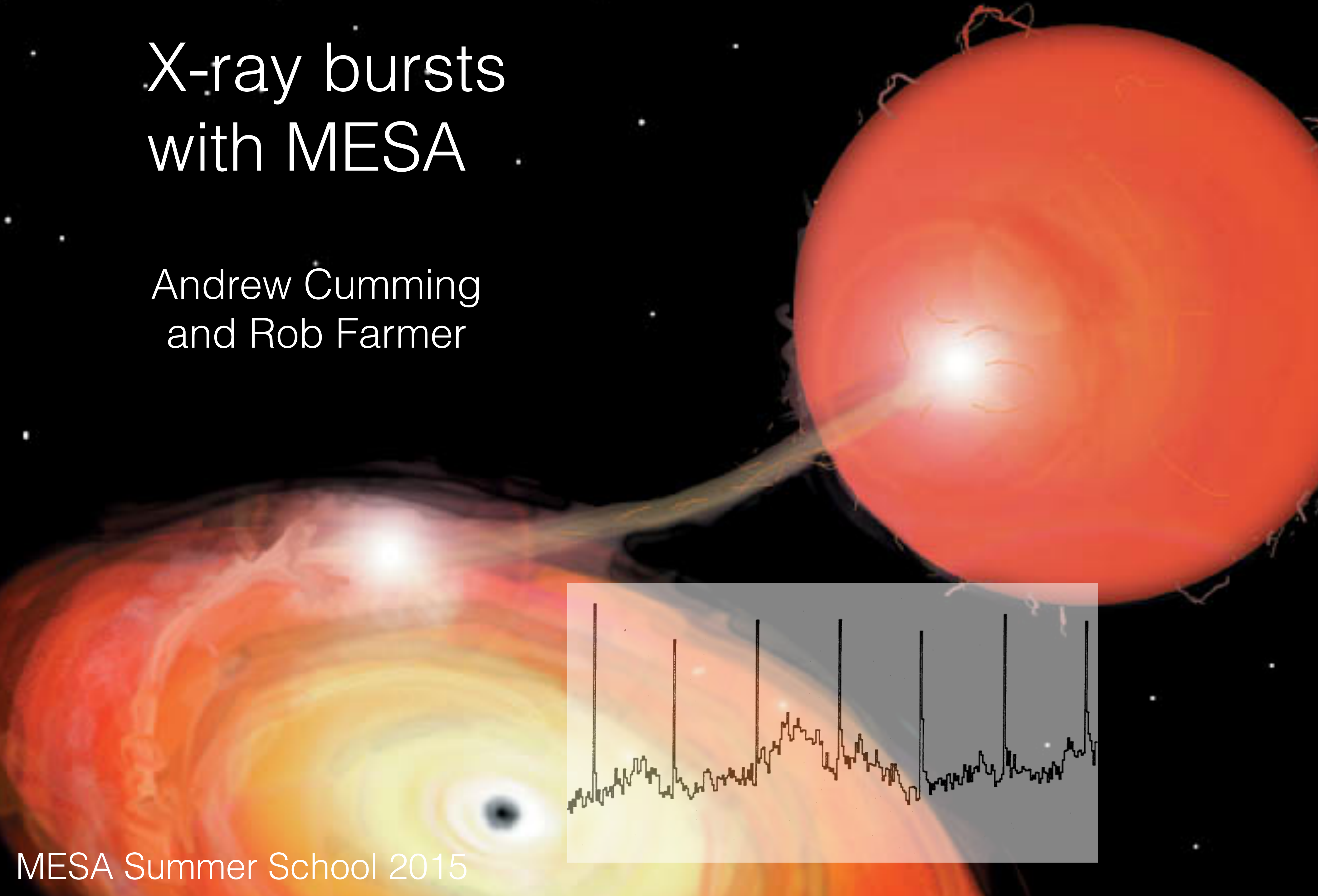
X-ray bursts with MESA

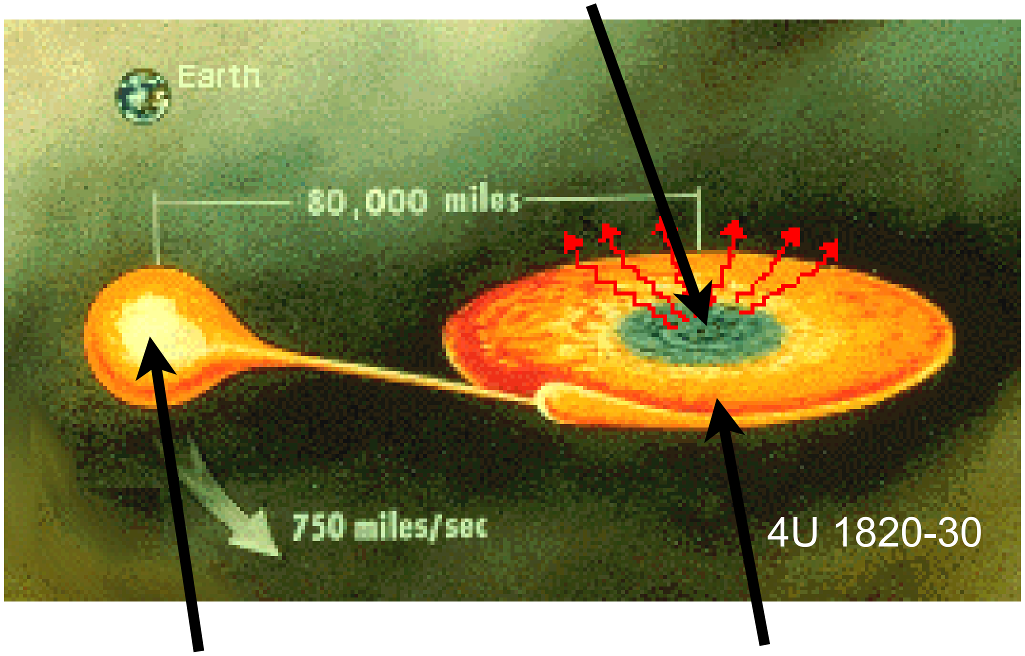
Andrew Cumming
and Rob Farmer



MESA Summer School 2015

Low mass X-ray binaries

neutron star



tidally-distorted companion

$M \lesssim 1 M_\odot$

accretion disk

neutron star accreting from a low mass companion

orbital periods range from 10 mins to >days, depending on the type of companion star

typical mass transfer rates are

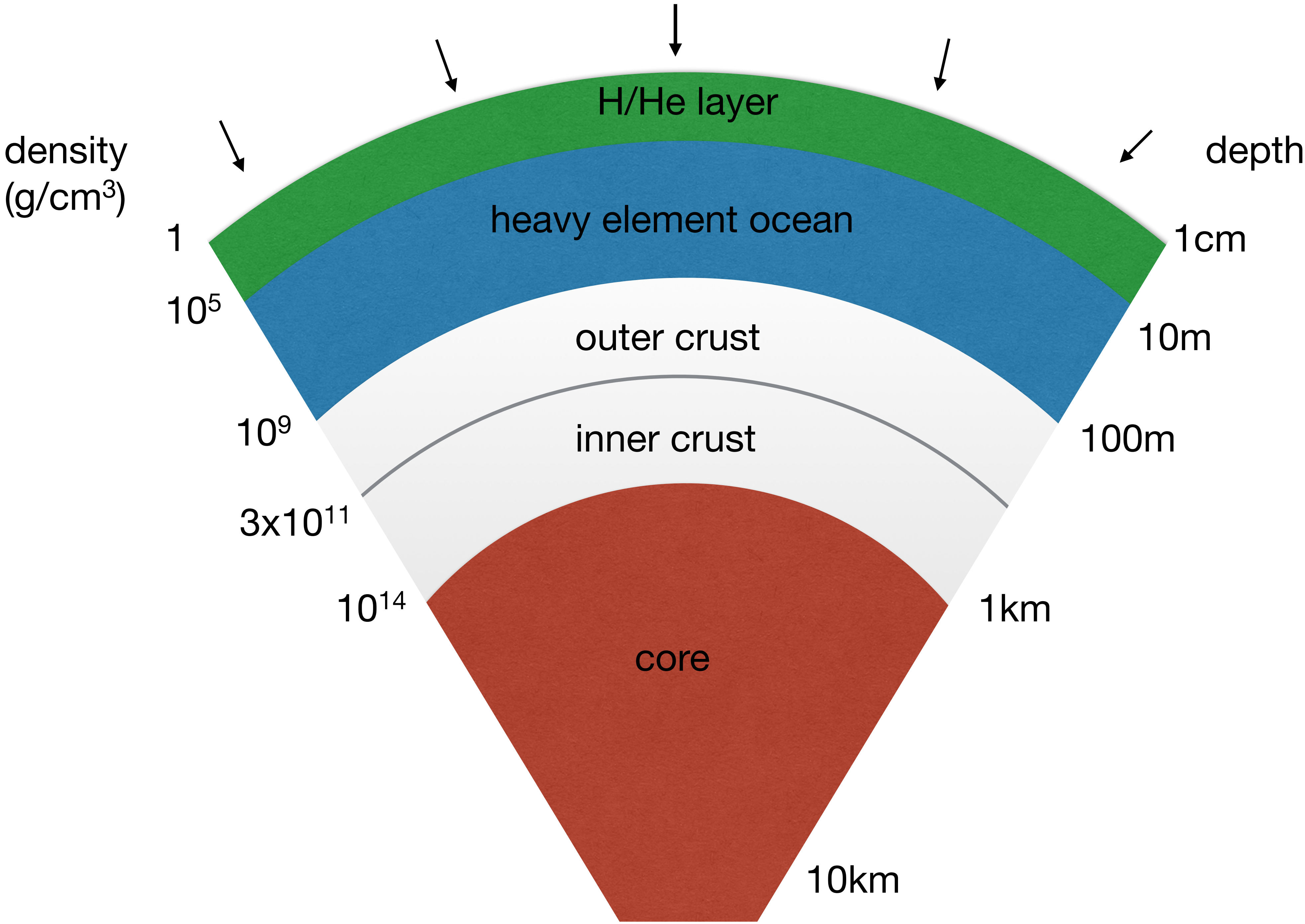
$$\dot{M} \sim 10^{-11} - 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$$
$$\sim 10^{15} - 10^{18}\ \mathrm{g\ s}^{-1}$$

giving an accretion luminosity

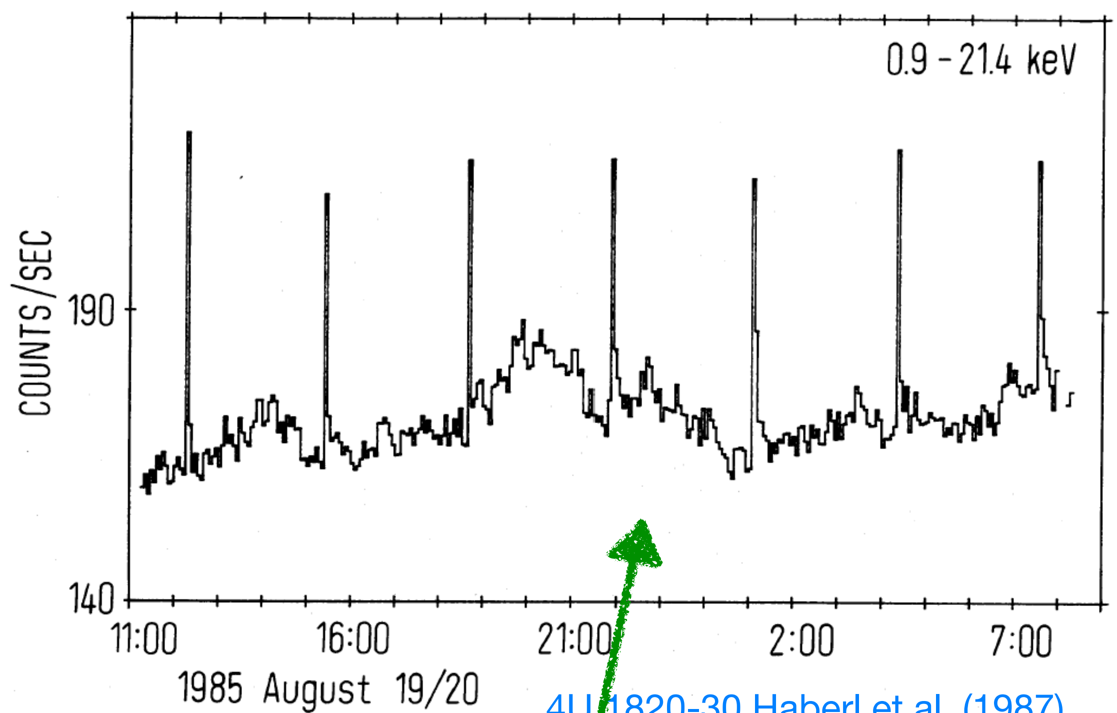
$$L_X \approx \dot{M}\frac{GM_{NS}}{R_{NS}}$$
$$\sim 10^{35} - 10^{38}\ \mathrm{erg\ s}^{-1}$$

(in outburst) these are bright X-ray sources

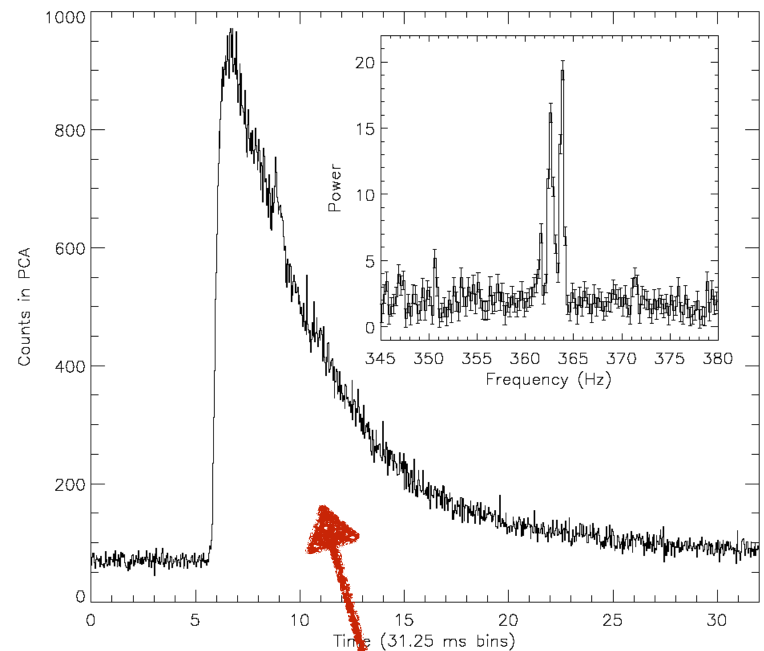
Structure of an accreting neutron star



Basic energetics of bursts



4U 1820-30 Haberl et al. (1987)



4U 1728-34 Strohmayer et al. (1996)

gravitational energy release

$$\frac{GM}{R} \approx 200 \text{ MeV per nucleon}$$

nuclear energy release

$$Q_{\text{nuc}} \approx (1-5) \text{ MeV per nucleon}$$

Their ratio is $\alpha \equiv \dfrac{\int F_p\, dt}{\int F_b\, dt} \approx \dfrac{GM/R}{Q_{\text{nuc}}} \approx (40-100)$

What is a thin shell flash?

In a thin layer, the pressure is fixed by the weight of overlying layers

$$P = gy$$

pressure

gravity $\frac{GM}{R^2}$

column depth (g/cm^2)

(an example of hydrostatic balance)

Column depth is a useful coordinate because it tells you about mass and pressure — we'll use it later in our pgstar plots

The pressure scale height is

$$H = -\frac{P}{dP/dr} = \frac{y}{\rho}$$

What is a thin shell flash?

The entropy equation is then

no dP term (constant pressure)

$$TdS = dU + PdV = c_P dT$$

$$c_P \frac{dT}{dt} = \epsilon_{\rm heat} - \epsilon_{\rm cool}$$

e.g. ideal gas

$$c_P = \frac{5}{2} \frac{k_B}{\mu m_p}$$

heating by nuclear reactions (erg g^{-1} s^{-1})

cooling of the layer (heat transport to the surface)

What is a thin shell flash?

$$c_P \frac{dT}{dt} = \epsilon_{\rm heat} - \epsilon_{\rm cool}$$

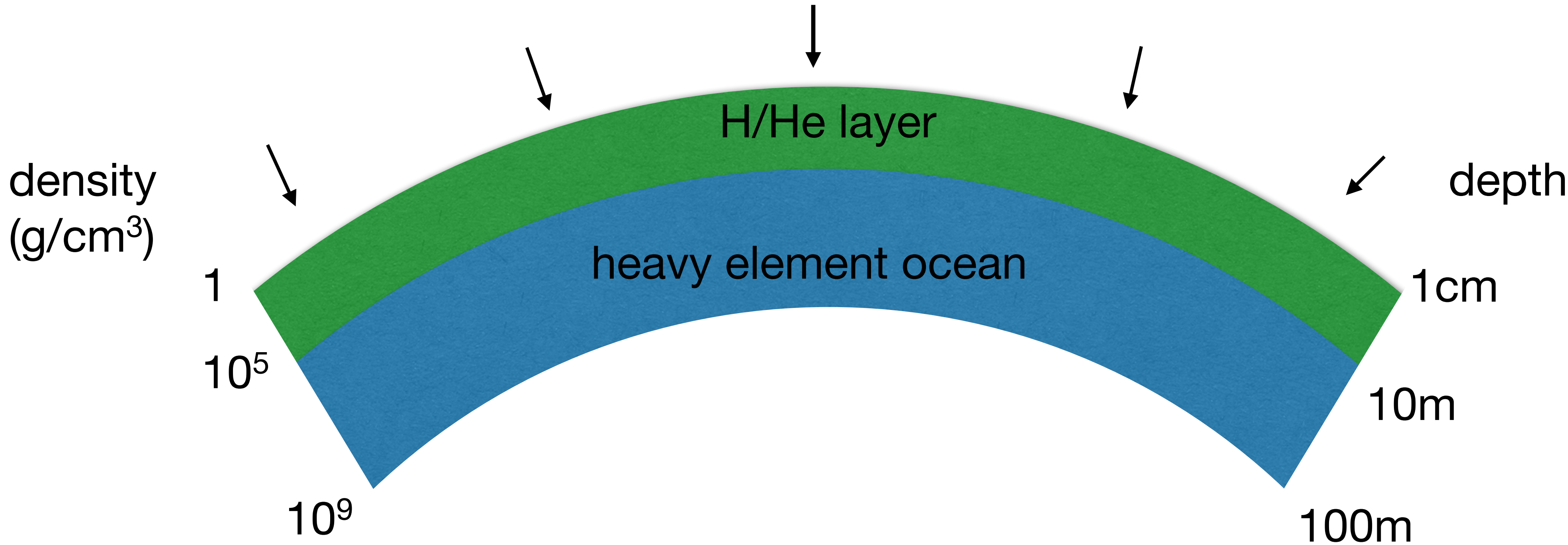
Perturb the temperature: $T \rightarrow T + \delta T$ (with pressure held constant)

$$c_P \frac{\partial \delta T}{\partial t} = \delta T \left[\frac{d\epsilon_{\rm heat}}{dT} - \frac{d\epsilon_{\rm cool}}{dT} \right]$$

We will get a thermal runaway if $\boxed{\frac{d\epsilon_{\rm heat}}{dT} > \frac{d\epsilon_{\rm cool}}{dT}}$

Examples: Type I X-ray bursts; classical novae; helium shell flashes in AGB stars

Structure of an accreting neutron star in MESA



Neutron stars in MESA: `neutron_star_envelope` test suite

HOW_TO

```
create envelope of about 10^-11 Msun pure Fe56
for 1.4 Msun neutron star with radius 10 km.
L from core = 1e33 erg/sec


1 change net and tau factor

      change_net = .true.
      new_net_name = 'cno_extras_plus_fe56.net'

      set_tau_factor = .true. ! change tau_factor without reconverging.
      set_to_this_tau_factor = 75

2 remove big part of inner mass

      remove_inner_fraction_q = 0.9

3 remove more mass

      remove_inner_fraction_q = 0.99

4 remove more and convert all to fe56

      remove_inner_fraction_q = 0.99

      set_to_xa_for_accretion = .true.
      set_nzlo = 1
      set_nzhi = 99999

      accrete_same_as_surface = .false.
      accrete_given_mass_fractions = .true.
      num_accretion_species = 1
      accretion_species_xa(1) = 1
      accretion_species_id(1) = 'fe56'
```

Line: 6 Column: 1 Plain Text Tab Size: 4 —

HOW_TO

```
5 remove more mass
      remove_inner_fraction_q = 0.999

6 remove more mass
      remove_inner_fraction_q = 0.999

7 change M_center
      relax_M_center = .true.
      new_mass = 1.4
      dlgm_per_step = 1d-3
      relax_M_center_dt = 3.1558149984d-1 ! secyer*1d-8

8 change R_center
      relax_R_center = .true.
      new_R_center = 1d6 ! in cm
      dlgR_per_step = 1d-2
      relax_R_center_dt = 3.1558149984d-1 ! secyer*1d-8

9 change L_center
      relax_L_center = .true.
      new_L_center = 1e34 ! in ergs/second
      dlgL_per_step = 1d-2
      relax_L_center_dt = 3.1558149984d-1 ! secyer*1d-8
```

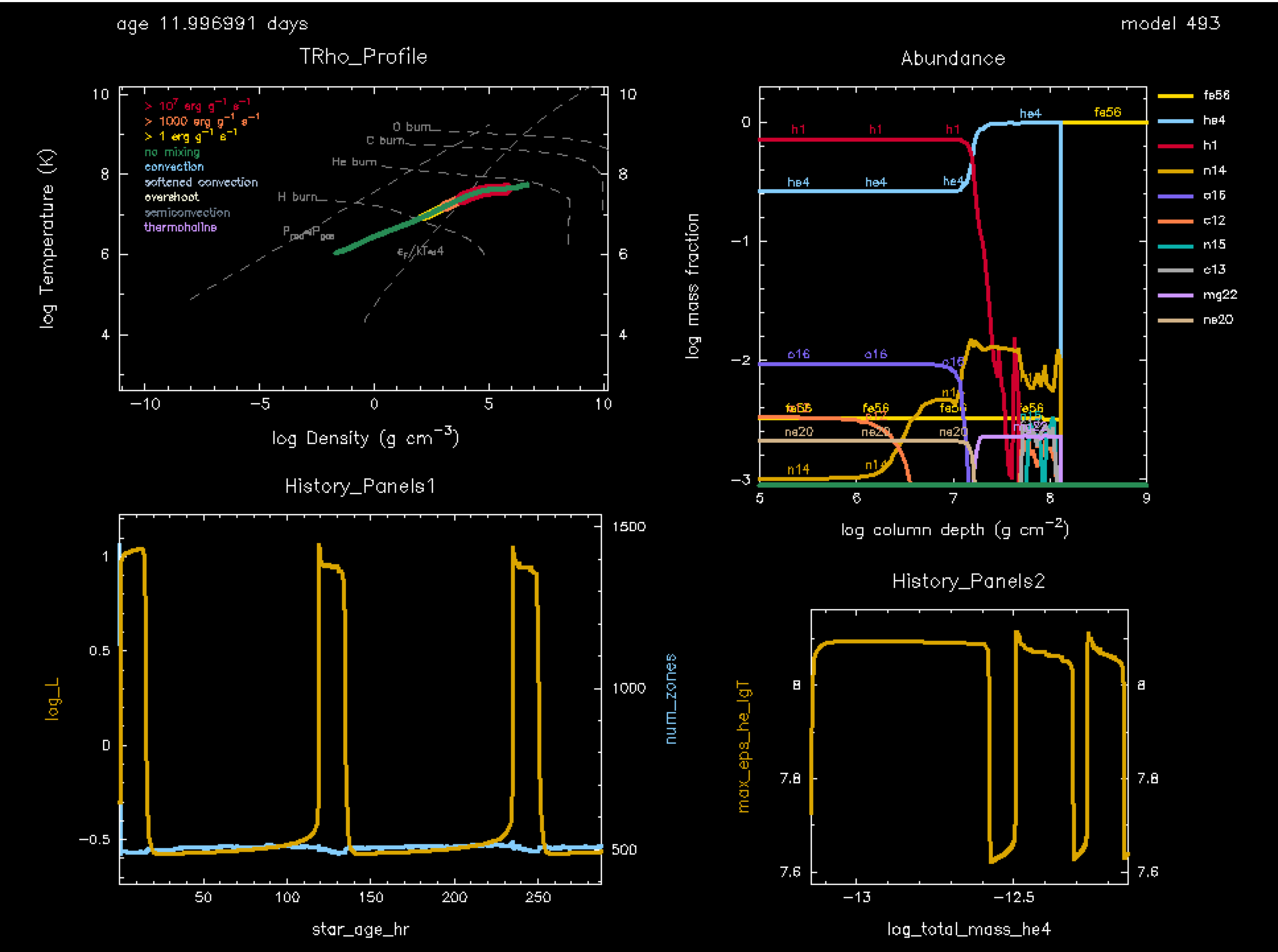
Line: 73 Column: 1 Plain Text Tab Size: 4 —

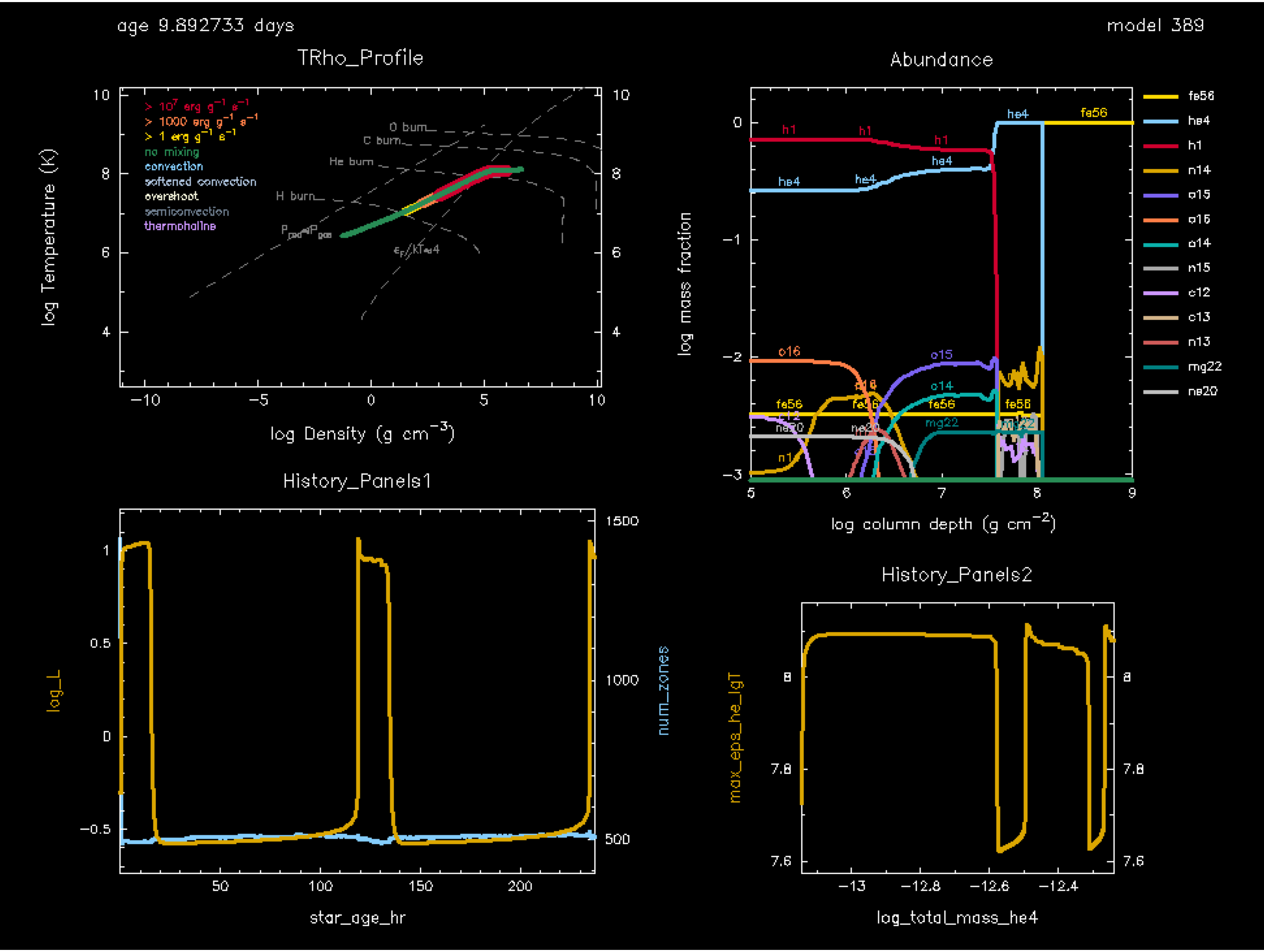
Minilab part 1: Up and running

- Copy the `ns_h` test suite and use it to generate a sequence of flashes
- Instructions are in the file `minilab.pdf`

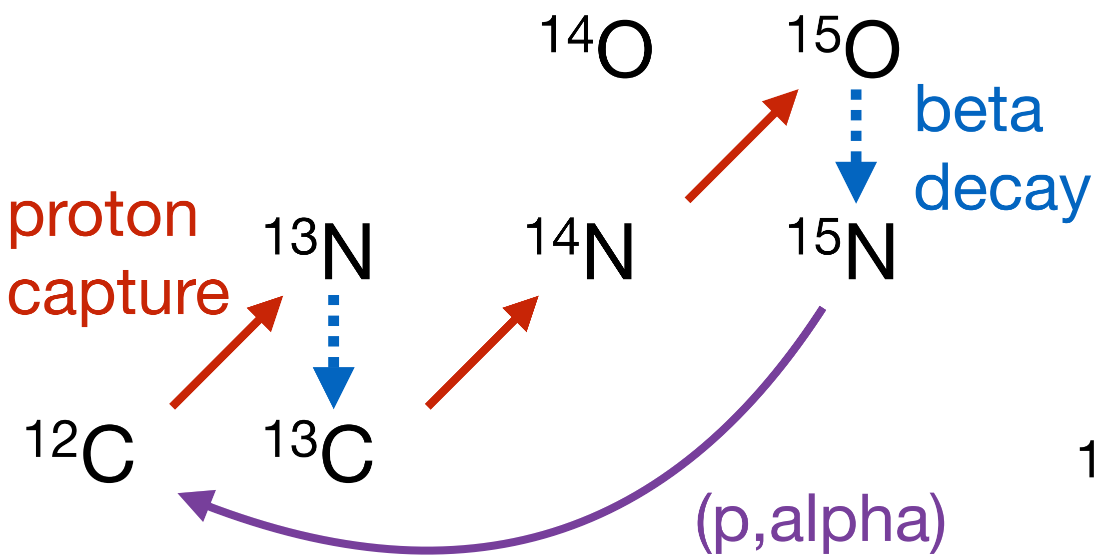
Questions

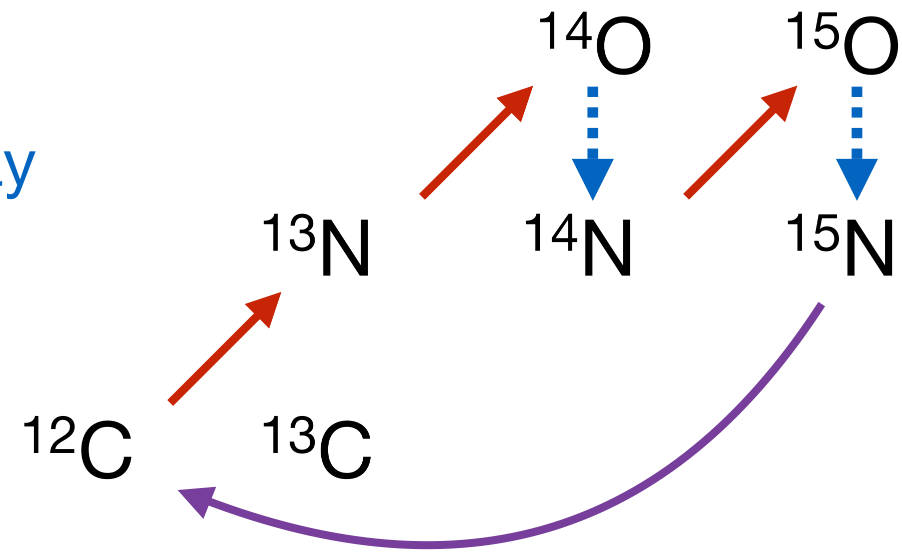
- What is the scale height of the layer?
- What is the recurrence time of the flashes?
- What is the peak luminosity, and what do you think sets this physically?
- What fuel is burning in the flash?
- What happens to the CNO elements in the layer?
- What do you think will happen if you run the simulation for a long time?


age 11.996991 days
model 493
TRho_Profile
log Temperature (K)
log Density (g cm^{-3})
> 10^7 erg g^{-1} s^{-1}
> 1000 erg g^{-1} s^{-1}
> 1 erg g^{-1} s^{-1}
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
$P_{rad}=P_{gas}$
$\epsilon_F/kT=4$
Abundance
log mass fraction
log column depth (g cm^{-2})
fe56
he4
h1
n14
o16
c12
n15
c13
mg22
ne20
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4


age 9.892733 days
model 389
TRho_Profile
log Temperature (K)
log Density (g cm^-3)
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
Abundance
log mass fraction
log column depth (g cm^-2)
fe56
he4
h1
n14
o15
o16
o14
n15
c12
c13
n13
mg22
ne20
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4

How hydrogen burns on an accreting neutron star





main sequence stars

$T < 8 \times 10^7$ K

(cold) CNO cycle

accreting neutron stars

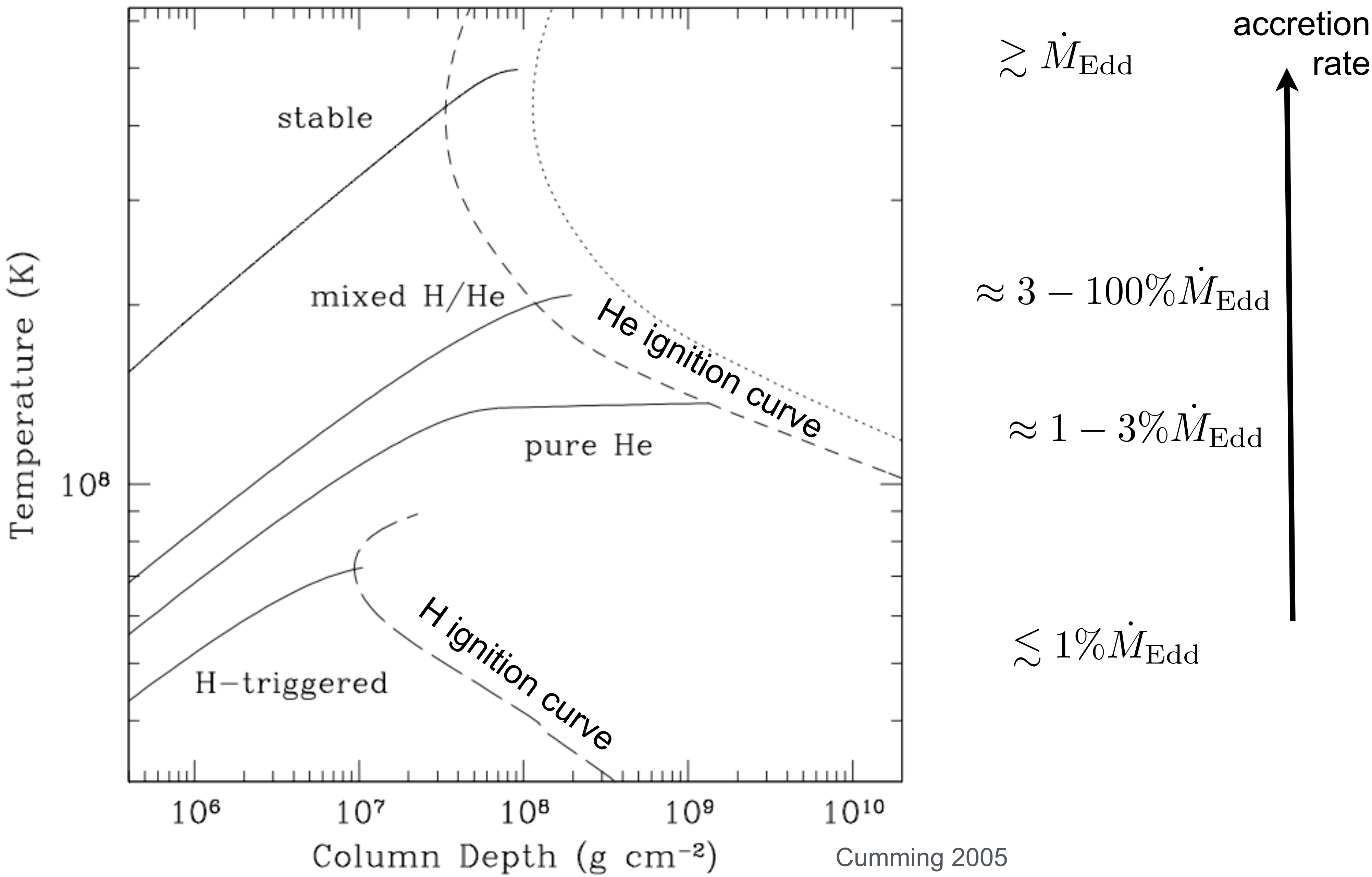
$T > 8 \times 10^7$ K

hot CNO cycle

(^{14}O and ^{15}O beta decay half-lives are 71 and 122s respectively)

$$\epsilon_H = 5.8 \times 10^{13} \left(\frac{Z_{\rm CNO}}{0.01} \right) \text{ ergs g}^{-1} \text{ s}^{-1}$$

Four different regimes of H/He burning



Taam, Woosley, Joss, Fujimoto (late 1970s, 1980s), Bildsten (1998)

Helium burning by the triple alpha reaction

$$3\alpha \rightarrow ^{12}\mathrm{C}$$

energy generation rate

$$\epsilon_{3\alpha} = 5.3 \times 10^{21}\ \mathrm{ergs\ g^{-1}\ s^{-1}}\ f\,\frac{\rho_5^2\, Y^3}{T_8^3}\exp\left(\frac{-44}{T_8}\right)$$

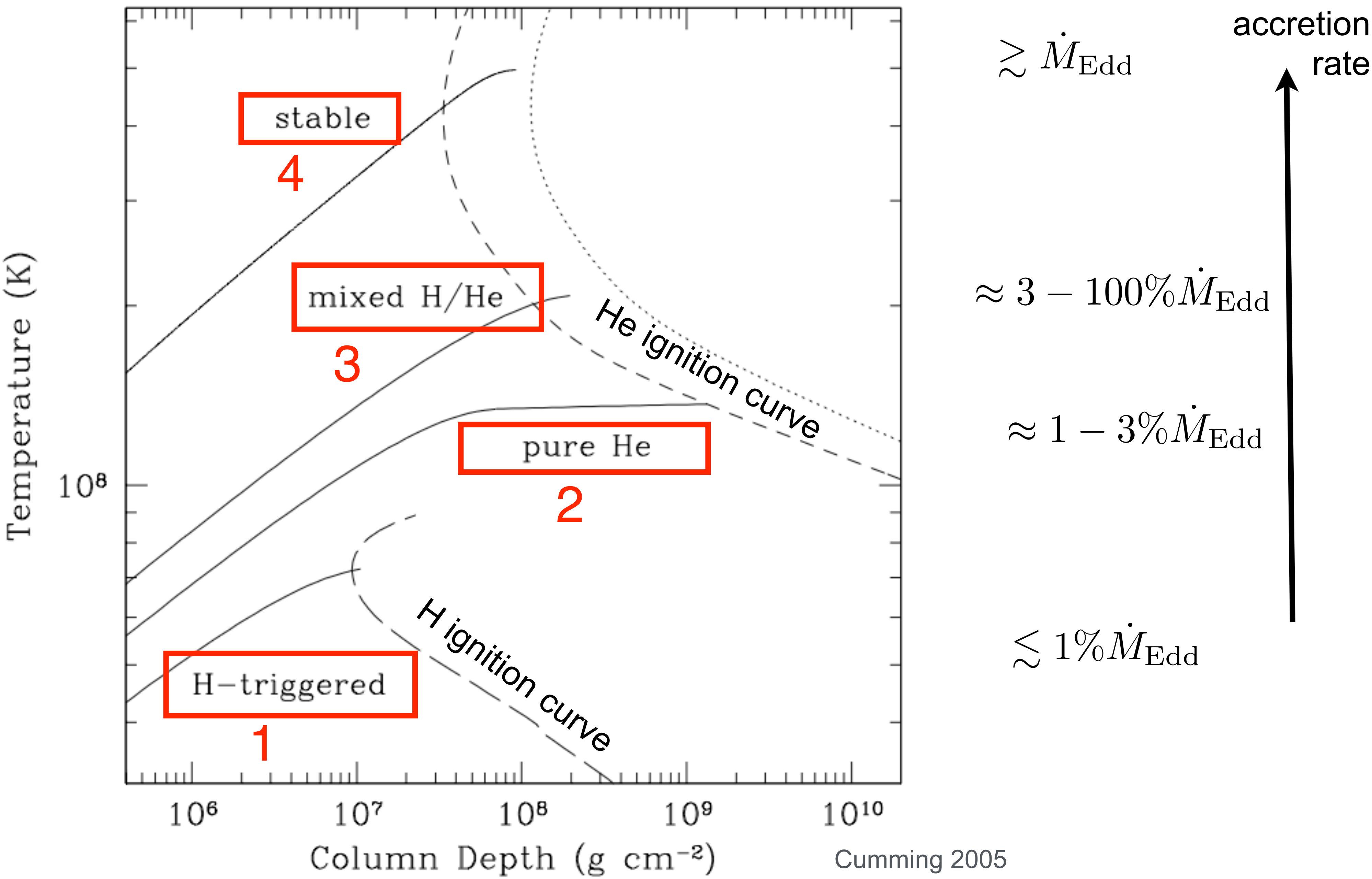
Fushiki & Lamb 1987

temperature sensitivity

$$\epsilon \propto T^{\nu} \qquad \nu = \frac{44}{T_8} - 3$$

the temperature sensitivity becomes <4 at high temperatures
=> stable burning at high accretion rates

Four different regimes of H/He burning

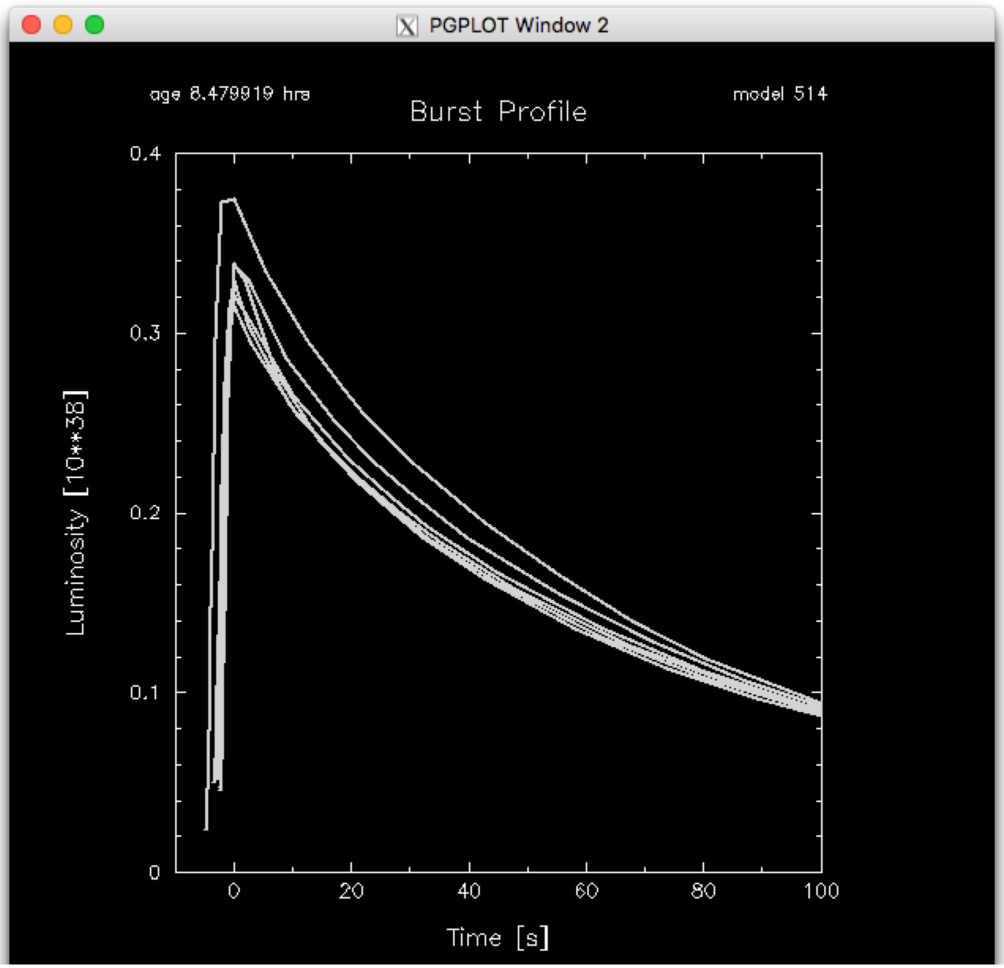


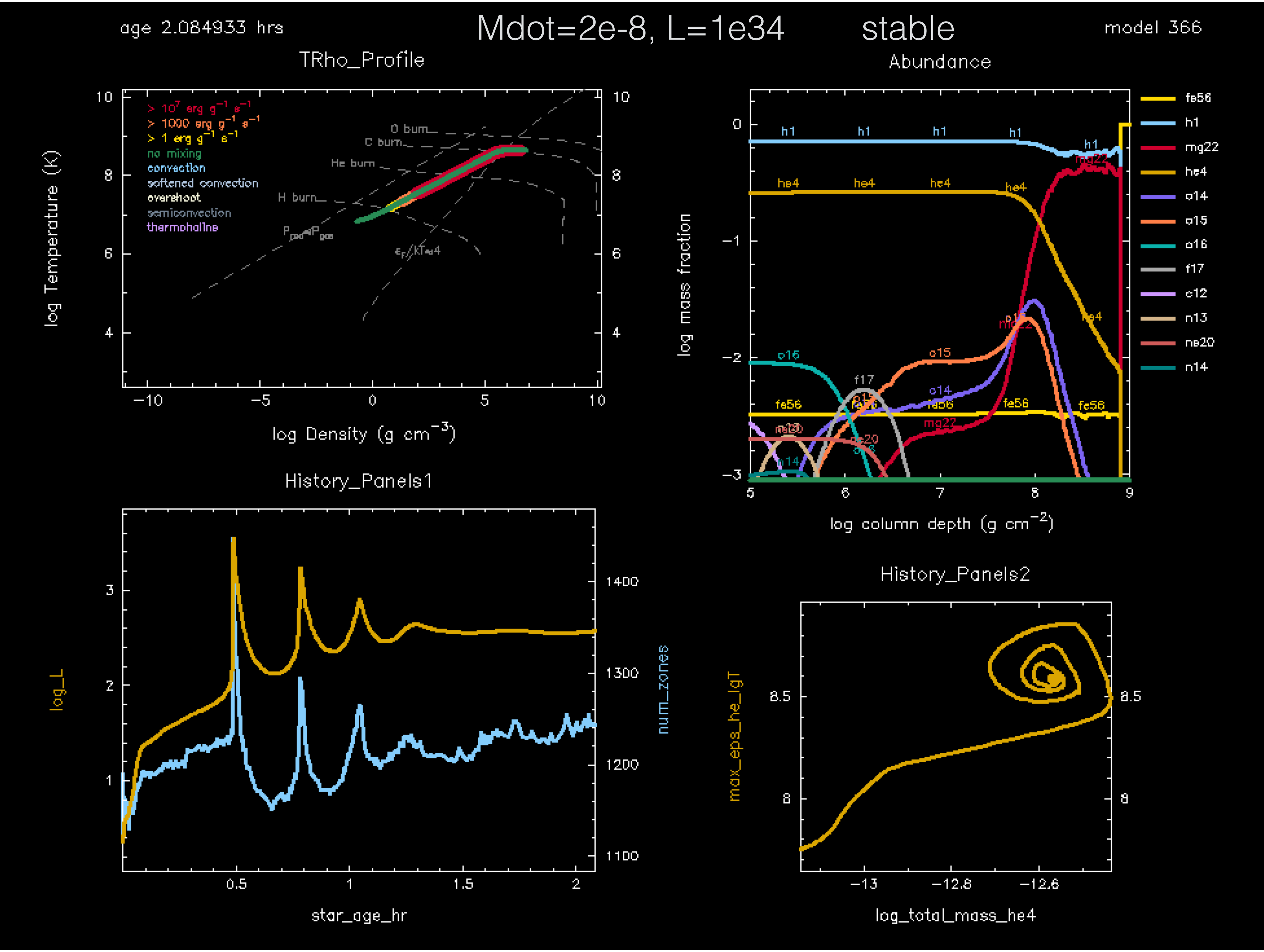
Cumming 2005

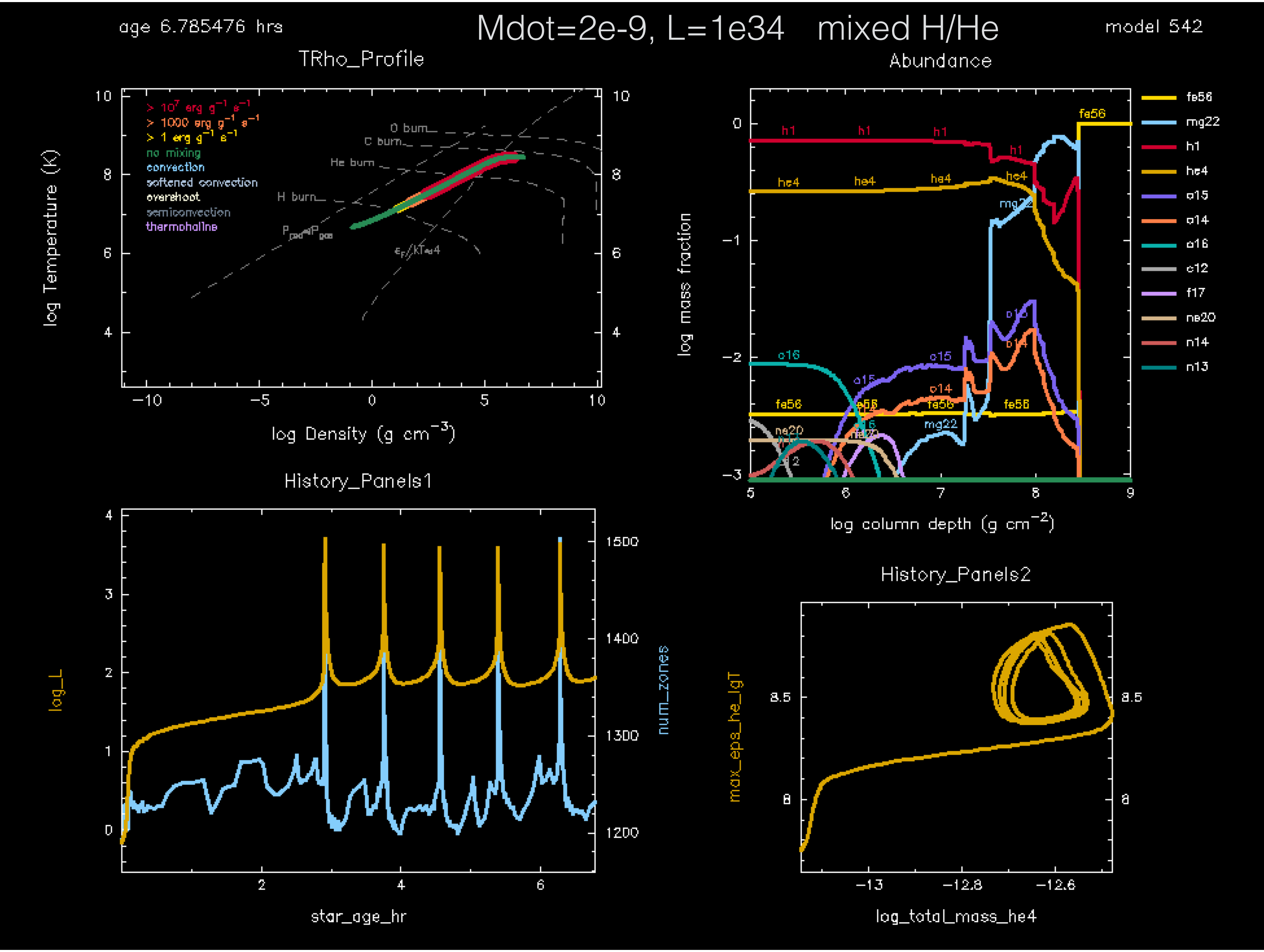
Taam, Woosley, Joss, Fujimoto (late 1970s, 1980s), Bildsten (1998)

Minilab part 2: Burning regimes

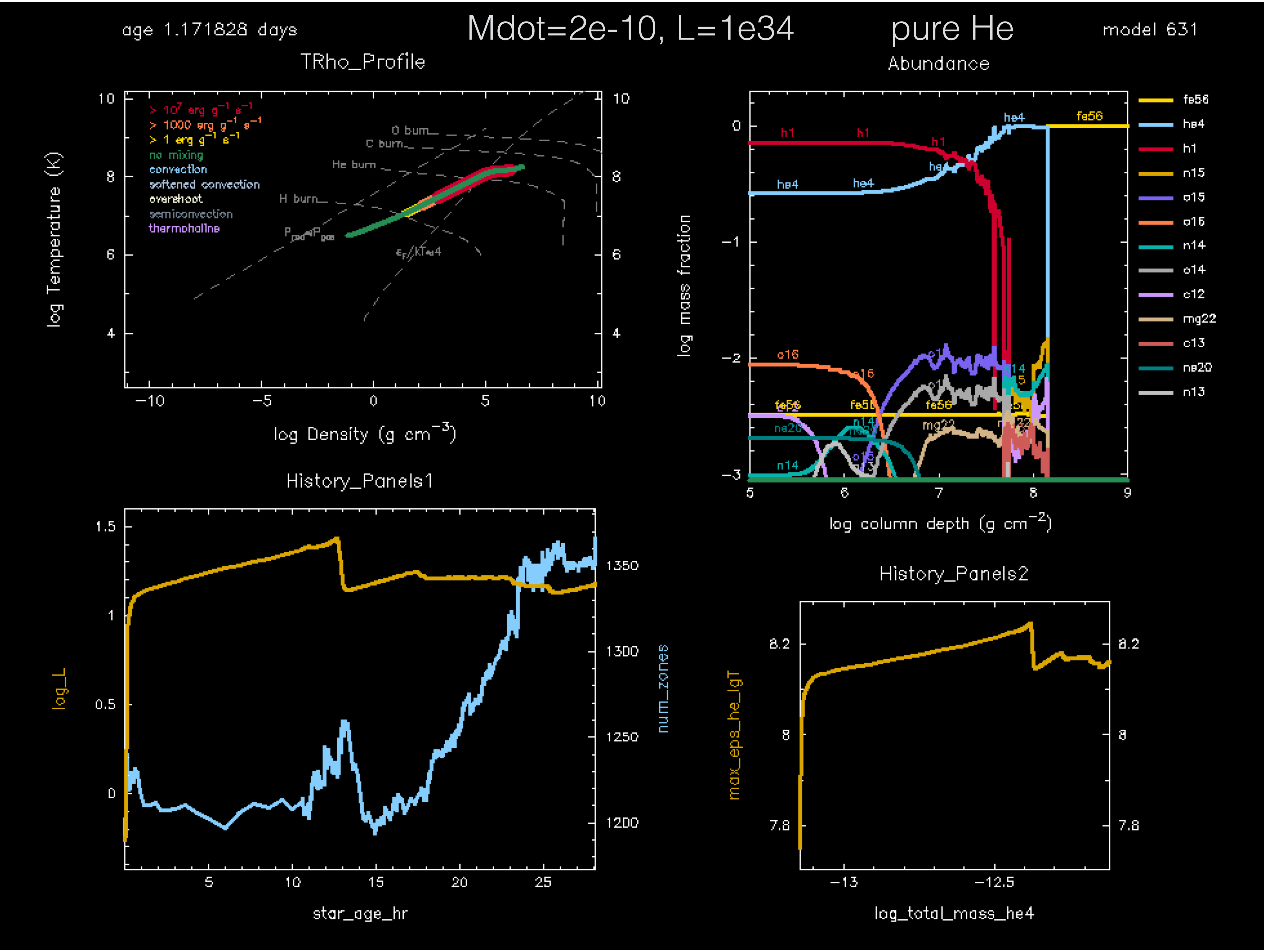
- Basic idea: Do we see the predicted burning regimes in MESA ?
- Every table choose a different accretion rate (on each table, each person choose a different base luminosity)
- New `pgstar` window:



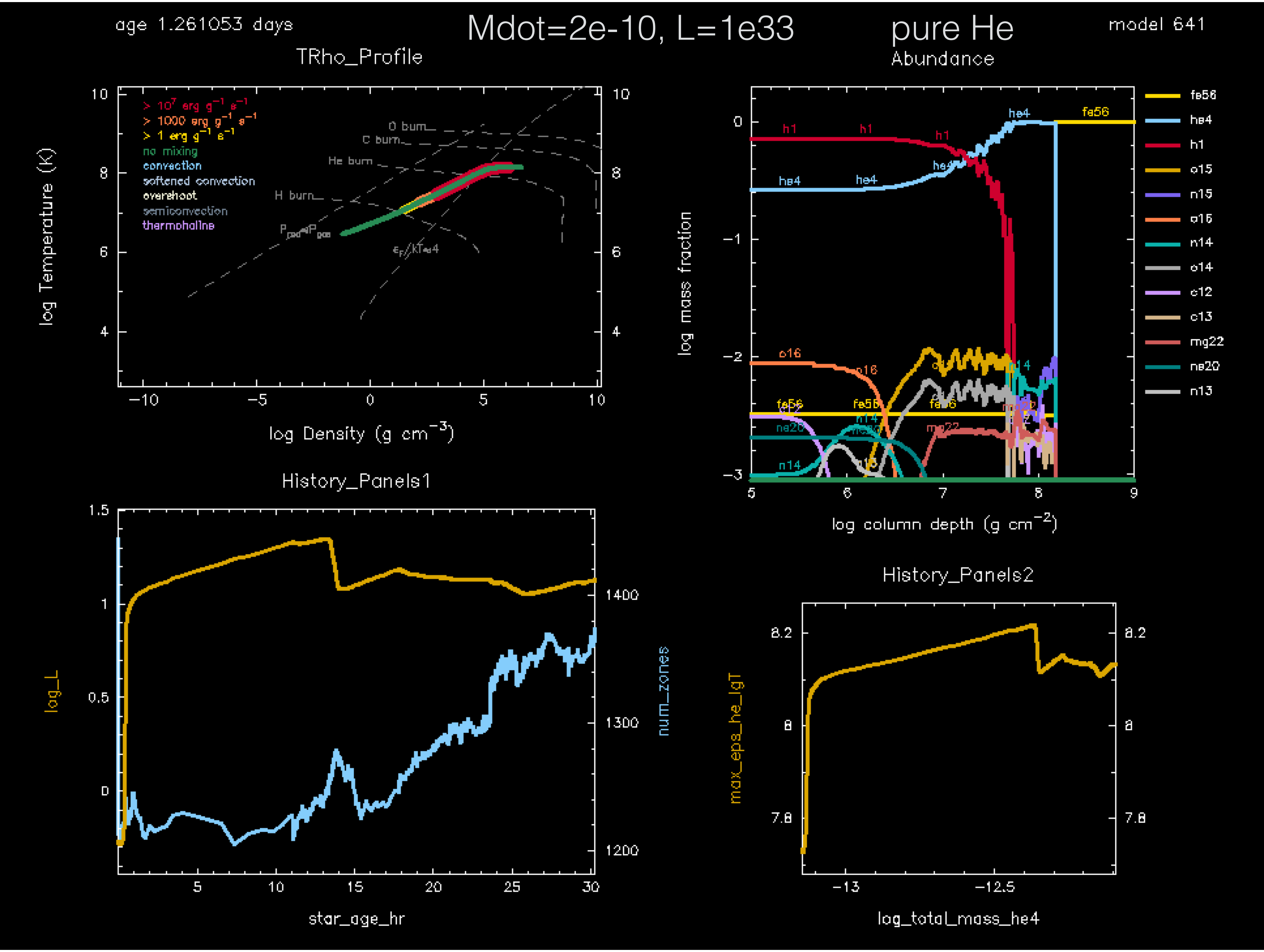

age 2.084933 hrs
Mdot=2e-8, L=1e34 stable
model 366
TRho_Profile
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
log Temperature (K)
log Density (g cm^-3)
Abundance
log mass fraction
log column depth (g cm^-2)
fe56
h1
mg22
he4
o14
o15
o16
f17
c12
n13
ne20
n14
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4

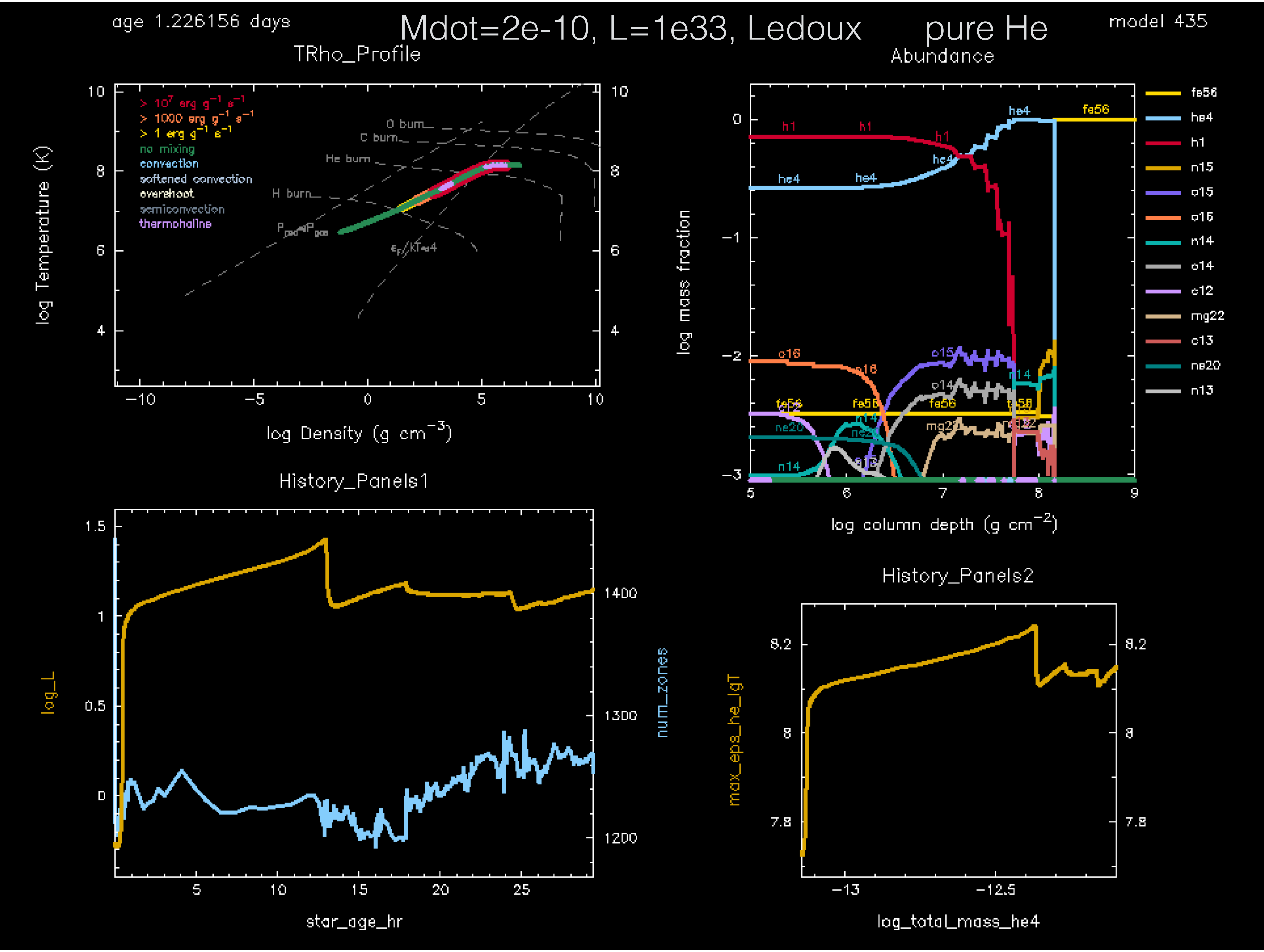


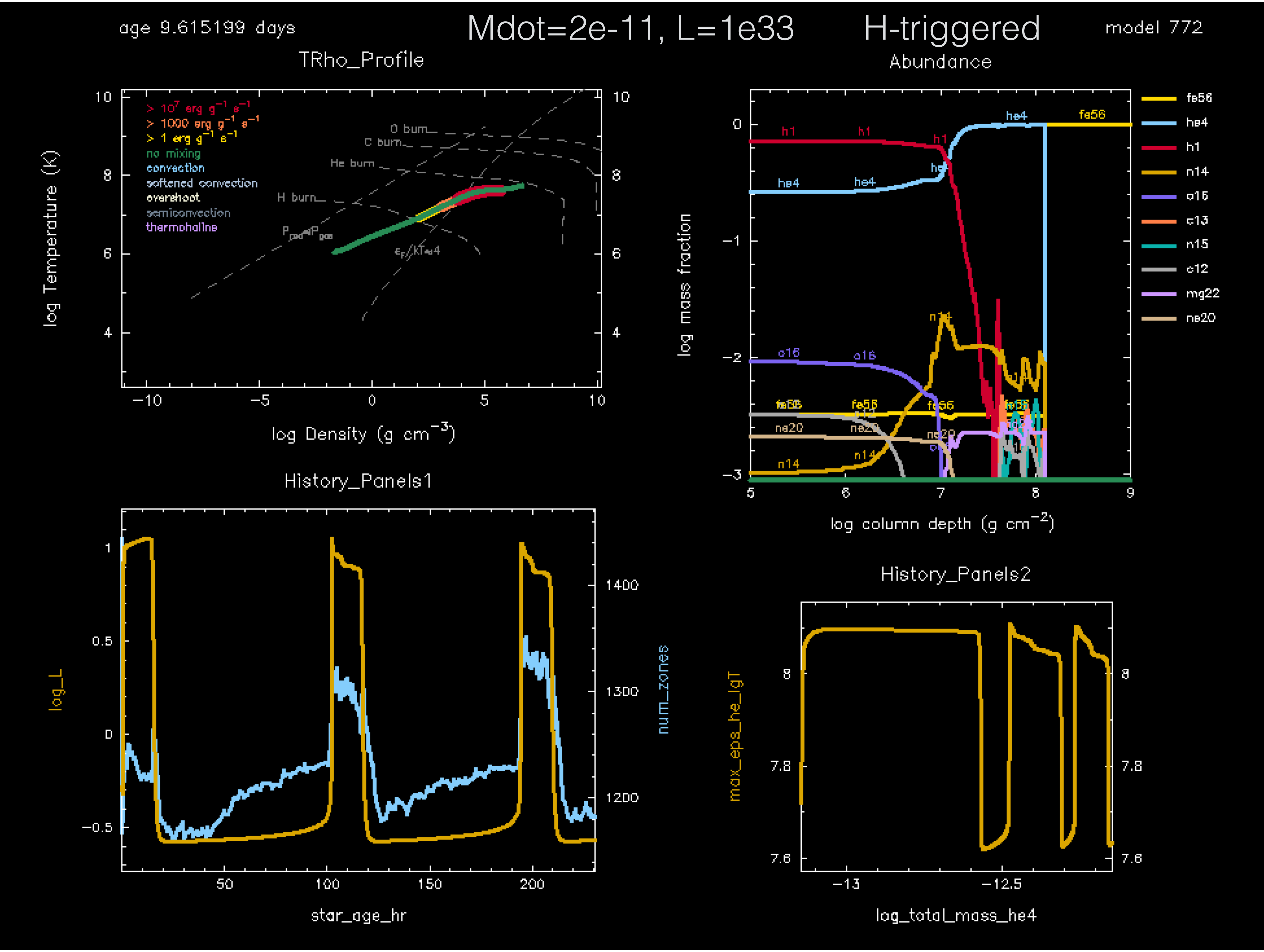
age 6.785476 hrs
Mdot=2e-9, L=1e34 mixed H/He
model 542
TRho_Profile
log Temperature (K)
log Density (g cm^{-3})
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
Abundance
log mass fraction
log column depth (g cm^{-2})
fe56
mg22
h1
he4
o15
o14
o16
c12
f17
ne20
n14
n13
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4



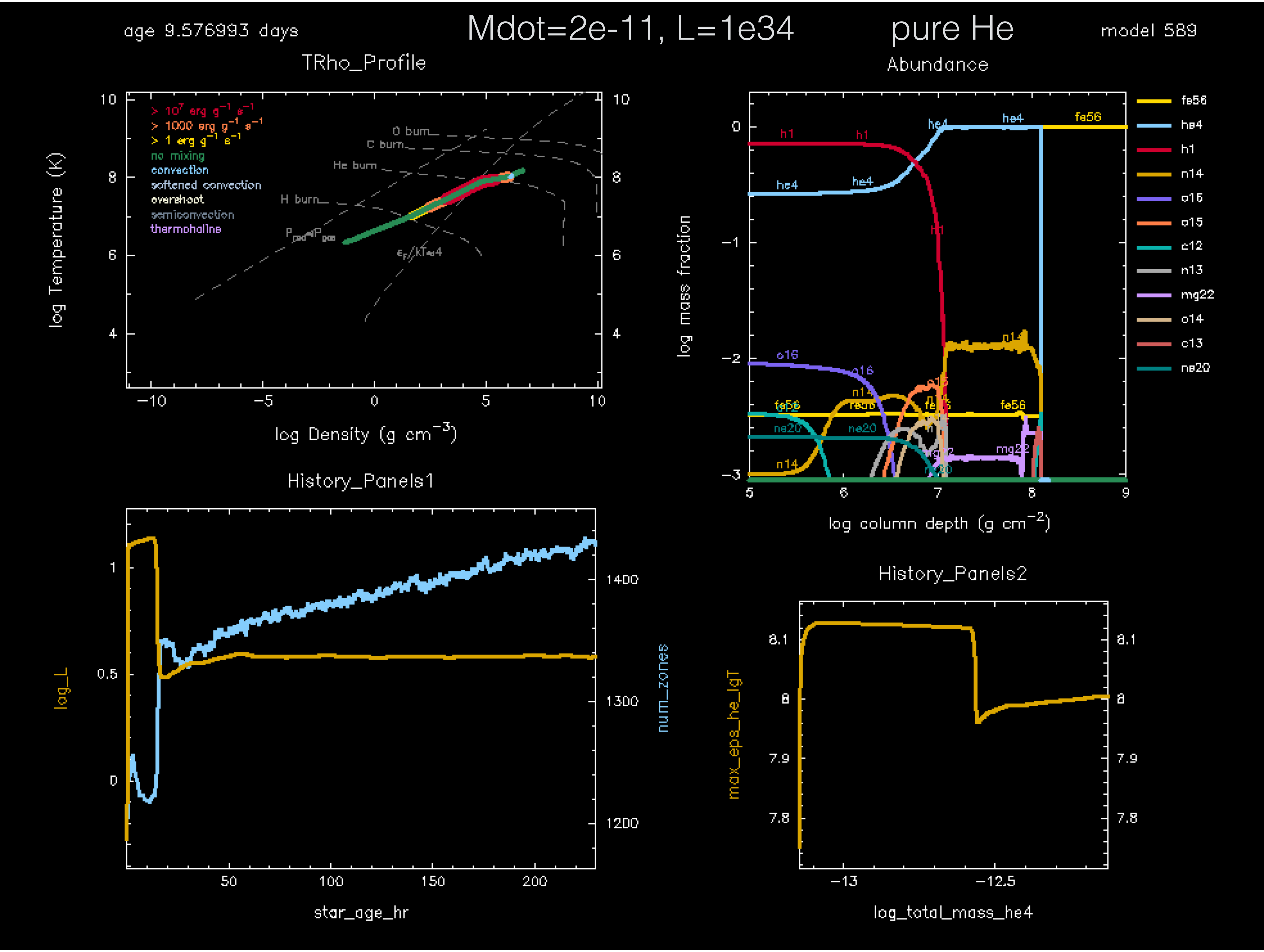
age 1.171828 days
Mdot=2e-10, L=1e34
pure He
model 631
TRho_Profile
log Temperature (K)
log Density (g cm^-3)
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
Prad=Pgas
εF/kT=4
Abundance
log mass fraction
log column depth (g cm^-2)
fe56
he4
h1
n15
o15
o16
n14
o14
c12
mg22
c13
ne20
n13
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4


age 1.261053 days
Mdot=2e-10, L=1e33
pure He
model 641
TRho_Profile
log Temperature (K)
log Density (g cm^{-3})
> 10^7 erg g^{-1} s^{-1}
> 1000 erg g^{-1} s^{-1}
> 1 erg g^{-1} s^{-1}
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
$P_{rad}=P_{gas}$
$\epsilon_F/kT=4$
Abundance
log mass fraction
log column depth (g cm^{-2})
fe56
he4
h1
o15
n15
o16
n14
o14
c12
c13
mg22
ne20
n13
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4

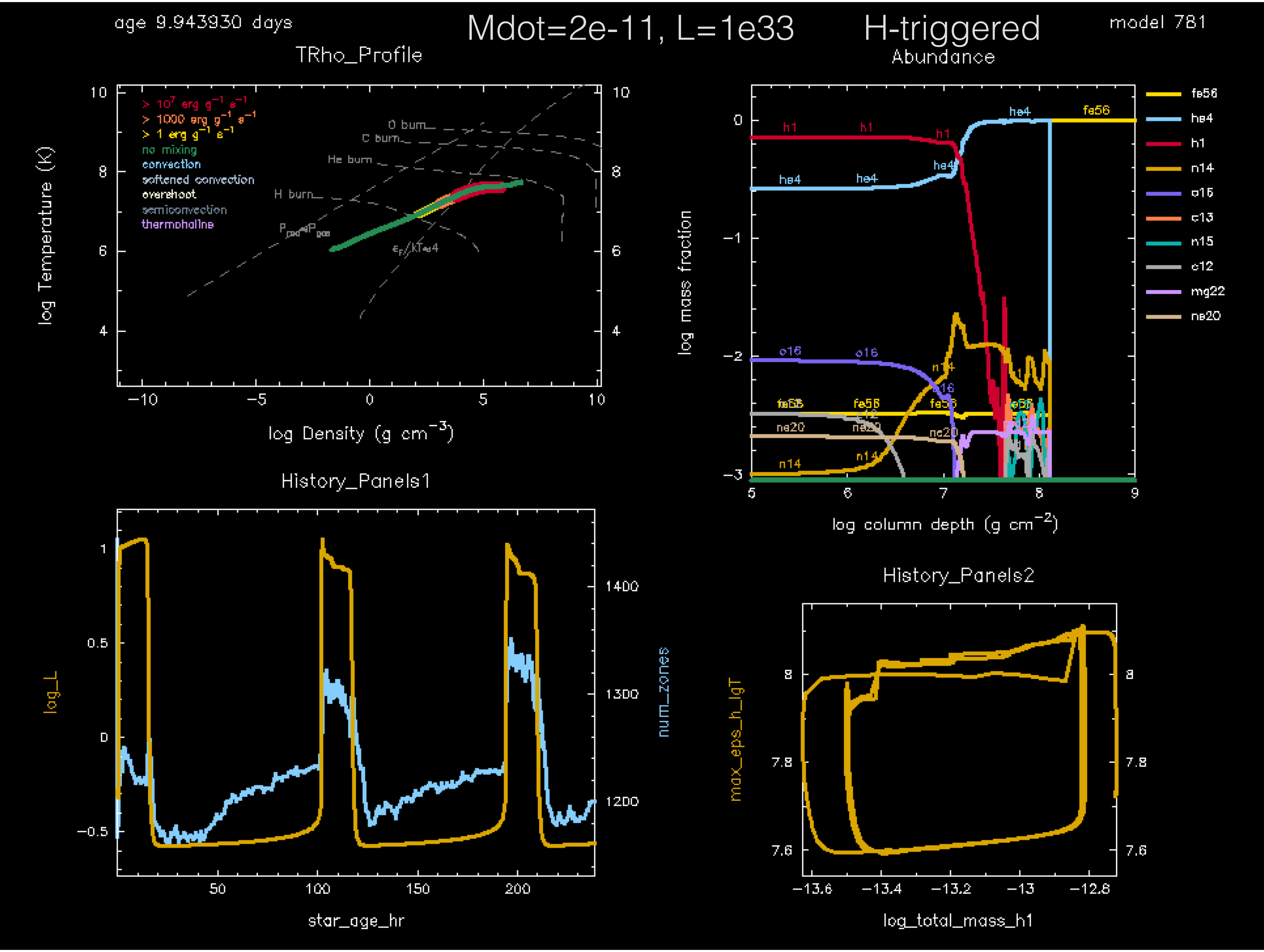

age 1.226156 days
Mdot=2e-10, L=1e33, Ledoux pure He
model 435
TRho_Profile
log Temperature (K)
log Density (g cm^-3)
O burn
C burn
He burn
H burn
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
Abundance
log mass fraction
log column depth (g cm^-2)
fe56
he4
h1
n15
o15
o16
n14
c14
c12
mg22
c13
ne20
n13
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4



age 9.615199 days
Mdot=2e-11, L=1e33
H-triggered
model 772
TRho_Profile
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
log Temperature (K)
log Density (g cm^-3)
Abundance
log mass fraction
log column depth (g cm^-2)
fe56
he4
h1
n14
o16
c13
n15
c12
mg22
ne20
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4



age 9.576993 days
Mdot=2e-11, L=1e34
pure He
model 589
TRho_Profile
log Temperature (K)
log Density (g cm^-3)
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
P_rad=P_gas
ε_F/kT=4
Abundance
log mass fraction
log column depth (g cm^-2)
fe56
he4
h1
n14
o16
o15
c12
n13
mg22
o14
c13
ne20
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4

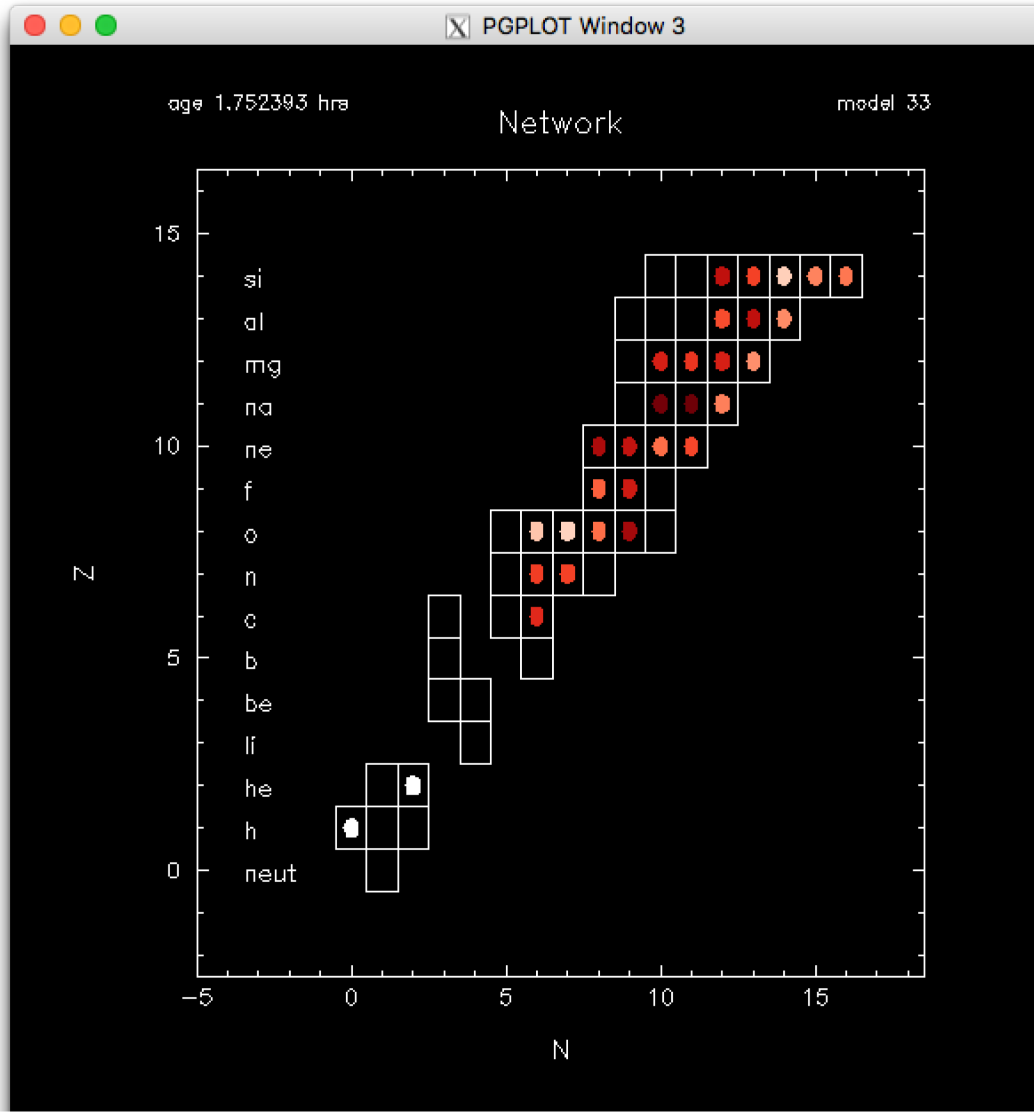


age 9.943930 days
Mdot=2e-11, L=1e33
H-triggered
model 781
TRho_Profile
Abundance
log Temperature (K)
log Density (g cm^-3)
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
O burn
C burn
He burn
H burn
log mass fraction
log column depth (g cm^-2)
fe56
he4
h1
n14
o16
c13
n15
c12
mg22
ne20
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_h_lgT
log_total_mass_h1

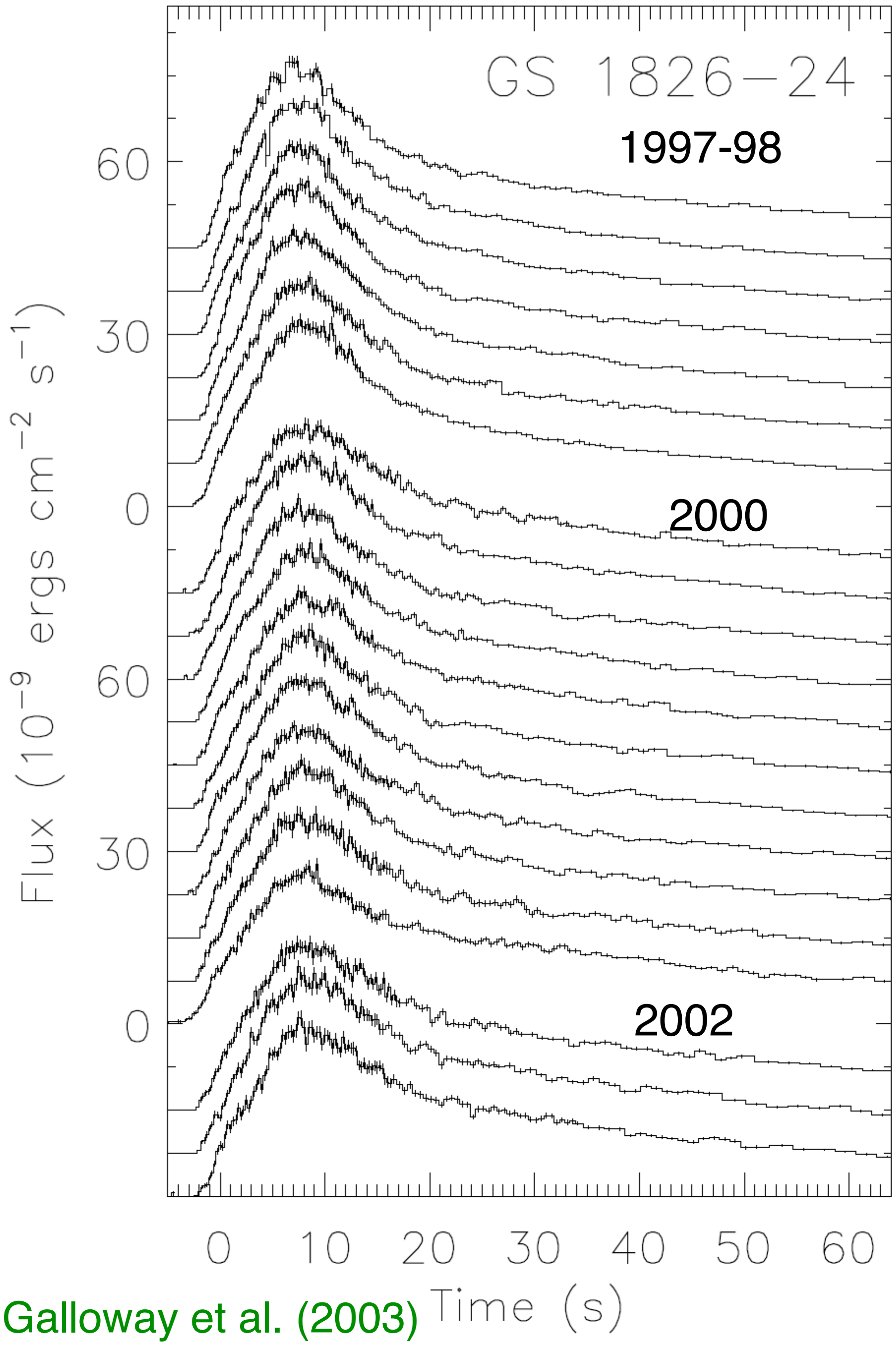
X-ray Burst Lab

- Look at mixed H/He ignitions, and how the burst properties depend on the nuclear network
- Compare to the “clocked burster” GS 1826-24
- Learn how to make your own network
- How to use MESA’s adaptive net

- New `pgstar` window:

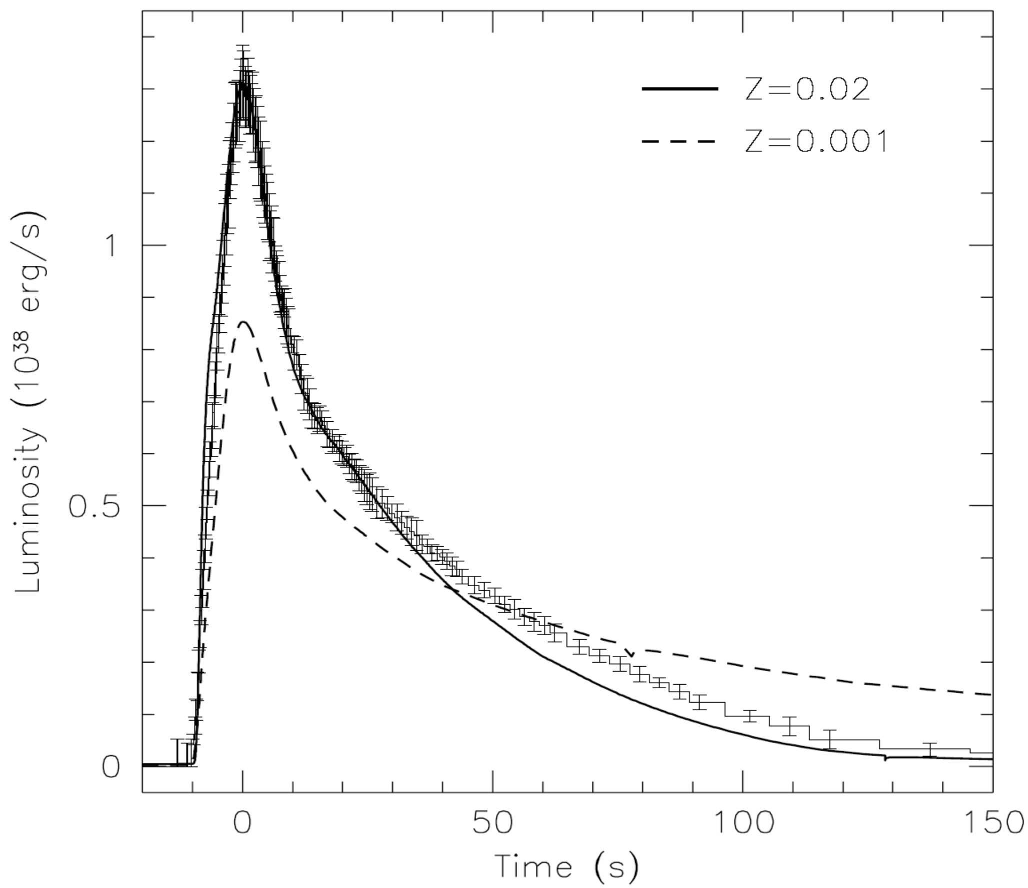


He ignition in a H-rich environment: GS 1826-24

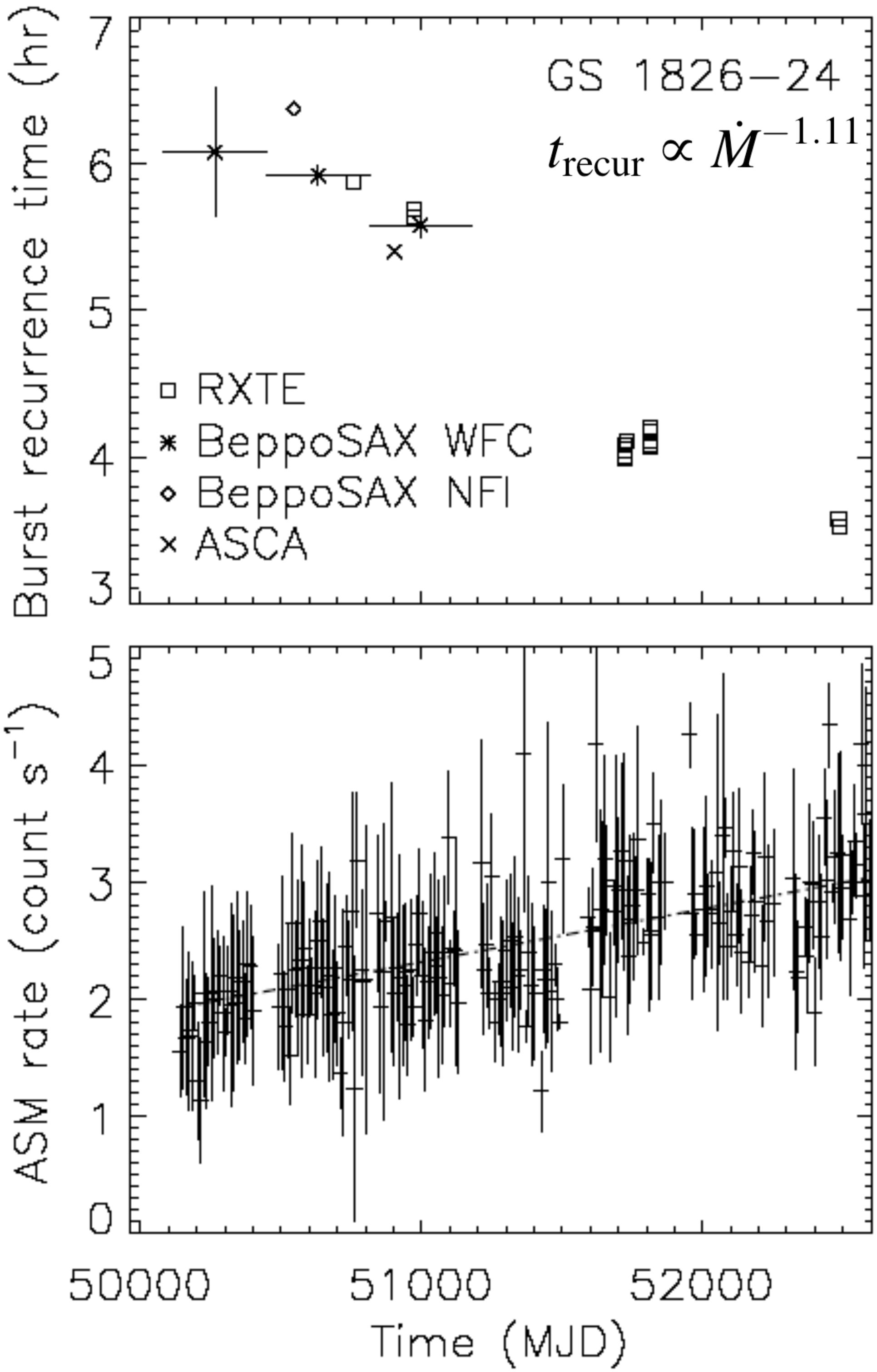


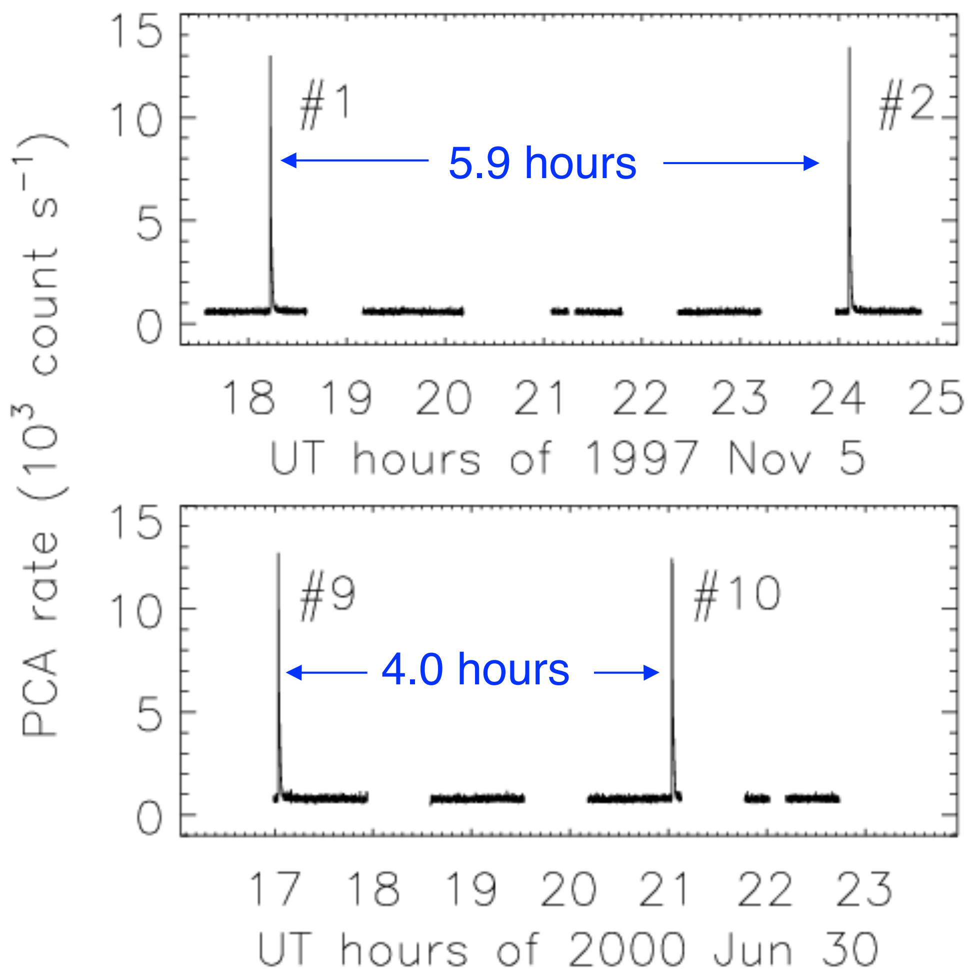
Galloway et al. (2003)

- very regular burster, recurrence times 3-6 hours
=> mixed H/He burning



Heger et al. (2007) comparison with Woosley et al. (2004) models



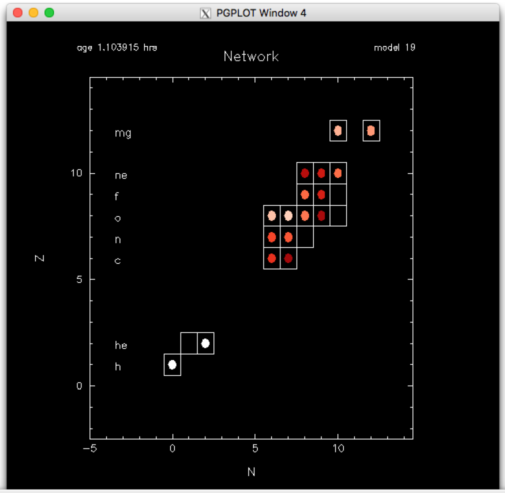


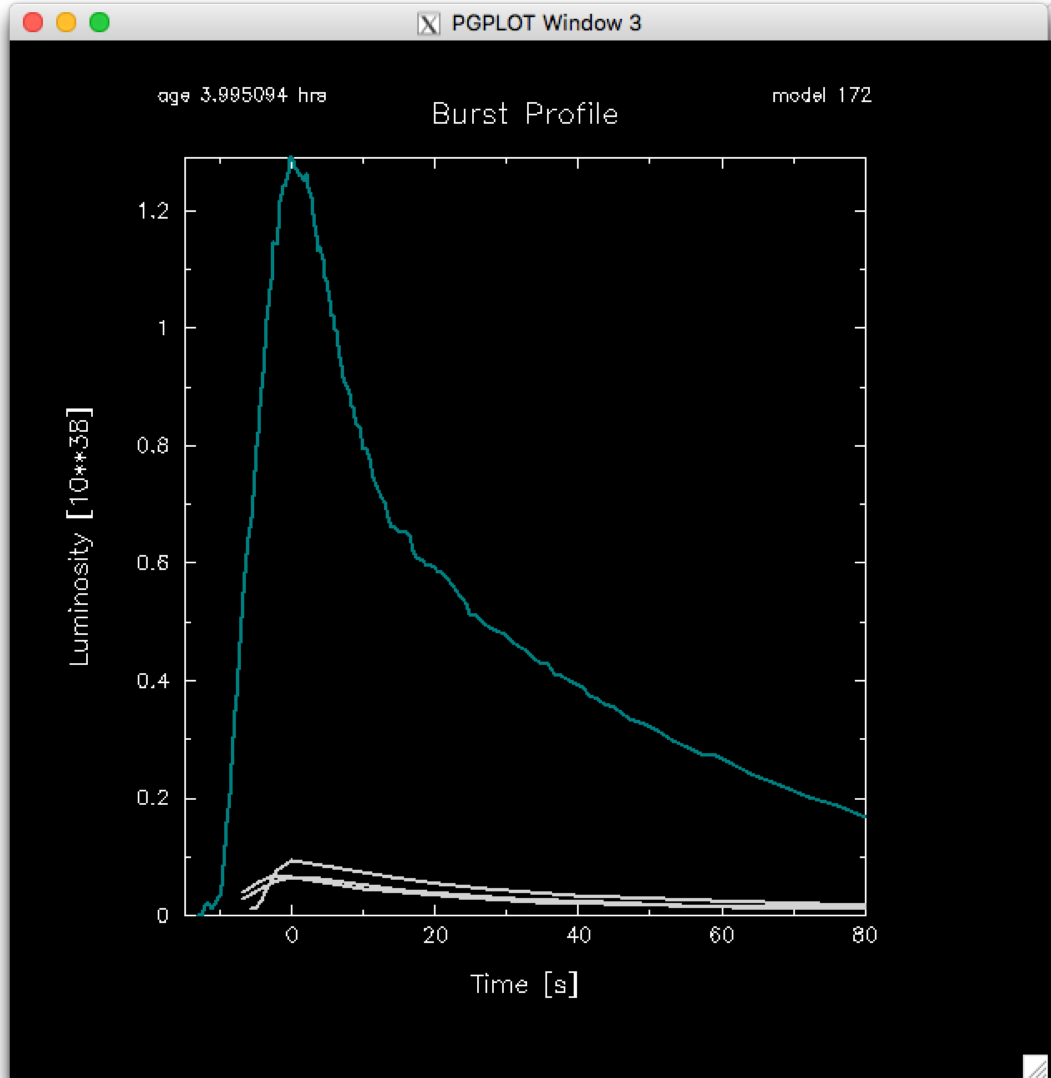
Galloway et al. (2003)

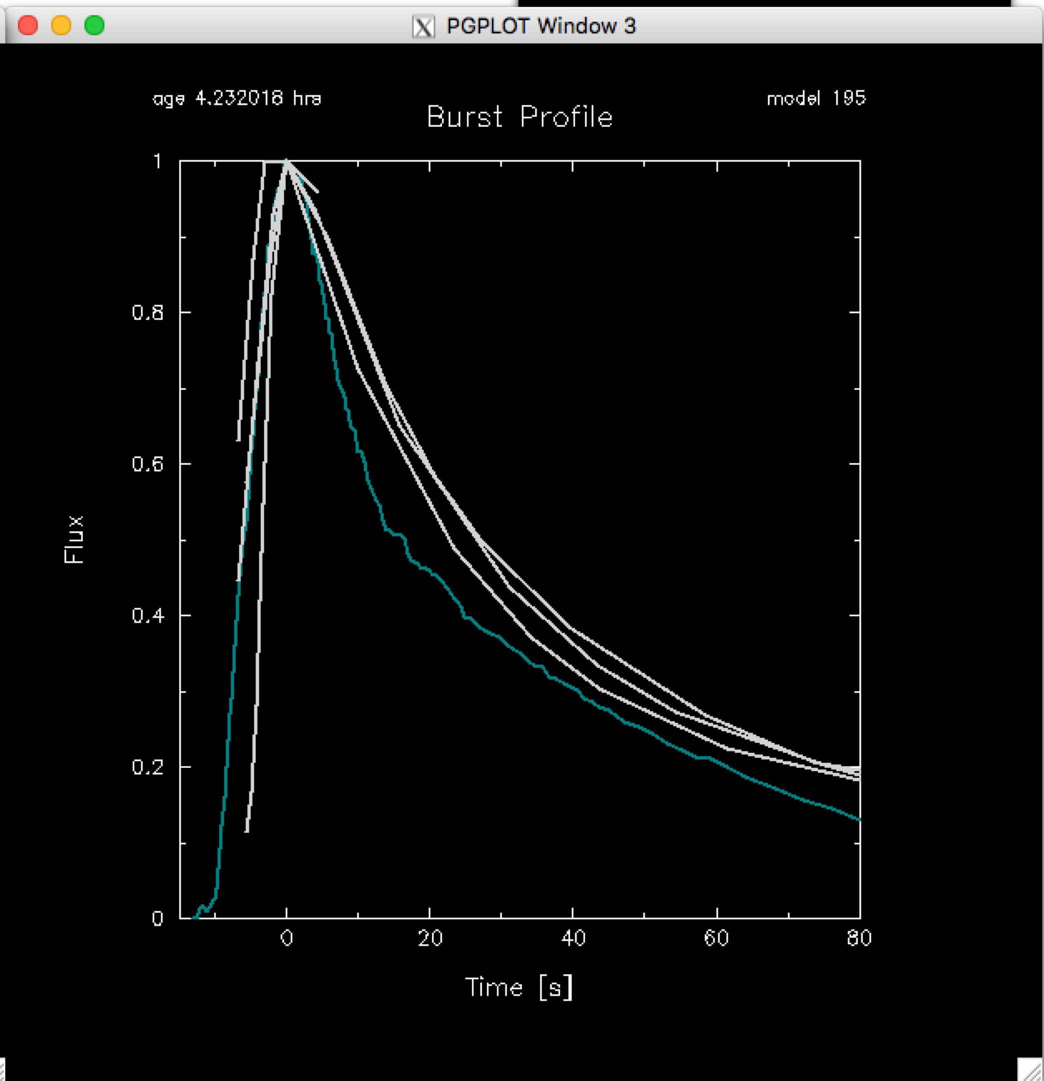
X-ray burst lab: Part 1

- Run your model in the mixed H/He regime and compare to the GS 1826-24 data
- Turn on the net window and see which nuclei are included in the net used in the test suite

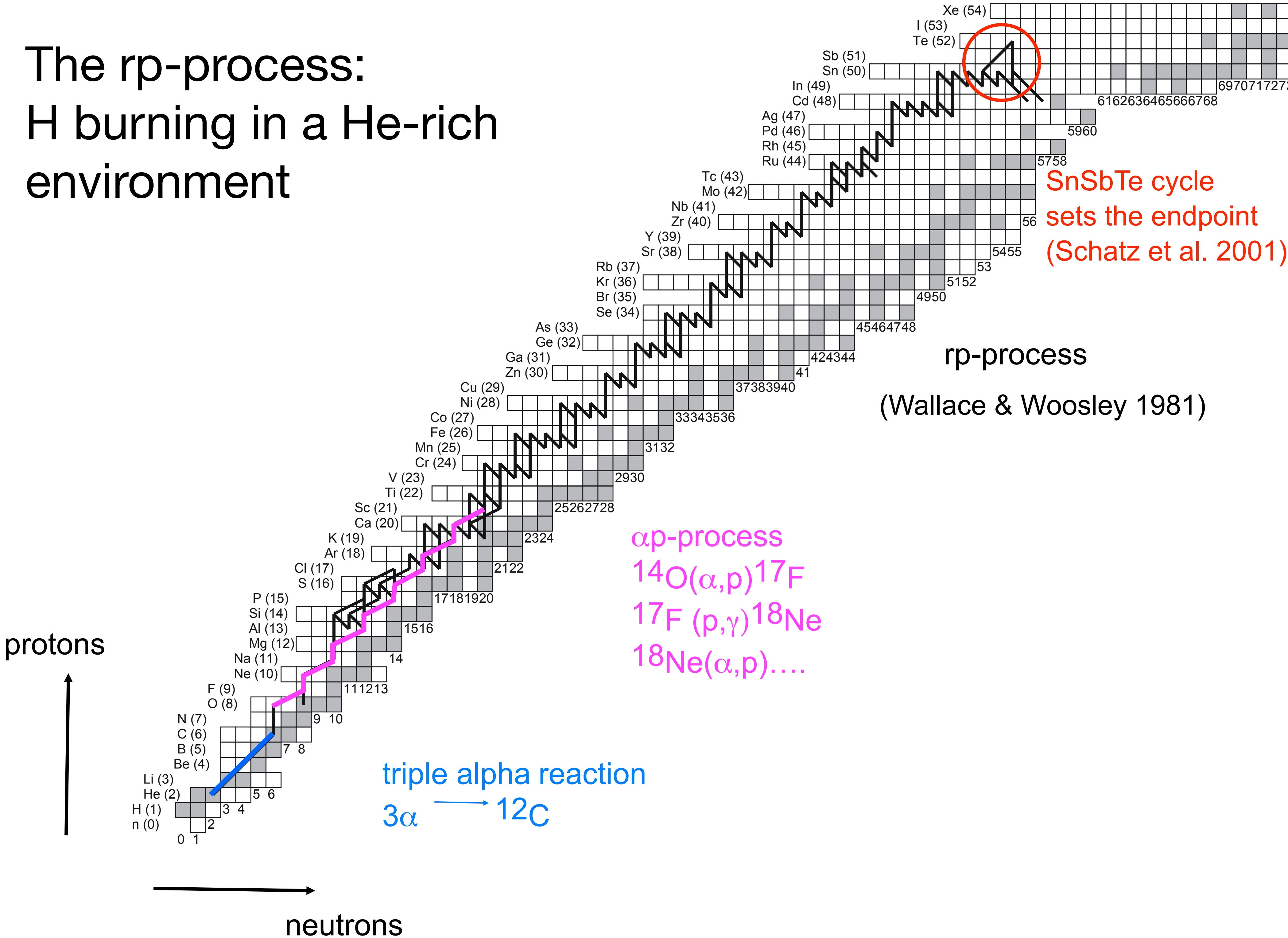
cno_extras_plus_fe56.net







The rp-process:
H burning in a He-rich environment



MESA III instrument paper, Rob Farmer

5.3. *X-ray Burst Models and Adaptive Nets*

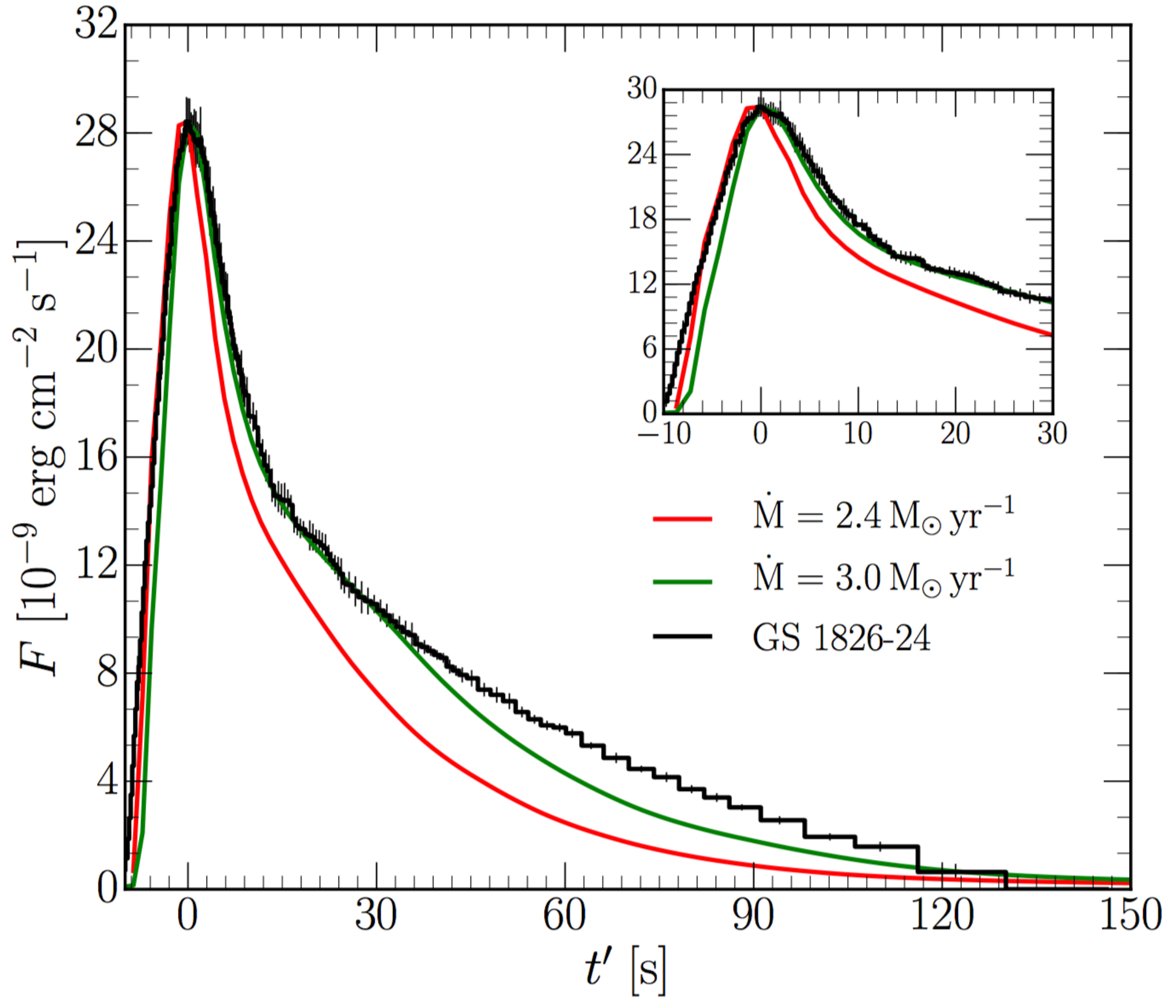


Figure 23. Folded burst light curve for the `rp_305` net, with a solar metallicity accretion composition, shown for $\dot{M} = 2.4 \times 10^{-9}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and $\dot{M} = 3 \times 10^{-9}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, normalized to the peak flux measured for GS 1826-24. The insert shows the first 30 s of the burst.

X-ray burst lab: Parts 2 and 3

- We’ll run models with a truncated rp-process network
- How well can we do with a limited run time of 10 minutes?

Make sure you copy the `rp.net` file into your work directory rather than edit MESA’s copy directly

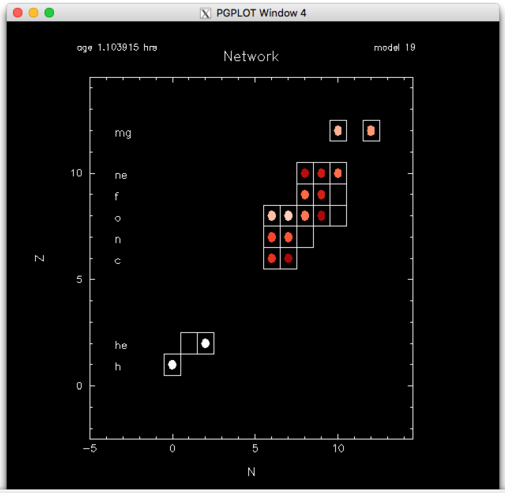
inlist_ns_extras

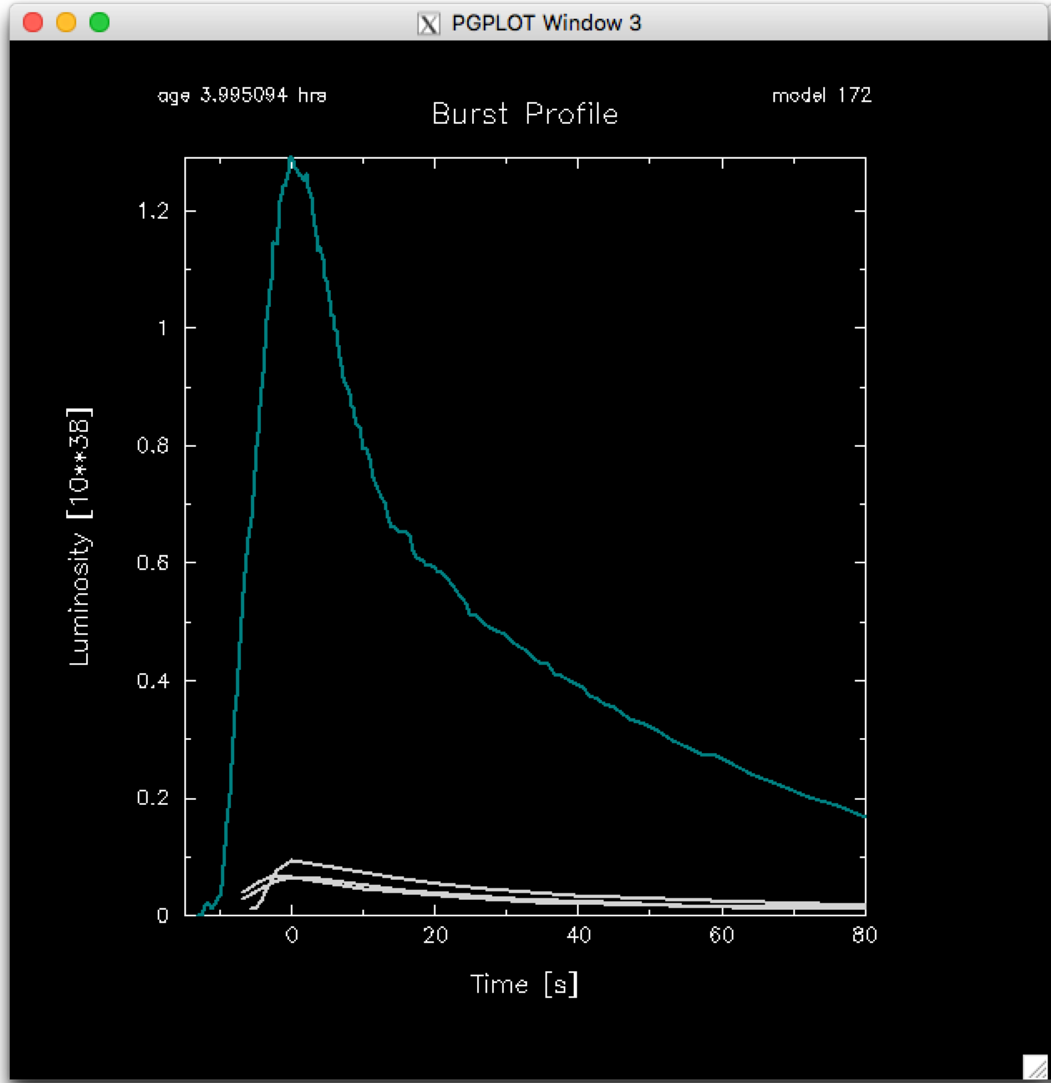
```
&controls
      varcontrol_target = 1d-2
      mesh_delta_coeff = 2.0

      mesh_min_dlnR = 1d-9
      merge_if_dlnR_too_small = .true.

       use_GR_factors = .true.
       Pextra_factor=2

        min_T_for_acceleration_limited_conv_velocity = 0.0

        okay_to_reduce_gradT_excess = .true.
        super_eddington_wind_eta = 1

        mixing_length_alpha = 1.5
        MLT_option = 'Henyey'

        use_Ledoux_criterion = .true.

        alpha_semiconvection = 0.1
        thermohaline_coeff = 2
        thermohaline_option = 'Kippenhahn'


        dX_nuc_drop_limit=7.5d-2
        dX_nuc_drop_limit_at_high_T=5d-3
        dX_nuc_drop_min_X_limit=7.5d-2
        dX_nuc_drop_max_A_limit=52

        max_timestep_factor = 0.d0
        delta_lgT_cntr_limit = 0.05
        delta_lgTeff_limit = 0.05
        delta_lgL_He_limit = 0.1



        mesh_dlog_pp_dlogP_extra = 2
        mesh_dlog_cno_dlogP_extra = 2

        mesh_dlog_3alf_dlogP_extra = 2
        mesh_dlog_burn_c_dlogP_extra = 2
        mesh_dlog_burn_n_dlogP_extra = 2
        mesh_dlog_burn_o_dlogP_extra = 2

        mesh_dlog_burn_ne_dlogP_extra = 2
        mesh_dlog_burn_na_dlogP_extra = 2
        mesh_dlog_burn_mg_dlogP_extra = 2

        mesh_dlog_cc_dlogP_extra = 2
        mesh_dlog_co_dlogP_extra = 2
        mesh_dlog_oo_dlogP_extra = 2

        mesh_dlog_burn_si_dlogP_extra = 2
        mesh_dlog_burn_s_dlogP_extra = 2
        mesh_dlog_burn_ar_dlogP_extra = 2
        mesh_dlog_burn_ca_dlogP_extra = 2
        mesh_dlog_burn_ti_dlogP_extra = 2
        mesh_dlog_burn_cr_dlogP_extra = 2
        mesh_dlog_burn_fe_dlogP_extra = 2

        mesh_dlog_pnhe4_dlogP_extra = 2
        mesh_dlog_other_dlogP_extra = 2
        mesh_dlog_photo_dlogP_extra = 2

/
```

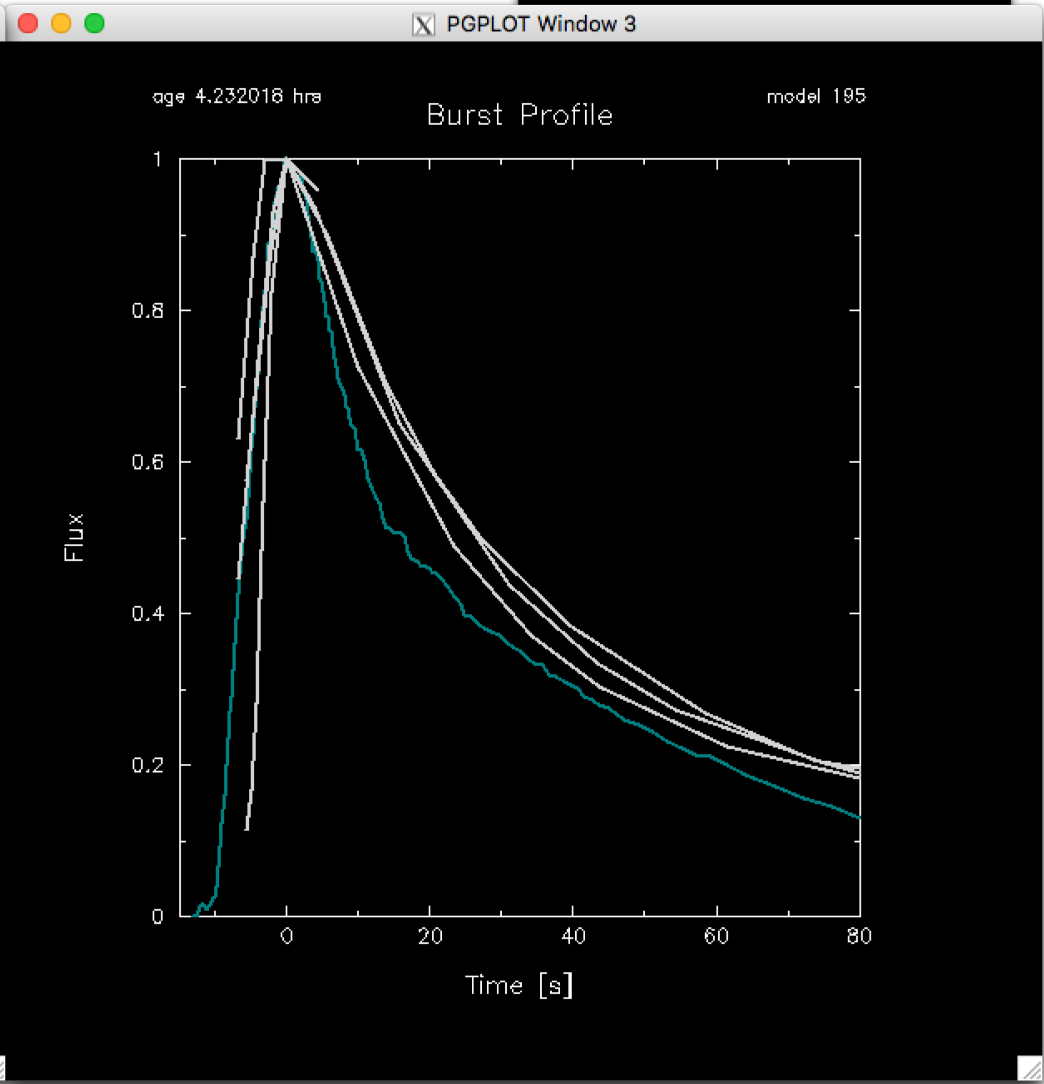
X-ray burst lab: Part 4

- Adaptive net

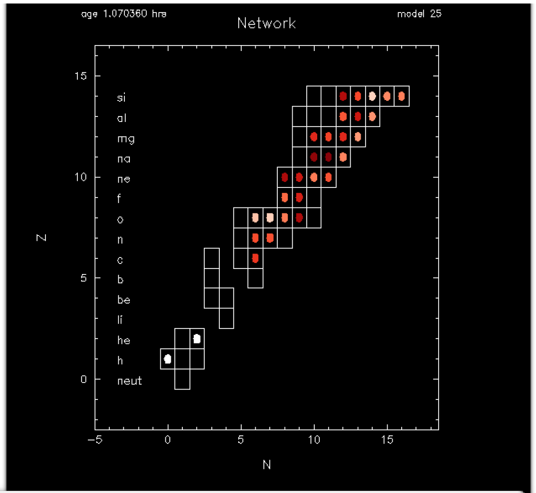
cno_extras_plus_fe56.net

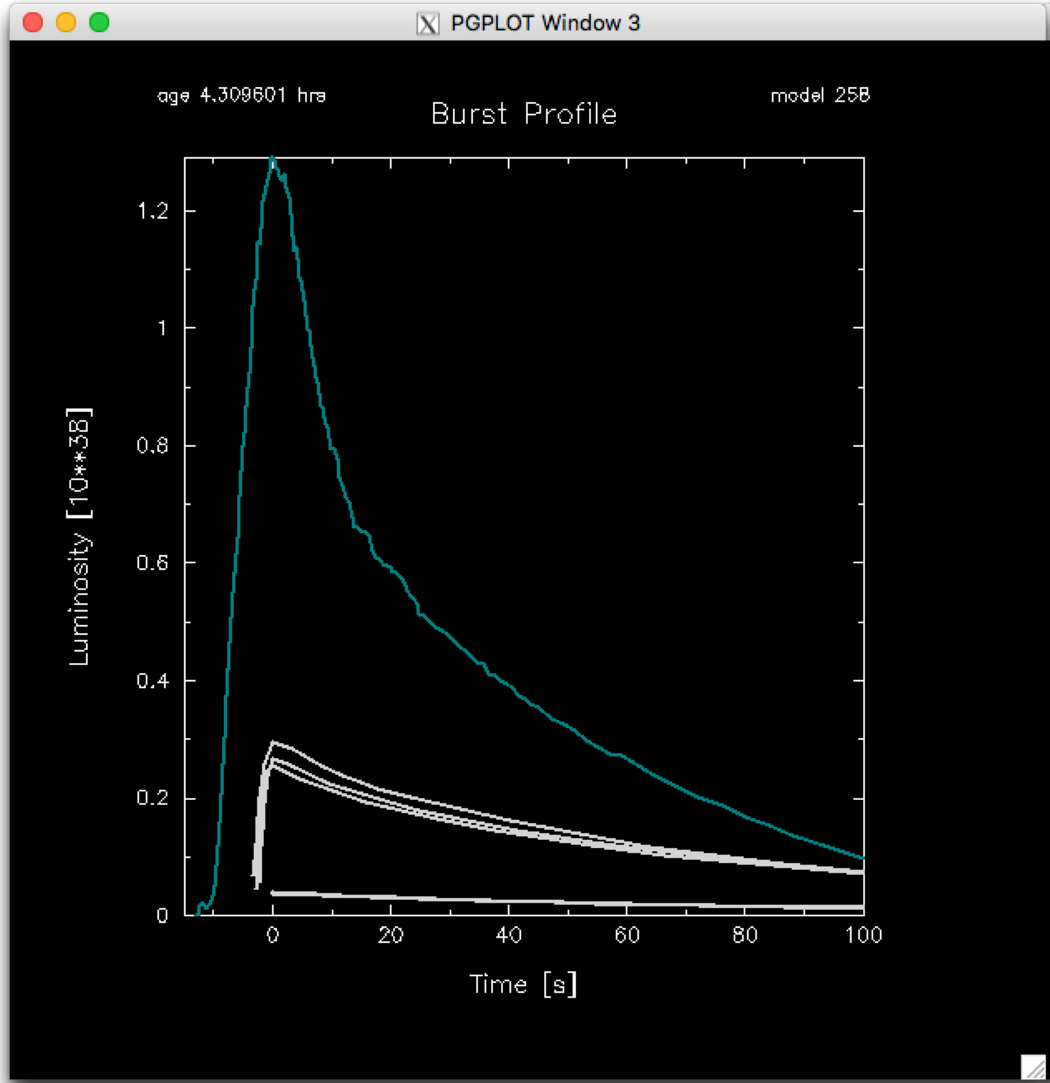


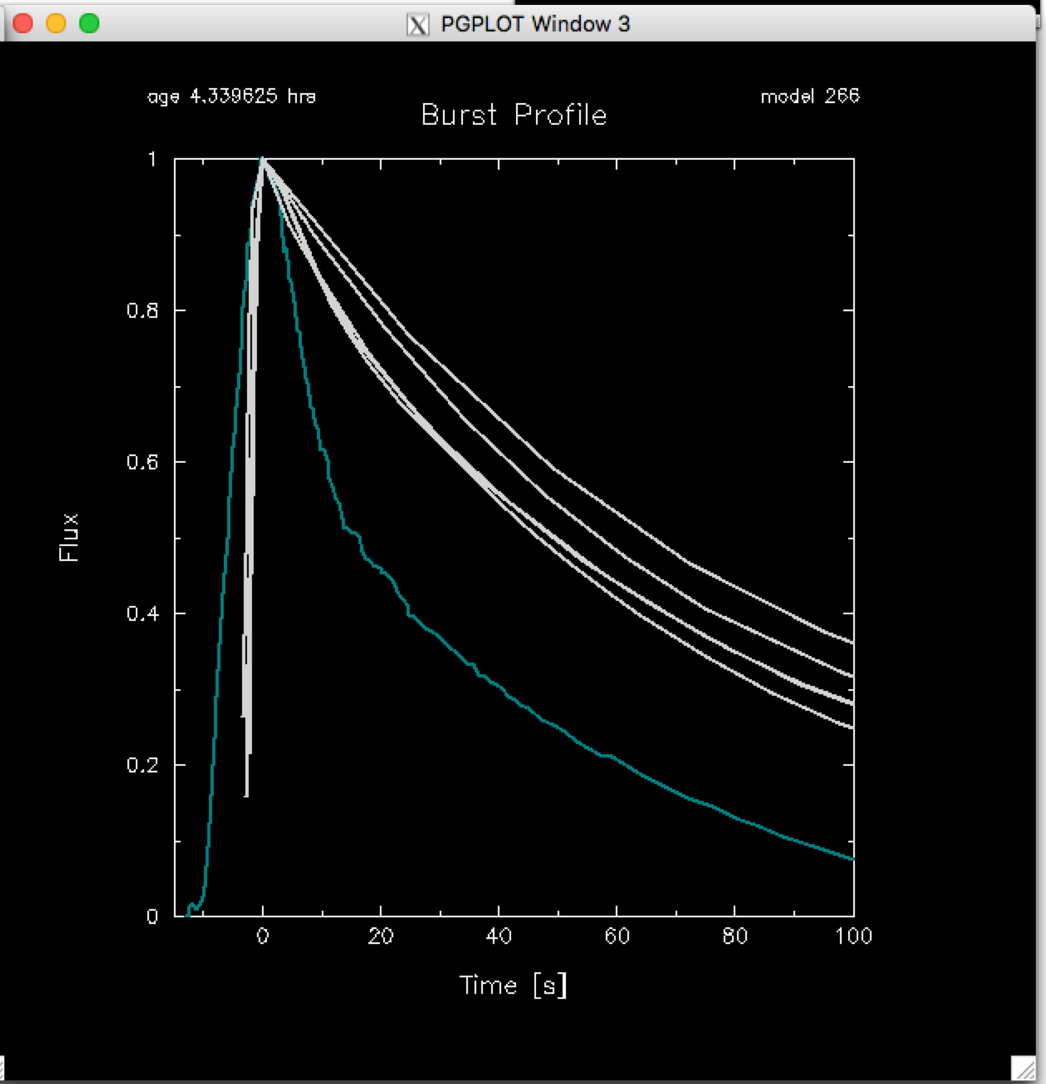




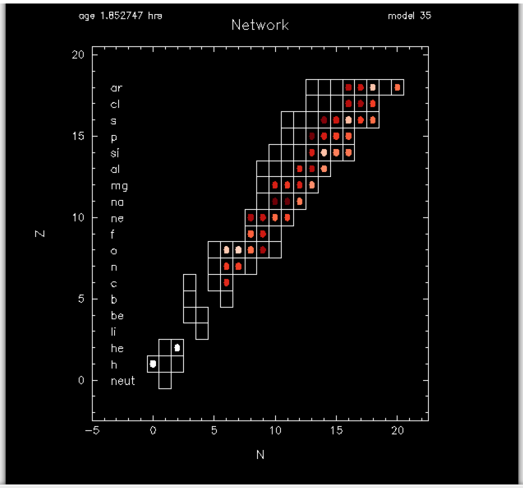
rp.net Si (Z=14), 54 species

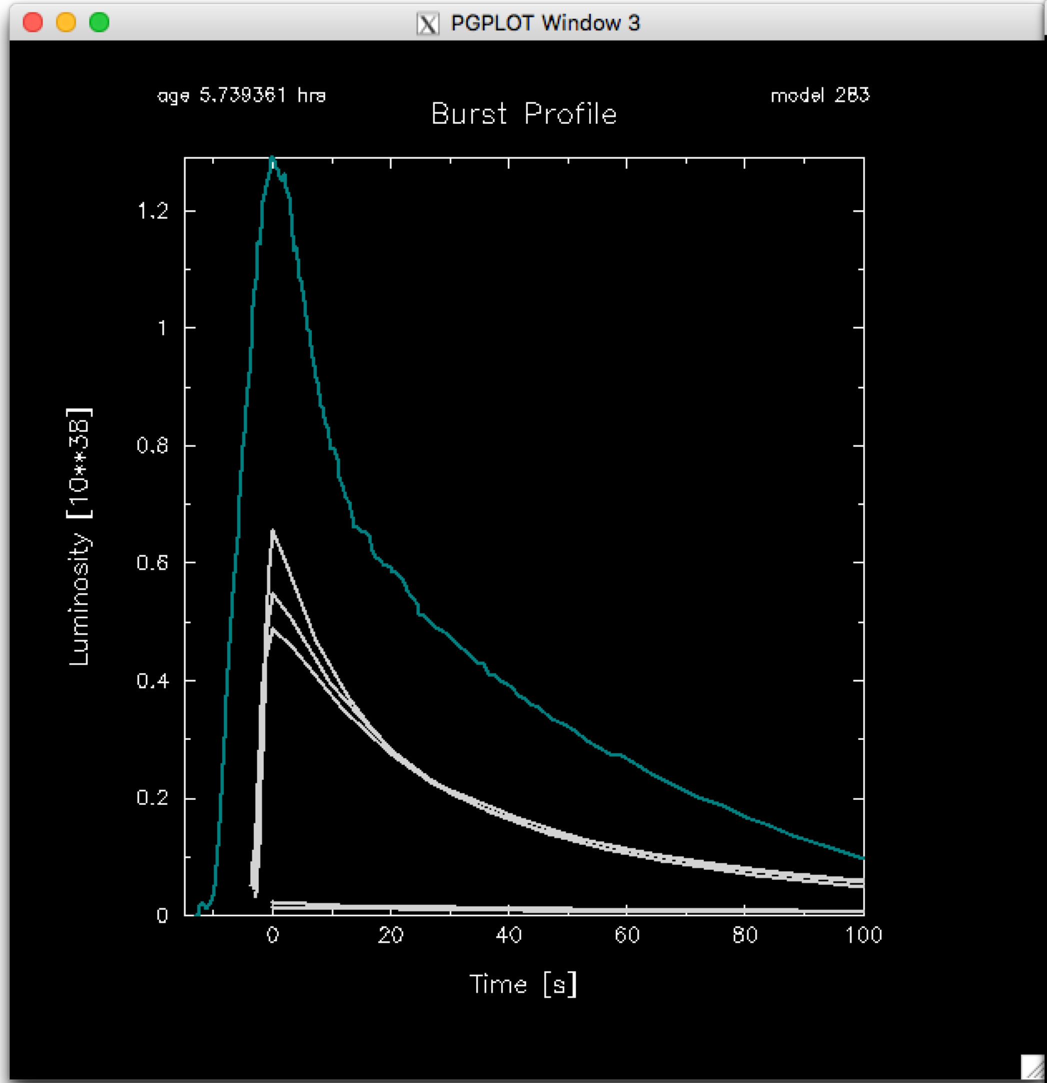


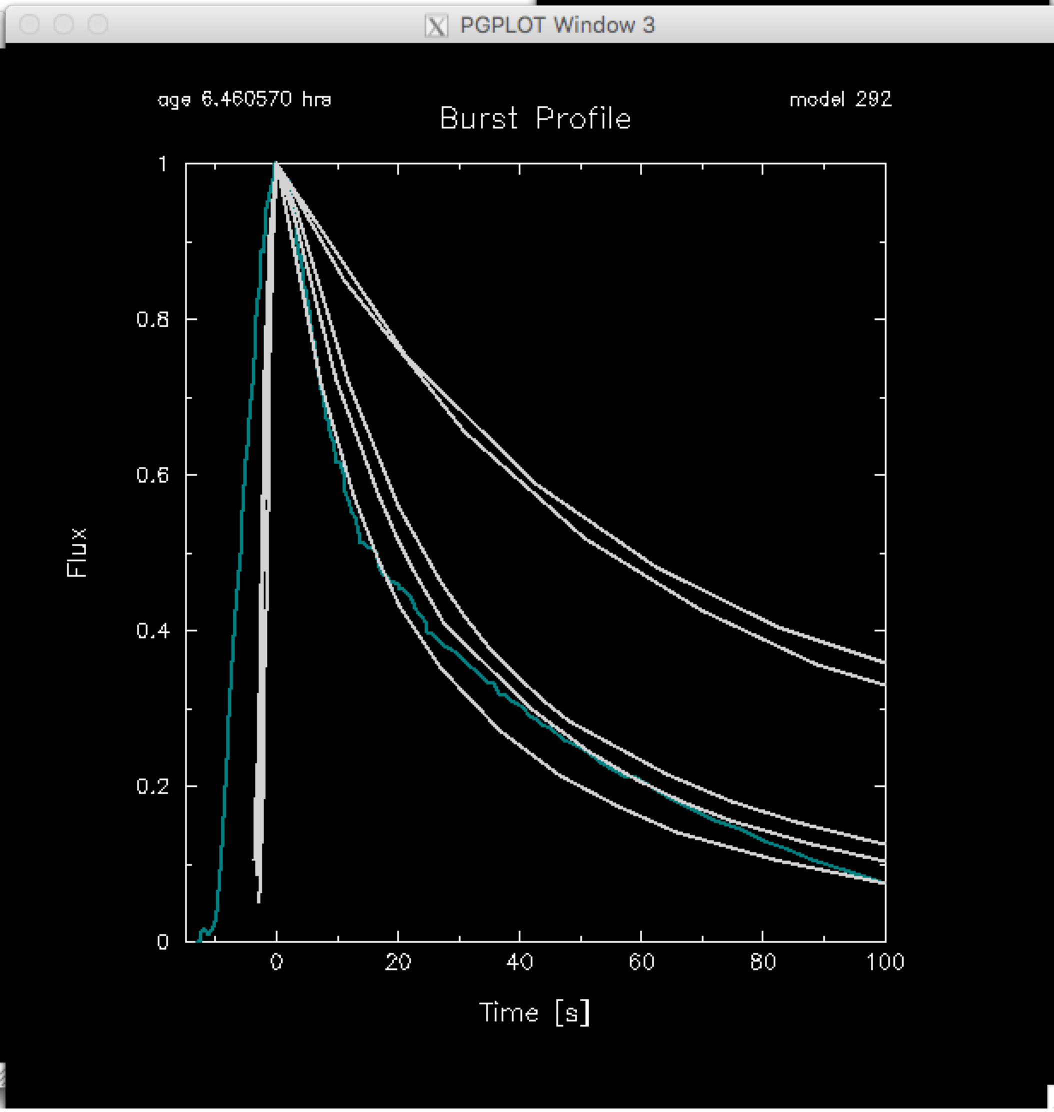




rp.net   Ar (Z=18), 82 species







Adaptive nets

from MESA III:

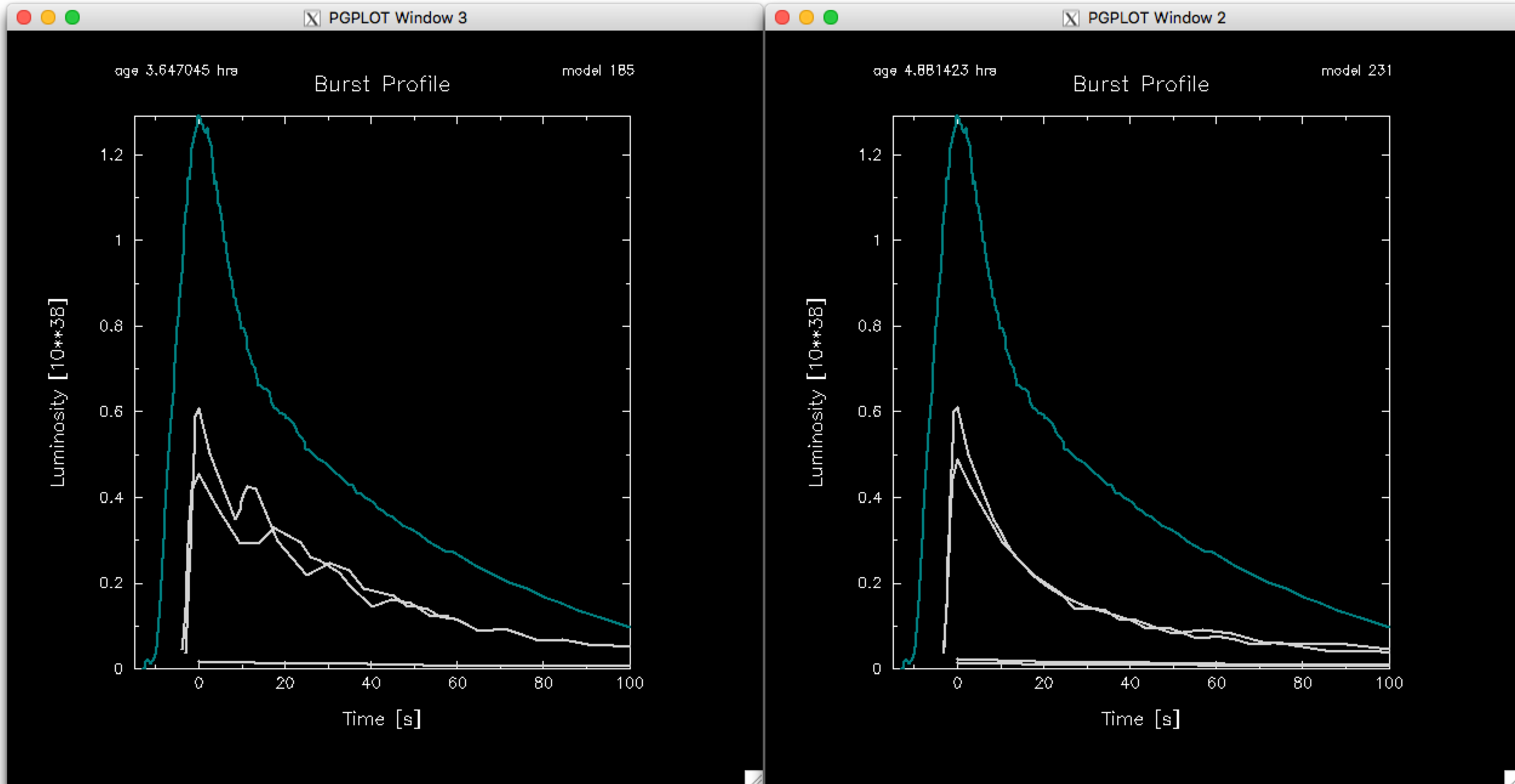
We now explore adaptive nets (Woosley et al. 2004), where we allow MESA to determine which isotopes (and reactions) are necessary by assessing the available reaction pathways for the most abundant isotopes. The network is constructed by first finding those isotopes with an abundance above a threshold, $X_{\rm keep}$, and then introducing those isotopes which are connected by adding or removing protons, neutrons, or α particles. That determination is made via the additional parameters $X_{\rm n}$ (i.e. neutron reactions) and $X_{\rm p}$ (i.e. proton and α reactions) potentially re-adding isotopes removed with the initiating $X_{\rm keep}$ threshold.

&star_job

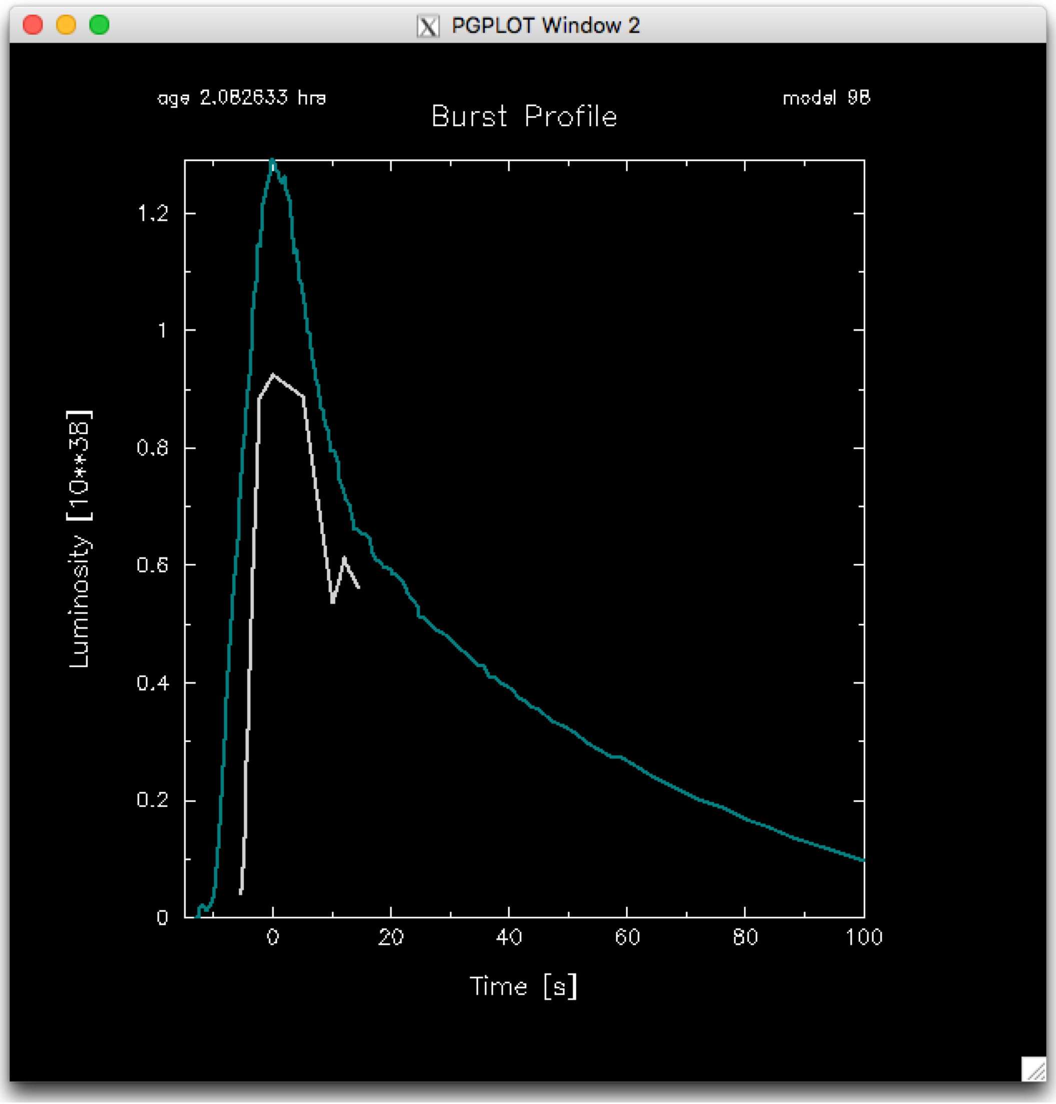
```
enable_adaptive_network = .true.
min_x_for_keep = 1d-4
min_x_for_n = 1d-3
min_x_for_add = 1d-3
max_Z_for_add = 16
max_N_for_add = 16
max_A_for_add = 32
```

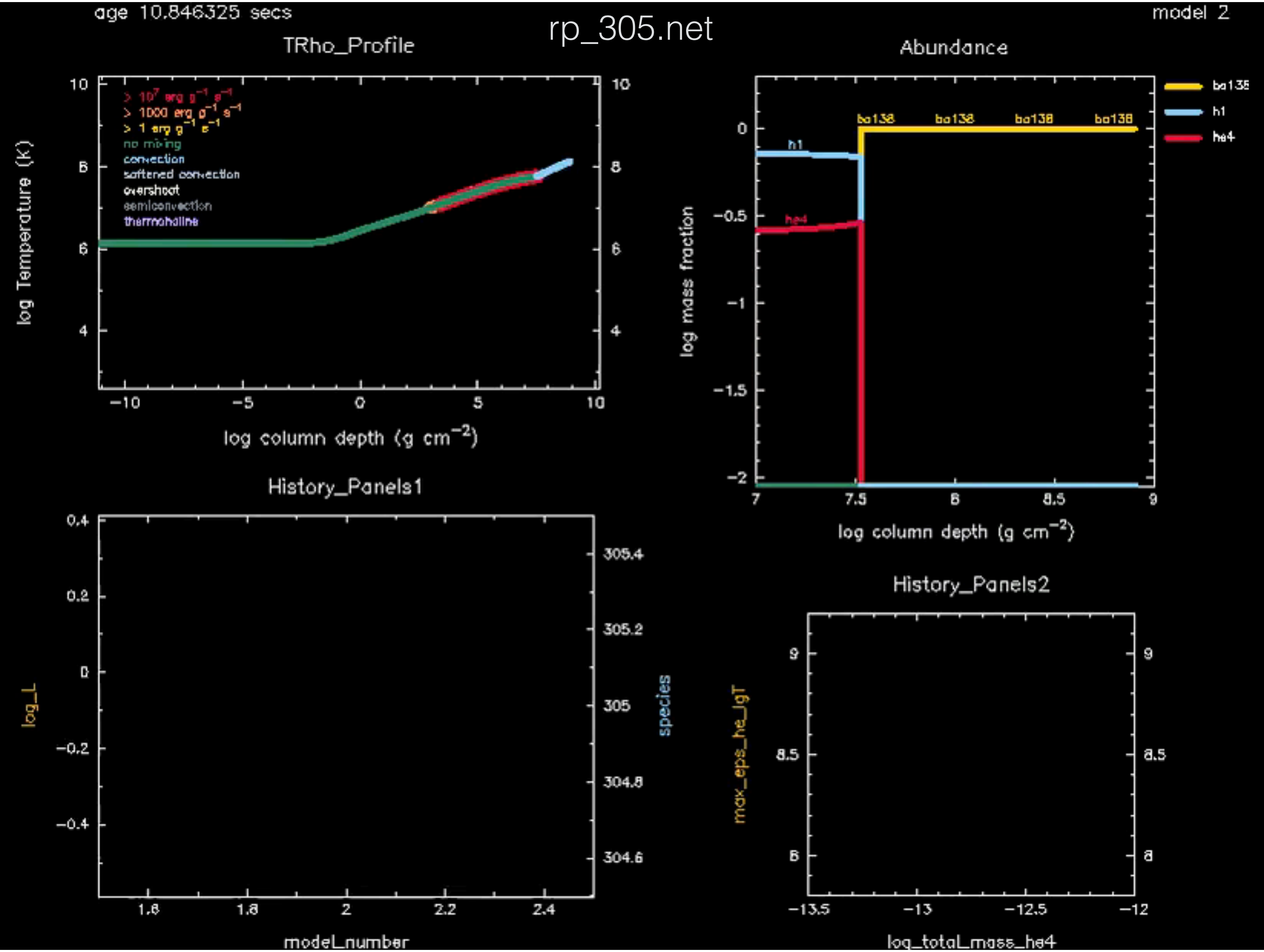
```
enable_adaptive_network = .true.
        min_x_for_keep = 1d-4
        min_x_for_n = 1d-3
        min_x_for_add = 1d-3
        max_Z_for_add = 18
        max_N_for_add = 18
        max_A_for_add = 36
```

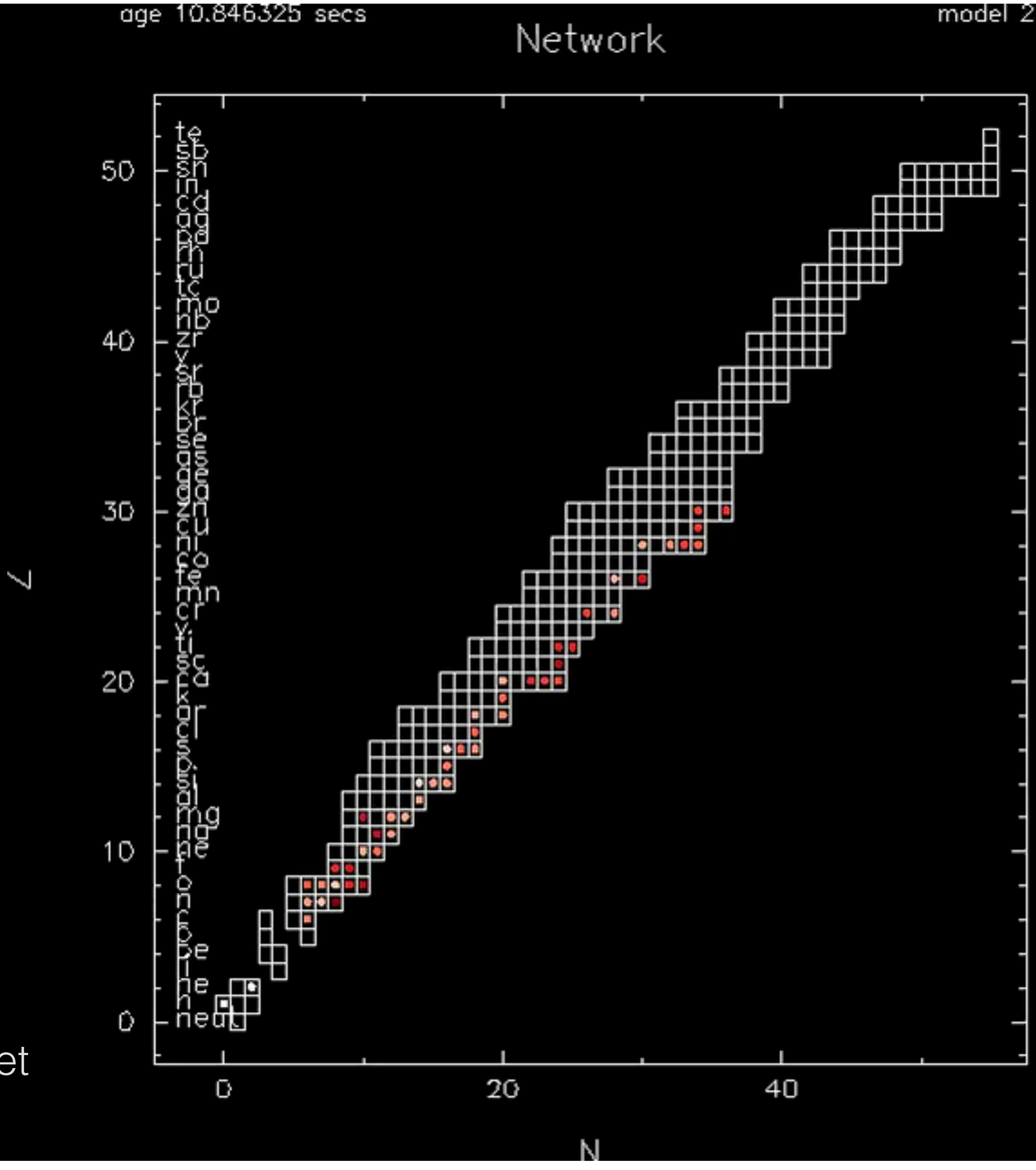
.. and with one small change to these controls:



```
enable_adaptive_network = .true.
        min_x_for_keep = 1d-4
        min_x_for_n = 1d-3
        min_x_for_add = 1d-3
        max_Z_for_add = 26
        max_N_for_add = 30
        max_A_for_add = 56
```




age 10.846325 secs
rp_305.net
model 2
TRho_Profile
> 10^7 erg g^-1 s^-1
> 1000 erg g^-1 s^-1
> 1 erg g^-1 s^-1
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
log Temperature (K)
log column depth (g cm^-2)
Abundance
ba138
h1
he4
log mass fraction
log column depth (g cm^-2)
History_Panels1
log_L
species
model_number
History_Panels2
max_eps_he_lgT
log_total_mass_he4


age 10.846325 secs
model 2
Network
Z
N
0
10
20
30
40
50
0
20
40
te
sb
sn
in
cd
ag
pd
rh
ru
tc
mo
nb
zr
y
sr
rb
kr
br
se
as
ge
ga
zn
cu
ni
co
fe
mn
cr
v
ti
sc
ca
k
ar
cl
s
p
si
al
mg
na
ne
f
o
n
c
b
be
li
he
h
neut

rp_305.net