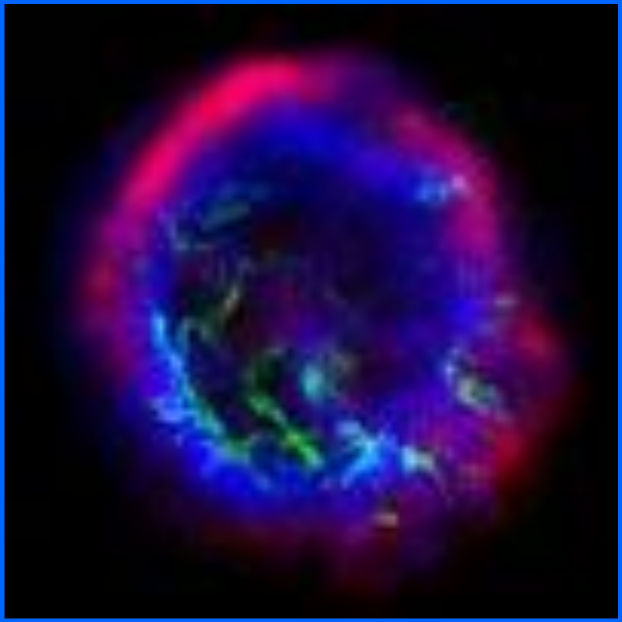
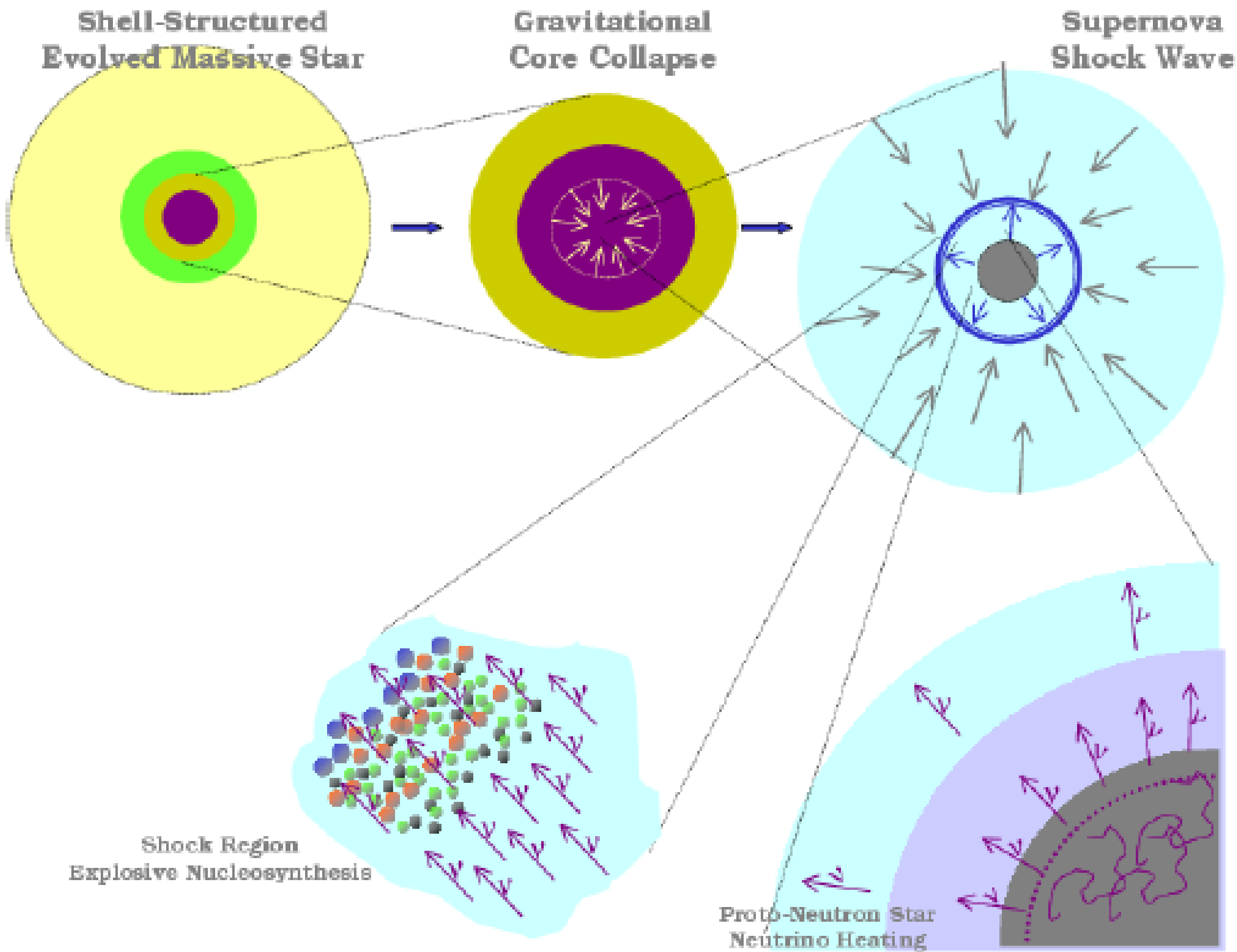
Neutrino-nucleus interaction and its role in supernova dynamics and nucleosynthesis



Karlheinz Langanke
GSI Helmholtzzentrum Darmstadt
Technische Universität Darmstadt

NDM'15, Jyvaeskylae, June 2, 2015

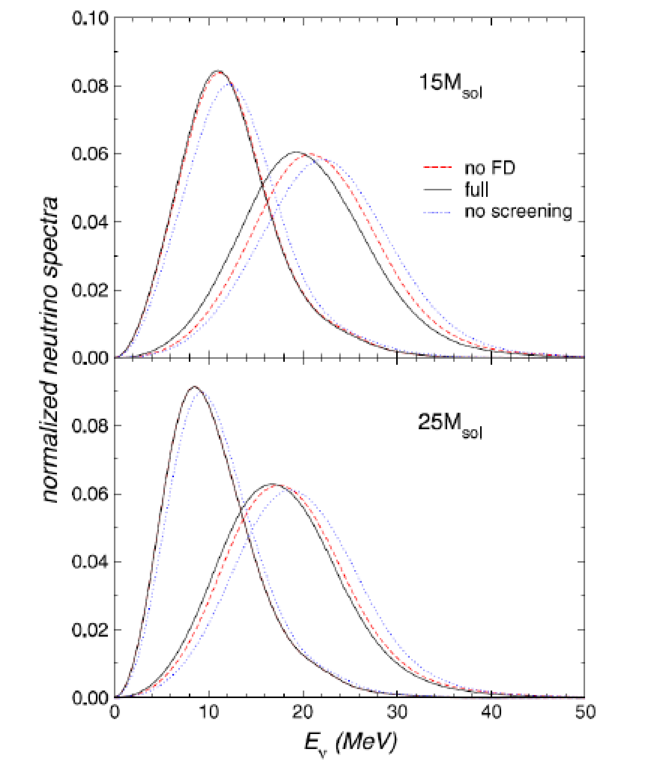
Core-collapse supernovae



Roland Diehl

Neutrino spectra

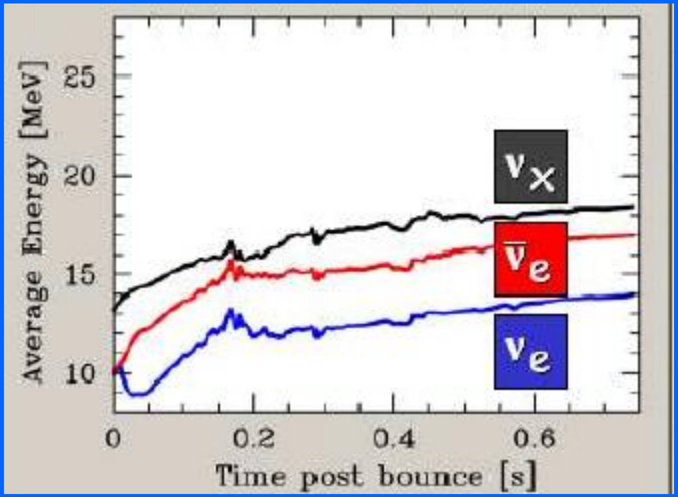
collapse phase:



electron captures on nuclei

(Juodagalvis, Martinez-Pinedo..)

after bounce



cooling of neutron star by nu pairs

energy hierarchy due to opacity

(Raffelt, Janka, Liebendoerfer,...)

Describing neutrino-nucleus reactions

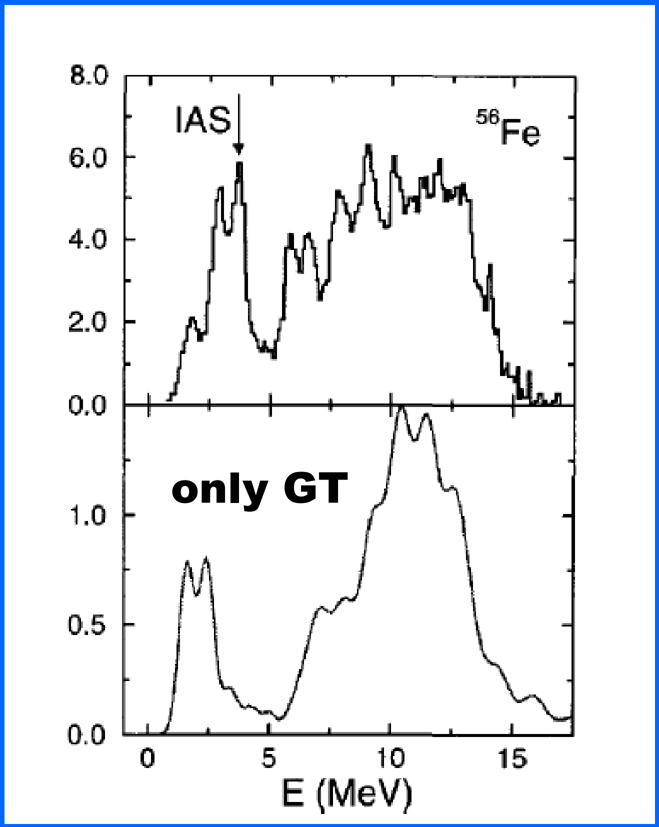
Neutrino energies (and momentum transfer) is low enough that allowed transitions (Gamow-Teller, Fermi) dominate. However, forbidden contributions become important at higher neutrino energies.

Hybrid model (Martinez-Pinedo, Kolbe):

allowed transitions: shell model

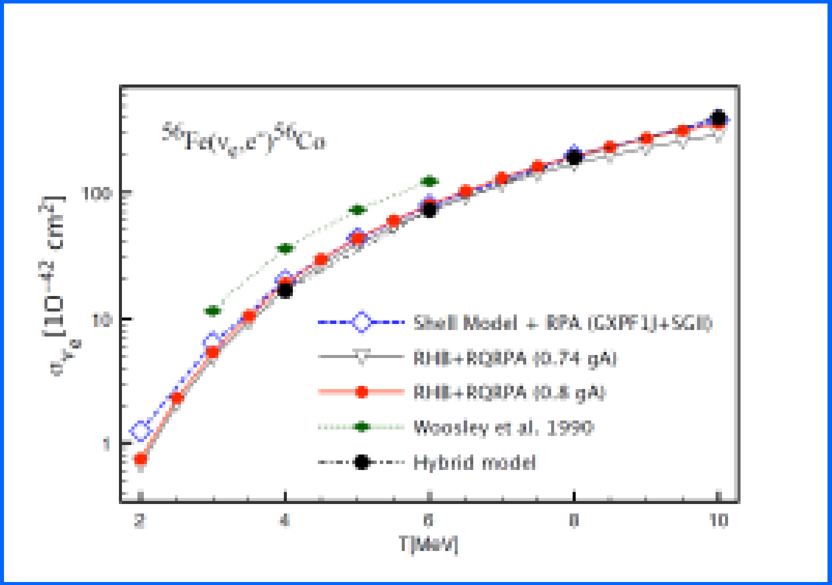
forbidden transitions: RPA

Validation: charged-current reaction



shell model vs (p,n) data

Martinez-Pinedo
Rapaport et al.

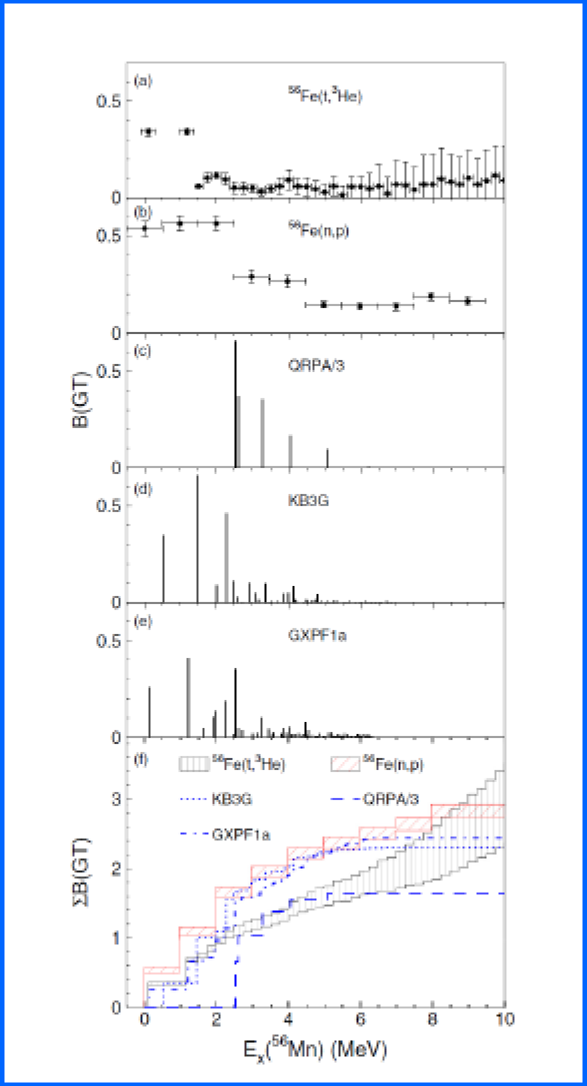


hybrid model vs QRPA

differences at small neutrino energies (sensitivity to GT details)

Paar, Marketin, Vretenar

Validation: charged-current reactions



anti-electron neutrino cross sections more sensitive to nuclear structure effects

(like in electron capture)

Zegers, Brown et al.

Neutrino-nucleus reactions in supernova simulations

charged-current reactions (nu+A, nubar+A) are inverse of electron and positron captures and are considered via detailed balance

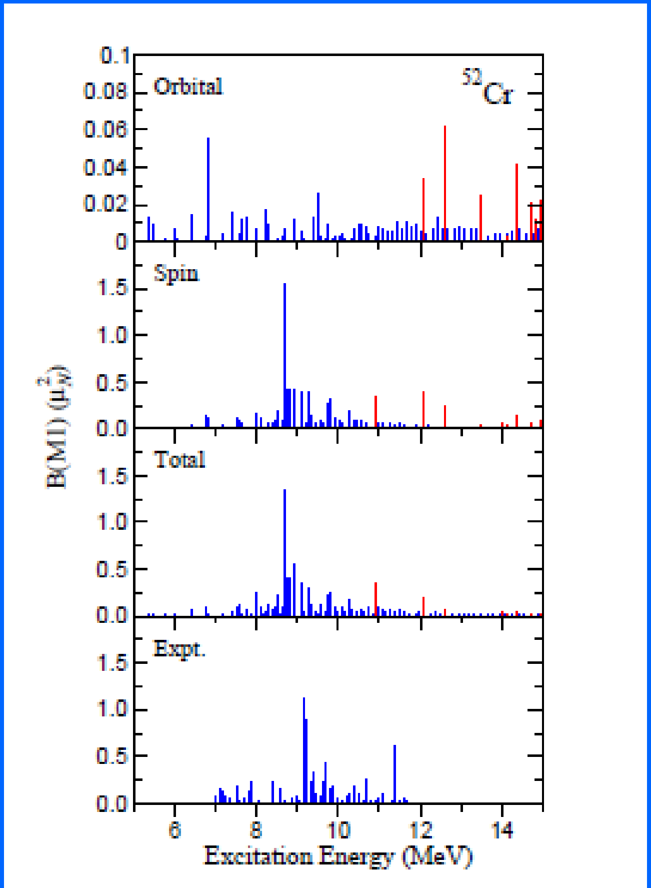
neutral-current reactions (inelastic scattering): not considered until recently

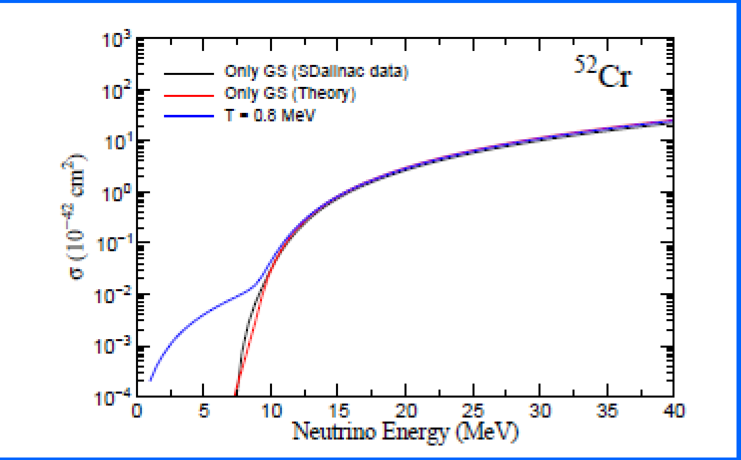
Inelastic neutrino-nucleus scattering at finite temperature

- Approach 1 (based on hybrid model):
  T=0 cross section +
  Gamow-Teller from (a few) excited states +
  contributions from inverted GT transitions
  (Juodagalvis, Martinez-Pinedo, Sampaio,...)

* Approach 2:
  Thermal Quasiparticle RPA
  consistent QRPA at finite temperature
  (Dzhioev, Wambach, Ponomarev)

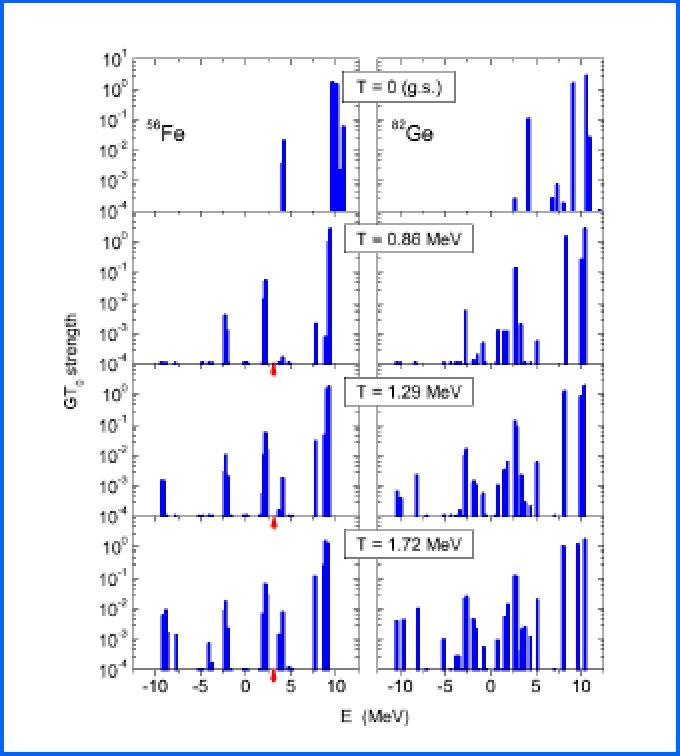
Approach 1: Hybrid model

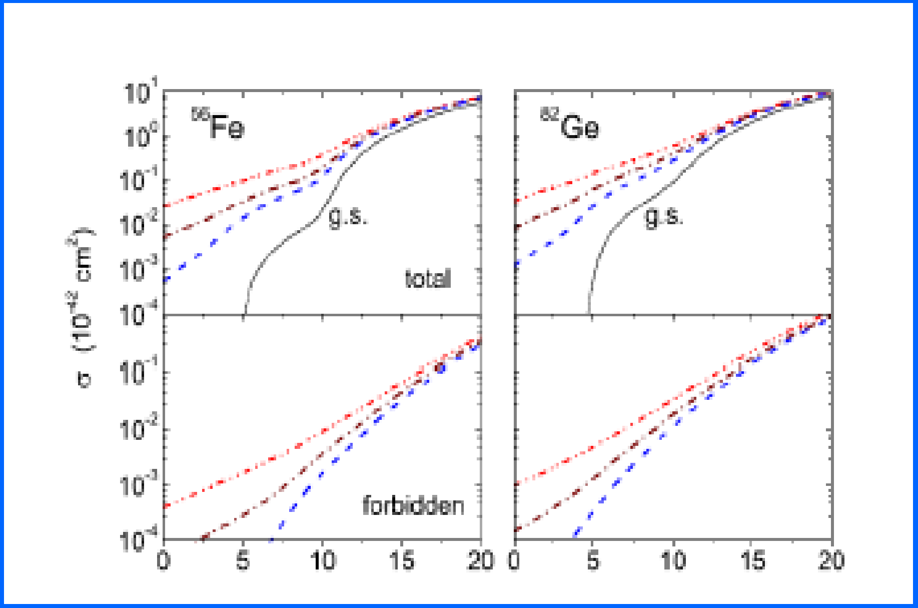




validation from high-precision electron scattering data scattering on excited states dominates at low energies (Martinez-Pinedo, Richter, von Neumann-Cosel)

Approach 2: Thermal QRPA

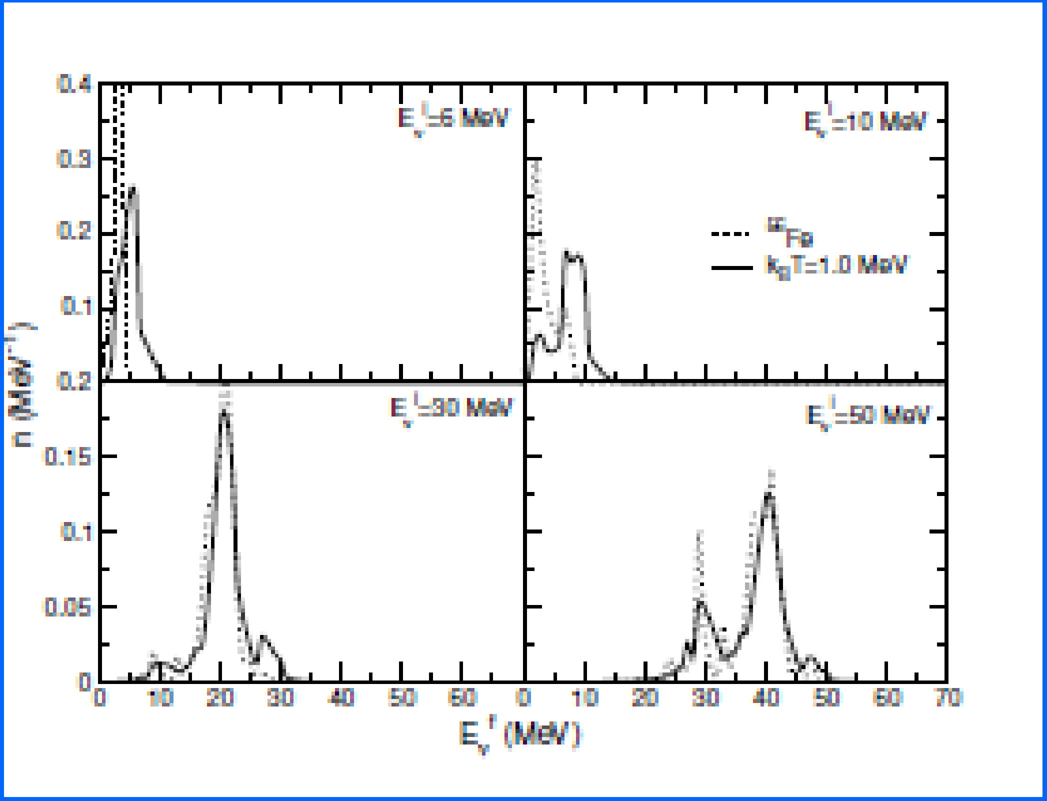




GT dominates, finite T effects only important at low neutrino energies

Dzhioev, Wambach, Ponomarev

Neutrino spectra from inelastic neutrino-nucleus scattering at finite T



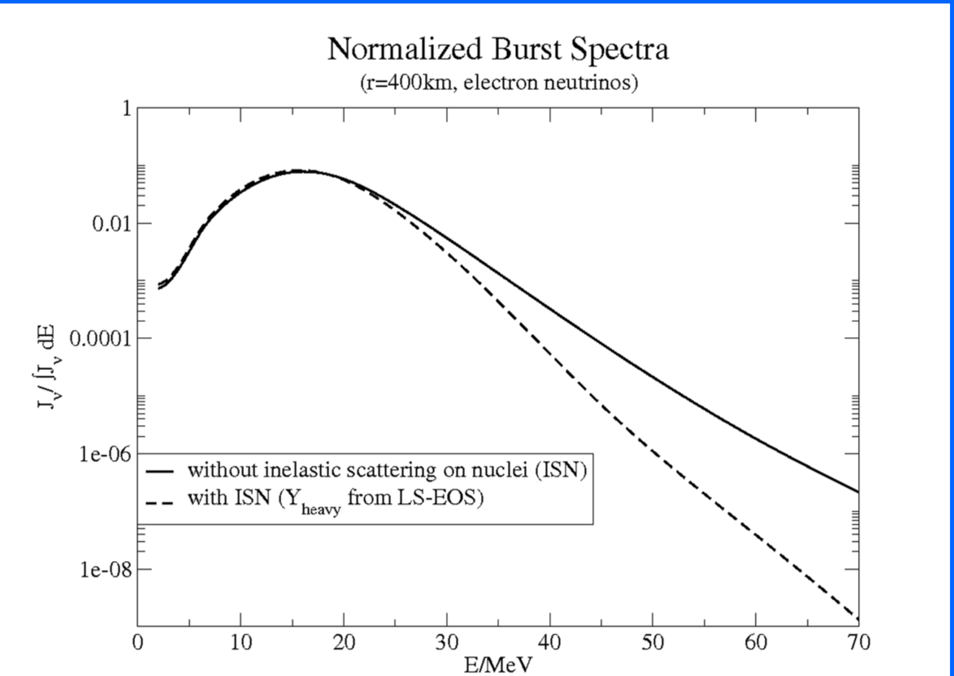
Nuclear deexcitation only important at low neutrino neutrino energies

(from Juodagalvis, Martinez-Pinedo, Sampaio..)

Effect of inelastic neutrino-nucleus scattering on in supernova simulations

little effect on collapse dynamics, thermalization dominated by nu+electron

no preheating of shock material



BUT:

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

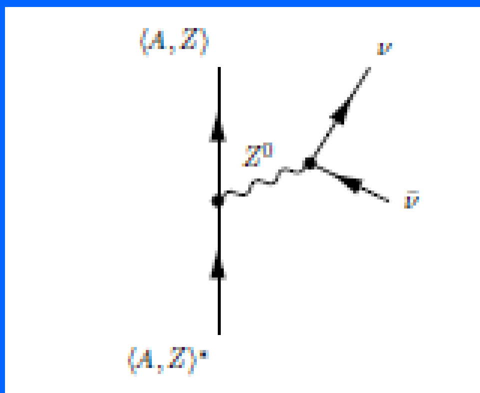
(Janka, Hix, Mueller, Martinez-Pinedo, Juogadalvis, Sampaio)

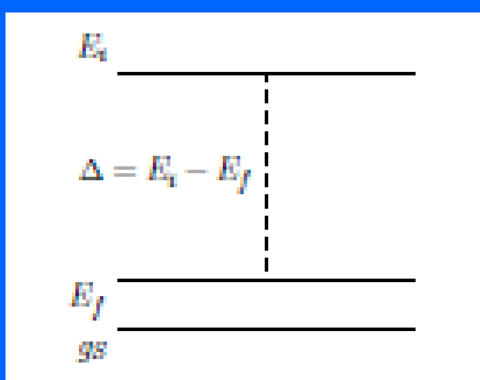
Consequences for supernova detectors

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

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

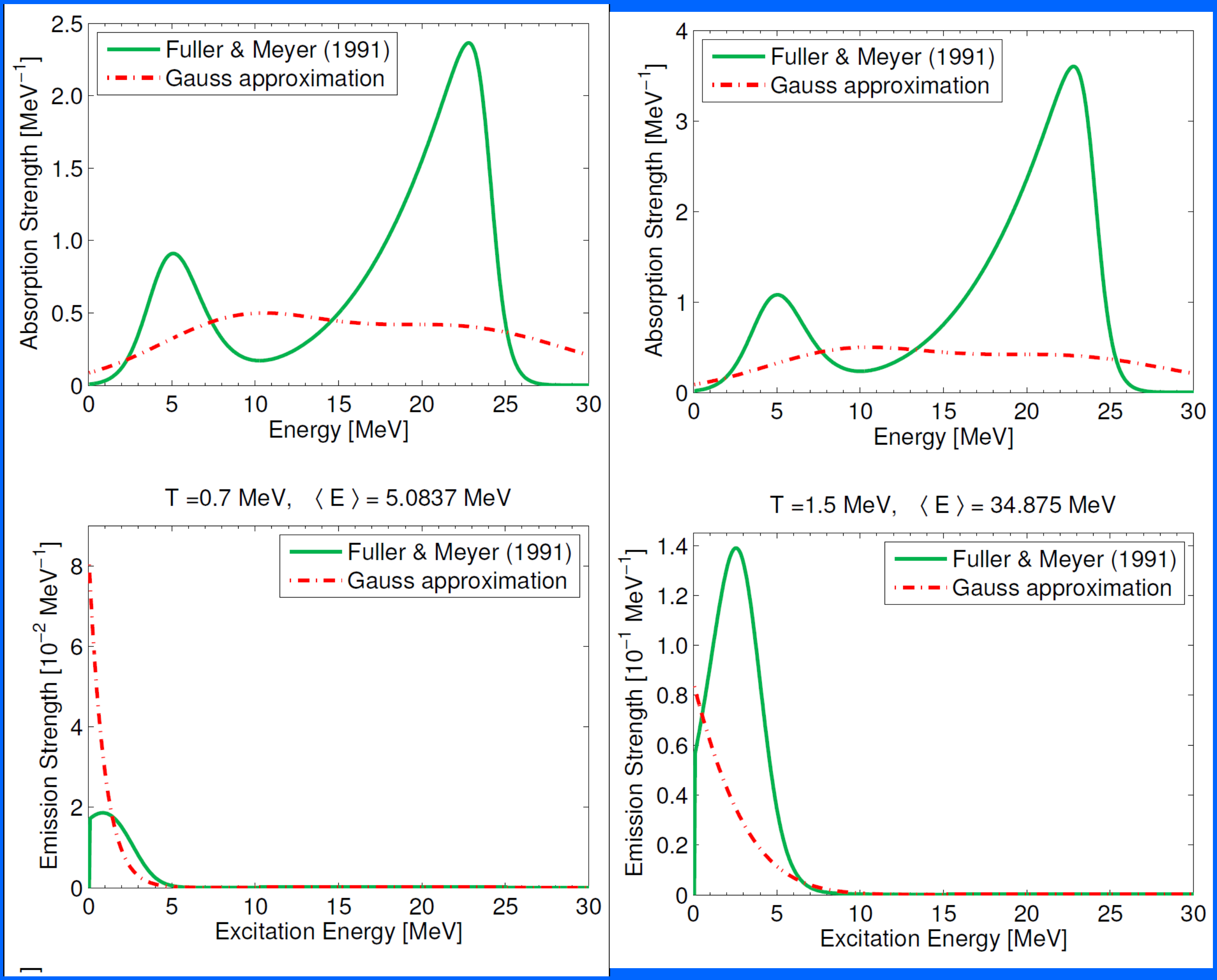
- Neutral current process
- At collapse conditions dominated by Gamow-Teller and first-forbidden transitions

two different approaches:

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

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

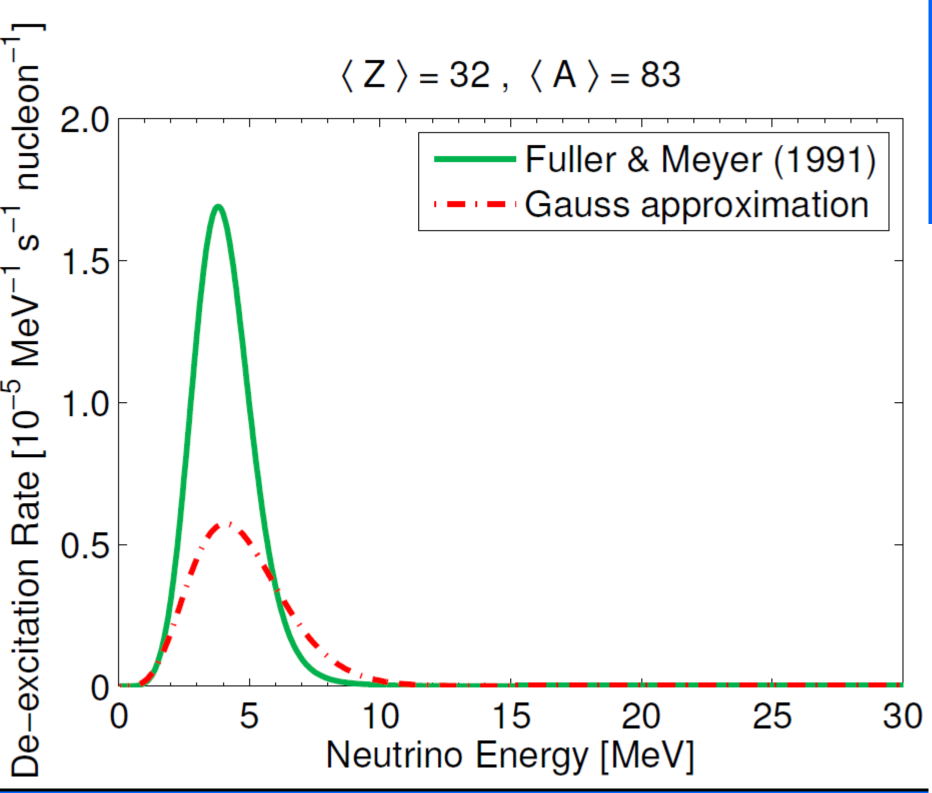
De-excitation strength



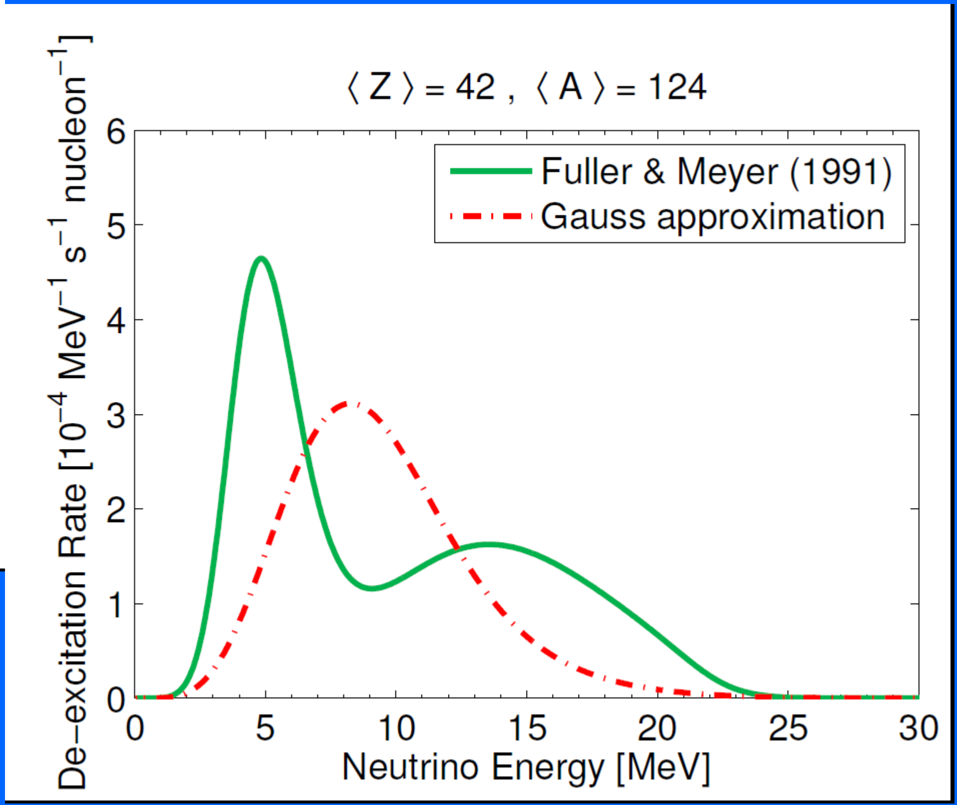
excitation strength

level density cuts strength tails

De-excitation rates

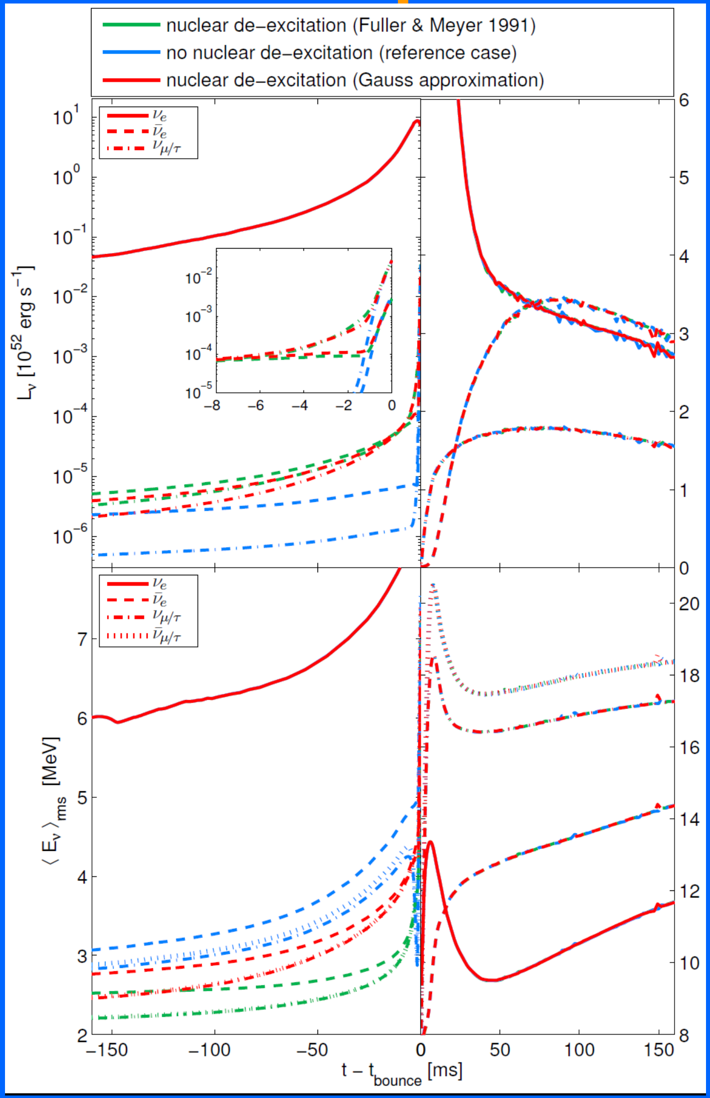


T=1.5 MeV



T=0.7 MeV

Role of nuclear de-excitation in supernova simulation



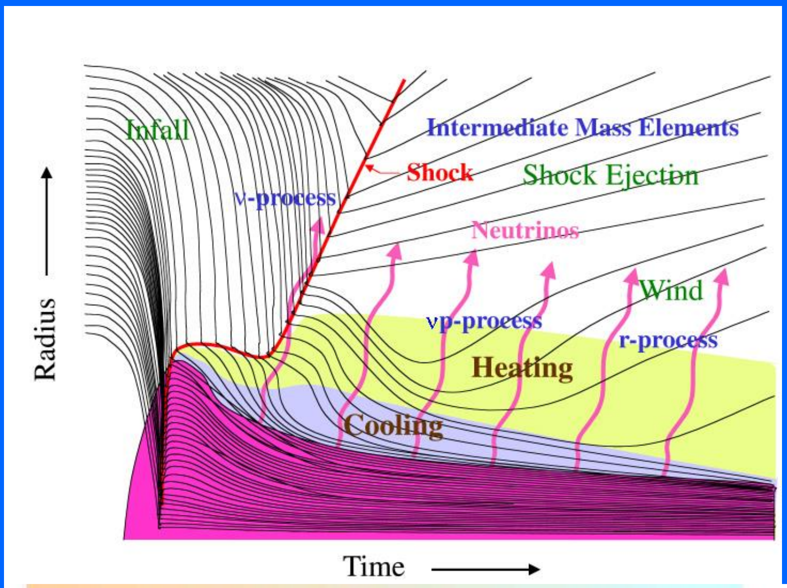
11.2 solar mass progenitor

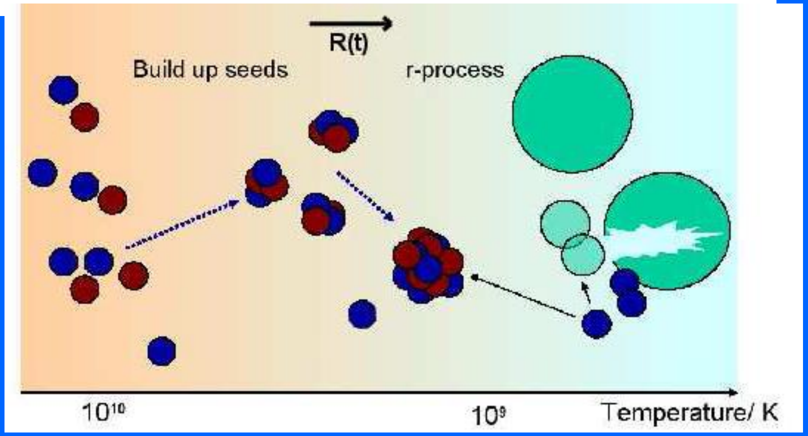
spherical symmetry, full neutrino transport (AGILE Boltztran code)

NUCLEAR DEEXCITATION HAS NO EFFECT ON SUPERNOVA DYNAMICS!

Source of other neutrino types

Neutrino-nucleus reactions and its role in nucleosynthesis





neutrino-driven wind on top of proto-neutron star:
neutrino absorption on nucleons sets proton/neutron ratio Ye

if Ye > 0.5: vp process
if Ye < 0.5: r-process

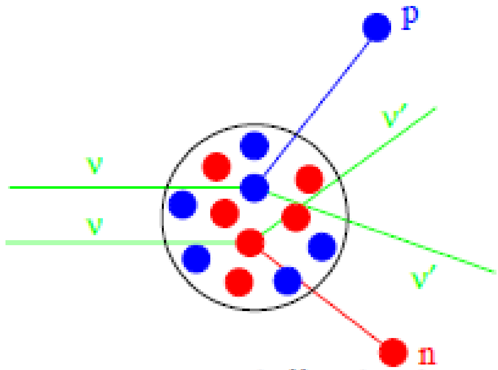
modern simulations predict only conditions for weak r-process (up to A~130)

neutrino process in outer burning shells

Neutrino nucleosynthesis

When the neutrinos pass through the outer shells of the star, they can interact with nuclei exciting them above particle thresholds. Examples are:

$^{12}\mathrm{C}(\nu,\nu'\mathrm{p})^{11}\mathrm{B}$; $^{12}\mathrm{C}(\nu,\nu'\mathrm{n})^{11}\mathrm{C}$



In this way, neutrino-induced reactions can contribute to nucleosynthesis. As a rule of thumb, neutrino nucleosynthesis is important if the abundance ratio of parent and daughter is 1000 or larger. Simulations of neutrino nucleosynthesis abundances require reliable nucleosynthesis calculations during hydrostatic burning (including s-process) and during the shock passage.

Neutrino nucleosynthesis

improved calculations (Sieverding, Huther, Martinez-Pinedo, Heger)

-> global differential neutrino-nucleus cross sections

-> modern supernova neutrino spectra (lower average energies)

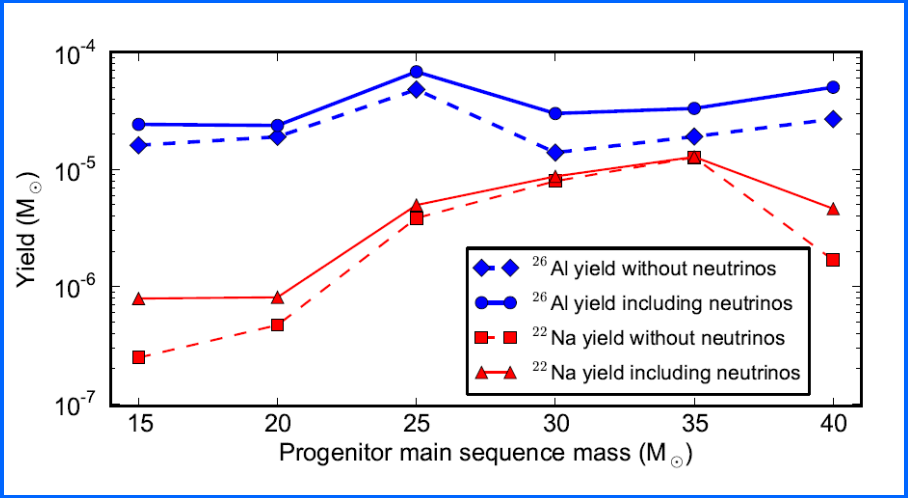
Star	Nucleus	no ν	Low energies[a]	High energies[b]
15 $M_\odot$	^{7}Li	0.001	0.28	2.84
	^{11}B	0.007	1.43	6.13
	^{15}N	0.87	0.68	0.79
	^{19}F	1.02	1.14	1.31
	^{138}La	0.07	0.67	1.18
	^{180}Ta	0.07	1.14	1.81
25 $M_\odot$	^{7}Li	0.0006	0.11	0.86
	^{11}B	0.003	0.80	2.81
	^{15}N	0.08	0.10	0.13
	^{19}F	0.06	0.24	0.43
	^{138}La	0.03	0.63	1.14
	^{180}Ta	0.14	1.80	2.81

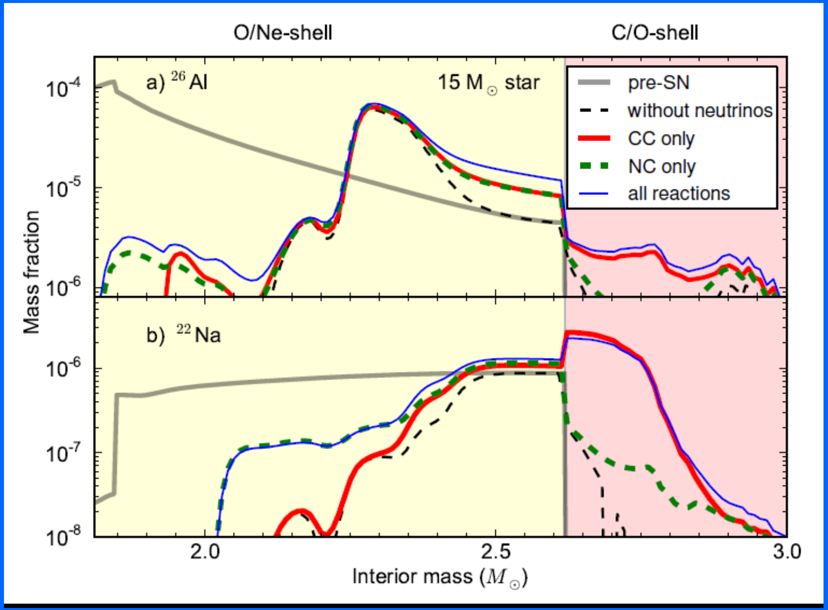
[a] $T_{\nu_e} = 2.8$ MeV, $T_{\bar{\nu}_e} = T_{\nu_{\mu,\tau}} = 4.0$ MeV

[b] $T_{\nu_e} = T_{\bar{\nu}_e} = 4.0$ MeV, $T_{\nu_{\mu,\tau}} = 6.0$ MeV

Neutrino nucleosynthesis is sensitive to those neutrino types not observed from SN1987a

Neutrino production of radio-isotopes





neutrinos contribute in two distinct ways:

i) by providing free protons by spallation from abundant nuclei like 20Ne, 24Mg

ii) by direct capture on nuclei like 26Mg or 22Ne

Detecting supernova neutrinos

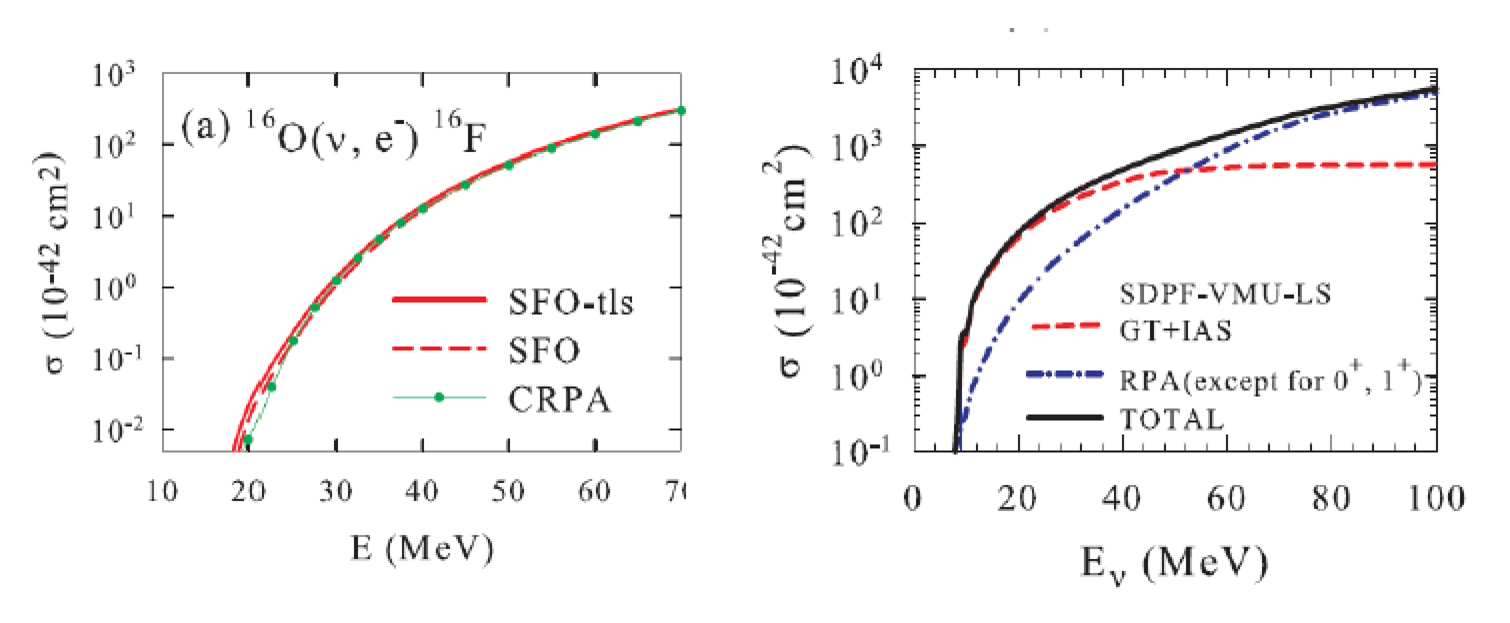
carbon (scintillator): BOREXINO, KamLAND,...
large Q values, transition to T=1 states fixed by experiment

oxygen: SuperKamiokande
large Q values, Gamow-Teller strongly suppressed

argon (liquid scintillator): ICARUS
hybrid model calculation for nu_e, nuclear challenge for anti nu_e

lead: HALO
large cross sections as (N-Z) large, fixed by sum rules and positions of giant resonances, neutron signal difficult to predict as GT strength resides around (2n) threshold

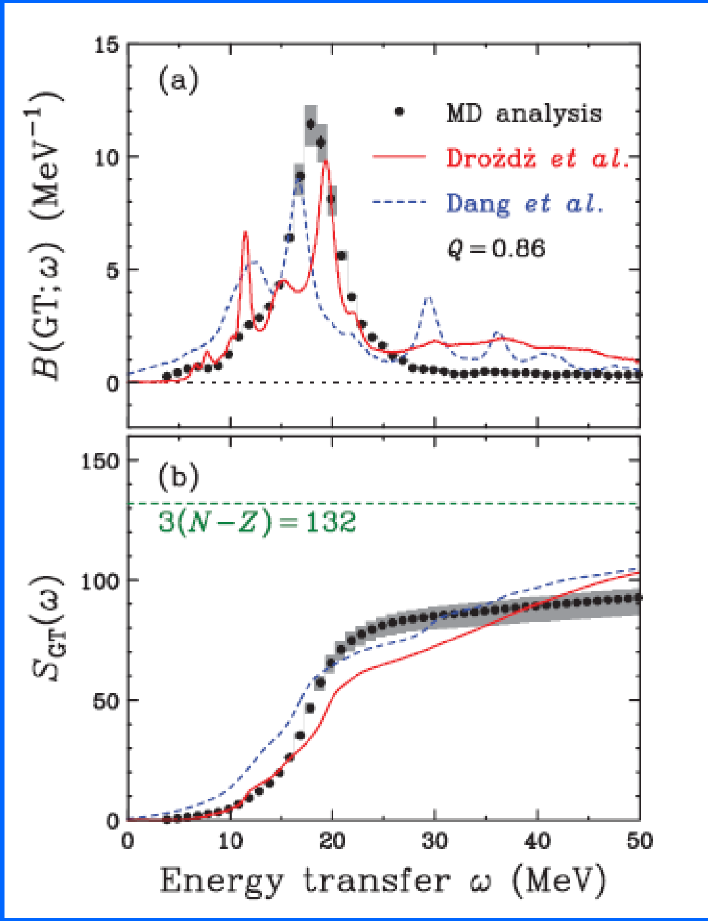
Cross sections for oxygen and argon

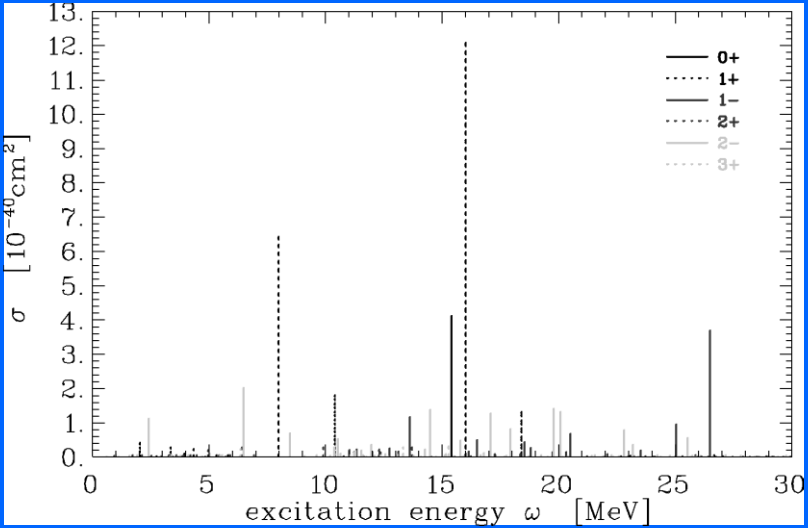


hybrid model applications

T. Suzuki, Otsuka

GT distribution in 208Pb





RPA calculation by Kolbe

-> QRPA/RPA calculations do not reproduce spreading and fragmentation of GT strength

important for neutron signal in lead detector, as GT strength resides around 2n-threshold at 14.9 MeV

(p,n) measurement at RCNP Osaka

Wakasa et al., PRC 85 (2012) 064606

Neutrino-nucleus reactions: Summary and outlook

description of neutrino-nucleus cross sections reasonably well under control

\`limited\` influence on supernova dynamics

effect on high-energy part of neutrino spectra

important role in nucleosynthesis of selected nuclides (nu process)