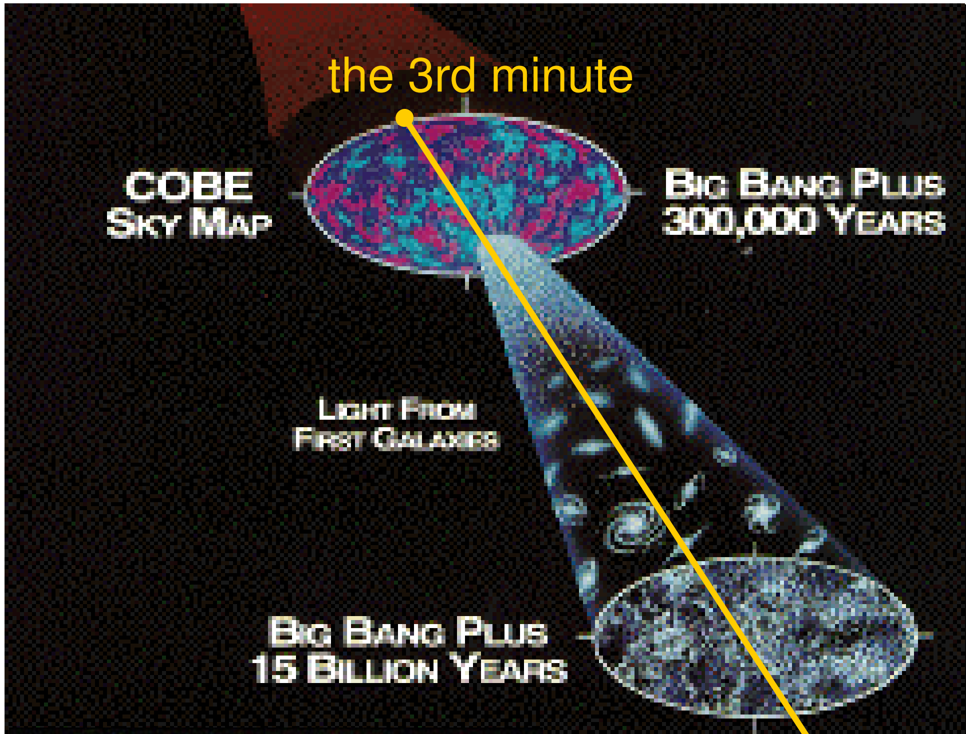
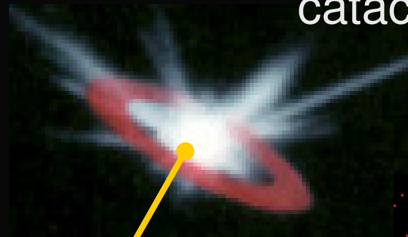
Nuclear Physics and Astrophysics

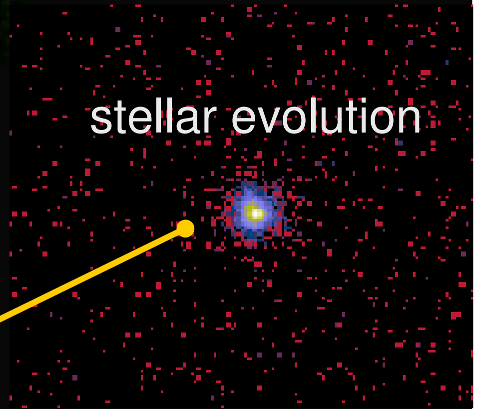
Research Activities
of the Nuclear Astrophysics Group
at the University of Basel

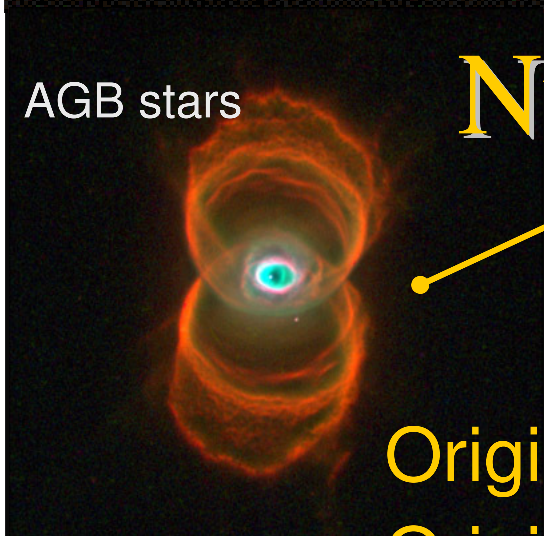
- PIs: M. Liebendörfer, T. Rauscher, F.-K. Thielemann

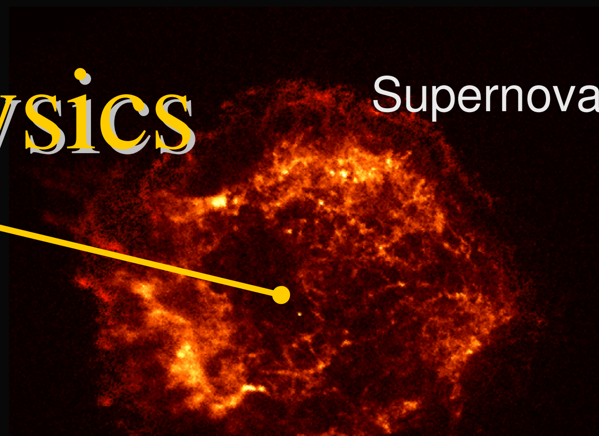
Nuclear Astrophysics









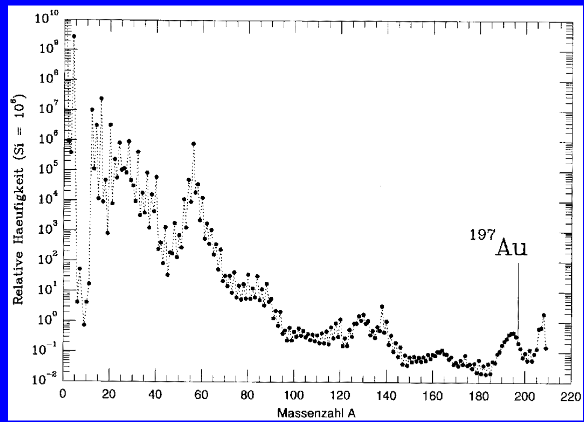


Origin and fate of the elements in our universe

Origin of radiation and energy in our universe

Nuclear Physics ⇔ Astrophysics

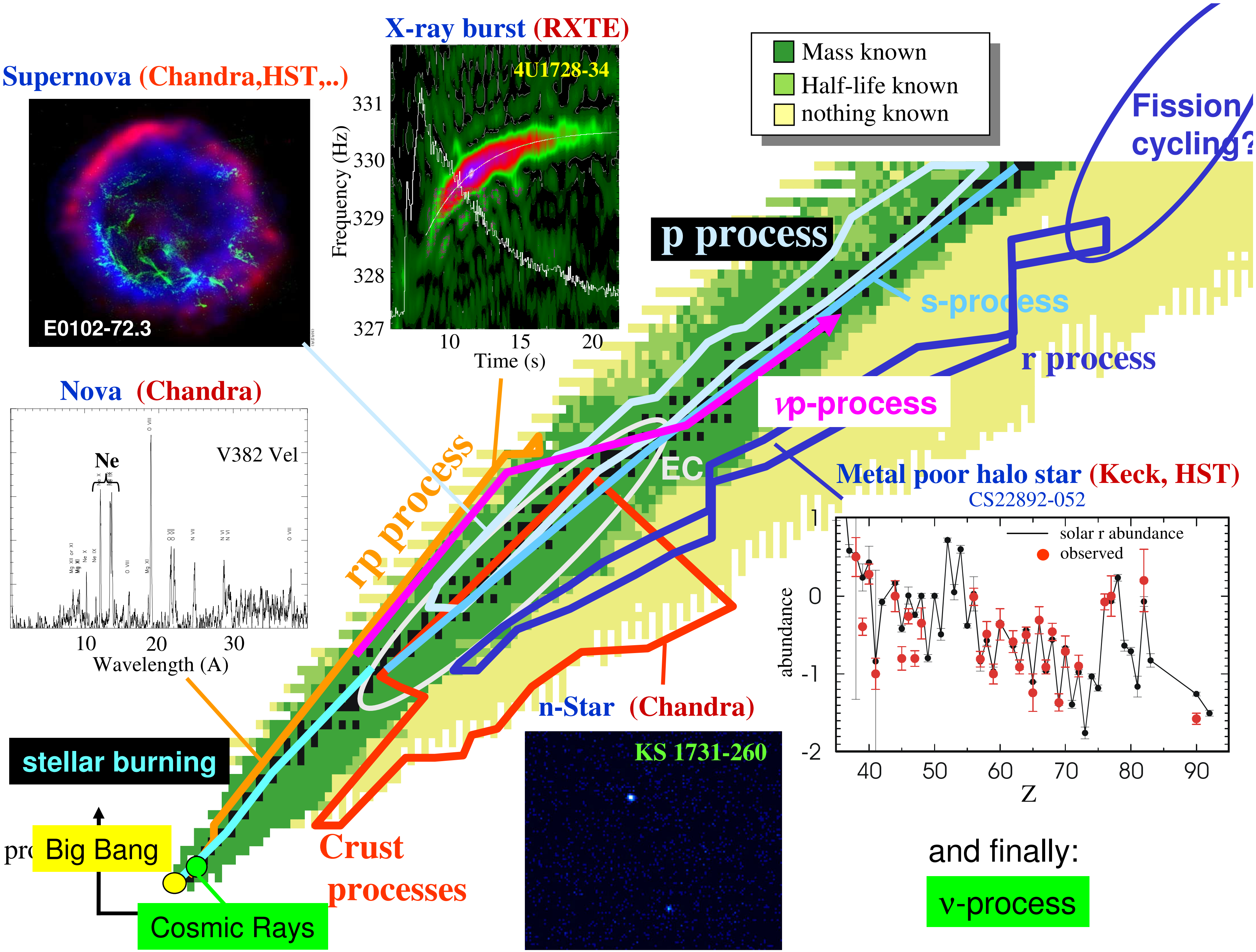
Energy generation



Nucleosynthesis

Equation of state

Nuclear Reactions

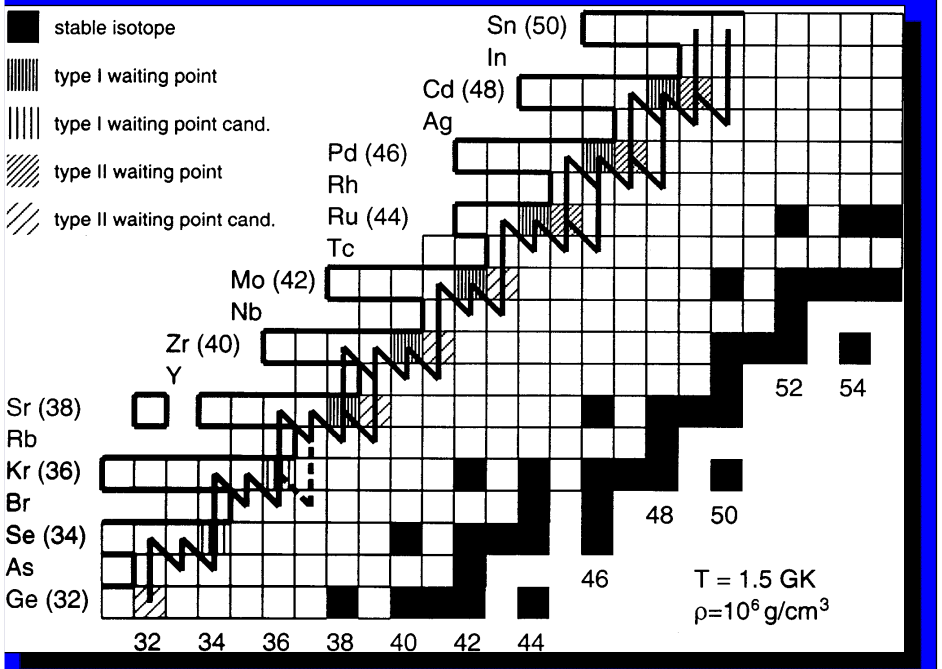


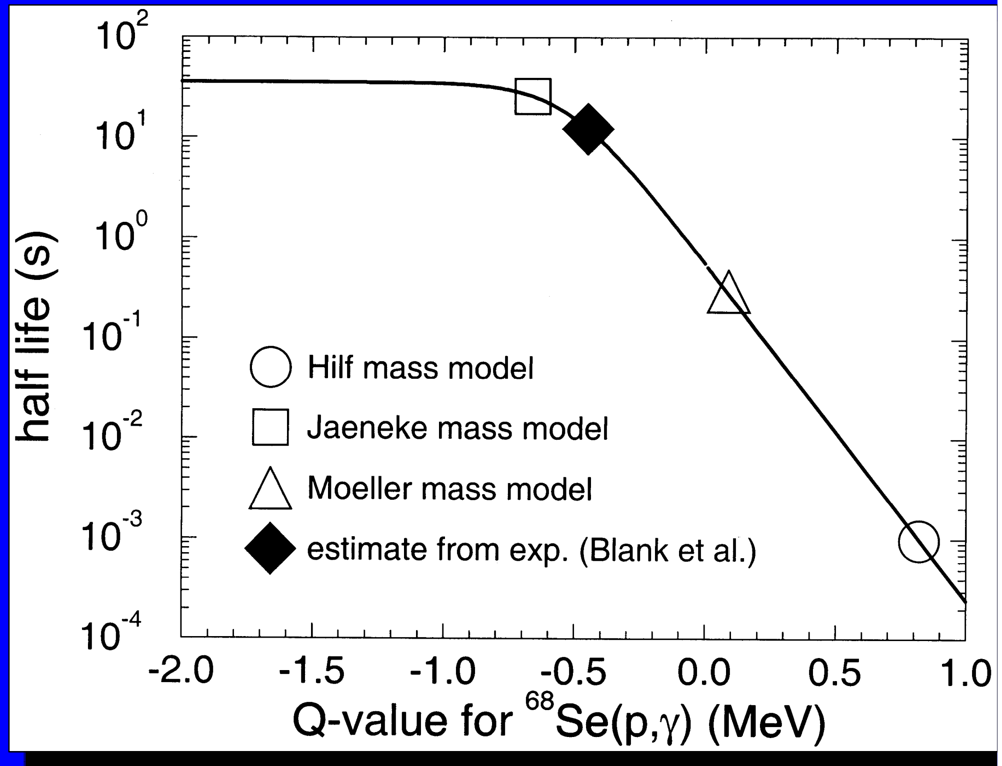
Supernova (Chandra,HST,..)
E0102-72.3
X-ray burst (RXTE)
4U1728-34
Frequency (Hz)
331
330
329
328
327
10
15
20
Time (s)
Mass known
Half-life known
nothing known
Fission cycling?
p process
s-process
r process
νp-process
rp process
EC
Nova (Chandra)
Ne
V382 Vel
10
20
30
Wavelength (A)
Metal poor halo star (Keck, HST)
CS22892-052
solar r abundance
observed
abundance
1
0
-1
-2
40
50
60
70
80
90
Z
n-Star (Chandra)
KS 1731-260
Crust processes
stellar burning
Big Bang
Cosmic Rays
and finally:
ν-process

Importance of nuclear inputs

- Energy generation
  - Evolution and lifetime of stars (+GCE)
  - Timescale and time structure of explosive events (eg. Novae, X-ray bursts, r-process)
- Nucleosynthesis
  - Products of stars, explosive events ⇒ galactic chemical evolution
  - Explain observed stellar and galactic abundances
- Equation of state
  - Collapse of massive stellar cores
  - Neutron star properties
  - Black hole formation
- Strong sensitivity of astrophysics to nuclear properties!!
  - Can rule out astrophysical scenario
  - (or point to need for improved nuclear physics)
  - Different sensitivities of different scenarios/processes

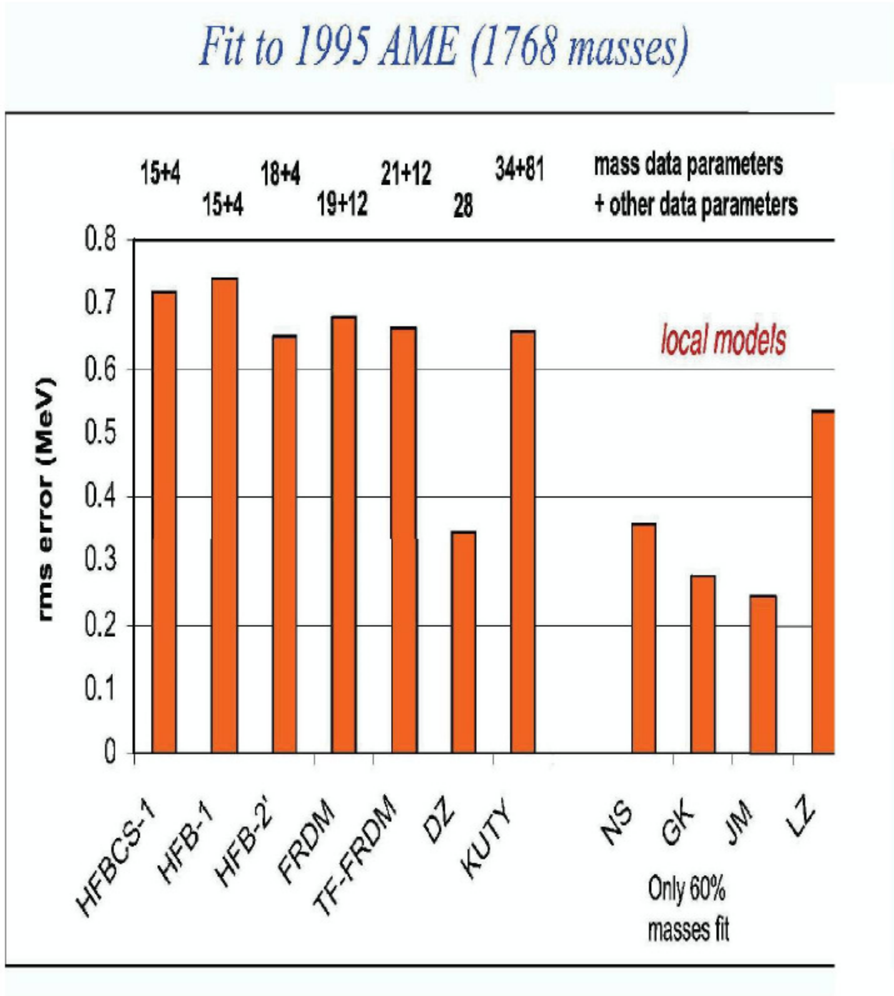
Nuclear Physics Uncertainties in the rp-Path (X-ray bursts)



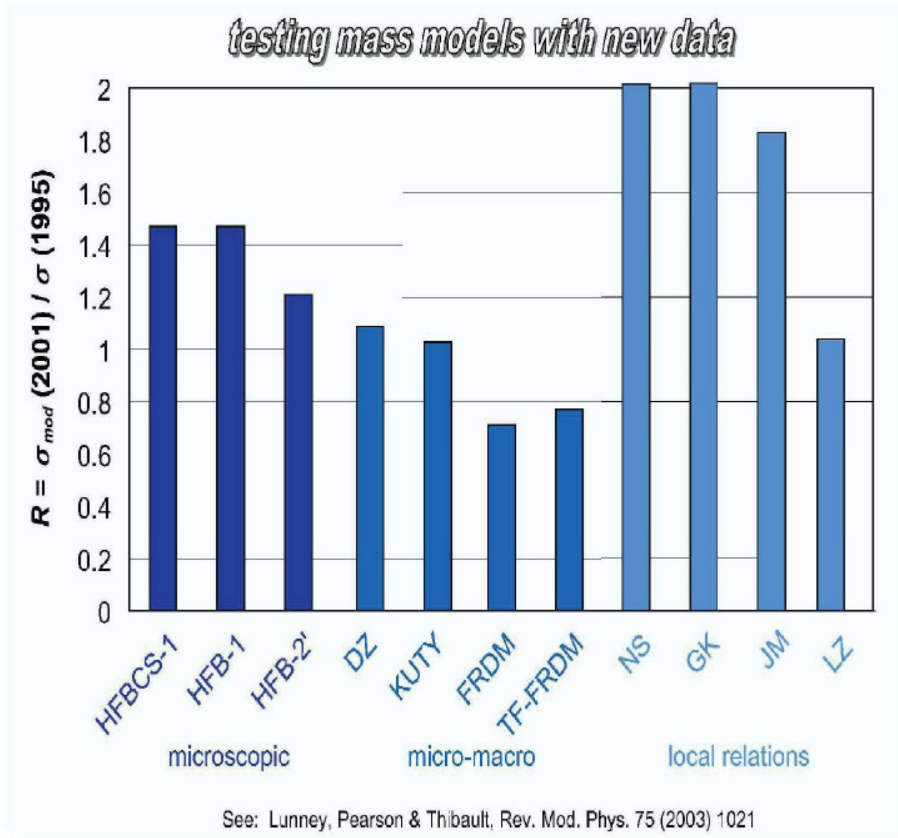


Schatz, et al. 1998

Mass Models

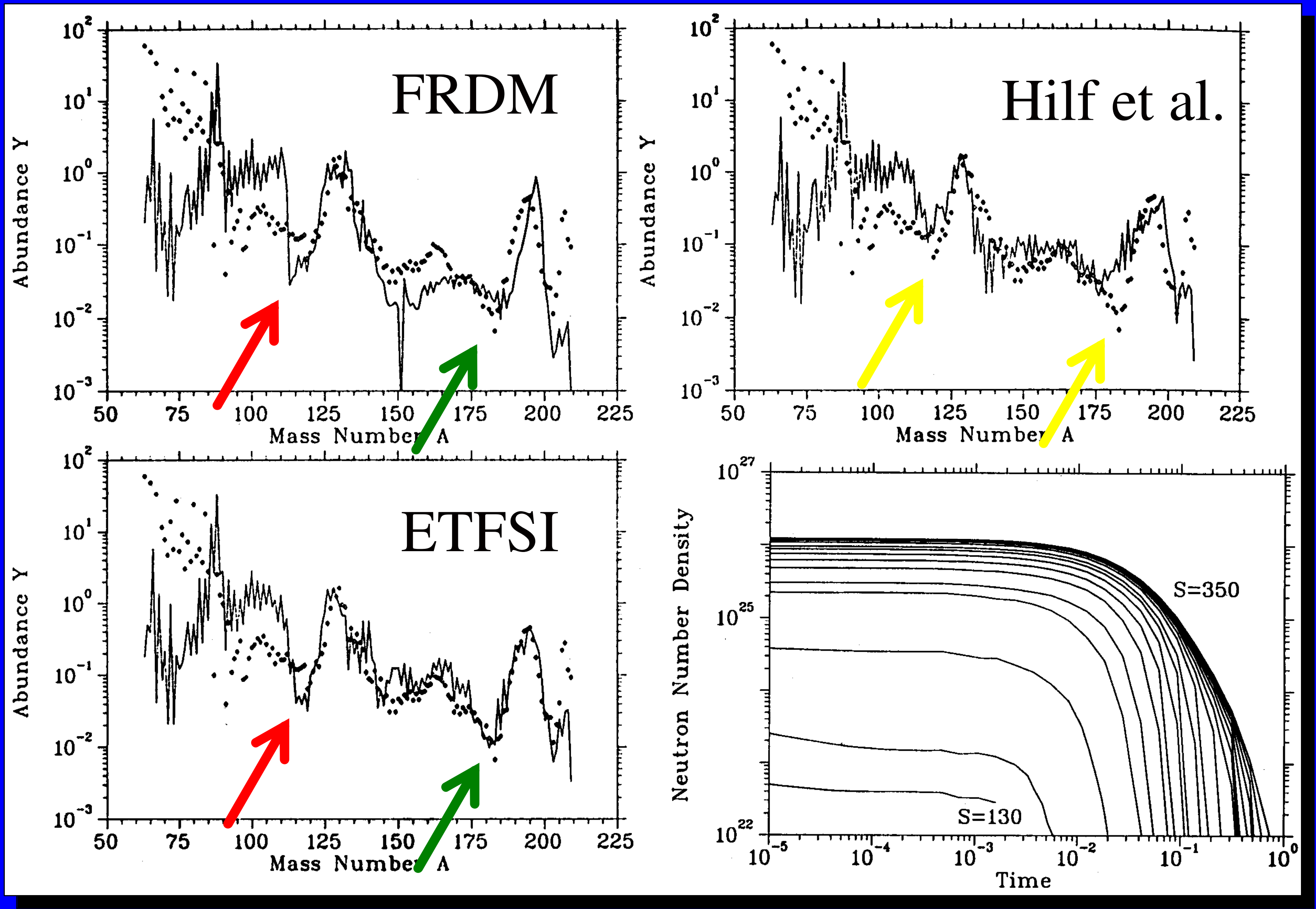


Fit accuracy



Prediction Test

r-Process: Dependence on Mass Formula



Freiburghaus et al. 1999

Nuclear Physics Problems

Experiment! (close to stab.)

- Reactions: Low energies, 0-10 MeV (reaction rates, mechanisms?)

Theory

Experiment! (close to stab.)

- Exotic Nuclei (properties needed for reactions, 6000 nuclei, 60000 reactions)

Theory

- Stellar Rates (thermal excitation, screening, β-decay in plasma)
  - (De)population of isomers (^{26}Al, ^{180}Ta)

Theory

- Nuclear equation of state
  - Early core collapse phase (e^- captures, ν trapping, collective effects)
  - Late core collapse phase
  - Neutron star properties
  - Neutron star merger

Theory

Activities in Basel

- Astrophysics
  - Parameterized reaction network studies
    - r-, rp-, p-, νp-process
    - X-ray bursts, type Ia and type II supernovae
  - Simulations
    - stellar evolution
    - collapse of massive stellar cores (type II SN)
    - galactical chem. evolution

- Nuclear Physics (relevant for astrophysics)
  - Reaction cross sections + astrophysical reaction rates (world leader!)
    - Strong, (weak), fission
  - Properties of nuclei
    - First principle (shell model, NN interaction)
    - Phenomenological (optical potentials, spectroscopy, GDR, masses)
  - Reaction theory
    - Hauser-Feshbach, direct, resonant
    - Interplay between mechanisms

Considered Nuclear Properties and Cross Sections

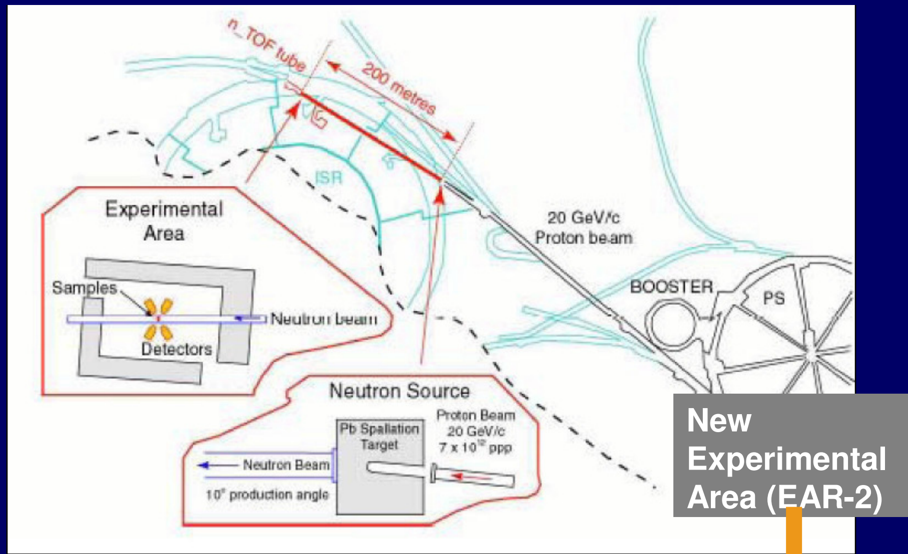
(in no particular order!)

- Reaction mechanisms, cross section, astrophys. Rates
  - n-, p-, α-induced (capture, transfer)
- Nuclear level density (stat. mod. input)
  - Also single low-lying states important (DC+stat. mod., from exp or shell model)
  - Shell quenching?
- Masses (Q-values, sep. energies, equilibria path location)
- Optical Potentials (stat. mod. inp., DC)
- Giant resonances (stat. mod. inp.)
  - Low energy behavior, Pygmy Resonances?
- Nucleon density distribution (deformation, neutron skin)
- Fission barriers (barrier heights, fragment distribution; endpoint of r-process (mainly (n,f), (β,f), few (ν,f))
- β-decay (time scales), weak rates (e^--capture, ν+nucleus; collapse and explosion)

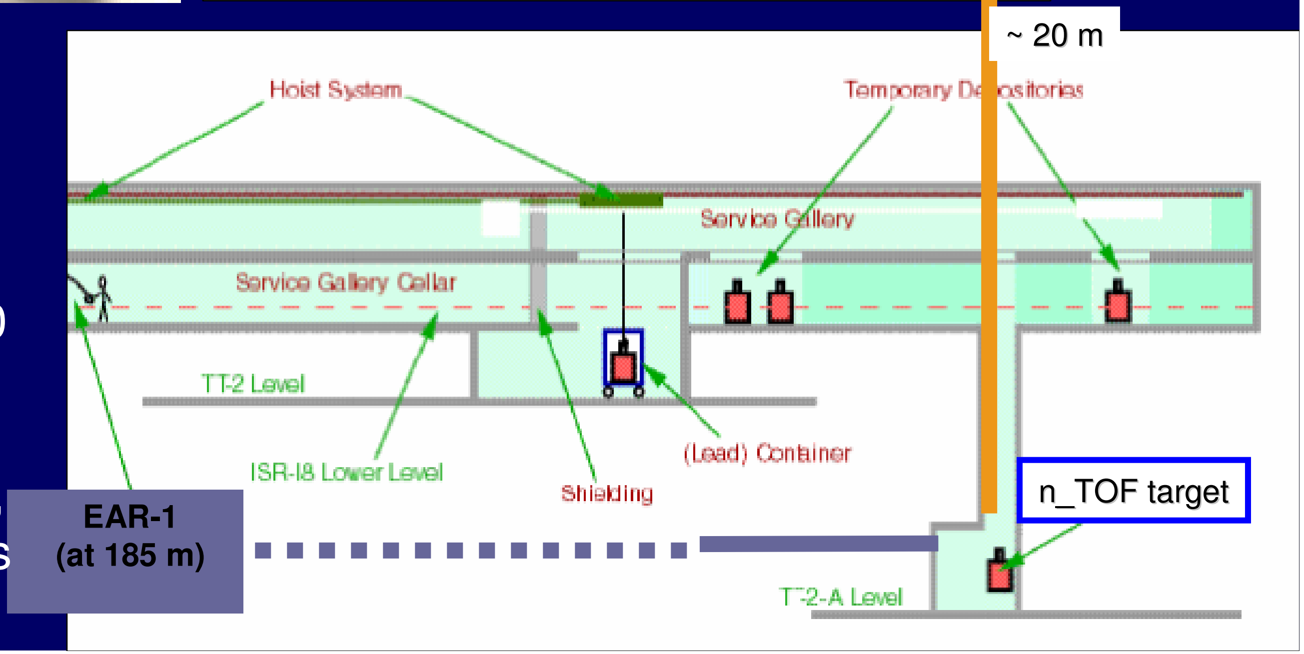
Collaborations

- Many individual collabs with scientists/groups in various countries (A, AUS, CA, CH, D, E, F, H, I, J, RUS, UK, USA): nuclear theory + experiment, astrophysics, astronomy
- International Graduate School Basel-Tübingen-Graz *"Hadrons in Vacuum, Nuclei, and Stars"* (SNF, DFG)
- JINA (Joint Institute for Nuclear Astrophysics, USA)
- KaDONiS (reaction rate compilations)
- Supernova Science Center (SciDAC (Scientific Discovery through Advanced Computing) initiative, USA)
- Swiss Stellar Evolution Network
- EU/SNF:
  - NUSTAR, EXEL (nucl. exp.), CARINA (exp+th NA), VISTARS (theory NA)
  - SCOPES (ITEP Moscow)
  - n_TOF (CERN), phase II starting
  - new: ESF project "New Physics of Compact Stars"
  - Proposals for JRA and Networks in 7th FP of the EU

The n_TOF facility at CERN

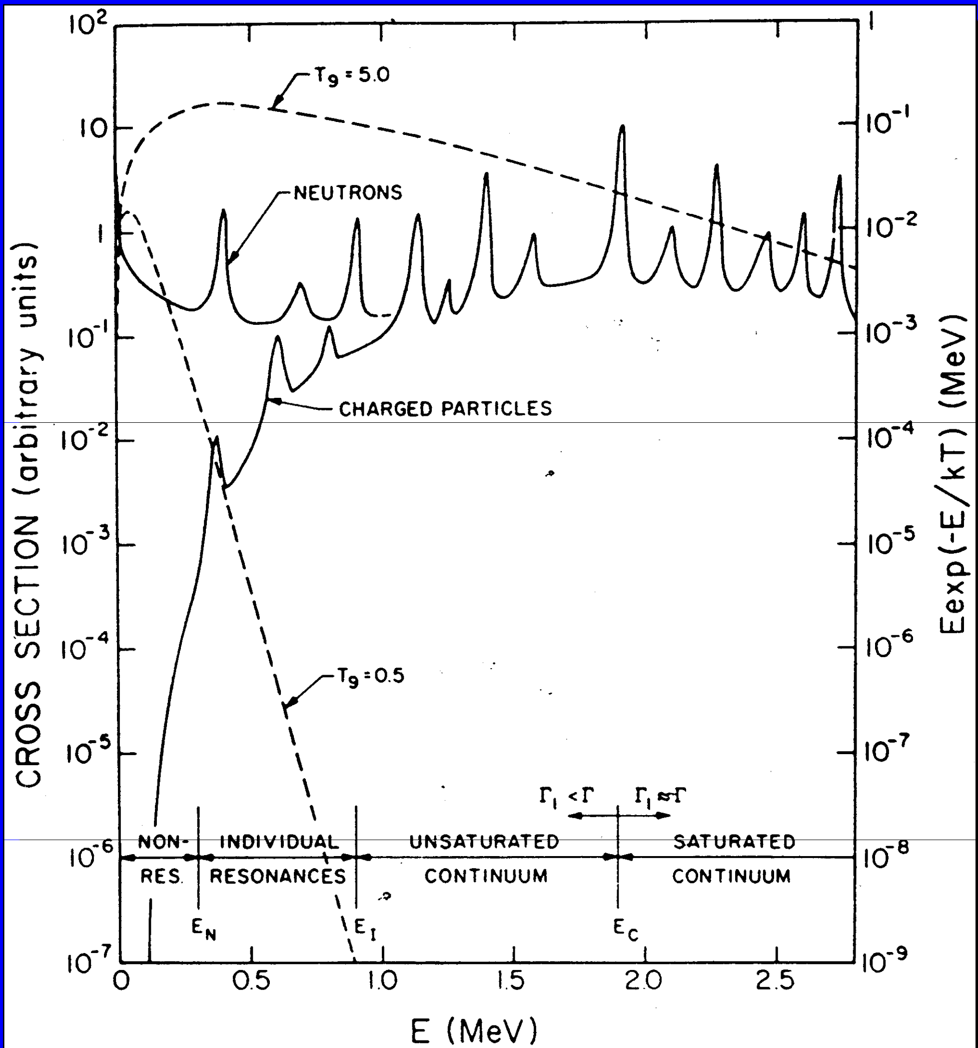


- Spallation neutron source
- 6x10^5 n/s/p-pulse, 1/E dep.
- Phase2:
  - flux boost by factor 100
  - sensitivity boost 5000 !
- Nuclear Astrophysics, ADS, fundamental neutron physics



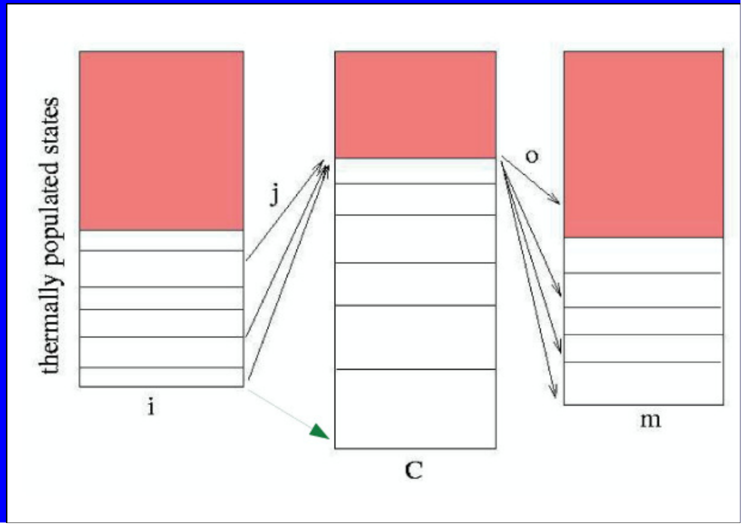
Massive Star Nucleosynthesis
(quiet and explosive burning)

Reaction Mechanisms



Regimes:

1. Overlapping resonances ⇒ statistical model (Hauser-Feshbach)
2. Single resonances ⇒ Breit-Wigner, R-matrix
3. Without or in between resonances ⇒ Direct reactions

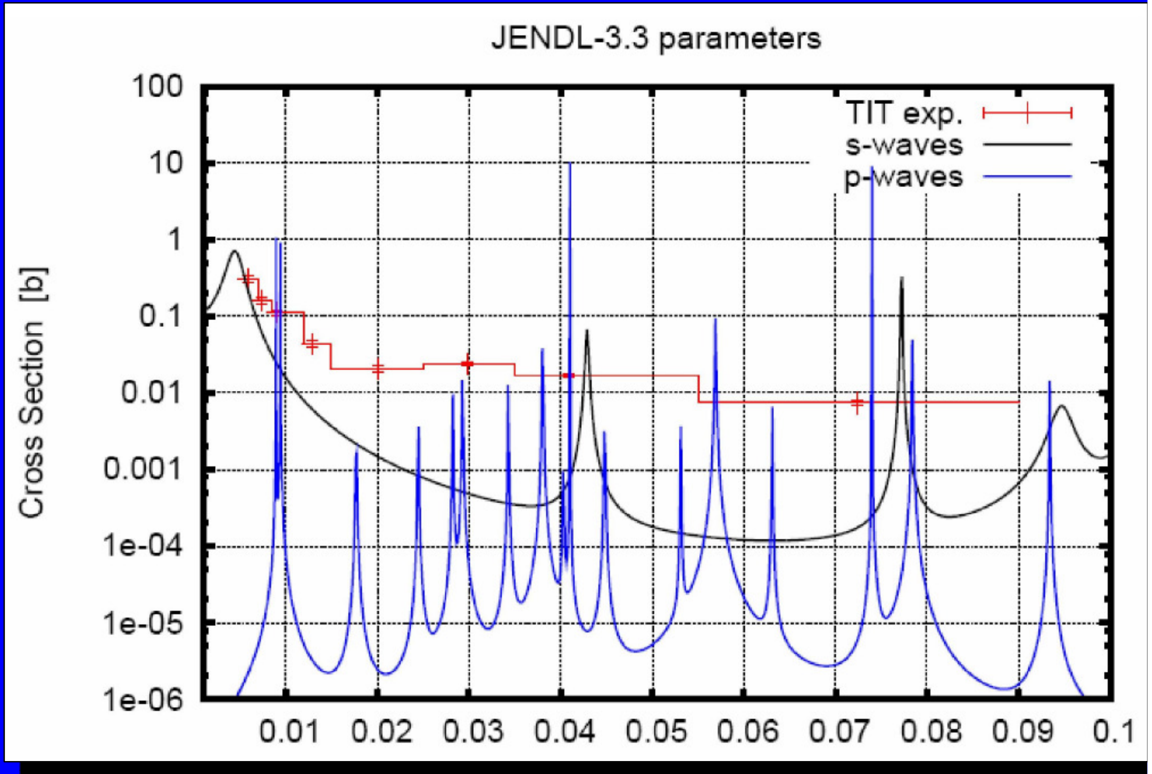


Massive Star Nucleosynthesis

$^{62}Ni(n,\gamma)^{63}Ni$ at 30 keV

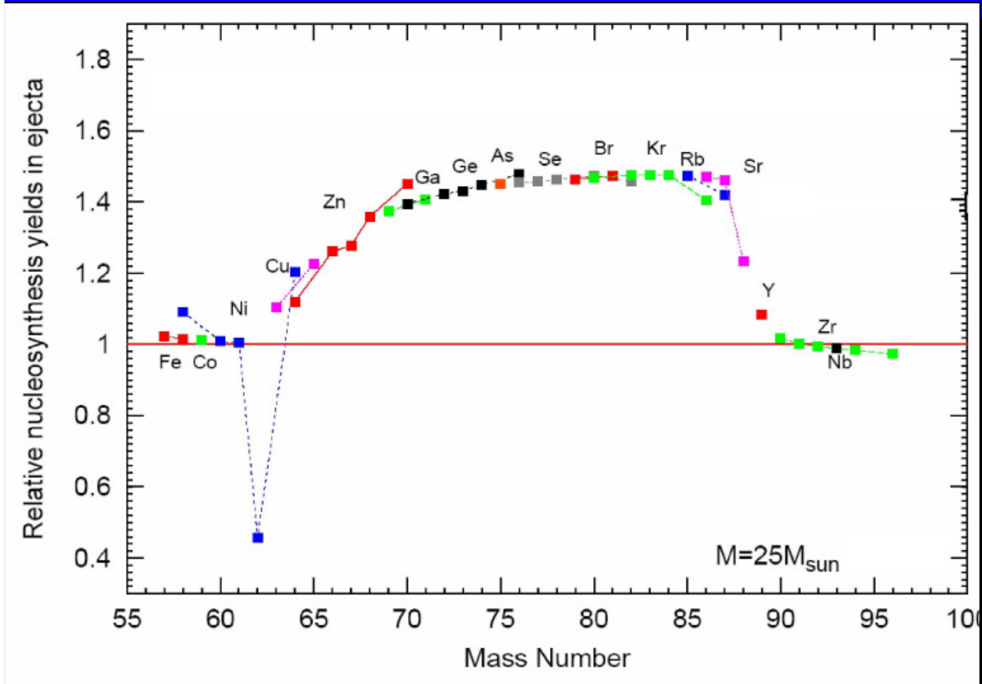
- Previous measurements vary between 12.5 and 36 mb
- Bao et al. 2000 recommended 12.5±4 mb; Rauscher et al 2002 find overproduction of ^{62}Ni
- Nassar et al. 2005: 26.1±2.5 mb
- Tomyo et al. 2005: 37.0±3.2 mb
- Mainly resonant capture, direct capture negligible
- NONSMOKER Warning: $T_9<0.18$ (16 keV)

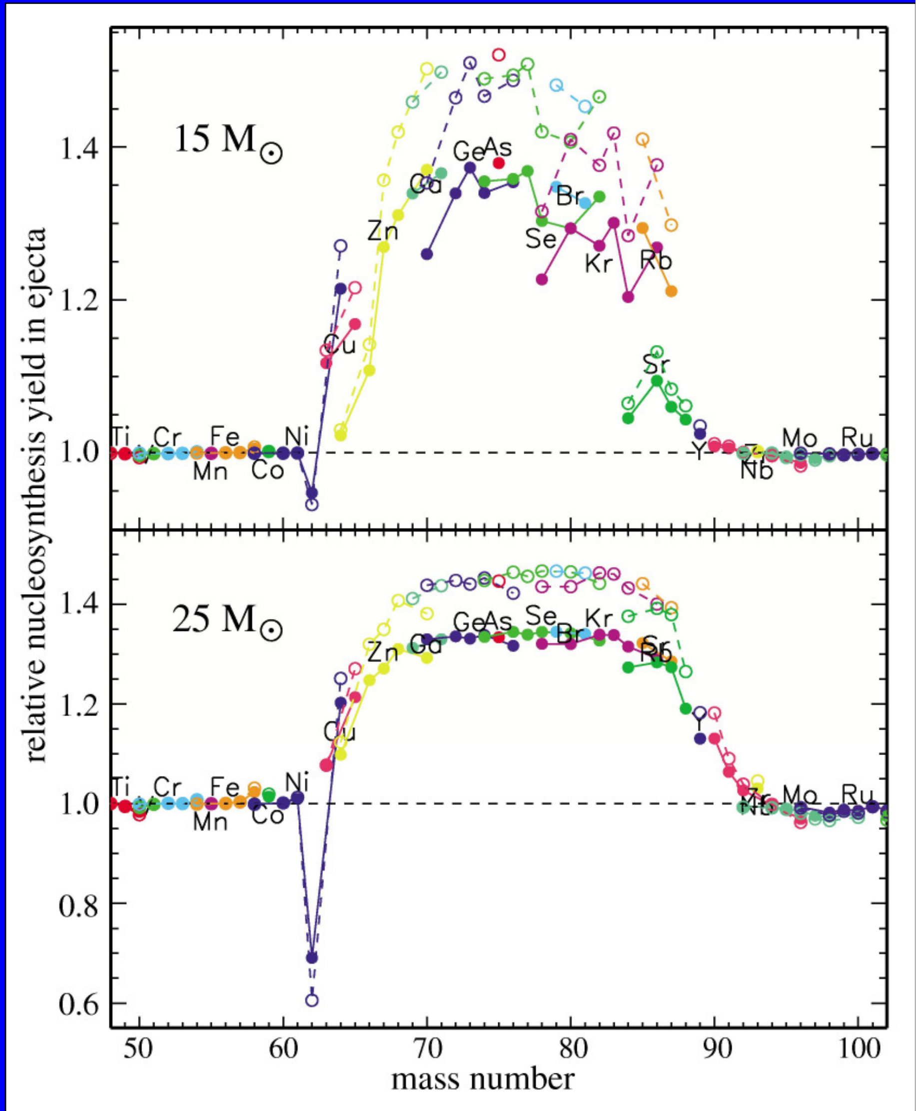
M. Heil



MeV

Impact of changed ^{62}Ni(n,γ) rate

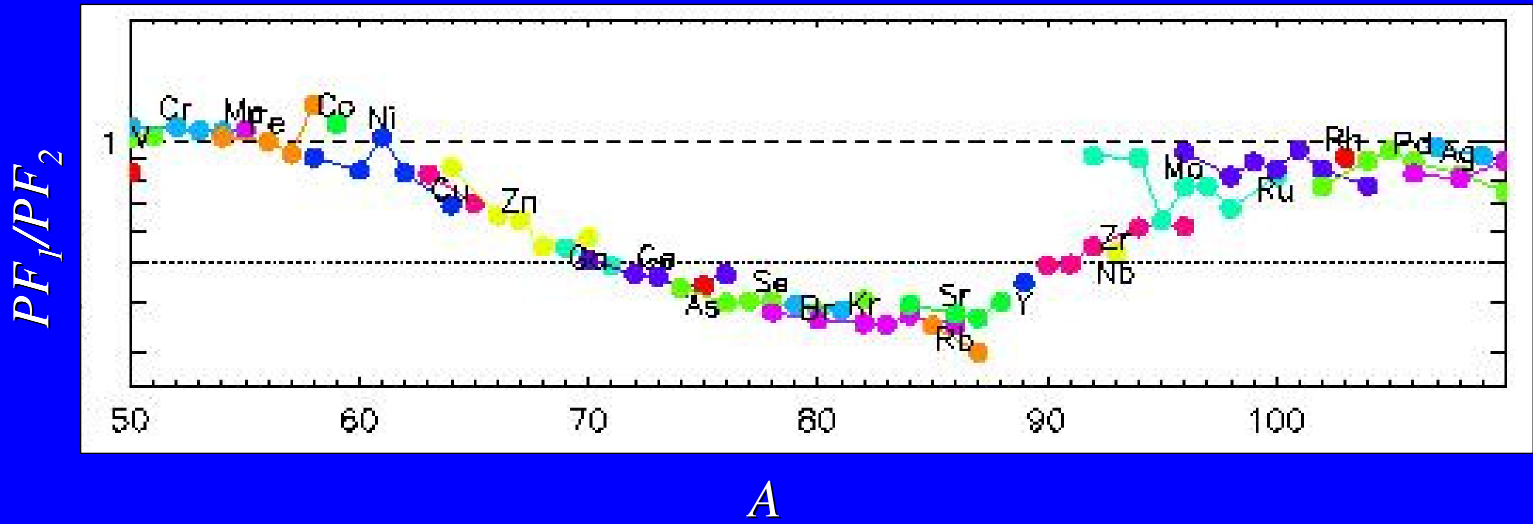




- For MACS (30 keV) of 26.1 mb and 35.5 mb
- Relative to MACS of 12.5 mb (Bao et al 2000)

A. Heger; Nassar et al 2005

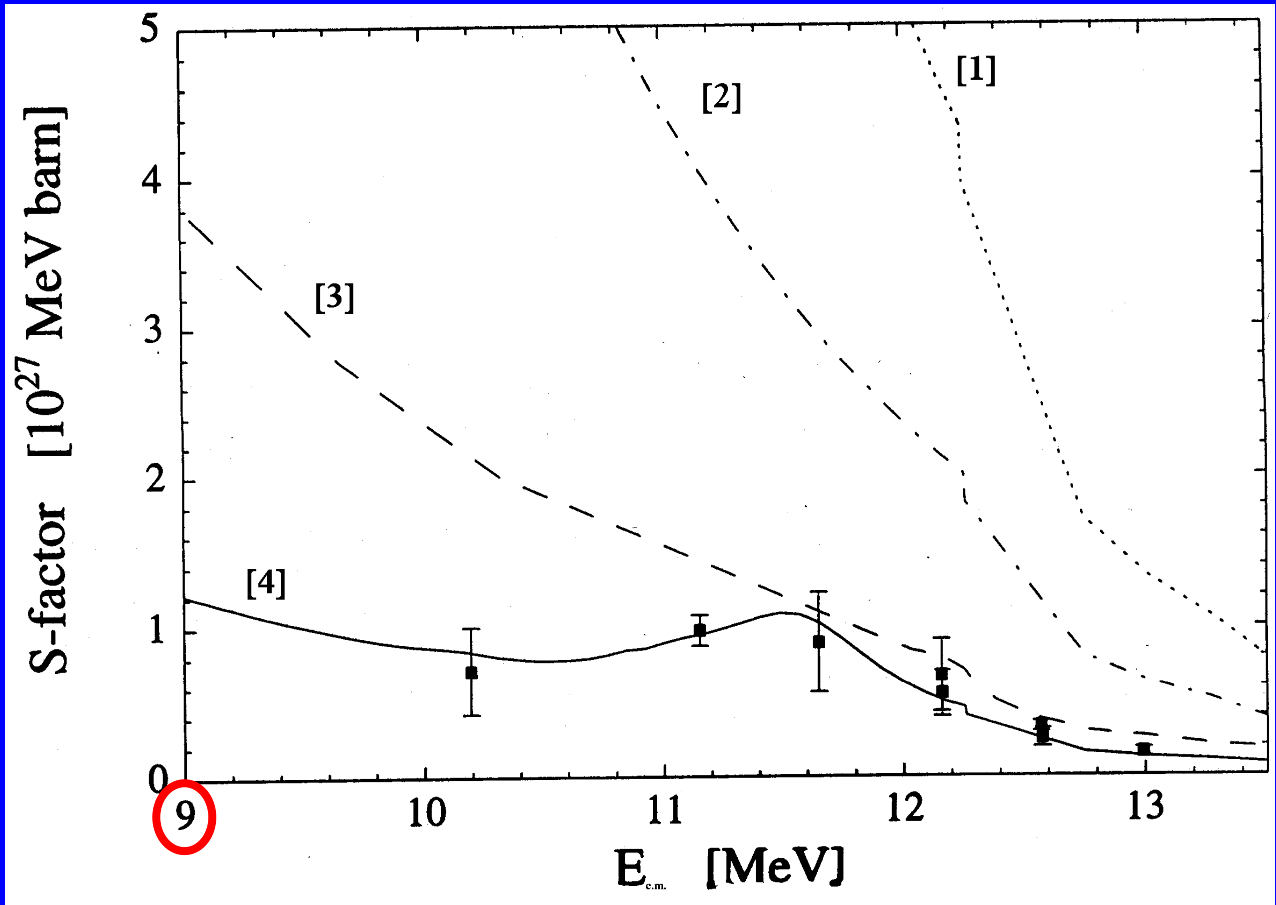
$(\alpha,n)/(\alpha,\gamma)$ Branching at ^{22}Ne



Ratio of results with $^{22}Ne(\alpha,n)^{25}Mg$ and $^{22}Ne(\alpha,\gamma)^{26}Mg$ rates varied within experimental uncertainties.
The branching ratio determines the production of the weak s-process component, because the neutron source is $^{22}Ne(\alpha,n)^{25}Mg$.

Rauscher et al. 2002 (with UCSC and LLNL)

Problem with α+Nucleus Potentials



$^{144}Sm(\alpha,\gamma)^{148}Gd$

[1] McFadden & Satchler Pot.

[2] Avrigeanu Pot.

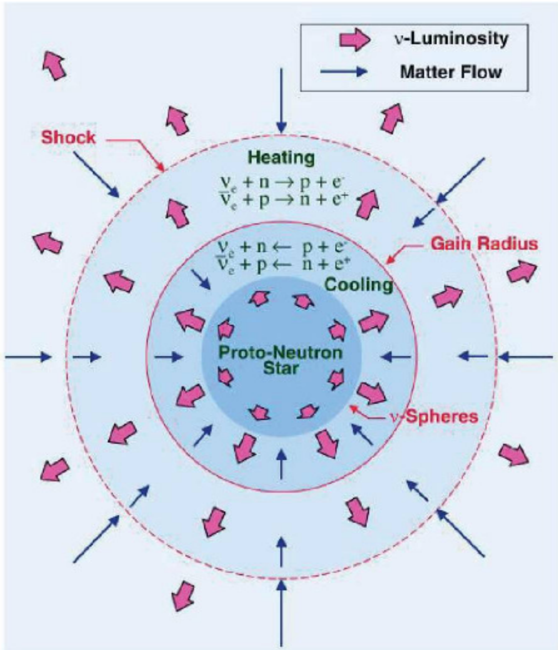
[3] Mohr & Rauscher 98 Pot.

[4]+exp: Somorjai et al. 1999

Application: Nd/Sm ratio in pre-solar grains

Core collapse supernovae
(r-Process Nucleosynthesis)

Neutrino-driven Core Collapse Supernovae



$\nu_e + n \leftrightarrow p + e^-$ heating

$\bar{\nu}_e + p \leftrightarrow n + e^+$

$\nu_e + A' \leftrightarrow A + e^-$ opacity

$\nu + N \leftrightarrow \nu + N$

$\nu + A \leftrightarrow \nu + A$

$\nu + e^- \leftrightarrow \nu + e^-$ thermalization

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\nu = \nu_e, \nu_\mu, \nu_\tau$ source terms

$e^+ + e^- \leftrightarrow \nu + \bar{\nu}$

$\gamma + \gamma \leftrightarrow \nu + \bar{\nu}$

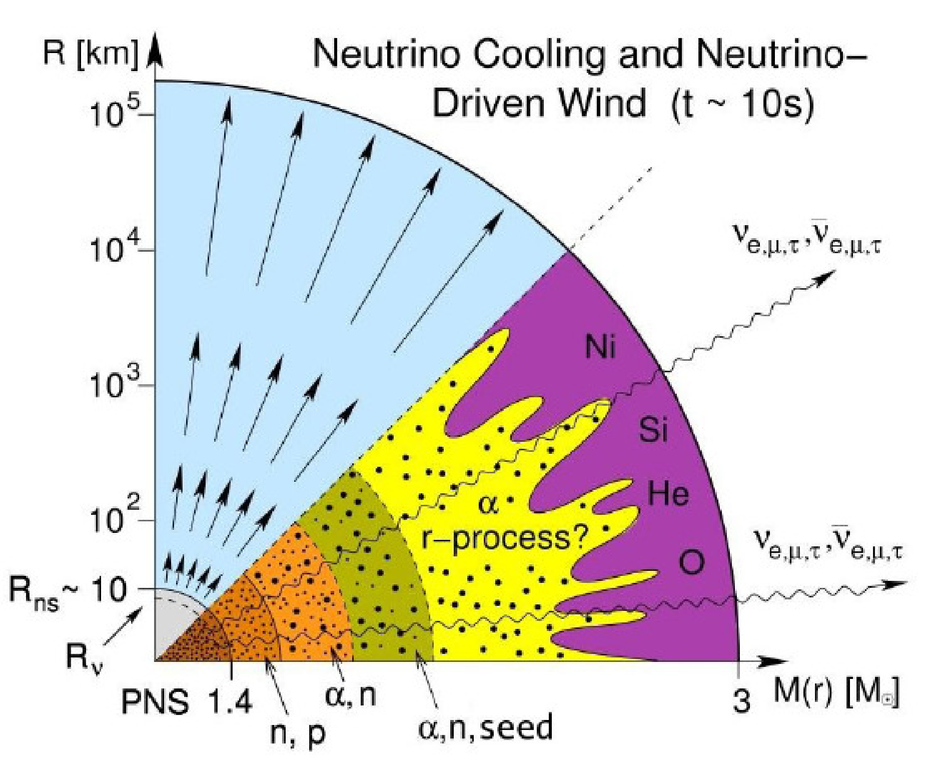
also

$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$

and

$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Inner Zones of the Exploding Star



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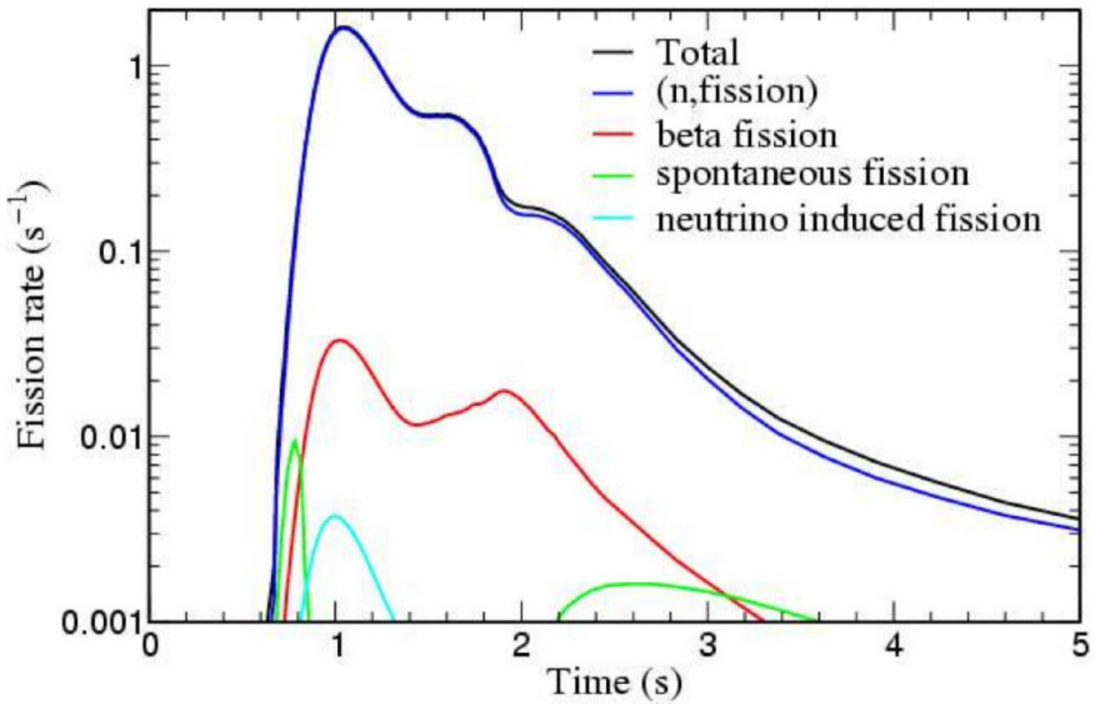
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$
$$\nu_e + n \leftrightarrow p + e^-$$

r-Zone n-rich but inner zone (earlier time) becomes p-rich!

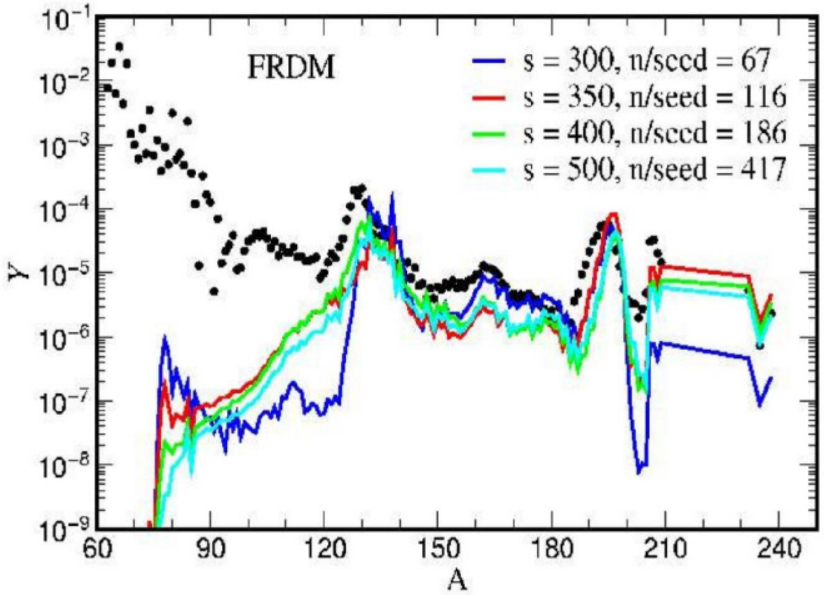
- To study nucleosynthesis:
  - Need to couple reaction networks to core-collapse simulations
  - Dependence on explosion mechanism, multi-D
  - Currently done via artificial explosion and postprocessing

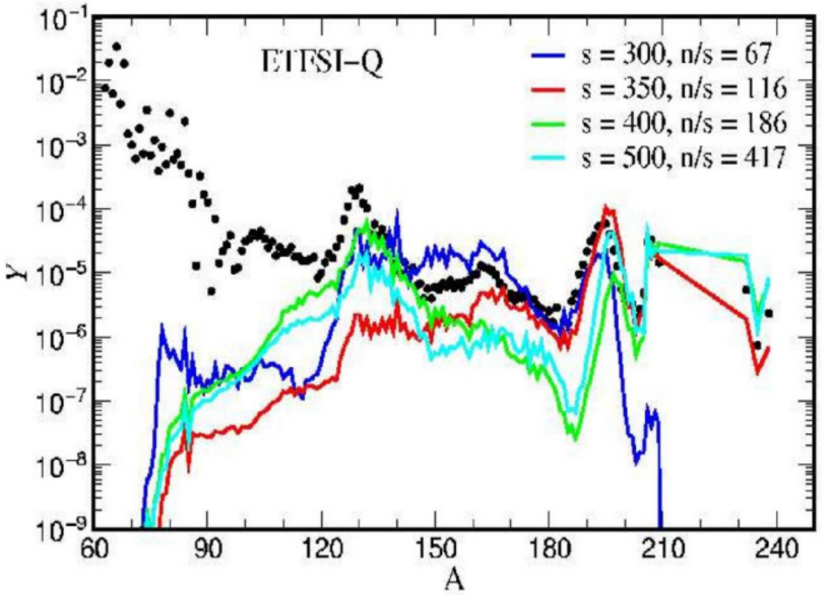
Importance of fission modes

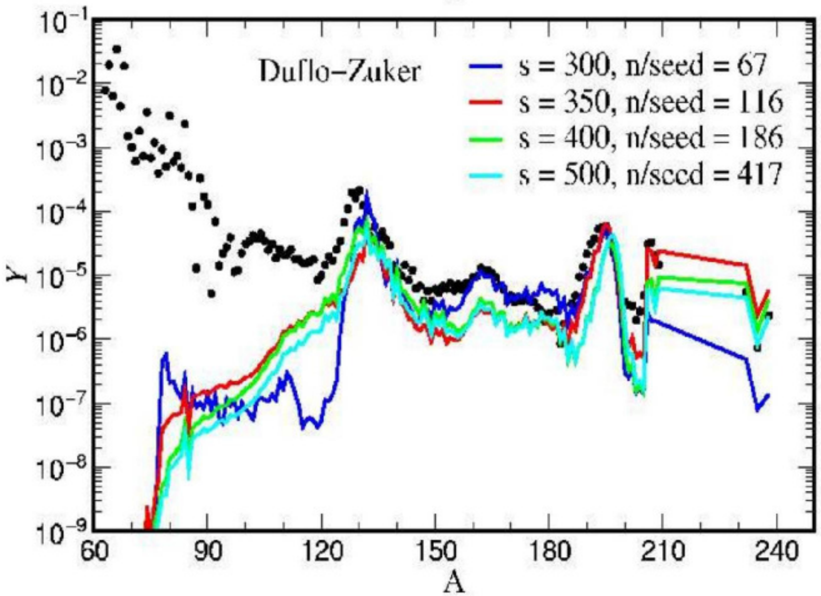


wiggles indicate several cycles through fission region

Full fission "cycling" for different mass models





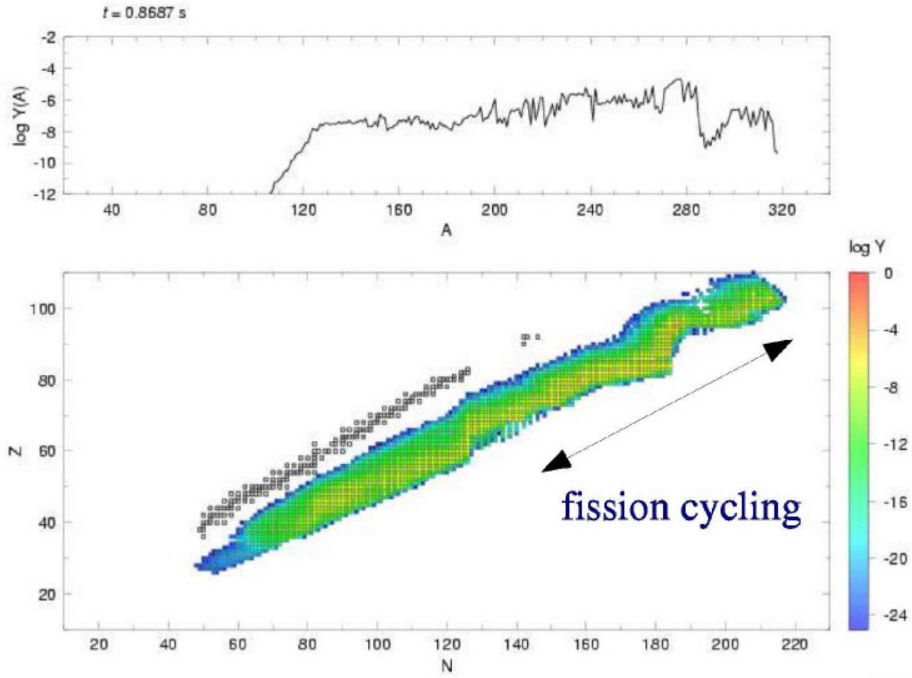


Differences are due to different shell structure at $N = 82$

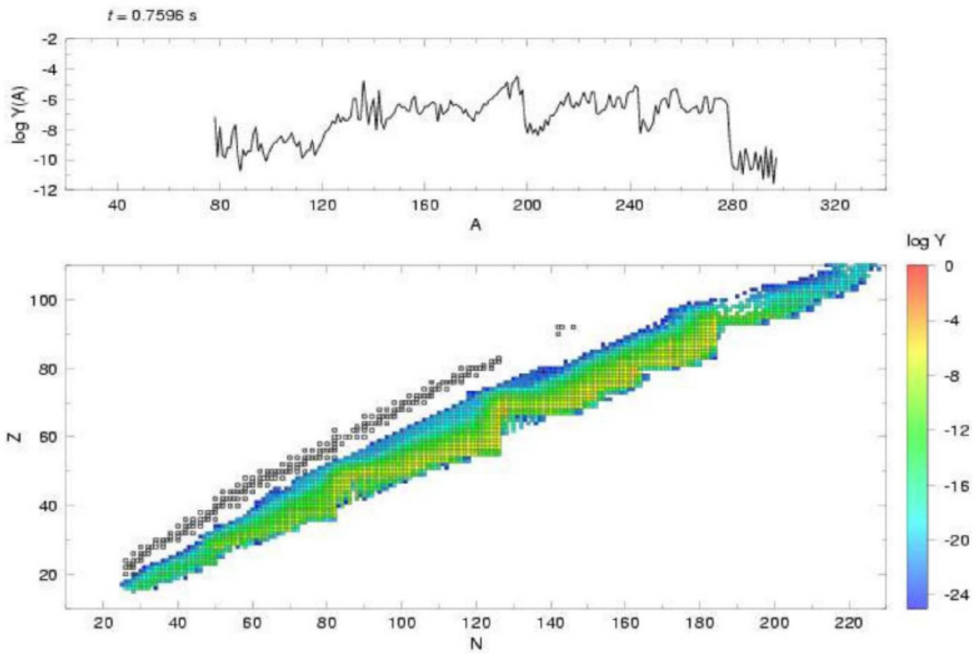
only one entropy component!

Martinez-Pinedo, Mocelj et al. (2007)

r-process progress



masses: ETFSI
barriers: Mamdouh et al. (2001)

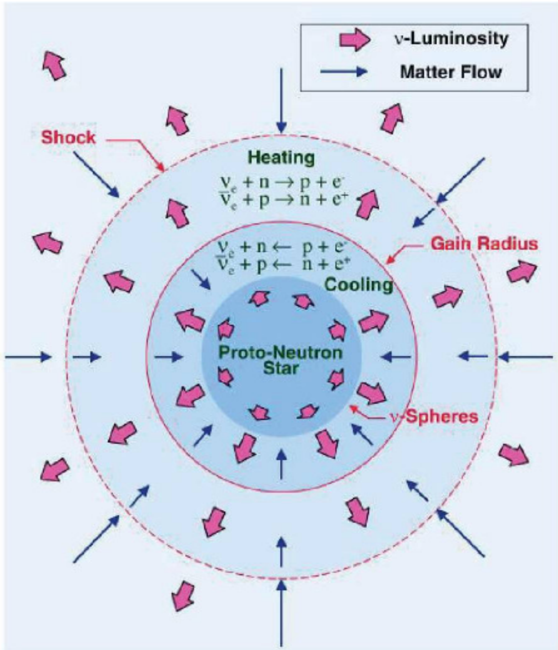


masses: FRDM
barriers: Myers & Swiatecki (99)

Martinez-Pinedo et al. (2007)

The νp-Process
(in core collapse supernovae)

Neutrino-driven Core Collapse Supernovae



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also

$e + \gamma \leftrightarrow e + \gamma + \nu + \bar{\nu}$

and

$\nu_e + \bar{\nu}_e \rightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Mimic multi-D Effects in 1D

Convective instabilities in multi-D models

1. Convection in proto neutron star

   Net result: enhanced neutrino luminosities

   By: reduce neutral current neutrino scattering opacities on free nucleons

   $$\nu_x + \mathrm{n} \rightarrow \mathrm{n} + \nu_x' \quad \text{and} \quad \nu_x + \mathrm{p} \rightarrow \mathrm{p} + \nu_x'$$

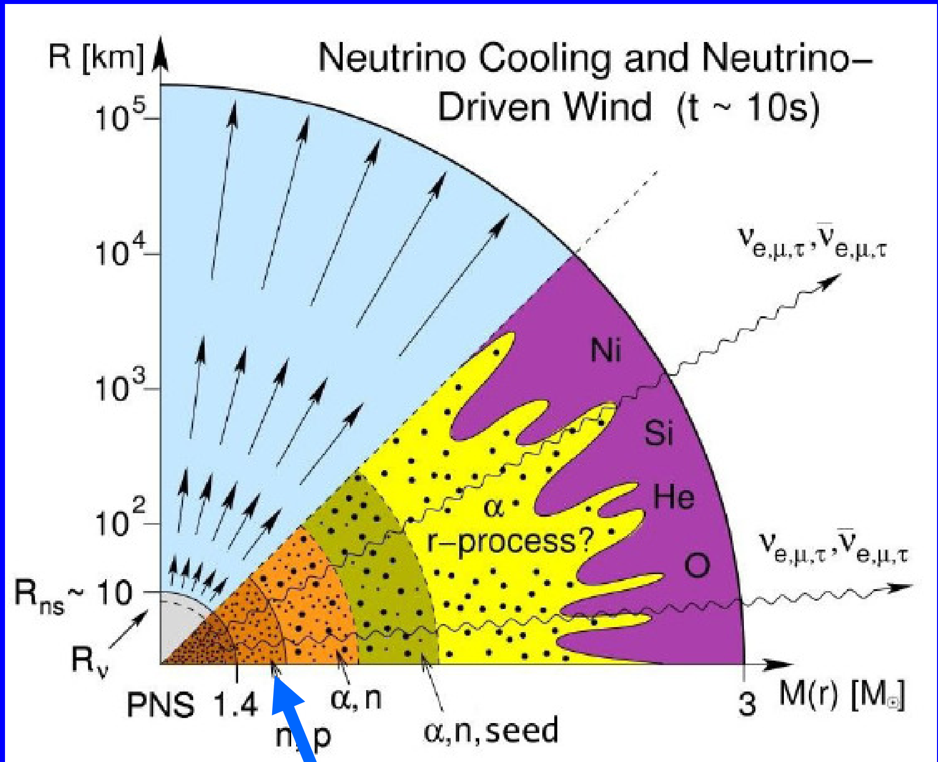
2. Convection in heating region

   Net result: enhanced energy deposition

   By: increase neutrino emission / absorption cross sections in heating region

   $$\nu_e + \mathrm{n} \leftrightarrow \mathrm{p} + e^- \quad \text{and} \quad \overline{\nu}_e + \mathrm{p} \leftrightarrow \mathrm{n} + e^+$$

Inner Zones of the Exploding Star



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νp-process

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$$\nu_e + n \leftrightarrow p + e^-$$

r-Zone n-rich but inner zone (earlier time) becomes p-rich!

- To study nucleosynthesis:
  - Need to couple reaction networks to core-collapse simulations
  - Dependence on explosion mechanism, multi-D
  - Currently done via artificial explosion and postprocessing

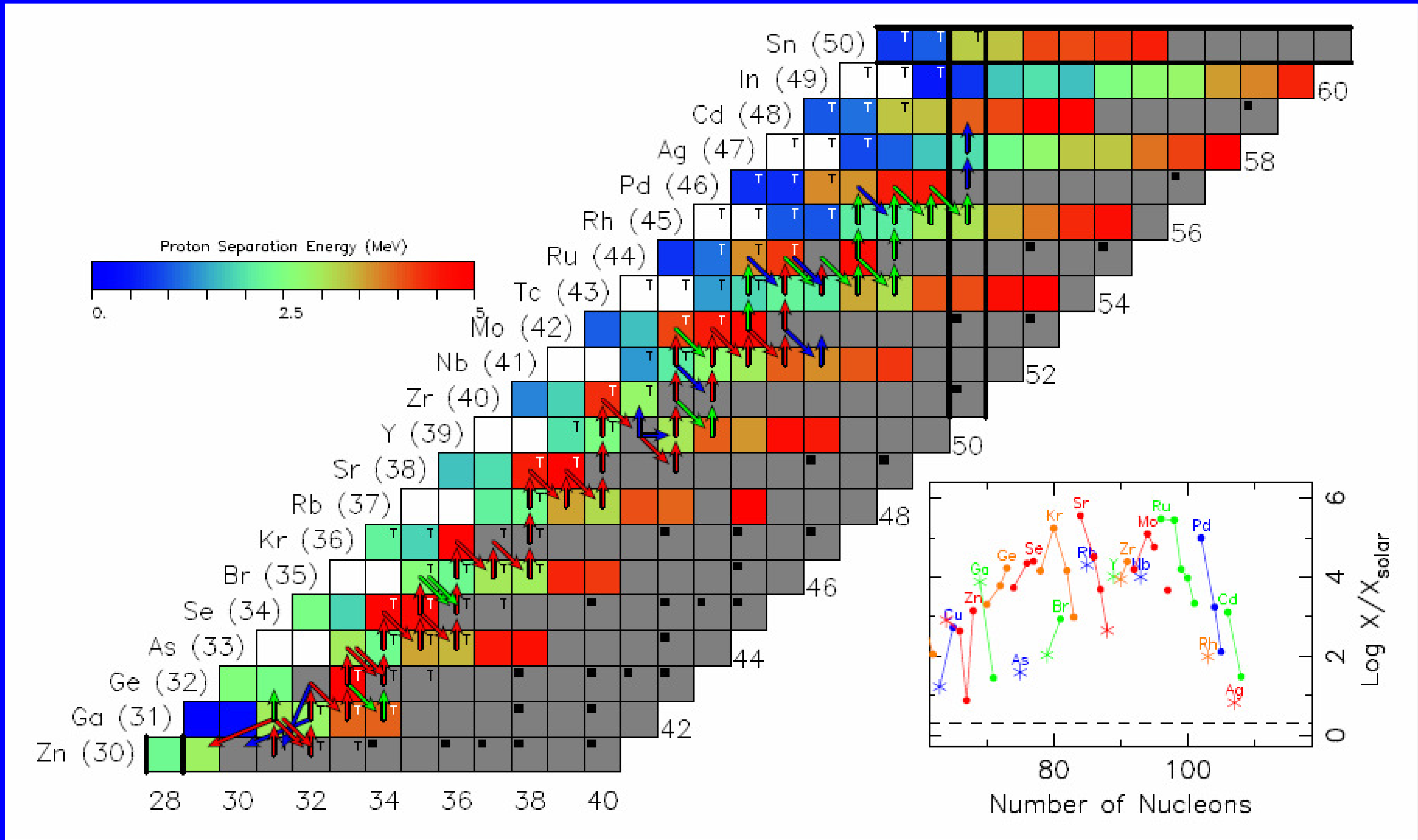
The basics of the νp-process

- proton-rich matter is ejected under the influence of neutrino interactions
- Nuclei form at distances where a substantial antineutrino flux is present
- true rp-process is limited by slow β decays, e.g. τ(64Ge) = 64 s
- $\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p; \quad {}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge}; \ldots$
  via (n,p) reactions

Phys. Rev. Lett. 96 (2006) 142502
Phys. Rev. Focus, April 21, 2006
CERN Courier 46 (2006) 7

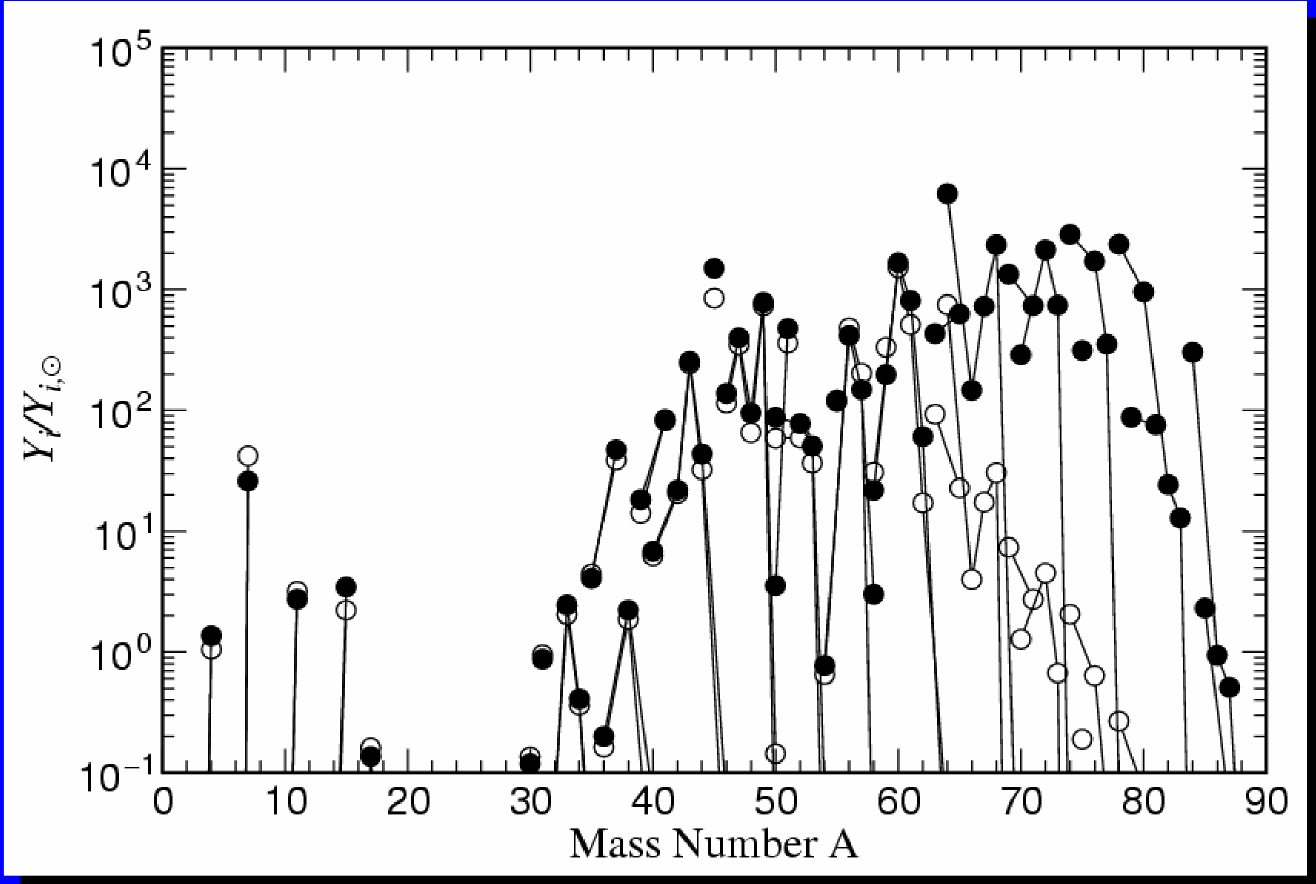
Nucleosynthesis Fluxes

Pruet *et al.*, 2006



Nucleosynthesis Results: ν-Effects

- Reduction in over-production of neutron-rich Fe, Ni
- *rp*-process pattern of elements from A=64 to 80+.
- May explain observations and GCE requirement of LEPP

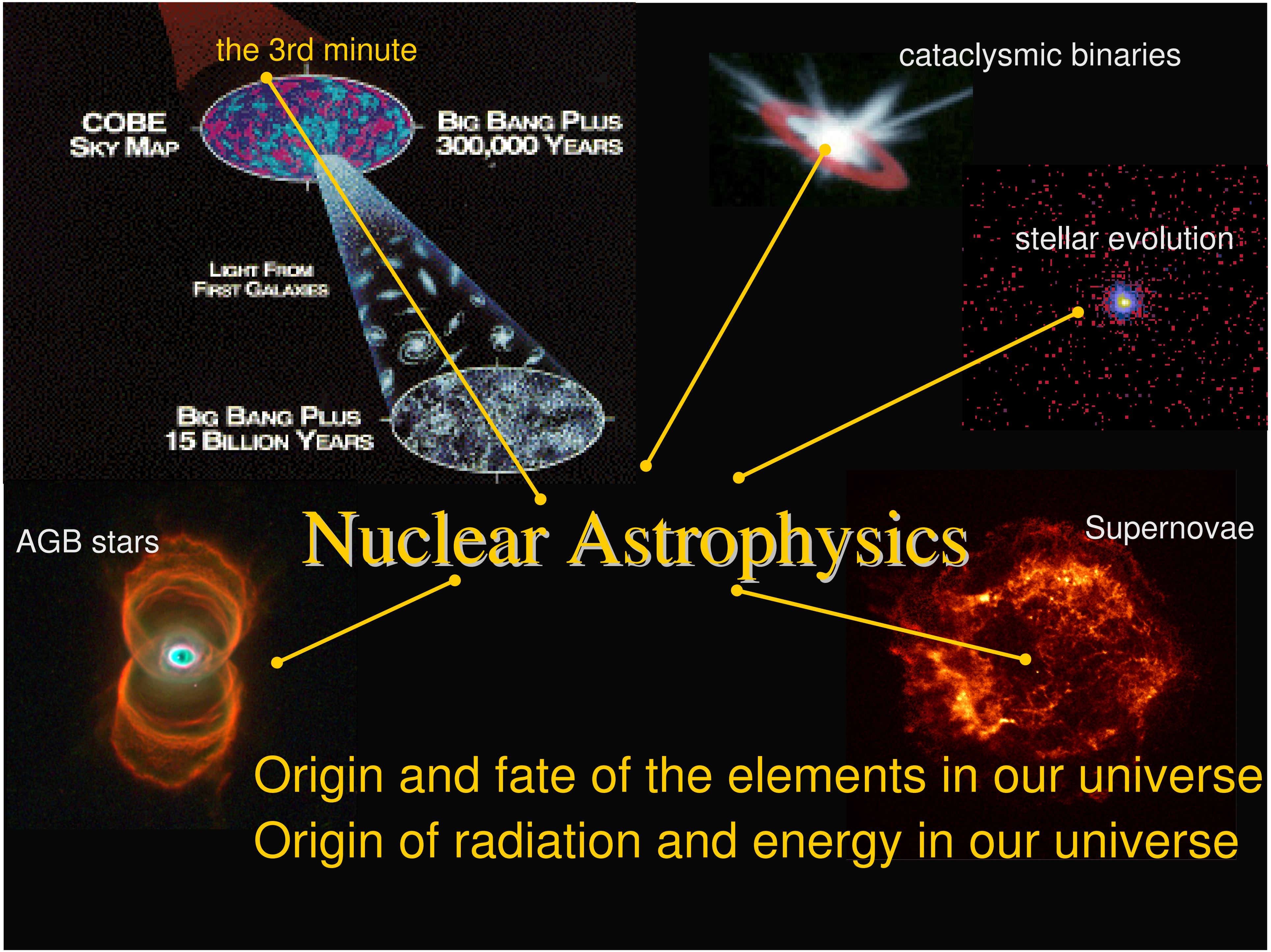


Enhancement of waiting-point nuclei:

^{64}Ge → ^{64}Zn
^{68}Se → ^{68}Zn
^{72}Kr → ^{72}Ge
^{76}Sr → ^{76}Se
^{80}Zr → ^{80}Kr
^{84}Mo → ^{84}Sr

Fröhlich *et al.*, PRL 2006 (astro-ph/0511376)

Conclusion


the 3rd minute
COBE
Sky Map
Big Bang Plus
300,000 Years
Light From
First Galaxies
Big Bang Plus
15 Billion Years
cataclysmic binaries
stellar evolution
AGB stars
Nuclear Astrophysics
Supernovae
Origin and fate of the elements in our universe
Origin of radiation and energy in our universe

Hans A. Bethe Prize 2008
(American Physical Society)

2008 Hans A. Bethe Prize Recipient

Friedrich K. Thielemann
University of Basel

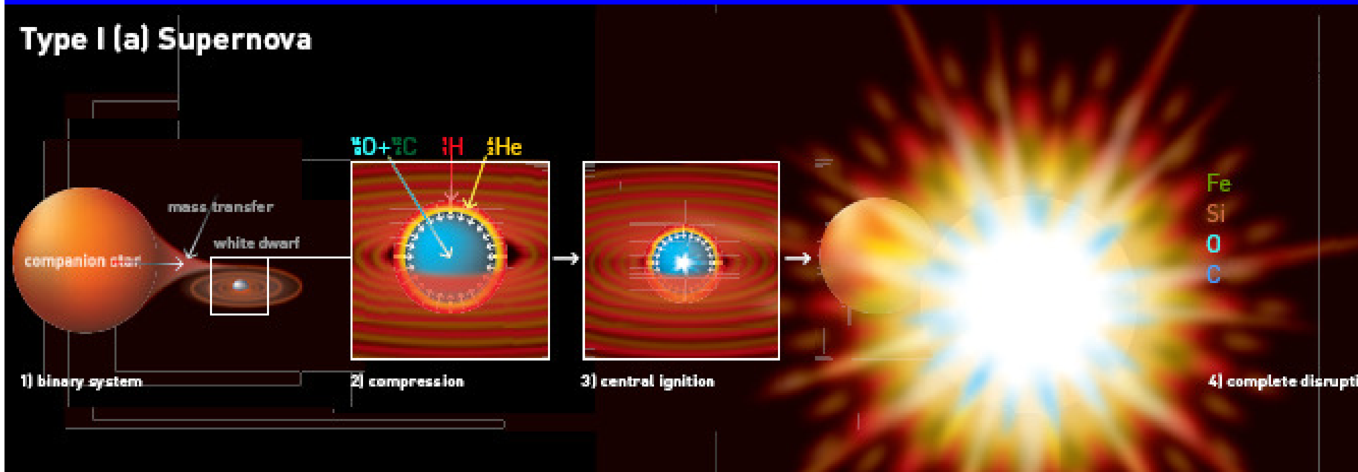
Citation:

"*For his many outstanding theoretical contributions to the understanding of nucleosynthesis, stellar evolution and stellar explosions through applications to individual objects and to cosmic chemical evolution.*"

Selection Committee:
Ronald Tribble (Chair), D. Hartmann, J.R. Wilson, R. Diehl, D. Geesaman

The End

Cataclysmic Binaries



Neutron star merger

X-ray burster