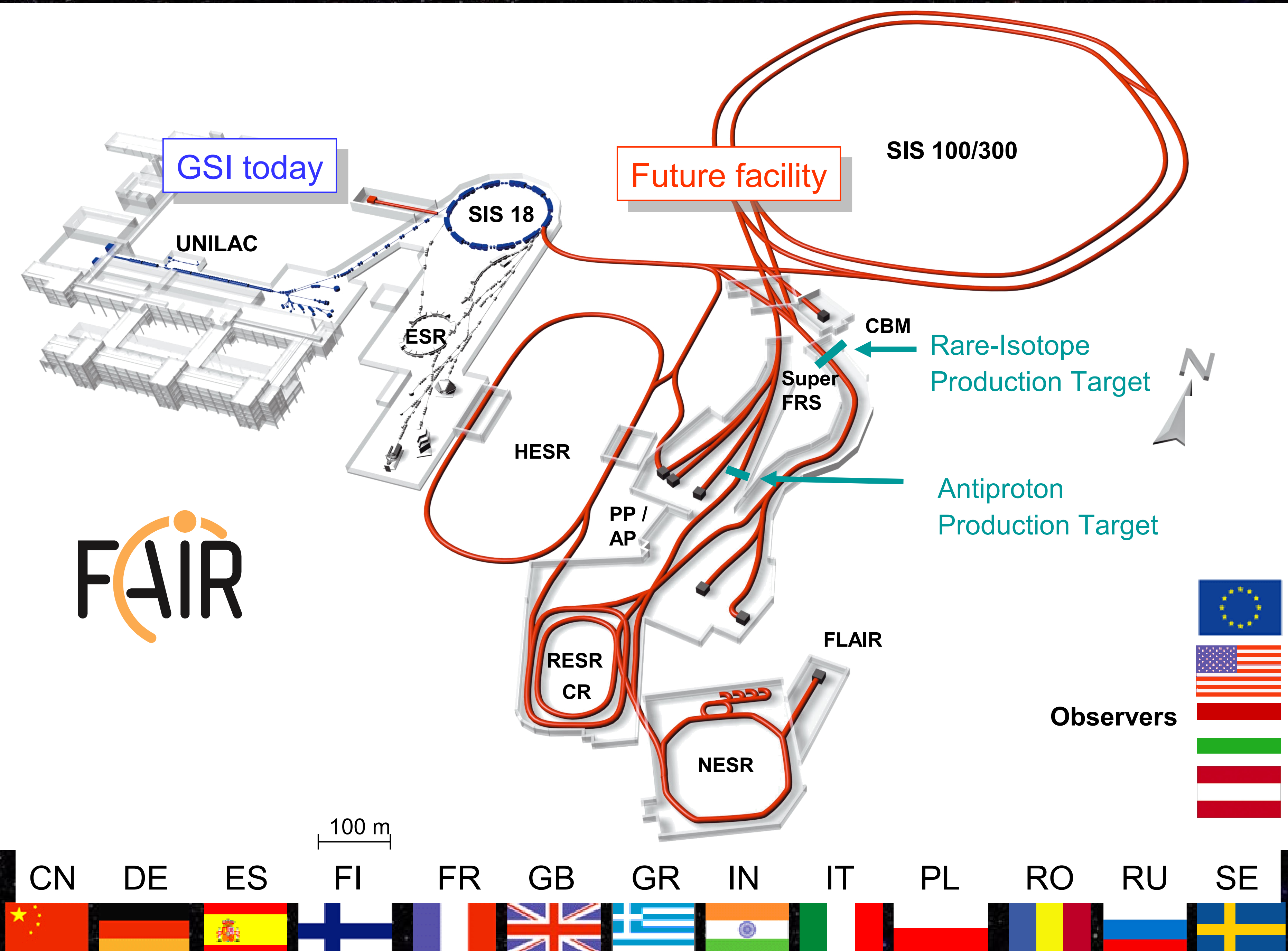
The FAIR Chance for Nuclear Astrophysics

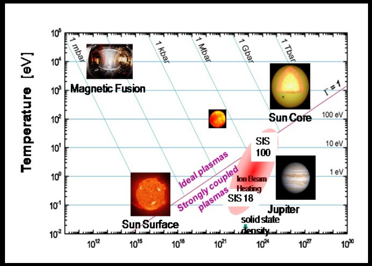
Karlheinz Langanke
GSI Helmholtzzentrum Darmstadt
TU Darmstadt
Frankfurt Institute forAdvanced Studies

Kolloquium, Heidelberg, June 26, 2012



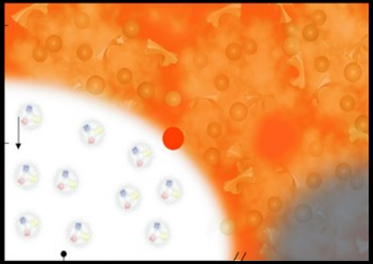
GSI today
Future facility
SIS 100/300
SIS 18
UNILAC
ESR
HESR
CBM
Rare-Isotope Production Target
Super FRS
Antiproton Production Target
PP / AP
RESR
CR
FLAIR
NESR
FAIR
Observers
100 m
CN
DE
ES
FI
FR
GB
GR
IN
IT
PL
RO
RU
SE

Experiment-Collaborations in FAIR



Atomic Physics, Plasma- & Applied physics:

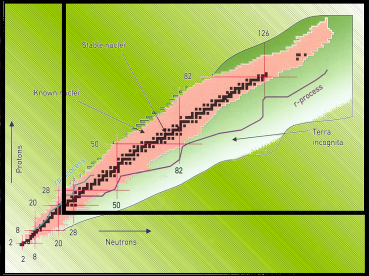
APPA



nuclear- and quark-matter:

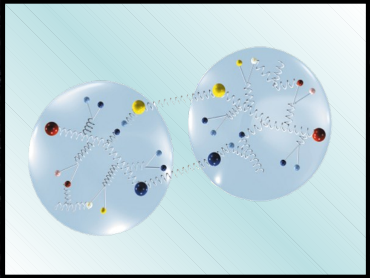
CBM

FAIR



exotic nuclei and
nucleare astrophysics:

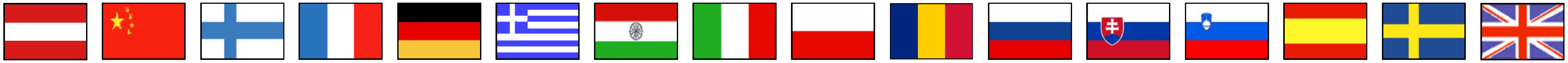
NuSTAR



structure and dynamics of hadrons:

PANDA

Google Earth: FAIR in 2020

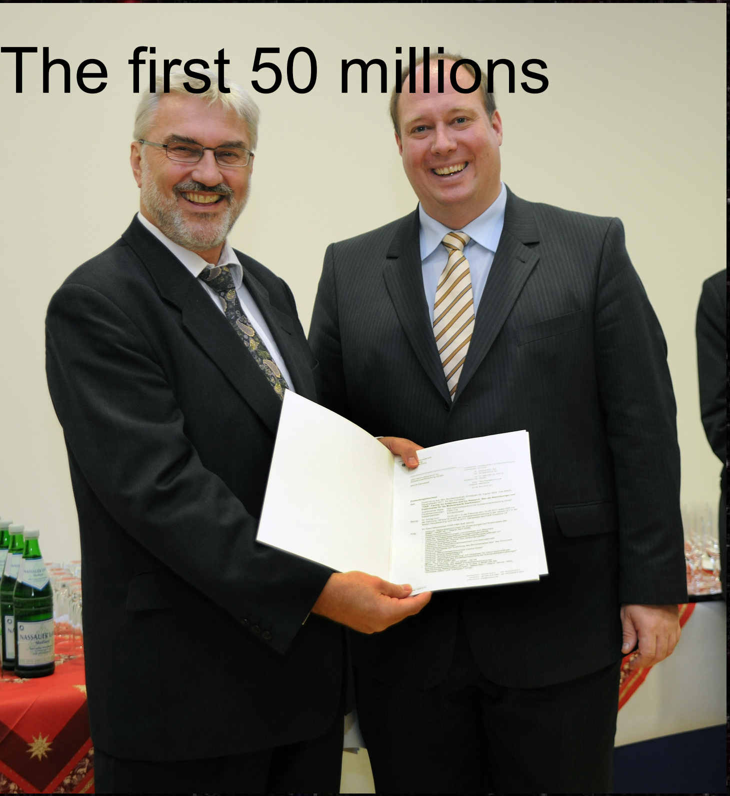


Austria China Finnland France Germany Greece India Italy Poland Romania Russia Slovakia Slovenia Spain Sweden Great Britain


PANDA
CBM
SPARC
Over 2500 scientists and technicians from more than 50 countries
NUSTAR
5

FAIR: it has started!

The first 50 millions



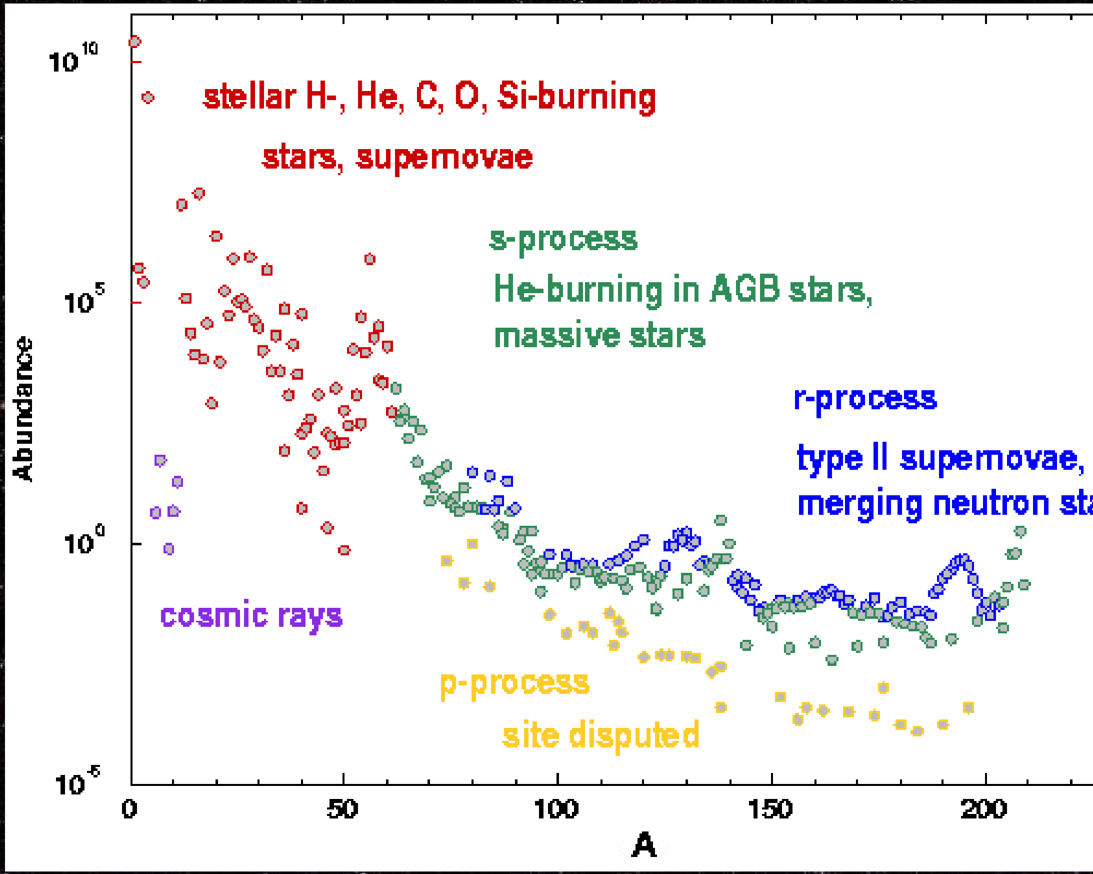
The first workers

Signatures of Nucleosynthesis

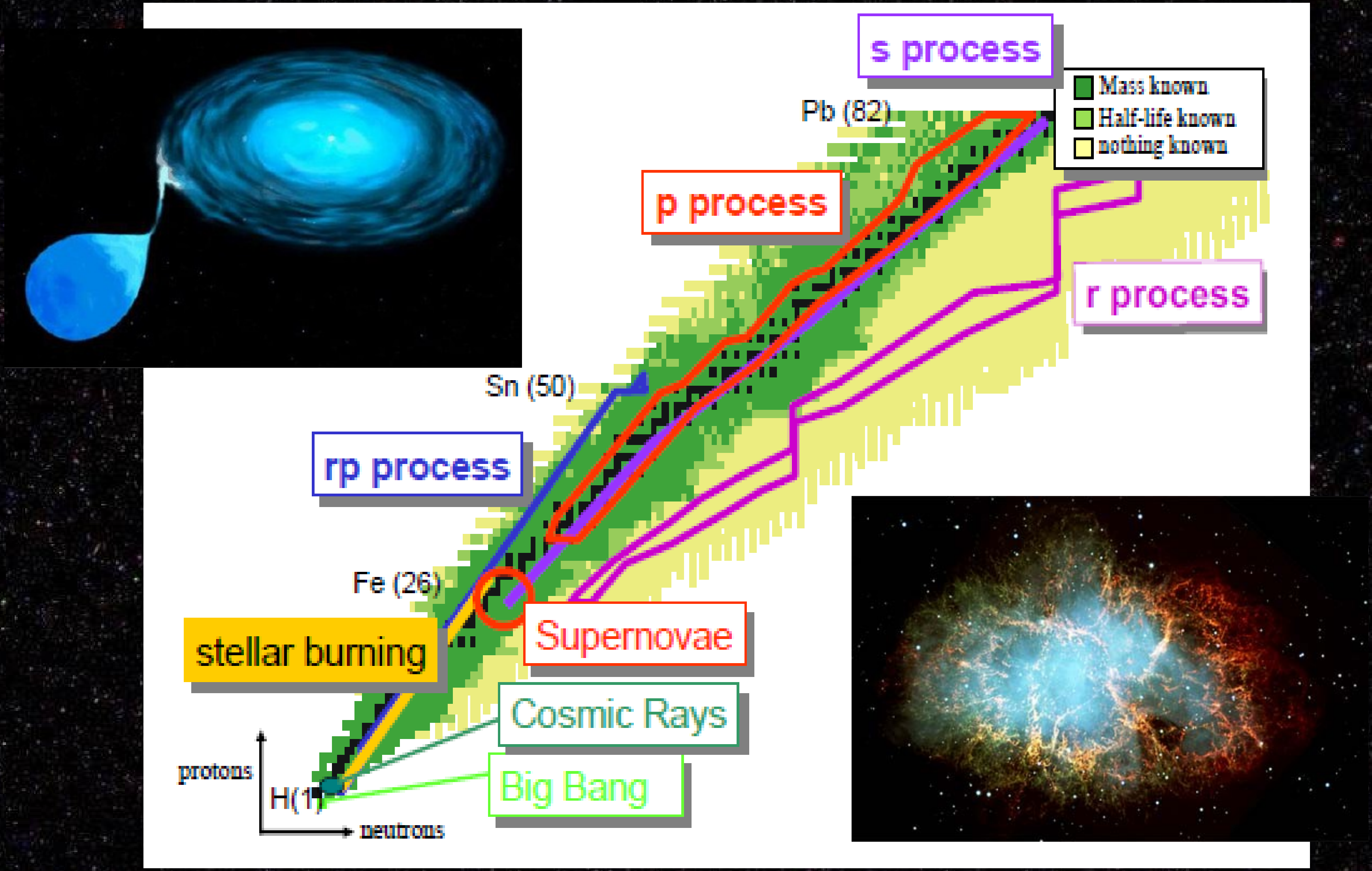
- nucleosynthesis processes
- nucleosynthesis history of our universe

The stellar abundance distribution is a reflection of nuclear structure and nuclear stability!

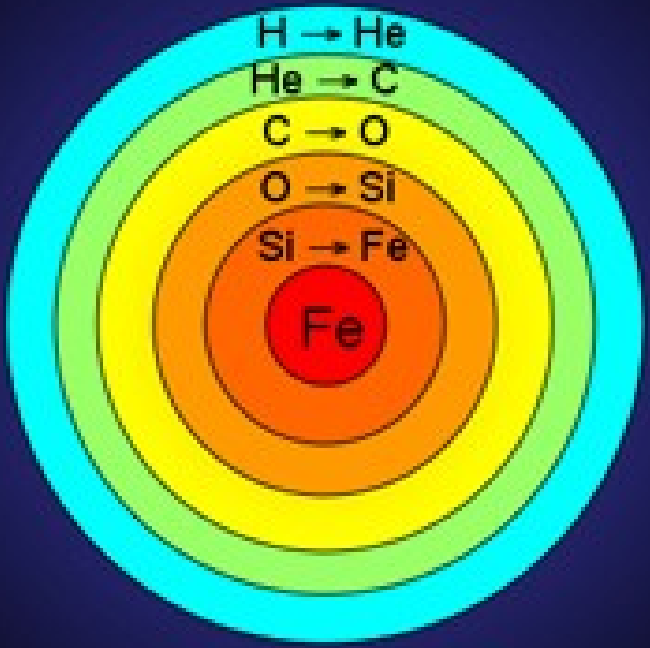
solar abundance distribution



Nucleosynthesis processes



Stellar Life



For a 25 solar mass star:

Stage	Duration
H → He	$7x10^6$ years
He → C	$7x10^5$ years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

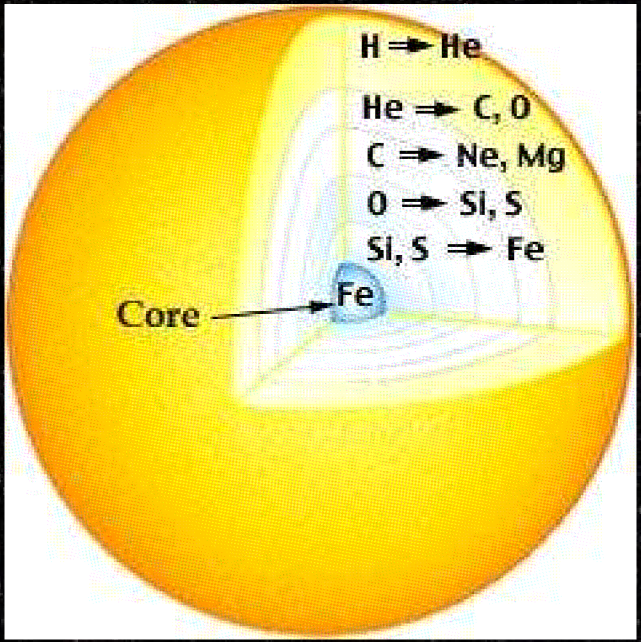
Star at the end of its life

Star has an onion-like structure

Iron is the end-product of stellar burning

After nuclear energy source has ceased, stellar core collapses under its gravity

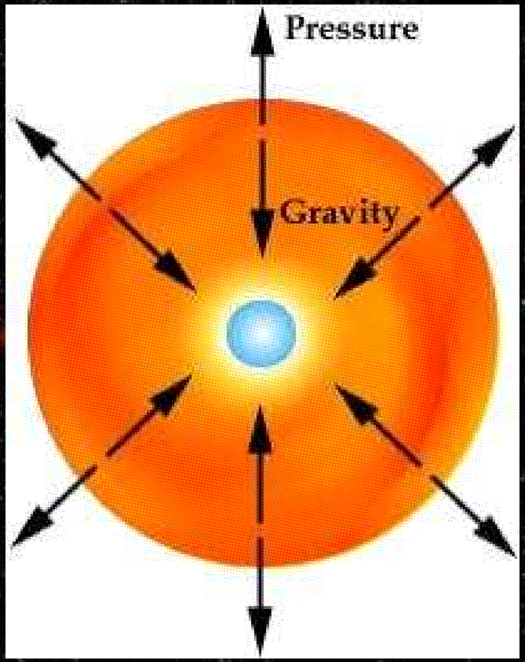
SUPERNOVA



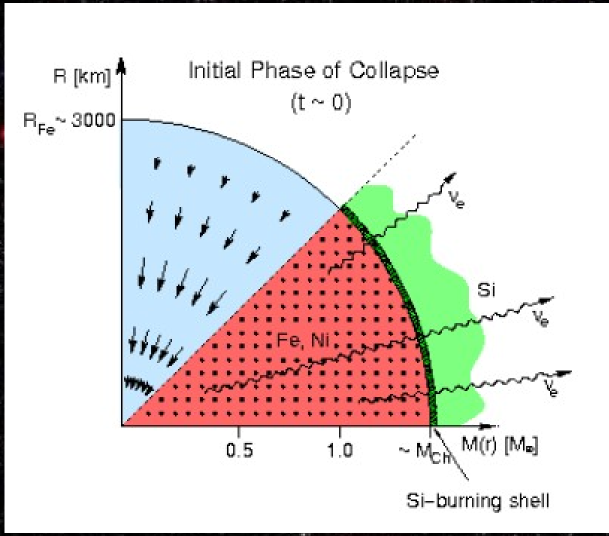
Supernova collapse and explosion

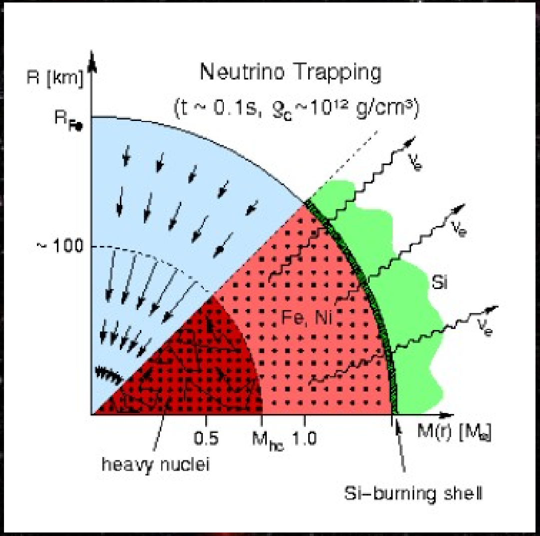
In about a second, the core radius reduces from 6000 km to 20 km

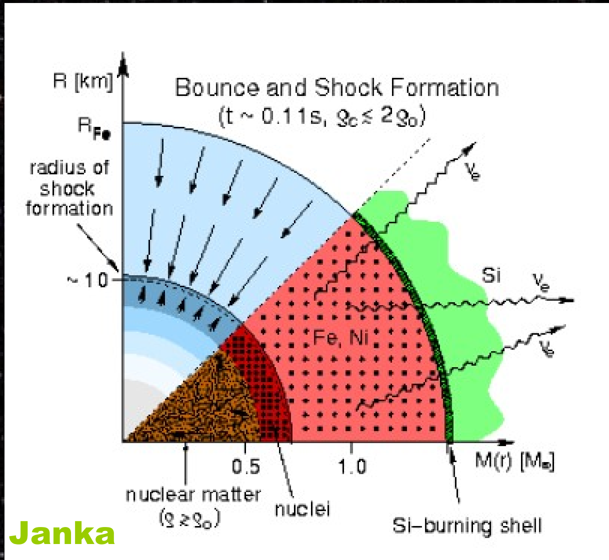
Collapse stops when the inner core corresponds to a gigantic nucleus with about half of a solar mass. Most of the gain in gravitational energy is released in the explosion. This energy corresponds to the production of 100 Suns during their entire life of 10 Billion years.



Supernova: collapse phase







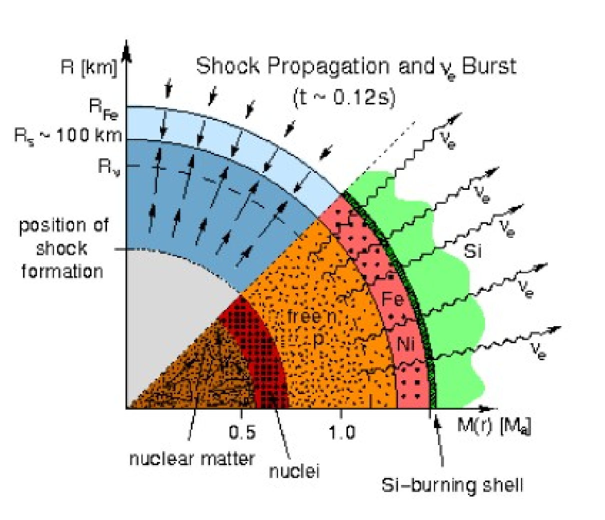
Important nuclear input:

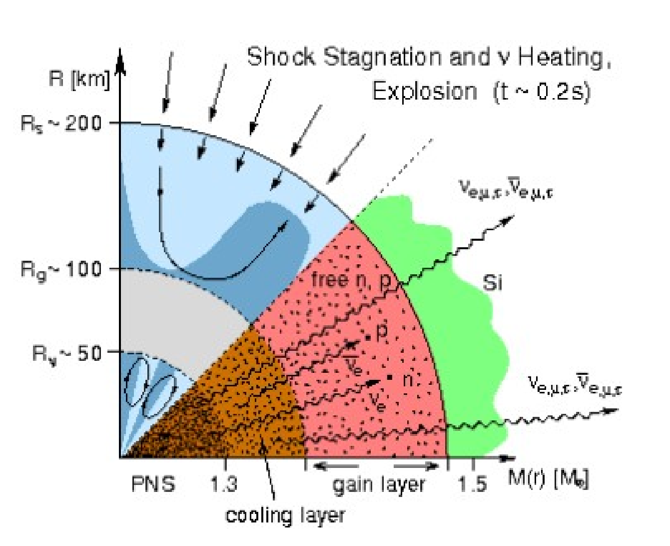
Electron capture on nuclei

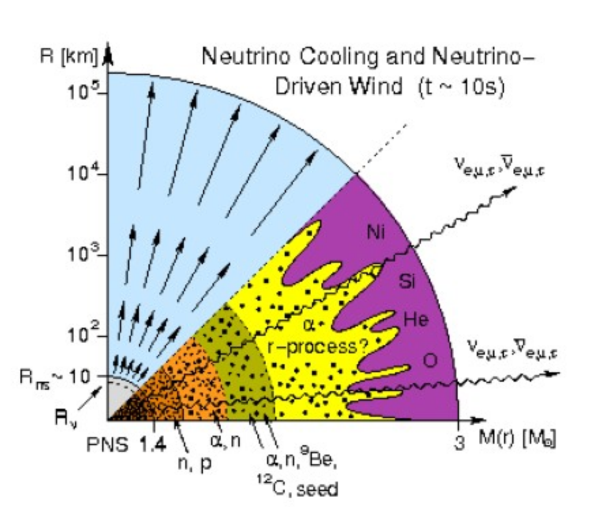
Neutrino-nucleus reactions

H.-Th. Janka

Supernova: explosion





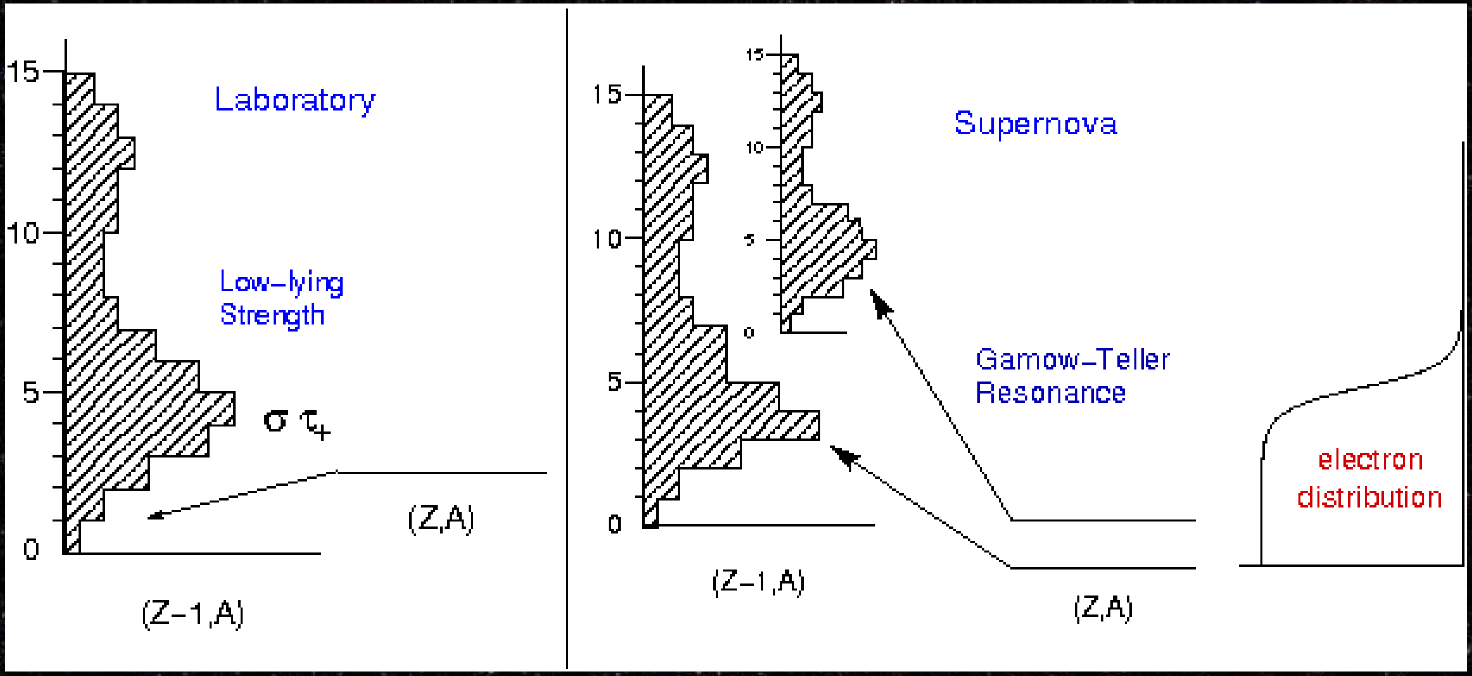


Important nuclear input

Equation of state

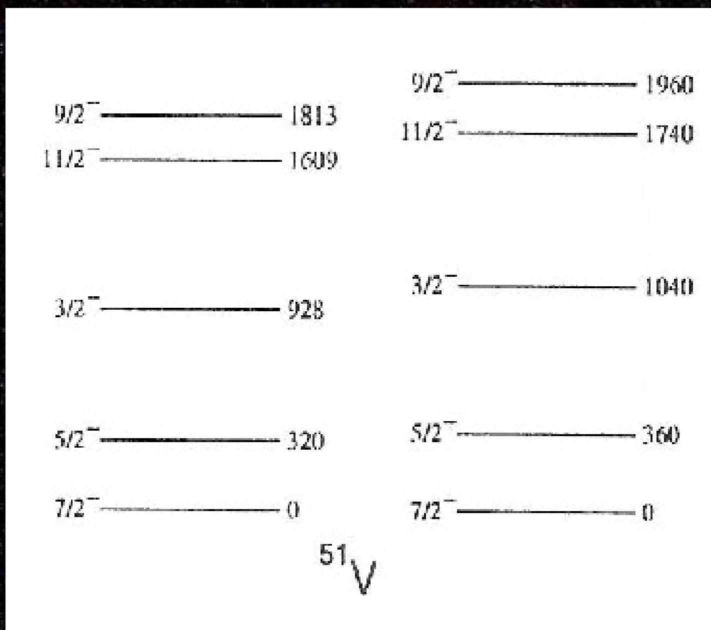
Neutrino processes

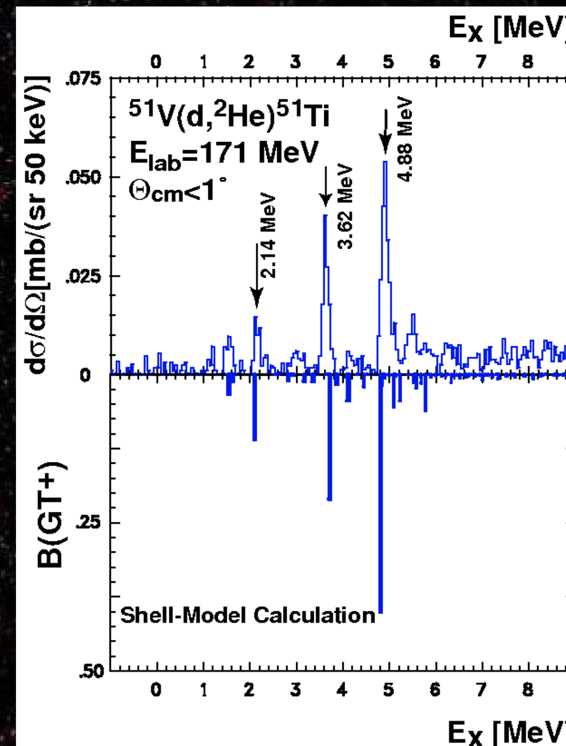
Electron capture: Lab vs Stars



Capture is dominated by Gamow-Teller transitions
During collapse, electrons are described by Fermi-Dirac distribution with chemical potentials of order a few MeV
Parent nuclei are described by thermal ensemble

Calculating stellar capture rates





data KVI Groningen

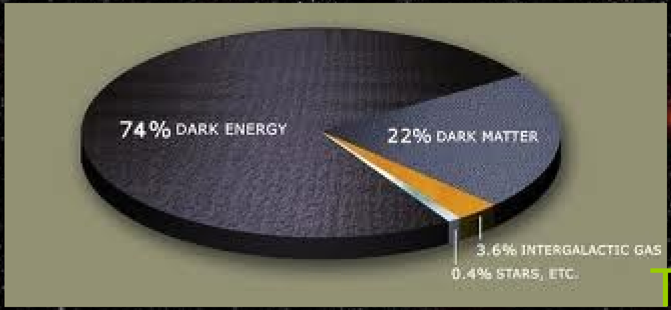
Capture on nuclei in mass range A~45-65 calculated by large-scale shell model

Capture rates are noticeably smaller than assumed before!

Digression: Type Ia supernovae

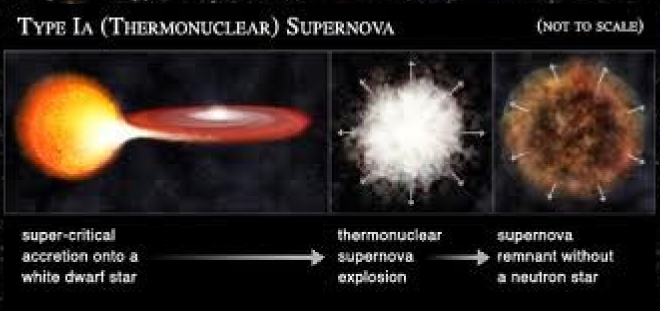

Schmidt vs Perlmutter

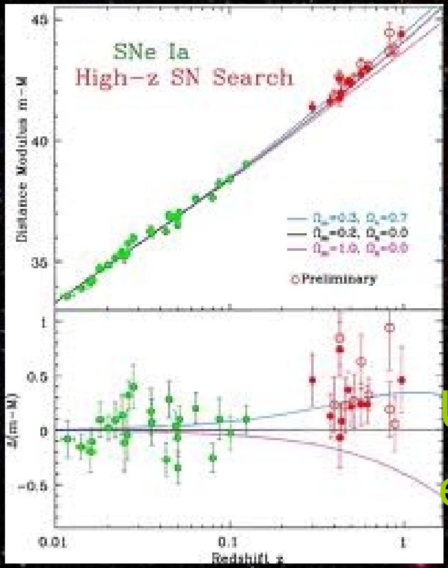

Riess



Content of universe:

Type Ia standard candle

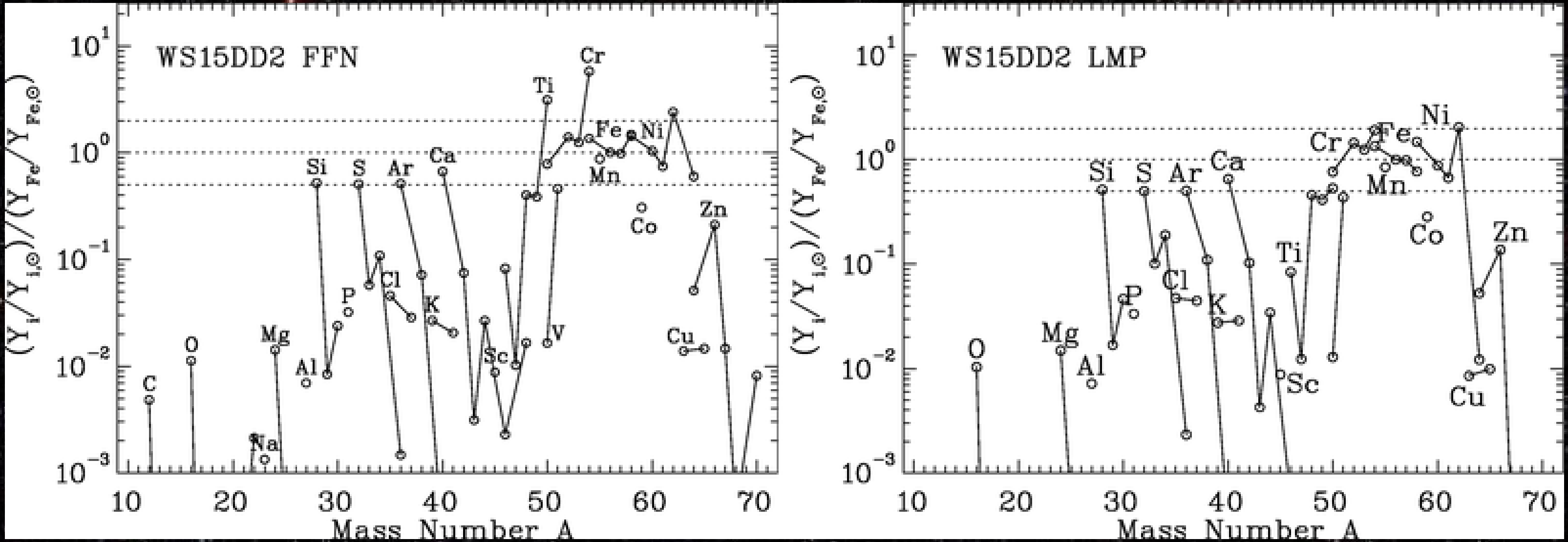




Universe expands!

Abundances in Type Ia‘s

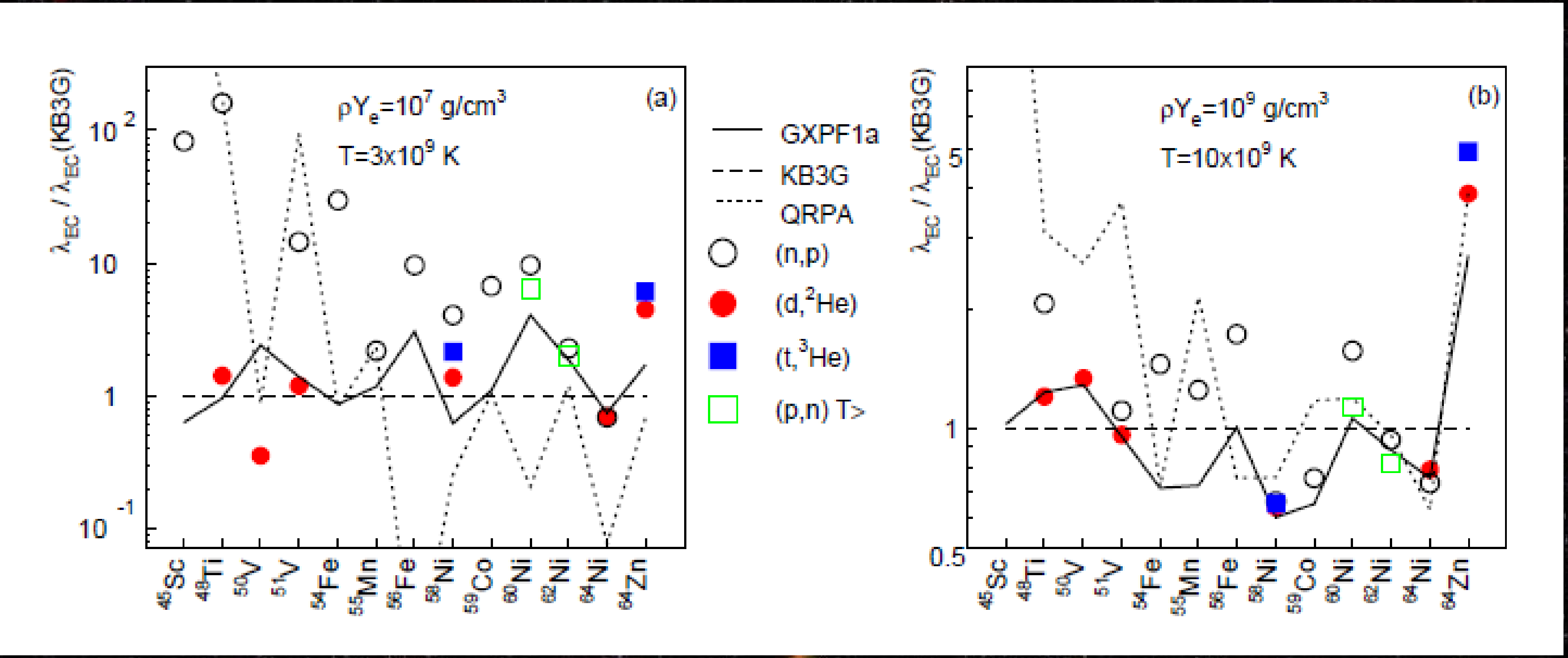
- Type Ia‘s have produced about half of the abundance of nickel-iron range nuclei in the Universe



Modern electron capture rates solve inconstency problem in Type Ia supernova abundance production

Experiment vs shell model

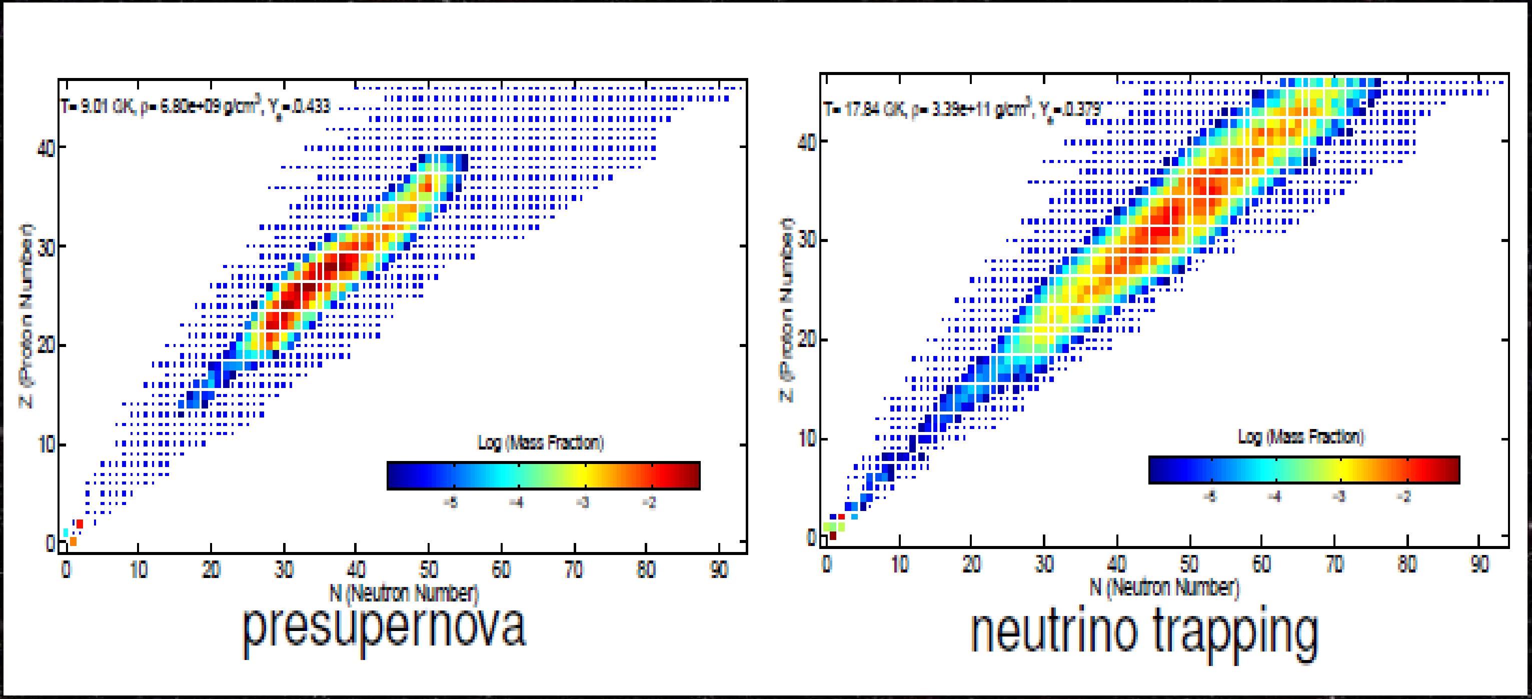
Cole, Zegers et al., PRC, in print



Iron-nickel mass range under control

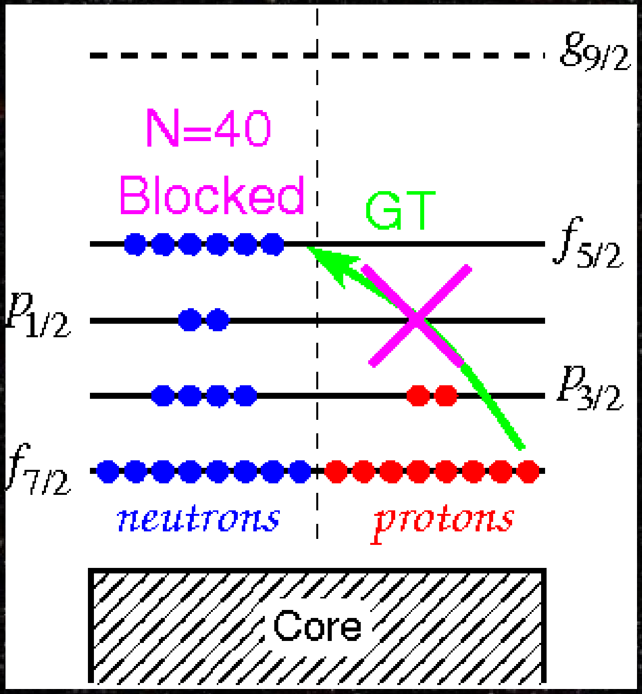
With increasing density, less sensitivity to details of GT distribution -> models less sophisticated than shell model suffice, e.g. QRPA

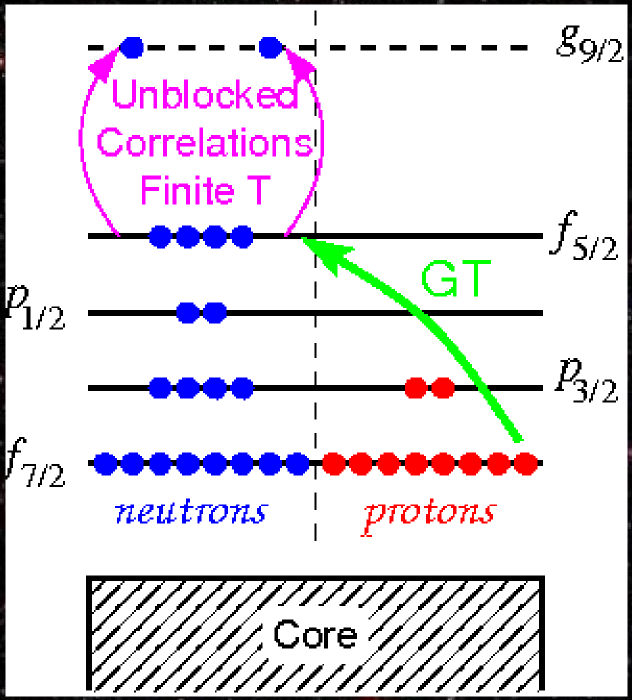
Abundance distribution during collapse



Electron captures drive nuclear composition towards neutron-rich unstable nuclei

Unblocking GT for nuclei with neutron numbers N>40

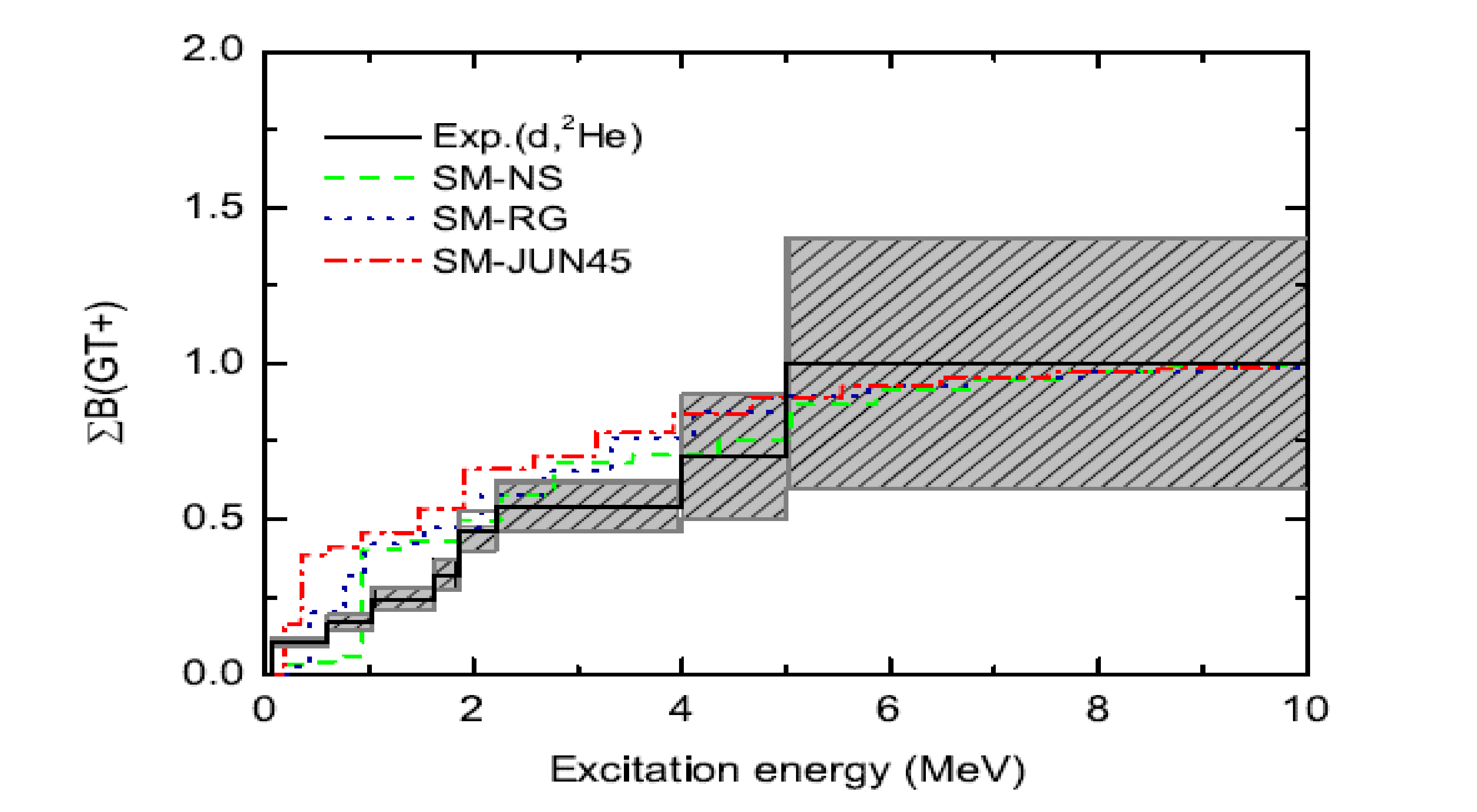




In Independent Particle Model, GT are Pauli-blocked for N>40
In reality, blocking does not occur due to correlations and finite T.
Calculations of rates by SMMC/RPA model.

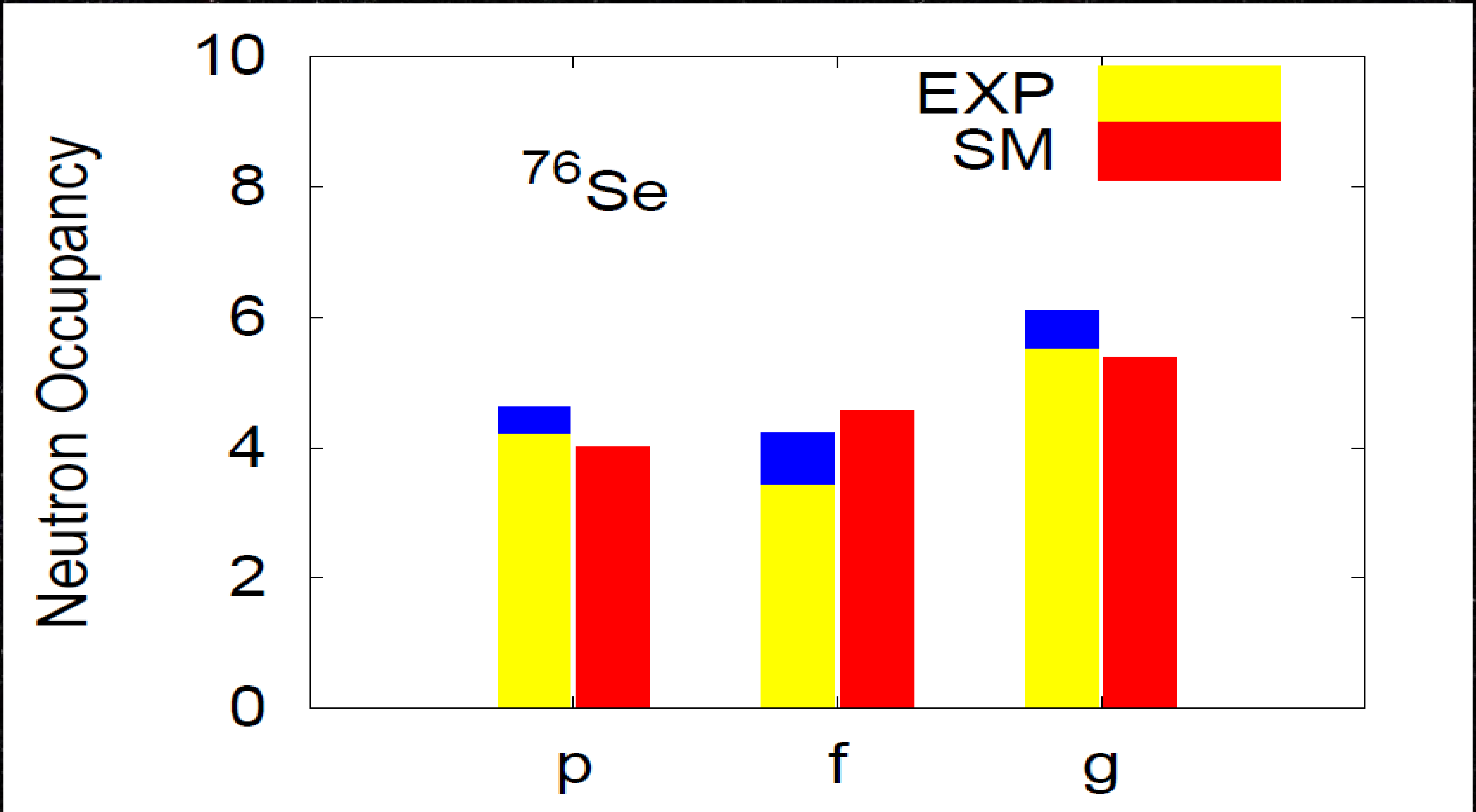
B(GT) strengths for 76Se

34 protons, 42 neutrons



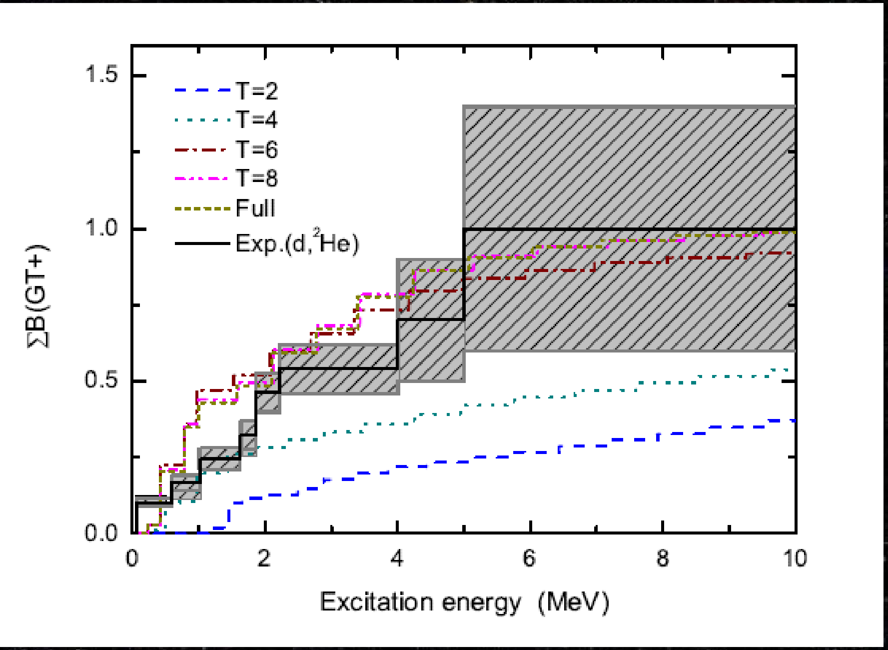
Zhi, Martinez-Pinedo, Sieja, Nowacki

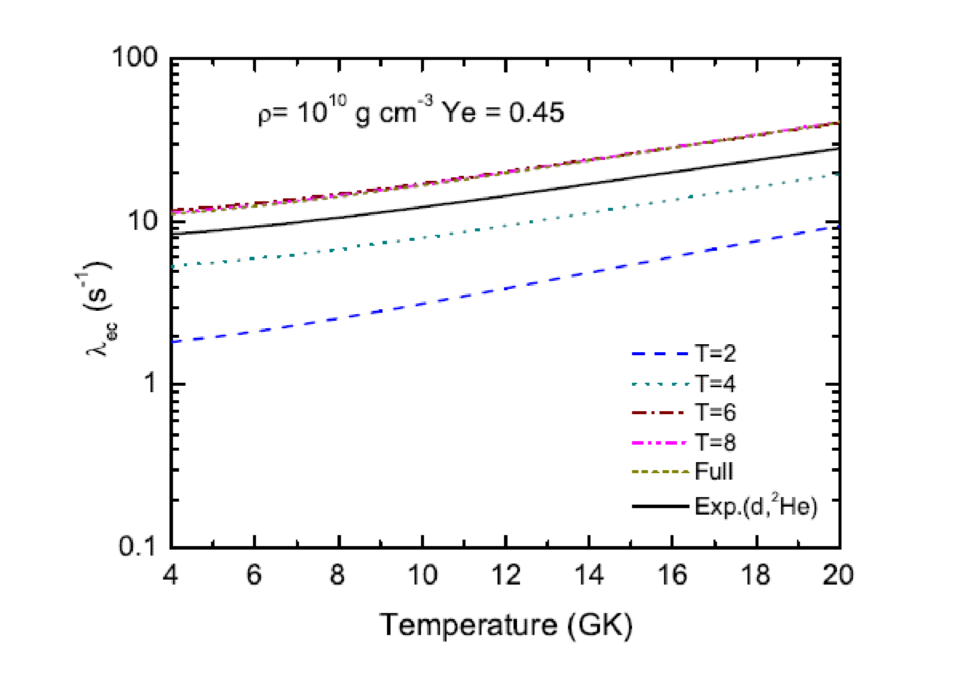
Neutron occupancies



Data from transfer reactions: J.P Schiffer and collaborators

Convergence with truncation level

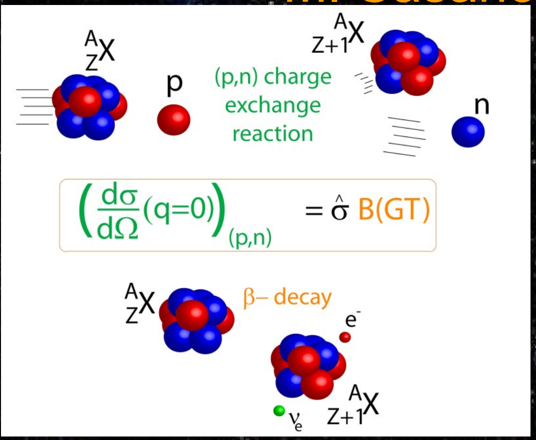




Cross-shell correlations converge slowly. Hence, models like thermofield dynamics model or finite temperature QRPA, which consider only 2p-2h correlations, do not suffice.

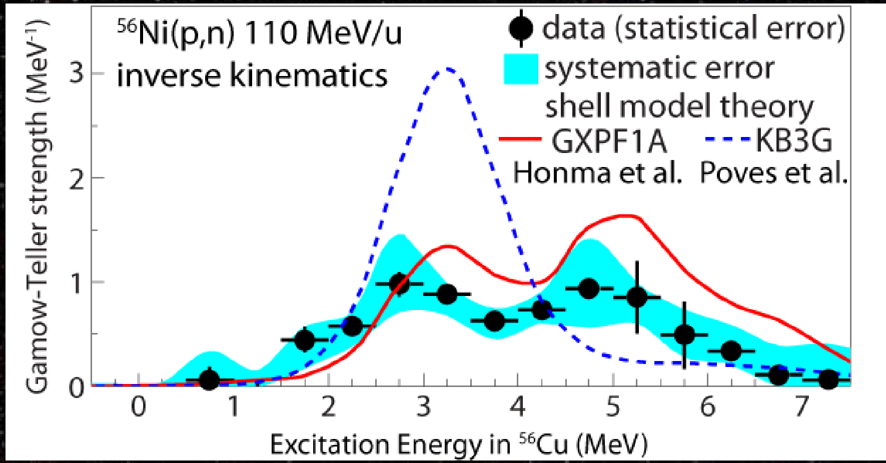
(p,n) charge-exchange reactions on rare isotopes

M. Sasano, R.G.T. Zegers et al. PRL 107, 202501 (2011)

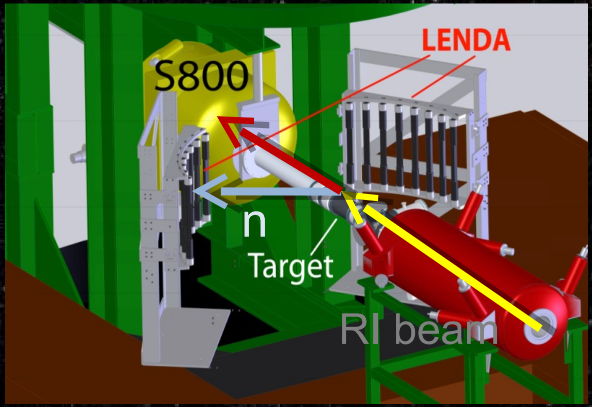


Extract Gamow-Teller strengths model-independently

- Weak reaction rates for late stellar evolution (supernovae)



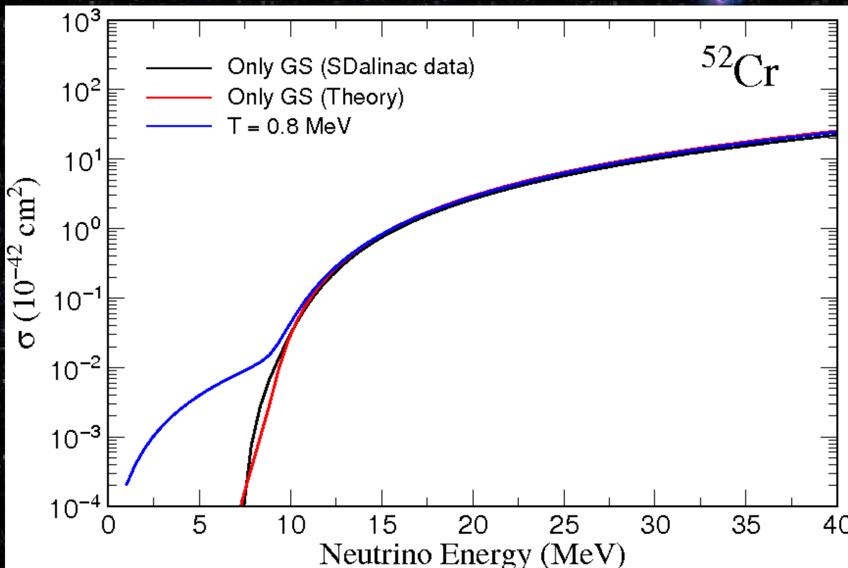
First successful experiment: ^{56}Ni(p,n) to extract Gamow-Teller strengths for supernova unstable isotope



New method for (p,n) in inverse kinematics: applicable to exotic nuclei of any mass and excitation energy.

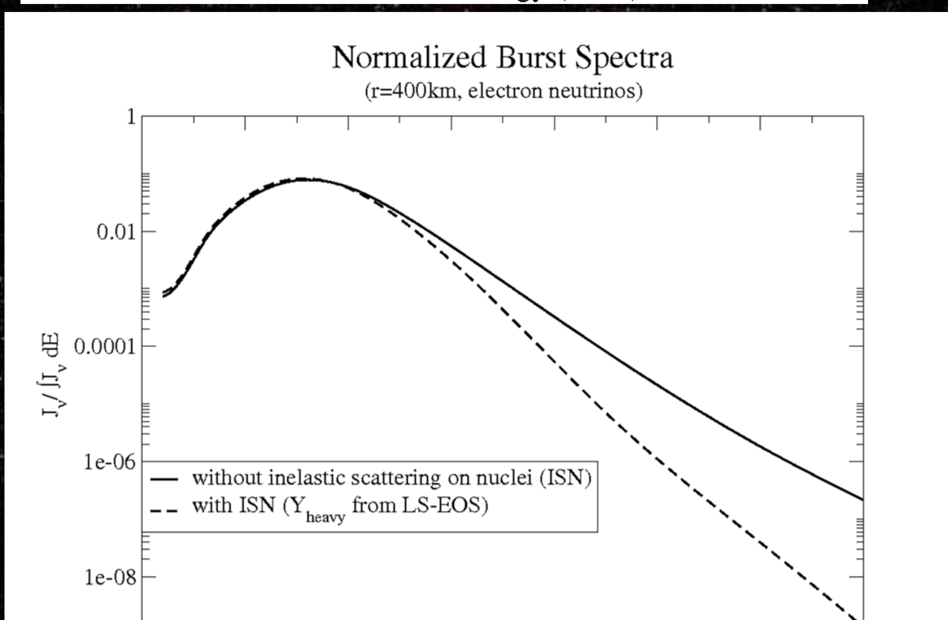
- Inverse kinematics
- Requires beam intensities >10^4 pps
- Explore very neutron rich nuclei in next generation RI beam facilities like FRIB@MSU

Inelastic neutrino-nucleus scattering



validation of nu-nucleus cross sections from precision (e,e') M1 data

Martinez-Pinedo, Richter, Neumann-Cosel



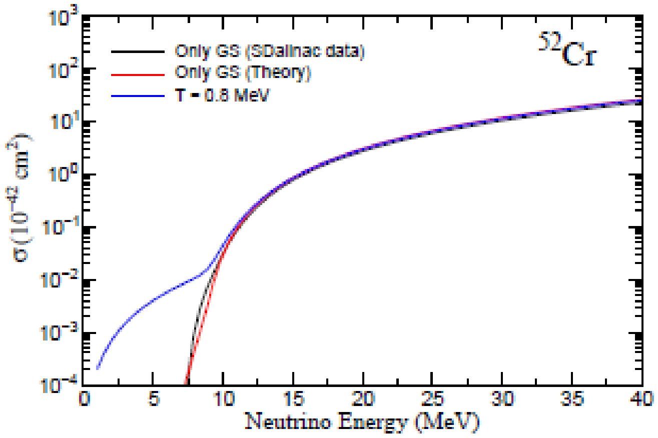
neutrino scattering on nuclei acts as additional obstacle – in particular for high-energy neutrinos
supernova neutrino spectrum shifts to lower energies
smaller event rates for earthbound supernova neutrino detectors

Janka, Hix, Martinez-Pinedo, Juogadalvis, Sampaio

Inelastic neutrino-nucleus scattering

Potential consequences:

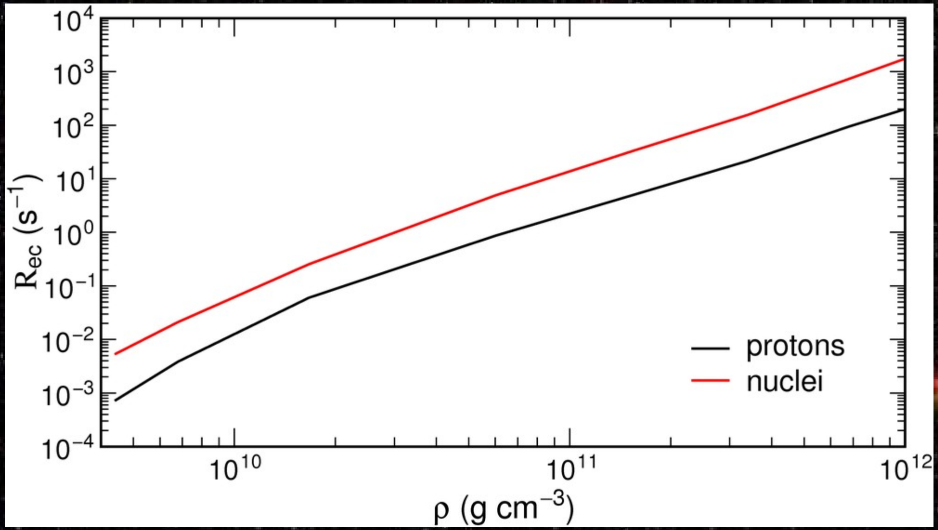
- thermalization of neutrinos during collapse
- preheating of matter before passing of shock
- nucleosynthesis, νp-process
- supernova neutrino signal

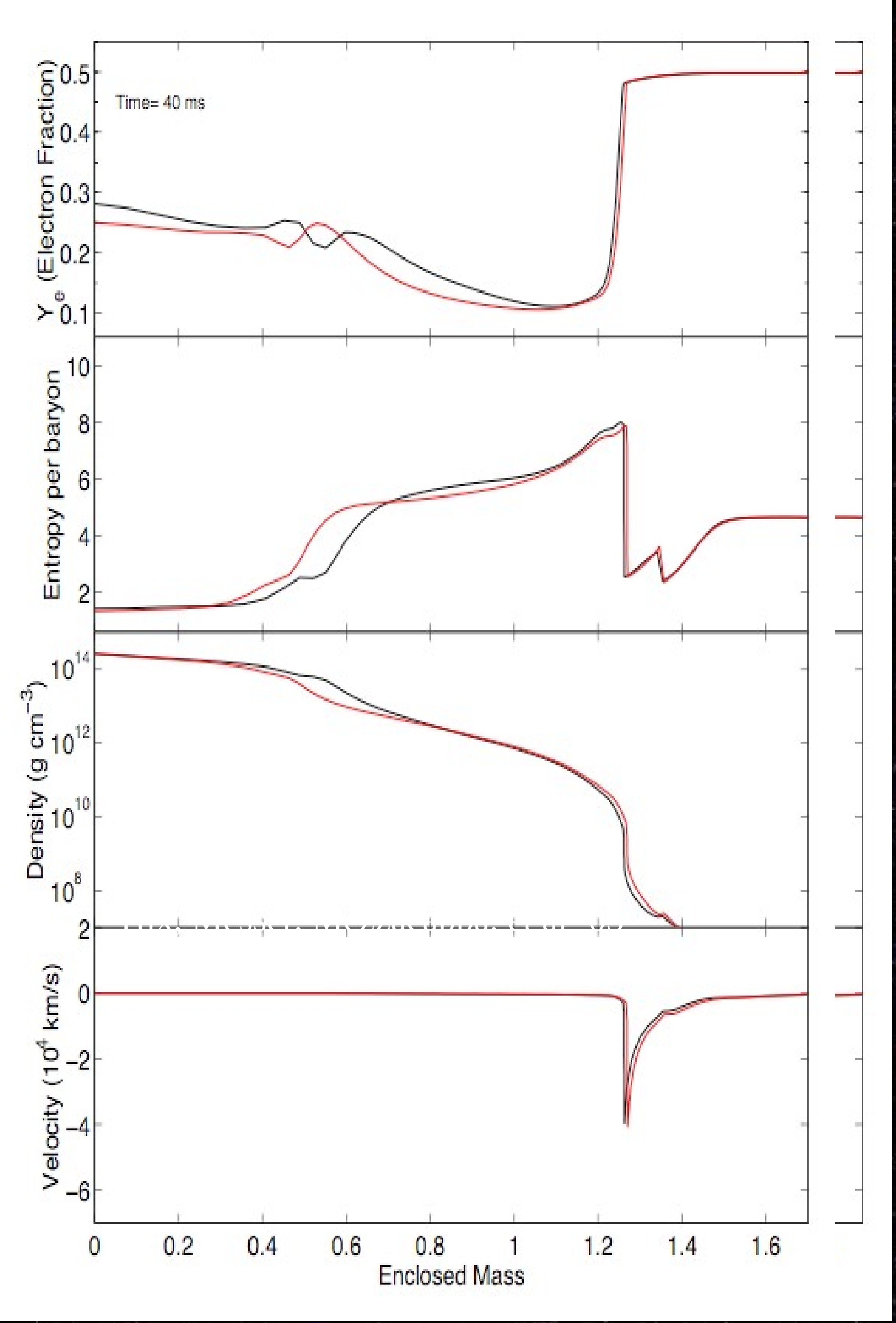


- neutrino cross sections from (e, e') data
- validation of shell model
- G.Martinez-Pinedo, P. v. Neumann-Cosel, A. Richter

Effects of Nuclear Elec Core Collapse

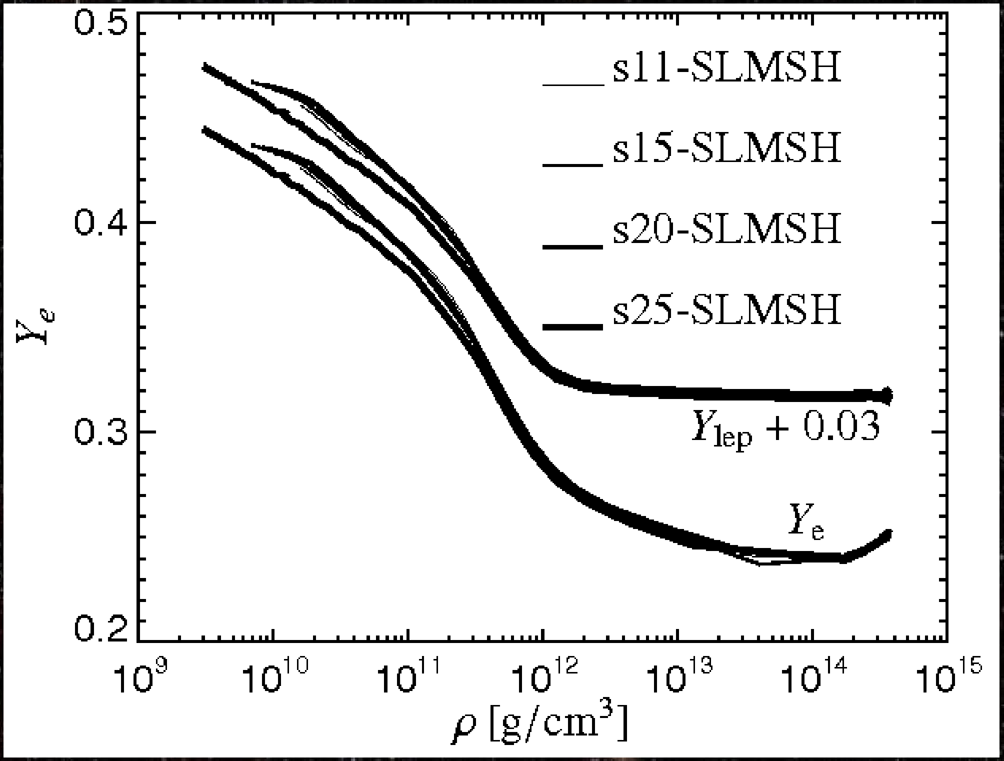
The electron capture at high densities results in lower Y_e and generates neutrino wind which is necessary for driving the shock.





Electron captures on nuclei dominate

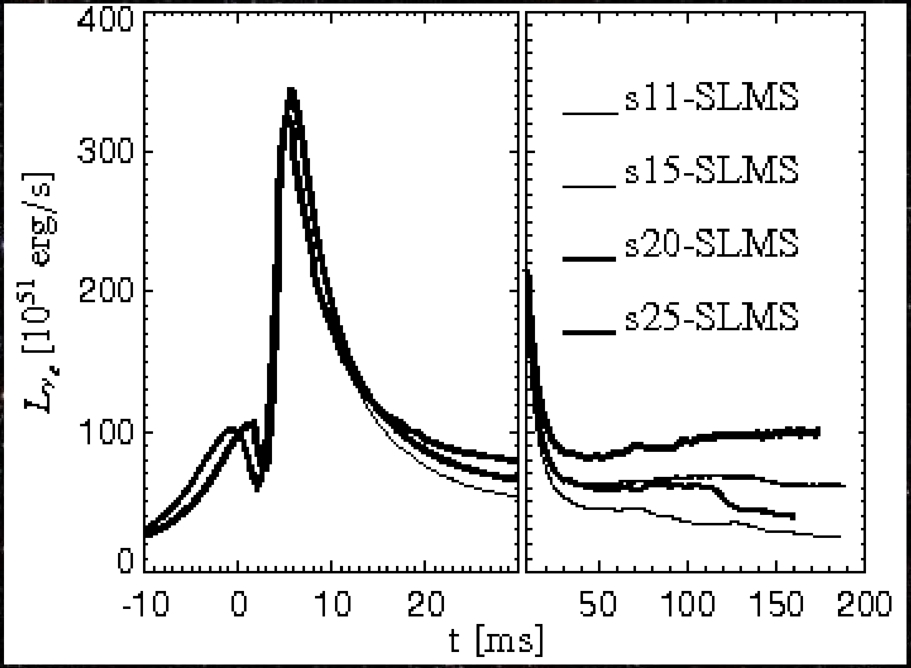
Collapse trajectories



Trajectories during final collapse are similar for different masses

A. Marek, H.-Th. Janka, G. Martinez-Pinedo

Neutrino signal after burst

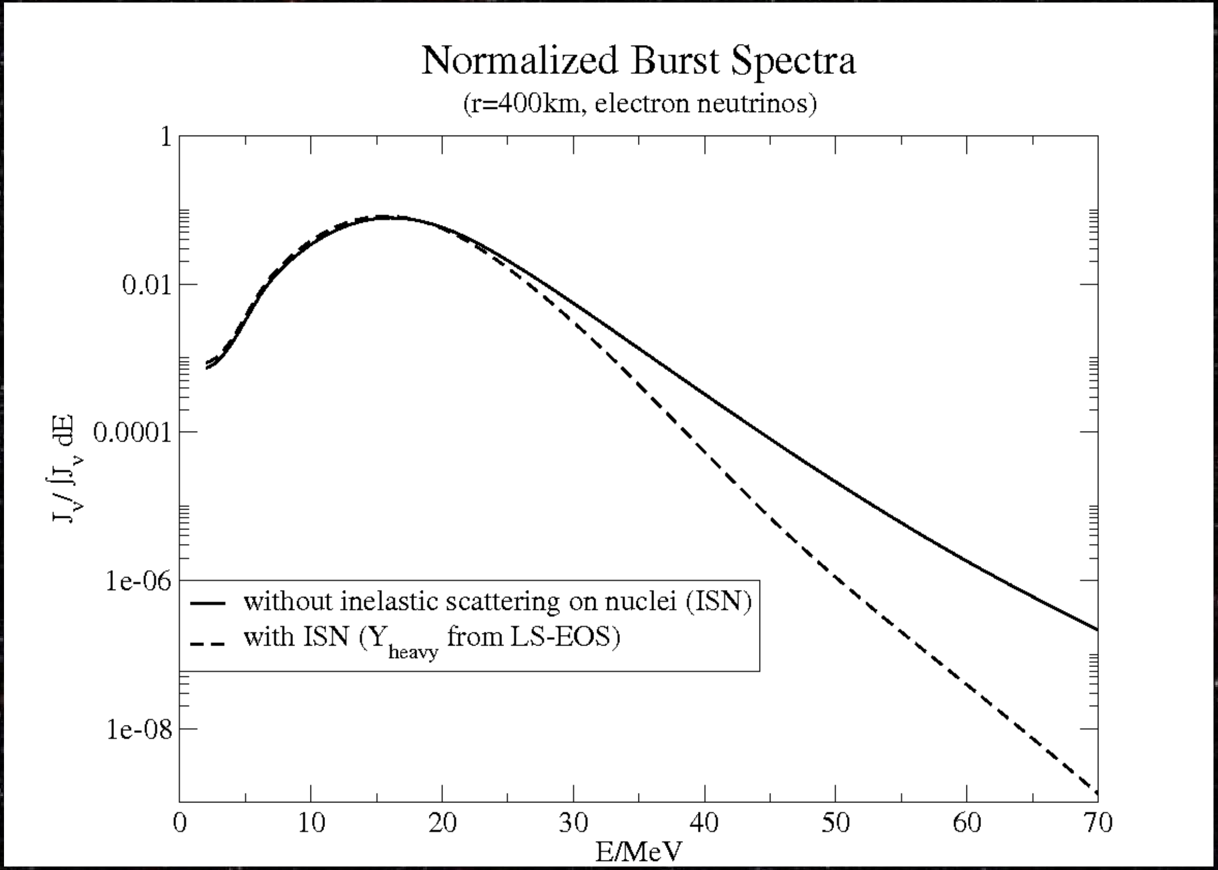


shock wave dissociates matter into free protons and neutrons
electron capture on protons gives strong neutrino signal
is this a 'standard candle'?

A. Marek, H.-Th. Janka, G. Martinez-Pinedo

Supernova neutrino signal

Inelastic neutrino-nucleus scattering adds to the opacity of high-energy neutrinos



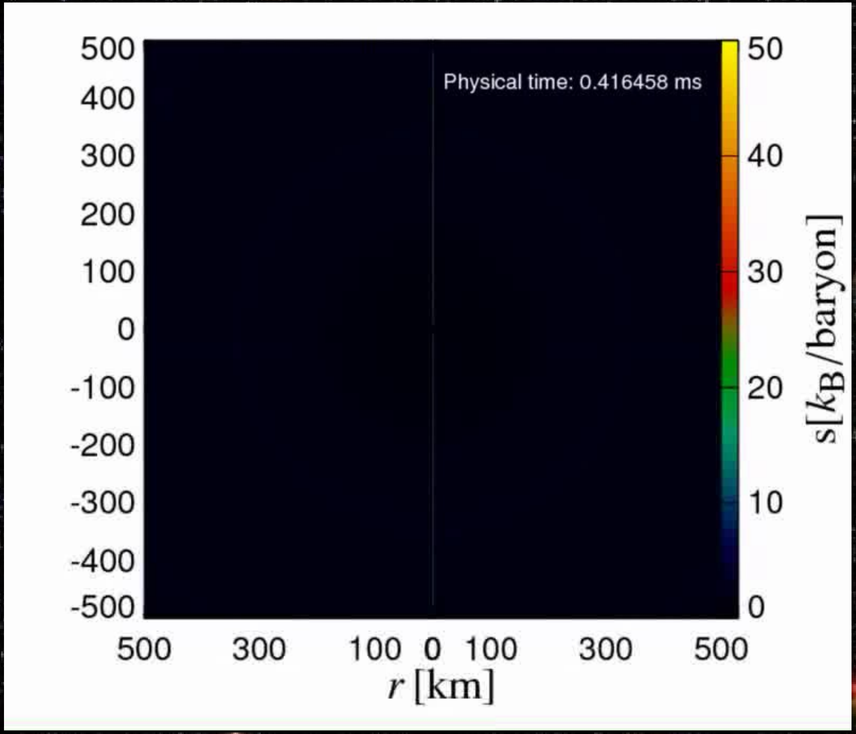
Hix, Janka, Juodagalvis, Martinez-Pinedo, Müller, Sampaio

Consequences for supernova detectors

Detector	Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With $A(\nu,\nu')A^*$	Without $A(\nu,\nu')A^*$	Change
SNO	d	5.92	7.08	16%
MiniBoone	^{12}C	0.098	0.17	43%
	^{12}C (N_{gs})	0.089	0.15	41%
S-Kamiokande	^{16}O	0.013	0.031	58%
Icarus	^{40}Ar	17.1	21.5	20%
Minos	^{56}Fe	8.8	12.0	27%
OMNIS	^{208}Pb	147.2	201.2	27%

Change in supernova neutrino spectra reduces neutrino detection rates

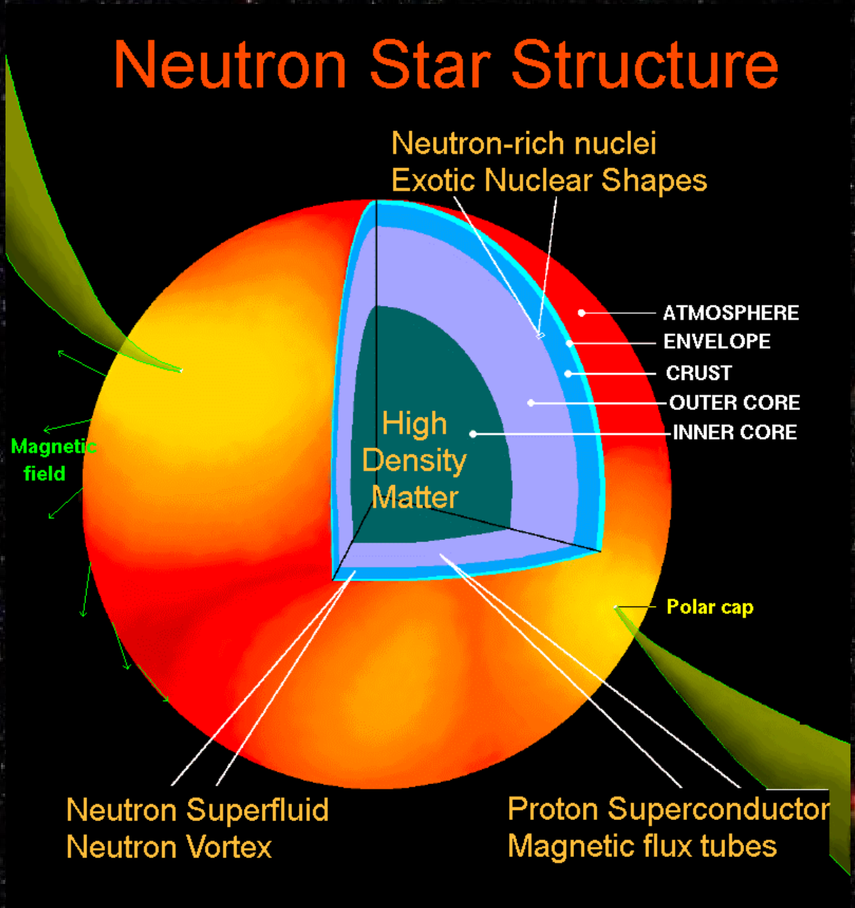
Supernova Simulation



- Recent progress:
- Multi-dimensional hydrodynamics
- Improved nuclear input
  - Electron capture
  - Neutrino-induced reactions

Courtesy: Hans-Thomas Janka

Neutron Stars: supernova remnants

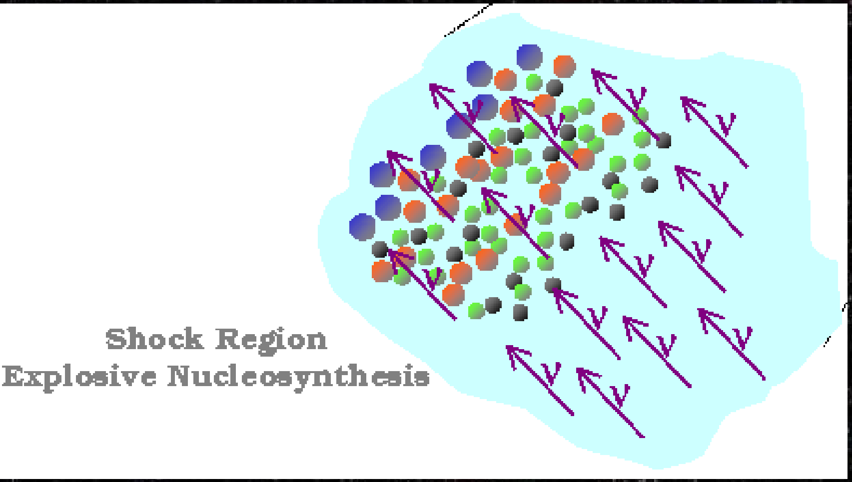


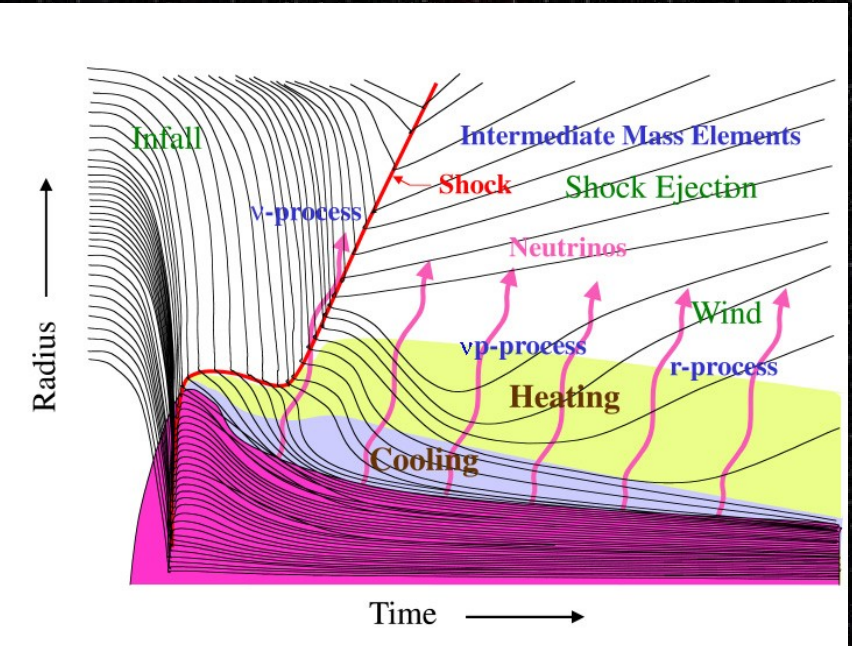
Courtesy: D. Paige

- Neutron Stars are laboratories for matter at extreme densities

- Neutron rich nuclei
- Equation of State for nuclear matter
- Exotic phases?

Explosive Nucleosynthesis

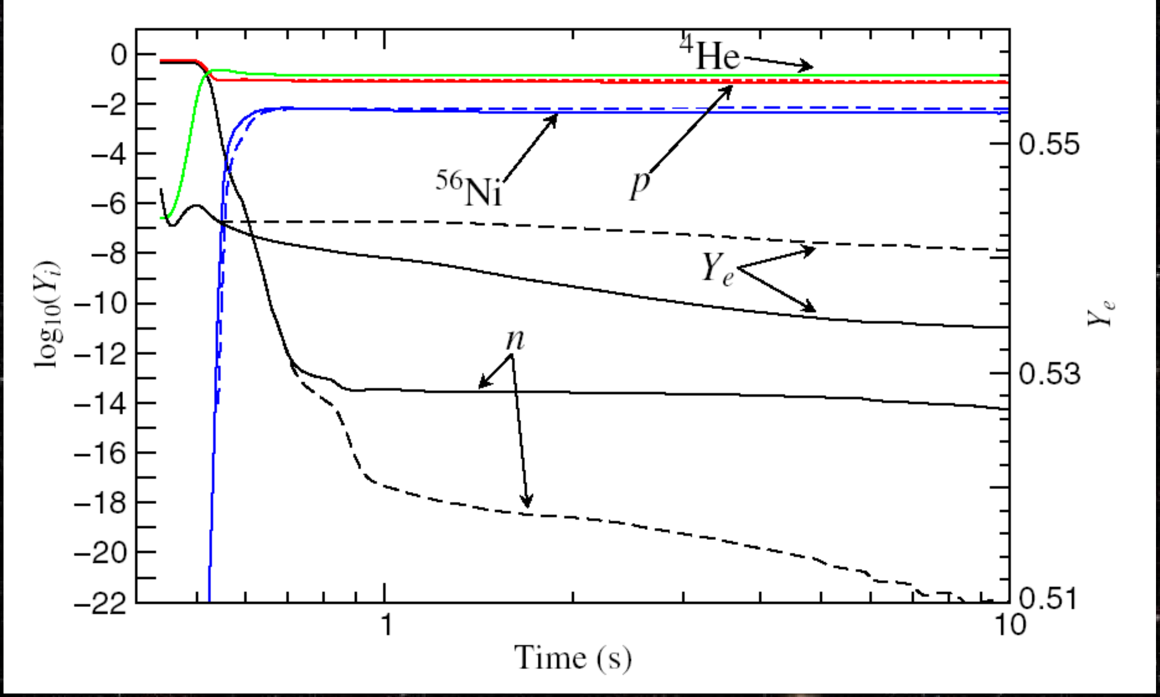




Neutrino reactions with nucleons determine the proton-to-neutron ratio

- Neutrino-Proton Process (early ejecta, proton rich)
- R-Process (late ejecta, neutron rich)

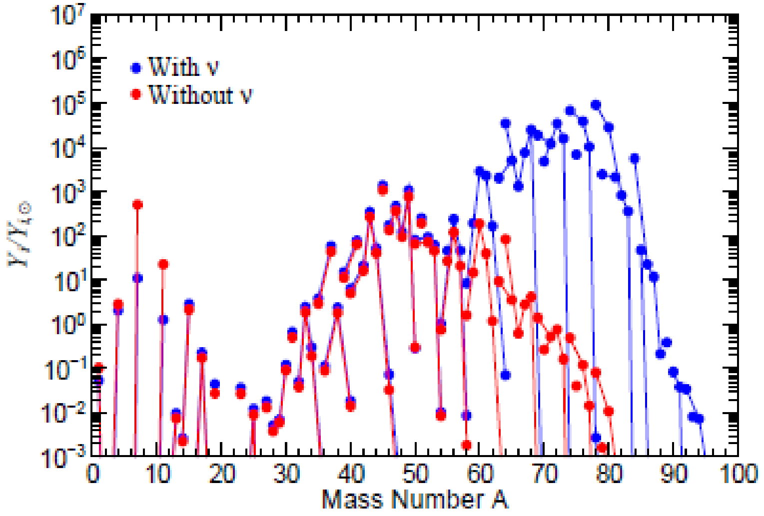
Possible consequences of high neutrino flux in shock-front



- Anti-neutrino capture on protons produce neutrons at late times
- (n,p) reactions simulate beta decays and overcome waiting points

The neutrino-proton process

- Protonrich matter is ejected under the influence of neutrino reactions
- Nuclei form at distance where a substantial antineutrino flux is present



Antineutrinos help to bridge long waiting points via (n,p) reactions

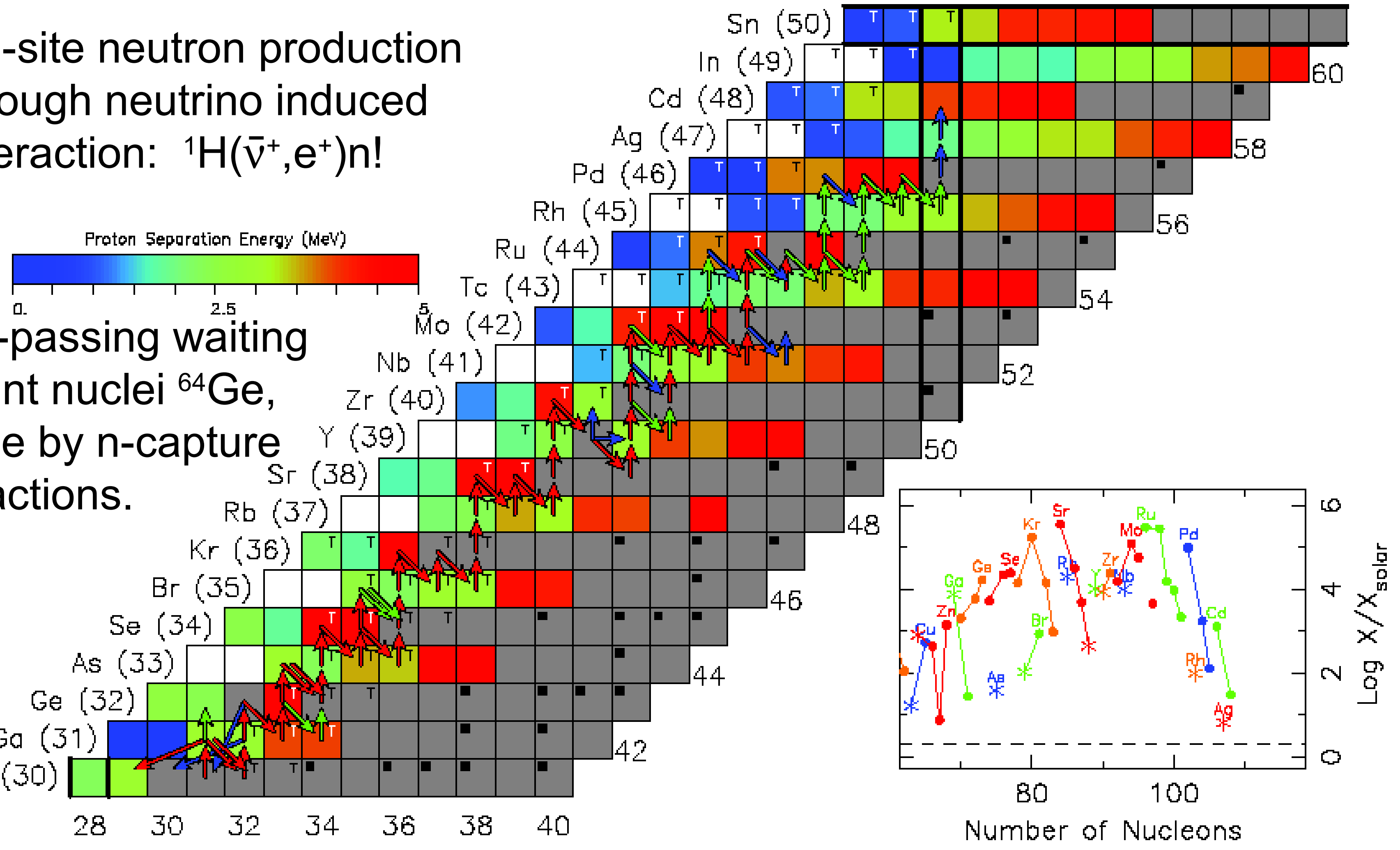
$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p; \quad {}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge}; \ldots$$

C. Fröhlich, G. Martinez-Pinedo, et al., PRL 96 (2006) 142502

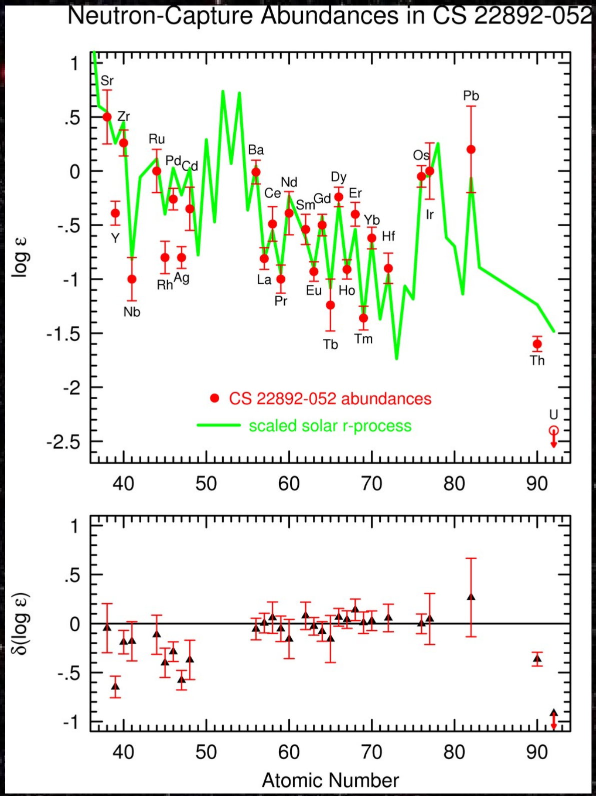
νp-process in hydrogen rich, high neutron flux environments

On-site neutron production through neutrino induced interaction: $^{1}H(\bar{\nu}^{+},e^{+})n$!

By-passing waiting point nuclei ^{64}Ge, ^{68}Se by n-capture reactions.



Making Gold!



Nature

vs

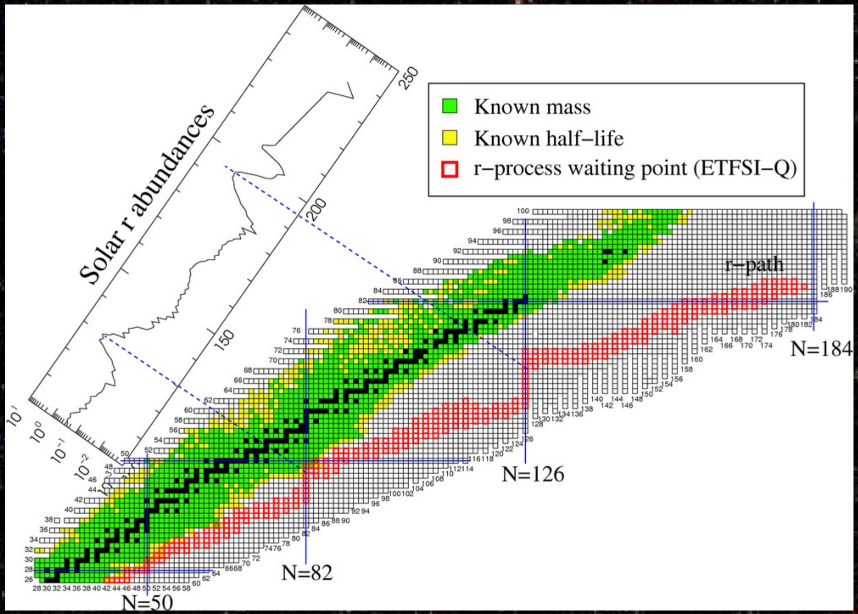
Humans

Old stars in galactic halo have the same r-process abundances as the solar system for A>130, but not below.

two distinct r-process sites?

Johann Friedrich Böttger, Alchemist
Inventor of European White China
In Meissen, Germany

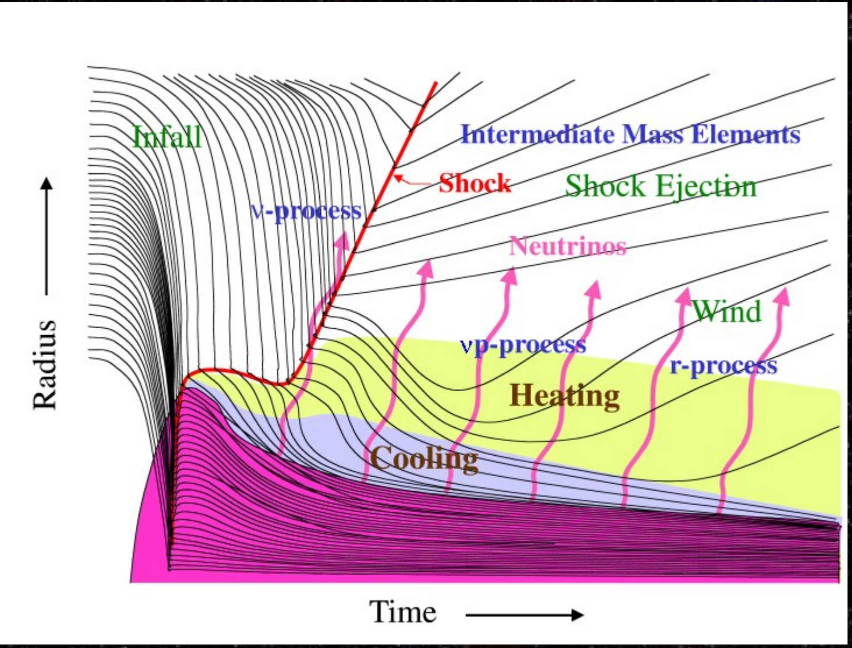
The R-Process

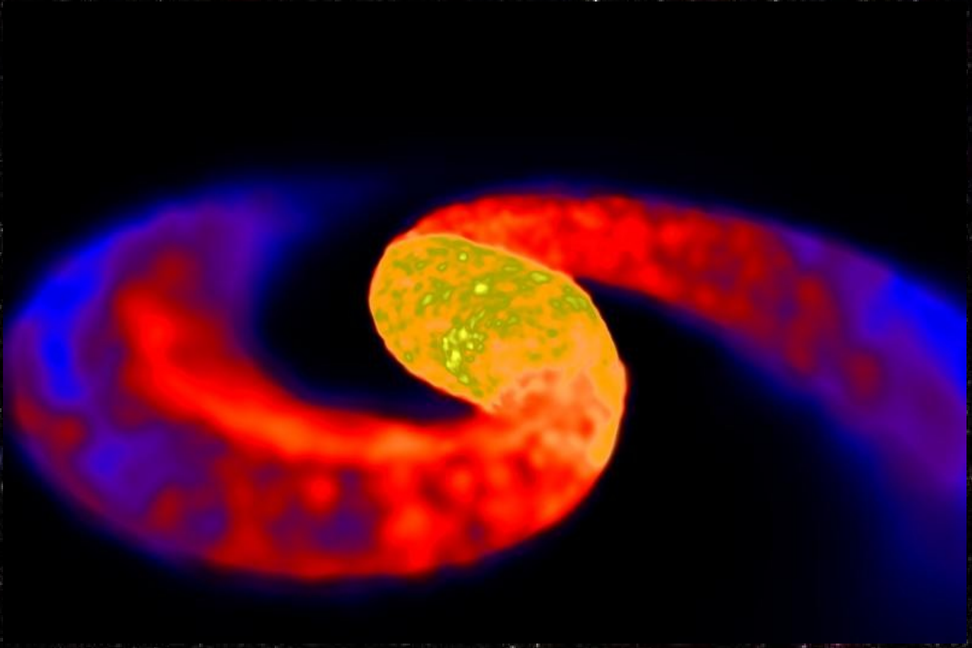


- Masses
- Half lives
- Neutron capture rates
- Fission
- Neutrino reactions

Courtesy: K.-L. Kratz

Potential r-process sites





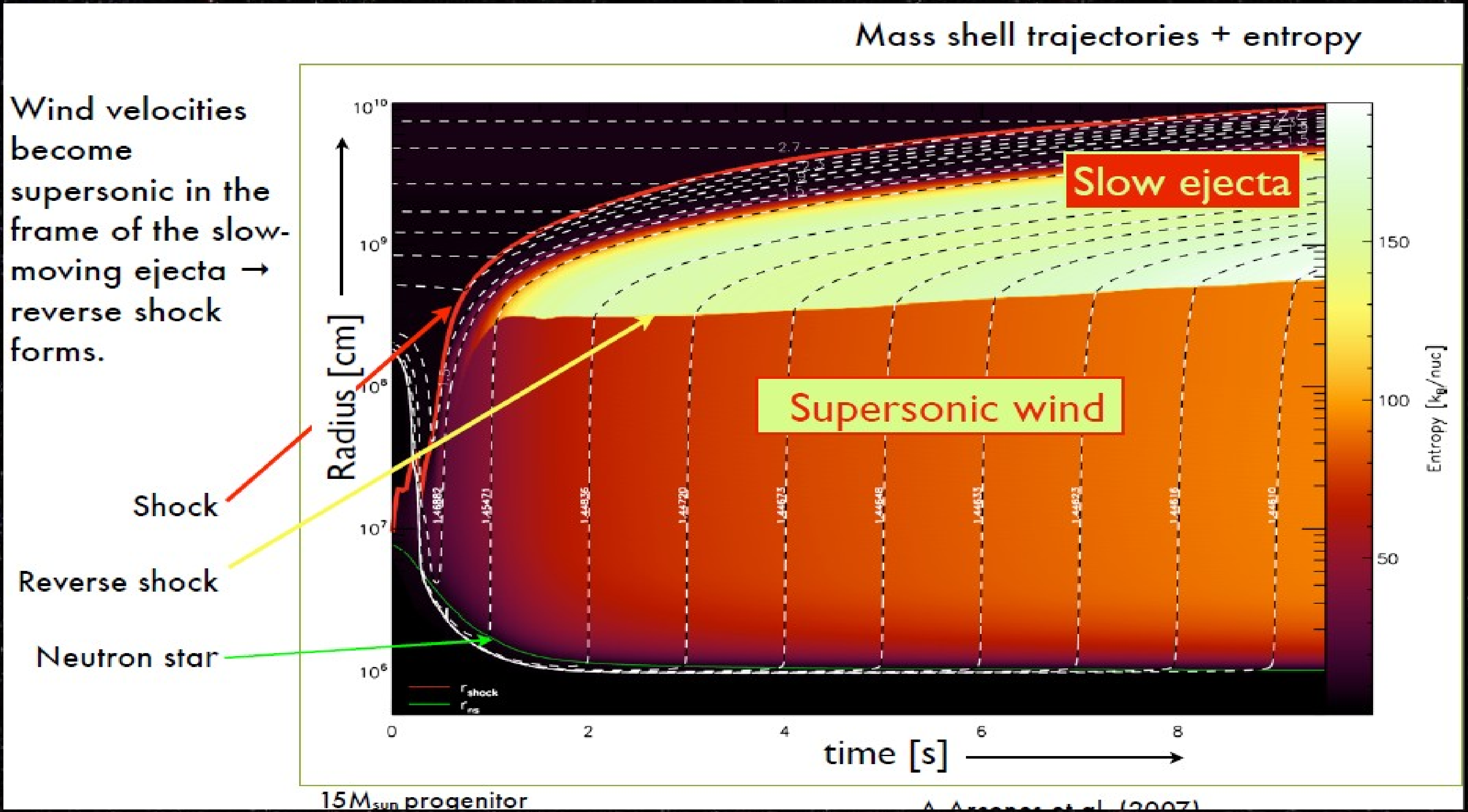
Neutrino-driven wind from a nascent neutron star in a supernova explosion

Woosley et al.

Neutron star mergers

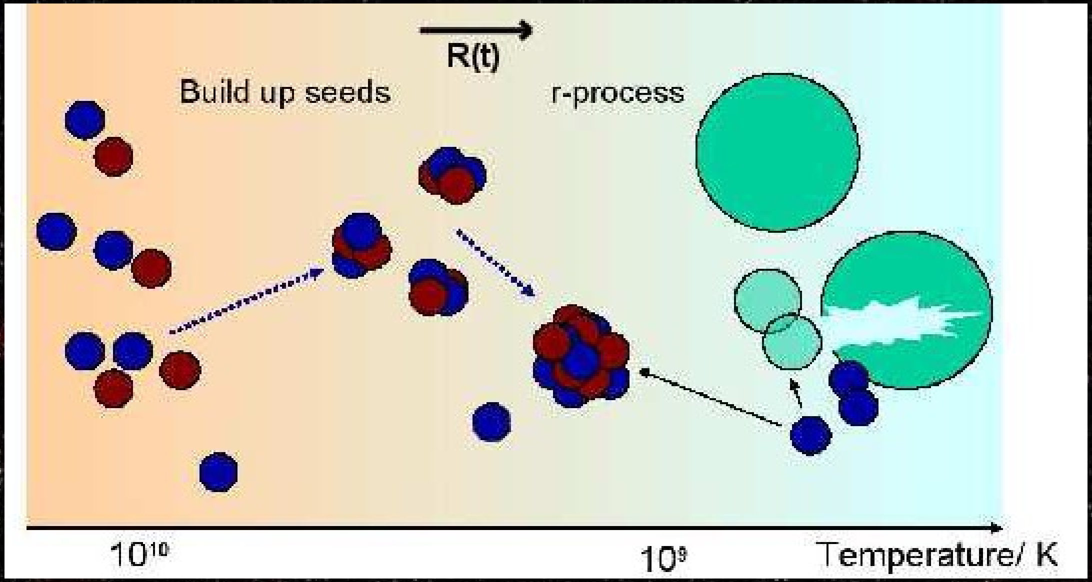
Freiburghaus et al.

Supernova trajectories



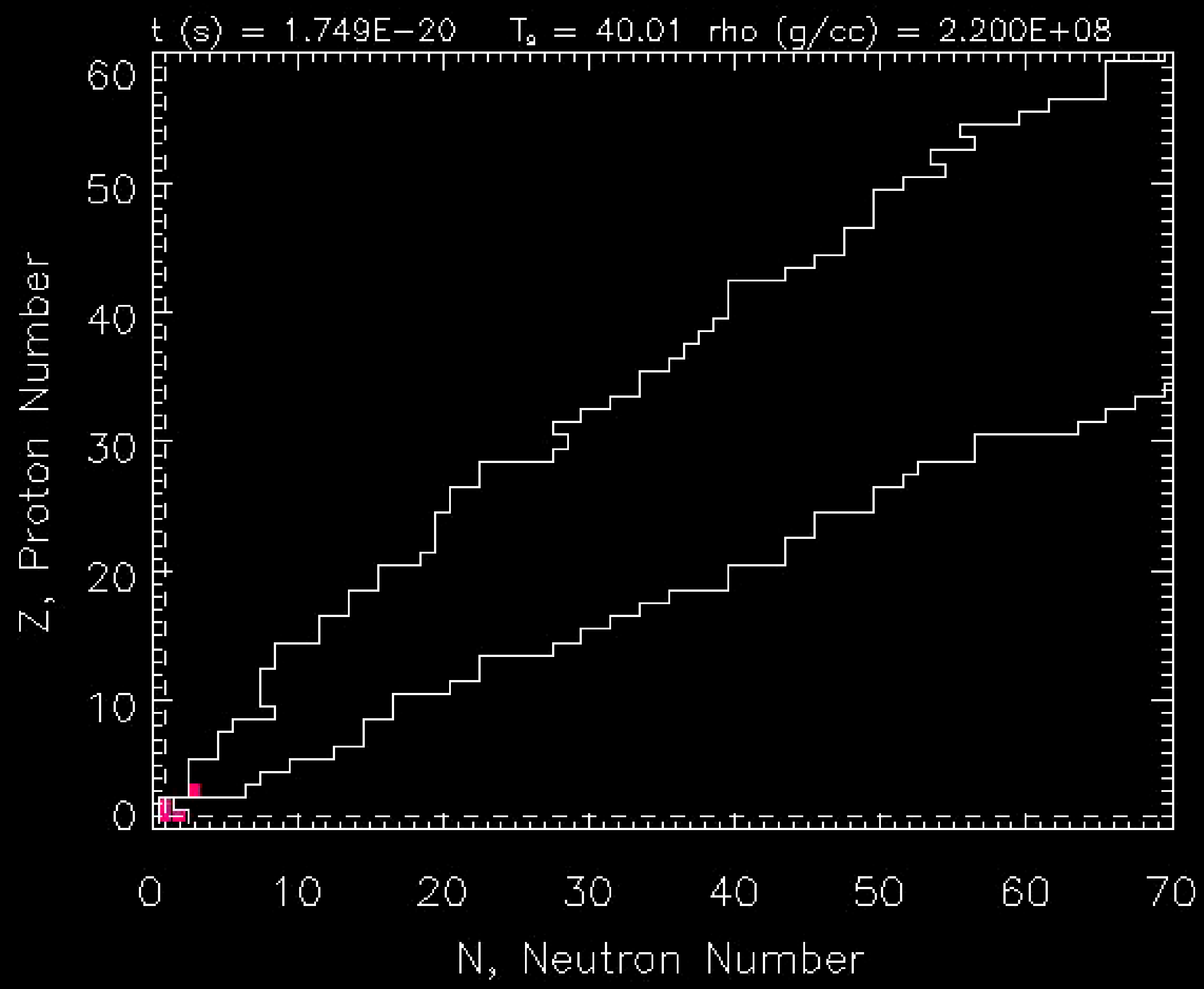
Courtesy: Almudena Arcones

Dynamical r-process



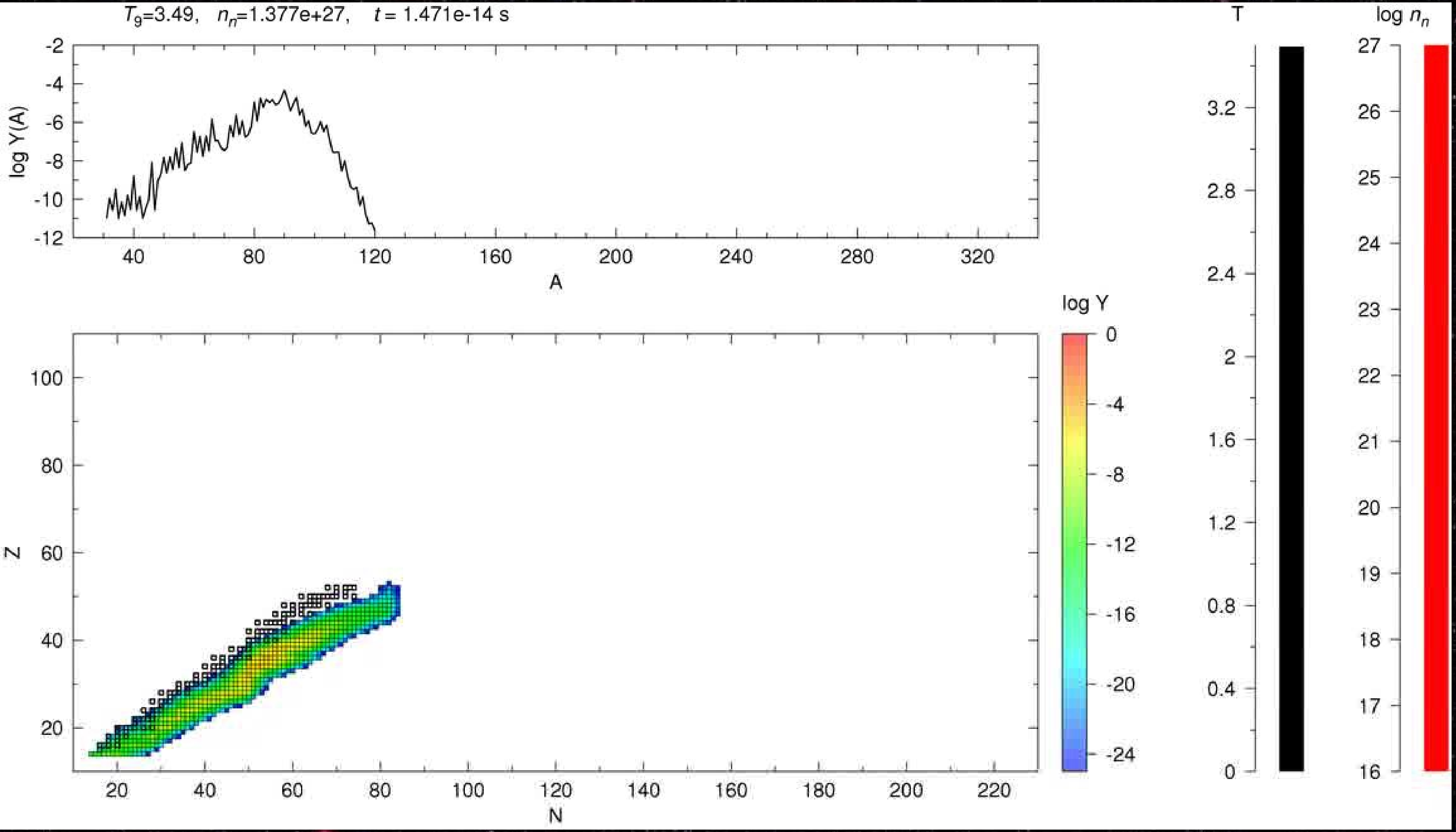
Free protons, neutrons are ejected at high temperature
matter cools, nuclei form by charged particle reactions
At T~3 GK charged particle reactions freeze out -> seed
Neutron captures on seed constitute r-process

Supernova shock front nucleosynthesis



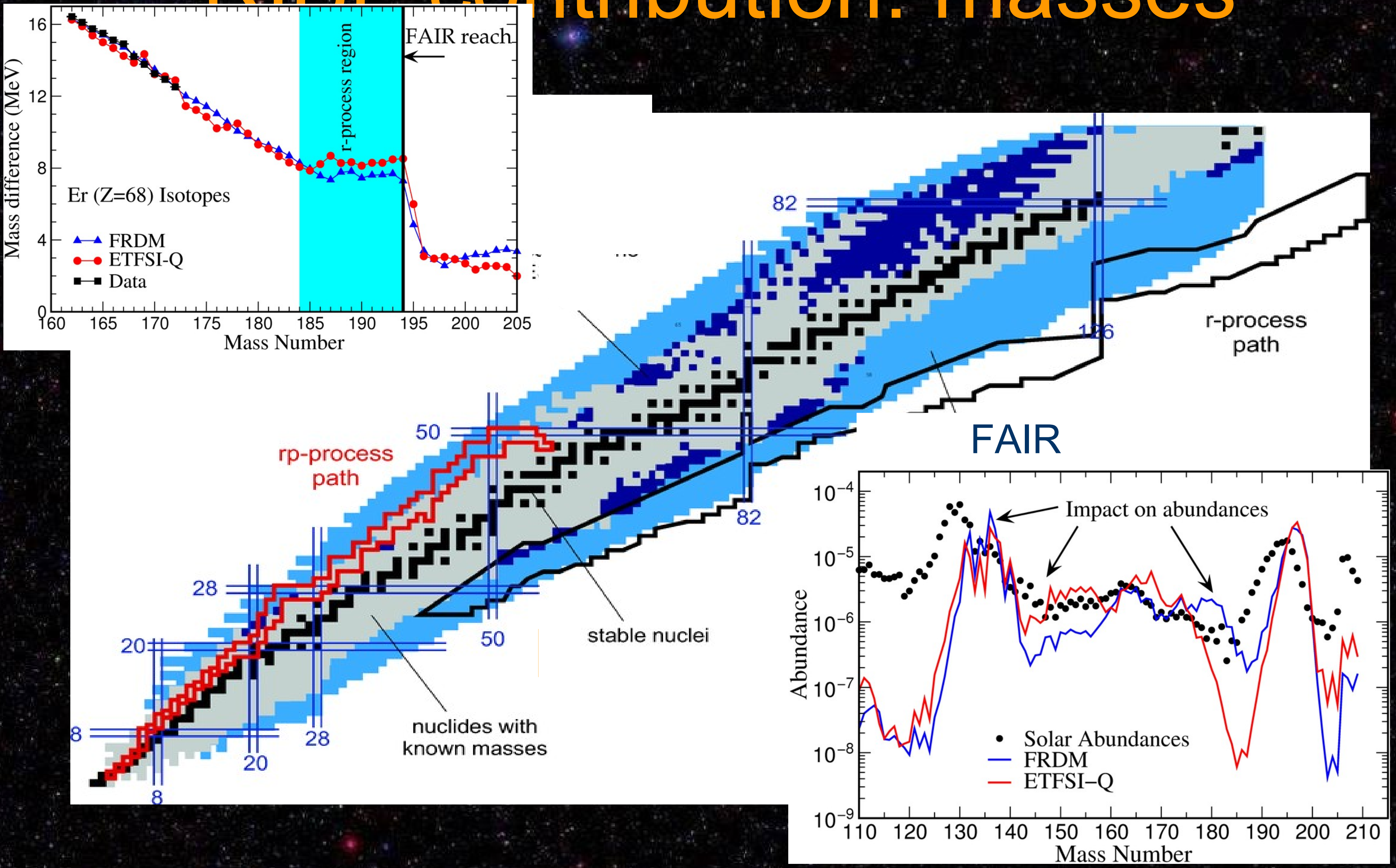
Brad Meyer

R-Process Simulation

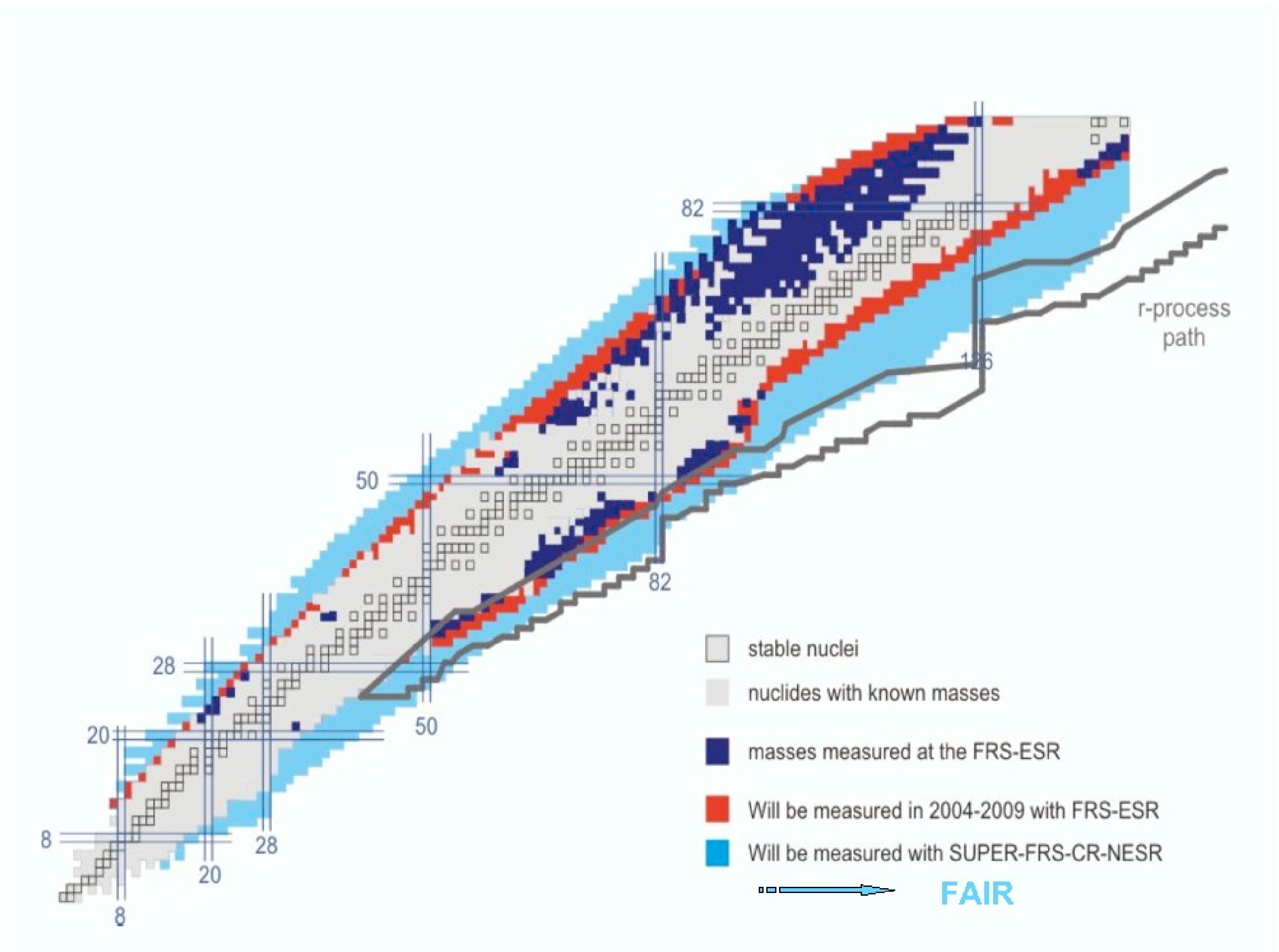


Courtesy: Gabriel Martinez-Pinedo

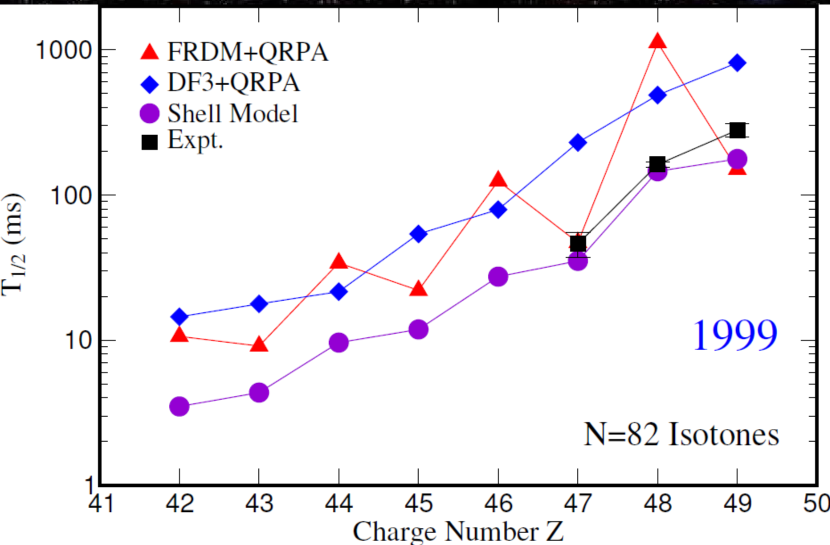
RIBF contribution: masses

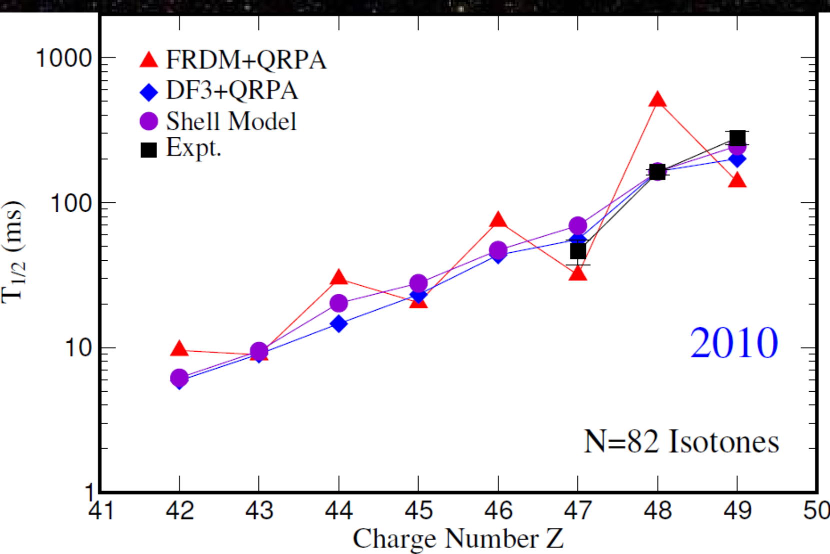


Mass measurements at FAIR

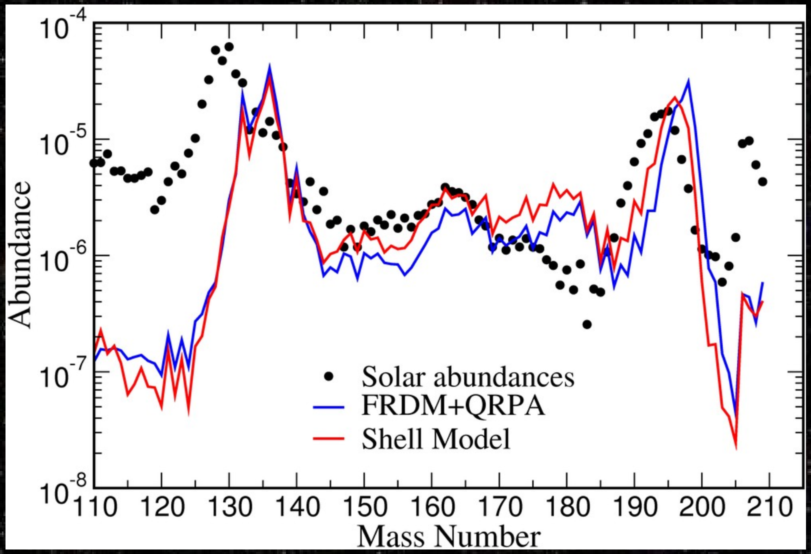


Impact of nuclear half-lives





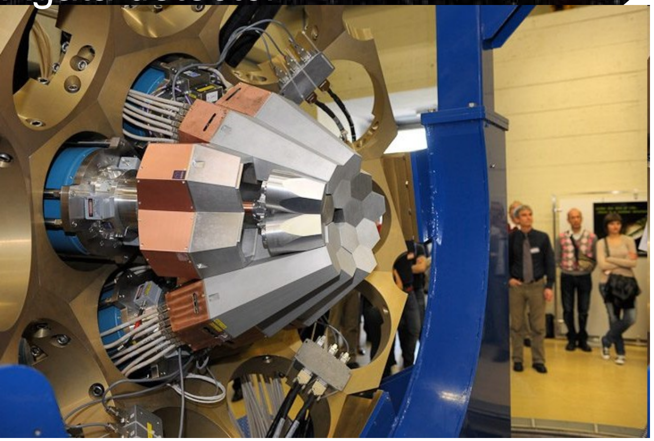
Impact of nuclear half-lives on r-process abundances

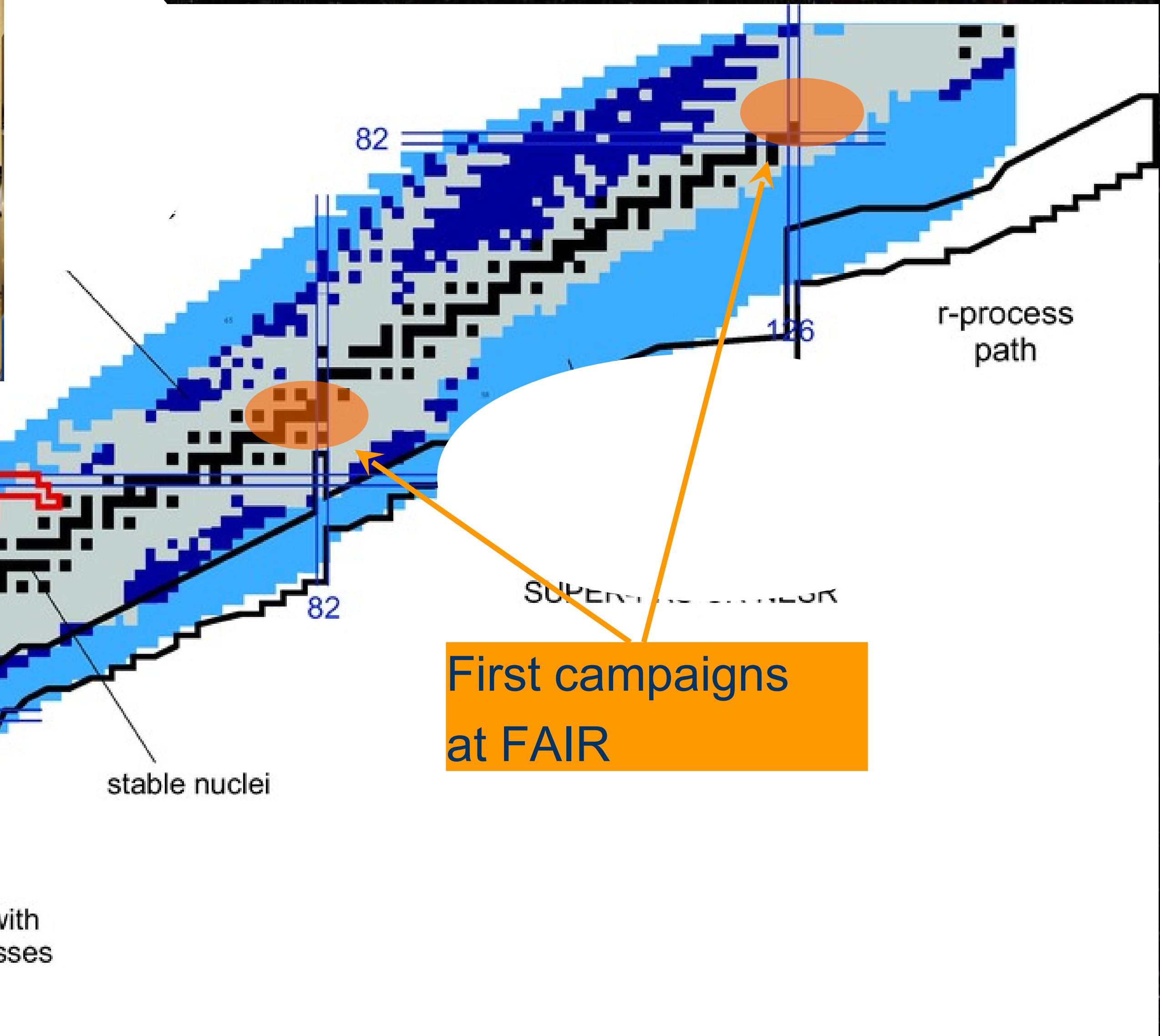


Knowing the half-lives we will constrain the dynamics of the supernova explosion

FAIR contribution to half-lives

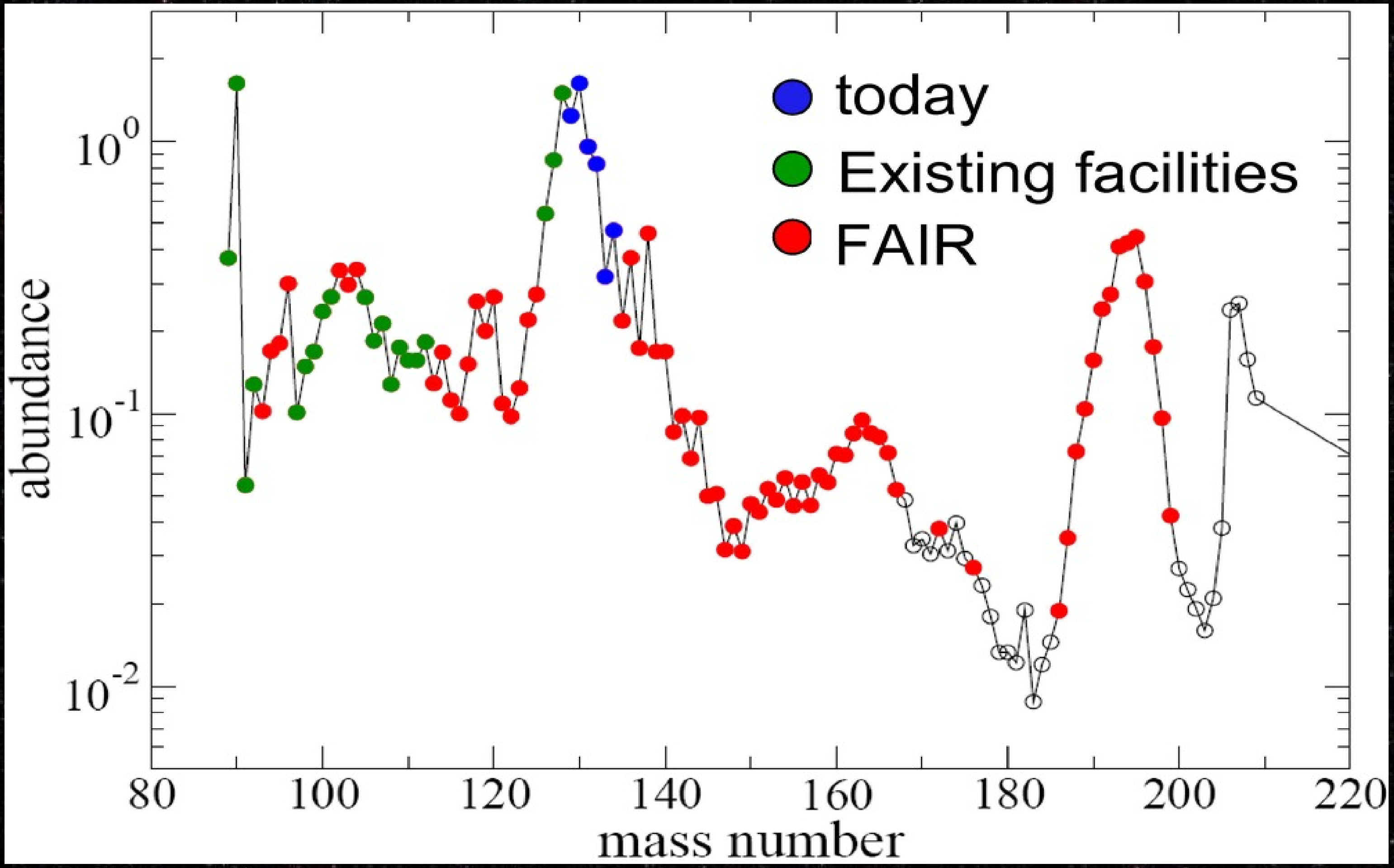
Agata detector





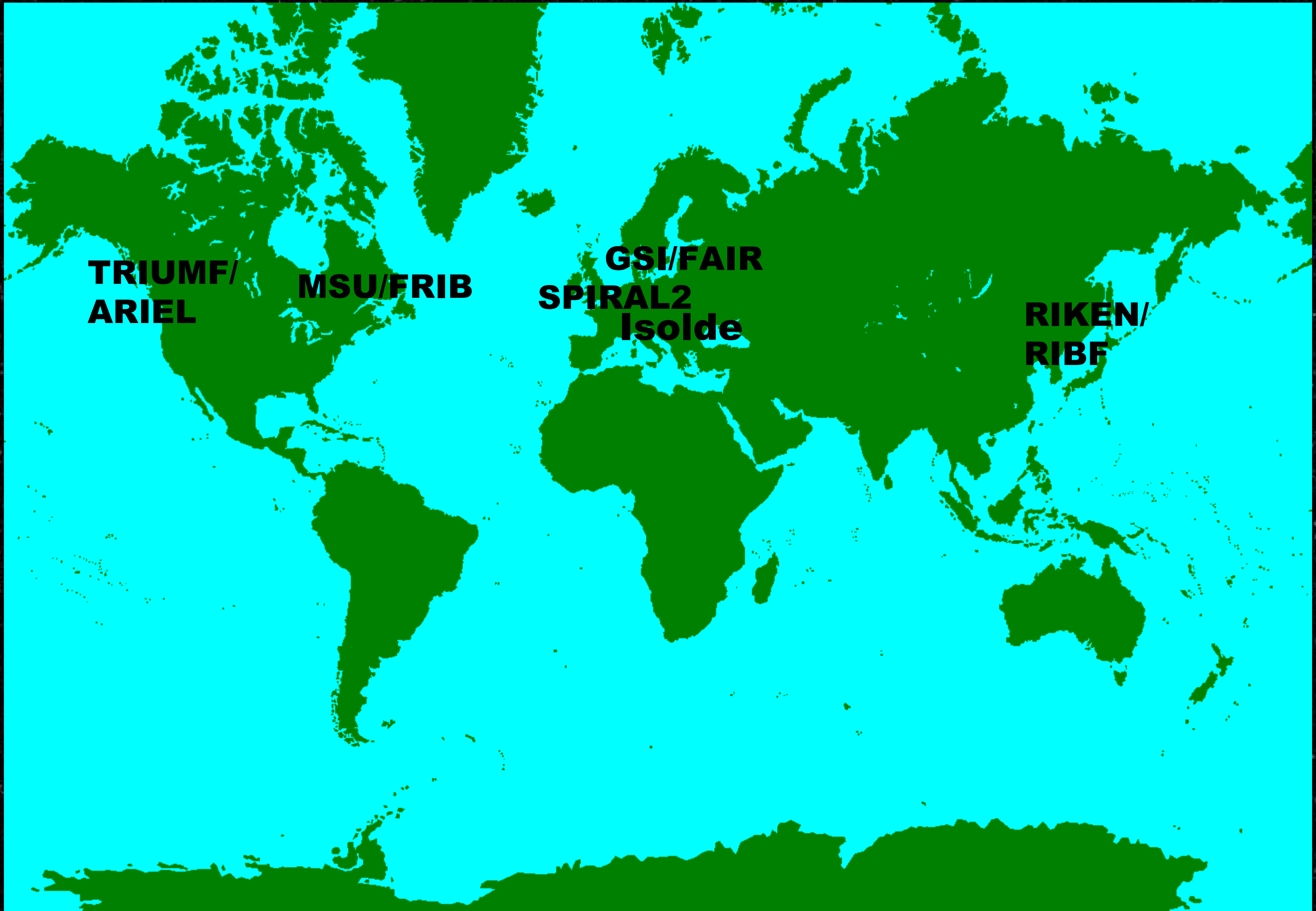
First campaigns at FAIR

The RIB era for r-process



Courtesy: Hendrik Schatz

Next-Generation Isotope Facilities



Willy Fowler: Father of Nuclear Astrophysics

The RIB Chance: New Horizons