# A review on the X17 anomaly from the theory side


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IP2I – UCBL


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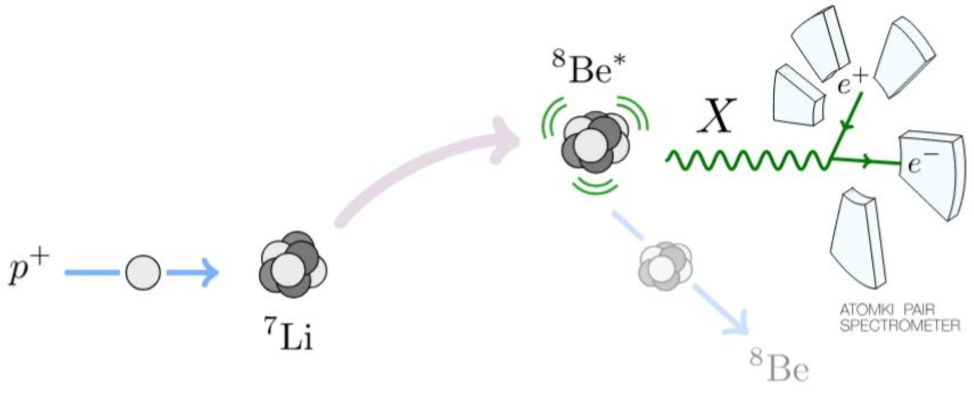
# Outline

General overview of the $X_{17}$ anomaly

The tortuous road in model building

An introduction to $e^{\pm}$-based $X_{17}$ searches

# Overview of the X17 anomaly

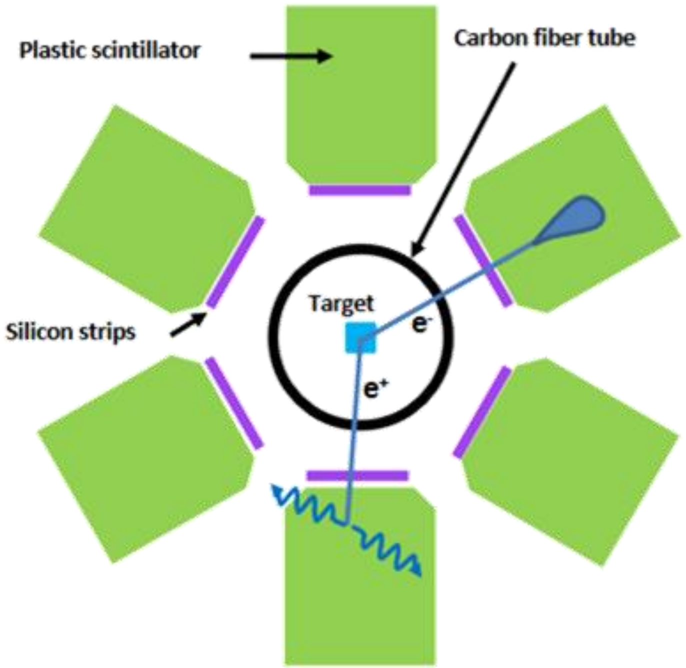



*Feng et al. 2016*

# ATOMKI experiments

2209.10795 1504.01527 , 2308.06473 2104.10075

- Production of excited nuclei $^{12}$C, $^{8}$Be and $^{4}$He, followed by radiative decays $N^* \to N\,\gamma^* \to N\,e^+e^-$
  - → The excited states are typically $15 - 20$ MeV above the ground states → sensitive to NP in this mass range



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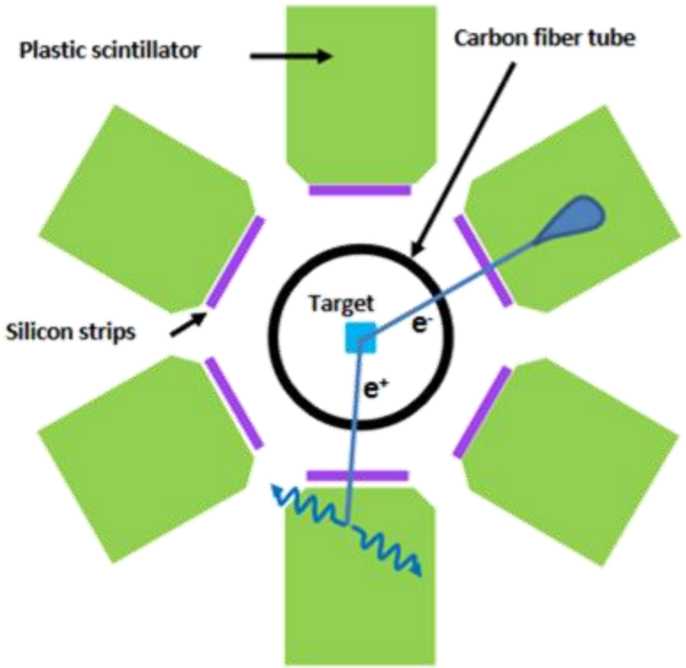
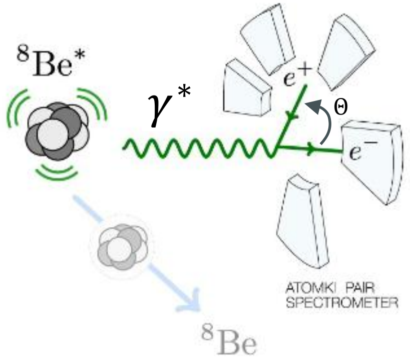
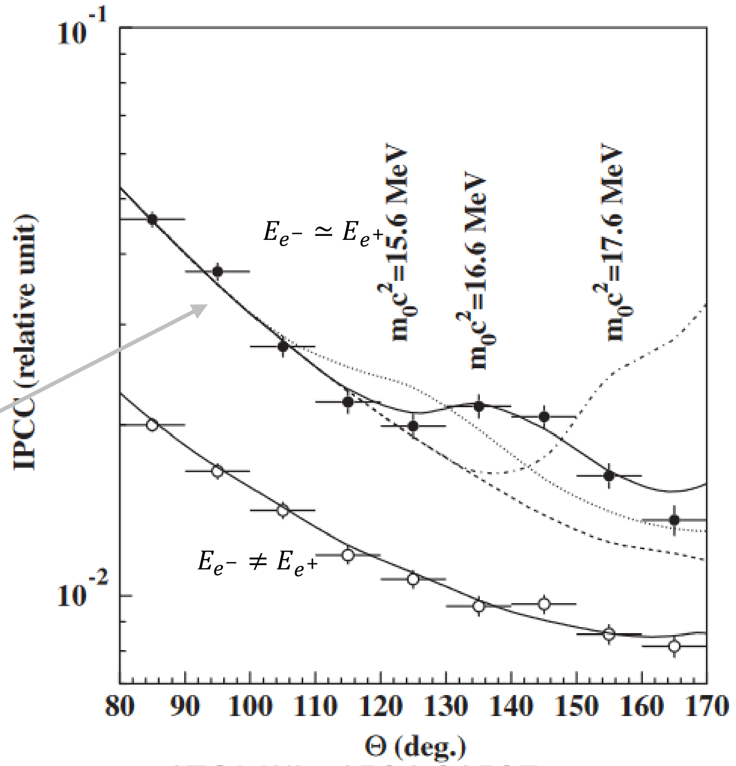



The SM signal: $N^* \to N\,\gamma^* \to N\,e^+e^-$




ATOMKI - 1504.01527

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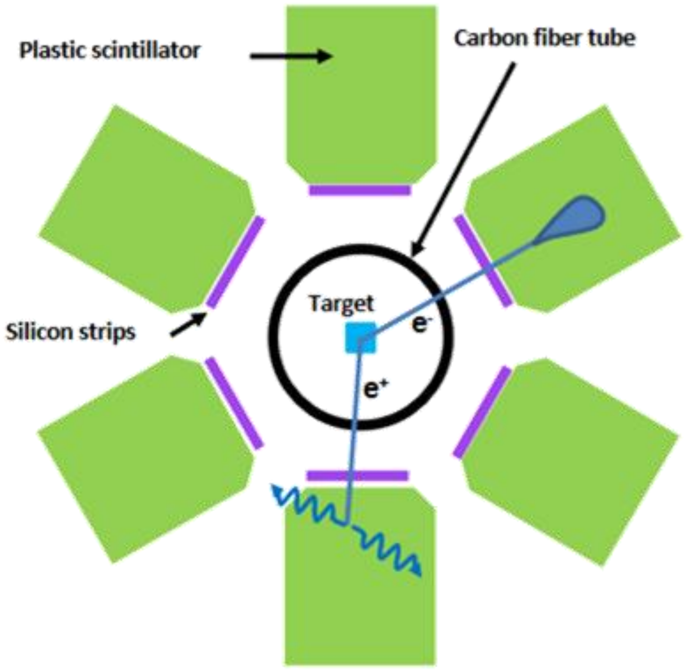


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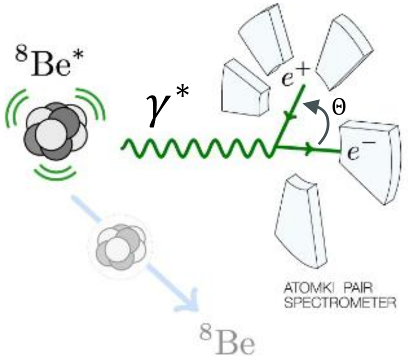
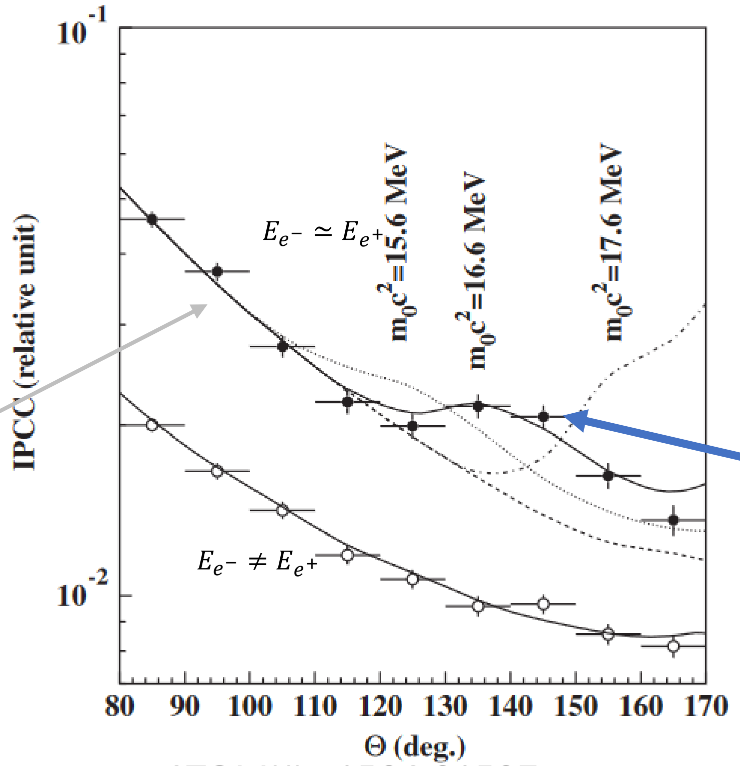
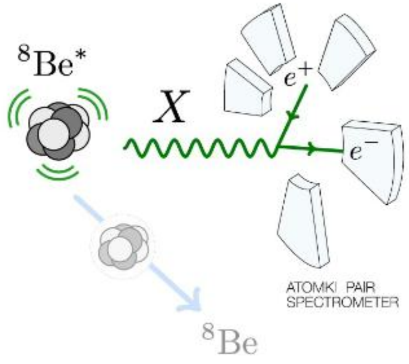



ATOMKI - 1504.01527

*NP sigma:* $N^* \to N\,V \to N\,e^+e^-$



# Experimental timelines

**ATOMKI**

- 2015 — $^{8}Be^{*}(18.15)$
- 2018 — $^{8}Be^{*}(18.15)$
- 2021 — $^{4}He^{*}(20.21/21.01)$
- 2022 — $^{12}C^{*}(17.23)$ $^{8}Be^{*}$ (off resonance)

17 MeV Resonance from nuclear processes

✓

**NA64**

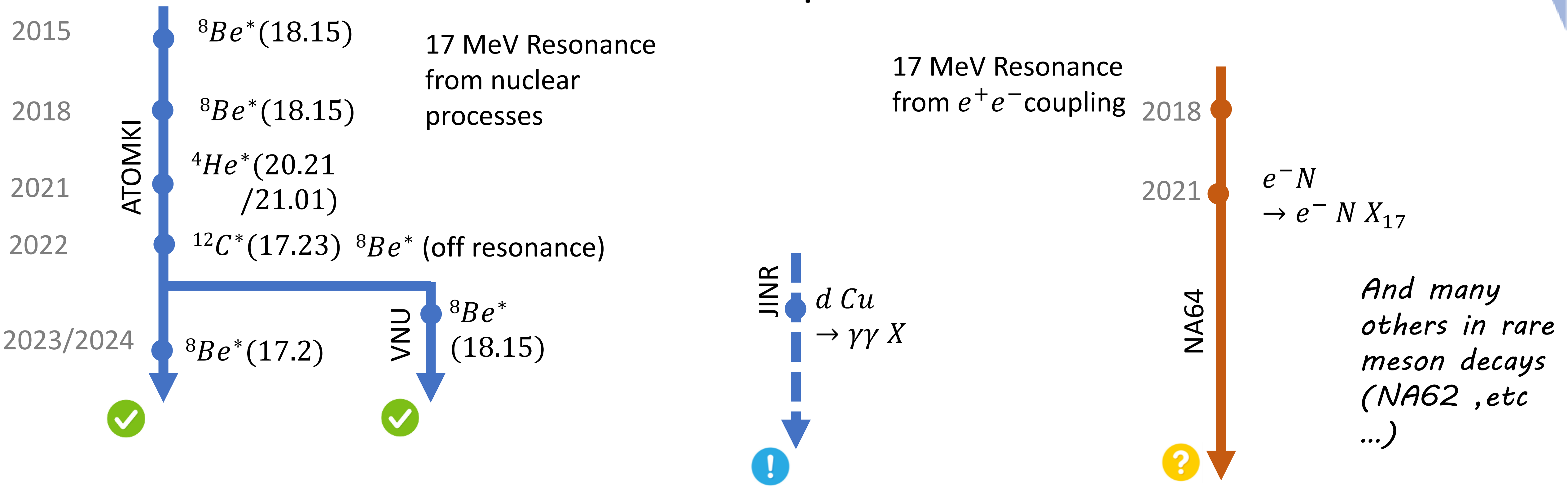
17 MeV Resonance from $e^{+}e^{-}$coupling

- 2018
- 2021 — $e^{-}N \rightarrow e^{-}\,N\,X_{17}$

?

*And many others in rare meson decays (NA62 ,etc …)*

# Experimental timelines



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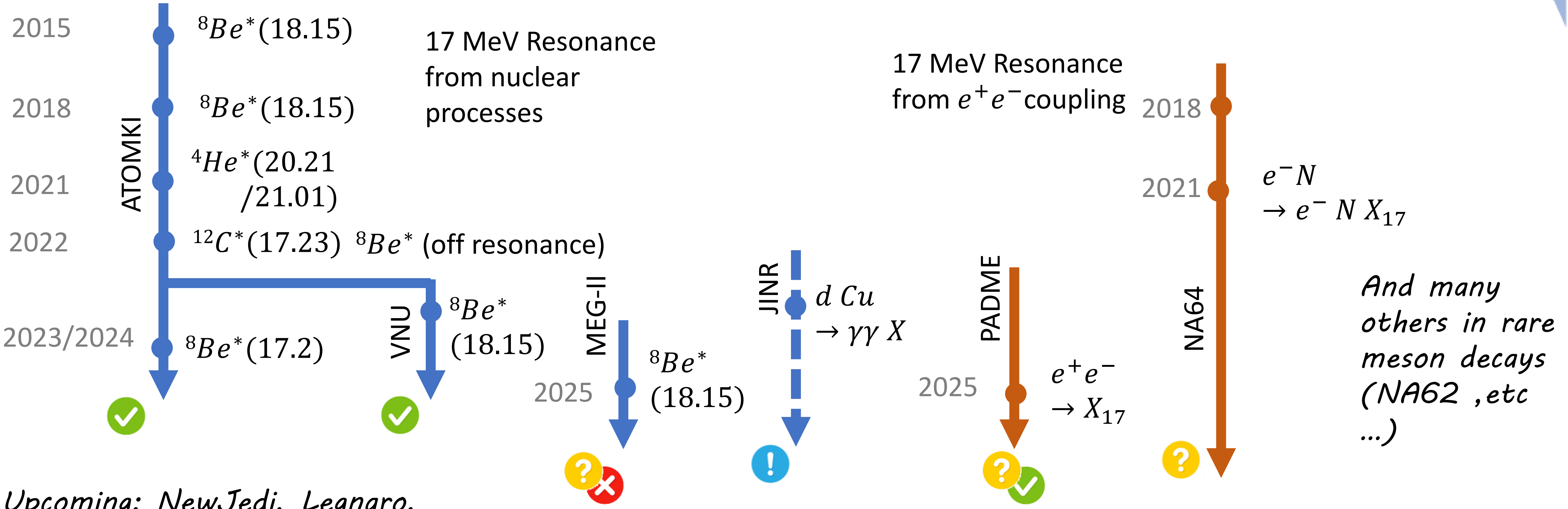
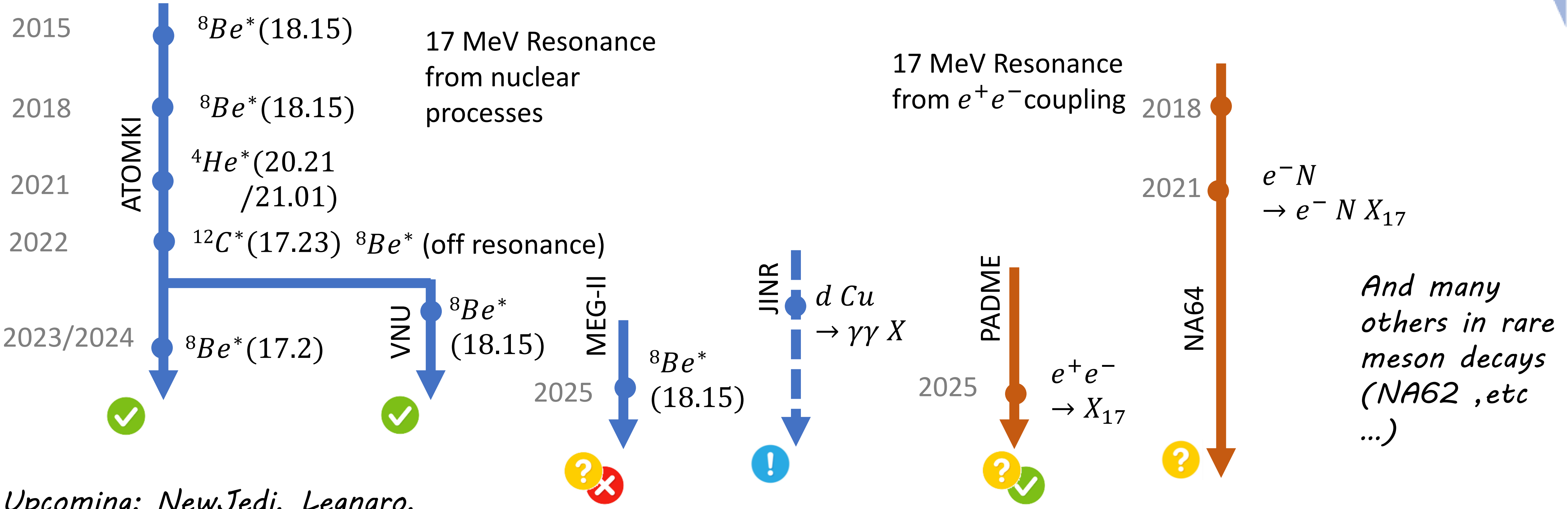



*Upcoming: NewJedi, Legnaro, nToF, Montreal X17*

# Experimental timelines




*Upcoming: NewJedi, Legnaro, nToF, Montreal X17*

- Altogether: the signal is still there on the nuclear physics side, no signal at MEG pushes it to somehow lower mass

→ No explanation on the nuclear physics side (although the modelling of the background by ATOMKI has come under some controversies)

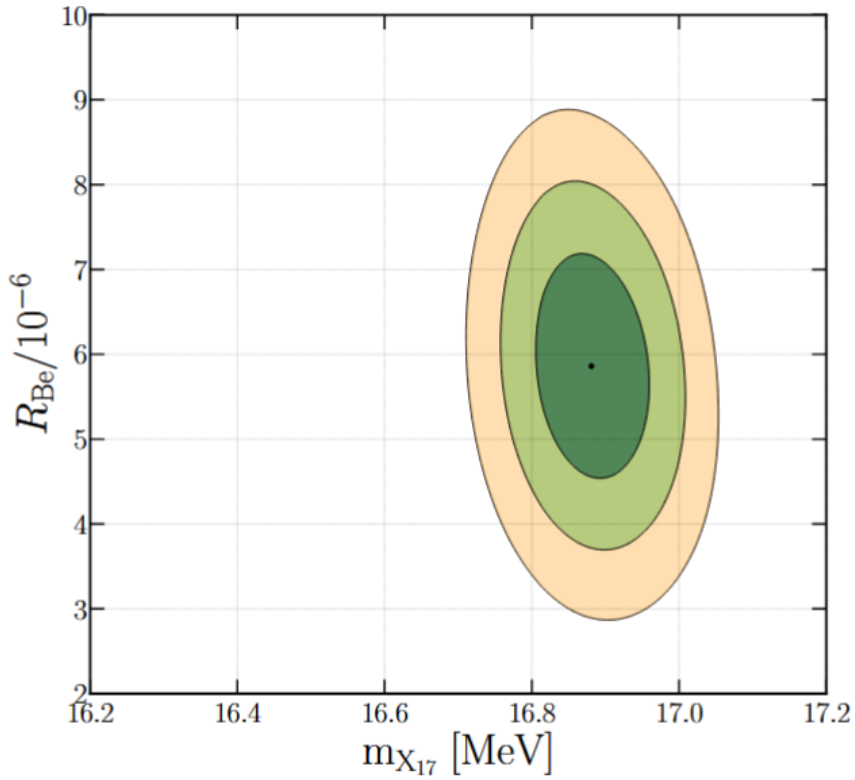
# A new boson ?

- If this is a new particle the most obvious requirements is on the mass !

Extracted from Arias-Aragon et al. 2504.11439

| Nucleus (MeV) | $m_X$ (MeV) | Experiment | Ref. |
|---|---|---|---|
| $^8$Be*(18.15) | $16.86 \pm 0.06 \pm 0.50$ | Atomki | [2, 6] |
| $^8$Be*(18.15) | $17.17 \pm 0.07 \pm 0.20$ | Atomki | [6] |
| $^4$He*(20.21/21.01) | $16.94 \pm 0.12 \pm 0.21$ | Atomki | [9] |
| $^{12}$C*(17.23) | $17.03 \pm 0.11 \pm 0.20$ | Atomki | [10] |
| $^8$Be*(GDR) | $16.95 \pm 0.48 \pm 0.35$ | Atomki | [11, 12] |
| $^8$Be*(18.15) | $16.66 \pm 0.47 \pm 0.35$ | VNU-UoS | [13] |
| $^8$Be*(17.64/18.15) | $< 16.81$ [$R_{Be} = 6 \cdot 10^{-6}$] | MEG II | [17] |
| $e^+e^- \to X_{17}$ | $16.90 \pm 0.02 \pm 0.05$ | PADME | [20, 21] |

2504.11439

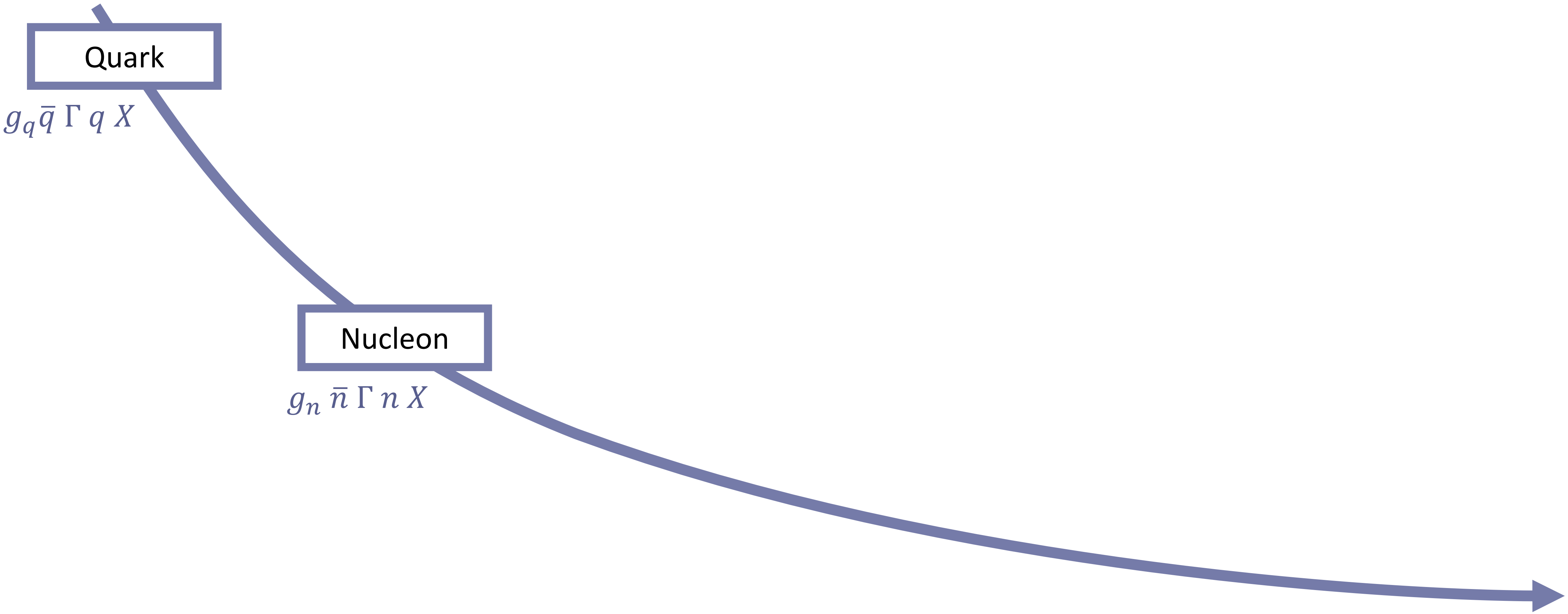



→ Altogether we know the possible mass extremely well $m_{X_{17}} \simeq 16.78 \pm 0.12$ MeV

→ That would make it a light and dark new particle! But how « dark » should this particle be ?

# Estimate of the X17 couplings: nuclear physics

Our goal : estimating the $N^* \to NX$ decay rate



# Estimate of the X17 couplings: nuclear physics

## Our goal : estimating the $N^* \to NX$ decay rate

Quark

$g_q \bar{q}\, \Gamma\, q\, X$

Use ChiPT + Low energy constraint (LEC)

- **Scalar** : $\pi N$ scattering / Lattice QCD $\sim O(30\ \%)$
- **Pseudo-Scalar** : large Nc, DIS processes, chiral limit, semi-leptonic decays $\sim O(1)$
- **Vector** : no need for data
- **Axial- Vector** : Lattice QCD $\sim O(10\ \%)$

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Nuclear Hamiltonian / NR point-like nucleon

Nuclear densities

$S, J^0, \vec{J}\,, H_{int}$

$$g_n\, \bar{n}\, \Gamma\, n\, X \;\to\; g_n \textstyle\sum_i \delta(\vec{r} - \vec{r_i}) \ldots \;\to\; H_{int} = \int d^3\vec{r}\; J_\mu(\vec{r}) X^\mu \ldots$$

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Multipole expansion on the densities

$$\Gamma_X^{s=0} = \frac{2k}{2J_* + 1}\left\{\sum_{J\geq 0} |\langle f||\mathcal{G}_J||i_*\rangle|^2\right\}$$

**Decay rates**

$\Gamma_{N^*}$

$g_n\, \bar{n}\, \Gamma\, n\, X \;\to\; g_n \sum_i \delta(\vec{r} - \vec{r_i}) \ldots \;\to\; H_{int} = \int d^3\vec{r}\; J_\mu(\vec{r}) X^\mu \ldots$

# Spin-parity study

- Since nuclear states have a definite spin and parity quantum number, we can find selection rules for the on-shell X17 production
  - → Scalar (0+) excluded by $^{8}$Be data
  - → $^{4}$He data mixes 0+ and 0- excited nuclei
  - → $^{12}$C data are incompatible with a pseudo-scalar X17

Adapted from Toni et al. 2212.06453

$$N^* \to N\, X$$

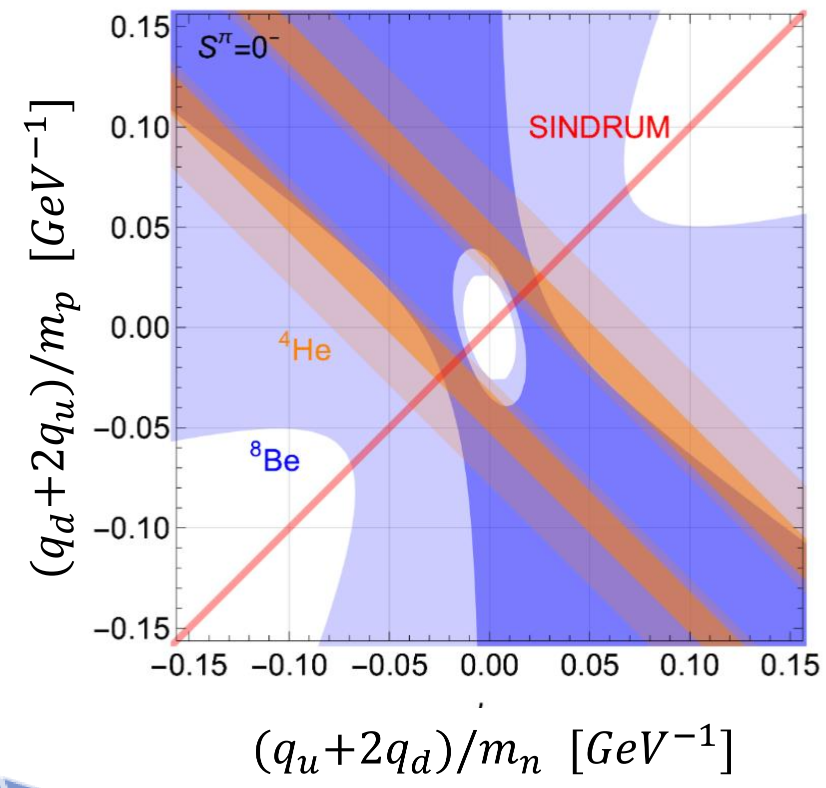
$$J_* = L \oplus J_X$$
$$P_* = (-1)^L P_X$$

| | | | X boson spin parity | | | |
|---|---|---|---|---|---|---|
| $N$ | $N^\star$ | $J^\pi$ | $S^\pi = 1^-$ | $S^\pi = 1^+$ | $S^\pi = 0^-$ | $S^\pi = 0^+$ |
| $^{8}$Be | | $0^+$ | (V) | (AV) | (PS) | (S) |
| | $^{8}$Be(18.15) | $1^+$ | 1 | 0, 2 | 1 | / |
| $^{4}$He | | $0^+$ | | | | |
| | $^{4}$He(21.01) | $0^-$ | / | 1 | 0 | / |
| | $^{4}$He(20.21) | $0^+$ | 1 | / | / | 0 |
| $^{12}$C | | $0^+$ | | | | |
| | $^{12}$C(17.23) | $1^-$ | 0, 2 | 1 | / | 1 |

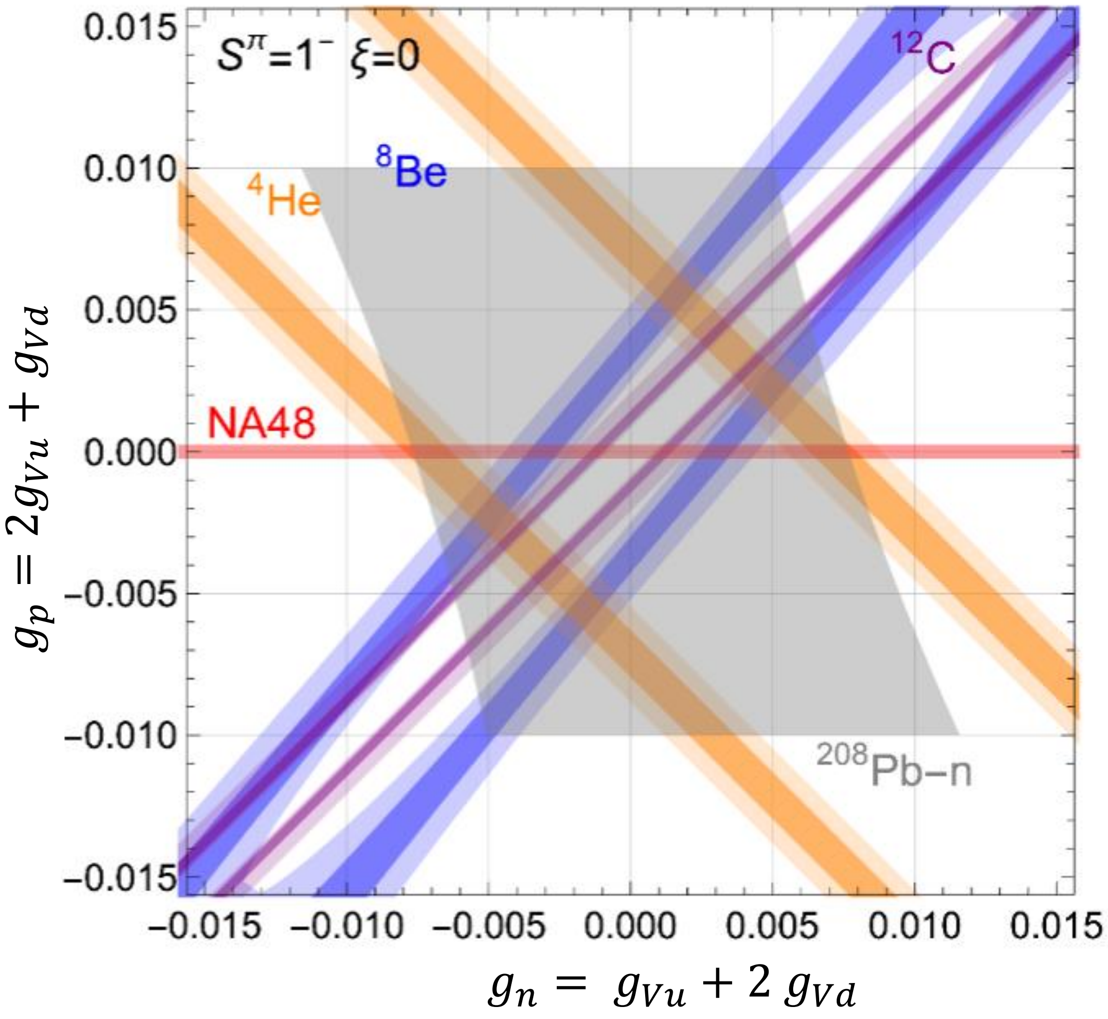
- Conclusion: both parity for a spin-1 particle are a priori possible, but one would need both scalar AND pseudo-scalar couplings to fit all excesses.

# Low energy couplings

- Need coupling to $e^+e^-$ AND a very large couplings to quarks to fit the excess
  - →Typically a few $10^{-3}$ for vectors, tens of GeV effective NP scale for ALPs, etc …
  - →There are plethora of low energy constraints relevant for such large couplings

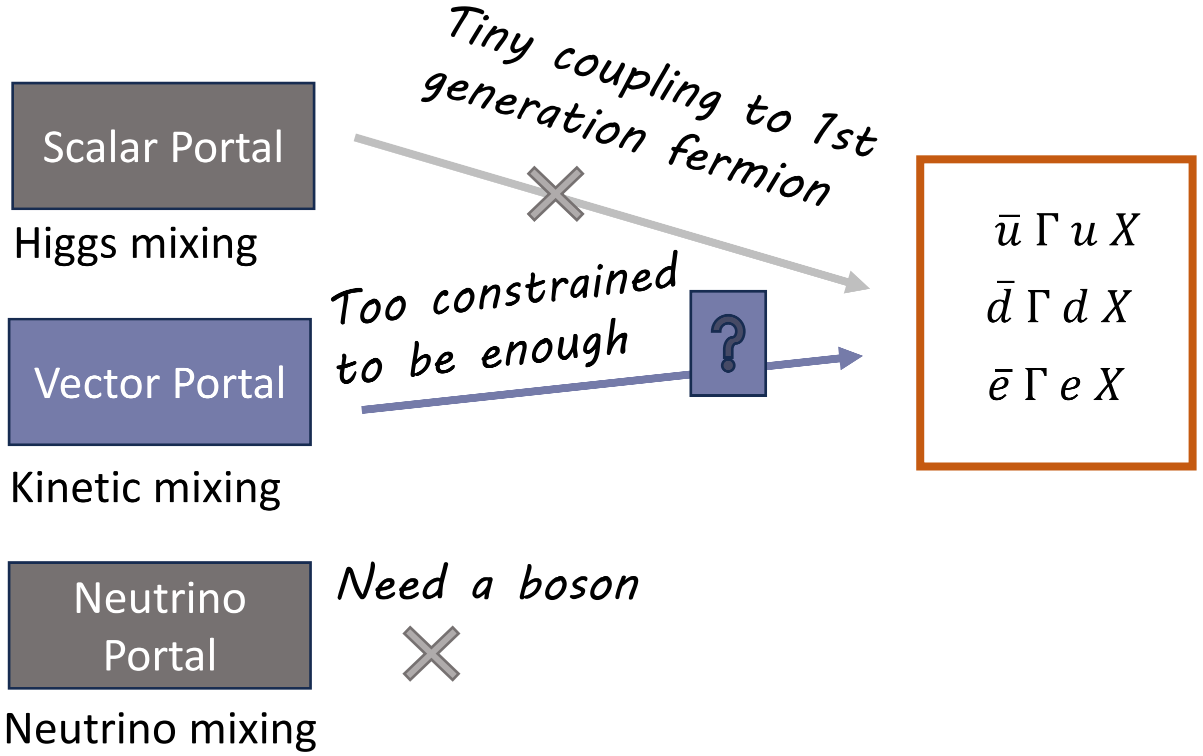



Fits from Toni et al. 2212.06453



# Phenomenology and model building

# Simplified models and UV construction



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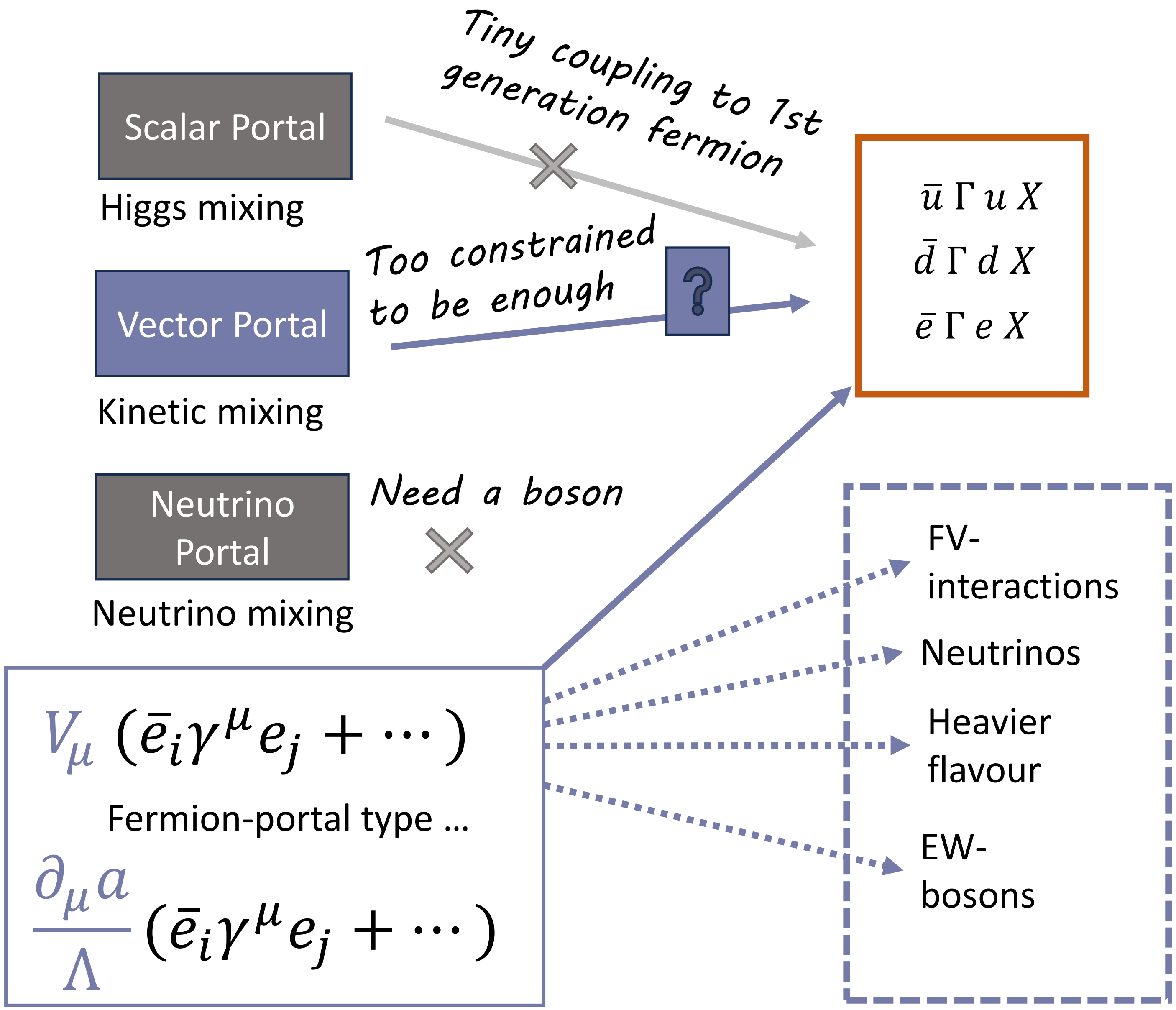

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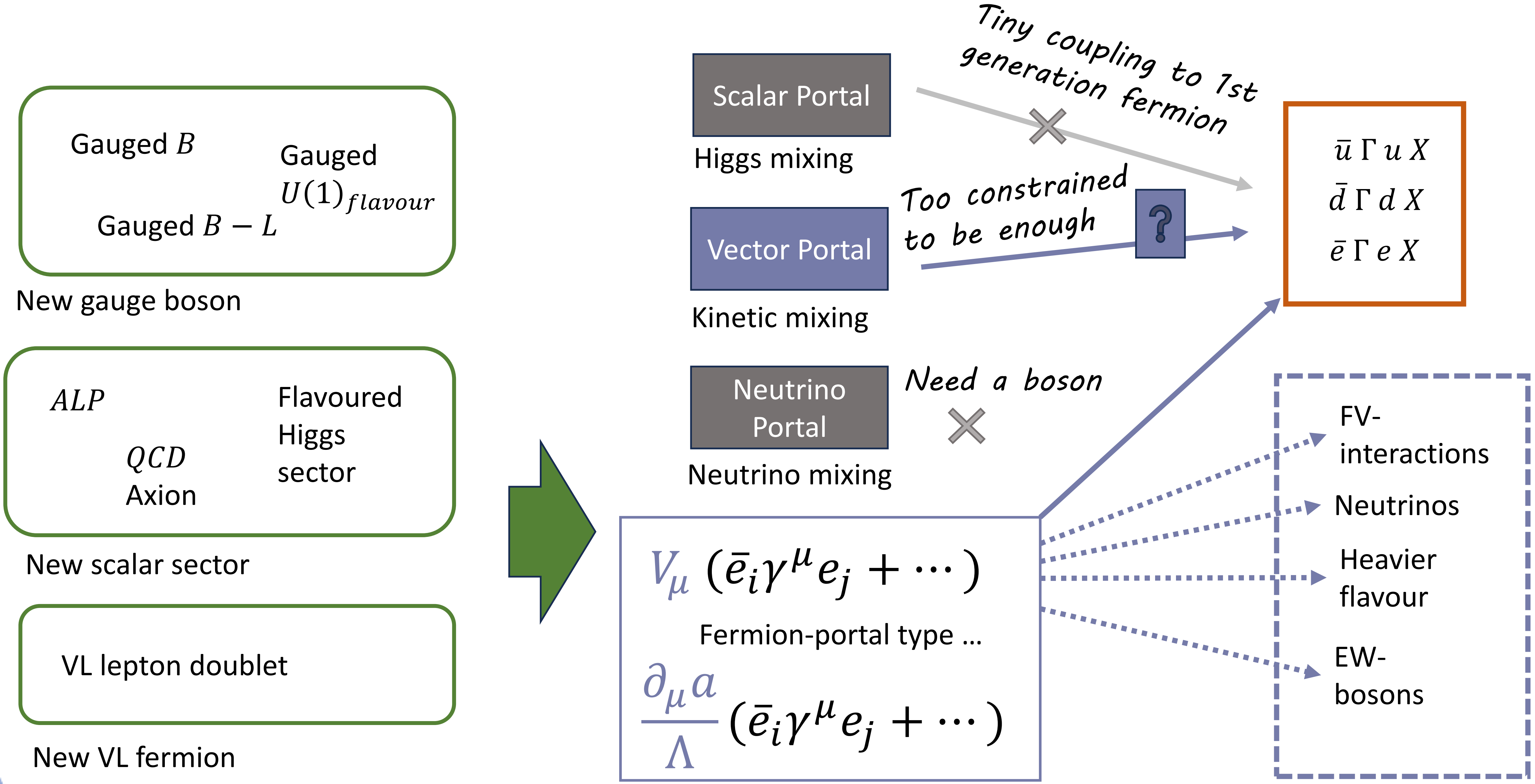
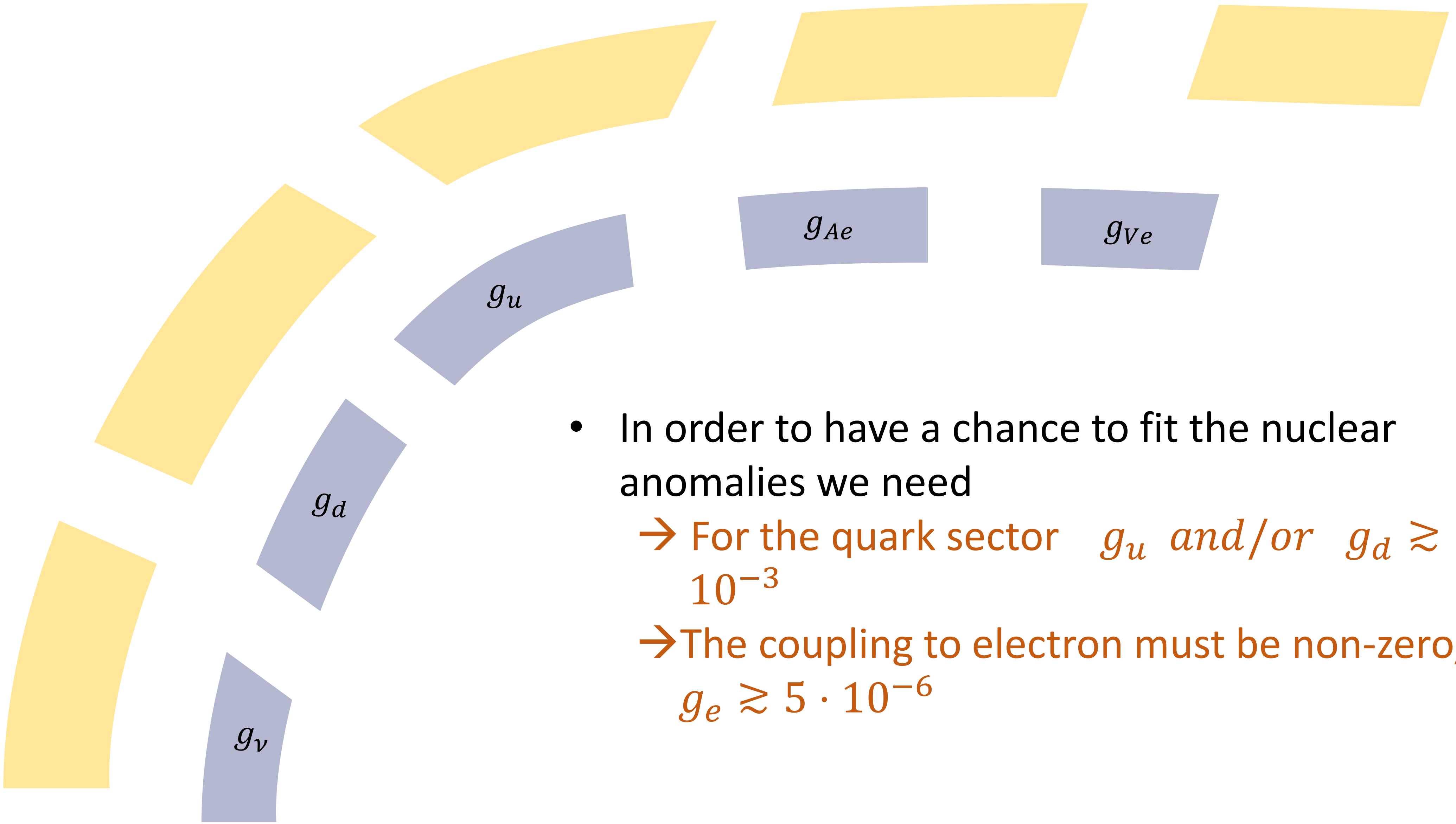
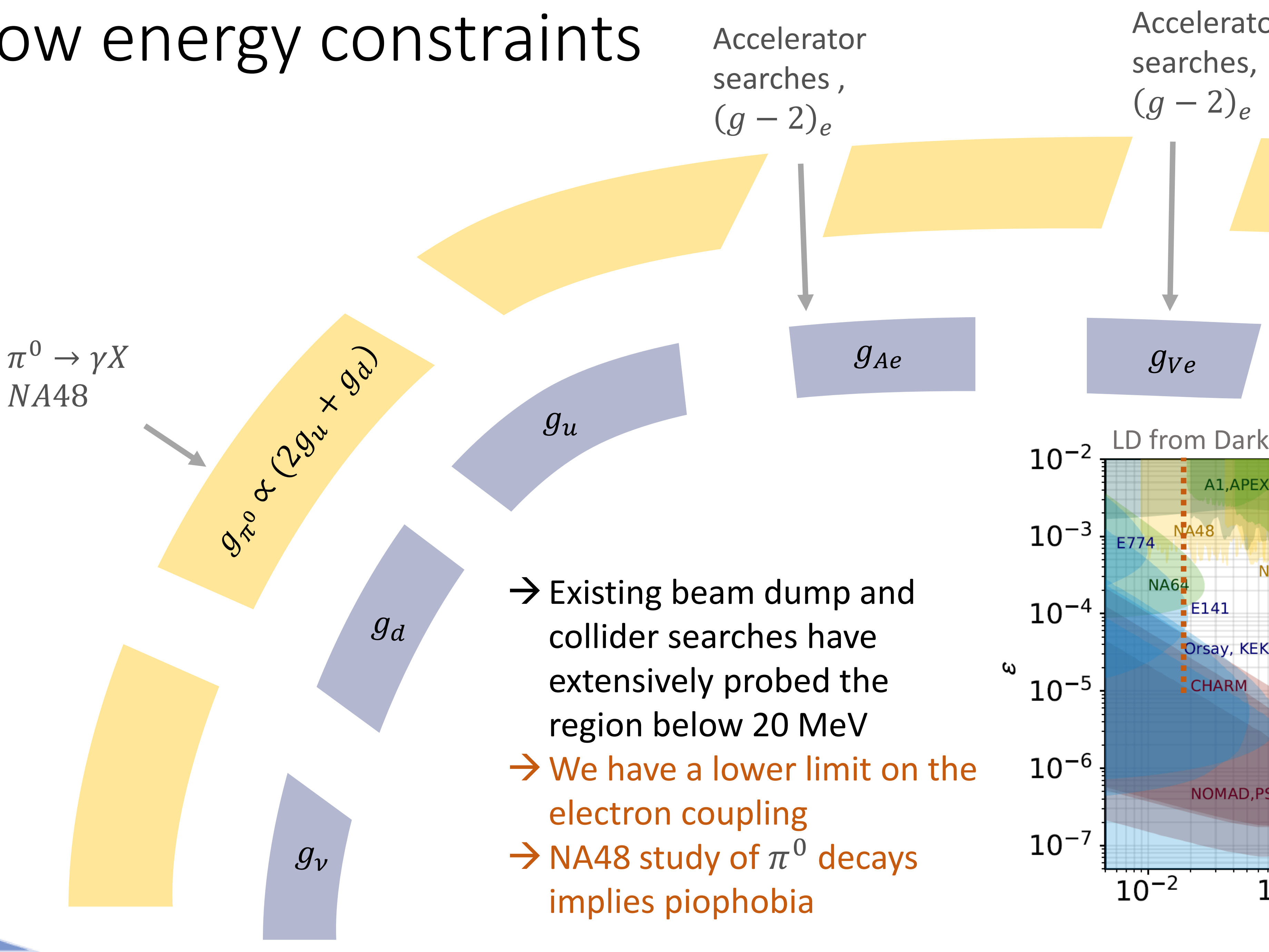


# Low energy constraints (vector case)




- In order to have a chance to fit the nuclear anomalies we need
  - → For the quark sector $g_u$ *and/or* $g_d \gtrsim 10^{-3}$
  - → The coupling to electron must be non-zero, $g_e \gtrsim 5 \cdot 10^{-6}$

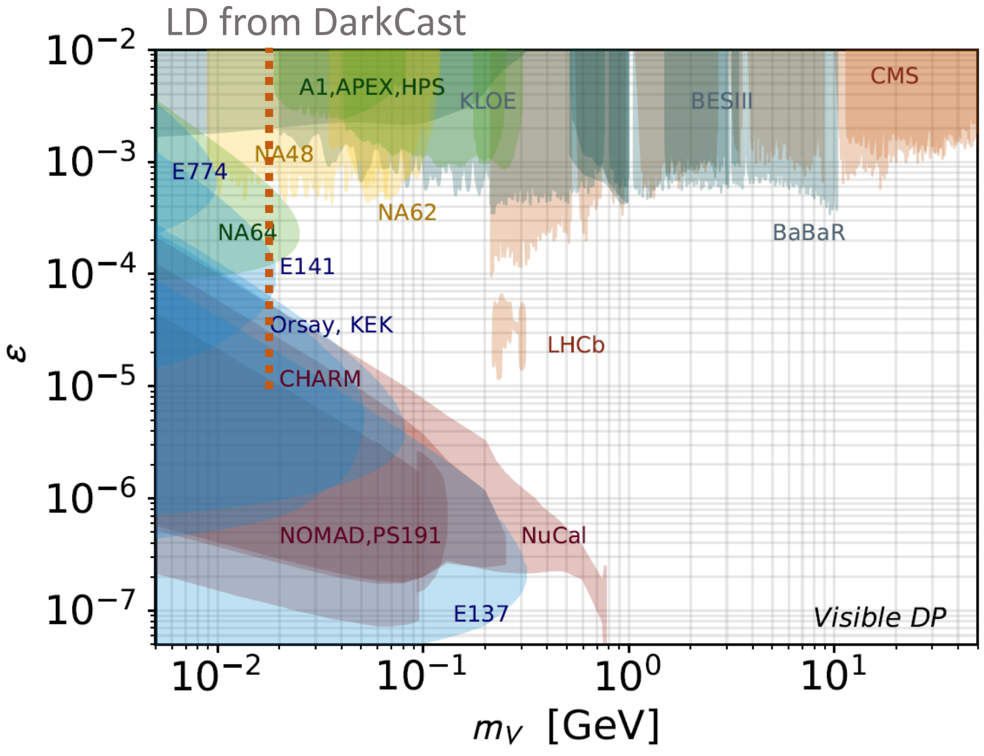
# Low energy constraints




→ Existing beam dump and collider searches have extensively probed the region below 20 MeV

→ We have a lower limit on the electron coupling

→ NA48 study of $\pi^0$ decays implies piophobia



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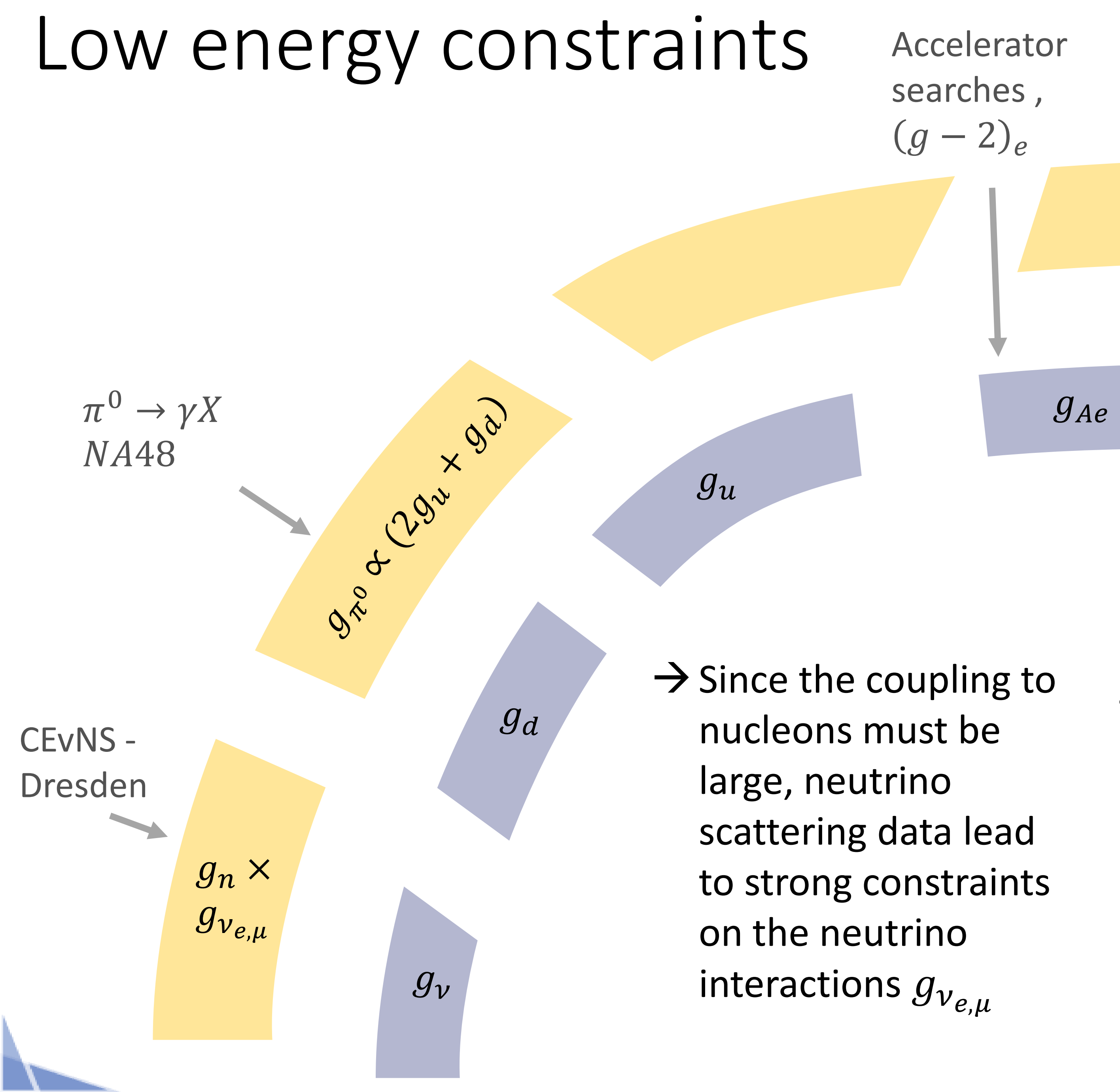
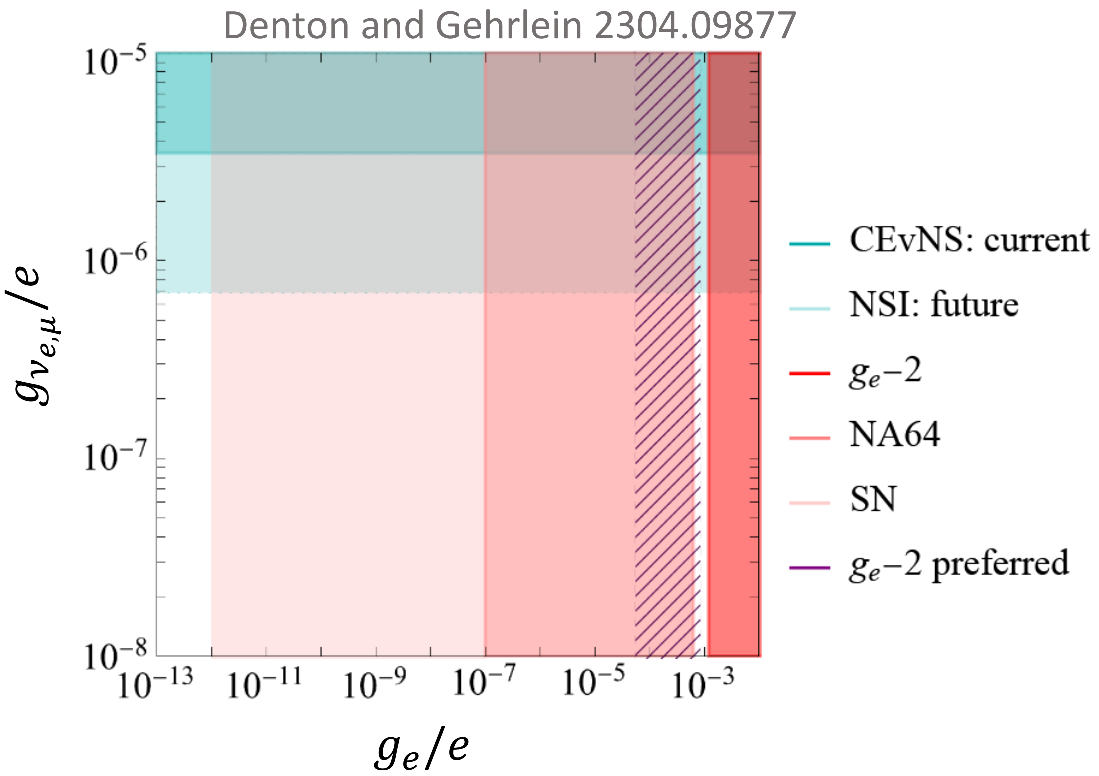



→ Since the coupling to nucleons must be large, neutrino scattering data lead to strong constraints on the neutrino interactions $g_{\nu_{e,\mu}}$



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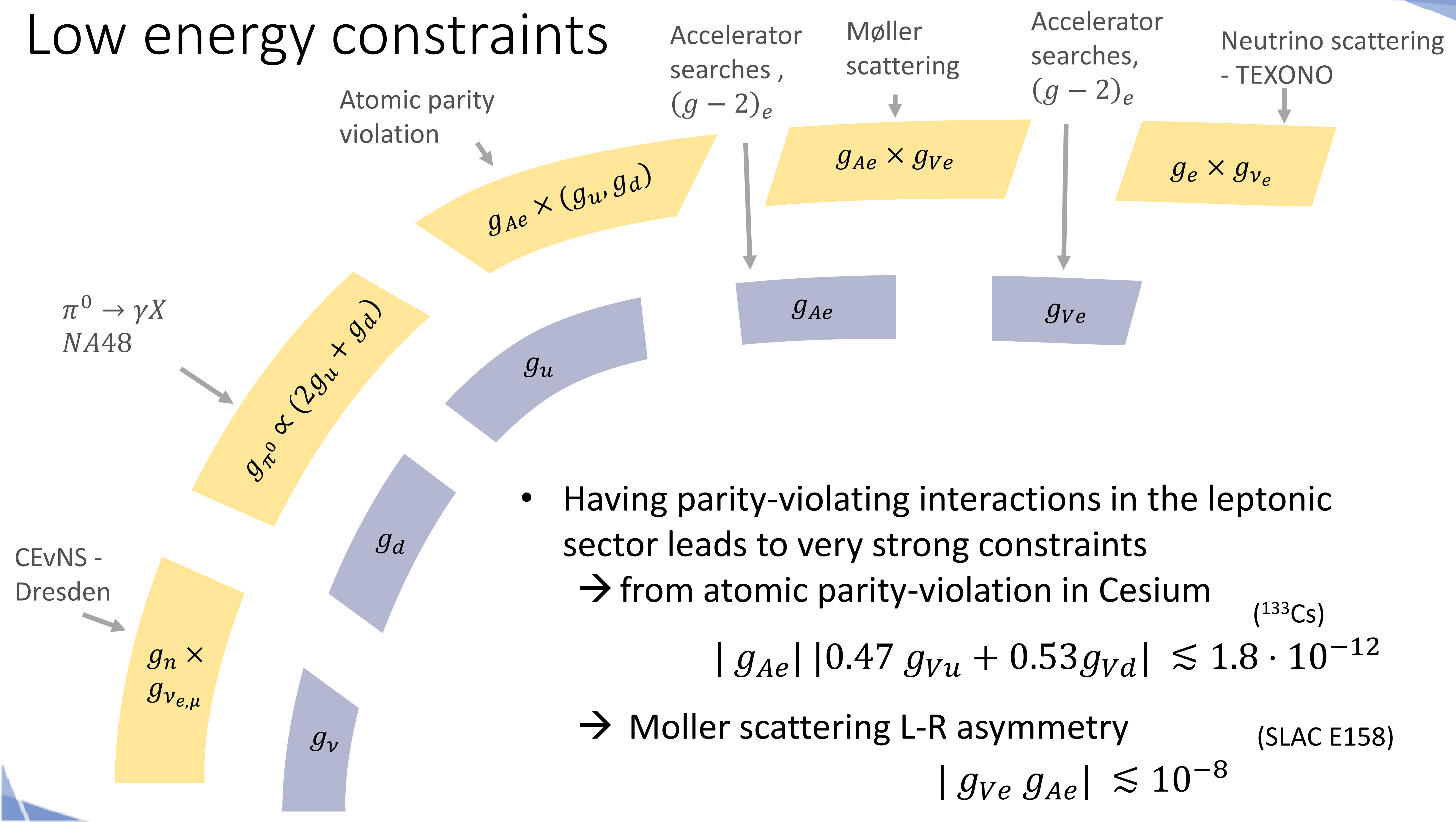



- Having parity-violating interactions in the leptonic sector leads to very strong constraints
  → from atomic parity-violation in Cesium ($^{133}Cs$)

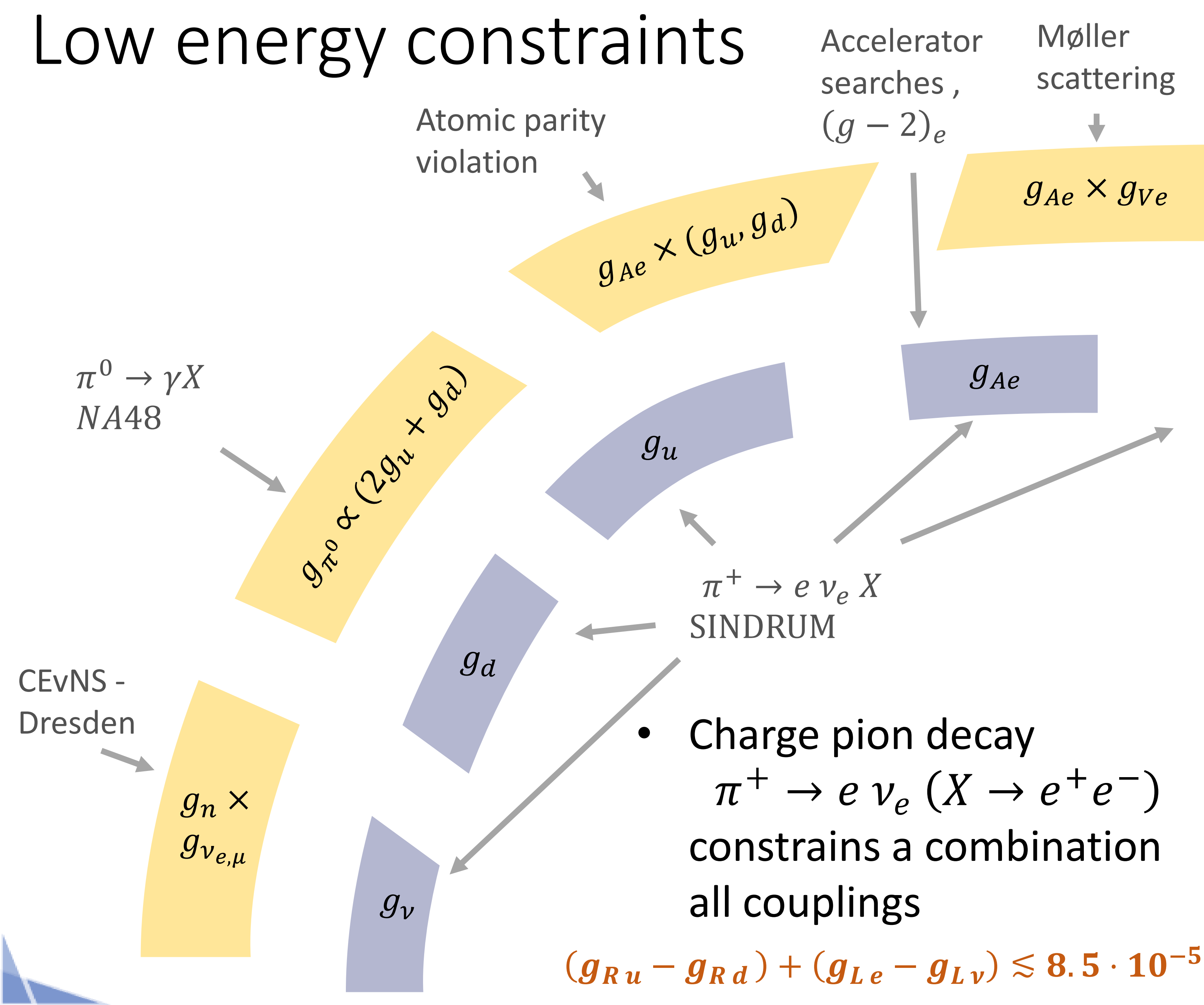
$$|g_{Ae}|\,|0.47\,g_{Vu} + 0.53 g_{Vd}| \lesssim 1.8 \cdot 10^{-12}$$

  → Moller scattering L-R asymmetry (SLAC E158)

$$|g_{Ve}\, g_{Ae}| \lesssim 10^{-8}$$

From 2212.06453

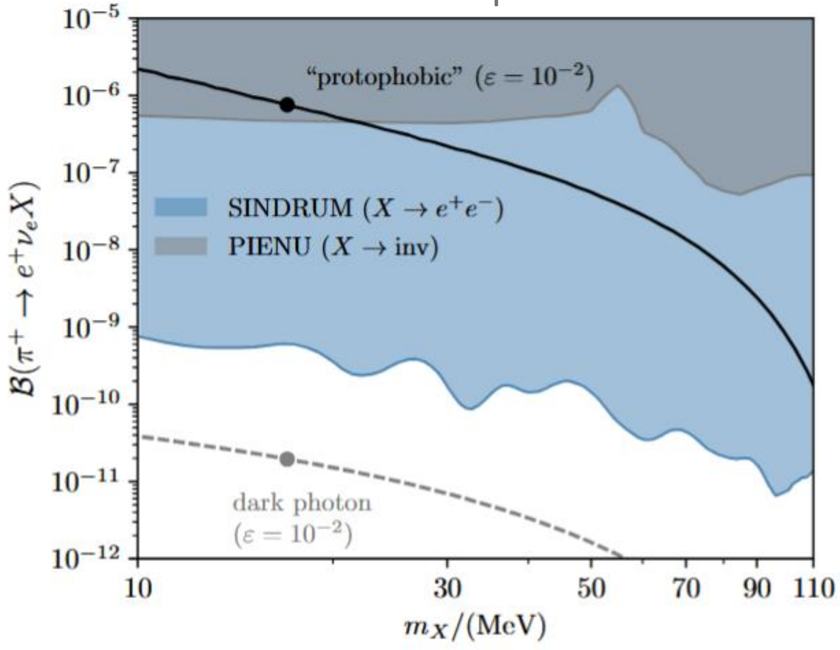
# Low energy constraints




- Charge pion decay $\pi^+ \to e\,\nu_e\,(X \to e^+e^-)$ constrains a combination all couplings

$$(g_{R\,u} - g_{R\,d}) + (g_{L\,e} - g_{L\,\nu}) \lesssim 8.5 \cdot 10^{-5}$$

Hostert and Pospelov 2306.15077



# Case study : the B-L pio-phobic line of research

- One of the earliest constructions, attracted significant interest during the last decade

$L \supset g_B X_\mu(\bar{q}\gamma^\mu q - \bar{\ell}\gamma^\mu \ell)$

Step 1 : Introduce a new B-L gauge group → conserved SM current

$g_{Vp} = g_{V\pi} = 2\, g_{Vu} + g_{Vd} \sim 3 g_B$ is unsuppressed : Exclude by $\pi^0$decays

$L \supset g_B\, X_\mu[(\bar{q}\gamma^\mu q - \bar{\ell}\gamma^\mu \ell) + \frac{e\,\varepsilon}{g_B} J^\mu_{em}]$

Step 2 : Add kinetic mixing to make it piophobic

$g_\nu g_n \sim g_B^2$ is too large : Excluded by neutrino dataset

$L \supset g_B\, X_\mu[(\bar{q}\gamma^\mu q - \bar{e}\gamma^\mu e) + \frac{e\,\varepsilon}{g_B} J^\mu_{em}] + \cdots$

Step 3 : Neutralise neutrinos with new VL mixing

The leptonic part of the current is now unconserved
-> exclusion from $\pi^+ \to e\, \nu_e\, X$ decays

$(\boldsymbol{g_B - g_B}) + (\boldsymbol{g_B}) \lesssim \mathbf{8.5 \cdot 10^{-5}}$

# Summary of model building status

- I am not aware of any published model with a $X_{17}$ new particle which concurrently

  → Fits all the excited nuclear decays simultaneously ($^{12}$C, $^{8}$Be and $^{4}$He)

  → Is compatible with all known low energy constraints (in particular pionic decays + neutrino limits)

That obviously does not imply that it is impossible, but it makes it clear that its hard

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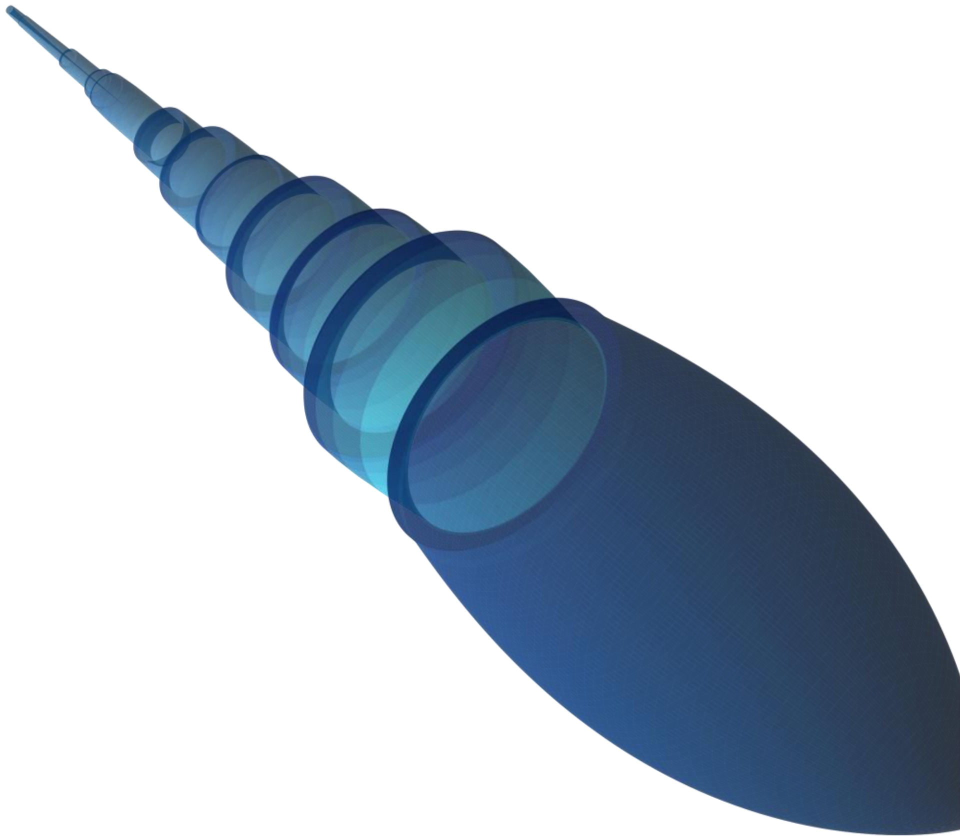
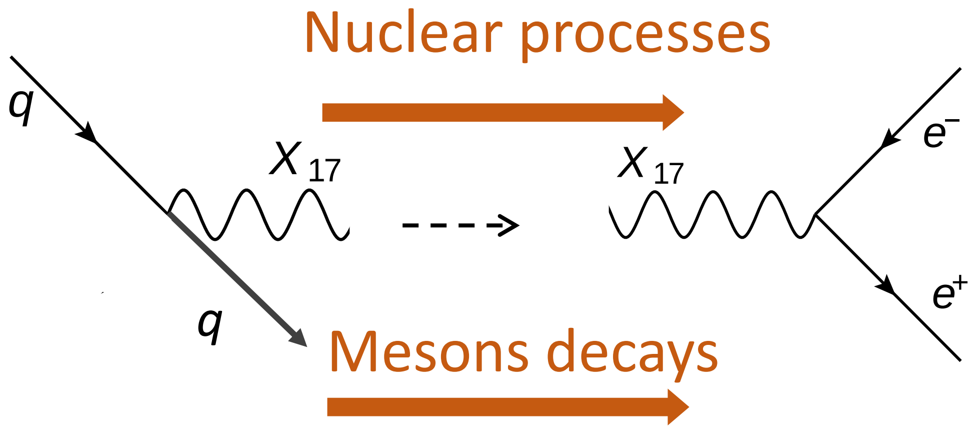
*Some directions pointed at in current literature include : (1) testing combined models scalar-pseudo scalar (2) relaxing some nuclear requirements (e.g using MEG-II non-result in Be)*

- The superposition of many constraints of different origins makes it difficult to have a final statement on the existence of the $X_{17}$
  - →More theory and experimental work needed,
  - →Use the electron coupling !

# Electron / Positron searches : towards a definitive answer ?



# An electronic search




- $e^+/e^-$ beam dump and $e^+/e^-$ collider

*Model independent + test NP origin of the signal*

- We look for a light boson decaying to mostly to $e^+e^-$ with mass:

$$m_{X_{17}} \simeq 16.78 \pm 0.12 \text{ MeV}$$

- The narrow mass range plus model-independent $e^\pm$ couplings makes this anomaly a perfect target for a resonant search !
- It is also in a mass regime that has been extensively explored for FIPs

# The vector case

- Current combination of N64 and PADME searches would have nearly covered the gap

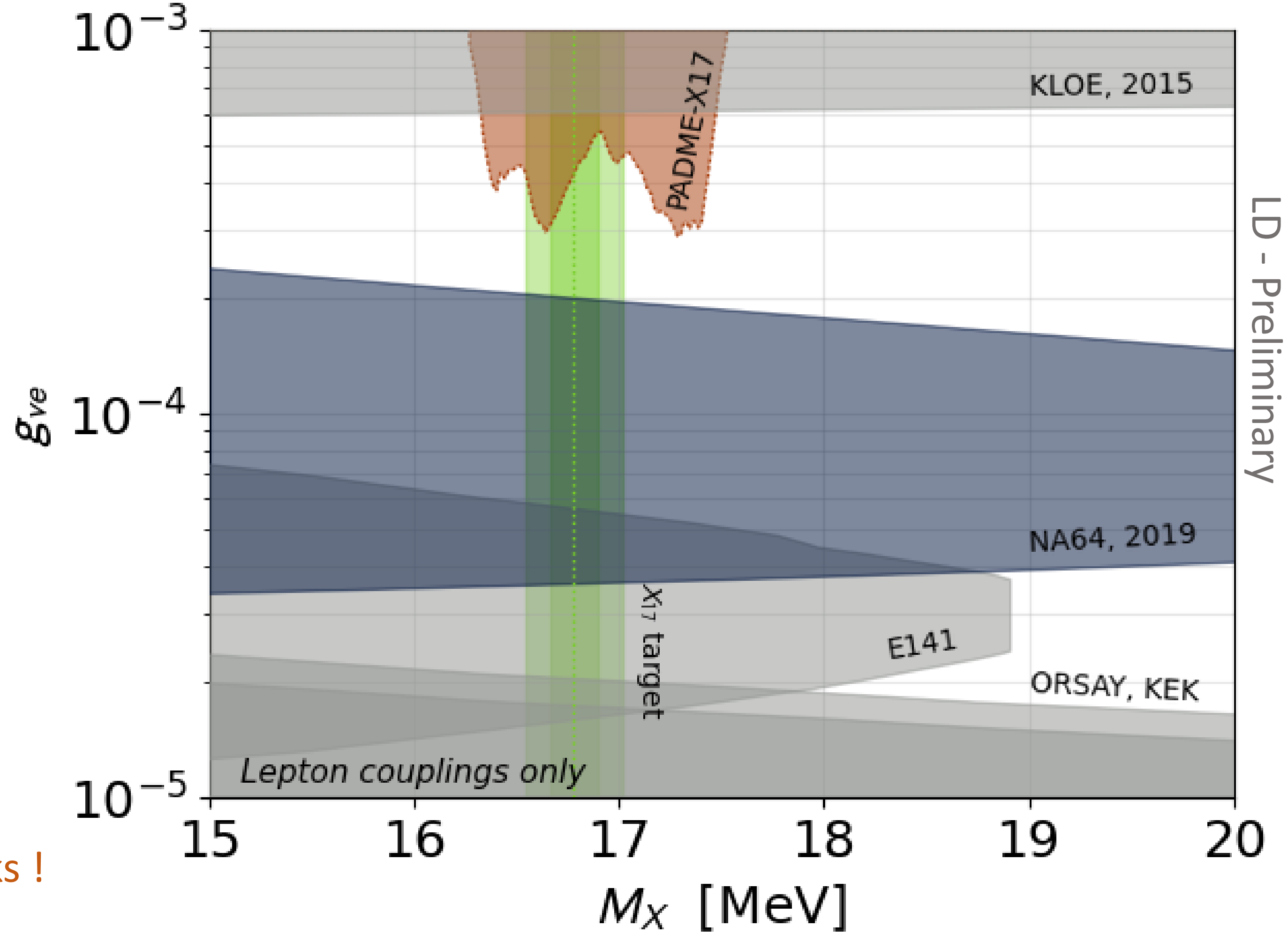
  → If only PADME didn't see an excess…

- An interesting combination of two very different analysis strategy

  →NA64 uses beam-dump approach and has an upper bound due to short life-time of the X17

  → See Paolo Crivelli's and Víctor Martín Lozano's talks !

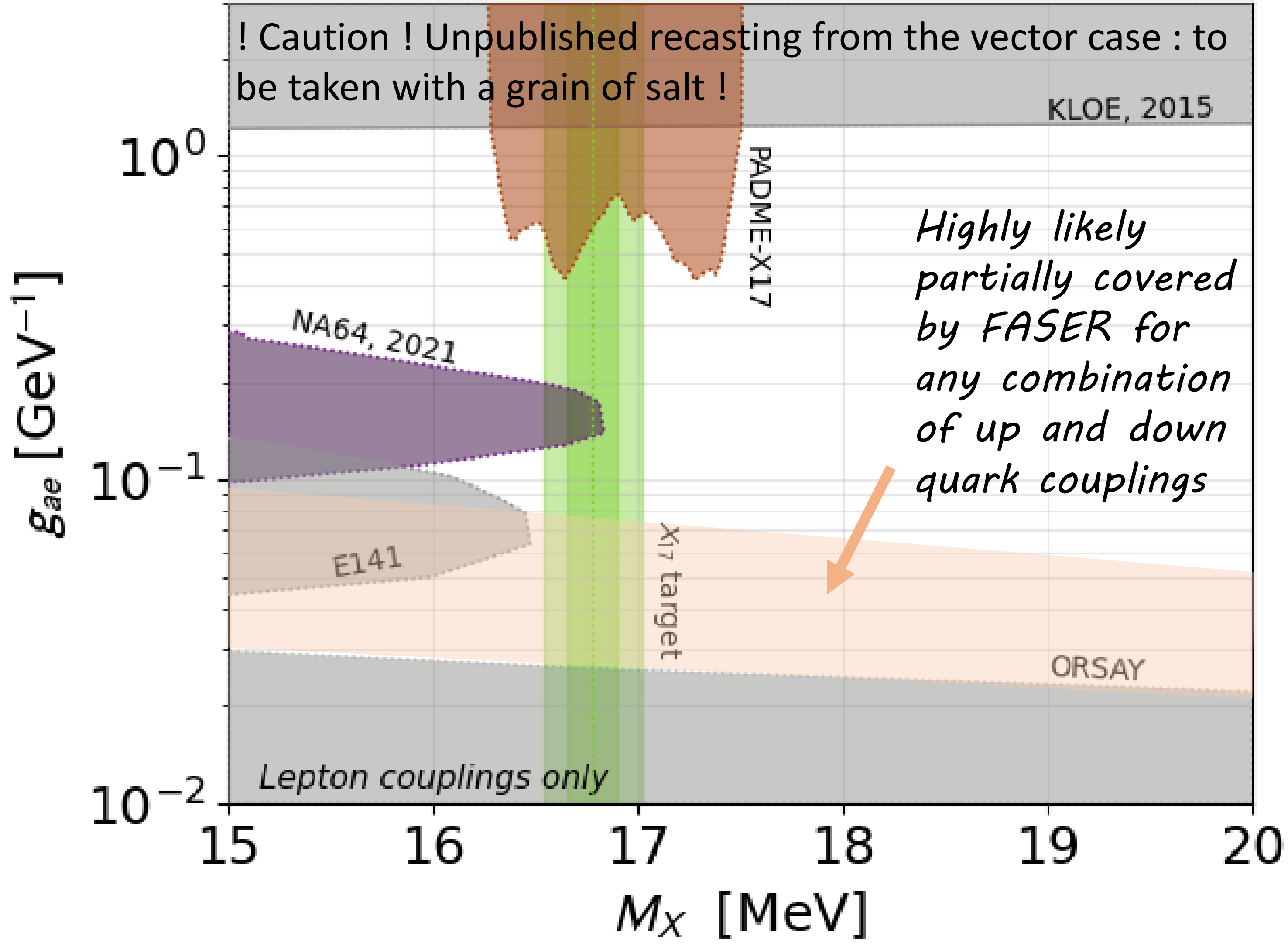
  →PADME relies on a « scanning » strategy, varying the energy of their positron beam and X17 prompt decay → See Mario Antonelli's talk !



# The ALP case

- The «  tip » of the NA64 search does not cover the relevant range
  - →Mostly due to somehow reduced production rates w.r.t the vector case

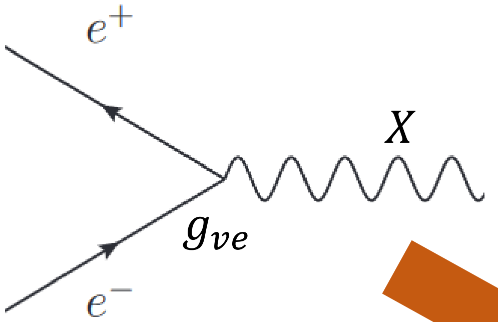
- The E141 exclusion sadly do not extend to the X17 line in that case
  - → It is however very likely that FASER constraints would cover a part of this regime if quark couplings were included



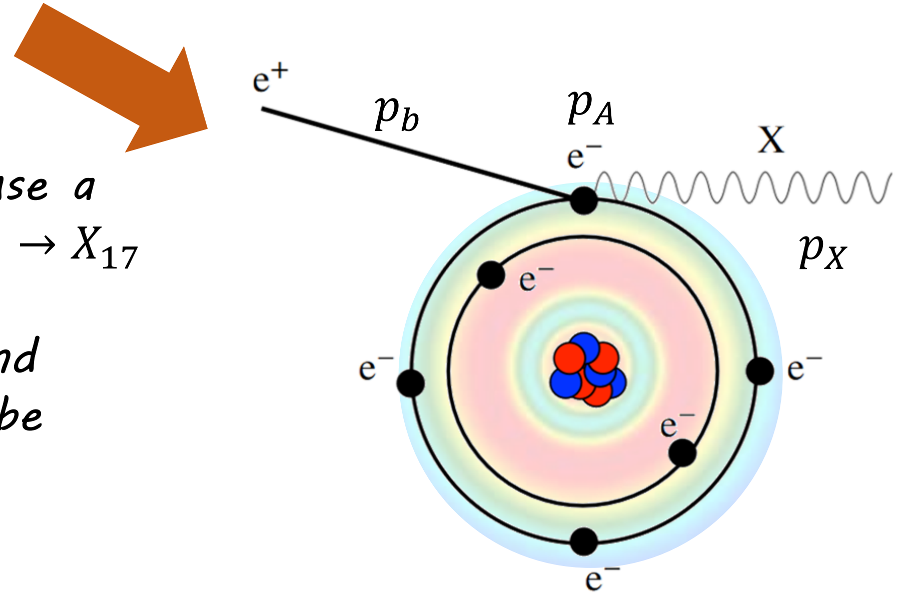
# Theoretical challenges in both cases

- For NA64 : X17 is at the tip of beam dump sensitivities
  → Strong sensitivity to details of the NP simulation process and location of production inside the target

- For PADME : the true process involves a positron interacting with an entire electronic cloud:
  → Electrons are in bound states and we must include their momentum density distribution




*We cannot use a simple $e^+e^- \to X_{17}$ process: the full bound state must be described*



# Strong effect on the signal shape

- The PADME sensitivity is dependent on the signal width
  → Modeled using Compton scattering experimental data

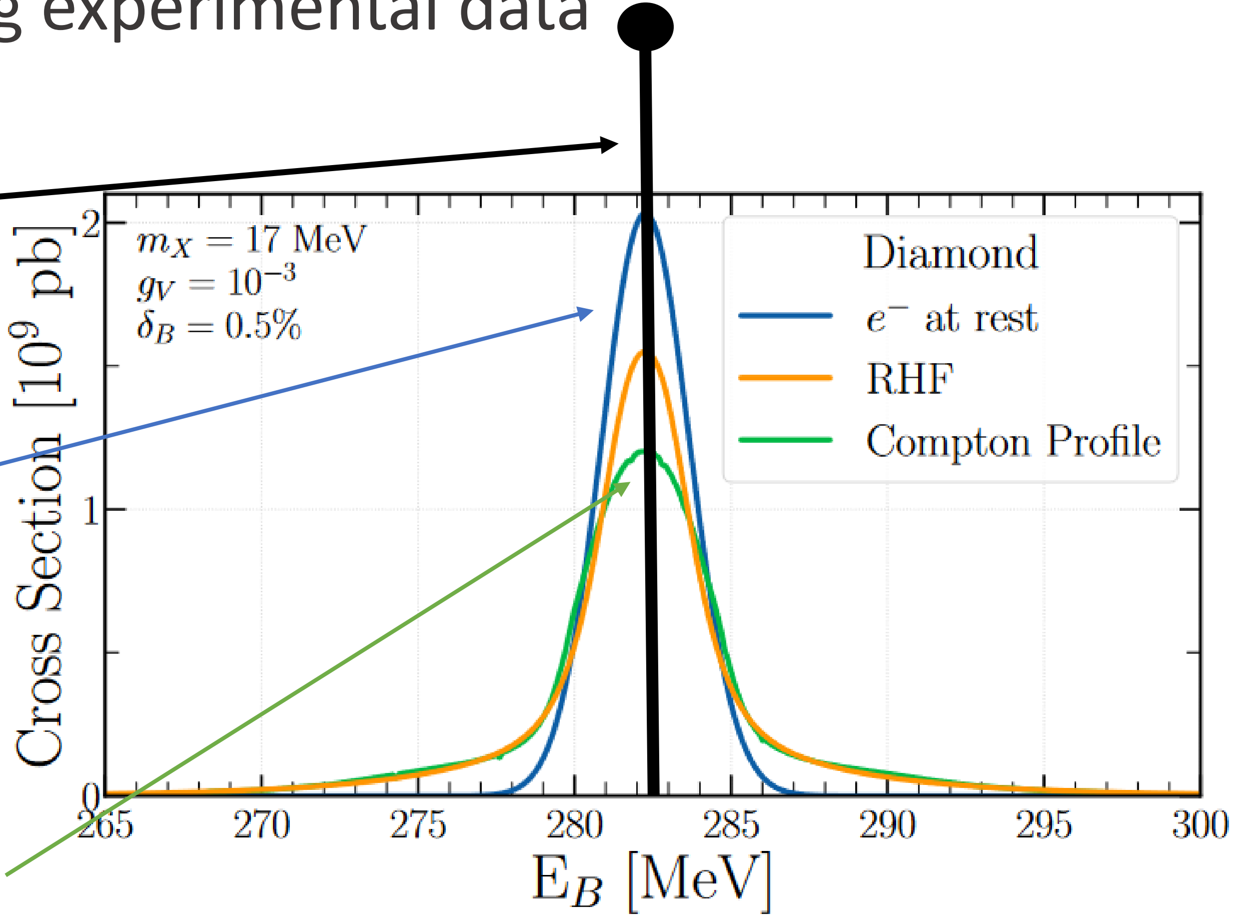
$$\sigma_{res} \sim \frac{g_{ve}^2}{2\, m_e} \pi\, Z\, \delta(E_B - E_{res})$$

*Include the beam energy spread*

$$\int dE_b\, \sigma_{res}(E_B)\, Gaussian(E_0, E_B, \delta_B)$$

*Include the electron motion via Compton scattering data*

$$\int dE_b \int dk_A\, f(k_A)\, \sigma_{res}(E_B, k_A)\, Gaussian(E_0, E_B, \delta_B)$$




*Resonant cross-check on Carbon Diamond*

# Conclusion

# Conclusion

- The X17 anomaly is now almost a decade-old !
- It has certainly proved to be a strong challenge for adventurous phenomenologists

  → And led to several new insights in exploring the dark word (in particular in the relevance of pionic decays, a temporary revival of MeV-scale QCD axion, exploration of neutrino neutralisation, etc…)

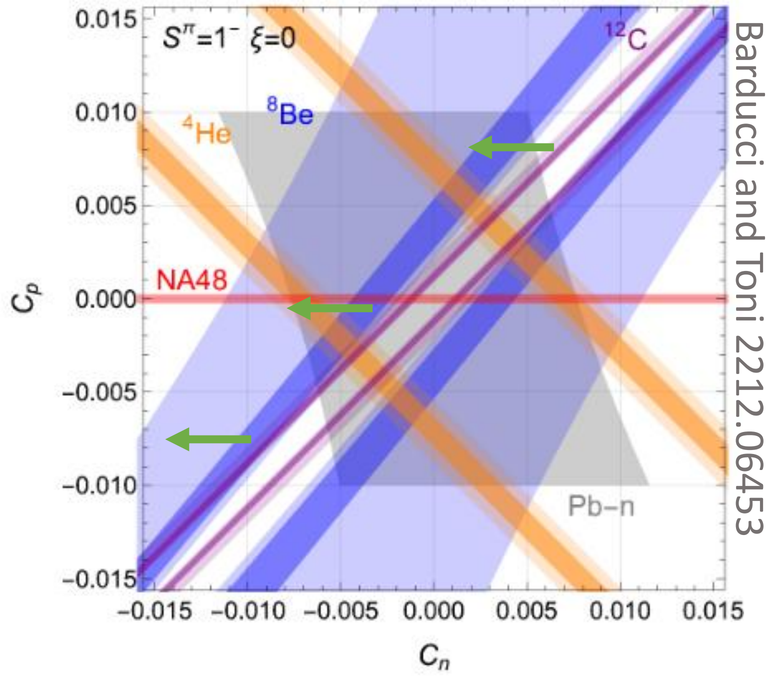
- There is a strong experimental effort to go the bottom of this question

  → Hopefully precise insights will help in orientating future model-building efforts

# Backup

# The X17 couplings

- The couplings and mass both enters in fitting the excess → simultaneous fit of $^{12}$C, $^{8}$Be and $^{4}$He required, not available yet with the latest data



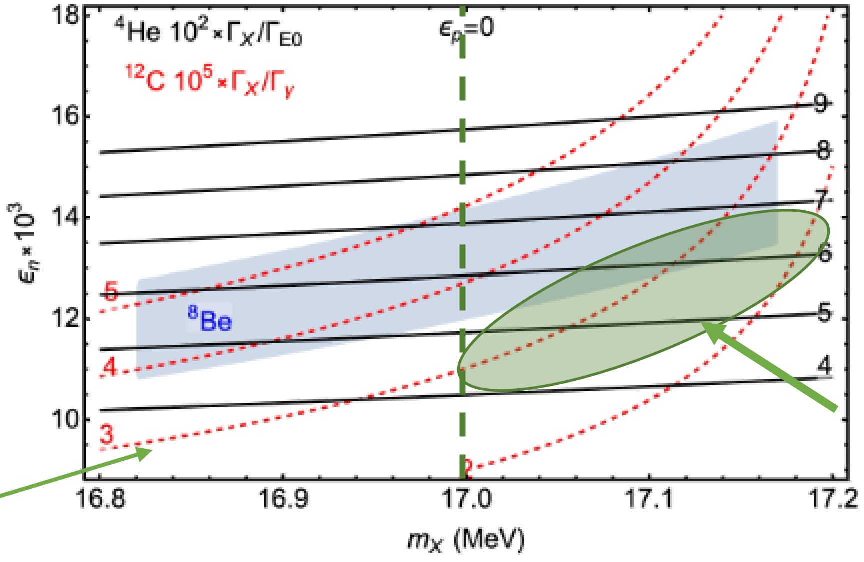

Barducci and Toni 2212.06453

*It may be that the central value for the mass will move to accomodate the fit in couplings!*

*Measured $^{12}$C is just below this line*

See also the recent 2406.08143

Feng et al. 2006.01151




*A full mass + couplings fit would put us around here ?*

- We need a clean way of testing the new physics explanation, which does not suffer from large nuclear uncertainties

# Rare decays searches

- Rare decays probes are both extremely effective in probing X17, often at the price of a large model dependence

- Mesons decay probes (example from mostly last year)

Vector state

  - $\pi^0 \rightarrow \gamma V_{17}$, for vector states: NA48 bounds implies proto-phobic (hep-ex/0610072) — Feng et al. (1604.07411,1608.03591) 2006.01151
  - $J/\Psi$ decays, charm couplings only — Ban et al. 2012.04190
  - $B^* \rightarrow B\, V_{17}, D^* \rightarrow D\, V_{17}$ for vector states — Castro and Quintero 2101.01865

Axion

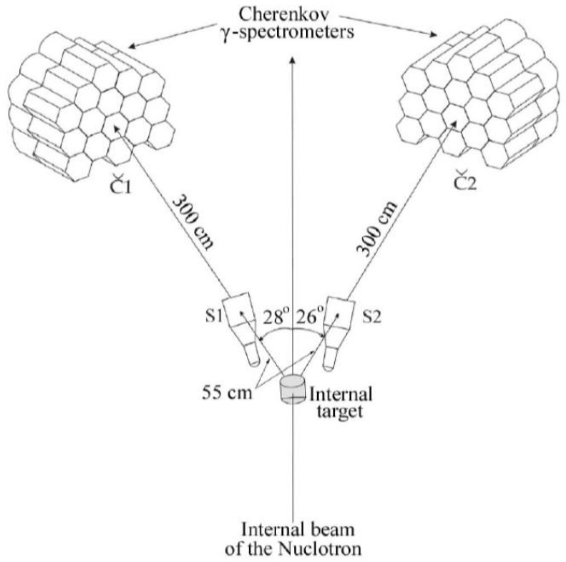
  - $\pi^0 \rightarrow a_{17} \rightarrow e^+e^-, K \rightarrow \pi(\pi)a_{17}, K \rightarrow \mu\nu\, a_{17}$ — e.g Alves et al. 1710.03764, 2009.05578
  - $\pi^0 \rightarrow a_{17}\, a_{17}\, a_{17}$ and other multi-leptons final states — Hostert and Pospelov 2012.02142

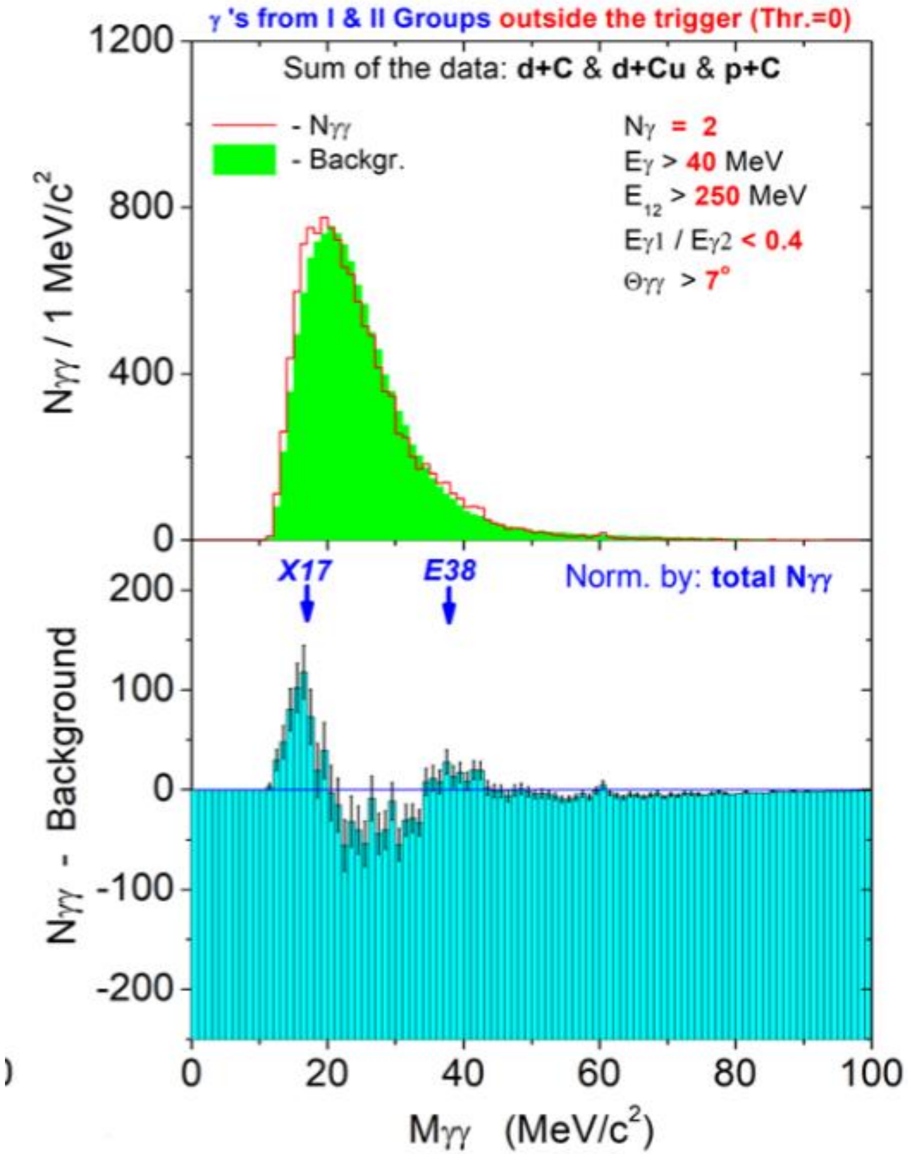
- If flavour-violation, many more available channels both in lepton decays and in “standard” flavoured meson decay.

- Also radiative emission from $\mu$ decay

# JINR - 2311.18632

- They studied the process
  $$d\left(2.0\,\frac{GeV}{nucl}\right) + C \rightarrow \gamma\gamma + X$$
  → The claim is that the invariant mass reconstruction of the di-photon pair lead to an excess of at 17 MeV



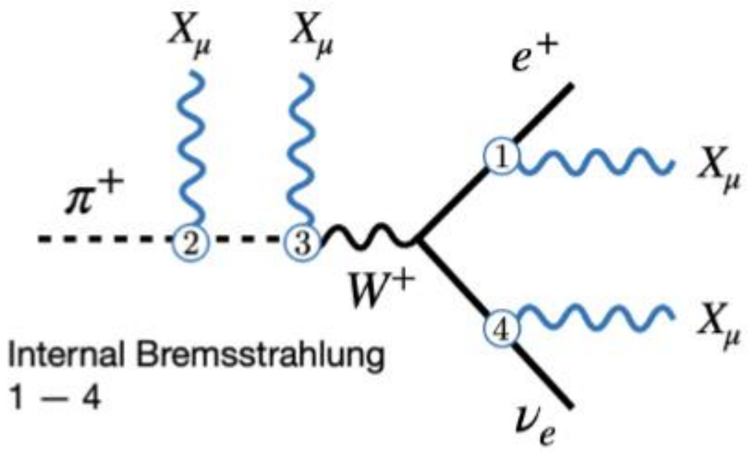
# Recent developments : pionic constraints

- Limits from $\pi^0 \to \gamma X$ processes have been included since 2016
  - → Use NA48 limit, leads to strong requirement on $g_{Vp} = 2\, g_{Vu} + g_{Vd} \lesssim 4 \cdot 10^{-4}$
  - → Key requirement behind the « pio-phobic » structure

- Charged pion decay $\pi^- \to e^- \nu_e\, X$ also lead to significant limits in case of non-conserved currents

$$(g_{R\,u} - g_{R\,d}) + (g_{L\,e} - g_{L\,\nu}) \lesssim 8.5 \cdot 10^{-5}$$

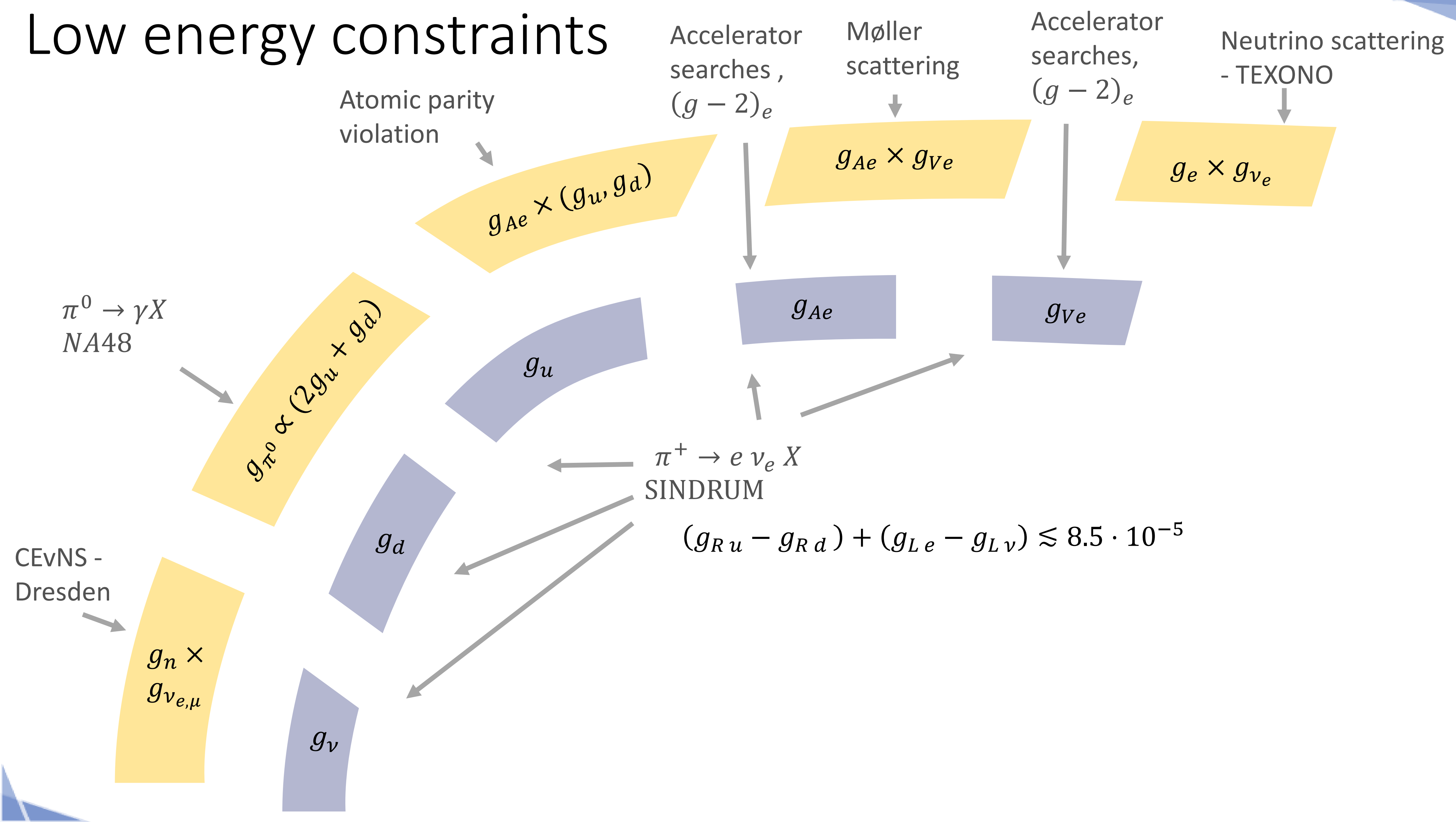
  - → Similar constraints exists for the ALP case



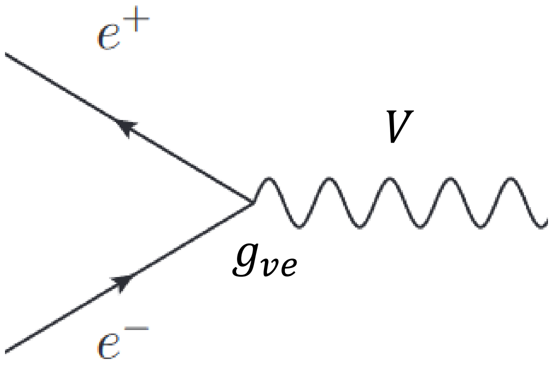

2306.15077

2209.00665

# Low energy constraints



# Going resonant …




- We will be interested into the simplest possible mechanism for new bosons : $e^+e^- \rightarrow V$, resonant production

$$\sigma_{res} \sim \frac{g_{ve}^2}{2\, m_e} \pi\, Z\, \delta(E_+ - E_{res})$$

- Significantly larger CS than $e^+e^- \rightarrow \gamma V, \pi^0 \rightarrow \gamma V$, and bremsstrahlung process

- What are the trade-offs for resonant production ?

  → First, we need to find positrons somewhere. Typically, this implies a certain loss in energy + beam intensity

  → Then we need to hit the resonant energy

$$s_{CoM} = 2\, m_e\, E_{res} = M_V^2$$

# Resonant production and CoM energy

- Several effects concur to make the CoM energy a not-so-precisely defined quantity

$$p^+ \simeq (E_b, E_b)$$
$$p^- = (\gamma m_e, \pm \gamma m_e \beta)$$

$$s = 2\,m_e^2 + 2\gamma m_e E_b\,(1 - \beta_z)$$

*Beam energy*

→ Typically a percent level effect for highest energy beam (e.g. CERN North Area)
→ Can be much lower (of at the cost of reducing the beam intensity), per-mil level

*Beam interaction with the target*

→ Use straggling and bremsstrahlung processes to degrade the beam energy
→ Effective to probe a large range of masses without varying the beam energy too much

*The electron is NOT at rest*

→ Depends on the target nature and electronic structure

$$\beta \sim \alpha Z_{eff}$$

*In high-Z material, core electrons are typically relativistic*

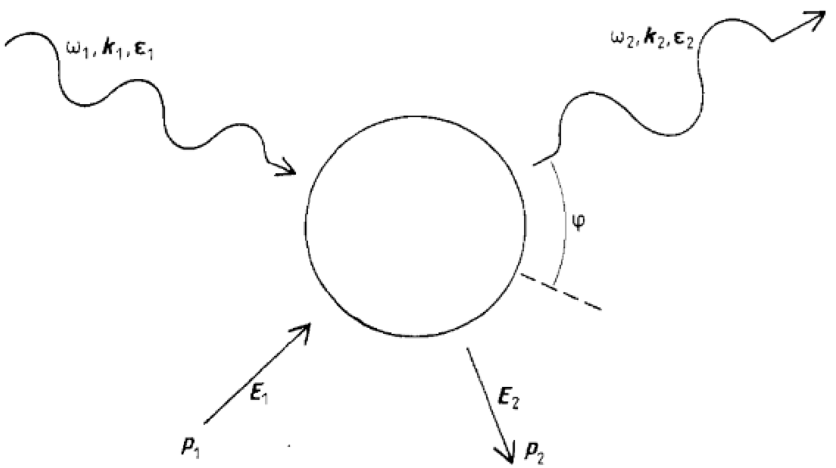
→ We compare the electron momentum to its mass

# Valence electrons : Compton

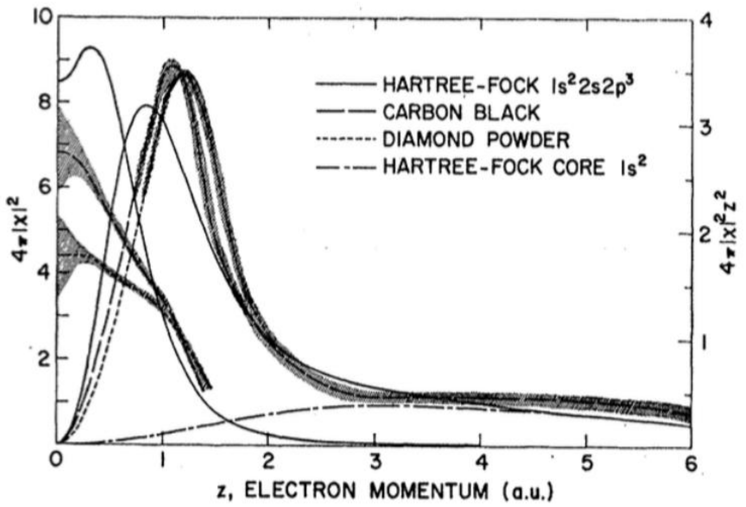
- Compton scattering $\gamma A \rightarrow \gamma e^{-} A^{+}$ has long been a tool a choice for atomic physicists to cross-checks there calculation of orbitals

  → There are an extensive dataset of electron density profile integrated along the beam axis, which is basically what we need here

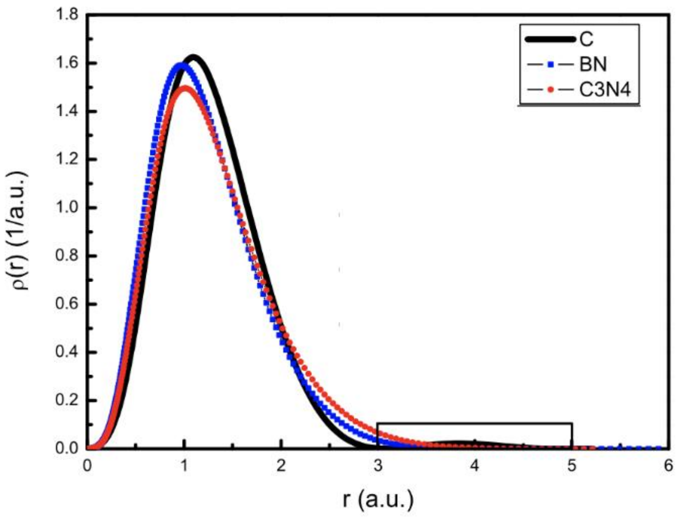
$$\frac{d\sigma}{d\omega_2 d\Omega} = C(\omega_2, \omega_1, \theta, p_{z_0}) J(p_z)$$




X-Ray determination of the Electron Momentum Density in Diamond, Graphite and Carbon Black [Phys. Rev. 176 (1968) 900]




Theoretical Compton profile of diamond, boron nitride and carbon nitride [Physica B 521 (2017) 361-364]



# Nuclear physics

*$^{8}$Be studies*

Zang&Miller - 1703.04588 ✓

Improved ATOMKI background

Hayes et al. - 2106.06834 ?

R-matrix study (fit to data) -> issue with ATOMKI bkd at large angle

Paneru et al. PRC 111, 064609 (2025) ? ✓

R-matrix study - reduced required X17 rates for PS case

Gysbers et al. - 2308.13751 ; ✓
Navratil et al. - 2212.00160 ✓

Ab initio studies

*$^{4}$He studies*

Viviani et al. - 2104.07808 ✓

Ab initio study from nuclear Hamiltonian + X17 included !

*$^{12}$C studies*

✓

Mommers et Vanderhaeghen. - 2406.08143

Ab initio particle-hole shell model → large uncertainty on axial vector case

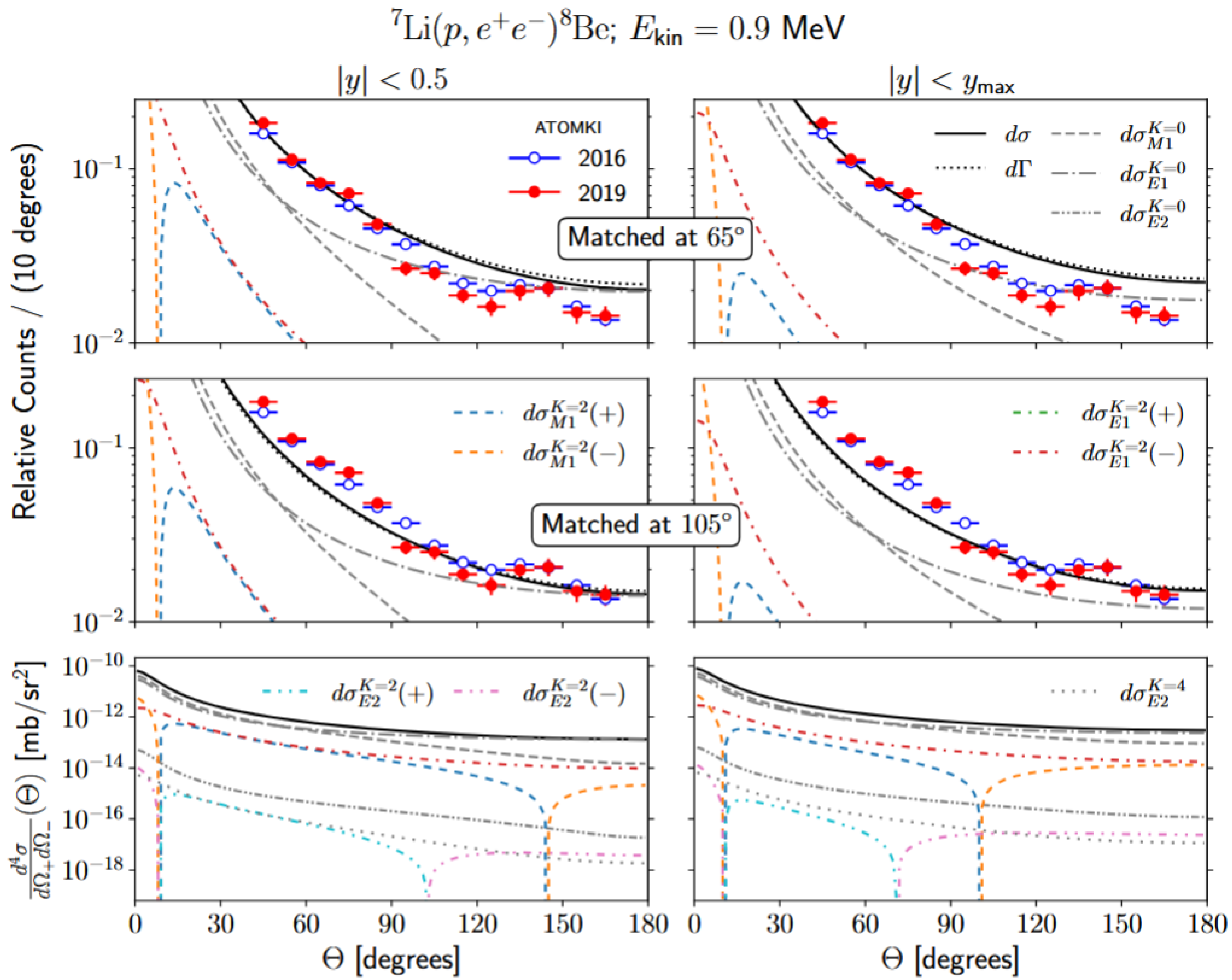
*SM studies*

Aleksejev et al. – 2102.01127 ?

Arbitrary normalizations for NLO QED effect could mimic the signal

# Ab-intio 8Be results

Gysbers et al. - 2308.13751



# MEG – II results

- Reproduce the 8Be ATOMKI process
  → No observation, but compatibility at 2sigma