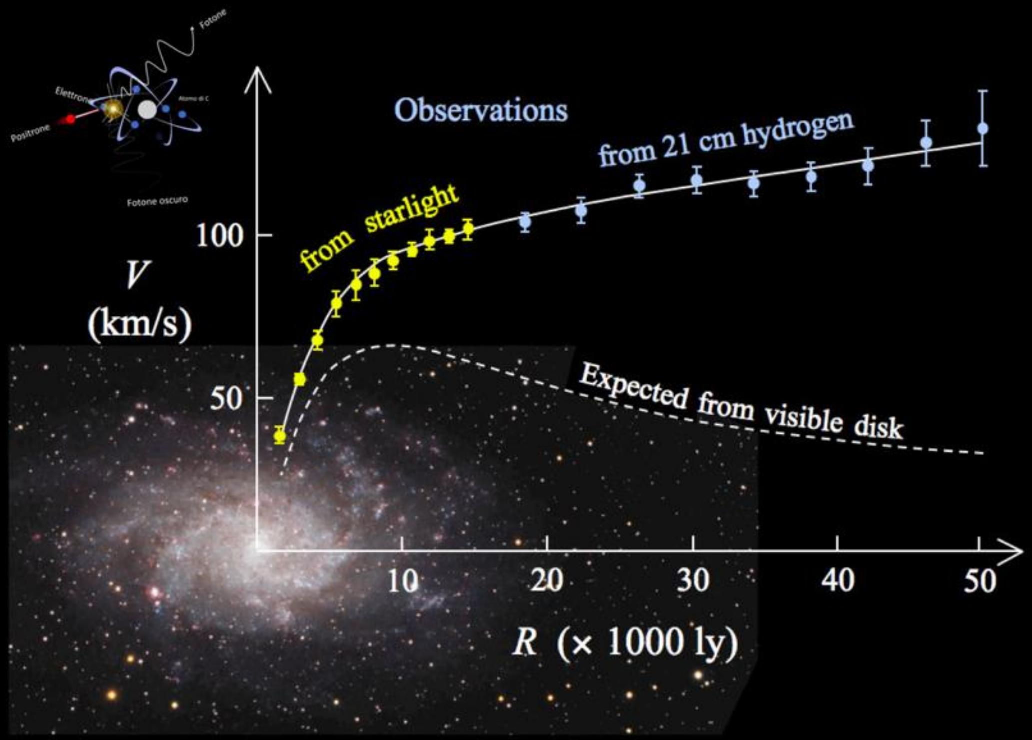
New evidence of hidden sectors in Atomki anomalies?

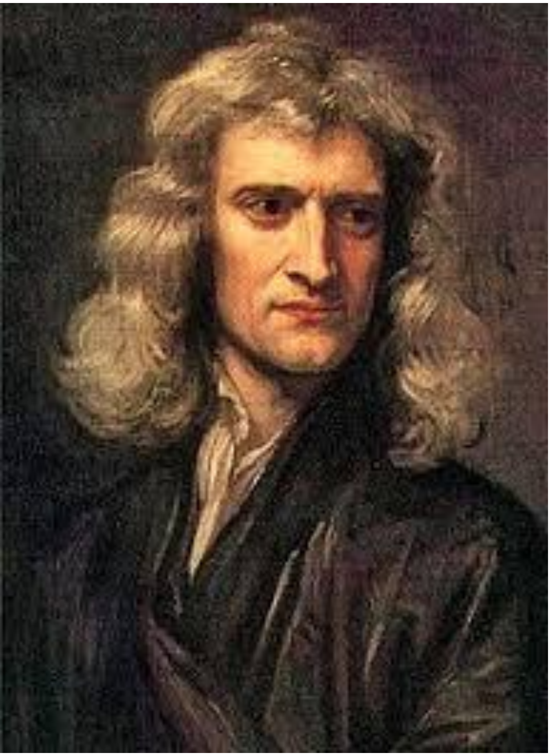


Prof. Mauro Raggi
CERN and Sapienza Università di Roma
EPFL Lausanne Seminar
May 6th 2024

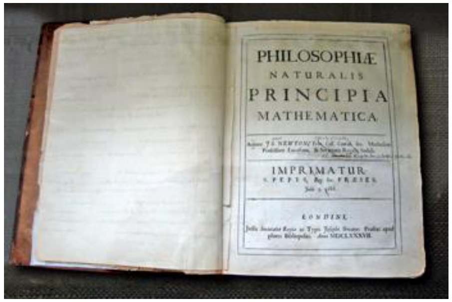
Outline

- The Dark Matter problem
- The ATOMKI anomaly and the X_{17}
- Experimental directions
- What is the nature of X_{17}? Is X_{17} a dark Matter Candidate?

Everything started with an apple!



Sir **Isaac Newton**
(1642 – 1726)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

IMPRIMATUR

LONDINI

Principia 1687

"It happened while he was sitting in contemplation, because of the fall of an apple." 1665

$$F = -G\frac{M_1 M_2}{d^2}$$

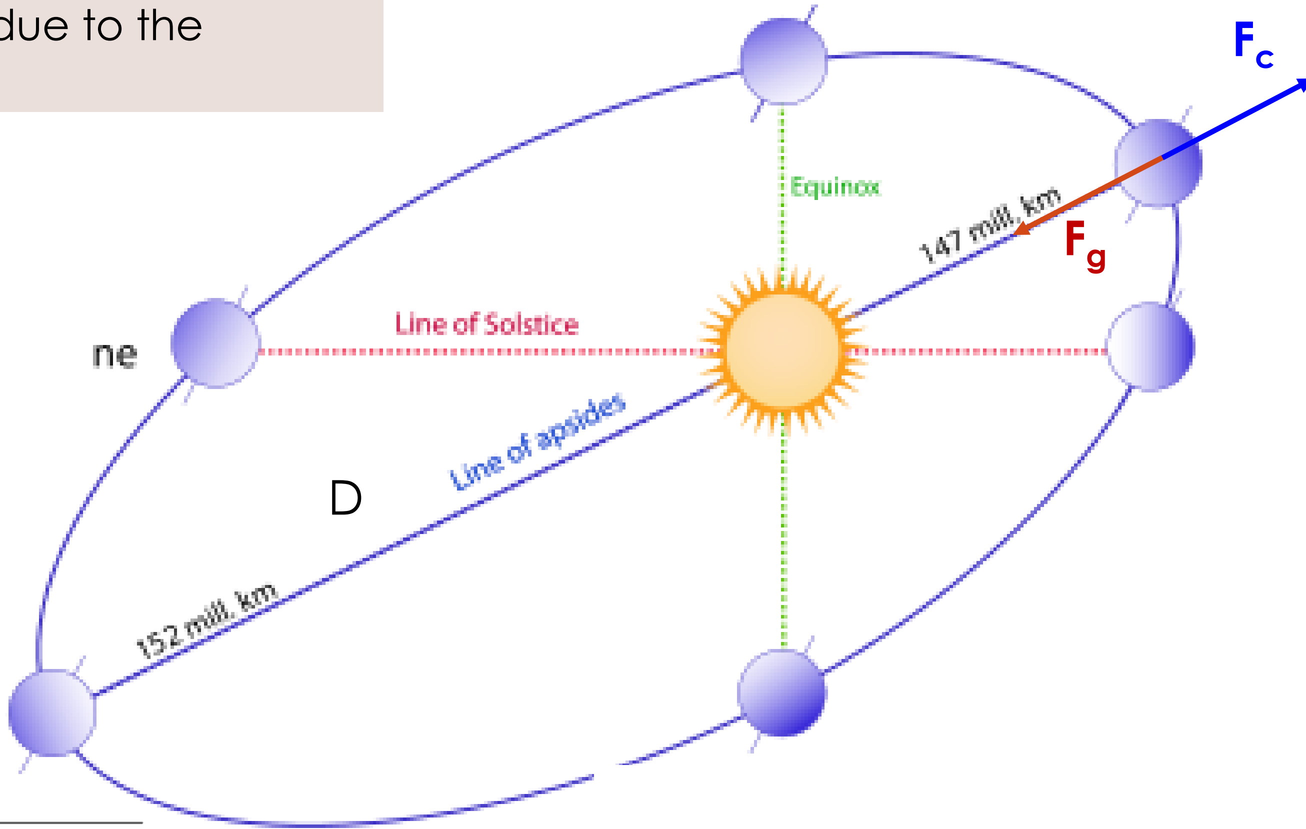
$$F = -G\frac{M_{Terra} M_{Mela}}{d^2}$$

He realized almost immediately that his law could explain Kepler's laws and therefore also applied to the planets motion!

The orbits of the planets: a subtle balance

The planet maintain its orbit due to the equilibrium of two forces:

$$\overset{F_c}{\boxed{m_T\frac{v^2}{D}}} = \overset{F_g}{\boxed{-G\frac{m_T M_S}{D^2}}}$$



Solving for the velocity

$$\cancel{m_T}\frac{v^2}{\cancel{D}} = -G\frac{\cancel{m_T} M_S}{D^{\cancel{2}}}$$

$$v^2 = -G\frac{M_S}{D}$$

$$|v| = \sqrt{G\frac{M_S}{D}} = \sqrt{6.67\times10^{-11}\frac{2\times10^{30}}{150\times10^{9}}} = 29.8\ km/s$$

The speed at which a planet orbits a massive body decreases as the distance from the body increases, following a 1/√D relationship.

Predicting planet’s velocities

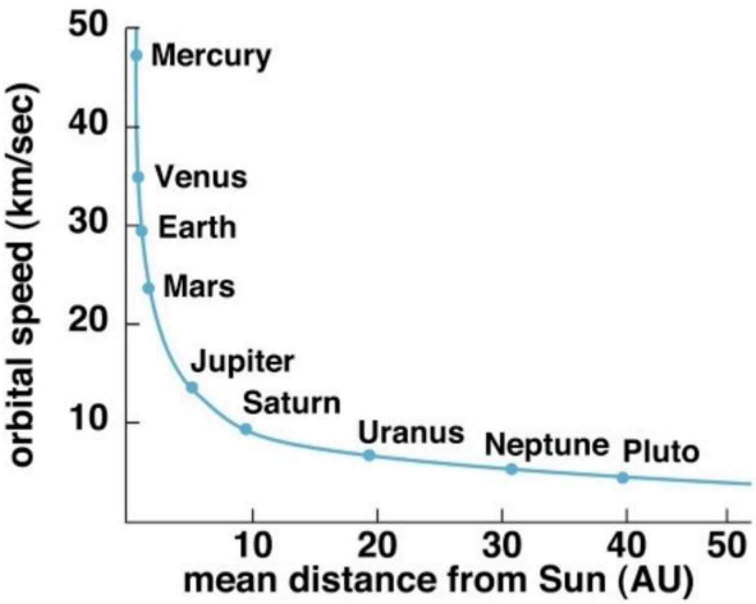
Given **Earth travels at ~29.8 km/s**, what conclusions can we draw about the velocities of the other planets?

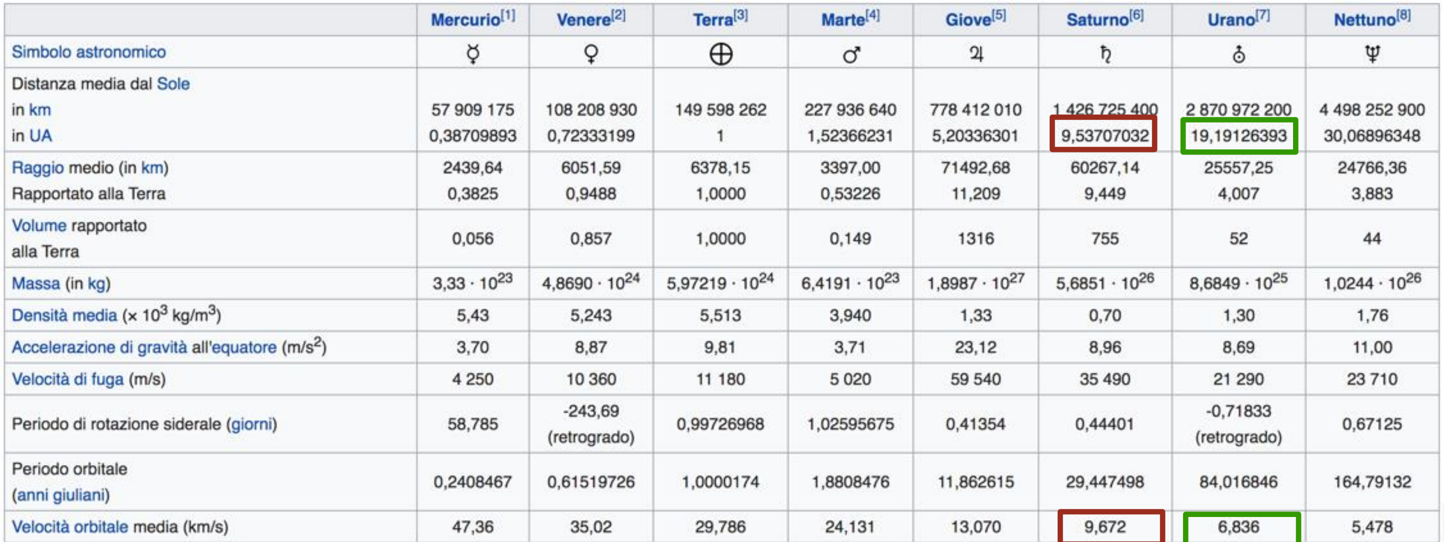
Saturn is ~10 times farther from the sun than the earth therefore:

$$v_S = \frac{v_E}{\sqrt{D}} = \frac{29.8}{\sqrt{9.53}} = 9.65\ km/s$$

Uranus is ~19 times farther from the sun than the earth therefore:

$$v_U = \frac{v_E}{\sqrt{D}} = \frac{29.8}{\sqrt{19.2}} = 6.8\ km/s$$



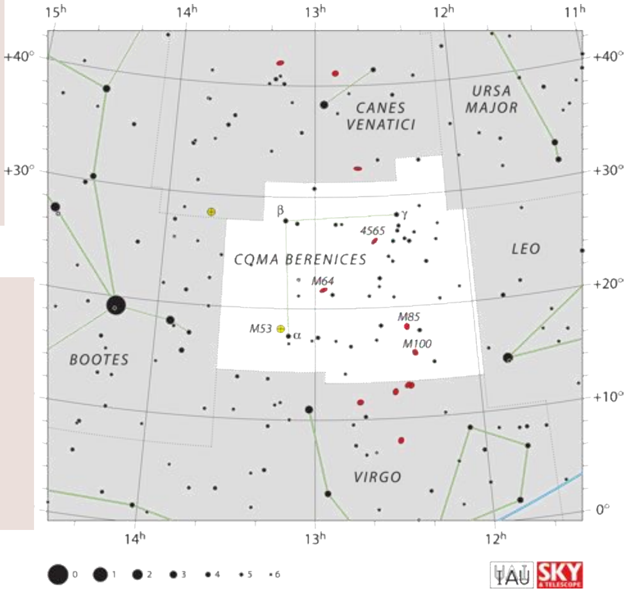


	Mercurio[1]	Venere[2]	Terra[3]	Marte[4]	Giove[5]	Saturno[6]	Urano[7]	Nettuno[8]
Simbolo astronomico	☿	♀	⊕	♂	♃	♄	⛢	♆
Distanza media dal Sole in km in UA	 57 909 175 0,38709893	 108 208 930 0,72333199	 149 598 262 1	 227 936 640 1,52366231	 778 412 010 5,20336301	 1 426 725 400 9,53707032	 2 870 972 200 19,19126393	 4 498 252 900 30,06896348
Raggio medio (in km) Rapportato alla Terra	2439,64 0,3825	6051,59 0,9488	6378,15 1,0000	3397,00 0,53226	71492,68 11,209	60267,14 9,449	25557,25 4,007	24766,36 3,883
Volume rapportato alla Terra	0,056	0,857	1,0000	0,149	1316	755	52	44
Massa (in kg)	$3,33 \cdot 10^{23}$	$4,8690 \cdot 10^{24}$	$5,97219 \cdot 10^{24}$	$6,4191 \cdot 10^{23}$	$1,8987 \cdot 10^{27}$	$5,6851 \cdot 10^{26}$	$8,6849 \cdot 10^{25}$	$1,0244 \cdot 10^{26}$
Densità media (× 10^3 kg/m^3)	5,43	5,243	5,513	3,940	1,33	0,70	1,30	1,76
Accelerazione di gravità all'equatore (m/s^2)	3,70	8,87	9,81	3,71	23,12	8,96	8,69	11,00
Velocità di fuga (m/s)	4 250	10 360	11 180	5 020	59 540	35 490	21 290	23 710
Periodo di rotazione siderale (giorni)	58,785	-243,69 (retrogrado)	0,99726968	1,02595675	0,41354	0,44401	-0,71833 (retrogrado)	0,67125
Periodo orbitale (anni giuliani)	0,2408467	0,61519726	1,0000174	1,8808476	11,862615	29,447498	84,016846	164,79132
Velocità orbitale media (km/s)	47,36	35,02	29,786	24,131	13,070	9,672	6,836	5,478

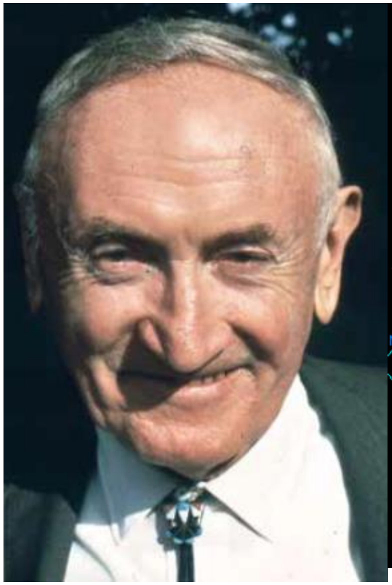
1AU = distance Earth-Sun

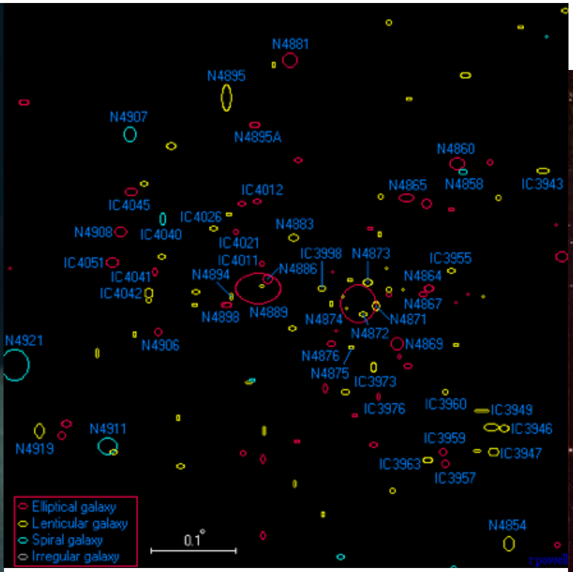
That's not the whole story: Zwicky's doubts

Fritz Zwicky (1898–1974)
Studying the speed of 8 galaxies in the Coma Cluster in 1933, he found that they were moving too fast to still be in the cluster!



From these measurements he calculated that the mass of the cluster was 400 times that derived from the mass of visible matter. He concluded that there must be some non-visible matter which he called "dark matter"





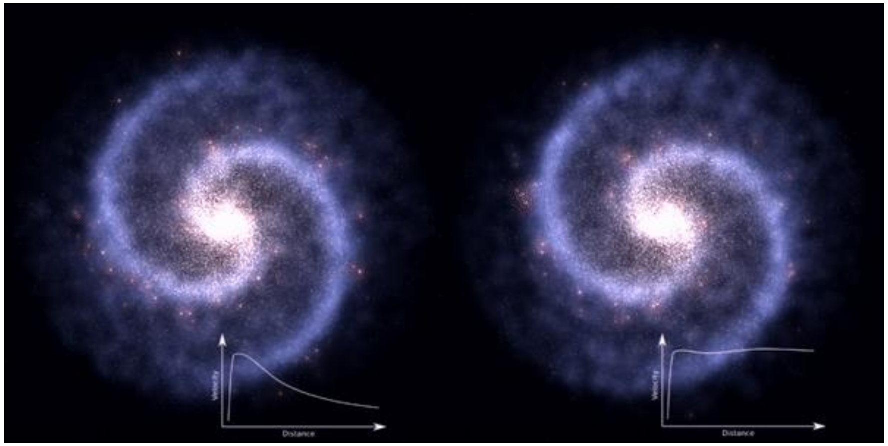
Vera Rubin rotation curves

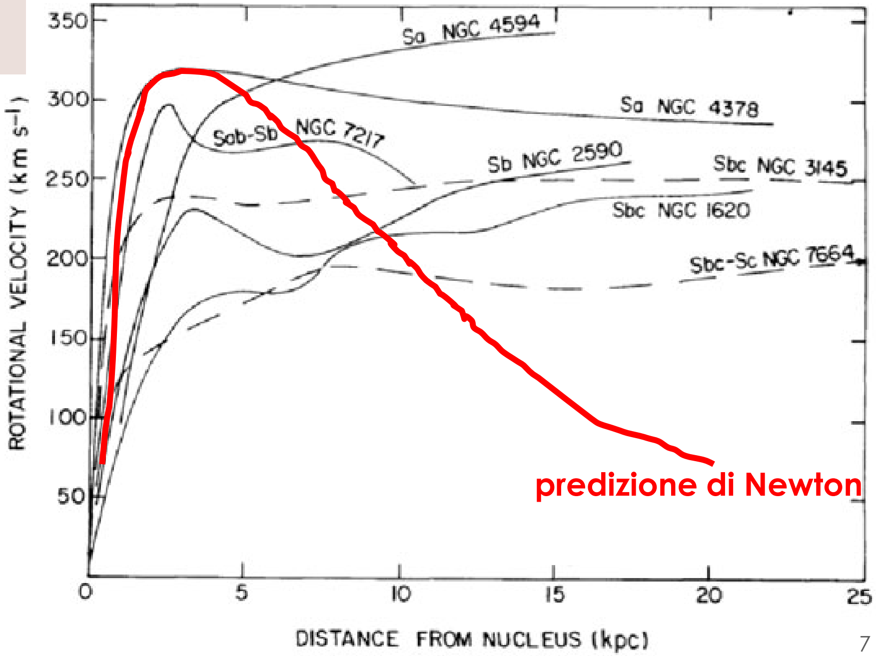
Vera Rubin - Kent Ford

In **1974** they measured the stars rotation speed in spiral galaxies, particularly the andromeda one. The observed star velocities were very different from Newton's predictions!

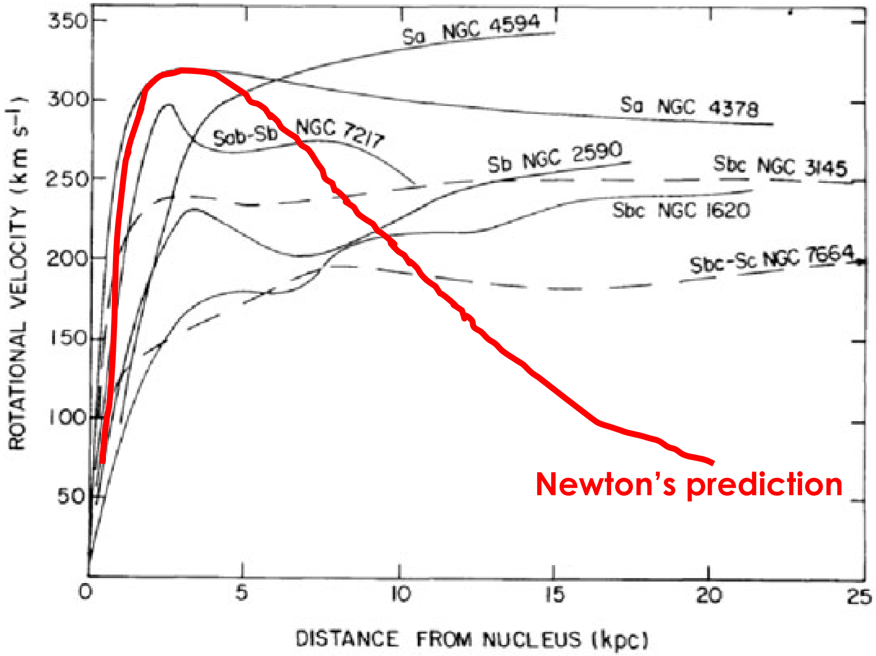
The **rotation speed was constant**!

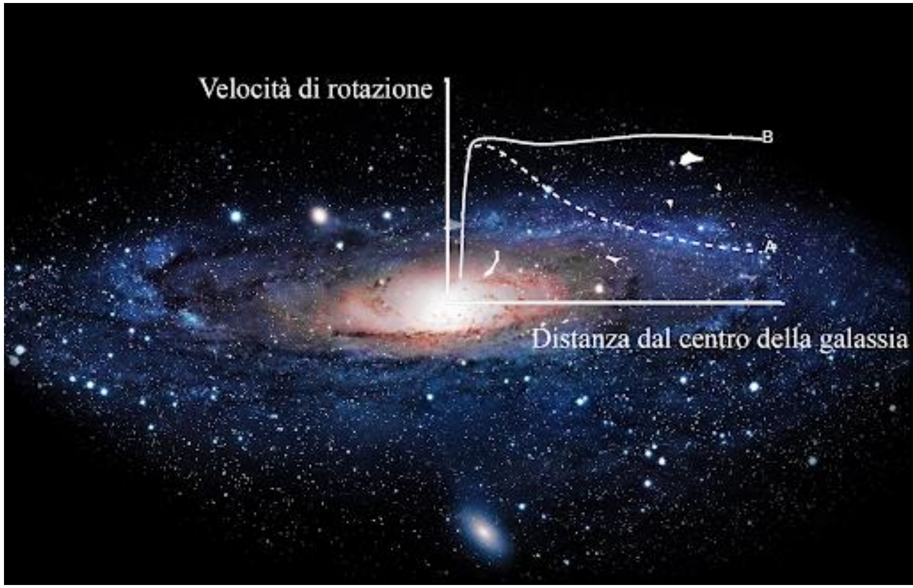
Rubin's calculation suggested that the **observed matter was less than one-fifth of what was needed**, leading to Zwicky's proposition of the existence of invisible matter as the only plausible explanation!





Understanding a rotation curve





According to Newton and Visible Matter

1) Inside the galaxy core using inner mass M(r)

$$v = \sqrt{\frac{GM(r)}{r}} = \sqrt{\frac{G\rho(4/3\pi r^{\cancel{3}})}{\cancel{r}}} = \sqrt{G\rho(4/3\pi r^2)} \approx Kr$$

2) Outside the galaxy core using full visible core mass

$$v = \sqrt{\frac{GM_{Core}}{r}} \sim \frac{K}{\sqrt{r}}$$

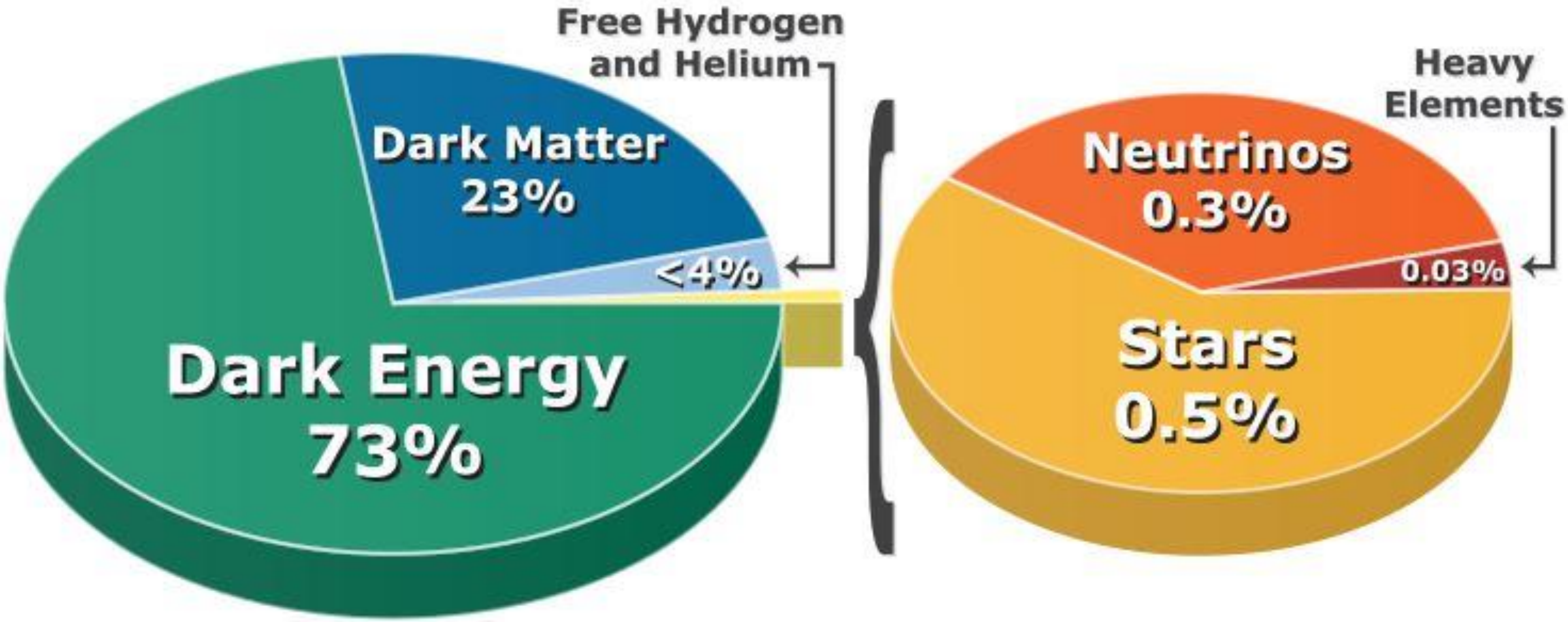
How to make the rotation curve flat outside the core?

$$v = \sqrt{\frac{GM(r)}{r}}$$

$$v = cost. \quad \Rightarrow \quad M(r) \propto r$$

this additional mass is what we call "the Dark Matter"!

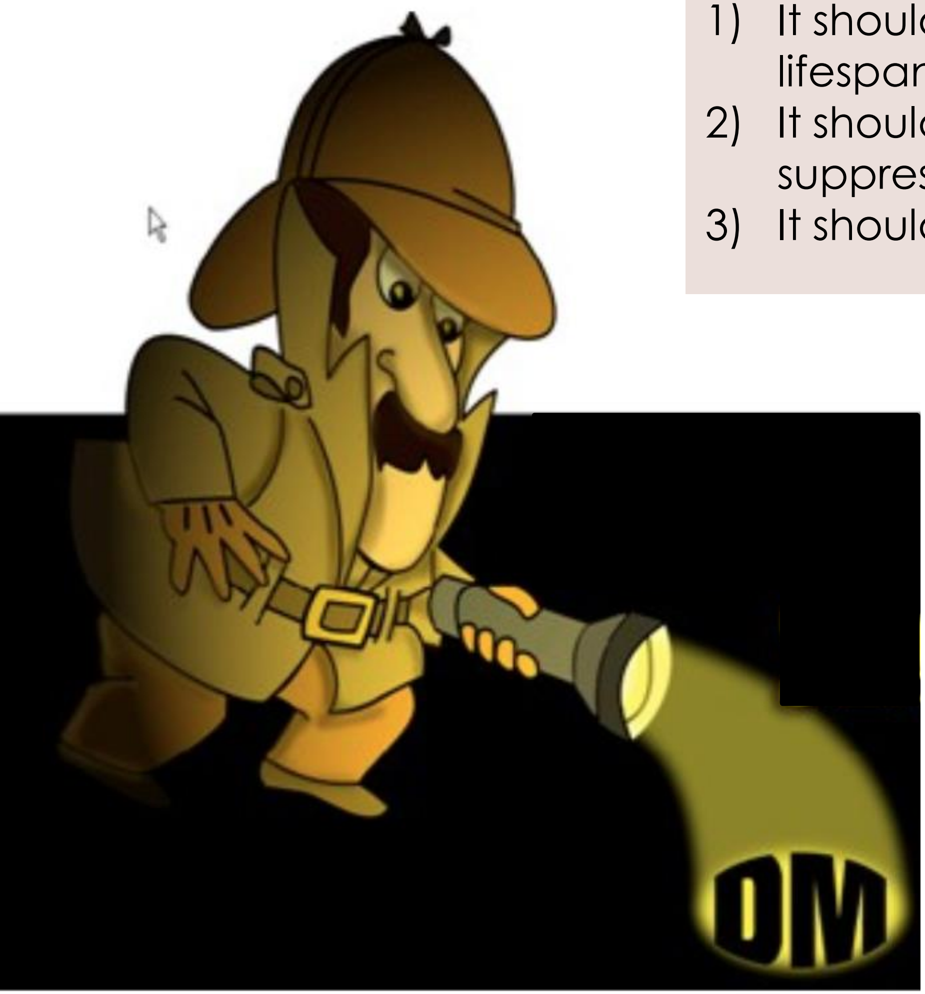
What is the universe made up of?



Ordinary matter accounts for less than 20% of the matter in the universe.
All planets, asteroids, etc., constitute less than 0.03% of the universe mass!

Are we sure that dark matter is not composed of ordinary matter?

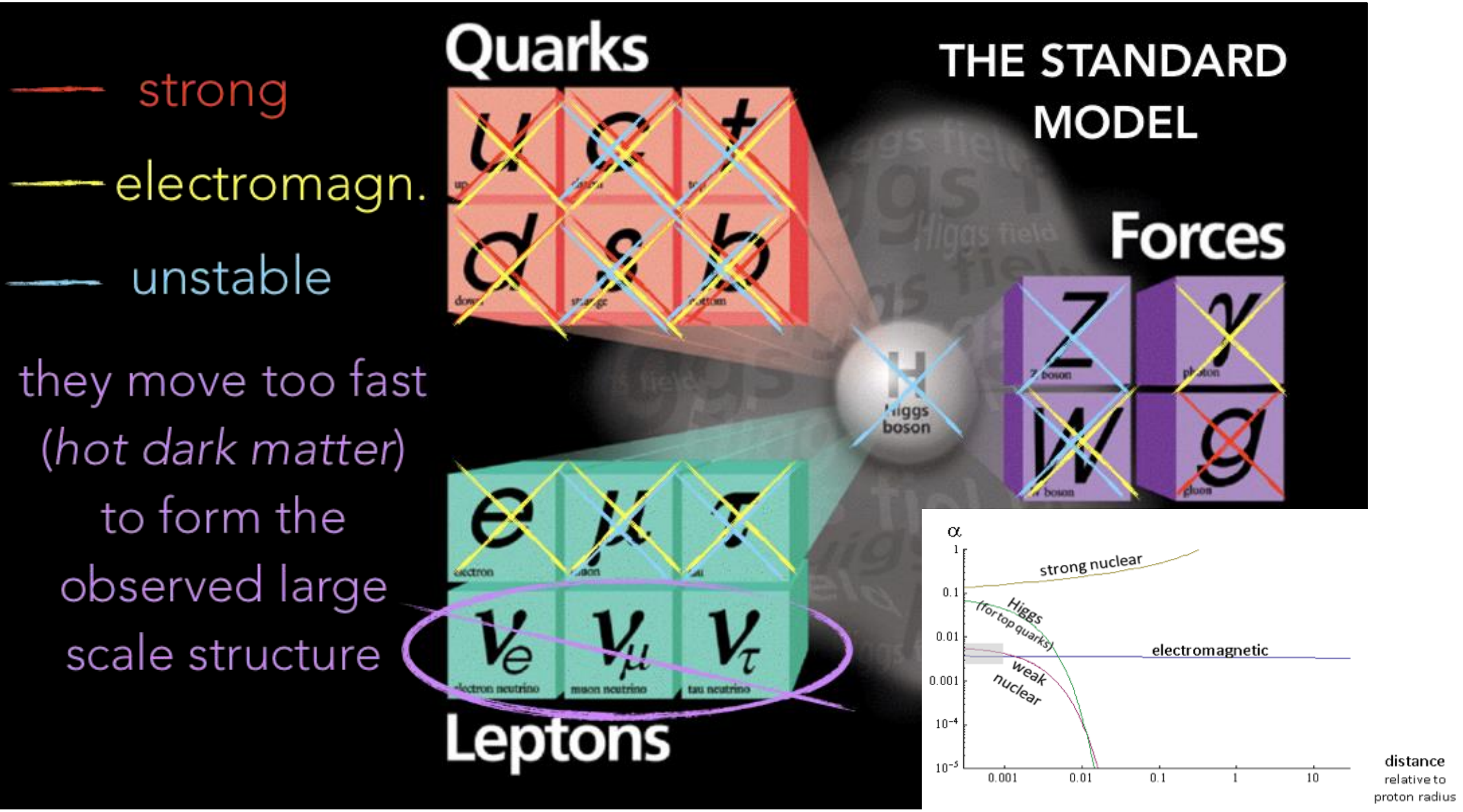
Identikit of the DM: particle hypothesis



Identikit of the Dark Matter

1) It should be stable (or at least have an average lifespan of over 13 billion years!).
2) It should be electrically neutral or have strongly suppressed interaction with ordinary matter.
3) It should be massive to have gravitational interaction

No candidate among the known particles



strong

electromagn.

unstable

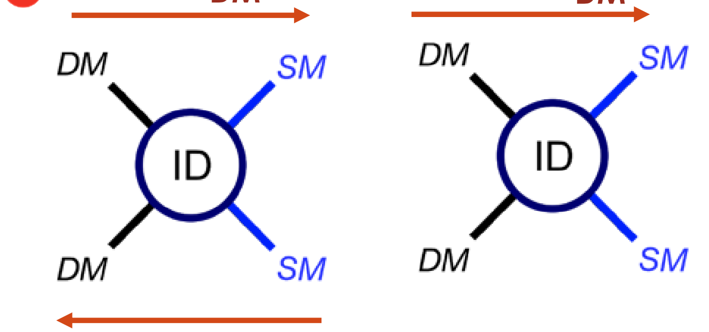
they move too fast
(*hot dark matter*)
to form the
observed large
scale structure

Neutrinos are almost what we are looking for, but they are too light and move too quickly!

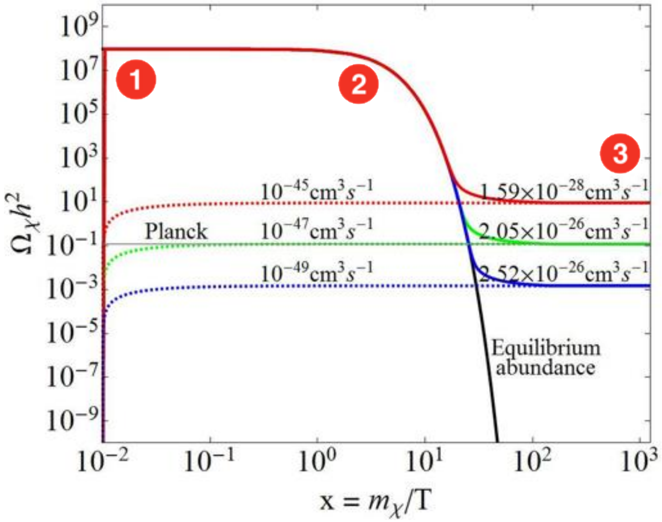
Solving Dark Matter: the WIMPs

Hot universe **Freezed universe**

① $T>M_{DM}$ ② $T<M_{DM}$



- ① DM produced in SM particle collisions.
- ② End of DM production density start decreasing
- ③ DM density reaches relic density equilibrium



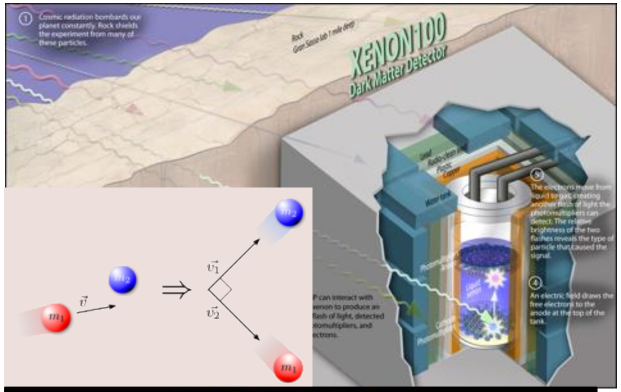
From freeze out theory

$$\Omega_{DM}h^2 \sim \frac{3\cdot 10^{-27} cm^3 s^{-1}}{\langle\sigma v\rangle}$$

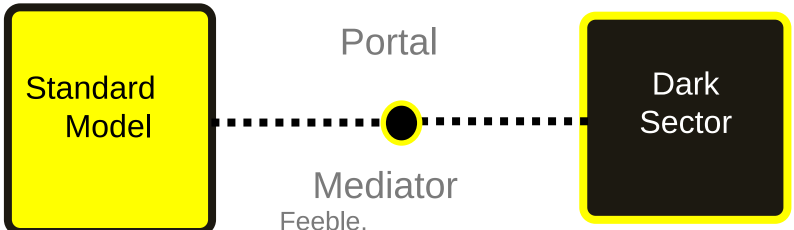
Using CMB we can measure $\Omega_{DM}h^2 \sim 0.1$

$$\langle\sigma v\rangle_{\text{WIMP}} \sim 3\times 10^{-26}\text{cm}^3\text{s}^{-1}\left(\frac{\text{TeV}}{m_\chi}\right)^2$$

need a GeV to TeV mass particle with weak interaction!



Solving dark Matter: the dark sectors



Standard Model

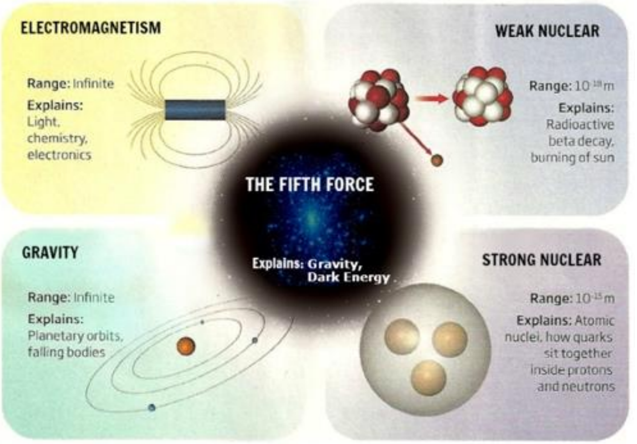
Portal

Mediator

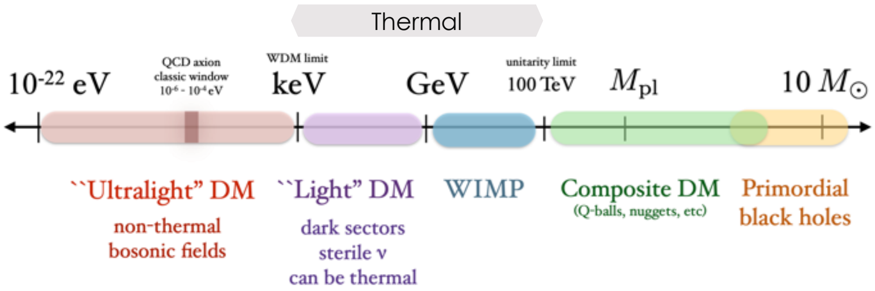
Dark Sector

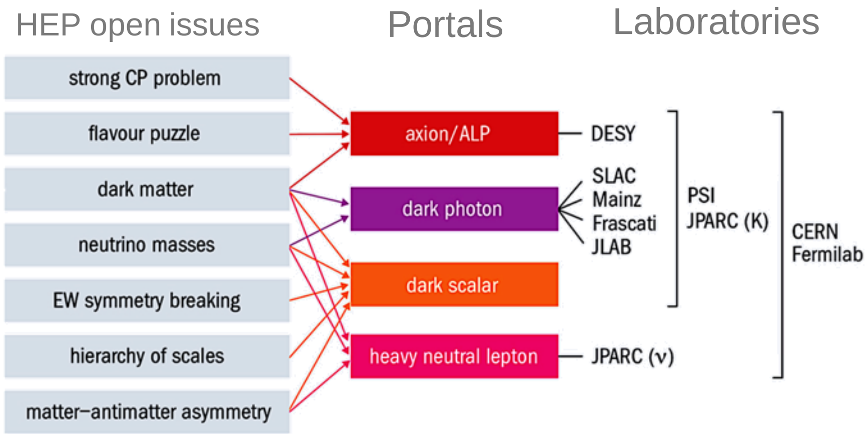
Feeble, non-gravitational interaction with ordinary matter

- **Dark matter**
- Dark forces
- Other dark particles



- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV - 1 GeV)**
- **Dark sectors particles can have their own new forces (dark forces)**
- Due to its **small mass** the mediator can be **produced at low energy accelerators**
- It can **decay back to ordinary matter, "visible"** decays, or **not, "invisible" decays.**





HEP open issues

- strong CP problem
- flavour puzzle
- dark matter
- neutrino masses
- EW symmetry breaking
- hierarchy of scales
- matter–antimatter asymmetry

Portals

- axion/ALP
- dark photon
- dark scalar
- heavy neutral lepton

Laboratories

- DESY
- SLAC
- Mainz
- Frascati
- JLAB
- PSI
- JPARC (K)
- CERN
- Fermilab
- JPARC (ν)

The Atomki anomaly and X17

New Physics in nuclear IPC transitions

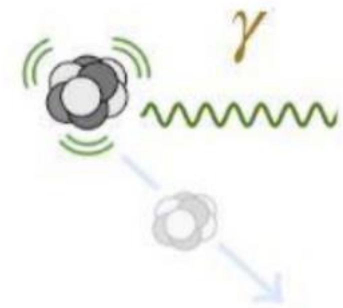
Excite the nucleus by proton capture:
choose the level by using appropriate p energy (few MeV)

Standard Model deexcitation mechanisms:

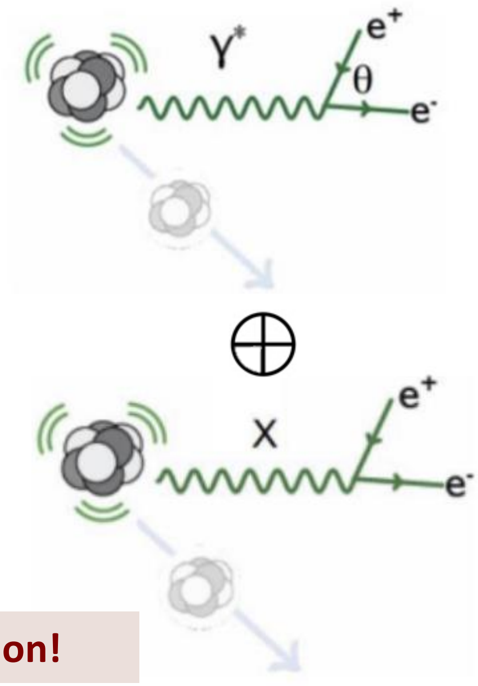
a) γ emission

b) Internal Pair Creation (IPC):
- **emit an off-shell photon γ***
- **γ* decays to ee pair**

γ emission



IPC



New Physics (NP) deexcitation mechanisms:
- **Produce an intermediate on shell new particle X (mass M_X)**
- **X decays to e^+e^- pair**

NP produce enhanced IPC rate and different θ_{ee} distribution!

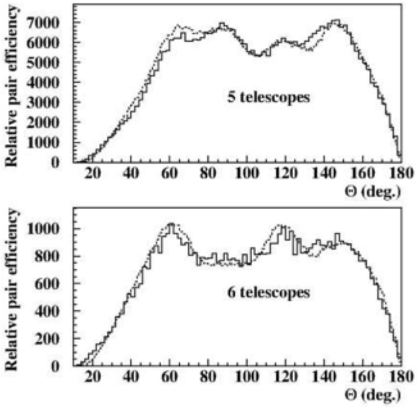
Need transitions with $\Delta E > M_X$

IPC experimental setup at Atomki

2 different setup used by Atomki for IPC measurements:

- **5 arms spectrometer (MWPC and 5 DE/E)**
- **6 arms spectrometer (Si strip and 6 DE/E)**

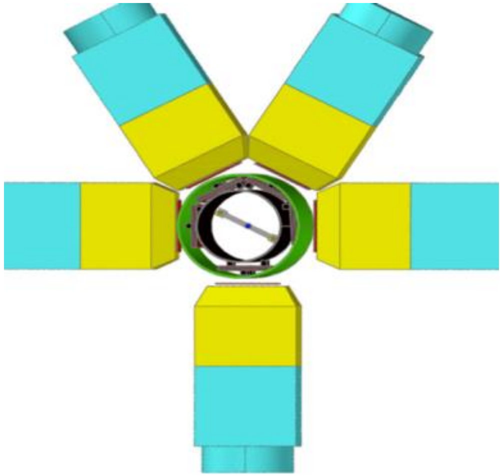
Different acceptance and detector types in ^{8}Be and ^{4}He



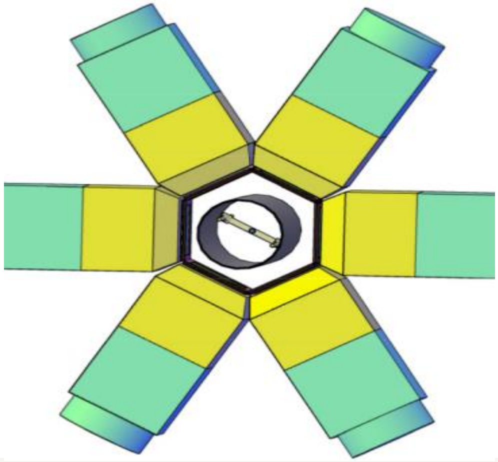
Tandetron Accelerator

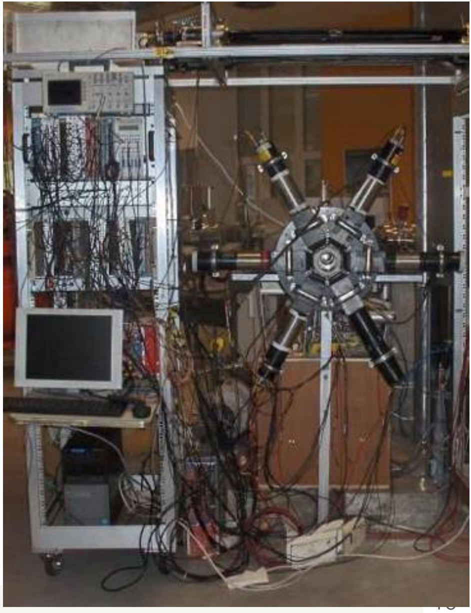
Beam current capability
at 2 MV: 200 μA protons

5 arm spectrometer ^{8}Be 2016

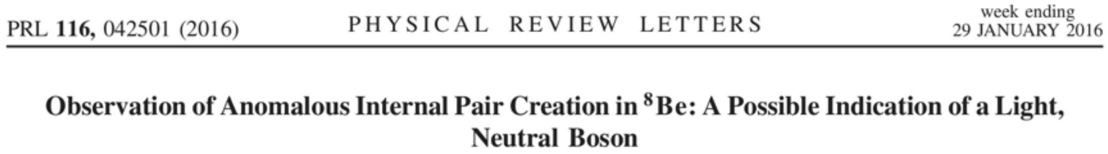


6 arm spectrometer ^{4}He 2020





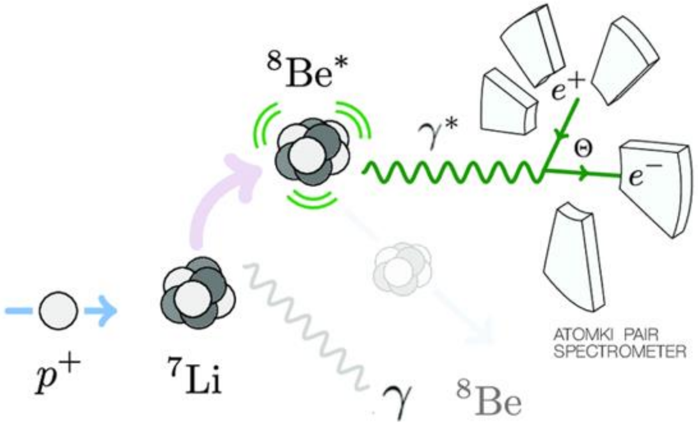
^{8}Be anomaly: first evidence

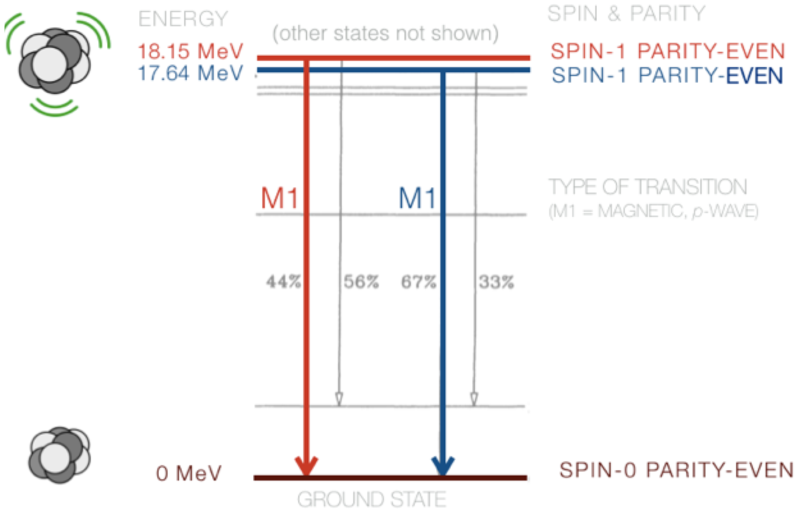


PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

PRL 116, 042501 (20



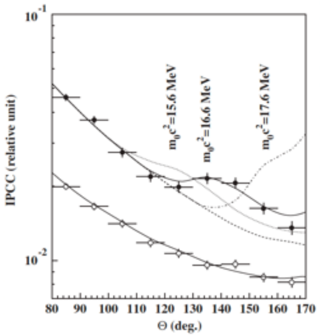


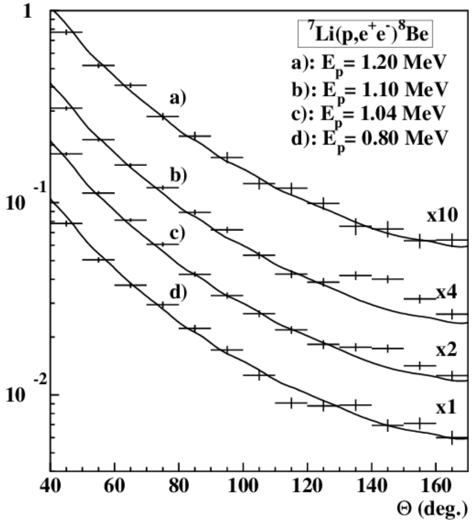
$p + {}^7\mathrm{Li} \longrightarrow {}^8\mathrm{Be}^*(18.15\ \mathrm{MeV}) \longrightarrow {}^8\mathrm{Be} + e^+e^-$

Anomaly observed only in 2 over 4 proton energies

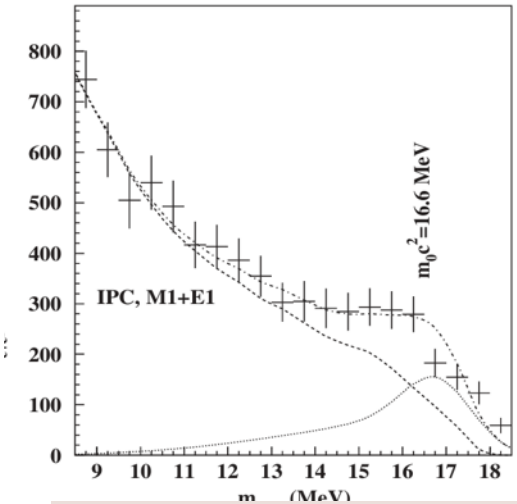
Anomaly observed only for symmetric track events

Anomaly observed only for ^{8}Be 18.15 MeV transition





6.8σ effect! not a fluctuation



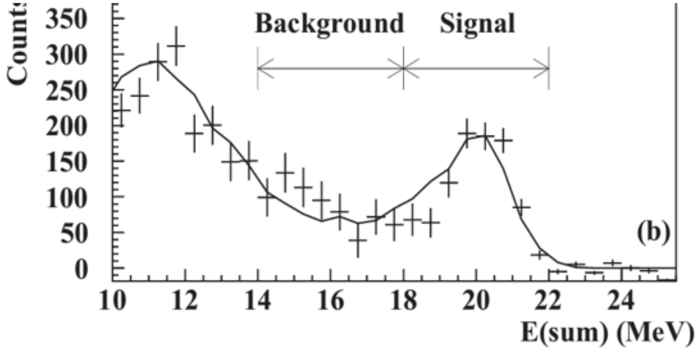
$m_X c^2 = 16.70.35_{stat}0.5_{syst}$ MeV

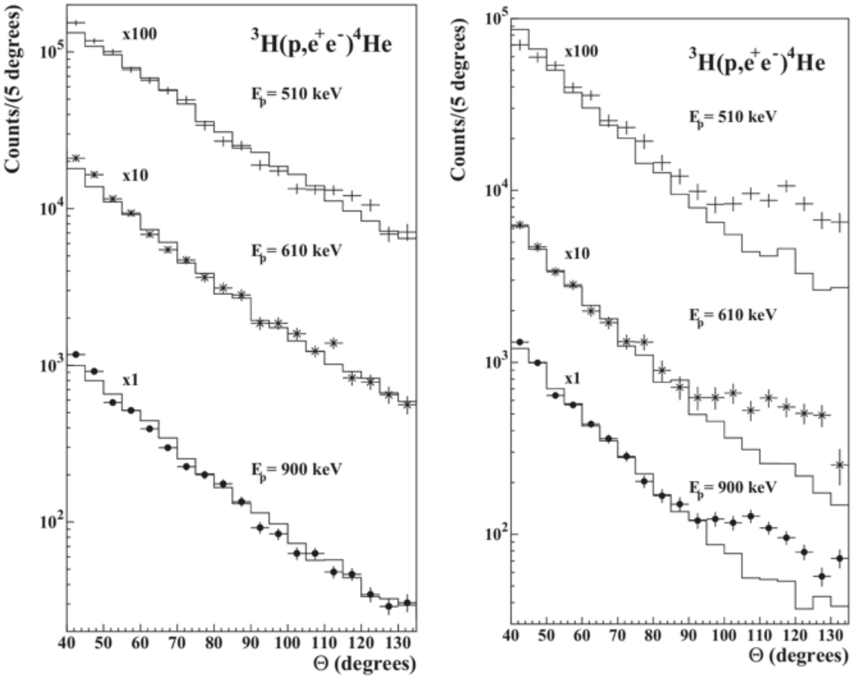
The ^{4}He Atomki anomaly: 2020

PHYSICAL REVIEW C **104**, 044003 (2021)

New anomaly observed in ^{4}He supports the existence of the hypothetical X17 particle

$p + {}^3H \longrightarrow {}^4He^* \longrightarrow {}^4He + e^+e^-$





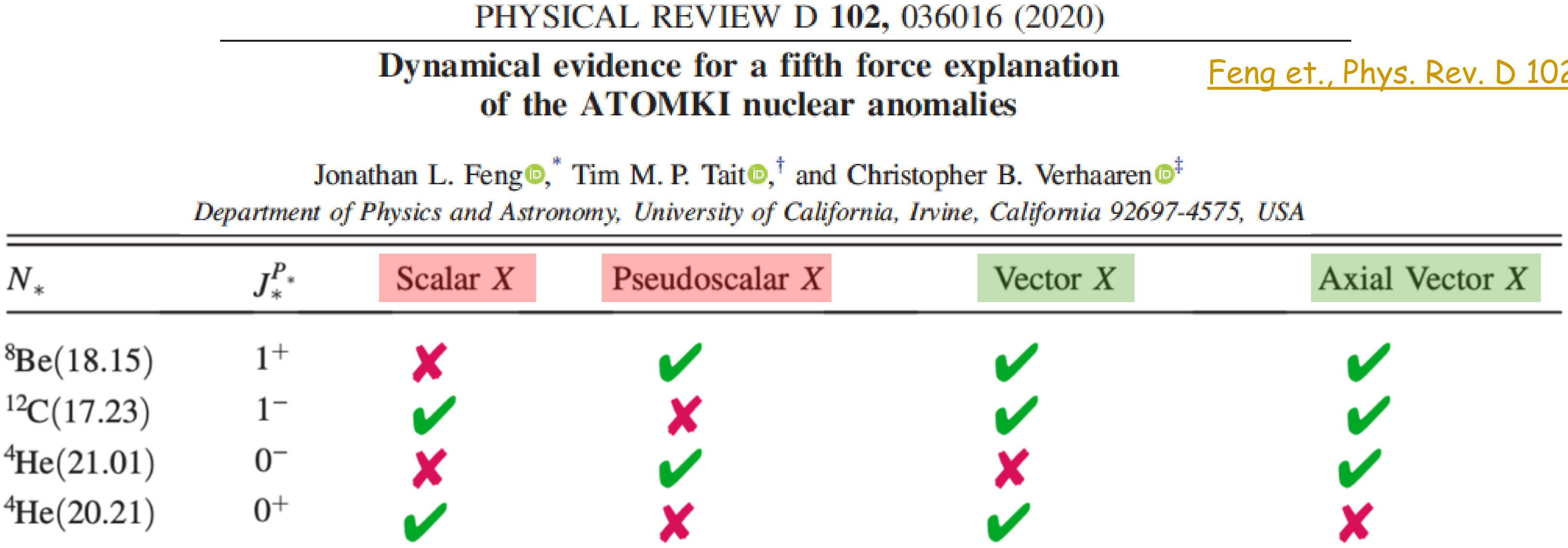
Atomki has confirmed the anomalous peak in the angular distribution of ^{8}**Be** IPC in ^{4}**He** transitions at different angle. The difference was expected **due to the higher ΔE in ^{4}He** The ^{4}He angle indicated **same X mass value.**

$$m_X c^2 = 16.94 \pm 0.12_{\text{stat}} \pm 0.21_{\text{syst}}\ \text{MeV}$$

Phys. Rev. C 104, 044003 (2021)

E_p (keV)	IPCC $\times 10^{-4}$	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
510	2.5(3)	6.2(7)	17.01(12)	7.3σ
610	1.0(7)	4.1(6)	16.88(16)	6.6σ
900	1.1(11)	6.5(20)	16.68(30)	8.9σ
Averages		5.1(13)	16.94(12)	
^{8}Be values		6	16.70(35)	

^{8}Be and ^{4}He consistency and ^{12}C



PHYSICAL REVIEW D **102,** 036016 (2020)

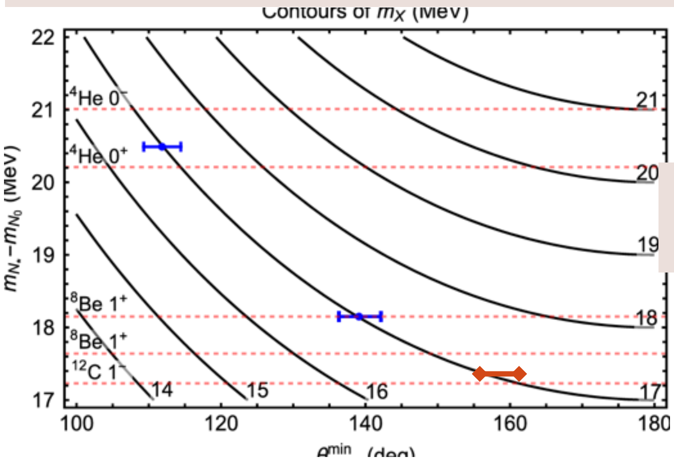
Dynamical evidence for a fifth force explanation of the ATOMKI nuclear anomalies

Jonathan L. Feng,[*] Tim M. P. Tait,[†] and Christopher B. Verhaaren[‡]
Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA

N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	✗	✓	✓	✓
^{12}C(17.23)	1^-	✓	✗	✓	✓
^{4}He(21.01)	0^-	✗	✓	✗	✓
^{4}He(20.21)	0^+	✓	✗	✓	✗

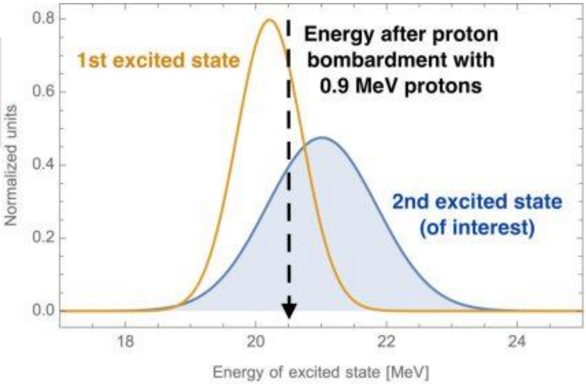
Feng et., Phys. Rev. D 102, 036016

Feng et al., suggested that the X17 should be observed in ^{12}C transitions
X17 observations in ^{12}C will point to a vector or axial vector nature for X17



$$\theta_{ee}^{min} \approx 2\arcsin\left(\frac{m_{X17}}{m_{N*} - mN}\right)$$

^{12}C angle expected to be at ~160°

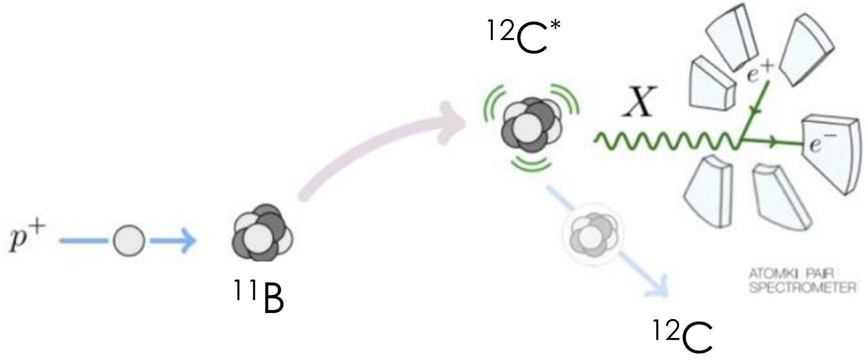


The ^{12}C : September 2022

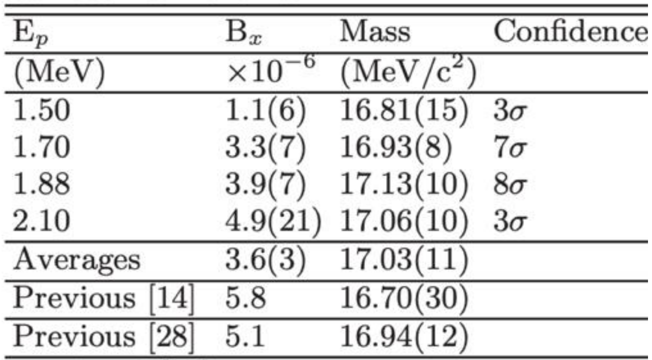
PHYSICAL REVIEW C **106**, L061601 (2022)

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

Phys. Rev.C 106 (2022) 6



$p+^{11}B \rightarrow ^{12}C^*(17.23\ MeV) \rightarrow ^{12}C + e^+e^-$

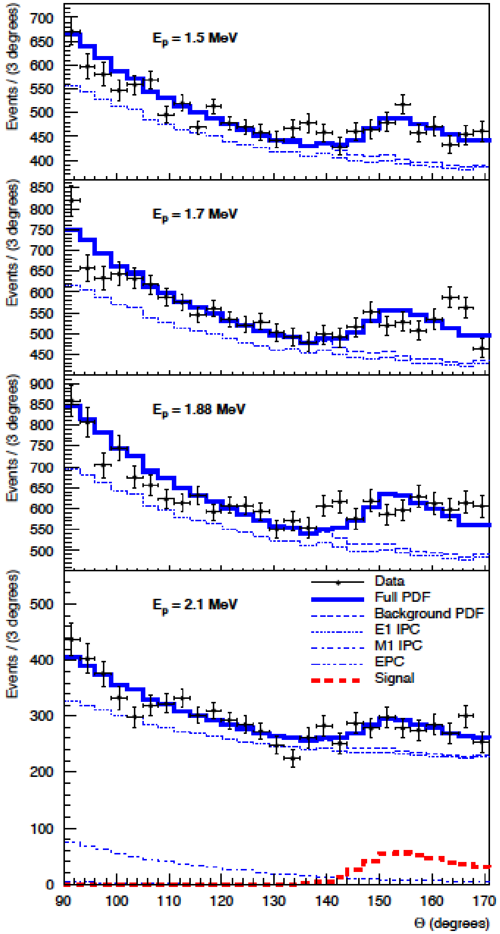


E_p (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	

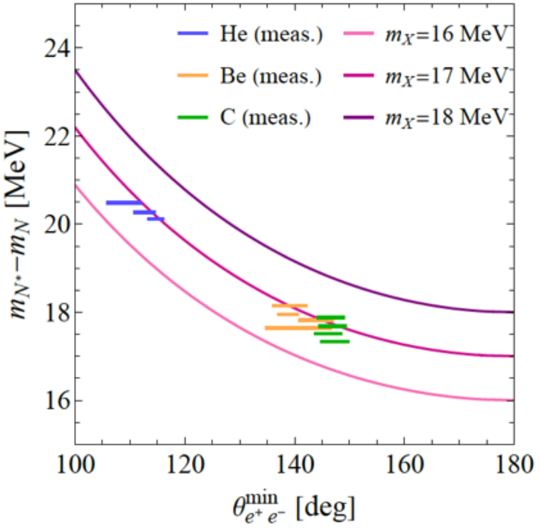
As predicted by J. Feng et al. excess at 160°

Same X17 particle suggested by the ^{8}Be and ^{4}He anomalies

M_X=17.03±0.11±0.20 MeV



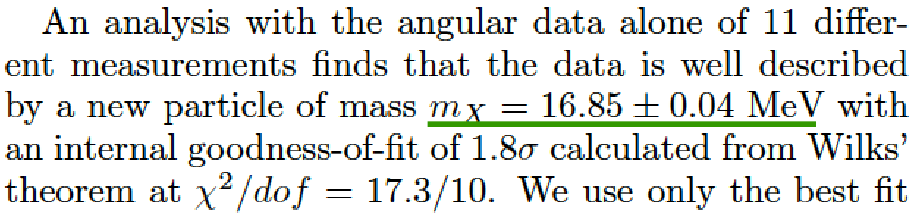
Global ΔE vs angle consistency



Neutrino Constraints and the ATOMKI X17 Anomaly

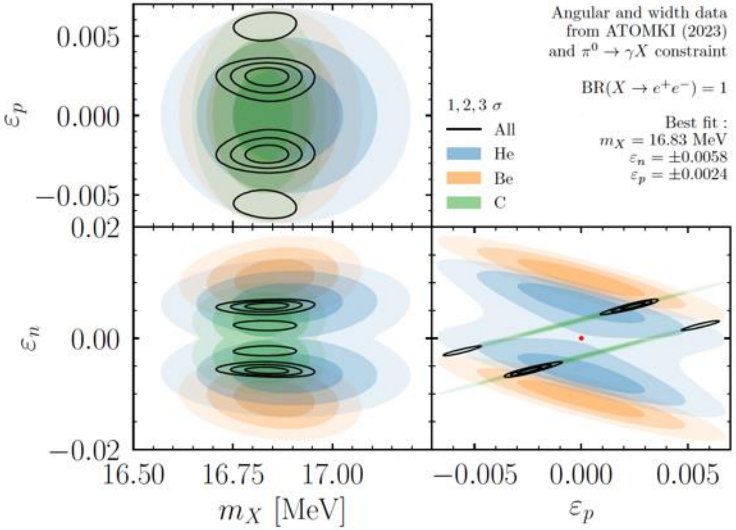
PHYS.REV. D 108, 015009 (2023)

Using angular data only: 11 measurements

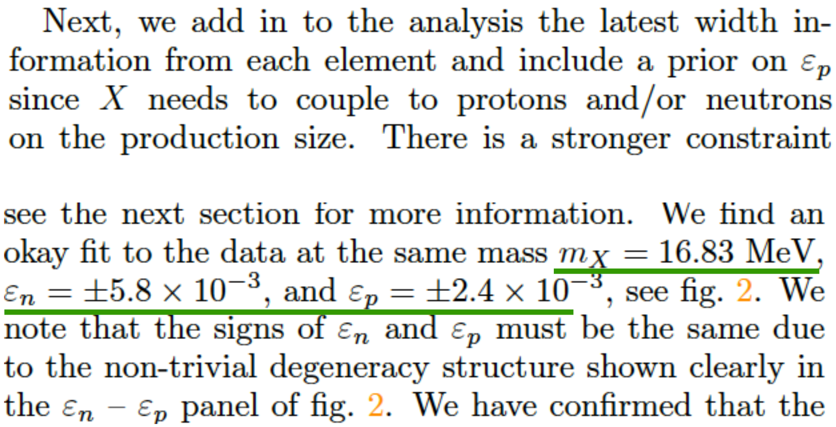


An analysis with the angular data alone of 11 different measurements finds that the data is well described by a new particle of mass $m_X = 16.85 \pm 0.04$ MeV with an internal goodness-of-fit of 1.8σ calculated from Wilks' theorem at $\chi^2/dof = 17.3/10$. We use only the best fit

$$\theta_{ee}^{min} \approx 2\text{arcsin}\left(\frac{m_{X17}}{m_{N*} - mN}\right)$$



Using width for each element: 3 measurements



Next, we add in to the analysis the latest width information from each element and include a prior on ε_p since X needs to couple to protons and/or neutrons on the production size. There is a stronger constraint

see the next section for more information. We find an okay fit to the data at the same mass $m_X = 16.83$ MeV, $\varepsilon_n = \pm 5.8 \times 10^{-3}$, and $\varepsilon_p = \pm 2.4 \times 10^{-3}$, see fig. 2. We note that the signs of ε_n and ε_p must be the same due to the non-trivial degeneracy structure shown clearly in the $\varepsilon_n - \varepsilon_p$ panel of fig. 2. We have confirmed that the

Data form ^{8}Be, ^{4}He, ^{12}C are consistent and point to: M_{X17}=16.85±0.04 MeV

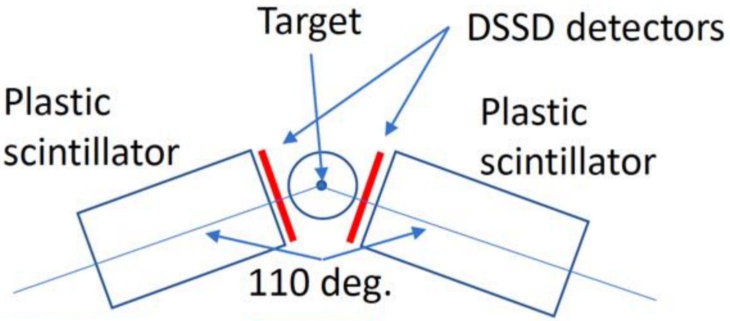
SAPIENZA
UNIVERSITÀ DI ROMA

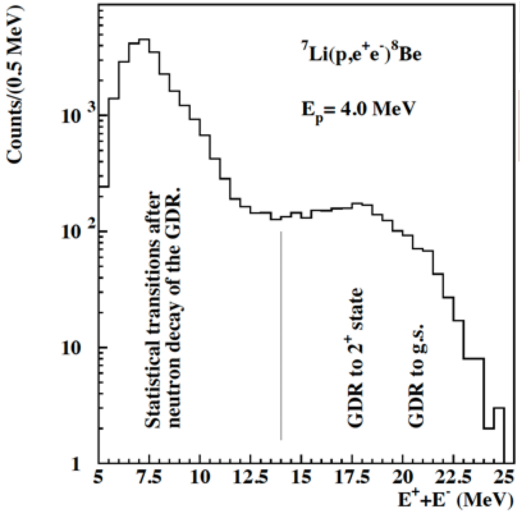
^{8}Be giant resonance anomaly: 2023

Observation of the X17 anomaly in the decay of the Giant Dipole Resonance of ^{8}Be

arXiv:2308.06473

Atomki group: ^{8}Be experiment in GDR region
New 2 arm spectrometer closer to the target

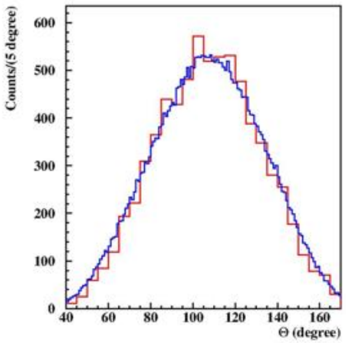




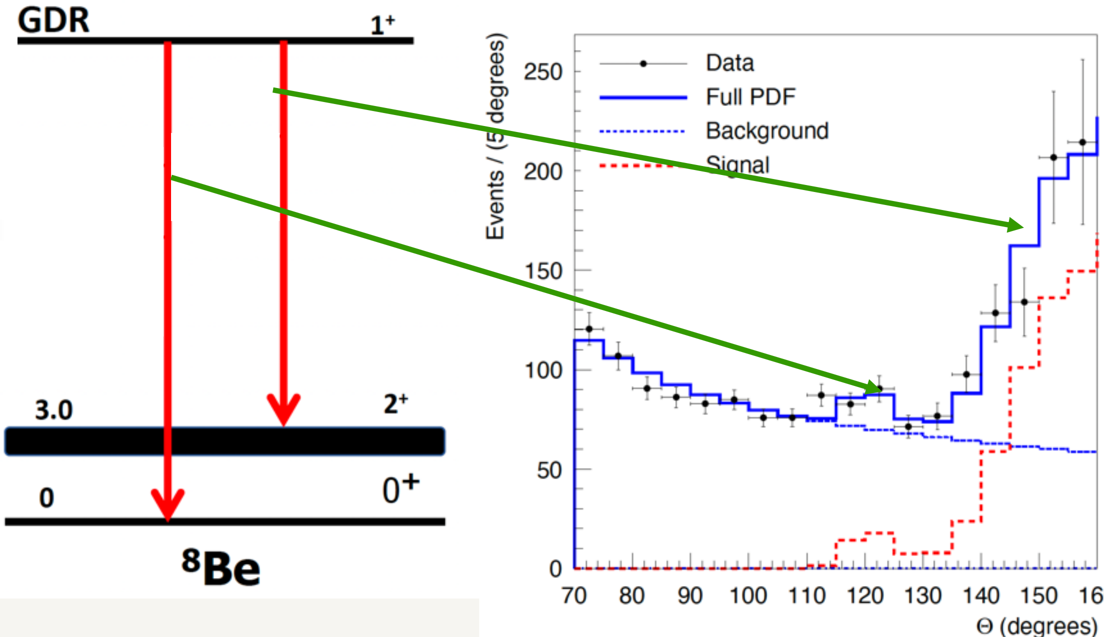
E$_P$ up to 4 MeV

1^{+} to 2^{+} ~17.5 MeV

1^{+} to 0^{+} ~20.5 MeV

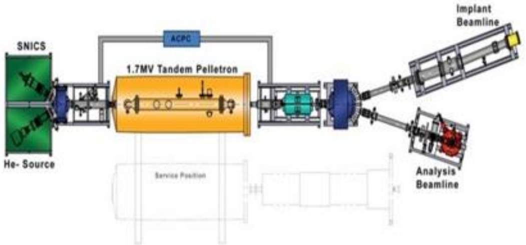


2 peak structure observed!
impressive angular agreement with particle hypothesis.



More information can be found here: ISMD 2023
https://indico.cern.ch/event/1258038/timetable/#20230822.detailed

Confirmed in Vietnam 2023?

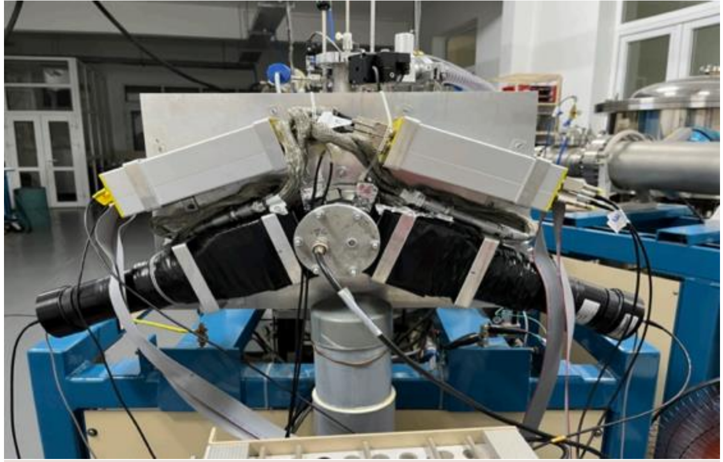


Pelletron Beamline, analysis beamline
Terminal Voltage: 1.7 MV
Ion: H^+, He^+, C^+, Si^+, Cu^+, Au^+...
Beam Current: 1nA – 2microA

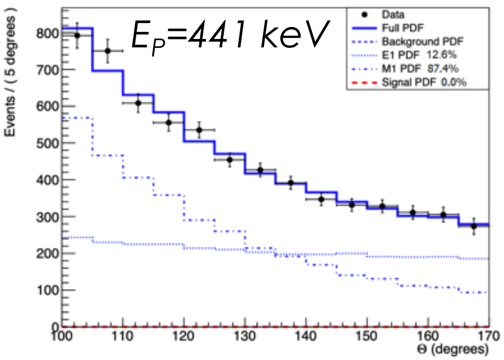
8/21/23 ISMD52

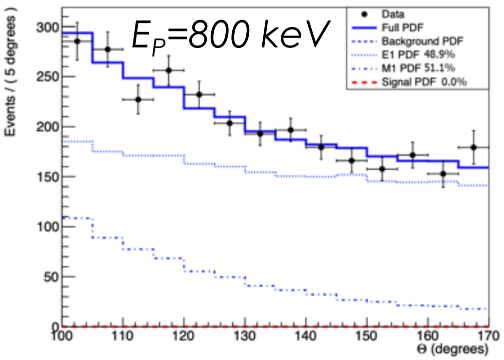
Main tasks:
RBS
PIXE
Ion implantaion
Astro nuclear reactions

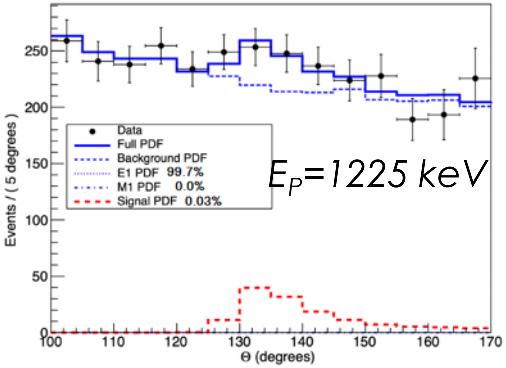
ISMD2023



2 arm spectrometer (ATOMKI like)
ATOMKI group participants
^{7}Li and ^{11}B target used.







Universe **2024**, *10*(4), 168;

Anomaly confirmed at 1225 KeV E_p. Not observed for lower bombarding energies.

Can we trust the Atomki anomaly?

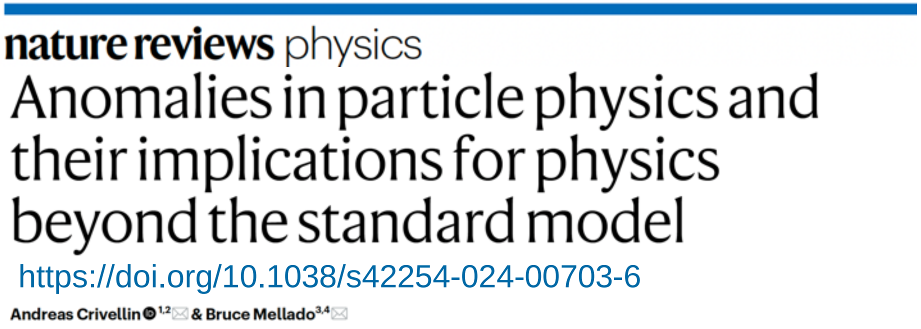
Evidence in favor:

- ✓ All the three anomalies $\gtrsim 6\ \sigma$, not a statistical fluctuation
- ✓ Bumps, not general excesses. Not a single bin or a last bin effect
  - ✓ Bumps disappear $\Delta E<17$MeV and for asymmetric tracks
  - ✓ Bumps are produced by different detector configurations (2-5-6 arms)
- ✓ By introducing a single new particle, remarkable improvement of all the fits
- ✓ SM explanation theoretically strongly disfavored:
  - ✓ 8Be [Zhang+, (2017), Gysbers+, (2023)]; 4He [Viviani+, (2021)]
  - ✓ No explanation so far including all three anomalies at the same time
- ✓ ^{8}Be-^{4}He-^{12}C anomalies kinematically & dynamically consistent for V (and A): Barducci & Toni, Eur.Phys.J.C 83 (2023) 3, 230 [arXiv:2212.06453])
- ✓ For ^{12}C the effect was predicted, and confirmed by experimental data
- ✓ Additional recent evidence in GDR experiment
- ✓ Partially independent confirmation from Hanoi University

Odds against:

- ✓ No independent confirmation so far
- ✓ Strong constraints on the parameter space from particle physics experiments

Judging the anomaly: nature reviews

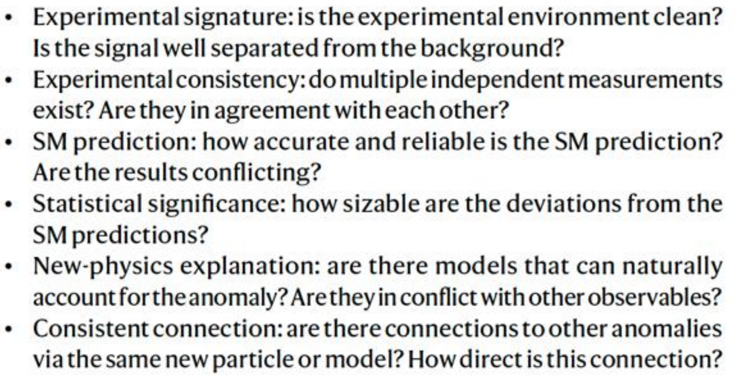


nature reviews physics

Anomalies in particle physics and their implications for physics beyond the standard model

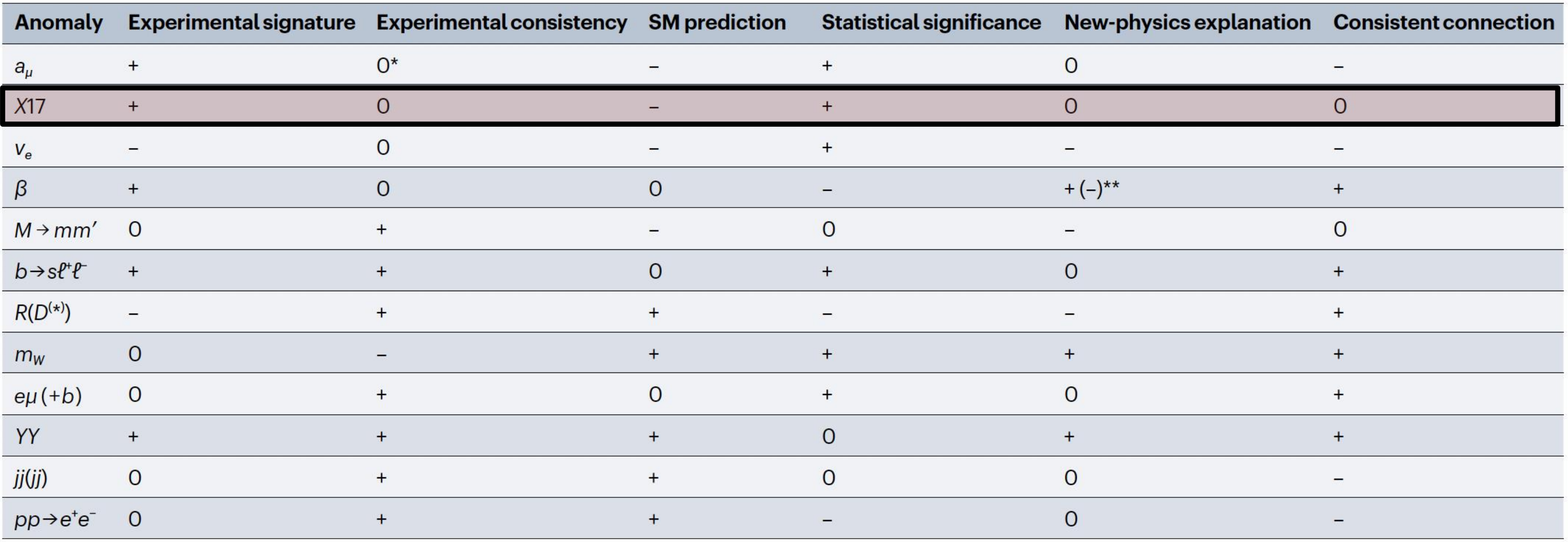
https://doi.org/10.1038/s42254-024-00703-6

Andreas Crivellin [1,2] **& Bruce Mellado** [3,4]



- Experimental signature: is the experimental environment clean? Is the signal well separated from the background?
- Experimental consistency: do multiple independent measurements exist? Are they in agreement with each other?
- SM prediction: how accurate and reliable is the SM prediction? Are the results conflicting?
- Statistical significance: how sizable are the deviations from the SM predictions?
- New-physics explanation: are there models that can naturally account for the anomaly? Are they in conflict with other observables?
- Consistent connection: are there connections to other anomalies via the same new particle or model? How direct is this connection?

Table 3 | Anomalies assessed (positively, negatively or neutrally) against various criteria



Anomaly	Experimental signature	Experimental consistency	SM prediction	Statistical significance	New-physics explanation	Consistent connection
a_μ	+	0*	–	+	0	–
X17	+	0	–	+	0	0
ν_e	–	0	–	+	–	–
β	+	0	0	–	+ (–)**	+
$M \to mm'$	0	+	–	0	–	0
$b \to s\ell^+\ell^-$	+	+	0	+	0	+
$R(D^{(*)})$	–	+	+	–	–	+
m_W	0	–	+	+	+	+
$e\mu\,(+b)$	0	+	0	+	0	+
YY	+	+	+	0	+	+
$jj(jj)$	0	+	+	0	0	–
$pp \to e^+e^-$	0	+	+	–	0	–

Status of theoretical understanding

Can we explain the effect?	Not in within the SM	Zhang & Miller PLB 773, 2017 [nucl-th] Aleksejevs+, arXiv:2102.01127 [nucl-th] Viviani+ Phys. Rev. C 105, 014001
Is the effect due to X17?	Kinematic Dynamic consistent	Feng+, PRL 1604.07411 [hep-ph] Feng+, PRD 1608.03591 [hep-ph] Toni+ JHEP02(2023)154 [hep-ph]
Is X17 a vector or a scalar?	Vector or Axial vector	Feng+, PRD 1608.03591 [hep-ph] Toni+ JHEP02(2023)154 [hep-ph]
What is the best X17 mass value?	Mass fit: 16.85±0.04 Mev	B. Denton+ Phys. Rev. D 108, 015009
Is there a BSM solution?	Several different one	Feng+, PRL 1604.07411 [hep-ph] Phys. Rev. D 103, 055018

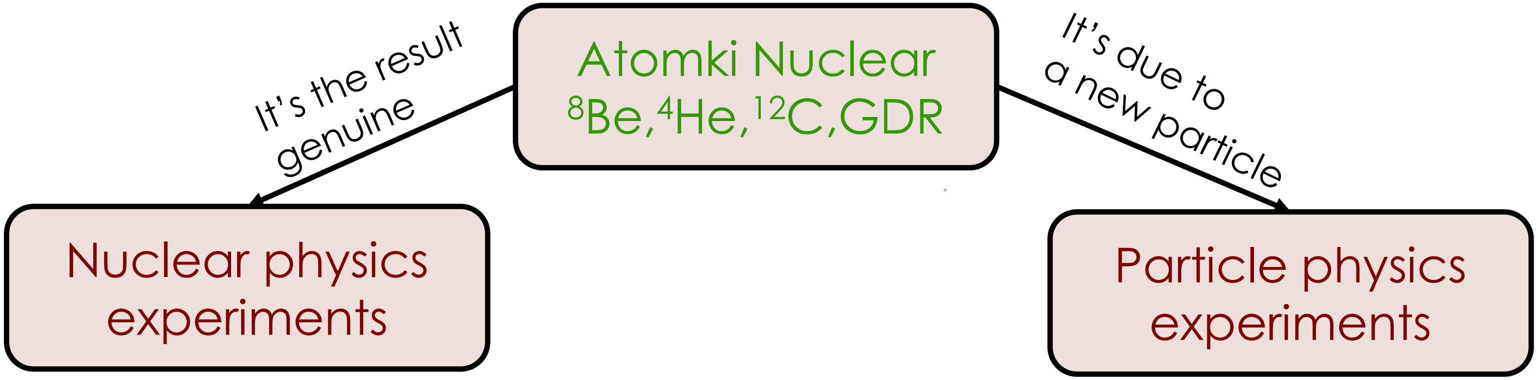
Experimental directions

Shedding light on X17
6–8 Sept 2021
Centro Ricerche Enrico Fermi

Conference Website

Conference Proceedings

Experimental directions



Atomki Nuclear
^{8}Be,^{4}He,^{12}C,GDR

It's the result genuine

It's due to a new particle

Nuclear physics experiments

Particle physics experiments

MEGII @ PSI
p^{7}Li->^{8}Be*->^{8}Be e$^+$e$^-$
ISMD:

AN2000 @ LNL
p^{7}Li->^{8}Be e$^+$e$^-$

n_ToF @ CERN:
n^{3}He->^{4}He e+e-
PRC 105, 014001

U Montreal:
p^{7}Li->^{8}Be*->^{8}Be e$^+$e$^-$
arXiv:2211.11900

NA48/2 CERN
π^0-> γ X17
PLB 746 (2015) 178-185

NA64 CERN
eN->eN X17
PRD 101, 071101 (2020)

NA62 CERN
π^0-> X17 X17
PRD 105, 015017 (2022)

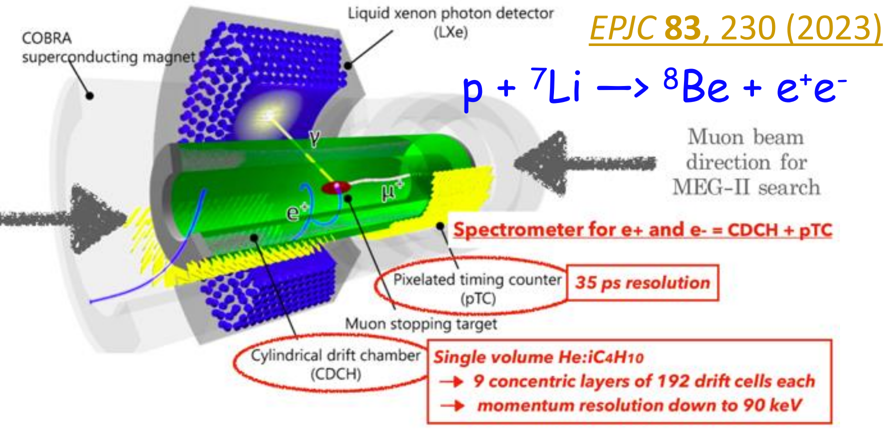
PADME LNF
e$^+$e$^-$->X17->e$^+$e$^-$
PRD 106,115036

^{8}Be nuclear experiments

MEG-II experiment @PSI special Run for X17

EPJC **83**, 230 (2023)

$p + {}^{7}Li \longrightarrow {}^{8}Be + e^{+}e^{-}$

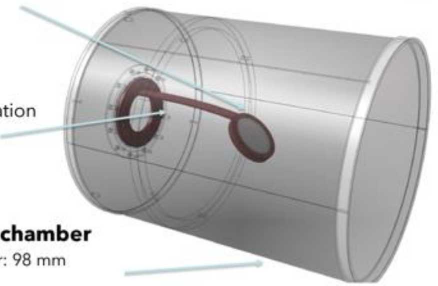


Spectrometer for e+ and e- = CDCH + pTC

35 ps resolution

Single volume He:iC4H10
- → 9 concentric layers of 192 drift cells each
- → momentum resolution down to 90 keV

Mechanical and heat dissipation simulations carried out

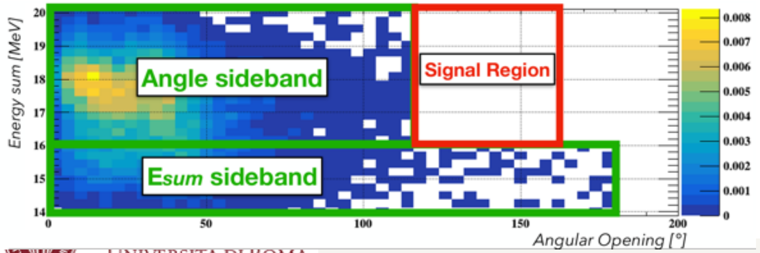


Li target
at COBRA center
45° slant angle

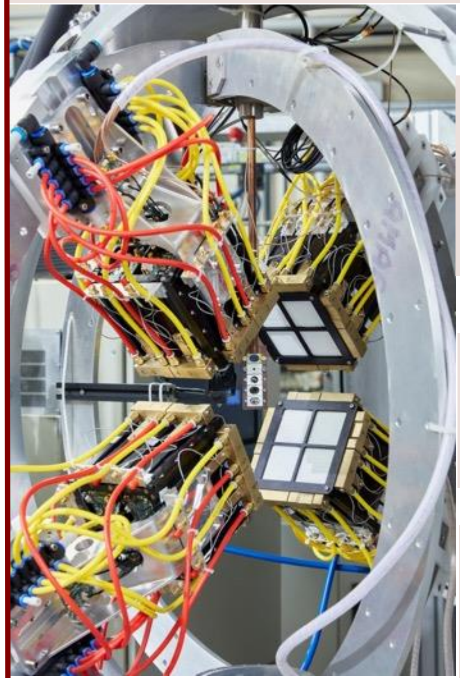
Target arm
Cu for heat dissipation

Carbon fiber vacuum chamber
Thickness: 400 μm, Diameter: 98 mm
Length: 226 mm

In February 2023, X17 physics run for 4 weeks at Ep = 1080 keV



4 arm spectrometer at INFN Laboratori Nazionali di Legnaro



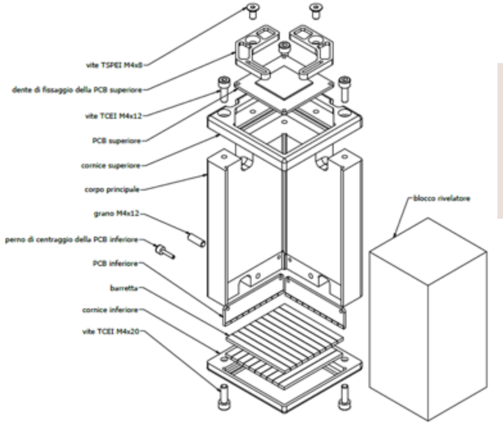
$p + {}^{7}Li \longrightarrow {}^{8}Be + e^{+}e^{-}$

For the first time in vacuum spectrometer

Scintillating fibre tracking

Using AN2000 accelerator
p energy up to 2 MeV
Engineering run 12/2023

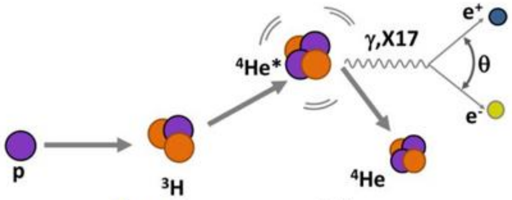
Using AN2000 accelerator
p energy ~1MeV
Engineering run 12/2023



BG studies with 400KeV proton beam ongoing during this week!

EPJC **83**, 230 (2023)

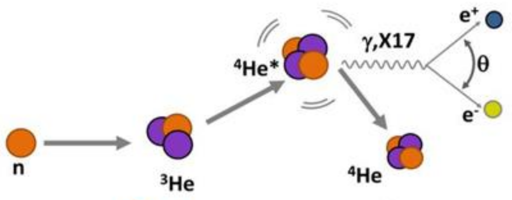
NToF: new approach to ^{4}He



^{3}H(p,e^{+}e^{-})^{4}He

ATOMKI REACTION

see Carlo Gustavino



^{3}He(n,e^{+}e^{-})^{4}He

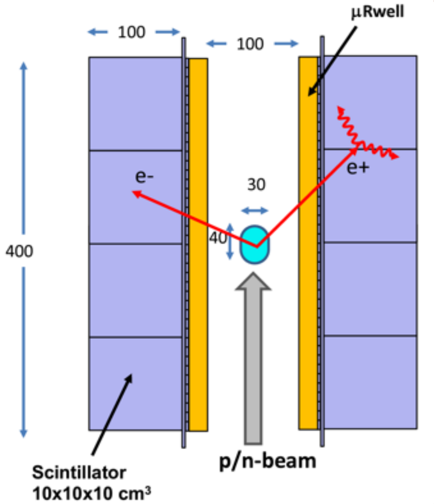
n_TOF REACTION

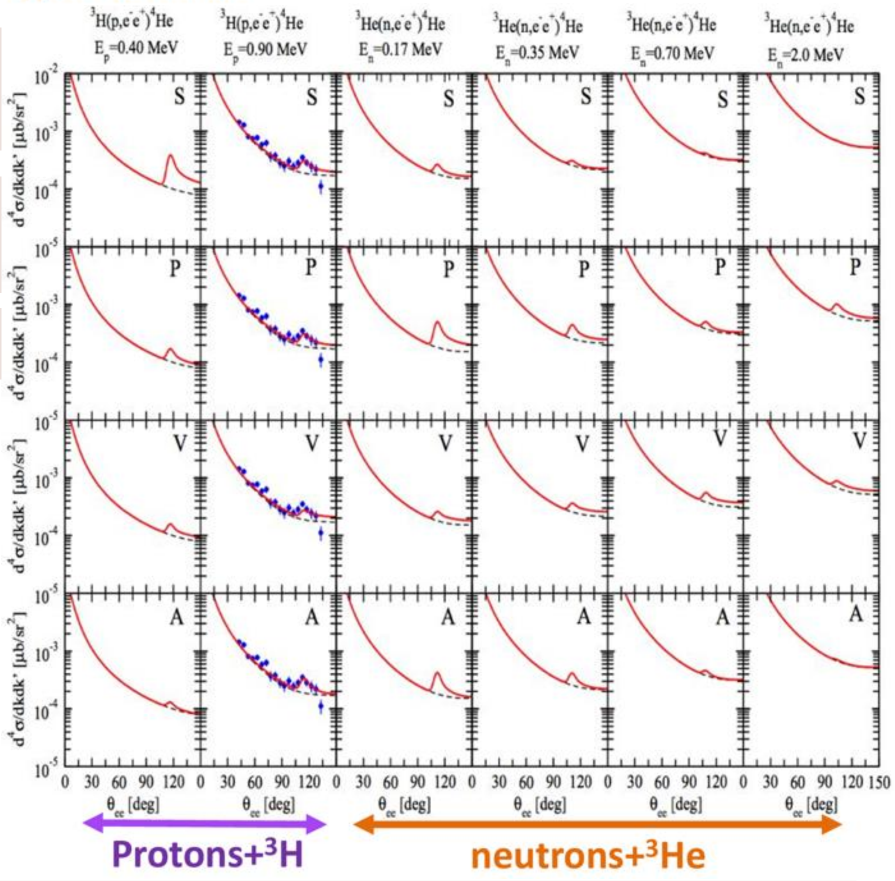
Innovative neutron beam based excitation mechanism

The only experiment proposed so far for to replicate ^{4}He anomaly

Thorough theoretical discussion to be found in: Phys. Rev. C 105, 014001

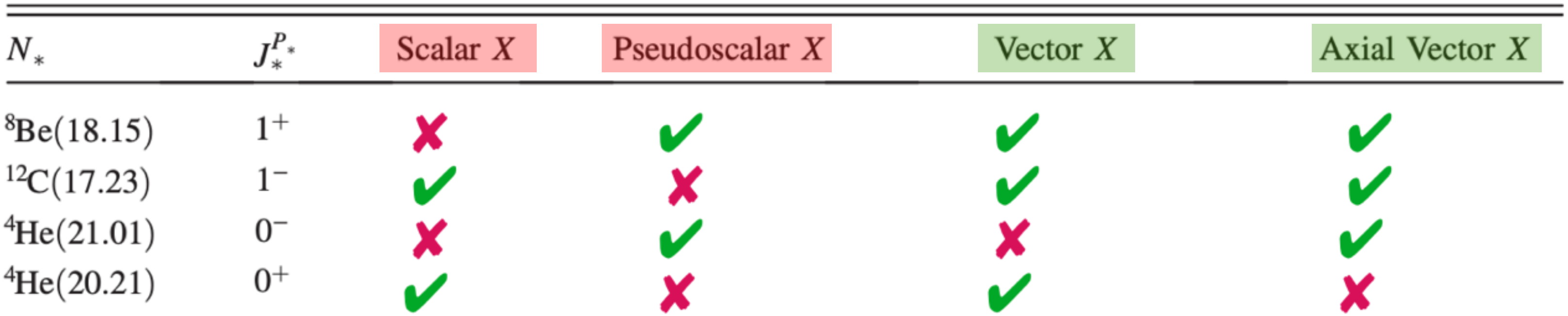
Chance to have data in late 2024 early 2025





X17: particle physics case

Theory insights based Atomki data :
Scalar excluded by parity conservation in ^{8}Be
Pseudo scalar disfavoured by the ^{12}C observation



N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	✗	✓	✓	✓
^{12}C(17.23)	1^-	✓	✗	✓	✓
^{4}He(21.01)	0^-	✗	✓	✗	✓
^{4}He(20.21)	0^+	✓	✗	✓	✗

What next in particle physics experiments:
Explore the all possible solution to search for signal outside nuclear physics
Concentrate attention on Vector and Axial Vector cases theoretically favoured solutions
Don’t forget Scalars and Pseudo scalars nature can always be different from what we expect!
Try to be as much model independent as possible

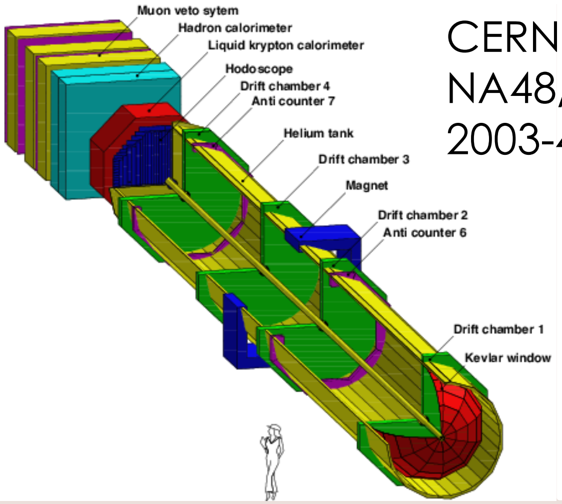
Pure dark photon: excluded NA48/2

For genuine A' $\varepsilon_f = \varepsilon q_f$ Feng et. al from the X17 rate:

$$\frac{B(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X)}{B(^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,\gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.8 \times 10^{-6}$$

[PRL 117, 071803 (2016)]

$$|\varepsilon_p + \varepsilon_n| \approx 0.011,$$



CERN
NA48/2
2003-4

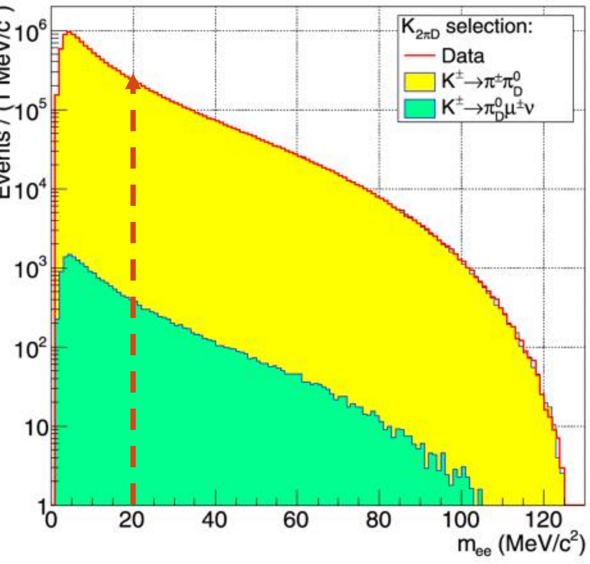
NA48/2 experiment limits for **A' in $K^{\pm}_{2pD}$**:

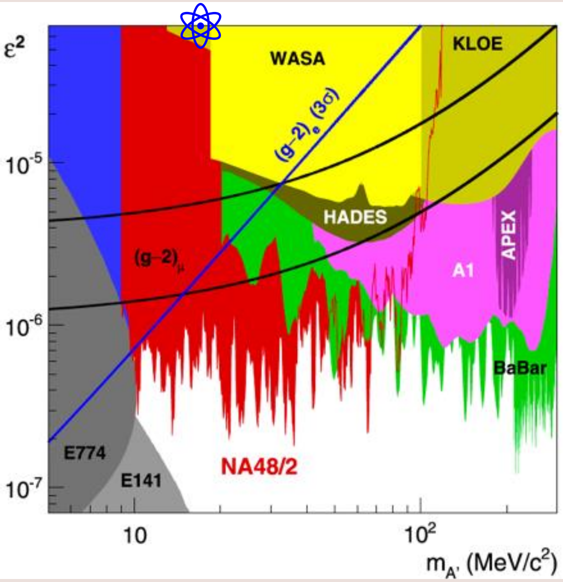
$K^{\pm} \to \pi^{\pm}\pi^0_D$ with $\pi^0_D = \gamma e^+e^-$ [PLB 746 (2015) 178-185]

In case X17 is a dark photon we should have in addition:

$\pi^0 \to \gamma X17 \to \gamma e^+e^-$

X17 should appear as a peak at 17 MeV in the m_{ee} spectrum.

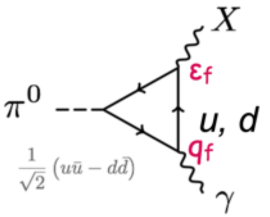




Universal coupled vector hypothesis A' firmly excluded

π-phobic/P-phobic vector particle:

[PRL 117, 071803 (2016)]



$\pi^0 \to X$ ©: $|2\varepsilon_u + \varepsilon_d| < \underline{8 \times 10^{-4}}$ (NA48/2)

$B_{X17}/B_{©}$: $|\varepsilon_u + \varepsilon_d| \approx \underline{4 \times 10^{-3}}$ (Atomki)

$\varepsilon_d \approx -2\,\varepsilon_u$ (±10%) ==> $\varepsilon_p = 2\varepsilon_u + \varepsilon_d \approx 0$;

$2\varepsilon_u + \varepsilon_d \approx 0$ ==> $\pi^0 \to X$© $= 0$ forbidden

π-phobic vector still alive!

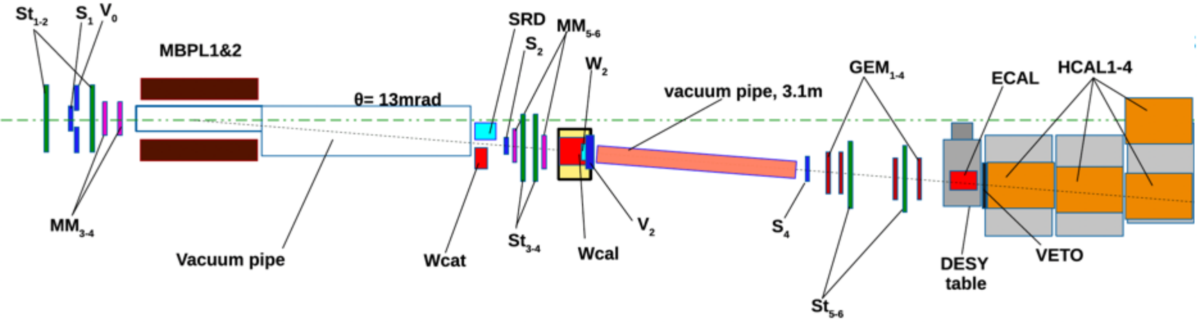
SAPIENZA
UNIVERSITÀ DI ROMA

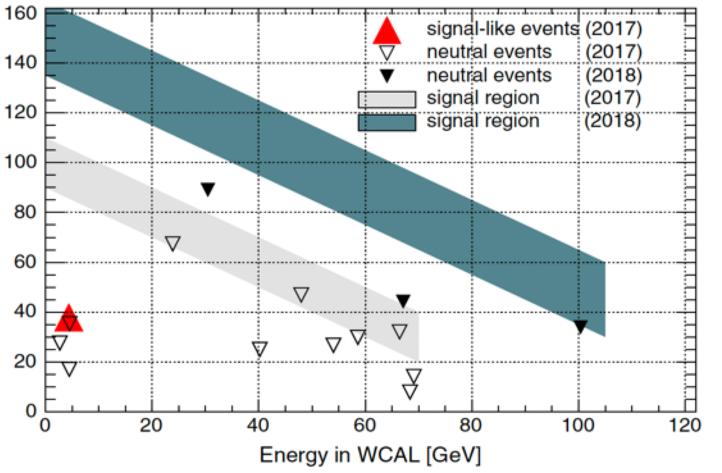
Generical vector constraints NA64

NA64 CERN NA, uses 150 GeV e^- beam on thick target.

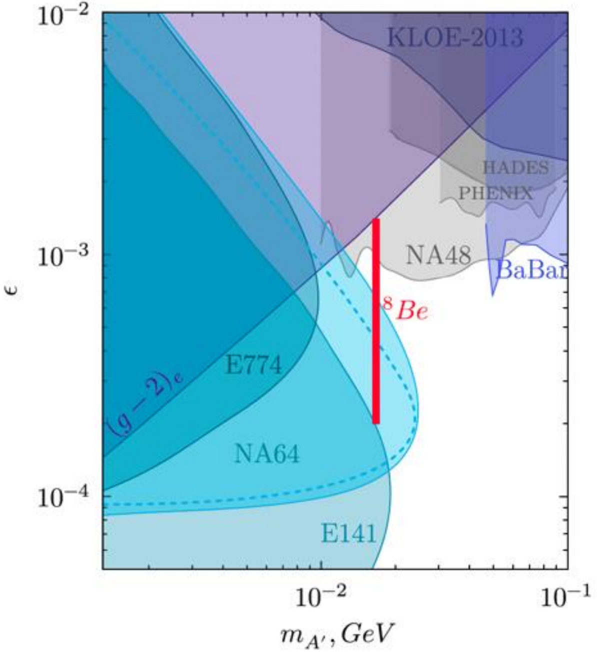
$$e^- + Z \to e^- + Z + A'(X), \qquad A'(X) \to e^+e^-$$

only e^- -> no problem with extra couplings!





[PRD 101, 071101 (2020)]



How it works:

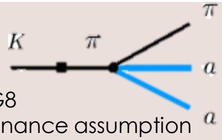
1) Beam e^- losses part of its energy in W_{cal} before radiating.
2) After radiating A' is absrobed by W_{cal} depsiting all of its energy.
3) A' is radiated and decays after the W_{cal}
4) Energy of the ee pair from the A' decay is measured by ECal

Dump experiment:

- limited in the high ε values by X17 lifetime
- No possibility to measure mass of eventually observed events
- just counts general event excess

Axion like X17: excluded by NA62

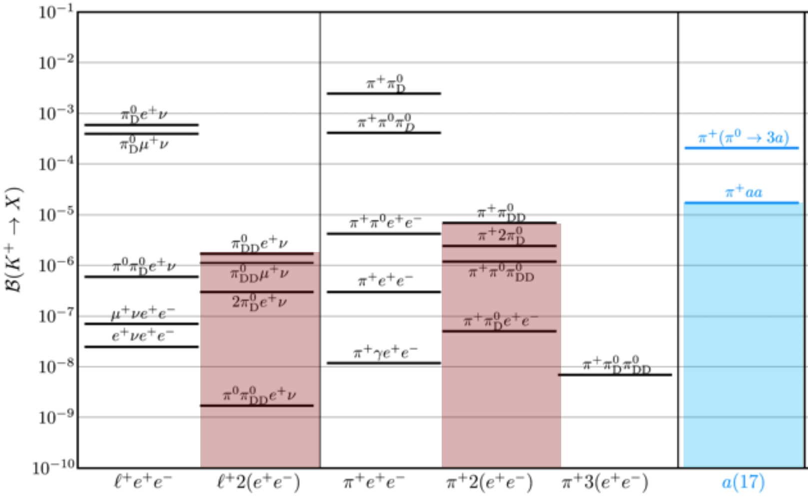
M. Pospelov noted: [PRD 105, 015017 (2022)]



χPT G8
dominance assumption

$$BR(K^+ \to \pi^+ aa) \simeq 1.7 \times 10^{-5}$$

If a=X17 X17–>e^+e^- and we have π^+4e final state
a) main SM background $K^+ \to \pi^+\pi^0_{DD}$ has lower rate
b) $m_{ee} = m_a$ is a strong kinematical constraint

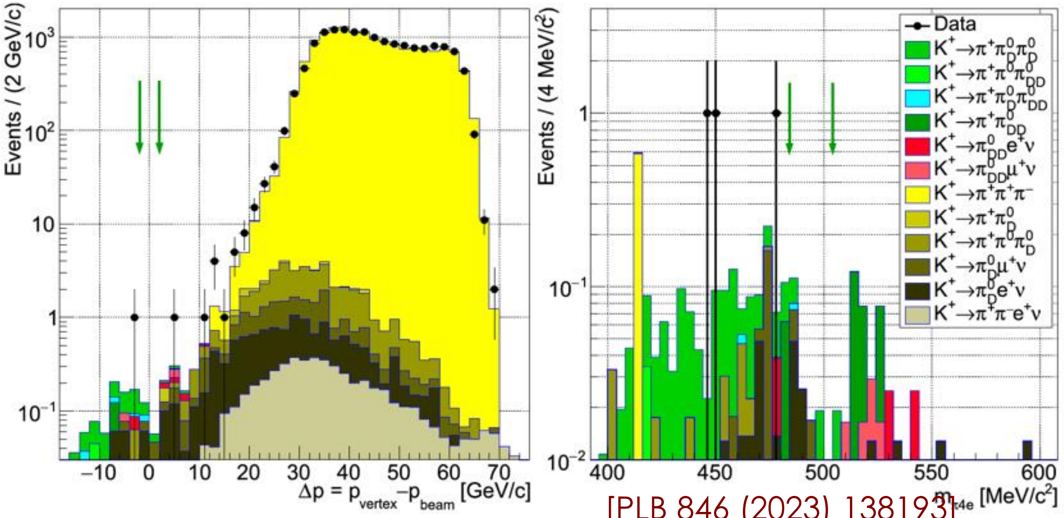


NA62 Search for $K^+ \to \pi^+ aa \to \pi^+ e^+e^-e^+e^-$ [PLB 846 (2023) 138193]

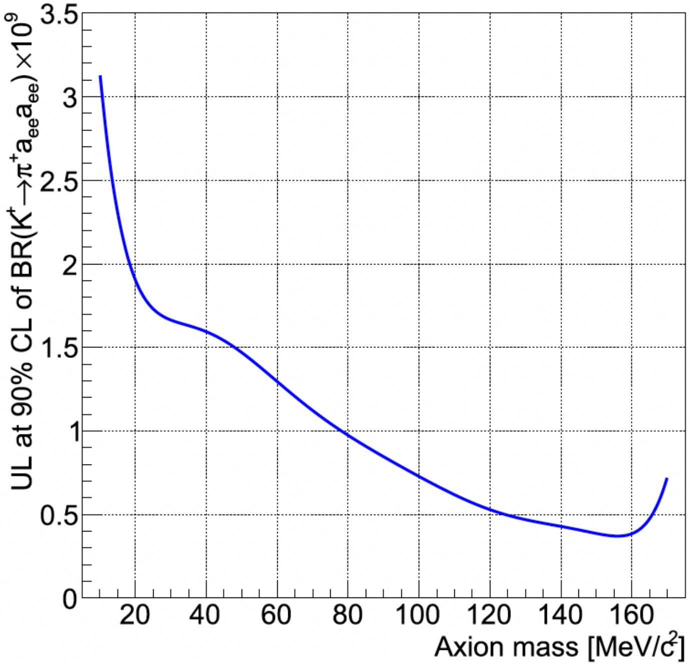
- Full NA62cdata set collected in 2017–2018
- Expected BG = 0.18±0.14 events
- No events are observed in the signal region $m_{\pi 4e} \sim m_{K+}$
- NA62 obtained:

$$BR(K^+ \to \pi^+ aa) \leq 2.1 \times 10^{-9} \; at \; 90\% \; CL$$

which rules out the QCD axion hypothesis for the X17.



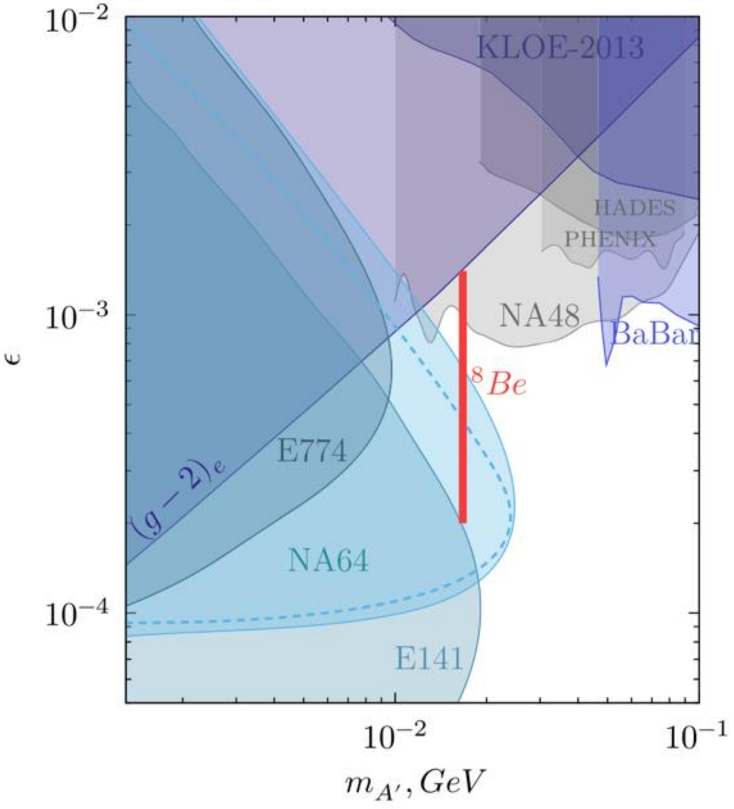
[PLB 846 (2023) 138193]



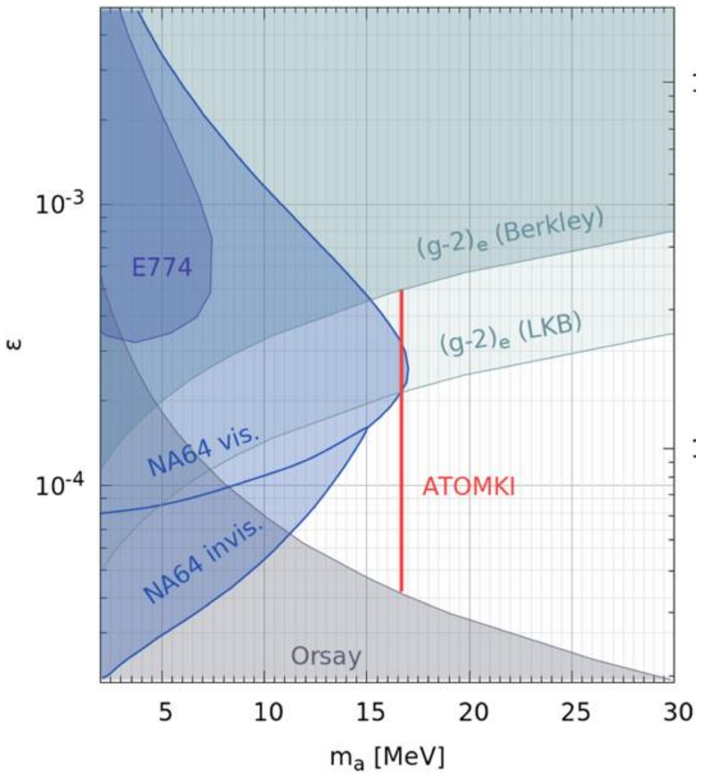
SAPIENZA
UNIVERSITÀ DI ROMA

Constraints on X17: pure lepton

Phys. Rev. D 101, 071101 (R) (2020)



Phys. Rev. D 104, L111102 (2021)



X17 as a vector (V) or axial vector (A) particle:

- Theoretically favoured by ATOMKI oboservations.
- NA48/2 bound not valid for “protophobic” V and A
- $(g-2)_e$ bound weaker for vectors
- Still a lot of free parameter space for vector X17

X17 as pseudo scalar particle:

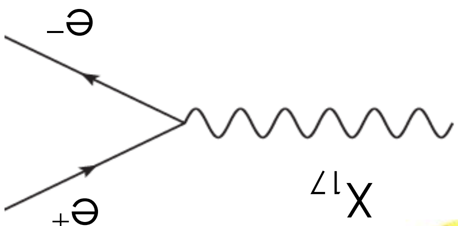
- Theoretically disfavoured by ^{12}C
- $(g-2)_e$ bound stronger for pseudo scalars
- Ruled out in pion decays (π^0->aa)
- Weak contraints in pure lepton-phillic models

As simple as possible: the resonance search

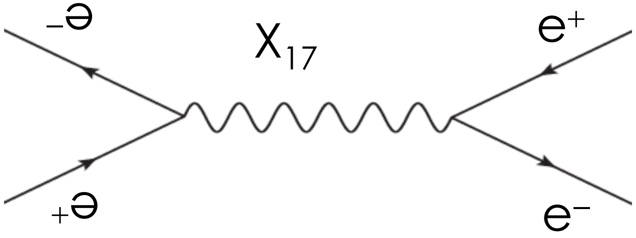
Atomki X_{17}

[M.R., E. Nardi et al. PRD 97, 095004 (2018)]

Just flip the diagram



and connect!



No model dependence just electron coupling!

Extremely high production rate Breit-Wigner enhancement

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak}\frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4} \qquad \sigma_{\rm peak} = 12\pi/m_{A'}^2$$

Lowest possible α suppression

Extremely small Γ_{X17} $\Gamma_{A'} \simeq \epsilon^2 \alpha m_{A'}/3$ $<10^{-2}$ eV

We need a lot of positrons in very limited COM energy range

[M.R. L. Darmé E. Nardi et al. PRD 106,115036]

We can have >1E10 e$^+$ in 20KeV CoM energy at LNF!

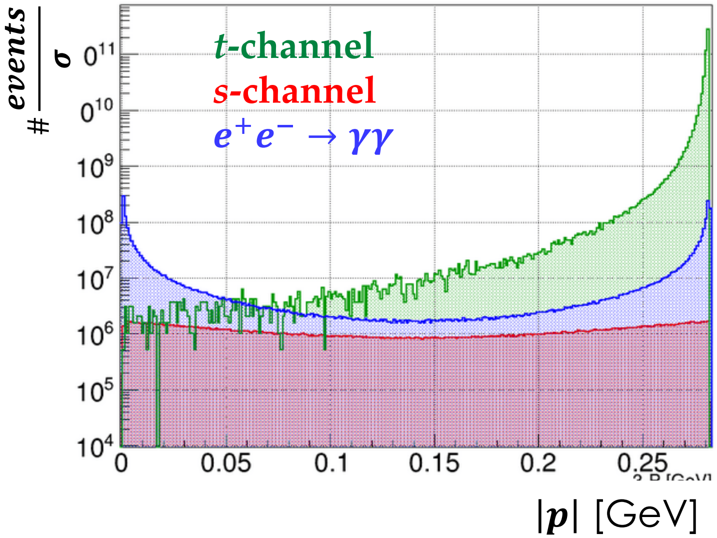
Ok **let's do that at PADME**!

The mass scan PAMDE search strategy

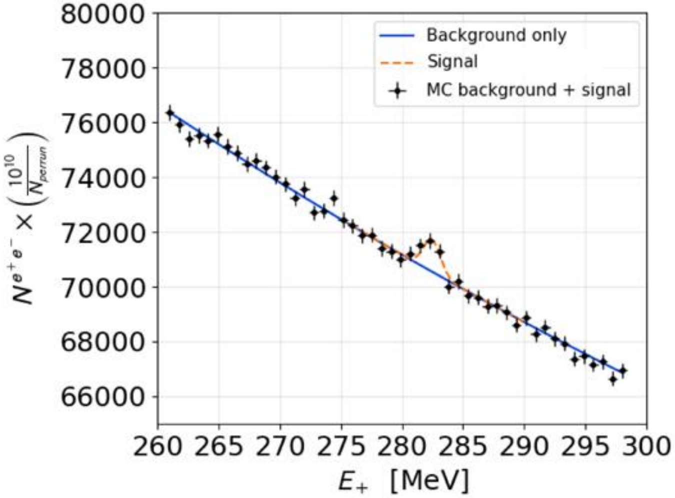
PADME, can use resonant X17 production process

- Extremely effective in producing X17 but in a very small mass range
- Scan E_{beam}=260–300 MeV in <1 MeV steps

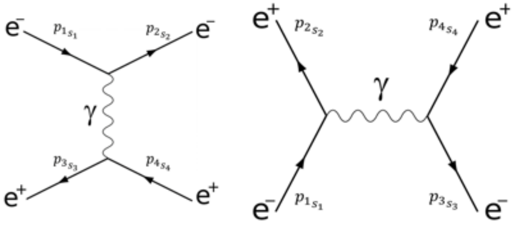
- Completely data driven no theory or MC inputs
- Signal should emerge on top of **Bhabha** BG in one or more points of the scan.
- Background estimated from surrounding bins



Cartoon view of the technique

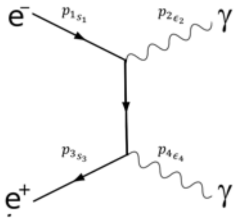


Bhabha scattering



t channel

s channel



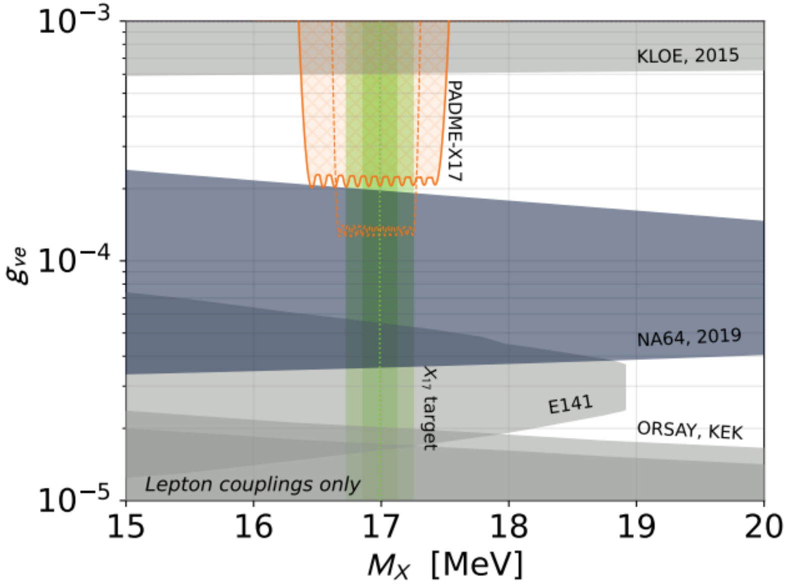
$e^+e^- \to \gamma\gamma$

PADME expected limits

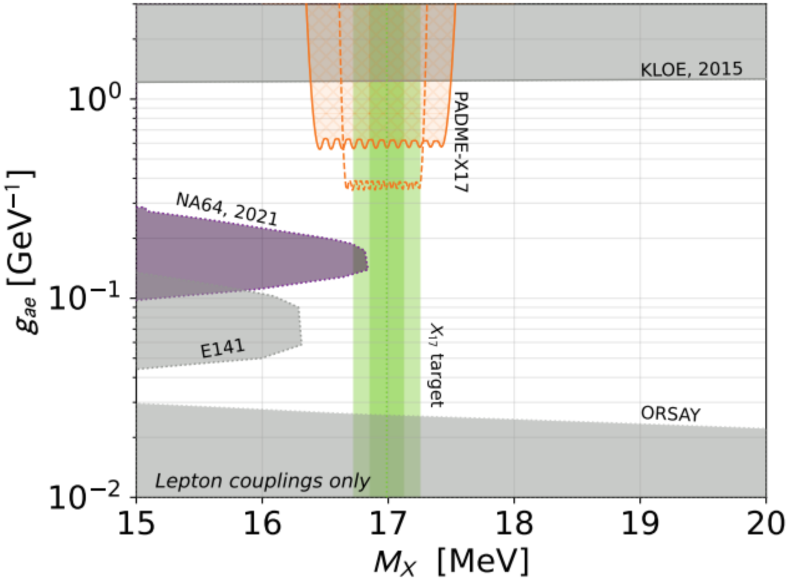
L. Darmé, M. Mancini, E. Nardi, M. Raggi

Darmé et al. Phys. Rev. D 106,115036

Vector X17



Pseudo scalar X17



BG from SM Bhabha scattering under control down to ε = few 10^{-4}

Need precise luminosity measurement and systematic errors control (<1%)

Need ~1E10 POT per each energy point

PADME maximum sensitivity in the vector case

PADME Run III data set: winter 2022

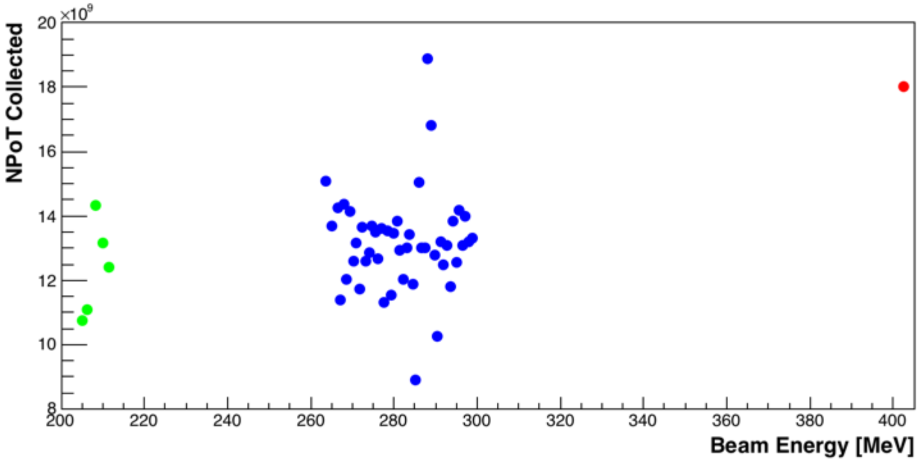
Run III PADME data set contains **3 subset**

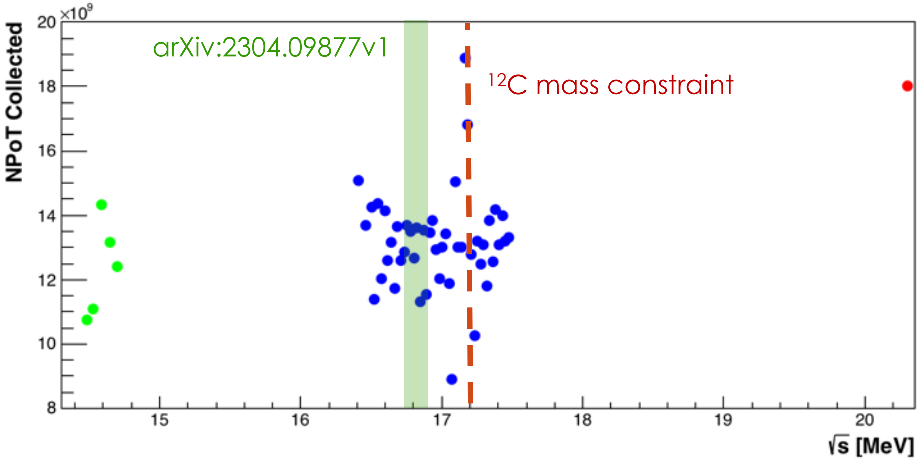
- **On resonance: 47 points (263-299) MeV**
- **Below resonance: 5 points (205-211) MeV**
- **Over resonance: 1 energy 402. MeV**

On resonance points **spaced** by **~0.75 MeV**
Point spacing equal to the energy resolution
Mass region 16.4 MeV<M_{X17}<17.5 MeV
statistics >1x10^{10} PoT per point

Below resonance **spaced** by **~1.5 MeV**
Statistics >1x10^{10} PoT per point
Used to validate analysis method

1 over resonance energy **5 different runs**
Statistics ~0.4x10^{10} PoT per run ~2E10 total
Used to validate NPoT measurement stability





GREEN mass range fit results in arXiv:2304.09877v1
Dots mass points explored by PADME
¦ Mass limit imposed by ^{12}C observation

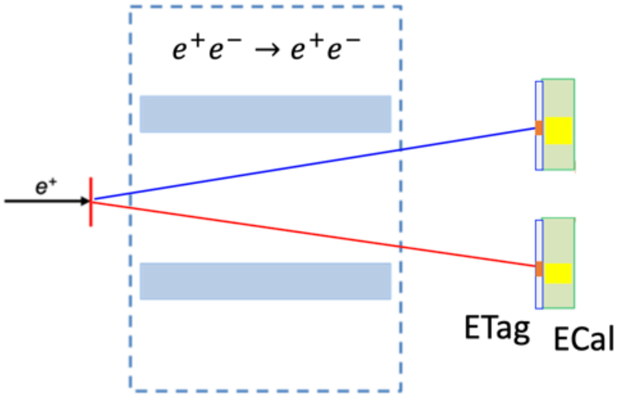
PADME Run III data analysis status

Scatter e+ on e- in the diamond target to select $e^+e^- \rightarrow e^+e^-$

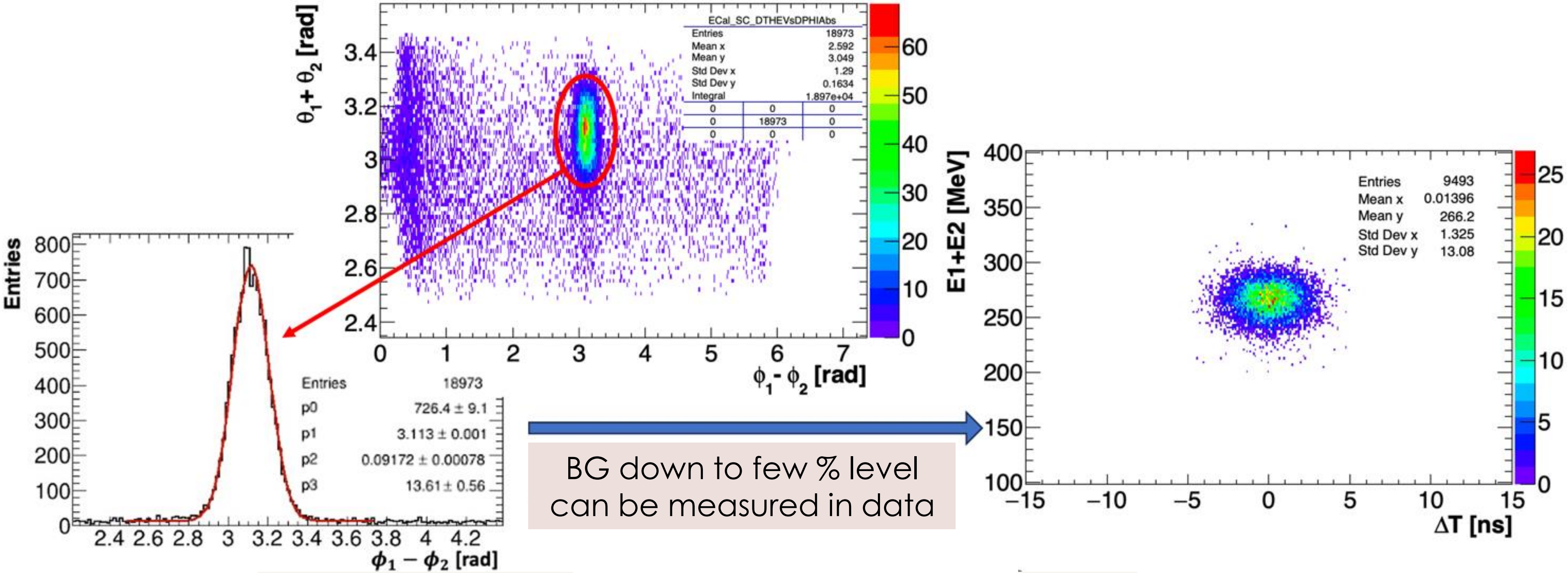
Measure, direction and energy of each track with Ecal

Transform back to the Centre of Mass: e^+e^- are back-to-back.

Select events with **$\theta_1+\theta_2=\pi$ and $\phi_1-\phi_2=\pi$**



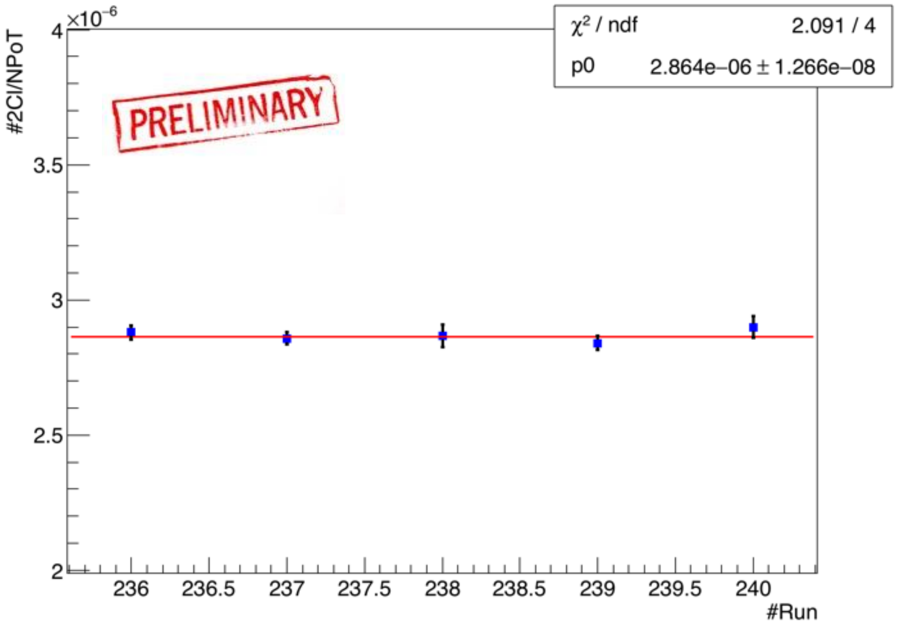
After selecting pure $e^+e^- \rightarrow e^+e^-$ search for unexpected excess from $e^+e^- \rightarrow X17 \rightarrow e^+e^-$ by scanning the X17 mass region.



BG down to few % level can be measured in data

PADME out of resonance data sets

Over resonance 402 MeV



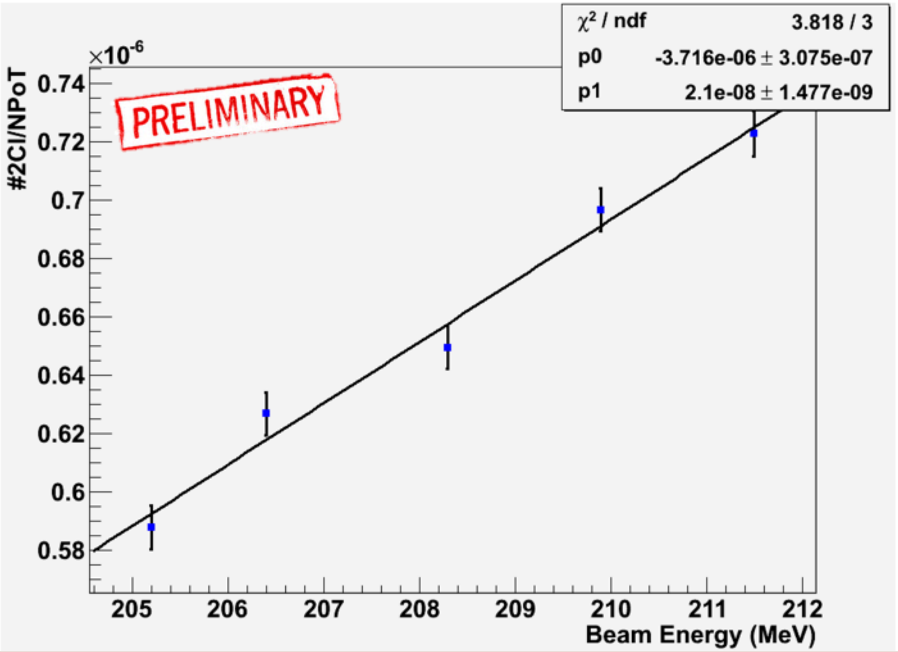
RMS ~0.7% over the 5 runs

Constant **fit has a good χ^2**

- No significant systematic errors

Vertical scale arbitrary

Below resonance 205-212



RMS <1% over the 5 energies

Good χ^2 of the linear fit

- Trend due to acceptance
- Vertical scale arbitrary:

Conclusions

8Be, 4He, 12 C GDR anomalies observed IPC at Atomki appear to be consistent with a particle physics **interpretation (X17)**
- Statistical evidence is very strong (~ 7σ for each nucleus)

SM explanations via higher order nuclear effects, interferences, higher multipoles contributions, are theoretically **(strongly) disfavoured…**

Present data from a single experiment.
- See, however, Hanoi experiment 22/08
- Additional independent validations are needed.

Intense effort for new Nucl. Phys. experiments is ongoing.
- First results expected not earlier than late 2024 early 2025.

Being based on resonant production, a particle physics experiment like **PADME will be decisive to validate/disprove the X17 hypothesis**.

Is X17 a dark matter candidate?

Is X17 is a good DM candidate? NO
- Violates the rule 1) "It should be stable" X17 decays to SM e^+e^- pairs.

Is X17 is a good WIMP candidate? NO
- X17 mass in too low for a WIMP

Is X17 a good Dark Sector candidate? maybe (too early)
- X17 mass is in the correct mass range (few MeV to < 1 GeV)
- X17 is weekly coupled to SM fermions
- X17 is similar a light mediator particle for dark sectors

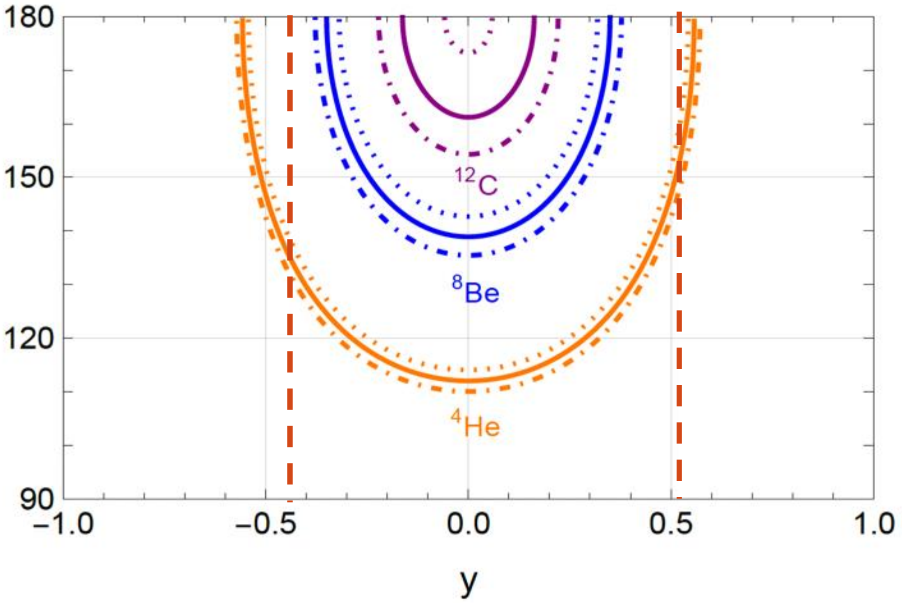
Could X17 be related to the DM problem?
- If X17 it's a vector particle could act as mediator for a new $U(1)_D$ symmetry?
- In this case the DM fermions need to be at higher mass scales ($M\chi$ >> 17MeV)

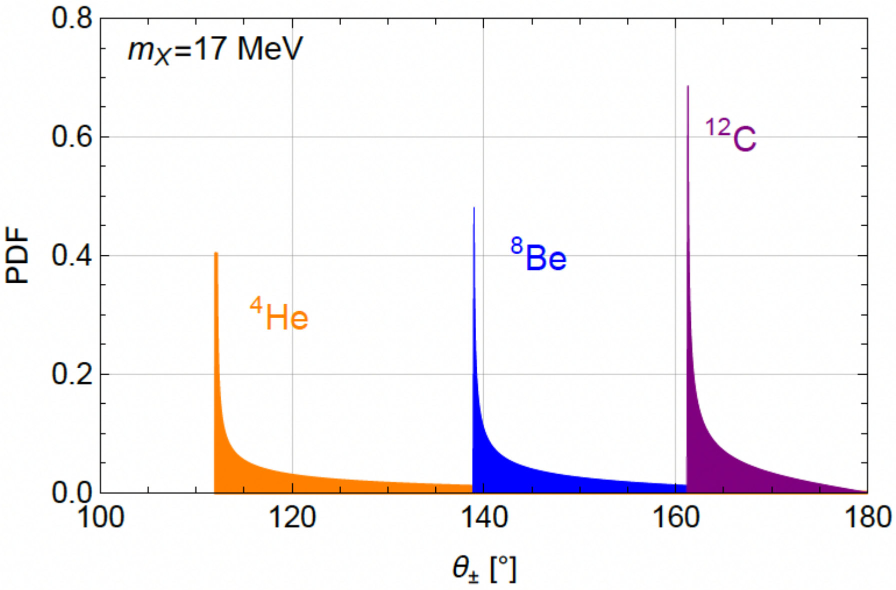
Could X17 help with other anomalies?
- If X17 it's a vector particle could help with $(g-2)_e$ and $(g-2)\mu$ anomalies

Thank you for your attention and Join the dark side!

Backup slides

Kinematics and the y cut.

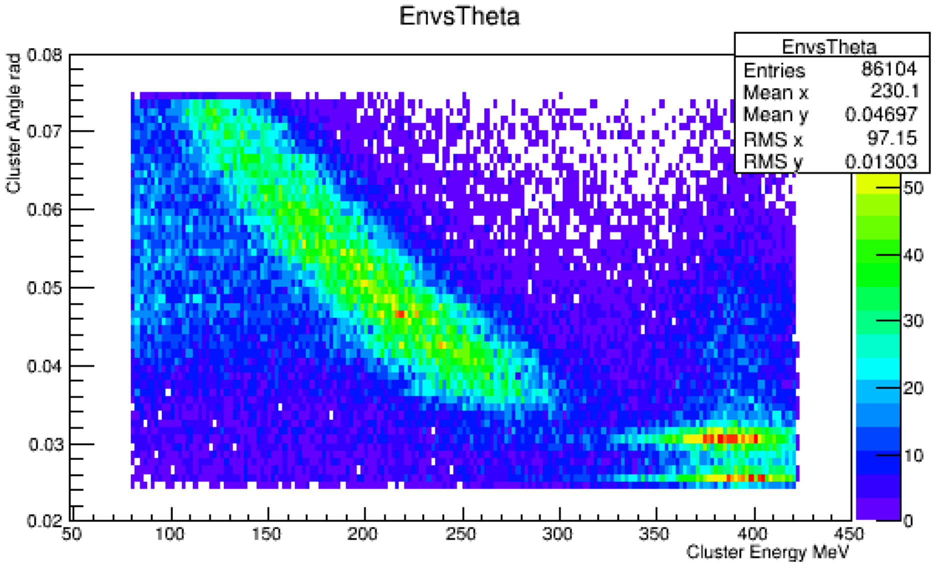




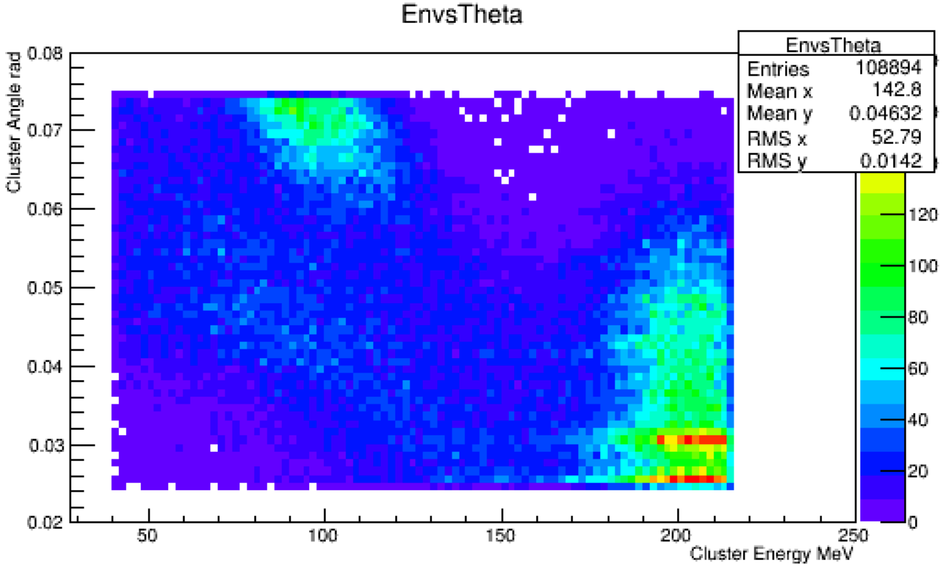
Looking on the mass sidebands

- PADME collected **two off resonance** data sets:
  - **Over Resonance: 402 MeV** 5 Runs for a total of **1.2E10 POT (collected 1w of October 2022)**
  - **Below Resonance: 205-211** MeV 5 energies for a total of **5E10 POT (last w of November 2022)**

- First selection aimed at **$N(2cl)/N_{PoT}$** studies:
  - 2 in time clusters in the $\Delta t < 5$ns in Ecal
  - Energy and radius cuts, reasonable Centre of Gravity
  - Cluster energy vs angle correlation compatible with a 2 body final state.

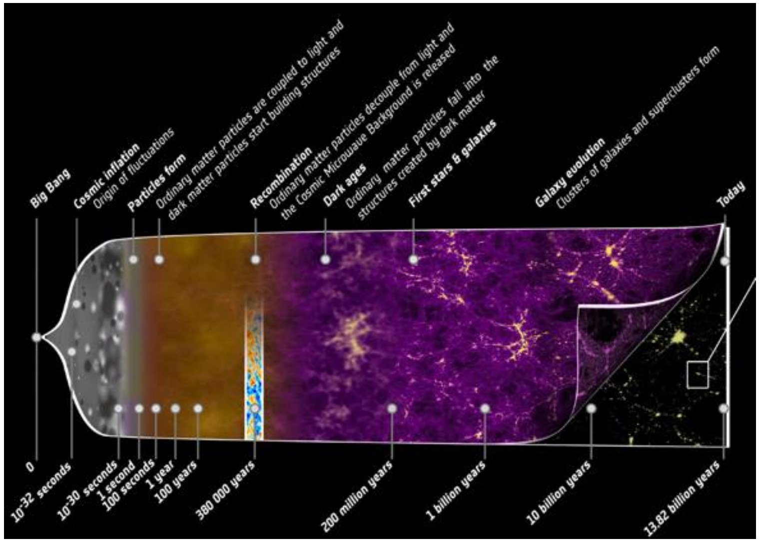


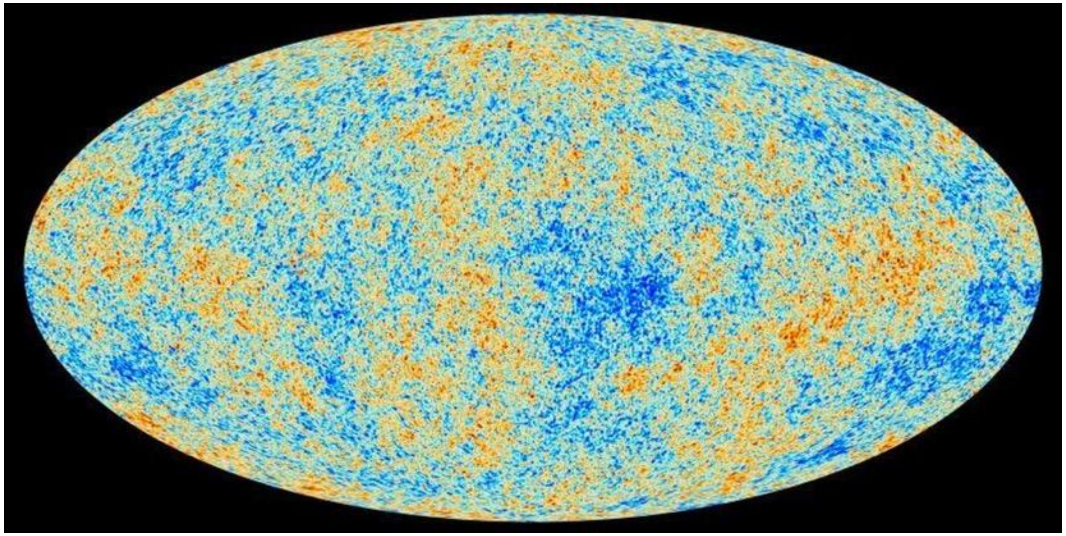
Over Resonance: 402 MeV



Below Resonance: 205 MeV

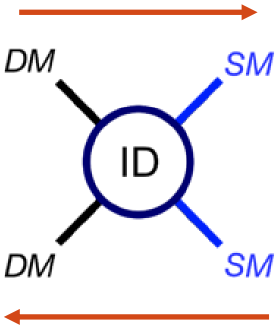
1. How Dark Matter was born





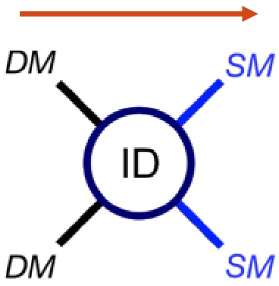
Universo caldo

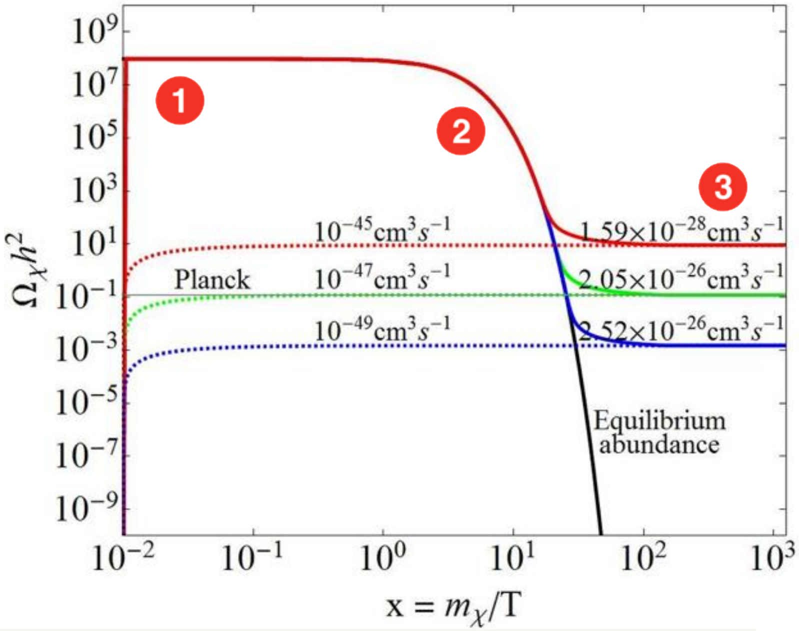
① **$T>M_{DM}$ $x<1$**



Cooled Universe

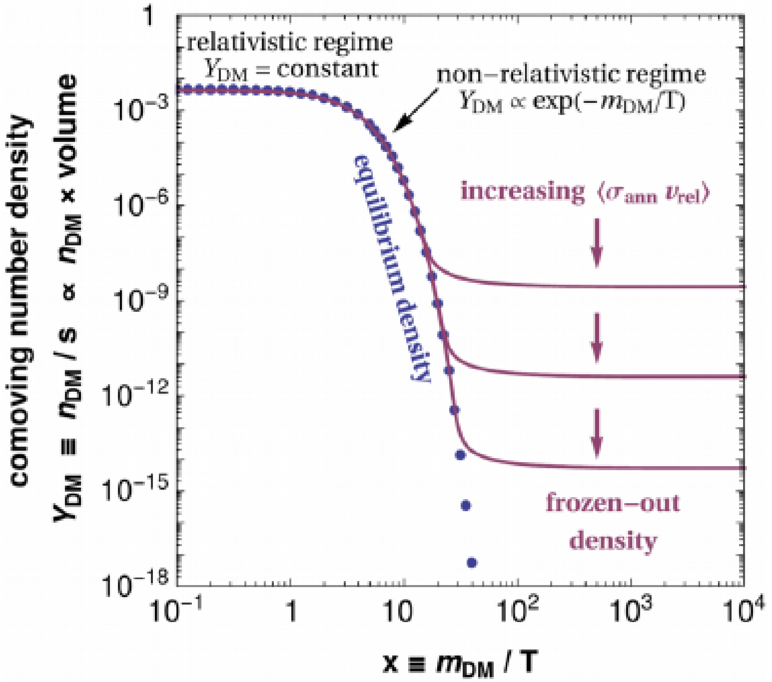
② **$T<M_{DM}$ $x>1$**





③ DM density too low, DM production stops
Freeze out produced a relic DM density

2. Non vogliamo nuove forze!



Dal freeze-out possiamo stabilire

$$\Omega_{DM} h^2 \sim \frac{3 \cdot 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$

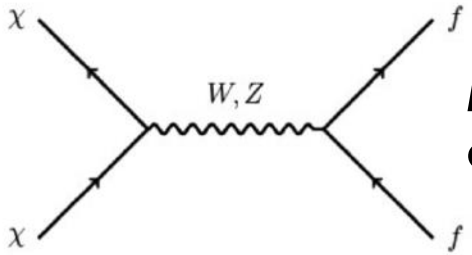
Dalle misure di CMB sappiamo che:

$\Omega_{DM} h^2 \simeq 0.1$, hence:
$\langle \sigma v \rangle \simeq 3 \cdot 10^{-26} cm^3 s^{-1}$

Senza introdurre una nuova forza ma utilizzando l'interazione debole che già abbiamo!

$$\langle \sigma v \rangle_{\mathrm{WIMP}} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1} \left(\frac{\mathrm{TeV}}{m_\chi} \right)^2$$

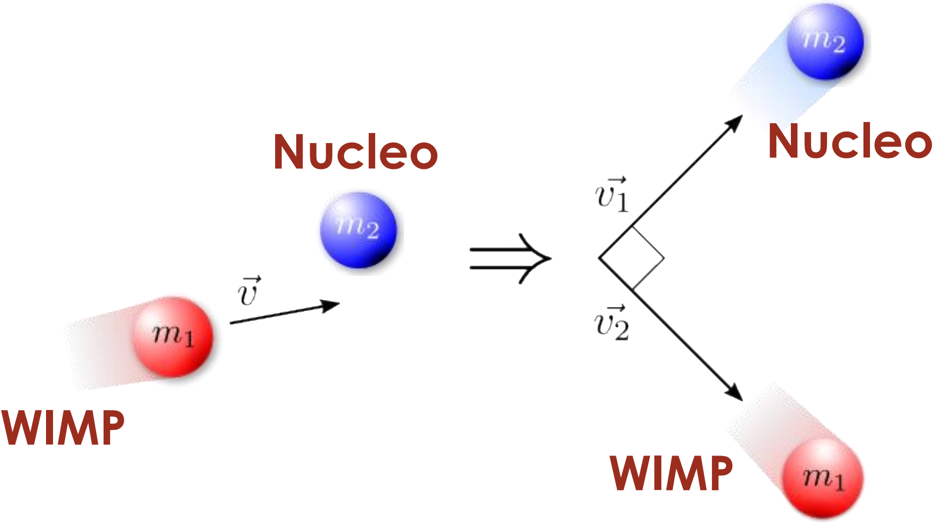
DM
Wimp

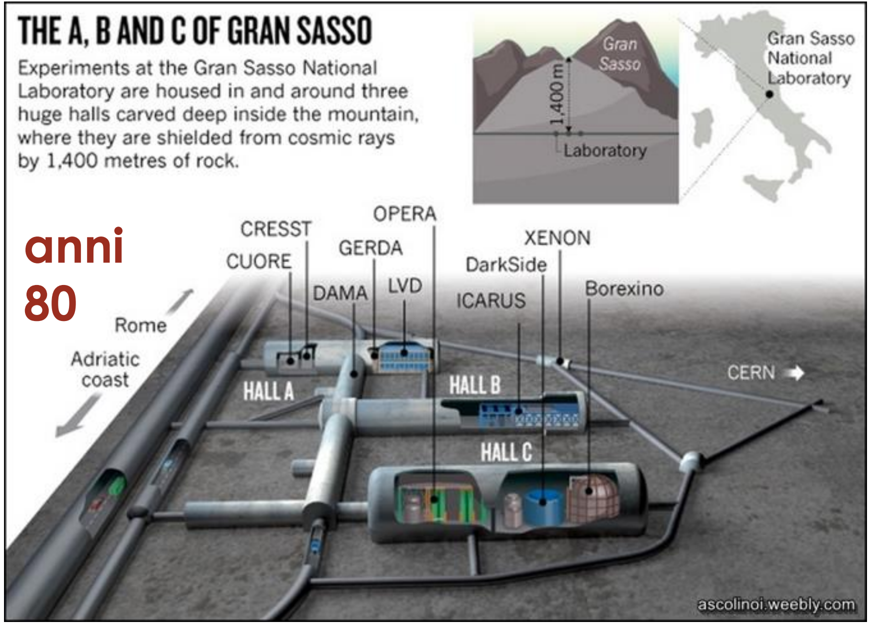


Materia
ordinaria

Ci serve soltanto una **particella pesante** con interazione debole ma **non nuove forze**!
Chiameremo questa **particella WIMP.**

Ricerca diretta di DM - Wimps



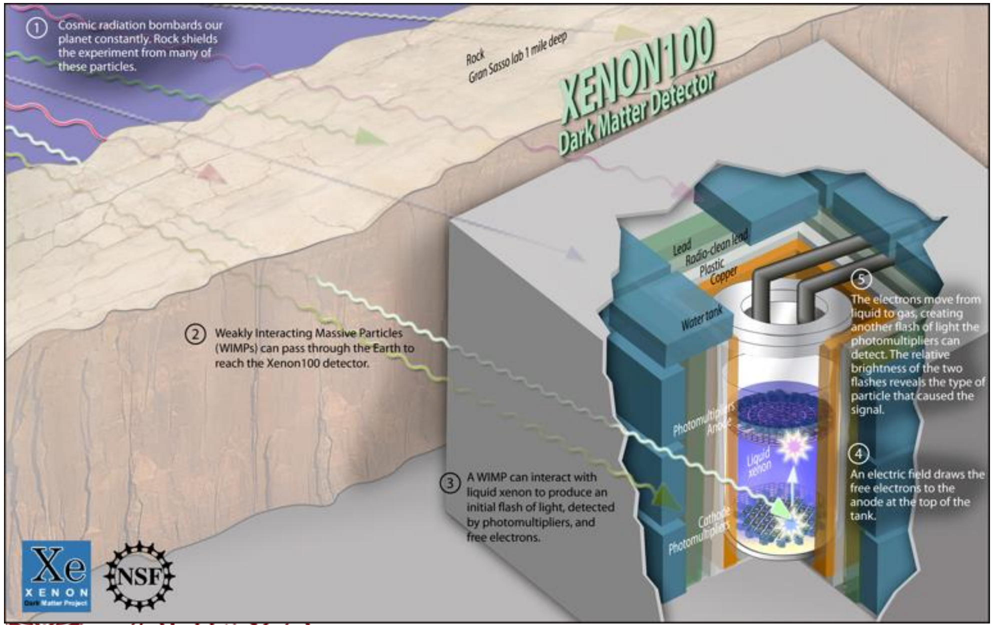


THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.

ascolinoi.weebly.com

anni 80



① Cosmic radiation bombards our planet constantly. Rock shields the experiment from many of these particles.

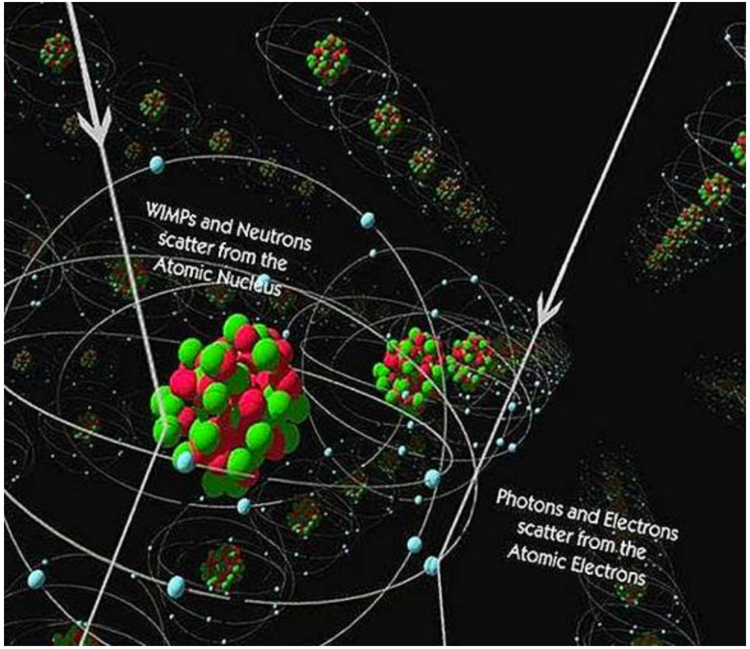
② Weakly Interacting Massive Particles (WIMPs) can pass through the Earth to reach the Xenon100 detector.

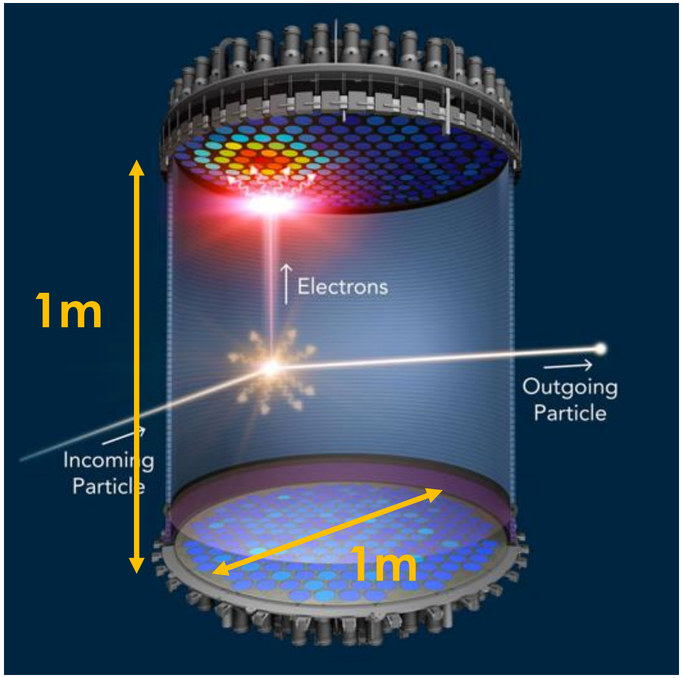
③ A WIMP can interact with liquid xenon to produce an initial flash of light, detected by photomultipliers, and free electrons.

④ An electric field draws the free electrons to the anode at the top of the tank.

⑤ The electrons move from liquid to gas, creating another flash of light the photomultipliers can detect. The relative brightness of the two flashes reveals the type of particle that caused the signal.

XENON1T ai laboratori del Gran Sasso

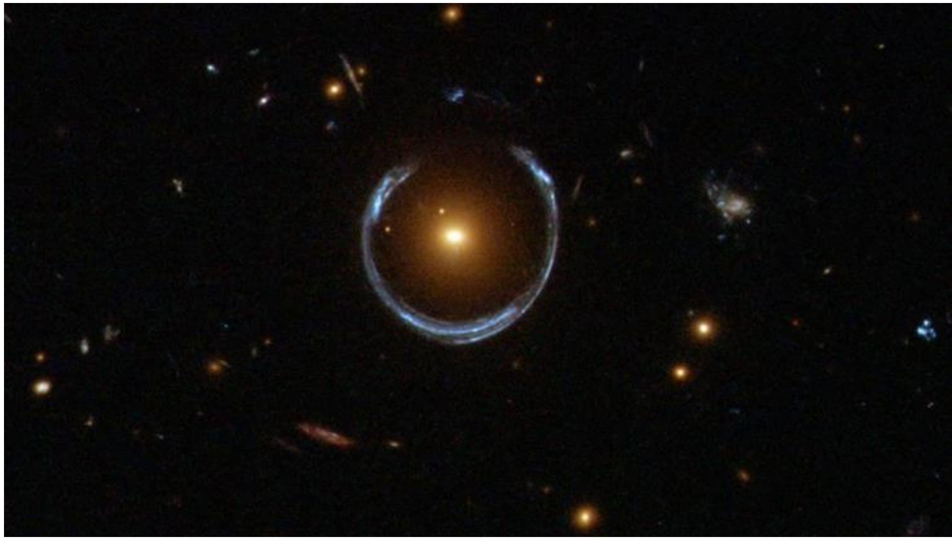


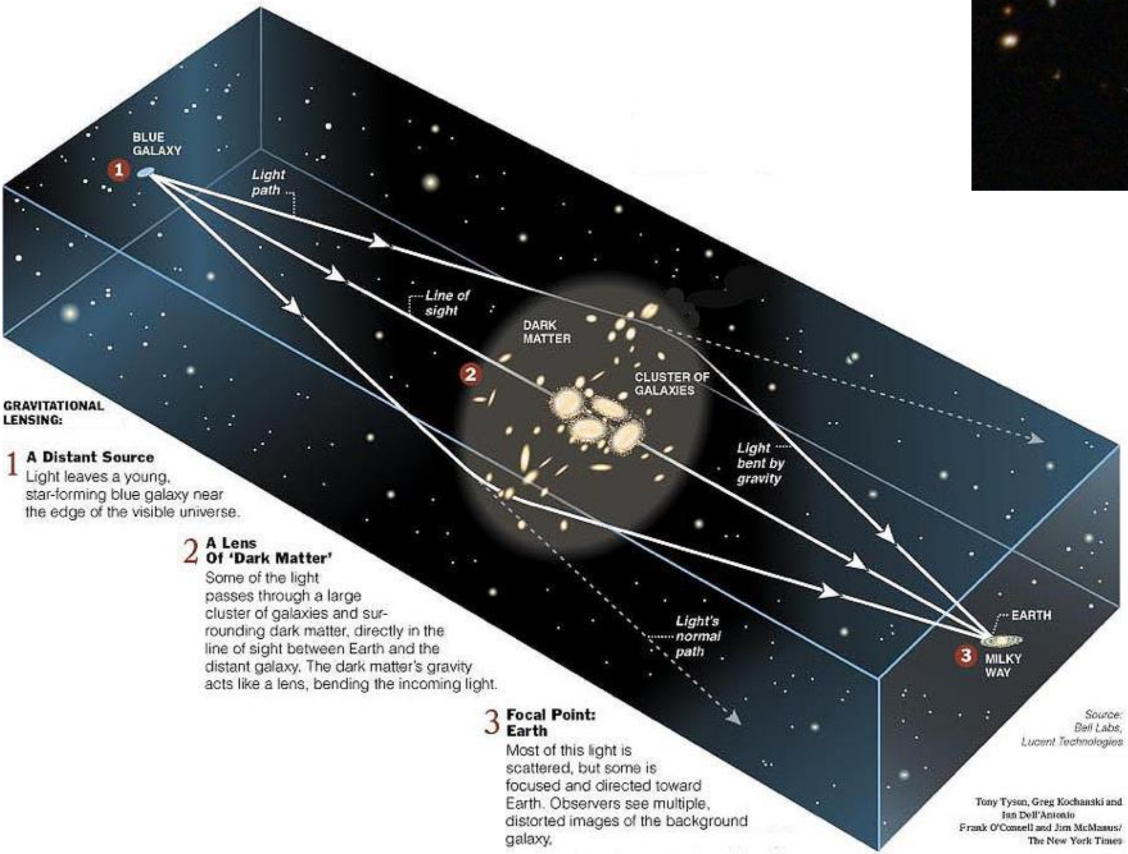


3.300 Kg di Xenon liquido alla temperatura di 95 gradi sotto zero

Measuring dark matter: Gravitational lensing

Light in the presence of large densities of matter does not travel in a straight line but along the lines of space-time warped by gravity locally.





GRAVITATIONAL LENSING:

1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

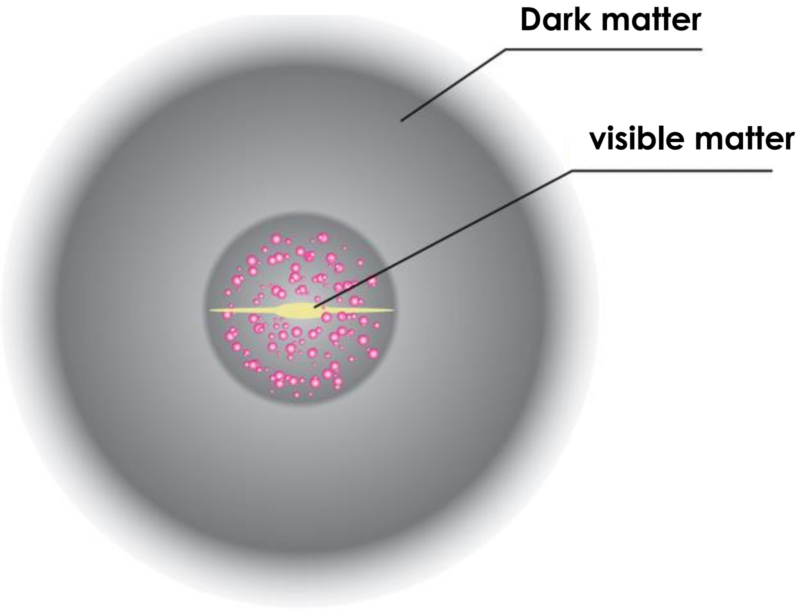
2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

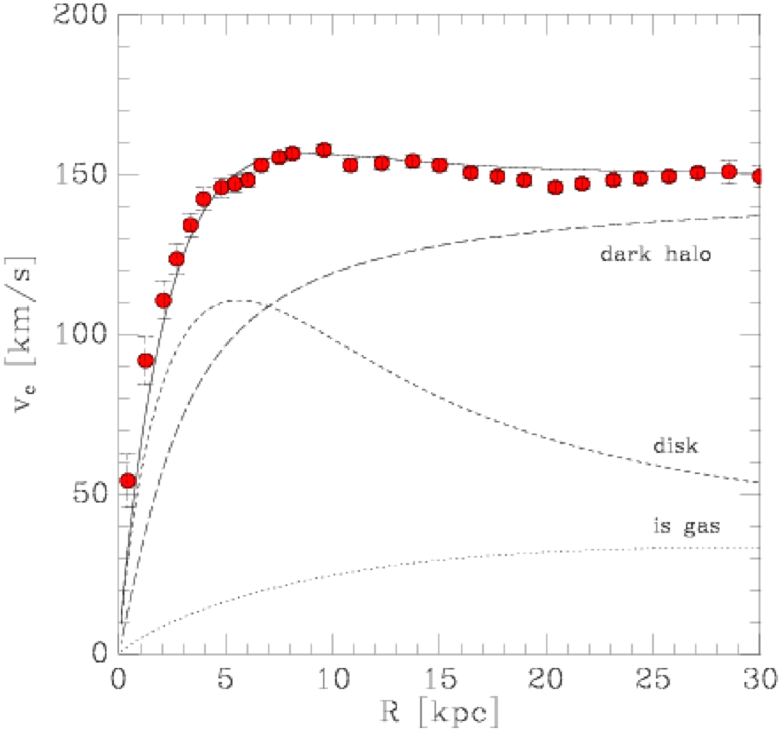
3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

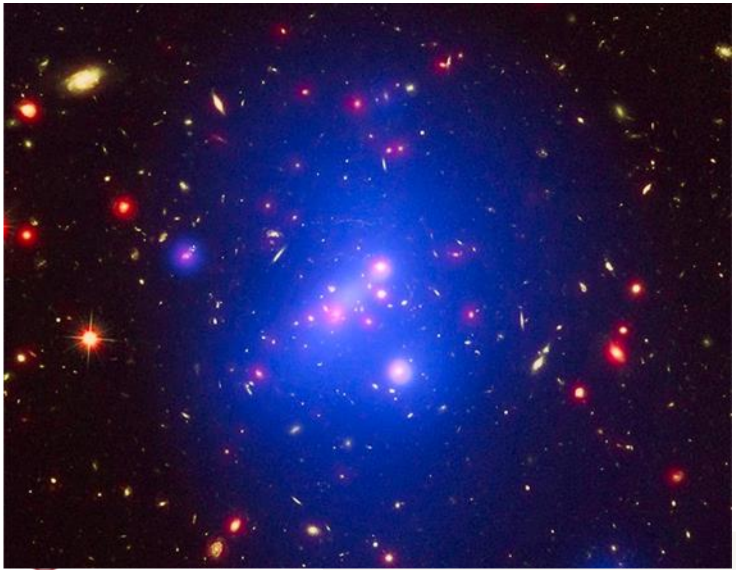
Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/
The New York Times

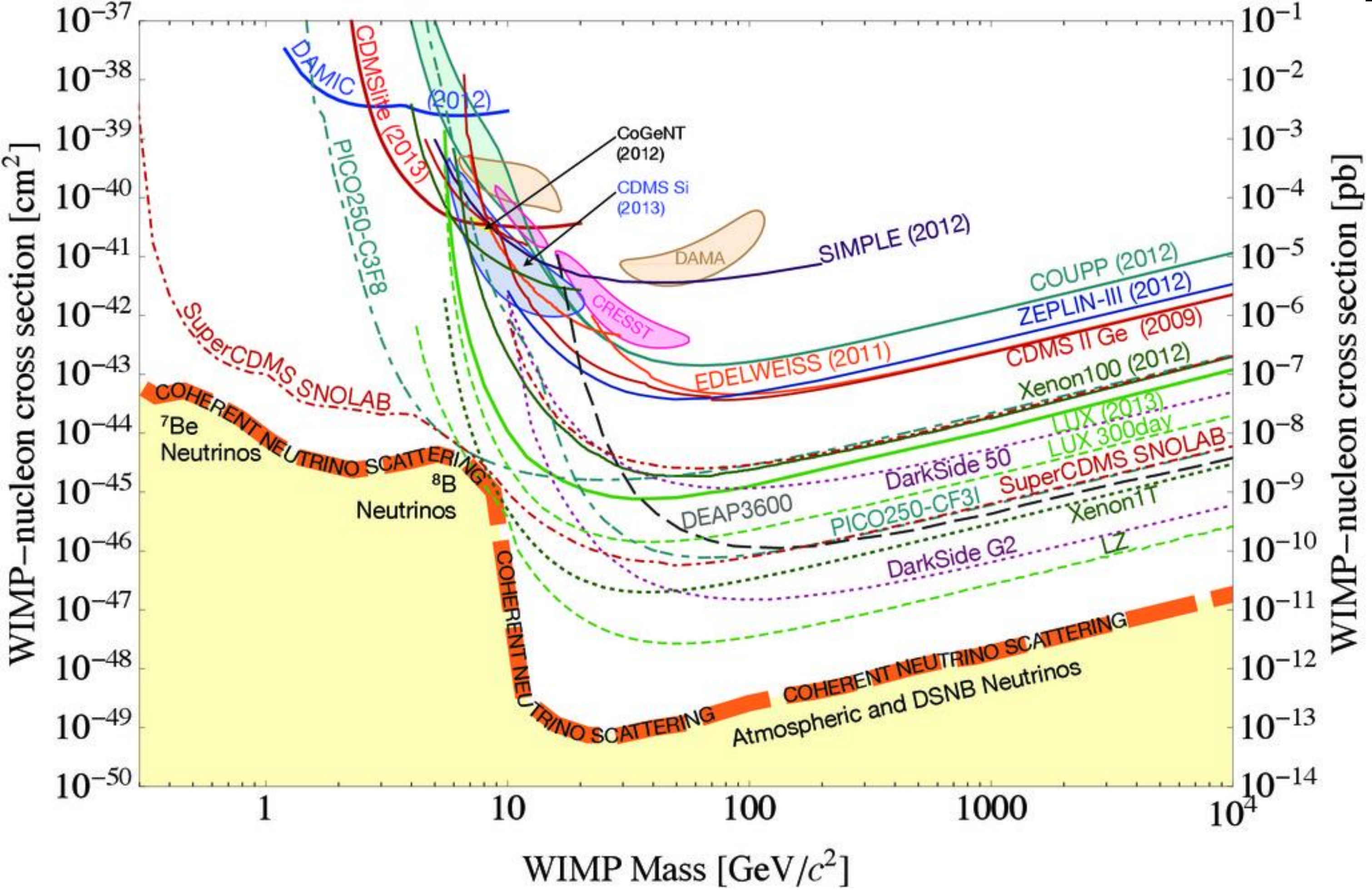
What does a galaxy look like?







Stato della ricerca diretta di DM



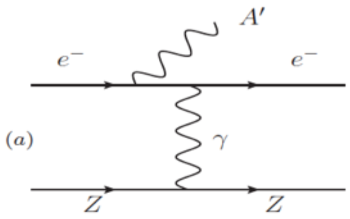
per ora nessuna buona notizia purtroppo!

DS search: experimental approaches

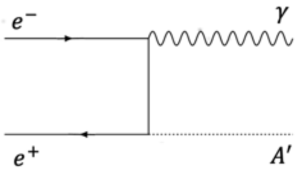
- **Electron beam experiments production**
  - **Just A'-strahlung**
- **Positron based experiments**
  - **A'-strahlung**
  - **Associated production** $e^+e^- \to A'(\gamma)$
  - **Resonant production** $e^+e^- \to e^+e^-$

- **Visible decays**: $A' \to e^+e^-$ $A' \to \mu^+\mu^-$
  - **Thick target electron/protons** beam is absorbed (NA64, old dump experiments)
  - **Thin target** searching for bumps in ee invariant mass
- **Invisible searches:** $A' \to \chi\chi$
  - **Missing energy/momentum**: A' produced in the interaction of an electron beam with **thick/thin target** (NA64/LDMX)
  - **Missing mass**: $e^+e^- \to A'(\gamma)$ search for invisible particle using kinematics (Belle II, **PADME**)

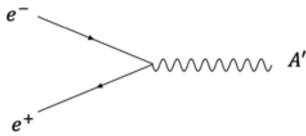
Brems.



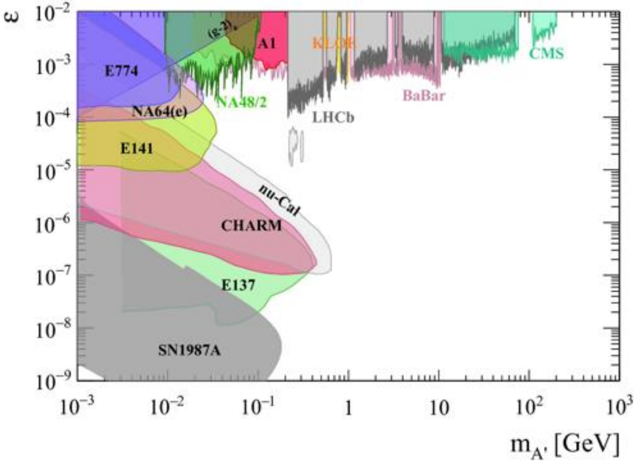
Associated production



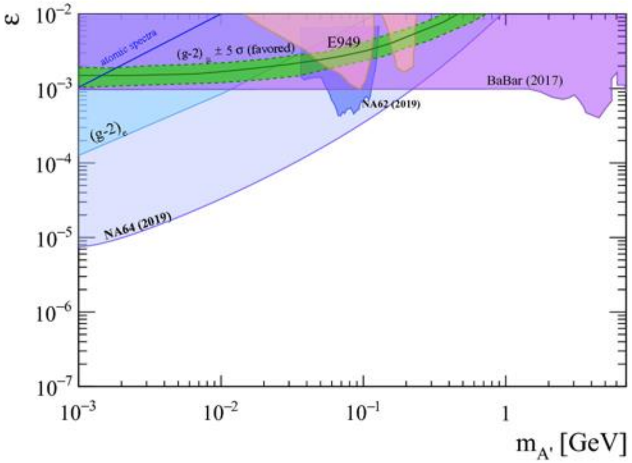
Resonant

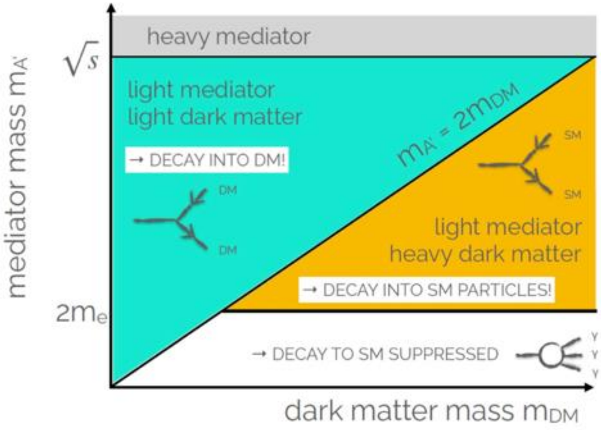


Visible decay



Invisible decay



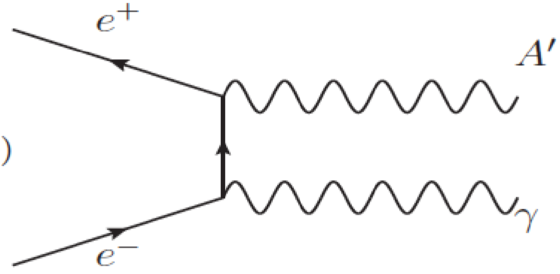


How can we make our life easier?

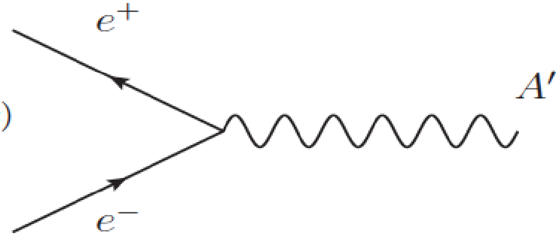
- We need higher production cross section!

Positron beams

(b)



(c)



- Can move from associated to resonant production
  - b) Radiative annihilation O(α^2)

$$\sigma_{nr} = \frac{8\pi\alpha^2}{s}\left[\left(\frac{s-m_{A'}^2}{2s} + \frac{m_{A'}^2}{s-m_{A'}^2}\right)\log\frac{s}{m_e^2} - \frac{s-m_{A'}^2}{2s}\right]$$

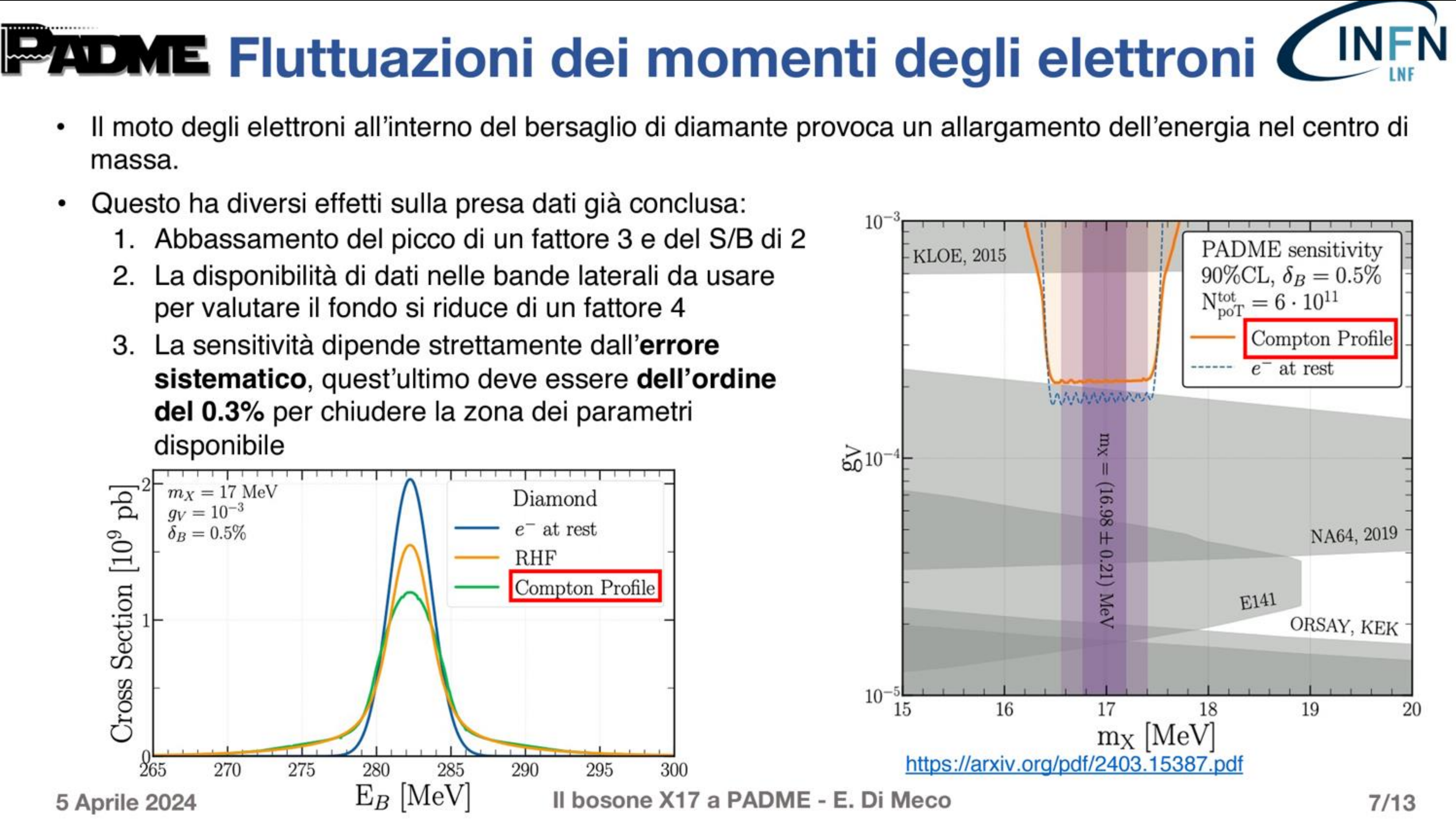
  - c) Resonant annihilation O(α)

$$\sigma_{\text{res}}(E_e) = \sigma_{\text{peak}}\frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2 + \Gamma_{A'}^2/4} \qquad \sigma_{\text{peak}} = 12\pi/m_{A'}^2$$

- Profit for a higher production in a tiny mass region

$$\mathcal{N}_{X_{17}}^{\text{Vect.}} \simeq 1.8\cdot 10^{-7} \times \left(\frac{g_{ve}}{2\cdot 10^{-4}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right) \qquad \mathcal{N}_{X_{17}}^{\text{ALP}} \simeq 5.8\cdot 10^{-7} \times \left(\frac{g_{ae}}{\text{GeV}^{-1}}\right)^2 \left(\frac{1\ \text{MeV}}{\sigma_E}\right)$$

Electron motion in C effect



PADME Fluttuazioni dei momenti degli elettroni

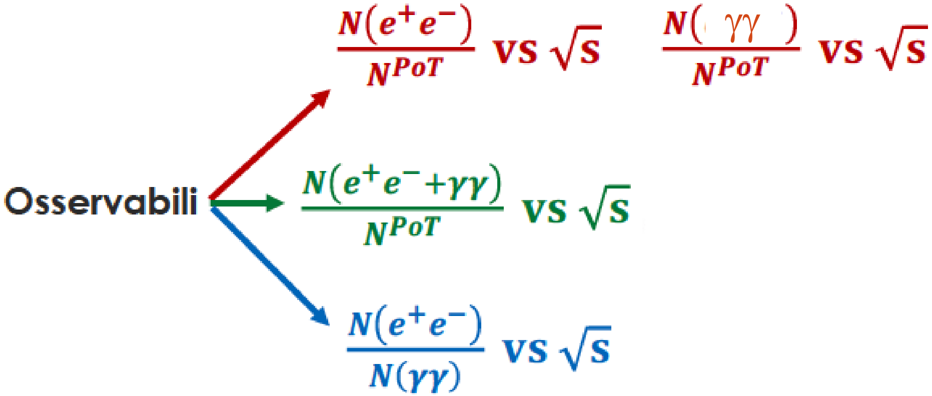
- Il moto degli elettroni all’interno del bersaglio di diamante provoca un allargamento dell’energia nel centro di massa.
- Questo ha diversi effetti sulla presa dati già conclusa:
  1. Abbassamento del picco di un fattore 3 e del S/B di 2
  2. La disponibilità di dati nelle bande laterali da usare per valutare il fondo si riduce di un fattore 4
  3. La sensitività dipende strettamente dall’**errore sistematico**, quest’ultimo deve essere **dell’ordine del 0.3%** per chiudere la zona dei parametri disponibile

https://arxiv.org/pdf/2403.15387.pdf

5 Aprile 2024 Il bosone X17 a PADME - E. Di Meco 7/13

X17 observables at PADME

Several different observables can be used with different systematics



Osservabili

$\frac{N(e^+e^-)}{N^{PoT}}$ vs $\sqrt{s}$ $\frac{N(\gamma\gamma)}{N^{PoT}}$ vs $\sqrt{s}$

$\frac{N(e^+e^-+\gamma\gamma)}{N^{PoT}}$ vs $\sqrt{s}$

$\frac{N(e^+e^-)}{N(\gamma\gamma)}$ vs $\sqrt{s}$

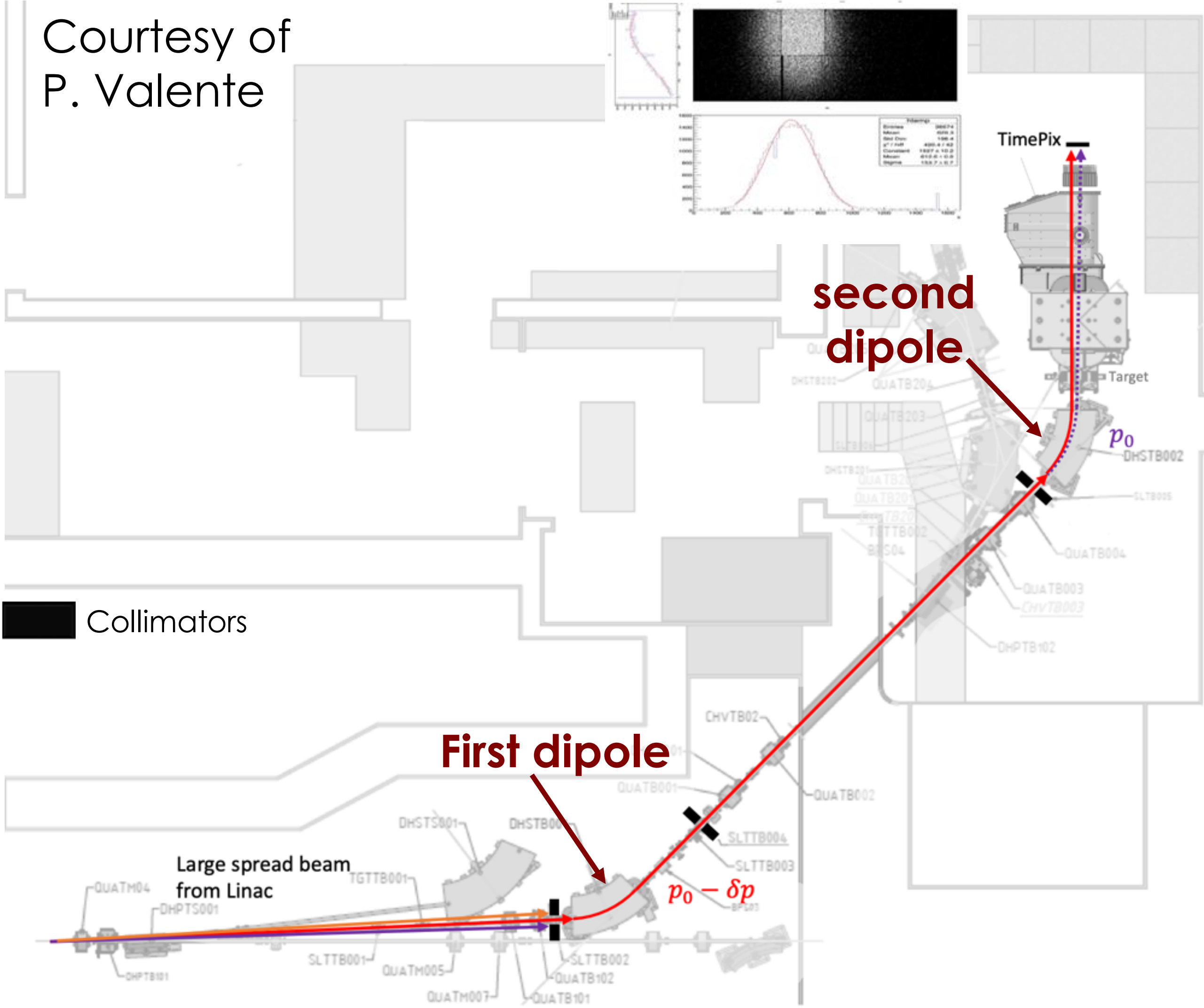
N(2cl)/NPoT ⇒ existence of X17
High statistical significance (small sensitivity loss due to small $\gamma\gamma$ BG)
No ETag related systematic errors

N(ee)/N($\gamma\gamma$) ⇒ existence of X17
Lower statistical significance due to smaller $\gamma\gamma$ cross section
Do not depend on N_{PoT} (no N_{PoT} systematic) error dominated by tagging efficiency

N_{e+e-}/N_{PoT} ⇒ vector nature of X_{17}
Systematic errors due to ETag tagging efficiency stability and N_{PoT}
$N_{\gamma\gamma}/N_{PoT}$ ⇒ pseudo-scalar nature of X_{17}
Systematic errors due to ETag tagging efficiency stability and N_{PoT}

Obtaining energy steps and resolution

Courtesy of
P. Valente



Use the first dipole magnet and collimators to select energy

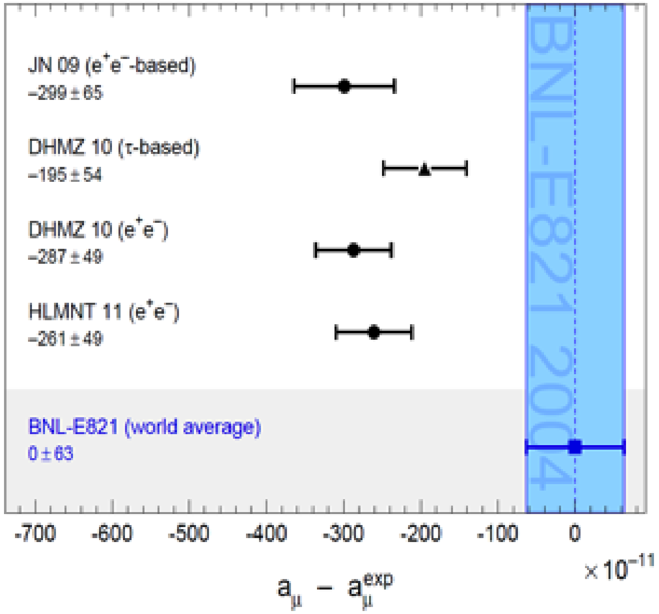
- dp ∝ collimator aperture.

Change the first dipole magnet current to change the energy

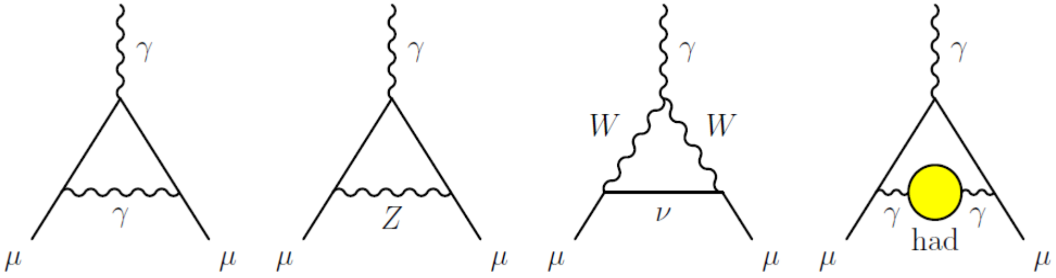
Correct the trajectory using second dipole to put the beam back on axis at PADME

Measure the displacement at the target and timePix to measure the energy step performed

Muon g-2 anomaly



g-2 in the standard model

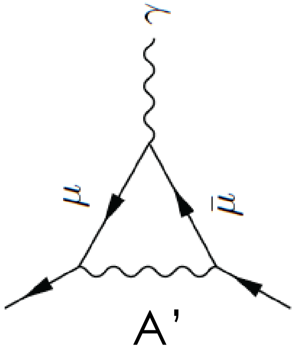


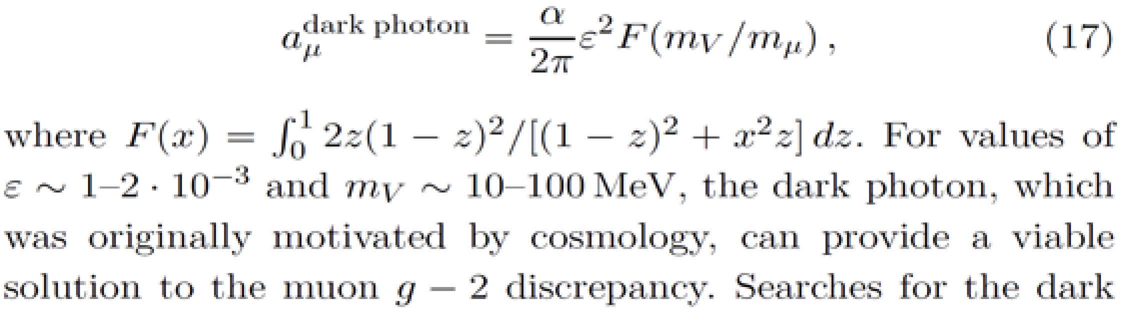
About 3σ discrepancy between theory and experiment (3.6σ, if taking into account only e+e–>hadrons)

Contribution to g-2 from dark photon

Additional diagram with dark photon exchange can fix the discrepancy (with sub GeV A' masses)

g-2 and A'



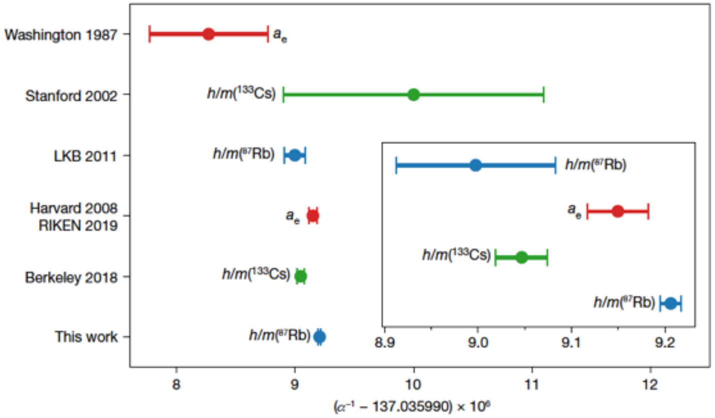


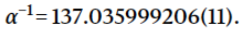
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1\text{–}2\cdot 10^{-3}$ and $m_V \sim 10\text{–}100$ MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

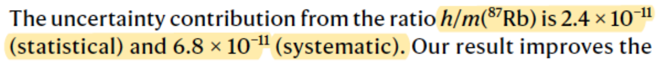
g-2e anomaly

- Significant discrepancy in the last two results on the α determination
- Produce a modified $(g\text{-}2)_e$ exclusion which allows a region of existence of X17



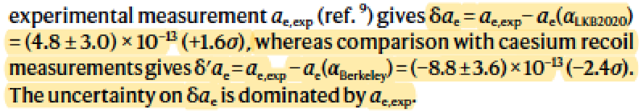


$\alpha^{-1} = 137.035999206(11)$.

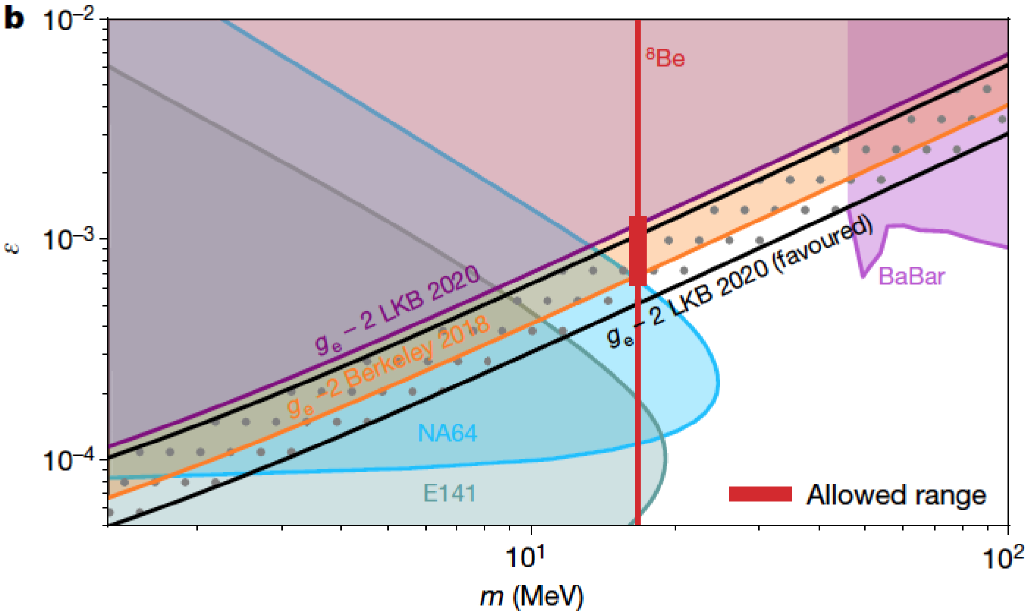


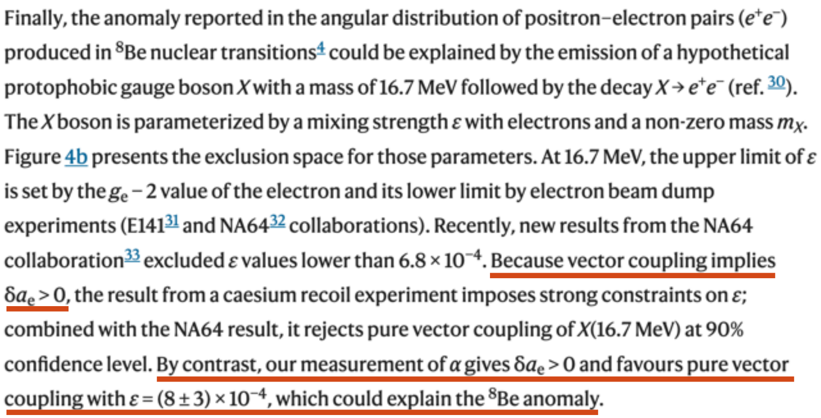
The uncertainty contribution from the ratio $h/m(^{87}\mathrm{Rb})$ is 2.4×10^{-11} (statistical) and 6.8×10^{-11} (systematic). Our result improves the

https://www.nature.com/articles/s41586-020-2964-7



experimental measurement $a_{e,\mathrm{exp}}$ (ref. [9]) gives $\delta a_e = a_{e,\mathrm{exp}} - a_e(\alpha_{\mathrm{LKB2020}}) = (4.8 \pm 3.0) \times 10^{-13}$ $(+1.6\sigma)$, whereas comparison with caesium recoil measurements gives $\delta' a_e = a_{e,\mathrm{exp}} - a_e(\alpha_{\mathrm{Berkeley}}) = (-8.8 \pm 3.6) \times 10^{-13}$ (-2.4σ). The uncertainty on δa_e is dominated by $a_{e,\mathrm{exp}}$.





Finally, the anomaly reported in the angular distribution of positron–electron pairs (e^+e^-) produced in ^{8}Be nuclear transitions[4] could be explained by the emission of a hypothetical protophobic gauge boson X with a mass of 16.7 MeV followed by the decay $X \to e^+e^-$ (ref. [30]). The X boson is parameterized by a mixing strength ε with electrons and a non-zero mass m_X. Figure 4b presents the exclusion space for those parameters. At 16.7 MeV, the upper limit of ε is set by the $g_e - 2$ value of the electron and its lower limit by electron beam dump experiments (E141[31] and NA64[32] collaborations). Recently, new results from the NA64 collaboration[33] excluded ε values lower than 6.8×10^{-4}. Because vector coupling implies $\delta a_e > 0$, the result from a caesium recoil experiment imposes strong constraints on ε; combined with the NA64 result, it rejects pure vector coupling of X(16.7 MeV) at 90% confidence level. By contrast, our measurement of α gives $\delta a_e > 0$ and favours pure vector coupling with $\varepsilon = (8 \pm 3) \times 10^{-4}$, which could explain the ^{8}Be anomaly.

SAPIENZA
UNIVERSITÀ DI ROMA

Montreal experiment

- Wire chamber surrounding the target