Electron Capture processes in intermediate mass stars

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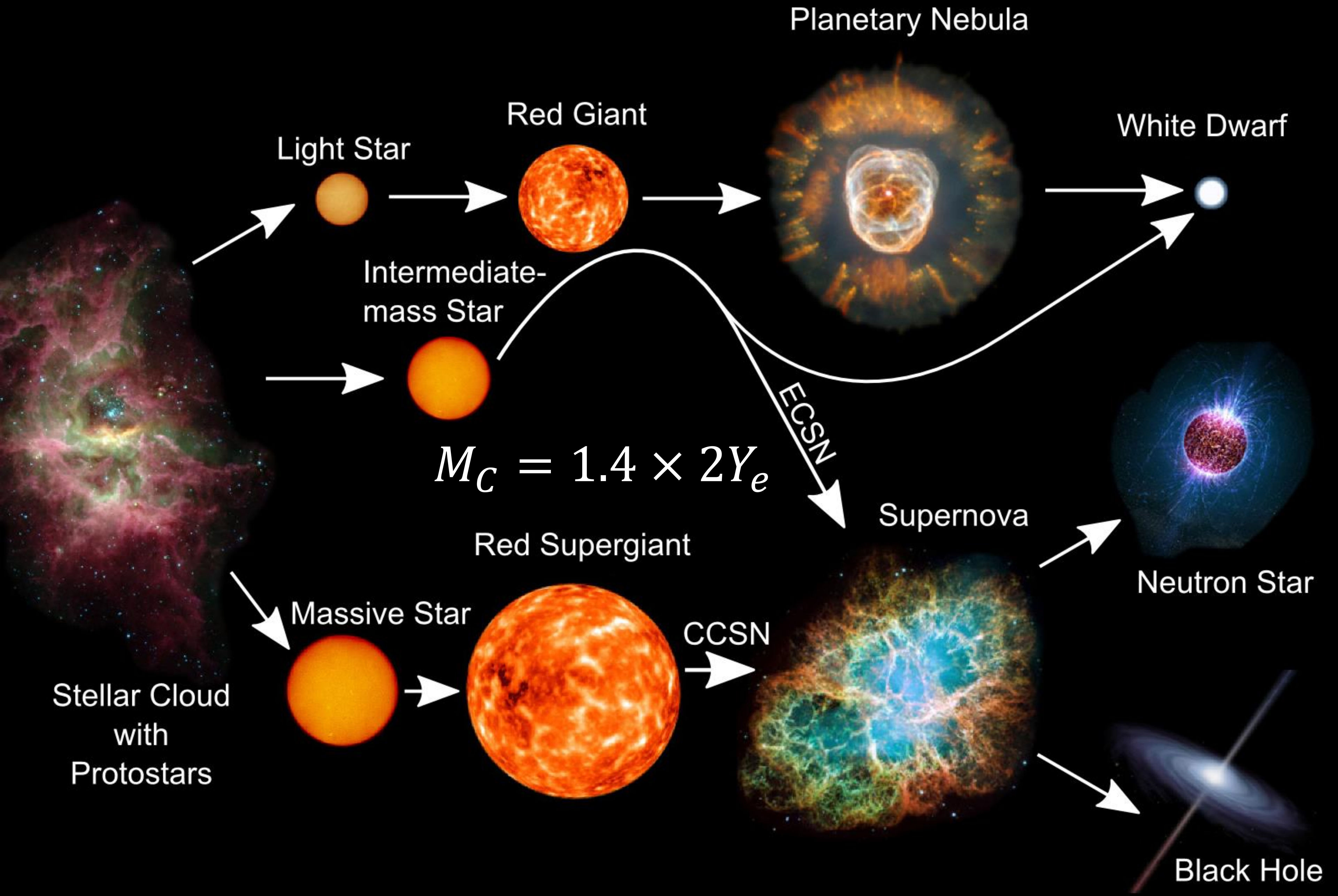
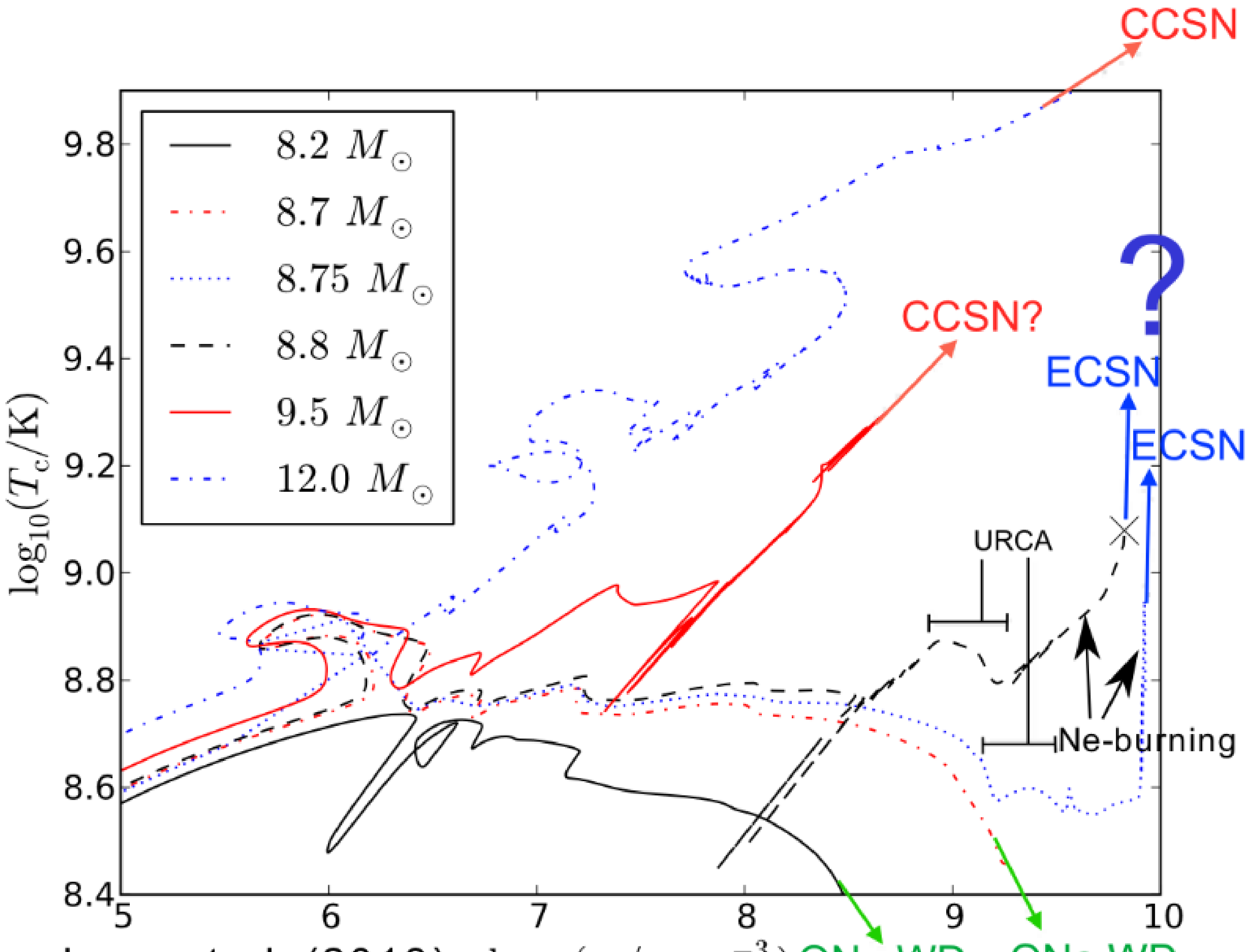

Planetary Nebula
Red Giant
Light Star
White Dwarf
Intermediate-
mass Star
ECSN
$M_C = 1.4 \times 2Y_e$
Supernova
Red Supergiant
Neutron Star
Massive Star
CCSN
Stellar Cloud
with
Protostars
Black Hole



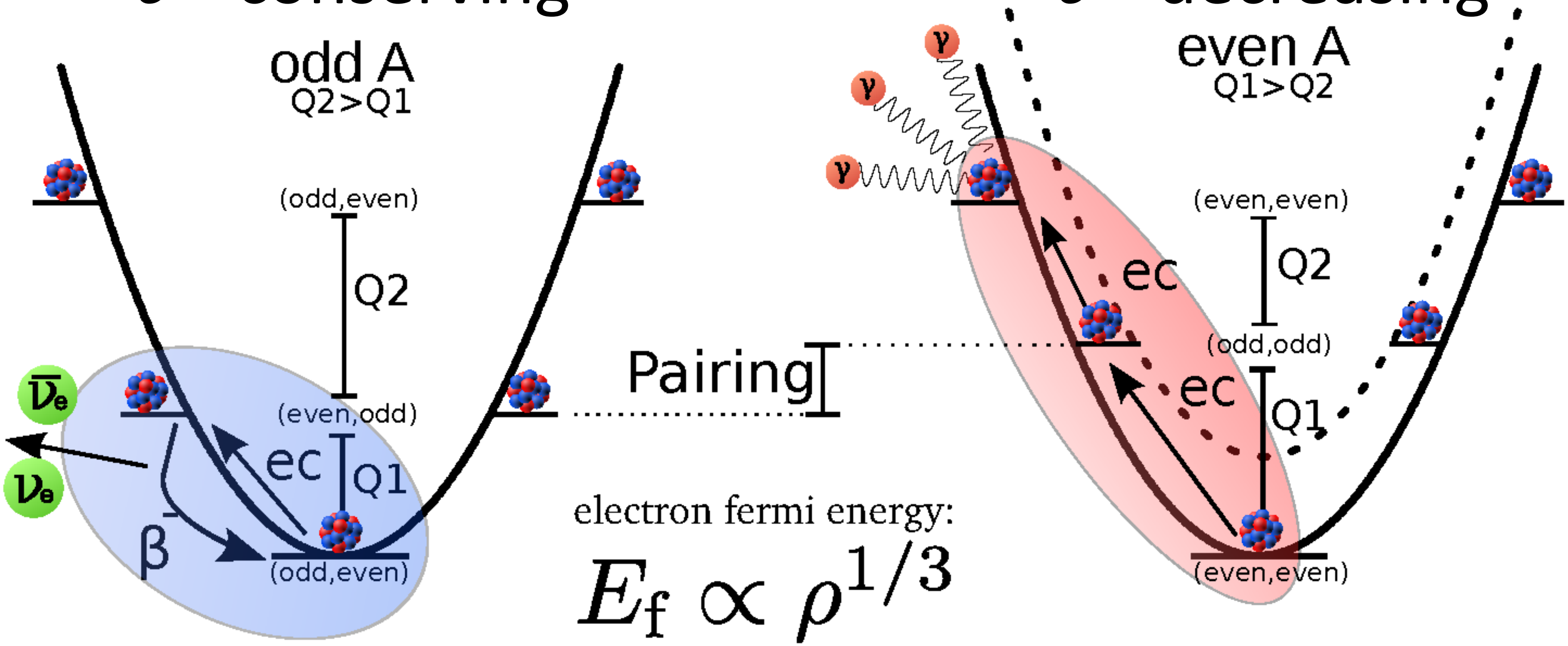
Jones et al. (2013)

$^{20}Ne\,(Q_{ec} = -7.5\ \mathrm{MeV})$

$^{24}Mg\,(Q_{ec} = -3.4\ \mathrm{MeV})$

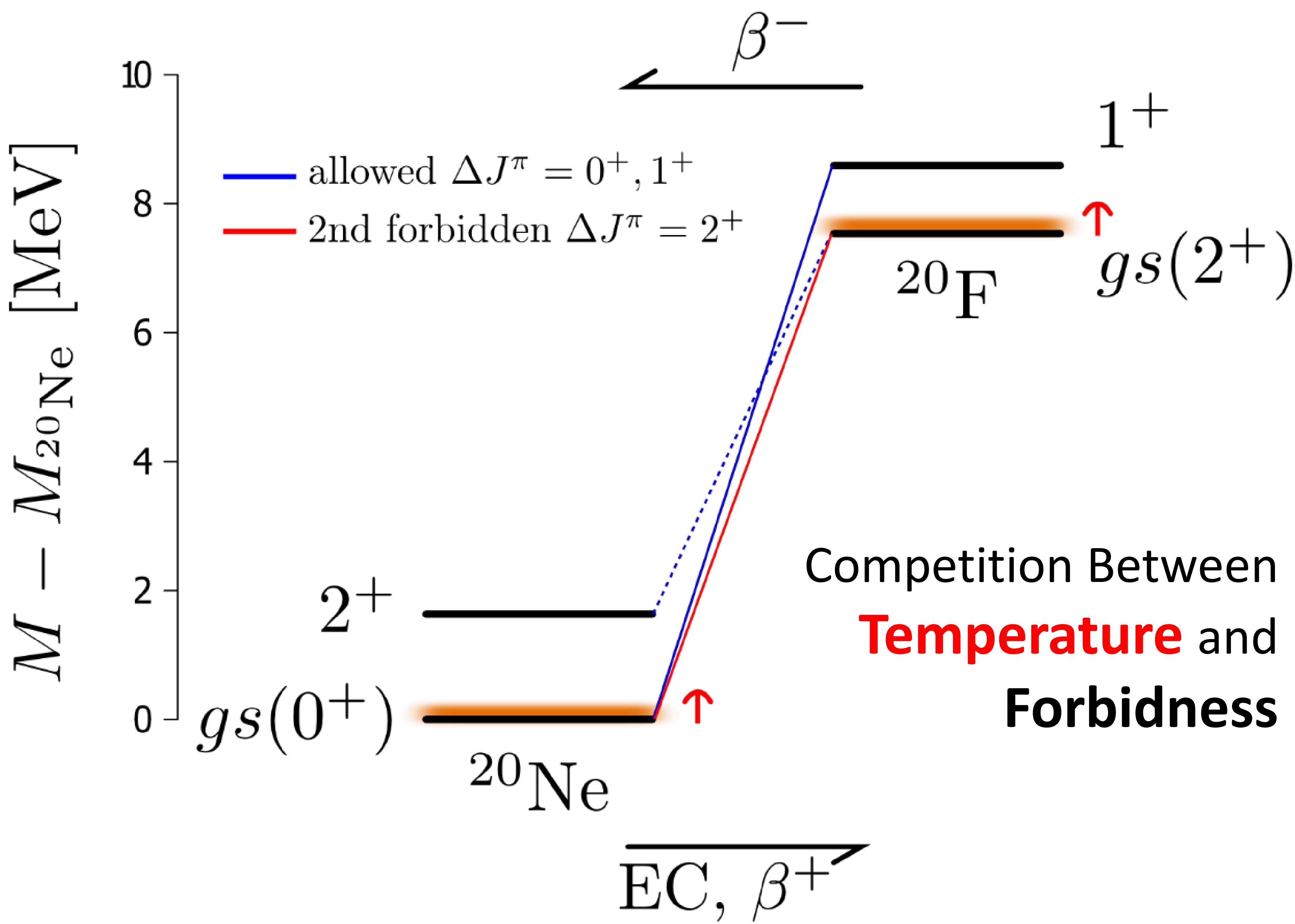
Urca **Cooling** | **Heating**

e^{-} conserving | e^{-} decreasing



$$(\mathrm{A,Z}) + e^{-} = (\mathrm{A,Z\text{-}1}) + \nu_e \qquad (\mathrm{A,Z}) + e^{-} = (\mathrm{A,Z\text{-}1}) + \nu_e$$

$$(\mathrm{A,Z\text{-}1}) = (\mathrm{A,Z}) + e^{-} + \bar{\nu}_e \qquad (\mathrm{A,Z\text{-}1}) + e^{-} = (\mathrm{A,Z\text{-}2})^{*} + \nu_e + \gamma$$



β^-
1^+
allowed $\Delta J^\pi = 0^+, 1^+$
2nd forbidden $\Delta J^\pi = 2^+$
$gs(2^+)$
^{20}F
$M - M_{^{20}\mathrm{Ne}}$ [MeV]
10
8
6
4
2
0
2^+
$gs(0^+)$
^{20}Ne
EC, β^+
Competition Between
Temperature and
Forbidness

Martinez-Pinedo et al. (2014)
PRC 89:045806

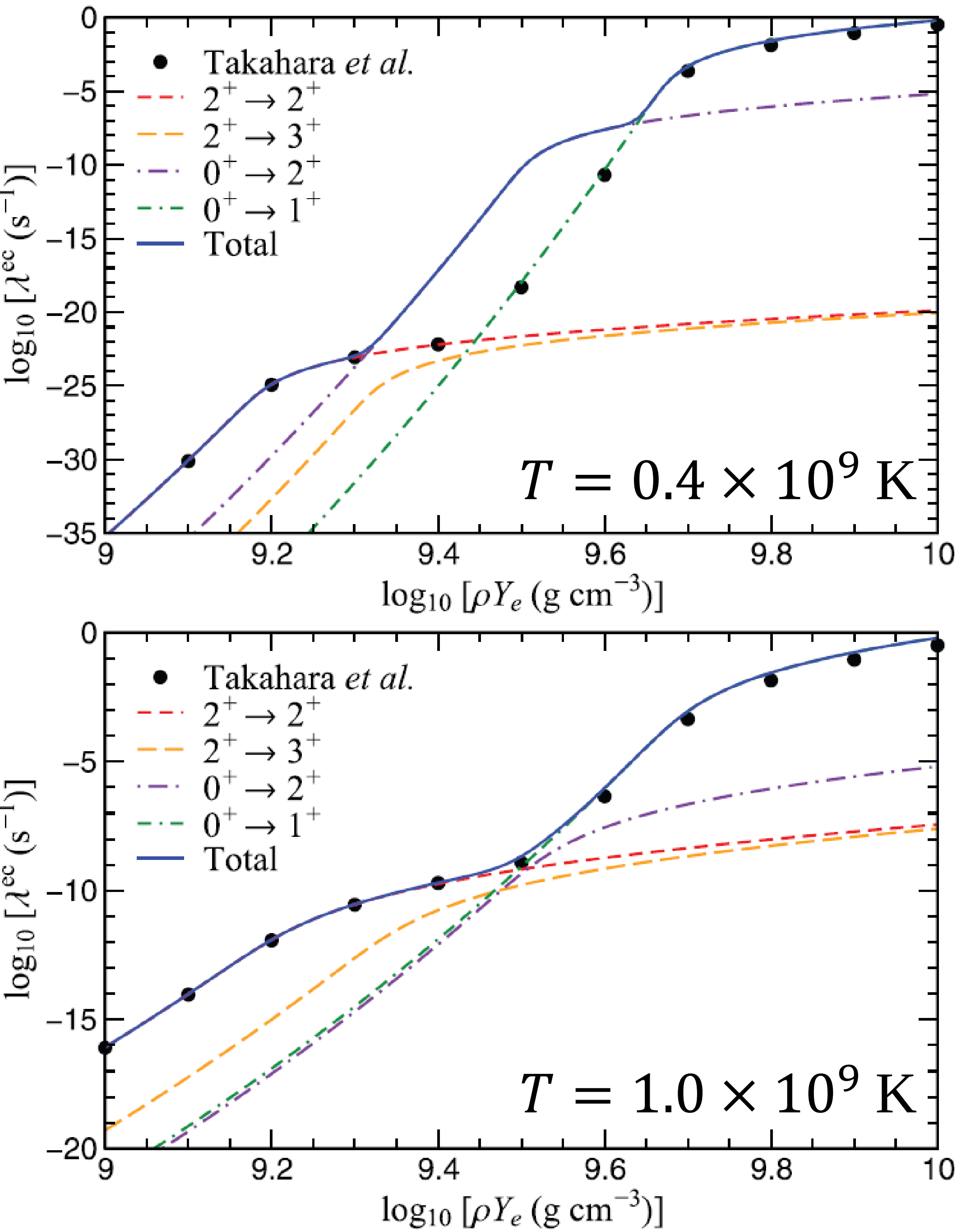
$BR \sim 1 \times 10^{-5}$

(exp. upper limit)

NPA 475, 1 ***(1987)***

Estimate needed!

(possibly experiment)



Shape Factor (Nuclear Physics)

Fermi Distribution (Statistical Description)

$$\lambda^{ec} = \frac{ln2}{K}\int_{|Q|}^{+\infty} E_\nu^2\, C(E)\, Ep\, f(E, kT, \mu)\, F(Z, E)\, dE$$

Kinematic

Fermi Function

$$C(E) \propto \sum \left| \langle f | H_\beta | i \rangle \right|^2$$

Combination of ↓

$$\vec{r}^{\,a},\ \vec{p}^{\,b}, \sigma, \tau$$

$|f, i\rangle$ USD-B Shell Model

$C = const$ (allowed)

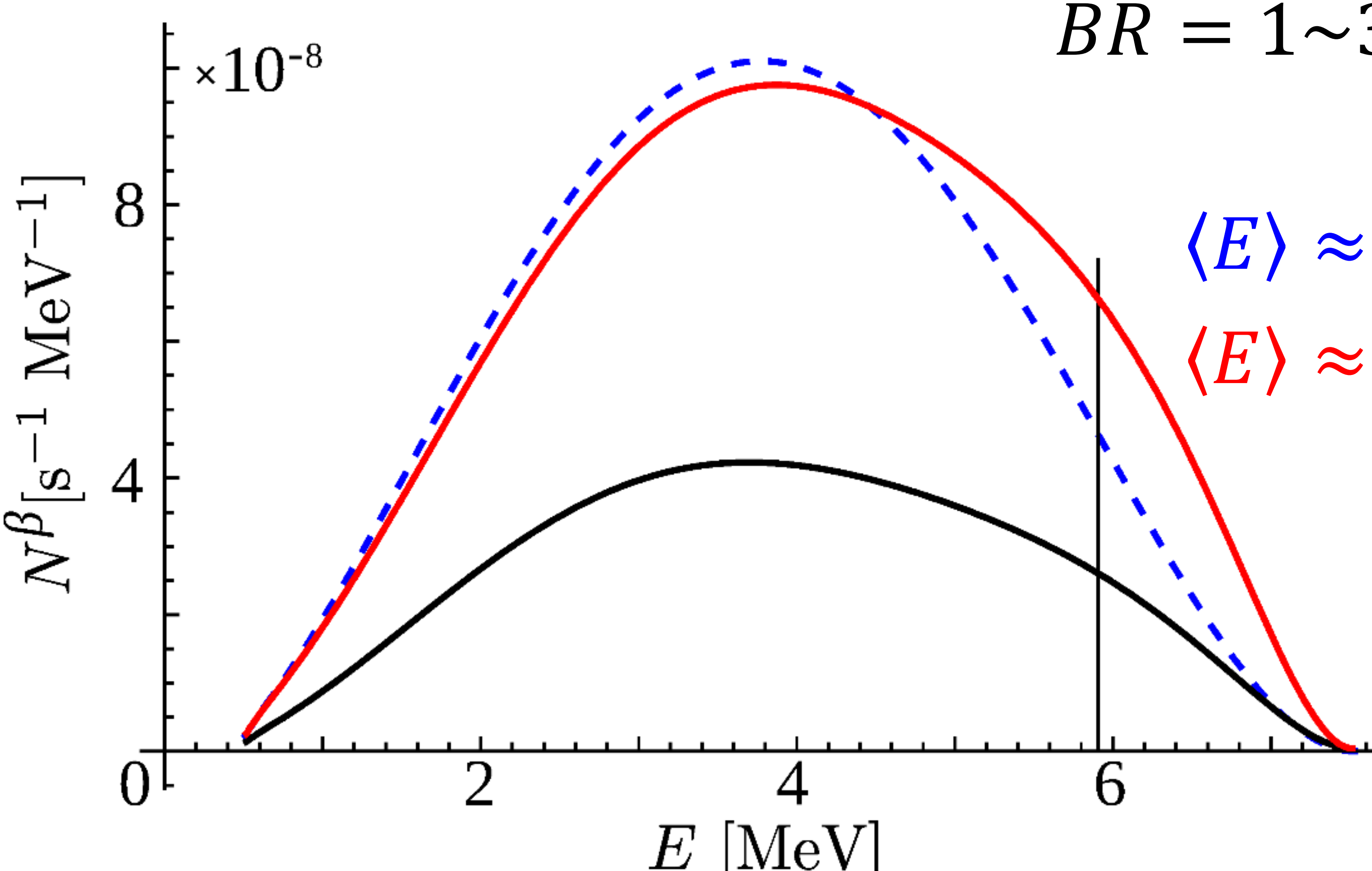
$C(E)$ (forbidden)

$C \sim E^4$ (2° forbidden)

$$\lambda^{\beta^-} = \frac{ln2}{K} \int_1^Q \underbrace{E_\nu^2 \, Ep \, C(E) F(Z,E) dE}_{\beta\text{-spectrum}}$$

$^{20}F(gs(2^+)) \rightarrow {}^{20}Ne(gs(0^+))$

$BR = 1 \sim 3 \times 10^{-6}$

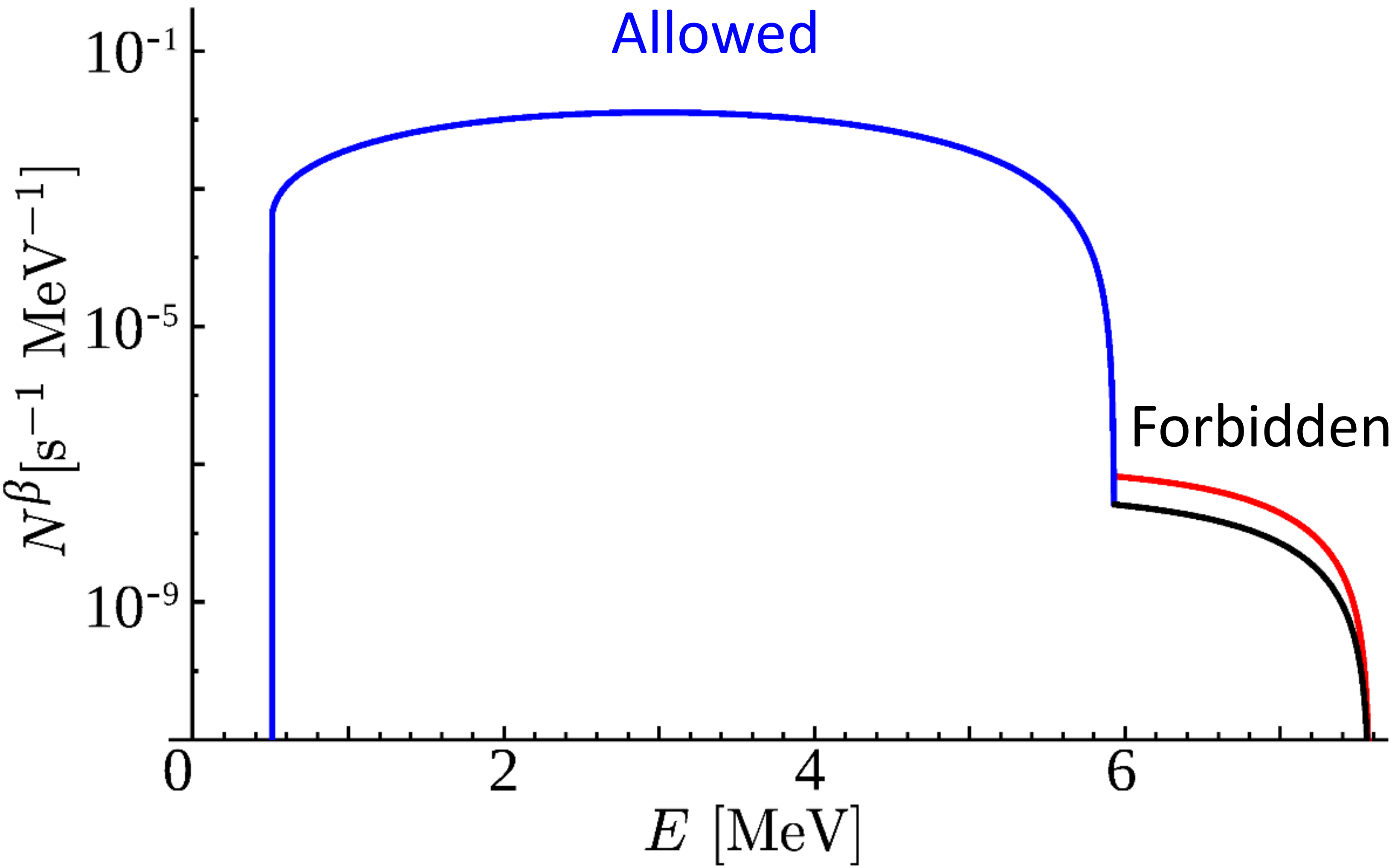


$\langle E \rangle \approx 3.8$ MeV

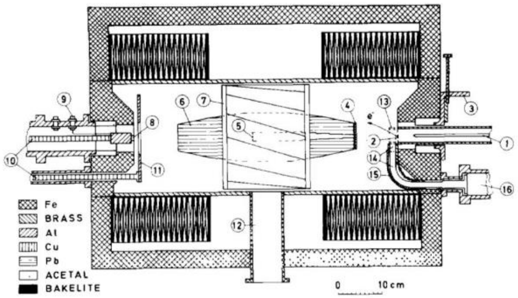
$\langle E \rangle \approx 4.0$ MeV

Total β-spectrum

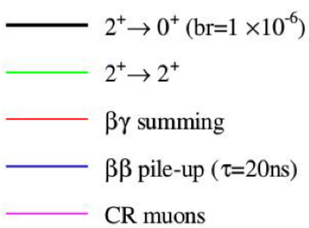
$^{20}F \rightarrow {}^{20}Ne$



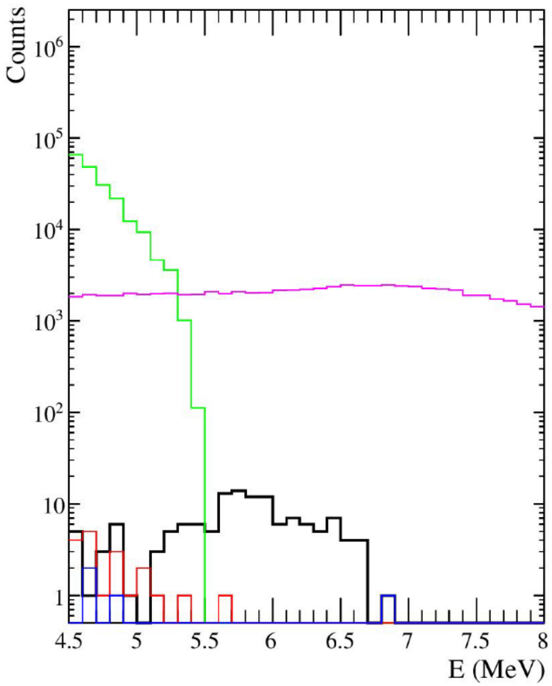
MARA Spectrometer
Jyväskylä



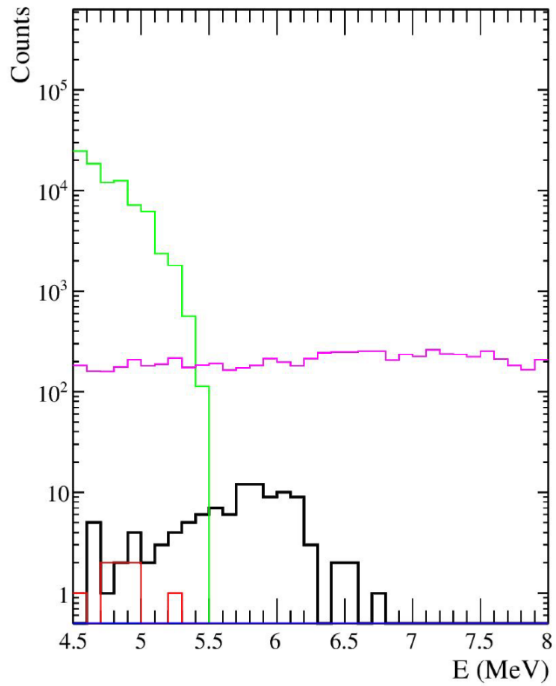
GEANT4 simulation (1 week @ 40 kHz)



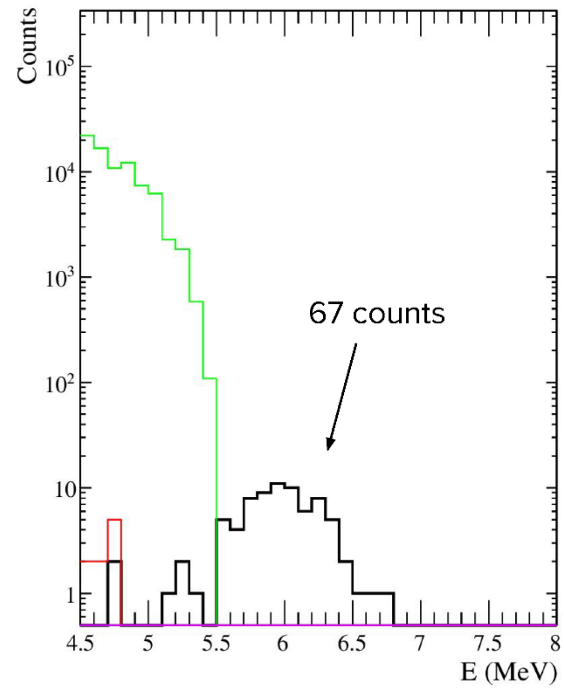
Single plastic detector



ΔE-E plastic telescope



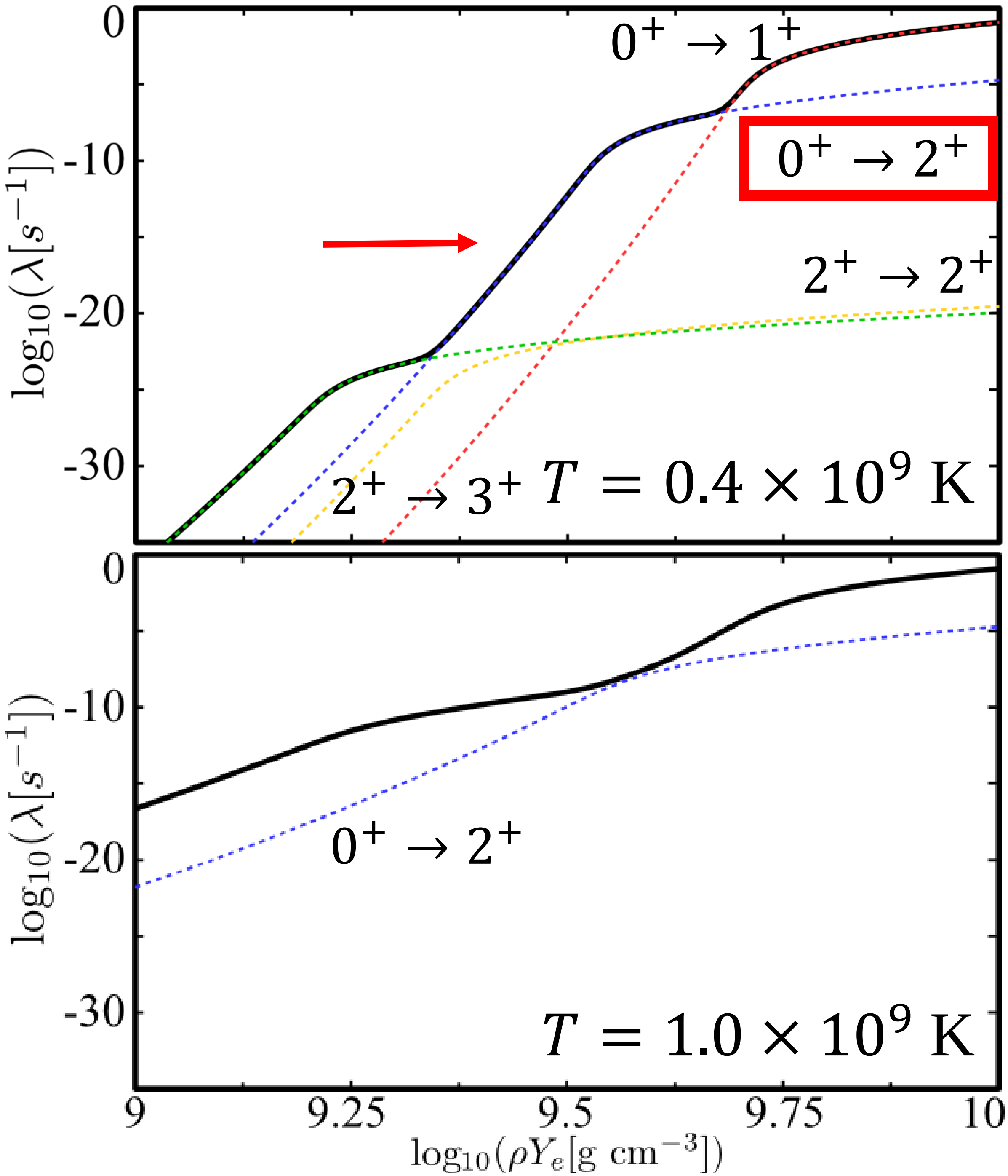
ΔE-E plastic telescope + μ veto



O. Kirsebom (2015)

e^- capture

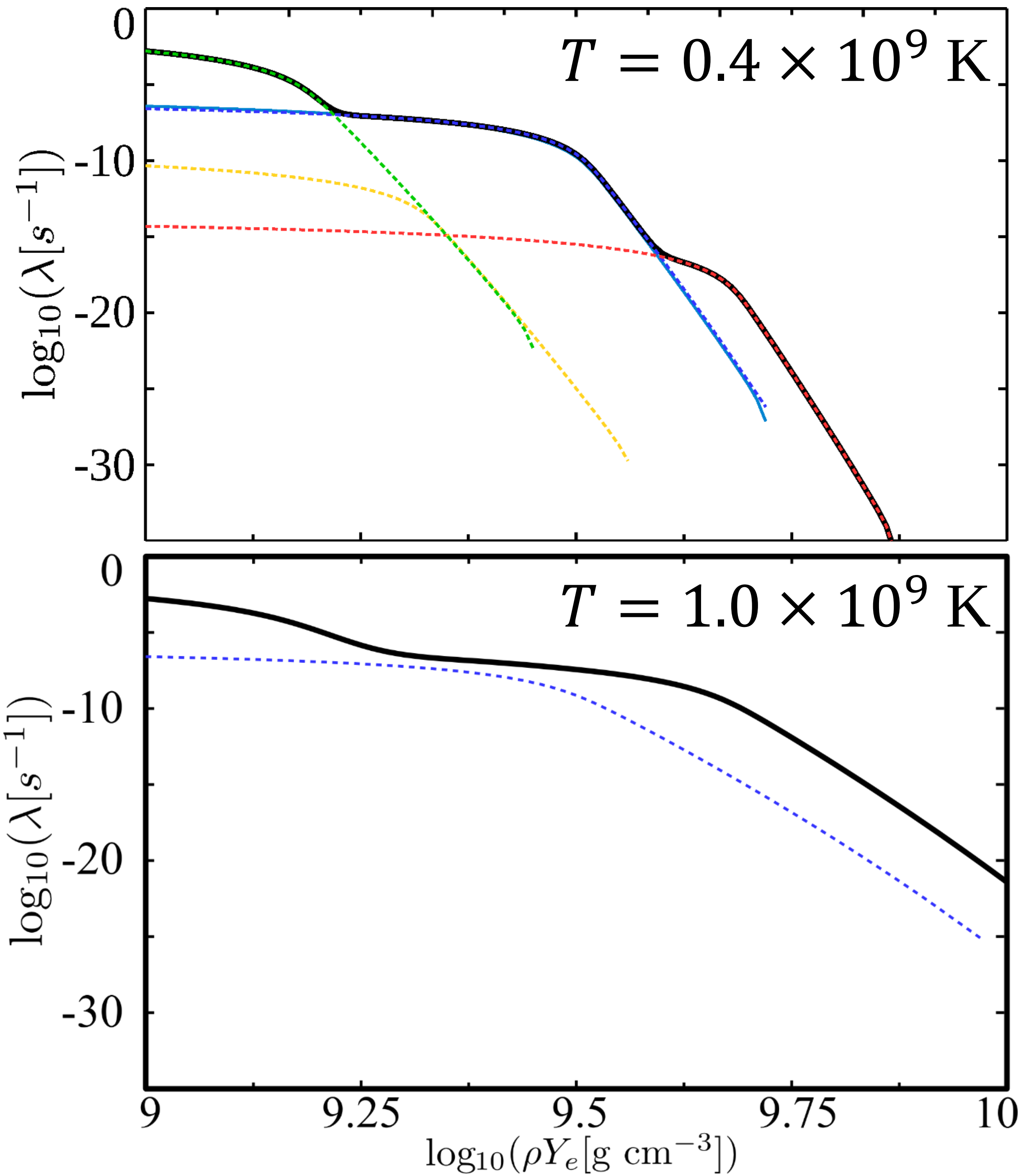
In Astrophysical Environment

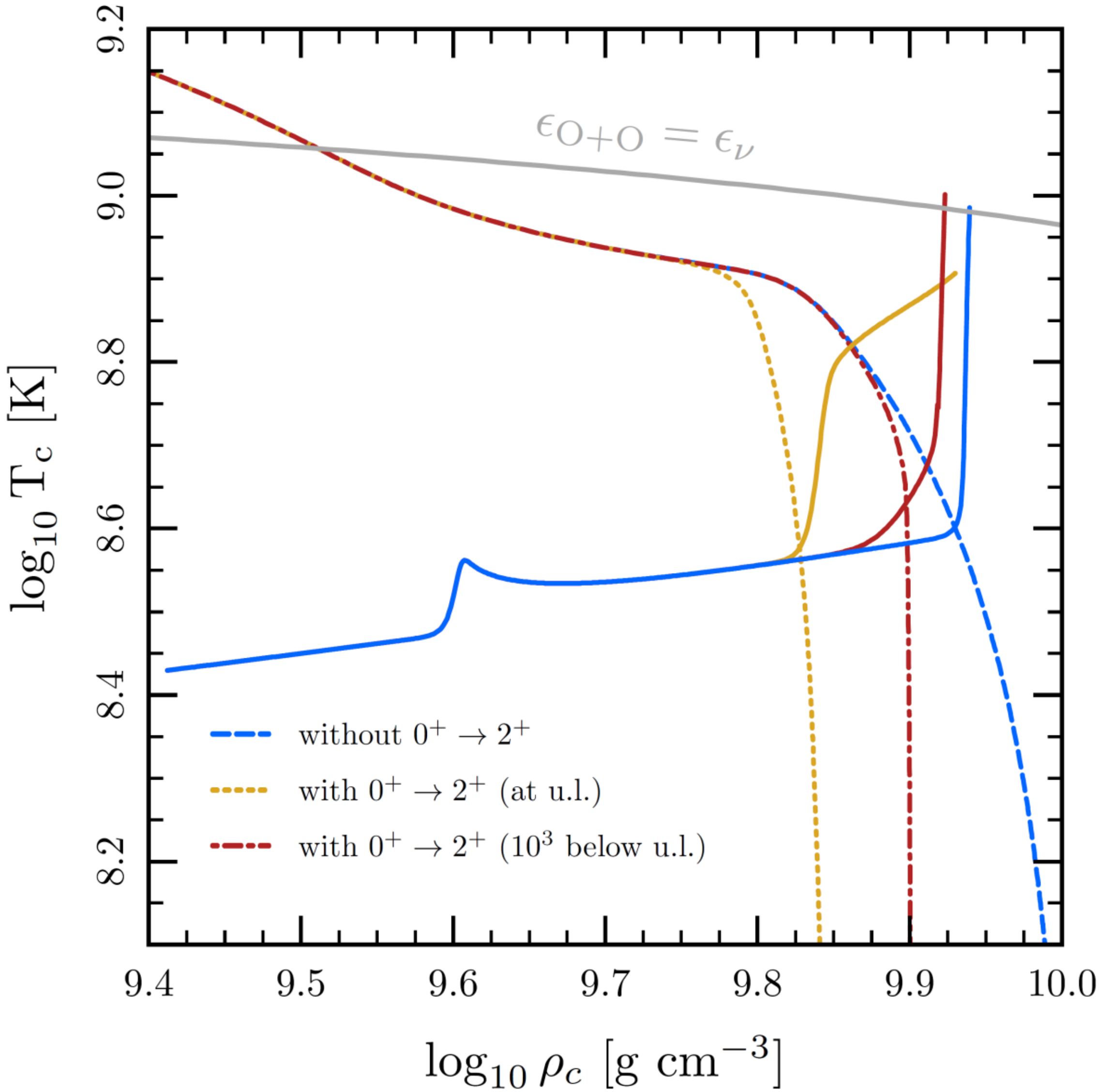


β^- decay

In Astrophysical Environment

$0^+ \rightarrow 2^+$
dominant until
$T \sim 0.7 \times 10^9$ K





Schwab et al., MNRAS 453, 1910–1927 (2015)

Intermediate mass stars are on the verge of electron capture supernovae or disrupting. Forbidden transitions play an unexpected central role in their fate.

Thank you

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For higher forbidden transitions, we have

$$M_L(k_x, k_\nu^{(1)}) = K_L(p_xR)^{k_x-1}(q_xR)^{k_\nu^{(1)}-1}\{-[(2L+1)/L]^{1/2}\,{}^VF^0_{LL-11} + (2k_x+1)^{-1/2}\alpha Z\,{}^VF^0_{LL0}(k_x,1,1,1)$$
$$+[(2k_x+1)^{-1}(2k_\nu^{(1)}+1)^{-1}q_xR]\,{}^VF^0_{LL0} - (2k_x+1)^{-1}\alpha Z[(L+1)/L]^{1/2}\,{}^AF^0_{LL1}(k_x,1,1,1)$$
$$-[(2k_x+1)^{-1}W_xR + (2k_\nu^{(1)}+1)^{-1}q_xR][(L+1)/L]^{1/2}\,{}^AF^0_{LL1}\}, \qquad (2.106a)$$

$$m_L(k_x, k_\nu^{(1)}) = K_L(p_xR)^{k_x-1}(q_xR)^{k_\nu^{(1)}-1}(2k_x+1)^{-1}R\{{}^VF^0_{LL0} - [(L+1)/L]^{1/2}\,{}^AF^0_{LL1}\}, \qquad (2.106b)$$

$$M_L(k_x, k_\nu^{(2)}) = -\tilde{K}_L(p_xR)^{k_x-1}(q_xR)^{k_\nu^{(2)}-1}(L+1)^{1/2}[(2k_x-1)(2k_\nu^{(2)}-1)]^{-1/2}\{{}^VF^0_{LL0} + (k_x-k_\nu^{(2)})(L+1)^{-1}[(L+1)/L]^{1/2}\,{}^AF^0_{LL1}\}, \qquad (2.106c)$$

$$M_{L+1}(k_x, k_\nu^{(2)}) = -\tilde{K}_L(p_xR)^{k_x-1}(q_xR)^{k_\nu^{(2)}-1}\,{}^AF^0_{(L+1)L1}. \qquad (2.106d)$$

$$ {}^{V}\mathfrak{M}^{N}_{KK0}(k_x, m, n, \rho) = \sqrt{2}(2J_i+1)^{-1/2}\Big\{ G_{KK0}(\kappa_f, \kappa_i) \int_0^\infty g_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{K+2N} I(k_x, m, n, \rho; r) g_i(r, \kappa_i) r^2\, dr $$

$$ + \operatorname{sign}(\kappa_f)\operatorname{sign}(\kappa_i) G_{KK0}(-\kappa_f, -\kappa_i) \int_0^\infty f_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{K+2N} I(k_x, m, n, \rho; r) f_i(r, \kappa_i) r^2\, dr \Big\}, \tag{2.84a} $$

$$ {}^{A}\mathfrak{M}^{N}_{KL1}(k_x, m, n, \rho) = \sqrt{2}(2J_i+1)^{-1/2}\Big\{ G_{KL1}(\kappa_f, \kappa_i) \int_0^\infty g_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{L+2N} I(k_x, m, n, \rho; r) g_i(r, \kappa_i) r^2\, dr $$

$$ + \operatorname{sign}(\kappa_f)\operatorname{sign}(\kappa_i) G_{KL1}(-\kappa_f, -\kappa_i) \int_0^\infty f_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{L+2N} I(k_x, m, n, \rho; r) f_i(r, \kappa_i) r^2\, dr \Big\}, \tag{2.84b} $$

$$ {}^{A}\mathfrak{M}^{N}_{KK0}(k_x, m, n, \rho) = \sqrt{2}(2J_i+1)^{-1/2}\Big\{ \operatorname{sign}(\kappa_i) G_{KK0}(\kappa_f, -\kappa_i) \int_0^\infty g_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{K+2N} I(k_x, m, n, \rho; r) f_i(r, \kappa_i) r^2\, dr $$

$$ + \operatorname{sign}(\kappa_f) G_{KK0}(-\kappa_f, \kappa_i) \int_0^\infty f_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{K+2N} I(k_x, m, n, \rho; r) g_i(r, \kappa_i) r^2\, dr \Big\}, \tag{2.84c} $$

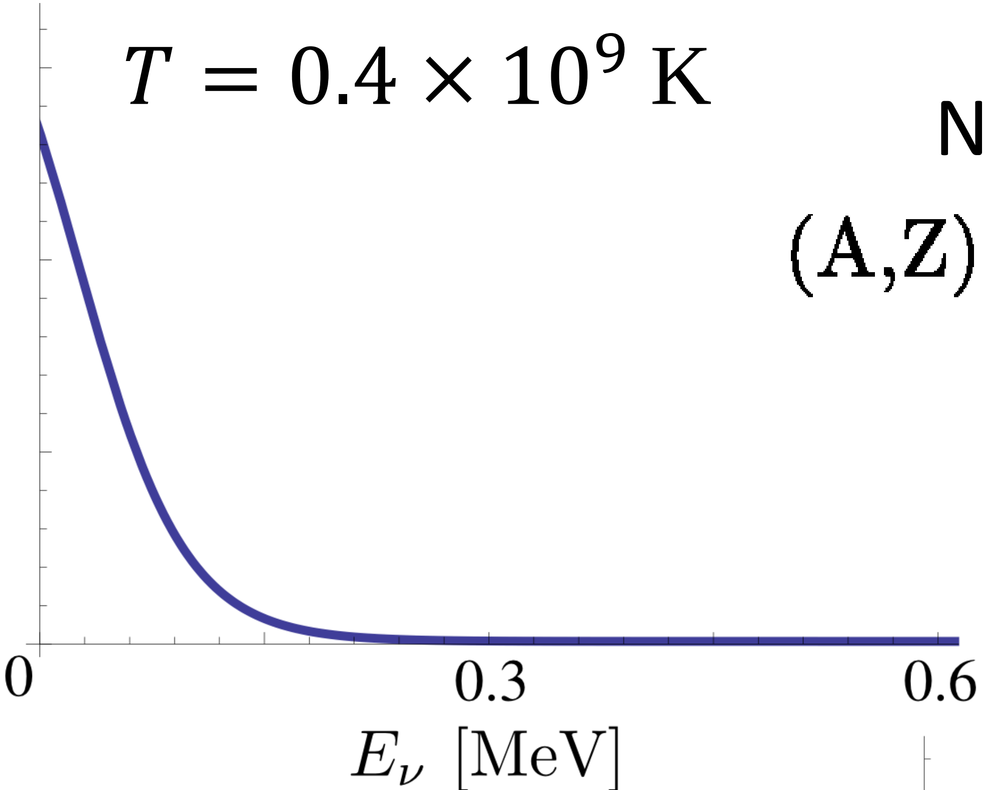
$$ {}^{V}\mathfrak{M}^{N}_{KL1}(k_x, m, n, \rho) = \sqrt{2}(2J_i+1)^{-1/2}\Big\{ \operatorname{sign}(\kappa_i) G_{KL1}(\kappa_f, -\kappa_i) \int_0^\infty g_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{L+2N} I(k_x, m, n, \rho; r) f_i(r, \kappa_i) r^2\, dr $$

$$ + \operatorname{sign}(\kappa_f) G_{KL1}(-\kappa_f, \kappa_i) \int_0^\infty f_f(r, \kappa_f)\Big(\frac{r}{R}\Big)^{L+2N} I(k_x, m, n, \rho; r) g_i(r, \kappa_i) r^2\, dr \Big\}. \tag{2.84d} $$

Neutrino EC-Spectrum

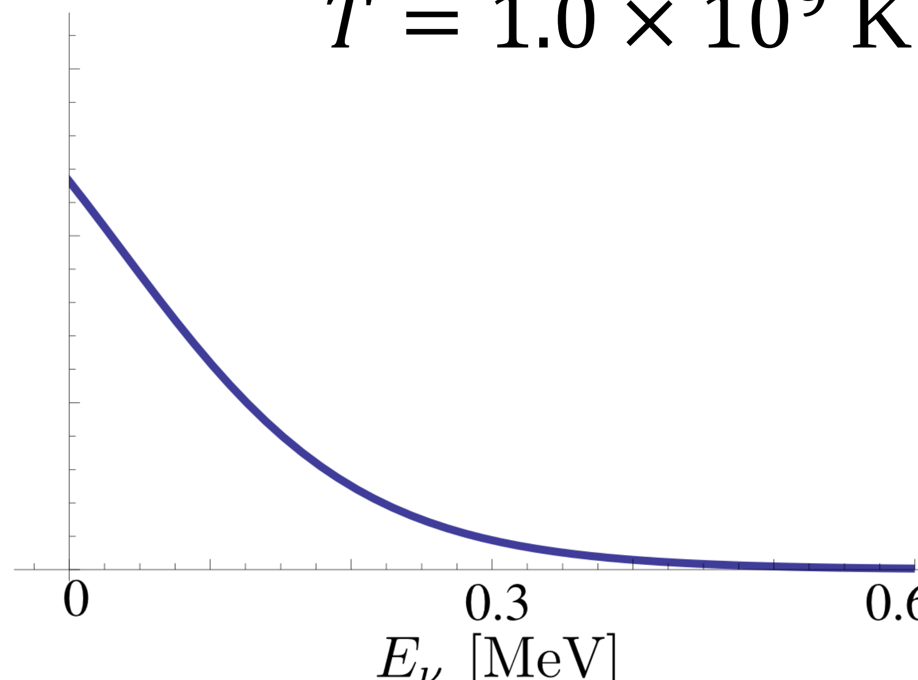
$$(\mathrm{A,Z}) + e^- = (\mathrm{A,Z\text{-}1}) + \nu_e$$

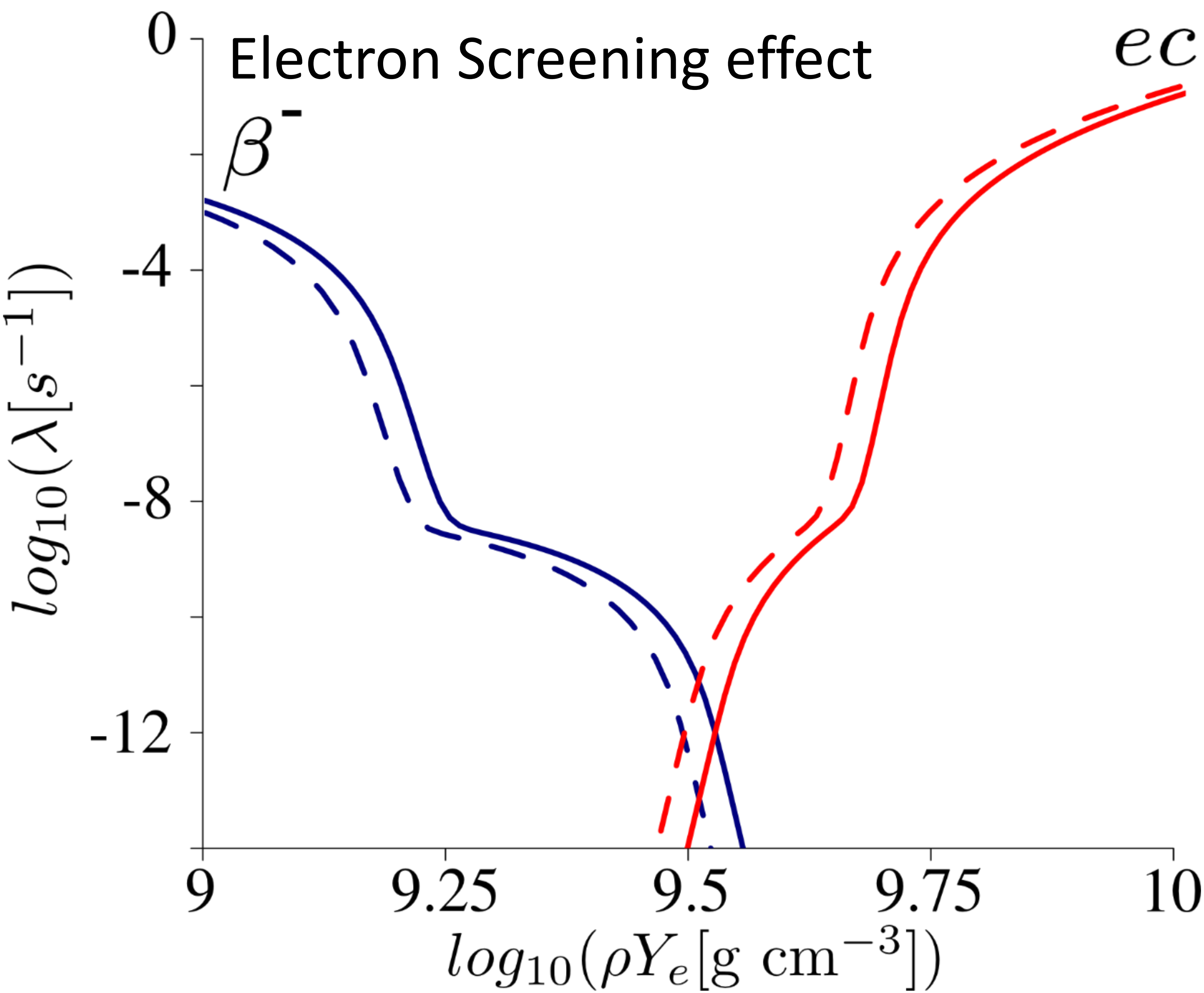
$T = 0.4 \times 10^9$ K



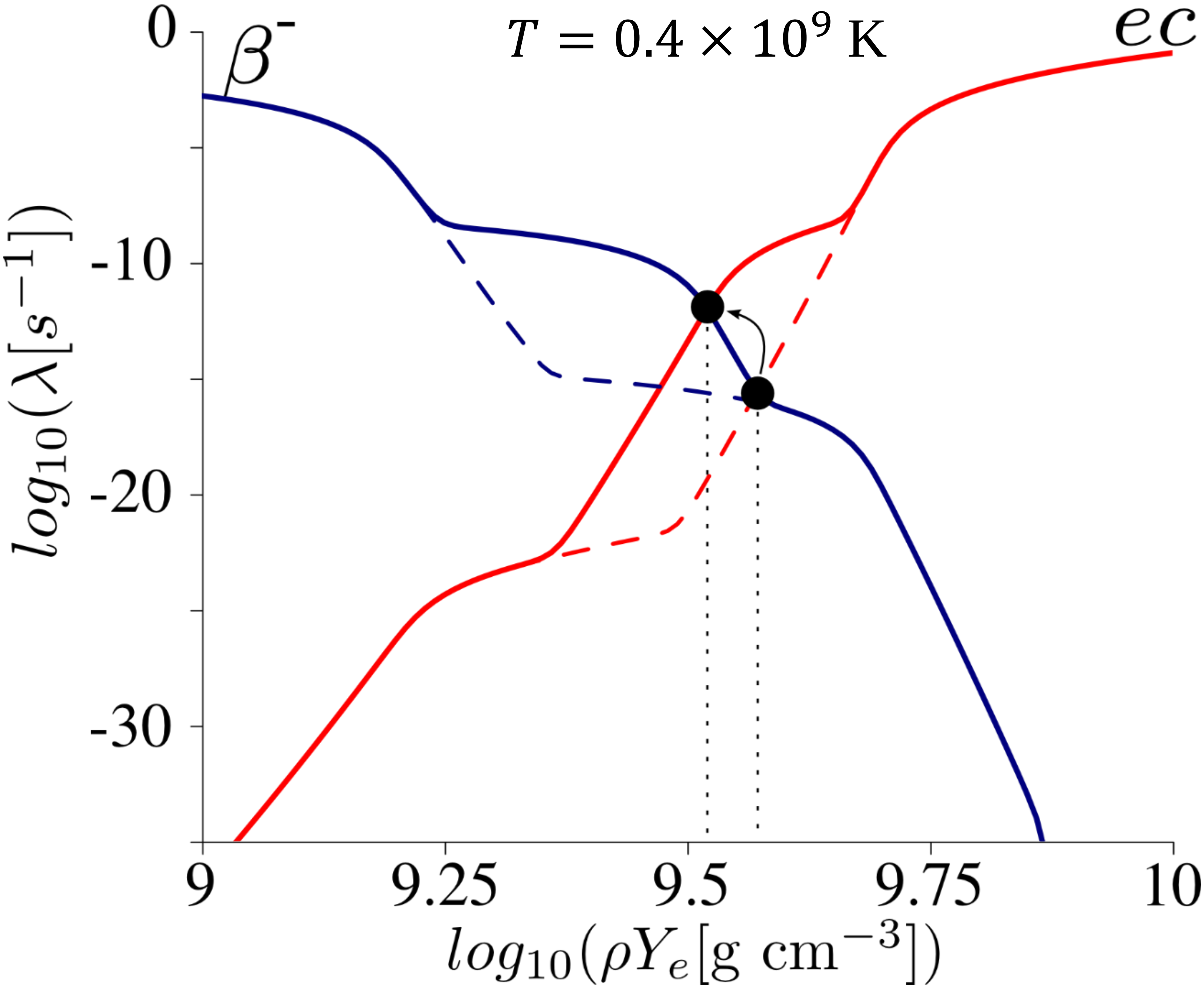
$\rho Y_e = 10^{9.5} g/cm^3$

$T = 1.0 \times 10^9$ K





Electron Screening effect
β^-
ec
0
-4
-8
-12
9
9.25
9.5
9.75
10
$log_{10}(\lambda[s^{-1}])$
$log_{10}(\rho Y_e[\mathrm{g\ cm^{-3}}])$



β^-
$T = 0.4 \times 10^9$ K
ec
0
-10
-20
-30
$log_{10}(\lambda[s^{-1}])$
9
9.25
9.5
9.75
10
$log_{10}(\rho Y_e[\mathrm{g\ cm^{-3}}])$

R. Julin *et al.*, "A setup for spectrometry of high-energy conversion electrons", Nucl. Instr. Meth. A 270 (1988) 74

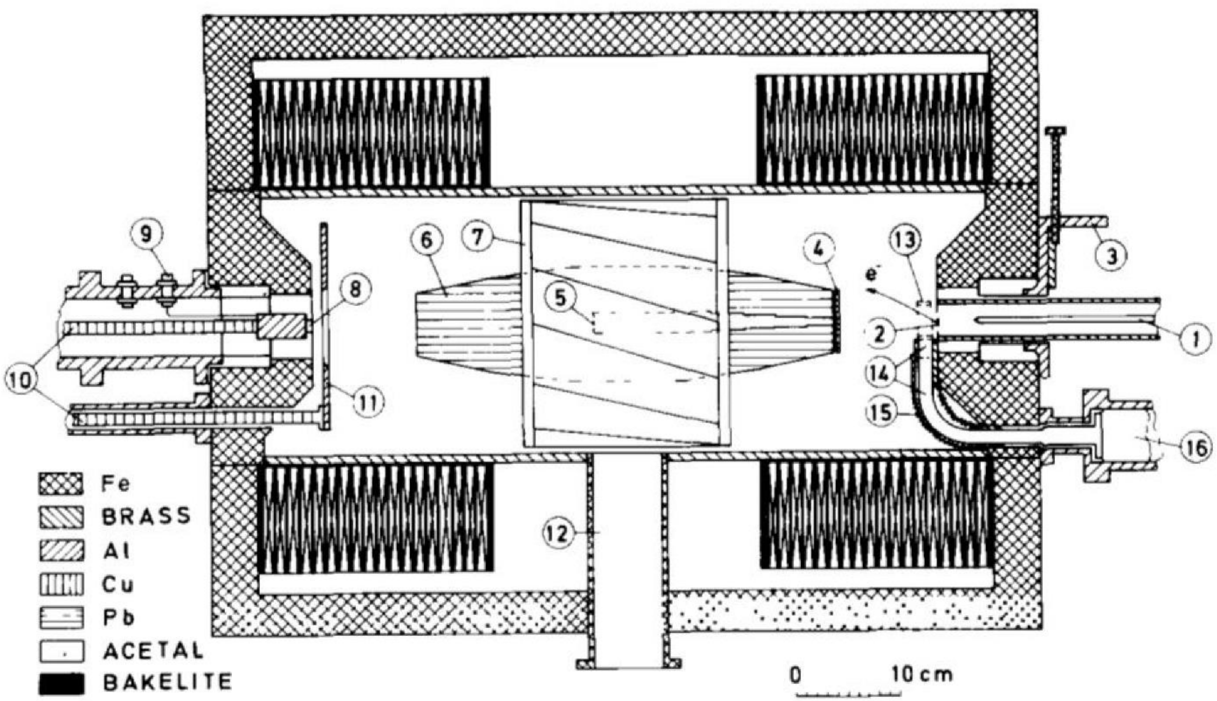


Fig. 1. Magnetic + semiconductor detector conversion-electron spectrometer based on an "old" Siegbahn–Slätis magnet used as the electron transporter: (1) beam, (2) target, (3) target-changing system, (4) collimator and current measurement, (5) Faraday cup, (6) lead shield, (7) antipositron baffle, (8) detector, (9) feedthrough, (10) coldfingers, (11) coldtrap, (12) to pump, (13) cylindrical plastic scintillator, (14) light guide, (15) bellows reflector, (16) PM tube.

Courtesy of O. Kirsebom