Double β decay, heavy ion collisions, and probing the early universe

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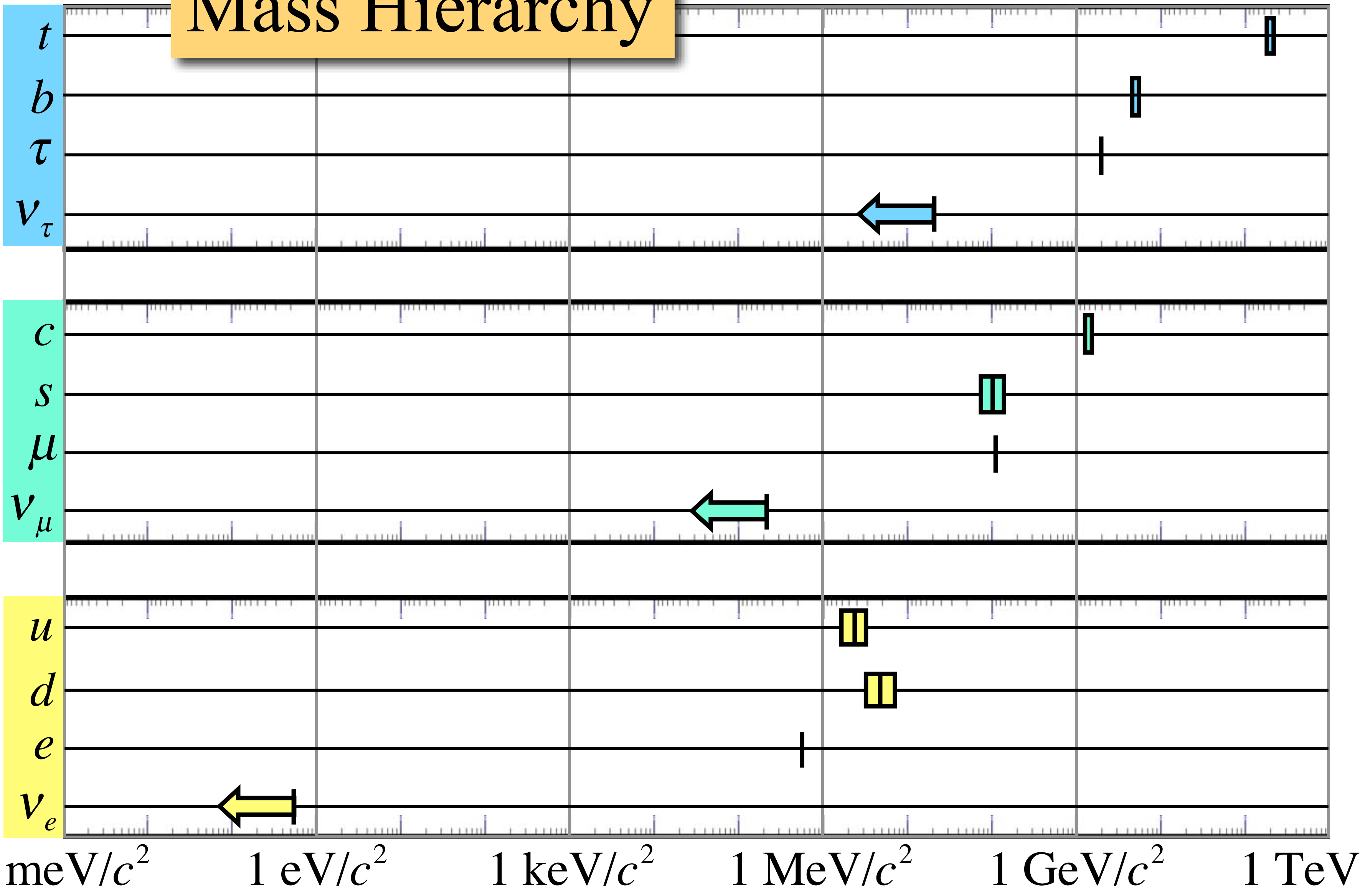
Michigan State University

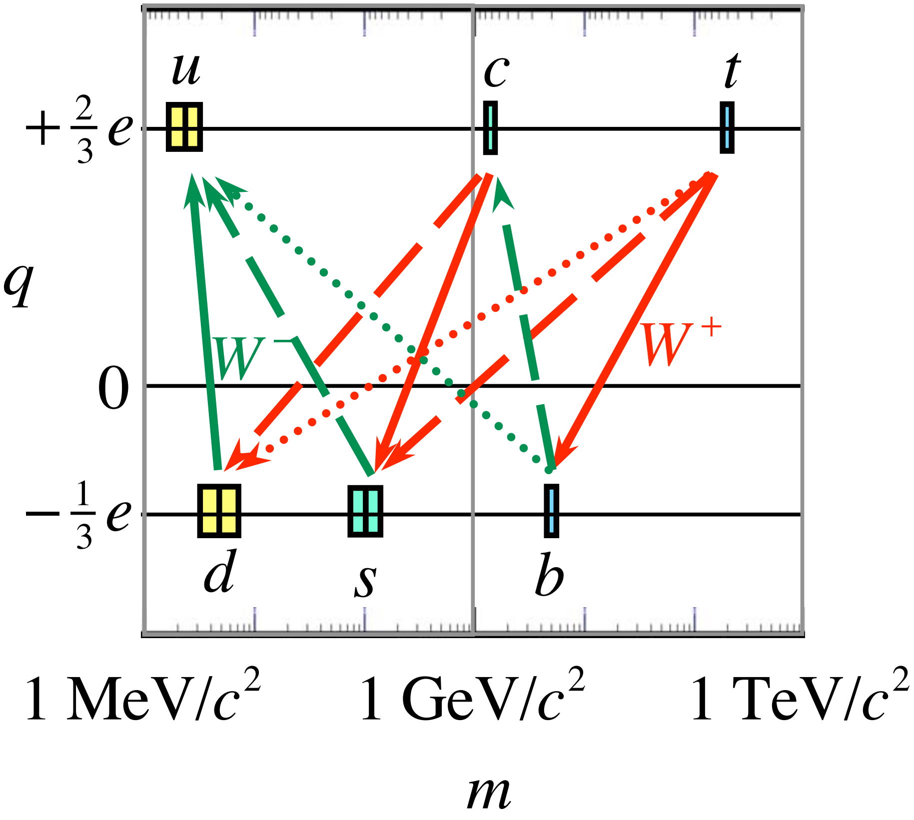
Mass Hierarchy



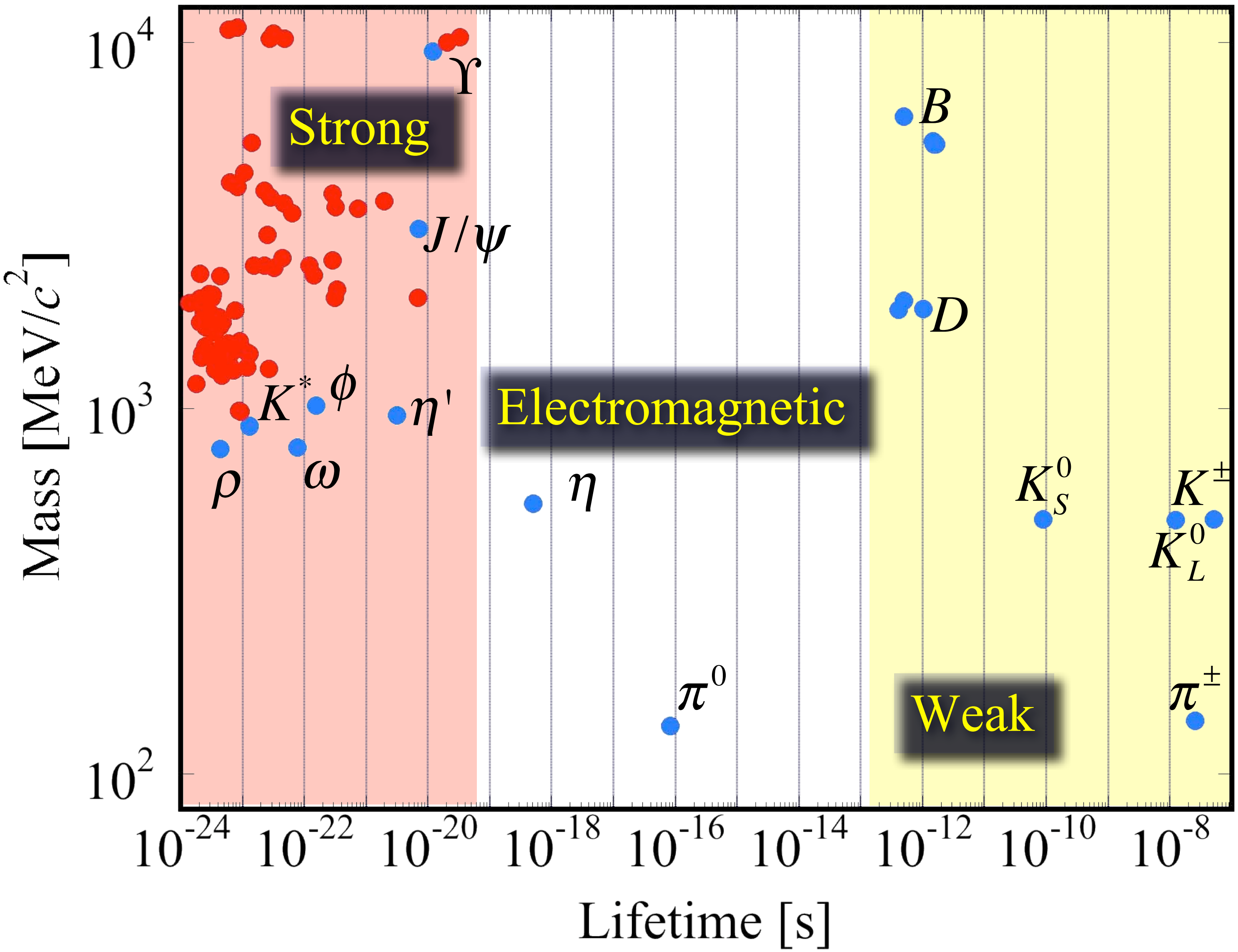
Beta Decays

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

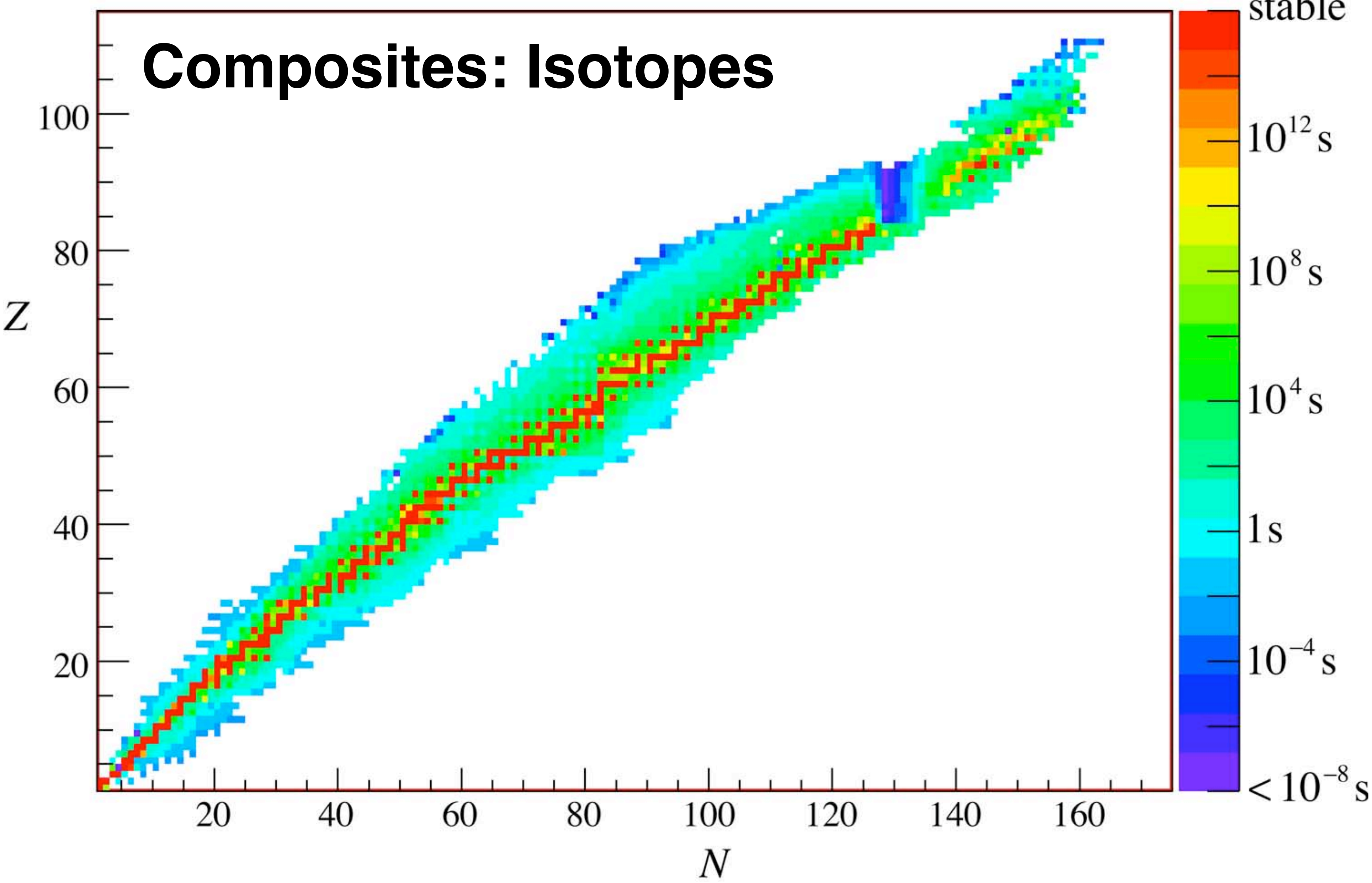
$$\beta^+ : \quad q \to q' + \ell^+ + \nu_\ell; \quad m_q > m_{q'} + m_\ell + m_\nu$$



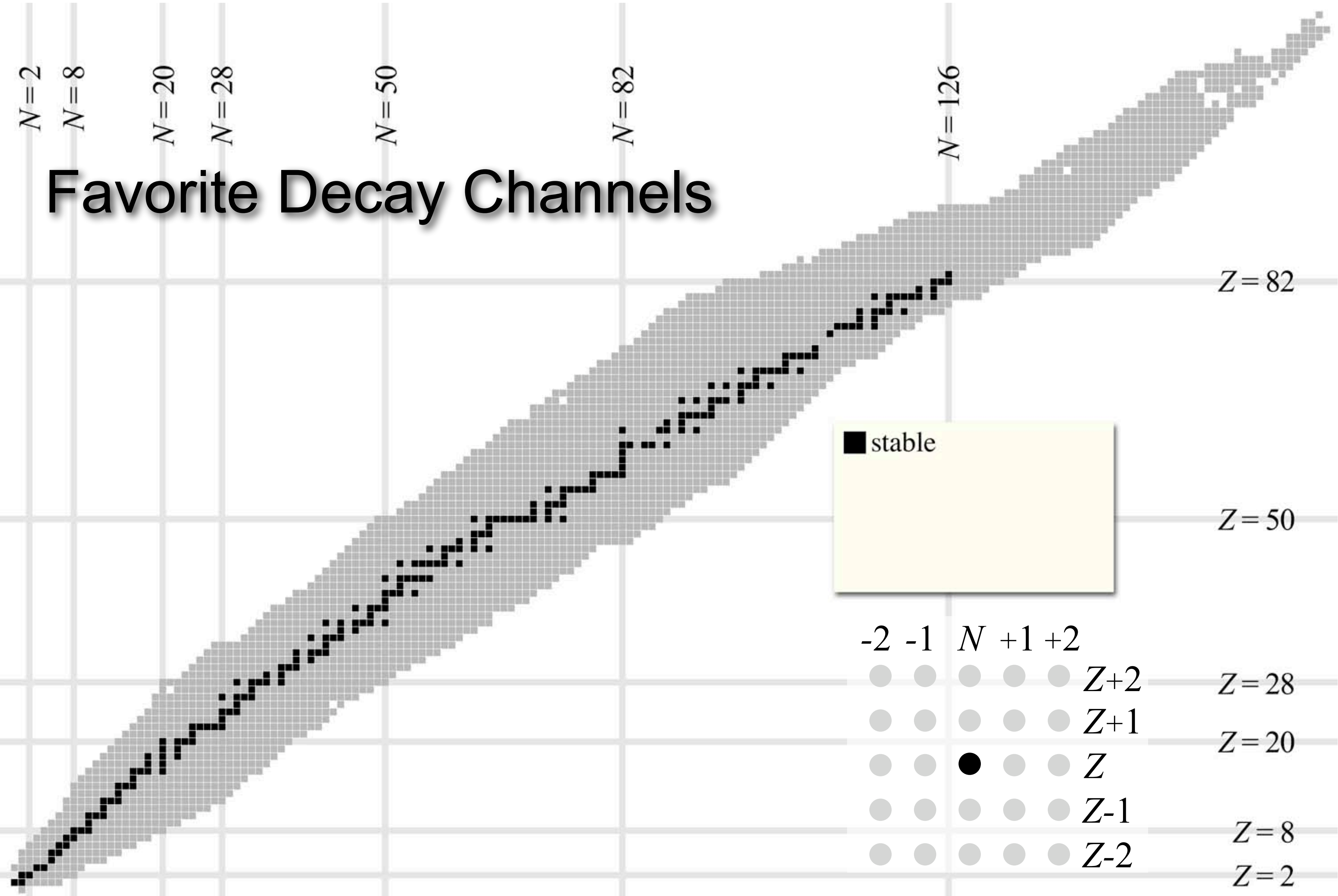
Composites: Mesons



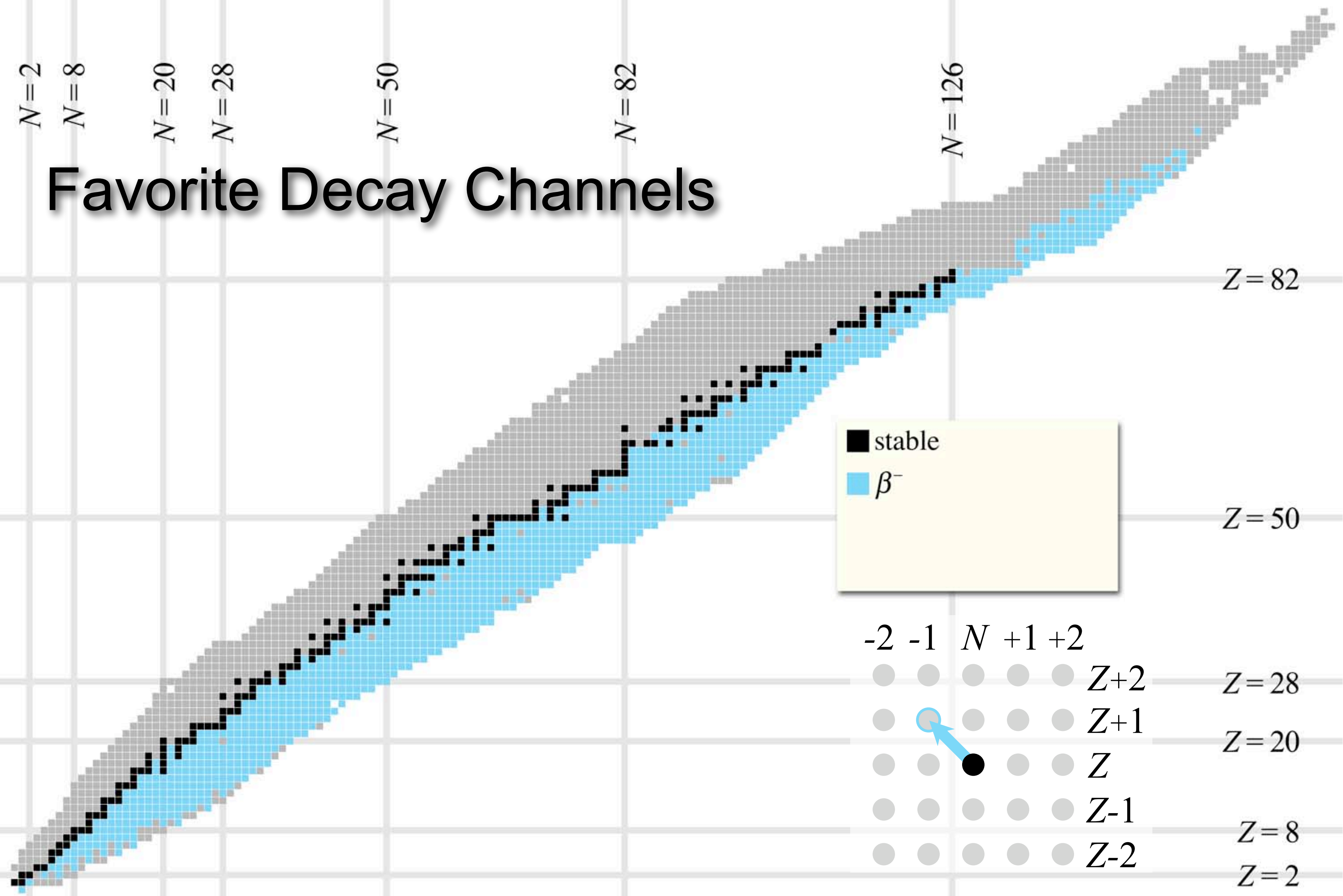
Composites: Isotopes



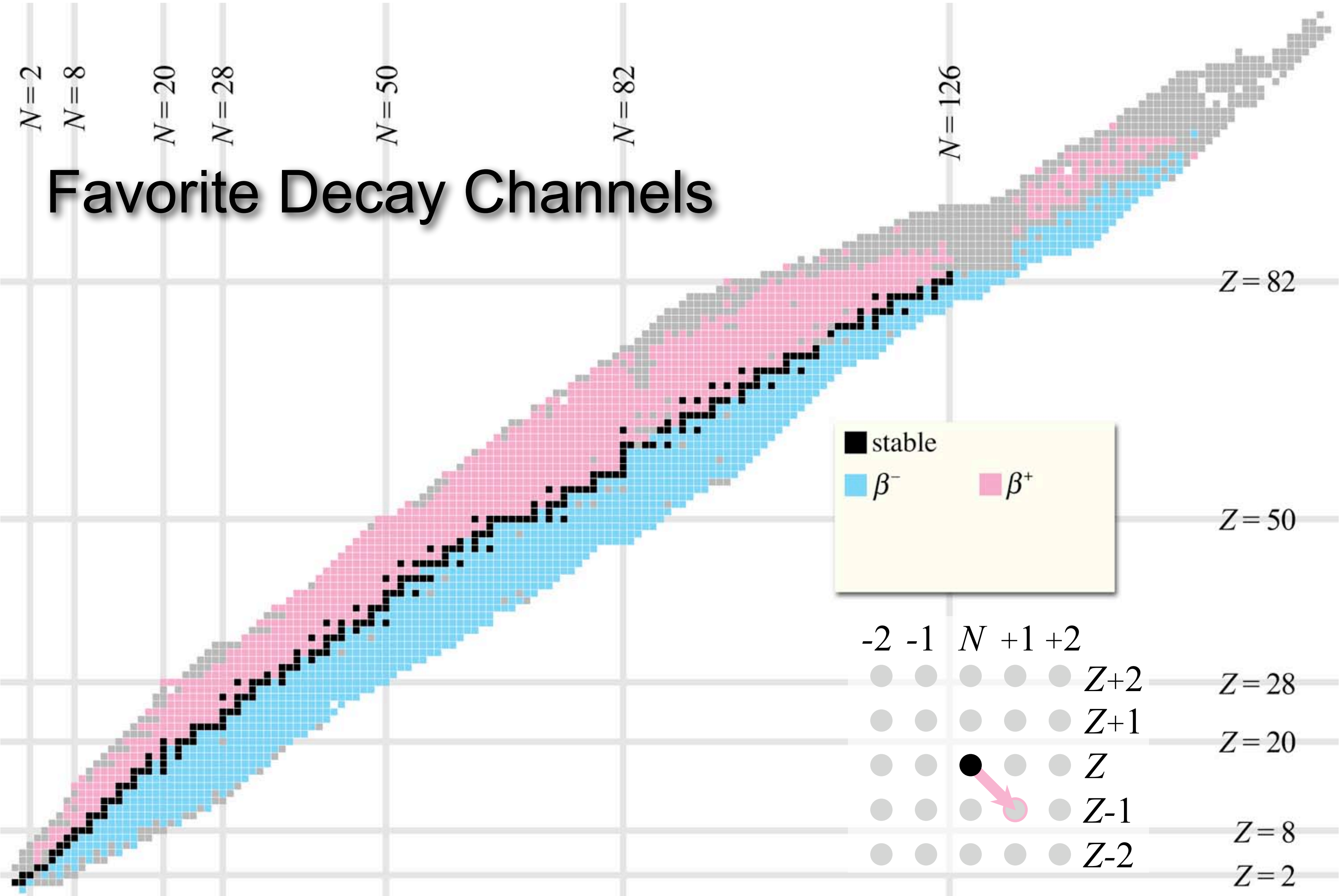
Favorite Decay Channels



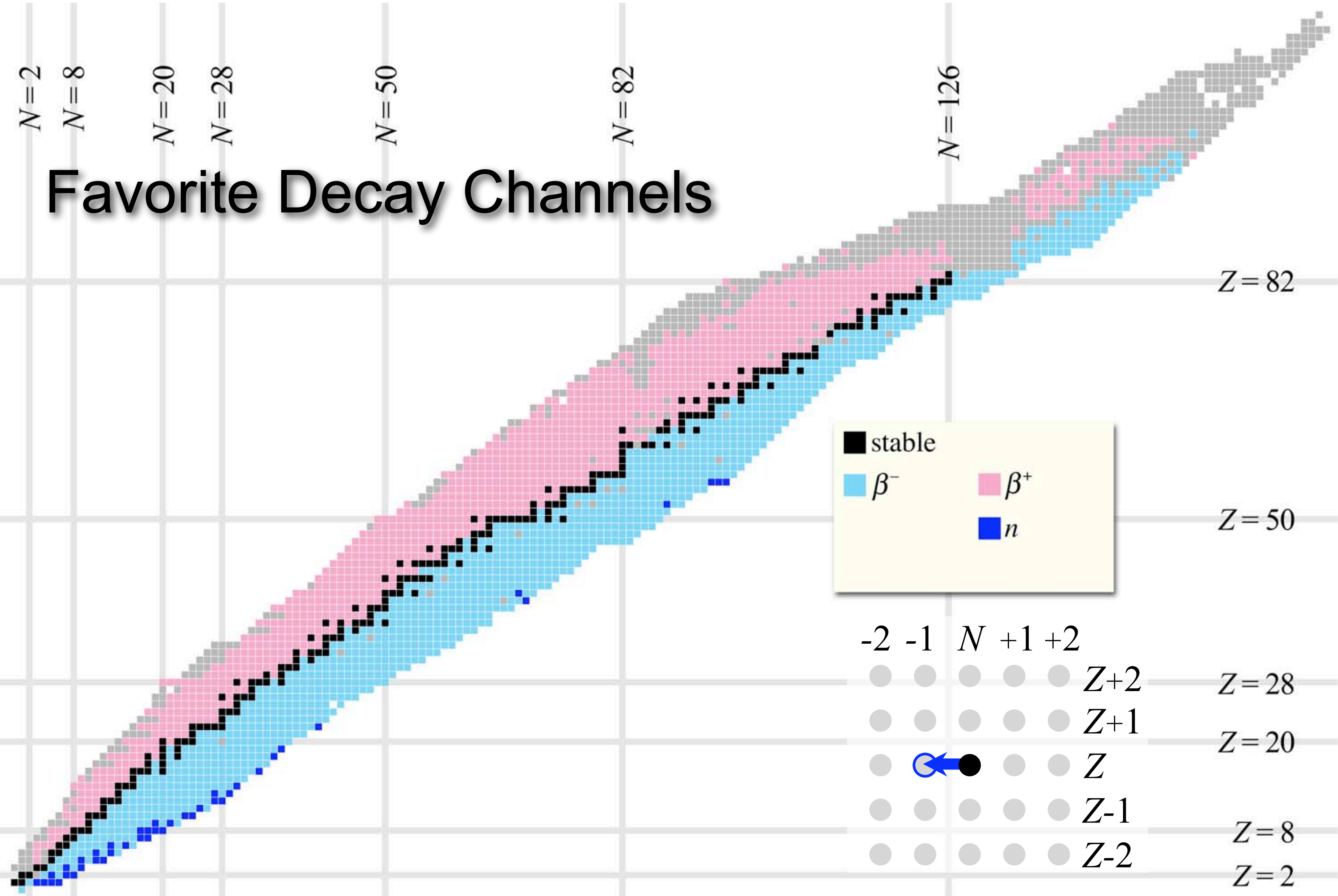
Favorite Decay Channels



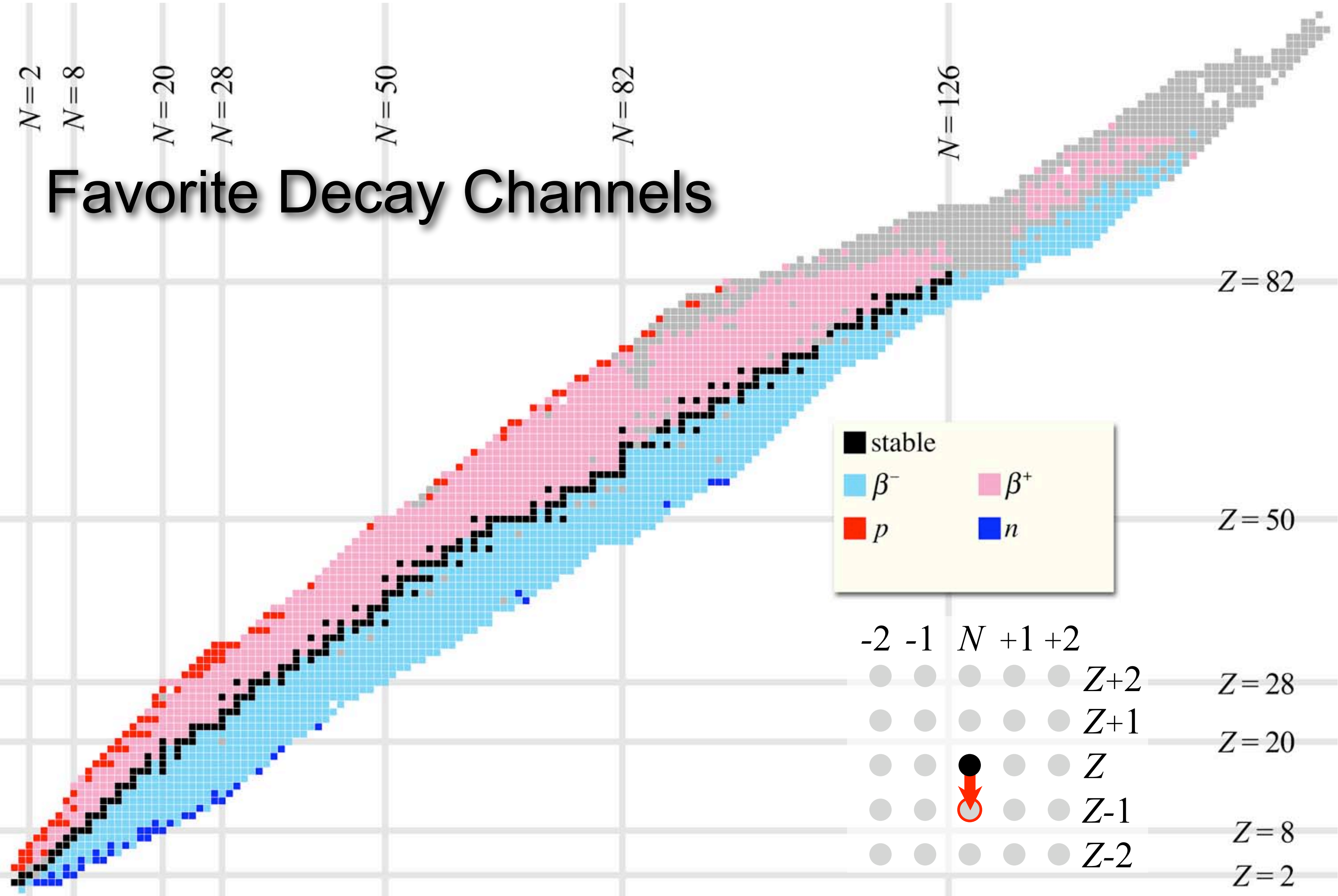
Favorite Decay Channels



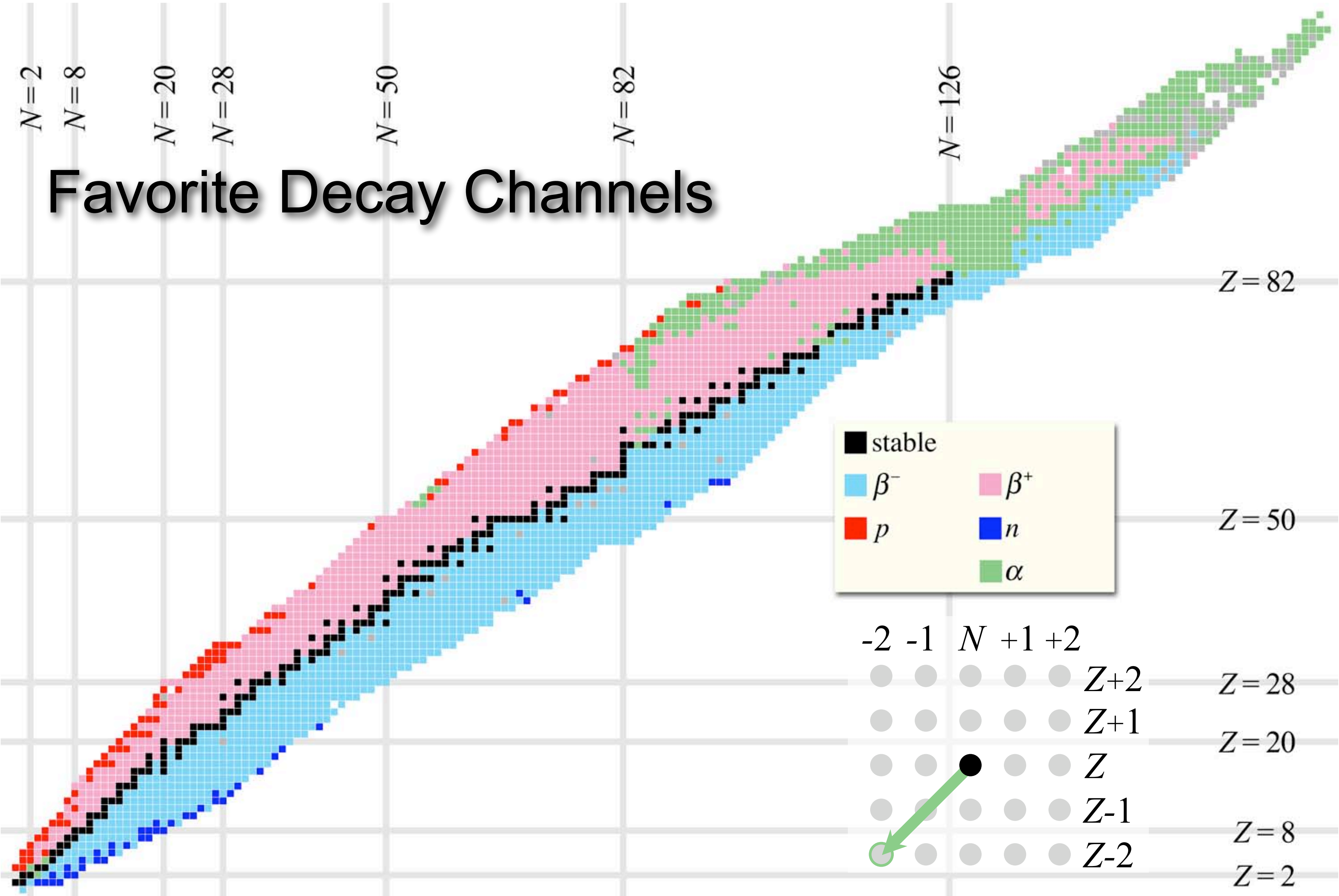
Favorite Decay Channels



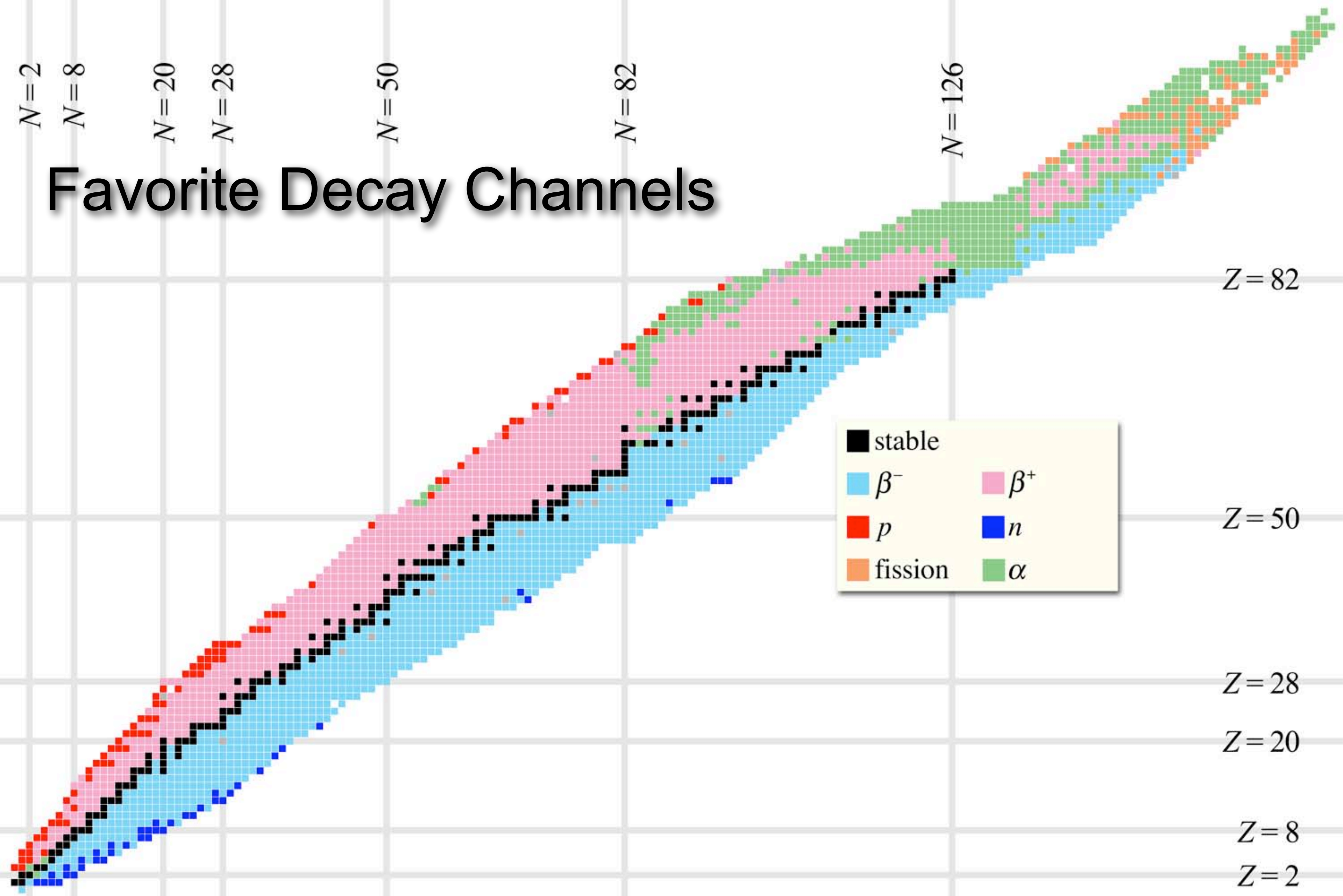
Favorite Decay Channels

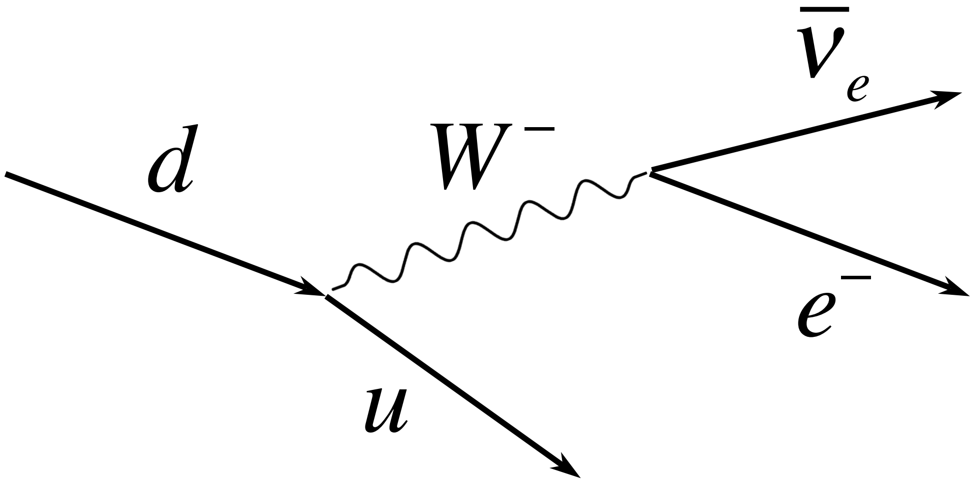


Favorite Decay Channels

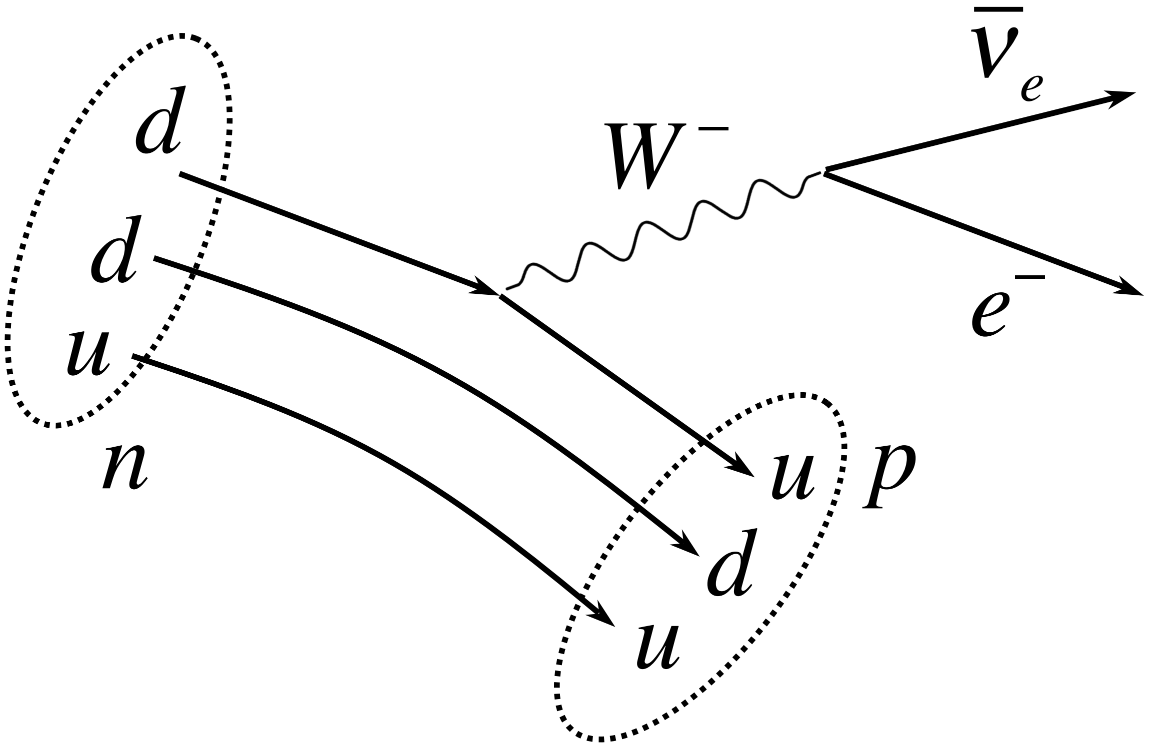


Favorite Decay Channels

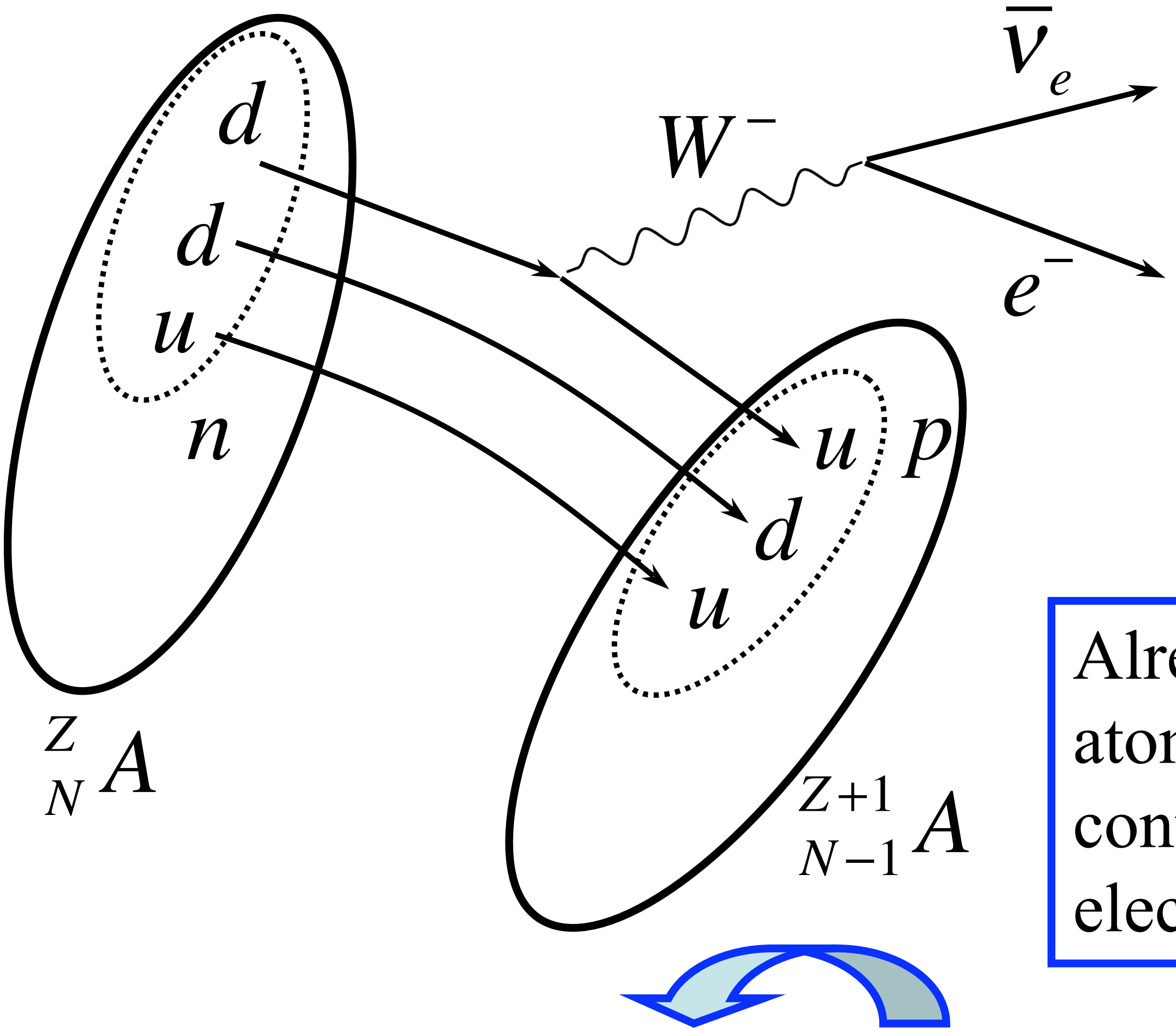




$$m_d > m_u + m_{e^-} + m_{\bar{\nu}_e}$$

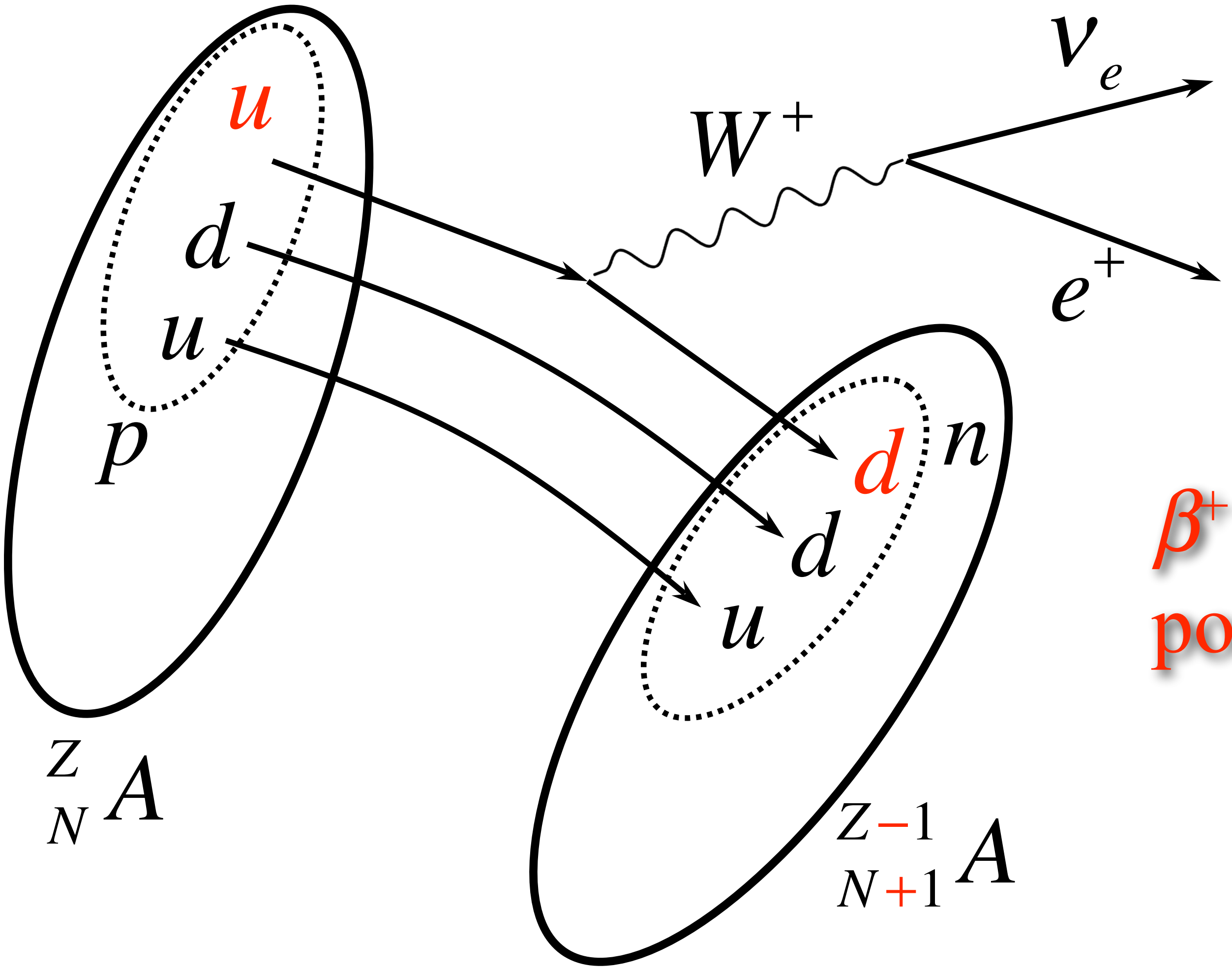


$$m_n > m_p + m_{e^-} + m_{\bar{\nu}_e}$$



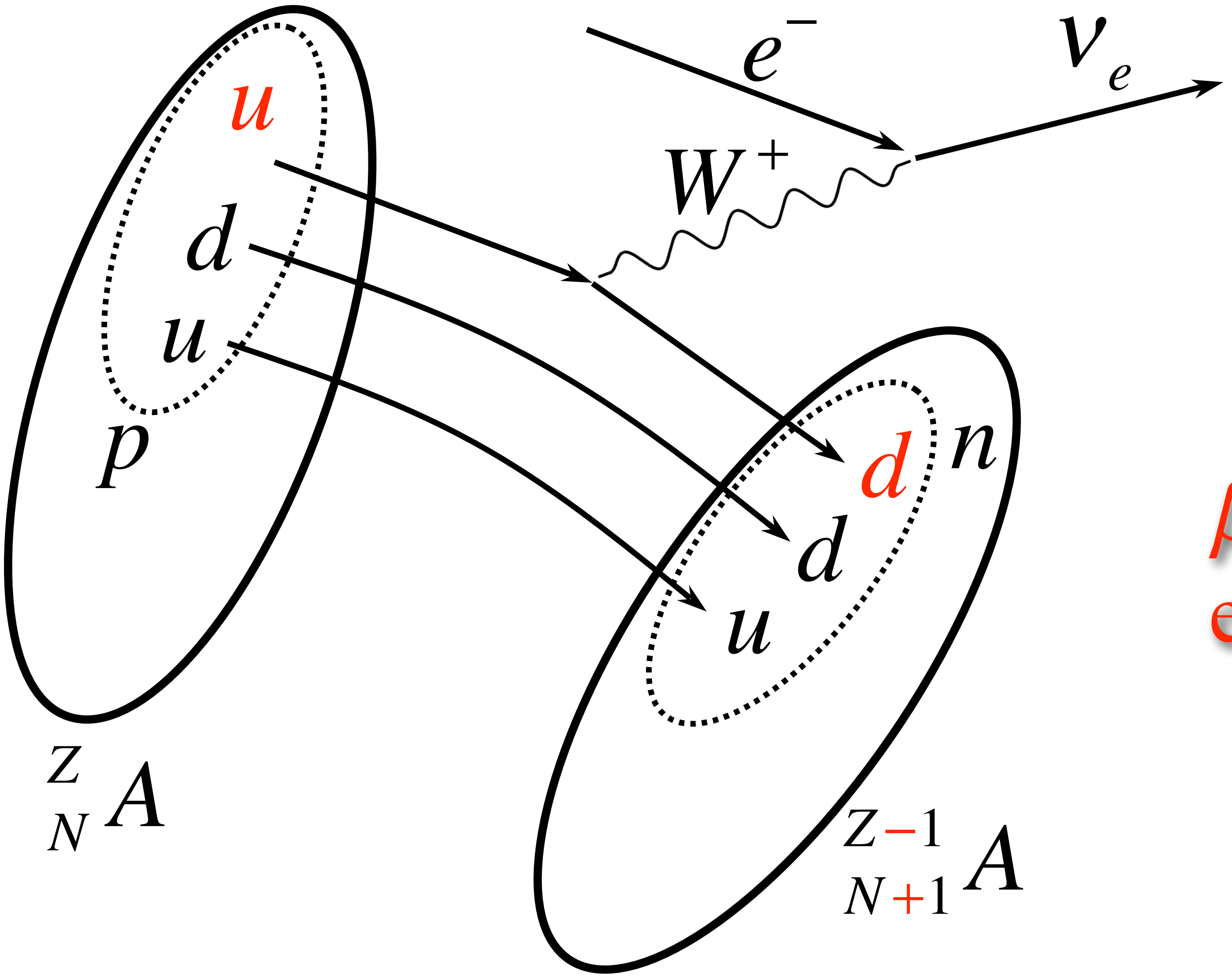
Already counted in atomic mass that contains Z+1 electrons

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



β^+ decay: positron emission

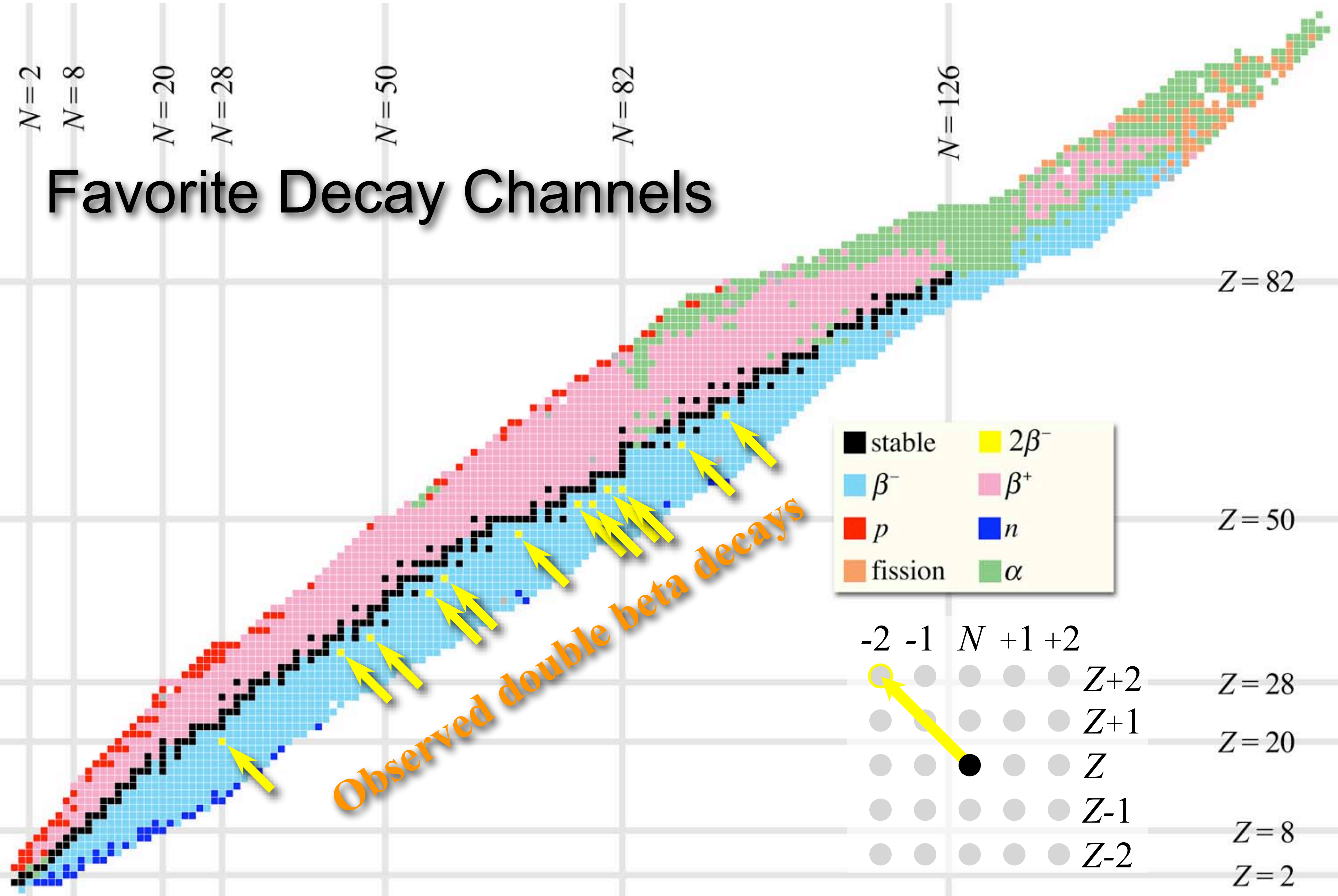
$$m_{{}^{Z}_{N}A} > m_{{}^{Z-1}_{N+1}A} + 2m_{e^+} + m_{\nu_e}$$

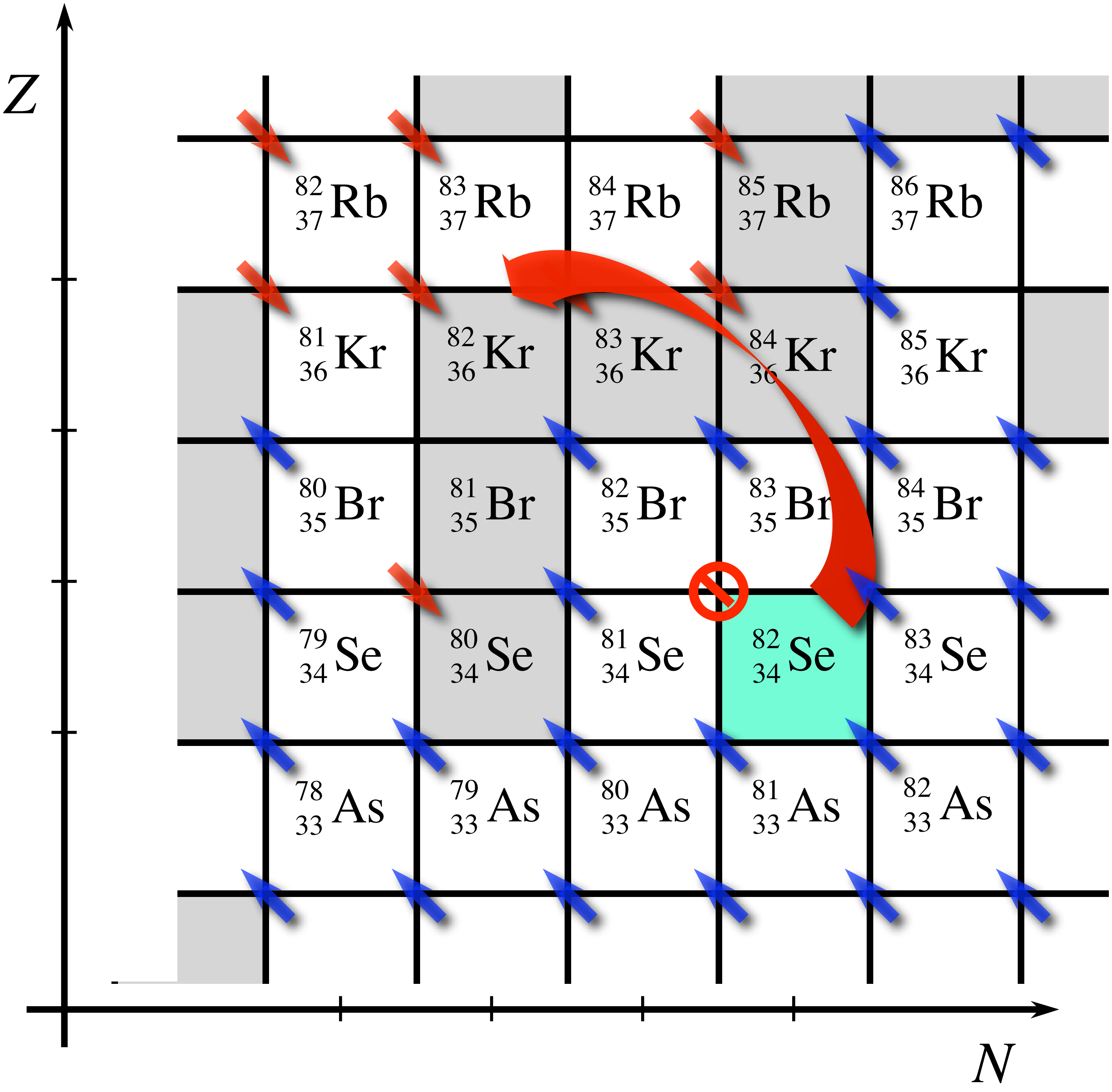


β^+ decay: electron capture

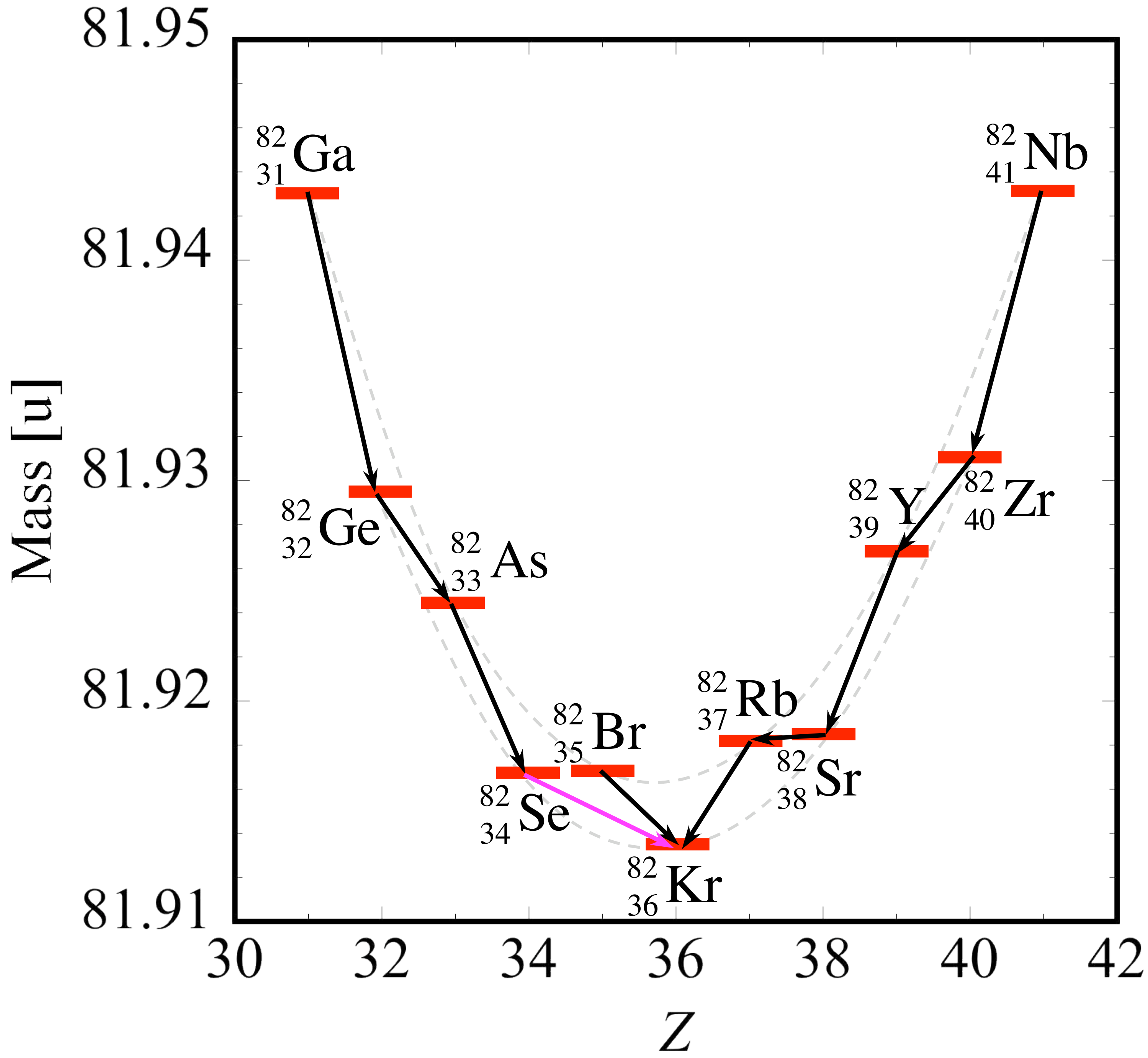
$$m_{{}^Z_N A} > m_{{}^{Z-1}_{N+1} A} + m_{\nu_e}$$

Favorite Decay Channels





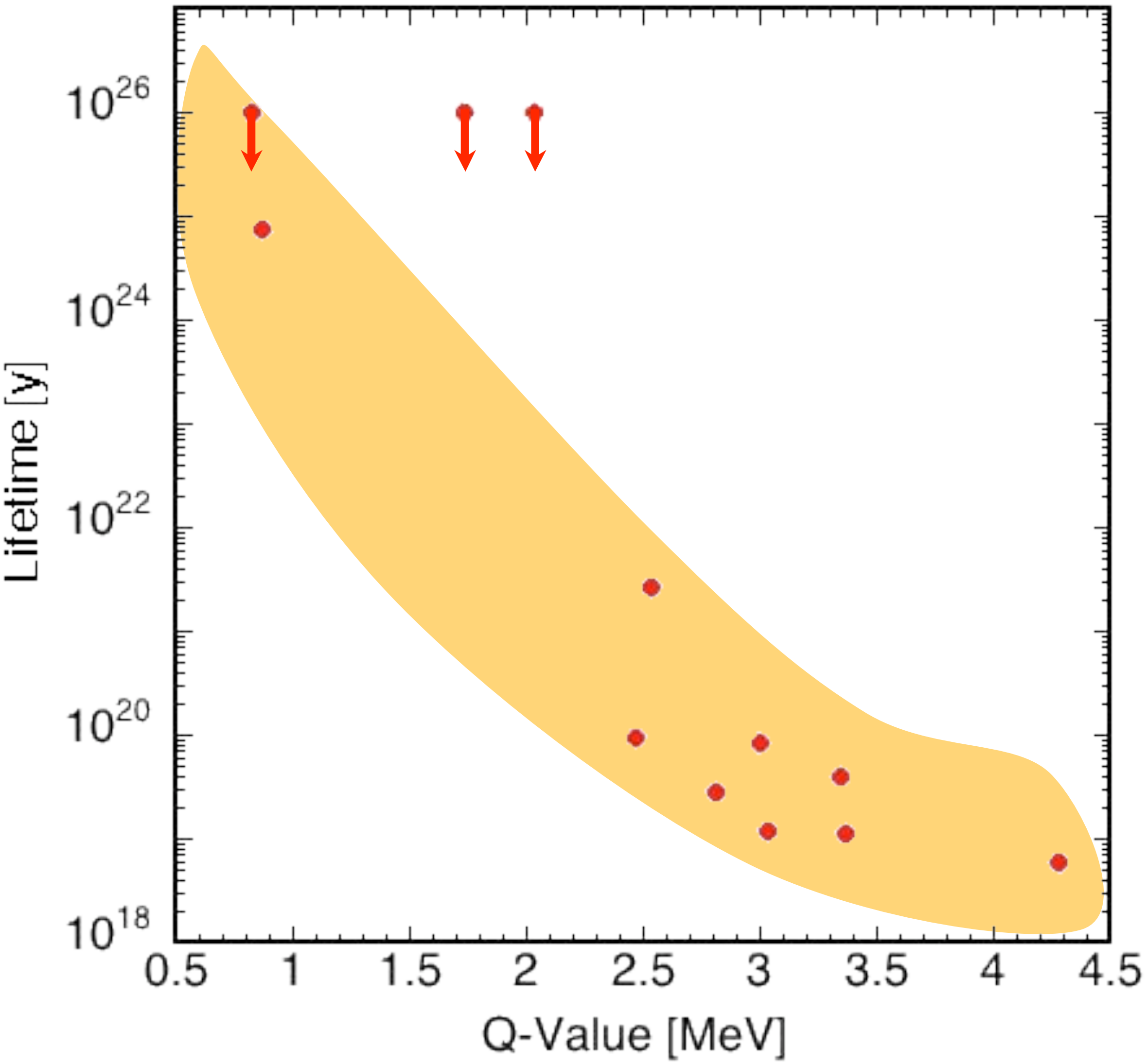
Z
$^{82}_{37}$Rb
$^{83}_{37}$Rb
$^{84}_{37}$Rb
$^{85}_{37}$Rb
$^{86}_{37}$Rb
$^{81}_{36}$Kr
$^{82}_{36}$Kr
$^{83}_{36}$Kr
$^{84}_{36}$Kr
$^{85}_{36}$Kr
$^{80}_{35}$Br
$^{81}_{35}$Br
$^{82}_{35}$Br
$^{83}_{35}$Br
$^{84}_{35}$Br
$^{79}_{34}$Se
$^{80}_{34}$Se
$^{81}_{34}$Se
$^{82}_{34}$Se
$^{83}_{34}$Se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

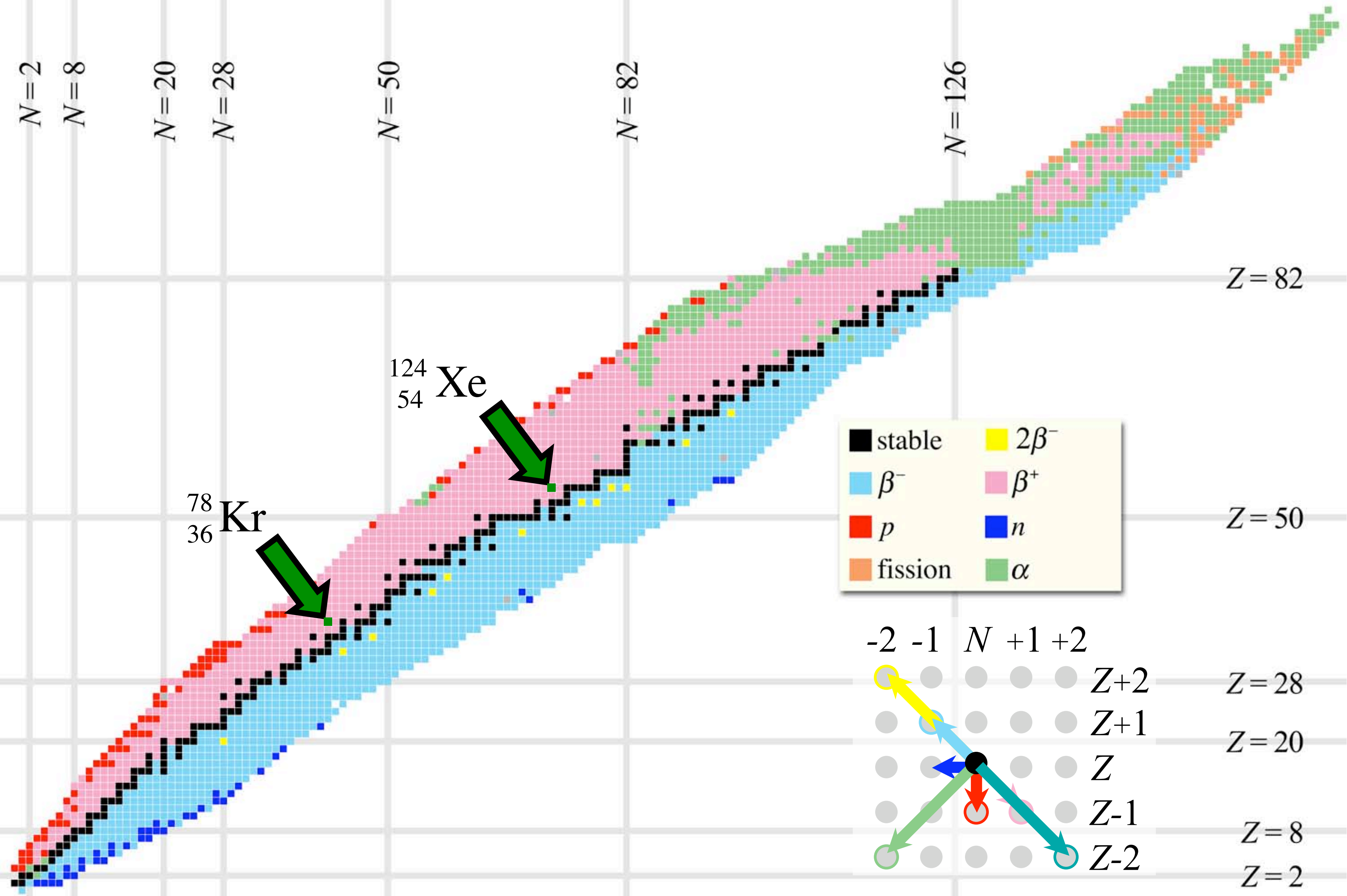

81.95
81.94
81.93
81.92
81.91
Mass [u]
30
32
34
36
38
40
42
Z
$^{82}_{31}$Ga
$^{82}_{32}$Ge
$^{82}_{33}$As
$^{82}_{34}$Se
$^{82}_{35}$Br
$^{82}_{36}$Kr
$^{82}_{37}$Rb
$^{82}_{38}$Sr
$^{82}_{39}$Y
$^{82}_{40}$Zr
$^{82}_{41}$Nb

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




$N=2$
$N=8$
$N=20$
$N=28$
$N=50$
$N=82$
$N=126$
$Z=82$
$Z=50$
$Z=28$
$Z=20$
$Z=8$
$Z=2$
$^{124}_{54}\mathrm{Xe}$
$^{78}_{36}\mathrm{Kr}$
stable
$2\beta^-$
β^-
β^+
p
n
fission
α
-2 -1 N +1 +2
Z+2
Z+1
Z
Z-1
Z-2

Double β^+ 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 β^+ Candidate ^{78}Kr

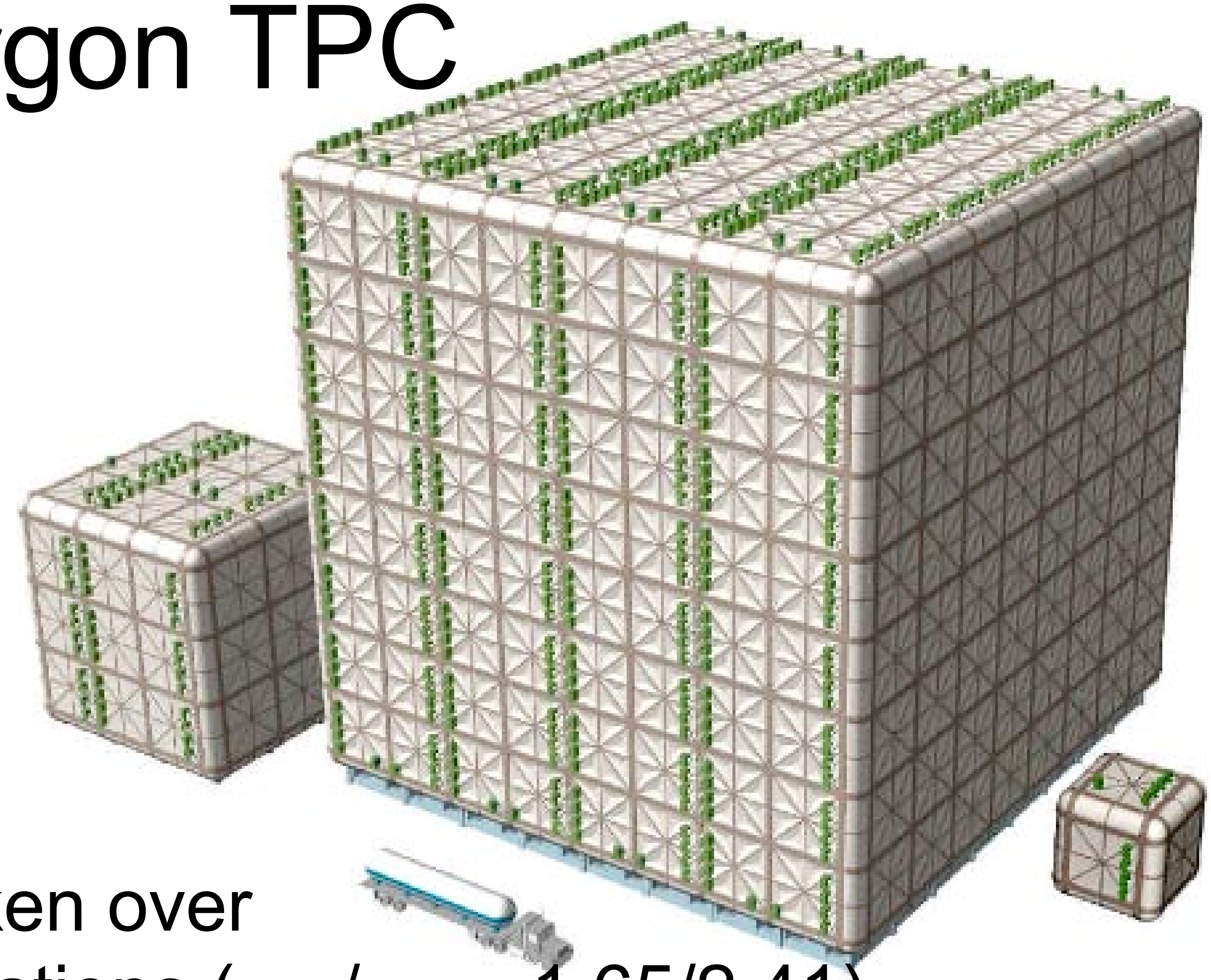
- Typical predicted half-life* $\tau \sim 10^{22}$ years
- Need $N \sim 10^{25}$ atoms of ^{78}Kr
- Natural abundance of ^{78}Kr = 0.35%
- Need $N \sim 3 \cdot 10^{28}$ atoms of $^{\mathrm{nat}}$Kr
- Need 0.168 kg*$(3 \cdot 10^{28})/(6 \cdot 10^{23})$ = 90 tons = 40,000 liters of $^{\mathrm{nat}}$Kr
- 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 (0.1g/cm^3)

Liquid Argon TPC

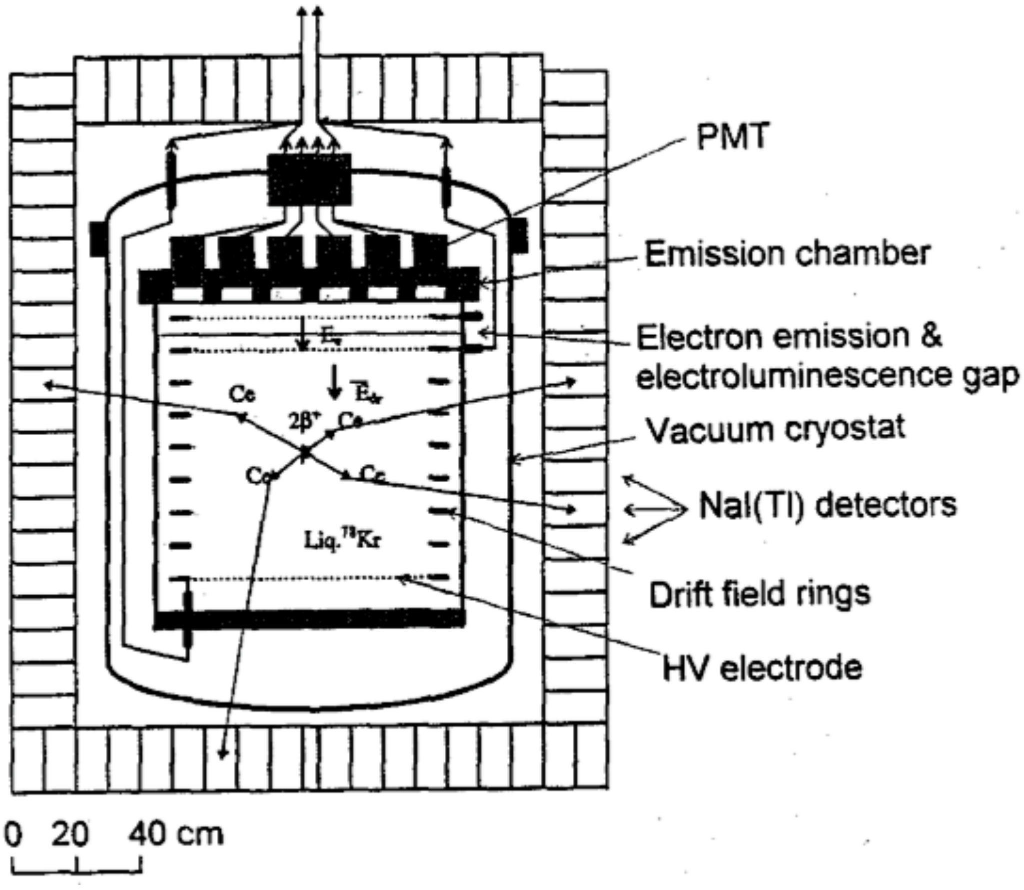


- One example for LANNDD (Liquid Argon Neutrino and Nucleon Decay Detector)
- Smallest shown: $V = 125\ \mathrm{m}^3$
- Design can be taken over with slight modifications ($\rho_{\mathrm{Ar}} / \rho_{\mathrm{Kr}} = 1.65/2.41$)

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

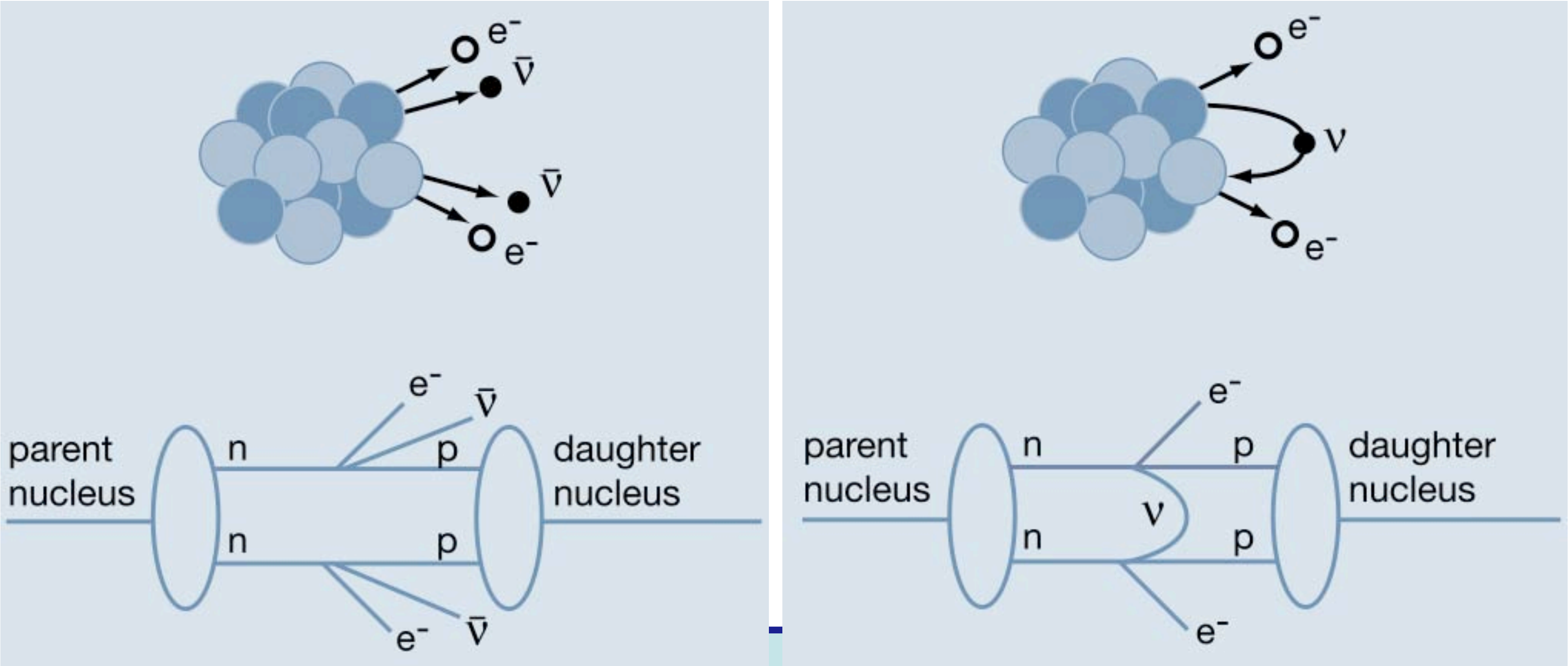
Previous Experiment

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



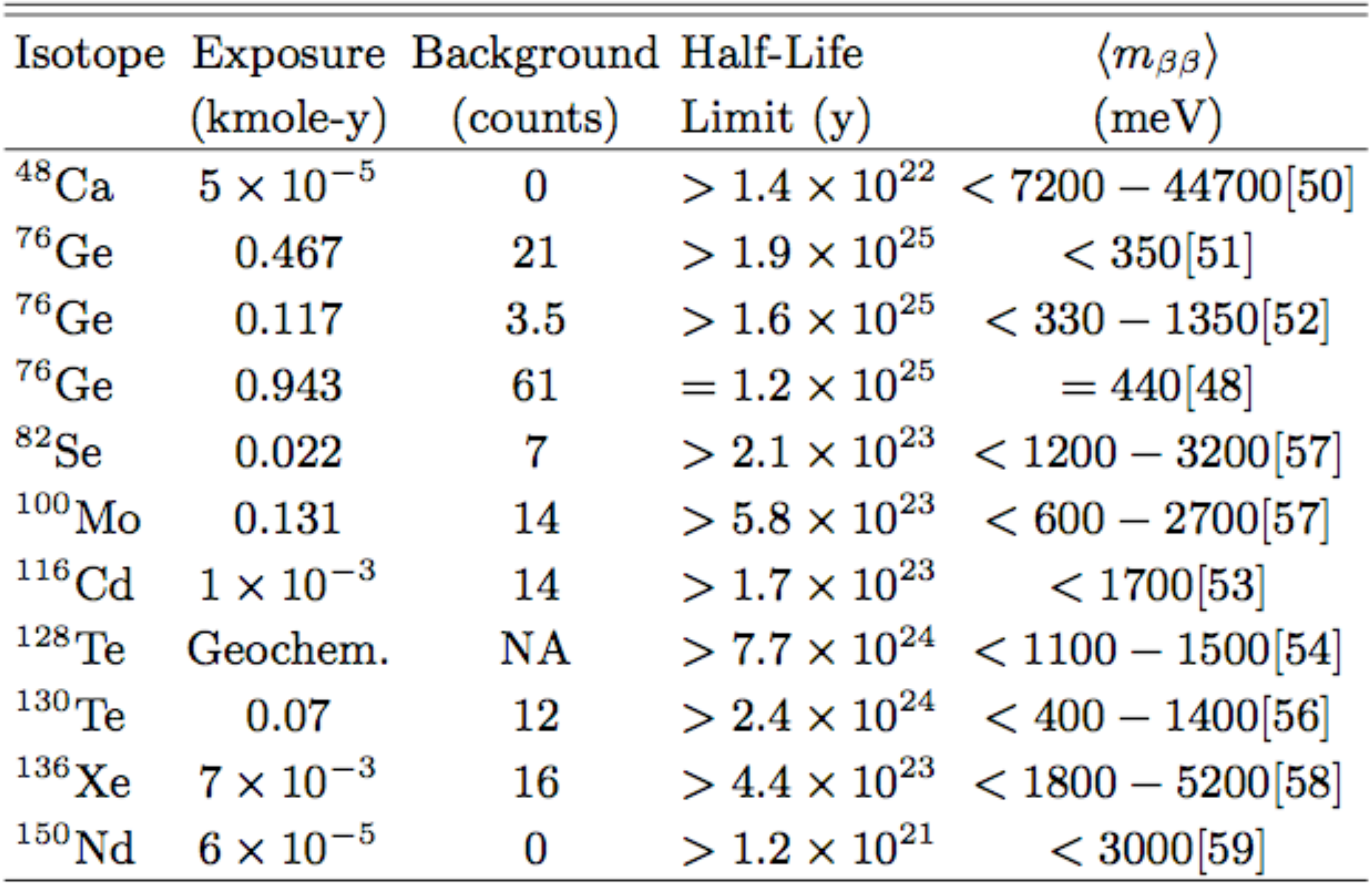
Neutrino-less Double β decay

- 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]

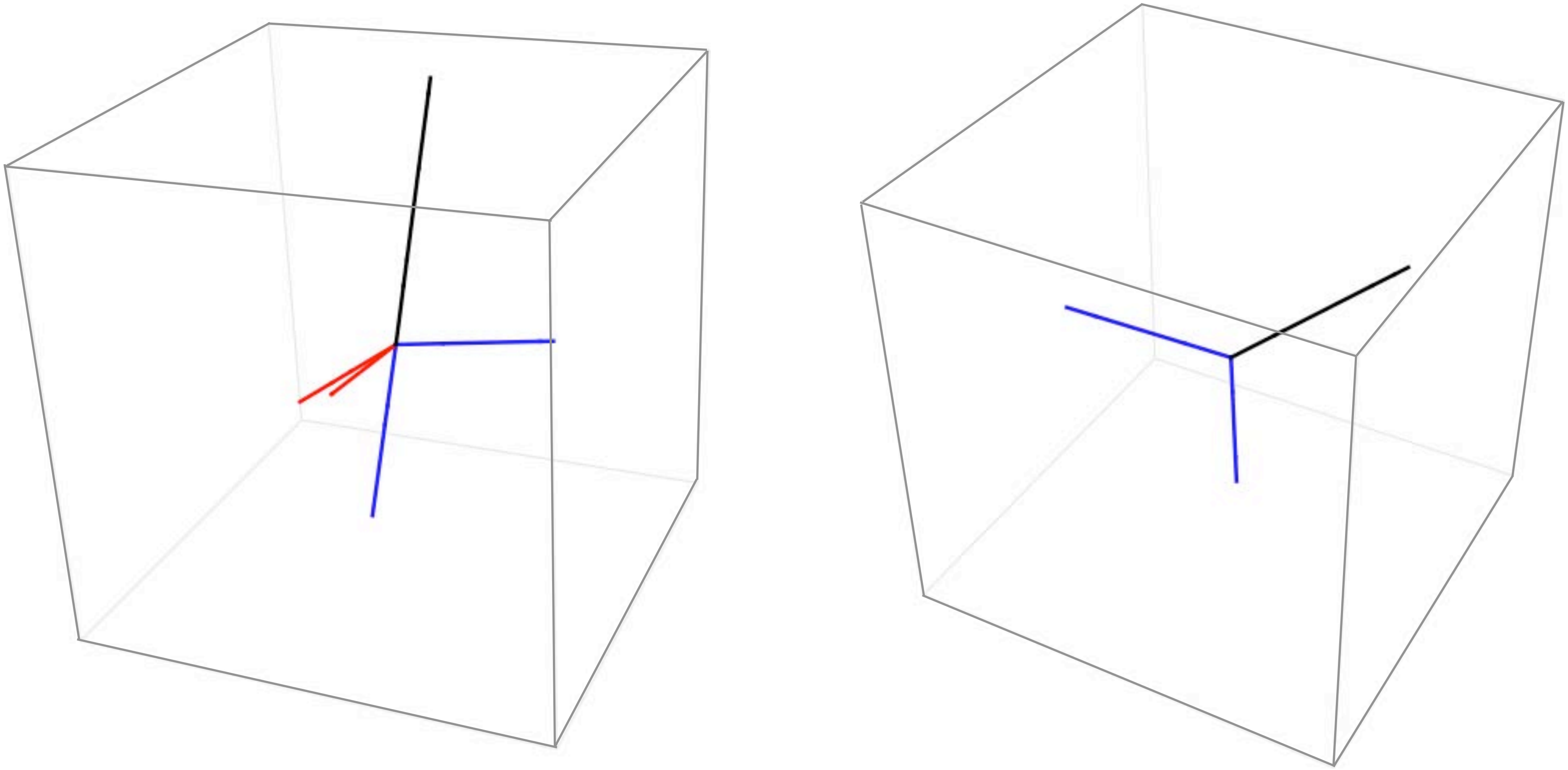
Compiled by Steven Elliott, LANL, 2006)

Could $0\nu\beta\beta$ 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

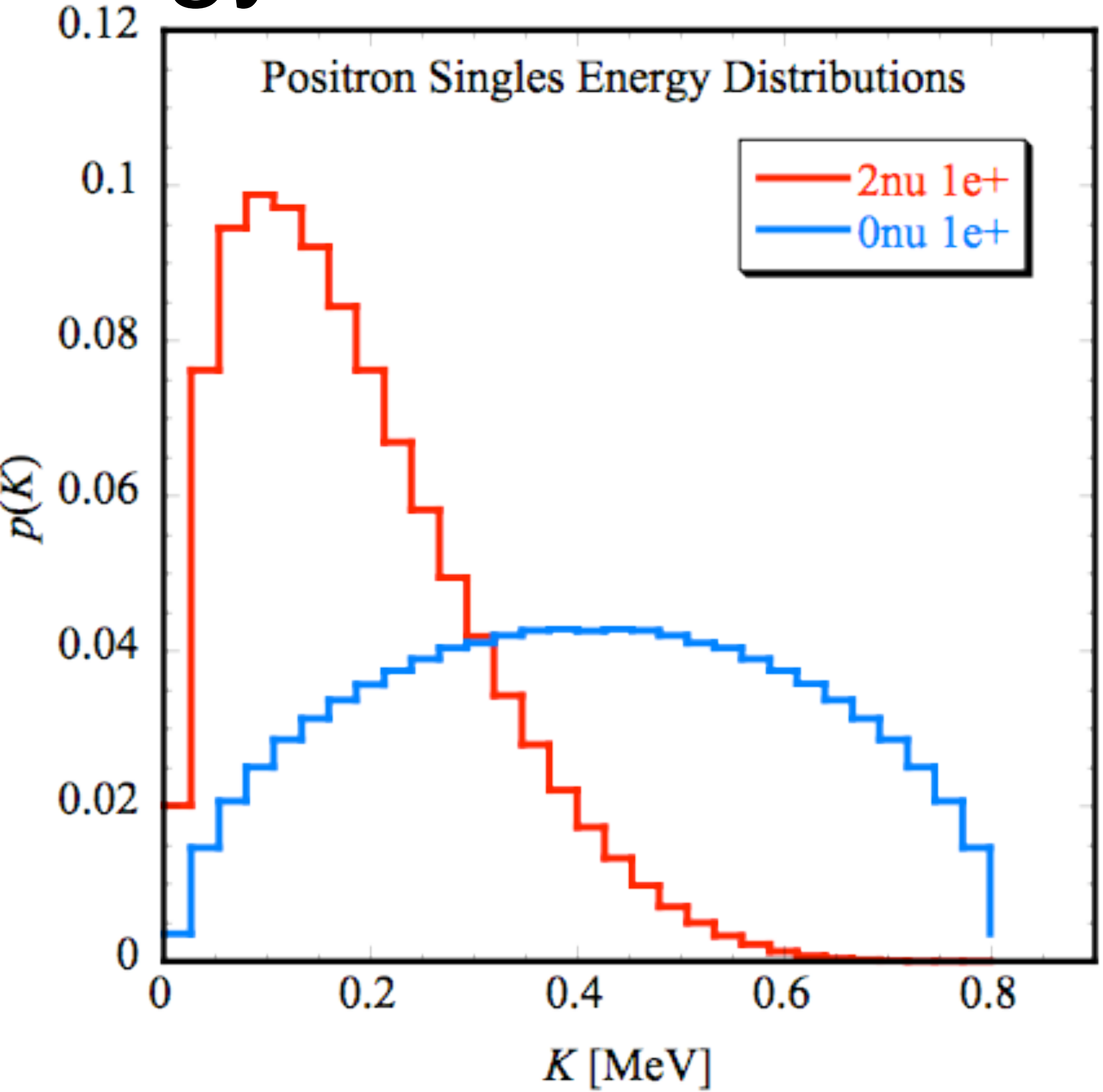
Neutrino Positron Recoil Nucleus



3d momentum space event displays in cm-system

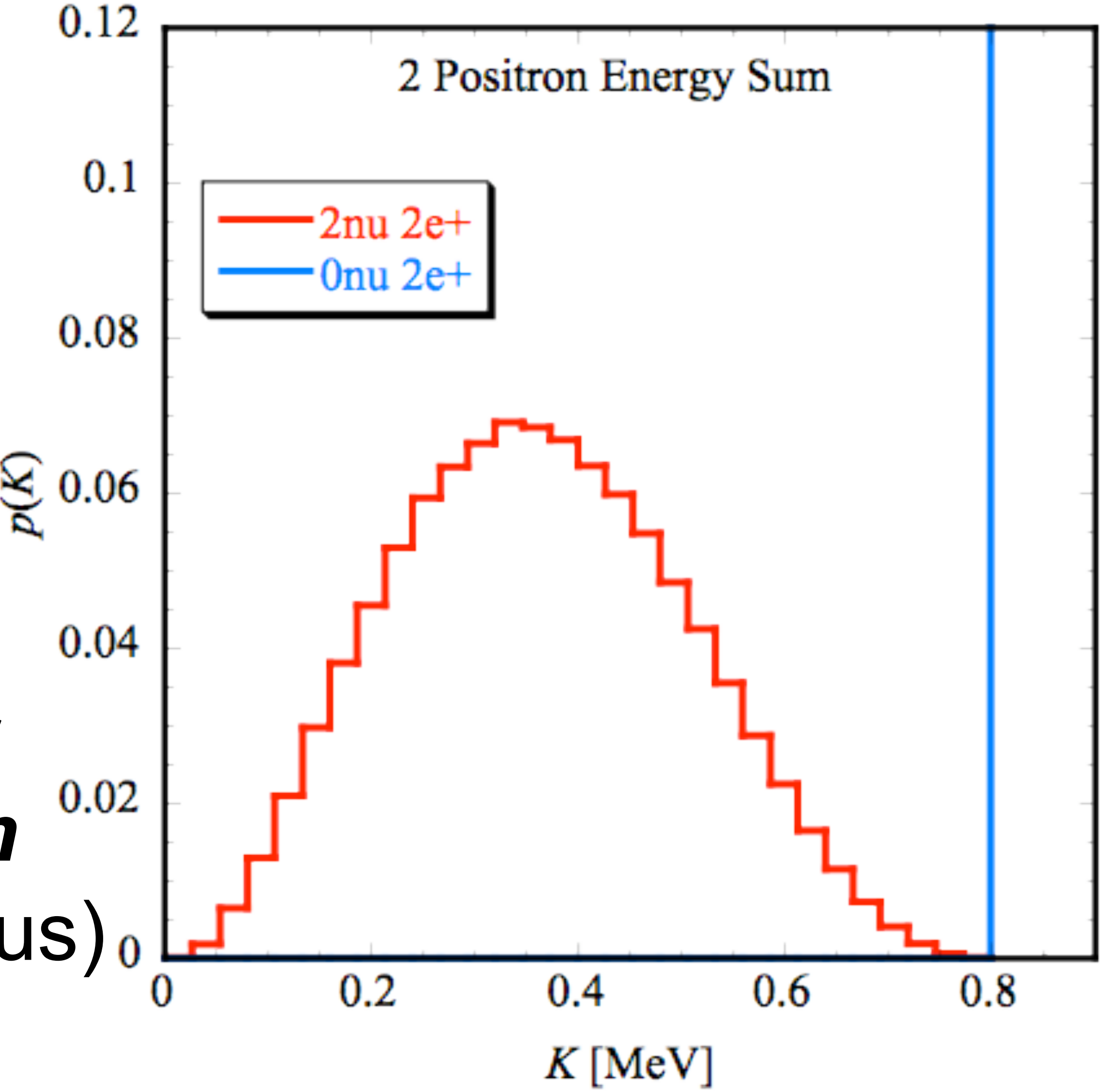
Positron Energy distributions

- 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, $\Delta p/p \sim 0.1$



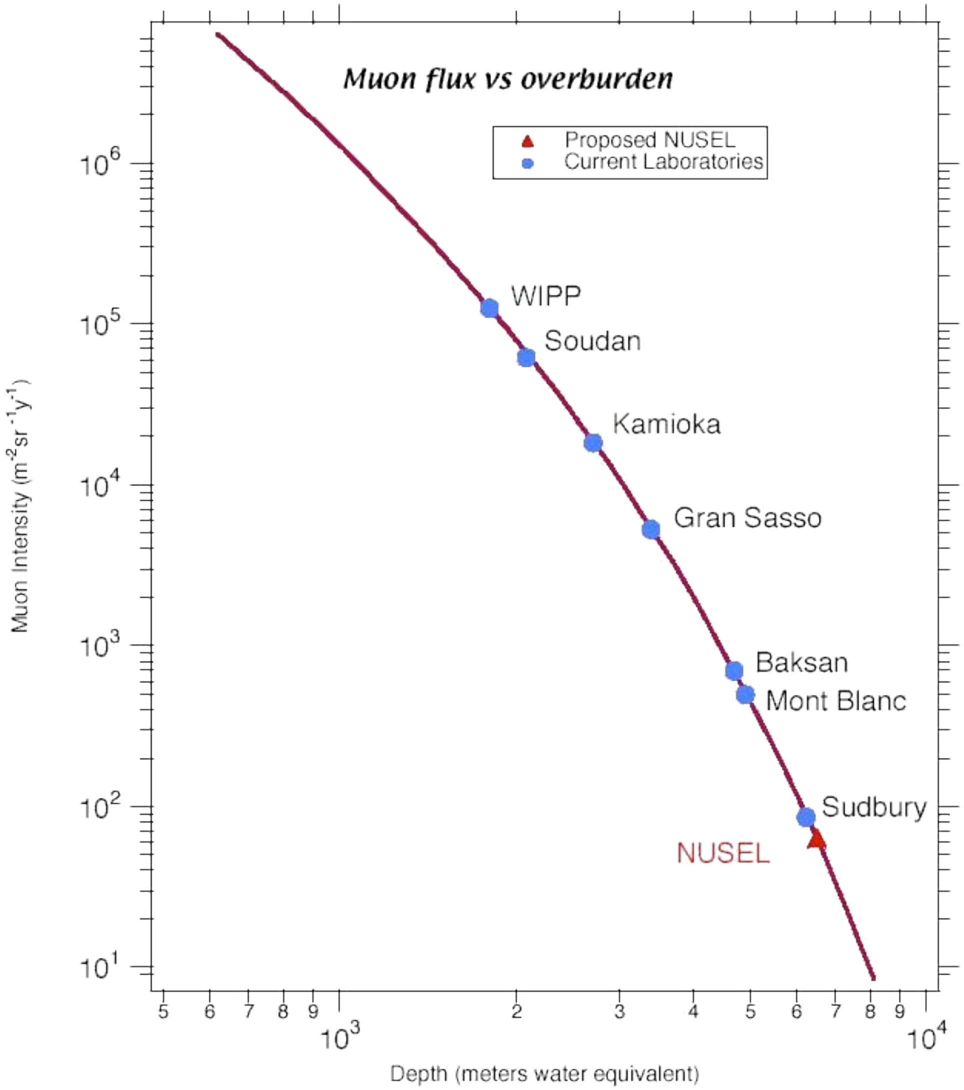
Coincidence Counts

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



Background: 2 simult. μ^{+} decays

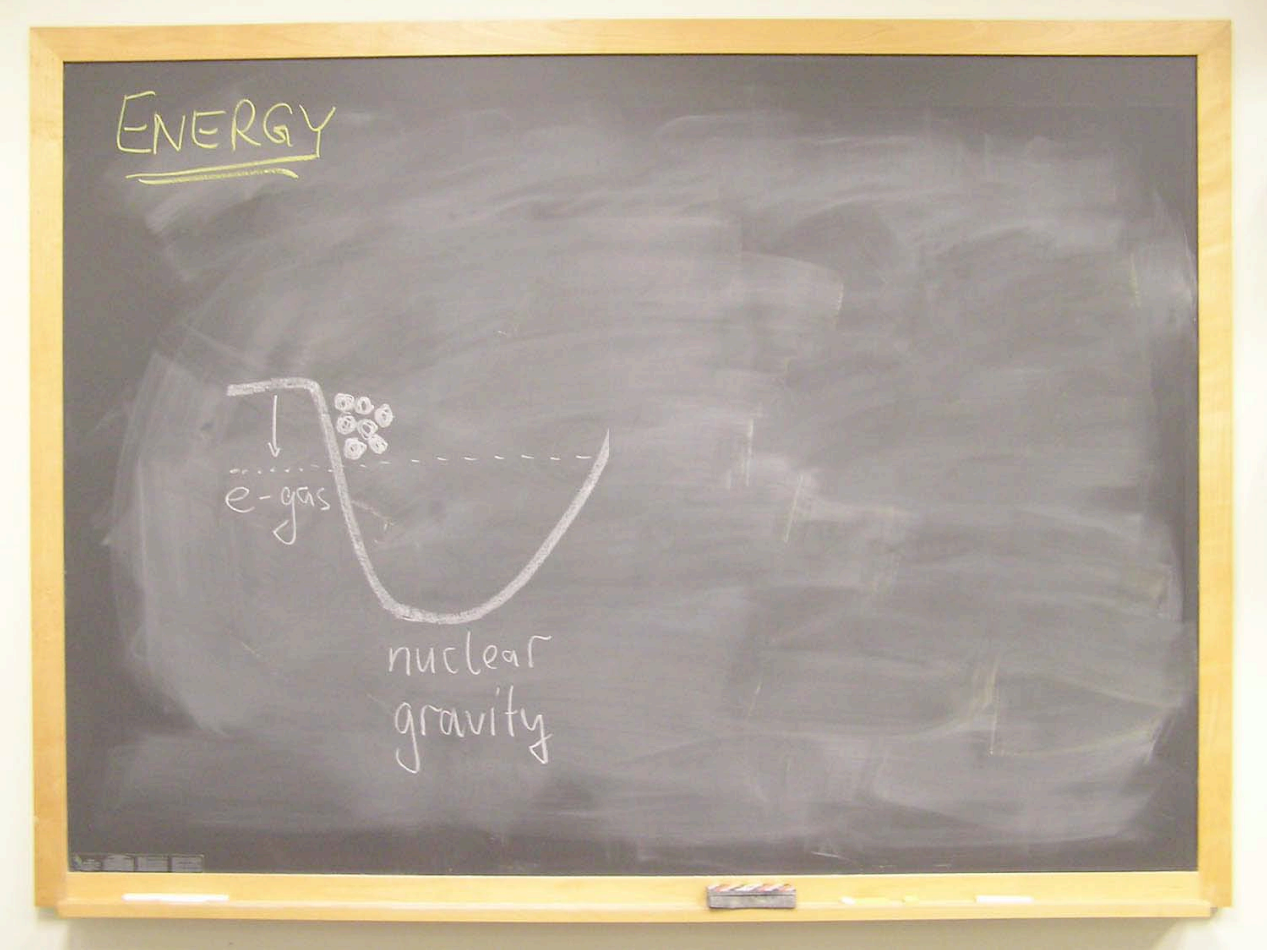
- Very rare
- But we are dealing a very rare signal!

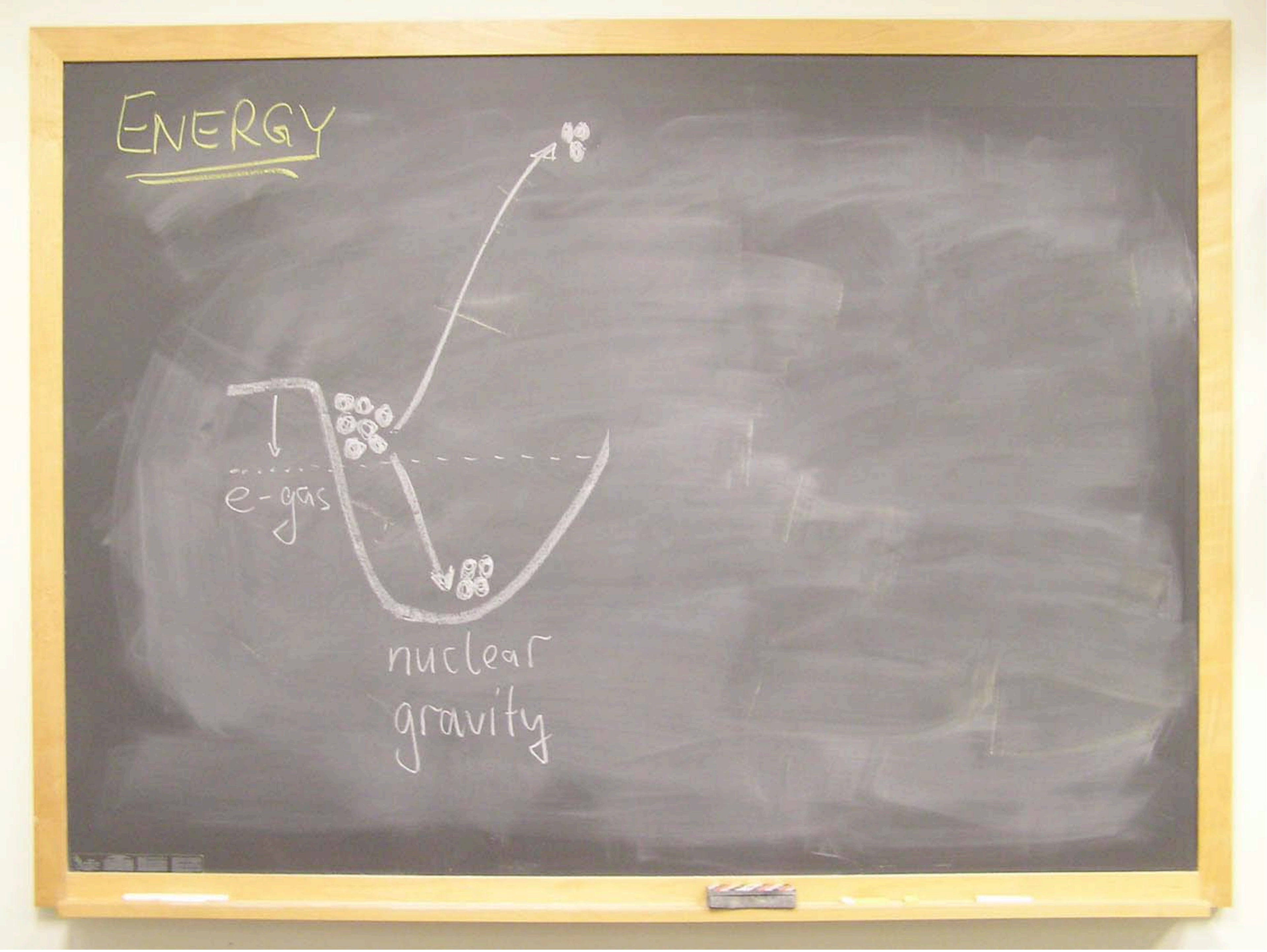


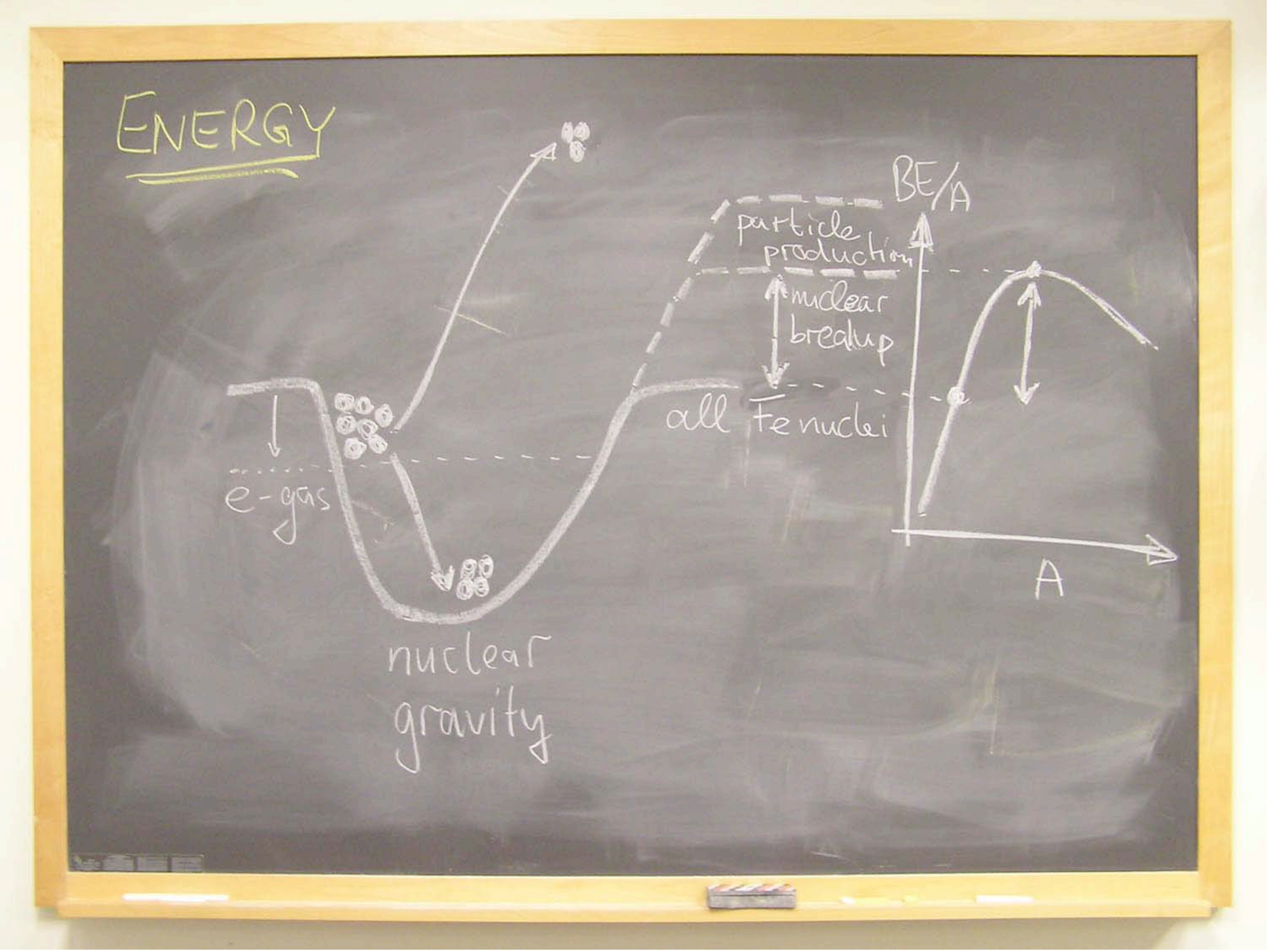
What is the connection between neutrinos and heavy ion collisions?

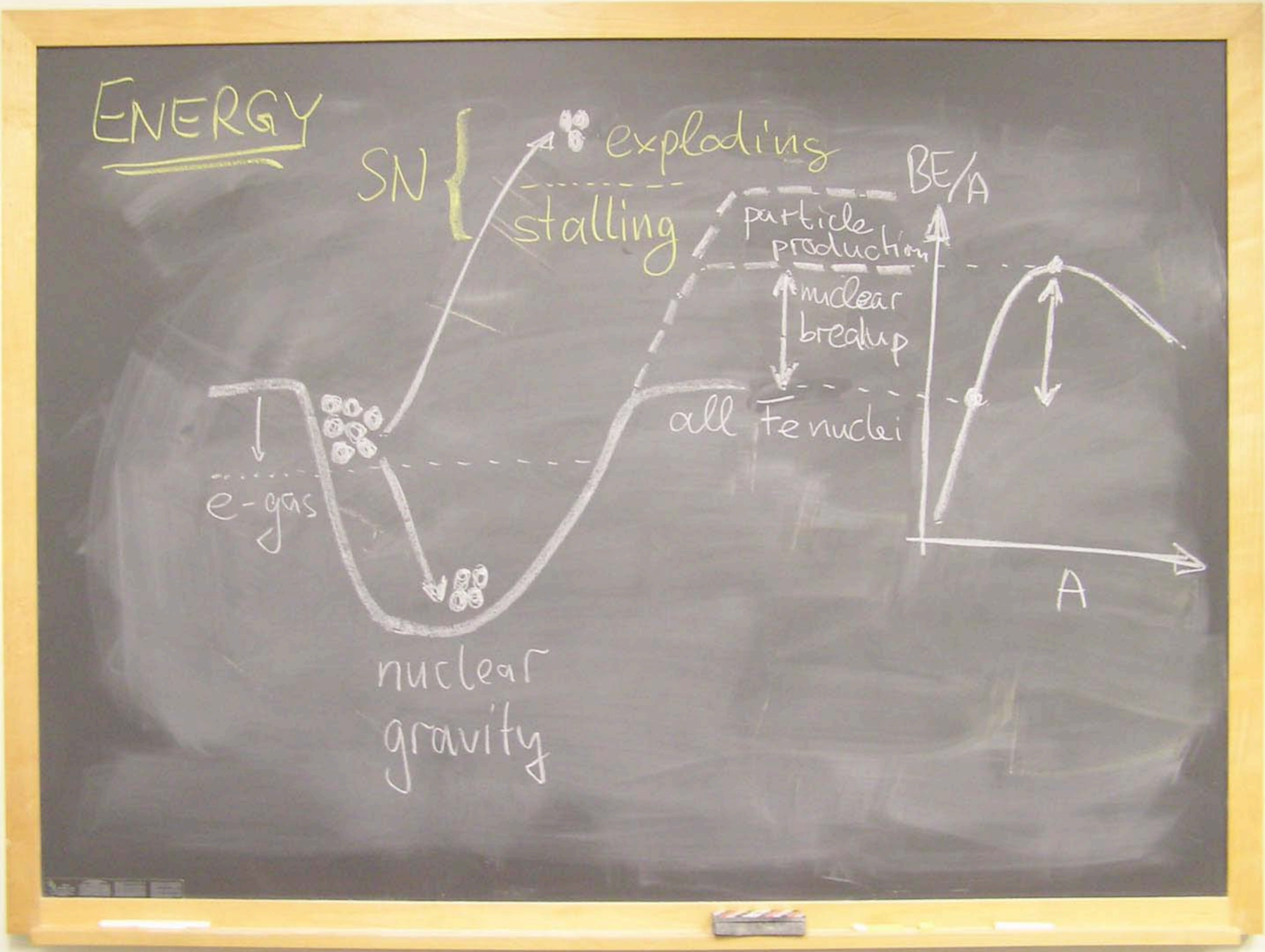
Supernovae

- Type 1
  - White dwarf exceeds its Chandrasekhar Mass (~1.4$M_\odot$) due to accretion and collapses
  - Standard candles (=> Dark Energy signal …)
- Type 2
  - Powered by gravitational energy released during star's late stage iron core collapse
  - Mass range 11 $M_\odot$ to 40 $M_\odot$ at ZAMS (zero age main sequence; mass of star at start of its evolution)
- Type 2 has hydrogen lines, type 1 does not
- Here: focus on type 2 and use M=15 $M_\odot$


ENERGY
e-gas
nuclear
gravity


ENERGY
e-gas
nuclear
gravity


ENERGY
BE/A
particle production
nuclear breakup
all Fe nuclei
e-gas
nuclear gravity
A


ENERGY
SN
exploding
stalling
particle production
nuclear breakup
all Fe nuclei
BE/A
A
e-gas
nuclear gravity

Hydro Simulations

- Tough problem for hydro
  - Length scales vary drastically in time
  - Multiple fluids
  - Strongly time dependent viscosity
  - Very large number of time steps
- Special relativity, causality, …
- Huge magnetic fields
- 3D simulations needed
  - Giant grids
- Need to couple all of this to radiation transport calculation and Boltzmann transport problem for neutrinos

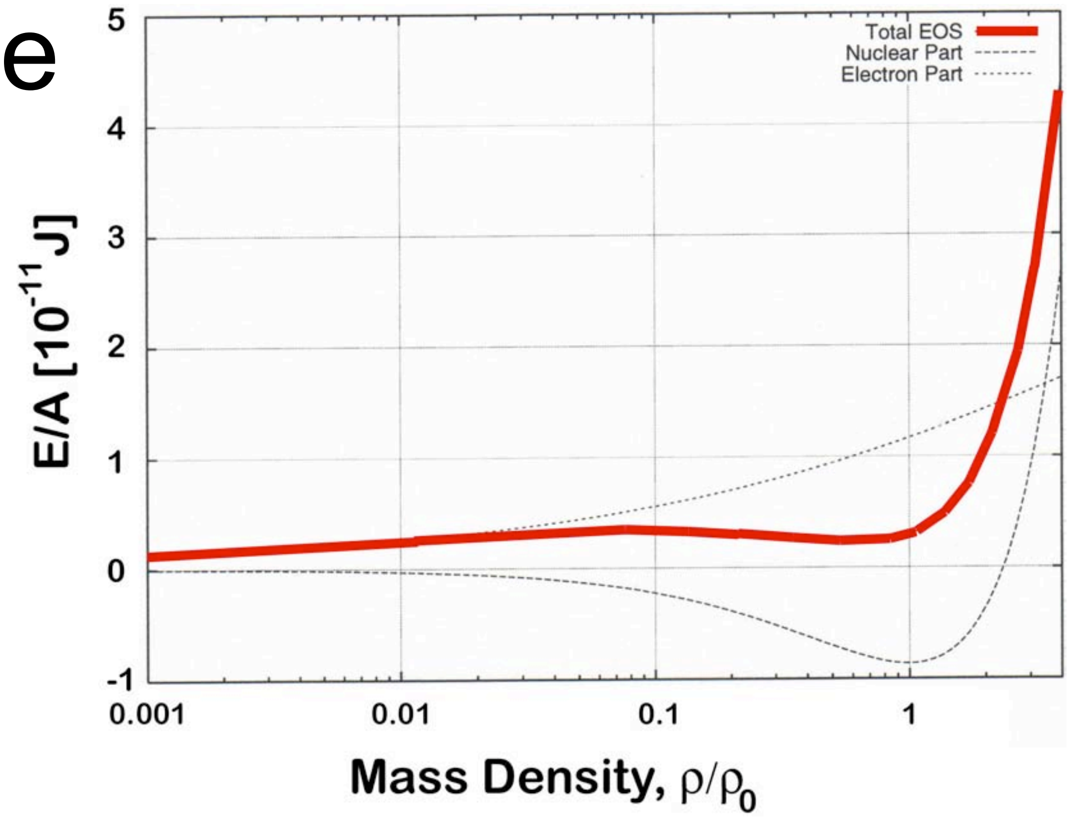
Simulations of Nuclear Collisions

- Hydro, mean field, cascades
- Numerical solution of transport theories
  - Need to work in 6d phase space => prohibitively large grids ($20^3 \times 40^2 \times 80 \sim 10^9$ lattice sites)
  - Idea: Only follow initially occupied phase space cells in time and represent them by test particles
  - One-body mean-field potentials (ρ, p, τ) via local averaging procedures
  - Test particles scatter with realistic cross sections => (exact) solution of Boltzmann equation (+Pauli, Bose)
  - Very small cross sections via perturbative approach
  - Coupled equations for many species no problem
  - Typically 100-1000 test particles/nucleon

Try this for Supernovae!

- 2 $M_{\odot}$ in iron core = 2×10^{57} baryons
- 10^7 test particles => 2×10^{50} baryons/test particle ☺
- Need time-varying grid for (non-gravity) potentials, because whole system collapses
- Need to think about internal excitation of test particles
- Can create ν-test particles and give them finite mean free path => Boltzmann solution for ν-transport problem
- Can address angular momentum question

Equation of State



- Low density:
  - Degenerate e-gas
- High density
  - Dominated by nuclear EoS
  - Isospin term in nuclear EoS becomes dominant
- For now:

$$u_{int}(\rho, Y_e) = a\,\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{\sigma} + \frac{9}{4}\left(\frac{\pi}{3}\right)^{\frac{2}{3}} \hbar c Y_e^{\frac{4}{3}} \left(\frac{\rho}{m_B}\right)^{\frac{1}{3}}.$$

- High density neutron rich EoS can be explored by FAIR@GSI and/or (mini)RIA

Neutrinos

- Neutrinos similar to pions at RHIC
  - Not present in entrance channel
  - Produced in very large numbers (RHIC: 10^3, here 10^{56})
  - Essential for reaction dynamics
- Different: No formation time or off -shell effects
- Represent 10^N neutrinos by one test particle
  - Populate initial neutrino phase space uniformly
  - Sample test particle momenta from a thermal distribution
- Neutrino test particles represent “2nd fluid”, do NOT escape freely (neutrino trapping), and need to be followed in time.
- Neutrinos created in center and are “light” fluid on which “heavy” baryon fluid descends
  - Inversion problem
  - Rayleigh-Taylor instability
  - turbulence

Coupled Equations

$$\begin{aligned}\frac{\partial f_b(xp)}{\partial t} + \frac{\Pi^i}{E_b^*(p)}\nabla_i^x f_b(xp) \quad - \quad & \frac{\Pi^\mu}{E_b^*(p)}\nabla_i^x U_\mu(x)\nabla_p^i f_b(xp) + \frac{M_b^*}{E_b^*(p)}\nabla_i^x U_s \nabla_p^i f_b(xp) \\ = \quad & I_{bb}^b(xp) + I_{b\nu}^b(xp)\end{aligned}$$

$$\frac{\partial f_\nu(xk)}{\partial t} + \frac{k\cdot\nabla^x}{E_\nu(k)} f_\nu(xk) = I_{b\nu}^\nu(xk)$$

$$\begin{aligned}I_{bb}^b(xp) \quad = \quad & \frac{\pi}{(2\pi)^9}\sum_{\alpha_1\alpha_2\alpha_3,m_s^b}\int\int\int d\boldsymbol{p}_1 d\boldsymbol{p}_2 d\boldsymbol{p}_3 \frac{M_b^* M_{\alpha_1}^* M_{\alpha_2}^* M_{\alpha_3}^*}{E_b^* E_{\alpha_1}^* E_{\alpha_2}^* E_{\alpha_3}^*} \\ \cdot \quad & \delta(E_b^*(p) + E_{\alpha_1}^*(p_1) - E_{\alpha_2}^*(p_2) - E_{\alpha_3}^*(p_3))\delta(\boldsymbol{p} + \boldsymbol{p}_1 - \boldsymbol{p}_2 - \boldsymbol{p}_3) \\ \cdot \quad & \langle\langle p\alpha_b p_1\alpha_1|\hat{G}|p_2\alpha_2 p_3\alpha_3\rangle\rangle \\ \cdot \quad & [\langle\langle p_2\alpha_2 p_3\alpha_3|\hat{G}|p\alpha_b p_1\alpha_1\rangle\rangle - \langle\langle p_2\alpha_2 p_3\alpha_3|\hat{G}|p_1\alpha_1 p\alpha_b\rangle\rangle] \\ \cdot \quad & [f_{\alpha_2}(xp_2) f_{\alpha_3}(xp_3)\overline{f}_{\alpha_1}(xp_1)\overline{f}_b(xp) - \overline{f}_{\alpha_2}(xp_2)\overline{f}_{\alpha_3}(xp_3) f_{\alpha_1}(xp_1) f_b(xp)]\end{aligned}$$

Similar to ***Wang, Li, Bauer, Randrup, Ann. Phys. '91***

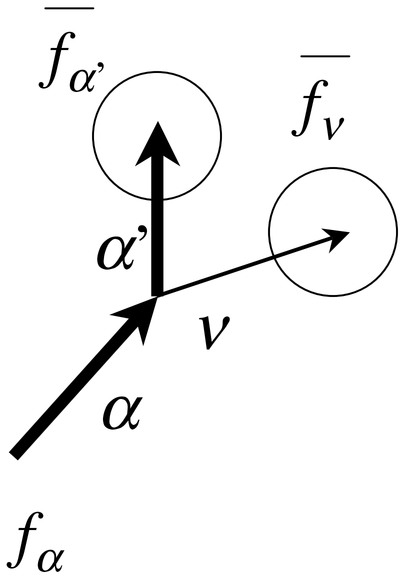
Neutrino Gain and Loss

WB, Heavy Ion Physics (2005)

$$I^{\nu}_{b\nu}(\boldsymbol{r},\boldsymbol{k},t) = I^{\nu}_{\text{gain}}(xk) - I^{\nu}_{\text{loss}}(xk)$$

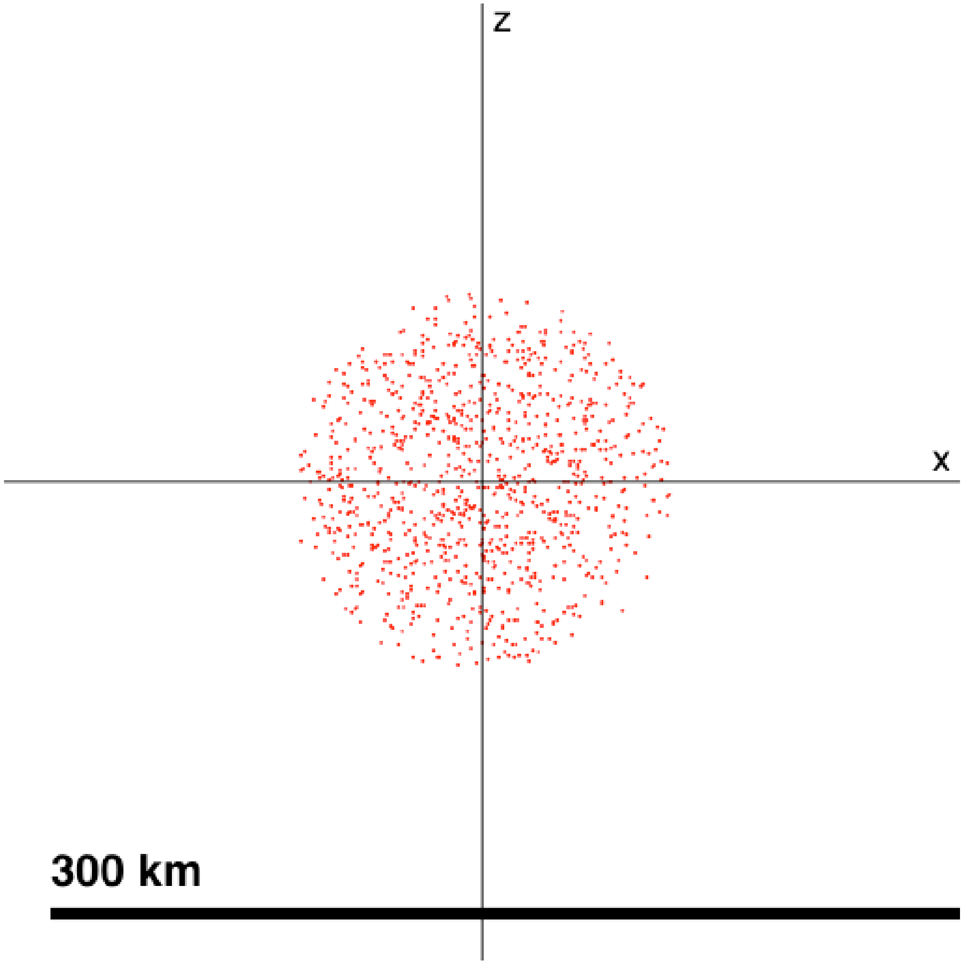
$$\begin{aligned} I^{\nu}_{\text{gain}}(xk) &= \frac{\pi}{16(2\pi)^6}\sum_{\alpha\alpha'}\int\int\frac{M^*_\alpha M^*_{\alpha'}}{E^*_\alpha(p)E^*_{\alpha'}(p')} \\ &\cdot \frac{\langle u_{\alpha'p'}|\underline{\hat{u}}(k)\hat{u}(p+p')^2|u_{\alpha p}\rangle \cdot \langle u_{\alpha p}|\underline{\hat{u}}(k)|u_{\alpha'p'}\rangle}{E^4_\nu(k)} \\ &\cdot \delta(E^*_{\alpha'}(p') - E_\nu(k) - E_\alpha(p))\ \delta(\boldsymbol{p}'-\boldsymbol{p}-\boldsymbol{k}) \\ &\cdot \bar{f}_\nu(xk)f_{\alpha'}(xp')\bar{f}_\alpha(xp)\ d\boldsymbol{p}d\boldsymbol{p}' \end{aligned}$$

$$\begin{aligned} I^{\nu}_{\text{loss}}(xk) &= \frac{\pi}{16(2\pi)^6}\sum_{\alpha\alpha'}\int\int\frac{M^*_\alpha M^*_{\alpha'}}{E^*_\alpha(p)E^*_{\alpha'}(p')} \\ &\cdot \frac{\langle u_{\alpha'p'}|\underline{\hat{u}}(k)\hat{u}(p+p')^2|u_{\alpha p}\rangle \cdot \langle u_{\alpha p}|\underline{\hat{u}}(k)|u_{\alpha'p'}\rangle}{E^4_\nu(k)} \\ &\cdot \delta(E^*_{\alpha'}(p') - E_\nu(k) - E_\alpha(p))\ \delta(\boldsymbol{p}'-\boldsymbol{p}-\boldsymbol{k}) \\ &\cdot f_\nu(xk)f_\alpha(xp)\bar{f}_{\alpha'}(xp')\ d\boldsymbol{p}d\boldsymbol{p}' \end{aligned}$$



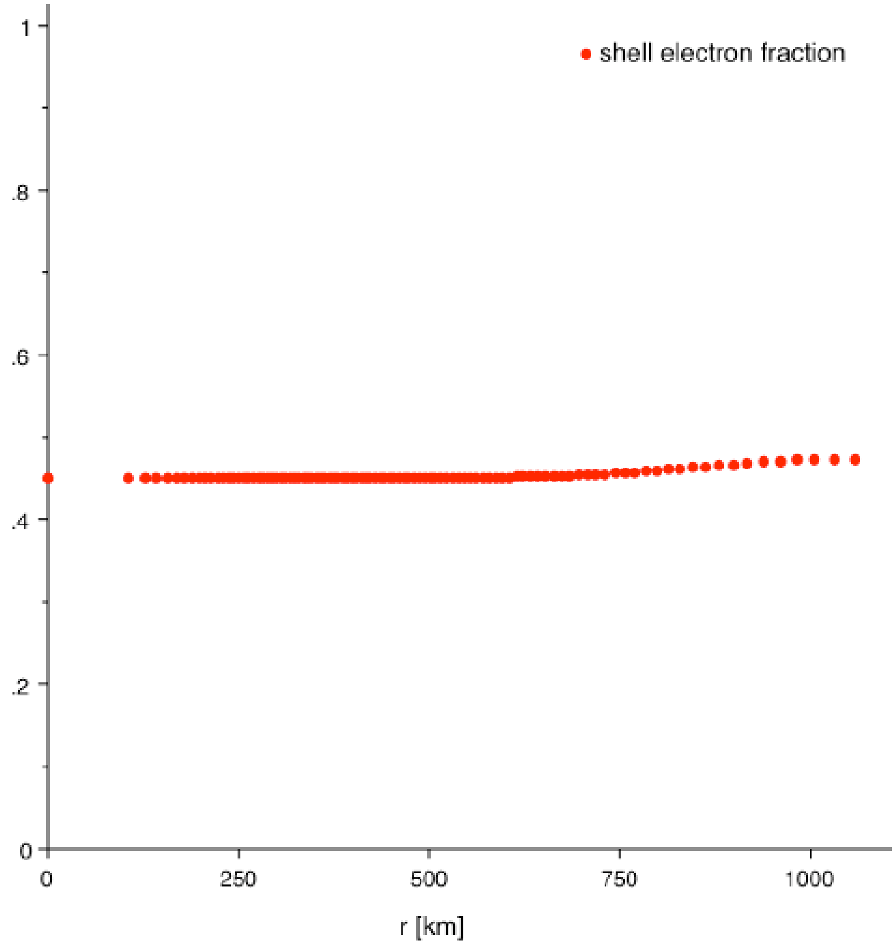
$$\bar{f} = 1 \pm f$$

Some Results



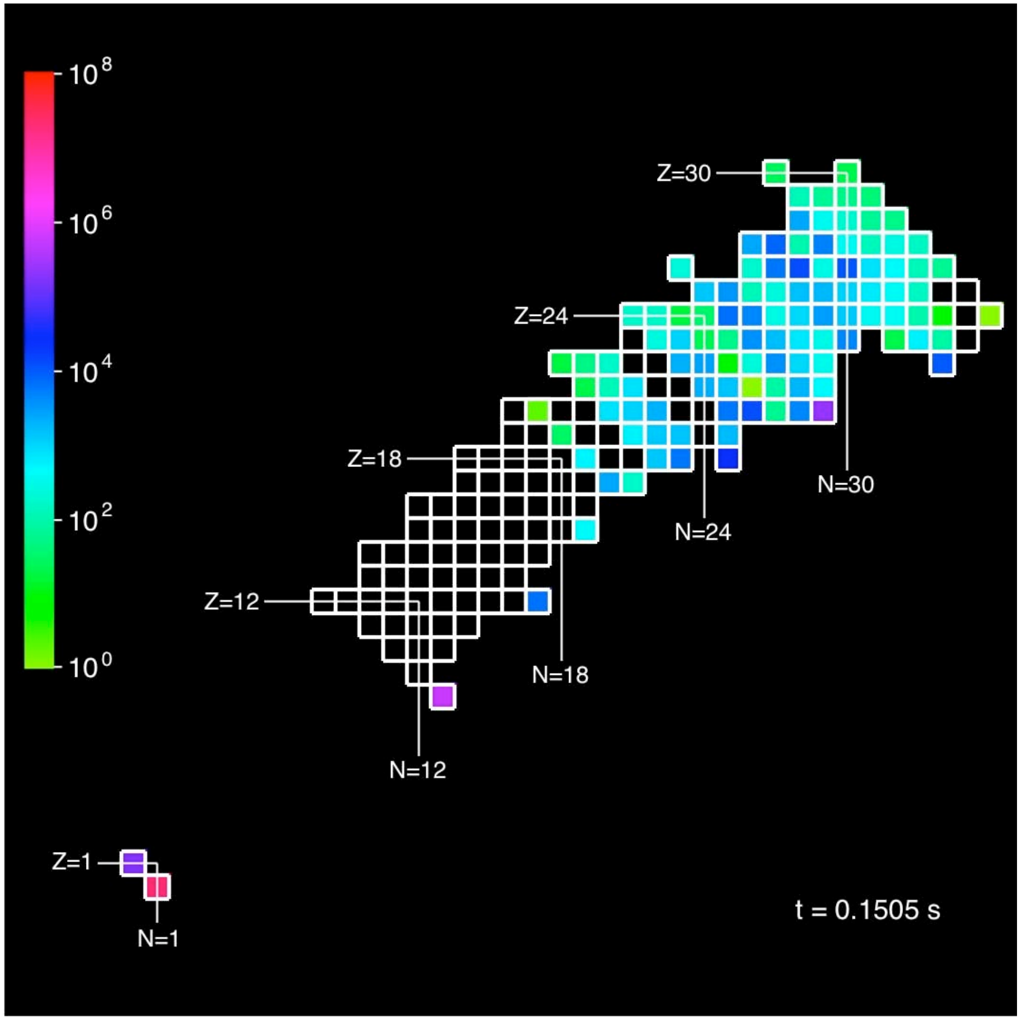
Terrance Strother

Some Results



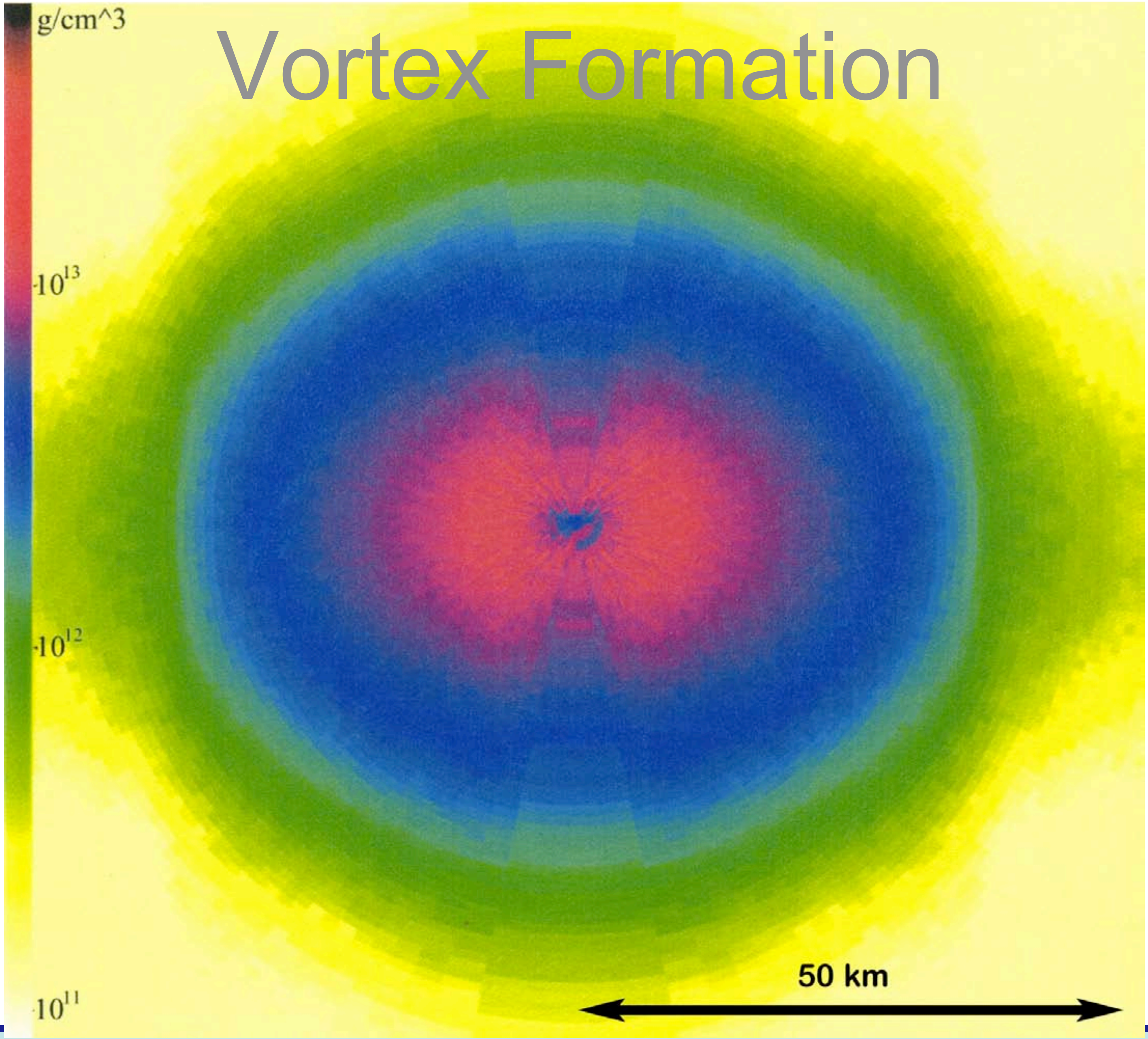
Terrance Strother

Some Results



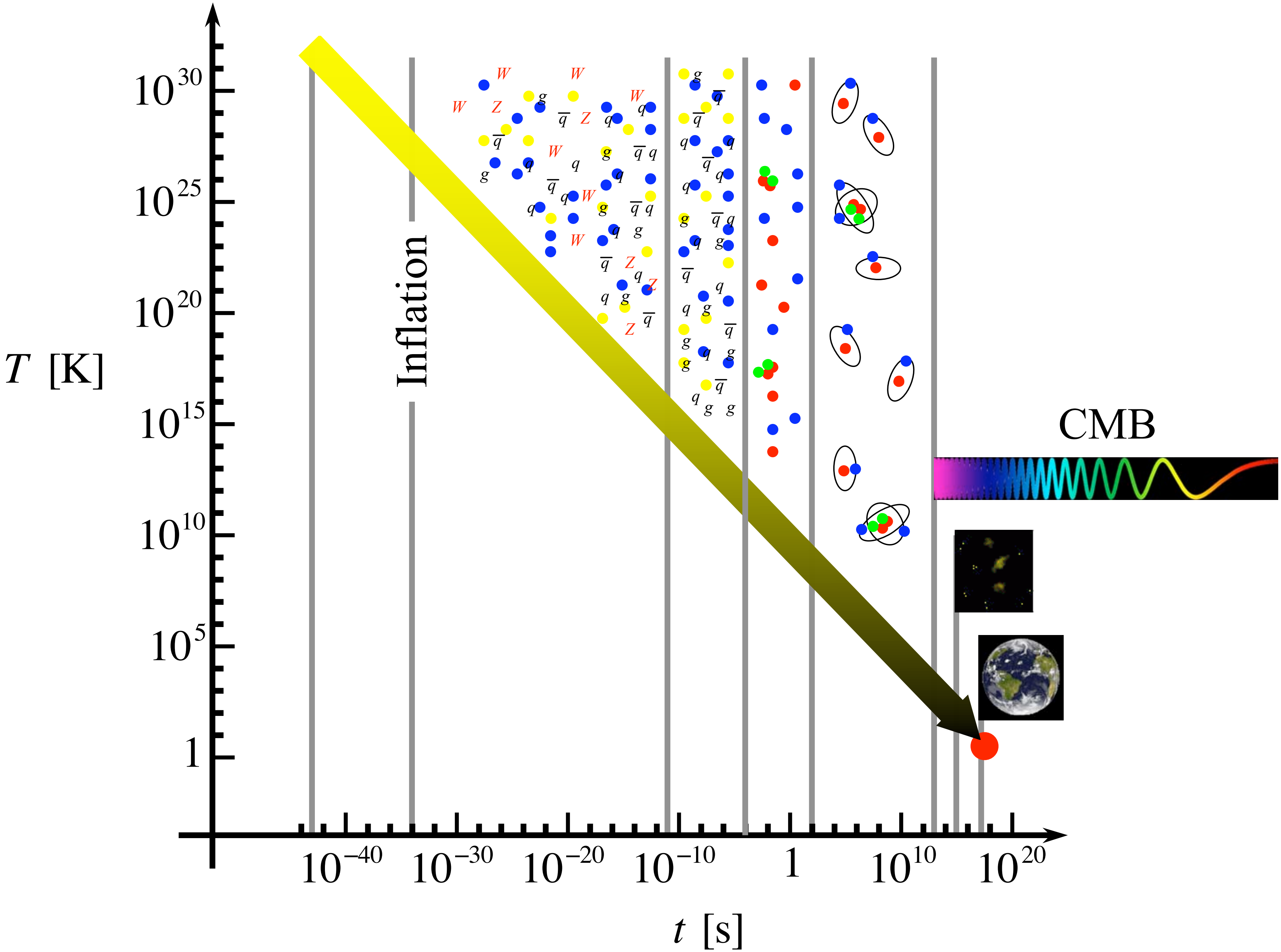
Terrance Strother

Vortex Formation



Some Supernovae are Not Spherical!

- 1987A remnant shows “smoke rings”
- Cylinder symmetry, but not spherical
- Consequence of high angular momentum collapse



T [K]
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
1
Inflation
W
Z
g
q
$\bar{q}$
CMB
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
10^{20}
t [s]