Neutrinos, Double Beta Decay, and Supernova Dynamics

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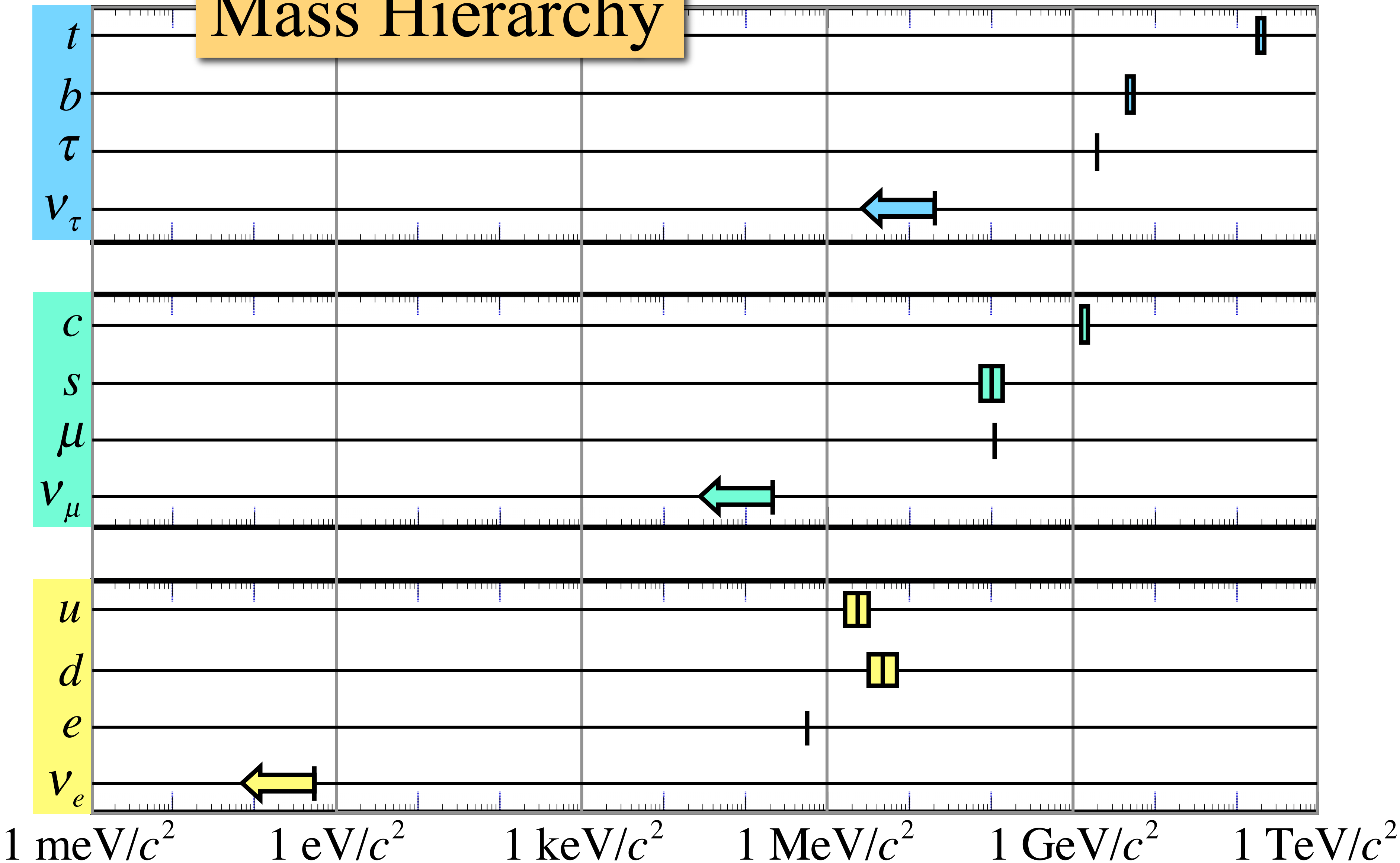
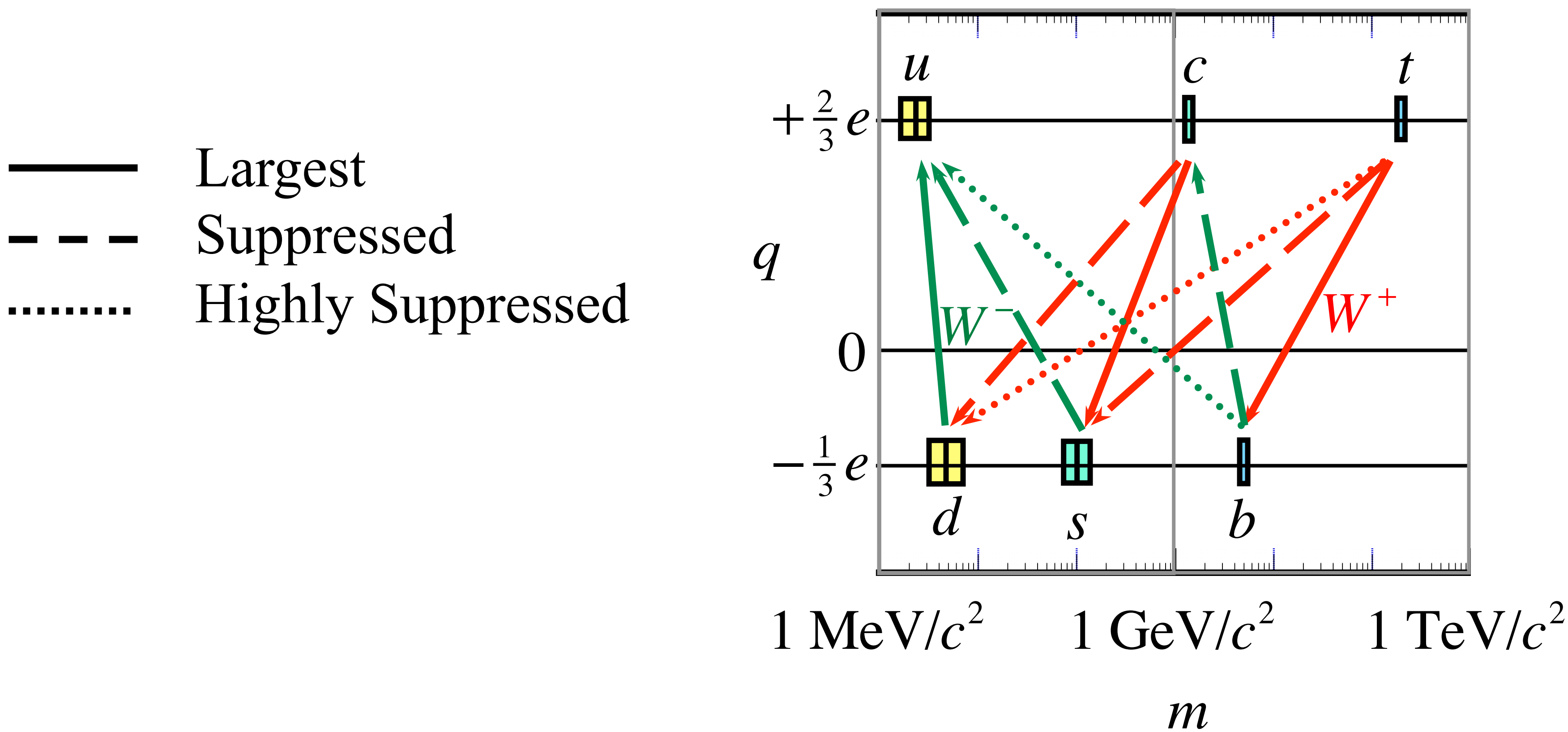
Mass Hierarchy



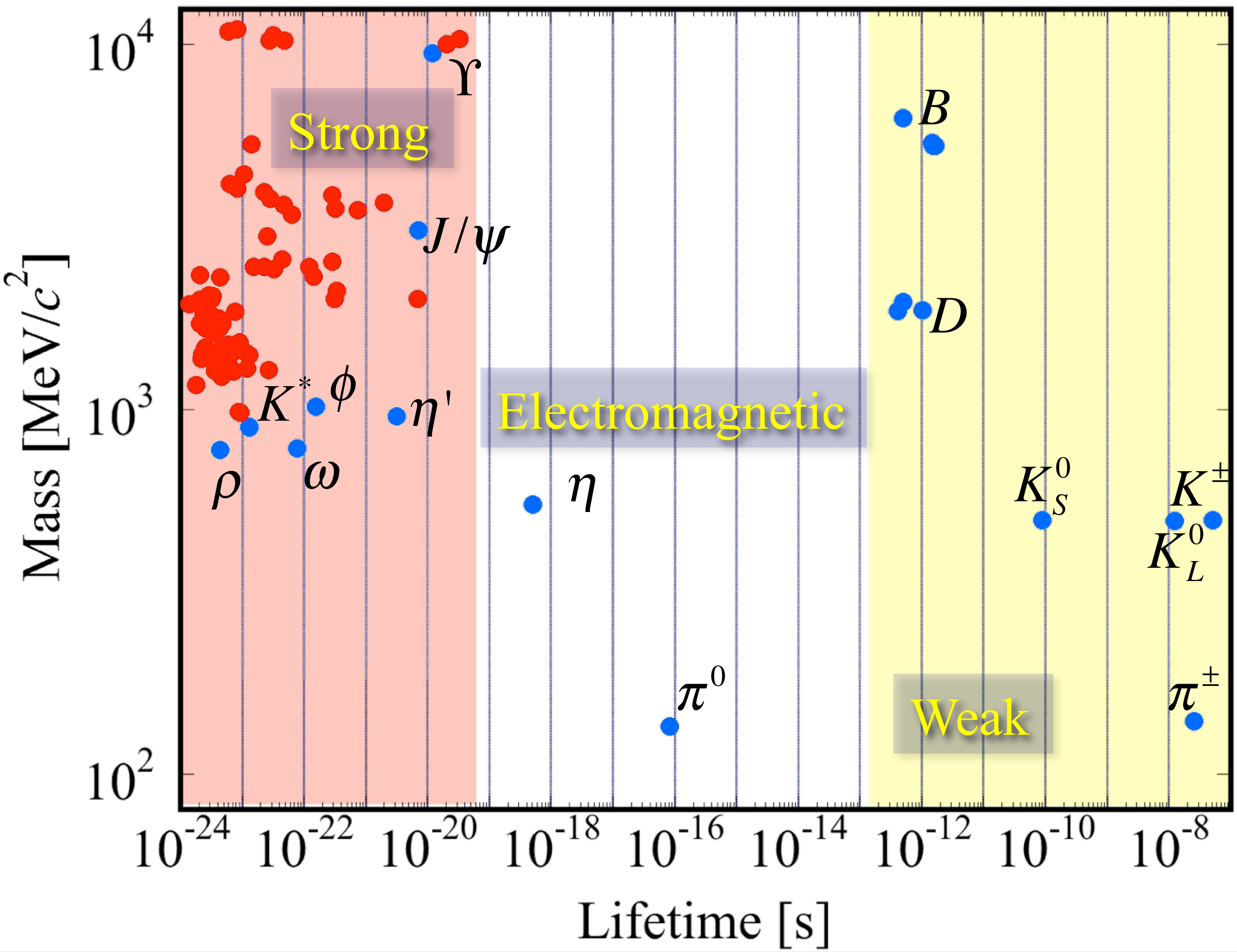
Beta Decays

$$\beta^- : \quad q \to q' + \ell^- + \bar{\nu}_\ell ; \quad m_q > m_{q'} + m_\ell + m_\nu$$

$$\beta^+ : \quad q \to q' + \ell^+ + \nu_\ell ; \quad m_q > m_{q'} + m_\ell + m_\nu$$



Composites: Mesons



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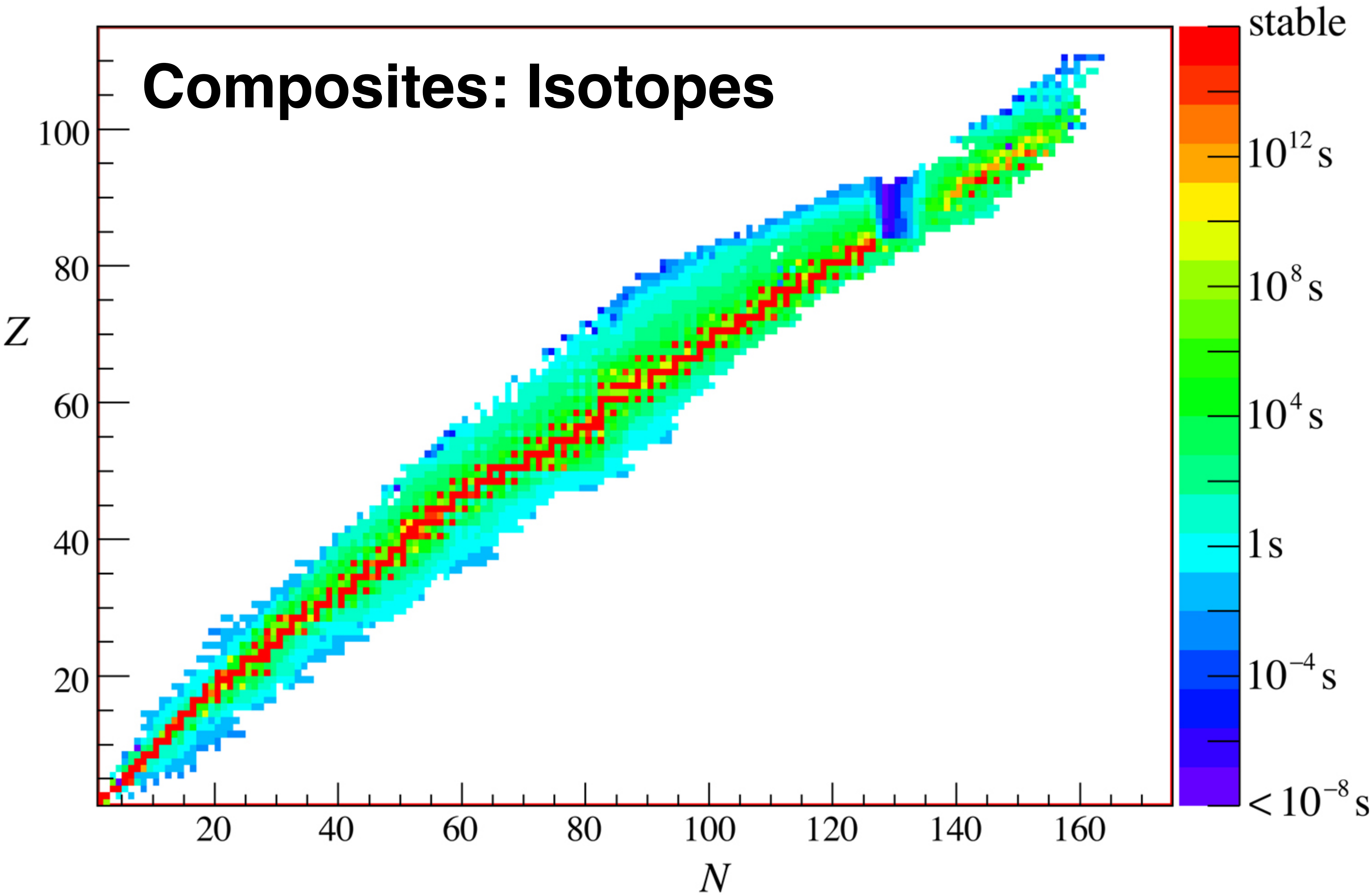
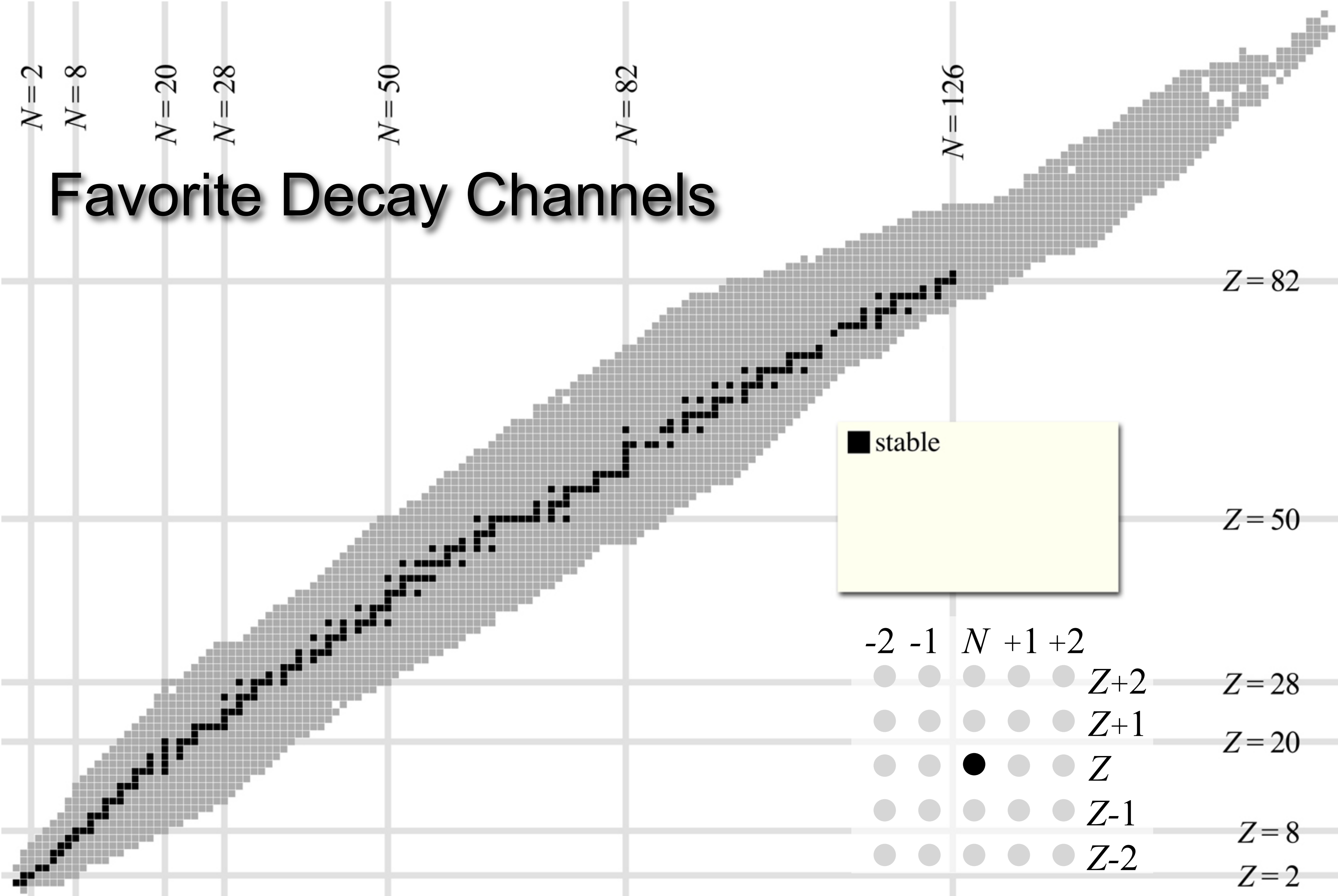
Composites: Isotopes



Favorite Decay Channels



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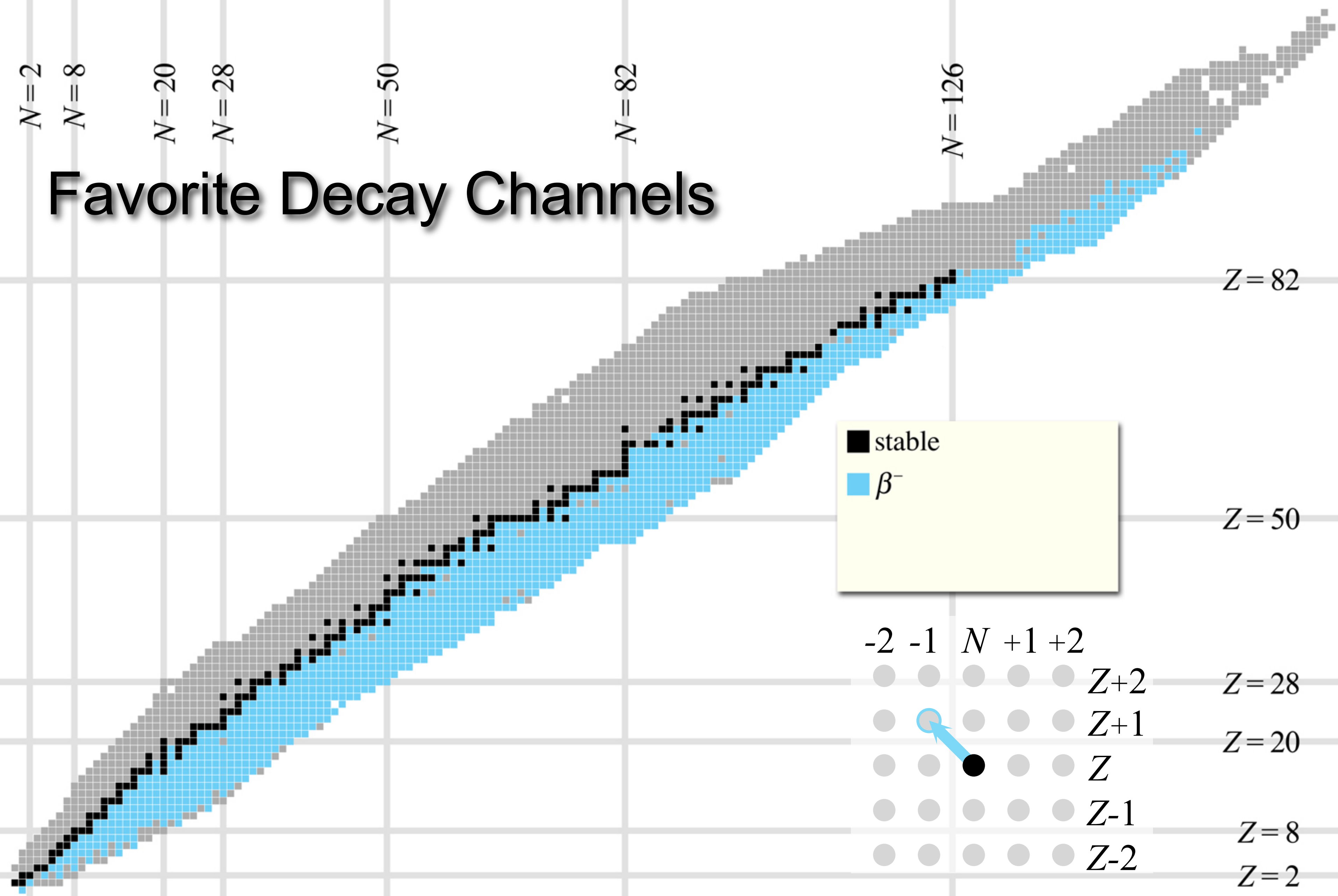

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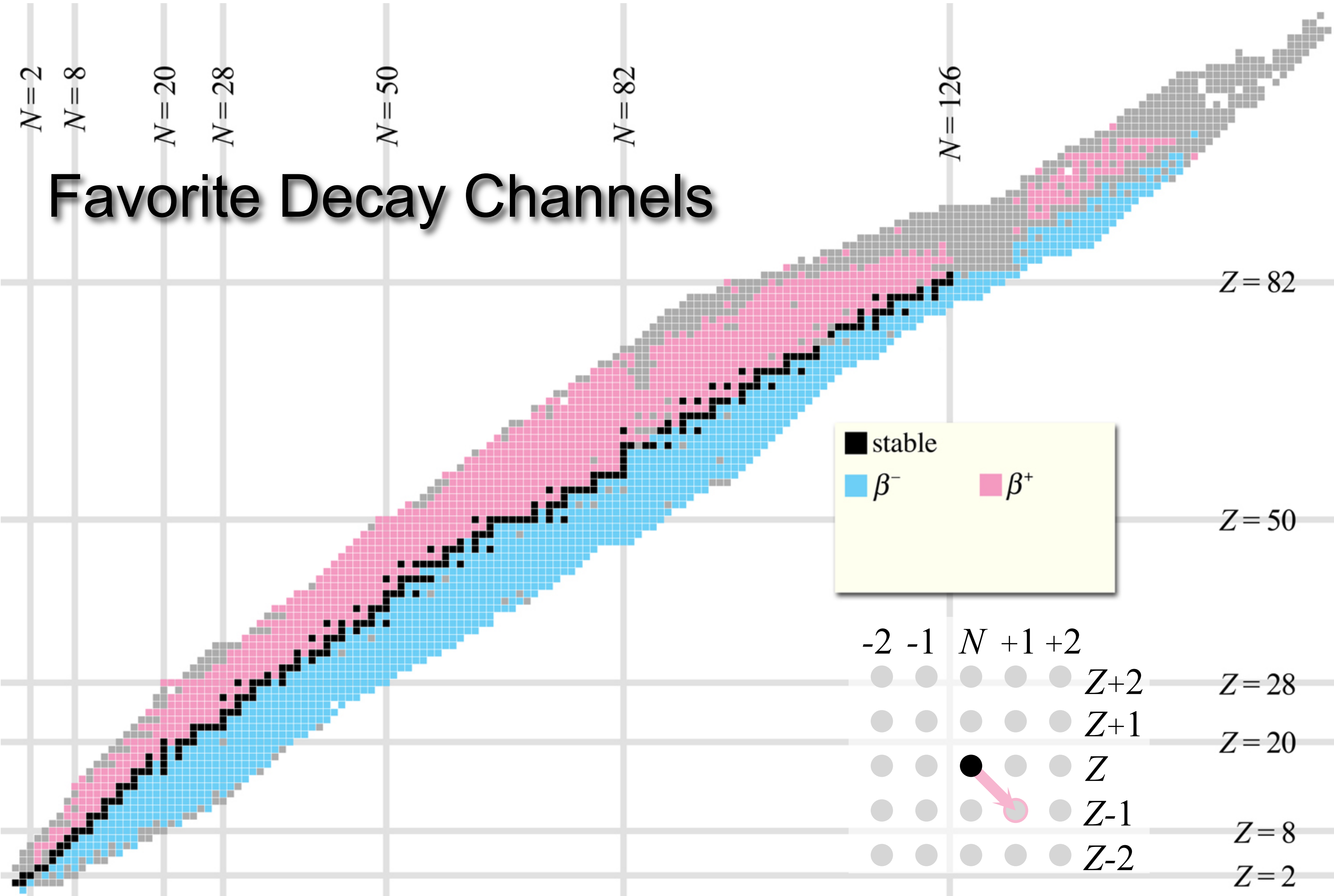

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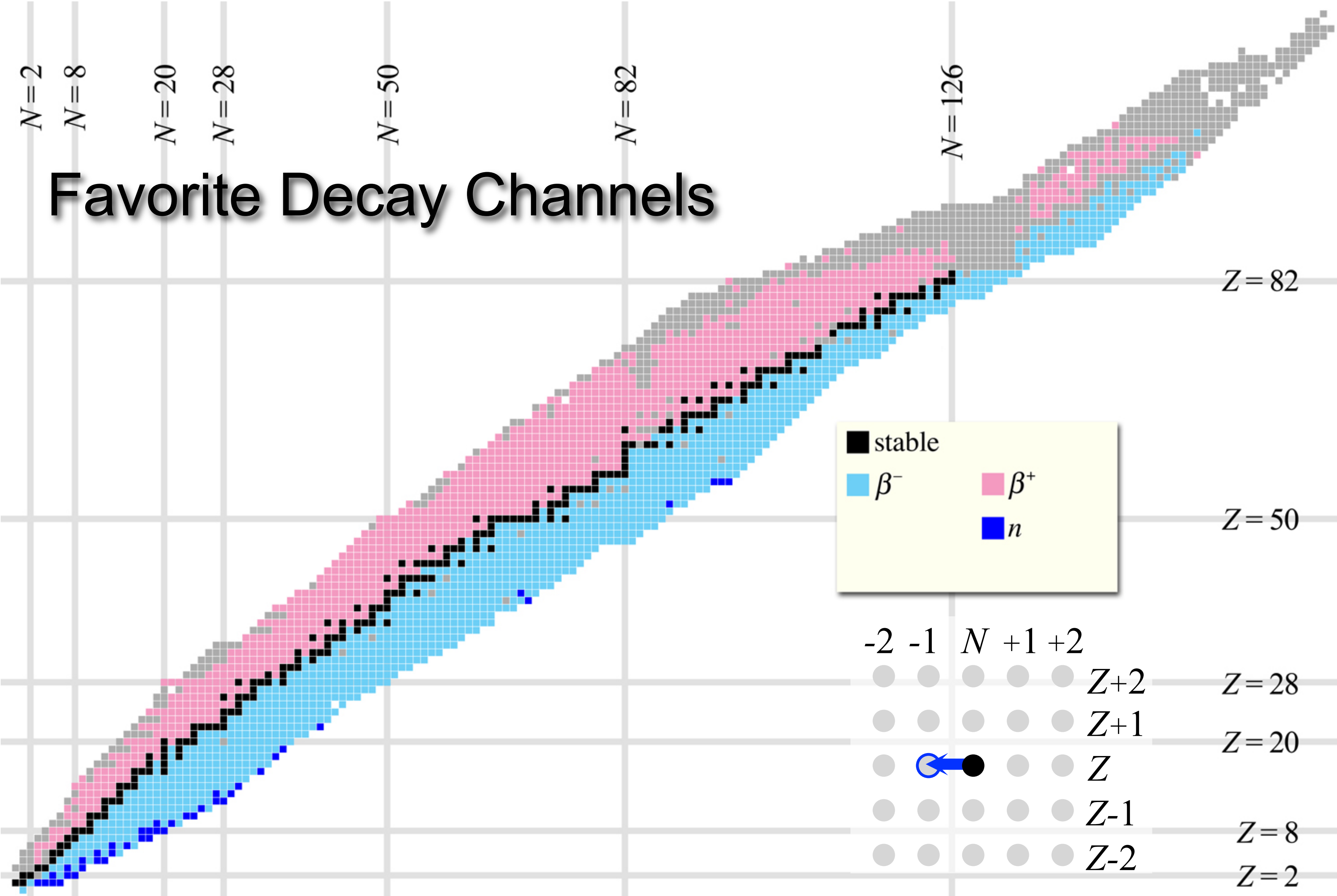
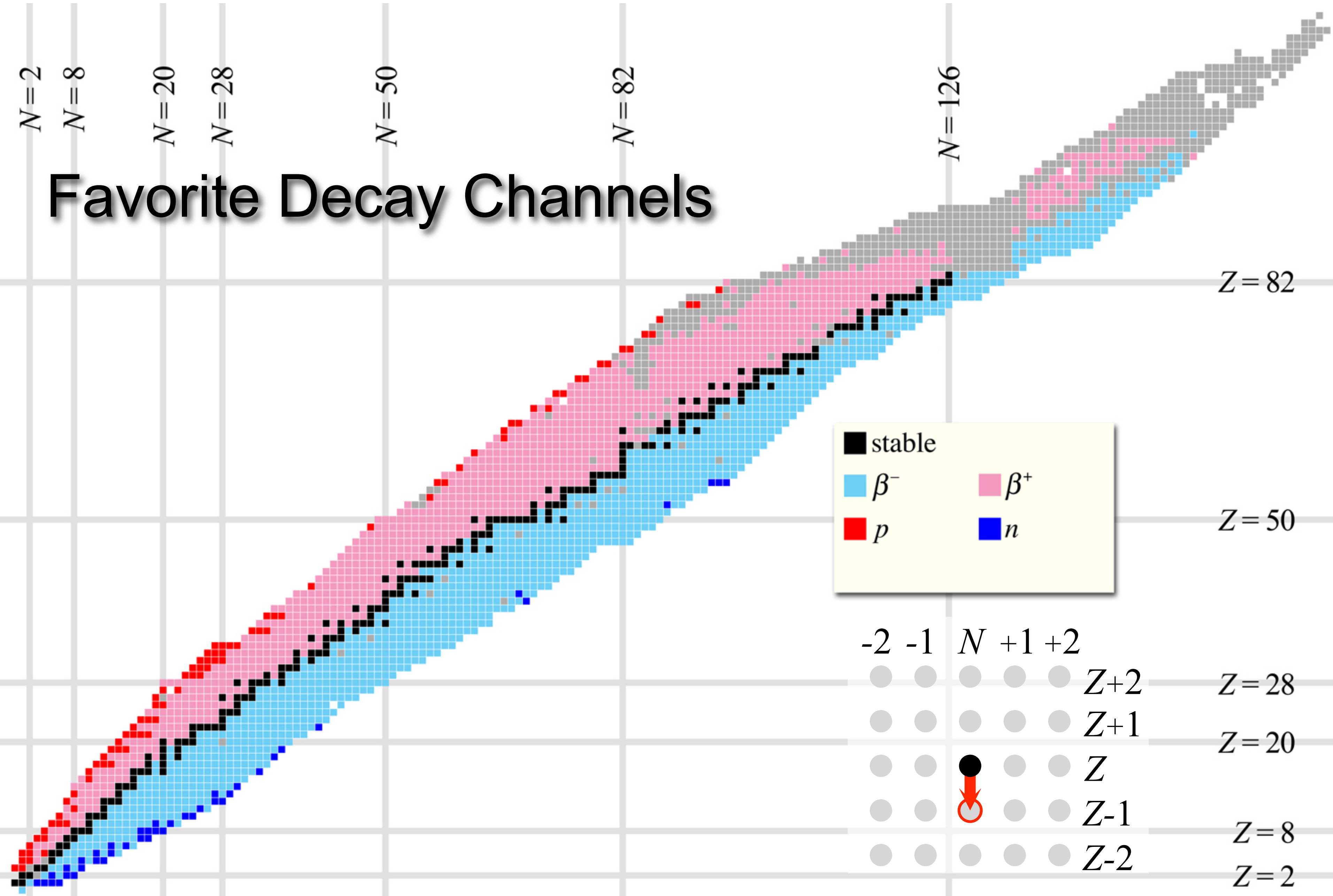


Favorite Decay Channels



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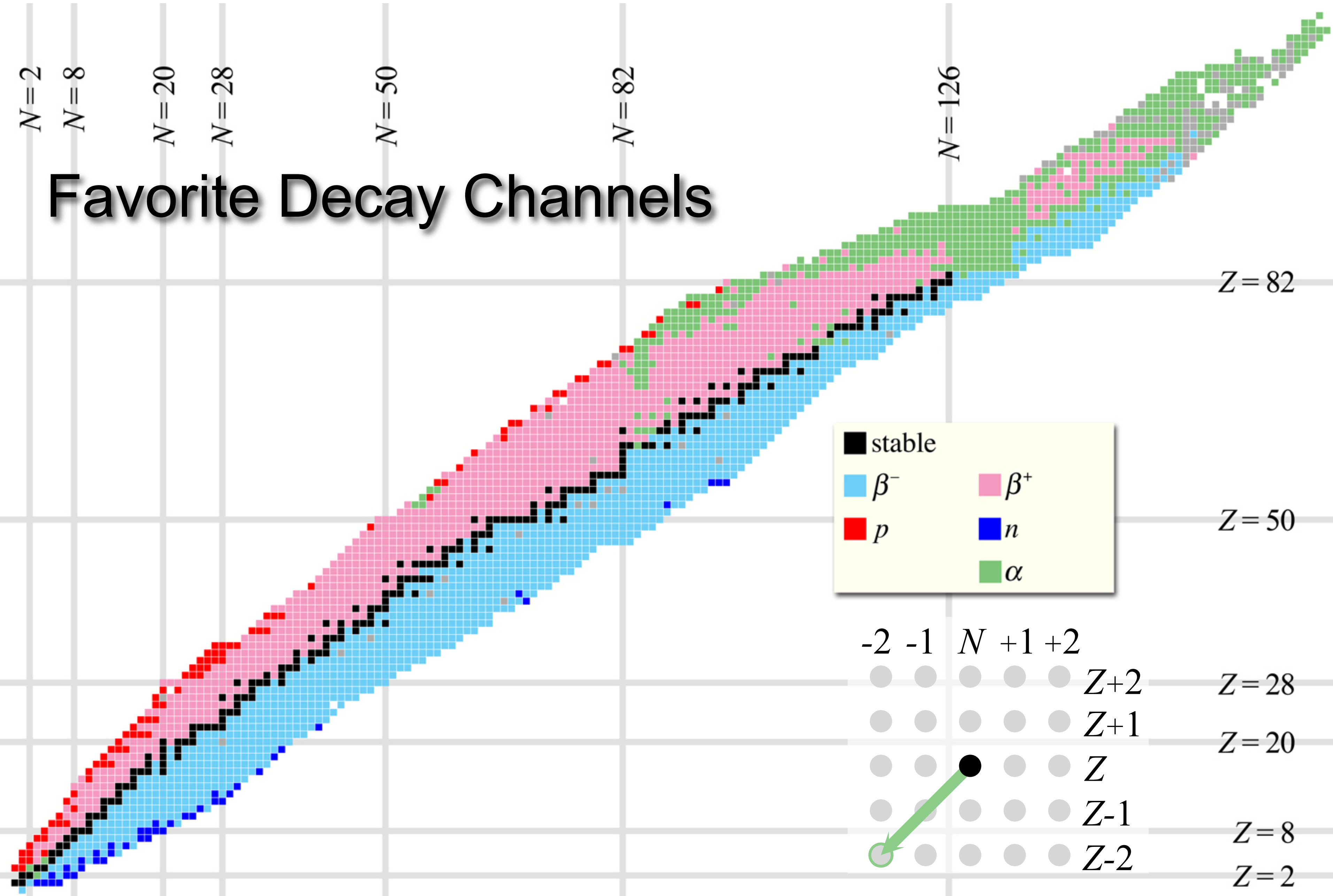

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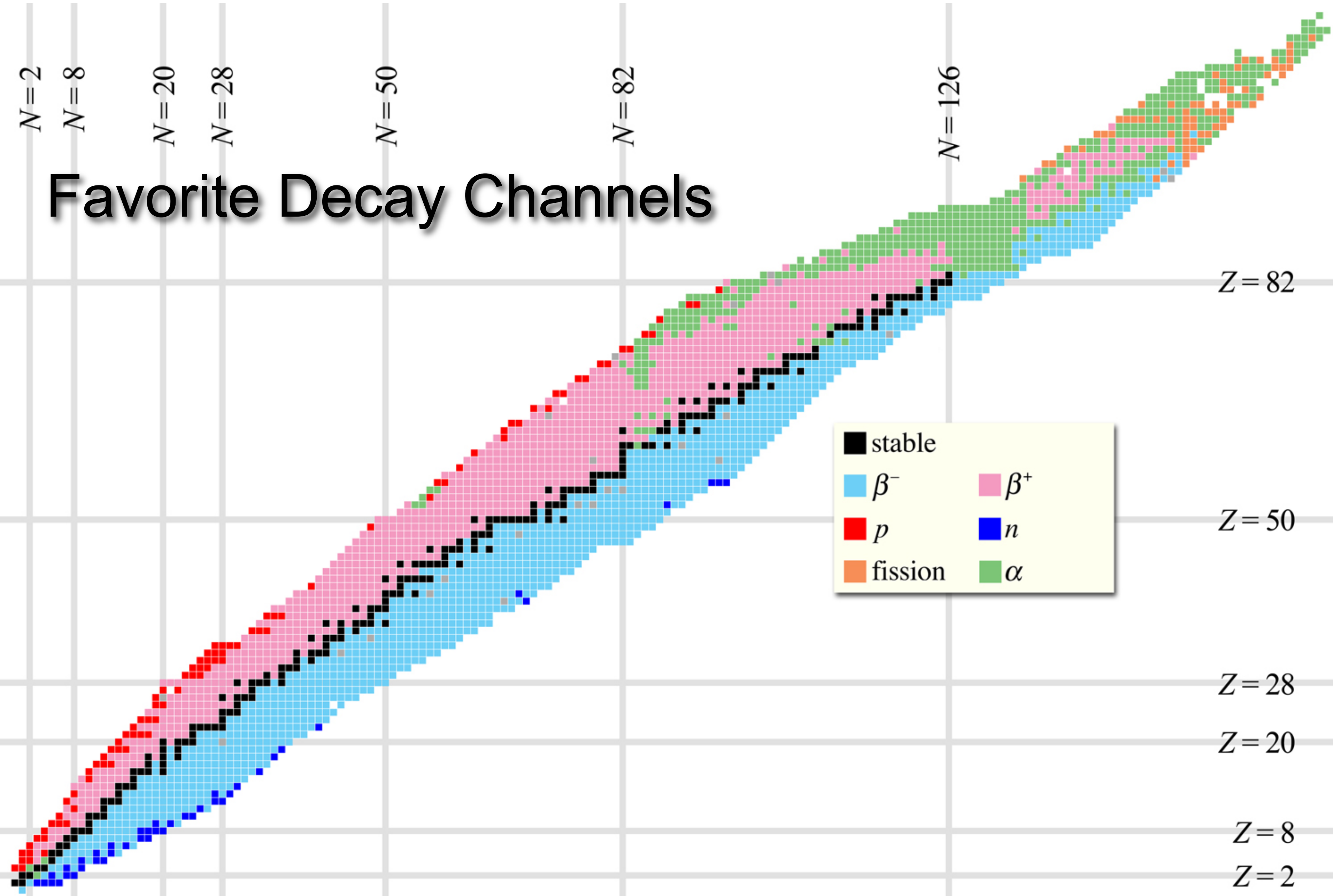
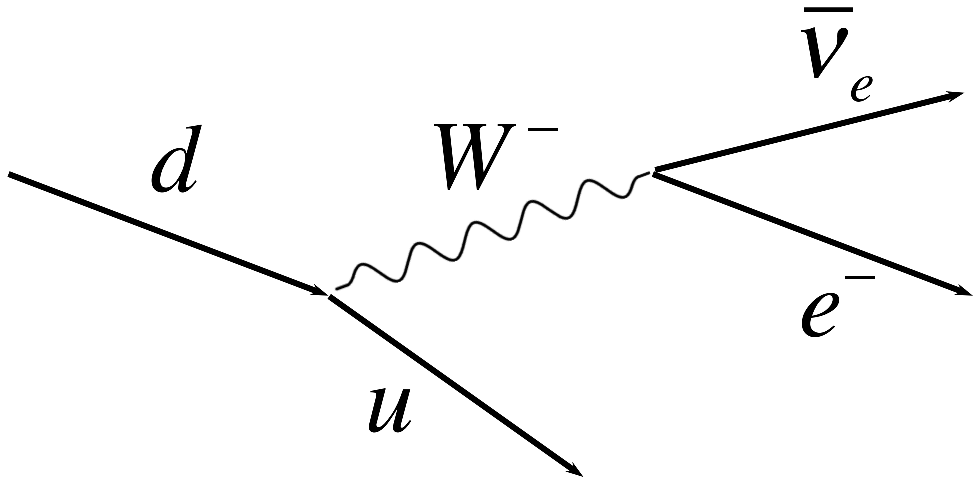
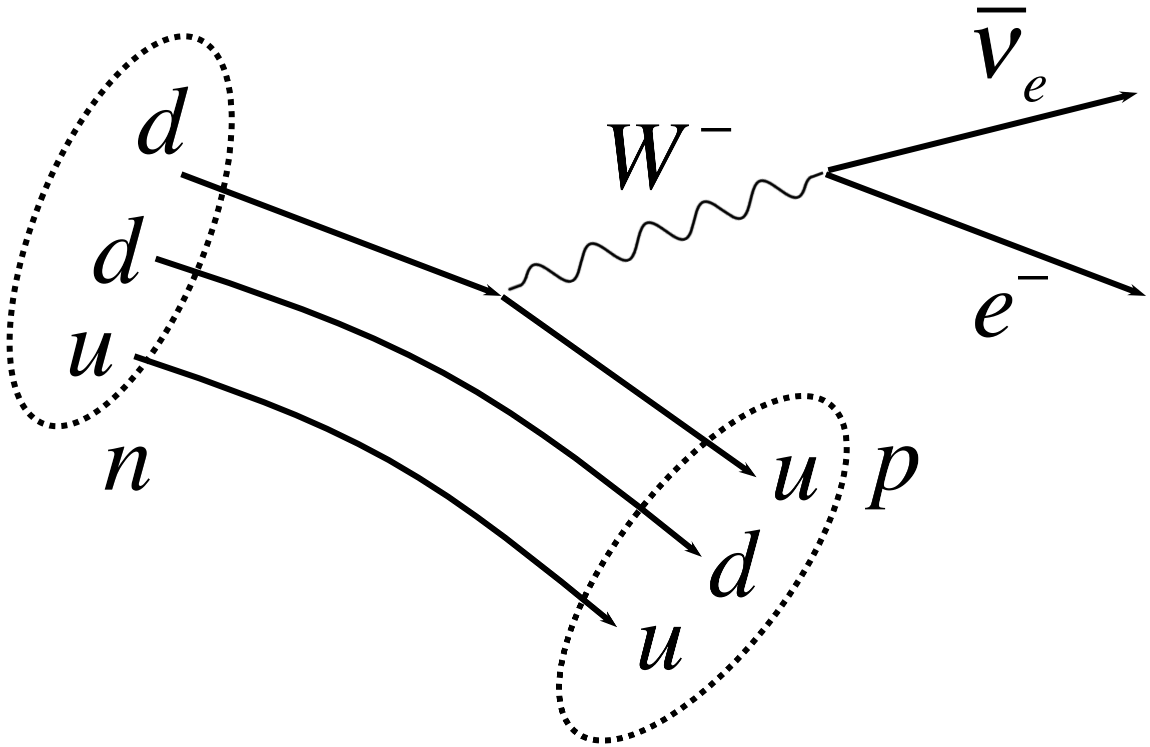
Favorite Decay Channels



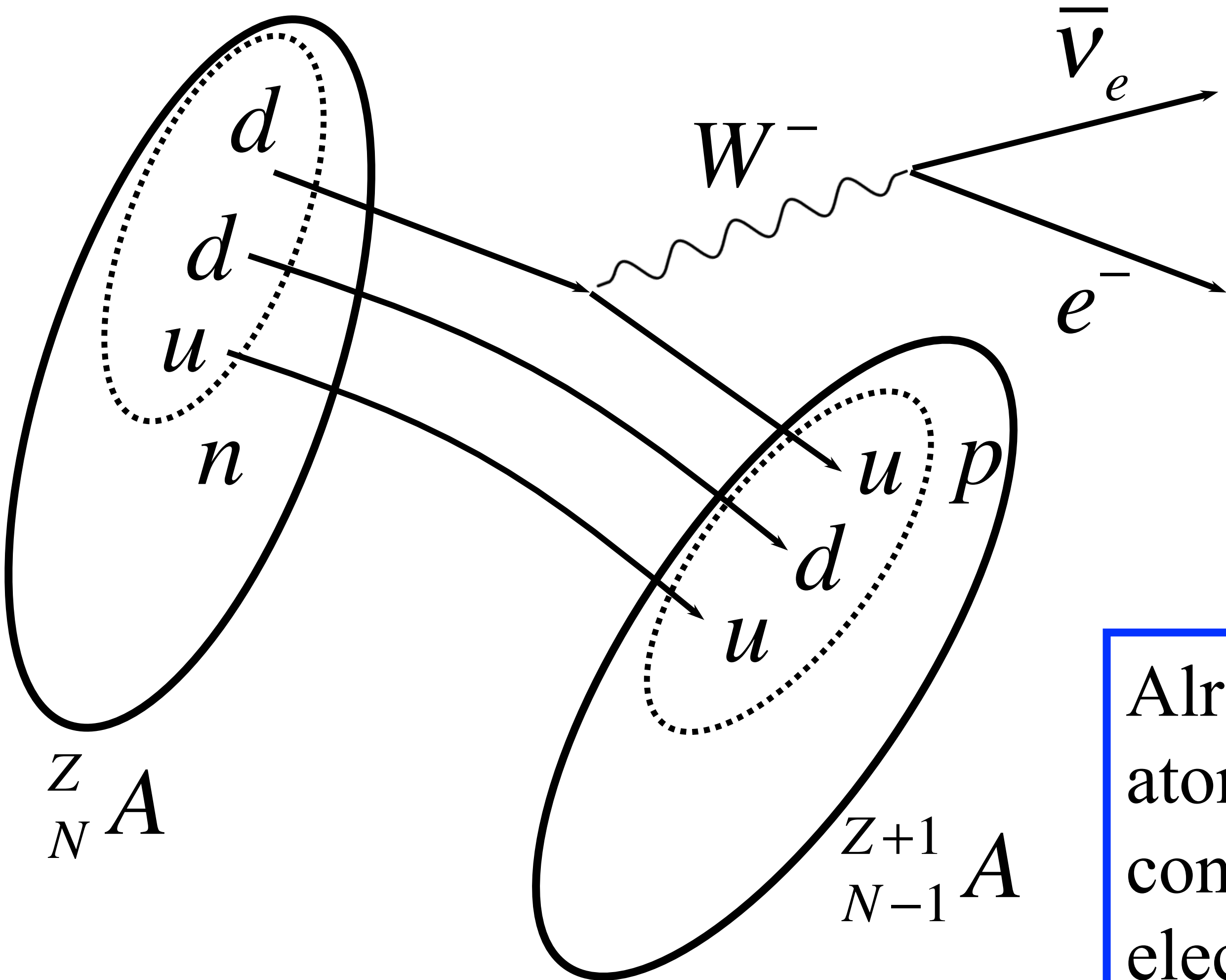
W. Bauer



$$m_d > m_u + m_{e^-} + m_{\bar{\nu}_e}$$

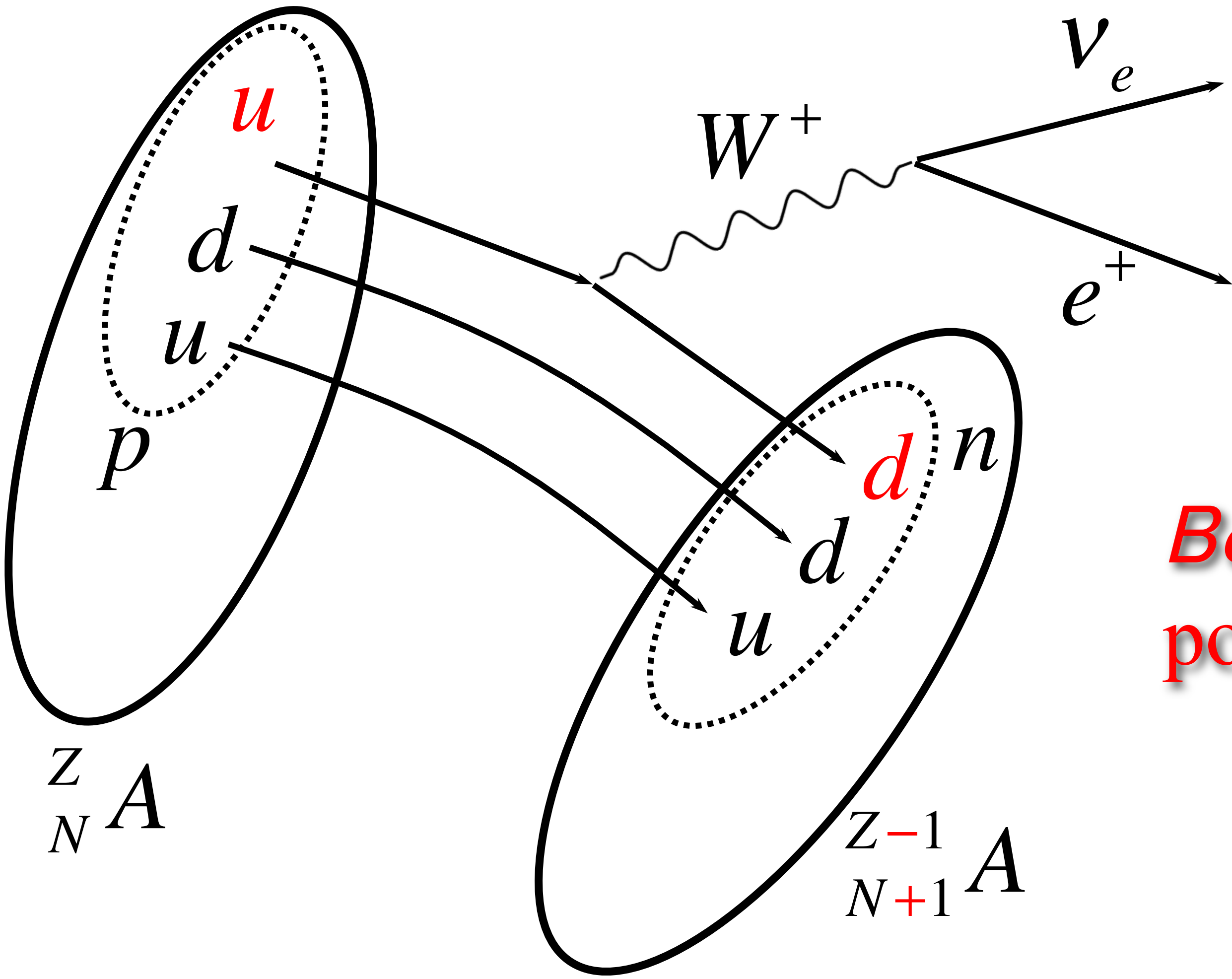


$$m_n > m_p + m_{e^-} + m_{\bar{\nu}_e}$$



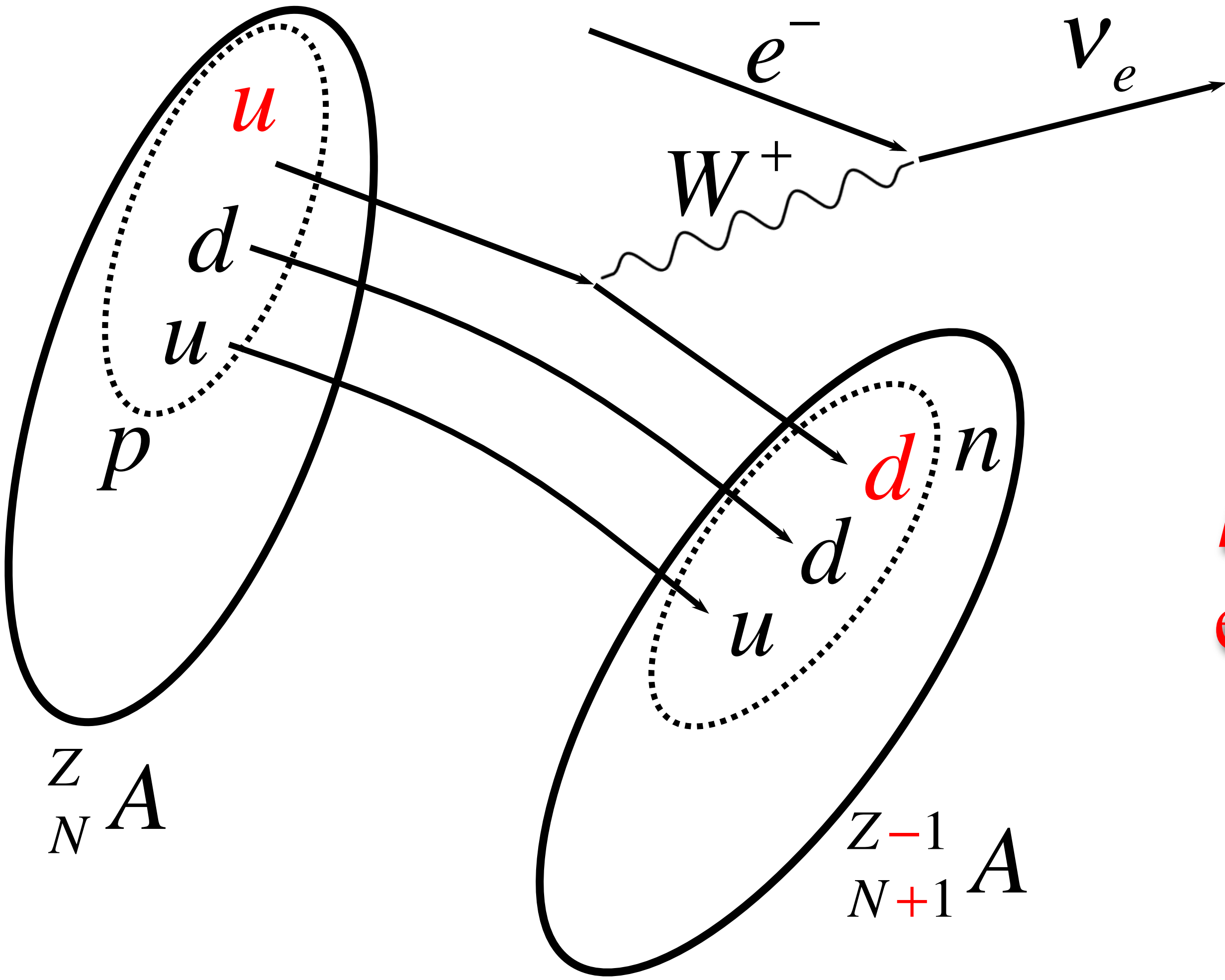
Already counted in atomic mass that contains Z+1 electrons

$$m_{{}^Z_N A} > m_{{}^{Z+1}_{N-1} A} + \cancel{m_{e^-}} + m_{\bar{\nu}_e}$$



***Beta*⁺ decay:**
positron emission

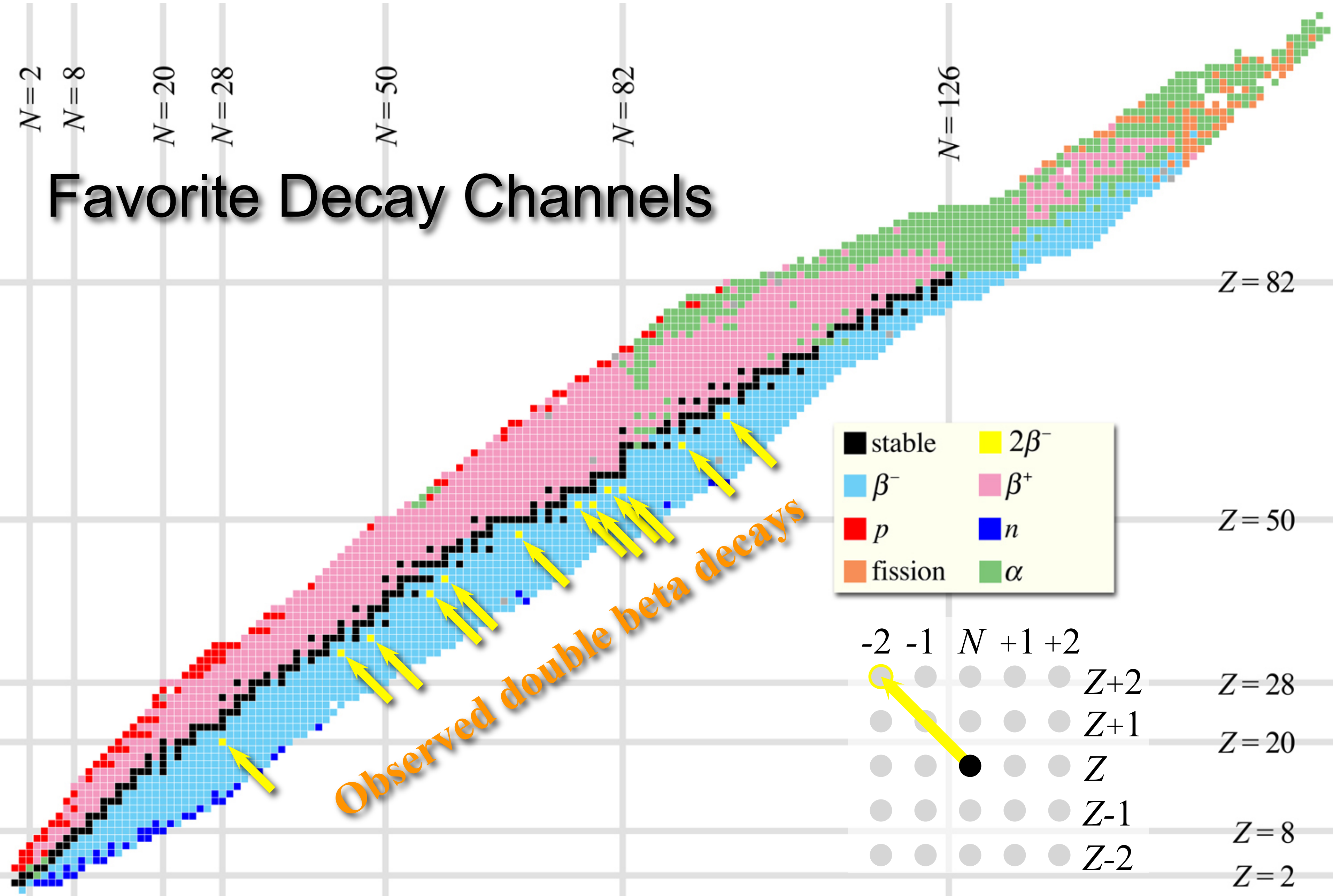
$$m_{{}^{Z}_{N}A} > m_{{}^{Z-1}_{N+1}A} + 2m_{e^+} + m_{\nu_e}$$

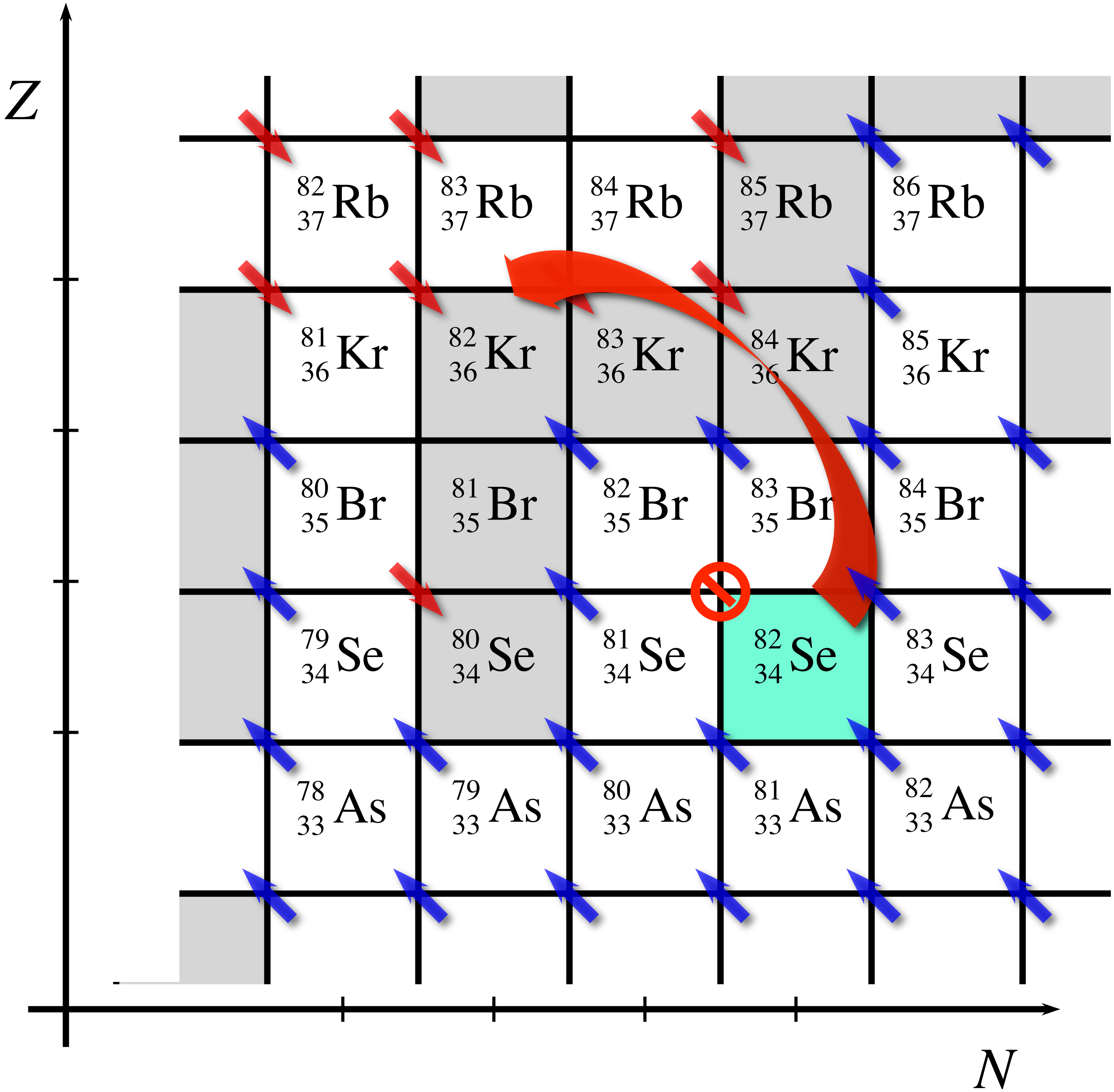


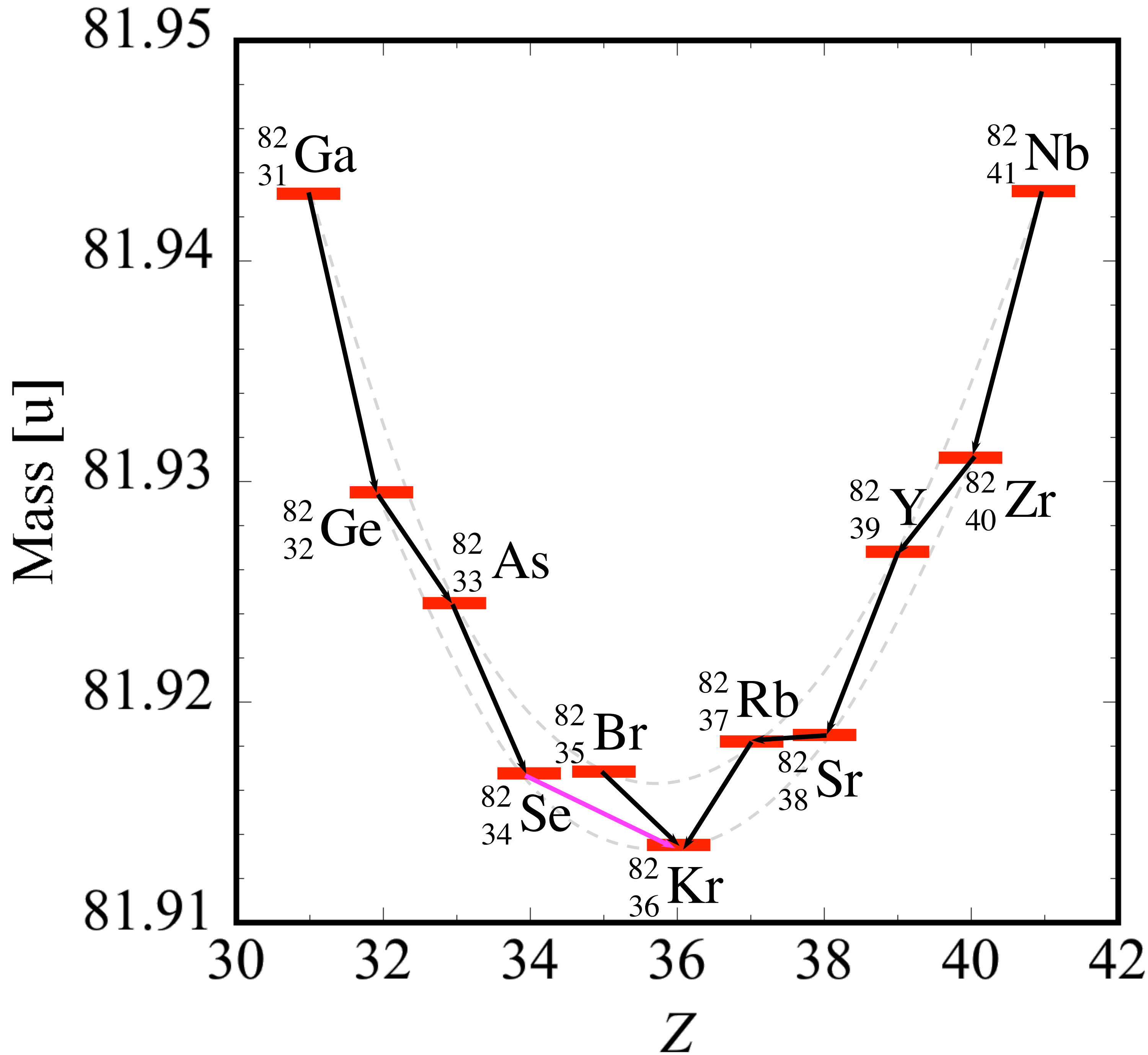
Beta⁺ decay: electron capture

$$m_{{}^{Z}_{N}A} > m_{{}^{Z-1}_{N+1}A} + m_{\nu_e}$$

Favorite Decay Channels




Z
N
82 37 Rb
83 37 Rb
84 37 Rb
85 37 Rb
86 37 Rb
81 36 Kr
82 36 Kr
83 36 Kr
84 36 Kr
85 36 Kr
80 35 Br
81 35 Br
82 35 Br
83 35 Br
84 35 Br
79 34 Se
80 34 Se
81 34 Se
82 34 Se
83 34 Se
78 33 As
79 33 As
80 33 As
81 33 As
82 33 As

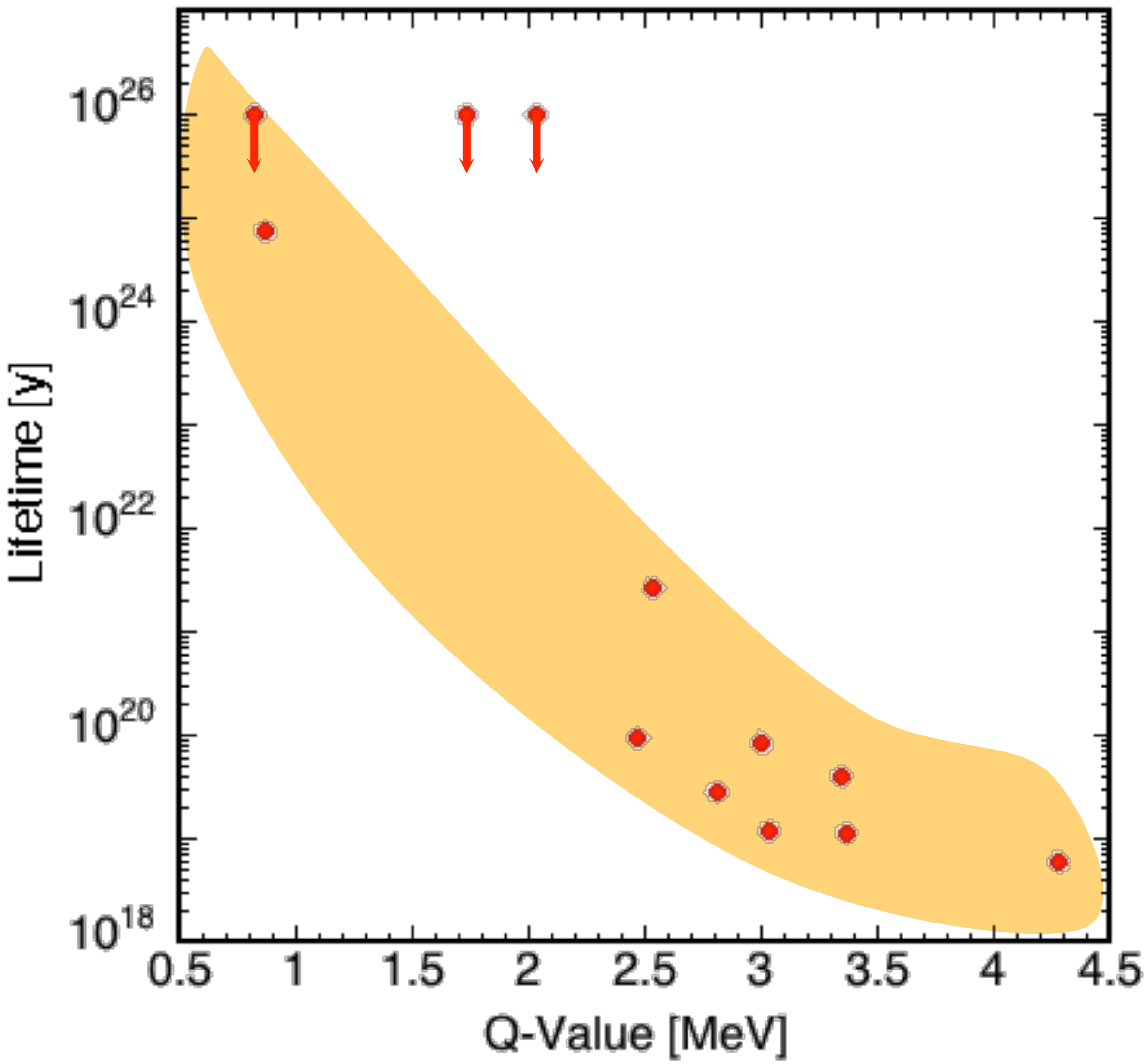


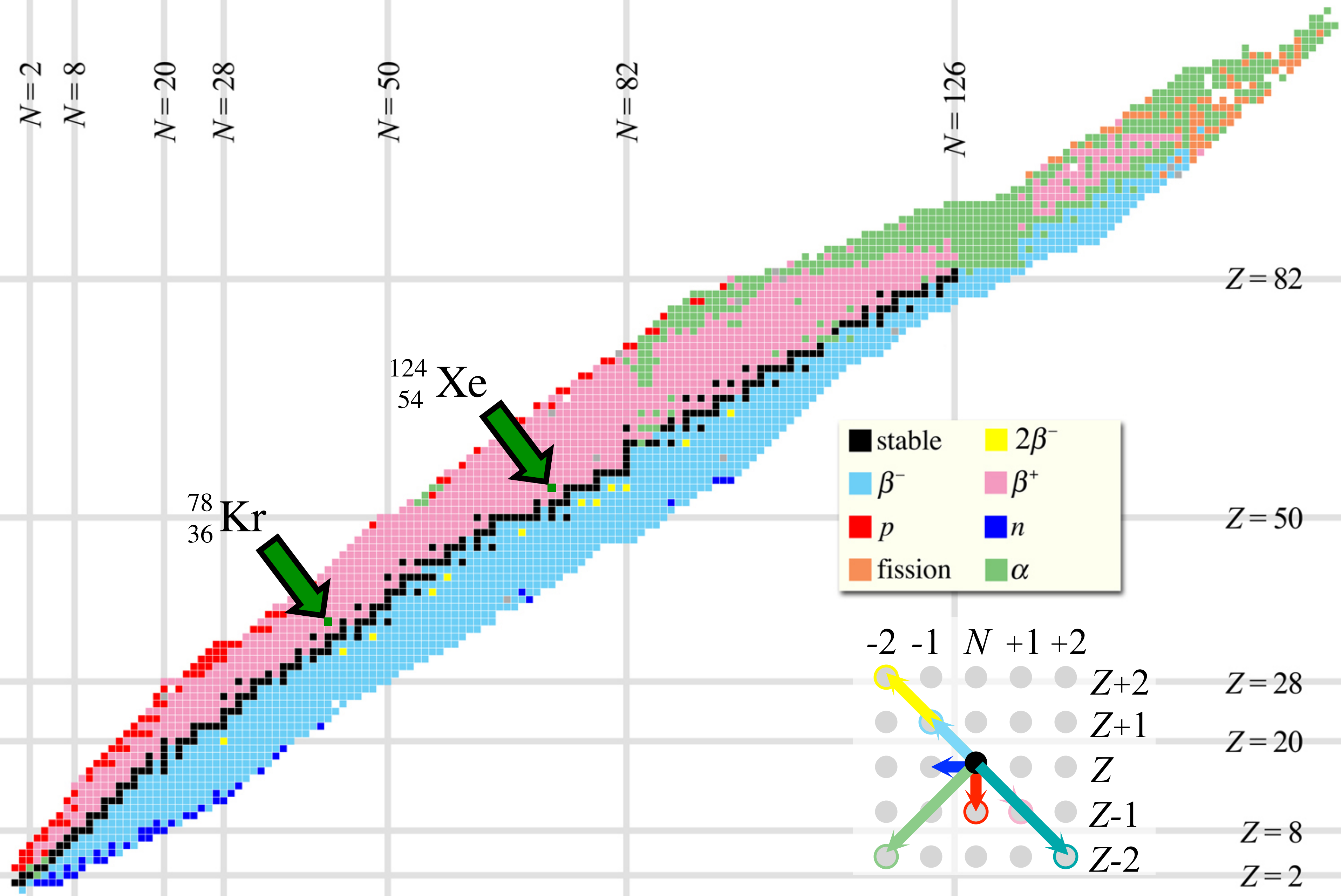
81.95
81.94
81.93
81.92
81.91
Mass [u]
30
32
34
36
38
40
42
Z
82 31 Ga
82 32 Ge
82 33 As
82 34 Se
82 35 Br
82 36 Kr
82 37 Rb
82 38 Sr
82 39 Y
82 40 Zr
82 41 Nb

Double Beta Decay Isotopes

- Only 12 known isotopes exhibit this decay
- ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{134}Xe, ^{136}Xe, ^{150}Nd, and ^{160}Gd
- Typical lifetimes ~ 10^{19} years (billion times the lifetime of universe)
- First observed in 1986 by Michael Moe *et al*. for ^{82}Se

Life Times and Q-Values




N = 2
N = 8
N = 20
N = 28
N = 50
N = 82
N = 126
Z = 82
Z = 50
Z = 28
Z = 20
Z = 8
Z = 2
124 54 Xe
78 36 Kr
stable
2β⁻
β⁻
β⁺
p
n
fission
α
-2 -1 N +1 +2
Z+2
Z+1
Z
Z-1
Z-2

Double *Beta*$^+$ Candidate ^{78}Kr

- Mass(^{78}Kr) = 77.9203 GeV
  Mass(^{78}Se) = 77.9173 GeV
  Mass difference = 2.85 MeV
- 2 EC, e^+EC (threshold 1.022 MeV), and e^+e^+ (threshold 2.044 MeV) channels are all open (in principle!)

Double *Beta*$^{+}$ Candidate ^{78}Kr

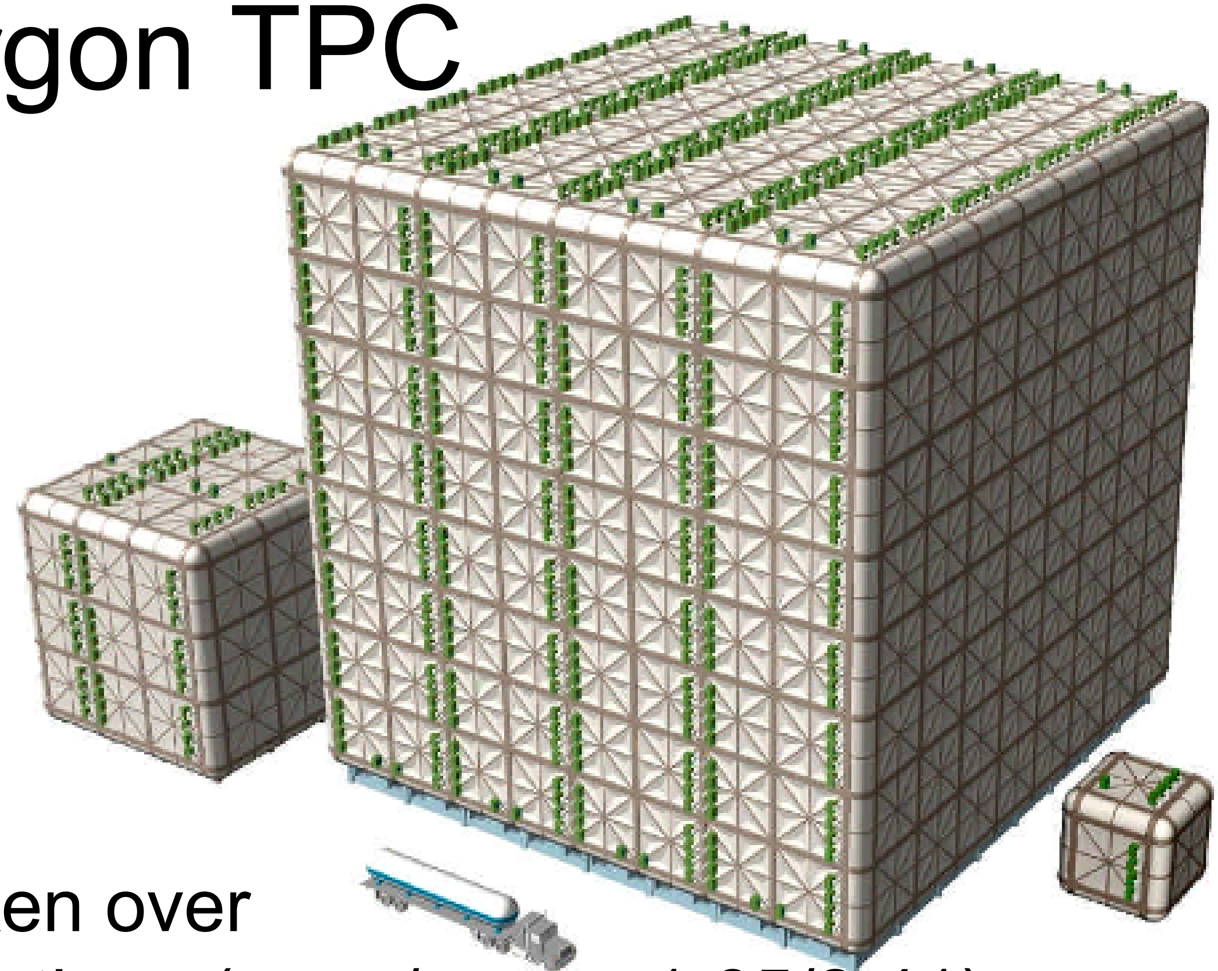
- Typical predicted half-life* ~ 10^{22} years
- Need N ~ 10^{25} atoms of ^{78}Kr
- Natural abundance of ^{78}Kr = 0.35%
- Need N ~ $3 \cdot 10^{28}$ atoms of ^{nat}Kr
- Need 0.168 kg*$(3 \cdot 10^{28})/(6 \cdot 10^{23})$ =
  90 tons = 40,000 liters of ^{nat}Kr
- Cost: ~$200,000

* A.Staudt, K.Muto and H.V.Klapdor-Kleingrothaus, "Nuclear matrix elements for double positron emission", Phys. Lett. **B268** (1991) 312

Detection

- Gamma ray detectors for 511 keV Photons and/or photons from K-shell ionization cascades
- Detection of single atom of Selenium a la Ray Davis
- Detection of positron paths in TPC (perhaps liquid Kr, or perhaps even better high pressure gas Kr ($0.1 g/cm^3$)

Liquid Argon TPC

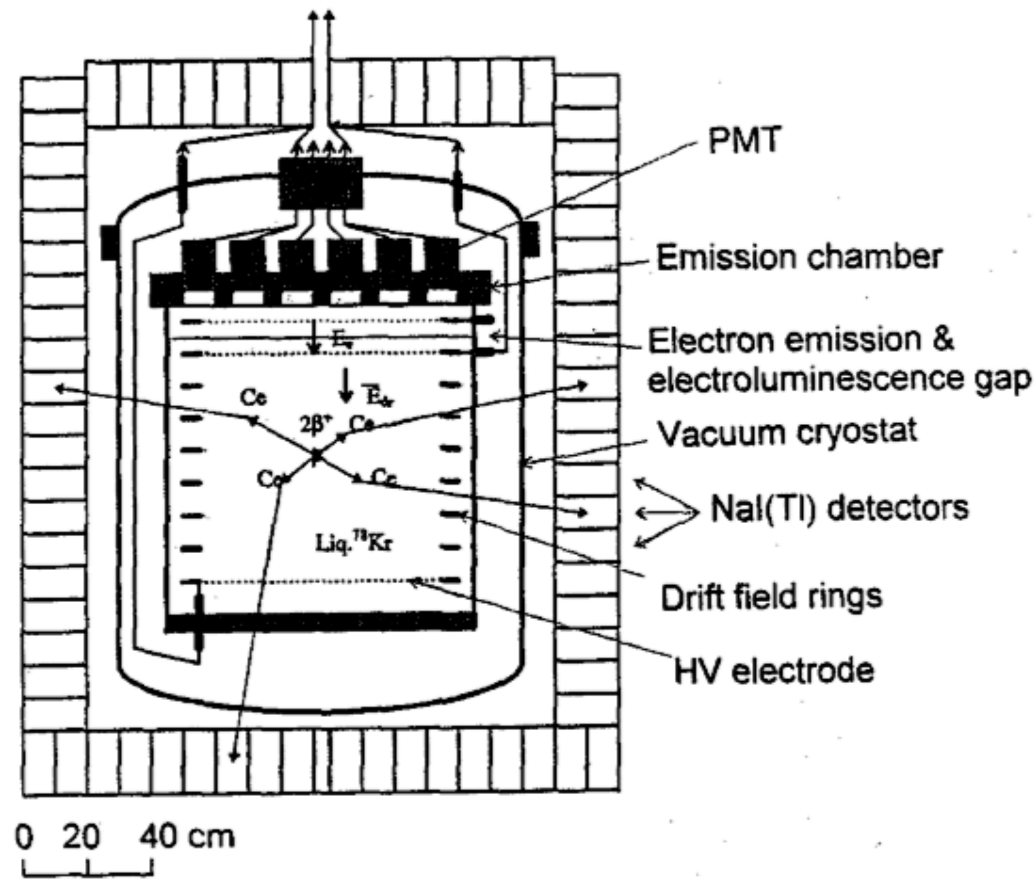


- One example for LANNDD (Liquid Argon Neutrino and Nucleon Decay Detector)
- Smallest shown: $V = 125\ \text{m}^3$
- Design can be taken over with slight modifications ($rho_{Ar} / rho_{Kr} = 1.65/2.41$)

D.B. Cline and F. Sergiampietri, "A Concept for a Scalable 2 kTon Liquid Argon TPC Detector for Astroparticle Physics", http://arxiv.org/abs/astro-ph/0509410

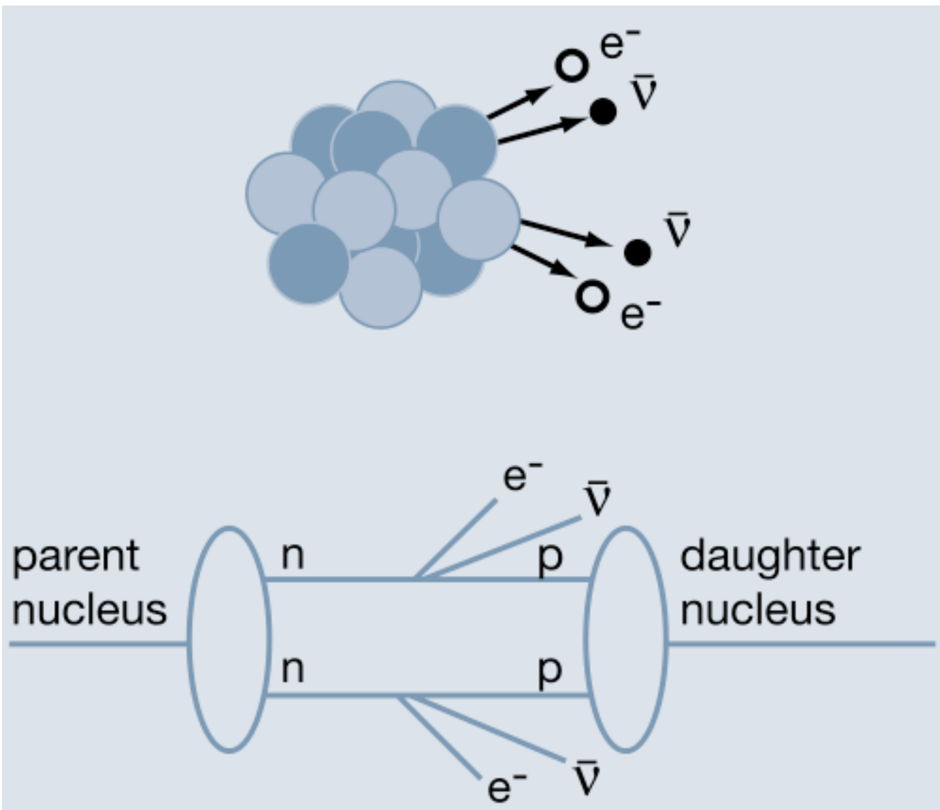
Previous Experiment

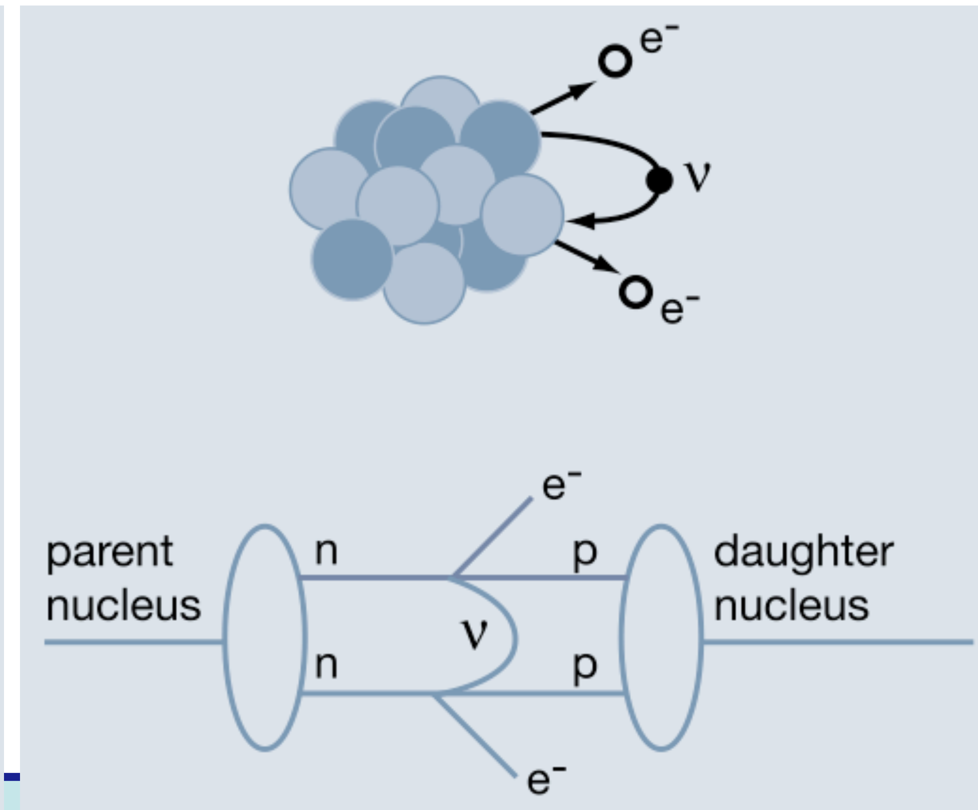
- *tau* > $0.9 \cdot 10^{20}$ years
- J.M. Gavriljuk et al., Phys. Atom. Nuclei 61, 1287 (1998)



Neutrino-less Double Beta decay

- Only possible if neutrino is its own anti-particle
- Violation of Standard Model





From: DUSEL_121306.pdf

Current lower half-life limits

Isotope	Exposure (kmole-y)	Background (counts)	Half-Life Limit (y)	$\langle m_{\beta\beta} \rangle$ (meV)
^{48}Ca	5×10^{-5}	0	$> 1.4 \times 10^{22}$	$< 7200 - 44700$[50]
^{76}Ge	0.467	21	$> 1.9 \times 10^{25}$	< 350[51]
^{76}Ge	0.117	3.5	$> 1.6 \times 10^{25}$	$< 330 - 1350$[52]
^{76}Ge	0.943	61	$= 1.2 \times 10^{25}$	$= 440$[48]
^{82}Se	0.022	7	$> 2.1 \times 10^{23}$	$< 1200 - 3200$[57]
^{100}Mo	0.131	14	$> 5.8 \times 10^{23}$	$< 600 - 2700$[57]
^{116}Cd	1×10^{-3}	14	$> 1.7 \times 10^{23}$	< 1700[53]
^{128}Te	Geochem.	NA	$> 7.7 \times 10^{24}$	$< 1100 - 1500$[54]
^{130}Te	0.07	12	$> 2.4 \times 10^{24}$	$< 400 - 1400$[56]
^{136}Xe	7×10^{-3}	16	$> 4.4 \times 10^{23}$	$< 1800 - 5200$[58]
^{150}Nd	6×10^{-5}	0	$> 1.2 \times 10^{21}$	< 3000[59]

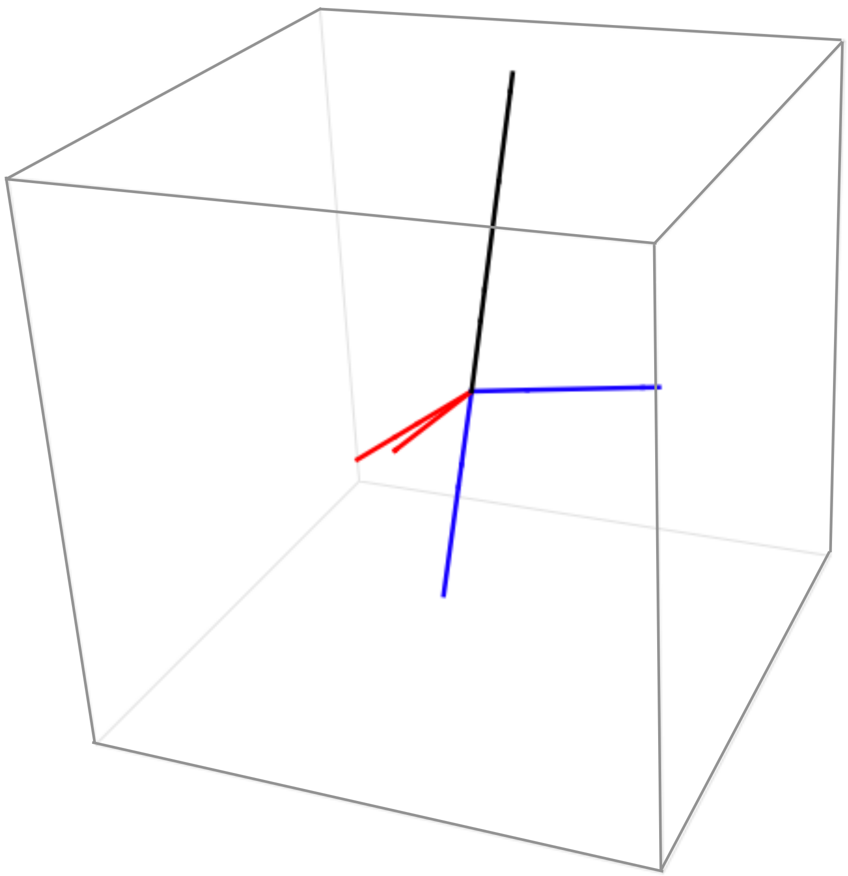
Compiled by Steven Elliott, LANL, 2006)

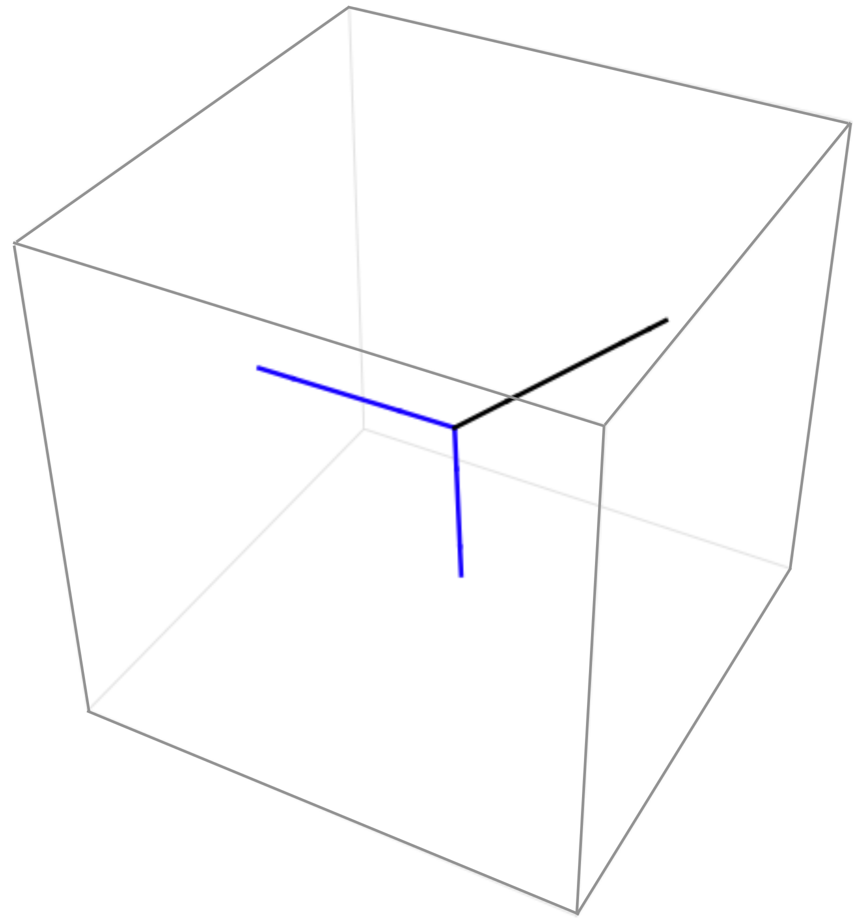
Could it be detected?

- Monte Carlo:
  5 body vs. 3 body phase space with constant or Fermi cross sections
- Importance sampling with N-body event generator GENBOD (F. James, CERN library)
- Lorentz-invariant Fermi phase space
- Respects all conservation laws (energy, momentum) and uses proper reaction Q-value

Monte Carlo Events

Neutrino Positron Recoil Nucleus

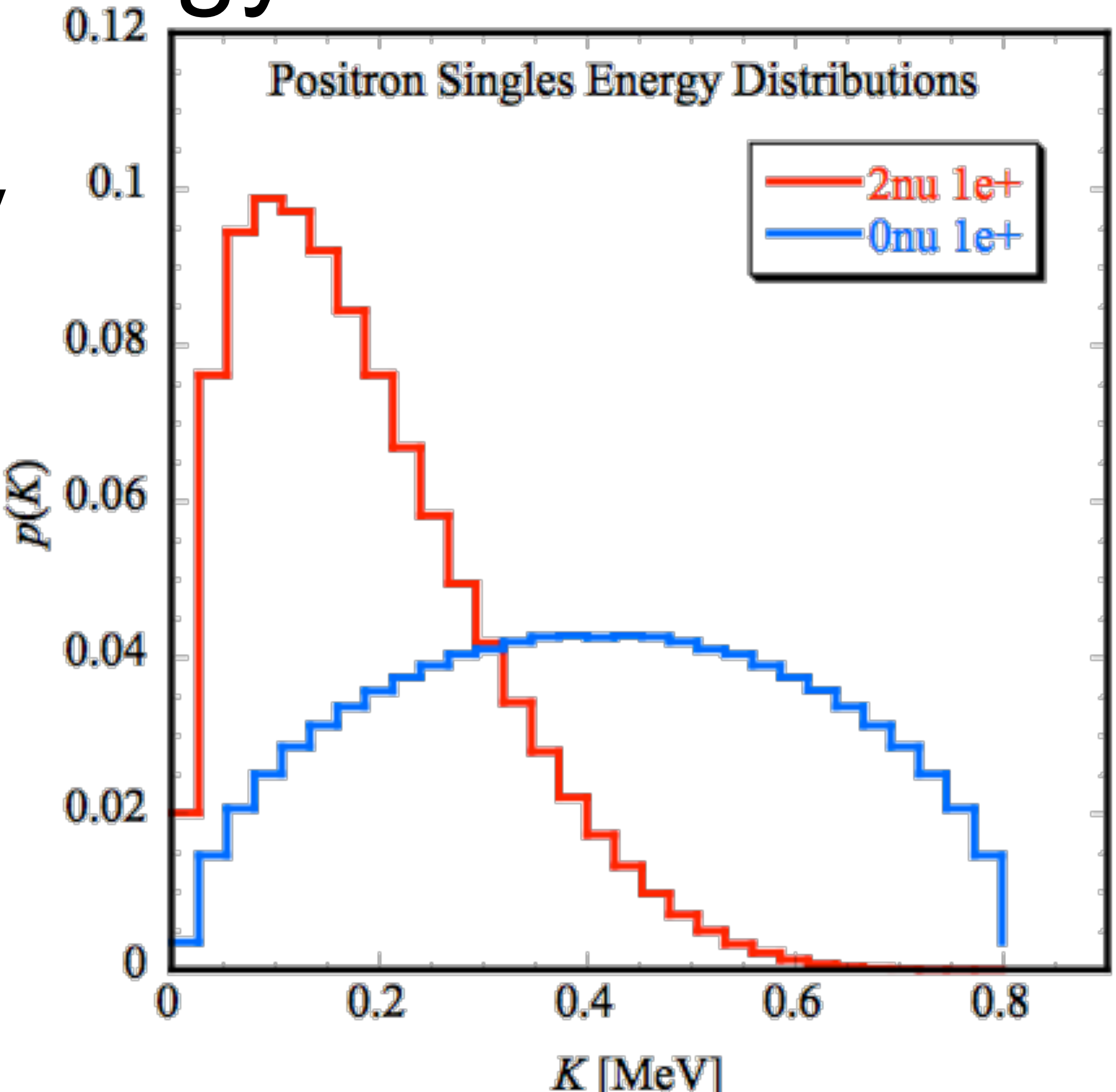




3d momentum space event displays in cm-system

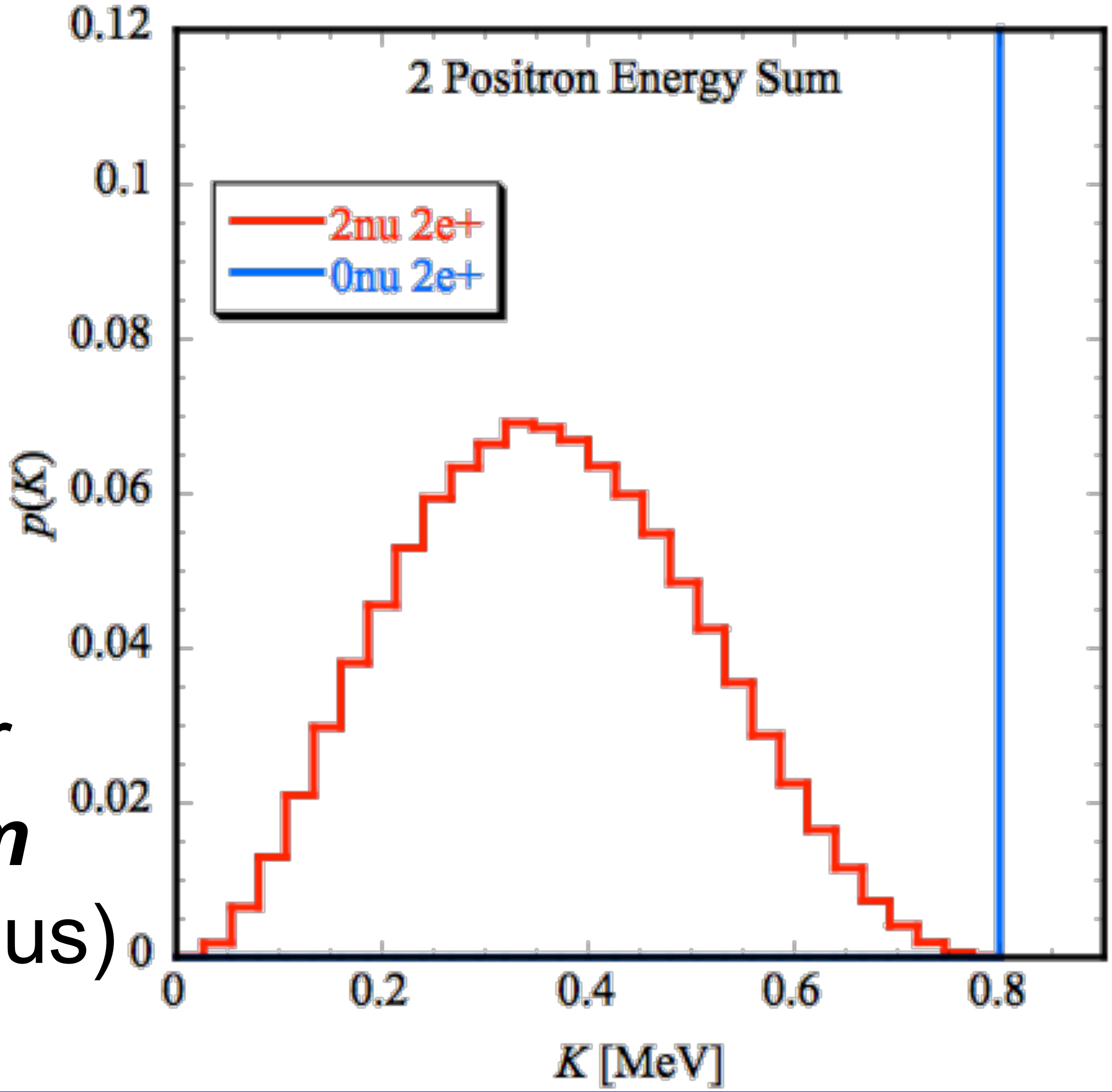
Positron Energy distributions

- Monte Carlo:
  5 body vs. 3 body phase space with constant or Fermi cross sections
- Here: 10^6 events
- More realistic: 10^1-10^2 events



Coincidence Counts

- In 0*nu* case the daughter nucleus receives almost vanishing recoil ***energy***
- Clear signal
- (Note: not true for recoil ***momentum*** of daughter nucleus)



Background: 2 simult. *Beta*$^+$ decays

- Very rare
- But we are dealing a very rare signal!