INFN

Università degli Studi di Padova

Neutrino physics from gamma-ray spectroscopy

D. Stramaccioni & J.J. Valiente Dobón – June 18th 2025

Overview

Università degli Studi di Padova

A new **bridge** between **neutrino** studies and **ɣ spectroscopy** can be built:

- Need for reliable **ν-nucleus interaction strengths**, both for **IBD** and **0νββ**
- Possibility to extract them with **ɣ spectroscopy**
- **Feasibility** of related experiments with **intense light ion beams**

Experimental campaign with LNL proton beams?

$\gamma \longleftrightarrow \nu$

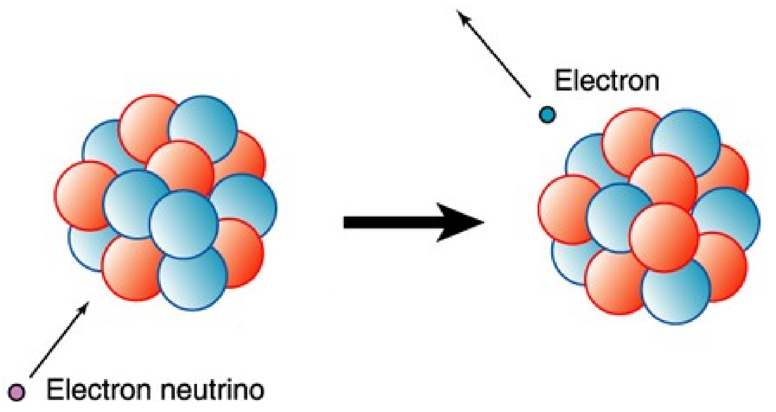
UNIVERSITÀ DEGLI STUDI DI PADOVA

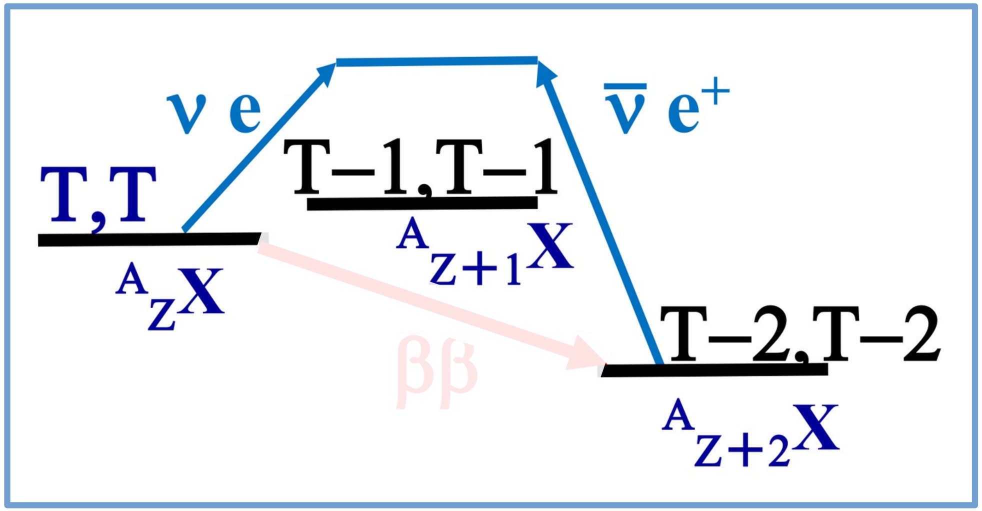
Inverse Beta Decay (IBD)

Low energy neutrinos studies

- **pp** / **CNO** neutrino **fluxes**
- Neutrino **anomalies**

$$\nu_l + (A, Z) \rightarrow (A, Z+1) + l^-$$
$$\bar{\nu}_l + (A, Z) \rightarrow (A, Z-1) + l^+$$

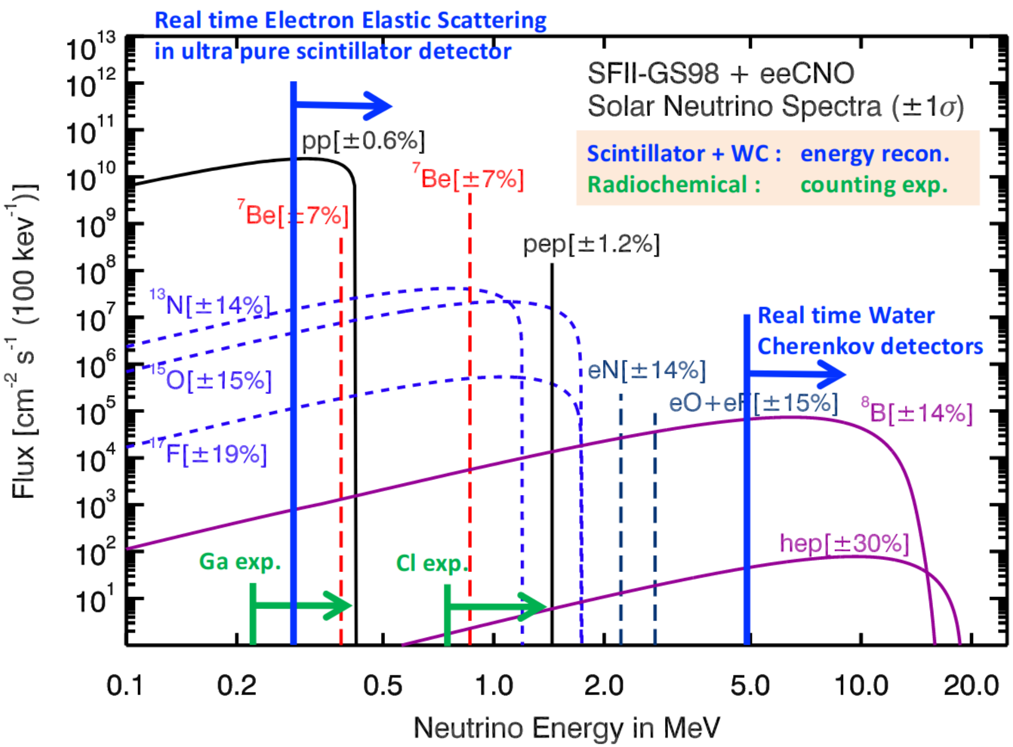




Inverse Beta Decays for neutrino studies

The **solar-ν** produced in the core of the sun is **mainly ν_e**, since the weak processes involved are the **low-energy nuclear** β decays and electron captures.

Nuclei with **large responses** for the **charged weak currents** are used to detect the **low-energy solar ν_e by inverse β decays**.



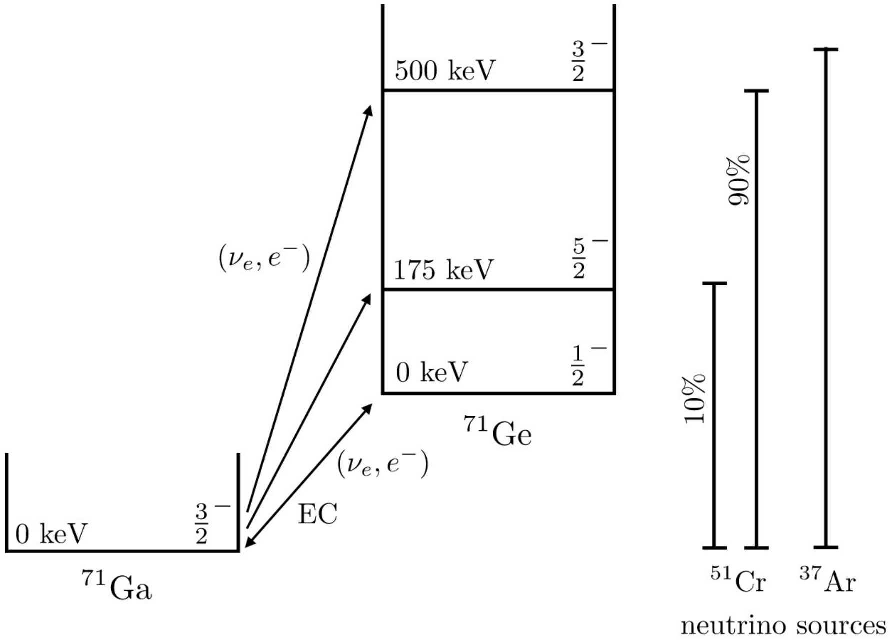
$$\left[\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-\right]$$

- **^{71}Ga low Q-value** probes uncharted regions of the **pp chain**!

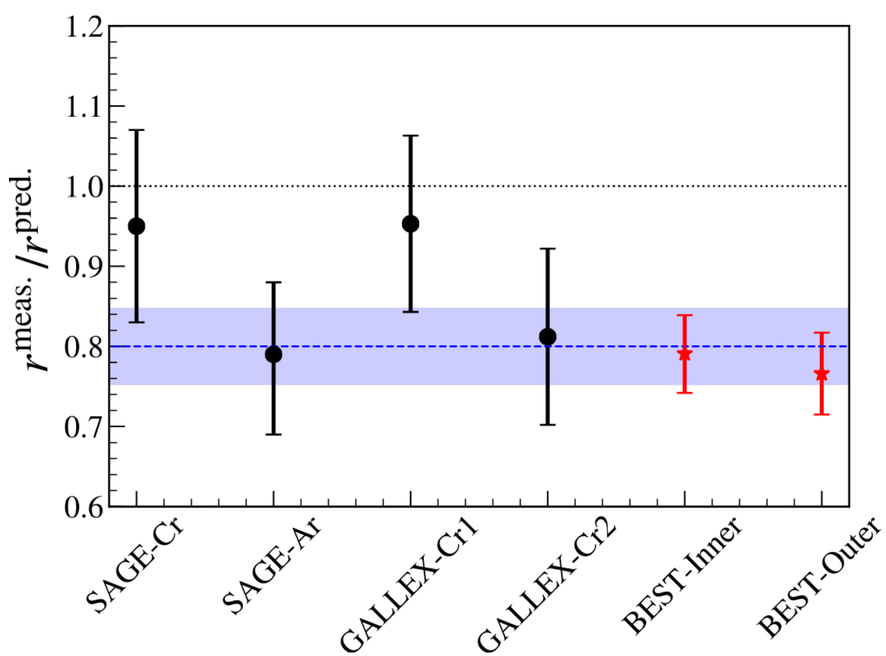
Need for for reliable **ν-nucleus interaction strength** to extract low-energy **ν flux**.

*“The measurements of the charged-current capture rate of neutrinos on ^{71}Ga from **strong radioactive sources** have yielded **results below those expected**”*

Sources: ^{51}**Cr** and ^{37}**Ar**



[S. R. Elliott et al., PRC (2023)]



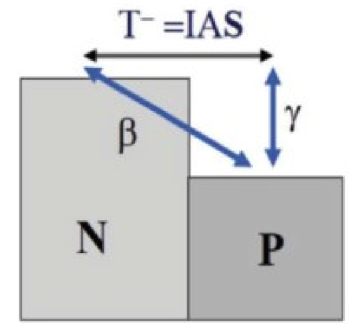
Hint of **sterile neutrino(s)**?

Need for reliable **ν-nucleus interaction strength** to explore it!

Electromagnetic transitions from isobaric analog states to study nuclear matrix elements for neutrinoless $\beta\beta$ decays and astro-neutrino inverse β decays

Hiroyasu Ejiri*

Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan



- ☺ Same **initial state**
- ☺ Same **final state**
- ☺ Same **interaction**

$$|i\rangle_\gamma \equiv |i\rangle_{IDB}(\text{IAS}) \propto T^-|i\rangle_{IBD}$$

$$|f\rangle_\gamma \equiv |f\rangle_{IDB}$$

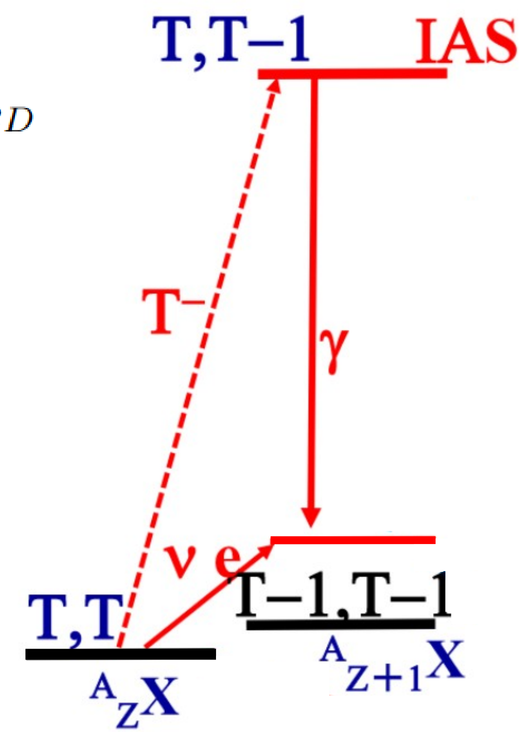
Weak

$$T(\text{AVL}) = g_A \tau^i r^{L-1}\left[\boldsymbol{\sigma}\mathbf{Y}_{L-1}\right]_L$$

EM

$$T(\text{ML}) = g_S r^{L-1}\left[\boldsymbol{\sigma}\mathbf{Y}_{L-1}\right]_L + g_L r^{L-1}\left[\mathbf{j}\mathbf{Y}_{L-1}\right]_L$$

$$\Rightarrow \quad \langle f|T^{W}_{1SLJ}|i\rangle \sim \frac{g^{W}_{1SLJ}}{g^{\gamma}_{1SLJ}}\sqrt{(2T_i)}\langle f|T^{\gamma}_{1SLJ}|IAS\rangle$$

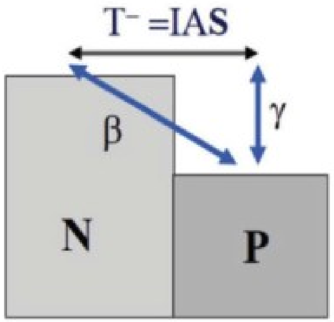


Gamma decays as analogous probe - pros

Electromagnetic transitions from isobaric analog states to study nuclear matrix elements for neutrinoless $\beta\beta$ decays and astro-neutrino inverse β decays

Hiroyasu Ejiri*

Research Center for Nuclear Physics, Osaka University, Osaka 567-0047, Japan

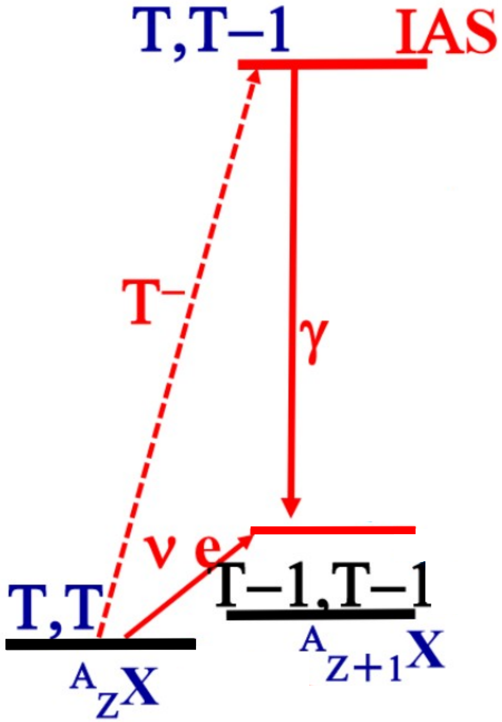


1) The **EM interaction is well known**, and the **lowest-multipole** transition is **dominant** because of the long-wave-length nature of the photon

2) The **IAS is a very sharp state**, reflecting the isospin symmetry. Thus **backgrounds** from non-IAS excitations are **small**

3) **High energy-resolution high-efficiency photon detectors** are used for studying the EM transitions

4) **No need for normalization** with external measurements



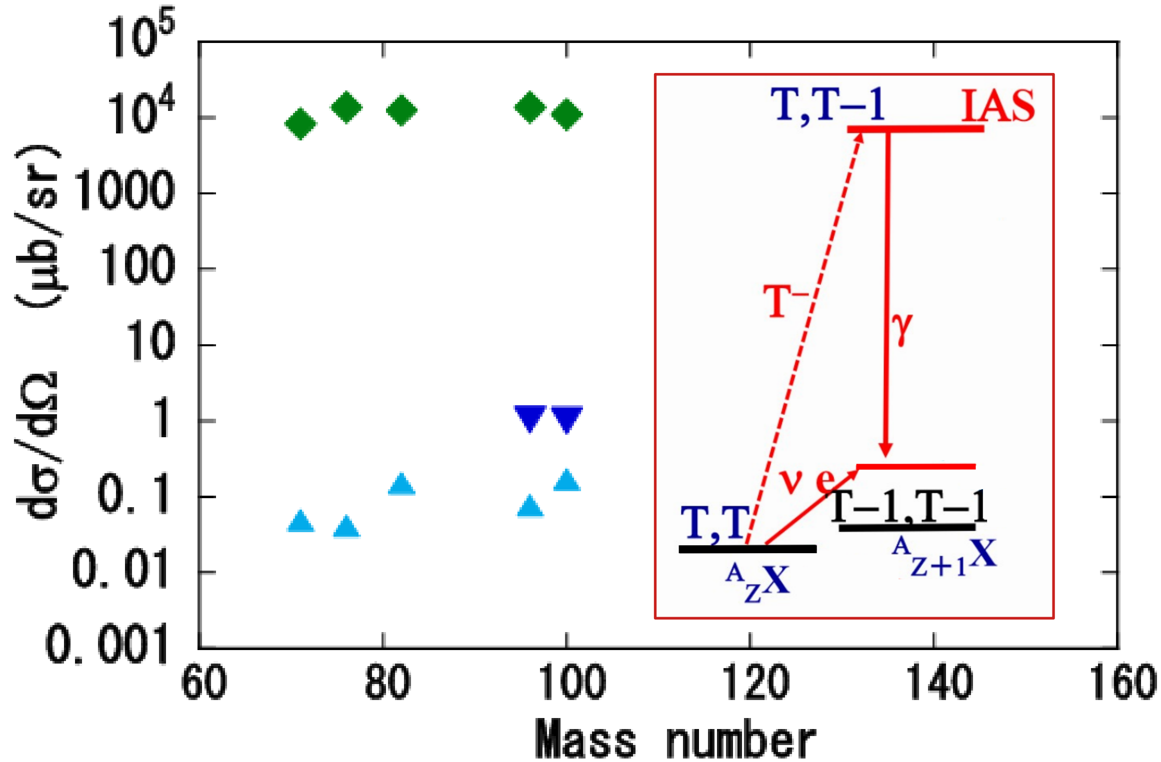
Gamma spectroscopy for IBD - experiments

1) Count # times the **IAS was populated**

$$d\sigma^{\mathrm{IA}}/d\Omega = kNJ_\tau^2 B(\mathrm{IAS})$$

2) Count # times the **IAS decayed γ**

$$\frac{d\sigma^{\mathrm{IA}}(\alpha')}{d\Omega} = \frac{d\sigma^{\mathrm{IA}}}{d\Omega}\,\frac{\Gamma^{\mathrm{IA}}(\alpha')}{\Gamma(T)}$$



We would like to extract Γ^{IA}:

$$\Gamma^{\mathrm{IA}}(\alpha') = K_{\alpha'} E_{\alpha'}^3\, g_{\alpha'}^2\, |M^{\mathrm{IA}}(\alpha')|^2 S^{-1}$$

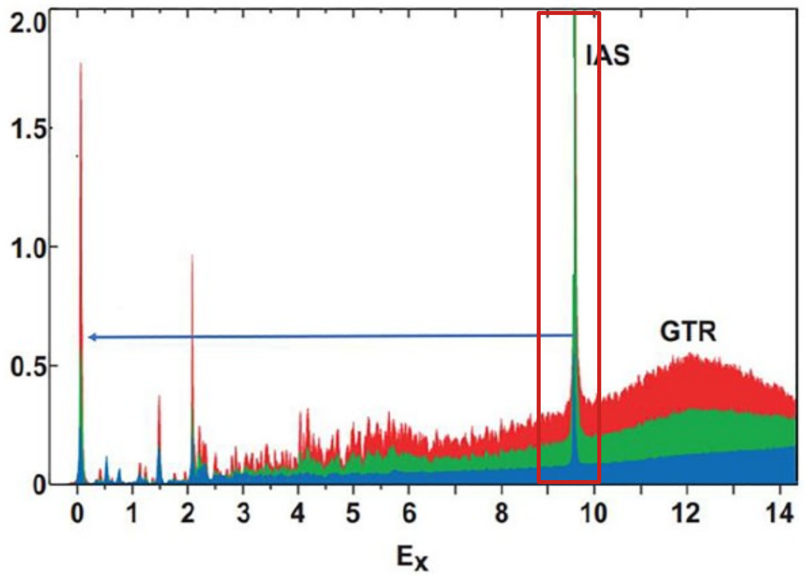
We need the **total state width Γ(T)**..
how can we get it?

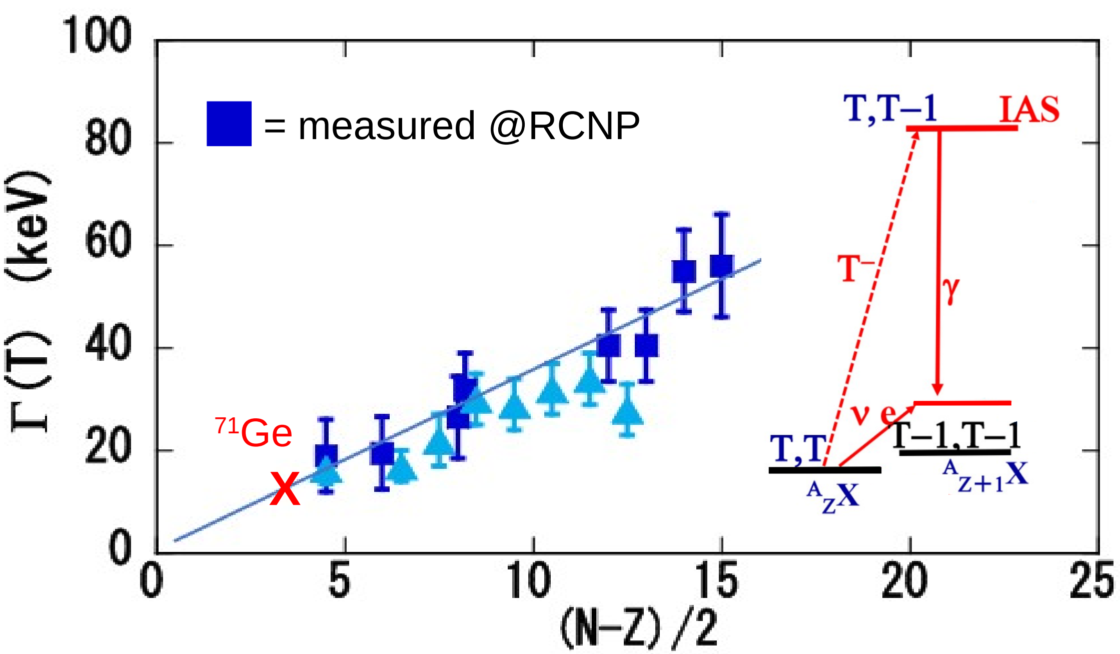
Gamma spectroscopy for IBD – RCNP method

(p,d) reaction to populate the IAS and reconstructing the **excitation energy** spectrum with **high energy resolution detector system**.

➡ **Γ(T)** corresponds to the **width of the IAS peak**

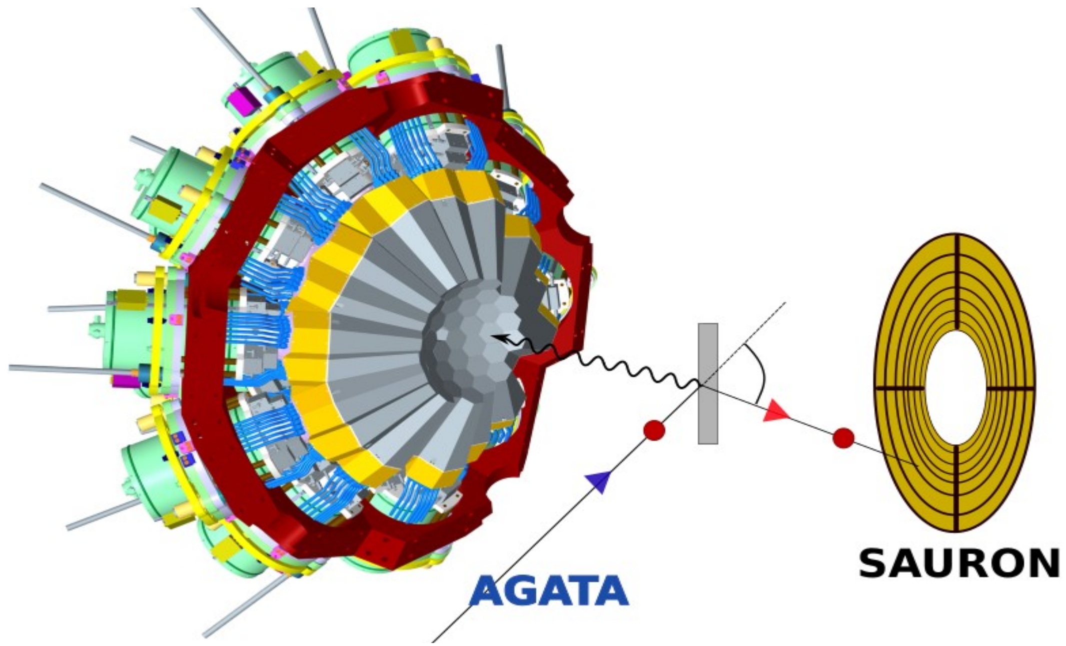
- Measured with **Grand Raiden splitpole**





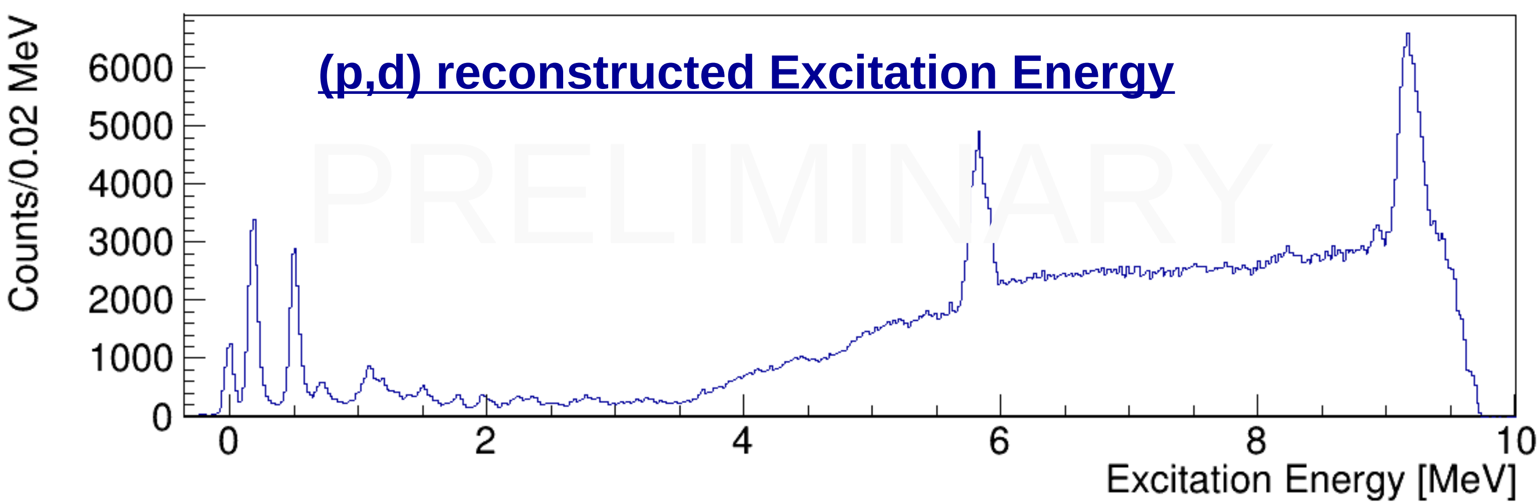
- We could employ **high resolution Si detector** (e.g. ion-implanted)
- **HPGe / scintillators** to measure the **γ rays** in coincidence

Università degli Studi di Padova



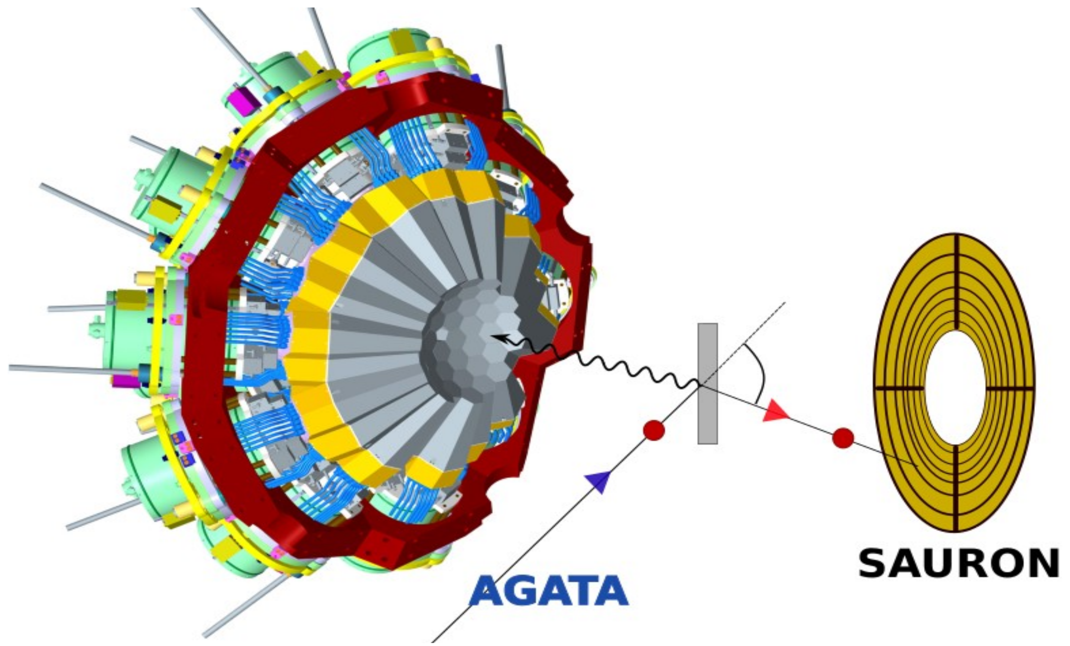
$^{72}Ge(p,d)^{71}Ge_{IAS}$ @28 MeV

- **γ rays** measured in **AGATA**
- **Light charged particles** energies measured in **SAURON Silicon** detector



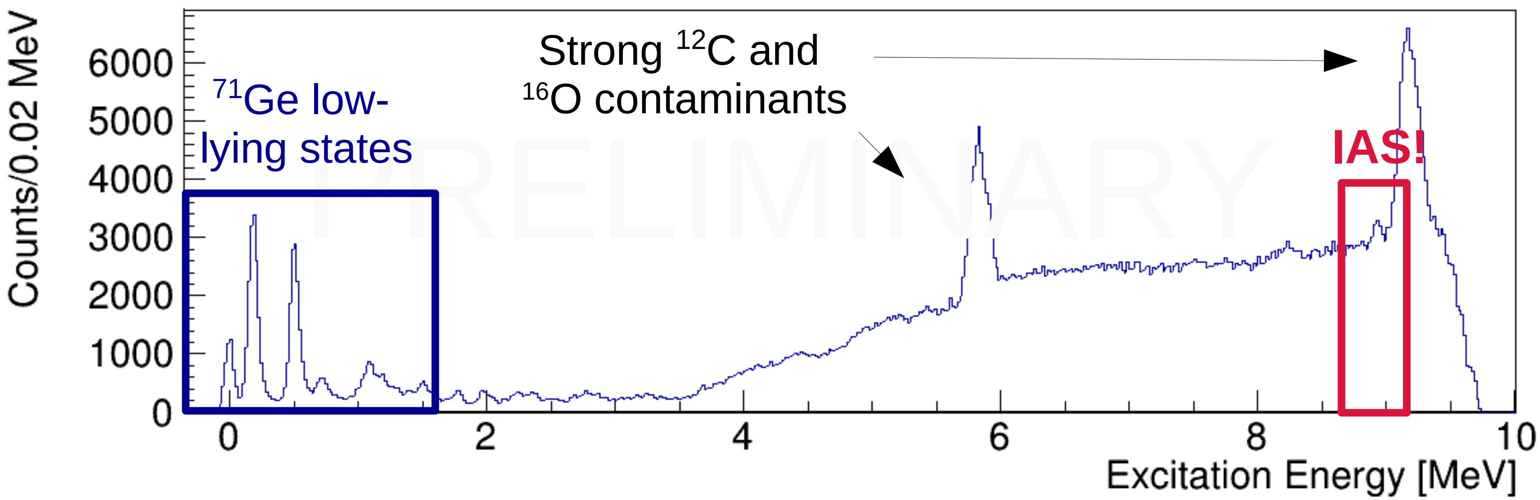
MSc thesis Federico Simioni

→ **Very preliminary** (~5% of statistics)



$^{72}Ge(p,d)^{71}Ge_{IAS}$ @28 MeV

- **γ rays** measured in **AGATA**
- **Light charged particles** energies measured in **SAURON Silicon** detector



MSc thesis
Federico Simioni

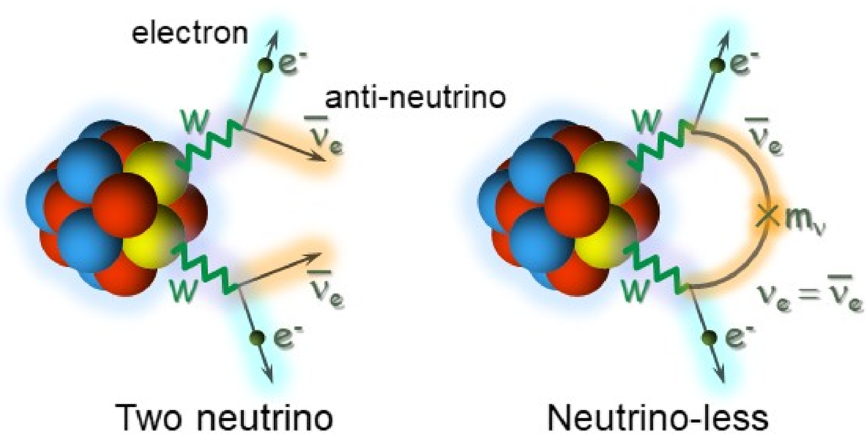
→ **Very preliminary** (~5% of statistics)

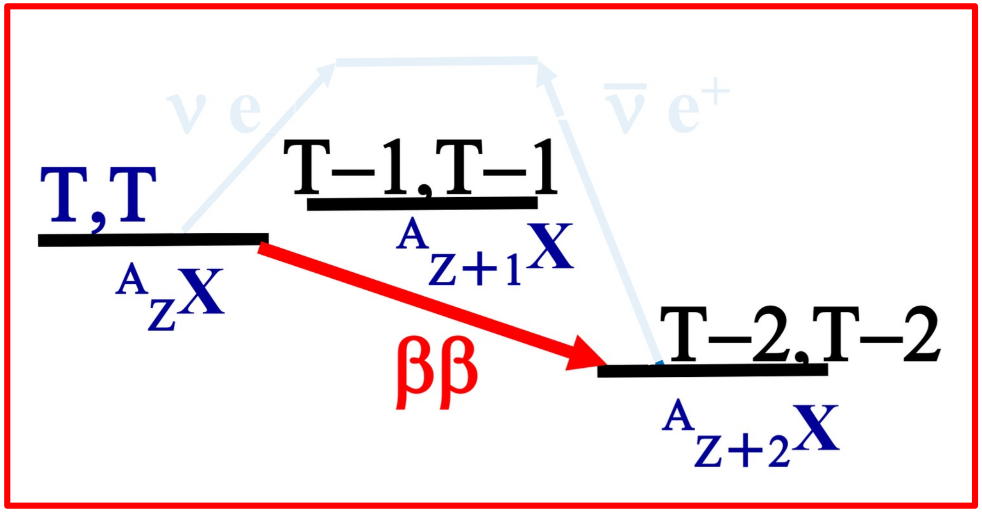
Neutrinoless ββ Decay (0νββ)

Promising **BSM** scenarios:

- **L violation** in laboratory
- **Majorana** nature of ν..

$$^{A}_{Z-2}X_{N+2} \rightarrow ^{A}_{Z} Y_N + 2e^-$$

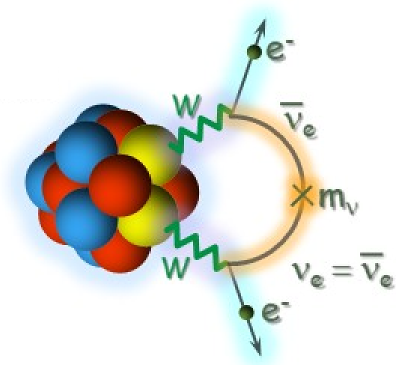




➡ Virtual **2-step** process of the **same type**!

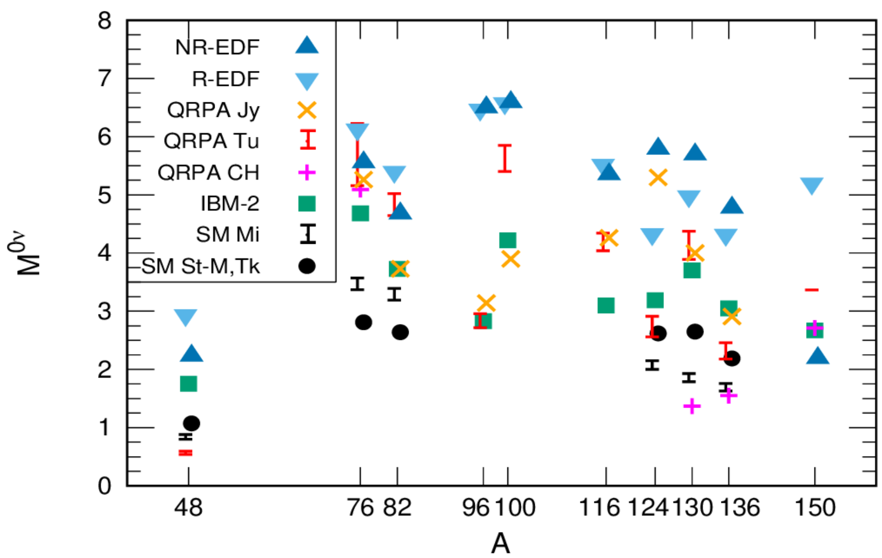
Università degli Studi di Padova

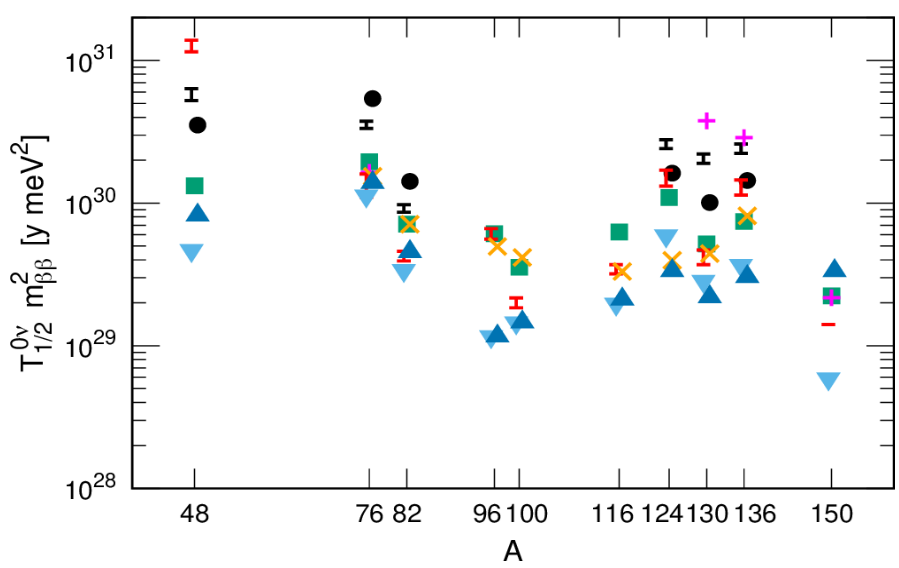
0νββ decay is a promising process to probe **BSM physics** scenarios: **L-violation** in laboratory, **ν** a **Majorana** particle, **ν mass...**



$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m_{\beta\beta}^2$$

Nuclear Matrix Element (NME) brings **large uncertainties** in DBD half-lifes





[J. Engel and J. Menéndez, Rept. Prog. Phys. 80 (2017)]

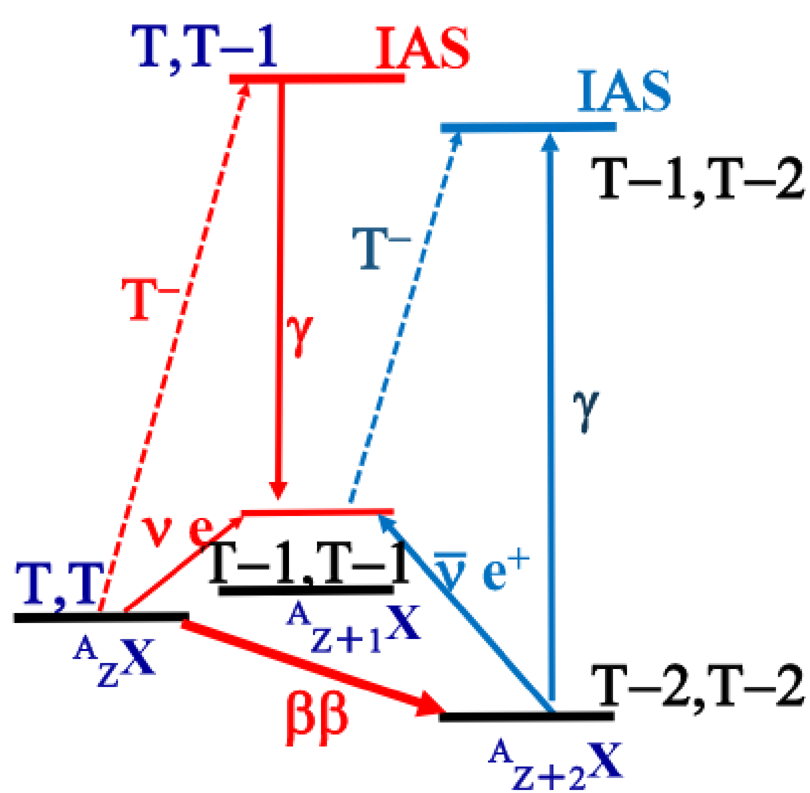
0νββ decay studies with the same method

With the **same setup and methods** discussed before, one can **access DBD nuclei**

Absolute experimental values for some representative **axial-vector dipole and vector dipole NMEs** can be used to check the **model calculations** and to get the **effective couplings**

$$M^{\mathrm{GT}}_{0\nu} = \sum_n \left\langle f \left| \sum_a \vec{\sigma}_a \tau_a^+ \right| n \right\rangle \left\langle n \left| \sum_b \vec{\sigma}_b \tau_b^+ \right| i \right\rangle$$

A	$E(\mathrm{IA})$	$E(\mathrm{GT})$	$B(\mathrm{GT})$	$B^{\mathrm{IA}}(M1)$	$\Gamma^{\mathrm{IA}}(M1)$	$\sigma^{\mathrm{IA}}(M1)$
^{76}Ge	8.31	1.07	0.14	1.45	6.4	41
^{82}Se	9.58	0.075	0.34	3.0	30.0	150
^{96}Zr	10.9	0.69	0.16	1.25	15.3	76
^{100}Mo	11.1	0	0.35	2.7	43.4	170
^{116}Cd	12.1	0	0.14	0.88	18.0	51
^{128}Te	12.0	0	0.079	0.41	8.2	17
^{130}Te	12.7	0	0.072	0.35	8.2	17
^{136}Xe	13.4	0.59	0.23	1.03	25	45
^{150}Nd	14.4	0.11	0.13	0.54	18.0	35
^{71}Ga	8.91	0	0.085	1.2	9.8	51



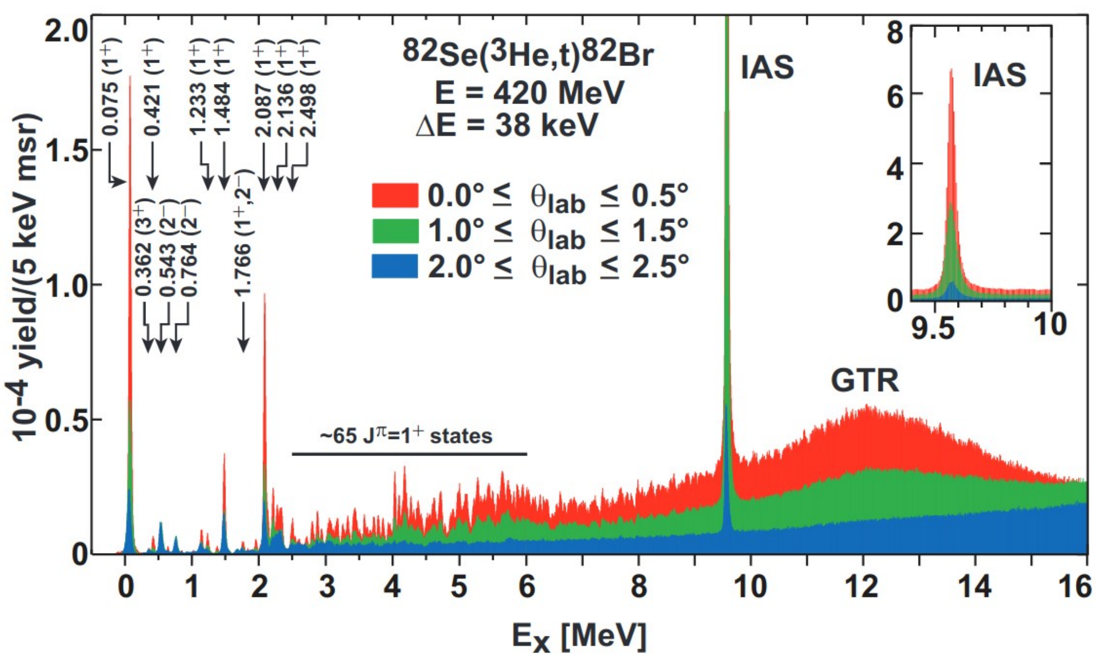
$0\nu\beta\beta$ decay studies with the same method: SSD

With the **same setup and methods** discussed before, one can **access DBD nuclei**

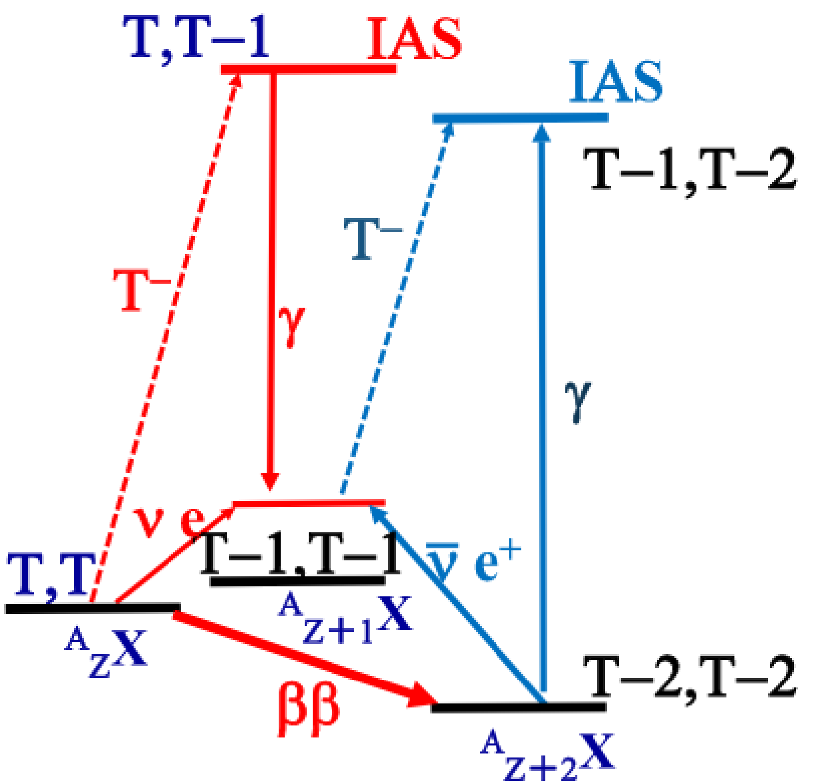
Determination of NME in case of **Single State Dominance (SSD)**

→ Suggested by measured **DBD energy spectra** in some cases

$$M^{GT}_{0\nu} = \sum_n \left\langle f \middle| \sum_a \vec{\sigma}_a \tau_a^+ \middle| n \right\rangle \left\langle n \middle| \sum_b \vec{\sigma}_b \tau_b^+ \middle| i \right\rangle$$



[Frekers et al., PRC 94 (2016)]



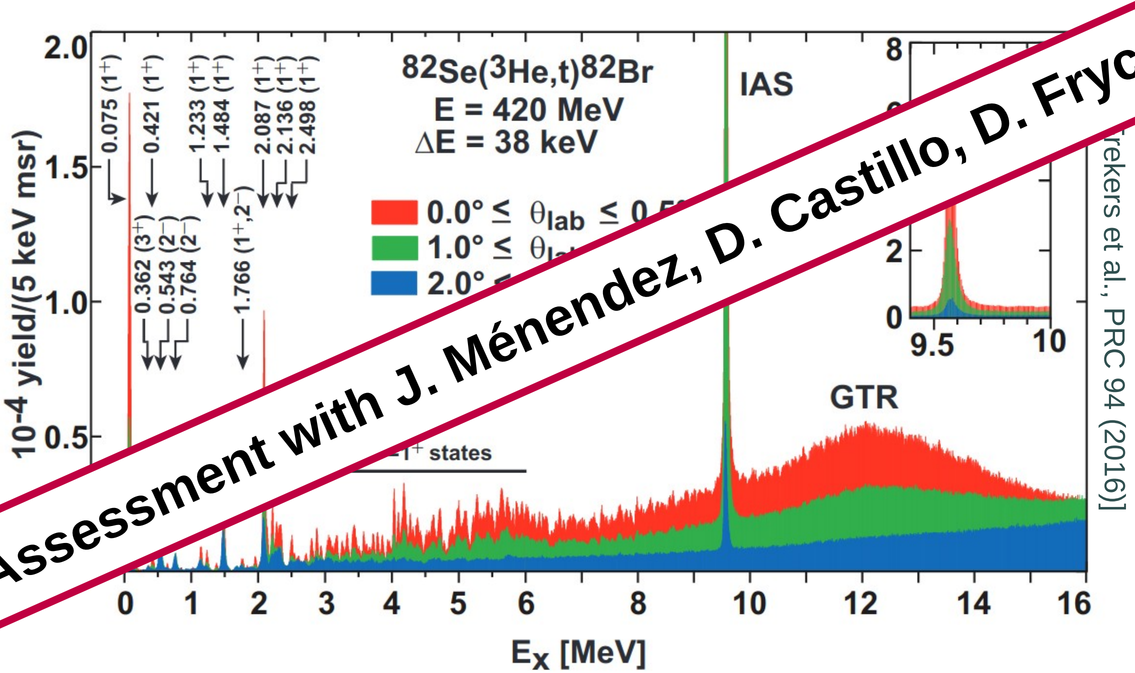
$0\nu\beta\beta$ decay studies with the same method: SSD

With the **same setup and methods** discussed before, one can **access DBD nuclei**

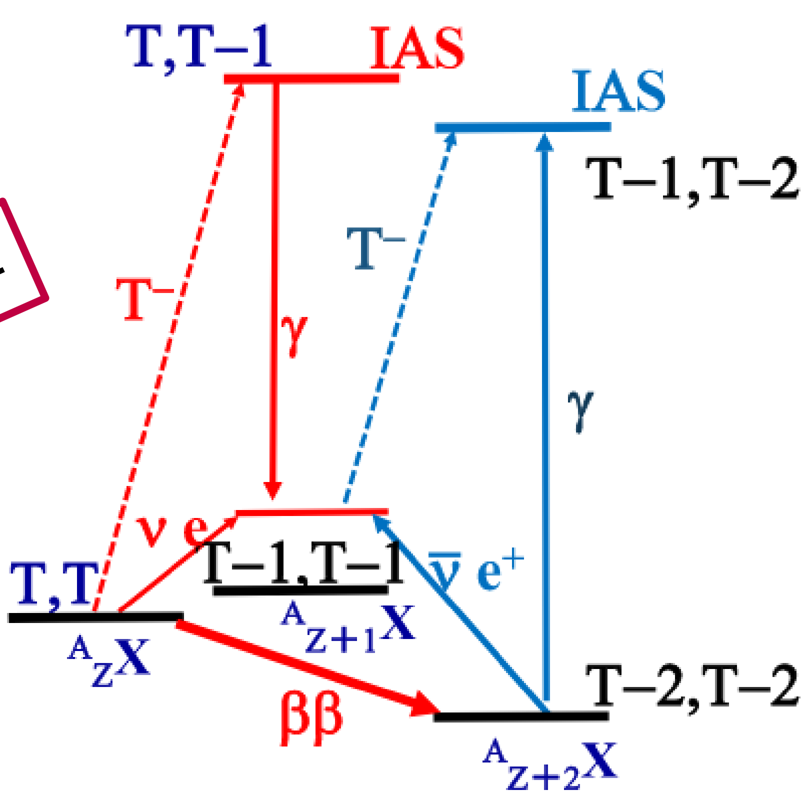
Determination of NME in case of **Single State Dominance (SSD)**

→ Suggested by measured **DBD energy spectra** in some cases

$$M^{GT}_{0\nu} = \sum_n \left\langle f \left| \sum_a \vec{\sigma}_a \tau_a^+ \right| n \right\rangle \left\langle n \left| \sum_b \vec{\sigma}_b \tau_b^+ \right| i \right\rangle$$



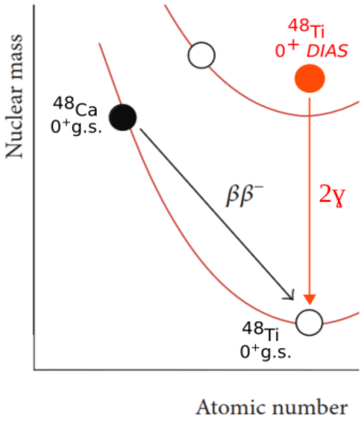
Assessment with J. Ménendez, D. Castillo, D. Frycz

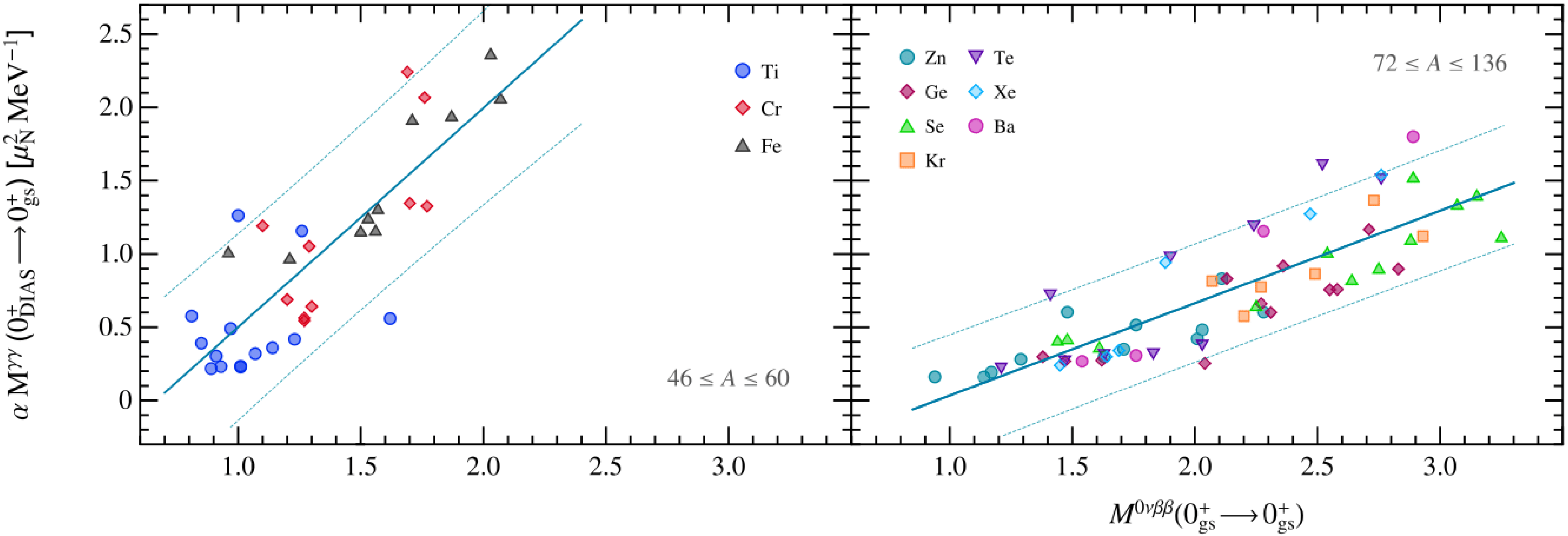


Double-ɣ spectroscopy for 0νββ - theory

In 2022, a strong correlation between **NMEs of 2ɣ-decays** from DIAS to g.s. and **0νββ** decays found.

➡ The correlation holds if we consider **M1M1 decays** with **equal-energy gammas**.



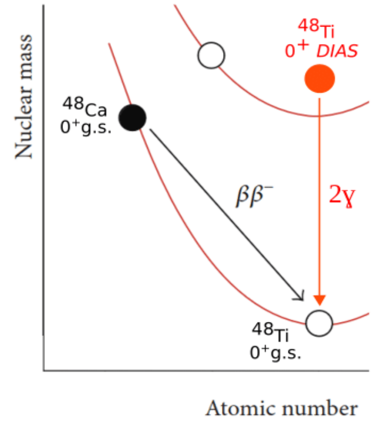


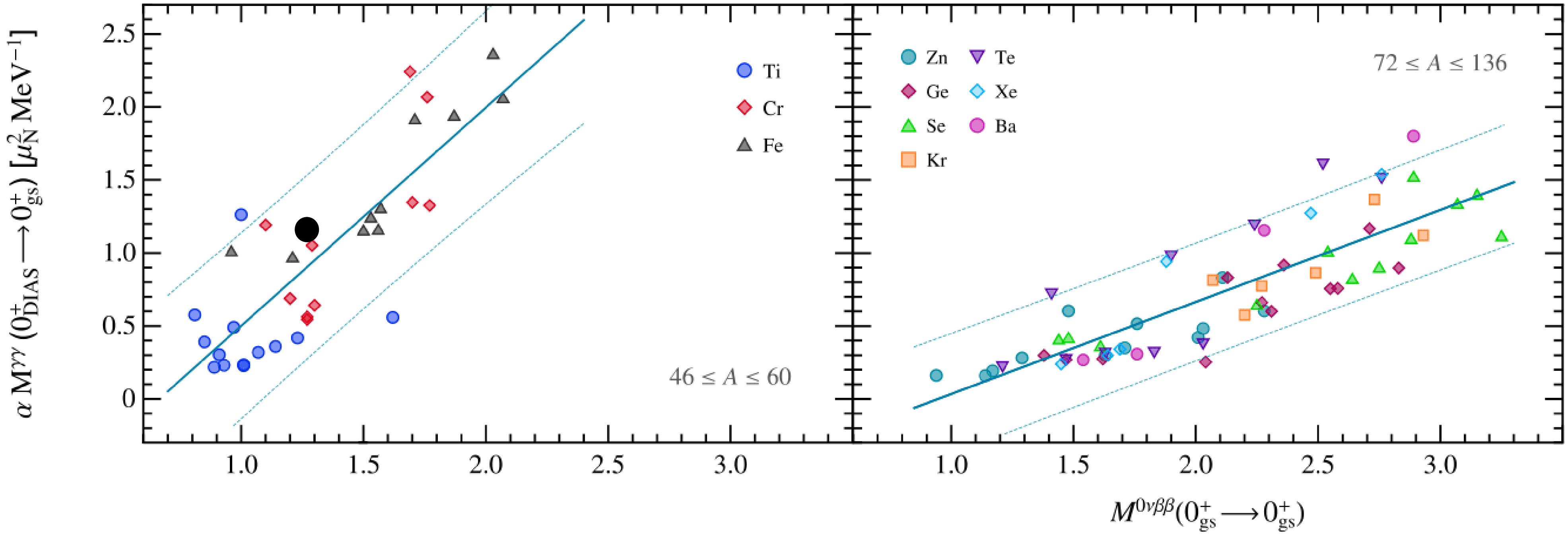
[B. Romeo et al., Phys. Lett. B 827 (2022)]

Double-γ spectroscopy for 0νββ - theory

In 2022, a strong correlation between **NMEs of 2γ-decays** from DIAS to g.s. and **0νββ** decays found.

➡ The correlation holds if we consider **M1M1 decays** with **equal-energy gammas**.





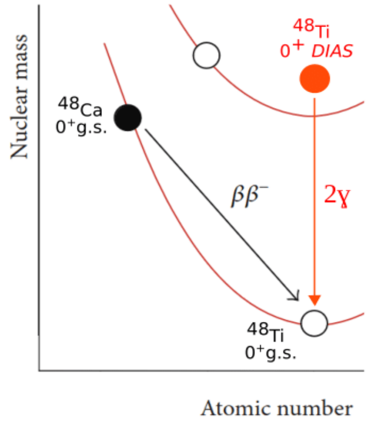
[B. Romeo et al., Phys. Lett. B 827 (2022)]

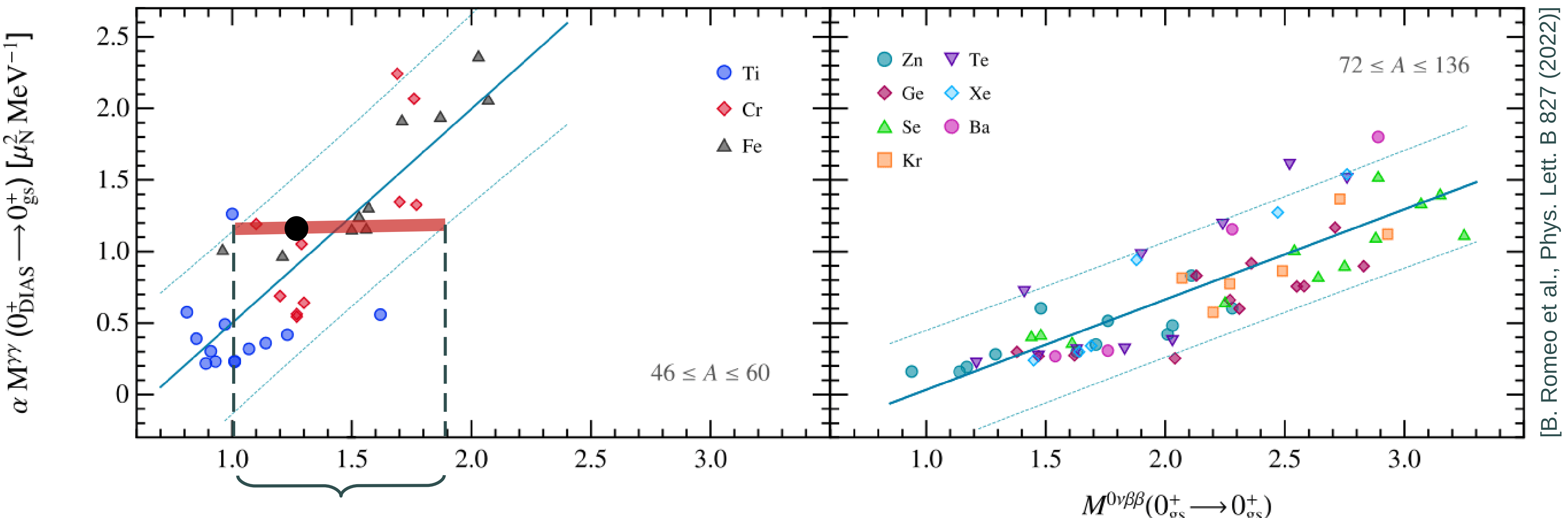
Double-γ spectroscopy for 0νββ - theory

UNIVERSITÀ DEGLI STUDI DI PADOVA

In 2022, a strong correlation between **NMEs of 2γ-decays** from DIAS to g.s. and **0νββ** decays found.

➡ The correlation holds if we consider **M1M1 decays** with **equal-energy gammas**.

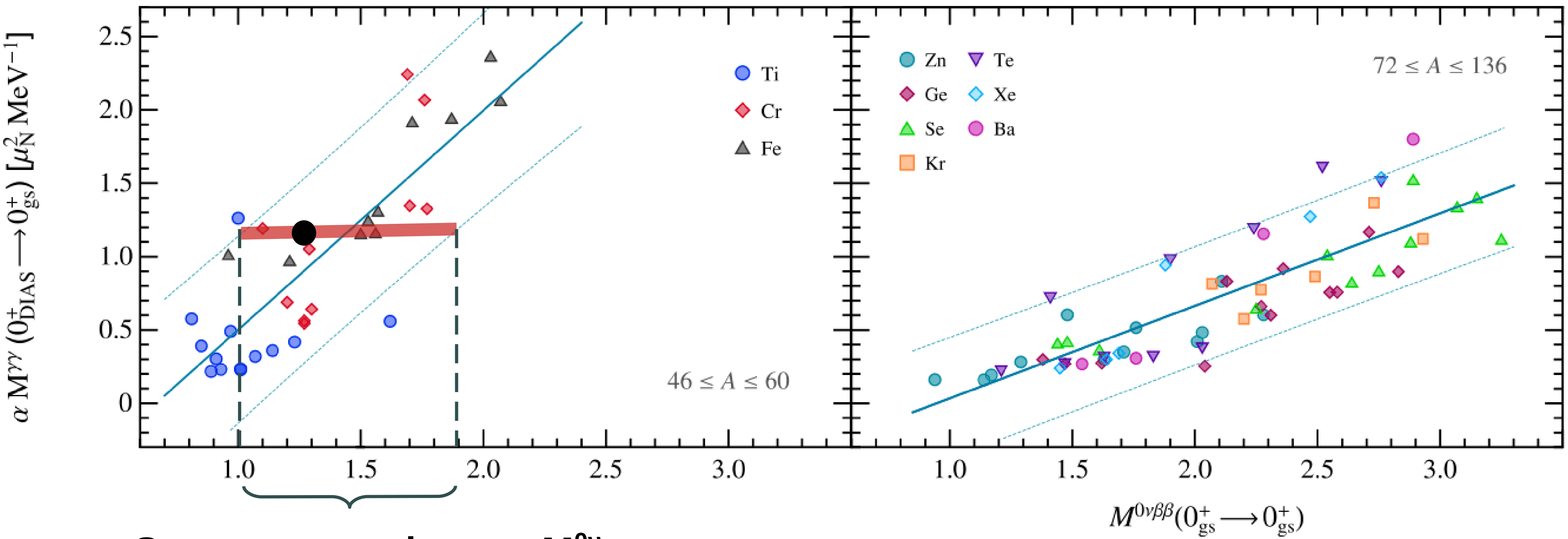




Strong constraints on M$^{0\nu}$

Double-ɣ spectroscopy for 0νββ - theory

Università degli Studi di Padova



[B. Romeo et al., Phys. Lett. B 827 (2022)]

Strong constraints on $M^{0\nu}$

Considering **analogue initial and final states** as in 0ν2β

$$|0_i^+\rangle_{\gamma\gamma} \equiv |0_i^+\rangle_{\beta\beta}(\mathrm{DIAS}) = \frac{T^-T^-}{K^{1/2}}|0_i^+\rangle_{\beta\beta}$$

$$|0_f^+\rangle_{\gamma\gamma} \equiv |0_f^+\rangle_{\beta\beta}$$

+

Focusing on a **similar transition operator**

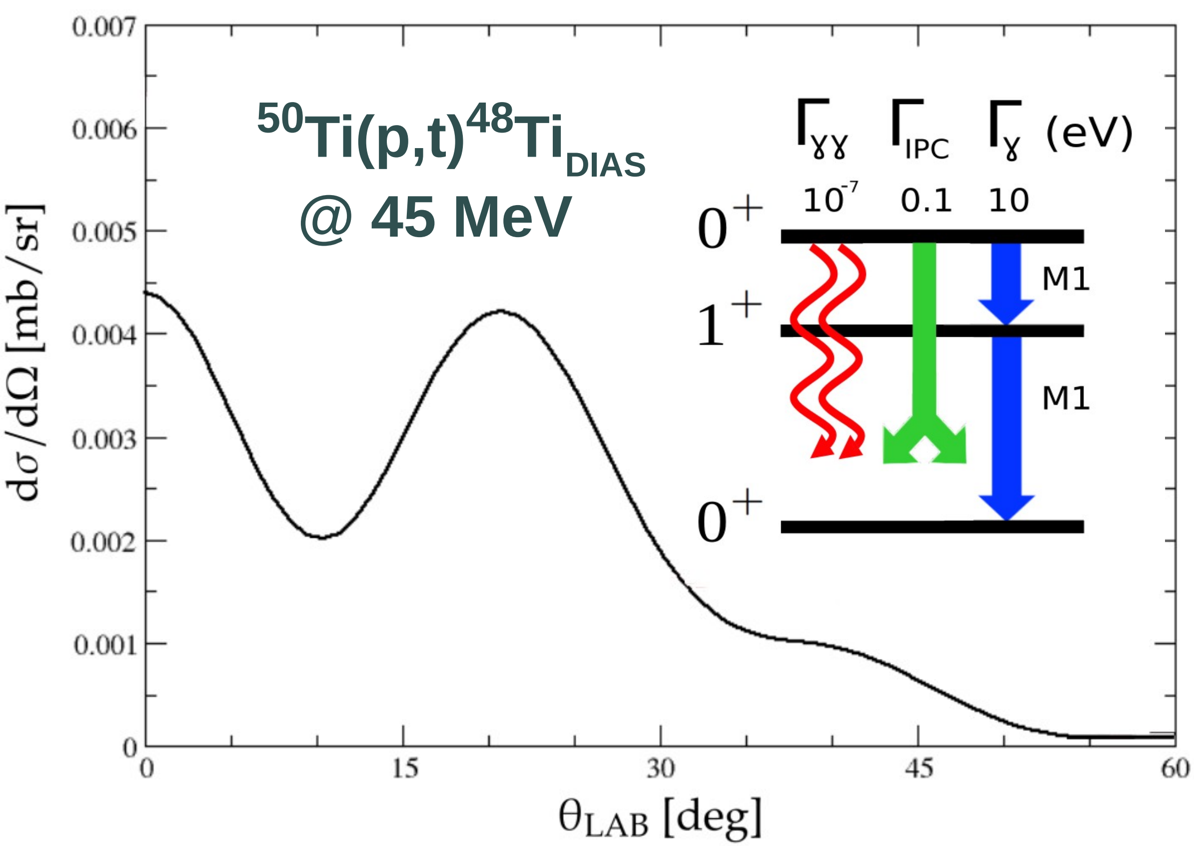
For **equal energy** gammas, 2ɣ magnetic dipole operator (**M1**) and the 0νββ Gamow-Teller (**GT**) operator share the same **isovector spin στ** term.

We took the first step...

- **We found a method to isolate and measure 2ɣ-decay BR**

... but we have to keep walking!

- **Perform the preparatory experiment**
  → To determine experimentally features of the Double Isobaric Analogue State in ^{48}Ti



Main intermediate goals:

1) determine the **cross section** to populate the DIAS

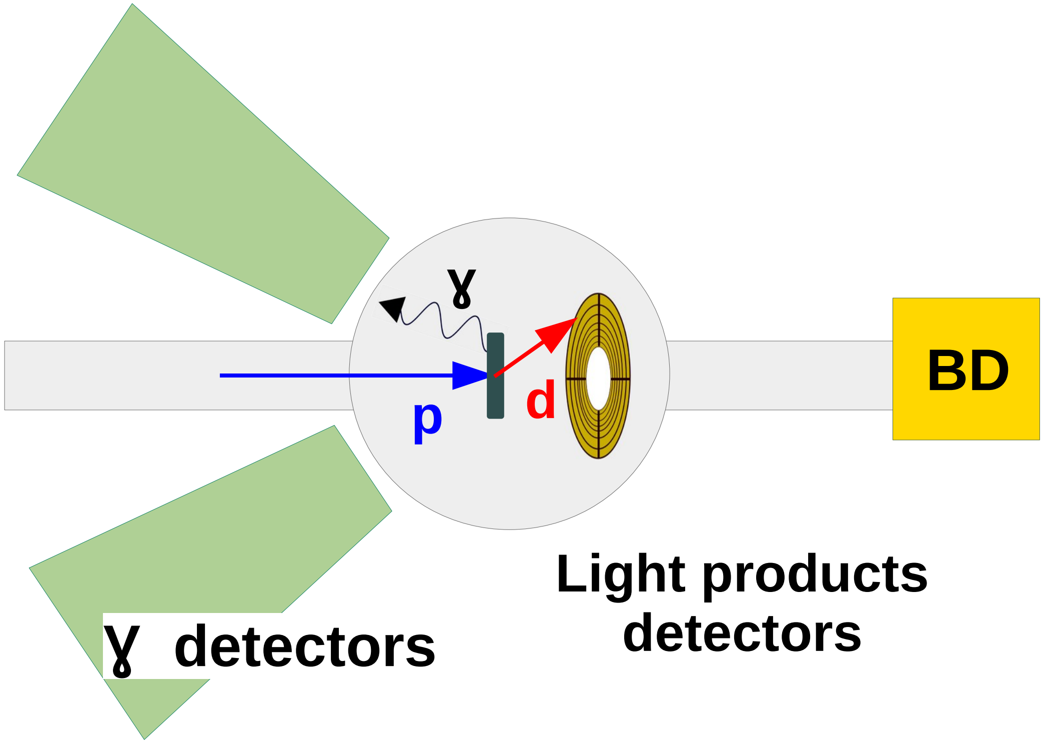
2) measure the **Branchings** for the dominant competing process
→ **single gamma decay BR**

➡ **Proposed @ IFJ-PAN!**

Università degli Studi di Padova

- It is possible to extract **ν-nucleus interaction strengths** with **γ spectroscopy**
- We can start with **simple experiments** (**IAS γ decay**) potentially leading to **high-impact** publications
- We can use the **LNL proton beams** for the reactions of interest

Reaction of interest: **(p,d)**



- Intense **proton** beam
- **Deuterons** tagging with **Silicon detectors**
- **γ-ray detectors** from **GAMMA**

BACKUP SLIDES