Darmstadt, March 18

Massive Stars: Nucleosynthesis, Nuclear Uncertainties & GCE

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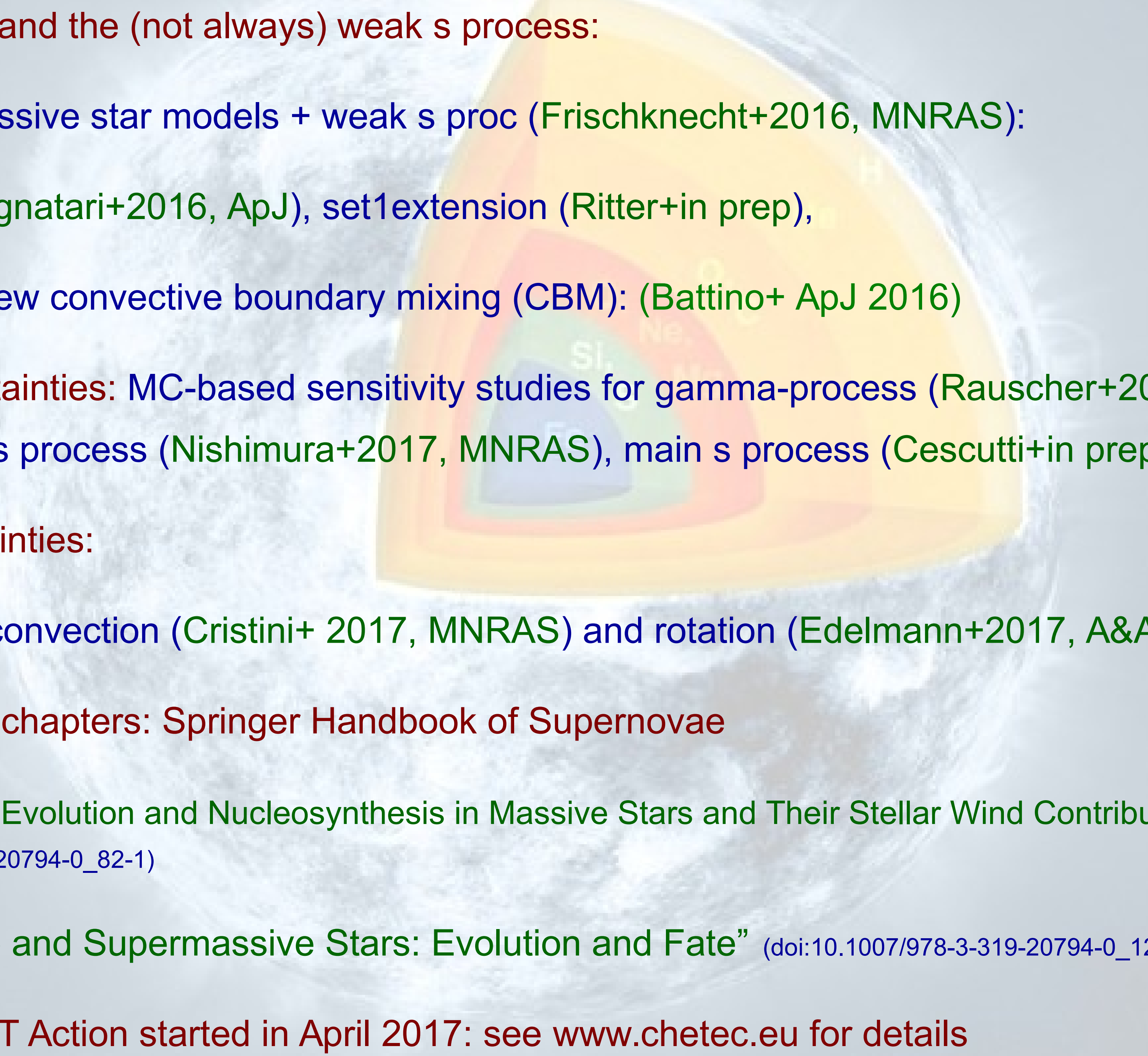
Recent work



- 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 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)

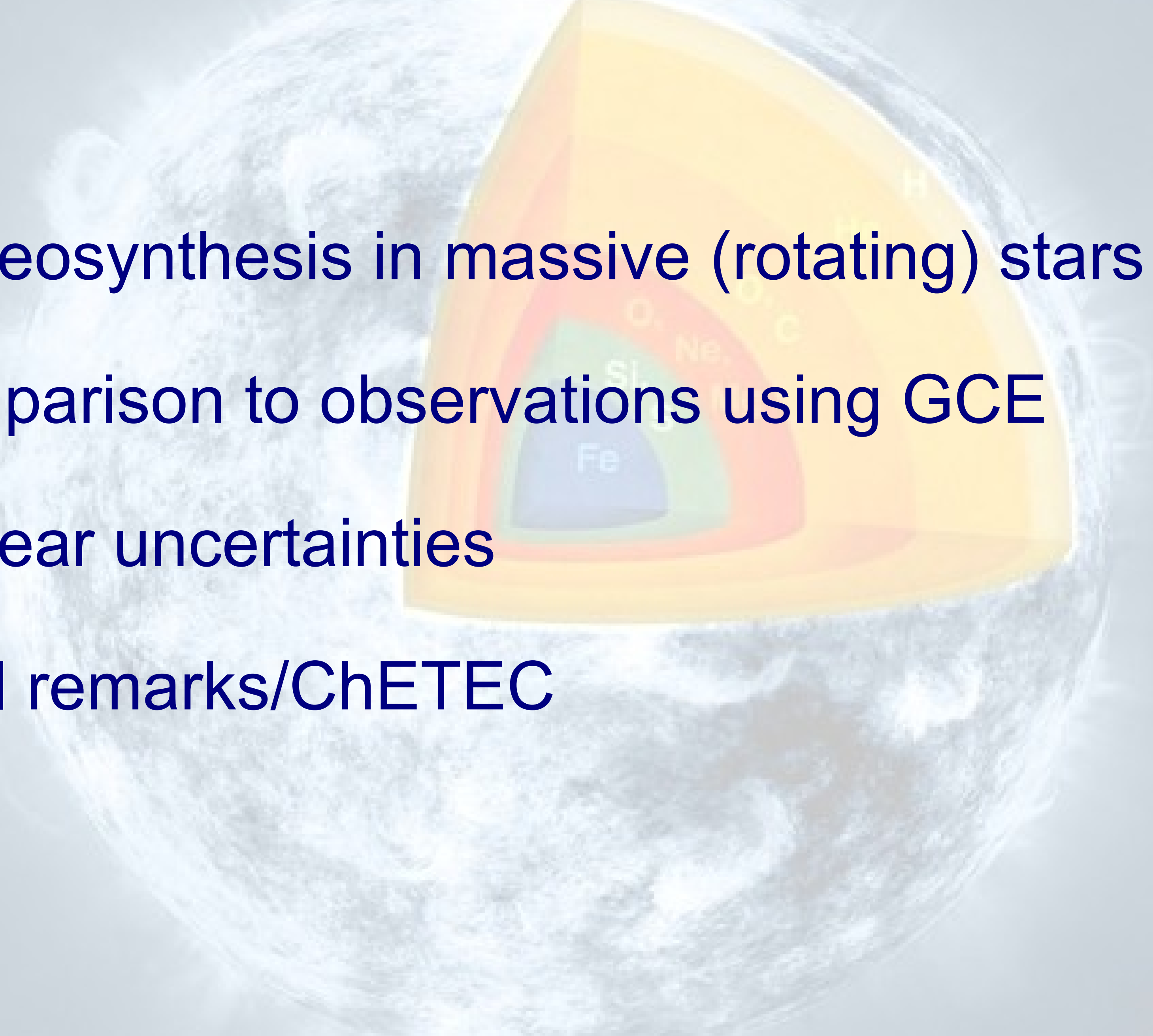
- Reviews/book chapters: Springer Handbook of Supernovae

"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

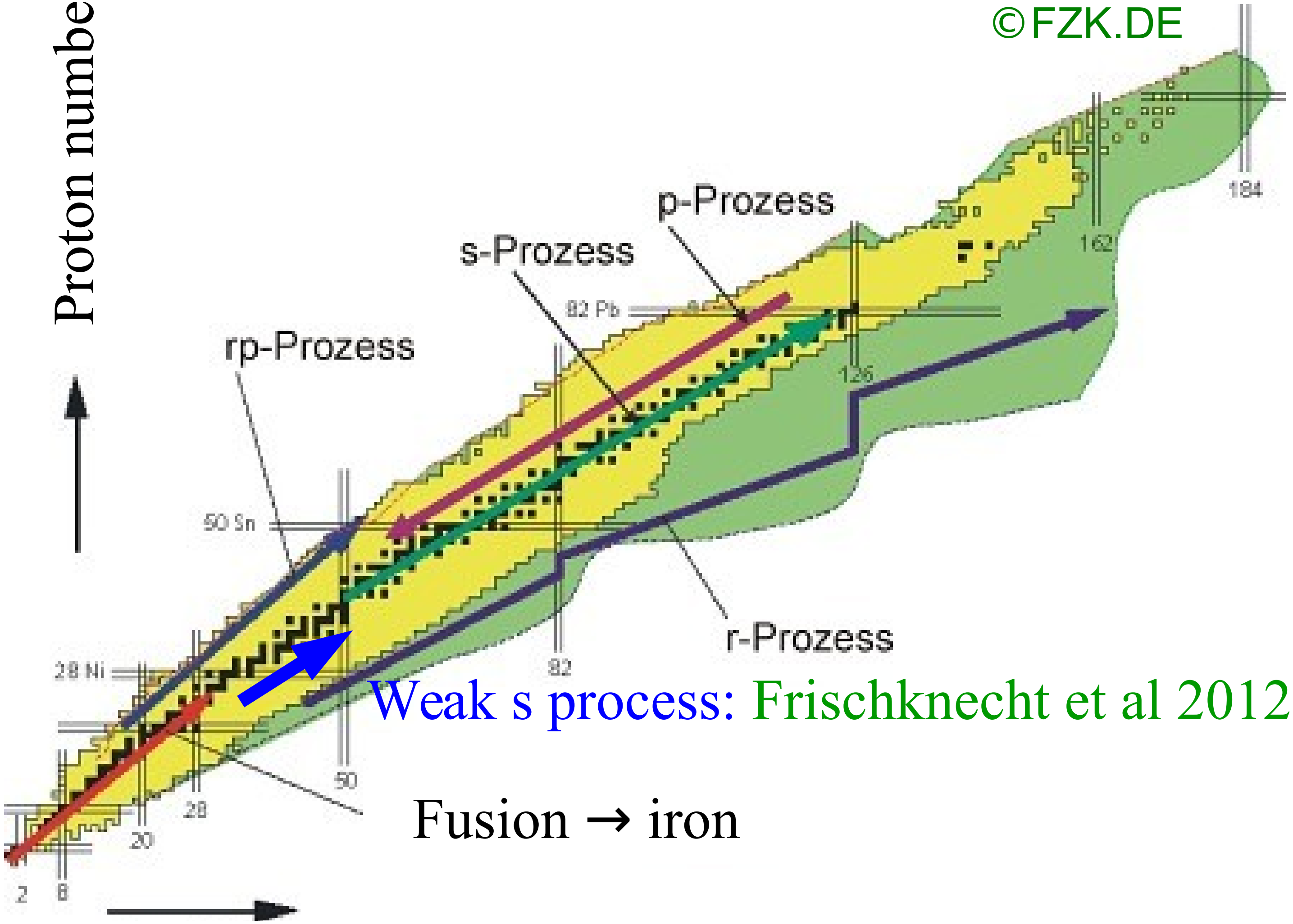
Plan



- Nucleosynthesis in massive (rotating) stars
- Comparison to observations using GCE
- Nuclear uncertainties
- Final remarks/ChETEC

Stars: Importance for Nucleosynthesis

Proton number



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Weak s process: Frischknecht et al 2012, 2016

Fusion → iron

Neutron number

Rotation-Induced Transport

Zahn 1992: strong horizontal turbulence

Transport of angular momentum:

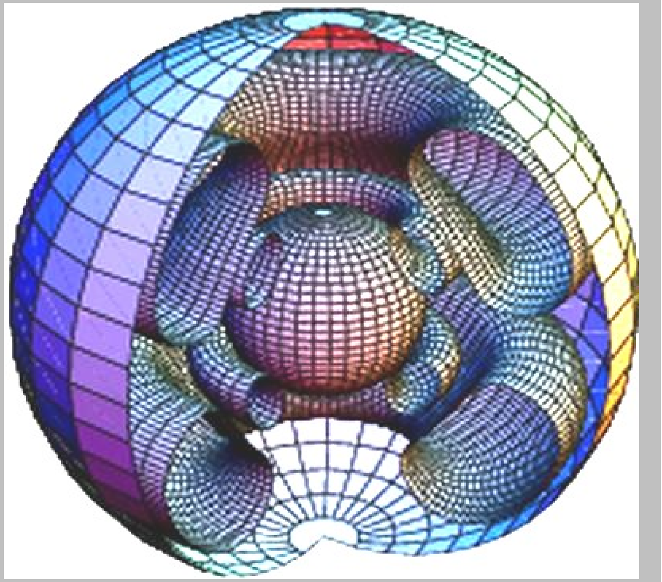
$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4\bar{\Omega}U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D r^4\frac{\partial\bar{\Omega}}{\partial r}\right)}_{\text{diffusion term}}$$

Transport of chemical elements:

$$\rho\frac{\mathrm{d}X_i}{\mathrm{d}t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2\left[D+D_{eff}\right]\frac{\partial X_i}{\partial r}\right) + \left(\frac{\mathrm{d}X_i}{\mathrm{d}t}\right)_{\text{nucl}}$$

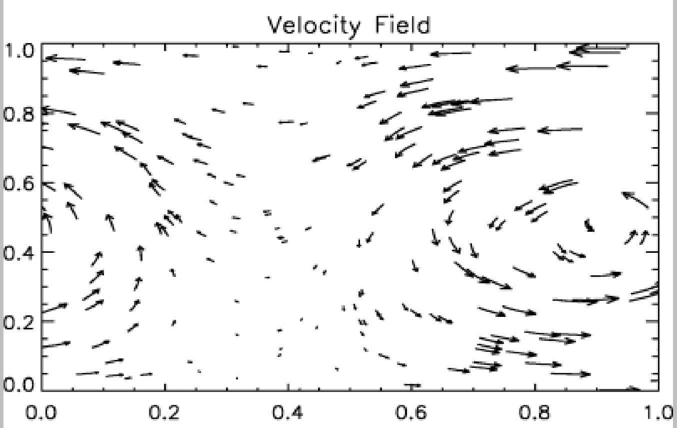
D: diffusion coeff. due to various transport mechanisms (convection, shear)

D_{eff}: diffusion coeff. due to meridional circulation + horizontal turbulence



Meynet & Maeder 2000

Shear instabilities

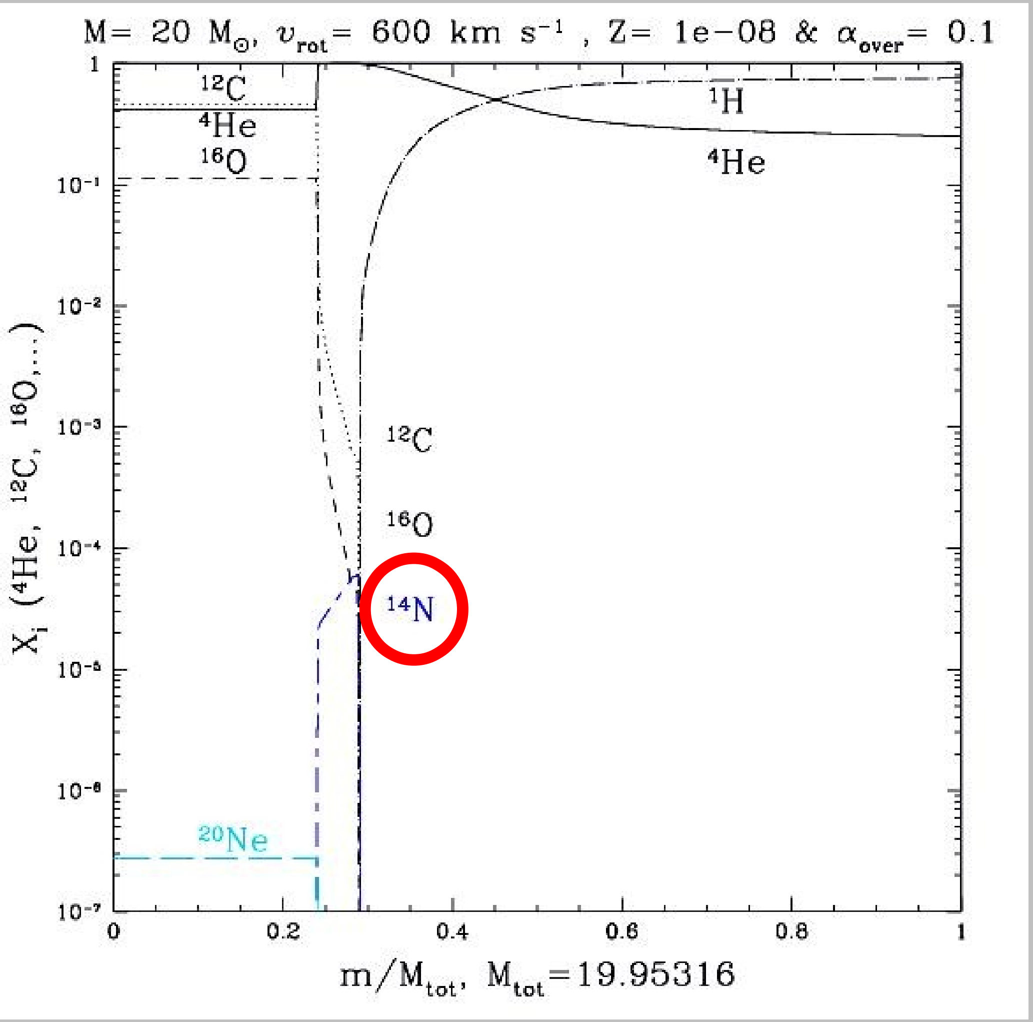


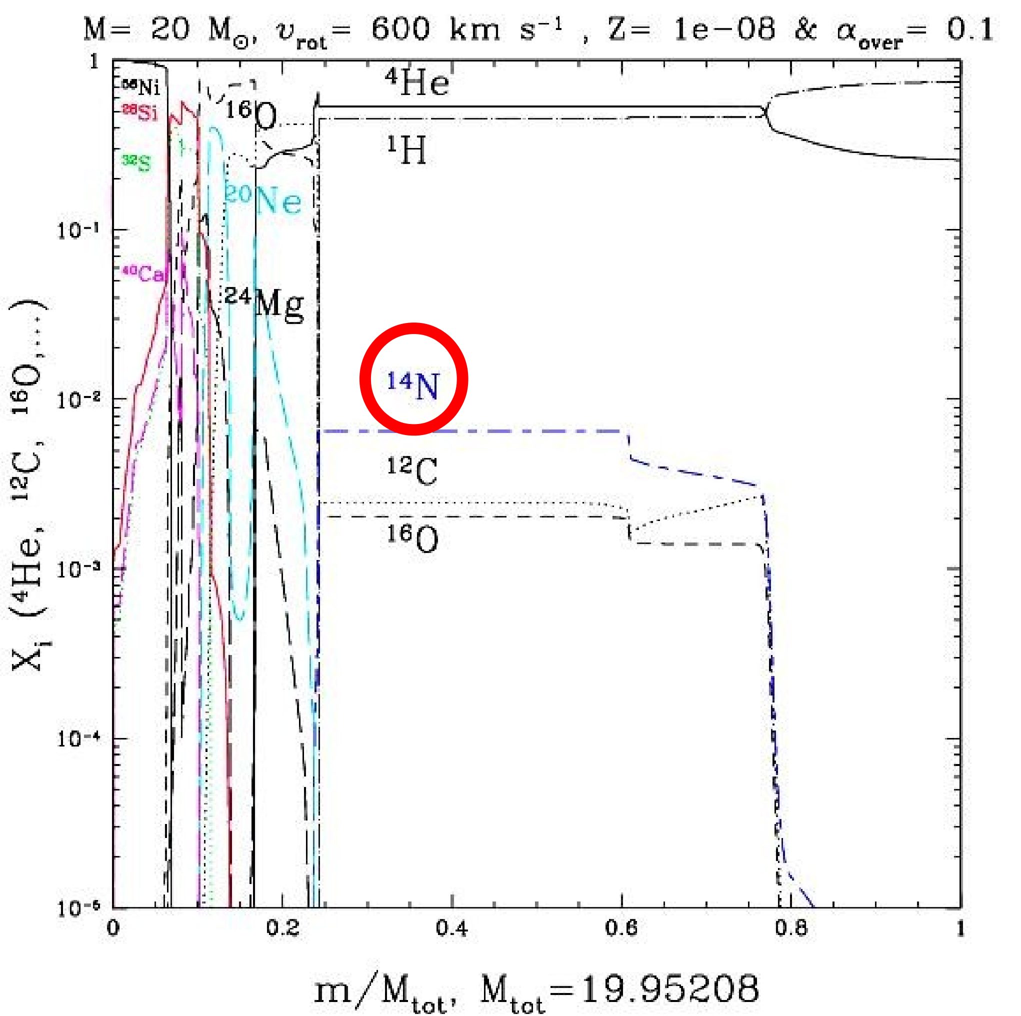
Brueggen & Hillebrandt 2000

Rotation induced mixing @ Low Z

Before H-shell boost

Pre-SN stage





Galactic Chemical Evolution: Primary ^{14}N

1) Evolution of [N/O] reproduced

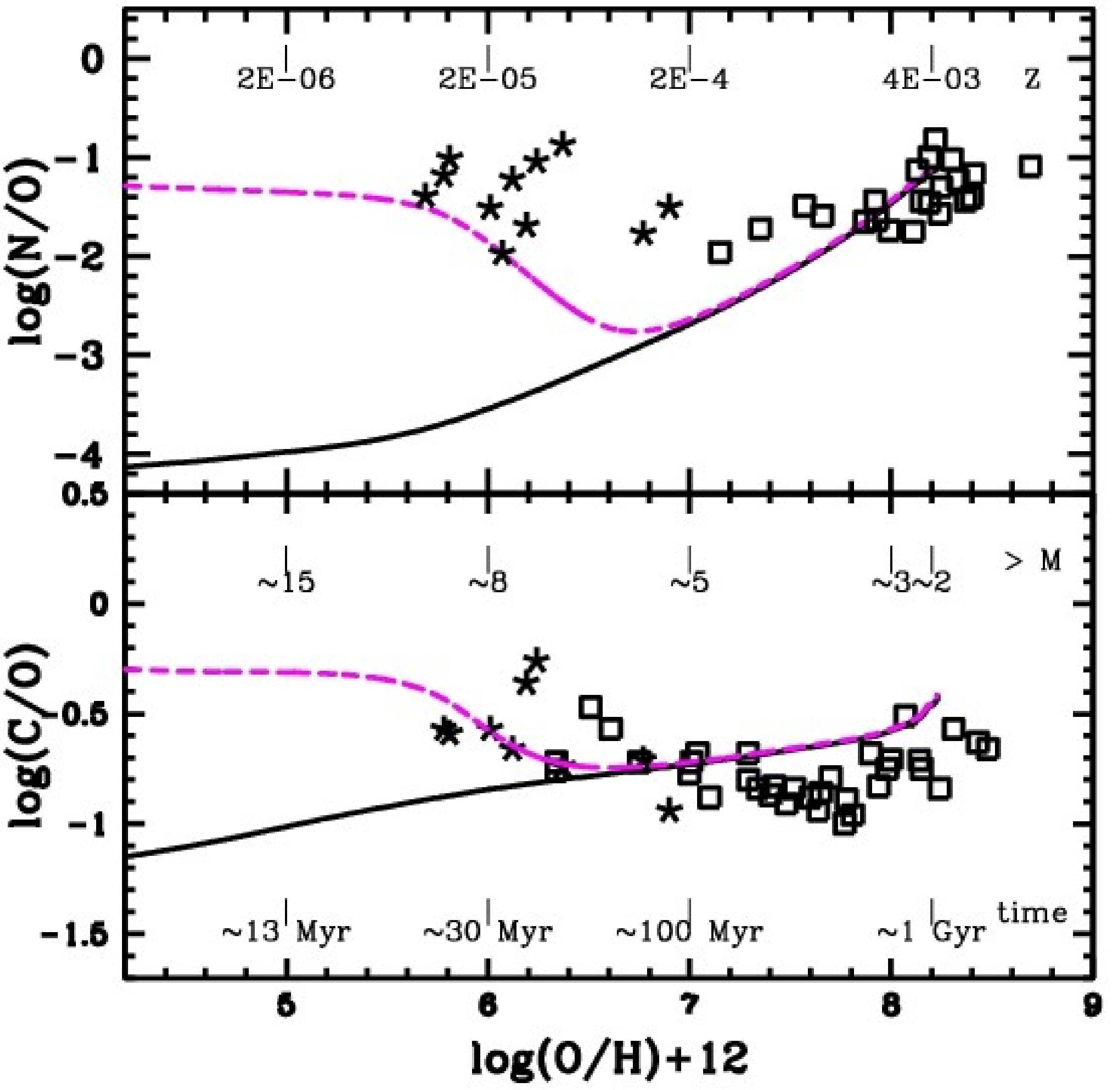
← using Z=10^{-8} yields

Hirschi 07: - - - - - - - -

2) Upturn of [C/O]

Observations:
Spite et al 2004 (asterisks)
Israelian et al 2004 (squares)

Fabbian et al 2008
DLAs Pettini et al 2008



(Chiappini et al 06, A&A)

Galactic Chemical Evolution: $^{12}C/^{13}C$ ratio

3) Evolution of [$^{12}C/^{13}C$]

better reproduced

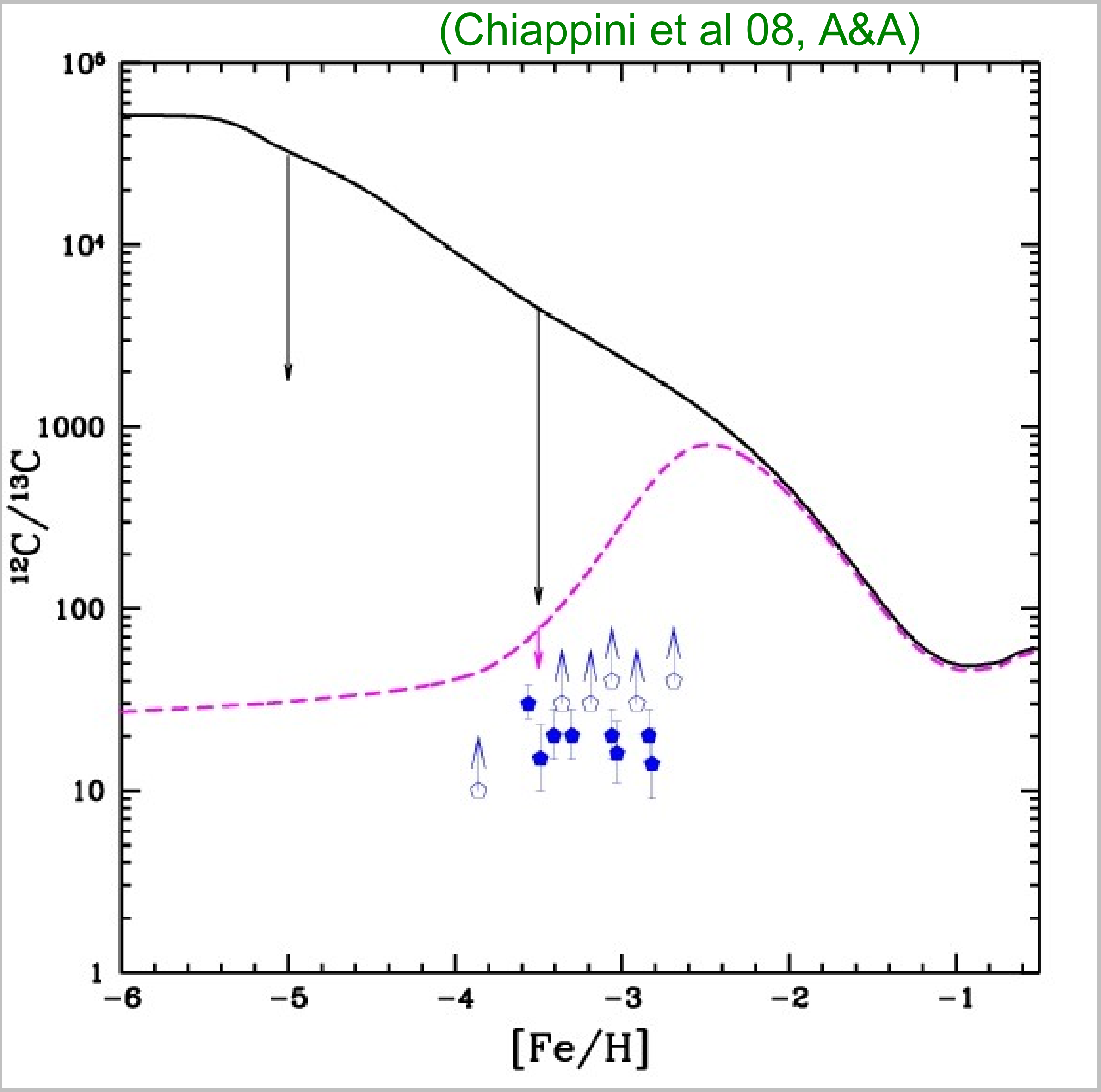
← using Z=10^{-8} yields

Hirschi 07: - - - - - - - -

Large differences expected at [Fe/H]~-5

4) Primary evolution of Be & B

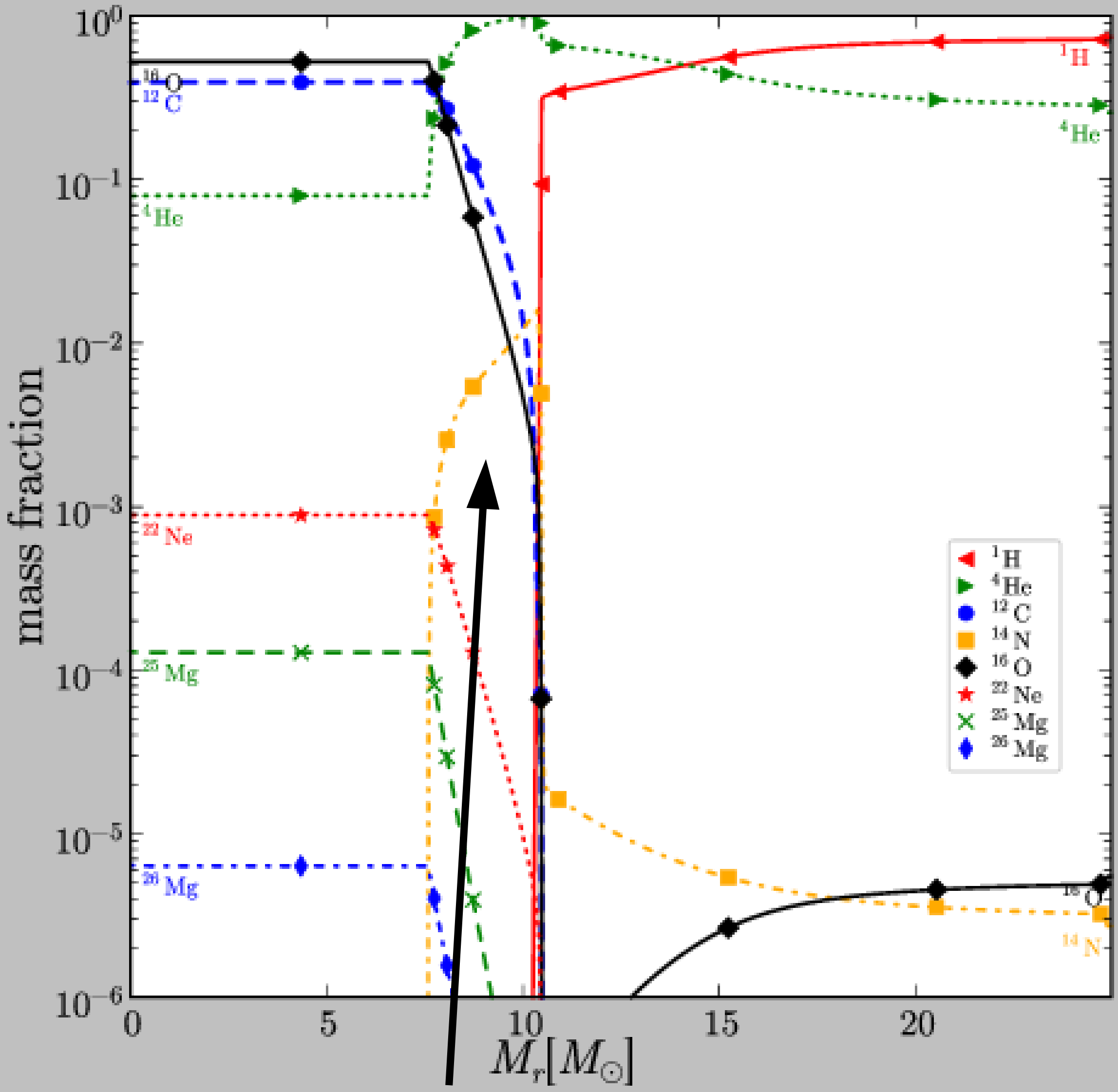
Prantzos (2012)


(Chiappini et al 08, A&A)

Observations: Spite et al 2004

Rotation-Induced Mixing → Primary ^{14}N & ^{22}Ne

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



Mixing between He and H-burning layers

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)

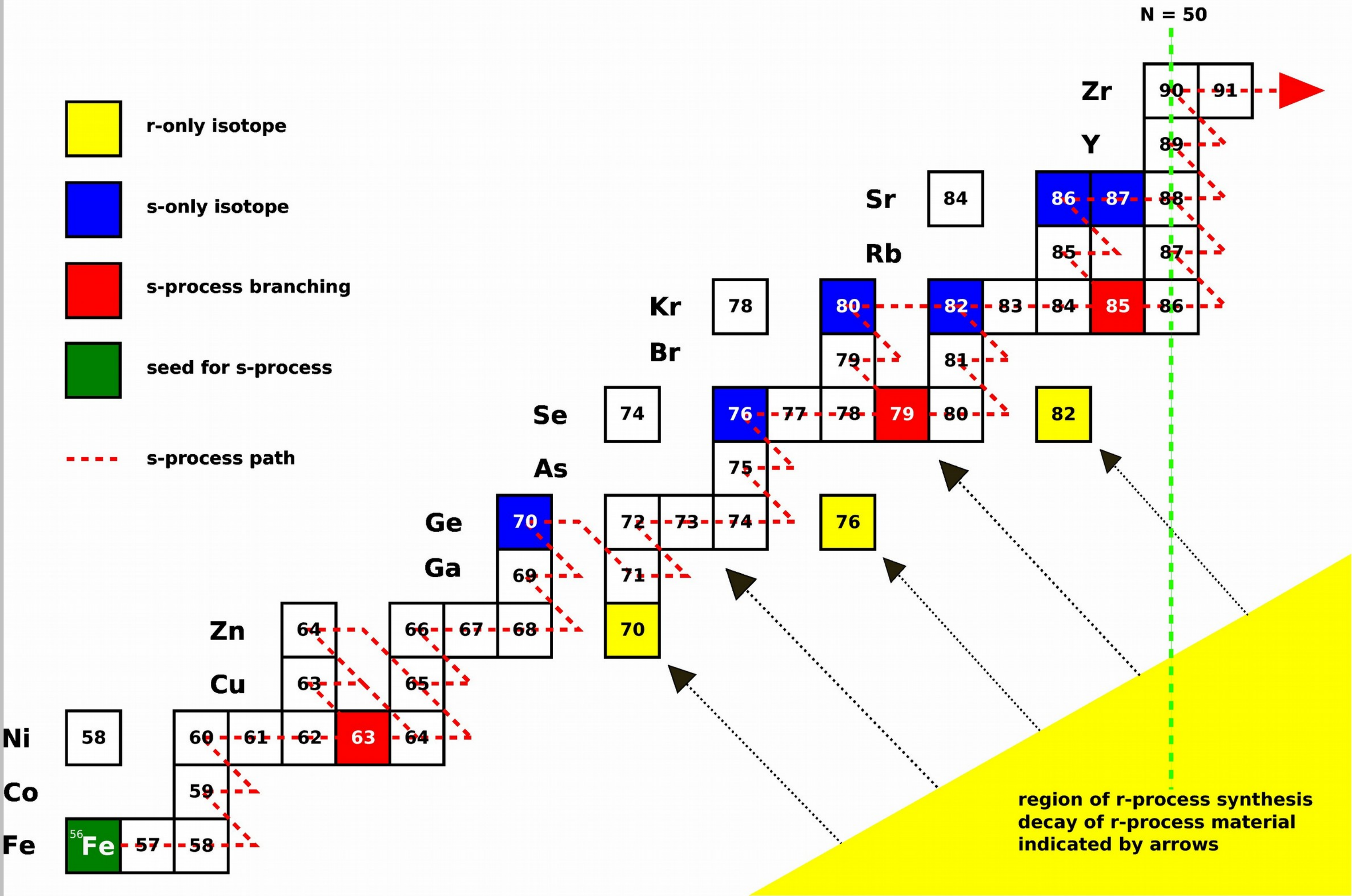
C: T ~ 1GK

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



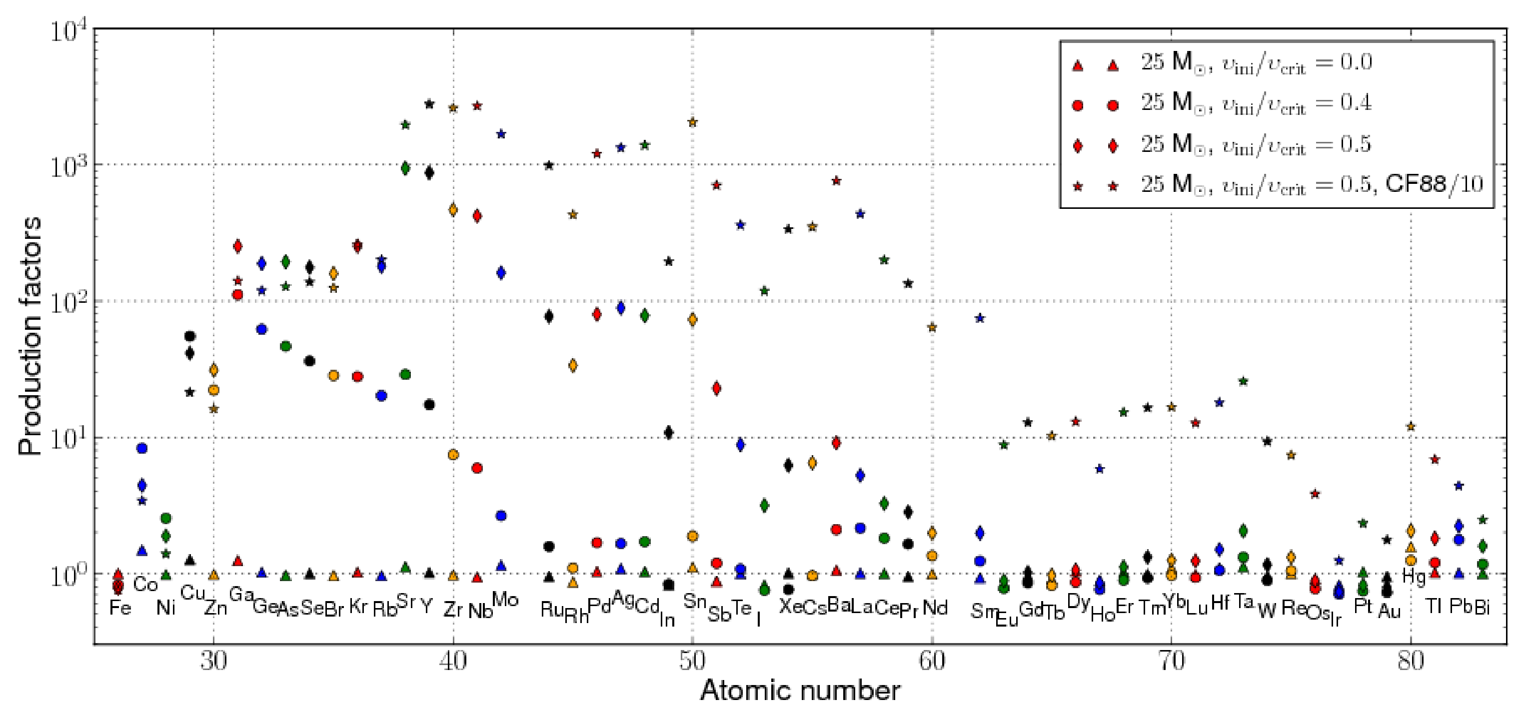
At solar Z: rotating models may produce up to 3x more s process

(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 2011, 2016

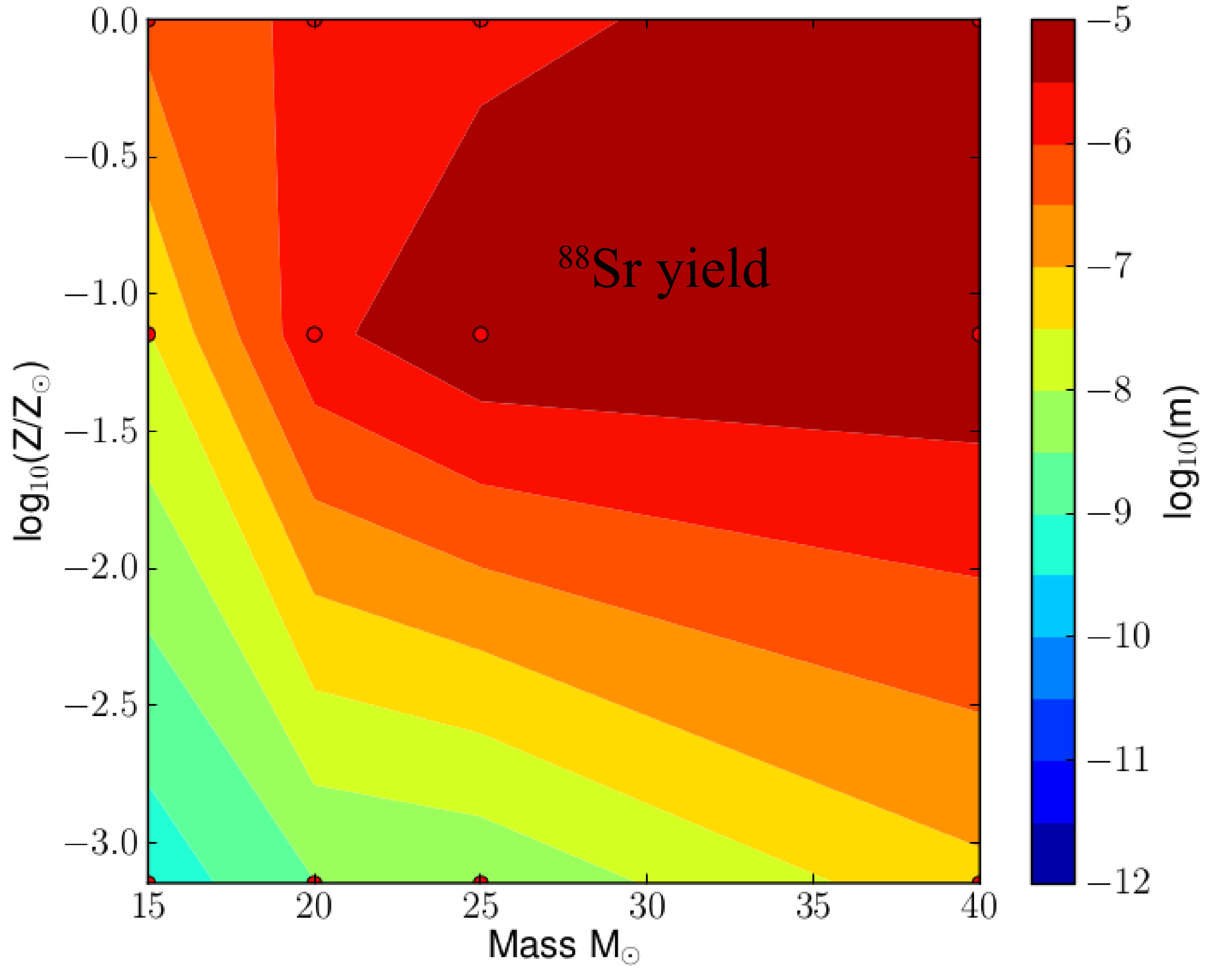
- STELLAR EVOLUTION CALCULATIONS WITH 600/700-ISOTOPE NETWORK!

- **^{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
- FULL GRID NOW PUBLISHED! Frischknecht, Hirschi et al, MNRAS, 2016

S-Process Models of Massive Rotating Stars

- FULL GRID NOW PUBLISHED!

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

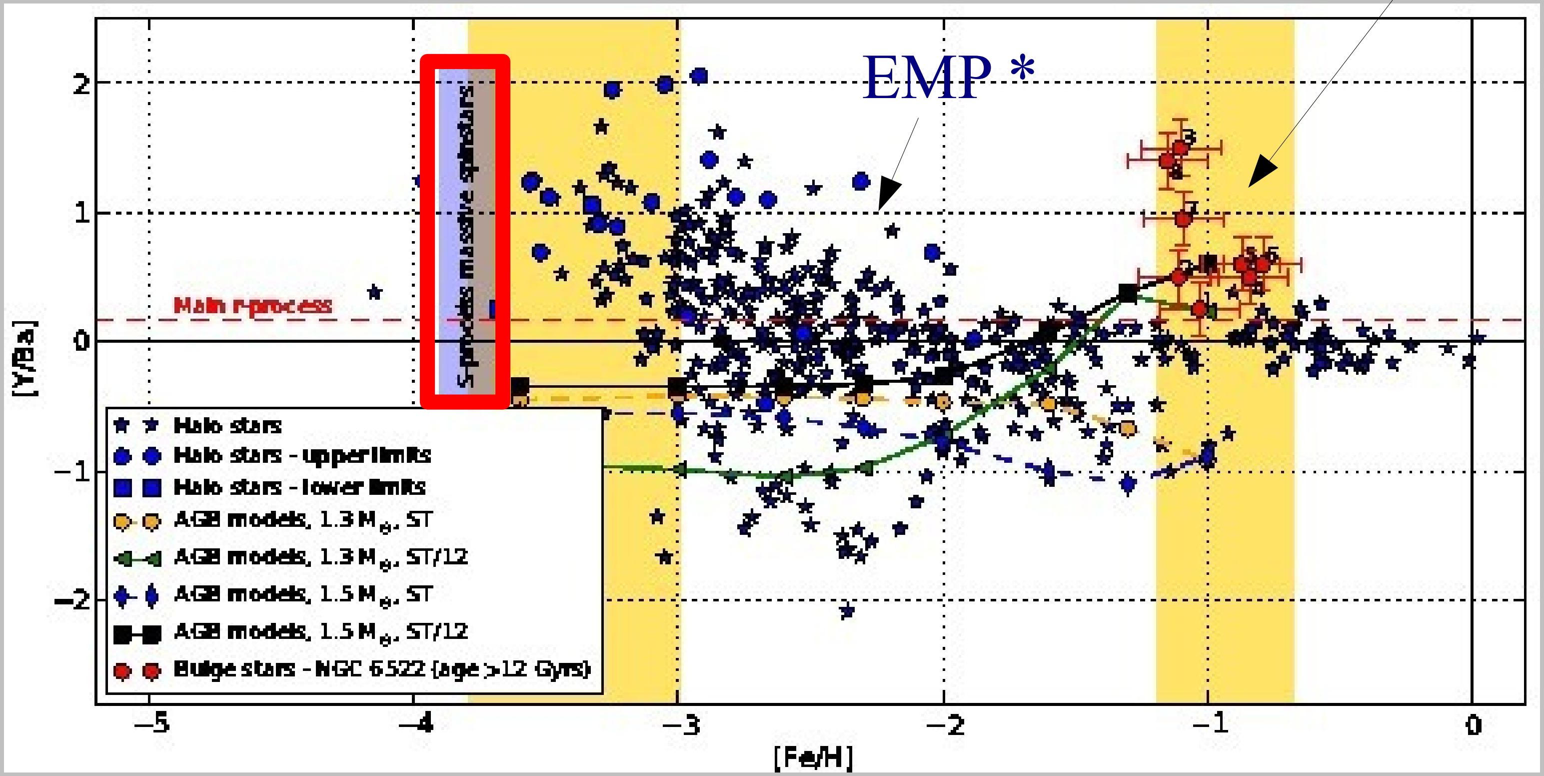


STELLAR EVOLUTION CALCULATIONS WITH 600/700-ISOTOPE NETWORK!

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

Chiappini et al, Nature Letter, 2011

Bulge GC *



- Strong variations in [Y/Ba] >~ 2 dex matches well observed range!

(EMP *: Frebel et al 2010)

- New models also explain abundances in one of the oldest clusters in galactic bulge

Other processes cannot explain all the observed stars in bulge GC NGC6522

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

* 5 signatures of rotation at low Z Cescutti,..., Hirschi et al, 2013, A&A, 553, A51

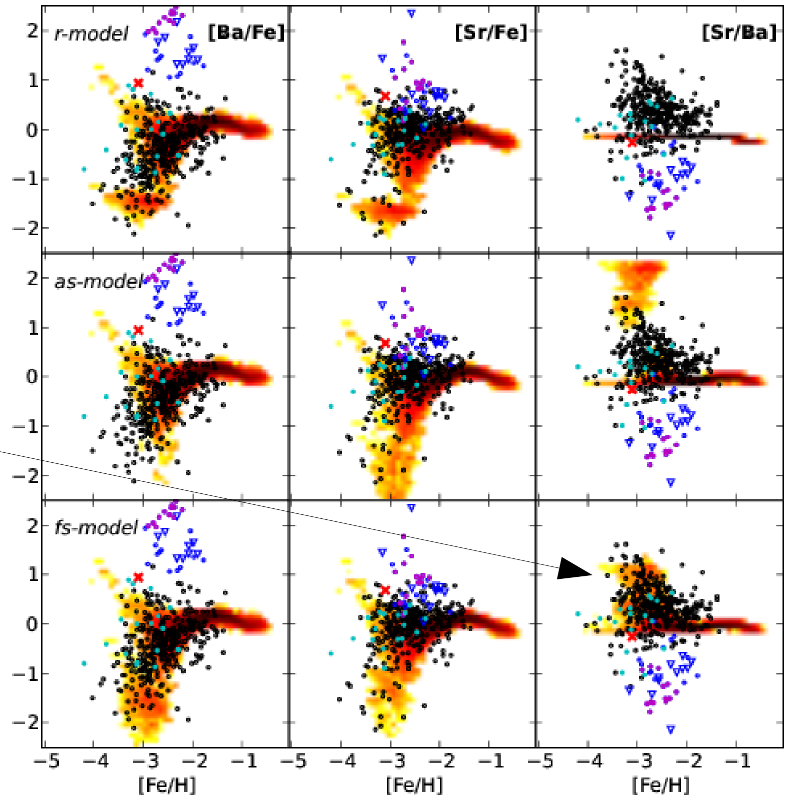
rise of N/O and C/O, low 12C/13C, and a primary-like evolution of Be and B, s process

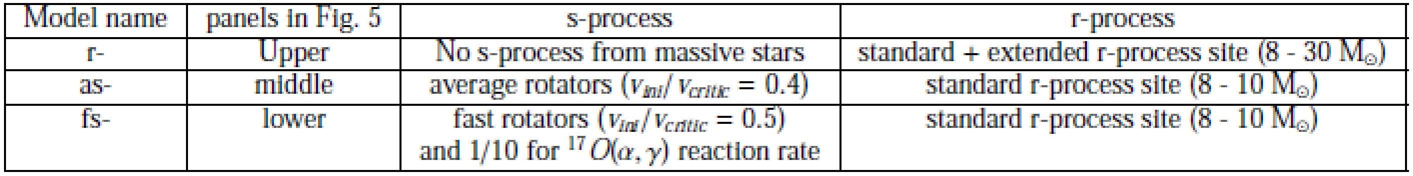
* Models explain abundances in one of the oldest clusters in galactic bulge Chiappini et al, Nature Letter, 2011

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)

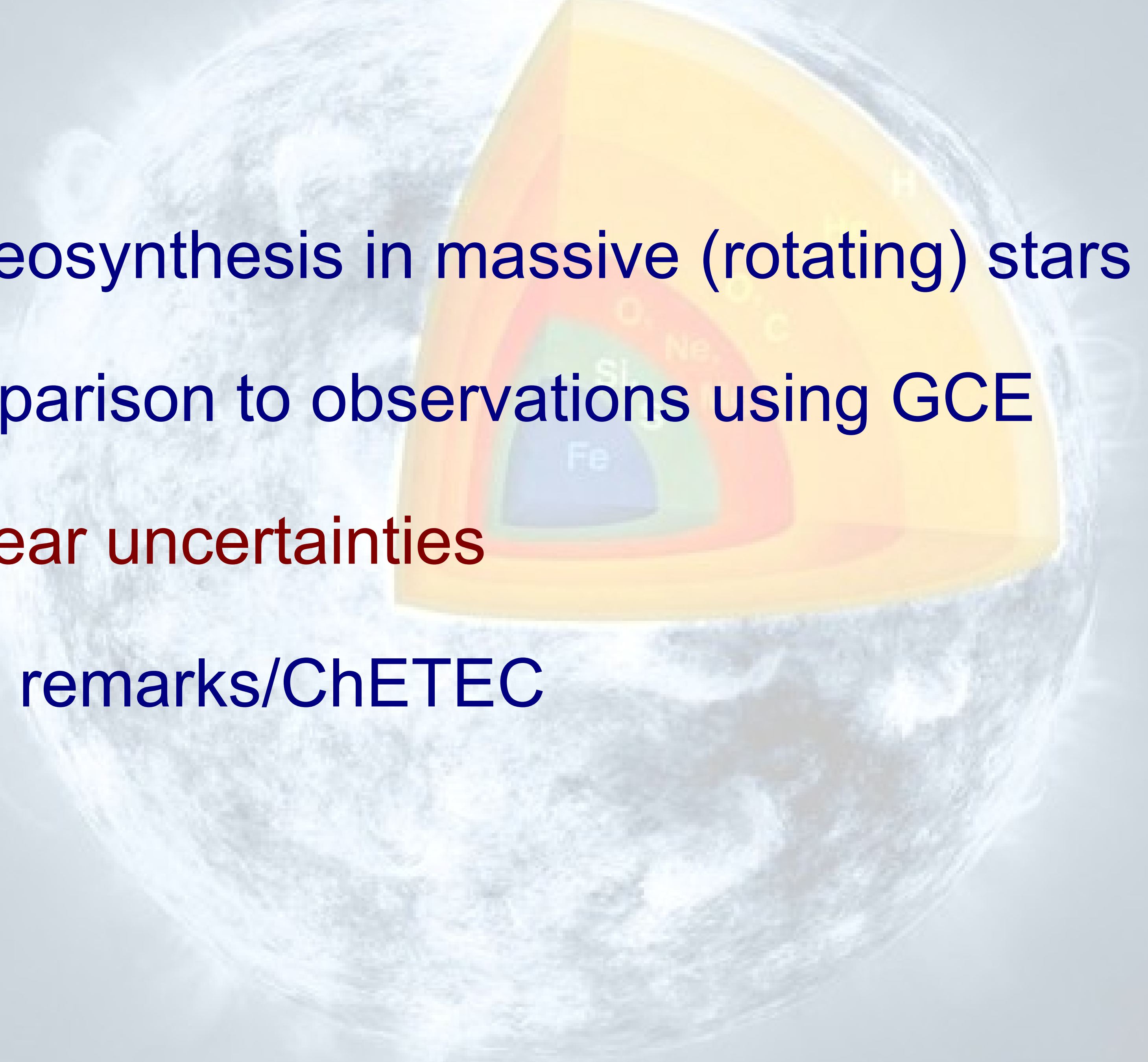




Model name	panels in Fig. 5	s-process	r-process
r-	Upper	No s-process from massive stars	standard + extended r-process site (8 - 30 $M_\odot$)
as-	middle	average rotators ($v_{ini}/v_{critic} = 0.4$)	standard r-process site (8 - 10 $M_\odot$)
fs-	lower	fast rotators ($v_{ini}/v_{critic} = 0.5$) and 1/10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

(EMP *: Frebel et al 2010)

Plan



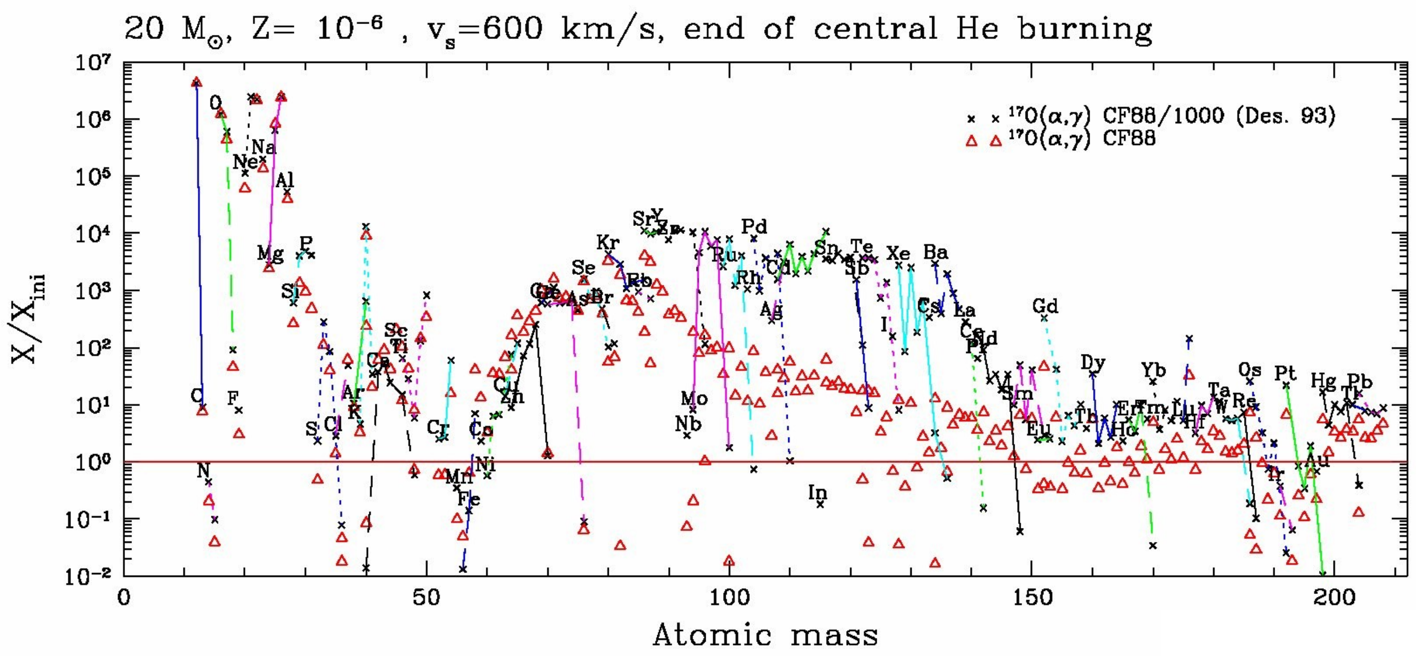
- Nucleosynthesis in massive (rotating) stars

- Comparison to observations using GCE

- Nuclear uncertainties

- Final remarks/ChETEC

S Process in Massive Stars: Nuclear Physics Uncertainty



Hirschi et al 2008, NICX

Pignatari et al 08, ApJ letter, 687,95

^{16}O(n,γ)^{17}O:

- ^{16}O poison if ^{17}O(α,γ)^{21}Ne dom.
- ^{16}O absorber if ^{17}O(α,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!

S Process in Massive Stars: Nuclear Uncertainty: ^{22}Ne+α

^{22}Ne+α are well known important reactions for s process, that are still uncertain.

see R. Longland, C. Iliadis, and A. I. Karakas, PRC, 065809, (2012) and references therein

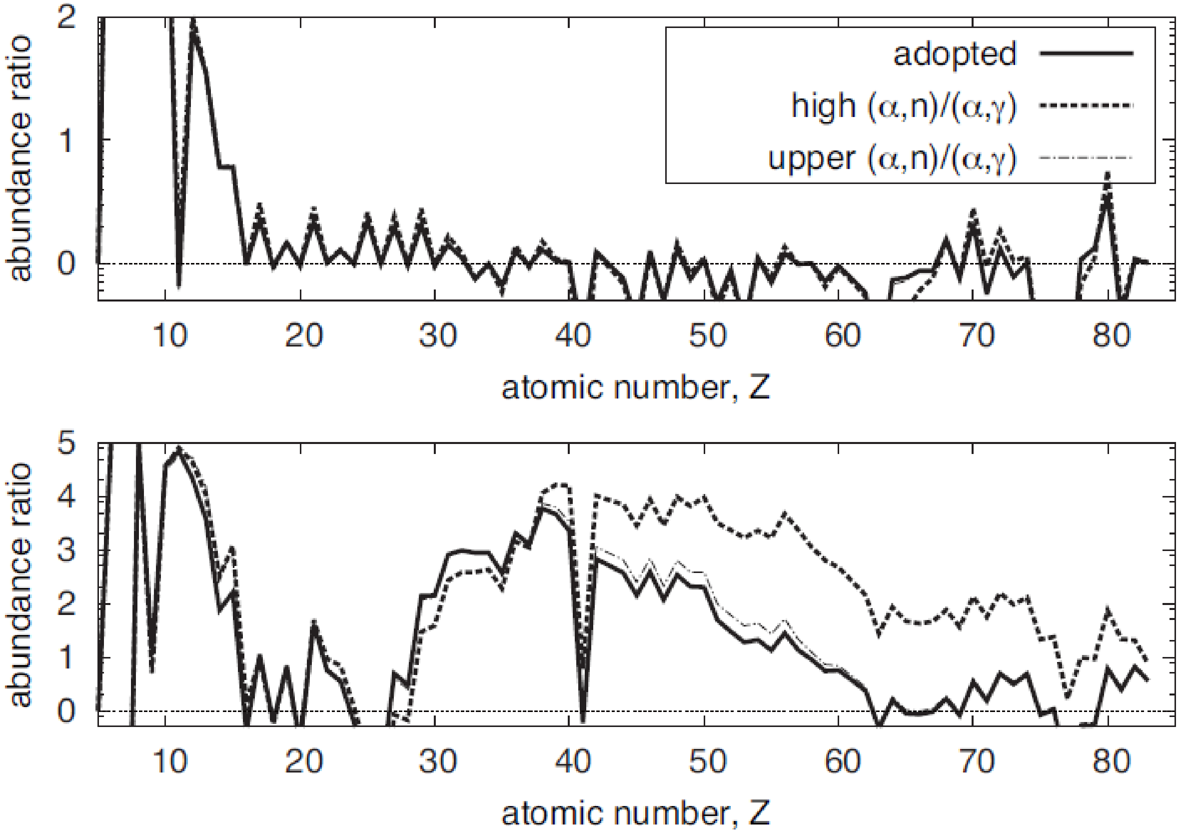


FIGURE 4. Abundance ratios of different reaction rates for α-captures by ^{22}Ne. All of the results are based on a one-zone trajectory mimicking the conditions in a 20 $M_\odot$ star of $Z = 10^{-6}$ (described in [10]) without rotation (upper) and with "effective rotation" via ^{14}N-enhancement (lower). Both panels show results using different reaction rate sets.

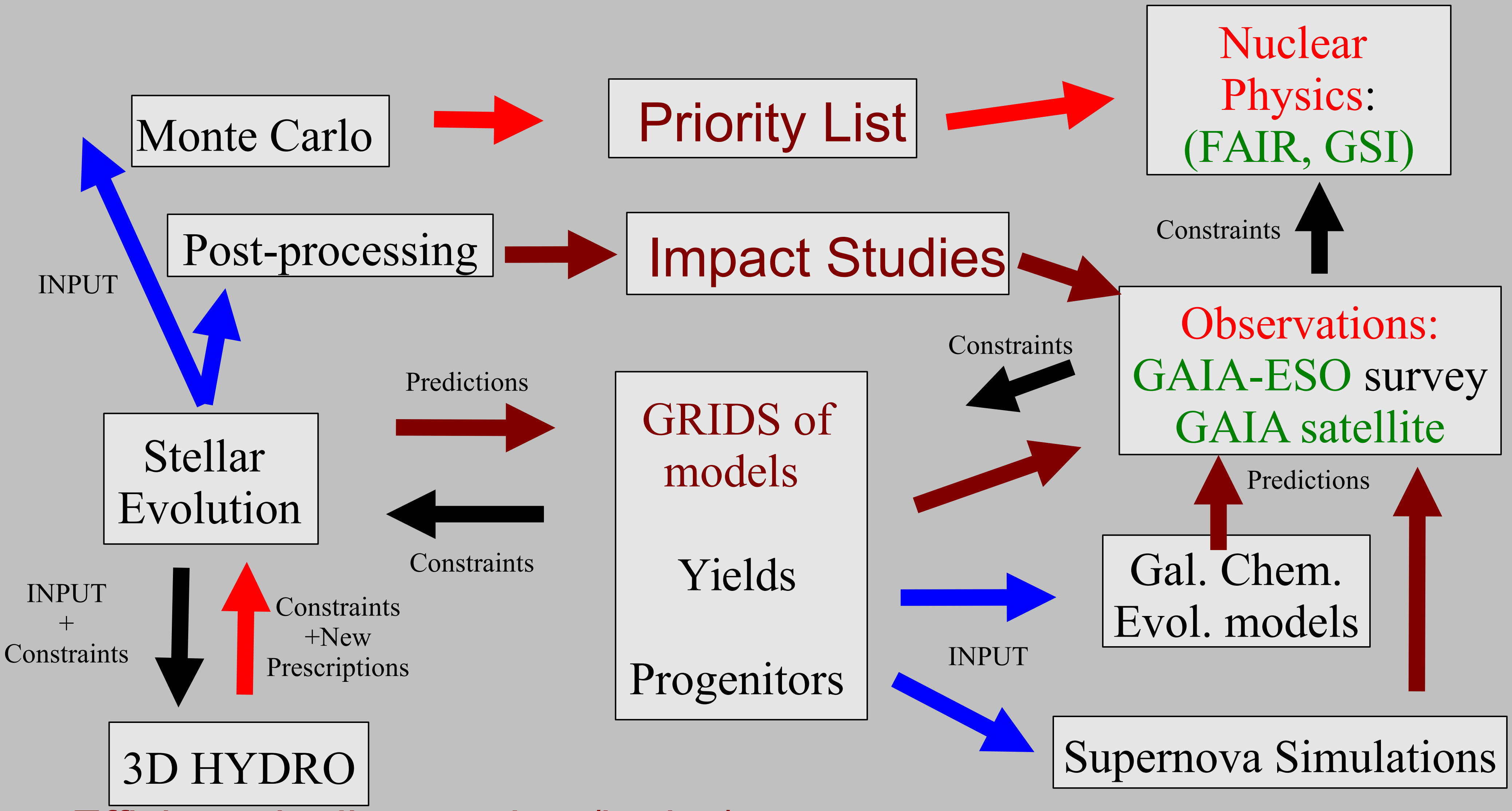
Nishimura et al 2013, OMEG12 proceedings

Reactions also strongly affect weak s process at low Z

Stellar HYdrodynamics Nucleosynthesis & Evolution (SHYNE) Project

ERC Starting grant: 5 year; 2 Postdocs; 2 PhDs; 1000+ CPU cluster

TOOL SUITE → DATASETS → IMPACT



Monte Carlo

Priority List

Nuclear Physics: (FAIR, GSI)

INPUT

Post-processing

Impact Studies

Constraints

Observations: GAIA-ESO survey GAIA satellite

Constraints

Predictions

Stellar Evolution

GRIDS of models

Yields

Progenitors

Constraints

Predictions

Gal. Chem. Evol. models

INPUT + Constraints

Constraints +New Prescriptions

INPUT

3D HYDRO

Supernova Simulations

- Efficient pipeline: nuclear/hydro/astro

The s-process in massive stars: uncertainties

T. Rauscher @NIC13 (arXiV:1412.6990)

Stellar environment

- Stellar thermal evolution
  - ZAMS mass and metallicity
  - convection, rotation and magnetic fields
- core He-burning
  - main fusion reactions: triple-α, ^{12}C(a,g)^{16}O, ...
  - n-source and n-poison reactions: ^{22}Ne(a,n)^{25}Mg, ... (see e.g., Nishimura et al., AIPC 1594 p 146, 2014)

Network calculation

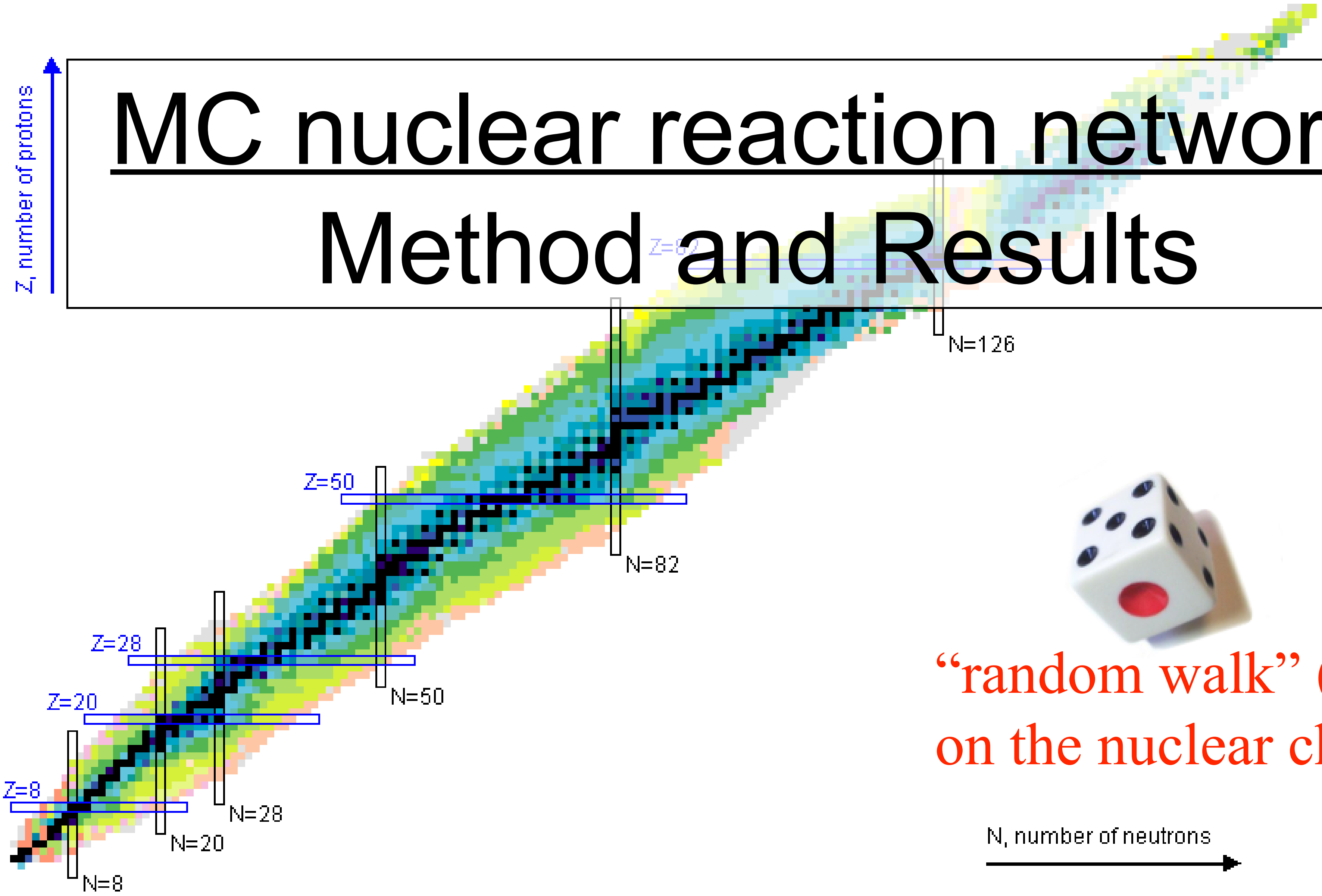
- Nucleosynthesis
  - (n,g) reactions
  - beta-decays

Monte-Carlo simulation →

uncertainty in the final abundances

← feedback (find key uncertain reactions/decays)

MC nuclear reaction network: Method and Results



“random walk” (?)
on the nuclear chart

Nuclear chart ： http://www.nndc.bnl.gov/nudat2/

Monte-Carlo network code

Piz Buin mountain

- Monte-Carlo framework
  - PizBuin MC-driver (T. Rauscher)
  - a simple “Brute-force” approach
  - parallelized by OpenMP for shared memory architectures (easier implementation)
- Nuclear Reaction network
  - Network solver:
    - WinNet: latest Basel network, Winteler et al., 2012
  - Reaction rates:
    - Reaclib: (Rauscher & Thielemann 2000)
    - T-dependent beta-decay (Takahashi & Yokoi 1987, Goriely 1999)
  - T-dependent uncertainty:
    - Provided by Reaclib format, based on Rauscher 2012

Stellar Environment: ← trajectories: T & ρ vs time

T-dependent uncertainty: (n,g)

(T. Rauscher, ApJL, 775, 2011)

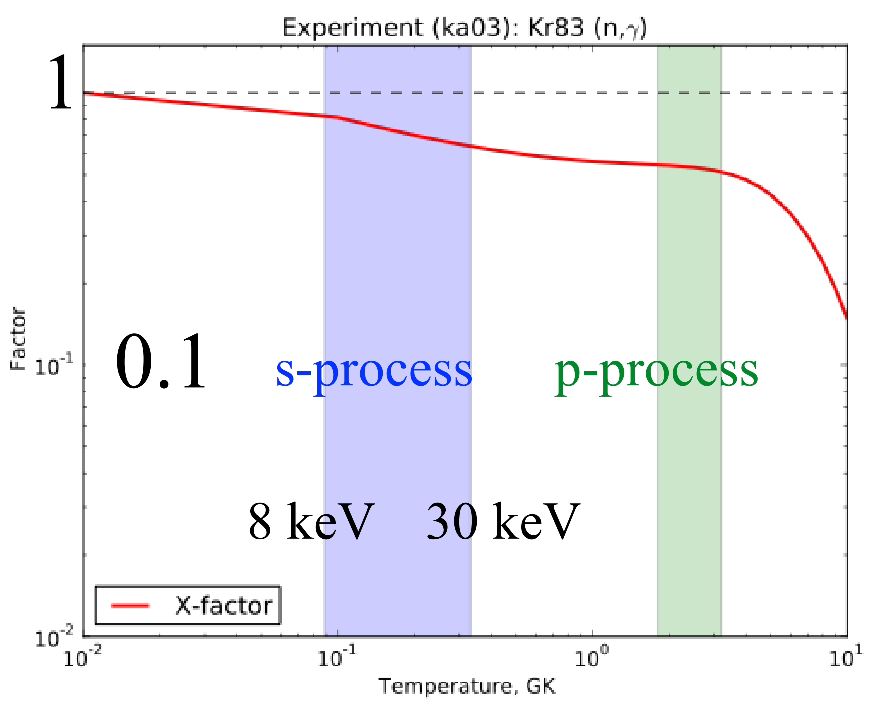
- Theoretical
  - basic rates: Reaclib (Rauscher & Thielemann 2000)
  - a constant factor 2
- Experimental
  - base rates: KADoNiS v0.3 (Dillemann el al., 2009)
  - the formula: Rauscher, ApJ, 775, 2011

$$U(T) = U_{\text{g.s.}} X + U_{\text{e.s.}} (1 - X)$$

- ground state (experimental based): $u_{\text{g.s.}} \sim 1.0 - 1.3$
- excited states (theory based): $u_{\text{e.s.}} = 5$ (given constant)

$X(T)$: the fraction of particles in the ground state

X for ^{83}Kr(n,g)^{84}Kr



T-dependent uncertainty: beta-decay

based on T. Rauscher (2011, 2012, 2013)

- beta-decay: only the ground state 1.3 (30%)
- beta-decay: T-dependent

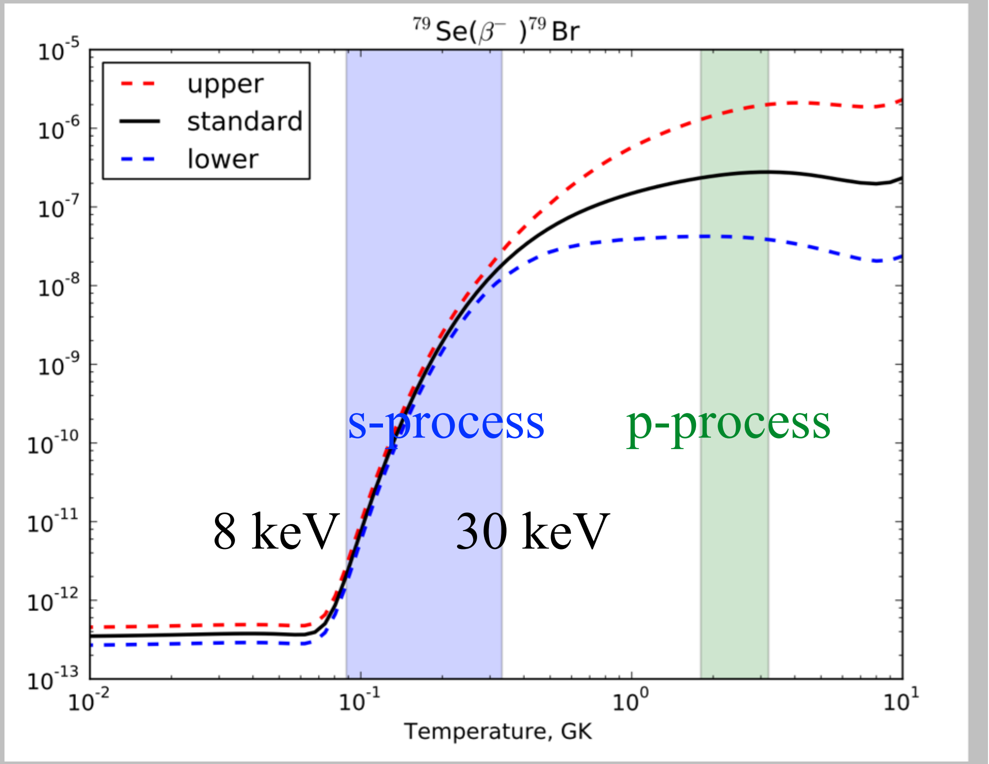
(Takahashi & Yokoi 1987, Goriely 1999)

$$U(T) = \frac{u_{\mathrm{g.s.}}}{g_0(T)} + u_{\mathrm{e.s.}} \left(1 - \frac{1}{g_0(T)}\right)$$

- ground state: $u_{\mathrm{g.s.}} = 1.3\ (30\ \%)$
- excited states: $u_{\mathrm{e.s.}} = 10$

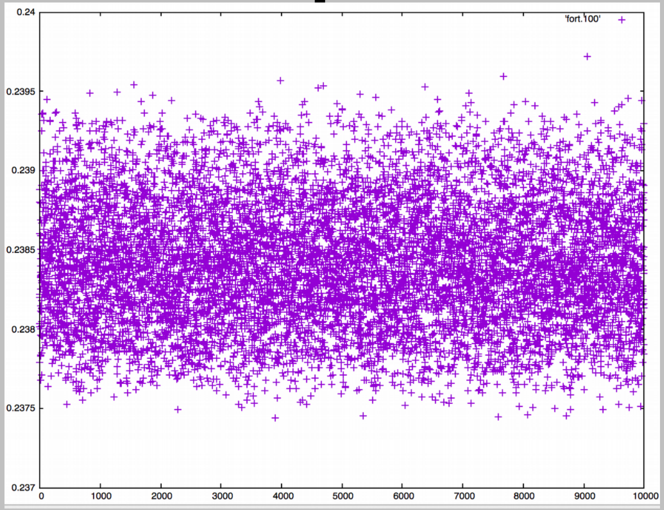
g_0: partition function of the ground state

Beta-decay: $^{79}\mathrm{Se} \rightarrow {}^{79}\mathrm{Br}$

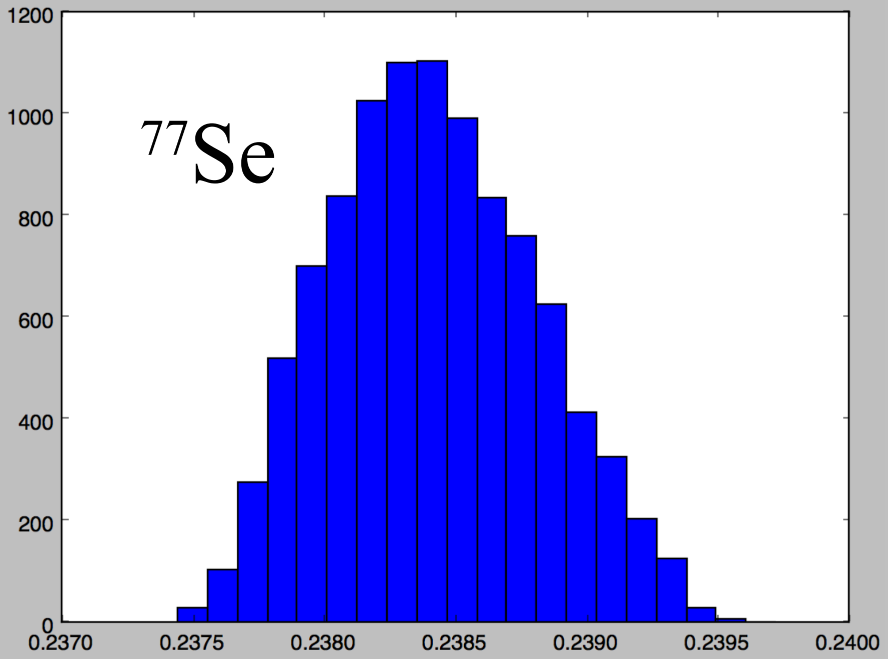


MC Outputs

^{77}Se



MC: 1000s trials



Abundances

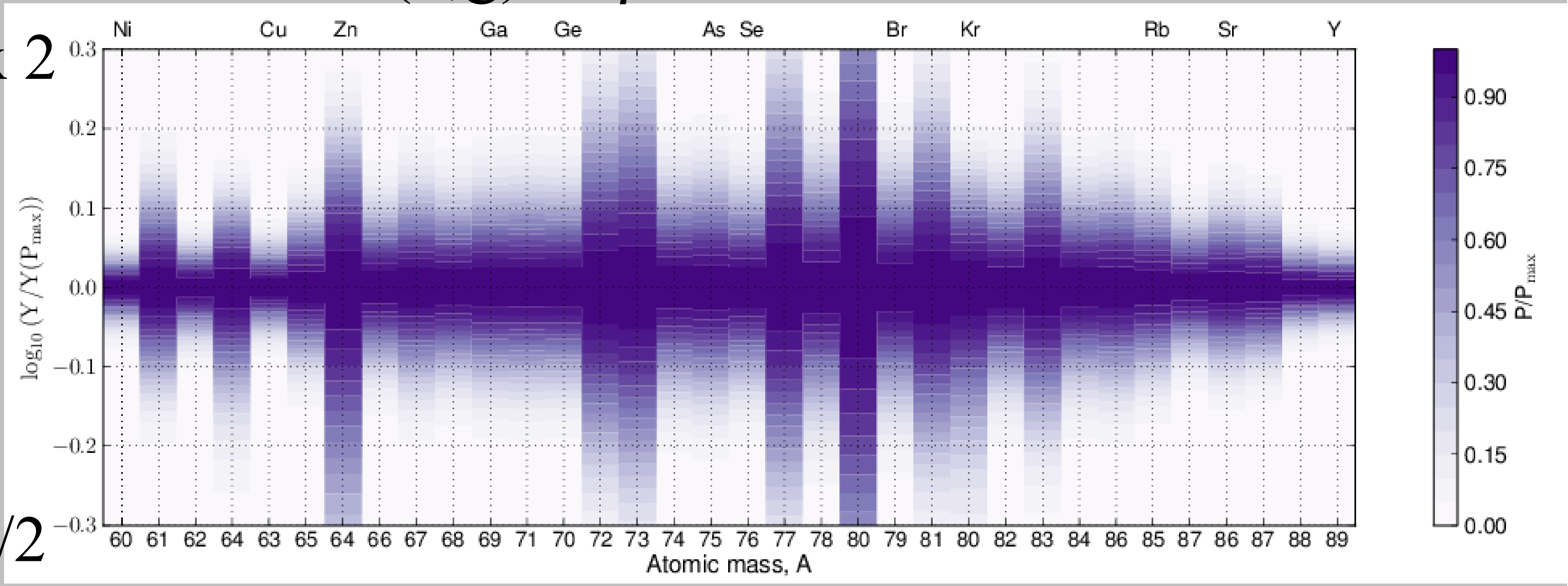
MC: (n,g) & $\beta^{\pm}$

x 2

x 1.25

1/1.25

1/2



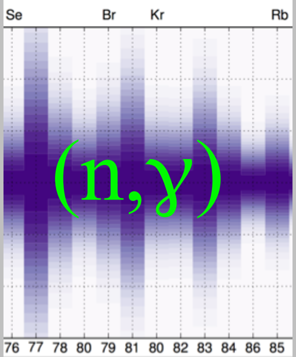
s-process flow: which reaction produces each isotope?

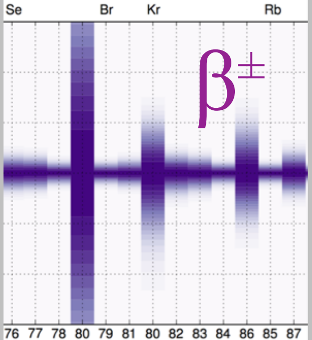
Rules of the game:

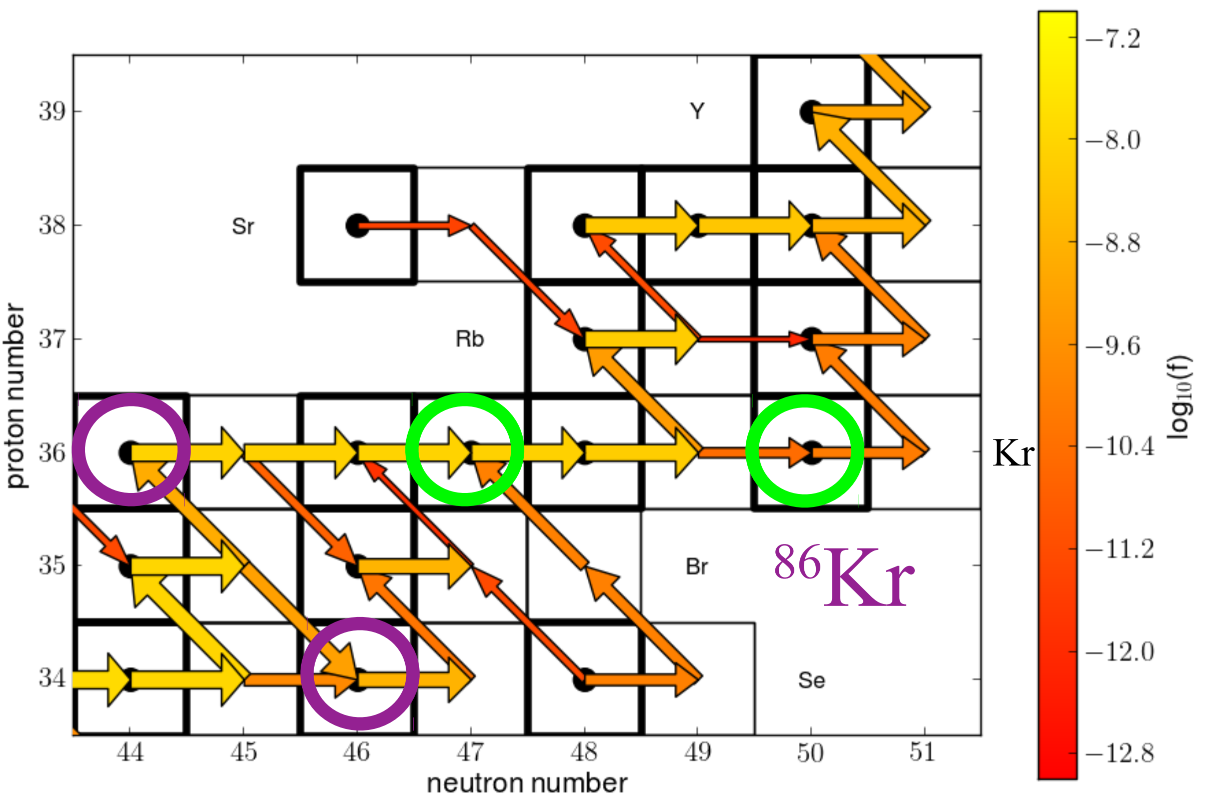
(1) nucleosynthesis flow goes from lower A to higher A

(2) (n,γ): right (→)

(3)beta-decay: diagonal (↖ or ↘)







key reactions:

^{79}Se(β^-)

^{80}Br(β^-)

^{80}Br(β^+)

^{82}Kr(n,g)

^{83}Kr(n,g)

^{85}Kr(β^-)

Key Reaction Levels 1-3:

N. Nishimura+ 2017

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

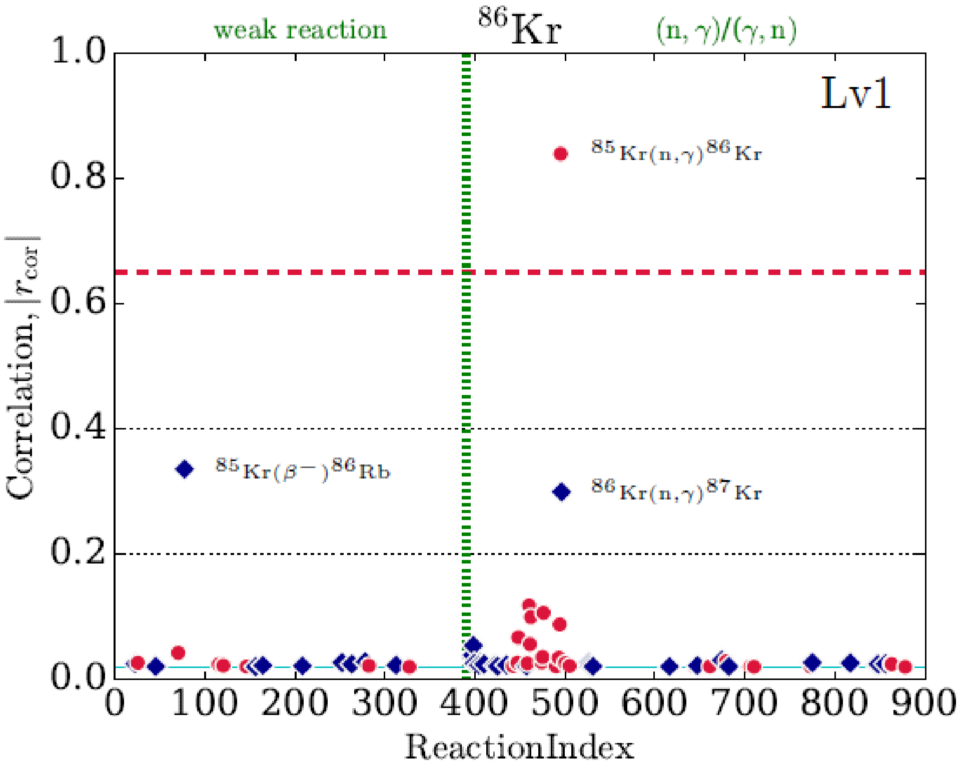
- Once level 1 rates are fixed, *then* Level 2 rates become dominant

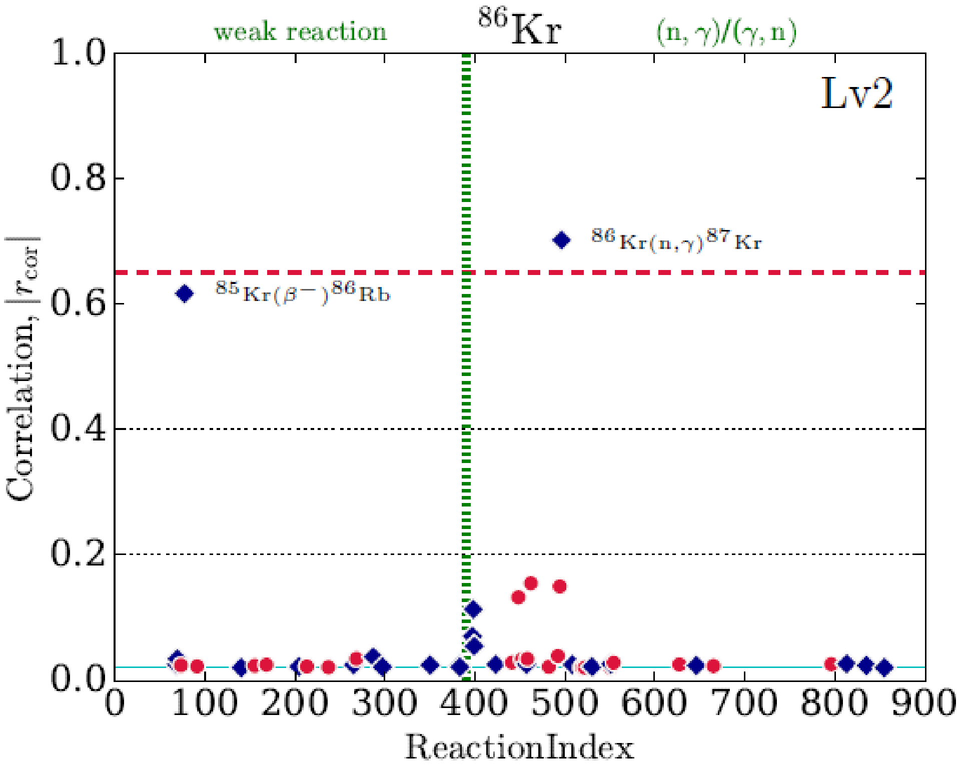
…

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

$$r_{\mathrm{cor}} = \frac{\sum_{i}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i}^{n}(y_i - \bar{y})^2}} \tag{4}$$

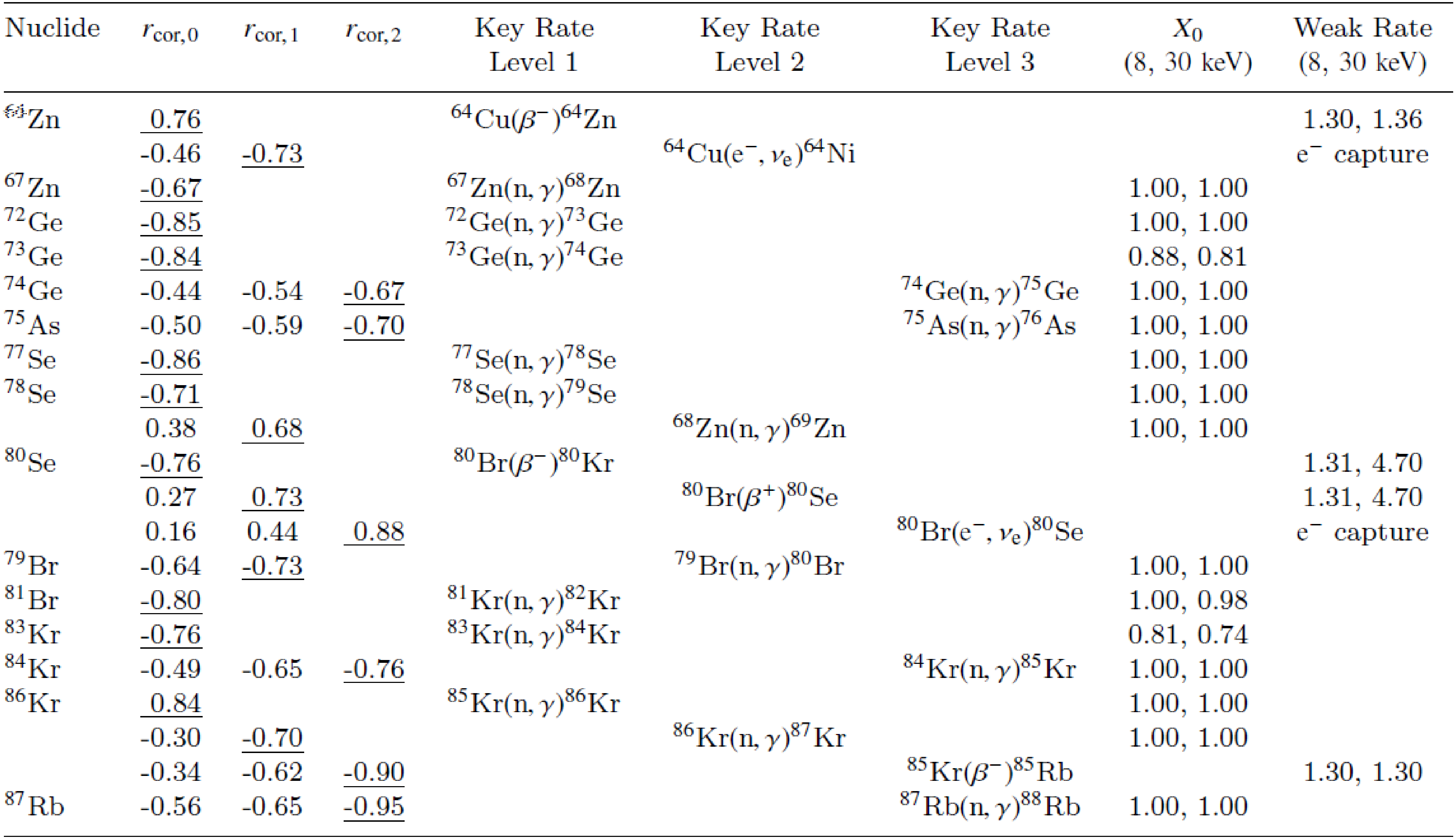
where x_i and y_i are variables with $\bar{x}$ and $\bar{y}$ being their arithmetic mean value, respectively. The summation is applied to all data for the MC runs $i = 1, 2, 3, \cdots, n$. Here, x and y in Equation 4 correspond to variation factors f and final abundances Y.





Key Reaction Lists for Weak s Process

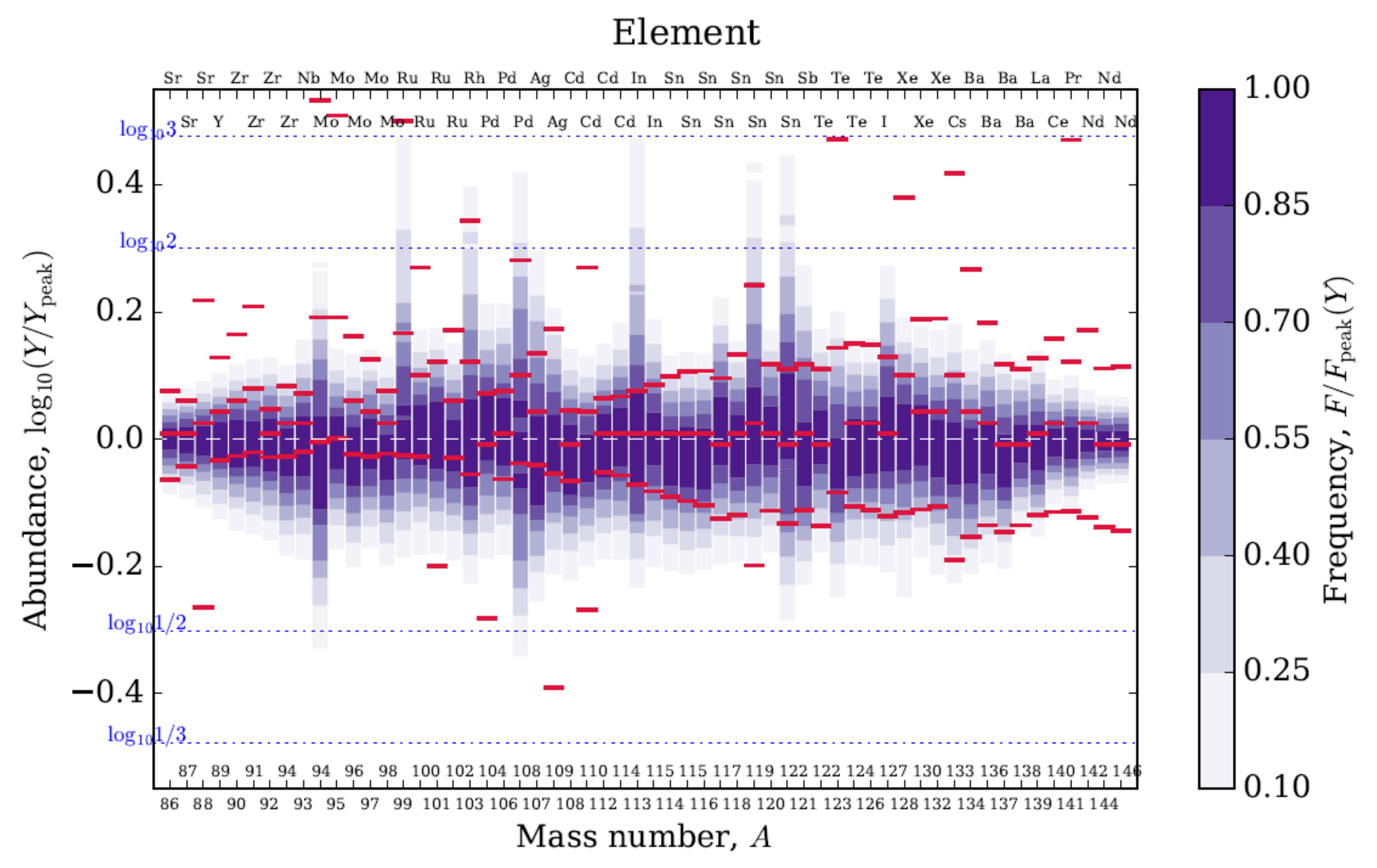
N. Nishimura+ 2017: http://adsabs.harvard.edu/abs/2017MNRAS.469.1752N



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}Zn	0.76			^{64}Cu(β^-)^{64}Zn				1.30, 1.36
	-0.46	-0.73			^{64}Cu(e$^-$, ν_e)^{64}Ni			e$^-$ capture
^{67}Zn	-0.67			^{67}Zn(n, γ)^{68}Zn			1.00, 1.00	
^{72}Ge	-0.85			^{72}Ge(n, γ)^{73}Ge			1.00, 1.00	
^{73}Ge	-0.84			^{73}Ge(n, γ)^{74}Ge			0.88, 0.81	
^{74}Ge	-0.44	-0.54	-0.67			^{74}Ge(n, γ)^{75}Ge	1.00, 1.00	
^{75}As	-0.50	-0.59	-0.70			^{75}As(n, γ)^{76}As	1.00, 1.00	
^{77}Se	-0.86			^{77}Se(n, γ)^{78}Se			1.00, 1.00	
^{78}Se	-0.71			^{78}Se(n, γ)^{79}Se			1.00, 1.00	
	0.38	0.68			^{68}Zn(n, γ)^{69}Zn		1.00, 1.00	
^{80}Se	-0.76			^{80}Br(β^-)^{80}Kr				1.31, 4.70
	0.27	0.73			^{80}Br(β^+)^{80}Se			1.31, 4.70
	0.16	0.44	0.88			^{80}Br(e$^-$, ν_e)^{80}Se		e$^-$ capture
^{79}Br	-0.64	-0.73			^{79}Br(n, γ)^{80}Br		1.00, 1.00	
^{81}Br	-0.80			^{81}Kr(n, γ)^{82}Kr			1.00, 0.98	
^{83}Kr	-0.76			^{83}Kr(n, γ)^{84}Kr			0.81, 0.74	
^{84}Kr	-0.49	-0.65	-0.76			^{84}Kr(n, γ)^{85}Kr	1.00, 1.00	
^{86}Kr	0.84			^{85}Kr(n, γ)^{86}Kr			1.00, 1.00	
	-0.30	-0.70			^{86}Kr(n, γ)^{87}Kr		1.00, 1.00	
	-0.34	-0.62	-0.90			^{85}Kr(β^-)^{85}Rb		1.30, 1.30
^{87}Rb	-0.56	-0.65	-0.95			^{87}Rb(n, γ)^{88}Rb	1.00, 1.00	

Other Key Reaction Lists

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



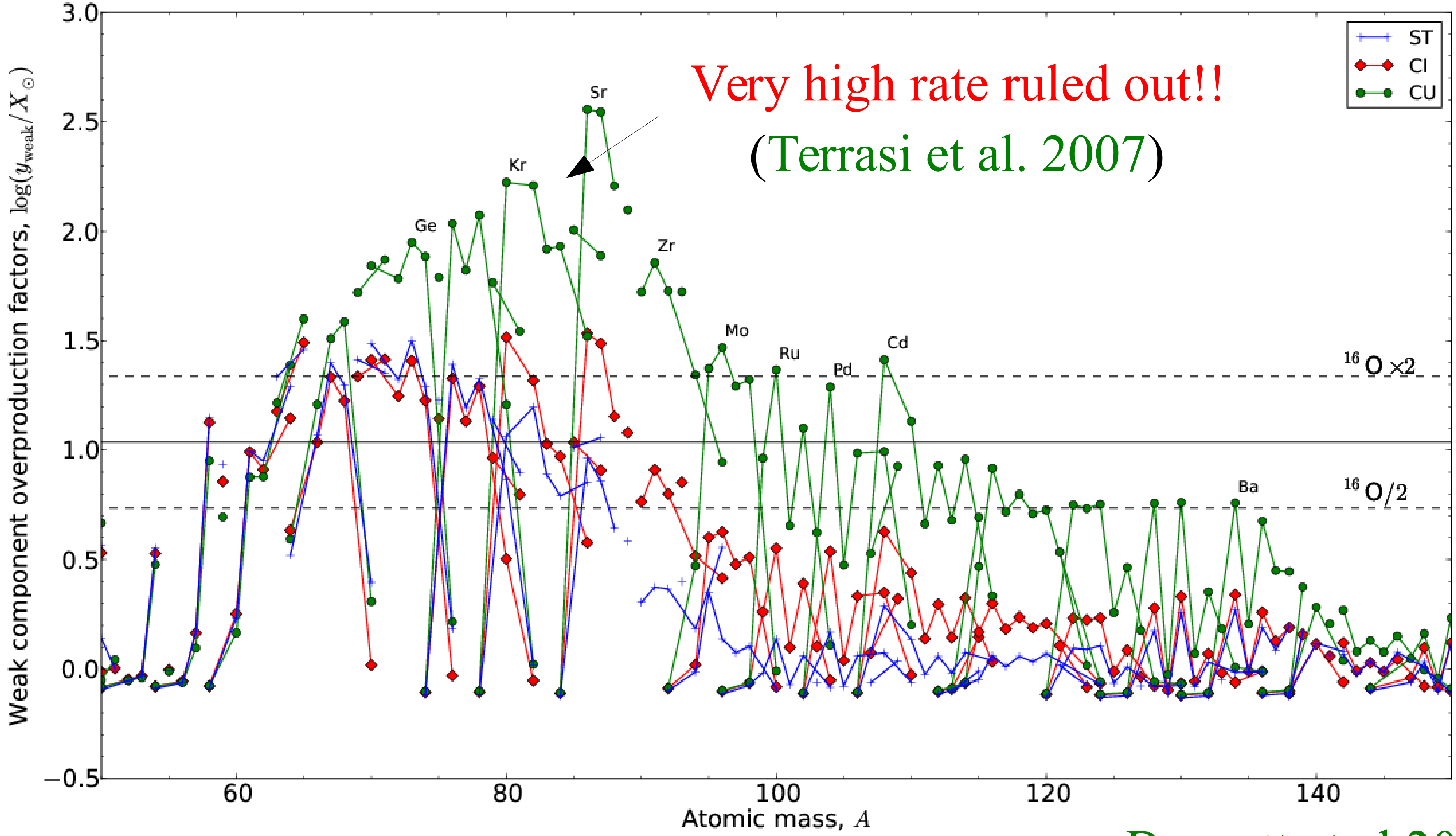
- Gamma (aka p) process in CCSNe: T. Rauscher+ 2016 http://adsabs.harvard.edu/abs/2016MNRAS.463.4153R

- Gamma (aka p) process in Sne Ia: Nishimura et al (2018): http://adsabs.harvard.edu/abs/2018MNRAS.474.3133N

- Main s process (C13-pocket) Cescutti + subm.

Constraints from stellar evolution: ^{12}C-^{12}C rate, 3α

- Full stellar models + post-processing using MPPNP (Nugrid)



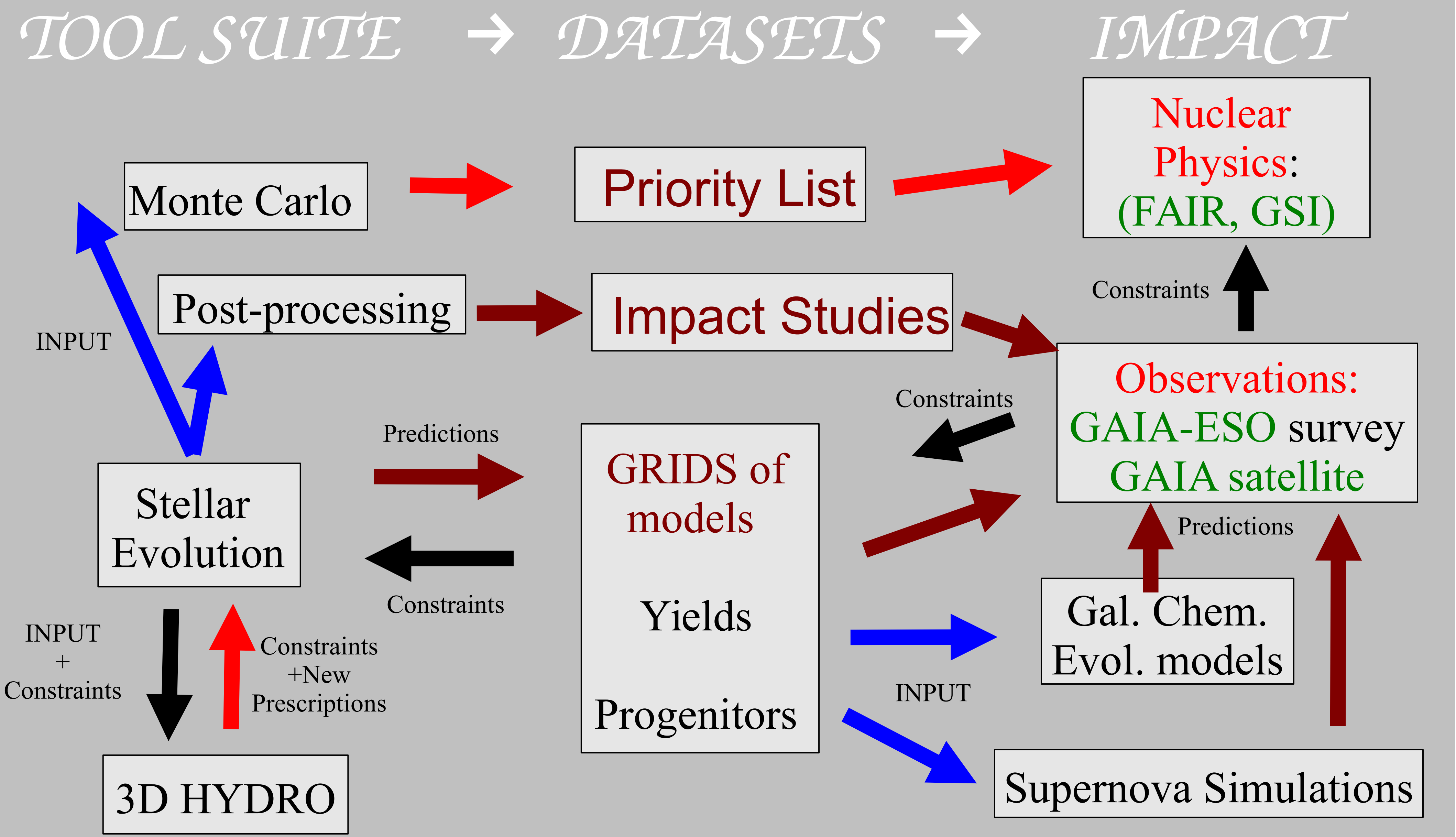
Very high rate ruled out!!

(Terrasi et al. 2007)

Bennett et al 2011

See Suda et al 2011 for a study constraining 3α reaction

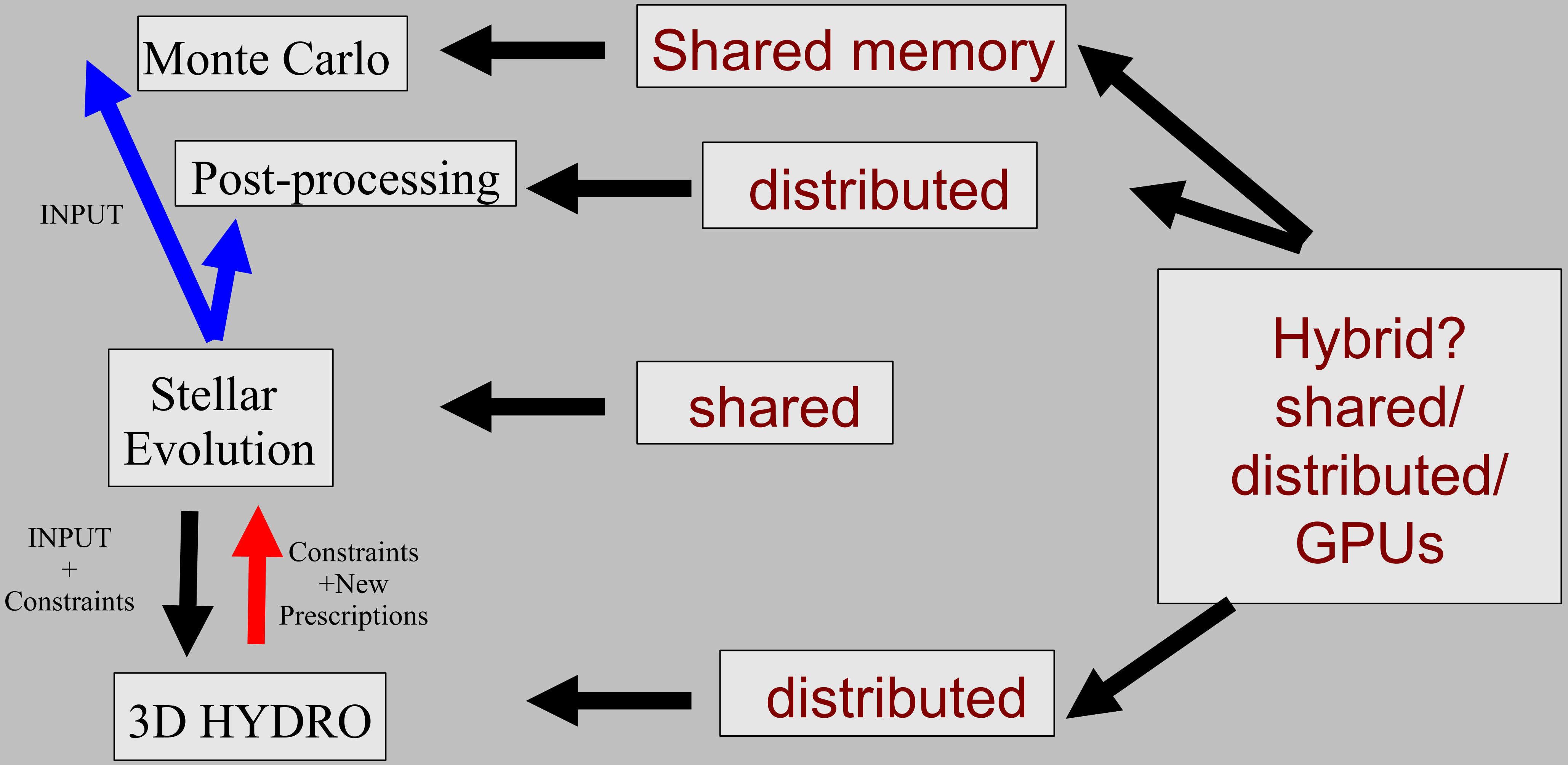
Stellar Hydrodynamics Nucleosynthesis & Evolution (SHYNE) Project



- Efficient pipeline: nuclear/hydro/astro

Tool Suite: Parallel Programming Platform

TOOL SUITE: Current Platform → Future Platform



Monte Carlo

Shared memory

Post-processing

distributed

INPUT

Stellar Evolution

shared

Hybrid? shared/ distributed/ GPUs

INPUT + Constraints

Constraints +New Prescriptions

3D HYDRO

distributed

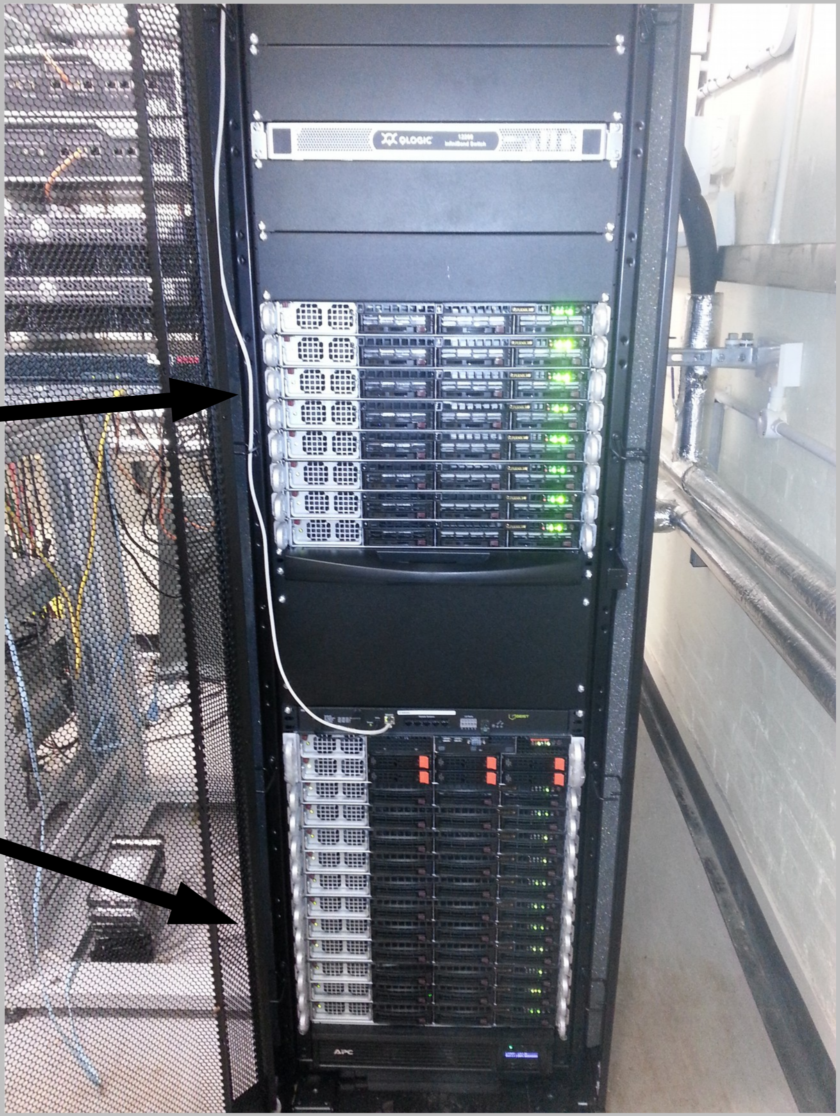
(shared memory: OpenMP / Distributed mem.: MPI)

SHYNE Computer Cluster

- The cluster comprises a total of 1056 AMD-based CPU-cores with 2GB RAM per core.

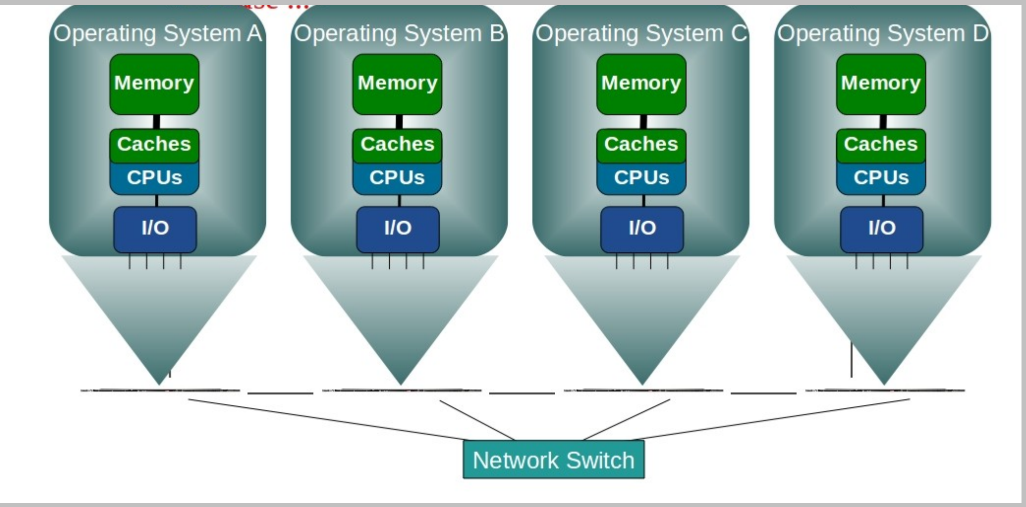
  The main specifications are the following:

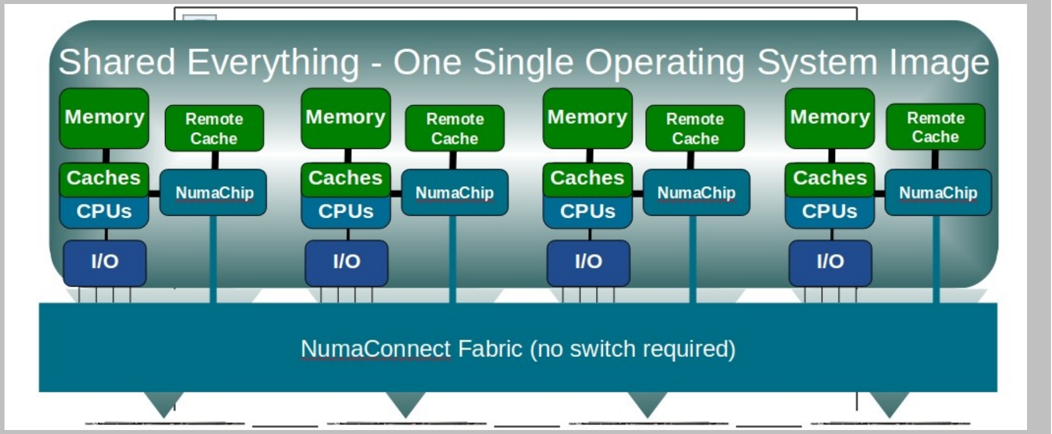
- 288 cores Numascale
  - 8 x 3 socket servers (each socket has 12-core CPUs, AMD opteron 6172, 2.1 MHz)
  - Single memory image 576GB
  - Single operating system image
  - Numascale inter-connect
- 768 cores QDR Infiniband
  - 12 x 4 socket servers (each socket has 16-core CPUs, AMD opteron 6272, 2.1MHz)
  - 1 O/S per server
  - Distributed memory image 128 GB per server
- Unified cluster management for both architectures
  - IBM Platform HPC
  - 2 LSF queues Numa and IB
  - Numa nodes visible as single machine with 288 cores and 576 GB RAM
- Dedicated water cooled environment up to 30kW in 1 rack



Link with Industry

numascale Norwegian HPC company





FROM: distributed memory clusters

TO: scalable shared memory clusters

For the same cost!

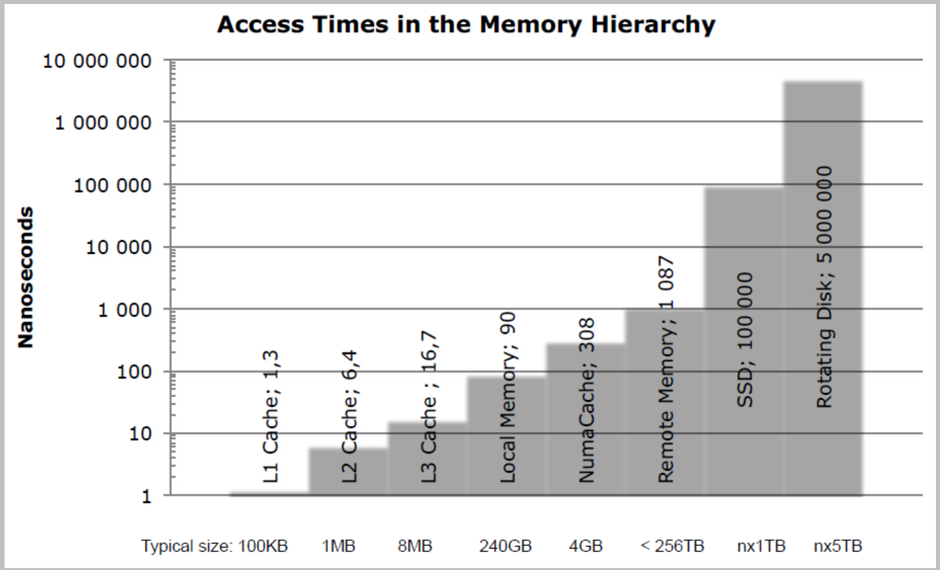
- Super-desktop: single OS, 288 cores, RAM 576 GB
- Large scale: better balance between shared/distributed memory

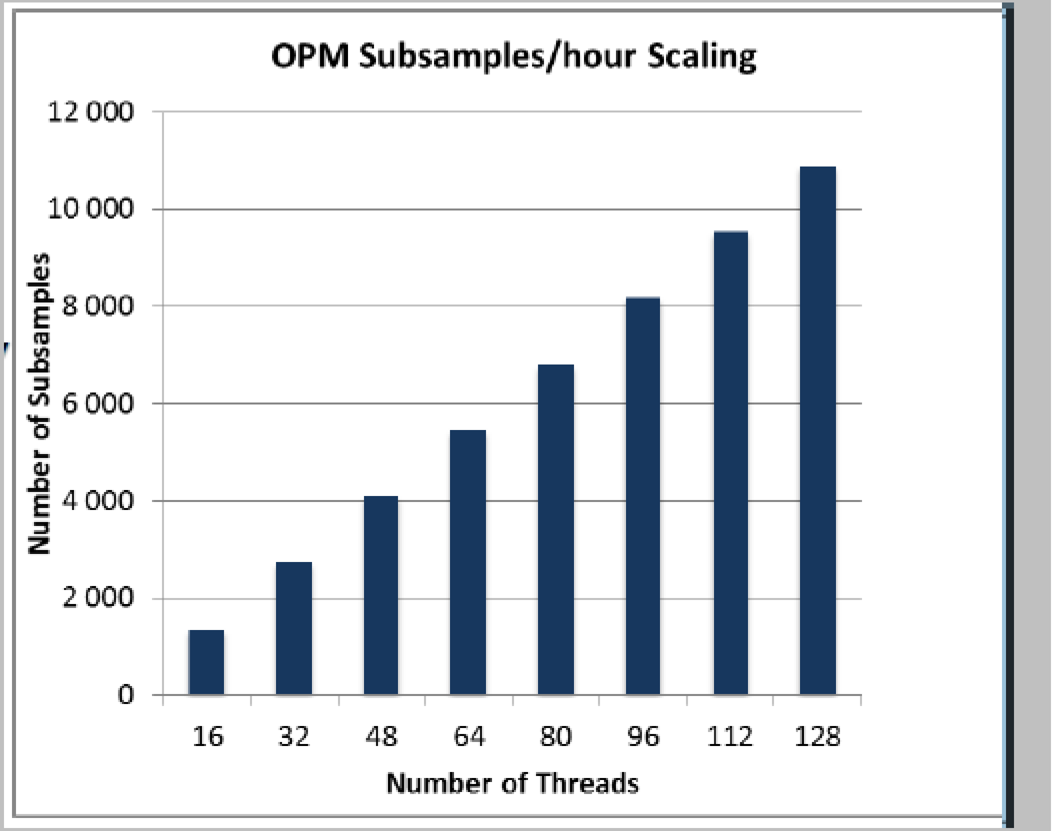
The Memory Hierarchy & Scaling

OpenMP easier to implement than MPI but might be harder to scale

Scaling:

Memory access time:





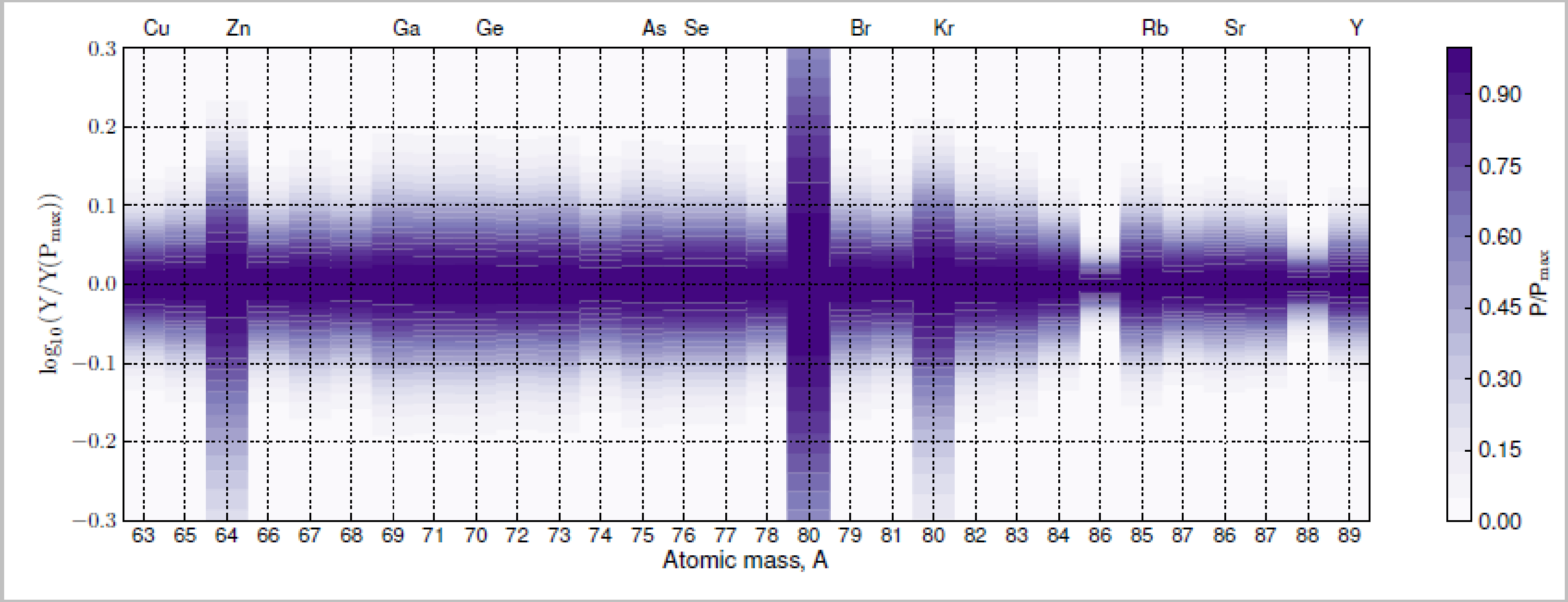
Excellent scaling possible on Numascale system!

Monte Carlo Sensitivity Studies

PizBuin Monte Carlo wrapper (T. Rauscher)

+ WinNet (Winteler+ 12) < Reaclib

= McWinNet



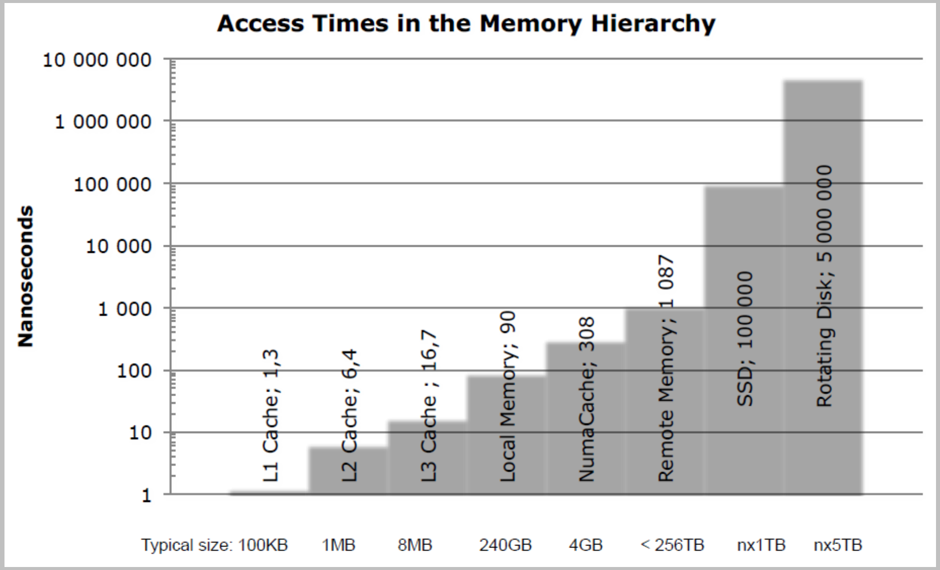
- beta-decay & (n,g) uncertainties are T-dependent

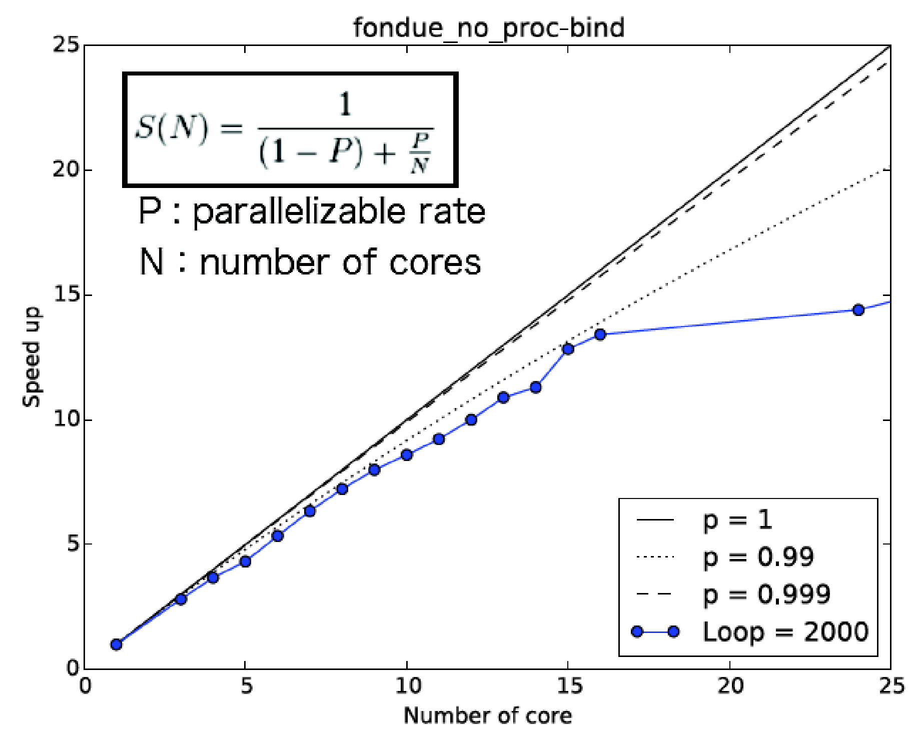
- Largest simulations: 1000 trajectories x 1hr run x 10,000 iterations

The Memory Hierarchy & Scaling

McWinNet Scaling:

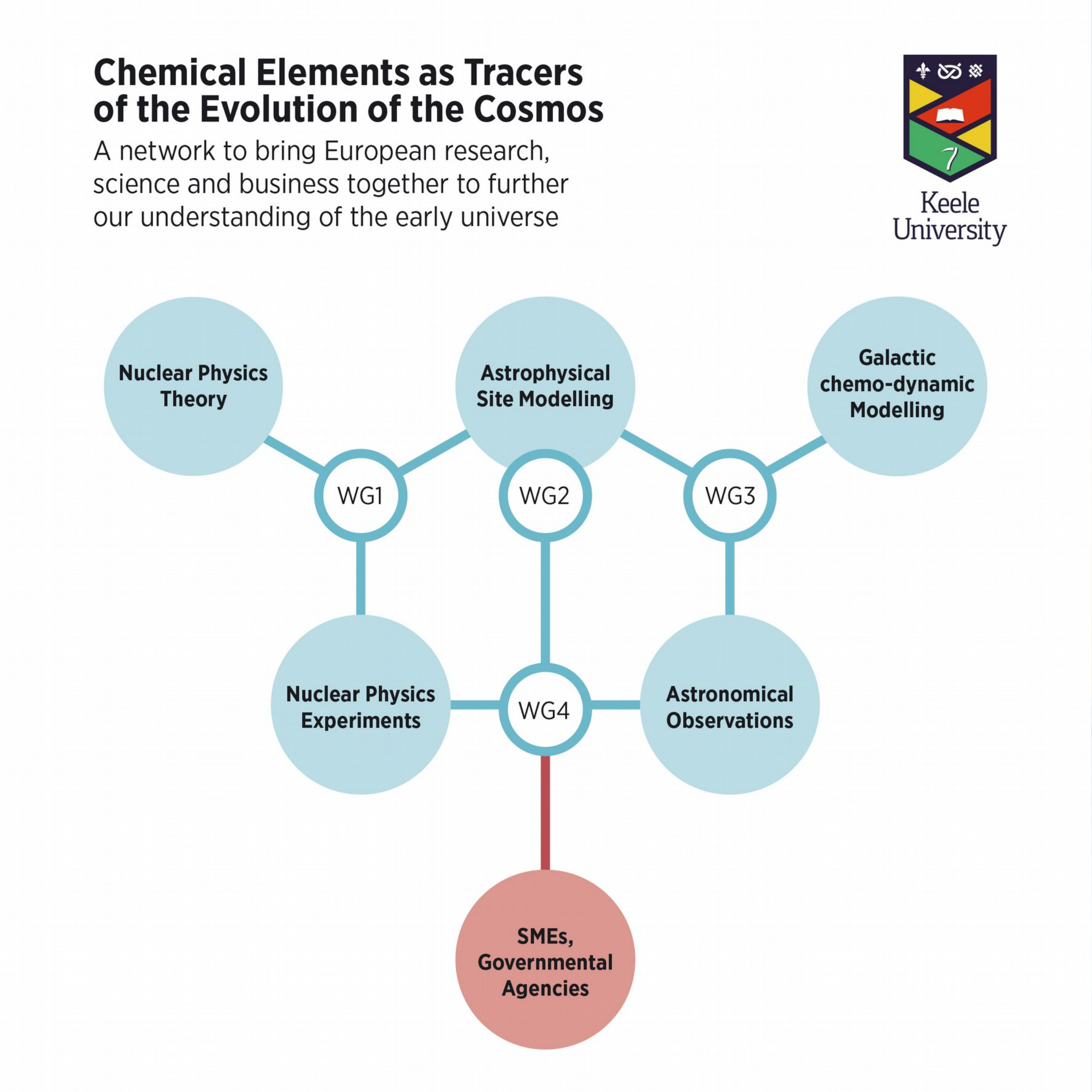
Memory access time:





$$S(N) = \frac{1}{(1-P) + \frac{P}{N}}$$

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



Chemical Elements as Tracers of the Evolution of the Cosmos

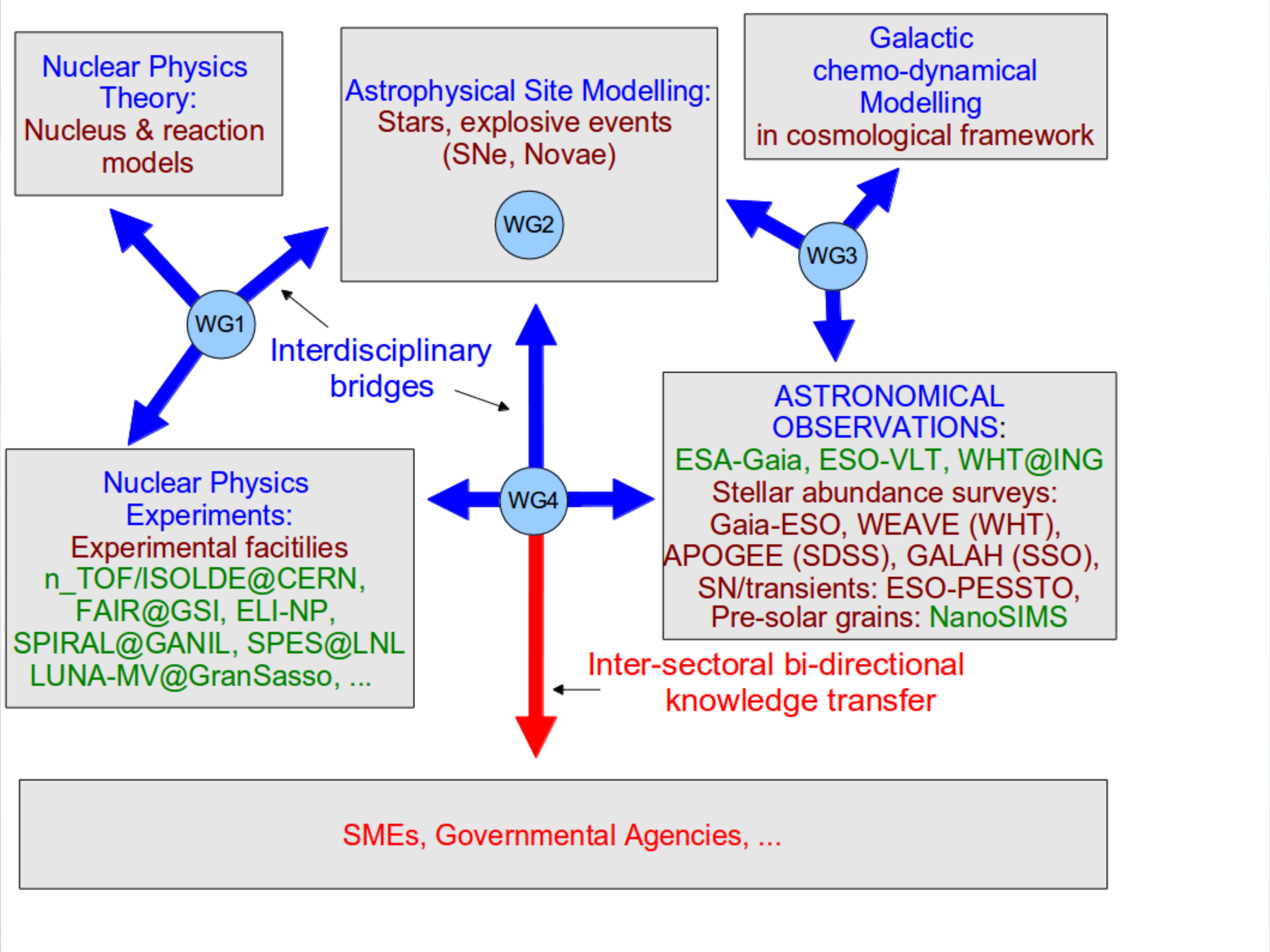
A network to bring European research, science and business together to further our understanding of the early universe

30 countries have joined ChETEC to coordinate research efforts in Nuclear Astrophysics: Austria, Belgium, Bulgaria, Croatia, Czech Republic, 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

ChETEC Objectives

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

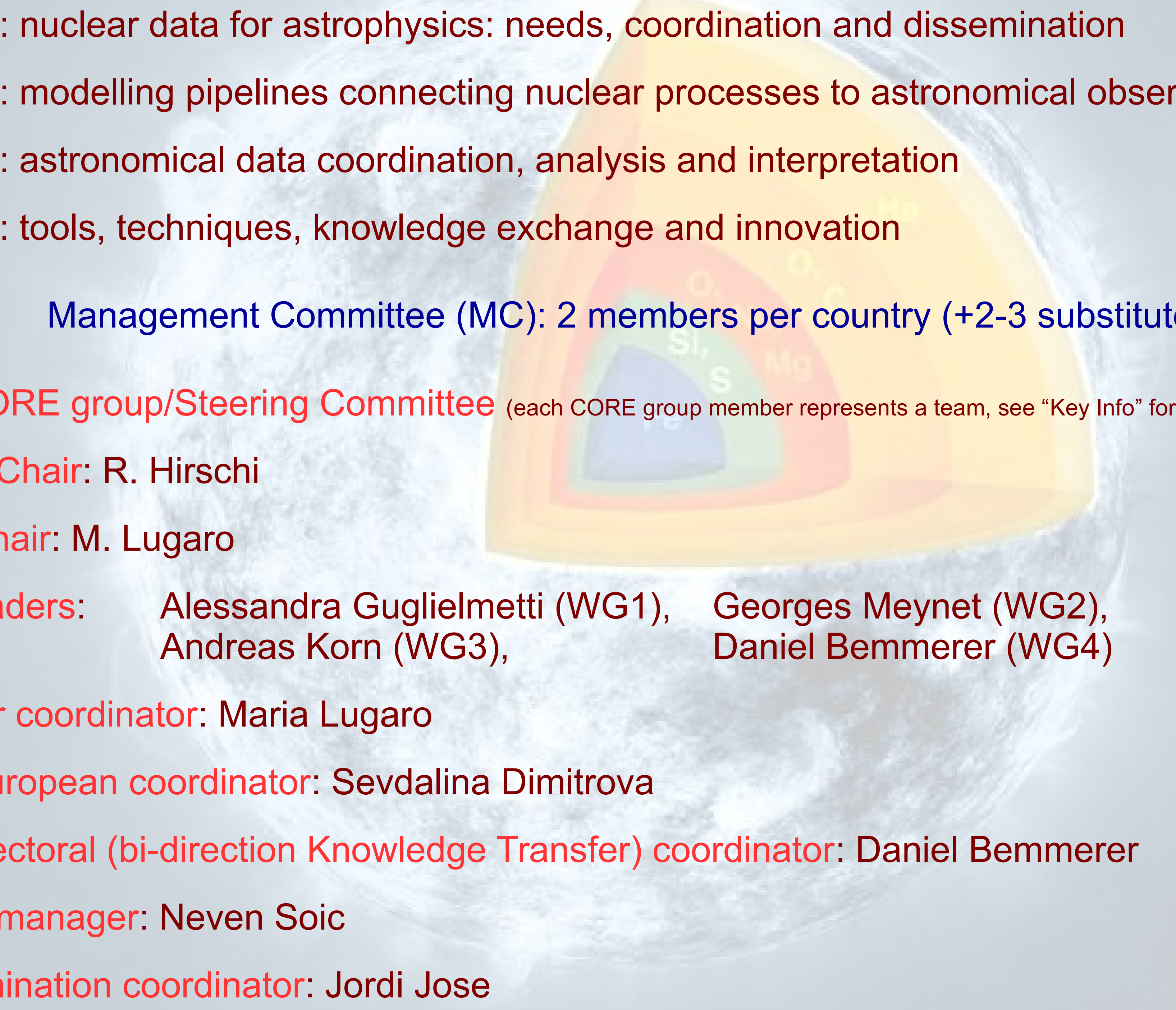
ASTRONOMICAL OBSERVATIONS:
ESA-Gaia, ESO-VLT, WHT@ING
Stellar abundance surveys:
Gaia-ESO, WEAVE (WHT),
APOGEE (SDSS), GALAH (SSO),
SN/transients: ESO-PESSTO,
Pre-solar grains: NanoSIMS

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

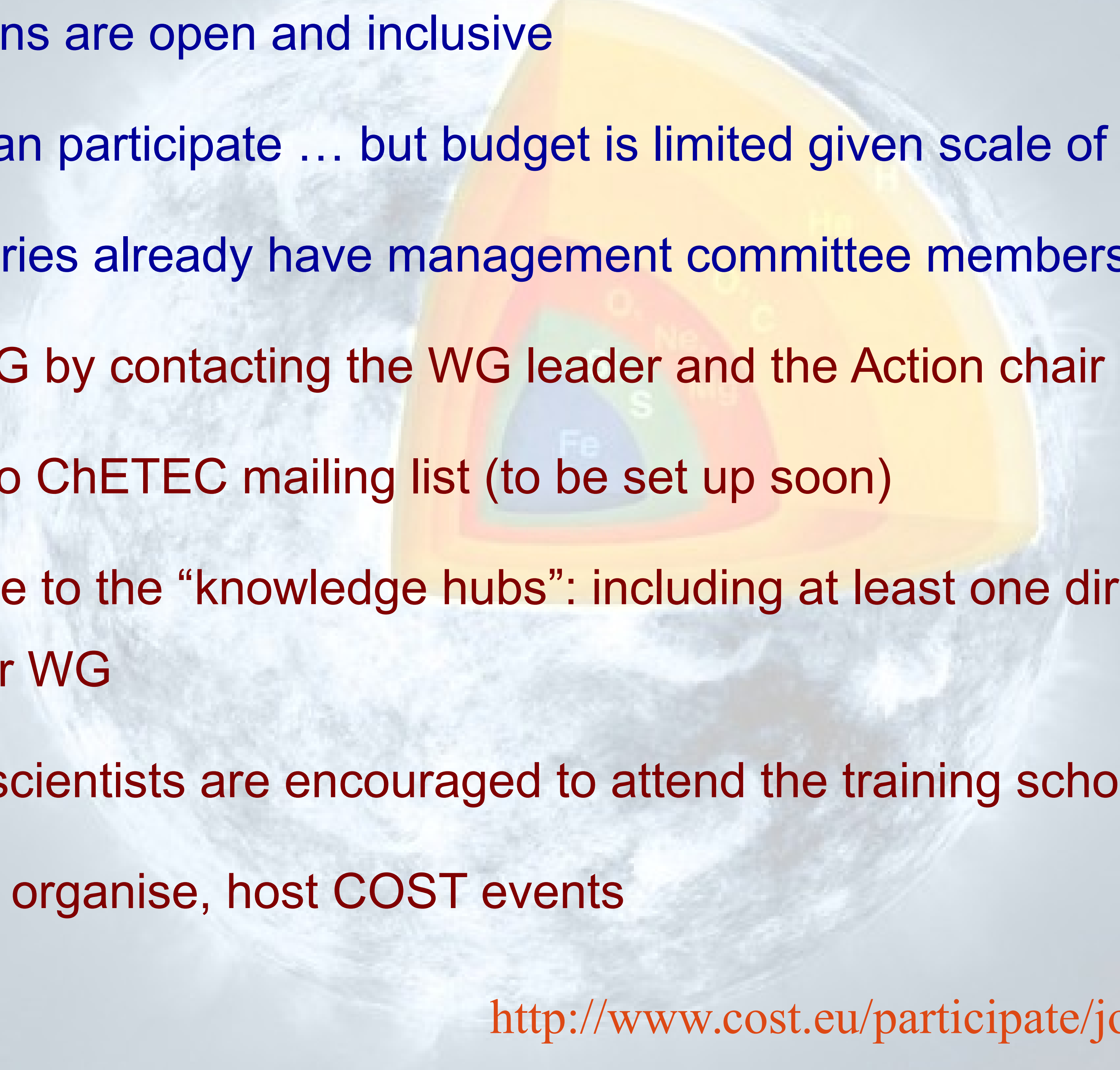
Pan-European coordinator: Sevdalina Dimitrova

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)

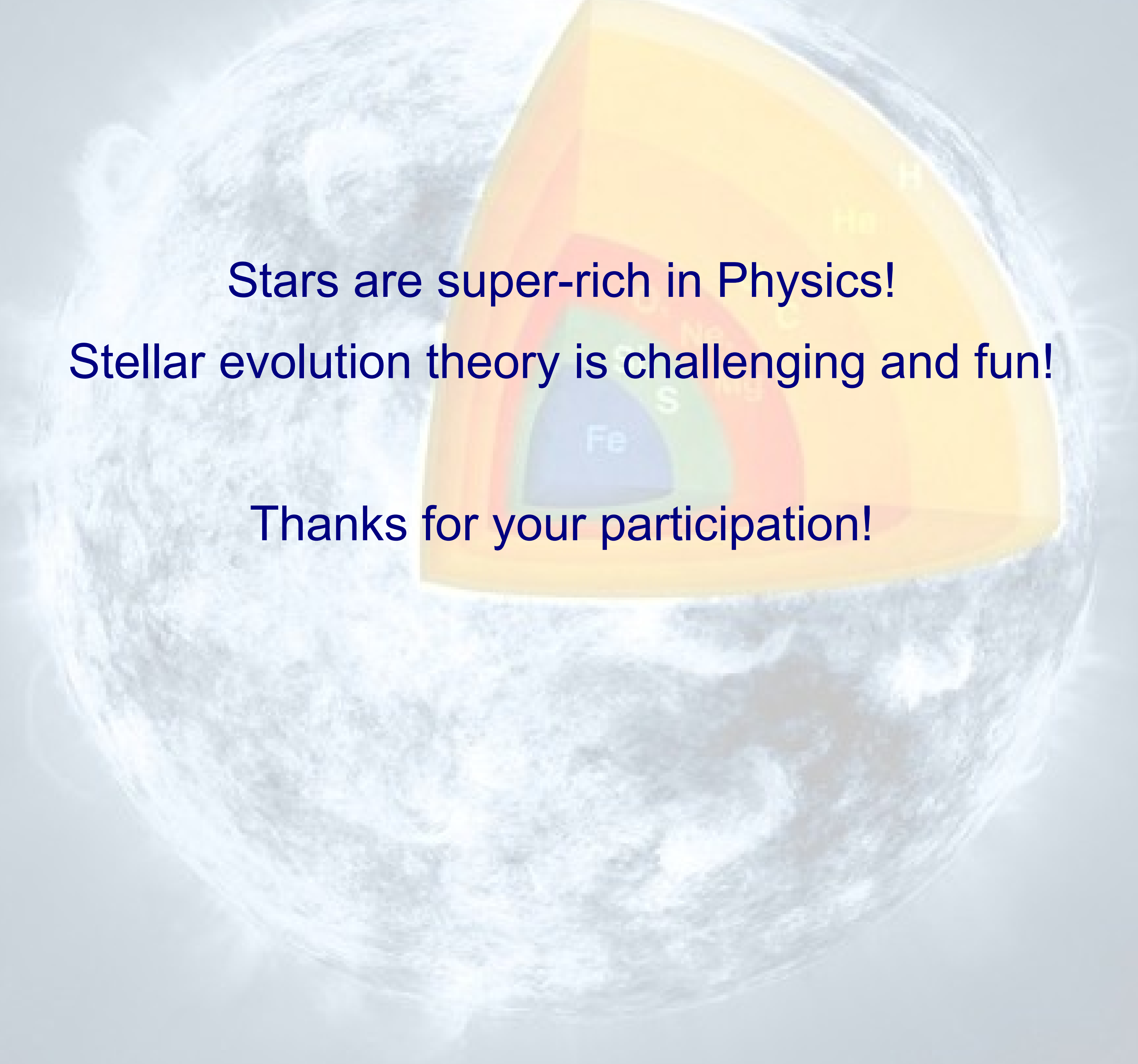
COST Acknowledgements

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.

cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

Conclusions



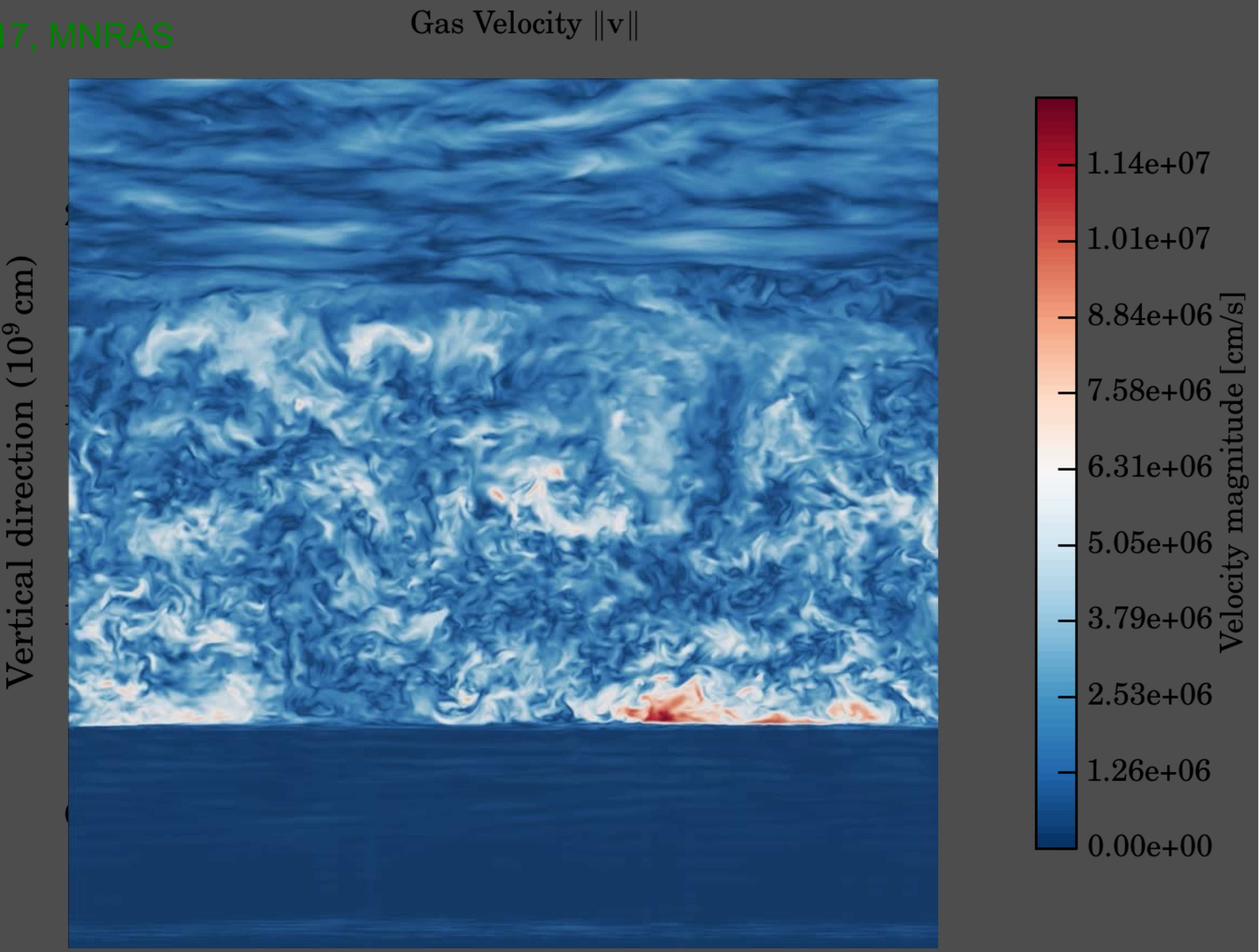
Stars are super-rich in Physics!

Stellar evolution theory is challenging and fun!

Thanks for your participation!

3D C-shell Simulations: |v| movie

Cristini+ 2017, MNRAS



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

Methods: performance/resources

for shared memory systems

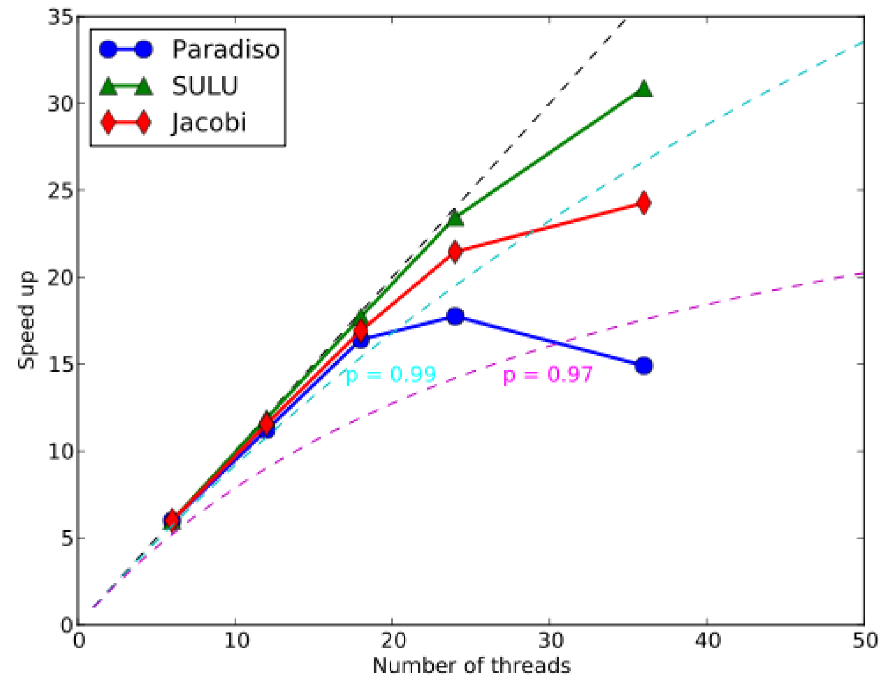
- Fortran + OpenMP
- parallelized well
- optimized code/matrix library for large scared memory computers (multi threads)

- Computer resources

numascale

Shyne cluster @Keele (ERC)

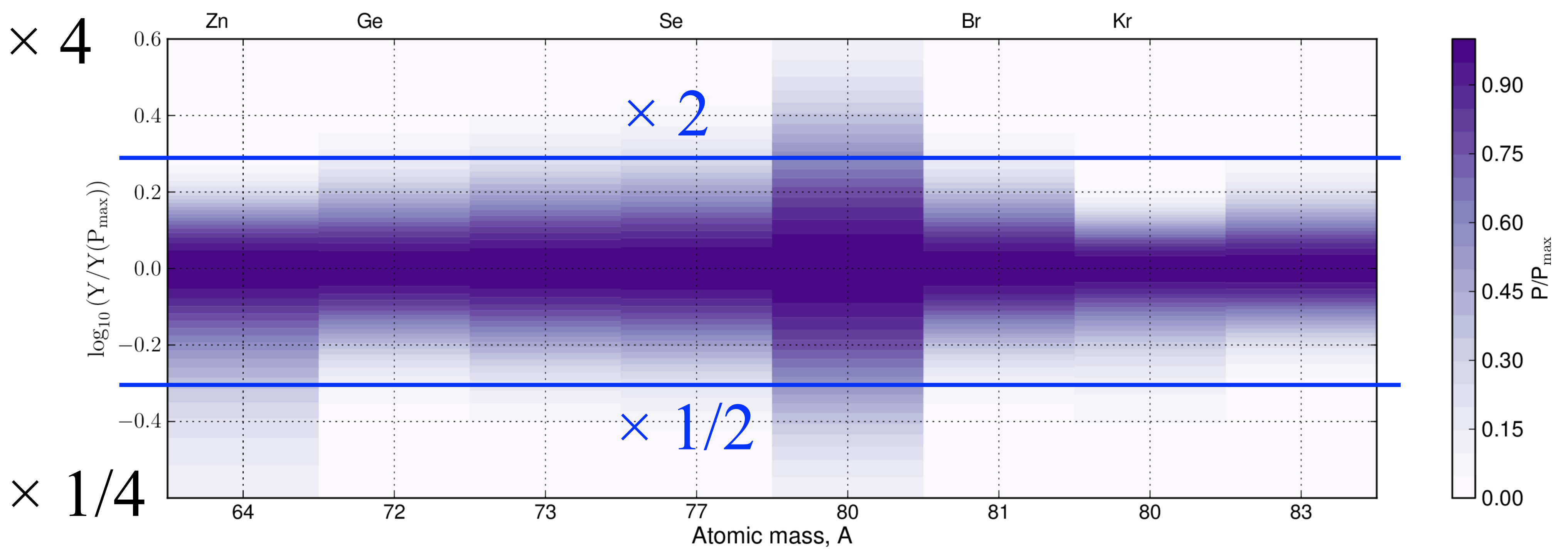
performance tests of matrix solvers on shared memory system



Cosmos2 @Cambridge (UK DiRAC facility, STFC)

Some nuclei show higher uncertainty

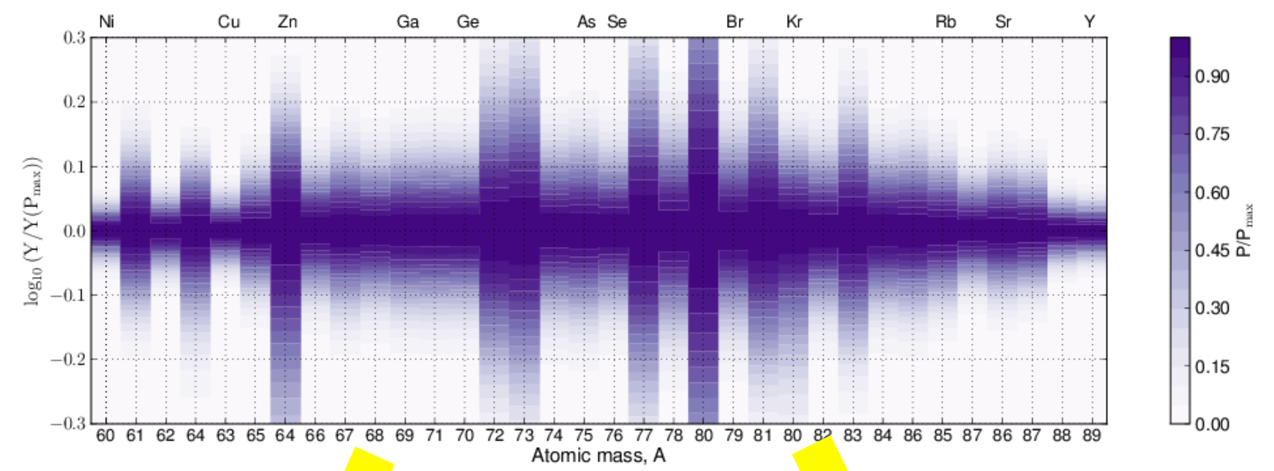
(uncertainty range factor 2 or more)



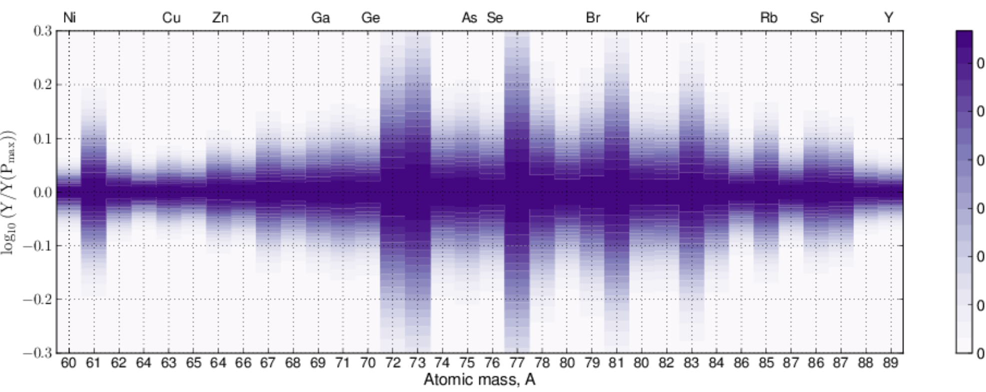
^{64}Zn, ^{72,73}Ge, ^{77,80}Se, ^{81}Br, ^{80,83}Kr

Origin of uncertainties?

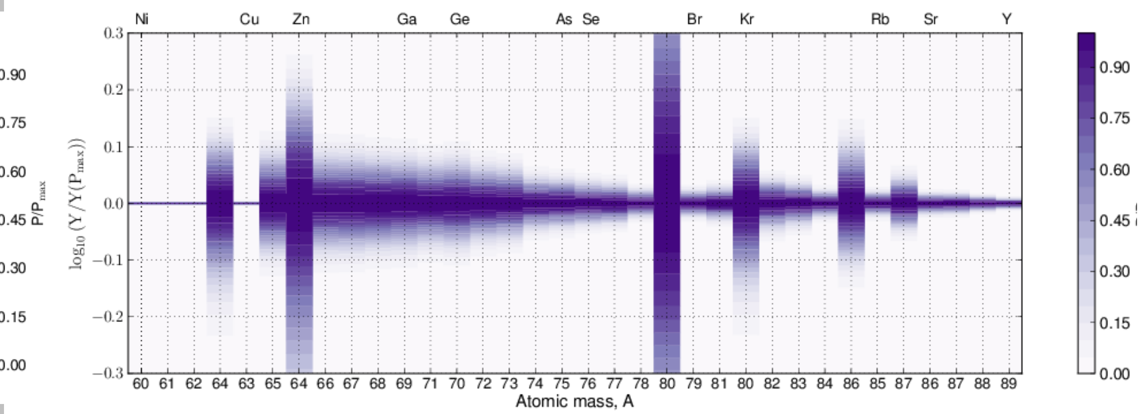
(n,γ) & $\beta^{\pm}$



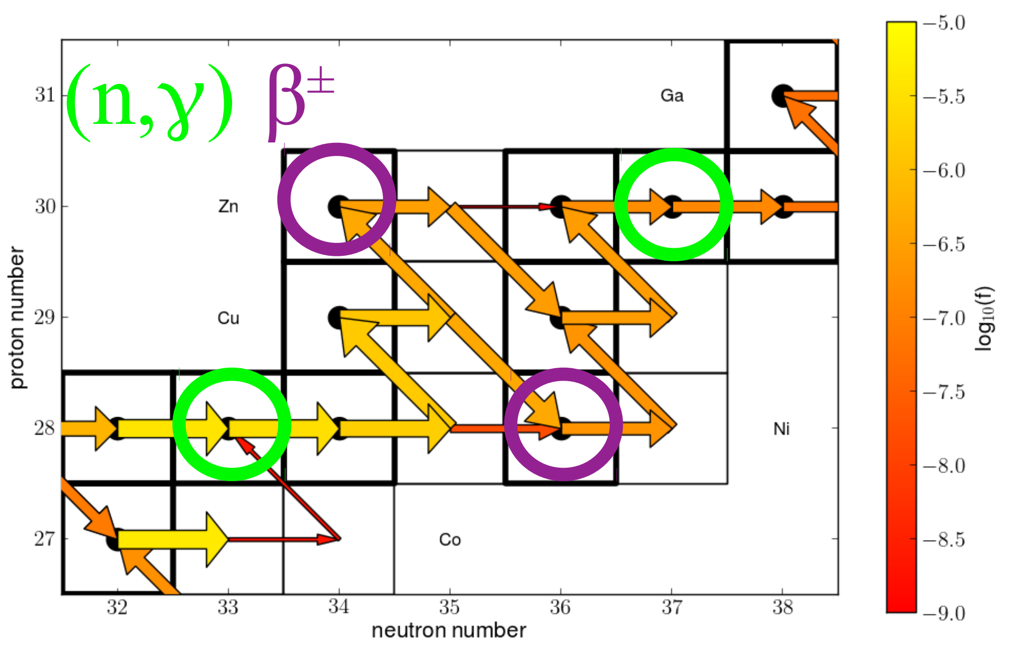
only (n,γ)

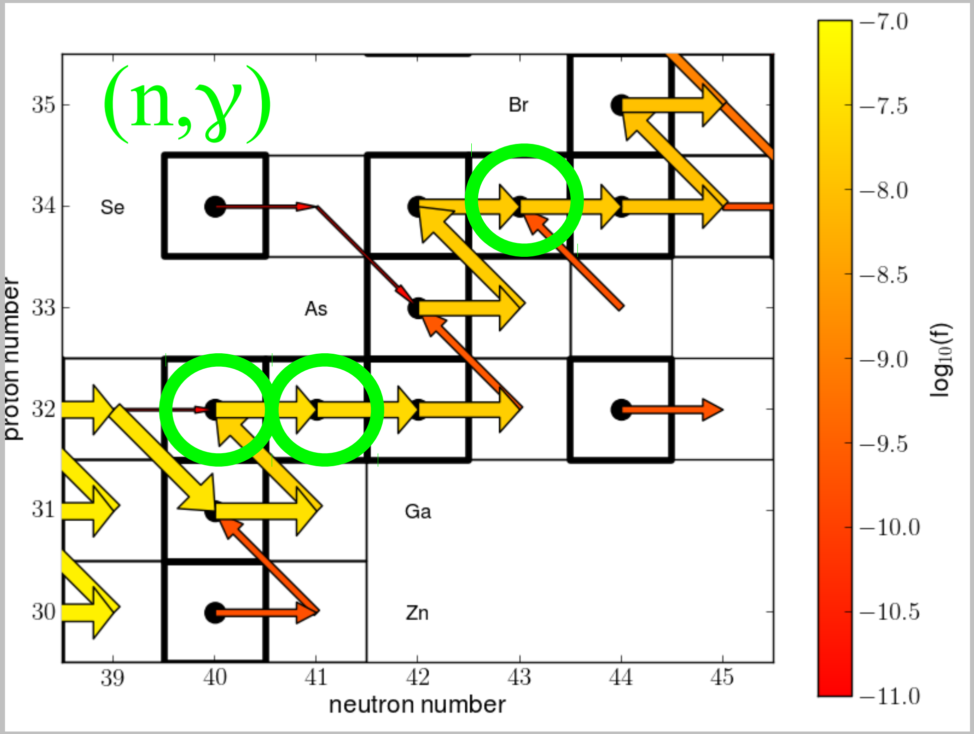


only $\beta^{\pm}$



s-process flow: which reaction produces each isotope?



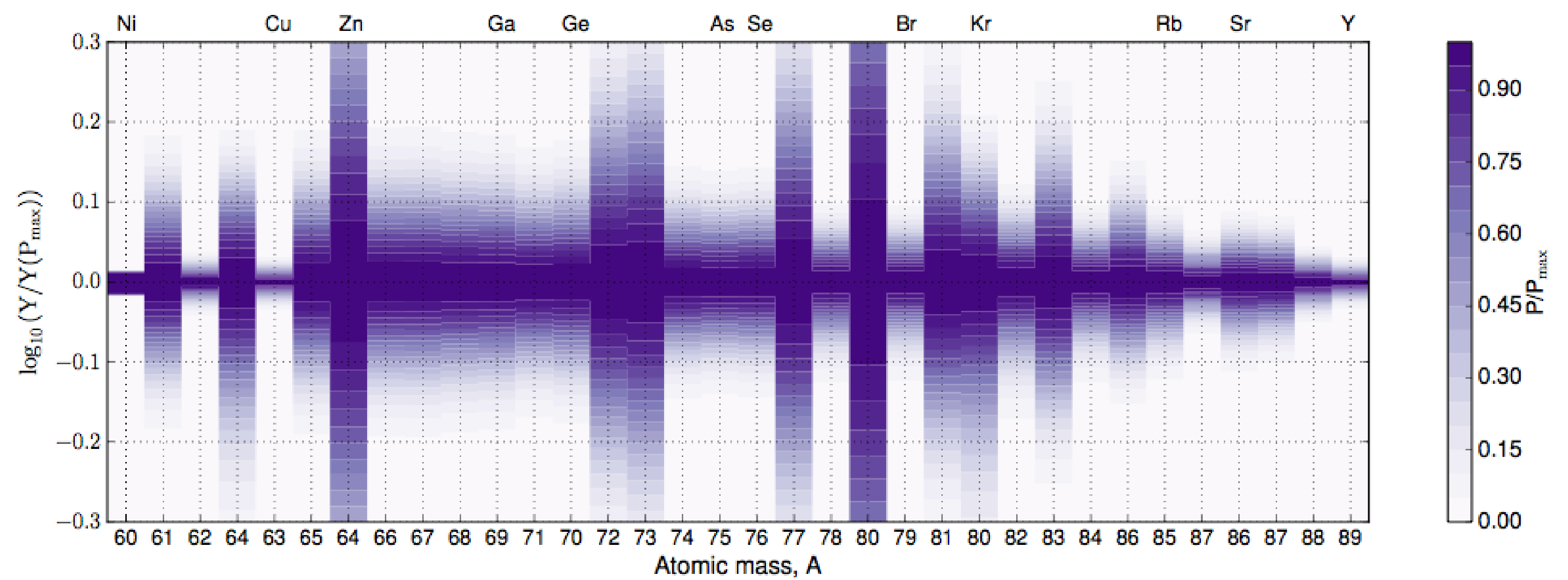


Key 15 reactions (candidates):

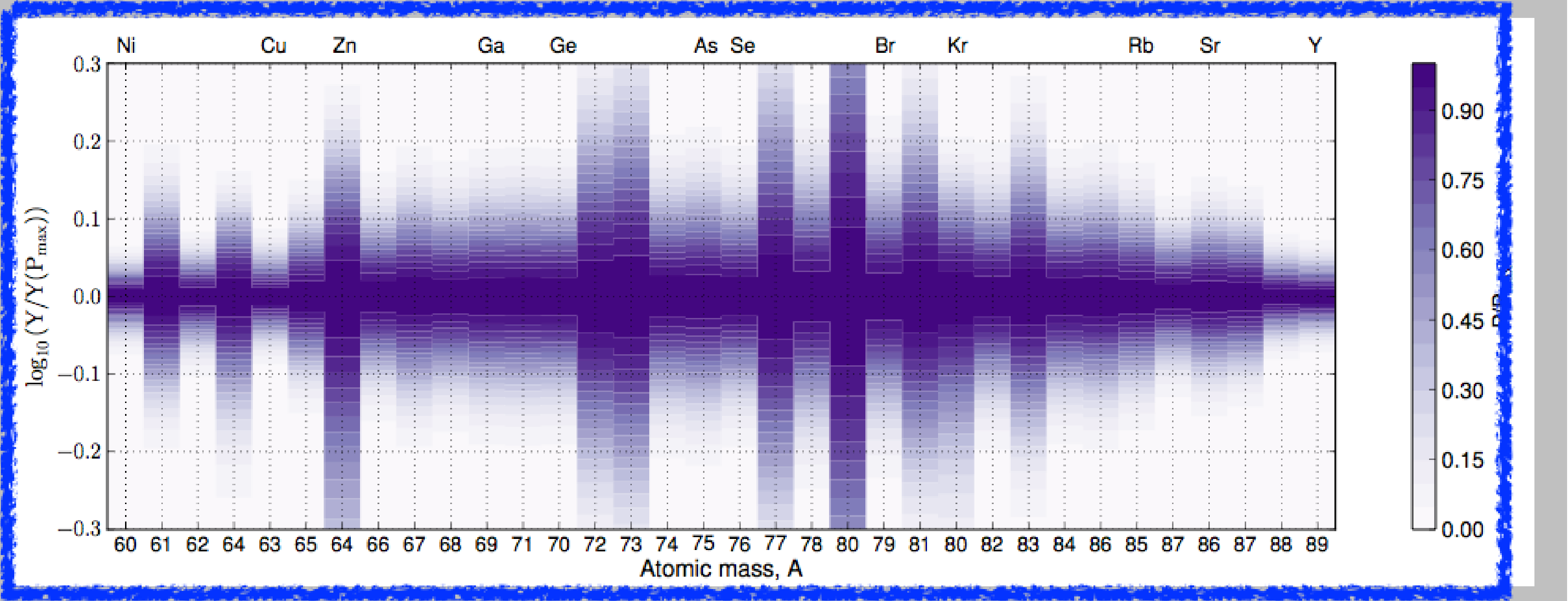
$^{60}\mathrm{Ni}\,(\mathrm{n},\gamma)\,^{61}\mathrm{Ni}$ $^{61}\mathrm{Ni}\,(\mathrm{n},\gamma)\,^{62}\mathrm{Ni}$ $^{64}\mathrm{Cu}\,(\beta-)\,^{64}\mathrm{Zn}$ $^{64}\mathrm{Cu}\,(\beta+)\,^{64}\mathrm{Ni}$
$^{72}\mathrm{Ge}\,(\mathrm{n},\gamma)\,^{73}\mathrm{Ge}$ $^{73}\mathrm{Ge}\,(\mathrm{n},\gamma)\,^{74}\mathrm{Ge}$ $^{76}\mathrm{Se}\,(\mathrm{n},\gamma)\,^{77}\mathrm{Se}$ $^{77}\mathrm{Se}\,(\mathrm{n},\gamma)\,^{78}\mathrm{Se}$
$^{79}\mathrm{Se}\,(\beta-)\,^{79}\mathrm{Br}$ $^{80}\mathrm{Br}\,(\beta+)\,^{80}\mathrm{Se}$ $^{80}\mathrm{Br}\,(\beta+)\,^{80}\mathrm{Kr}$ $^{81}\mathrm{Kr}\,(\mathrm{n},\gamma)\,^{82}\mathrm{Kr}$
$^{82}\mathrm{Kr}\,(\mathrm{n},\gamma)\,^{83}\mathrm{Kr}$ $^{83}\mathrm{Kr}\,(\mathrm{n},\gamma)\,^{84}\mathrm{Kr}$ $^{85}\mathrm{Kr}\,(\beta-)\,^{85}\mathrm{Rb}$

Candidates key reactions vs All rates

only 15 reactions sampled



all (n,g) & decay varied



Summary: uncertainty in the weak s-process

- MC nuclear reaction network code
  - applicable to general nucleosynthesis
  - parallelized by OpenMP for shared memory systems
- (weak) s-process in massive stars
  - We evaluated T-dependent uncertainty including the effect of exited states
  - key reactions (n,g) and $\beta^{\pm}$-decay are identified
    - a list of minimum key rates (15 reactions/decay)
  - different uncertainty: higher T and different hydro models

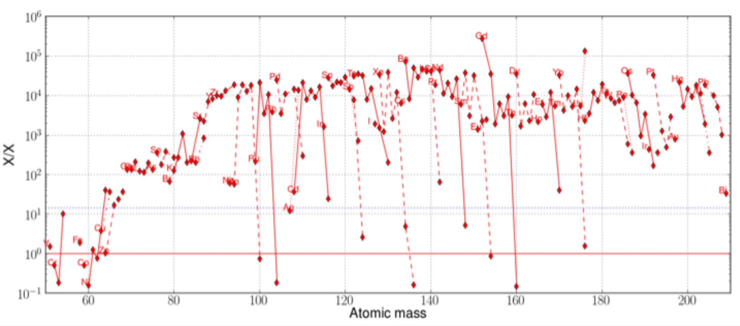
- Further investigation
  - non-standard weak s-process in metal-poor stars
  - other nucleosynthesis, i.e., rp, νp, and r processes

Other nucleosynthesis sites (in prep.)

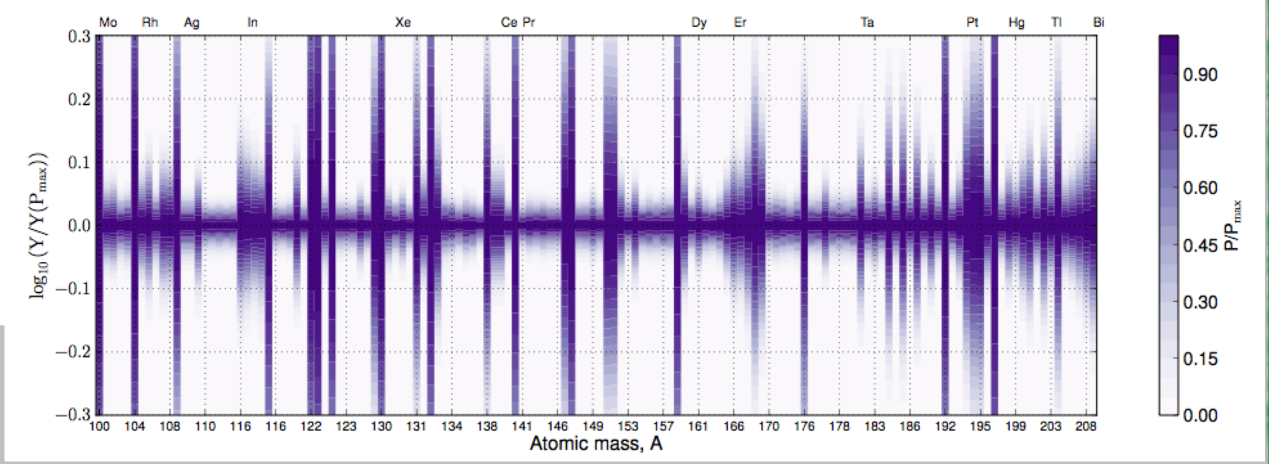
Our MC code applicable to general nucleosynthesis

- main s

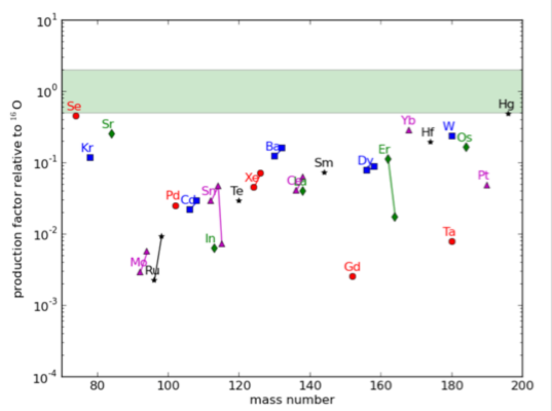
stable isotopes (A > 100) (n,γ) & β



AGB star by MESA code
(by J. den Hartogh @Keele)



- gamma (p)-process



25 M⊙ ccSN model
Rauscher et al. 2002, ApJ 576

35 p-nuclei (n,γ)/(p,γ)/(α,γ)