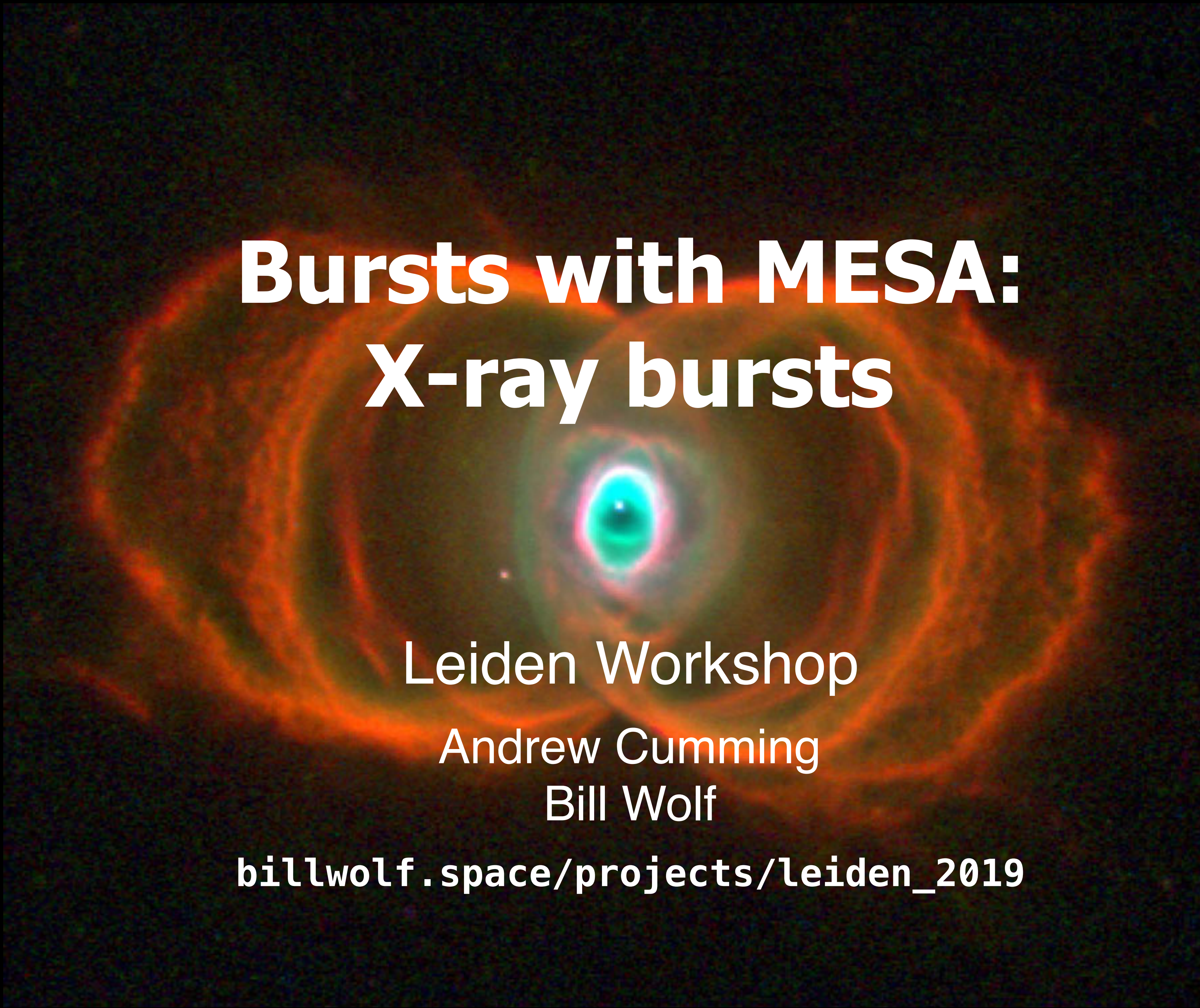

Bursts with MESA: X-ray bursts

Leiden Workshop

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billwolf.space/projects/leiden_2019

Goal for this session

- overview of using MESA to model nuclear burning on accreting neutron stars

Activities:

- Part 1: A first model of an accreting neutron star
- Part 2: Reproducing the different burning regimes
- Part 3: Extending MESA: implementing new opacities

Materials for today can be found at:

`http://45.56.103.199/Leiden_2019/`

Q: what needs to be done to make MESA a general purpose tool for burst studies?

Part 1 : A first model of an accreting neutron star

First make new MESA work directory somewhere in your local filesystem:

```
cp -r $MESA_DIR/star/work part1
```

and have a look inside:

```
cd part1
ls
```

Anatomy of a MESA work directory

`inlist` → `inlist_project` — sets physics and numerical parameters for the run

`inlist` → `inlist_pgstar` — parameters for plotting

`LOGS/` → `history.data`

`LOGS/` → `profiles.index`, `profileN.data`

this is where MESA puts output files

`photos/` — model files that you can use to restart MESA, e.g. `./re x050` instead of `./rn`

`src/run_star_extras.f` — where you can extend MESA for more advanced use

`*.mod` — model files that you can use to initialize the run, save at the end, distribute etc.

Download `part1.tgz` and unpack it inside the work directory:

```
tar -zxvf part1.tgz
```

Inside the tar file are:

- replacements for `inlist_project` and `inlist_pgstar`
- a starting model `ns_1.4M.mod`
- `history_columns.list` which adds extra columns to MESA’s output, specifically

```
star_age_hr
max_eps_he_lgT
log_total_mass he4
```

Now make and run the code :

```
./mk
./rn
```

inlist_project

```
&star_job
      show_log_description_at_start = .false.

      load_saved_model = .true.
      saved_model_name = 'ns_1.4M.mod'

      save_model_when_terminate = .true.
      save_model_filename = 'final.mod'

      change_initial_net = .true.
      new_net_name = 'cno_extras_plus_fe56.net'

      set_rate_3a = 'FL87' ! Fushiki and Lamb, Apj, 317, 368-388, 1987
      kappa_file_prefix = 'gs98'

      set_initial_age = .true.
      initial_age = 0
      set_initial_model_number = .true.
      initial_model_number = 1

      pgstar_flag = .true.

      relax_L_center = .false.
      relax_initial_L_center = .false.
      new_L_center = 1d34
      dlgL_per_step = 5d-2
      relax_L_center_dt = 100.0


/ ! end of star_job namelist
```

inlist_project

```
&controls

      use_gold_tolerances = .false.
      use_eosDT2 = .true.
      use_eosELM = .true.
      use_dedt_form_of_energy_eqn = .false.
      use_eps_mdot = .false.
      warn_when_stop_checking_residuals = .false.

      min_T_for_acceleration_limited_conv_velocity = 1e6
      !min_timestep_limit = 1d-10

      max_model_number = 3000
      !max_age_in_seconds = 1e4

      use_Type2_opacities = .true.
      Zbase = 0.02d0

      varcontrol_target = 1d-4
      mesh_delta_coeff = 1.0

      which_atm_option = 'grey_and_kap'

      use_Ledoux_criterion = .false.
      alpha_semiconvection = 0.1
      thermohaline_coeff = 2
      thermohaline_option = 'Kippenhahn'

      accrete_same_as_surface = .false.
      accrete_given_mass_fractions = .false.
      accretion_h1 = 0.7 ! mass fraction
      accretion_h2 = 0 ! if no h2 in current net, then this is automatically added to h1
      accretion_he3 = 0
      accretion_he4 = 0.28
      accretion_zfracs = 3 ! one of the identifiers for different Z fractions from chem_def

      mass_change = 3e-8  ! rate of accretion (Msun/year)

      photo_interval = 50
      profile_interval = 50
      history_interval = 1
      terminal_interval = 10
      write_header_frequency = 10


/ ! end of controls namelist
```

To see the many different inlist options look on the MESA website

http://mesa.sourceforge.net

You can also look in `$MESA_DIR/star/defaults`

```
Andrews-MacBook-Pro:~ cumming$ ls $MESA_DIR/star/defaults/*.defaults
/Applications/mesa/star/defaults/controls.defaults
/Applications/mesa/star/defaults/pgstar.defaults
/Applications/mesa/star/defaults/star_job.defaults
```

`inlist_pgstar` controls MESAs plotting window

To see the many different options look on the MESA website

http://mesa.sourceforge.net

We've set the flag `Grid1_file_flag = .true.` in `inlist_pgstar` so that MESA will output png files.

To make a movie:

```
images_to_movie 'png/grid*.png' movie.mp4
```

Note that before running it's good to delete old png files from previous runs

```
rm -rf png/*
```

MESA output

`LOGS/history.data`

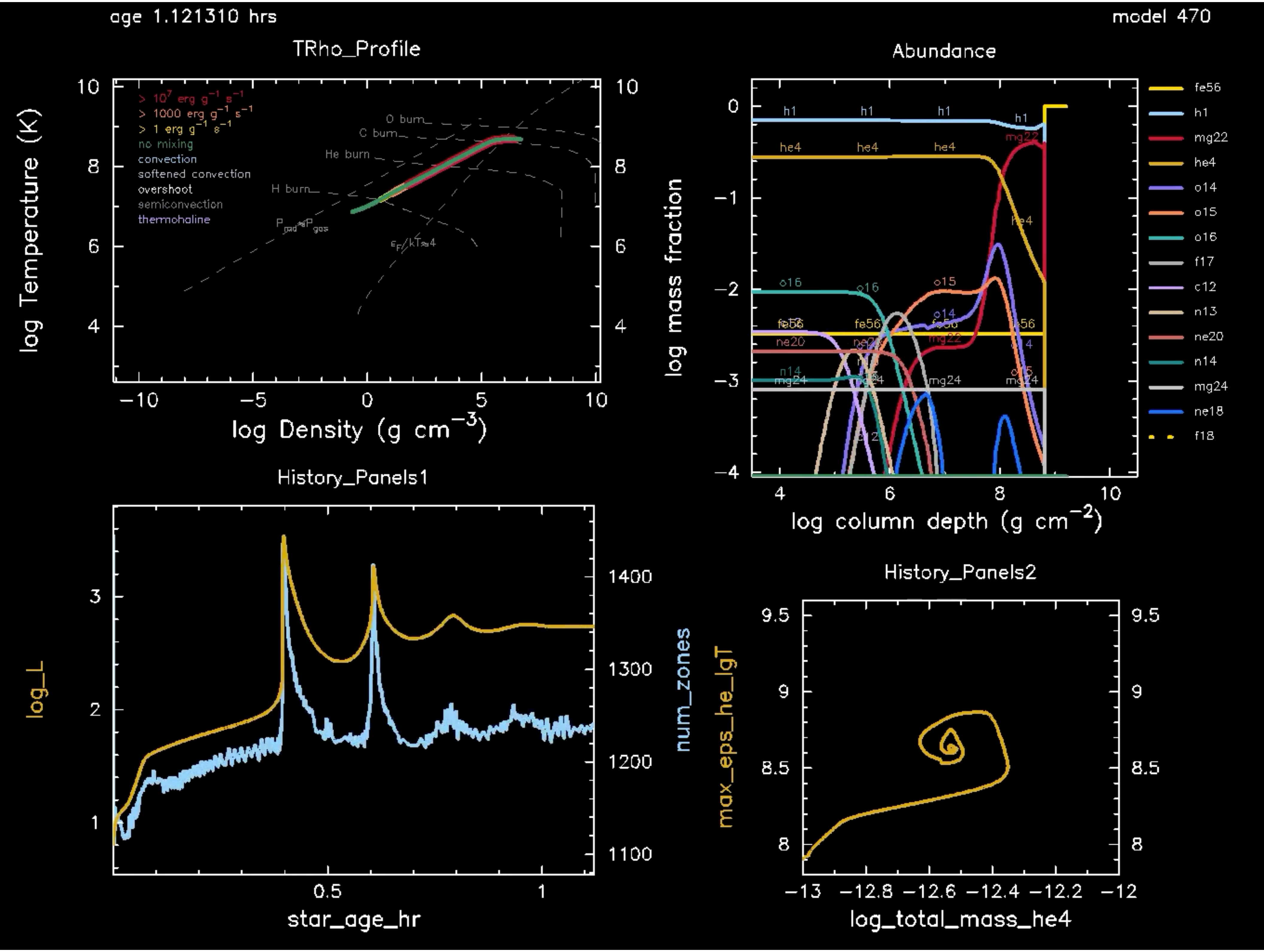
One line per model with information such as the age, luminosity, mass etc. so you can see how things change over time

`LOGS/profileN.data`

One file per model with the internal structure of each model, e.g. composition profile, temperature profile etc.

To make changes, you can copy the defaults to your work directory and edit: (uncomment / comment out lines you want to add / remove from the output)

```
cp $MESA_DIR/star/defaults/profile_columns.list .
cp $MESA_DIR/star/defaults/history_columns.list .
```



age 1.121310 hrs
model 470
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
$P_{rad} \approx P_{gas}$
$\epsilon_F/kT \approx 4$
Abundance
log mass fraction
log column depth (g cm^{-2})
fe56
h1
mg22
he4
o14
o15
o16
f17
c12
n13
ne20
n14
mg24
ne18
f18
History_Panels1
log_L
num_zones
star_age_hr
History_Panels2
max_eps_he_lgT
log_total_mass_he4

The equations of stellar structure (1D spherical symmetry)

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \varrho} ,$$

mass continuity

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} ,$$

hydrostatic balance

$$\frac{\partial l}{\partial m} = \varepsilon_{\mathrm{n}} - \varepsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\varrho}\frac{\partial P}{\partial t} ,$$

energy equation

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla ,$$

heat transport

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\varrho}\left(\sum_j r_{ji} - \sum_k r_{ik}\right) , \quad i = 1, \ldots, I .$$

composition changes

Details and applications of the code are described in the MESA "instrument papers" **Paxton et al. (2011,2013,2015,2018,2019)**

https://ui.adsabs.harvard.edu/abs/2019arXiv190301426P/abstract

Equation of state

$P(\rho, T, X_i)$

e.g. ideal gas $P = nk_BT$

radiation $P = \frac{1}{3}aT^4$

degenerate electrons $P = \frac{3}{5}n_eE_F = K\rho^{5/3}$

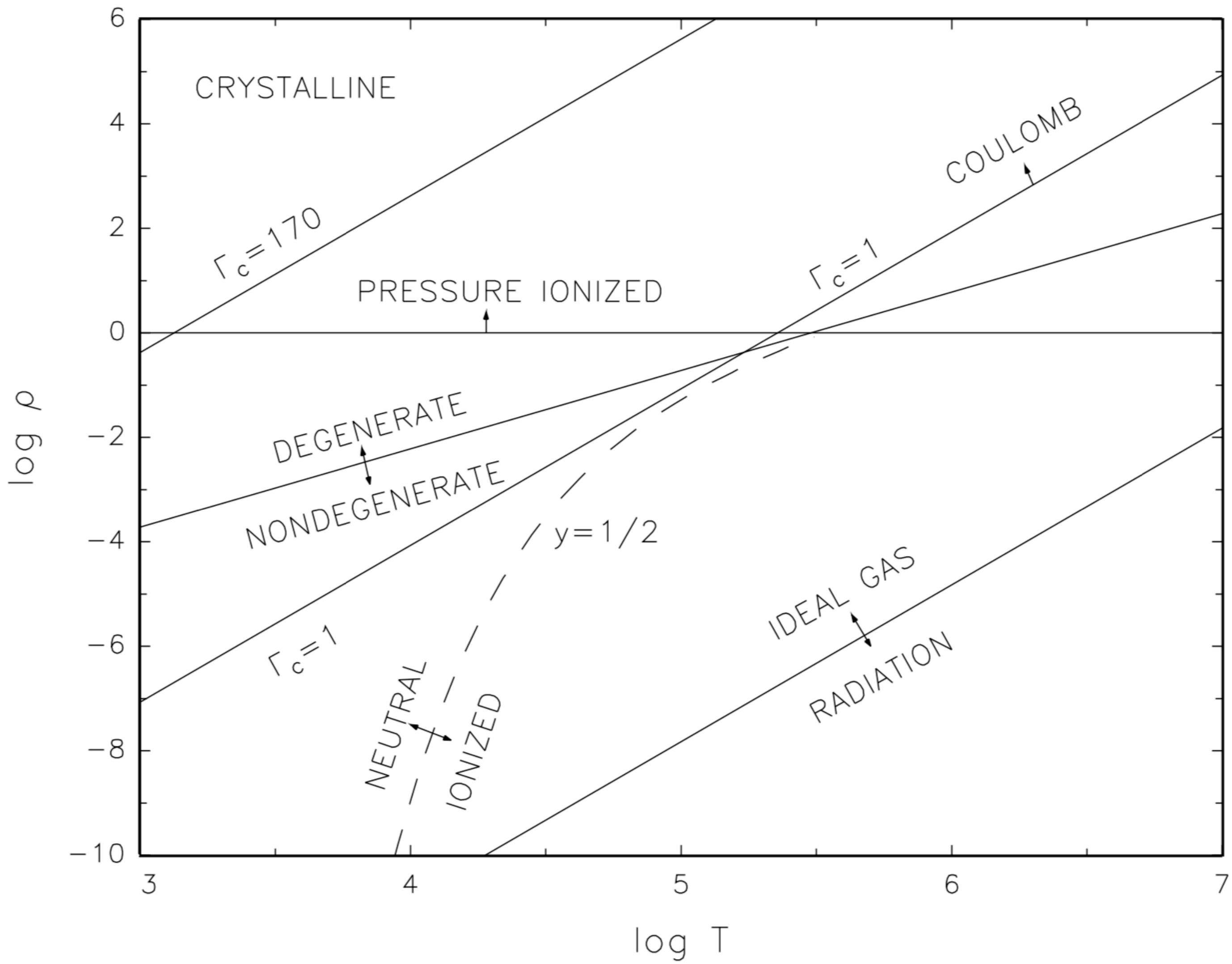
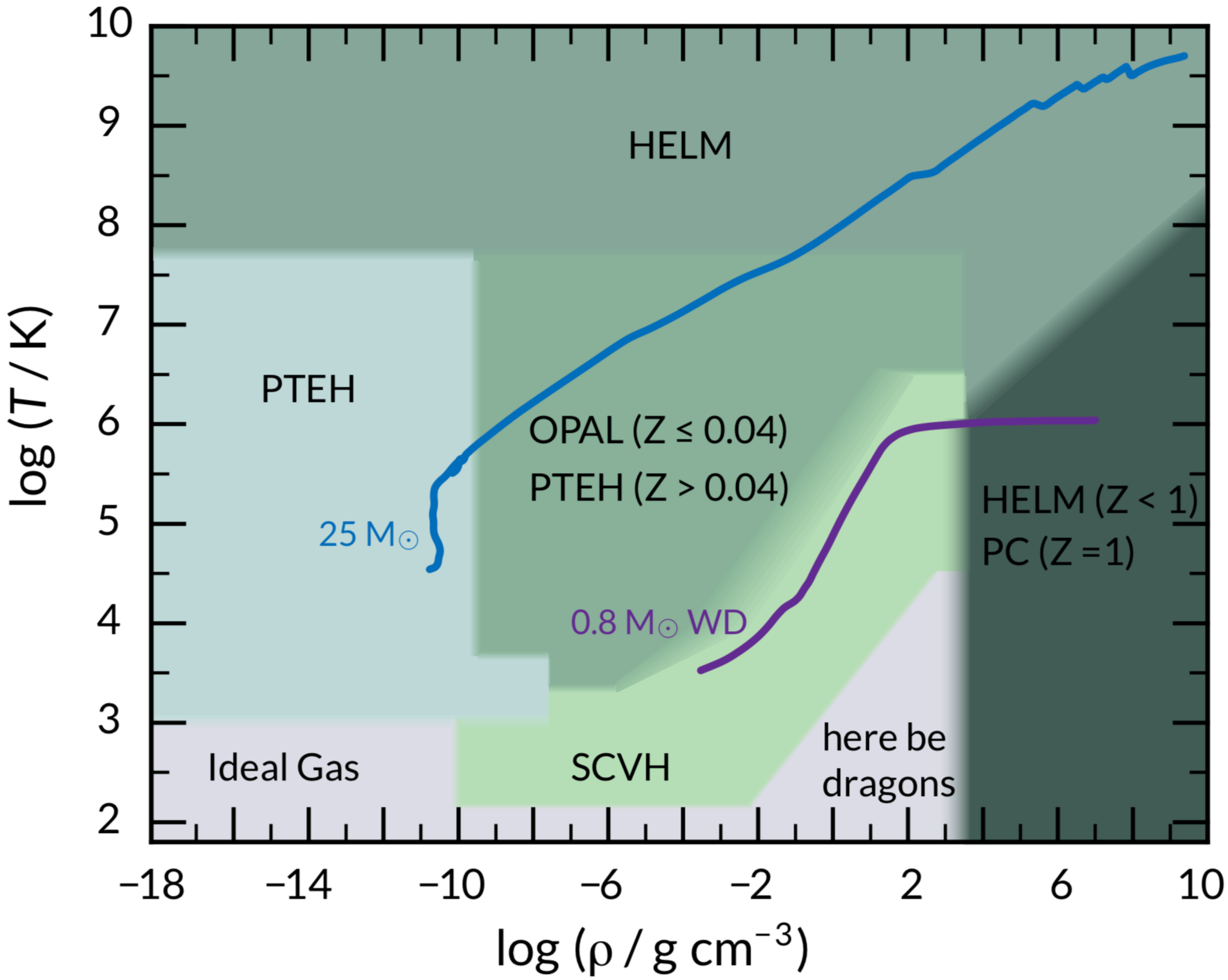


Fig 3.9 from Hansen & Kawaler



Complete ionization:

HELM = Timmes & Swesty 2000 (includes e+e- pairs)

PC = Potekhin & Chabrier 1999 (treats heavy elements & Coulomb interactions, freezing)

Partial ionization:

OPAL = Rogers et al. 1996 (pressure ionization of mixtures)

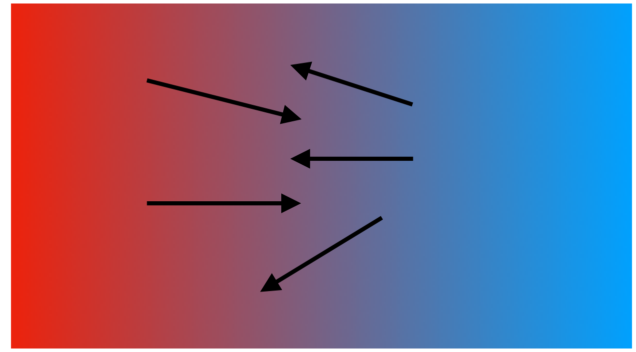
PTEH = Pols et al. 1995 (partial ionization of H,He)

SCVH = Saumon et al. 1995 (H/He EOS for planetary/brown dwarf interiors)

Details:

- Paper I section 4.2
- Paper II section A.2 - adds high Z EOS tables
- Paper 2019 section A.1
    - adds PTEH for low density (partial ionization of H,He)
    - adds DT2 and ELM options for more accurate partial derivatives

Heat transfer I: photon diffusion



mean free path $\ell \approx \dfrac{1}{n_e \sigma} = \dfrac{1}{\rho \kappa}$

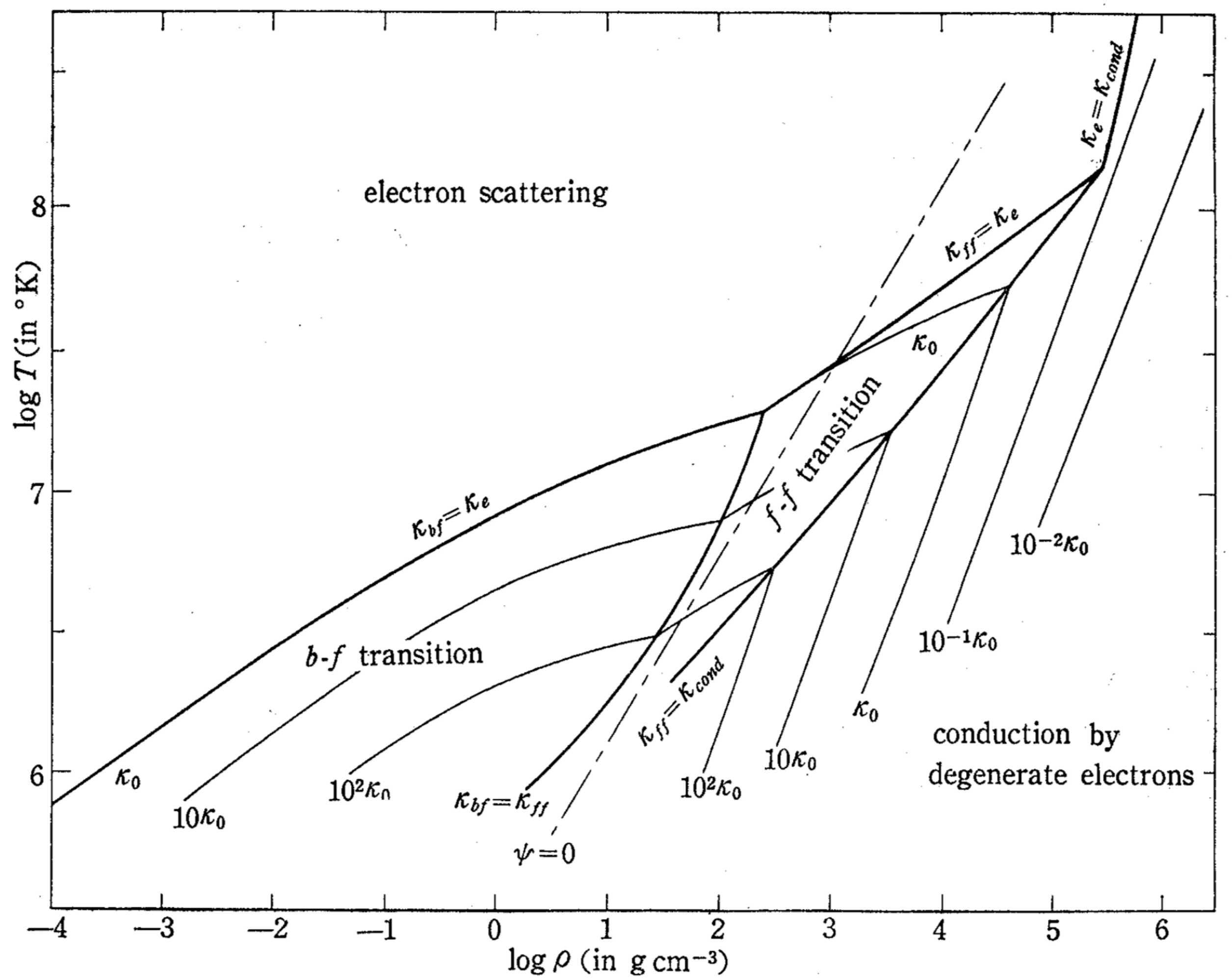
Contributions to the opacity:

* electron scattering (Thomson cross-section σ_T)

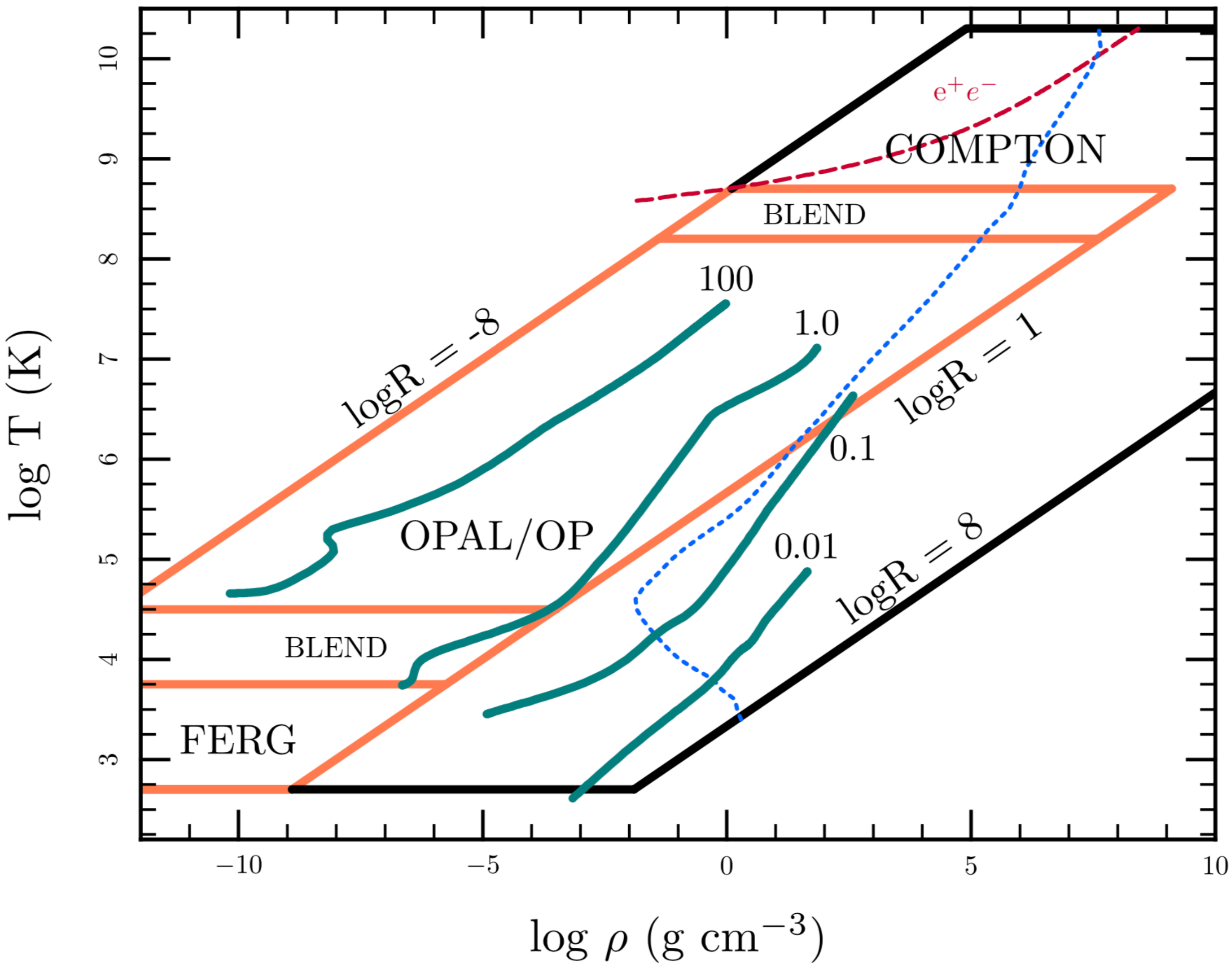
$$\kappa = 0.2\ \mathrm{cm}^2\ \mathrm{g}^{-1}\ (1+X)$$

* free-free and bound-free absorption

$$\kappa \propto \rho T^{-7/2}$$



Hayashi et al. (1962); reproduced in Fig 4.7 of Hansen & Kawaler



COMPTON = Cassisi et al. 2007
electron scattering

OPAL = Iglesias & Rogers 1996
for different mixtures
(note that the heaviest is CO!)

FERG = Ferguson et al. 2005
or Freedman et al. 2008
includes molecules at low T

Details:

- Paper I section 4.3
- Paper II section A.3 - adds Freedman to low T opacity; expands range of e-scattering

Heat transfer II: convection

* hot fluid elements can become buoyant and rise, transporting energy

* an intrinsically multi-D process!

1D model: mixing length theory

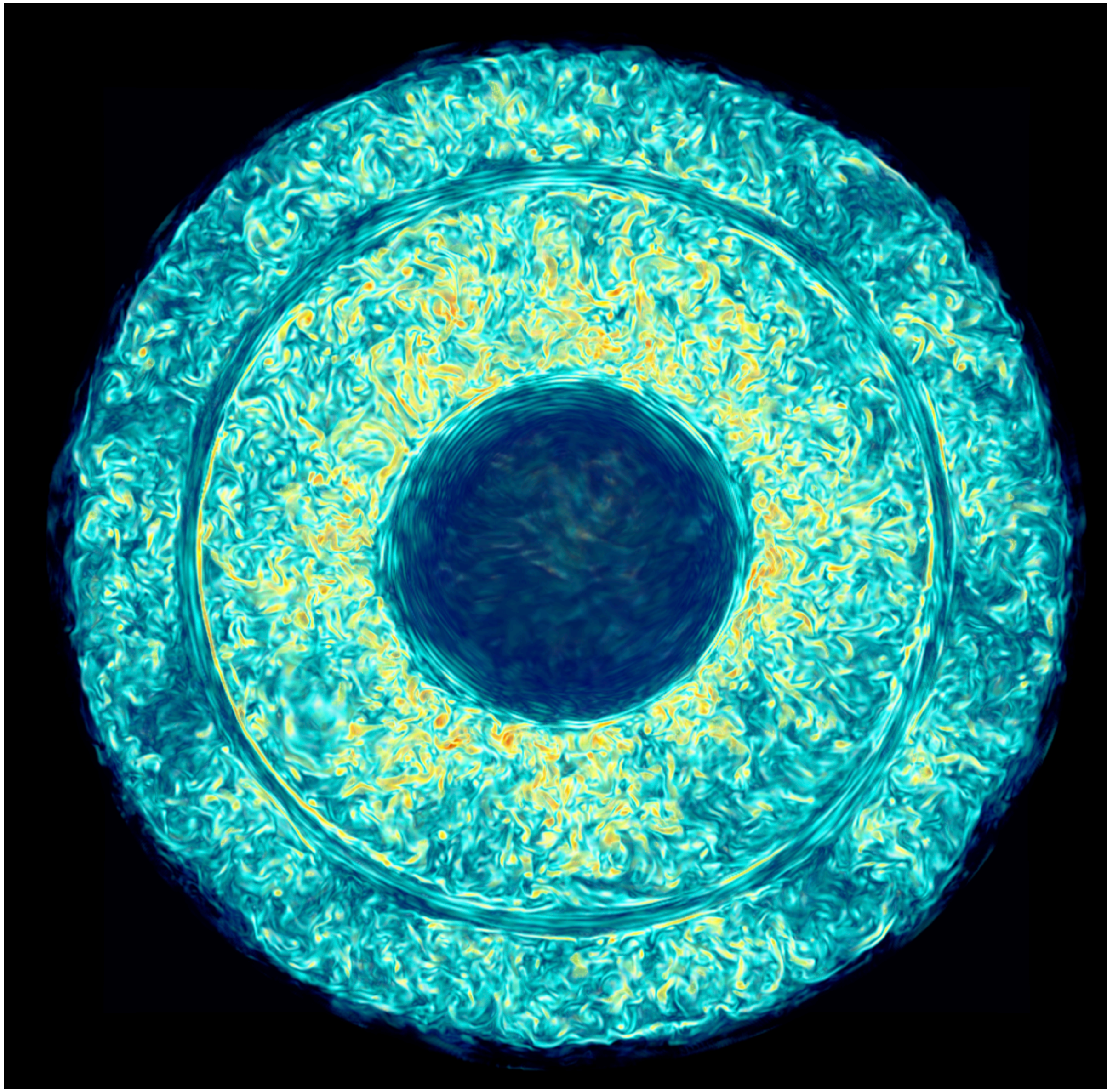
$$F_{\rm conv} \sim \rho v_{\rm conv} c_P T(\nabla - \nabla_{\rm ad})$$
$$v_{\rm conv}^2 \sim g\ell(\nabla - \nabla_{\rm ad})$$

when

$$\nabla \equiv \frac{d\ln T}{d\ln P} > \nabla_{\rm ad} \equiv \left.\frac{\partial \ln T}{\partial \ln P}\right|_S$$

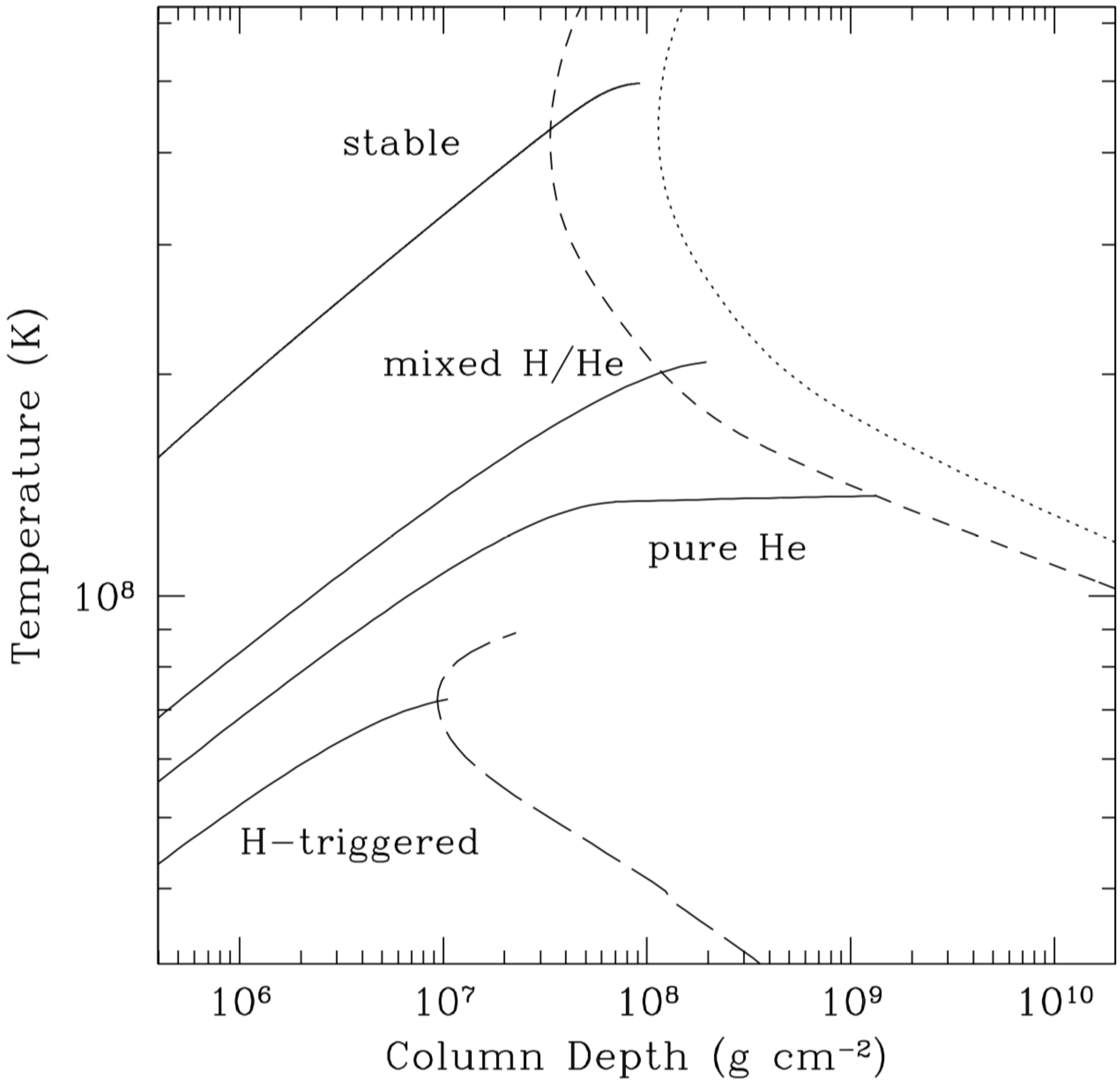
where the mixing length ℓ is a parameter calibrated to observations

MESA has many different options for MLT, e.g. set the mixing length, deal with convective/radiative boundaries, semiconvection or thermohaline, …



Clarkson et al. (2018)

Part 2 : Burning regimes



stable = both H and He burning are thermally stable

$\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$

mixed H/He = stable H burning (hot CNO cycle) but unstable He burning. He ignites in a H-rich environment (-> rp process)

$\sim 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$

pure He = stable H burning depletes all H before He ignites

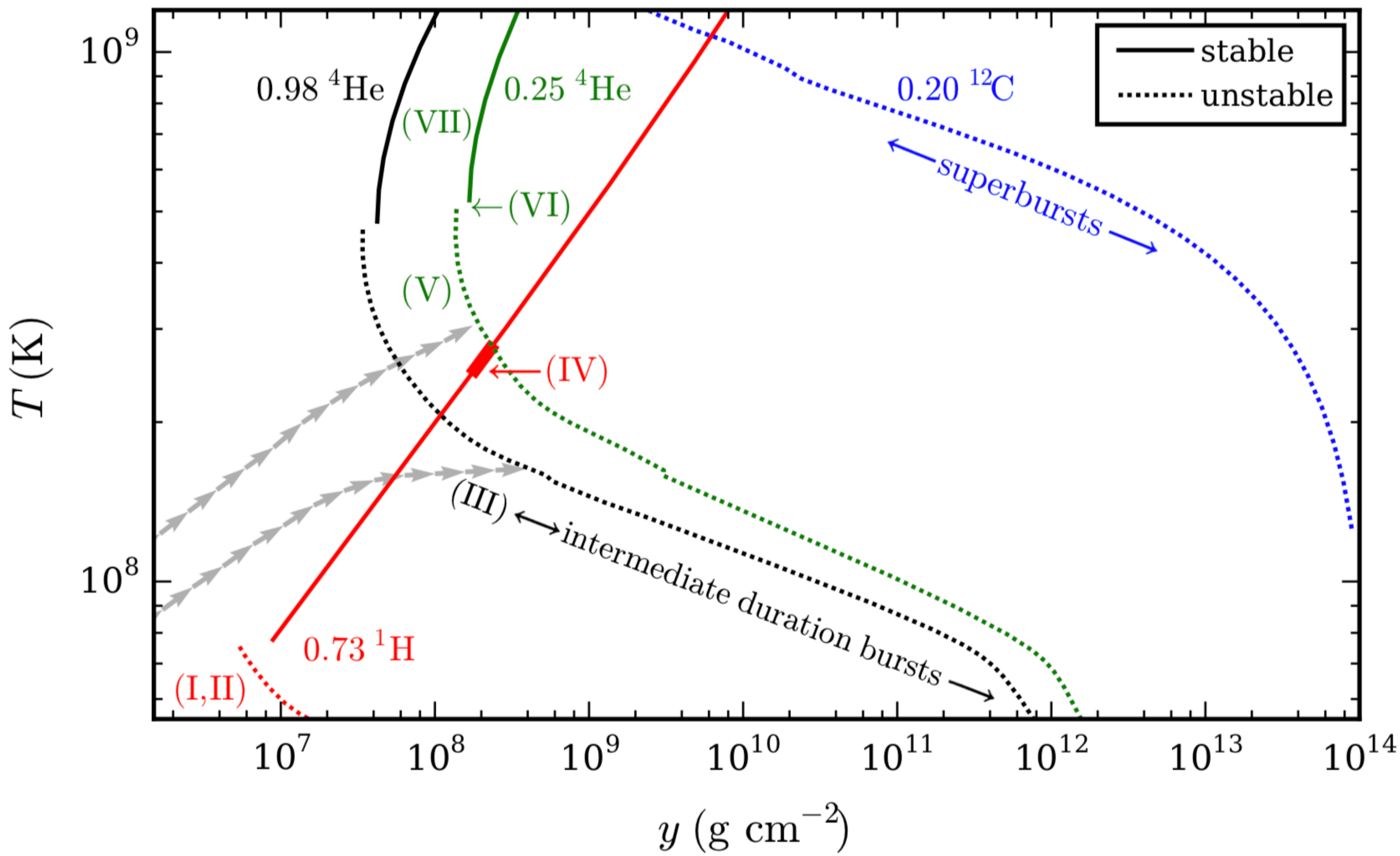
$\sim 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$

H triggered = unstable H burning

$\sim 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$

Cumming (2003)

new regime where stable He burning produces C before the He has time to ignite (Keek & Heger 2016)



Galloway & Keek (2018)

Can we reproduce these burning regimes with our model so far?

- Choose an accretion rate and run
- Observe the burning: what regime are you in?

As an example of plotting the MESA output, we've a routine to extract a single burst light curve and plot it

```
python plot_lc.py
```

- Does your burst look like a Type I X-ray burst?

You can find my results for different masses here:

http://45.56.103.199/Leiden_2019/grid_hotcno

What is missing from these models?
(why 1D X-ray burst models are hard)

mixed H/He bursts: need large network to follow rp-process — our model has a lot of leftover H, and low peak luminosities

helium flashes: reach Eddington; need to be able to follow the expansion/wind — you will find that the code has trouble for low hydrogen fractions when the luminosity approaches Eddington

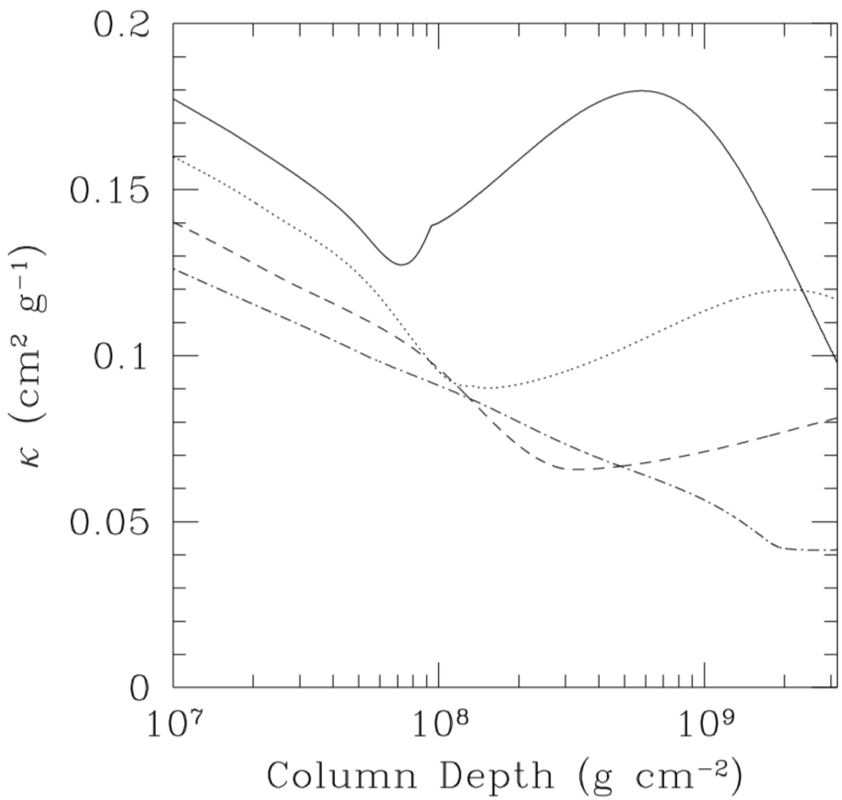
hydrogen flashes: these run smoothly, but at low accretion rates we should include diffusion/settling (there is a prescription in MESA for this)

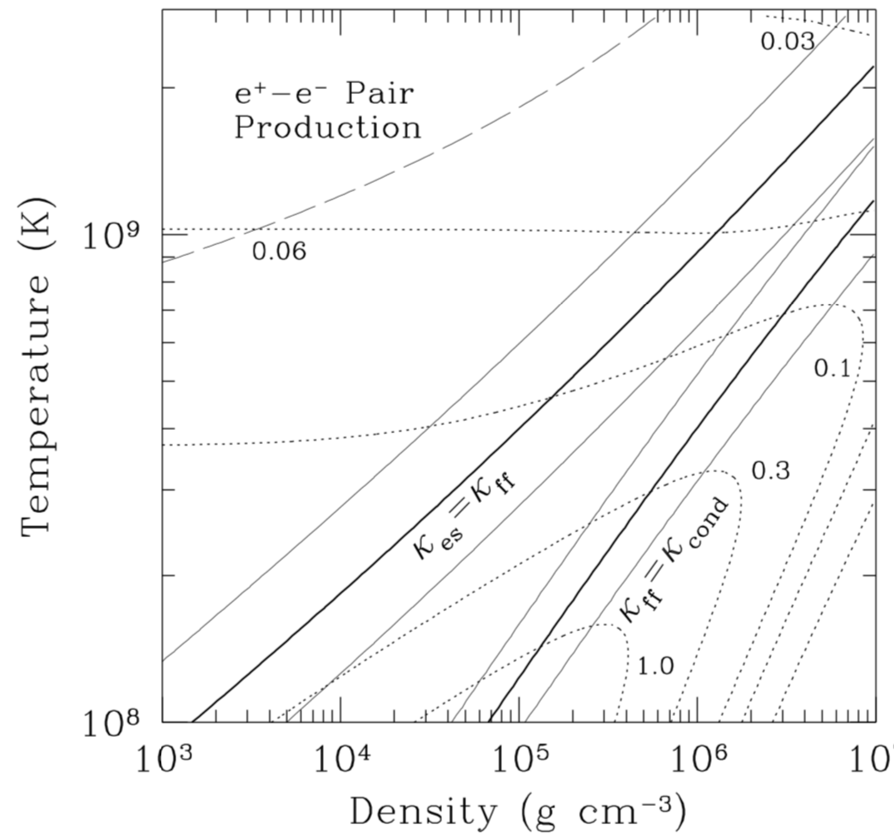
Part 3: Extending MESA

Type I X-ray burst opacities: challenging because complex mixture of elements not known in advance

Schatz et al. made an analytic fit to the free-free Gaunt factor from Itoh et al. (1991)

$$\kappa_{\mathrm{ff}} = 0.753\,\frac{\mathrm{cm}^2}{\mathrm{g}}\,\frac{\rho_5}{\mu_e T_8^{7/2}} \sum \frac{Z_i^2 X_i}{A_i}\, g_{\mathrm{ff}}(Z_i,\, T,\, n_e)$$





Non-additivity factor $\kappa = (\kappa_{es} + \kappa_{ff})A(\rho, T)$ (Potekhin & Yakovlev 2001)

Inside $MESA_DIR

MESA is built on modules

```
Andrews-MacBook-Pro:Leiden 2019 cumming$ ls $MESA_DIR
README                      crlibm                      interp_1d                 package_template
README_mesa_numerics        cv                          interp_2d                 package_template_make_copy
adipls                      data                        ionization                rates
atm                         each_package_check_crlibm   kap                       release
binary                      each_package_do             lgpl.txt                  sample
build.log                   empty_caches                lib                       star
check_crlibm                eos                         mesa_manifesto.pdf        stella
chem                        gyre                        mk                        svnup
clean                       help                        mtx                       touch
co                          include                     my_kap_config_file.txt    utils
colors                      install                     ndiffInstall.sh           website
com                         install_mods_in_parallel    net
comk                        install_num_only            neu
const                       install_numerics_only       num
```

Each has a similar structure

```
Andrews-MacBook-Pro:Leiden 2019 cumming$ ls $MESA_DIR/kap
AESOPUS_AGS09.h5          clean      i1_preprocessors    make            private
build_and_test            data       i1p                 mk              public
build_and_test_parallel   export     kap_data.tar.xz     notes           test
build_data_and_export     i1         kapcn_data.txz      preprocessor
```

Useful places to look

`$MESA_DIR/star/defaults` Default parameters and output columns

`$MESA_DIR/star/other` Different options for providing “other” routines

`$MESA_DIR/data/net_data/nets`

The different nuclear network choices (and how to construct new ones)

`$MESA_DIR/const/public/const_def.f90`

The values of constants used by MESA

`$MESA_DIR/star/test_suite`

Test problems - can be a useful place to start

`$MESA_DIR/star/public/star_data.inc`

Content of the star structure you can use to access variables in run_star_extras

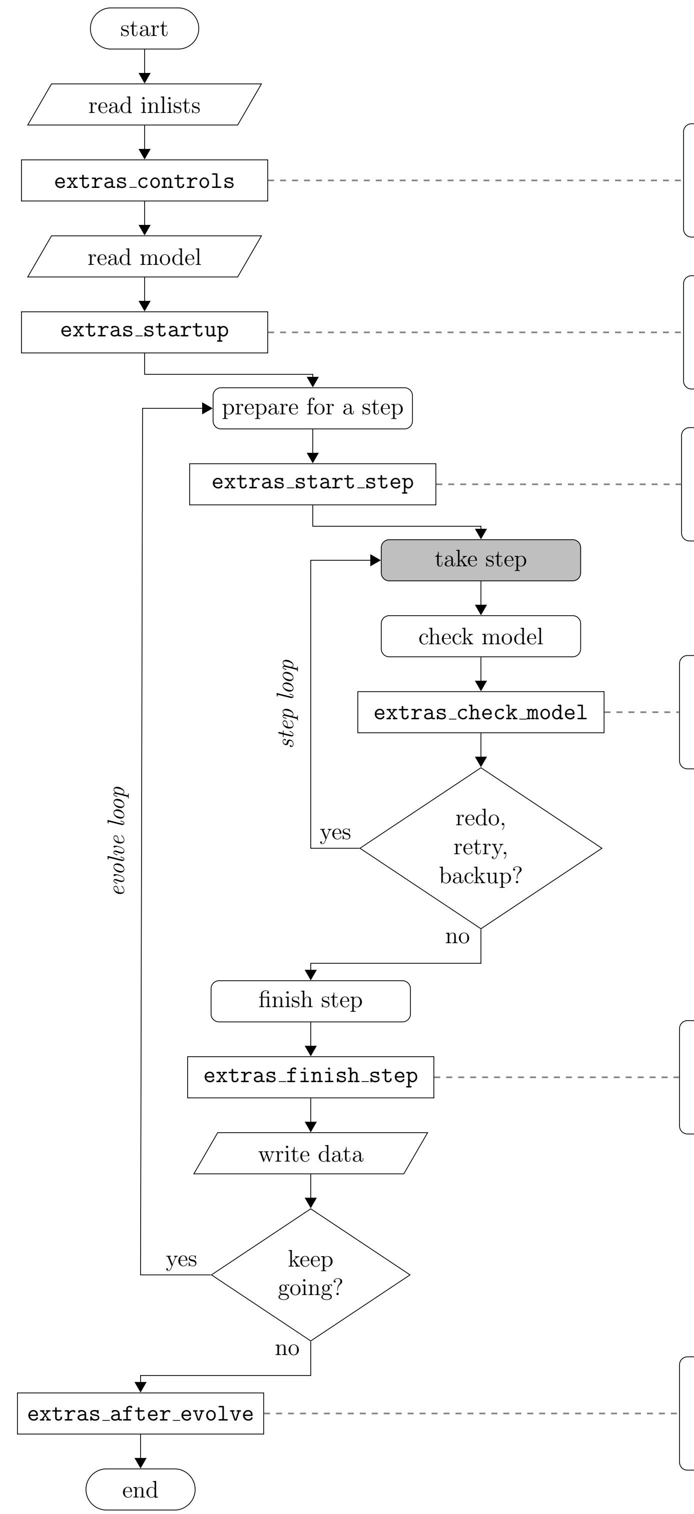
`run_star_extras`

MESA provides several places where we can hook into the code

We do this by providing (Fortran) code in the work directory in `src/run_star_extras.f`

A good place to get started is the “Beyond inlists” tutorial by Josiah Schwab

https://jschwab.github.io/mesa-2018/



Let's implement the Schatz et al. opacities in MESA:

Unpack `part3.tgz` in your work directory. It has two files:

- `run_star_extras.f` - the fortran code that implements the opacity. This needs to go in the `src` directory inside your work directory

- `inlist_pgstar` - to visualize the opacity, I added a panel that shows the opacity as a function of column depth

When you change `run_star_extras.f`, you need to recompile (`./mk`) before running

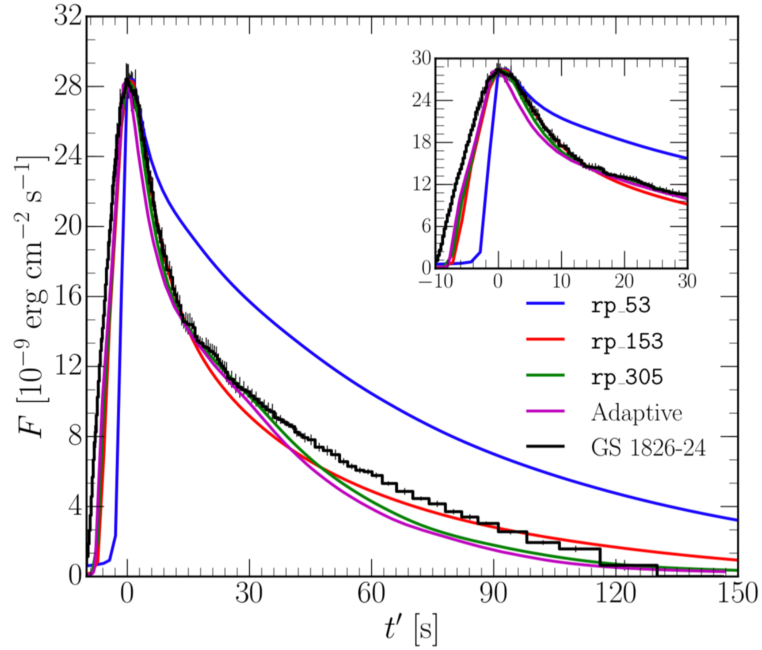
To turn on the new opacities:

```
use_other_kap = .true.
```

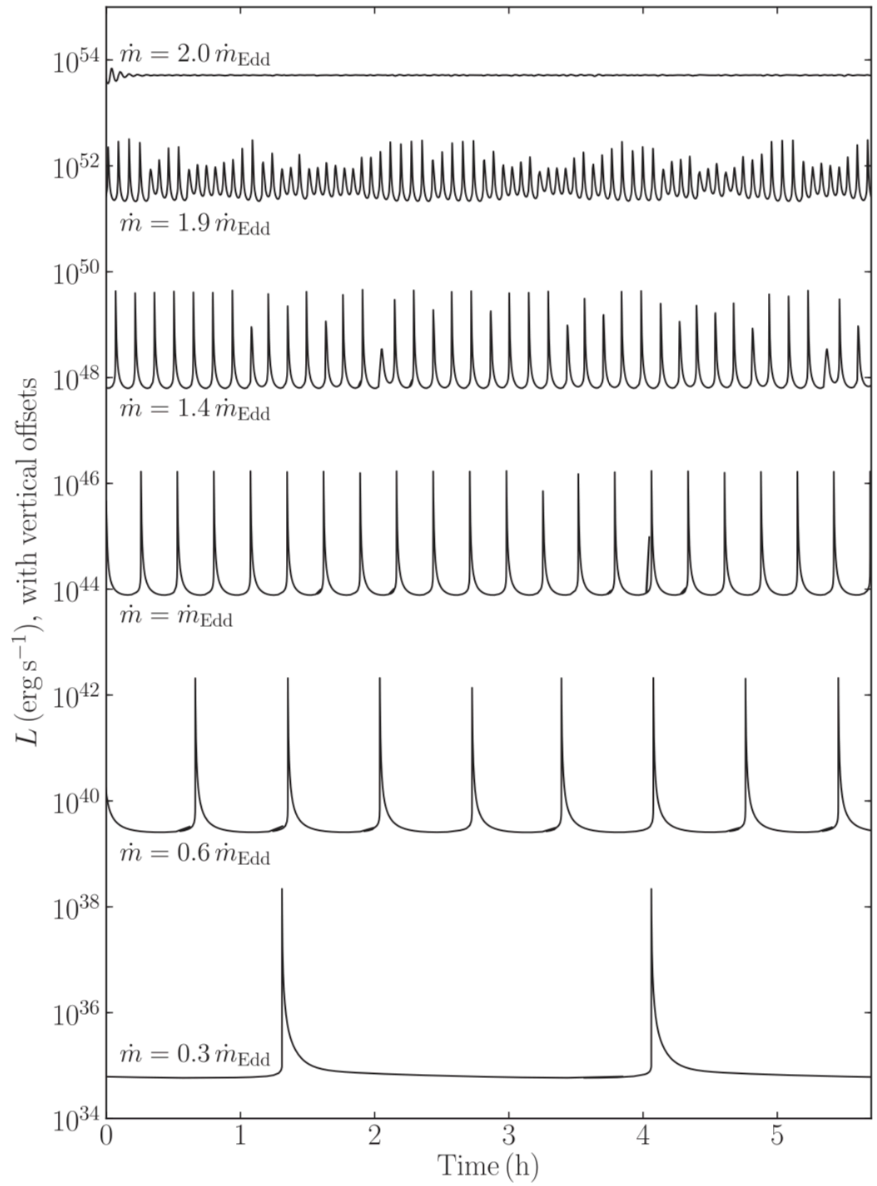
in the controls section of the inlist.

X-ray burst work with MESA

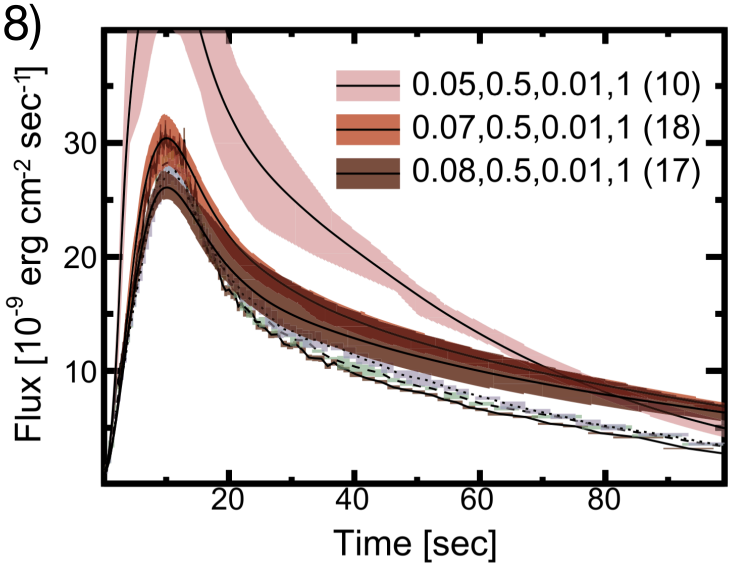
Paxton et al. (2015) - Rob Farmer



Zamfir et al. (2014)



Meisel (2018)



inlists are on MESA marketplace: **http://cococubed.asu.edu/mesa_market/**

MESA resources

The mailing list — you will get a quick answer!

`mesa-users@lists.mesastar.org`

MESA webpage: **http://mesa.sourceforge.net/index.html**

MESA Marketplace: **http://cococubed.asu.edu/mesa_market/**

MESA Summer schools:

http://cococubed.asu.edu/mesa_summer_school_2019/index.html

“Beyond inlists”

https://jschwab.github.io/mesa-2018/

The MESA “instrument papers”
Paxton et al. (2011,2013,2015,2018,2019)

https://ui.adsabs.harvard.edu/abs/2019arXiv190301426P/abstract