MESA/NuGrid Physics Package

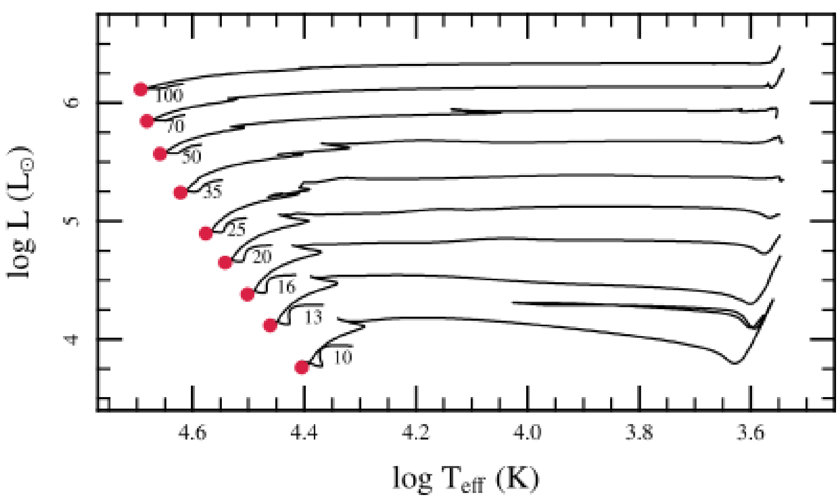
Marco Pignatari, University of Basel, Switzerland

Modules for Experiments in Stellar Astrophysics

MESA

Paxton+ (2011)
http://mesa.sourceforge.net

Massive stars to collapse



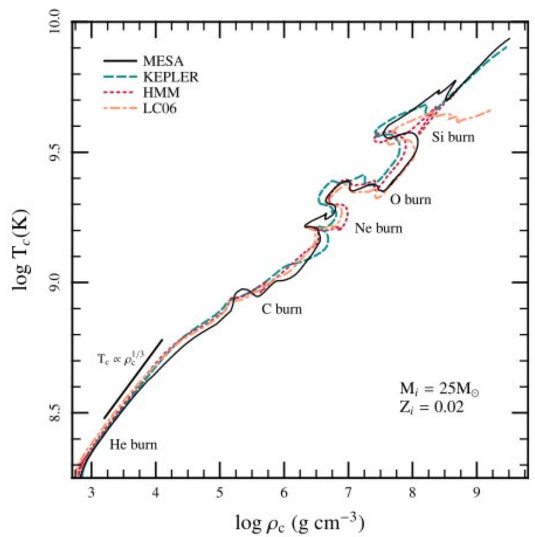


Figure 30. Evolution of the central temperature and central density in solar metallicity $M_i = 25\,M_\odot$ models from different stellar evolution codes. The locations of core helium, carbon, neon, oxygen, and silicon burning are labeled, as is the relation $T_c \propto \rho_c^{1/3}$.

AGB evolution

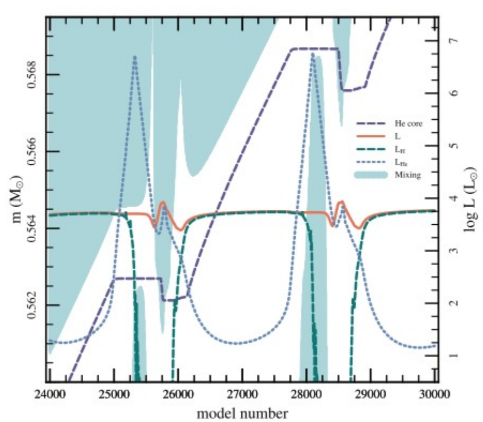


Figure 26. Kippenhahn diagram with luminosities for the second and third thermal pulses with third dredge-up of the $2\,M_\odot$, $Z = 0.01$ MESA star track shown in Figure 24.

- CO and ONe nova
- white dwarfs
- solar model
- planets
- X-ray bursts
- binaries
- brown dwarfs, VLM

- hydrodynamic/-static
- fully coupled solution
- different atmosphere options
- rotation/magnetic fields
- several microphysics options (opacities, EOS)

MESA code solves:
conservation laws of mass, momentum and energy in 1D (spherical symmetric) approximation, hydrostatic or -dynamic (implies significant limits on predictive power for macro physics)

Conservation laws:

$$\frac{d\mathcal{M}}{dr} = 4\pi r^2 \rho(r)$$ mass

$$\frac{dP}{dr} = -\frac{G\mathcal{M}(r)}{r^2}\rho$$ momentum

$$\frac{d\mathcal{L}}{dr} = 4\pi r^2 \rho\,\epsilon$$ energy

Assumptions:
- Spherical symmetry
- Hydrostatic equilibrium (u=0)

Appropriate for more general stellar conditions.

$\tau_{mix} << \tau_{burn}$
Quiescent burning regime

$\tau_{mix} \sim \tau_{burn}$
Combustion regime

The fluid equations of motion

Conservation laws:

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0\,,$$ mass

$$\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{\nabla P}{\rho} - g\hat{z}\,,$$ momentum

$$\partial_t(\rho E) + \nabla \cdot (\boldsymbol{u}\rho E) = -\nabla \cdot (\boldsymbol{u}P - \kappa \nabla T)\,,$$ energy

where the total energy density per unit mass is given by

$$E = \tfrac{1}{2}u^2 + \epsilon + gz\,.$$

Why A New 1D Stellar Evolution Code?

✔ ***open code, everybody can look at source, verify implementation;***
✔ ***capable of doing simulations for a wide range of applications.***
-> This allows simultaneous validation of physics (implementation) over a wide range of environments, e.g. validates rotation simultaneously for low-mass and massive stars and thereby breaks the degeneracy of observables coming only from one source;
✔***common platform, modern software design***
-> modular: means there is never just one MESA answer because MESA provides for most things several options.
For instance, for both micro-physics (opacities, equation of state, nuclear physics) and macro-physics (convection criteria, mass loss) that represent what is presently used and available for up-to-date stellar evolution codes.

* **key point**: simultaneous solution of mixing, network and structure operator
-> enhanced numerical stability BUT limits number of species for production runs to < 100
-> post-processing for complete nucleosynthesis **(NuGrid)**.

Fresh MESA download and install :

```
adipls                install_numerics_only  num
alert                 install_num_only       package_template
astero                interp_1d              package_template_make_copy
atm                   interp_2d              rates
chem                  ionization             reaclib
clean                 kap                    README
colors                lgpl.txt               README_mesa_numerics
const                 lib                    sample
create_mesa_numerics  mesa_manifesto.pdf     screen
data                  mesa_test_check_out    sourceforge_release
diffusion             mesa_test_update       star
each_package_do       mk                     utils
empty_caches          mlt                    weaklib
eos                   mtx                    website
include               net
install               neu
```

Copy star/work in star/my_work_directory, and you are ready to play.
All basic settings can be done in the <u>inlist</u> file.

* **MESA has a large test-suite:** start by finding a problem similar to the one you want to do -> **mesa/star/test_suite/**
Warning: test suite problems are not guaranteed in any way, in particular they may not reflect what is the state of the art for refereed publications, and they are not necessarily verified and validated
* for cases that have gone through a refereeing process (or of similar quality) go to http://www.mesastar.org.

* The key ingredient of a MESA run is the inlist which has three parts: **@star_job**, **@controls** and @pgplot.
    -> each of them has a master default file in the MESA star/public: run_star_defaults.dek and star_defaults.dek.
    -> look through these as a first step to see what the options are, and start to modify your inlist
* Additional physics and modules can easily be added:
    -> MESA provides interfaces for that, see star/public/other_????.f routines
    -> additional code can also be inserted in a run directory via the stub in star/your_work/src/run_star_extras.f

Part of an inlist as example:

```
&star_job

      mesa_data_dir = '/Users/bpaxton/mesa/data'
  ! << edit this


      create_pre_main_sequence_model = .true.

      change_net = .true. ! switch nuclear reaction network
      new_net_name = 'o18_and_ne22.net'

      eos_file_prefix = 'mesa'
      kappa_file_prefix = 'gs98'

      pgstar_flag = .true.

/ !end of star_job
```

For his tutorial, Denissenkov will use **nova.net**.

* **The MESA nuclear physics package:**

-> different choices for the most important energy producing reactions are available

-> weak rates, reaclib format

```
! nuclear reactions

  change_net = .false. ! switch nuclear reaction network
  new_net_name = ''

  set_rates_preference = .false. ! for use by net + rates modules
  new_rates_preference = 1
     ! 1 = NACRE rates -- this is the default
     ! 2 = jina reaclib rates

  set_rate_c12ag = '' ! empty string means ignore this control
     ! one of 'NACRE', 'Buchmann', or 'Kunz'
  set_rate_n14pg = '' ! empty string means ignore this control
     ! one of 'NACRE', 'Imbriani', or 'CF88'
  set_rate_3a = '' ! empty string means ignore this control
     ! one of 'NACRE', 'Fynbo', 'CF88', or 'FL87'
        ! FL87 is Fushiki and Lamb, Apj, 317, 368-388, 1987
        ! and includes both strong screening and pyconuclear
  set_rate_1212 = '' ! empty string means ignore this control
     ! one of 'CF88' or 'G05'
     ! G05 is Gasques, et al. Phys Review C, 72, 025806 (2005)
     set_rate_1212_to_ne20 = '' ! OLD NAME for set_rate_1212
```

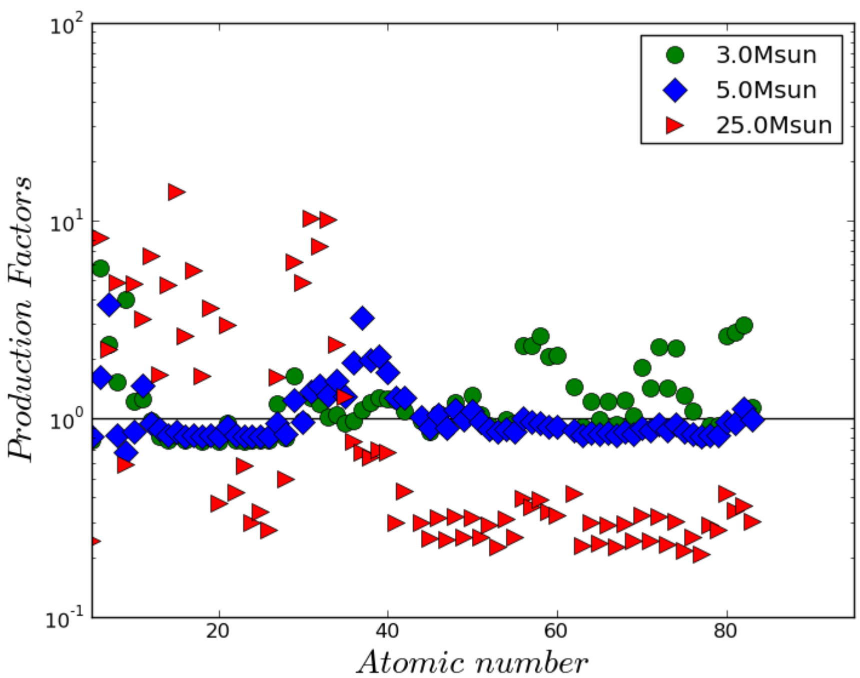
change_net = .true.
new_net_name = 'nova.net'

For instance,
I want to use the
3a reaction by
Fynbo et al. 2005
instead of NACRE
(default):
In the inlist I write:
set_rate_3a = 'Fynbo'

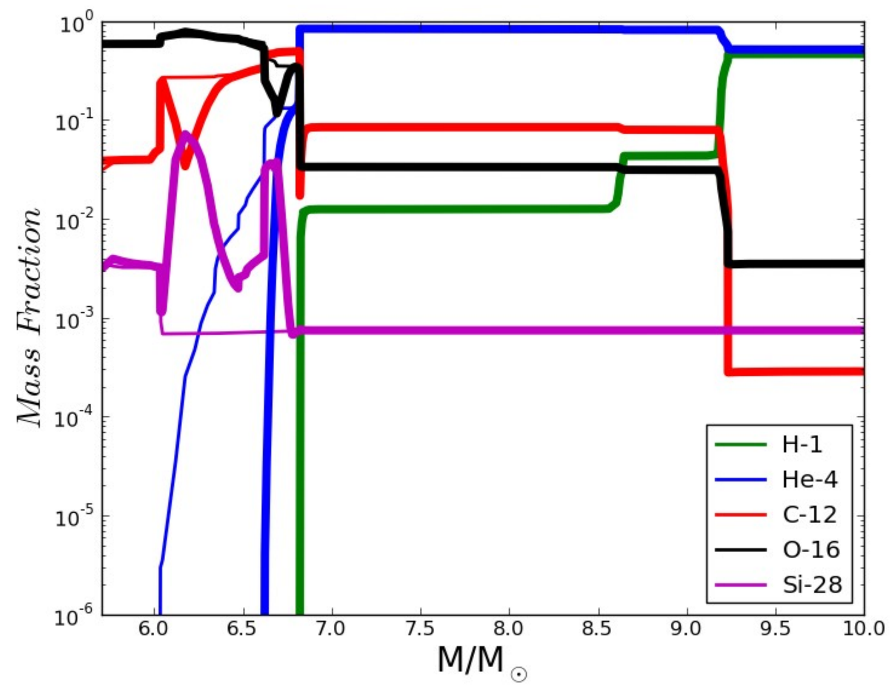
NuGrid :

- http://forum.astro.keele.ac.uk:8080/nugrid (just google nugrid)
- comprehensive post-processing code suite for nucleosynthesis simulations

The Nucleosynthesis Grid (NuGrid) project develops and maintains tools for large scale post-processing nucleosynthesis simulations, and applies these to complete sets of quiescent and explosive nuclear production environments.



Final elemental production factors for a low mass AGB star (3 Msun), a massive AGB star (5 Msun), and a massive star (25 Msun).



Abundances versus mass coordinate before and after core collapse SN (thin and thick lines) for a 25 Msun star, Z = 0.02.

NuGrid and MESA

The stellar evolution code **MESA** provides the right thermodynamic evolution in different stellar phases.

-> for this includes only those reactions that provide most of the energy

-> these are typically ≤ 50 species for any given environment (AGB stars, massive stars, etc) but may not always be the same (-> e.g. agb.net for AGB stars, aprox21.net for massive stars, or ***nova.net*** for ***Nova*** -> ***Pavel's tutorial***).

MESA does not solve the complete nucleosynthesis.

Using a comprehensive set of isotopes and nuclear reactions, ***NuGrid*** tools provide the ***complete nucleosynthesis*** from different stellar conditions.
Post-processing -> operator split of mixing and nuclear burning

-> <u>NuGrid and MESA complementary to provide complete sets of stellar yields</u>.

Primary application: alignment of goals and needs of different fields of nuclear astrophysics.

The NuGrid framework

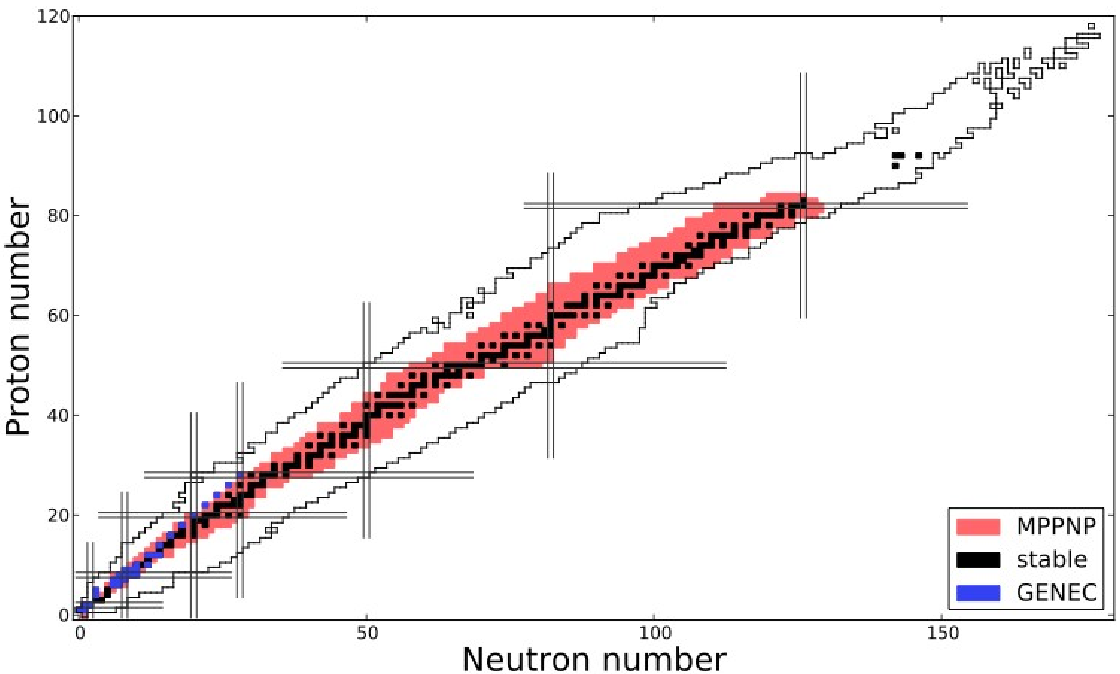
stellar evolution with minimal network for energy production

↓

multi-zone nucleosynthesis post-processing and mixing with adaptive, complete network for all nucleosynthesis

↓

all abundance data at all times in all locations inside the star



Example of SEE network and PPN network in NuGrid framework (Bennett etal 2012).

Stellar evolution & explosion codes

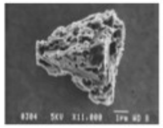
↓

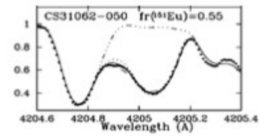
MPPN - Multi-zone Post-Processing Network | Single-zone post-processing

Physics package | Solver package

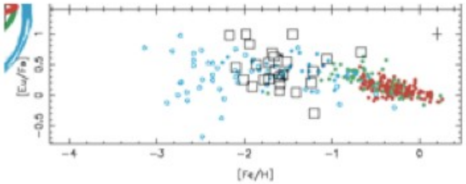
↕

Validation through astronomy observations





Application in astronomy



NuGrid research areas and projects

- pre-supernova stellar evolution and mixing processes and their implication for nucleosynthesis
- supernova explosions and explosive nucleosynthesis in SN type II and Ia
- stellar evolution properties of stellar populations, correlating CMDs with yield information
- recurrent nova (see P. Denissenkov tutorial)
- super-AGB star nucleosynthesis
- nucleosynthesis in double-degenerate mergers
- impact of reaction rate uncertainties in stellar yields, including:
  - (n,p), (n,a) reactions
  - $^{12}C+^{12}C$
  - n-source reactions
  - n-capture and charged particle reactions
- s process in stars
- evolution and nucleosynthesis of low- and intermediate mass stars
- r process in SN fall-back and parametric conditions
- Pop III stars, stellar rotation
- nucleosynthesis in H-^{12}C combustion regime

Physics package:

One physics package for all applications!

- **5100+ isotopes**
- **Reaction rate libraries:**

✓ JINA REACLIB 2008 revision, V1.0 (2011)
✓ Basel REACLIB revision 20090121
✓ KADoNIS (Dillmann et al. 2006)
✓ NACRE (Angulo et al. 1999)
✓ Iliadis et al. 2001
✓ Caughlan et al. 1988
✓ Weak interaction: Fuller et al. 1985, Oda et al. 1994, Goriely et al. 1999, Langanke & Martinez-Pinedo 2000

- **BRUSLIB Netgen interface** (Aikawa et al. 2005)
- **NSE:**

✓ T-dependent partition function & mass excess (REACLIB)
✓ Coulomb screening (Calder et al. 2007)
✓ Weak interaction feed-back considered

- **Isomeric state network**: Al26, Kr85, Cd115, Lu176, Ta180
- **Sandbox:** N14(p,g) from LUNA, 3a by Fynbo et al. 2005, C12(a,g)O16 by Kunz et al. 2002, etc.

Drivers:

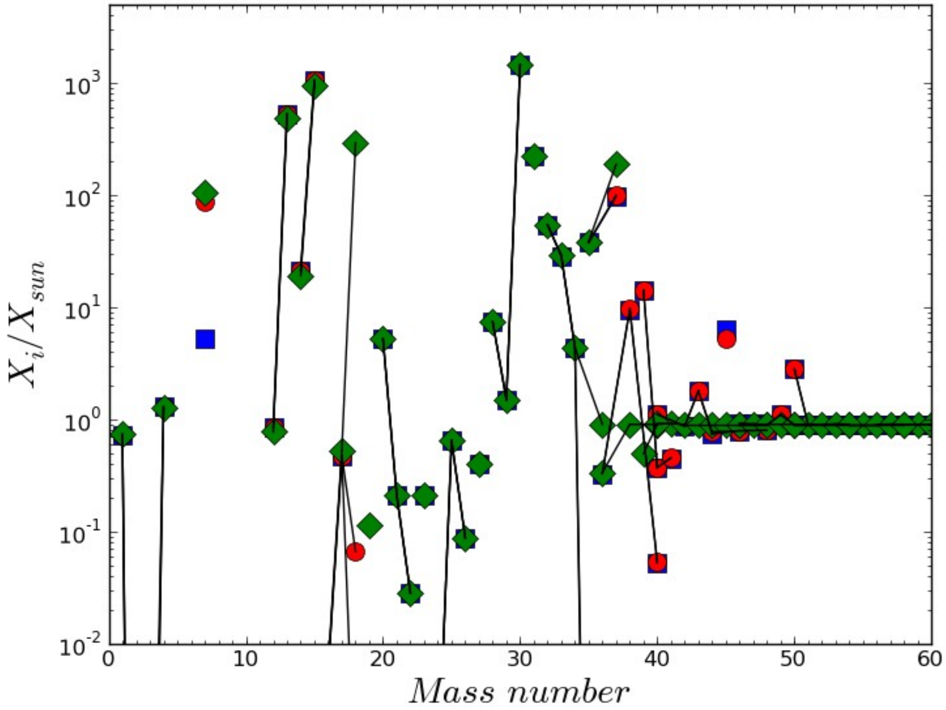
SPPN:
⌘single zones, trajectories, analytic prescriptions
MPPNP (multi-zone PPN)
⌘MPI-parallel (typical runs on 100-200 procs)
⌘USEEPP (Unified Stellar Evolution and Explosion Post-processing) IO hdf5 library
⌘grid options:
✓Static
✓Input
✓(AMR)
⌘Flexible restart and re-grid options (batch queuing system enabled)
(TPPN (->BMPPN))

Solver package:

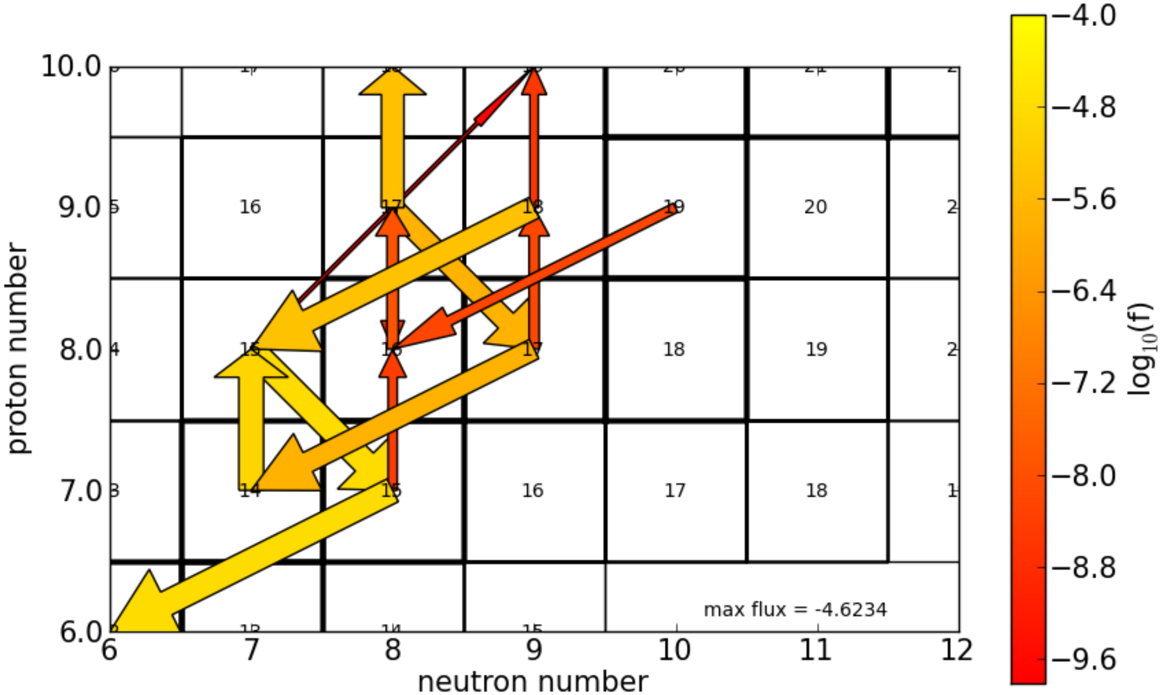
- Newton-Raphson, fully implicit
- Integrated dynamic network at iteration level
- (Adaptive, flux-guided time steps)
- Sparse solver

The physics package is designed as a **compilation** of different nuclear rate compilations and single rates included in the sandbox.

Therefore there is not a unique solution. Different nuclear network sets can be selected, and **multiple set of yields can be provided starting from the same stellar models.**



Example: Isotopic distributions for the same Nova simulation, but using different nuclear physics sets (see Pavel's tutorial).



Different plotting tools are provided to analyze in detail the nucleosynthesis and to perform **nuclear sensitivity studies**.

As an example, on the left the strongest nucleosynthesis fluxes (dYi/dt) in the mass region N - O - F during ONeMg Nova calculations.

Snapshot of the master network file, for ^{15}N: **It can be modified for specific sensitivity studies, to create different set of yields, etc.**

306	T	1	N	15	+	1	NEUT	->	1	N	16	+	0	OOOOO	0.745E+06	KADON	(n,g)	1	1.000E+00	2.401E+18
307	T	1	N	15	+	0	OOOOO	->	1	N	14	+	1	NEUT	0.100E-98	JINAC	(g,n)	2	1.000E+00	-1.045E+19
308	T	1	N	15	+	1	NEUT	->	1	C	15	+	1	PROT	0.100E-95	JINAC	(n,p)	3	1.000E+00	-8.674E+18
309	T	1	N	15	+	1	NEUT	->	1	B	12	+	1	HE 4	0.100E-95	JINAC	(n,a)	4	1.000E+00	-7.354E+18
310	T	1	N	15	+	1	PROT	->	1	O	16	+	0	OOOOO	0.105E+04	NACRR	(p,g)	5	1.000E+00	1.170E+19
311	T	1	N	15	+	0	OOOOO	->	1	C	14	+	1	PROT	0.100E-98	JINAC	(g,p)	6	1.000E+00	-9.849E+18
312	T	1	N	15	+	1	PROT	->	1	O	15	+	1	NEUT	0.100E-95	NACRR	(p,n)	7	1.000E+00	-3.413E+18
313	T	1	N	15	+	1	PROT	->	1	C	12	+	1	HE 4	0.466E+07	NACRR	(p,a)	8	1.000E+00	4.790E+18
314	T	1	N	15	+	1	HE 4	->	1	F	19	+	0	OOOOO	0.229E-04	NACRR	(a,g)	9	1.000E+00	3.872E+18
315	T	1	N	15	+	1	HE 4	->	1	F	18	+	1	NEUT	0.100E-95	JINAC	(a,n)	11	1.000E+00	-6.194E+18
316	T	1	N	15	+	1	HE 4	->	1	O	18	+	1	PROT	0.154E-61	JINAC	(a,p)	12	1.000E+00	-3.841E+18

T or F:
Reaction considered or not?

Reference label

production factor applied to the rate