Exotic Nuclear Decay

Experiments at the limits of stability

CONGRESS 2021

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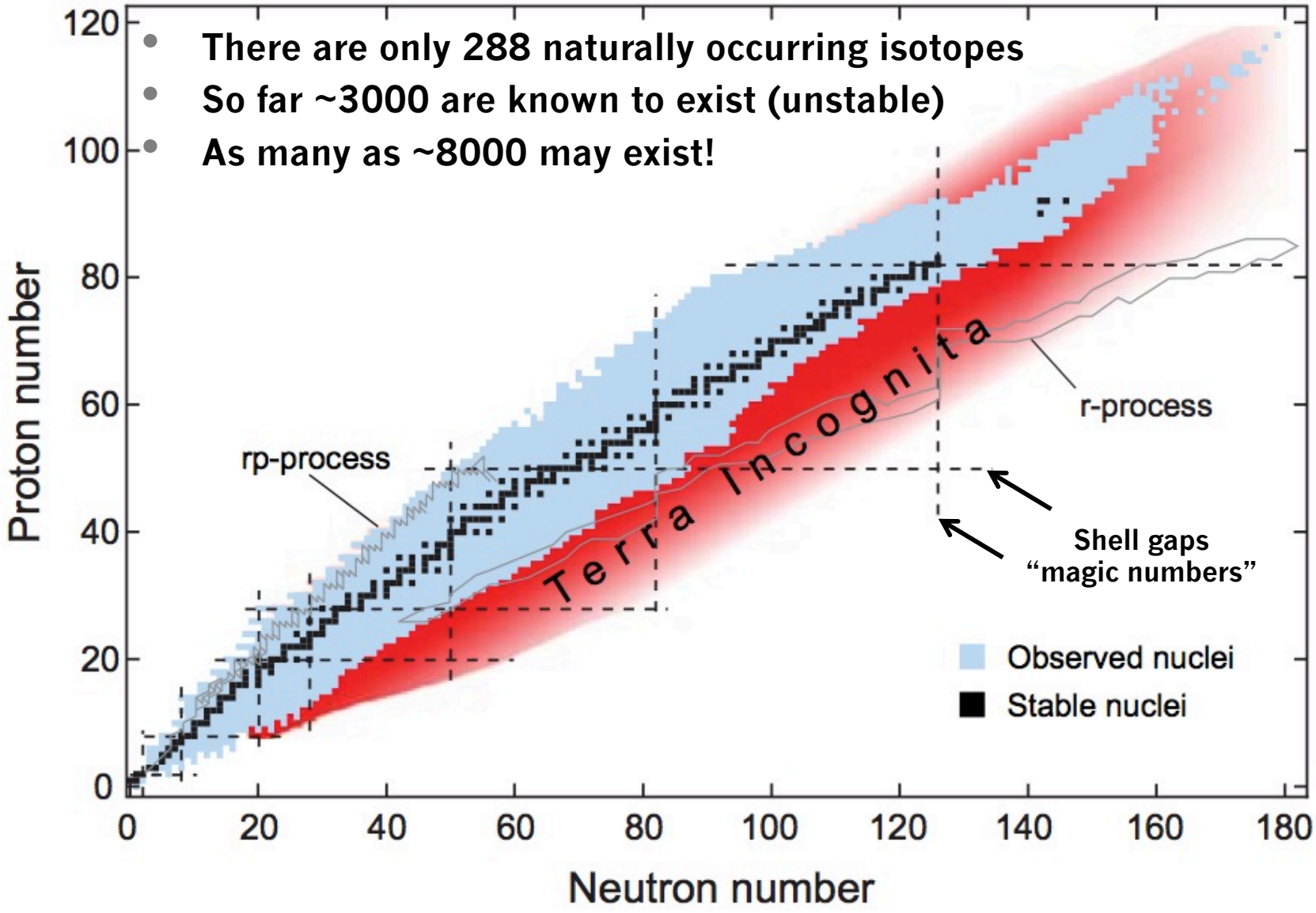
Chart of the nuclei



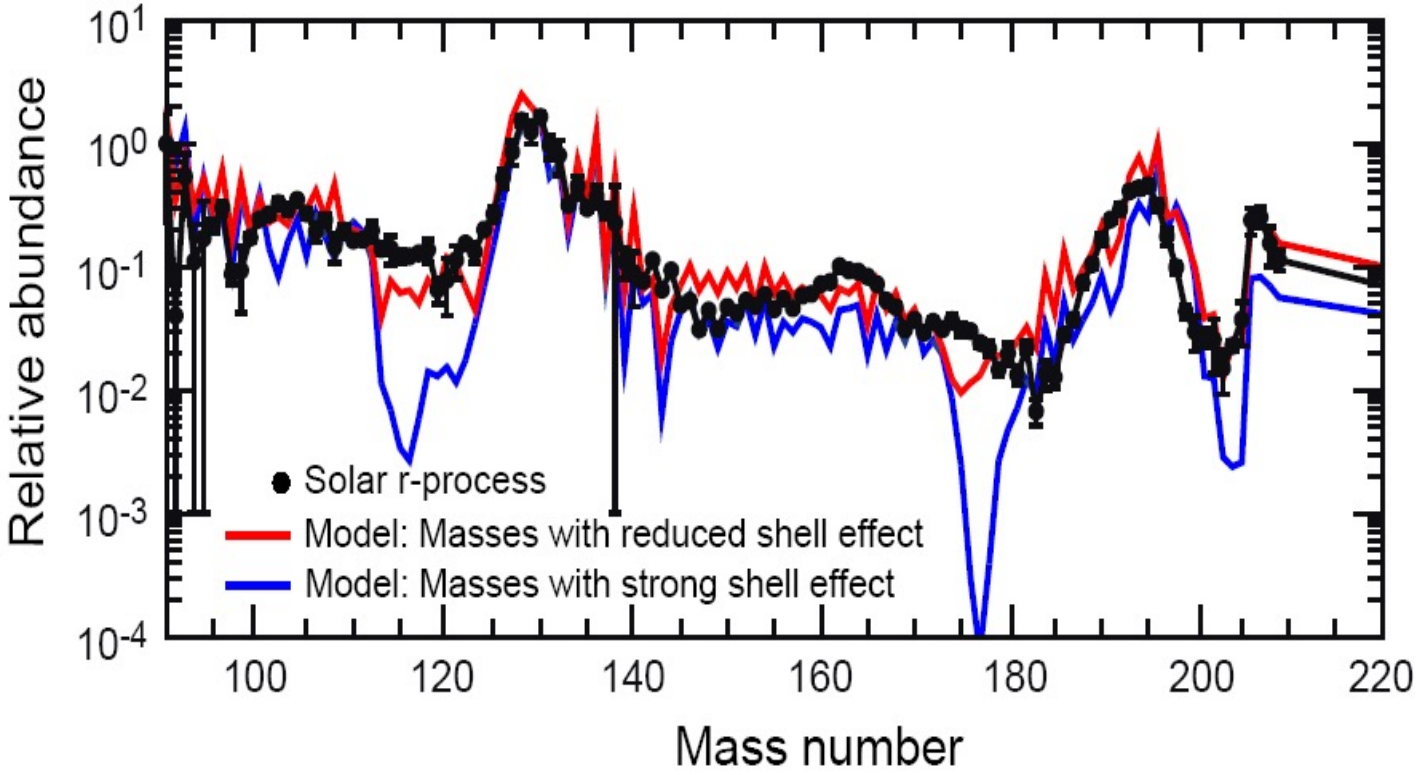
Putting this into perspective…

- **Imagine ⅜ of Canada. What would we predict the rest would look like?**
  - **What would be the accuracy of these predictions?**

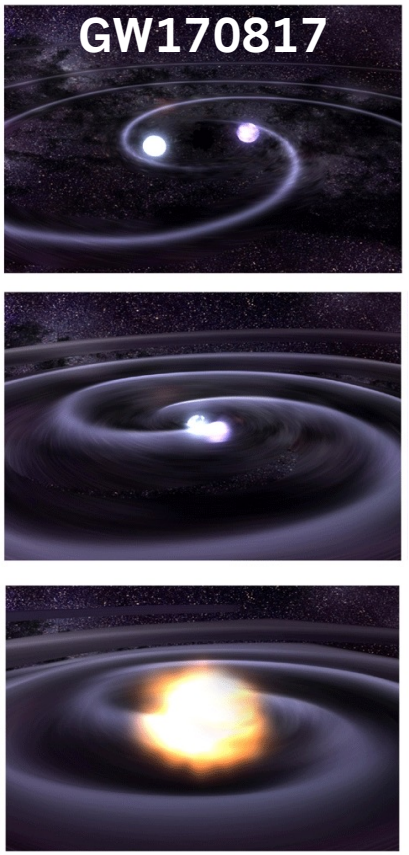
Origin of the elements

B.P.Abbott *et al.* PRL 119, 161101 (2017)

- **Nearly 50% of elements heavier than Fe produced by the r-process**
  - **Cannot explain elemental abundances by extrapolation from stable nuclei**
  - **Nuclear structure inputs (masses, half-lives and decay modes) are essential**
  - **Experiment: most nuclei very difficult to access**
  - **Theory: predictions have large uncertainties**

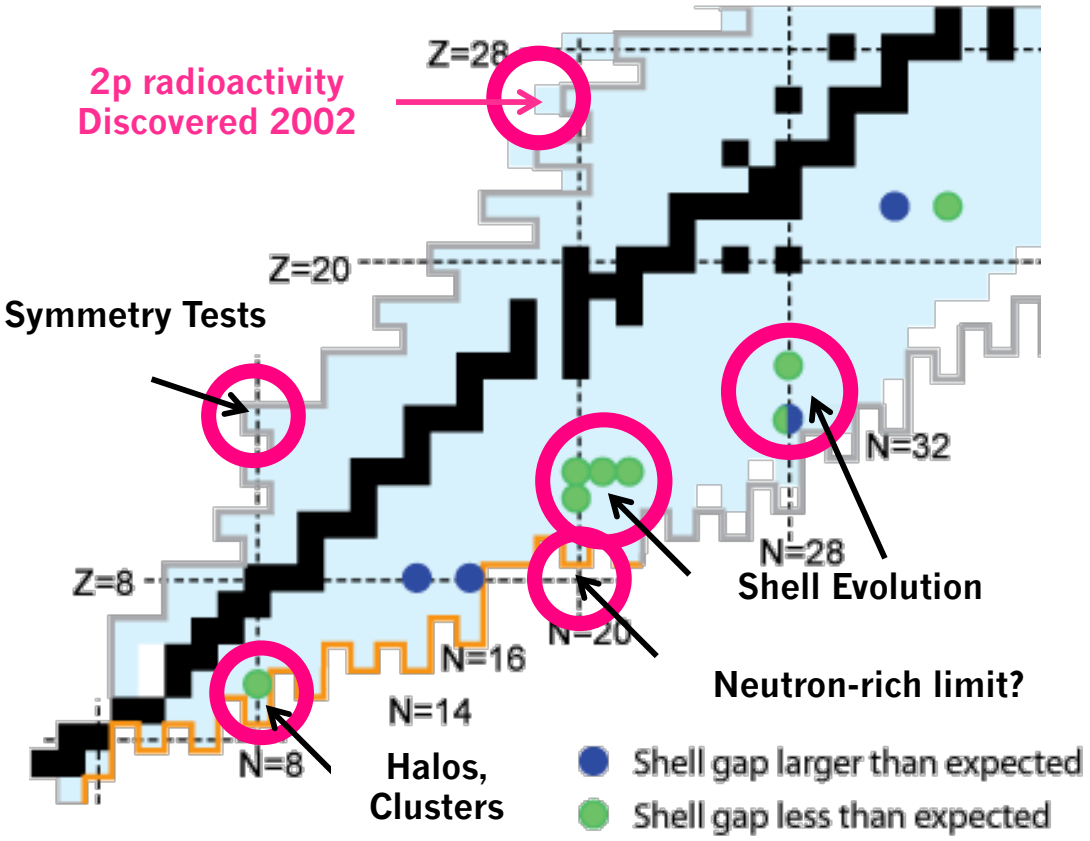


LIGO – Neutron star merger



Nuclear science far from stability

- For exotic nuclei, experiments have uncovered new phenomena
  - Delicate interplay between weak binding and the forces between nucleons
  - Theoretical models cannot reliably predict the onset of these changes



Big questions in subatomic physics

- What is the nature of physics at the electroweak scale and beyond?
- How does the structure of nuclei emerge from the nuclear forces?
- How are the natural elements formed in the universe?

Canadian Subatomic Physics LRP 2017-2021

www.subatomicphysics.ca

Nuclear β decay

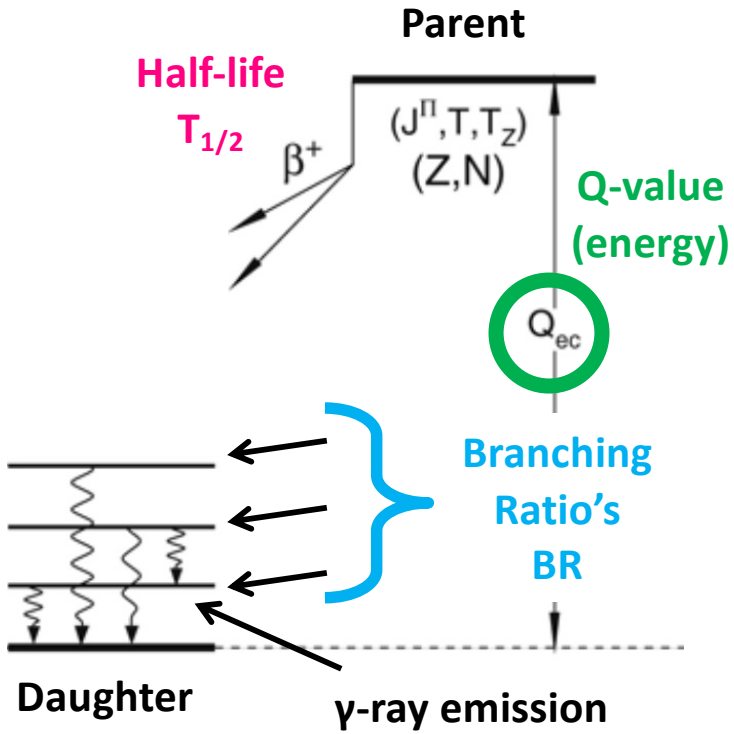
- **Powerful technique to study nuclear structure**

β⁻ $${}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^- + \overline{\nu_e},$$

neutron ⟶ proton

β⁺ $${}^{A}_{Z}X_N \rightarrow {}^{A}_{Z-1}W_{N+1} + e^+ + \nu_e.$$

proton ⟶ neutron



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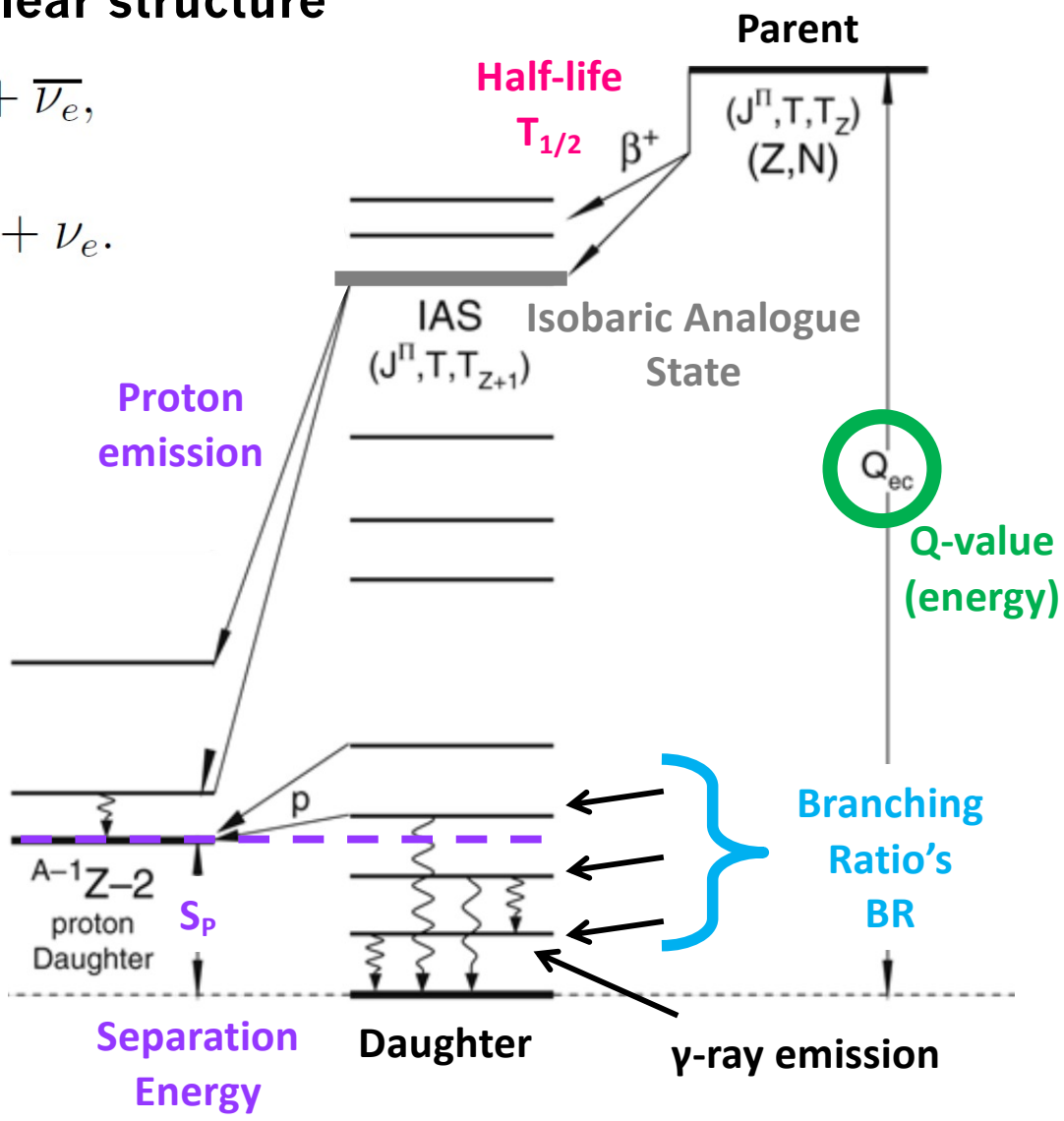
proton ⟶ neutron

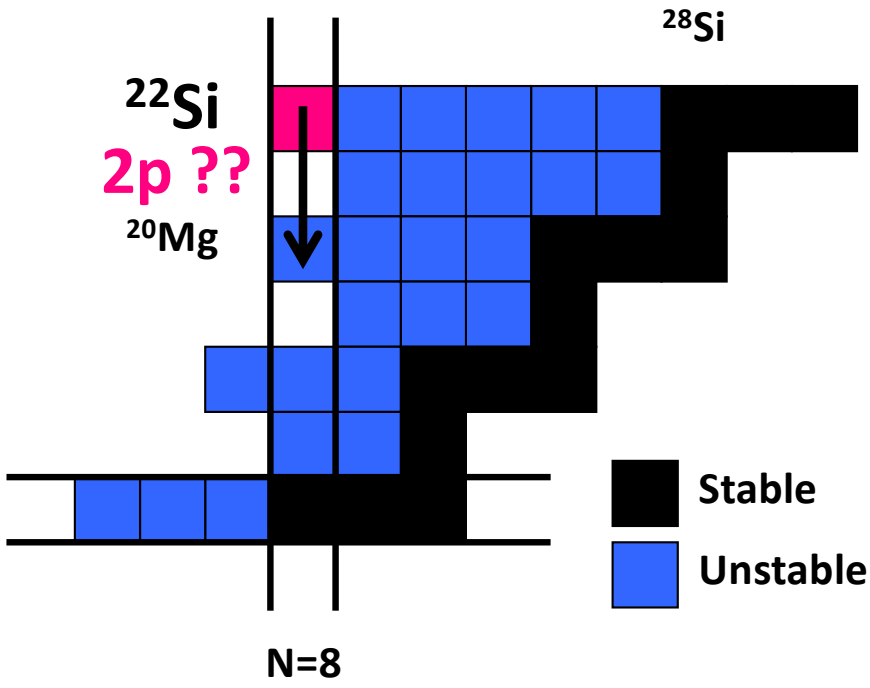
- **Further from stability**
  - **β delayed proton decay (βp)**
  - **β delayed 2 proton decay (β2p)**
  - **2p radioactivity and more!**

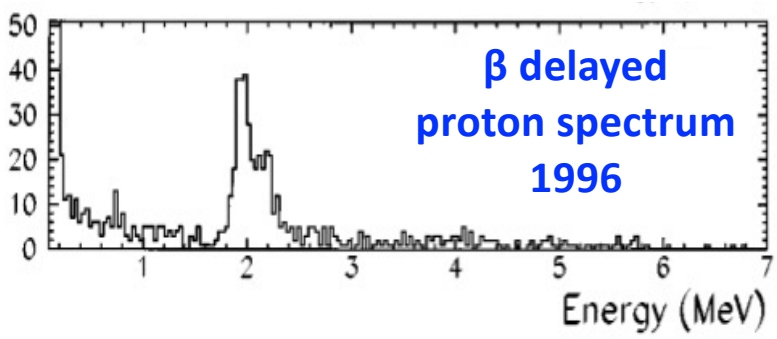
- **Measurement principle**
  - **Produce the parent nuclei**
  - **Detect β's, γ rays & particles**
  - **Decay scheme, $T_{1/2}$, BR, …**



Furthest from stability: ^{22}Si

- Most neutron deficient Si isotope
  - Located on the proton "drip line"
- Isotope discovered in 1987 @ GANIL
  - 6 neutrons away from stable ^{28}Si
- First spectroscopy 1996 @ GANIL
  - Production rate: 3 ions/minute
  - β delayed proton emitter ($T_{1/2}$ = 29 ms)
- Q-value/mass of ^{22}Si is unknown
  - AME03: S_{2p} = – 16 ± 202 keV
  - AME16: S_{2p} = – 1201 ± 504 keV
- Can ^{22}Si decay by 2p radioactivity?



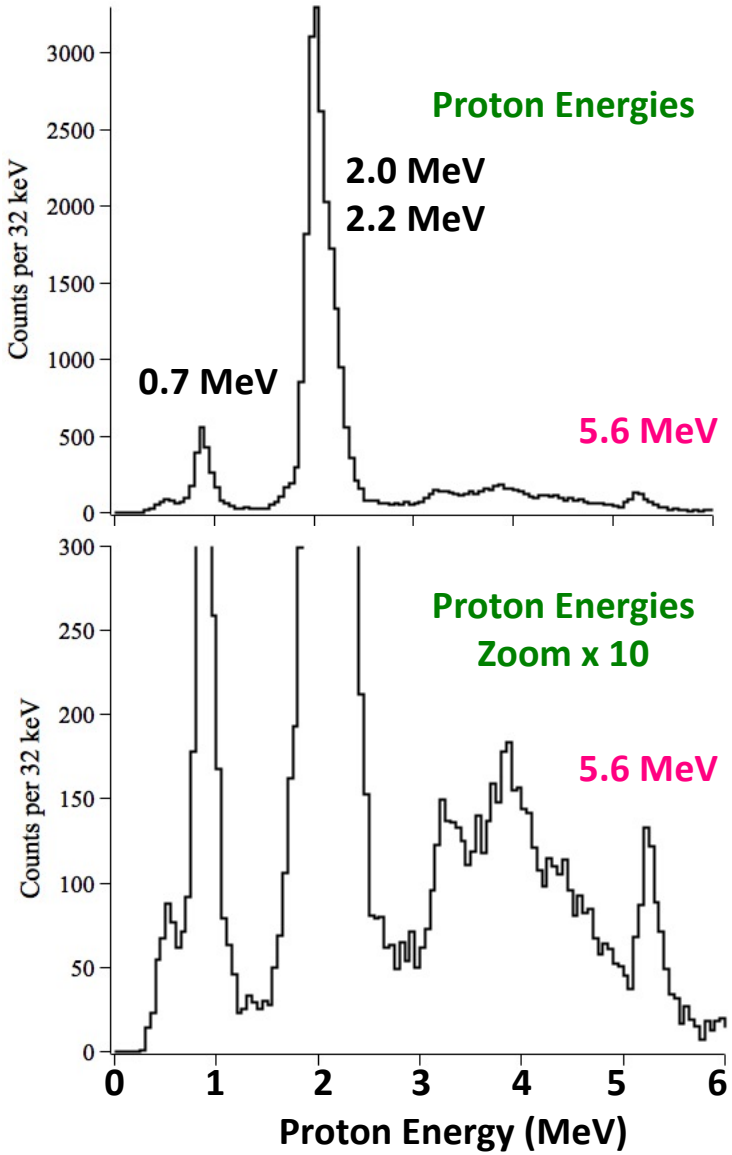


B.Blank *et al.* PRC 54, 247 (1996)

Experimental results

Mathieu Babo, PhD Université de Caen

- Experiment at NSCL (USA)
  - ^{22}Si production rate ~15 ions/s
  - Detected protons in DSSD
- Proton spectra
  - Identified 15 new protons
  - Candidate for β2p = 5.6 MeV
  - E_{IAS} = 9.1 MeV and BR = 1.5(4)%



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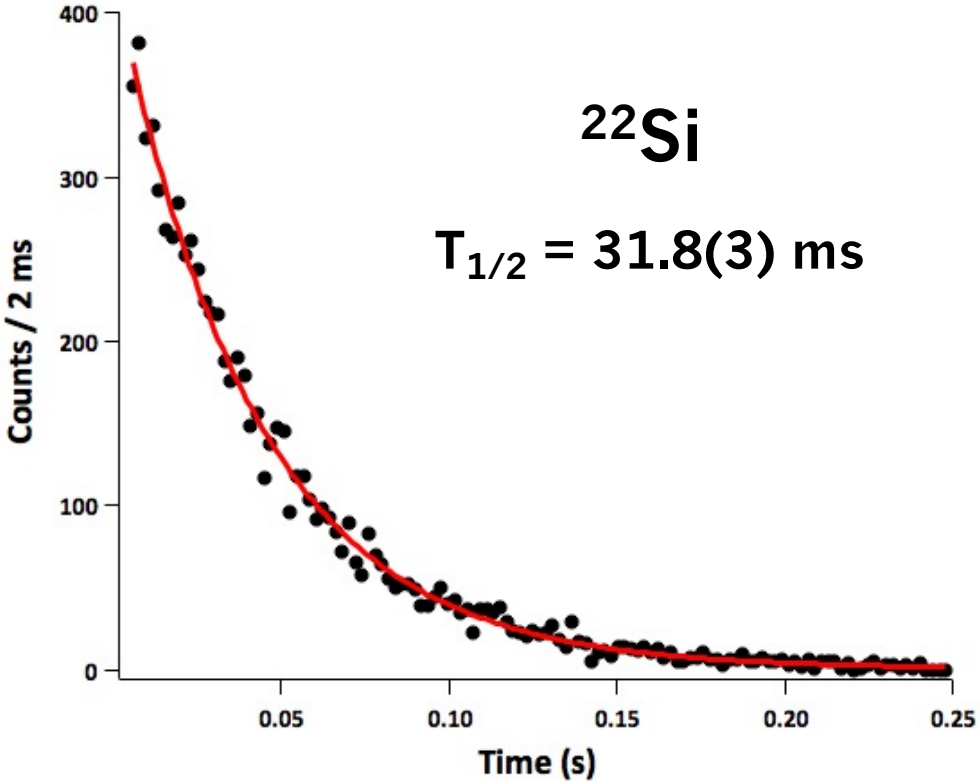
- New half-life measurement
  - $T_{1/2}$ = 31.8(3) ms (previous 29(2) ms)



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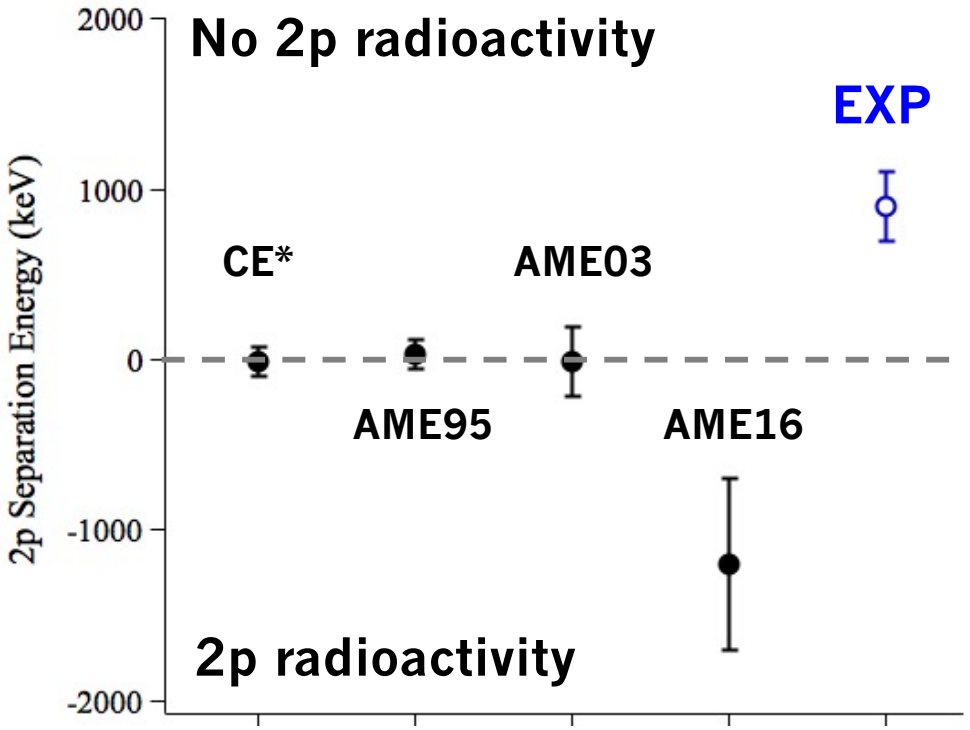
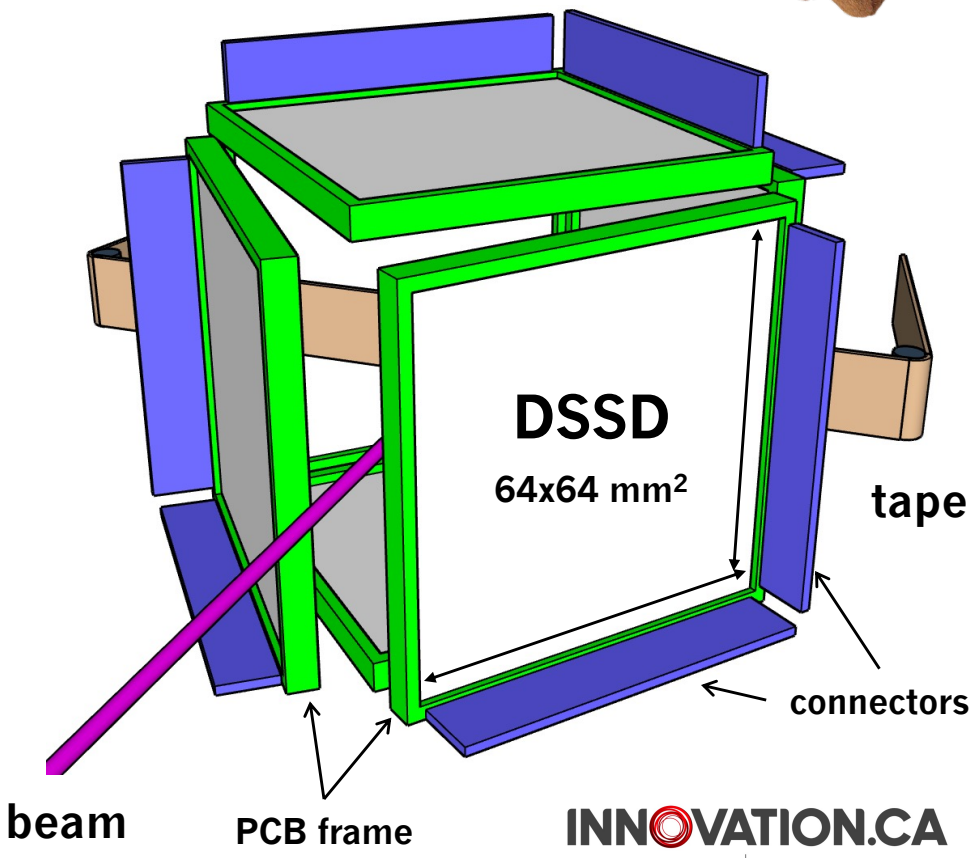
- New half-life measurement
  - $T_{1/2}$ = 31.8(3) ms (previous 29(2) ms)
- Proton energy analysis (Q-value)
  - Mass of ^{22}Si = 31.30(15) MeV
  - S_{2p} = +900(200) keV
  - Cannot decay via 2p radioactivity!



* B.J.Cole PRC 58 2831 (1998)

Regina Cube for Multiple Particles (RCMP)

- Auxiliary detector for TRIUMF
  - New charged particle detector!
  - α decay and β delayed particles
  - Multiple particles (β2p, βαp, …)
- 6 DSSD detectors (micron BB7)
  - Active area: 64 x 64 mm^2
  - 6x(32+32) strips = 384 channels
  - Resolution ≤ 50 keV (FWHM)
- Fully funded project $147k
  - CFI, Innovation SK, NSERC, UofR
  - 2 years: 2020 – 2021 (end)
- Design, construction, tests (UofR)
  - When ready, ship to TRIUMF



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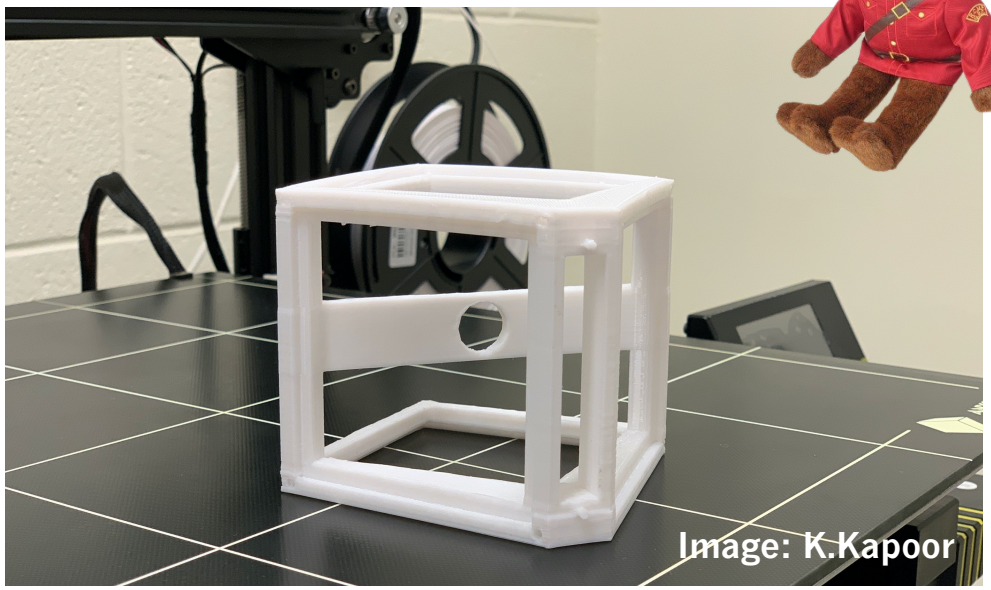
John R. Evans Leaders Fund
innovation SASKATCHEWAN

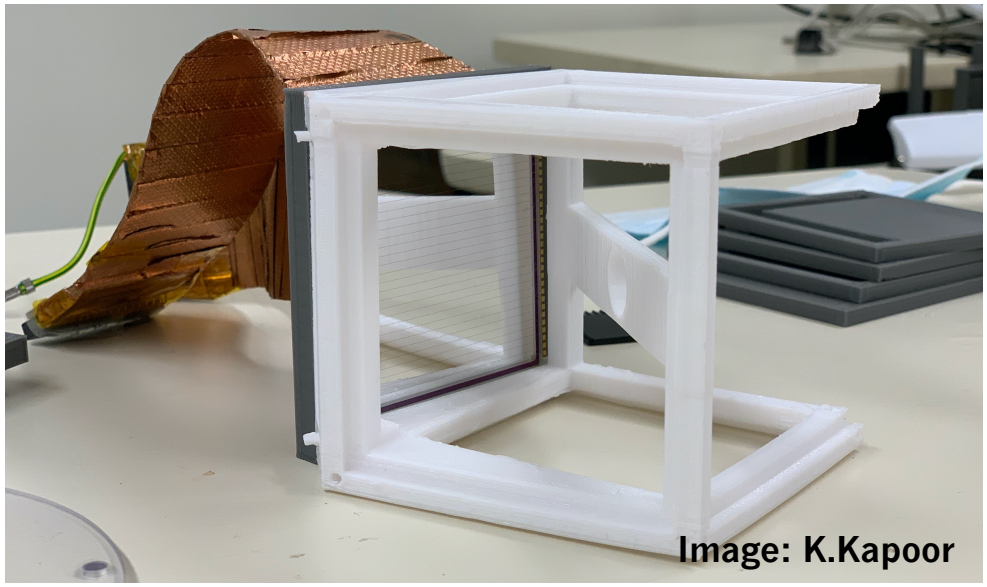
Regina Cube for Multiple Particles (RCMP)

- **Silicon detectors arrived in October 2020!**

Regina Cube for Multiple Particles (RCMP)

- Mechanical support structure
  - 3D printed in our lab!
- We also do face shields…
  - Dr. Mehran Talebitaher (UofR)





Regina Cube for Multiple Particles (RCMP)

- **Beamline drawing (upstream)**
  - **Assembly at UofR this summer!**
  - **Ship to TRIUMF in 2022!**

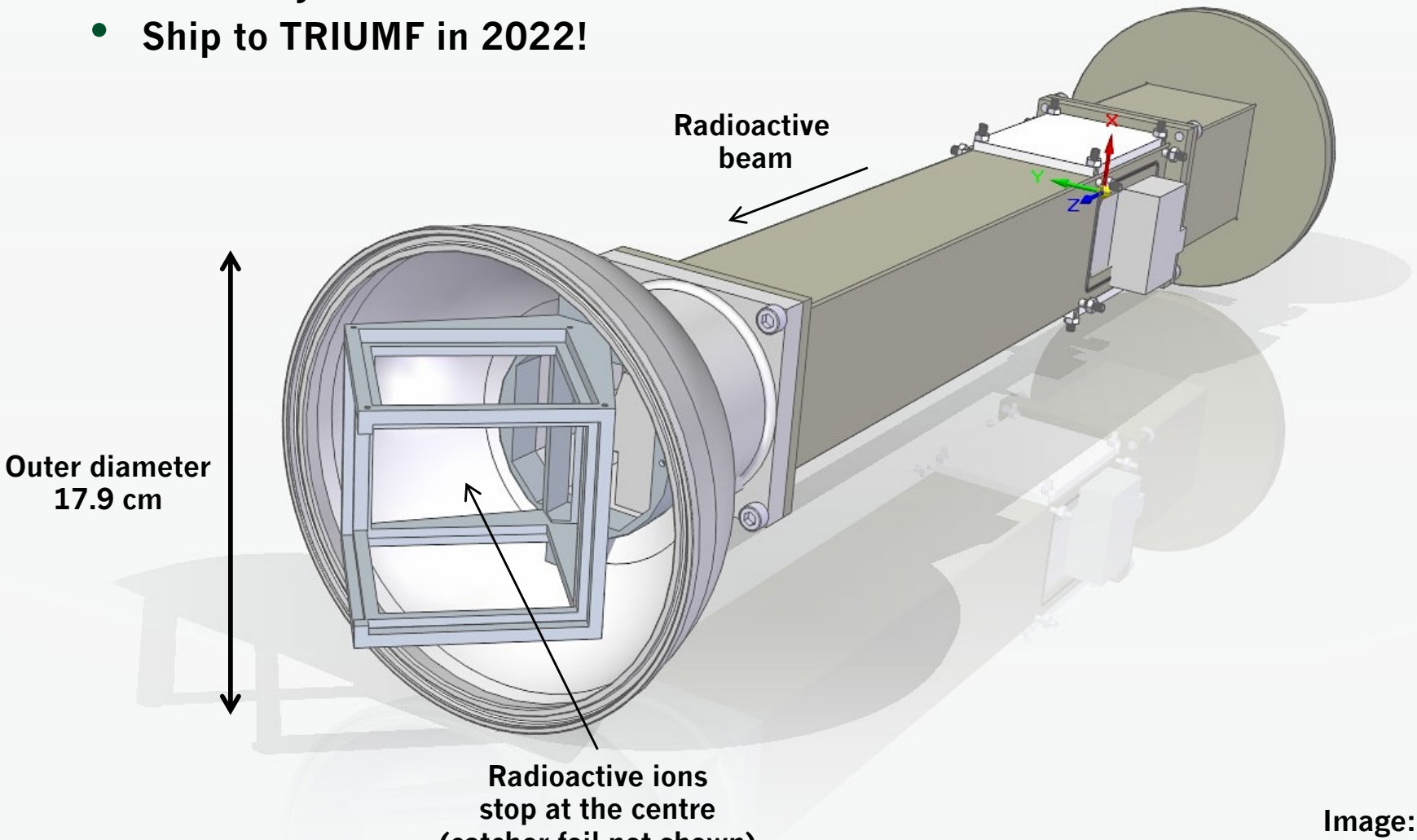
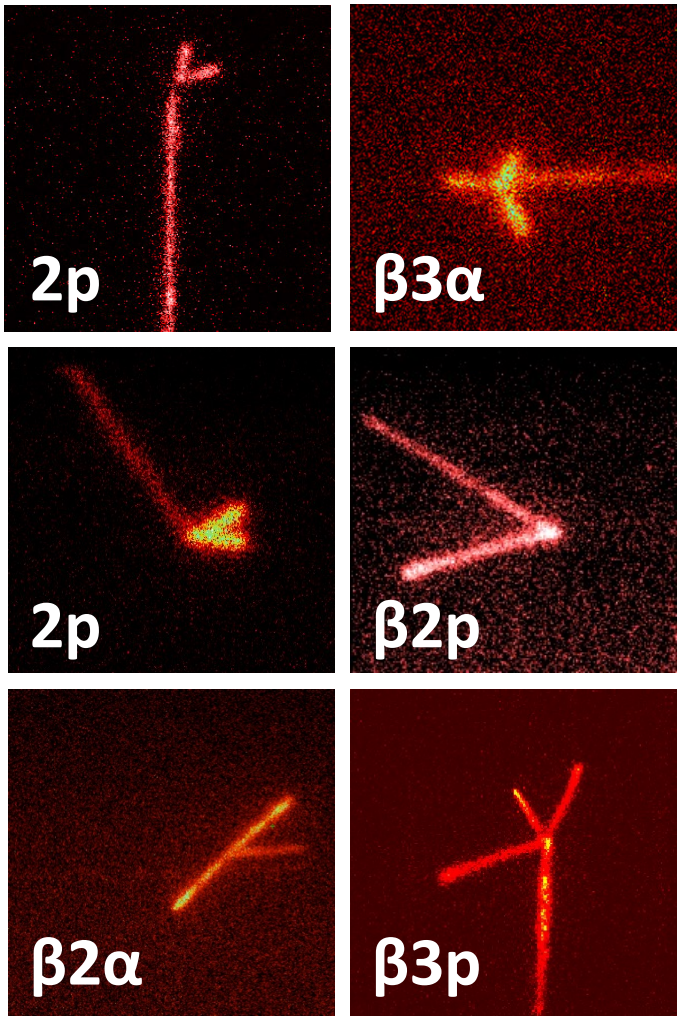


Image: K.Kapoor

Time Projection Chambers (TPC)

- Not everything can be done with Si
  - Implant activity into Si (NSCL)
    - Unwanted tails from β particles
    - Loss of resolution and sensitivity
  - Surround the activity by Si (RCMP)
    - Ideal for multi-particle decays
    - Lower efficiency (less solid angle)
    - Unwanted losses in the catcher
- Solution: Gas detectors!
  - Nearly transparent to β particles
  - High efficiency and good resolution
- Time projection chambers (TPC)
  - Event-by-event "images" of radioactivity
  - Identify the rarest decays with only 1 event



M.Pfutzner *et al.* Optical TPC

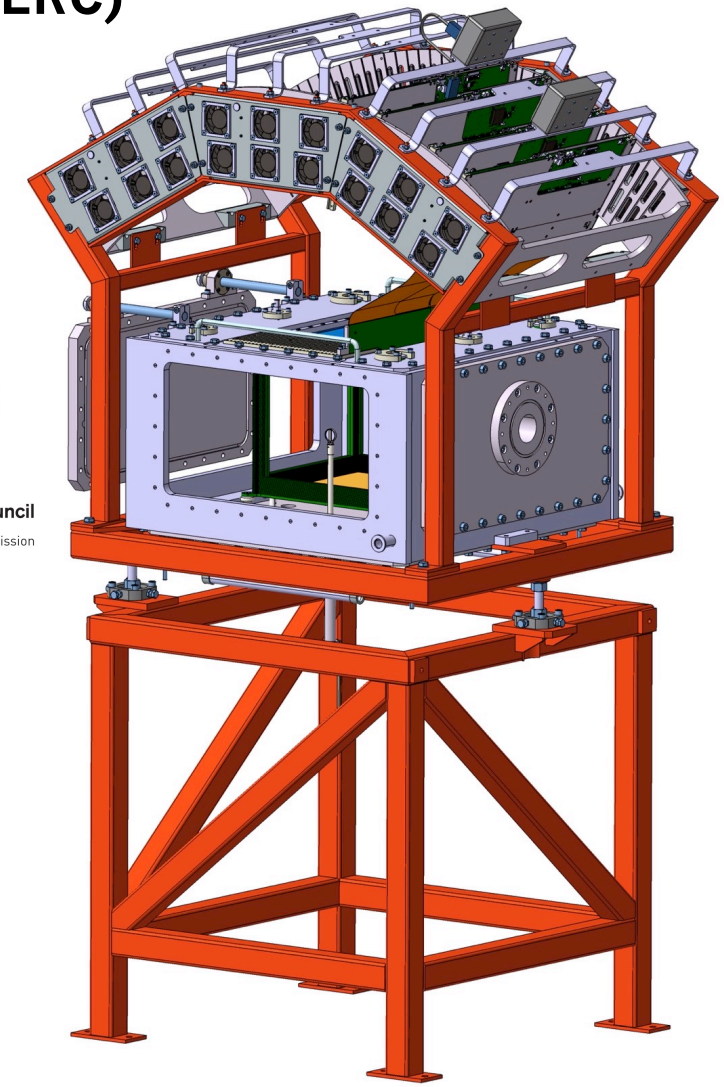
Time Projection Chamber ERC Project

- 1.3M€ grant from European Research Council (ERC)
  - 5-year project (2014 to 2019)
  - Design and construct detector (16k channels)
  - Begin “day 1” physics program

- Milestones:
  - 2014: Built a small prototype (2k)
  - 2015: First in-beam test
  - 2016: Mechanical design (16k)
  - 2017: Construction begins (February)
  - 2017: Commissioning run (November)
  - 2018: First physics experiment!

- Project ended on January 31, 2019
  - Two experiments performed in 2019
  - Three experiments scheduled in 2021!
  - Regina team will be participating remotely…

European Research Council
Established by the European Commission



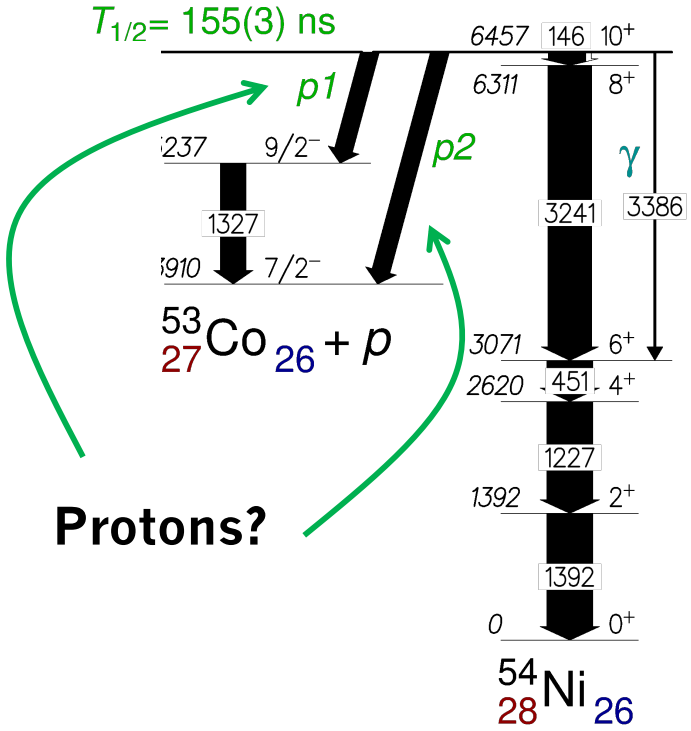
Final Design: P.Gangnant (2017)

E690: Proton decay of a 10^+ isomer in ^{54}Ni

- **Proton decay of an excited state!**
  - **Incredibly challenging…**
- **How does it work?**
  - **Produce the radioactive ^{54}Ni**
  - **Only a fraction of it is 10^+ (0.4%)**
  - **Deliver it to the experiment**
  - **Measure the protons**
  - **And do it all in < a few 100 ns!**
- **Experiment performed at GANIL**
  - **LISE3 fragmentation facility**
  - **First decay experiment with TPC**
- **What does this look like in a TPC?**
  - **Movie time!**

Excited 10^+ state

$T_{1/2}$ = 155 ns!

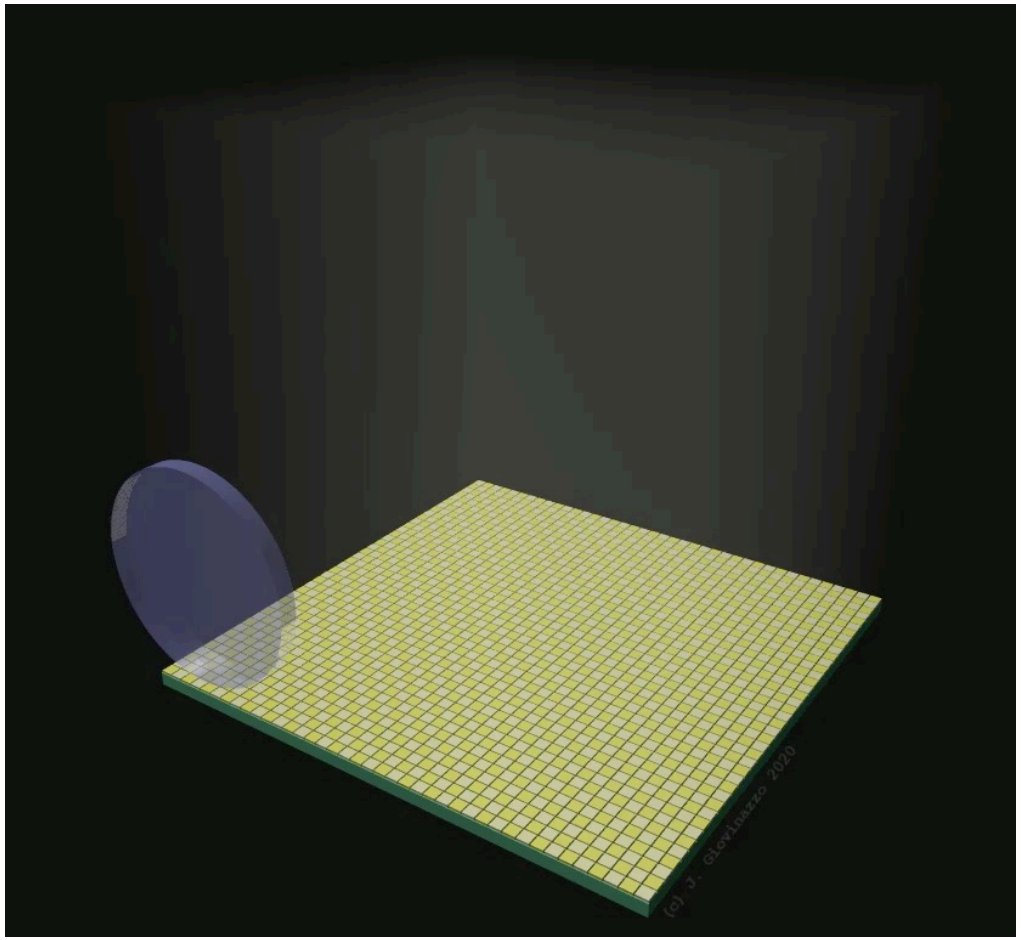


Ground State

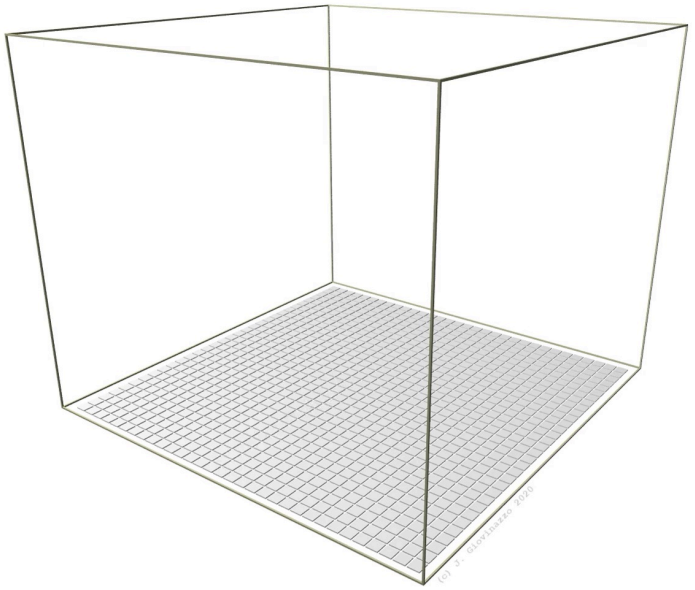
$T_{1/2}$ = 114 ms

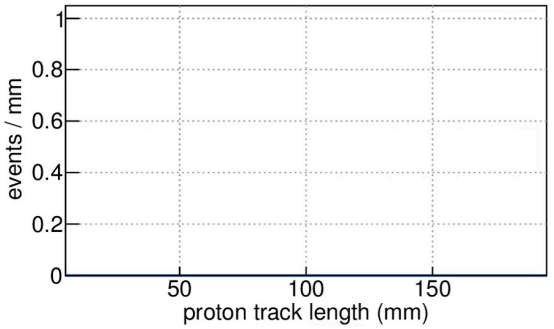
Movie Time: Proton decay in a TPC!

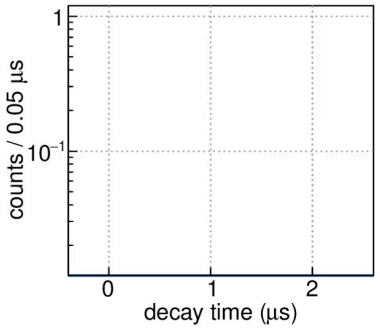
- **Full 3D images of exotic radioactivity!**



Real Data
Not a simulation!



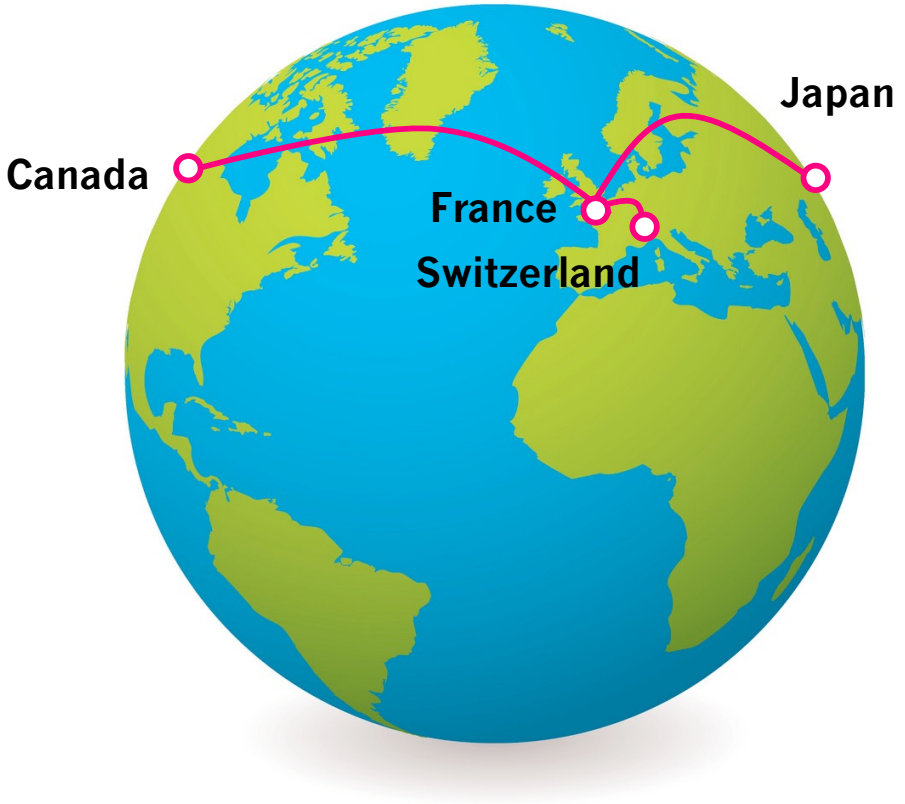




Videos: Jérôme Giovinazzo (CENBG)
This work: Accepted Nature Physics (2021)

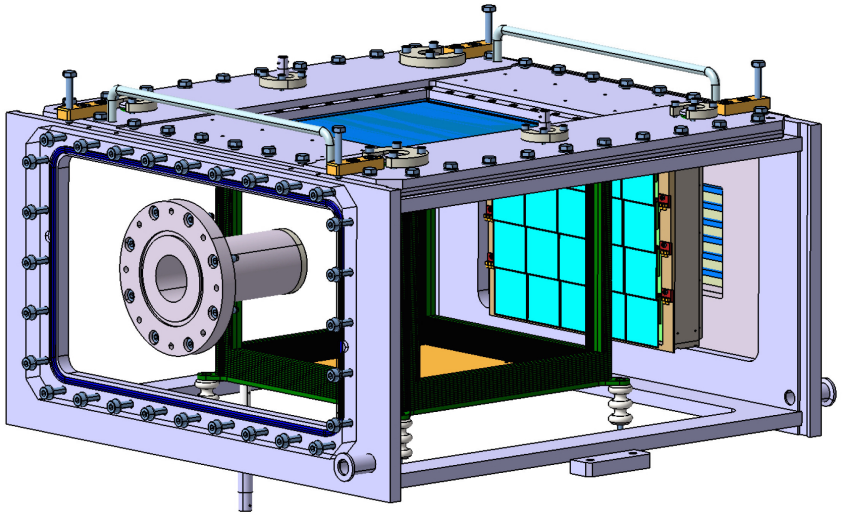
Future Plans with ACTAR TPC

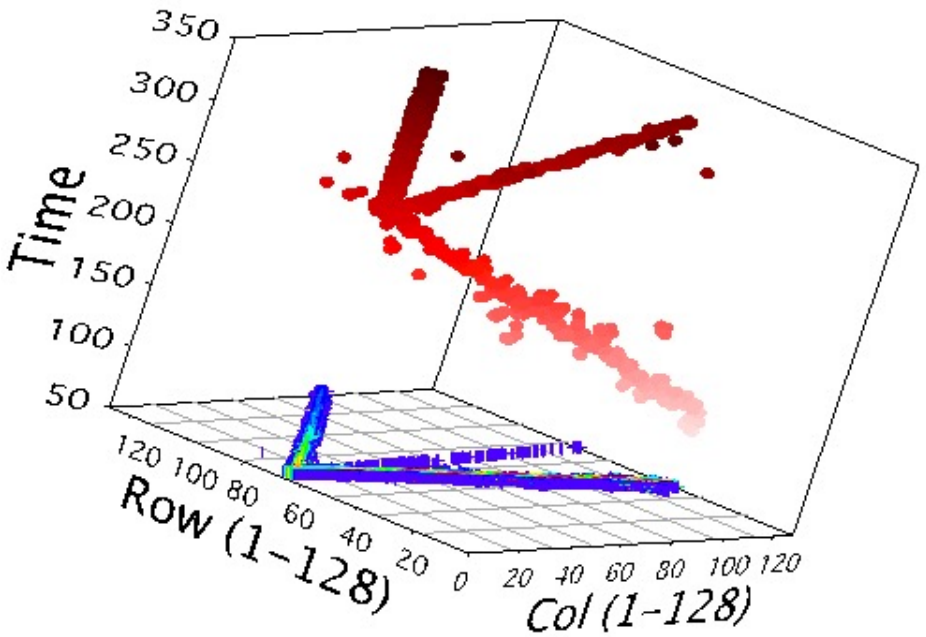
- **GANIL (France)**
  - **3 experiments scheduled in 2021**
  - **Campaign planned Spring 2022**
- **TRIUMF (Canada)**
  - **Endorsed LOI to bring to ISAC!**
  - **1 experiment approved**
  - **Possible campaign in 2023?**
- **RIKEN (Japan)**
  - **1 experiment approved**
- **ISOLDE (CERN)**
  - **1 experiment approved**
- **Lots of amazing physics to come!**



Exotic Nuclei Active Target (EXACT–TPC)

- **An Active Target for TRIUMF!**
  - **Powerful addition to ISAC**
- **Broad scientific program**
  - **Exotic nuclear decay**
  - **Resonant elastic scattering**
  - **Capture and transfer reactions**
  - **Reactions on ^{3}He, ^{4}He targets**
- **Collaboration**
  - **Saint Mary's (P.I. Ritu Kanungo)**
  - **TRIUMF, SFU, Guelph, Regina**
  - **McMaster, GANIL, Michigan State**
- **TRIUMF Letter of Intent**
  - **Endorsed (priority 1) June 2021!**





Thank you so much!

- Exotic Nuclear Decay Experiments
  - Powerful tool to study nuclei
  - Challenging experiments!
  - Requires novel detection systems
- These are just a few things we do!
  - Regina Cube for Multiple Particles
  - ACTAR TPC and EXACT TPC
- Many other projects in my group!
  - Always looking for students!
  - Please contact me if interested!!

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