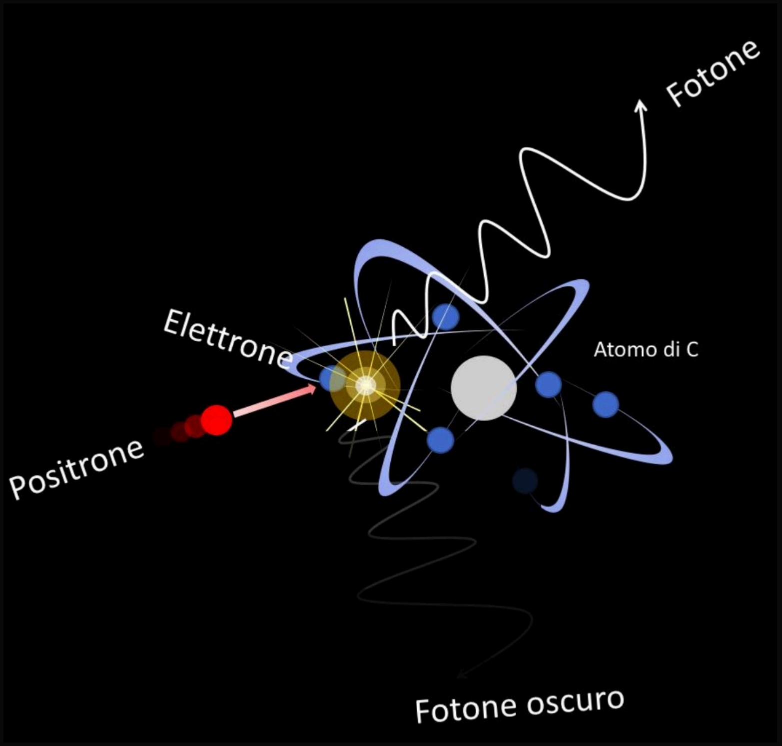
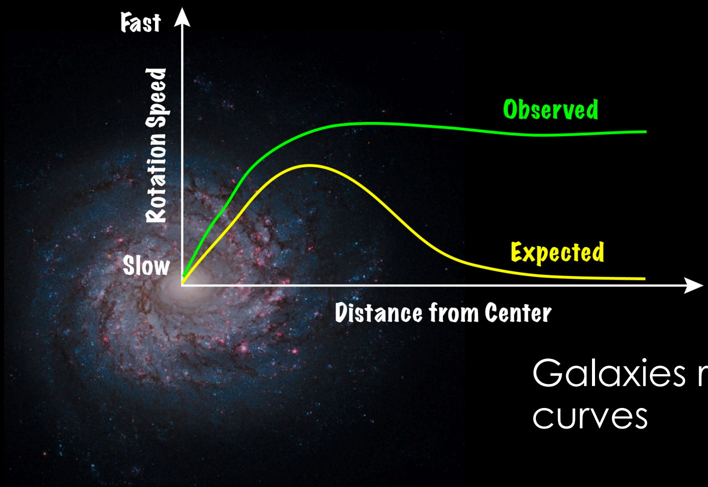
Searching for light dark matter at accelerators



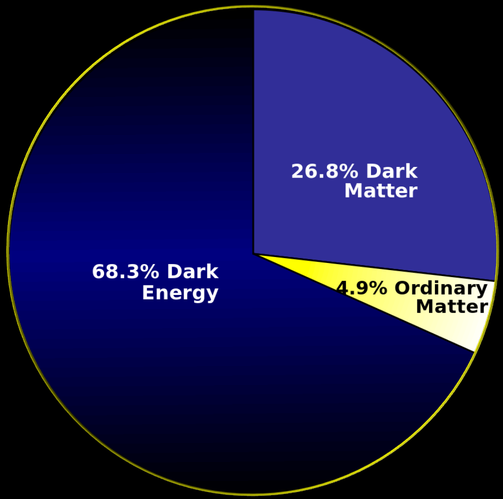
Mauro Raggi,
Sapienza Università di Roma e INFN Roma

Menu 2019 Workshop
1-7 June 2019 Carnegie Mellon University

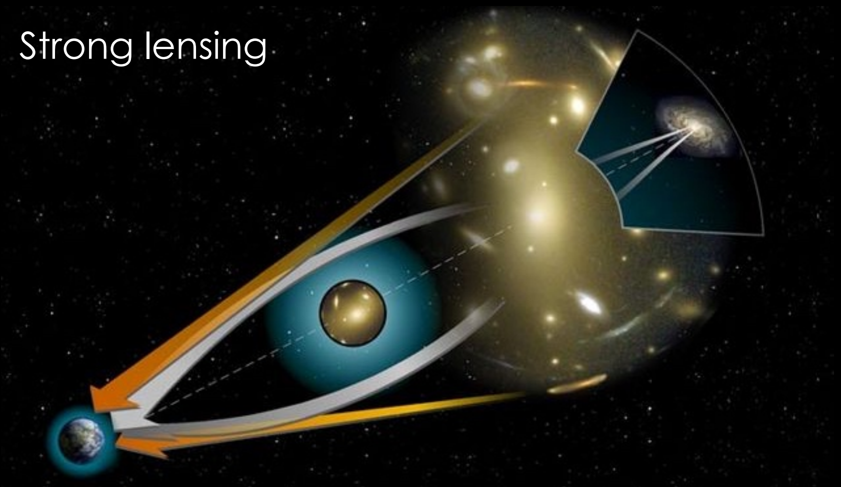
The dark matter problem

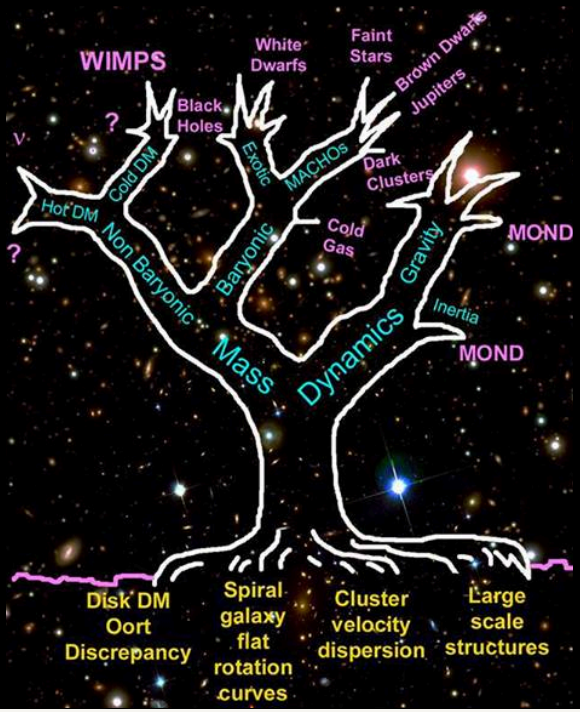


Galaxies rotation curves



Strong lensing





Many solutions and open questions.
Is dark matter made of new particles?

Is the dark matter a known particle?

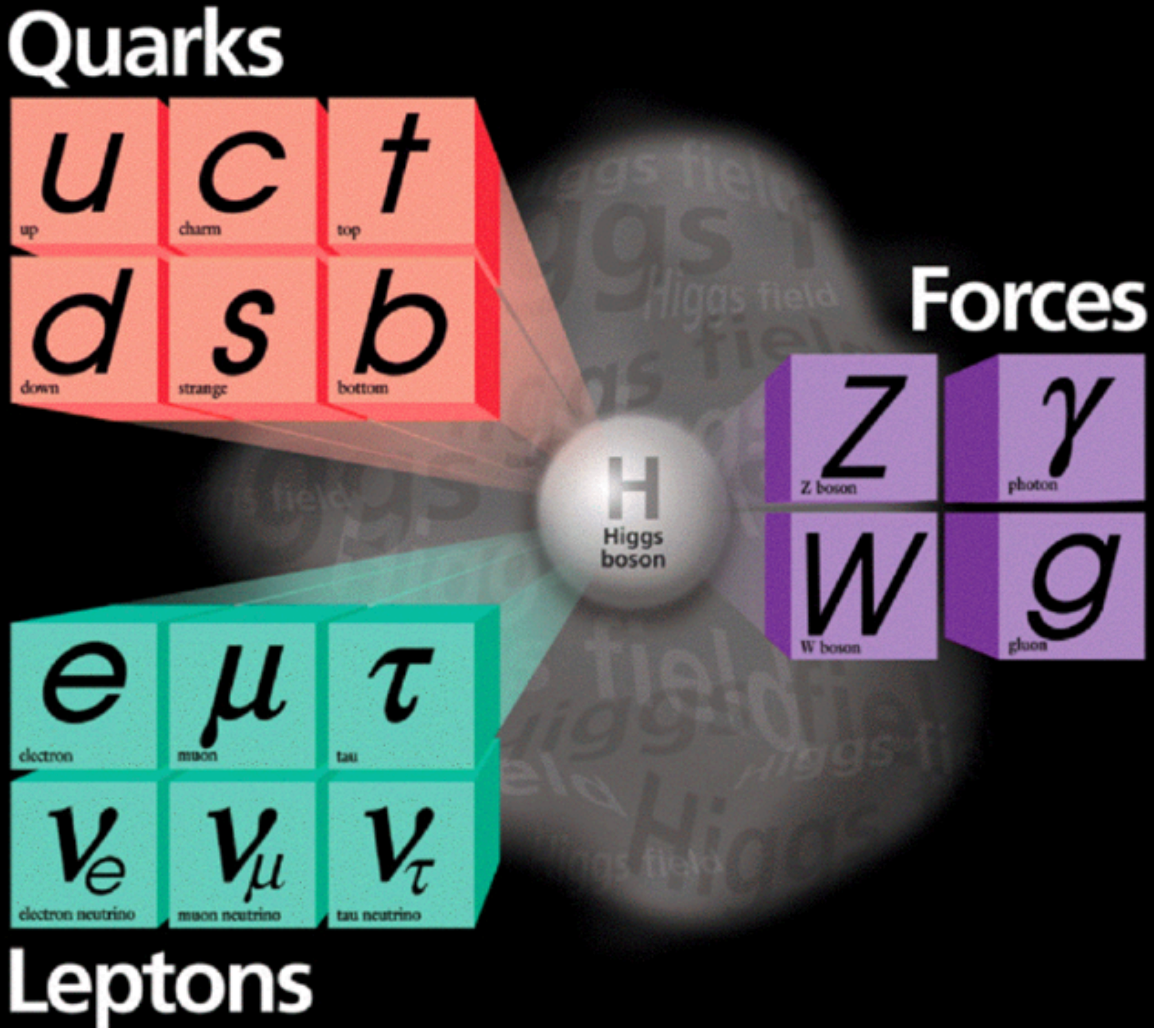
Dark matter has a mass.

Dark matter has gravitational interaction.

Dark matter interacts weakly with SM particles.

Dark matter contains one or more stable particles.

Is any particle we know a good dark matter candidate?



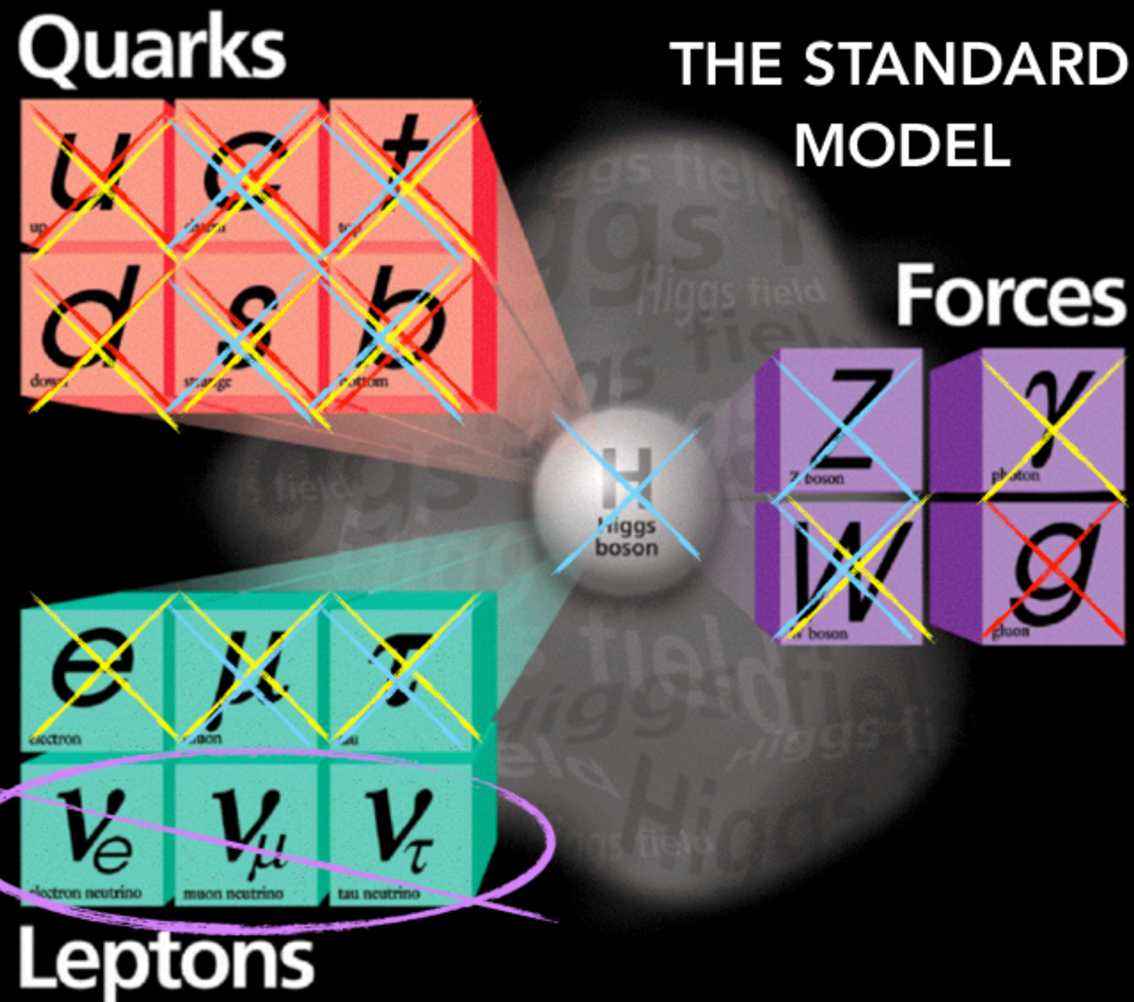
Is the dark matter a known particle?

strong

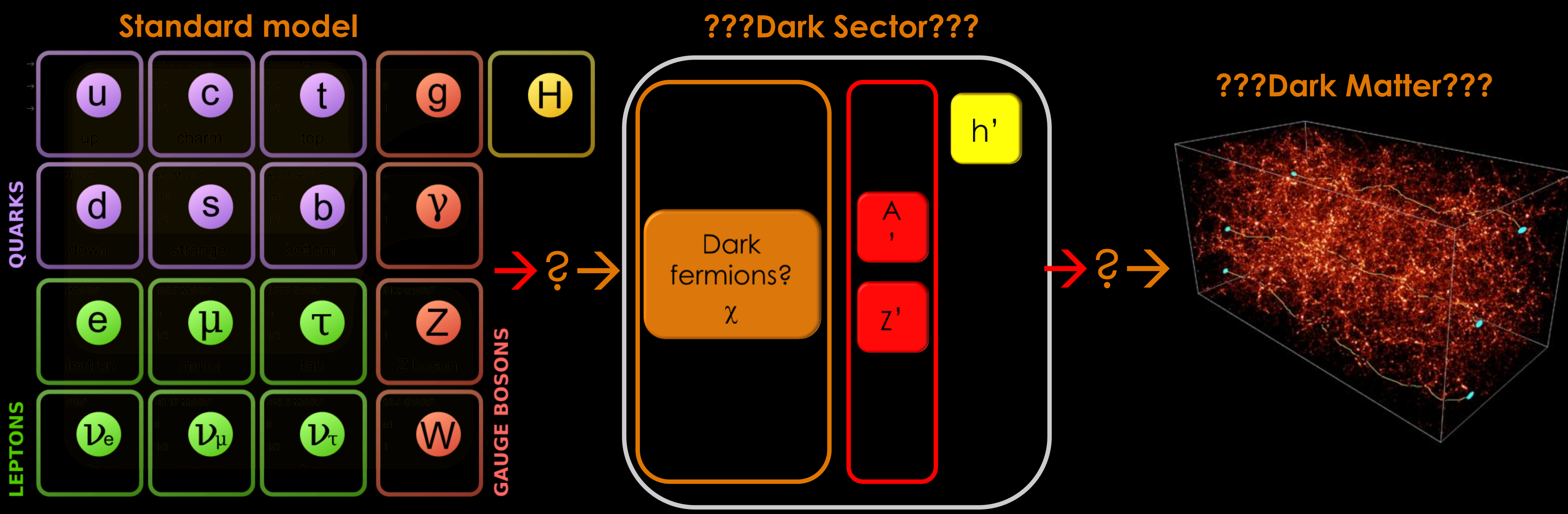
electromagn.

unstable

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



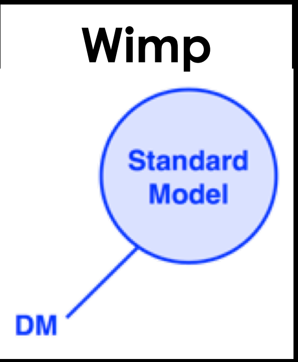
Dark sectors a possible solution

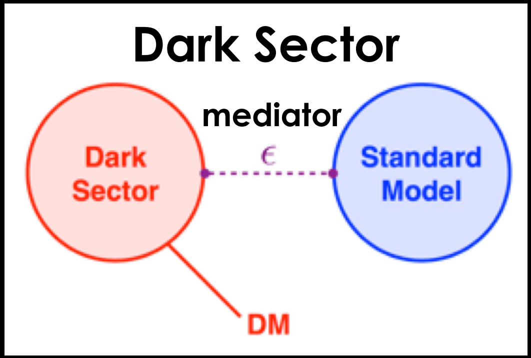


- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally

- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?

Dark sectors and portal interactions



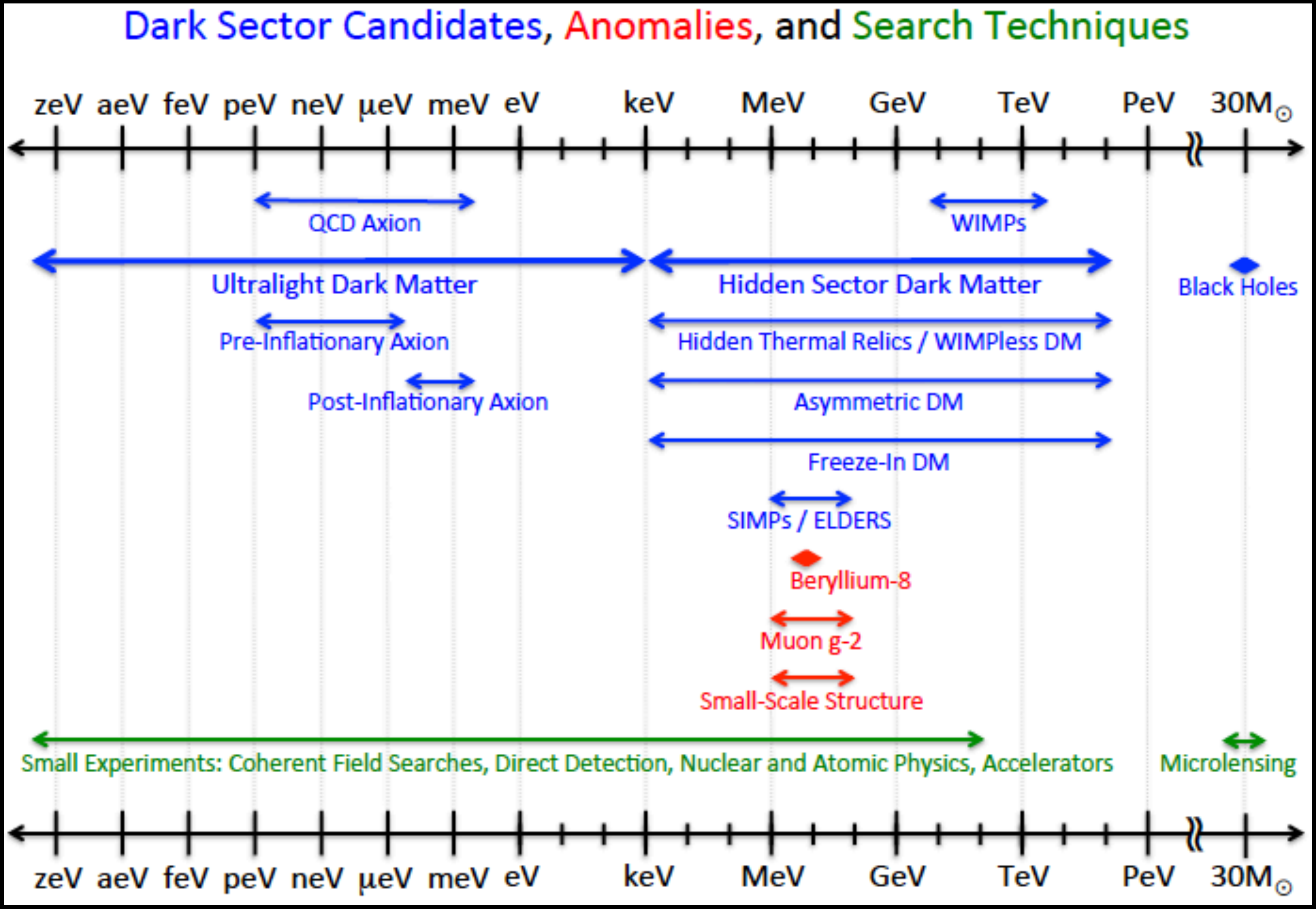


Dark (or hidden) sector:
DM particles completely neutral under SM forces, posses new interactions
Mediator:
A mediator particle of the new interaction, interacting very weekly with SM particles
Portal interaction:
New interaction connecting dark mediator and SM particles

The **mediator** can be scalar, fermion, vector, axion…
The relic **dark matter (DM)** can be **either the mediator** particle or just coupled to SM via a hidden interaction
Different portals can co-exist: e.g. dark photon and Higgs, or dark photon and axion
Dark sectors can conceal **not only the DM** problem, other **SM anomalies**:
- Muon g−2 anomaly, proton radius, inflation, ^{8}Be anomaly, …

The **vector portal** is the **simplest** both from the **theoretical [additional U(1)** gauge symmetry] and **experimental** point of view [just replace an ordinary γ with a dark photon **A’** in any QED processes]

Many candidates: how to choose?



A very wide panorama but some anomalies at low energy are interesting to guide the eye

arXiv:1707.04591v1

Simplest dark photon model

- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or **A'** boson.
- The coupling constant and the charges can be generated effectively through the **kinetic mixing** between the QED and the new U(1) gauge bosons

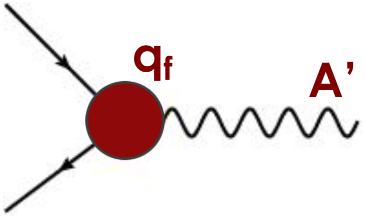
$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

B. Holdom Phys.Lett. B166 (1986) 196

  - In this **case the new coupling constant = eε** is just proportional to electric charge and it is equal for both quarks and leptons.

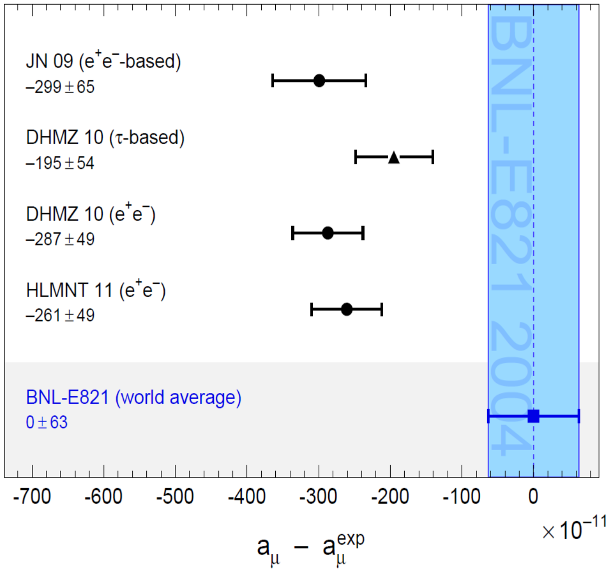
- **As in QED**, this will generate new interactions with SM fermions of type:

$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

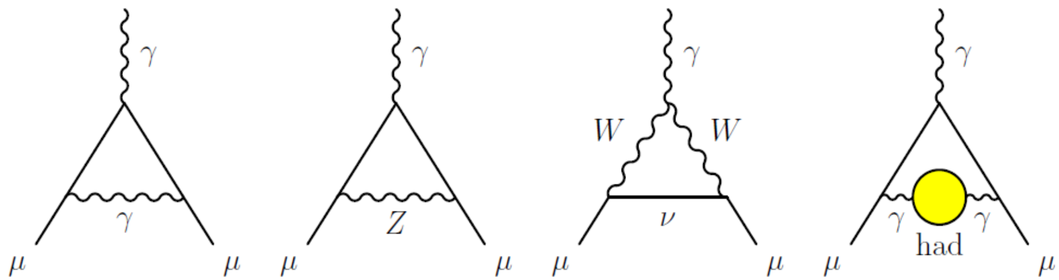


  - Not all the SM particles need to be charged under this new symmetry
  - In the **most general case q_f is different in between leptons and quarks** and can even be 0 for quarks. **P. Fayet, Phys. Lett. B 675, 267 (2009)**

Dark photon and g-2$_\mu$

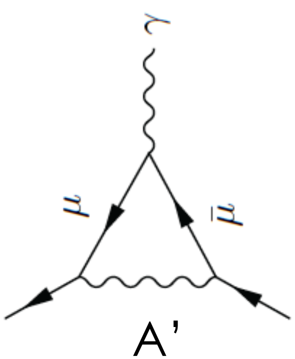


g-2 in the standard model

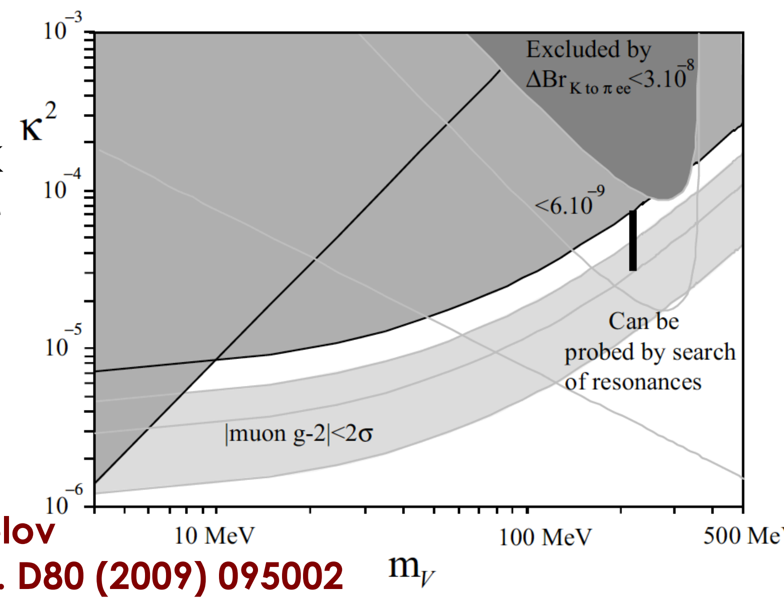


About 3σ discrepancy between theory and experiment. Could be due to hadronic uncertainties on the Light by Light scattering?

g-2 and A'

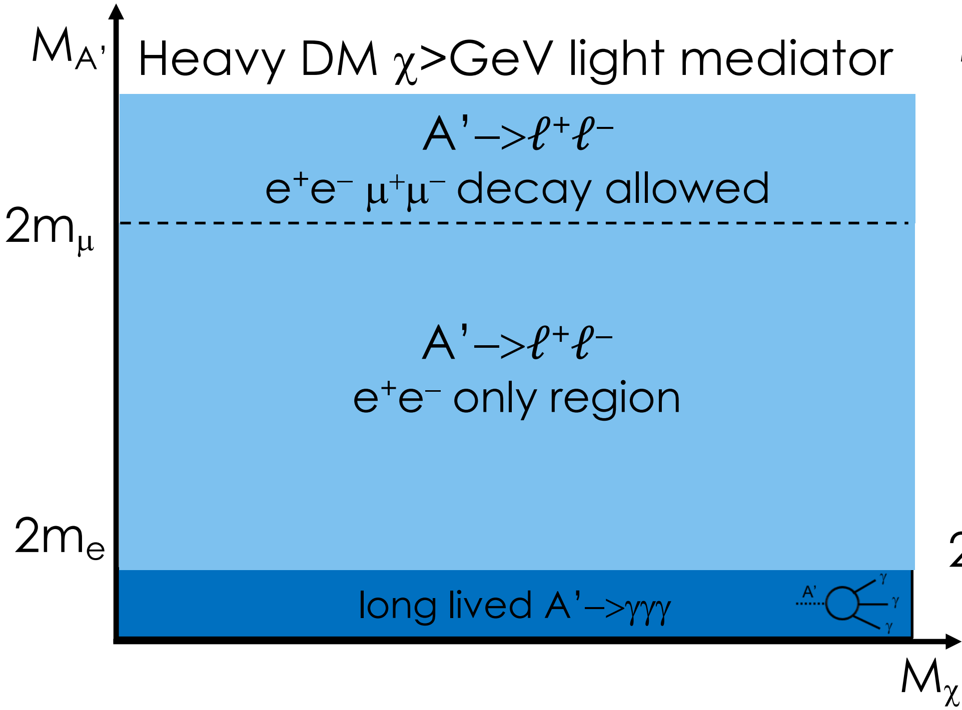


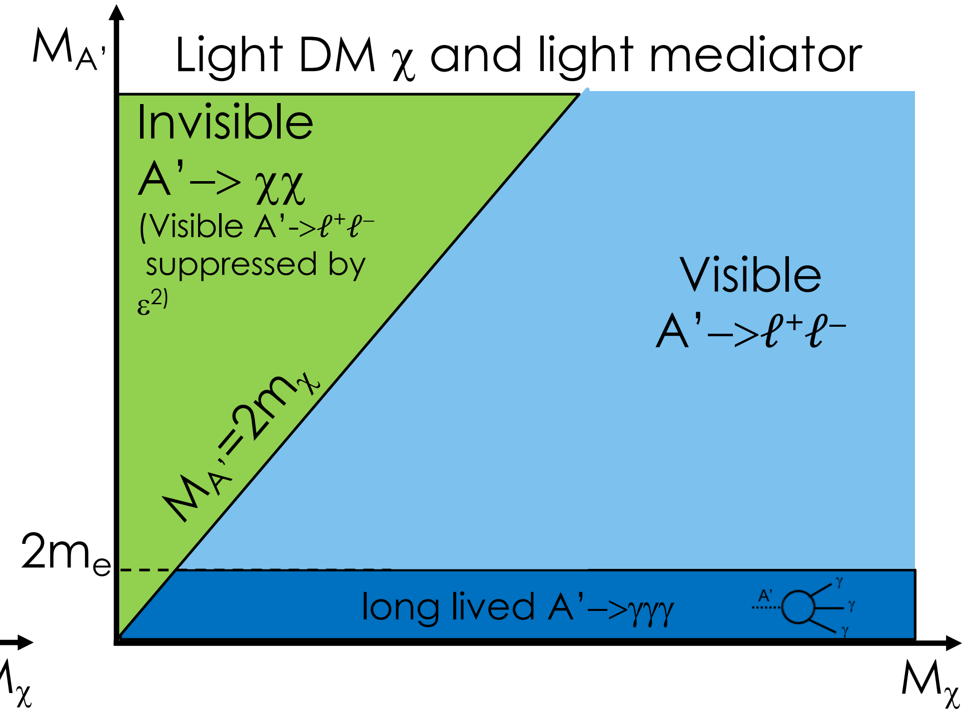
Additional diagram with dark photon exchange can fix the discrepancy!
(with sub GeV A' masses ☺)



M. Pospelov
Phys.Rev. D80 (2009) 095002

A’ decay modes MeV-GeV scale

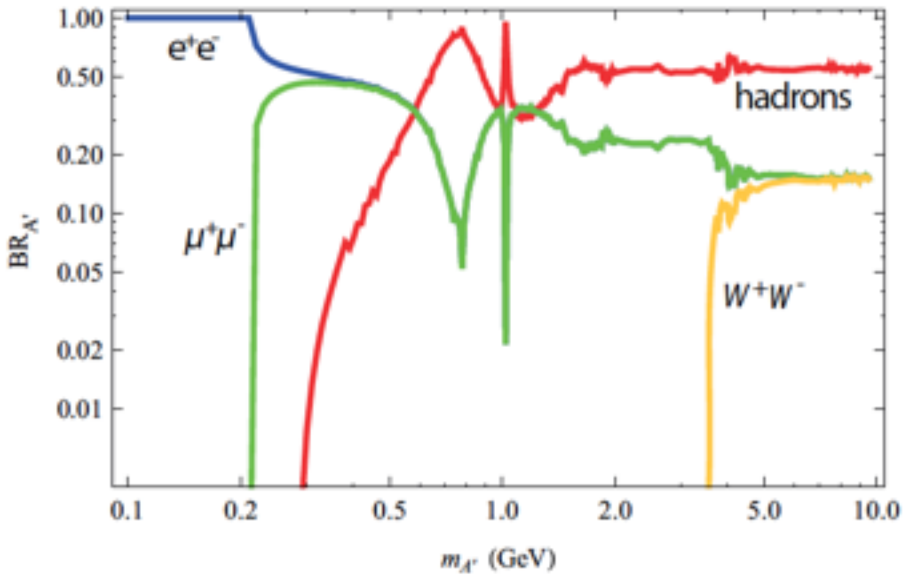




- If 1MeV <$M_{A'}$< $2m_\chi$ dilepton decays “visible” decays
  - Min $M_{A'}$>1MeV lifetime depends mostly on ε^2 long lived
- $2m_\chi$<$M_{A'}$ dark matter decays “invisible” decays
  - Min $M_{A'}$<1MeV lifetime depends mostly on α_D^2 short lived
- Decays in 3γ are not interesting for the accelerator searches

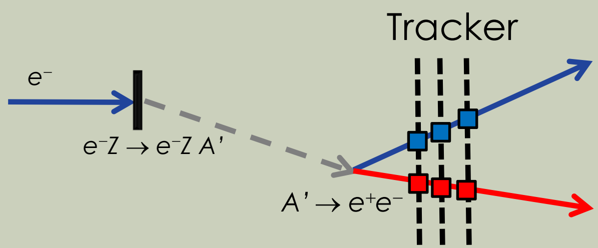
A' decays in SM particles

- BR visible is =1 if dark matter is massive.
- A' "visible" decay modes
  - A'→e^+e^-,
  - A'→$\mu^+\mu^-$,
  - A'→hadrons,
- For $M_{A'}$<210 MeV A' only decays to e^+e^- with BR(e^+e^-)=1
- At higher masses hadronic decay are also allowed



How to search for A' visible decays?

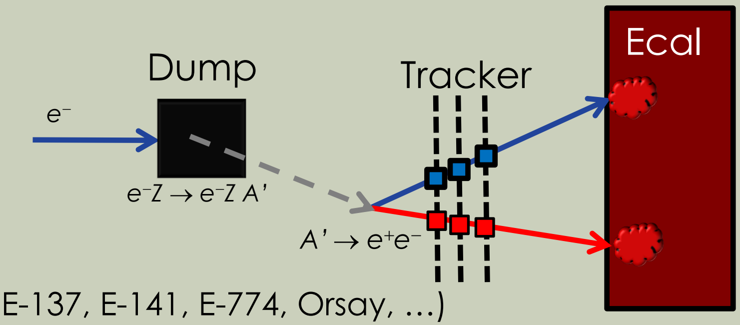
A) Thin target experiments



(APEX, HPS, A1)

N∝ε^2 ~$10^{14\text{-}16}$ EOT (ε^2,$M_{A'}$)

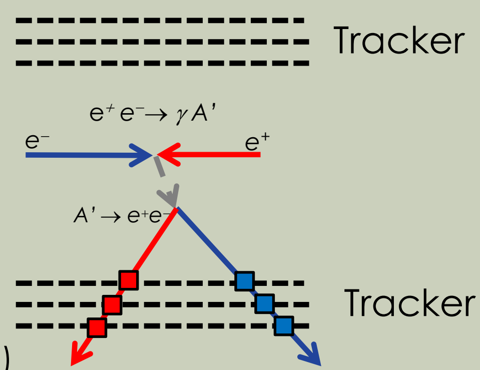
B) e⁻ dump experiments



(E-137, E-141, E-774, Orsay, …)

N∝ε^2 ~$10^{19\text{-}20}$ EOT (ε^2,$M_{A'}$)

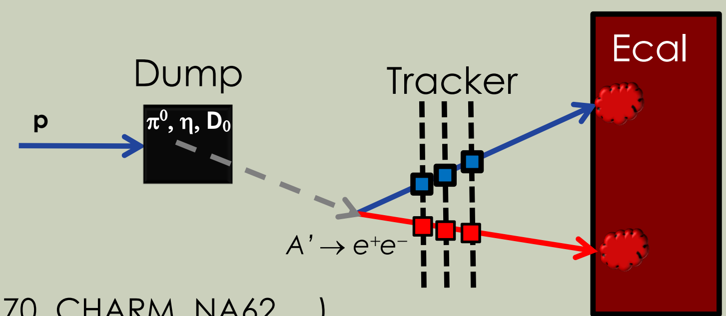
C) Collider experiments



(KLOE, BaBar, A1)

N∝ε^2 sensitive to (ε,A') mass
Limited by $M_{A'}$<sqrt(s)

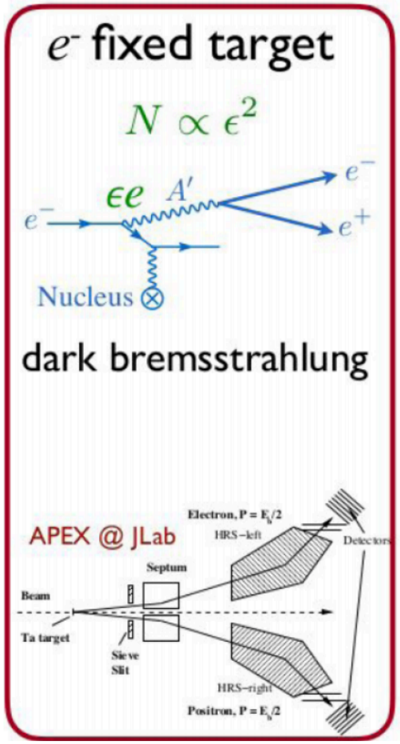
D) Proton dump experiments

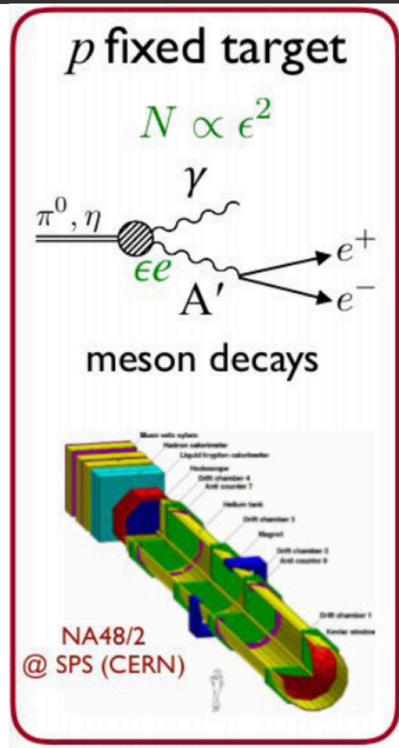


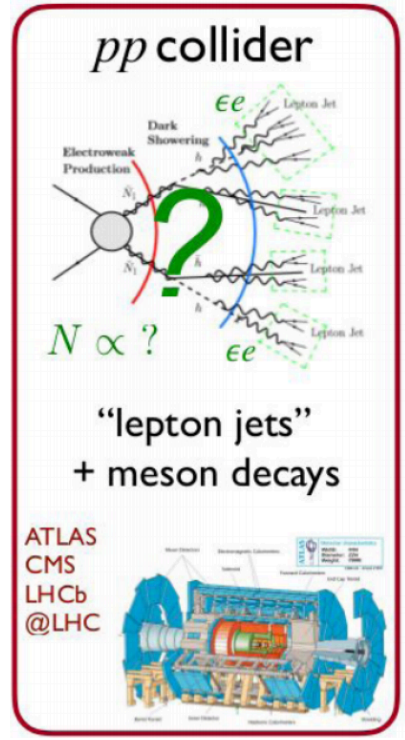
(U70, CHARM, NA62 …)

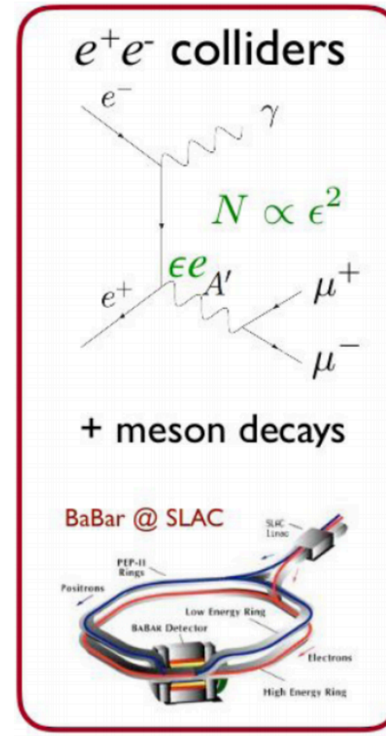
N∝ε^2 ~$10^{19\text{-}20}$ POT (ε^2,$M_{A'}$)

A’ production in “visibile” decay exp.



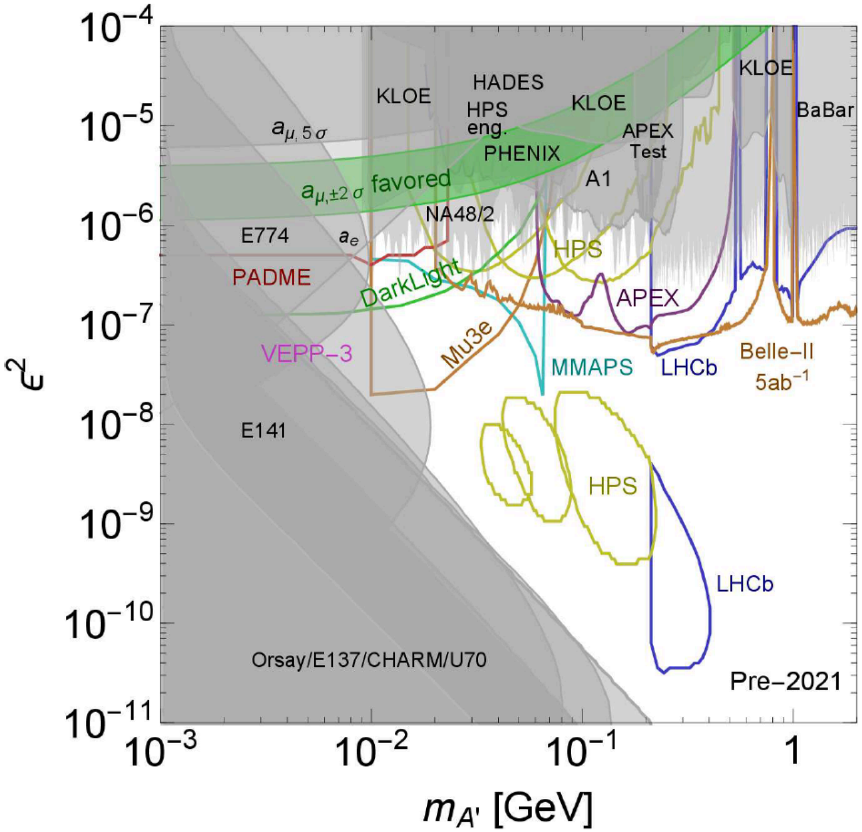






- Proton machines production:
  - Mesons decays π^0,η,D^0
  - QCD production lepton jets
- Electron machines production
  - e^- Bremsstrahlung
  - $e^- e^+$ annihilation + meson decays

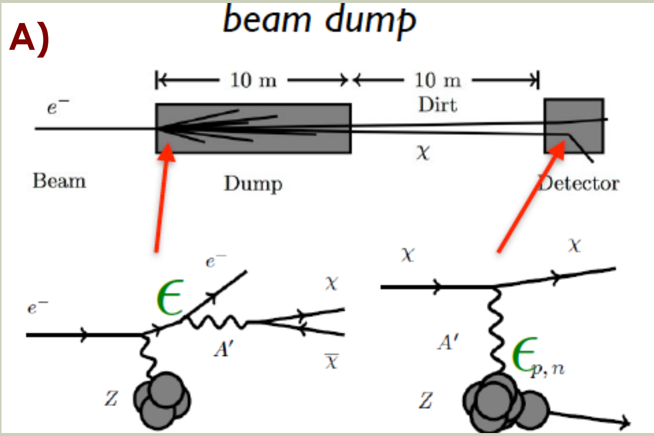
A'→ℓ⁺ℓ⁻ visible searches status



- Grey regions: excluded regions
- Colored lines: future experiments projections
- Green band: region in which A' will explain g-2 anomaly

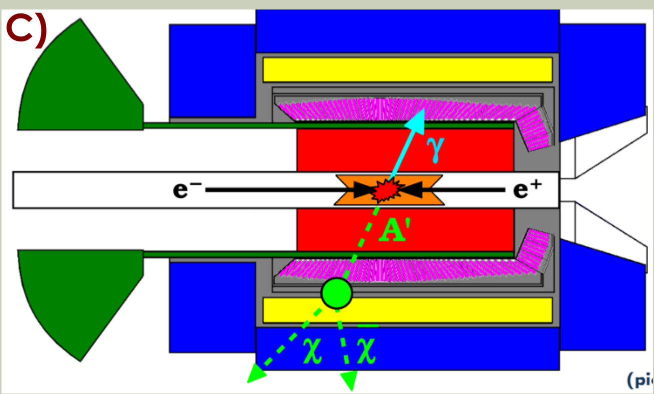
How to search for A' invisible decays?

Positive evidence



$N \propto \varepsilon^4$ ~10^{20} EOT (α_D and ε^2)

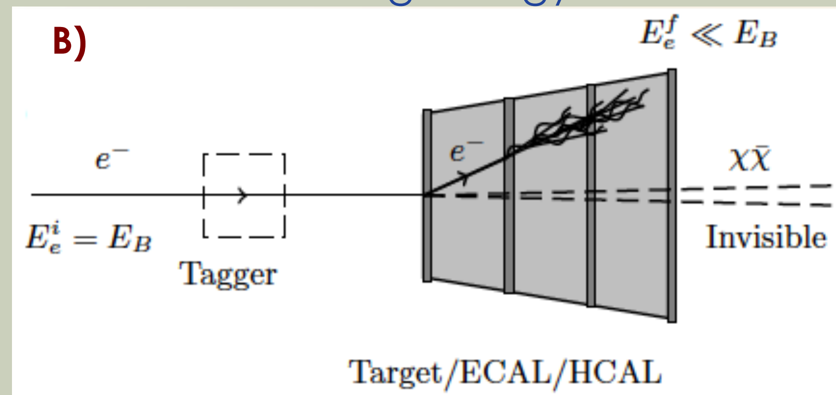
Missing Mass



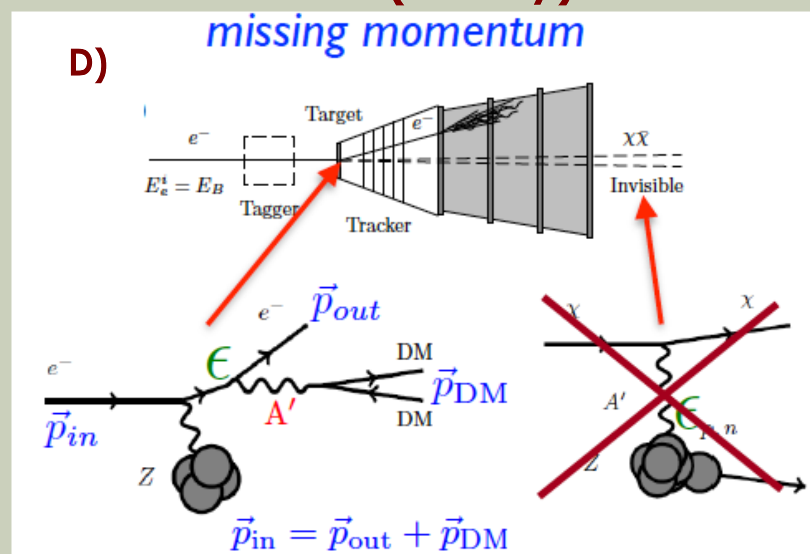
$N \propto \varepsilon^2$ sensitive to (ε,A') mass
Limited by $M^{A'}$<sqrt(s)

Negative evidence

Missing energy

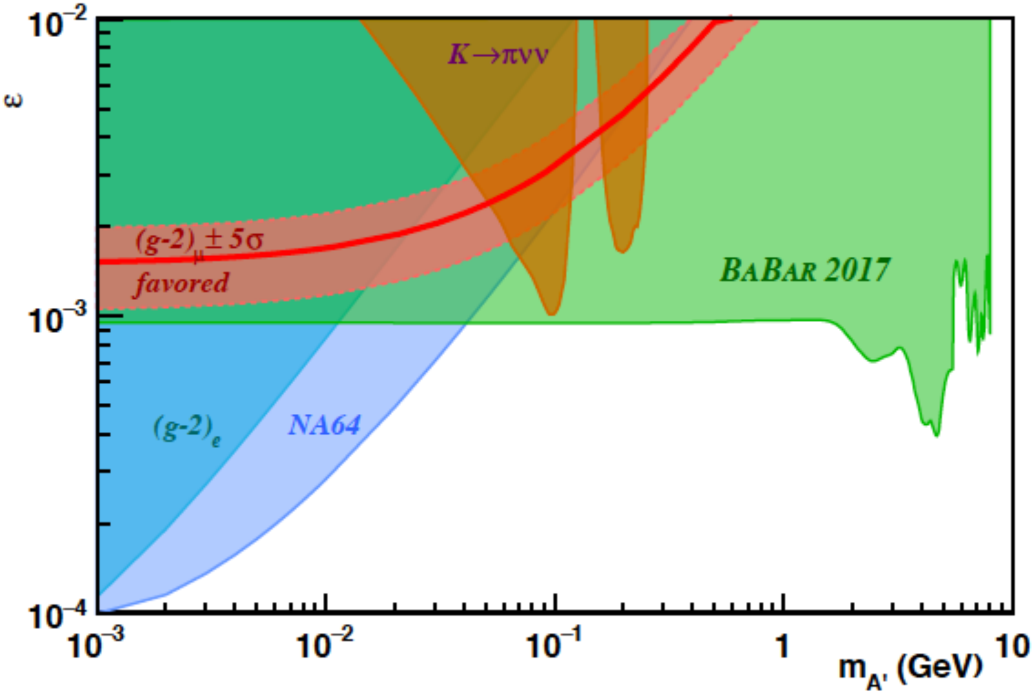


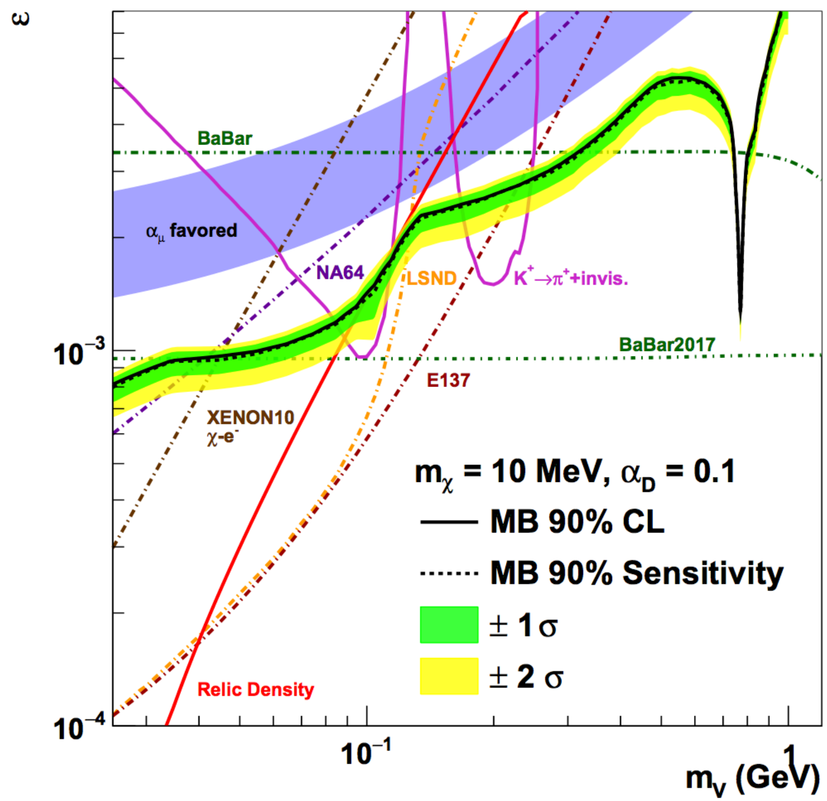
$N \propto \varepsilon^2$ (ε^2 only)



$N \propto \varepsilon^2$ contains E_{miss} exp.

Invisible decays present status





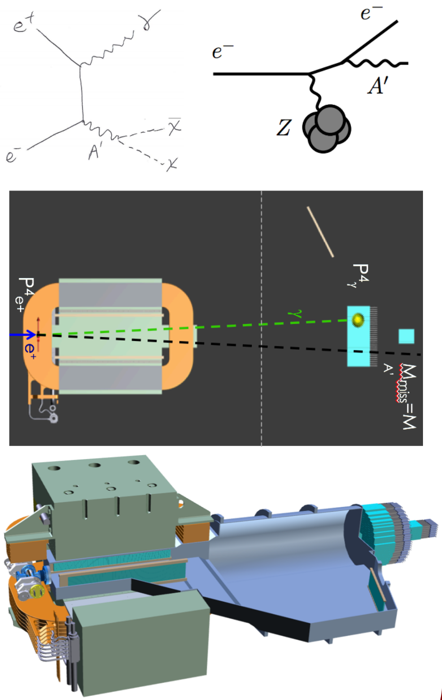
- Great progress in the beginning of 2017
  - Still large regions of parameter space unexplored
  - Only 1 experiment in most of the parameter space covered

New result by NA62 see P. Massarotti's talk

Few invisible decay examples

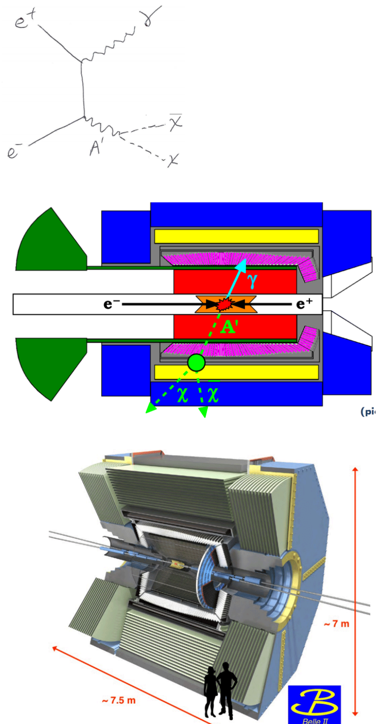
Running experiments **Future experiments**

PADME



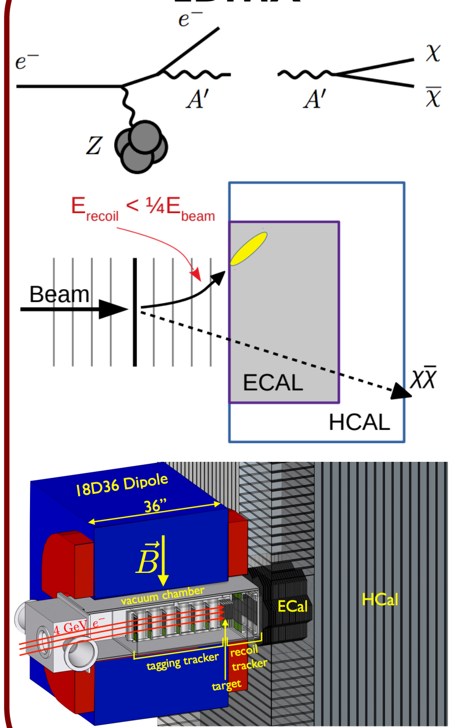
INFN LNF

BELLE II



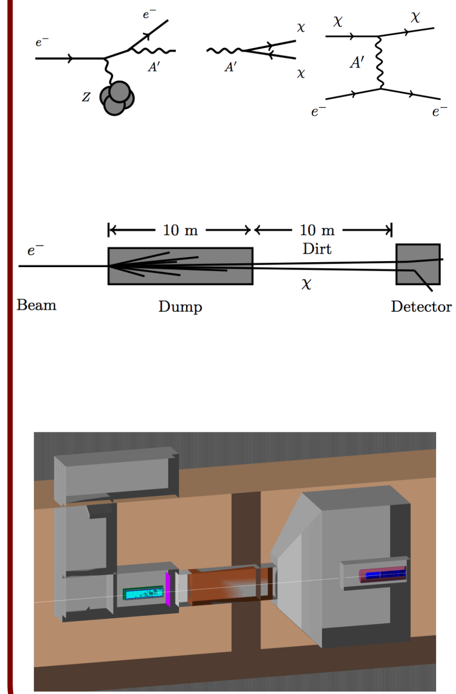
Super KEKB

LDMX



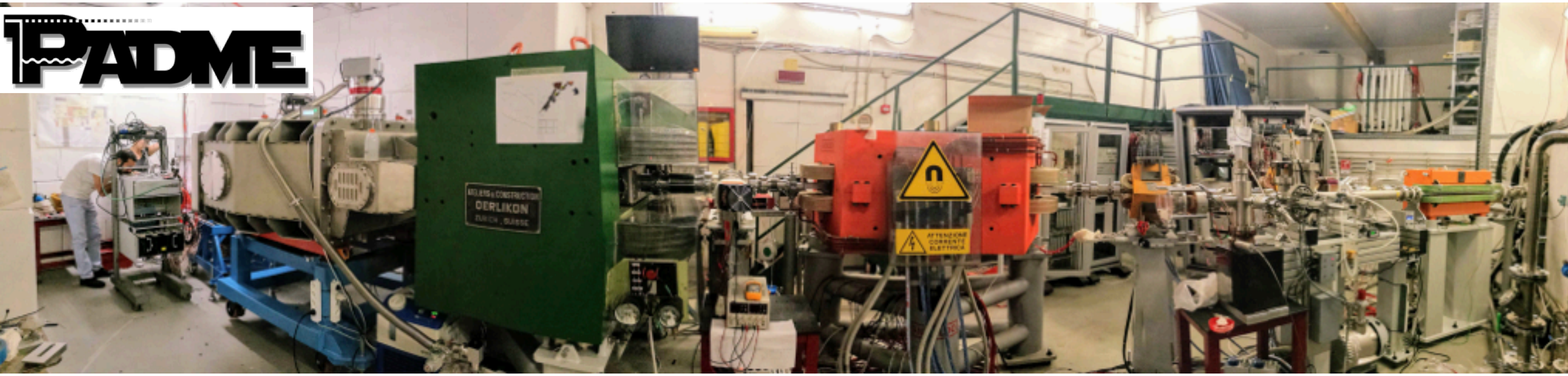
SLAC? CERN?

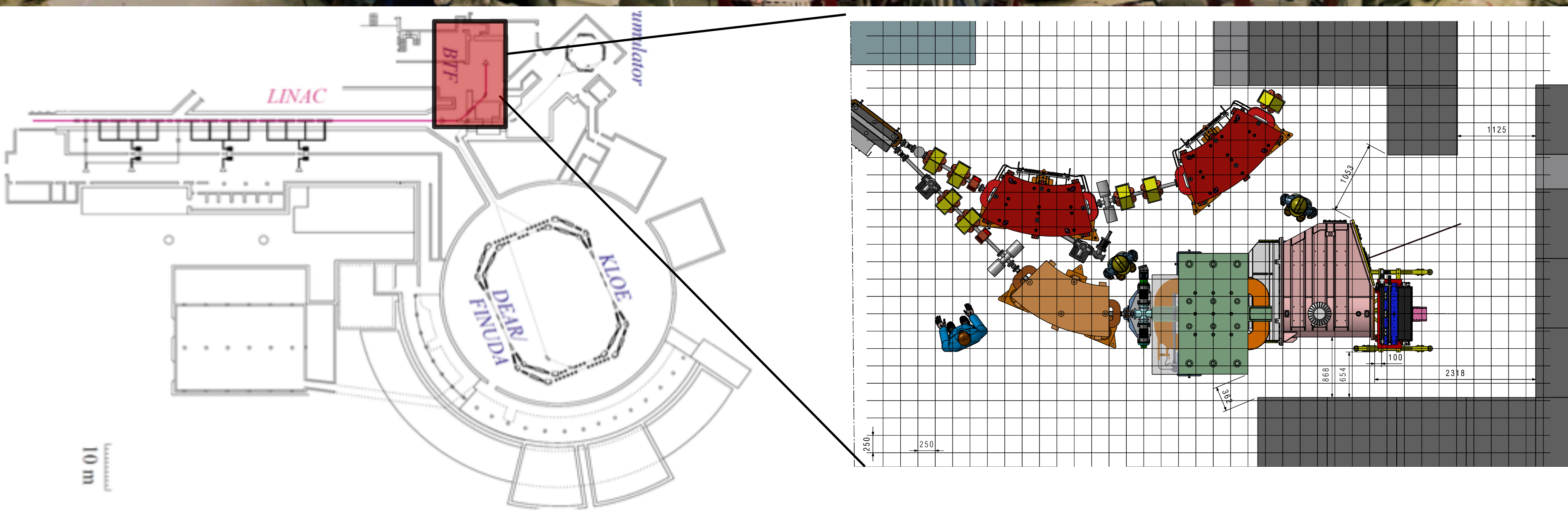
BDX



JLAB? MAMI?

The PADME experiment @LNF

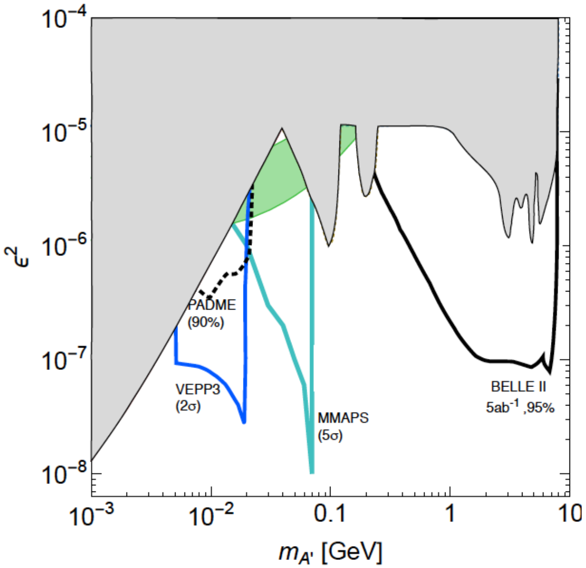




- First fixed target A’ experiment with positron running since October 2018

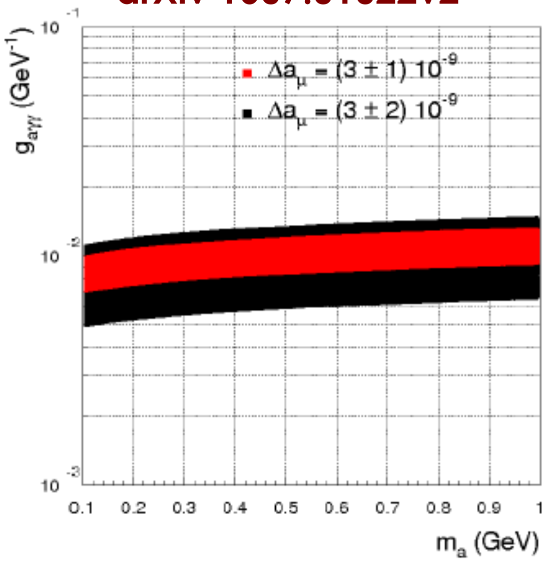
The PADME physics cases

Dark Photon
arXiv:1608.08632v1



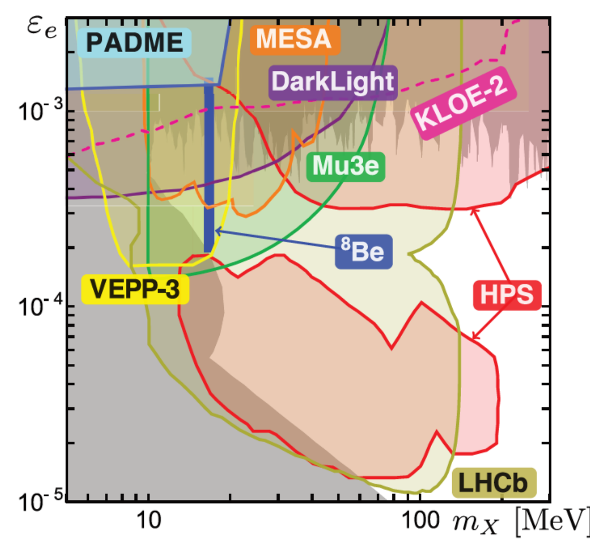
Invisible final state:
$e^+e^- \to \gamma A'$ and $A' \to \chi\chi$

ALPs and g-2
arXiv 1607.01022v2



ALPs final state $a \to \gamma\gamma$

BE anomaly- Fifth force
arXiv:1608.03591v1

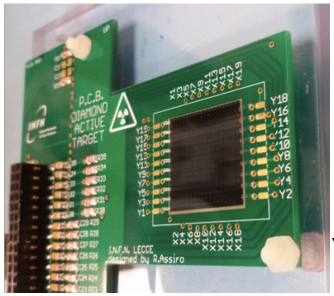


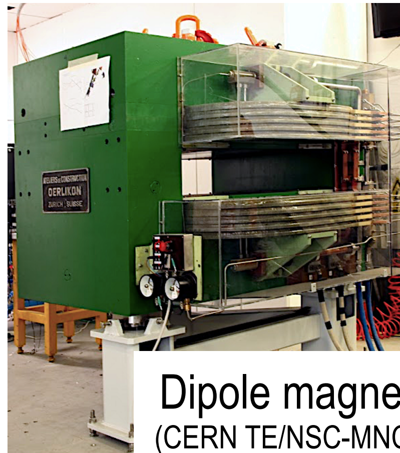
Final state $X \to ee$

- Measurement of low energy (100-500 MeV) EM-cross sections
  - **Bremsstrahlung cross section $e^+N \to e^+N\gamma$**
  - **Annihilation cross sections: $e^+e^- \to \gamma\gamma$ $e^+e^- \to \gamma\gamma(\gamma)$**

PADME detector in a nutshell

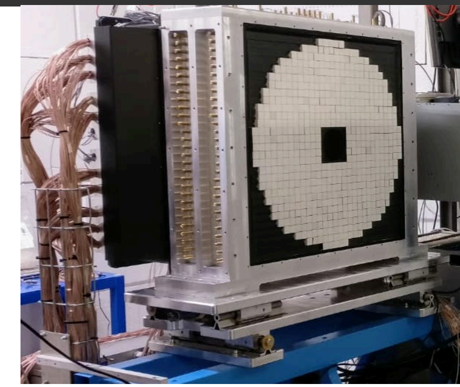
Active target
Lecce & University Salento





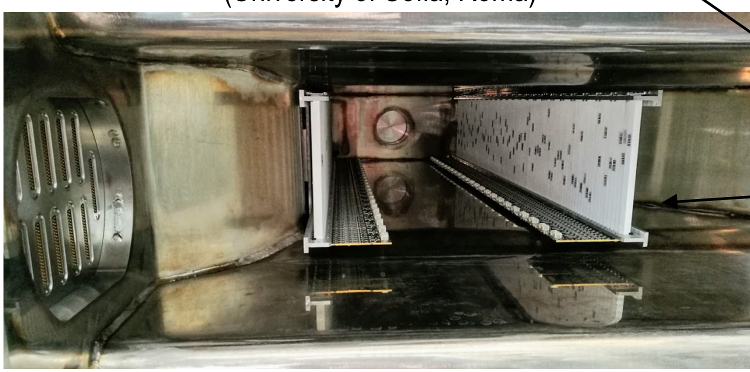
Dipole magnet
(CERN TE/NSC-MNC)

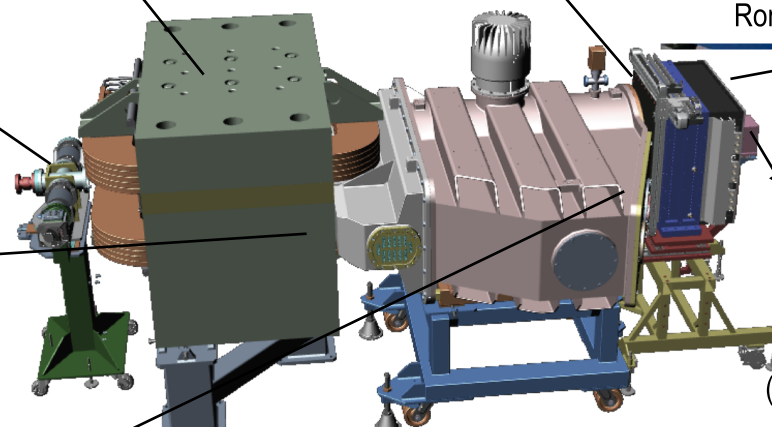
C-fiber window

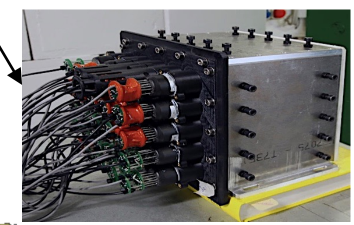


BGO calorimeter
(616 L3 endcap crystals:
Roma, Cornell U., LNF, LE)

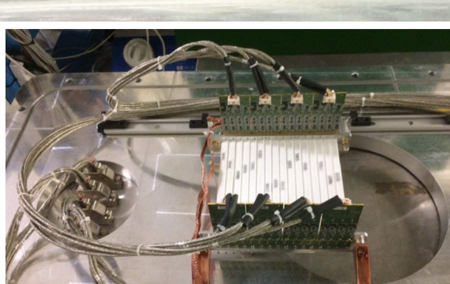
Veto scintillators
(University of Sofia, Roma)





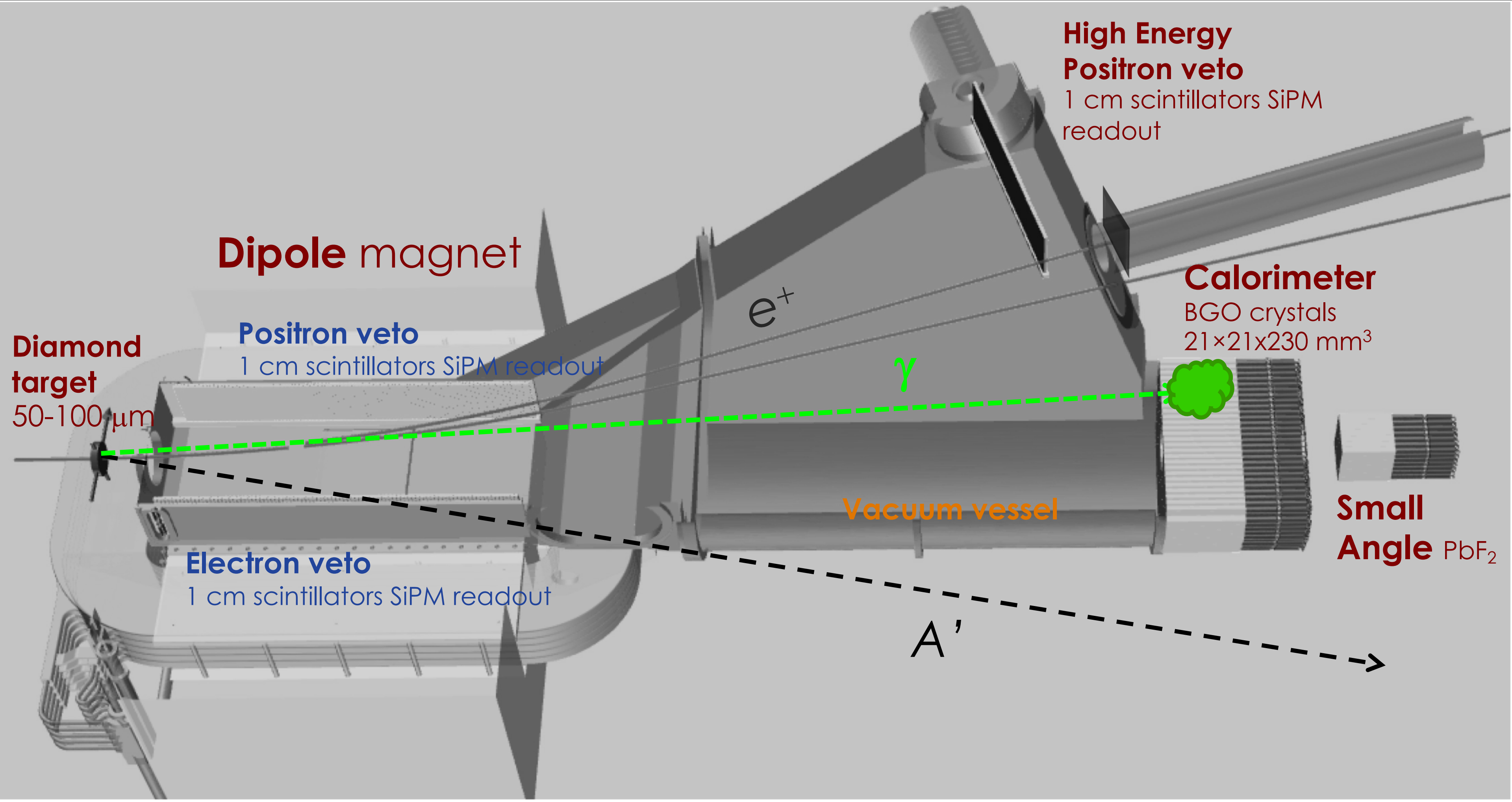


PbF$_2$ calorimeter
(MTA Atomki, Cornell U., LNF)



TimePIX3 array
(ADVACAM, LNF)

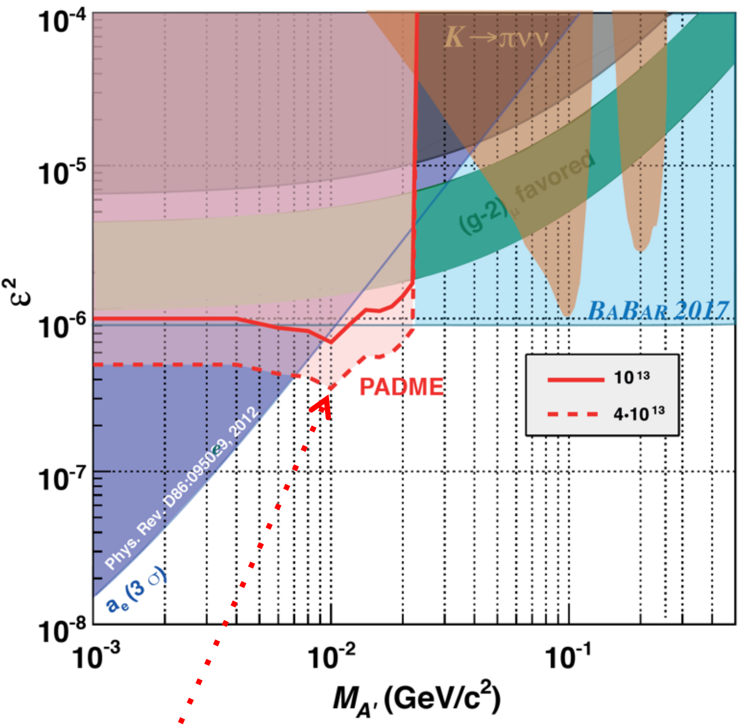
PADME experiment technique



- Search for $e^+e^- \rightarrow \gamma + \text{nothing}$
  - Measure the visible gamma missin mass
  - Be sure no other photons or e+ e- is around.

PADME A'-invisible decay sensitivity

Sensitivity 10^{13}e+ on target



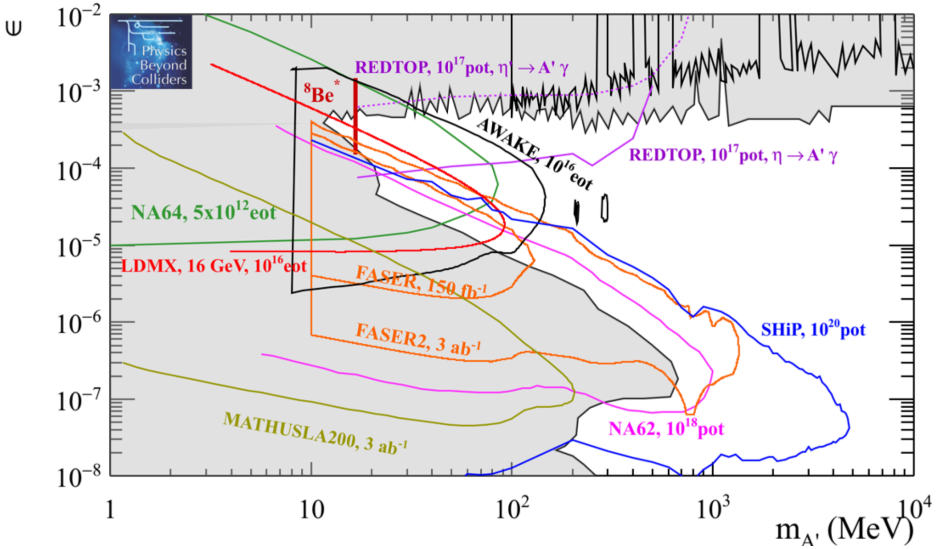
- Based on 2.5×10^{10} fully GEANT4 simulated 550 MeV e+ on target events
  - Number of BG events is extrapolated to 1×10^{13} electrons on target
- Using $N(A'\gamma)=\sigma(NBG)$

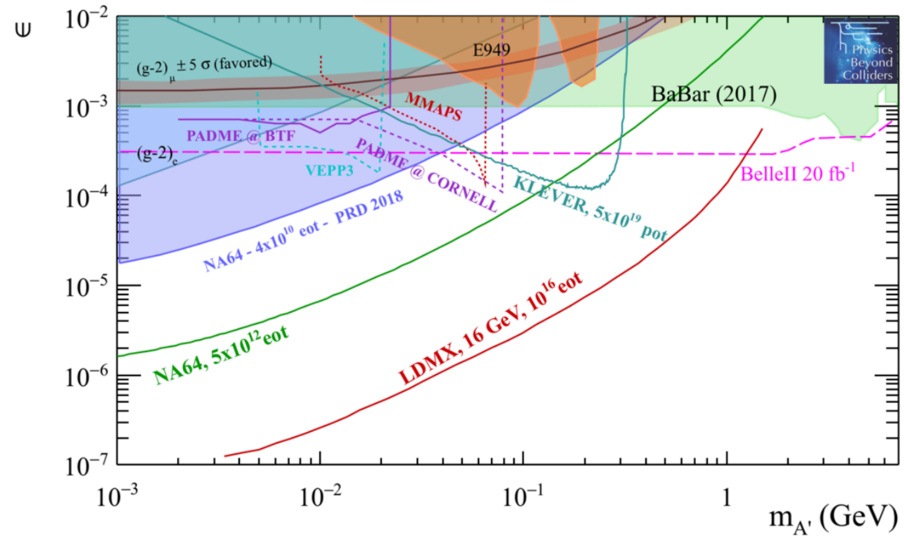
$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \cdot \delta$$

- δ enhancement factor: $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$ due to A' mass

PADME 2-years of data taking **at 60%** efficiency with bunch length **of 200 ns**
4×10^{13} EOT = 20000 e+/bunch$\times 2 \times 3.1 \cdot 10^7s\times 0.6 \times 49$ Hz

Future of the dark sector searches





Conclusions

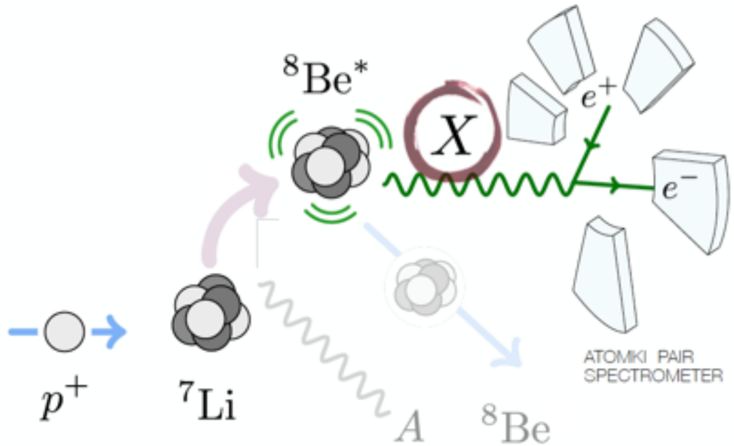
- Dark sectors searches are an extremely vital in the last 5-10 years
  - Recast of old experiment
  - New experiments are running
  - New experimental proposals are approved

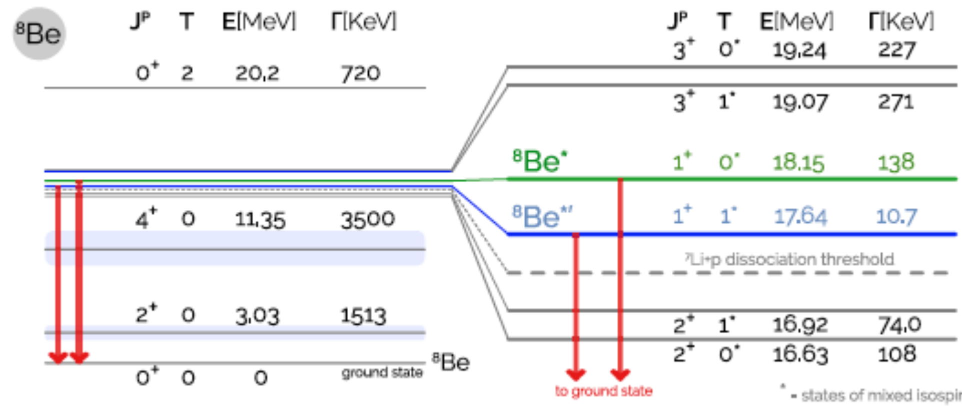
- New generation of dedicated experiment is on the way to explore the dark sectors
  - Different techniques and different final states searches are needed to provide reliable exclusions.

A bright future is awaiting the dark sectors

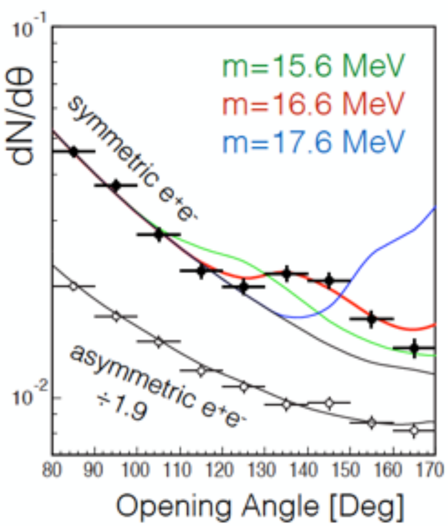
SPARE slides

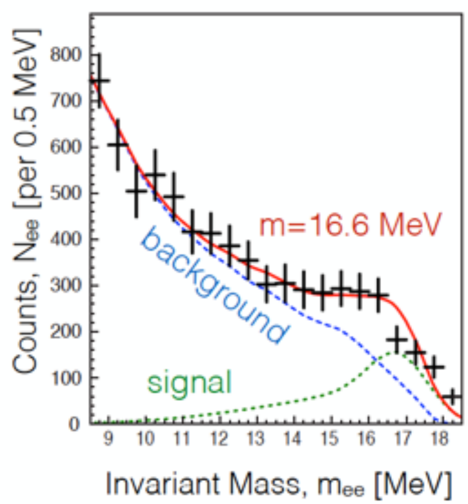
The ^{8}Be anomaly





Is this an evidence of a new light dark photon?





$$m_X = 16.7 \pm 0.35(\text{stat}) \pm 0.5(\text{sys})\ \text{MeV}$$

- Sanity checks performed
  - Excess disappears as one scans through the proton beam resonance kinetic energy of 1.03 MeV
  - excess becomes more pronounced when restricting to the subset of events with E>18 MeV and is absent for lower energy events.

Can nuclear physics explain the anomaly observed in the internal pair production in the Beryllium-8 nucleus?

Xilin Zhang[1,*] and Gerald A. Miller[1,†]

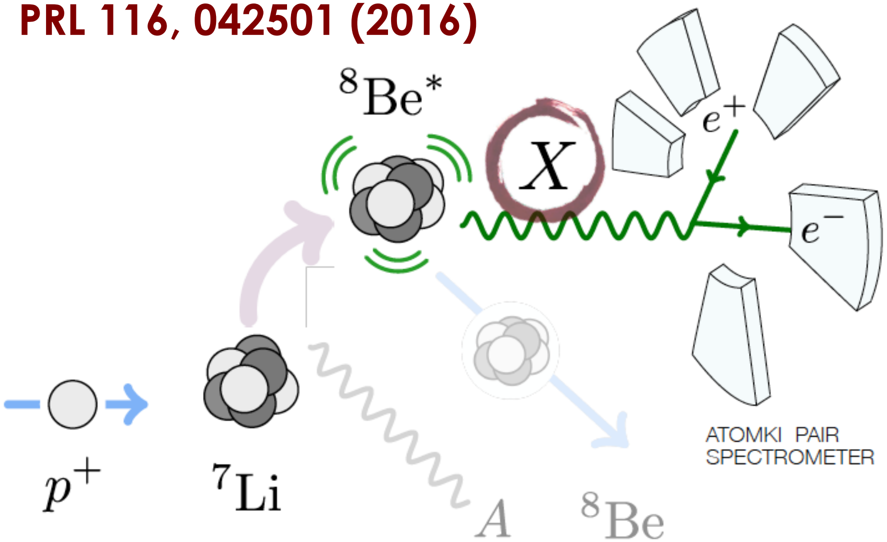
[1]*Department of Physics, University of Washington, Seattle, WA 98195, USA*

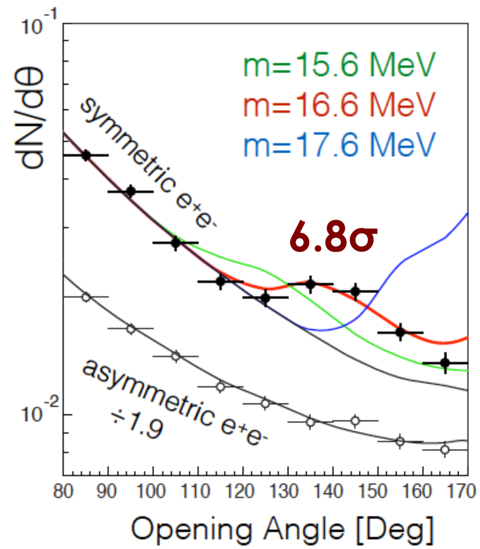
(Dated: March 16, 2017)

Can only mitigate the anomaly by 1σ by improving nuclear treatment.
j.physletb.2017.08.013

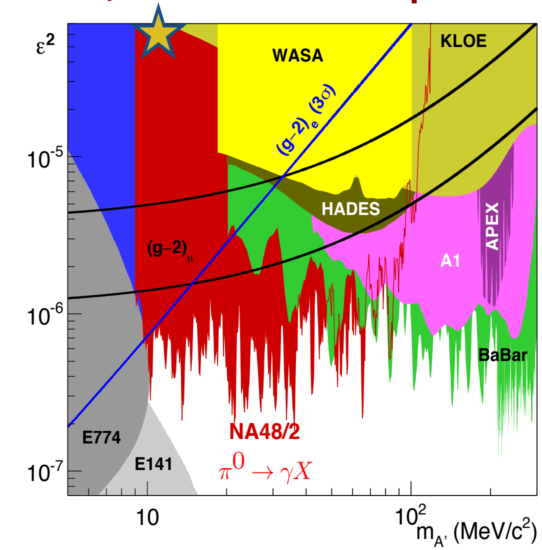
^{8}Be* anomaly: the proto-phobic 5Th force

PRL 116, 042501 (2016)





NA48/2 it's not a dark photon!



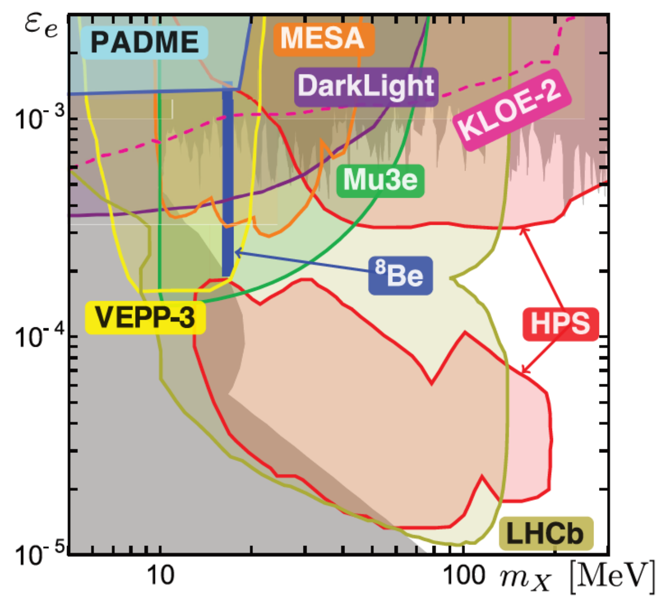
π^0-phobia = p^+-phobia

To avoid NA48/2, prohibit π^0 decay to $X\gamma$

FROM QUARK CONTENT

$Q_u Q'_u - Q_d Q'_d = 0$ $\quad Q'_d = -2Q'_u$

ProtoPhobic coupling

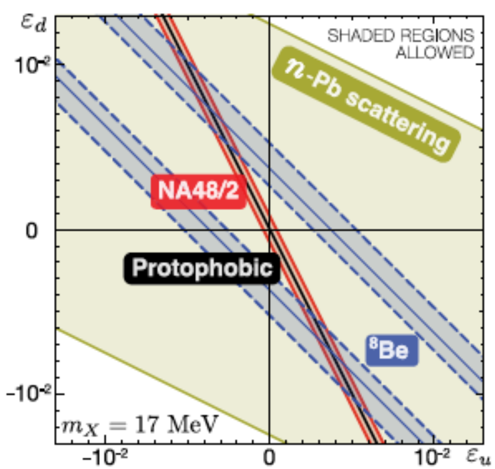


The ^{8}Be anomaly interpretation

PRL 117, 071803 (2016) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2016

Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions

Jonathan L. Feng,[1] Bartosz Fornal,[1] Iftah Galon,[1] Susan Gardner,[1,2] Jordan Smolinsky,[1] Tim M. P. Tait,[1] and Philip Tanedo[1]

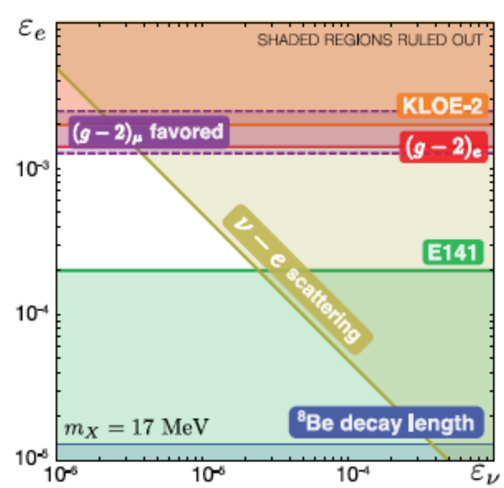


Protophobia

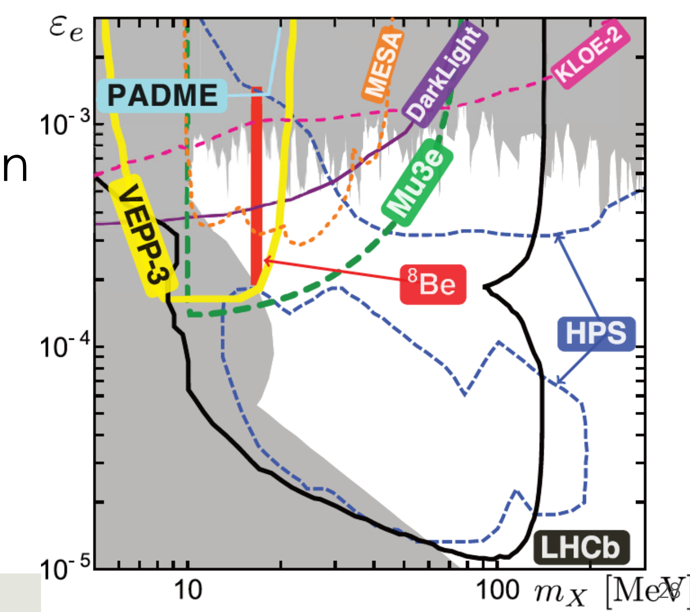
Equations (5) and (8) may be satisfied with a mild ∼10% cancellation, provided the charges satisfy

$$-2.3 < \frac{\varepsilon_d}{\varepsilon_u} < -1.8, \qquad -0.067 < \frac{\varepsilon_p}{\varepsilon_n} < 0.078. \quad (9)$$

Given the latter condition, we call the general class of vector models that can both explain the ^{8}Be anomaly and satisfy pion decay constraints “protophobic.”



Strongest experimental limit on the electron coupling comes from KLOE data: ε_e<2E-3

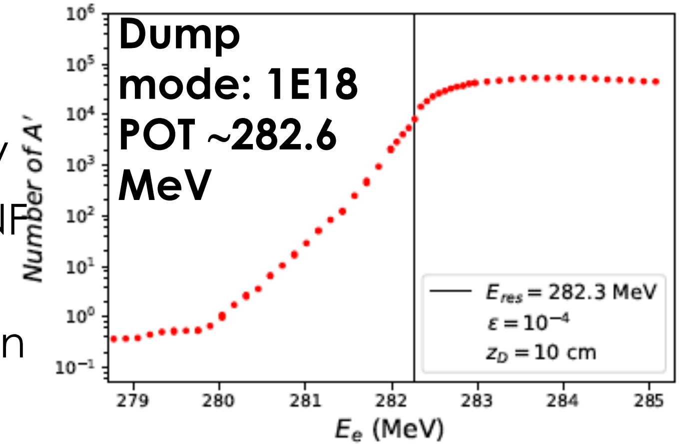


^{8}Be anomaly at PADME

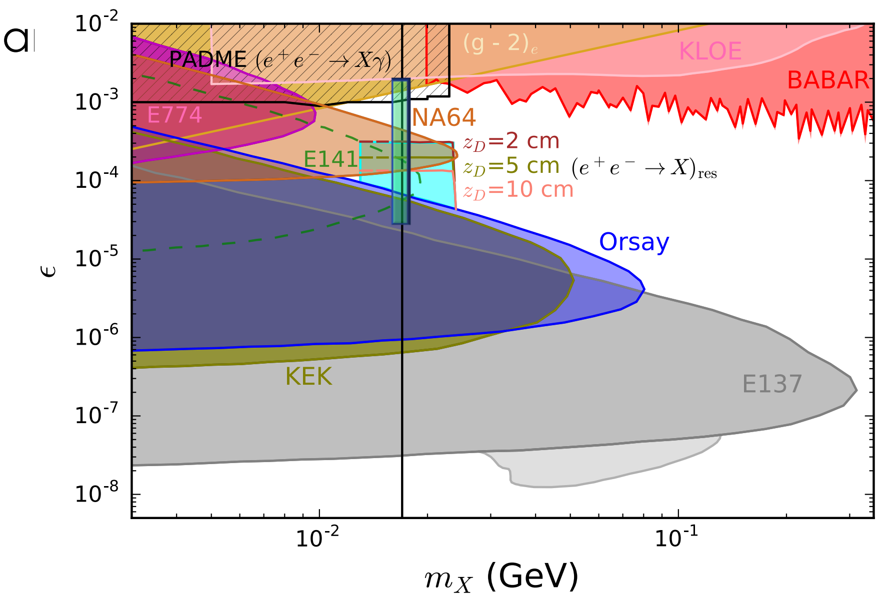
PHYSICAL REVIEW D **97,** 095004 (2018)

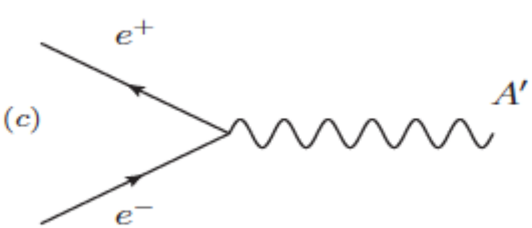
Resonant production of dark photons in positron beam dump experiments

Enrico Nardi,[1,*] Cristian D. R. Carvajal,[2] Anish Ghoshal,[1,3] Davide Meloni,[3,4] and Mauro Raggi[5]



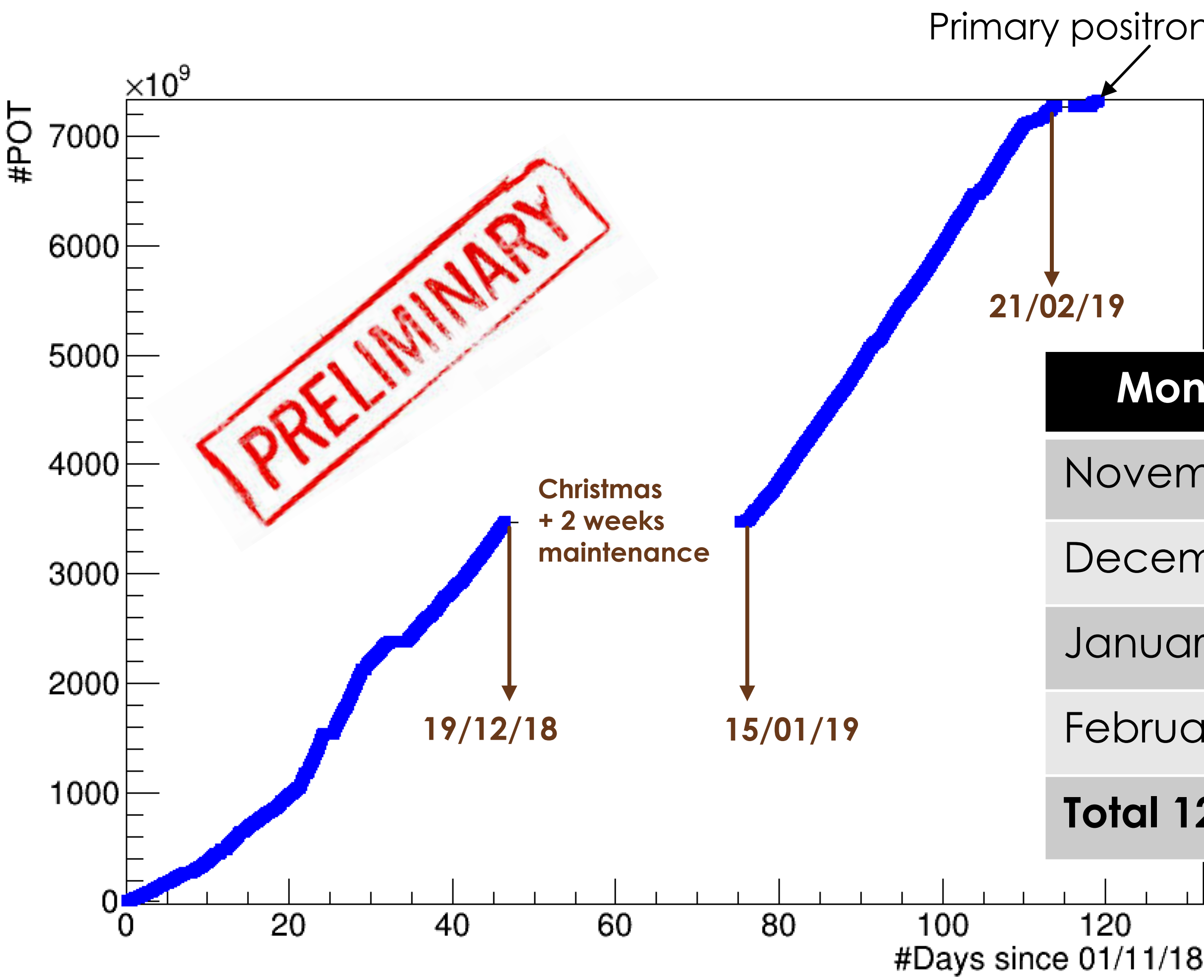
- Exploit the fact that you "know" where to search 17 MeV
- Exploit the unique possibility to have e^+ at 282.7MeV @LNF
- Tune E_{e+} such that E_{CM}=sqrt(2*m_e*E_B)=17MeV
  - Produce A' of 17MeV on shell through direct annihilation ee->A'
  - Parametrically enhanced ee->A' O(α) wrt ee->A'γ O(α^2)
- Use threshold effect to have solid evidence if a
- Absorb any SM BG in W dump
- Work ongoing on thin target reaches





$\epsilon / N_{A'}^{prod}$	E_{res} ($v_e = 0$)	E_{res}	$E_{res} + 2\sigma_b$
1.0×10^{-3}	7.69×10^{11}	1.51×10^{11}	4.72×10^{11}
5.0×10^{-4}	1.81×10^{11}	3.79×10^{10}	1.17×10^{11}
1.0×10^{-4}	7.25×10^{9}	1.49×10^{9}	4.73×10^{9}

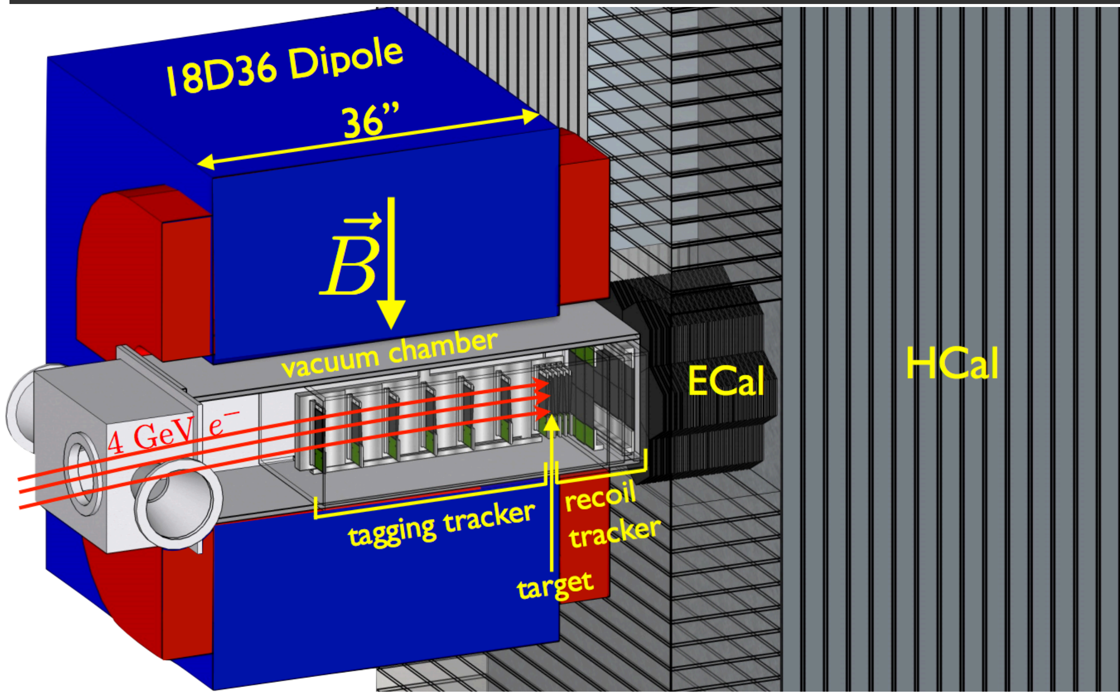
PADME data taking during Run I



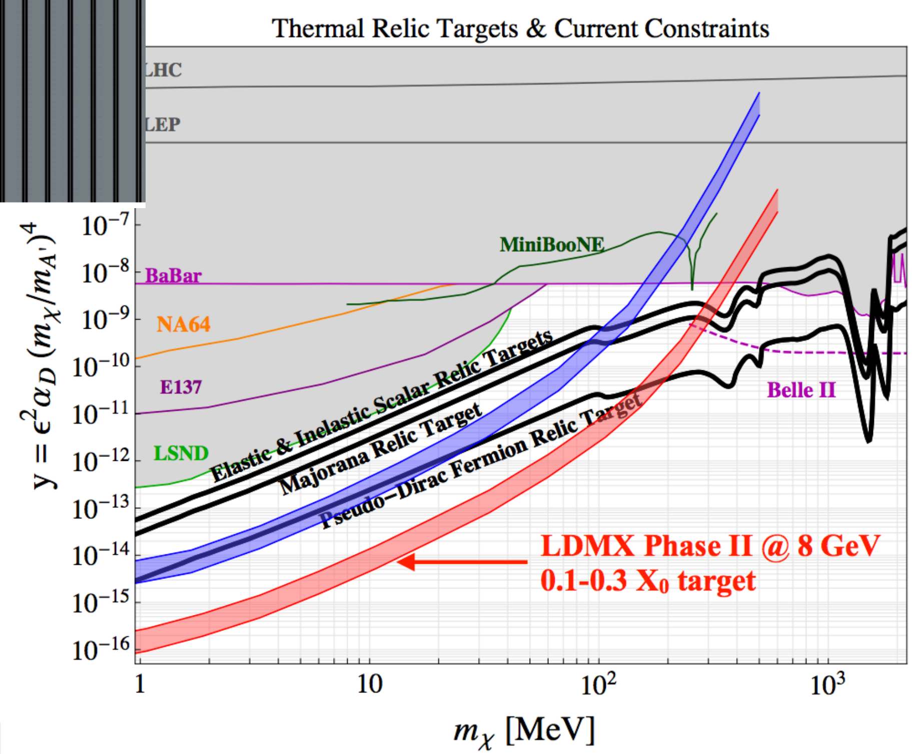
PRELIMINARY

Month	#days	N_{POT}	N_{POT}/day
November	30	2.2E12	0.76E11
December	16	1.4E12	0.875E11
January	15	1.7E12	1.1E11
February	21	2.1E12	1.E11
Total 12/02	**82**	**7.4E12**	**0.9E11**

LDMX: P_{Miss} experiment



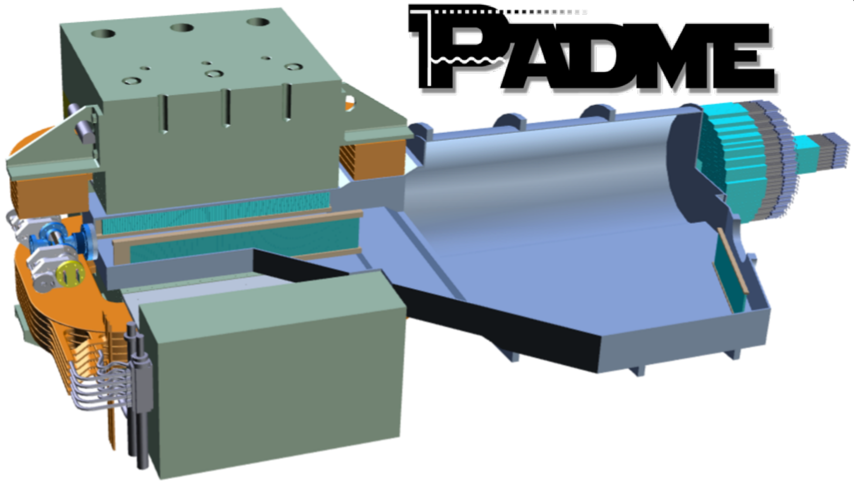
Two-stage approach to LDMX:
4×10^{14} “Phase I” late 2021?
$1\text{x}10^{16}$ “Phase II” late 2023-2024?



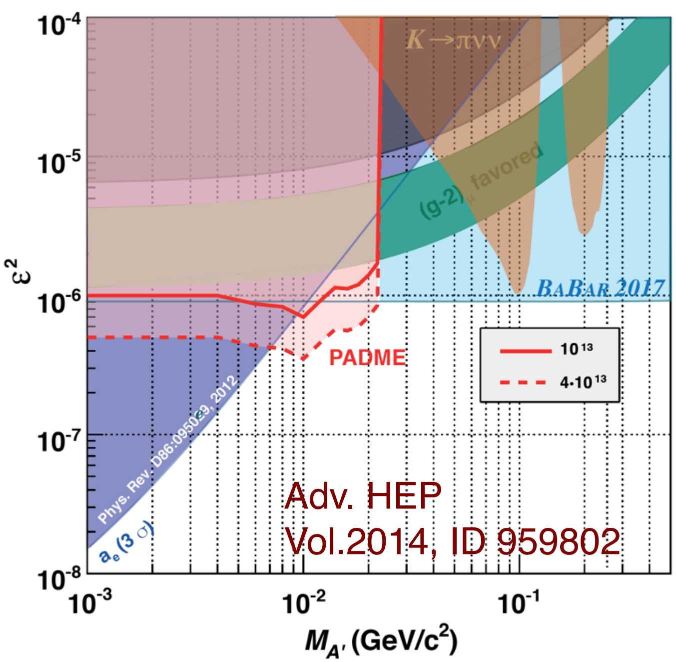
Beam: individual tag of 10^{16} incident e-
- A low-current, multi-GeV, e− beam (10^{16}/year ≈ 1 e- /3 ns).

Possibilities:
- DASEL@SLAC (4/8 GeV)
- CEBAF@JLab (up to 11 GeV).
- Recently SPS extracted e−
- Large beam spot (~10 cm²)

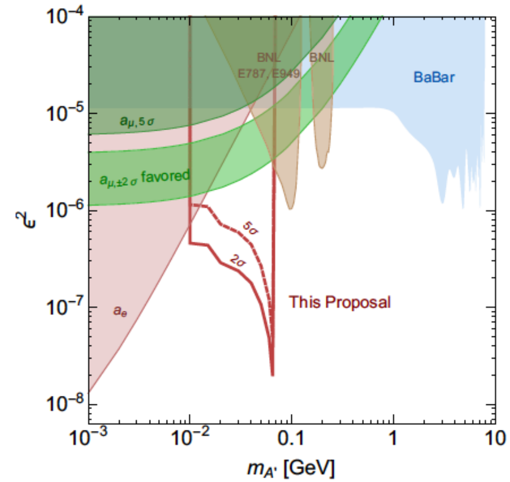
Future M_{Miss} fixed target experiments

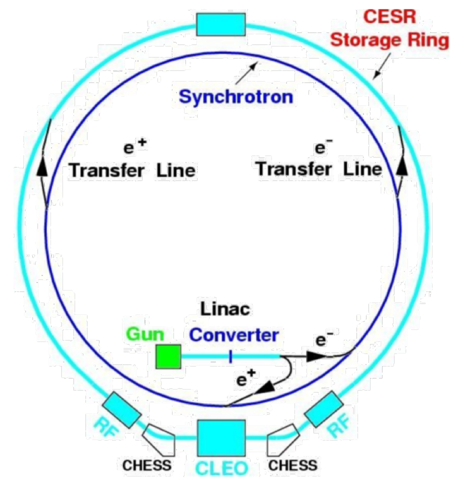


10^{13}e+ on target at LNF 2018

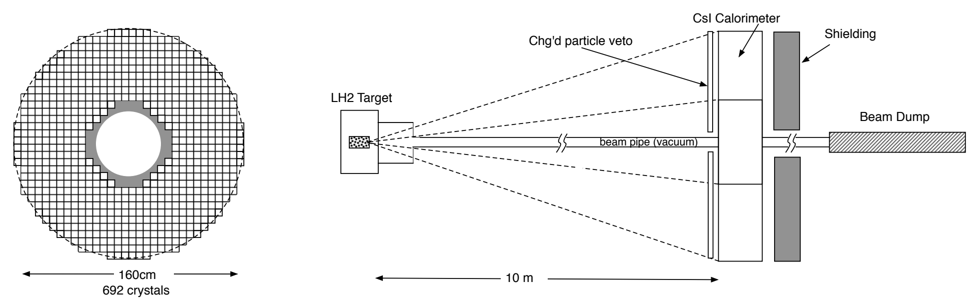


MMAPS @ Cornell





EPJ Web of Conferences 142, 0 01 (2017)



PADME + MMAPS? (2020?)

PADME: E_B~500 MeV, 2 year @ INFN BTF

Cornell: 12x E_B, **10^4x EOT**

PADME: Better M_{miss}, faster detector