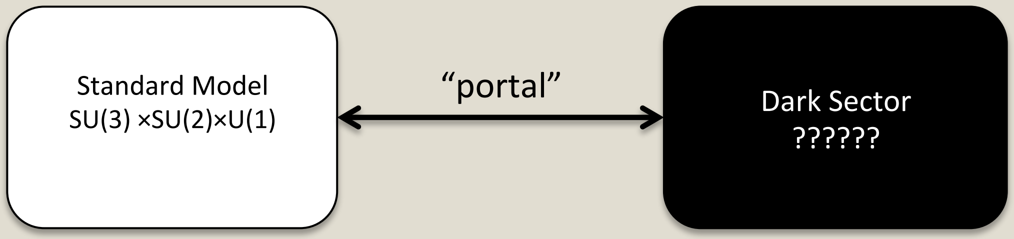
The PADME experiment at LNF

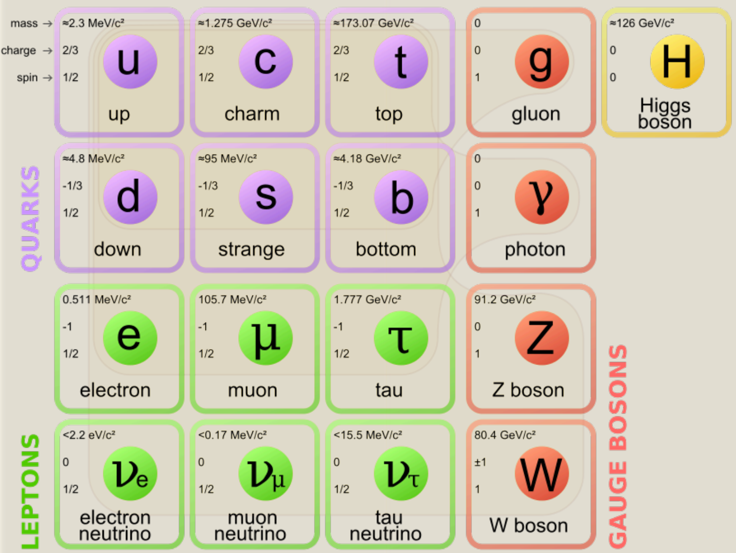


Mauro Raggi,
INFN Laboratori Nazionali di Frascati
IAXO meeting, 18/04/2016

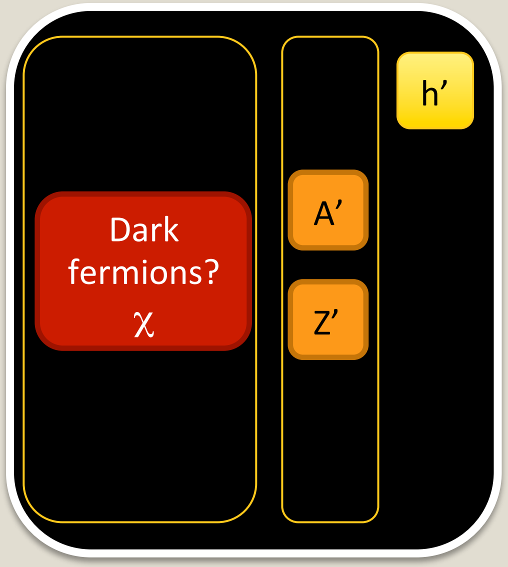
More info on PADME at:

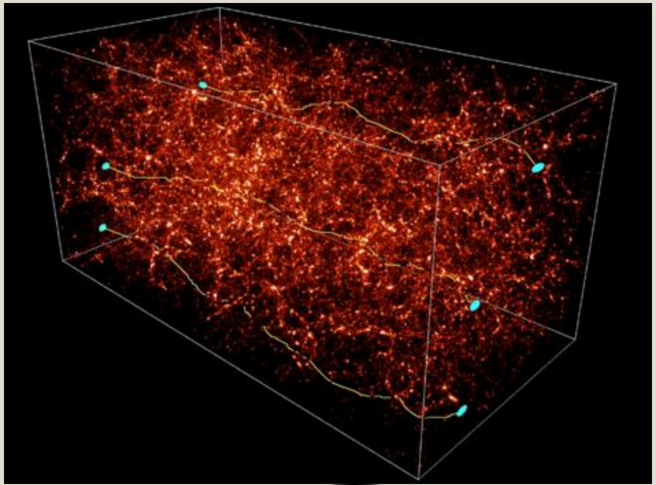
- M. Raggi and V. Kozhuharov, Advances in High Energy Physics Vol. 2014 ID 959802
- Kick-off meeting di PADME: **http://agenda.infn.it/event/padme-kickoff**
- Indico PADME: **https://agenda.infn.it/categoryDisplay.py?categId=782**
- M. Raggi and V. Kozhuharov, "Results and perspectives in dark photon physics": **http://www.sif.it/riviste/ncr/econtents/2015/038/10/article/0**

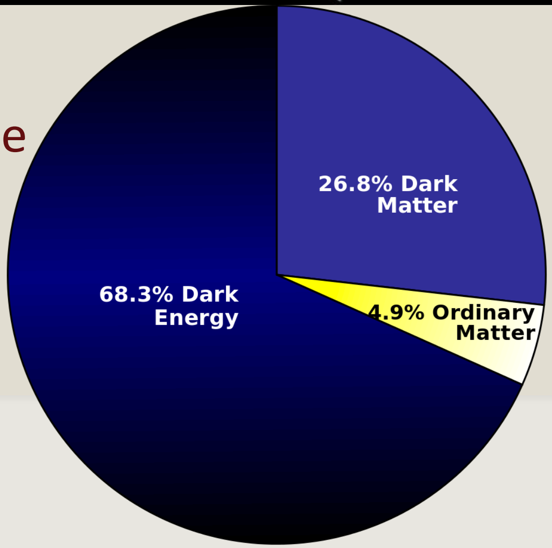
What the universe made of?



???Dark Sector???

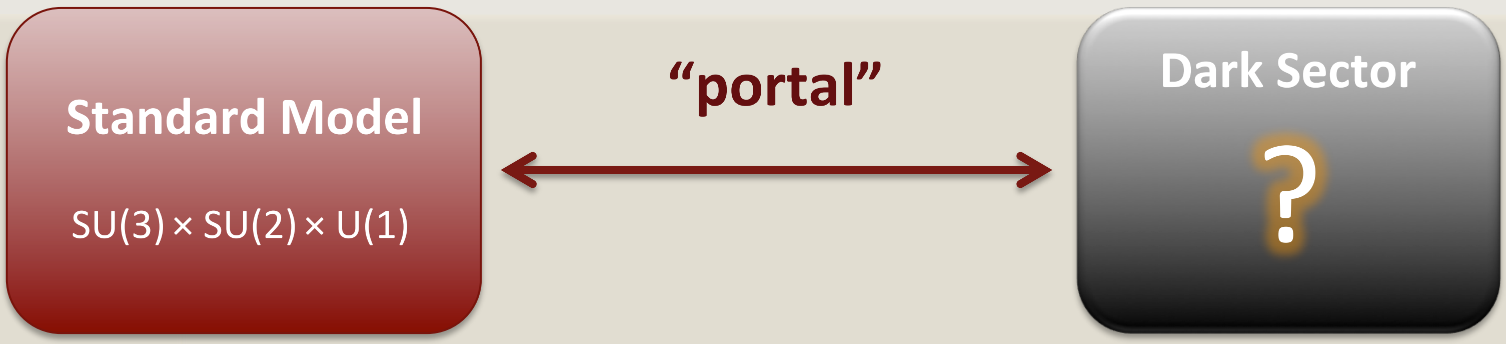






- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interact gravitationally
- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?

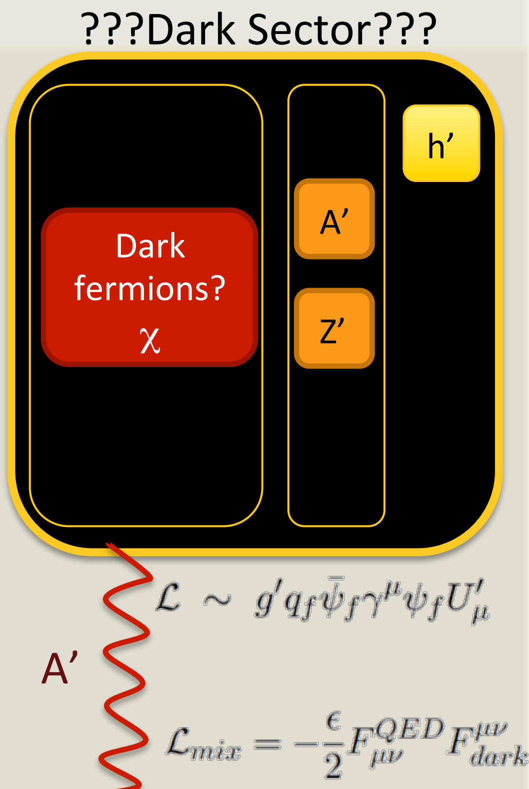
Portals to secluded sector

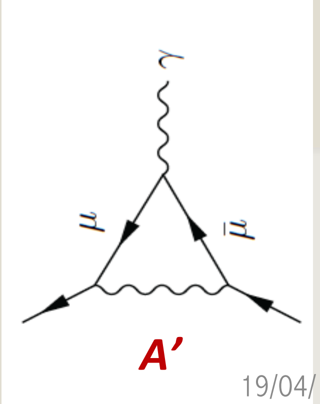


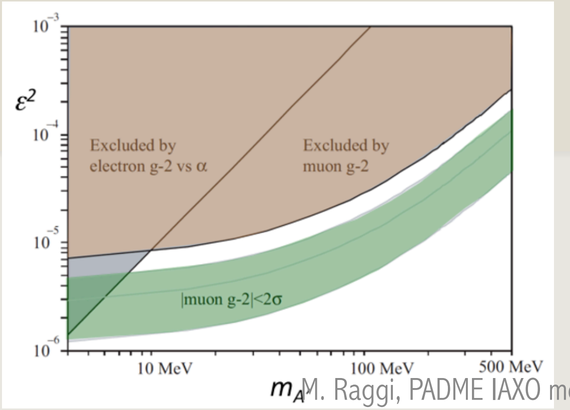
Vector	$\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$	**dark photon A'**
Higgs	$\epsilon_h \lvert h\rvert^2 \lvert\phi\rvert^2$	dark scalar
neutrino	$\epsilon_\nu (hL)\psi$	sterile neutrino
Axion	$\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$	**ALPs**

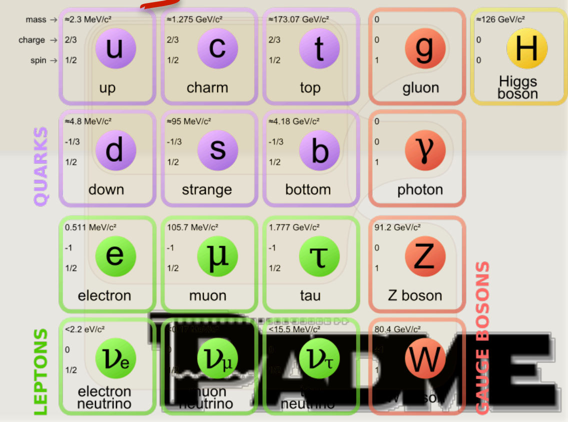
Dark photon model

- If there is a new force in the dark sector we need a new particle with quantum numbers of the new force and of one of the SM forces. These particle is called "portal"
- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or A'
- This scenario is natural in many SM extensions and in particular in some classes of string theories
- The model become popular for its capability of reconciling experimental value with theory prediction for (g-2)μ



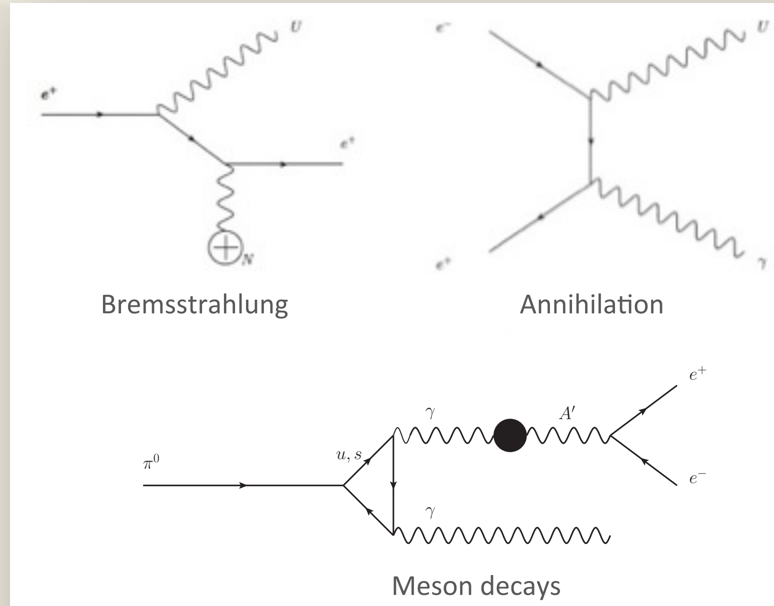


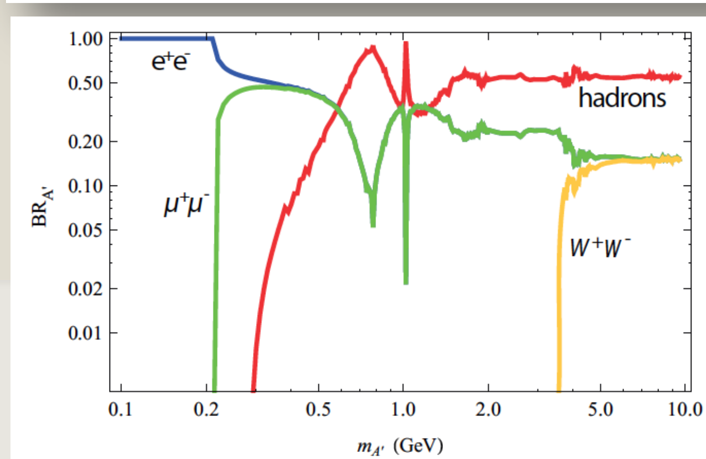




A' production and decays

- A' can be produced in e^+ collision on target by:
  - Bremsstrahlung: $e^+N \rightarrow e^+NA'$
  - Annihilation: $e^+e^- \rightarrow \gamma A'$
  - Meson decays
- If no dark matter candidate lighter than the A' boson exists:
  - $A' \rightarrow e^+e^-$, $\mu^+\mu^-$, hadrons, "visible" decays
  - For $M_{A'}$<210 MeV A' only decays to e^+e^- with $BR(e^+e^-)=1$
- If any dark matter particle χ with $2M_\chi < M_{A'}$ exists
  - A' will dominantly decay into pure DM
  - BR(l+l-) suppressed by factor ε^2
  - $A' \rightarrow \chi\chi$ ~ 1. These are the so called decays to "invisible"

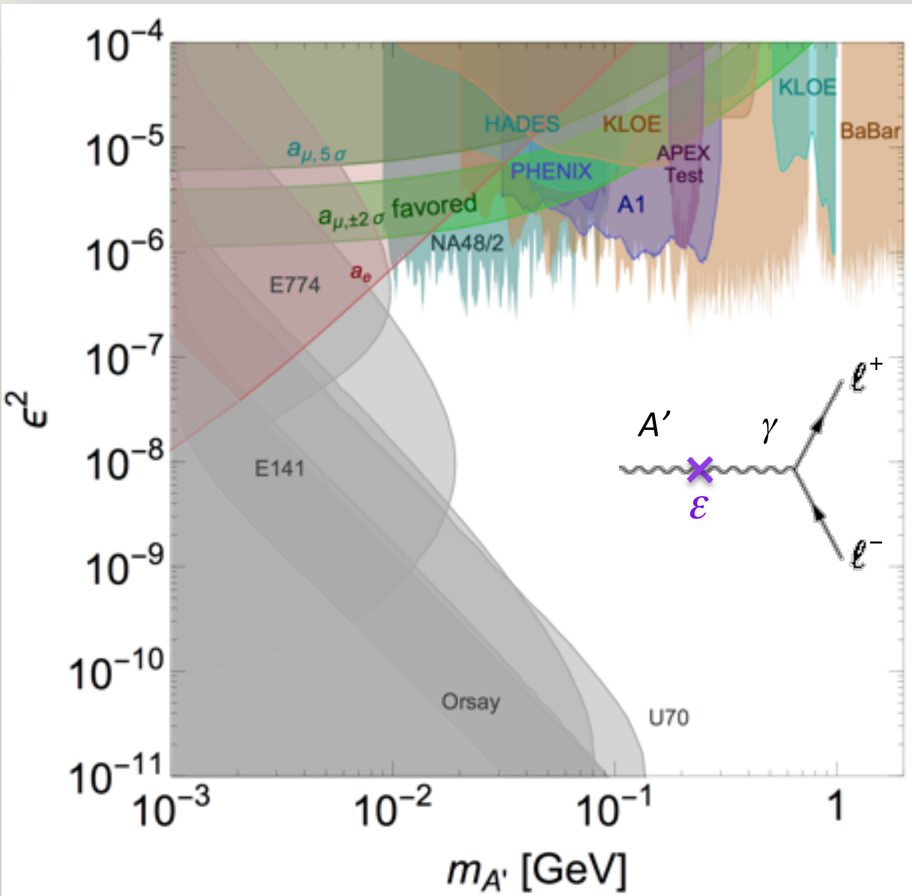


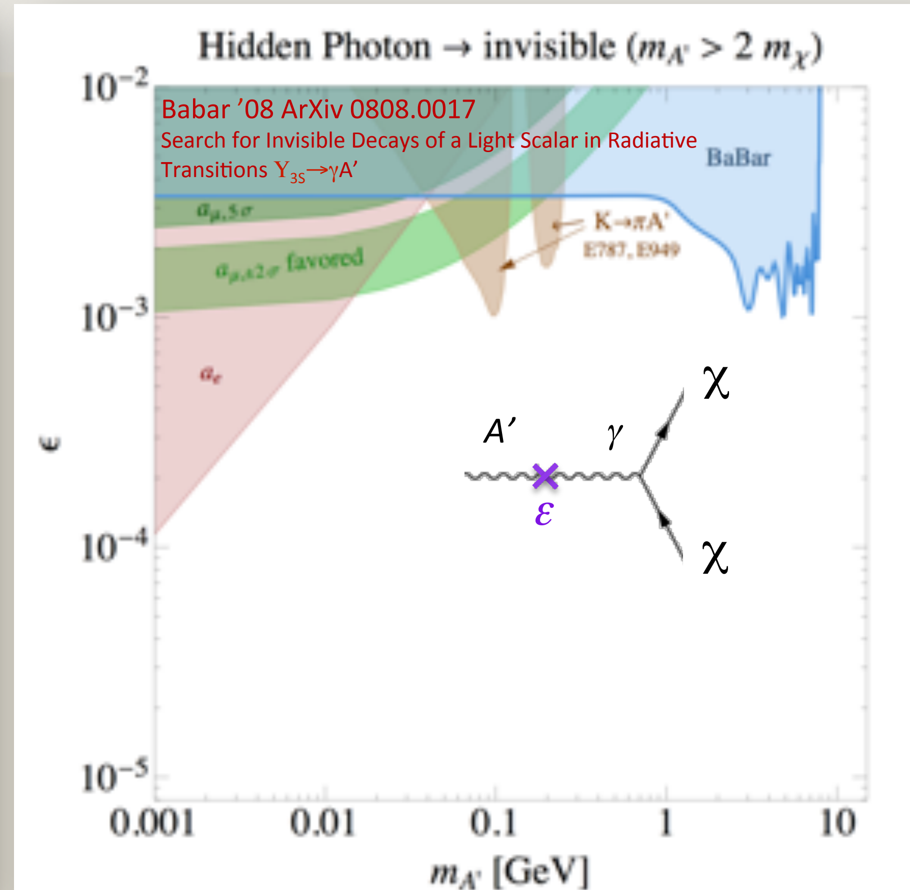


Dark photons searches

Many active experiments in the field with several different techniques

Status of "visible" and "invisible" A' searches





La banda favorita da $(g\text{-}2)_\mu$ è praticamente tutta esclusa NA48/2, **nell'ipotesi che A' decada in SM leptons**

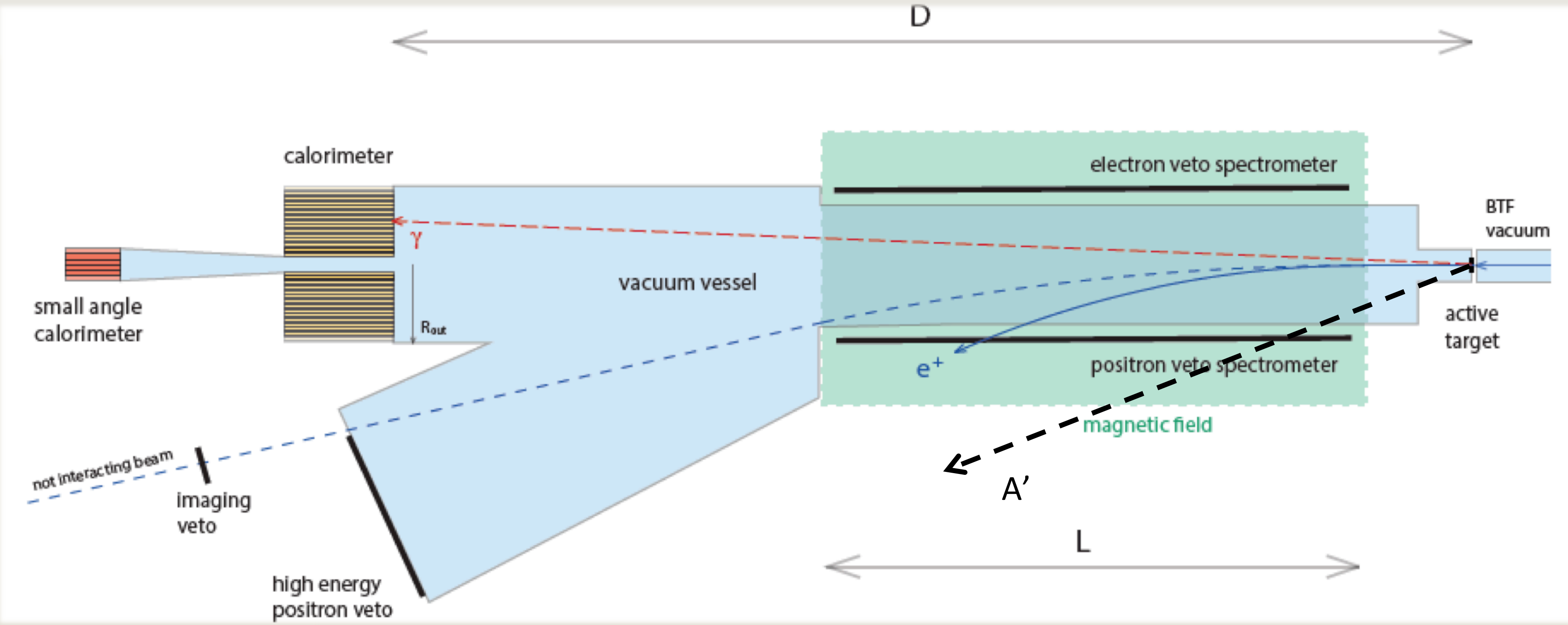
Ancora molto spazio dei parametri da esplorare $m_{A'}$*<1 GeV*

Invece lo spazio dei parametri escluso **ammettendo che il dark photon possa decadere in particelle del settore oscuro** χ ($M_\chi < M_{A'}/2$) è molto ridotto

The PADME approach

- At present all experimental results rely on at least one of the following model-dependent assumptions:
  - A' decays to e^+e^- (visible decays assumption) and thus BR(A'→e^+e^-) = 1
  - A' couples with the same strength to all SM fermions (kinetic mixing)
- In the most general scenario:
  - A' can decay to dark sector particles χ with $m_\chi < M_{A'}/2 \Rightarrow$ BR(A'→e^+e^- <<1)
  - Dump and meson decay experiment results suppressed by ε^2
  - A' can even be stable ($M_{A'}$=0 or $M_{A'}<2m_e$)
- PADME aims at detecting A' produced in e^+e^- annihilation and decaying into any final state by searching for missing mass in $e^+e^- \to \gamma A'$, $A' \to \chi\chi$ process
  - No assumption on the A' decays products PADME serches for $e^+e^- \to \gamma + M_{Miss}$
  - Only minimal assumption: A' couples to leptons
  - PADME will limit the coupling of any new light particle produced in e^+e^- collisions: scalars (h'), vectors (A') or pseudoscalars (ALP)

PADME invisible technique

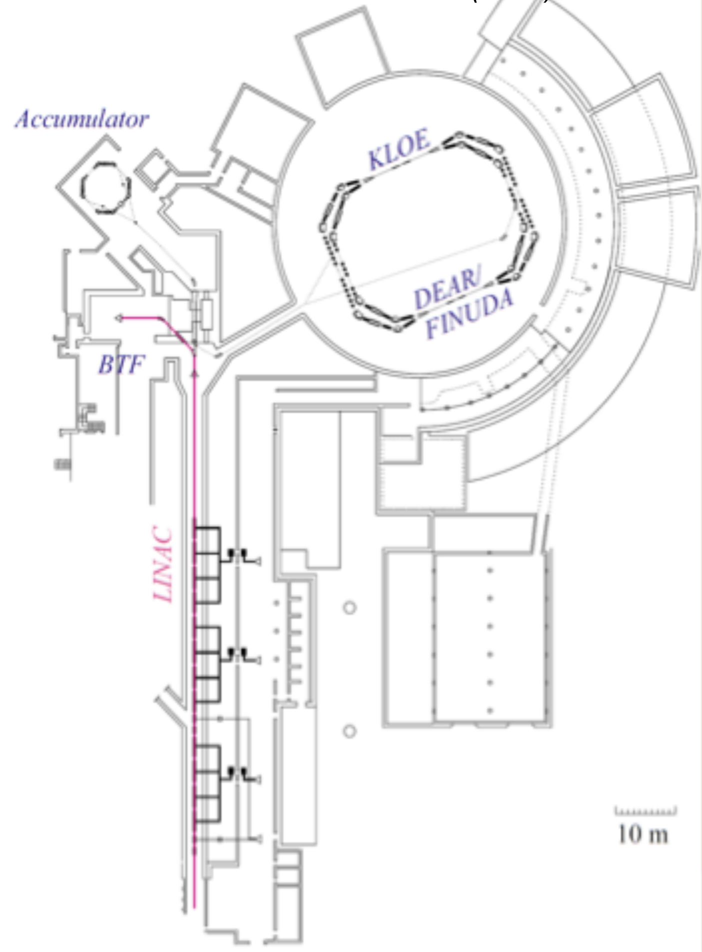


- Search for the process: e+e- → γA' on target e⁻ at rest electrons
- (5000 550 MeV e^+)/bunch on a 100 μm diamond target with 50 bunch/s
  - Collect 1×10^{13} e^+ on target in one-two year of data taking period at BTF
- Measure in the E_{Cal} the $E\gamma$ and $\theta\gamma$ angle wrt to beam direction
- Compute the $M_{miss}^2 = (P4_{e-} + P4_{beam} - P_{4\gamma})^2$
  - $P^4_{e-} = (0,0,0,m_e)$ and $P^4_{beam} = (0,0,P_{Beam}, \mathrm{sqrt}(P_{Beam}^2 + m_e^2))$

DAΦNE Beam Test Facility (BTF)

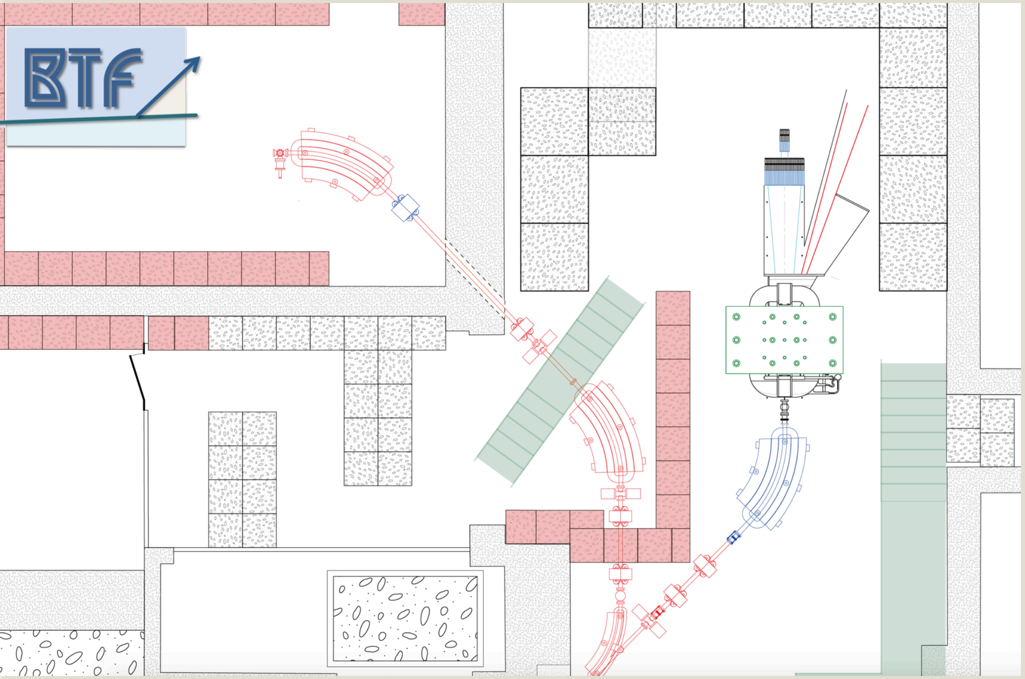
	electrons	positrons
Maximum beam energy (E_{beam})[MeV]	750 MeV	550 MeV
Linac energy spread [Δp/p]	0.5%	1%
Typical Charge [nC]	2 nC	0.85 nC
Bunch length [ns]	1.5 - 40	
Linac Repetition rate	1-50 Hz	1-50 Hz
Typical emittance [mm mrad]	1	~1.5
Beam spot σ [mm]	<1 mm	
Beam divergence	1-1.5 mrad	

NIM A 515 (2003) 524–542



- Able to provide electrons and positrons
  - Duty cylcle 50*40 ns= $2x10^{-7}$ s
    work in progress to reach 160 ns ideas for 480 ns
  - Request submitted for energy upgrade to reach ~1GeV.
- The accessible $M_{A'}$ region is limited by E_{beam}
  - 0-22 MeV can be explored with 550 MeV e^+ beam
  - Up to ~30 MeV with 1 GeV positrons

PADME at DAFNE BTF



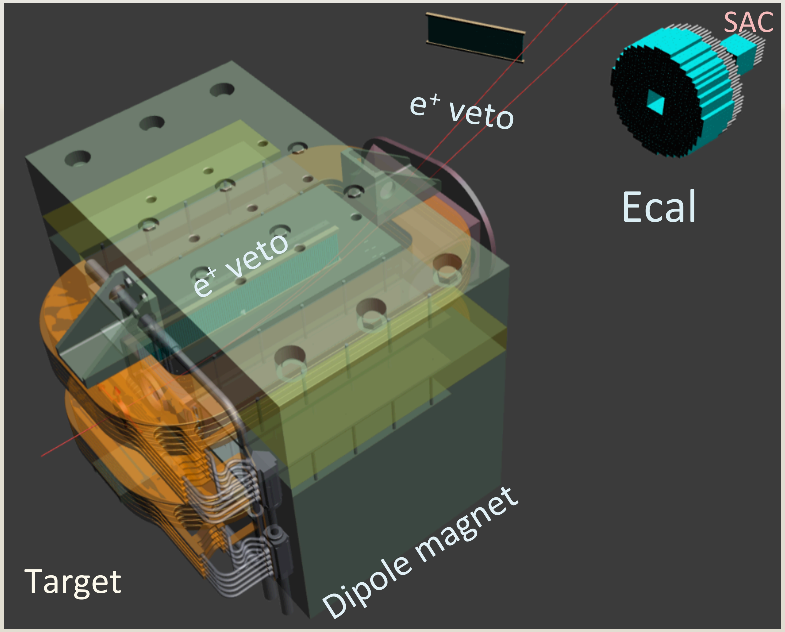
Splitting of the present BTF line need

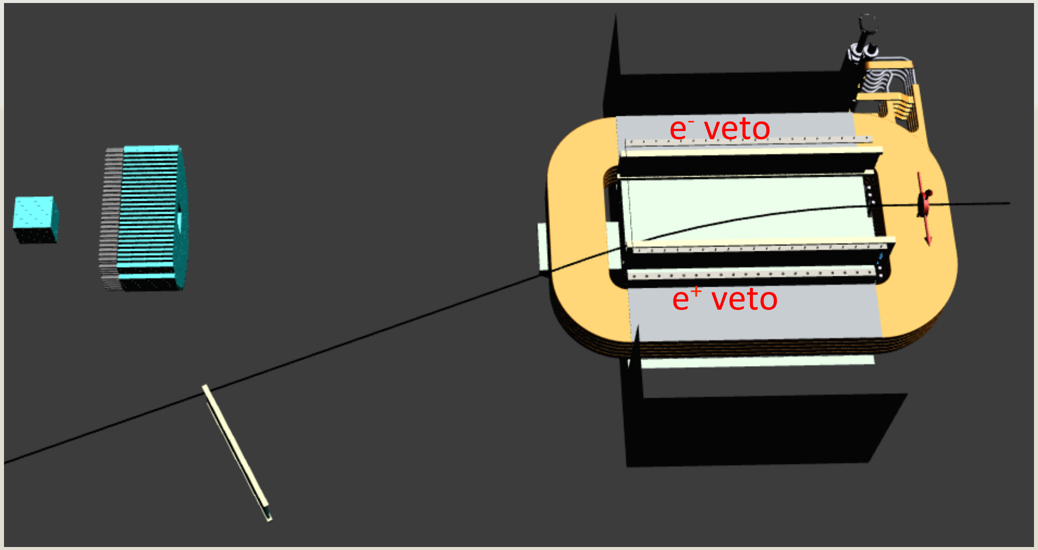
- Could be realized in early 2017
- Dedicated line for PADME in the present experimental hall

Limits to the experiment dimention

- No more than 4m in between target and Ecal
- If distance shorter than 3 meter additional optics could be installed to improve beam quality

The PADME experiment



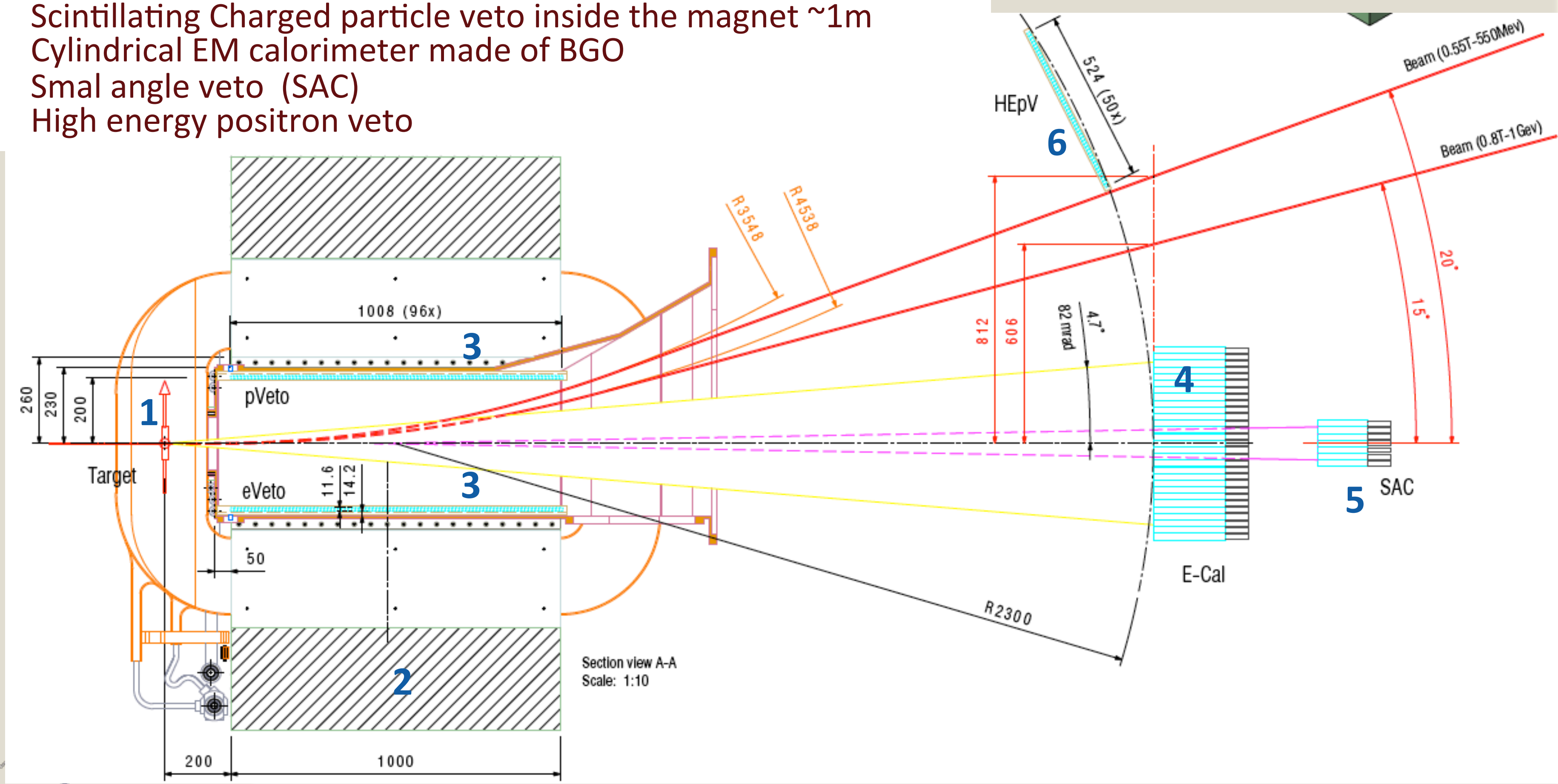


- Beam: 10^3-10^4 e+ on target per 40 ns bunch, at 50 bunch/s (10^{13}-10^{14} e+/year)
- Main detector components:
  - Active target, thin: 50-100μm diamond (Time, Ne-, beam position and spot size)
  - Scintillating veto ~1m length
  - Conventional magnet, B≈0.6T but large gap for gaining acceptance
  - Cylindrical BGO crystal EM calorimeter
- Measures: time, energy and direction of photons
- Compute the $Mmiss^2 = (P^4e^- + P^4_{beam} - P^4_{\gamma})^2$
- $P^4_{e-} = (0,0,0,m_e)$ and $P^4_{beam} = (0,0,550,\mathrm{sqrt}(550^2 + m_e^2))$
- Veto additional charged particles and photons

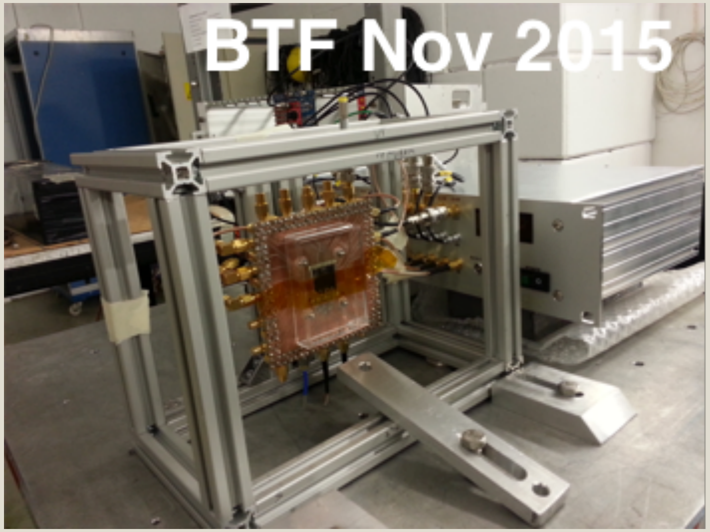
PADME detector

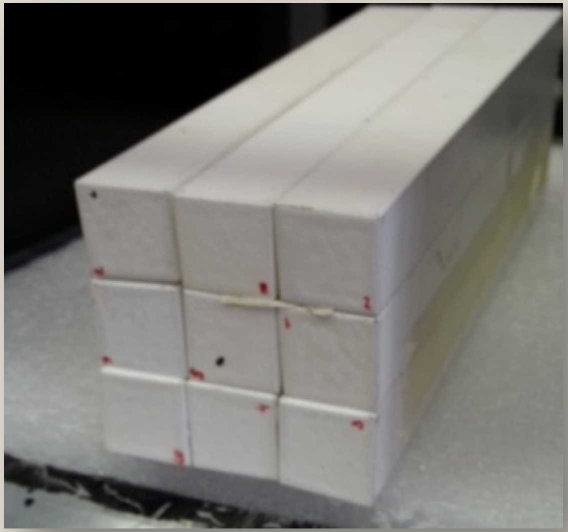
Main detector components

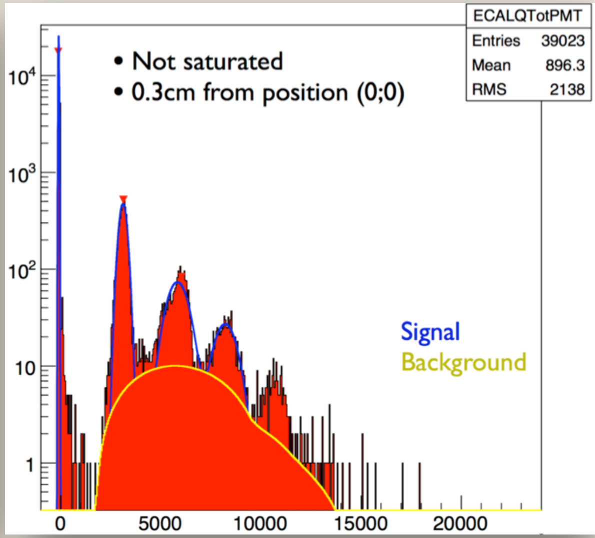
1. Active target: 50-100μm Diamond (time, Ne-, position and beam spot size)
2. Magnet, B≈0.6T with large gap
3. Scintillating Charged particle veto inside the magnet ~1m
4. Cylindrical EM calorimeter made of BGO
5. Smal angle veto (SAC)
6. High energy positron veto



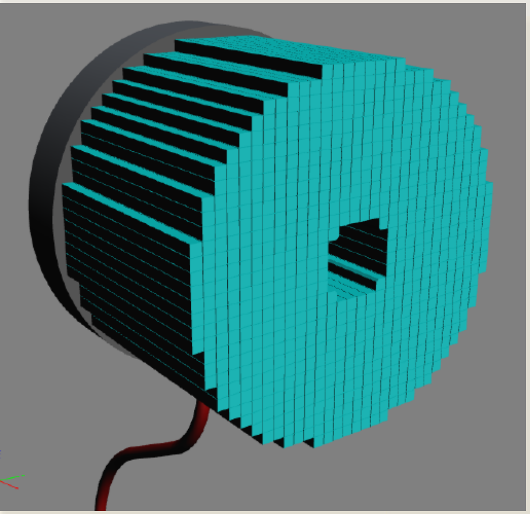
PADME detector status







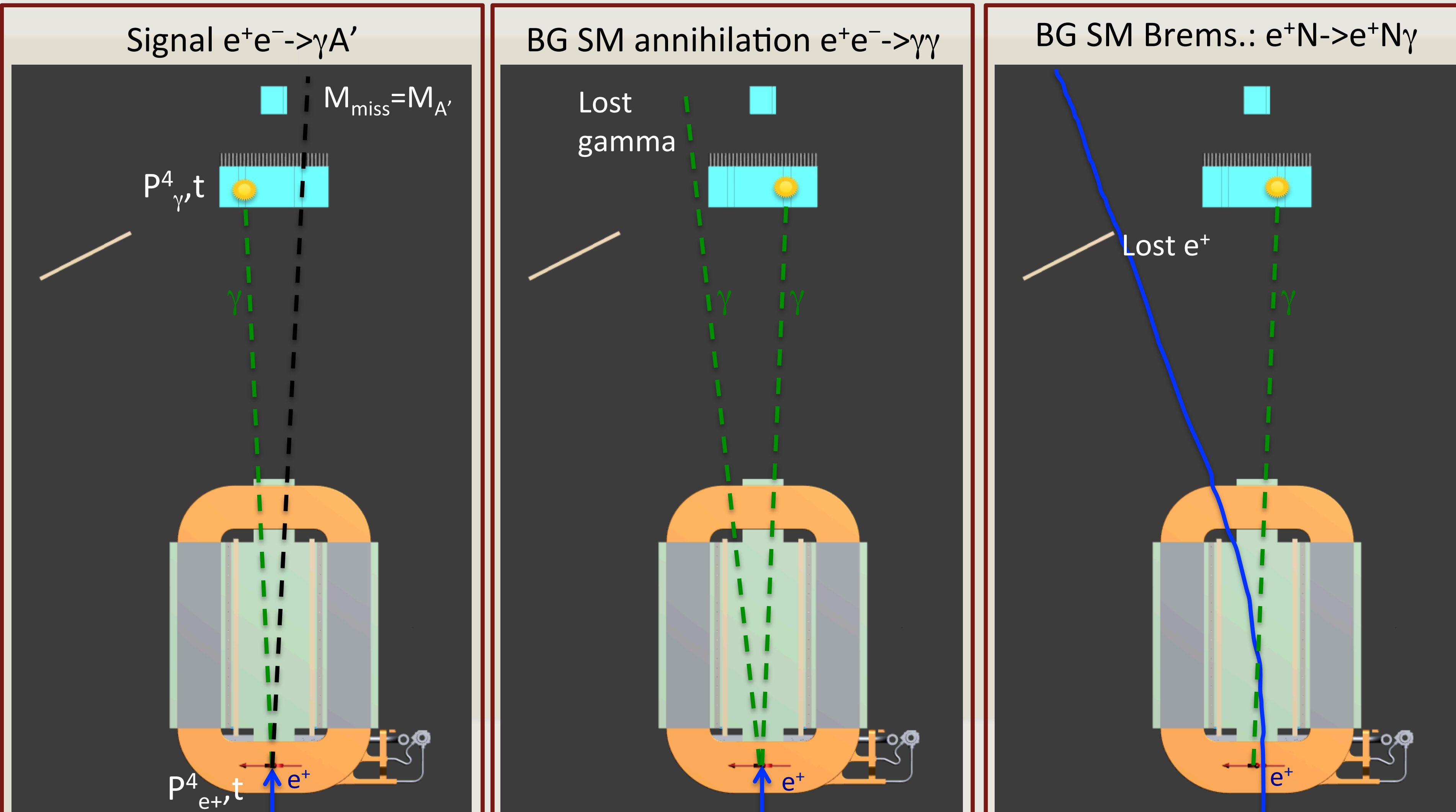
PADME ECal



Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	420^s	1.95	3.6^s	slight	−1.4
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

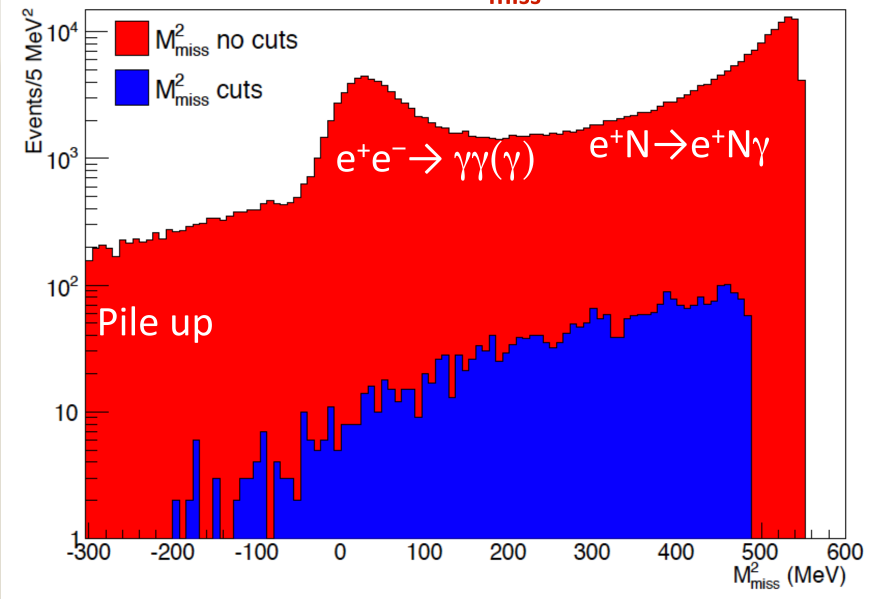
- Cylindrical shape: radius 300 mm, depth of 220 mm
  - Inner hole 60-80 mm radius
  - 656 crystals 20x20x220 mm^3
- Material BGO: high LY, high ρ, small X_0 and RM, long τ_{decay}, (free form L3 calorimeter)
- Expected performance:
  - $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ superB calorimeter test at BTF [NIM A 718 (2013) 107–109]
  - $\sigma(\theta)$ ~ 1-2 mrad
  - Angular acceptance (20 – 75) mrad

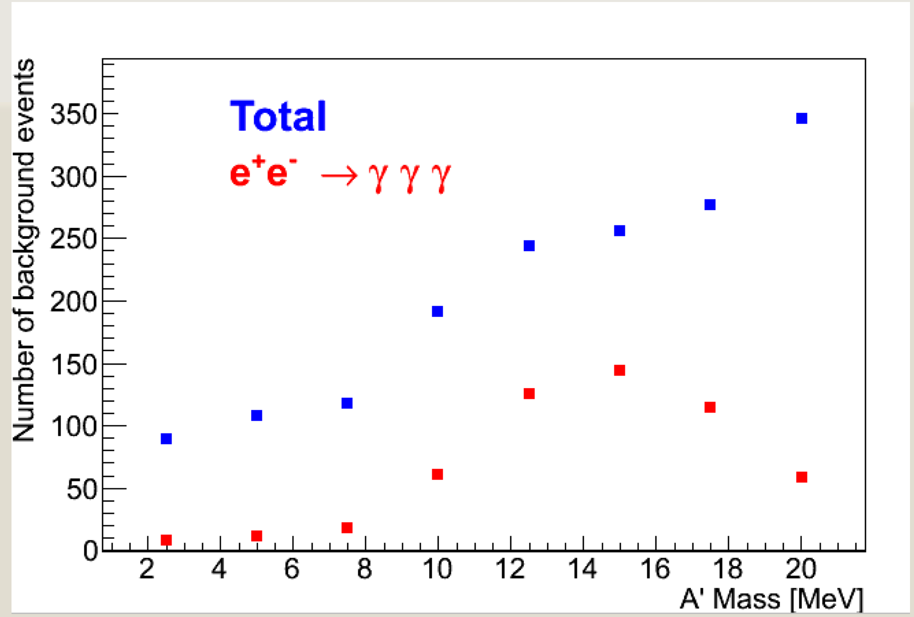
PADME backgrounds A'



Background estimates

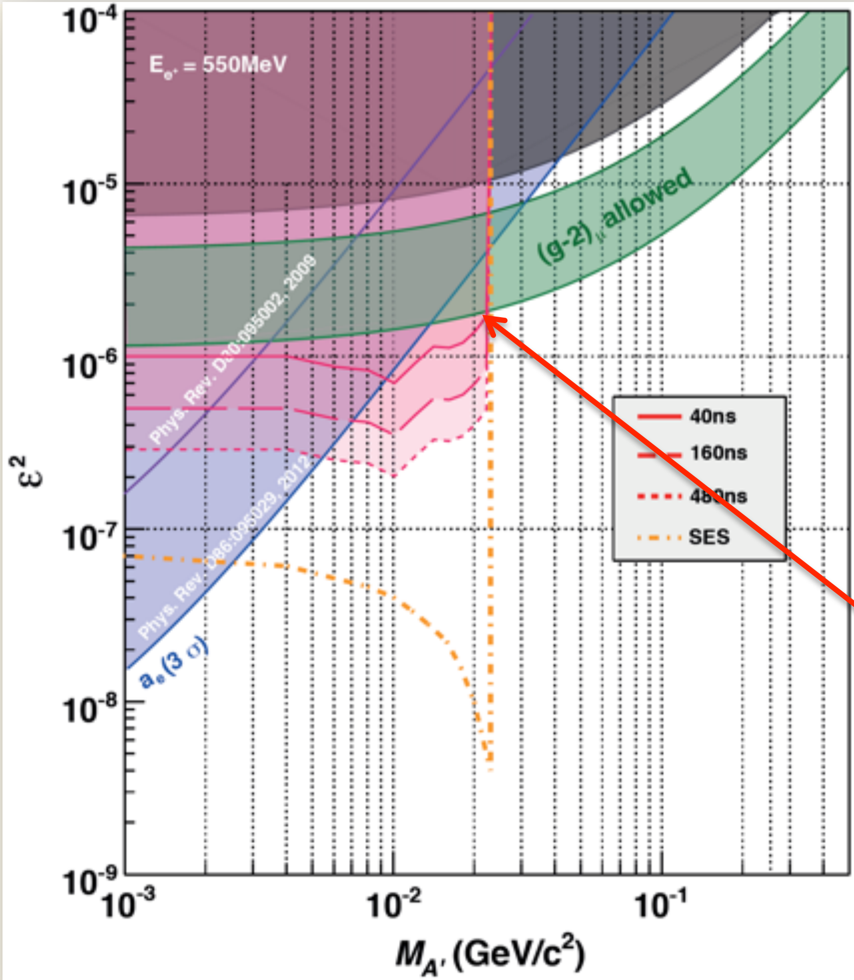
Data M_{miss}^2





- BG sources are: $e^+e^- \to \gamma\gamma$, $e+e- \to \gamma\gamma(\gamma)$, $e+N \to e+N\gamma$, Pile up
- Pile up contribution is important but rejected by the maximum cluster energy cut and M_{Miss2}.
- Veto inefficiency at high missing mass (E(e+)≃ E(e+)beam)
  - New Veto detector introduced to reject residual BG
  - New sensitivity estimate ongoing

PADME-invisible decay sensitivity



- Based on 2.5×10^{10} fully GEANT4 simulated 550MeV e+ on target events
  - Number of BG events is extrapolated to 1×10^{13} electrons on target
- Using $N(A'\gamma)=s(N_{BG})$
- δ enhancement factor $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$

$$\frac{\Gamma(e^+e^- \to U\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(U\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(U\gamma)} = \epsilon^2 * \delta$$

PADME 2 years of data taking at 50% efficiency with bunch length of 40 ns
10^{13} EOT = **6000 e$^+$**/bunch × **$3.1\cdot10^7$**s · **49 Hz**

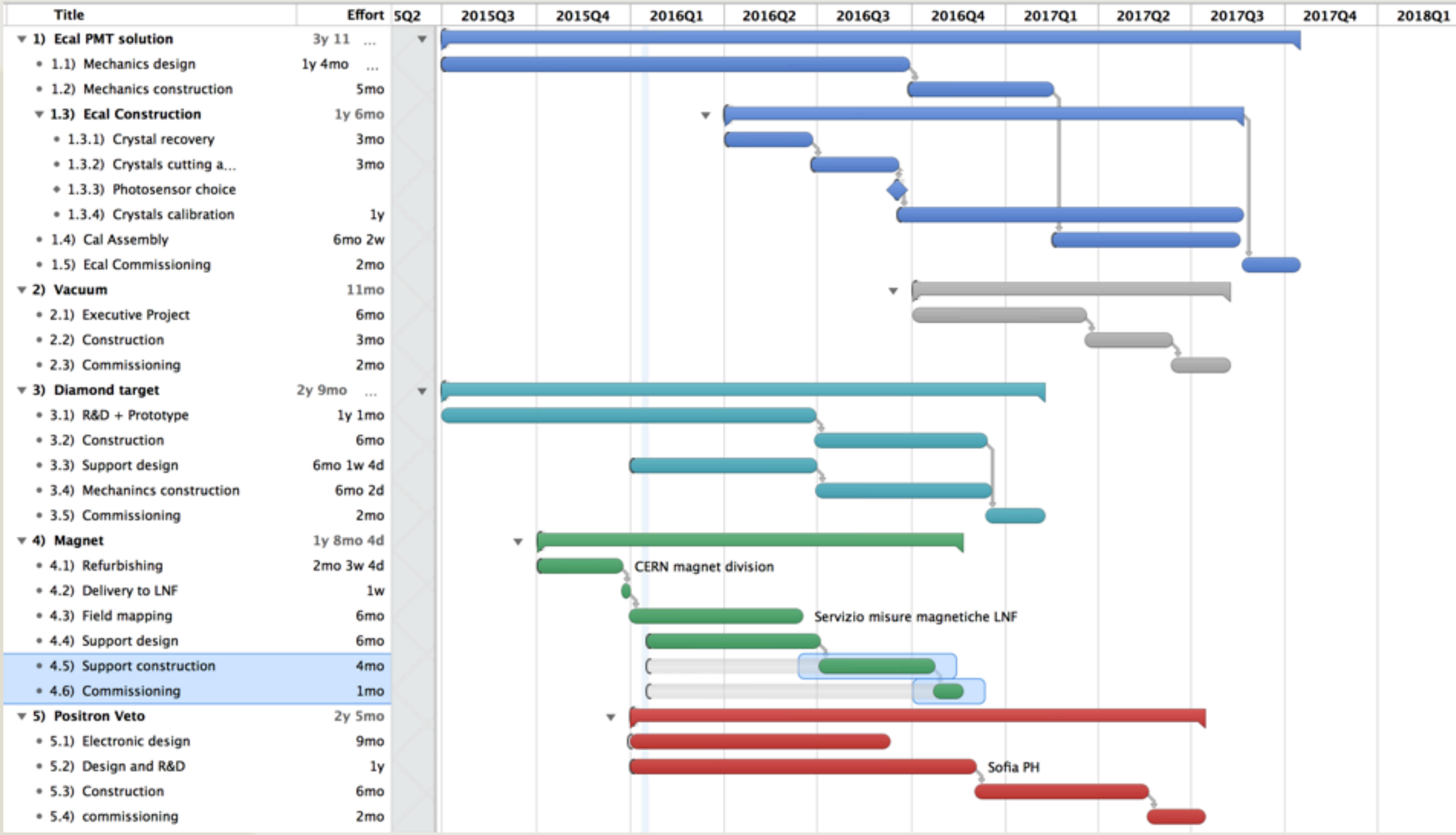
PADME can explore in a ***model-independent way the*** favourite by $(g\text{-}2)_\mu$ band up to $\boldsymbol{M^2_{A'} = 2m_eE_{e+}}$

E_{e+}=550 MeV: $M_{A'}$ < 23.7 MeV/c^2

E_{e+}=750 MeV: $M_{A'}$ < 27.7 MeV/c^2

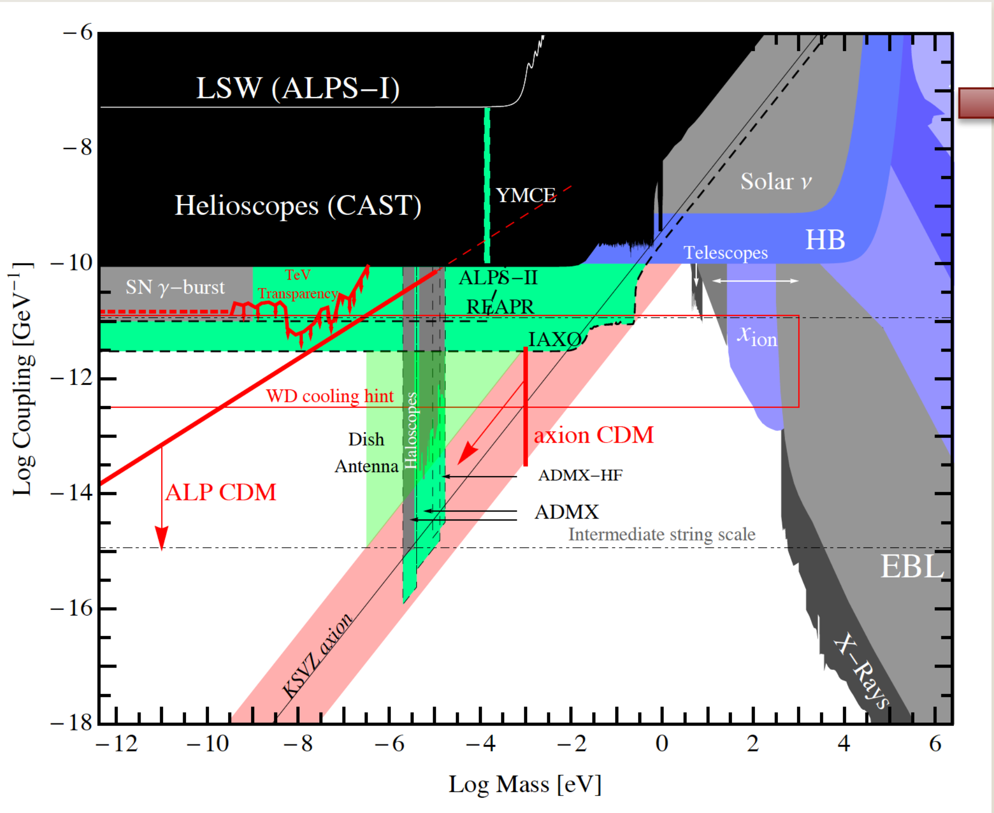
E_{e+}=1 GeV: $M_{A'}$ < 32 MeV/c^2

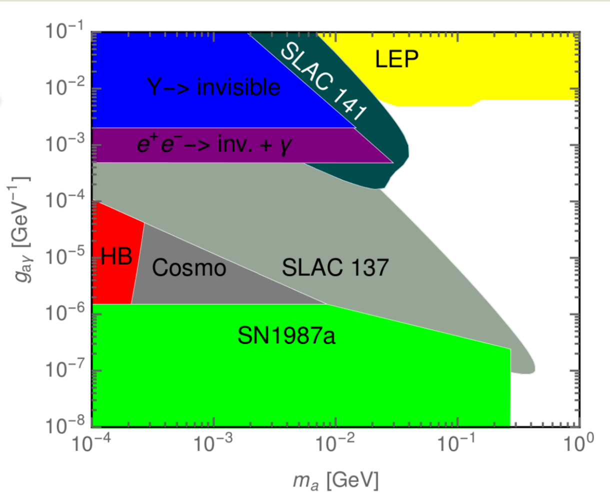
PADME schedule

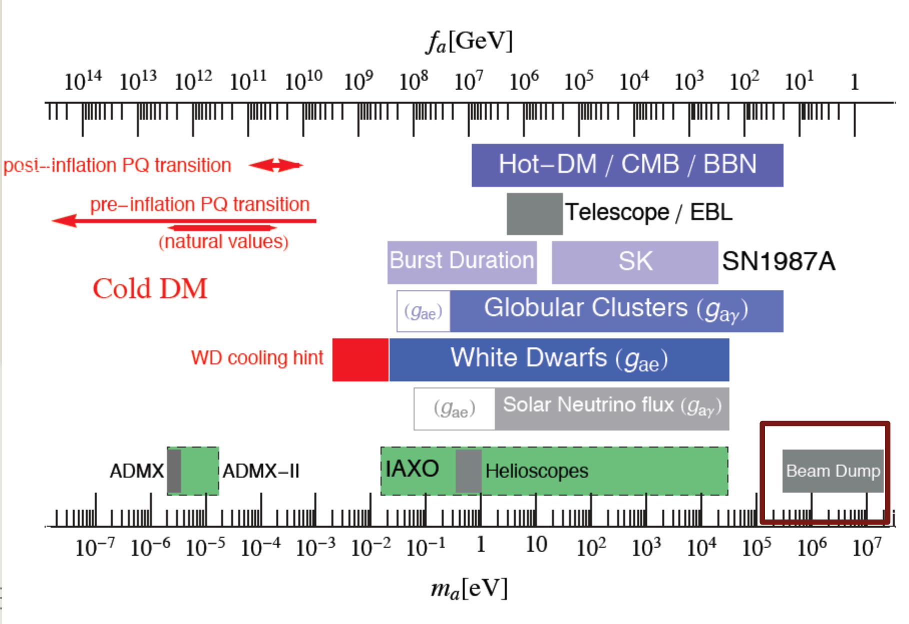


Technical run in late 2017 and first physics run in 2018 are foreseen

ALPs landscape

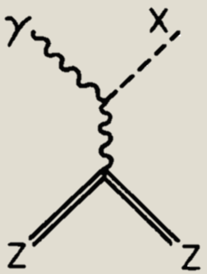






ALP physics at PADME

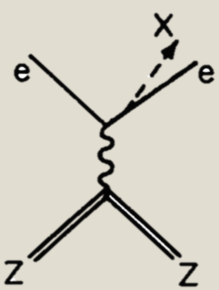
Primakoff



PADME can search for invisible decaying or long living ALP by searching for

$1\,\gamma + M^2_{miss}$ final states

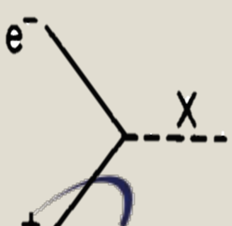
Bremsstrahlung



In the visible final state a->γγ all production mechanisms can be explored extending the mass range in the region of ~100MeV

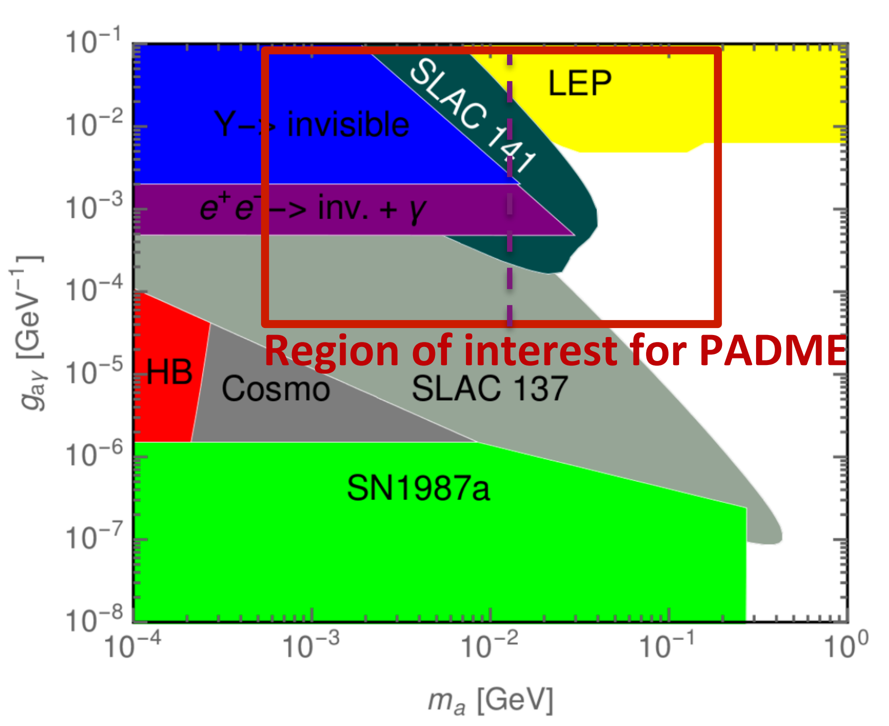
The observables at PADME will be: eγγ or γγγ

Annihilation



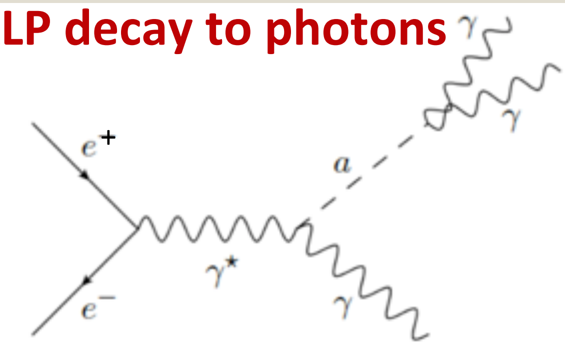
Phys rev D 38 11 1998

Limits on ALPs coupling to photons

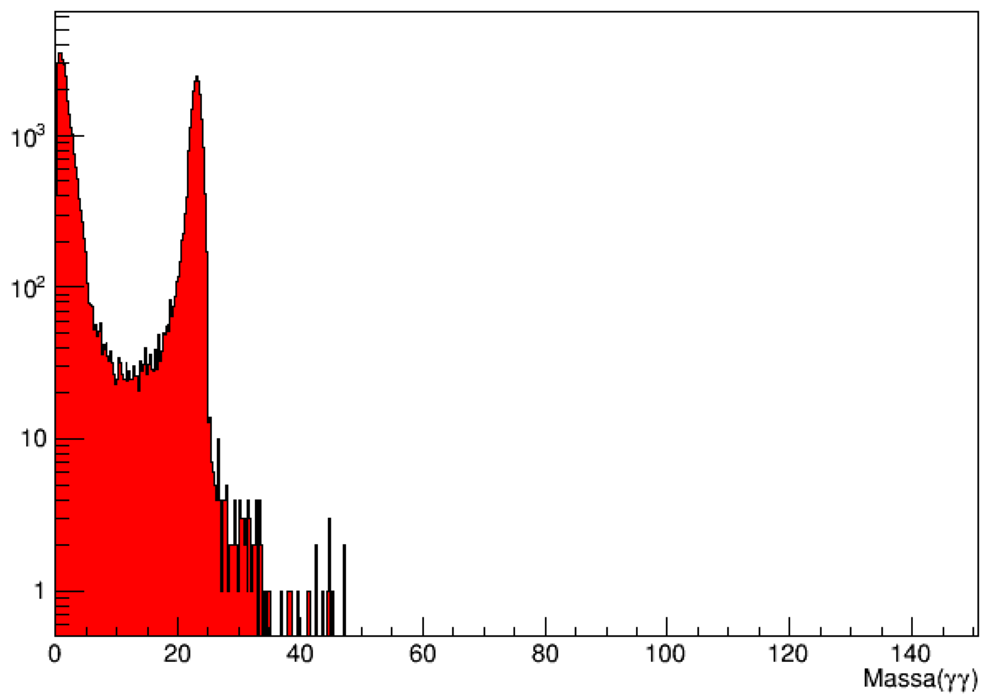


arXiv:1512.03069

ALP decay to photons



ALPs background at PADME



MC invariant mass for γγ in time in the PADME Ecal (~1e10 e+).

Even without any selection PADME is almost background free for masses >40-50MeV

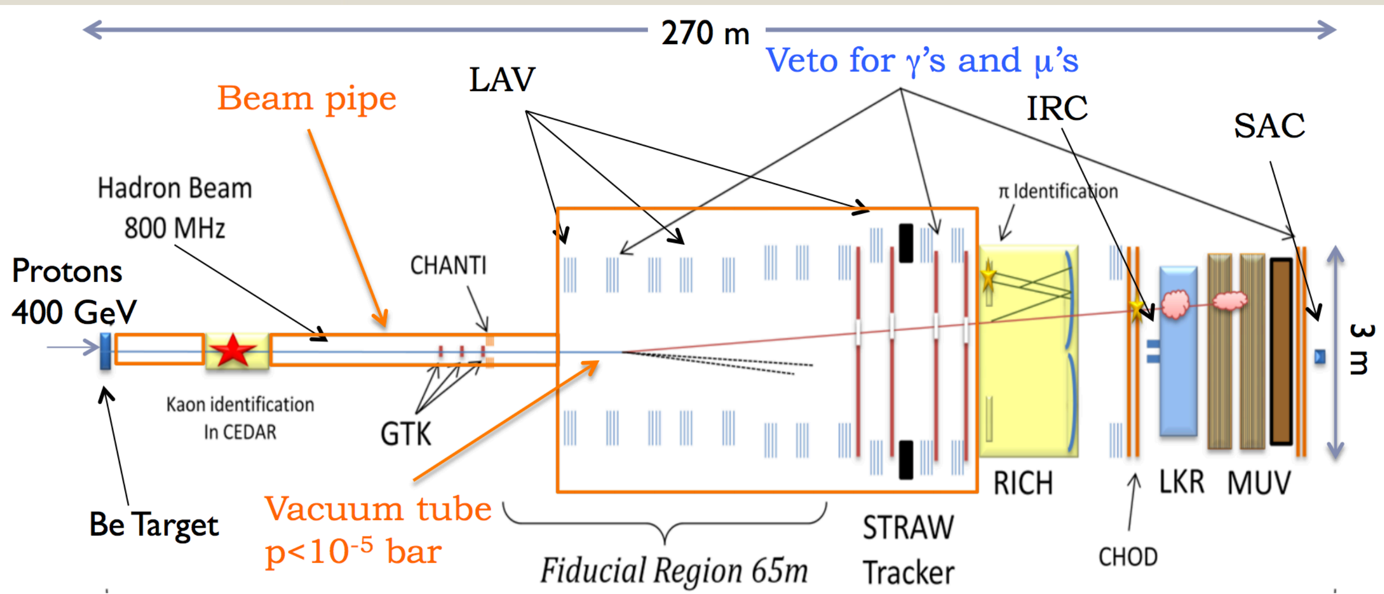
- Main backgrounds: $e^+e^- \to \gamma\gamma$, $e^+e^- \to \gamma\gamma(\gamma)$
  - M(γγ) limited to ~24 MeV being the electron at rest
- Higher mass background events come from pileup of multiple bremsstrahlung coming from different primary positrons

Conclusions

- The PADME construction phase is just starting
  - Magnete delivered at LNF in December
  - First diamond target tests (20x20mm^2 e 50um di spessore)
  - First Ecal test beam with just 3x3 crystal matrix
- Approval status
  - Project has been endorsed by both LNF scientific committee and INFN CSN1
  - Crystals from L3 collaborations obtained
  - 2016 budget secured in INFN CSN1 by "What Next" program
  - Expected to take data already during 2018
- PADME can search for ALPs in the range from ~0.1 to 100 MeV
  - Sensitivity studies required to asses the real potential and to optimise the detector and beam is needed

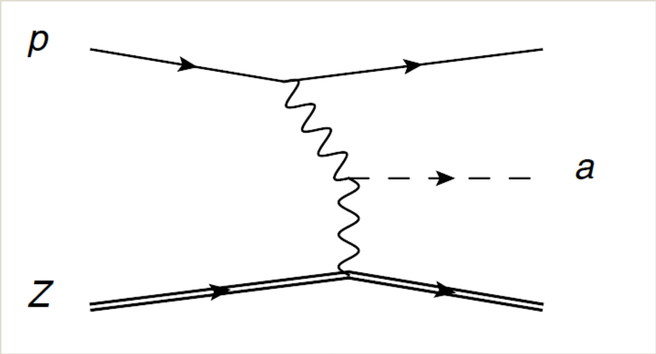
NA62 experiment at CERN

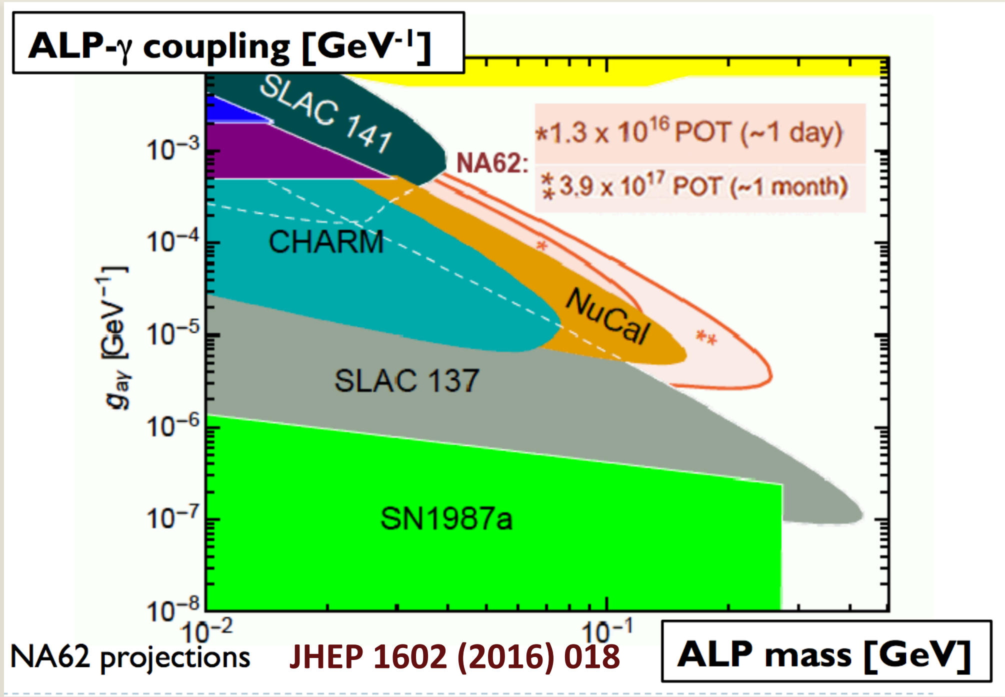
- Already running to search for $K^+ \to \pi^+ \nu\nu$
  - Aims to a 10% measurement in 2 years of data taking
- Running until 2018
- Different dark sector searches possible
  - A', ALPs, Heavy neutral leptons
- Closing the beam dump system can be used as dump experiment with ~10^{12} pps on target per effective second



ALPs search at NA62

Primakov production in p-N interactions



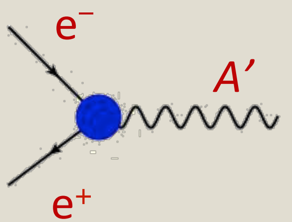


- NA62 can be used as dump experiment to produce ALPs through Primakov effect
- ALPs could fly in the decay region for proper lifetime values
- Decay of ALPs into two photons can be detected in NA62 LKr electromagnetic calorimeter
- Few hours run collected in 2015 to understand backgrounds

Spare slides

The simplest dark sector model

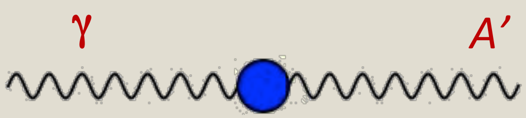
- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon” or A’
  - Two type of interactions with SM particles should be considered
- As in QED, this new force will generate new interactions of the type:



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

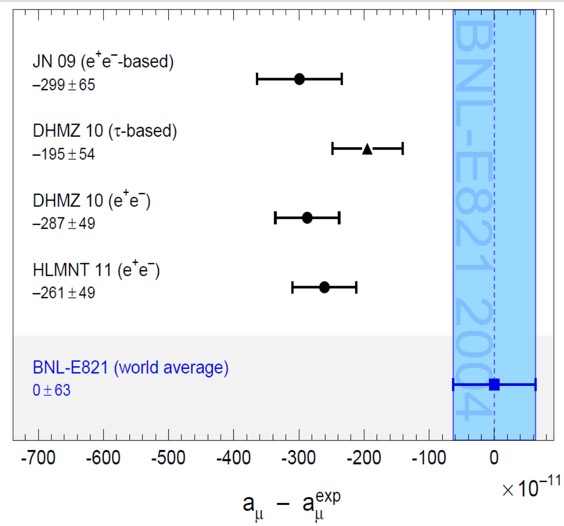
  - Not all the SM particles need to be charged under this new symmetry
  - In the most general case qf can be different in between leptons and quarks and can even be 0 for quarks. [P. Fayet, Phys. Lett. B 675, 267 (2009), arXiv:1408.4256]
- The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons

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

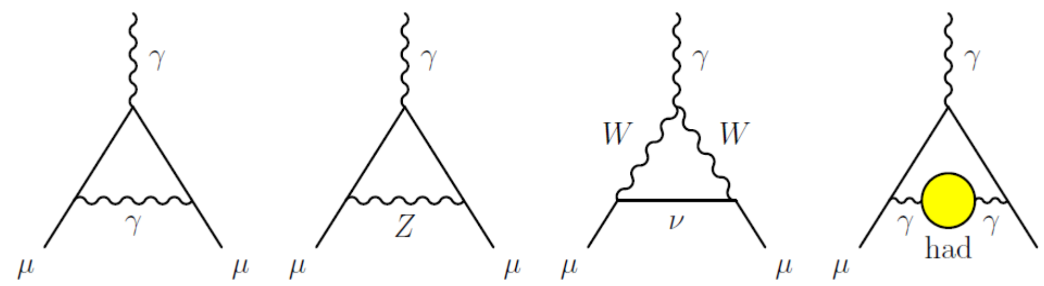


  - In this case q_f is just proportional to electric charge and it is equal for both quarks and leptons.

Muon g-2 SM discrepancy



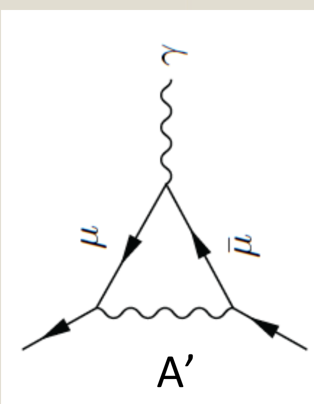
g-2 in the standard model



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

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

g-2 and A'



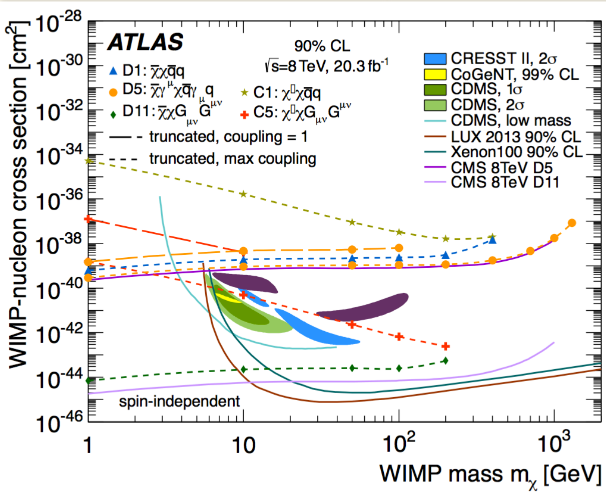
Contribution to g-2 from dark photon

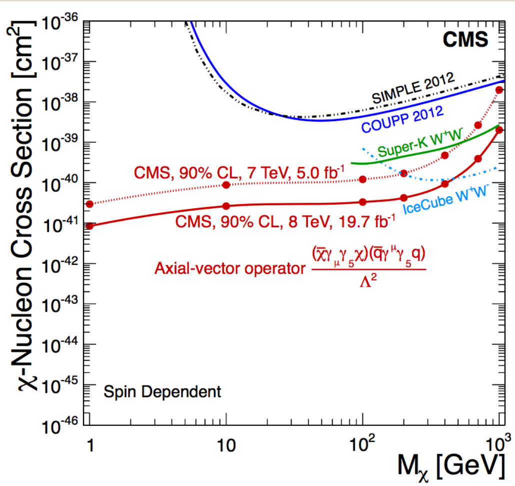
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

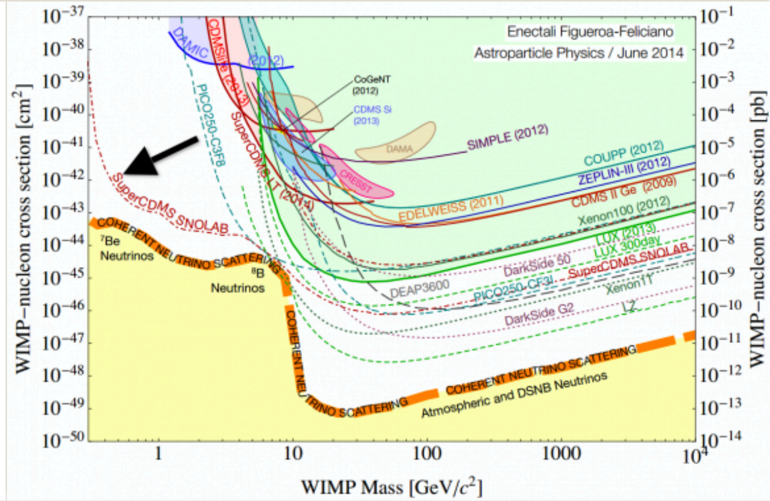
where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1\text{–}2 \cdot 10^{-3}$ and $m_V \sim 10\text{–}100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

Dark matter where to search

- Without introducing a new force in SM: $U(1)_Y + SU(2)_{Weak} + SU(3)_{Strong}$
  - Dark matter can't be strong interacting (scattering cross section too high)
  - Cannot be electrically charge it would not be dark!
  - It can be weakly interacting and massive!
- The WIMP has all the characteristics needed to solve the dark matter problem…
- But more than 20 years of unsuccessful attempt to detect WIMPs
  - Strong constraints from the LHC and direct searches at masses up to 1TeV







What about introducing a new dark force?