Shaken, Not Stirred: White Dwarf Cocktails

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Why are white dwarfs important?

The Sun will become one

Age of the universe

Probe of strong equivalence principle

Progenitors of supernovae

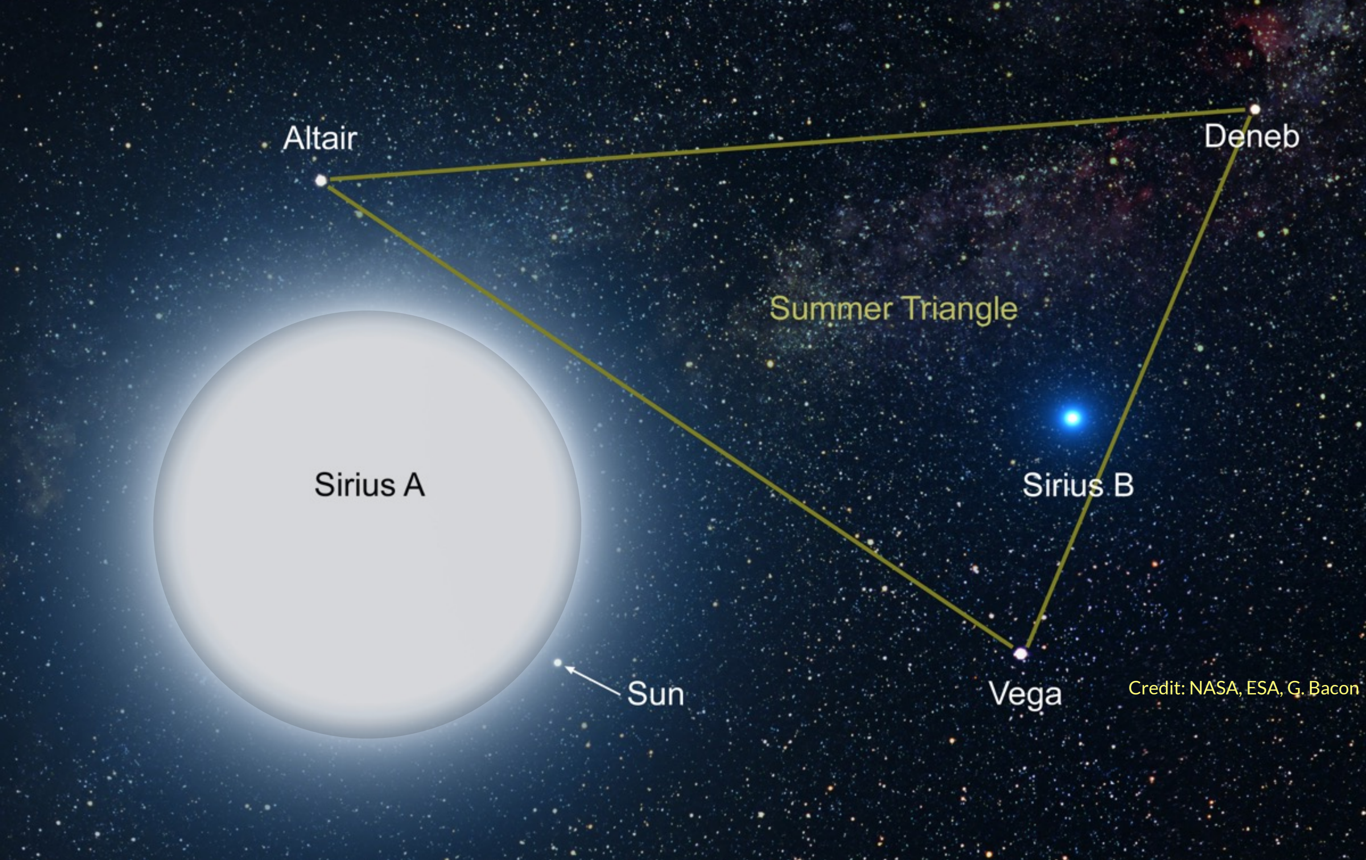
Element factories

Kinetic energy sources for galaxies

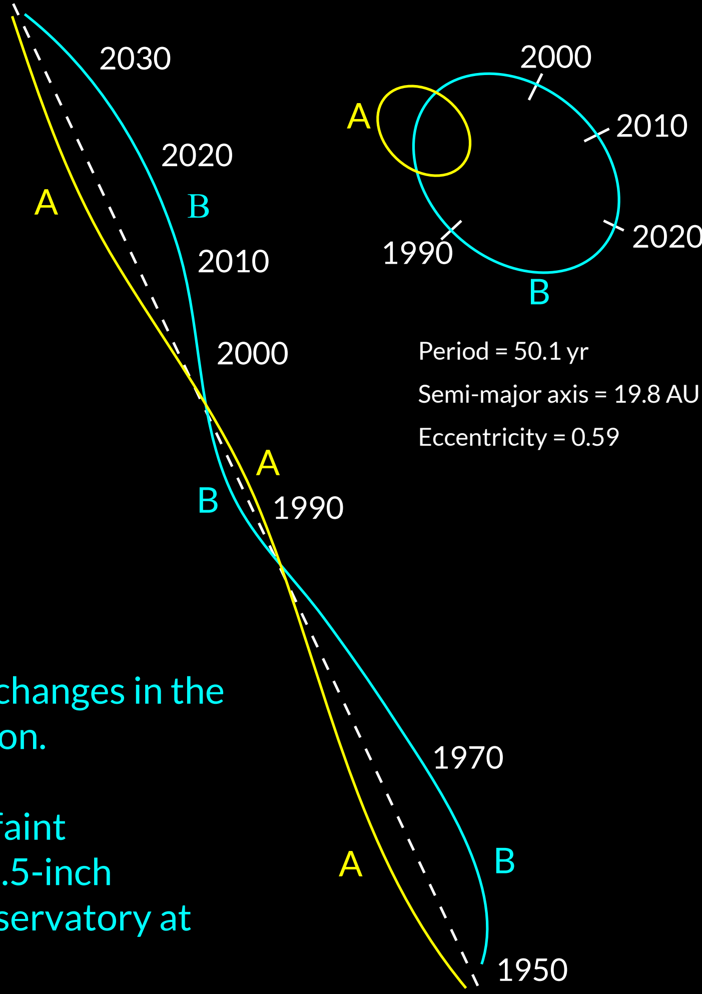
Records the nuclear physics of a star's life

Probes of electron degenerate material

Sirius, only ~8.60 ± 0.04 light-years from Earth, is the fifth closest stellar system.



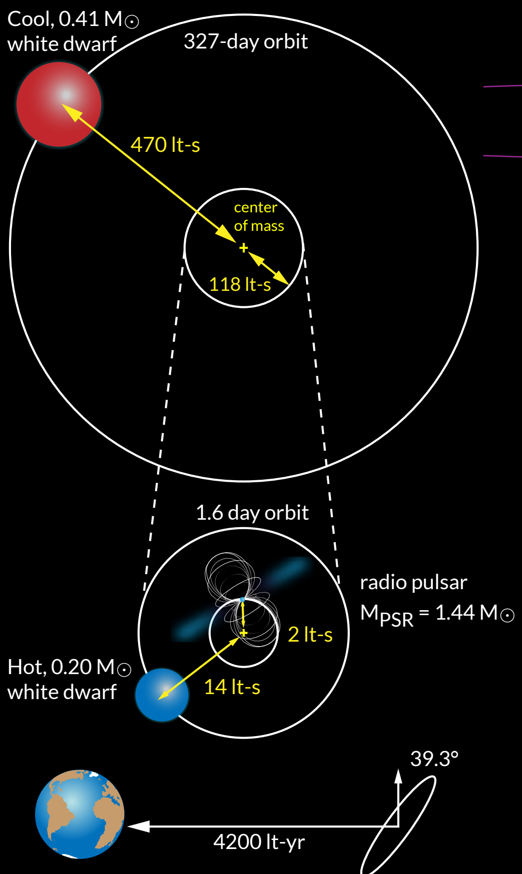
The Egyptians used Sirius, the brightest star in the sky and which rose with the Sun in early July when the Nile was in flood, to mark the first day of a New Year.

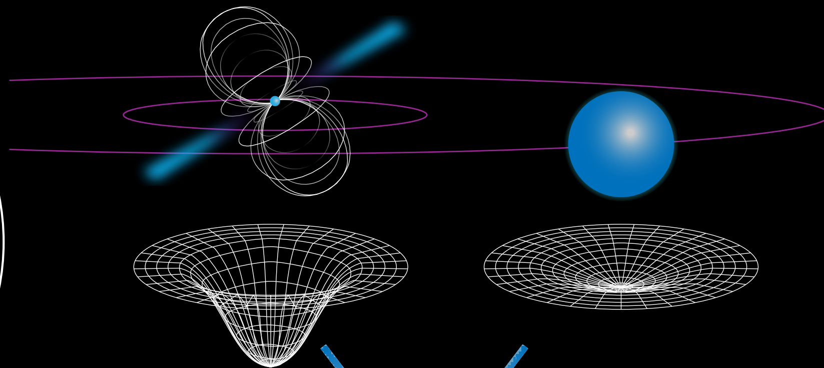


In 1844 Friedrich Bessel deduced from changes in the orbit that Sirius had an unseen companion.

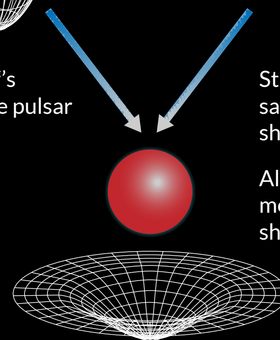
In 1862, Alvan Clark first observed the faint companion during testing of the new 18.5-inch refractor telescope in the Dearborn Observatory at Northwestern University.

Does Strong Gravity Change How Things Fall?
The Triple System PSR J0337+1715





The outer white dwarf's gravity accelerates the pulsar and inner white dwarf.



Strong Equivalence Principle says accelerations should be the same.

Alternative theories of gravity mostly say the accelerations should be different

Microsecond accurate measurements of the radio pulse arrival times show no difference between the accelerations to 3 parts per million.

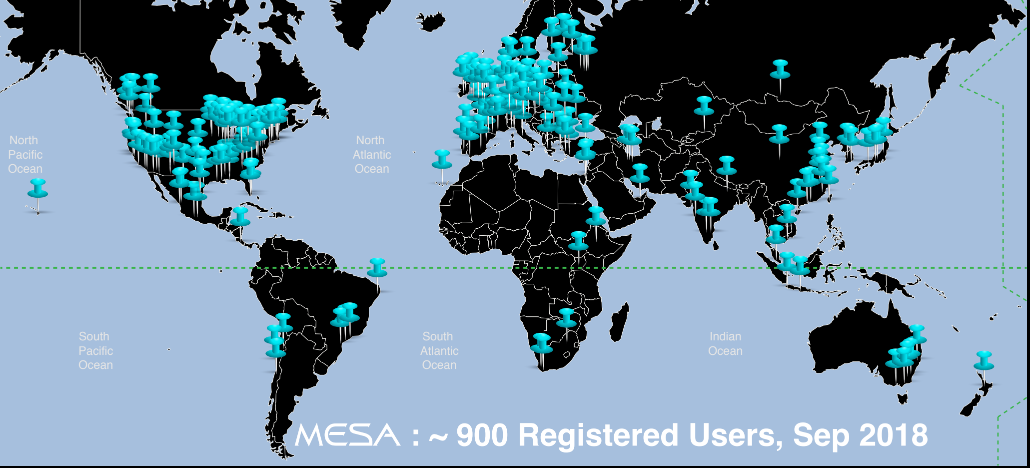
Archibald et al 2018

Let’s make a white dwarf.

Modules for Experiments in Stellar Astrophysics

MESA

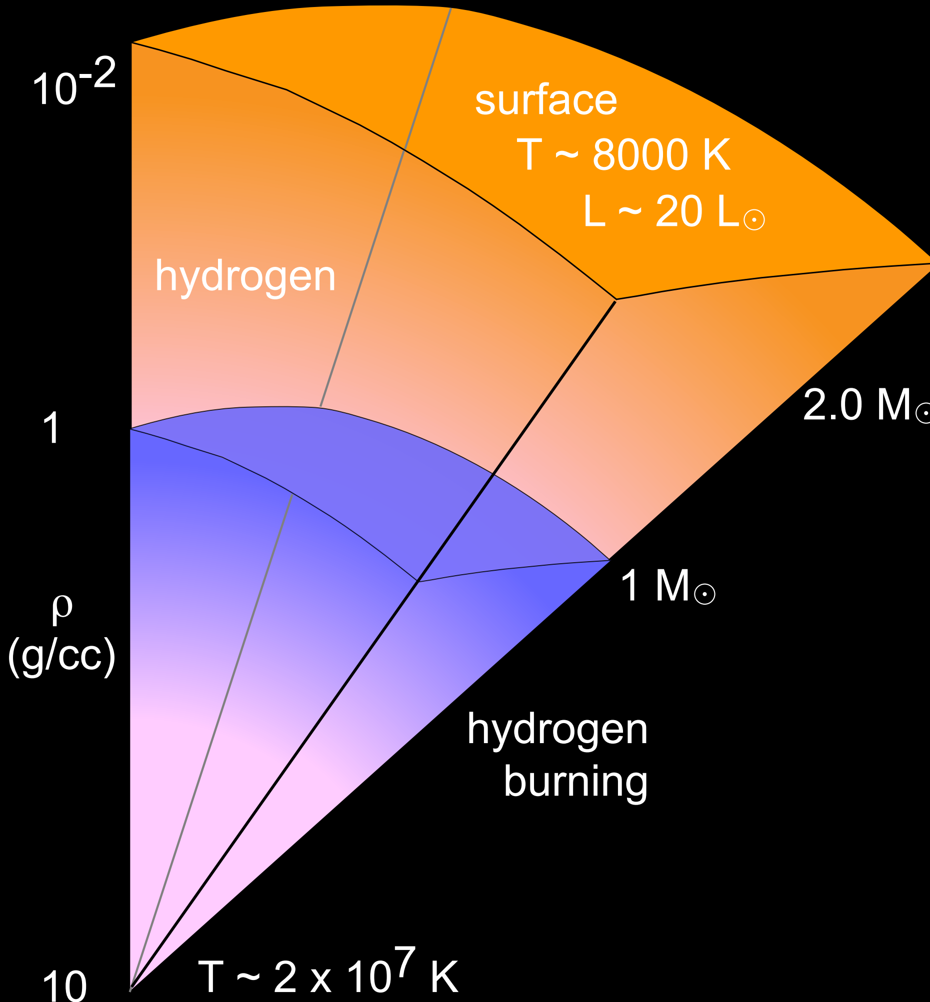
MESA solves the 1D fully coupled structure, mixing, and composition equations governing stellar evolution.



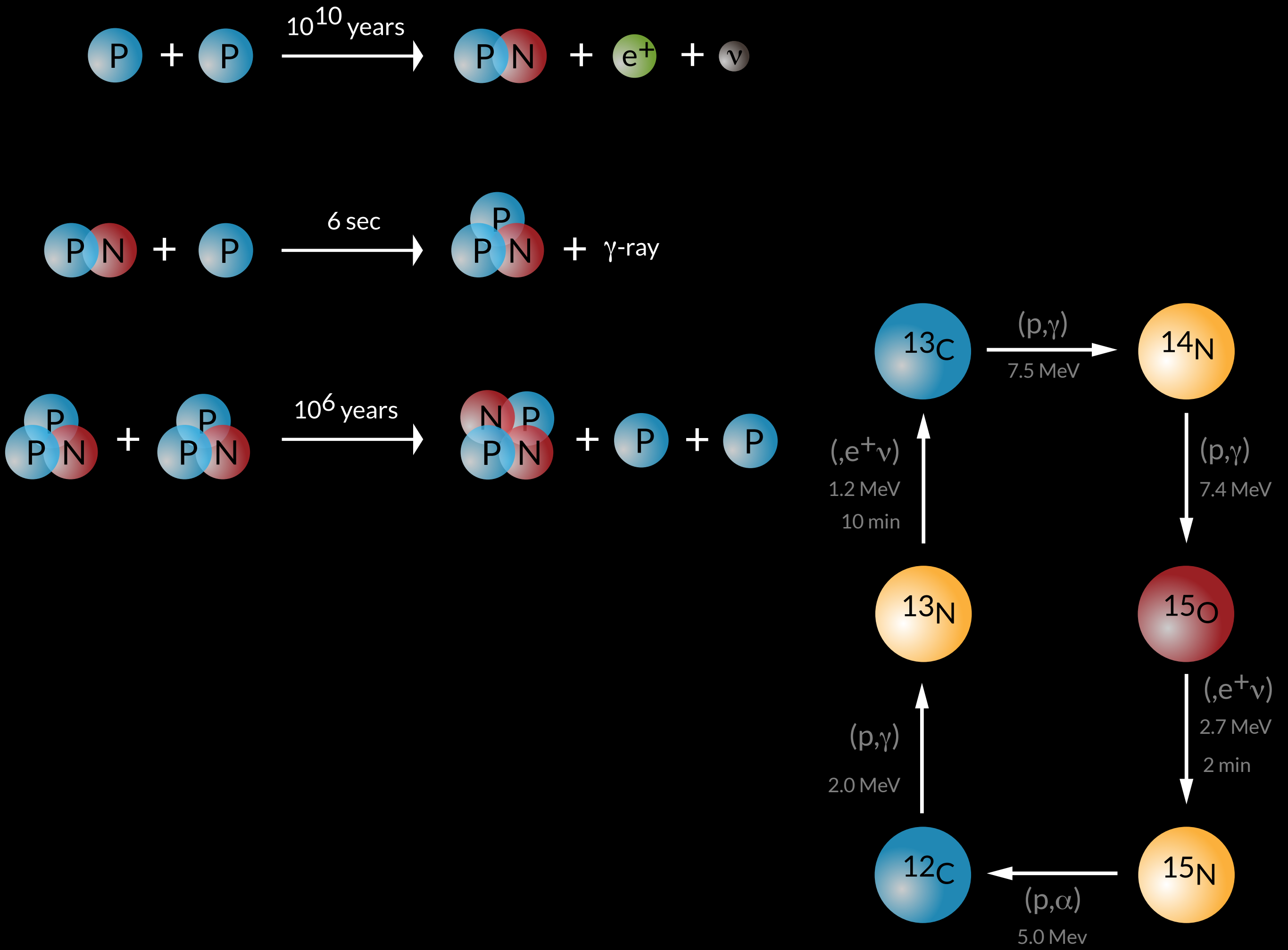
Open-Knowledge

Open-Science

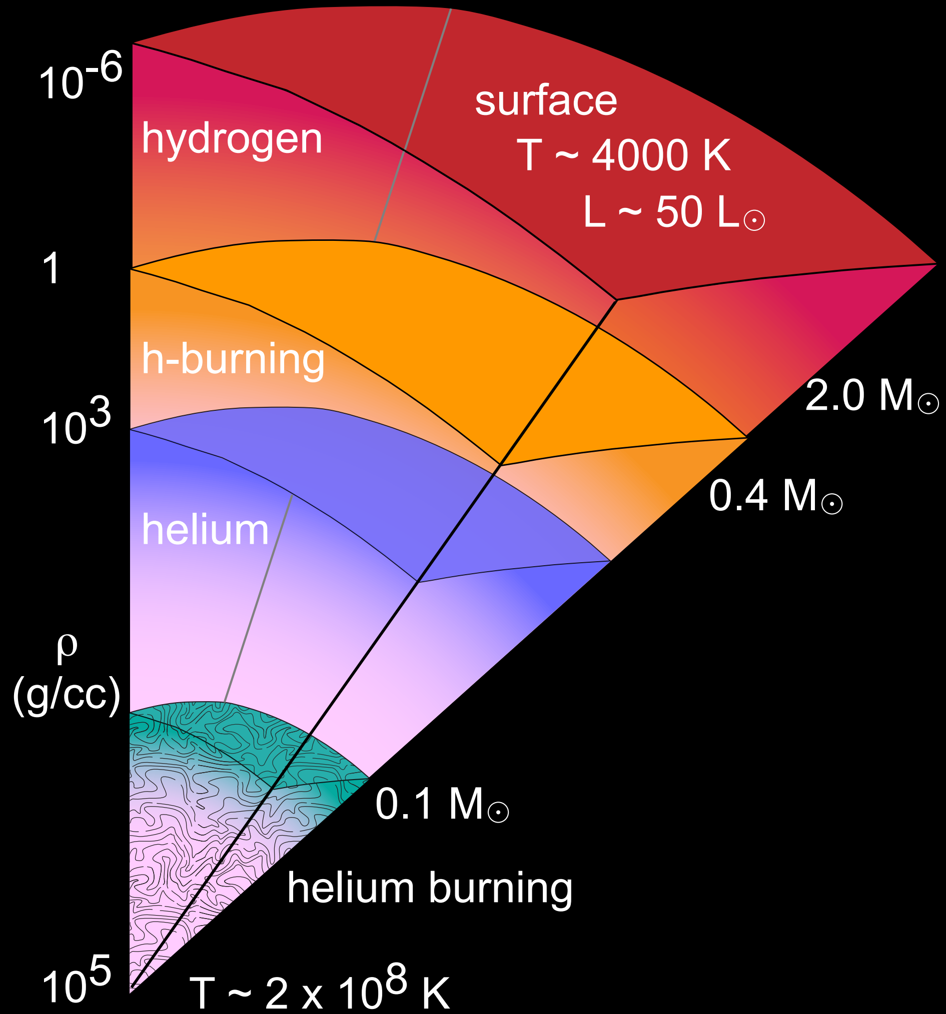
Open- Source



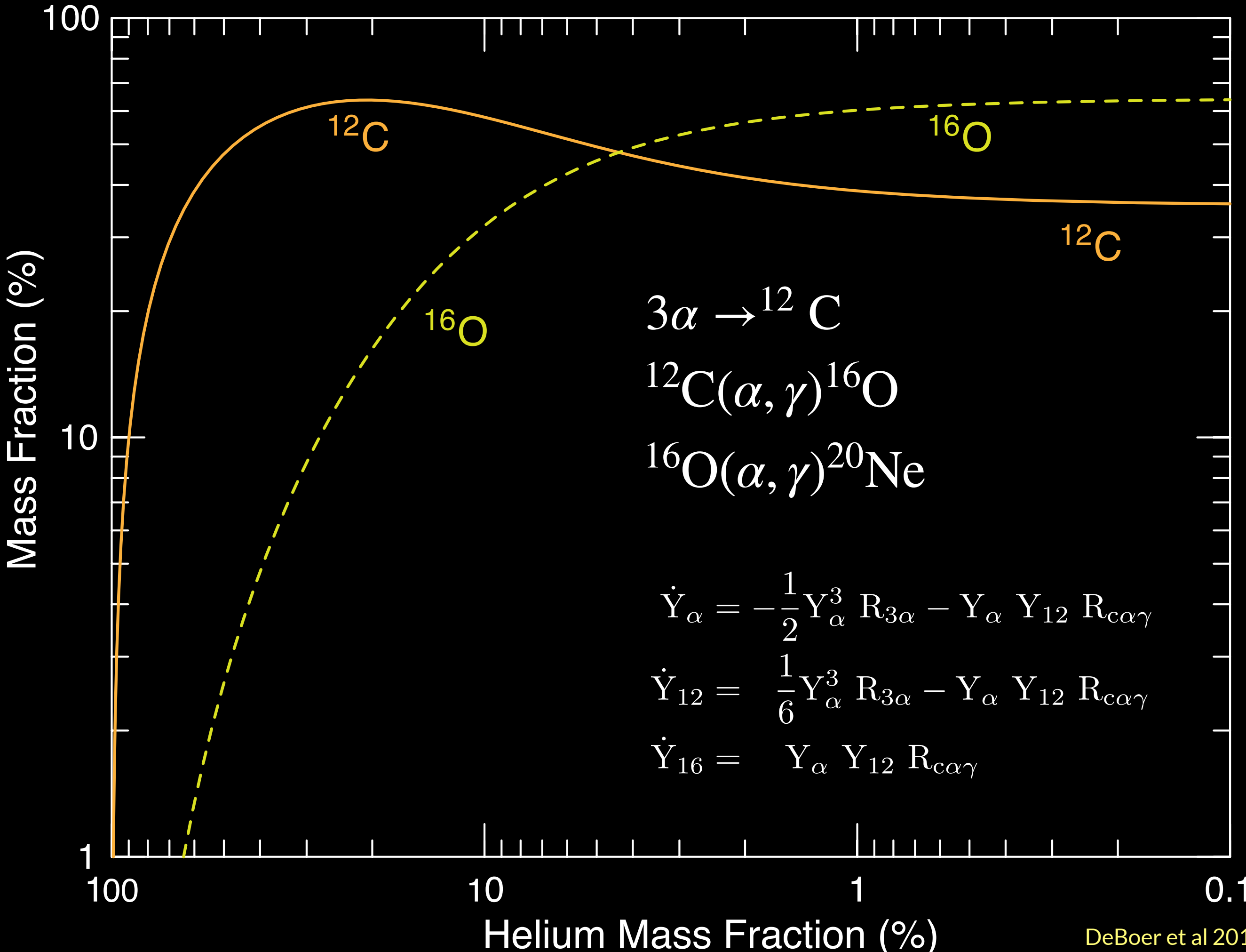
10^{-2}
surface
T ~ 8000 K
L ~ 20 $L_\odot$
hydrogen
1
2.0 $M_\odot$
1 $M_\odot$
ρ
(g/cc)
hydrogen
burning
10
T ~ 2 x 10^7 K



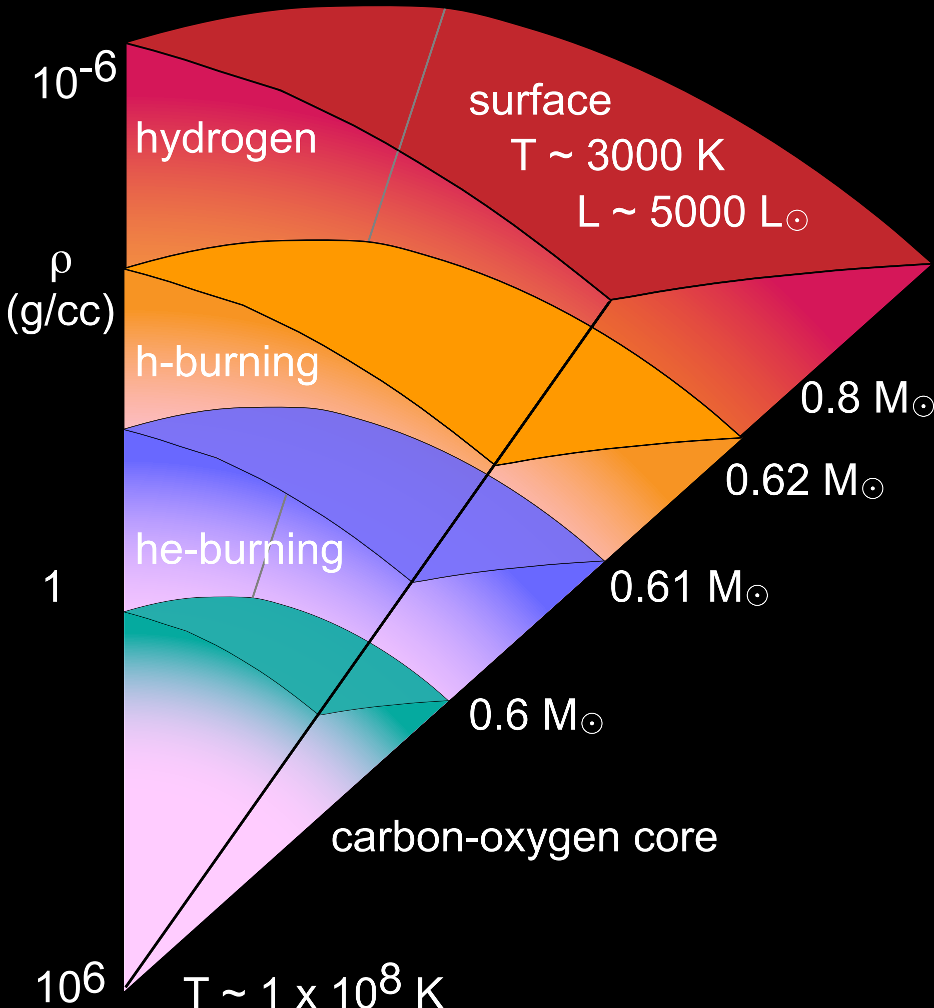
P + P
10^10 years
P N + e+ + ν
P N + P
6 sec
P
P N + γ-ray
P
P N
+
P
P N
10^6 years
N P
P N + P + P
13C
(p,γ)
7.5 MeV
14N
(,e+ν)
1.2 MeV
10 min
(p,γ)
7.4 MeV
13N
15O
(,e+ν)
2.7 MeV
2 min
(p,γ)
2.0 MeV
12C
(p,α)
5.0 Mev
15N



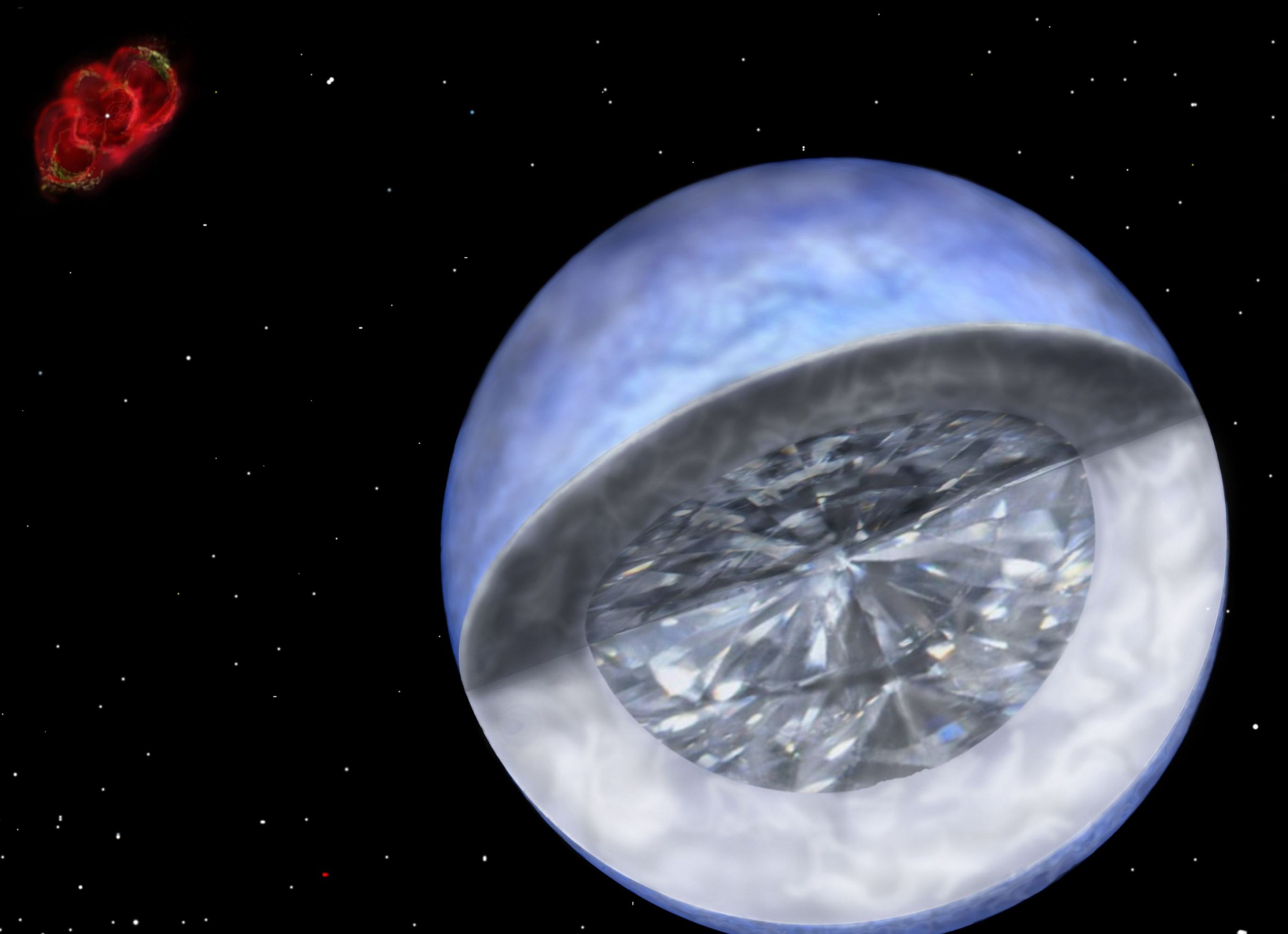
10^{-6}
1
10^3
ρ
(g/cc)
10^5
hydrogen
h-burning
helium
surface
T ~ 4000 K
L ~ 50 $L_\odot$
2.0 $M_\odot$
0.4 $M_\odot$
0.1 $M_\odot$
helium burning
T ~ 2 x 10^8 K



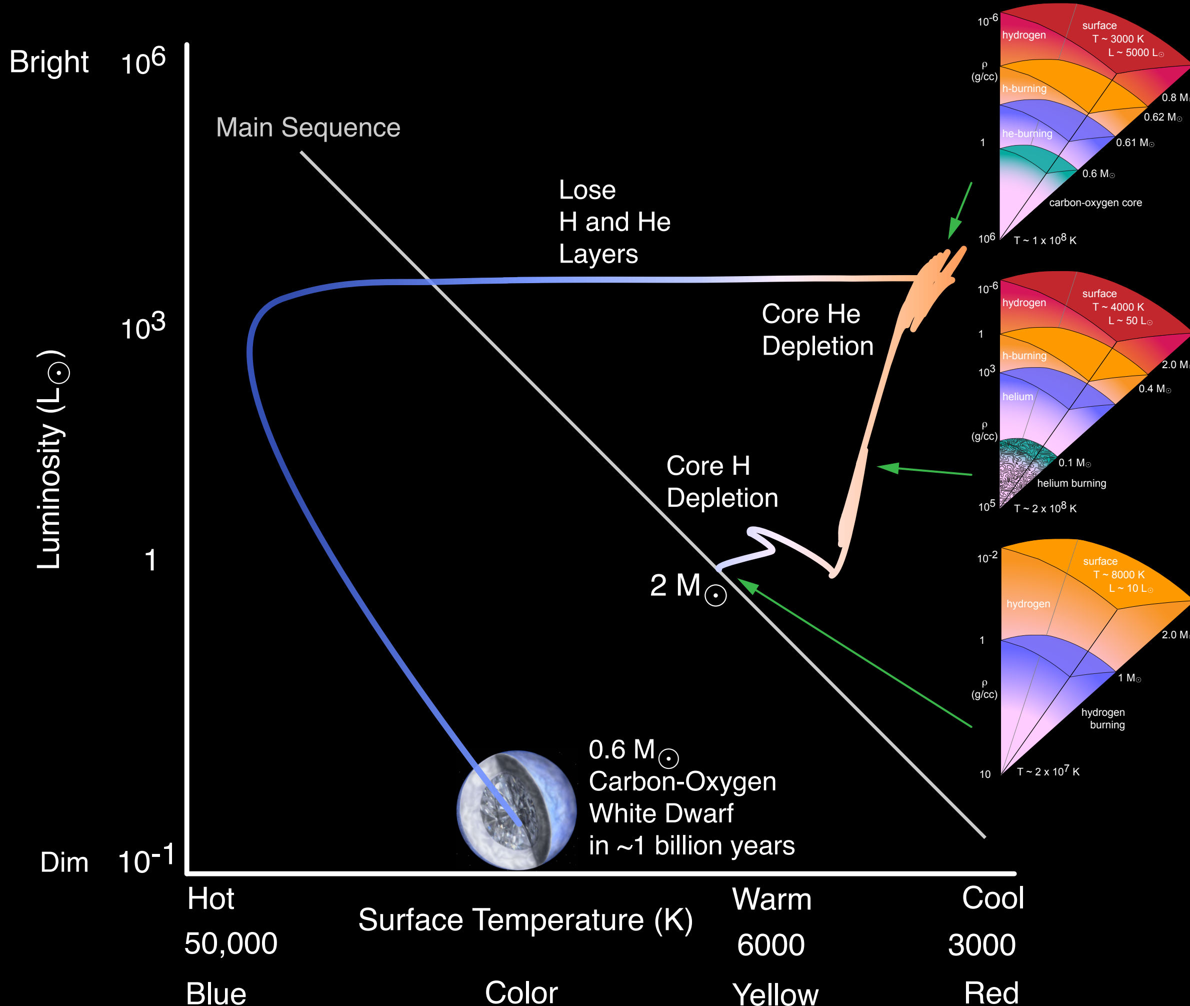
DeBoer et al 2017



10^{-6}
ρ
(g/cc)
1
10^6
hydrogen
h-burning
he-burning
surface
T ~ 3000 K
L ~ 5000 L☉
0.8 M☉
0.62 M☉
0.61 M☉
0.6 M☉
carbon-oxygen core
T ~ 1 x 10^8 K



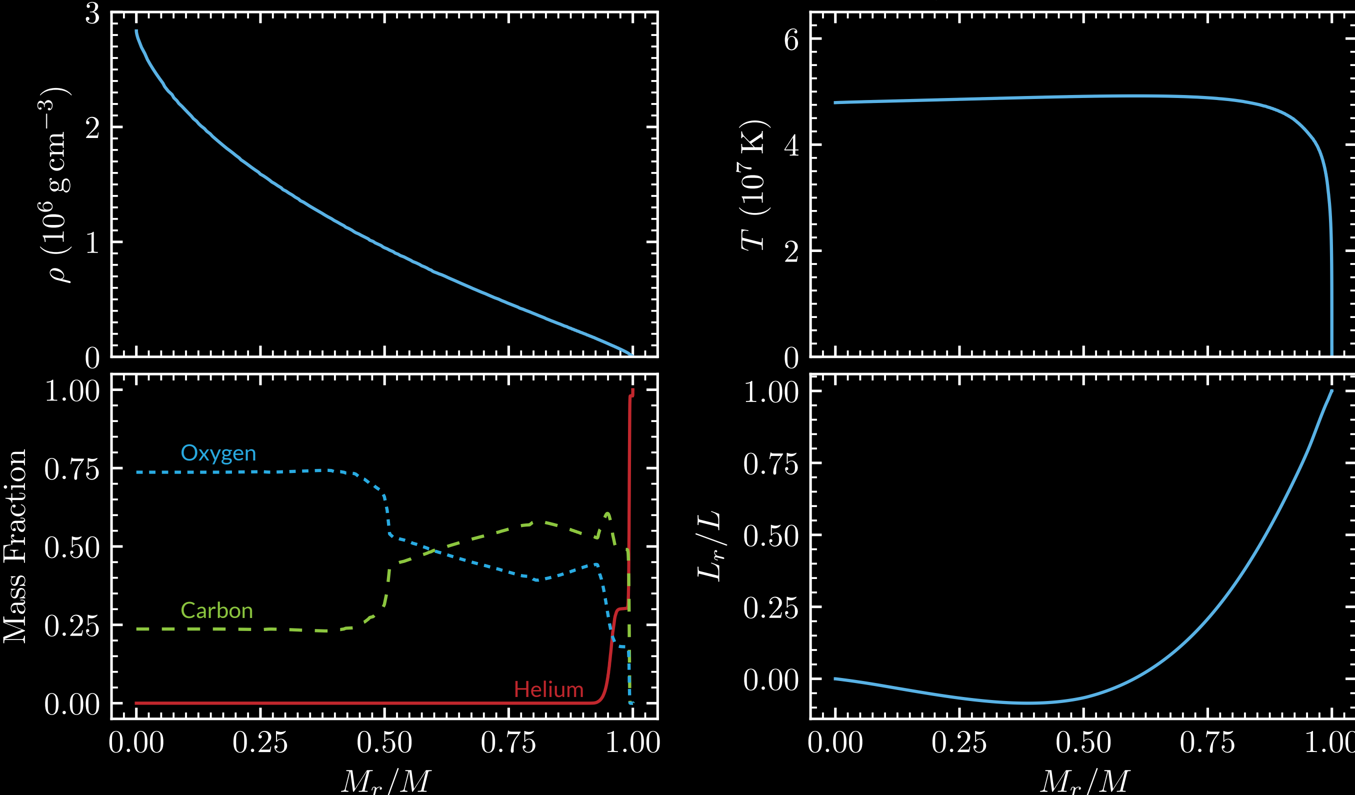
Credit:Travis Metcalfe and Ruth Bazinet



Bright
Dim
10^6
10^3
1
10^{-1}
Luminosity ($L_\odot$)
Main Sequence
Lose
H and He
Layers
Core He
Depletion
Core H
Depletion
2 $M_\odot$
0.6 $M_\odot$
Carbon-Oxygen
White Dwarf
in ~1 billion years
Hot
50,000
Blue
Surface Temperature (K)
Color
Warm
6000
Yellow
Cool
3000
Red
10^{-6}
hydrogen
surface
T ~ 3000 K
L ~ 5000 $L_\odot$
ρ (g/cc)
h-burning
0.8 $M_\odot$
0.62 $M_\odot$
he-burning
1
0.61 $M_\odot$
0.6 $M_\odot$
carbon-oxygen core
10^6
T ~ 1 x 10^8 K
10^{-6}
hydrogen
surface
T ~ 4000 K
L ~ 50 $L_\odot$
1
h-burning
10^3
2.0 $M_\odot$
0.4 $M_\odot$
helium
ρ (g/cc)
0.1 $M_\odot$
helium burning
10^5
T ~ 2 x 10^8 K
10^{-2}
surface
T ~ 8000 K
L ~ 10 $L_\odot$
hydrogen
2.0 $M_\odot$
1
ρ (g/cc)
1 $M_\odot$
hydrogen
burning
10
T ~ 2 x 10^7 K

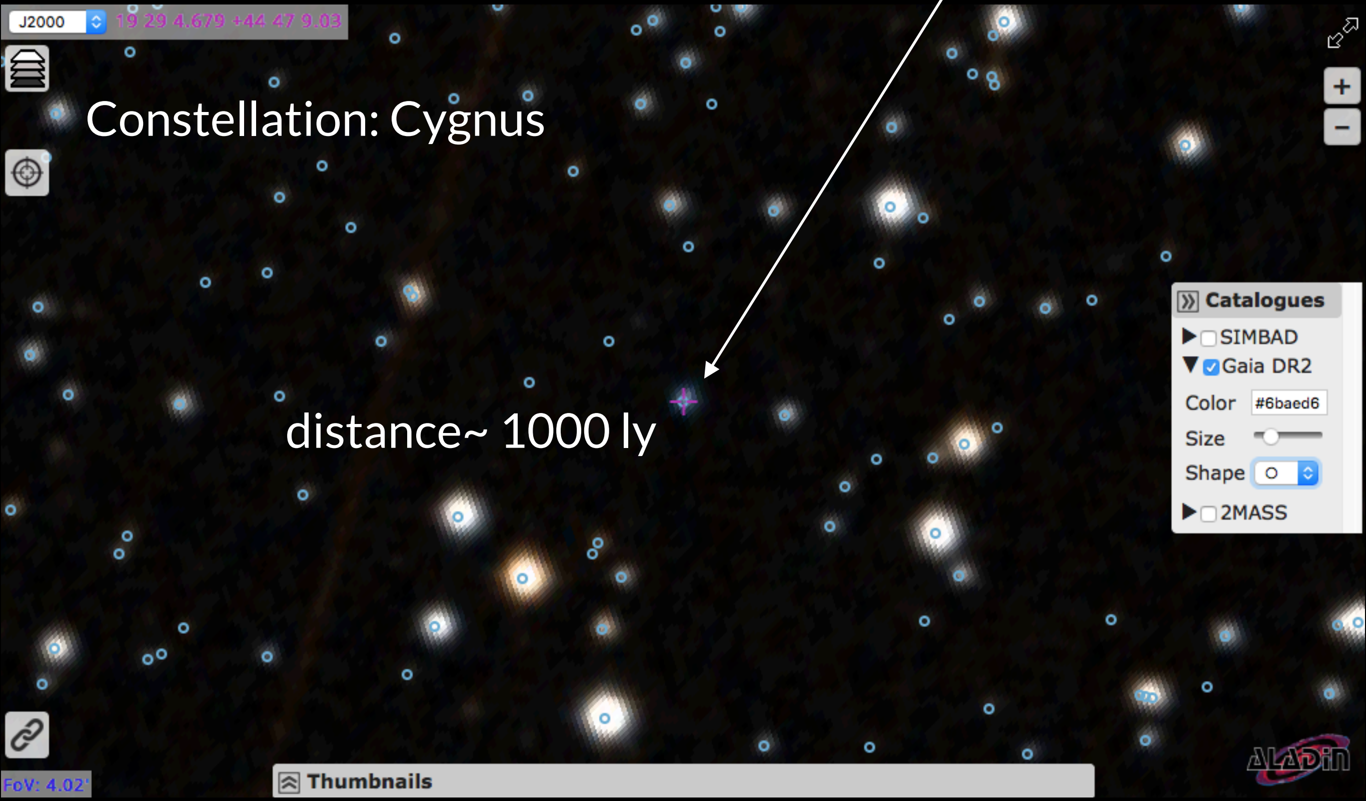
An Evolution Model Aiming At KIC 08626021

M =0.59 M⊙   L = 0.137 L⊙   Teff ~ 29,000 K

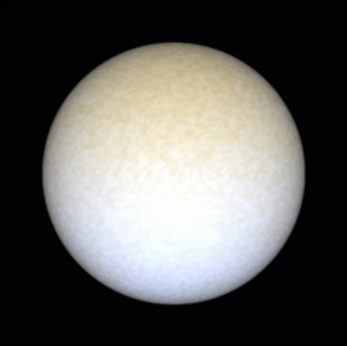


Timmes et al 2018

KIC 8626021



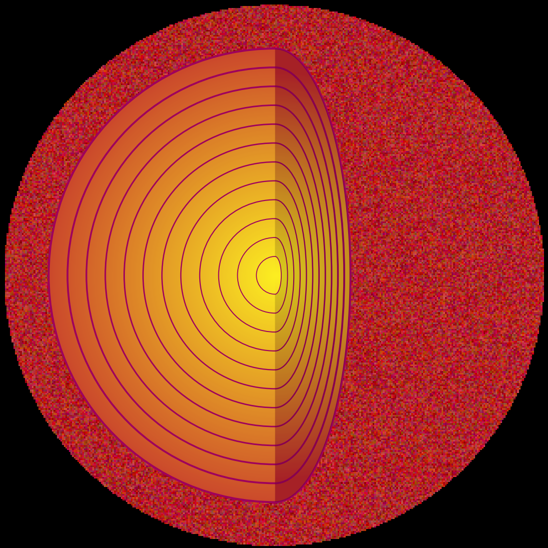
J2000
19 29 4.679 +44 47 9.03
Constellation: Cygnus
distance~ 1000 ly
Catalogues
SIMBAD
Gaia DR2
Color
#6baed6
Size
Shape
2MASS
Thumbnails
FoV: 4.02'



Let’s shake a white dwarf.

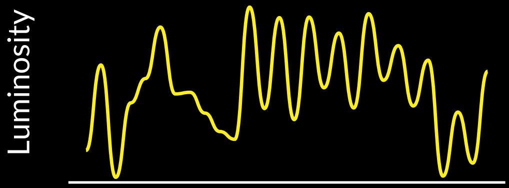
Like a sound wave resonating in an organ pipe, sound waves can resonate inside a star. By measuring these wave frequencies, we learn about the star's internal structure.

Vibrations are generated by ionization and turbulence near the star's surface.

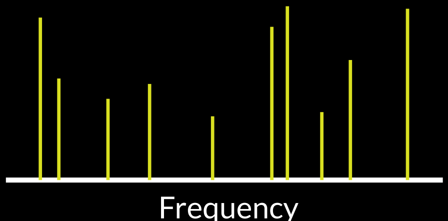


The vibrations penetrate into the interior, setting up resonances at frequencies dependent on density, temperature, and abundance profiles.

We see these oscillations as subtle, rythmic changes in the star's luminosity.



Resonant frequencies can vary from one every few minutes in Sun-like stars to one every few hundred days in red giants.



GYRE

GYRE solves the system of equations governing small periodic perturbations to an equilibrium stellar state.

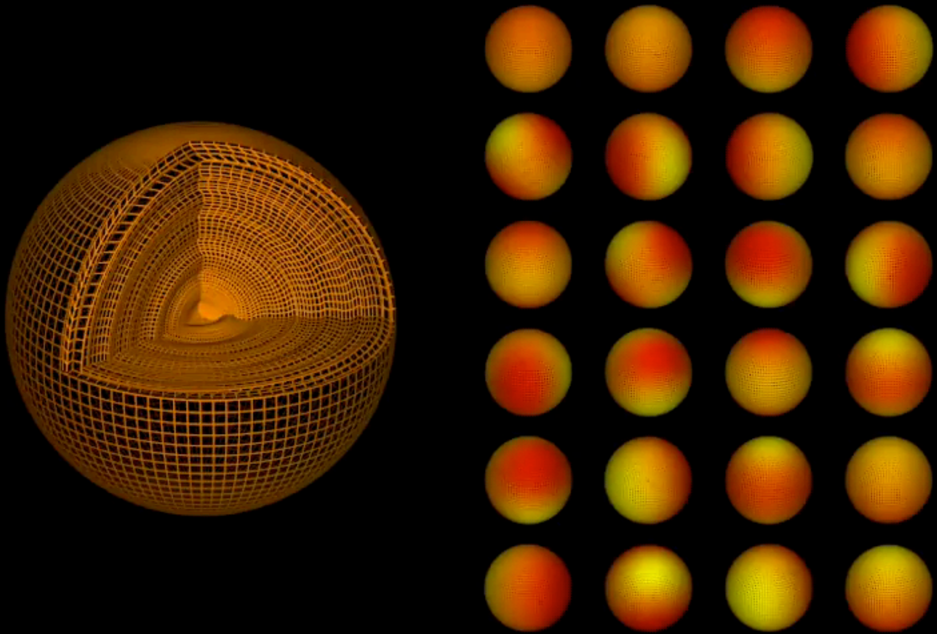
Solutions take the form

$$\xi_r(r,\theta,\phi,t) = \mathrm{Re}\left[\sqrt{4\pi}\;\;\tilde{\xi}_r(r)\;Y_\ell^m(\theta,\phi)\;\exp(-i\omega t)\right]$$

$$\xi_h(r,\theta,\phi,t) = \mathrm{Re}\left[\sqrt{4\pi}\;\tilde{\xi}_h(r) r\,\nabla_h\;Y_\ell^m(\theta,\phi)\;\exp(-i\omega t)\right]$$

$$f'(r,\theta,\phi,t) = \mathrm{Re}\left[\sqrt{4\pi}\;\tilde{f}'(r)\;Y_\ell^m(\theta,\phi)\;\exp(-i\omega t)\right]$$

Solutions which satisfy the boundary conditions only occur for discrete values of the frequency ω - these are the *eigenfrequencies* of the star.



Credit: Stéphane Charpinet

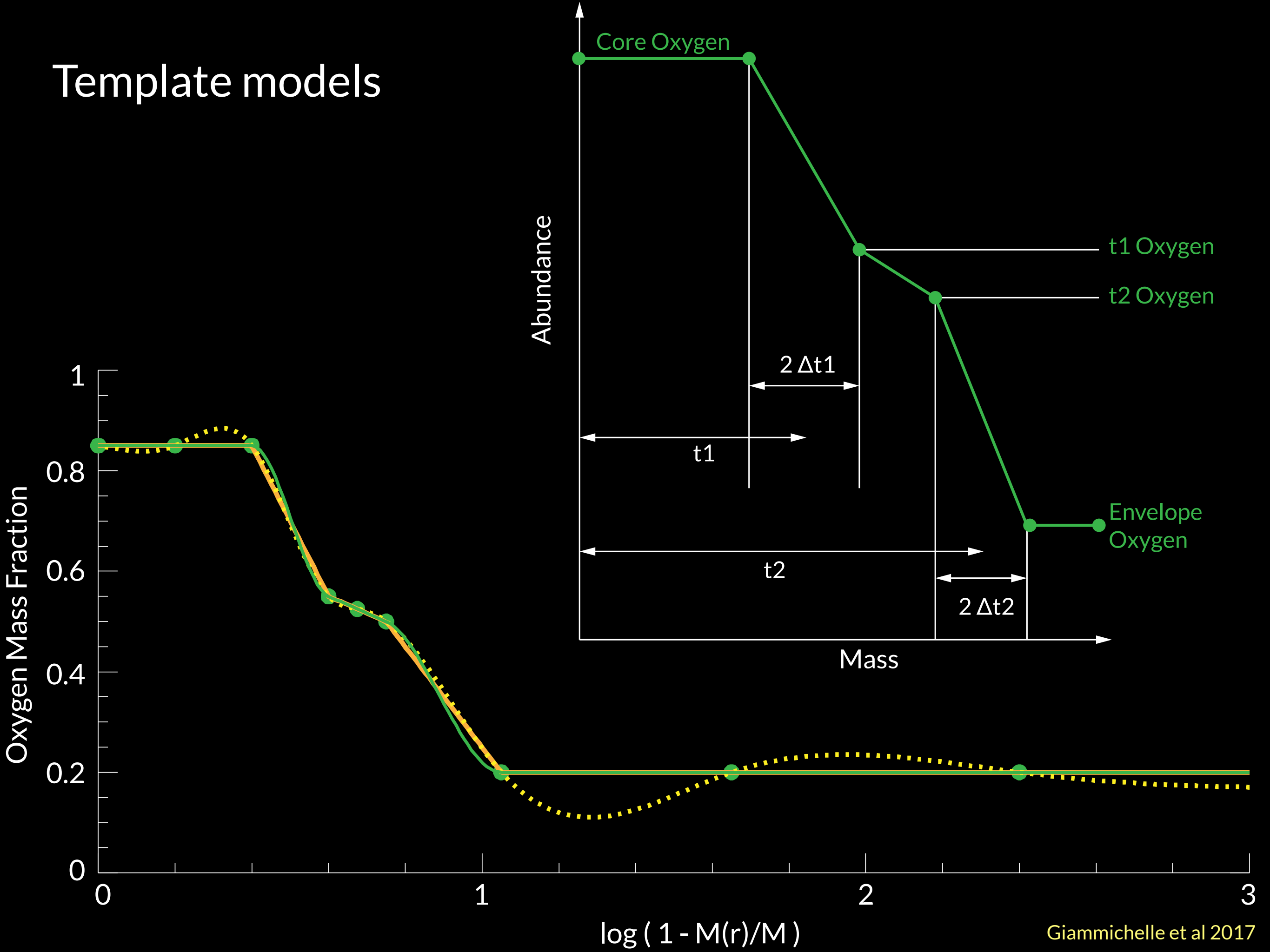
Cocktails to fit a white dwarf model's eigenfrequencies to those derived from the Kepler mission's photometric data:

1) Evolve a model from the main sequence to a white dwarf with the observed surface properties

2) Evolve a hot white dwarf to the observed surface properties

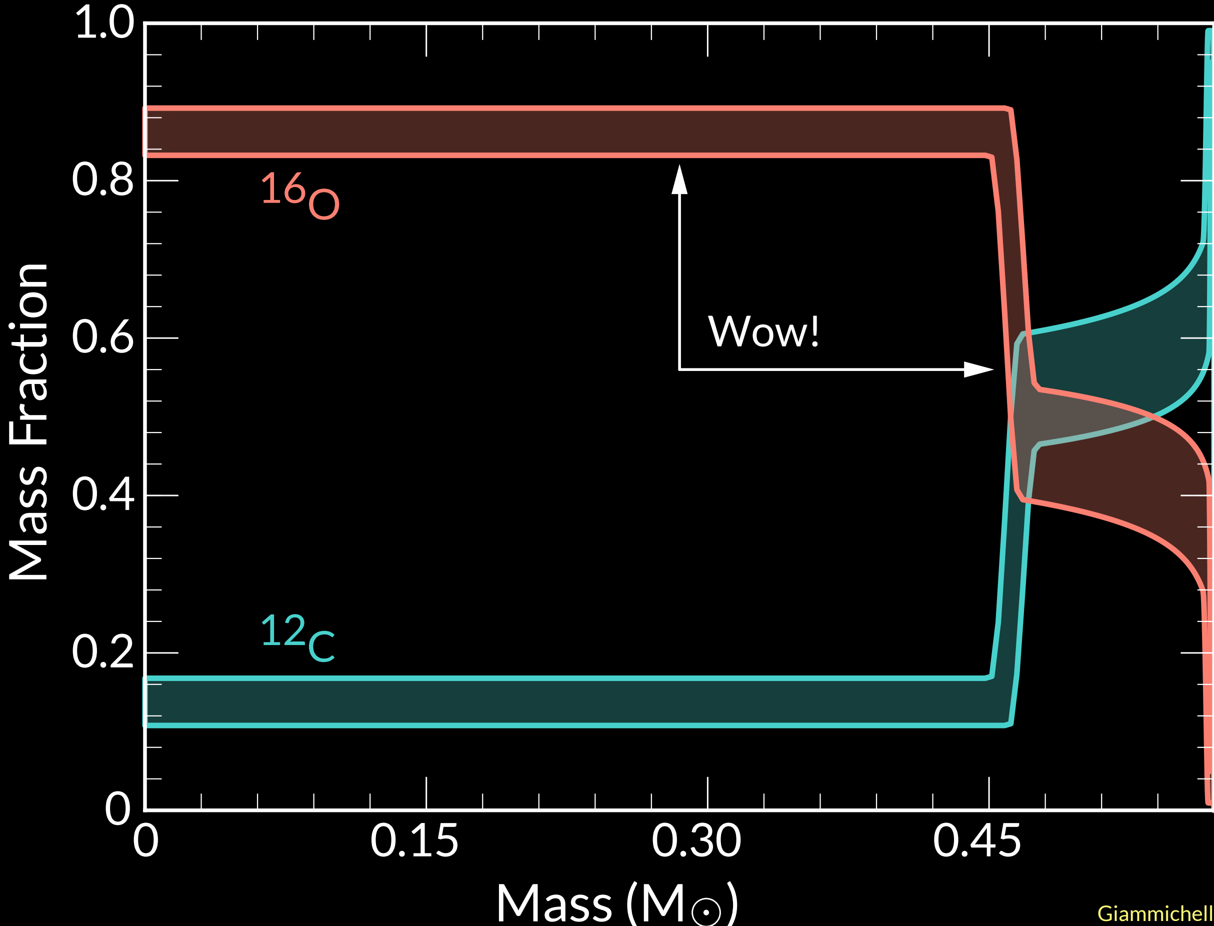
3) Flexible templates of the interior profiles

Template models

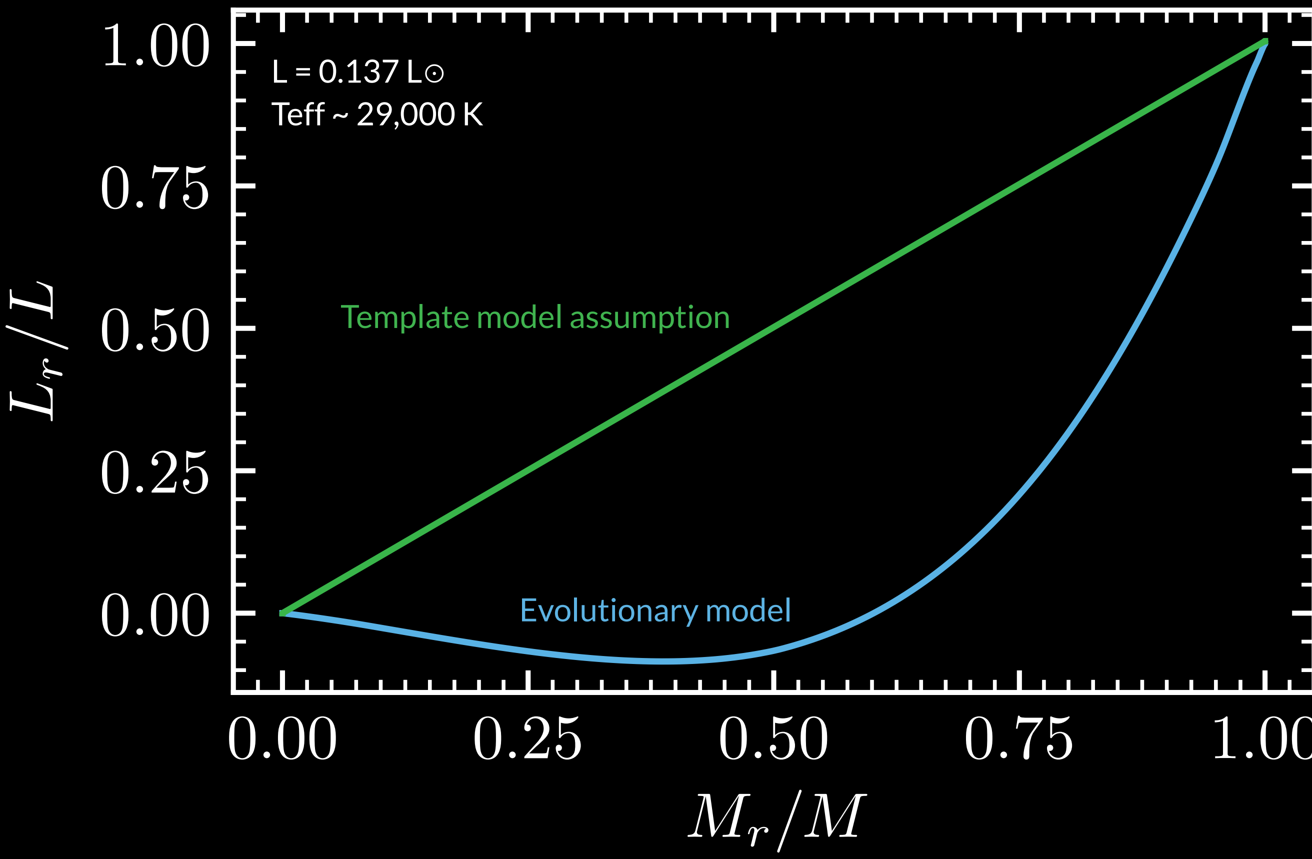


Giammichelle et al 2017

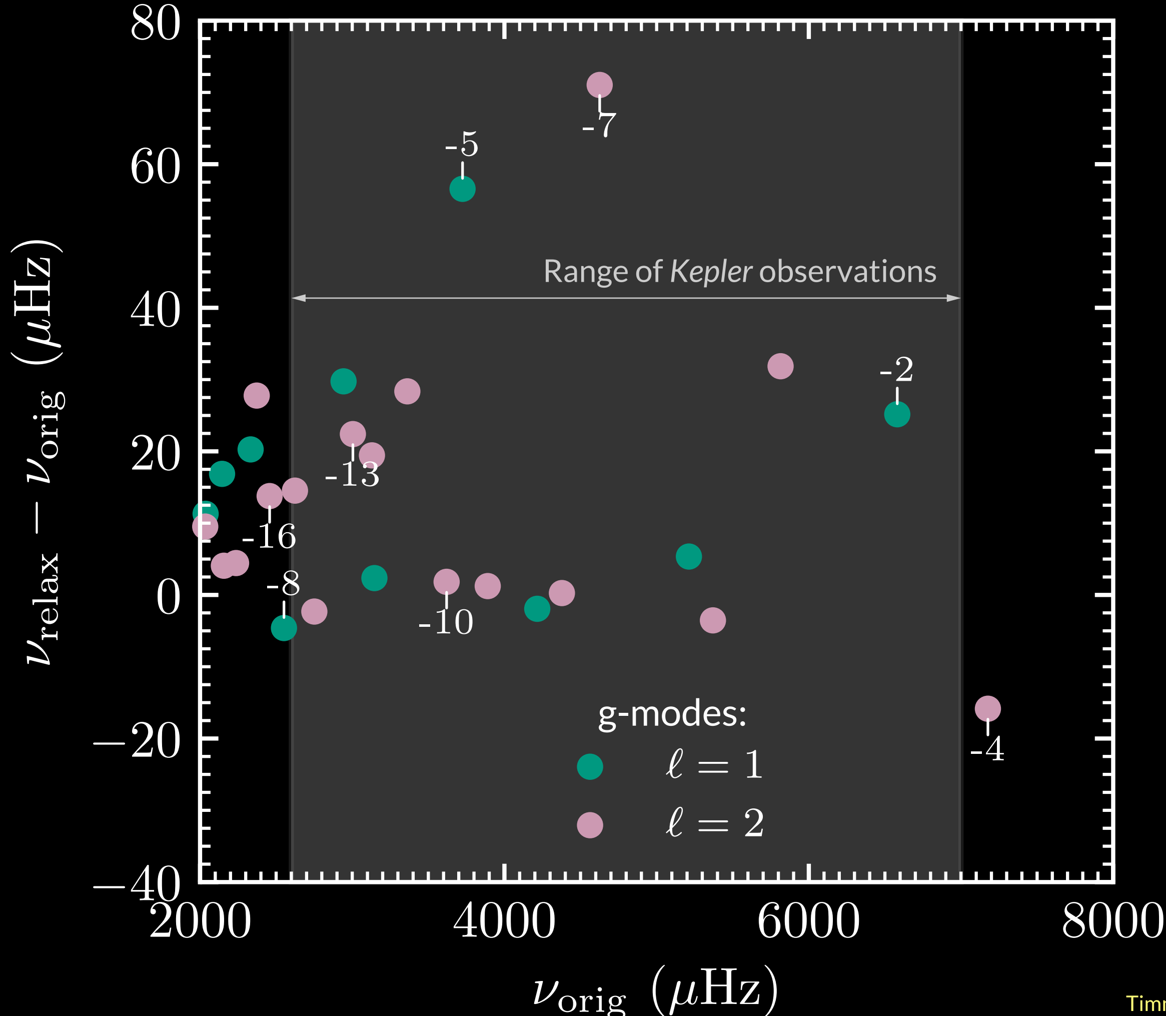
Template model for KIC 08626021



Giammichelle et al 2018



Timmes et al 2018

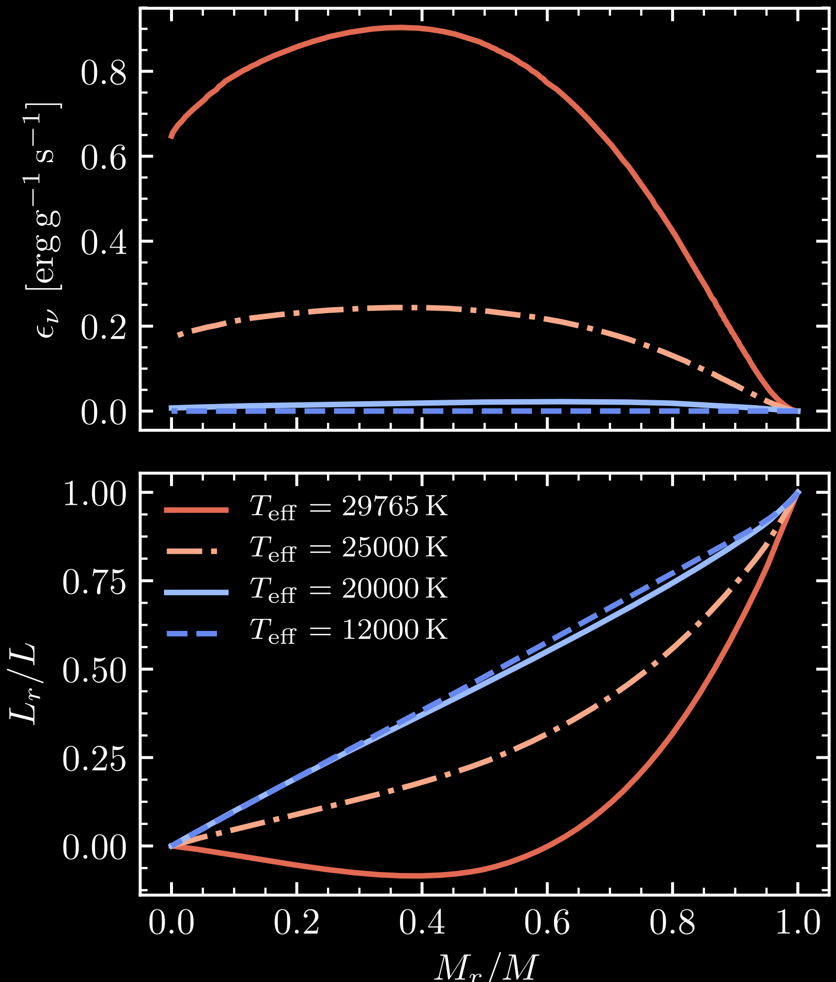


Timmes et al 2018

We find the low order g-mode frequencies differ by up to $\simeq$ 70 μHz over the range of Kepler observations for KIC 08626021.

By neglecting the proper thermal structure of the star (e.g., accounting for plasmon ν losses), model frequencies calculated by assuming an $L_r \propto M_r$ profile may have uncorrected, effectively random errors at $\simeq$ tens of μHz.

Extrapolating known uncertainties, a 30 μHz error causes a ~12% error in the white dwarf mass, a ~9% error in its radius, and a ~3% error in its central oxygen abundance.



Evolution of the luminosity profiles show $L_r \propto M_r$ does not occur until $T_{eff} \lesssim$ 20, 000 K

Timmes et al 2018

Questions and Discussion

JINA-CEE

SPIDER

SCORPION

MESA

Starlib

100 isotopes project

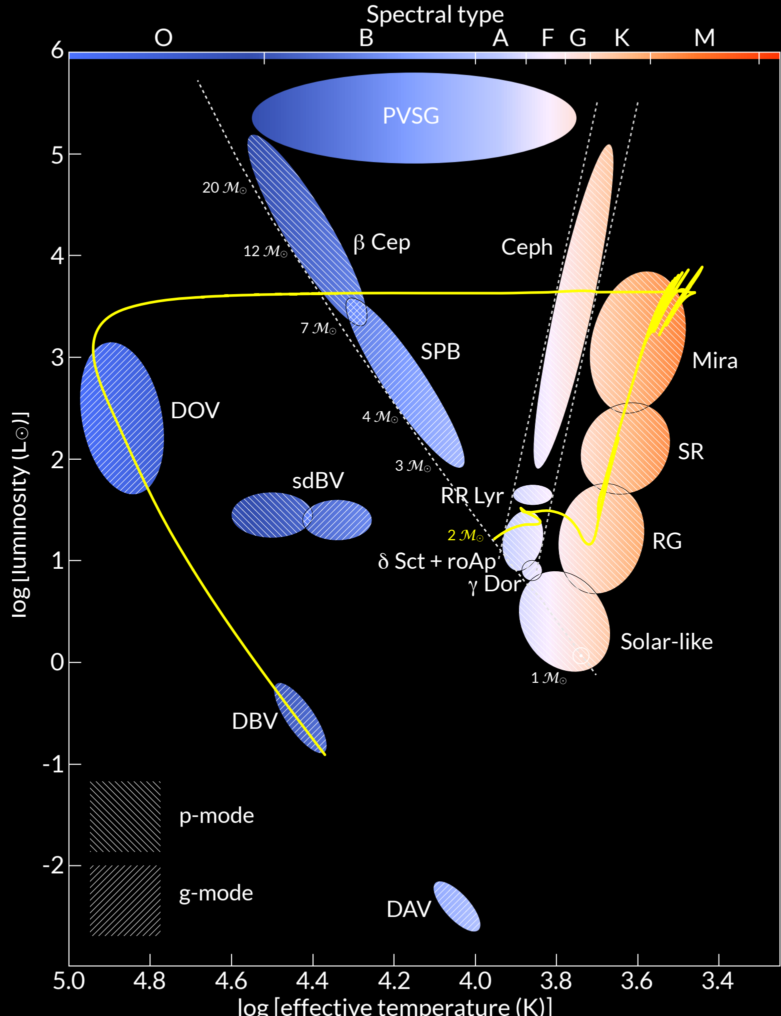
edX

NSF

THE ASTROPHYSICAL JOURNAL

SIMONS FOUNDATION

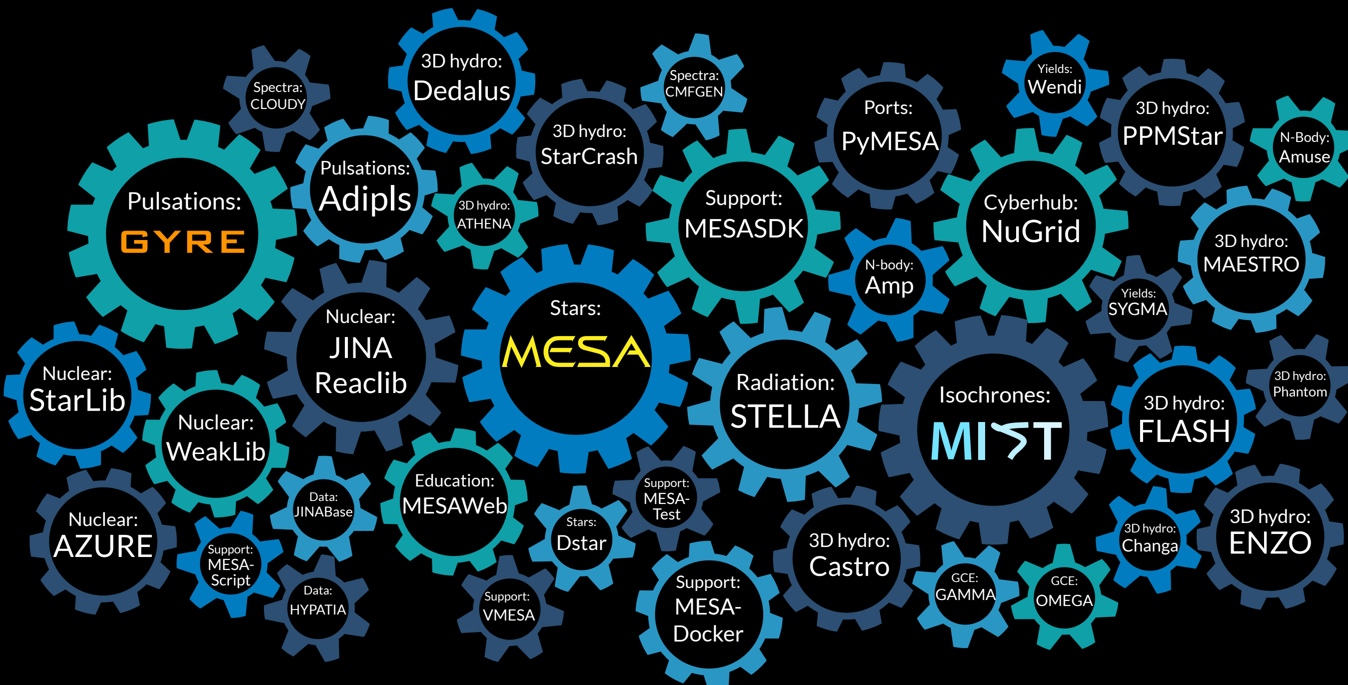
NASA



Spectral type
O
B
A
F
G
K
M
6
5
4
3
2
1
0
-1
-2
log [luminosity (L⊙)]
PVSG
β Cep
Ceph
20 ℳ⊙
12 ℳ⊙
7 ℳ⊙
4 ℳ⊙
3 ℳ⊙
2 ℳ⊙
1 ℳ⊙
SPB
Mira
DOV
SR
sdBV
RR Lyr
RG
δ Sct + roAp
γ Dor
Solar-like
DBV
p-mode
g-mode
DAV
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
log [effective temperature (K)]

Critical community-driven software and data for new science.

LIGO Gaia LCO ZTF ASAS-SN Kepler TESS NuSTAR



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