β⁻decay half-lives using the ANN model: Input for the r-process

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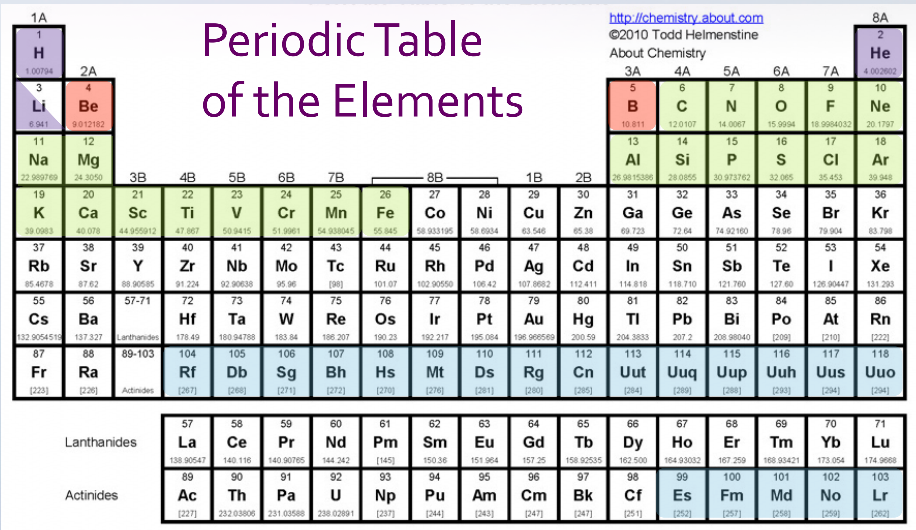
PYTHAiM GROUP
PYTHAGORAS ARTIFICIAL INTELLIGENCE MODELING

Origin of the Elements

- ✓ Almost all of the **H**, **He** along with some of the **Li** in nature was created in **the first three minutes** after the Big Bang.
- ✓ Two more light elements, **Be** and, **B** are synthesized in interstellar space by **collisions** between cosmic rays and gas nuclei (spallation).
- ✓ The rest elements up to **^{56}Fe**, are formed by exothermic **fusion** reactions inside stellar cores.
- ✓ The heavier elements, **beyond Fe** are almost exclusively formed in **n-capture** processes (i.e. r,s, ...), avoiding Coulomb barrier and endothermic reactions (Q-values<0).
  「B²FH「1」, Cameron「2」 - 50 years ago」
- ✓ The superheavy elements are produced via spontaneous **fission**.



「1」E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. 29, 547 (1957)
「2」A. G. W. Cameron, Chalk River Lab. Rep. CRL-41, A.E.C.L. No. 454, Ontario (1957)

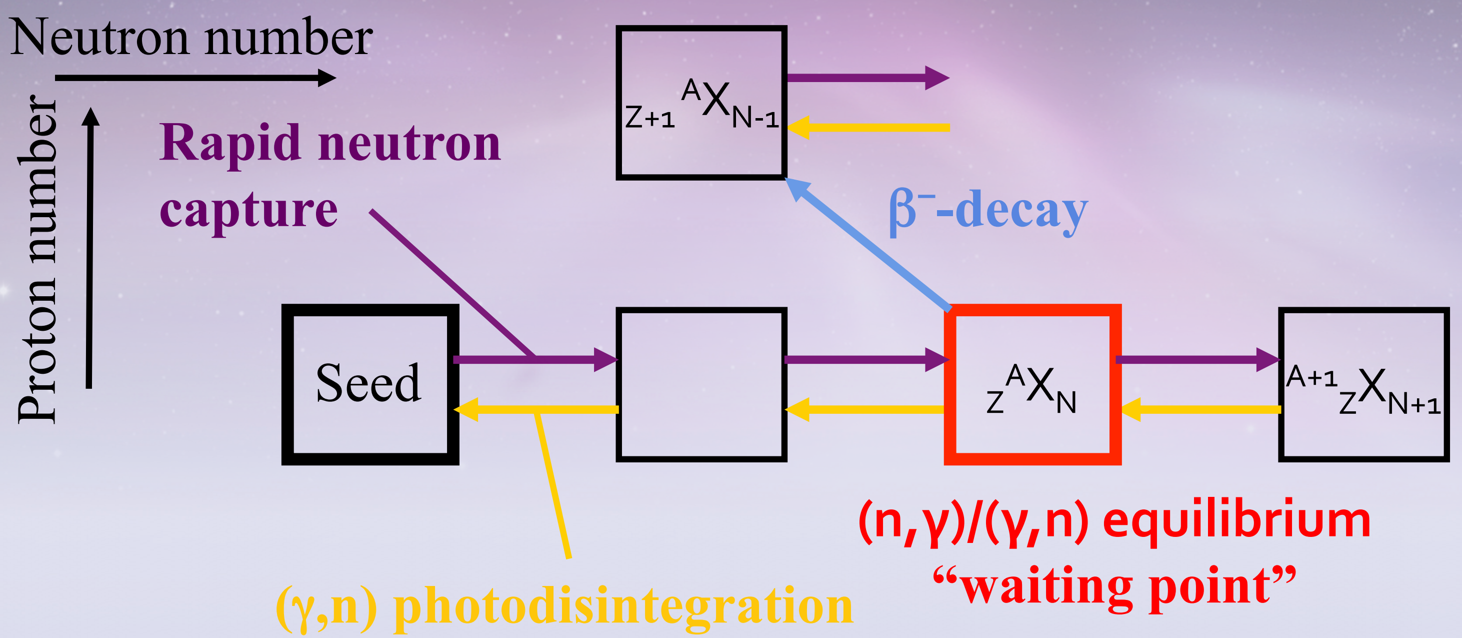
The R-Process Nucleosynthesis

R → Rapid neutron-capture

T~1-2 GK, n_n~10^{20}-10^{26} /cm^3
Density: 300 g/cm3 (~60% neutrons !)

n-capture timescale (τ_n): ~ 0.2 μs

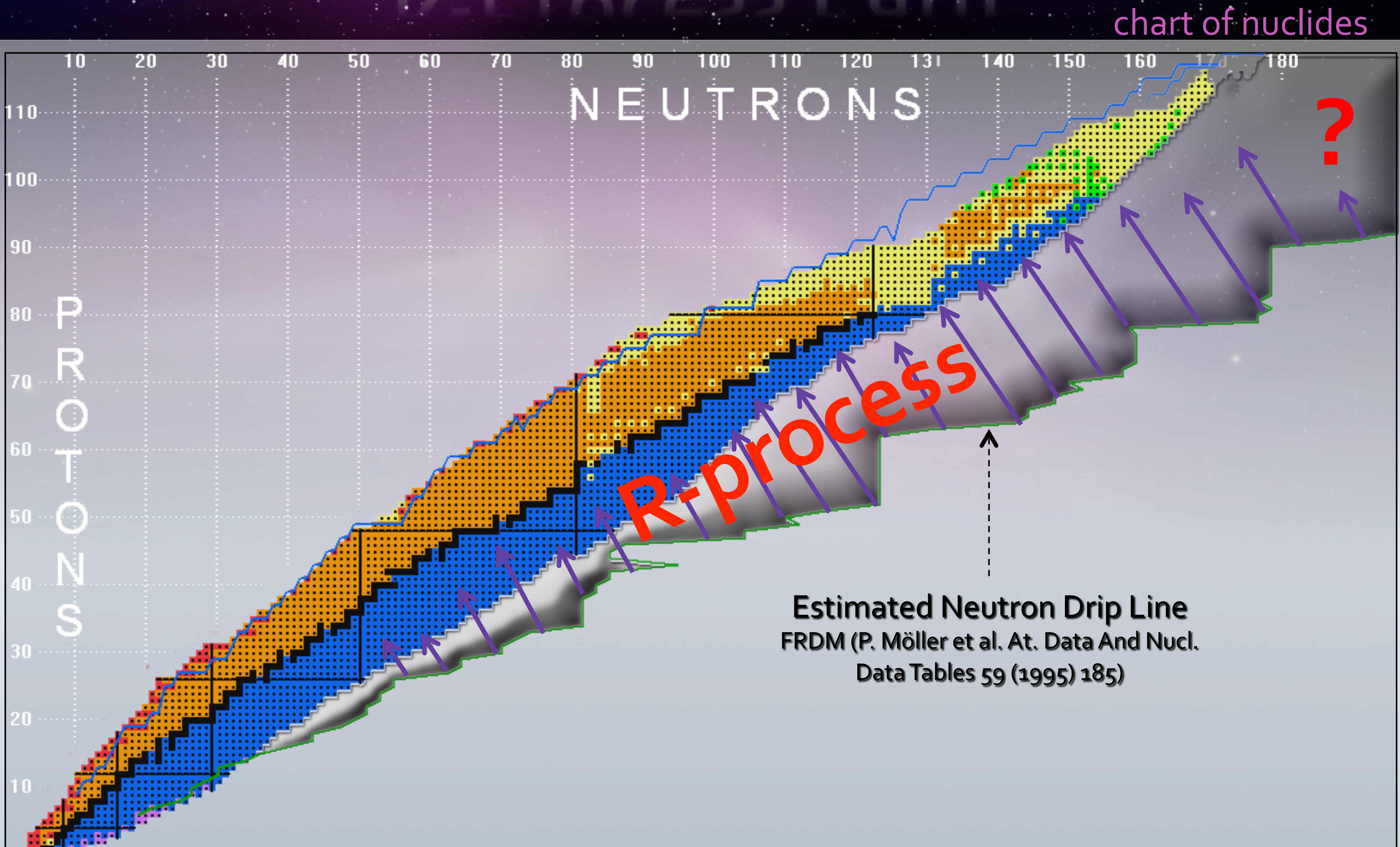
$\tau_n << \tau_{\beta^-}$



The **rapid n-capture process** (r-process) is today understood to be responsible for the synthesis of about **half of all** the nuclei abundances present in Solar System matter in the mass region from approximately Zinc through the Actinides (e.g., Thorium, Uranium, and Plutonium), as well as the bulk of the heavy elements in the mass region A ≥ 60 in our Galactic and Cosmos matter.

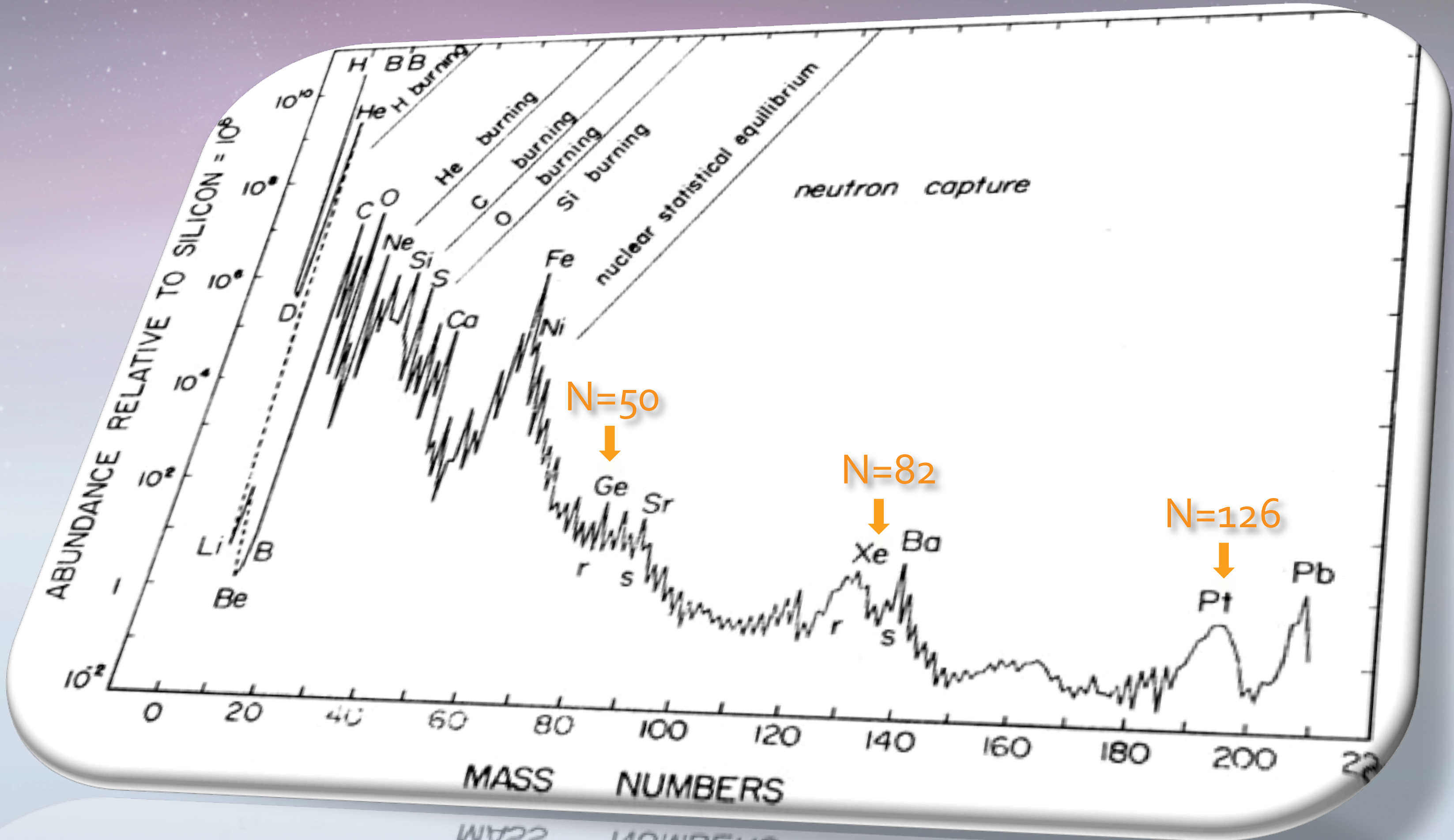
R-process still remains one of the most challenging open questions in modern nuclear astrophysics, since both the astrophysical scenarios where this process occurs and the needed nuclear physics input have not yet been unambiguously identified.

R-Process Path



n- captures must occur much faster than β⁻-decays far from stability → the r-process "runs up" along the neutron drip line.

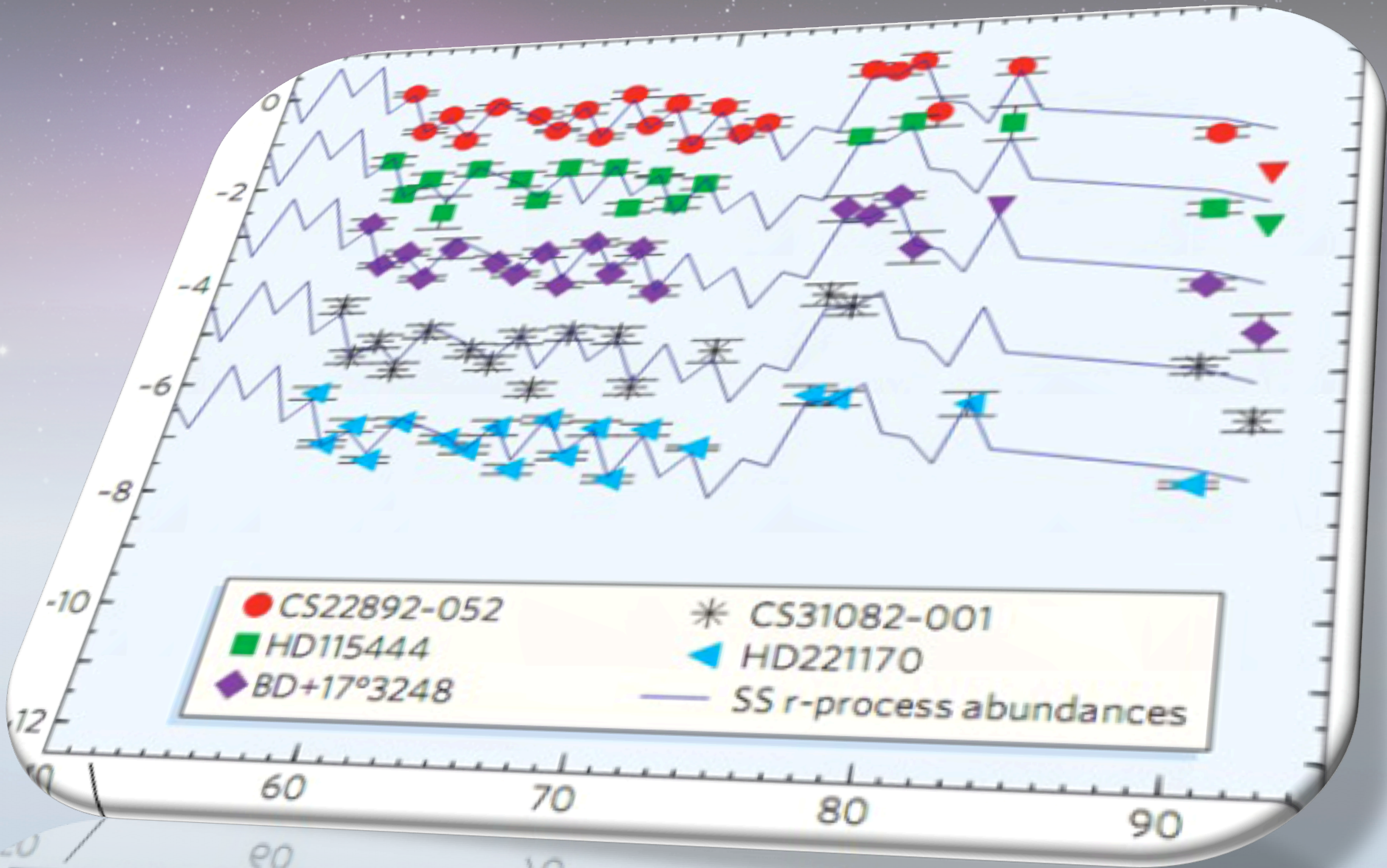
Relative Solar System Abundances



The solar elemental abundance distribution beyond Fe, shows peaks near A = 80, 130, and 195, corresponding to progenitors with closed neutron shells N = 50, 82, and 126.

Old Metal Poor Galactic Halo Stars

The r-process operating over the history of the Galaxy



→ **R-process is unique in nature!**

Understanding of R-Nucleosynthesis

r-abundances reproduction

Astrophysical Conditions

temperature (T_9)

matter density

neutron density (n_n)

...

radiation entropy (S_{rad})

r-process duration (τ_r)

Nuclear Physics Input

nuclear-masses (Q_β, S_n)

β-decay properties ($T_{1/2}$, P_n)

n-capture rates

fission properties

neutrino interactions

nuclear-structure-properties (J^π ...)

for 1000's of isotopes FAR-OFF β-stability

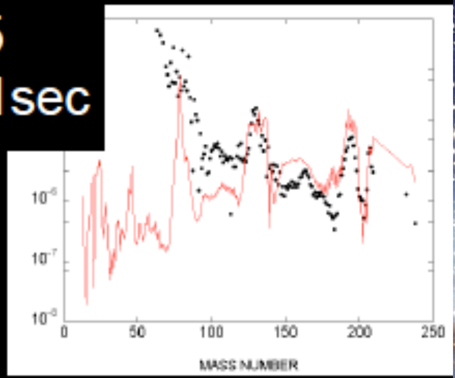
Astrophysical Site(s)

Dominant Candidates for the "main" r-process

Neutrino-driven wind in SNe II

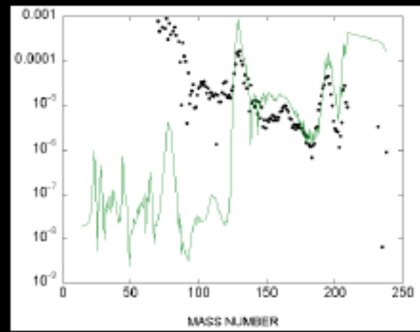
SN1987A

S~400
Ye~0.45
τ_{dyn}~ 0.1sec



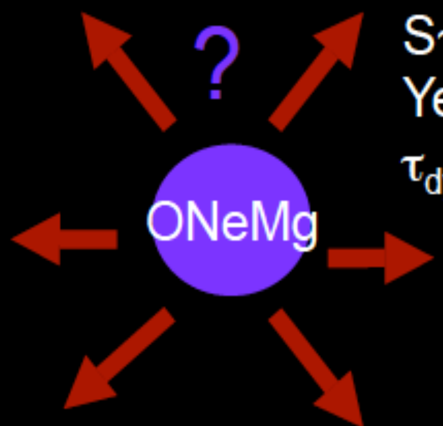
Neutron star mergers

Simulation of NS mergers
(from Hayden planetarium)

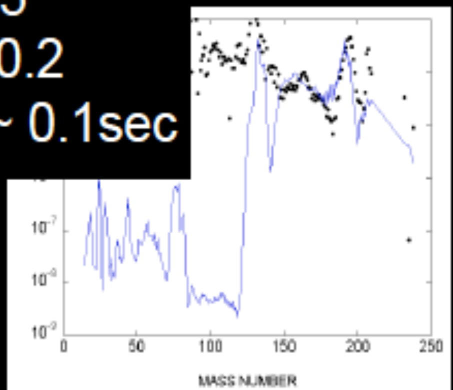


S<4
Ye<0.2

Prompt explosion of low mass supernovae



S~15
Ye~0.2
τ_{dyn}~ 0.1sec



The most widely believed candidate site for the r-process are core-collapse supernovae (spectral Type Ib, Ic and II), which provide the necessary physical conditions for the r-process. However, the abundance of r-process nuclei requires that either only a small fraction of supernovae eject r-process nuclei to the interstellar medium, or that each supernova ejects only a very small amount of r-process material. A recently proposed alternative solution is that neutron star mergers (a binary star system of two neutron stars that collide) may also play a role in the production of r-process nuclei, but this has yet to be observationally confirmed.

If nuclear physics uncertainties are reduced, we could indentify astrophysical site via observations.

Understanding of R-Nucleosynthesis

r-abundances reproduction

Astrophysical Conditions

temperature (T_9)

matter density

neutron density (n_n)

...

radiation entropy (S_{rad})

r-process duration (τ_r)

Nuclear Physics Input

nuclear-masses (Q_β, S_n)

β-decay properties ($T_{1/2}$, P_n)

n-capture rates

fission properties

neutrino interactions

nuclear-structure-properties (J^π ...)

for 1000's of isotopes FAR-OFF β-stability

Nuclear Physics Input

$T_{1/2}$ of very neutron-rich nuclei

Nuclear masses

- S_n-values ⇒ r-process paths (i.e. $S_n \sim 3$ MeV)

β-decay properties

β^- Half-lives ⇒ duration – speed – time scale
⇒ r-process clock

$T_{1/2}$ (g.s., is.) ⇒ r-process progenitor abundances ($N_{r,prog}$)

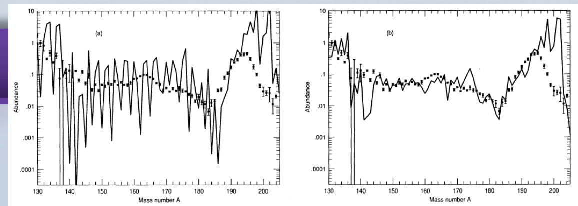
$T_{1/2}$ of waiting points ⇒ pre freeze-out isobaric abundances and regulate the speed of the process towards heavier elements.

$T_{1/2}$ of heavy neutron-rich radionuclides ⇒ time scale for the matter flow from the r-process seeds to even heavier nuclei.

Sum of $T_{1/2}$ ⇒ total r-process duration (τ_r)

β-delayed n-emission branching probabilities

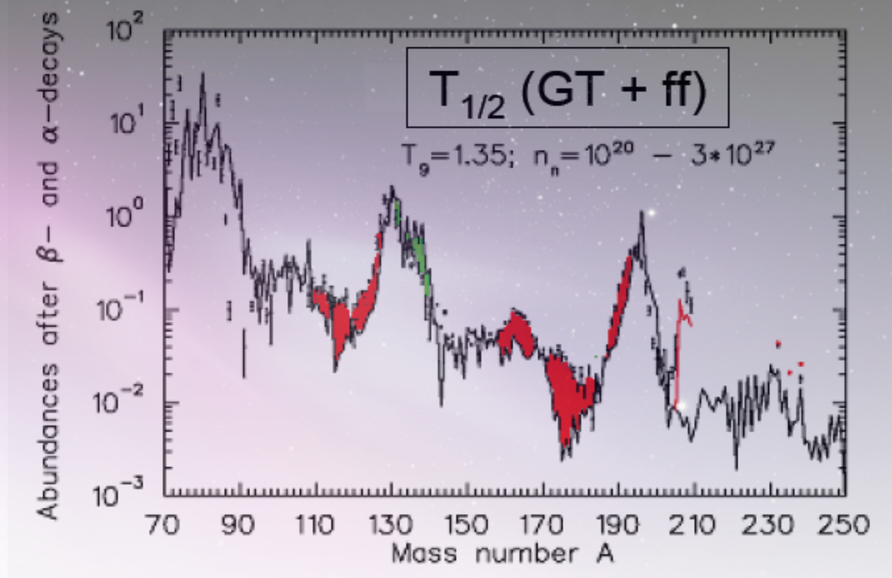
P_n ⇒ smoothing $N_{r,prog}$ → $N_{r,final}$ ($N_{r,\odot}$)

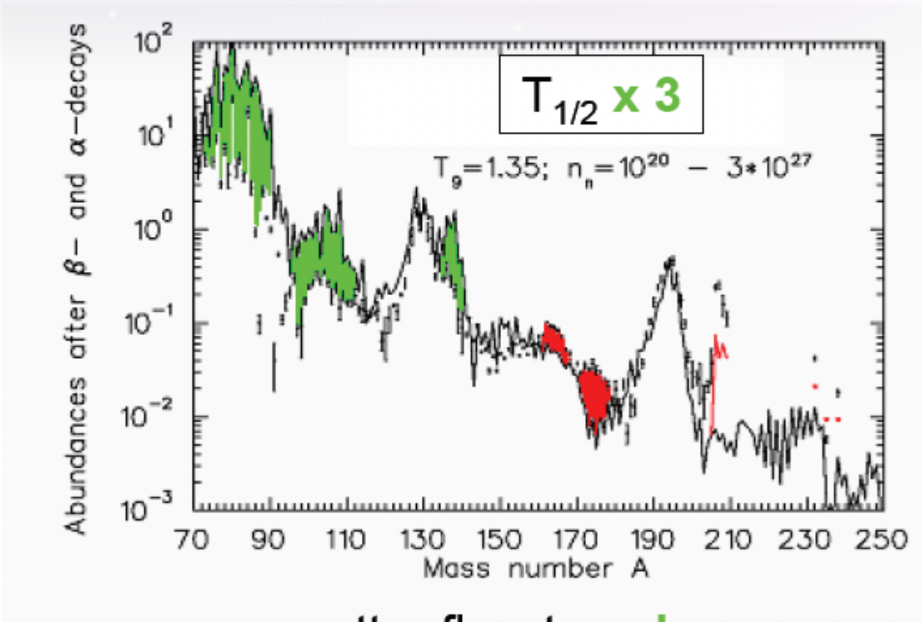


Effects of $T_{1/2}$ on matter flow

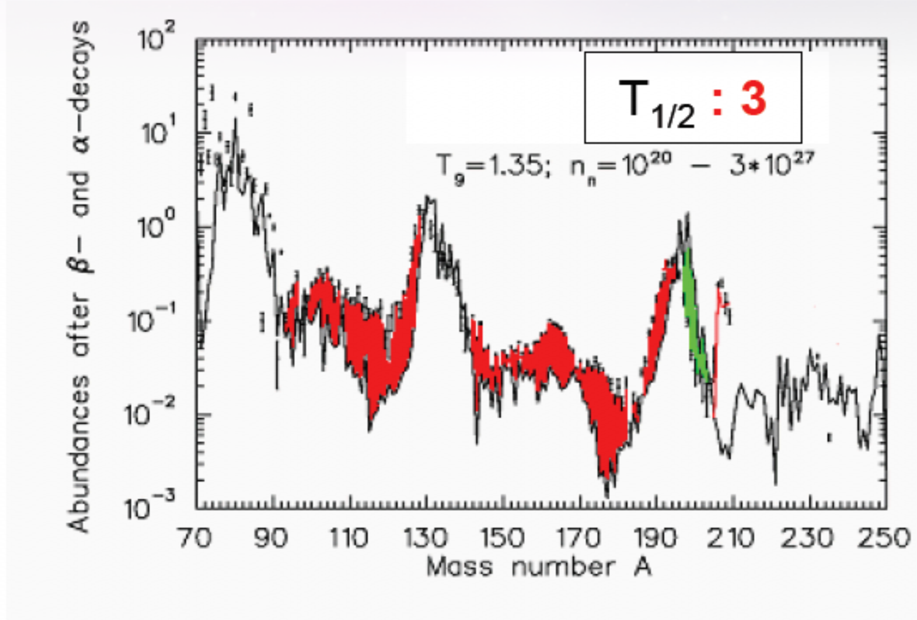
Mass model: **ETFSI-Q**
-all astro parameters kept constant

r-process model:
"waiting-point approximation"



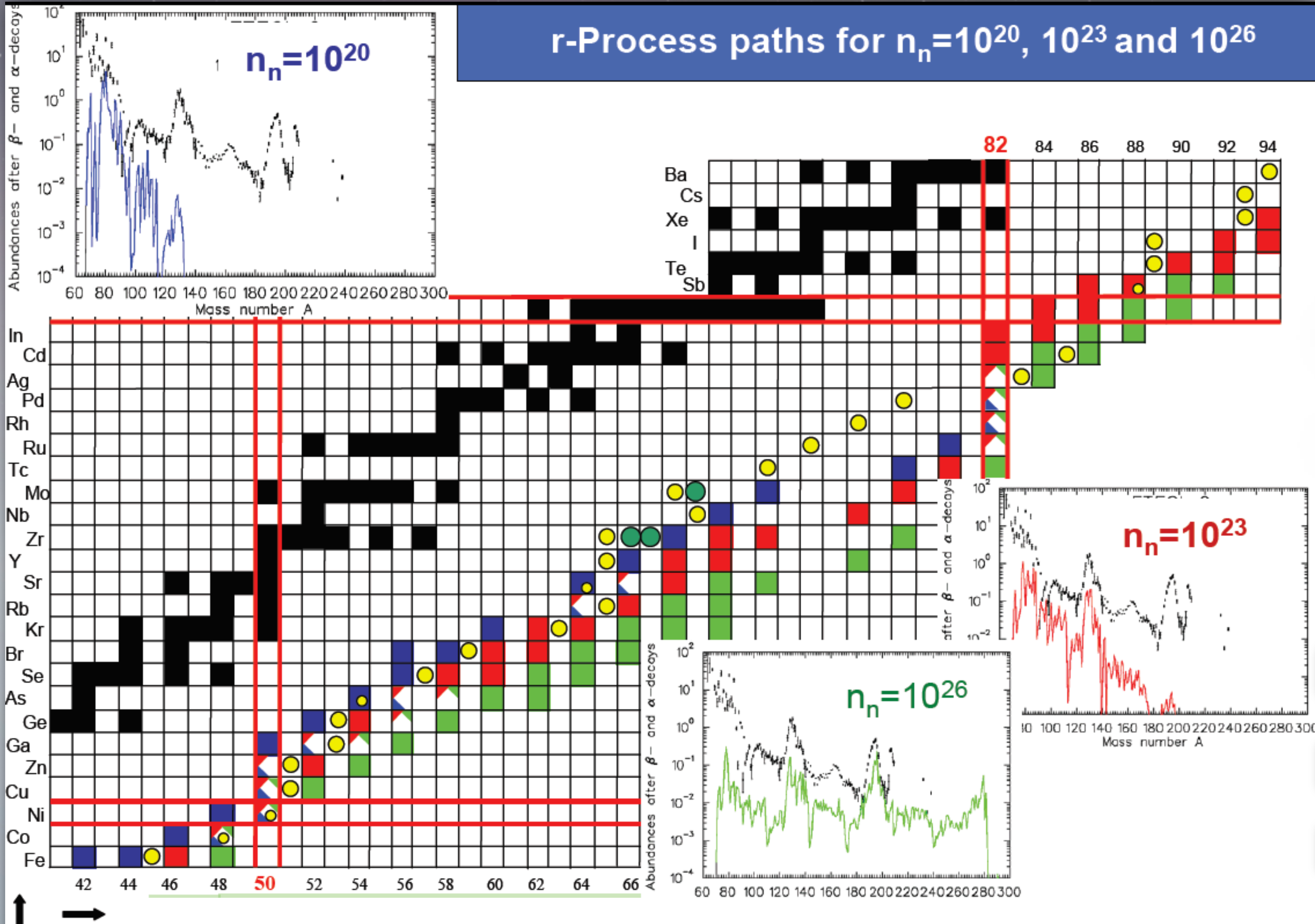


r-matter flow too **slow**



r-matter flow too **fast**

Today's Exp. Info - R-process paths



K.-L. Kratz, 7th Workshop on Nuclear Astrophysics, Russbach 2010

Today, altogether 60 r-process nuclei are only known!

- Heaviest isotopes with measured $T_{1/2}$
- new (MSU, 2009)

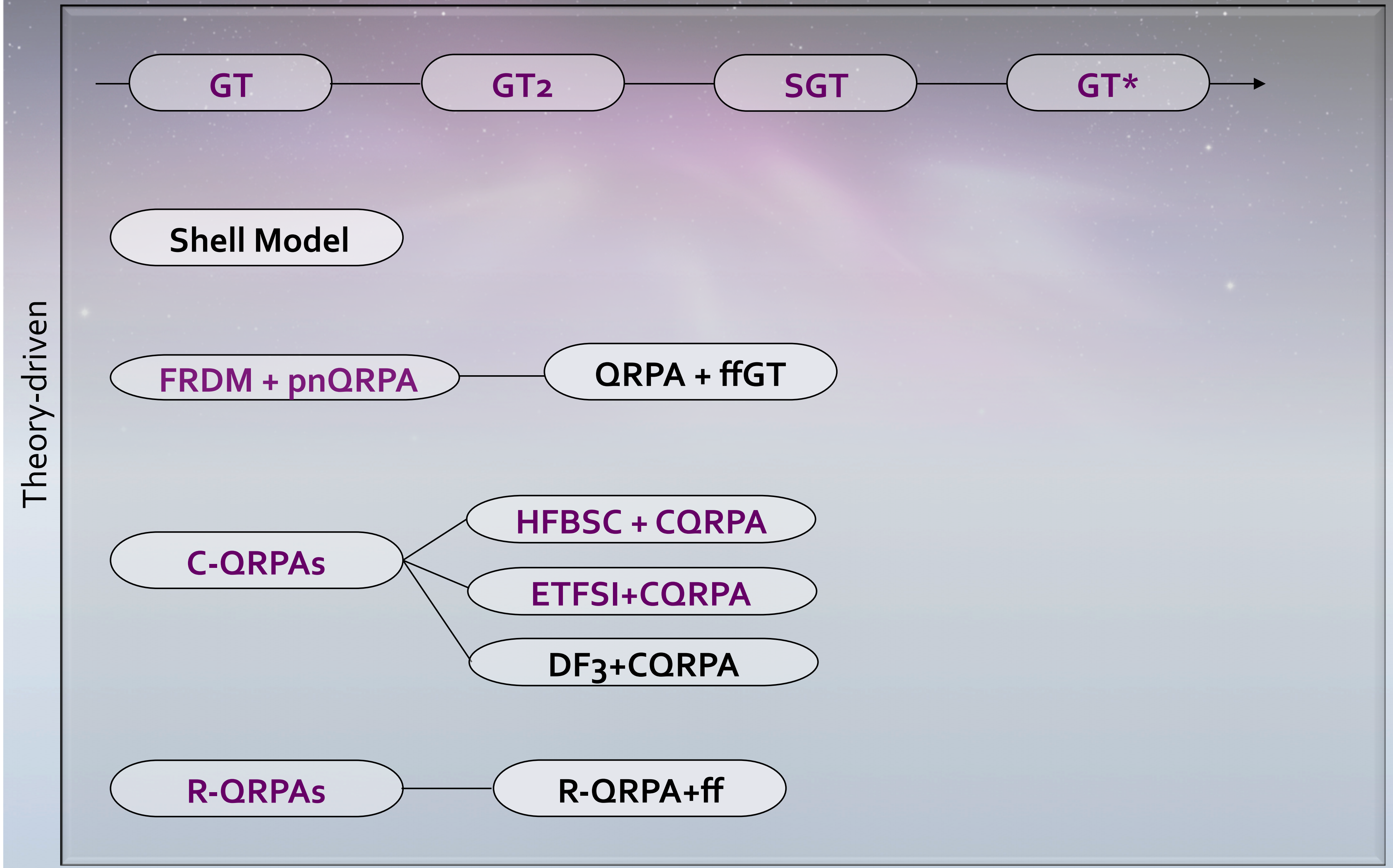
"Waiting point" isotopes at:

- $n_n = 10^{20}$
- $n_n = 10^{23}$
- $n_n = 10^{26}$

freeze-out networks.

The r-process should be a dynamical process with continuously altered conditions and paths.

β^--decay Half-lives Approaches



Statistical Modeling

Learning Machines

Data- driven

Artificial Neural Networks (ANNs)
Support Vector Machines (SVMs)

Ref: V. N. Vapnik, Statistical Learning Theory, Wiley-Interscience , 1998.

Statistical Modeling Using ANNs

data-driven, stand-along statistical approaches

Fundamental Question

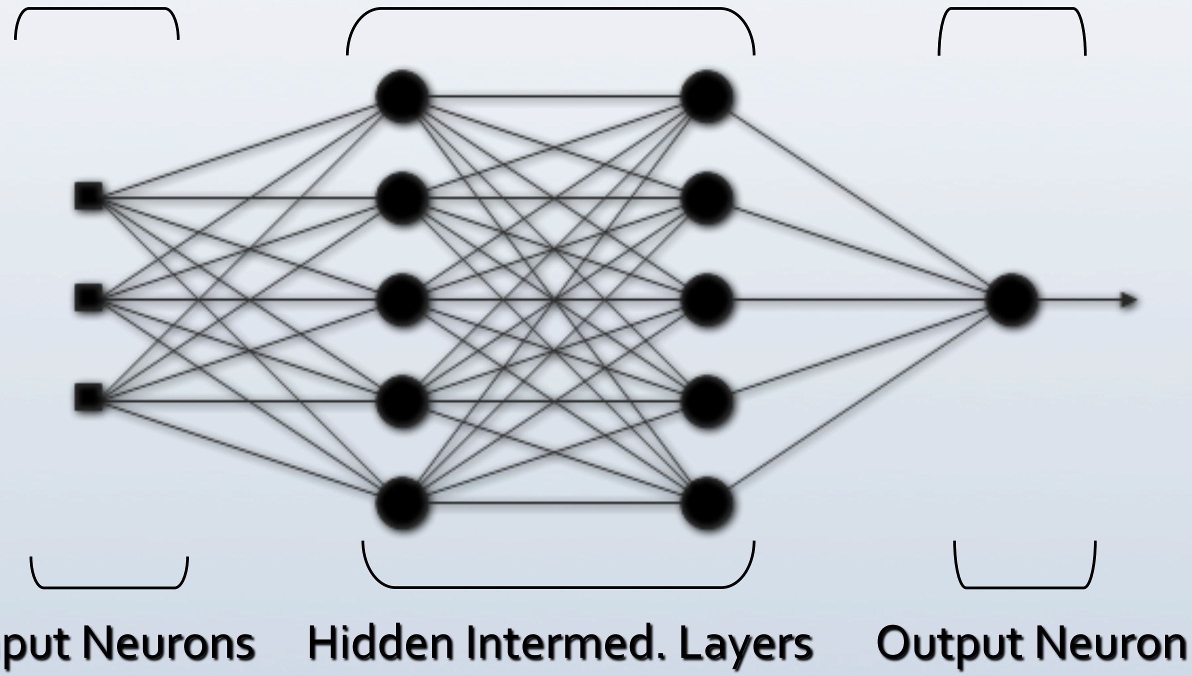
To what extend can mature learning machines (i.e. ANNs) decode the underlying β-decay half-lives systematics by **only** utilizing the hidden information over the **minimal input** of the **Z** and **N** nucleonic numbers?

Artificial Neural Networks

Learning Machines

classification – function approximation

Fully-connected Feed-forward Neural Network



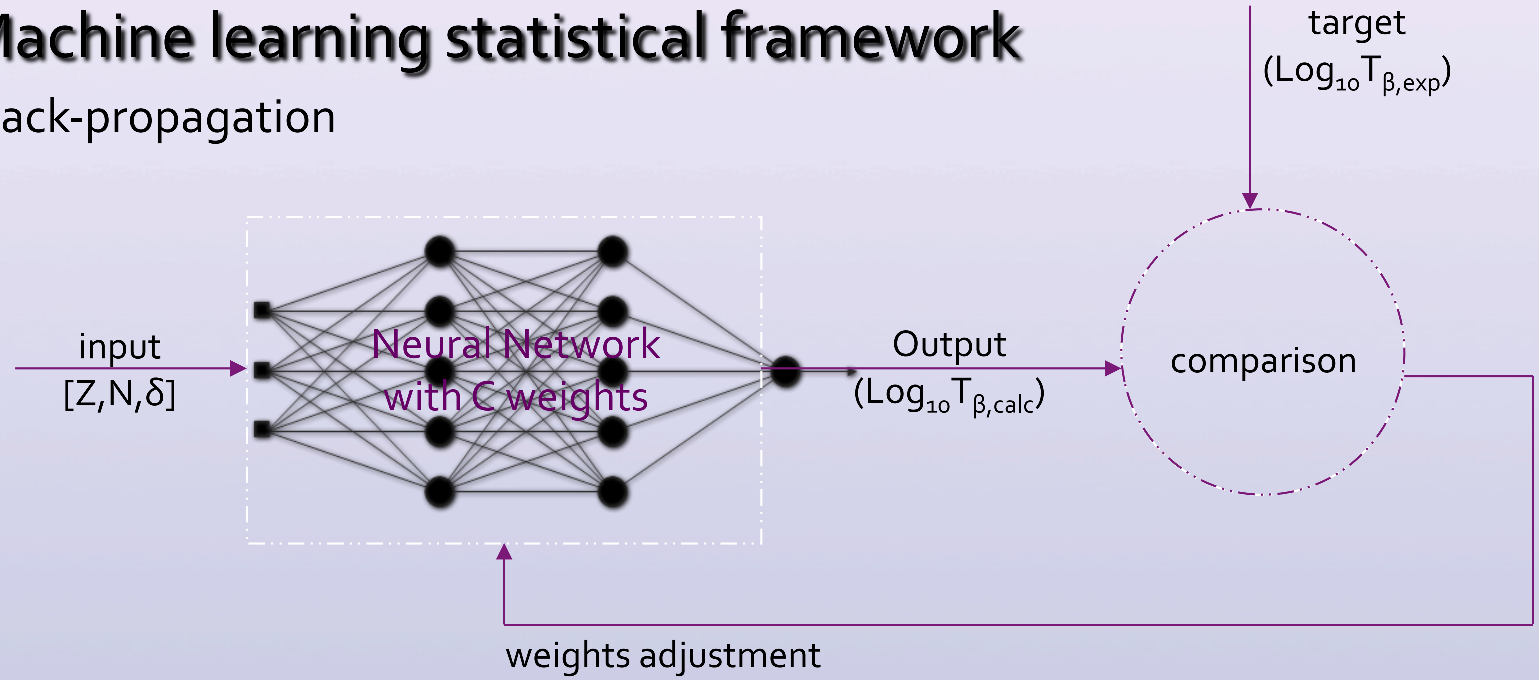
Learning Procedure

Objective: minimization of cost function

$$E_D = \sum_{i=1}^{N} \left(\log_{10} \left(T^i_{\beta,exp} \right) - \log_{10} \left(T^i_{\beta,cal} \right) \right)^2$$

Machine learning statistical framework

Back-propagation



Levenberg-Marquardt BP update rule

$$\vec{w}_{k+1} = \vec{w}_k - \left[\vec{J}_k^T \vec{J}_k + \mu I \right]^{-1} \vec{J}_k^T \vec{e}_k$$

The ANN Model

General ANN Model Features

Network	Architecture		Activation Functions
Feed-forward Fully-connected	**Size:**	3-5-5-5-5-1	tanh-tanh-tanh-tanh-satlins
	Weights:	116	

Mode	Training Algorithm	Initialization Method
Batch	Bayesian Regularization	Nguyen-Widrow

Input Scaling [-1, 1]		Output Scaling [-1, 1]		Max Fail
Z	[0, 230]	$\mathrm{Log}_{10}T_{1/2}$ (ms)	[0.18 - 8.98]	300 epochs
N	[0, 230]			
Parity	[-1, 1]			

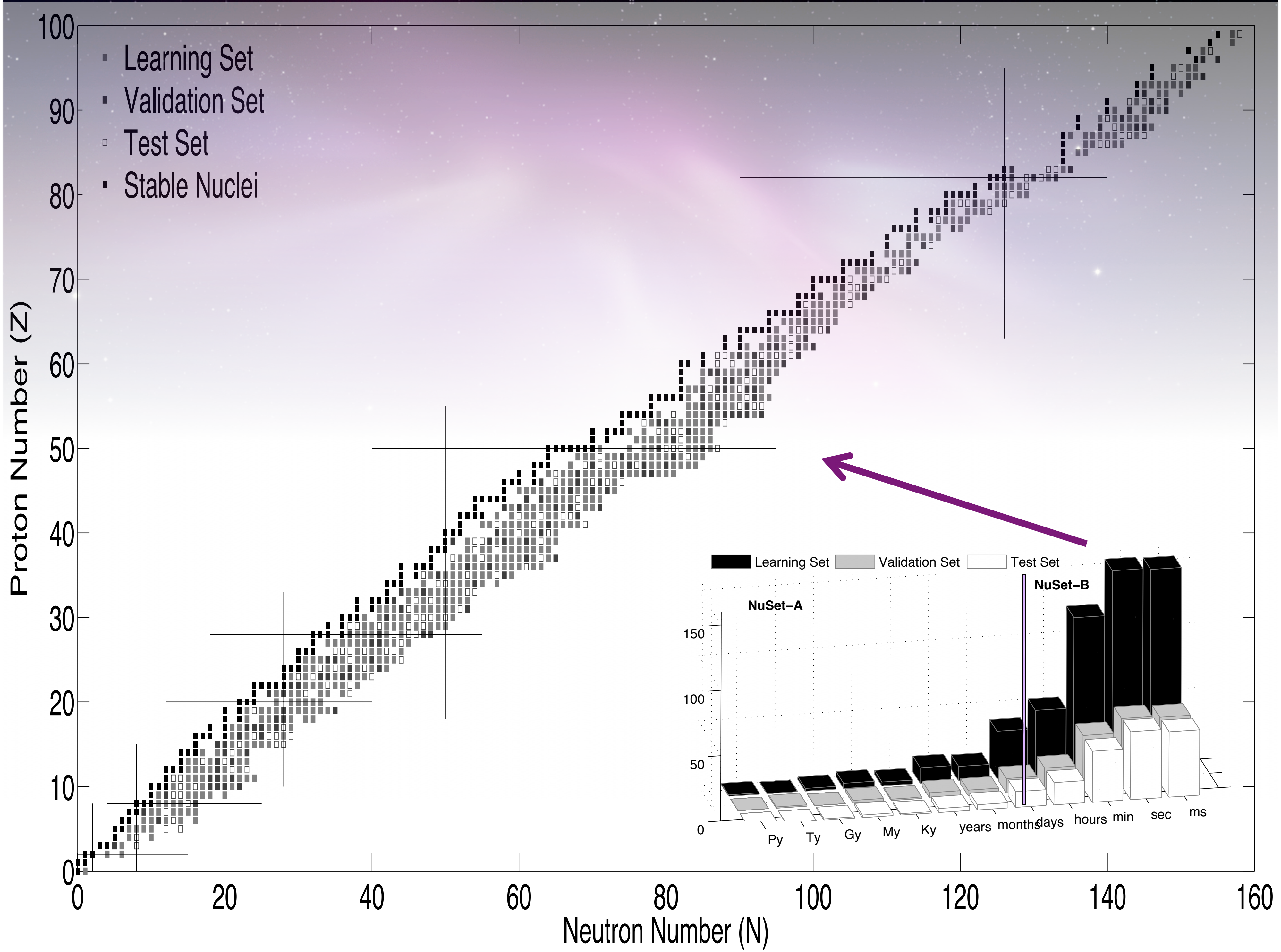
N. J. Costiris, E. Mavrommatis, K. A. Gernoth, and J. W. Clark, Phys. Rev. C80, 044332 (2009)

Database	Half-life Range	Decay Mode	NuSet-B	
NuBase2003 *	0.15×10^{-2} s → ^{35}Na 2.43×10^{23} s → ^{113}Cd	100% β^-	Cutoff	10^6 s

* A.H. Wapstra, G. Audi et al., Nucl Phys. A729 (2003) 337

To avoid overfitting effects		
Early Stopping		
Training Set	Validation Set	Test Set

NuSet-B. Uniform Nuclides Distribution over Half-lives			
All Nuclides	Training Set (60%)	Validation Set (20%)	Test Set (20%)
843	503	167	168



Learning Set
Validation Set
Test Set
Stable Nuclei
Proton Number (Z)
Neutron Number (N)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
Learning Set
Validation Set
Test Set
NuSet-A
NuSet-B
150
100
50
0
Py
Ty
Gy
My
Ky
years
months
days
hours
min
sec
ms

ANN Performance

Set	RMSE
Learning	0.53
Validation	0.60
Test	0.65
Overall	**0.57**

$$RMSE=\sqrt{\frac{1}{N}\sum_i\left(Log_{10}\, t^i_{\beta,calc} - Log_{10}\, t^i_{\beta,exp}\right)^2}$$

fact	$T_{1/2}$ Exp (s)	Overall Mode			NBSC+pnQRPA		
		m(%)	$\langle x\rangle_K$	σ_K	m(%)	$\langle x\rangle_K$	σ_K
<10	$<10^6$	90.5	2.46	1.72	76.7	3.00	-
	<60	96.5	2.21	1.52	87.2	2.81	-
	<1	97.6	2.10	1.39	95.7	2.64	-
<2	$<10^6$	53.5	1.41	0.27	33.8	1.43	-
	<60	60.6	1.41	0.27	42.0	1.41	-
	<1	61.9	1.41	0.26	50.7	1.43	-

$$\bar{x}_K = \frac{1}{N}\sum_i x_i, \quad x_i = \begin{cases} T_{\beta,\exp}/T_{\beta,calc} & if \quad T_{\beta,\exp} \geq T_{\beta,calc} \\ T_{\beta,calc}/T_{\beta,\exp} & if \quad T_{\beta,\exp} < T_{\beta,calc} \end{cases} \quad \sigma_K = \left[\frac{1}{N}\sum_i (x_i - \bar{x}_K)^2\right]^{1/2}$$

N. J. Costiris, E. Mavrommatis, K. A. Gernoth, and J. W. Clark, Phys. Rev. C80, 044332 (2009)

Results

Recently measured T_β for very neutron-rich nuclides.

Nucleus	Experiment	T_β (ms) ANN Model	*pn*QRPA+*ff*GT
^{36}Mg	3.9 ± 1.3	14.5	15.9
^{37}Al	10.7 ± 1.3	15	9.9
^{38}Al	7.6 ± 0.6	7.7	4.7
^{39}Al	7.6 ± 1.6	7.2	4.3
^{39}Si	47.5 ± 2.0	27.7	101.5
^{40}Si	33.0 ± 1.0	48.5	30.6
^{42}Si	12.5 ± 3.5	15.5	43.4
^{44}P	18.5 ± 2.5	12.7	17.2
^{46}S	50 ± 8	39.5	30.8
^{47}Cl	101 ± 6	77.9	51.5
^{48}Ar	475 ± 40	447.6	181.9
^{49}Ar	170 ± 50	130.2	54.9
^{64}V	19 ± 8	23.4	7.6
^{73}Co	41 ± 4	103.6	30.7
^{115}Tc	73^{+32}_{-22}	84.2	70.7
^{118}Ru	123^{+48}_{-35}	69.1	211.8
^{120}Rh	136^{+14}_{-13}	196.2	82.7
^{121}Rh	151^{+67}_{-58}	90.7	62.3
^{122}Pd	175 ± 16	227.2	951.2
^{124}Pd	38^{+38}_{-19}	124.2	288.7
^{163}Eu	7.8 ± 5 (s)	7.8 (s)	17.2 (s)
^{164}Eu	4.2 ± 2 (s)	3.3 (s)	8.6 (s)
^{165}Eu	2.3 ± 2 (s)	3.1 (s)	5.7 (s)
^{199}Ir	6^{+5}_{-4} (s)	73 (s)	370.6 (s)
	$\sigma_{\rm rms}$	0.31	0.53

Relevant to R-process Results

Some r-process waiting-point nuclei at N = 50 and N = 82 regions.

			T_{β^-} (ms)		
Nuc.	Exp. Data	ANN Model	*pn*QRPA+*ff*GT	*pn*-RQRPA+*ff*	DF3+CQRPA
$^{78}Ni_{50}$	110^{+100a}_{-60}	57	224	150	108
$^{79}Cu_{50}$	188 ± 25	115	157	-	257
$^{80}Zn_{50}$	545 ± 16	371	$1.26(s)$	970	839
$^{128}Pd_{82}$	-	81	74	63	43
$^{129}Ag_{82}$	44 ± 7	77	32	-	56
$^{130}Cd_{82}$	162 ± 7	158	502	299	147
$^{131}In_{82}$	280 ± 30	307	139	-	201
$^{132}Sn_{82}$	$39.7 \pm 0.5(s)$	$30(s)$	$23.8(s)$	$472.5(s)$	29.8(s)

[a] Recent first time experimentally deduced half-life value at the CCF of the NSCL at MSU by Hosmer et al.

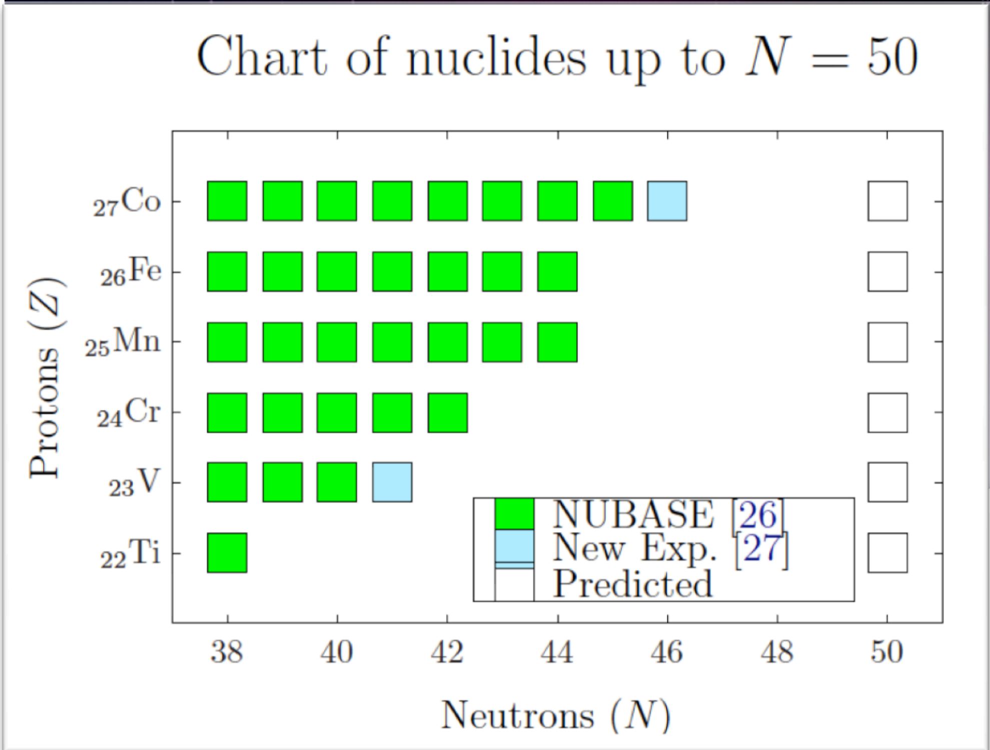
Recently measured* T_β of eight heavier abuse to ff neutron-rich isotopes close to the neutron shell N = 126 around A = 195.

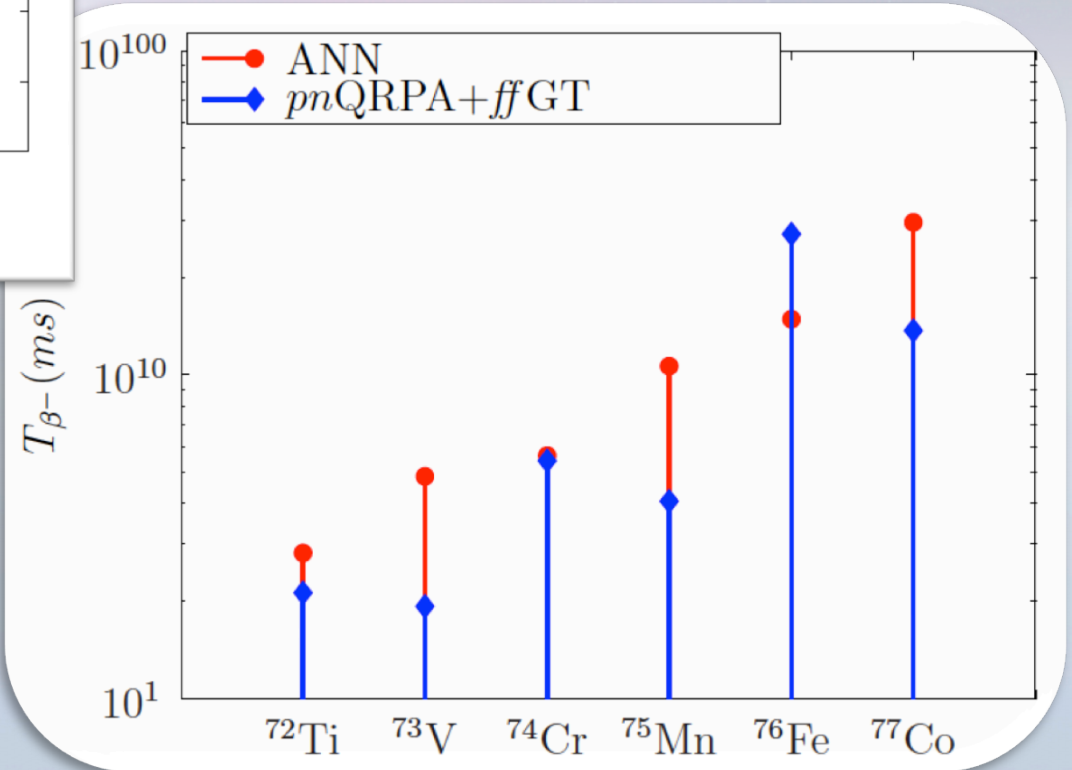
Nucleus	Exp. Data	ANN Model	*pn*QRPA+*ff*GT	DF3+CQRPA	Gr. Th.
^{194}Re	$1^{+0.5}_{-0.5}$	20.8	70.8	2.1	16.1
^{195}Re	6^{+1}_{-1}	23.9	3.3	8.5	10.3
^{196}Re	3^{+1}_{-2}	8.8	3.6	1.4	5.1
^{199}Os	5^{+4}_{-2}	13.6	106.8	6.6	17.2
^{200}Os	6^{+4}_{-3}	21.7	187.1	6.9	16
^{198}Ir	8^{+2}_{-2}	57.6	377.1	19.1	-
^{199}Ir	6^{+5}_{-4}	73	370.6	46.7	96.6
^{202}Ir	11^{+3}_{-3}	8.6	68.4	9.8	8.5
	σ_{rms}	0.77	1.33	0.39	-

*T. Kurtukian-Nieto et al.

N=50 Closed Shell

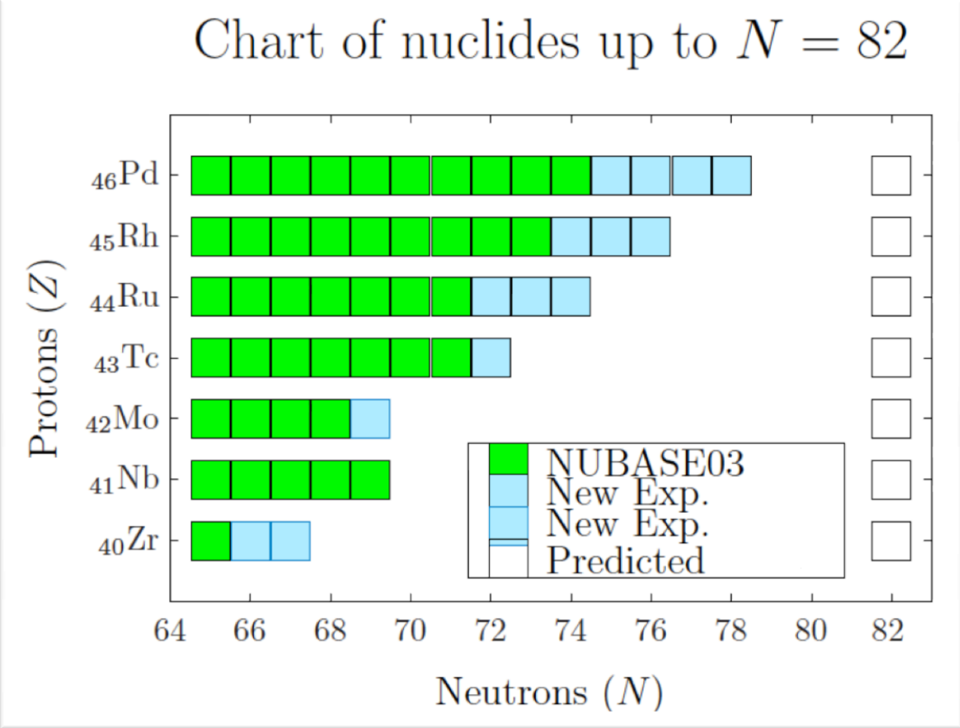
A = 70 – 80 mass region

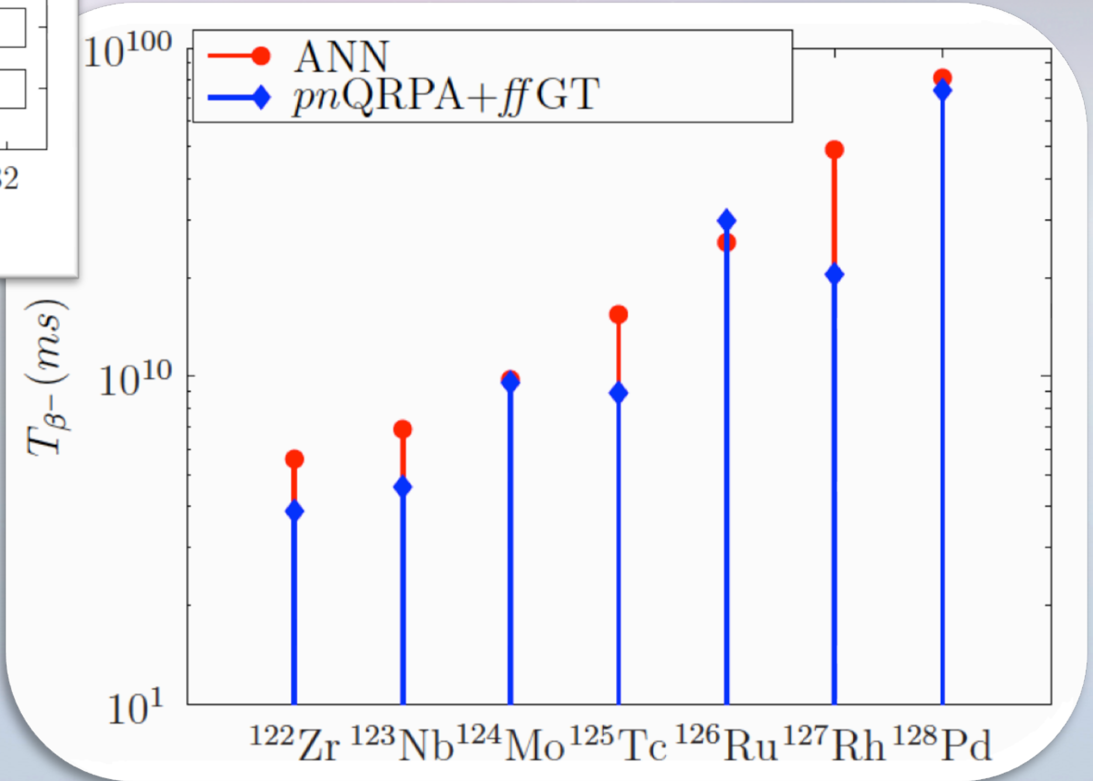




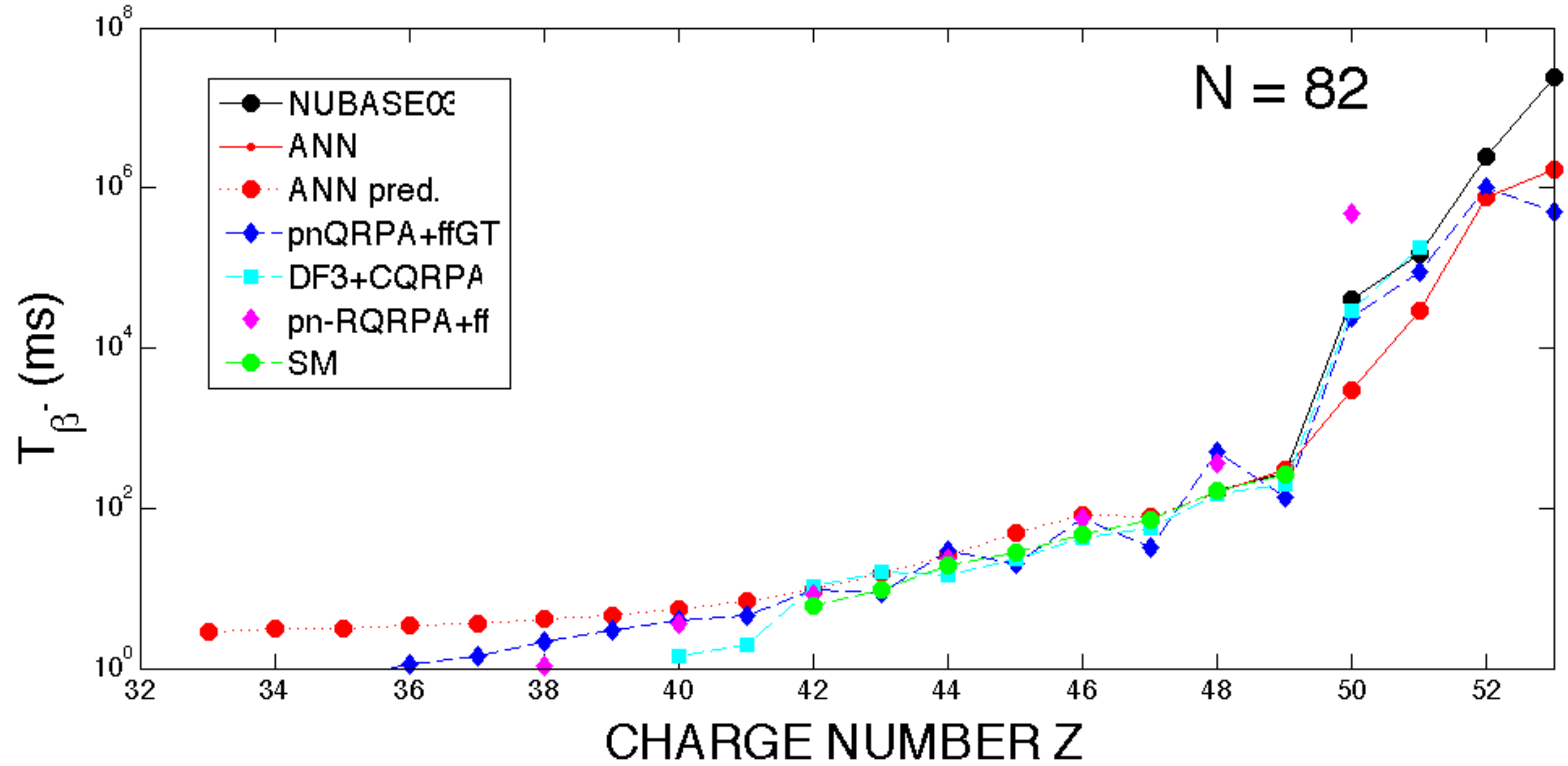
N=82 Closed Shell

A = 120 – 130 mass region



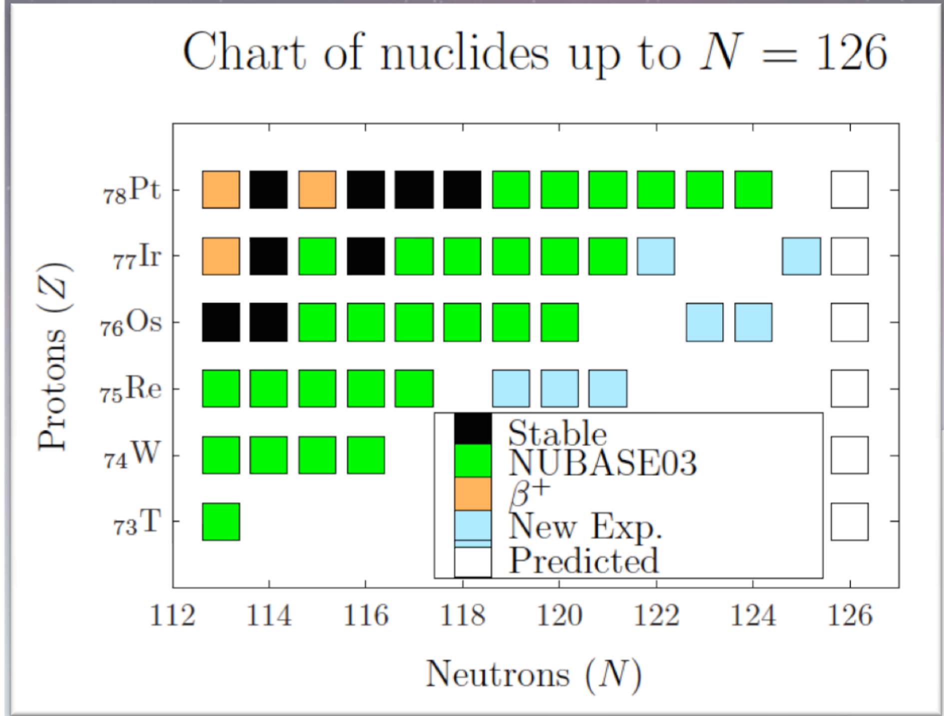


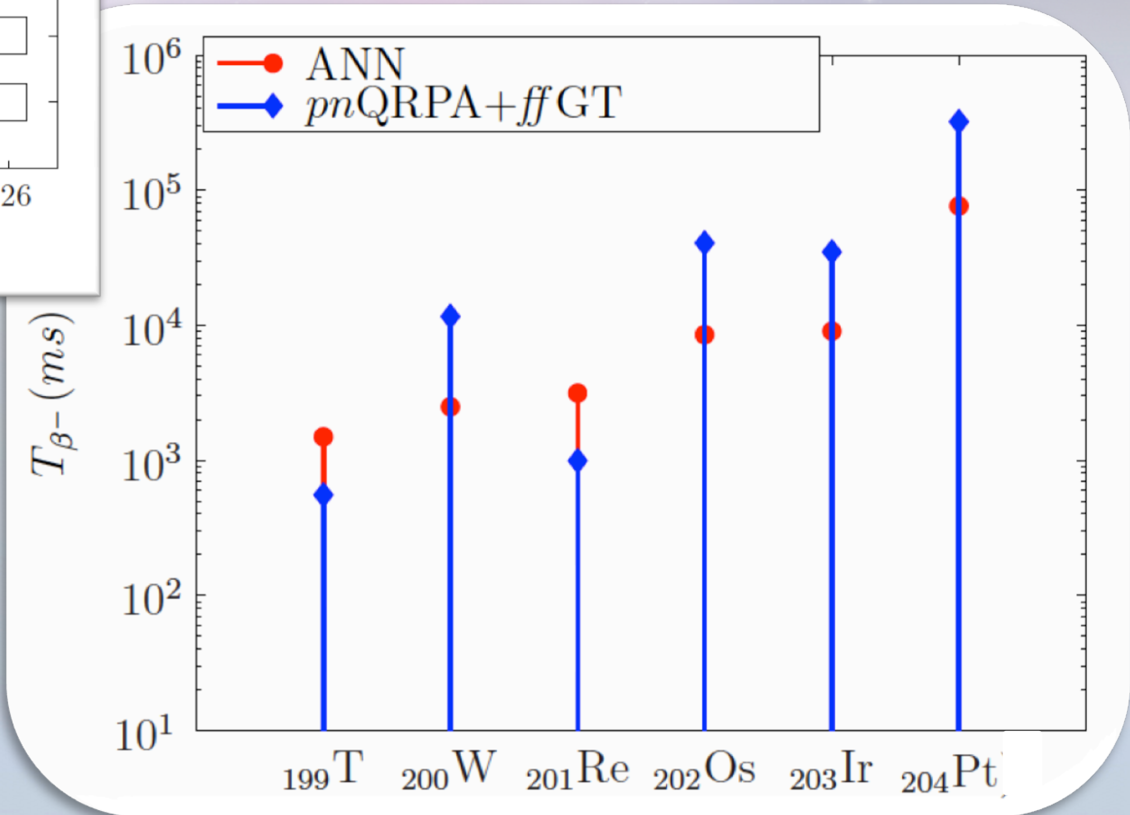
N=82 Isotonic Chain



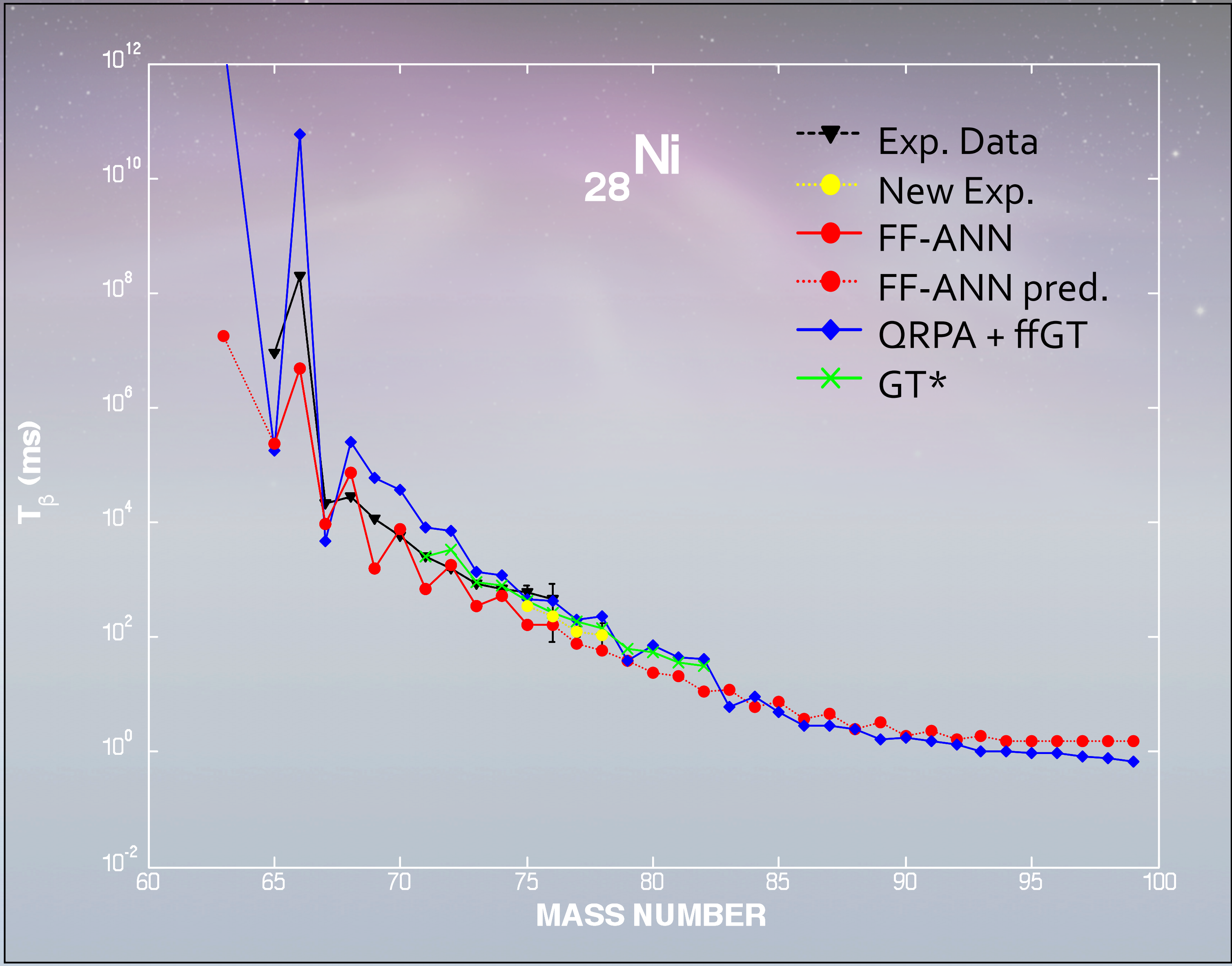
N=126 Closed Shell

A = 195 – 205 mass region

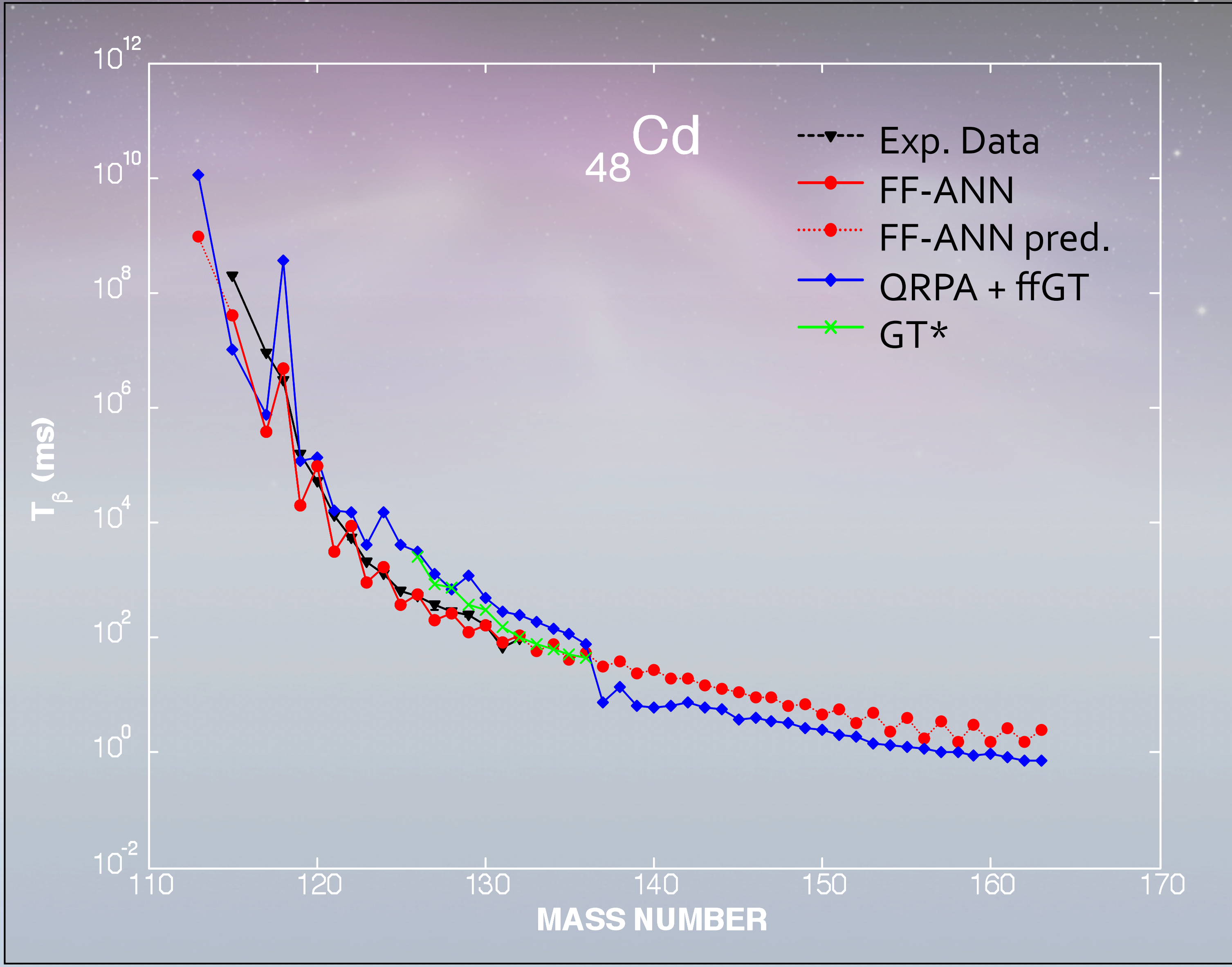




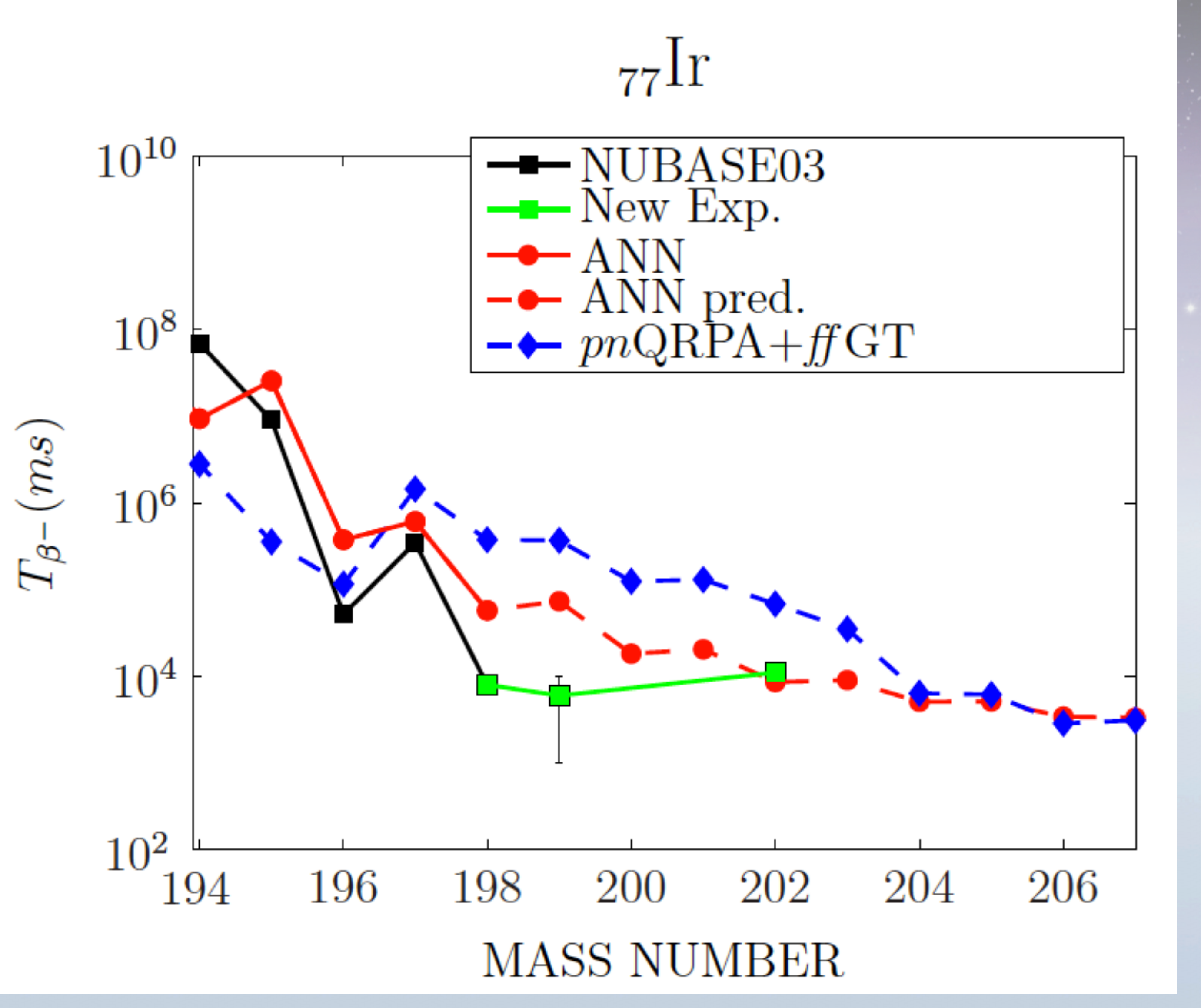
Isotopic Chain of $_{28}Ni$



Isotopic Chain of $_{48}Cd$

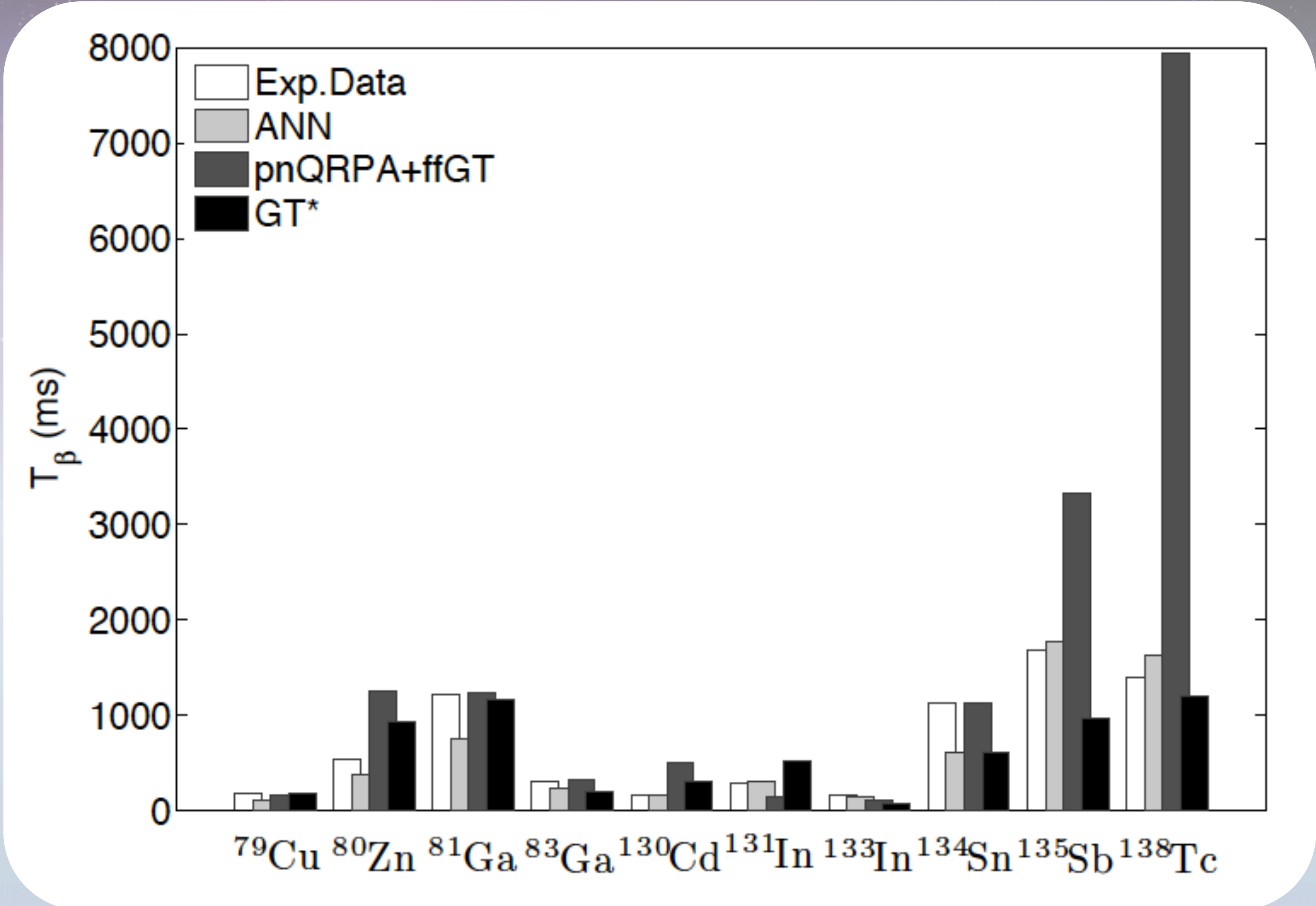


Isotopic Chain of $_{77}Ir$

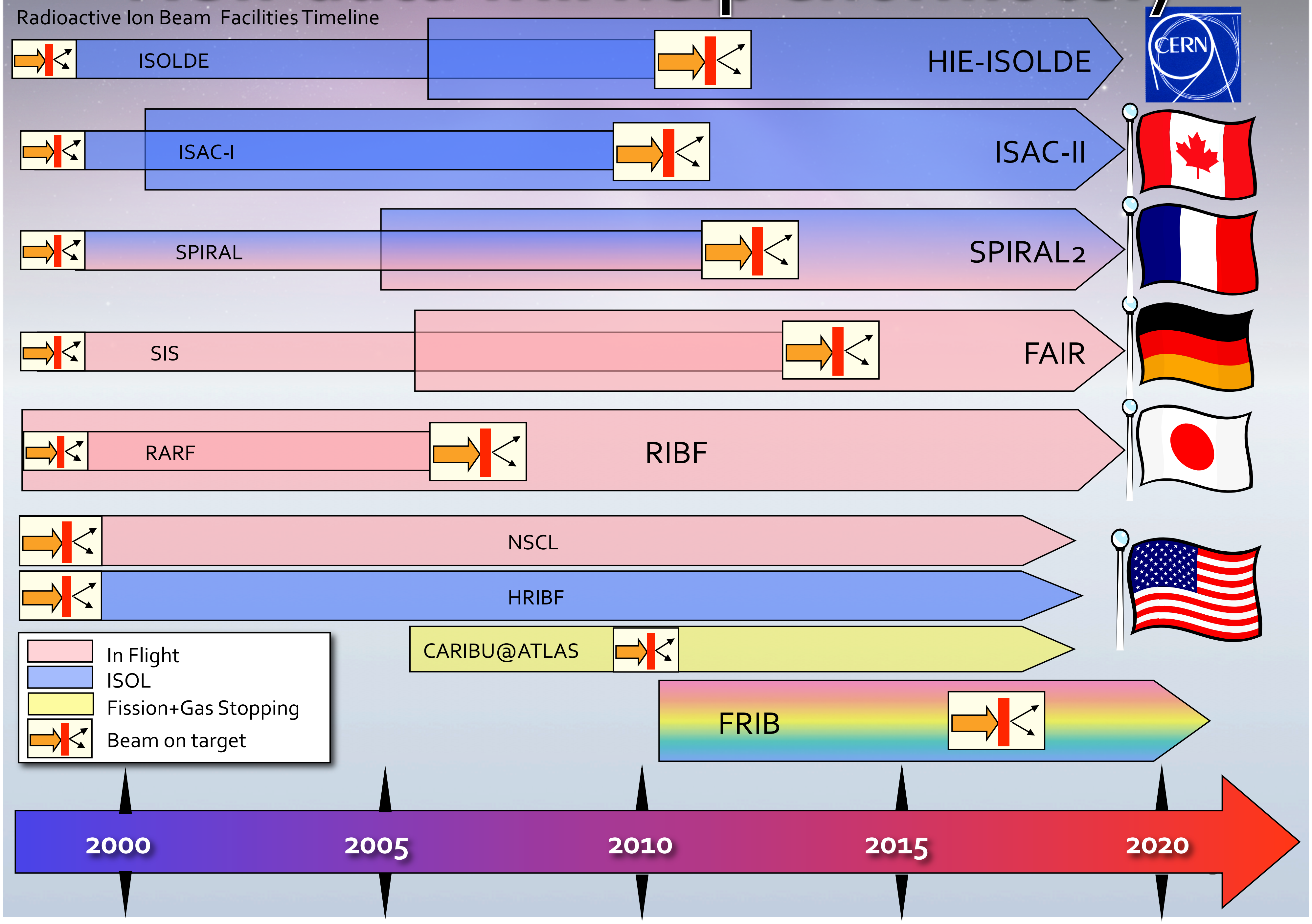


Nuclides on or near a typical r-process path

with S_n up to 3 MeV



New data will help enormously



Conclusions & Prospects

- **Conclusions**

  Theory-thin statistical global models of nuclear properties developed by learning machines should provide a valuable, robust additional tool to **complement** the nuclear systematics studies **beyond the standard nuclear landscape** planned with the present and future very neutron- rich, rare-isotope experimental facilities.

- **Prospects**

  We plan further studies of nuclear properties relevant to r-process: masses, neutron capture cross-sections with the already developed by us ANN and SVM techniques.

  We also plan further studies of nuclear properties using Artificial Intelligence's more mature learning strategies, such as **committee of machines** (CoM) - a collection of different feed-forward Artificial Neural Networks (ANNs) instead of a single ANN, with a view to refine current results.

Questions

Thank You

β^- decay half-lives using the ANN model: Input for the r-process*

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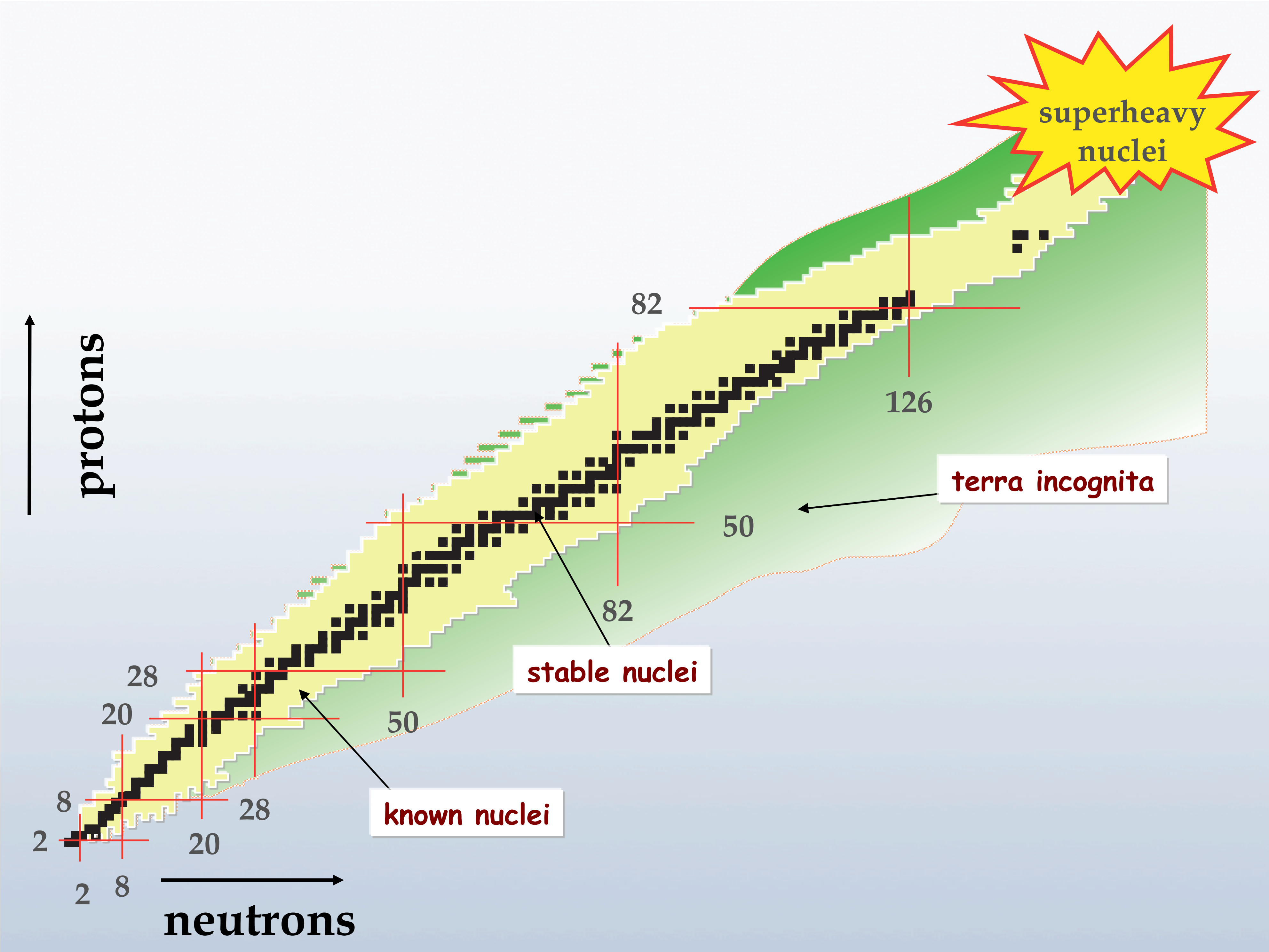
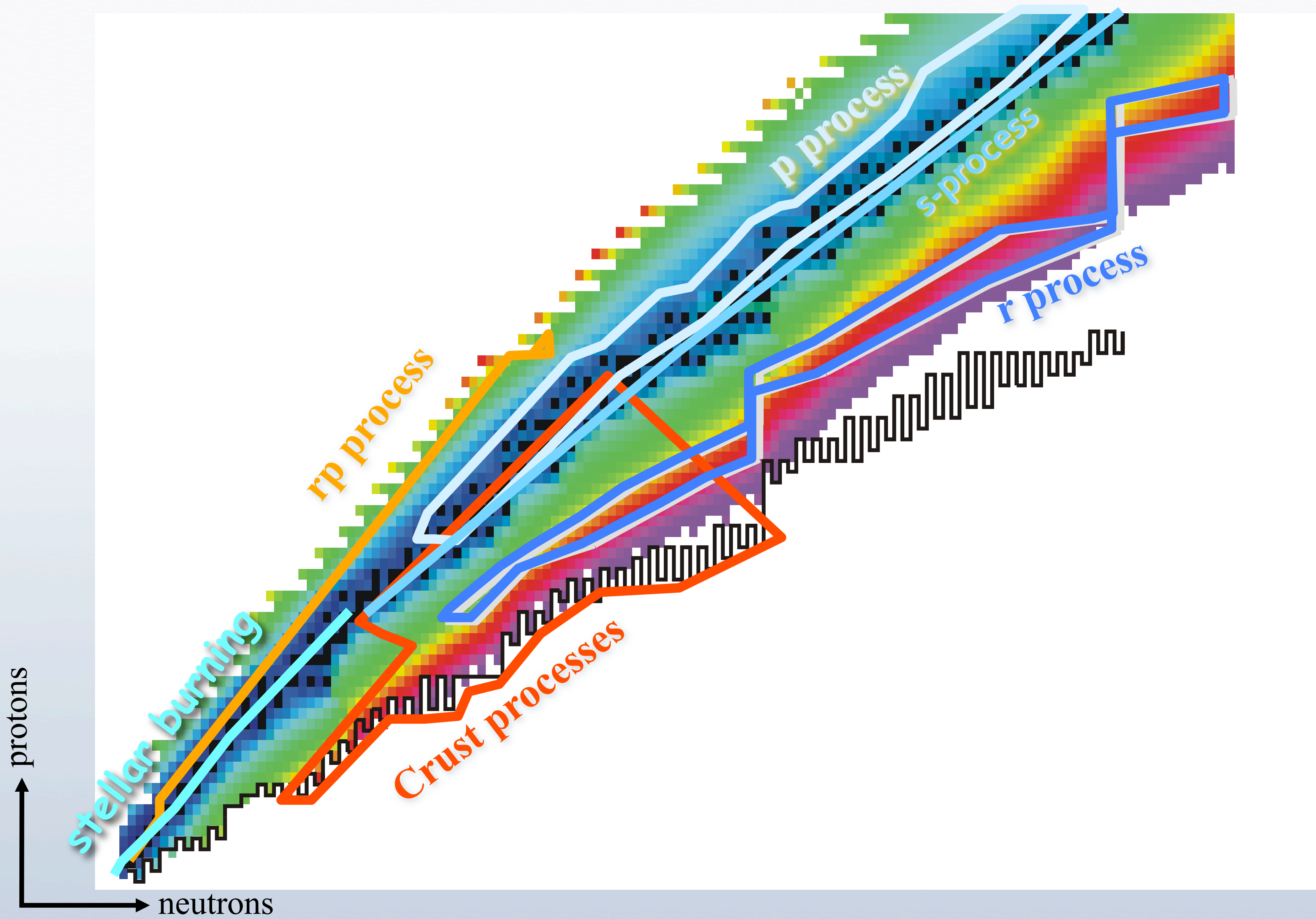
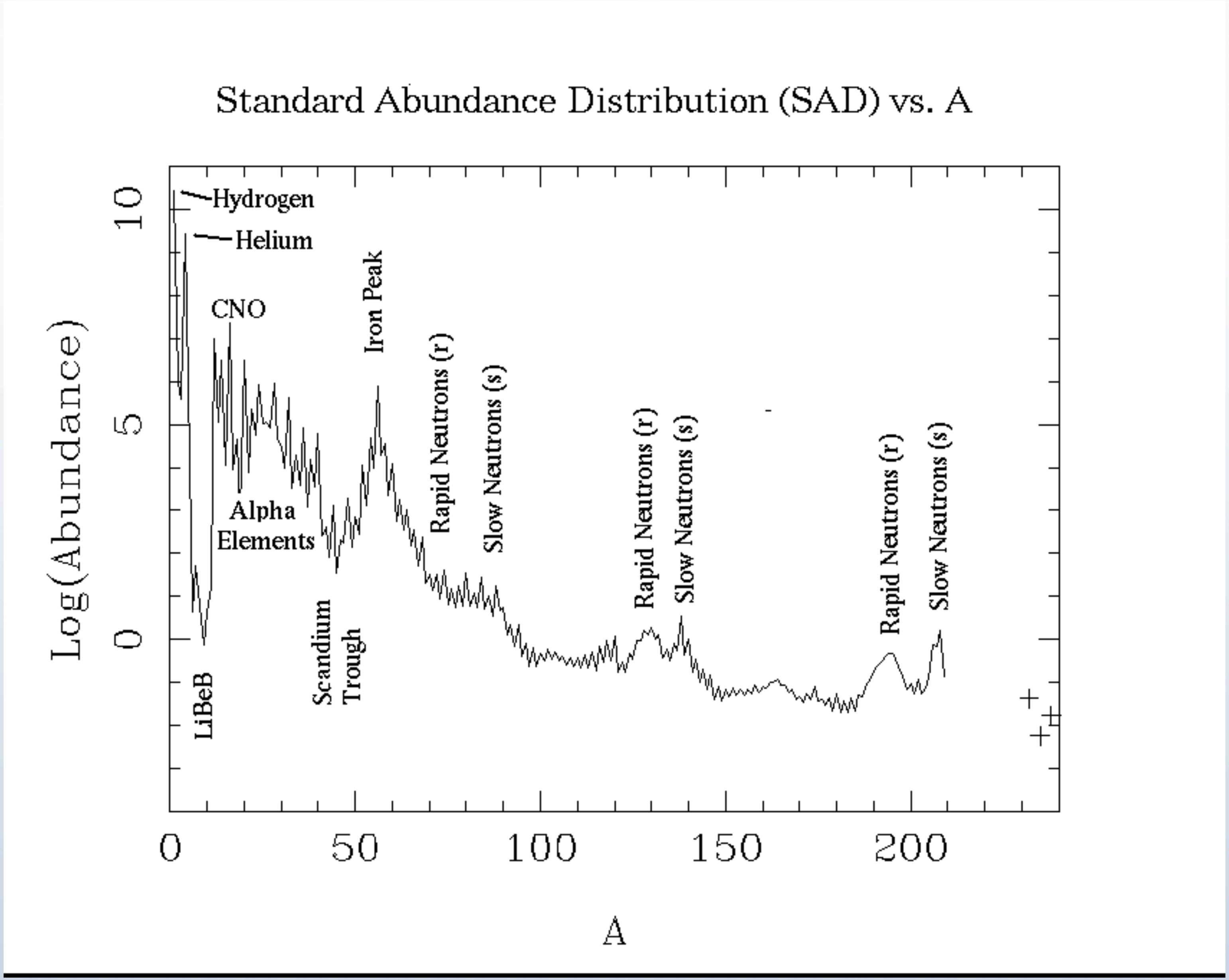
*To be submitted to Phys. Rev. C

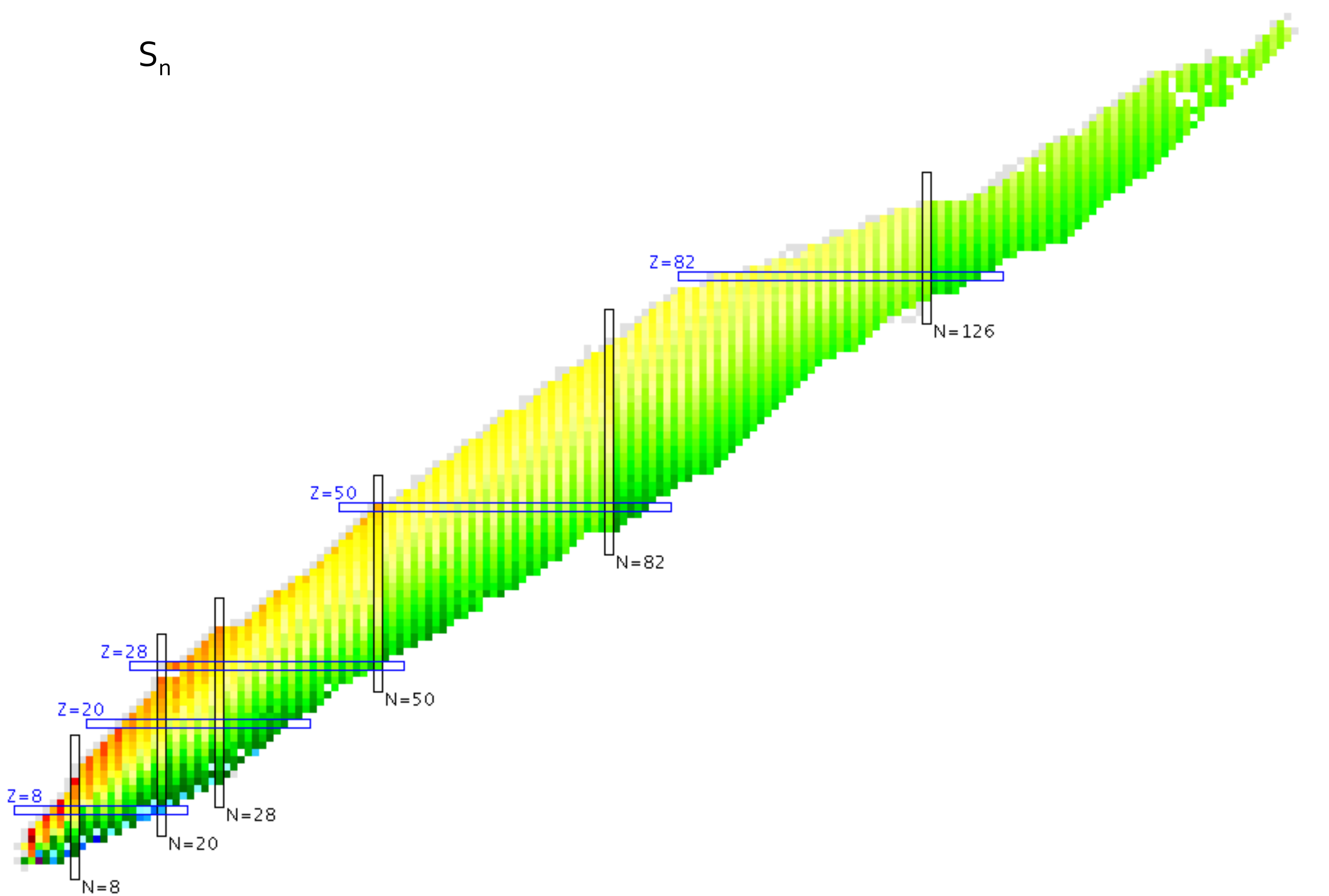
Backup Slides


superheavy
nuclei
protons
neutrons
82
126
50
82
terra incognita
stable nuclei
known nuclei
28
20
50
8
2
28
20
2
8

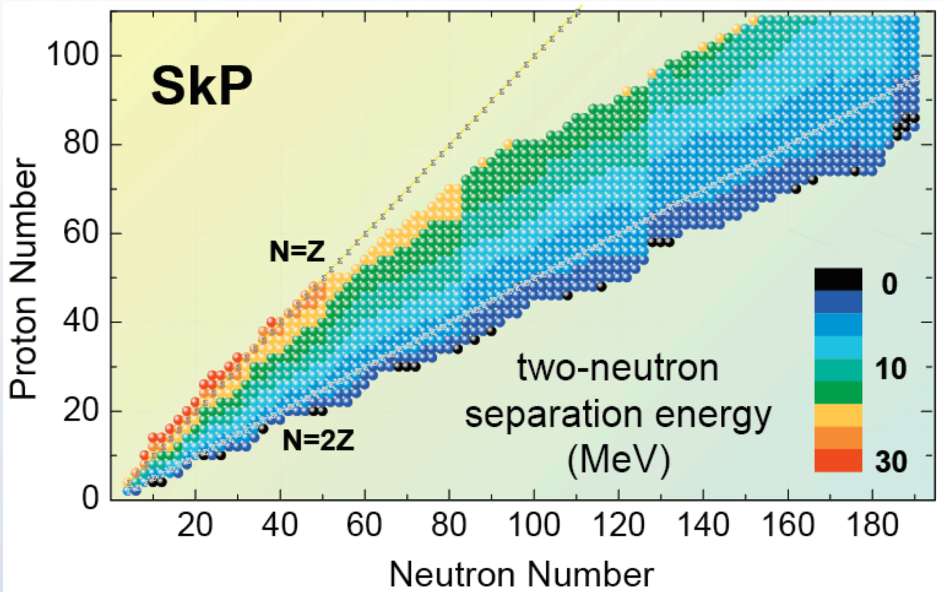

p process
s-process
rp process
r process
stellar burning
Crust processes
protons
neutrons



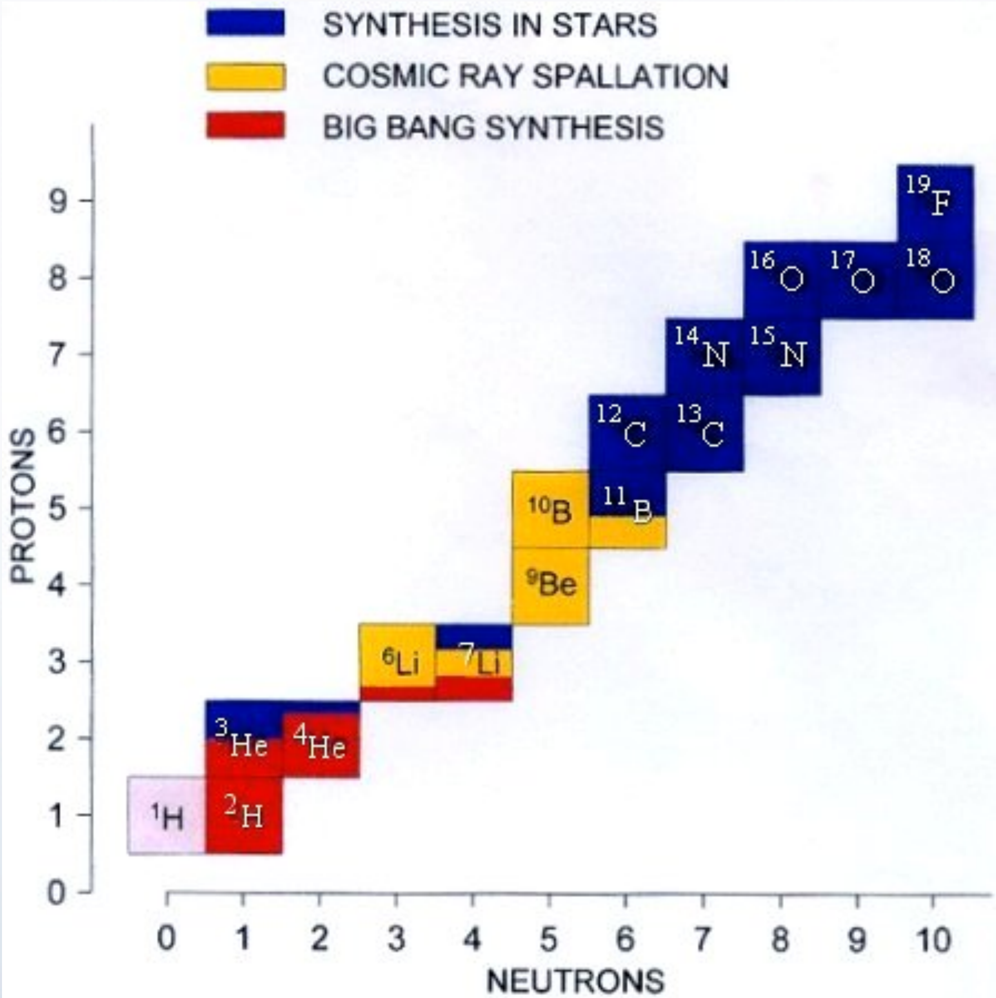
Standard Abundance Distribution (SAD) vs. A
Log(Abundance)
A
0
5
10
0
50
100
150
200
Hydrogen
Helium
CNO
Iron Peak
Alpha Elements
LiBeB
Scandium Trough
Rapid Neutrons (r)
Slow Neutrons (s)
Rapid Neutrons (r)
Slow Neutrons (s)
Rapid Neutrons (r)
Slow Neutrons (s)



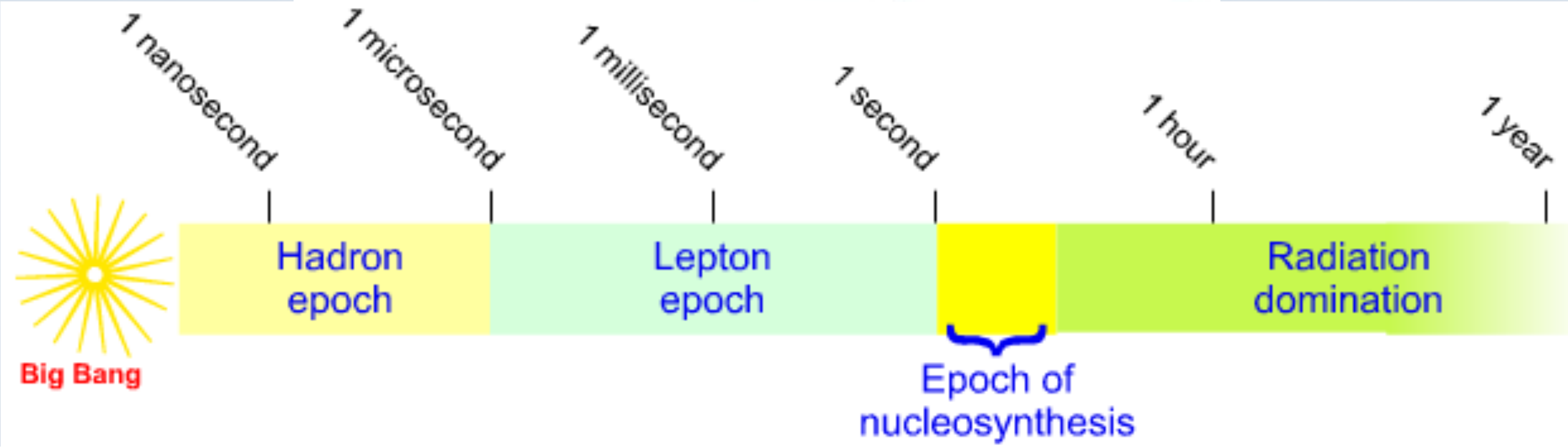
S_n
Z=82
N=126
Z=50
N=82
Z=28
N=50
Z=20
N=28
Z=8
N=20
N=8



SkP
N=Z
N=2Z
Proton Number
Neutron Number
two-neutron separation energy (MeV)
0
10
30
100
80
60
40
20
0
20
40
60
80
100
120
140
160
180

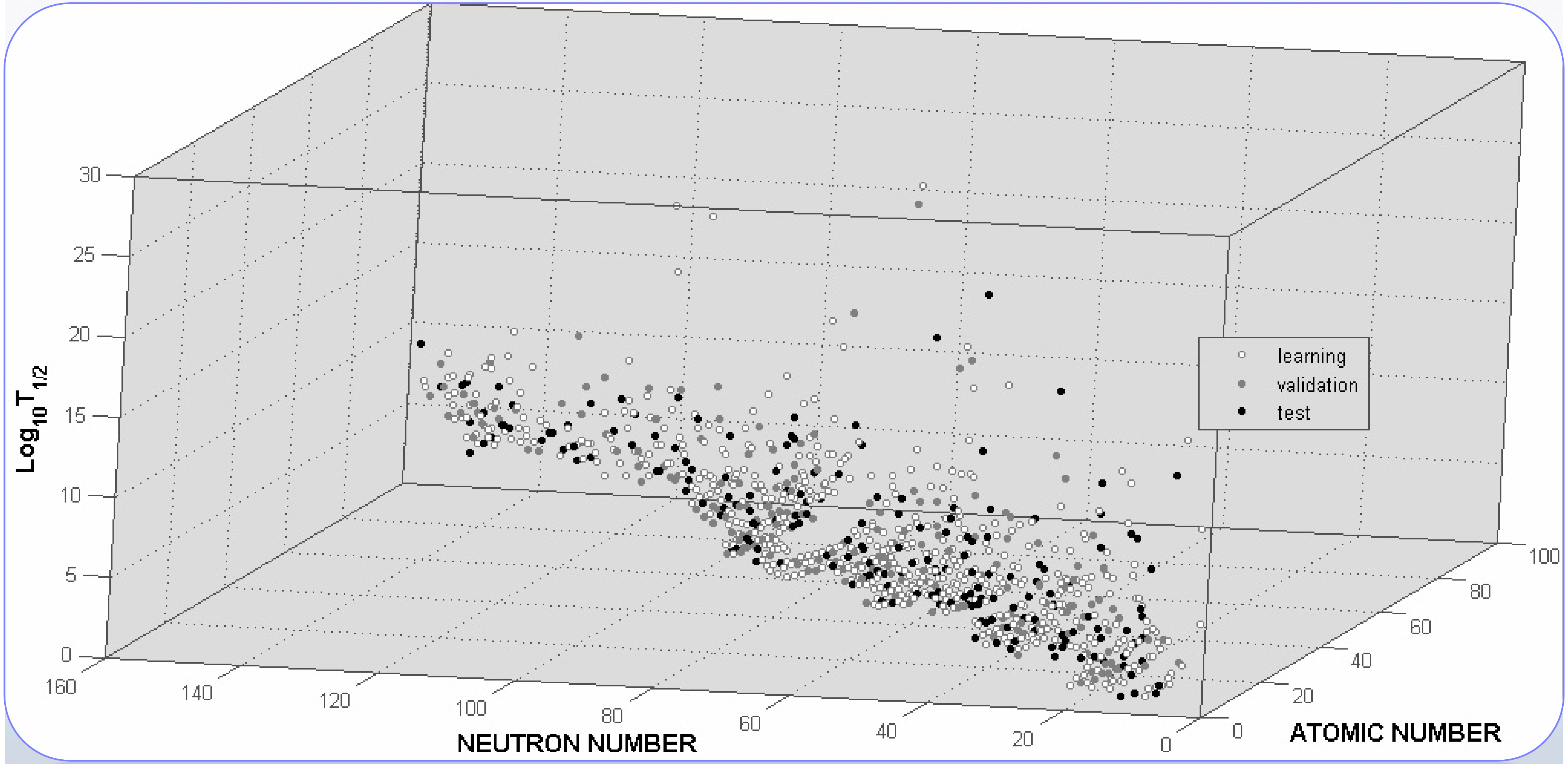


SYNTHESIS IN STARS
COSMIC RAY SPALLATION
BIG BANG SYNTHESIS
PROTONS
NEUTRONS
1H
2H
3He
4He
6Li
7Li
9Be
10B
11B
12C
13C
14N
15N
16O
17O
18O
19F



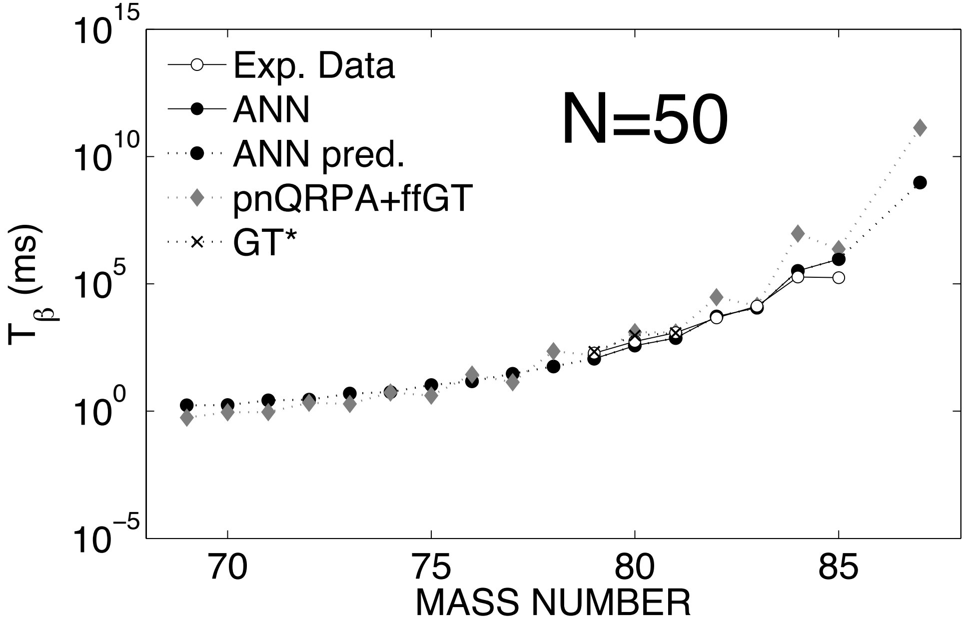
1 nanosecond
1 microsecond
1 millisecond
1 second
1 hour
1 year
Big Bang
Hadron epoch
Lepton epoch
Radiation domination
Epoch of nucleosynthesis

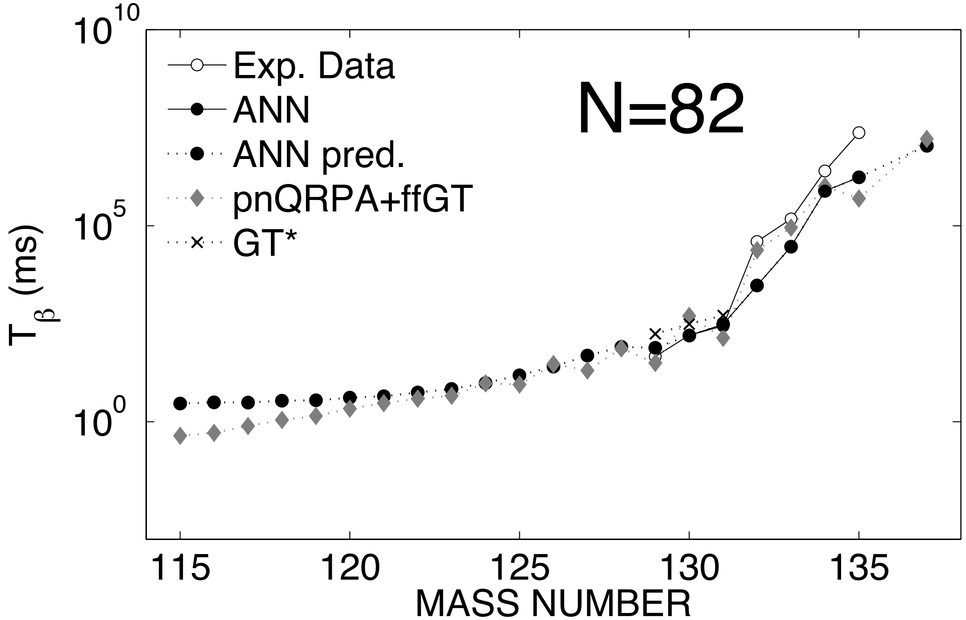
NuBase03

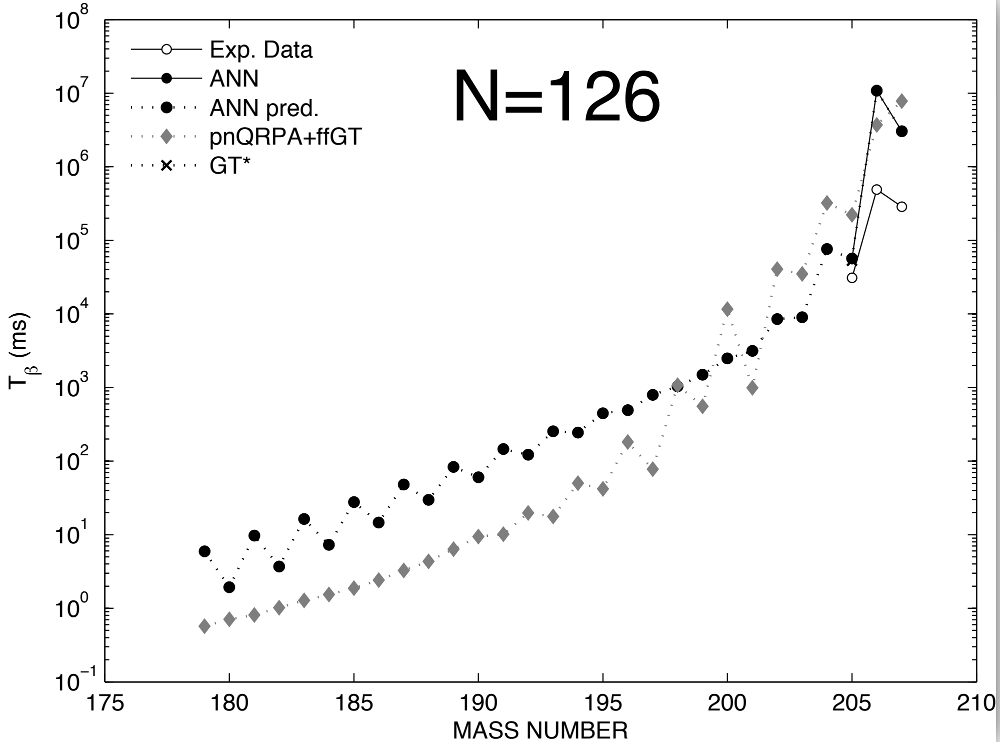


Log10 T1/2
30
25
20
15
10
5
0
160
140
120
100
80
60
40
20
0
NEUTRON NUMBER
0
20
40
60
80
100
ATOMIC NUMBER
learning
validation
test

Isotonic Chains

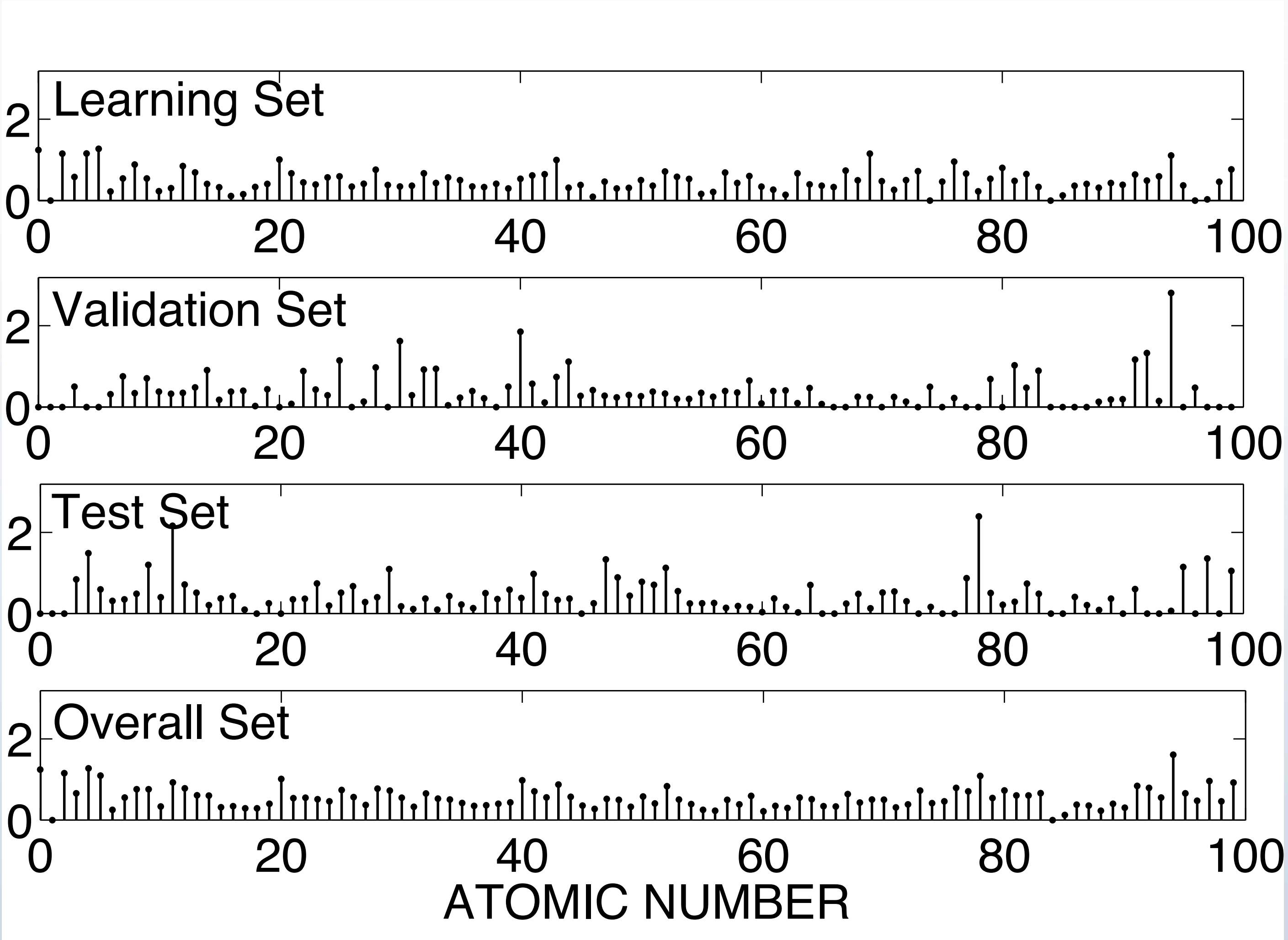






Nucleus	$T_{\beta^-}(s)$				
	NUBASE03	ANN Model	*pn*QRPA+*ff*GT	*pn*-RQRPA	*pn*-RQRPA+*ff*GT
^{70}Ni	6.00 (0.30)	7.58	36.72	35.28	4.89
^{72}Ni	1.57 (0.05)	1.83	7.03	9.11	1.42
^{74}Ni	0.680 (0.120)	0.530	1.20	3.57	0.563
^{76}Ni	0.470 (0.390), $0.238^{+0.015}_{-0.018}$	0.164	0.433	2.13	0.279
^{78}Ni	$0.110^{+0.100}_{-0.600}$	0.057	0.224	1.71	0.150
^{122}Cd	5.24 (0.03)	8.74	15.17	0.549	2.40
^{124}Cd	1.25 (0.02)	1.71	15.20	0.416	1.21
^{126}Cd	0.515 (0.017)	0.560	3.23	0.329	0.673
^{128}Cd	0.280 (0.040)	0.265	0.695	0.297	0.429
^{130}Cd	0.162 (0.007)	0.158	0.502	0.299	0.299
^{132}Cd	0.097 (0.010)	0.107	0.243	0.184	0.172
^{198}Ir	8^{+2}_{-2}	57.6	377.1	19.1	-
^{199}Ir	6^{+5}_{-4}	73	370.6	46.7	96.6
^{202}Ir	11^{+3}_{-3}	8.6	68.4	9.8	8.5

RMSE



Learning Set
Validation Set
Test Set
Overall Set
2
0
0
20
40
60
80
100
ATOMIC NUMBER

Klapdor's Metrics*

* H. Homma, M. Bender et al., Phys. Rev. C 54:6 (1996) 2972

fact	$T_{1/2}$ Exp (s)	Overall Mode			Prediction Mode			NBSC+pnQRPA		
		m(%)	$<x>_K$	σ_K	m(%)	$<x>_K$	σ_K	m(%)	$<x>_K$	σ_K
<10	<10^6	90.5	2.46	1.72	90.5	2.69	1.85	76.7	3.00	-
	<60	96.5	2.21	1.52	96.1	2.48	1.64	87.2	2.81	-
	<1	97.6	2.10	1.39	98	2.24	1.30	95.7	2.64	-
<5	<10^6	82.8	1.99	0.95	79.2	2.10	0.97	-	-	-
	<60	90.2	1.88	0.84	87.3	2.05	0.91	-	-	-
	<1	93.7	1.88	0.8	94	2.04	0.89	-	-	-
<2	<10^6	53.5	1.41	0.27	49.4	1.48	0.28	33.8	1.43	-
	<60	60.6	1.41	0.27	53.9	1.48	0.27	42.0	1.41	-
	<1	61.9	1.41	0.26	60	1.50	0.27	50.7	1.43	-

$\bar{x}_K$ must tends towards 1 while σ_K must tends towards 0.

$$\bar{x}_K = \frac{1}{N}\sum_i x_i, \quad x_i = \begin{cases} T_{\beta,\exp}/T_{\beta,calc} & if \quad T_{\beta,\exp} \geq T_{\beta,calc} \\ T_{\beta,calc}/T_{\beta,\exp} & if \quad T_{\beta,\exp} < T_{\beta,calc} \end{cases} \qquad \sigma_K = \left[\frac{1}{N}\sum_i (x_i - \bar{x}_K)^2\right]^{1/2}$$