Weak s Process in Massive Stars:
Predictions & Nuclear and Stellar Uncertainties

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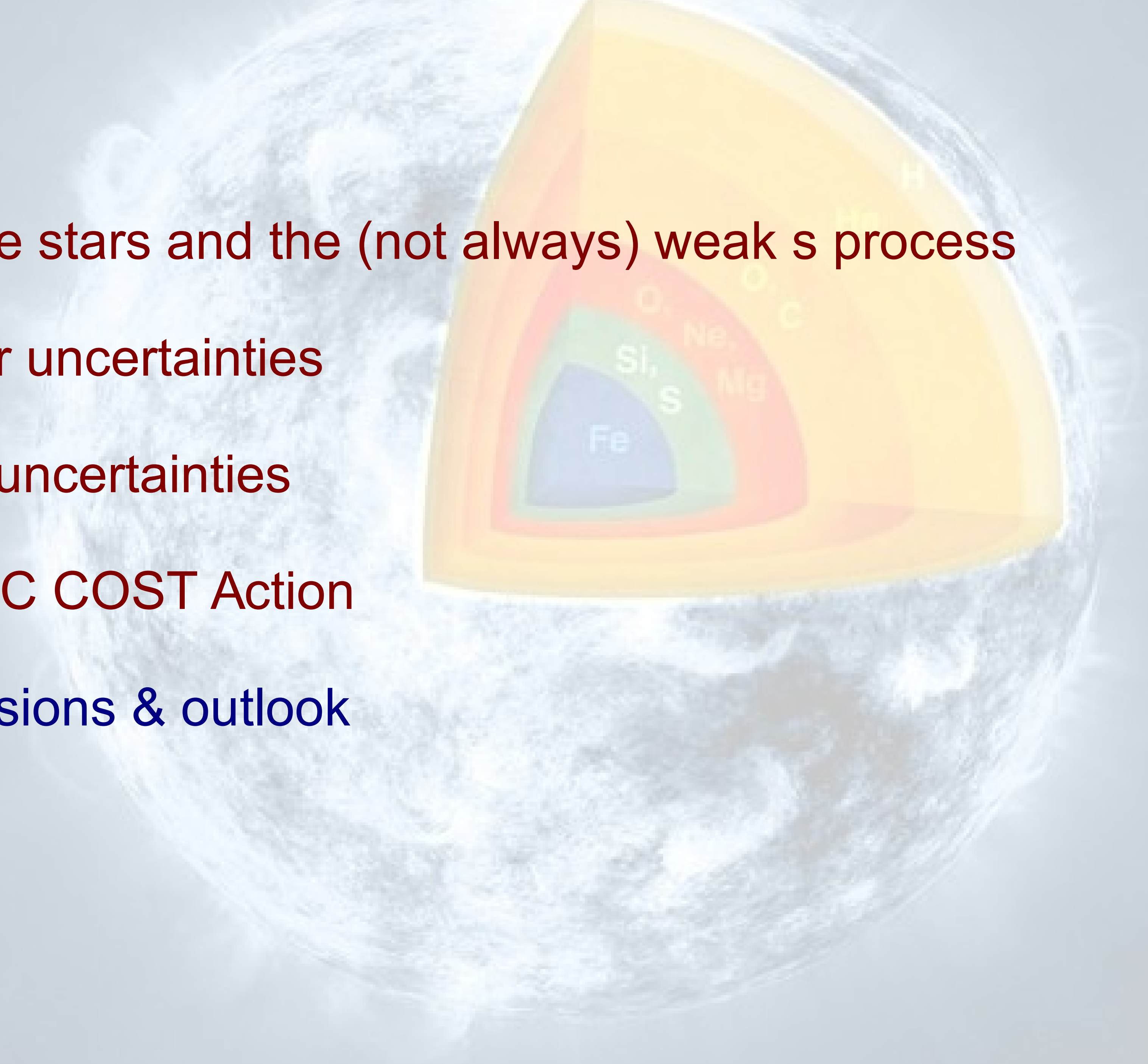
Plan



- Massive stars and the (not always) weak s process
- Nuclear uncertainties
- Stellar uncertainties
- ChETEC COST Action
- Conclusions & outlook

What has happened since NPA7? … Lots

- 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 prep),

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

S Process in Massive Stars

Kaeppeler, et al, 2011, RvMP, 83, 157, ...

Weak s process: (slow neutron capture process) during core He- and shell C-burning

He: T > 0.25 GK

(~ 21.6keV)

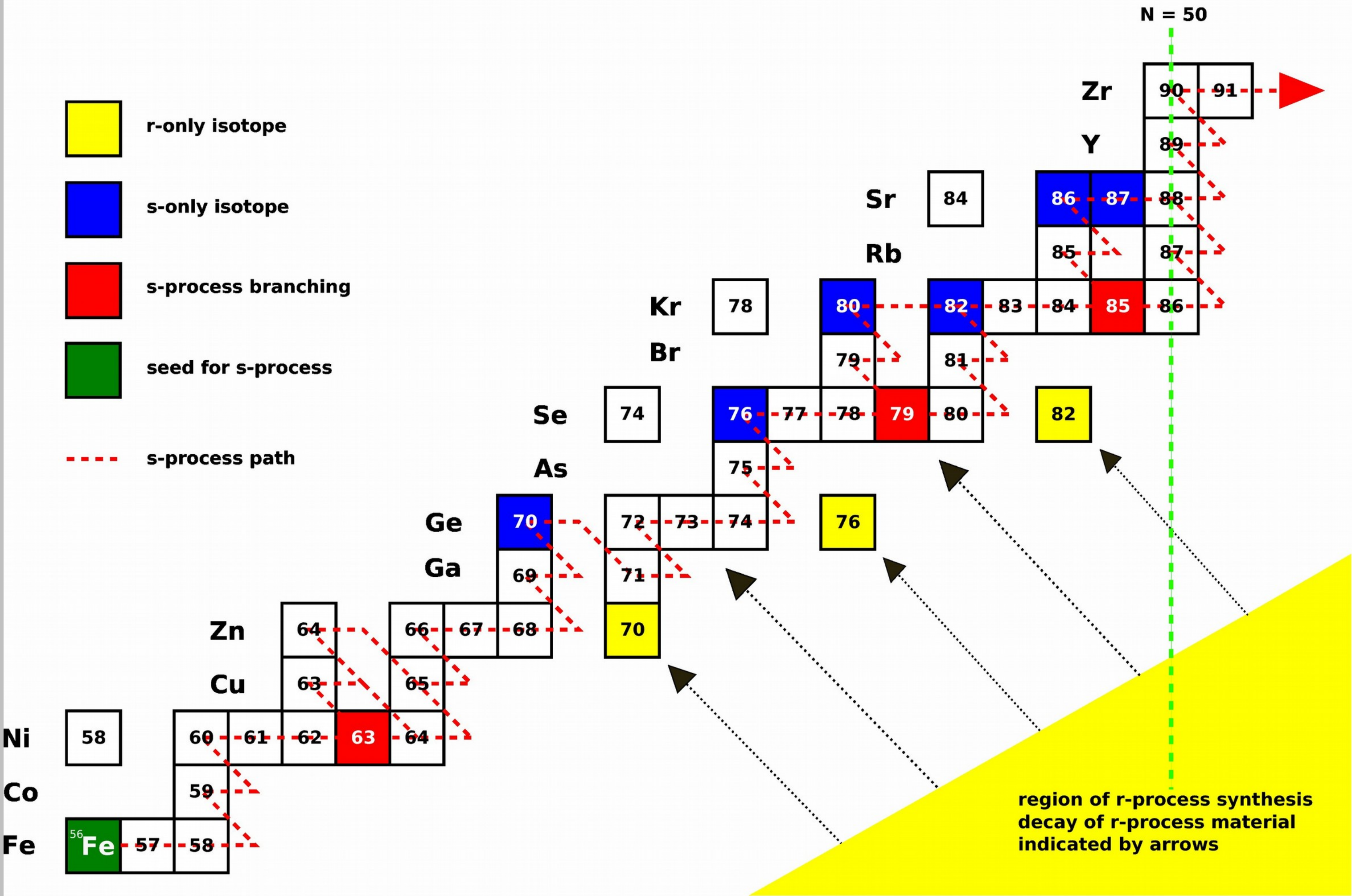
C: T ~ 1GK

N-source: $^{22}Ne(a,n)$

Seed: iron

Poisons:

- He-b.: ^{22}Ne, ^{25}Mg, ^{16}O, ^{12}C
- C-b.: ^{24}Mg, ^{25}Mg, ^{16}O, ^{20}Ne



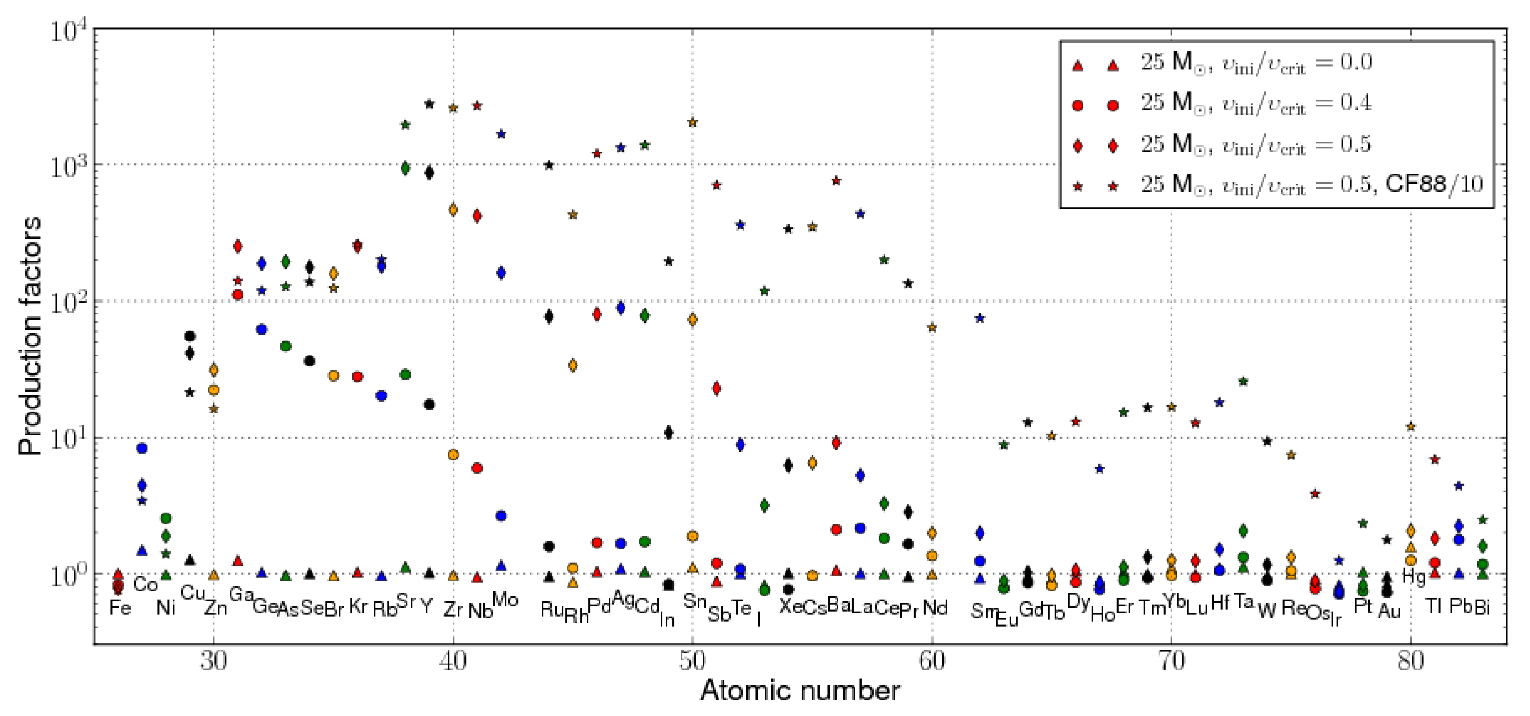
At solar Z: rotating models may produce up to 3x more s process

(See also Chieffi, Limongi, 2012ApJS..199...38L)

How much s process do massive rotating stars produce at low Z?

S-Process Models of Massive Rotating Stars

Z=10^{-5}, rotating models with different ^{17}O(a,g) rates; V_{ini}



Frischknecht et al, A&A letter 2012, 2016 MNRAS

- STELLAR EVOLUTION CALCULATIONS WITH 600/700-ISOTOPE NETWORK!

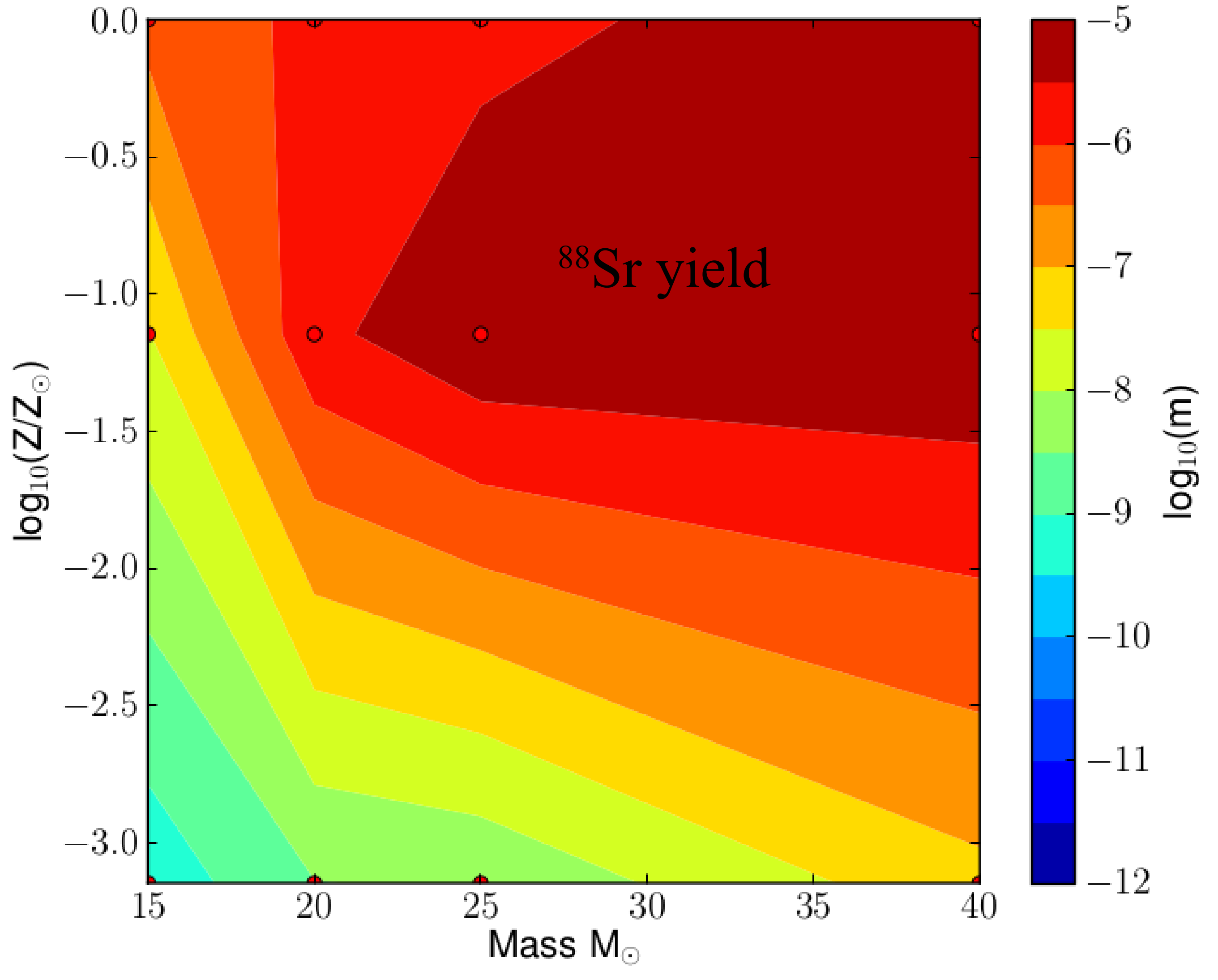
- **^{22}Ne production almost primary but still varies with Z & especially V_{ini}.** M_{ini}
- Secondary seeds (Fe) limit production (^{22}Ne cannot act as seed)
- Strong variations in [Sr,Y/Ba] up to 2 dex dep. on Z,V_{ini}, and ^{17}O(a,g)

- Possibility of explosive n-capture process in He-shell

S-Process Models of Massive Rotating Stars

- FULL GRID NOW PUBLISHED!

Frischknecht, Hirschi et al, MNRAS, 2016, 456, 1803



STELLAR EVOLUTION CALCULATIONS WITH 600/700-ISOTOPE NETWORK!

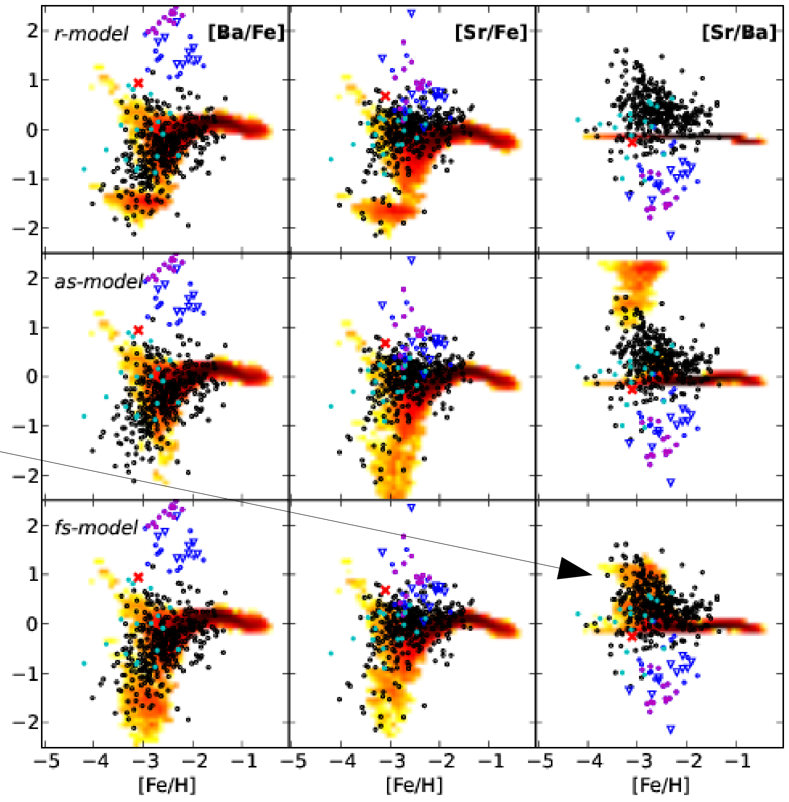
*New S-Process Models Compared to EMP * & Bulge GC*

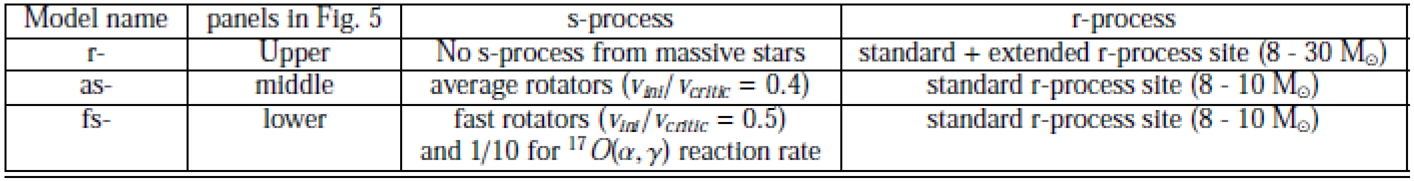
* New models also explain abundances in one of the oldest clusters in galactic bulge Chiappini et al, Nature Letter, 2011

Inhomogeneous GCE models by Cescutti et al 2013 A&A,553,51, 2015 A&A, 577, 139

- Strong variations in [Sr/Ba] > 1 dex matches well observed range for EMP stars (black circles)!

(no main s process included so cannot explain CEMP-s stars in blue)

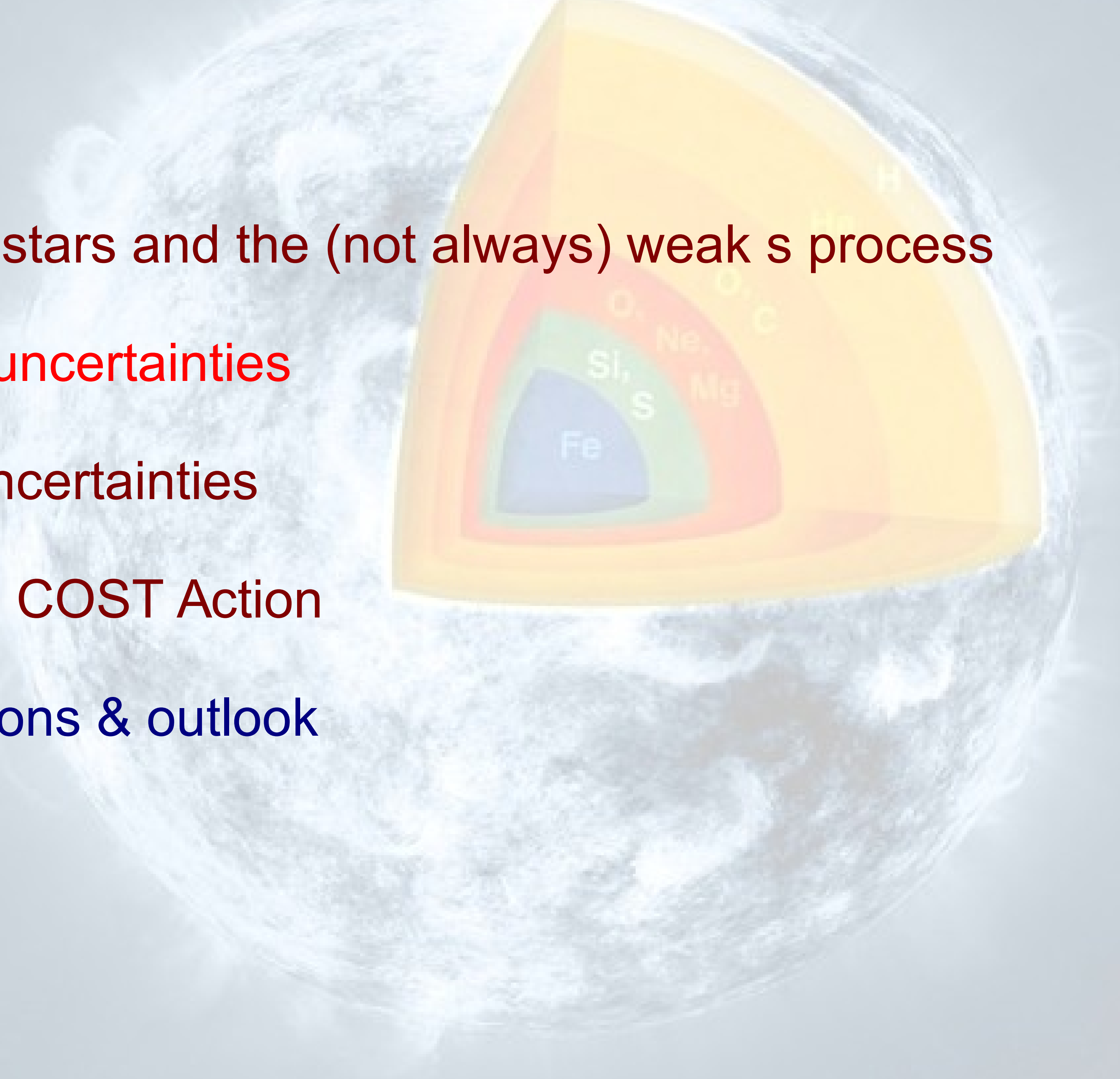




Model name	panels in Fig. 5	s-process	r-process
r-	Upper	No s-process from massive stars	standard + extended r-process site (8 - 30 $M_\odot$)
as-	middle	average rotators ($v_{ini}/v_{critic} = 0.4$)	standard r-process site (8 - 10 $M_\odot$)
fs-	lower	fast rotators ($v_{ini}/v_{critic} = 0.5$) and 1/10 for $^{17}O(\alpha,\gamma)$ reaction rate	standard r-process site (8 - 10 $M_\odot$)

(EMP *: Frebel et al 2010)

Plan



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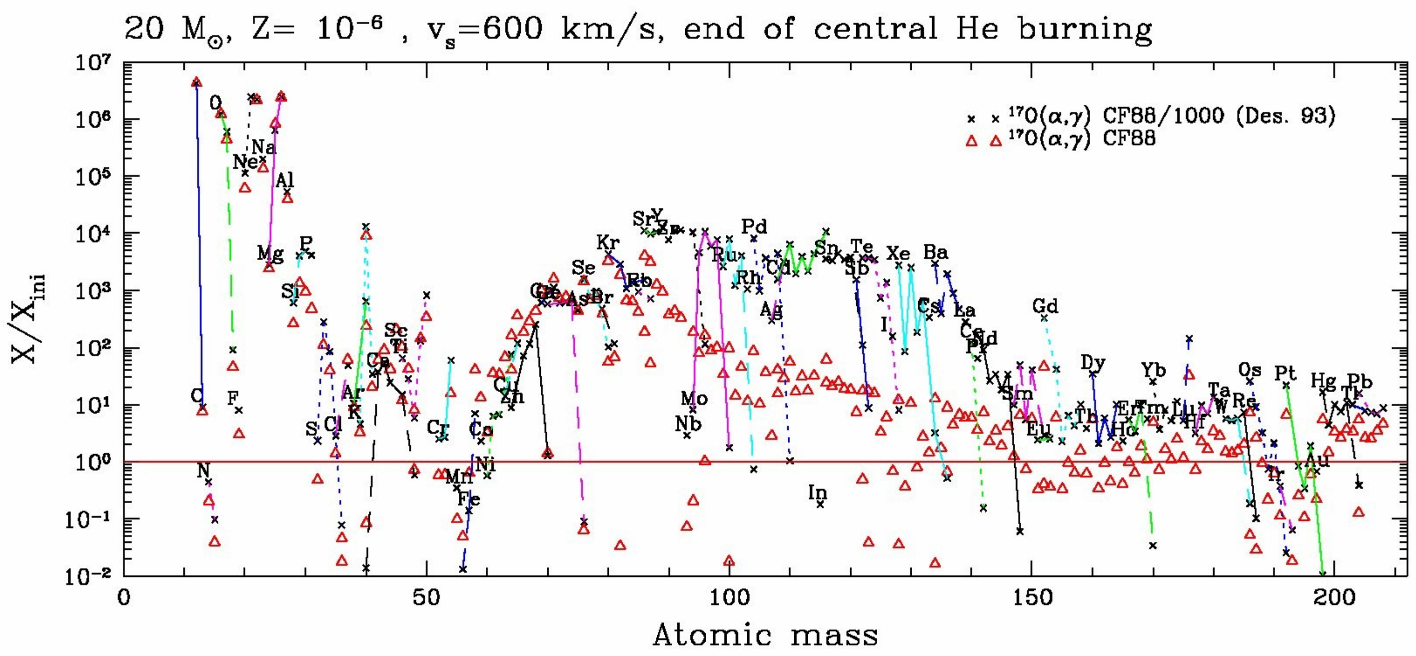
S Process in Massive Stars: Nuclear Physics Uncertainty



Hirschi et al 2008, NICX

Pignatari et al 08, ApJ letter, 687,95

$^{16}O(n,\gamma)^{17}O$:

- ^{16}O poison if $^{17}O(\alpha,\gamma)^{21}Ne$ dom.
- ^{16}O absorber if $^{17}O(\alpha,n)^{20}Ne$ dom.

Measurement of ^{17}O(a,g)^{21}Ne at TRIUMF

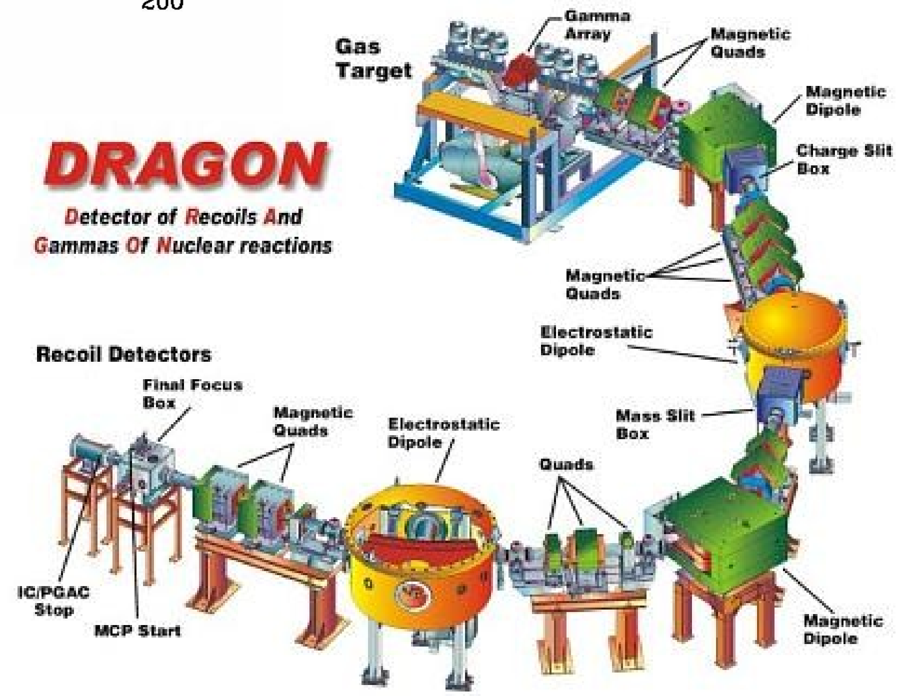
Taggart et al NICXI:

^{17}O(a,g) lower than CF88!

Best et al 2011 (@ Notre Dame):

But much higher than

Descouvemont 1993!



$^{22}Ne(\alpha,\gamma)/(\alpha,n)$ also key

(see e.g., Nishimura et al., AIPC 1594 p 146, 2014)

Monte Carlo Sensitivity Studies

Piz Buin mountain

Monte Carlo Framework:

- PizBuin MC-wrapper

Rauscher+ 2016MNRAS.463.4153R

- Simple “brute force” approach
- Parallelised using OpenMP

Nuclear Reaction Network:

- Solver: WinNet (Winteler+ 12)
- Reaction rates ← reaclib (Rauscher & Thielemann 00)

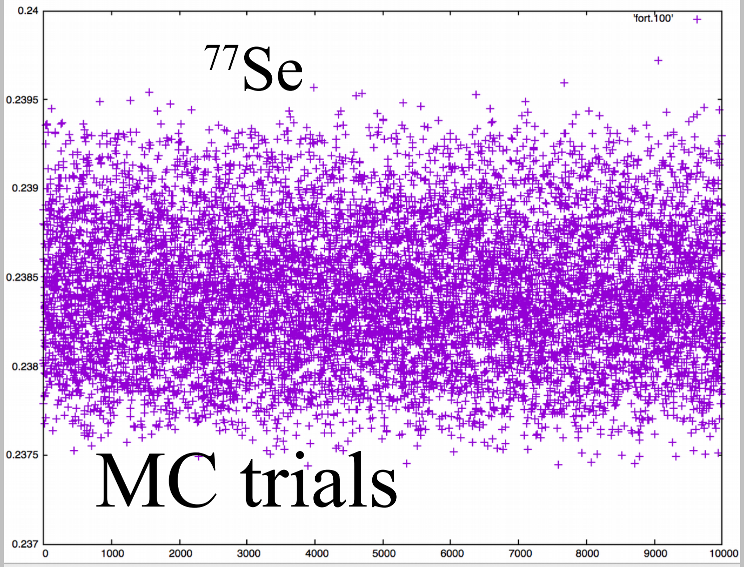
= McWinNet

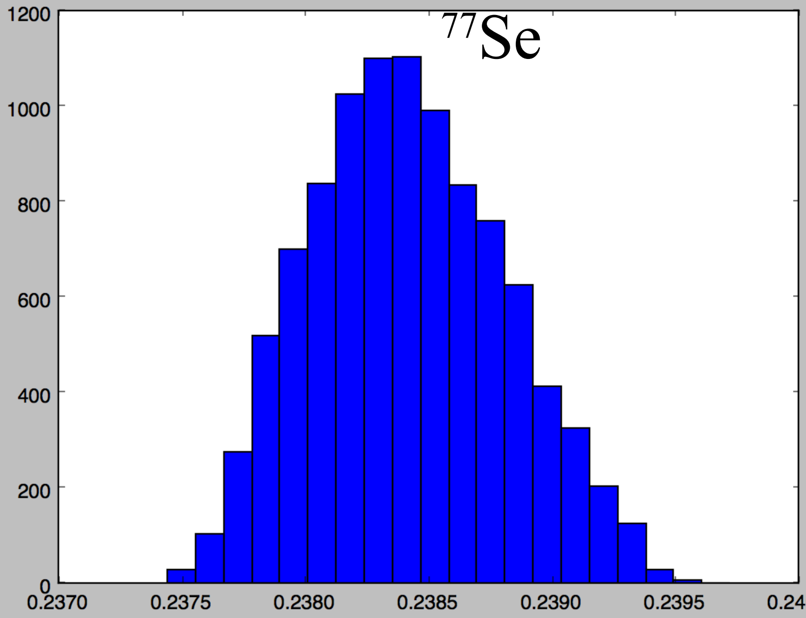
beta-decay & (n,g) uncertainties are T-dependent!

Largest simulations: 1000 trajectories x 1hr run x 10,000 iterations

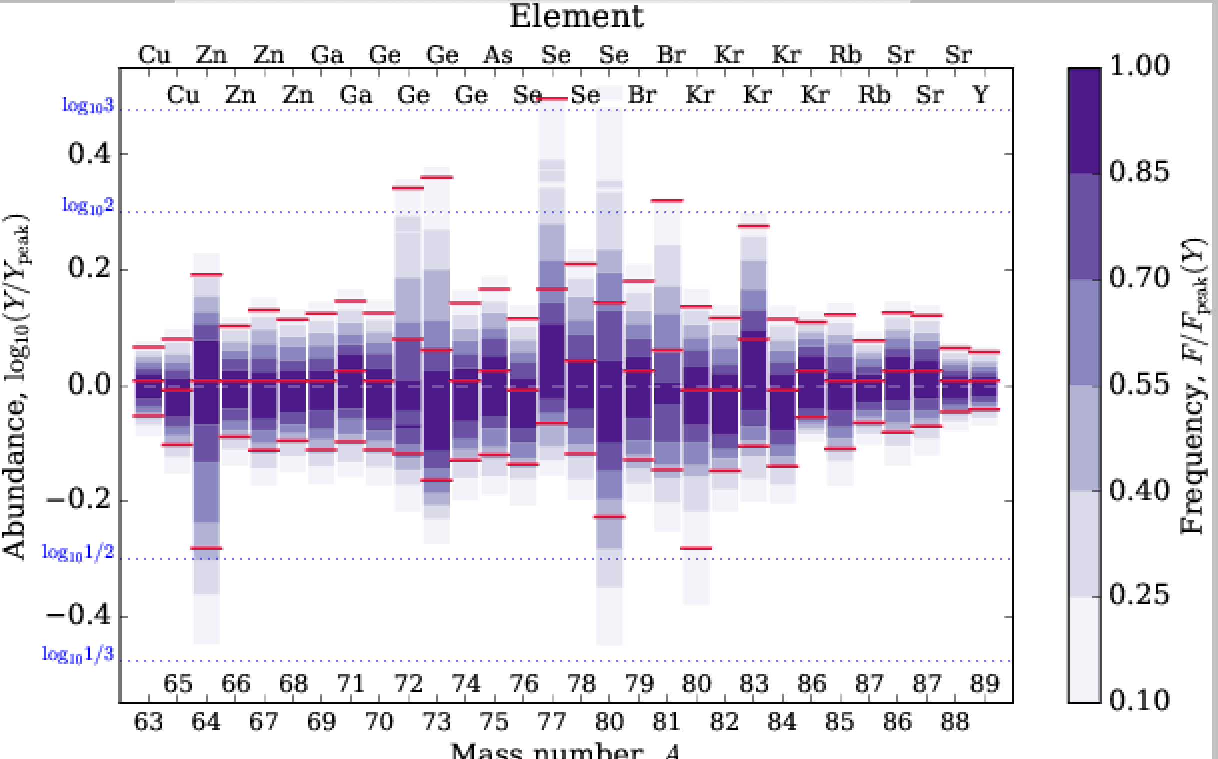
Results for Weak s Process

N. Nishimura+ 2017: http://adsabs.harvard.edu/abs/2017MNRAS.469.1752N





Abundances

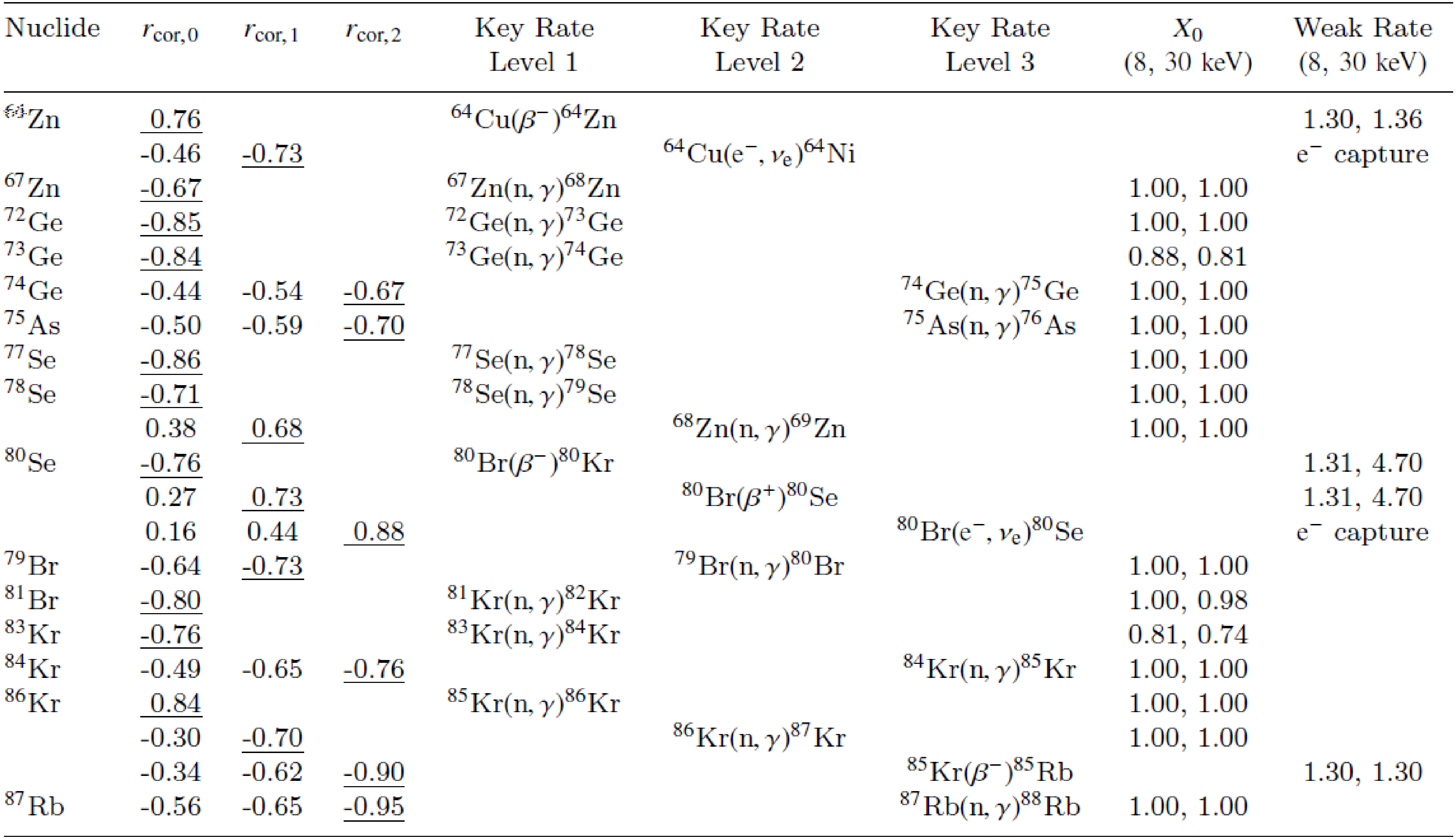


← MC: varying both

(n,g) & $\beta^{\pm}$

Key Reaction Lists for Weak s Process

N. Nishimura+ 2017: http://adsabs.harvard.edu/abs/2017MNRAS.469.1752N



Nuclide	$r_{\mathrm{cor},0}$	$r_{\mathrm{cor},1}$	$r_{\mathrm{cor},2}$	Key Rate Level 1	Key Rate Level 2	Key Rate Level 3	X_0 (8, 30 keV)	Weak Rate (8, 30 keV)
$^{64}\mathrm{Zn}$	$\underline{0.76}$			$^{64}\mathrm{Cu}(\beta^-)^{64}\mathrm{Zn}$				1.30, 1.36
	-0.46	$\underline{-0.73}$			$^{64}\mathrm{Cu}(\mathrm{e}^-, \nu_\mathrm{e})^{64}\mathrm{Ni}$			e^- capture
$^{67}\mathrm{Zn}$	$\underline{-0.67}$			$^{67}\mathrm{Zn}(\mathrm{n}, \gamma)^{68}\mathrm{Zn}$			1.00, 1.00	
$^{72}\mathrm{Ge}$	$\underline{-0.85}$			$^{72}\mathrm{Ge}(\mathrm{n}, \gamma)^{73}\mathrm{Ge}$			1.00, 1.00	
$^{73}\mathrm{Ge}$	$\underline{-0.84}$			$^{73}\mathrm{Ge}(\mathrm{n}, \gamma)^{74}\mathrm{Ge}$			0.88, 0.81	
$^{74}\mathrm{Ge}$	-0.44	-0.54	$\underline{-0.67}$			$^{74}\mathrm{Ge}(\mathrm{n}, \gamma)^{75}\mathrm{Ge}$	1.00, 1.00	
$^{75}\mathrm{As}$	-0.50	-0.59	$\underline{-0.70}$			$^{75}\mathrm{As}(\mathrm{n}, \gamma)^{76}\mathrm{As}$	1.00, 1.00	
$^{77}\mathrm{Se}$	$\underline{-0.86}$			$^{77}\mathrm{Se}(\mathrm{n}, \gamma)^{78}\mathrm{Se}$			1.00, 1.00	
$^{78}\mathrm{Se}$	$\underline{-0.71}$			$^{78}\mathrm{Se}(\mathrm{n}, \gamma)^{79}\mathrm{Se}$			1.00, 1.00	
	0.38	$\underline{0.68}$			$^{68}\mathrm{Zn}(\mathrm{n}, \gamma)^{69}\mathrm{Zn}$		1.00, 1.00	
$^{80}\mathrm{Se}$	$\underline{-0.76}$			$^{80}\mathrm{Br}(\beta^-)^{80}\mathrm{Kr}$				1.31, 4.70
	0.27	$\underline{0.73}$			$^{80}\mathrm{Br}(\beta^+)^{80}\mathrm{Se}$			1.31, 4.70
	0.16	0.44	$\underline{0.88}$			$^{80}\mathrm{Br}(\mathrm{e}^-, \nu_\mathrm{e})^{80}\mathrm{Se}$		e^- capture
$^{79}\mathrm{Br}$	-0.64	$\underline{-0.73}$			$^{79}\mathrm{Br}(\mathrm{n}, \gamma)^{80}\mathrm{Br}$		1.00, 1.00	
$^{81}\mathrm{Br}$	$\underline{-0.80}$			$^{81}\mathrm{Kr}(\mathrm{n}, \gamma)^{82}\mathrm{Kr}$			1.00, 0.98	
$^{83}\mathrm{Kr}$	$\underline{-0.76}$			$^{83}\mathrm{Kr}(\mathrm{n}, \gamma)^{84}\mathrm{Kr}$			0.81, 0.74	
$^{84}\mathrm{Kr}$	-0.49	-0.65	$\underline{-0.76}$			$^{84}\mathrm{Kr}(\mathrm{n}, \gamma)^{85}\mathrm{Kr}$	1.00, 1.00	
$^{86}\mathrm{Kr}$	$\underline{0.84}$			$^{85}\mathrm{Kr}(\mathrm{n}, \gamma)^{86}\mathrm{Kr}$			1.00, 1.00	
	-0.30	$\underline{-0.70}$			$^{86}\mathrm{Kr}(\mathrm{n}, \gamma)^{87}\mathrm{Kr}$		1.00, 1.00	
	-0.34	-0.62	$\underline{-0.90}$			$^{85}\mathrm{Kr}(\beta^-)^{85}\mathrm{Rb}$		1.30, 1.30
$^{87}\mathrm{Rb}$	-0.56	-0.65	$\underline{-0.95}$			$^{87}\mathrm{Rb}(\mathrm{n}, \gamma)^{88}\mathrm{Rb}$	1.00, 1.00	

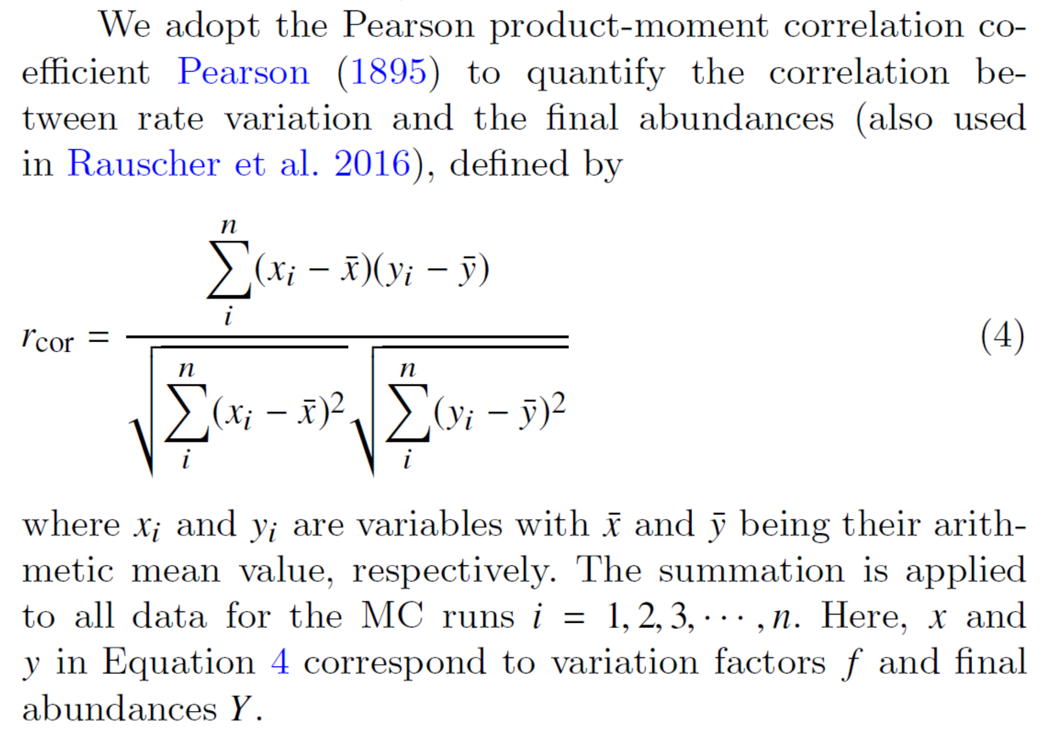
Key Reaction Levels 1-3:

N. Nishimura+ 2017

- Level 1 key rates dominate the uncertainty for a given isotope

- Once level 1 rates are fixed, *then* Level 2 rates become dominant

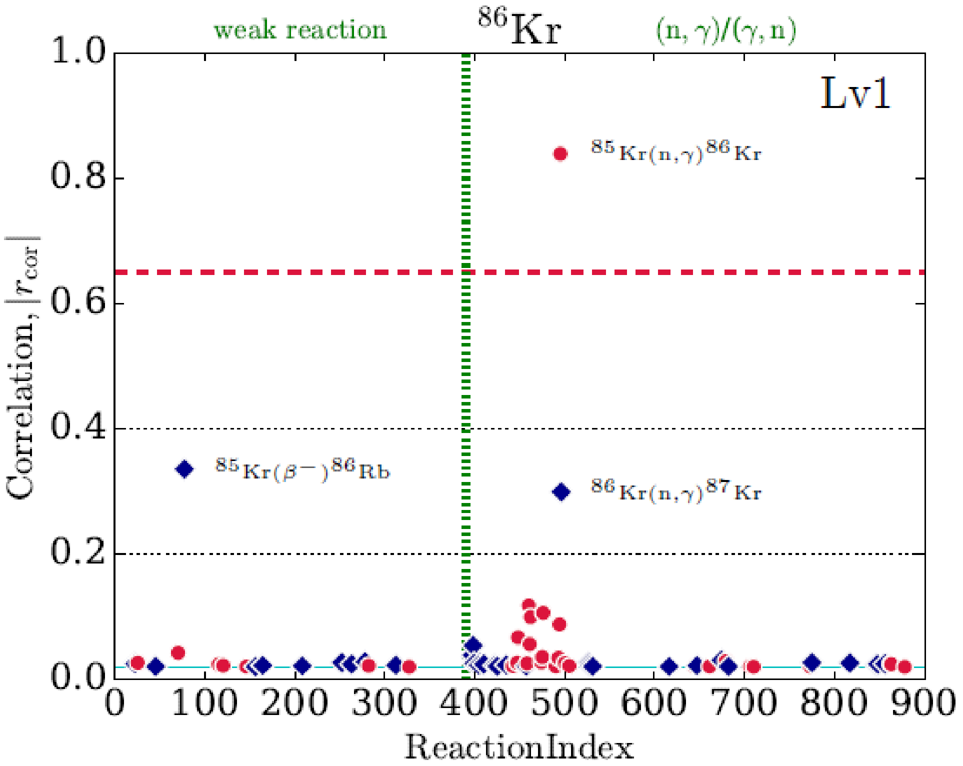
…

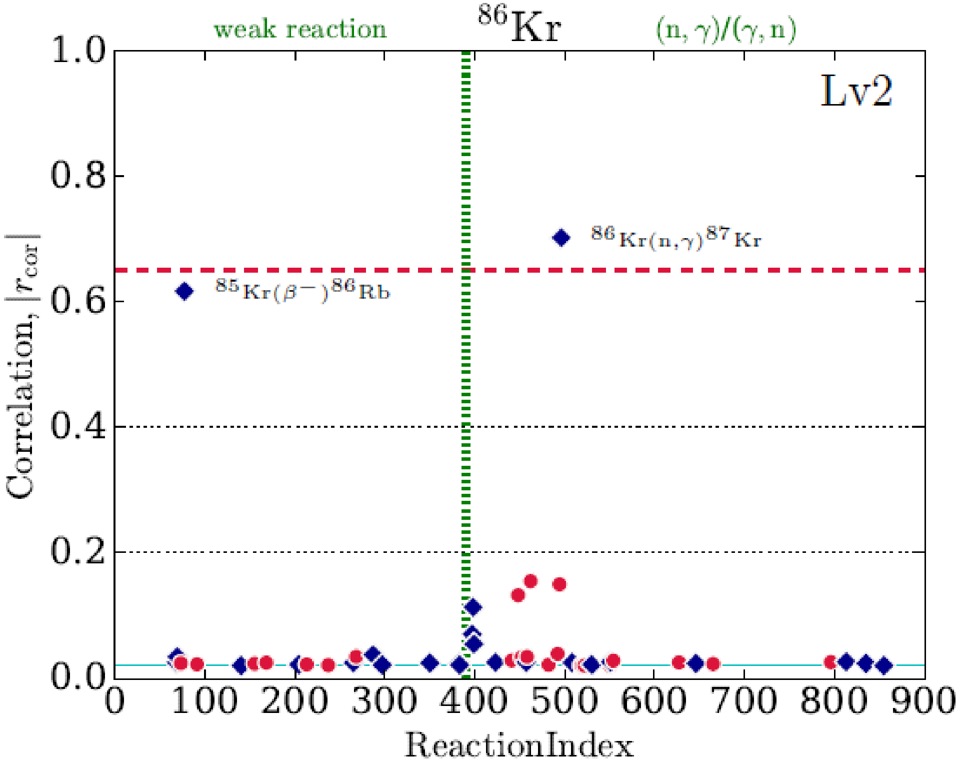


We adopt the Pearson product-moment correlation coefficient Pearson (1895) to quantify the correlation between rate variation and the final abundances (also used in Rauscher et al. 2016), defined by

$$r_{\rm cor} = \frac{\sum_i^n (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_i^n (x_i-\bar{x})^2}\sqrt{\sum_i^n (y_i-\bar{y})^2}} \qquad (4)$$

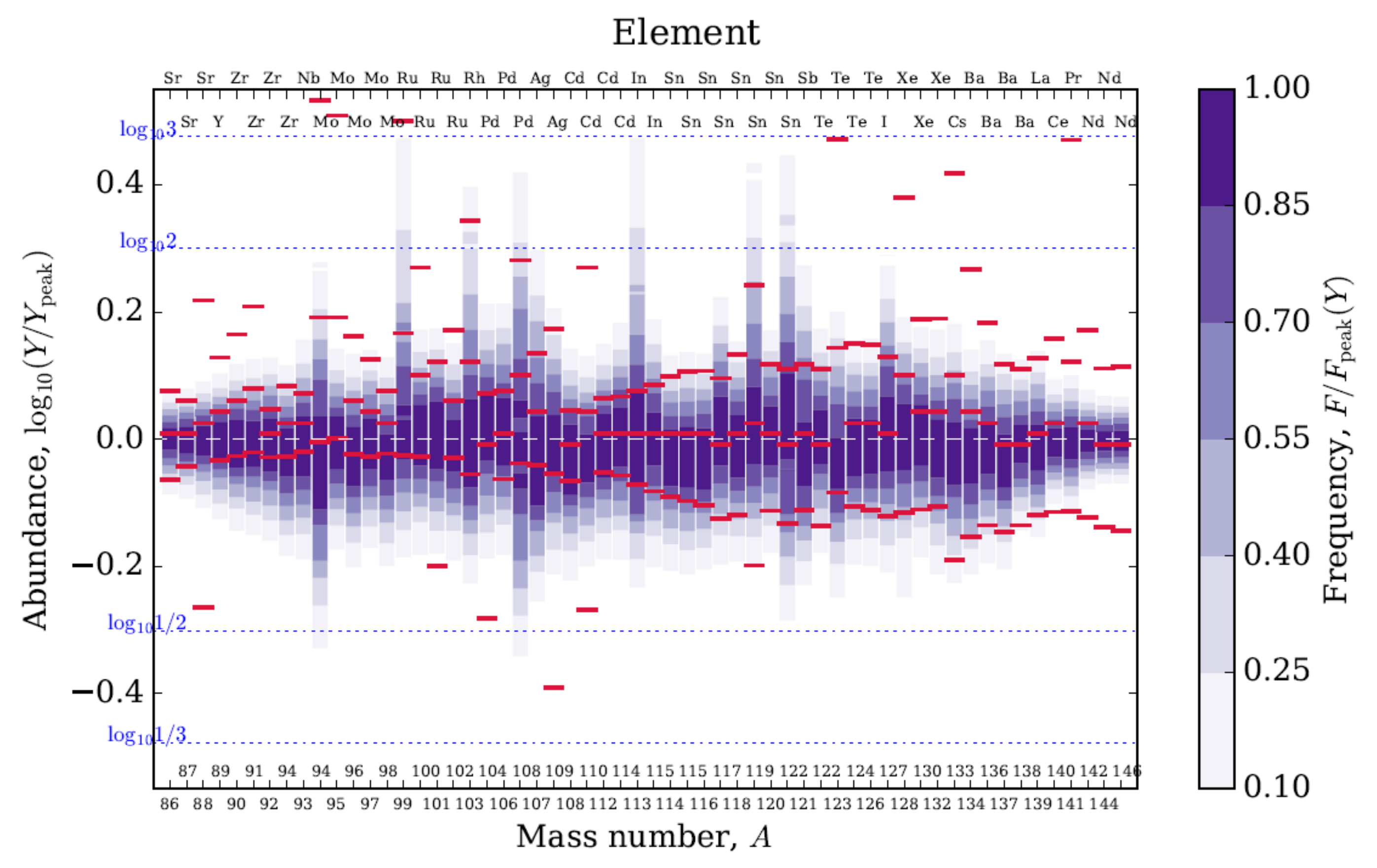
where x_i and y_i are variables with $\bar{x}$ and $\bar{y}$ being their arithmetic mean value, respectively. The summation is applied to all data for the MC runs $i = 1, 2, 3, \cdots, n$. Here, x and y in Equation 4 correspond to variation factors f and final abundances Y.





Other Key Reaction Lists

Priority lists established for:
- Enhanced (weak) s proc. in low-Z fast rotating stars: N. Nishimura+ 2017



- Gamma (aka p) process in CCSNe: T. Rauscher+ 2016
http://adsabs.harvard.edu/abs/2016MNRAS.463.4153R

- Gamma (aka p) process in Sne Ia: Nishimura/Rauscher + in prep

- Main s process (C13-pocket) Cescutti + in prep.

Plan

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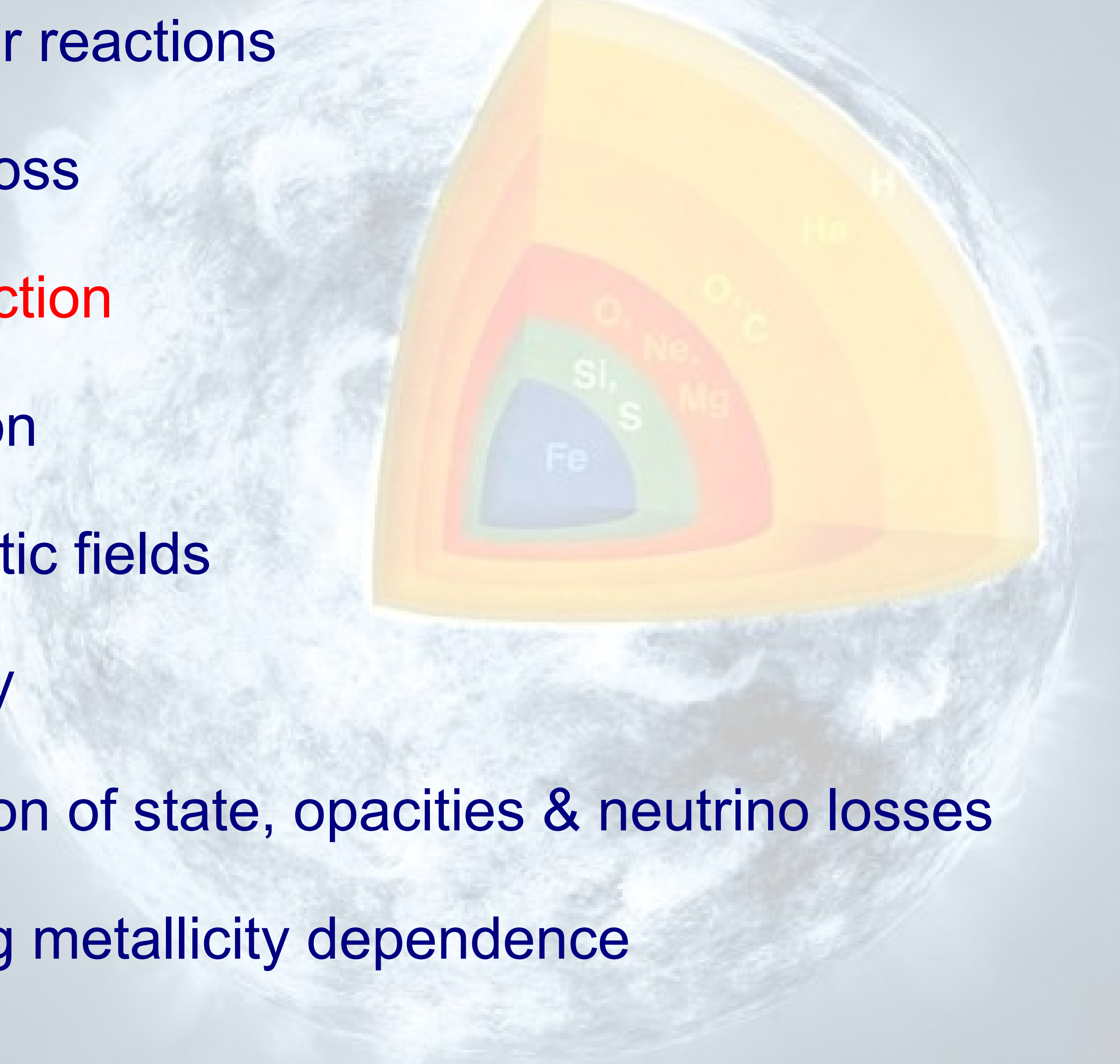
Physical Ingredients



- Nuclear reactions

- Mass loss

- Convection

- Rotation

- Magnetic fields

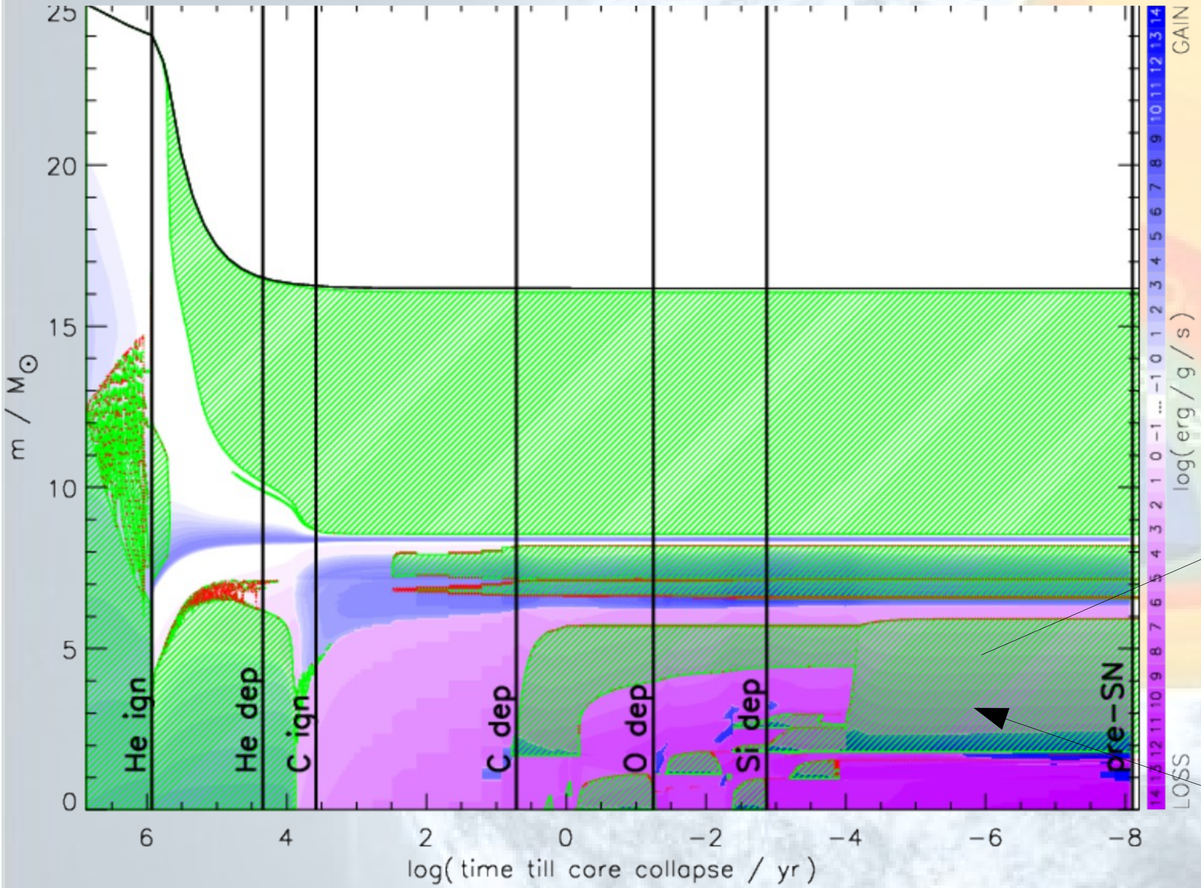
- Binarity

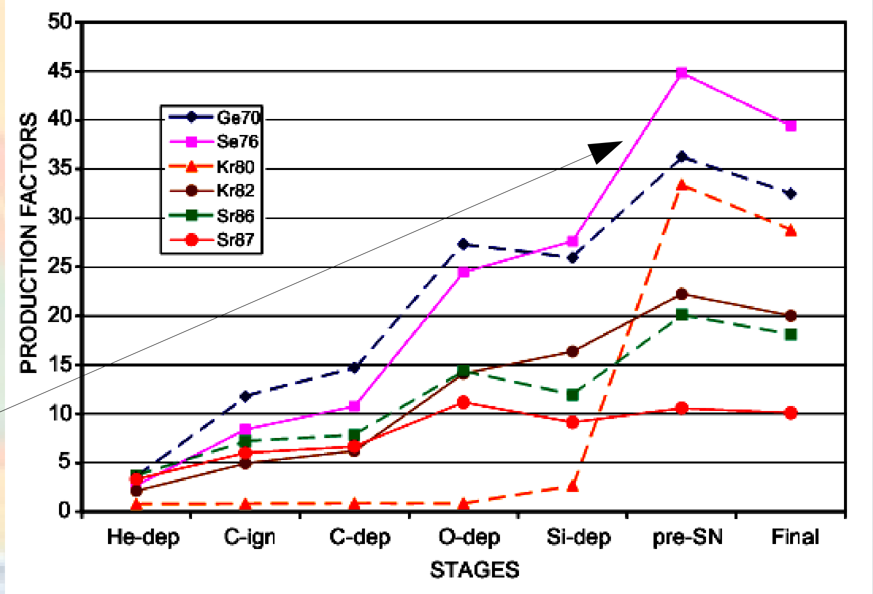
- Equation of state, opacities & neutrino losses

including metallicity dependence

1D Model Uncertainties: Possible Shell Mergers

Tur, Heger et al 07/09/10





C/Ne/O shell mergers

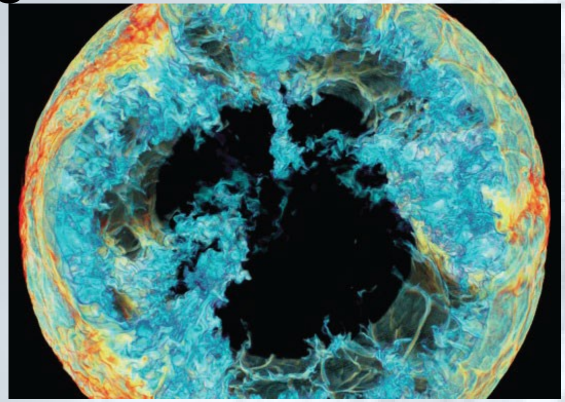
Rauscher, Heger and Woosley 2002: “Interesting and unusual nucleosynthetic results are found for one particular 20M model as a result of its special stellar structure.”

Shell mergers also affect compactness

Convection physics uncertainties affect fate of models: strong/weak/failed explosions!!!

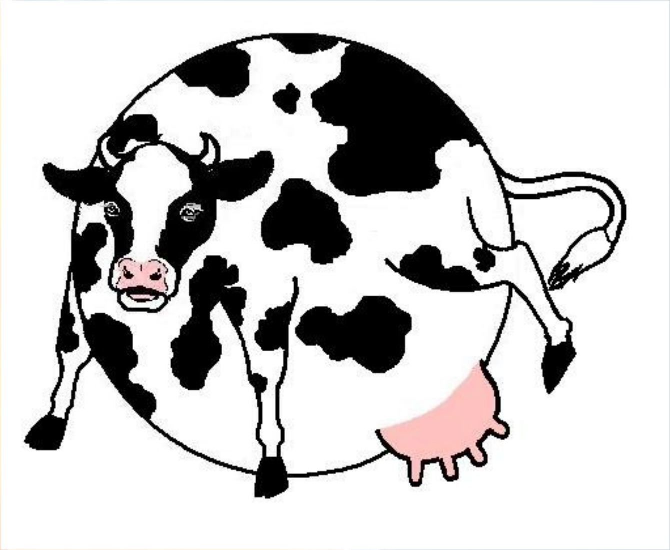
Way Forward: 1 to 3 to 1D link

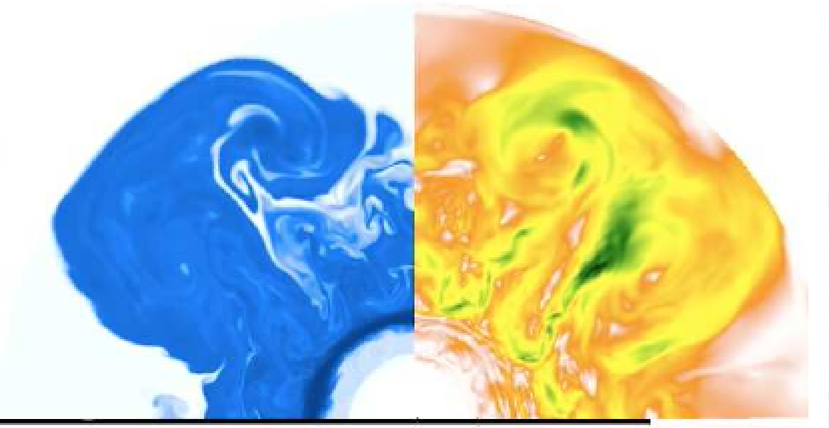
Targetted 3D simulations



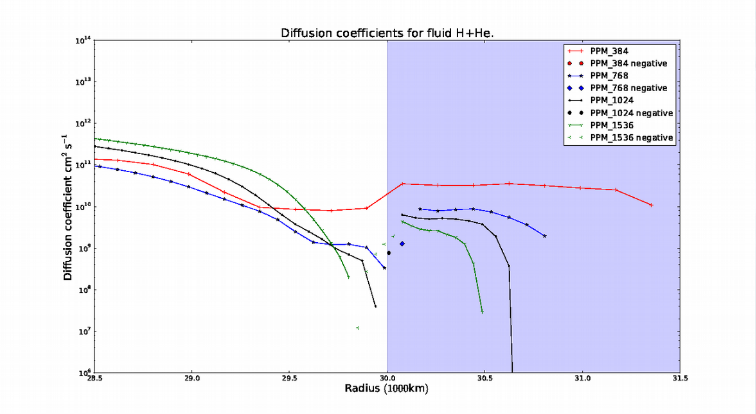
Herwig et al 06, Herwig, Woodward et al 2013

Uncertainties in 1D





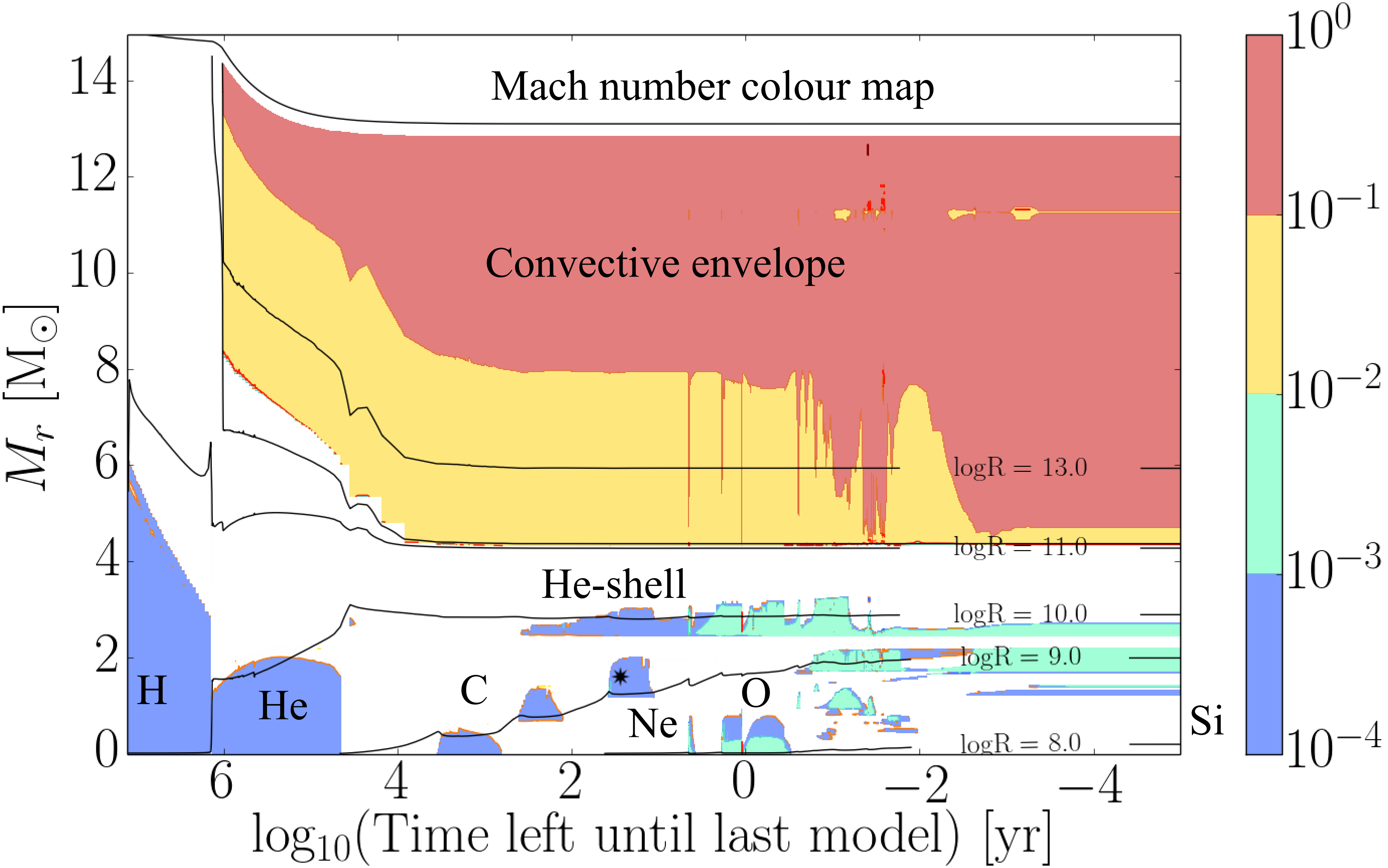
e.g. Arnett & Meakin 2011, ...
Mocak et al 2011,
Viallet et al 2013, ...



Meakin et al 09 ; Bennett et al (thesis), Jones et al 16

→ Determine effective coefficient / improve theoretical prescriptions

Where to Start?

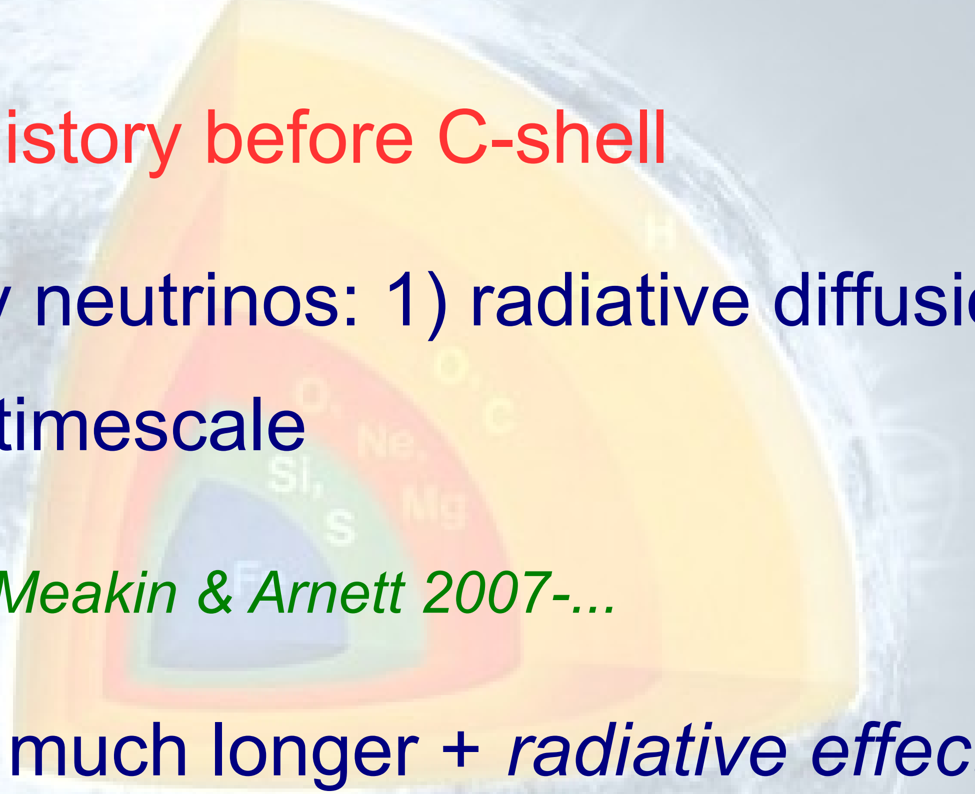


Convection takes place during most burning stages

Priority List

* Convective boundary mixing during core hydrogen burning:
- +: many constraints (HRD, astero, ...)
- -: difficult to model due to important thermal/radiative effects
- -: long time-scale
-
- * Silicon burning:
- +: important to determine impact on SNe of multi-D structure in progenitor (Couch et al 2015a,b, Mueller & Janka aph1409.4783, Mueller et al ArXiV1605.01393)
- +: possible shell mergers occurring after core Si-burning (e.g. Tur et al 2009ApJ702.1068; Sukhbold & Woosley 2014ApJ783.105) strongly affect core compactness
- +: radiative effects small/negl.
- -: ~ 10^9 CPU hours needed for full silicon burning phase will be ok soon;
- -: might be affected by convective shell history
-
- * AGB thermal pulses/H-ingestion:
- +: already doable (e.g. Herwig et al 2014ApJ729.3, 2011ApJ727.89, Mocak et al 2010A&A520.114, Woodward et al 2015)
- +: thermal/radiative effects not dominant
- ?: applicable to other phases?
-
- * Oxygen shell: (Meakin & Arnett 2007ApJ667.448/665.448, Viallet et al 2013ApJ769.1, Jones et al ArXiV1605.03766)
- +: similar to silicon burning but smaller reaction network needed
- -: might be affected by convective shell history
-
- * Carbon shell: (PhD A. Cristini)
- +: not affected by prior shell history
- +: first stage for which thermal effects become negligible
-
- * Envelope of RSG (e.g. Viallet et al. 2013, Chiavassa et al 2009-2013),
- * Solar-type stars (e.g. Magic et al. 2013A&A557.26, ...)
-

Where to Start? Carbon burning shell



- “Simple” convective history before C-shell

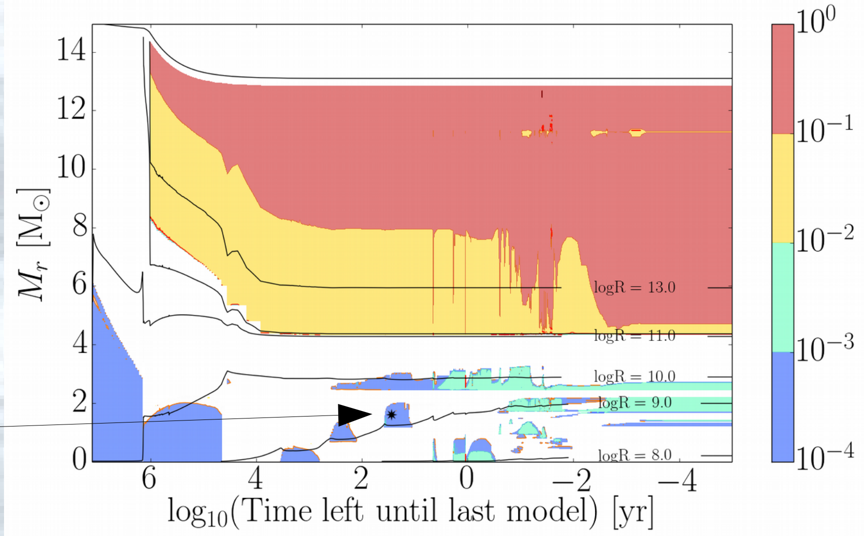
- Cooling dominated by neutrinos: 1) radiative diffusion can be neglected, 2) “fast” timescale

- O-shell done before *Meakin & Arnett 2007-...*

- H/He burning lifetime much longer + *radiative effects important*

- Si-burning: complex reaction network

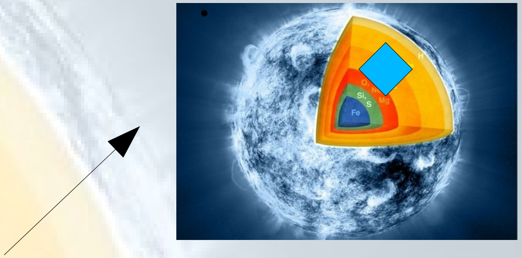
C-shell



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

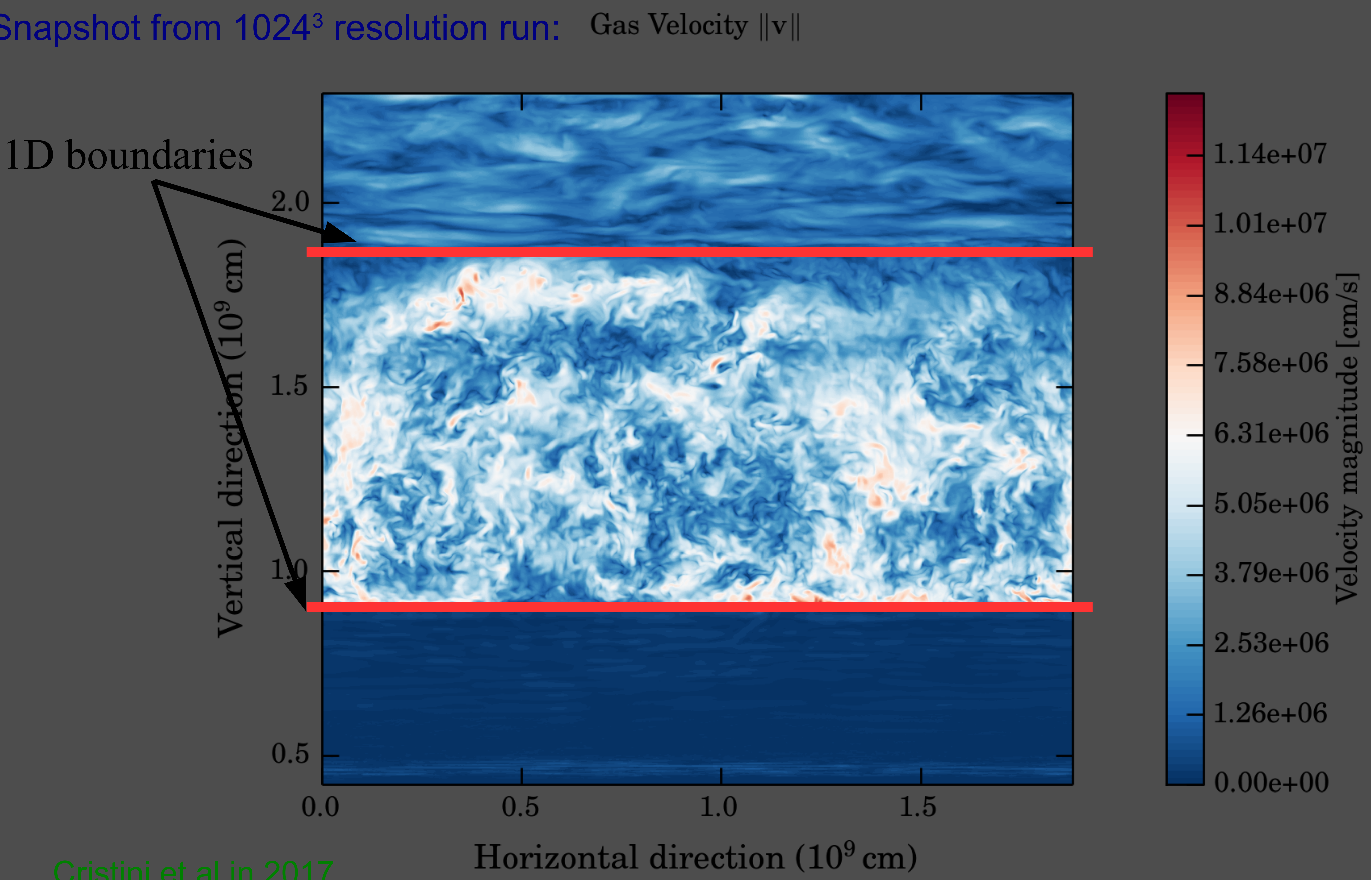
- Turbulence initiated through random low-amplitude perturbations in temperature and density

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

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

C-shell Simulations

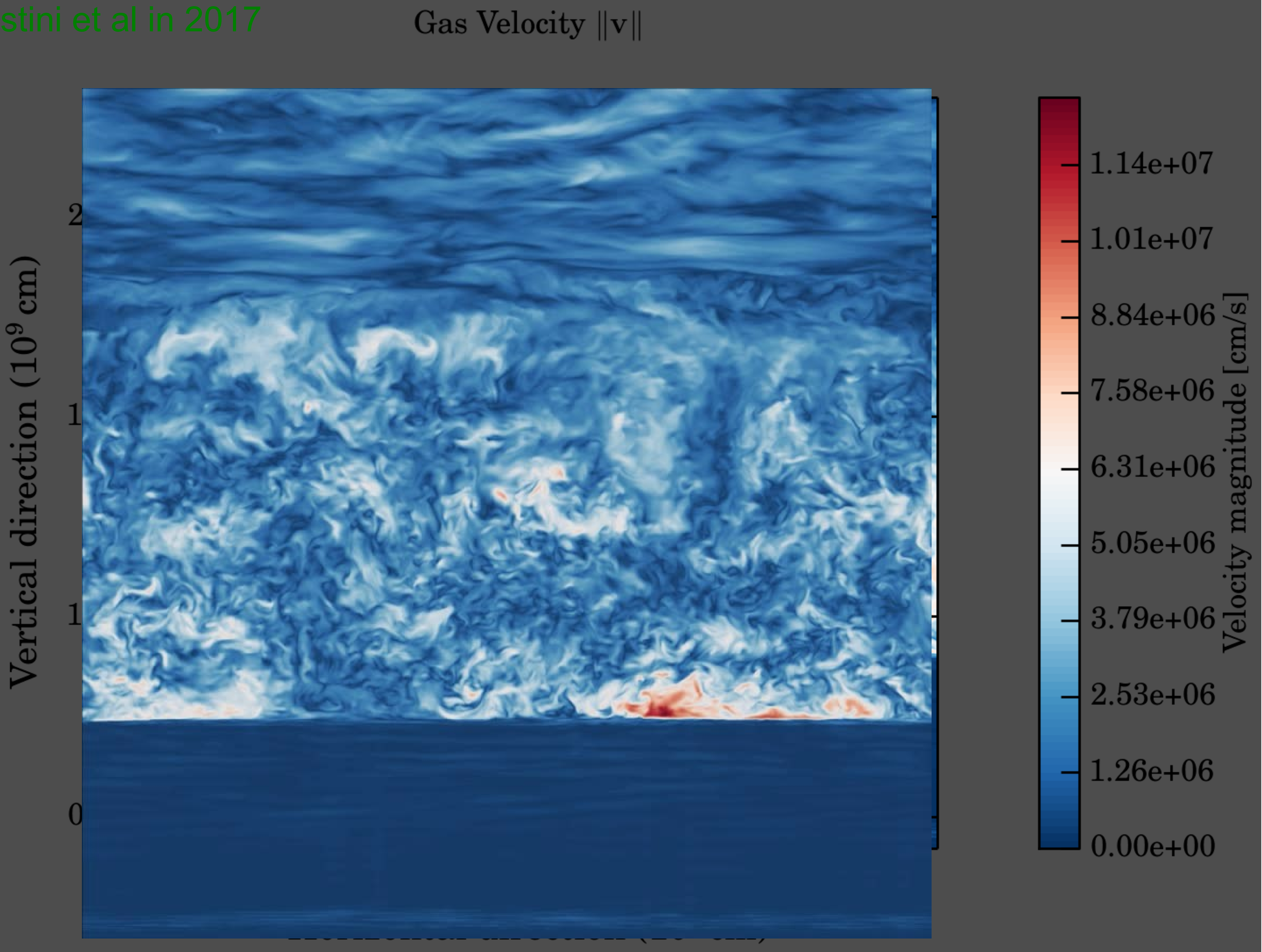
Snapshot from 1024^3 resolution run:



Cristini et al in 2017

C-shell Simulations: |v| movie

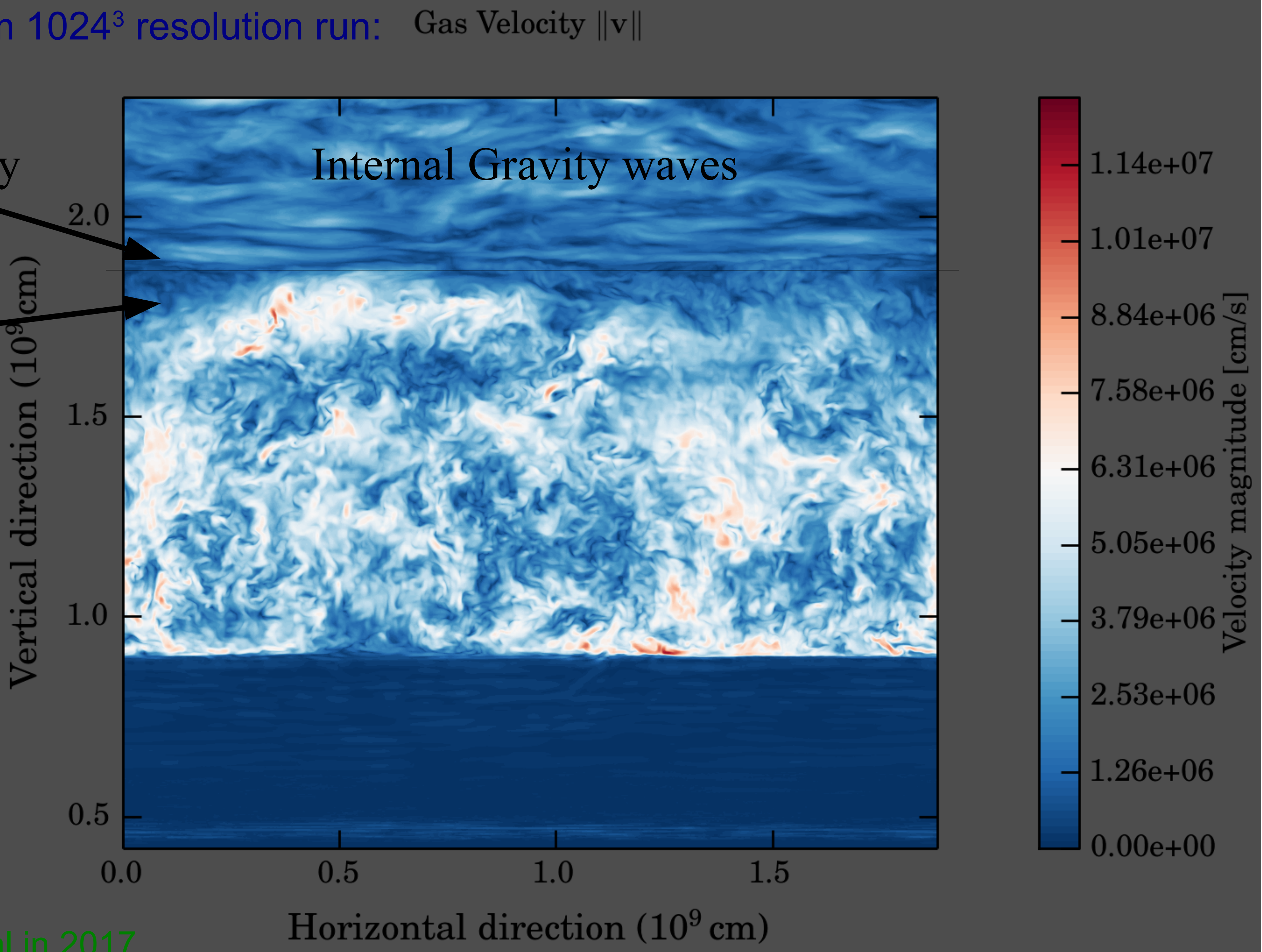
Cristini et al in 2017



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

C-shell Simulations

Snapshot from 1024^3 resolution run:

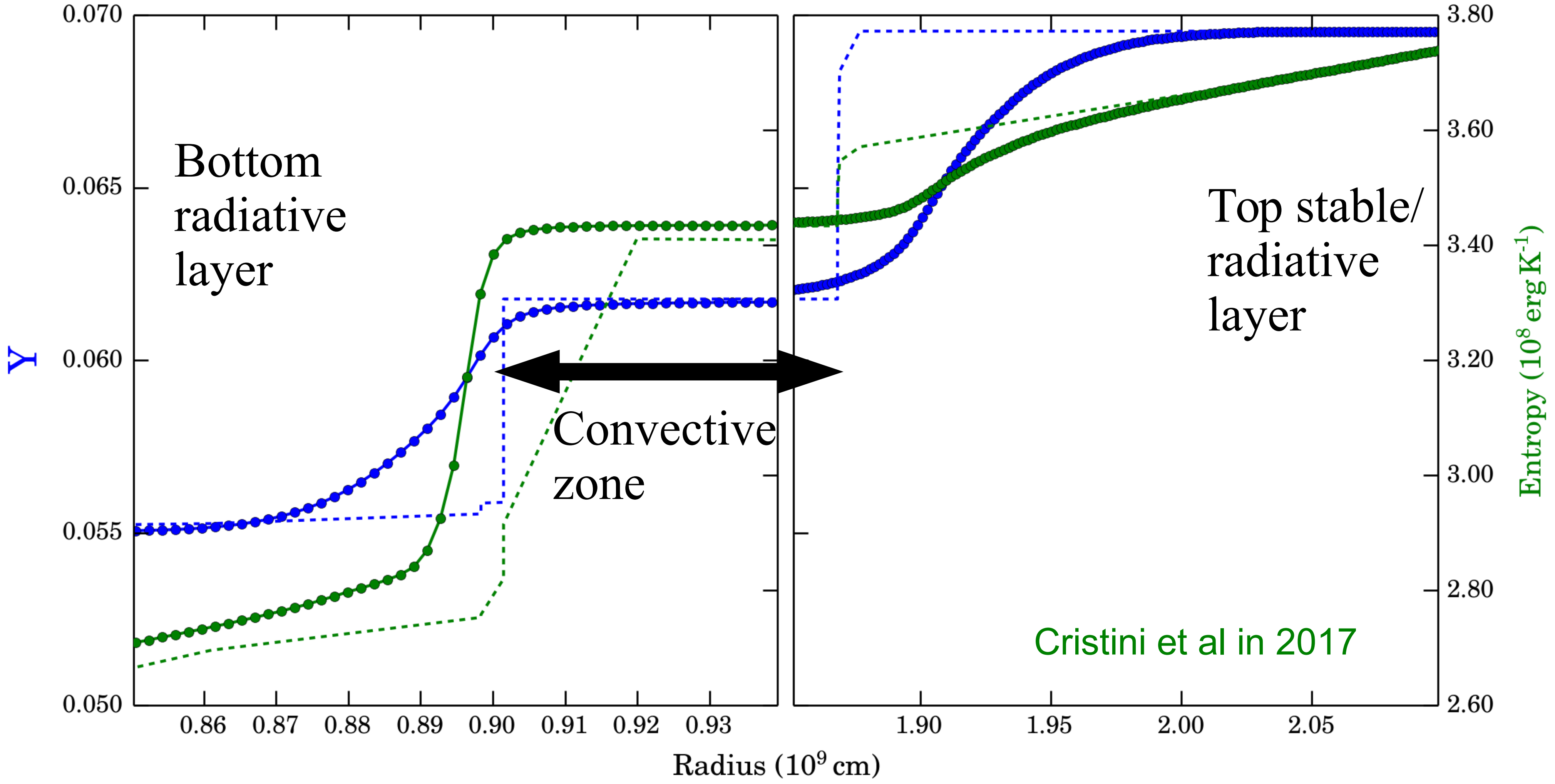


1D boundary

KH inst.
(shear)

Cristini et al in 2017

3D versus 1D

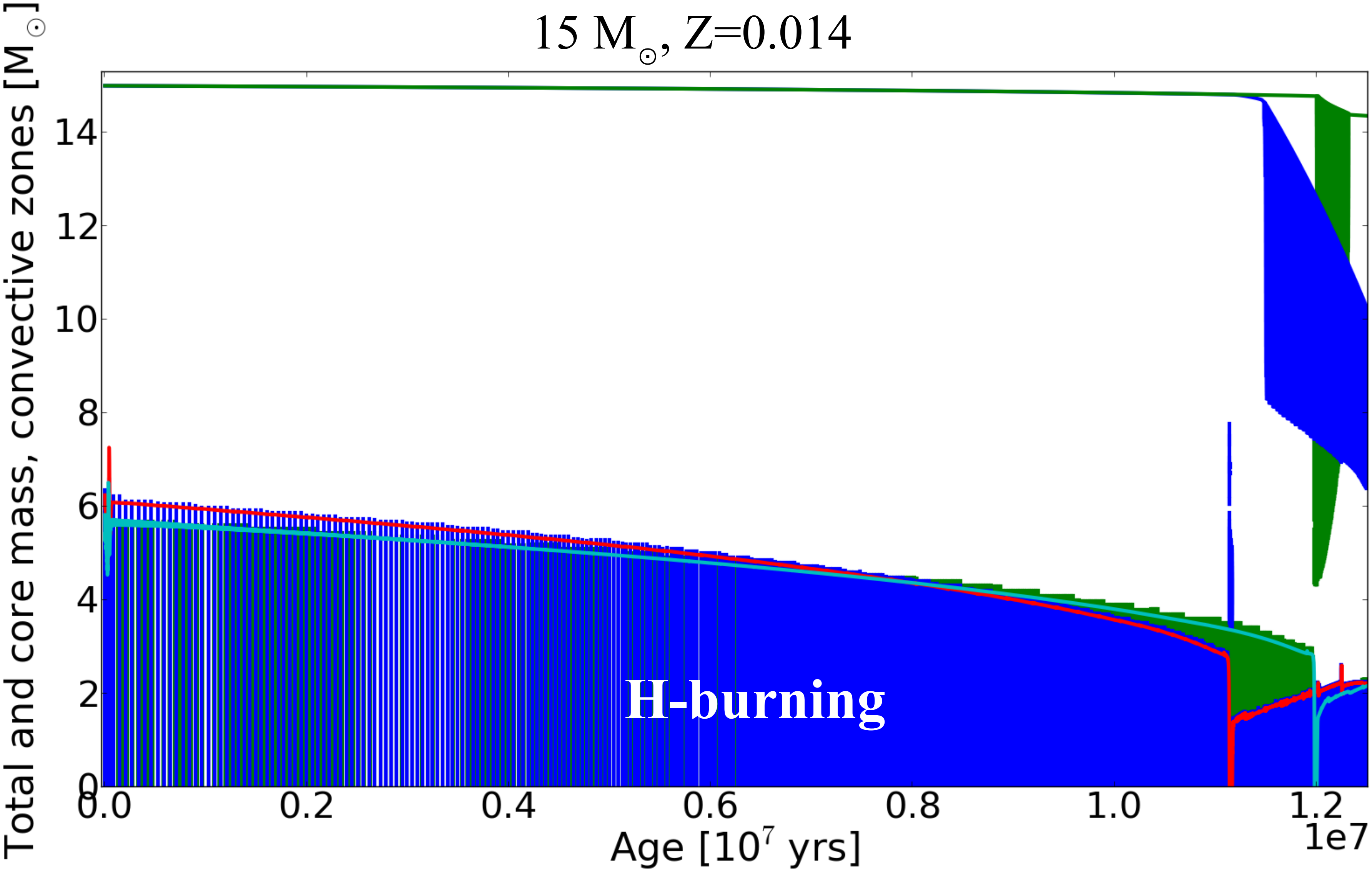


Cristini et al in 2017

- Improved prescriptions for CBM needed!

Back to 1D

Penetrative vs exp-D CBM: prescription choice affects results

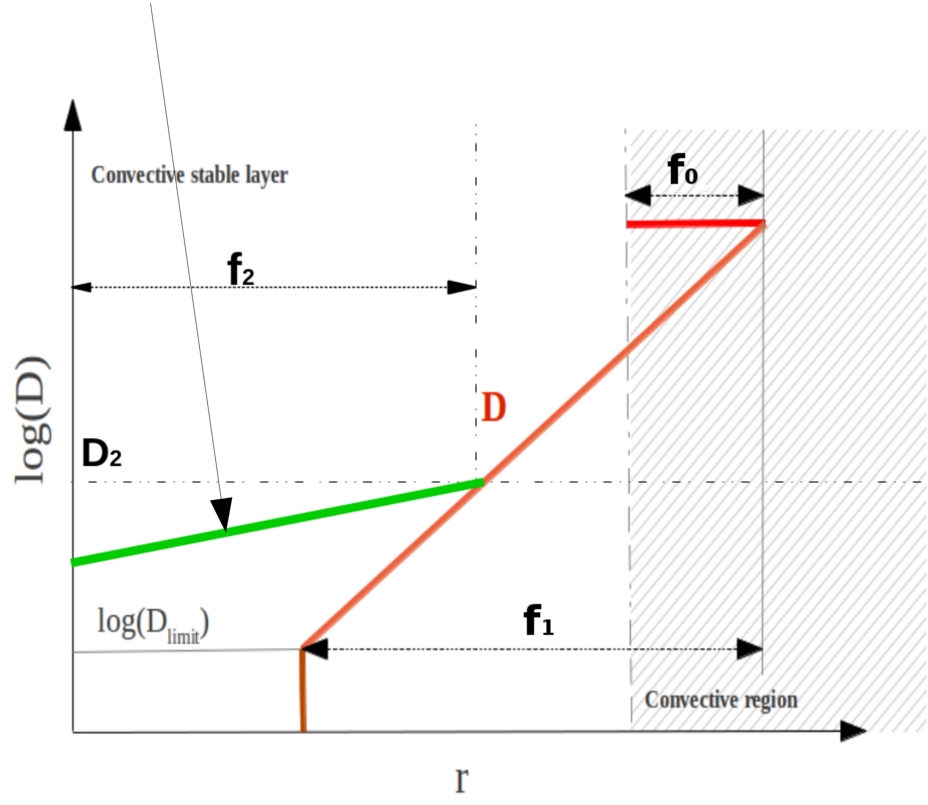


Cristini et al in prep

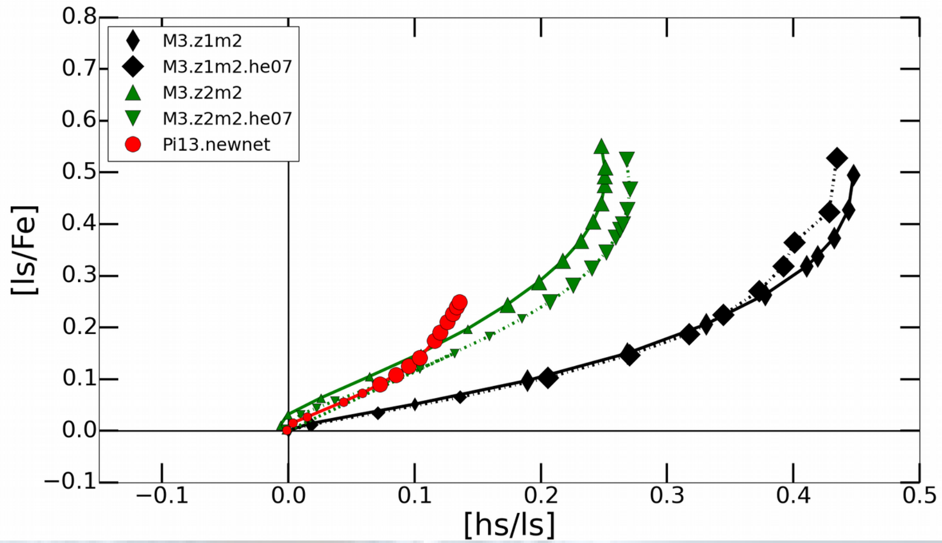
Back to 1D: CBM in AGB Stars (NuGrid project)

Internal gravity wave (IGW) driven mixing

Battino,…,Hirschi et al ApJ 2016



$2\text{-}3\ M_\odot$, Z=0.01-0.02

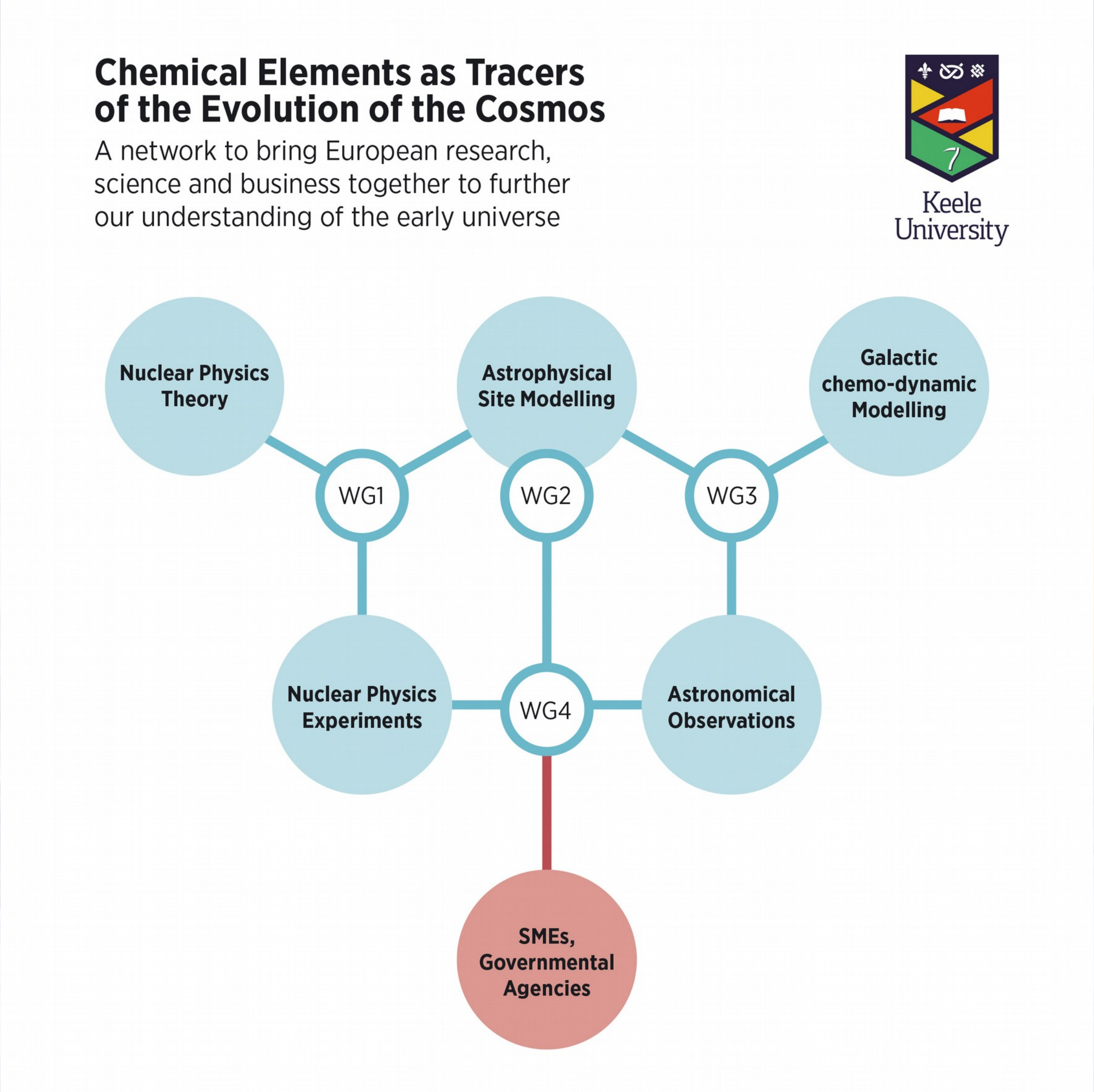


1) CBM (first f) plays a key role both for the C13 pocket via CBM below CE (needed for TDU) and for the c12 & o16 abundances in the intershell via CBM below TPs

2) IGW (second f) plays a key role for the C13 pocket (not so much for mixing below the Tps)

Study of the effects of rotation and B-field underway (den Hartogh, Hirschi, Herwig et al in prep)

ChETEC COST Action (2017-2021) www.chetec.eu



Chemical Elements as Tracers of the Evolution of the Cosmos

A network to bring European research, science and business together to further our understanding of the early universe

Keele University

Nuclear Physics Theory

Astrophysical Site Modelling

Galactic chemo-dynamic Modelling

WG1

WG2

WG3

Nuclear Physics Experiments

WG4

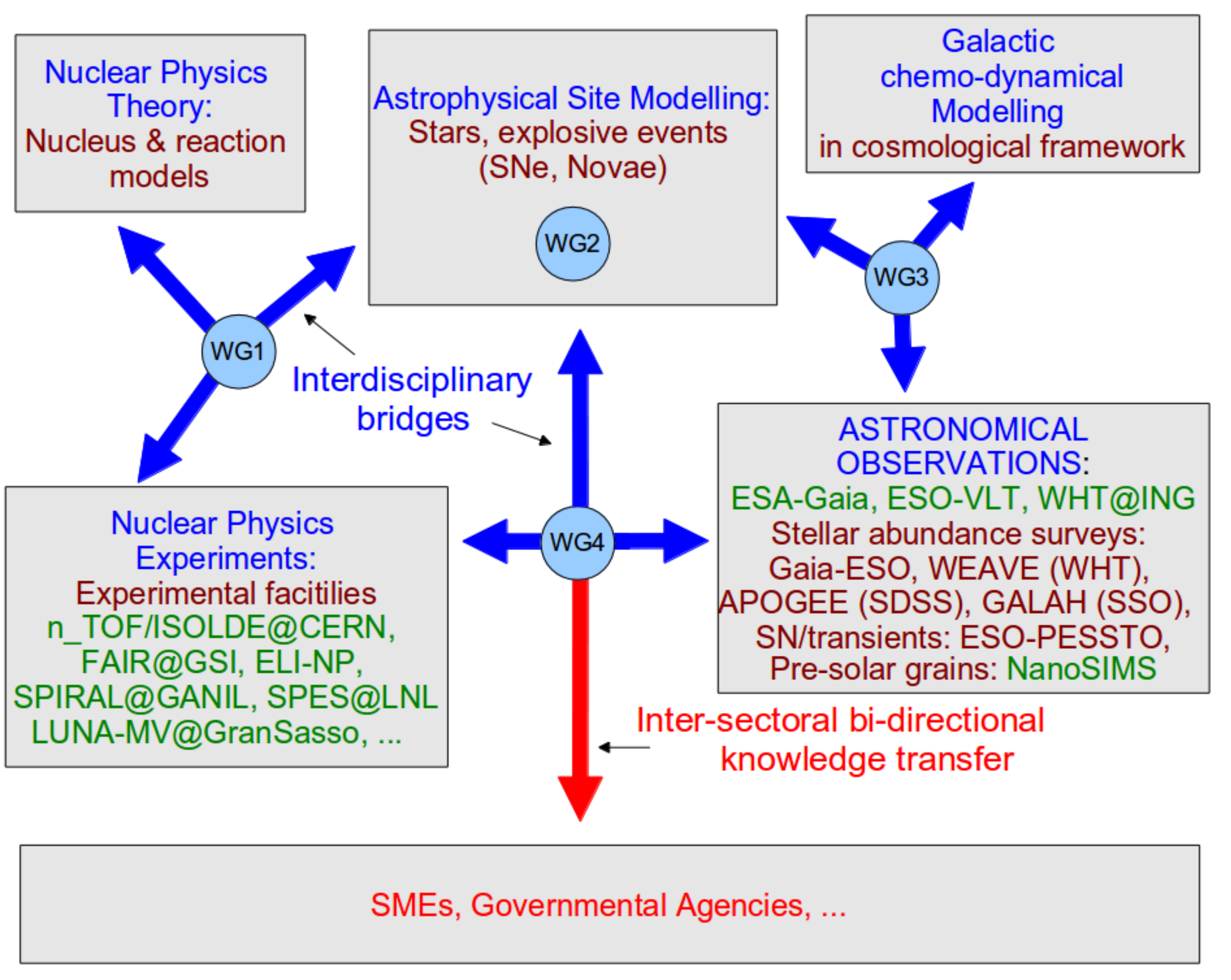
Astronomical Observations

SMEs, Governmental Agencies

29 countries have already joined ChETEC to coordinate research efforts in Nuclear Astrophysics: Austria, Belgium, Bulgaria, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom

What is ChETEC about? (pronounced [ketek])

Main challenge: tackle key open questions and link European facilities.



Nuclear Physics Theory:
Nucleus & reaction models

Astrophysical Site Modelling:
Stars, explosive events (SNe, Novae)

Galactic chemo-dynamical Modelling
in cosmological framework

Interdisciplinary bridges

ASTRONOMICAL OBSERVATIONS:
ESA-Gaia, ESO-VLT, WHT@ING
Stellar abundance surveys:
Gaia-ESO, WEAVE (WHT),
APOGEE (SDSS), GALAH (SSO),
SN/transients: ESO-PESSTO,
Pre-solar grains: NanoSIMS

Nuclear Physics Experiments:
Experimental facitilies
n_TOF/ISOLDE@CERN,
FAIR@GSI, ELI-NP,
SPIRAL@GANIL, SPES@LNL
LUNA-MV@GranSasso, ...

Inter-sectoral bi-directional knowledge transfer

SMEs, Governmental Agencies, ...

Working Groups (WG) & Management Structure (MC)

- WG1: nuclear data for astrophysics: needs, coordination and dissemination
- WG2: modelling pipelines connecting nuclear processes to astronomical observables
- WG3: astronomical data coordination, analysis and interpretation
- WG4: tools, techniques, knowledge exchange and innovation

Management Committee (MC): 2 members per country (+2-3 substitutes)

CORE group/Steering Committee (each CORE group member represents a team, see “Key Info” for more details)

Action Chair: R. Hirschi

Vice Chair: M. Lugaro

WG leaders: Alessandra Guglielmetti (WG1), Georges Meynet (WG2),
Andreas Korn (WG3), Daniel Bemmerer (WG4)

Gender coordinator: Maria Lugaro

Pan-European coordinator: Sevdalina Dimitrova

Inter-sectoral (bi-direction Knowledge Transfer) coordinator: Daniel Bemmerer

STSM manager: Neven Soic

Dissemination coordinator: Jordi Jose

How to Get Involved?

COST Actions are open and inclusive

Everyone can participate … but budget is limited given scale of network

(Most countries already have management committee members)

1) Join a WG by contacting the WG leader and the Action chair

2) Sign up to ChETEC mailing list (to be set up soon)

3) Contribute to the “knowledge hubs”: including at least one directory of datasets per WG

4) “Young” scientists are encouraged to attend the training schools

5) Propose, organise, host COST events

http://www.cost.eu/participate/join_action

Activities Planned in 2017-2018 (Year 1)

1) Short-term Scientific Missions (STSMs): throughout the year with evaluation deadlines every 3-4 months

2) *Proposed* Training schools (confirmed by next week):

- Gamma-ray measurements and target preparation (main contact: Livius Trache):
  April 2018 @ IFIN-HH (ELI-NP), Bucharest, Romania
- R-matrix calculations for nuclear astrophysics (main contact: Fairouz Hammache)
  13-15 September 2017 @ IPN, Orsay, France

3) Main Action workshop involving all WGs: October 9-11, Keele University, UK (main contact R. Hirschi)

COST Acknowledgements

The ChETEC Action (CA16117) is supported by COST (www.cost.eu). COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.

Funded by the Horizon 2020 Framework Programme of the European Union

Conclusions & Outlook

- Large grids of models with comprehensive nucleosynthesis for weak s process published
- Key nuclear reaction list established for weak s proc
- 1D to 3D to 1D work underway for convection (and rotation). Priority list established: large effort needed!
- ChETEC COST Action started: see www.chetec.eu for more info