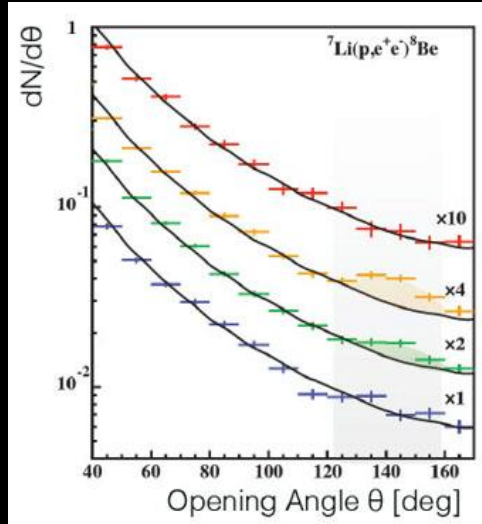
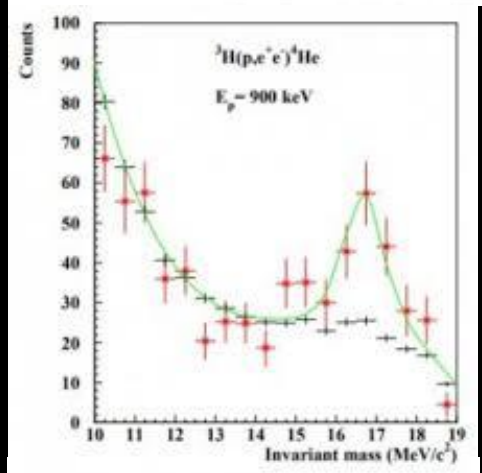
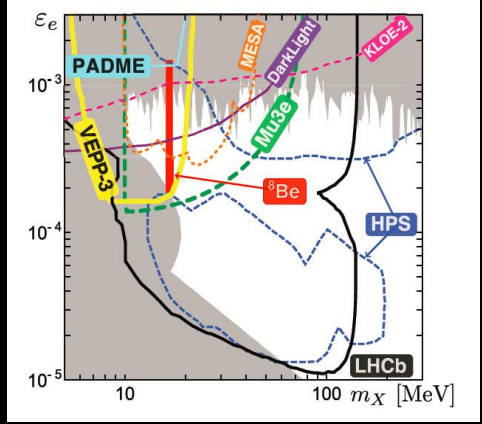
New Evidence for a Dark Sector?
Search for the X17 Resonance

- The ATOMKI Anomalies in ^{8}Be* and ^{4}He*
- The X17 boson & theor. interpretations
- Ongoing & planned verifications
- The X17 - project at U. of Montreal

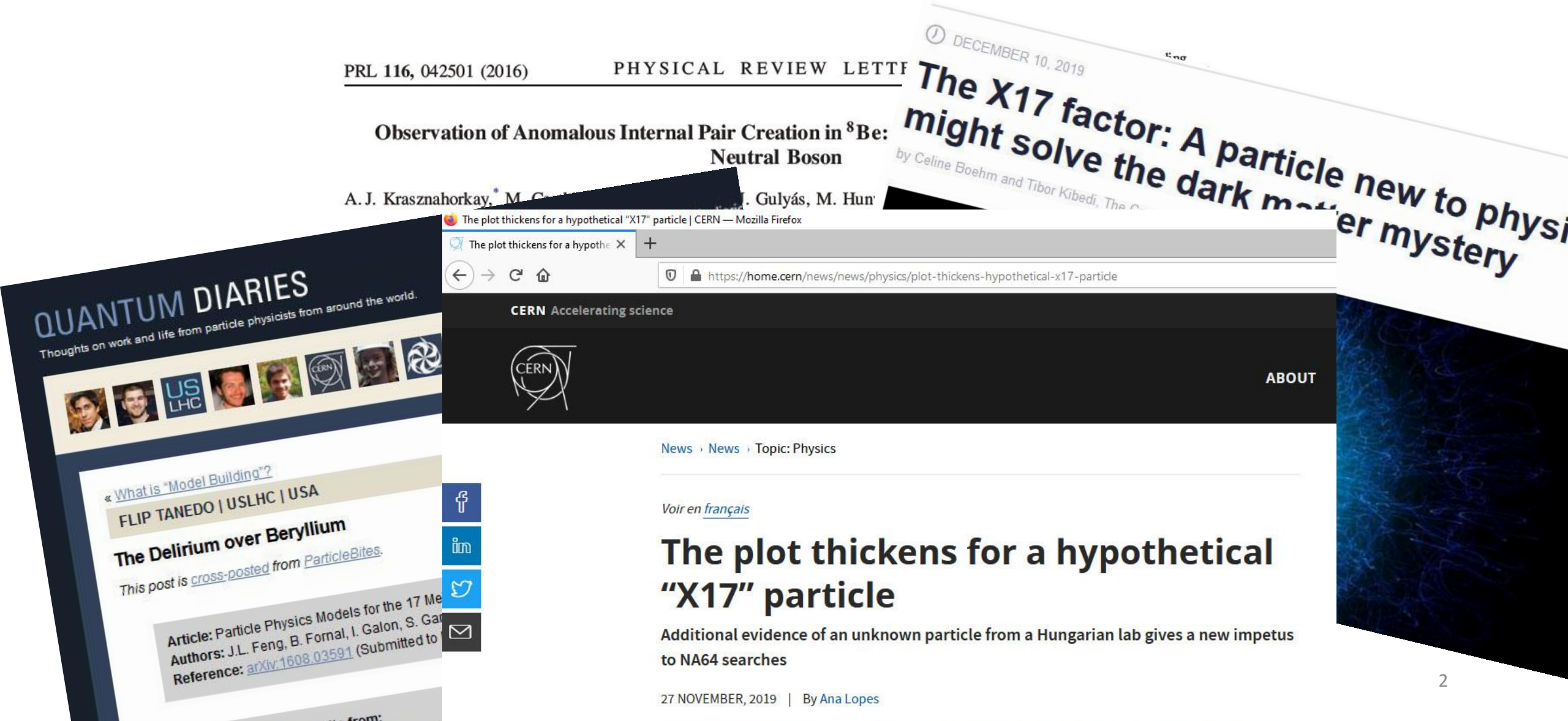




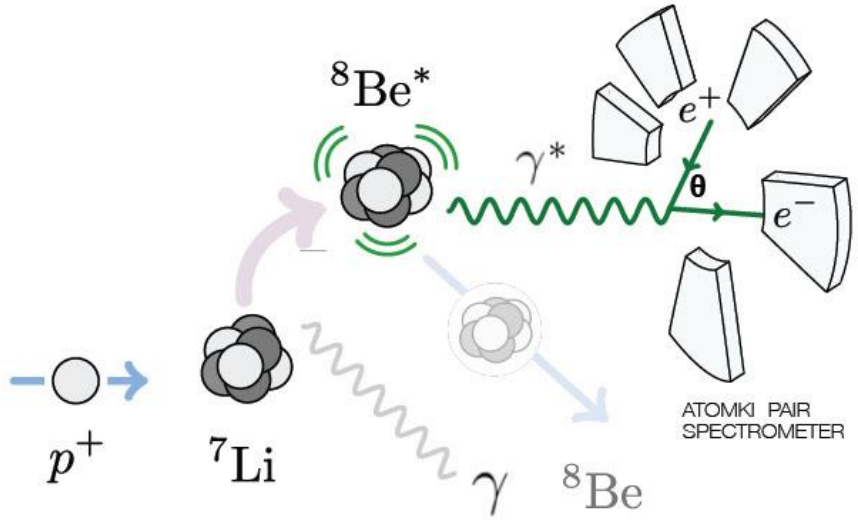


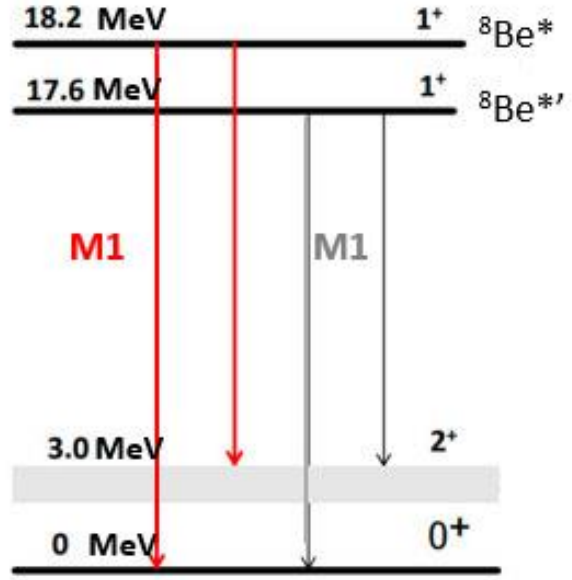
V. Zacek, Université de Montréal, CAP 2021

A 7σ Evidence for a New 17 MeV Boson?



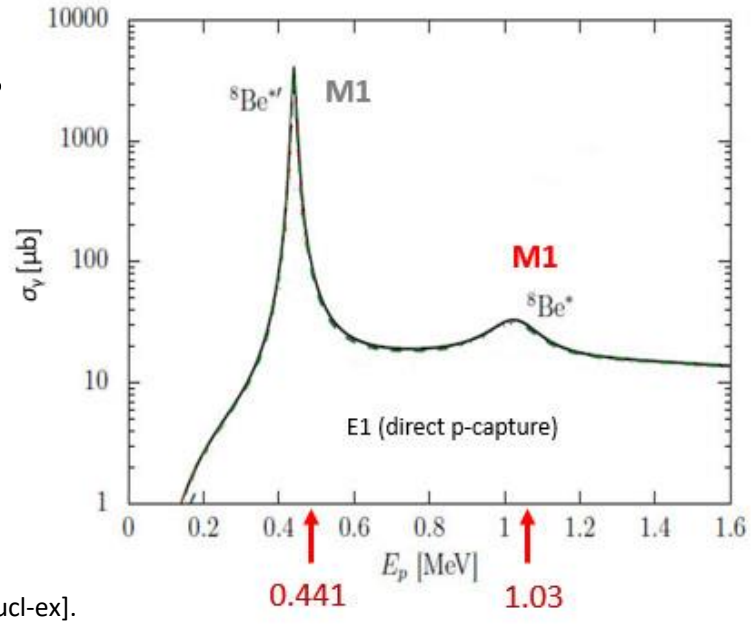
The ATOMKI Experiment!





- Excited states of ^{8}Be produced through p +^{7}Li - reaction with high statistics
- Beam energy around 1 MeV adjusted to select various resonances
- γ's are converted by IPC into e^+e^- pairs
- Measure angular distribution of e^+e^- pairs

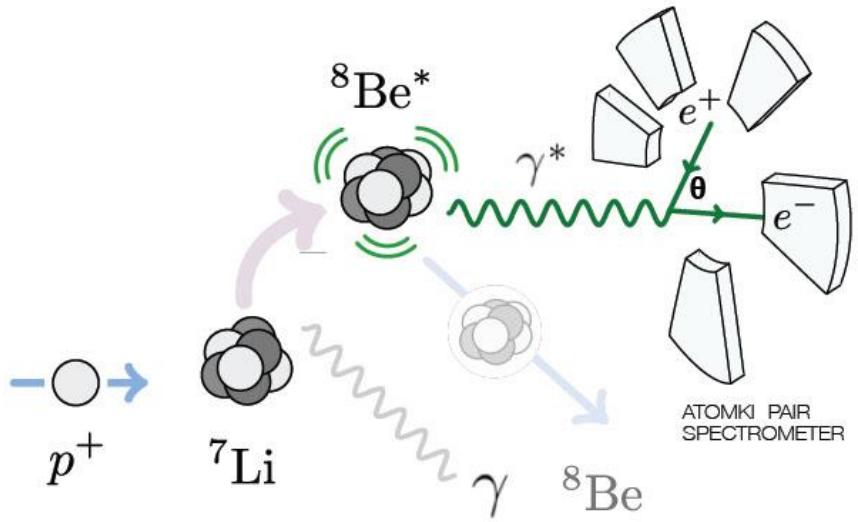
γ – production X-section:



(Graphics J. Feng et al; arxiv:1707.09749)

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501, arXiv:1504.01527 [nucl-ex].

The ATOMKI Experiment!



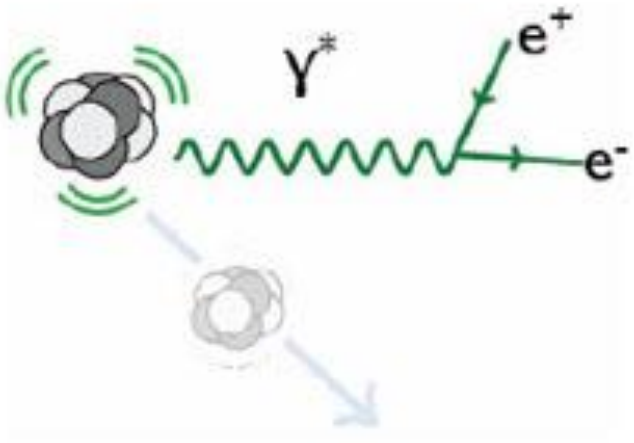
ATOMKI @ Institute for Nuclear Research
Debrecen, Hungary

- Excited states of ^{8}Be produced through p +^{7}Li - reaction with high statistics
- Beam energy around 1 MeV adjusted to select various resonances
- γ's are converted by IPC into e^+e^- pairs
- Measure angular distribution of e^+e^- pairs

(Graphics J. Feng et al; arxiv:1707.09749)

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501, arXiv:1504.01527 [nucl-ex].

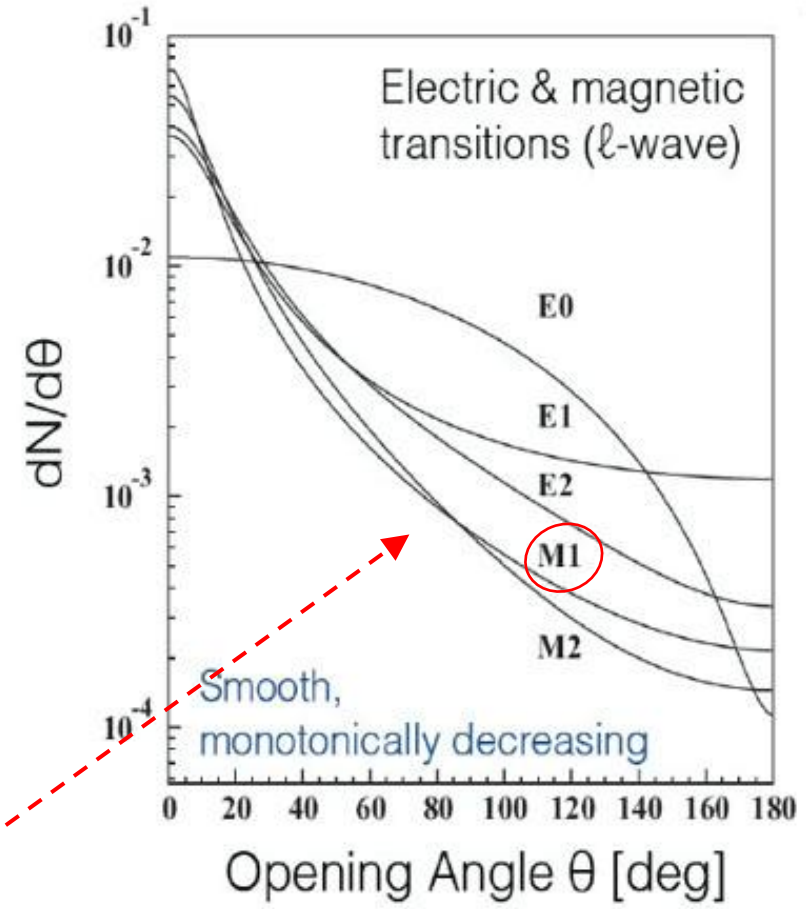
$^{8}Be^{*}$ - Decay and Internal Pair Creation (IPC)



- IPC - Branching ratio:

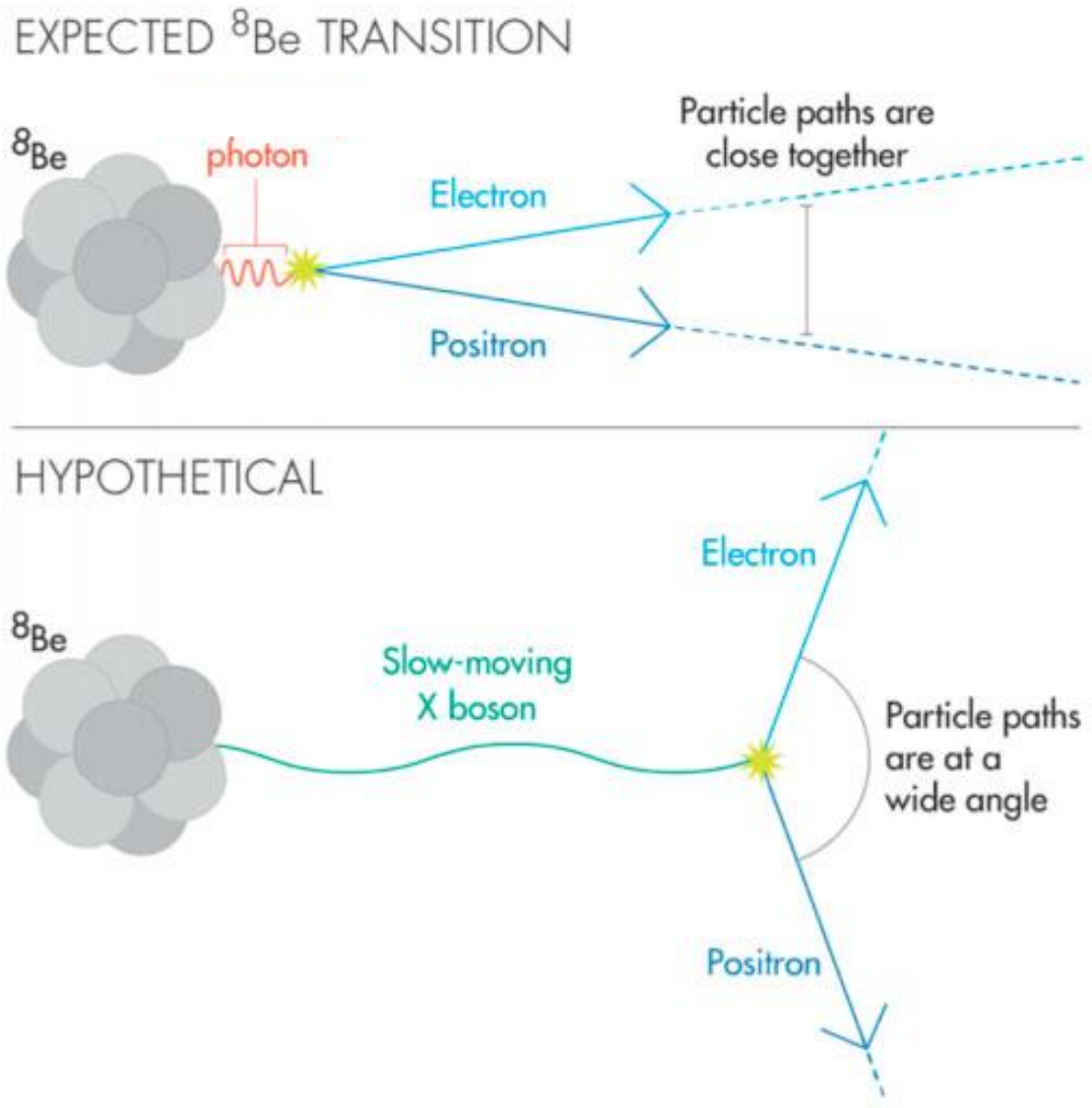
$$\frac{\Gamma[Be^{*} \rightarrow \gamma(M1)]}{\Gamma[(Be^{*} \rightarrow e^{+}e^{-}]} = 3.9 \times 10^{-3}$$

- dN/dθ decreases steadily with increasing θ



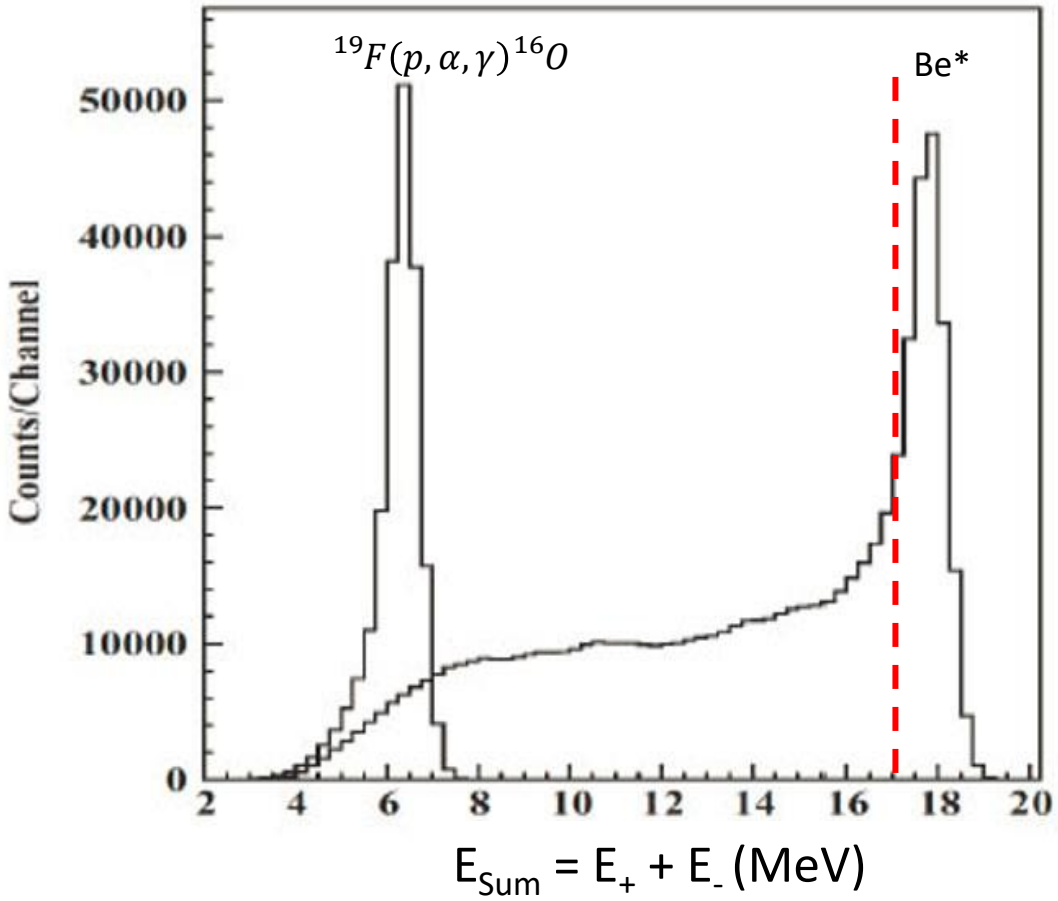
Gulyas et al.; http://arxiv.org/abs/1504.00489v1

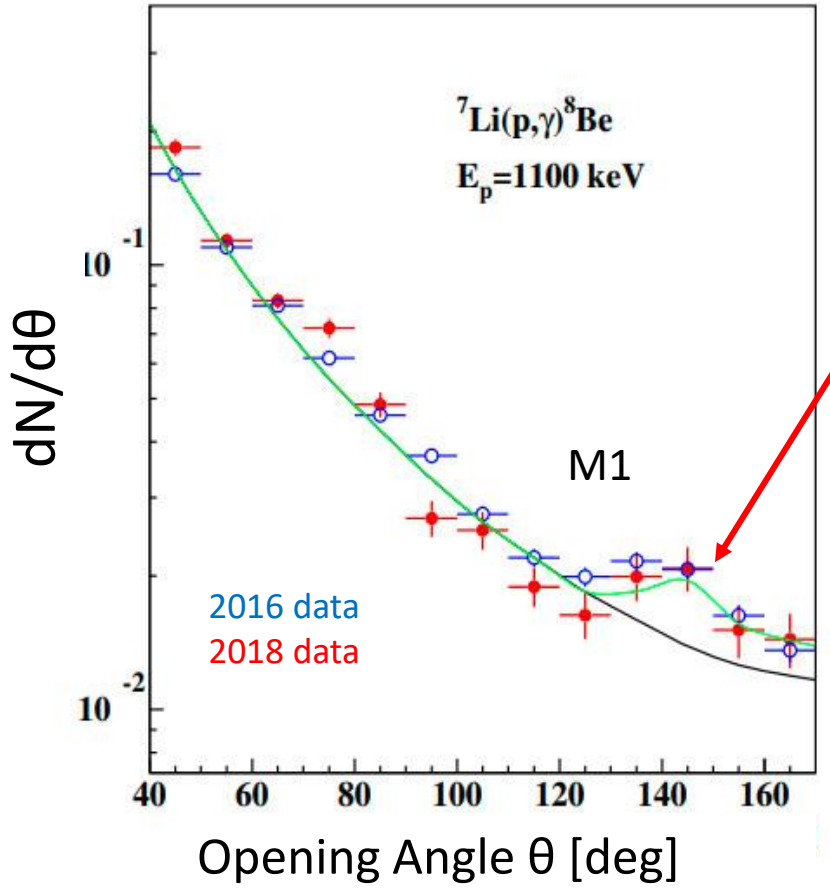
^{8}Be* - A Particle Physics Lab!



Promising environment to search for new MeV-scale physics!

The ATOMKI ^{8}Be* - Experiment





The Anomaly!

$$E_{Sum} = E_+ + E_- \geq 17\ MeV$$

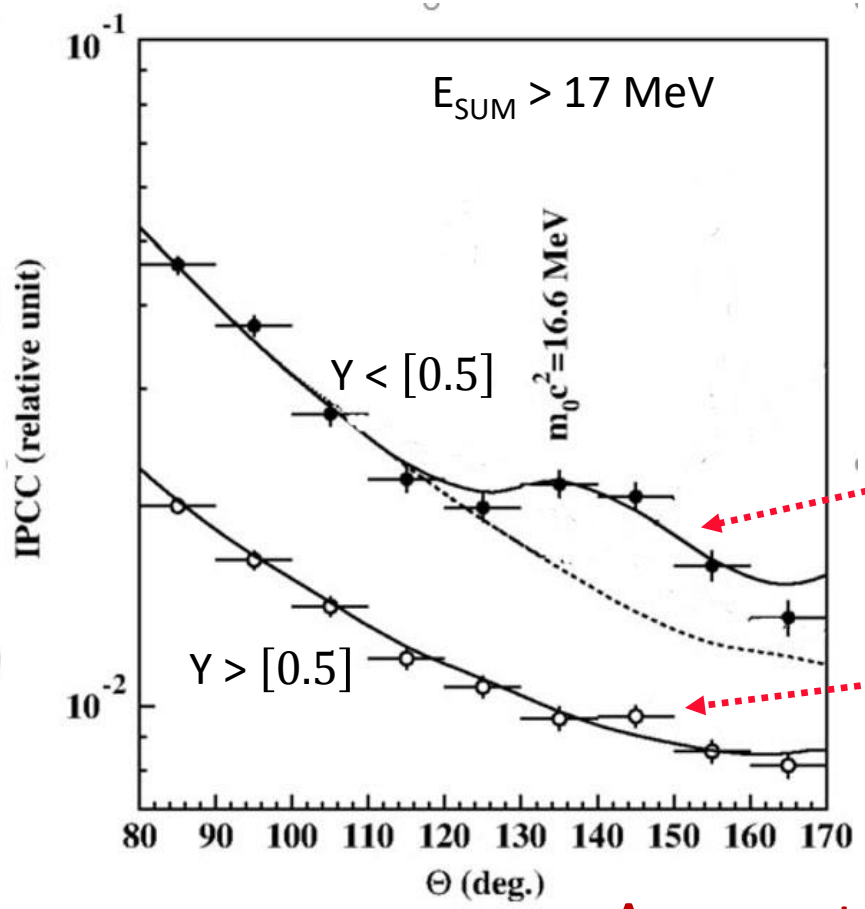
$$|Y| = |(E^+ - E^-)|/(E^+ + E^-) \geq 0.5$$

A. J. Krasznahorkay et al.; Acta Physica Polonica B, Vol.50 (2019)

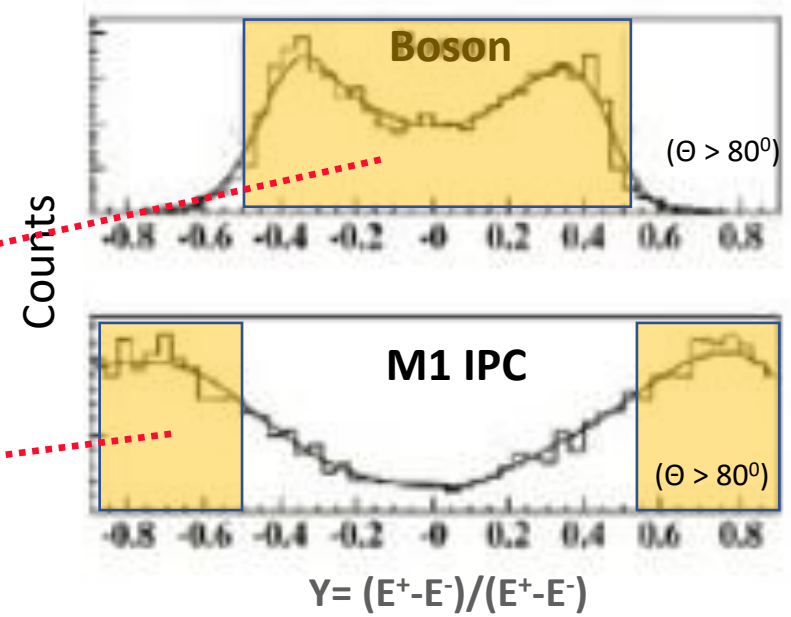
A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

The ATOMKI ^{8}Be* - Experiment

An important variable: the energy asymmetry

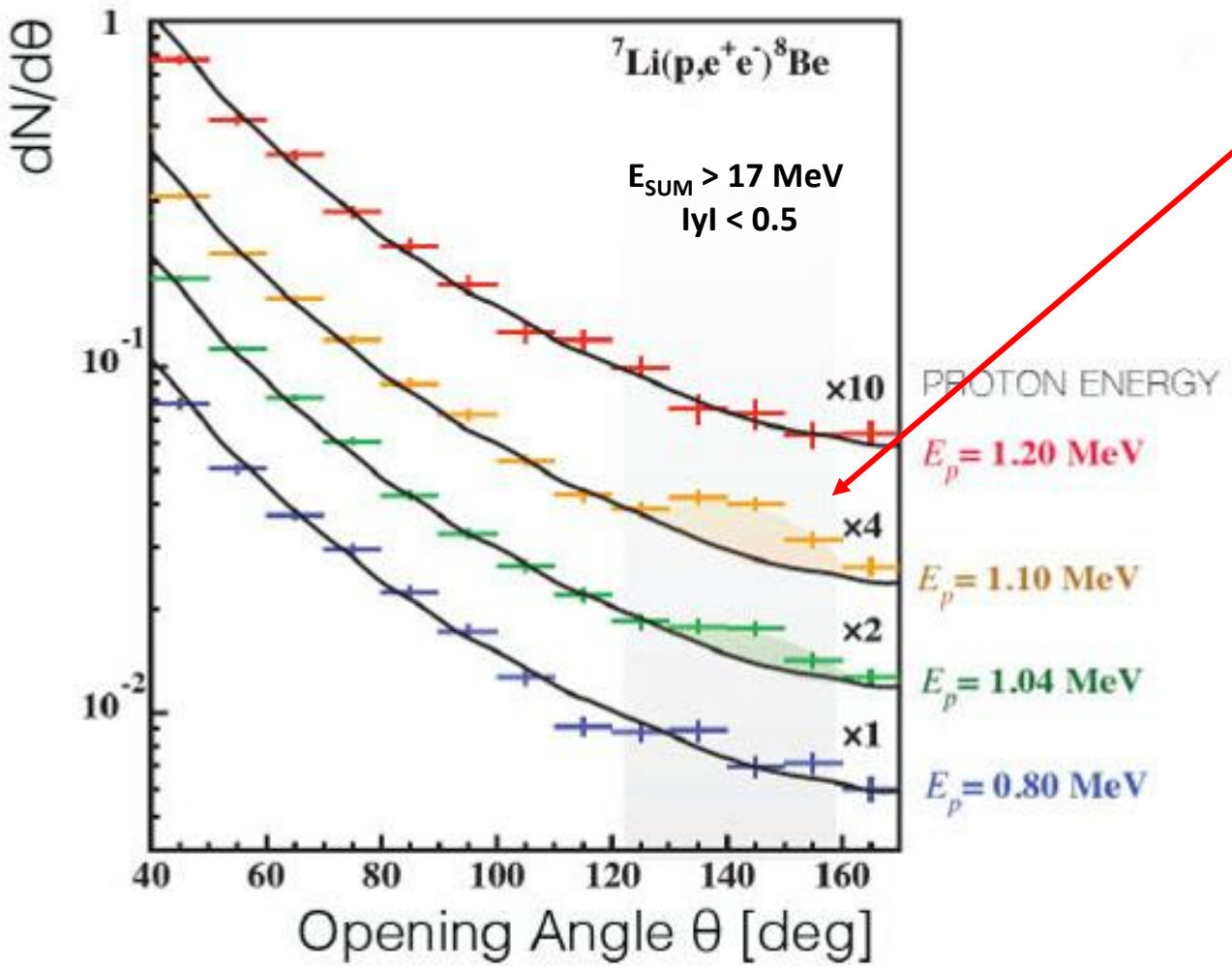


$$y = \frac{E^+ - E^-}{E^+ + E^-}$$



Asymmetry consistent with the decay of a new particle

The ATOMKI ^{8}Be* - Experiment

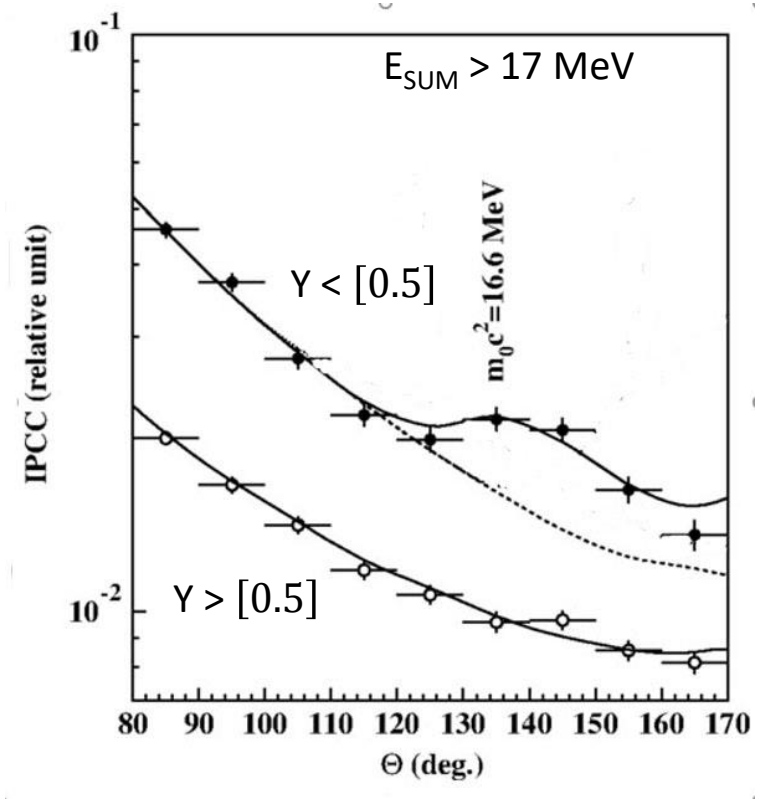


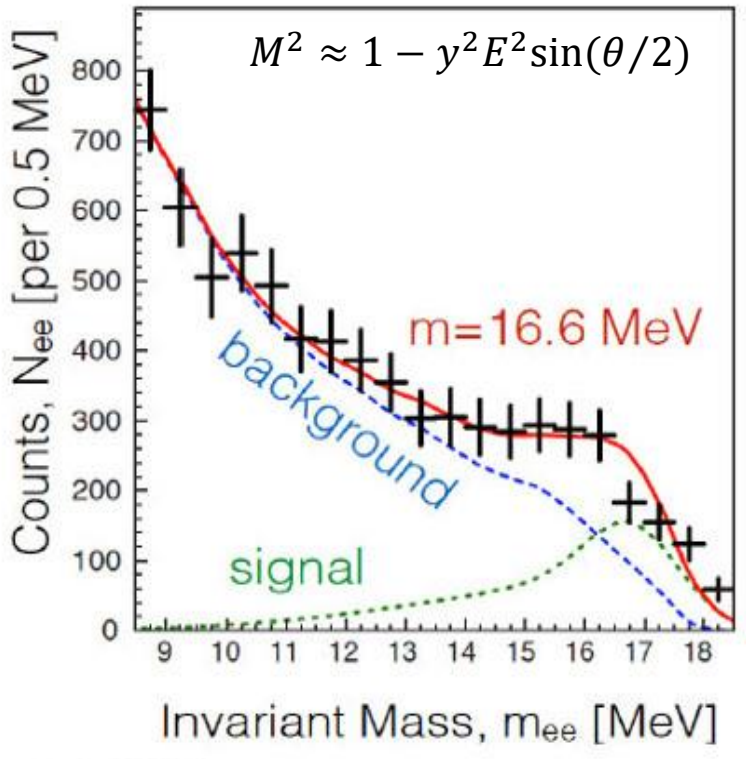
The Anomaly!

- Excess around θ = 140° passing through 18 MeV ^{8}Be*resonance
- Probability for backg. fluctuation: 5.6 x 10^{-12} (6.8σ)
- $\frac{\Gamma(\,^8Be \rightarrow\ ^8Be\ X)}{\Gamma(\,^8Be \rightarrow\ ^8Be\ \gamma)} = 5.6 \times 10^{-6}$

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

The ATOMKI ^{8}Be* - Experiment



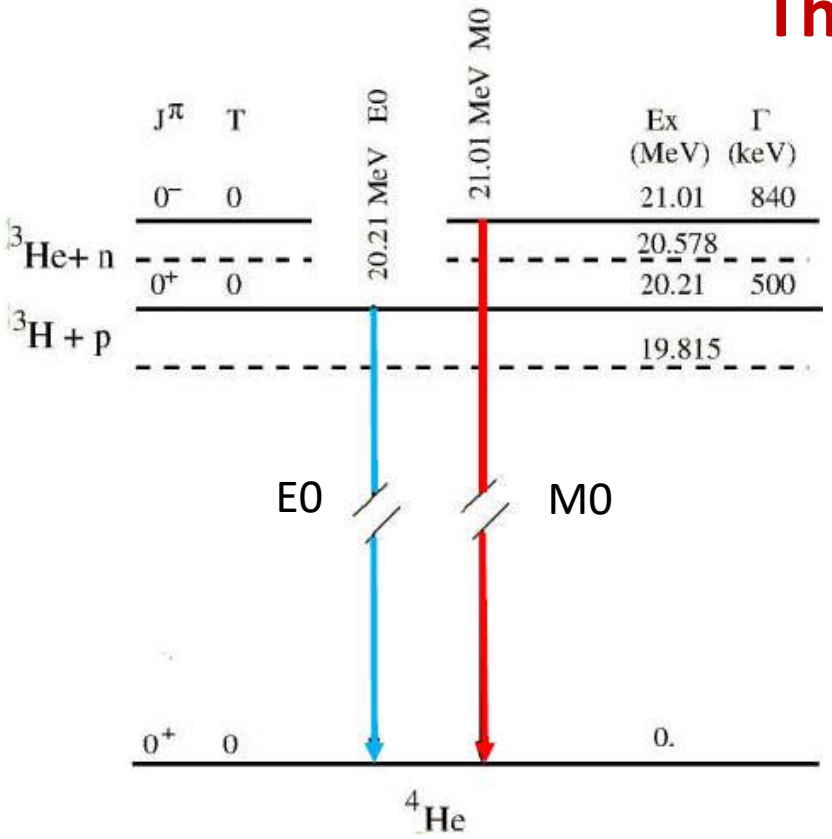


Opening angle, asymmetry and invariant mass consistent with decay of new particle

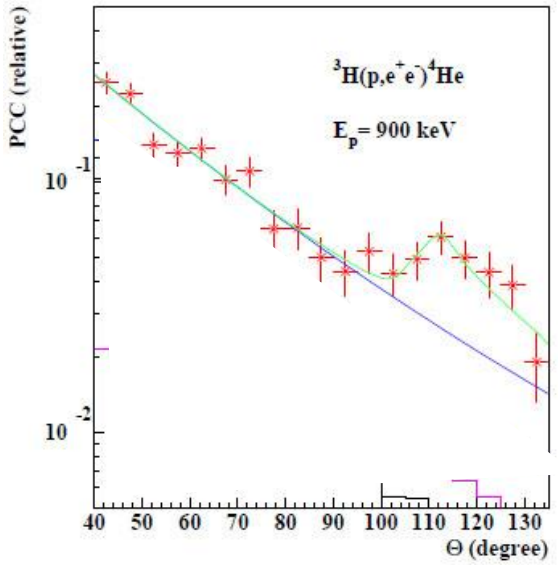
M_X = 16.7 ± 0.35 (stat) ± 0.5 (sys) MeV

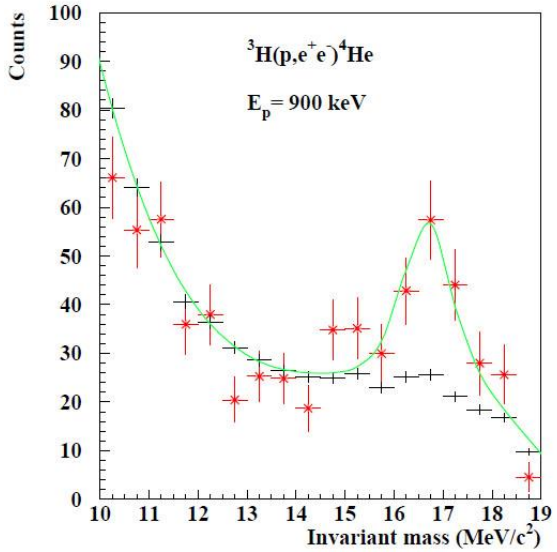
A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

The ATOMKI ^{4}He* - Experiment



Capture via: $p + {}^3H \rightarrow {}^4He^*$
into overlapping 0^+ & 0^- states





Recently confirmed at 3 different beam energies arXiv:2104.10075

Opening angle and invariant mass consistent with decay of new particle as in Be*

M_X = 16.84 ± 0.16 (stat) ± 0.2 (sys) MeV

A. J. Krasznahorkay et al., arXiv:1910.10459v1

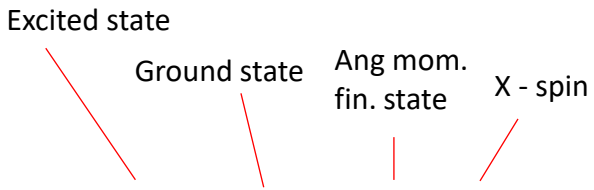
The ATOMKI $^{8}Be^{*}$ / $^{4}He^{*}$ - Experiments

Sanity Checks:

- Signal rises and falls when scanning through the resonance (Be*)
- Excess of symmetric $e^{+}e^{-}$ pairs → suggests massive particle
- Opening angles *and* invariant masses in $^{8}Be^{*}$ and $^{4}He^{*}$ agree
- Up to now no convincing SM explanation!
- Cannot be stat. fluctuation….maybe uncontrolled systematic errors?
- Couple of anomalies or puzzles could be solved with new BSM particles
  Dark matter, $(g-2)_{\mu}$, p- charge radius, QCD axions….

Independent exp. verification needed!
….but what particle could it be?

….what Particle could it be?



$$J_* = J_{GS} \oplus L \oplus J_X$$

$$P_* = (-1)^L \, P_{GS} \, P_X$$

$$J_{GS} = 0$$

$$P_{GS} = +1$$

$$J_* = L \oplus J_X$$

$$P_* = (-1)^L \, P_X$$

Be* 18.15 MeV state: $1^+ \rightarrow 0^+$

→ X can be pseudoscalar (L=1)!

→ X can be vector (L=1)!

→ X can be axial vector in (L=0, 2)!

Overlap!

He* 20.2/ 21.0 MeV states: $0^+ / 0^- \rightarrow 0^+$

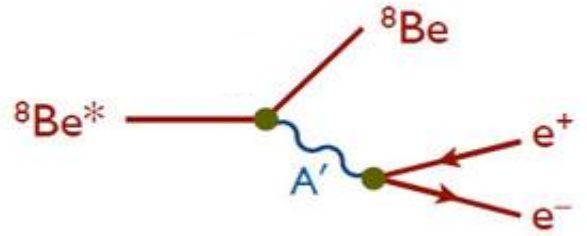
→ X can be pseudoscalar (L=0)!

→ X can be vector in (L=1)!

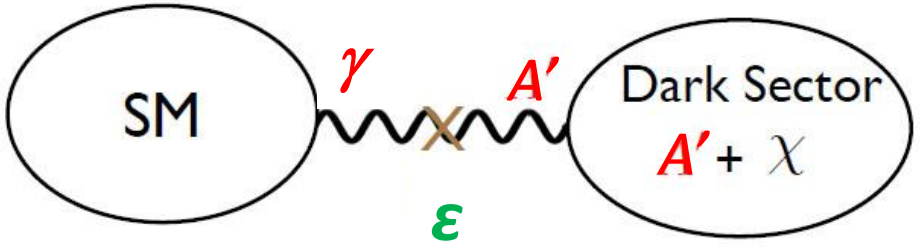
→ X can be axial vector

X17 with $J^\pi = 1^{-/+}$ or 0^- could fit the bill!

Maybe a Dark Photon A' ($J^{\pi} = 1^{-}$) ?



- Interaction with ord. matter mediated by “dark ” A'
- Gauge boson A' mixes kinetically with γ and $\varepsilon \sim 10^{-3}$
- A' couples to SM – particles prop. to ε and SM charges
- Vector mediator decays to low mass WIMPs

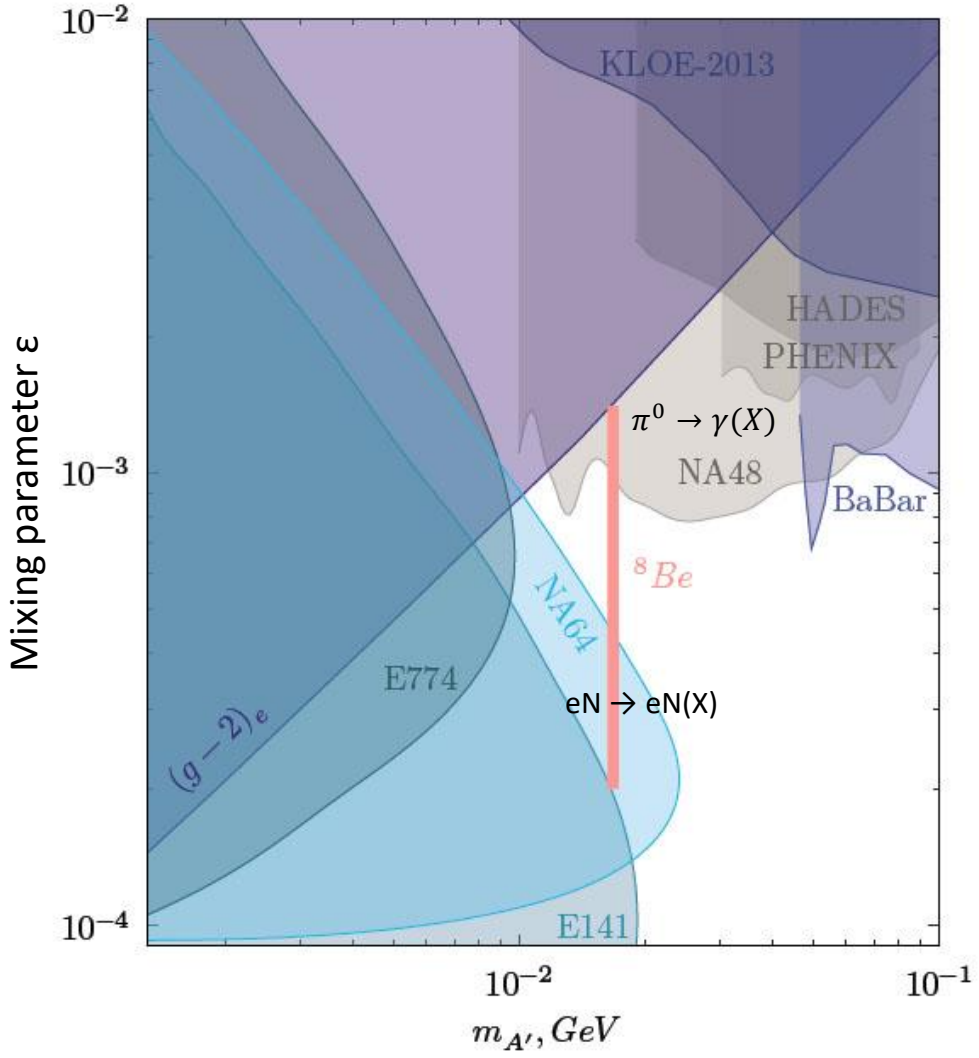


But…..

But…Parameter Space for Dark Photons limited

J. L. Feng, et al, *Phys.* arXiv:2006.01151 [hep-ph].

…but bounds, especially $\pi^0 \to \gamma(X)$ (NA48/2) can be fine – tuned away!



Na64 (Dec. 2019 arXiv:1912.11389v1)

The anomaly in Be & He can be explained by a "proto-phobic" vector gauge boson with:

Hadronic couplings:

$\varepsilon_u \approx \pm 3.7 \times 10^{-3}$

$\varepsilon_d \approx \mp 7.4 \times 10^{-3}$

Range ≈ 200 fm

Proto-phobic: $\left|\frac{\varepsilon_p}{\varepsilon_n}\right| < 8\%$

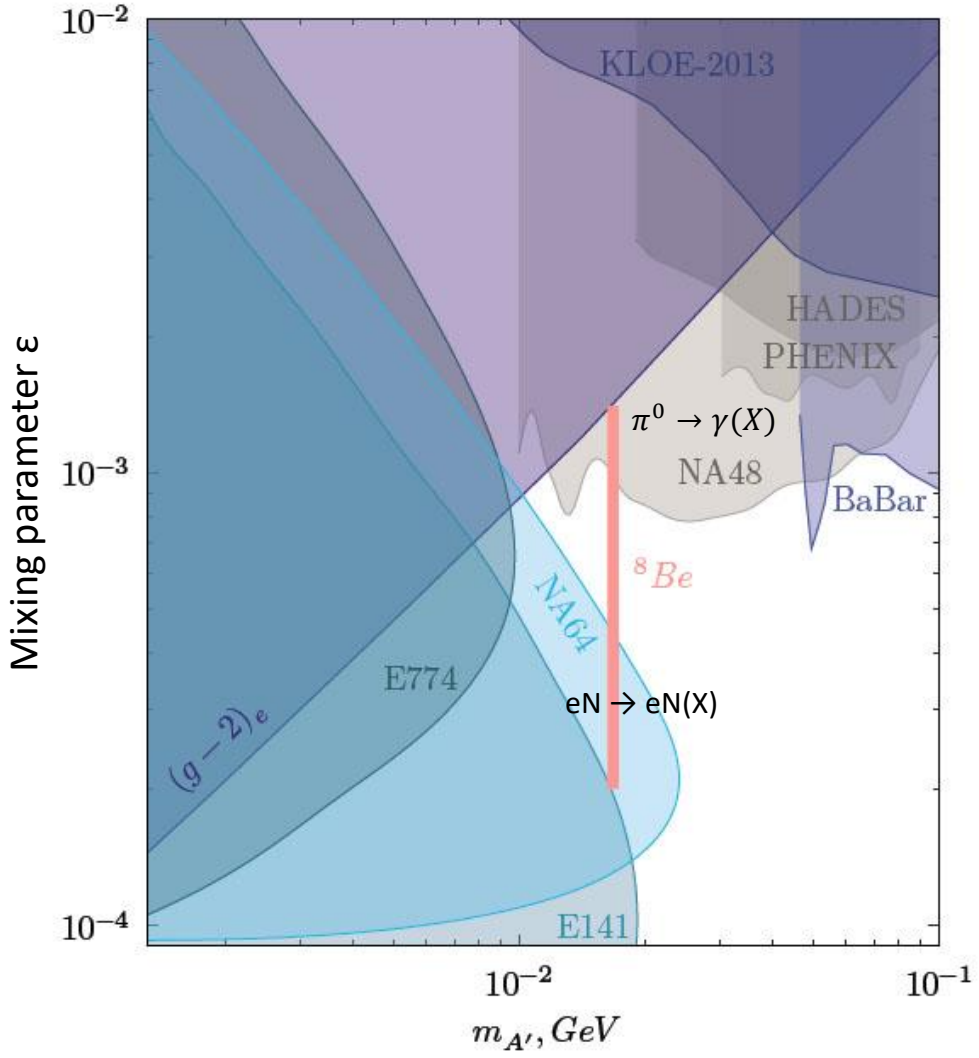
Similar coupling as for Z^o at low energy (7%)

J. L. Feng, *Phys. Rev.* **D95** no. 3, (2017) 035017, arXiv:1608.03591 [hep-ph].

But…Parameter Space for Dark Photons limited

J. L. Feng, et al, *Phys.* arXiv:2006.01151 [hep-ph].

…but bounds, especially $\pi^0 \to \gamma(X)$ (NA48/2) can be fine – tuned away!



Na64 (Dec. 2019 arXiv:1912.11389v1)

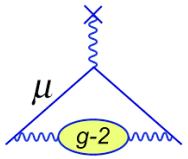
The anomaly in Be & He can be explained by a "proto-phobic" vector gauge boson with:

Leptonic couplings:

$$\sqrt{\varepsilon_e \varepsilon_\nu} \leq 7 \times 10^{-5}$$ (ν – e scatt.)

$$2 \times 10^{-4} \leq |\varepsilon_e| \leq 10^{-3}$$

Range ≈ 200 fm



These lepton couplings could also resolve the (g_μ – 2) anomaly!

J. L. Feng, *Phys. Rev.* **D95** no. 3, (2017) 035017, arXiv:1608.03591 [hep-ph].

Model Building, Implications for DM Searches, etc

One of many other examples…

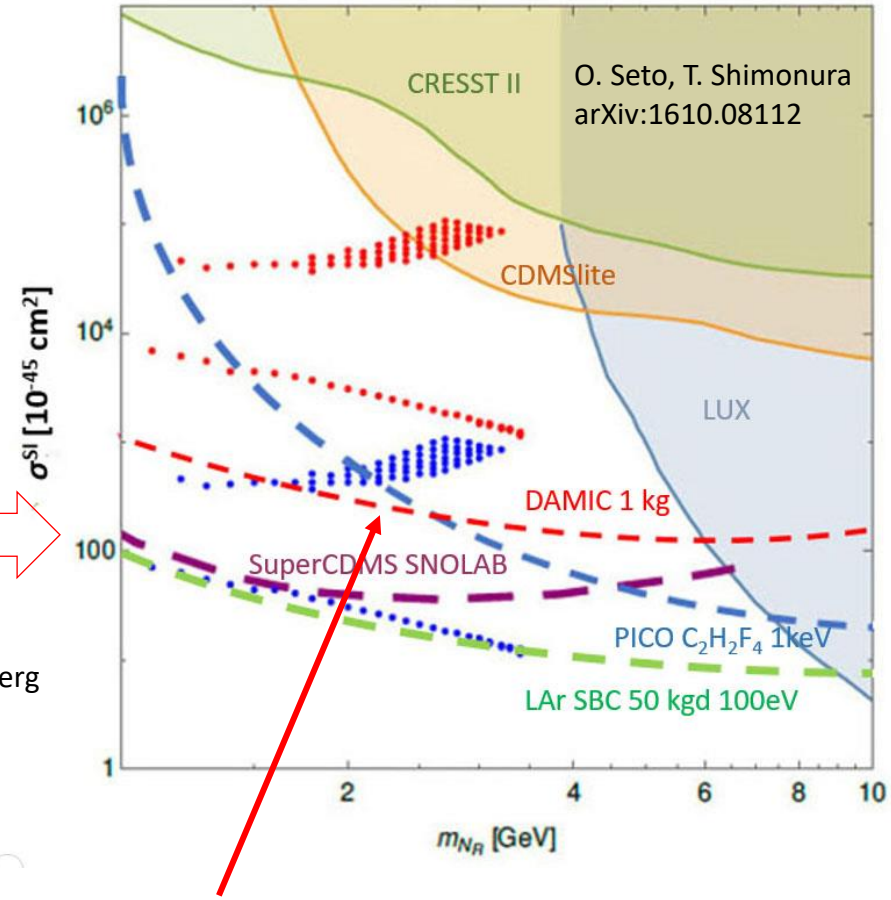
- Gauged U(1) $_{B-L}$ symm. with Z_2 parity
- 17 MeV X- gauge vector boson (^{8}Be*)
- Radiative see-saw for RH-$\nu's$ with $m_\nu \neq 0$
- RH - ν masses ~ GeV
- RH $\nu's$ are DM w. relic abundance ok

…or an axial vector? J. Kozaczuk, D.E. Morrissey,S. R. Stroberg arXiv:1612.01525v2

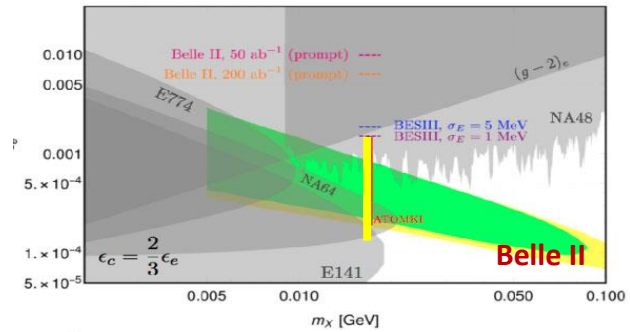
…or a QCD axion? D. Alves arXiv:200905578 J. Liu et al.; arXiv: 2102.1011

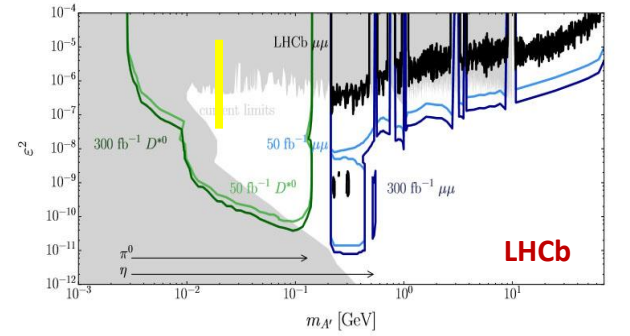
… or a protophobic Z'? C. Hati et al. arXiv: 2005.00028 L. Delle Rose et al. arXiv: 1708.0886

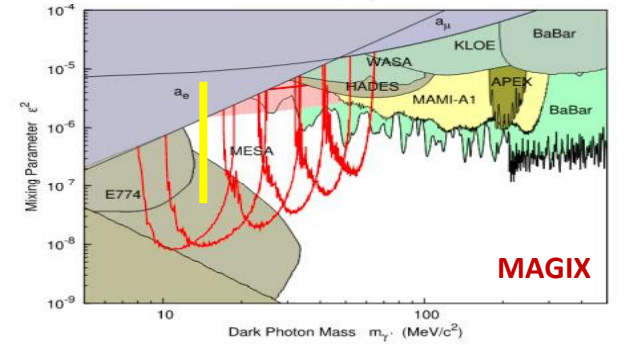
… or ?

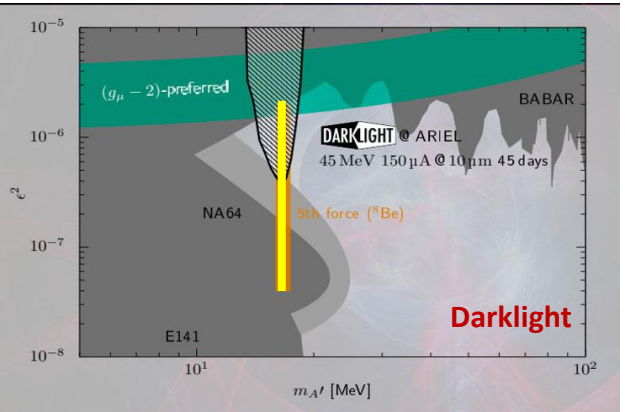


SI - X-sections in reach of NEWS-G, PICO (H), DAMIC et al.



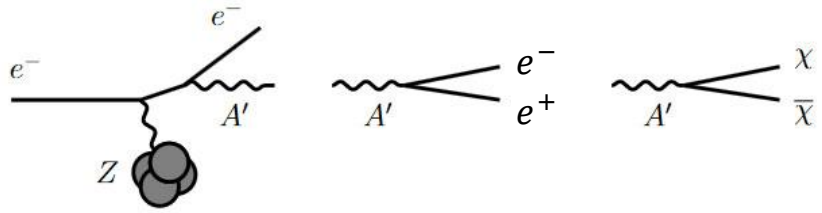






Where Else Can We look?

Dark photon searches @ accelerators and beam dumps



Belle II: $D^{+*} \rightarrow D^+ + e^+e^-$; statistics! >2025 (→ Miho Wakai's talk)

LHCb: ; $D^{0*} \rightarrow D^0 + e^+e^-$ after upgrade 2025

MAGIX@ MESA, Mainz - operates > 2024/25

LDMX@JLAB/SPS? - operates > 2024, statistics!

NA64 @CERN/SPS – needs detector upgrade, statistics!

PADME@Frascati - to reach sensitivity needs modif.

Darklight @ Ariel, TRIUMF 45 GeV e^- approved; > 2023;

Window of opportunity for fast moving new intitatives !

Where Else Can We look? Other nuclei!

$^{7}Li(p,\gamma)\,^{8}Be$ →

$^{11}B(p,\gamma)^{12}C$ →

$^{3}H(p,\gamma)\,^{4}He$ →

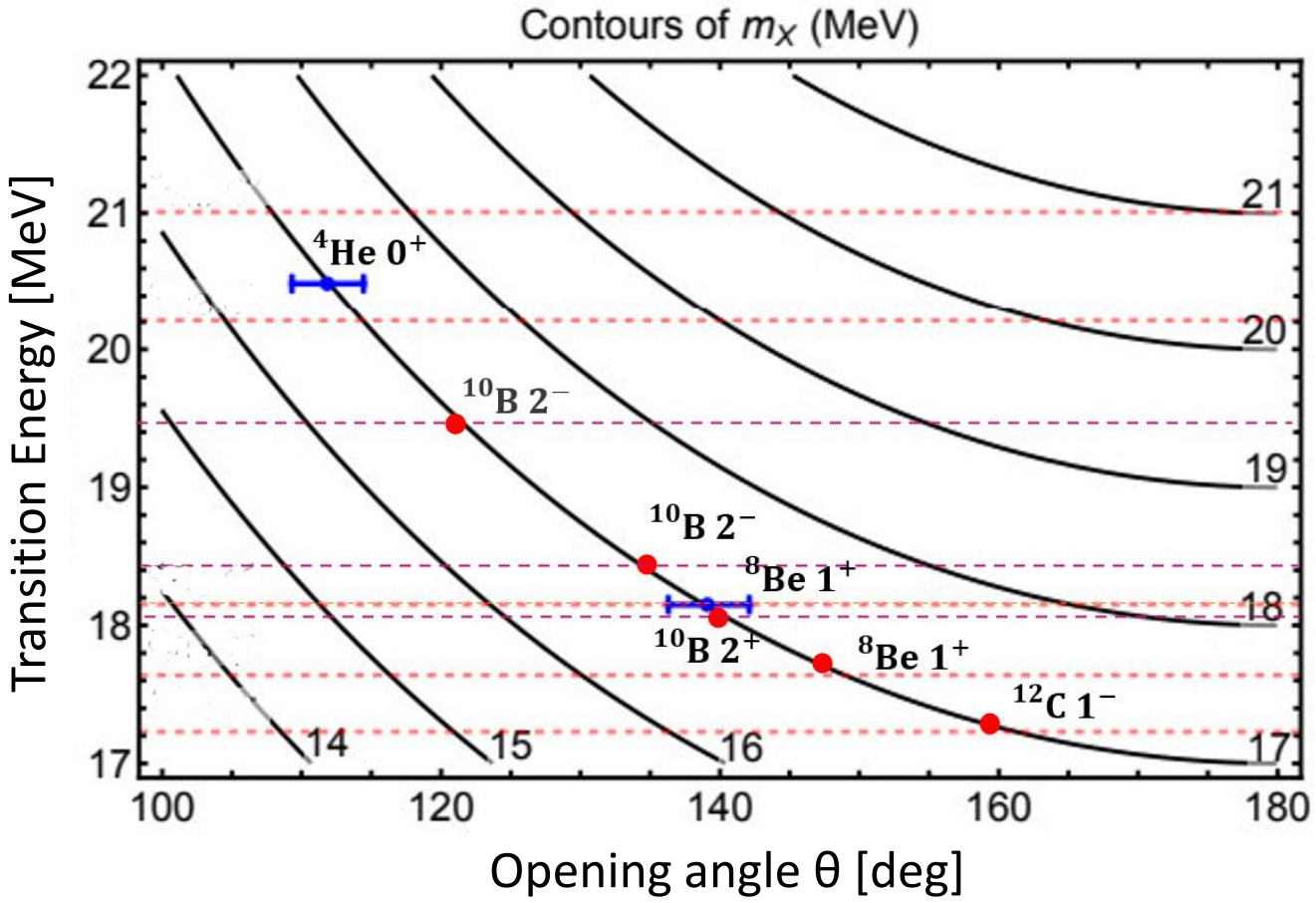
$^{7}Li(\,^{3}He,\gamma)^{10}B$ →

N_*	$J^{P_*}_*$	T_*	Γ_{N_*} (keV)
^{8}Be(18.15)	1^+	0	M1 IV 138
^{8}Be(17.64)	1^+	1	M1 IS 10.7
^{12}C(17.23)	1^-	1	E1 IV 1150
^{4}He(21.01)	0^-	0	M0 840
^{4}He(20.21)	0^+	0	E0 500
^{10}B(19.3)	2^- (-3^+)	1	E1 280
^{10}B(18.1)	$2+$ (-1^+)	1	M1 <600
^{10}B(18.4)	2^- (-3^+)	1	E1 280
^{10}B(17.0)	1^- (-2^+)	1	E1 280

Motivation for an X17 Project @ Montreal Van de Graaff facility!

^{3}He – beams available ☺

X17 – Consistency Checks



- Has been measured
- Could be measured

- $^7Li(p,\gamma)\,^8Be$
- $^{11}B(p,\gamma)^{12}C$
- $^7Li(\,^3He,\gamma)^{10}B$
- $^3H(p,\gamma)\,^4He$

X17 – Parameter Space to Explore in Nuclei

Transition	Vector	Axial vector	Scalar	Pseudo scalar	Isospin
^{8}Be: 1^+ 0^+ M1-IS	L=1	L=0,2		L=1	ΔT=0
^{8}Be: 1^+ 0^+ M1-IV	L=1	L=0,2		L=1	ΔT=1
^{12}C: 1^- 0^+ E1-IV	L=0,2	L=1	L=1		ΔT=1
^{10}B: 2^- 3^+ E1-IV	L=0,2	L=1	L=1		ΔT=1
^{10}B: 2^+ 1^+ M1-IV	L=1	L=0,2		L=1	ΔT=1
^{10}B: 2^- 3^+ E1-IV	L=0	L=1	L=1		ΔT=1
^{4}He: 0^- 0^+ M0		L=1		L=0	ΔT=1
^{4}He: 0^+ 0^+ E0	L=1		L=0		ΔT=0

He & Be suggest proto-phobic V boson (Feng et al.)

⬇

Then also observable in ^{12}C and ^{10}B

He & Be data allow AV boson

⬇

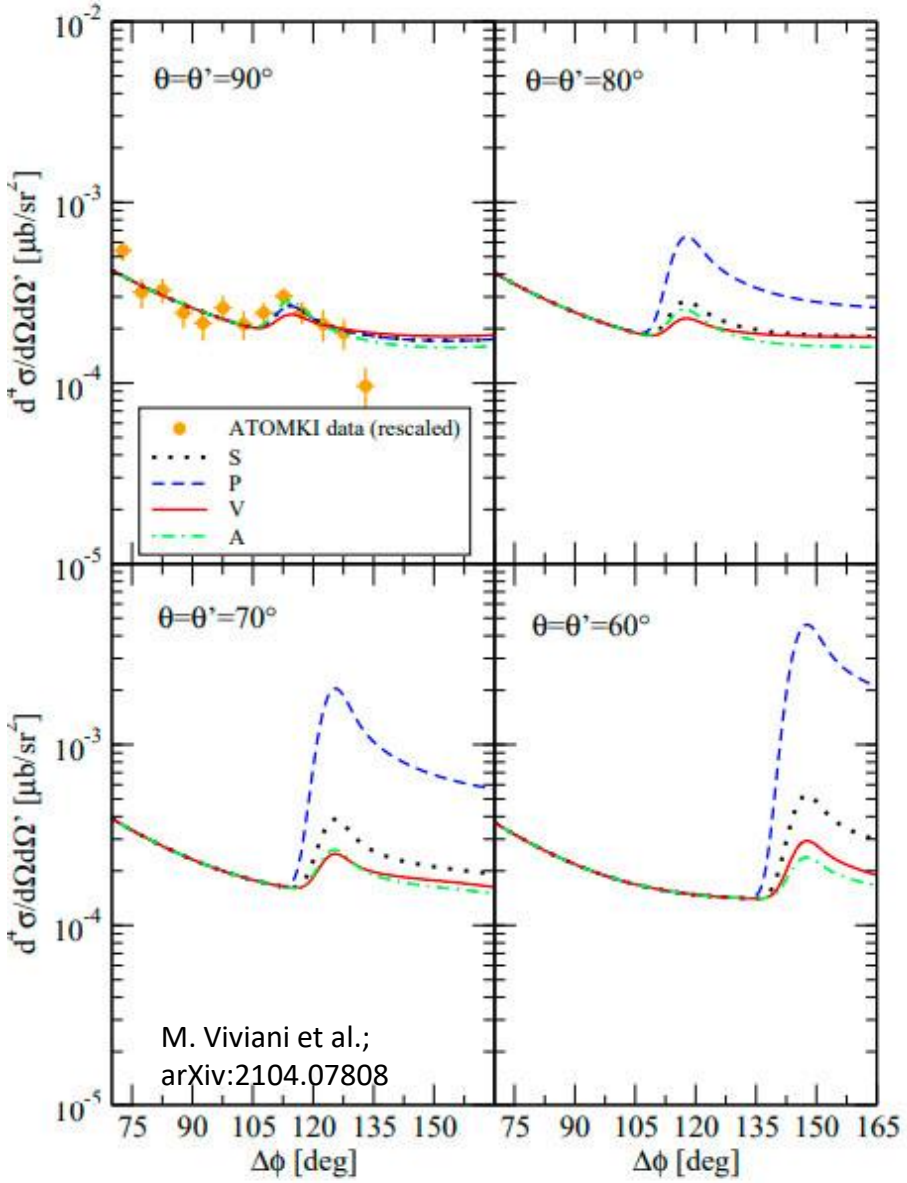
Then signal suppressed in ^{12}C and ^{10}B!

No signal in ^{12}C (E1) &^{10}B (E1) compatible w. PS

⬇

PS nature could be tested in 2γ decays, but He & Be data difficult to reconcile with S & PS

X17 – Parameter Space to Explore



M. Viviani et al., arXiv:2104.07808v1

If X17 produced in direct E1-capture (^{4}He,^{10}B..)

↓

Angular distribution of the e^+e^- pair depends on the X17 quantum numbers

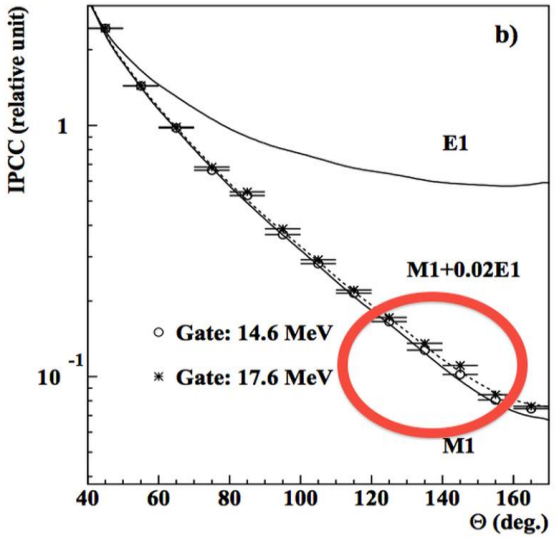
↓

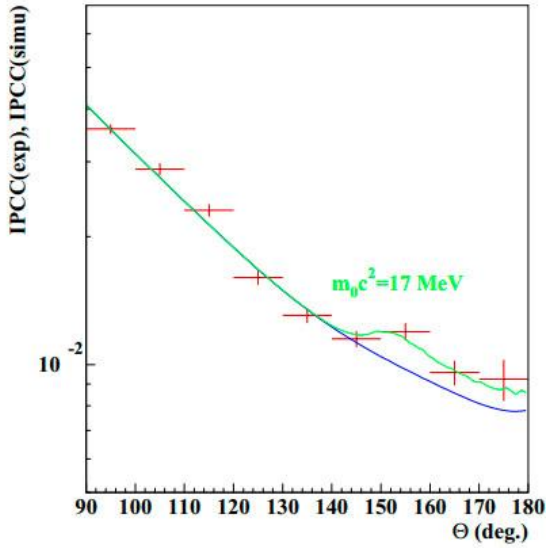
Large angular acceptance allows discrimination btw. different options

↓

More motivation for an X17 Project @ the Montreal Van de Graaff facilility

Some Puzzles…and/or Inconsistencies?





EPJ Web of Conferences 142, 01019 (2017)

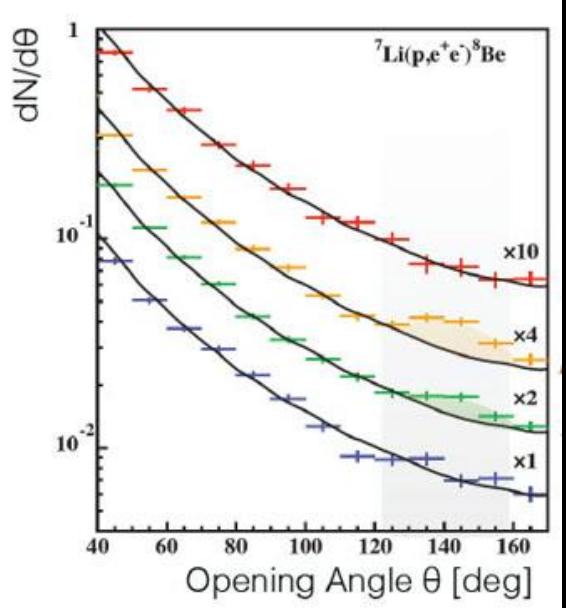
- **What is going on at the Be*' 17.6 MeV M1 IV transition?**
  - not seen in 2016 pub. - observed in 2017- no more > 2017?
  - kinematically suppressed? (Feng et al.)
  - evidence for AV boson? J. Kozaczuk, D.E. Morrissey,S. R. Stroberg / arXiv:1612.01525v2
- **What is going on at the Be* 18.2 MeV M1 IS transition?**
  - if protophobic then X produced off-res. in E1 direct capture (X. Zhang, Miller; arXiv:1703.04588)
  - in conflict with exp. evidence for res. production!
- **What is going on at the overlapping He* 0^+0^- resonances?**
  - no change in X - rate by scanning through the 2 resonances
  - then X produced via E1 in direct capture! (M. Viviani et al.; arXiv:2104.07808)
  - then why not also in Be*?

Independent nucl. physics verification needed!

The Montreal X-17 Project

G. Azuelos[1], D. Bryman[2], W.C. Chen[1], L. Doria[3], M. Laurin[1], K. Leach[4], H. de Luz[5], J.P. Martin[1], A. Robinson[1], N. Starinski[1], R. Sykora[5], U Wichoski[6], V. Zacek[1],

[1]U. Montreal, [2]UBC, [3]U. Mainz, [4]C.S. Mines, [5]CTU Prague, [6]Laurentian U.



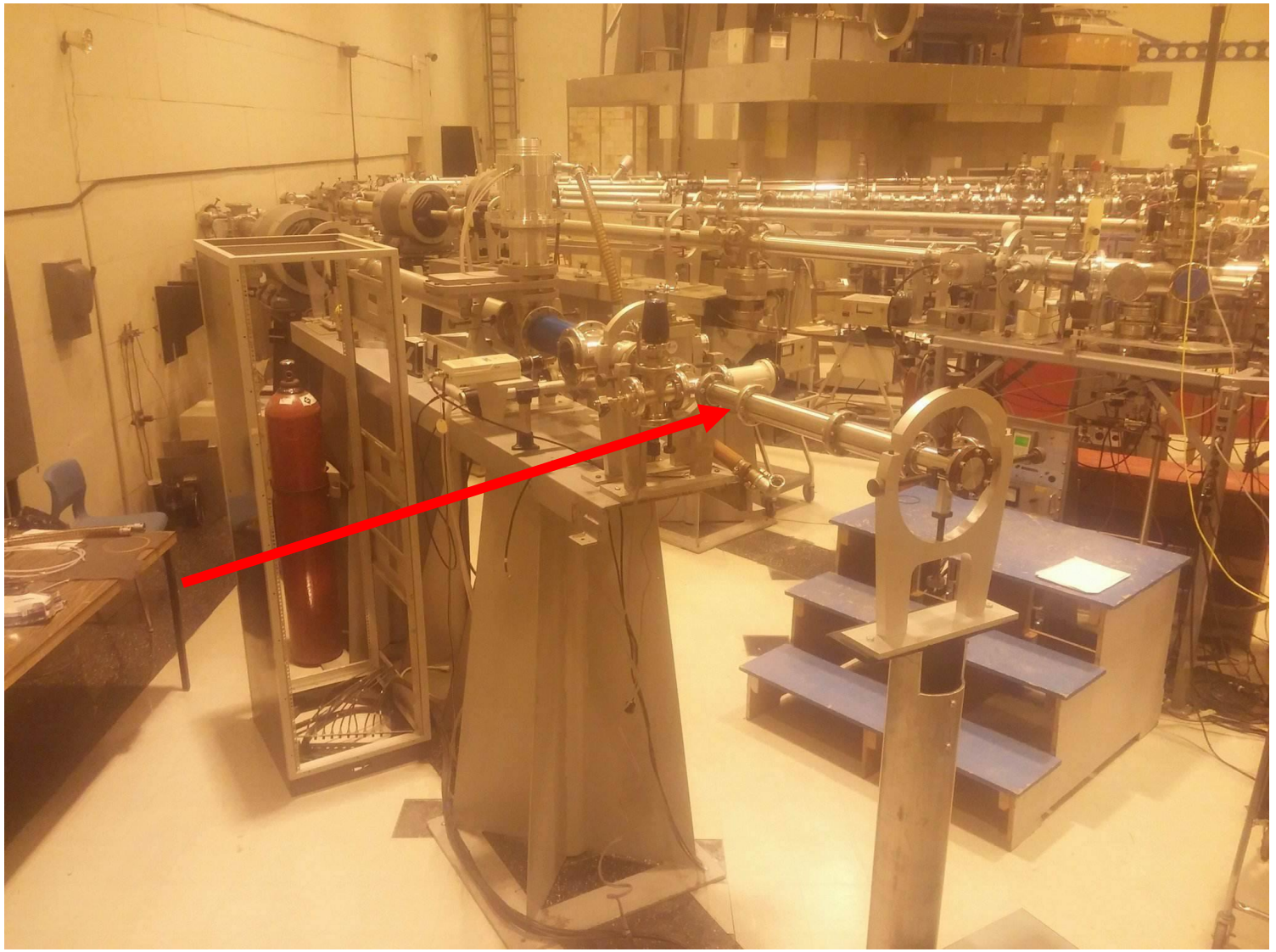
Main goals:

- Verification of ATOMKI results
- Start with existing equipment
- Increase acceptance → 0.95 x 4π
- Improve statistics & angular resolution
- Eventually extend to other nuclei: ^{10}B , ^{12} C, ^{4}He

The Montreal X-17 Project

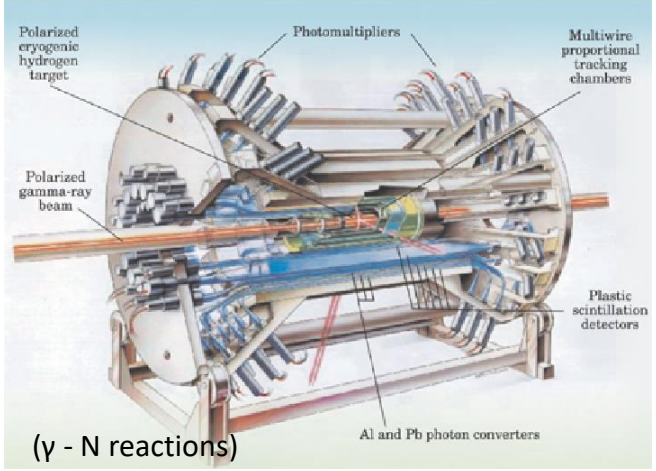
UdeM 6 MV Tandem
Van de Graaff Facility

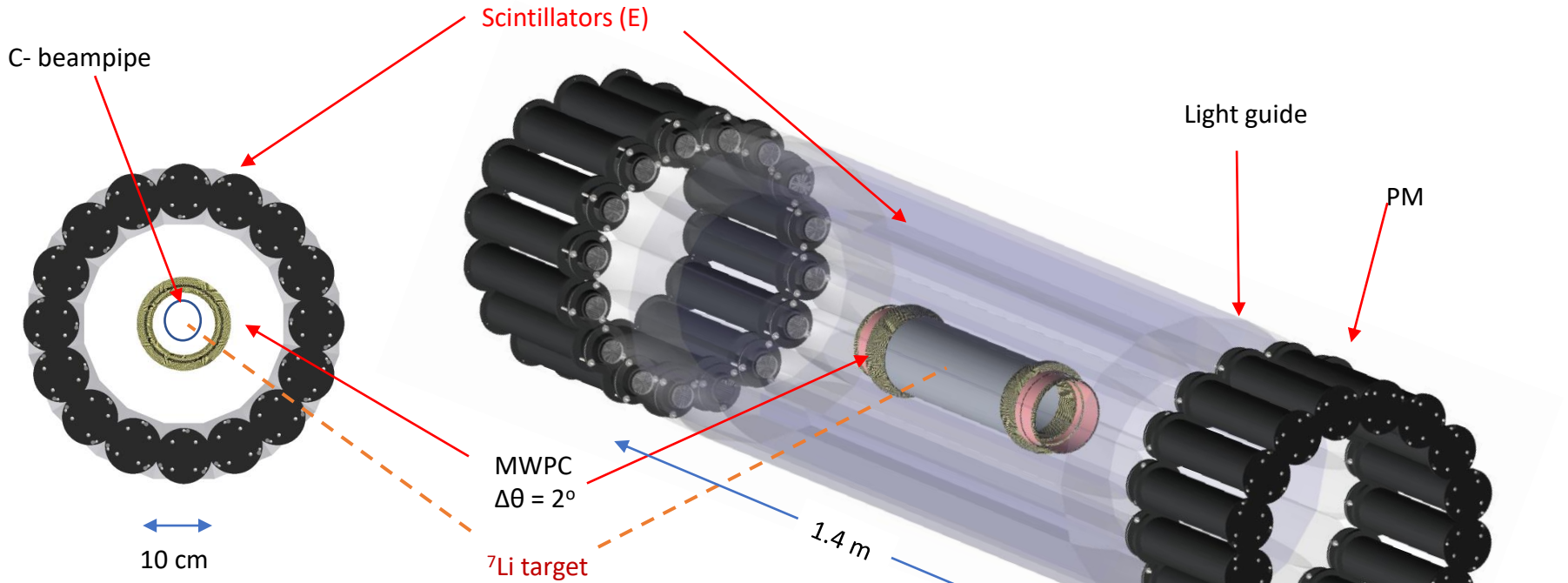
- E - resolution of 2kev for E_p = 0.4 - 1 MeV
- Dedicated Beam Line for X17 – project
- ^{3}He – beam available!



The Montreal X-17 Project

- Use parts of the DAPHNE experiment (Saclay/Mainz*)
- Tracking MWPC chamber & 16 scintillators (NE102A)
- Scints & MWPC from U. Mainz → now @ Montreal



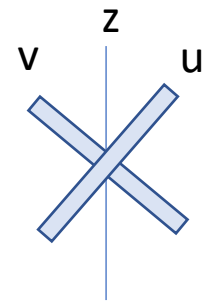


Large solid angle coverage → 0.95 x 4π

*Many thanks to L. Doria, U. Mainz

The DAPHNE Tracking Chamber

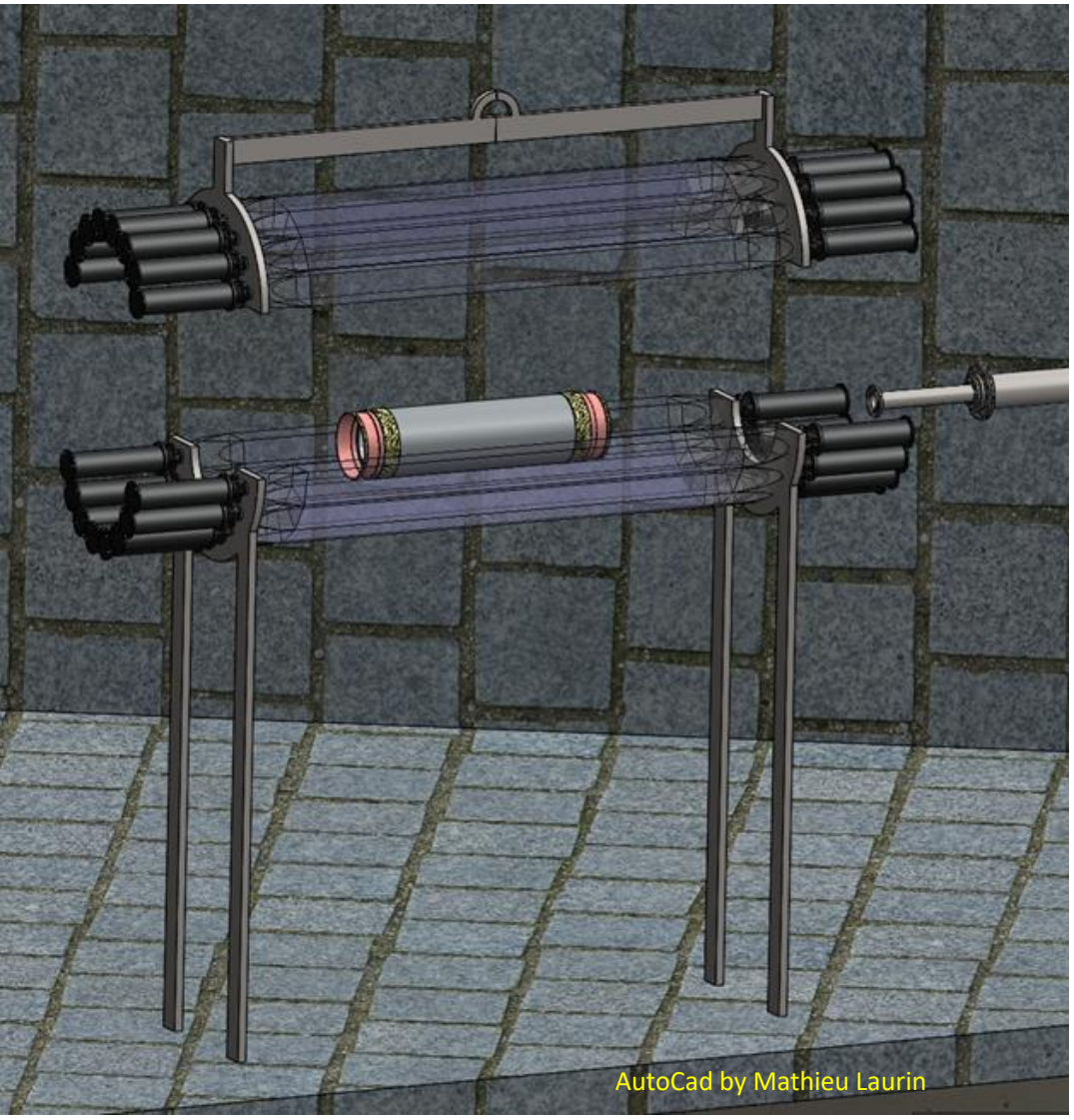
- ID 12 cm / OD 14 cm - Length 36 cm
- Cathode-anode distance: 4 mm;
- 192 Anode wires: 20 µm diam; spacing: 2mm
- 60/68 cathode strips at 45^0 w.r. to wires; width 4mm
- Gas mixture: « magic gas »*



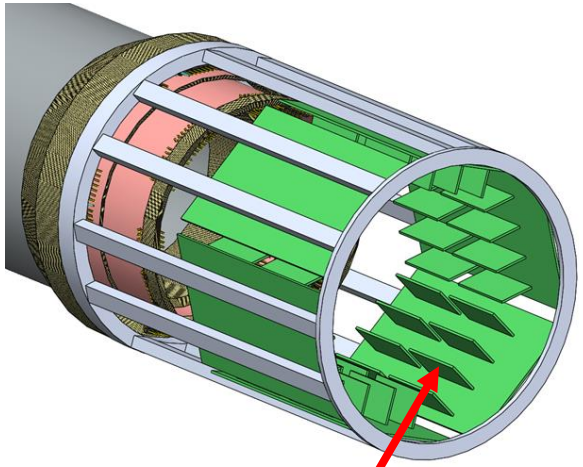
- Angular res.: $\Delta\theta \sim 2^0$ (FWHM)
- Low density material to avoid EPC!

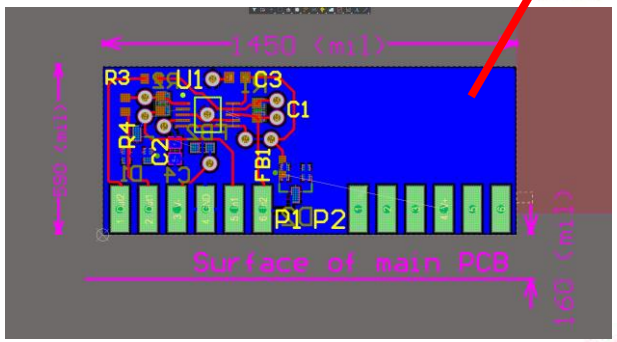
* 74.5% Ar, 25% Ethane, 0.5% Freon

Status Set-UP

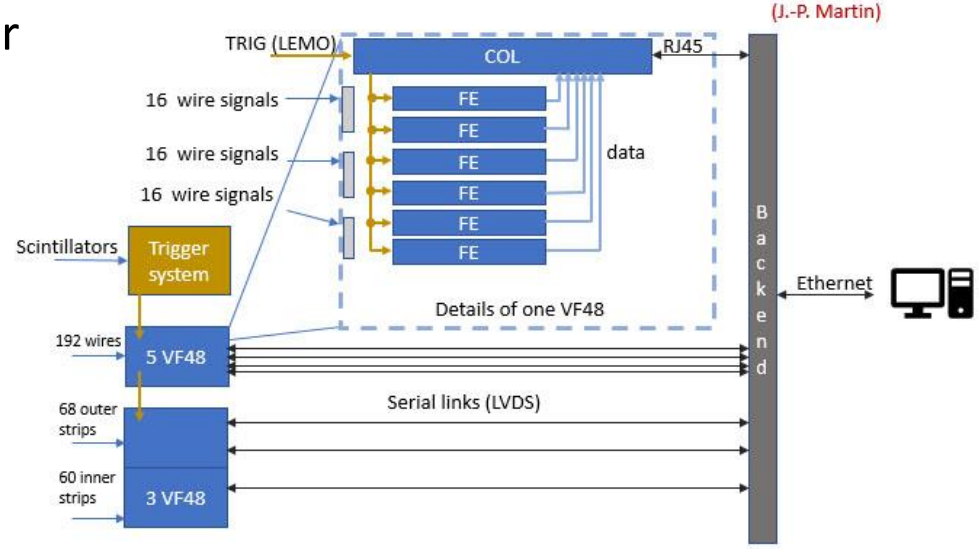


- MWPC: first wires tested with preamps & complete R/0
- 332 channels total → VF48 digitizers (TRIUMF)
- FPGA firmware ready
- Max. R/O speed: 40 kHz
- Add ΔE –scint. layer
- Add Cosmics veto





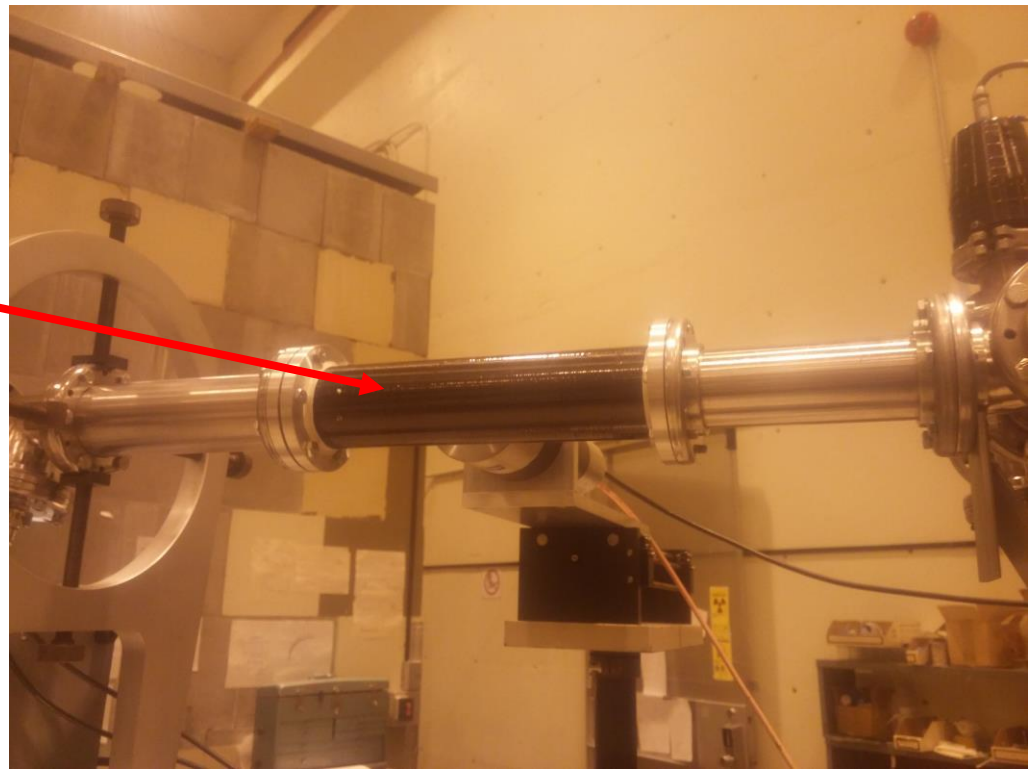
(J.-P. Martin)

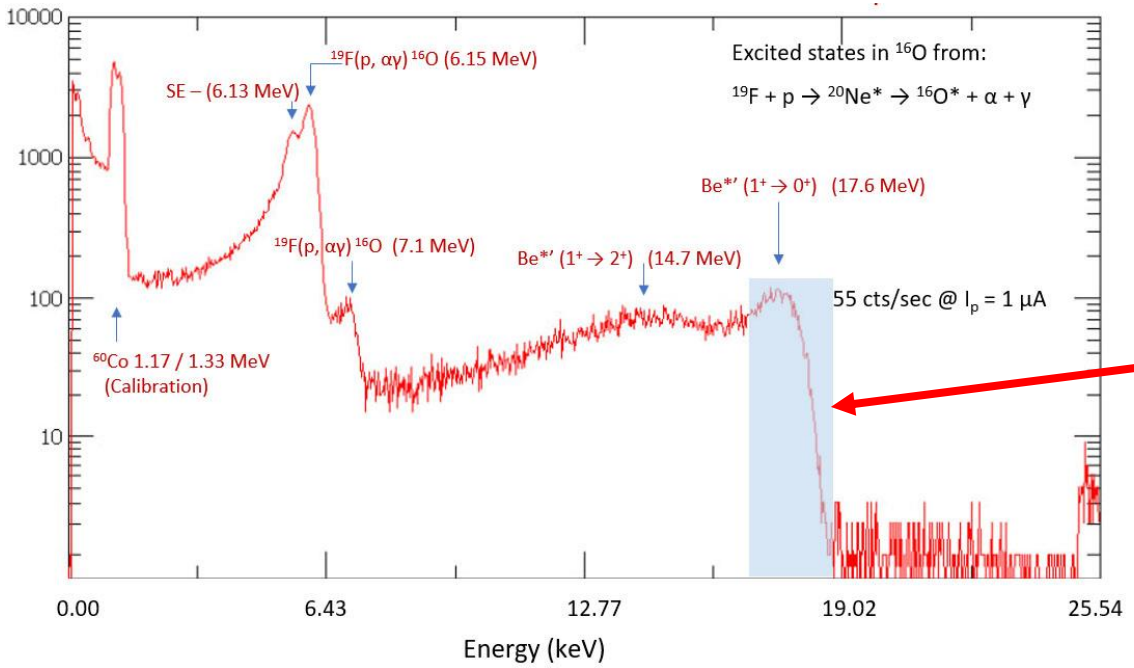


Test – Beam Measurements

Exploring Be* physics

- 0.8 mm thick C-beam pipe
- Target: 0.2 µm LiF (52 µg/cm^2)
- Beam current: I_p = 2 µA
- γ – spectra with BGO , HPGe



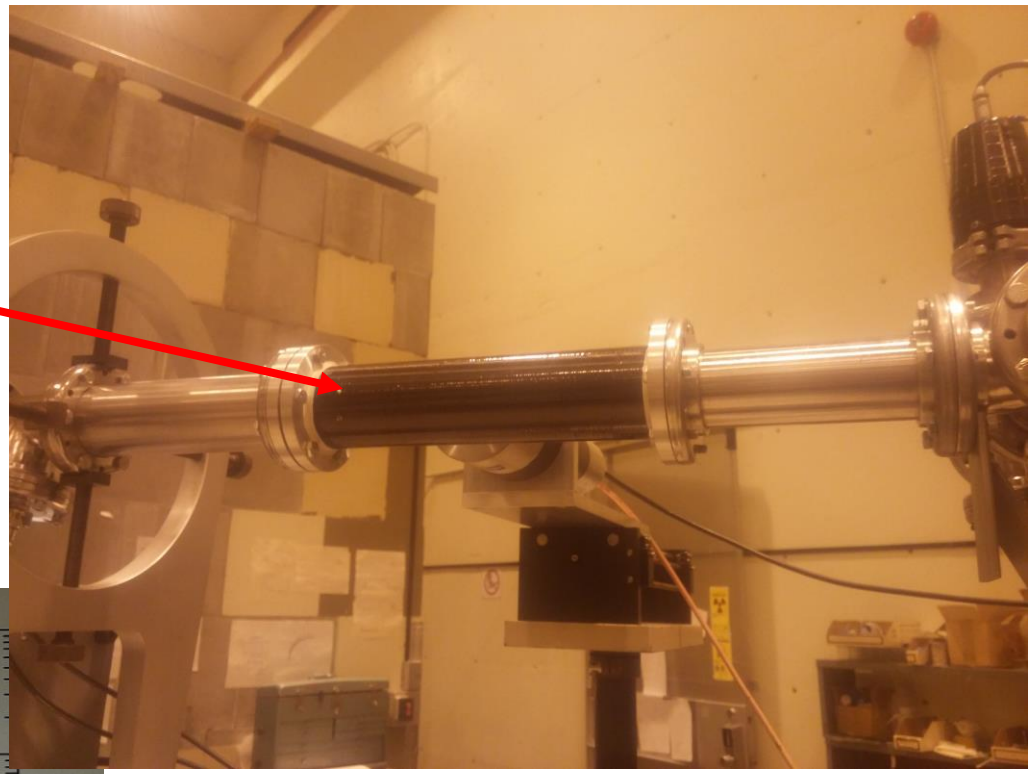


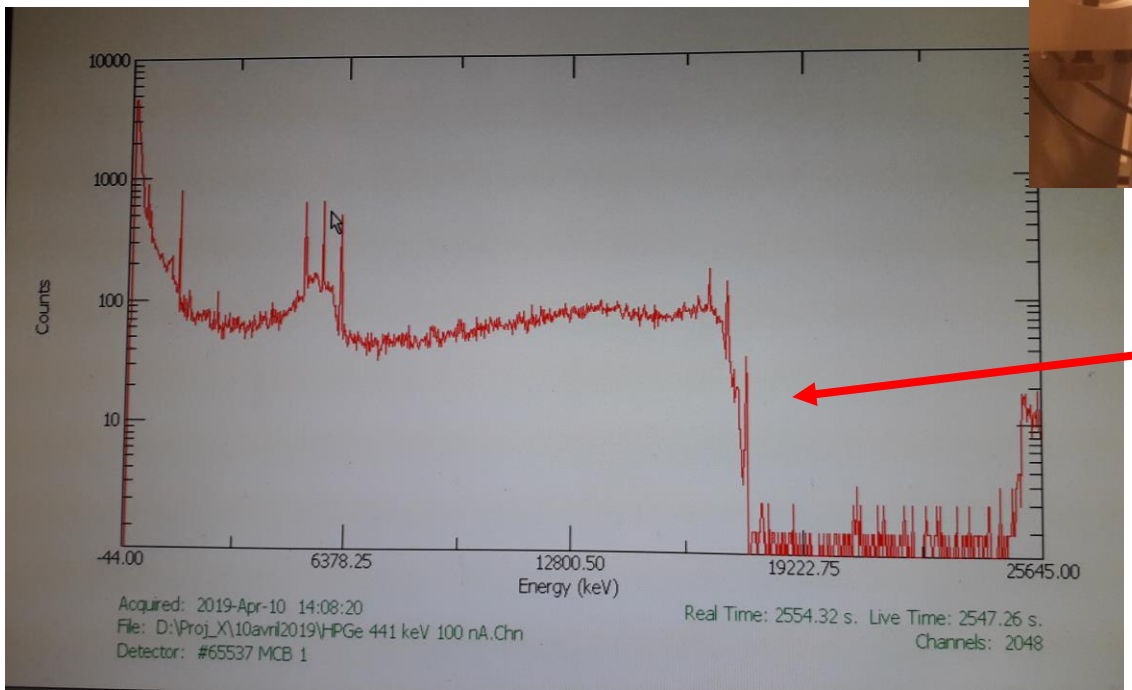
BGO
17.6 MeV resonance
(E_p = 440 keV)

Test – Beam Measurements

Exploring Be* physics

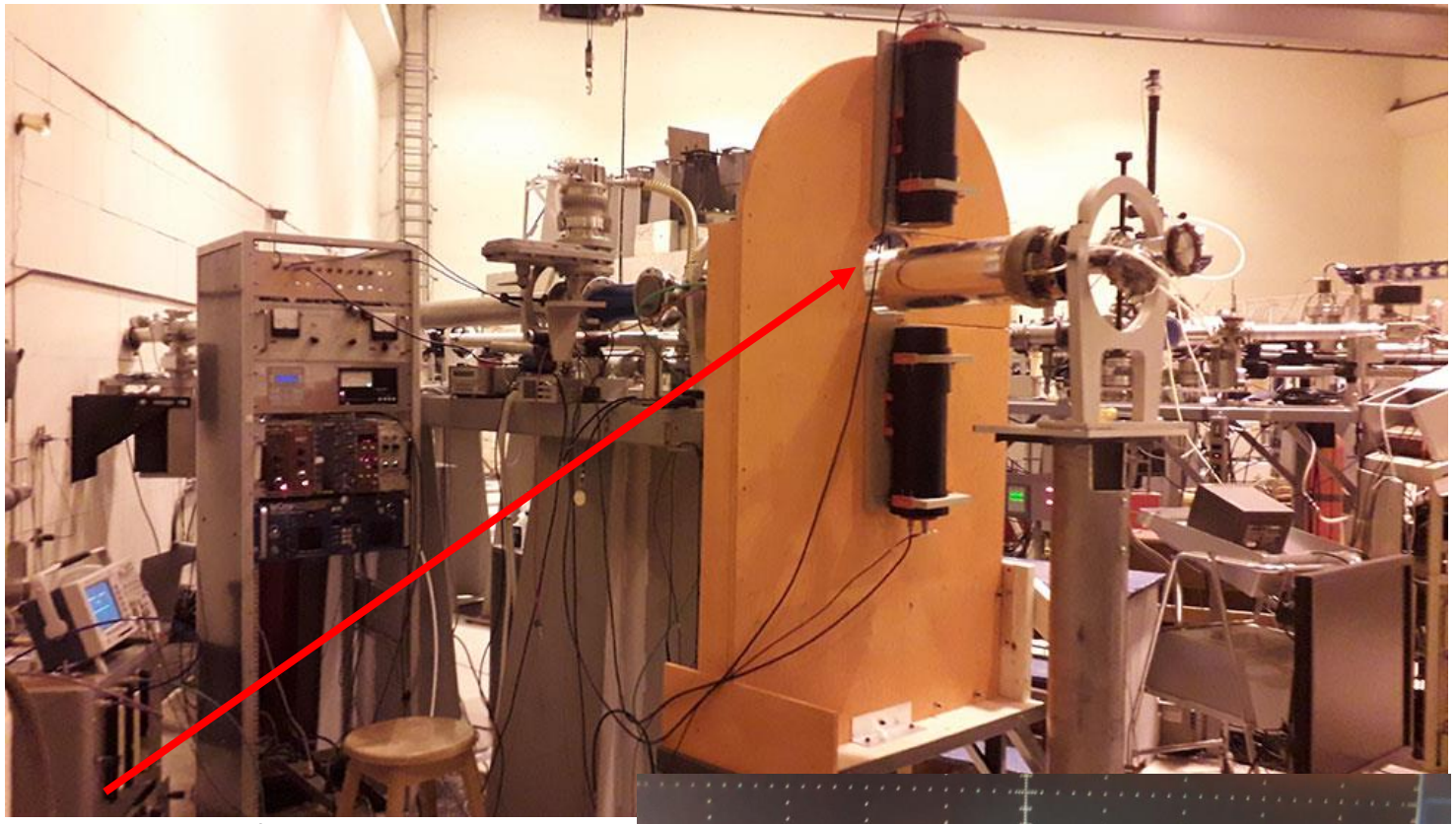
- 0.8 mm thick C-beam pipe
- Target: 0.2 µm LiF (52 µg/cm^2)
- Beam current: I_p = 2 µA
- γ – spectra with BGO , HPGe





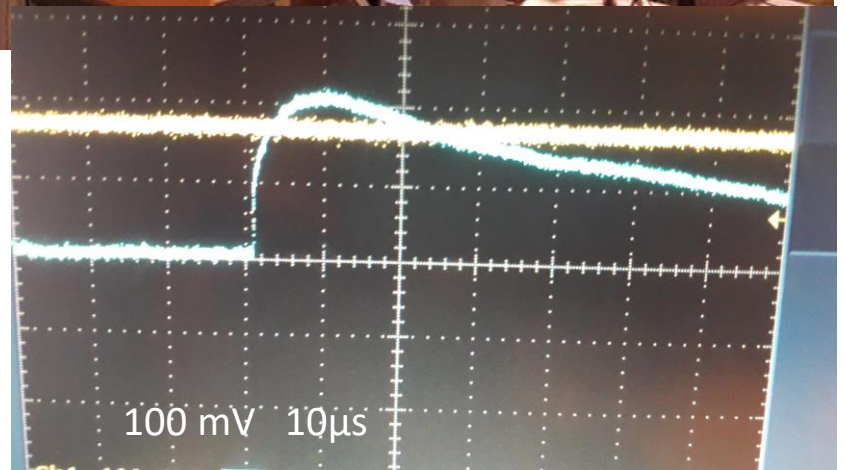
HPGe
17.6 MeV resonance
(E_p = 440 keV)

Test – Beam Measurements



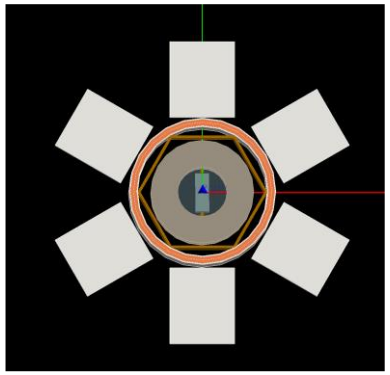
On - going:

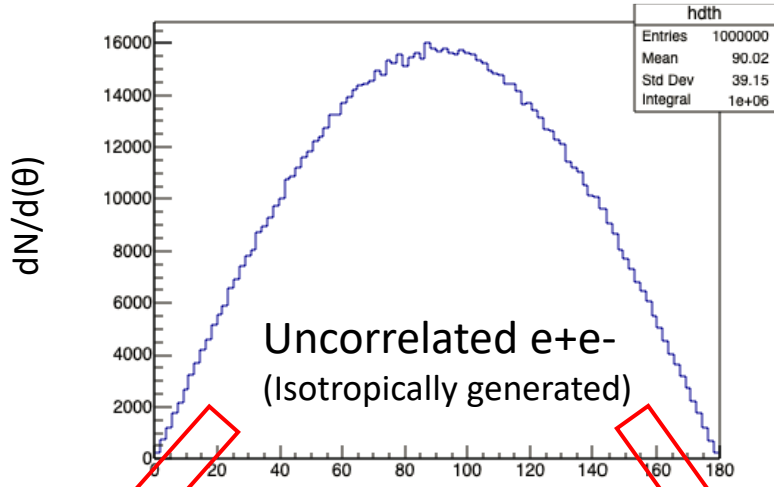
- Testing of DAPHNE MWPC (cosmics + beam)
- Deploy full MWPC read-out
- Be* e+ e- coincidences w. MWPC
- Next: deploy the 16 DAPHNE scintillators



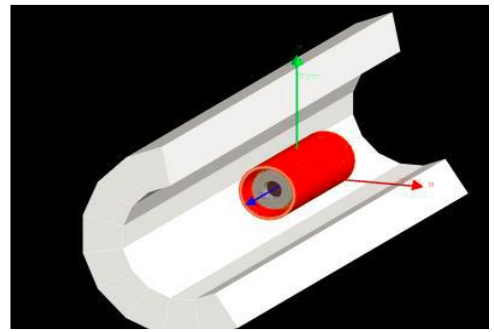
Geant4 Sim.: Acceptances

G. Azuelos, J. Pothier-Leboef (U. Montreal)
K. Leach, I. Bisset (Colorado School of Mines)

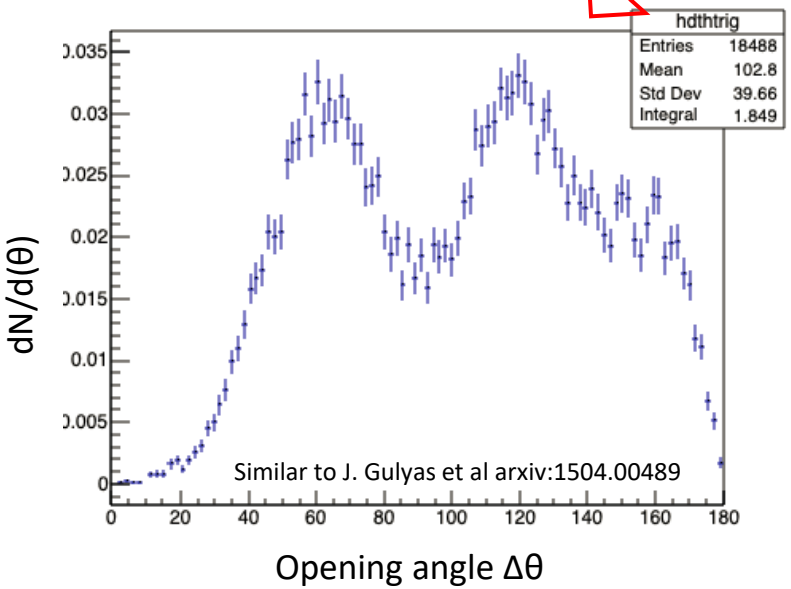




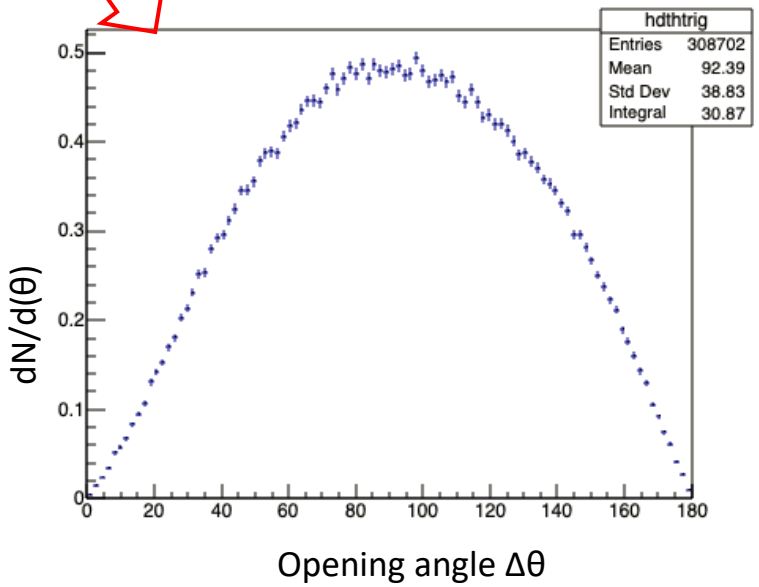
Uncorrelated e+e-
(Isotropically generated)



ATOMKI geometry



Montreal geometry



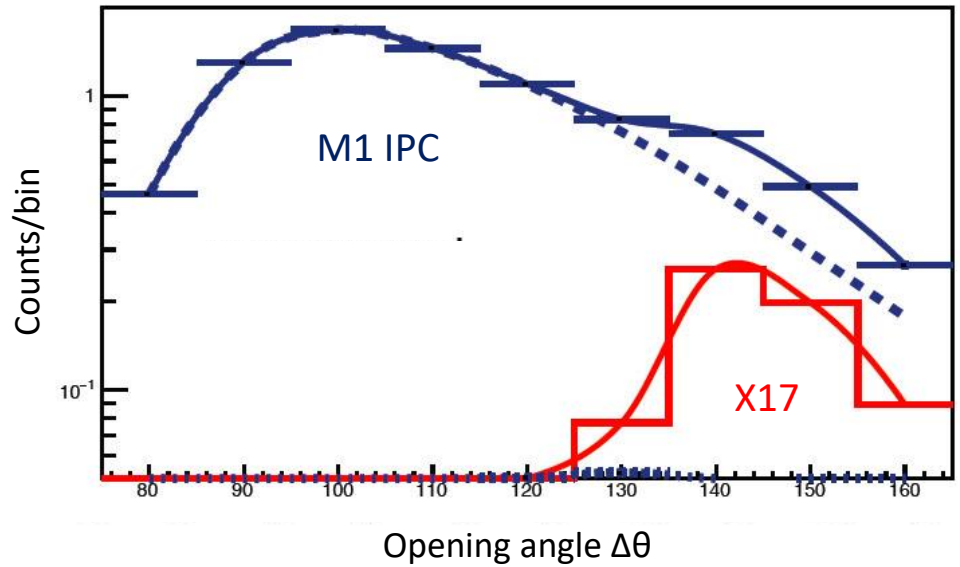
Simulation – ^{8}Be* (IPC & X17)

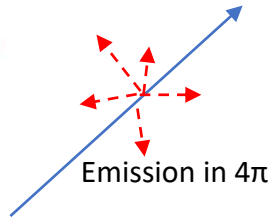
Full detector geometry:

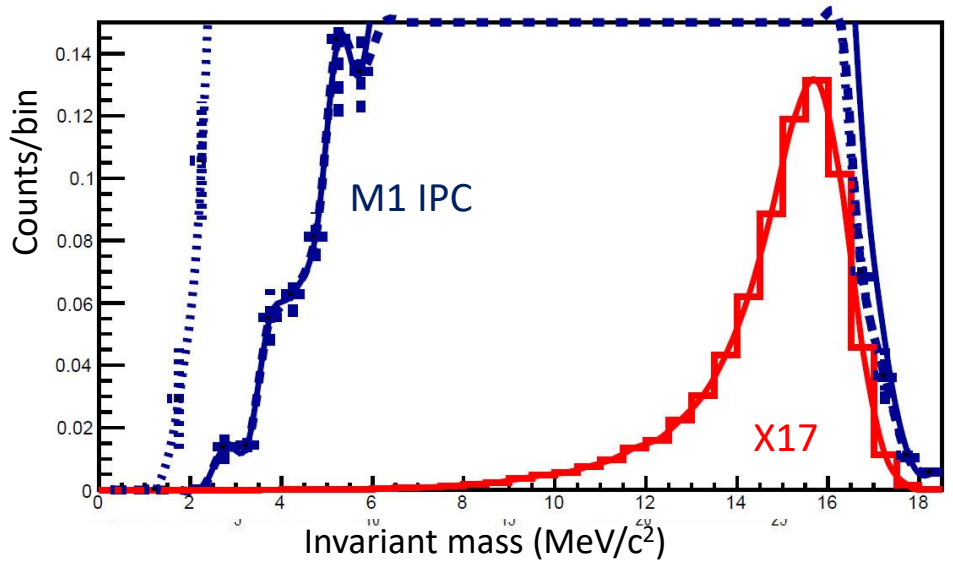
- M1- IPC: E_γ = 18.15 MeV
- $\Delta\theta \sim 2^0$ (FWHM); $\Delta E/E \sim 7.4\%/\sqrt{E}$
- |y| < 0.45; m(ee) > 12 MeV/c^2
- $B(X/IPC) = \frac{B(X/\gamma)}{B(IPC/\gamma)} = \frac{5.8\times10^{-6}}{3.9\times10^{-3}} = 1.5 \times 10^{-3}$
- Signal/Background in region of interest:

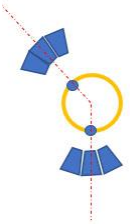
$$S/B \approx 0.6$$ $(135^0 \leq \theta \leq 180^0)$

- ….later optimization w. neural net analysis





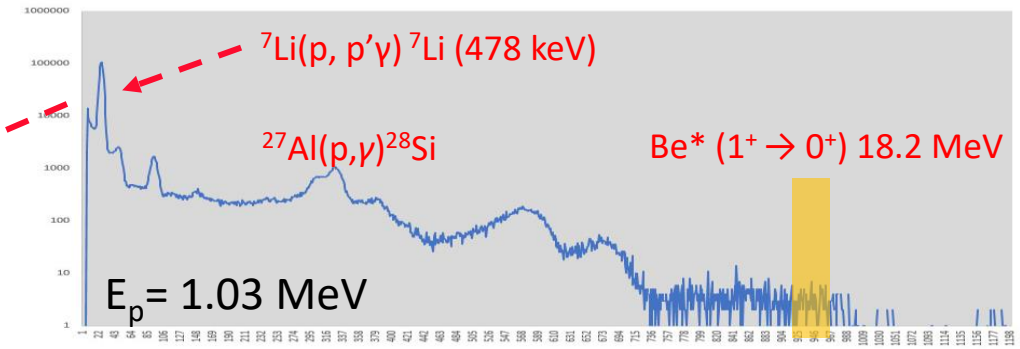




Signal Rates: ^{8}Be* IPC / X17

- Measured BGO rates @ I_p = 2μA extrapolated to 0.9 x 4π – coverage:

E_γ = 478 keV: $R_\gamma = 5.7 \times 10^5\ s^{-1}$



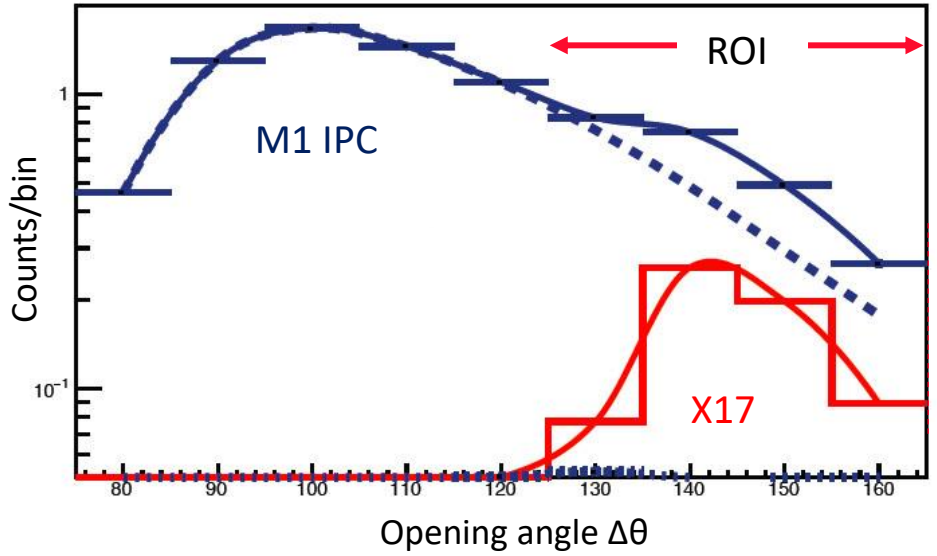
$$\frac{\sigma\ ^{7}Li(p,\gamma)\ ^{8}Be^{*}}{\sigma\ ^{7}Li(p,\gamma)\ ^{7}Li} = 7.5 \times 10^{-4}$$

R_{IPC} (18.2 -> GS) = 1.7 s^{-1}

Geant4

R_{IPC} (in ROI) = 15 h^{-1}

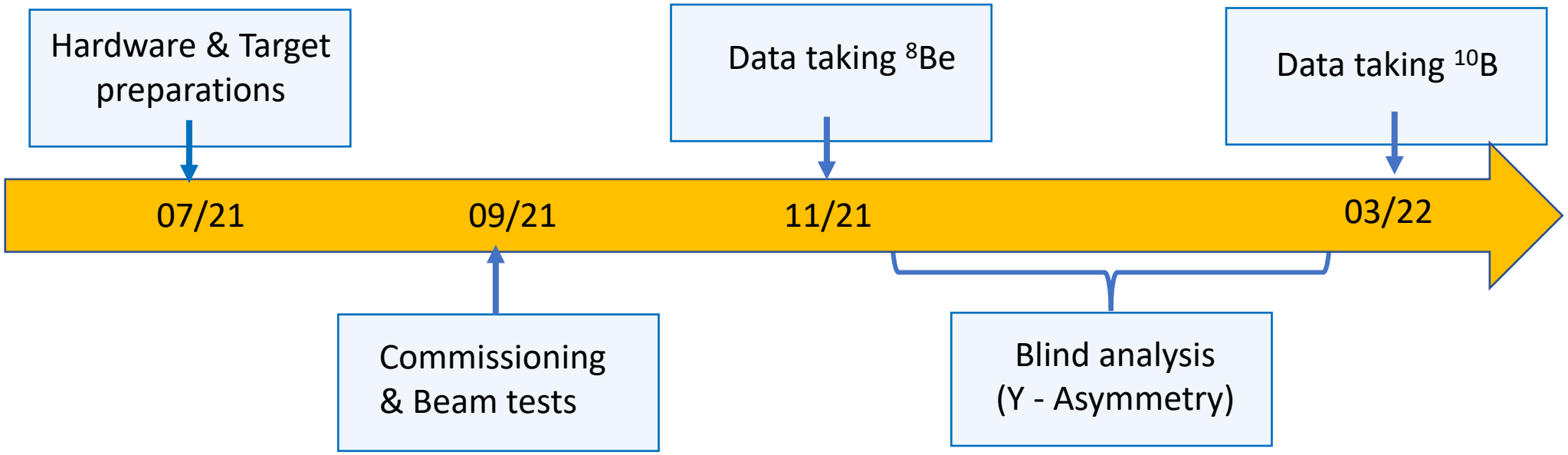
R_{X17} (in ROI) = 9 h^{-1}



(few weeks of running@ I_p = 2μA)

(Expected $R_{trigger}$ (E_γ > 1 MeV; $E_1 \wedge E_2$) = 200 Hz)

The Montreal X-17 Project - Strategy



Hints for Pseudo Scalar?

⇩

Replace scints with CsI (BNL, RNCP Osaka)

Hints for Vector, Axial V. ?

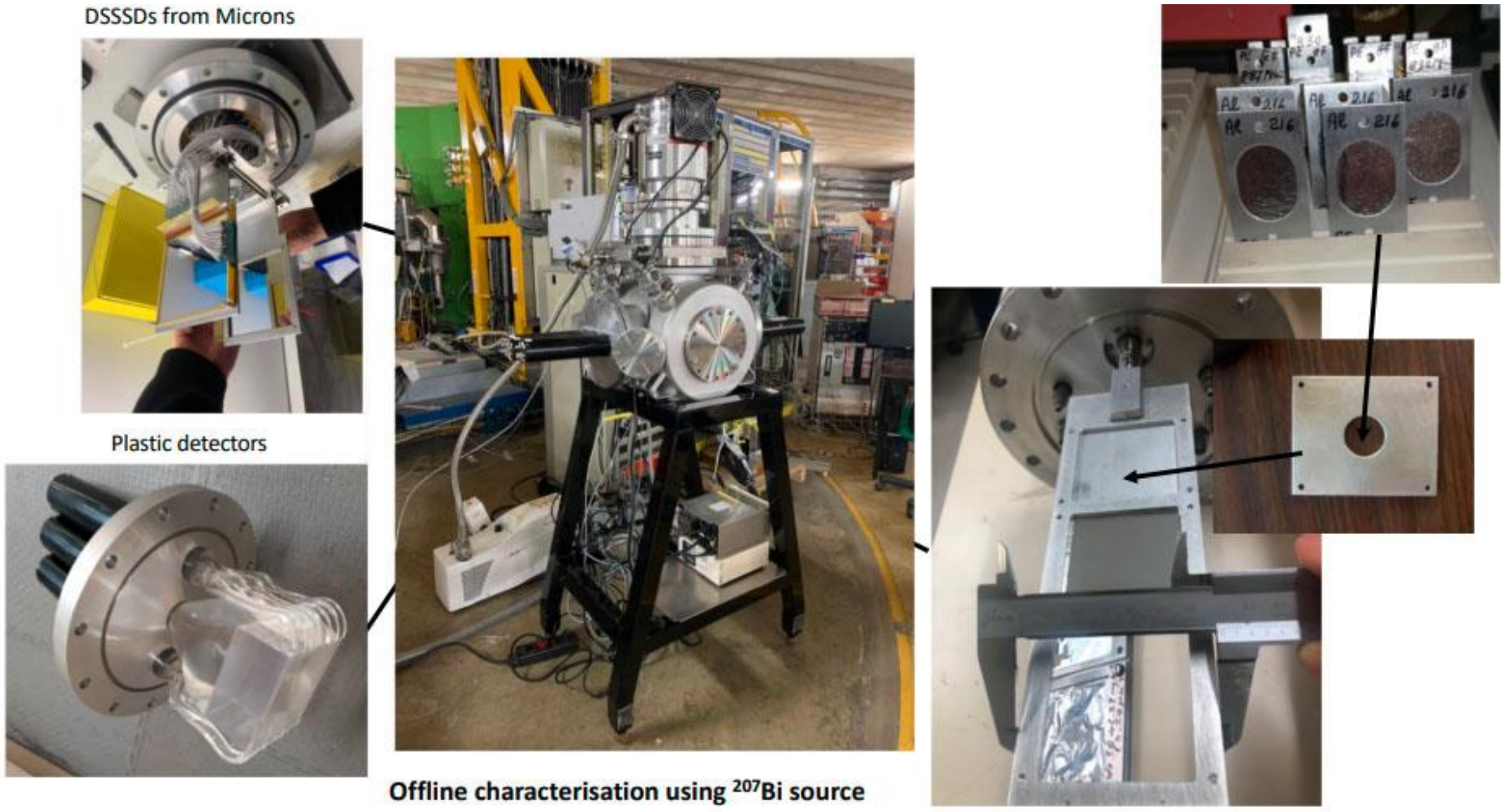
⇩

4He or 12C

….but we are not alone!

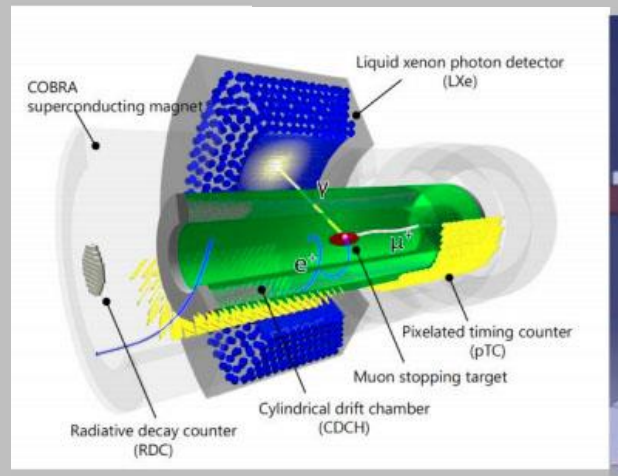
Other Ongoing Efforts: New JEDI

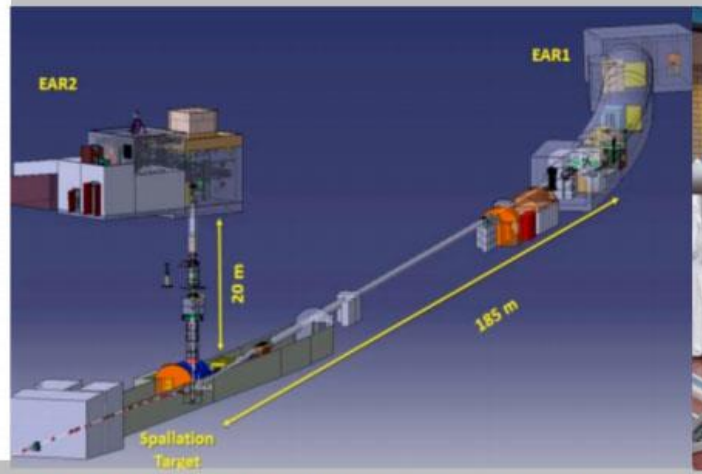
GANIL (F); IJCLab (F), IAP (F); Minnessota U. (US); NPI(CZ); ULB (B); INFN LNS (I); Ithemba Labs (SA)



Fall 2021 → '23: Series of experiments @ IJCLab (Be), GANIL (He) and Ithemba (Be)

Other Ongoing Efforts: NuCReX17





- **MEGII @ PSI:** Cockcroft Walton (1 MeV) + very well suited apparatus (accurate tracking and 4-momenta measurement

$^{7}Li(p,X17)^{8}Be \rightarrow e^{+}e^{-}$

Measurement:
End of 2021/2022 (scheduled)

- **n_ToF @ CERN:** pulsed neutron beam in a wide energy range (thermal<E_n<100 MeV).
- Time of flight to establish the single neutron energy (10-10^8 eV)
- dedicated detector

$^{3}He(n,X17)^{4}He$ (new!) $\rightarrow e^{+}e^{-}$

Measurement:
2022 (CERN LoI)

- **LUNA-MV @ LNGS:** high intensity proton beam and low bacground
- Terminal Voltage ≈ 0.2 – 3.5 MV
- I_{max} ≈ 100 μA of protons
- Underground operation
- dedicated detector

$^{3}H(p,X17)^{4}He \rightarrow e^{+}e^{-}$

Measurement:
2022 (LoI in preparation)

LUNA / n_ToF : UNITO, INFN LNL, INFN ROMA, ENEA, UNIBOLOGNA, INFN BARI, INFN LNS, ENEA ROMA, CNR BARI
MEG: INFN ROMA
Theory: UNIPISA, INFN PISA, INFN PISA, UNISALENTO
Detector R&D: ISS, INFN PISA

Conclusions

- Intriguing results by the ATOMKI collaboration in Be*and He*
- UdeM – experiment for independent & timely verification
- Extend to other states & nuclei: ^{10}B(17.8), ^{10}B(19.3), ^{4}He (22 MeV)
- Large solid angle increases coverage of param. space (V, AV P, PS)
- Other searches: New JEDI, NuCReX17, Darklight, Na64, SHiP, SeaQuest, LHCb, PADME…

Collaborators welcome !