Observation of the ground-state transition in the β decay of ^{20}F

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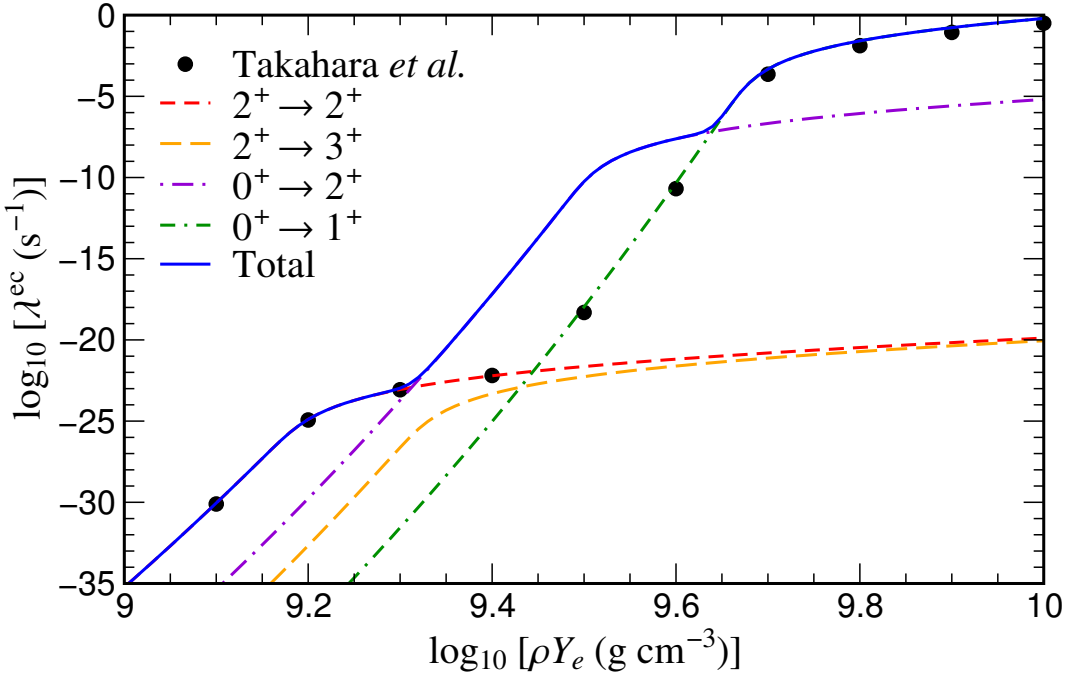
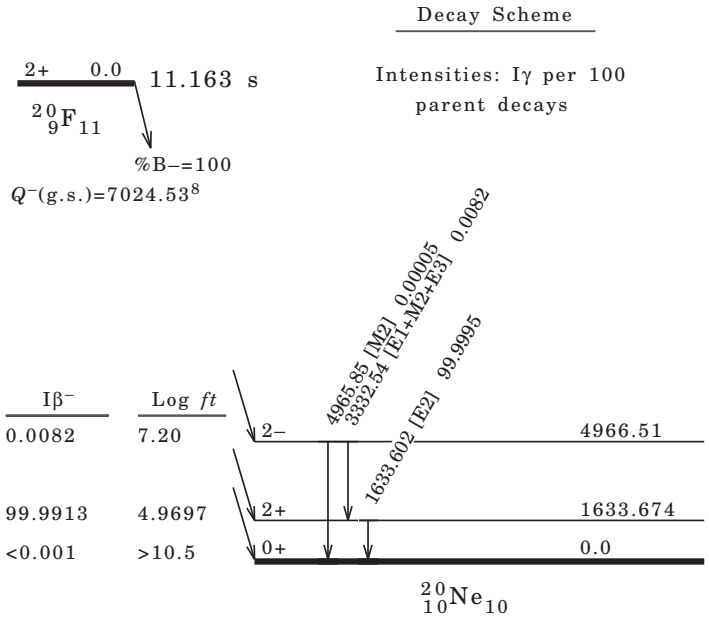
Astrophysical motivation





▸ Martínez-Pinedo *et al.* PRC 89, 045806 (2014)

What is the ultimate fate of medium-mass stars?

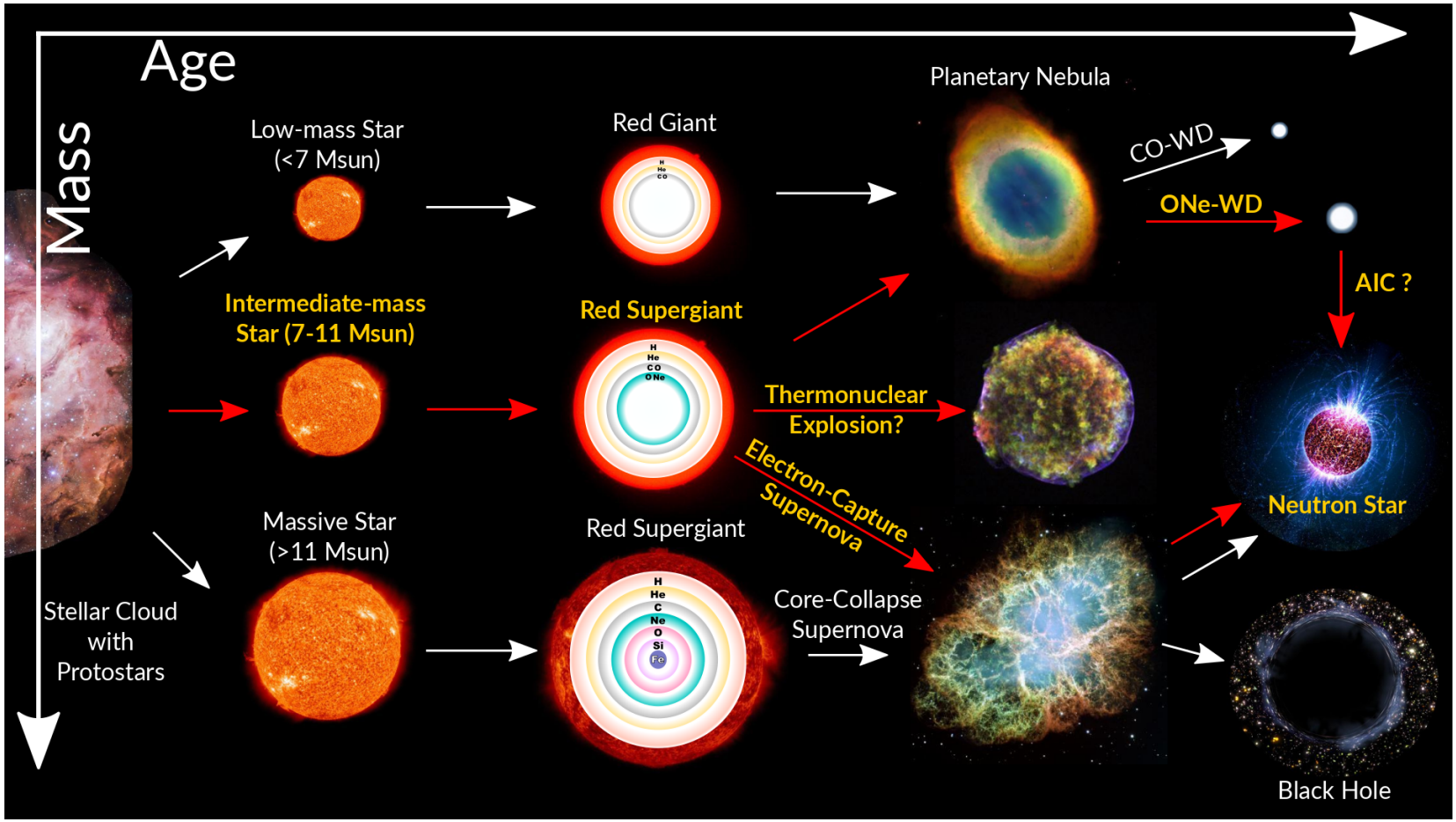


Image credit: H. Möller

Electron-capture supernovae (EC-SN)

A dim core-collapse supernova

- Low explosion energy
  (10^{50} erg vs. 10^{51} erg)
- Low ^{56}Ni yield
  ($1\text{–}3 \times 10^{-3} M_\odot$ vs. $5 \times 10^{-2} M_\odot$)

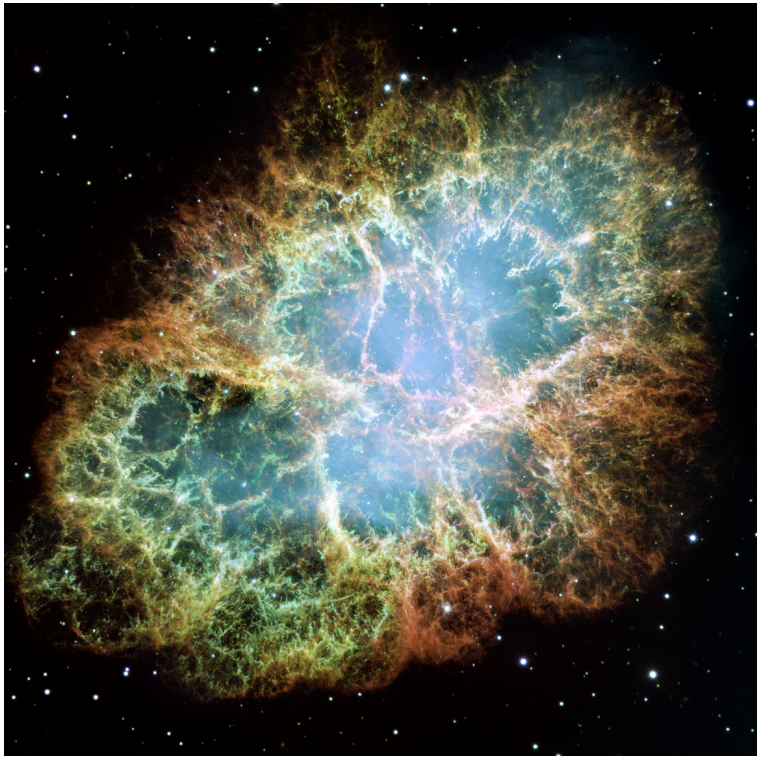
Could accout for 4–30% of all supernovae in the local universe

- May have created the Crab Nebula
  - Tominaga *et al.* ApJ 771:L12 (2013)

Could make a significant contribution to Galactic chemical evolution

- Efficient producers of ^{60}Fe
  - Wanajo *et al.* ApJ 774:L6 (2013)

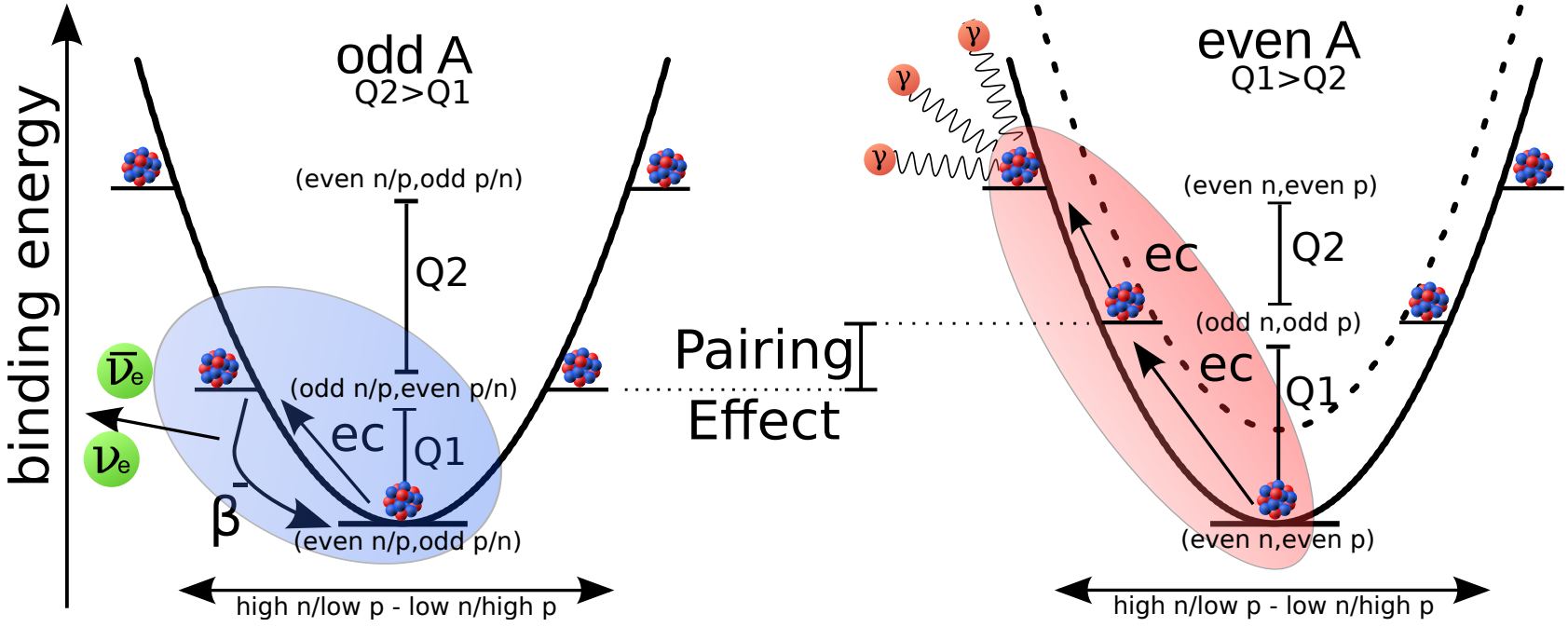
The Crab nebula



Remnant of supernova observed in 1054.

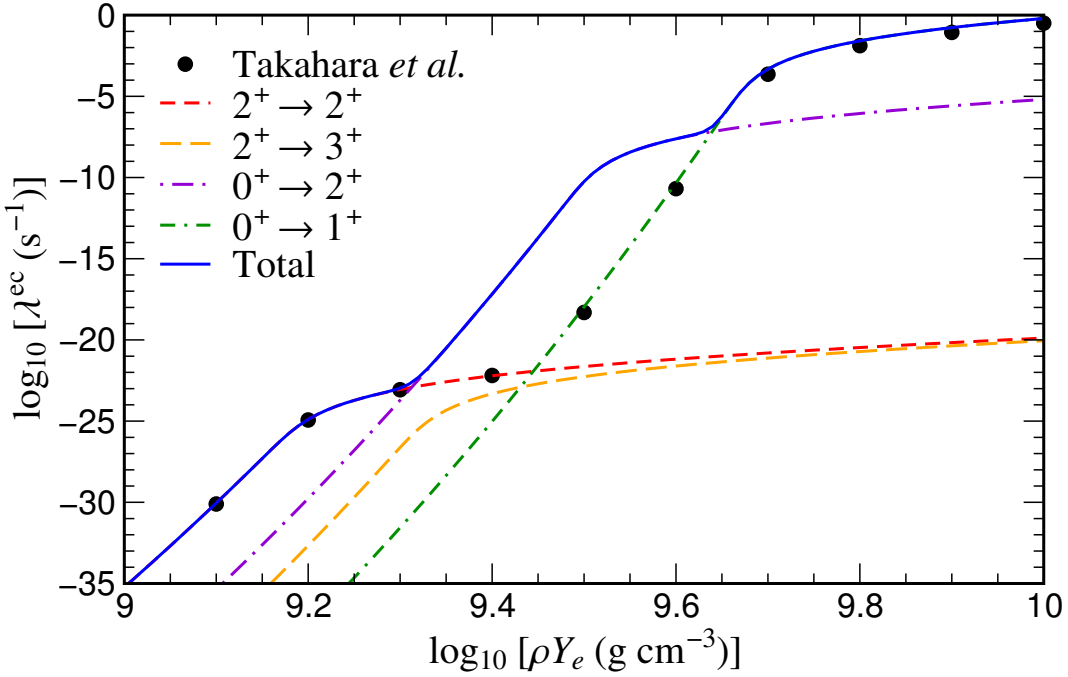
The role of EC reactions

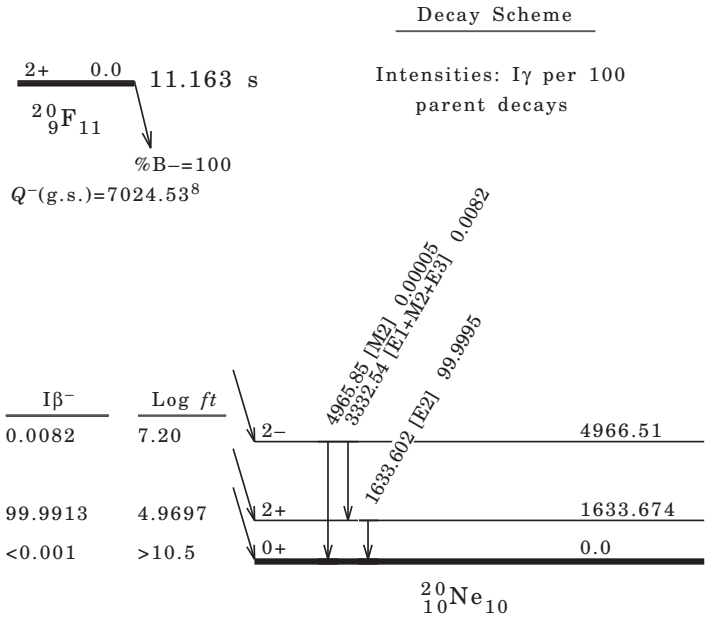
Fermi energy: $E_F \propto \rho^{1/3}$



▸ Möller *et al.* PoS(NIC XIII)125 (2014)

The EC rate on ^{20}Ne





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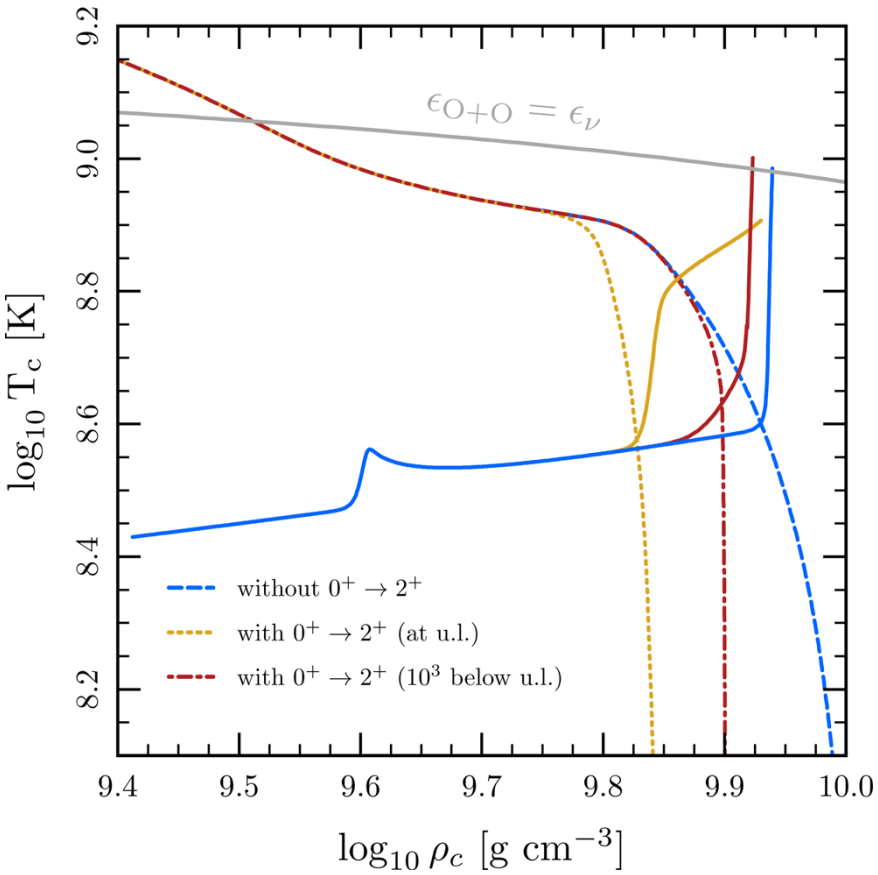
The importance of the $0^+ \rightarrow 2^+$ transition



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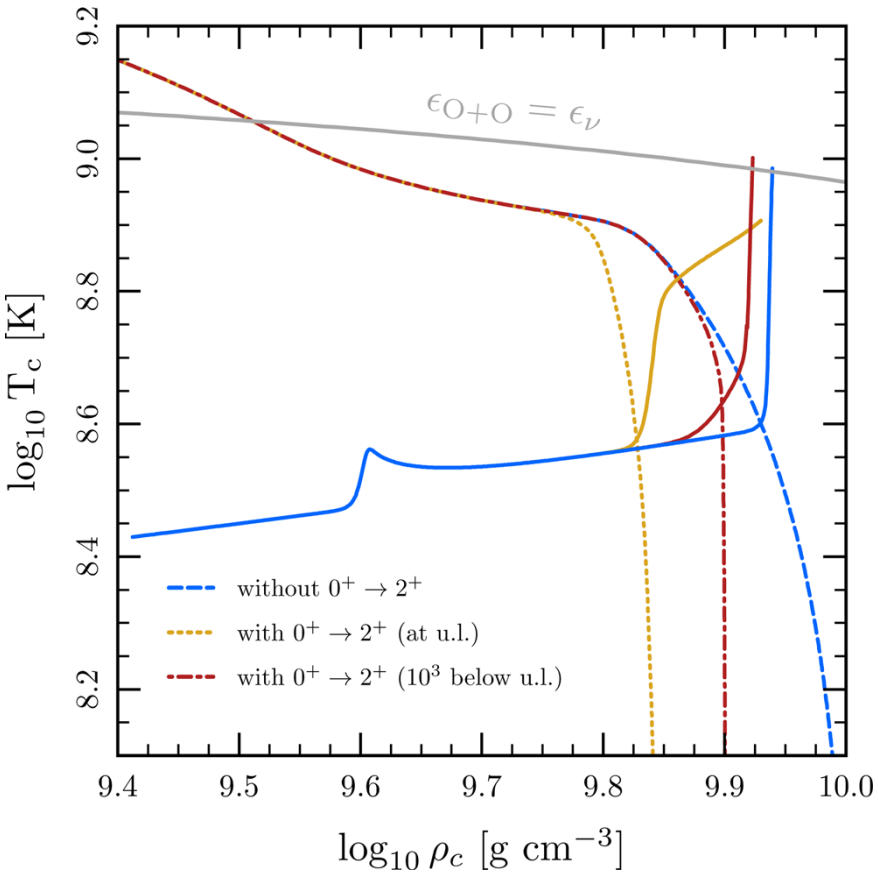

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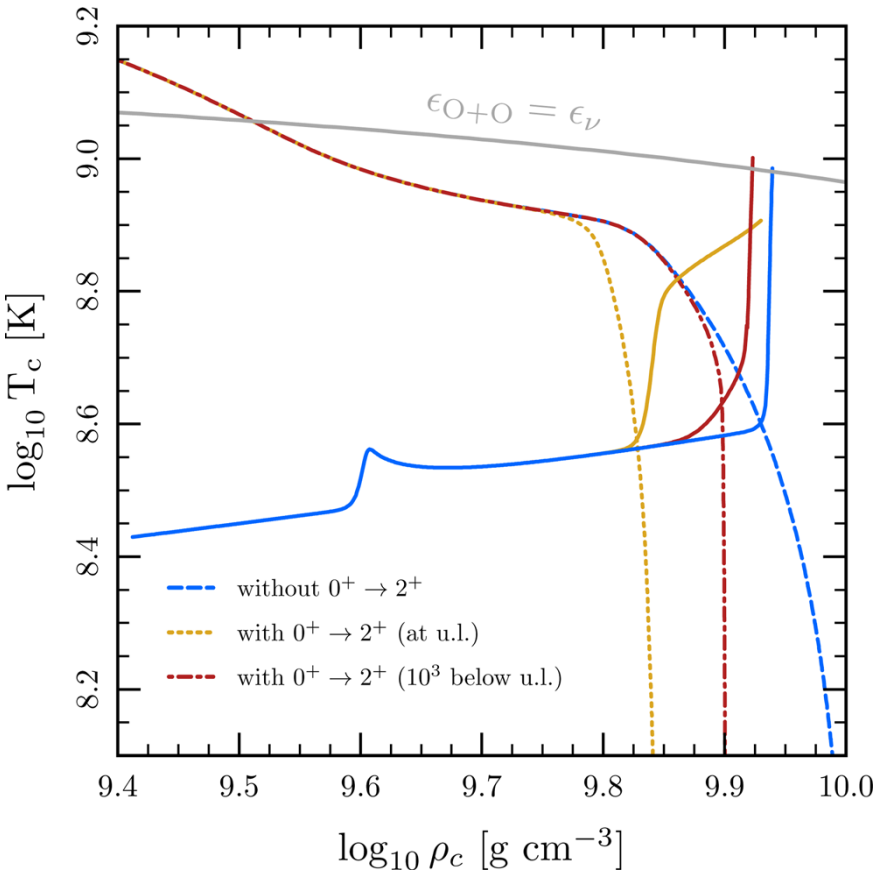

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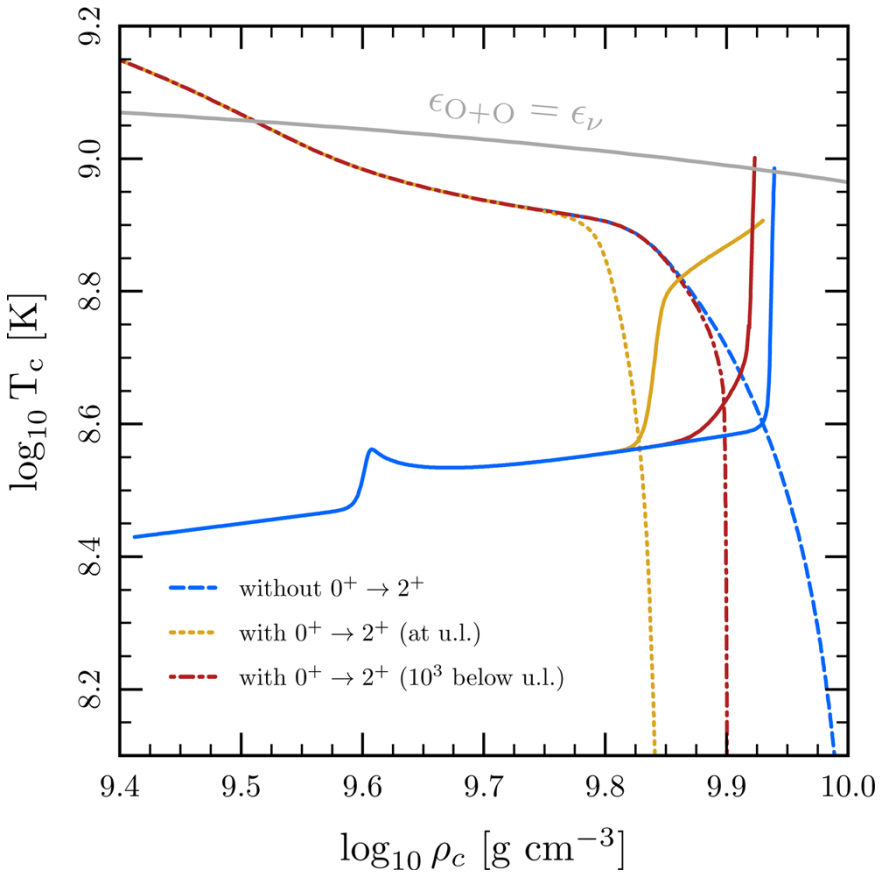

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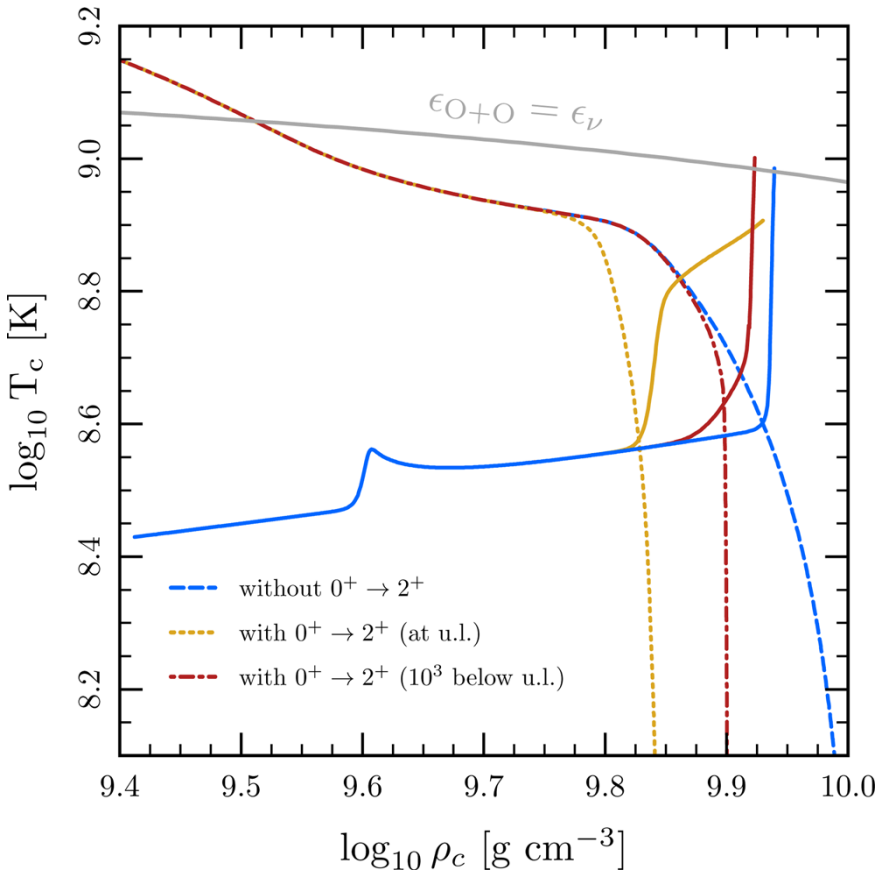

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- Energy release from the wave competes against energy loss from electron captures on ashes
- 3D hydrodynamical simulations:

  ▸ Jones *et al.* A&A 593, A72 (2016)

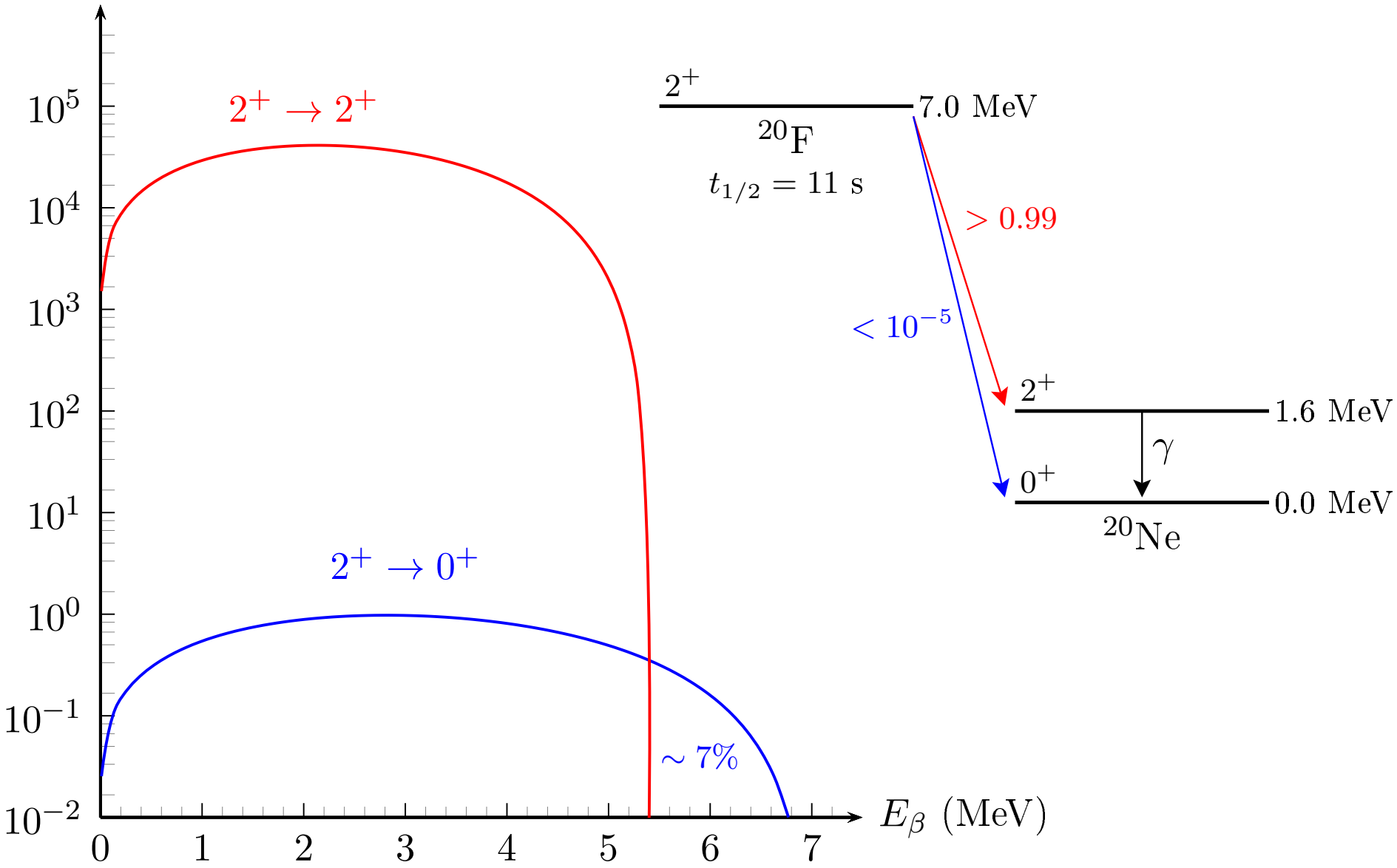
  $\log_{10} \rho_c = 9.95 \Rightarrow$ wave ejects portion of the core and leaves behind a ONeFe white dwarf

  $\log_{10} \rho_c = 10.3 \Rightarrow$ wave stalls and core collapses to a neutron star

Shell-model calculations

- Calculations of 2nd forbidden, *unique* transitions in the *sd* shell are accurate within a factor of two or better.
  - Martínez-Pinedo and Vogel, PRL 81, 281 (1998)
- But what about *non-unique* transitions?
- For the 2nd forbidden, non-unique $2^+ \rightarrow 0^+$ transition in the β decay of ^{20}F two groups obtain rather different results:
  - b.r. $= 1.3 \times 10^{-5}$
    - Idini *et al.* PoS(NIC XIII)002 (2014)
  - b.r. $= 0.53 \times 10^{-5}$
    - Suhonen, private communication

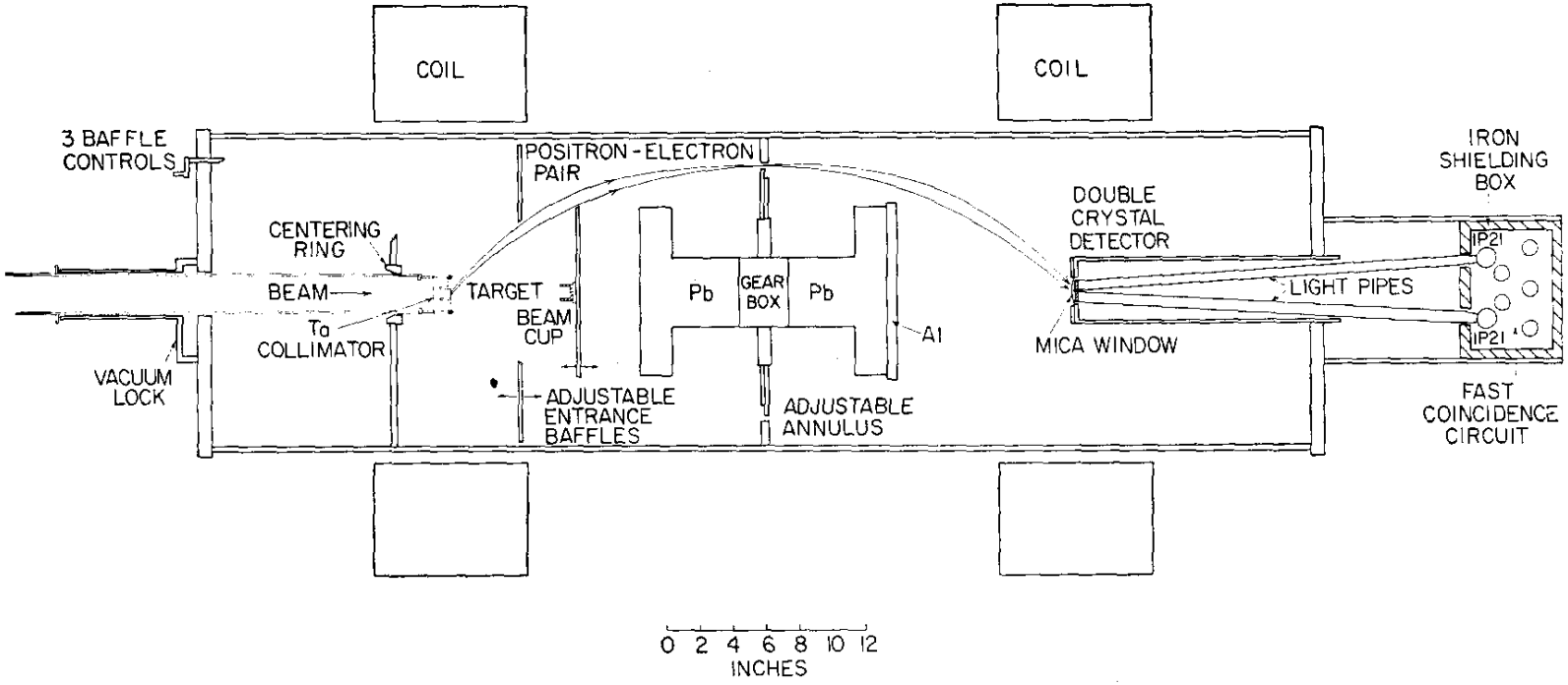
How do we detect the $2^+ \rightarrow 0^+$ transition?



The measurement of Calaprice and Alburger

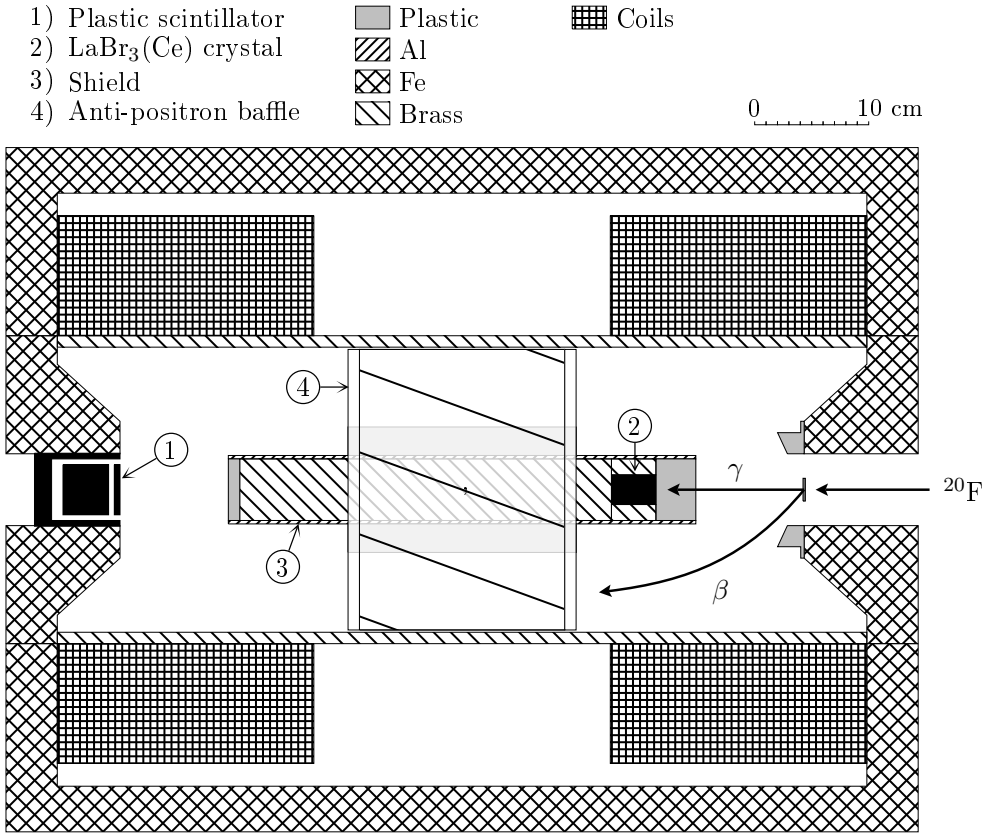
- Reaction: $^{19}\mathrm{F}(d,p)^{20}\mathrm{F}$ at $E_d = 2.5$ MeV
- Targets: $\mathrm{CaF_2}$ and $\mathrm{BaF_2}$ (1 mg/cm^2)
- Result: b.r. $< 1 \times 10^{-5}$

Calaprice and Alburger, PRC 17 (1978) 730



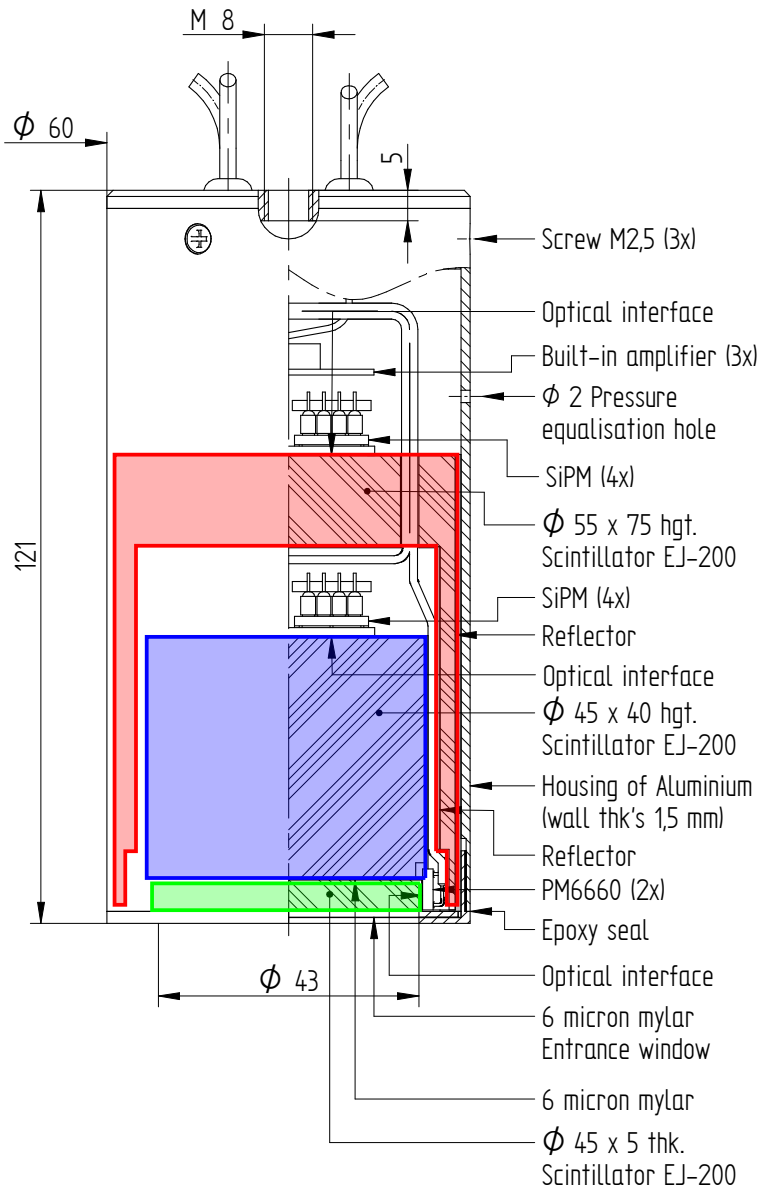
Alburger, Rev. Sci. Instrum. 27, 991 (1956)

Veikon Kone

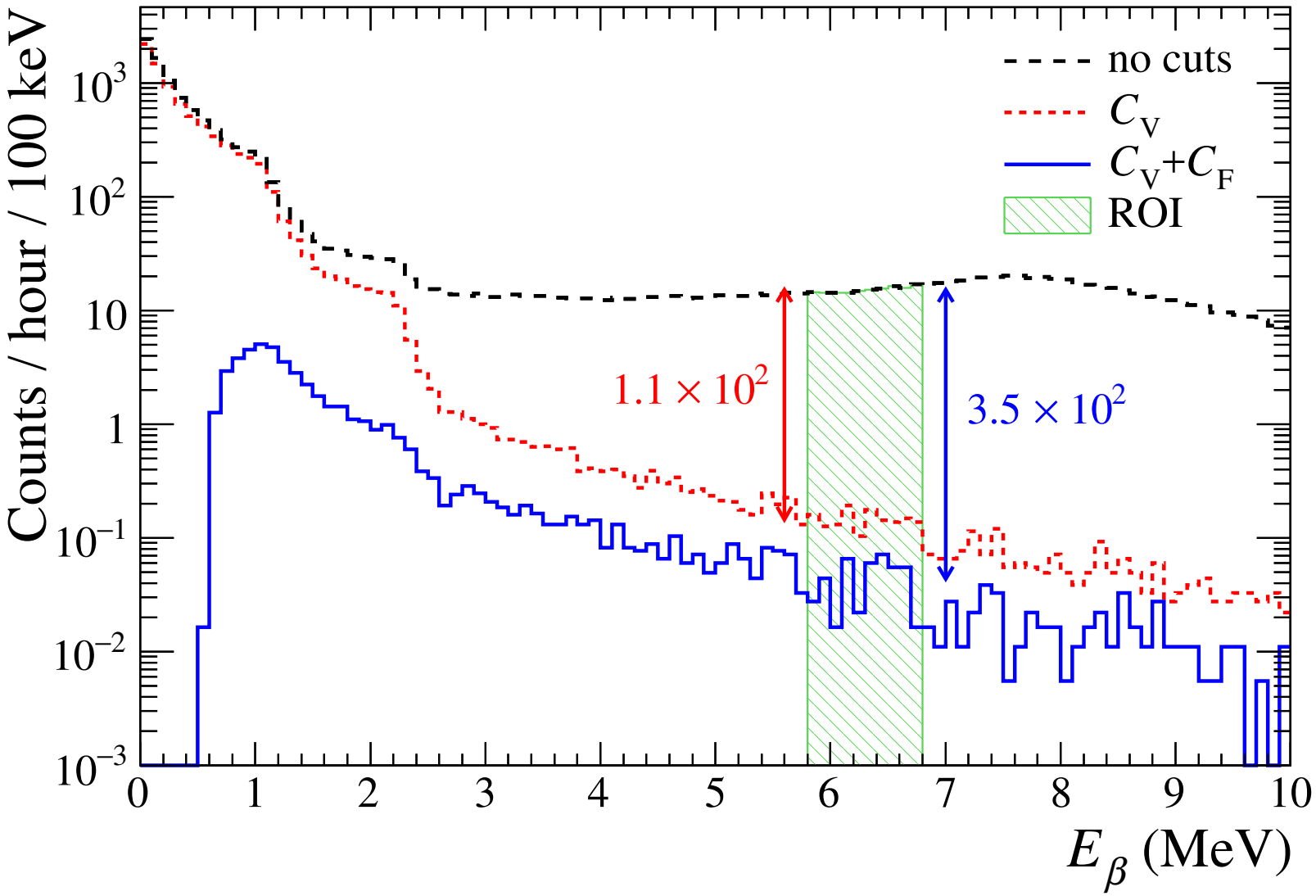


▸ Julin *et al.* Nucl. Instrum. Meth. A 270 (1988) 74

Focal-plane detector



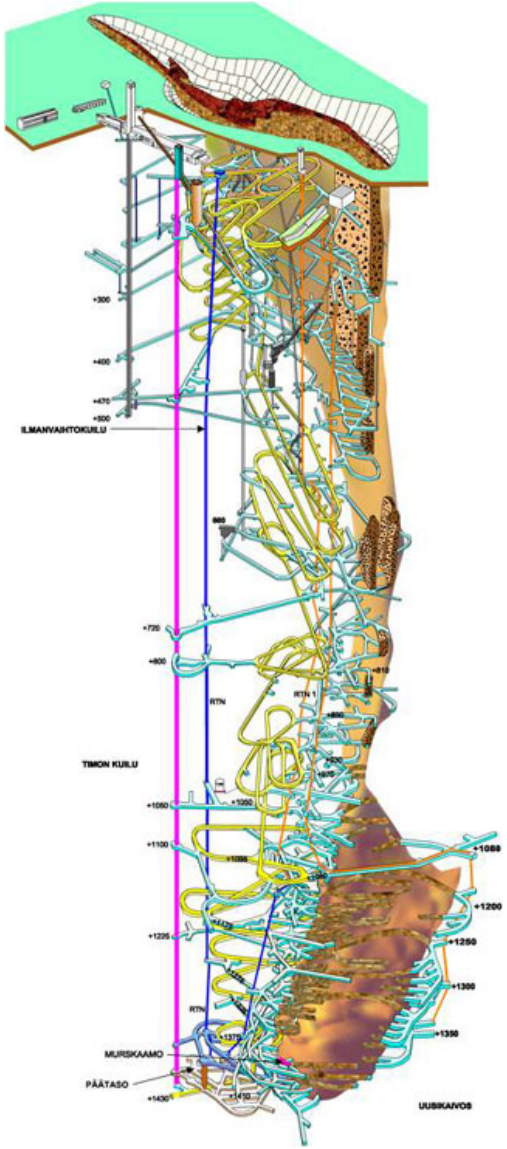
Background suppression



Visit to the Pyhäsalmi mine

The Pyhäsalmi mine

- Copper and zinc mine located in central Finland
- Owned by First Quantum Minerals (Canadian mining corporation)
- Depth: 1,444 metres (4,738 feet) (second deepest metal mine in Europe)
- Home of the worlds deepest sauna



The underground laboratory (Callio lab)

- 4,000 m.w.e.
- Muon fluxes:
  - Surface: 180 m^{-2} s^{-1}
  - Lab: 10 m^{-2} day^{-1}

▸ Jalas *et al.* J. Phys.: Conf. Ser. 888 (2017) 012156

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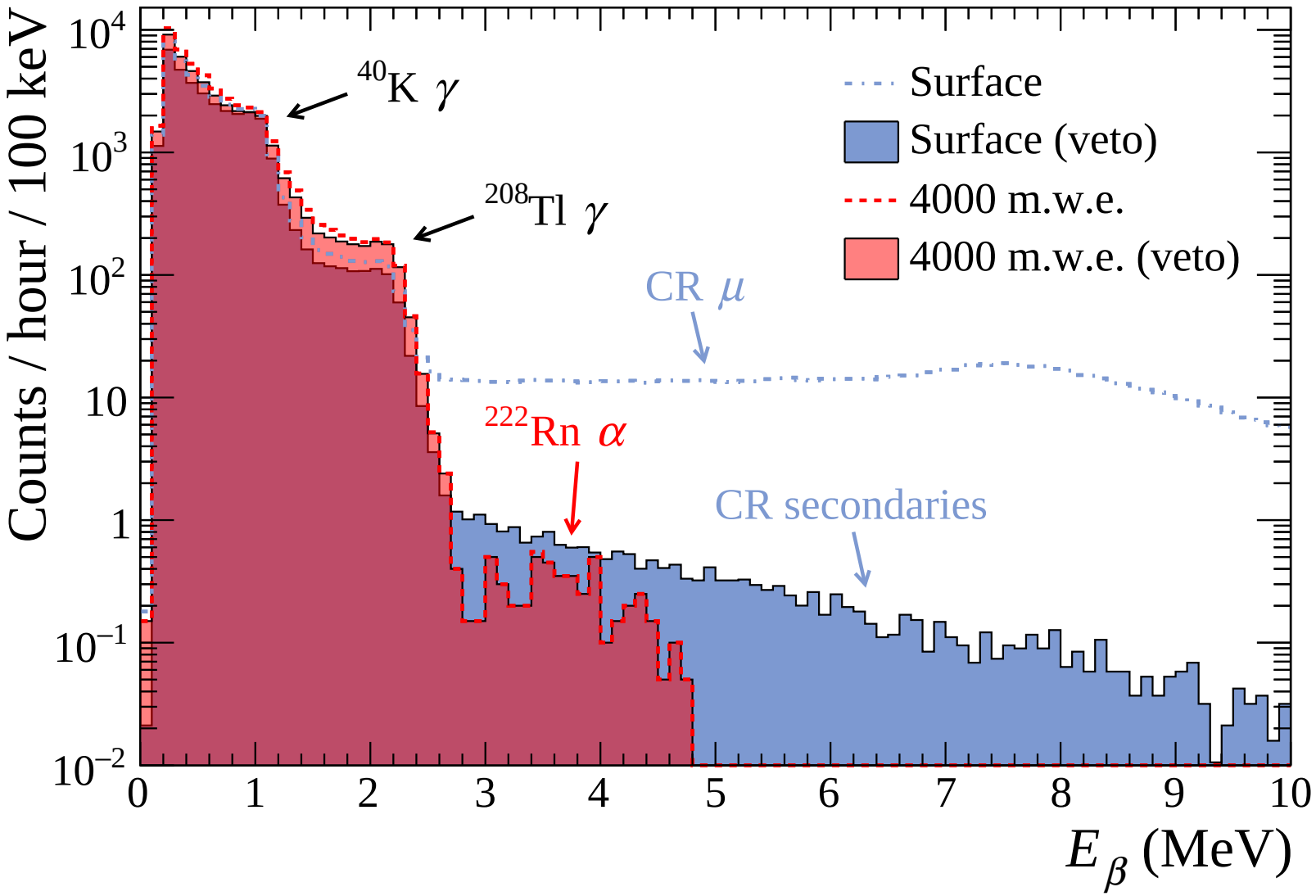
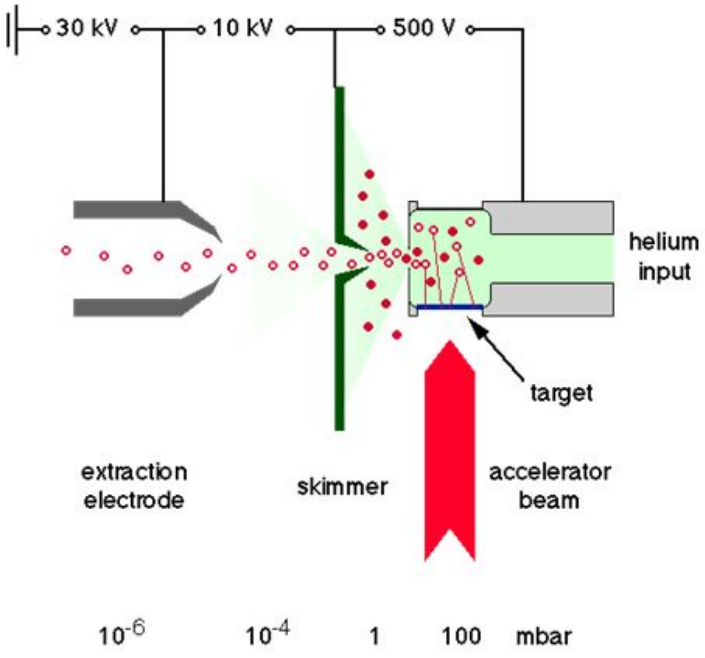
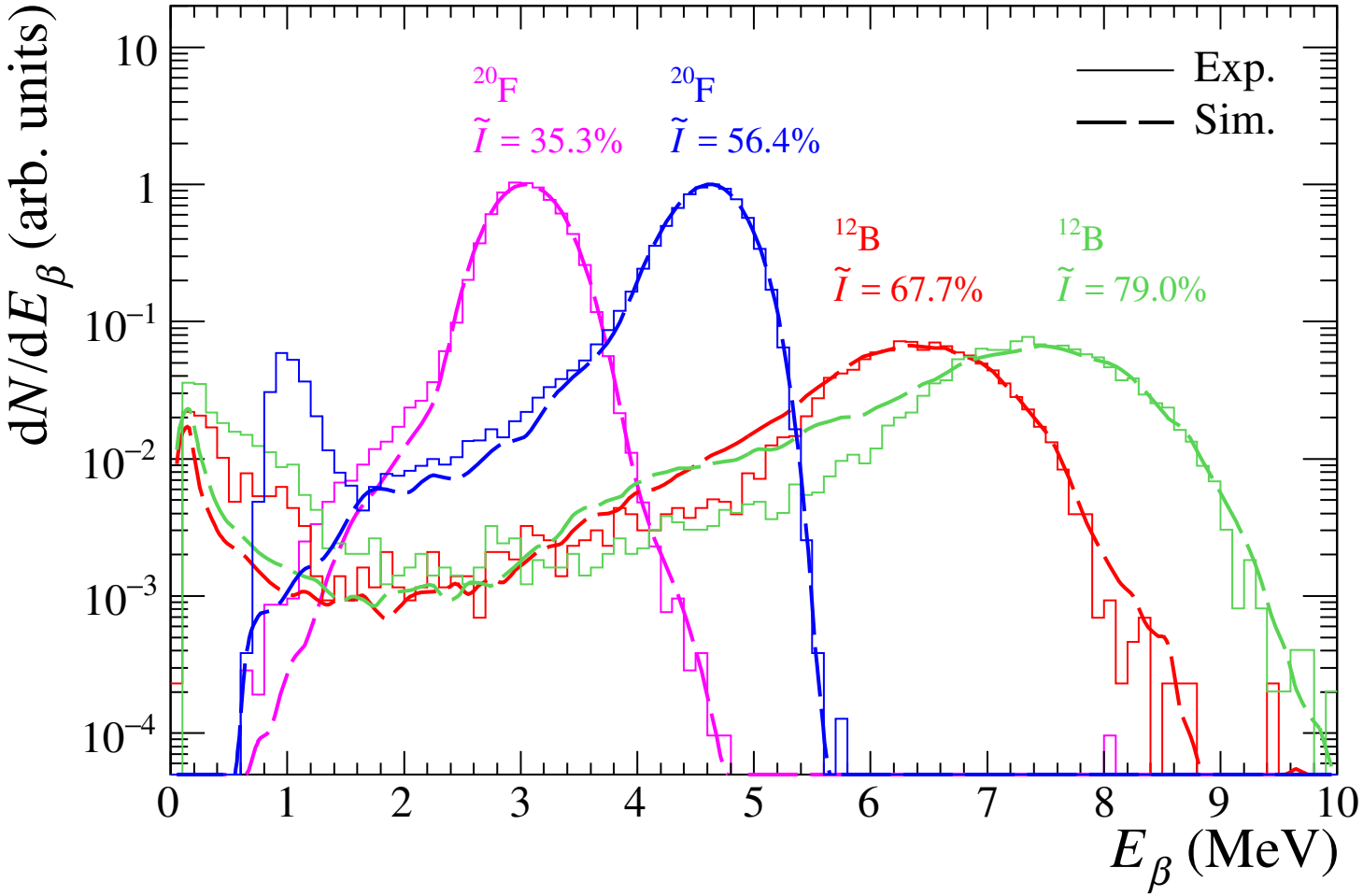


^{20}F beam production at IGISOL-4

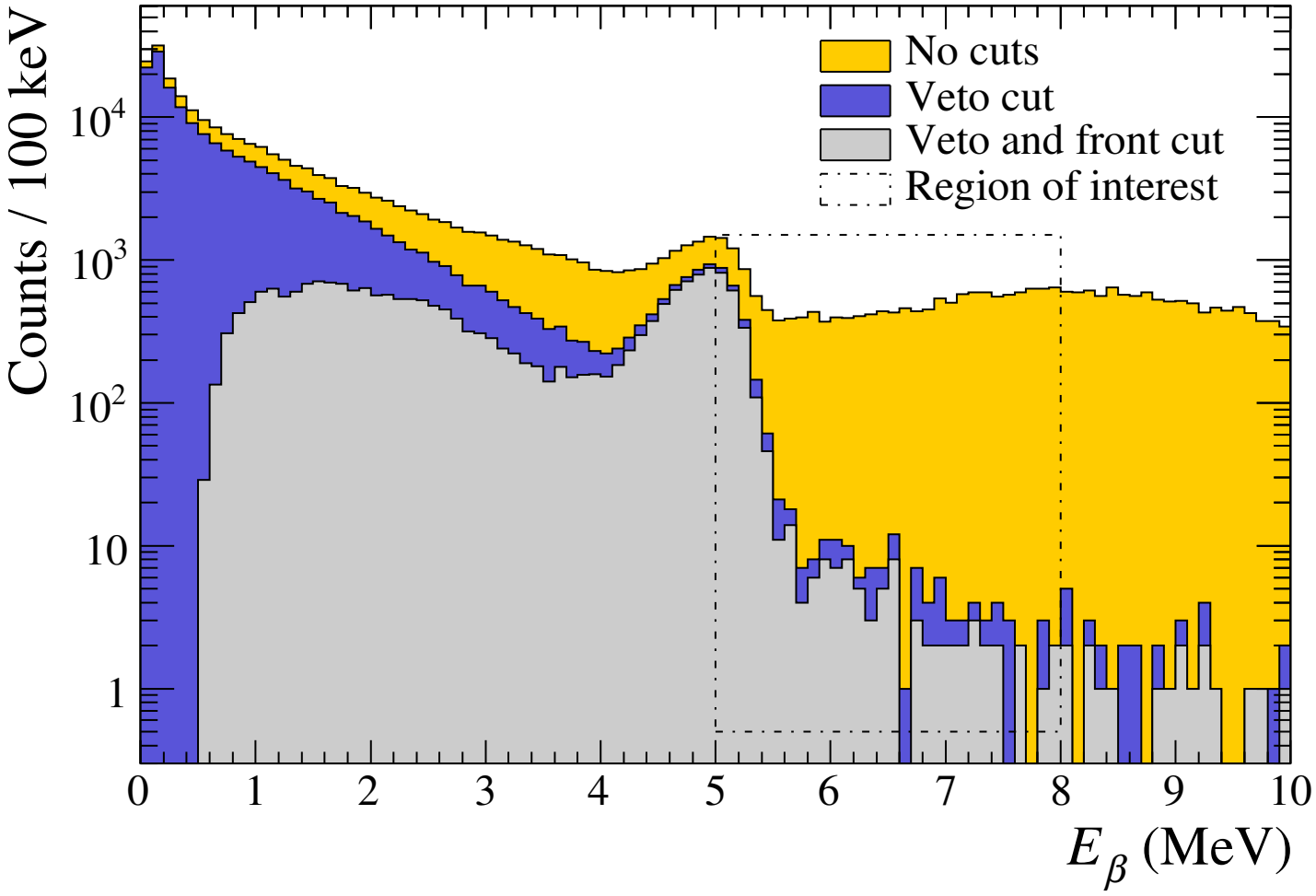
- IGISOL technique
  (Ion Guide Isotope Separator On-Line)
  ▸ J. Ärje, J. Äystö *et al.* PRL 54 (1985) 99
- Reaction: $^{19}F(d,p)^{20}F$
- 52 μm Ta degrader $\Rightarrow$ Beam energy reduced from 9 MeV to 6 MeV
- Target: 1.2 mg/cm^2 BaF on 0.6 mg/cm^2 W backing
- Recoils stopped in He gas
- Charge-exchange reactions
  $\Rightarrow$ good fraction of 1^+ ions
- Dipole magnet selects $A/q = 20$



Measured β energy spectra



Long-duration measurement at $\tilde{I} = 67.7\%$



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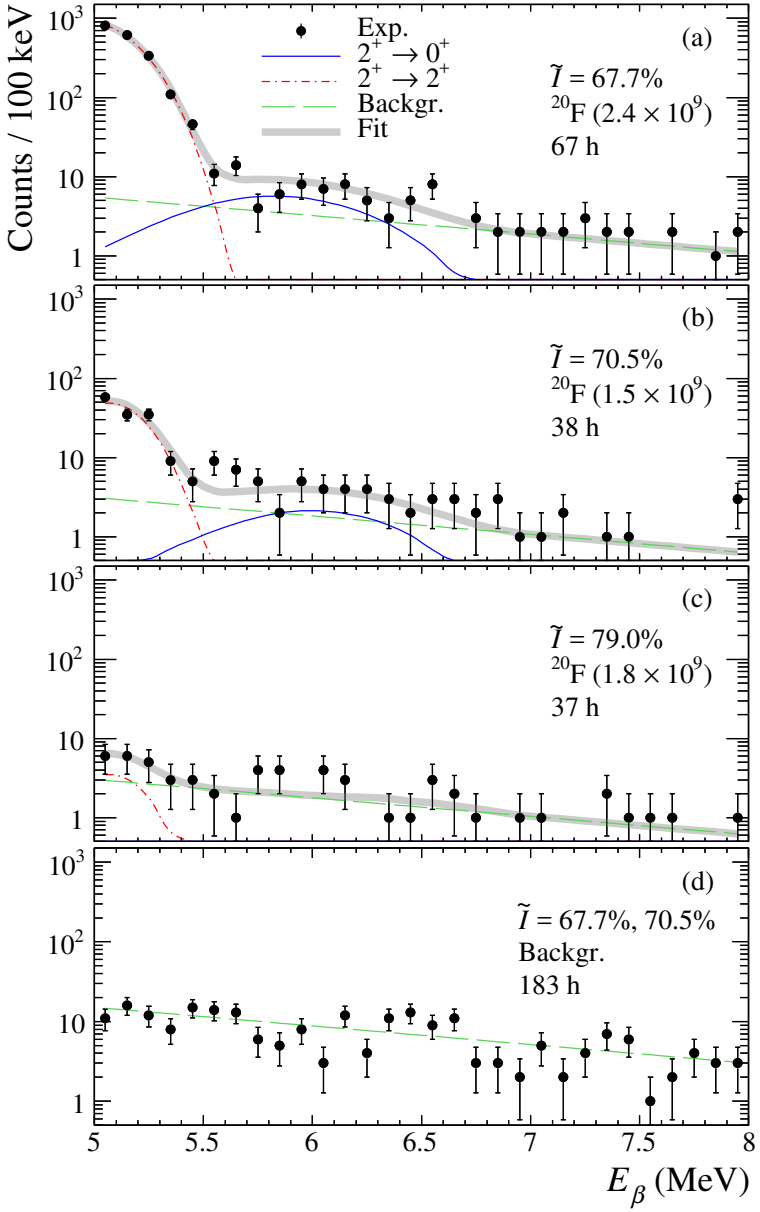

$$\text{b.r.} = [1.10 \pm 0.21(\text{stat}) \pm 0.17(\text{sys})] \times 10^{-5}$$

$$\log ft = 10.47 \pm 0.11$$

Strongest 2nd-forbidden, non-unique transition ever observed!

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- Efforts are underway to explore the astrophysical implications.

Collaboration

O. S. Kirsebom[a,*], M. Hukkanen[b], A. Kankainen[b], W. H. Trzaska[b], K. Andersen[a], L. Canete[b], J. Cederkäll[c], T. Enqvist[d], T. Eronen[b], H. O. U. Fynbo[a], S. Geldhof[b], R. de Groote[b], D. G. Jenkins[e], A. Jokinen[b], P. Joshi[e], A. Khanam[b,**], J. Kostensalo[b], P. Kuusiniemi[d], I. Moore[b], M. Munch[a], D. A. Nesterenko[b], J. D. Ovejas[f], H. Penttilä[b], I. Pohjalainen[b], M. Reponen[b], S. Rinta-Antila[b], K. Riisager[a], A. de Roubin[b], P. C. Srivastava[g], J. Suhonen[b], J. A. Swartz[a], O. Tengblad[f], M. Vilen[b], S. Viñals[f], J. Äystö[b]

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