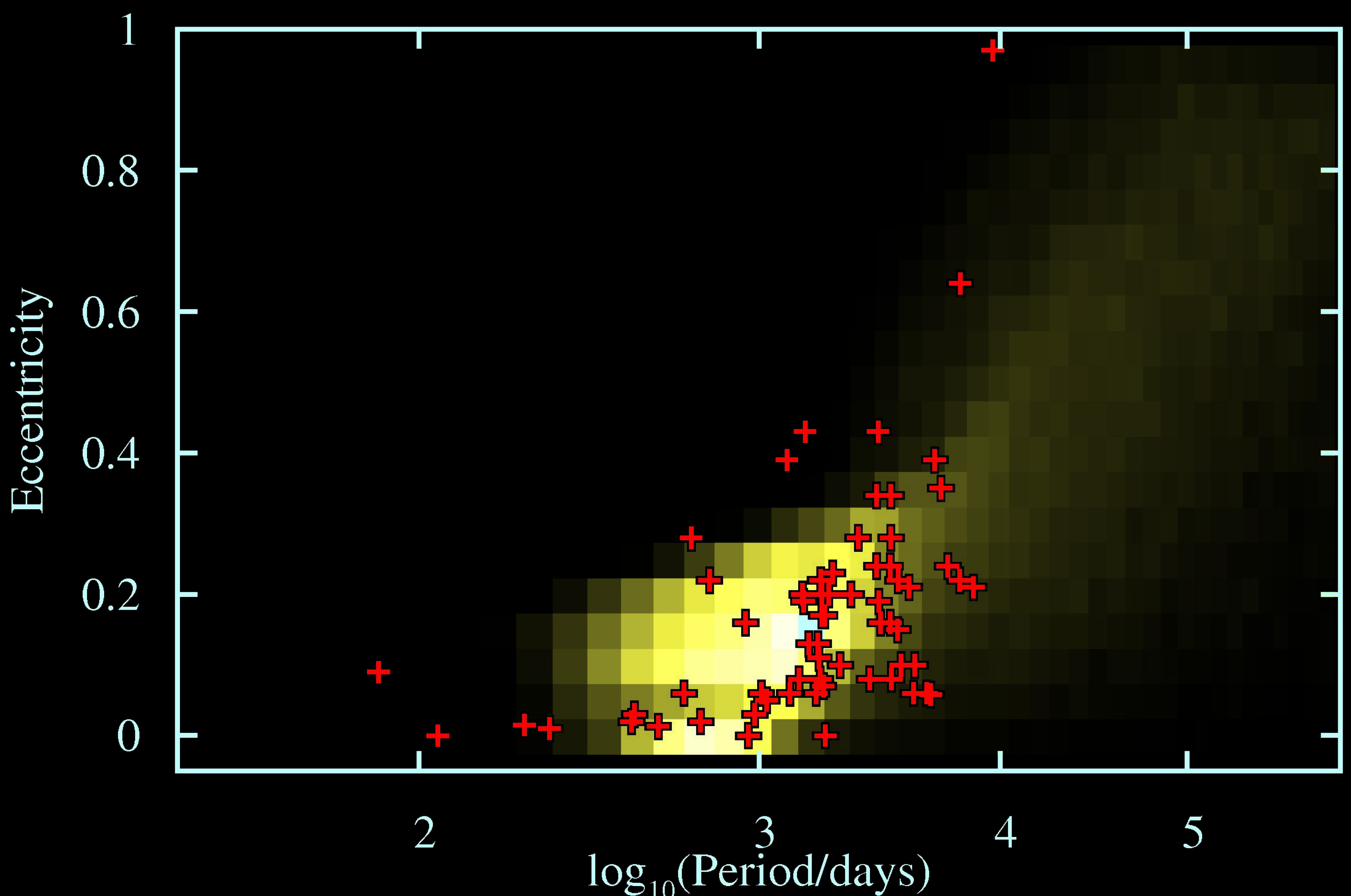
Barium Stars



Izzard et al 2009

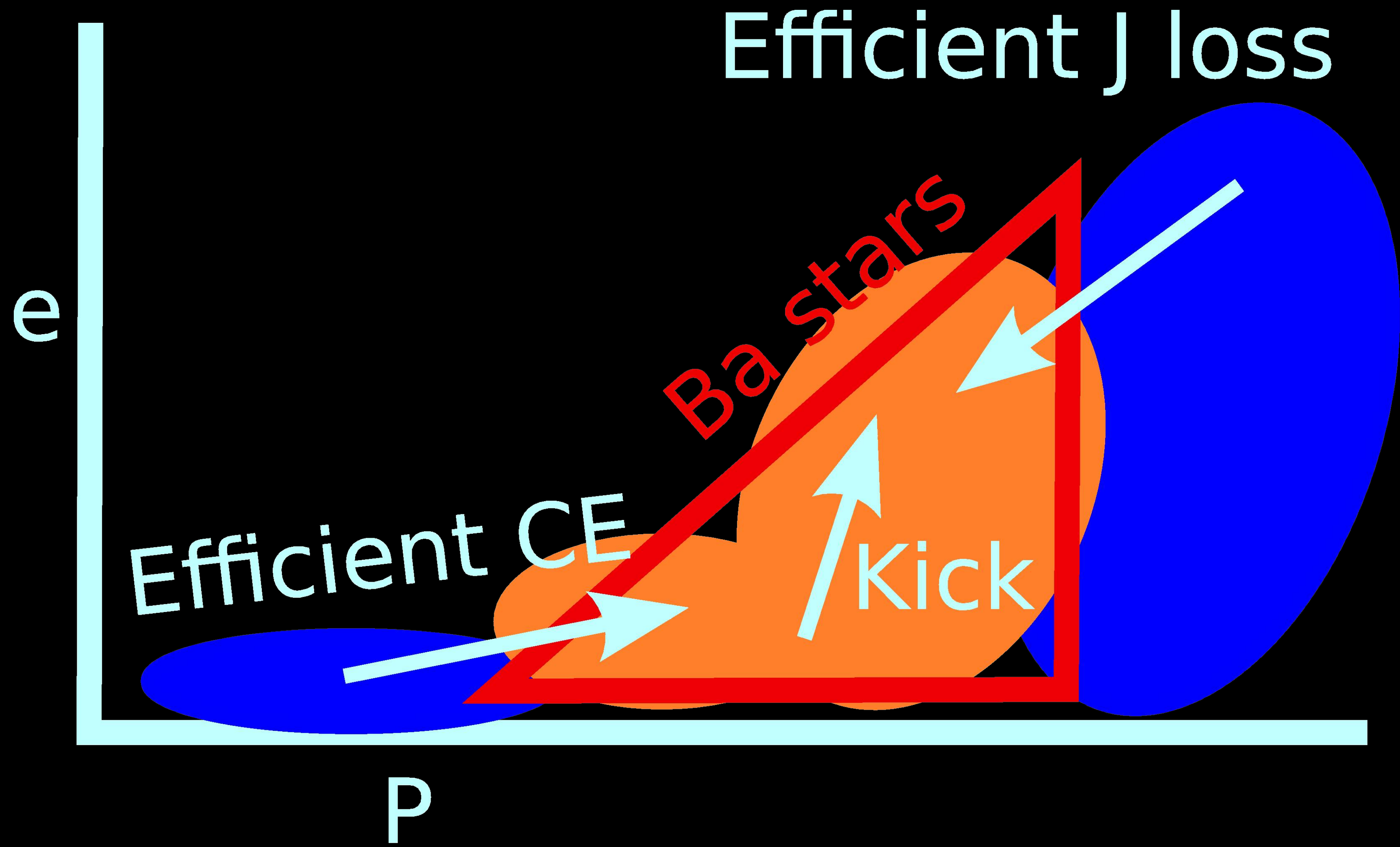
Argelander Institut für Astronomie

Barium Stars



Izzard et al 2009

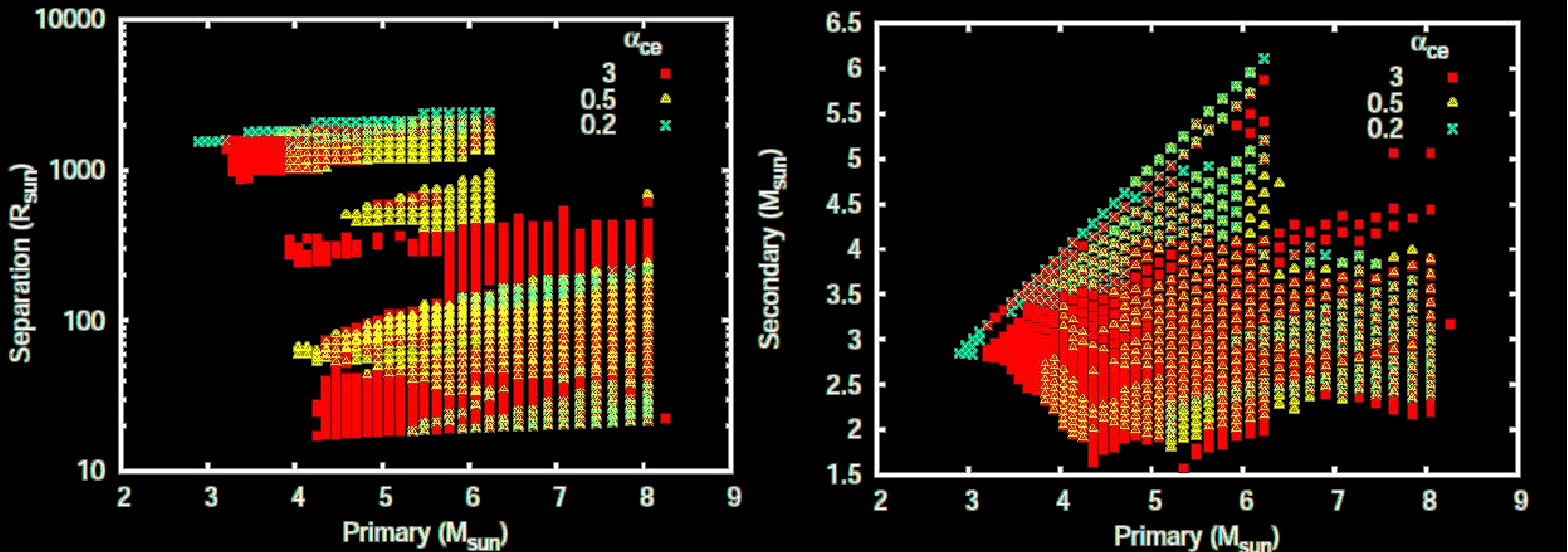
Barium Stars



Izzard et al 2009

Argelander Institut für Astronomie

Ia Supernovae



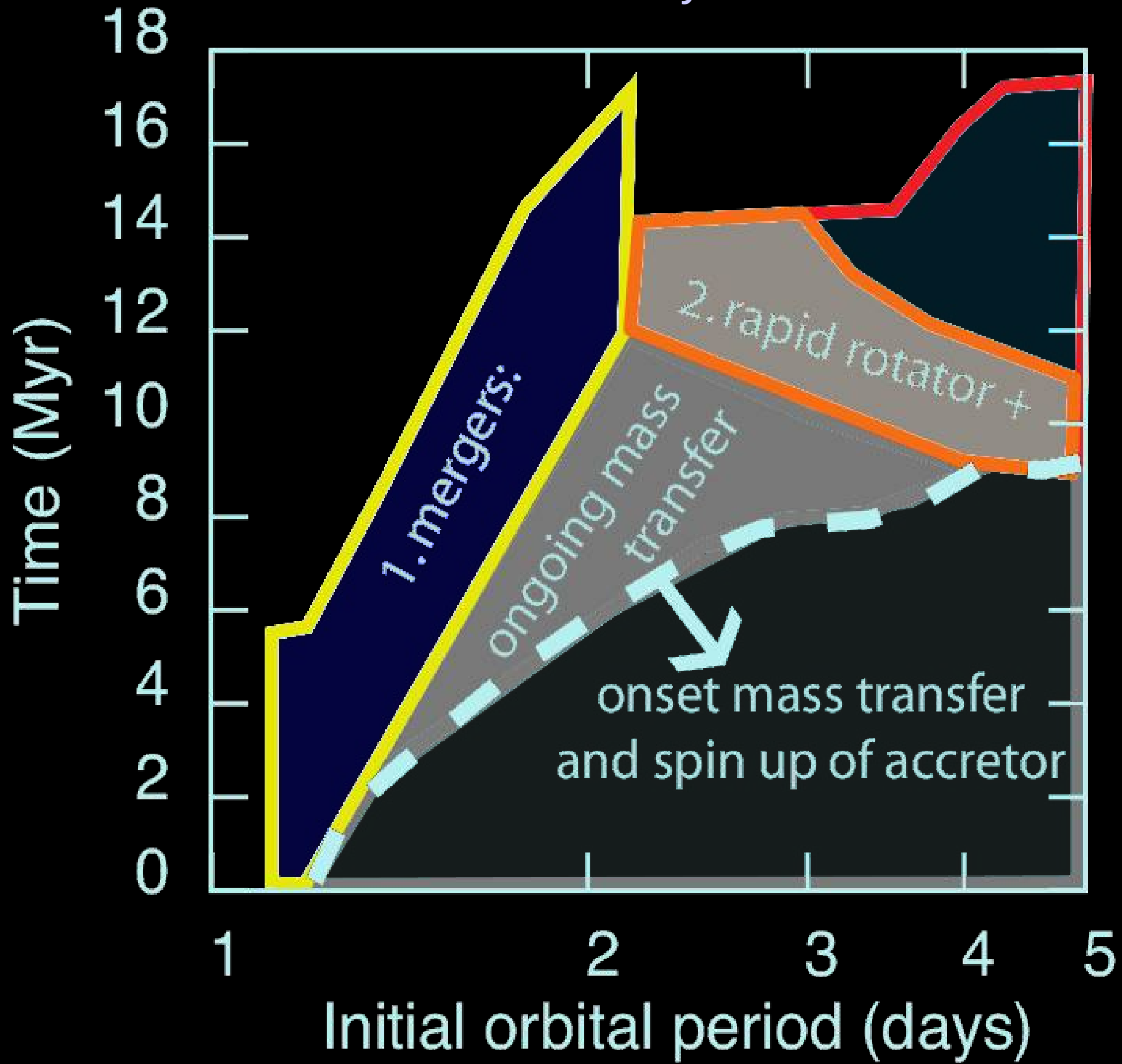
Initial systems that evolve towards a type Ia SN according to the DD channel.
Different colors indicate different α_{ce}. λ_{ce} is 1.

Joke Claeys (work in progress!)

Argelander Institut für Astronomie

Massive Stars

The fate of a 20+15 M⊙ close binary as a function of initial period.



De Mink et al. 2010/11

The end!

- Exam:

  Tuesday 17th July

  10.00–11.30am

  Herbert Lau will be supervising you.

- Good luck! Thanks for coming :)

Argelander Institut für Astronomie