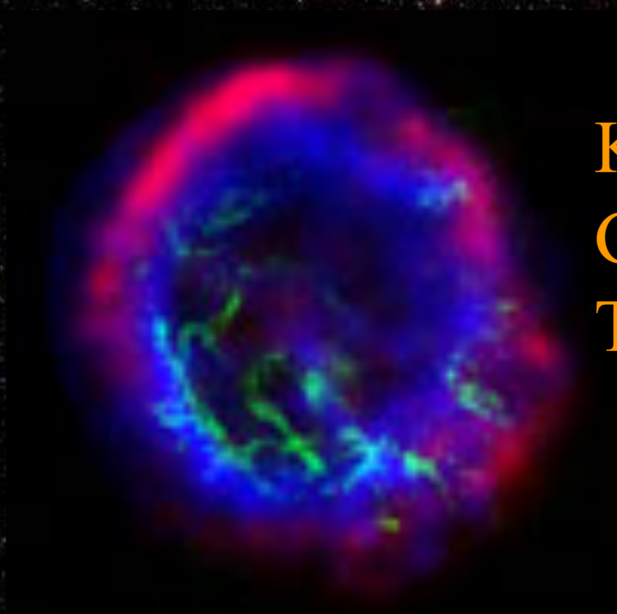
Nuclear Physics and Supernova Dynamics



Karlheinz Langanke
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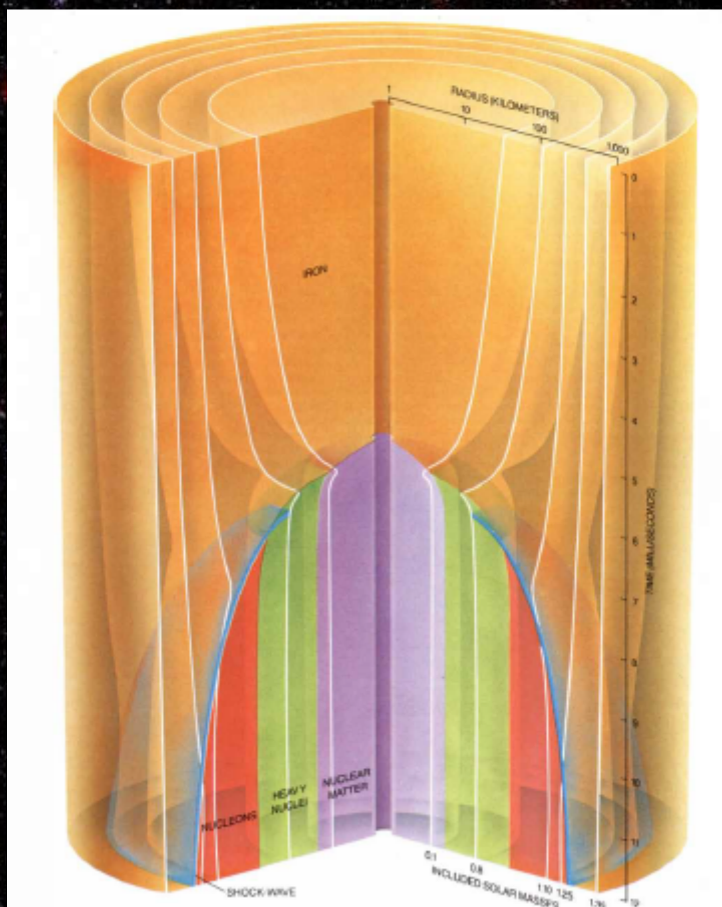
Tribute to Gerry - Stony Brook, November 26, 2013

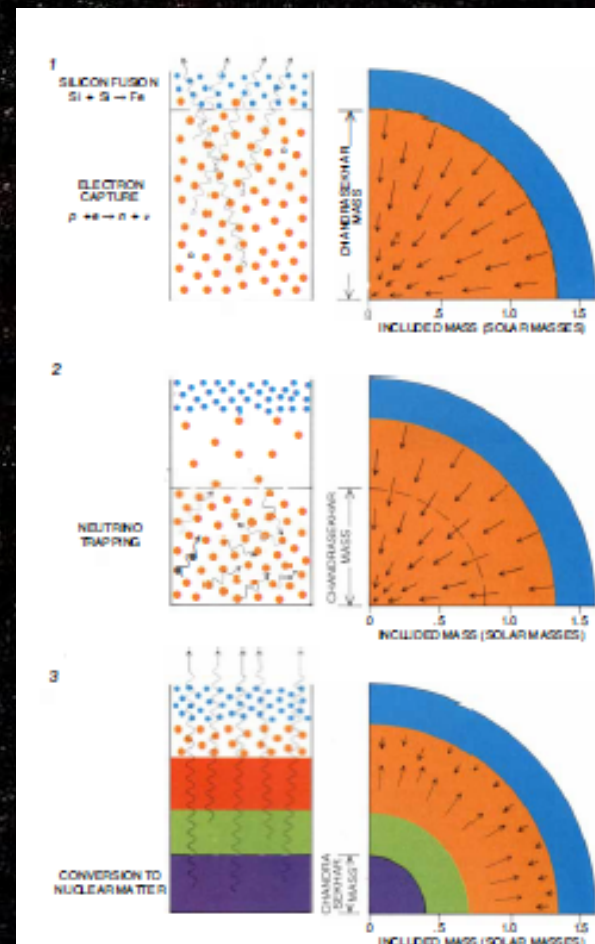
Hans Bethe's Centennial at Caltech

How a Supernova Explodes

When a large star runs out of nuclear fuel, the core collapses in milliseconds. The subsequent "bounce" of the core generates a shock wave so intense that it blows off most of the star's mass

by Hans A. Bethe and Gerald Brown





EQUATION OF STATE IN THE GRAVITATIONAL COLLAPSE OF STARS

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Received 12 February 1979

Abstract: The equation of state in stellar collapse is derived from simple considerations, the crucial ingredient being that the entropy per nucleon remains small, of the order of unity (in units of k), during the entire collapse. In the early regime, $\rho \sim 10^{10}$–10^{13} g/cm^3, nuclei partially dissolve into α-particles and neutrons; the α-particles go back into the nuclei at higher densities. At the higher densities, nuclei are preserved right up to nuclear matter densities, at which point the nucleons are squeezed out of the nuclei. The low entropy per nucleon prevents the appearance of drip nucleons, which would add greatly to the net entropy.

We find that electrons are captured by nuclei, the capture on free protons being negligible in comparison. Carrying the difference of neutron and proton chemical potentials $\mu_n - \mu_p$ in our capture equation forces the energy of the resulting neutrinos to be low. Nonetheless, neutrino trapping occurs at a density of about $\rho = 10^{12}$ g/cm^3. The fact that the ensuing development to higher densities is adiabatic makes our treatment in terms of entropy highly relevant.

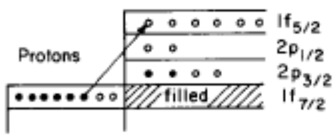


Fig. 1. Shell-model description of the electron capture. In the capture, protons will go to the $f_{\frac{5}{2}}$ level of the daughter nucleus, which then decays by γ-emission down to the 2p orbitals.

What we are saying in shell-model language is that ground-state to ground-state or low excited-state transitions are hindered through admixture of the giant Gamow–Teller state, whereas in the electron capture process the transition occurs to the giant Gamow–Teller state itself.

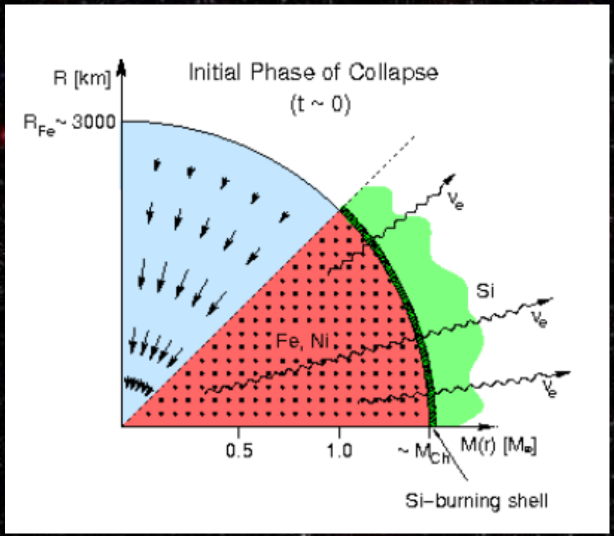
In its role of hindering low-lying β-transitions, the Gamow–Teller state is analogous to the giant dipole state, admixture of which retards low-lying E1 transitions by factors of ~100 to 1000. On the other hand, the Gamow–Teller strength has not been found in one relatively concentrated state, as in the case of the giant dipole resonance. This should not matter for the discussion here, since the strength, even if fragmented, should play the same role in hindering low-lying transitions.

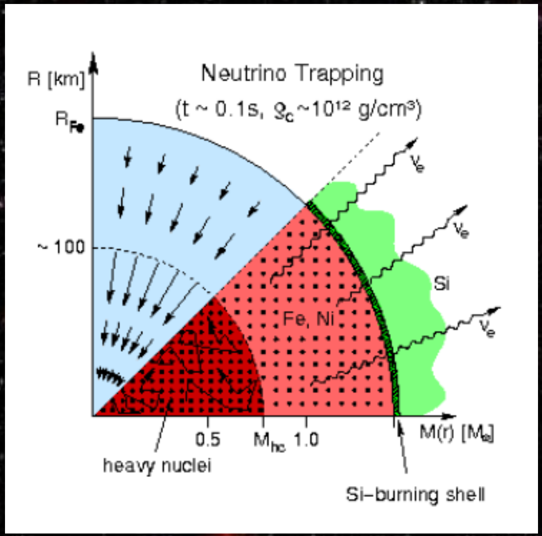
Gerry's insight:

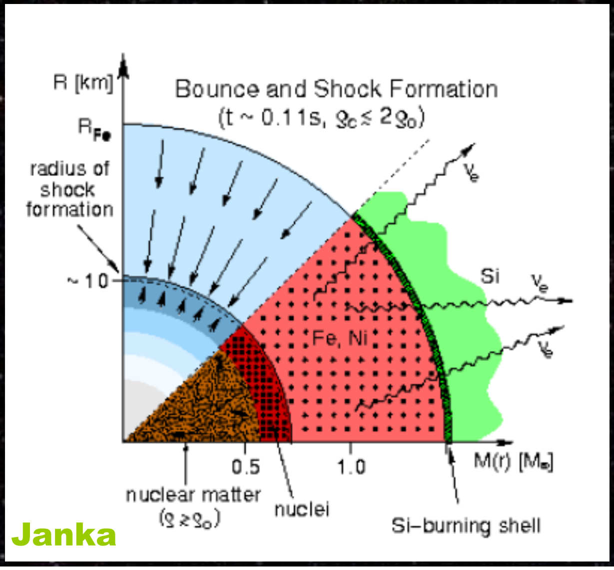
great thesis for George Fuller

many years of work for me

Supernova: collapse phase







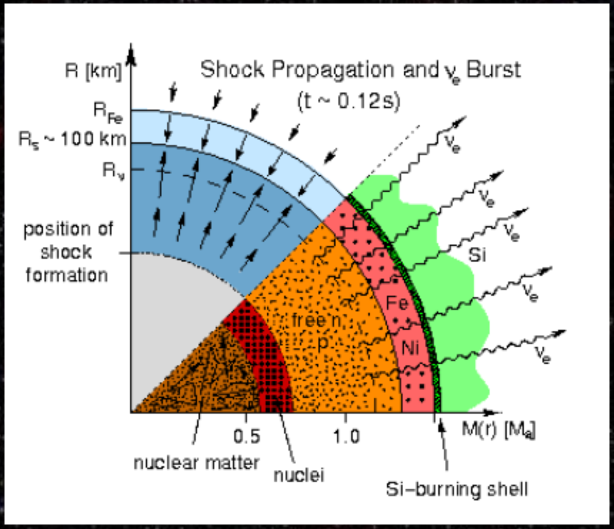
Important nuclear input:

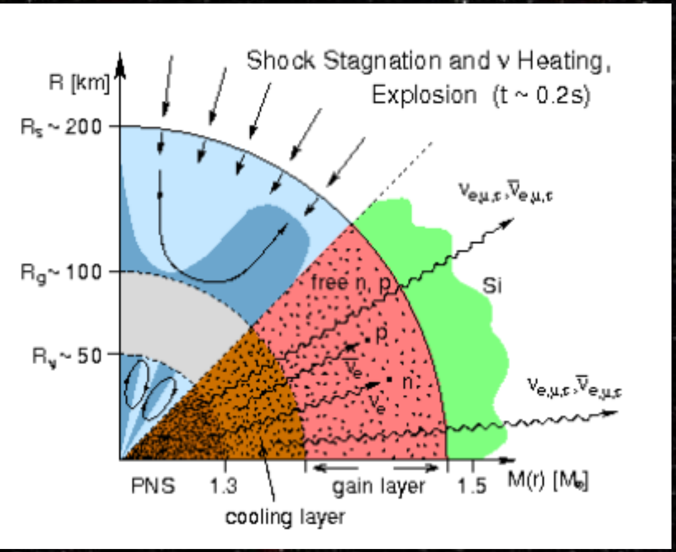
Electron capture on nuclei

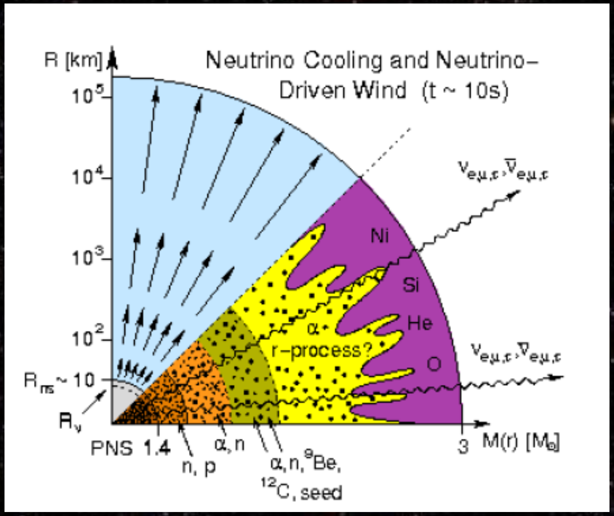
Neutrino-nucleus reactions

H.-Th. Janka

Supernova: explosion







Important nuclear input

Equation of state

Neutrino processes

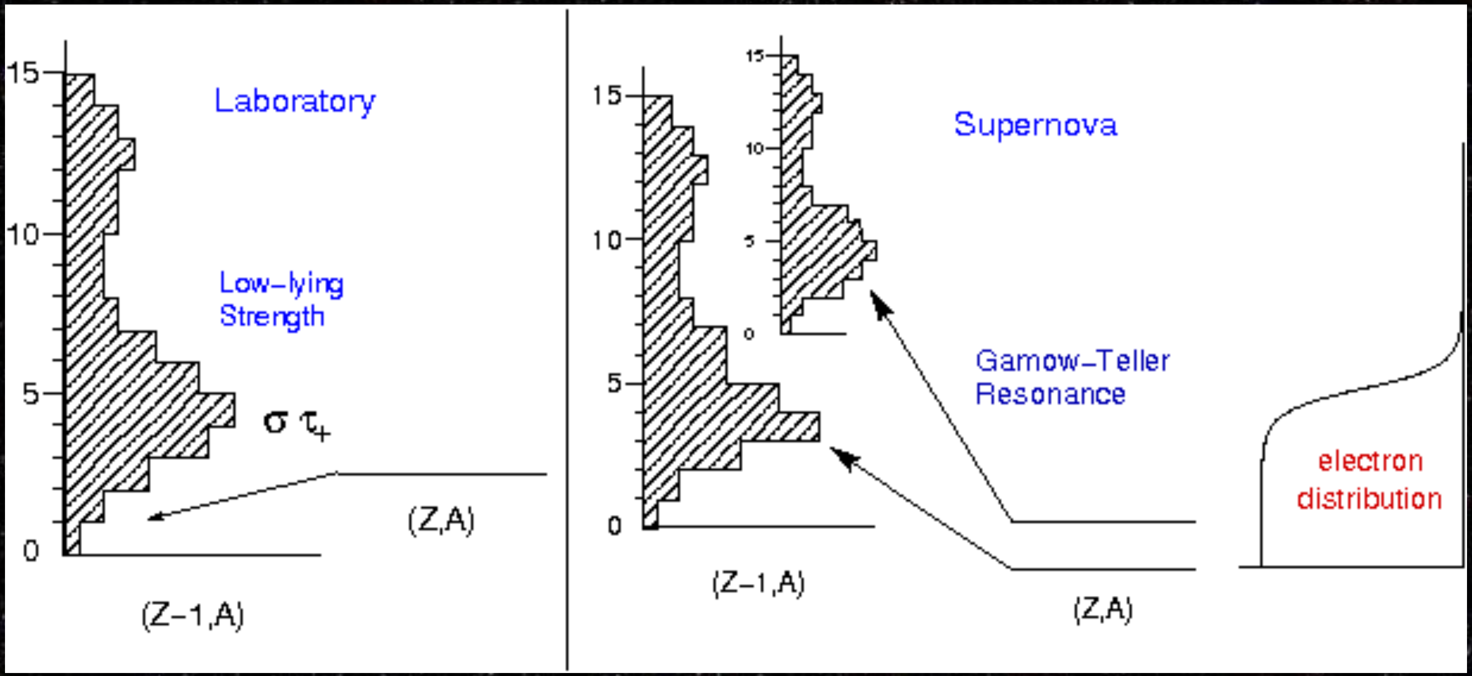
Closer look on

- electron capture in presupernova phase
  (nuclear composition A ~ 60)

- electron capture during collapse
  (nuclear composition A > 65)

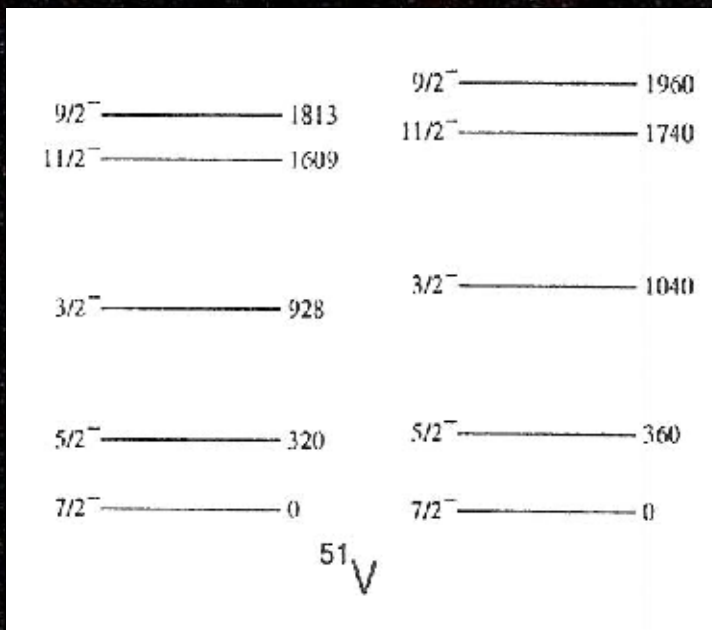
- nuclear deexcitation by neutrino pairs

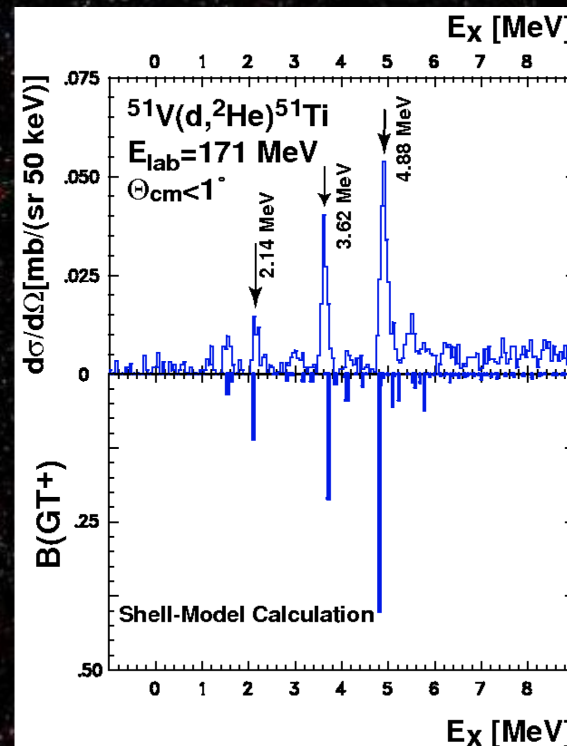
Electron capture: Lab vs Stars



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



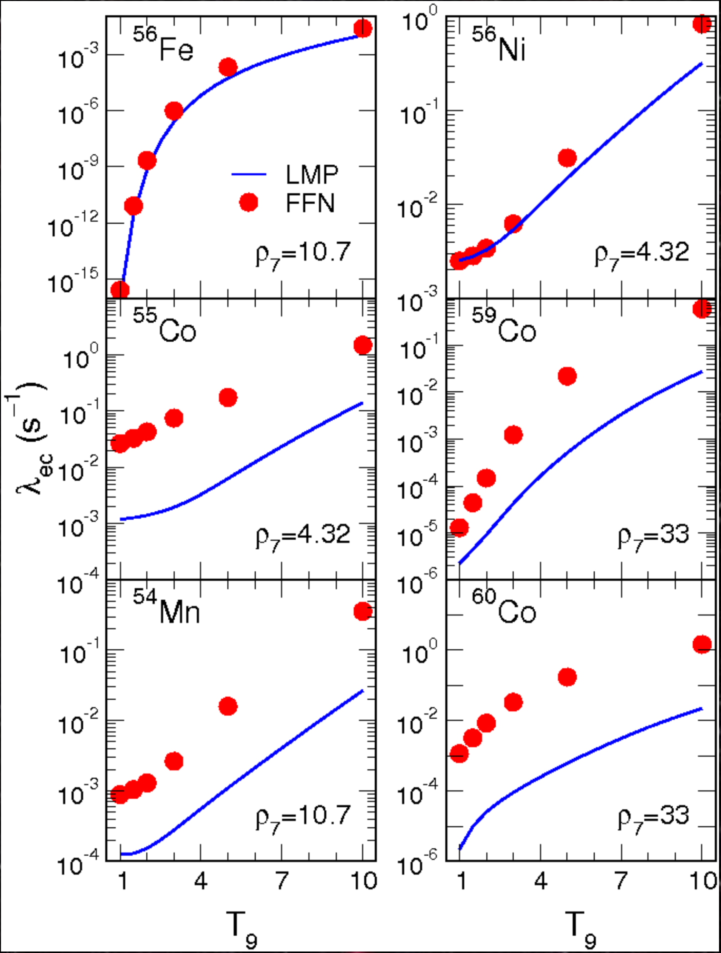


data KVI Groningen

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

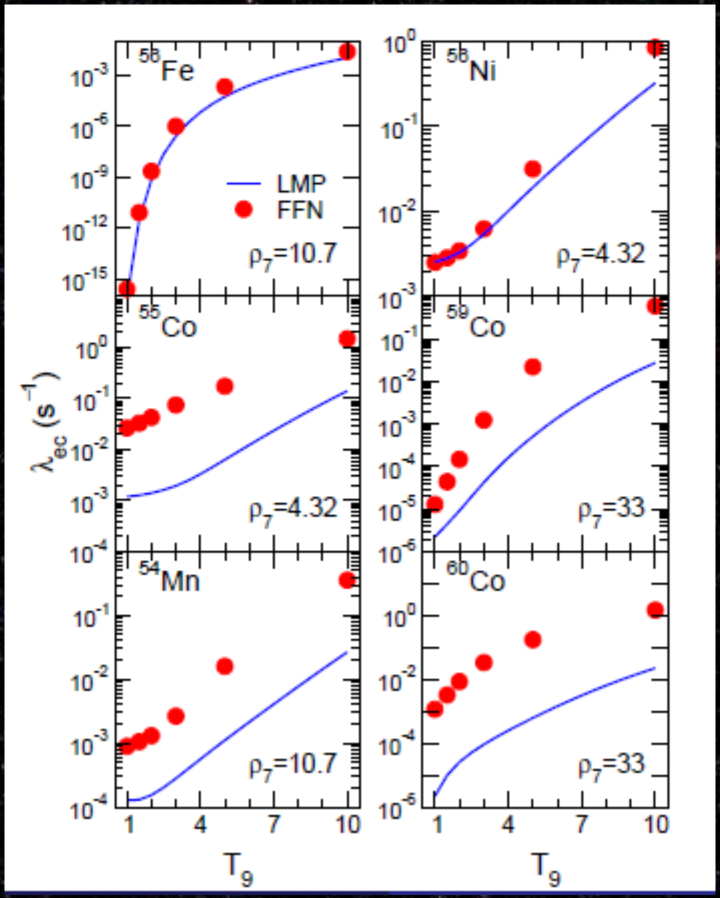
Capture rates are noticeably smaller than assumed before!

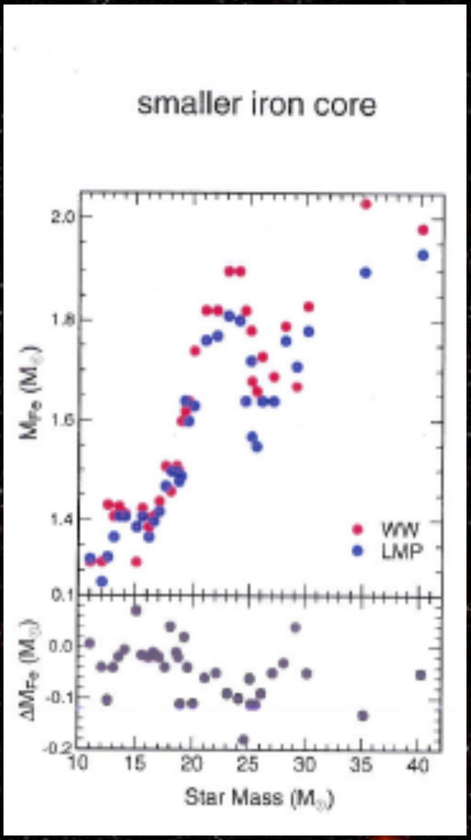
Shell model electron capture rates



shell model rates are noticeably smaller than rates from independent particle model (Fuller, Fowler, Newman)

Consequences of capture rates





Heger

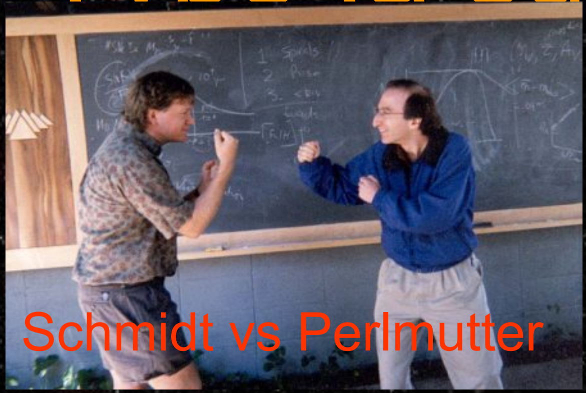
Woosley

Martinez Pinedo

shell model rates for Fe-Ni nuclei slower by order of magnitude

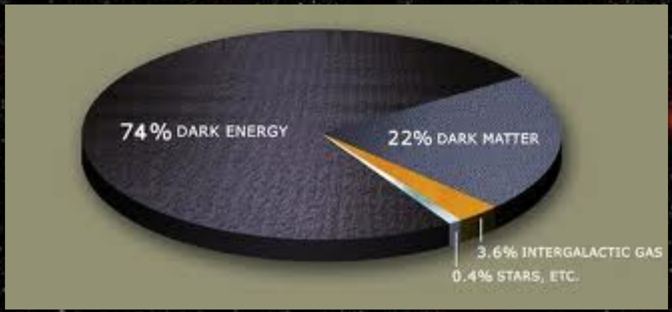
important changes in collapse trajectory

Digression: Type Ia supernovae

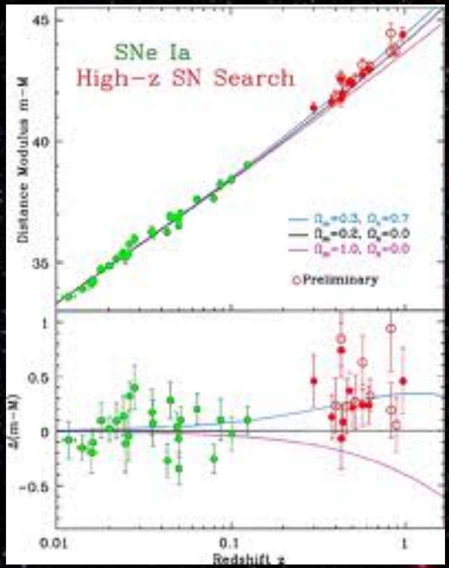


Schmidt vs Perlmutter

- Riess

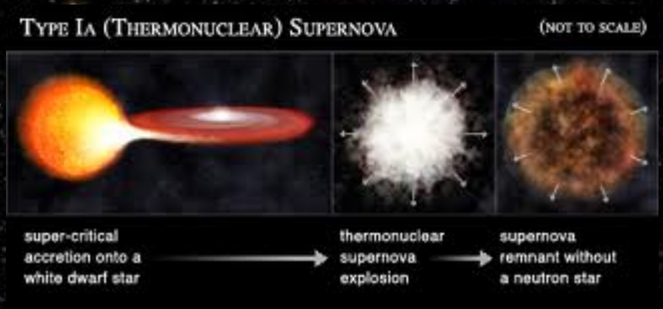


Content of universe:



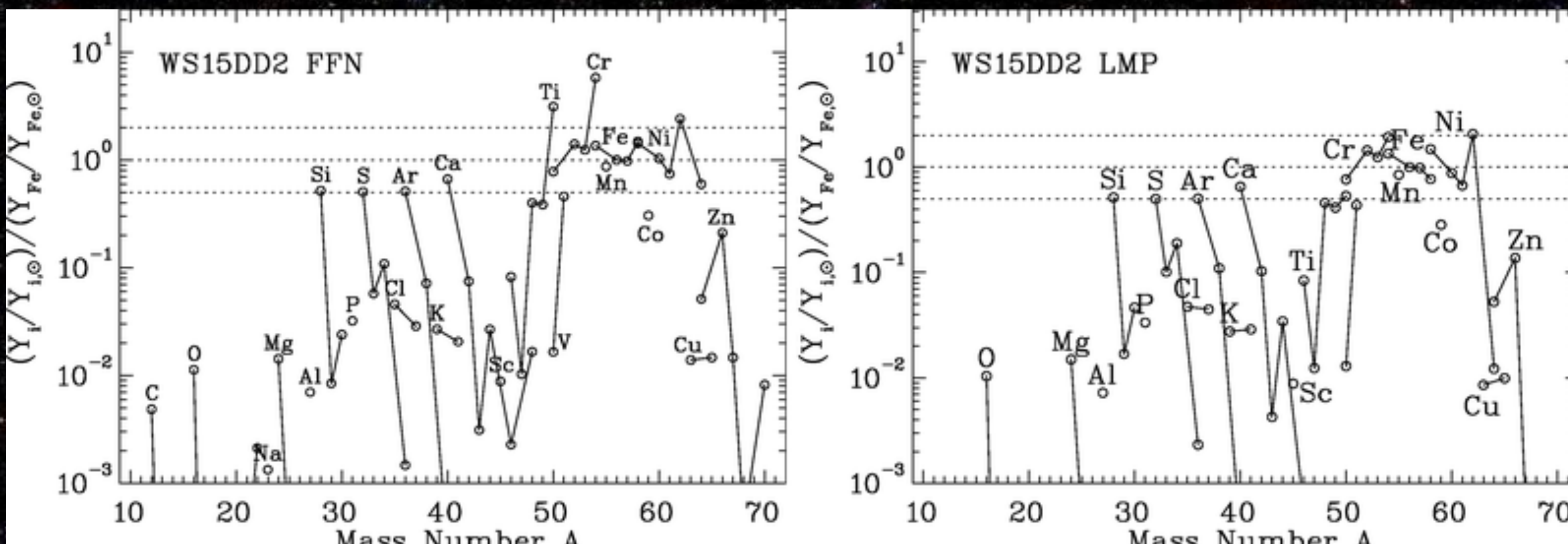
Universe expands!

Type Ia standard candle



Abundances in Type Ia's

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

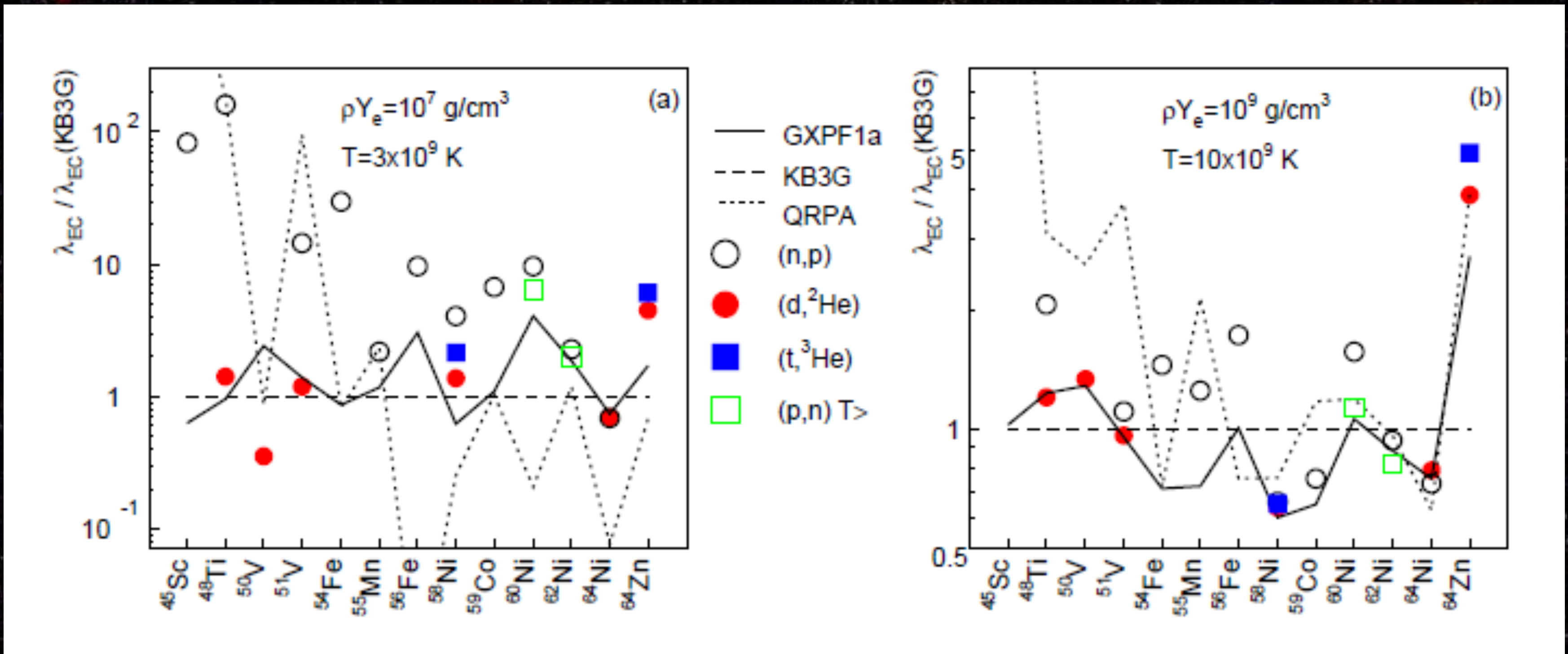


Modern electron capture rates solve inconstency problem in Type Ia supernova abundance production

Martinez-Pinedo, Thielemann

Experiment vs shell model

Cole, Zegers et al., PRC 86 (2012) 015809

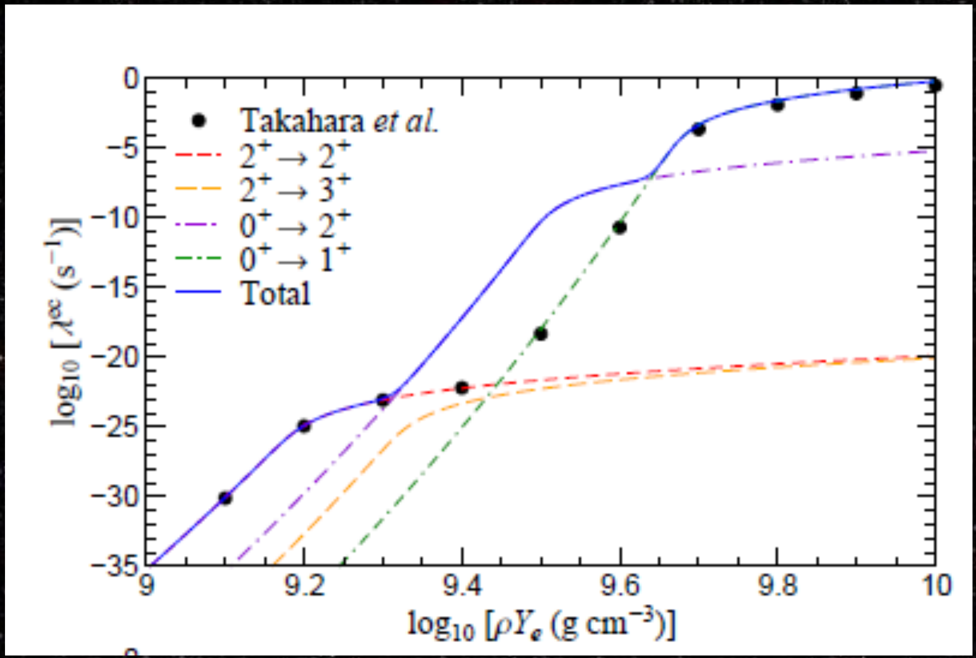


Iron-nickel mass range under control

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

Electron Capture on 20Ne

- Important for late evolution of O-Ne-Mg
- cores of 8-10 solar mass stars



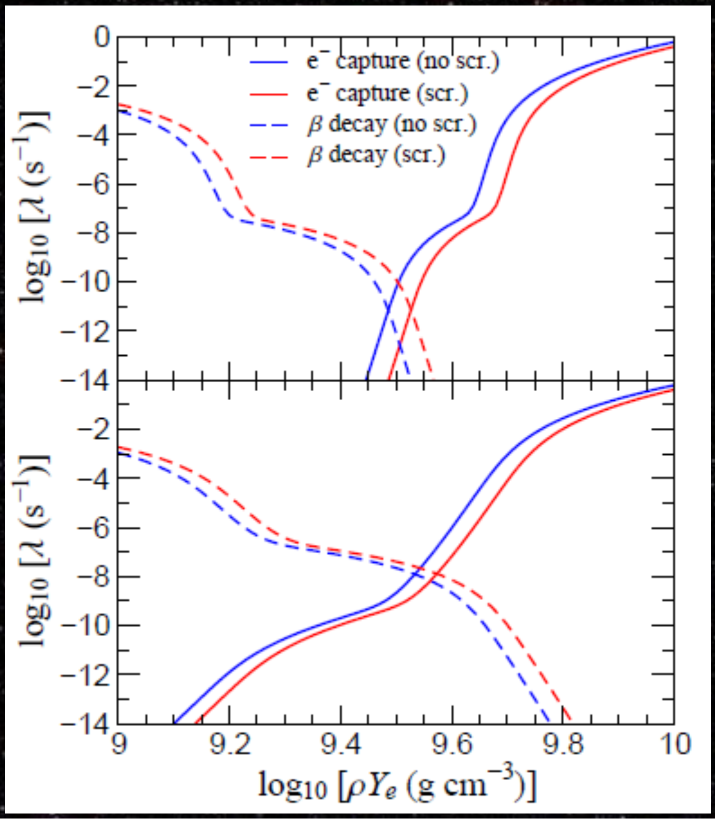
Rate determined by experimental data from beta-decay and (p,n) data!

except for ground-state ground-state-transition where only limit exists

Martinez-Pinedo, Lam,

Effect of screening

- beta decay rate enhanced, but electron capture rate reduced



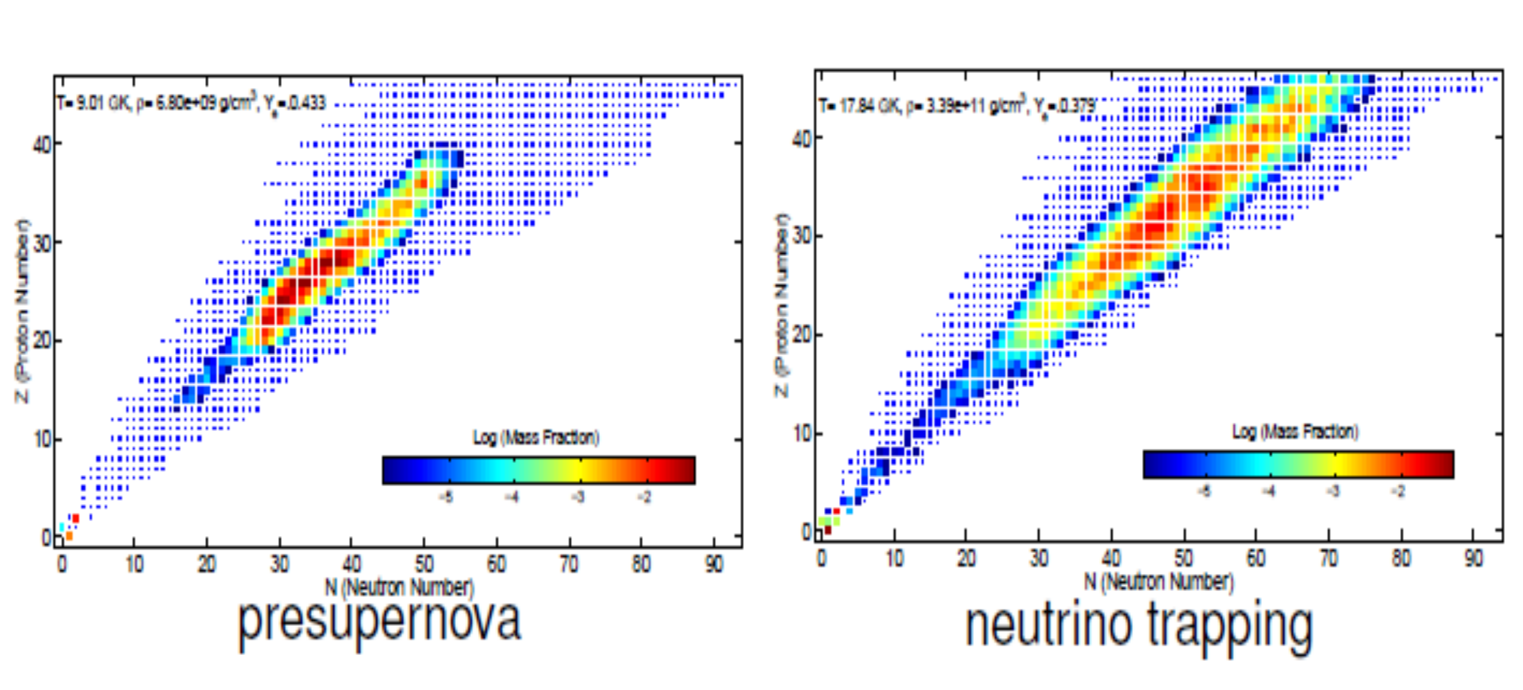
beta: 20F -> 20Ne

e-capture: 20Ne -> 20F

shifts URCA process to higher densities

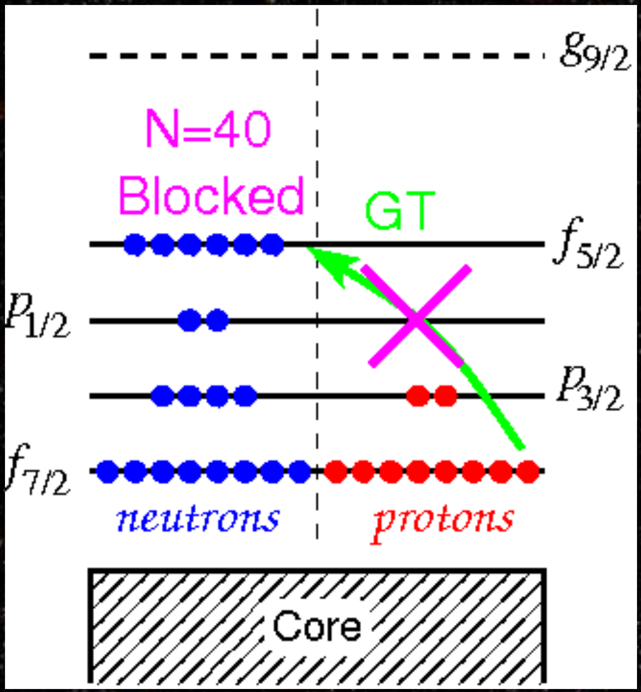
Marrtinez-Pinedo, Lam

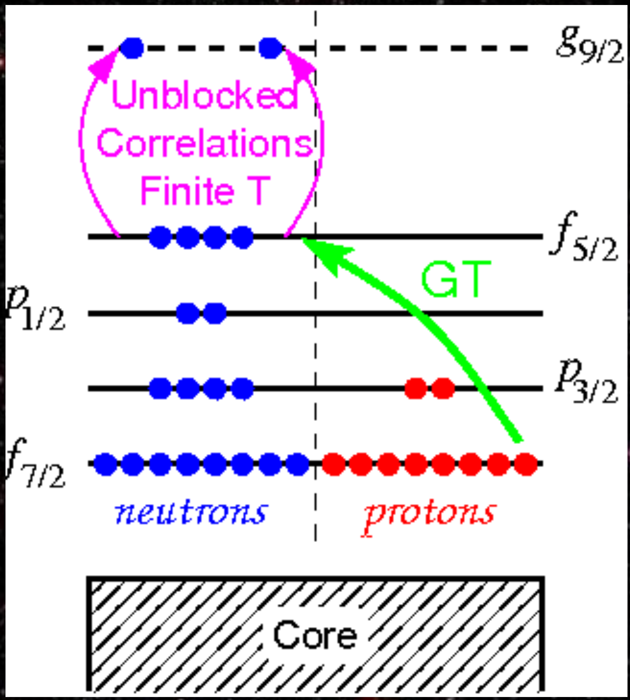
Abundance distribution during collapse



Electron captures drive nuclear composition towards neutron-rich unstable nuclei

Unblocking GT for nuclei with neutron numbers N>40

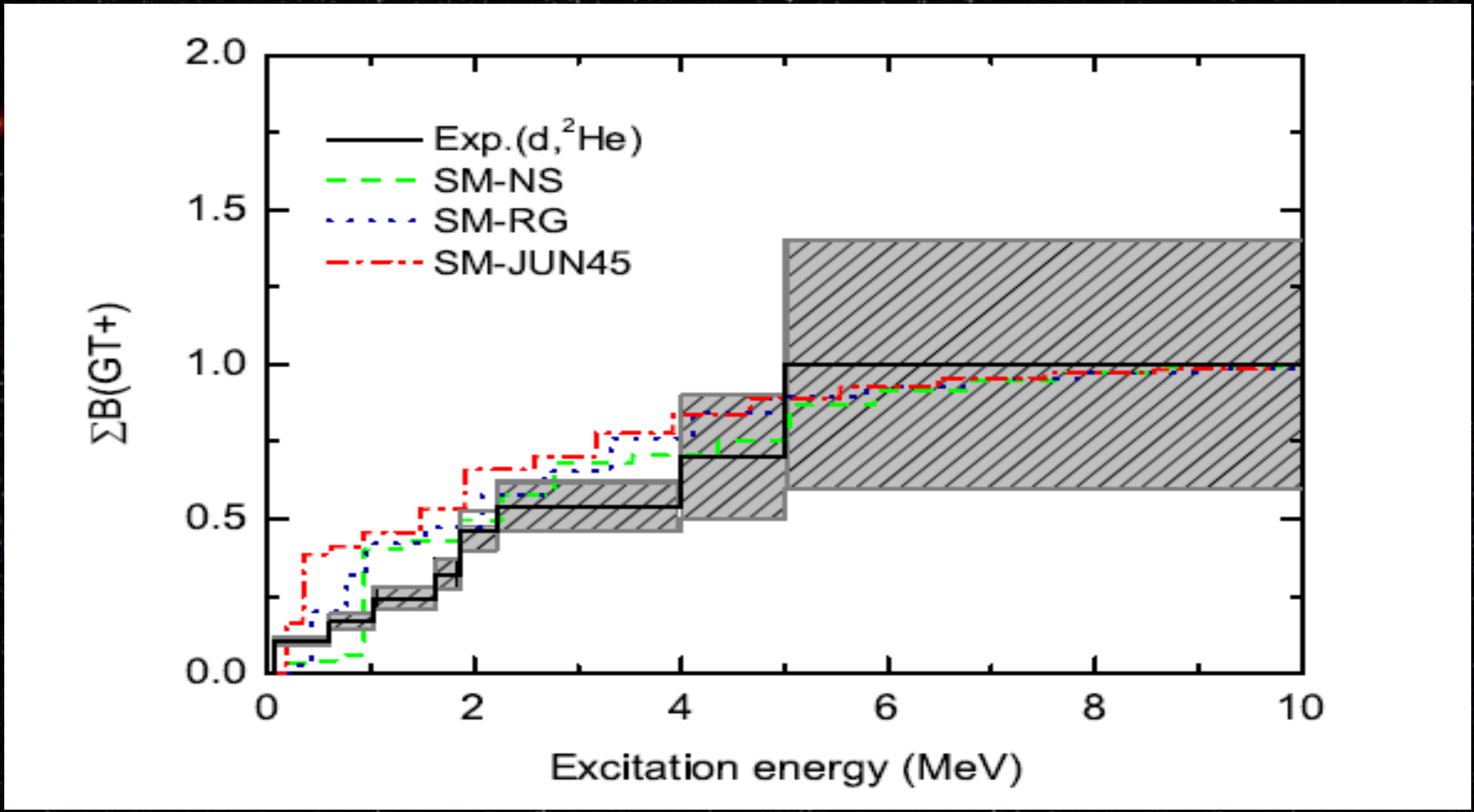




In Independent Particle Model, GT are Pauli-blocked for N>40
In reality, blocking does not occur due to correlations and finite T.
Calculations of rates by SMMC/RPA model.

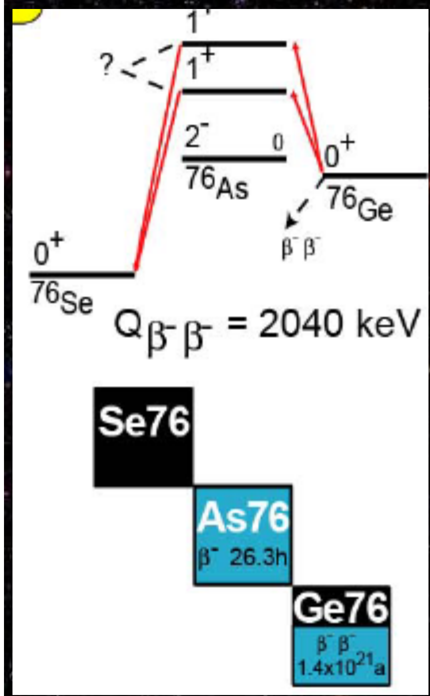
B(GT) strengths for 76Se

34 protons, 42 neutrons

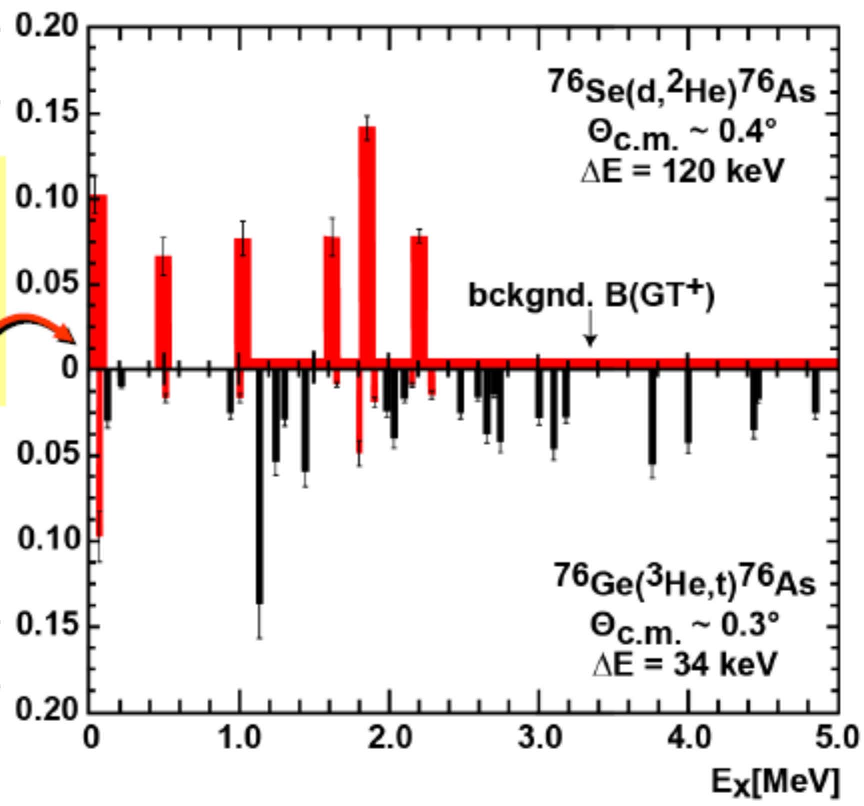


Zhi, Martinez-Pinedo, Sieja, Nowacki

Experimental GT distributions

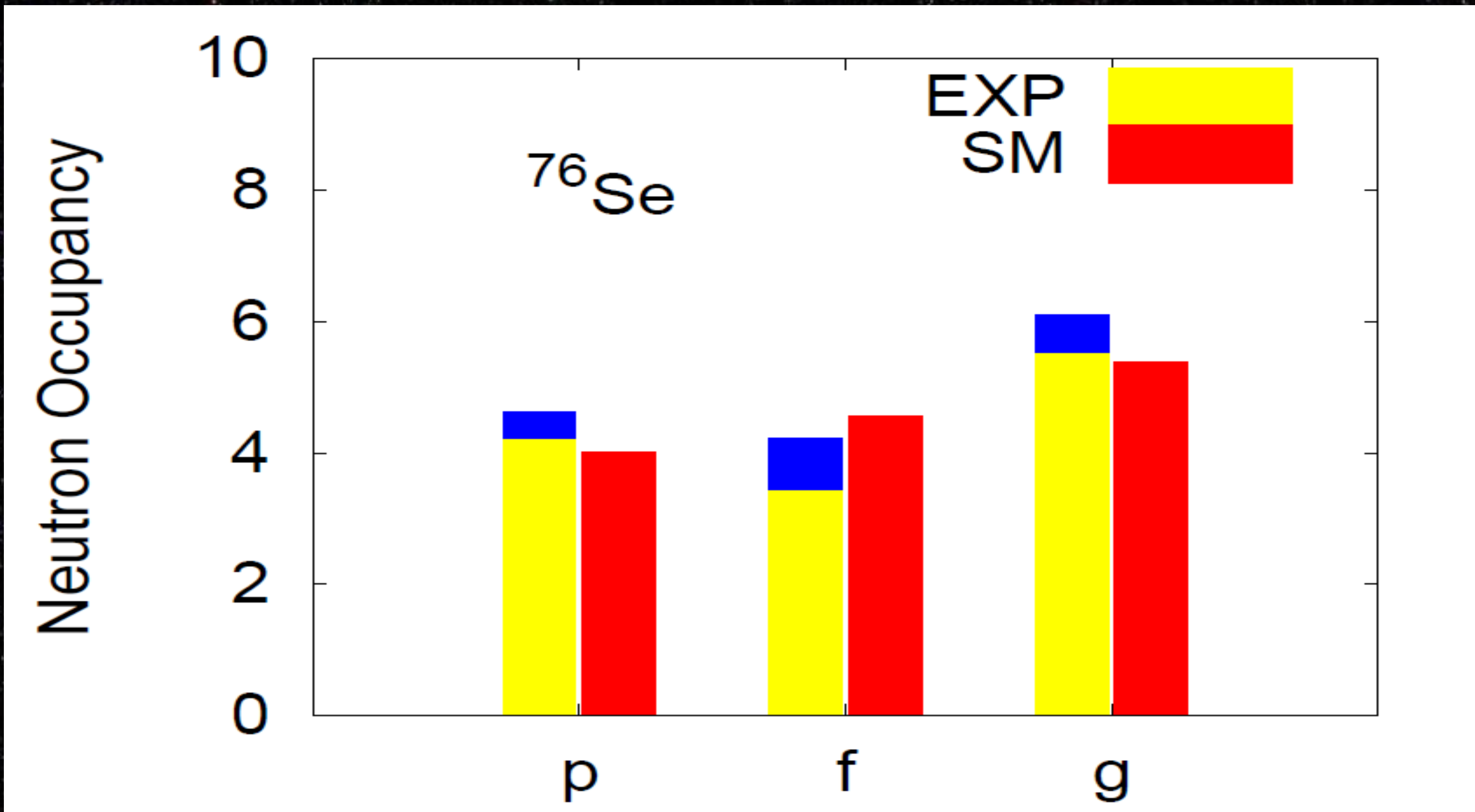


triplet of states: 0.044, 0.082, 0.12 MeV



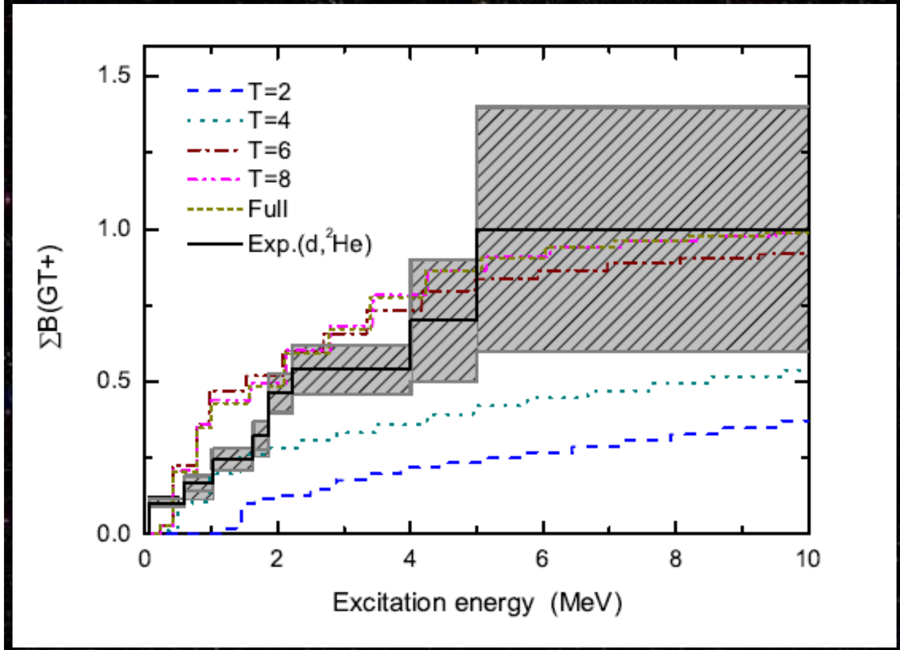
courtesy Dieter Frekers

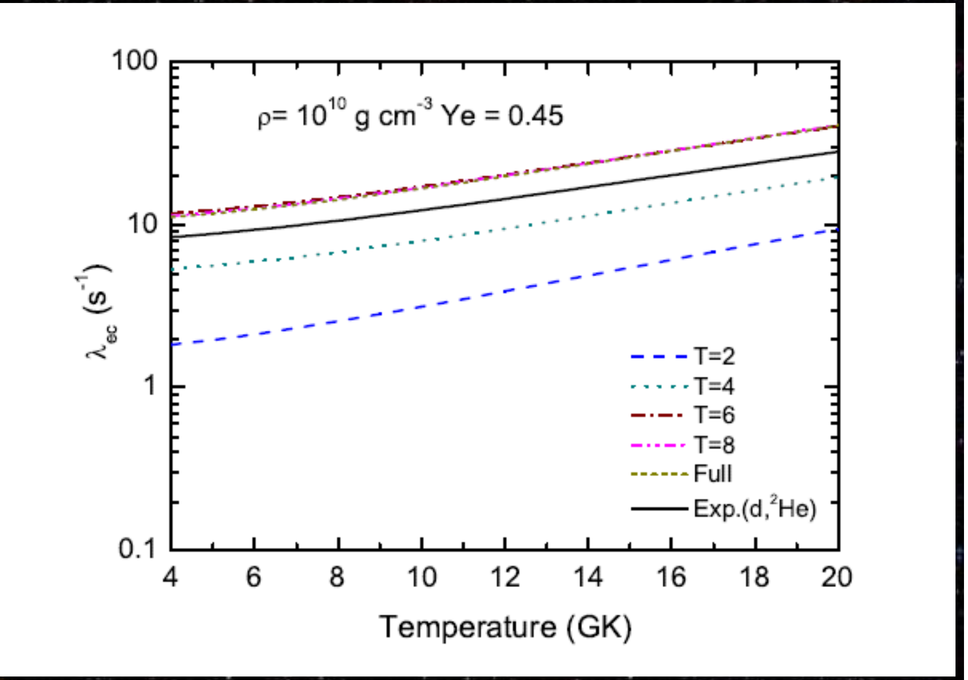
Neutron occupancies



Data from transfer reactions: J.P Schiffer and collaborators

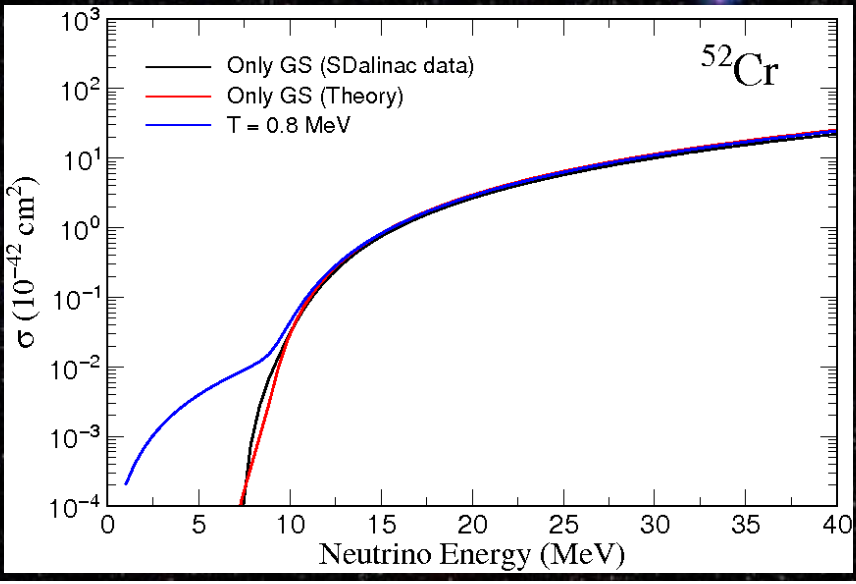
Convergence with truncation level





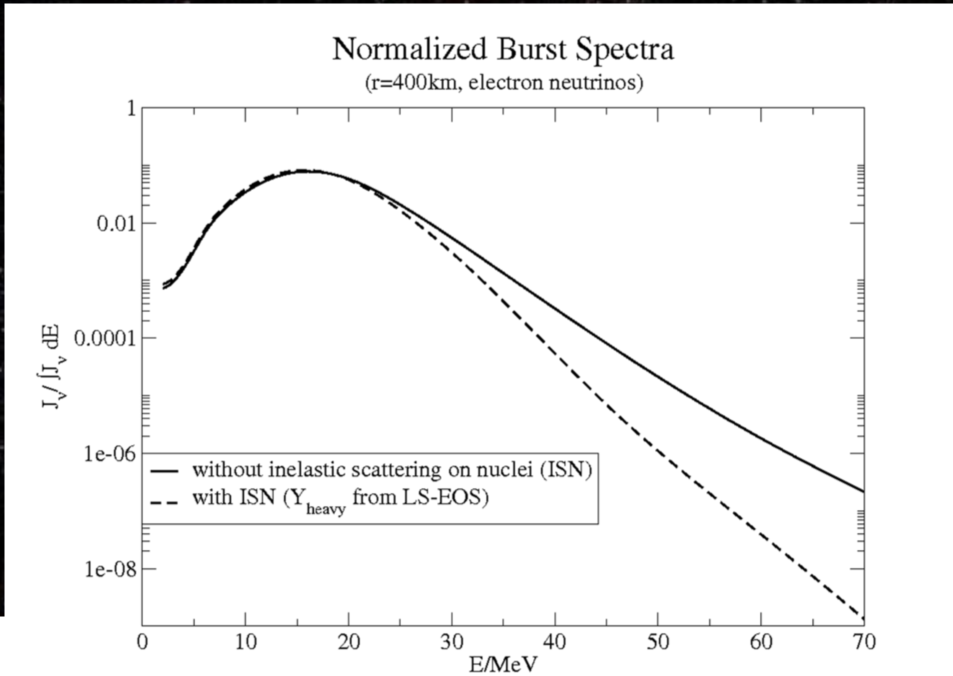
Cross-shell correlations converge slowly. Hence, models like thermofield dynamics model or finite temperature QRPA, which consider only 2p-2h correlations, do not suffice. (Zhi et al.)

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

Consequences for supernova detectors

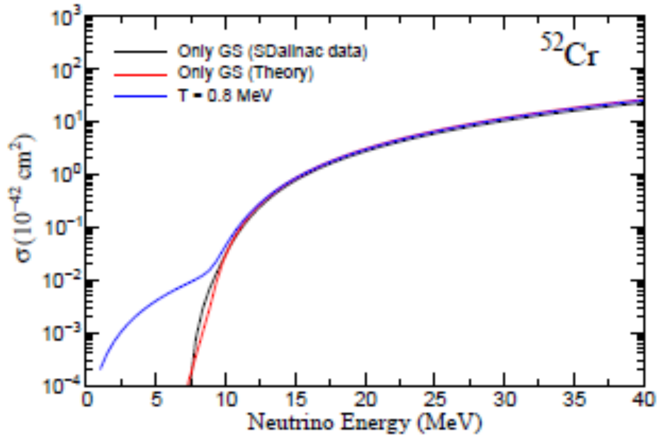
Detector	Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With $A(\nu,\nu')A^*$	Without $A(\nu,\nu')A^*$	Change
SNO	d	5.92	7.08	16%
MiniBoone	^{12}C	0.098	0.17	43%
	^{12}C (N_{gs})	0.089	0.15	41%
S-Kamiokande	^{16}O	0.013	0.031	58%
Icarus	^{40}Ar	17.1	21.5	20%
Minos	^{56}Fe	8.8	12.0	27%
OMNIS	^{208}Pb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

Change in supernova neutrino spectra reduces neutrino detection rates

Inelastic neutrino-nucleus scattering

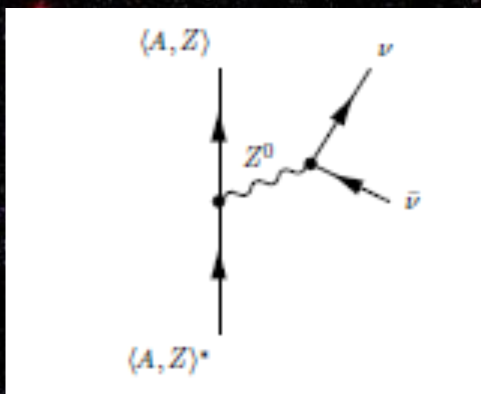
Potential consequences:

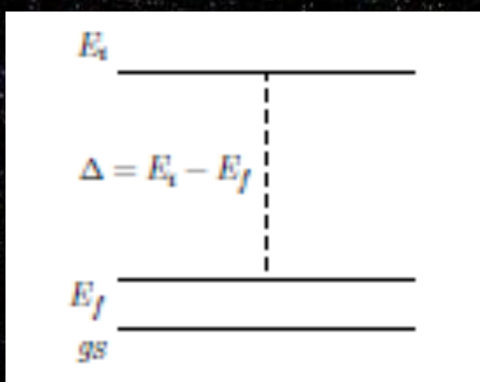
- thermalization of neutrinos during collapse
- preheating of matter before passing of shock
- nucleosynthesis, νp-process
- supernova neutrino signal



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

Nuclear de-excitation





Fuller and Meyer (1991):

In hot stellar environment nuclei can de-excite by emission of neutrino pairs

-additional cooling mechanism, besides electron capture
-source of neutrinos other than electron neutrinos

De-excitation rates

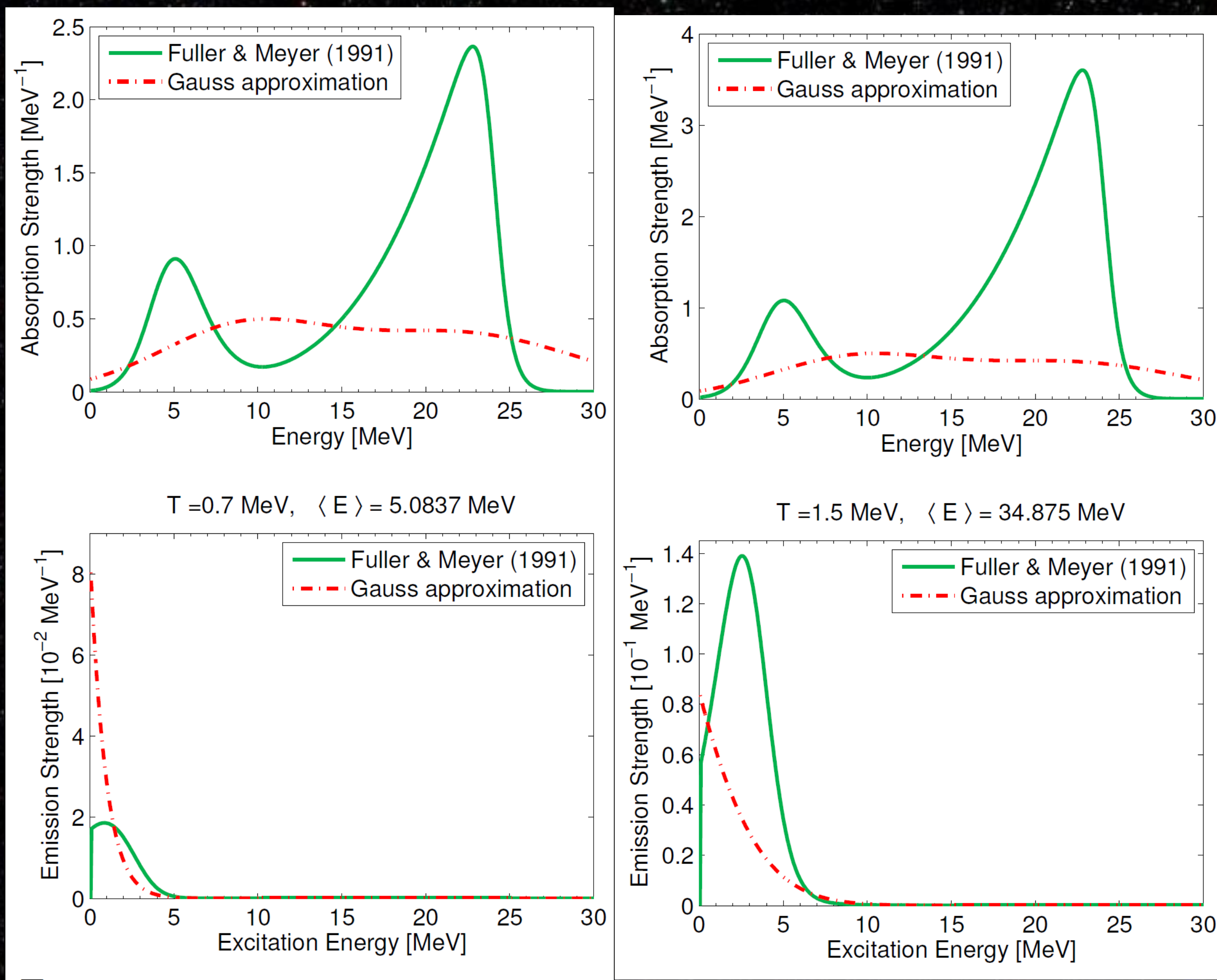
- Neutral current process
- At collapse conditions dominated by Gamow-Teller and first-forbidden transitions

two different approaches:

Fuller+Meyer:
independent particle model, „Brink hypothesis“

Fischer, Martinez-Pinedo:
phenomenological Gaussians for excitation
(guided by data)
„Brink hypothesis“
de-excitation by detailed balance

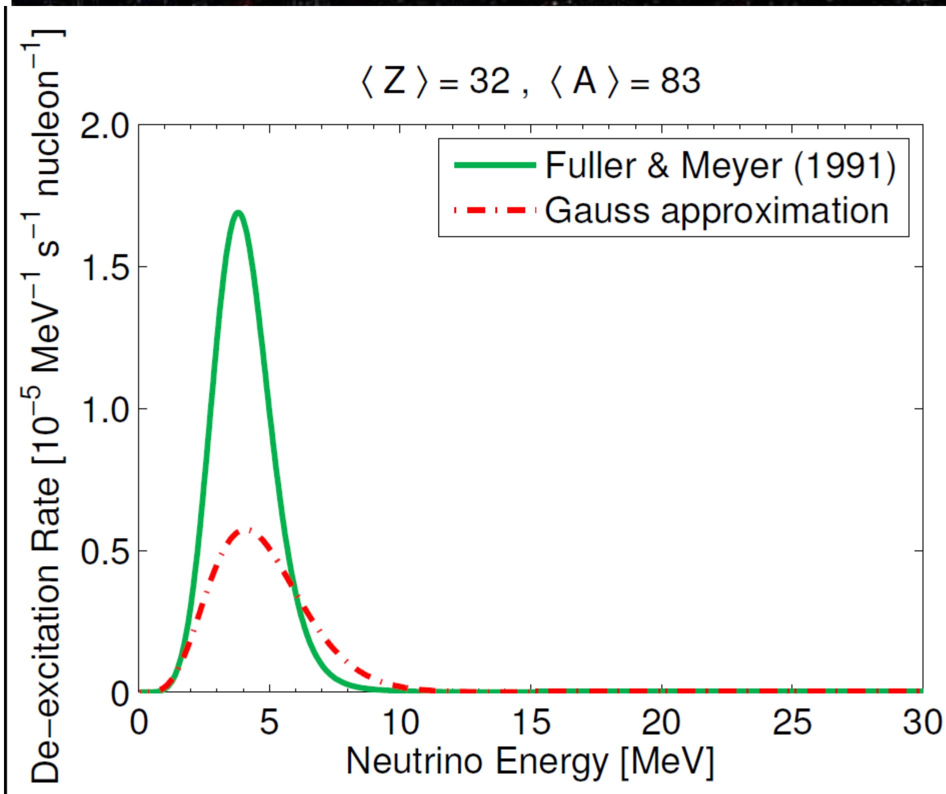
De-excitation strength



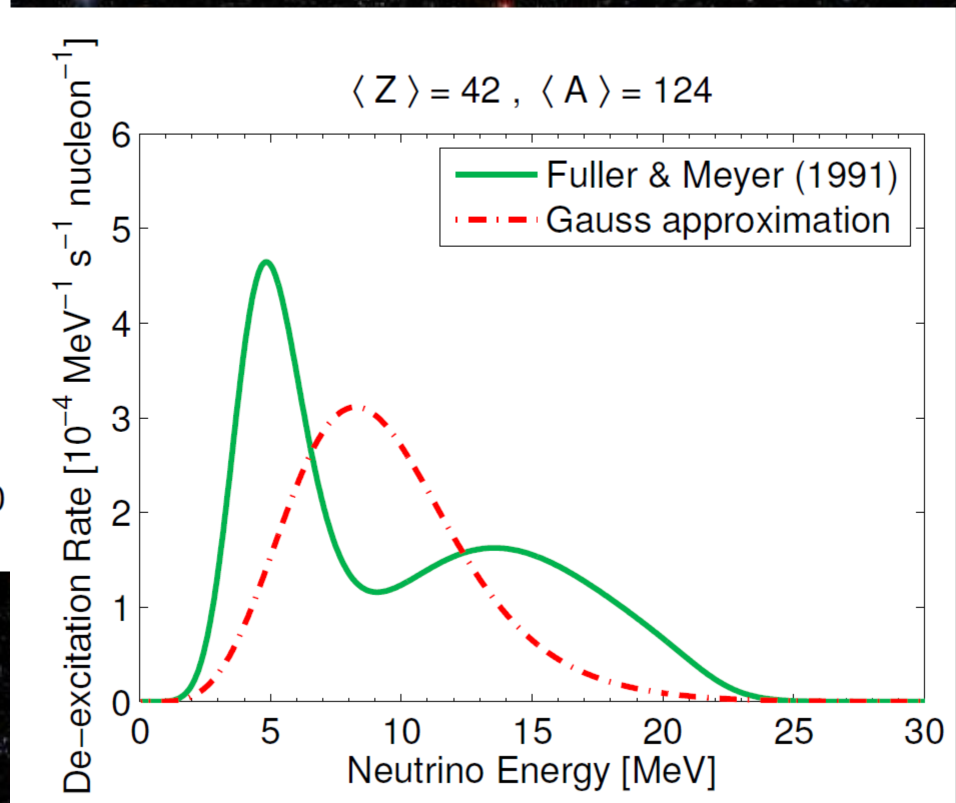
excitation strength

level density cuts strength tails

De-excitation rates

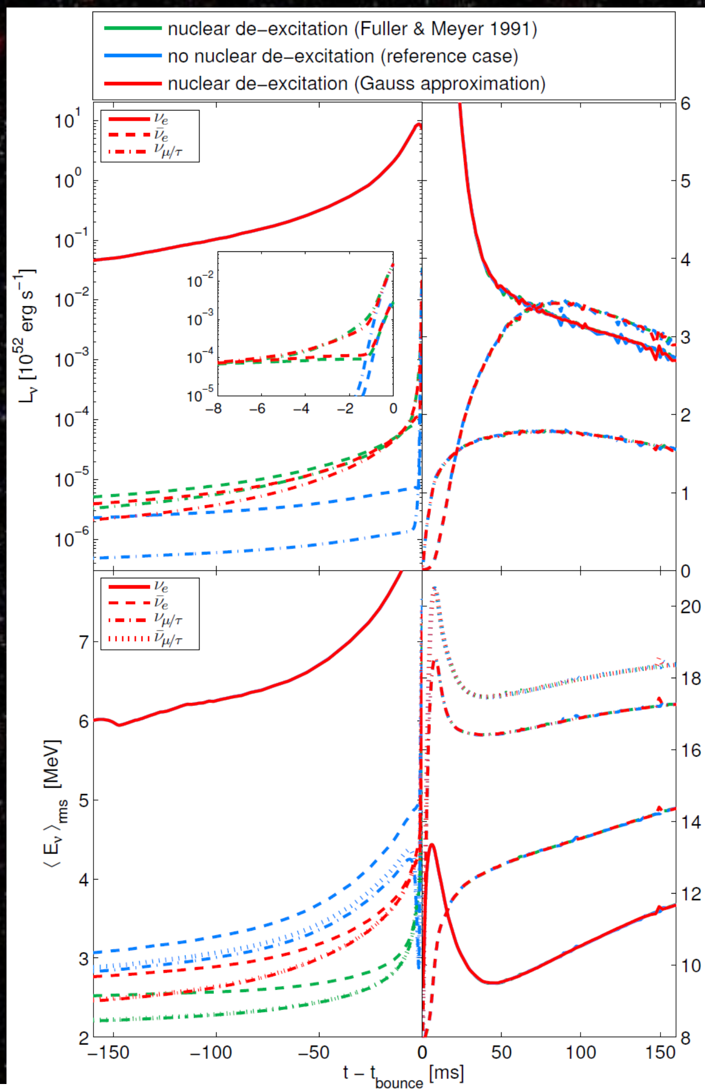


T=1.5 MeV



T=0.7 MeV

Role of nuclear de-excitation in supernova simulation



11.2 solar mass progenitor

spherical symmetry, full neutrino transport (AGILE Boltztran code)

NUCLEAR DEEXCITATION HAS NO EFFECT ON SUPERNOVA DYNAMICS!

Source of other neutrino types

Thanks Gerry

Visit of Gerry and Hans Bethe
January 1993, Pasadena

The RIB Chance: New Horizons