Darmstadt, March 18

Stellar Evolution: Course Overview, Importance and Introduction

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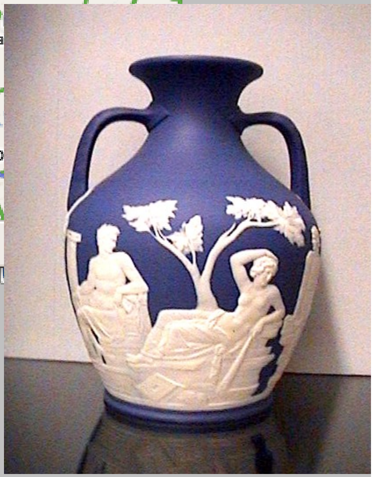
Keele is Not Kiel (Germany) But Where is it?

West Midlands:

Keele



Keele area

is famous for pottery: Wedgwood, ...

and football: Stoke city fc in premier league

Plan

- Course overview

- Importance, evolution and fate of stars

- Stellar models & their physical ingredients

- EOS and partial degeneracy

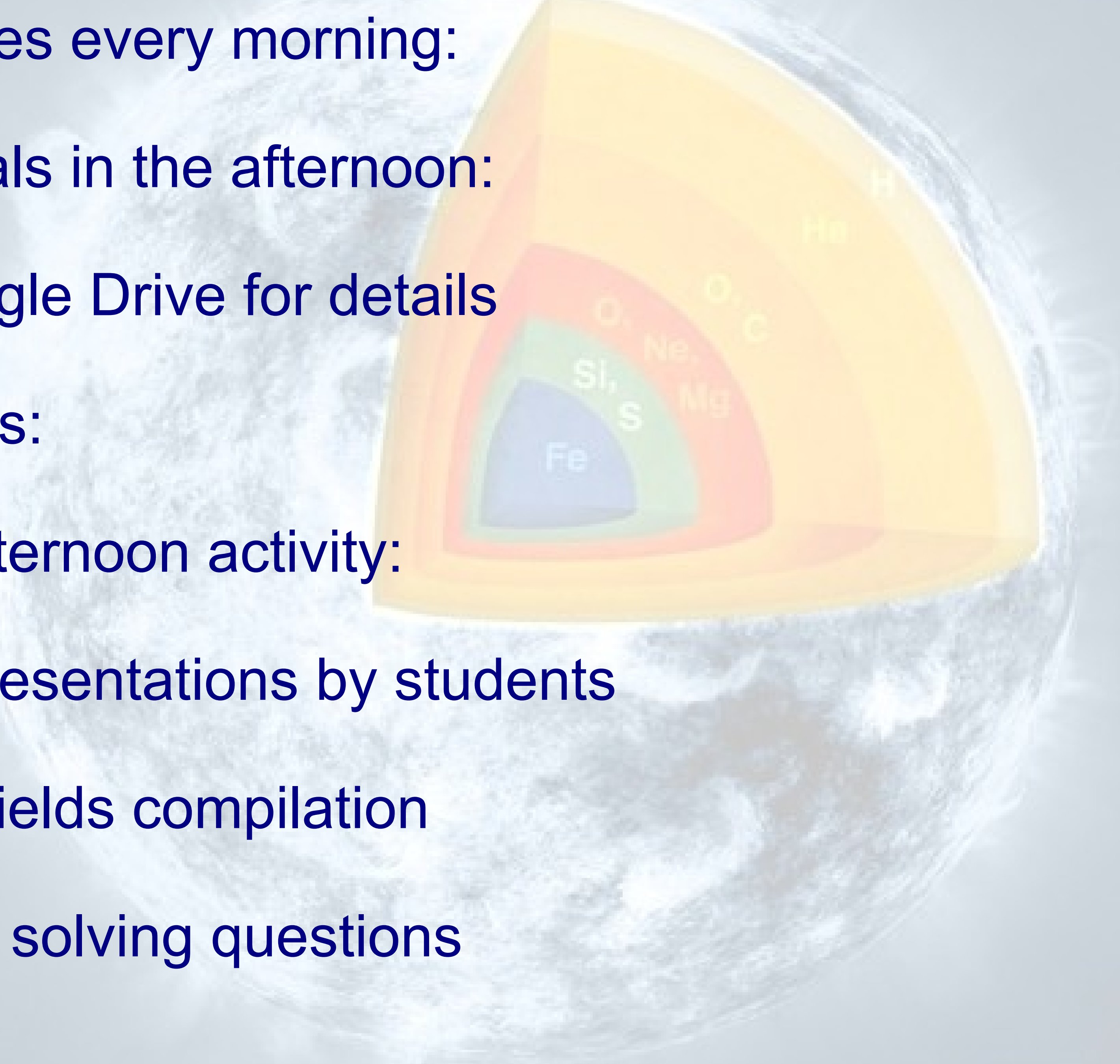
- Mass domains

- Standard massive stars

- The most massive stars

- Stars at the boundary between massive and intermediate-mass stars

Lecture Plan



- 2 lectures every morning:

- Practicals in the afternoon:

See Google Drive for details

Questions:

Friday afternoon activity:

- 1-plot presentations by students

- Stellar yields compilation

- problem solving questions

Acknowledgements & Bibliography

- Slides in white background (with blue title) were taken from Achim Weiss' lecture slides, which you can find here: http://www.mpa-garching.mpg.de/~weiss/lectures.html

- A lot of content and some graphs were taken from Onno Pols' lecture notes on stellar evolution, which you can find here:

http://www.astro.ru.nl/~onnop/education/stev_utrecht_notes/

- Some slides (colourful ones) and content was taken from George Meynet's summer school slides.

- Link to slides from my lectures at the NICXIII school:

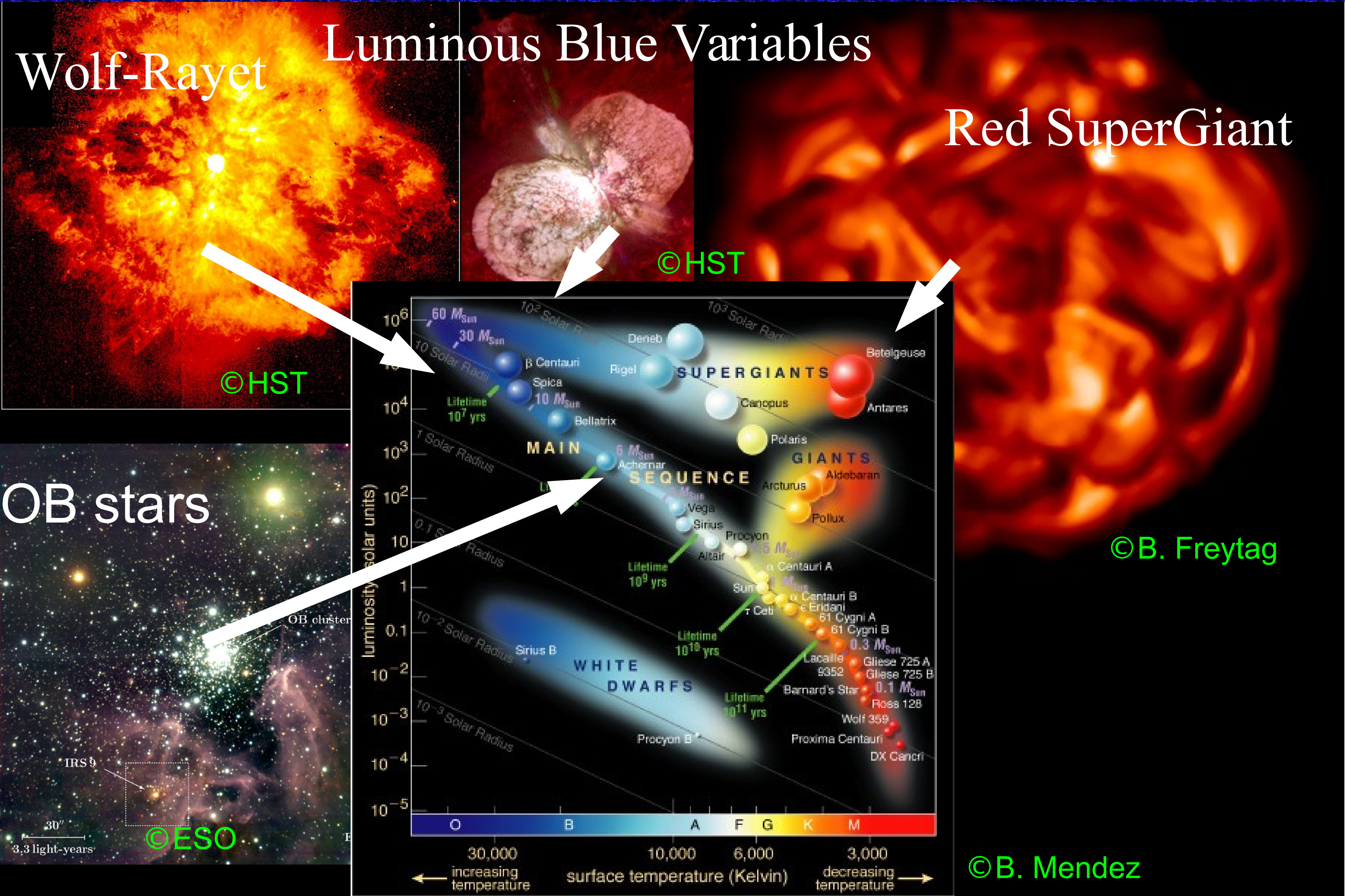
http://www.atomki.hu/nic2014school/

Acknowledgements & Bibliography

Recommended further reading:

- R. Kippenhahn & A. Weigert, Stellar Structure and Evolution, 1990, Springer-Verlag, ISBN 3-540-50211-4 (Recent update by Weiss et al.)
- A. Maeder, Physics, Formation and Evolution of Rotating Stars, 2009, Springer-Verlag, ISBN 978-3-540-76948-4
- D. Prialnik, An Introduction to the Theory of Stellar Structure and Evolution, 2000, Cambridge University Press, ISBN 0-521-65937-X
- C.J. Hansen, S.D. Kawaler & V. Trimble, Stellar Interiors, 2004, Springer-Verlag, ISBN 0-387-20089-4
- M. Salaris & S. Cassisi, Evolution of Stars and Stellar Populations, 2005, John Wiley & Sons, ISBN 0-470-09220-3

Massive Stars: Importance as Stellar Objects



Wolf-Rayet

©HST

Luminous Blue Variables

©HST

Red SuperGiant

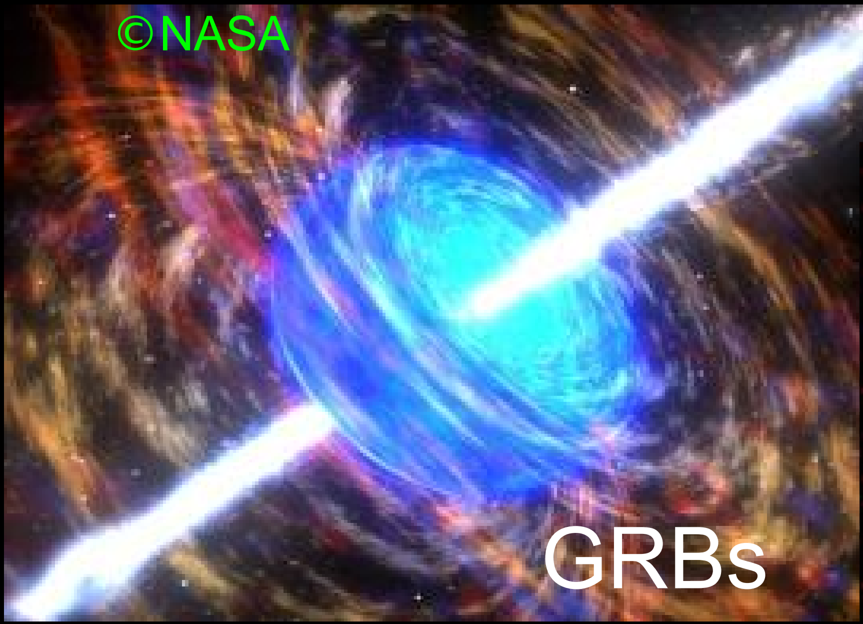
©B. Freytag

OB stars

©ESO

©B. Mendez

Importance as Progenitors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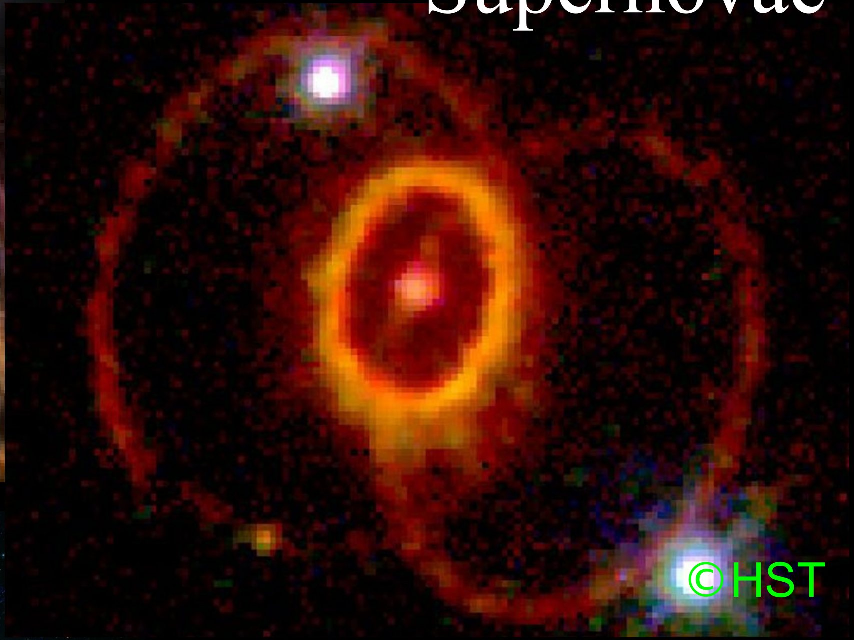
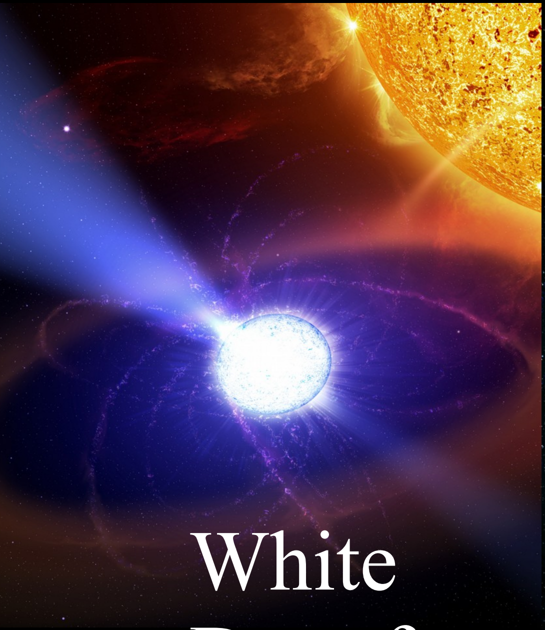
GRBs


Supernovae

©HST


White Dwarfs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Neutron Stars


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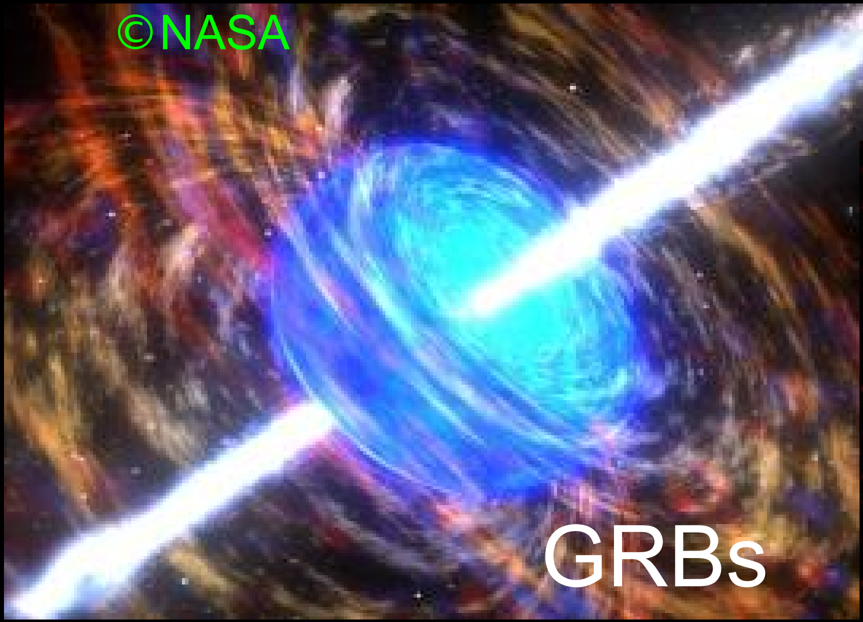
Black Holes + Gravit. Waves

Massive Stars: Importance as Progenitors



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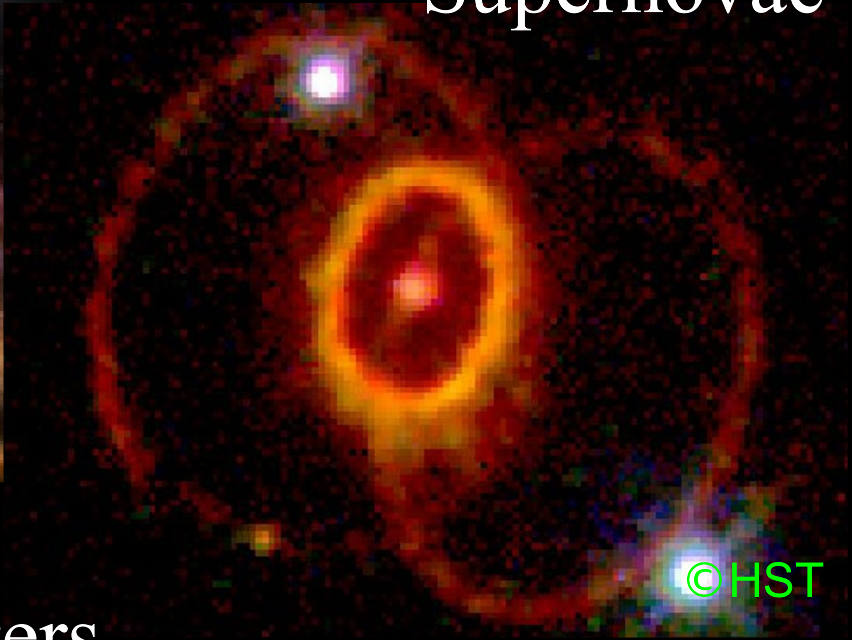
GRBs

Supernovae



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Neutron Stars

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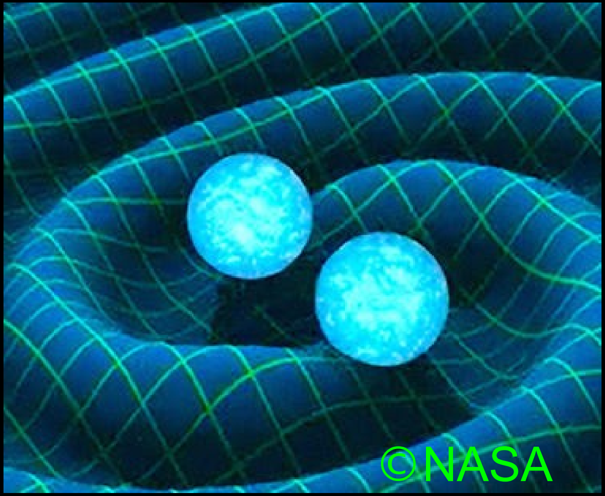
GWs ← mergers



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Black Holes

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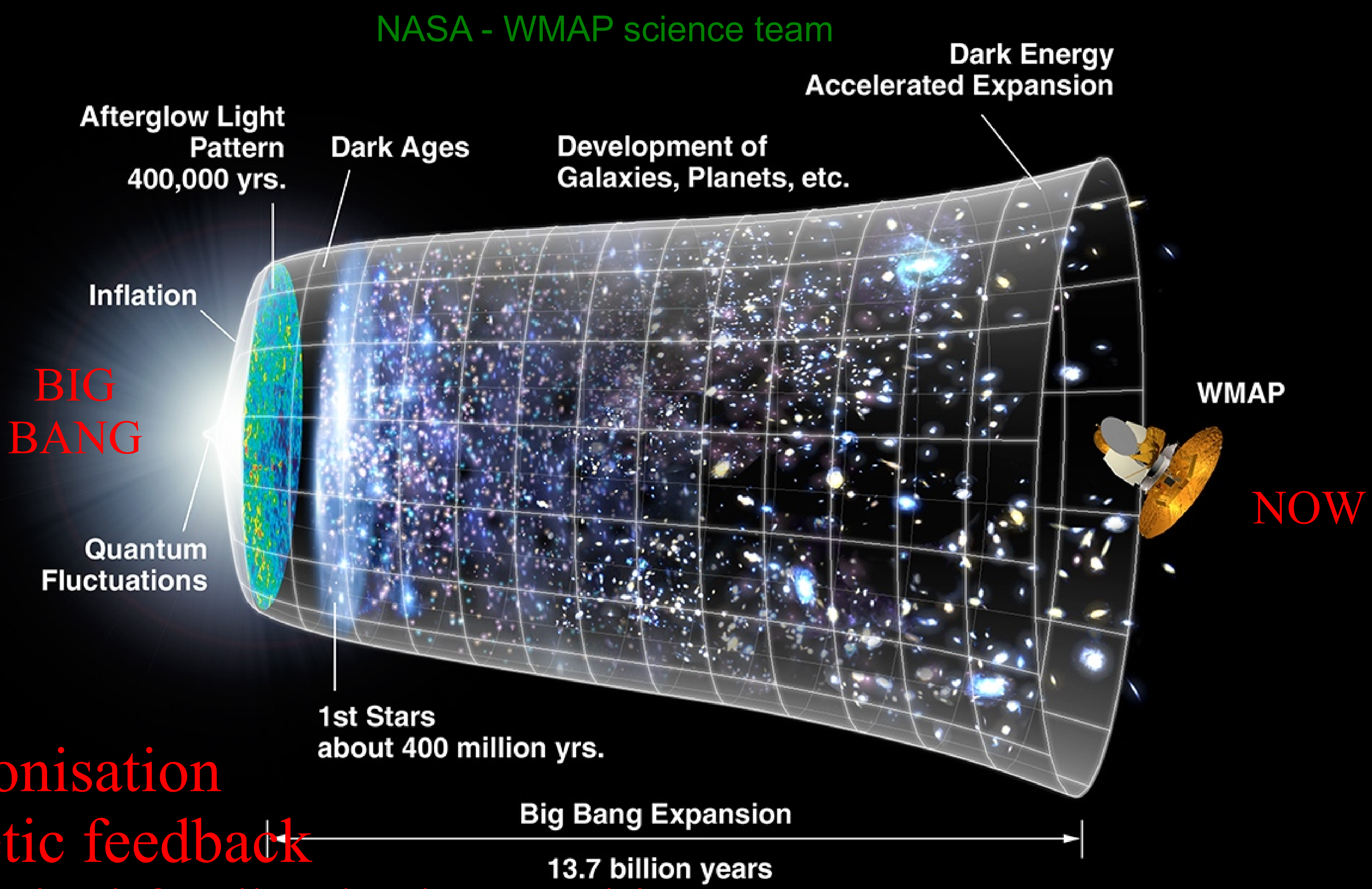
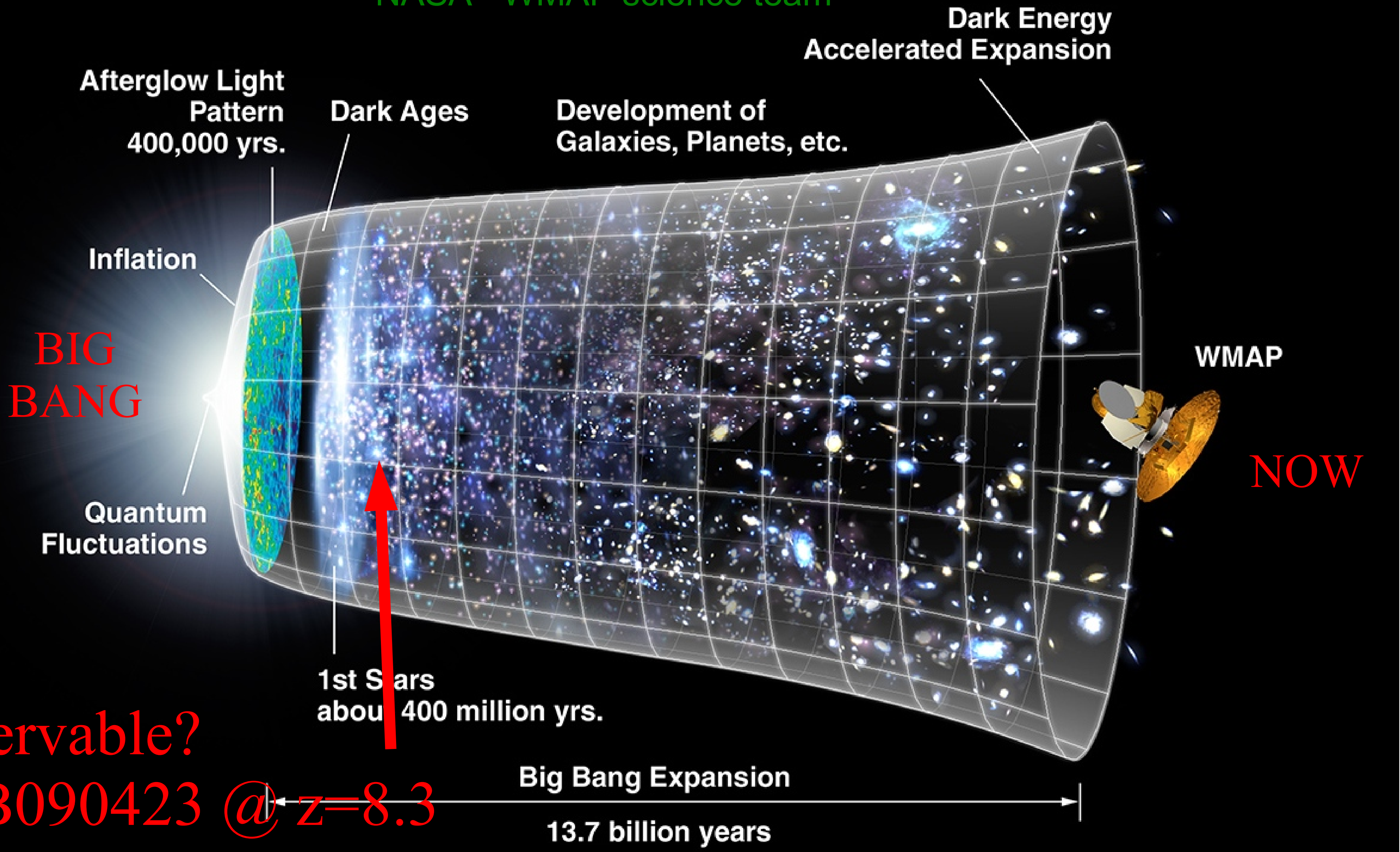
First Stellar Generations: Importance


NASA - WMAP science team

- Re-ionisation
- Kinetic feedback
- Chemical feedback observed in EMP stars

First Stellar Generations: Importance



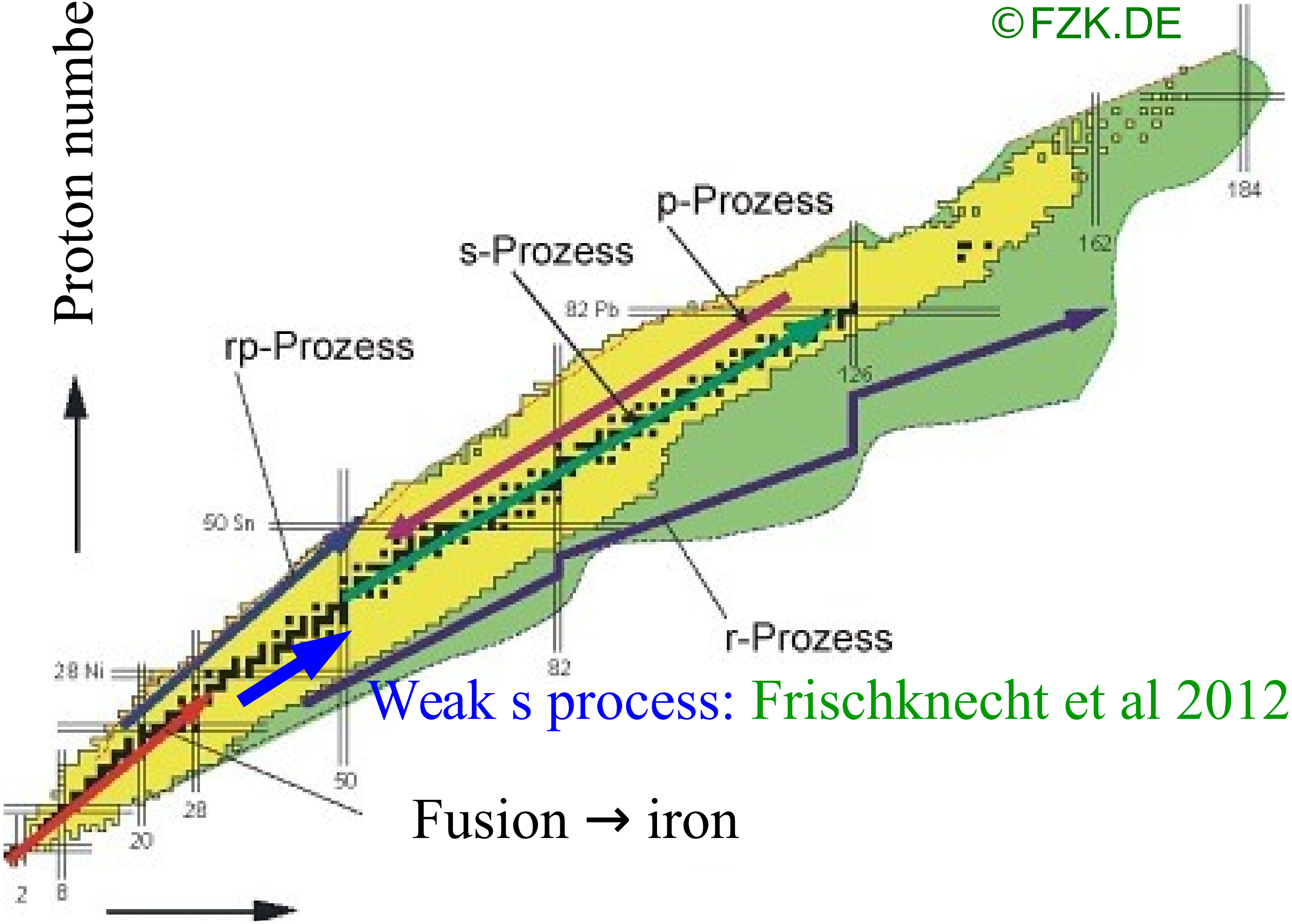
NASA - WMAP science team

- Observable?
- GRB090423 @ z=8.3

Universe age ~ 600 Myr (Tanvir et al 09 Nature: arXiv:0906.1577)

Stars: Importance for Nucleosynthesis

Proton number



Weak s process: Frischknecht et al 2012, 2016

Fusion → iron

Neutron number

Information about Stars from Observations

- Photometry → apparent brightness

- astrometry (parallax) → distances

- Spectroscopy → many surface properties:

temperature, gravity, chemical composition, rotation, winds

- Orbit+eclipses of binary stars → masses, radii

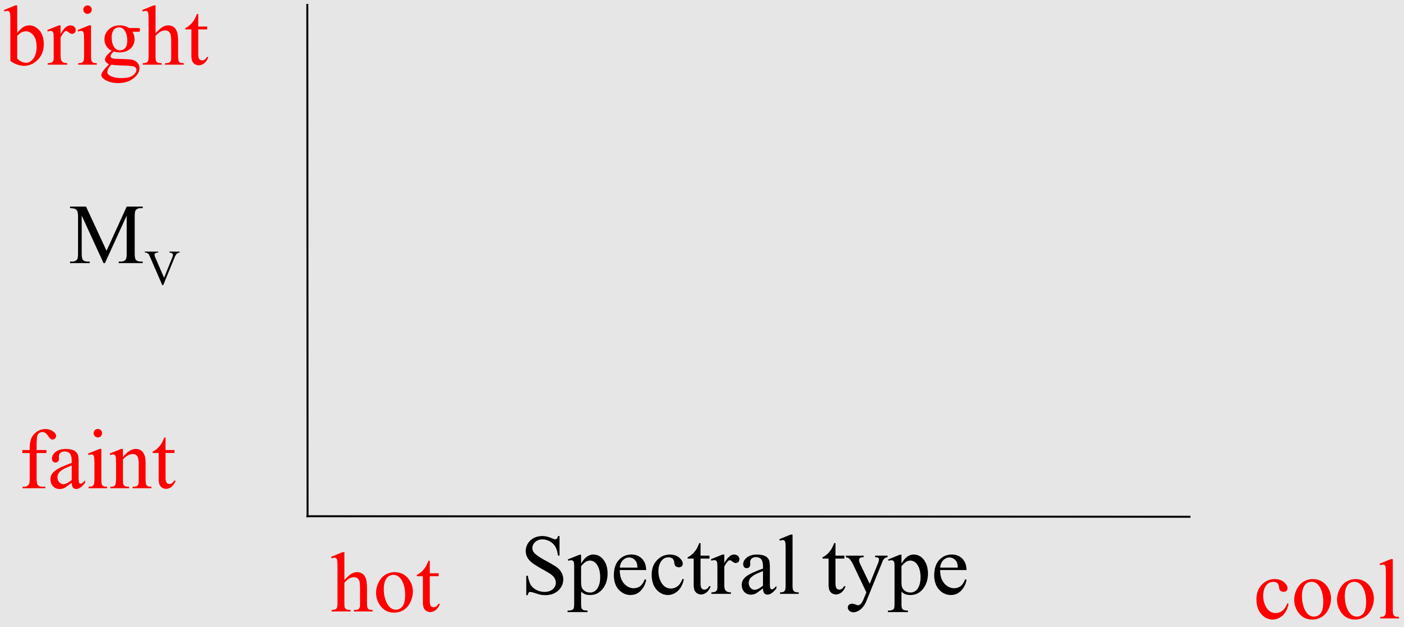
- Interferometry → angular diameter → radius

- Asteroseismology → speed of sound → internal structure

- Neutrinos / gravitational waves → core properties

The Hertzsprung-Russell Diagram

- A very useful diagram for understanding stars
- We plot two major properties of stars:
    - Temperature (x) vs. Luminosity (y)
    - Spectral Type (x) vs. Absolute Magnitude, M_V (y)



bright

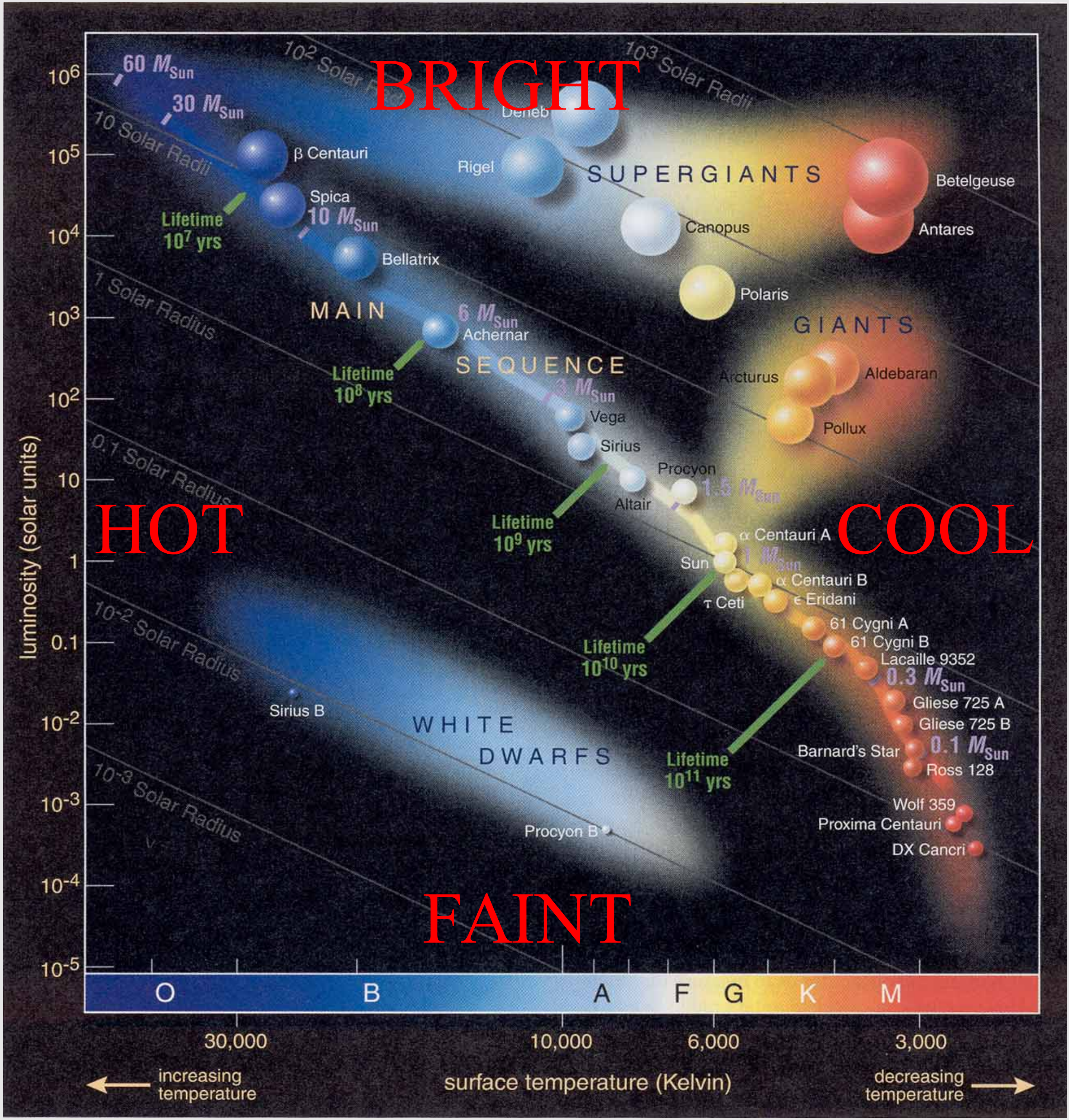
M_V

faint

hot

Spectral type

cool



BRIGHT

HOT

COOL

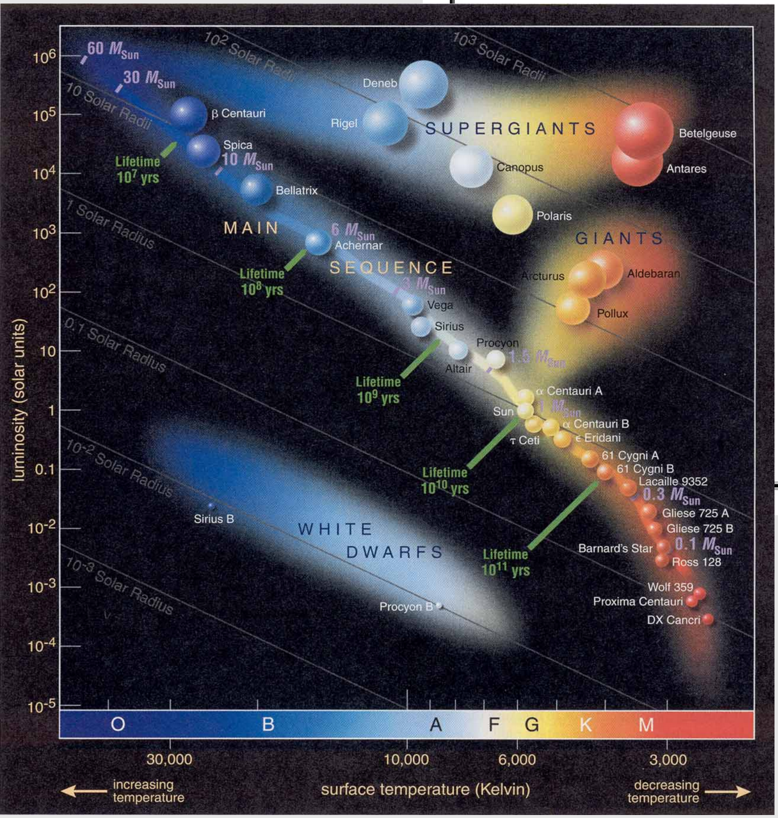
FAINT

Stellar Luminosity

How can two stars have the same temperature, but vastly different luminosities?

Stellar Luminosity Classes

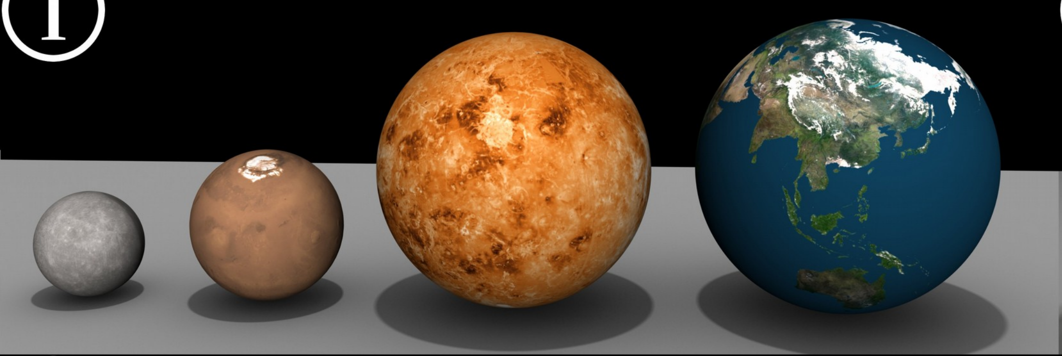
Class	Description
I	Supergiants
II	Bright giants
III	Giants
IV	Subgiants
V	Main sequence



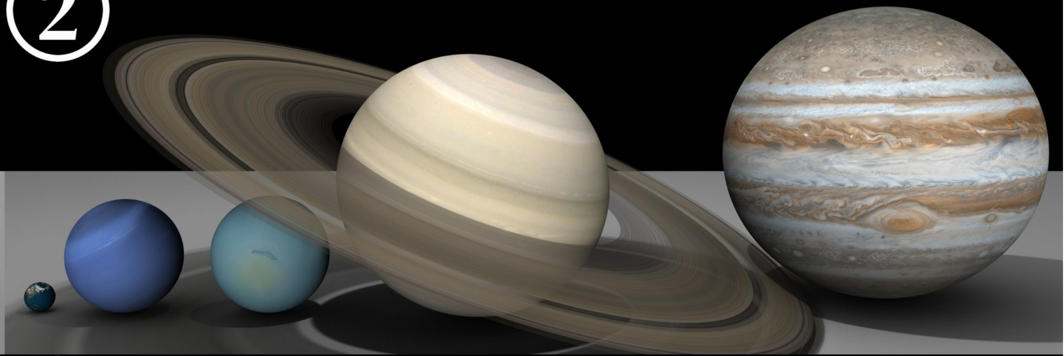
Radius of largest stars is larger than 1 AU!

The Most Voluminous Stars

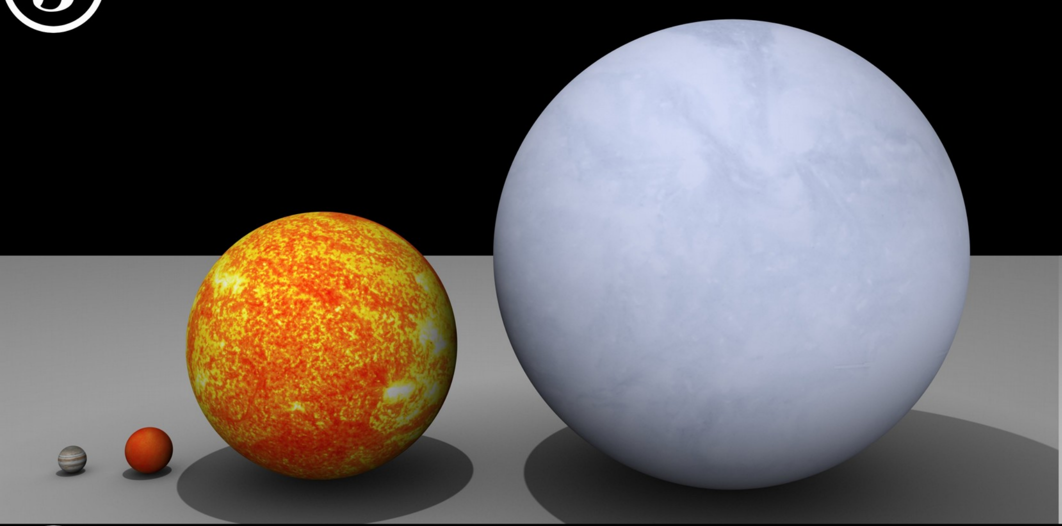
① Mercury < Mars < Venus < Earth



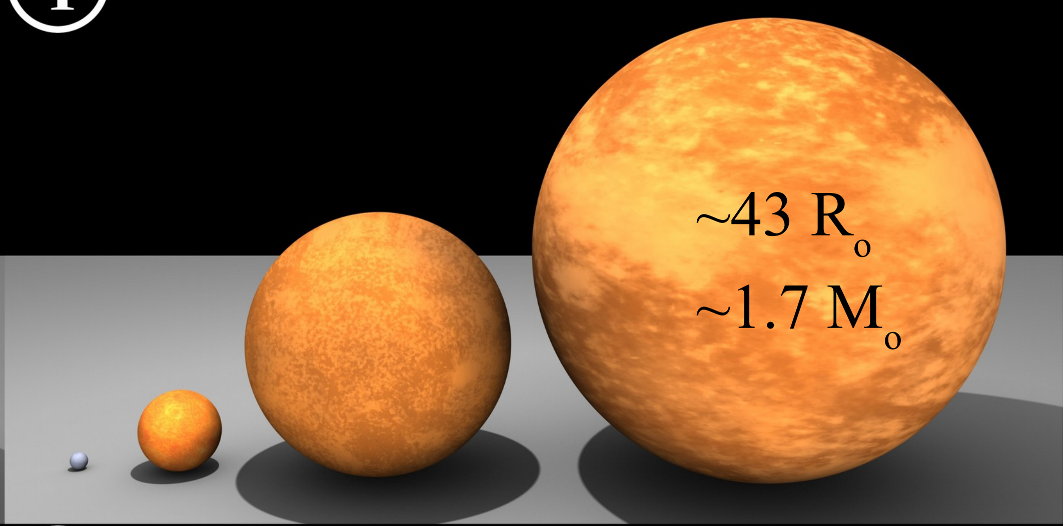
② Earth < Neptune < Uranus < Saturn < Jupiter



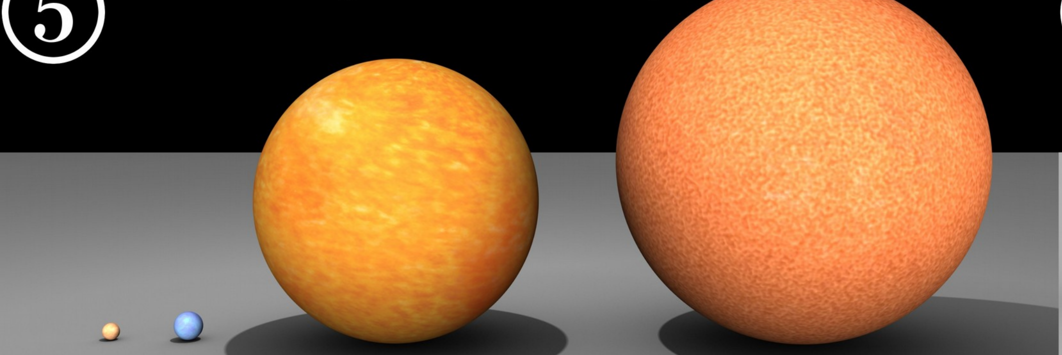
③ Jupiter < Wolf 359 < Sun < Sirius



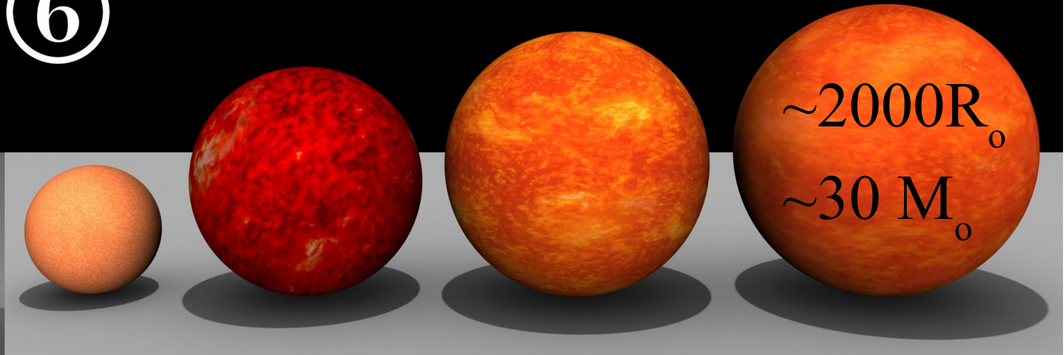
④ Sirius < Pollux < Arcturus < Aldebaran



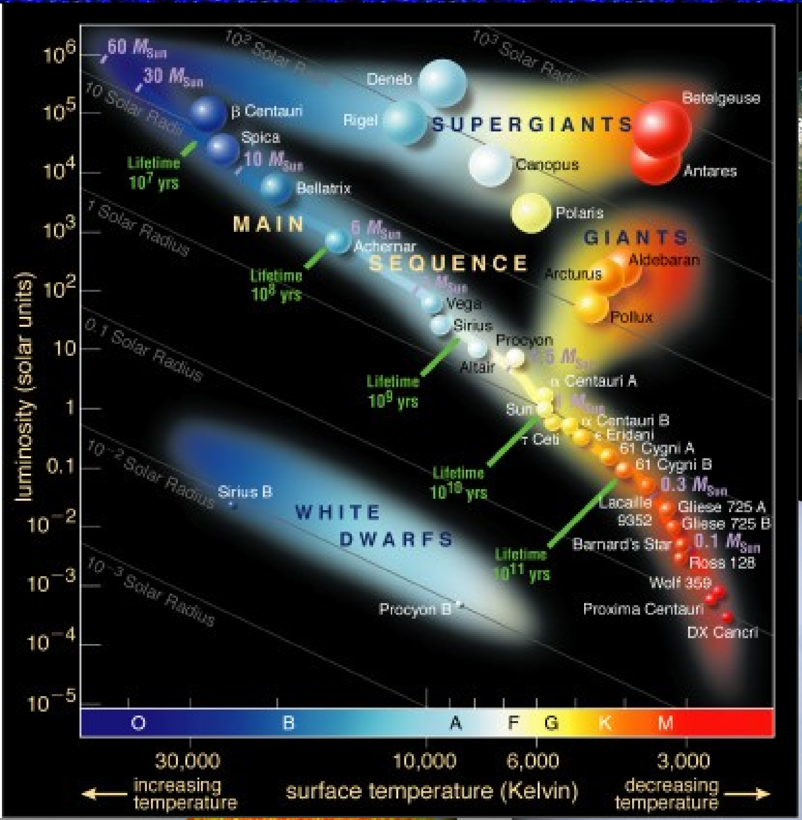
⑤ Aldebaran < Rigel < Antares < Betelgeuse



⑥ Betelgeuse < Mu Cephei < VV Cephei A < VY Canis Majoris



The Most Voluminous Stars



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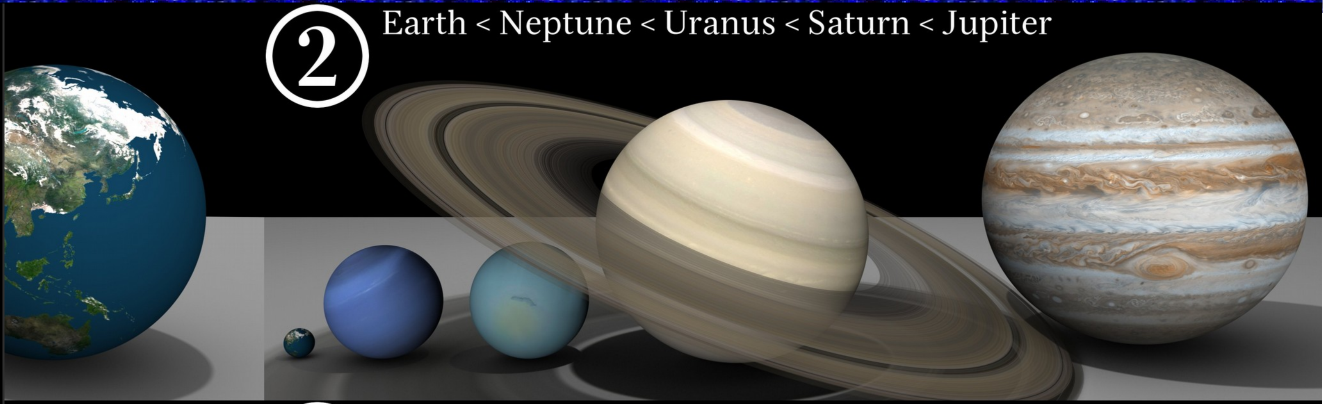

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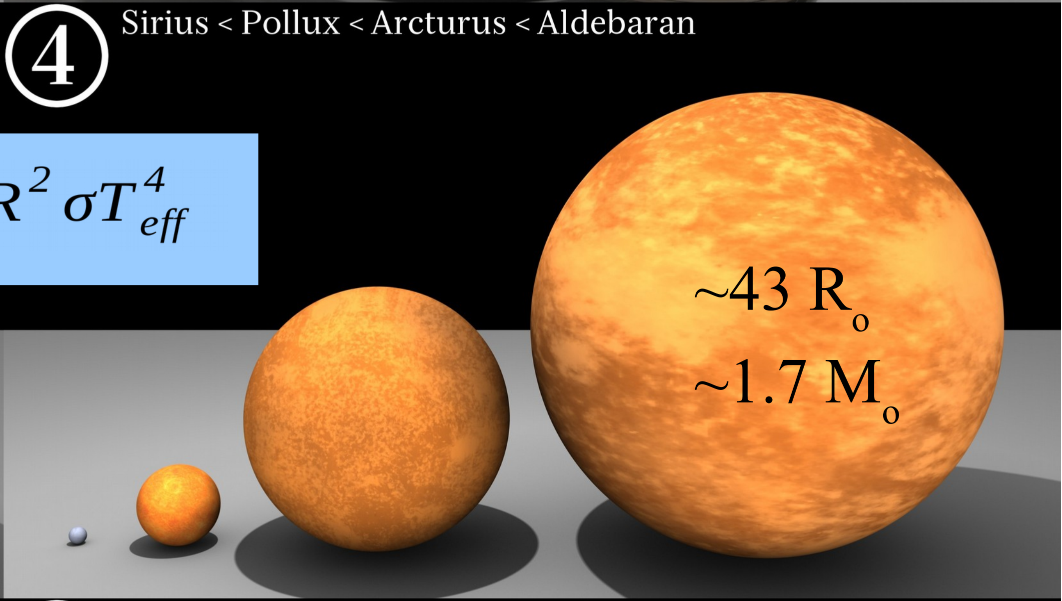
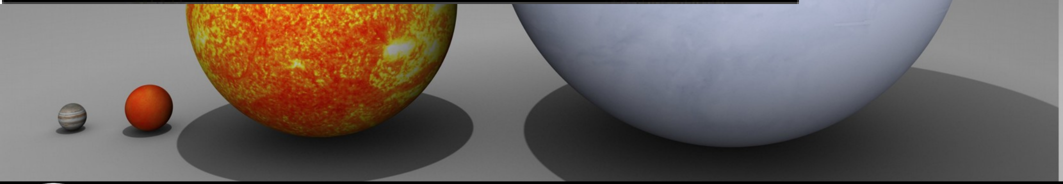


$$L = 4\pi R^2 \sigma T_{eff}^4$$



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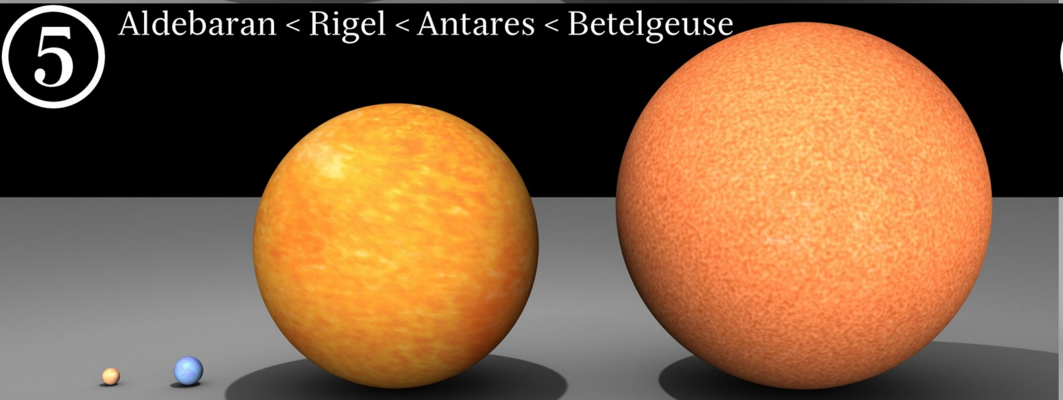

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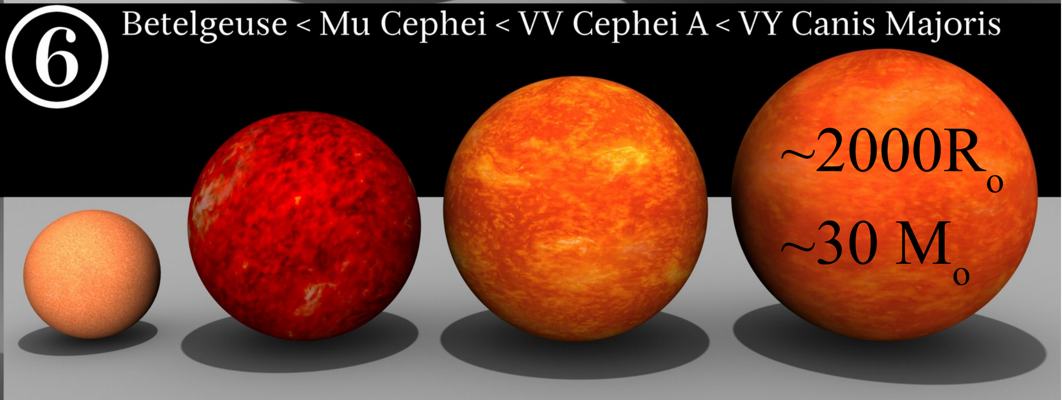


Goals of Stellar Evolution Theory

- Explain observed properties of stars and stellar populations using known laws of physics
- Explain and predict evolution and fate of stars
- Explain and predict radiative, chemical and mechanical impact of stars on environment (e.g. galaxies)
- Study physics under extreme conditions not found in the laboratory (plasma/nuclear physics)
- Study early Universe (e.g. EMP stars, GRBs)

Stellar Structure Equations

The four structure equations to be solved are:

$$
\begin{aligned}
\frac{\partial r}{\partial m} &= \frac{1}{4\pi r^2 \rho} \\
\frac{\partial P}{\partial m} &= -\frac{Gm}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2} \\
\frac{\partial L_r}{\partial m} &= \epsilon_n - \epsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t} \\
\frac{\partial T}{\partial m} &= -\frac{GmT}{4\pi r^4 P}\nabla
\end{aligned}
$$

(Assuming spherical symmetry: one-dimensional model)

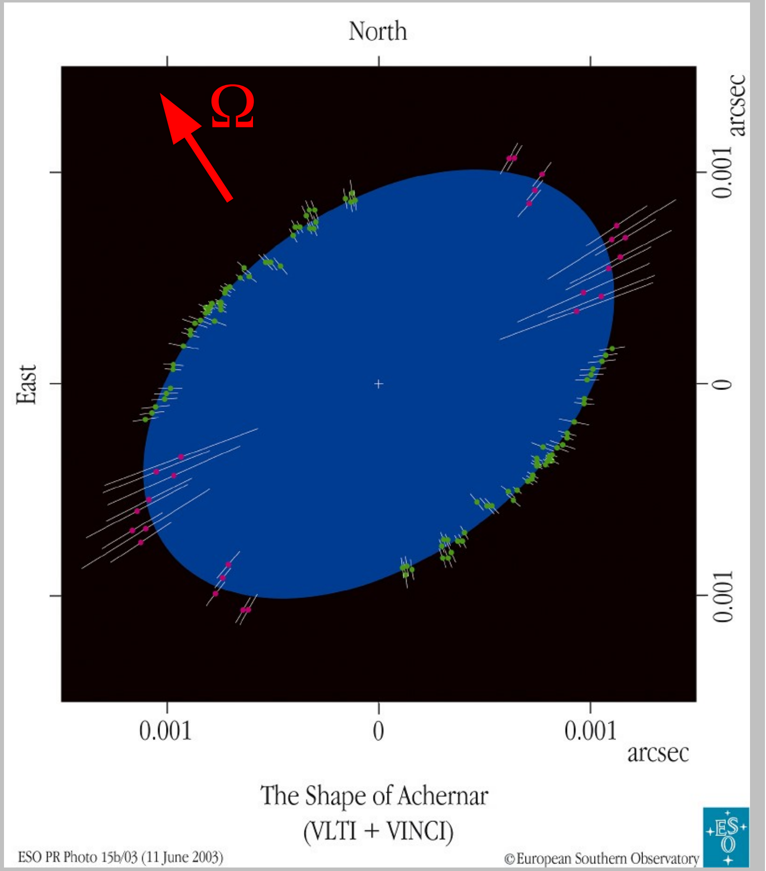
Lecture notes slide from Achim Weiss

Physical Ingredients

- Nuclear reactions
- Mass loss
- Convection
- Rotation
- Magnetic fields
- Binarity
- Equation of state, opacities & neutrino losses

including metallicity dependence

Geneva Stellar Evolution Code



1.5D hydrostatic code (Eggenberger et al 2008)

Rotation: (Maeder & Meynet 2008)

Centrifugal force: KEY FOR GRB prog.

Mass loss: enhanced and anisotropic

Mixing: meridional circ. & shear

Mass loss dep. on Z & Ω

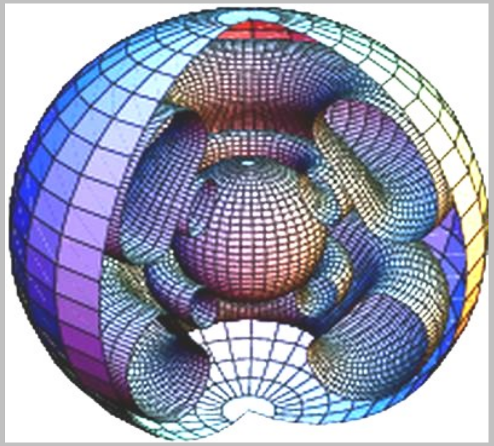
Convection: Schwarzschild + 0.1 H_P

Large nuclear reaction network: rates from NACRE/reaclib → s process (600-700 isotopes)!

B-fields (Spruit 02, Maeder 05),

see also α-Ω dyn. models by Potter et al 2012

Models ZAMS until Silicon burning



Meynet & Maeder 2000

Evolution of Surface Properties

Main sequence:

hydrogen burning

After Main Sequence:

Helium burning

Low and intermediate-mass stars:

MS → RG → HB/RC → AGB → WD

Massive stars:

Supergiant stage (red or blue)

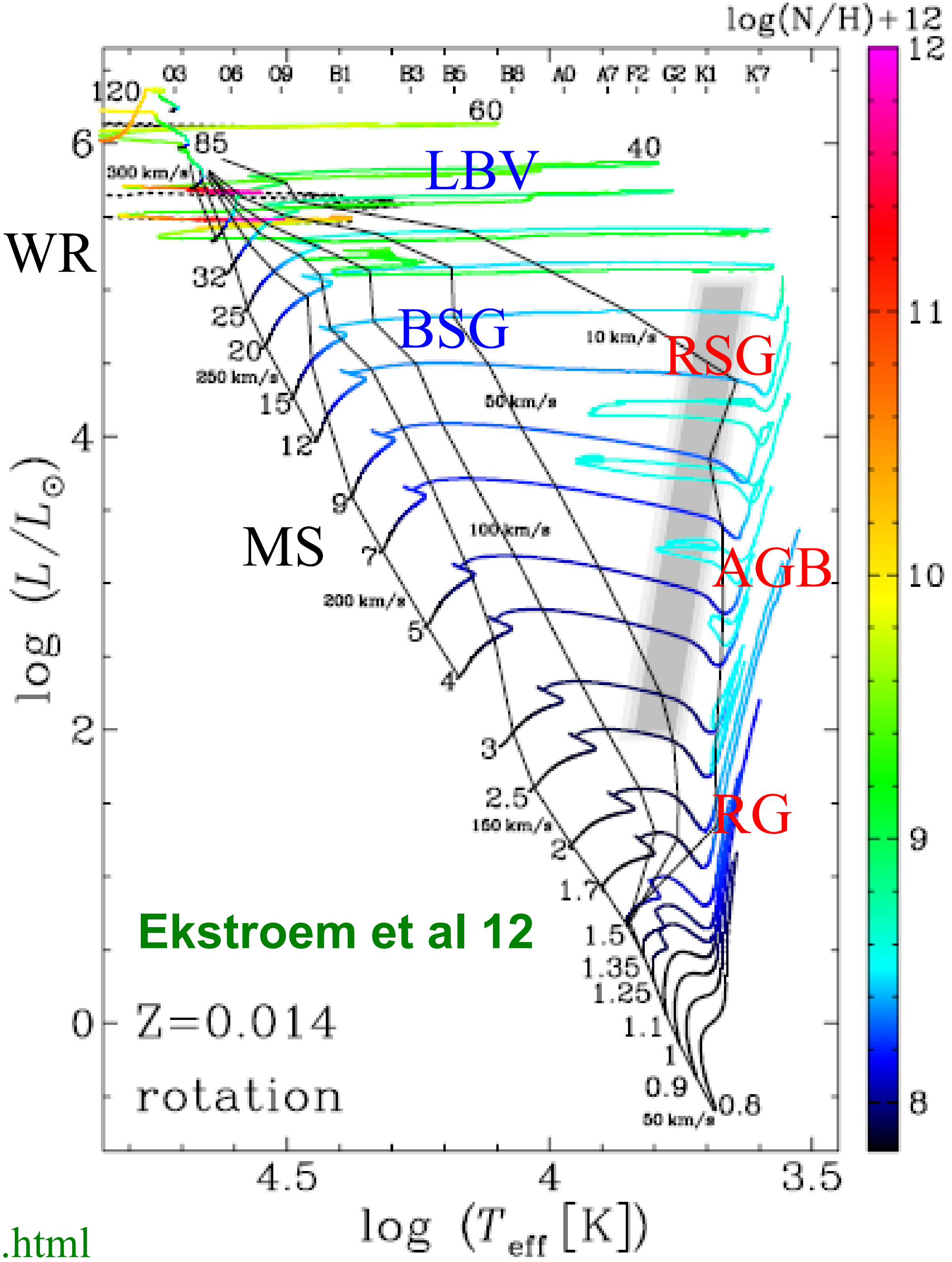
Wolf-Rayet (WR): $M > 20\text{-}25\ M_o$

WR without RSG: $M > 40\ M_o$

Advanced stages: C,Ne,O,Si

→ iron core → SN/NS/BH

http://www.astro.keele.ac.uk/~hirschi/animation/anim.html



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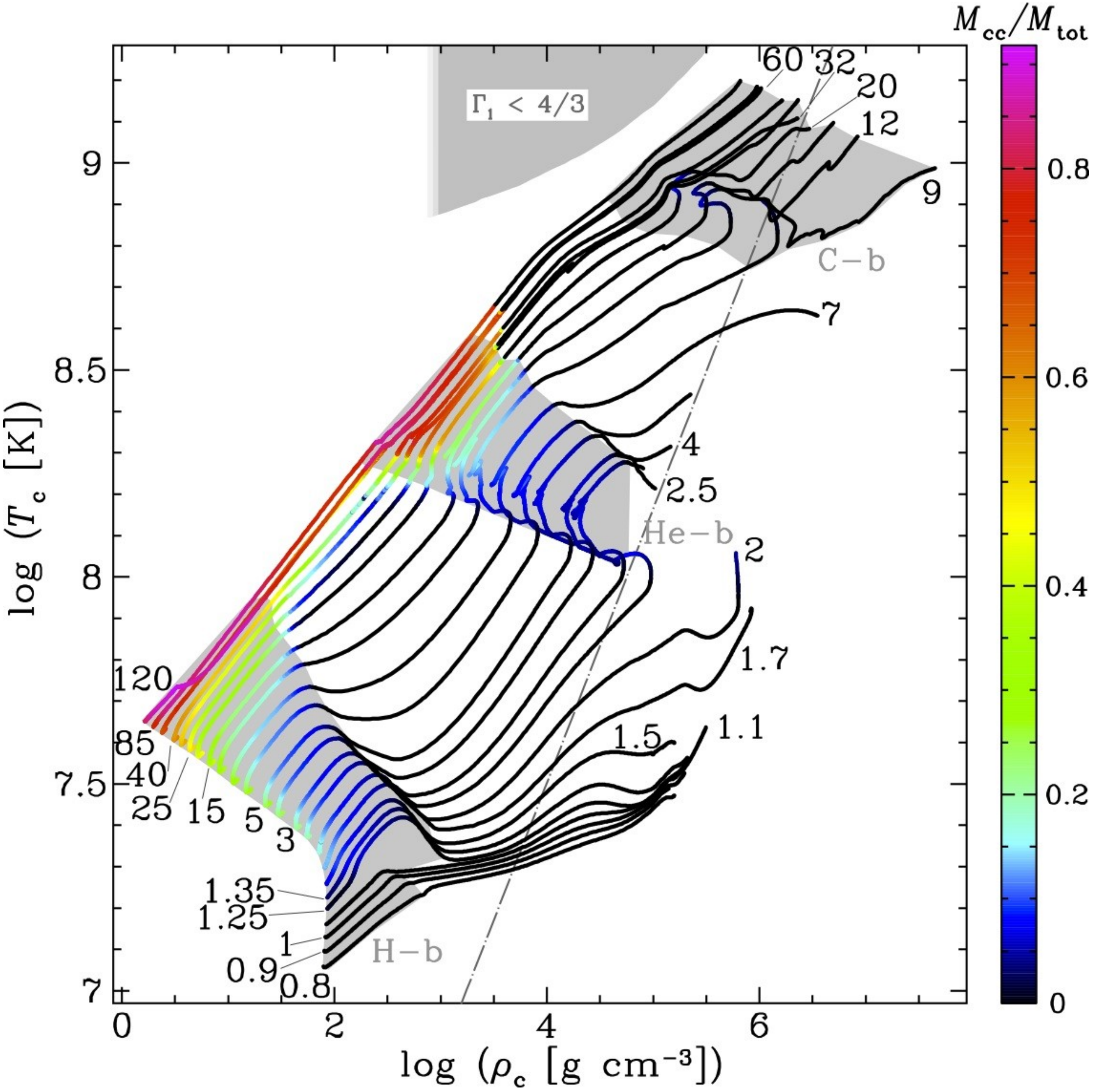
Animations

http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

Central Temperature vs Central Density Diagram

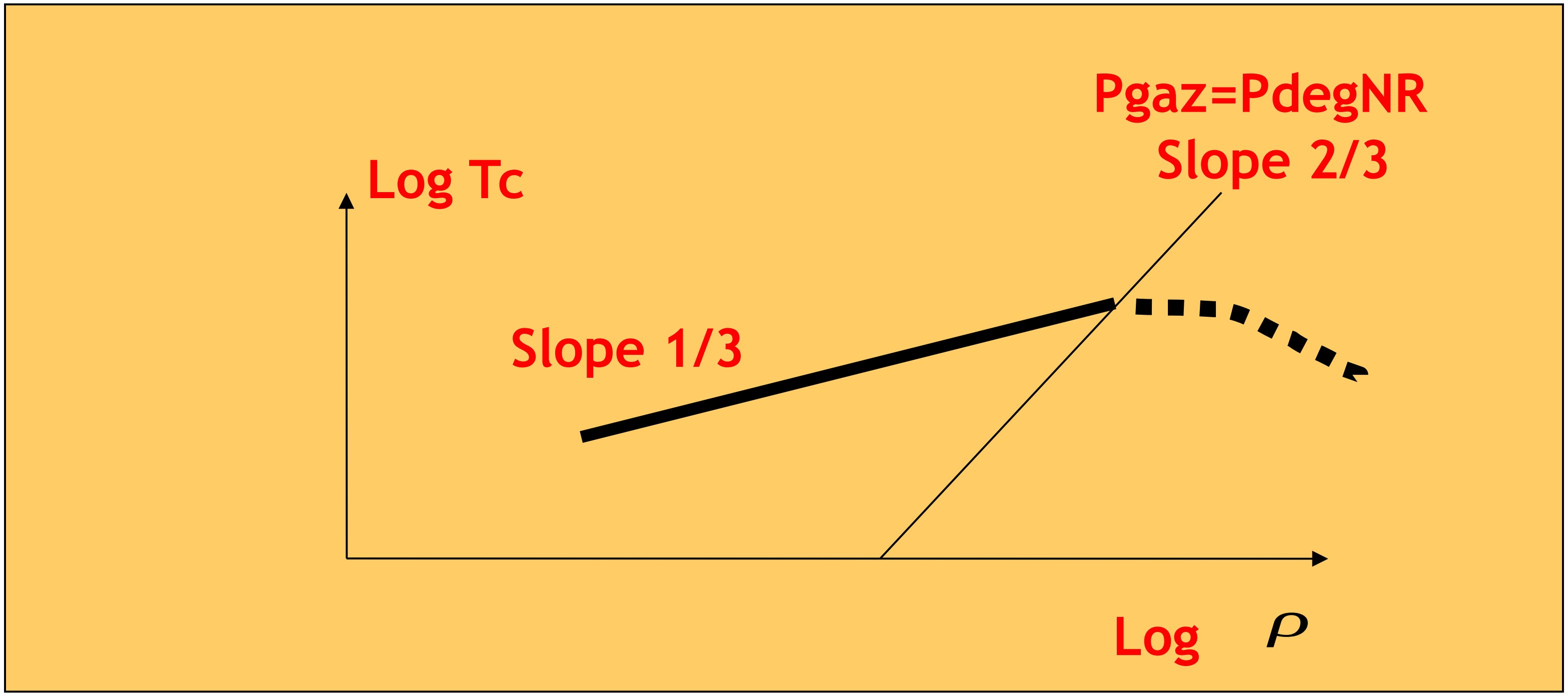
Evolution of central properties

What is the slope of the evolutionary tracks?



Ekstroem et al 12

Evolution of the temperature and density at the centre



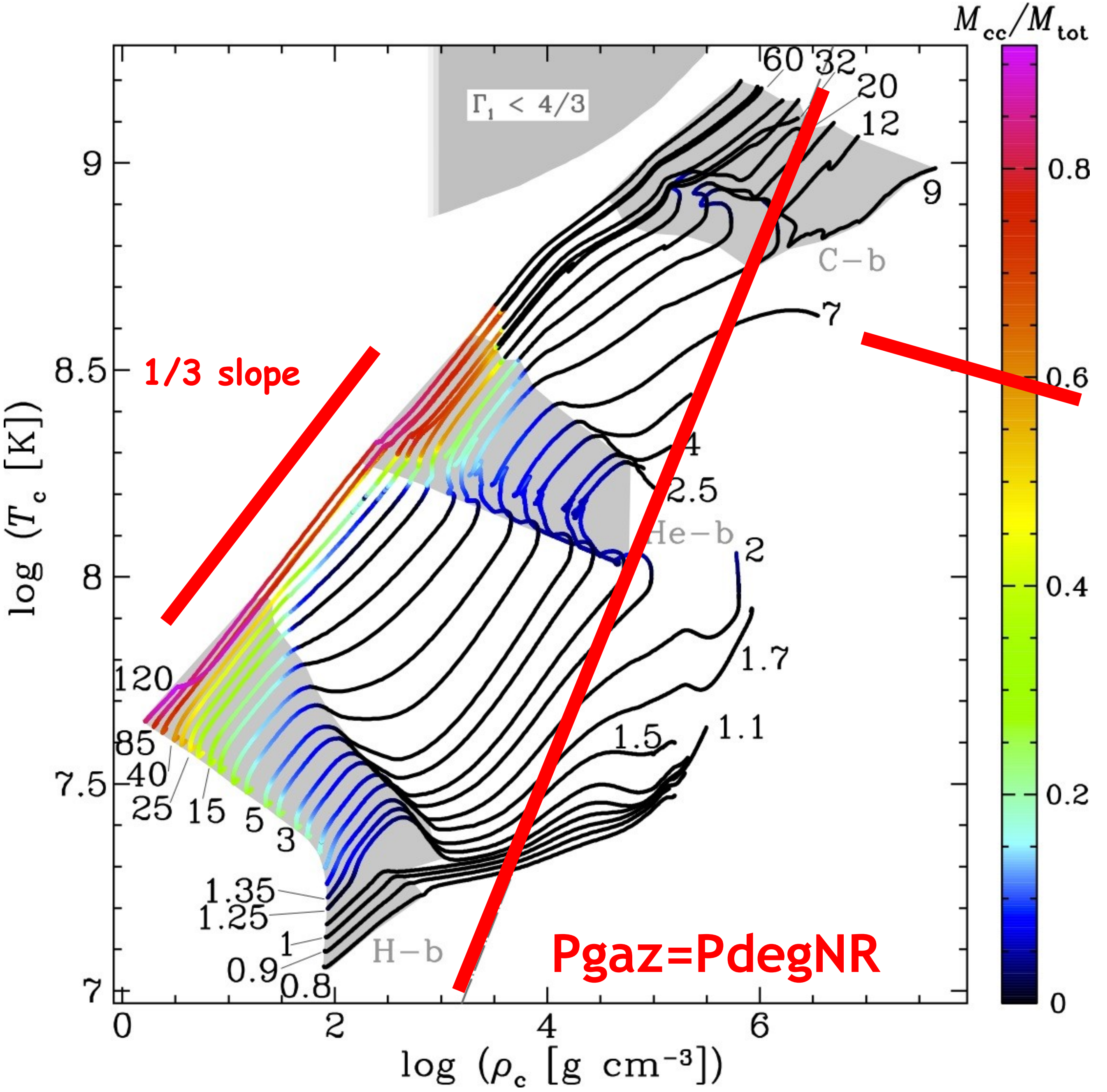
Pgaz=PdegNR

$$\frac{k}{\mu m_H}\rho T = K_1\left(\frac{\rho}{\mu e}\right)^{5/3} \quad \rightarrow T = K_1 \frac{\mu m_H}{k}\frac{1}{\mu_e^{5/3}}\rho^{2/3}$$

Non → Degenerate Conditions

Evolution of central

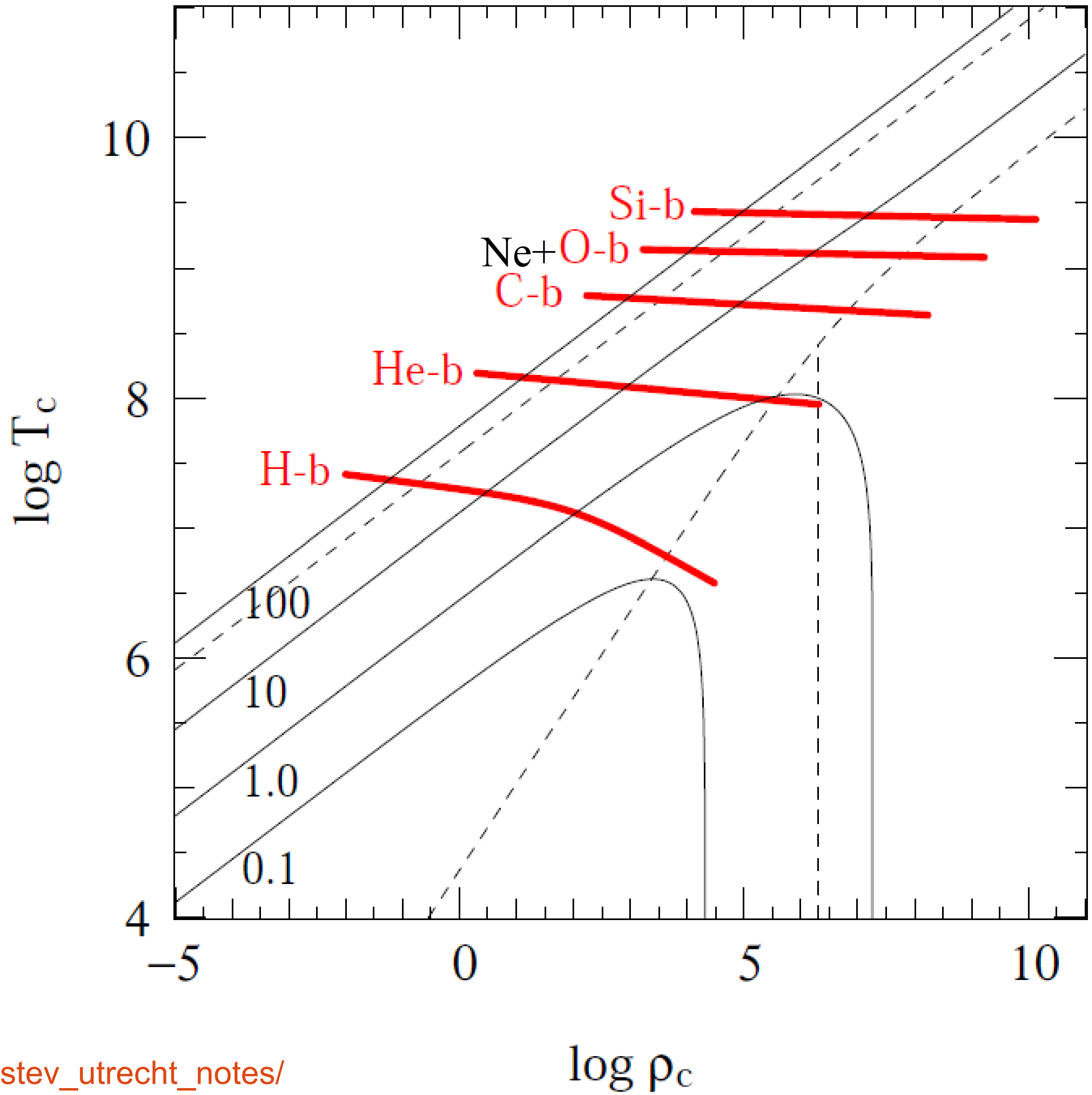
properties



Ekström et al. (2012)
A&A, 537, A146)

Mass Domains

$$\epsilon_{\rm nuc} = \epsilon_0\, \rho^{\lambda}\, T^{\nu}$$



Lecture notes from O. Pols taken from:
http://www.astro.ru.nl/~onnop/education/stev_utrecht_notes/

Mass Domains

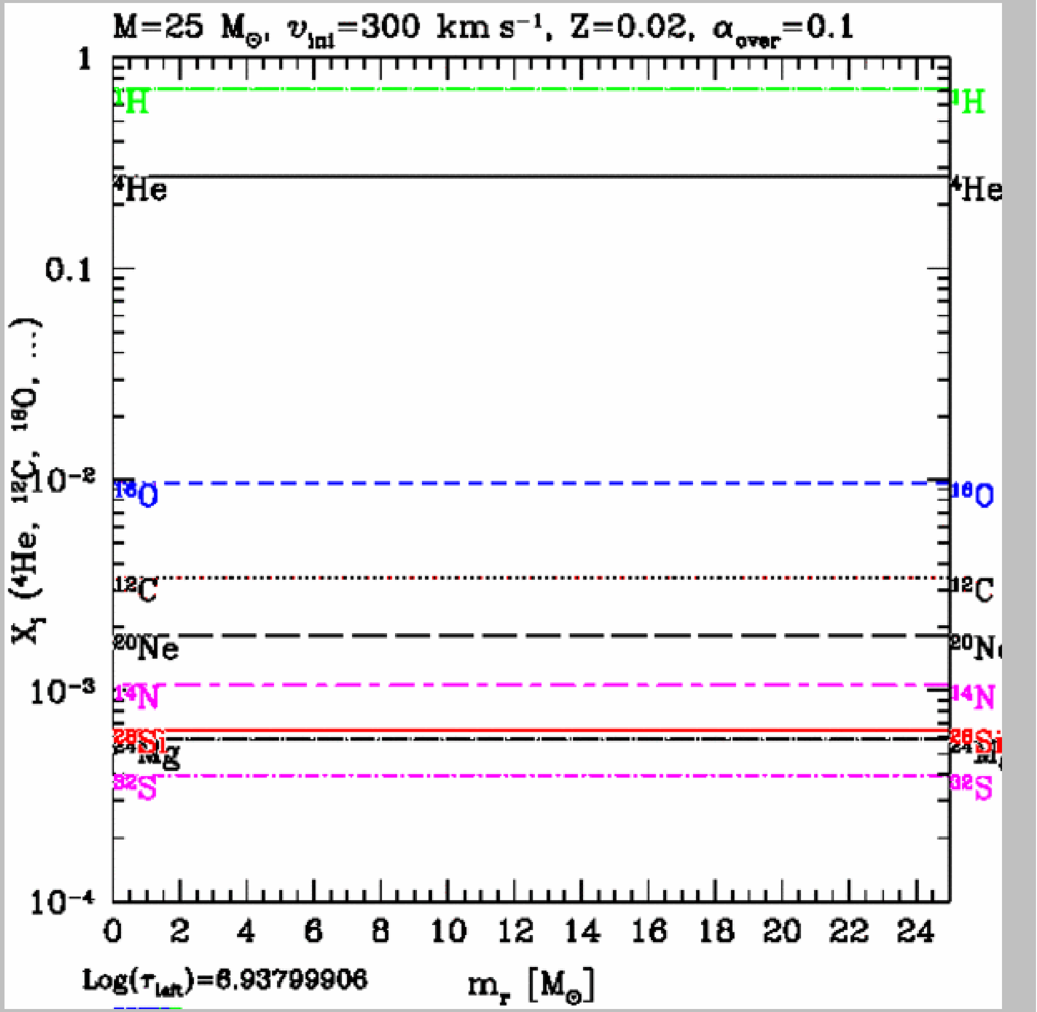
Stars: radiate energy produced internally & are bound by their own gravity

- 0.08 M_{sun} inferior mass limit for core H-burning : Brown Dwarfs
- 0.08 M_{sun} – 0.5M_{sun}: H burning OK, degenerate before core He-burning (lifetime > Hubble time→ no He white dwarf from single stars)
- 0.5-7M_{sun}: core H OK, core He OK (He-flash below 1.8 M_{sun}), degenerate CO white dwarf
- 7-9 M_{sun}: Core C burning OK→ WD(?) or Complete destruction (?) or collapse through electron captures (?)

- 9 - 150 M_{sun}: core H, He, C, Ne, O, Si-→ Fe cores
- 150-250 M_{sun}: Pair Creation/instability Supernovae

Massive Stars: Evolution of the chemical composition

Burning stages (lifetime [yr]):



Hydrogen ($10^{6\text{-}7}$): ^{1}H → ^{4}He

& ^{12}C, ^{16}O → ^{14}N

Helium ($10^{5\text{-}6}$): ^{4}He → ^{12}C, ^{16}O

& ^{14}N → ^{18}O → ^{22}Ne

Carbon ($10^{2\text{-}3}$): ^{12}C → ^{20}Ne, ^{24}Mg

Neon (0.1-1): ^{20}Ne → ^{16}O, ^{24}Mg

Oxygen (0.1-1): ^{16}O → ^{28}Si, ^{32}S

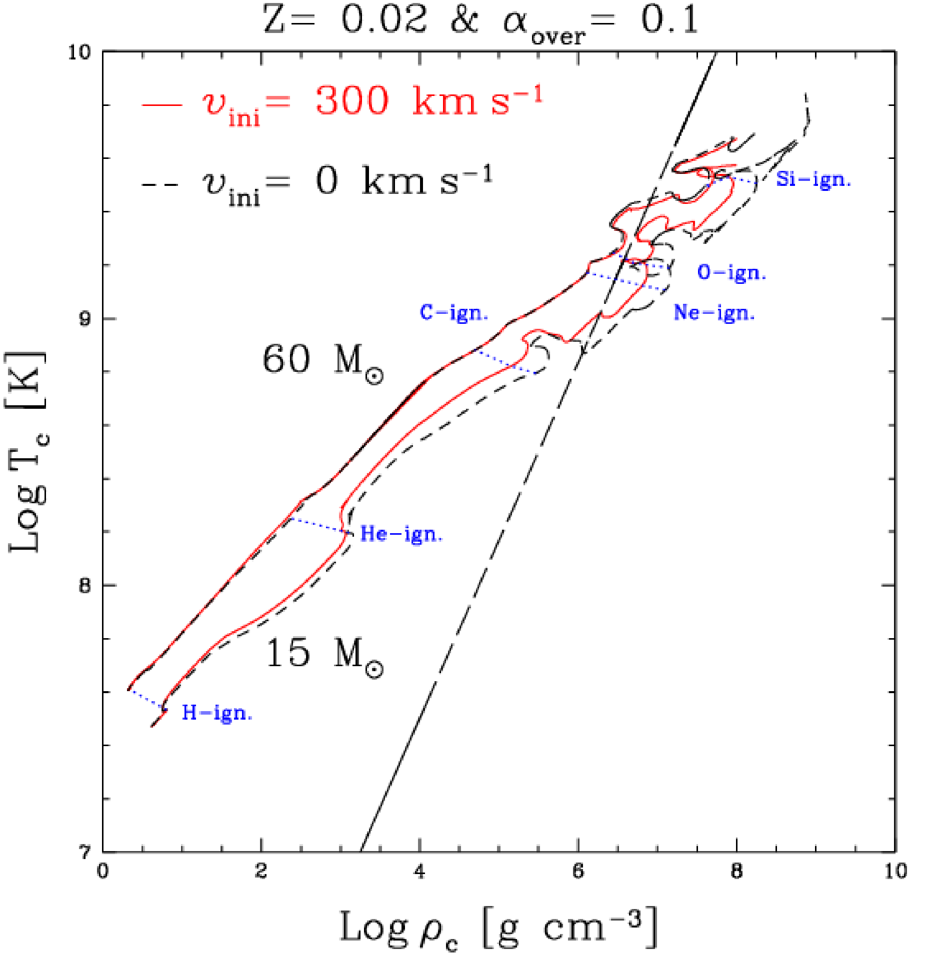
Silicon (10^{-3}): ^{28}Si, ^{32}S → ^{56}Ni

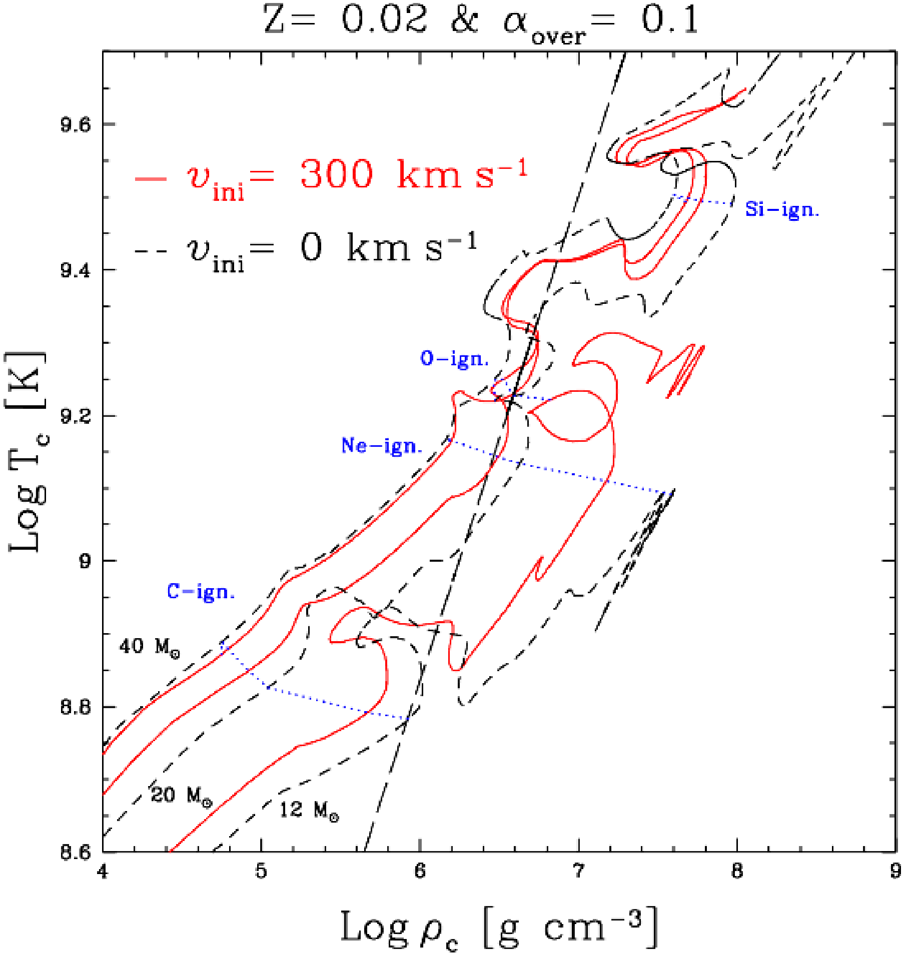
http://www.astro.keele.ac.uk/~hirschi/animation/anim.html

Massive Stars

M<~20 M_o : Rotational mixing dominates → bigger cores

M>~30 M_o : mass loss dominates → ~ or smaller cores





CO-core mass & C/O ratio: key parameters that determine evolution during late stages

Hirschi et al, 2004, A&A, 425, 649

How massive can stars be?

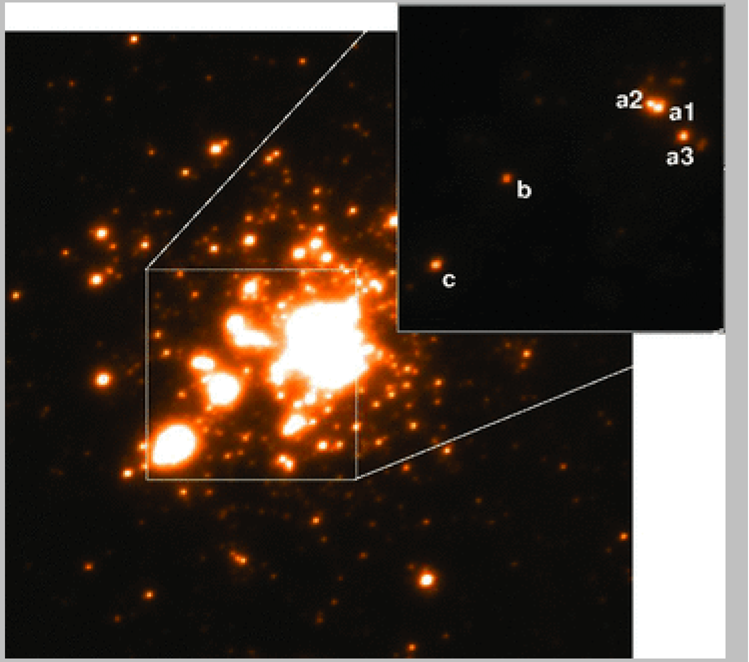
Do very massive stars (VMS: $M>100M_o$) exist?

Very Massive Stars in the Local Universe, 2014, Springer, Ed. Jorick S. Vink

- Star formation: already difficulties with 30 M_o stars but 2/3D simulations are promising (Kuiper et al 11, Krumholz 2014)
- Stellar evolution: possible up to ~ 1,000 M_o (BUT mass loss/rad.) (Baraffe et al 01)

Can we see them?

- Rare and short-lived
- Need to look at youngest and most massive clusters:
    - Arches: M<~150 Mo (Figer 05, Martins et al 08)
    - NGC 3603 & R136: new **M_{max}=320M_o!** **(Crowther et al 10, MNRAS)**



R136 cluster

Mass Loss: Types, Driving & Recipes

Mass loss driving mechanism and prescriptions for different stages:

- O-type & “LBV” stars (bi-stab.): line-driven Vink et al 2000, 2001
- WR stars (clumping effect): line-driven Nugis & Lamers 2000, Gräfener & Hamann (2008)
- RSG: Pulsation/dust? de Jager et al 1988
- RG: Pulsation/dust? Reimers 1975,78, with η=~0.5
- AGB: Super winds? Dust Bloecker et al 1995, with η=~0.05
- LBV eruptions: continuous driven winds? Owocki et al
- …

What changes at low Z?

- Stars are more compact: $R \sim R(Z_o)/4$ (lower opacities) at $Z=10^{-8}$
- Rotation at low Z: stronger shear, weaker mer. circ.
- Mass loss weaker at low Z: → faster rotation

$$\dot{M}(Z)=\dot{M}(Z_0)(Z/Z_0)^{\alpha}$$

- α = 0.5-0.6 (Kudritzki & Puls 00, Ku02)

(Nugis & Lamers, Evans et al 05)

- α = 0.7-0.86 (Vink et al 00,01,05)

$Z(LMC) \sim Z_o/2.3$ => Mdot/1.5 – Mdot/2

$Z(SMC) \sim Z_o/7$ => Mdot/2.6 - Mdot/5

Mass loss at low Z still possible?

RSG (and LBV?): no Z-dep.; CNO? (Van Loon 05, Owocky et al)

Mechanical mass loss ← critical rotation/ Eddington limit

(e.g. Hirschi 2007, Ekstroem et al 2008, Yoon et al 2012)

The fate of VMS: PCSN/BH/CCSN?

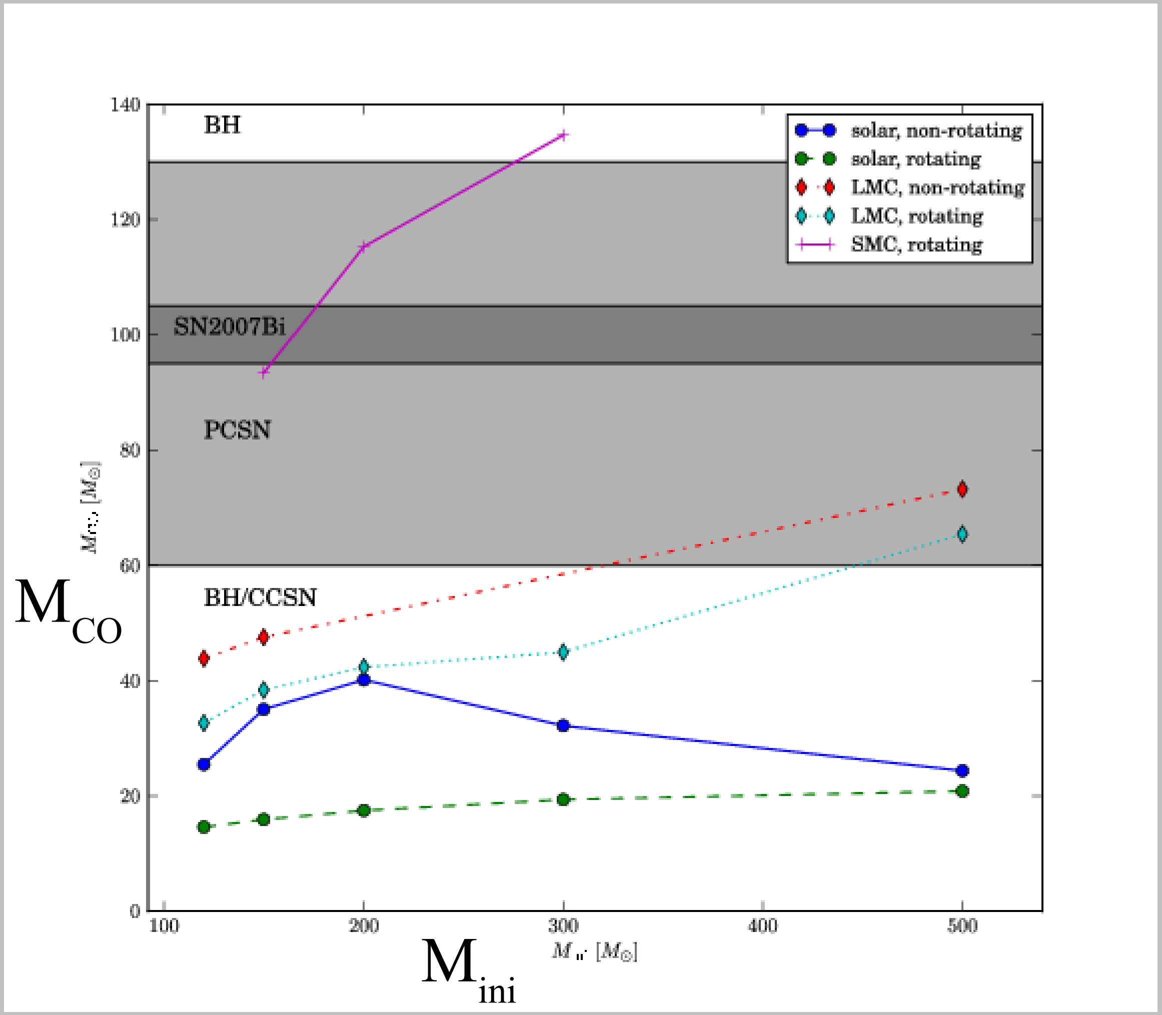
(Yusof et al 13 MNRAS, aph1305.2099)

Z_{solar}: no PCSN

(Rotating) models with Z<Z(LMC) lose less mass,

and enter the PCSN instability region!

BUT mass loss uncertain!



PCSN range from Heger & Woosley (2002)

Consistent with Langer et al (2007): PCSN for $Z<Z_\odot/3$

Key Open Questions Concerning Mass Loss

- Mass loss in cool parts of HRD: LBV & RSG, especially at low Z
- Position in & evolution across HRD: effects of rotation-induced mixing, feedback from mass loss Yusof et al 13, Langer 07, Sanyal et al 15, Kohler et al 15...
- **Mass loss near Eddington limit** Graefener & Hamann 08, Vink et al 11, ...
- Importance of clumping, porosity, inflation Fullerton et al 06, Graefener et al. 12, Vink et al, ...
- Which stars may explode in the LBV phase? Smith et al 11, ... ,Vink et al, ...
- Look of WR stars: radius, spectra Graefener et al. 2012, Groh et al 2013-...
- Additional mass loss mechanisms? Critical rotation at low Z? Shell mergers in late phases of evolution? ... Hirschi 2007, Meynet et al 2006, … , Smith & Arnett 2014, ...

- …

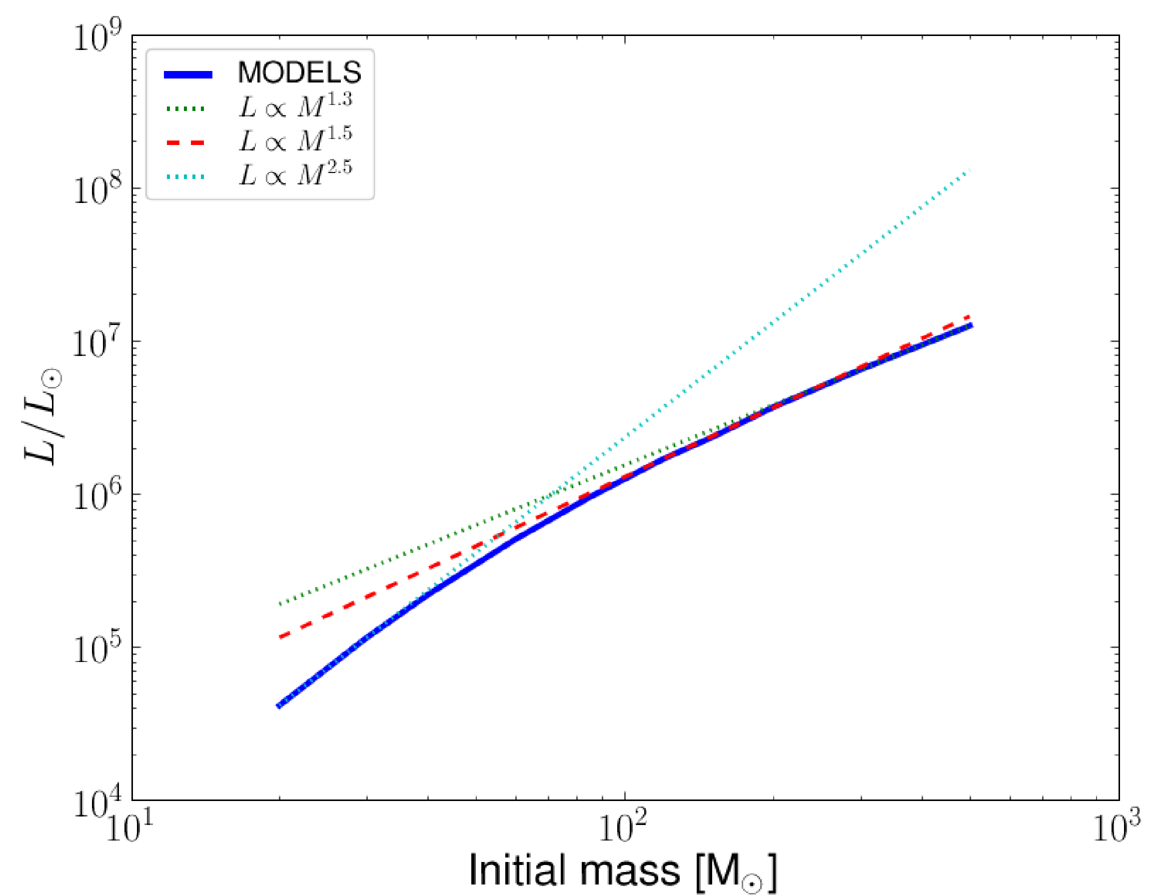
Very Massive Stars are Very Luminous (~10^7 $L_\odot$)

R136a1 ($10^7 L_\odot$) alone supplies 7% of the ionizing flux of the entire 30 Doradus region!

What is the shape of the luminosity vs mass relation in this mass range?

Textbooks: $L \sim M^3$ for stars in the solar mass range

Above 100 M_o: $L \sim M^{1.5}$



Yusof et al 13 MNRAS, aph1305.2099

Very Massive Stars, $M > 100\ M_{sun}$

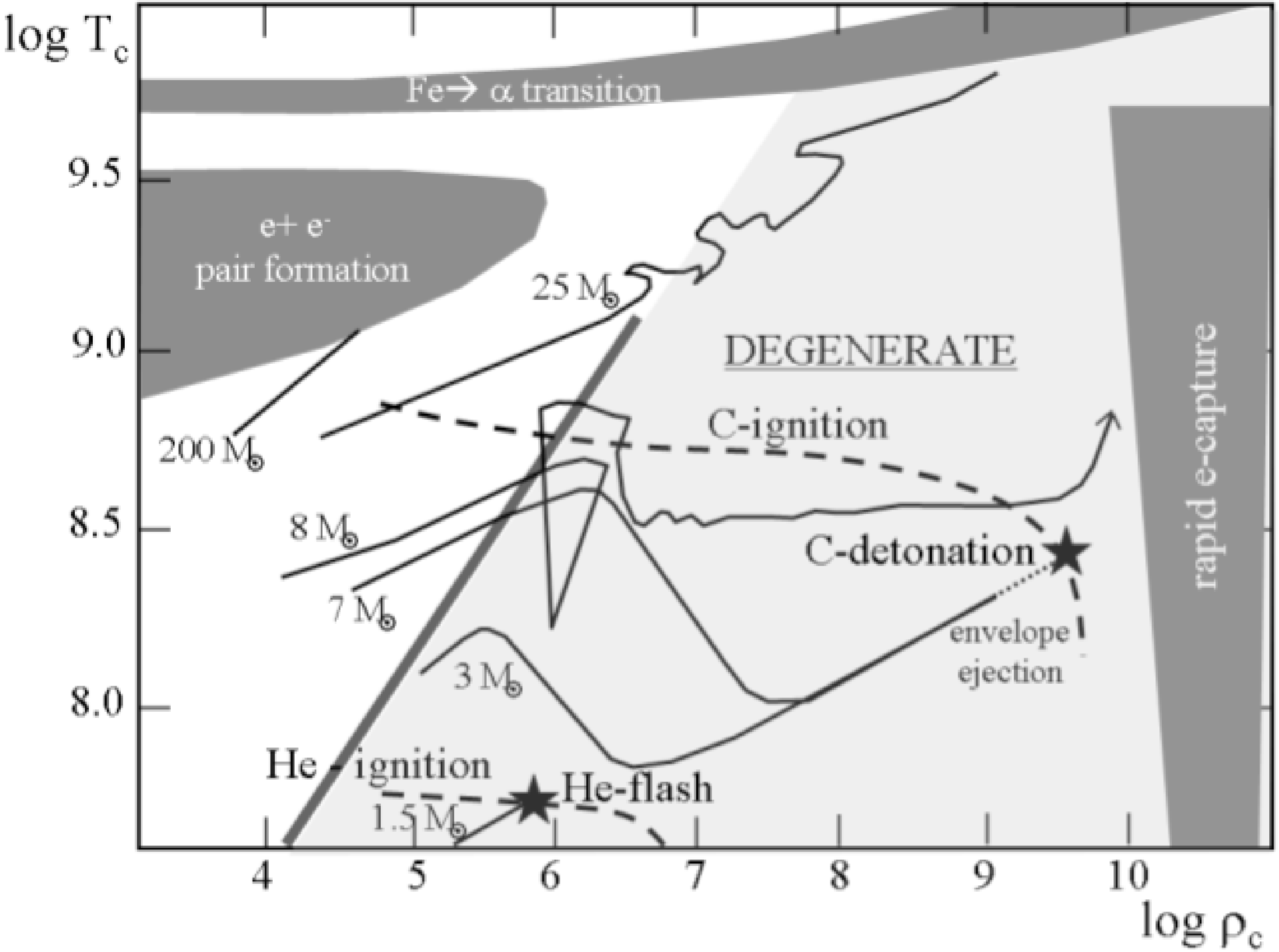
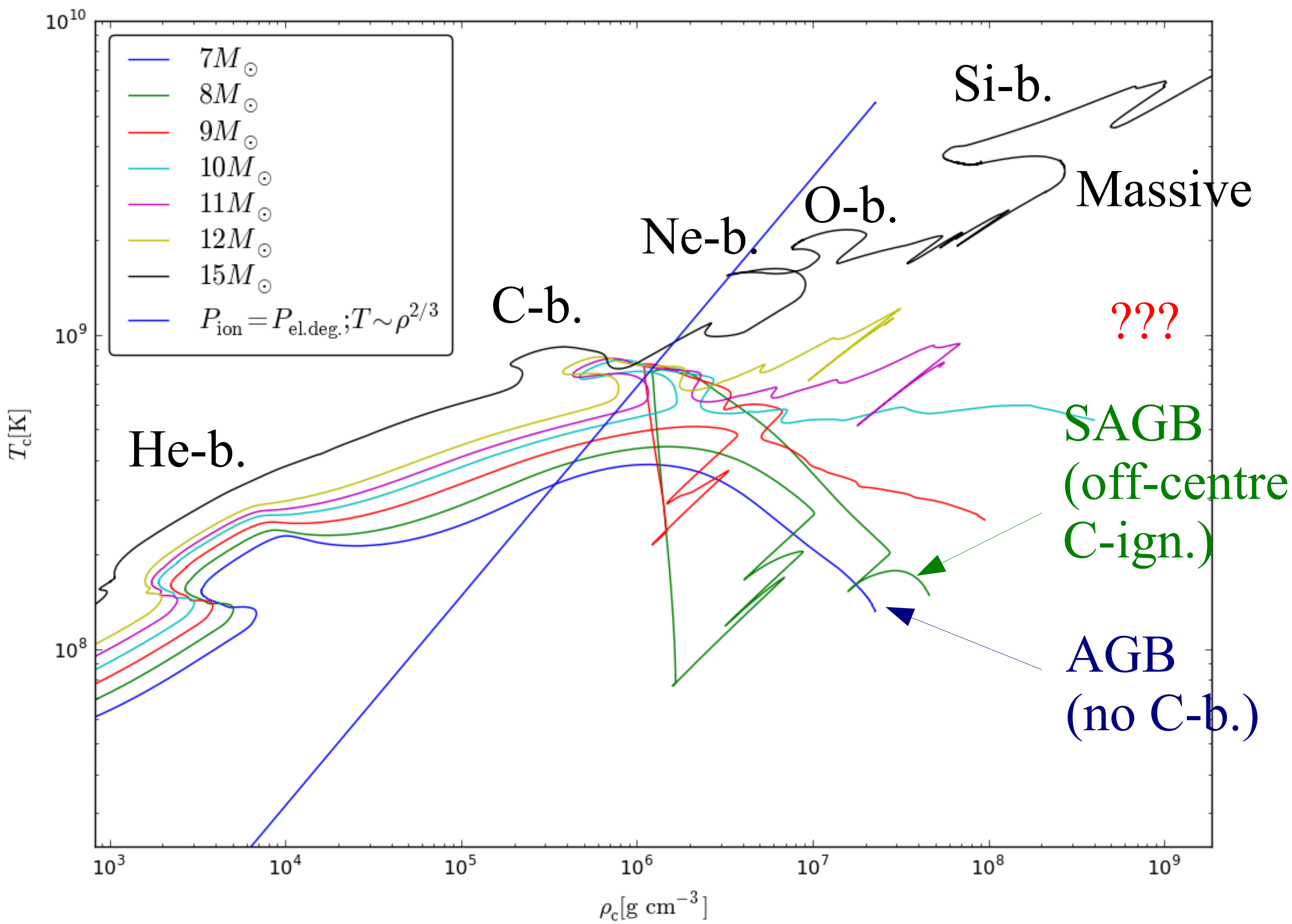


Fig. 26.10. Evolution of central conditions for different masses with indications of instability domains (Sect. 7.8), the Fe–α transition indicates the photodesintegration of Fe nuclei into α particles. The degenerate region is light gray. Dashed lines show the place where nuclear energy generation rates balance neutrino losses. Adapted from T.J. Mazurek and J.C. Wheeler [401]

Massive/AGB Stars Transition

7-15 M_o models ← MESA stellar evolution code: http://mesa.sourceforge.net/

Paxton et al 10

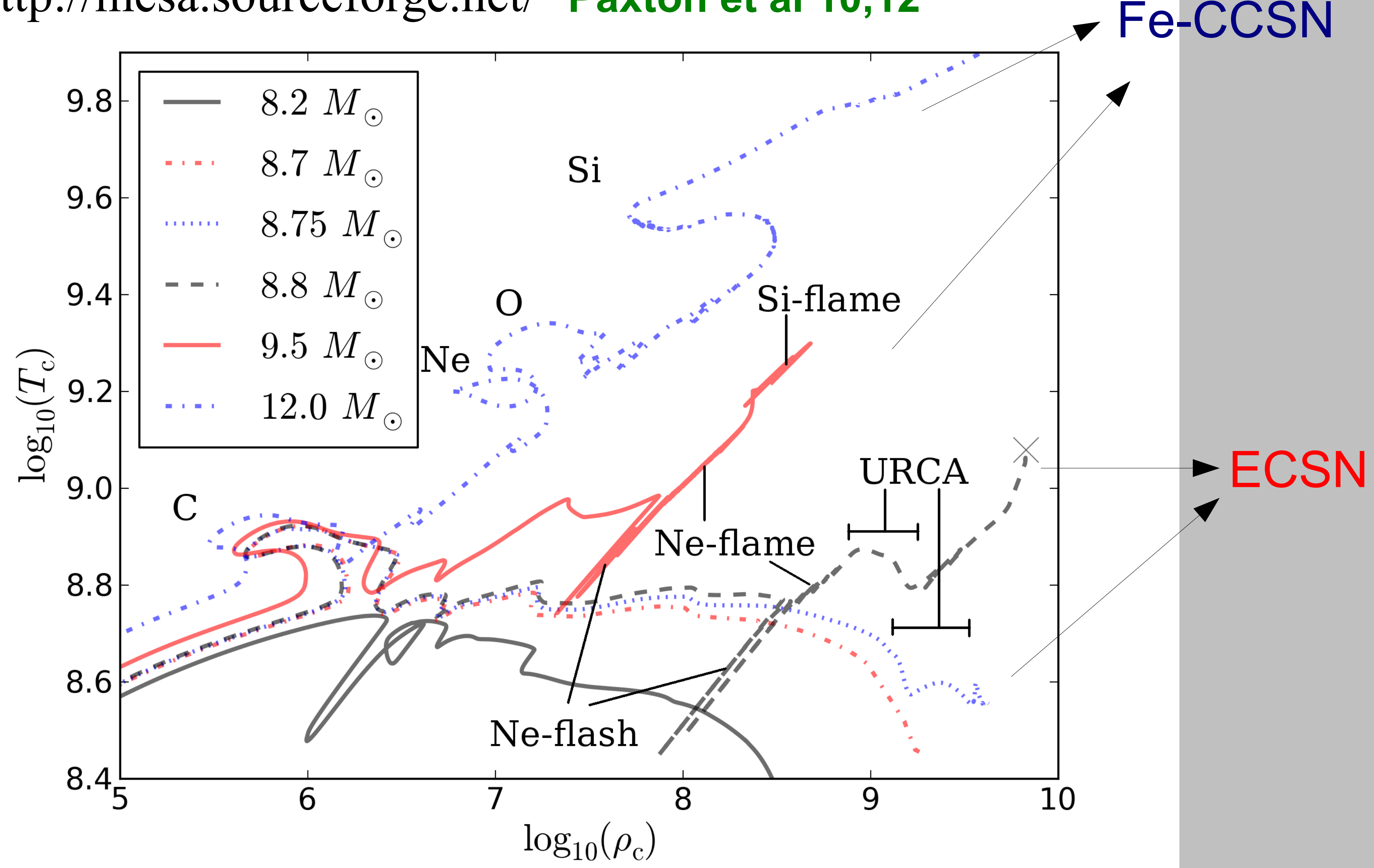


Jones et al 2013; Takahashi et al 13;see also Mueller et al 12, Umeda et al 12

Fate of Least-Massive MS: ECSN/Fe-CCSN?

7-15 M_o models ← MESA stellar evolution code:

http://mesa.sourceforge.net/ **Paxton et al 10,12**

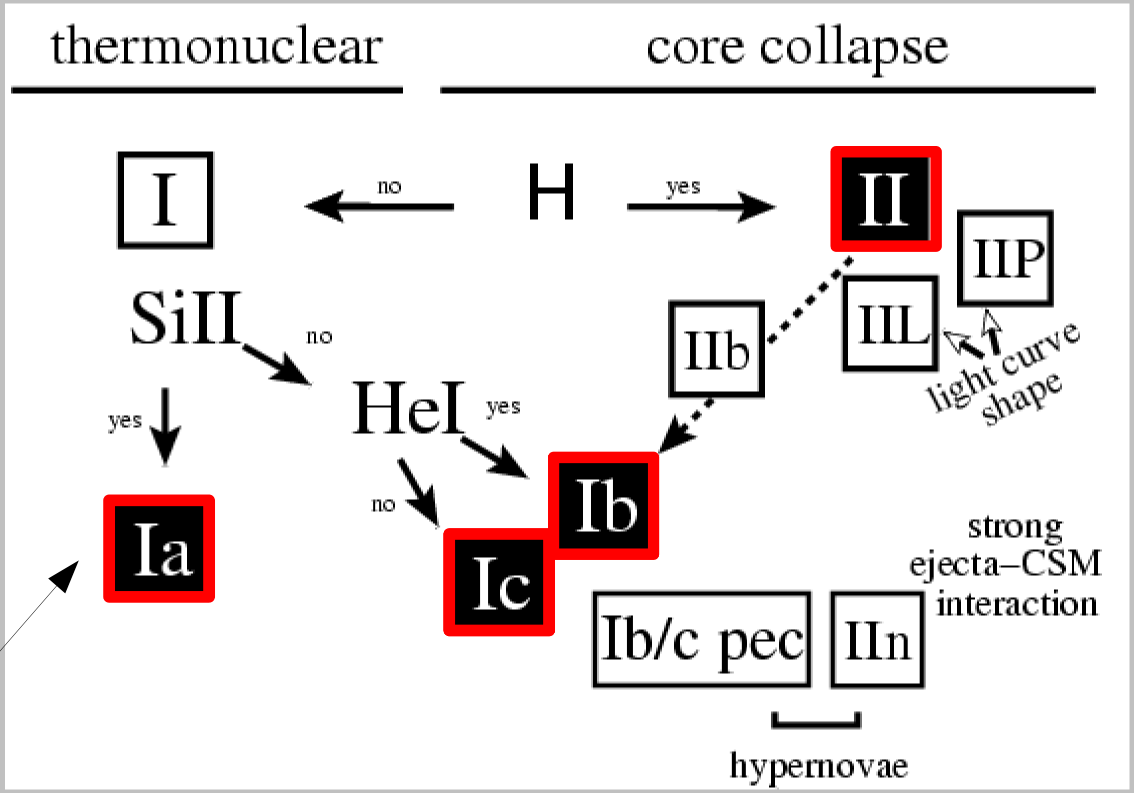


Both SAGB and failed massive stars may produce ECSN

Samuel W Jones et al. (2013), ApJ 772, 150

Supernova Explosion Types

Massive stars: → SN II (H envelope),
Ib (no H), Ic (no H & He) ← WR

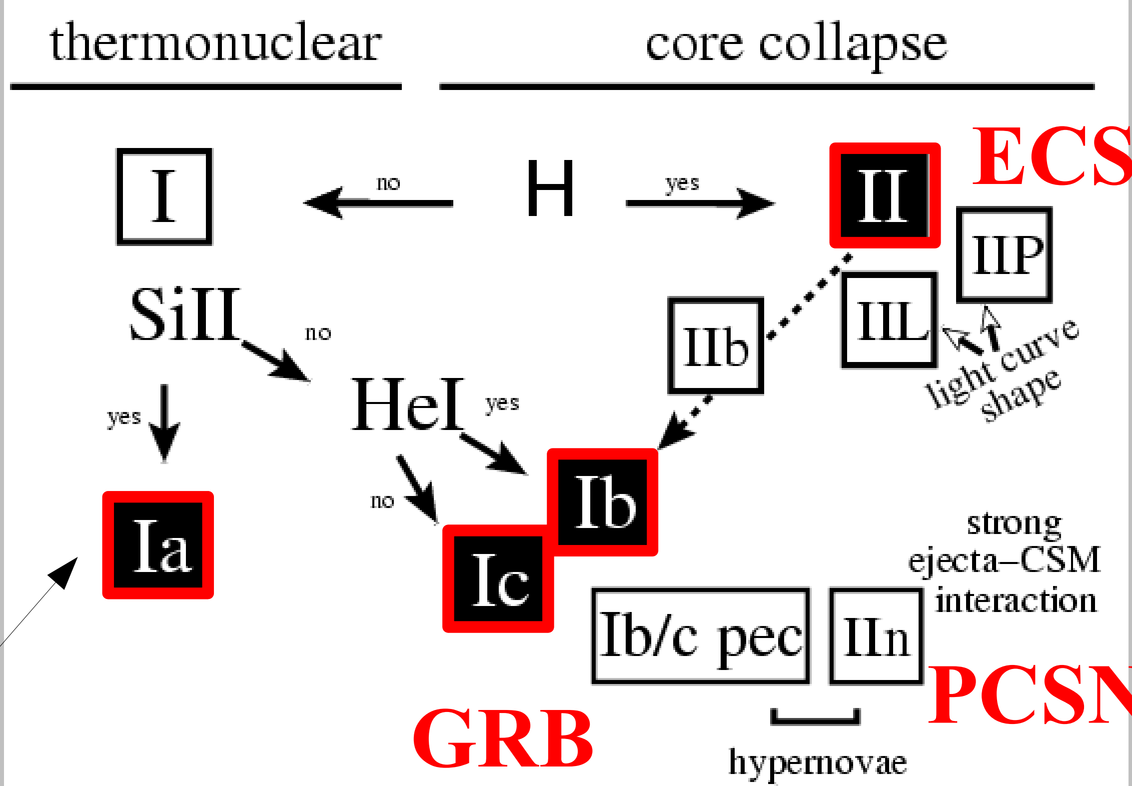


White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

(Turatto 03)

Supernova Explosion Types

Massive stars: → SN II (H envelope),
Ib (no H), Ic (no H & He) ← WR



ECSN?

GRB

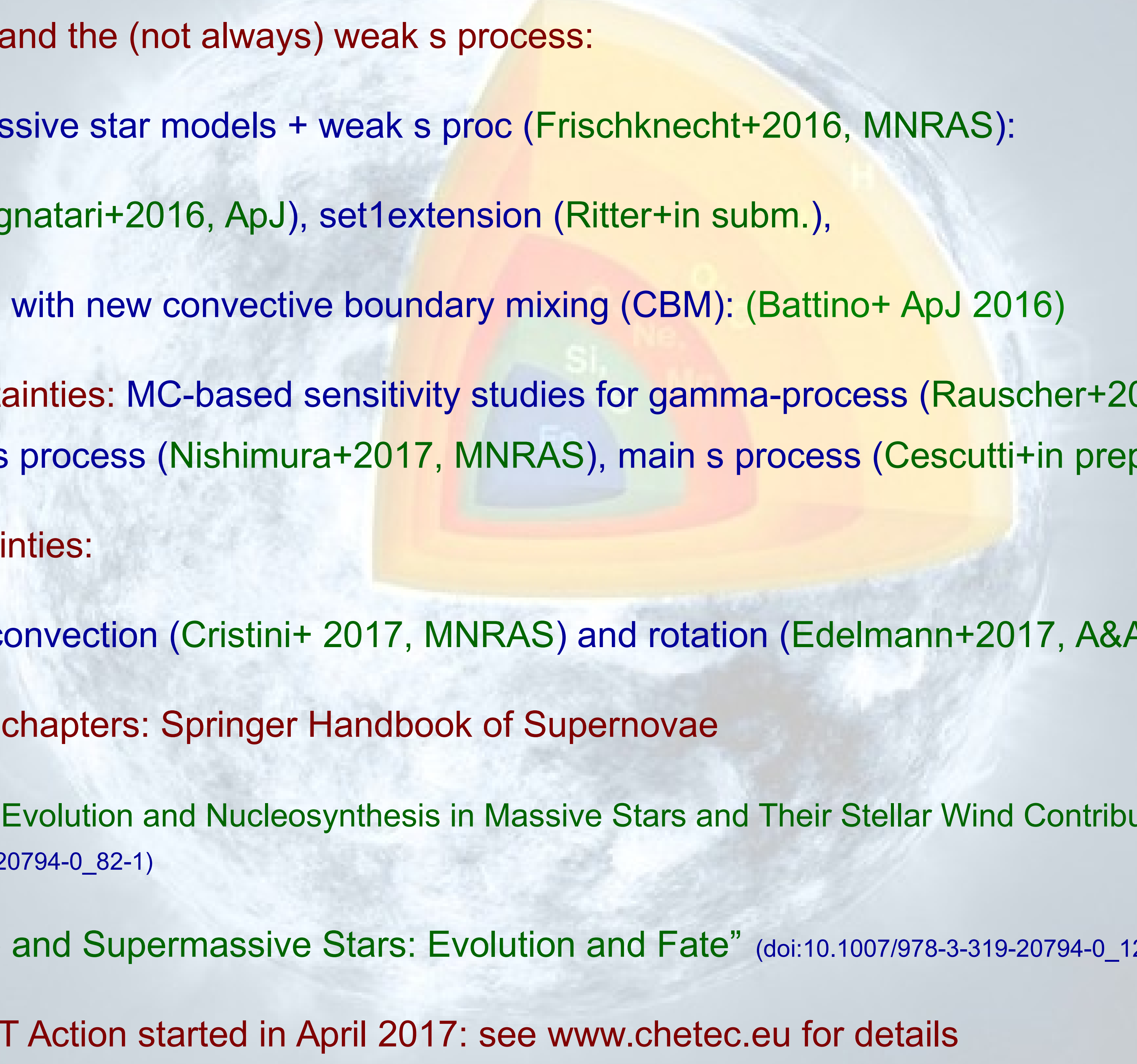
PCSN(=PISN)?

(Turatto 03)

(Hirschi+05
Woosley+06
Yoon+06, ...)

White dwarfs (WD):
in binary systems
Accretion →
Chandrasekhar
mass → SN Ia

Recent work



- Massive stars and the (not always) weak s process:

Large grid of massive star models + weak s proc (Frischknecht+2016, MNRAS):

Nugrid: set 1 (Pignatari+2016, ApJ), set1extension (Ritter+in subm.),

(main) s process with new convective boundary mixing (CBM): (Battino+ ApJ 2016)

- Nuclear uncertainties: MC-based sensitivity studies for gamma-process (Rauscher+2016, MNRAS), weak s process (Nishimura+2017, MNRAS), main s process (Cescutti+in prep)

- Stellar uncertainties:

Multi-D tests of convection (Cristini+ 2017, MNRAS) and rotation (Edelmann+2017, A&A)

- Reviews/book chapters: Springer Handbook of Supernovae

“Pre-supernova Evolution and Nucleosynthesis in Massive Stars and Their Stellar Wind Contribution” (doi:10.1007/978-3-319-20794-0_82-1)

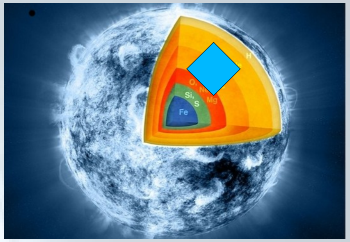
“Very Massive and Supermassive Stars: Evolution and Fate” (doi:10.1007/978-3-319-20794-0_120-1)

- ChETEC COST Action started in April 2017: see www.chetec.eu for details

C-shell Setup & Approximations

- PROMPI code Meakin, Arnett et al 2007-...

- Initial conditions provided by stellar model from GENEC:



$15M_\odot$, non-rotating at solar metallicity (see previous slide)

- “Box in a star” (plane-parallel) simulation using Cartesian co-ordinates

- Parameterised gravitational acceleration and ^{12}C+^{12}C energy generation rate
  (energy rate boosted by a factor of 1000 for parameter study)

- Radiative diffusion neglected

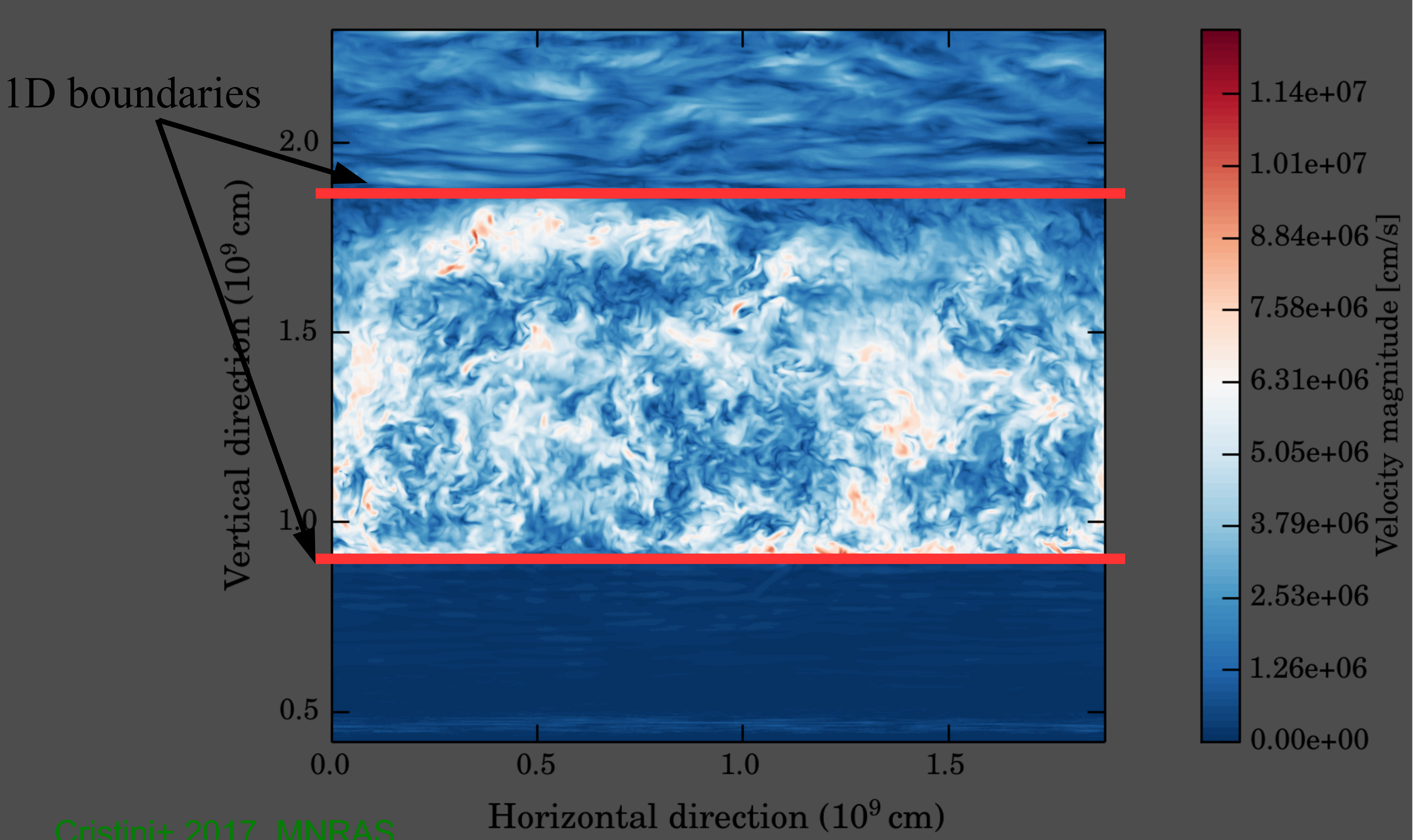
- Turbulence initiated through random low-amplitude perturbations in temperature and density

- Constant abundance of ^{12}C fuel over simulation time

- 4 resolutions: lrez: 128^3, mrez: 256^3, hrez: 512^3, vhrez: 1024^3

3D C-shell Simulations

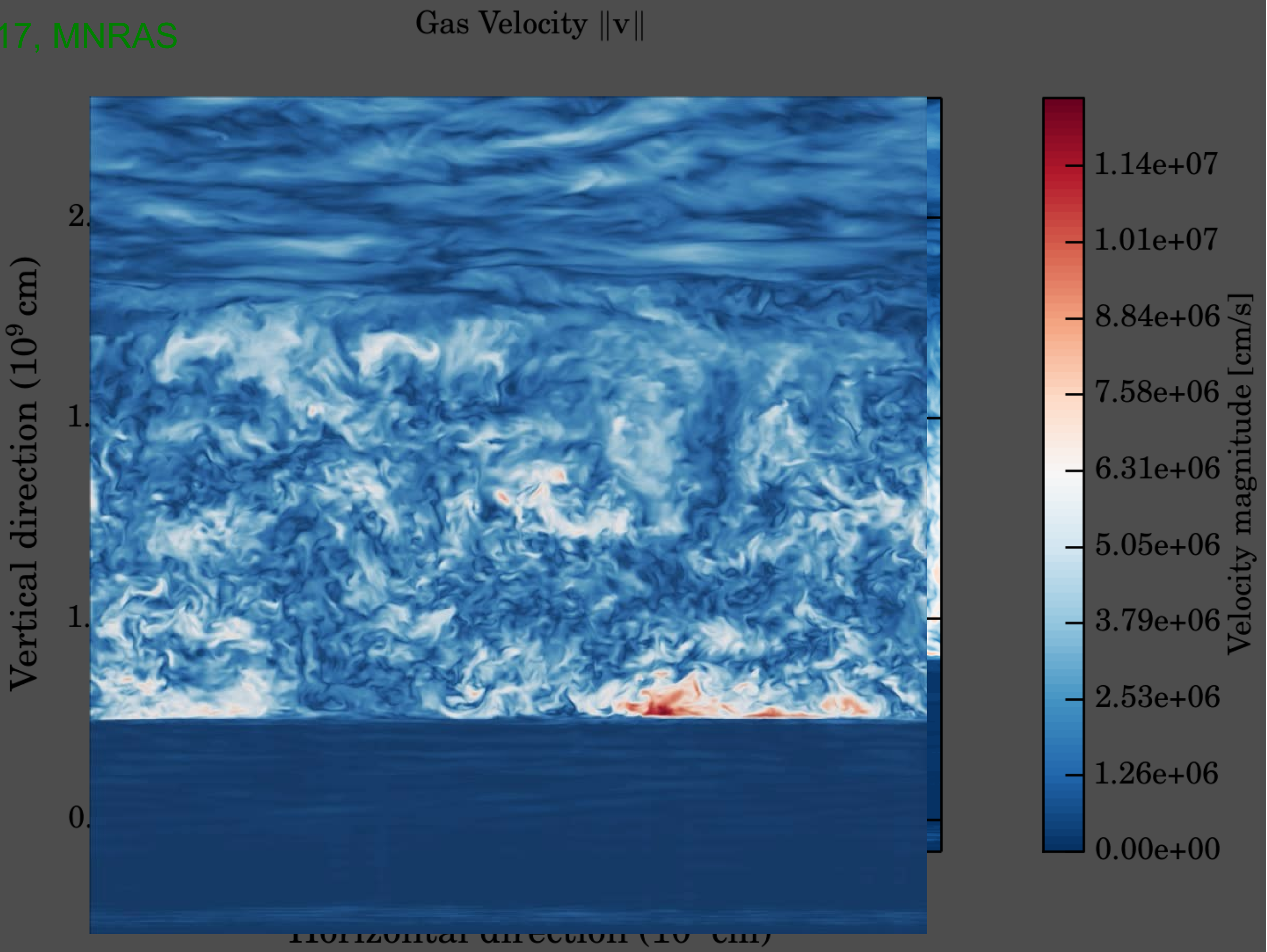
Snapshot from 1024^3 resolution run: Gas Velocity $\|v\|$



Cristini+ 2017, MNRAS

3D C-shell Simulations: $|v|$ movie

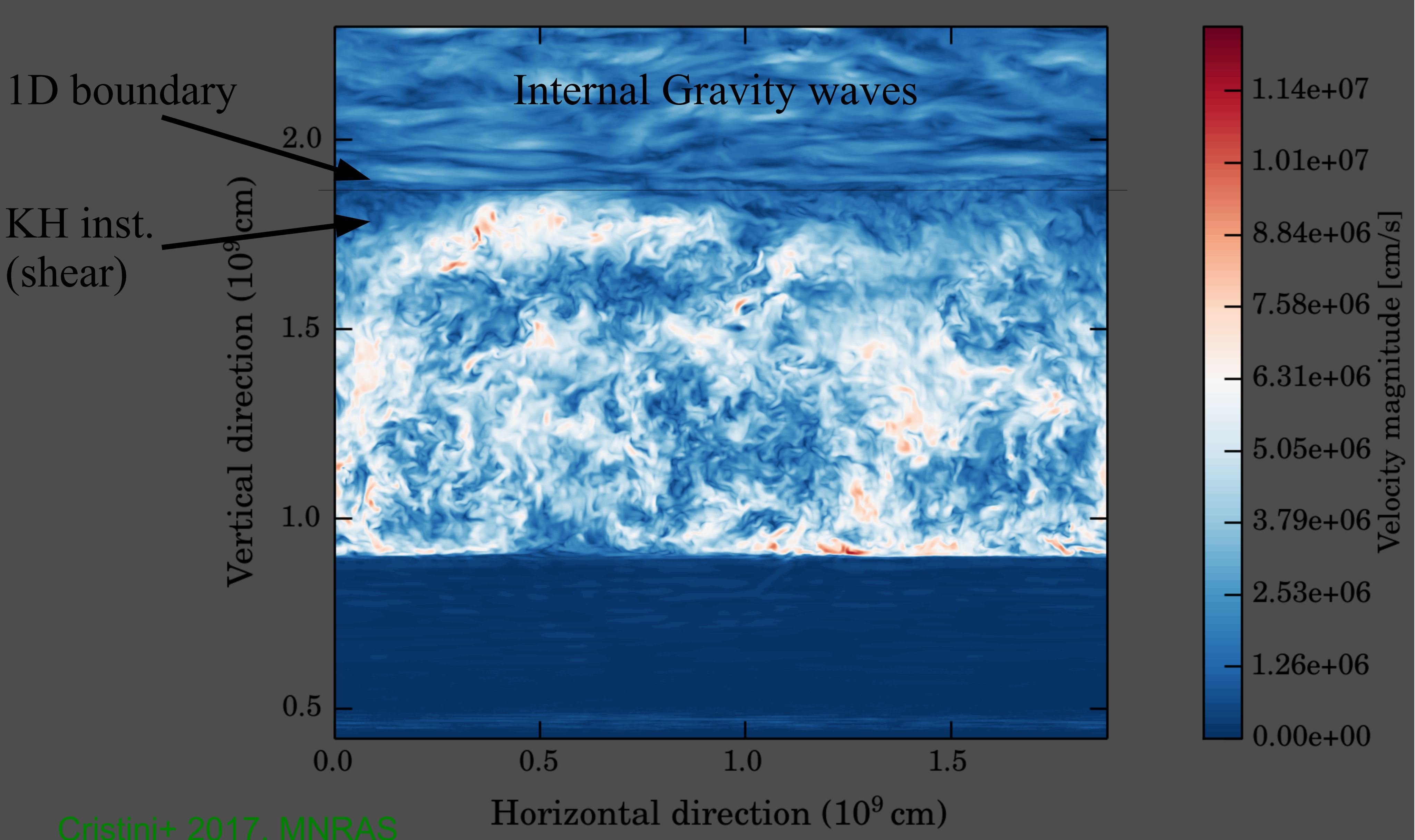
Cristini+ 2017, MNRAS



http://www.astro.keele.ac.uk/shyne/321D/convection-and-convective-boundary-mixing/visualisations

3D C-shell Simulations

Snapshot from 1024^3 resolution run: Gas Velocity $\|\mathbf{v}\|$



Cristini+ 2017, MNRAS