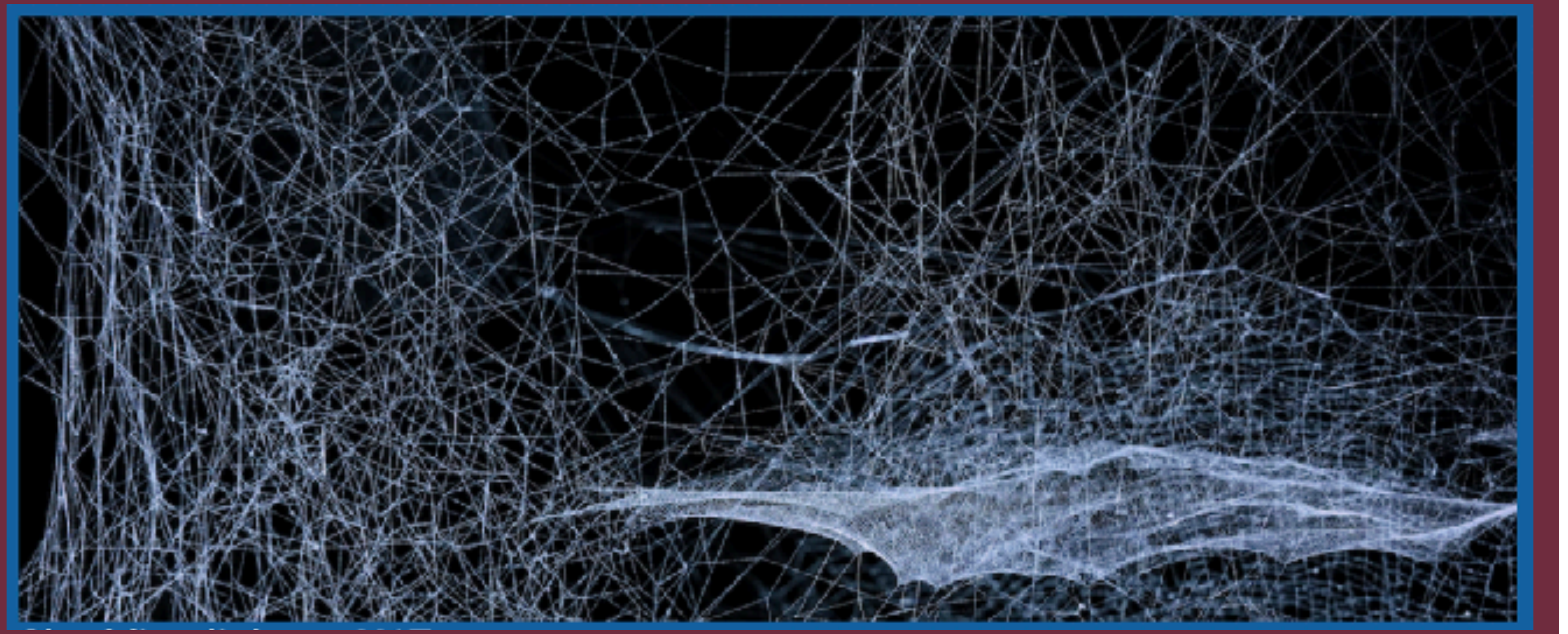
Searching for "heavy light": what can electron scattering tell us about the ATOMKI X(17) anomaly.



Dipangkar Dutta

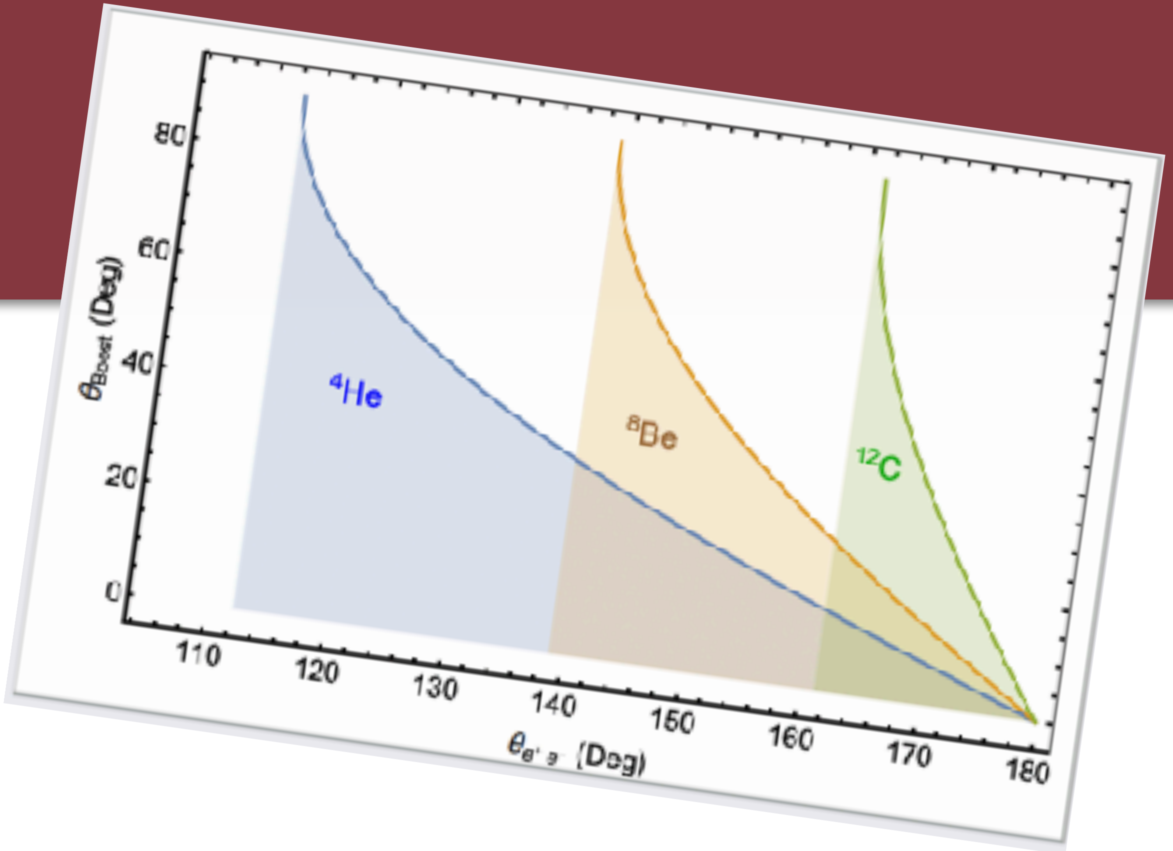
MISSISSIPPI STATE

Jefferson Lab
Exploring the Nature of Matter

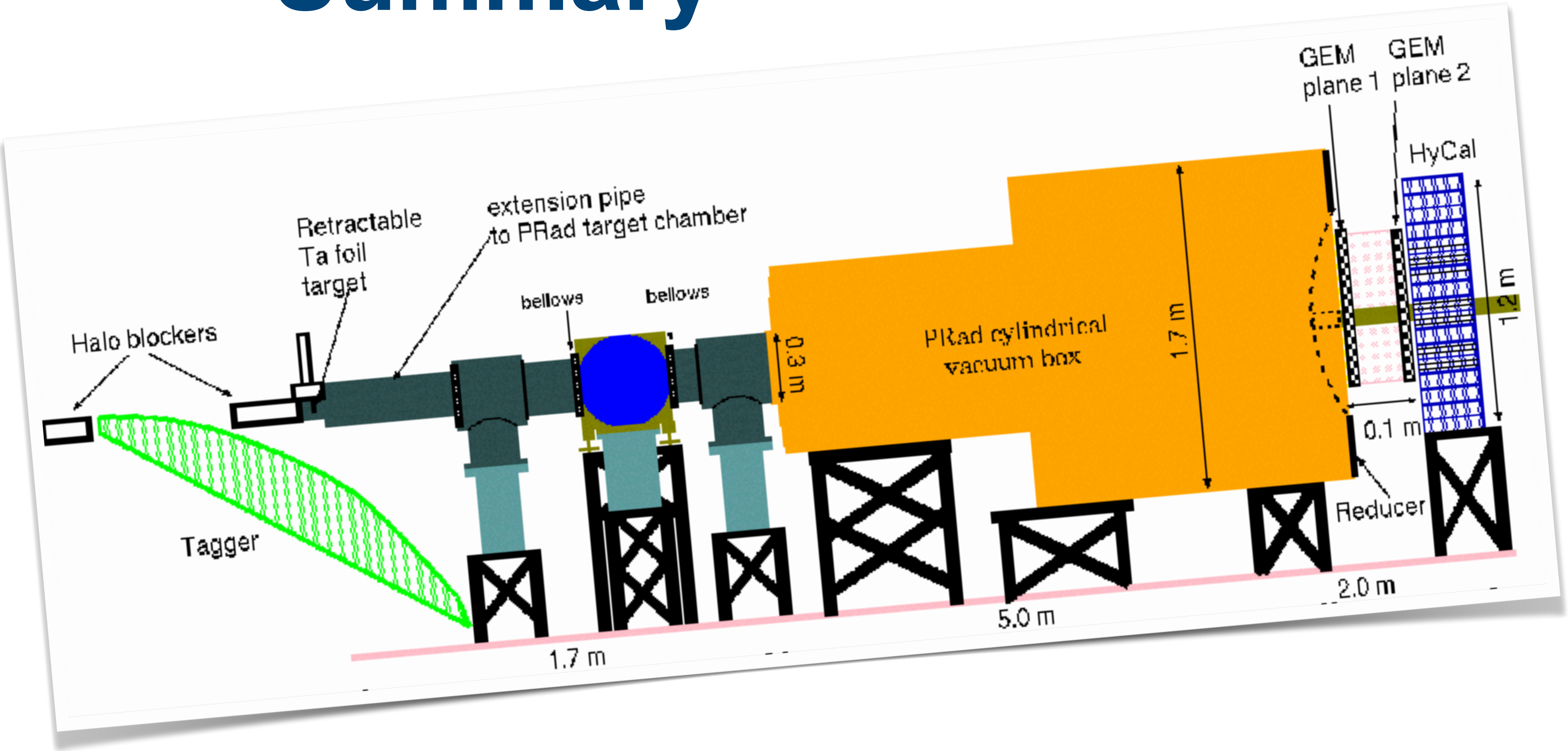
INT Workshop
(Interplay of Nuclear, Neutrino and BSM Physics at Low-Energies)

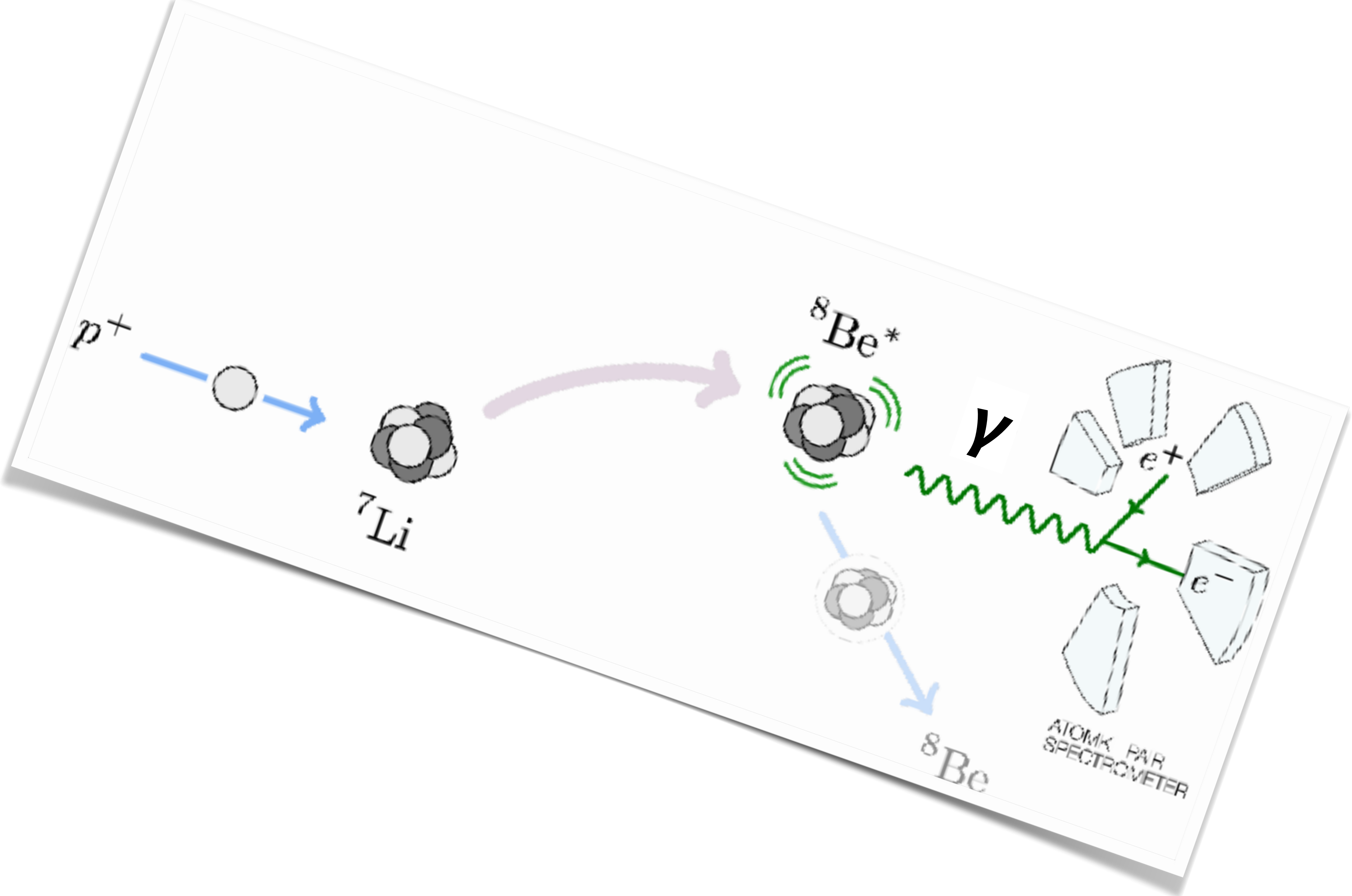
April 17-21, 2023

Outline



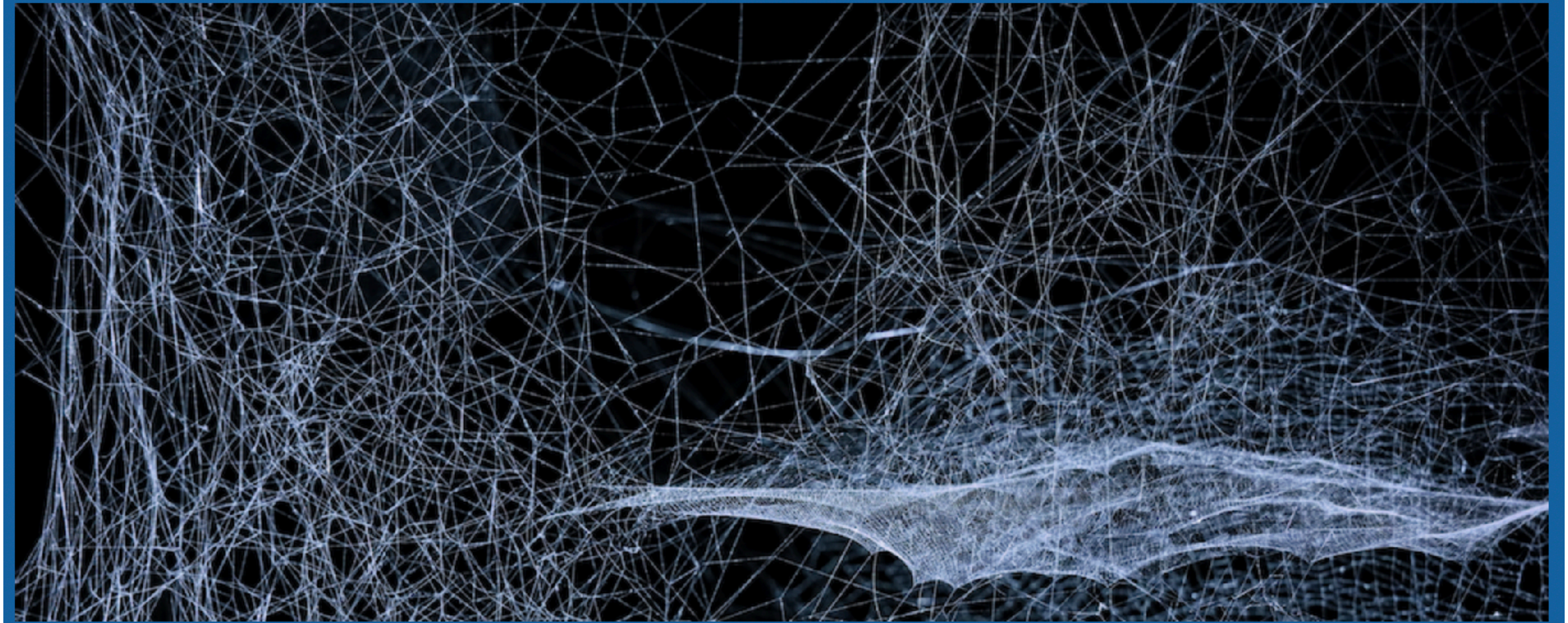
- A recent anomalous nuclear physics observation: X(17)
- A new electron scattering experiment to probe it
- Other experiments and possibilities
- Summary





The ATOMKI anomaly published in ~2016 created quite a stir in the media

ATOMKI slides adapted from talks at a recent workshop on the X17 anomaly



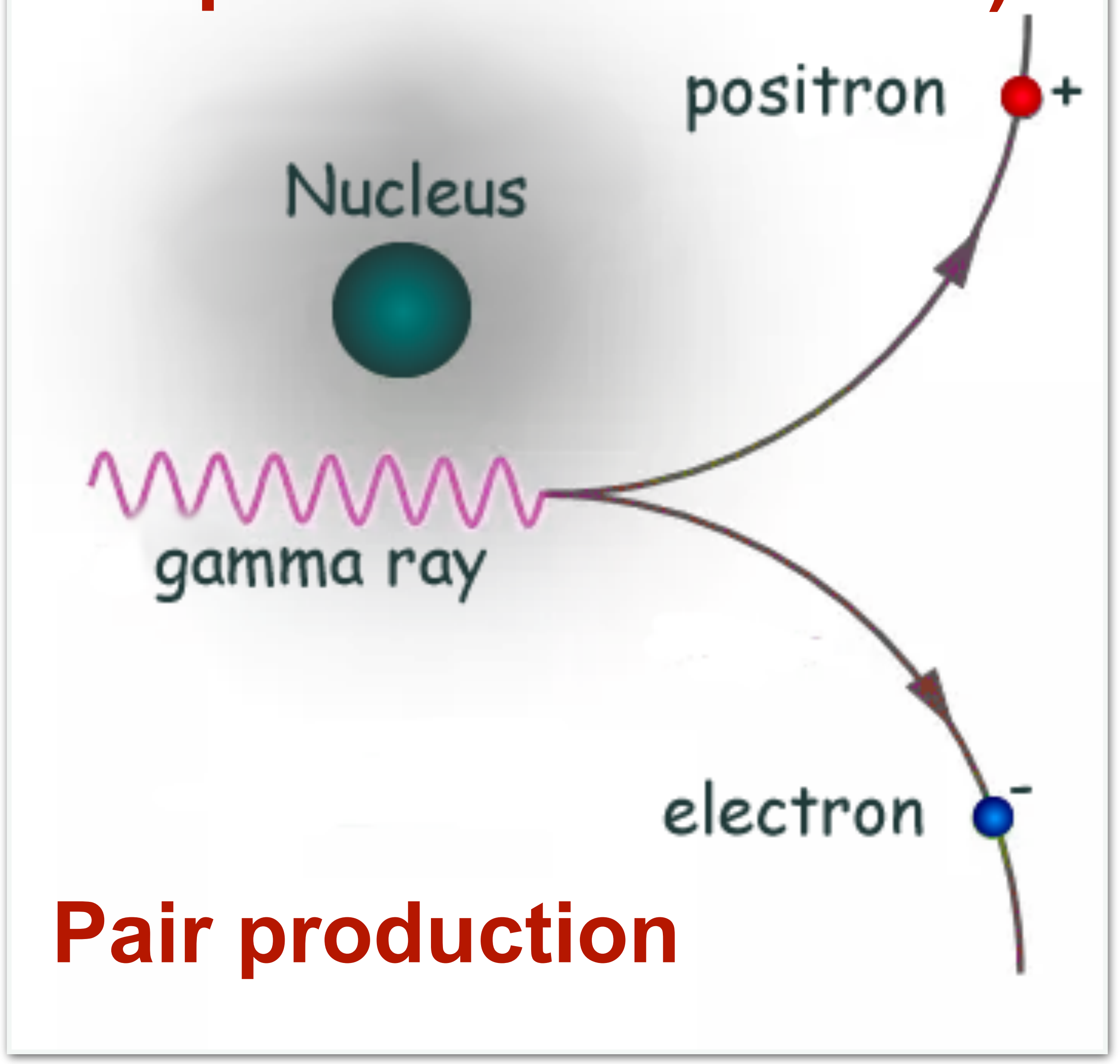
Shedding light on X17

6-8 September 2021
Centro Ricerche Enrico Fermi

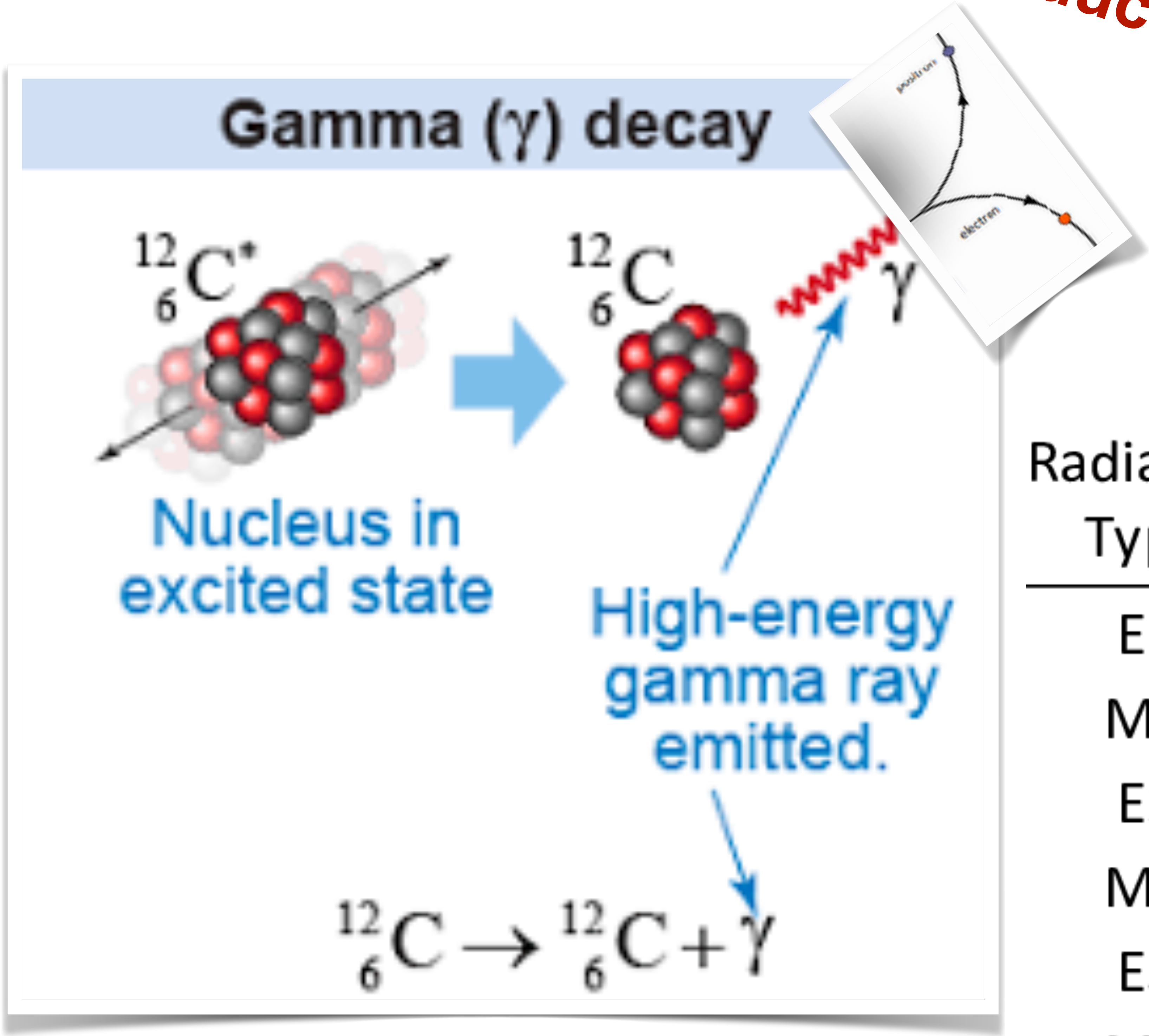
https://agenda.infn.it/event/26303/

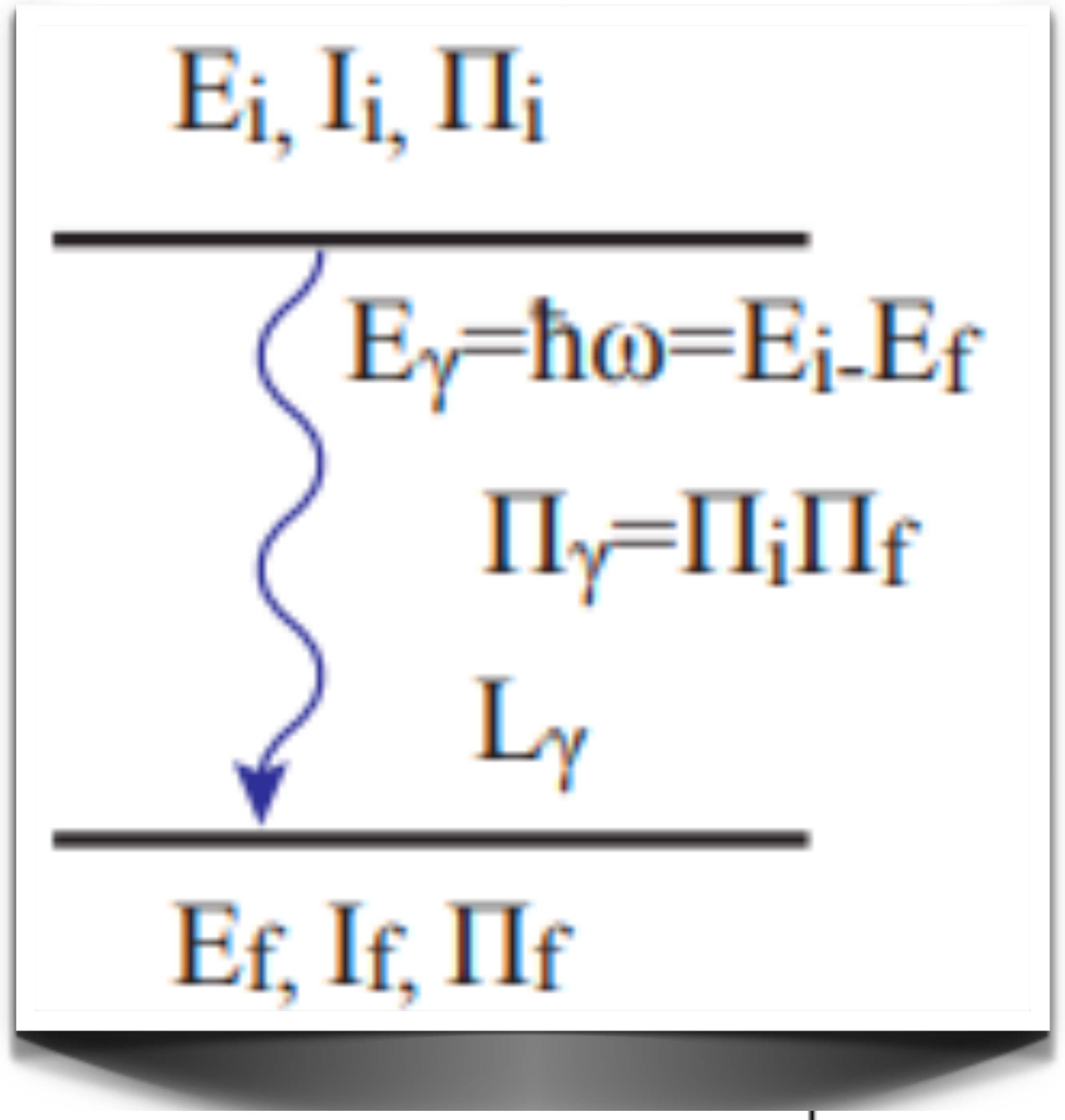
Pair production & internal pair production: a quick primer

Gamma rays with energy > 1.02 MeV can turn into an electron positron pairs (but not possible in vacuum)



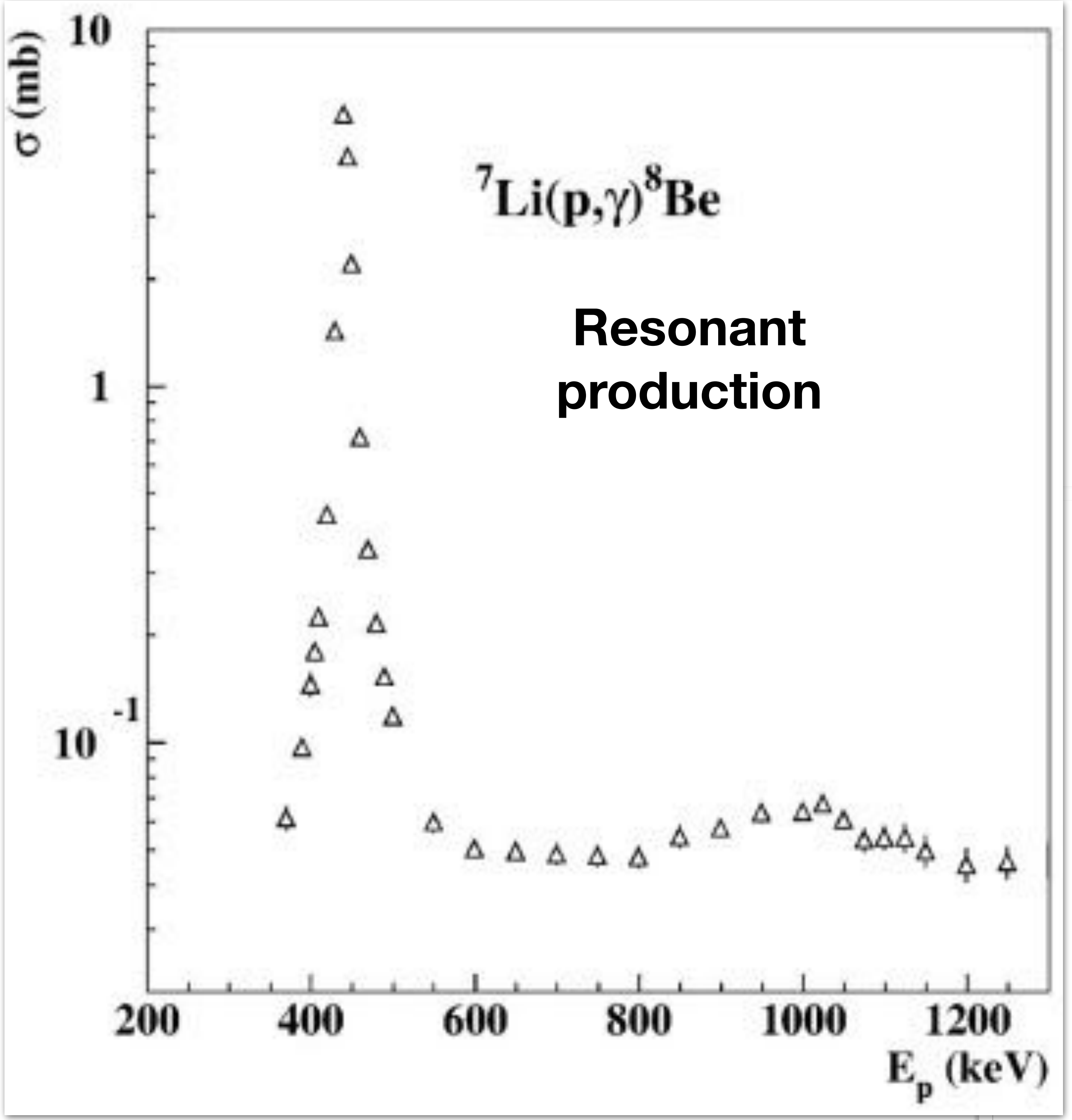
internal pair production





Radiation Type	Name	$l = \Delta I$	$\Delta\pi$
E1	electric dipole	1	Yes
M1	magnetic dipole	1	No
E2	electric quadrupole	2	No
M2	magnetic quadrupole	2	Yes
E3	electric octupole	3	Yes
M3	magnetic octupole	3	No
E4	electric hexadecapole	4	No
M4	magnetic hexadecapole	4	Yes

In 2016 the ATOMKI collaboration reported on the angular correlation for pair production in ^{8}Be de-excitation



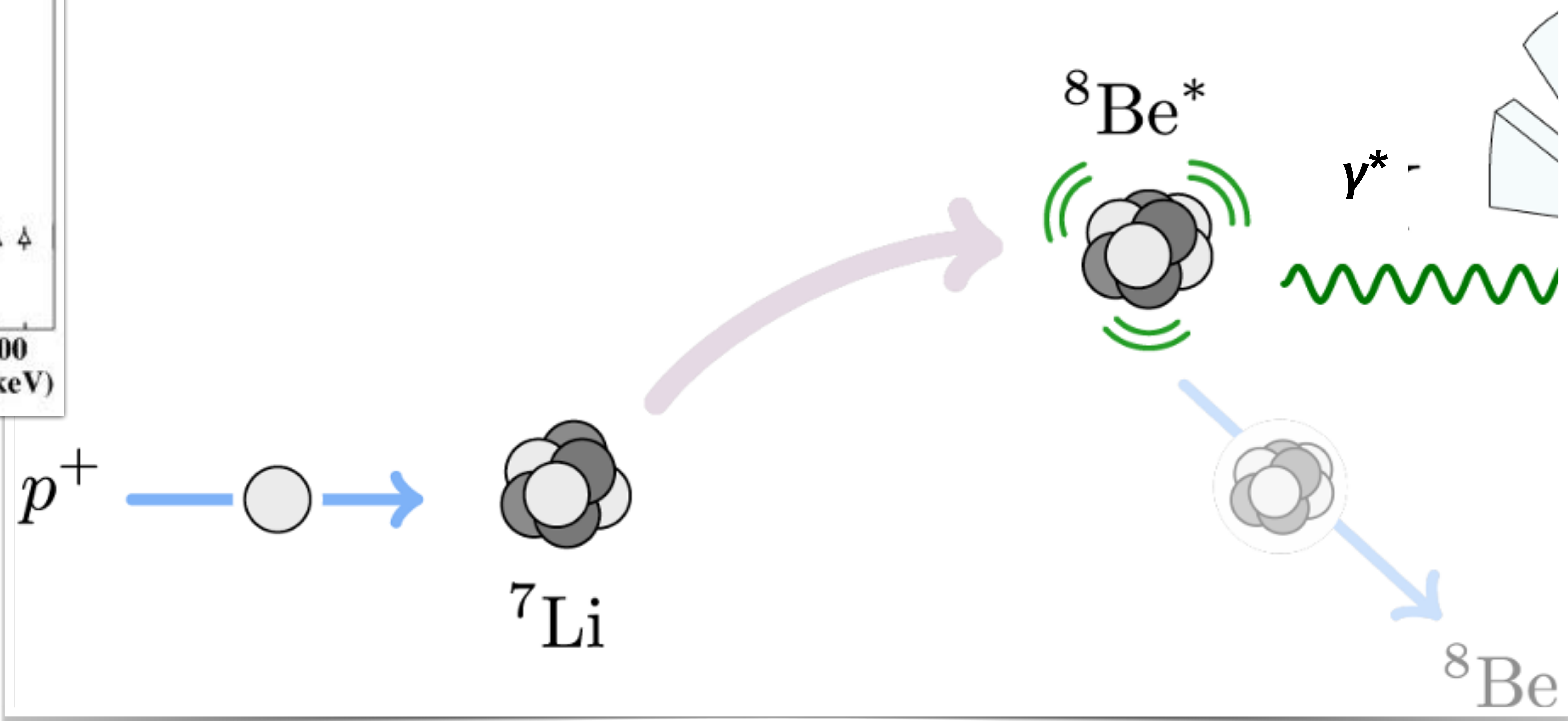
	N_*	E_{beam} [MeV]
$p + {}^7\text{Li} \rightarrow$	^{8}Be(18.15)	1.03
$p + {}^7\text{Li} \rightarrow$	^{8}Be(17.64)	0.45

^{8}Be → 2α ≈ 100%

1.03 → B(^{8}Be + γ) ≈ 1.5 x 10^{-5}

0.45 → B(^{8}Be + γ) ≈ 1.5 x 10^{-3}

protons from a 2MV Tandem accelerator

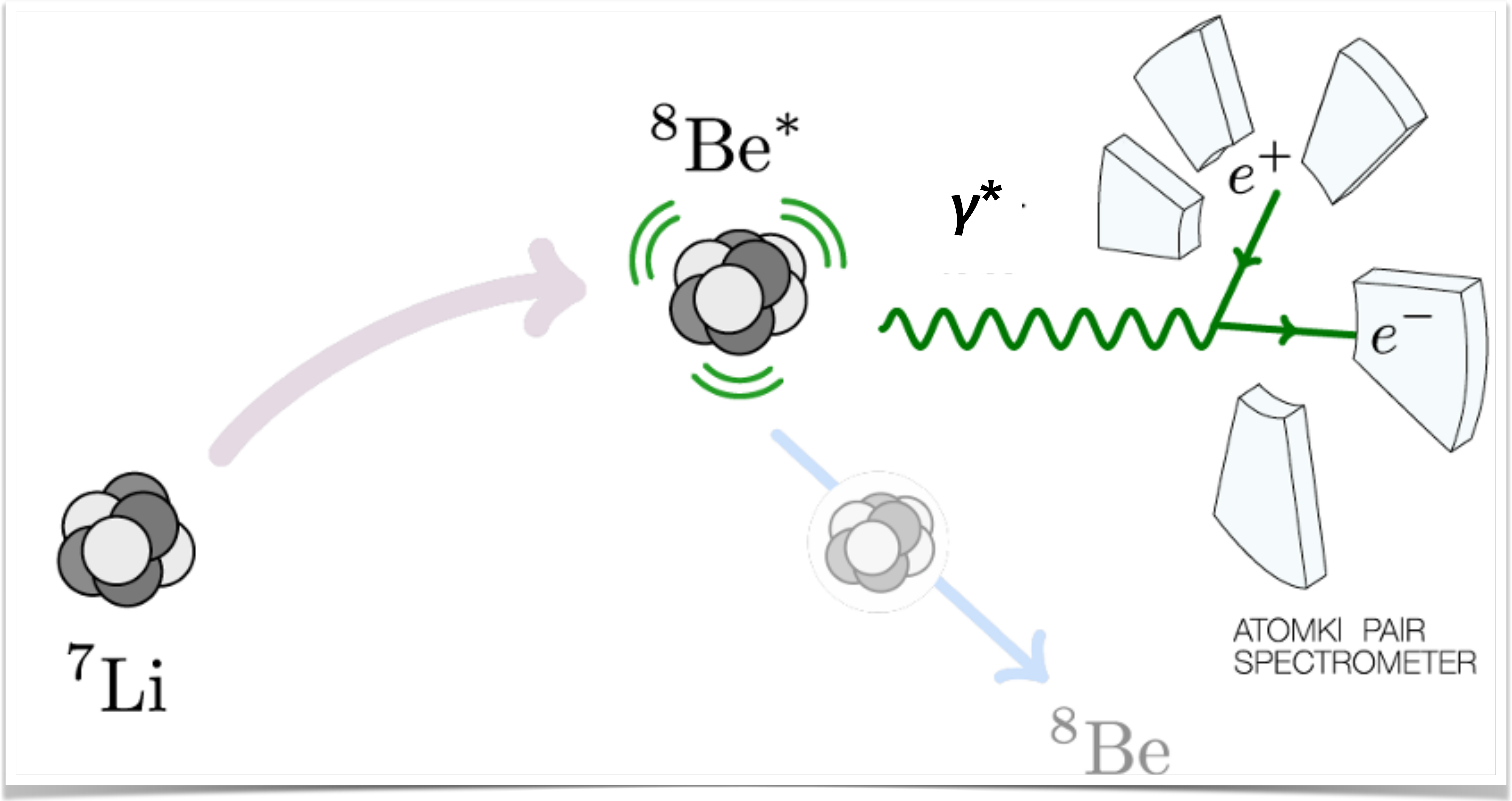


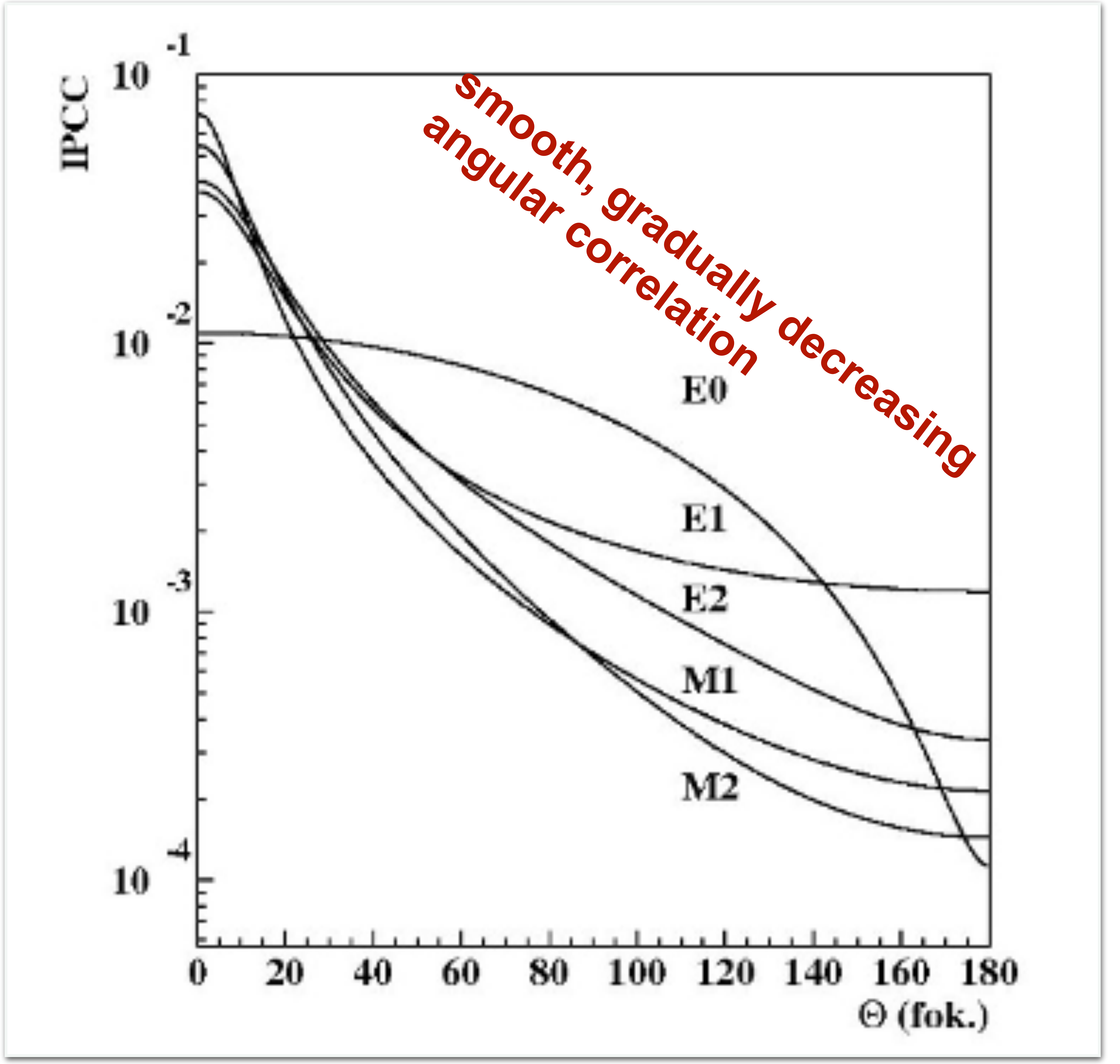
images courtesy of ATOMKI collaboration

In 2016 the ATOMKI collaboration reported on the angular correlation for pair production in ^{8}Be de-excitation

N_*	E_{beam} [MeV]	
^{8}Be(18.15)	1.03	→ $B(^8Be + \gamma) \approx 1.5 \times 10^{-5}$
^{8}Be(17.64)	0.45	→ $B(^8Be + \gamma) \approx 1.5 \times 10^{-3}$

$^8Be \rightarrow 2\alpha \approx 100\%$

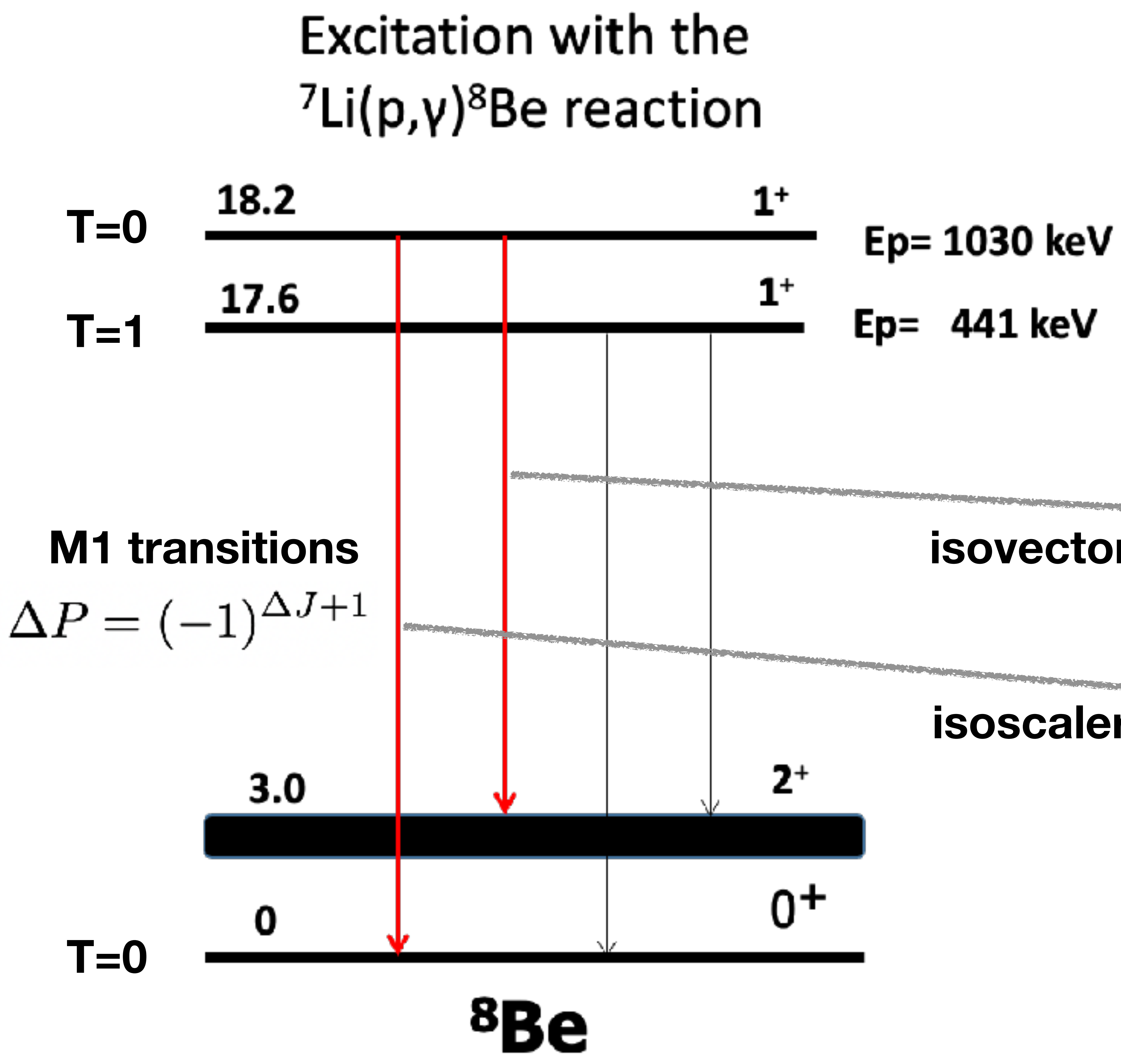




^{8}Be(18.15) **Internal pair creation has a branching ratio $B(^8Be + e^+ e^-) \approx 5.5 \times 10^{-8}$**

images courtesy of ATOMKI collaboration

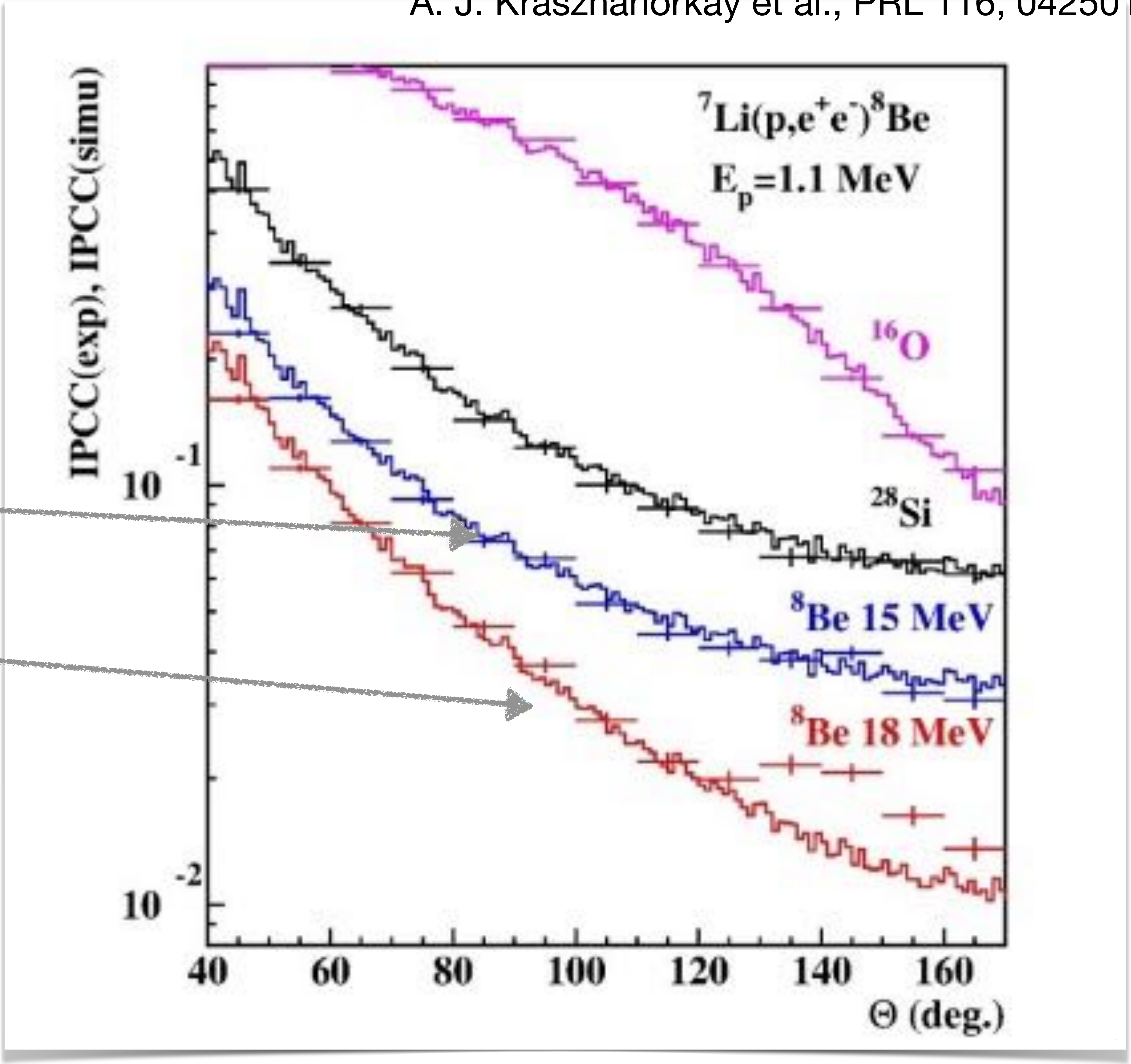
The ATOMKI collaboration reported an anomalous (> 5σ) excess in the internal pair production in ^{8}Be de-excitation at large angles.



isovector (ΔT=1)

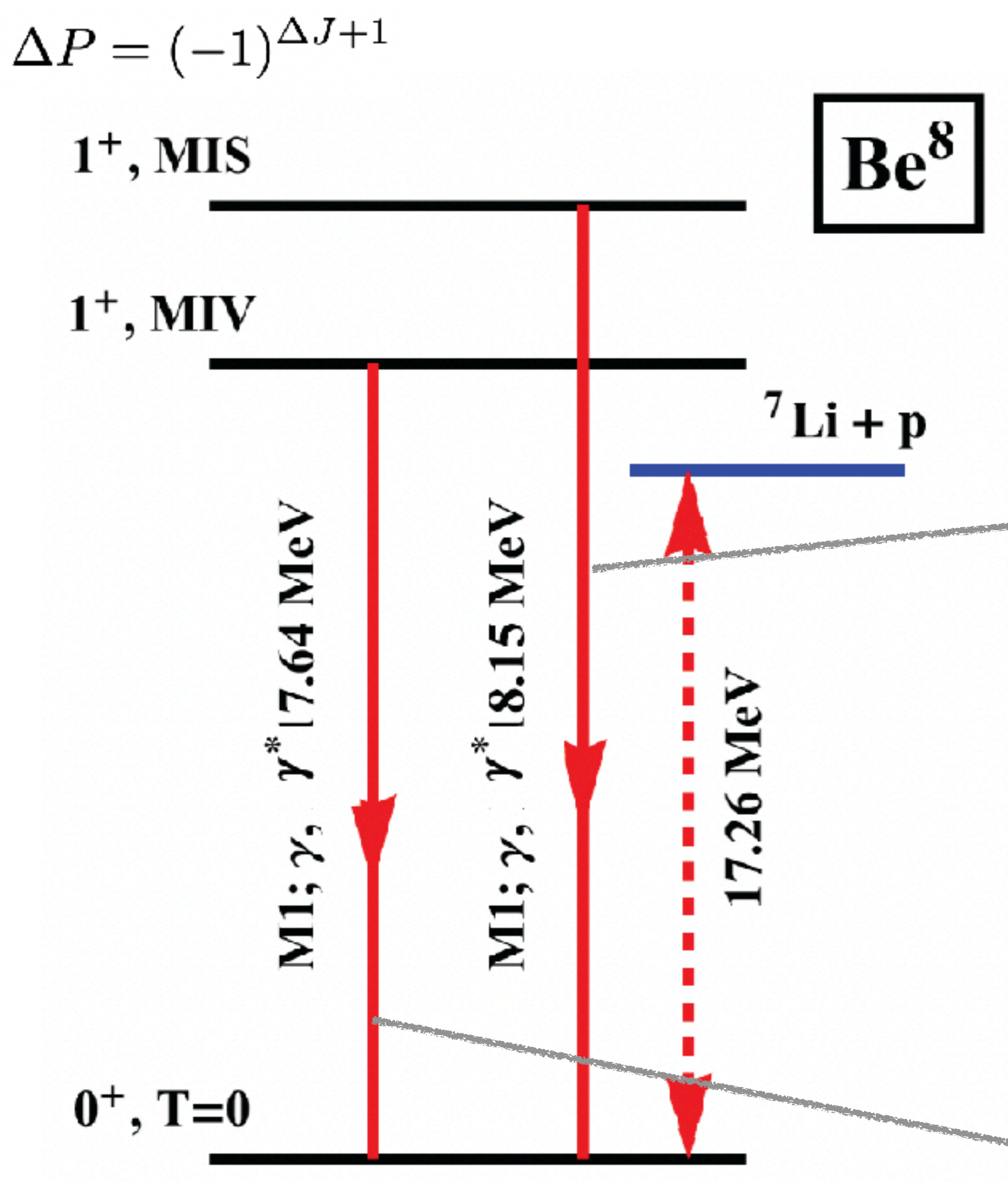
isoscaler (ΔT=0)

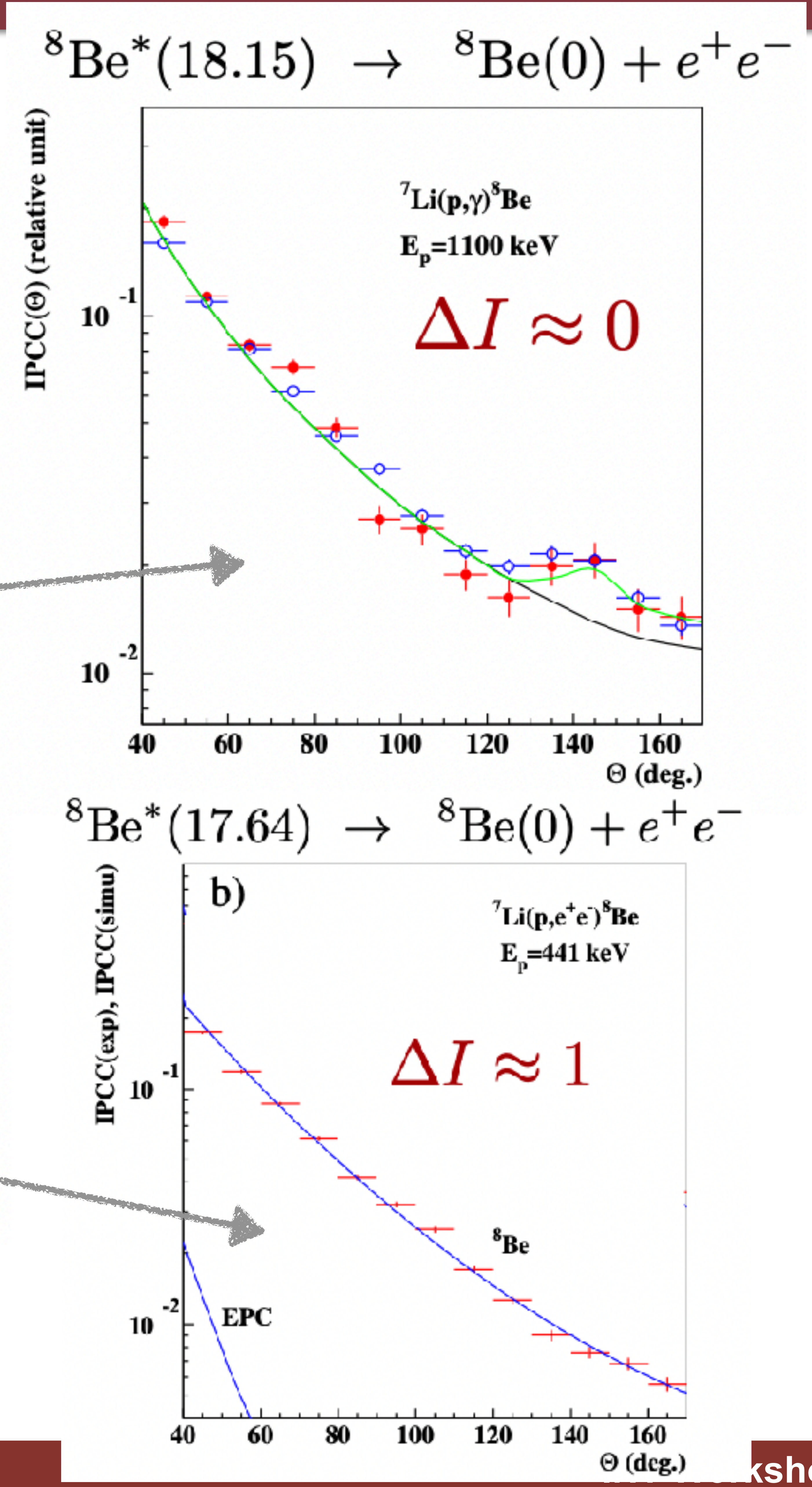
A. J. Krasznahorkay et al., PRL 116, 042501 (2016)



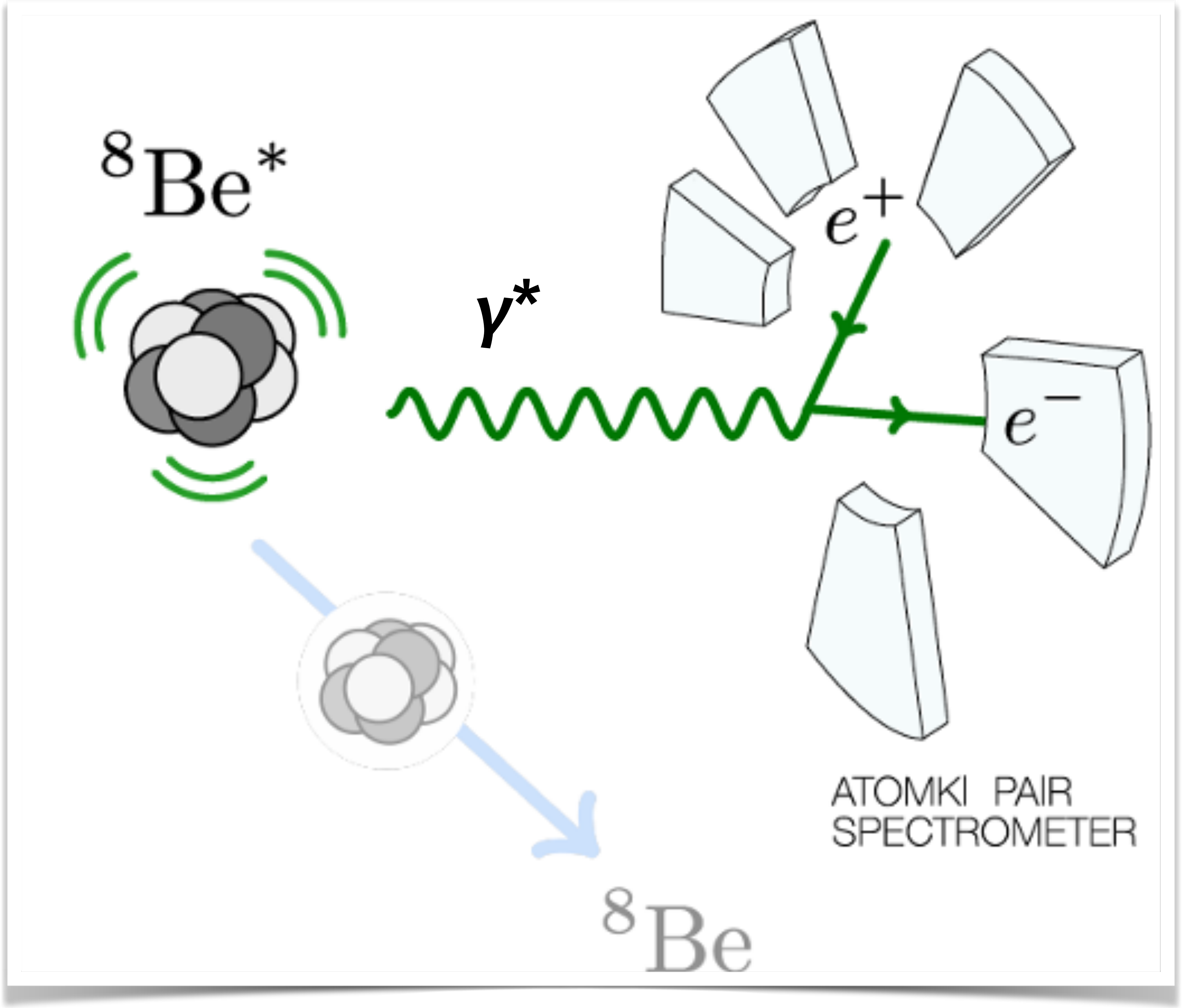
images courtesy of ATOMKI collaboration

The ATOMKI collaboration has since confirmed their results in a new improved setup





A. J. Krasznahorkay et al., PRL 116, 042501 (2016)

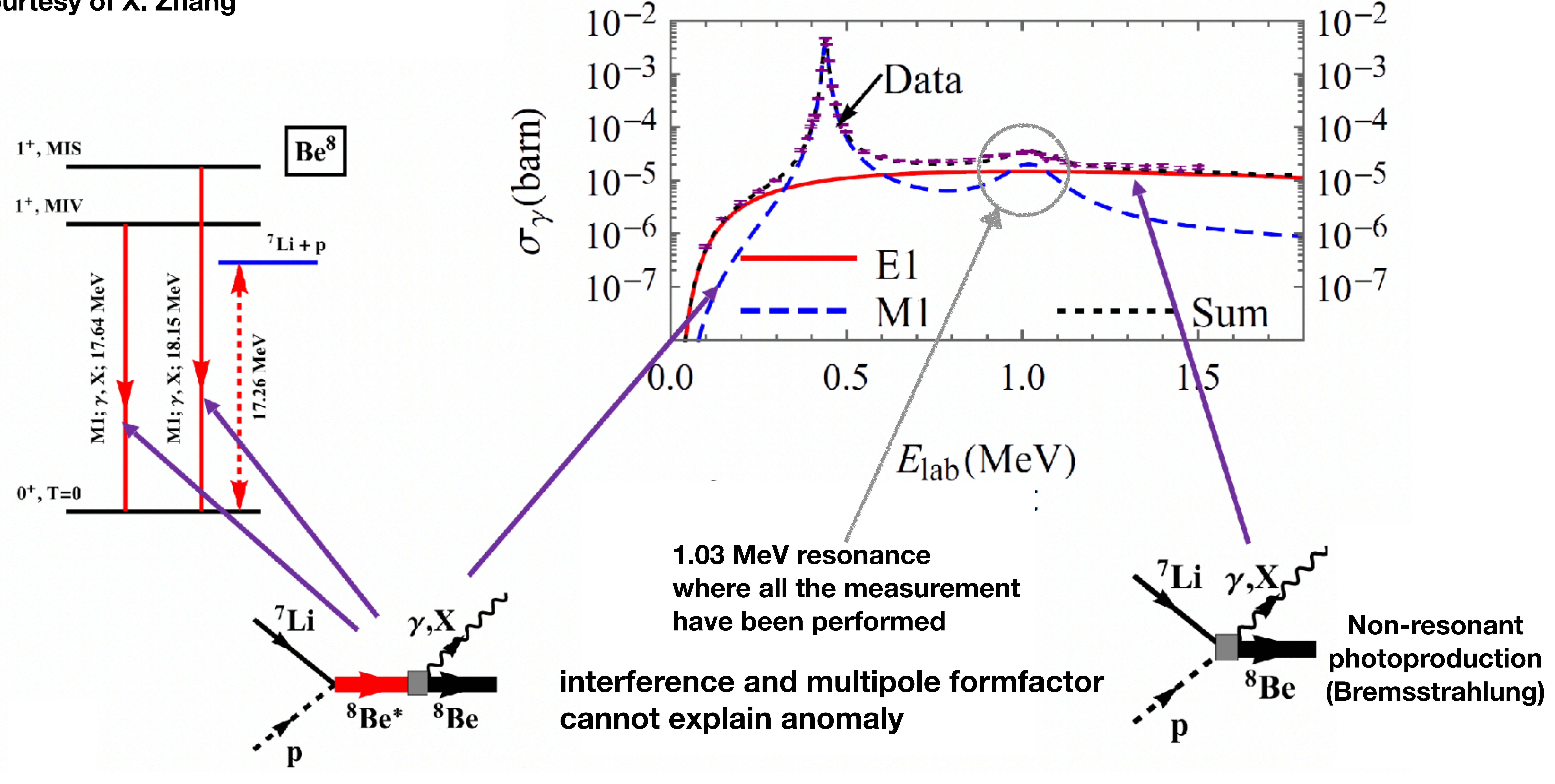


images courtesy of ATOMKI collaboration

Nuclear Physics possibilities such as kinematic interference between E1 and M1 transitions have been ruled out.

images courtesy of X. Zhang

X. Zhang & G. A. Miller, PLB 813, 136061 (2021)



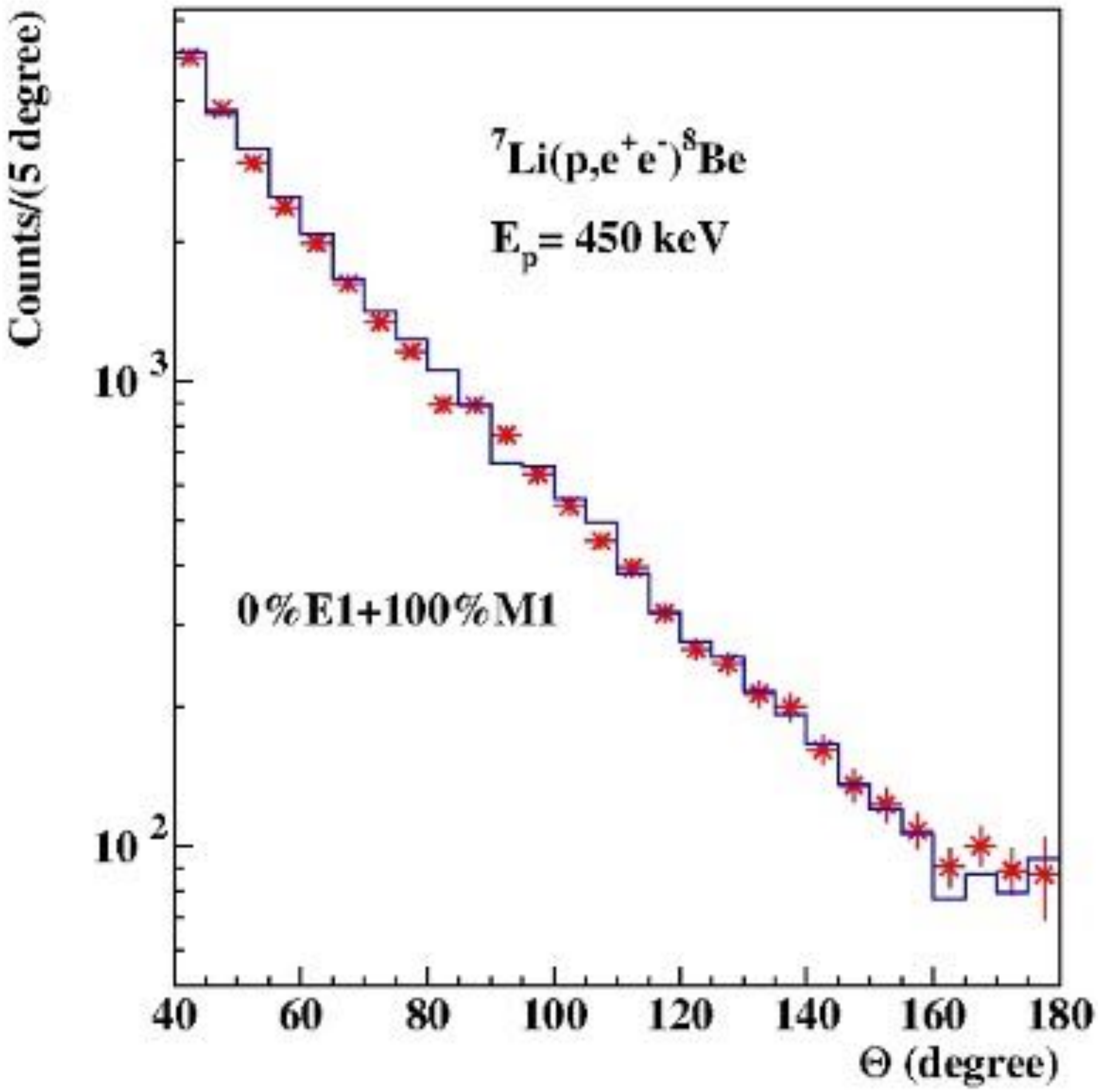
1.03 MeV resonance where all the measurement have been performed

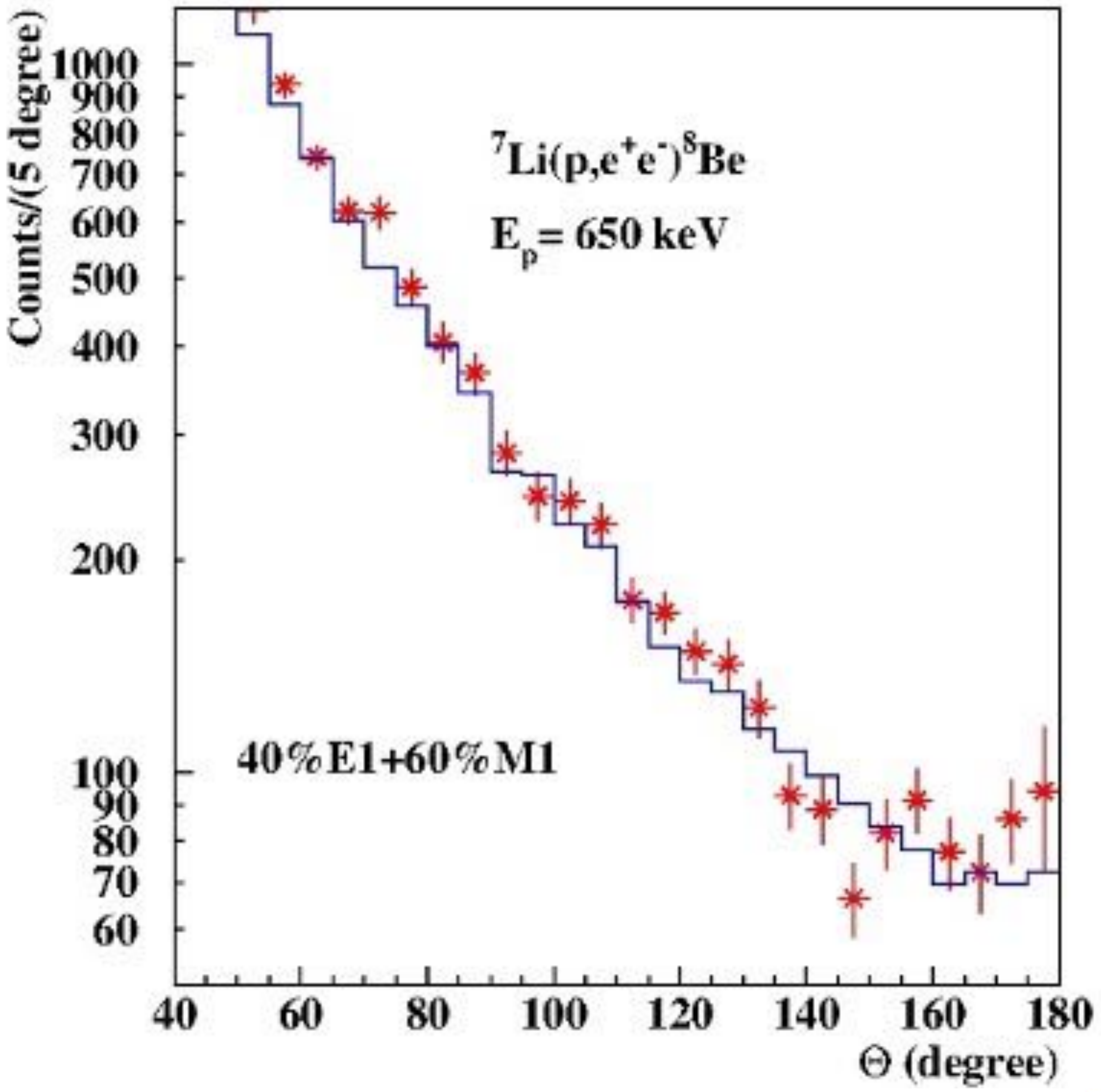
interference and multipole formfactor cannot explain anomaly

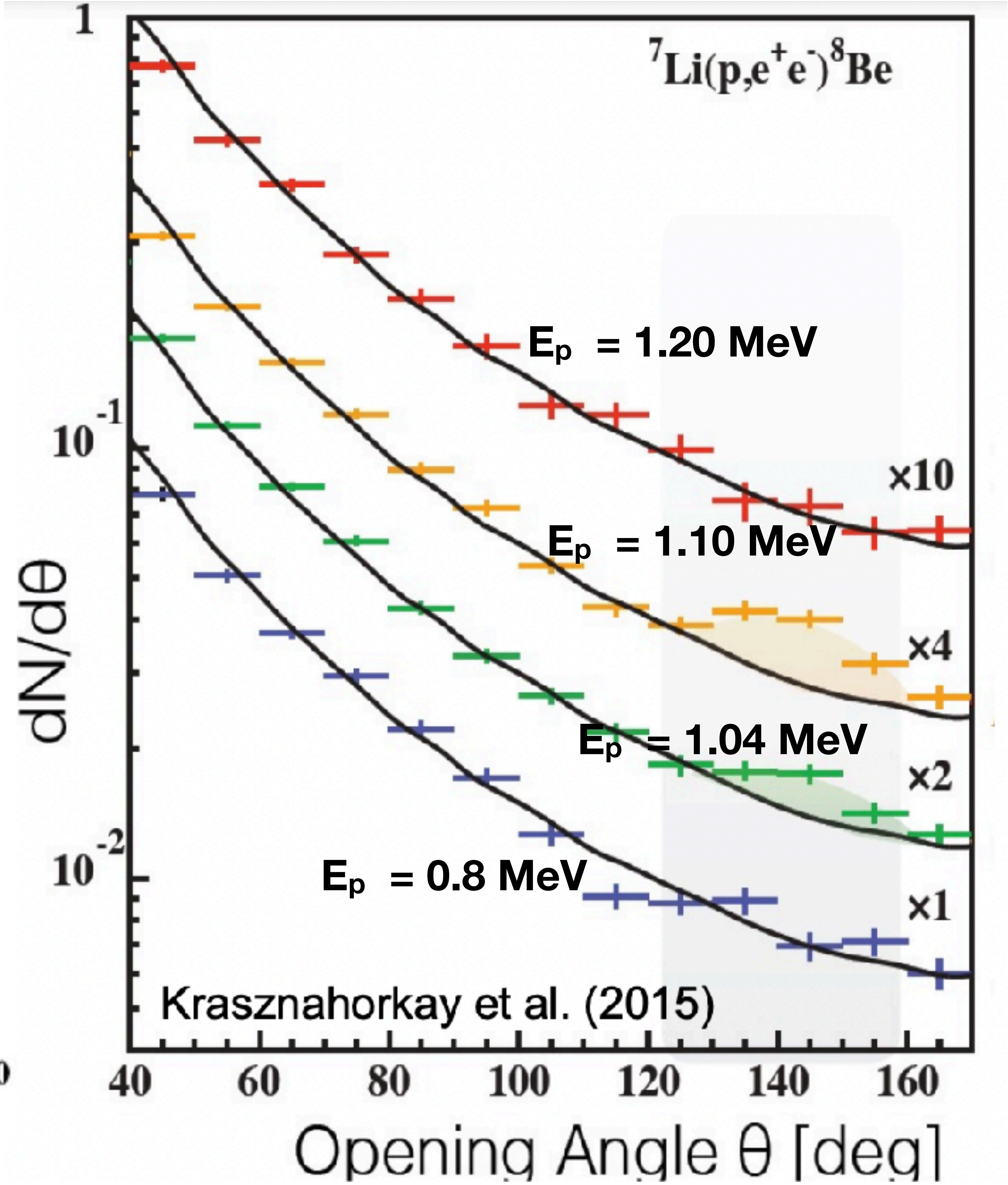
Non-resonant photoproduction (Bremsstrahlung)

Nuclear Physics possibilities such as kinematic interference between E1 and M1 transitions would produce peak at all energies.

interference and multipole formfactor cannot explain anomaly





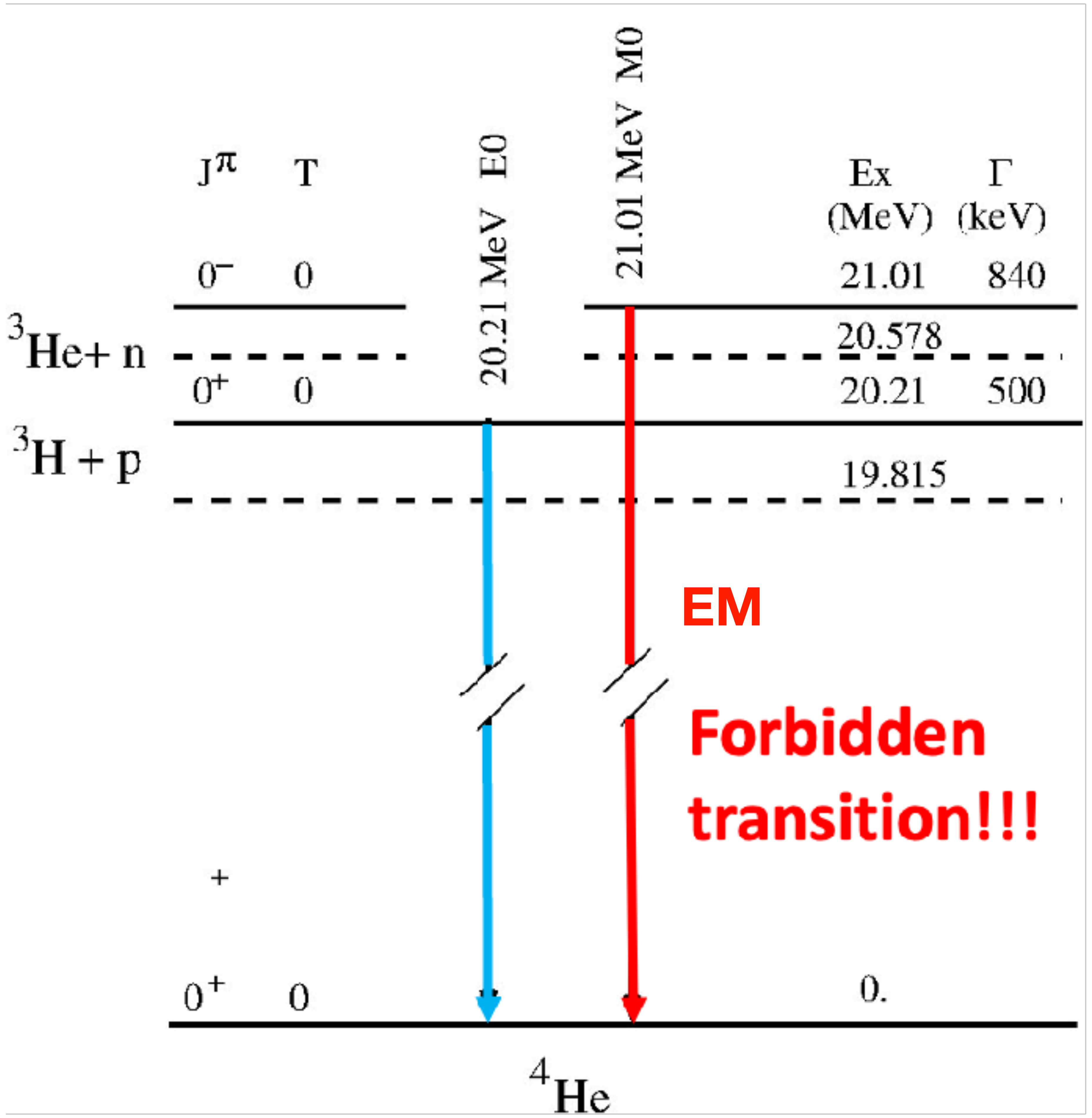


images courtesy of ATOMKI Collaboration

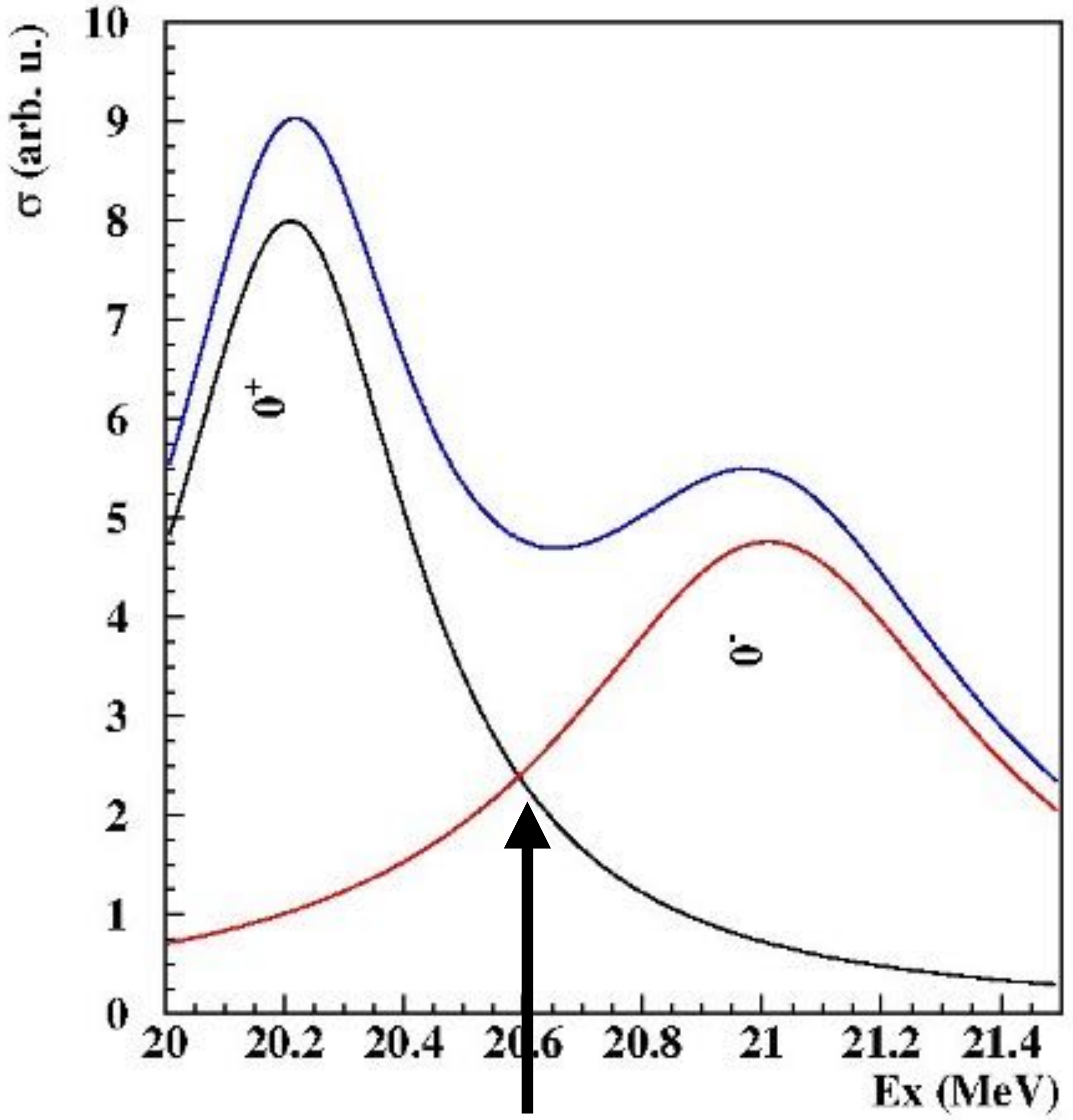
The ATOMKI collaboration has reported a > 6.5σ anomaly in $^3H(p,e^+e^-)^4He$ in the new improved setup

A. J. Krasznahorkay et al., Phys. Rev. C 104, 044003 (2021)

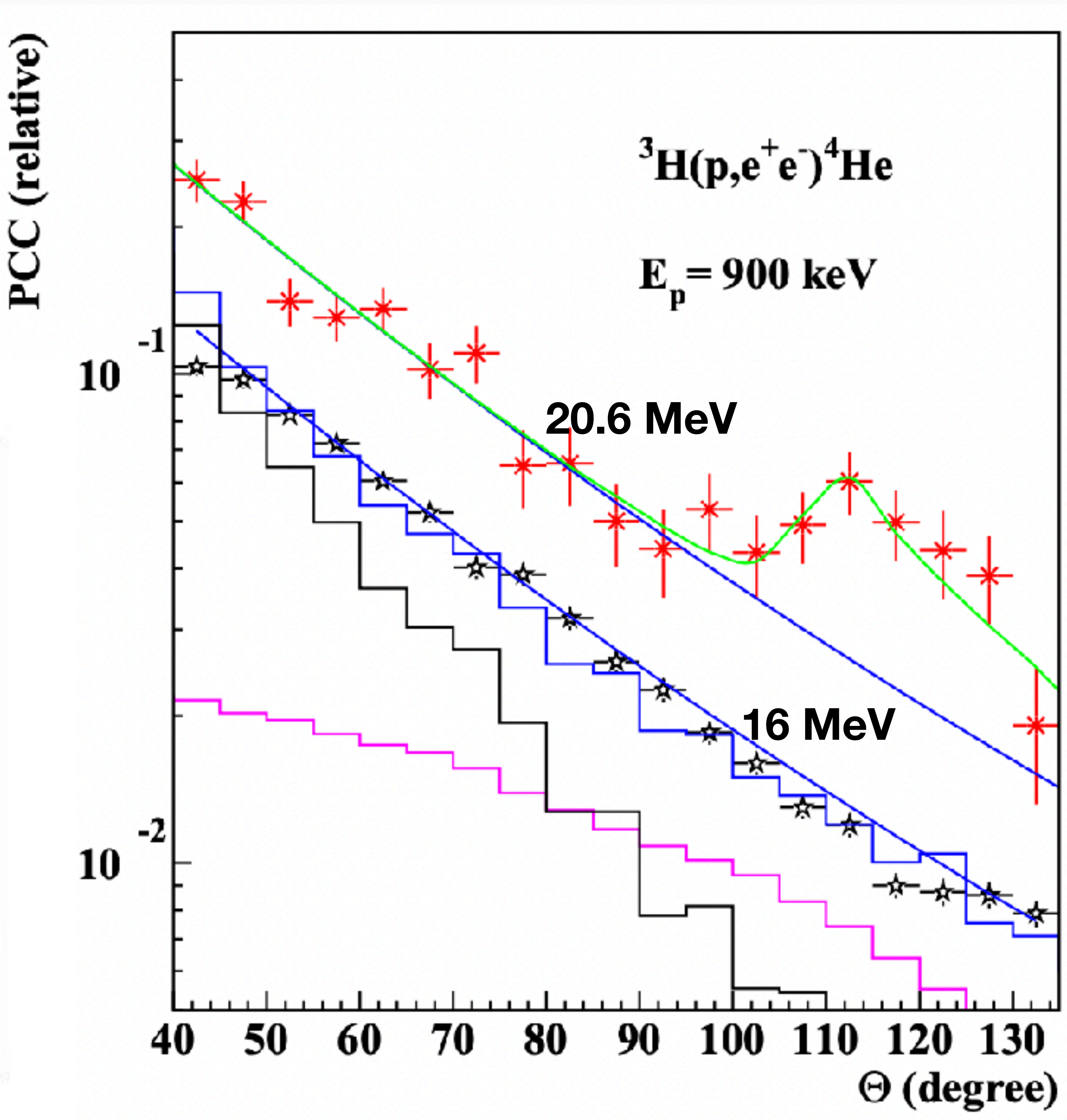
E_p = 0.5, 0.6 and 0.9 MeV to induce radiative capture and to populate the overlapping $J^\pi = 0^+$ first, and $J^\pi = 0^-$ second excited states in ^4He



γ ray production from direct proton capture

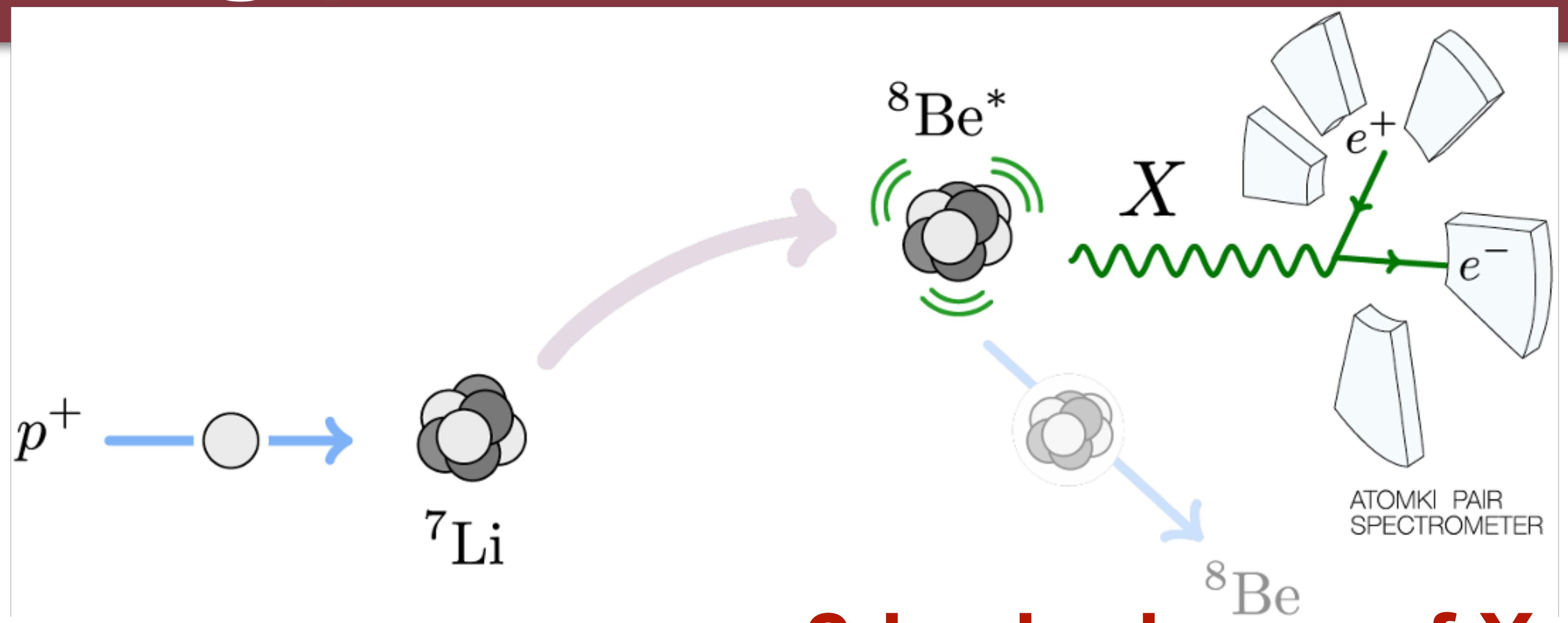


measurement energy: to stay below (p,n) threshold

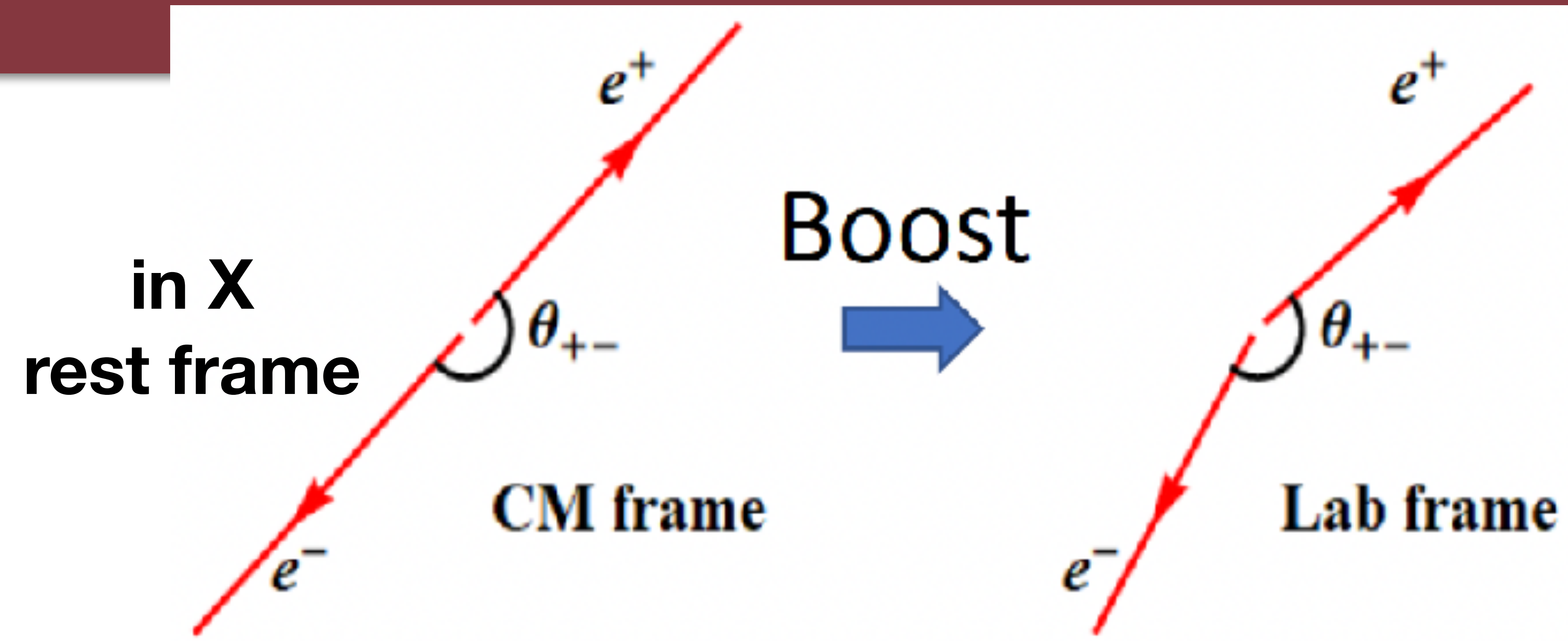


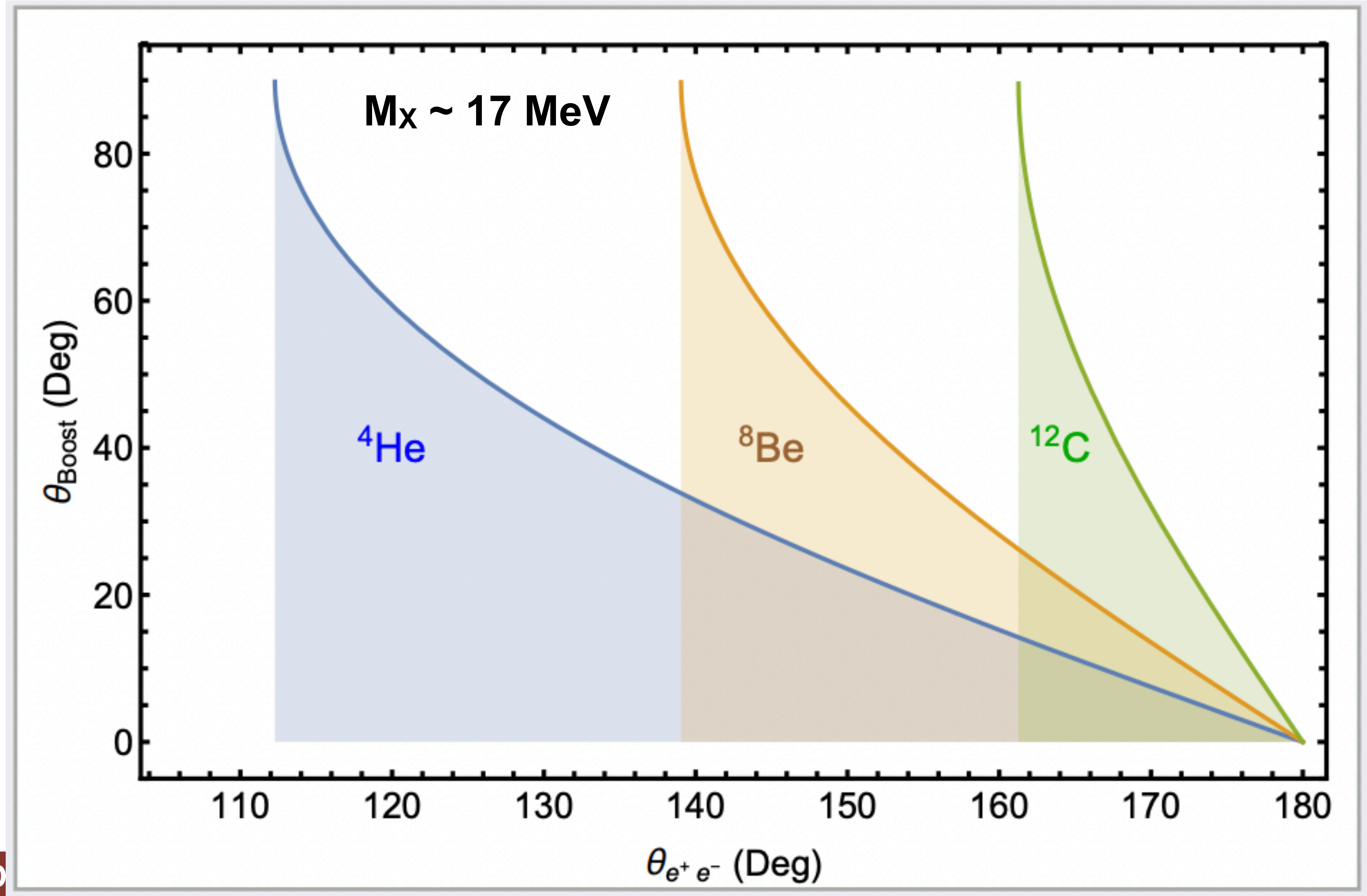
images courtesy of ATOMKI collaboration

The ATOMKI anomaly introduced the possibility of a new 17 MeV weakly interacting particle

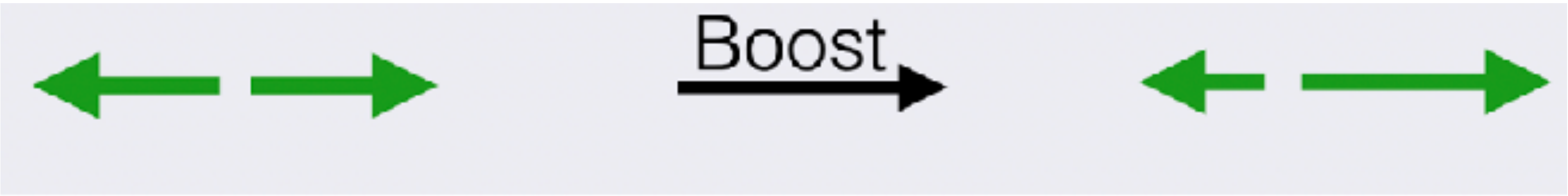


2-body decay of X

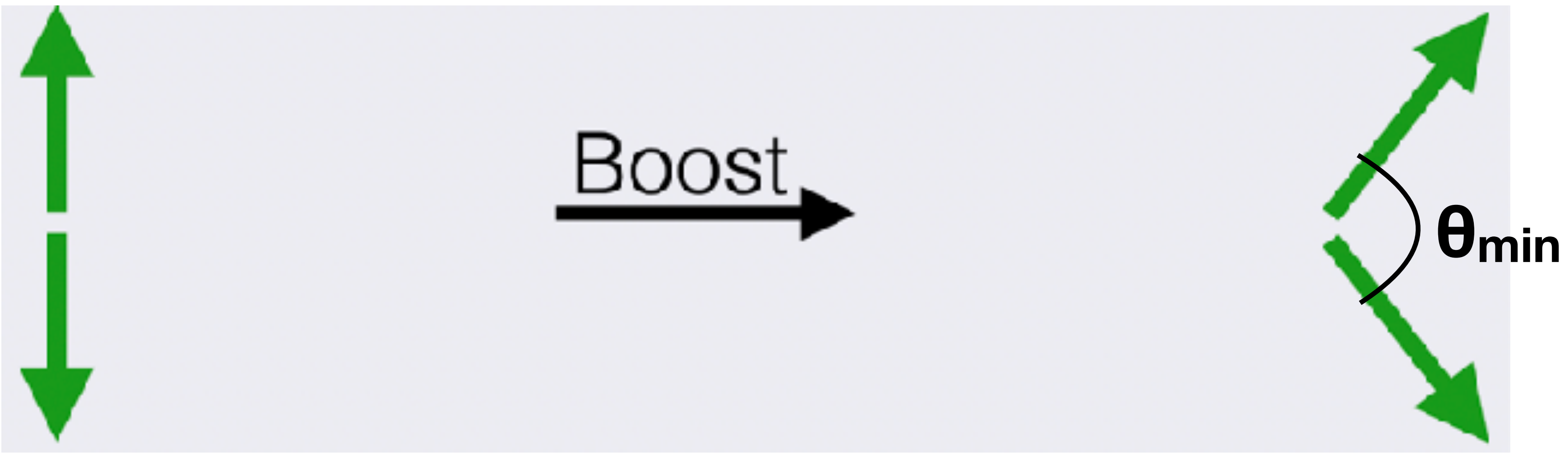




θ along X — opening angle = 180



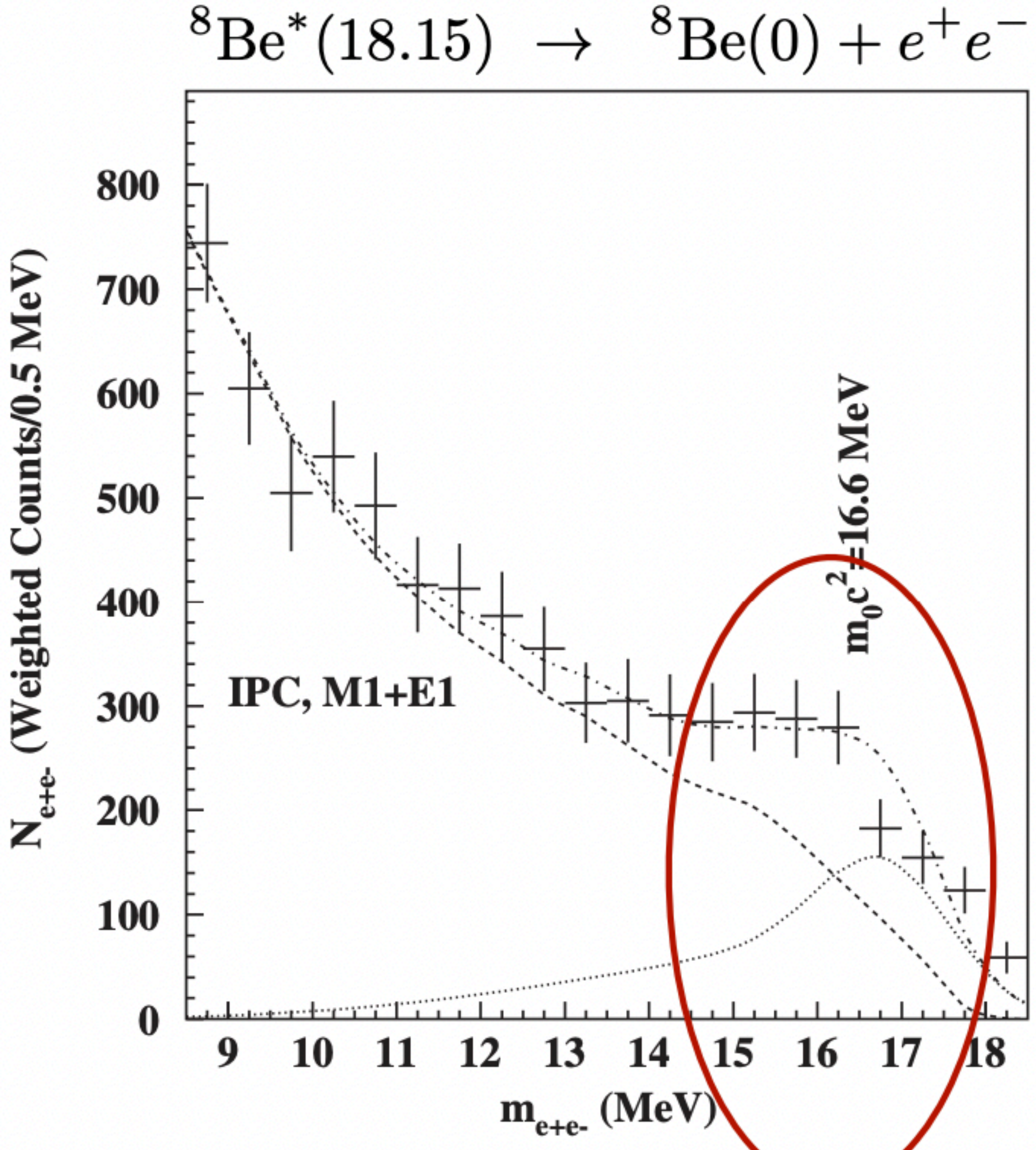
θ transverse to X — opening angle = θ_{min}



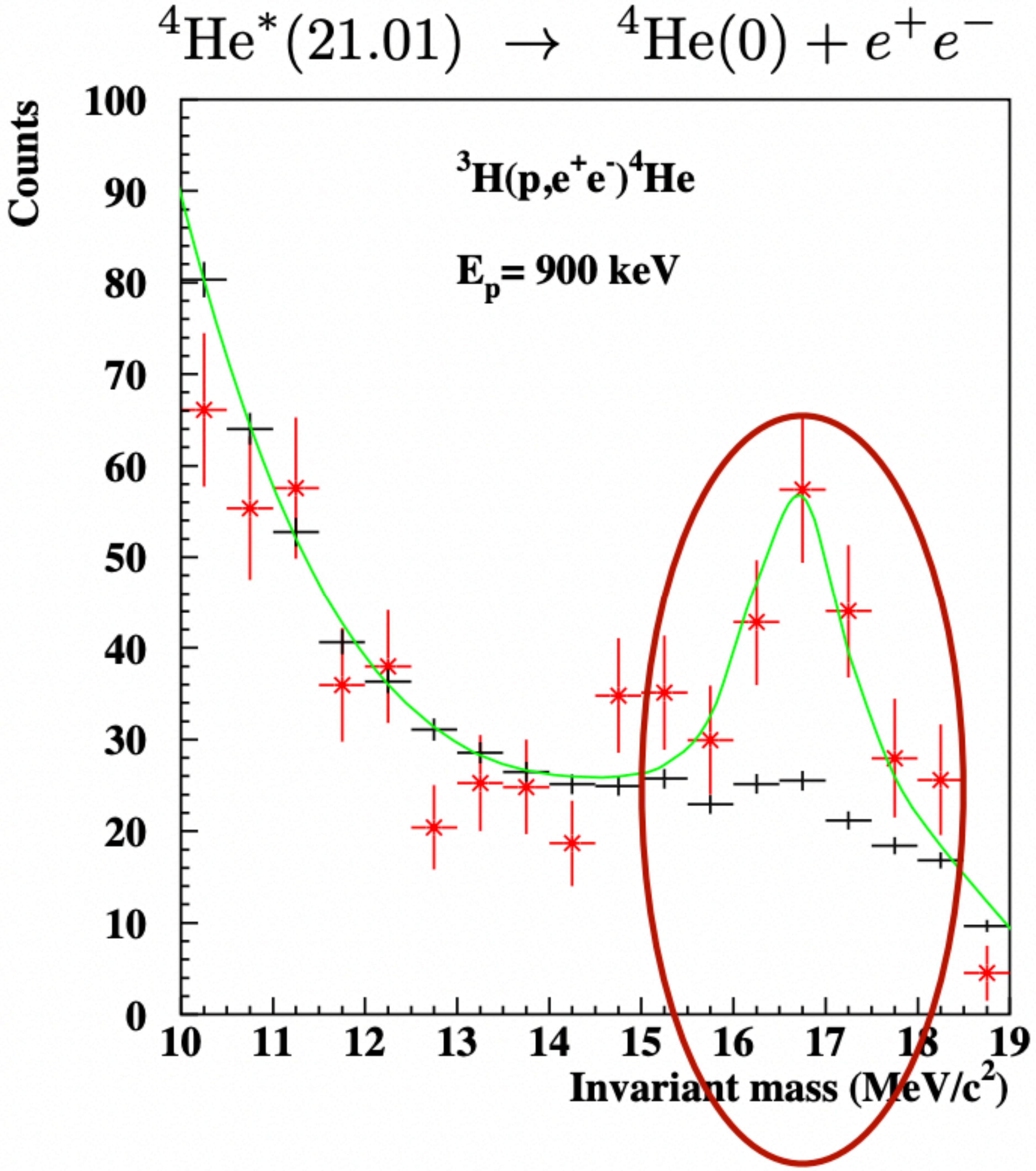
in lab frame the angular distribution peaks towards θ_{min}

plot from talk by T. Tait

The ATOMKI anomaly introduced the possibility of a new 17 MeV weakly interacting particle



Krasznahorkay *et al.*,
PRL **116** (2016)



A. J. Krasznahorkay et al.,
B. Phys. Rev. C 104, 044003 (2021)

The spin and parity of the nuclear decays favor a vector X particle.

For ground state = 0^+

Final state OAM

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

N_* \ X	Scalar 0^+	Pseudoscalar 0^-	Vector 1^-	Axialvector 1^+
^{4}He 0^+	—	S	—	P
^{4}He 0^-	S	—	P	—
^{12}C 1^-	P	—	S, D	P
^{8}Be 1^+	—	P	P	S, D

Assuming parity conserving interaction

EFT calculations of decay widths (new force with range of 12 fm)

J. Feng et al. PRD 95, 035017 (2017)

Nuclear couplings from rate: $\sigma(^8\text{Be}^* \to {}^8\text{Be}\, X)\, \text{BR}(X \to e^+e^-)$

Electron couplings: from limit on decay length (< 1 cm)

For Pseudoscalar X

$$\frac{\Gamma_P^{^8\text{Be}}}{\Gamma_P^{^4\text{He}}} \approx 1.7 \times 10^{-6}$$

experiment ~ 1
(assuming nuclear effects ~ 1)

For Axialvector X

$$\frac{\Gamma_P^{^8\text{Be}}}{\Gamma_P^{^4\text{He}}} \approx 1.8 \times 10^{-2}$$

experiment ~ 1
(assuming nuclear effects ~ 1)

For Vector X

$$\frac{\Gamma_X^{^8\text{Be}}}{\Gamma_\gamma^{^8\text{Be}}}$$ and $$\frac{\Gamma_X^{^4\text{He}}}{\Gamma_{\text{E0}}}$$

consistent with experiment

from photon decay

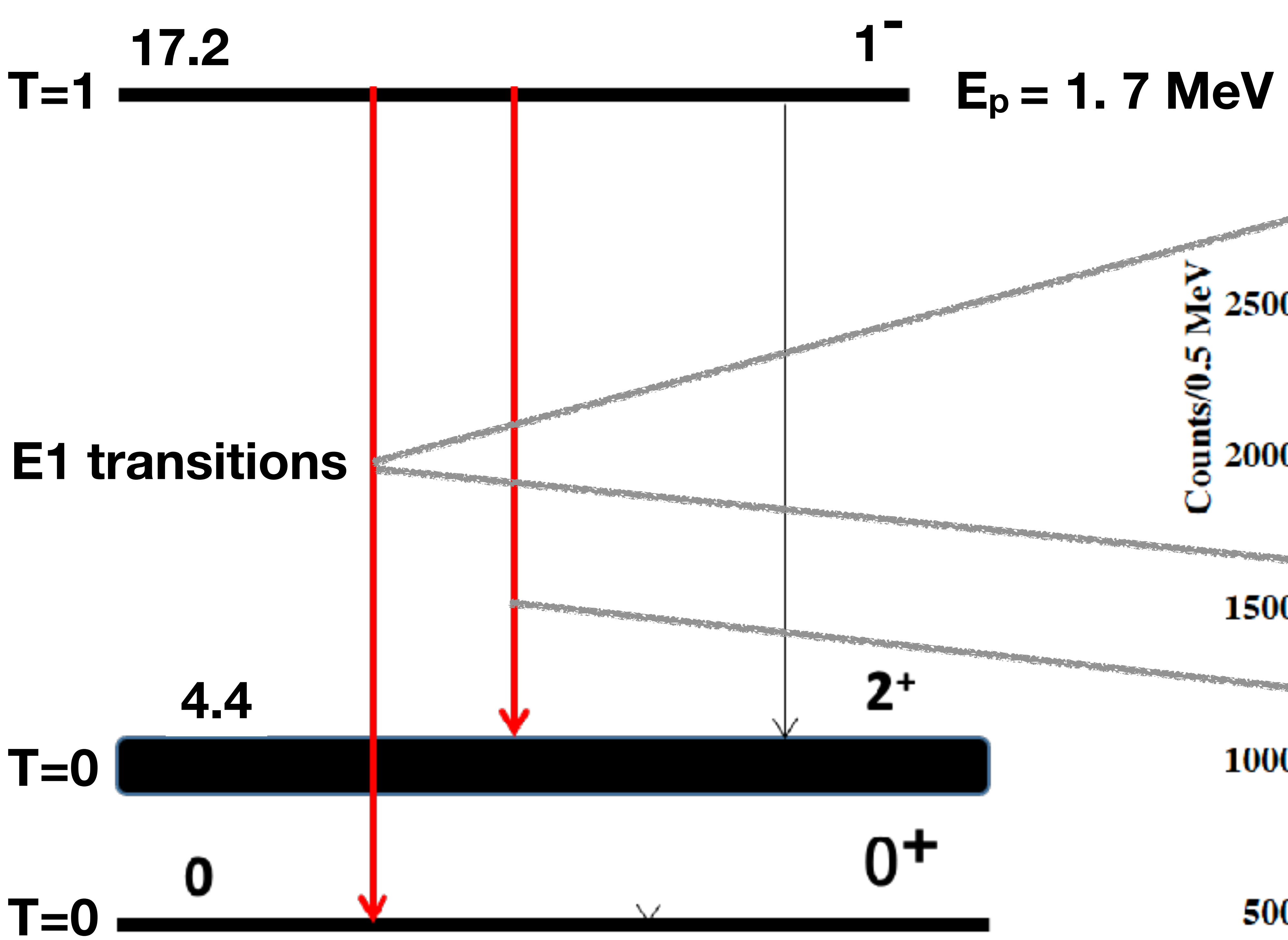
from inelastic e-He scattering

from talk by T. Tait

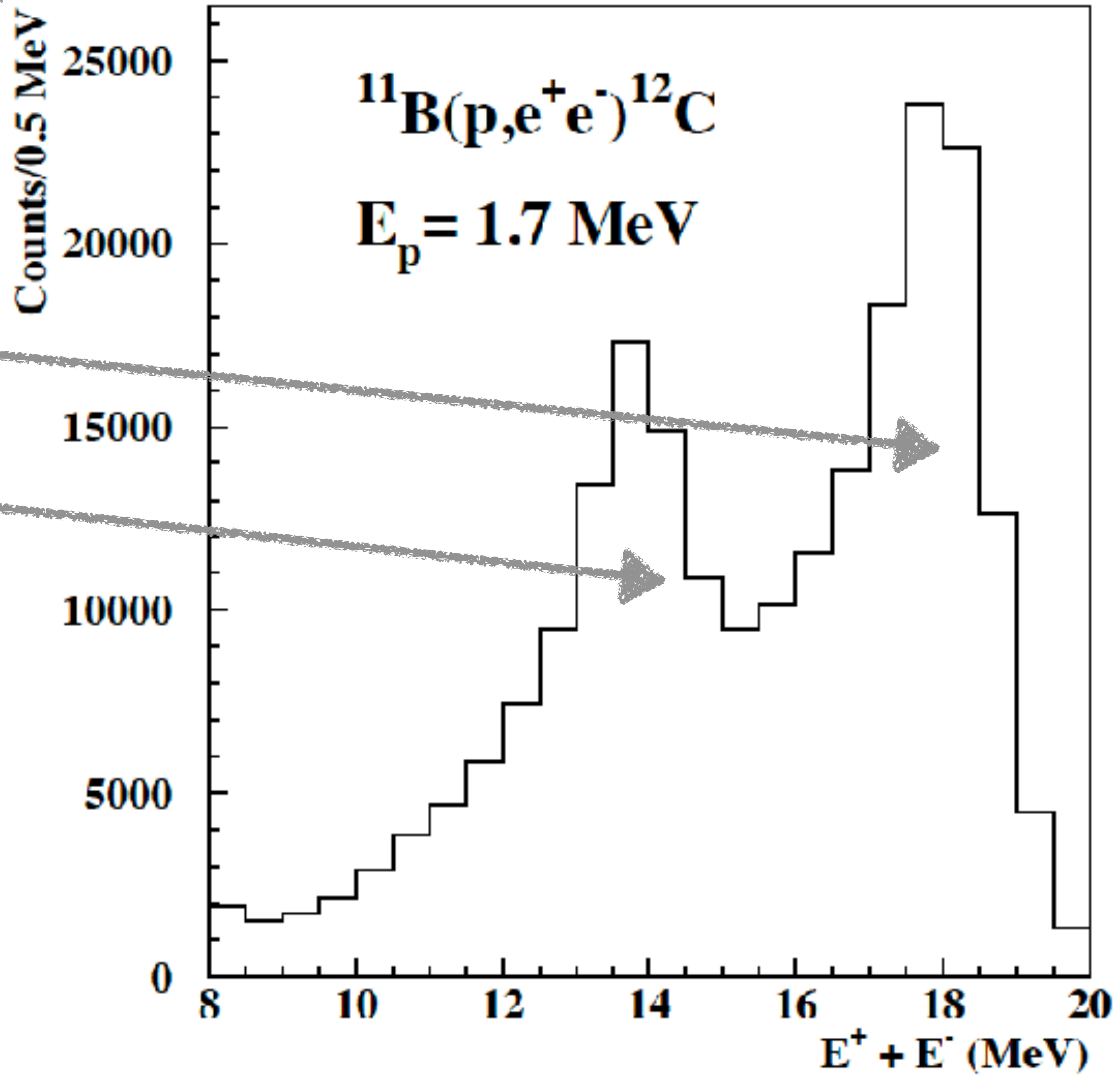
The ATOMKI collaboration recently reported a 6 - 11σ anomaly in $^{11}B(p,e^+e^-)^{12}C$ supporting a vector X17

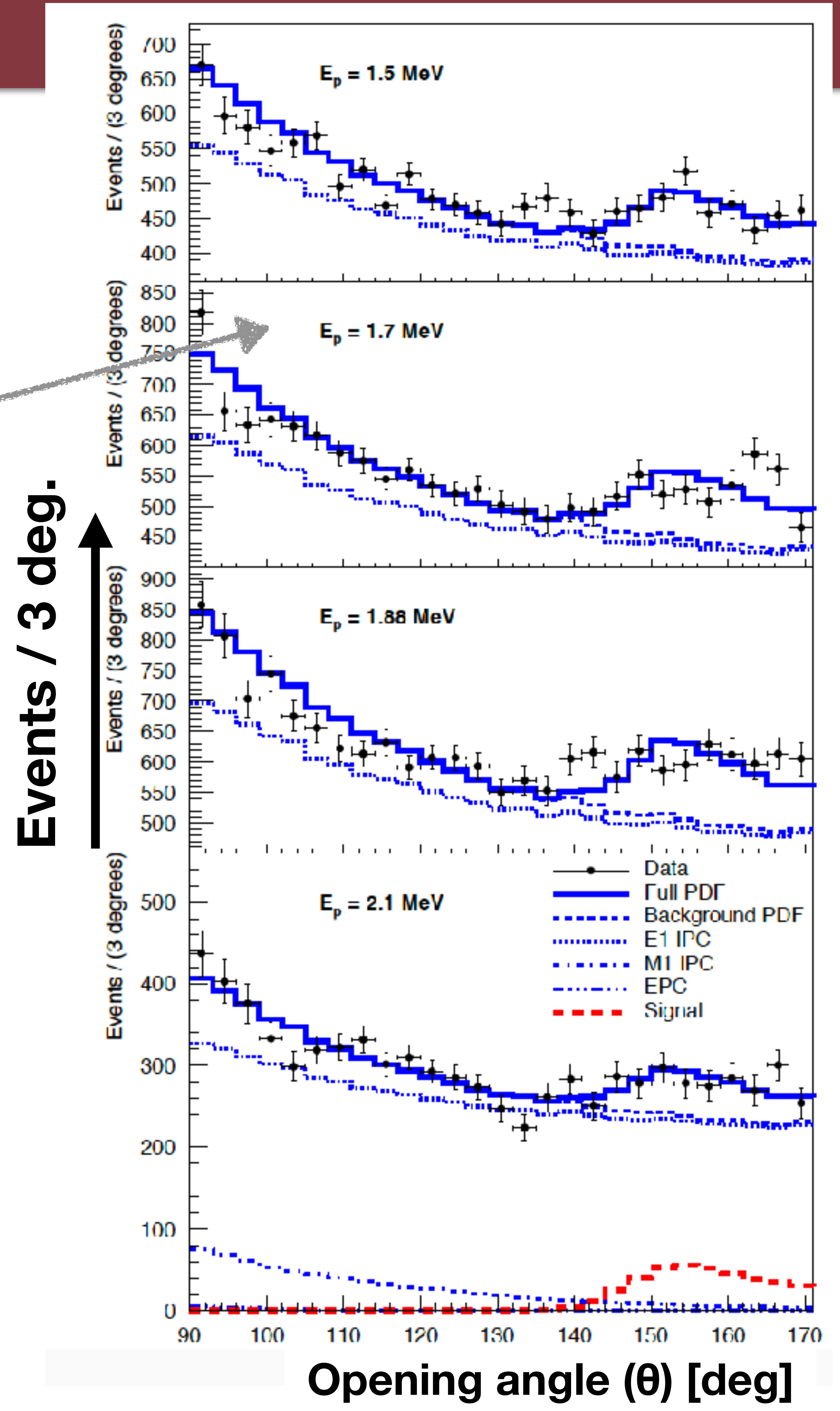
A. J. Krasznahorkay et al., Phys. Rev. C 106, L061601 (2022).

Excitation with the $^{11}B(p,\gamma)^{12}C$ reaction

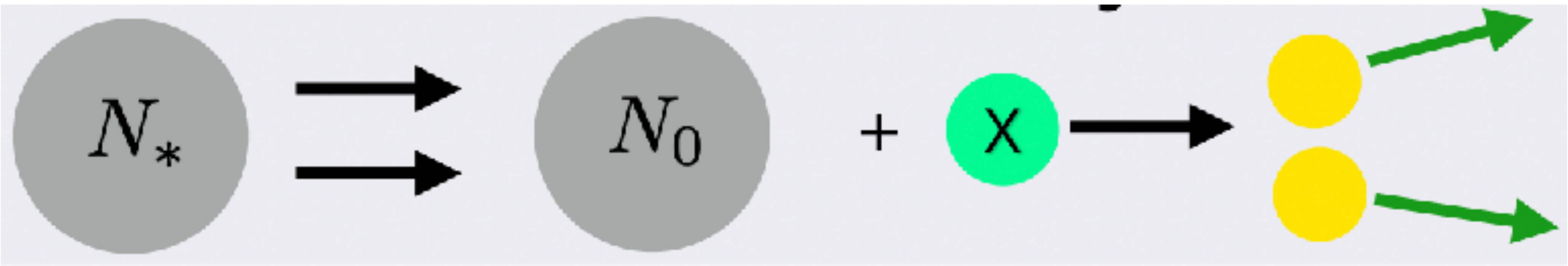


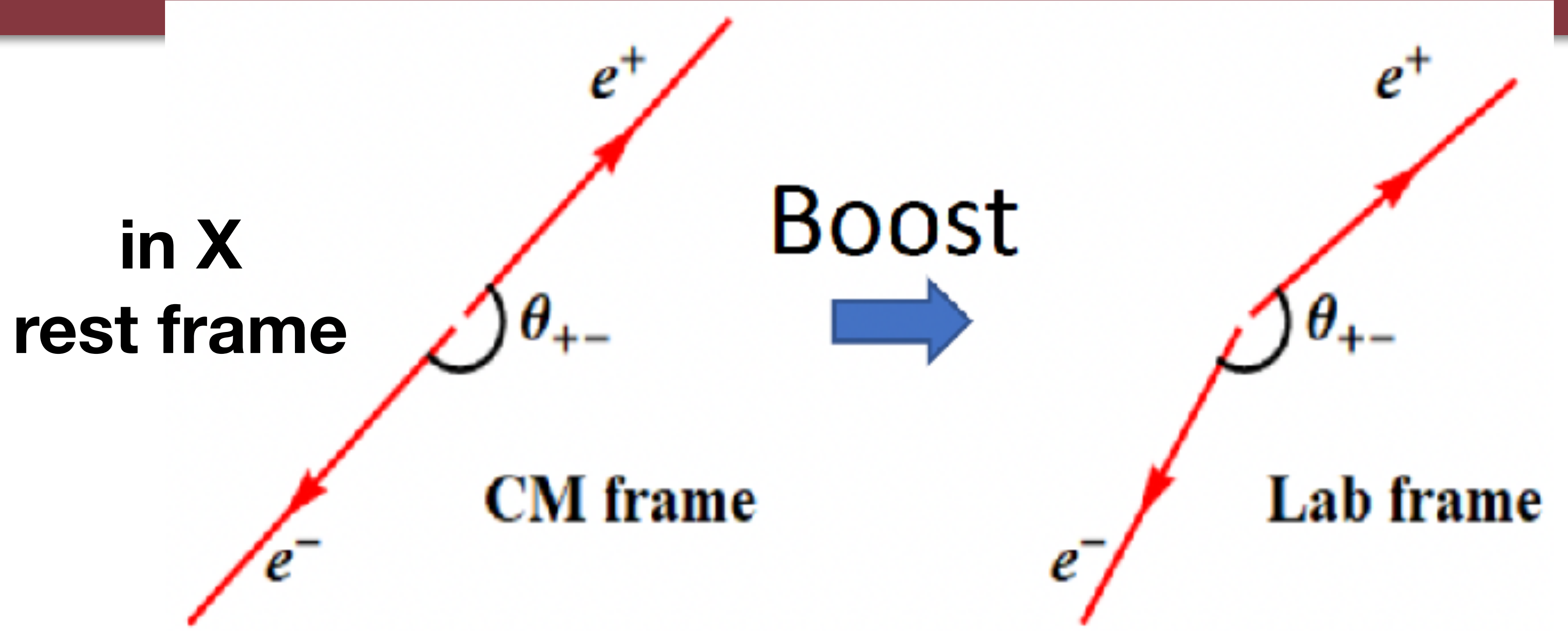
$B(^{12}C + e^+e^-) \approx 3.6(3) \times 10^{-6}$





The ATOMKI anomaly introduces the possibility of a new 17 MeV vector Boson.

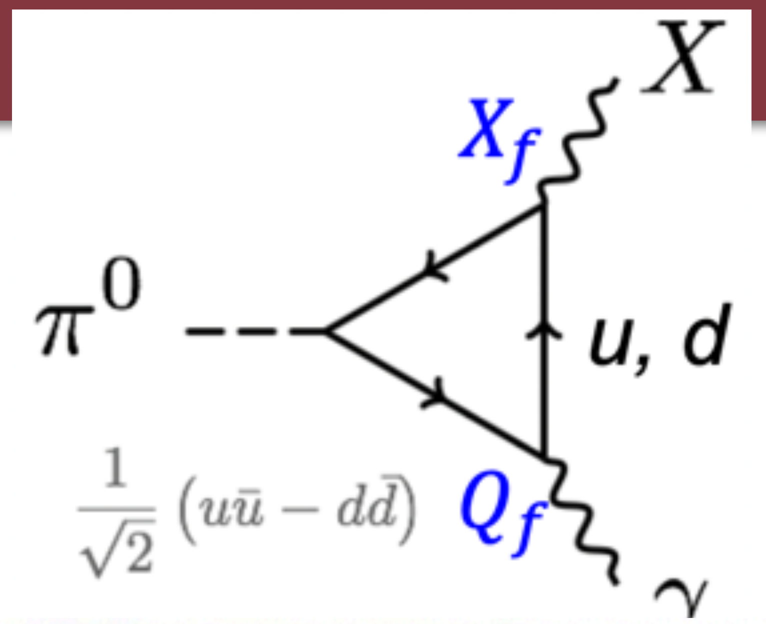




$p+\ A$	$\to$	N_*	E_{beam} (MeV)	m_A (MeV)	m_{N_*} (MeV)	v_{N_*}/c	v_X/c	$\theta_{e^+e^-}^{\text{min}}$
$p+{}^7\text{Li}$	$\to$	${}^8\text{Be}(18.15)$	1.03	6533.83	7473.01	0.0059	0.350	139°
$p+{}^7\text{Li}$	$\to$	${}^8\text{Be}(17.64)$	0.45	6533.83	7472.50	0.0039	0.267	149°
$p+{}^{11}\text{B}$	$\to$	${}^{12}\text{C}(17.23)$	1.40	10252.54	11192.09	0.0046	0.163	161°
$p+{}^3\text{H}$	$\to$	${}^4\text{He}(21.01)$	1.59	2808.92	3748.39	0.0146	0.587	108°
$p+{}^3\text{H}$	$\to$	${}^4\text{He}(20.49)$	0.90	2808.92	3747.87	0.0110	0.557	112°
$p+{}^3\text{H}$	$\to$	${}^4\text{He}(20.21)$	0.52	2808.92	3747.59	0.0084	0.540	115°

from talk by T. Tait

A protophobic 17 MeV gauge boson is consistent with all three results.



Exotic pions decay $\pi^0 \to X\,\gamma \to e^+e^-\,\gamma$ searches by NA48/2 constrains proton coupling

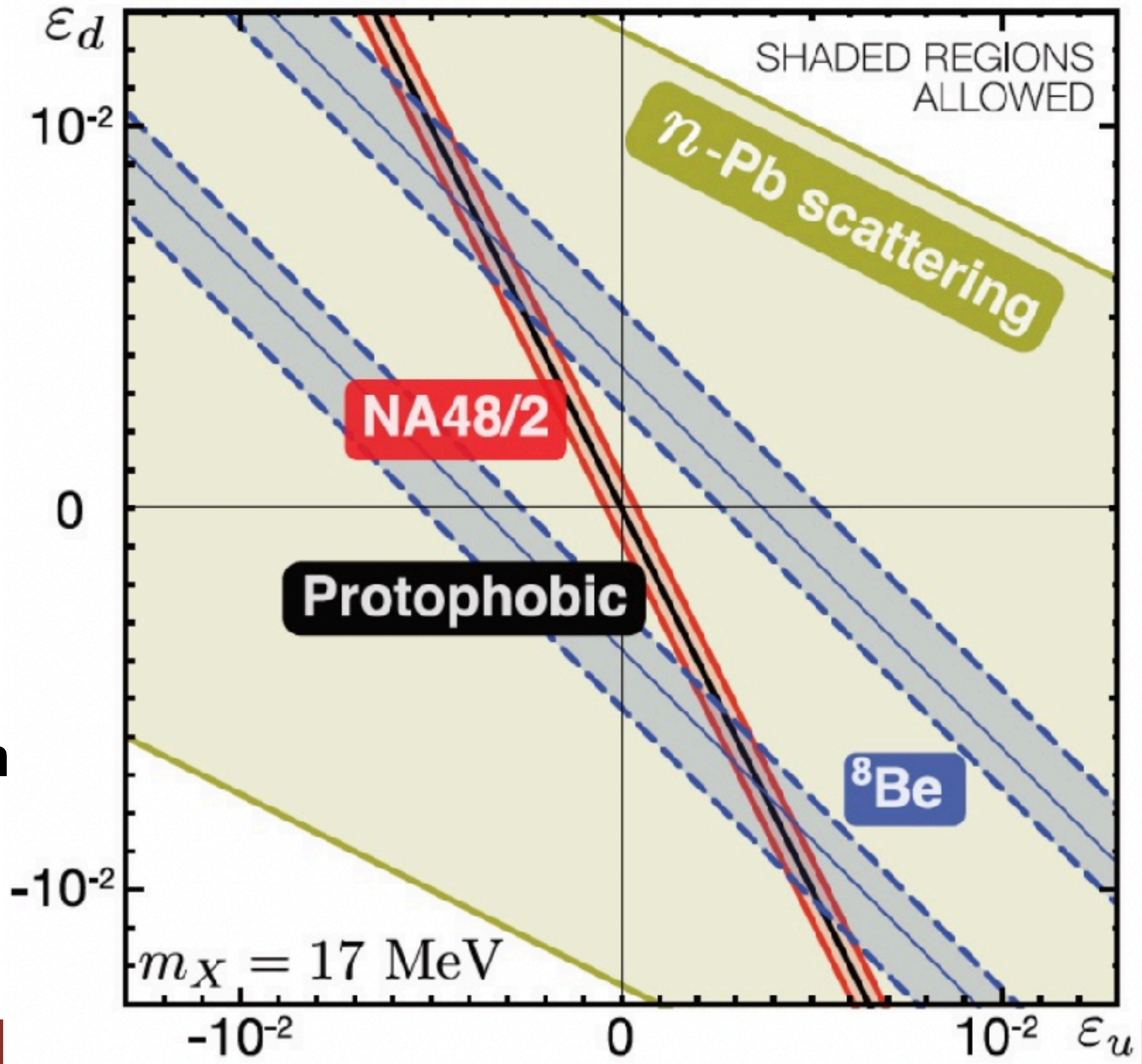
eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$.

$$|\varepsilon_p| < 1.2 \times 10^{-3}$$

Weaker neutron constrained from Lead-neutron scattering

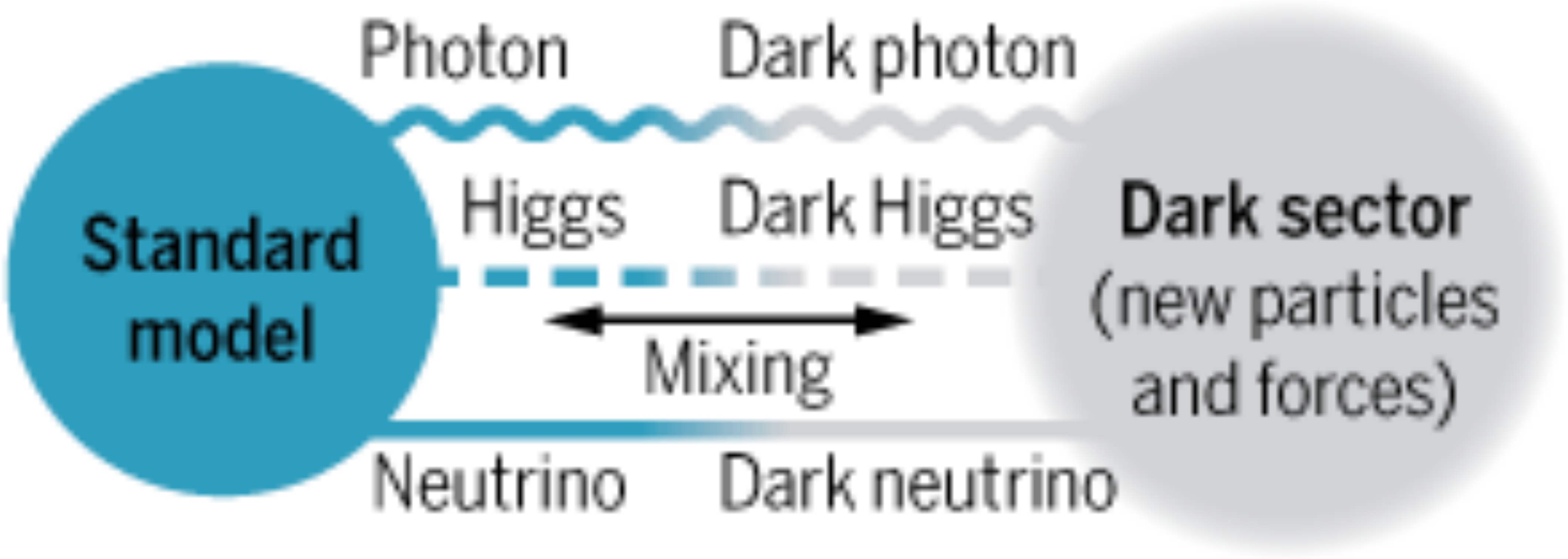
$$|\varepsilon_n| < 2 \times 10^{-2}$$

$10^{-5} < \varepsilon_e$ **for X decay length < 1 cm**



from talk by J. Feng

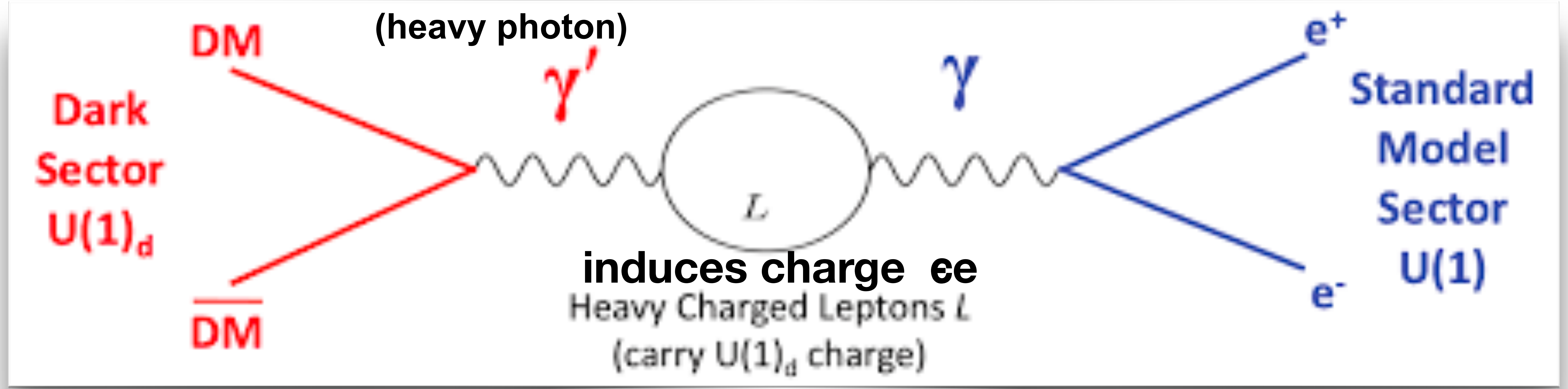
The 17 MeV gauge boson could be a “heavy light” (dark photons)



Hidden sector dark matter
(interacts with SM only through subtle mixing)

B. Holdom, PLB **166** (1986) 196
J. D. Bjorken et al, PRD **80** (2009) 075018

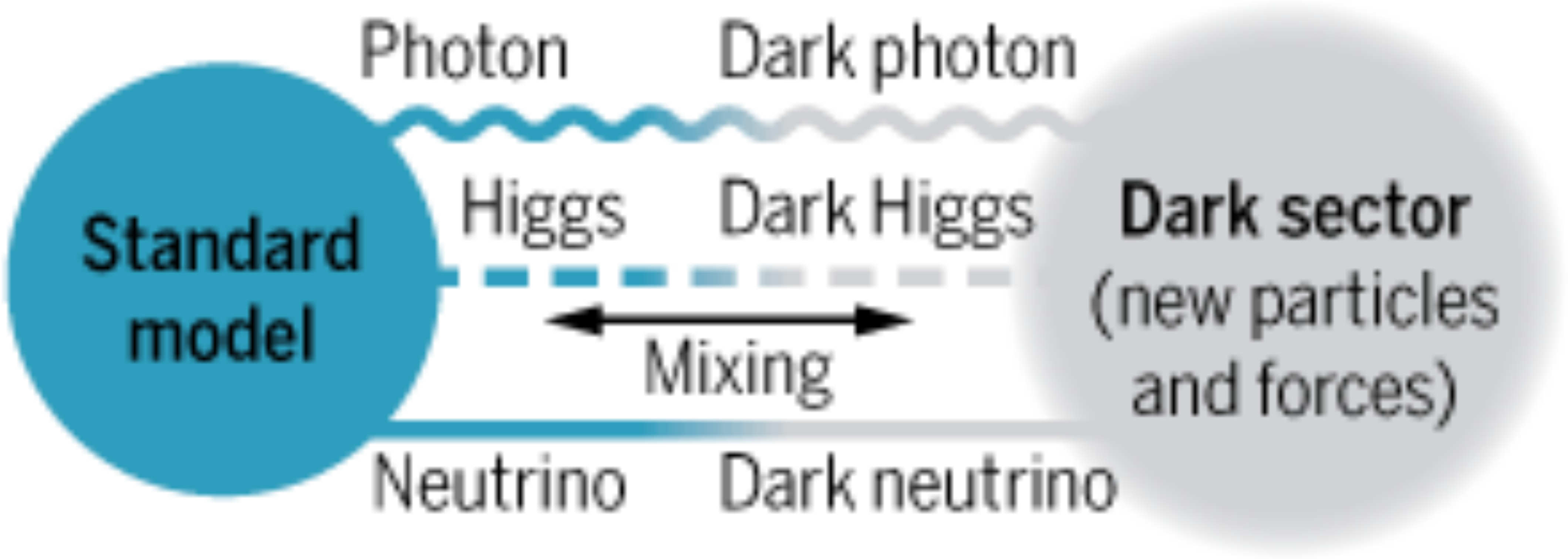
Kinetic mixing between SM & DM could provide a portal to DM



Mixing generated by matter fields with EM charge and dark EM charge, dark photon can have mass.
The coupling (ϵ) is suppressed as it is induced by a loop.

Images courtesy of A. Denis (Mainz)

The 17 MeV gauge boson could be a "heavy light" (dark photons)



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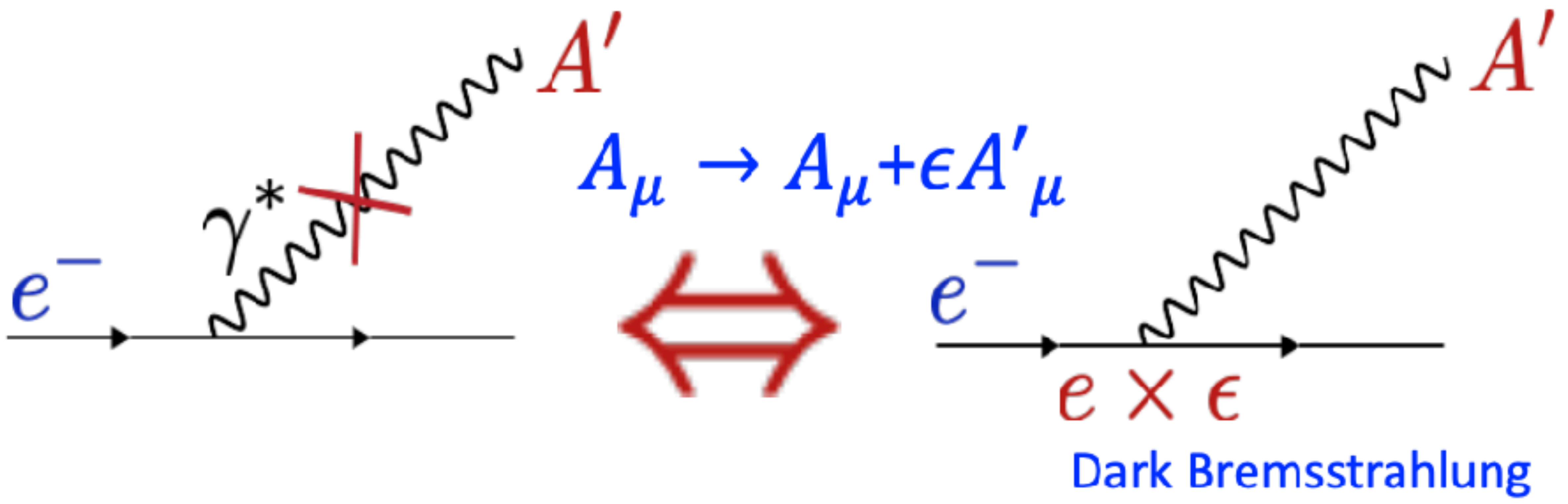
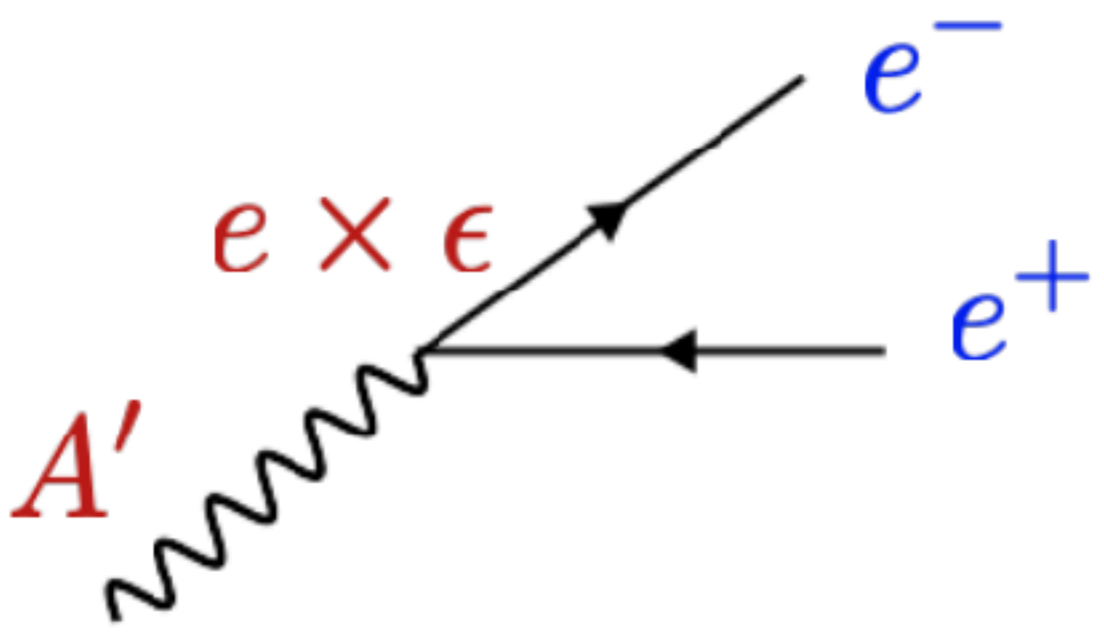


ϵ and $M_{A'}$ are parameters of the theory



in "visible decay" searches

A' will produce pairs :

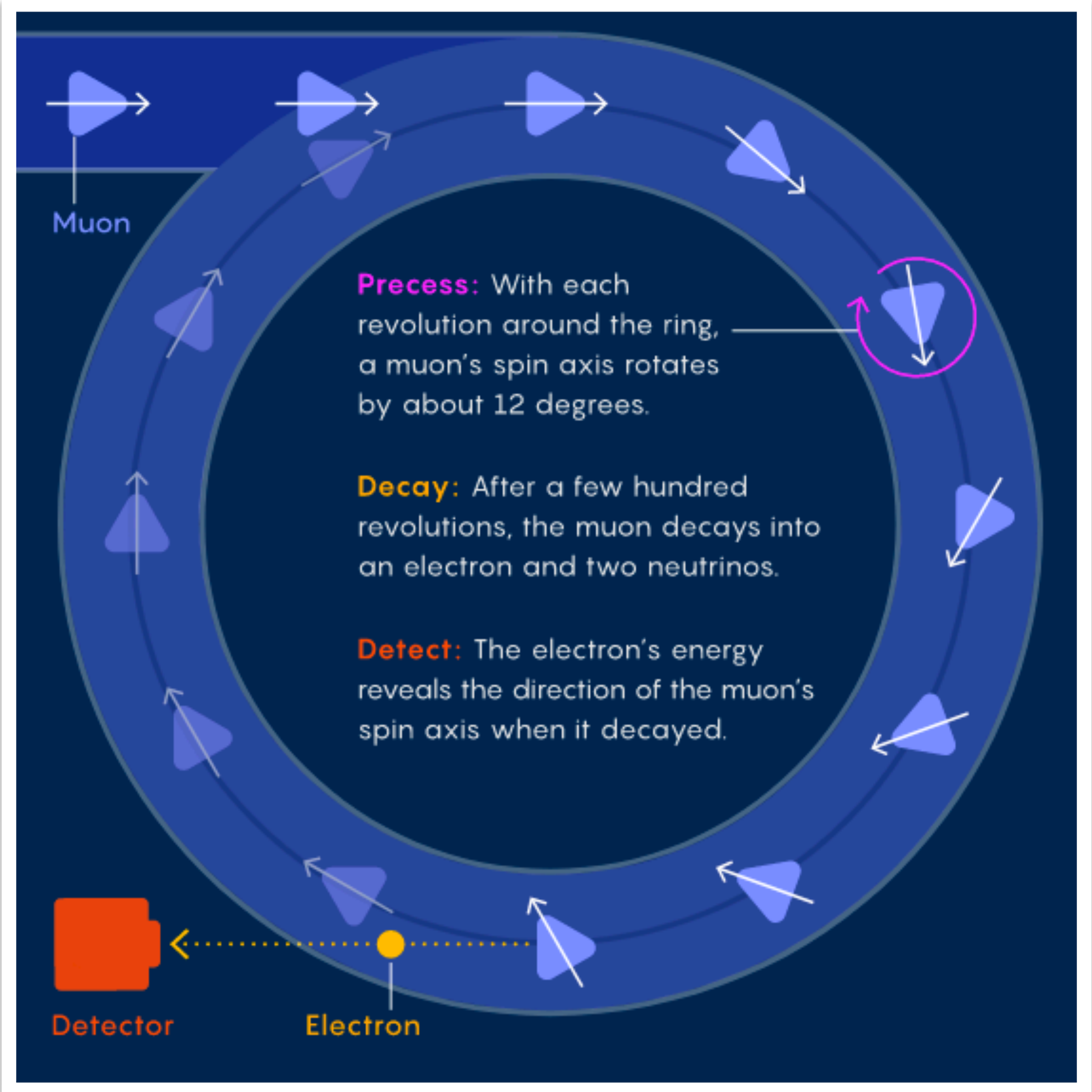
e^+e^-,
$\mu^+\mu^-$,
$\pi^+\pi^-$, ...

photon - dark photon mixing is equivalent to ordinary matter acquiring a milli-charge ϵe

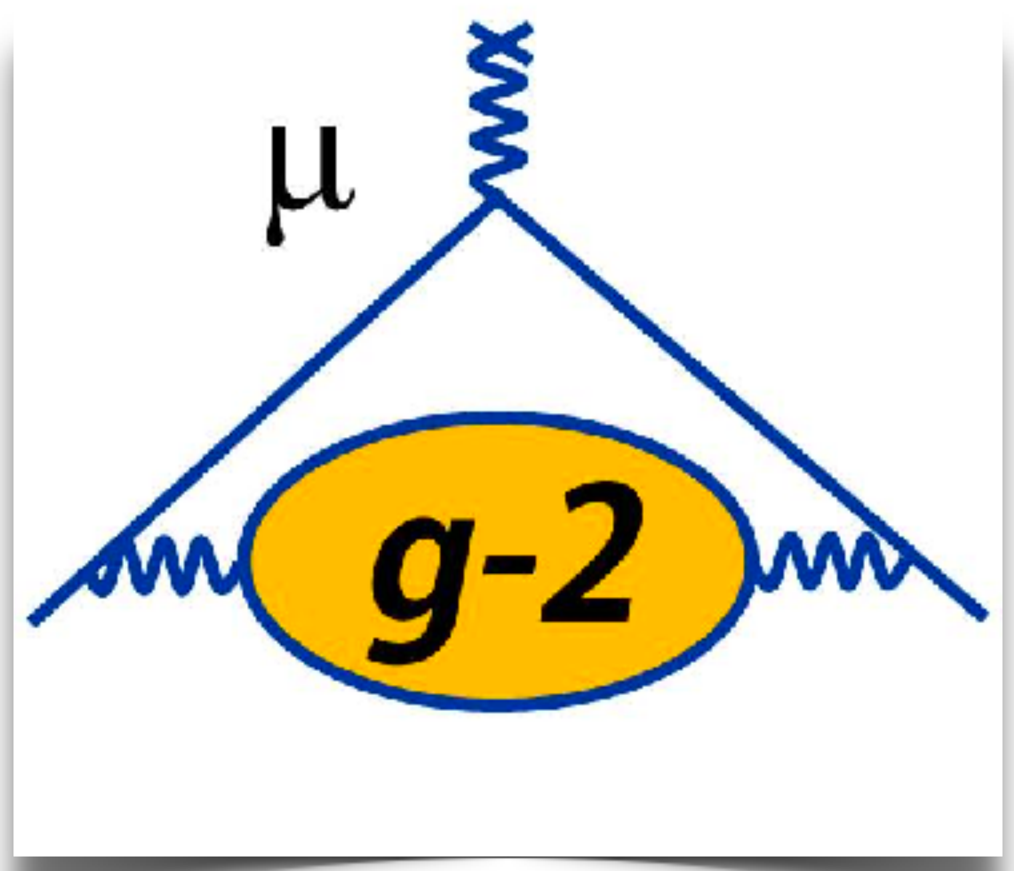
Images courtesy of HPS collaboration

They have been proposed as a possible source of the anomalous muon g-2 observations!

> 4 σ discrepancy between SM prediction and measurement of muon g-2

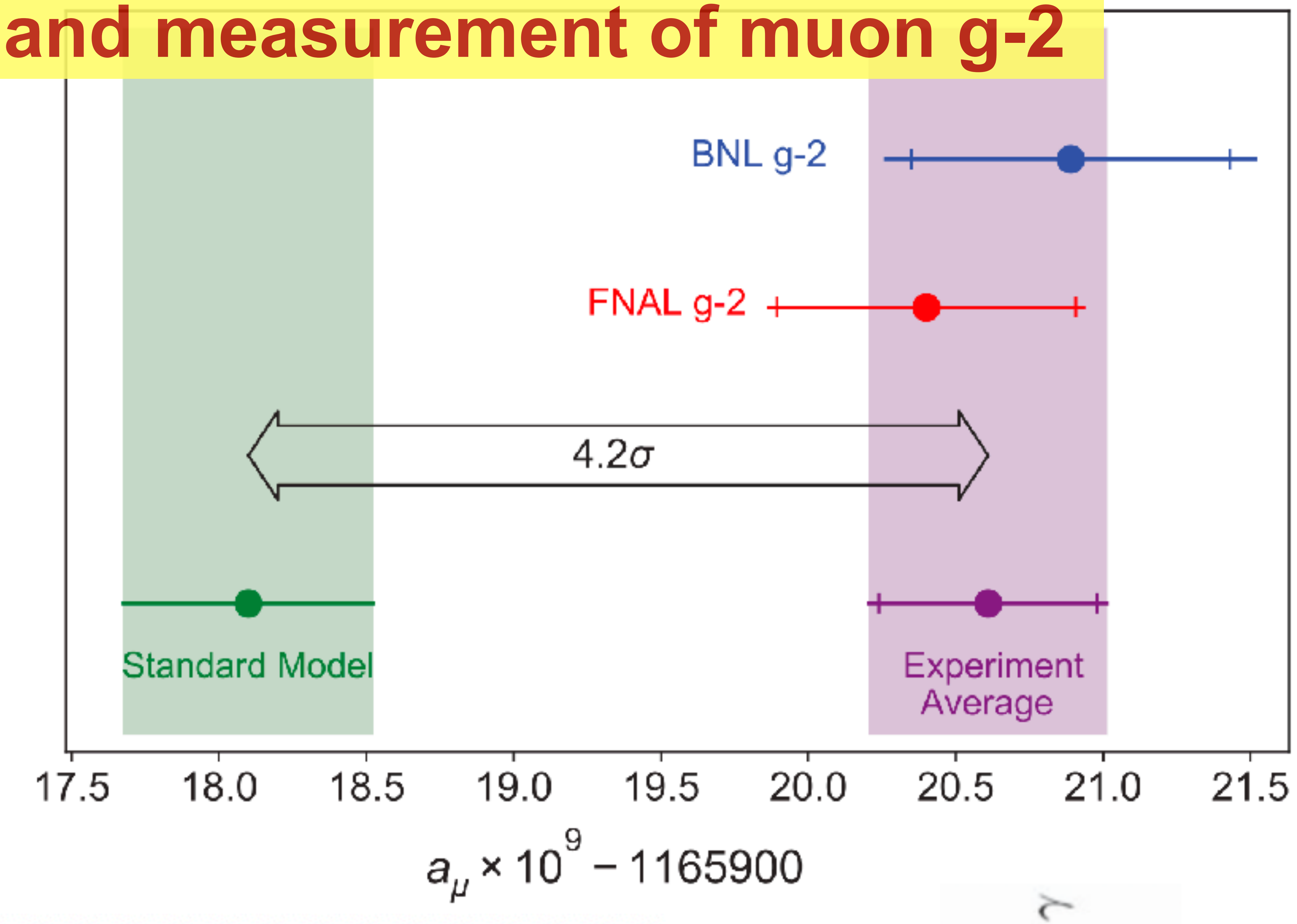


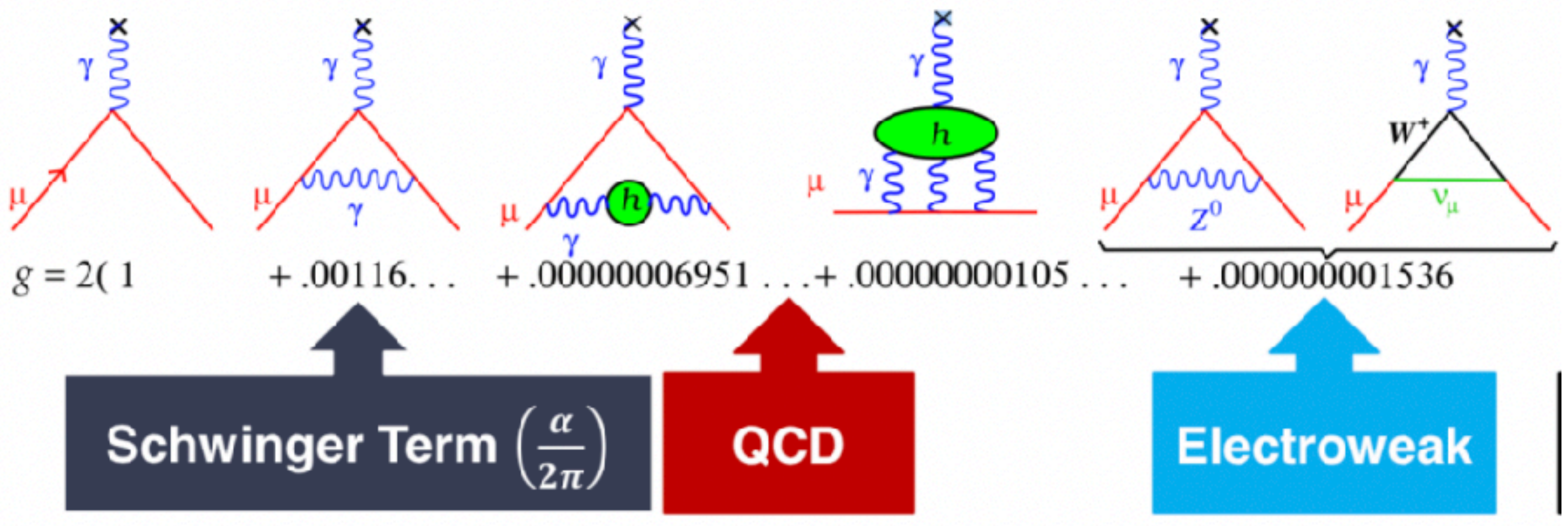
Measuring the precession of muon's spin as it travels through a magnetic field

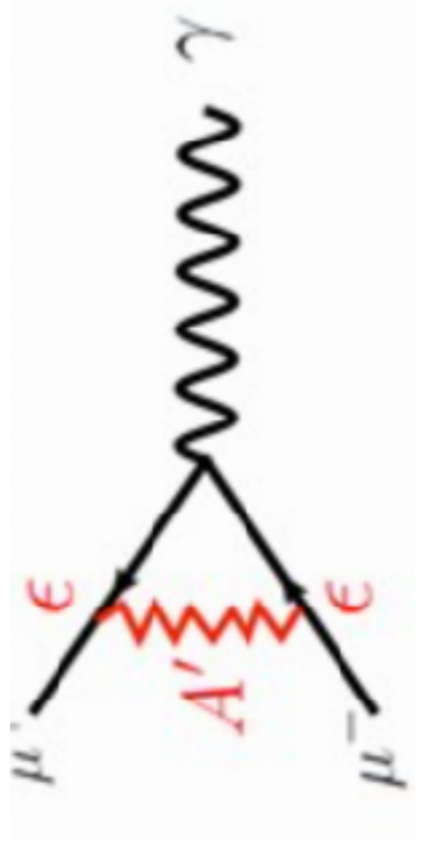


@Fermilab

vacuum fluctuations cause small corrections; precisely calculable in the SM

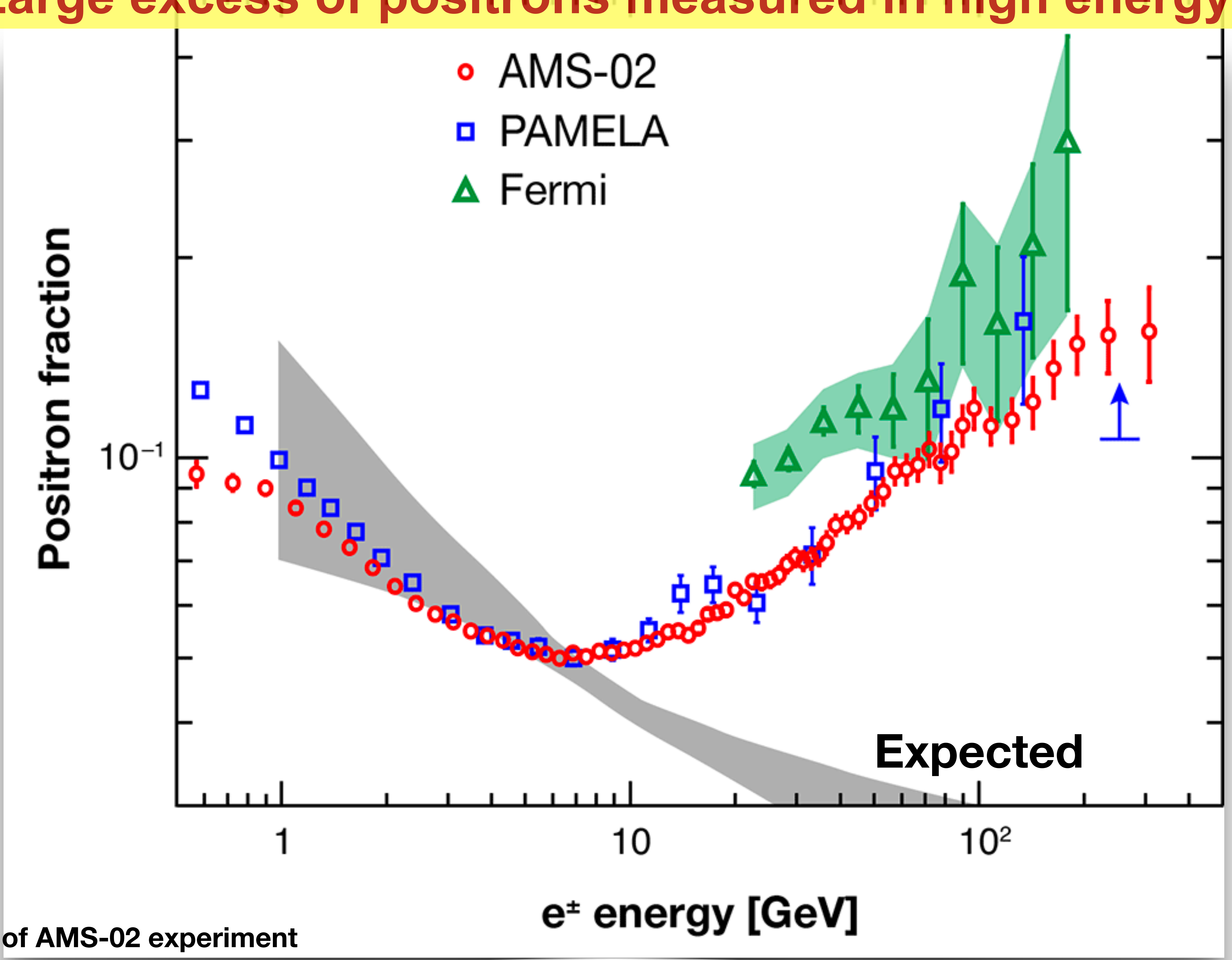






They can explain some other recent anomalous observations!

Large excess of positrons measured in high energy cosmic rays



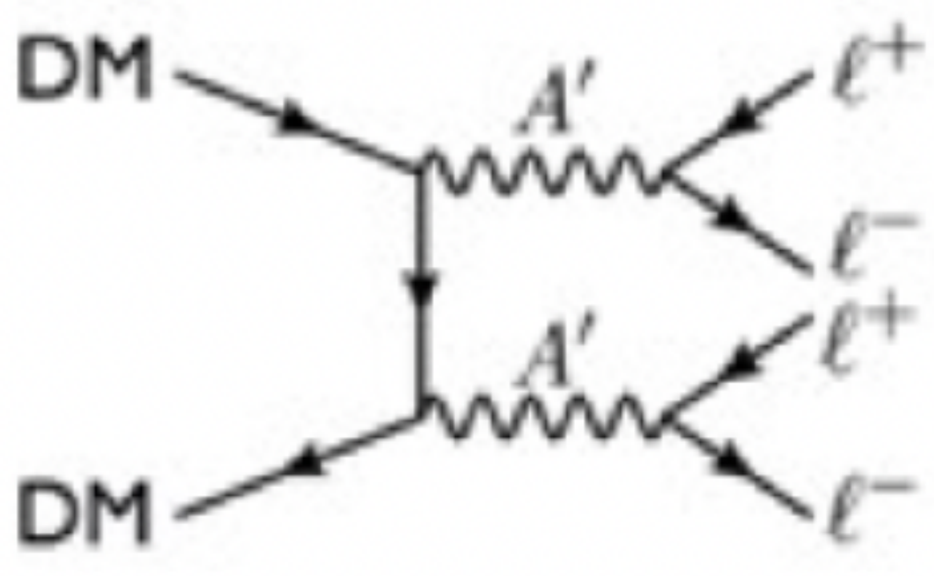
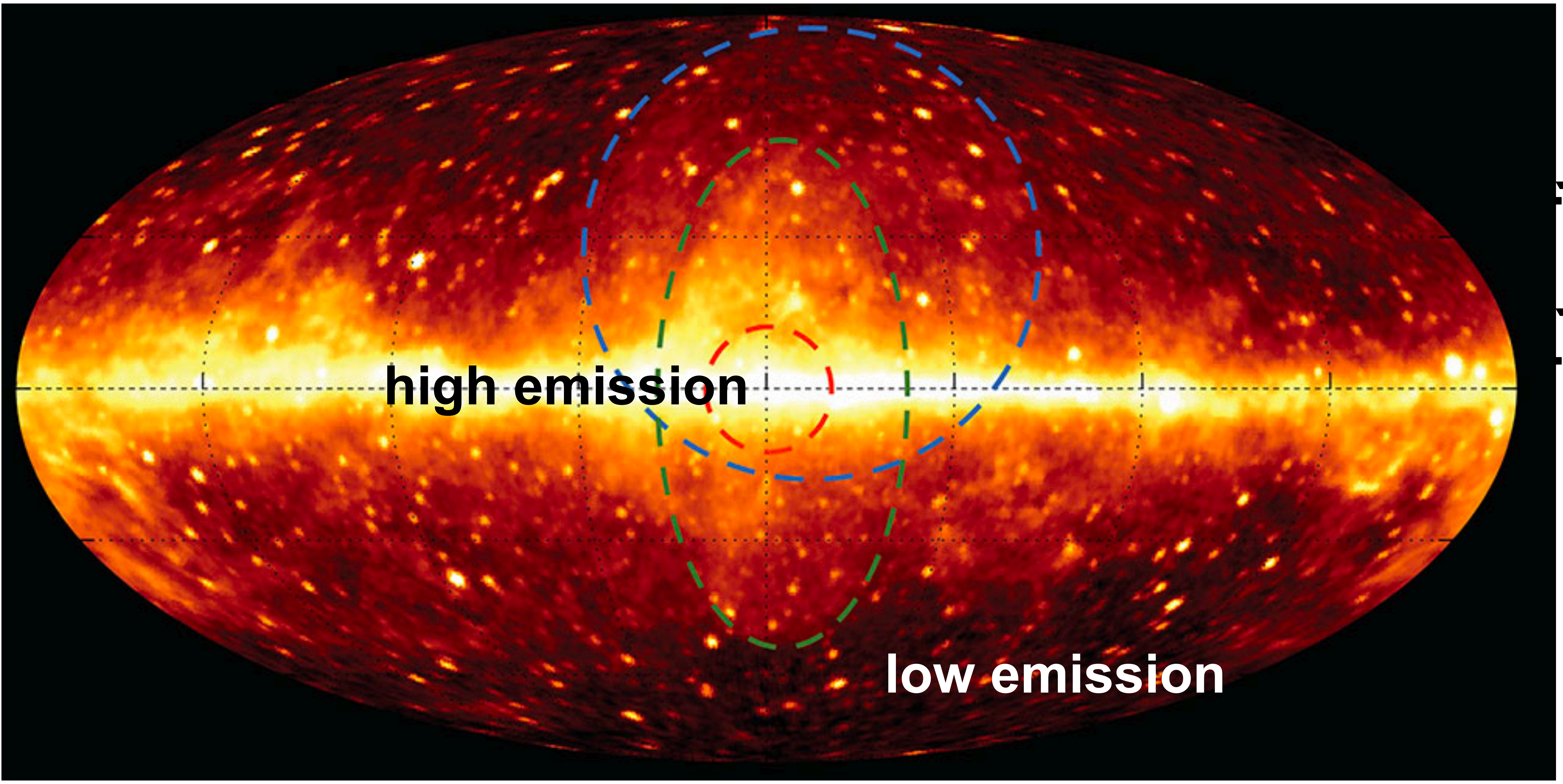
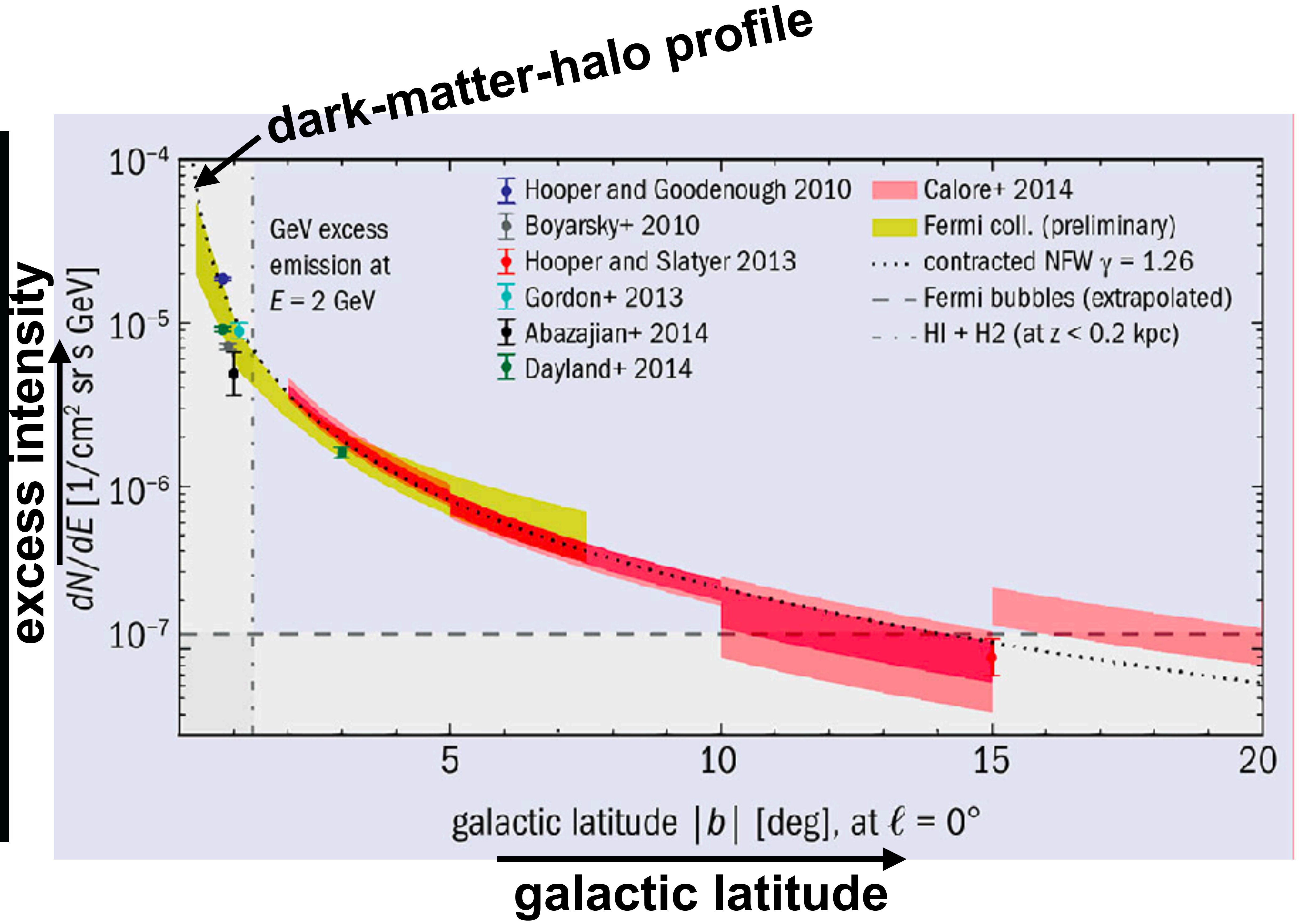


Image courtesy of AMS-02 experiment

Dark matter annihilation is most likely source of excess gamma rays from the galactic center of the milky way



View of the gamma-ray sky from the Fermi-LAT telescope.



Calore et al. 2015

See also Yen-Hsun Lin's talk from yesterday

Image courtesy of Fermi-LAT

Dark photons may even explain mass extinctions on earth!

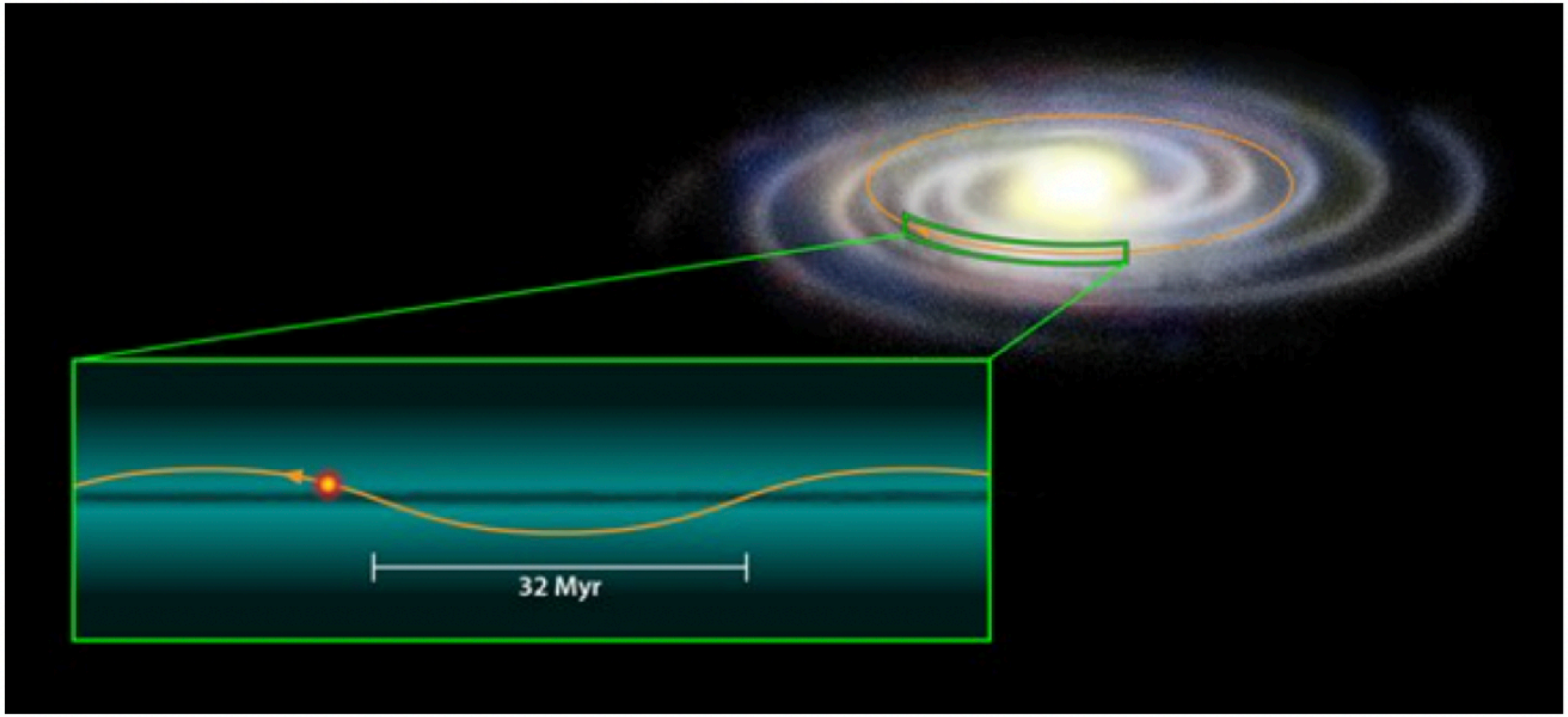
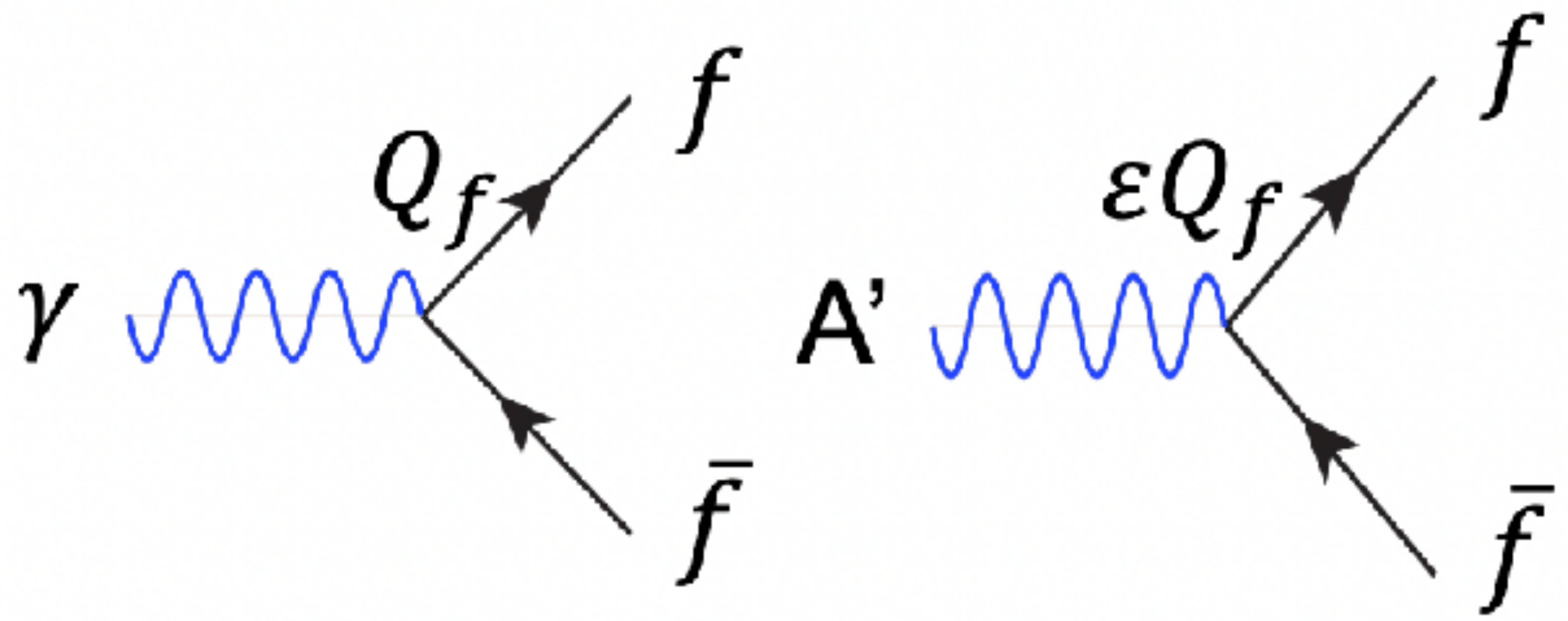


FIG. 2: Our Solar System orbits around the Milky Way's center, completing a revolution every 250 million years. Along this path, it oscillates up and down, crossing the galactic plane about every 32 million years. If a dark matter disk were concentrated along the galactic plane, as shown here, it might tidally disrupt the motion of comets in the Oort cloud at the outer edge of our Solar System. This could explain possible periodic fluctuations in the rate of impacts on Earth. (APS/Alan Stonebraker)

L. Randall and M. Reece, PRL 112 (2014) 161301; J. I. Read et al, Mon. Not. Roy. Astro. Soc 389 (2008) 1041

Image courtesy of R. Holt (ANL)

The estimated quark couplings rule out dark photons (A') as possible source of X17.



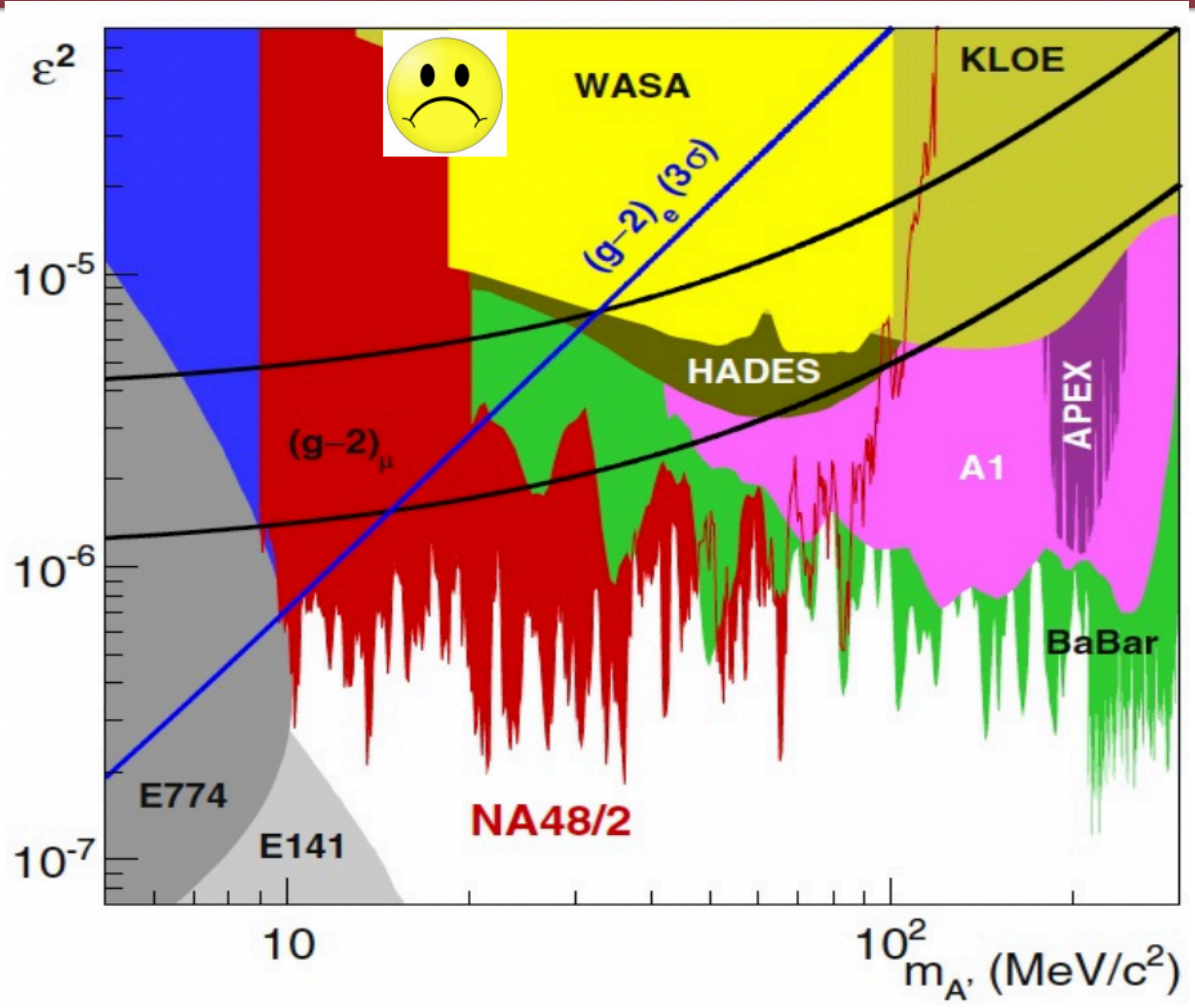
A' : spin-1 gauge Bosons with photon like coupling suppressed by a factor ε

$$\varepsilon_f = \varepsilon Q_f$$

Atomki experiment gives

$$|\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$$

$\Rightarrow$ **ε ~ 0.01**



from
talk by J. Feng

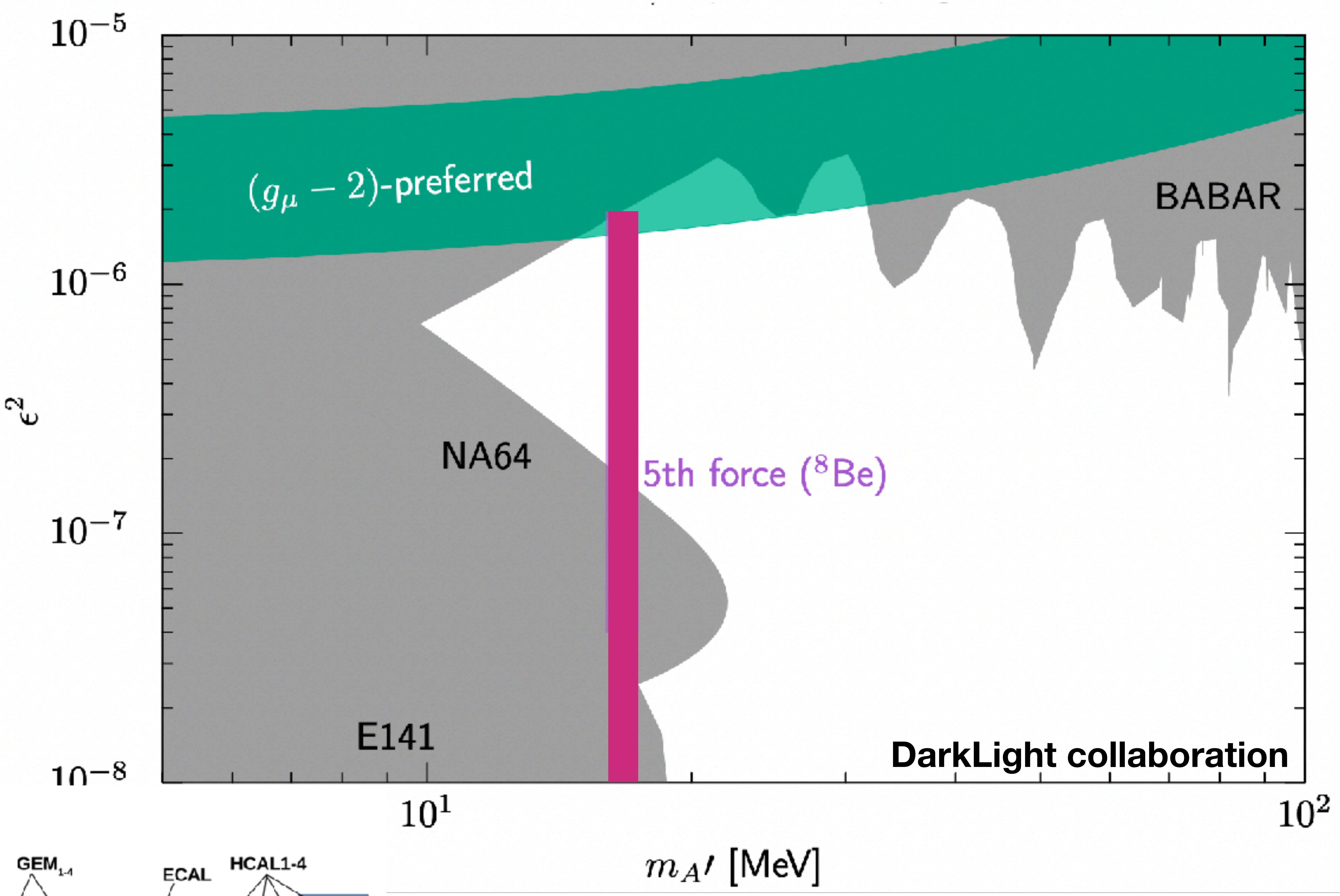
A' search experiments are also sensitive to the X17 via the electron/positron coupling.

$10^{-5} < \varepsilon_e$

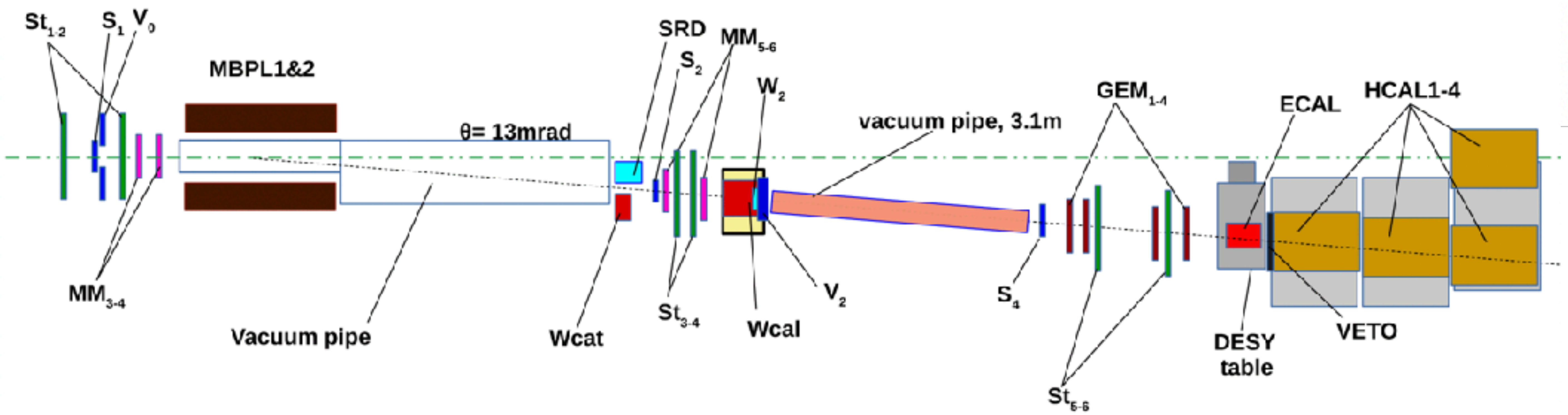
for X decay length < 1 cm

Recent results from NA64 show the way, more coming soon.

D. Banerjee et al. PRD 101, 071101 (2020)



150 GeV
e + Z (W cal active target) → e + Z + X
↓
e^+e^- (in ECAL)

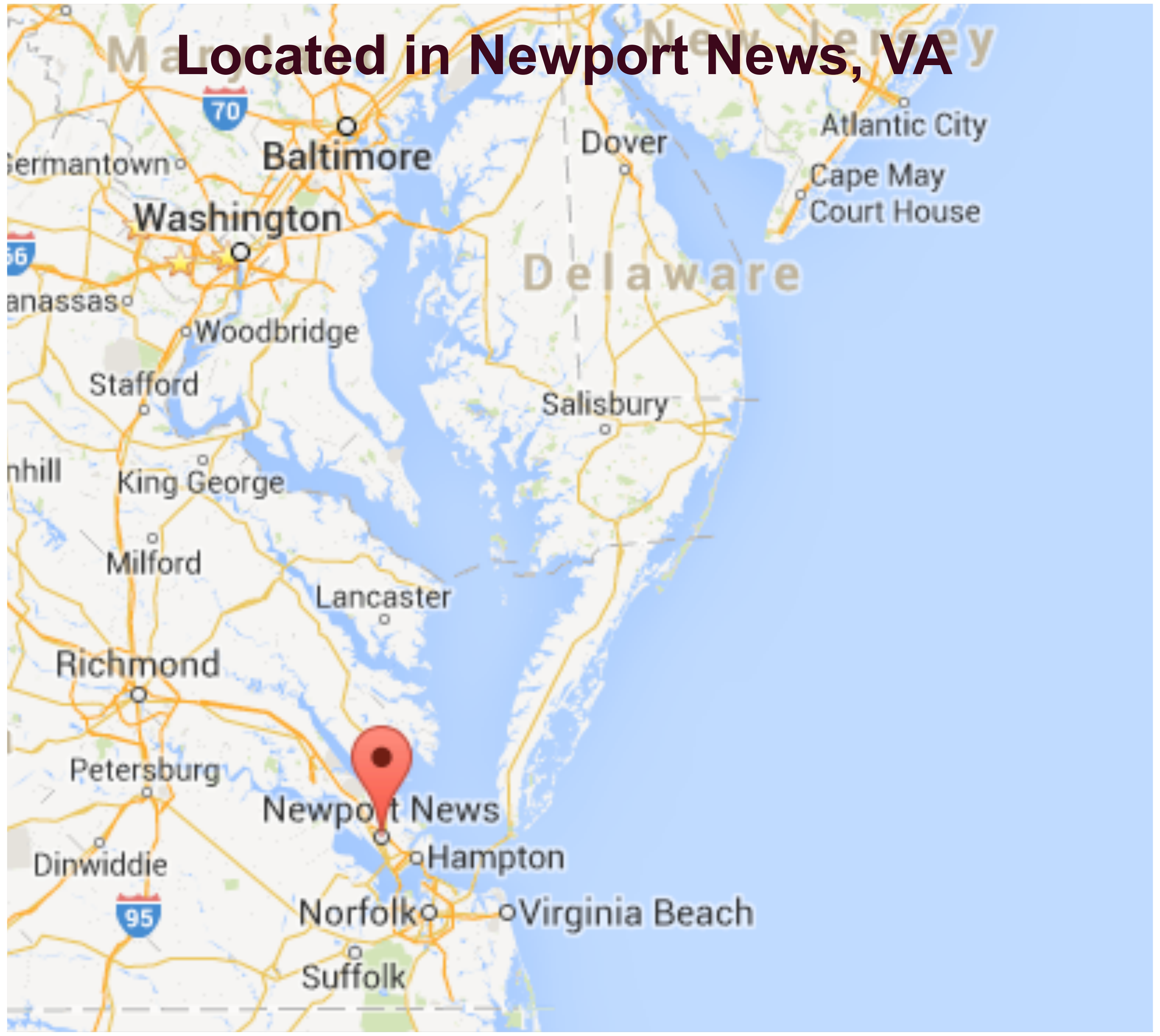


A new electron scattering experiment is being put together at Jefferson Lab.

Jefferson Lab (JLab), is the most intense electron accelerator in the world

The only CW polarized electron accelerator in the US (1 – 12 GeV energy, 80% polarization)
recently upgraded from 6 to 12 GeV

Highest luminosity in the world by several orders of magnitude (10^{38} cm^{-2}/s)



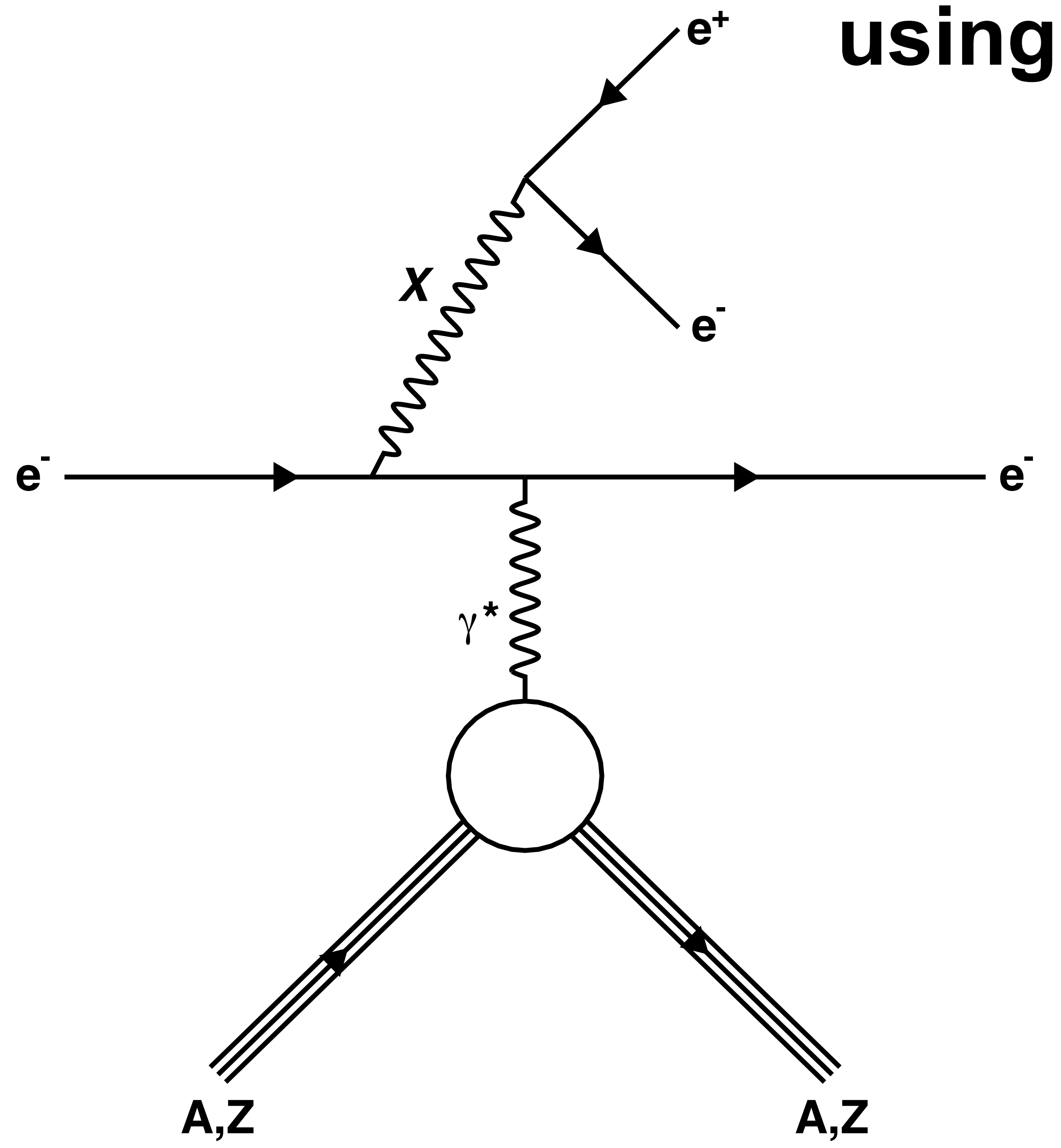
A JLab electron scattering based X(17) search is the only experiment where all three final state particles are detected.

Forward angle electroproduction on a heavy nucleus

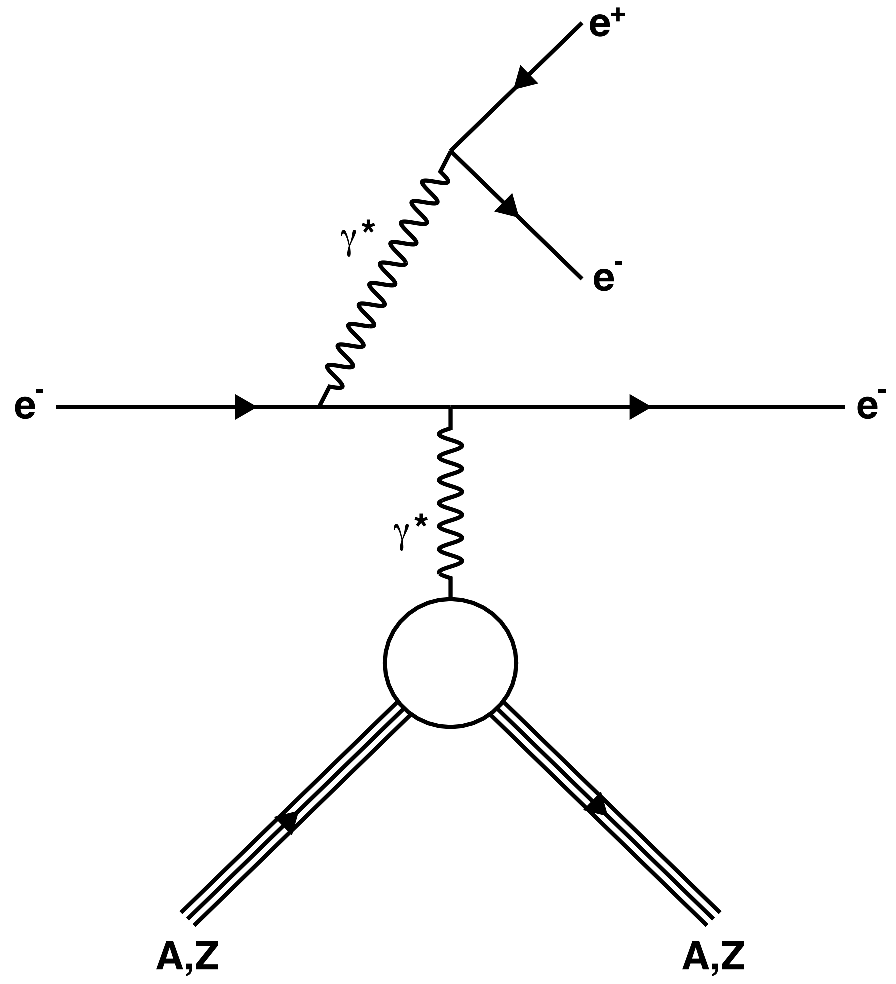
$$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta, \quad \text{with} \quad X \rightarrow e^+e^-$$

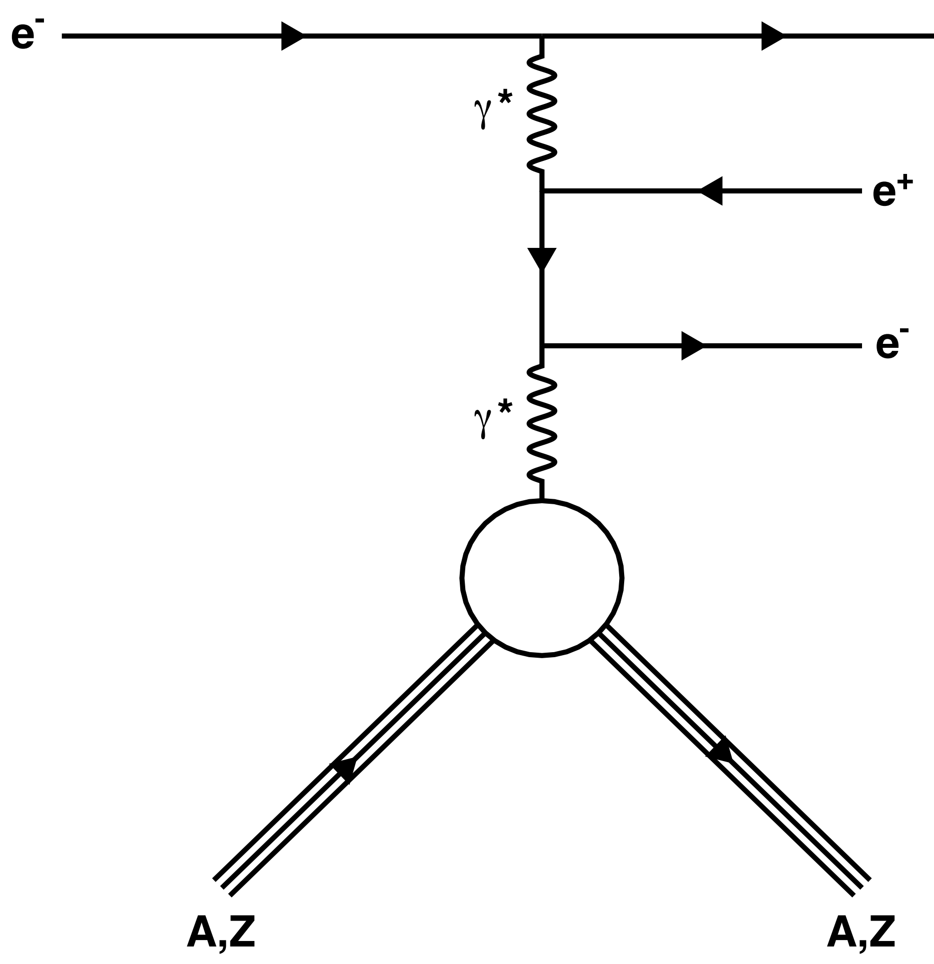
All 3 final state particles will be detected in this experiment:

The scattered electron and the pair produced e^+e^- will be detected using a pair of coordinate detectors and high resolution calorimeter



Signal: Bremsstrahlung production of X





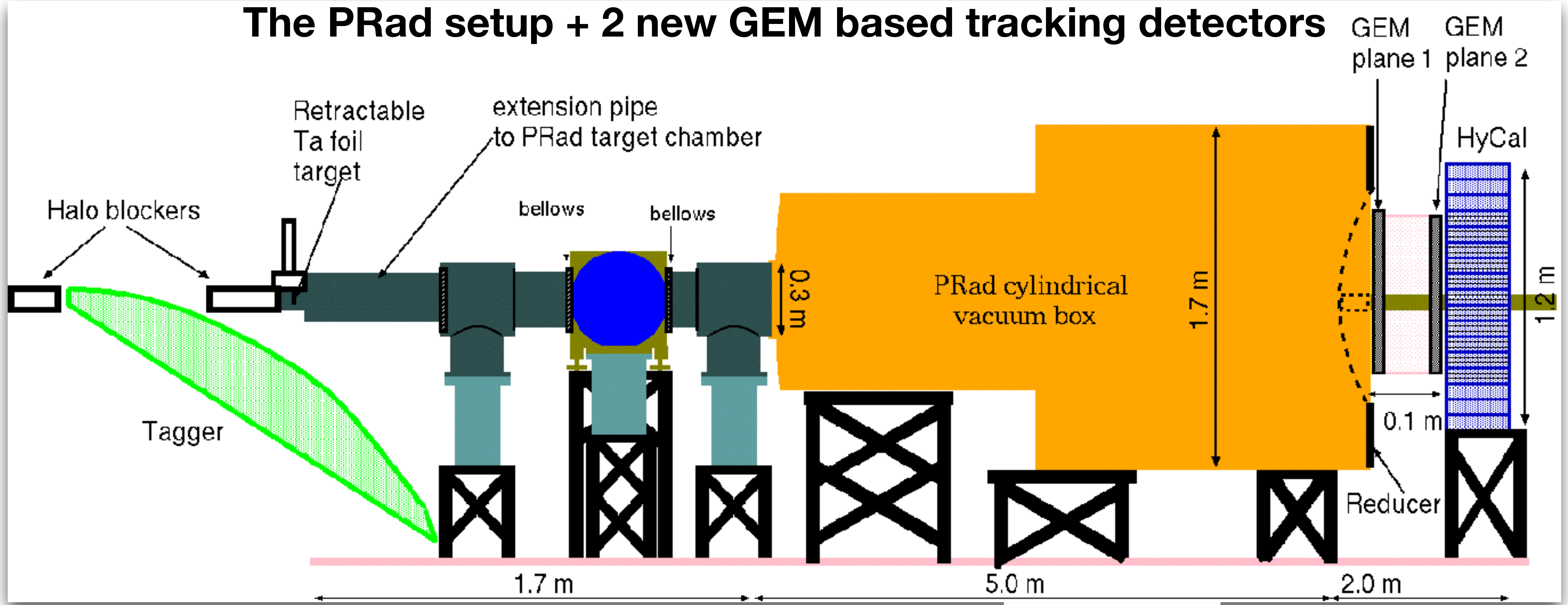
Background: radiative pair production (Trident) and Bethe-Heitler process

As the only magnetic spectrometer free experiments the JLab experiment has an unique technique for background suppression

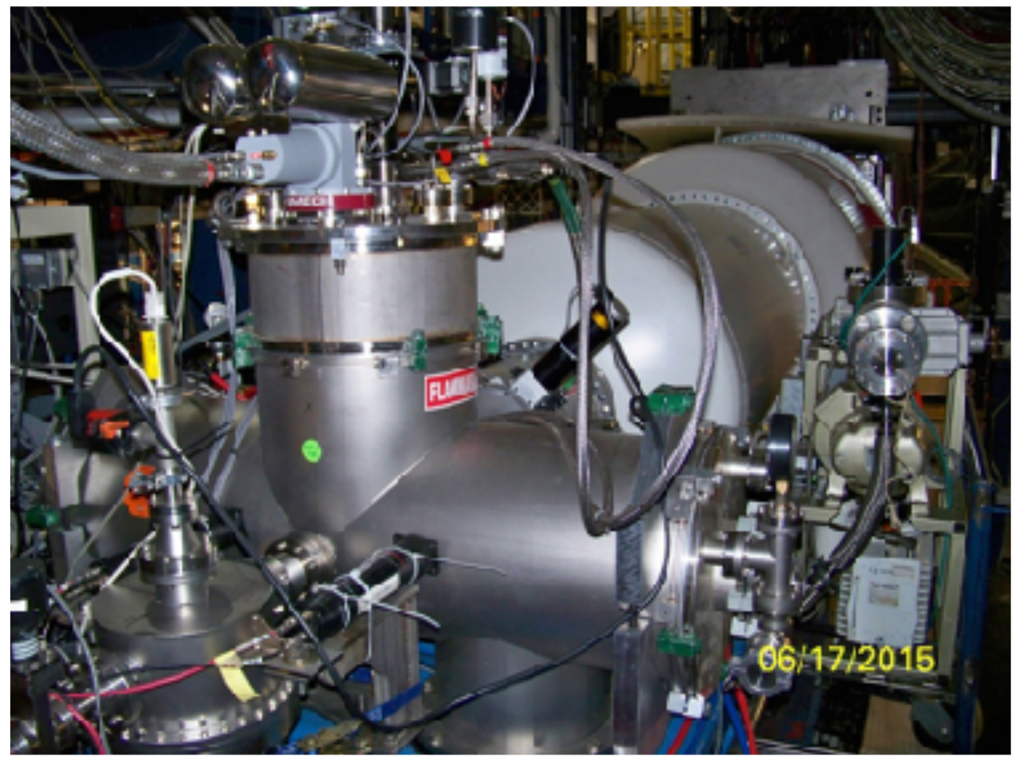
A. Ahmidouch et al., arXiv: 2108.13276

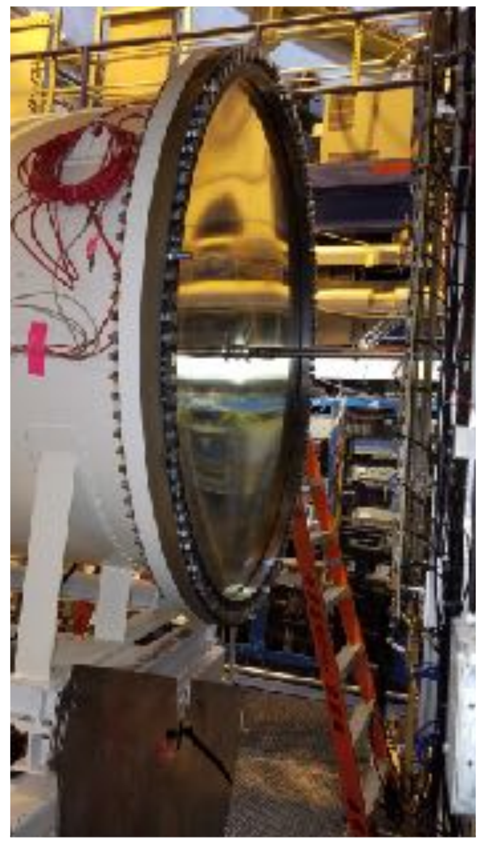
Spokespersons:
A. Gasparian, T. Hague, DD, C. Peng, N. Layanage, H. Gao, R. Paremuzyan

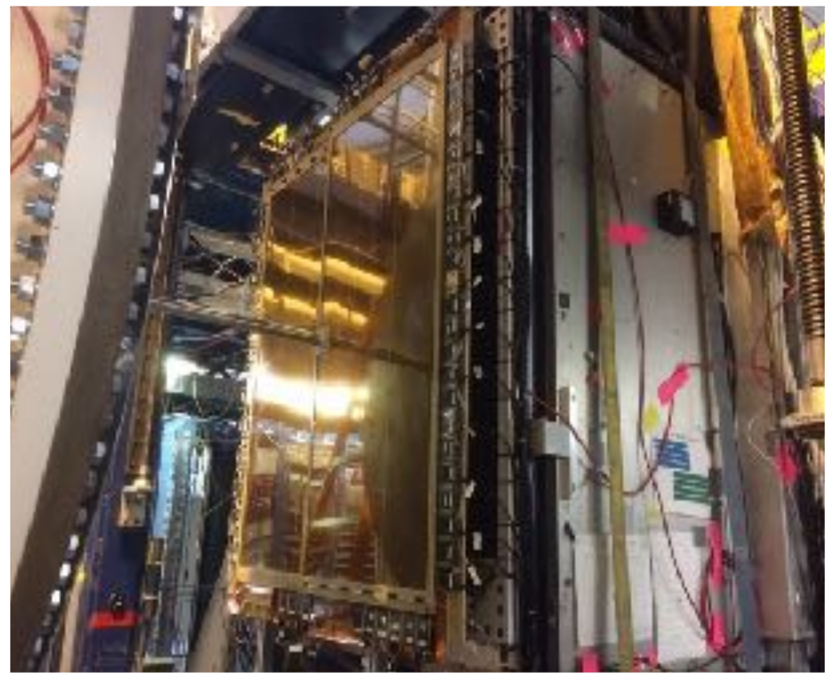
A JLab X(17) search will use the well established apparatus that was used for PRad -the recent proton charge radius experiment

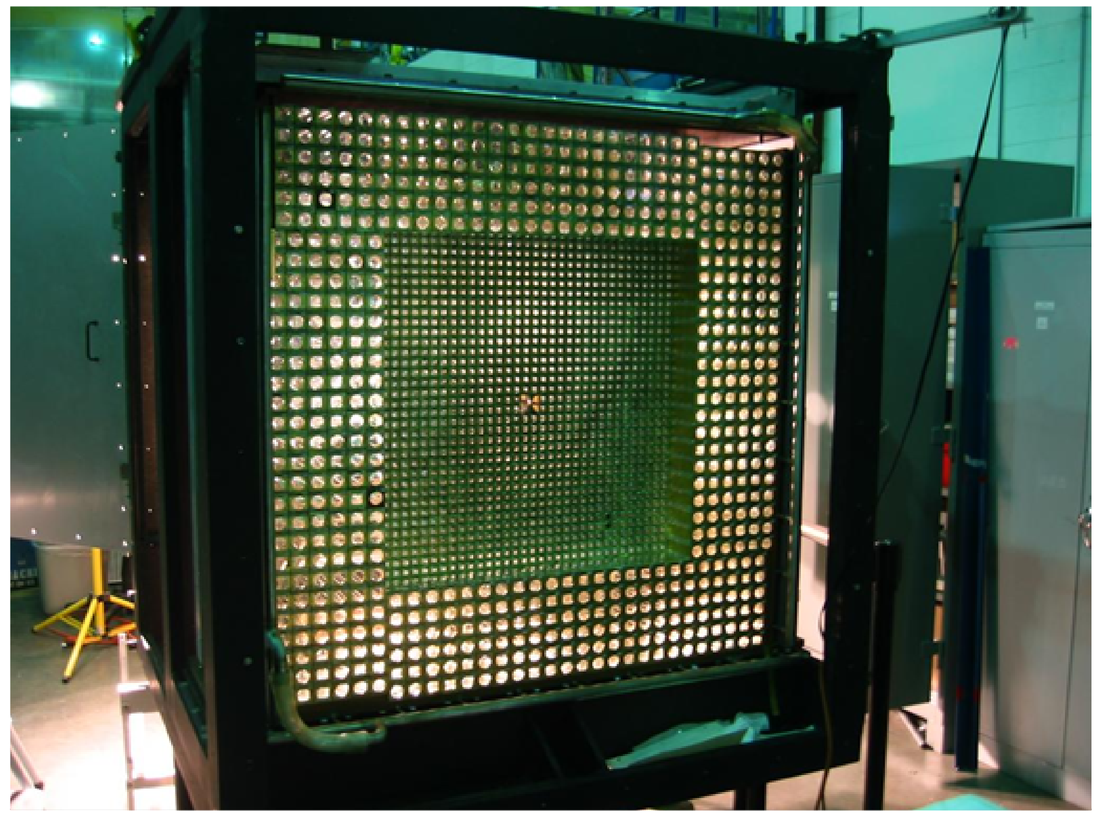


the JLab experiment is also a uniquely cost-effective experiment









The only experiment to use a magnetic spectrometer free method, successfully demonstrated PRad.

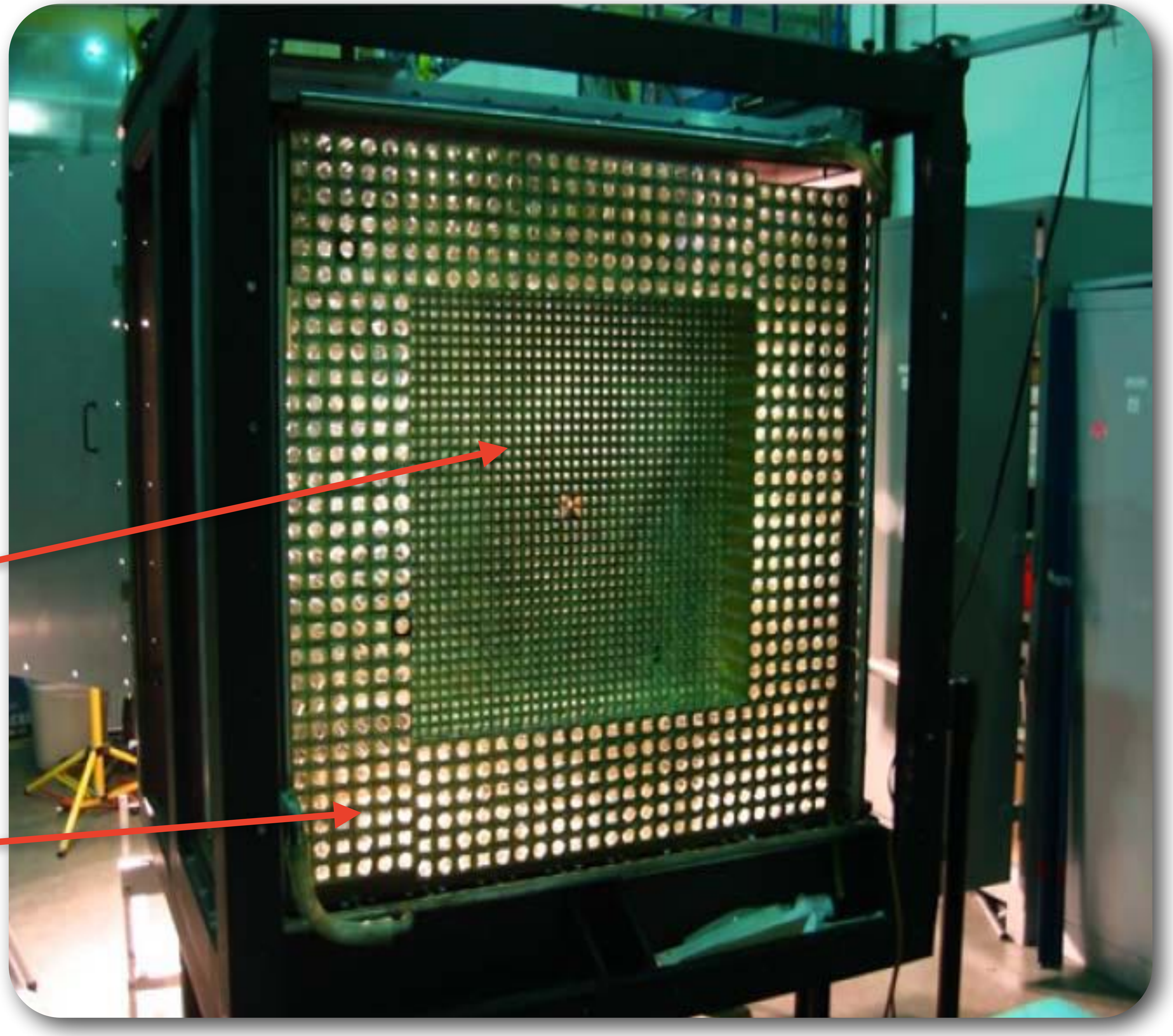
Reused PRad Hybrid Calorimeter

- $PbWO_4$ and Pb-glass calorimeter (118x118 cm^2)
- 34x34 matrix of 2.05 x 2.05 cm^2 x18 cm $PbWO_4$
- 576 Pb-glass detectors (3.82x3.82 cm^2 x45 cm)
- 7.5 m from the target,
- 0.5 sr acceptance

Allows coverage of extreme forward angle (0.7^o - 7.5^o) in a single setting and complete azimuthal angle coverage

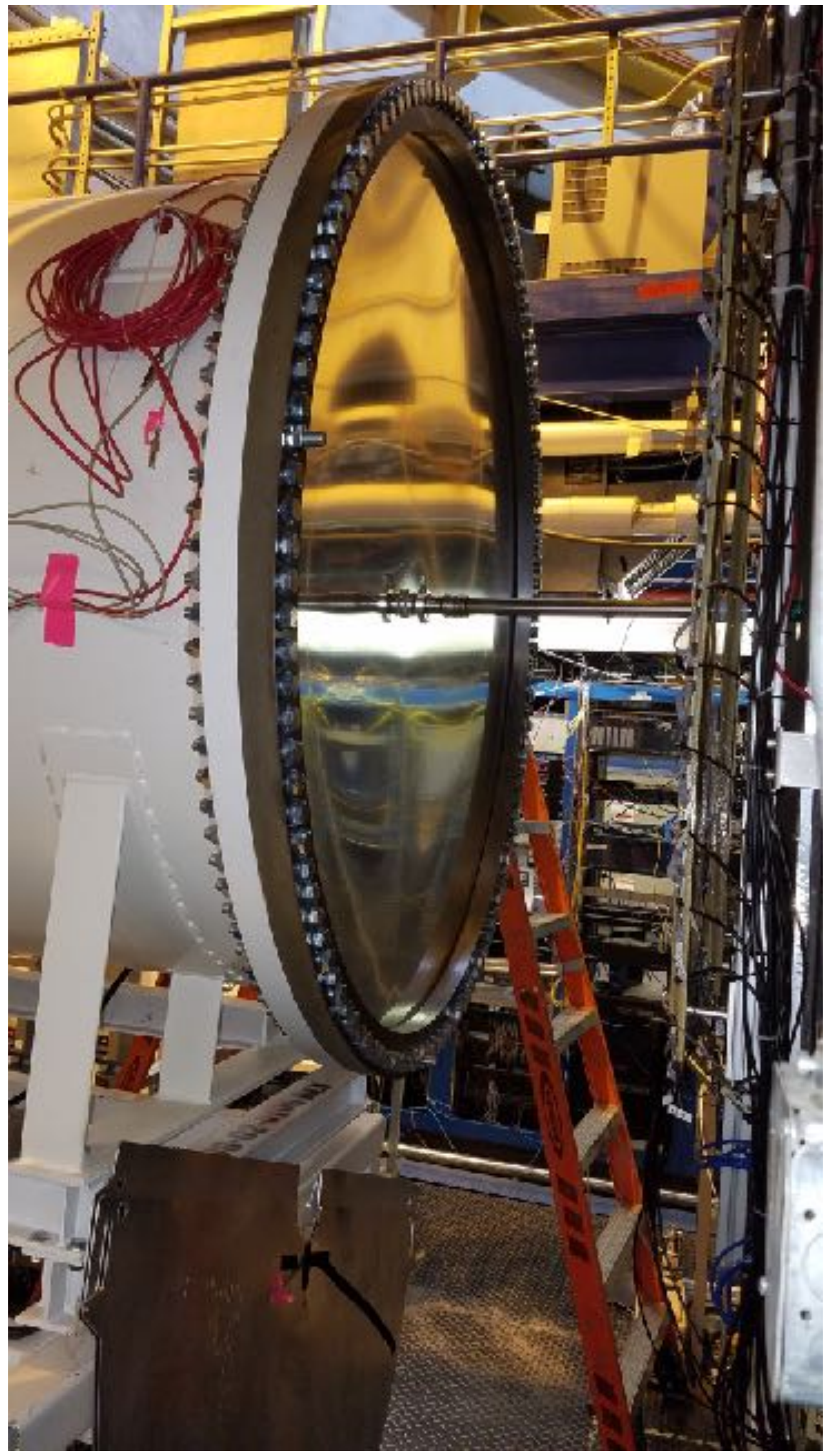
Only the inner $PbWO_4$ part of calorimeter will be used

Convert to FADC based readout of HyCal

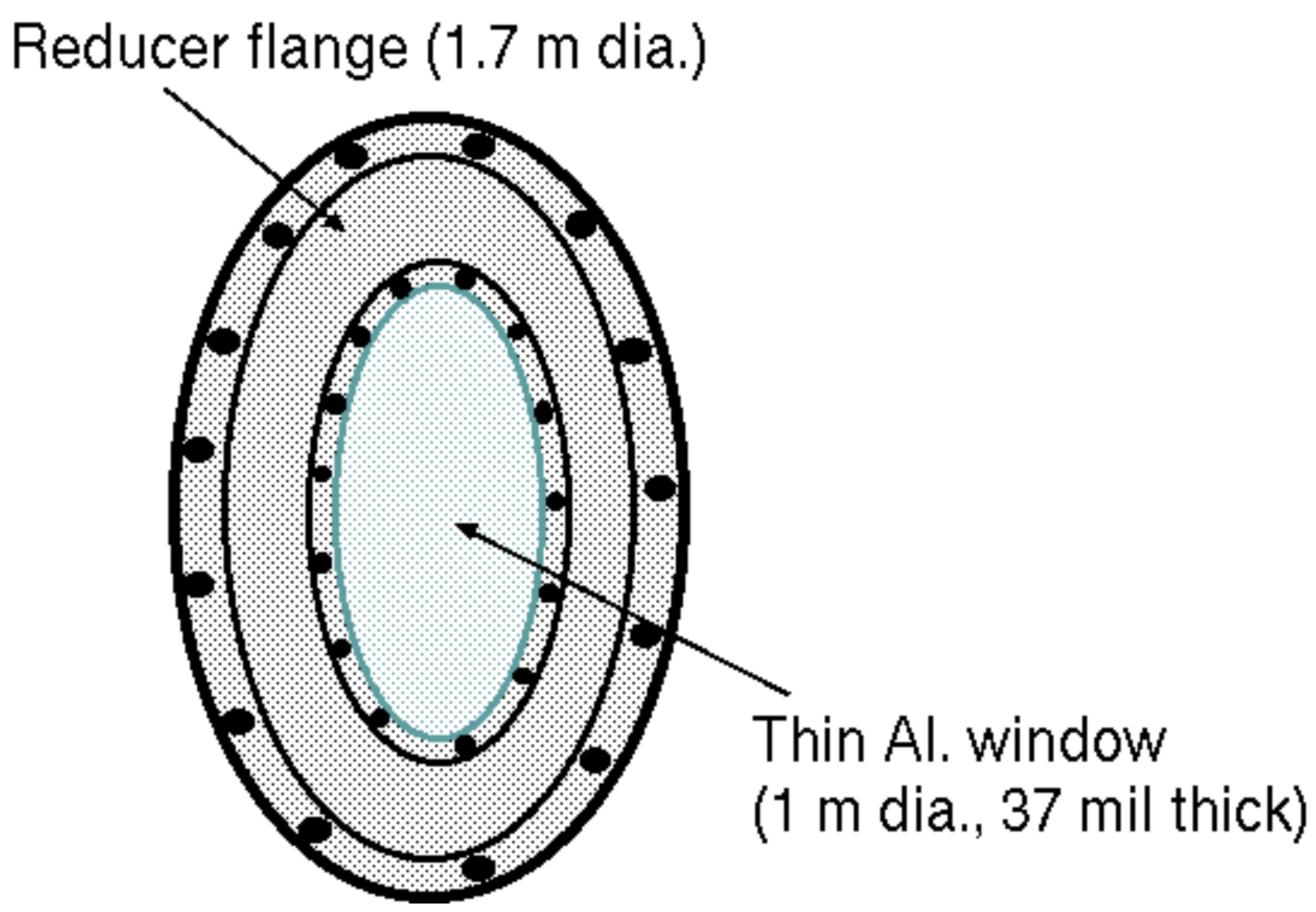


Target to detector enclosed in one large vacuum chamber with one thin window

two stage, 5 m long vacuum chamber



1.7 m dia, 2 mm thick
Al window



Two planes of large area GEM coordinate detectors for tracking

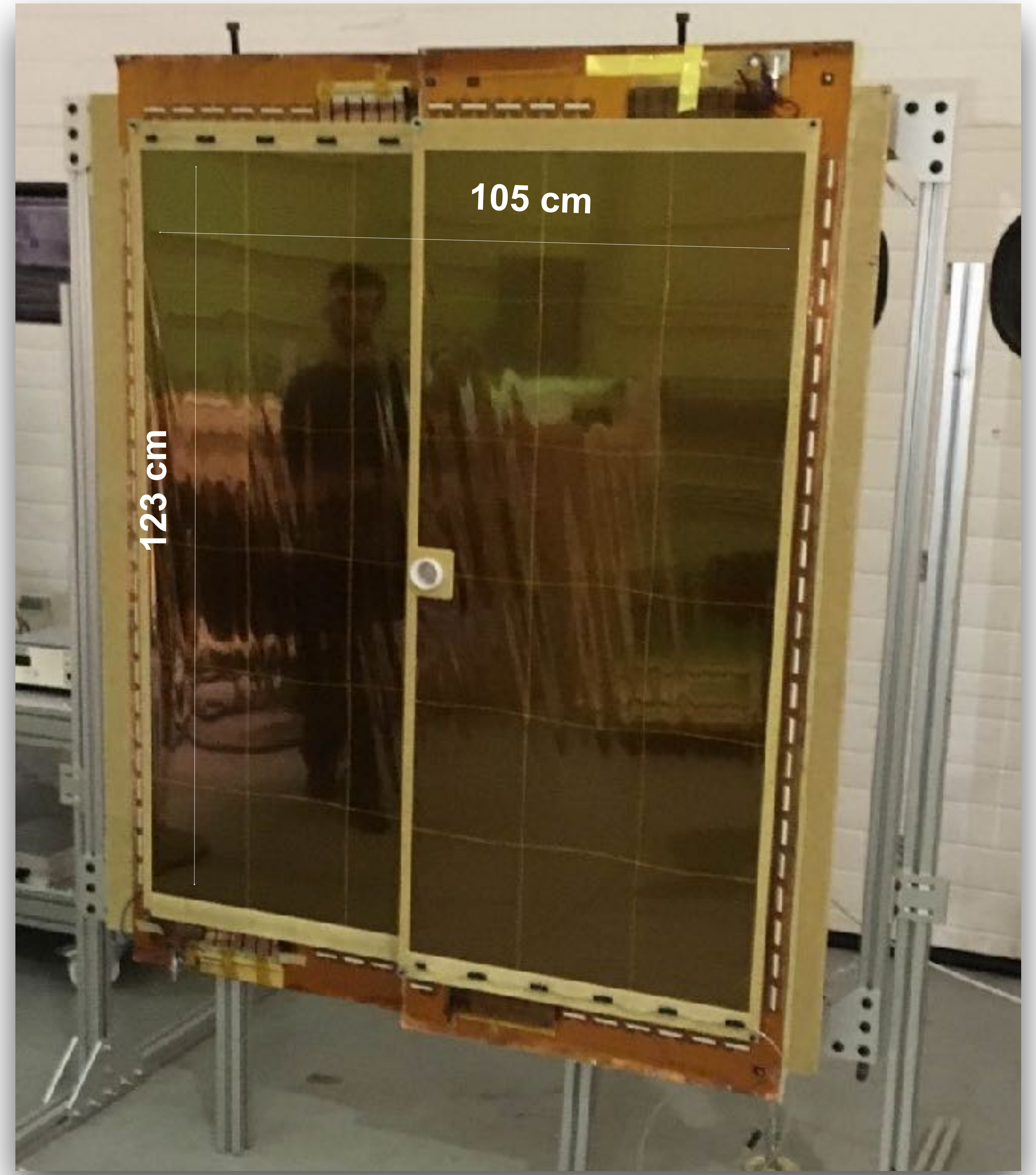
- **Two large GEM based X and Y- coordinate detectors with 100 μm position resolution**

- **The GEM detectors provided:**
  - **factor of >20 improvements in coordinate resolutions**

Add a second GEM plane between HyCal and vacuum chamber to further reduce the backgrounds and improve vertex resolution.

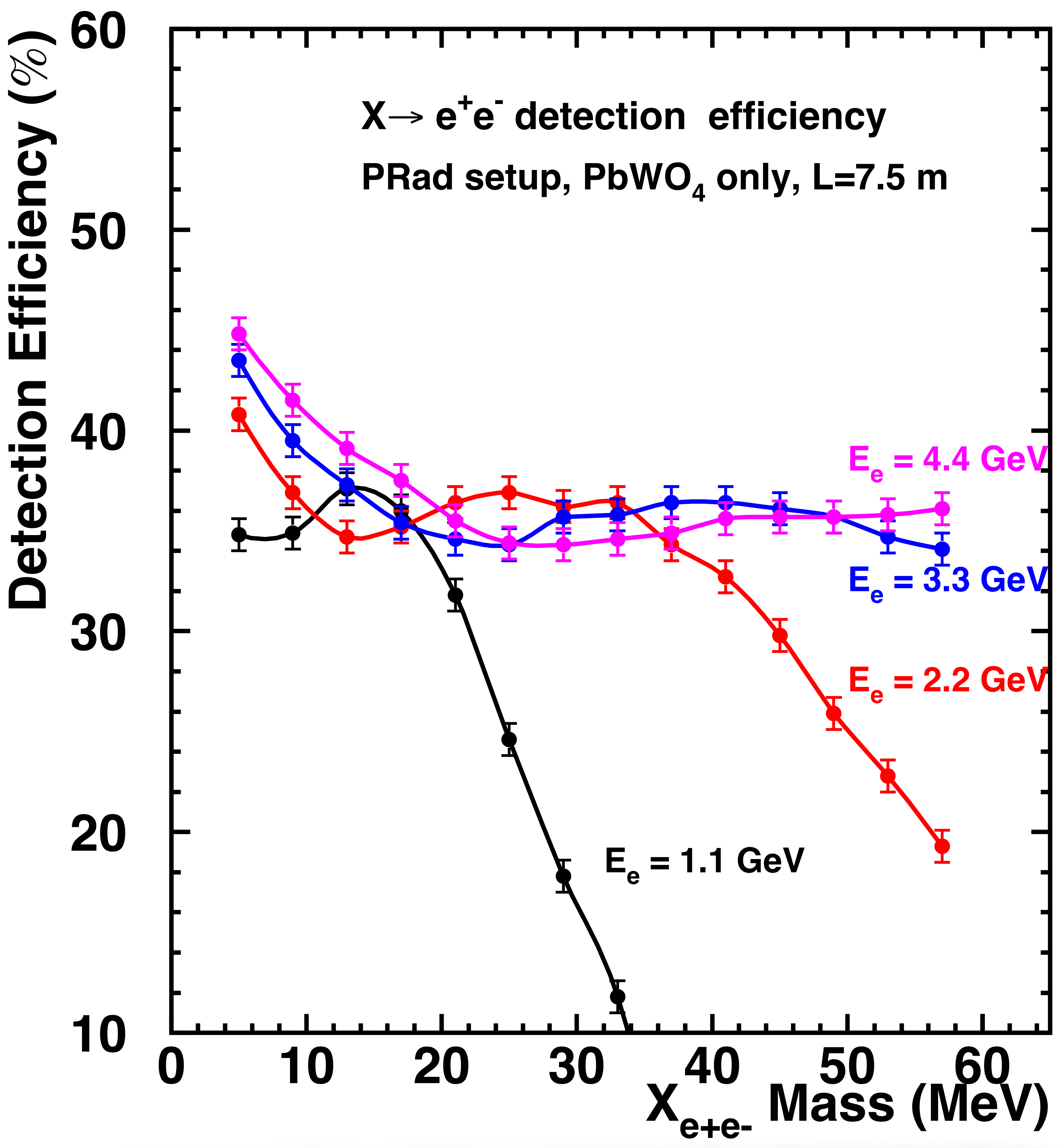
Allows reduction of backgrounds contribution from vacuum chamber window.

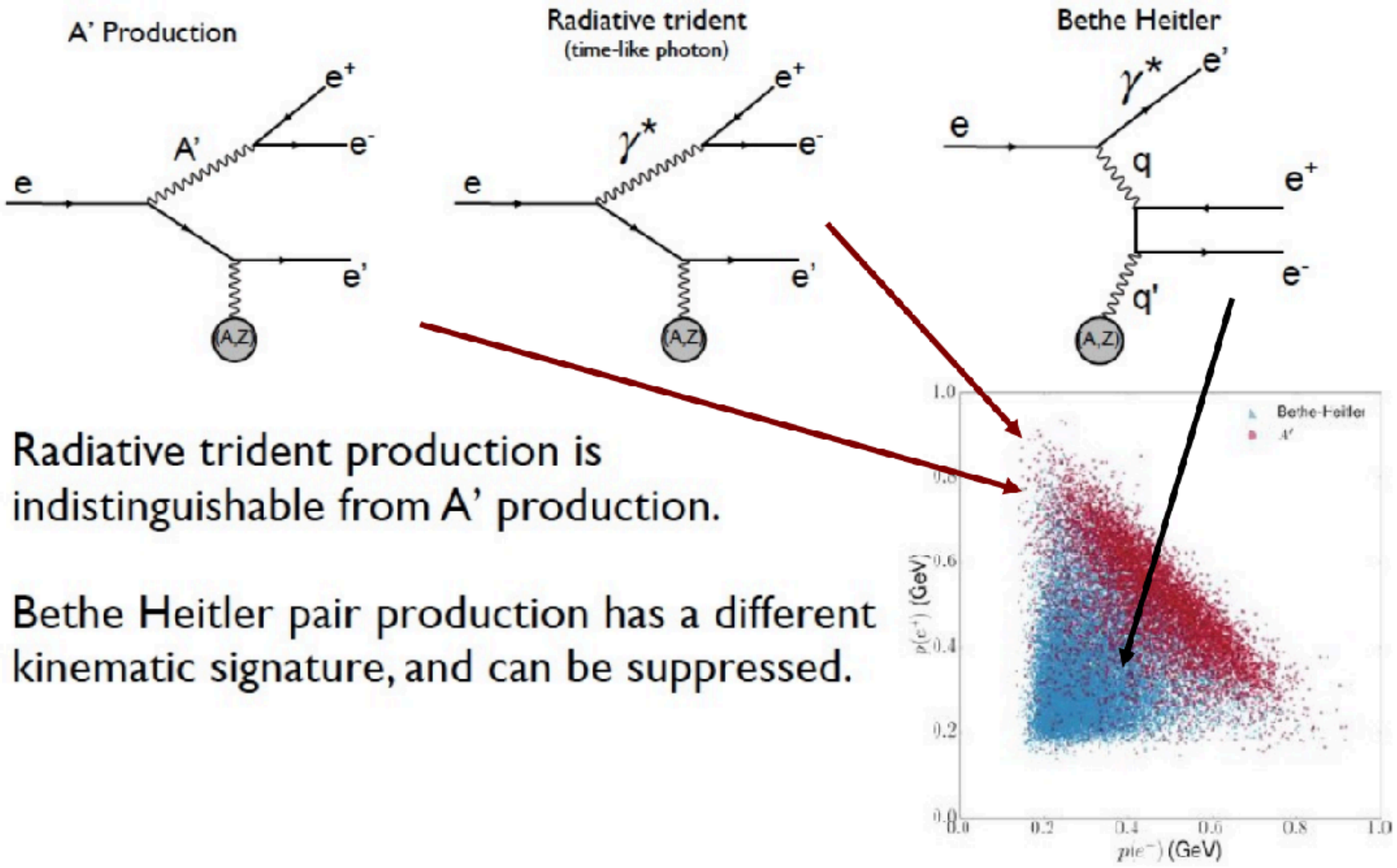
- **Designed and built at University of Virginia (UVa)**



Sensitivity estimates for the JLab X(17) search is based on well established simulation package for PRad

2.2 - 4.4 GeV, CW electron beam will be used

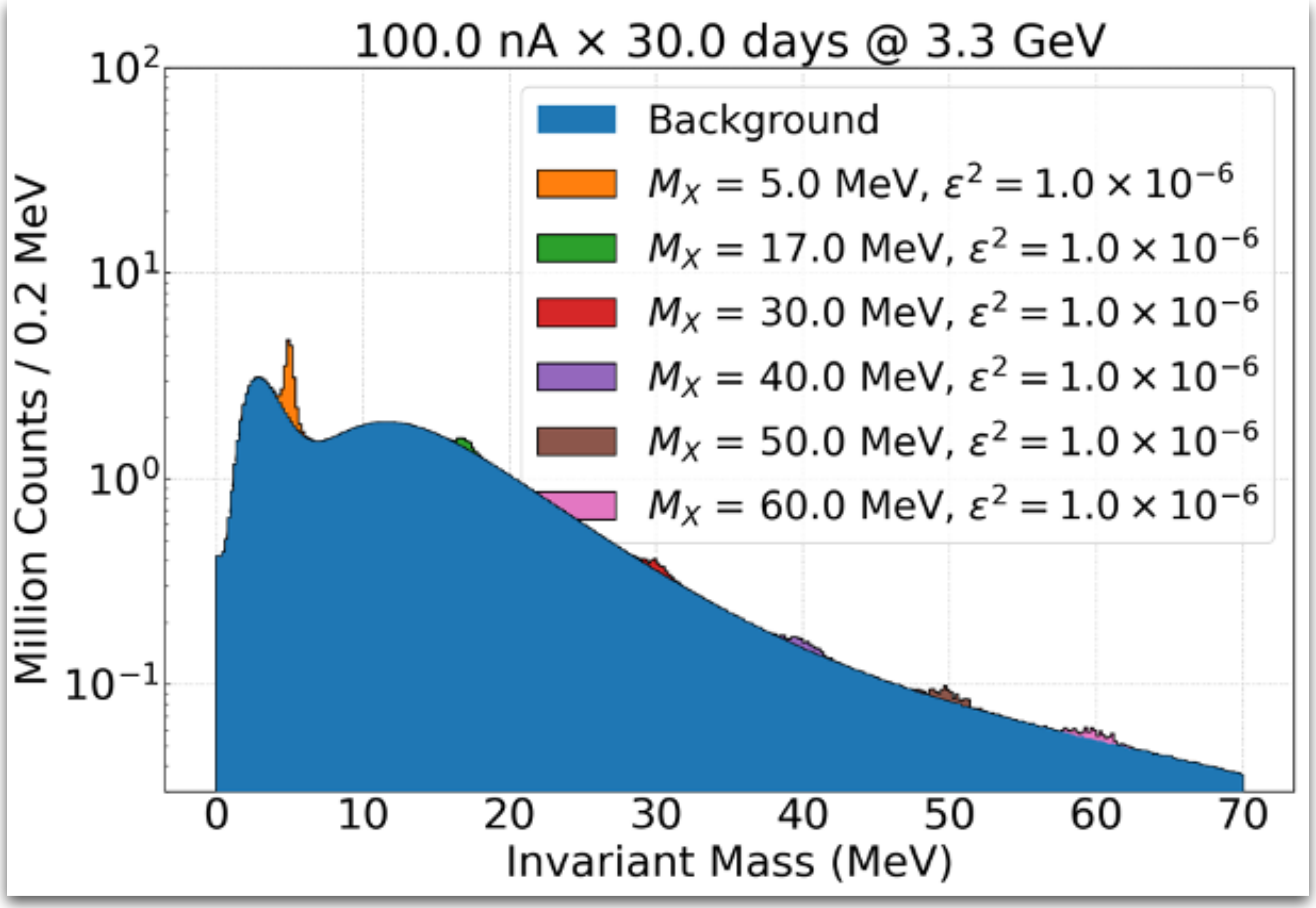




Radiative trident production is indistinguishable from A' production.

Bethe Heitler pair production has a different kinematic signature, and can be suppressed.

Sensitivity estimates for the JLab X(17) search is based on well established simulation package for PRad



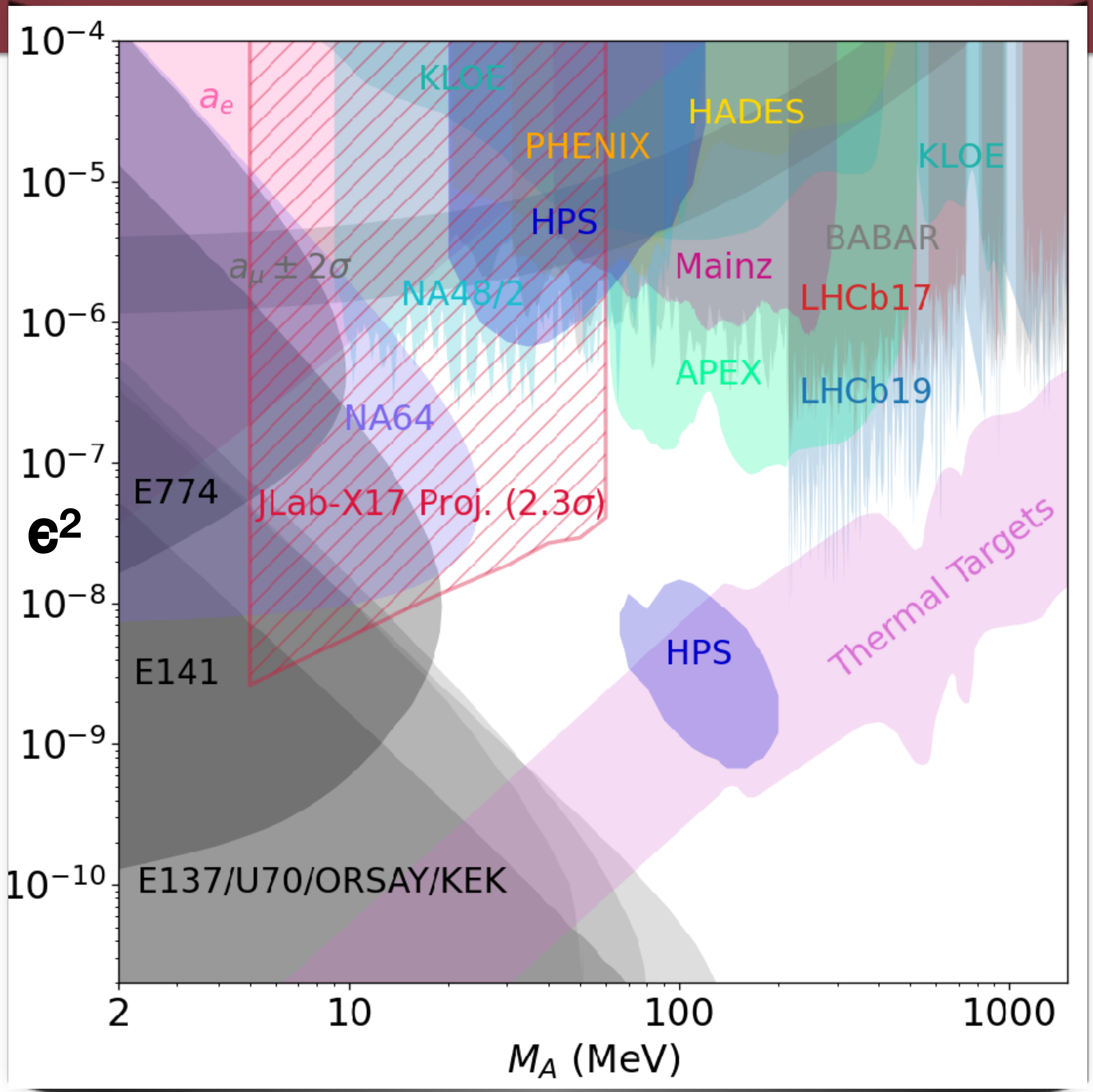
simulated background was scaled to 30 days of beam time

projected signal events with $\varepsilon^2 = 1.0\text{x}10^{-6}$

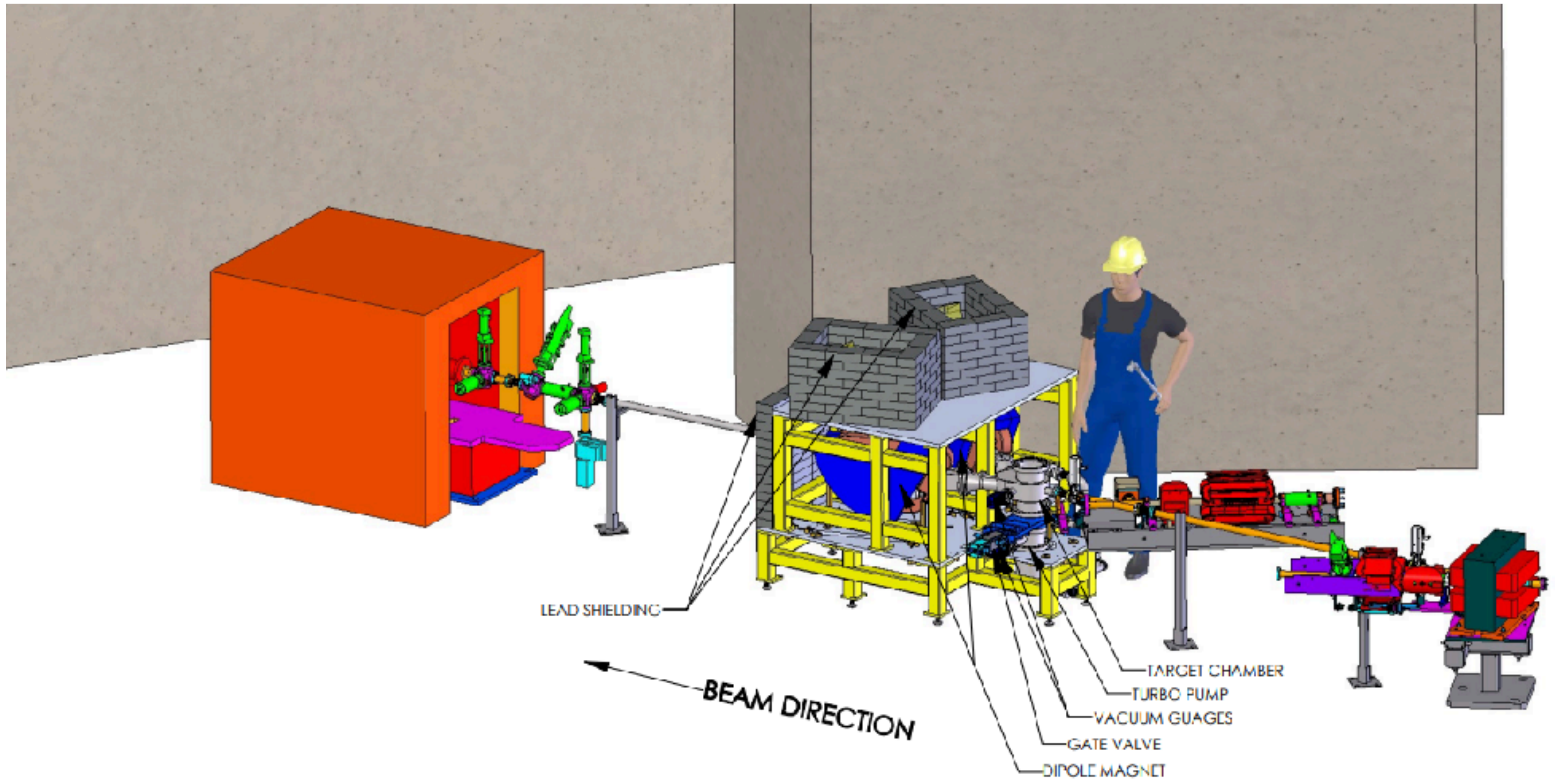
The recently approved JLab X(17) search experiments will cover the remaining phase space

Will also be sensitive to the
X $\rightarrow \gamma\gamma$ channel
but without optimal tracking

Expected to run in 2024

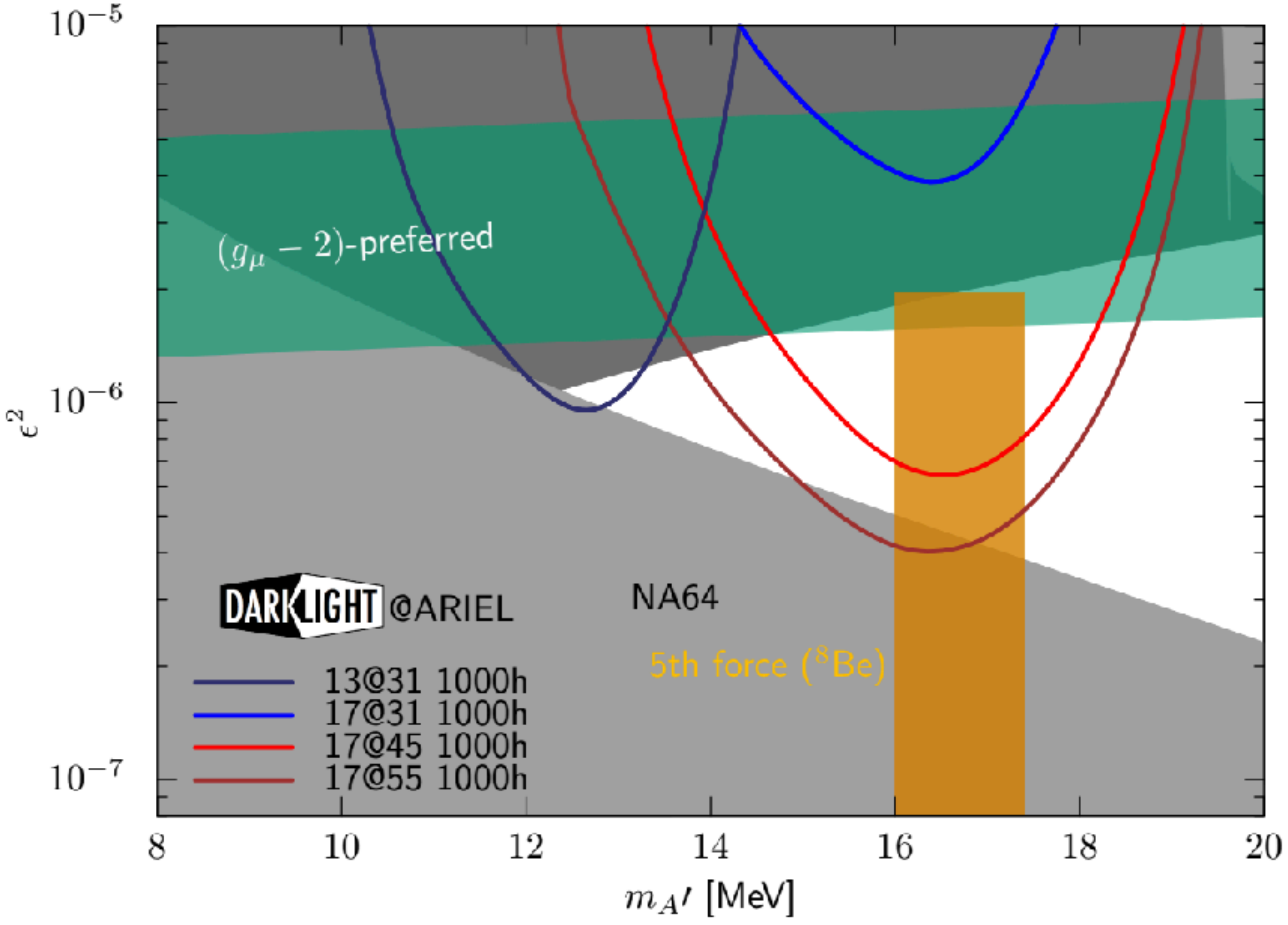


There are other efforts such as the DarkLight experiment at TRIUMF



DarkLight collaboration:
R. Milner, P. Fisher, J. Bernauer et al.

Uses the ARIEL e-linac, currently 31 MeV, will be upgraded to 50 MeV



two spectrometer setup, optimized for the 17 (MeV/c)^2 invariant mass region

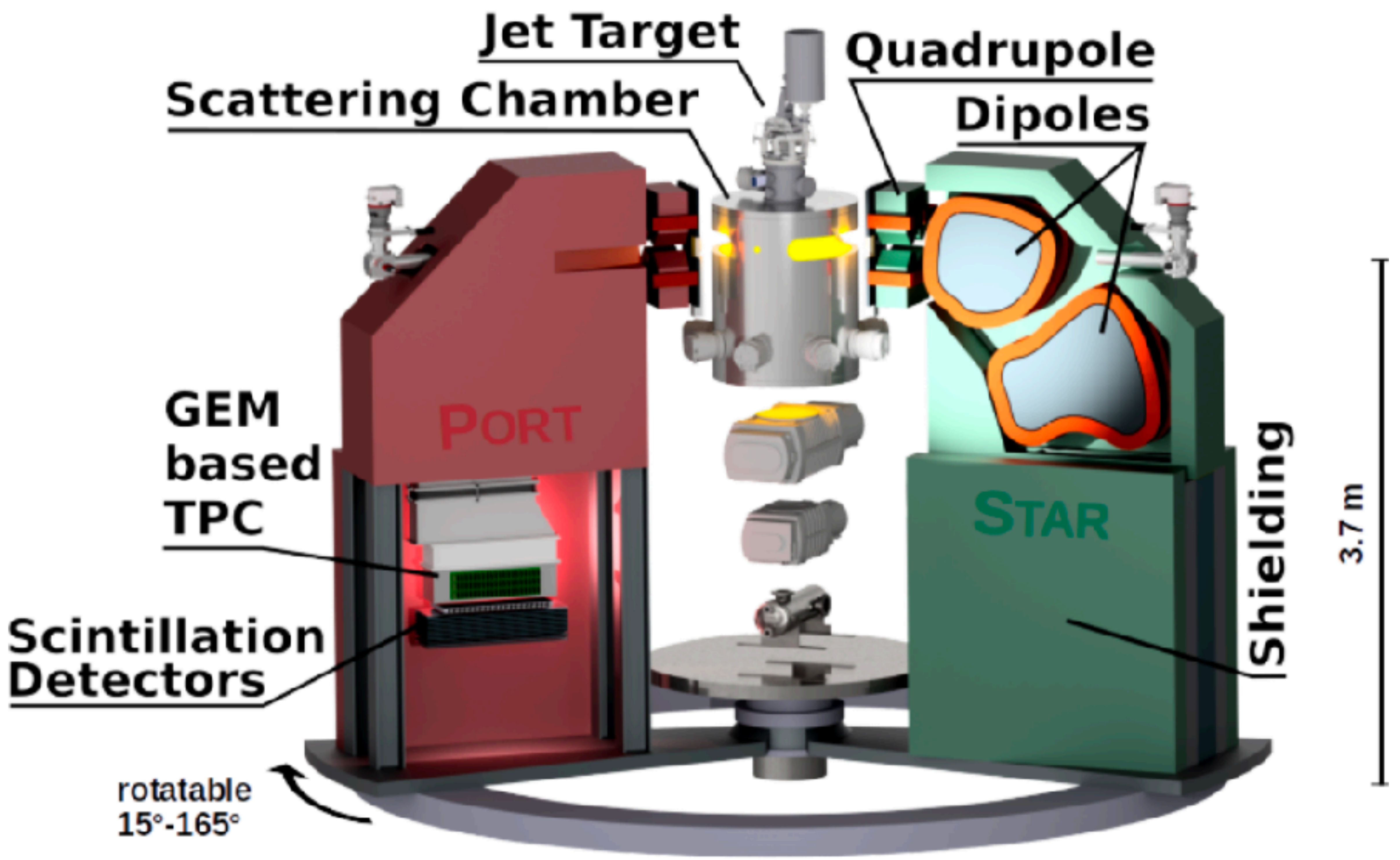
$$e^- + Ta \rightarrow e' + \gamma^* + Ta \rightarrow e' + X + Ta, \quad \text{with} \quad X \rightarrow e^+e^-$$

looking for resonant excess of e+e-

And the MAGIX experiment at Mainz

MAinz Gas Injection Target EXperiment

MAGIX (proposed experiment with MESA at Mainz)
search for A’ → e^+e^- in $M_{A'}$ = [8 - 70] MeV;
magnetic spectrometer method;
only e^+e^- detected, $\varepsilon^2 \approx [2\times10^{-7} - 8\times10^{-9}]$

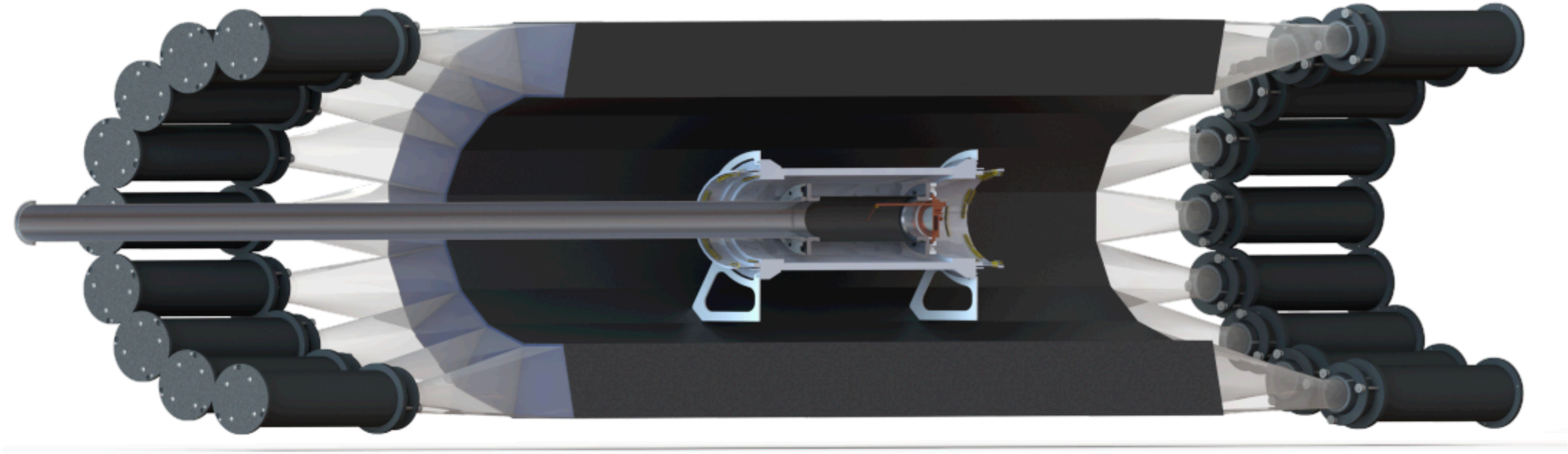


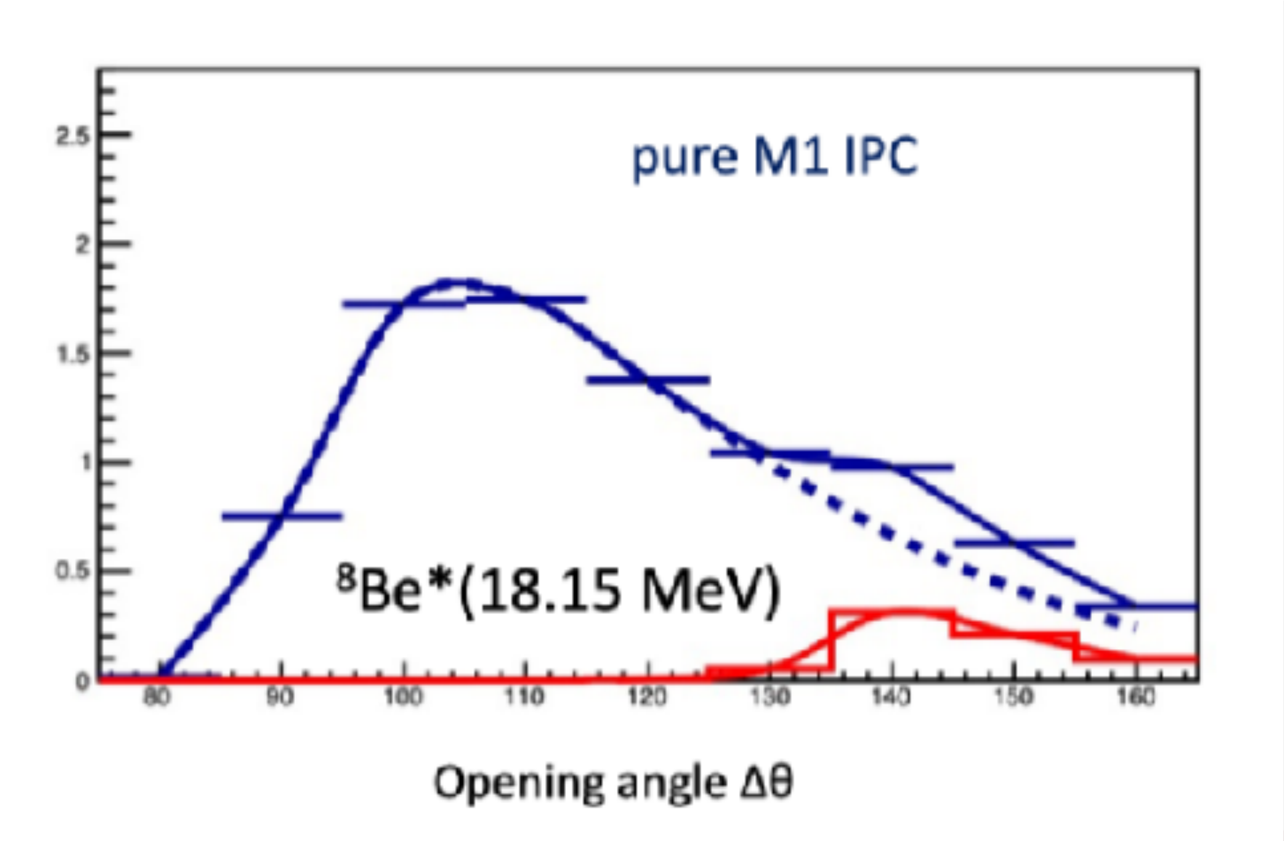
Another new effort is an ATOMKI like experiment at Montreal

Uses the University of Montreal 6 MV tandem

will measure internal pair creation from the decay of nuclear excited states

a cylindrical multiwire proportional chamber (MWPC)
and surrounded by 16 scintillator bars of length



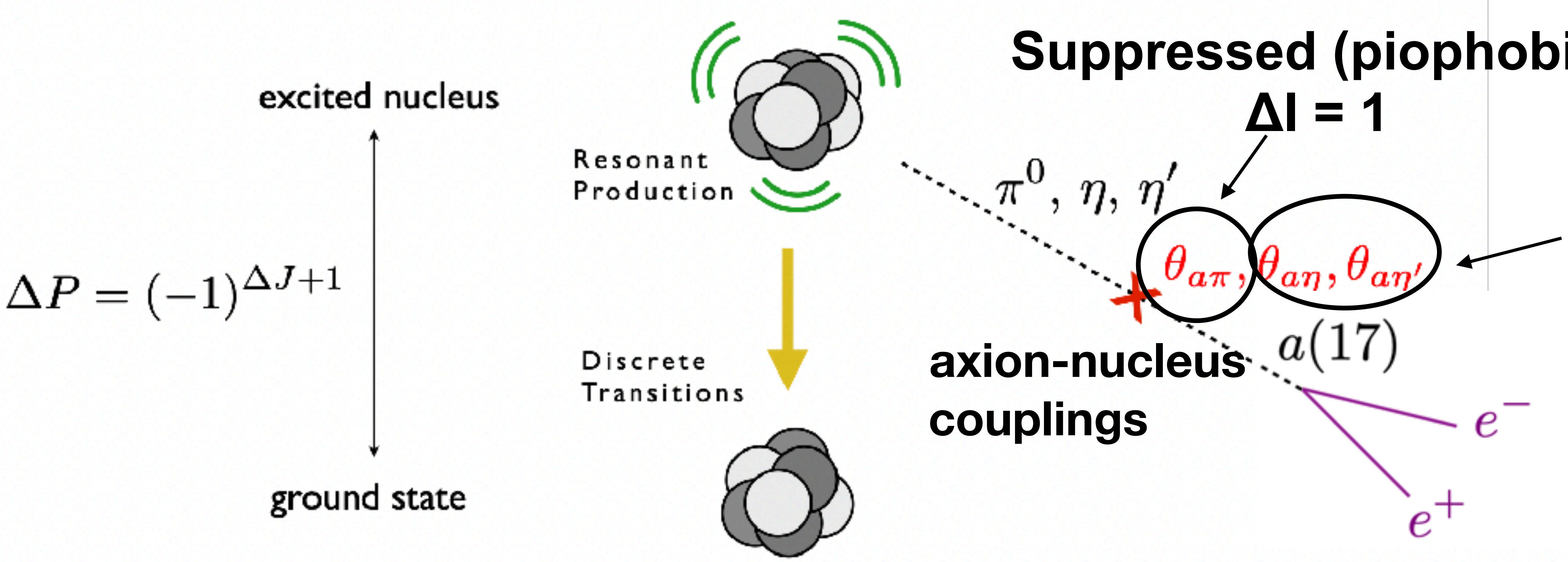


predicted opening angle distribution

G. Azuelos et al, J. Phys.: Conf. Ser. 2391 012008 (2022)

The ATOMKI anomaly can also be explained by a 17 MeV QCD Axion.

Emission possible in *magnetic* nuclear transitions with $\Delta E > m_a$

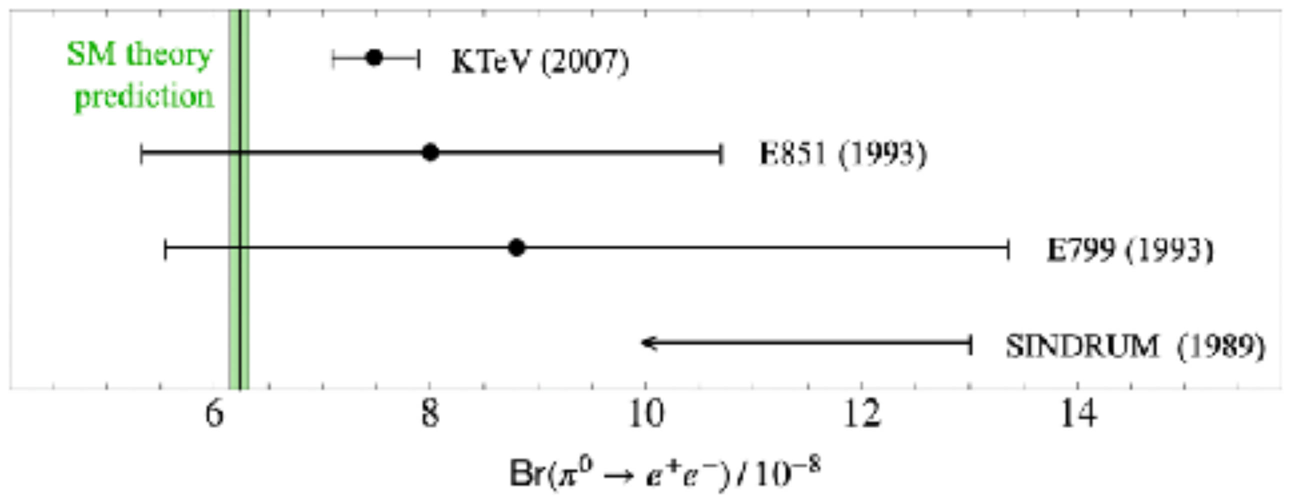


ΔI = 0 (Axion emission rates in nuclear transitions)
10^{-3} - 10^{-4} T. Donnelly et al., PRD 18 (1978)

Additional experimental constraints from rare π^0 decay and muon g-2

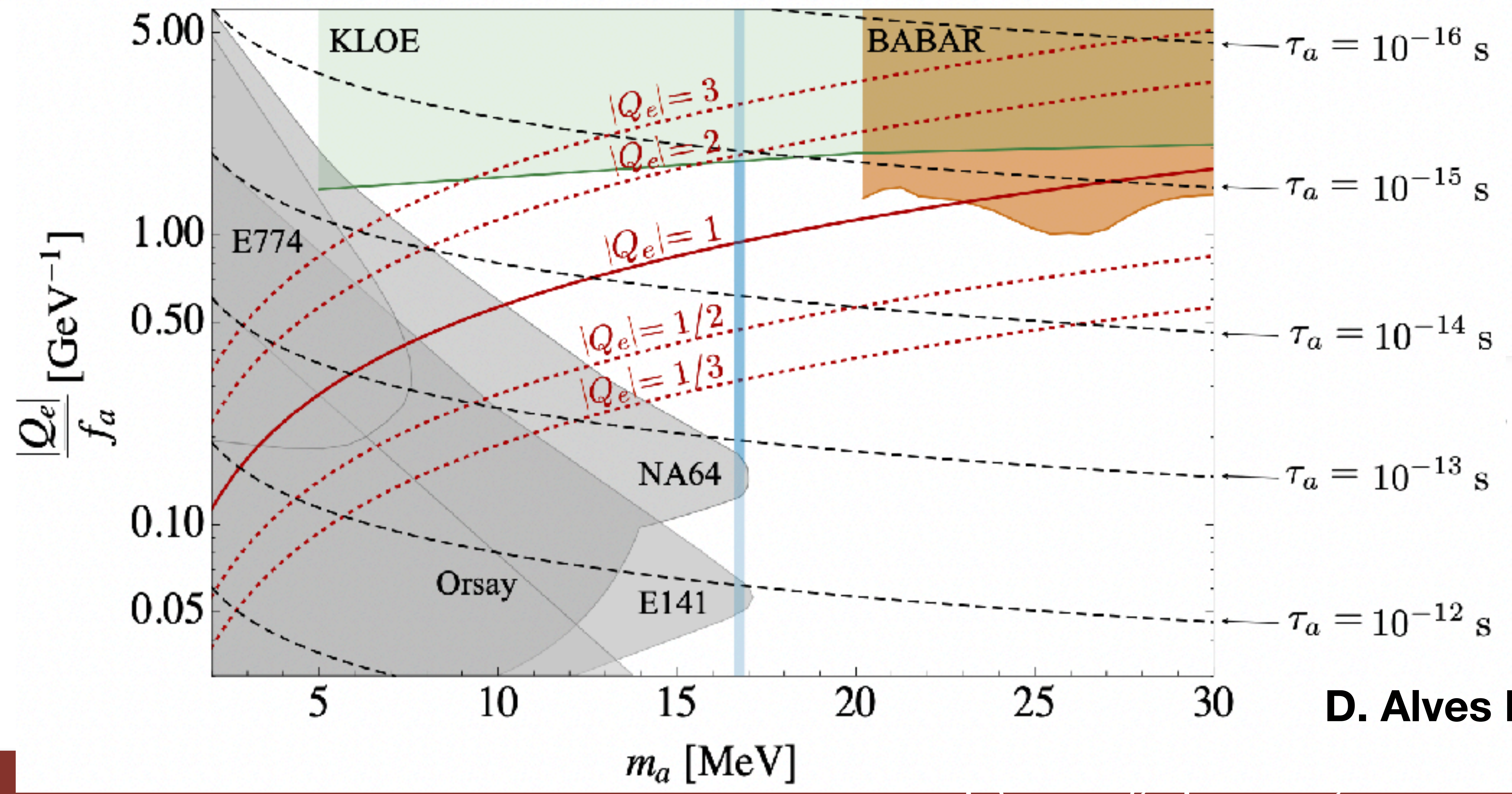
Experimentally viable QCD axion variants in the O(10 MeV) mass range must be:

- piophobic
- electrophilic
- 2nd and 3rd generation-phobic
  (i.e., muon-phobic, charm-phobic, bottom-phobic, etc)



Also explains the KTeV anomaly

from talk by D. Alves

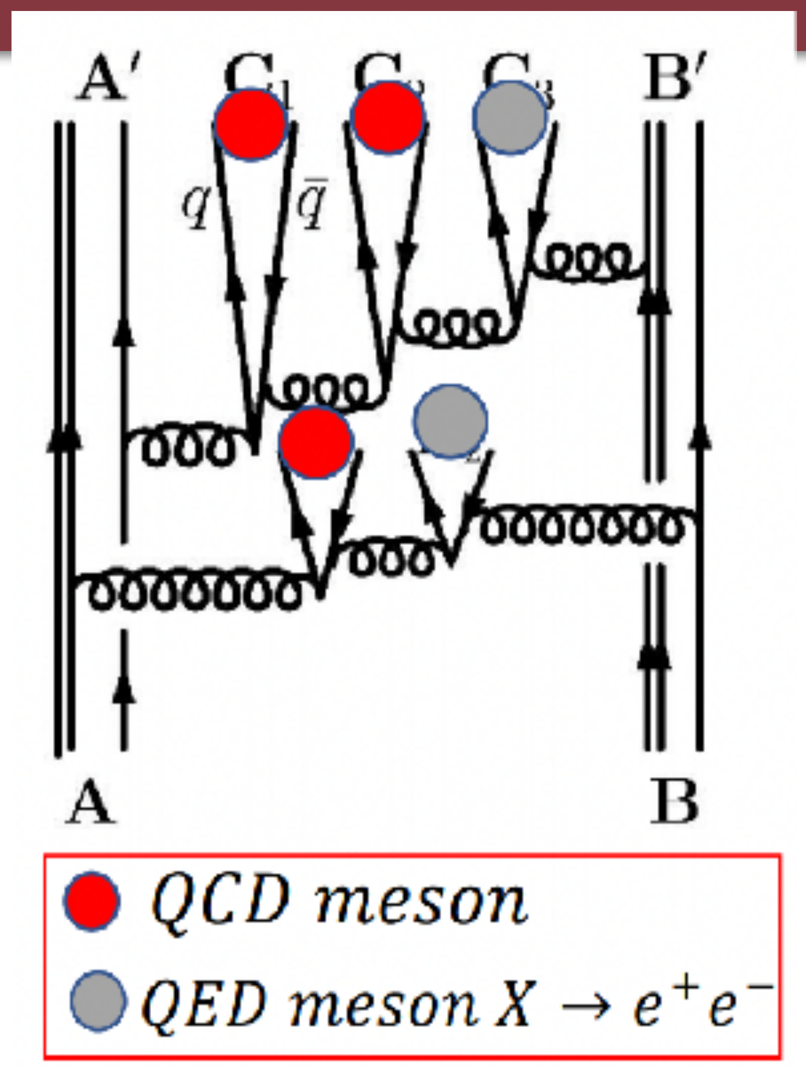


constraints on electronic coupling from ^{8}Be anomaly

$$1/5 \lesssim Q_e^{PQ} \lesssim 2$$

D. Alves PRD 103, 055018 (2021)

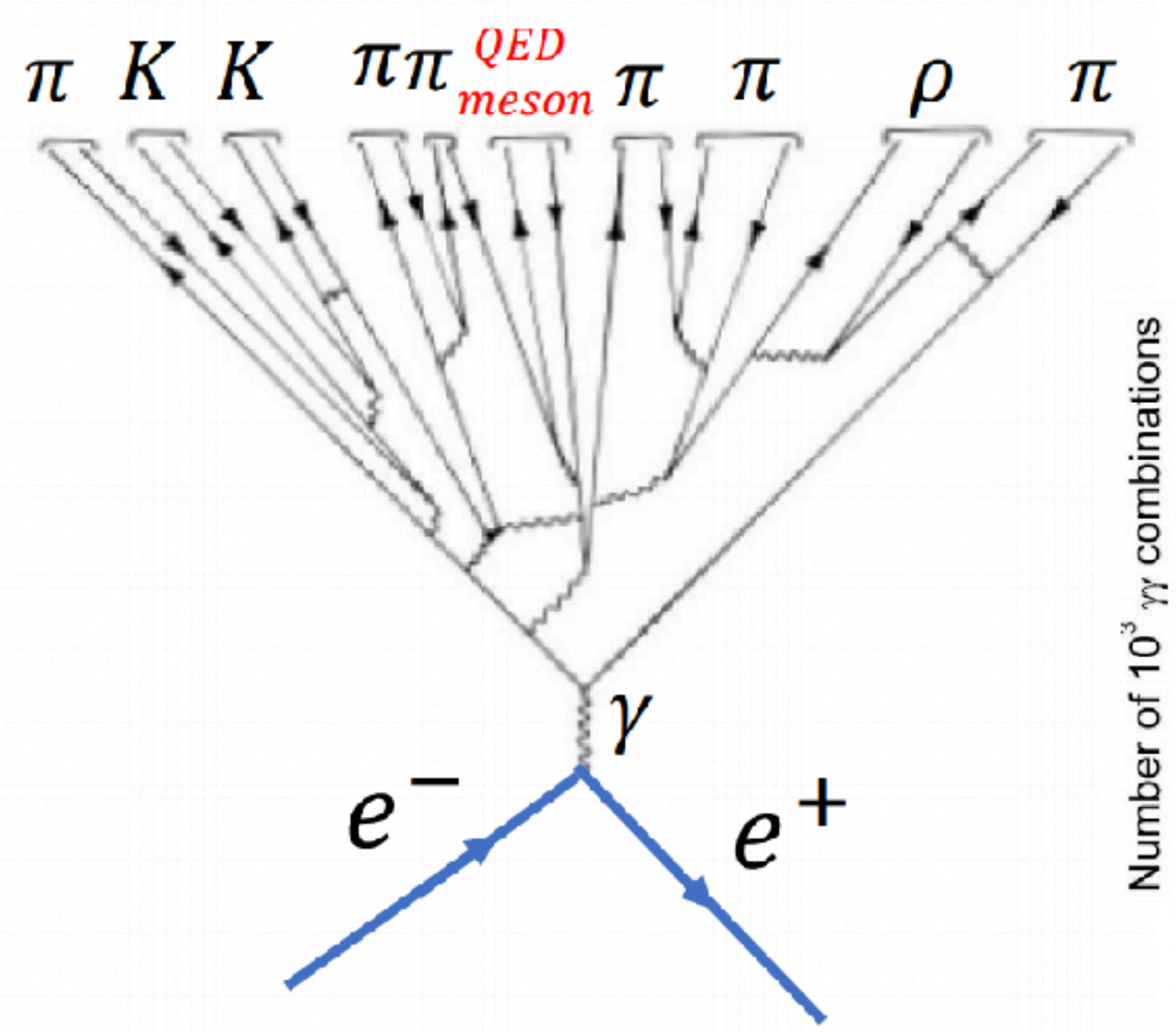
Yet another possibility is QED mesons, should be accessible at JLab



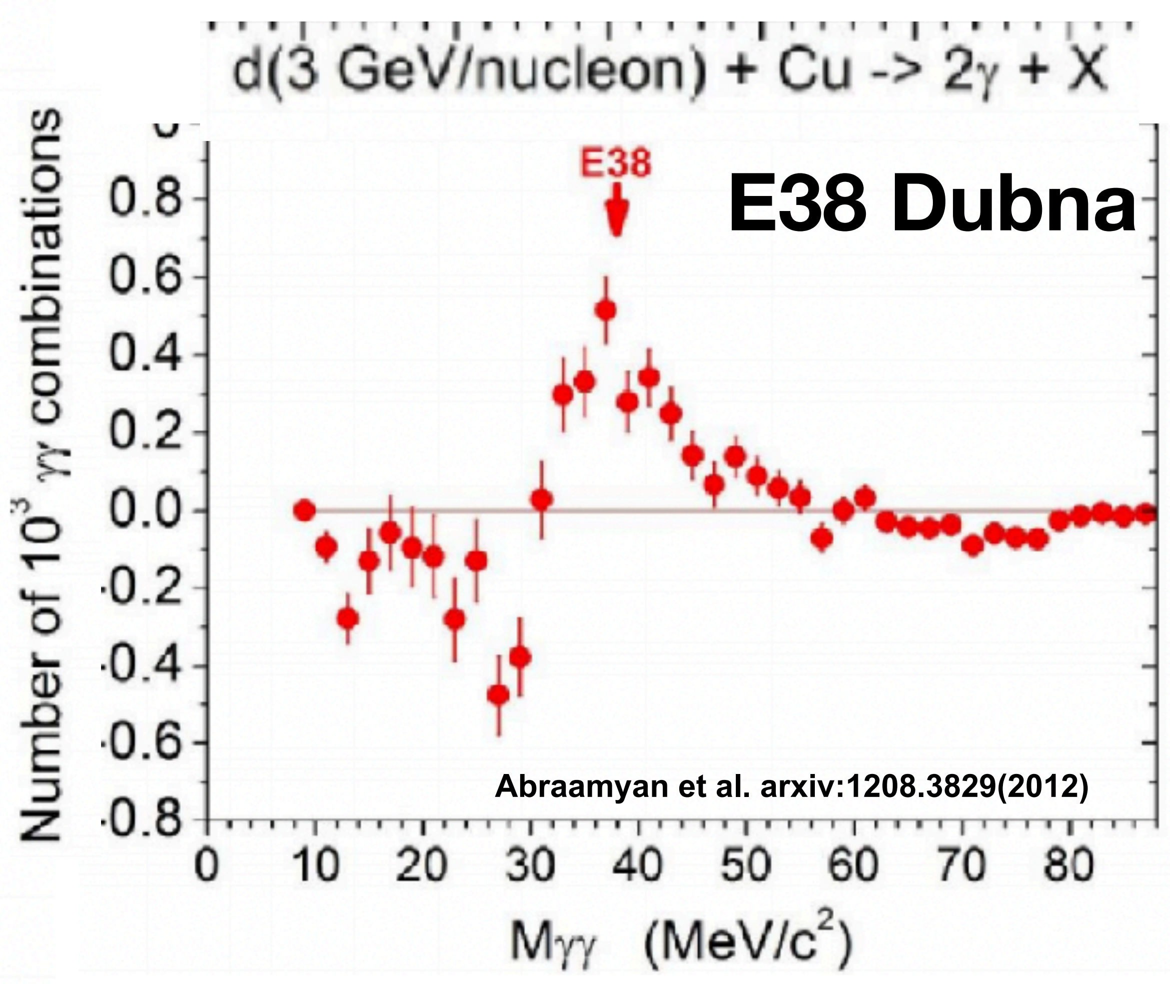
There is extensive experimental evidence that ASP - anomalous soft photons (excess e^+e^-) are produced whenever hadrons are produced. ASP yield is ~ 1/100 the hadron yield.

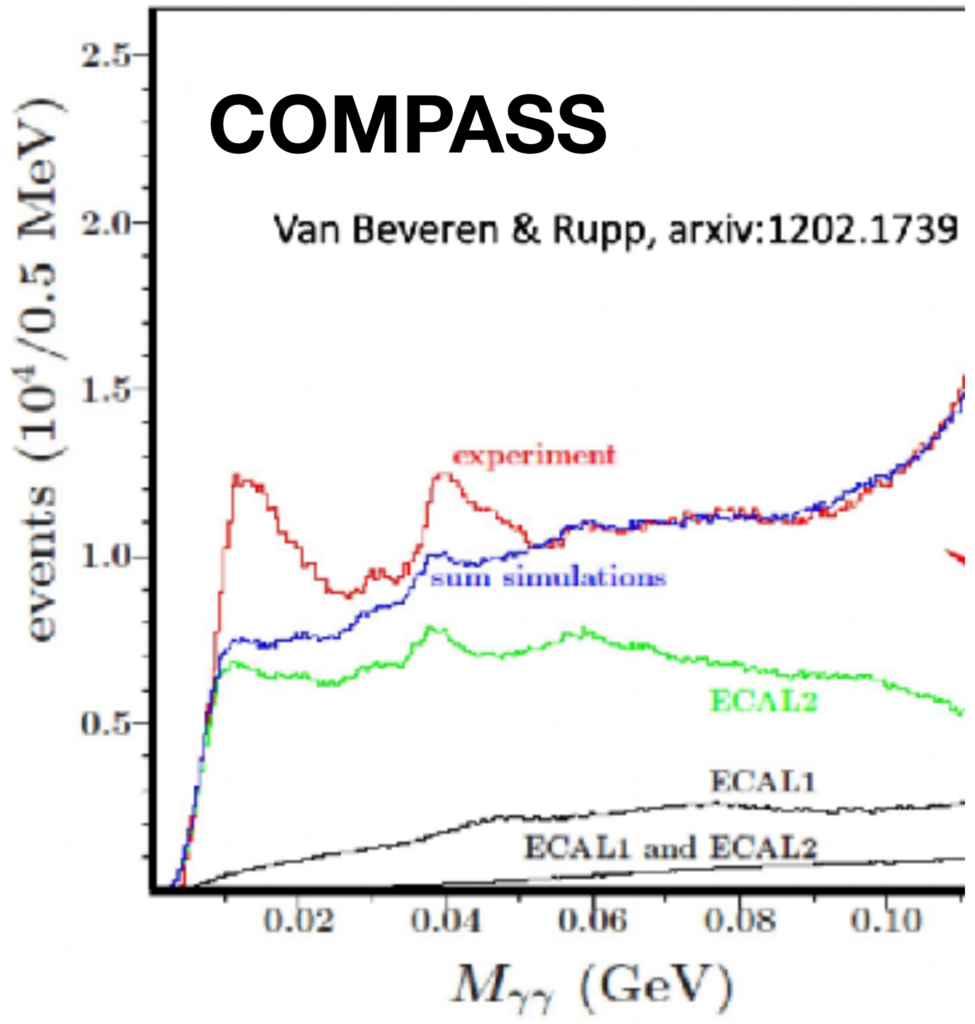
ASP could be the QED excitations of the color singlet subgroup, unlike the QCD excitations of the color octet subgroup (π^0, η, n', K, ρ....)

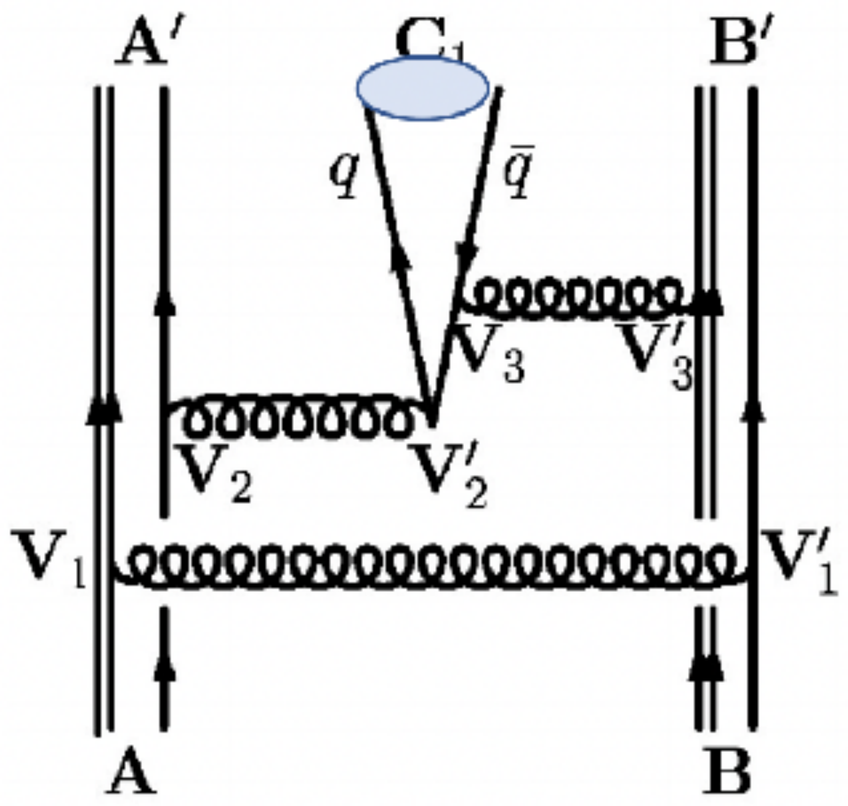
It has been shown that light quark-antiquark as massless fermions can be confined in QED (Schwinger, 1962 (1+1D) and Gribov, 1982 (3+1D))



QED mesons can be detected by $\gamma\gamma$, $\gamma^*\gamma^*$, e^+e^-
ASP, X17 and other anomalies may be due to QED mesons



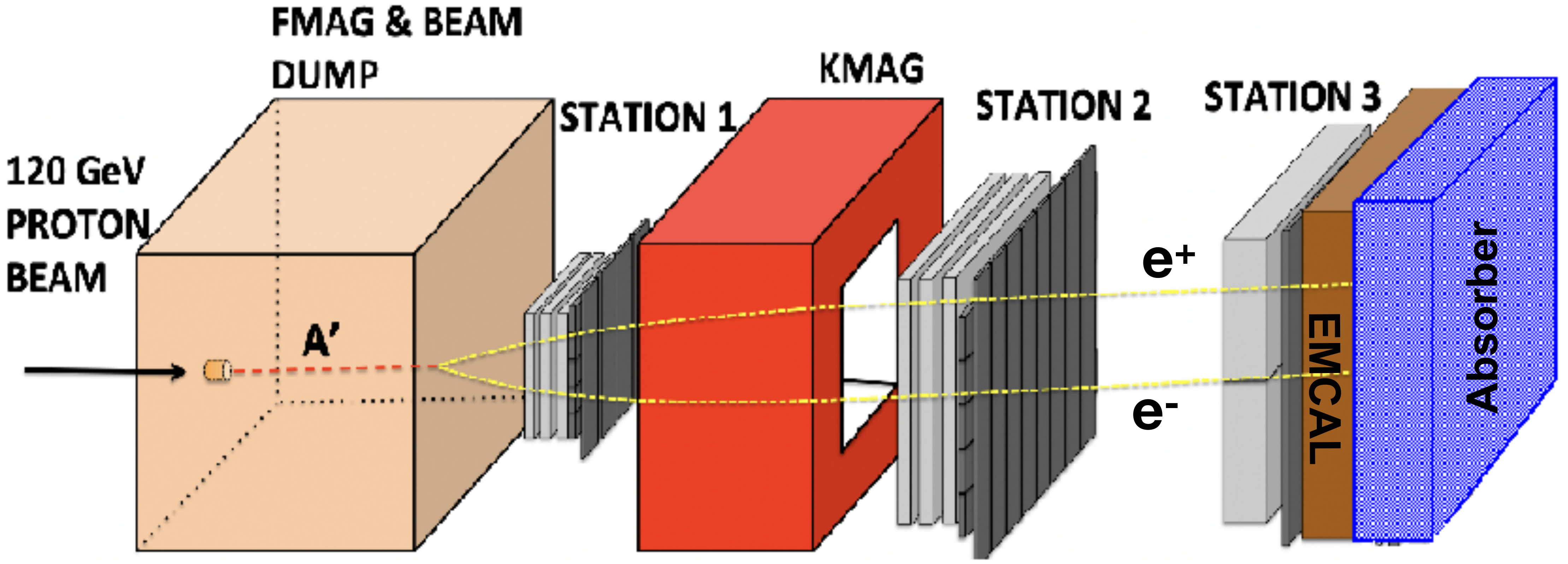




from
talk by C. Y. Wong

C.Y.Wong, arXiv:2108.00959, C.Y. Wong, PRC 81,064903(2010), [arXiv:1001.1691]

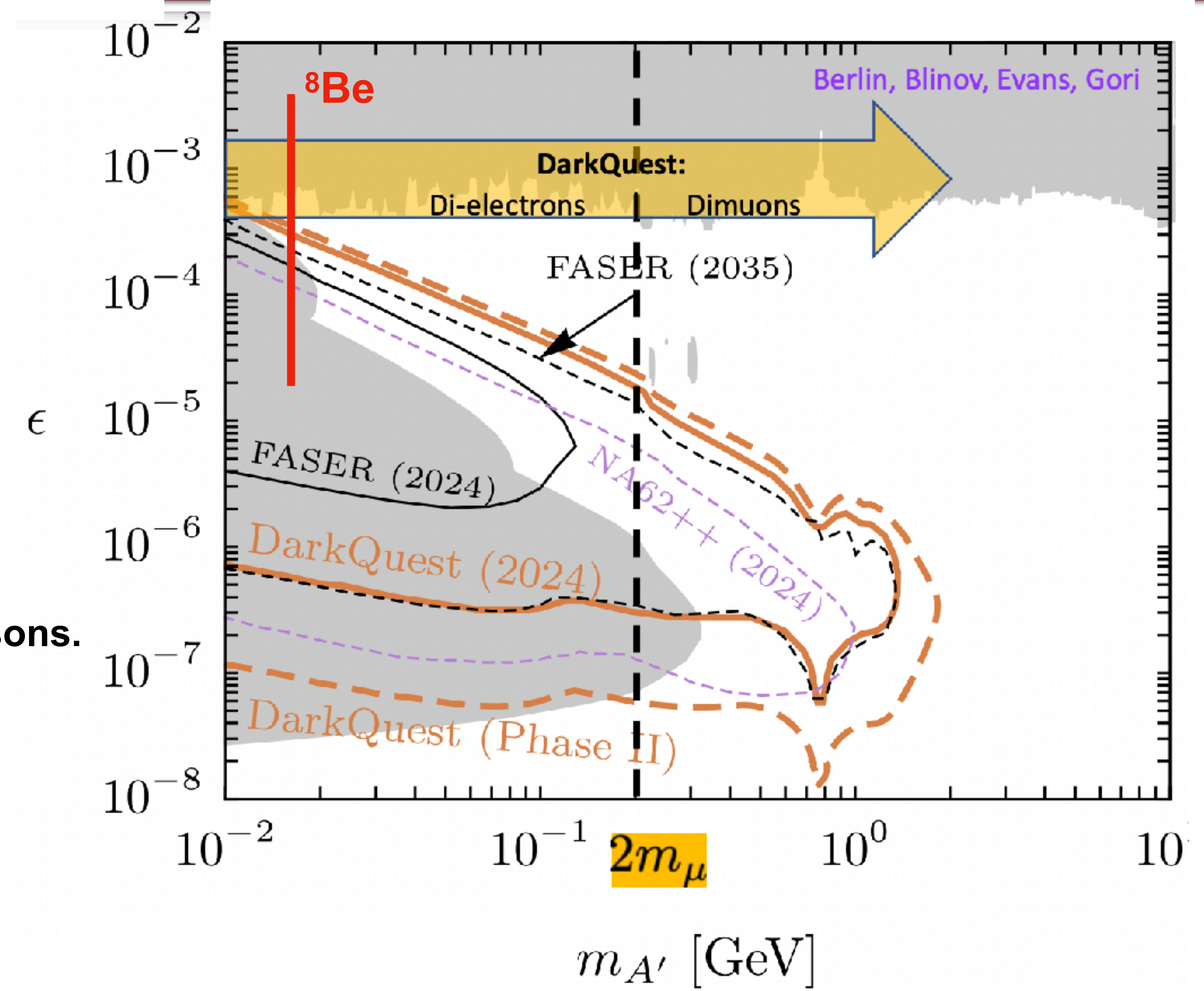
DarkQuest one of the few hadronic experiments to cover some of the remaining phase space.



Adapted from Phys. Rev. D 93, 115015 (2016)

One of the few proton induced experiments, sensitive to the X17, QCD axion, ASP and QED mesons.

unique sensitivity as a hadronic experiment



from talk by M. Liu

Summary

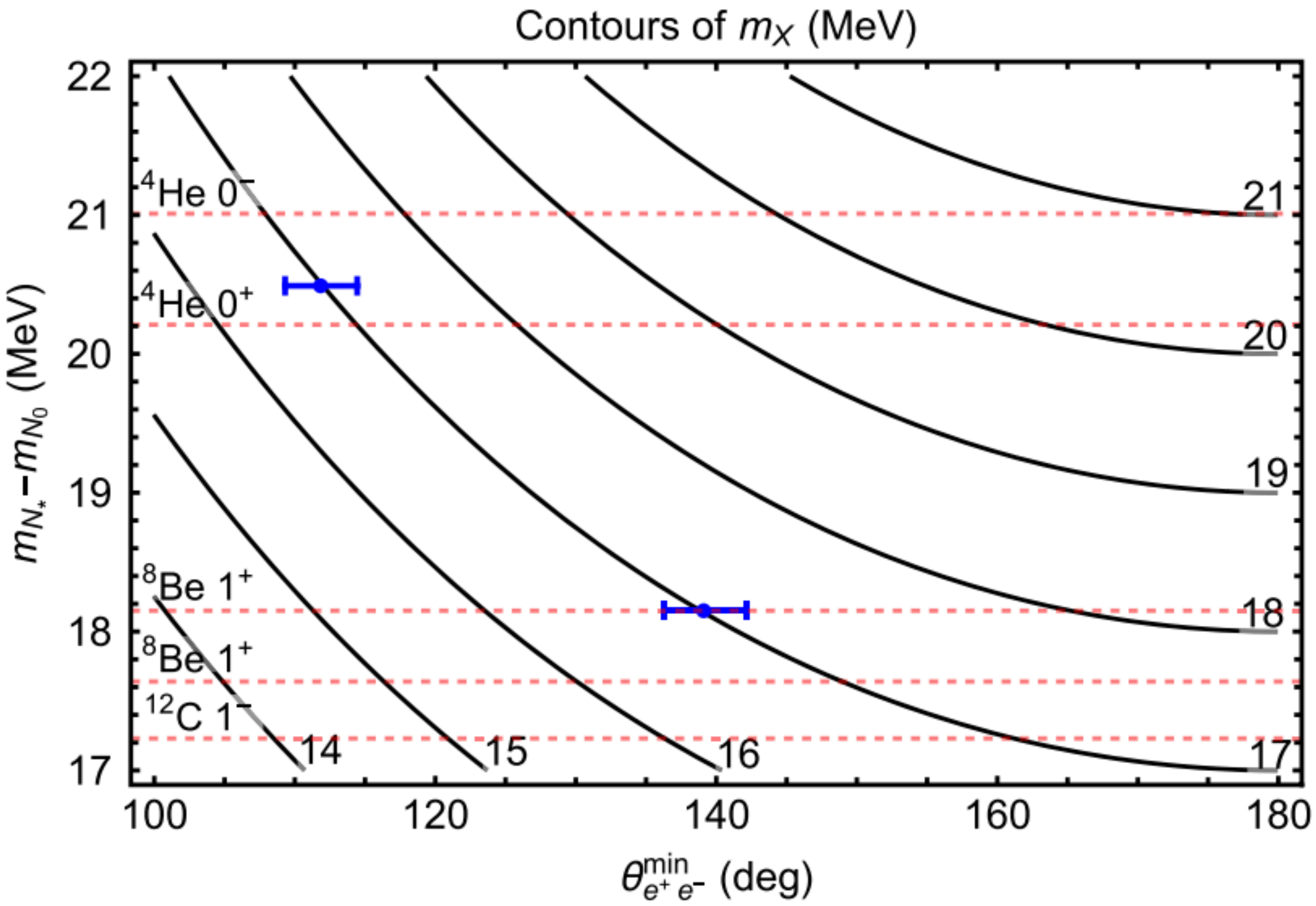
The ATOMKI ^{8}Be results, a tantalizing anomaly from about 6 years ago has been confirmed and supplemented with ^{4}He and ^{12}C results.

Beyond Standard Model explanations require a weakly interacting light ~17 MeV particle which has implications for dark matter.

Several interesting ideas have been put forward to explain these results and a number of new experiments are underway or are approved to run.

The upcoming JLab experiment has a unique role to play in the search for the X17 and testing a number of proposed explanations.

This work was supported by US DOE grant DE-FG02-07ER41528



N_*	$J_*^{P_*}$	T_*	Γ_{N_*} [keV]	$B(N_* \to N_0\gamma)$
^{8}Be(18.15)	1^+	0	138	1.4×10^{-5}
^{8}Be(17.64)	1^+	1	10.7	1.4×10^{-3}
^{12}C(17.23)	1^-	1	1150	3.8×10^{-5}
^{4}He(21.01)	0^-	0	840	0
^{4}He(20.21)	0^+	0	500	6.6×10^{-10} (E0)