
Monday, 16 April
THE ERA OF PRECISION STELLAR PHYSICS

9h00 Aldo Serenelli	Open questions in solar models and lessons for other stars
9h30 Yvonne Ellsworth	Solar and Stellar Variability
10h00 Matteo Cantiello	The Era of High Precision Stellar Physics
10h30 Saskia Hekker	Stellar Oscillations

Tuesday, 17 April
CHEMISTRY, DUST, GAS DYNAMICS, ATMOSPHERES OF PLANETS AND STARS

9h00 Edwin Bergin	Thinking Broadly about Molecules in Astrophysics
9h30 John Lattanzio	Stars and their composition and evolution

I am free to talk rubbish!

~~STARS AND THEIR COMPOSITION AND EVOLUTION~~

JOHN LATTANZIO

MONASH CENTRE FOR ASTROPHYSICS

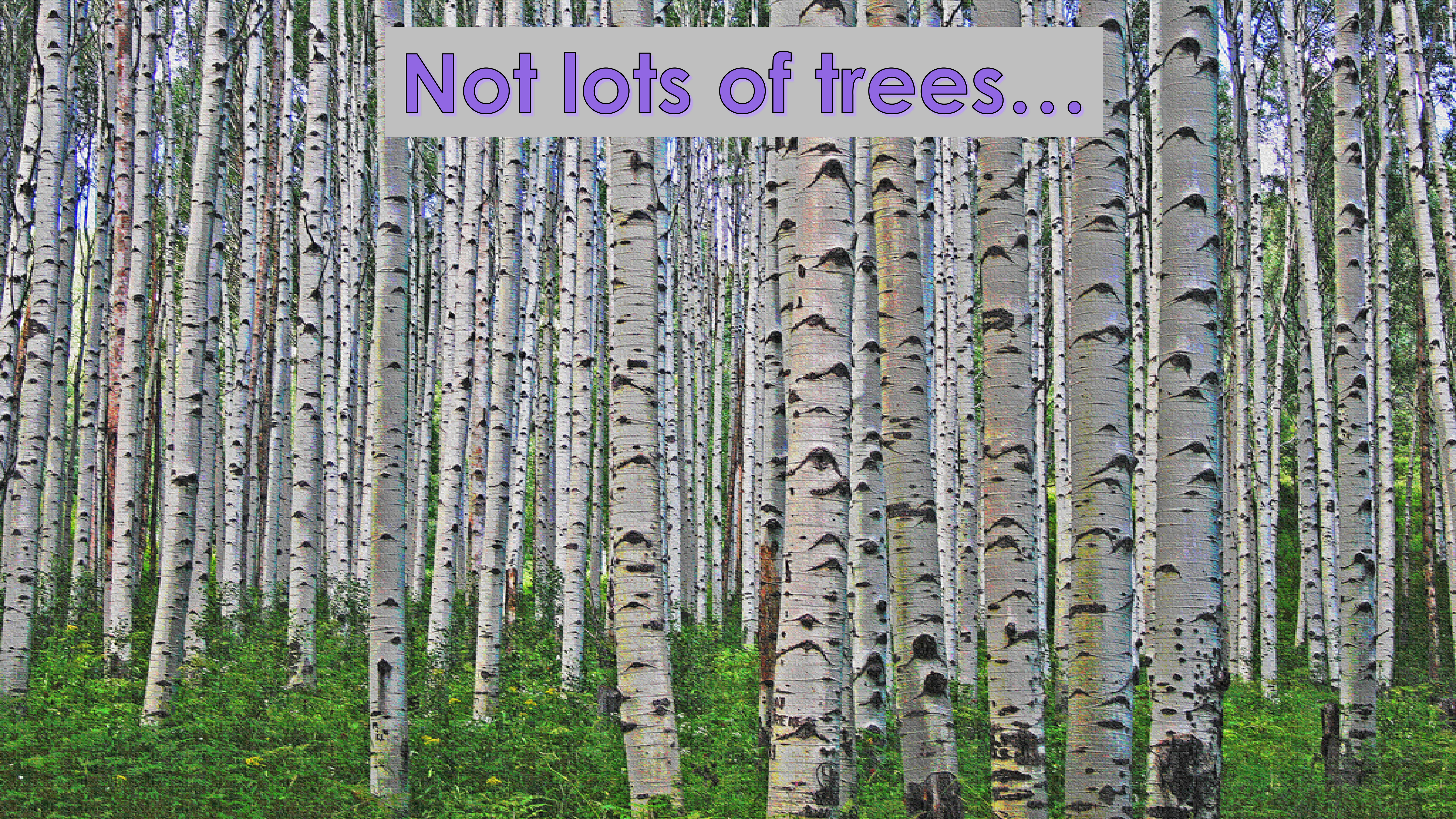
With input from, and thanks to:
Simon Campbell
George Angelou
Matteo Cantiello
Amanda Karakas

FOR THOSE WHO WANT TO SLEEP

1. Stellar models are tools we can use to understand many things
2. There is feedback from the applications which aids in improving the models
3. Be very careful when using codes that you did not write yourself!
4. Be very careful in trusting papers written by people who used codes they did not write…

YOU MAY NOW TAKE A NAP…

WHAT DOES THIS AUDIENCE WANT?


Not lots of trees…


Perhaps properties of the forest?

ON STARS AND HAMMERS

JOHN LATTANZIO

MONASH CENTRE FOR ASTROPHYSICS

With input from, and thanks to:
Simon Campbell
George Angelou
Matteo Cantiello
Amanda Karakas

MoCA
Monash Centre for Astrophysics

MONASH University

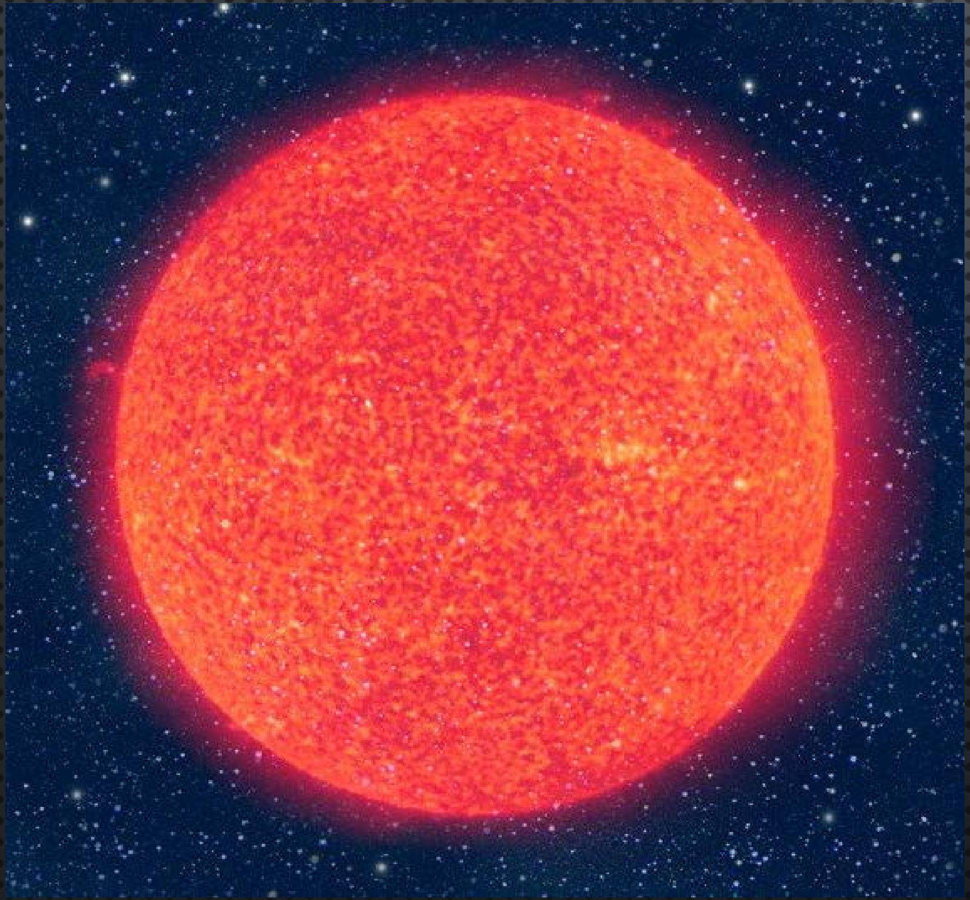
IF I HAD A HAMMER

- I'd build a bridge

IF I HAD A HAMMER

- Different requirements need different tools
- Need to develop a range of hammers
  - Special hammers for different jobs
- Better hammers make better bridges
- I get paid for making bridges, not for making hammers

Need to do both simultaneously

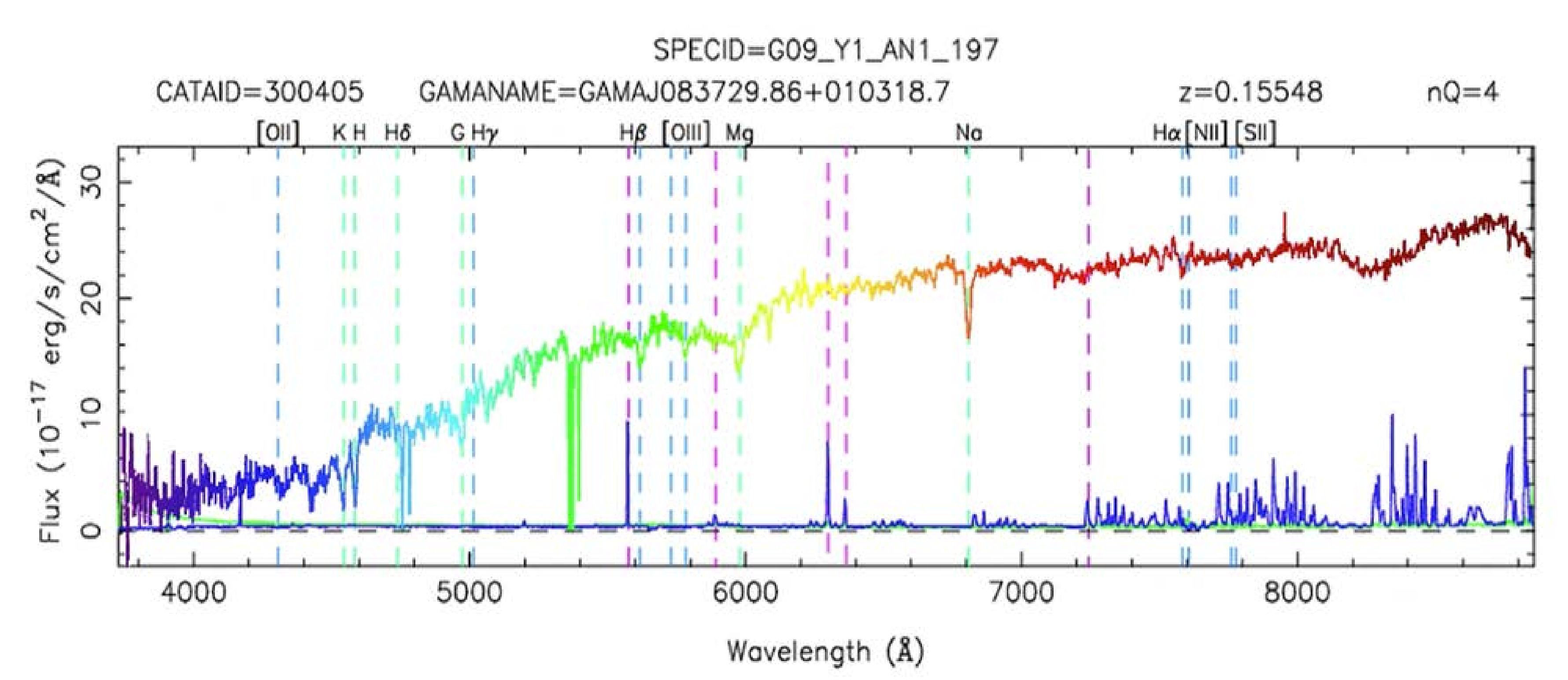


=


Stalwart
16oz.
Stalwart

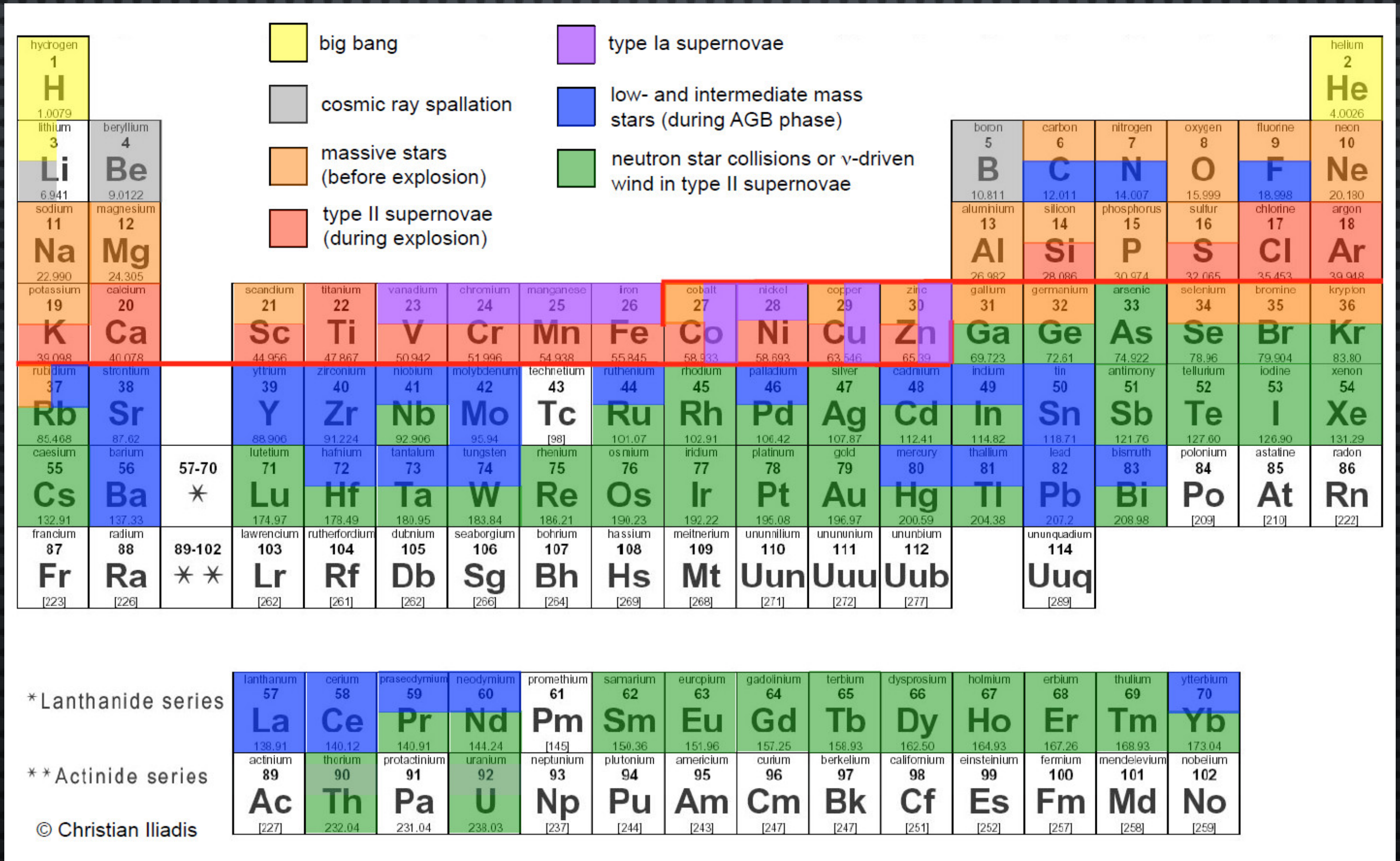
STARS: THE MOST FUNDAMENTAL ASTRONOMICAL OBJECTS

- Light
  - Almost all observations use starlight



STARS: THE MOST FUNDAMENTAL ASTRONOMICAL OBJECTS

- Composition
  - Essentially every element was made in stars

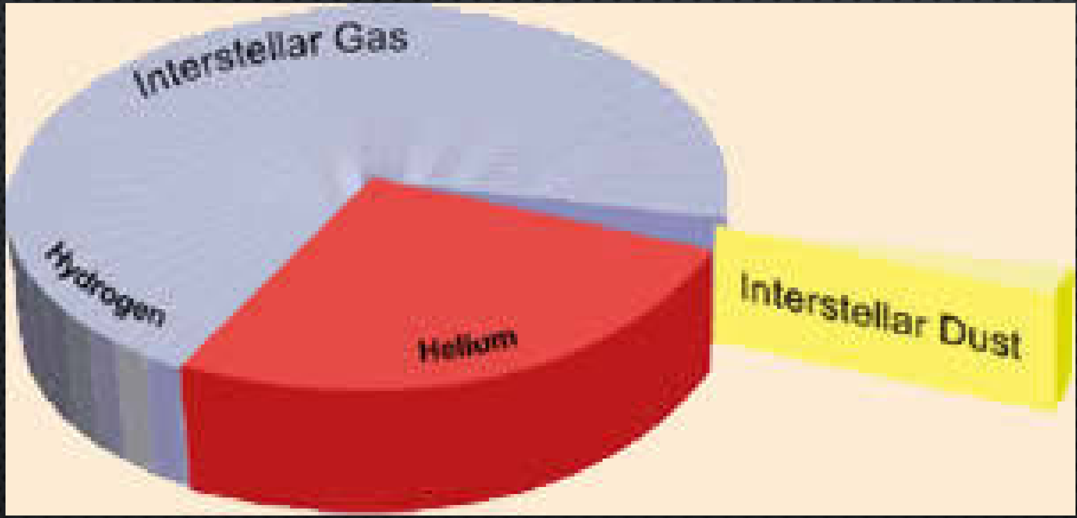


STARS: THE MOST FUNDAMENTAL ASTRONOMICAL OBJECTS

- Large-scale structure
  - Drive much galactic structure
  - Stir ISM

STARS: THE MOST FUNDAMENTAL ASTRONOMICAL OBJECTS

- Small-scale astrophysics
  - Make dust
  - Return recycled gas



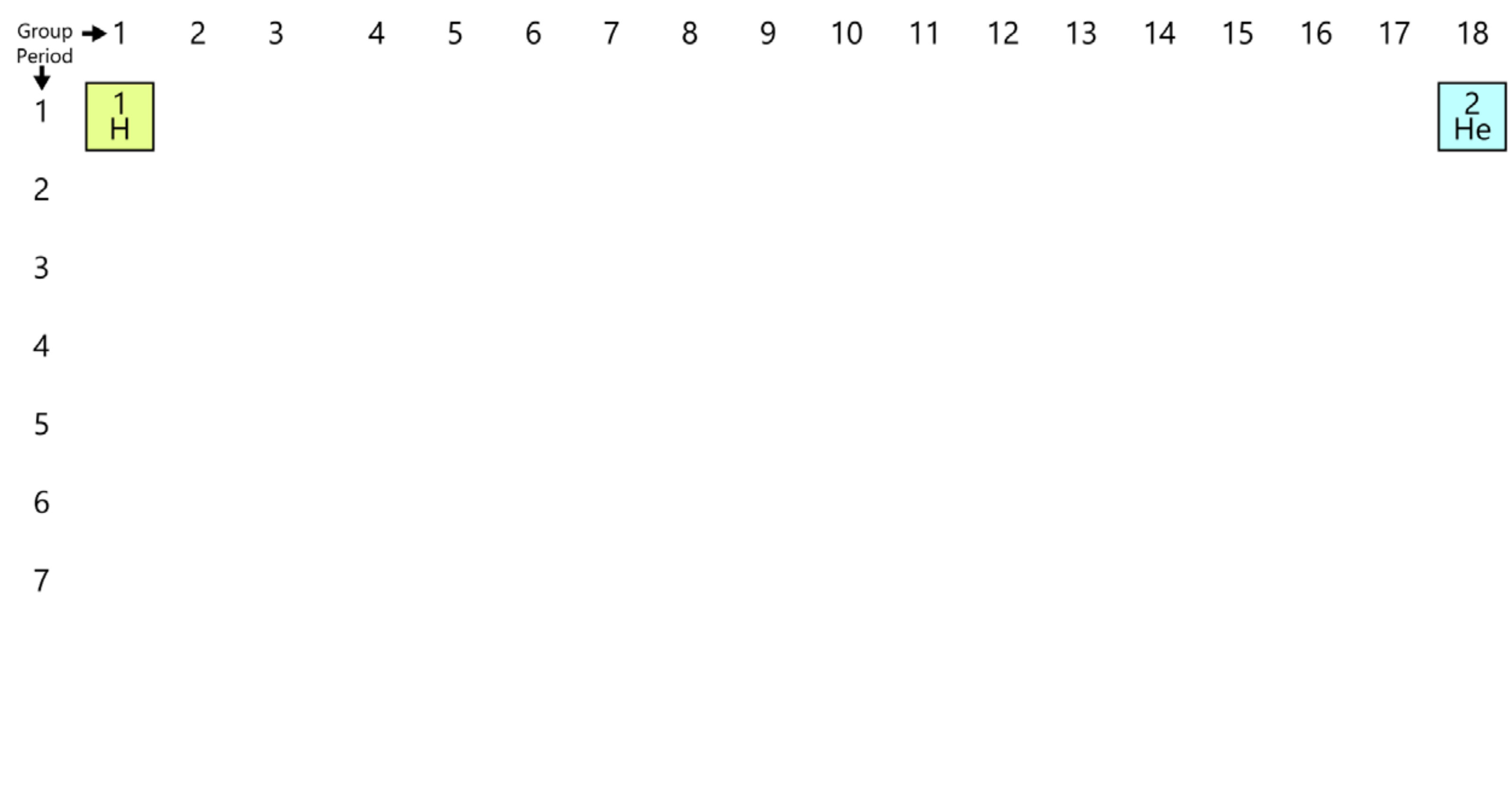
STELLAR MODELS ARE HAMMERS

- Basic hammers get the job done
- Basic stellar models get the job done

- How basic?
- Follow the Light?
- Need structure and evolution

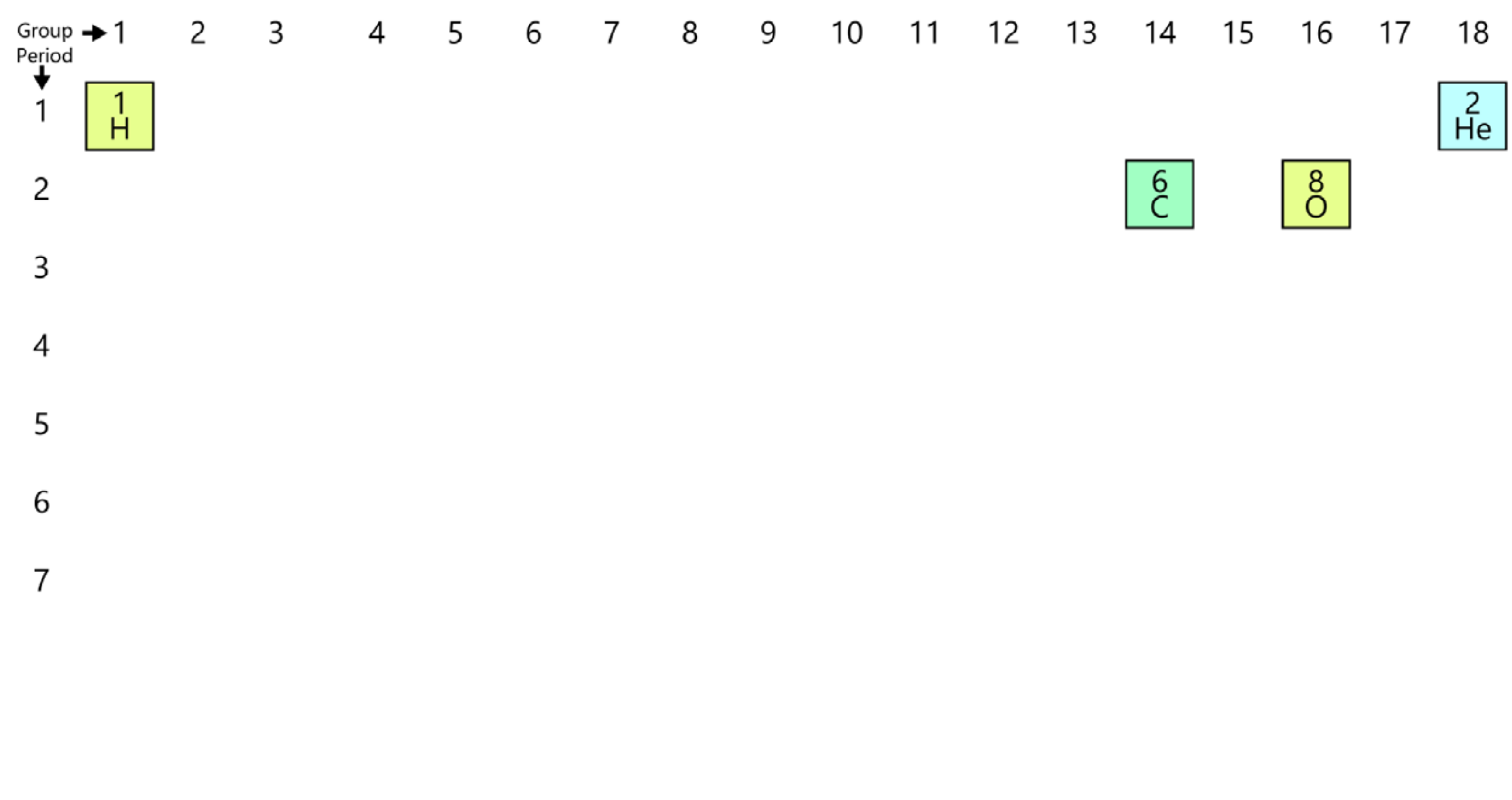
STELLAR MODELS ARE HAMMERS

- Need structure and evolution
- Composition? H and not-H will do pretty well!



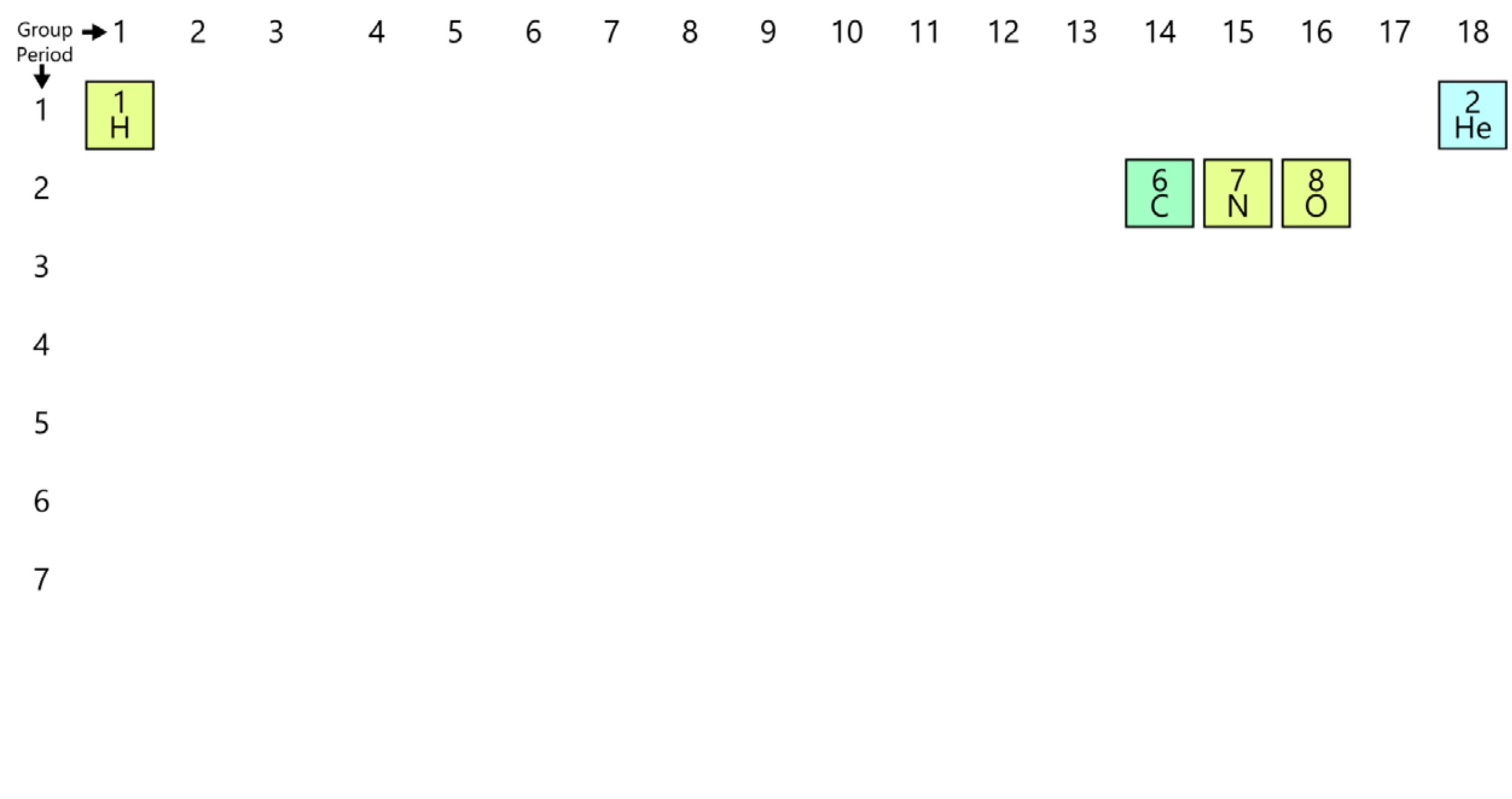
STELLAR MODELS ARE HAMMERS

- Need structure and evolution
- Composition? H and not-H will do pretty well!
- Add C and O to get through He burning…



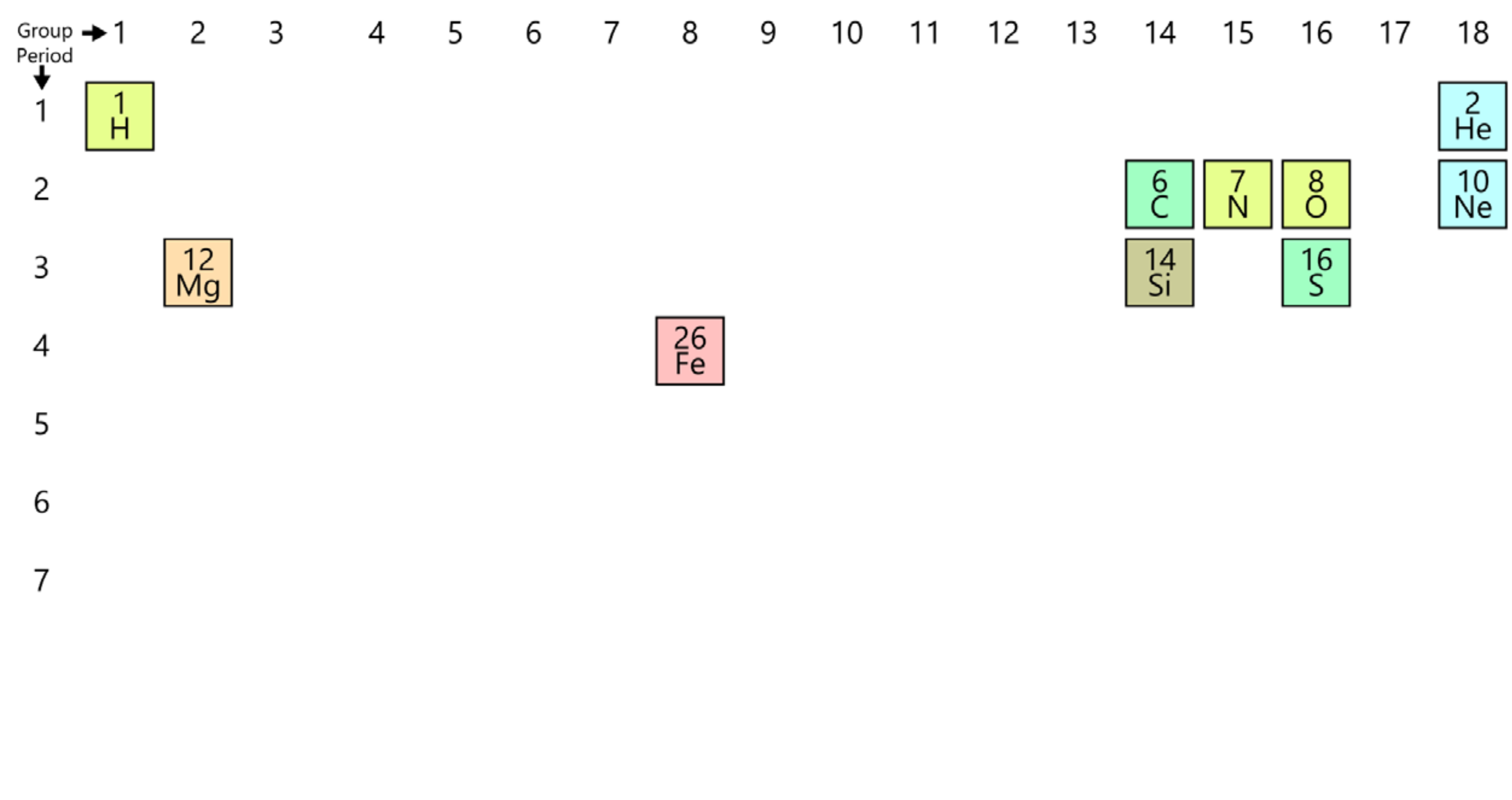
STELLAR MODELS ARE HAMMERS

- Need structure and evolution
- Composition? H and not-H will do pretty well!
- Add C and O to get through He burning…
- Sophisticated?
    - Add CNO…



STELLAR MODELS ARE HAMMERS

- Need structure and evolution
- Composition? H and not-H will do pretty well!
- Add C and O to get through He burning…
- Sophisticated?
  - Add CNO…
  - A few other things?
- Six to ten species is fine!



WHY DO SUCH SIMPLE MODELS WORK SO WELL?

- The composition occurs in three places

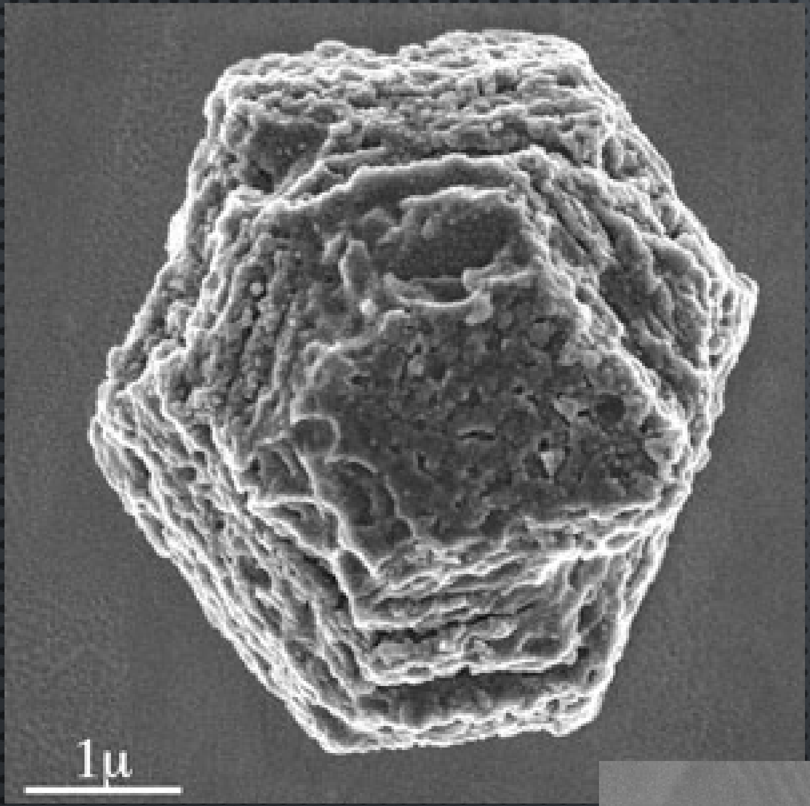
- Equation of State $$P = \frac{\rho R T}{\mu}$$

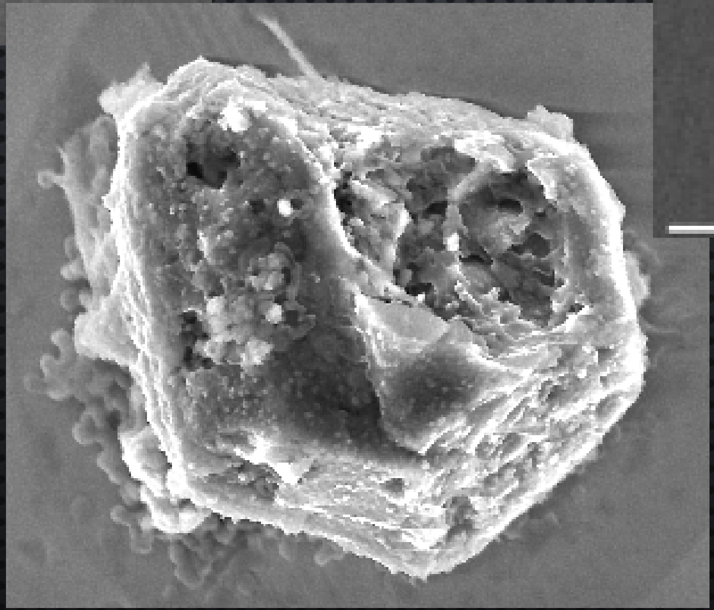
- Opacity $$\kappa = \kappa(\rho, T, \{X_i\})$$

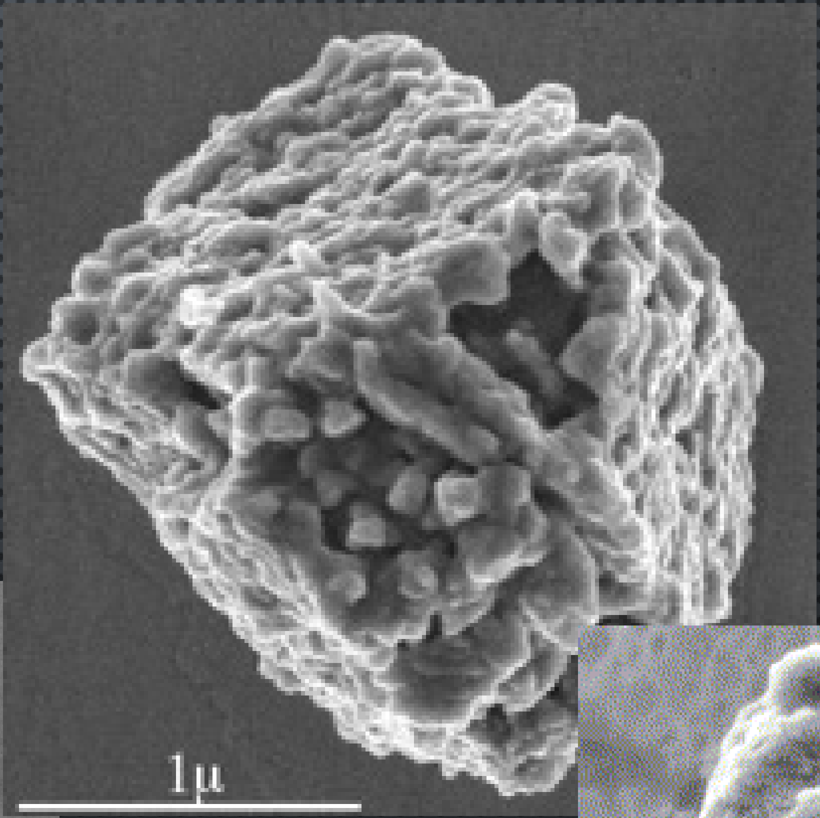
- Nuclear Reactions $$r_{ij} = R X_i X_j \rho^a T^b$$

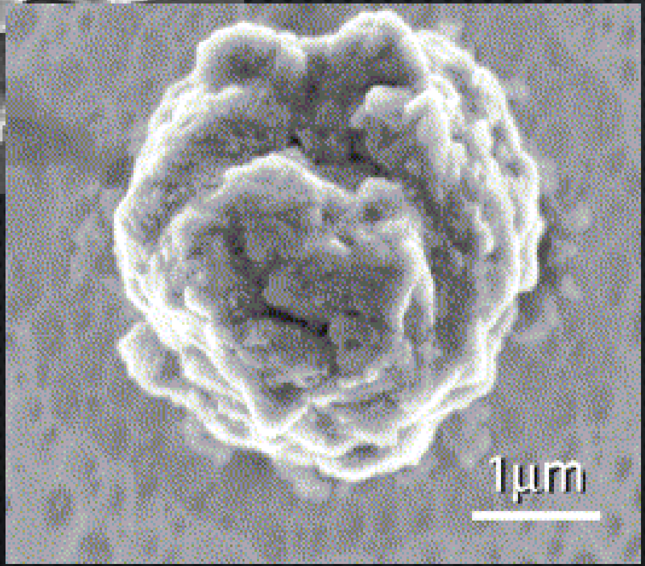
- Hence very few species are needed!
- Only the most abundant!

Pre-solar Grains

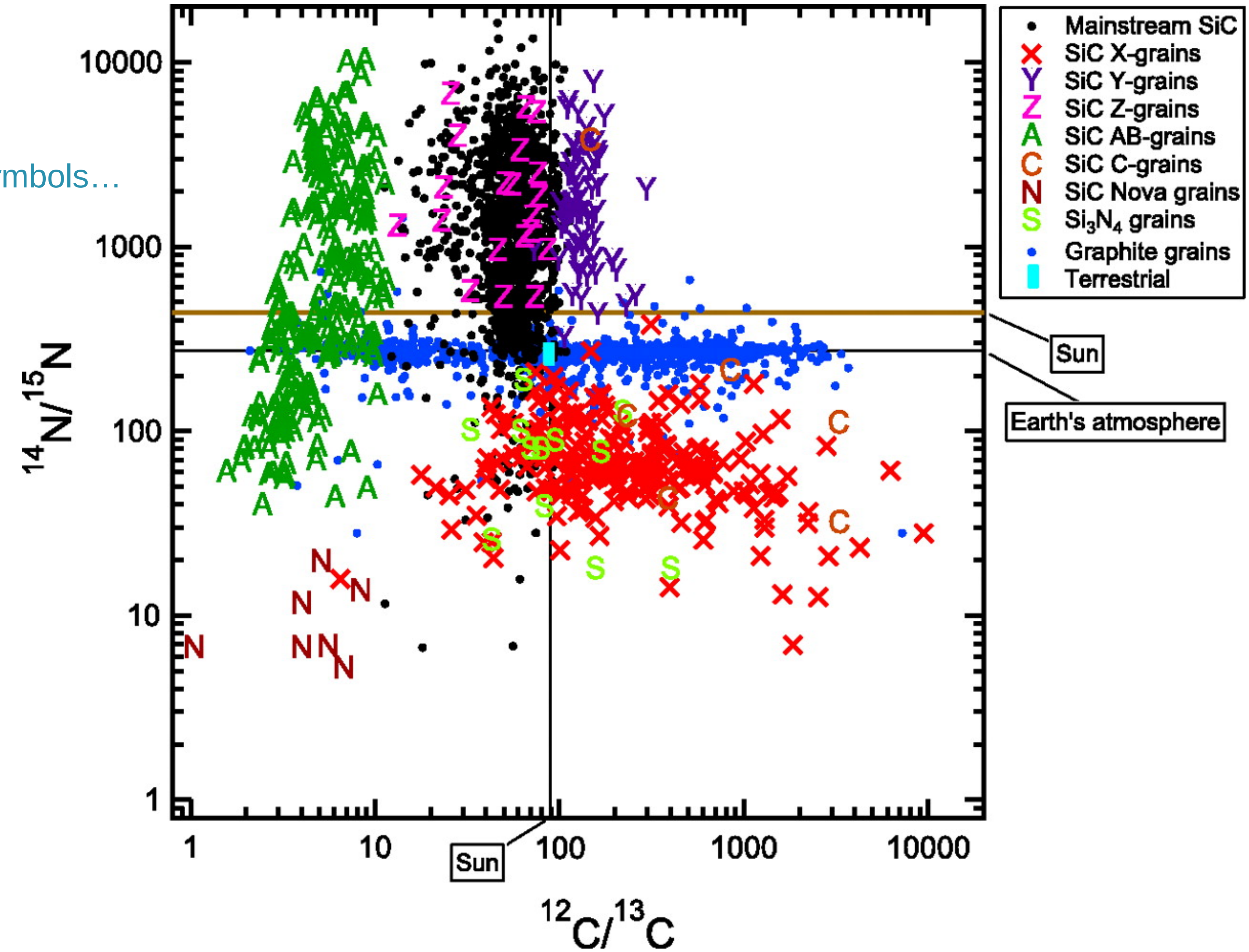






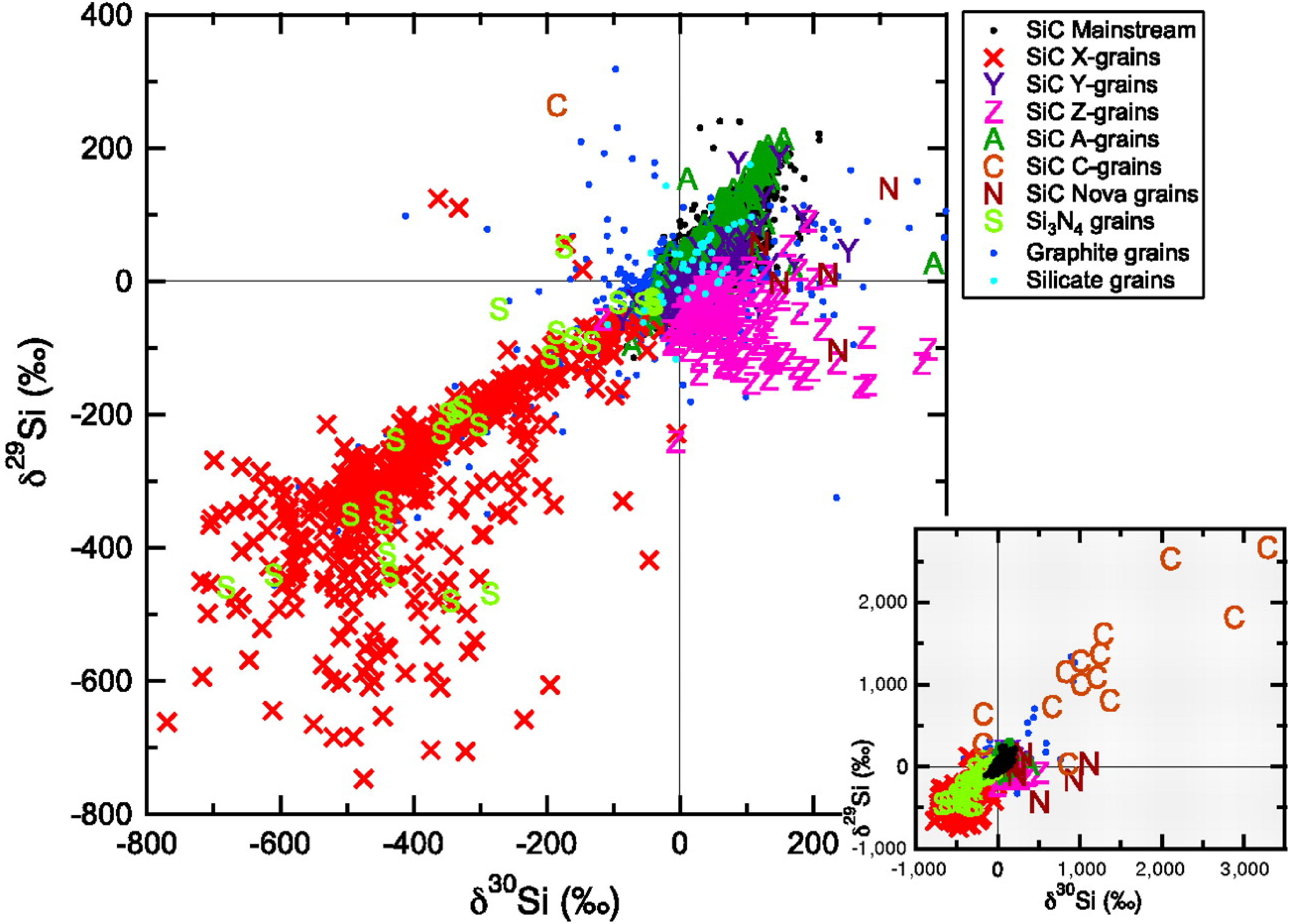


Error bars smaller than the symbols…



Andrew M. Davis

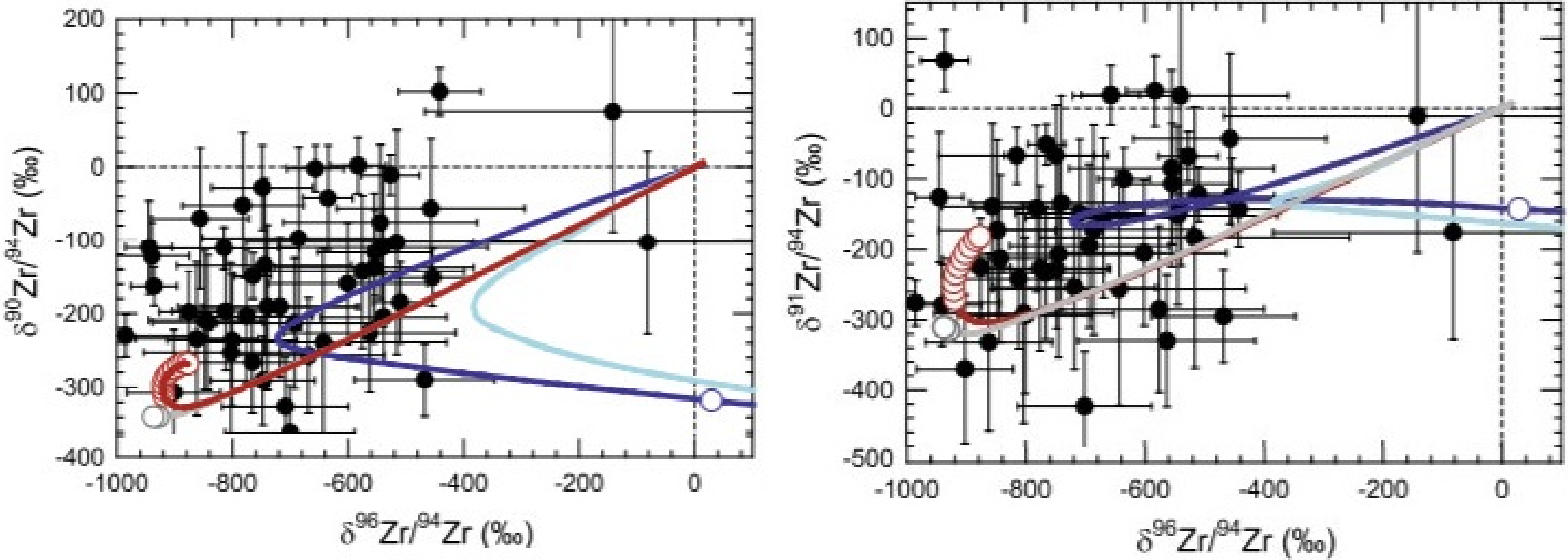
PNAS November 29, 2011. 108 (48) 19142-19146; https://doi.org/10.1073/pnas.1013483108



Andrew M. Davis

PNAS November 29, 2011. 108 (48) 19142-19146; https://doi.org/10.1073/pnas.1013483108

$\delta^{xx}Si = [(^{xx}Si/^{28}Si)_{sample}/(^{xx}Si/^{28}Si)_{Earth} - 1] \times 1000.$



M. Lugaro et al. / Geochimica et Cosmochimica Acta 221 (2018) 6–20

$$\delta^{xx}\mathrm{Si} = [(^{xx}\mathrm{Si}/^{28}\mathrm{Si})_{\mathrm{sample}}/(^{xx}\mathrm{Si}/^{28}\mathrm{Si})_{\mathrm{Earth}} - 1] \times 1000.$$

AN AVALANCHE OF QUESTIONS…

"How much ^{13}C do your models make?"

There is a carbon-13?

"Can your stars make Pb?"

Lead? Are you serious?

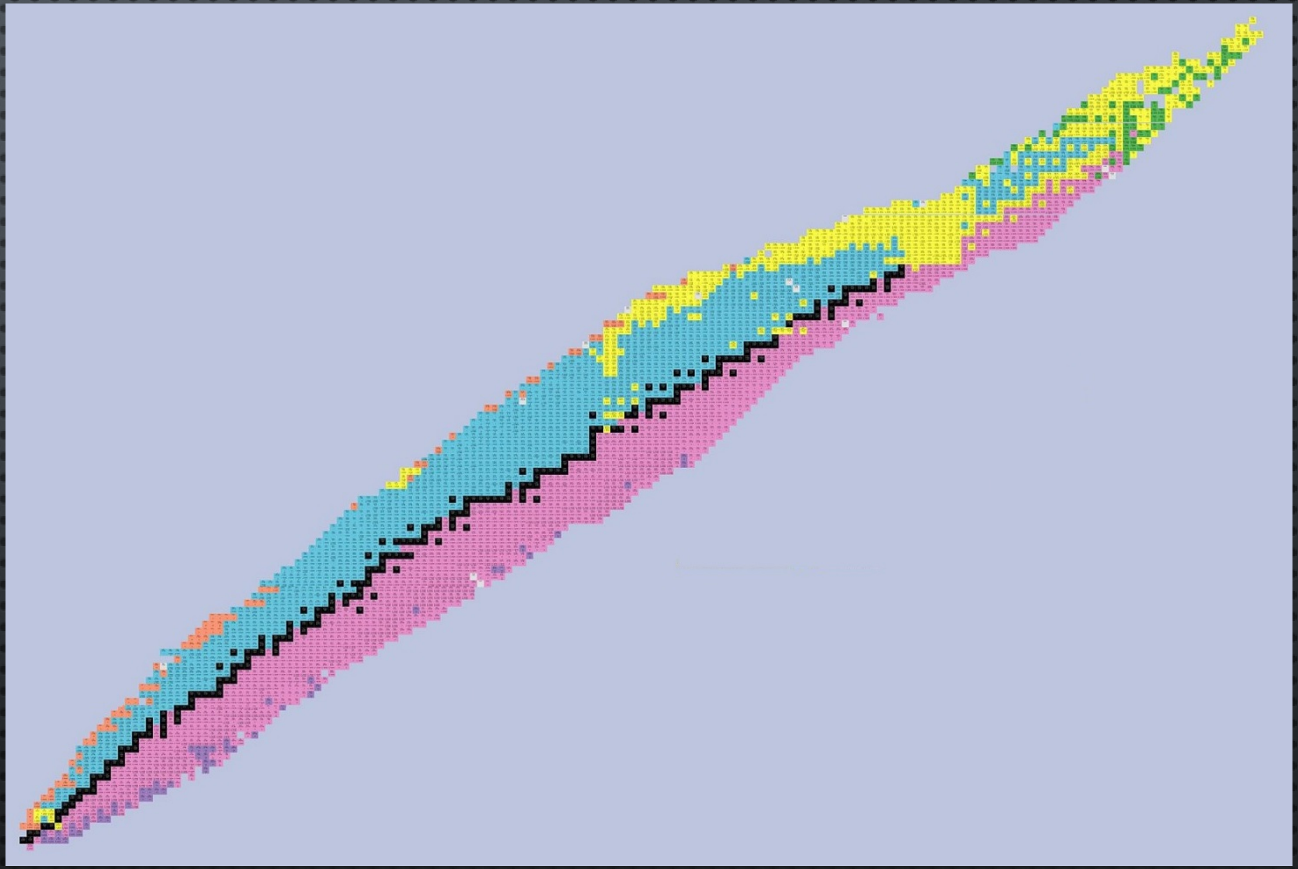
"How much strontium can you make?"

What is strontium?

I need a new hammer!

NEW HAMMER FOR NUCLEOSYNTHESIS

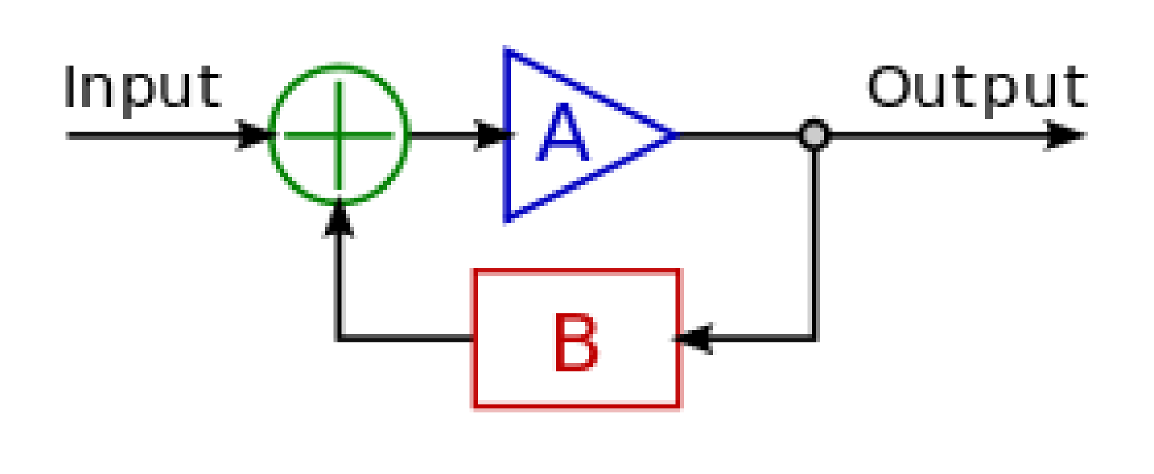
- Hundreds of isotopes
- Specialized meshing
- Custom time-stepping



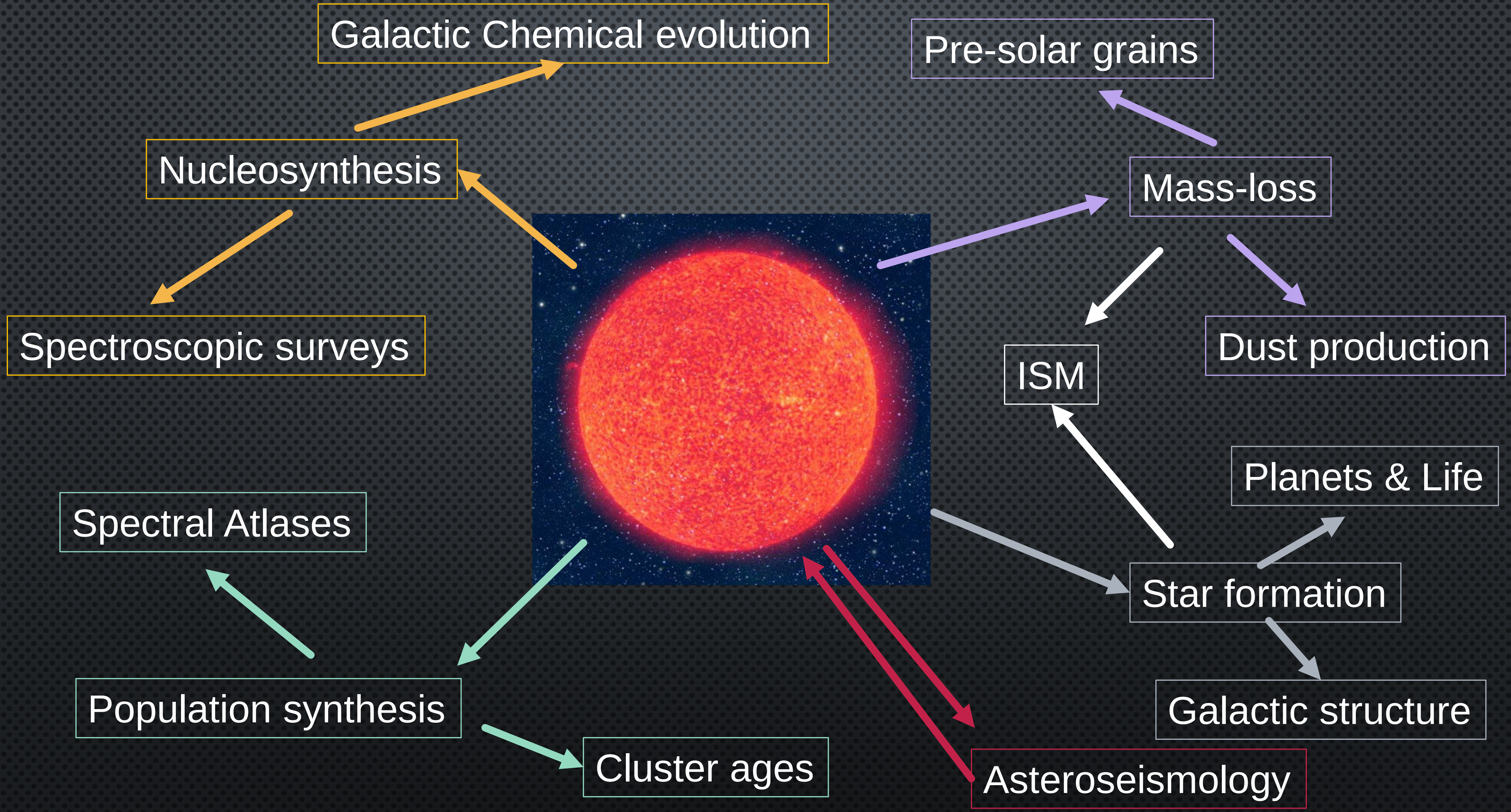
Specialized Hammer

IMPROVEMENTS IN MODELS

- Stellar model = background
- Nuclear reactions are the focus
- Observations tell us of problems



- Reaction rates
- Stellar Structure
- Mixing
- etc


Galactic Chemical evolution
Pre-solar grains
Nucleosynthesis
Mass-loss
Spectroscopic surveys
ISM
Dust production
Planets & Life
Spectral Atlases
Star formation
Population synthesis
Galactic structure
Cluster ages
Asteroseismology

I can make many things with my hammer

...and they help me to improve my hammer


UNDERSTANDING AND USING STARS:
WITH A LITTLE HELP FROM MY FRIENDS

Hammers aren't perfect for all jobs.
Sometimes we need different tools...

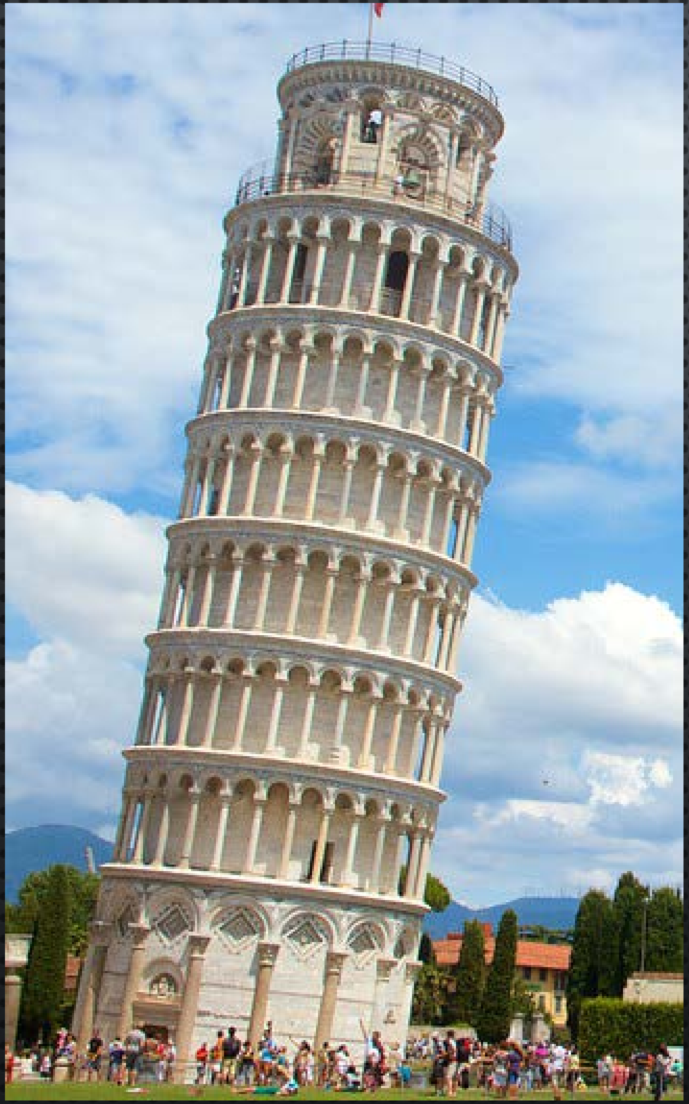
Develop a complete toolbox!

SPECIAL HAMMERS

- Main sequence stars
- Massive stars
- AGB stars
- Supernovae
- Rotating stars
- Different physical regimes
- Different numerical demands
- Specialized codes
- People specialize also…

Codes are not interchangeable

NOT EVERYONE CAN USE A HAMMER PROPERLY



GENERAL PURPOSE HAMMER FOR ALL?

- Let’s make a good hammer
- Make it versatile!
- Use hammer experts to help design it
- Try to make it foolproof

THE AGE OF PUBLIC CODES – BLACK BOXES??

- We are at the interface between disciplines
- We are in a computational age
- Open codes are common
- Expert usage is *not so common*

- *Code may be OPEN SOURCE*
  but used as if were a black box!

- SPH in pre-Cambrian days…

- I will use MESA as an example
  - Nothing special about MESA!
  - Its just the example I most meet
  - Principles apply to *all open source codes*

MESA
Modules for Experiments in Stellar Astrophysics

- Versatile evolution code
- Well written
- Well documented
- Enables many to make stellar models
- Schools train people in its use

- But…

MESA

You may also want to visit ***the MESA marketplace****, where users share the inlists from their published results, tools & utilities, and teaching materials.*

Why a new 1D stellar evolution code?

The MESA Manifesto discusses the motivation for the MESA project, outlines a MESA code of conduct, and describes the establishment of a MESA Council. Before using MESA, you should read the **manifesto document**. Here's a brief extract of some of the key points

Stellar evolution calculations remain a basic tool of broad impact for astrophysics. New observations constantly test the models, even in 1D. The continued demand requires the construction of a general, modern stellar evolution code that combines the following advantages:

- **Openness**: anyone can download sources from the website.
- **Modularity**: independent modules for physics and for numerical algorithms; the parts can be used stand-alone.
- **Wide Applicability**: capable of calculating the evolution of stars in a wide range of environments.
- **Modern Techniques**: advanced AMR, fully coupled solution for composition and abundances, mass loss and gain, etc.
- **Comprehensive Microphysics**: up-to-date, wide-ranging, flexible, and independently useable microphysics modules.
- **Performance**: runs well on a personal computer and makes effective use of parallelism with multi-core architectures.

WARNINGS

David Arnett:

"To the extent that it is possible,
it is the isotopes that keep
the theorists honest."

WARNINGS

I would add:
Consistency between different modellers and different codes

Relying on any single code is *dangerous*.

RELIABLE AND TRANSPARENT

- We need to use *more* codes…

- Open-source codes include *MESA* and the Cambridge *STARS* code
- MESA is easier to use and hence is more commonly used by people
- It becomes the default – which is not wise

- Other codes are freely available, even if not “open”
  - Usually they are shared after a training period
  - …an apprenticeship
  - …so the user knows more about the code and potential problems

RELIABLE AND TRANSPARENT

- We need to use *more* codes…
- Maybe we need *more* well-supported codes
  - Diversity of numerical methods etc
  - More reliable results
- But supporting codes at this level is expensive
- Who will pay?
- Will funding agencies support more than one such code?

WARNING SIGNS

- "I used the most advanced stellar evolution code, MESA."
  - A seminar speaker
    - There are many well tested codes…they are different…
- "Whatever MESA produces is correct."
  - "It was written by stellar and software experts!"
  - A user
    - No code is correct!
    - But most are useful ☺

Very dangerous view!

WARNING SIGNS

- “MESA is great – it does everything!”
  - A user
    - If you know how, it is indeed very versatile

- “We used initial_condition = 3”
  - A paper
    - What will history make of this in 10 years? 50 years?
    - This should not be accepted!

Please do include the input parameters *and MESA version number* so the work can be reproduced. But please give physics descriptions in the paper.
REFEREES PLEASE NOTE!

WARNING SIGNS

- “Why does your code crash? MESA doesn’t!”
  - A referee

- It was due to over-smoothing opacity….so it would continue to run…

    - Crashes are places where we learn…
    - The skill is in examining why it crashed…
      - Physics?
      - Numerical?

A SINGLE CODE FOR EVERYTHING

DESIGN PHILOSOPHY: **ALWAYS RUNS**

- Many things are done to make it “foolproof”
- Smoothing of variables is very common

```
!### smooth_convective_bdy

! This is an option to smooth composition gradients
! in newly non-convective regions trailing behind a retreating convection zone.
! This effectively erases (most) of the stair-casing that happens without it.
! But you should be aware that the smoothing process does not conserve species mass --
! e.g., if have retreating He burning core below H shell,
! then the smoothing will convert some H into He in the newly non-convective region
! (this can be hand waved away as modeling partial burning of those regions
! during the substep period before the convection had retreated past the location).

! set this true to have the stair-casing removed at the price of some changes in abundances.


  smooth_convective_bdy = .true.
```

The warning is there…if you know what you are doing!

A VERY SPECIAL HAMMER

- Works fine for the first 6 times it hits the nail
- On the next strike it just passes straight through the nail

DESIGN PHILOSOPHY: ALWAYS RUNS

After 6 iterations we no longer ensure solution satisfies the equations.

Uses a technique designed to get closer to the solution but does not check it *is an actual* solution…

The warning is there…if you know what you are doing!

RECENT DEVELOPMENT:

“Gold Tolerances”

- There are now “gold tolerances” in MESA
- These should be used as defaults
- These should be changed only when you know the consequences

CONVERGENCE IS MESSY

- All codes use some sorts of tricks or massaging during difficult phases!
- You need to know what you are doing…

IN SUPREMÆ DIGNITATIS
1343

UNIVERSITÀ DI PISA

Dipartimento di Fisica

Tesi di Laurea Magistrale

Anno Accademico 2013/14

Systematic Study of Mass Loss in the Evolution of Massive Stars

Candidate:
Mathieu Renzo

Advisors:
Prof. Steven N. Shore
Prof. Christian D. Ott

APPENDIX B

From a naive use of MESA toward physically sound Results

We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover up all the tracks, to not worry about the blind alleys or describe how you had the wrong idea first, and so on. So there really isn't any place to publish, in a dignified manner, what you actually did in order to get to do the work.
[R. Feynman, Nobel Lecture, December 11, 1965]

B.1 Warning to the Naive MESA User

MESA is a very well designed code that rarely crashes, forcing the new user to look for the problem(s) to fix. Most of the time, MESA does *not* crash, but instead it is able to find a solution, which – too often – may not be physically sound. The burden of understanding the solutions MESA finds, and more importantly, of determining how realistic these are, is left to the user. "MESA is a tool, not a theory".

The aim of this appendix is to summarize part of the work I did to improve my results. I focus on issues found in the evolution of non-rotating, solar metallicity, massive stars of $M_{\mathrm{ZAMS}} \leq 40 M_{\odot}$, however the careful analysis of the results is needed for any problem the code can handle. The take-home point is *to not believe any result the MESA code can and will produce, but analyze it very carefully each time.* In my experience, MESA often converges to unphysical solutions rather than crashing when something is wrong. Because of the non-linearity of the equations for a stellar structure, a small inaccuracy in an aspect believed to be secondary, might have rather significant effects. The aspect causing unexpected and undesired behaviors may be very hard to individuate. Most of the work is left to do once a numerical model has been found for the problem considered.

In §B.2 I describe the issue of unphysical oscillations of the stellar surface (see also §2.3), which can be solved by using a more realistic determination of the outer boundary condition. This provides an example of the effects that an inaccurate treatment of an aspect initially thought to be secondary can have on the results. In §B.3, I describe the ongoing work to improve the resolution of the stellar cores during late burning stages, emphasizing the need for large nuclear reaction networks.

B.1 Warning to the Naive MESA User

MESA is a very well designed code that rarely crashes, forcing the new user to look for the problem(s) to fix. Most of the time, MESA does *not* crash, but instead it is able to find a solution, which – too often – may not be physically sound. The burden of understanding the solutions MESA finds, and more importantly, of determining how realistic these are, is left to the user. "MESA is a tool, not a theory".

The aim of this appendix is to summarize part of the work I did to improve my results. I focus on issues found in the evolution of non-rotating, solar metallicity, massive stars of $M_{\mathrm{ZAMS}} \leq 40 M_{\odot}$, however the careful analysis of the results is needed for any problem the code can handle. The take-home point is *to not believe any result the MESA code can and will produce, but analyze it very carefully each time.* In my experience, MESA often converges to unphysical solutions rather than crashing when something is wrong. Because of the non-linearity of the equations for a stellar structure, a small inaccuracy in an aspect believed to be secondary, might have rather significant effects. The aspect causing unexpected and undesired behaviors may be very hard to individuate. Most of the work is left to do once a numerical model has been found for the problem considered.

In §B.2 I describe the issue of unphysical oscillations of the stellar surface (see also §2.3), which can be solved by using a more realistic determination of the outer boundary condition. This provides an example of the effects that an inaccurate treatment of an aspect initially thought to be secondary can have on the results. In §B.3, I describe the ongoing work to improve the resolution of the stellar cores during late burning stages, emphasizing the need for large nuclear reaction networks.

True of any numerical code!!!

(ost of the work is left to do once a
numerical model has been found for the problem considered.

A LARGER PROBLEM

- This contributes to the view that “stellar modelling is easy.”
- It’s not.
- Main sequence? Yes
- But other phases

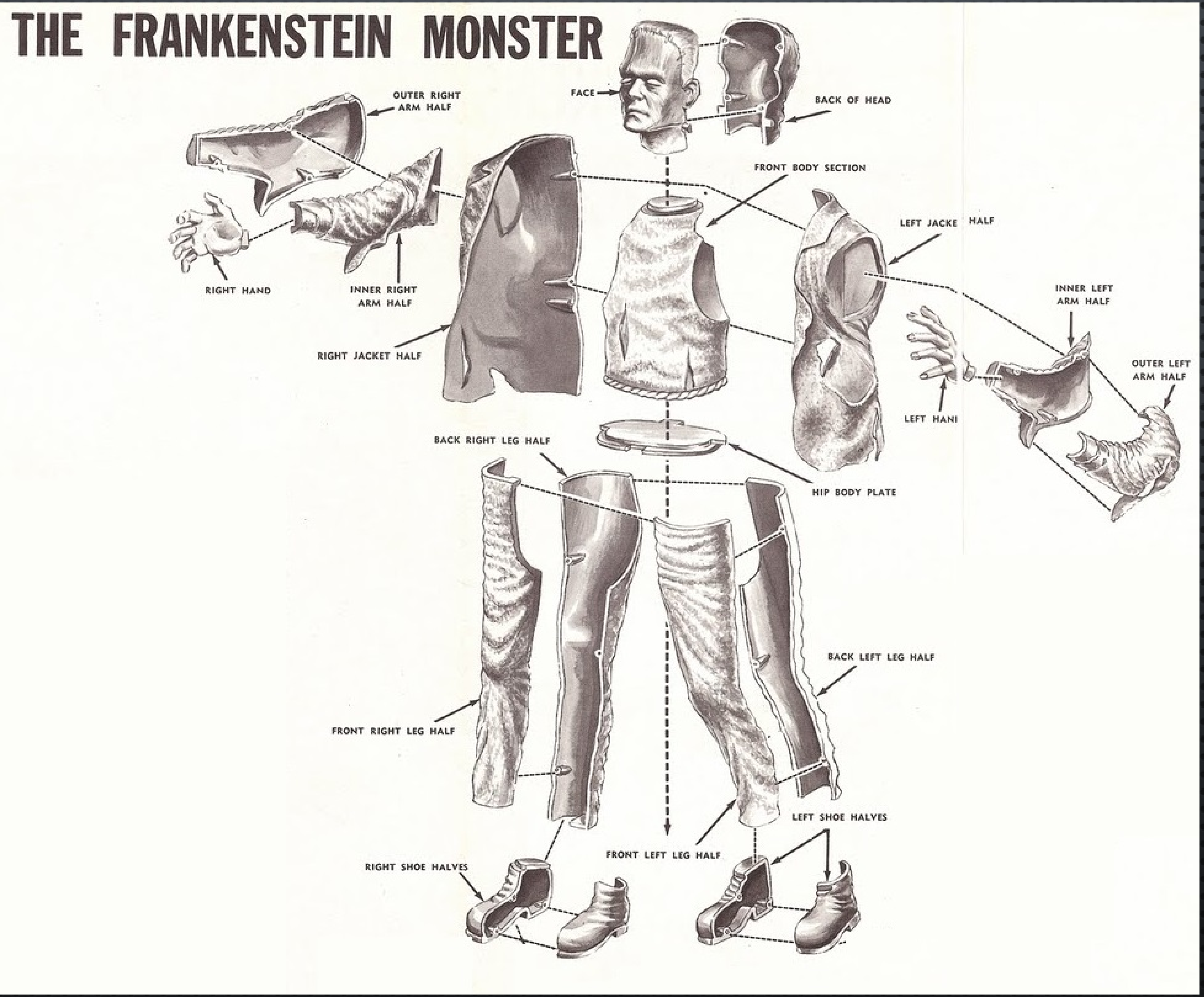
    are NOT TRIVIAL!!!

MESA PEOPLE/PROJECT ARE NOT TO BLAME!

- The info is all there!
- They run Schools in how to use MESA
- They have good physics in it
- They are good programmers

But the *tool* is being misused…

An evolution code is a Frankenstein's monster!



An evolution code is a Frankenstein's monster!

- Various parts are patched together
- Solutions are found for specific problems that arise
- Different patches are included for various cases

- MESA is open and these are clearly documented
- That is not true in many other codes…

- Knowledge is required – in both cases!

To control the monster you may need to be Dr Frankenstein…

…and not some clown!


"…not a bunch
of amateurs…"

The code may start off being nice to you...

…but eventually
it will turn on you!

SUGGESTION FOR MESA

- Set all default parameters to their MOST ACCURATE
- Code will not just run – it will crash often ☺
- Provide documentation on most common causes of crashes….
- Suggest parameters for fixing it
- INCLUDING the effect this has on the models and the accuracy
- This forces the user to choose when and how to compromise

- More reliable models and better use of the tool?

ONE EXAMPLE WILL REALLY TIE THE TALK TOGETHER…

- Core He burning is very difficult
- Convection
- Semi-convection
- Induced overshoot
- Core breathing pulses
- It's very messy

A non-expert can easily make rubbish models.

We use feedback from friends to help make better models

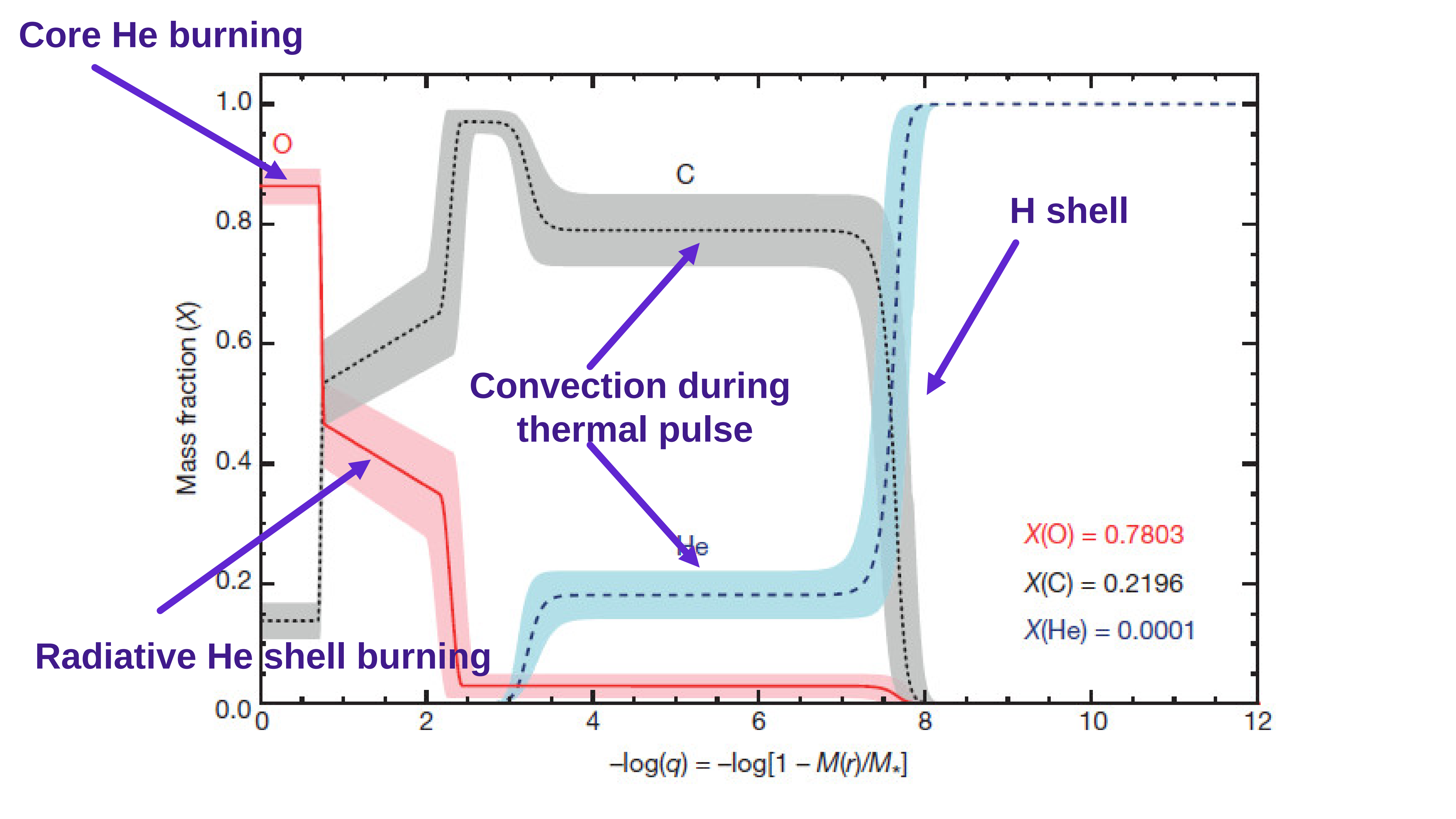
LETTER

doi:10.1038/nature25136

A large oxygen-dominated core from the seismic cartography of a pulsating white dwarf

N. Giammichele[1,2], S. Charpinet[1], G. Fontaine[2], P. Brassard[2], E. M. Green[3], V. Van Grootel[4], P. Bergeron[2], W. Zong[1,5] & M.-A. Dupret[4]

- Use highly accurate seismology
- Determine composition of interior
- He, C and O



Core He burning
H shell
Convection during thermal pulse
Radiative He shell burning
O
C
He
Mass fraction (X)
−log(q) = −log[1 − M(r)/M*]
X(O) = 0.7803
X(C) = 0.2196
X(He) = 0.0001

CONSTANTINO ET AL

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **452,** 123–145 (2015) doi:10.1093/mnras/stv1264

Asteroseismology

The treatment of mixing in core helium burning models – I. Implications for asteroseismology

Thomas Constantino,[1★] Simon W. Campbell,[1,2] Jørgen Christensen-Dalsgaard,[3] John C. Lattanzio[1] and Dennis Stello[3,4]

[1] *Monash Centre for Astrophysics (MoCA), School of Physics and Astronomy, Monash University, Victoria, 3800, Australia*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85748 Garching bei München, Germany*
[3] *Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*
[4] *Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia*

CONSTANTINO ET AL

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **452,** 123–145 (2015) doi:10.1093/mnras/stv1264

Asteroseismology

The treatment of mixing in core helium burning models – I. Implications for asteroseismology

Thomas Constantino,[1★
John C. Lattanzio[1] and
[1]Monash Centre for Astrophysics (MoCA
[2]Max-Planck-Institut für Astrophysik, Ka
[3]Stellar Astrophysics Centre, Department
[4]Institute for Astronomy (SIfA), School of

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **456,** 3866–3885 (2016) doi:10.1093/mnras/stv2939

HST photometry

The treatment of mixing in core helium burning models – II. Constraints from cluster star counts

Thomas Constantino,[1,2★] Simon W. Campbell,[2,3] John C. Lattanzio[2]
and Adam van Duijneveldt[2]
[1]*Physics and Astronomy, University of Exeter, Exeter EX4 4QL, UK*
[2]*Monash Centre for Astrophysics (MoCA), School of Physics and Astronomy, Monash University, VIC 3800, Australia*
[3]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85748 Garching bei München, Germany*

CONSTANTINO ET AL

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **452,** 123–145 (2015) doi:10.1093/mnras/stv1264

Asteroseismology

The treatment of mixing in core helium burning models – I. Implications for asteroseismology

Thomas Constantino,[1★
John C. Lattanzio[1] and
[1]*Monash Centre for Astrophysics (MoCA*
[2]*Max-Planck-Institut für Astrophysik, Ka*
[3]*Stellar Astrophysics Centre, Department*
[4]*Institute for Astronomy (SIfA), School of*

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **456,** 3866–3885 (2016) doi:10.1093/mnras/stv2939

HST photometry

The treatment of mixing in core helium burning models – II. Constraints from cluster star counts

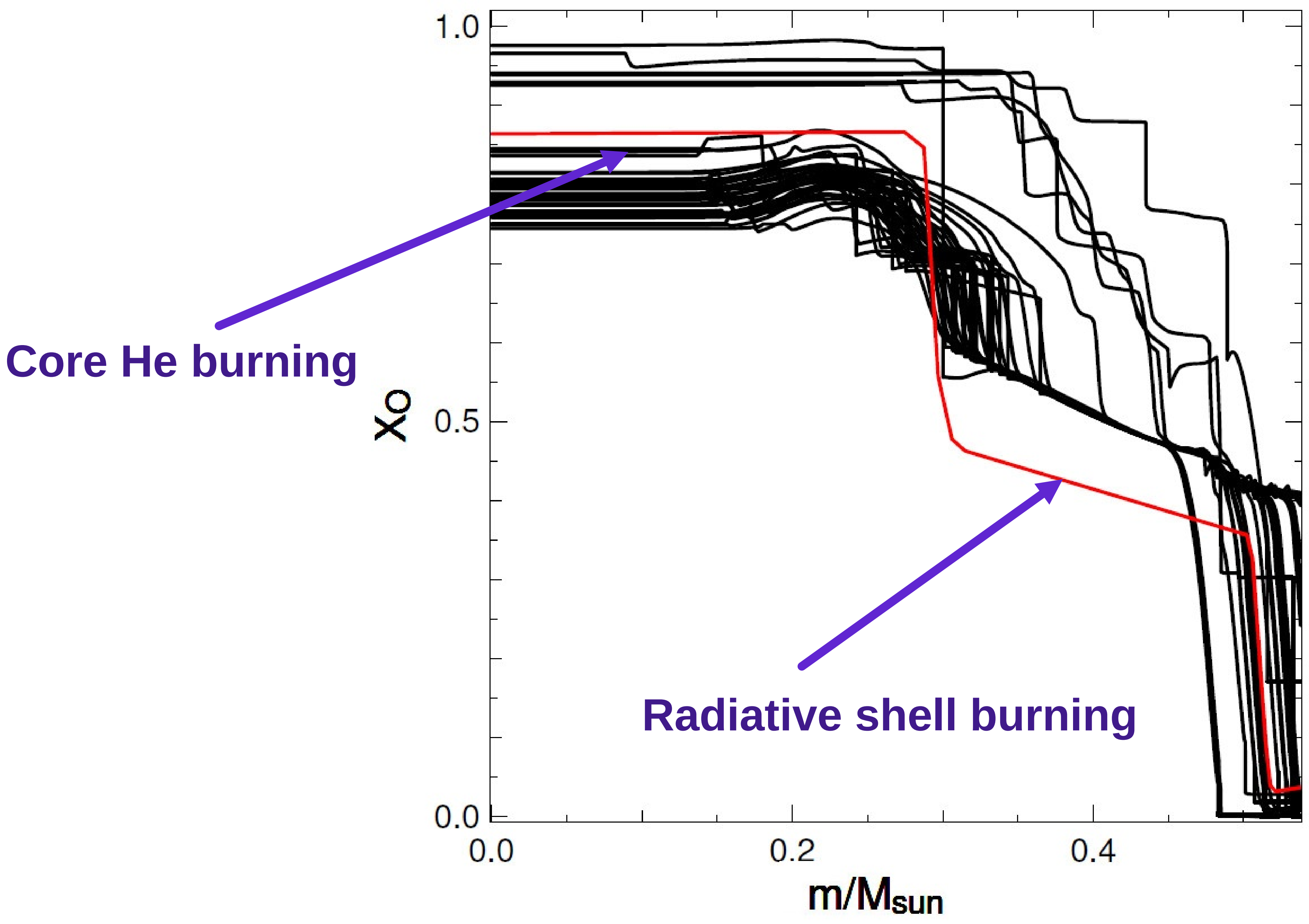
Thomas Constantino,[1,2★] Si
and Adam van Duijneveldt[2]
[1]*Physics and Astronomy, University of Exeter, Exete*
[2]*Monash Centre for Astrophysics (MoCA), School of*
[3]*Max-Planck-Institut für Astrophysik, Karl-Schwarzs*

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **472,** 4900–4909 (2017) doi:10.1093/mnras/stx2321
Advance Access publication 2017 September 9

Implementing Henk Spruit theory

The treatment of mixing in core helium-burning models – III. Suppressing core breathing pulses with a new constraint on overshoot

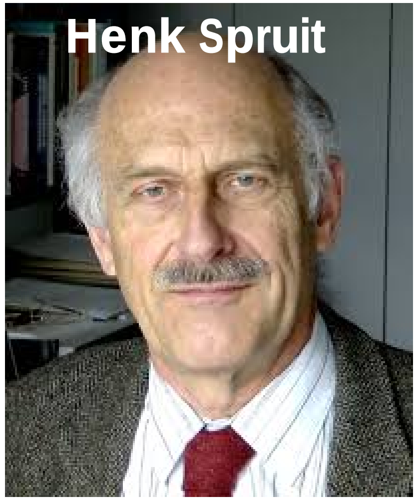
Thomas Constantino,[1,2★] Simon W. Campbell[3,2] and John C. Lattanzio[2]
[1]*Physics and Astronomy, University of Exeter, Exeter, EX4 4QL, United Kingdom*
[2]*Monash Centre for Astrophysics (MoCA), School of Physics and Astronomy, Monash University, Victoria, 3800, Australia*
[3]*Max–Planck–Institut für Astrophysik, Karl–Schwarzschild-Straße 1, D-85748 Garching bei München, Germany*

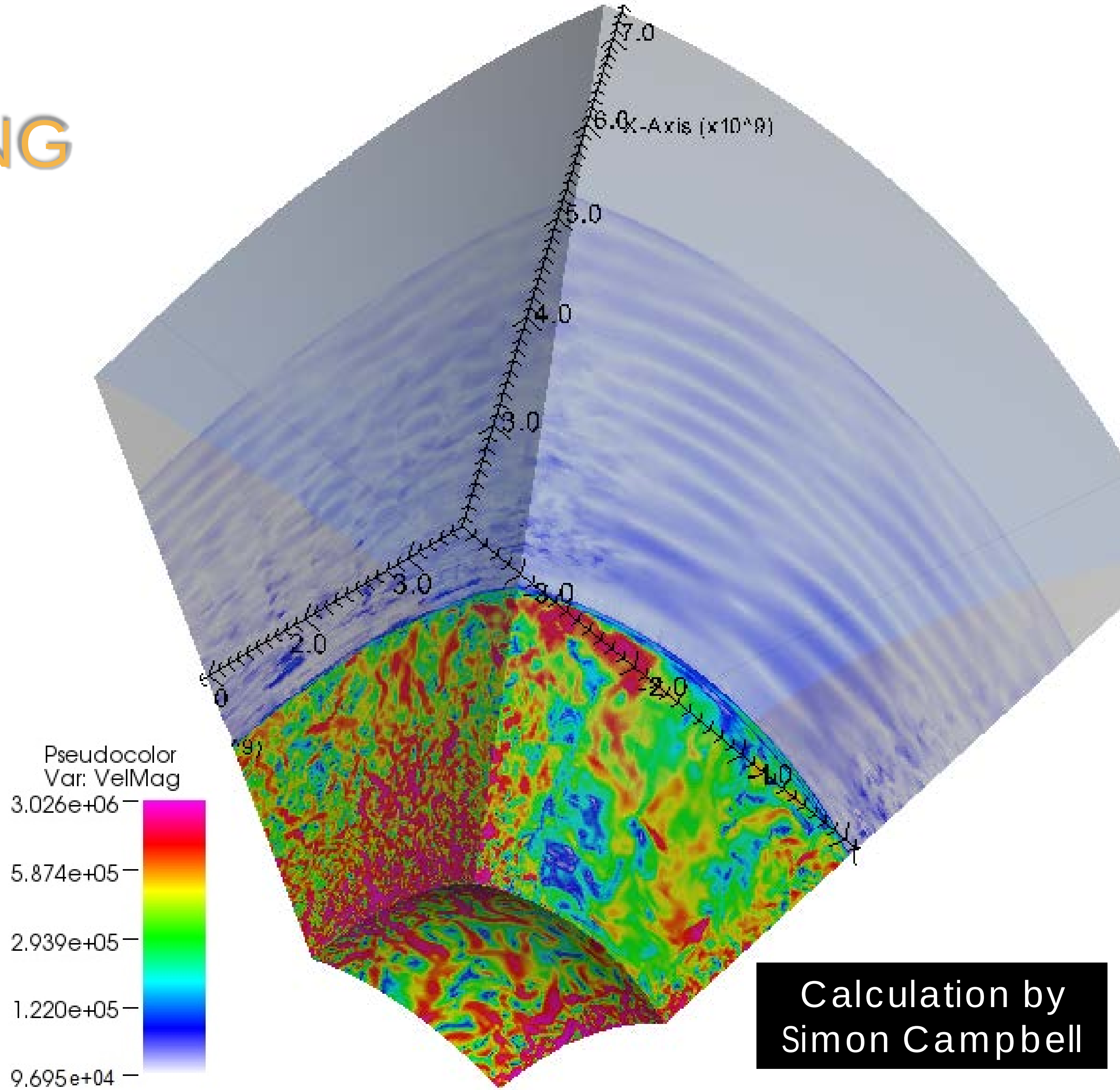


Core He burning
Radiative shell burning
1.0
0.5
0.0
X_O
0.0
0.2
0.4
m/M_{sun}

CORE HELIUM BURNING

- Progress being made
- Attacked from multiple directions
  - 3D hydro
  - Seismology
  - Space photometry
  - Good old grey matter





A PLEA TO REFEREES

- Do not accept poorly documented/written papers.
- Do not accept “it’s MESA so its reliable.”
- Do not accept “parameter_something = 4”
- *Is this suitable for a journal of scientific record?*

What about all the other codes being used by non-experts???

STARS AND HAMMERS

- Stars are tools for most people
- Stellar modellers will calculate stuff for you with their tools
- But please help us to *use the new data to improve the models*


WITH A LITTLE HELP FROM MY FRIENDS