Nuclear effects on burst behavior

First results

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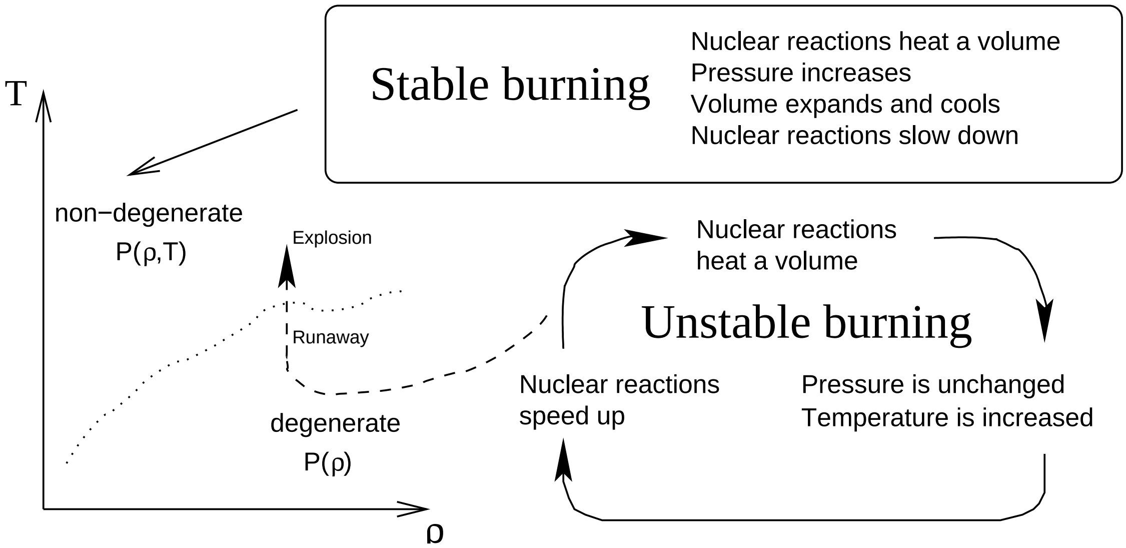
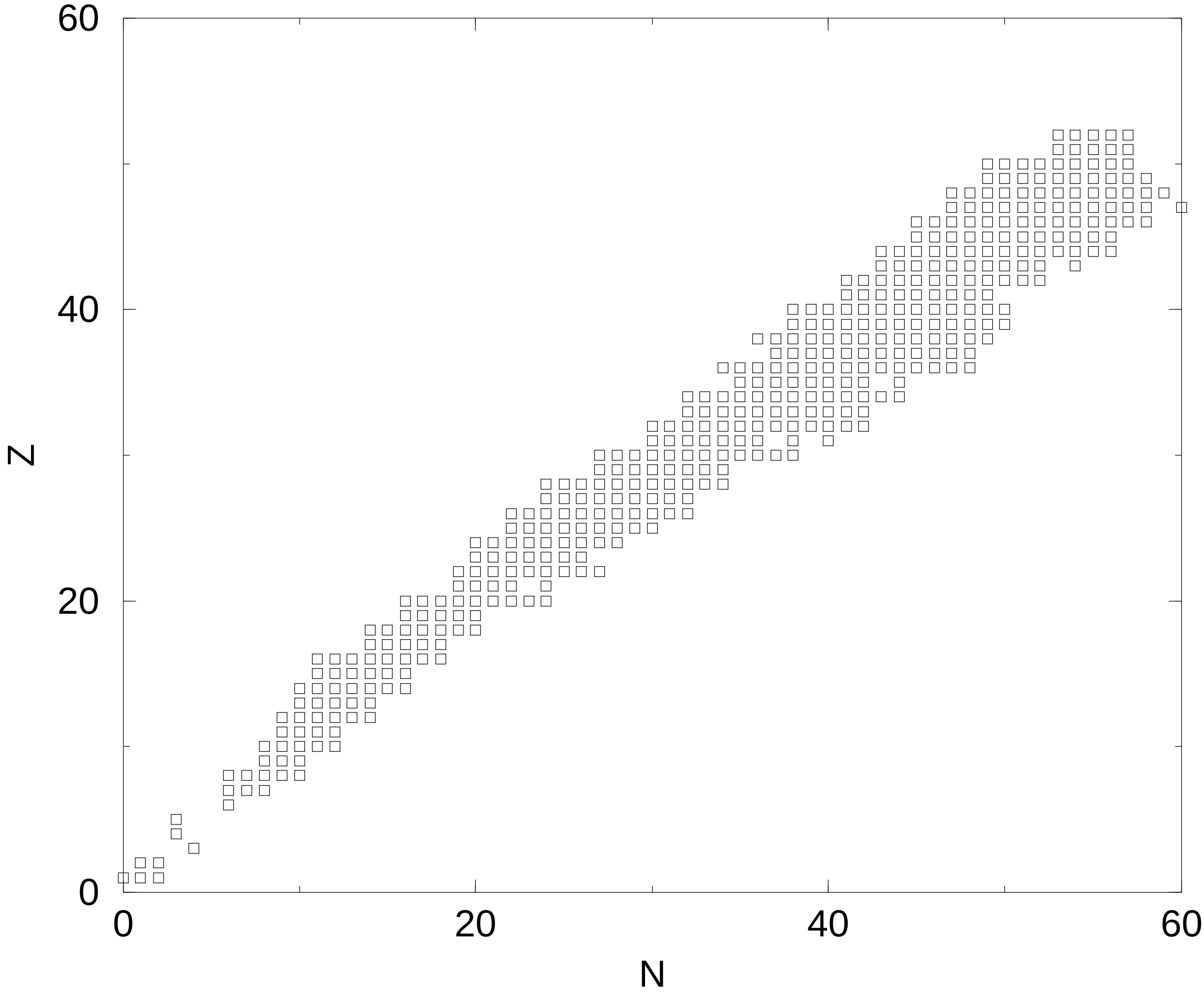
Stable/unstable nuclear burning



$$\Delta u = \left(\epsilon_{\mathrm{nuc.}} - \epsilon_{\mathrm{cool}}\right) \Delta t - P \Delta v$$

Microphysics: Nuclear reactions, radiative transport, conductive transport, neutrino cooling, ...

Nuclear reaction network



426 isotopes

pp+He+$\left[{}^{12}\mathrm{C}-{}^{109}\mathrm{Te}\right]$

(p,γ), (γ,p), (α,γ), (γ,α), (α,p), (p,α)

How to solve a network

Mass fractions: $\sum_i X_i = 1$

Abundance: $Y_i = X_i/A_i$

Accounting all rates.

$$\begin{aligned}\frac{dY_i}{dt} &= \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A \langle j,k \rangle Y_j Y_k \\ &+ \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A^2 \langle j,k,l \rangle Y_j Y_k Y_l \,,\end{aligned}$$

Implicit - not explicit!

$$\frac{Y(t+\Delta t) - Y(t)}{\Delta t} = \dot{Y}(t+\Delta t) + O^2(t)$$

The Numerics: Multi-D Newton-Raphson iterations.

$$f(x+\Delta x) = f(x) + \frac{\partial f(x)}{\partial x}\Delta x + O^2(\Delta x)$$

This should be zero when we get the correct $Y(t+\Delta t)$.

$$L(Y(t+\Delta t)) = \frac{Y(t+\Delta t) - Y(t)}{\Delta t} - \dot{Y}(t+\Delta t)$$

Guess $Y(t+\Delta t)$ and calculate the correction.

$$\Delta Y = -\left(\frac{\partial L(Y(t+\Delta t))}{\partial Y(t+\Delta t)}\right)^{-1} L(Y(t+\Delta t))$$

1D Hydrodynamics

AGILE [Astrophys. J. Suppl. 141(2002)229]:

- → Finite difference code
- → Adaptive grid
- → Conservative
- → Implicit evolution
- → Discretized in shift vectors
  → wide range in zone masses.

Solve $G = 8\pi T$

$$ds^2 = -\alpha^2 dt^2 + \left(\frac{r'}{\Gamma}\right)^2 da^2 + r^2(a,t)\left(d\theta^2 + \sin^2(\theta) d\phi^2\right)$$

$$T = \begin{bmatrix} \rho(1+e) & q & 0 & 0 \\ q & p+Q & 0 & 0 \\ 0 & 0 & p-\frac{1}{2}Q & 0 \\ 0 & 0 & 0 & p-\frac{1}{2}Q \end{bmatrix}$$

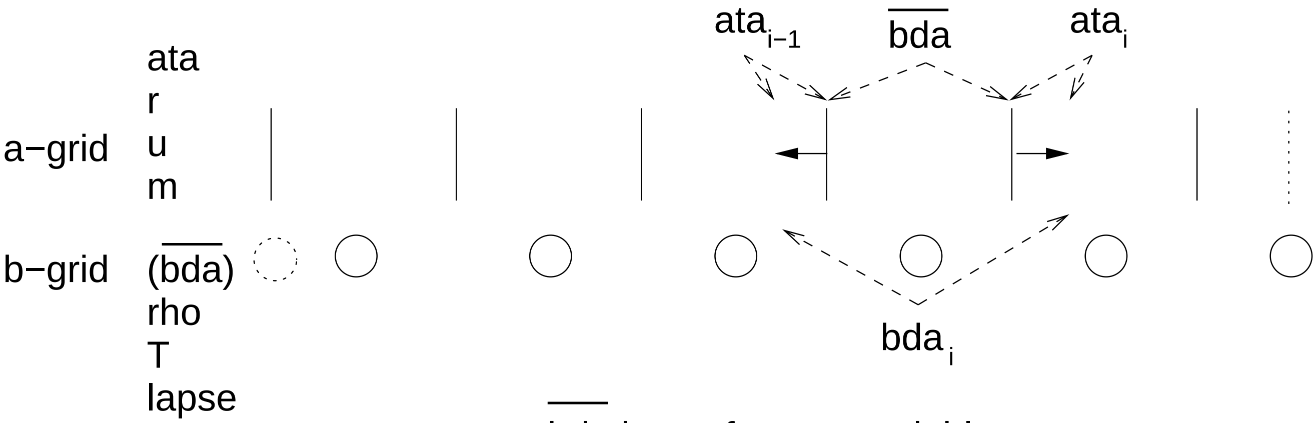
Continuity, Momentum, Energy, Lapse function, Gravitational Mass, Volume restraint, Grid equation

Solution

- ➡ Discretize on a grid
  (7 variables on 103 zones = <u>721</u> independents)

- ➡ Rewrite differential equations as
  <u>721</u> difference equations

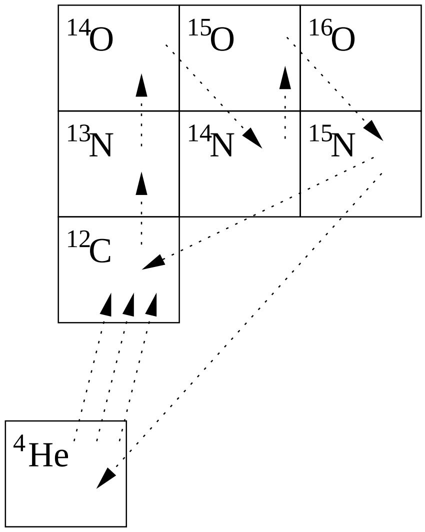
- ➡ Solve the system.



bda is a reference variable
ata is an independent variable
bda is a derived quantity

Solar composition accretion

$T_9 = 0.1 - 0.2,\ \rho \sim 10^5 \mathrm{g/cm}^2$



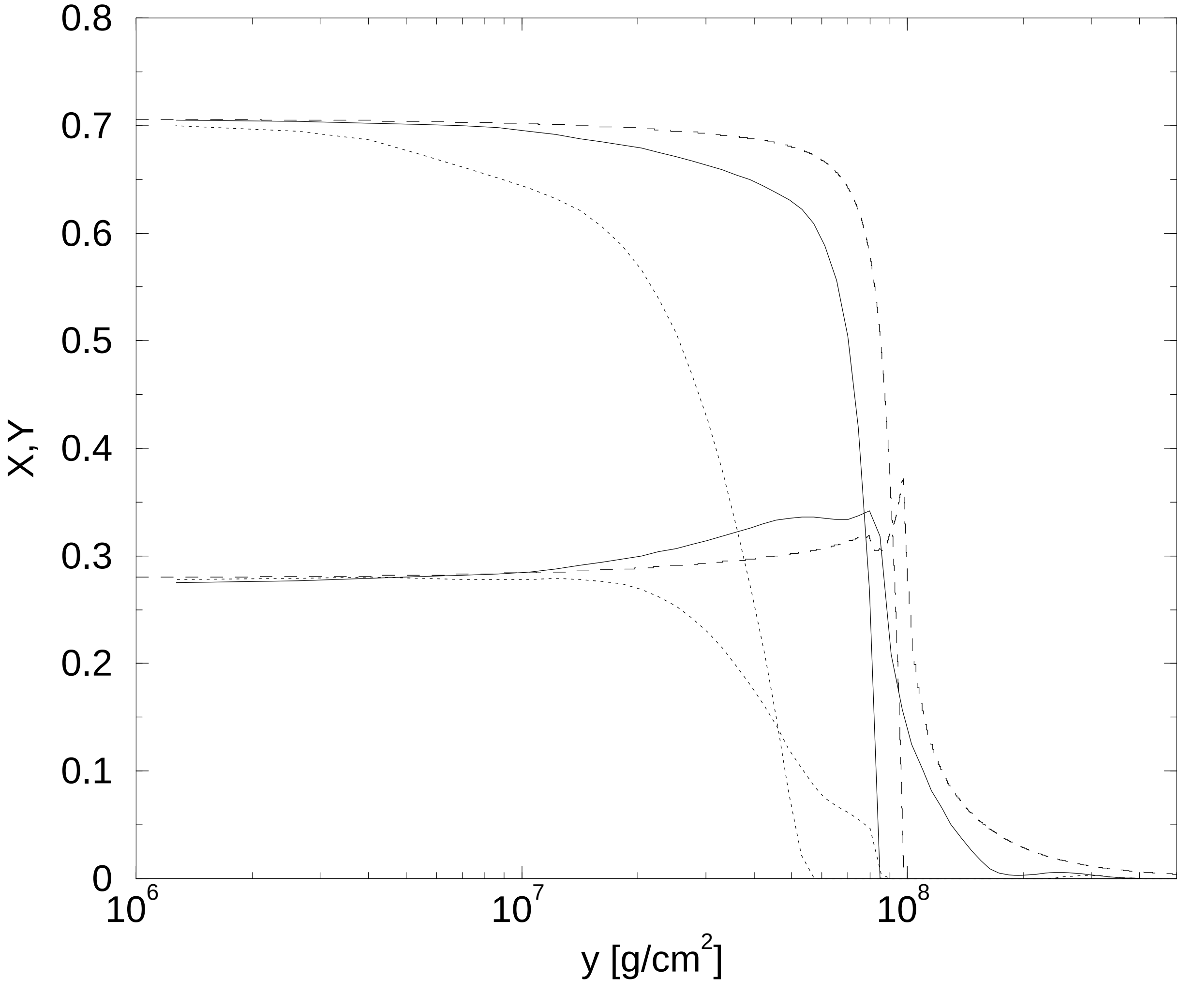
$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}(e^+,\nu)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(e^+,\nu)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$$

The beta-limited HCNO-cycle approximation

$$r_\mathrm{H} = \frac{1}{4}\frac{\lambda_{^{15}\mathrm{O}}\lambda_{^{14}\mathrm{O}}}{\lambda_{^{15}\mathrm{O}} + \lambda_{^{14}\mathrm{O}}} X_\mathrm{HCNO}$$

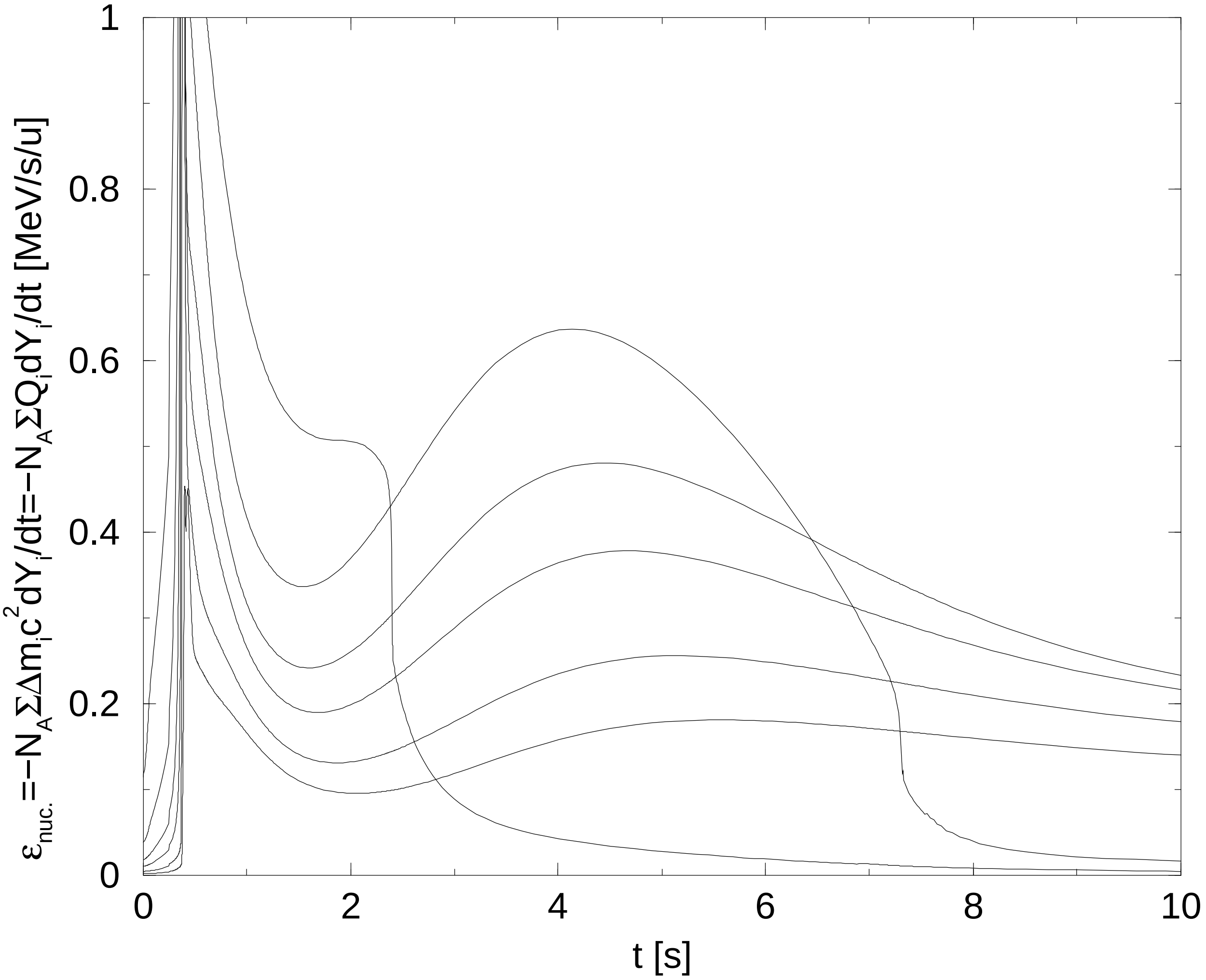
$$\begin{aligned} \frac{dX_\mathrm{H}}{dt} &= -r_\mathrm{H} \\ \frac{dX_\mathrm{He}}{dt} &= -4r_\mathrm{He} + r_\mathrm{H} \\ \frac{dX_\mathrm{HCNO}}{dt} &= 4r_\mathrm{He} \end{aligned}$$

The fuel surfaces



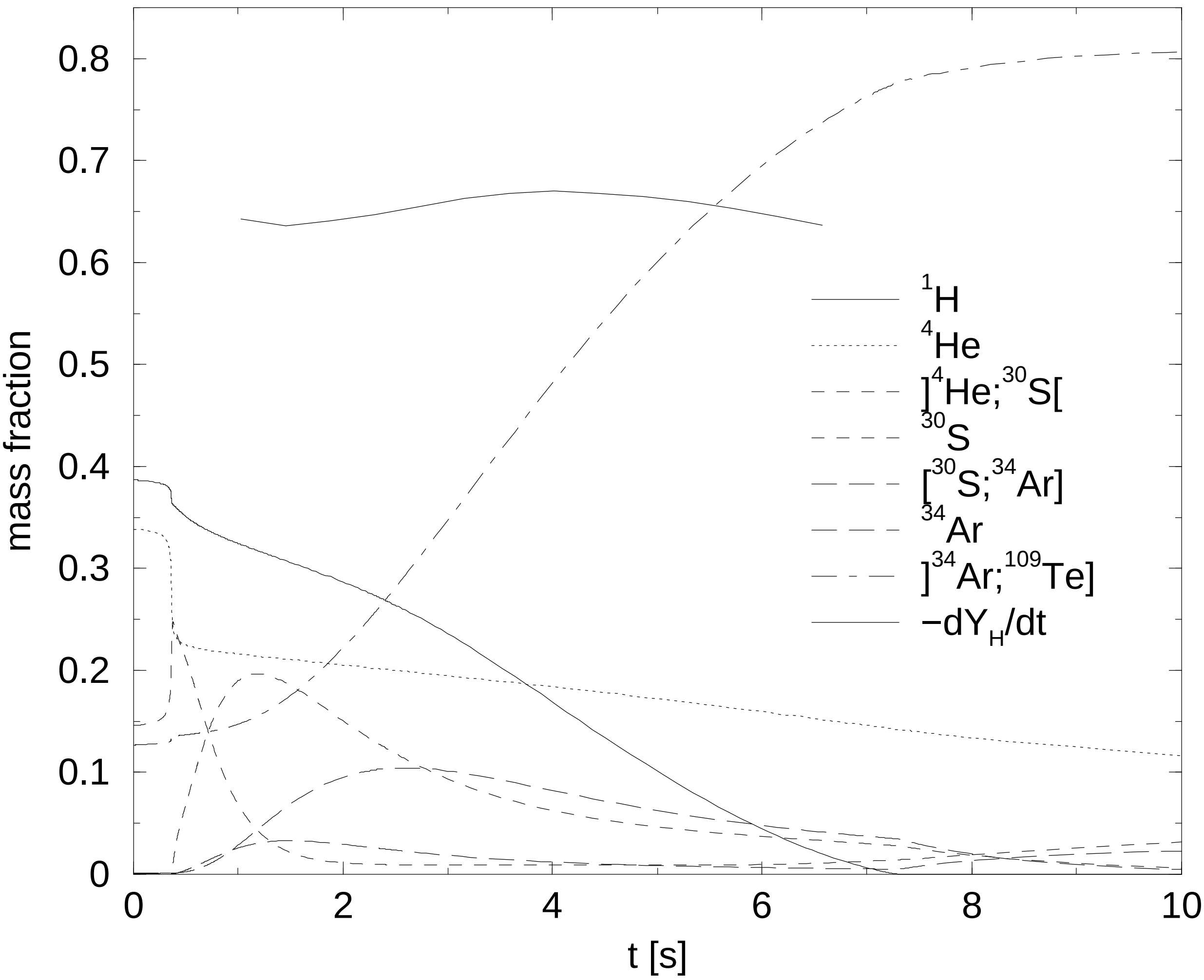
$$\frac{1}{\rho}\frac{dP}{dr} - g = \frac{dv}{dt},\; P(r) = gy(r),\; y = \int_{R-r}^{R} \rho dr$$

Nuclear energy generation



$y = 7.96 \times 10^7$g/cm^2, $y = 7.46 \times 10^7$g/cm^2, $y = 7.01 \times 10^7$g/cm^2, $y = 6.57 \times 10^7$g/cm^2, $y = 5.70 \times 10^7$g/cm^2, $y = 4.93 \times 10^7$g/cm^2

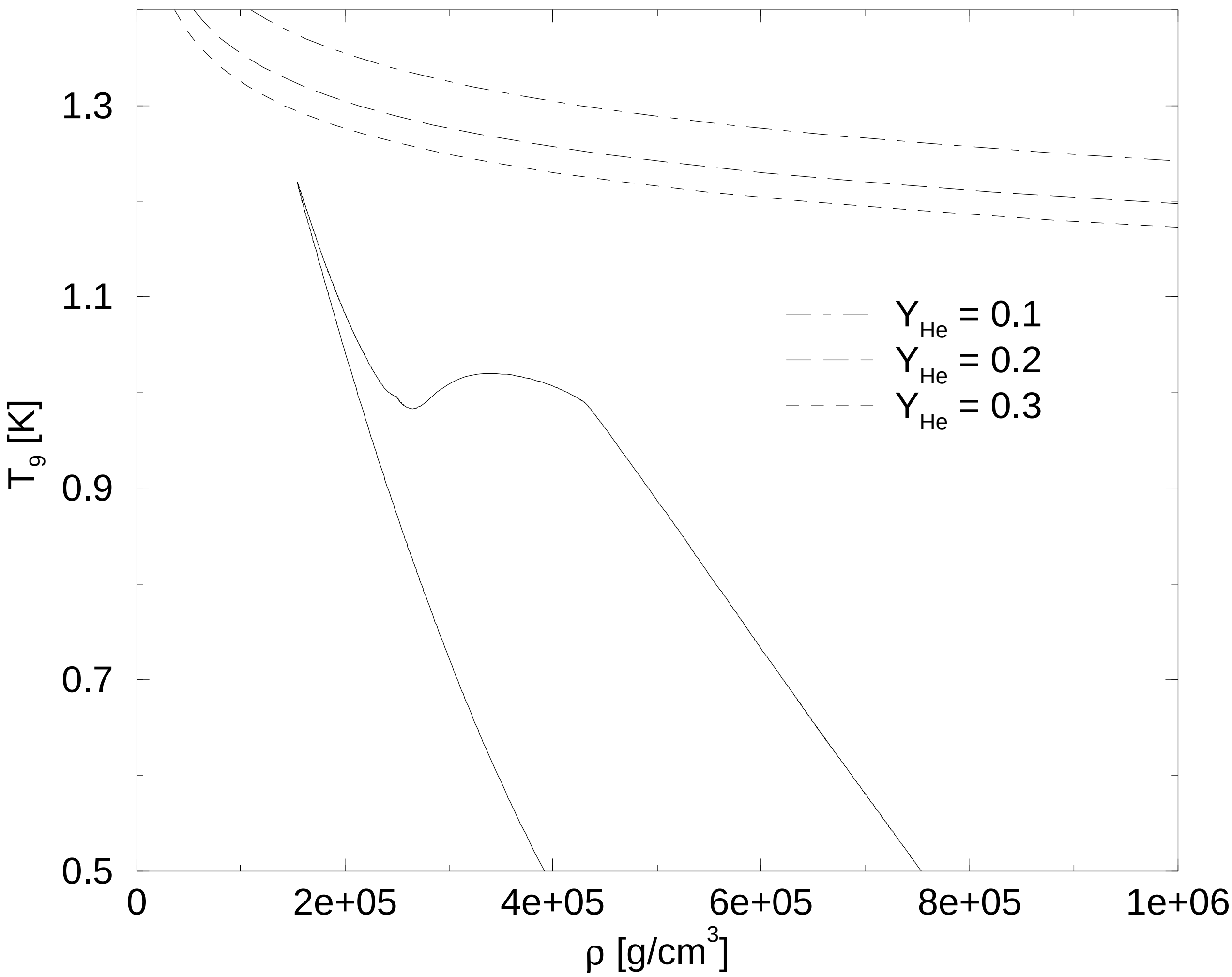
Mass fraction evolution



Waiting points:
^{30}S ($T_{1/2} = 1.18$s) and ^{34}Ar ($T_{1/2} = 0.844$s)

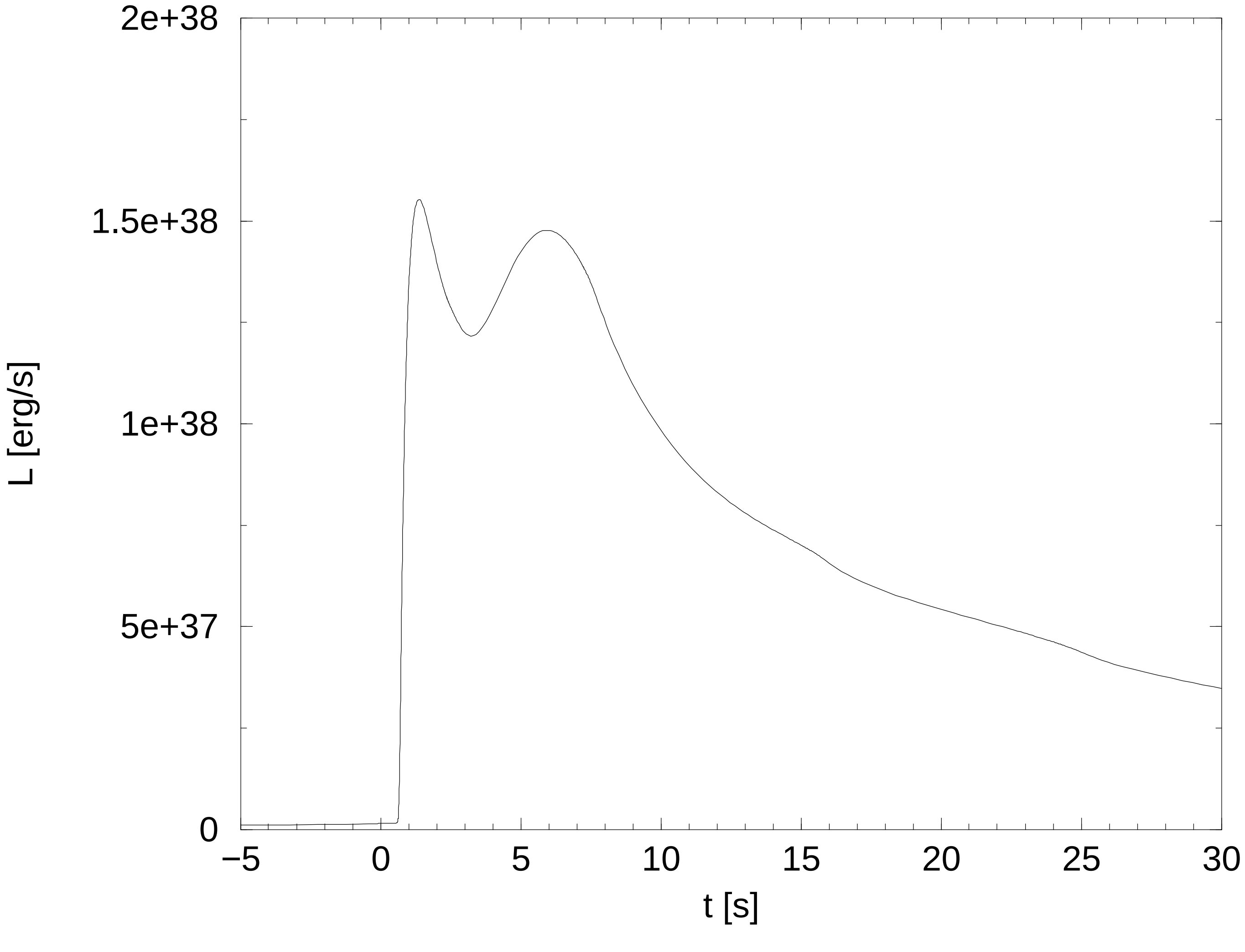
(α, p)-process bottleneck

Burst trace at $y = 7.46 \times 10^7$g/cm^2



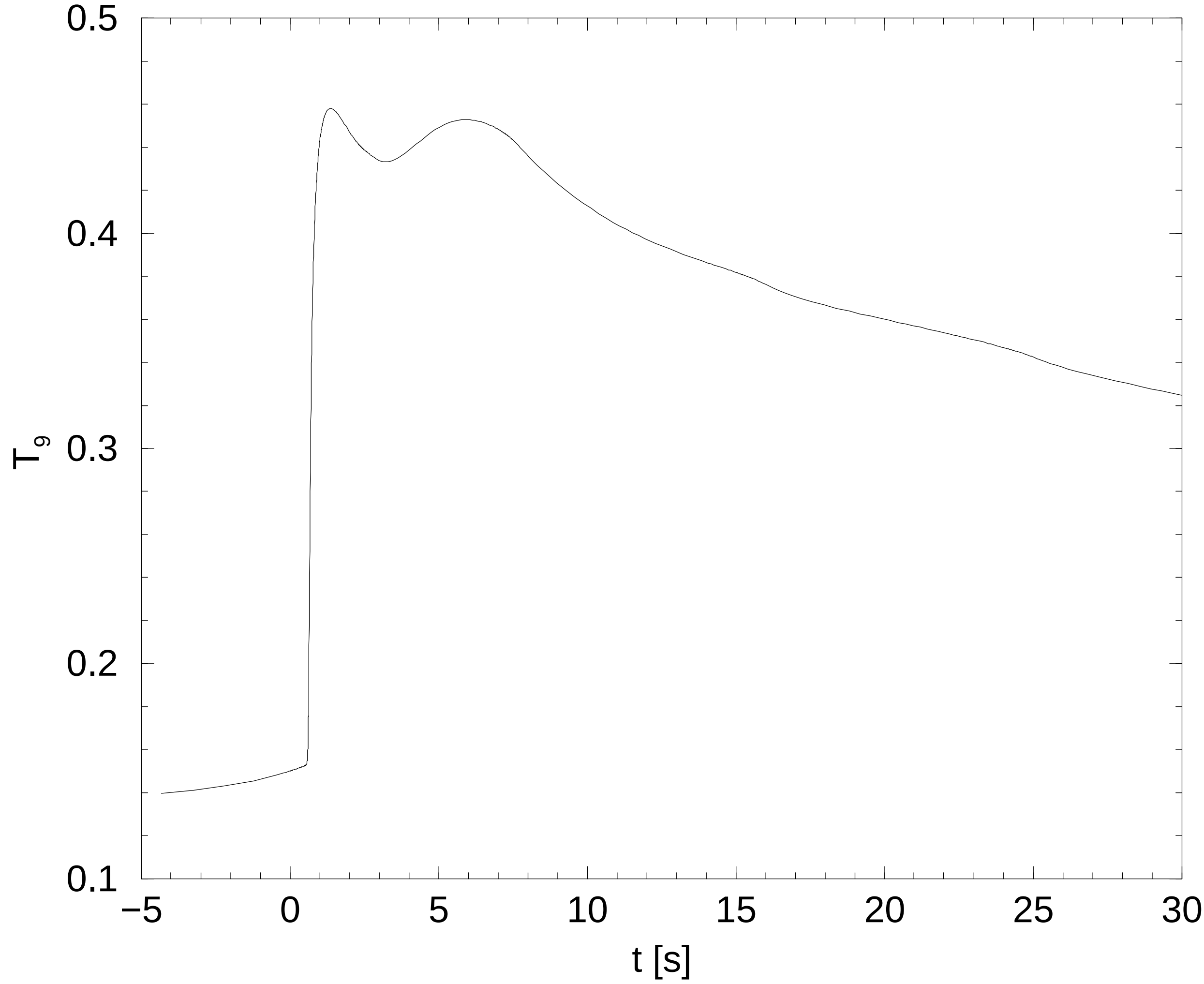
^{30}S$(e^+, \nu_e)^{30}$P vs. ^{30}S$(\alpha, p)^{33}$Cl

Observable effects



$M = 1.41 M_{\odot}$, $R = 10$km, $\dot{M} = 10^{17}$g/s

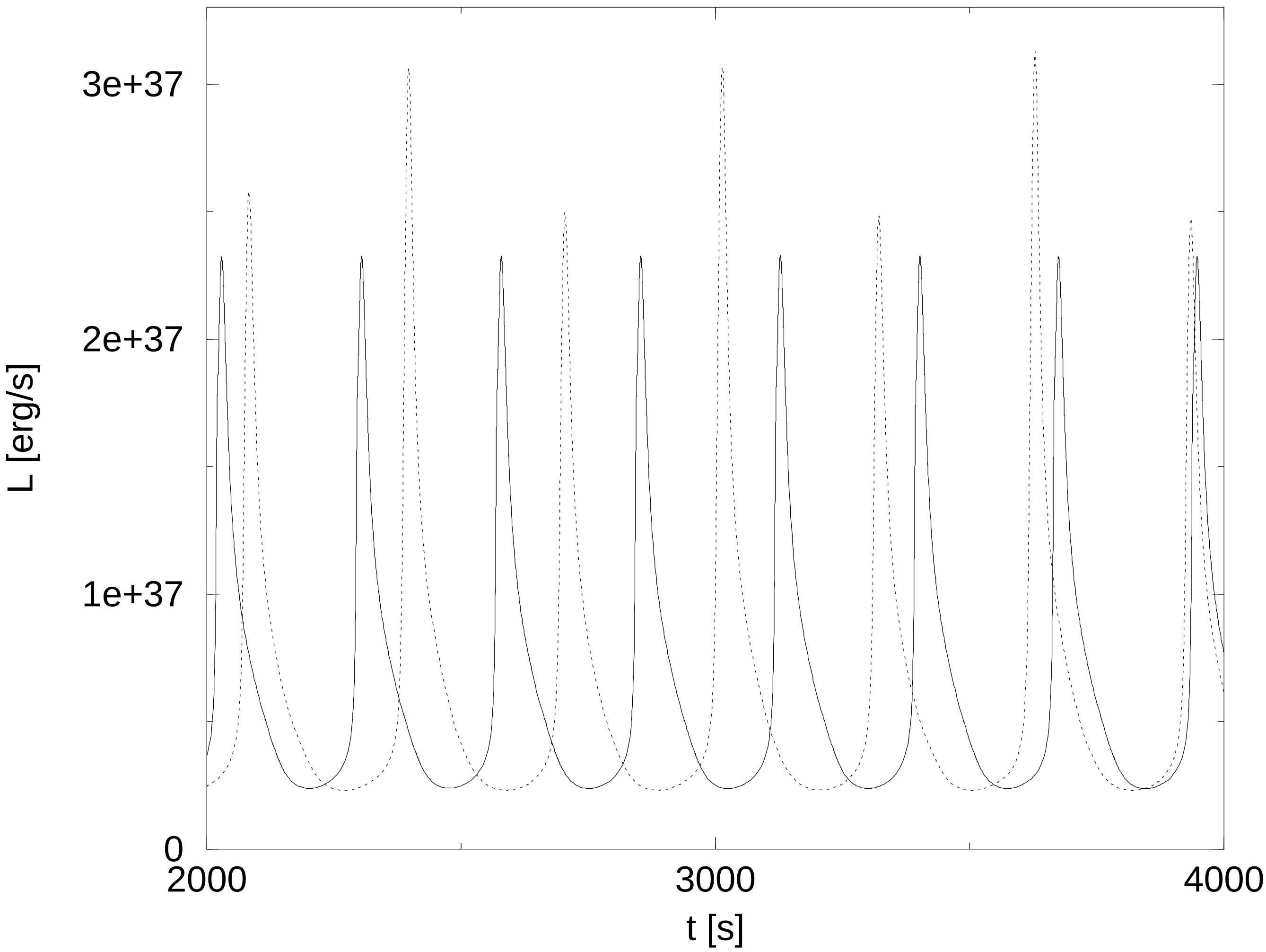
Temperature evolution



$M = 1.41 M_\odot$, $R = 10$km, $\dot{M} = 10^{17}$g/s

The importance of reaction rates

REACLIB95 (solid)
vs.
REACLIB95+pfSM
^{45}V(p,γ), ^{46}V(p,γ), ^{47}V(p,γ) ,^{49}Mn(p,γ)



$\dot{M} = 10^{18}$g/s, $R = 10$km, $M = 1.41 M_\odot$

Conclusion & Outlook

- Important to consider dynamical burning effects
- Nuclear reaction rates determine:
  Hydrogen fuel surface & Recurrence time
- Exhaust model capabilities (inner boundary, super-bursts, supernova fallback, critical accretion rate)