Photon probes of the Low Energy Frontier

... easy experiments have already been done ...

Giovanni Cantatore
Università and INFN - Trieste

Summary

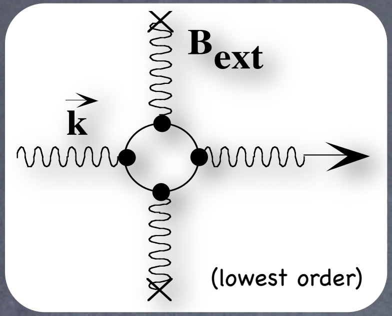
- Physics themes at the Low Energy Frontier
- Photon probes (brief intro to photon-photon colliders...)
- History and state of the art
- Not-so-crazy ideas for the future

Physics themes

- Which physics problems can one attack?
  - QED effects at low energies
  - ALPs, MCPs ... WISPs in general
  - ...
- Basic experimental technique
  - Send a beam of photons on a "photon target"
    - measure small (1 part in 10^{10} or better) changes in the polarization state of the scattered photons
    - measure excess scattered photon intensity over dark background

QED effects

- Non linearities in the Maxwell equations predicted by the Heisenberg-Euler effective Lagrangian (1936). Photon-photon scattering in QED (also Schwinger, 1951, Adler, 1971)

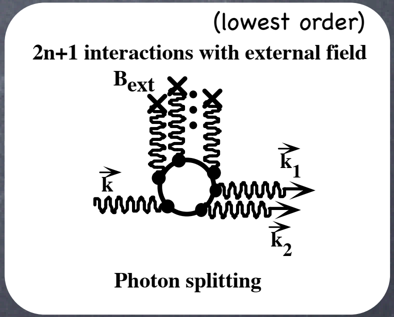


$$\psi = \left(\frac{\pi L}{\lambda}\right)\Delta n = \left(\frac{\pi L}{\lambda}\right)(n_{\parallel} - n_{\perp}) = \frac{3\alpha^2 B L \omega}{45 m_e^4}$$

  - Polarization selective phase delay. "Detectable" as an ellipticity on a linearly polarized laser beam propagating in vacuum in an external magnetic field

- Photon splitting (Adler 1971)

$$\alpha = \left(\frac{\pi L}{\lambda}\right)\Delta\kappa = \left(\frac{\pi L}{\lambda}\right)(\kappa_{\parallel} - \kappa_{\perp}) = \left(\frac{L}{2}\right)(0.27)\left(\frac{\omega}{m_e}\right)^5\left(\frac{B}{B_{cr}}\right)^6 \text{ cm}^{-1}$$



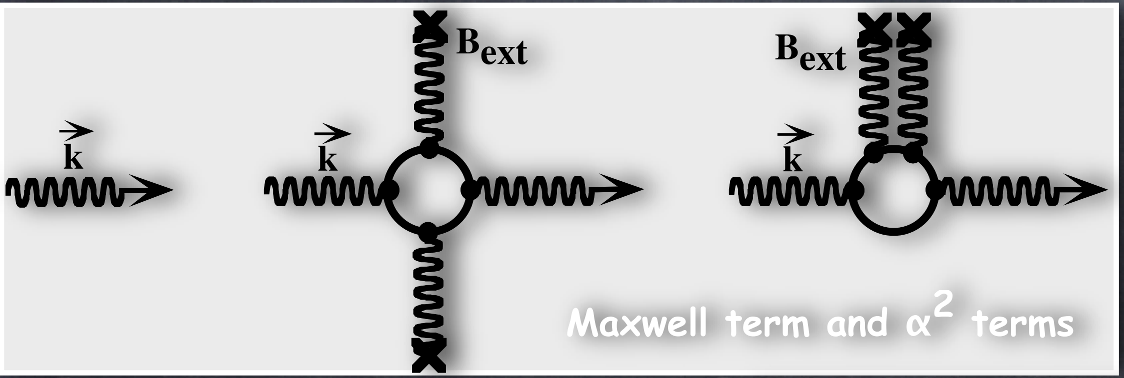
  - Polarization selective absorption. "Detectable" as an apparent rotation of the polarization plane (dichroism) when using a resonant cavity

Photon-photon scattering in QED

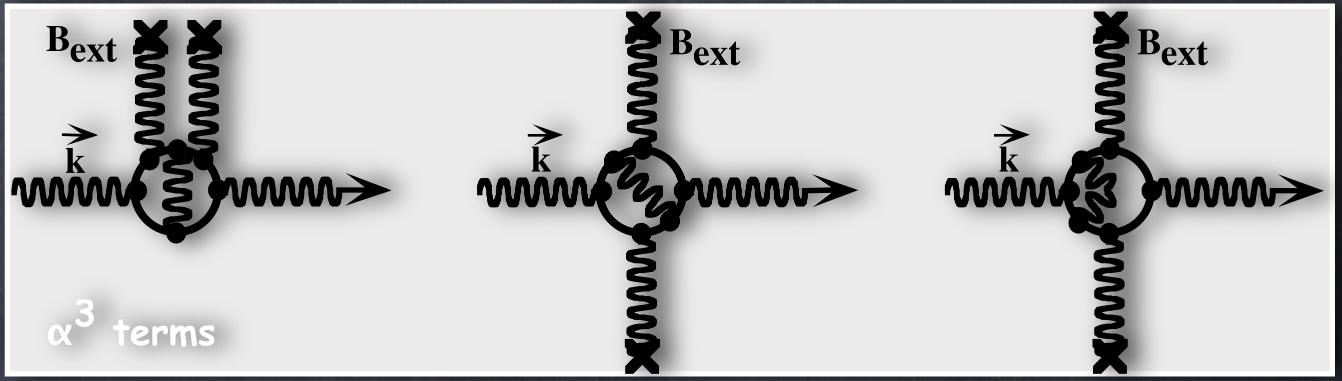
- Photon-photon scattering can be described in QED by the Heisenberg-Euler effective lagrangian (Adler, Ann. Phys. vol. 67, p. 599, 1971)
  - in gaussian units

$$L = L_{em} + L_{HE} = \frac{1}{8\pi}\left(\vec{E}^2 - \vec{B}^2\right) + \frac{2\alpha^2}{720\pi^2}\frac{\left(\hbar/m_e c\right)^3}{m_e c^2}\left[\left(\vec{E}^2 - \vec{B}^2\right)^2 + 7\left(\vec{E}\cdot\vec{B}\right)^2\right] + \mathrm{o}\left(\alpha^2\right)$$

  - α is the fine structure constant, fields are subcritical and slowly varying



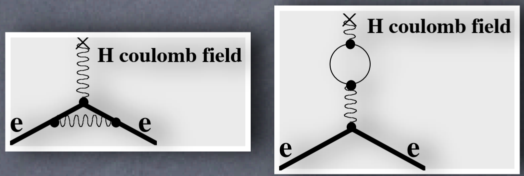
Corresponding Feynman diagrams



Experiments on microscopic QED interactions

- **Lamb-shift in hydrogen**

Vacuum polarisation

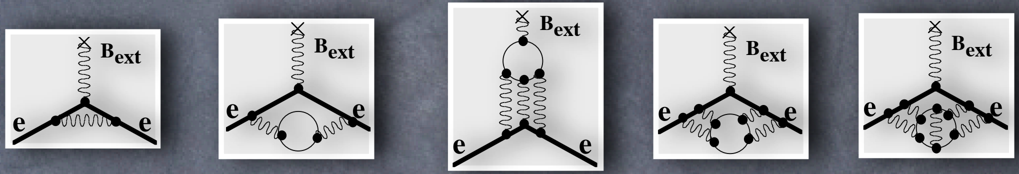


correction of order α α ~ 2 % of the measured effect

- **(g-2)**

Vacuum polarisation

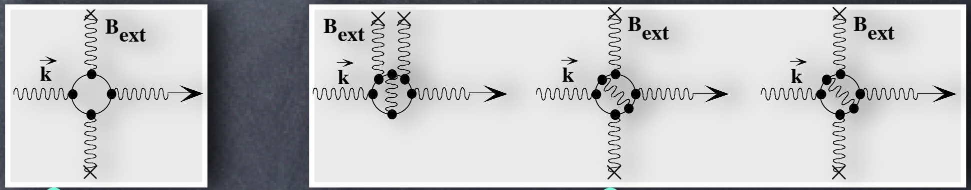
Photon-Photon scattering



correction of order α α^2 α^3 α^4 α^5

~5 % of the measured effect

Photon-Photon scattering



- **Photon-photon** correction of order α^2 entire measured effect α^3 ~ 1 % of the measured effect

A practical case...

- Target: pneumatic vacuum is perturbed by a uniform magnetic field
- Incoming photon beam is a linearly polarized light beam

Insert in the H-E lagrangian:

$$\vec{E} = \vec{E}_{wave} \quad ; \quad \vec{B} = \vec{B}_{ext} + \vec{B}_{wave}$$
$$\left|\vec{B}_{ext}\right| >> \left|\vec{B}_{wave}\right|$$

Two cases follow

$\vec{E}_{wave} \parallel \vec{B}_{ext}$

$$\varepsilon_{\parallel} = 1 + 10AB_{ext}^2 \quad ; \quad \mu_{\parallel} = 1 + 4AB_{ext}^2$$
$$\Rightarrow \quad n_{\parallel} = \sqrt{\varepsilon_{\parallel}\mu_{\parallel}} \approx 1 + 7AB_{ext}^2$$

$\vec{E}_{wave} \perp \vec{B}_{ext}$

$$\varepsilon_{\perp} = 1 - 4AB_{ext}^2 \quad ; \quad \mu_{\perp} = 1 + 12AB_{ext}^2$$
$$\Rightarrow \quad n_{\perp} = \sqrt{\varepsilon_{\perp}\mu_{\perp}} \approx 1 + 4AB_{ext}^2$$

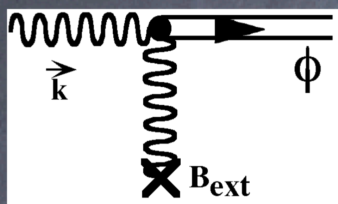
An anisotropy results leading to a difference in refractive indices (known in optics as **birefringence**)

$$\Delta n_{QED} = n_{\parallel} - n_{\perp} = 3AB_{ext}^2 \quad \left(\approx 4 \times 10^{-32} B_{ext}^2 [Gauss]\right)$$

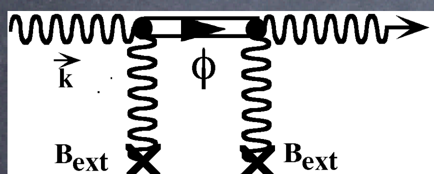
$$A = \frac{\alpha^2}{90\pi} \frac{(\hbar / m_e c)^3}{m_e c^2} \approx 1.32 \cdot 10^{-32} \quad cm^3/erg$$

ALPs, MCPs, ... (WISPs)

- ALPS from two photon effective vertex (Maiani, Petronzio and Zavattini 1986)

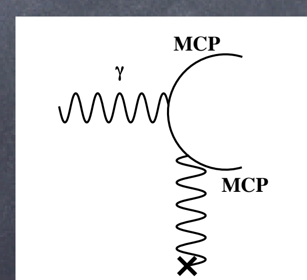


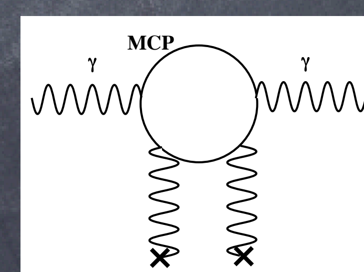
$$\alpha = \frac{B^2\omega^2}{M^2m^4}\left[\sin\left(\frac{m^2L}{2\omega}\right)\right]^2$$



$$\psi = \frac{B^2\omega^2}{2M^2m^4}\left[\left(\frac{m^2L}{2\omega}\right) - \sin\left(\frac{m^2L}{2\omega}\right)\right]$$

- MCPs -> see Ahlers et al., PRD 75, 035011 (2007) for discussion and formulas

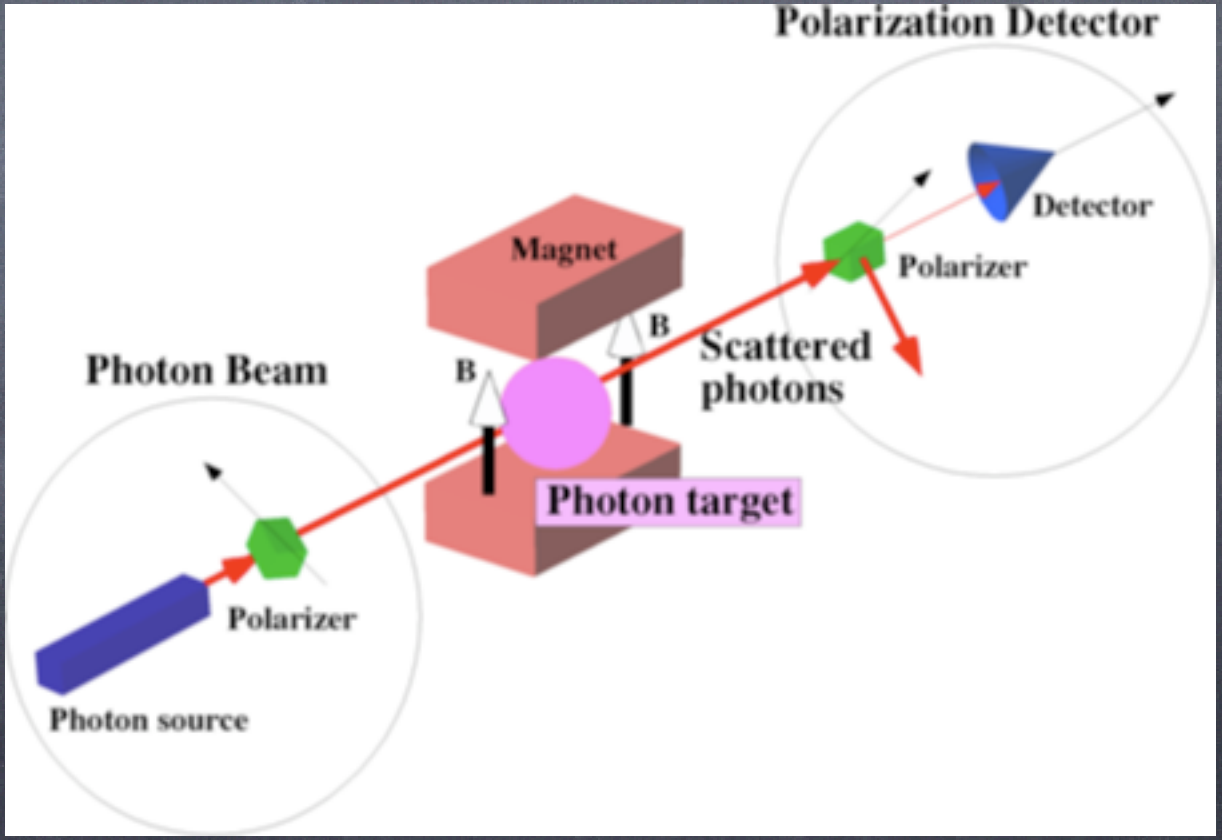




Photon Colliders

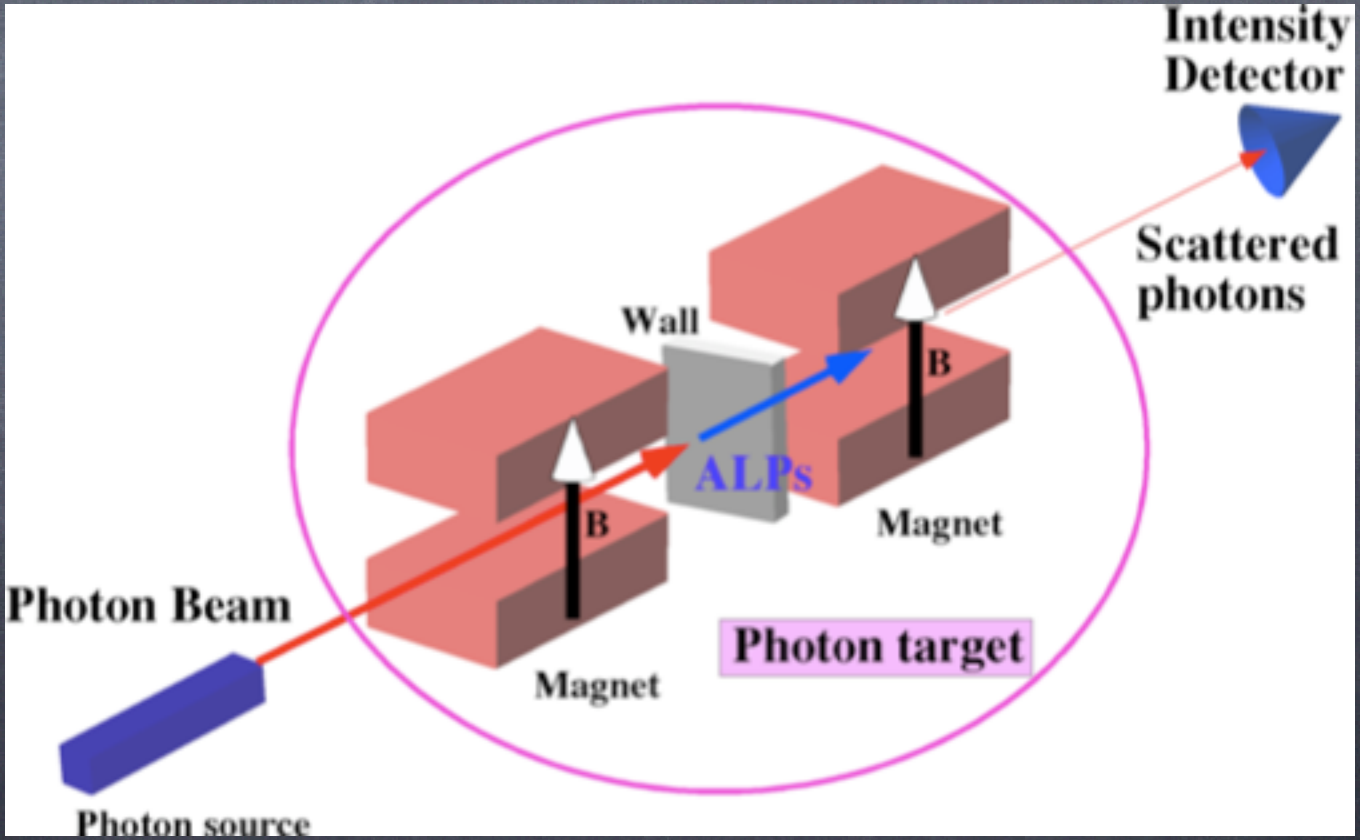
Photon Colliders

- Polarization measurements

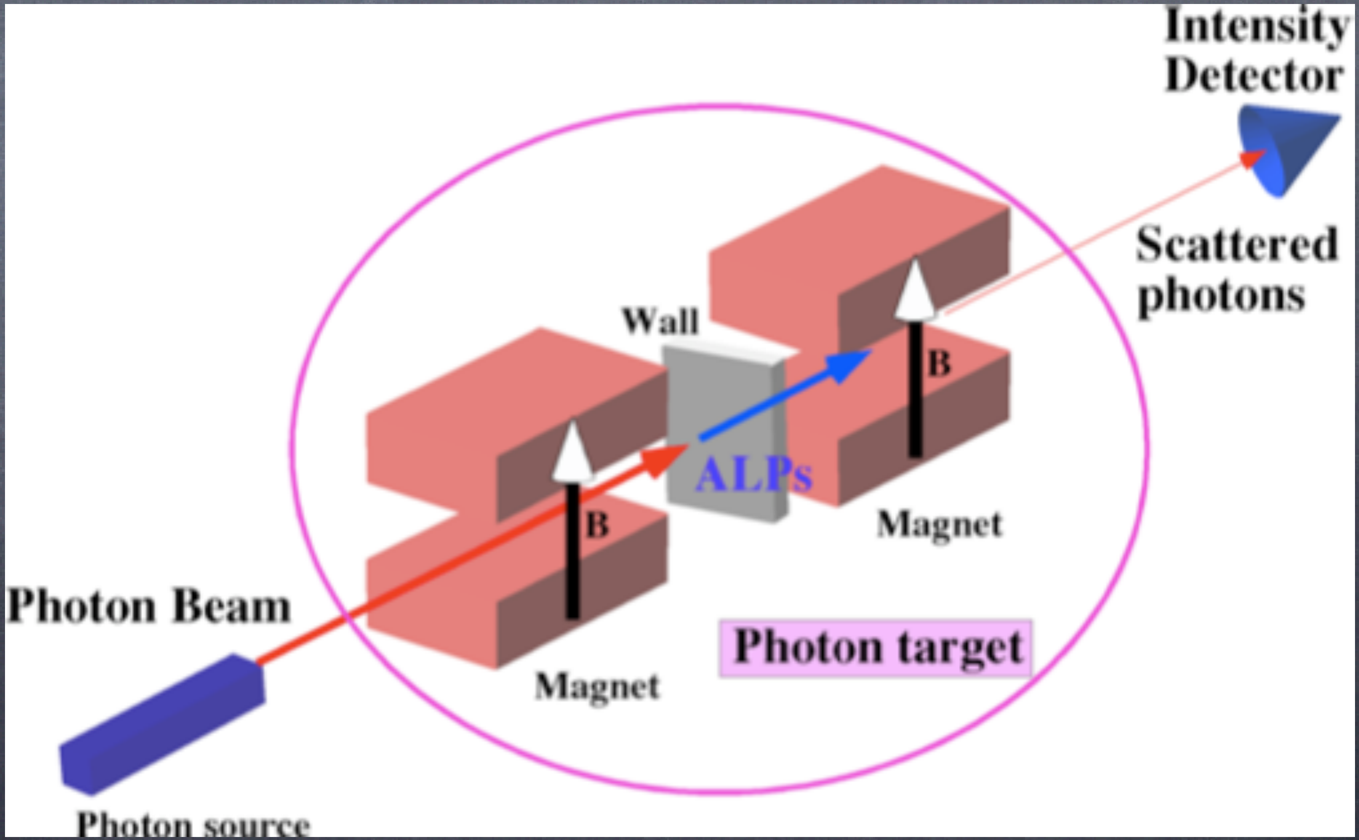


Photon Colliders

- Intensity measurements

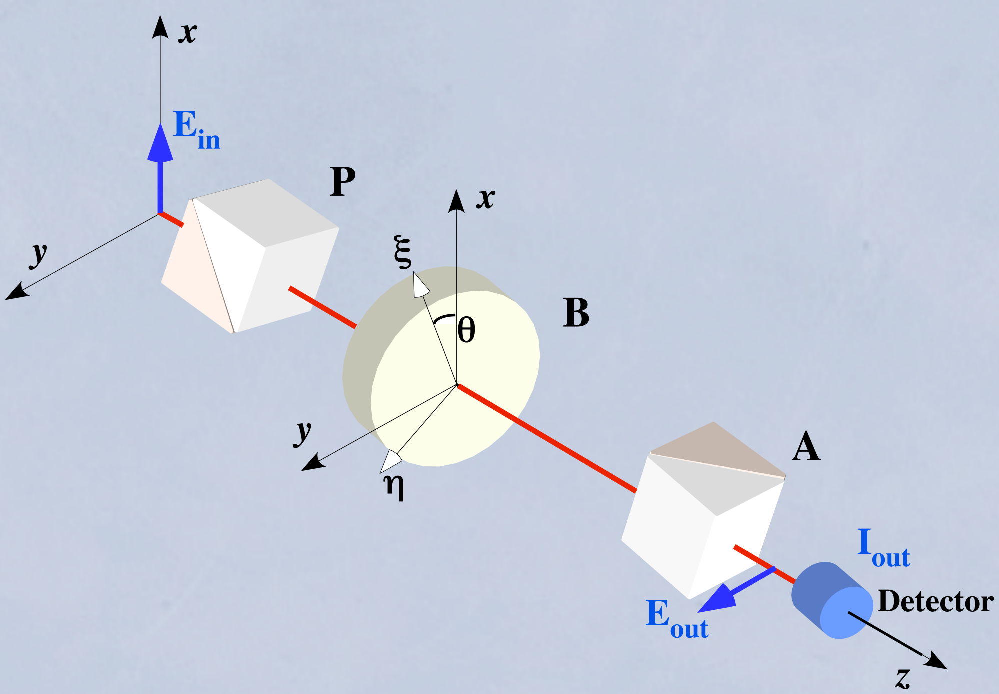


Photon Colliders



Basic principle of polarization measurements

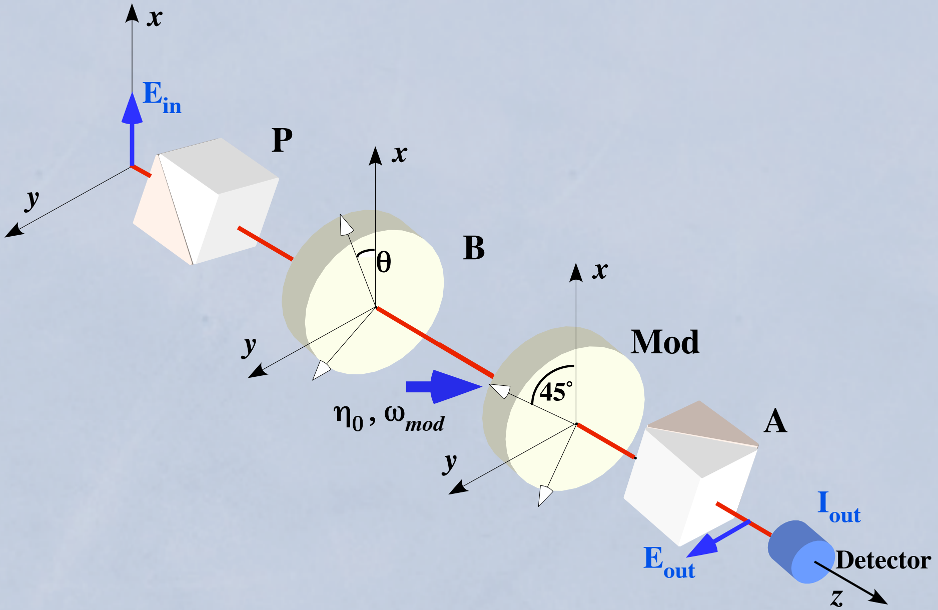
Basic principle of polarization measurements



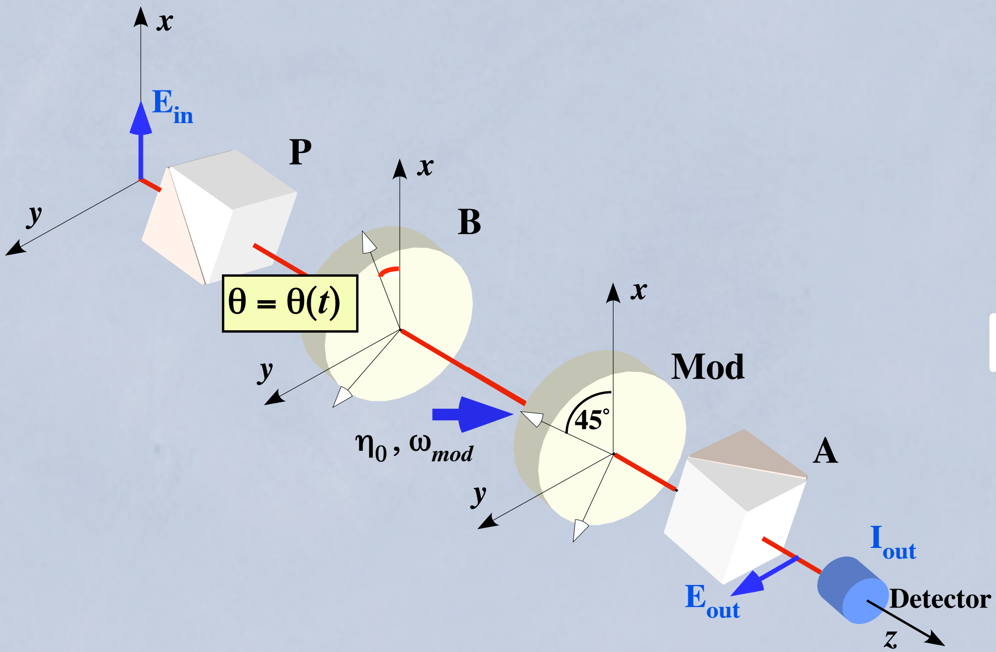
Static detection

Basic principle of polarization measurements

Homodyne detection

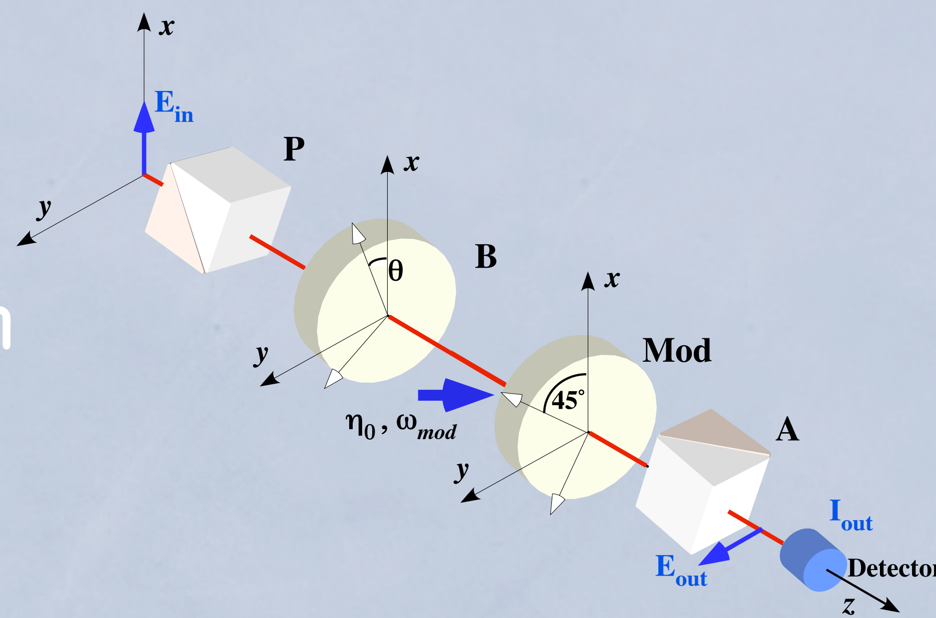


Basic principle of polarization measurements



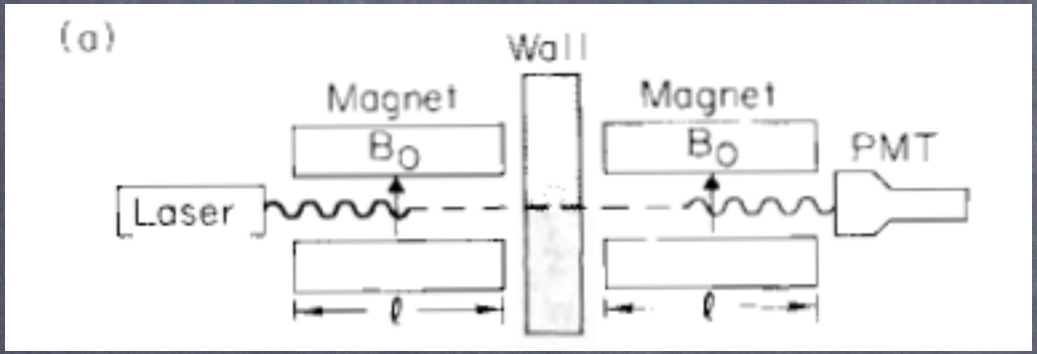
Heterodyne detection

Homodyne detection



Photon regeneration (intensity detection)

- The "experimentum crucis" to prove beyond reasonable doubt that one has seen ALPs is photon regeneration
- Originally proposed by Van Bibber et al., Phys. Rev. Lett. vol. 59, no. 7, (1987), p 759.



$$p_{0,reg} = \left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega} \right) \right]^4$$

in vacuum and with $m_a \ll \omega$

- It is poetically known as "shining light through a wall". A better descriptive title could be "ALP production and photon regeneration", since strictly speaking also CAST produces regenerated photon from solar axions

Polarization measurements

The Precursors

- Iacopini and Zavattini - 1979
  - location: CERN
  - main concern: QED vacuum polarization
- Brookhaven, Fermilab, Rochester, Trieste collaboration (BFRT) - 1988-1992
  - location: BNL - U.S.

The Precursors

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

- **Iacopini an**
  - location:
  - main concern: QED vacuum polarization
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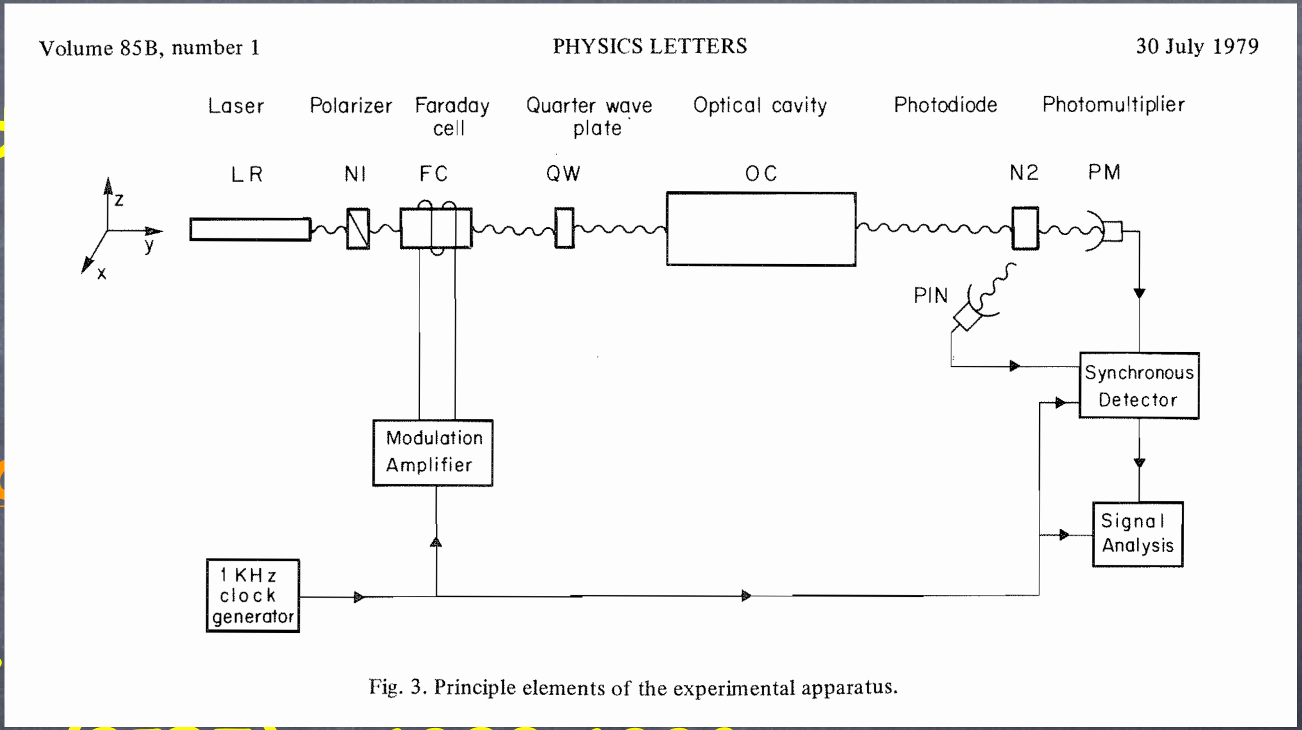

Fig. 3. Principle elements of the experimental apparatus.

- **Brookhaven, collaboration (BFRT) - 1988-1992**
  - location: BNL - U.S.

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The Precursors

- Iacopini and Zavattini - 1979

PHYSICAL REVIEW D VOLUME 47, NUMBER 9 1 MAY 1993

ARTICLES

Search for nearly massless, weakly coupled particles by optical techniques

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Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

H. J. Halama, D. M. Lazarus, and A. G. Prodell
Brookhaven National Laboratory, Upton, New York, 11973

F. Nezrick
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

C. Rizzo and E. Zavattini
Dipartimento di Fisica, University of Trieste and Istituto Nazionale di Fisica Nucleare Sezione di Trieste, 34127 Trieste, Italy
(Received 5 October 1992)

We have searched for light scalar and/or pseudoscalar particles that couple to two photons by studying the propagation of a laser beam ($\lambda = 514$ nm) through a transverse magnetic field. A limit of 3.5×10^{-10} rad was set on a possible optical rotation of the beam polarization for an effective path length of 2.2 km in a 3.25 T magnetic field. We find that the coupling $g_{a\gamma\gamma} < 3.6 \times 10^{-7}$ GeV^{-1} at the 95% confidence level, provided $m_a < 10^{-3}$ eV. Similar limits can be set from the absence of ellipticity in the transmitted beam. We also searched for photon regeneration in a magnetic field and found the limit $g_{a\gamma\gamma} < 6.7 \times 10^{-7}$ GeV^{-1} for the same range of particle mass.

PACS number(s): 14.80.Gt, 12.20.Fv, 14.80.Am

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The Precursors

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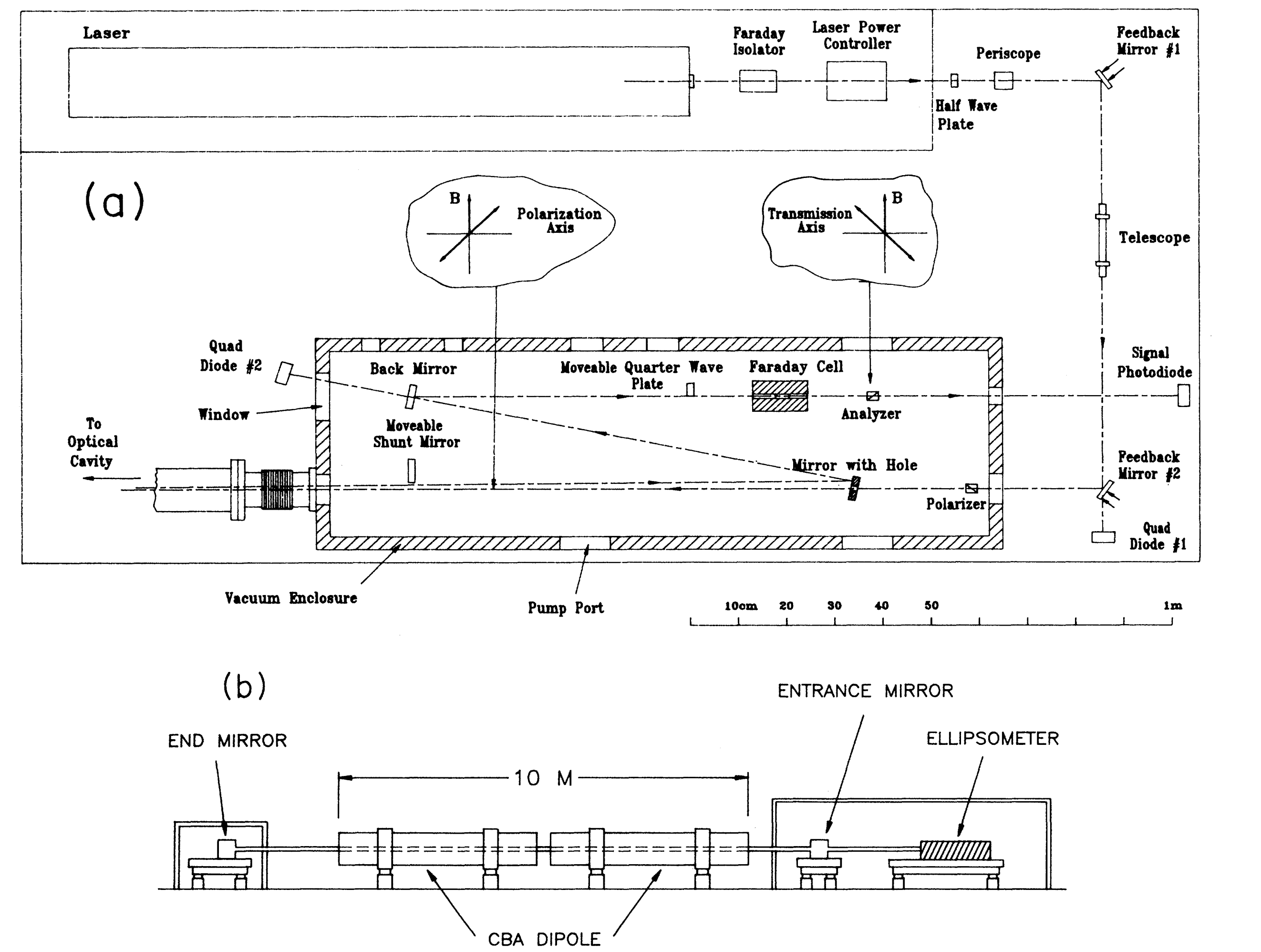

FIG. 4. (a) Schematic view of the ellipsometer; the volume inside the hatched area is evacuated. (b) Layout of the experiment and of the superconducting magnets.

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Panorama of polarization experiments

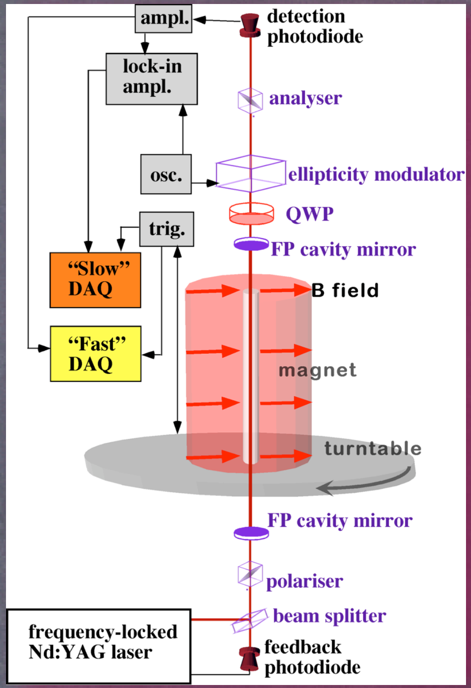
- Recently closed
  - PVLAS (INFN Italy)
- Current
  - BMV (Toulouse) -> nearly completed
  - OSQAR (CERN) -> development stage
  - Q&A (Taiwan)
- Starting-up
  - PVLAS Phase II (INFN Italy)

Common features

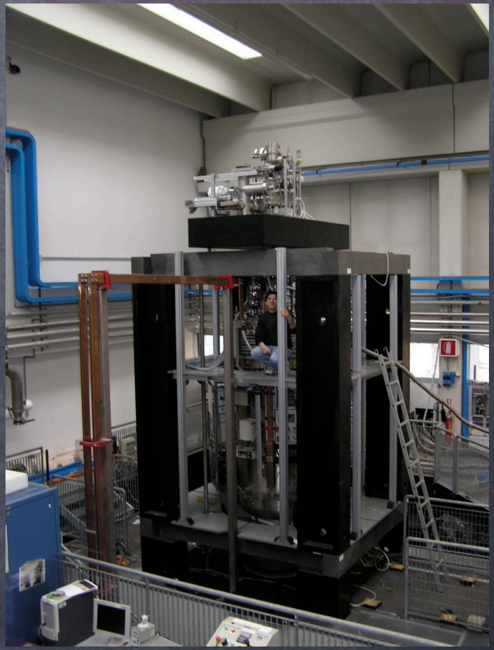
- Polarized laser beam probes a magnetic field region
  - low energy (1-2 eV)
  - low flux (1 W continuous at most ->$3\text{-}6 \cdot 10^{18}$ ph/s
- Time-varying effect
- Optical path amplification
- Main problem: noise background

PVLAS Phase I mission completed ...

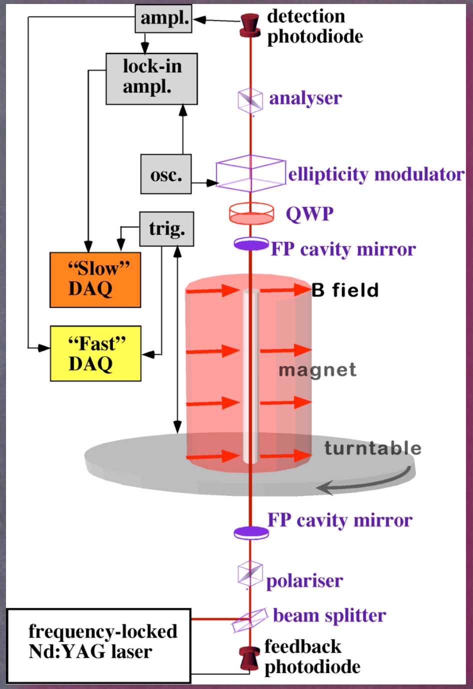
- INFN experiment at Legnaro labs (Trieste, Ferrara, LNL, LNF, Pisa)
  - Polarization measurements
  - Low energy (1-2 eV photons), relatively low intensity (a few mW -> ~10^{17} ph/s)
  - 5 T field, long optical path (Fabry-Pérot resonator), heterodyne detection)



- Optics (structure) built around large cryostat, not the the other way around
- Tower movements transfer directly to optical components (especially mirrors)
  - impossible to control unless structure is dismantled and rebuilt from scratch
  - beam movement on optical surfaces prime suspect for birefringence noise
  - measured movement induced birefringence on mirrors = 0.4 1/m -> $5 \cdot 10^{-7}$ 1/√Hz sensitivity in ellipticity means that relative movement between top and bottom optical benches must be be < $2 \cdot 10^{-7}$ m/√Hz
- Very hard to control overall thermal and acoustic noise
- No basic reason for having a large optical tower



PVLAS Phase I mission completed ...



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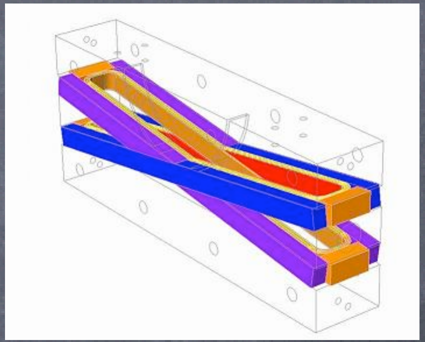
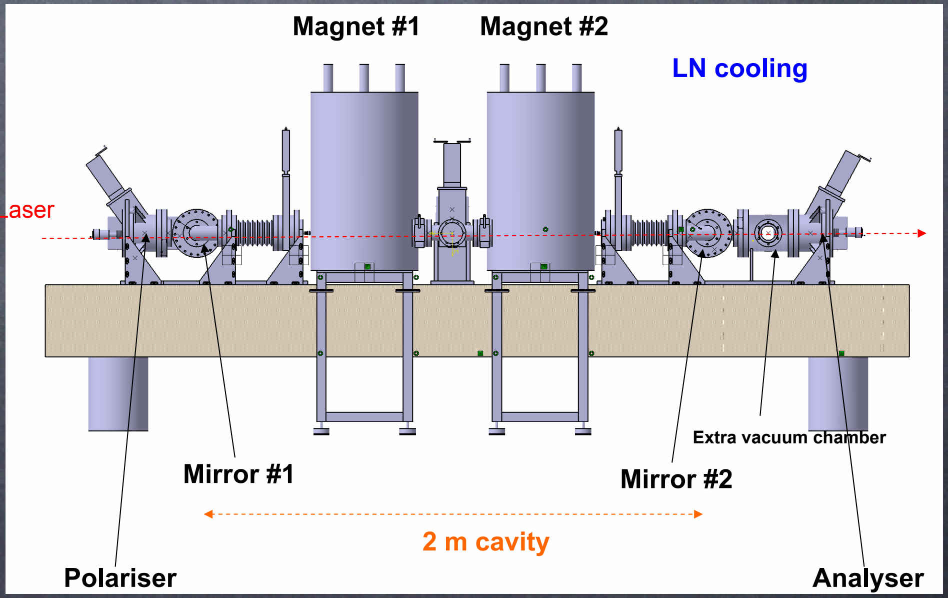
BMV

- BMV (Toulouse, C. Rizzo group leader)
  - 1 eV photons, few mW power, pulsed magnetic fields up to 12 T (ms duration), homodyne detection, Fabry-Perot resonator (R. Battesti et al., Eur. Phys. J. D 46, 323-333 (2008))
  - Status: first tests on gases and in vacuum in summer 2008 reporting

$$\Delta n_{\text{vide}} = (-9.8 \pm 22.9) \times 10^{-17} T^{-2}$$

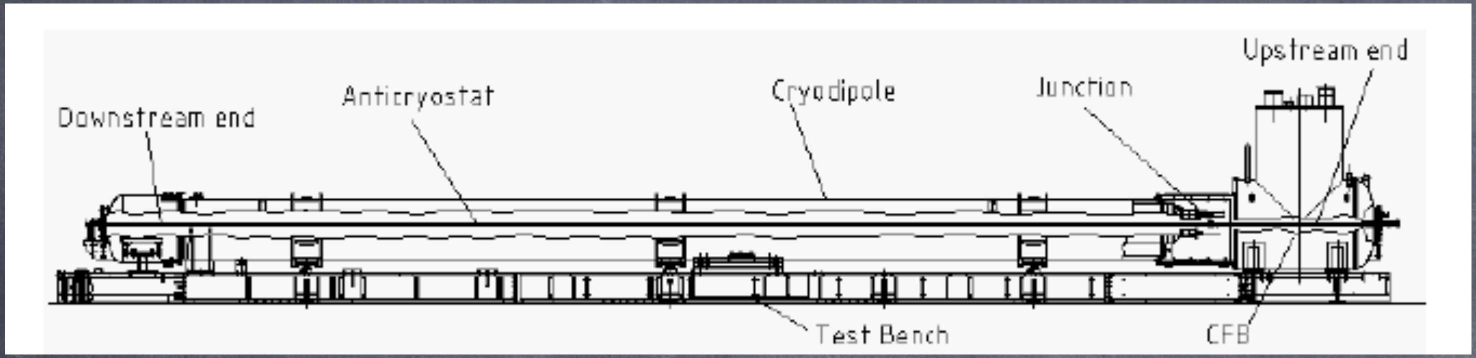
  - Goal is ~$4 \cdot 10^{-24}$ T^{-2}





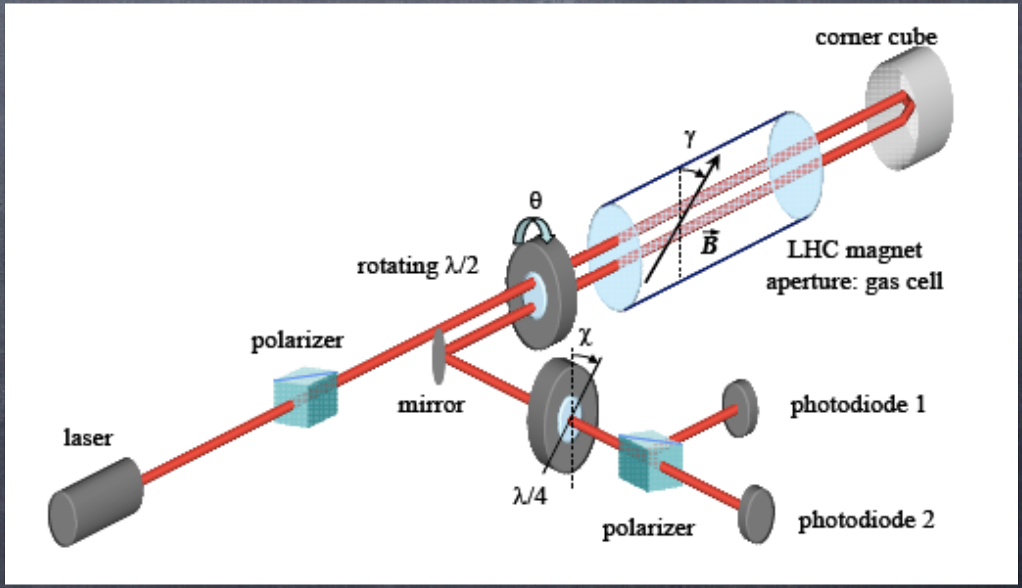
OSQAR

- OSQAR (CERN - A. Siemko group leader)
  - 2 LHC dipoles with rotating $\lambda/2$ plate
  - P. Pugnat et al. CERN-SPSC-2006-035



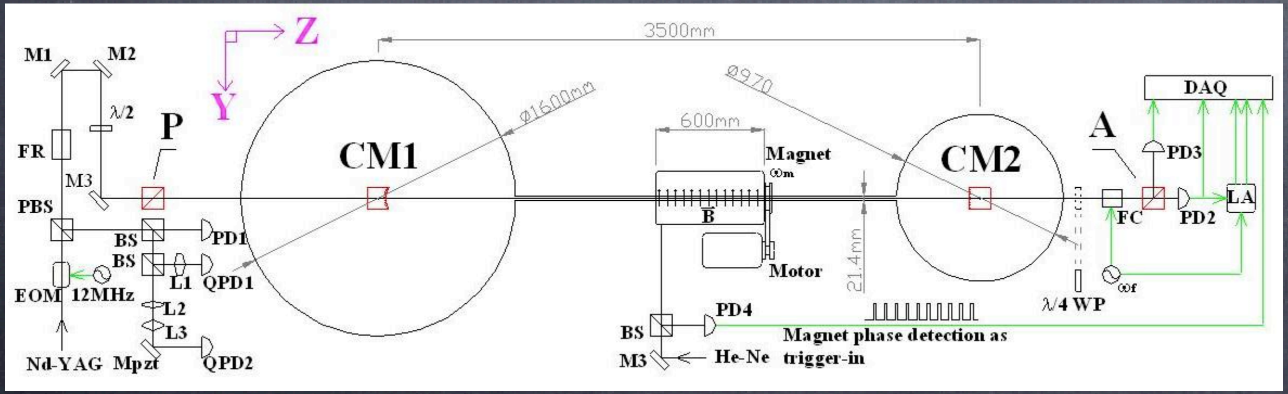
LHC dipoles

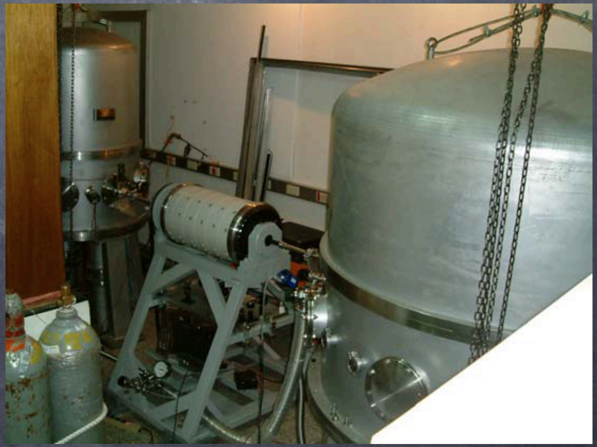
simplified optical setup



Q&A

- **Q&A (Taiwan, W.T. Ni group leader)**
  - 1 eV photons, few mW power, rotating 2.2 T permanent magnet, heterodyne detection, Fabry-Perot resonator
  - Status: gas magnetic birefringence tests in 2008 (arXiv: 0812.3328v2)





Intensity measurements: photon regeneration

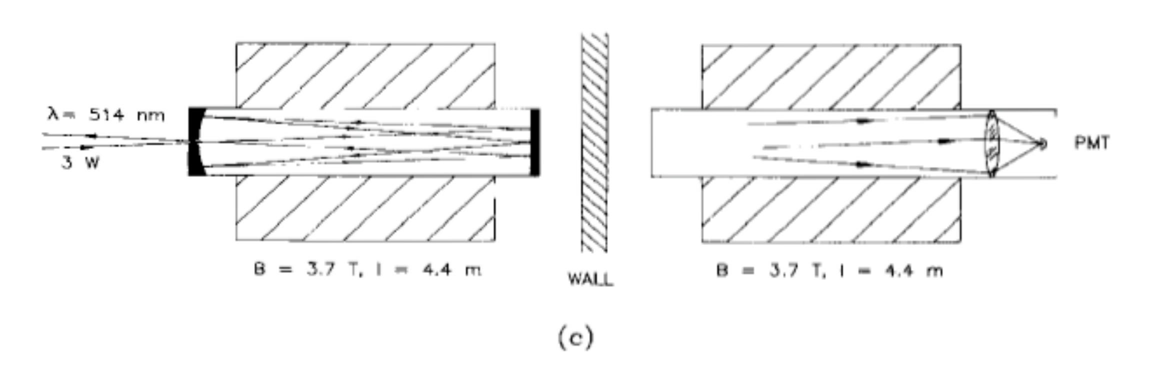
Photon regeneration through the ages...

I. The ancients...

an important improvement is already present: light path in the production region is amplified by means of a multipass cavity

$$p_{reg} = N p_{0,reg} = N \left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega} \right) \right]^4$$

N is the number of passes in the cavity



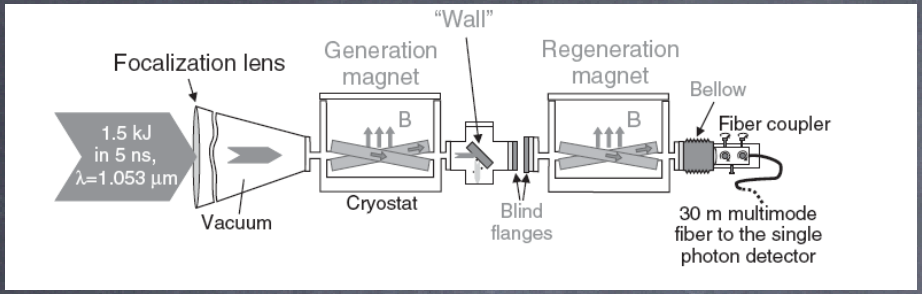
Ruoso et al., Zeitschrift für Physik C Particles and Fields (1992) vol. 56 (4) pp. 505-508

Cameron et al., Phys. Rev. D (1993) vol. 47 (9) pp. 3707-3725

Photon regeneration through the ages... (cont.)

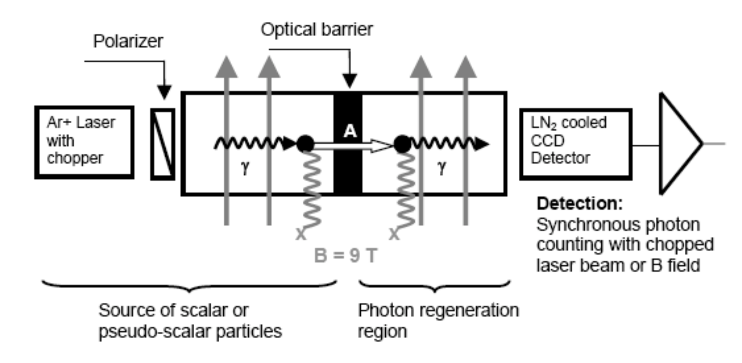
II.The contemporaries...

BMV@LULI



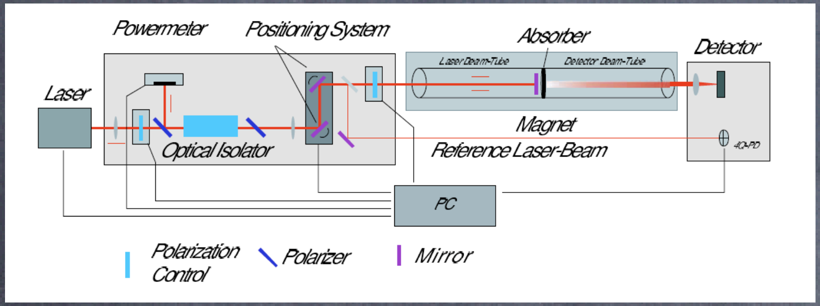
Robilliard et al, Phys. Rev. Lett. (2007) vol. 99 (19) pp. 4

OSQAR



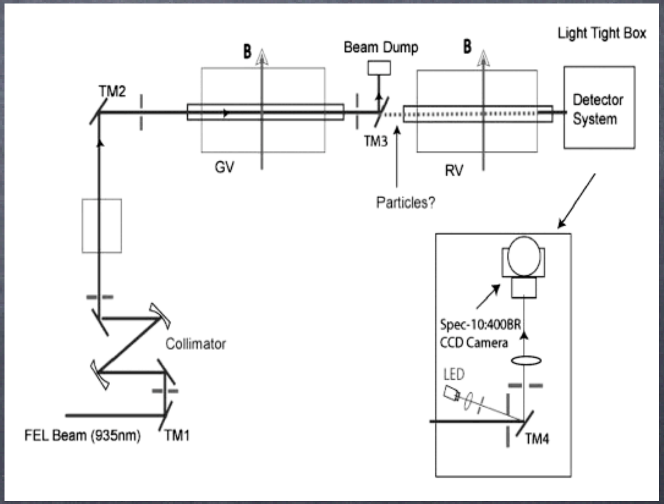
Pugnat et al., arXiv:0712.3362

ALPS



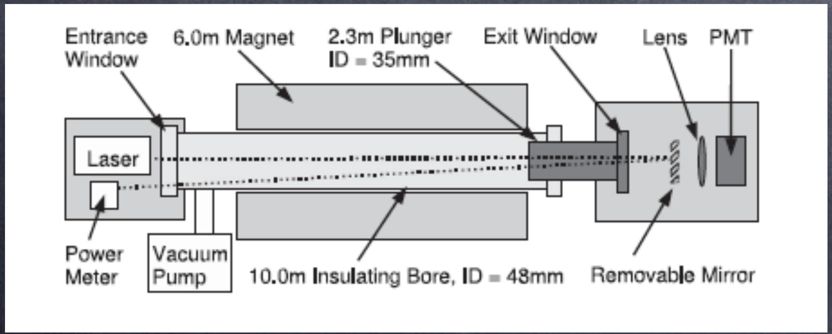
Ehret et al., arXiv (2007) vol. hep-ex

LIPSS



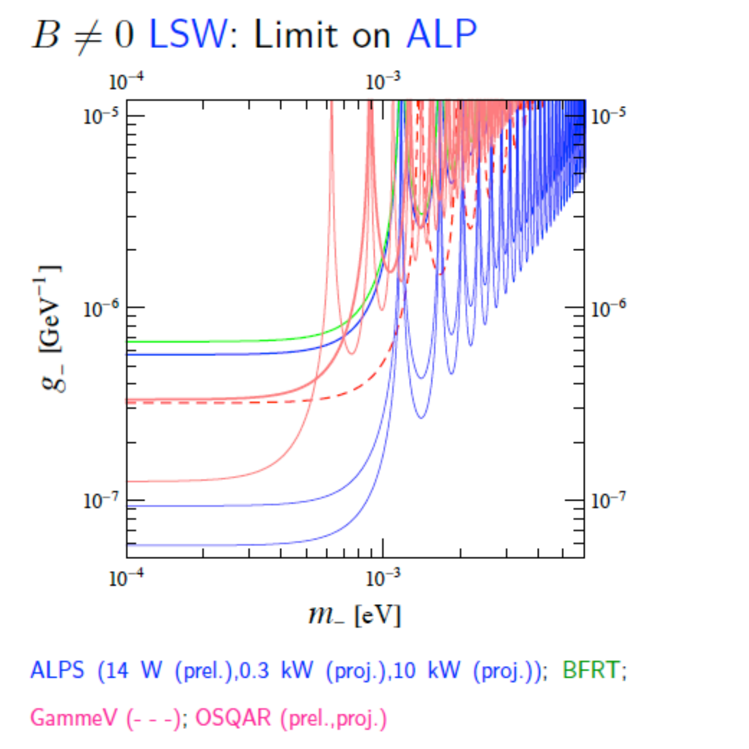
Afanasev et al., Phys. Rev. Lett. (2008) vol. 101 (12)

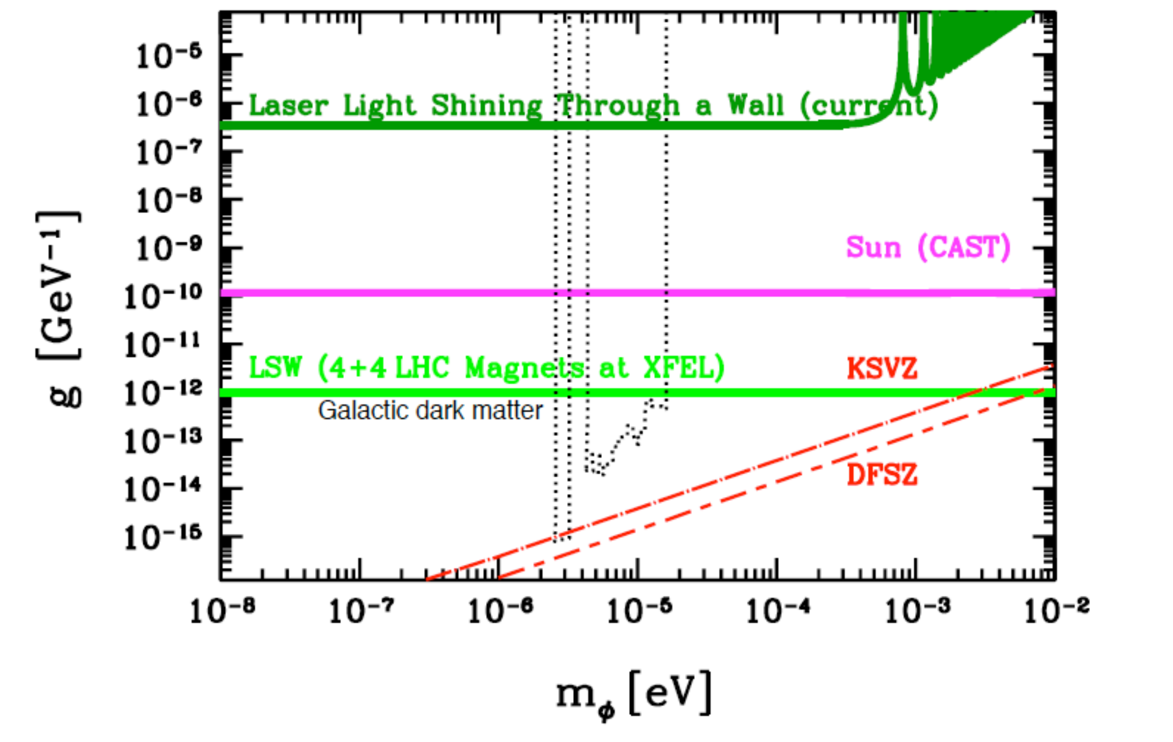
GammeV



Chou et al., Phys. Rev. Lett. (2009) vol. 102, 030402

Current reach of photon regeneration experiments





- Plots taken from A. Ringwald's talk "Search for New Physics at the Milliscale", Graz/A, November 2008

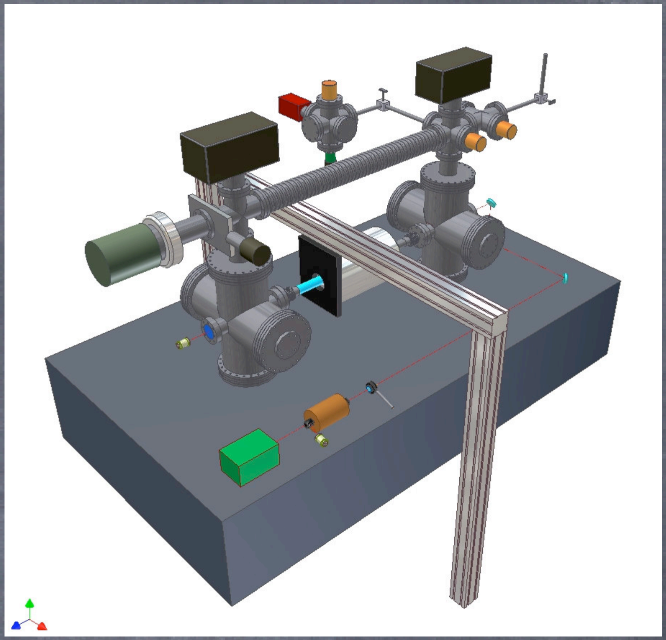
Polarization measurements with PVLAS Phase II

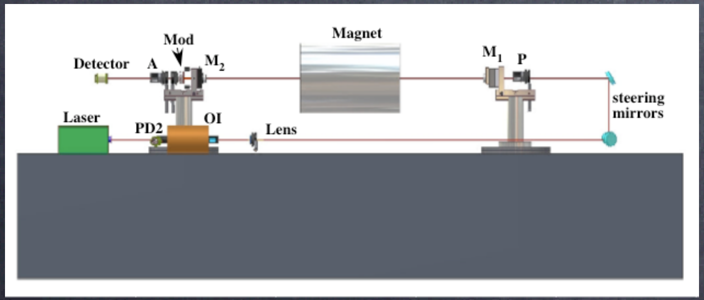
Moving on to Phase II

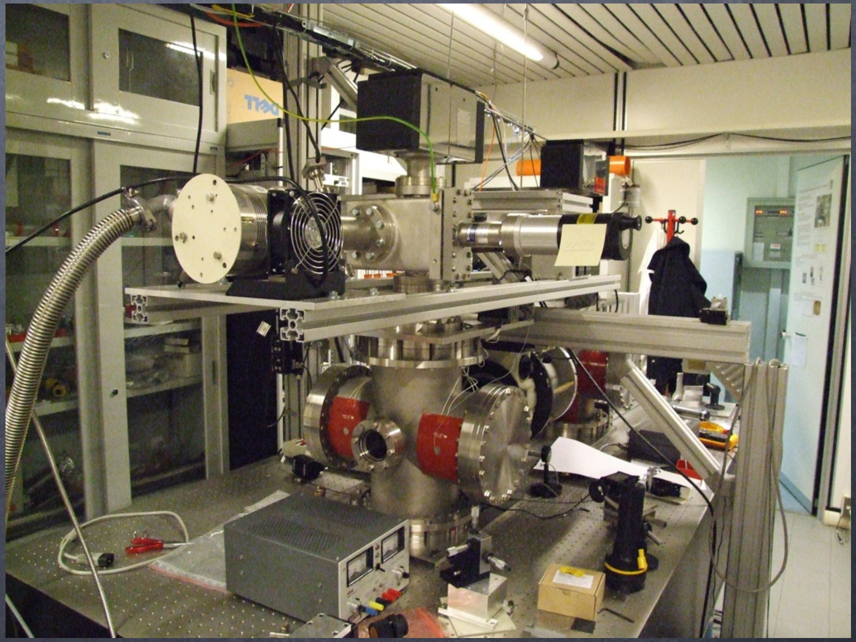
- The PVLAS signal is gone: challenge is now noise
- The PVLAS apparatus in Legnaro is limited by size, cost and duty cycle
- We plan a scaling down of the ellipsometer down to table top dimensions
  - Fabry-Perot finesse ~200000
  - better overall control
  - hope to reach at least 10^{-8} $1/\sqrt{Hz}$
  - use permanent magnets -> high duty cycle, no fringe fields
- QED (and other effects...) detectable in a reasonable time on table top if goal sensitivity is reached
- Future plans -> move up in energy to FEL-like photon source
- Not-so-future plans -> resonant regeneration!

Table-top setup

- Table-top ellipsometer
  - double λ Nd:YAG laser (1064 nm, 532 nm)
  - rotating permanent magnet, 2.3 T, 50 cm
  - Fabry-Perot with F = 220000







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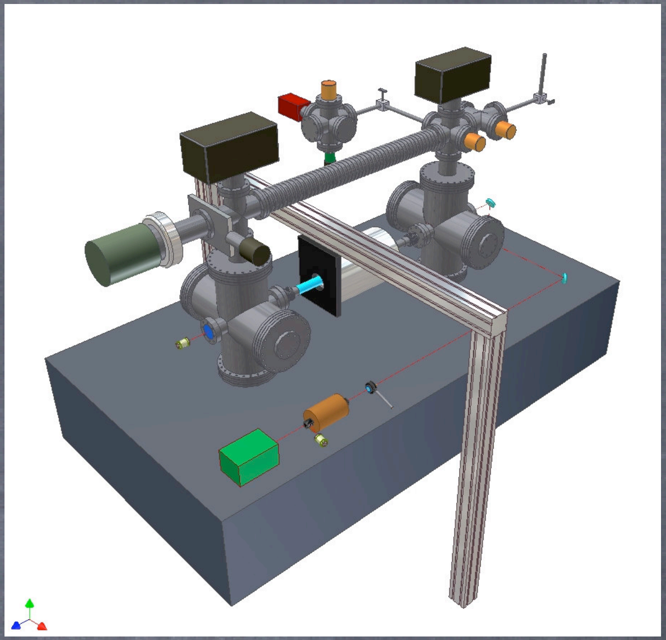

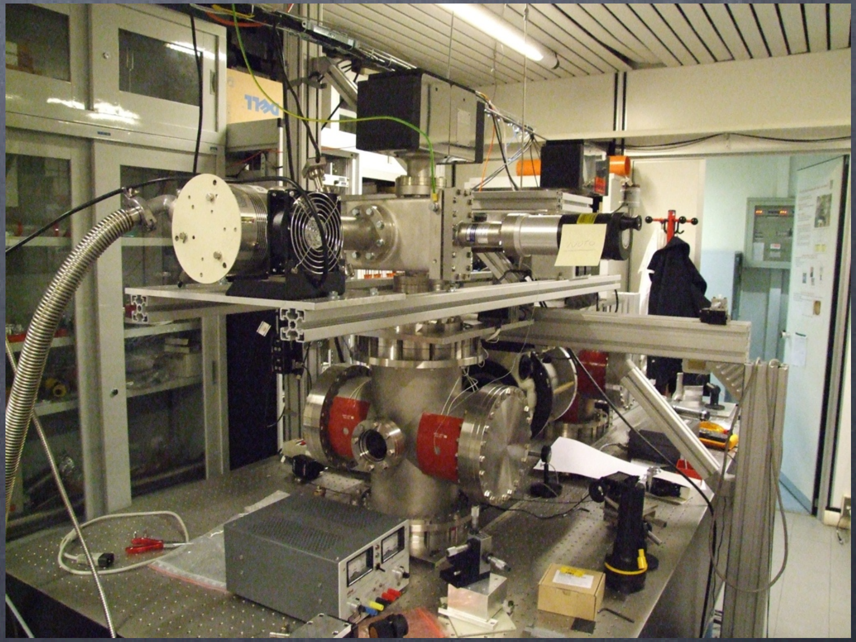

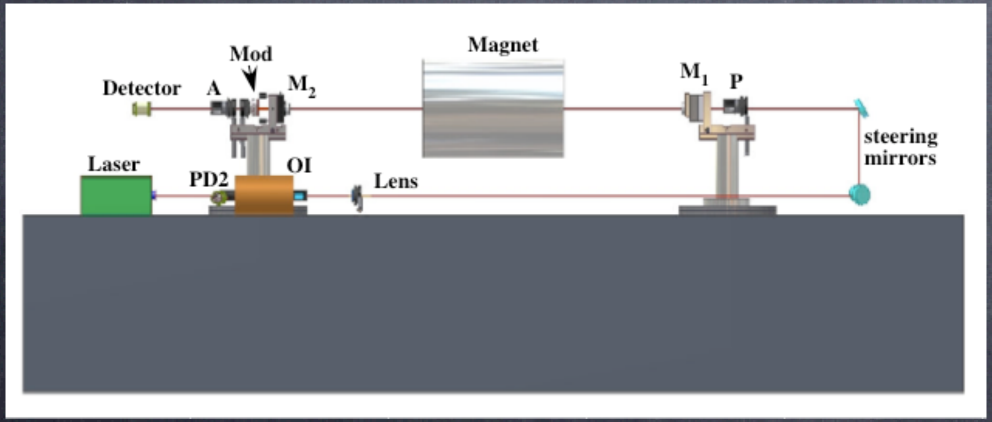

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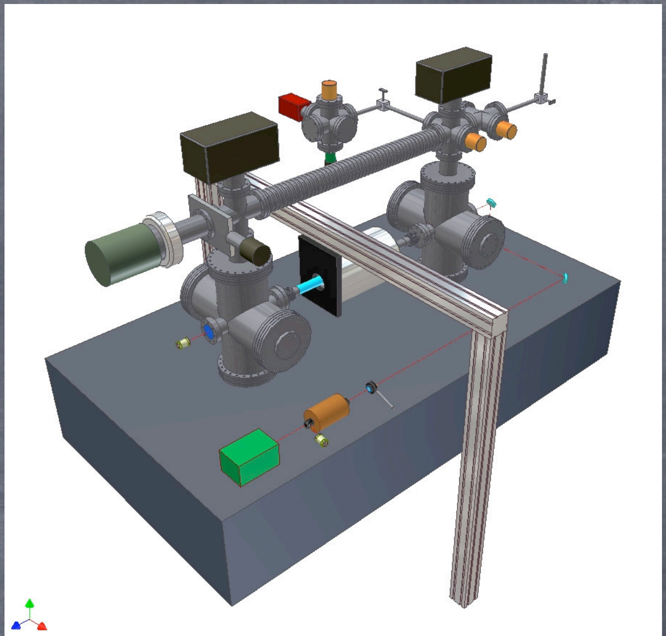
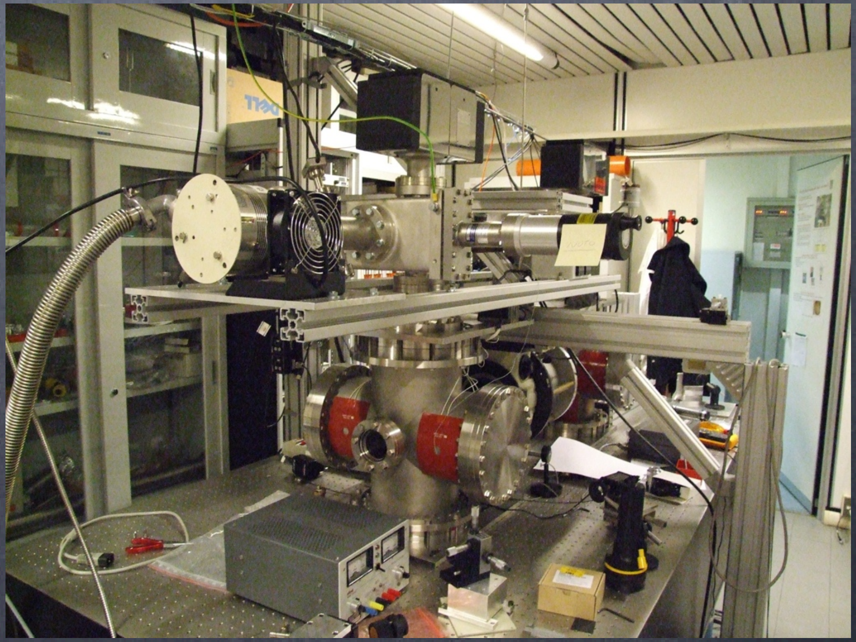
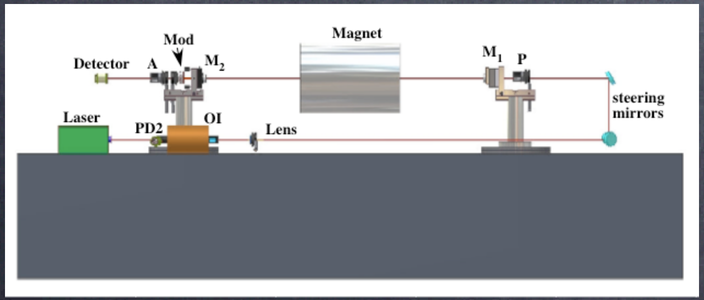
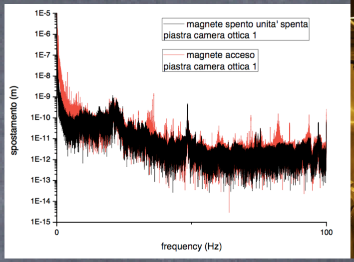


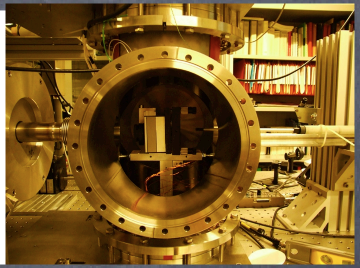


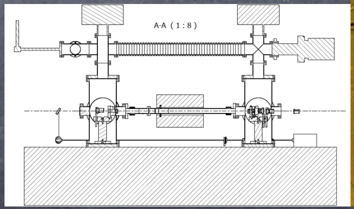


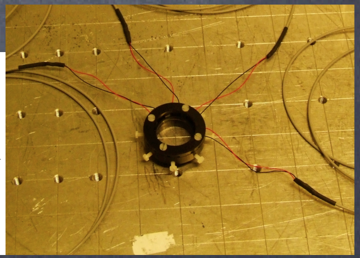
PVLAS Phase II solutions

- Compact apparatus down to table-top size, mount everything on a single table
- Carefully implement from the start all "passive" means of noise reduction
  - vibration isolation
  - environmental shields
  - optics mounts -> solid, vacuum compatible, remotely controllable
- Build optimized and well characterized vacuum system
- Reduce number of components with new modulation scheme (protype MIM modulator under test)
- Use rotating permanent magnet
- Integrated computer control of all instrument parameters









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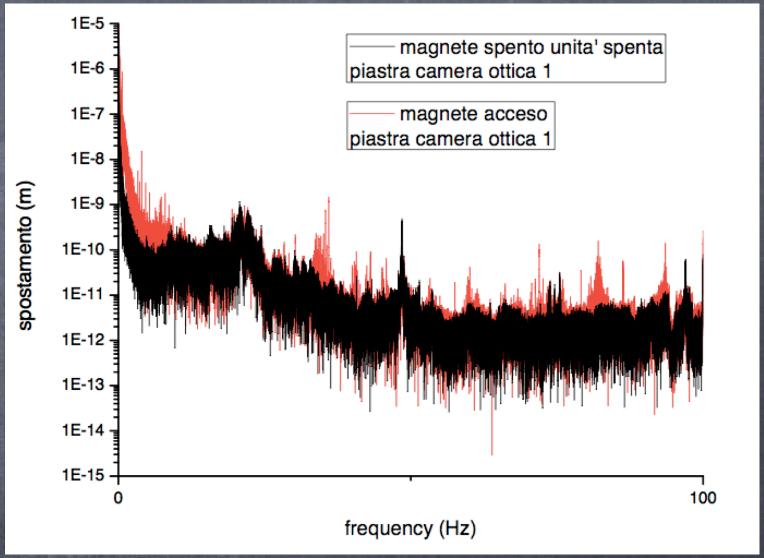

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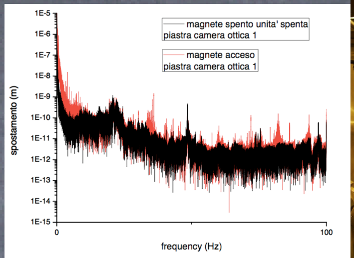

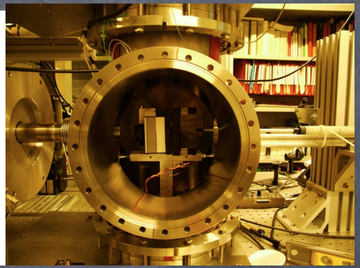

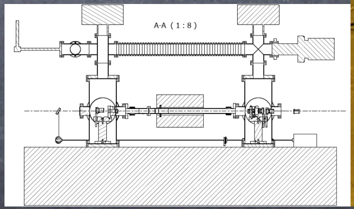

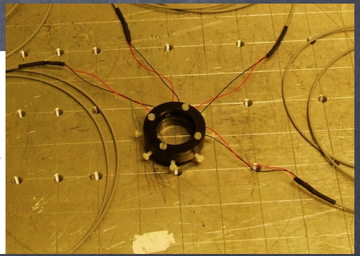

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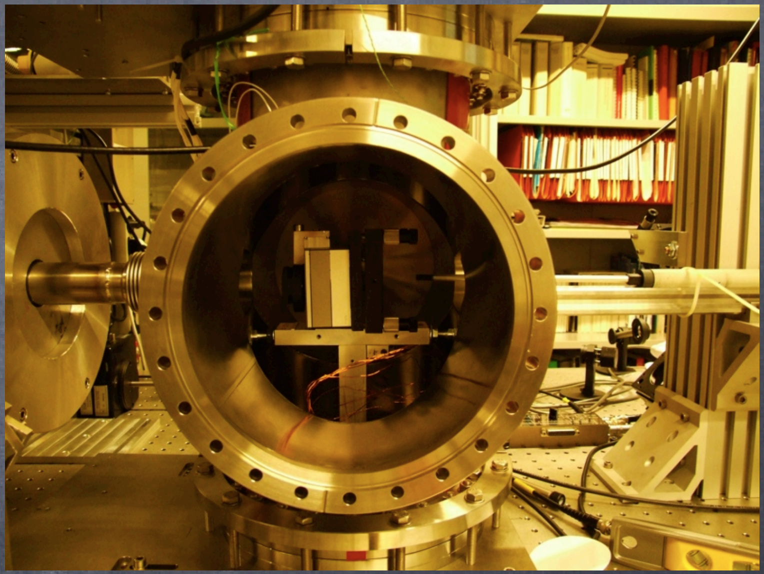

- Use rotating permanent magnet
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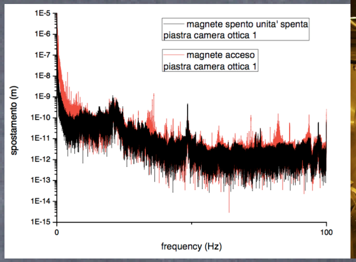

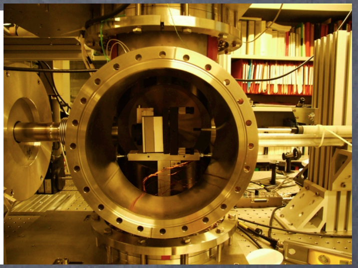

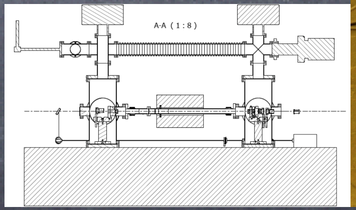

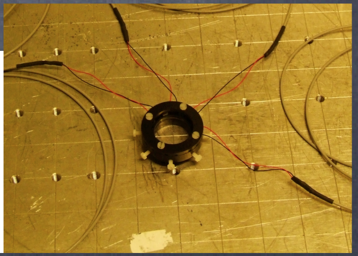

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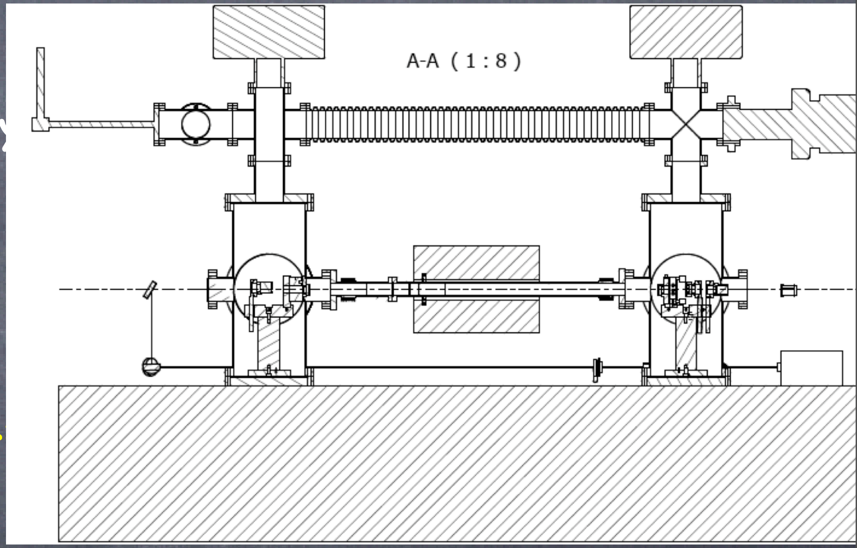

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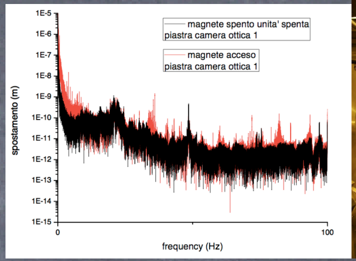

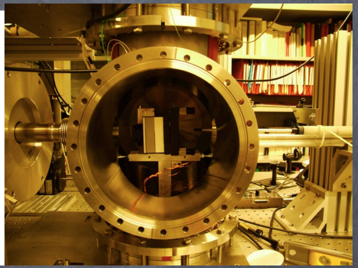

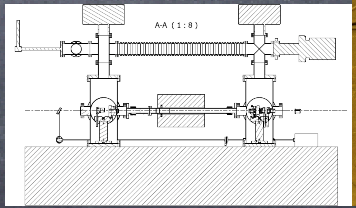

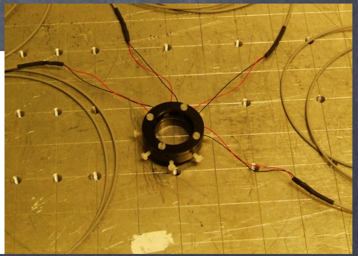

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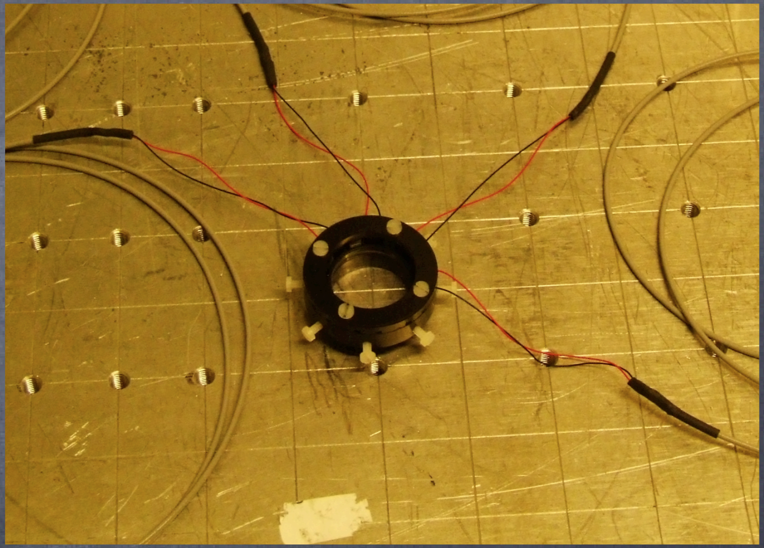

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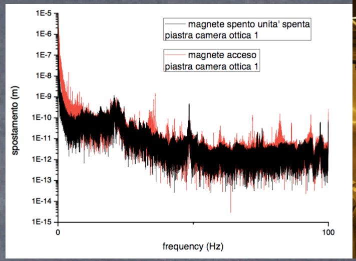
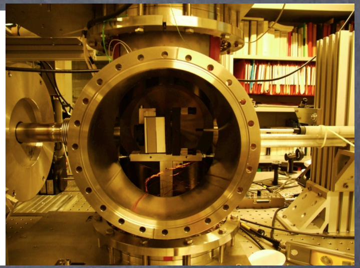
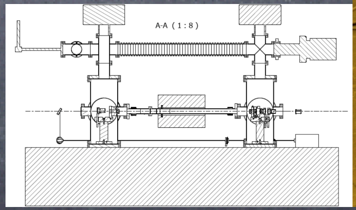
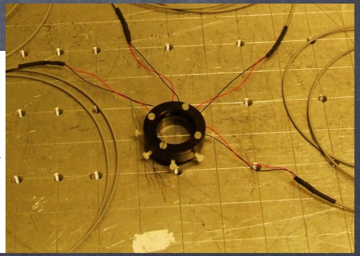




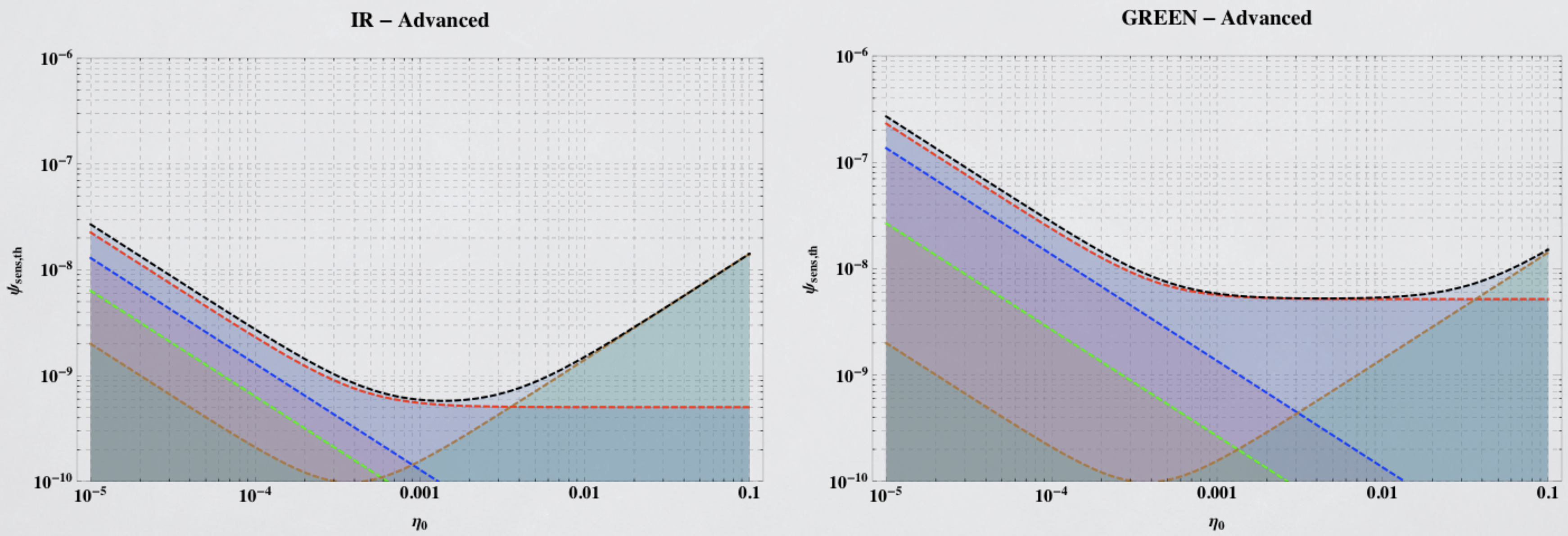




PVLAS Phase II ellipsometer development stages

- Prototype (already existing)
  - 900 mW at 1064 nm, 20 mW at 532 nm
  - Mirror Integrated Modulator
  - 1 m long Fabry-Perot with F≈220000
  - 2.3 T, 50 cm long, permanent dipole magnet
  - analog frequency locking, environmental screens
- Advanced
  - intensity stabilization to reduce laser Residual Intensity Noise
  - birefringence modulation directly on cavity mirrors
  - low noise electronics
  - digital frequency locking, improved acoustic isolation
- Advanced Power Upgrade
  - 600 mW at 532 nm
  - light injection and extraction via optical fiber

Some noise considerations



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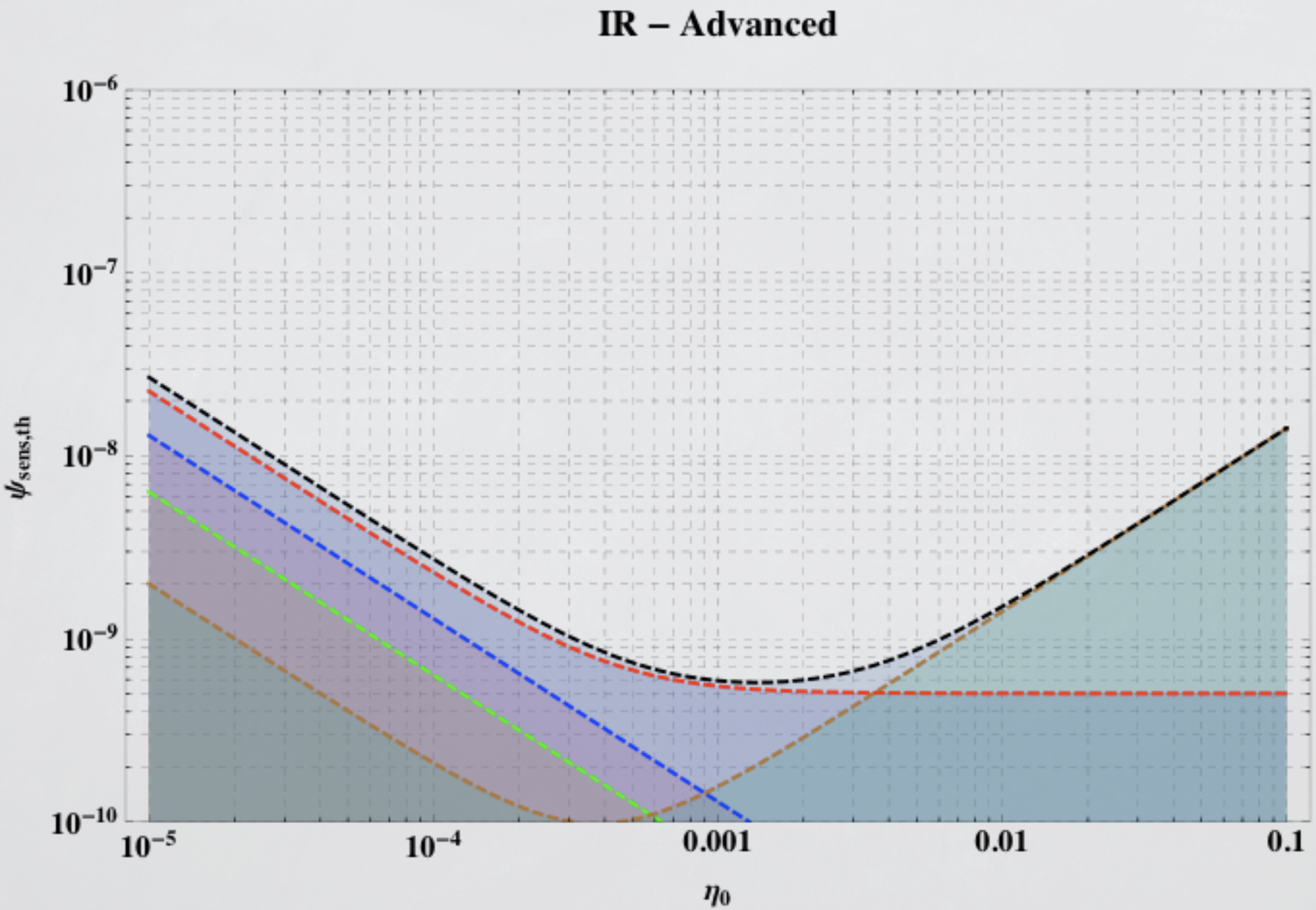

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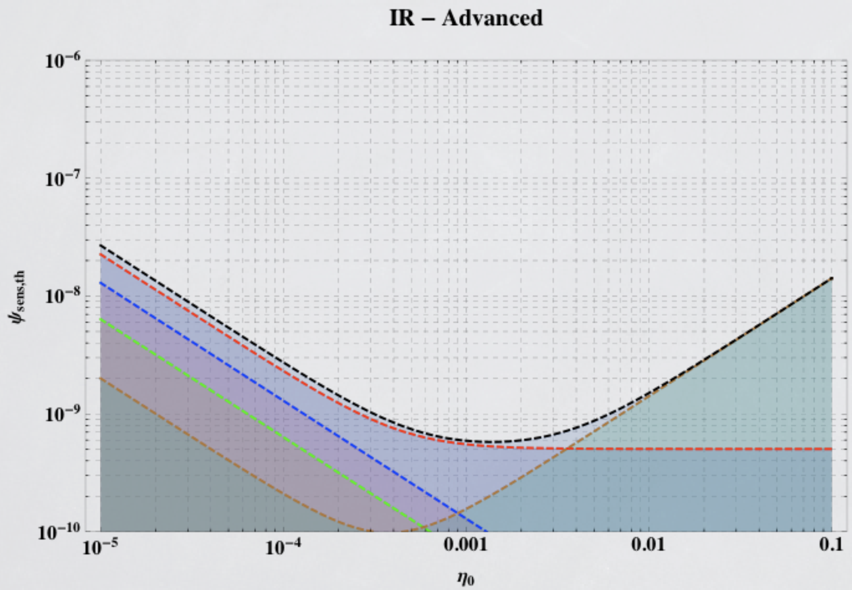

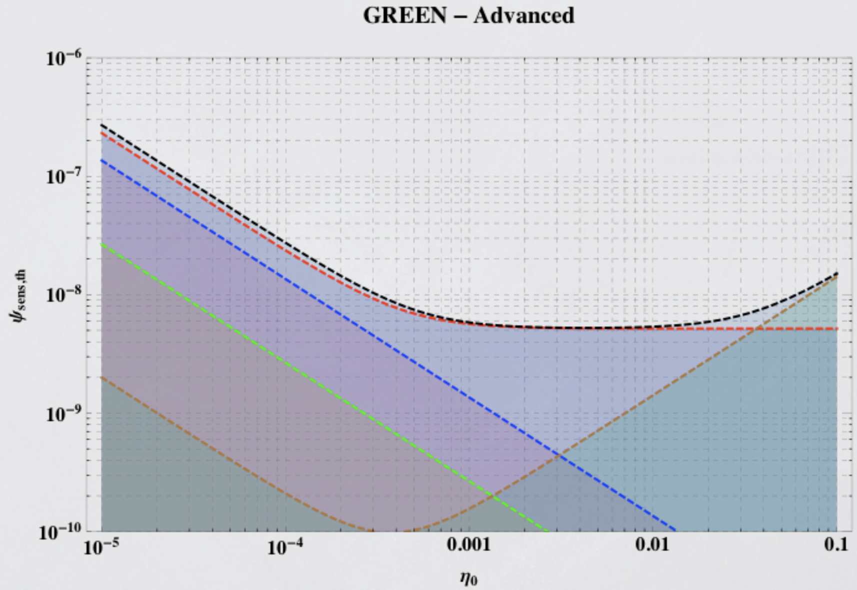

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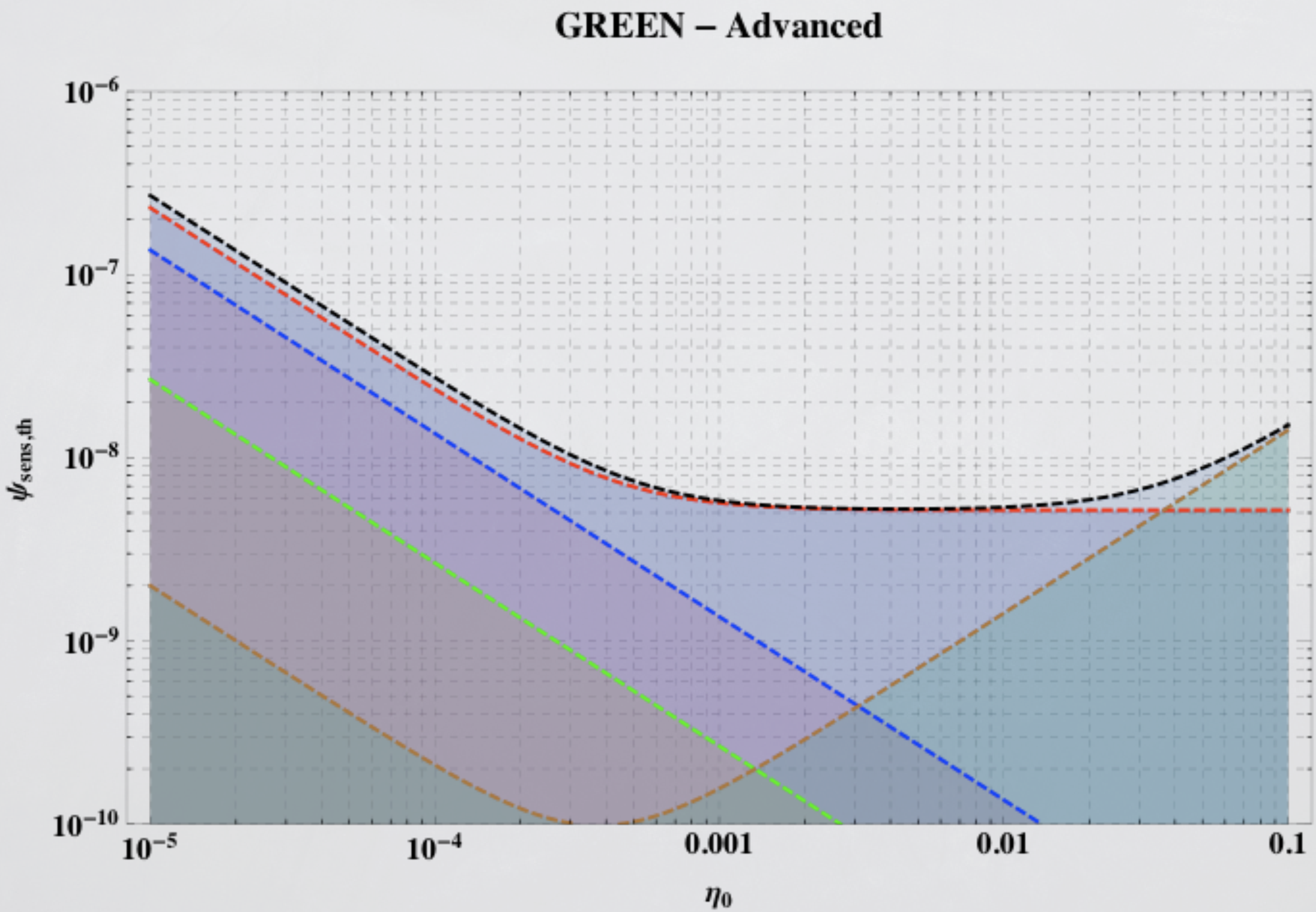

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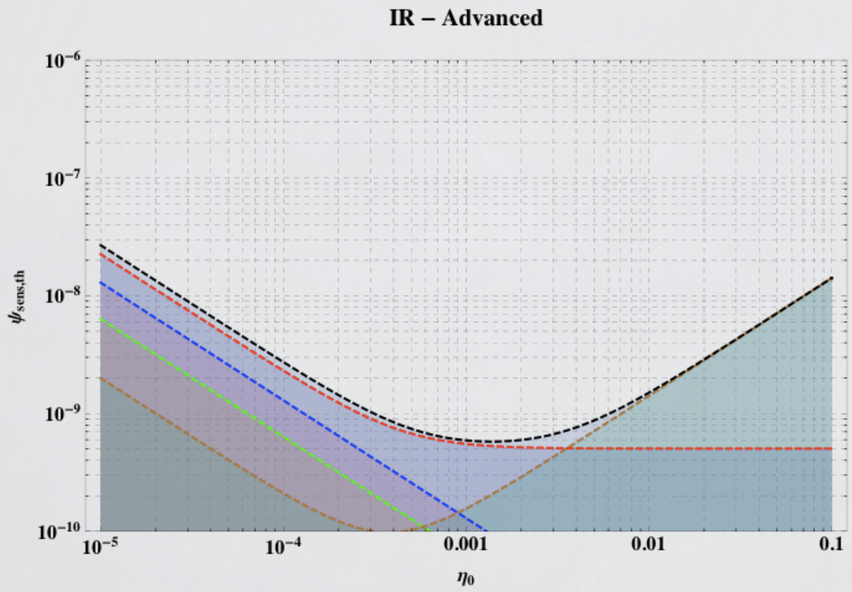
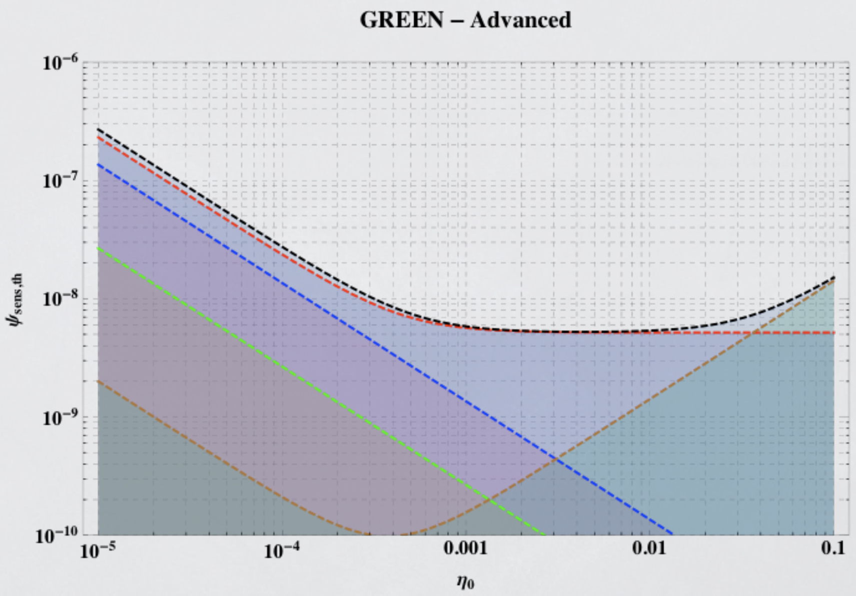
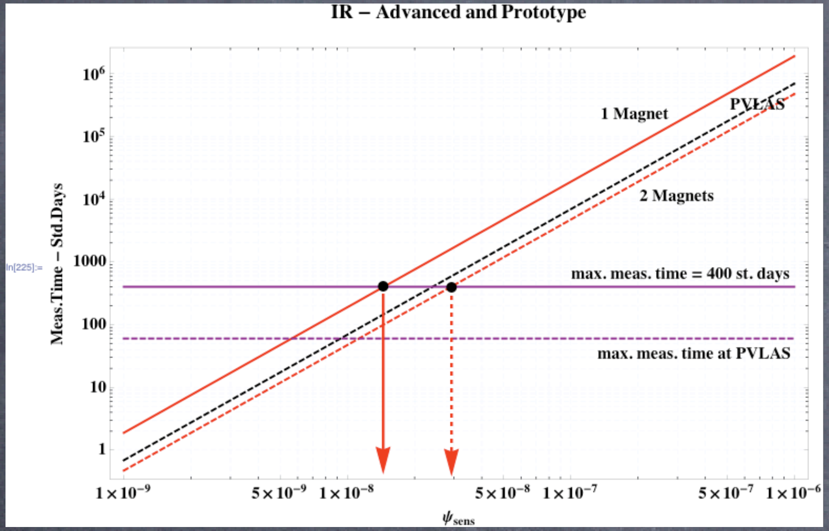
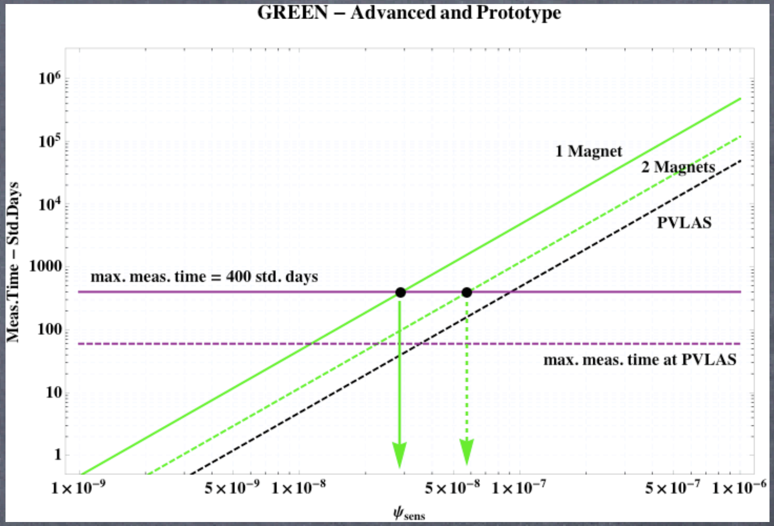




Measurement times for QED





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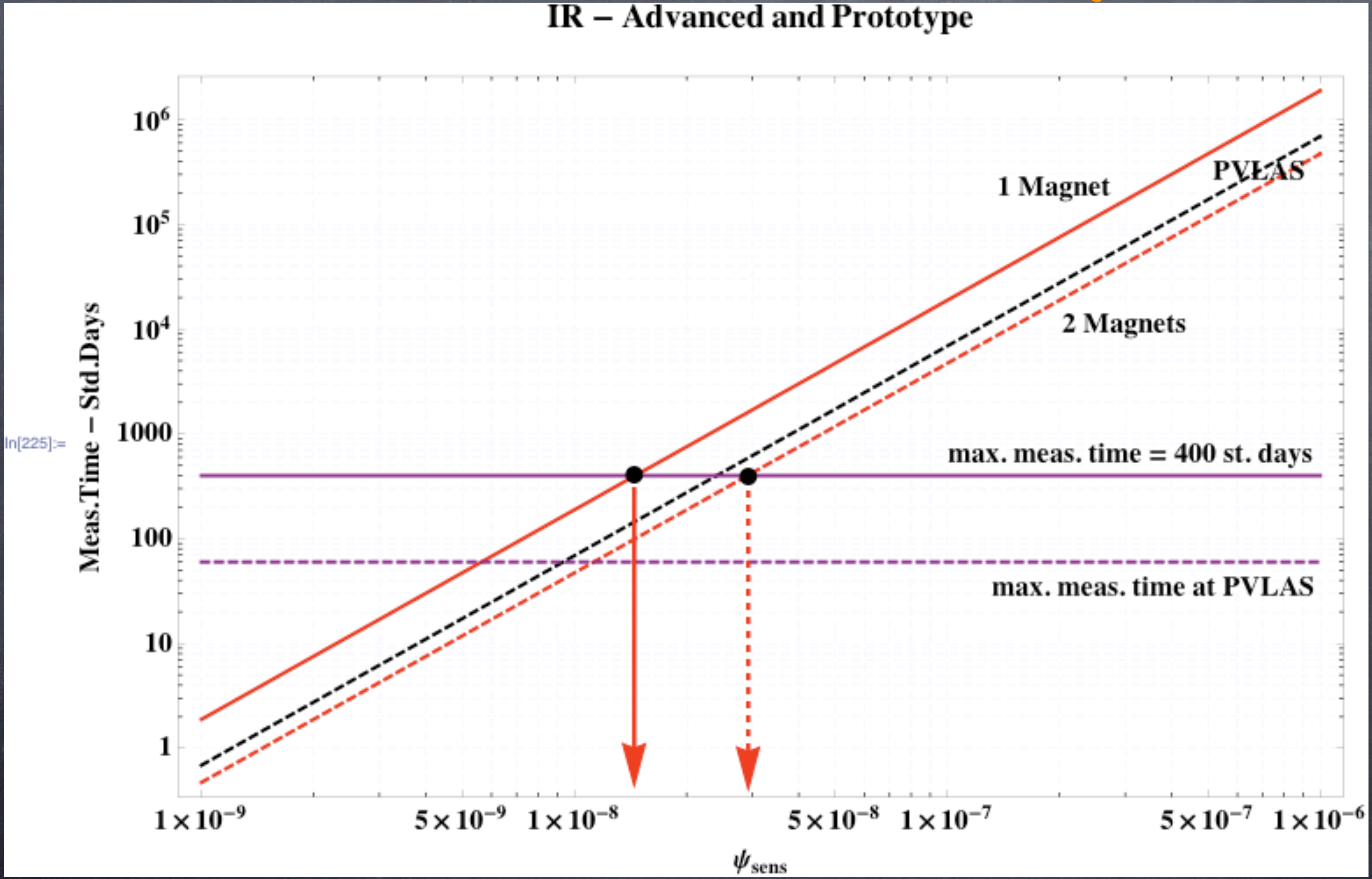

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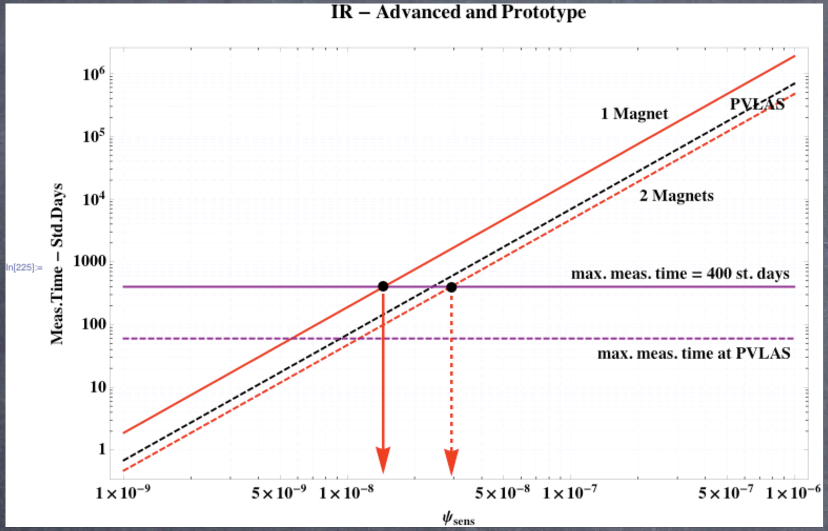

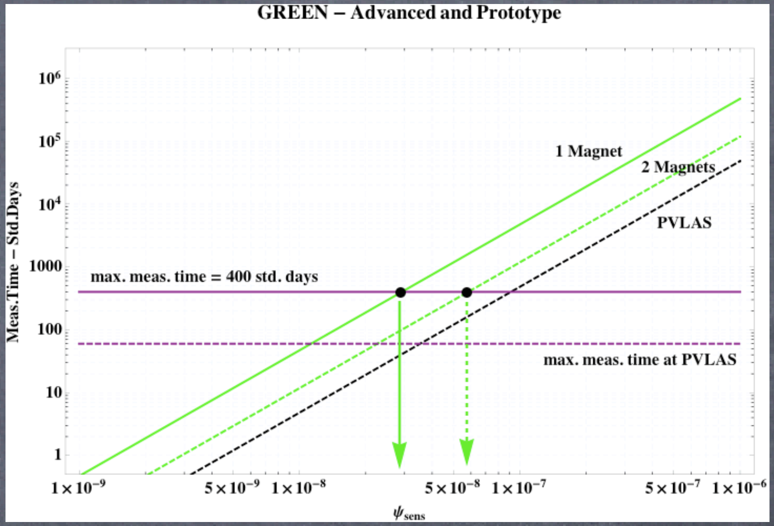

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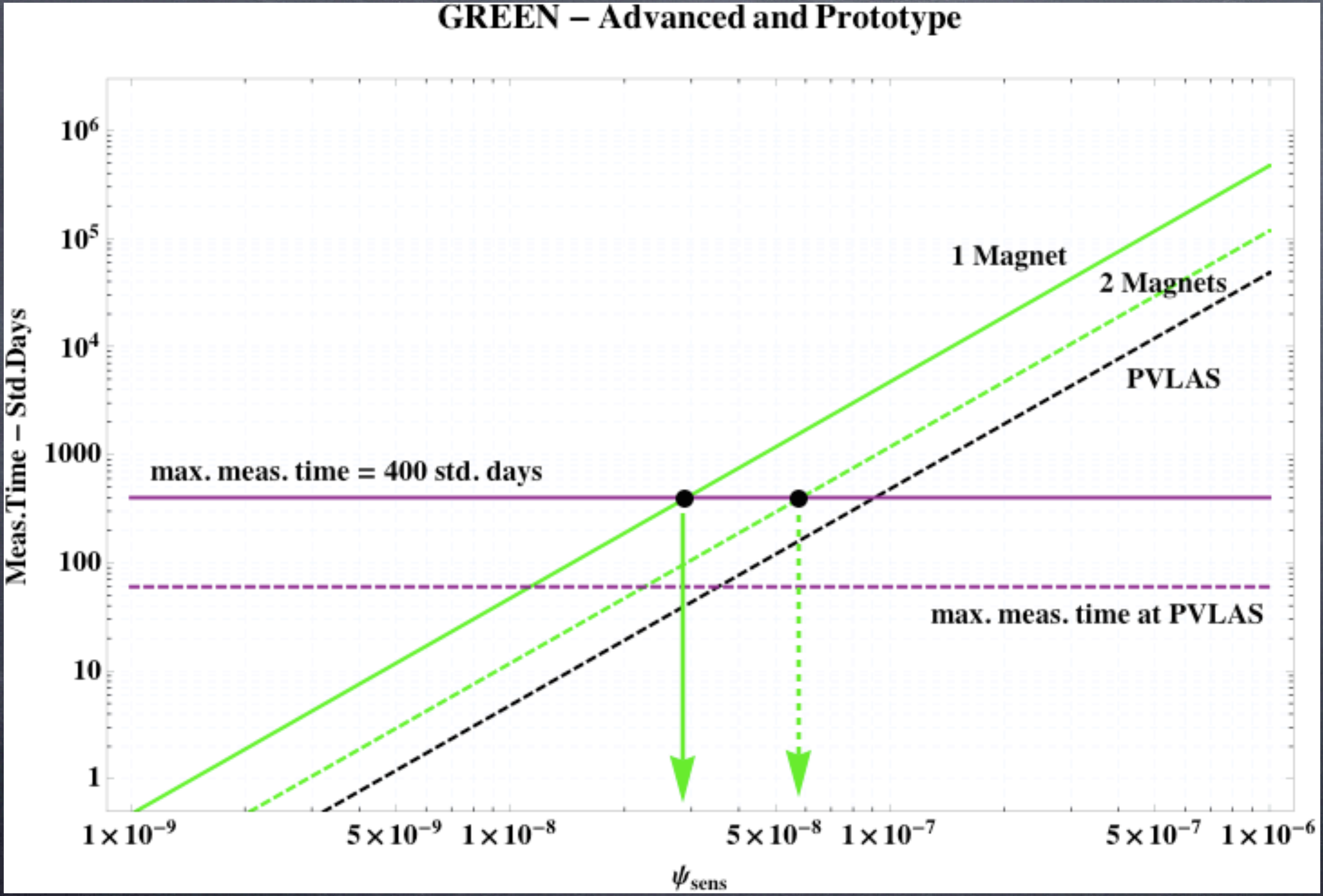

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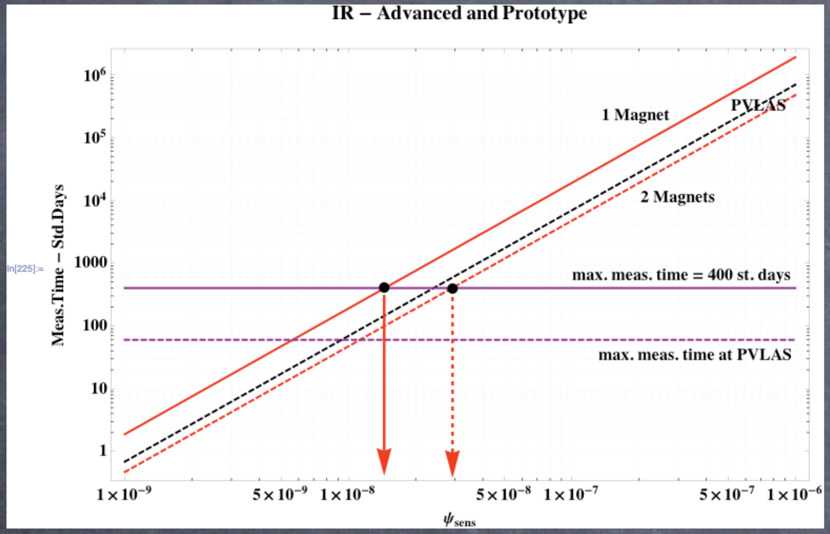

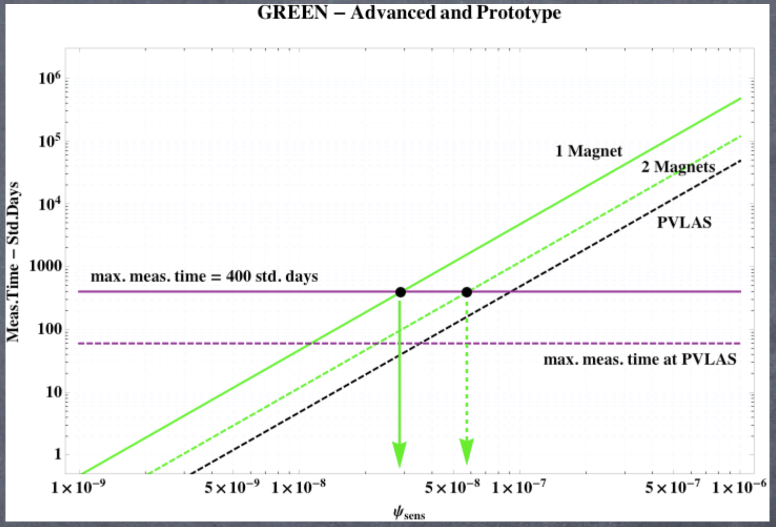

Config.		IR		GREEN		
		Prototype	Advanced	Prototype	Advanced	Adv. power upg.
	Sens. $[1/\sqrt{\text{Hz}}]$	10^{-8}	$6 \cdot 10^{-10}$	10^{-8}	$6 \cdot 10^{-9}$	10^{-9}
	Min. det. angle in 400 std. days	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-13}$	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-12}$	$3 \cdot 10^{-13}$
One magnet 2.3 T, L = 0.5 m	ψ^0_{QED}	$3.1 \cdot 10^{-17}$	$3.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$
	ψ_{QED} (F=220000)	$4.3 \cdot 10^{-12}$	$4.3 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$
	Min. meas. time (std. 8-hr. days)	188	0.675	47.1	16.9	0.471
Two magnets 2.3 T, L = 0.5 m	ψ^0_{QED}	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$
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Table IV: Minimum measurement times necessary to detect QED photon-photon scattering for several apparatus configurations.

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	Min. meas. time (std. 8-hr. days)	188	0.675	47.1	16.9	0.471
Two magnets 2.3 T, L = 0.5 m	ψ^0_{QED}	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$
	ψ_{QED} (F=220000)	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$1.7 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$
	Min. meas. time (std. 8-hr. days)	47.1	0.169	11.7	4.2	0.12

Table IV: Minimum measurement times necessary to detect QED photon-photon scattering for several apparatus configurations.

Config.		IR		GREEN		
		Prototype	Advanced	Prototype	Advanced	Adv. power upg.
	Sens. $[1/\sqrt{\text{Hz}}]$	10^{-8}	$6 \cdot 10^{-10}$	10^{-8}	$6 \cdot 10^{-9}$	10^{-9}
	Min. det. angle in 400 std. days	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-13}$	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-12}$	$3 \cdot 10^{-13}$
One magnet 2.3 T, L = 0.5 m	ψ^0_{QED}	$3.1 \cdot 10^{-17}$	$3.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$
	ψ_{QED} (F=220000)	$4.3 \cdot 10^{-12}$	$4.3 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$	$8.6 \cdot 10^{-12}$
	Min. meas. time (std. 8-hr. days)	188	0.675	47.1	16.9	0.471
Two magnets 2.3 T, L = 0.5 m	ψ^0_{QED}	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$
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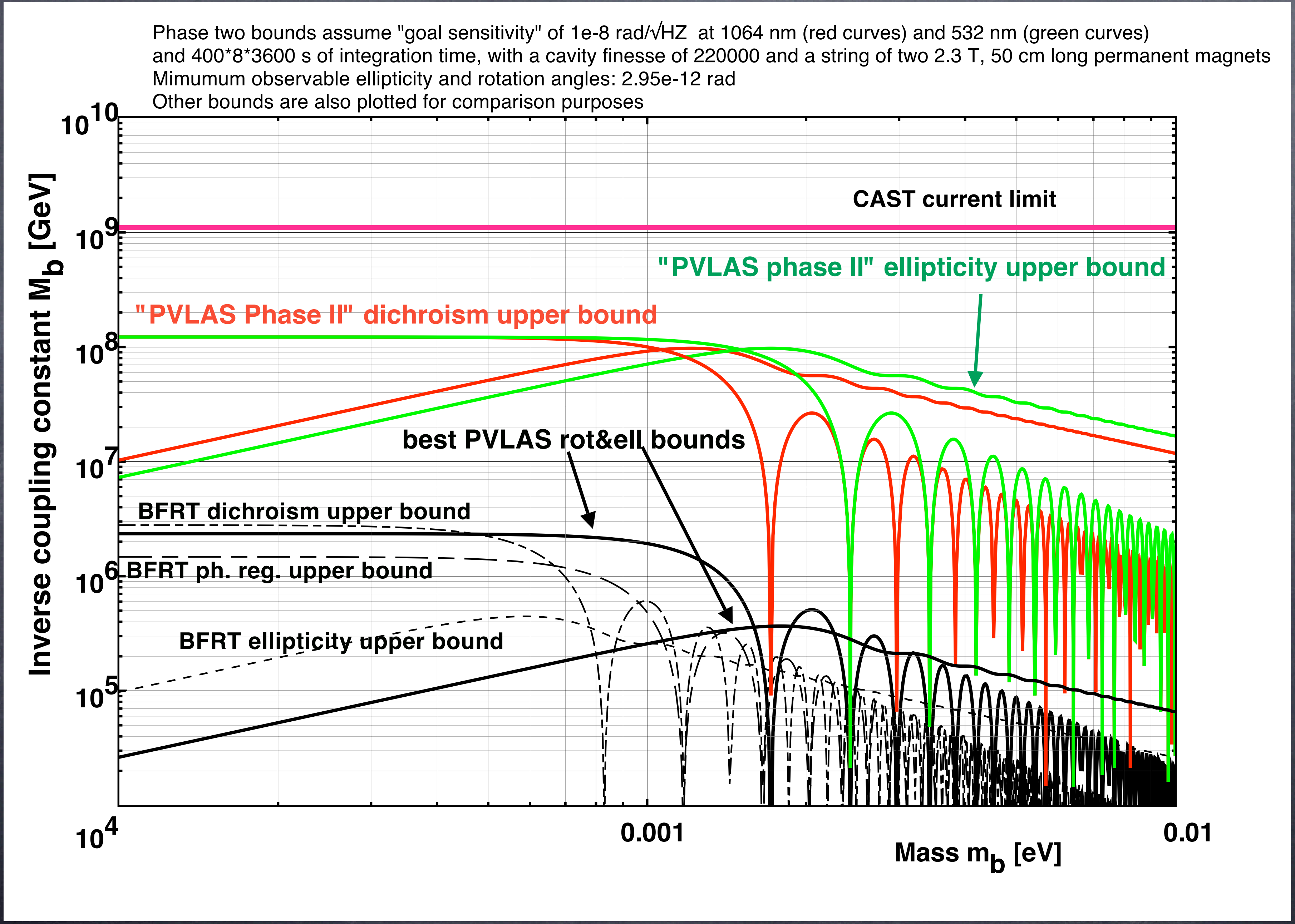
Table IV: Minimum measurement times necessary to detect QED photon-photon scattering for several apparatus configurations.

ALP parameter space coverage

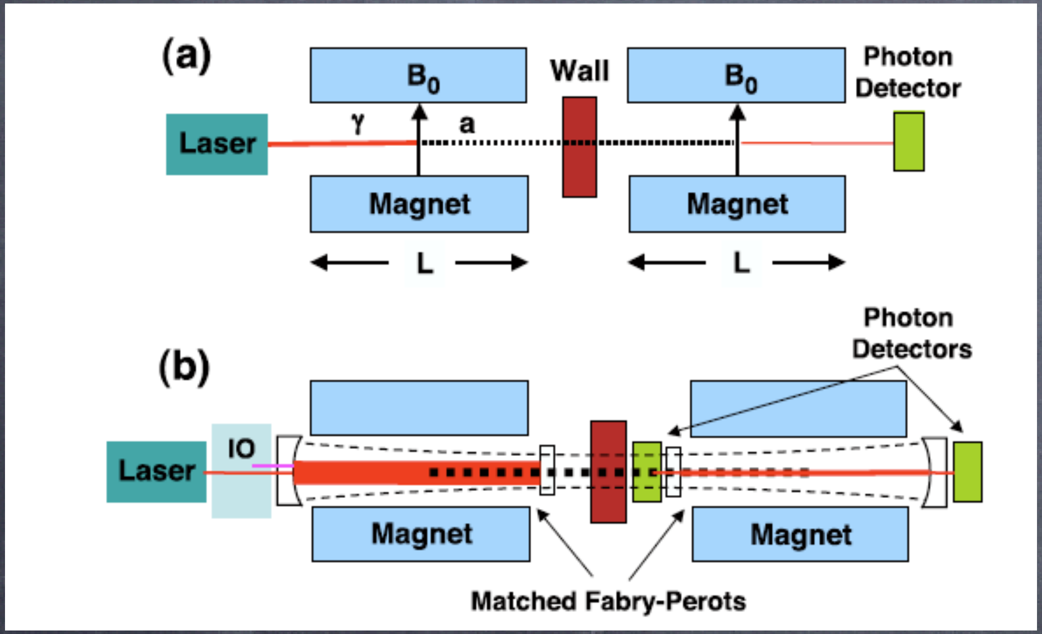


... not-so-crazy ideas for the future...

The Next Step: Resonant Regeneration

i. A Fabry-Perot cavity in the production magnet (left side of (b) in the figure) has the effect of multiplying the production probability by the finesse

ii. A second Fabry-Perot, frequency-matched to the first, placed in the conversion magnet (right side of (b)) multiplies the overall probability by the square of the finesse



normal regeneration

$$p_{0,reg} = \left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega}\right)\right]^4$$

resonant production

$$p_{res.prod.} = (F/\pi) \left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega}\right)\right]^4$$

resonant regeneration

$$p_{res.reg.} = 2\,(F/\pi)^2 \left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega}\right)\right]^4$$

Sikivie et al., Resonantly Enhanced Axion-Photon Regeneration, Phys. Rev. Lett. (2007) vol. 98 (17) pp. 4

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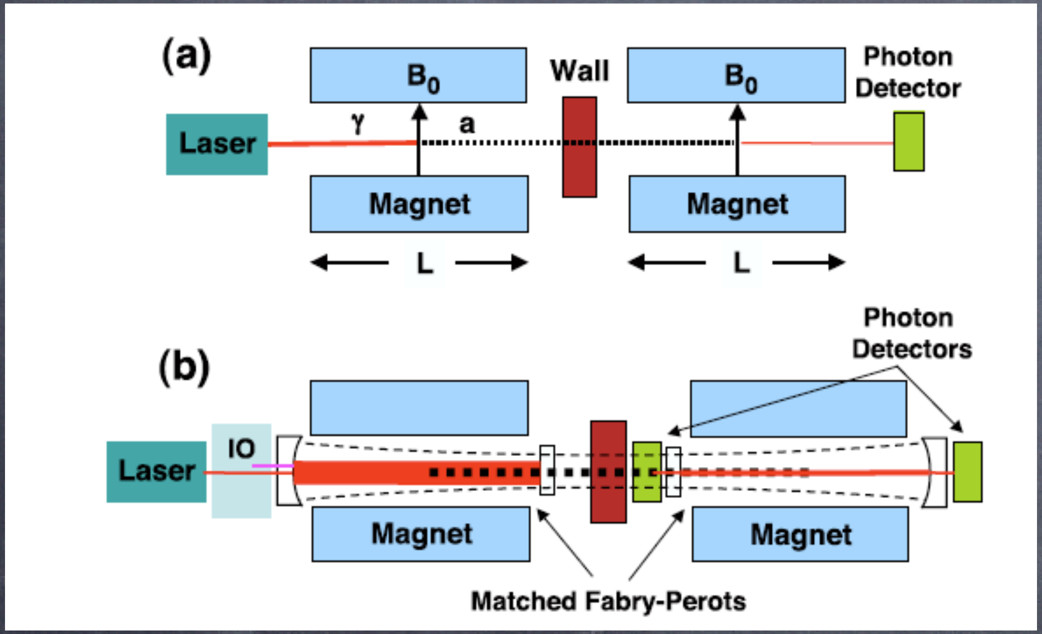


normal regeneration

$$p_{0,reg} = \left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega}\right)\right]^4$$

resonant production

$$p_{res.prod.} = (F/\pi)\left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega}\right)\right]^4$$

resonant regeneration

$$p_{res.reg.} = 2\,(F/\pi)^2\left[\frac{2\omega B_0}{M_a m_a^2} sin\left(\frac{m_a^2 L}{4\omega}\right)\right]^4$$

Sikivie et al., Resonantly Enhanced Axion-Photon Regeneration, Phys. Rev. Lett. (2007) vol. 98 (17) pp. 4

Bounding the coupling for ALPs

- Assume one measures for a time T with a detector having a given background DCR.
- If no signal is observed when the laser is on this corresponds to a SNR = 1
- Inverse coupling M_a can then be written as follows as a function of mass m_a

$$M_2 = 2^{\frac{1}{4}} \left(\frac{T\epsilon^2}{2 \cdot DCR} \right)^{\frac{1}{8}} \left(\frac{P_{laser}}{\omega} \right)^{\frac{1}{4}} \sqrt{F/\pi} \left(\frac{2\omega B}{m_a} \right) \sin \left(\frac{m_a^2 L}{4\omega} \right)$$

(production cavity with two detectors)

$$M_1 = \left(\frac{T\epsilon^2}{DCR} \right)^{\frac{1}{8}} \left(\frac{P_{laser}}{\omega} \right)^{\frac{1}{4}} \sqrt{F/\pi} \left(\frac{2\omega B}{m_a} \right) \sin \left(\frac{m_a^2 L}{4\omega} \right)$$

(production cavity with one detector)

The challenge(s)

I. Two frequency-locked high finesse Fabry-Perot resonators

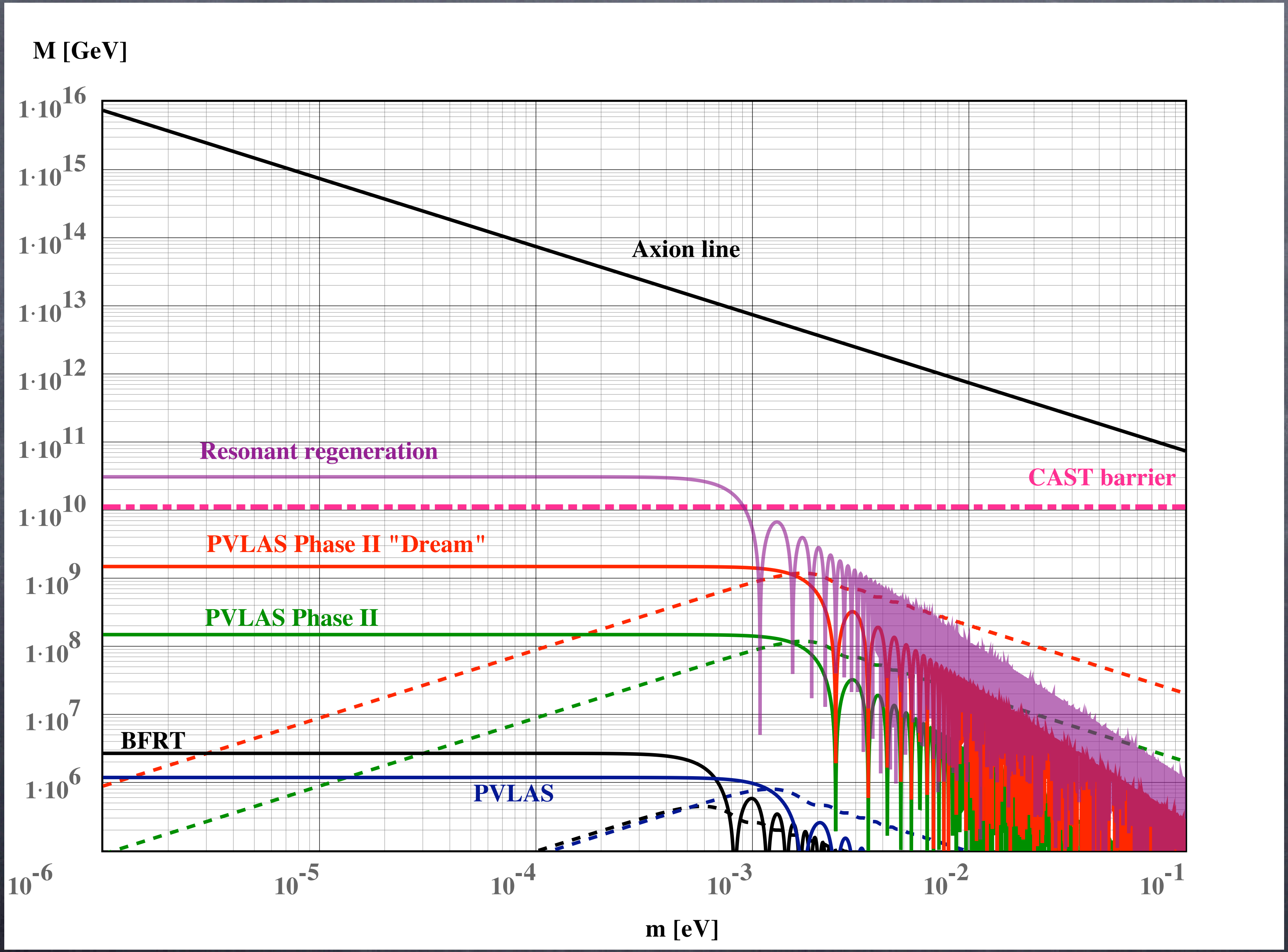
II. Low background detectors

III. High-power laser

IV. Accumulate statistics

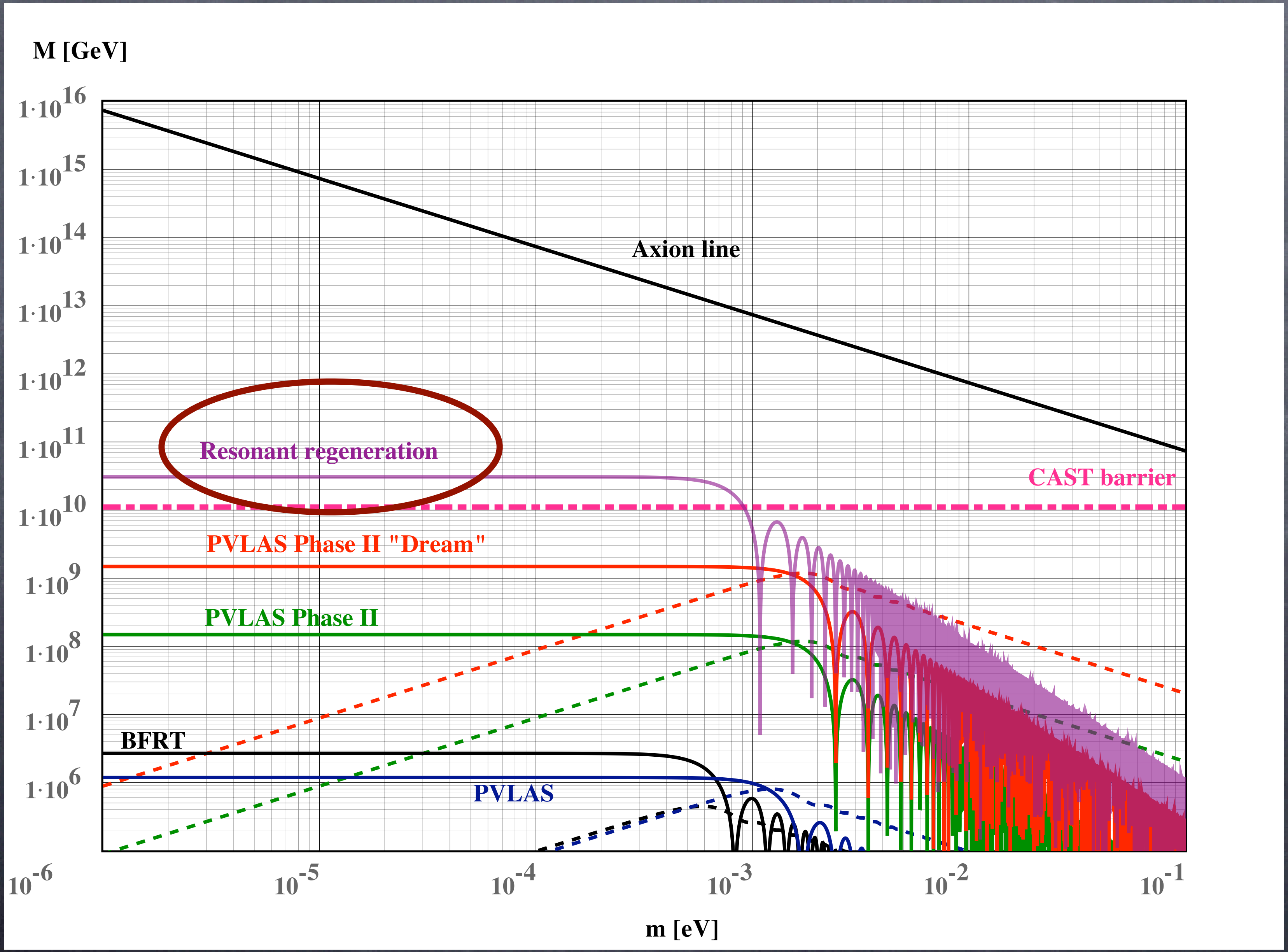
The reward

- Breaking the CAST barrier



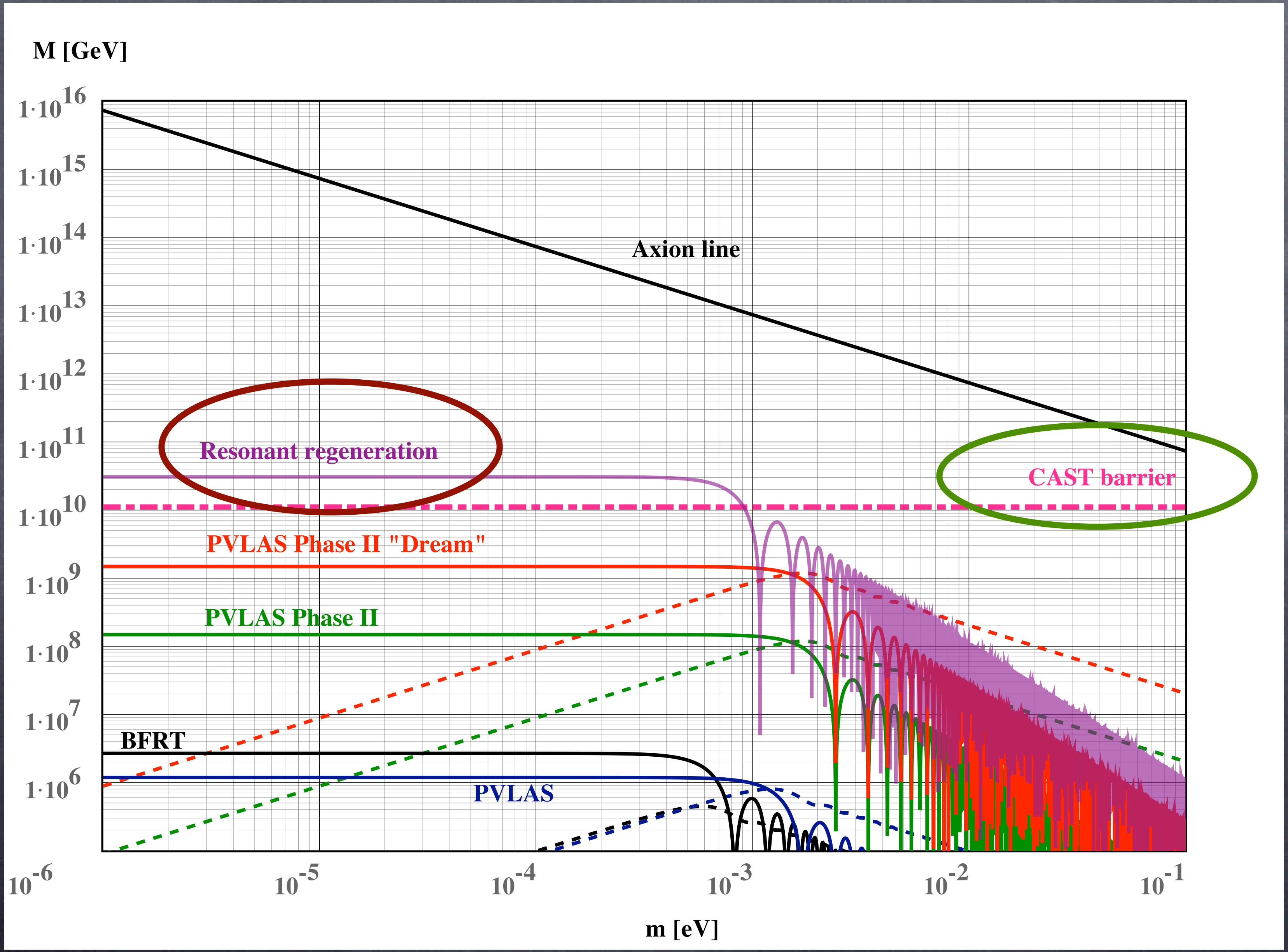
The reward

- Breaking the CAST barrier



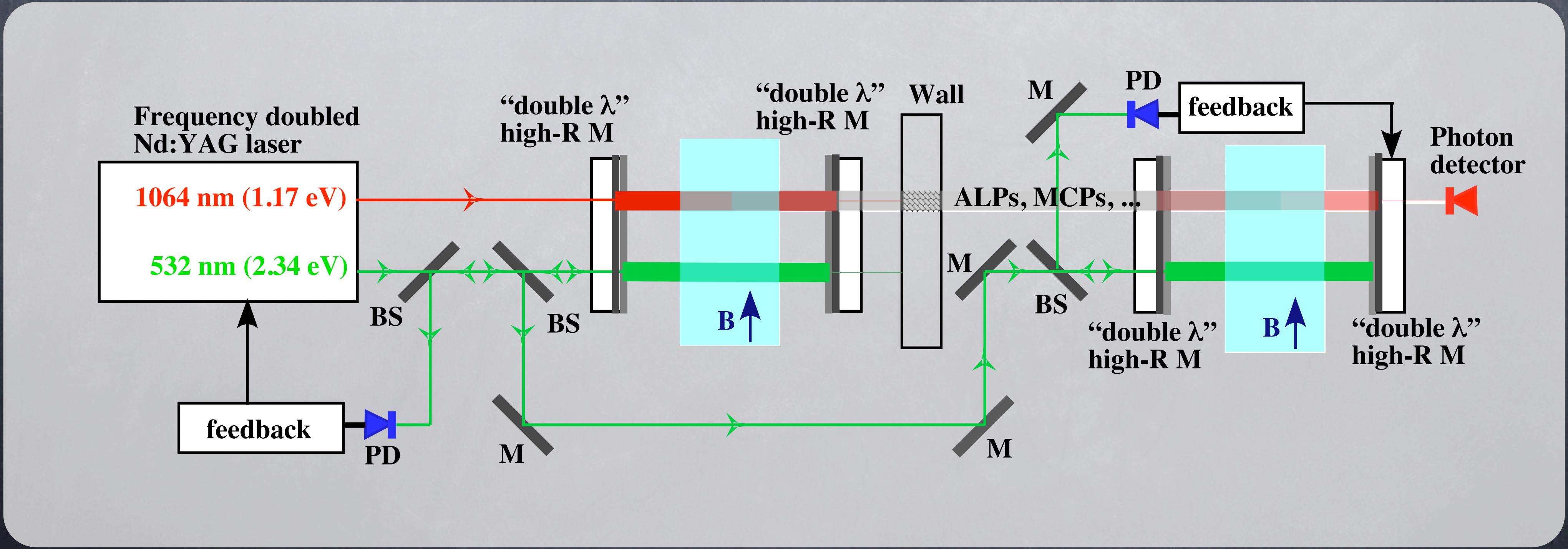
The reward

- Breaking the CAST barrier



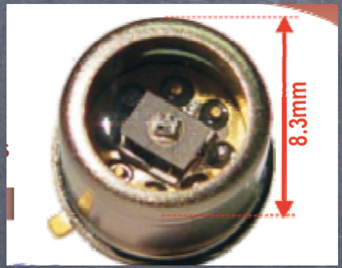
Challenge I - matching two cavities

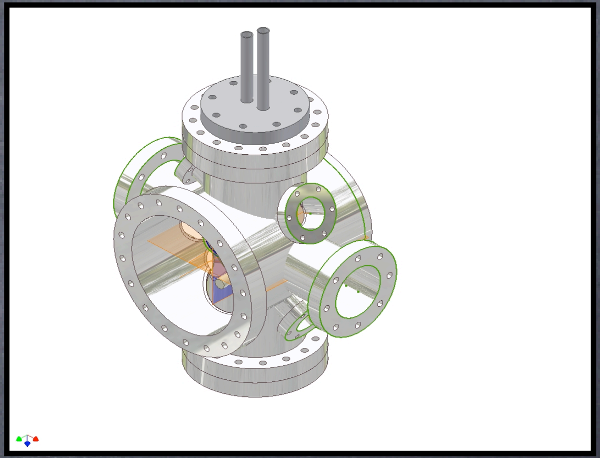
- Frequency doubled Nd:YAG laser emitting two mutually coherent beams at different wavelengths, 1064 nm and 532 nm
- Two "identical" Fabry-Perot cavities made with "double λ" mirrors coated for high reflectivity at the two laser wavelengths
- Use "green" low-power beam to lock and match cavities
- Use "IR" high-power beam to produce and detect ALPs



Challenge II - low background detector

- Common problem of ALP search experiments
- CAST experience
  - started with a PMT and an APD (0.35 Hz DCR)
  - will move to LN2-cooled APD





- Resonant regeneration measurements can begin with a cooled APD (DCR?, maybe 10^{-2} Hz, BaRBE will find out)
- Dream detector: a TES (no background!)

Challenges III-IV : laser power and statistics

- Lasers up to 10 W CW in the IR -> commercially available (e.g. Innolight - Hannover)
- 100 W IR and above -> look at the VIRGO and LIGO experience
  - 100 W should be within reach and will not thermally stress the optics
  - above 100 W things get harder, but feasible
- Statistics: remotely controllable apparatus with large duty cycle

Dreams

- 10 T and above magnet(s)
- very low background detectors
- high performance optics
- large duty cycle
- good laboratory environment and support

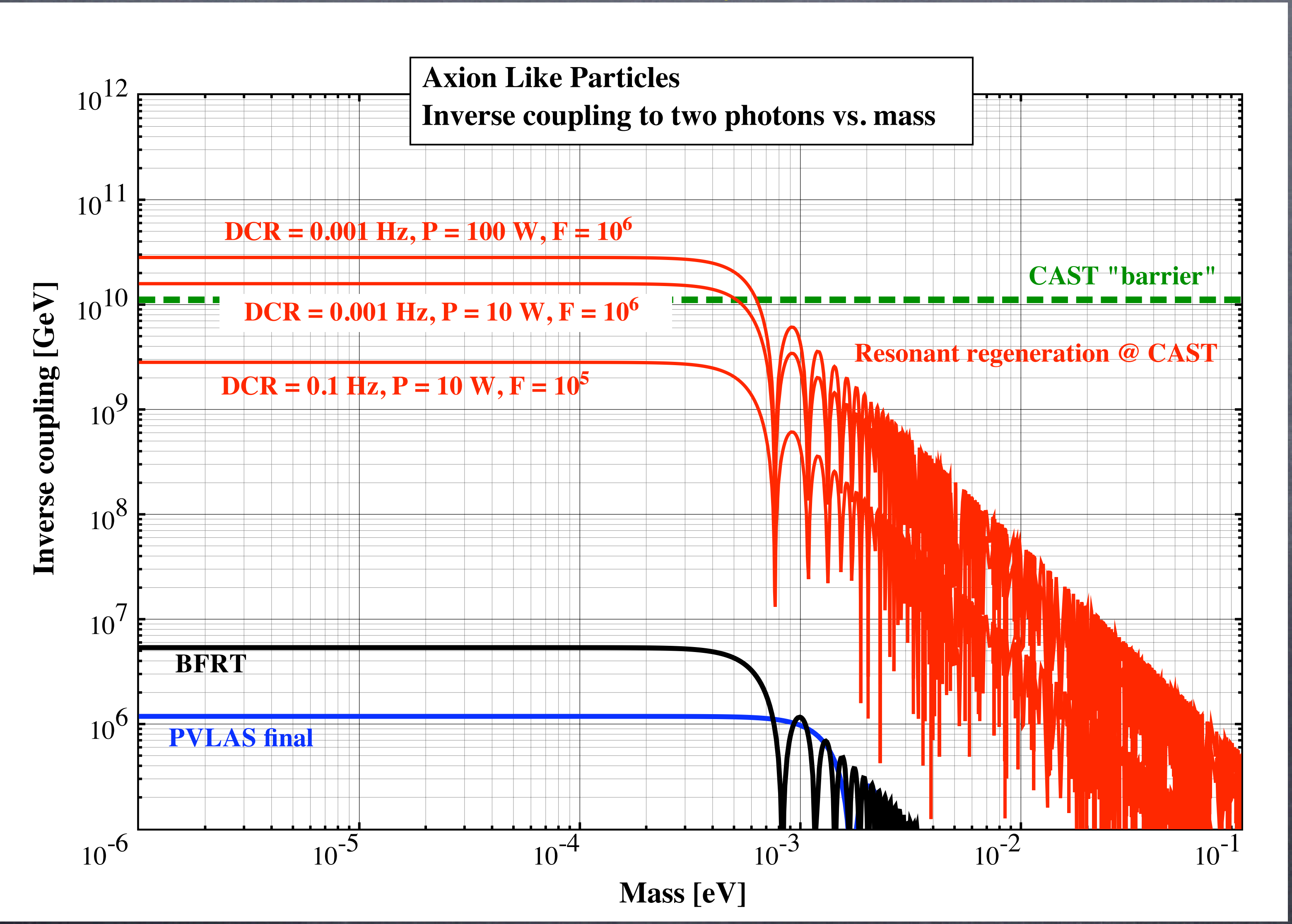
Reality check

- Experimental parameters: from reality to dream

	Available	Desirable	Dream
Det. efficiency	0.5	0.5	0.5
Meas. time [s]	$8.64 \cdot 10^6$	$8.64 \cdot 10^6$	$8.64 \cdot 10^6$
DCR [Hz]	0.1	0.001	0.001
Laser power [W]	10	10	100
Photon energy [eV]	1.17	1.17	1.17
Cavity Finesse	100000	1000000	1000000
Field intensity [T]	10	10	10
Cavity length [m]	5	5	5

Dreams vs. reality

- Reach in the M-m plane



Outlook for resonant regeneration

- Is it worthwhile?
  - It is the only way to make purely laboratory bounds competitive with astrophysics-based bounds
  - Better coverage of the parameter space means larger discovery potential
- What is needed to start
  - careful design and work on cavity locking
  - prototype detector completion and tests
  - double wavelength laser
- What would be nice to have
  - 10 W and above double wavelength laser
  - two short magnets or one long magnet with B~10 T
  - single-photon counting detector with DCR $< 10^{-2}$ Hz
  - interested researchers
- Possible timing
  - the Trieste group has applied for funds to build a table-top pilot resonant regeneration set-up -> timeline: 2 years (can proceed even if funding is not approved)
  - a cooled APD detector system for "visible CAST" is under construction in Trieste -> timeline: 6 months-1 year

Conclusions

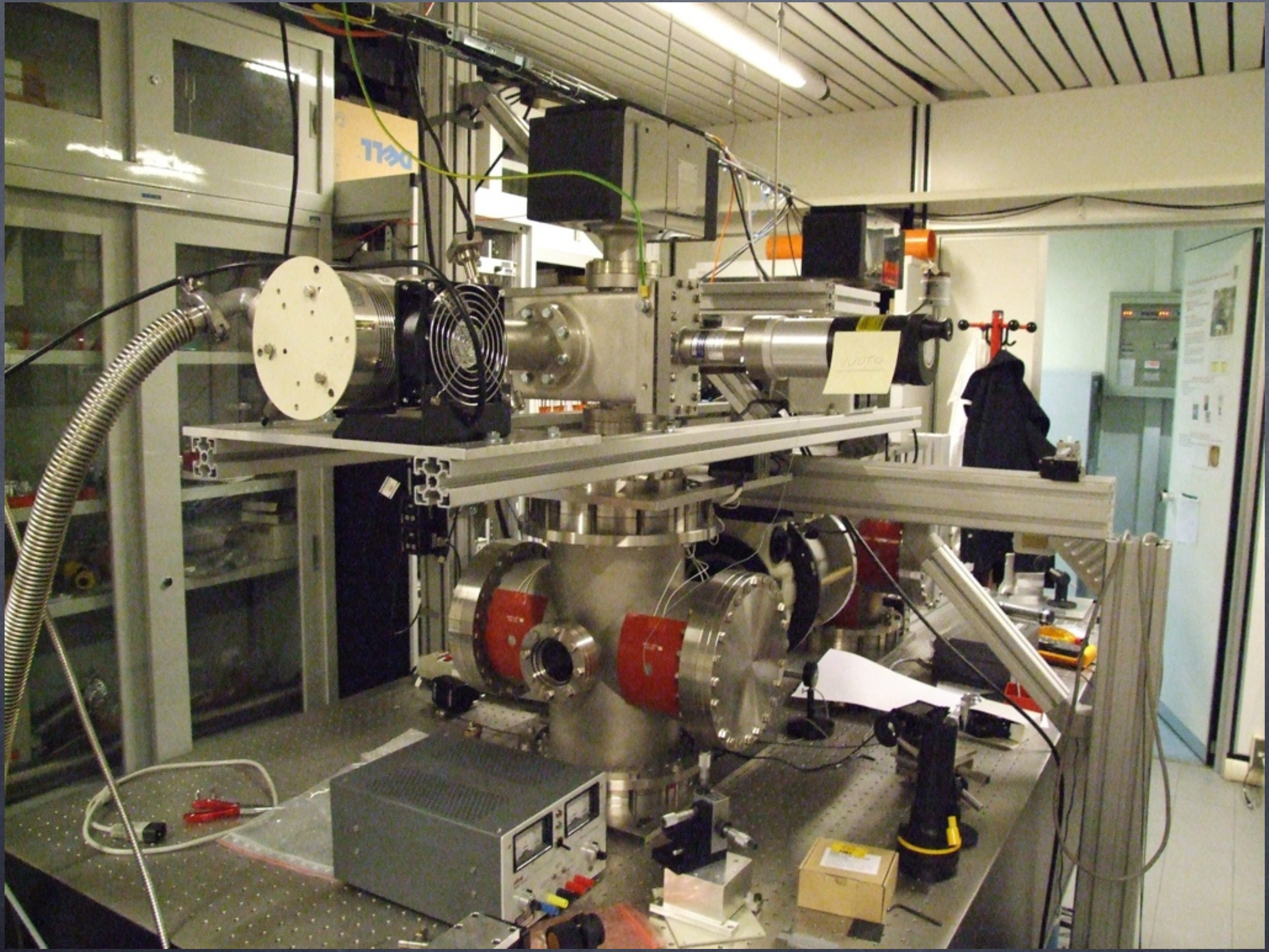
- Fundamental physical phenomena live on the Low Energy Frontier
- Low energy "photon colliders" are prime tools tho explore this Frontier
- Two main types of experiments
  - polarization experiments
  - photon regeneration experiments
- Polarization measurements are well suited for probing QED effects, while photon regeneration is the most promising technique to search for ALPs in the laboratory
- Many difficult challenges await experimentalists and theorists alike, but the reward might prove handsome

Backup slides

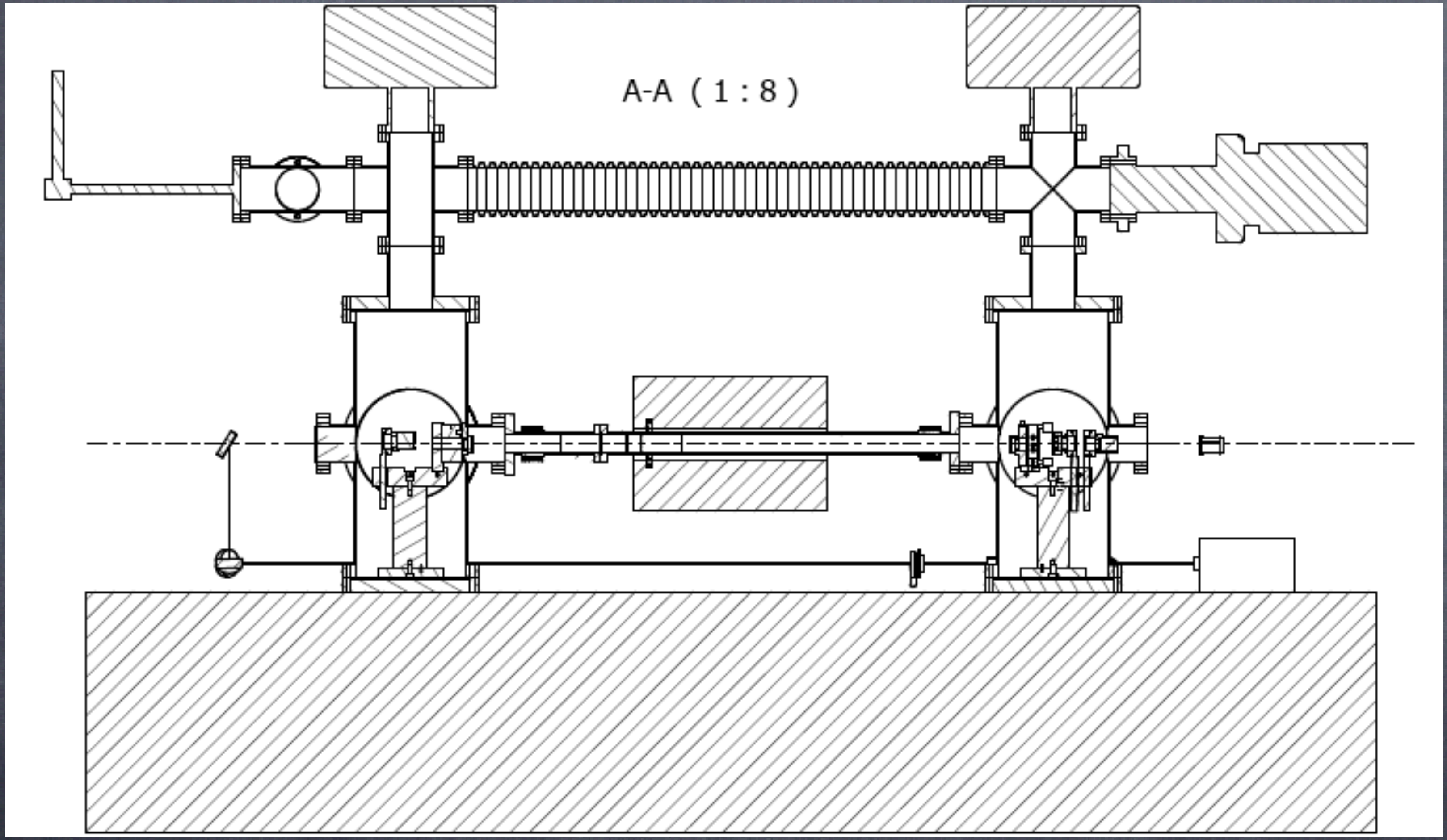
Apparatus parameters

Parameter	IR	GREEN
Wavelength	1064 nm	532 nm
Laser output power	900 mW	20 mW
ϵ_{FP}	0.25	0.25
G	10^7 V/A	10^9 V/A
σ^2	10^{-7}	10^{-7}
q	0.7 A/W	0.3 A/W
T	300 K	300 K
RIN	$10^{-6}\ 1/\sqrt{\mathrm{Hz}}$	$10^{-6}\ 1/\sqrt{\mathrm{Hz}}$
$\hat{V}_d$	$8 \cdot 10^{-6}\ \mathrm{V}/\sqrt{\mathrm{Hz}}$	$2 \cdot 10^{-6}\ \mathrm{V}/\sqrt{\mathrm{Hz}}$

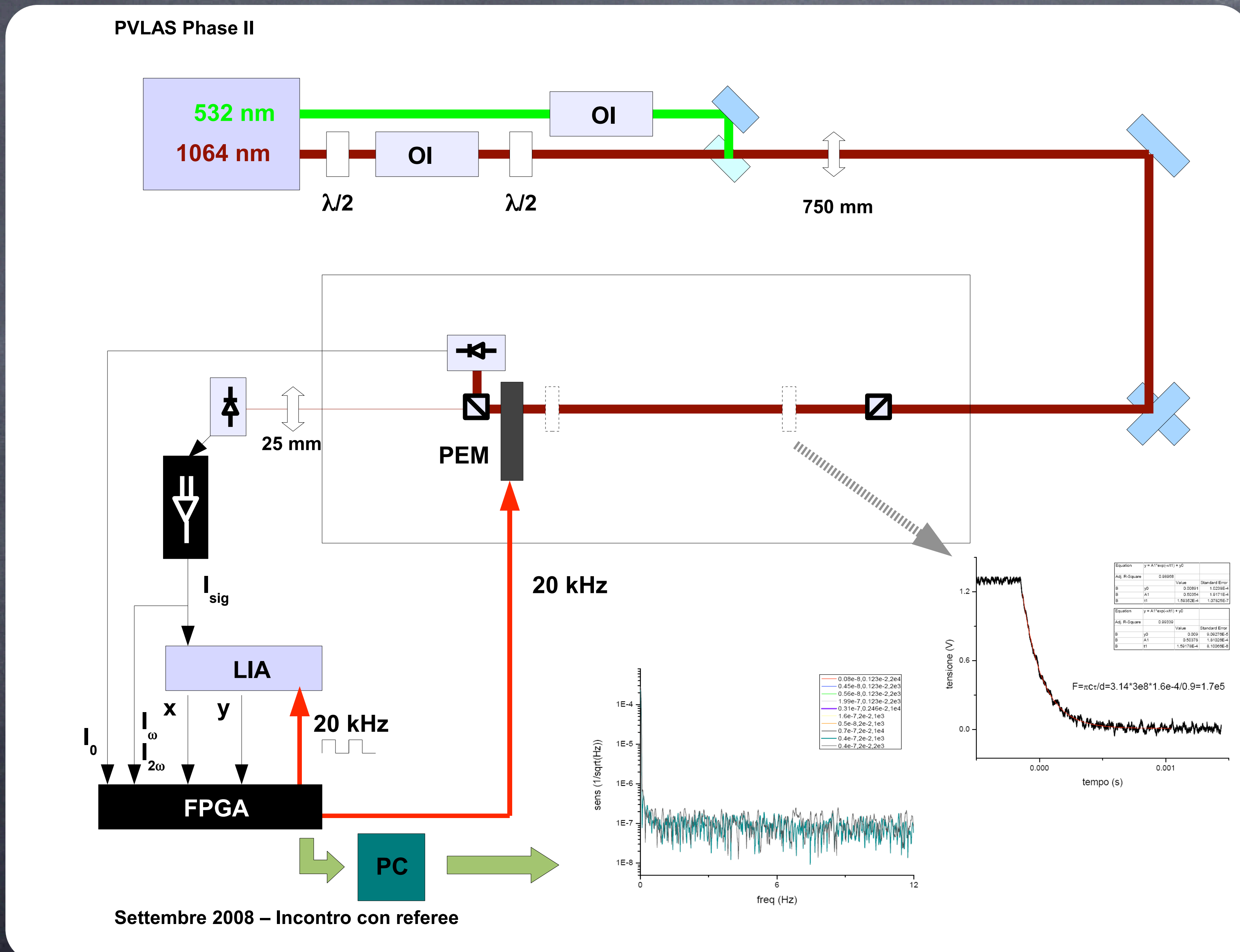
Vista generale II



Sezione ellissometro



Schema preliminare dell'ottica



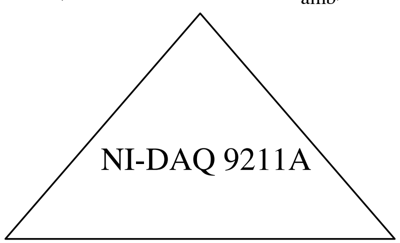
Stumentazione per misure di pressione e temperatura dei gas test

Misurazioni congiunte di pressioni e temperature (custom-made LabVIEW software)

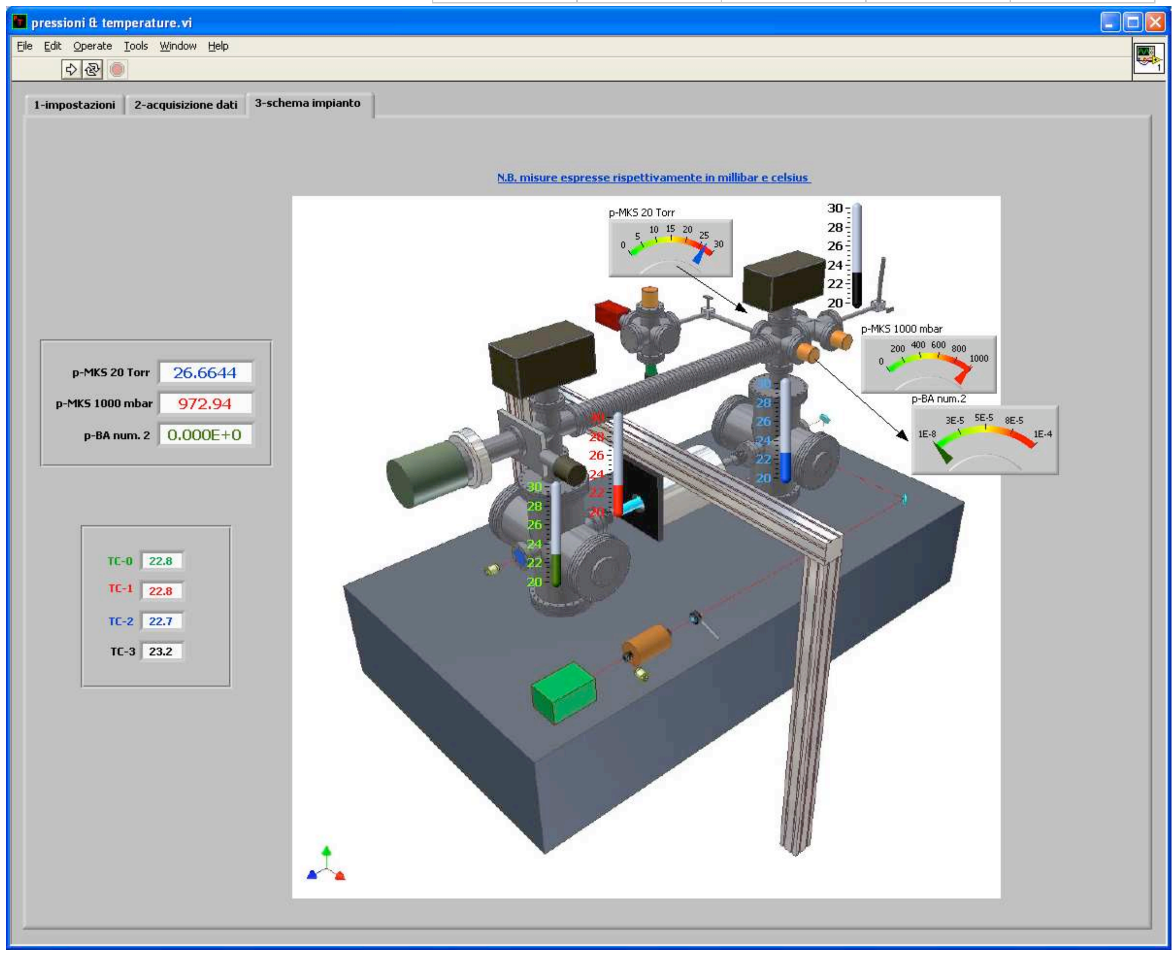
Catena di riferibilità interna per le misure di temperatura

Trif	TC-0 [°C]	TC-1 [°C]	TC-2 [°C]	TC-3 [°C]
0.00	-0.17	-0.26	0.04	0.08
24.67	24.80	24.70	24.88	24.94

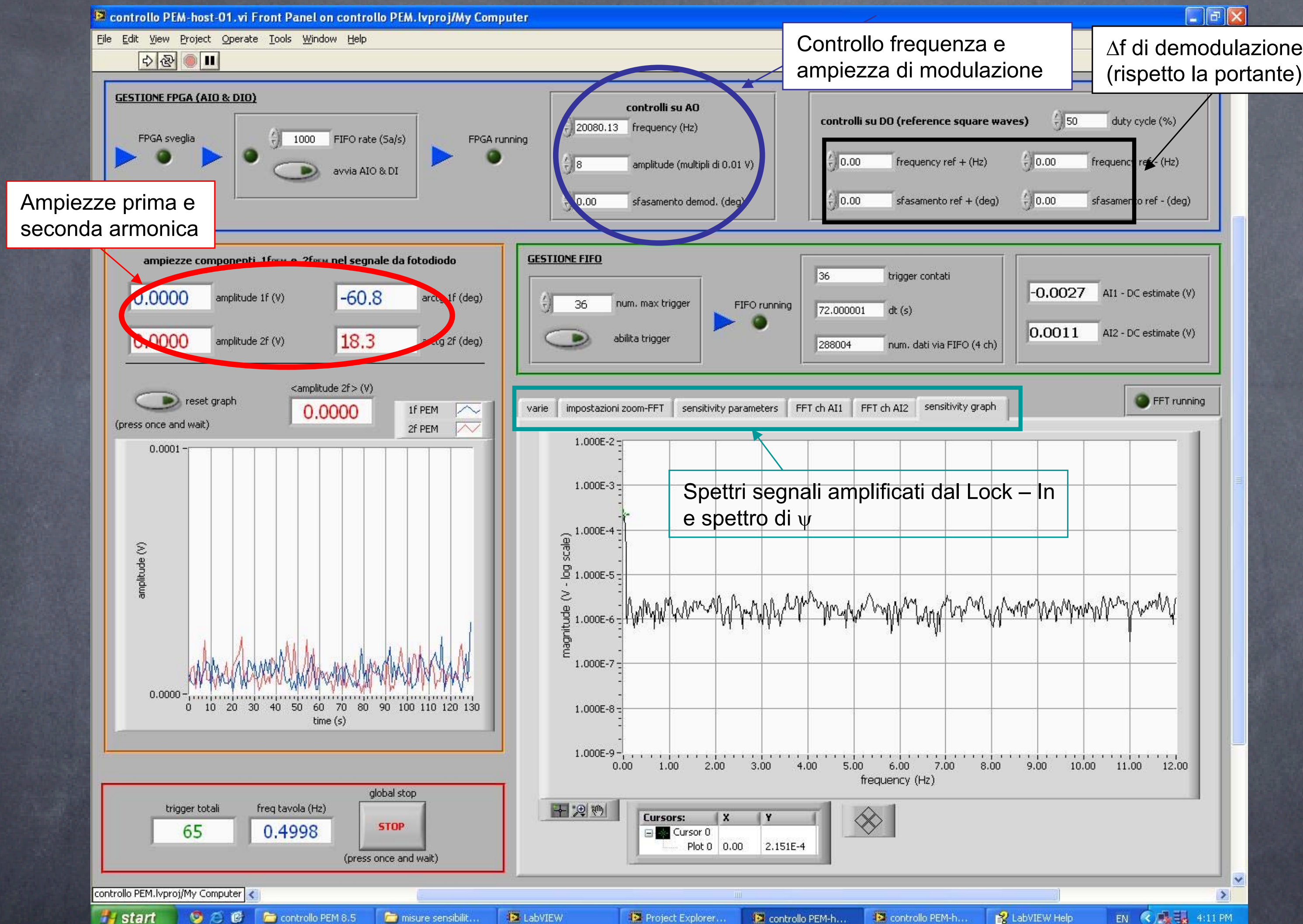
Fluke 20T-150U temp probe
(verifica a 0 °C e T_{amb})



quattro termocoppie tipo J



DAQ e analisi dati



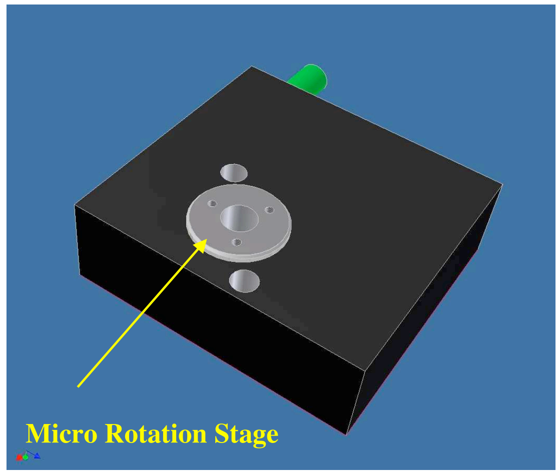
Dati acquisiti con scheda FPGA della NI

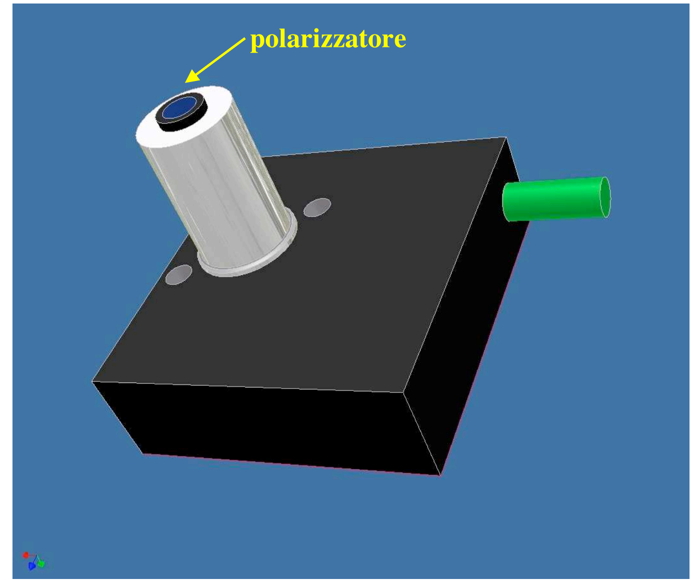
Analisi con software LabView

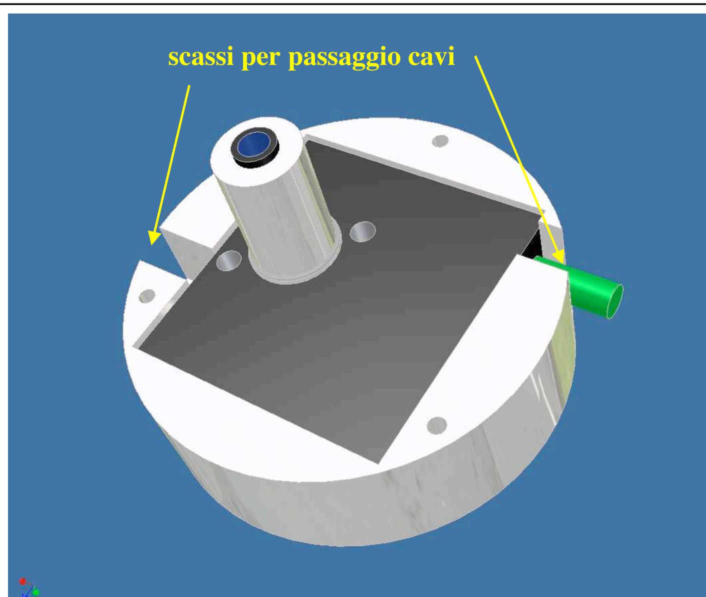
Lavori in corso

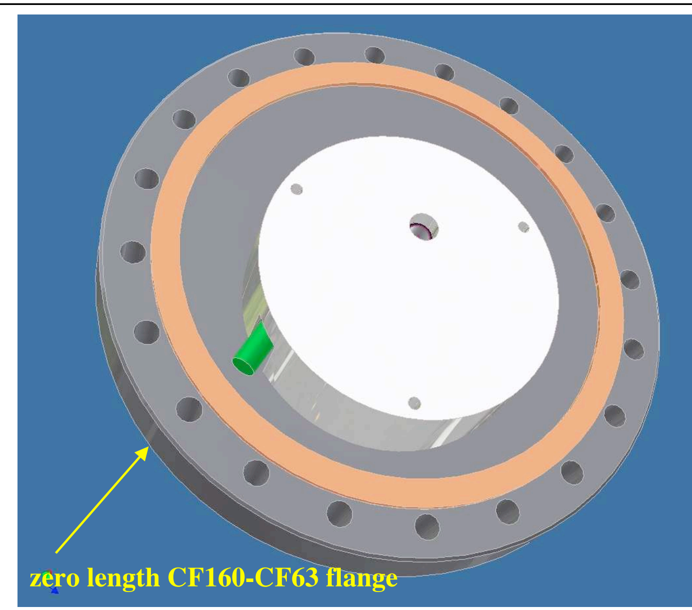
Progetto camera da vuoto per ruota-analizzatore

min.incremental motion: 50 μrad – vacuum compatible



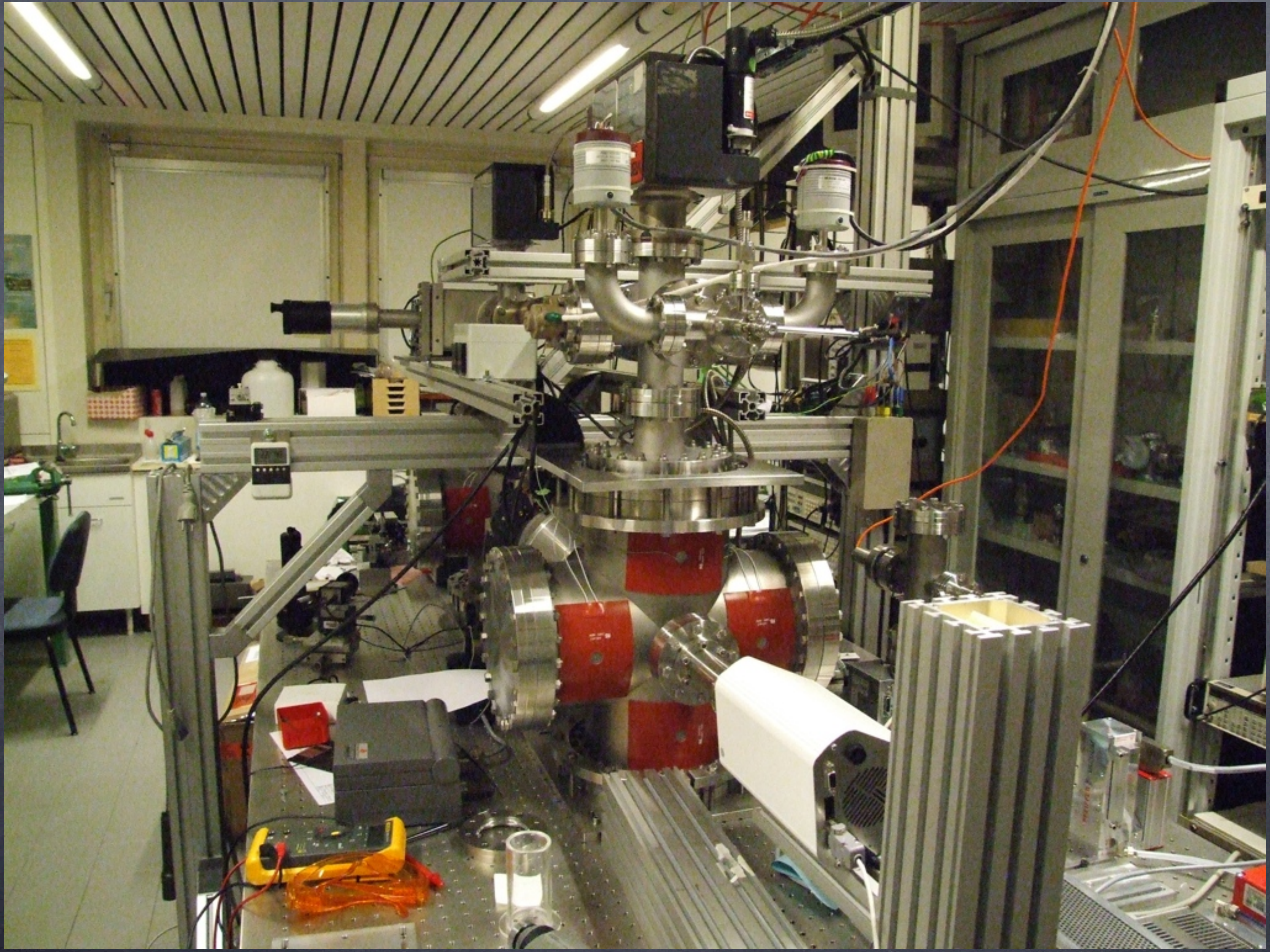




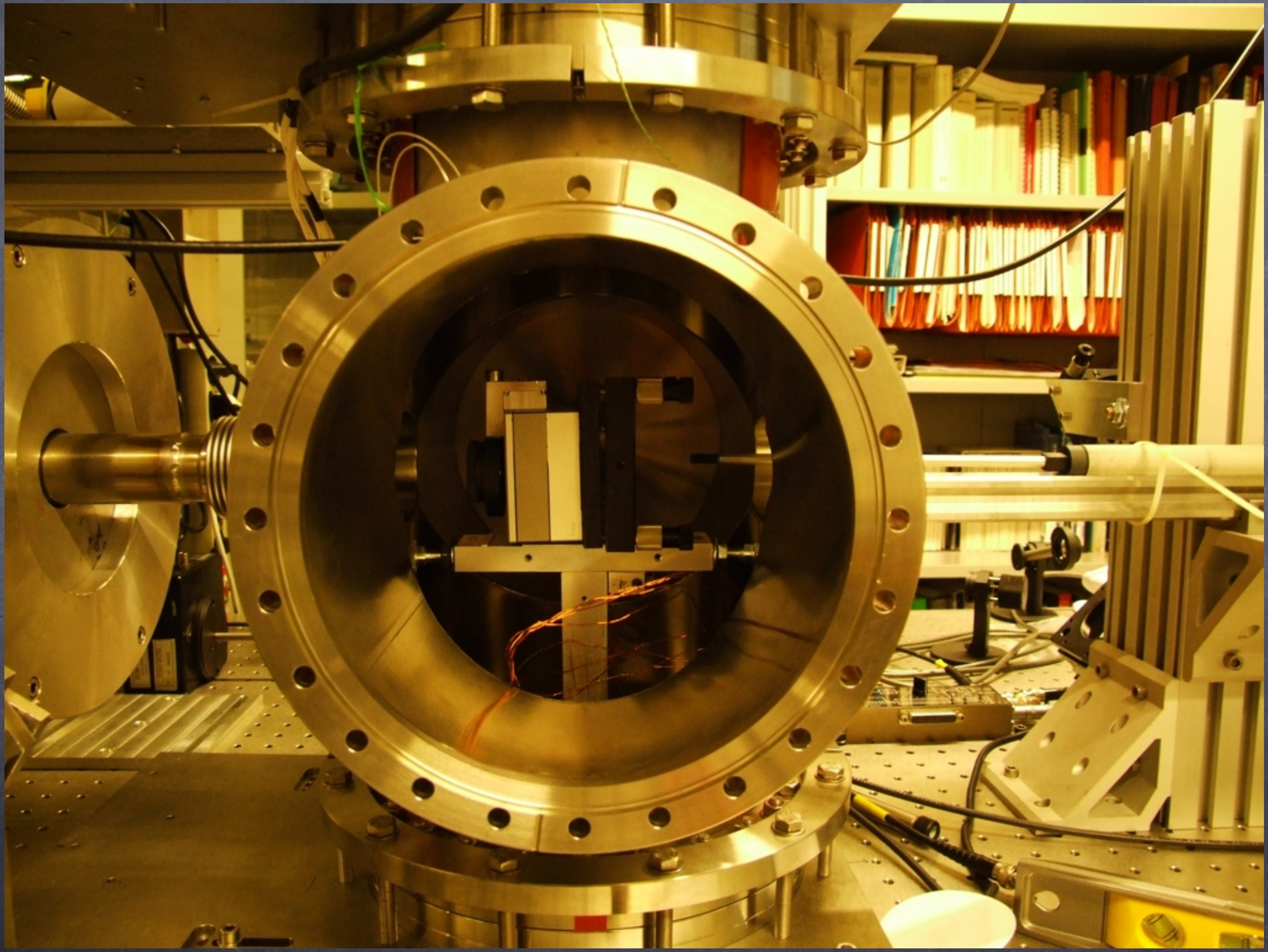


Settembre 2008-Trieste-Incontro con i referee di PVLAS fase II *G. Raiteri*

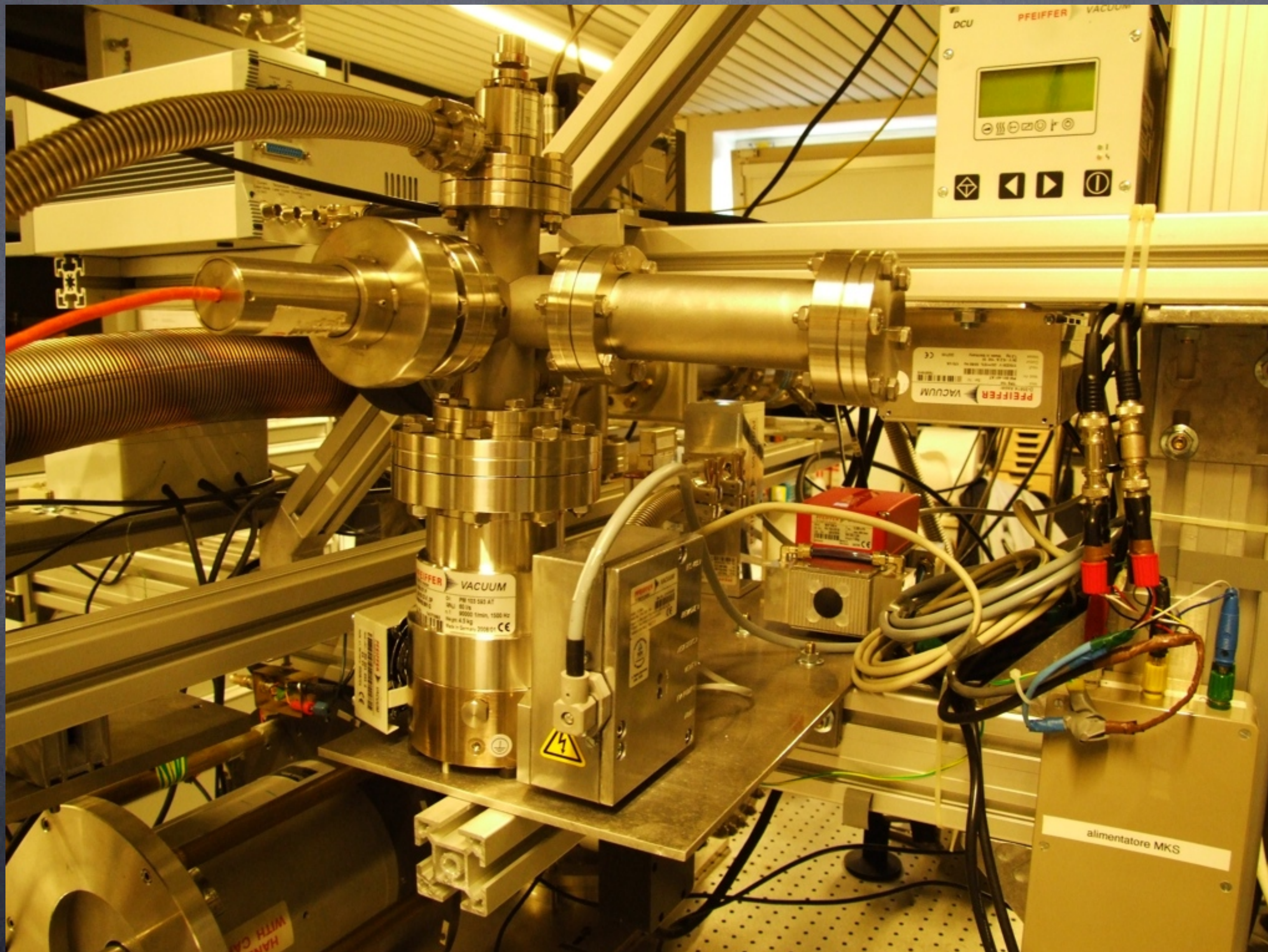
Vista generale I



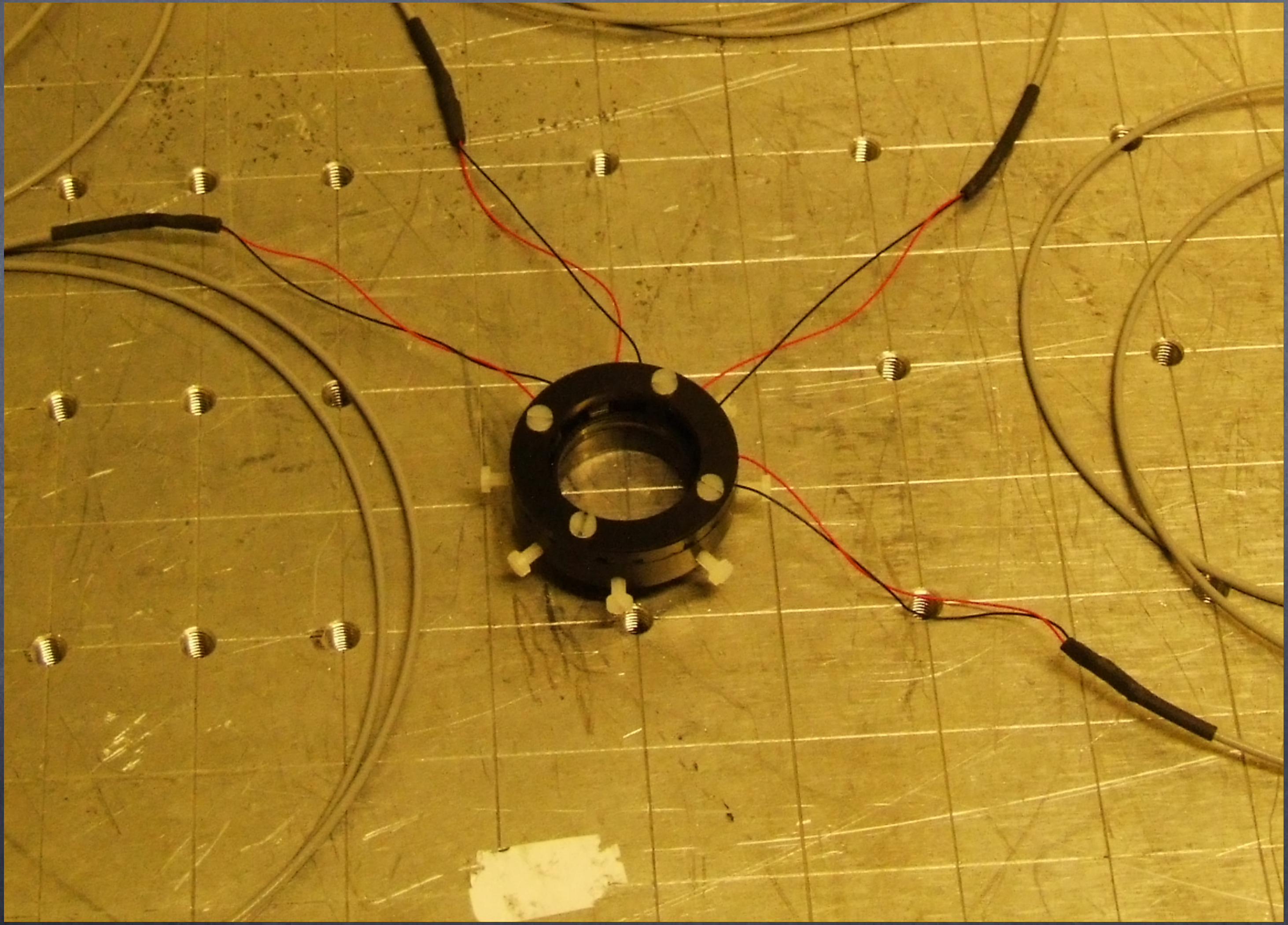
Dettaglio portaspecchi



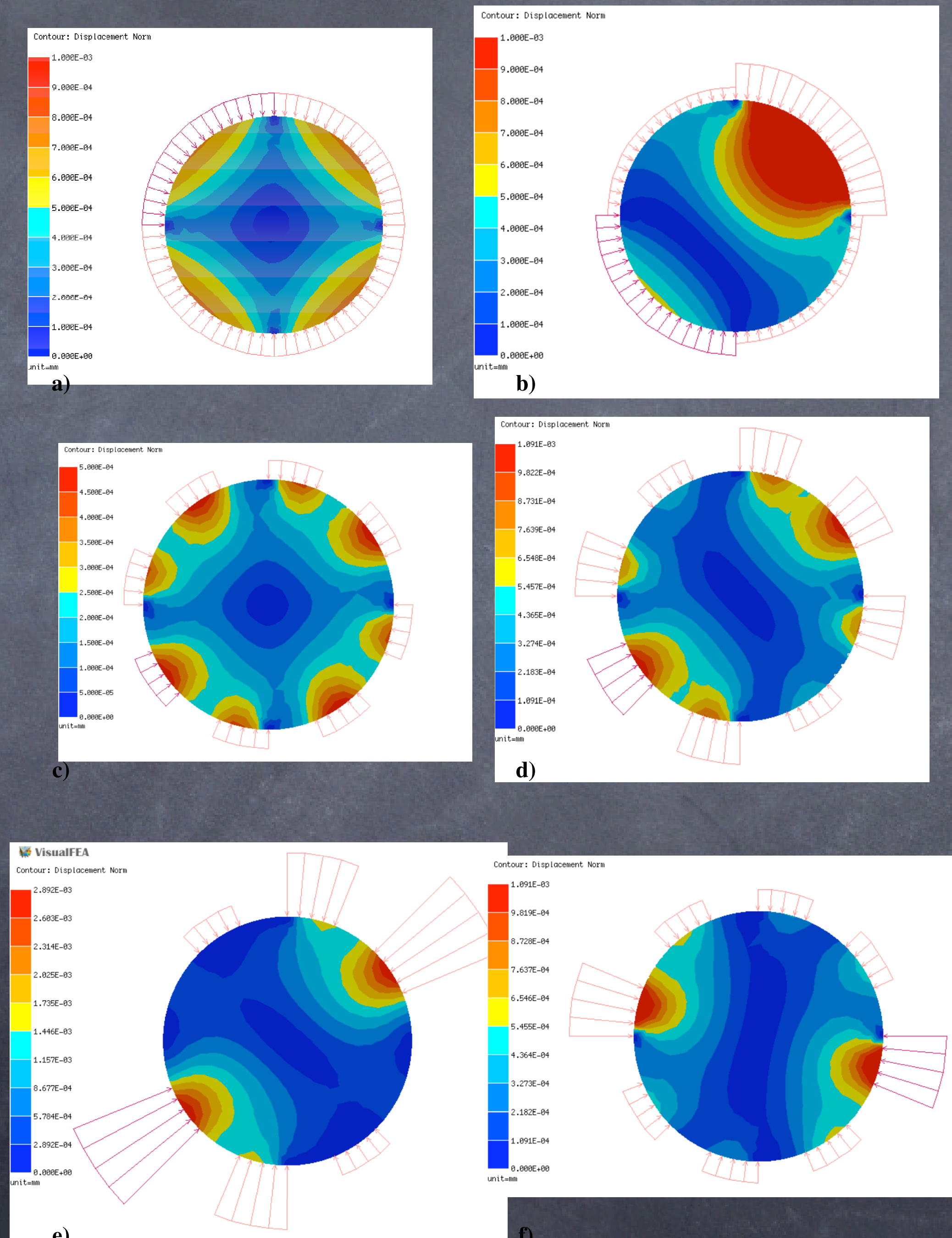
Camera di campionamento



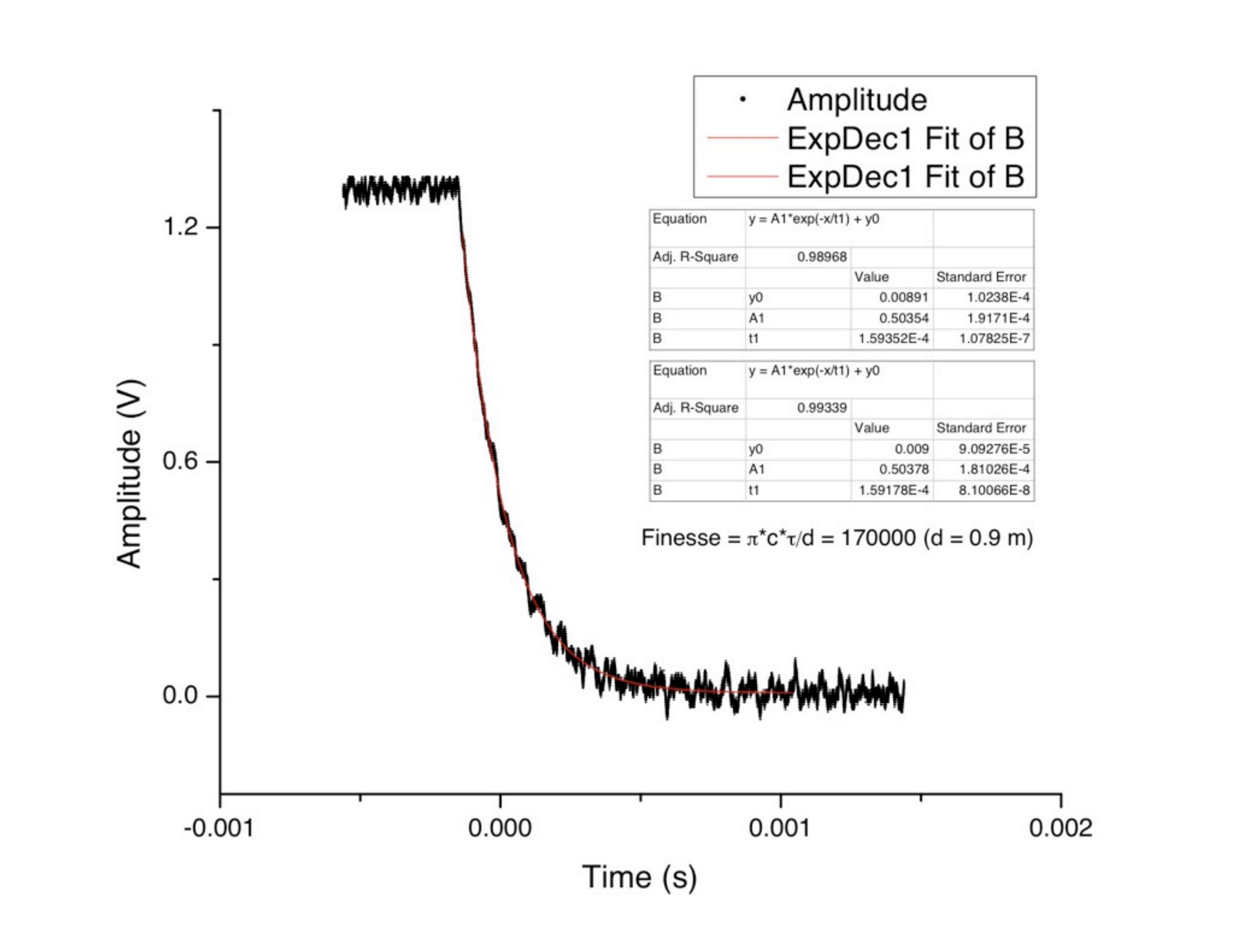
Modulatore MIM
(Mirror Integrated Modulator)



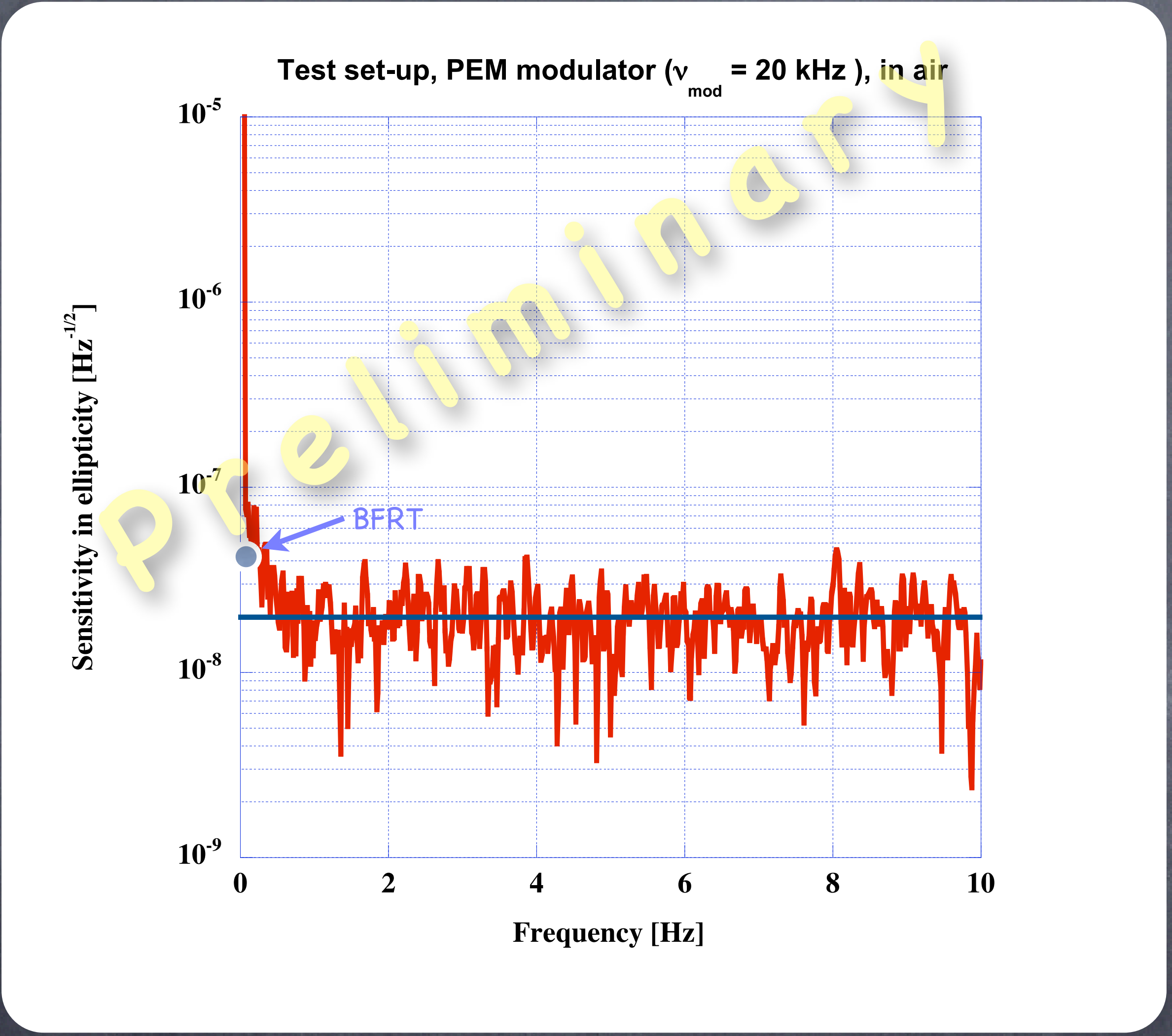
Simulazioni MIM



Test di Finesse a 1064 nm

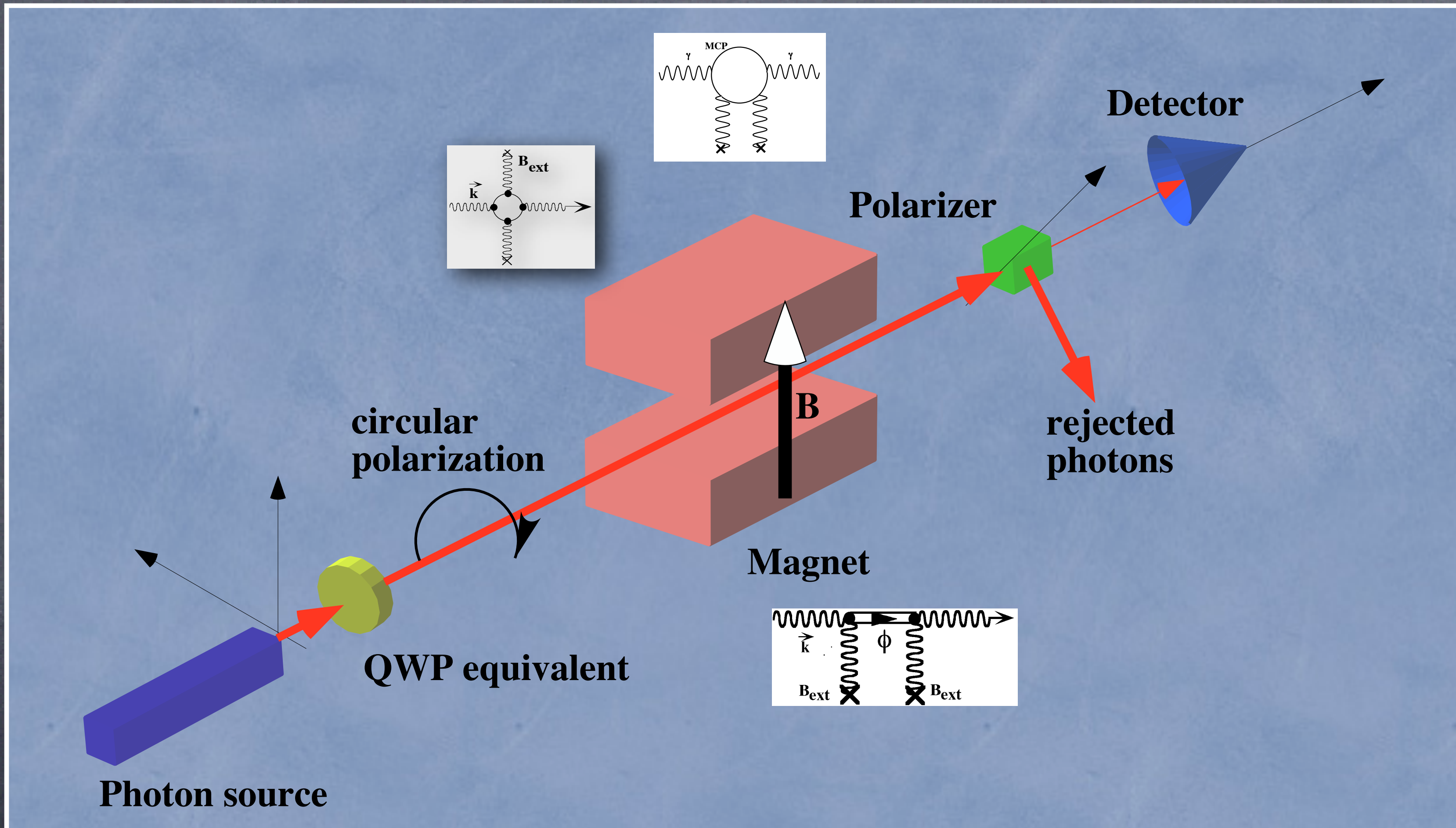


Test di sensibilità



Test set-up in aria senza cavità

Idealized photon-photon scattering experiment with "high energy" photon source



Relevant quantities

- Use Mueller matrix formalism to represent action of optical elements (including the magnetic field) on Stokes vectors representing the polarized photon beam
- Δ is some birefringence induced by interaction in the magnetic field region (QED, ALPs, MCPs...)
- In the QED case

$$\Delta = \frac{\pi}{\lambda} L \Delta n \approx (2 \cdot 10^{-17}) \left(\frac{E_\gamma}{\mathrm{eV}} \right) \left(\frac{L}{\mathrm{m}} \right) \left(\frac{B^2}{\mathrm{T}^2} \right).$$

$$\mathrm{signal} = R_{on} - R_{off} = N_\gamma \frac{(1-\epsilon^2)}{2} sin 2\Delta \qquad \mathrm{noise} = \sqrt{N_\gamma \frac{(1+\epsilon^2)}{2}}$$

$$\mathrm{SNR} = \sqrt{2}\Delta \frac{(1-\epsilon^2)}{\sqrt{1+\epsilon^2}} \sqrt{N_\gamma \sqrt{T}}$$

Assuming Δ<<1 and polarizer with unit transmittivity

Detection Times at FEL's

Source	Energy [eV]	Flux [ph/s]	Δ (10 T, 10 m)	T(SNR=1) [s]	T[8 hr d.]
FLAME (LNF)	1.55	2.00E+20	3.1E-14	2.60E+06	90.33
FLASH (DESY)	90	5.60E+15	1.8E-12	2.76E+07	956.85
SPARX (LNF)	400	1.20E+14	8E-12	6.51E+07	2,260.56
XFEL (DESY)	3000	6.00E+17	6E-11	2.31E+02	0.01

Pro's and con's

- Pro's
  - larger effect
  - single-photon detection -> low noise
  - possible test at different energies
- Con's
  - need circularly polarized photons
  - need a good polarizer for high energy photons