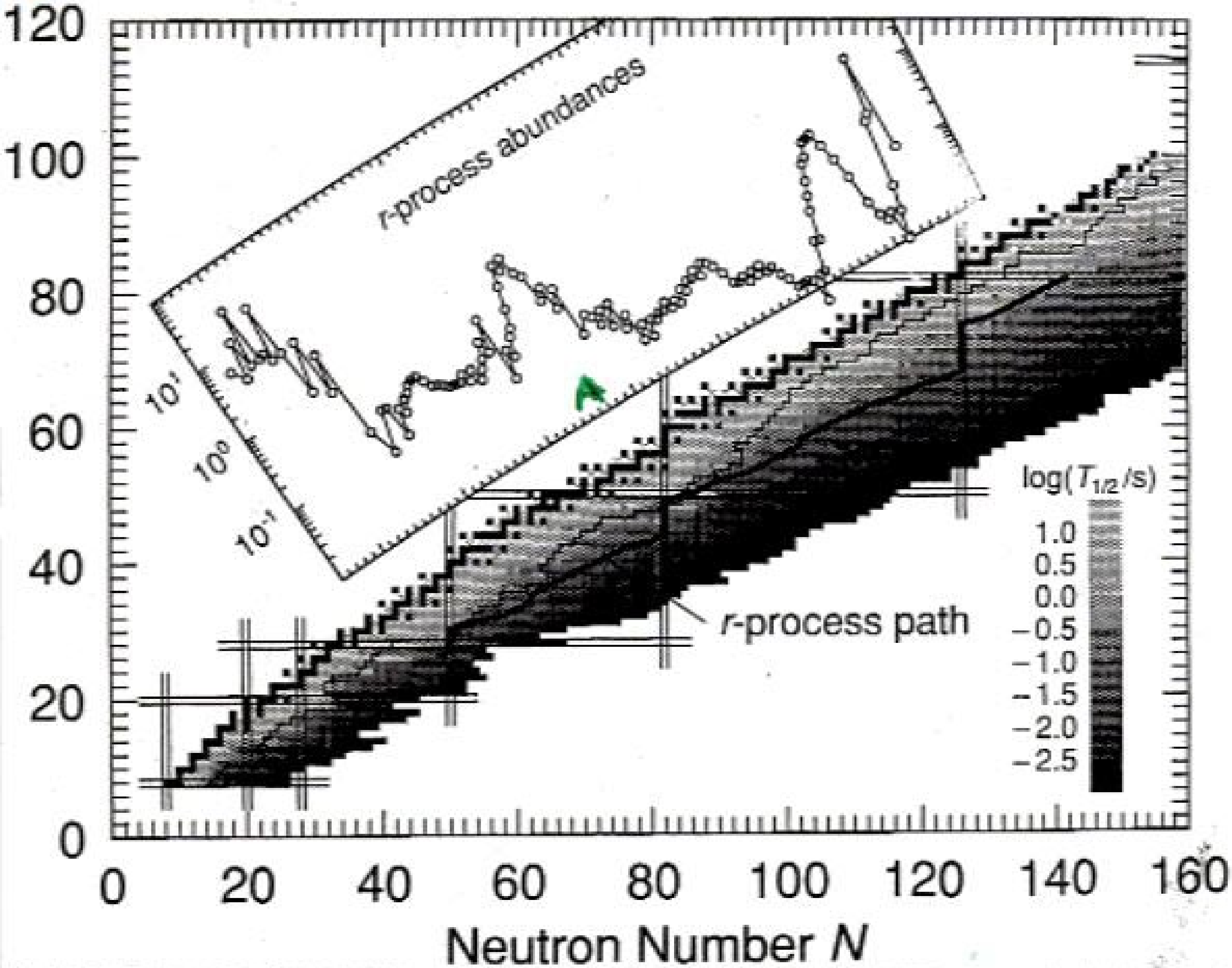
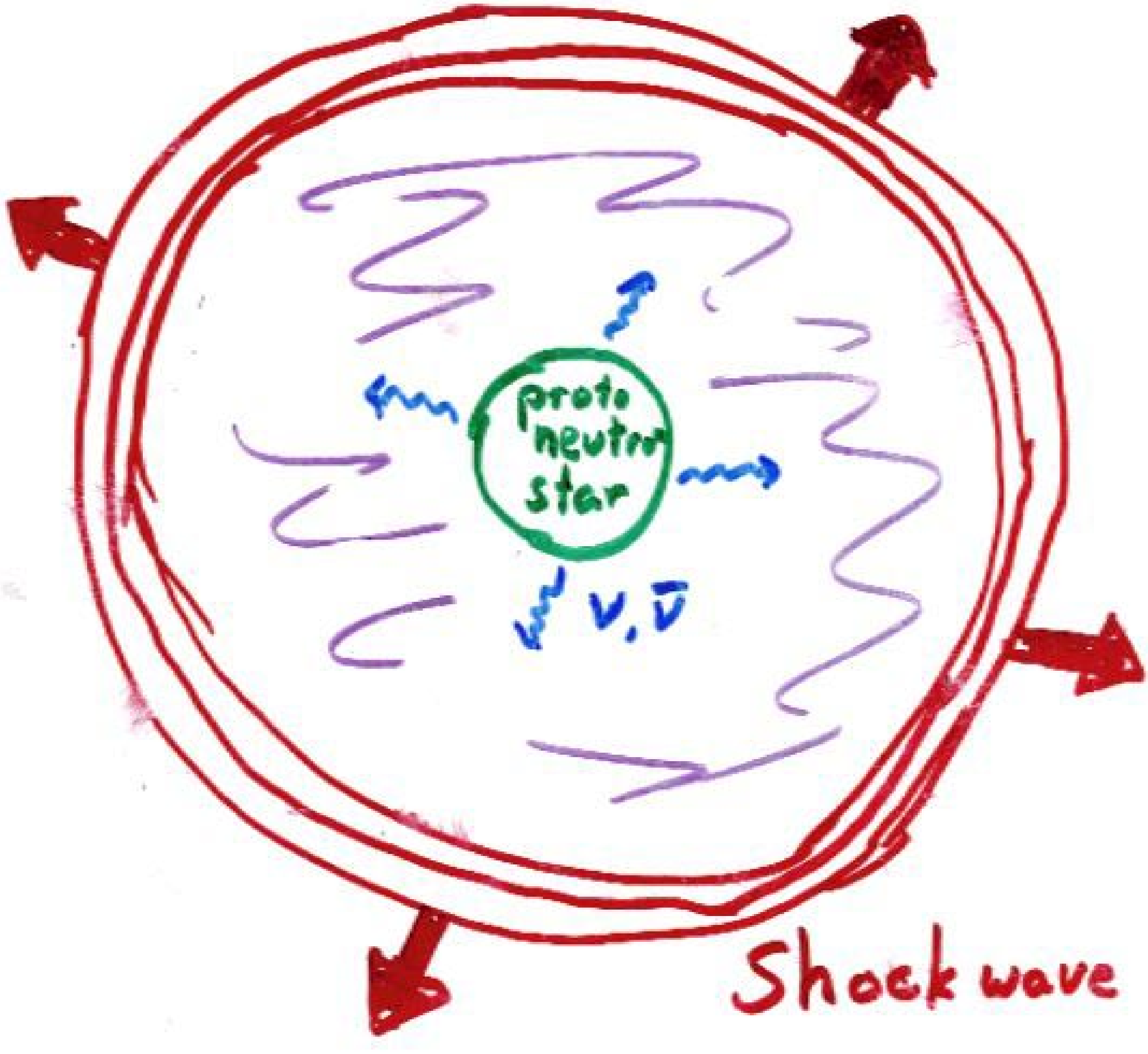
"Schematic"

proton number Z



Neutrino-driven wind



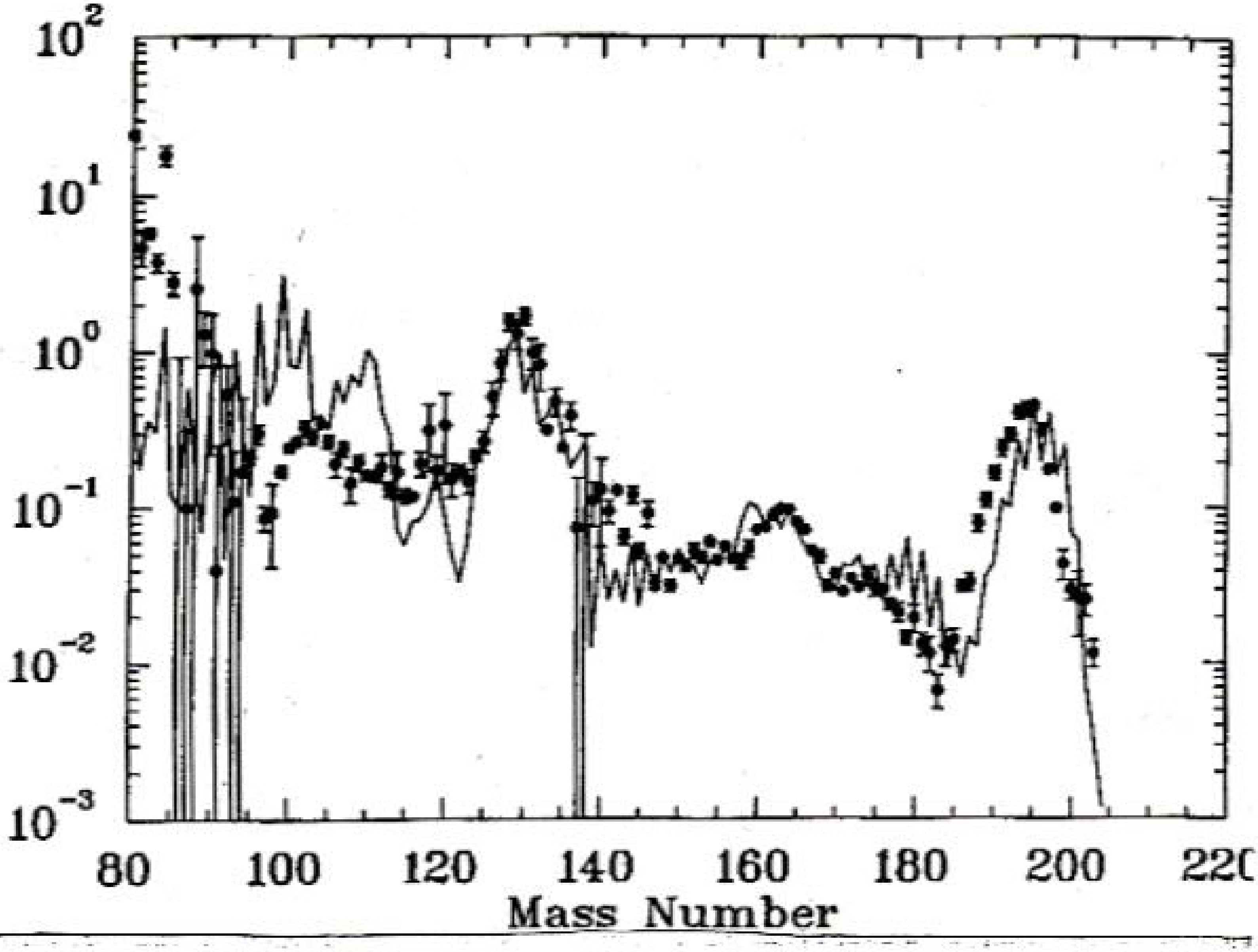
$\langle E_\nu \rangle \approx 11$ MeV

$\langle E_{\bar{\nu}} \rangle \approx 16$ MeV

$\Rightarrow \boxed{\frac{n}{p} \approx 1.5}$

$\nu + n \rightarrow p + e^-$

$\bar{\nu} + p \rightarrow n + e^+$



10^2
10^1
10^0
10^-1
10^-2
10^-3
80
100
120
140
160
180
200
220
Mass Number

But the ν is a double-edged sword...

The α effect

Equilibrium neutron/proton ratio not stable!!!

Protons are captured and stuck into α particles as soon as they're created!!!

n/p **shrinks!!!**

The upshot:

Must... get away... from neutrinos...

Neutrinos do everything

- power an expansion that causes T and ρ to fall (varying the conditions)
- set the neutron/proton ratio via

$$\nu + n \rightarrow p + e^-$$
$$\bar{\nu} + p \rightarrow n + e^+.$$

  The $\bar{\nu}$'s have higher energy and give an excess of neutrons.
- eject $\approx 10^{-5} M_\odot$ of stuff.

not to mention exploding the star!

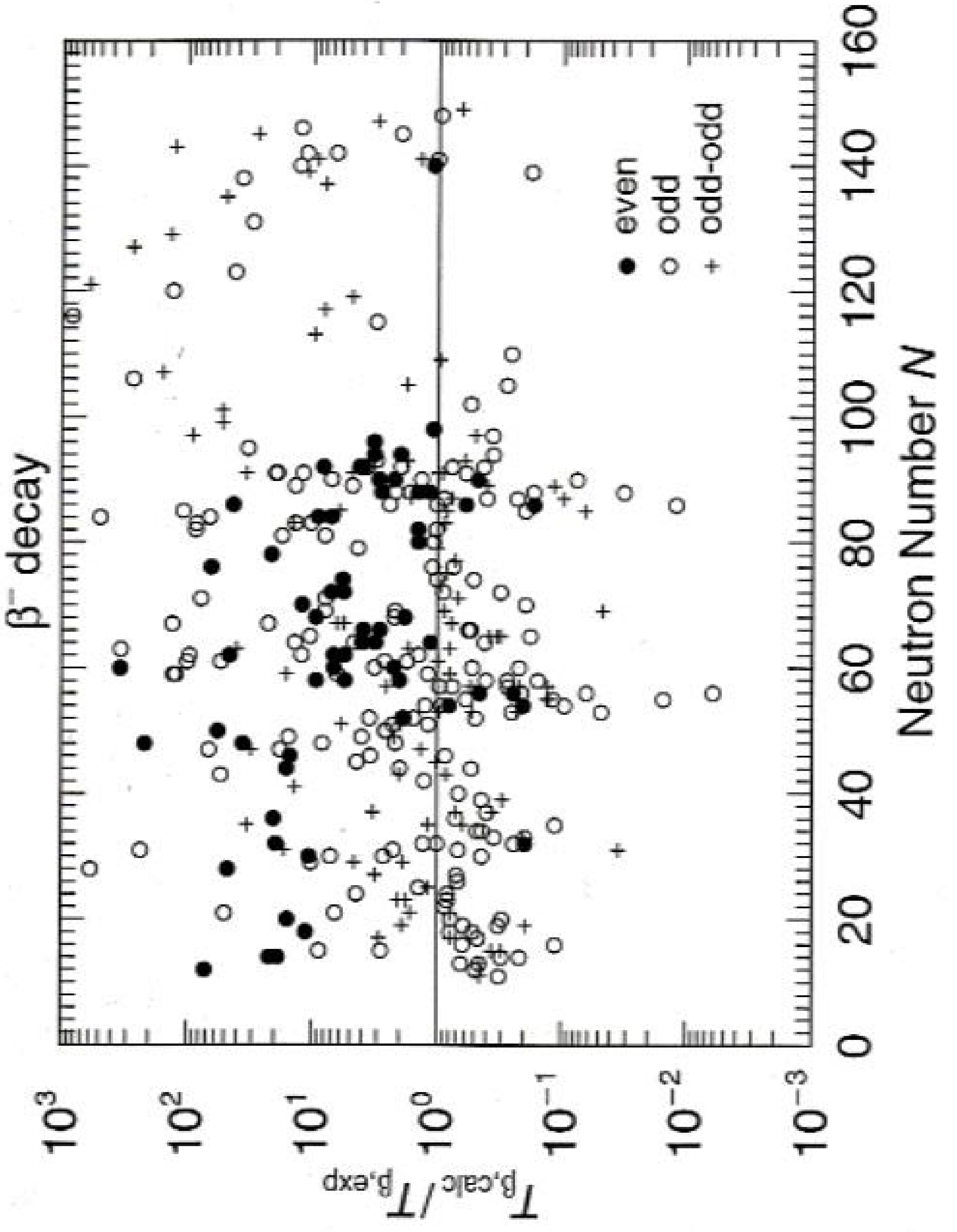
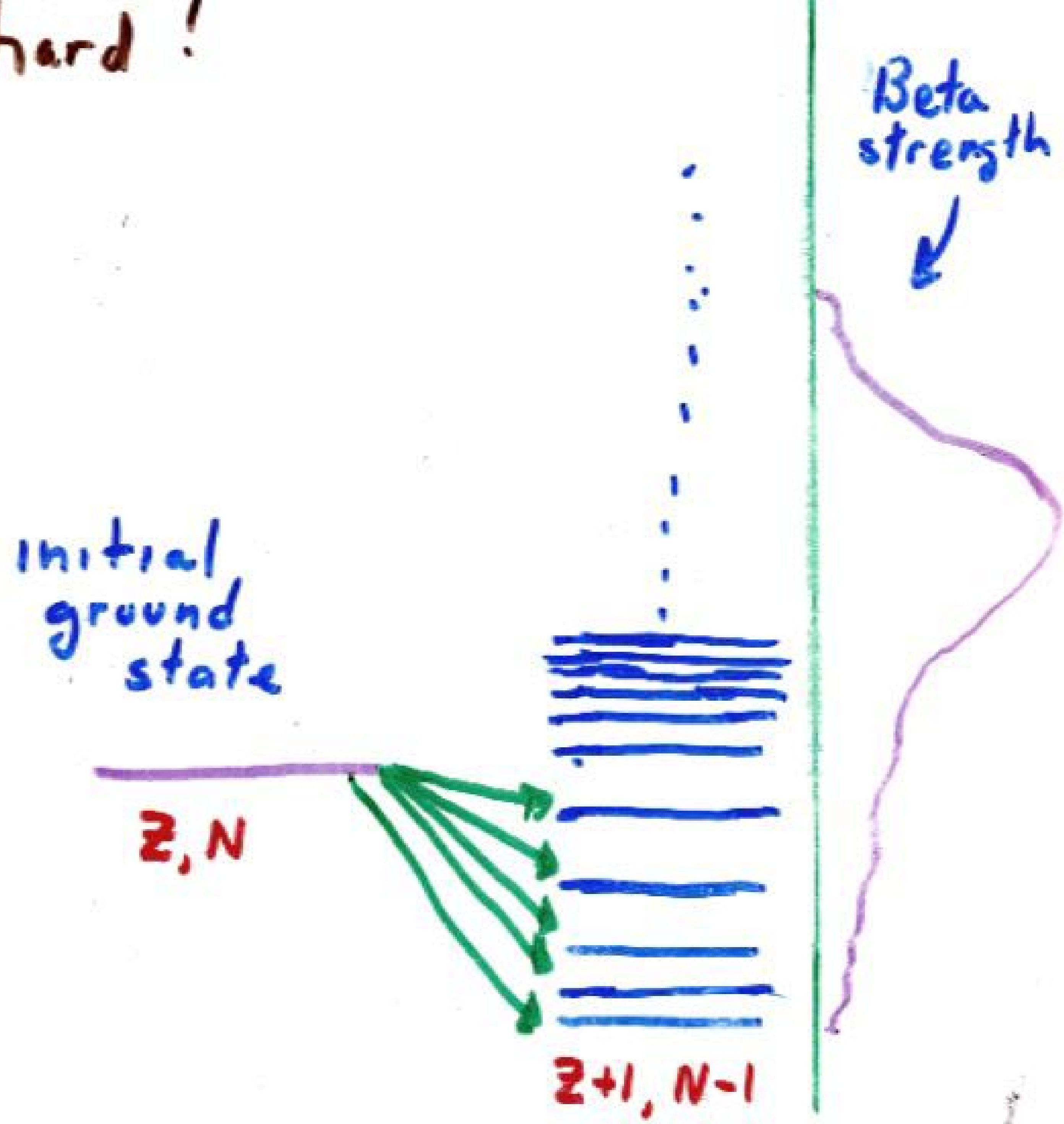
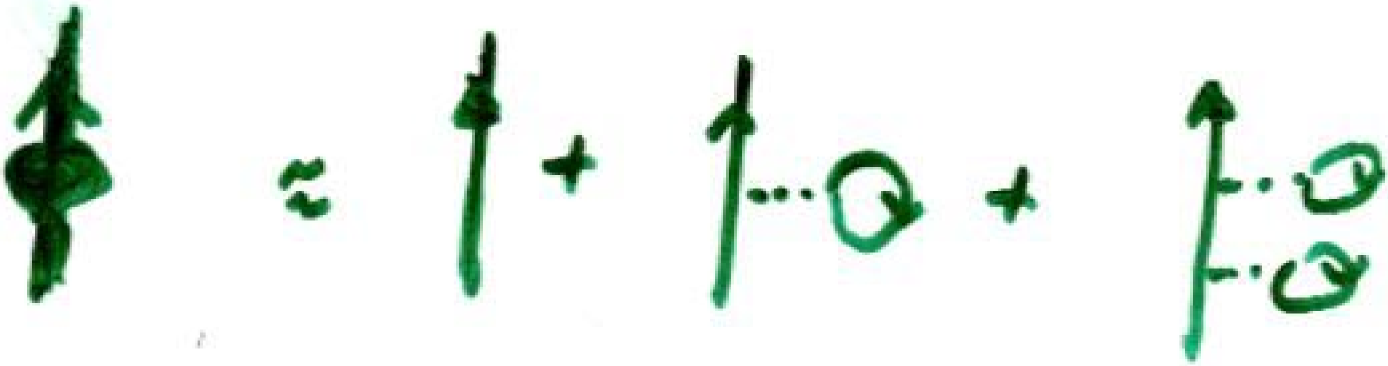

β⁻ decay
even
odd
odd-odd
Neutron Number N
T β,calc / T β,exp
0
20
40
60
80
100
120
140
160
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³

Figure 22

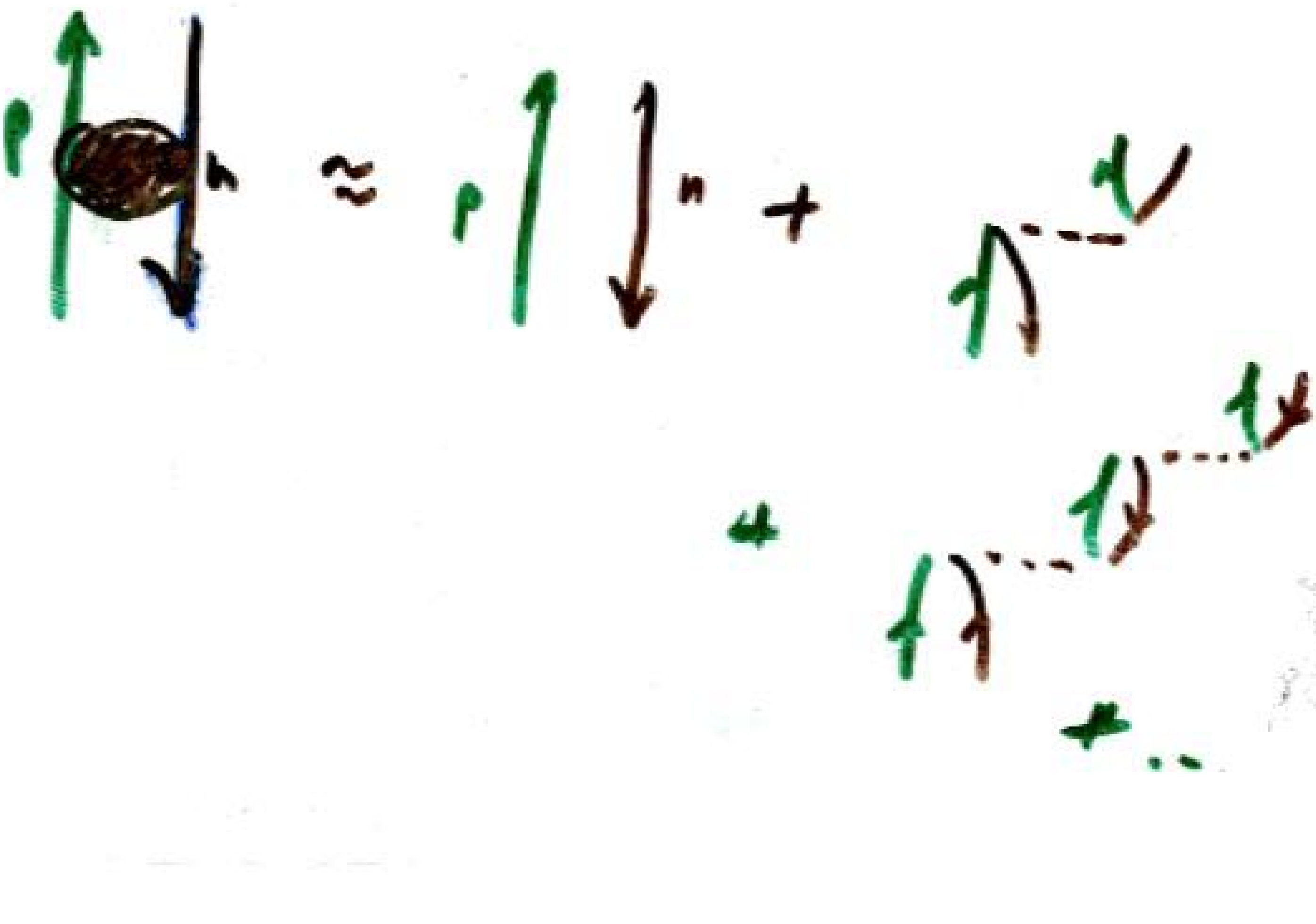
Calculating β-decay is hard!



Usual Approach



&



Our goal:

Completely self consistent HFB + QRPA calculation, so that daughter states correspond to collective spin-isospin oscillations of ground-state density.

Steps:

in 20 fm Box → ① coordinate-space HFB

② p-n QRPA in "canonical basis" for energies of and transitions to daughters

~50 of these with "T=0 pairing" →

Self consistency means using the <u>same</u> <u>interaction</u> everywhere in the steps above. We use one from the "Skyrme class"

Skyrme Interaction:

$$v_{12} = t_0(1+x_0 P_\sigma)\delta^3(\vec{r_1}-\vec{r_2}) + \tfrac{1}{2}t_1(1+x_1 P_\sigma)\left[\vec{\nabla}^2\delta(\vec{r_1}-\vec{r_2}) + h.c.\right]$$

$$+ t_2(1+x_2 P_\sigma)\left[\vec{\nabla}\cdot\delta^3(\vec{r_1}-\vec{r_2})\vec{\nabla}\right] + \tfrac{1}{6}t_3(1+x_3 P_\sigma)\rho^\alpha\delta^3(\vec{r_1}-\vec{r_2})$$

$$+ i W_0(\vec{\sigma_1}+\vec{\sigma_2})\cdot\vec{\nabla}\times\delta^3(\vec{r_1}-\vec{r_2})\vec{\nabla}$$

$$\vec{\nabla} = \vec{\nabla_1 - \nabla_2} \quad ; \quad P_\sigma = \tfrac{1}{2}(1+\vec{\sigma}_1\cdot\vec{\sigma}_2)$$

Skyrme Energy functional

$$\mathcal{H}(r) = \frac{t_0}{2}\left[(1+\tfrac{1}{2}x_0)\rho^2 - (x_0+\tfrac{1}{2})(\rho_p^2+\rho_n^2)\right]$$

$$+ \tfrac{1}{4}t_1\left[(1+\tfrac{1}{2}x_1)(\rho\tau + \tfrac{3}{4}(\vec{\nabla}\rho)^2\right] - (x_1+\tfrac{1}{2})\left[\rho_n\tau_n + \rho_p\tau_p + \tfrac{3}{4}(\vec{\nabla}\rho_p)^2 + \tfrac{3}{4}(\vec{\nabla}\rho_n)^2\right]$$

+ lots more . . . .

$$\tau = \sum_i |\vec{\nabla}\varphi_i|^2 \qquad \varphi_i = \text{"orbits"}$$

including "time odd currents"
(like the spin density)

Unfortunately, predictions of most Skyrme interactions for the Gamow-Teller distribution bear no resemblance to reality.

Can easily see this by looking at Landau parameter g_0':

$$V_{12} \longrightarrow f_0\,\delta^3(\vec{r}_1-\vec{r}_2) + f_1\,\delta^3(\vec{r}_1-\vec{r}_2)\,\vec{\tau}_1\cdot\vec{\tau}_2 + g_0\,\delta^3(\vec{r}_1-\vec{r}_2)\,\vec{\sigma}_1\cdot\vec{\sigma}_2 + g_0'\,\delta^3(\vec{r}_1-\vec{r}_2)\,\vec{\sigma}_1\cdot\vec{\sigma}_2\,\vec{\tau}_1\cdot\vec{\tau}_2$$

nuclear matter

g_0' determines energy & strength of GT resonance in nuclear matter

Force	go'
SG II	.93
SkM*	.94
SkP	.06
Sly4	.90
Sly5	−.15
Sly6	.90
SkI4	.88
SkO'	.80 *
Empirical	~ 1.80

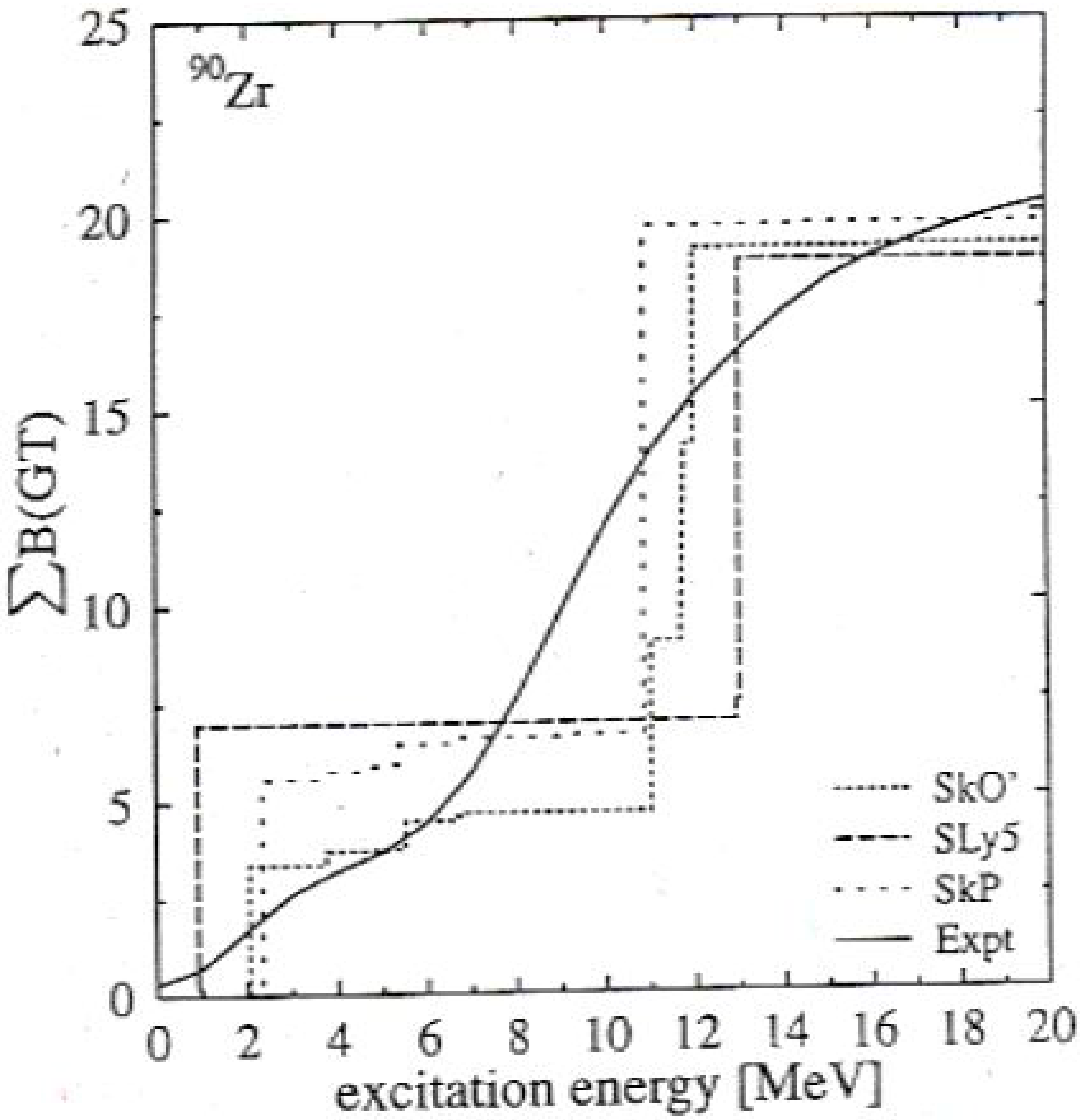


FIG. 1. Summed GT strength up to 20 MeV as a function of excitation energy for the closed-shell nucleus ^{90}Zr, calculated with the SkO', SLy5, and SkP Skyrme forces. We also plot the measured strength reported in Ref. [59] The calculated strength, as is customary, is multiplied by $(1/1.26)^2$; the quenching corresponds to setting g_A to 1.0 in our calculations of beta decay.

128

V_1

T=0 pairing

This interaction enters the QRPA, shifting intermediate strength down. Ignoring it leads to lifetimes that are systematically too long

In this channel we use a simple 2-Gaussian force, though a simple Skyrme interaction would do just as well, provided it contains some derivatives

The strength of the interaction in this channel is the only free parameter

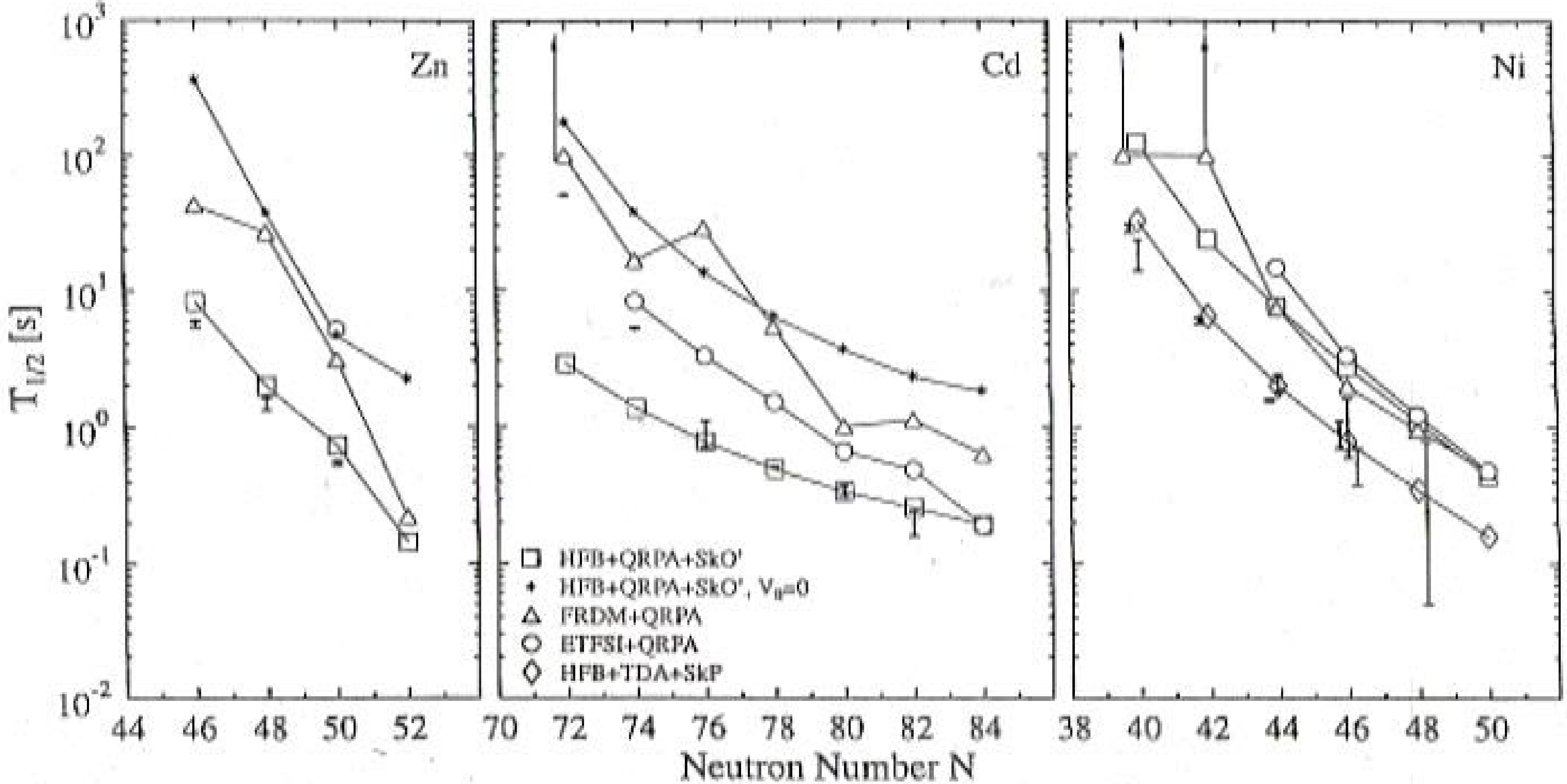


FIG. 6. Comparison of calculated half-lives for Zn, Cd, and Ni isotopes with (HFB+QRPA+SKO') and with (HFB+QRPA+SkO', $V_0 = 0$) the residual particle-particle interaction, and results from Refs. [12] (FRDM+QRPA), (ETFSI+QRPA), and [16] (HFB+TDA+SkP, only for the Ni isotopes), with experimental values taken from Ref. [54] wh possible. For the nickel isotopes recent results from [51,52] are shown as well. When predicted half-lives are larger than 10 the FDRM collaboration reports only this lower bound, which is marked here with arrows pointing up. The ETSFI collaborat reports half-lives only when the predicted deformation β_2 is less that 0.1.

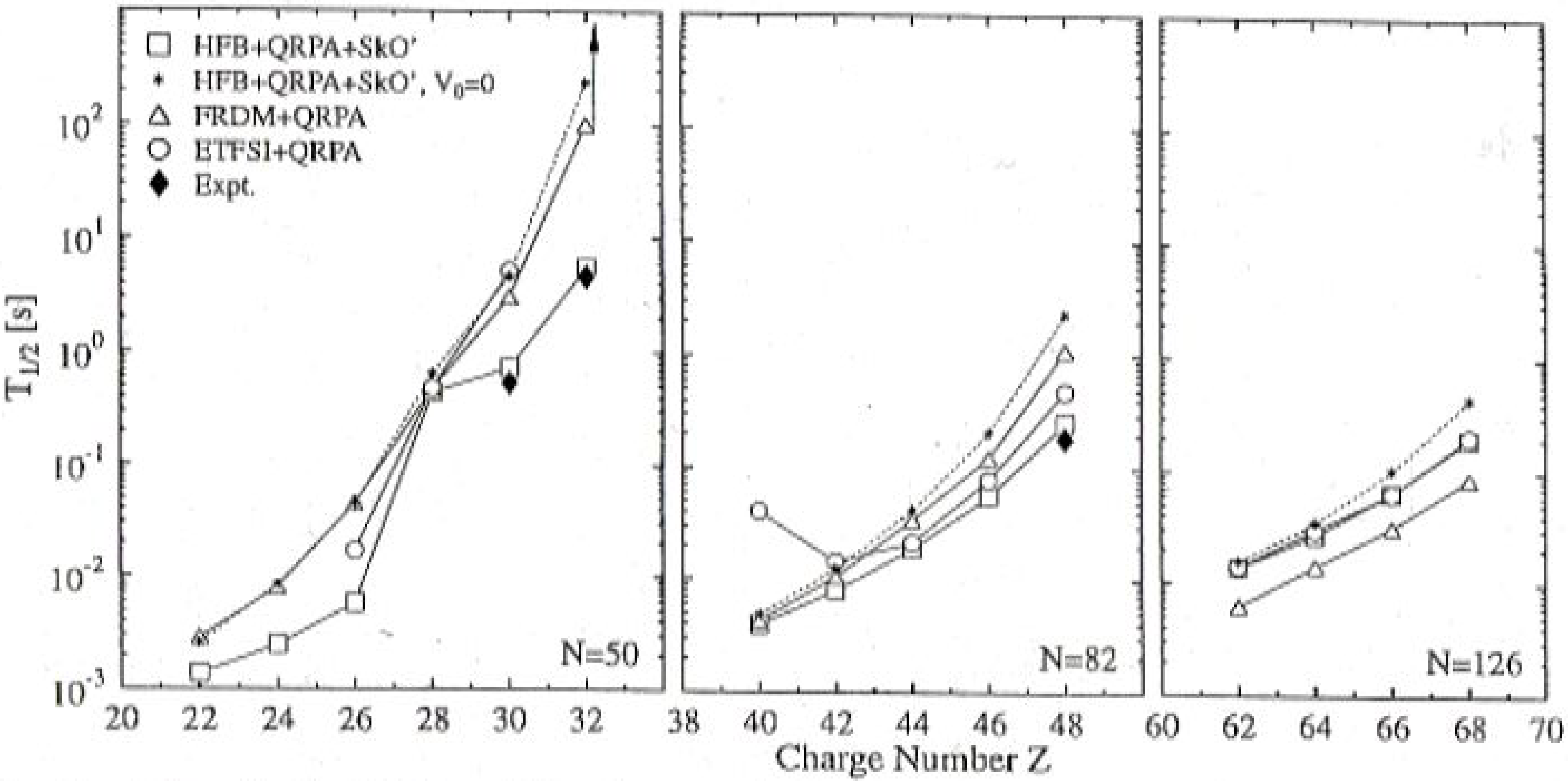


FIG. 9. Predictions for the half-lives of closed neutron-shell nuclei along the r-process path. Our results appear wi (HFB+QRPA+SKO') and without (HFB+QRPA+SkO', $V_0 = 0$)the pn particle-particle interaction. Also plotted are t results of Ref. [12] (FRDM+QRPA), Ref. [19] (ETFSI+QRPA), and experimental data where available.

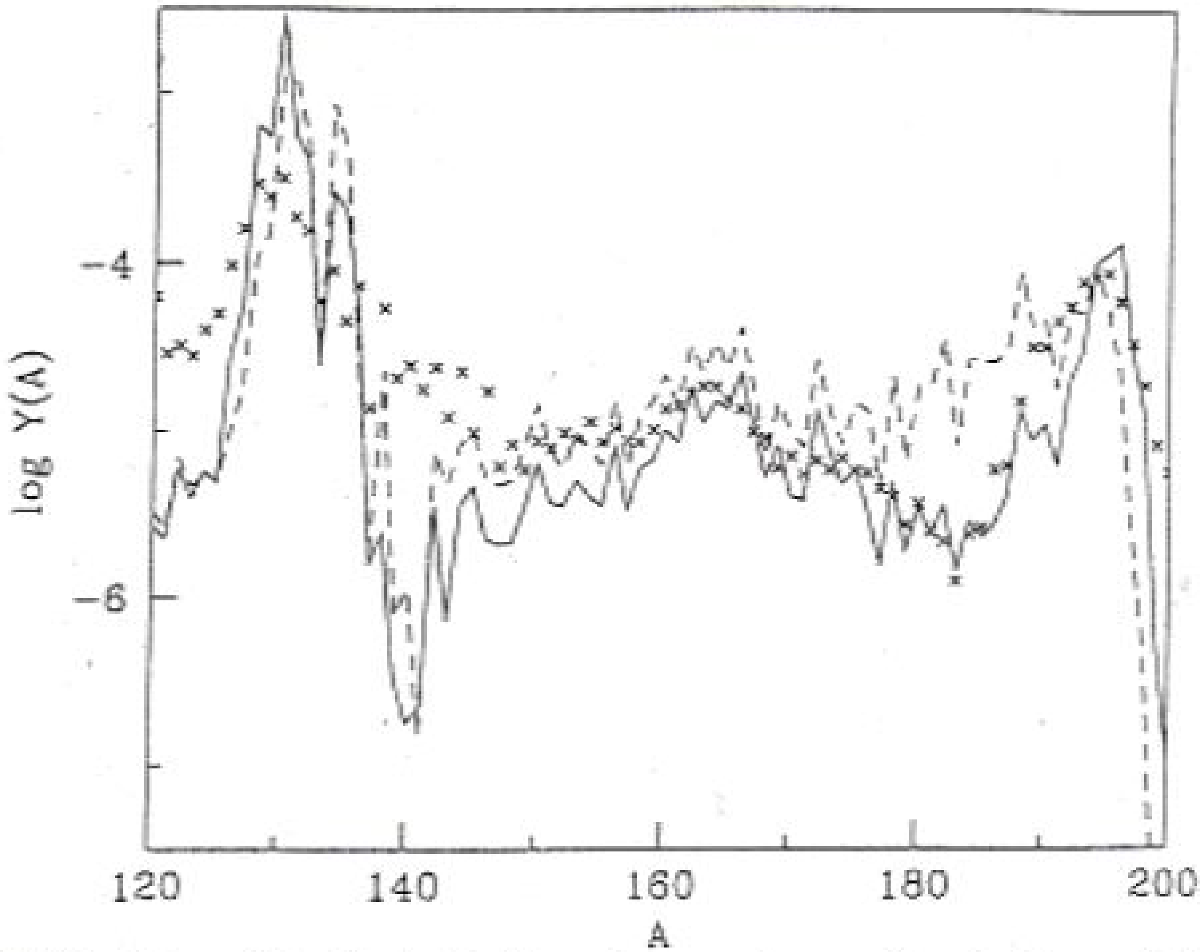


FIG. 10. Predicted abundances in a simulation of the r-process. The solid line corresponds to the rates of Ref. [12], and the dotted line to the rates obtained here around N=82 and 126. All other nuclear and astrophysical parameters are the same for the two lines. The crosses are observed solar-system abundances.

The whole process can speed up by a factor * of 2 or so

*say something here

The near future

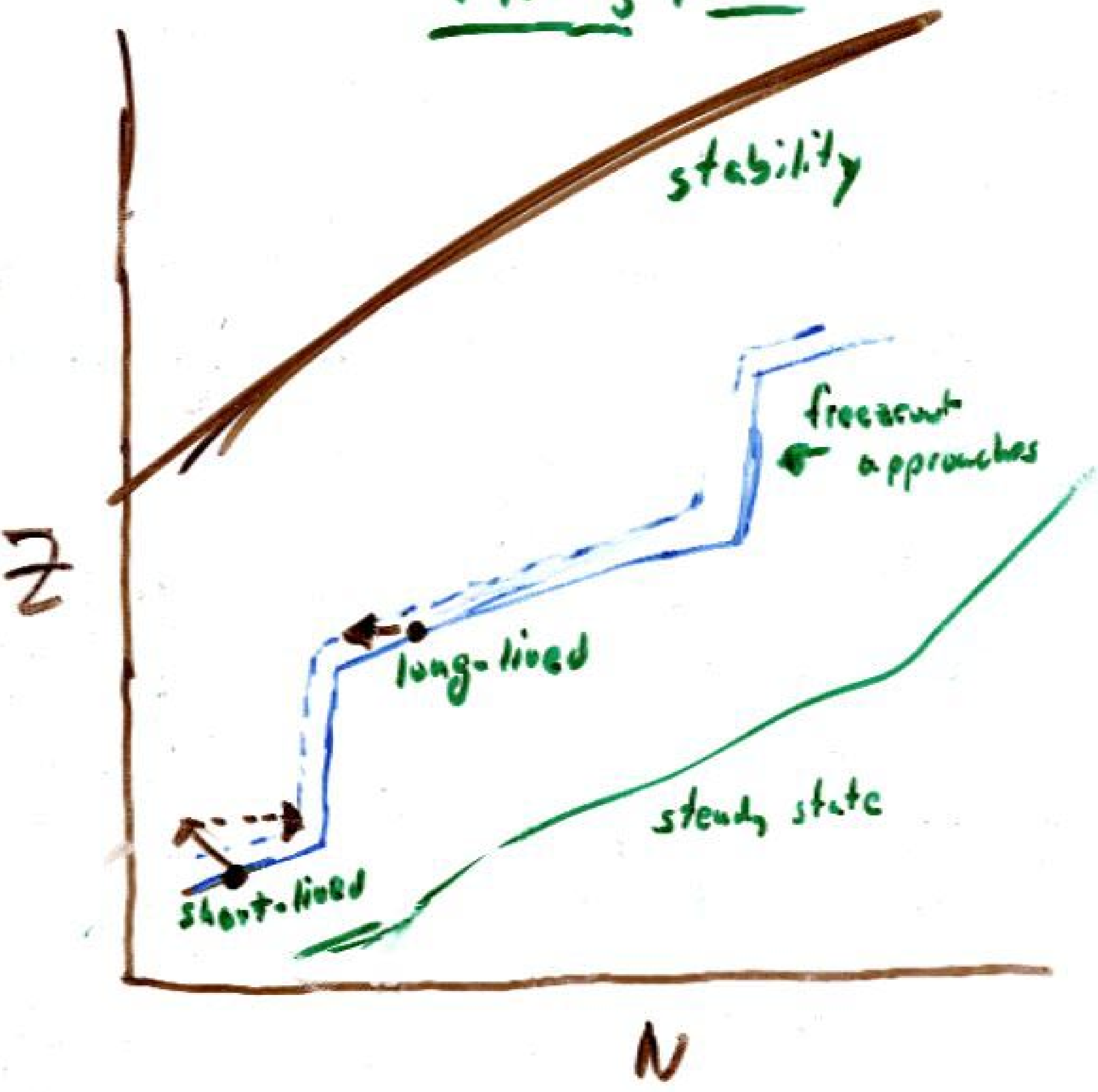
① Decoupling the time-even and time-odd terms in the Skyrme energy functional. This has ~~never~~ rarely been done because people haven't cared enough about states with non-zero angular momentum

② A more comprehensive investigation of T=0 pairing in the Skyrme framework

③ Deformed nuclei and full r-process simulations

The far future: Beyond RPA?

Moving "path"


stability
forecast approaches
long-lived
short-lived
steady state
Z
N

Conclusions

1) Neutrinos cause problems for the "hot-bubble" r-process. It would be nice if the nucleosynthesis took less time

2) It actually <u>does</u> take a little less time than usually thought because β-decay rates have been systematically underestimated. How much less? Don't really know yet

3) Peaks could form just prior to "freezeout". This would <u>really</u> shorten the time.