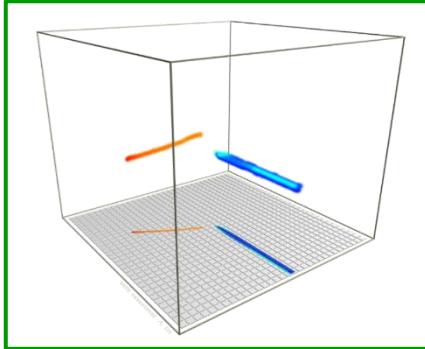


# proton radioactivity studies with ACTAR TPC

J. Giovinazzo – LP2iB (former CENBG) – Bordeaux  
**(for E690 and E791 collaborations + ACTAR TPC + GANIL/LISE)**  
D. Rudolph, T. Roger, B. Blank, A. Ortega Moral...

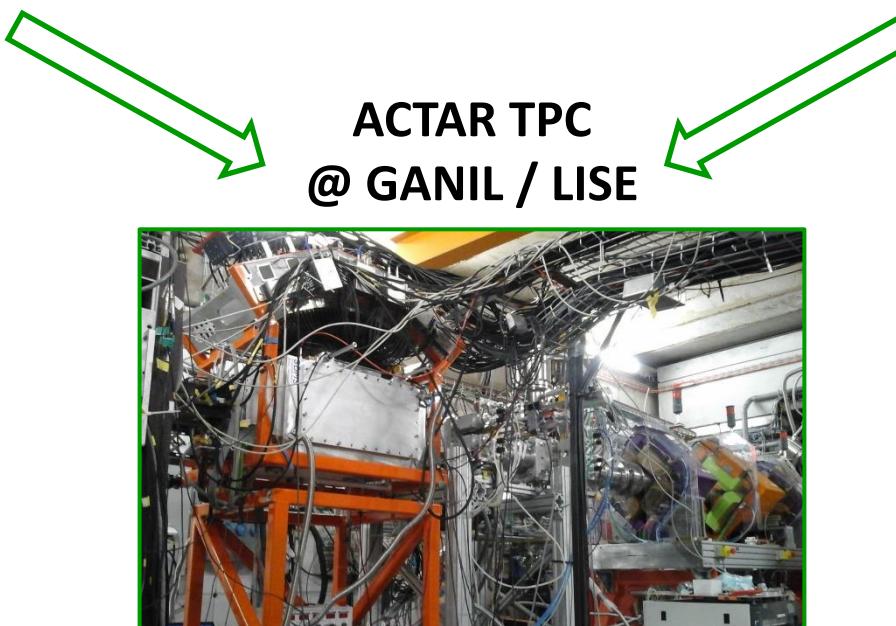
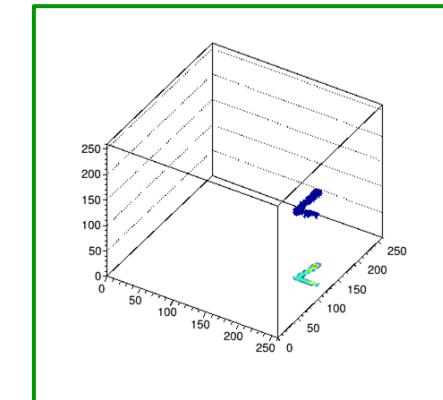
**1 proton radioactivity**

$^{53m}\text{Co}$  &  $^{54m}\text{Ni}$



**2 proton radioactivity**

$^{48}\text{Ni}$

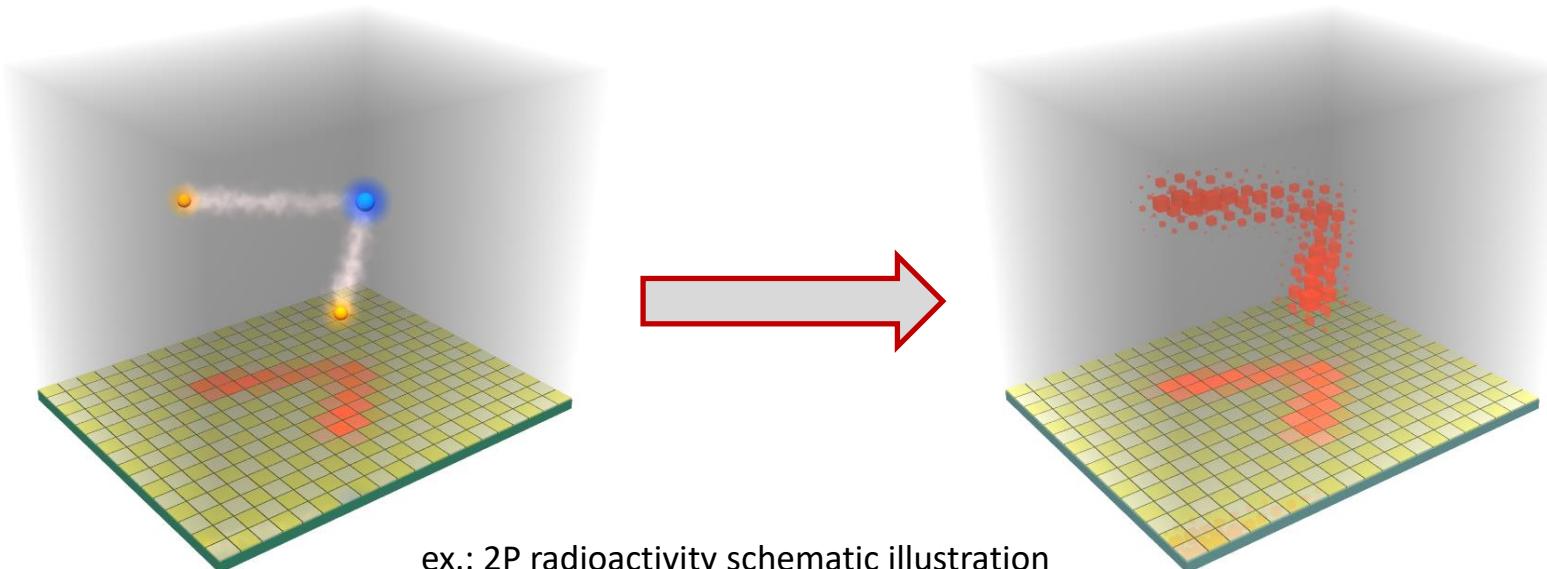


**ACTAR TPC**

# ACTAR TPC, a 4D detector: tracking and energy

- 2D collection plane (pads/pixels)
- time projection chamber: drift of ionization signal
- time sampling of vertical dimension (ionization drift)

→ full 3D “voxelization” of the energy loss distribution  
(for tracks analysis)

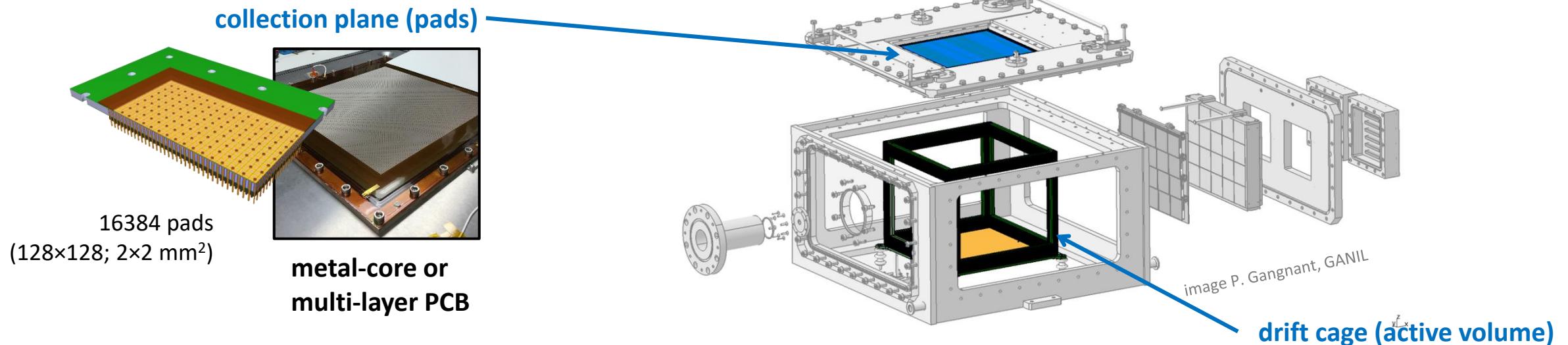


a versatile detector

**Active Target mode:** inelastic scattering, transfer,...

**Decay TPC mode:** implantation-decay experiments

# the ACTAR TPC device



## readout electronics

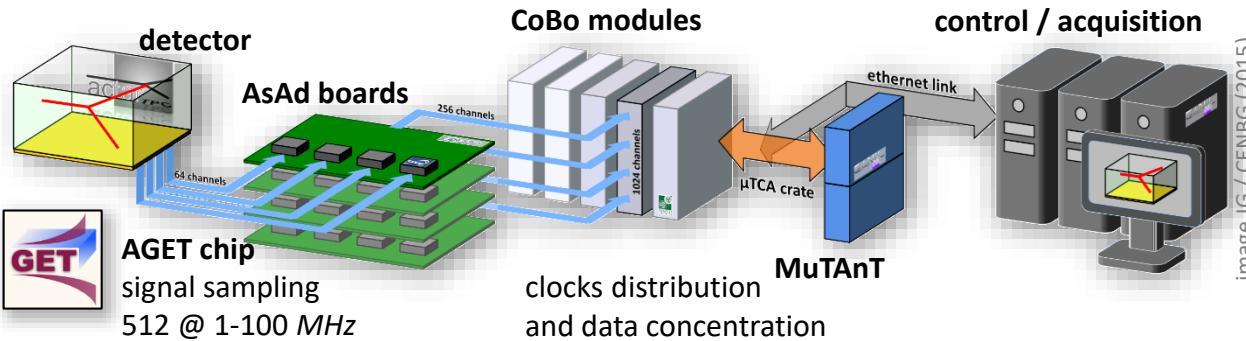


image JG / CENBG (2015)

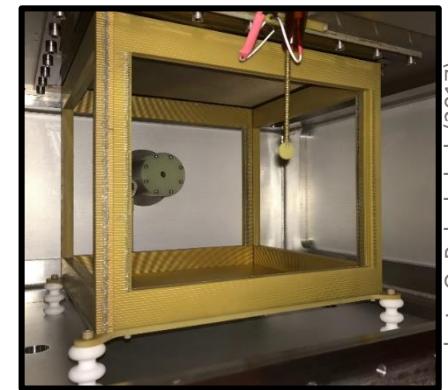


photo O. Poleschuk (2017)

## decay experiments (GANIL/LISE)

2019: proton radioactivity of  $^{54m}\text{Ni}$  and isospin symmetry ( $^{54m}\text{Fe}$ )

2021: 2-proton radioactivity of  $^{48}\text{Ni}$  & other exotic decays

E690

1-proton radioactivity

# isospin symmetry: the case of $^{54}\text{Fe}$ & $^{54}\text{Ni}$

## mirror nuclei $^{54}\text{Fe}$ and $^{54}\text{Ni}$

- comparison of  $10^+$  isomers
- near  $N = Z = 28$  shell closures
- test isospin symmetry (breaking)  
**very few cases for such comparison...**
- test coupling to the continuum

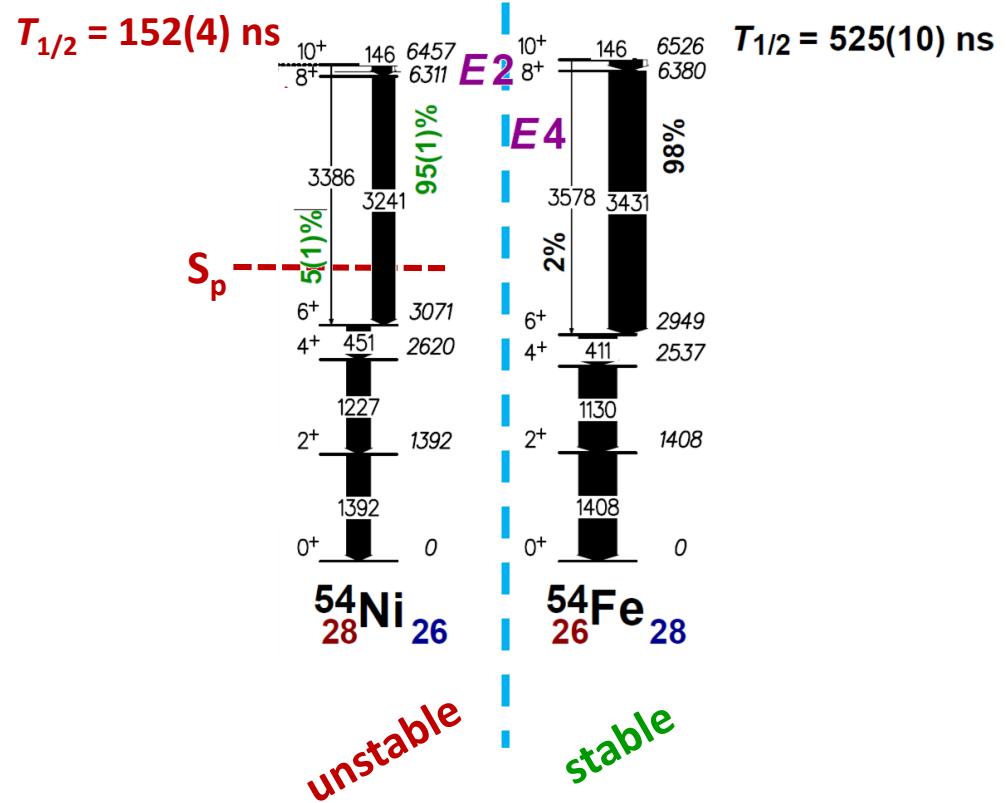
## $^{54}\text{Fe}$ isotope

- stable ground state
- decay of isomer: known from gamma spectroscopy

## $^{54}\text{Ni}$ isotope

- unstable (proton rich)  
→ low proton separation energy
- decay of isomer  
→ short half-life

only accessible at fragmentation facilities (+ separator)  
→ partially known from gamma spectroscopy (GSI /RISING)  
→ above proton emission threshold



# isospin symmetry: the case of $^{54}\text{Fe}$ & $^{54}\text{Ni}$

## $^{54}\text{Ni}$ isomer decay

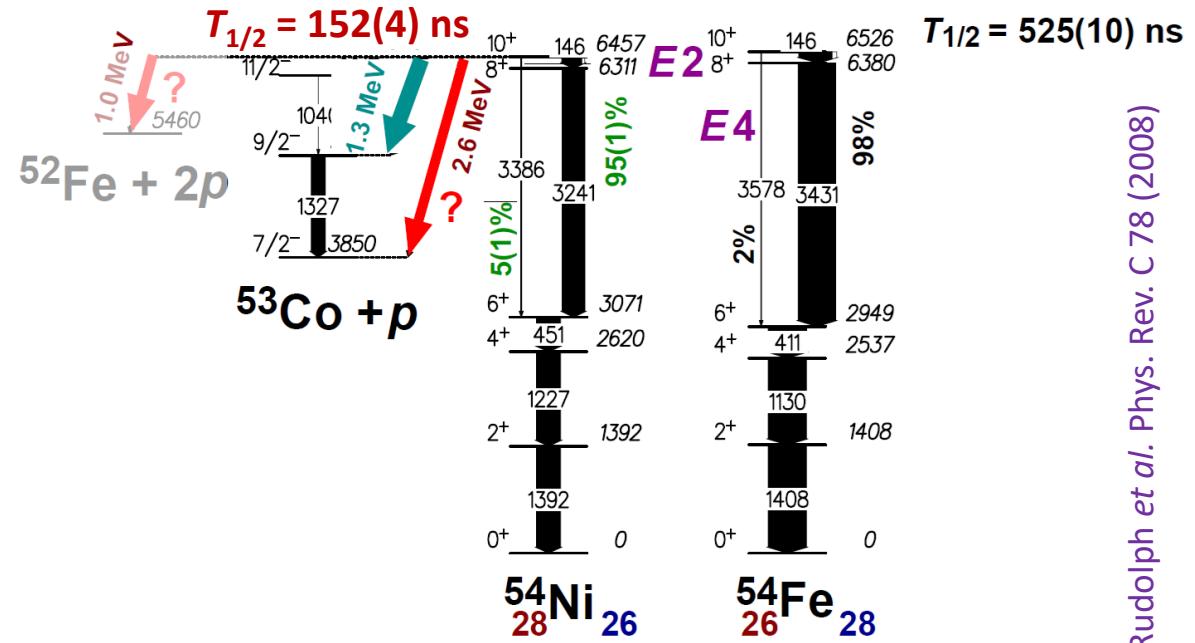
→ above proton emission threshold

**but very high angular momentum**

**1.3 MeV proton ( $\ell = 5$ )** deduced  
from gamma coincidence (RISING)

**2.6 MeV proton ( $\ell = 7$ )** may exist  
(not observed)

possible 2P branch  
(expected extremely small)

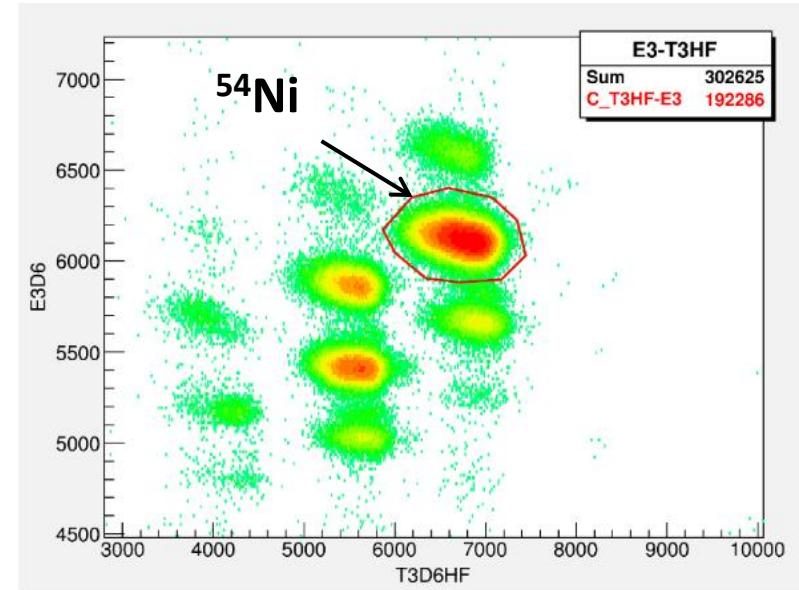
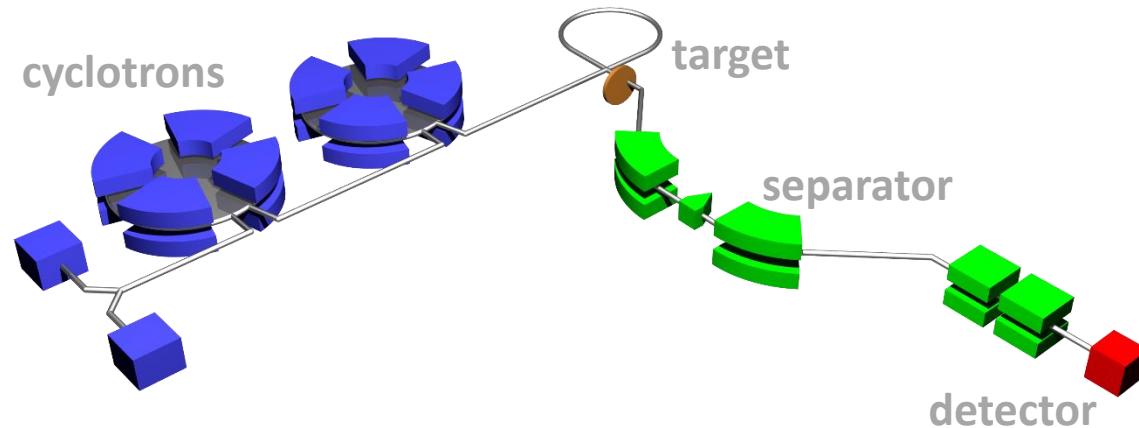


need for the full  
decay scheme

# decay of the $10^+$ isomer in $^{54}\text{Ni}$ : GANIL/LISE experiment (E690)

## standard fragmentation production

75 MeV/A  $^{58}\text{Ni}^{26+}$  stable beam, 200  $\mu\text{m}$  nat. Ni target  
LISE3 fragment separator  
(A,Z) separation, standard ToF –  $\Delta E$  (Si) ident.



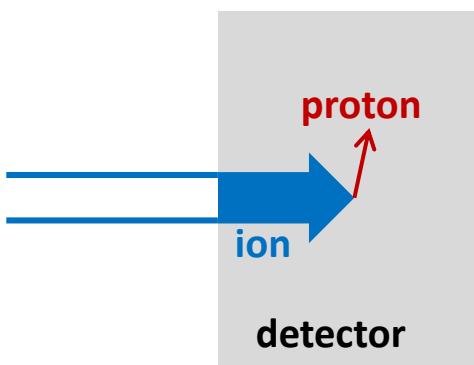
## protons detection

- about **0.1%** of ions produced in isomeric state
- **few MeV proton signal on top of 1 GeV ion signal !**

→ no standard implantation/decay in a silicon detector

→ **tracking in a gas detector (ACTAR TPC)**

**protons emitted out of the ion track  
can be observed !**

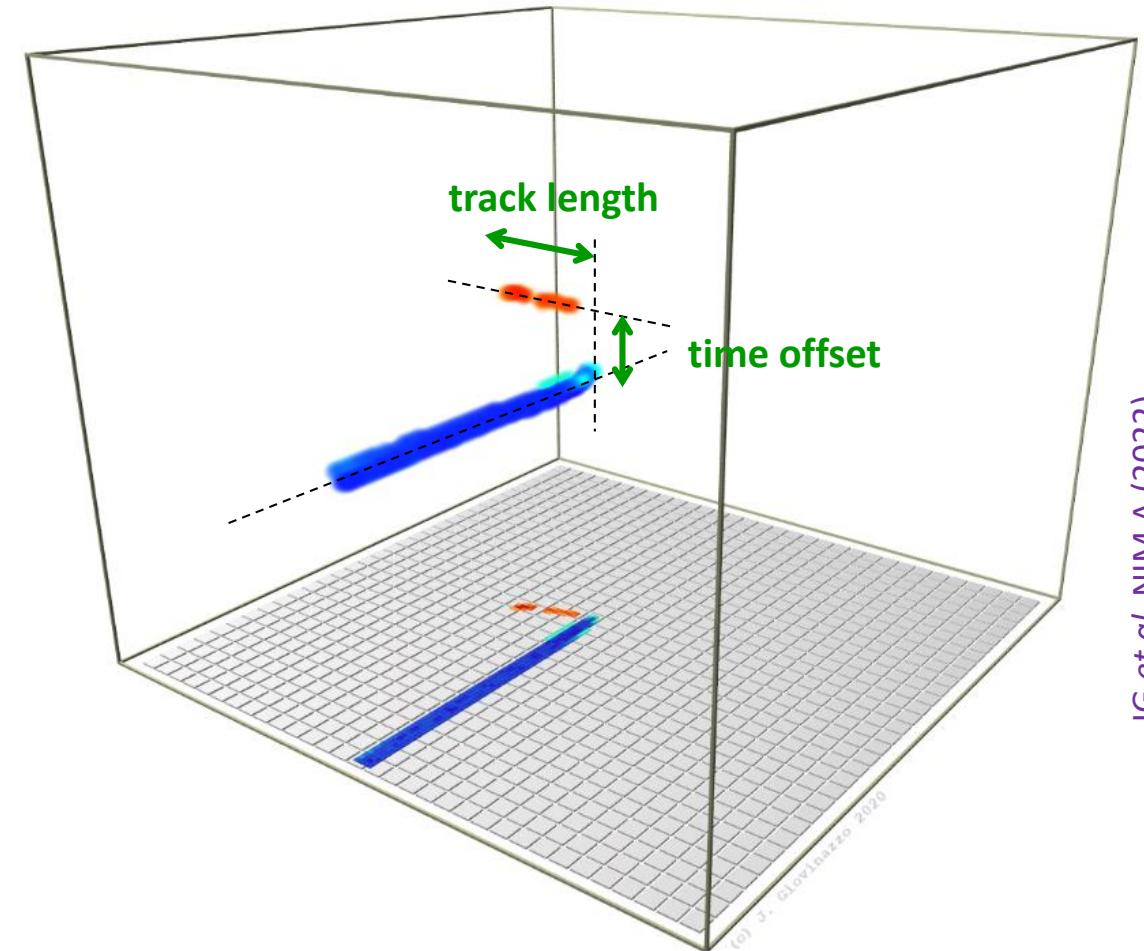


# extracting experimental information

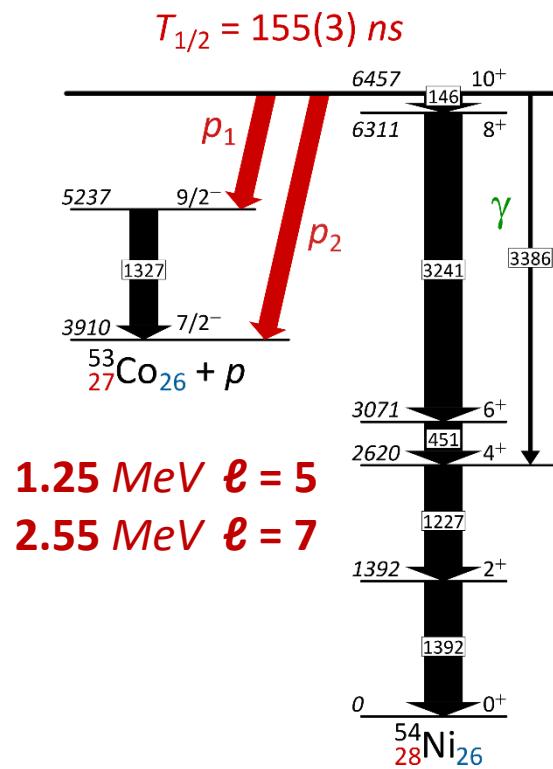
- selection of  $^{54}\text{Ni}$  and isomer decay events
- identify and separate ion and proton signal  
(degraded pad plane)
- drift velocity estimate  
TPC principle:  $(X, Y, T) \rightarrow (X, Y, Z = v_d \cdot T) \rightarrow$  track length  
from protons signal
- 3D proton tracks fit
  - trajectory points
  - + Bragg peak model
  - + signal dispersion

track length → energy

proton start / ion stop time offset → decay time



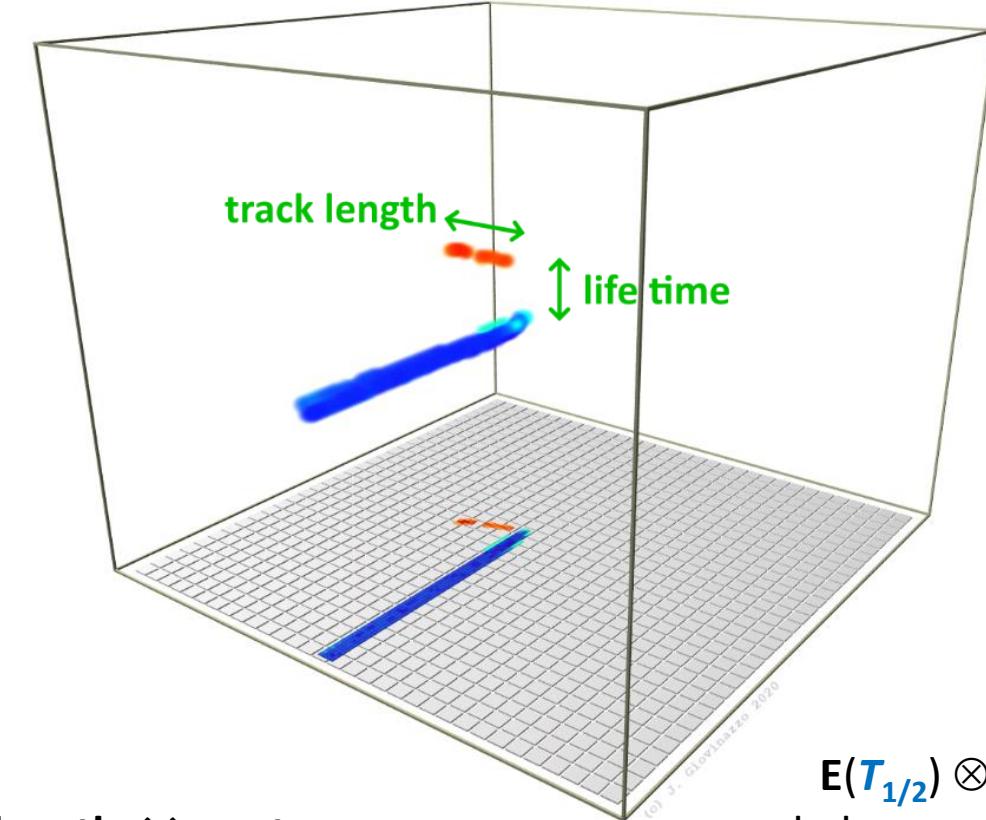
# 4D imaging of proton radioactivity



different detection efficiency for  
1.2 and 2.5 MeV

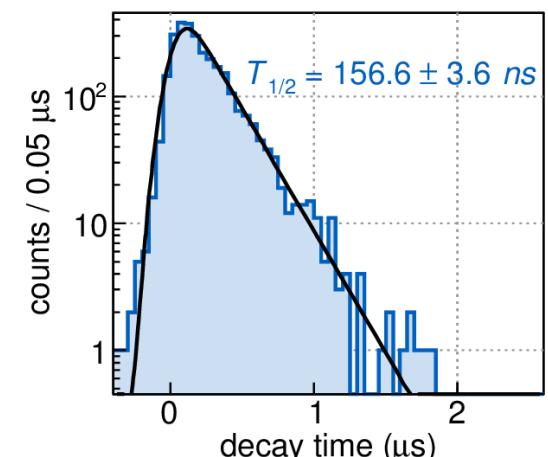
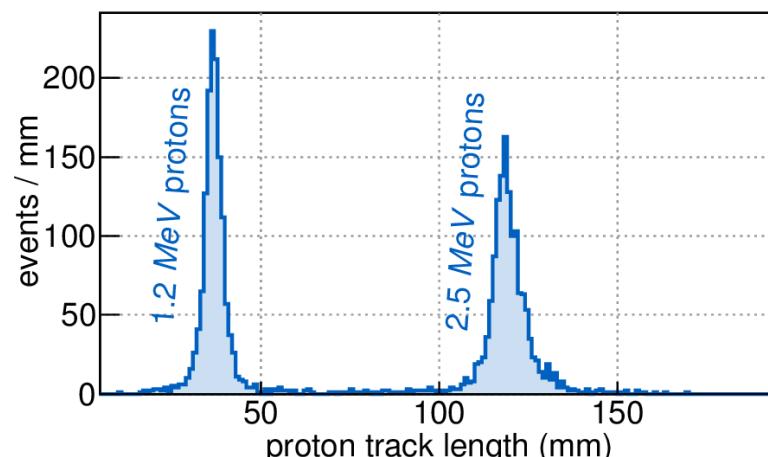
full simulation

branching ratio



JG et al. Nature Comm. (2021)

track length ↔ proton energy



$$E(T_{1/2}) \otimes G(\sigma_T)$$

rad. decay exp. resol.

# final result: protons from ACTAR TPC and gammas from RISING

ACTAR TPC exp.:  $R \left( \frac{P_1}{P_1+P_2} \right) = 57.33 \pm 1.90 \%$

RISING campaign:  $R \left( \frac{\gamma}{\gamma+P_1} \right) = 64.0 \pm 2.0 \%$

Global:

- $I_{p1} = 28.4 \pm 1.3 \%$
- $I_{p2} = 21.1 \pm 1.6 \%$
- $I_\gamma = 50.5 \pm 2.3 \%$

→ comparison with theory (shell model)

proton decay half-life:  $\Gamma = (C^2 S) \cdot \Gamma_{SP}$

(B.A. Brown, NuShellX, with GFPX1A and KB3G interactions)

calculations in the *fp* shell + **high  $\ell$**  orbitals:

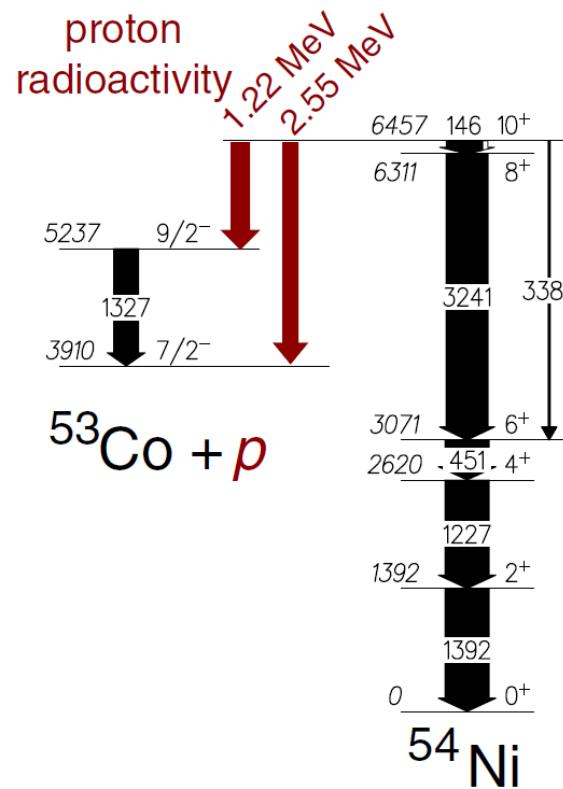
→ 1 proton in  **$0h_{11/2}$**  ( $\ell = 5$ ) or  **$0j_{13/2}$**  and  **$0j_{15/2}$**  ( $\ell = 7$ )

→  $T_{1/2}$  governed by very weak components of the wave functions ( $\sim 10^{-6}$ )

**fairly good agreement** for the **2.55 MeV** transition to the  **$7/2^-$  state**

**not satisfying** for the **1.22 MeV** transition to the  **$9/2^-$  state**

(mixing with a 2<sup>nd</sup> 10+ state, less truncated space...)

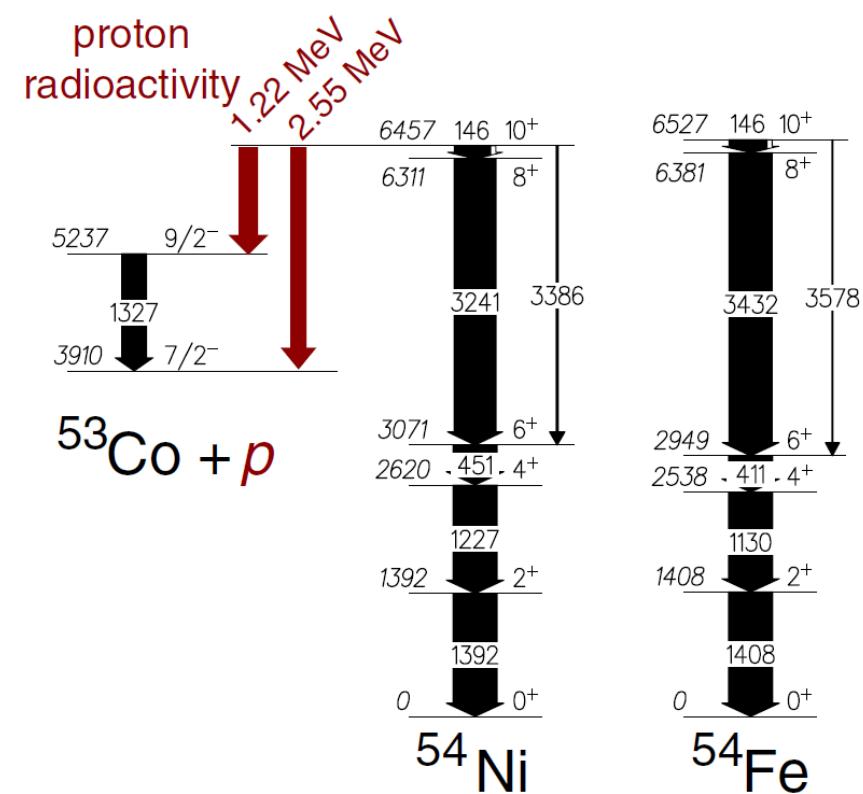


# $^{54}\text{Fe}$ and $^{54}\text{Ni}$ mirror symmetry

complete decay scheme allows for a detailed analysis

- test of isospin non-conserving terms of the interaction
- constraints on effective isoscalar and isovector effective charges from  $B(E4)$

observable	$^{54}\text{Fe}$ exp	$^{54}\text{Ni}$ exp
$B(E2; 2^+ \rightarrow 0^+)$	11.1(3)	10.0(19)
$B(E2; 6^+ \rightarrow 4^+)$	3.25(5)	—
$B(E2; 10^+ \rightarrow 8^+)^a$	1.70(3)	1.91(10)
$B(E4; 10^+ \rightarrow 6^+)$	0.80(9)	4.42(98)
$br_{\gamma+IC}(10^+ \rightarrow 6^+)$	1.8(2)	5.1(11)
$T_{1/2}(10^+)_{\gamma+IC}$ (ns)	364(7)	307(15)
$Q(10^+)$ (efm $^2$ )	52(8) <sup>b</sup>	—
$\mu(10^+)$ ( $\mu_N^2$ )	7.281(10)	—
$E_x(10^+)$ (keV)	6527.1(11)	6457.4(9)



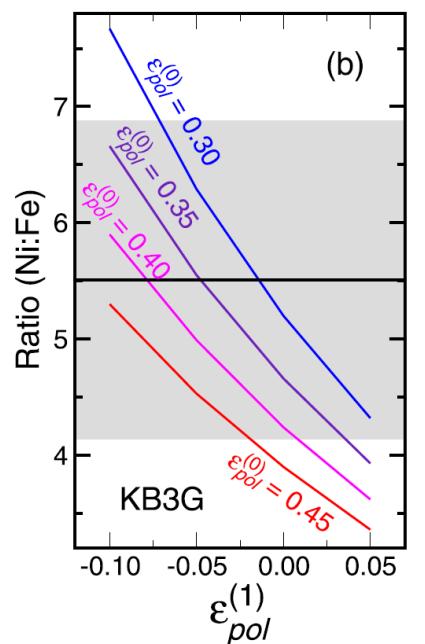
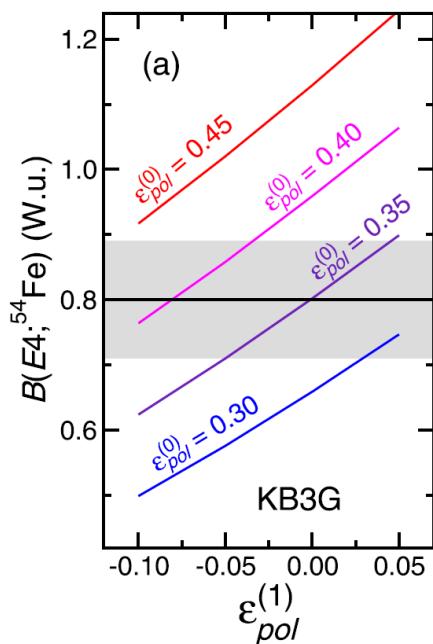
# $^{54}\text{Fe}$ and $^{54}\text{Ni}$ mirror symmetry

(D. Rudolph, with code ANTOINE)

very good agreement with experiment can be achieved  
for mirror energy differences

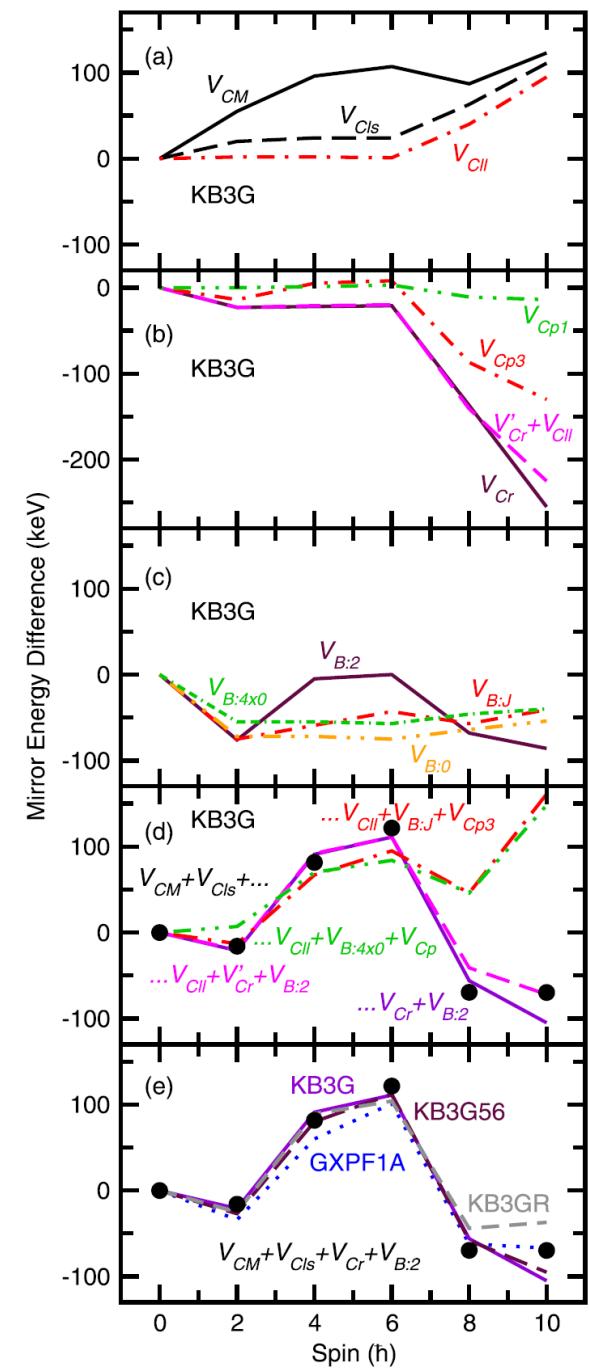
but some inconsistencies in the mass region

- not satisfying  $V_{Cp}$  parametrization  
p-orbital occupation numbers very different  
for  $A = 54$ ,  $A = 56$  and  $A = 58$
- deduced effective charges: large discrepancies in  $B(E4)$   
for neighbor nuclei  $^{52}\text{Mn}$ ,  $^{53}\text{Fe}$  and  $^{52}\text{Fe}$



D. Rudolph et al. Phys. Lett. B (2022)

study of isospin non-conserving terms  
different SM interactions



D. Rudolph et al. Phys. Lett. B (2022)

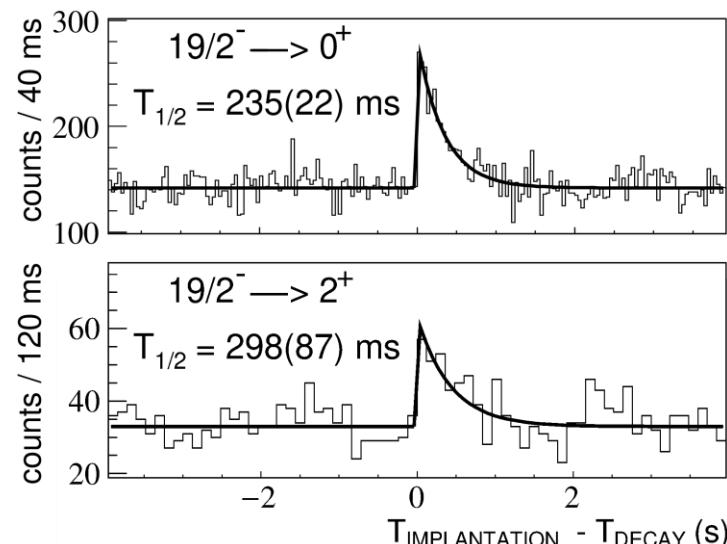
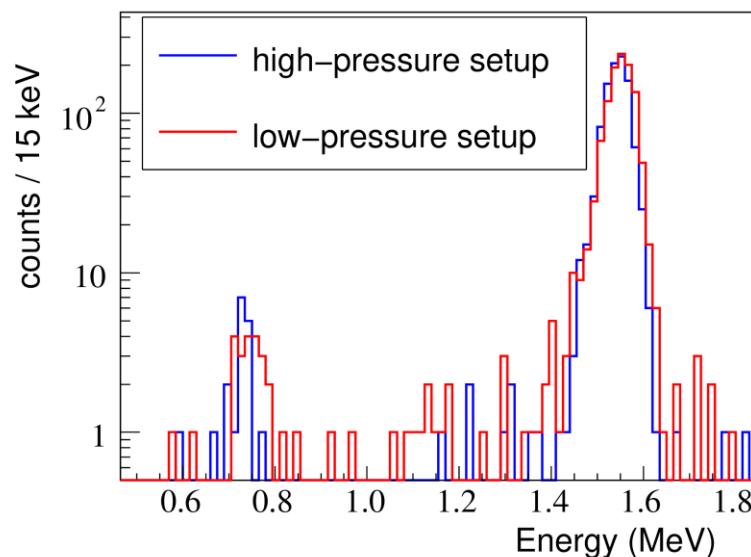
# isomer proton radioactivity conclusion

**new type of measurement** (short lived proton decay)

- 3D tracking + decay time
- complete decay pattern of  $^{54m}\text{Ni}$  with  $\ell = 5$  and  $\ell = 7$  proton branches

**similar measurement for  $^{53m}\text{Co}$  with  $\ell = 7$  and  $\ell = 9$**

first observed proton radioactivity, 1970



L.G. Sarmiento, T. Roger,  
accepted Nature Comm. (2023)

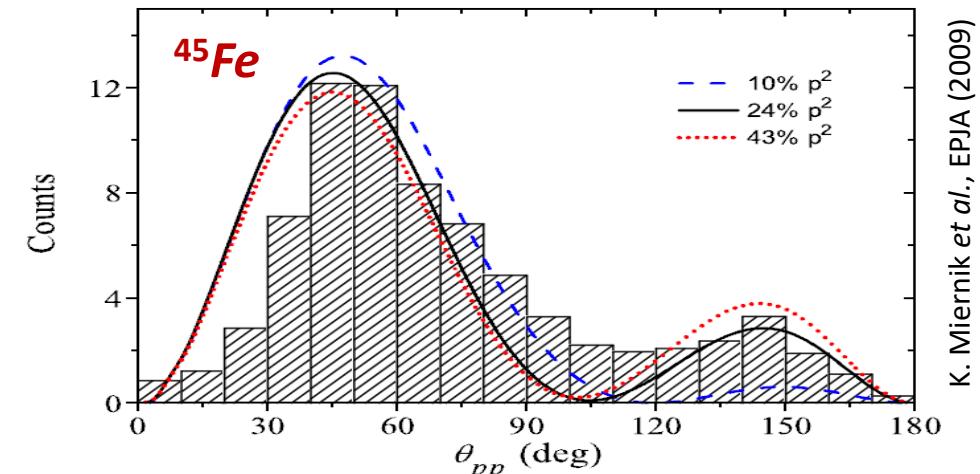
E791  
2-proton radioactivity

# 2-proton radioactivity

## experimental status

4 known cases (long-lived)

- **$^{45}\text{Fe}$** : first **indirect** evidence (J.G. *et al.* 2002, M. Pfützner *et al.* 2002)  
**angular distribution** (K. Miernik *et al.*, 2009)
- **$^{54}\text{Zn}$** : B. Blank *et al.* 2005  
few p-p correlations (P. Ascher *et al.*, 2011)
- **$^{48}\text{Ni}$** : indication (B. Blank *et al.* 2005)  
few p-p correlations (K. Miernik *et al.*, 2007)
- **$^{67}\text{Kr}$** : J.G. *et al.* 2015 → **half-life problem...**



## theoretical interpretations

- **models based on nuclear structure**  
R-matrix formalism, shell model wave functions, p-p resonance (Barker & Brown)  
shell-model embedded in the continuum (SMEC)  
→ no dynamics, limited comparison:  $T_{1/2}(Q_{2p})$
- **3-body model**  
core+p+p system (Grigorenko)  
→ emission dynamics (angular & energy correlations), no intrinsic structure prediction
- **recent approaches**
  - **hybrid model** (Brown)
  - **Gamow Coupled Channels (GCC)** (Wang & Nazarewicz)

# the problem of $^{67}\text{Kr}$ half-life

“hybrid” model

3-body model (L.V. Grigorenko)  
good dynamics  
 $T_{1/2}$  for  $(s^2)$ ,  $p^2$  and  $f^2$  config.

shell-model (B.A. Brown)  
2-proton amplitudes  
for  $(s^2)$ ,  $p^2$  and  $f^2$  config

“Shell model  
corrected half-lives”  
 $A = A(f^2) + A(p^2) \rightarrow T_{1/2}(2\text{P})$

B.A. Brown et al., PRC 2019

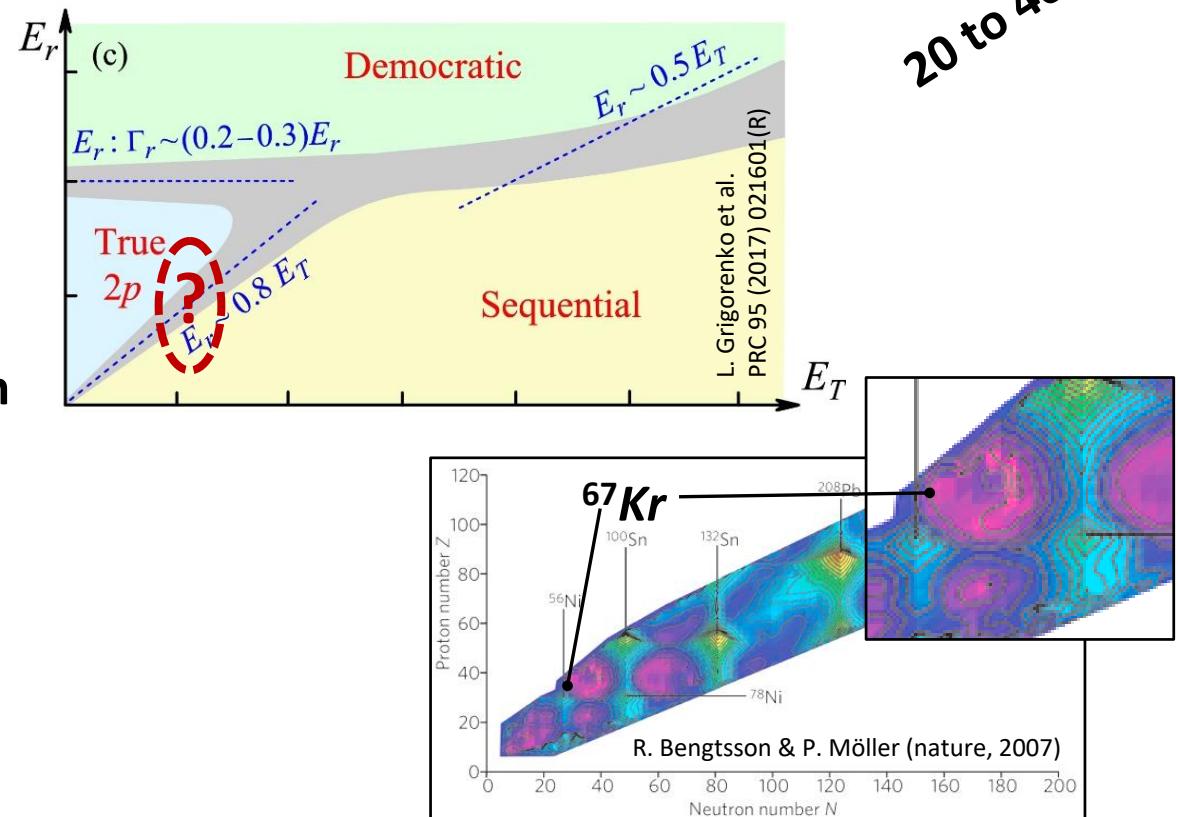
	calculation	experiment(s)	
$^{45}\text{Fe}$	$1.8 - 5.9 \text{ ms}$	$3.6 \pm 0.4 \text{ ms}$	OK
$^{48}\text{Ni}$	$0.4 - 1.3 \text{ ms}$	$4.1 \pm 0.4 \text{ ms}$	~OK
$^{54}\text{Zn}$	$0.6 - 1.7 \text{ ms}$	$1.98^{+0.73}_{-0.41} \text{ ms}$	~OK
$^{67}\text{Kr}$	$300 - 900 \text{ ms}$	$21 \pm 12 \text{ ms}$	!?

B.A. Brown, B.J. Blank,  
J.G., PRC 2019

factor 20 to 40 off !!!

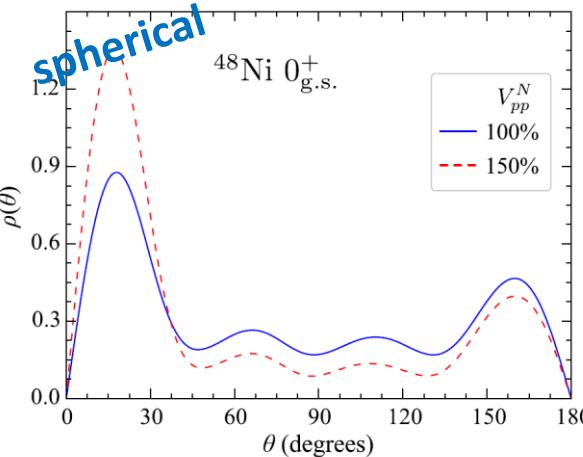
## 2 proposed hypothesis

- transition between direct and sequential 2P emission  
(L.V. Grigorenko)  
→ different energy sharing
- nuclear deformation  
(S. Wang & W. Nazarewicz)  
→ angular distribution prediction



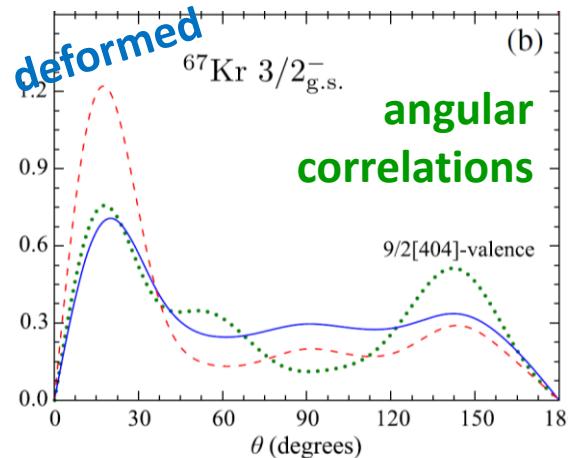
# new measurements needed

48Ni



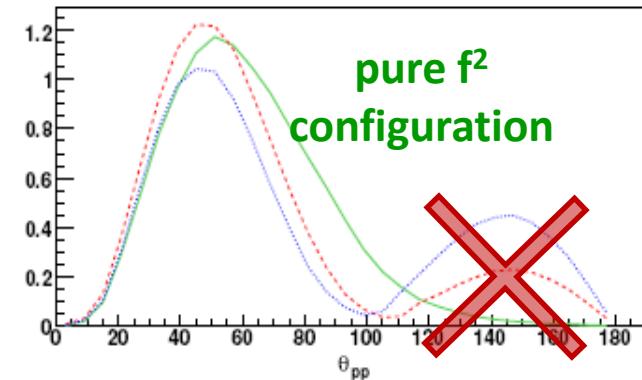
consistent structure  
and dynamics description

67Kr



3-body model

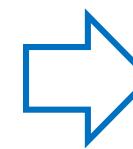
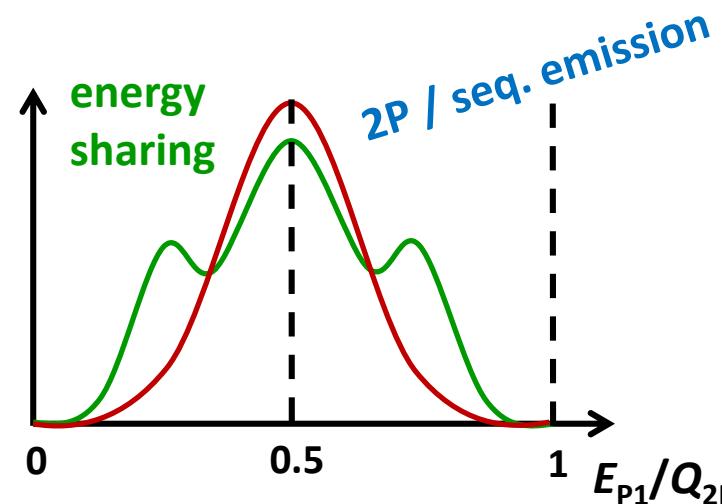
not available for  ${}^{48}\text{Ni}$   
extrapolation from  ${}^{45}\text{Fe}$  &  ${}^{54}\text{Zn}$



good agreement  
in the case of  ${}^{45}\text{Fe}$ ...



GANIL



RIKEN

# GANIL exp. 2021 (E791): aiming at $^{48}\text{Ni}$ 2-proton radioactivity

fragmentation of a 5  $\mu\text{A}$   $^{58}\text{Ni}$  beam on a  $^{\text{nat}}\text{Ni}$  target

fragments selection with LISE3 spectrometer

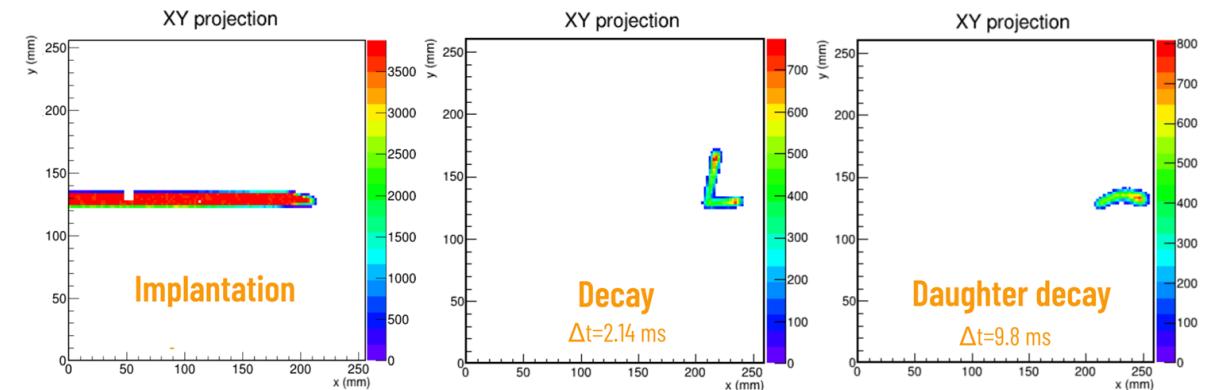
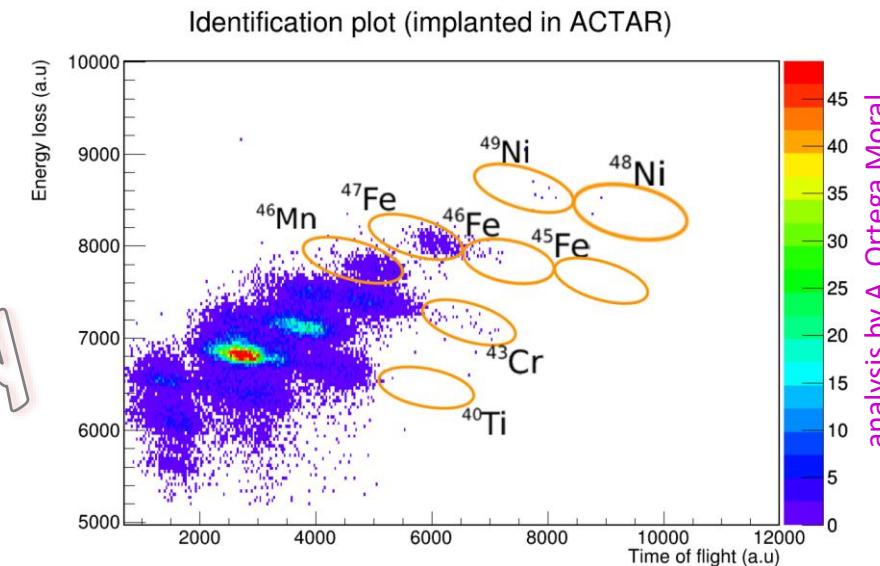
**implantation in ACTAR TPC**

**production rates did not  
fulfil our expectations...**

identified  
stopped  
in ACTAR

$^{40}\text{Ti}$	6100	362
$^{43}\text{Cr}$	21000	4300
$^{46}\text{Mn}$	41000	4700
$^{47}\text{Fe}$	12100	2200
$^{46}\text{Fe}$	960	550
$^{45}\text{Fe}$	80	13
$^{49}\text{Ni}$	170	60
$^{48}\text{Ni}$	11	7

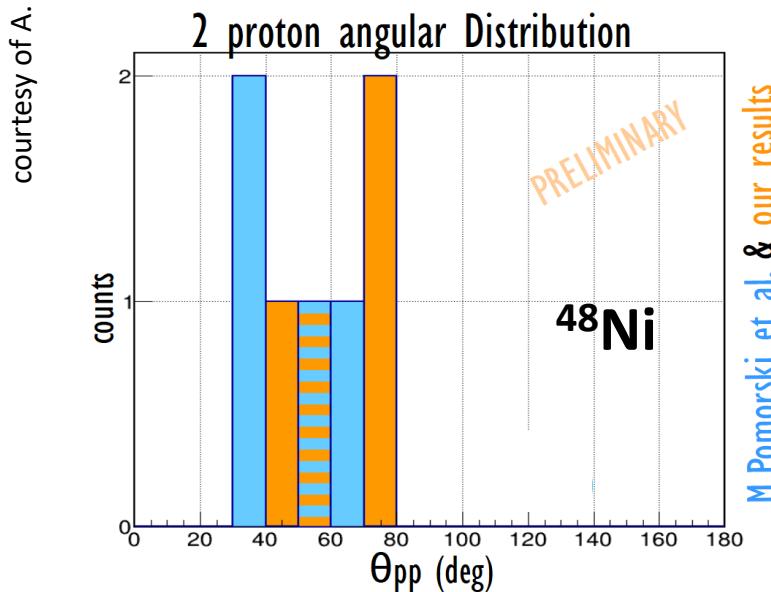
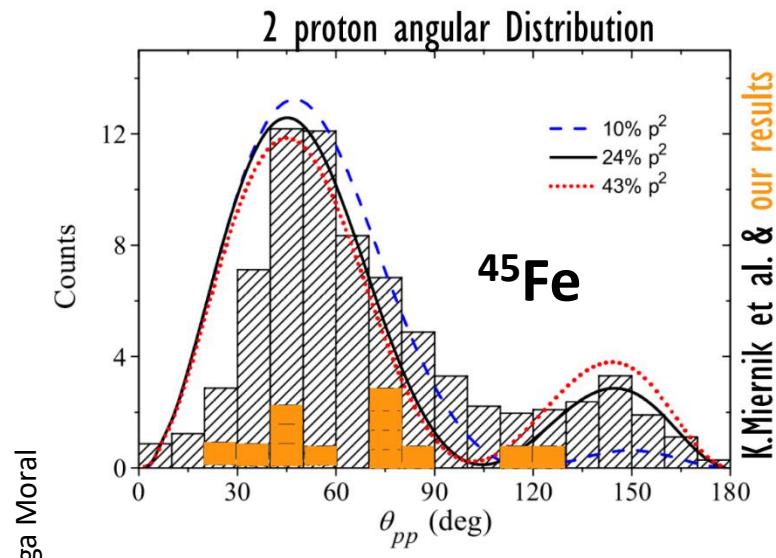
*preliminary*



**only few 2P decay events ( $^{48}\text{Ni}$  &  $^{45}\text{Fe}$ )**

courtesy of A. Ortega Moral

# 2-proton radioactivity events



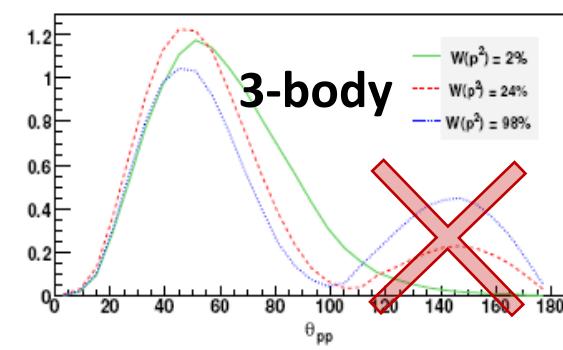
low additional statistics

$^{45}\text{Fe}$

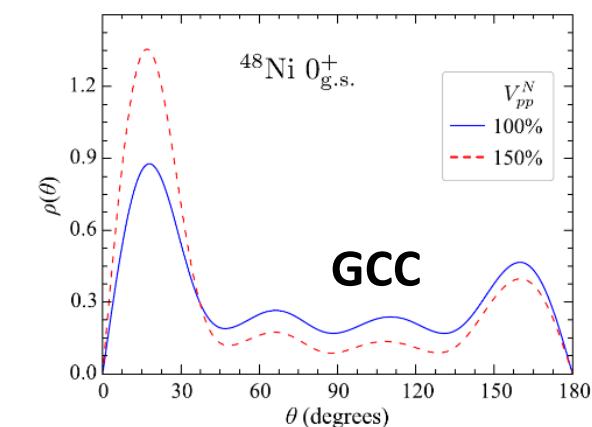
agreement with previous distribution  
no significant change  
side product of the experiment

$^{48}\text{Ni}$

limited comparison with theory  
but...

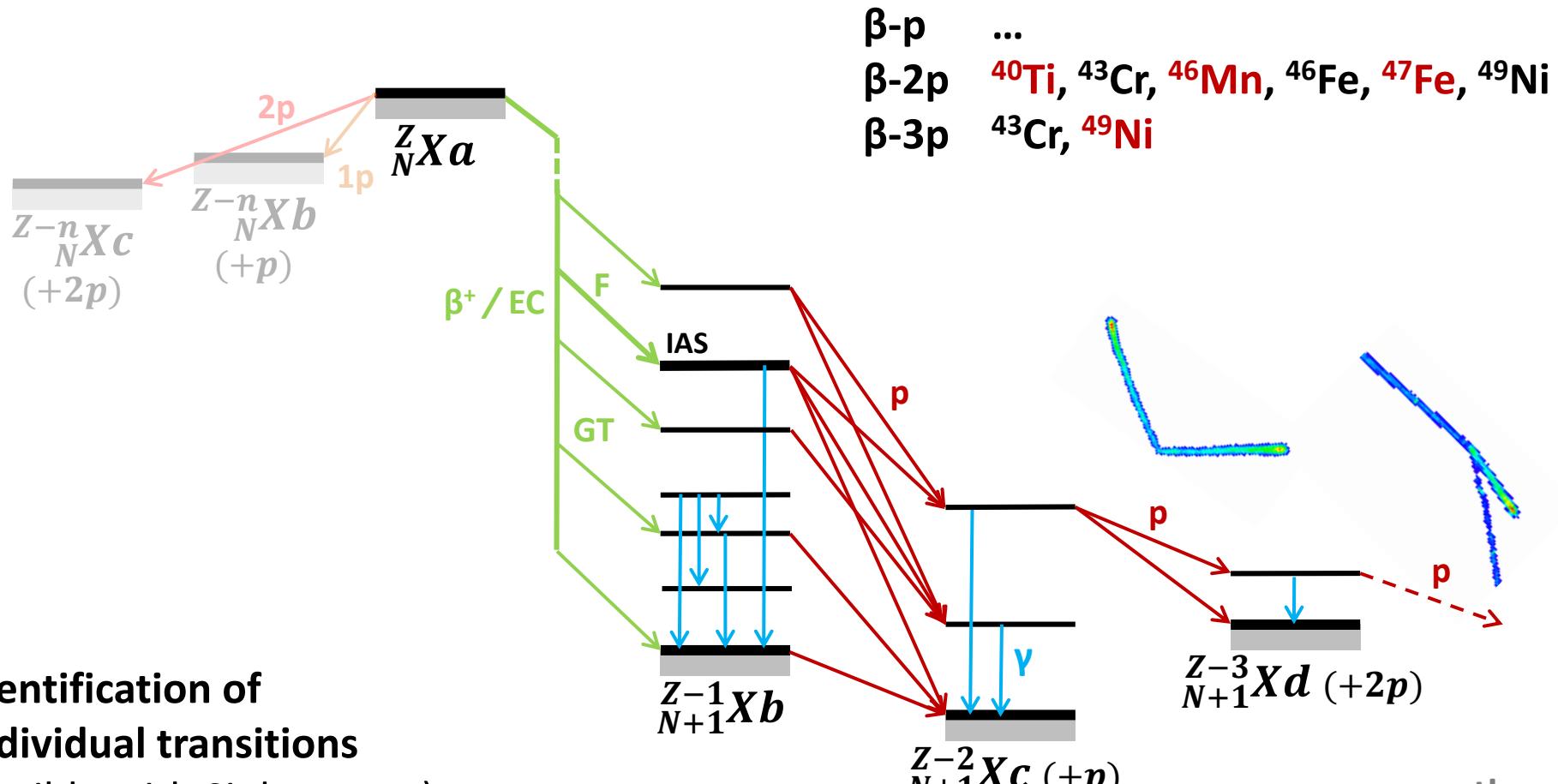


measurement for  $^{67}\text{Kr}$  required !  
(→ RIKEN)



# beta-delayed proton(s) emissions

decay spectroscopy of very exotic nuclei in the  $^{48}\text{Ni}$  region



TPC: identification of  
individual transitions  
(not possible with Si detectors)

currently under analysis  
(A. Ortega Moral PhD)

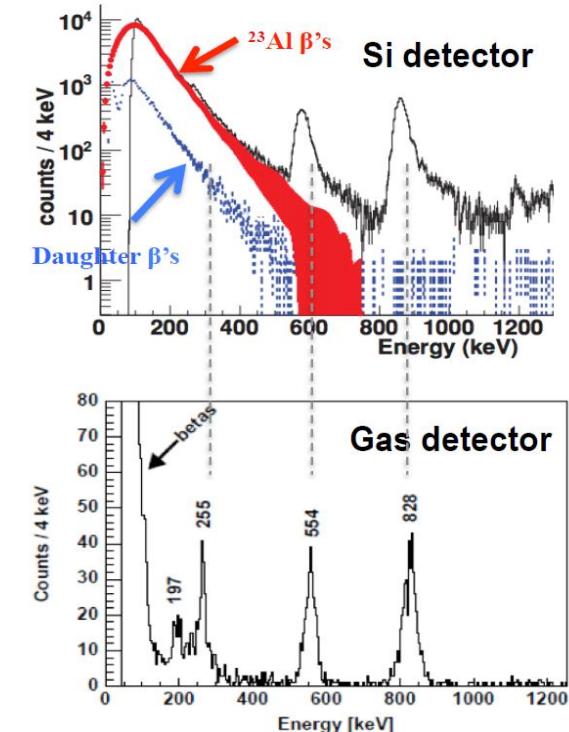
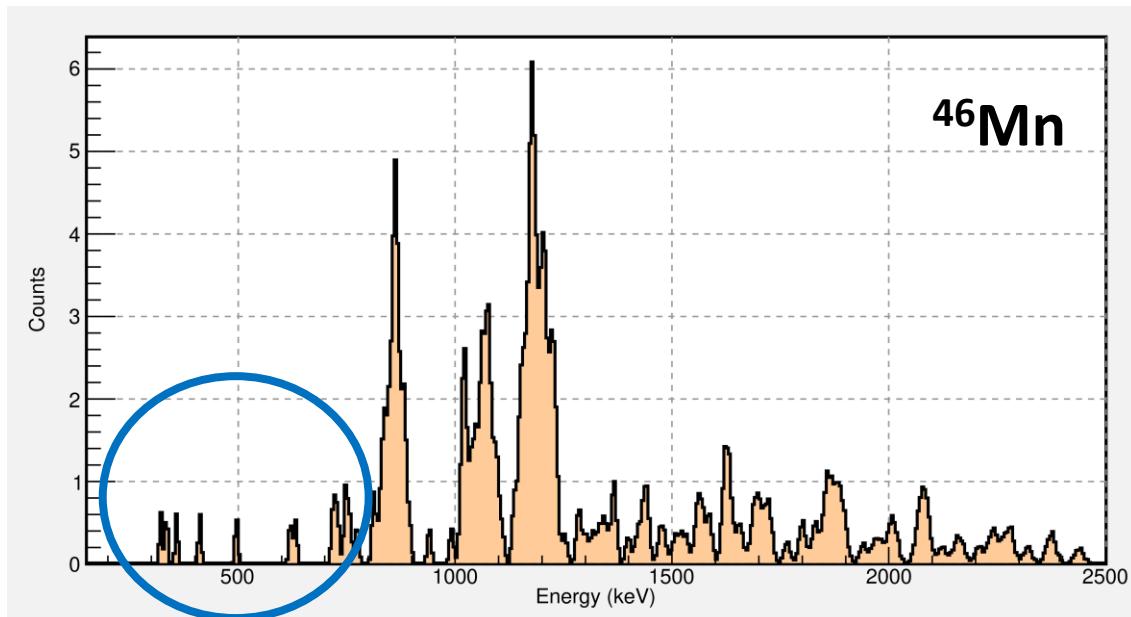
# low energy protons

just above separation threshold  
astrophysics: ( $p,\gamma$ ) resonances

huge beta background with Si detectors

TPCs can be transparent to beta particles !  
(ex.: AstroBox (Texas), AstroTPC (TRIUMF)... program)

$^{46}\text{Mn}$  decay (in 2021 E791 exp. data)



(A.M. Sanchez)

- obs. of protons below 1 MeV
- study of  $^{46}\text{Cr} \leftarrow ^{45}\text{V} + p$   
inverse reaction  
missing ingredient for  
type II supernovae models

# concluding remarks

**first campaigns of ACTAR TPC detector**

2019 & 2021 (active target and decay experiments)

**very well suited for exotic decays involving charged particles !!**

**2-proton radioactivity ( $^{48}\text{Ni}$ )**

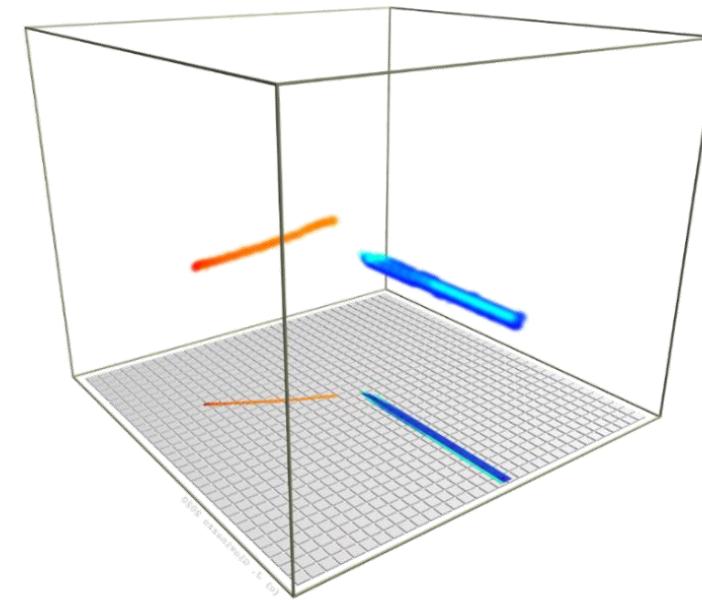
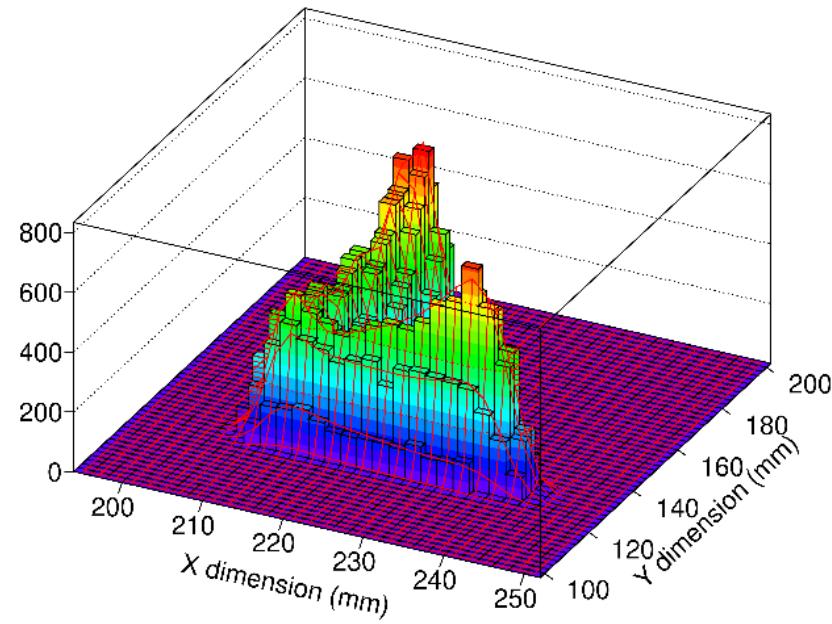
- under analysis (limited statistics)
- experimental technique is well adapted
- results to be extracted for other exotic decays in the mass region

(short-lived) **isomers proton radioactivity**

- unique access to the full decay pattern
- first measurement of this kind
- $^{54\text{m}}\text{Ni} / ^{54\text{m}}\text{Fe}$  isospin symmetry: it makes the study possible  
(even if not satisfying today)

**plenty of room for more interesting measurements...**

thanks to the **E690** ( $^{54m}\text{Ni}$ ) collab. (D.Rudolph et al.), the **E791** ( $^{48}\text{Ni}$ ) collab. (J.G. et al.),  
the ACTAR TPC collab. (T. Roger et al.), and the GANIL staff and LISE team  
and the PhD students (**J. Lois Fuente, A. Ortega Moral, A. Cassisa, Q. Delignac**)



thank you for your attention

# **backup slides**

# mixing structure and dynamics ?

L.V. Grigorenko: good dynamics

half-lives:

$T_{1/2}$  for pure ( $s^2$ ,)  $p^2$  and  $f^2$  config.

B.A. Brown: good structure

2-proton amplitudes:

for pure ( $s^2$ ,)  $p^2$  and  $f^2$  config

“hybrid” model

“Shell model corrected half-lives”

$$A = A(f^2) + A(p^2) \longrightarrow T_{1/2}(2P)$$

B.A. Brown et al.,  
PRC 2019

calculation

experiment(s)

$^{45}Fe$        $1.8 - 5.9\ ms$        $3,6 \pm 0,4\ ms$       OK

$^{48}Ni$        $0.4 - 1.3\ ms$        $4.1 \pm 0,4\ ms$       ~OK

$^{54}Zn$        $0.6 - 1.7\ ms$        $1.98^{+0.73}_{-0.41}\ ms$       ~OK

$^{67}Kr$        $300 - 900\ ms$        $21 \pm 12\ ms$       !?

(Goigoux et al., PRL 2016)

2016

factor  
20 to 40 off !!!

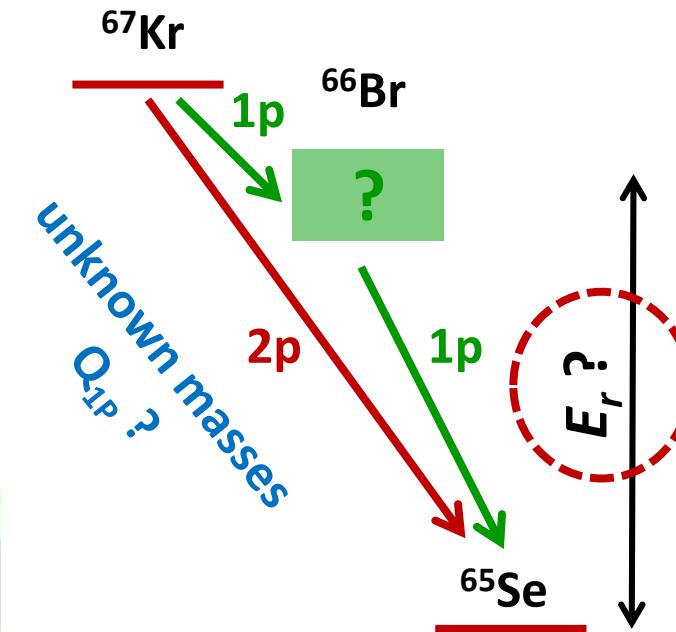
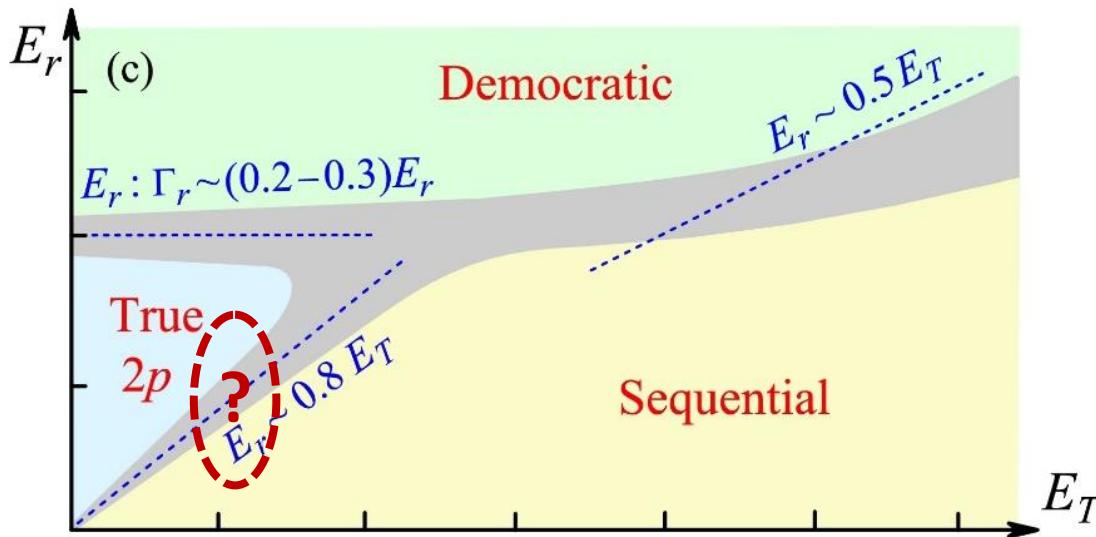
“puzzling two-proton decay of  $^{67}Kr$ ” ?

(title from Wang & Nazarewics, PRL 2019)

# first hypothesis: transition from 2P to sequential decay ?

- possible transition region depending on intermediate state position

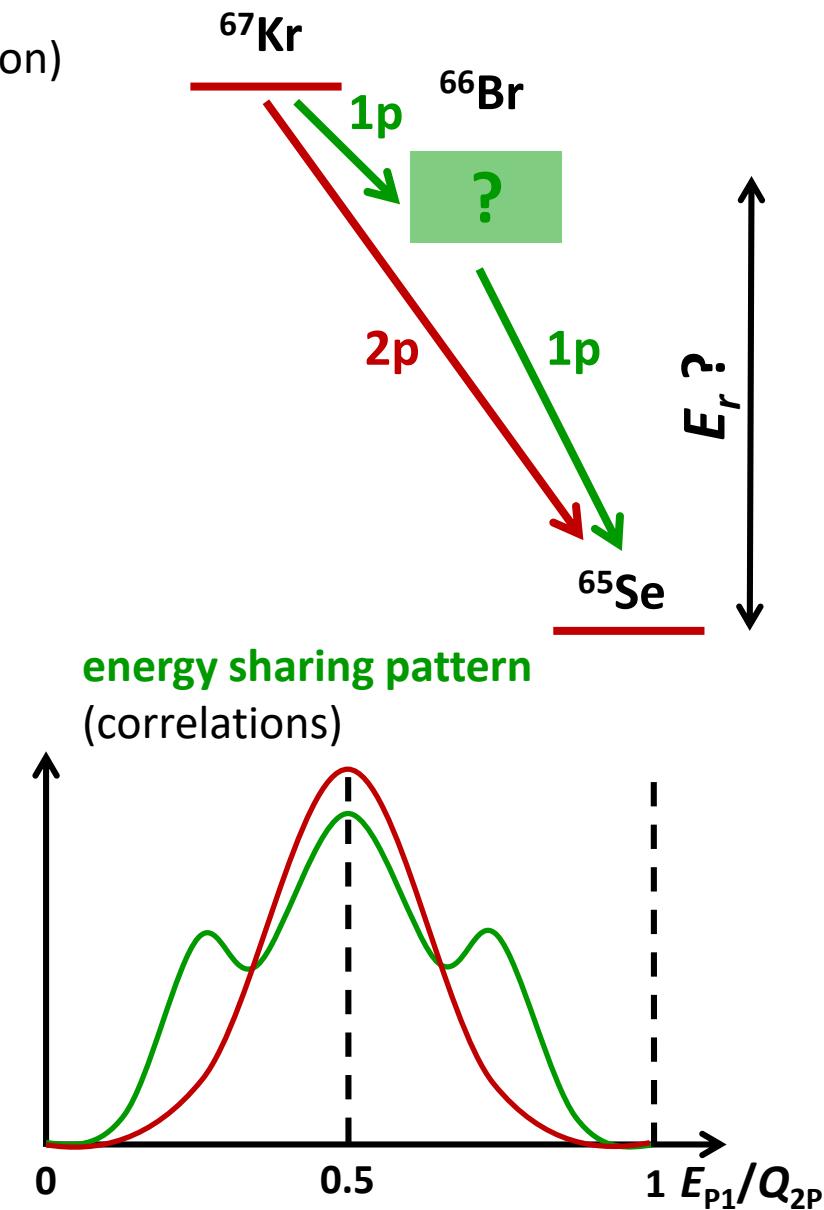
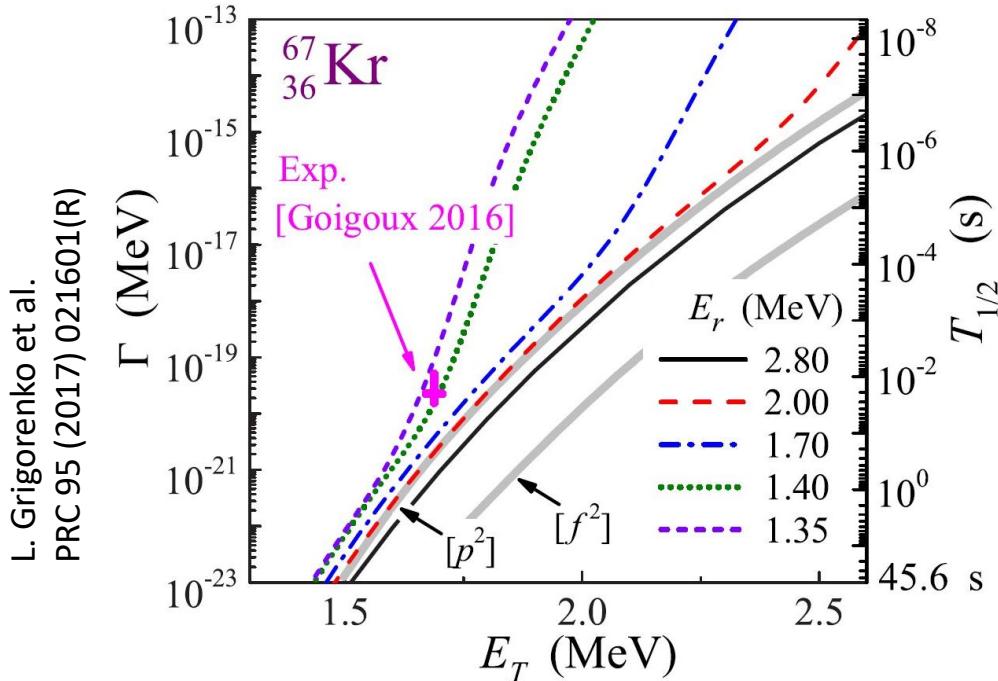
L. Grigorenko et al.  
PRC 95 (2017) 021601(R)



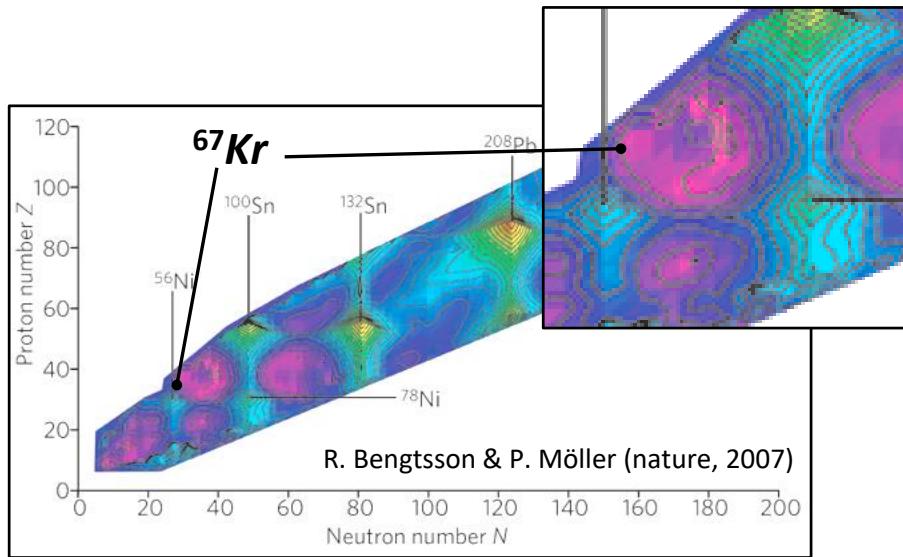
# first hypothesis: transition from 2P to sequential decay ?

(L.V. Grigorenko, semi-analytical R-matrix calculation)

- indication of a 1p channel opening ?
- possible transition from 2P to seq. emission  
**transition region:  $S_p = [-340 ; -270] \text{ keV}$**



## second hypothesis: influence of deformation ?



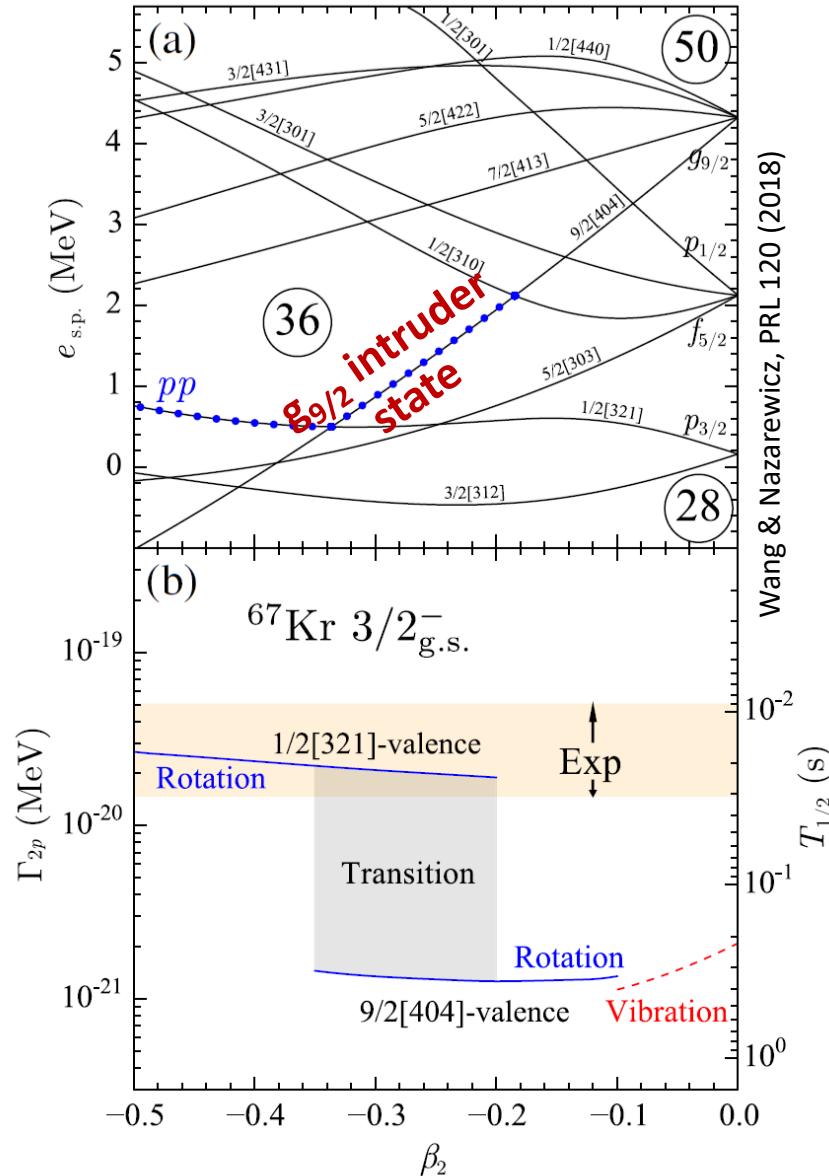
calculations by Wang & Nazarewicz, PRL 120 (2018)  
**(Gamow Coupled Channels + coupling to core exc.)**

with  $|\beta_2| < 0.1 \rightarrow T_{1/2}^{2P} > 220 \text{ ms}$

with  $\beta_2 = -0.3 \rightarrow T_{1/2}^{2P} = 24^{+10}_{-7} \text{ ms}$   
agreement with exp. !

+ angular correlation prediction

(consistent treatment of structure and emission dynamics)



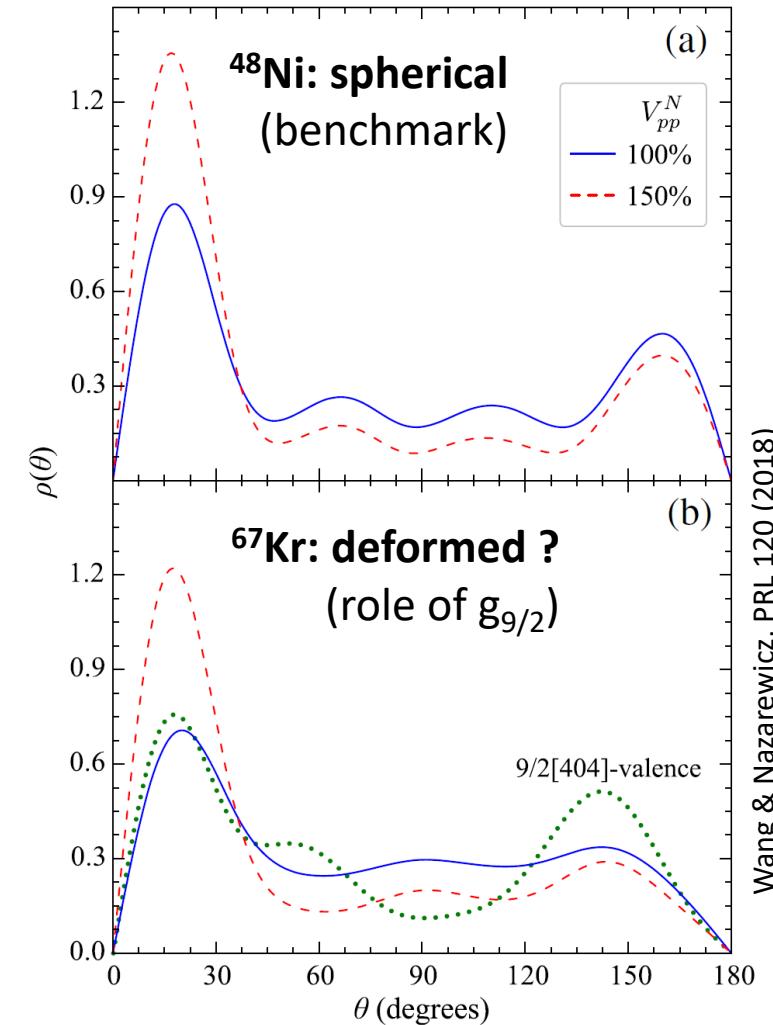
## second hypothesis: influence of deformation ?

### angular correlation prediction

recent work by Wang & Nazarewicz, PRL 120 (2018)  
**(Gamow Coupled Channels + coupling to core exc.)**

with  $|\beta_2| < 0.1 \rightarrow T_{1/2}^{2P} > 220 \text{ ms}$

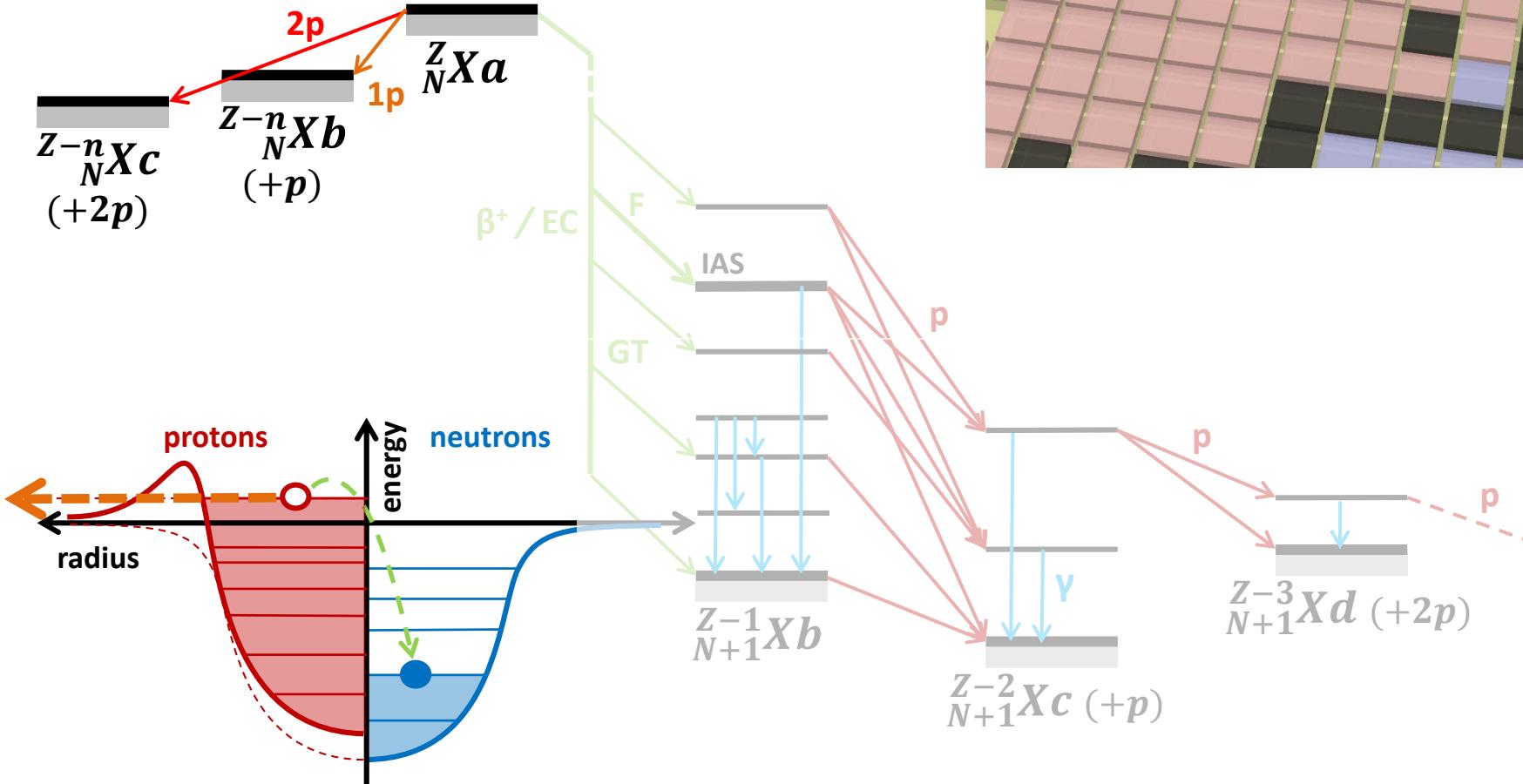
with  $\beta_2 = -0.3 \rightarrow T_{1/2}^{2P} = 24^{+10}_{-7} \text{ ms}$   
agreement with exp. !



# *towards the proton drip-line*

unbound with respect to proton(s) emission

$$S_p(Xa) < 0 \text{ and/or } S_{2p}(Xa) < 0$$



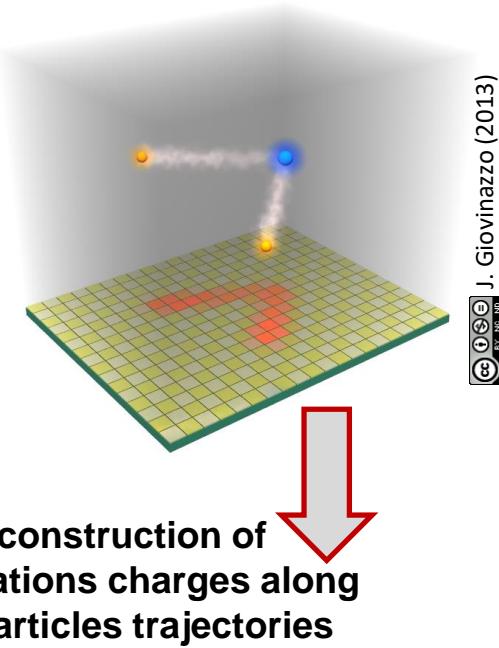
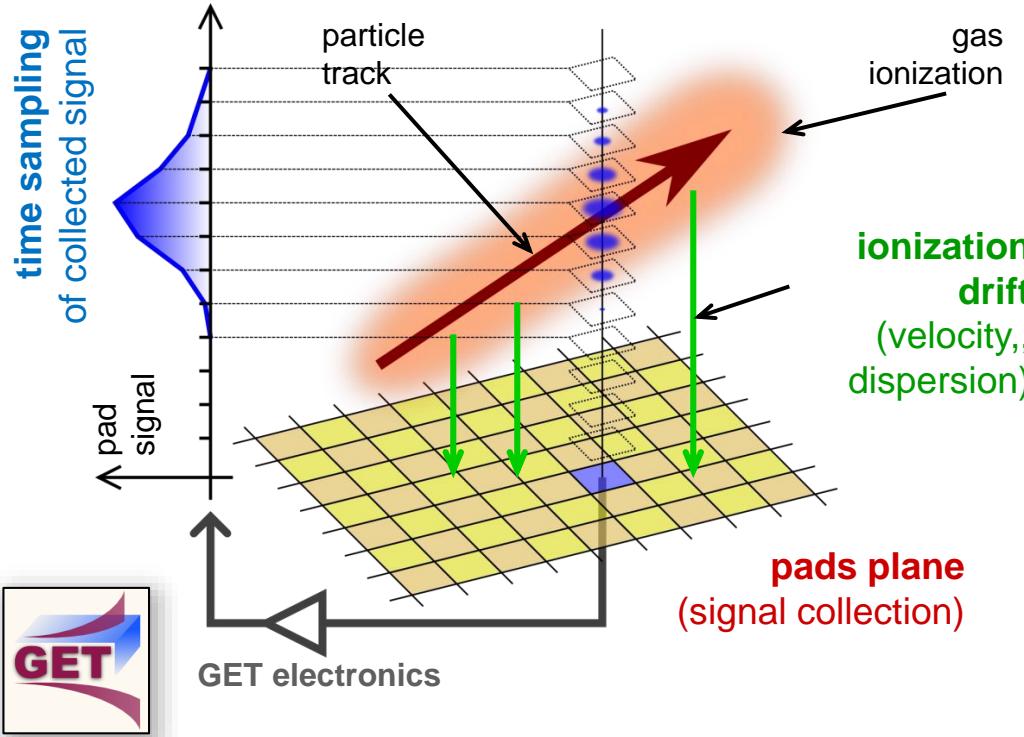
# a 4D detector: tracking and energy

pads plane  
(signal collection)  
2D digitization

TPC principle  
 $z \Leftrightarrow t$

time sampling  
of signal  
3D digitization

$$\Delta E(x,y,z) \iff \Delta E[x_i, y_j](z) \iff \Delta E[x_i, y_j](t) \iff \Delta E[x_i, y_j, t_k]$$



# simulation

**purpose:** detection efficiency estimate (**branching ratio**)

**hidden proton signal:** implantation track and masking of pads  
**protons escaping active volume**

→ evaluation of “missed” events...

## simulation processes

- **event generator**
  - simplified implantation track
  - random proton emission from stop point and decay time
- **tracking** (Geant4)
  - only for proton
- **signal drift and collection**
  - adjust to experimental / fit data (dispersion, gain)
- **signal processing** (electronics)
  - noise / fluctuations
  - amplification

→ **analysis selection procedures**

