I. Stellar evolution modelling

Sam Jones

STELLAR EVOLUTION

AN OVERVIEW

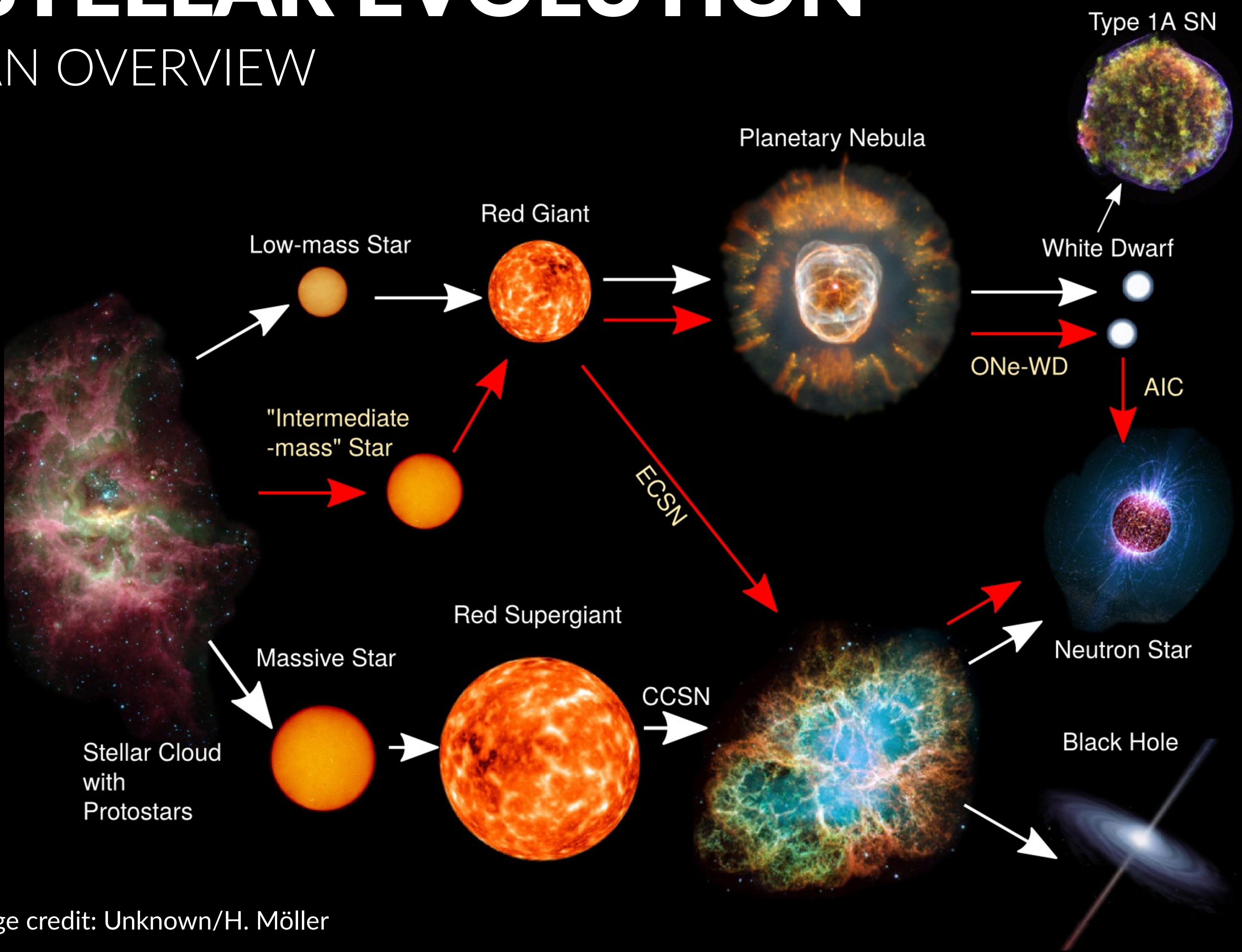
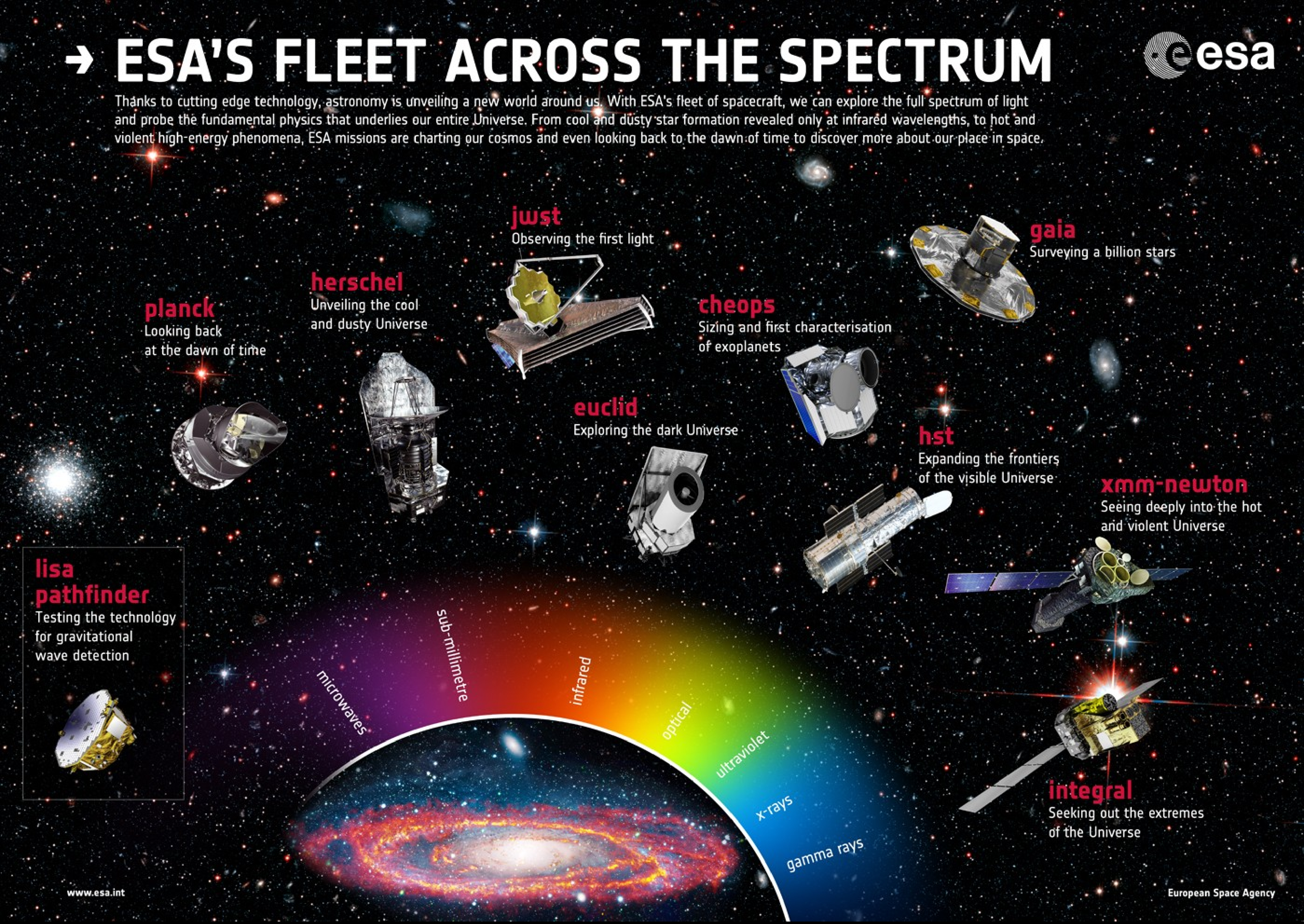


Image credit: Unknown/H. Möller



ESA'S FLEET ACROSS THE SPECTRUM

Thanks to cutting edge technology, astronomy is unveiling a new world around us. With ESA's fleet of spacecraft, we can explore the full spectrum of light and probe the fundamental physics that underlies our entire Universe. From cool and dusty star formation revealed only at infrared wavelengths, to hot and violent high-energy phenomena, ESA missions are charting our cosmos and even looking back to the dawn of time to discover more about our place in space.

planck
Looking back at the dawn of time

herschel
Unveiling the cool and dusty Universe

jwst
Observing the first light

euclid
Exploring the dark Universe

cheops
Sizing and first characterisation of exoplanets

gaia
Surveying a billion stars

hst
Expanding the frontiers of the visible Universe

xmm-newton
Seeing deeply into the hot and violent Universe

integral
Seeking out the extremes of the Universe

lisa pathfinder
Testing the technology for gravitational wave detection

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European Space Agency

(WG5)

ALMA

Image credit: ALMA (ESO/NAOJ/NRAO)/L. Calçada (ESO)/H. Heyer (ESO)/H. Zodet (ESO)

La Scilla

Image credit: ESO/B. Tafreshi

ESO

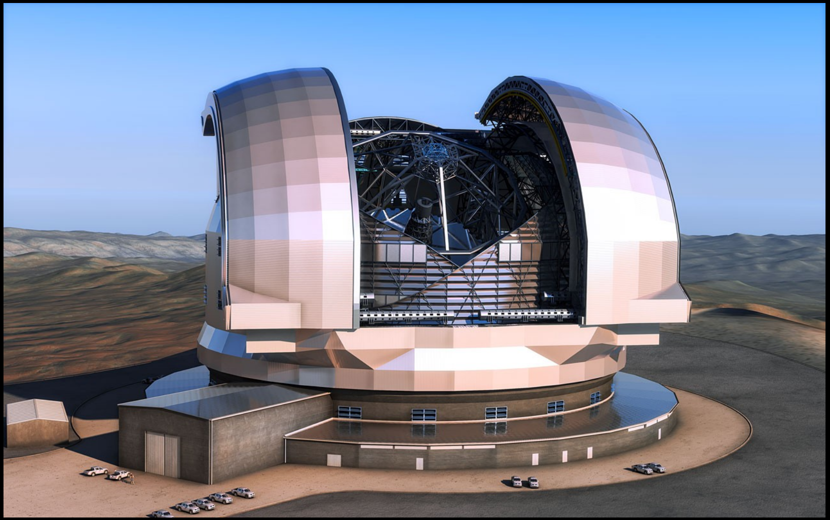
(WG5)

VLT

Image credit: ESO/H.H.Heyer

E-ELT

Image credit: ESO/L. Calçada



GAIA

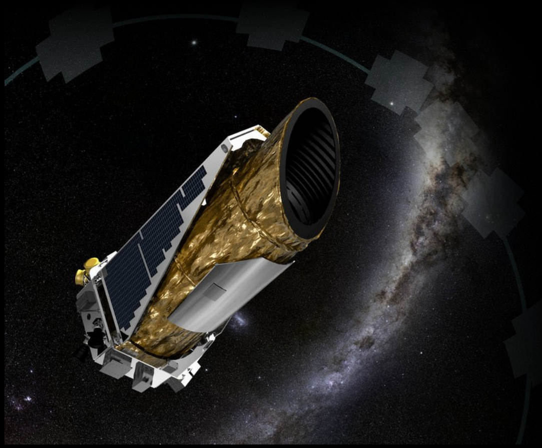
LAUNCH: Dec 2013
FIRST DATA: 2016

JWST

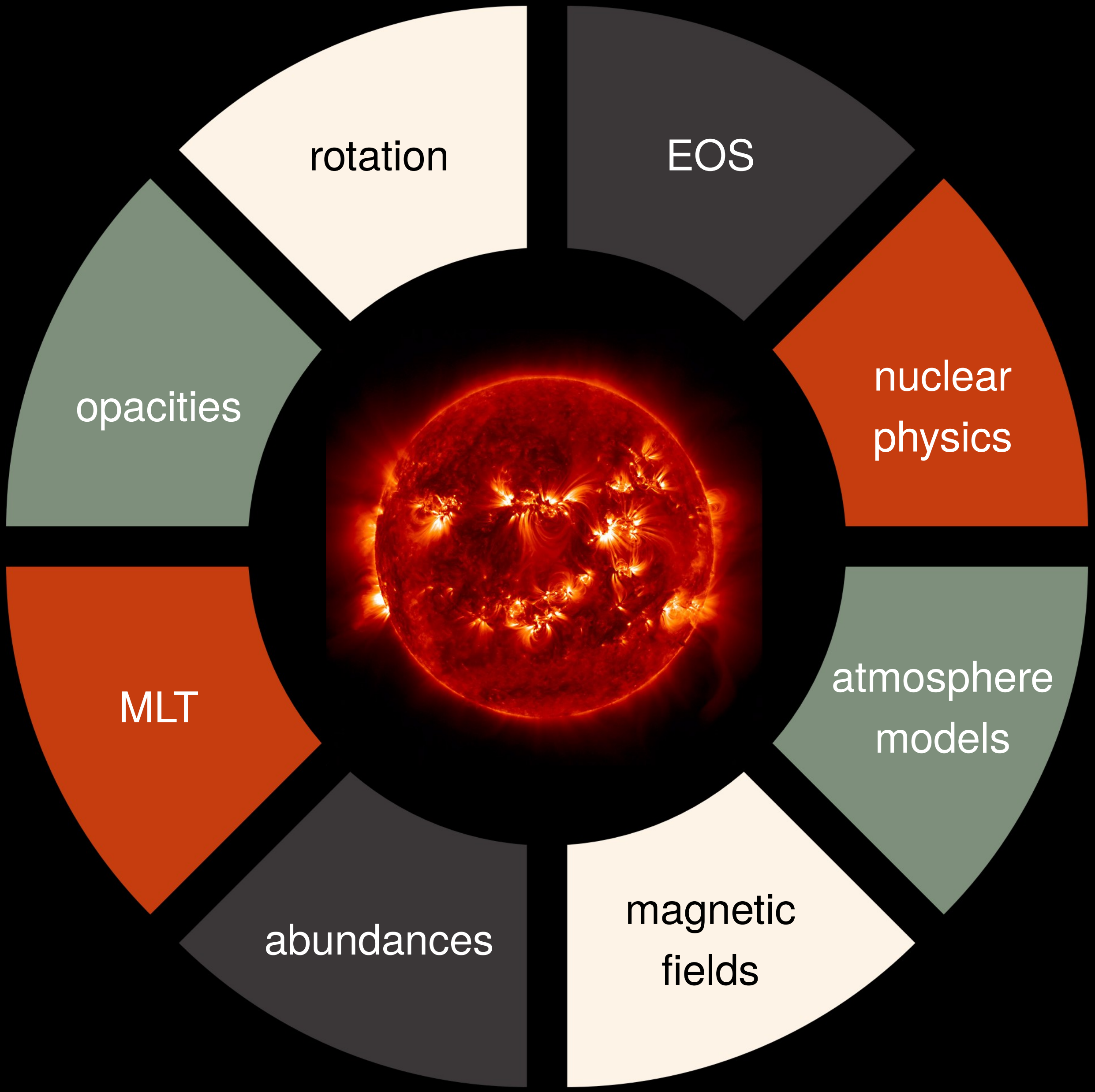
LAUNCH: Oct 2018

K2

OPERATIONAL:
Jun 2014 – 2018?



1D MODELS



rotation

EOS

nuclear physics

atmosphere models

magnetic fields

abundances

MLT

opacities

GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

1D MODELS

Goals of the 1D approach:

- Predictive models
- Include the full star; whole lifetime
- Initial—final (WD) mass relation
- Connect IMF to NS and BH mass function
- Progenitor models for SN simulations
- Yields for GCE
- Isochrones for age determinations
- Photometric characteristics for mass determinations
- Input for population synthesis

GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

1D MODELS

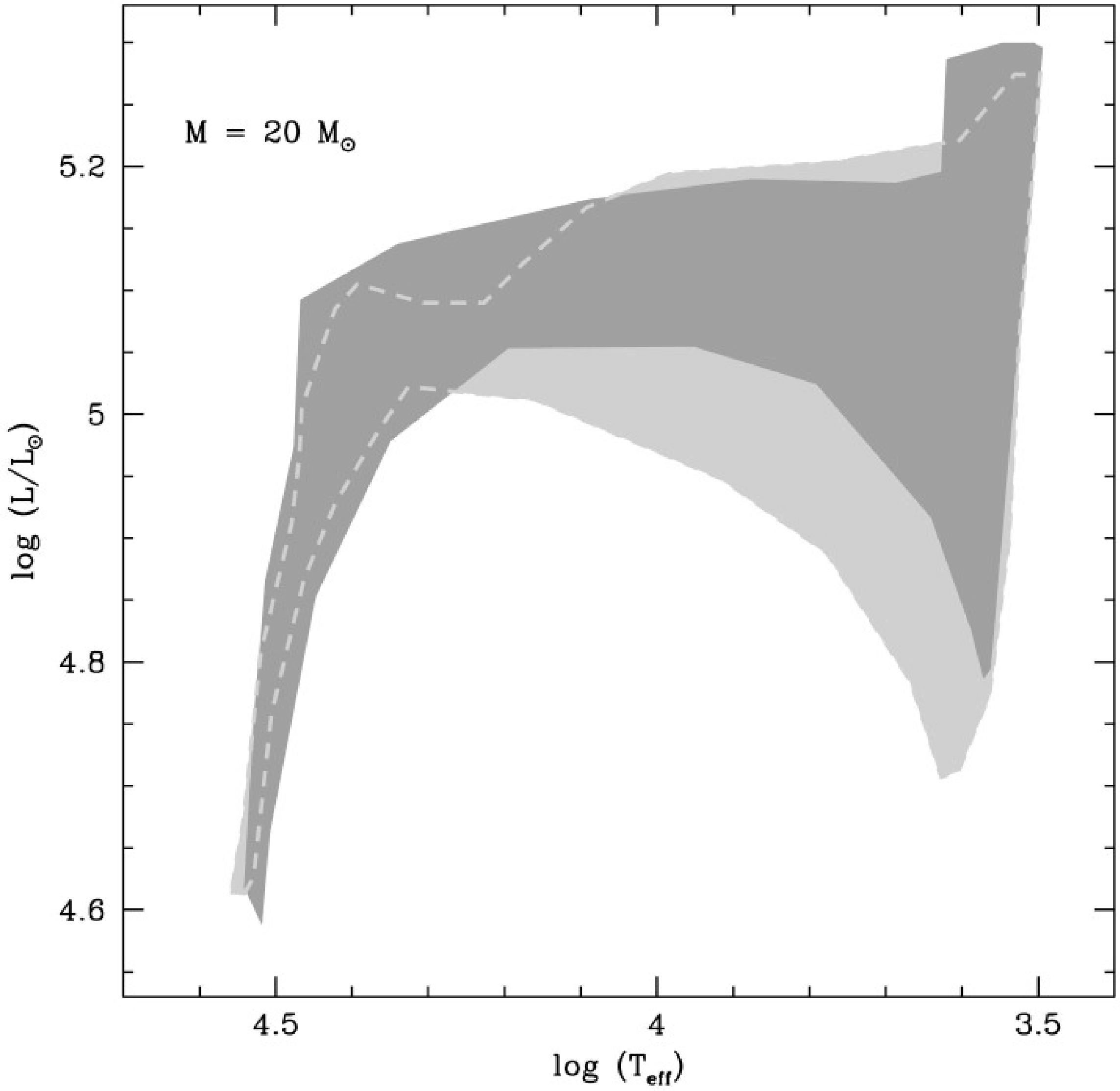


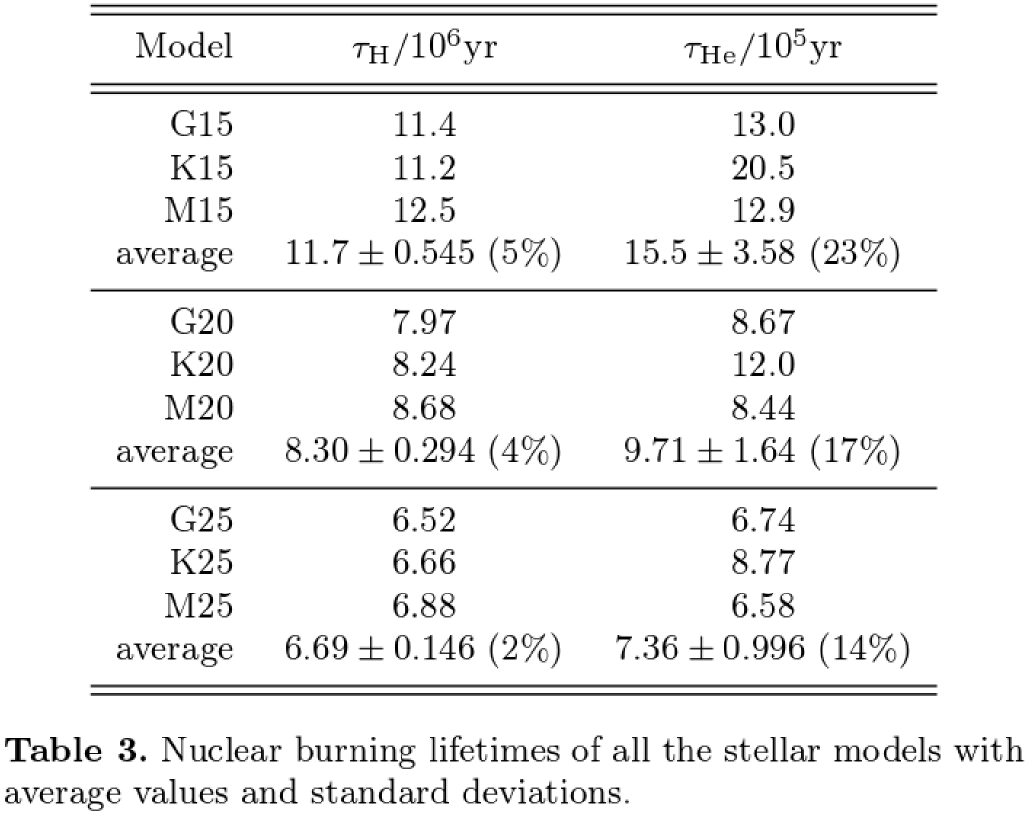
Fig. 7. Uncertainty on the location of the evolutionary path for a 20 $M_\odot$ stellar model with (dark grey envelope) and without (light grey delimited by dashes lines) rotation. We have considered tracks generated by five different codes (Geneva, STERN, FRANEC, MESA and Starevol) with similar (yet not exactly the same) initial rotation rates.

Martins & Palacios (2013)

GENEC
FRANEC
STERN
STAREVOL
MESA

HRD

1D MODELS



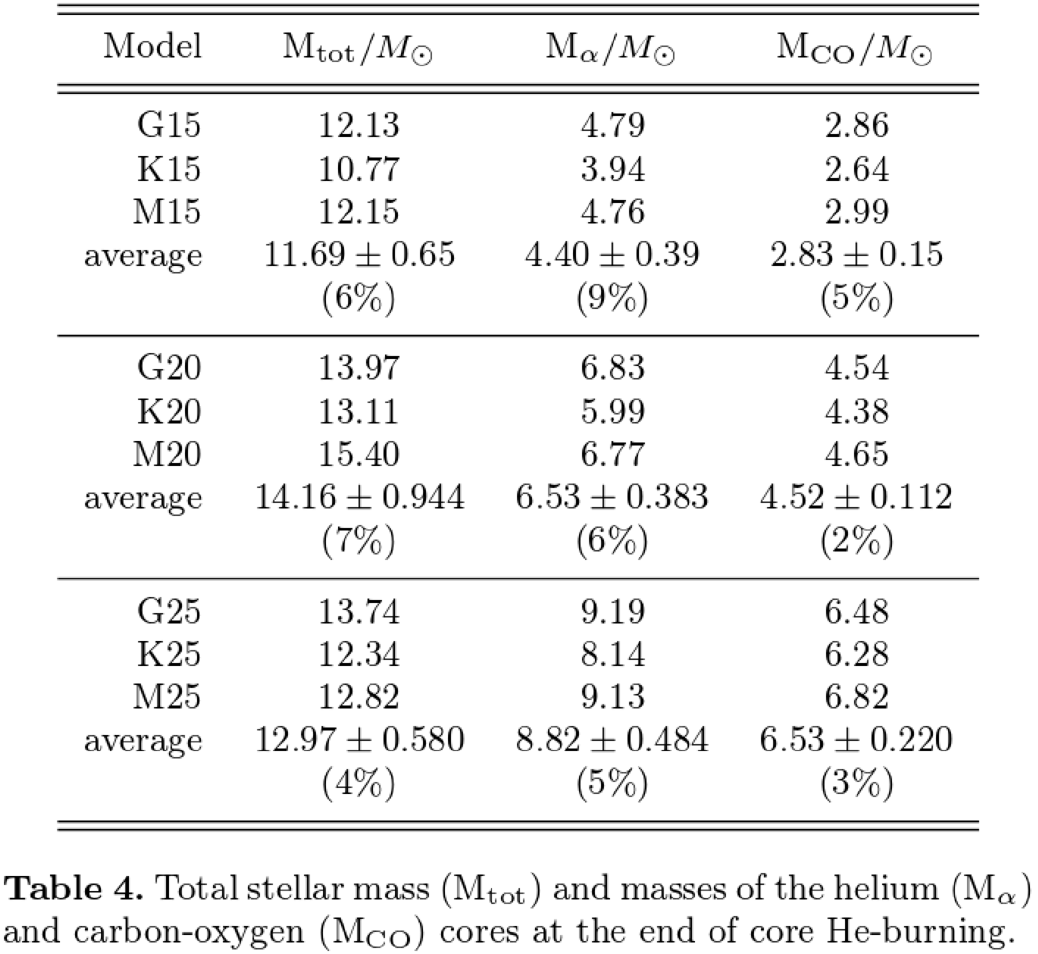
Model	$\tau_{\mathrm{H}}/10^6\mathrm{yr}$	$\tau_{\mathrm{He}}/10^5\mathrm{yr}$
G15	11.4	13.0
K15	11.2	20.5
M15	12.5	12.9
average	11.7 ± 0.545 (5%)	15.5 ± 3.58 (23%)
G20	7.97	8.67
K20	8.24	12.0
M20	8.68	8.44
average	8.30 ± 0.294 (4%)	9.71 ± 1.64 (17%)
G25	6.52	6.74
K25	6.66	8.77
M25	6.88	6.58
average	6.69 ± 0.146 (2%)	7.36 ± 0.996 (14%)

Table 3. Nuclear burning lifetimes of all the stellar models with average values and standard deviations.

Lifetimes

GENEC
KEPLER
MESA

Jones, Hirschi+ (2015)

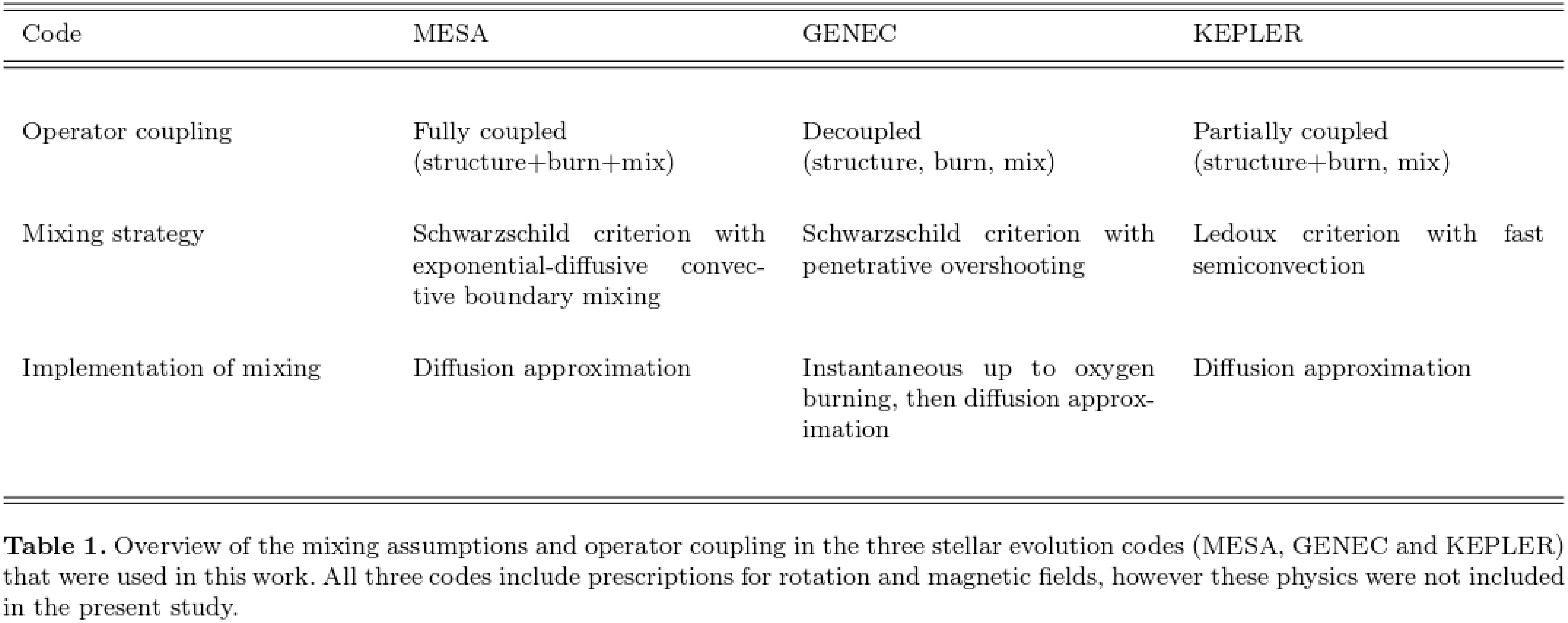


Model	$\mathrm{M_{tot}}/M_\odot$	$\mathrm{M}_\alpha/M_\odot$	$\mathrm{M_{CO}}/M_\odot$
G15	12.13	4.79	2.86
K15	10.77	3.94	2.64
M15	12.15	4.76	2.99
average	11.69 ± 0.65 (6%)	4.40 ± 0.39 (9%)	2.83 ± 0.15 (5%)
G20	13.97	6.83	4.54
K20	13.11	5.99	4.38
M20	15.40	6.77	4.65
average	14.16 ± 0.944 (7%)	6.53 ± 0.383 (6%)	4.52 ± 0.112 (2%)
G25	13.74	9.19	6.48
K25	12.34	8.14	6.28
M25	12.82	9.13	6.82
average	12.97 ± 0.580 (4%)	8.82 ± 0.484 (5%)	6.53 ± 0.220 (3%)

Table 4. Total stellar mass ($\mathrm{M_{tot}}$) and masses of the helium (M_α) and carbon-oxygen ($\mathrm{M_{CO}}$) cores at the end of core He-burning.

Core masses

Jones, Hirschi+ (2015)



Code	MESA	GENEC	KEPLER
Operator coupling	Fully coupled (structure+burn+mix)	Decoupled (structure, burn, mix)	Partially coupled (structure+burn, mix)
Mixing strategy	Schwarzschild criterion with exponential-diffusive convective boundary mixing	Schwarzschild criterion with penetrative overshooting	Ledoux criterion with fast semiconvection
Implementation of mixing	Diffusion approximation	Instantaneous up to oxygen burning, then diffusion approximation	Diffusion approximation

Table 1. Overview of the mixing assumptions and operator coupling in the three stellar evolution codes (MESA, GENEC and KEPLER) that were used in this work. All three codes include prescriptions for rotation and magnetic fields, however these physics were not included in the present study.

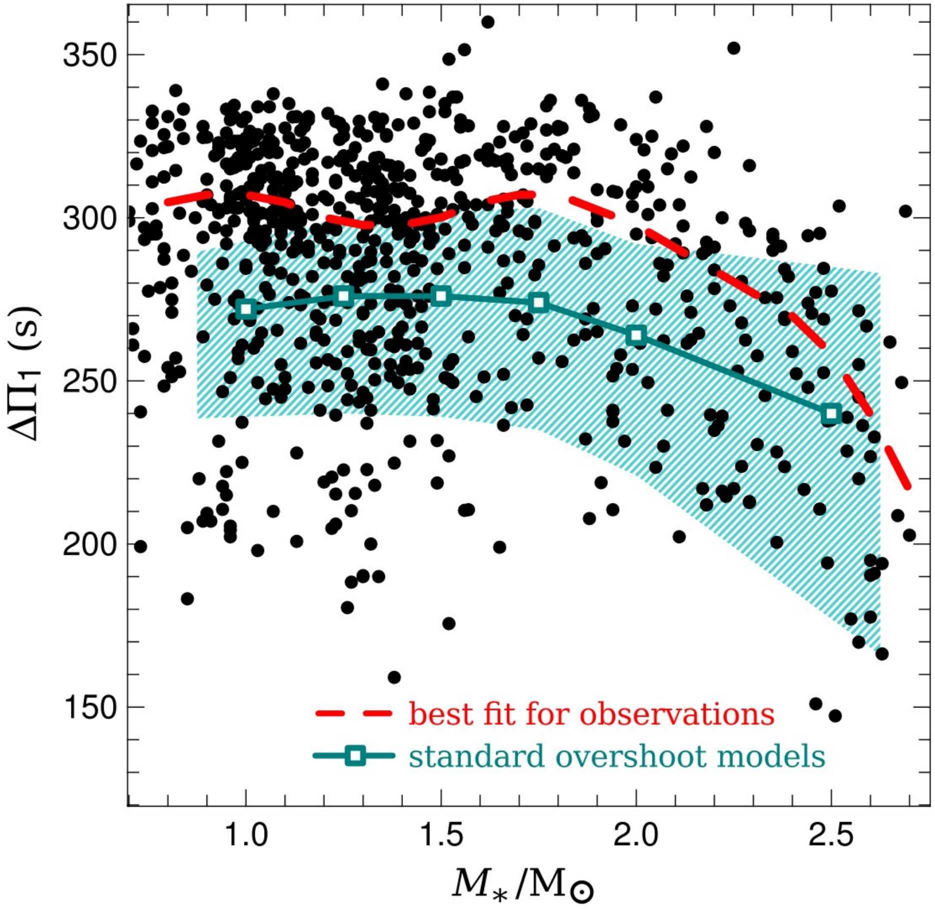
1D MODELS

GENEC
KEPLER
MESA

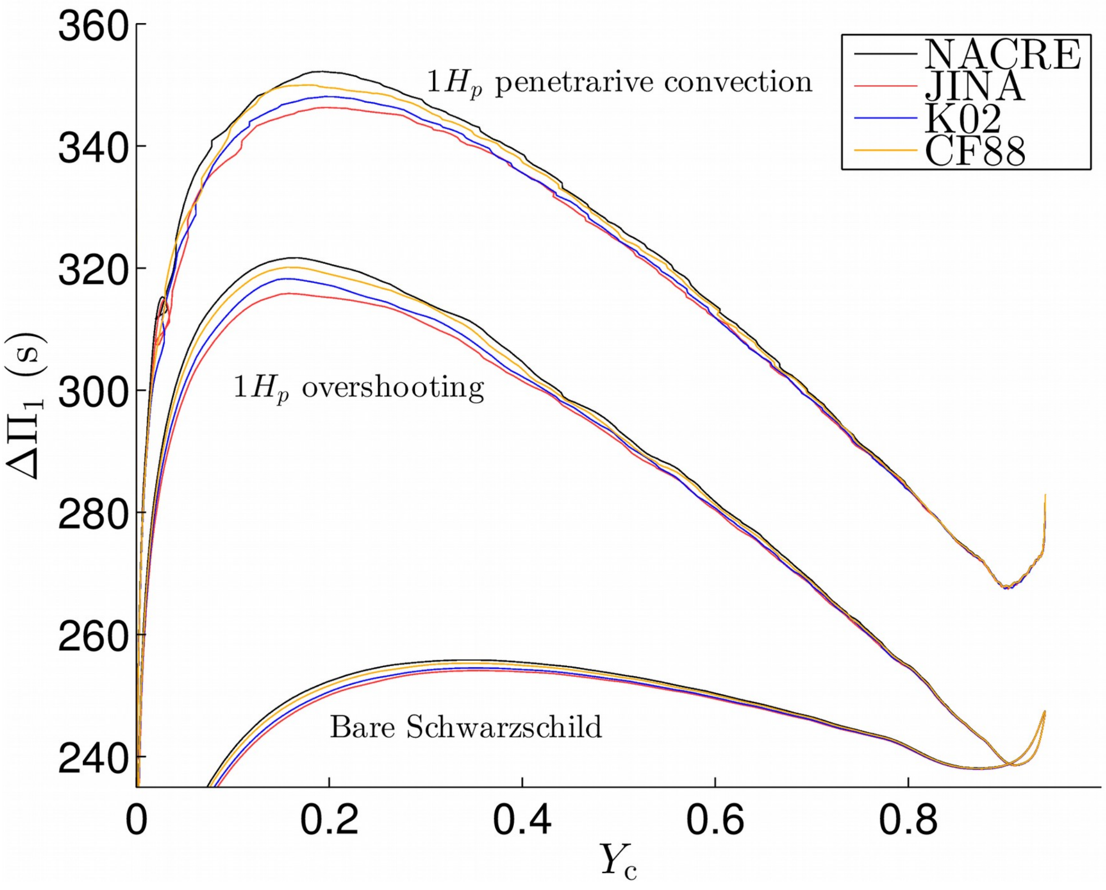
ASTEROSEISMOLOGY

MIXING CONSTRAINTS

Constantino+ (2015)



Credit: Diego Bossini; see Bossini+ (2015)

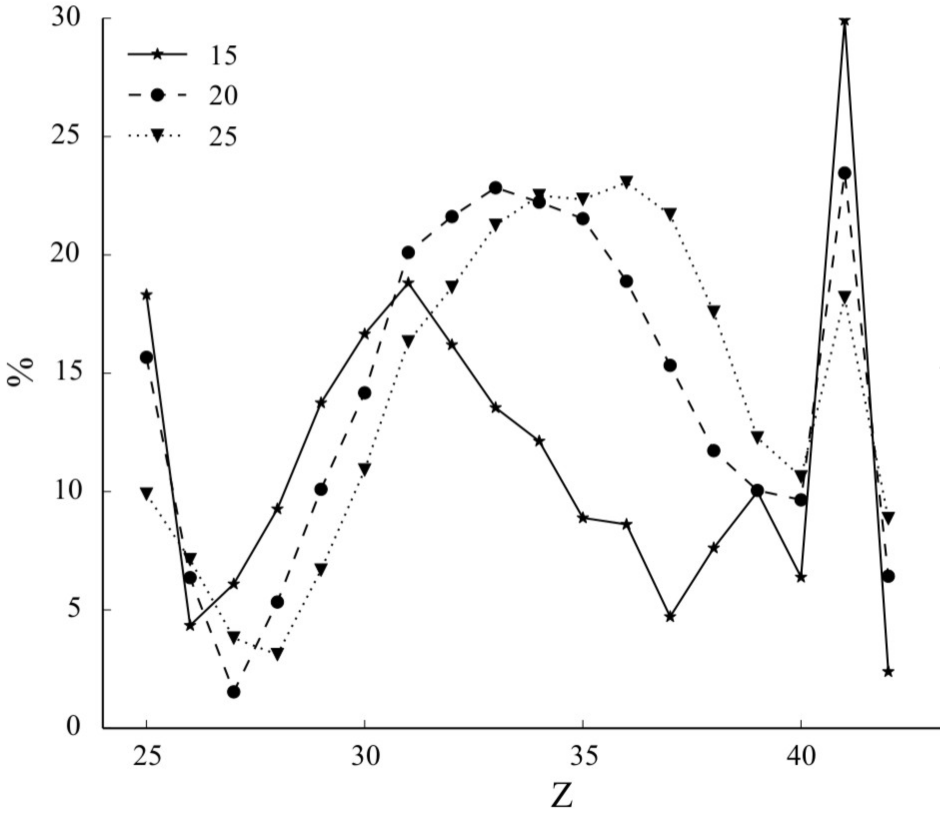


Detection of mixed modes in core He-burning stars makes it possible to measure l=1 mode period spacing, giving tighter constraints for stellar models

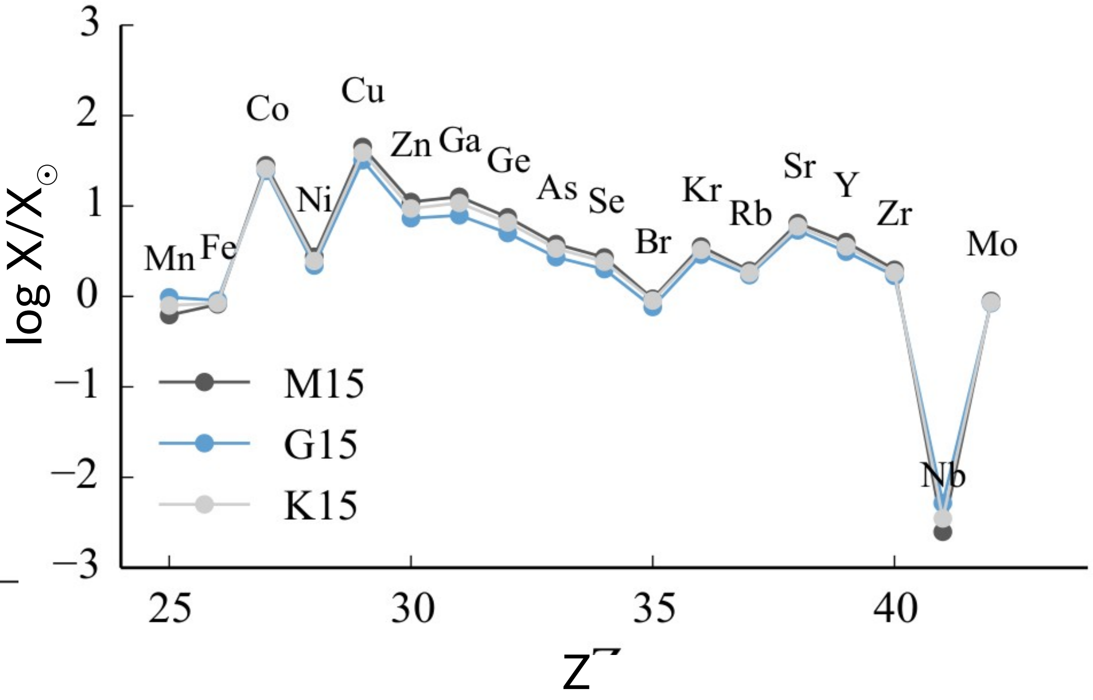
WEAK S PROCESS

CODE DEPENDENCIES

Spread in s-process overabundances in the He-depleted core from **3 different codes** (GENEC, KEPLER and MESA) is **smaller than the impact of the nuclear physics uncertainties** (e.g. Pignatari+ 2010).



Jones, Hirschi+ 2015

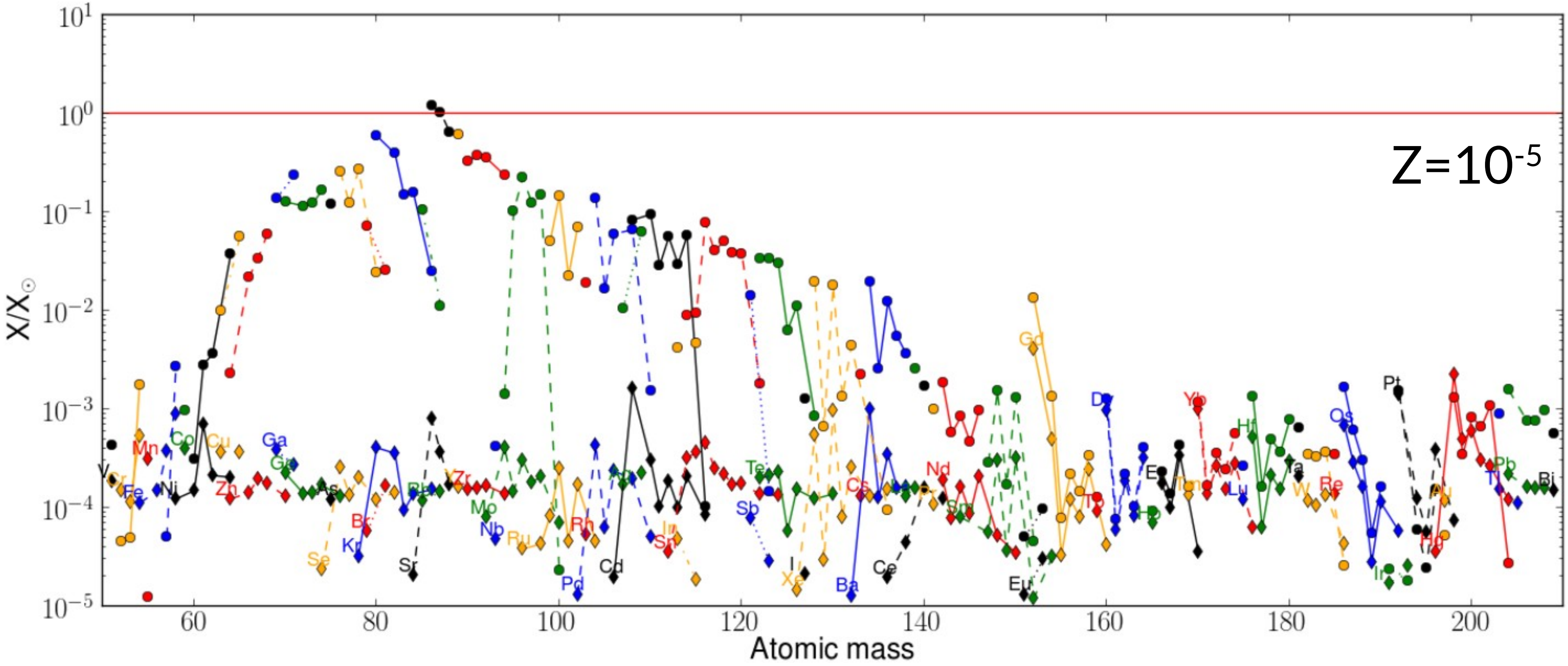


WEAK S PROCESS

Rotation at low Z

s process **production boosted at low Z** due to creation of primary ^{22}Ne by **rotational mixing** between the H shell and He core

Frischknecht & Hirschi+ 2016



$Z=10^{-5}$

Figure 8. Isotopic abundances normalised to solar abundances of 25 $M_\odot$ models with with $Z = 10^{-5}$ after He exhaustion. The rotating model (C25s5, circles) has much higher factors than the non-rotating model (C25s0, diamonds).

MAIN S PROCESS

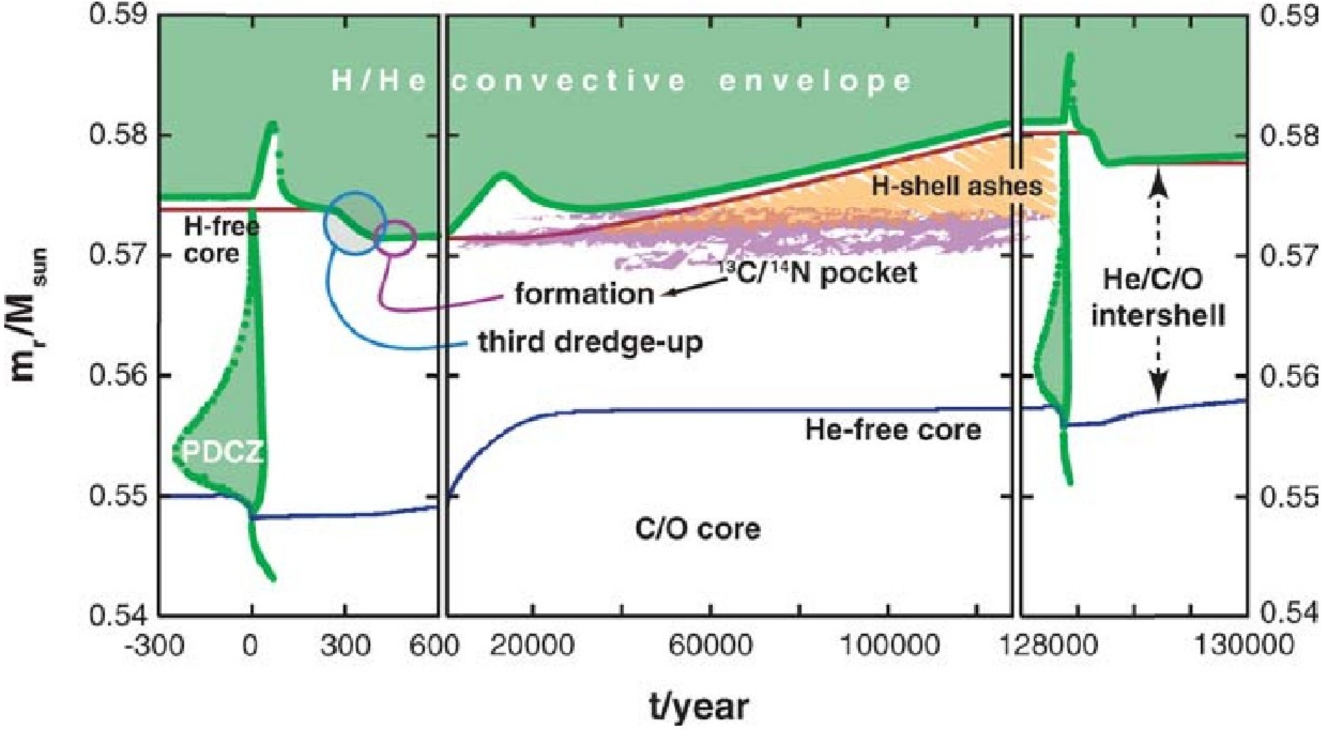
HOW DOES IT HAPPEN?

We think in the **^{13}C pocket**; we even think we know how big the pocket should be, but we **do not know what mixing process** is responsible for its formation

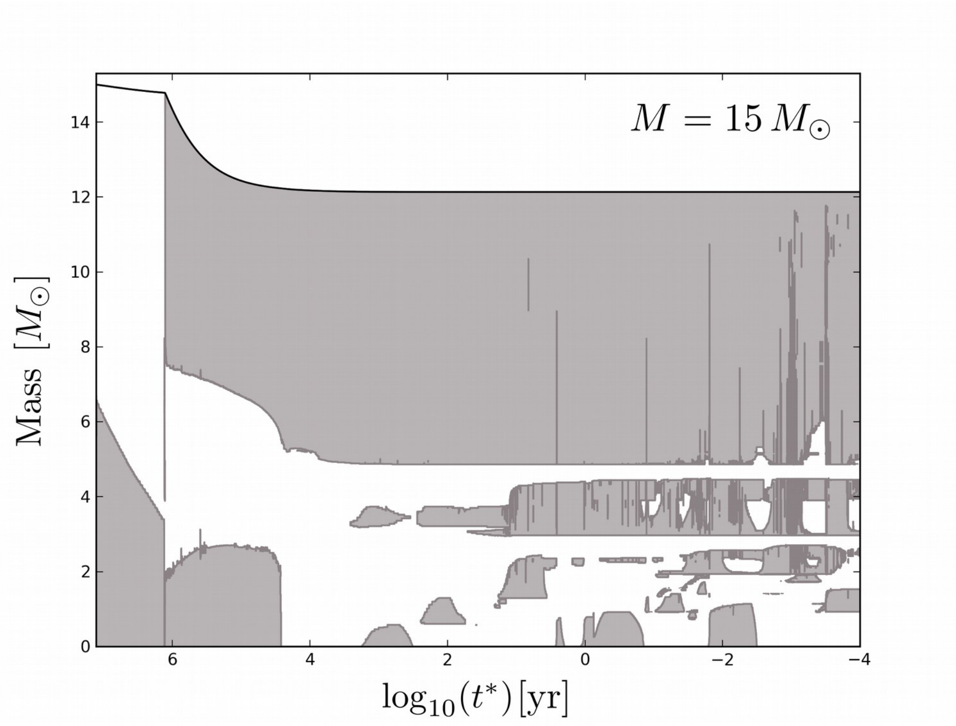
Rotation alone is not enough, but mechanism of CBM not clear. Gravity waves? Magnetic fields? (Piersani+ 2013, Battino 2016, subm.)

Still some way to go …

Herwig 2005



Nucleosynthesis in massive stars, disentangling between nuclear uncertainties and stellar uncertainties



Element production from the nucleosynthesis in the pre-explosive evolution:

C, O, Mg, Na

- The production of the bulk of these elements In CCSNe does not depend much on the SN explosion.

- What is the error of the main nuclear rates affecting their production in He-burning (C,O) and C-burning conditions (Mg,Na) ? Provide a table with errors, and we can get back to you soon.

M. Pignatari

1D MODELS

It is encouraging that 1D models can agree *reasonably* well.
It is encouraging that 1D models can reproduce observations.

However, all of these 1D models are based on the same/similar approximate underlying physics models, which limits their **predictive** power

e.g.:

If the ^{13}C pocket size in a 2 $M_{\odot}$, solar *Z* stellar evolution model is a parameter that is calibrated to reproduce an observation, it is tenuous to use the same parameterization to make predictions for a 2 $M_{\odot}$, $Z=10^{-4}$ star without implying something about the physical mechanism creating the ^{13}C pocket

These are mature codes but have **intrinsic limitations:**

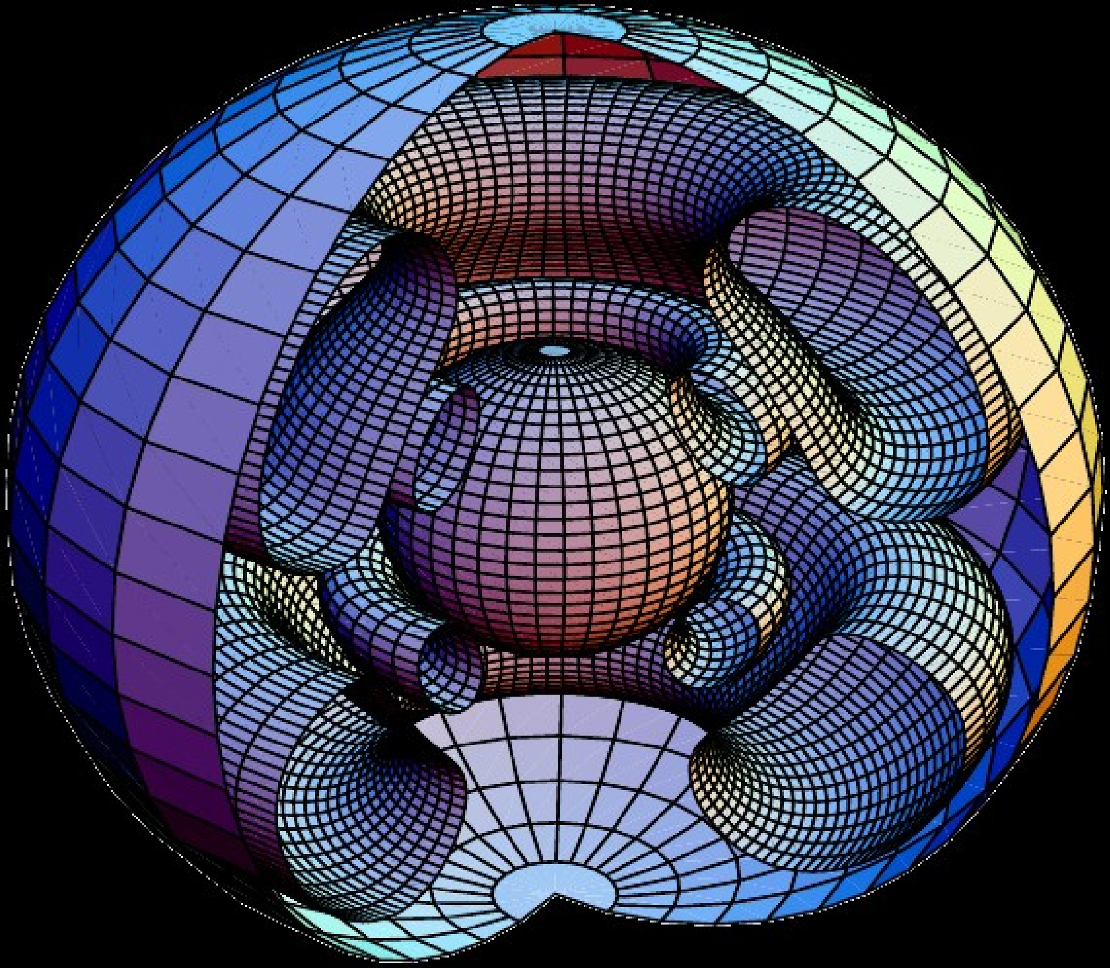


Image credit: André Maeder

GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

rotation

1D MODELS

1D MODELS

These are mature codes but have **intrinsic limitations:**

- GENEC
- KEPLER
- STARS
- FRANEC
- TYCHO
- STERN
- EVOL
- GARSTEC
- MONSTAR
- STAREVOL
- MESA

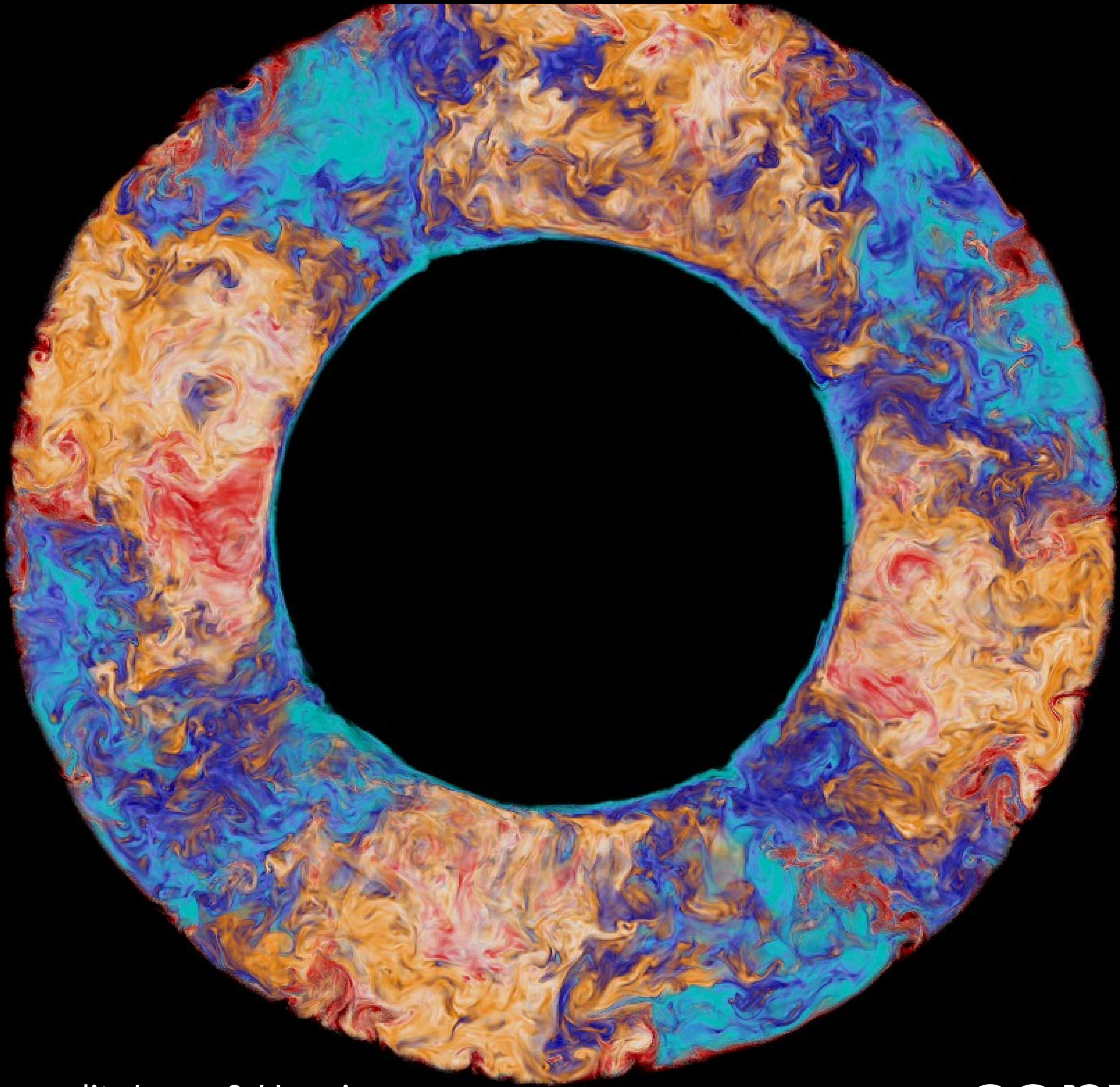


Image credit: Jones & Herwig

convection

These are mature codes but have **intrinsic limitations:**

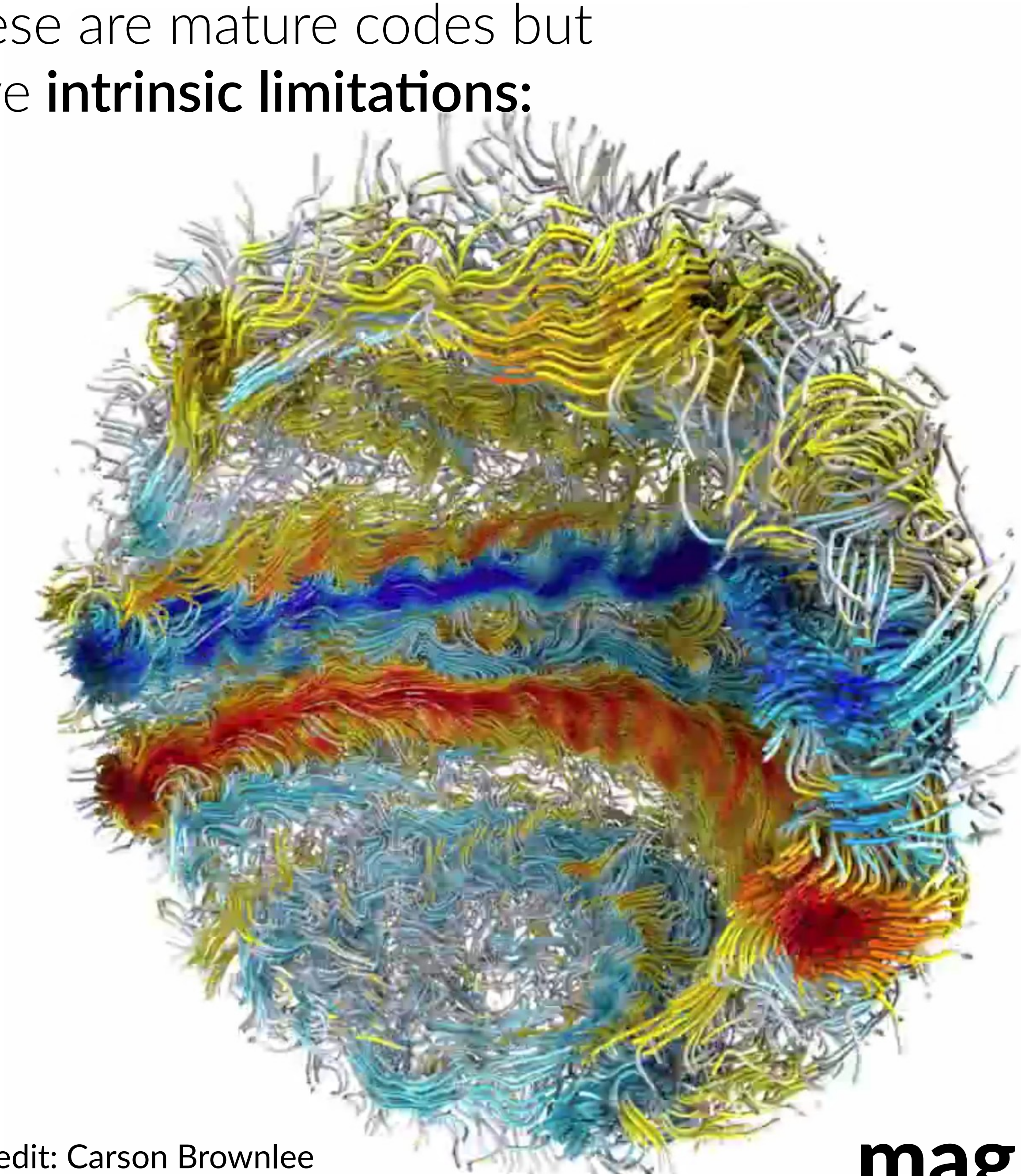


Image credit: Carson Brownlee

GENEC
KEPLER
STARS
FRANEC
TYCHO
STERN
EVOL
GARSTEC
MONSTAR
STAREVOL
MESA

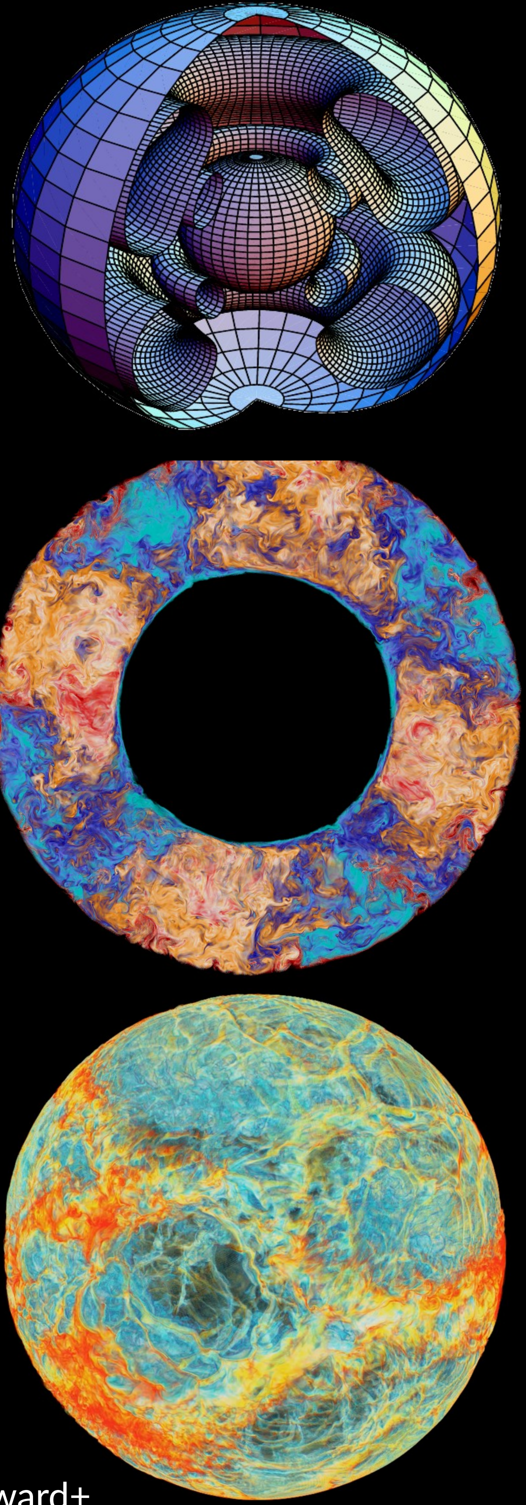
magnetic fields

1D MODELS

Approach of **3D modelling of stars:**

- Simulate inherently multi-dimensional phenomena
- Simulate dynamic phases and hydrodynamic instabilities in stars
- Improve predictive power of 1D models:
  - Testing prescriptions
  - Fixing free parameters

Long-term goal:
Develop improved models for convection, rotation, binary interactions, magnetic fields and winds in 1D models



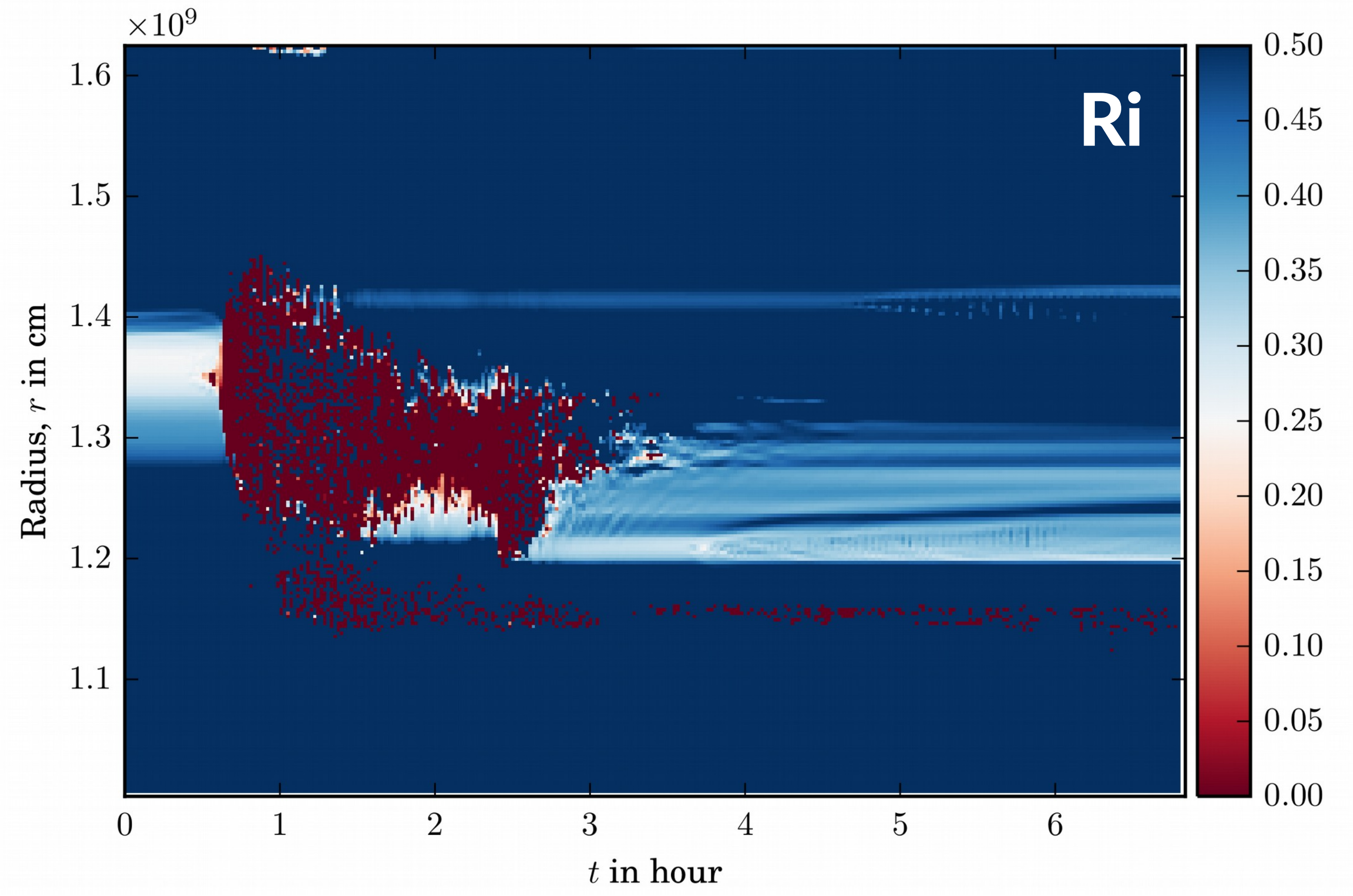
Herwig & Woodward+

3D MODELS

ROTATION

HOW GOOD IS “1D ROTATION”?

Edelmann, Röpke, Hirschi & Georgy 2016, in prep

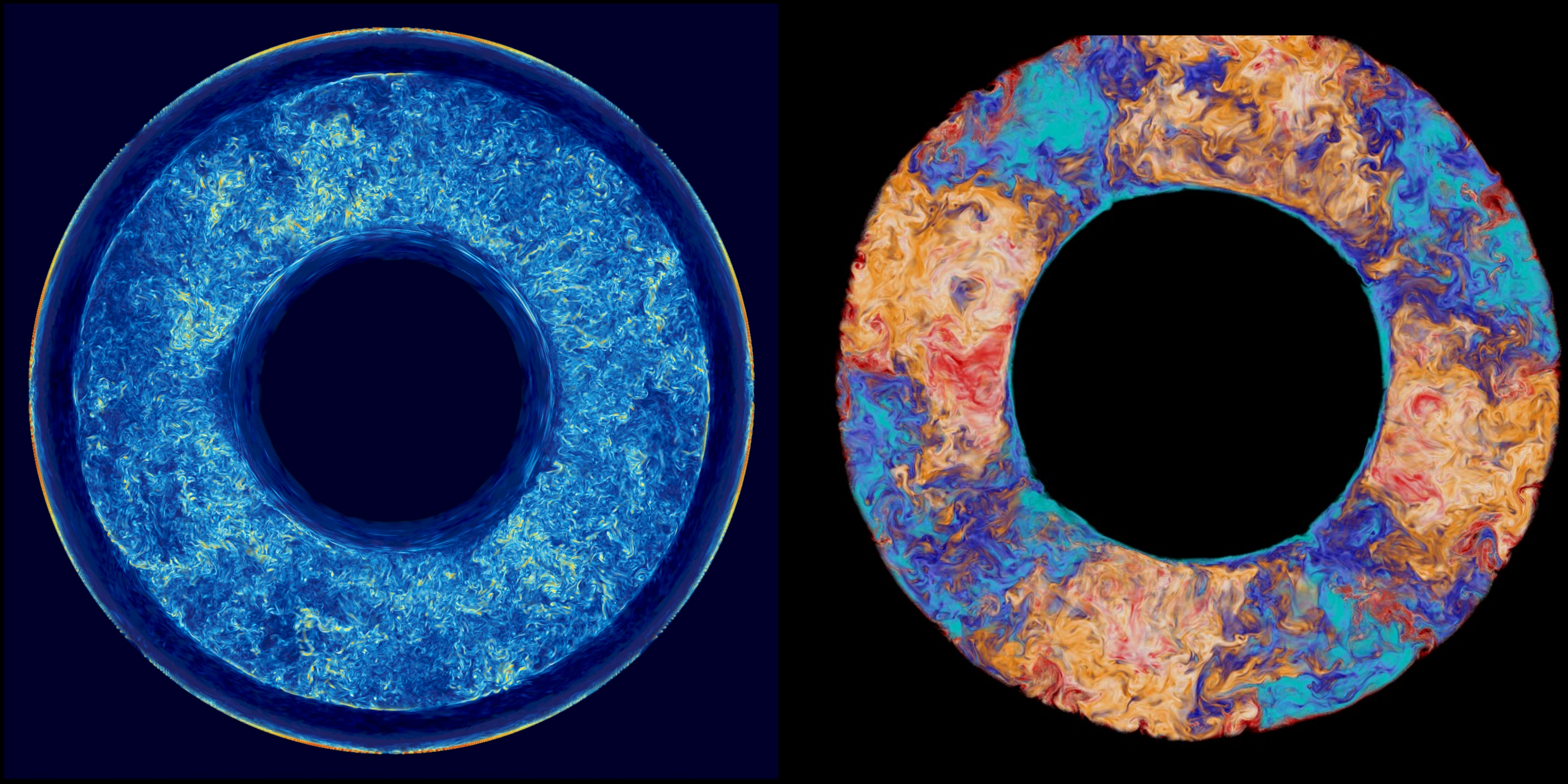


New numerical methods developed to follow such low Mach number flows, with which prescriptions for rotation in 1D codes can be tested

CONVECTION SIMULATIONS

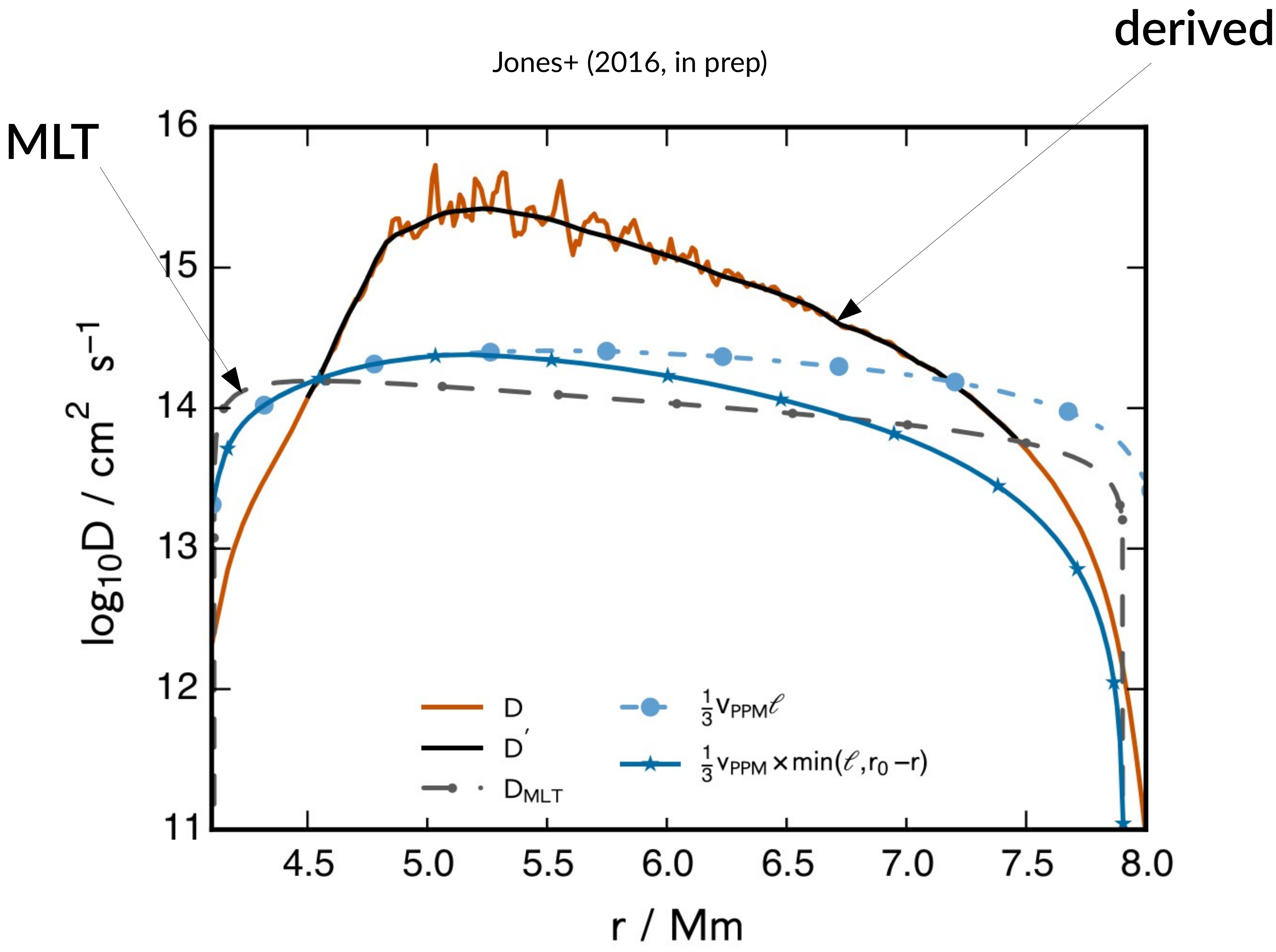
O SHELL BURNING

Jones+ (2016, in prep)



CONVECTION SIMULATIONS

MLT UPGRADES?



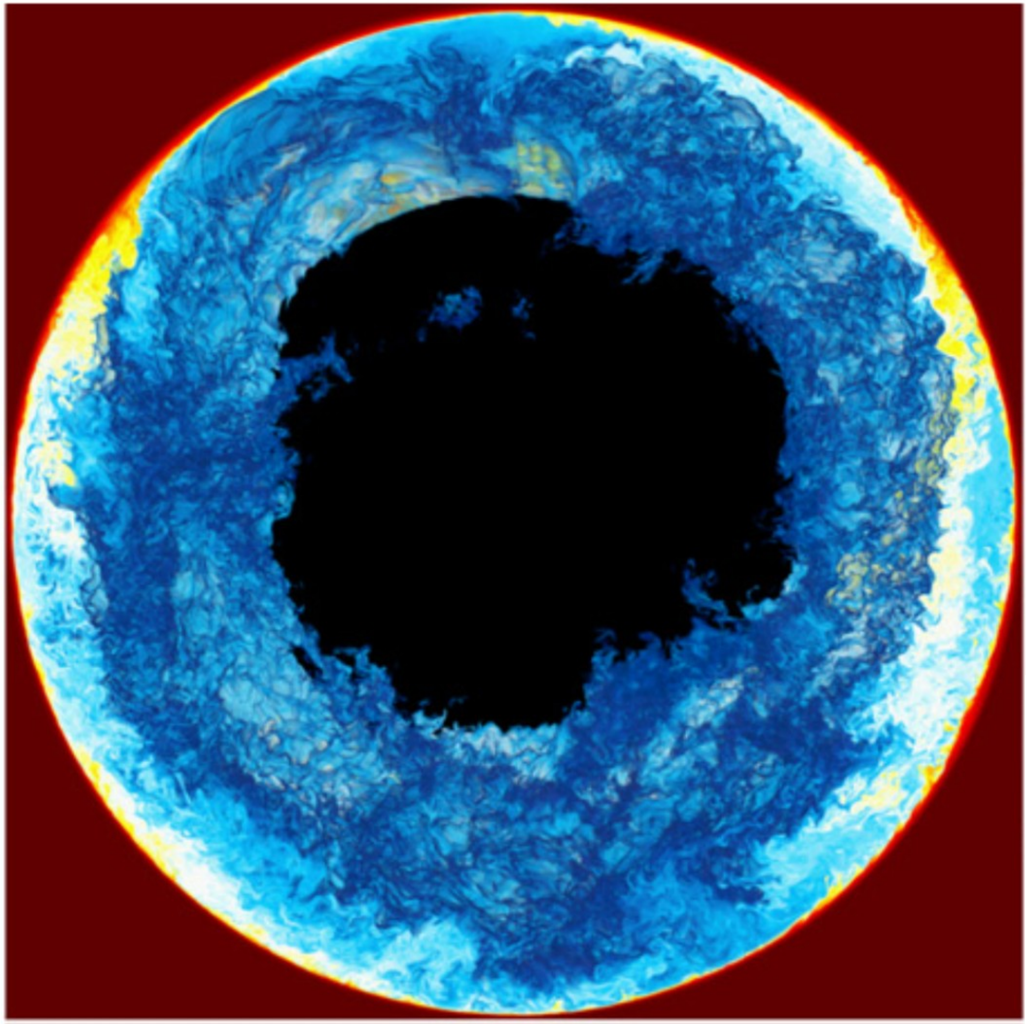
Jones+ (2016, in prep)

MLT

derived

DYNAMICAL EVENTS

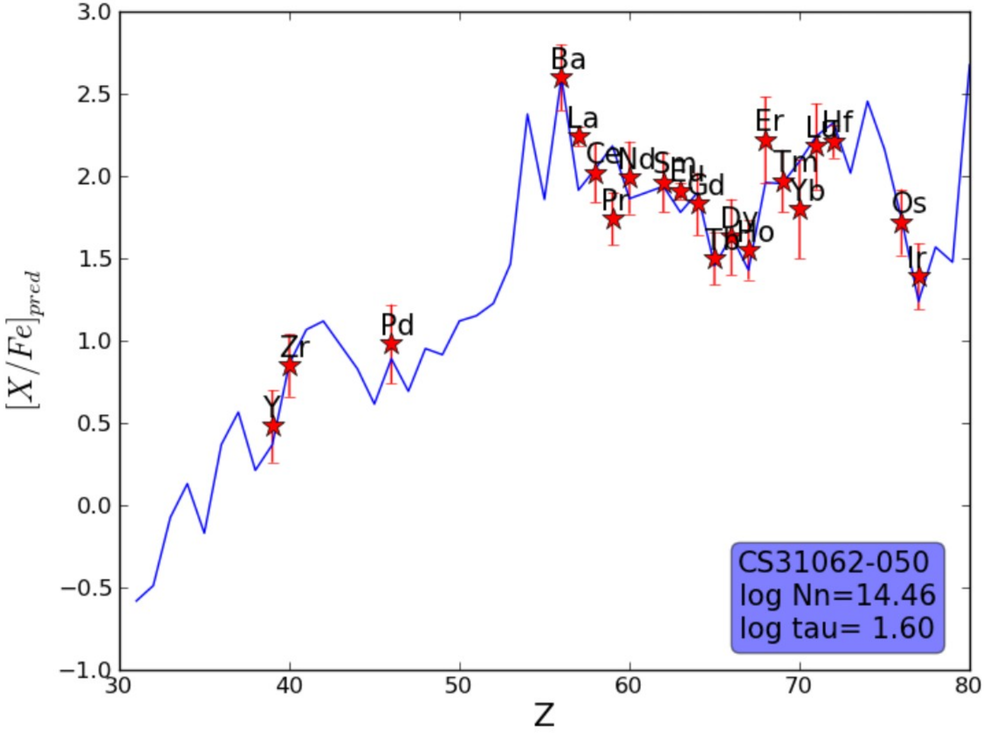
H INGESTION: I-PROCESS NUCLEOSYNTHESIS?



Herwig 2014

The i process is very interesting for nuclear physics experiments, but **more work is needed** on the site

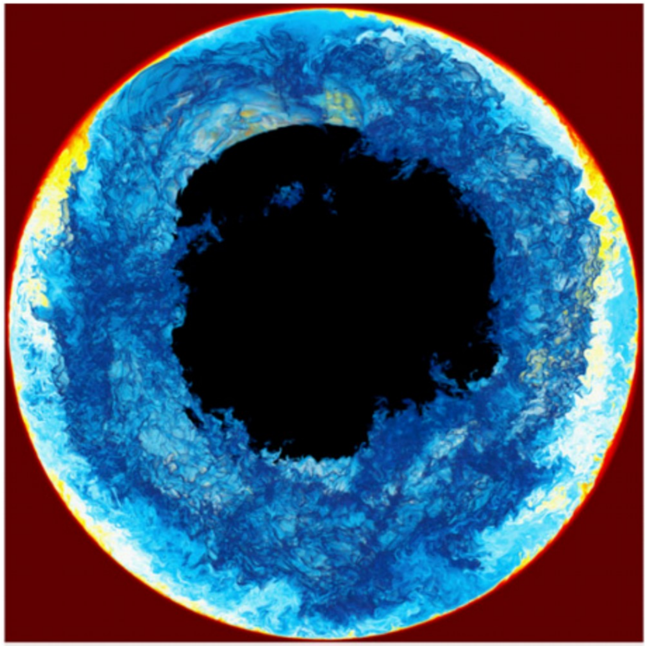
GCE significance unclear



Dardelet, Jones+ (2014)

DYNAMICAL EVENTS

H INGESTION: I-PROCESS NUCLEOSYNTHESIS?



Herwig 2014

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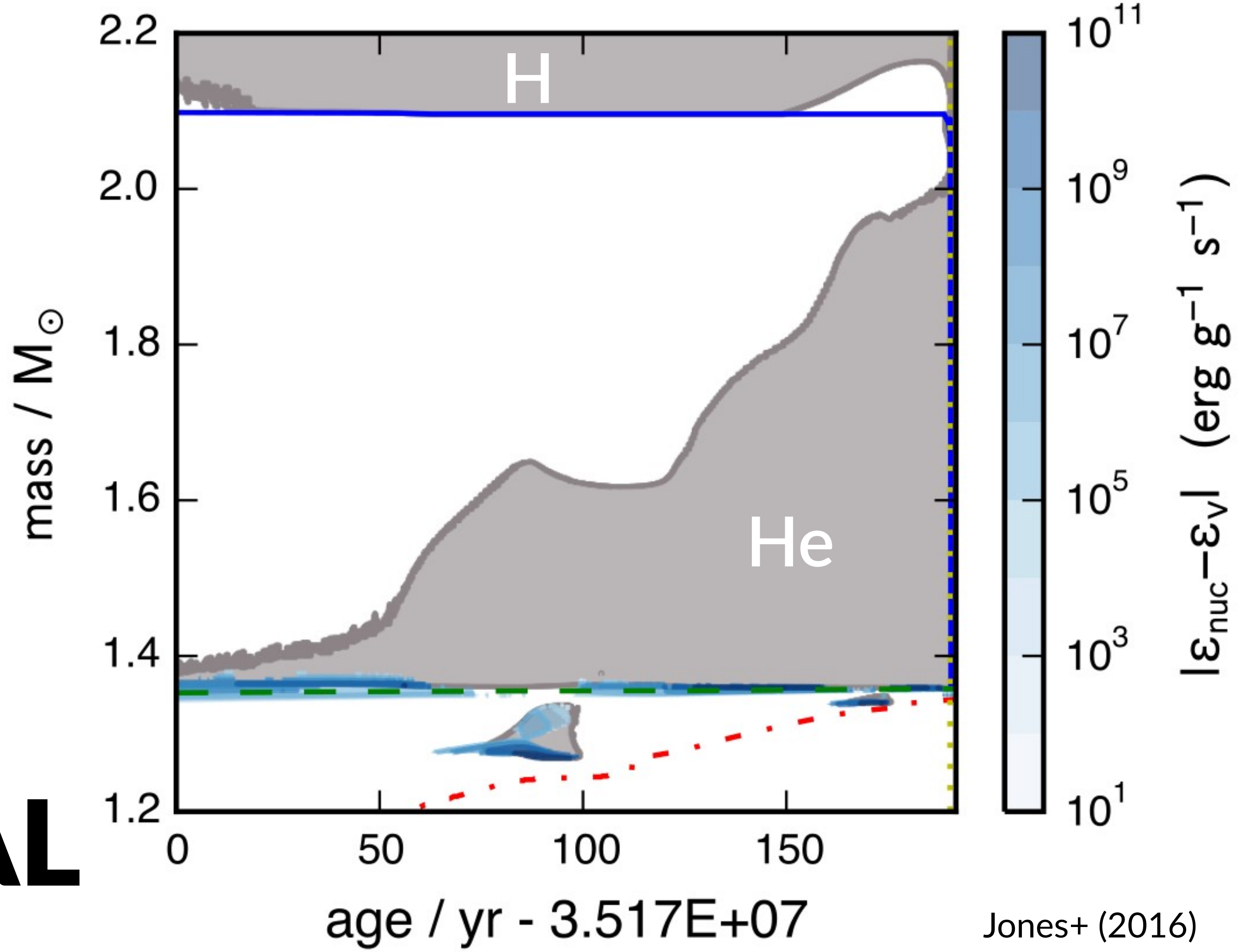
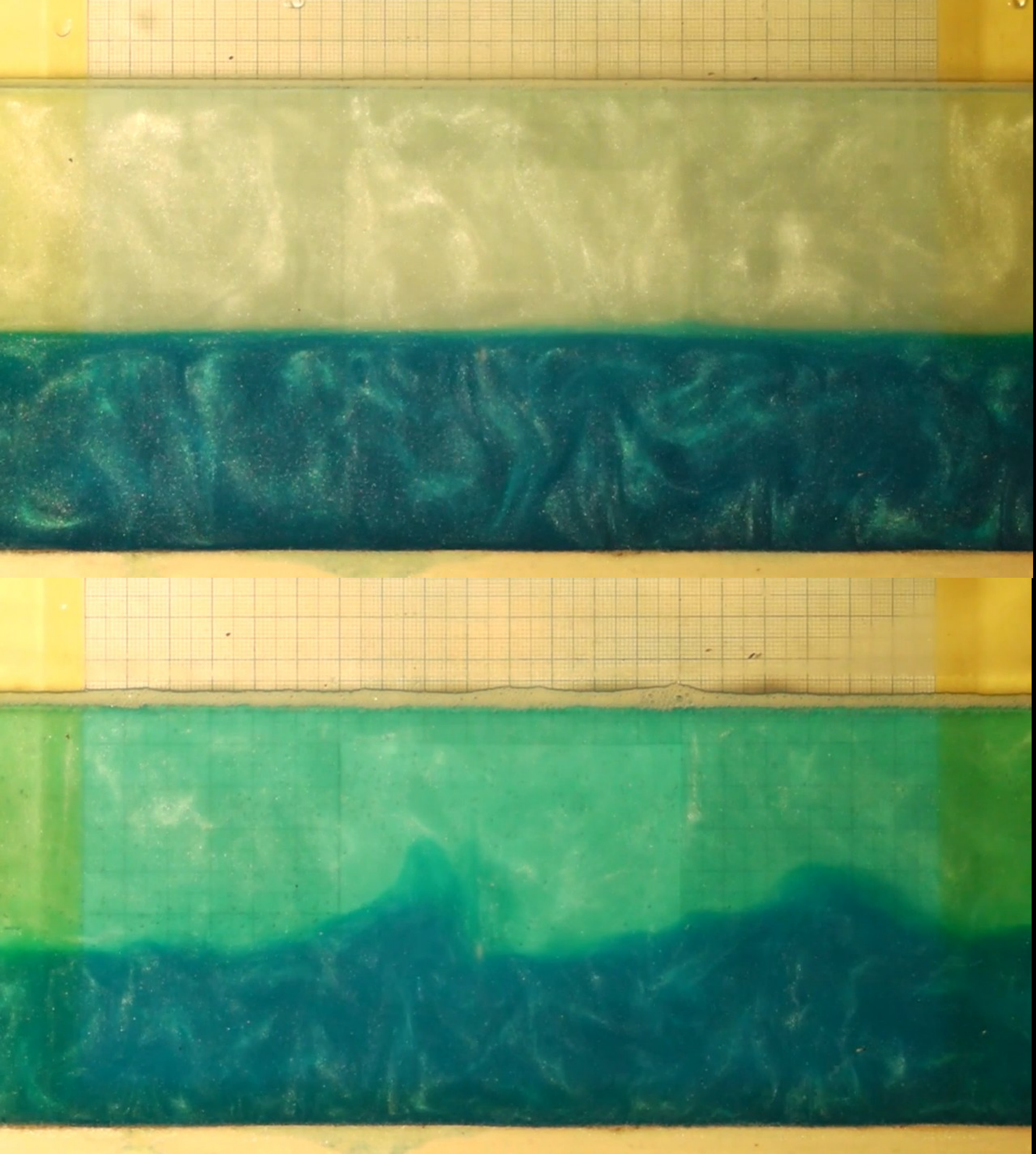


Jones+ (2016)

SEMICONVECTION



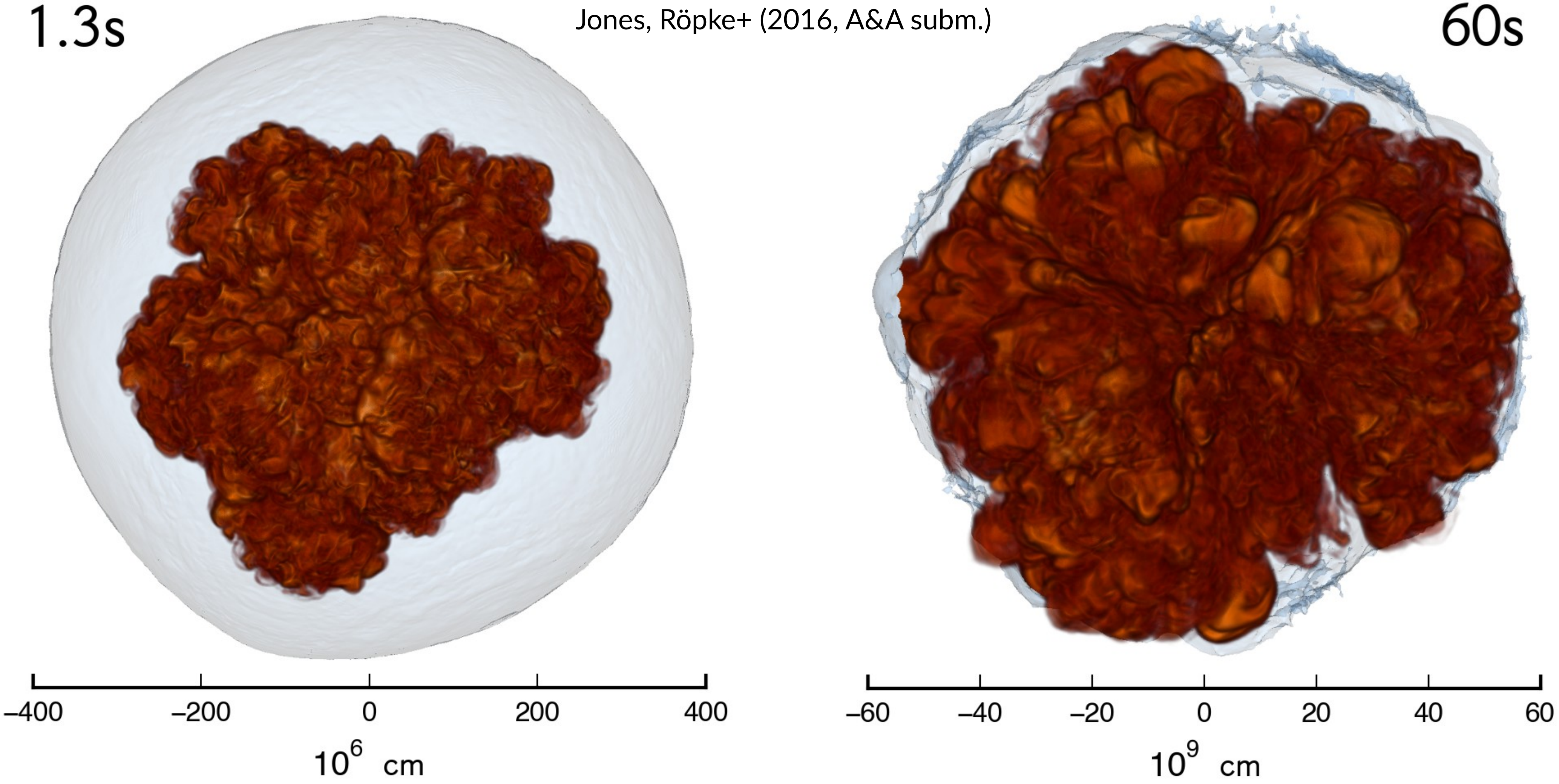
- **De-stabilizing T gradient**
- **Stabilizing μ gradient**
- **Realised during He-core burning**
- **Secular instability (low Mach No. methods?)**

$5 semiconvection experiment by Austin Davis (UVic)

“8-10 SOLAR-MASS” STARS

ELECTRON-CAPTURE SUPERNOVAE?

First 3D O deflagration simulations in ECSN progenitor stars

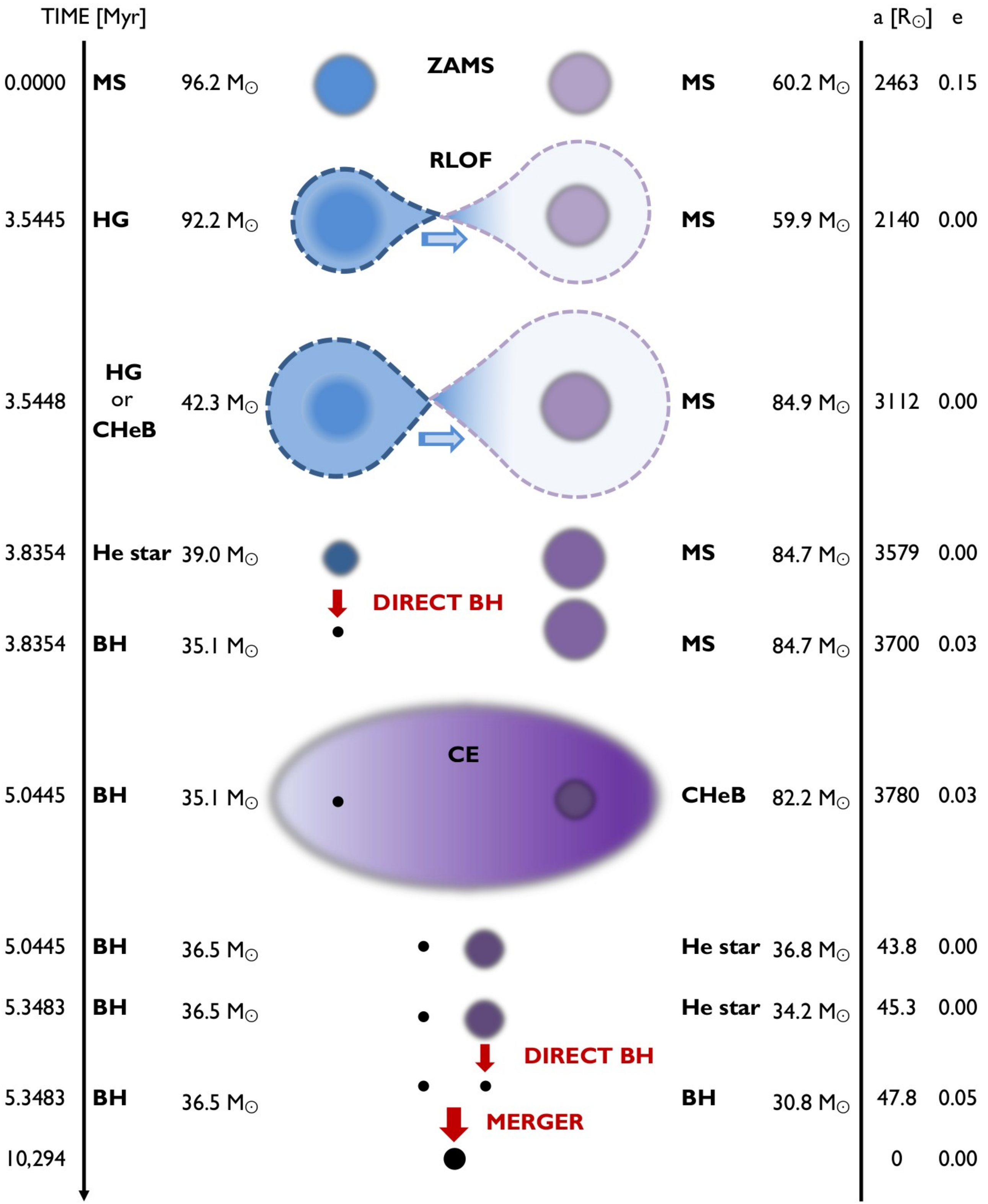


Jones, Röpke+ (2016, A&A subm.)

BINARY STARS

At least 70% of massive stars will interact with a binary companion during their lifetime

Sana+ (2012)

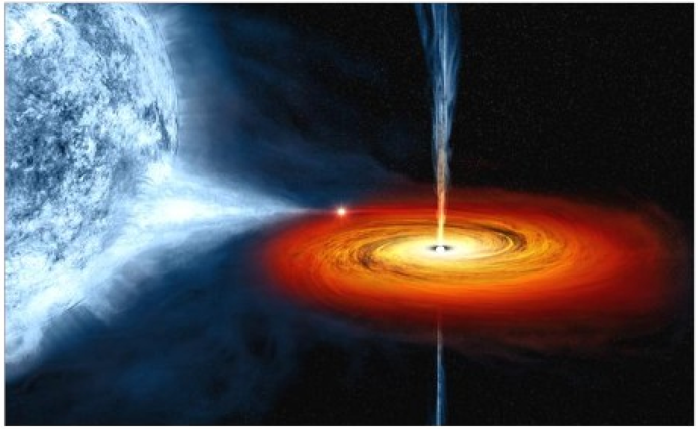


Population synthesis predictions (e.g. BH-BH merger rates; see Belczynski+ 2015) **inherit uncertainties from underlying models**:

- Stellar radii
- **Binary interactions**
- NS/BH masses
- BH natal kicks

Image credit: Wojciech Gladsyz (Warsaw)

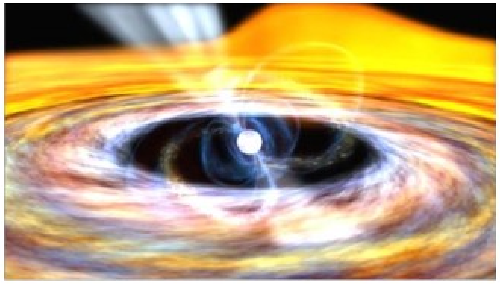
Neutron Stars in Binaries – from stellar evolution to explosions



- Stellar evolution from cradle to grave
- Accretion physics (X-ray binaries)
- Recycling of neutron stars (spin-up and mass accumulation)
- Ultra-stripped supernovae (SNe)
- Dynamical effects of asymmetric SNe (neutron star kicks)
- Population synthesis: neutron star/black hole mergers (LIGO rates, sGRBs)
- Formation and evolution of millisecond radio pulsars
- Properties and cooling of low-mass helium white dwarf companions

Max-Planck-Institut
für Radioastronomie

PD Dr. Thomas Tauris
Max-Planck-Institut für Radioastronomie
AIfA, Universität Bonn



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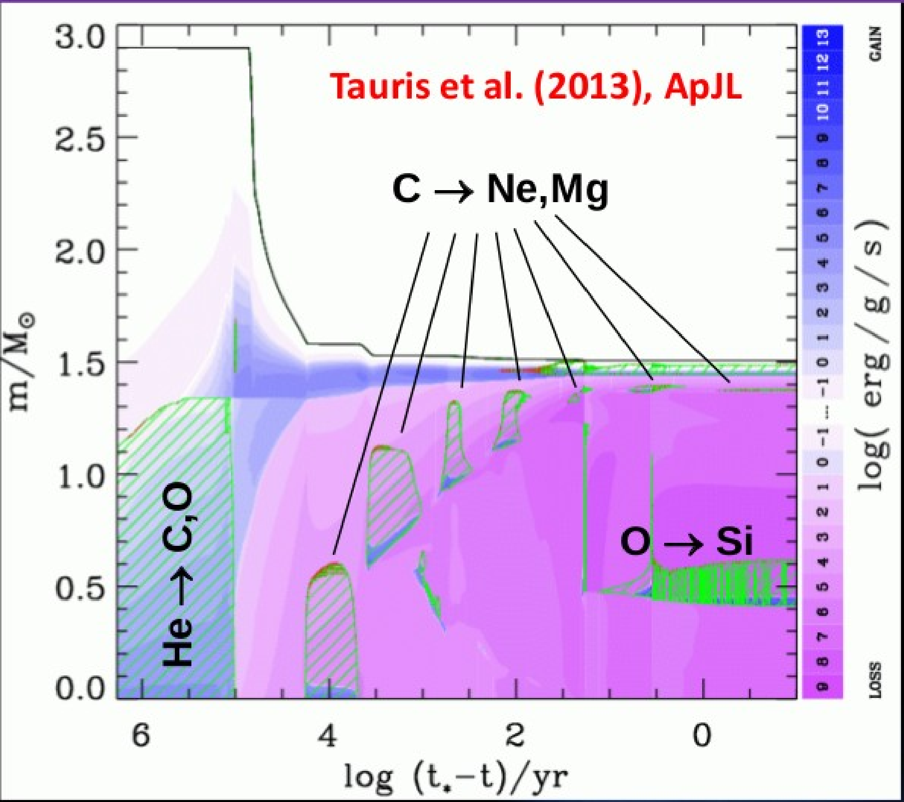
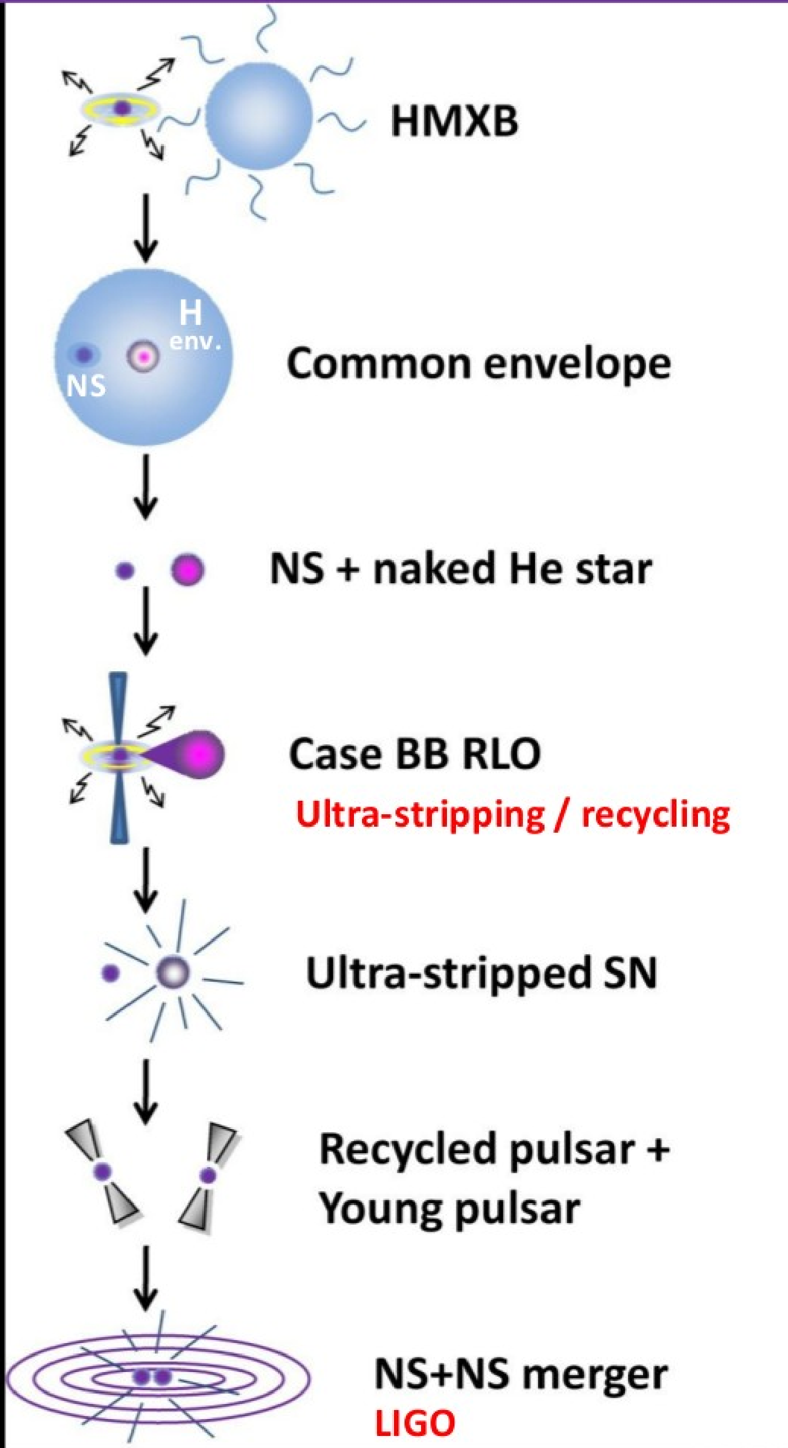
Neutron Stars in Binaries – ultra-stripped SNe



Thomas Tauris – MPIfR / Uni. Bonn



HMXB

Common envelope

NS + naked He star

Case BB RLO

Ultra-stripping / recycling

Ultra-stripped SN

Recycled pulsar +
Young pulsar

NS+NS merger

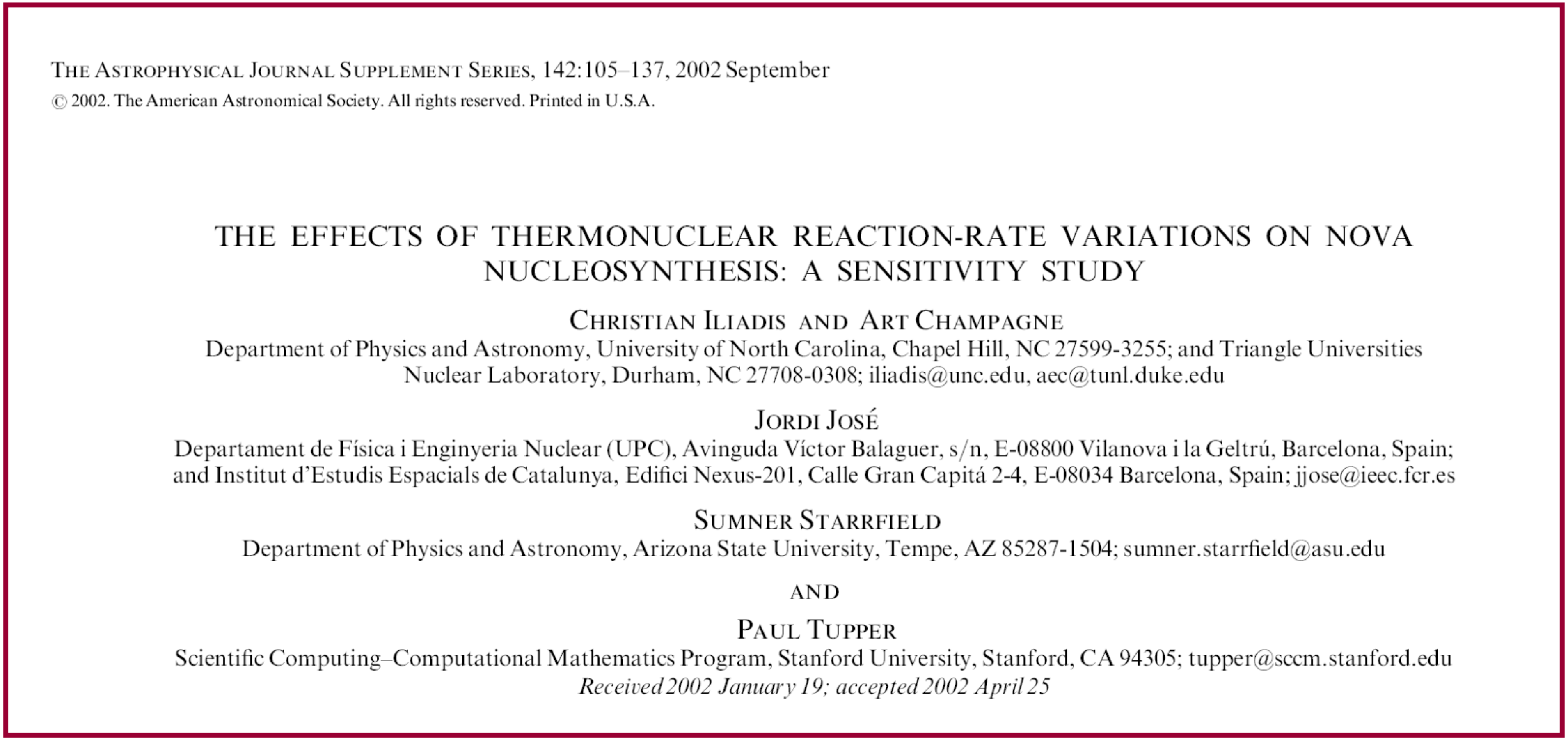
LIGO

COMMON ENVELOPE

AREPO SIMULATIONS

Ohlmann, Röpke+ (2016 ApJL)

Nuclear Uncertainties



The Astrophysical Journal Supplement Series, 142:105–137, 2002 September

THE EFFECTS OF THERMONUCLEAR REACTION-RATE VARIATIONS ON NOVA NUCLEOSYNTHESIS: A SENSITIVITY STUDY

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and

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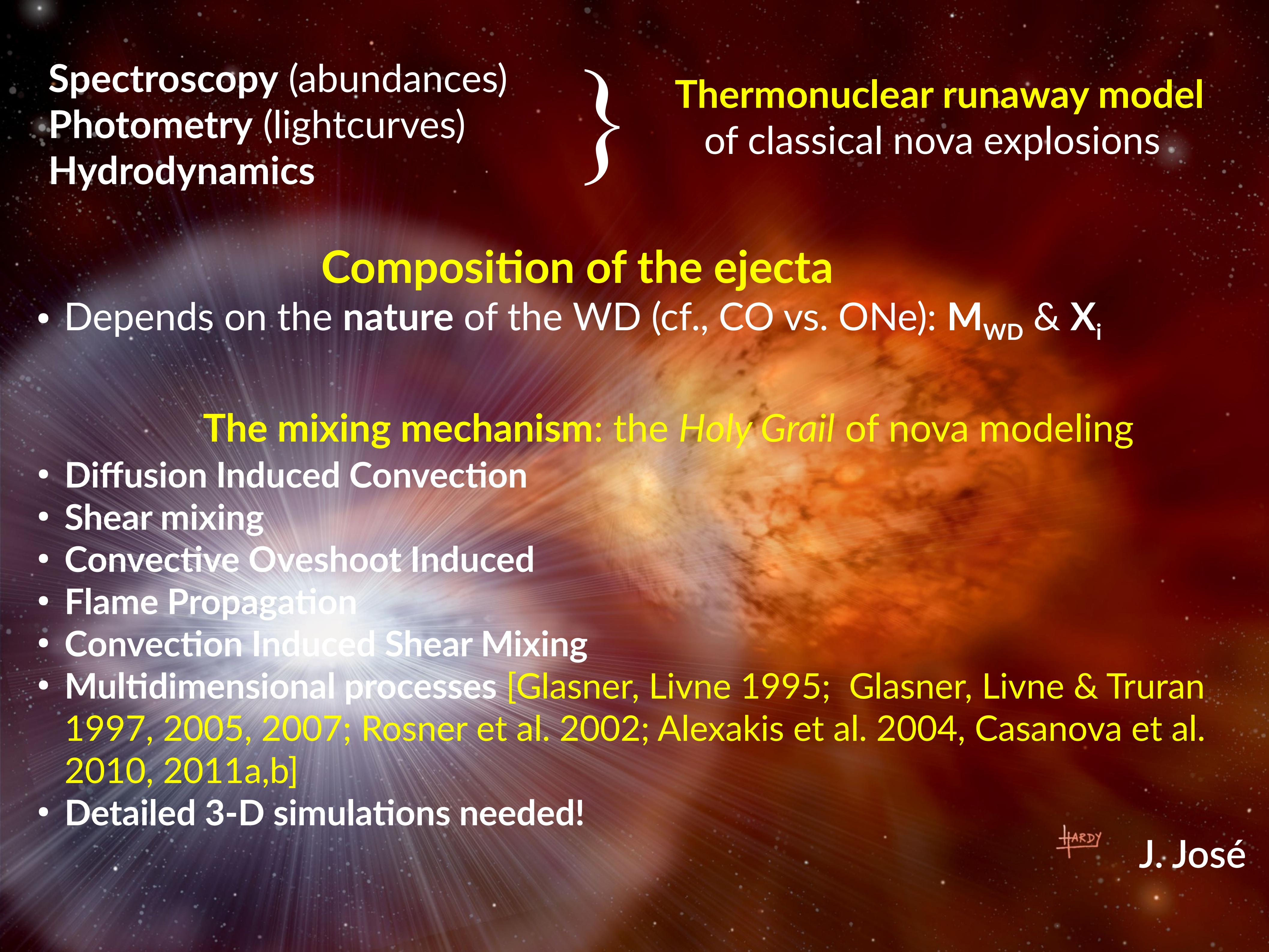
Received 2002 January 19; accepted 2002 April 25

$\approx$7350 nuclear reaction network calculations

Main nuclear uncertainties remaining:

^{18}F(p,α)^{15}O, ^{25}Al(p,γ)^{26}Si, ^{30}P(p,γ)^{31}S



Spectroscopy (abundances)
Photometry (lightcurves)
Hydrodynamics

} **Thermonuclear runaway model** of classical nova explosions

Composition of the ejecta

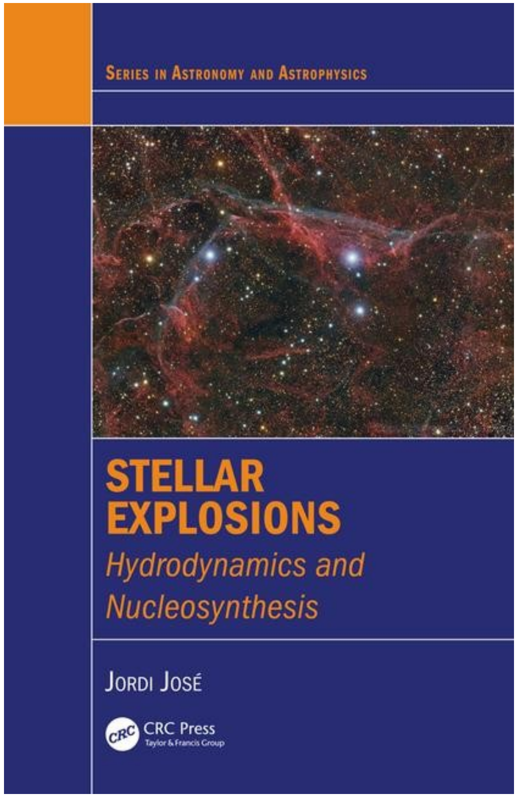
- Depends on the **nature** of the WD (cf., CO vs. ONe): $\mathbf{M_{WD}}$ & $\mathbf{X_i}$

The mixing mechanism: the *Holy Grail* of nova modeling

- **Diffusion Induced Convection**
- **Shear mixing**
- **Convective Oveshoot Induced**
- **Flame Propagation**
- **Convection Induced Shear Mixing**
- **Multidimensional processes** [Glasner, Livne 1995; Glasner, Livne & Truran 1997, 2005, 2007; Rosner et al. 2002; Alexakis et al. 2004, Casanova et al. 2010, 2011a,b]
- **Detailed 3-D simulations needed!**

J. José

Stellar Explosions: Classical Novae



Box I. The Nova “Hall of Fame”

A selection of facts on classical and recurrent novae

1. Classical and recurrent novae are thermonuclear explosions that take place on the white dwarf component of a close stellar binary system.

2. Novae represent the second, most frequent type of thermonuclear explosions in the Galaxy (after X-ray bursts), with an estimated frequency of ~ 30 events yr^{-1}.

3. Nova light curves are characterized by a constant bolometric luminosity phase.

4. Theoretical (1D hydrodynamic) models reproduce reasonably well the main observational features of nova outbursts (atomic abundances, light curves).

5. Infrared and ultraviolet observations often reveal dust-forming episodes in the ejected nova shells; presolar nova candidate grains have been identified by low $^{12}\mathrm{C}/^{13}\mathrm{C}$ and $^{14}\mathrm{N}/^{15}\mathrm{N}$ ratios, and excesses of $^{26}\mathrm{Mg}$ (from $^{26}\mathrm{Al}$ decay), $^{22}\mathrm{Ne}$ (from $^{22}\mathrm{Na}$ decay), and $^{30}\mathrm{Si}$.

6. The explosion propagates subsonically (deflagration). The outburst is likely quenched by envelope expansion (rather than by fuel consumption), and is driven by the energy released from the short-lived species $^{13}\mathrm{N}$, $^{14,15}\mathrm{O}$, and $^{17}\mathrm{F}$, which are convectively transported to the outer envelope layers. Their decay heats the envelope and lifts degeneracy.

7. Nova nucleosynthesis is driven by proton-capture reactions and β^+-decays operating close to the valley of stability.

8. Calcium is the likely endpoint for nova nucleosynthesis.

9. Novae are major contributors to the Galactic abundances of $^{15}\mathrm{N}$, $^{17}\mathrm{O}$, $^{13}\mathrm{C}$, and, to a lesser extent, $^{7}\mathrm{Li}$ and $^{26}\mathrm{Al}$.

NOVA EXPLOSIONS

HYDRODYNAMIC MIXING PROCESSES

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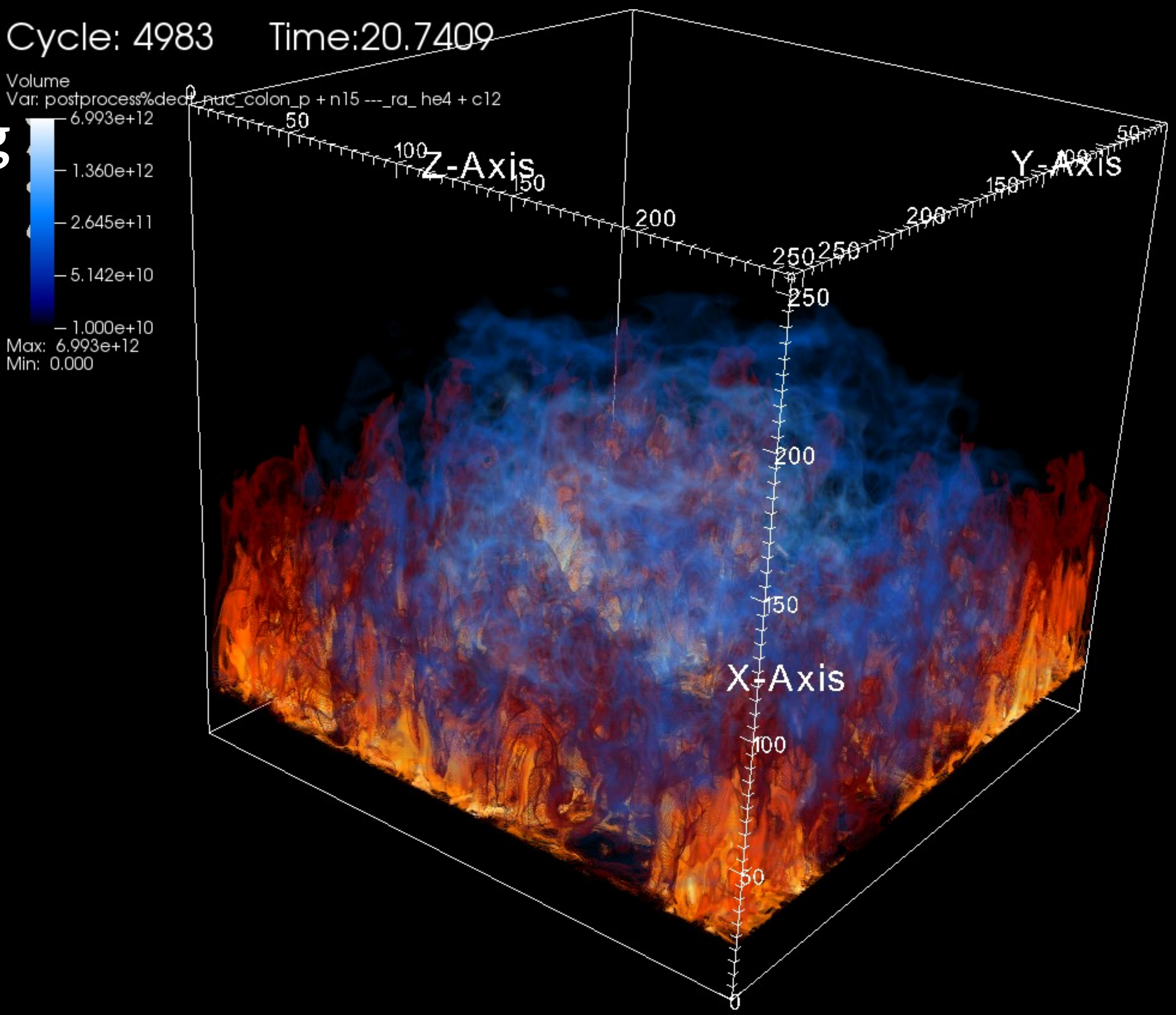

Convective boundary mixing (CBM) can reproduce observed enrichment of C and O (Denissenkov+ 2013) in novae and post-AGB stars (Werner & Herwig 2006)

The provides a handy constraint, but how good is the parametrized diffusive CBM model for this?