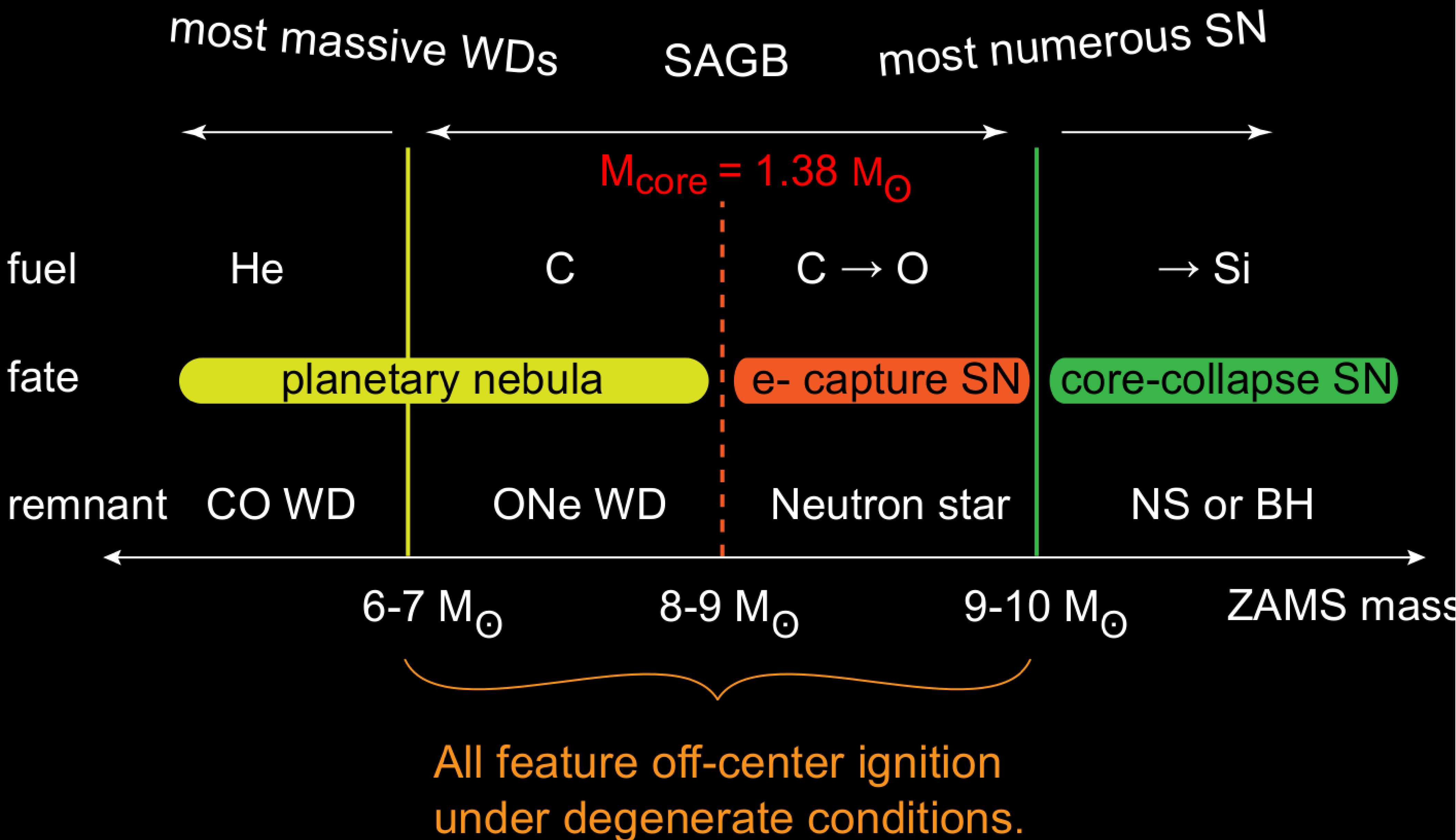
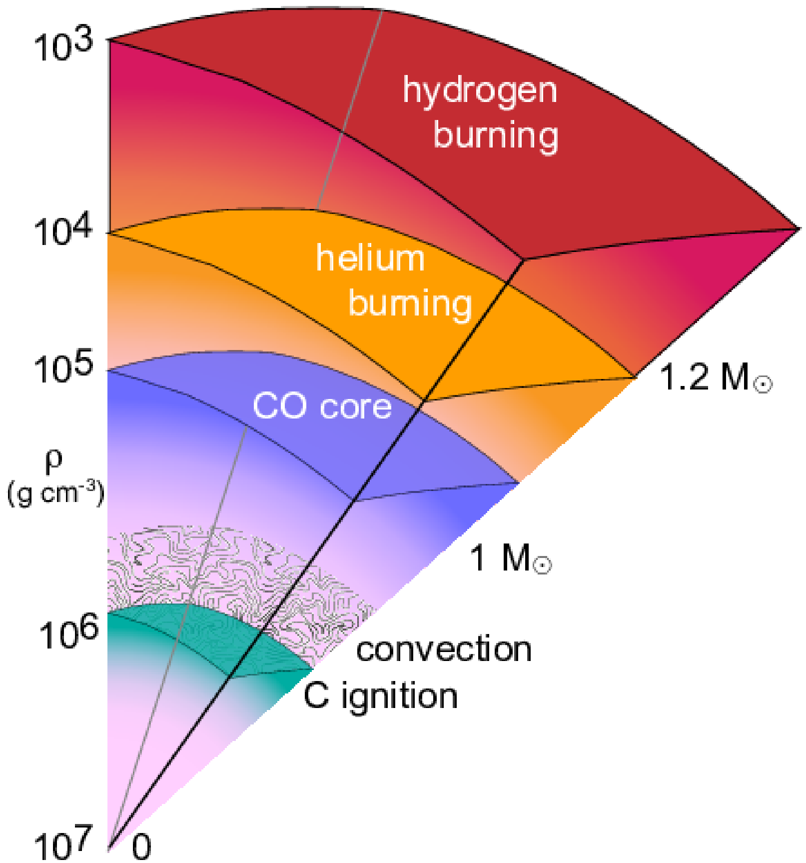
Carbon burning in SAGB stars

Farmer, R; Fields, C, E; Timmes, F,X


most massive WDs
SAGB
most numerous SN
M_{core} = 1.38 $M_\odot$
fuel
He
C
C → O
→ Si
fate
planetary nebula
e- capture SN
core-collapse SN
remnant
CO WD
ONe WD
Neutron star
NS or BH
6-7 $M_\odot$
8-9 $M_\odot$
9-10 $M_\odot$
ZAMS mass
All feature off-center ignition
under degenerate conditions.

What is a Super Asymptotic Giant branch (SAGB) star?



Farmer et al 2015

~7-10$M_\odot$

C/O degenerate core

Neutrino cooling in the core

Sets up a temperature inversion

Carbon ignition
- Why?
- Where?
- What happens?

Previously in SAGB stars

- Doherty 2015
  - 8.0$M_\odot$ carbon ignites off center (solar Z)
- Jones 2013
  - ~8.2$M_\odot$ for off center
  - >8.7$M_\odot$ centrally ignite
- Seiss 2006-2010
  - Off center between 9-11.3$M_\odot$ (No overshooting)
- Lots of variation in the models and parameters used

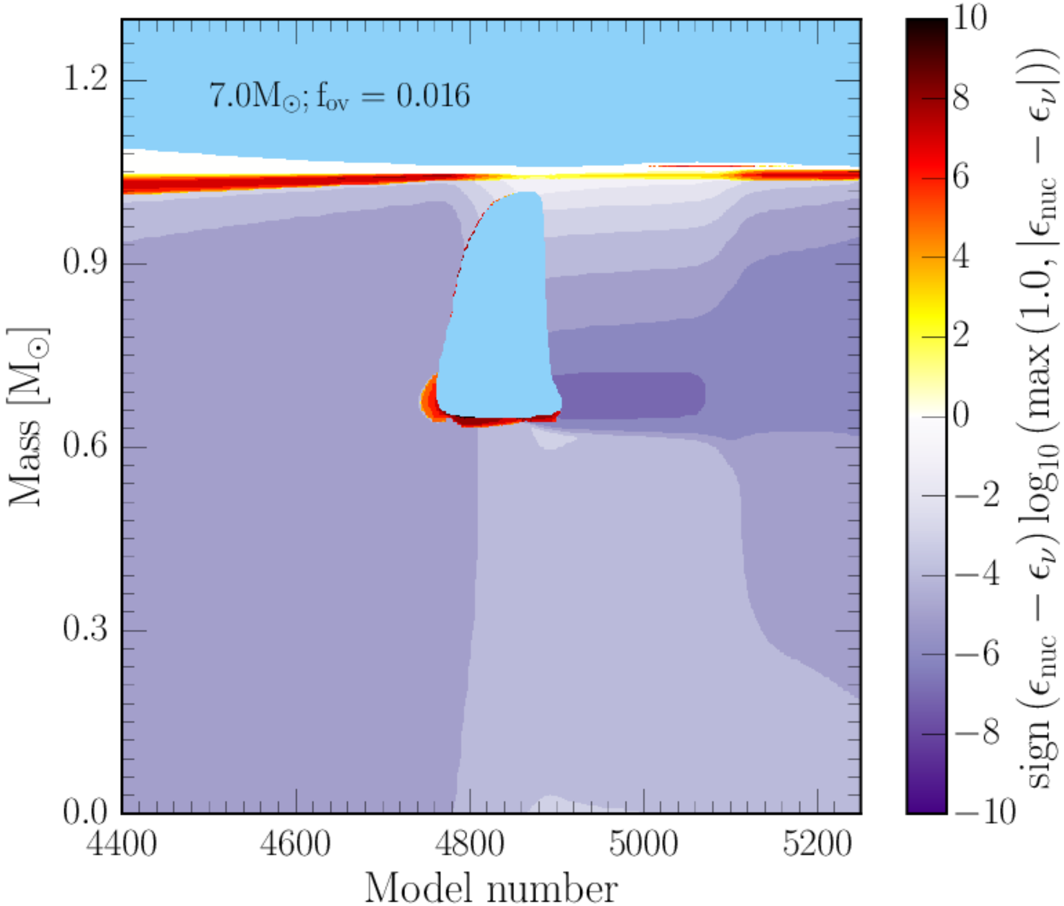
MESA

- 1D stellar evolution code
- Stars between 6-11$M_{\odot}$
- Pre-MS to end of carbon burning
- 22 isotope nuclear network
- Mixing (CBM, thermohaline, semiconvection)
- Rotation, magnetic fields and mass loss

Carbon burning

- $^{12}C+^{12}C \rightarrow {}^{*24}Mg \rightarrow {}^{20}Ne$ or ^{23}Na
- $X(^{20}Ne) > X(^{23}Na) > X(^{24}Mg)$ & $eps_{nuc} >> eps_{neut}$
  - Vigorous burning
  - Degeneracy is lifted
- Some stars have “flashes” some have “flames”

Whats a flash?



Temperature ~ 7*10[8] K
(Timmes et al 1994)

Must overcome neutrino cooling

Ignition drives a convection zone
(Garica-Berro et al 1997)

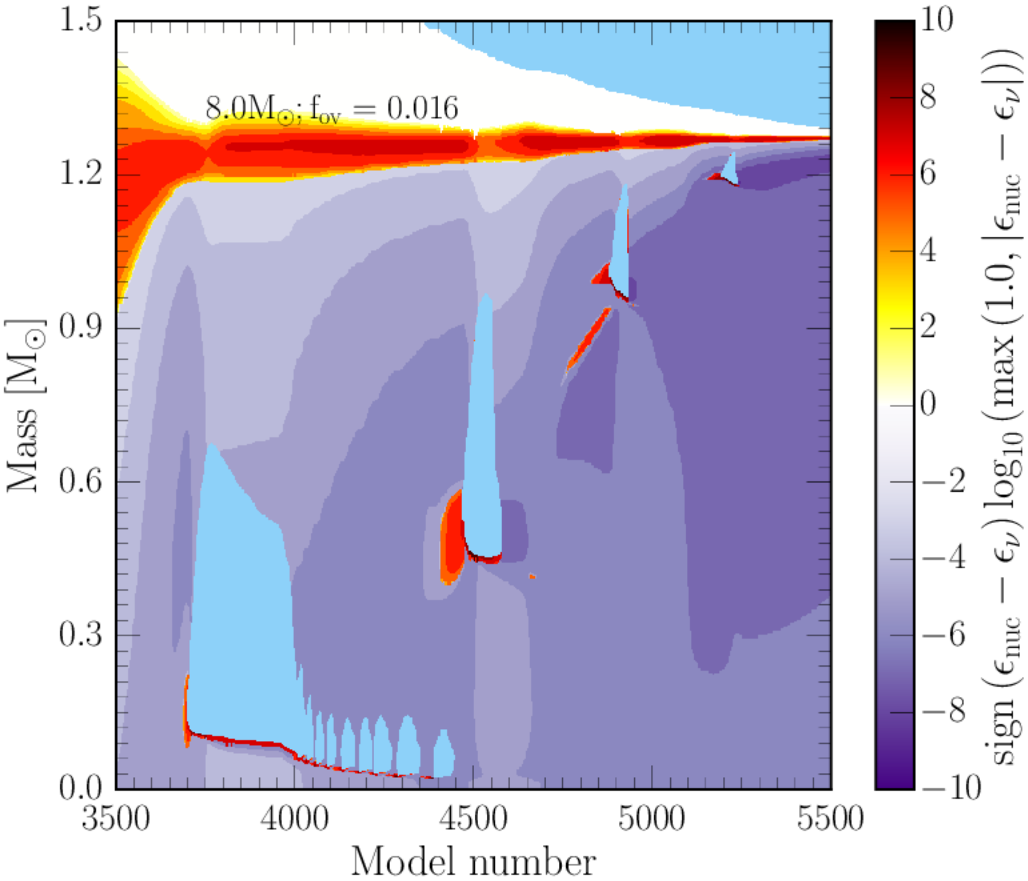
Convection sets an upper bound on T

Draws in fresh fuel to burn

Flash is ~stationary

$7.0M_\odot$ Single Flash

Whats a flame?



$8.0M_\odot$ Flame

Convectively bounded flame

Convection sets temperature also mixes in fresh fuel

Steady state flame burning balances neutrino losses

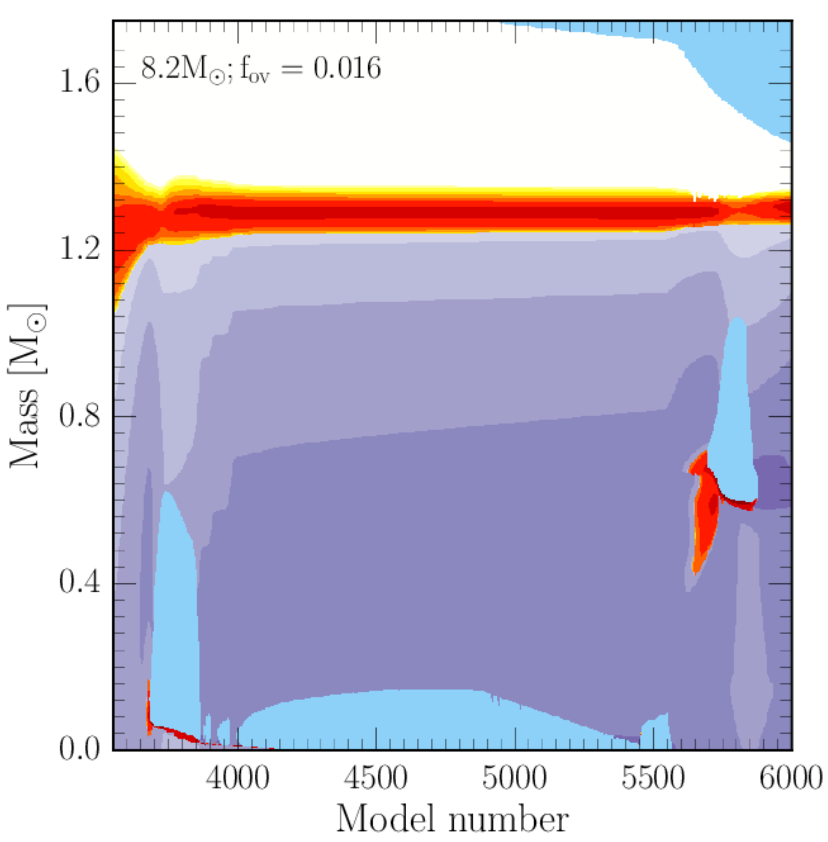
Flame propagates inwards on thermal diffusion timescale (Nomoto & Iben 1985)

Velocity ~ 0.1 cm s^{-1}

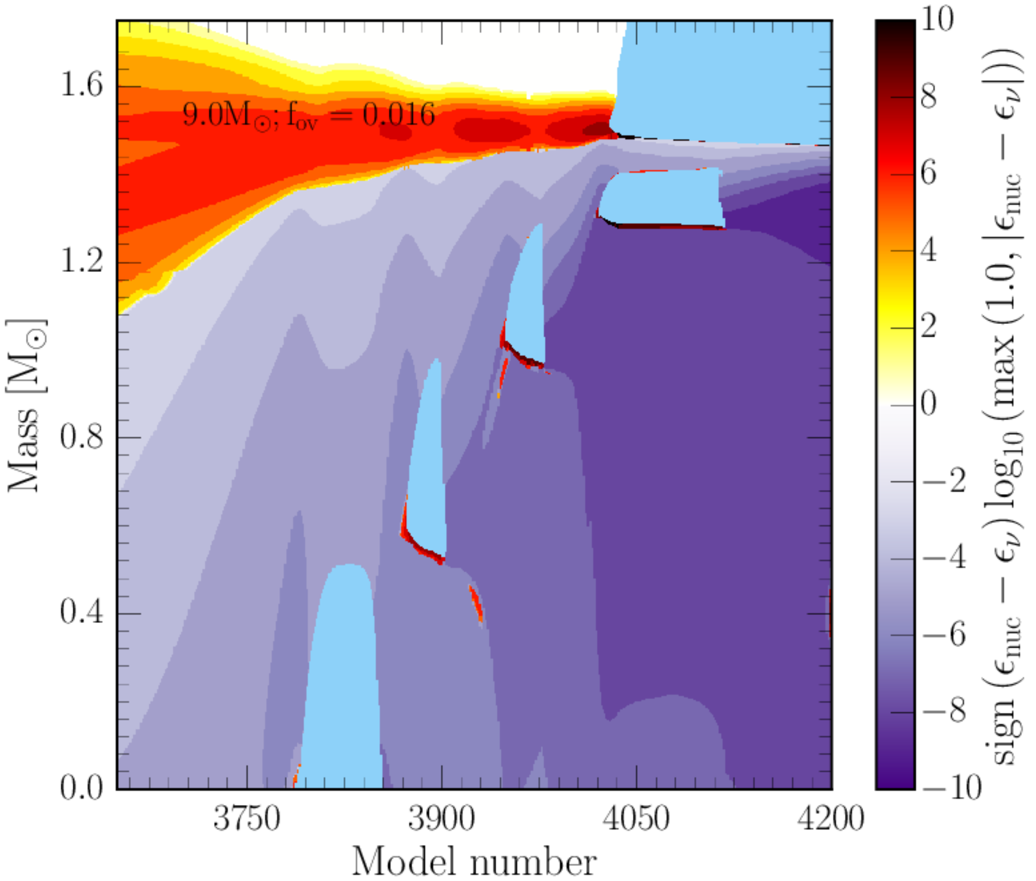
Lifetime ~ 20kyrs

May or may not reach the center

Others

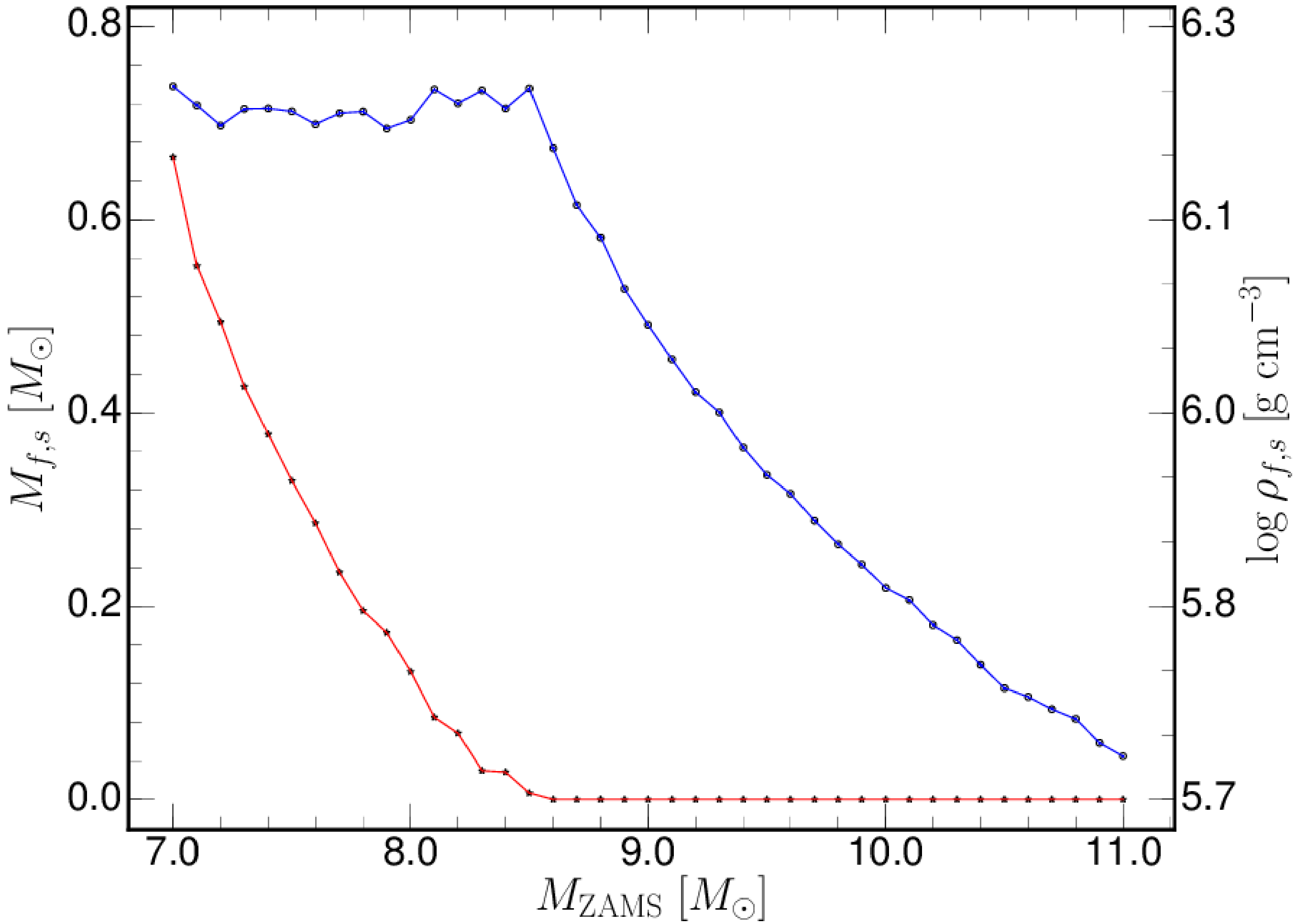


8.2M$_\odot$ flame reaches the center



9.0M$_\odot$ Center ignition

Where does carbon ignite?



Location of first ignition decreases linearly with mass

Density at ignition point constant

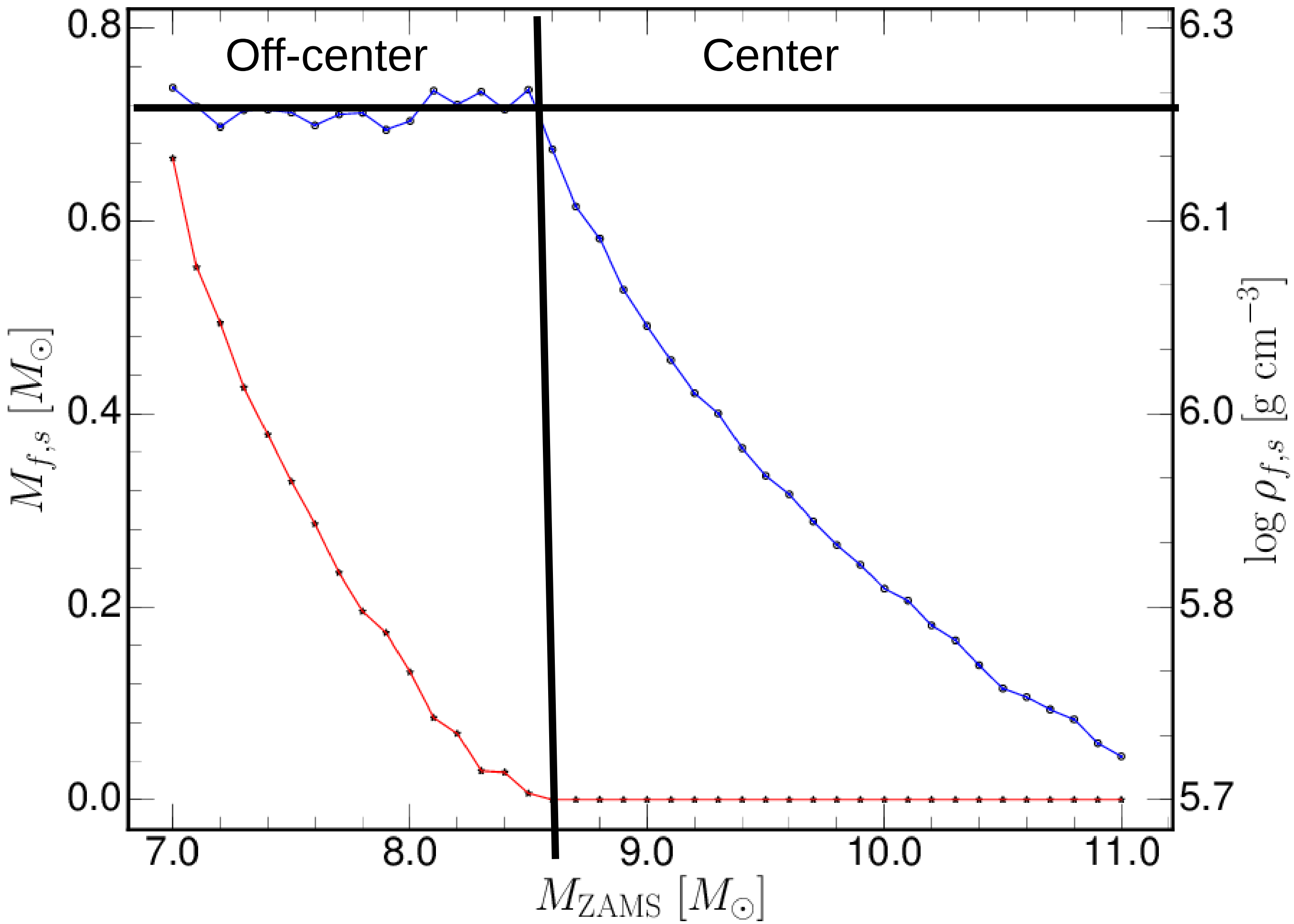
~8.6$M_\odot$ switch to center ignition

Ignition density decreases

Will eventually form ONe/NS

Ignore for rest of talk

Where does carbon ignite?



Location of first ignition decreases linearly with mass

Density at ignition point constant

~8.6$M_\odot$ switch to center igniting

Ignition density decreases

Will eventually form ONe/NS

Ignore for rest of talk

Can we predict where the flame ignites?

$$\tau_{\text{burn}} = 5.1 \times 10^9 \left(\frac{T}{7 \times 10^8}\right)^{-32} \left(\frac{\rho}{2 \times 10^6}\right)^{-0.8}$$

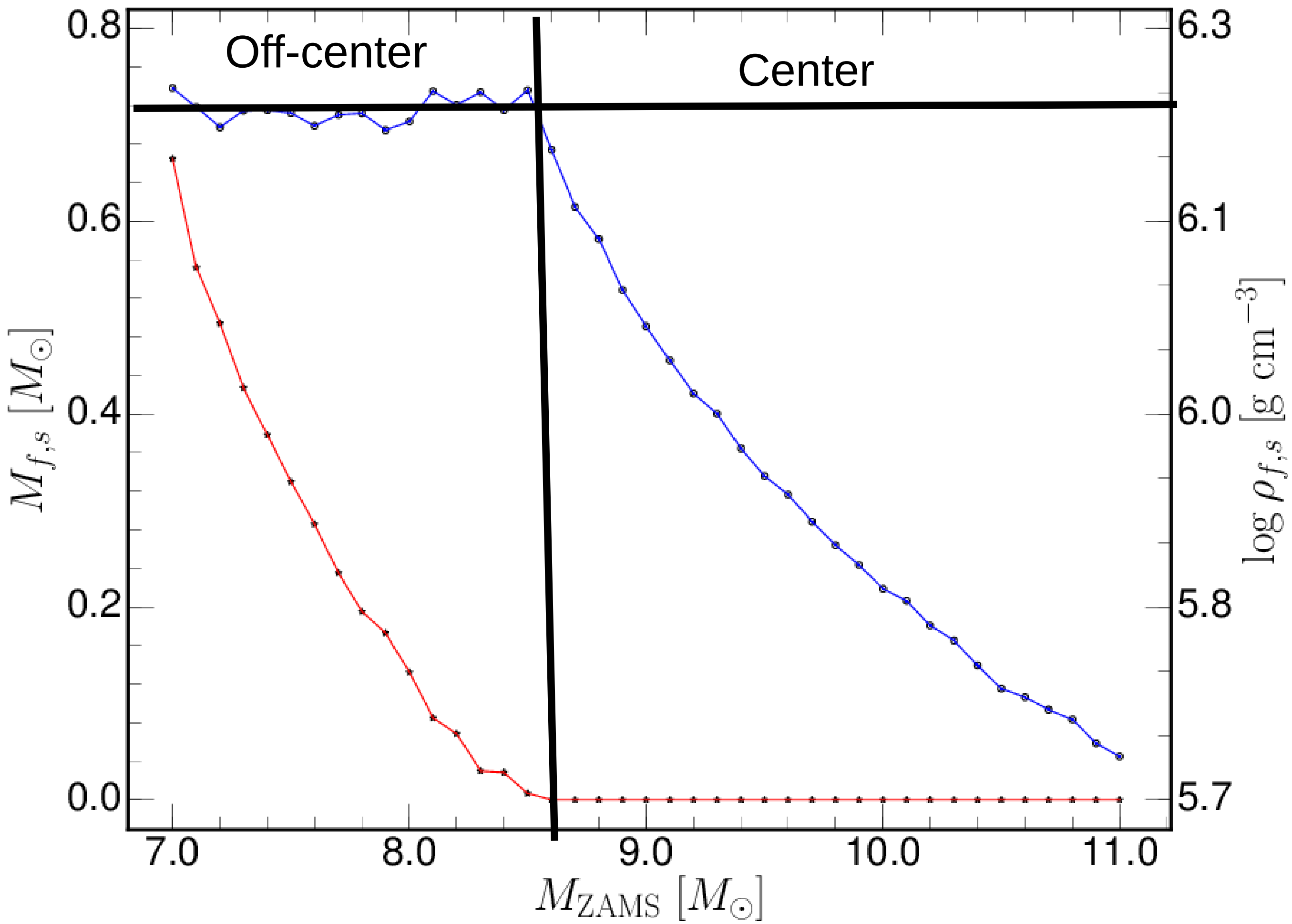
$$\tau_{\text{diff}} = 4.0 \times 10^9 \left(\frac{T}{7 \times 10^8}\right)^{-2.4} \left(\frac{\rho}{2 \times 10^6}\right)^{-1}$$

$$\left(\frac{T}{7 \times 10^8}\right)^{29.6} \left(\frac{\rho}{2 \times 10^6}\right)^{-0.2} = 1.3$$

Balance the burning timescale to the diffusion timescale

Temp must be $7*10^8$K for significant burning

Can we predict where the flame ignites?

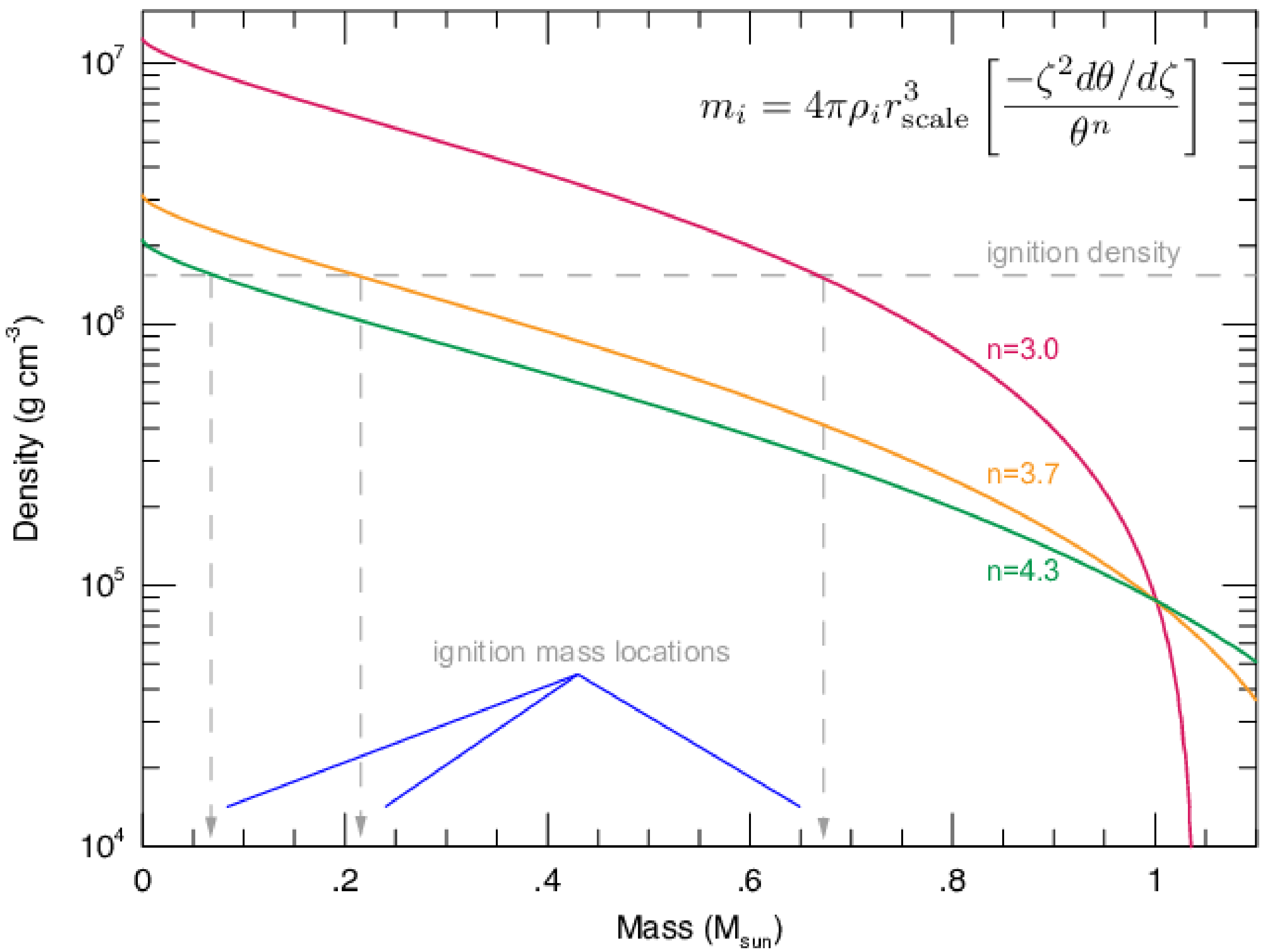


Theory:
Rho=2.1 *10^6 g cm^{-3}

Model:
Rho=1.7 *10^6 g cm^{-3}

Theory assumed pure C/O mixture (30/70%)

Can we predict where the flame ignites?



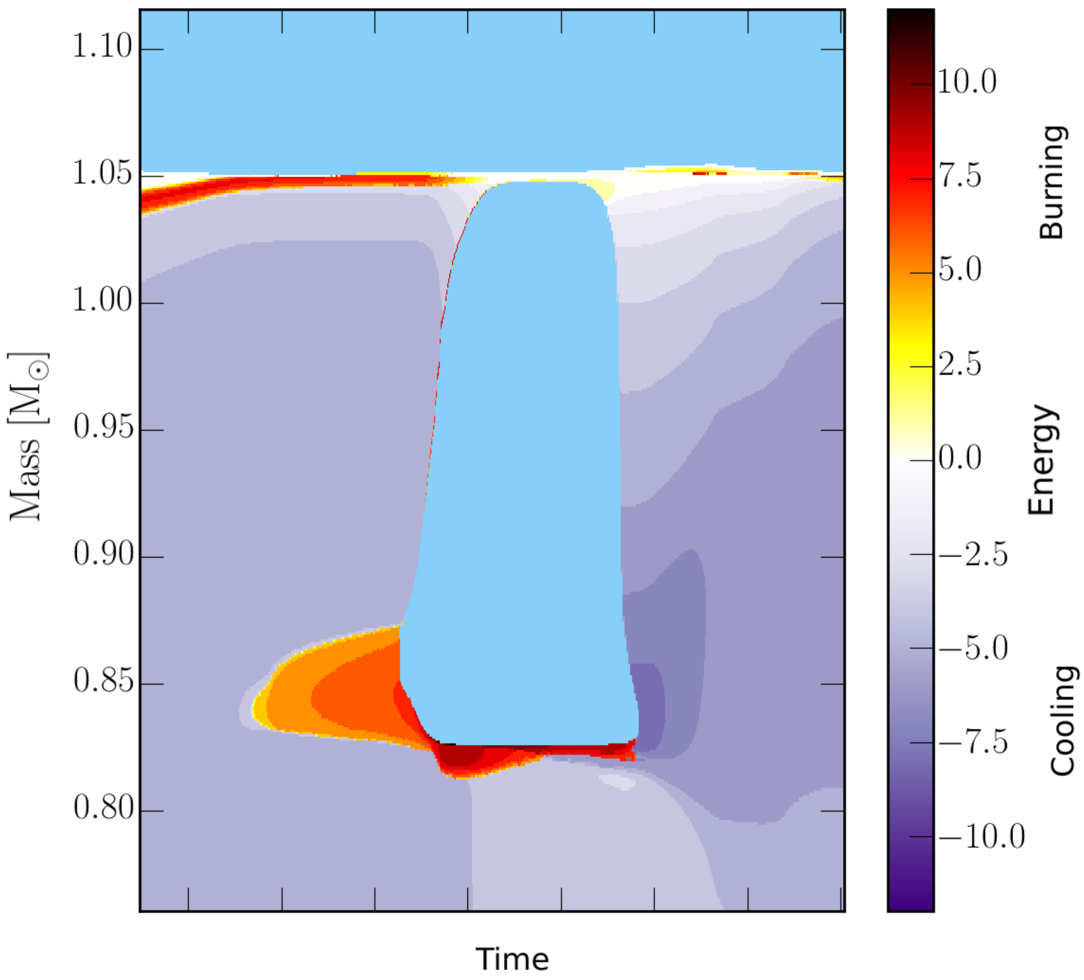
Describe cores as polytropes

Polytrope index increases as mass increases

Ignition point occurs at constant density

Read of the ignition mass

Why a flash?



Degeneracy is lifted at ignition point

Core expands

Moves location of critical density away from peak temperature

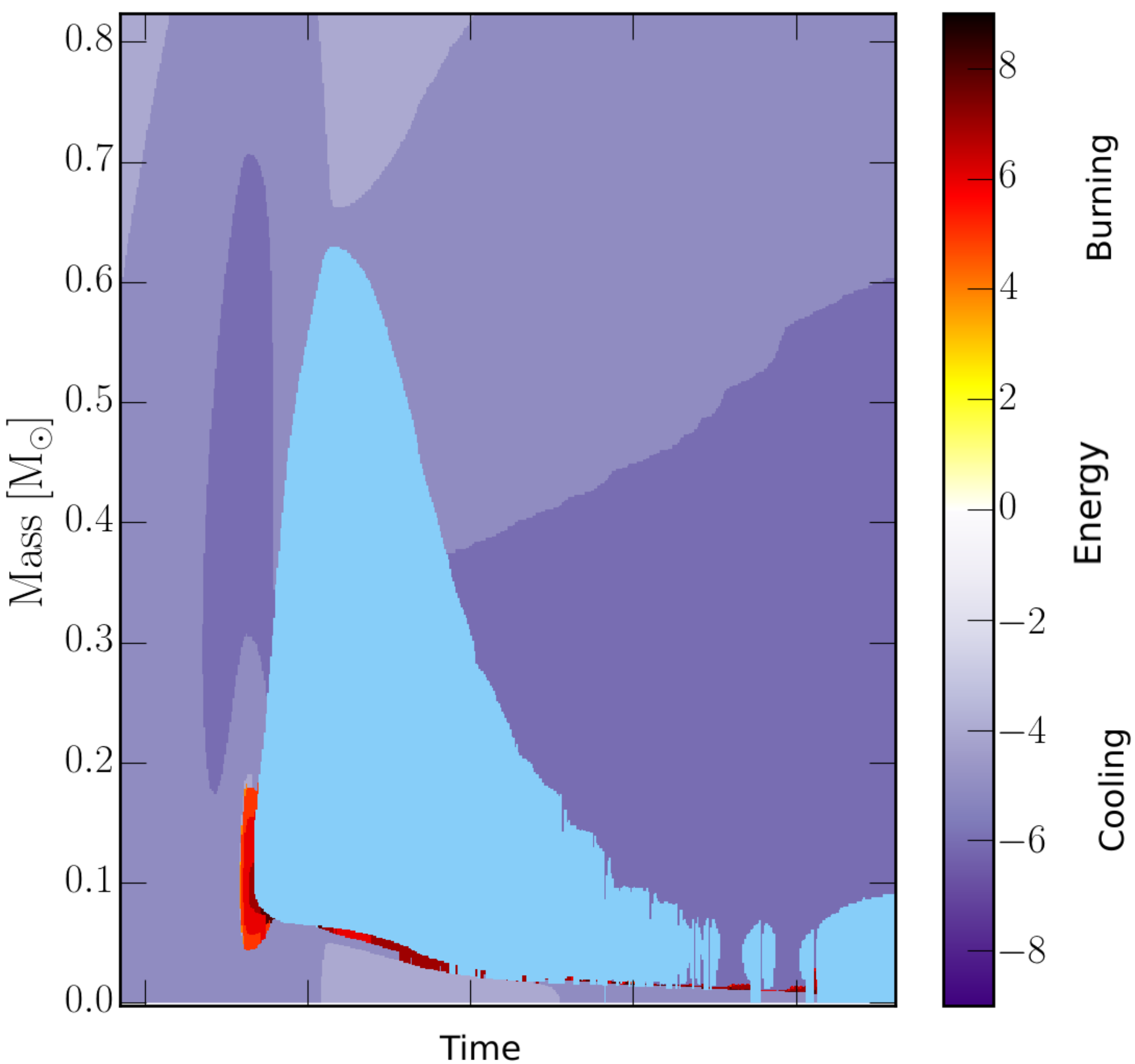
Temperature increases a little from burning but convection limits the increase

Flash dies

Fuel is burnt in region, thus needs higher T and Rho to ignite again

But, He shell is depleted so core can't grow anymore

Why a flame?



Core tries to expand

But, ignition is deeper in the star

Star is less degenerate thus less energy is needed to break degeneracy

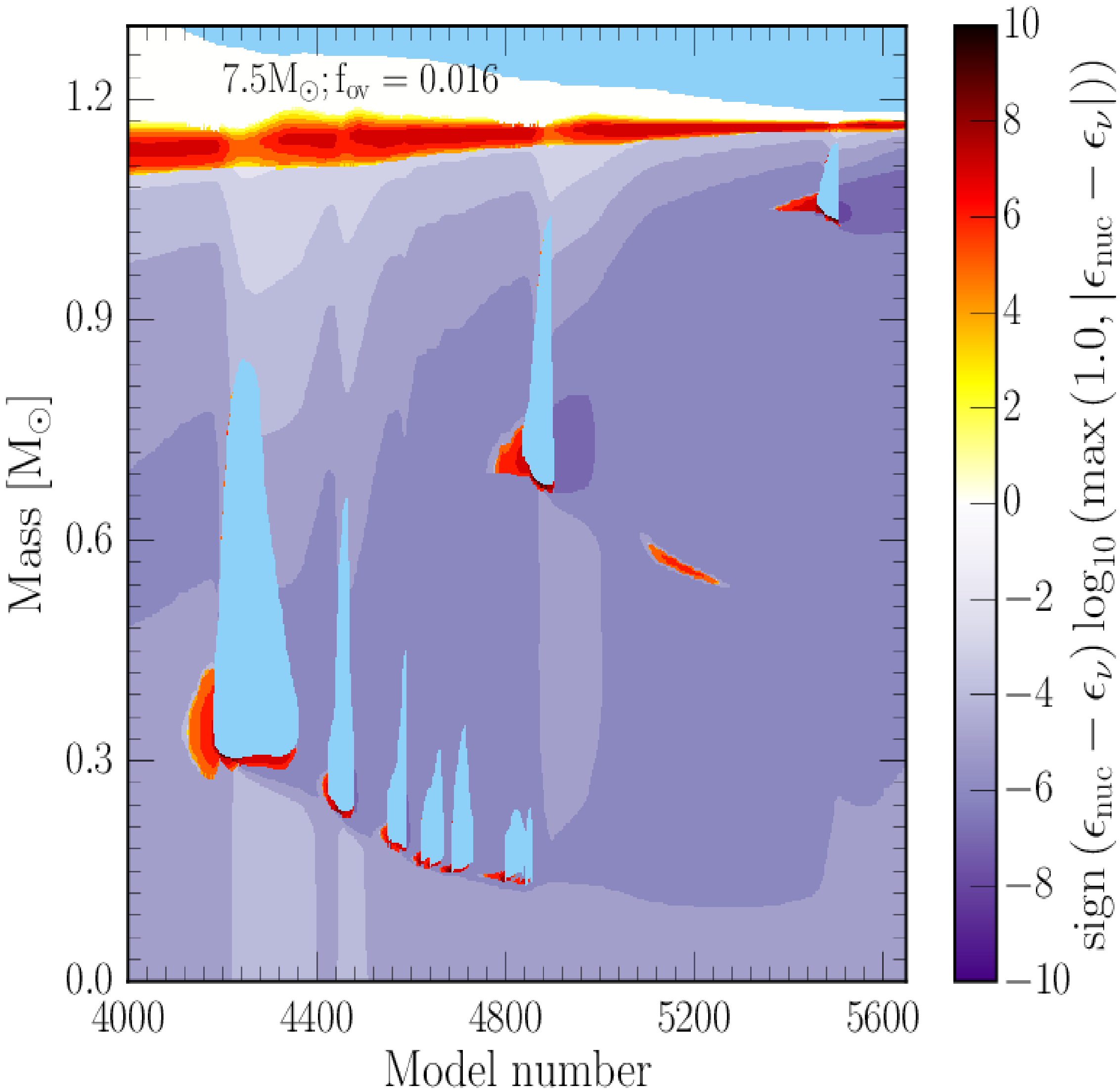
Burning is less energetic

Core doesn't expand as much

Critical density moves inwards as He accreates onto the C/O core

Spluttering at end due to low C abundance

Whats this?



Multiple flashes moving inwards, flashes themselves don't move.

But location of ignition does.

Intermediate between single flash and flame

Core is able to expand extinguishing the flash

But still have C accretion from He shell

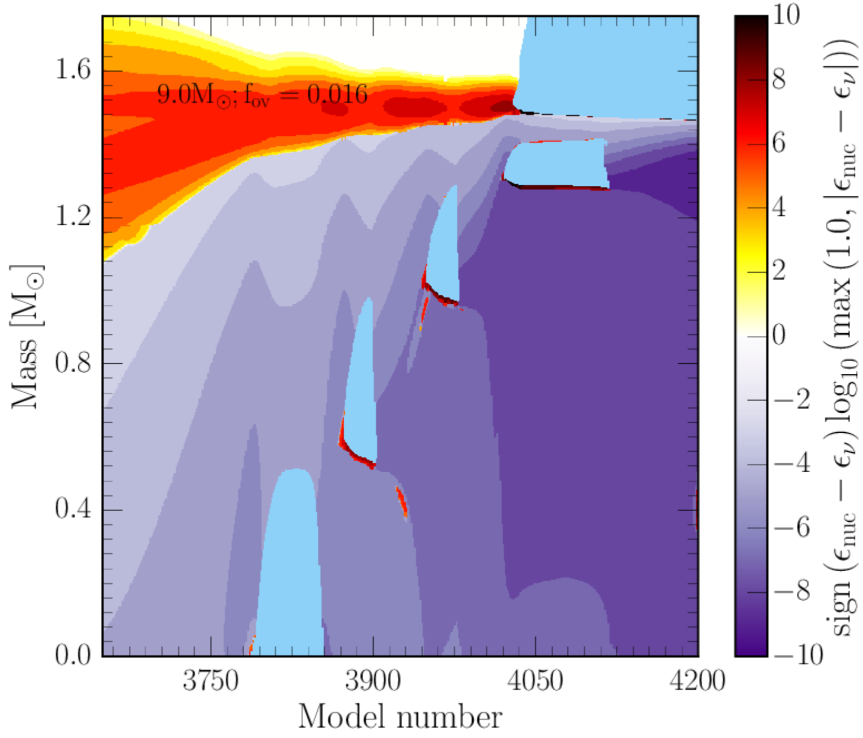
Density increases, able to ignite a flash at lower mass where there is fresh fuel.

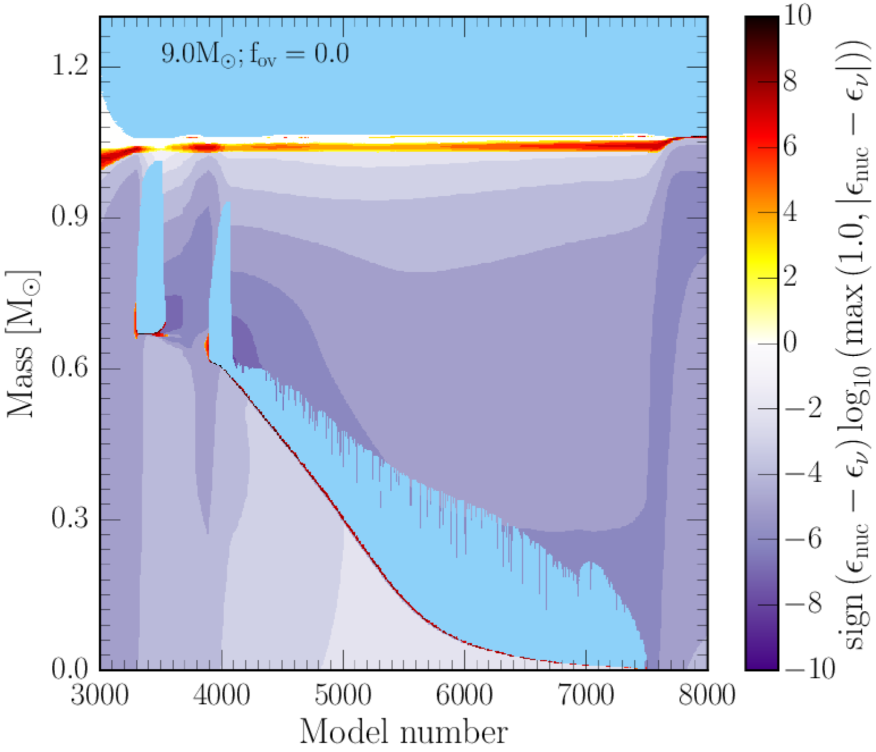
Each flash is shorter and the time between them decreases

Flames are just when the time between flashes is 0

Whats make a flash or a flame?

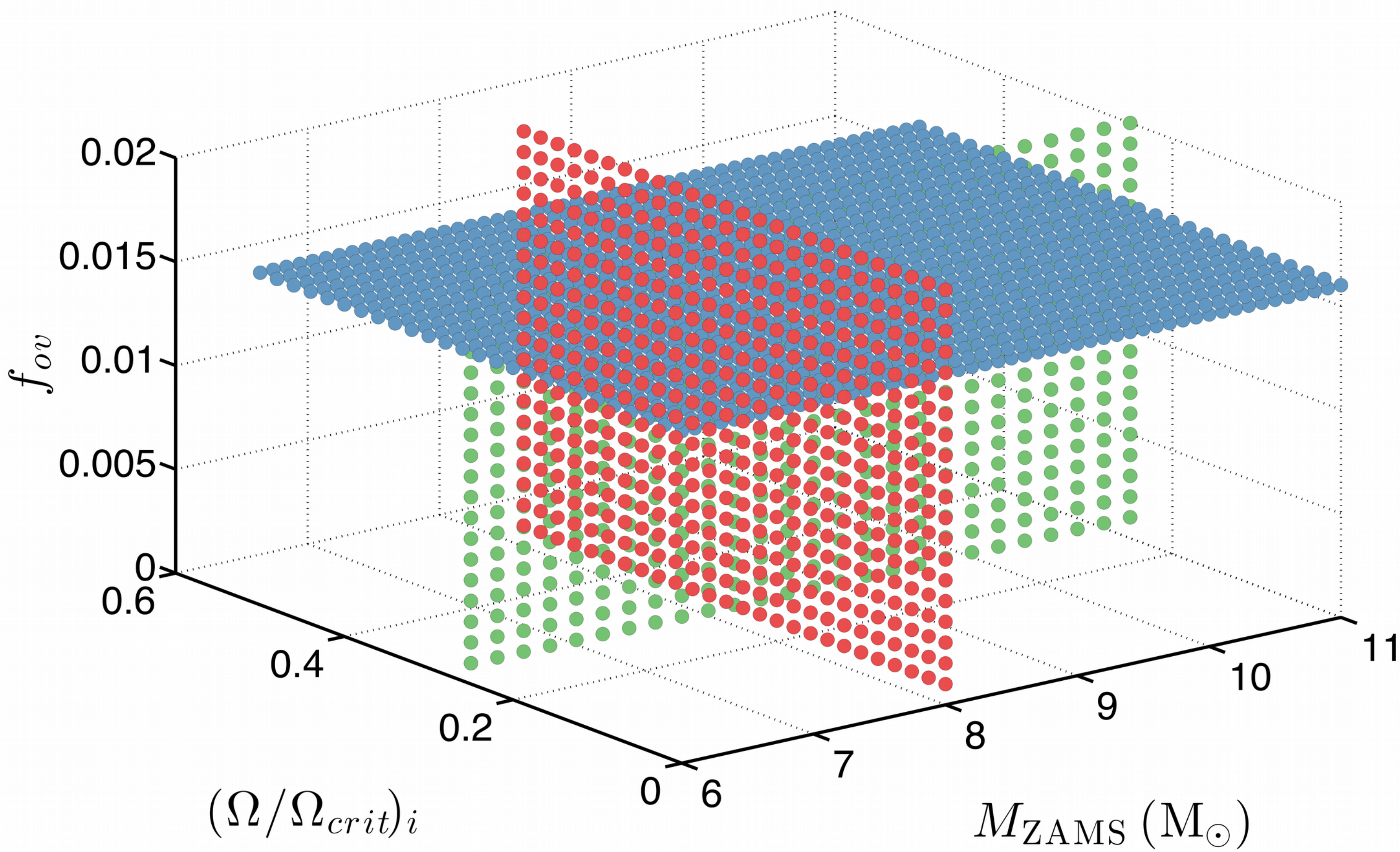
Mass is certainly driving the ignition point and type of burning





But, convective overshoot is also playing a role

When in doubt try everything



Three grids:
- Mass-Overshoot
- Mass-rotation
- Overshoot-Rotation

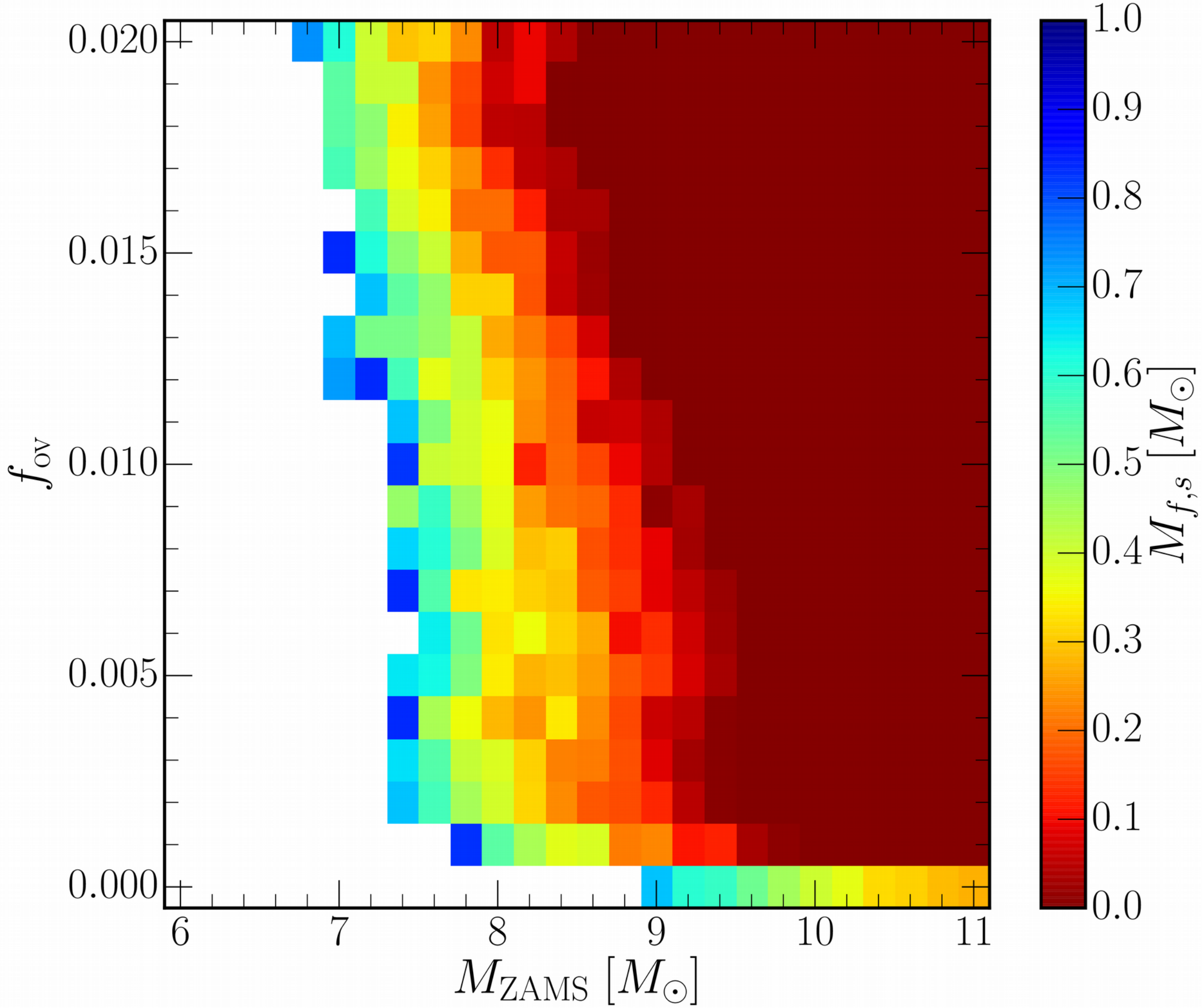
Also explored:
- Mixing strengths
- Resolution

~3000 models

~200K CPU hours

~2Tb of disk space

What about overshoot?



Larger F implies more overshoot and more mixing

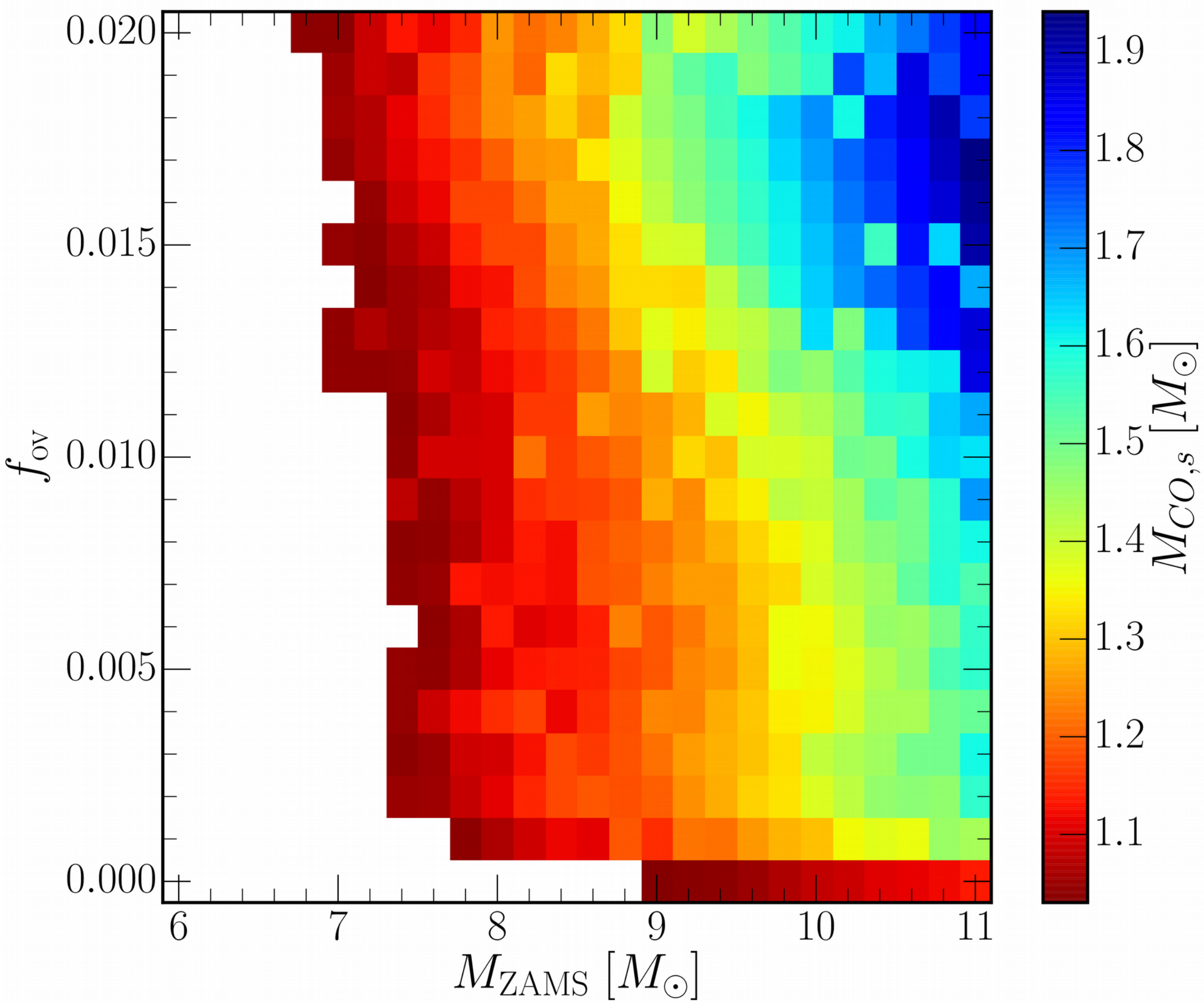
Overshoot decreases the ignition mass coordinate

Overshoot applied at all convective boundaries

There is no overshoot in vicinity of the ignition point at ignition

So how does overshoot alter the flame location?

What about overshoot?



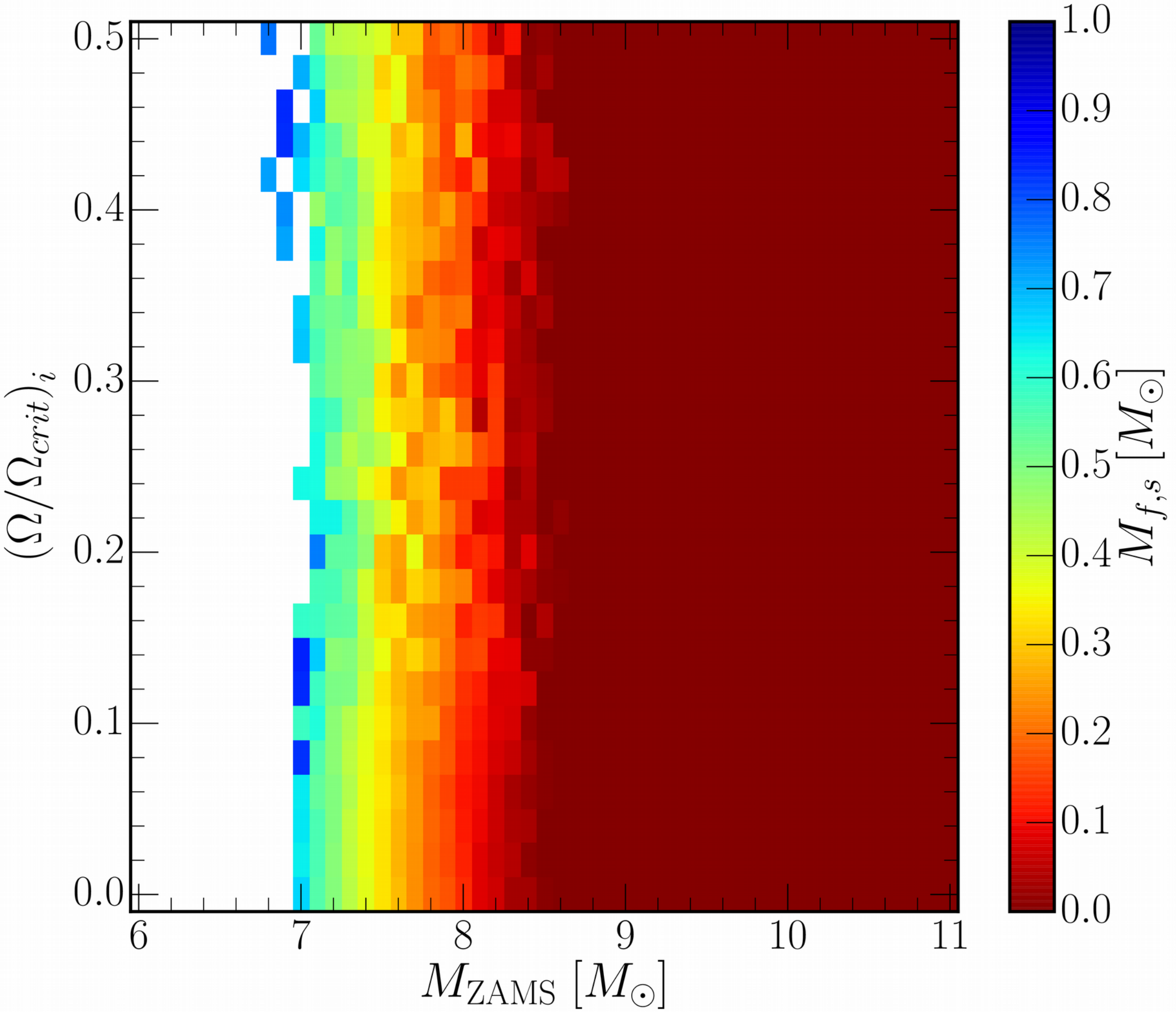
Overshoot increases the mass of the C/O core

Minimum mass needed to ignite ~1.05$M_\odot$ (Independent of overshoot)

Maximum mass of a single C/O WD (1.05$M_\odot$, solar Z)

Overshooting during Che burning most important

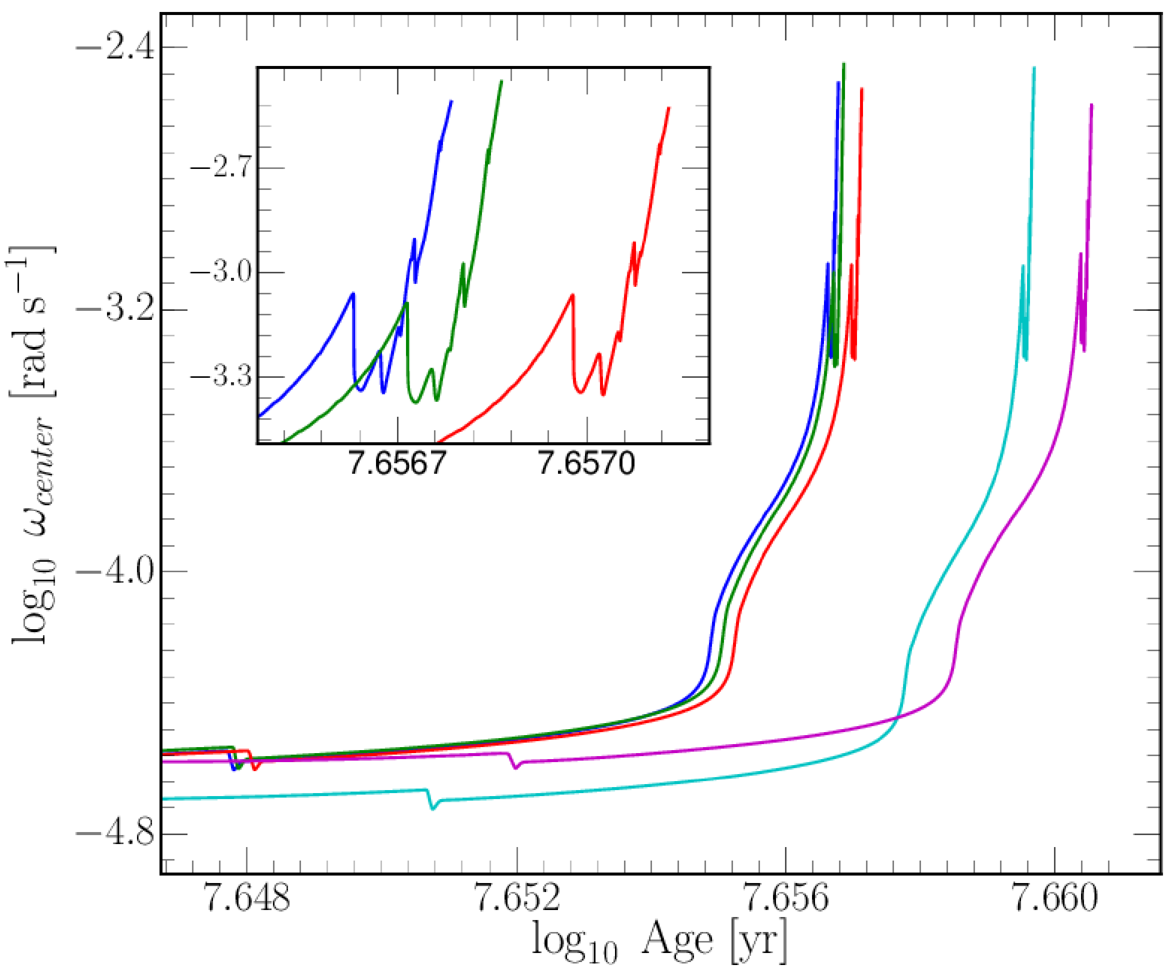
Stars rotate



Rotation doesn't seem to play a role in the ignition

Why?

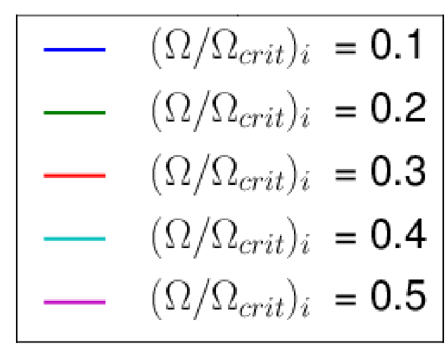
Why does rotation not play a role?



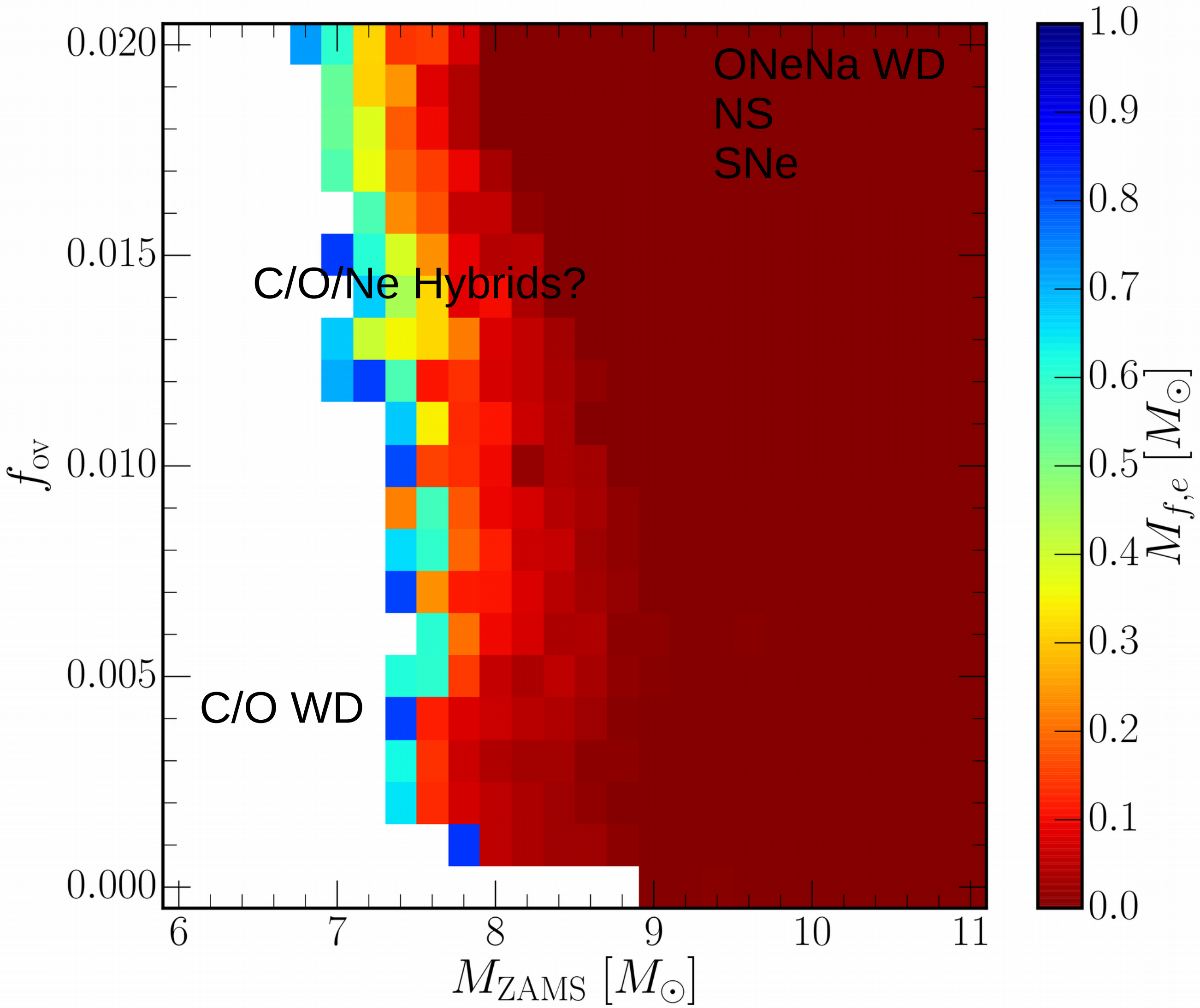
By time the C/O forms the star's cores are rotating at the same rate

Goes through more contraction spinning up the core.

Stars ignite at similar core rotation rates.



Final fates?



Hybrid C/O/Ne WD's formed?

Flames ignite off center

But which don't propagate to the center

Leaves a C/O core surrounded by a O/Ne layer

Needs strong overshoot

Type Iax supernovae?

Next time...

- Extend analysis to different fuels?
  - He flash?
  - Ne flames?
- Observational signals?
  - Can we detect the different amounts of carbon burnt?
- Grid over metalicities?

Summary

- Analytically shown where 12C ignites:
  - Constant density (~ $2.1 * 10^6$ g cm^{-3})
  - This determines how the star behaves after ignition.
- Initial mass is main driver for flame physics, followed by overshoot
  - Really its all about how big the C/O core gets
- Rotation seems unimportant
- Can produce hybrid C/O/Ne WD's, though depends on overshoot
- Files needed to reproduce this work available at http://mesastar.org/