Polarization measurements and their perspectives at the Low Energy Frontier

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

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Summary

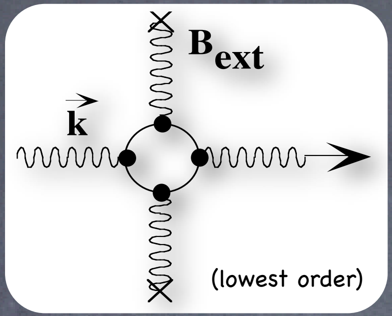
- Physics themes at the Low Energy Frontier
- Photon probes (brief intro to polarization detection)
- State of the art and status of PVLAS Phase II
- Hopes (and limitations) for the future

Physics themes

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

QED effects

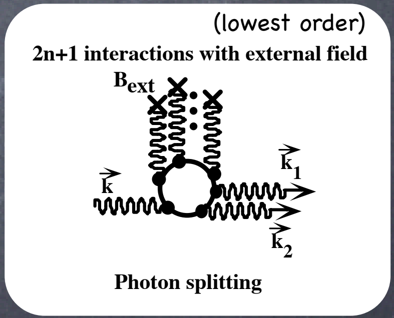
- Non linearities in the Maxwell equations predicted by the Heisenberg-Euler effective Lagrangian (1936). Photon-photon scattering in QED (also Schwinger, 1951, Adler, 1971)



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

  - 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)

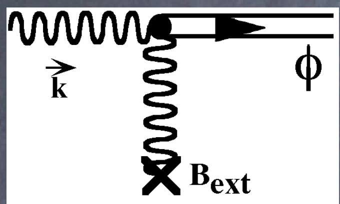


$$\alpha = \left(\frac{\pi L}{\lambda}\right) \Delta \kappa = \left(\frac{\pi L}{\lambda}\right) (\kappa_{\parallel} - \kappa_{\perp}) = \left(\frac{L}{2}\right) (0.27) \left(\frac{\omega}{m_e}\right)^5 \left(\frac{B}{B_{cr}}\right)^6 \text{ cm}^{-1}$$

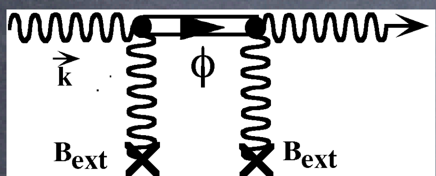
  - Polarization selective absorption. "Detectable" as an apparent rotation of the polarization plane (dichroism) when using a resonant cavity

ALPs, MCPs, ... (WISPs)

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

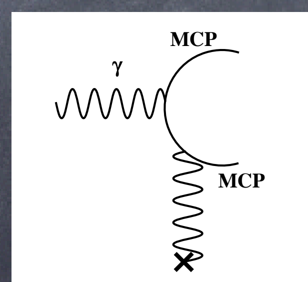


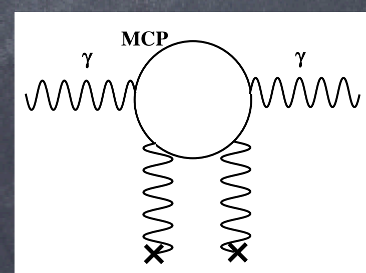
$$\alpha = \frac{B^2\omega^2}{M^2 m^4}\left[\sin\left(\frac{m^2 L}{2\omega}\right)\right]^2$$



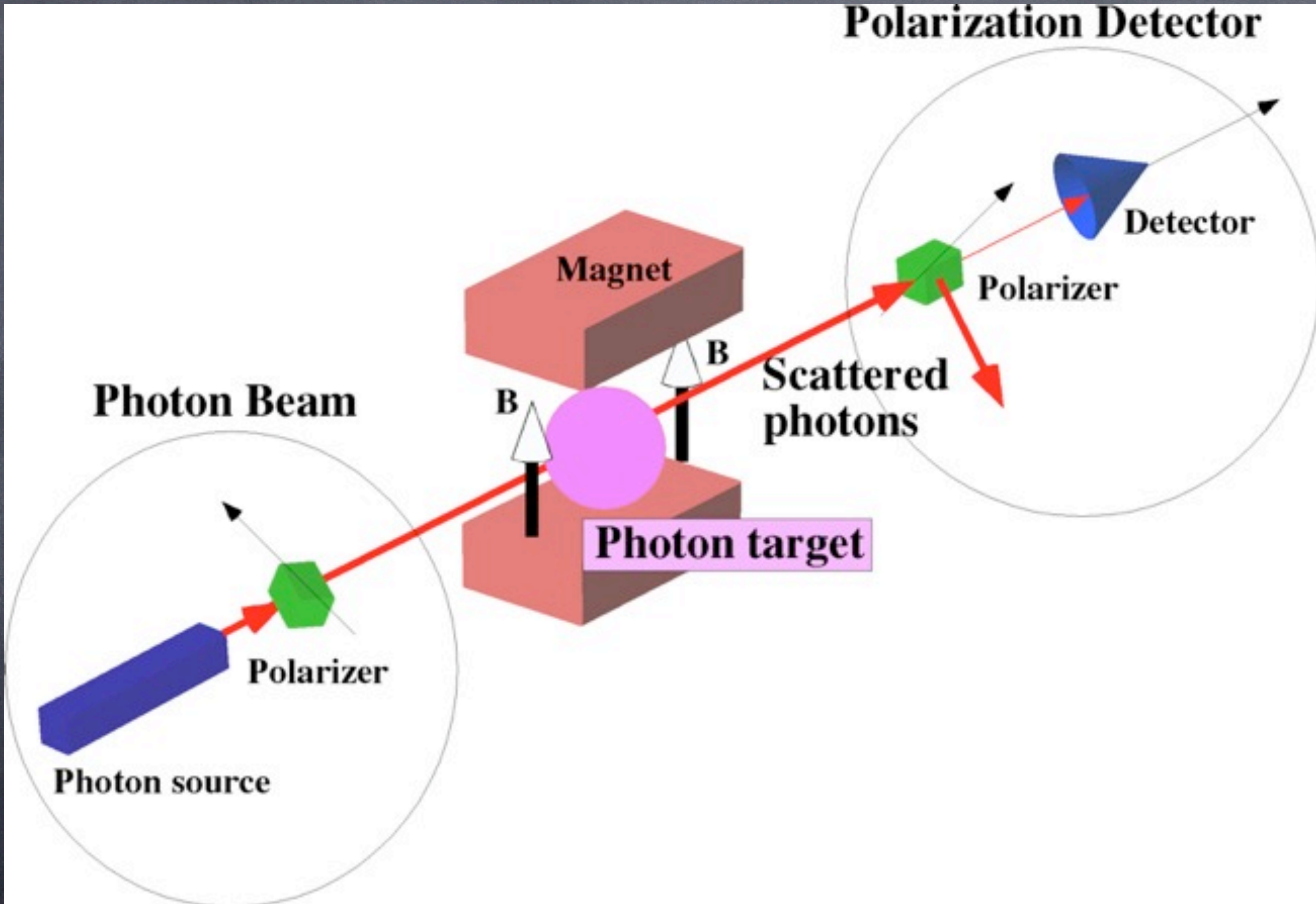
$$\psi = \frac{B^2\omega^2}{2M^2 m^4}\left[\left(\frac{m^2 L}{2\omega}\right) - \sin\left(\frac{m^2 L}{2\omega}\right)\right]$$

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



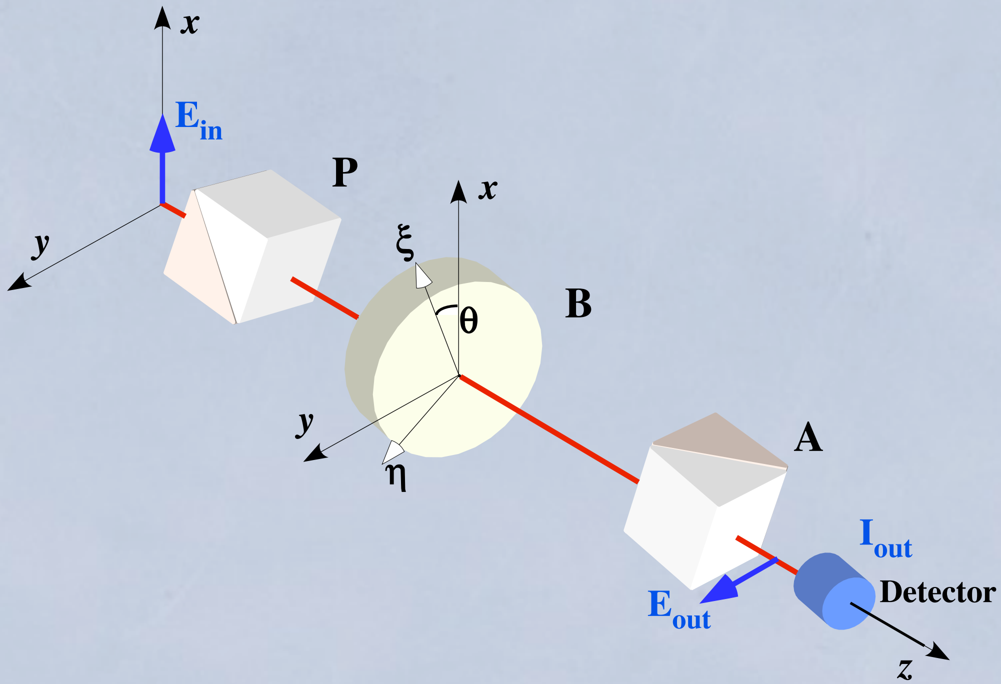


General scheme of polarization measurements



Basic techniques of polarization detection

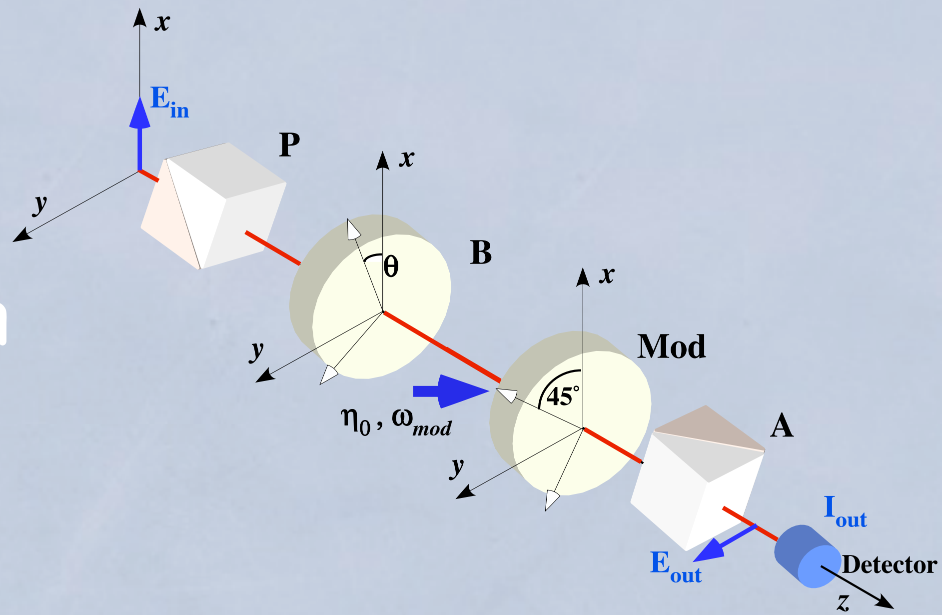
Basic techniques of polarization detection



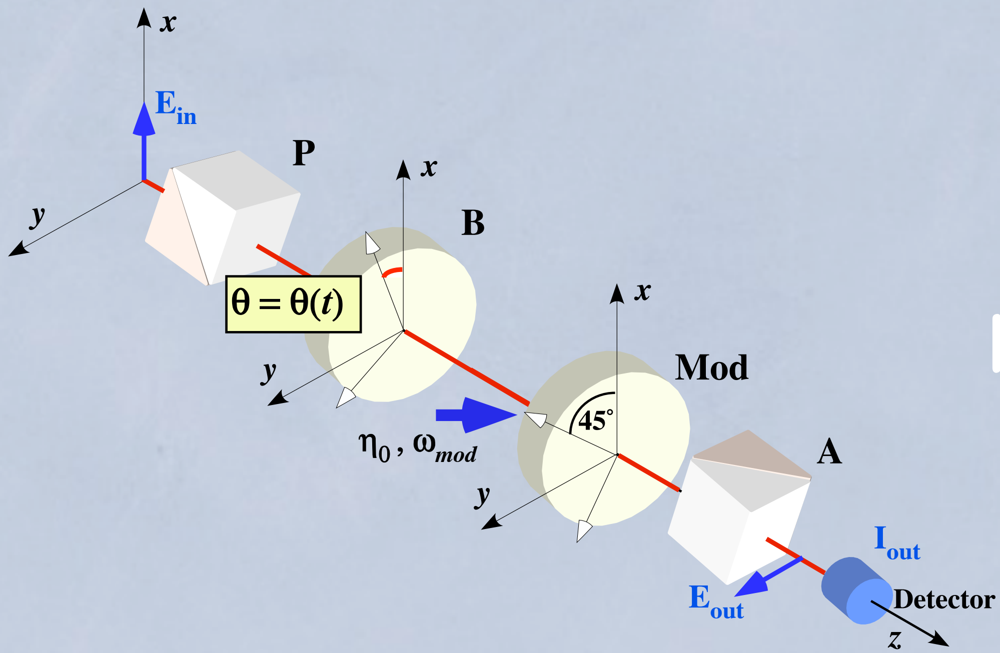
Static detection

Basic techniques of polarization detection

Homodyne detection

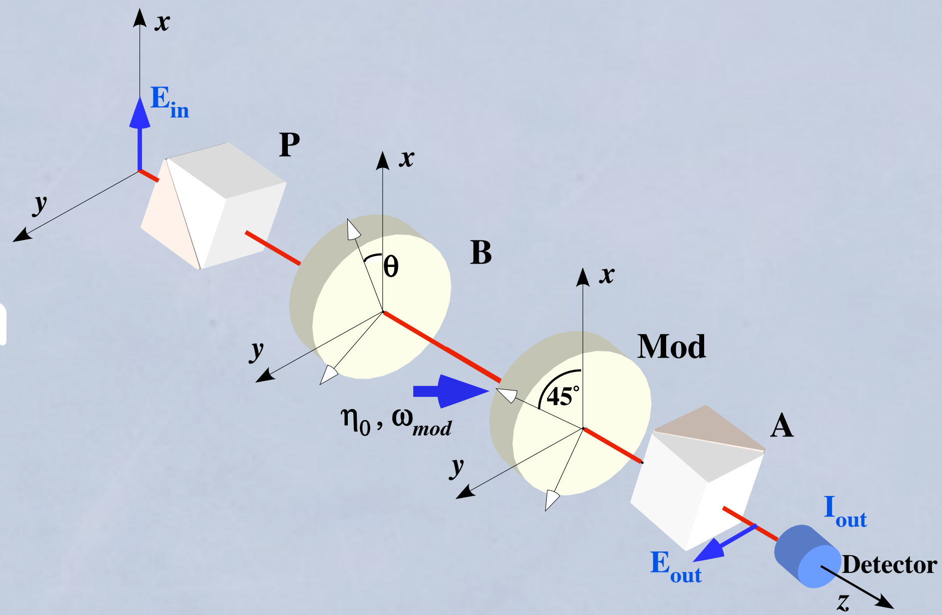


Basic techniques of polarization detection



Heterodyne detection

Homodyne detection



Panorama of polarization experiments

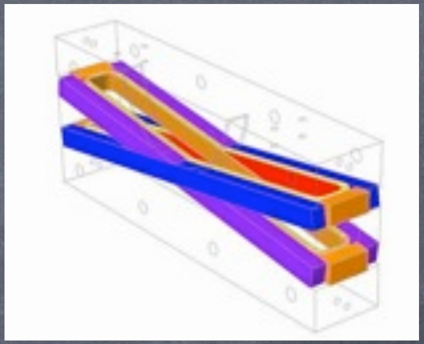
- Current
  - BMV (Toulouse) -> C. Rizzo in this meeting
  - OSQAR (CERN) -> A. Siemko in this meeting
  - Q&A (Taiwan) -> H.-H. Mei in this meeting
- Starting-up
  - PVLAS Phase II (INFN Italy)

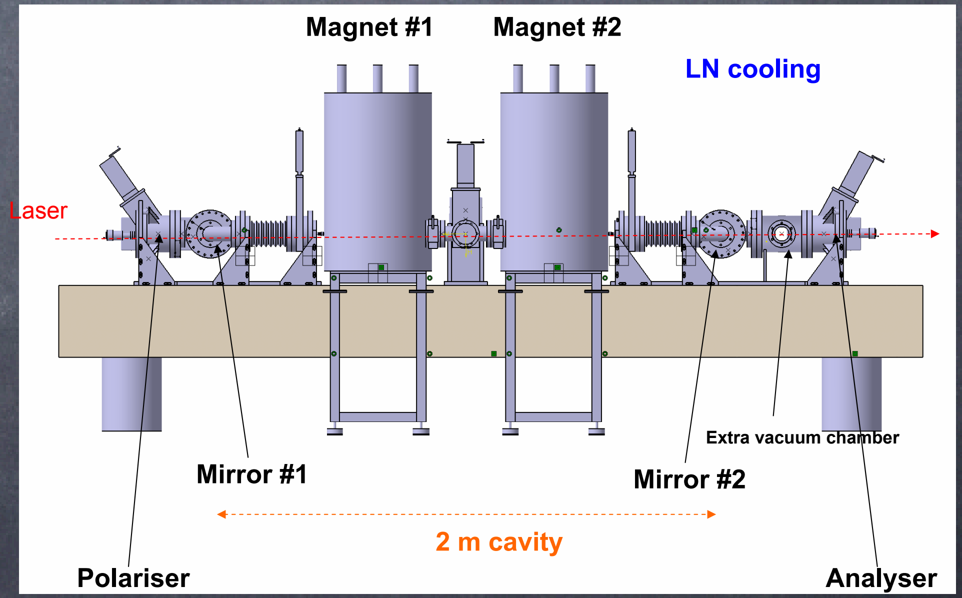
Common features

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

BMV

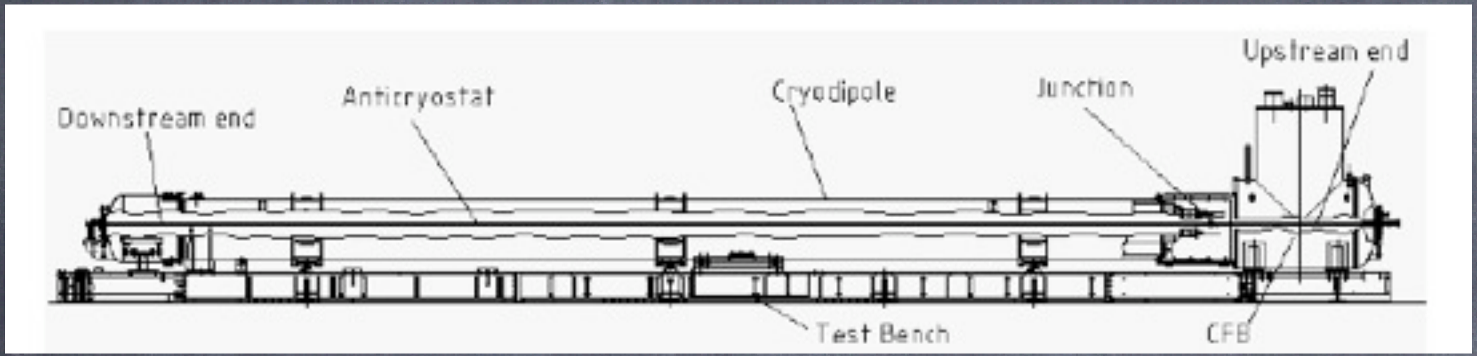
- BMV (Toulouse, C. Rizzo group leader)
  - 1 eV photons, few mW power, pulsed magnetic fields up to 12 T (ms duration), homodyne detection, Fabry-Perot resonator (R. Battesti et al., Eur. Phys. J. D 46, 323-333 (2008))
  - Website reports $\Delta n_{vide} = (-9.8 \pm 22.9) \cdot 10^{-17}\,T^{-2}$ Goal is ~$4 \cdot 10^{-24}$ T^{-2}
  - Status: see talk by C. Rizzo





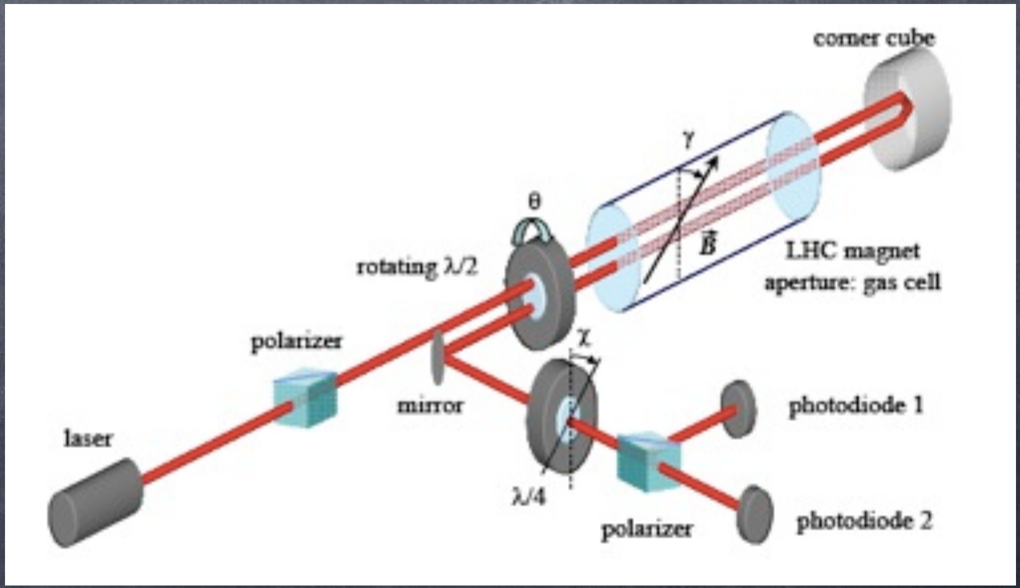
OSQAR

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



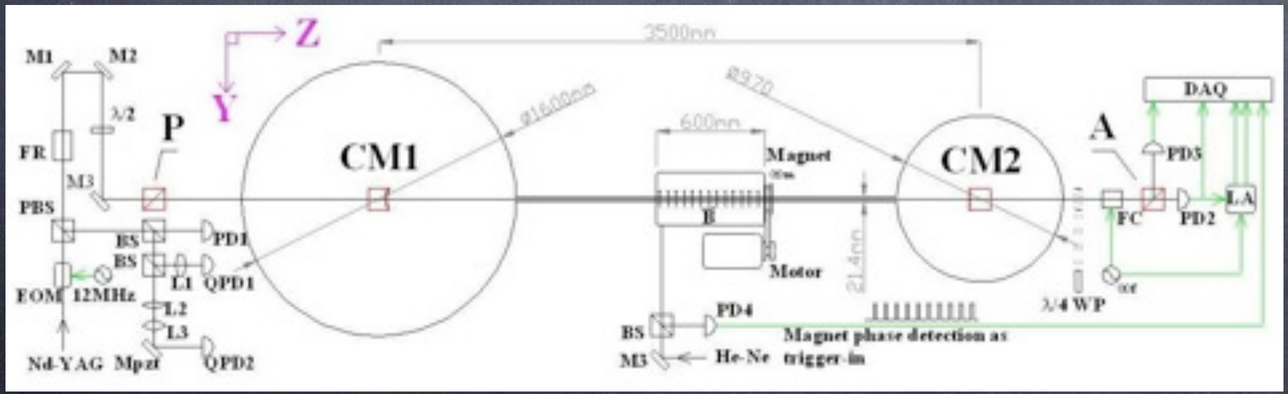
LHC dipoles

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)



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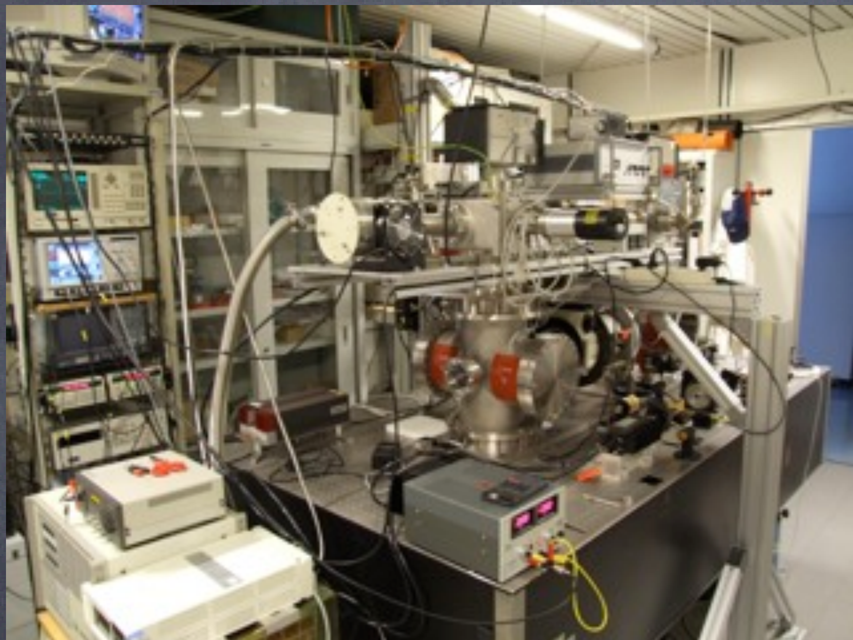
Moving on to PVLAS Phase II

G. Cantatore, M. Karuza, V. Lozza (Univ. and INFN Trieste) and R. Cimino (INFN Frascati)

- The PVLAS signal is gone: challenge is now noise
- The PVLAS apparatus in Legnaro was limited by size, cost and duty cycle
- Solution: scale 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

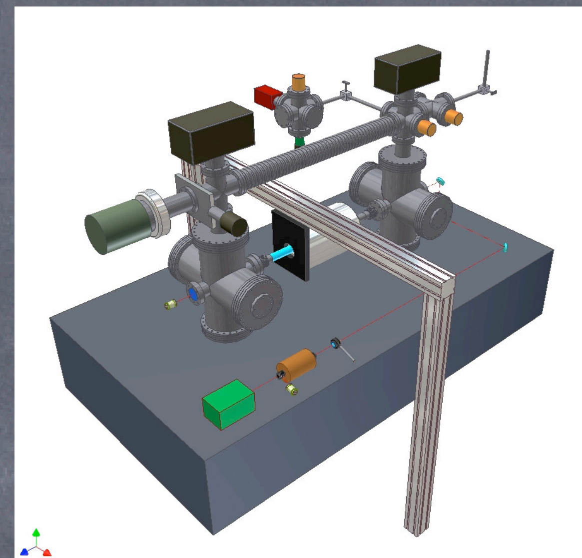
PVLAS Phase II

R&D to achieve high sensitivity polarimetry with a table-top heterodyne ellipsometer
Ellipsometric test measurements on gas and vacuum with a rotating permanent magnet



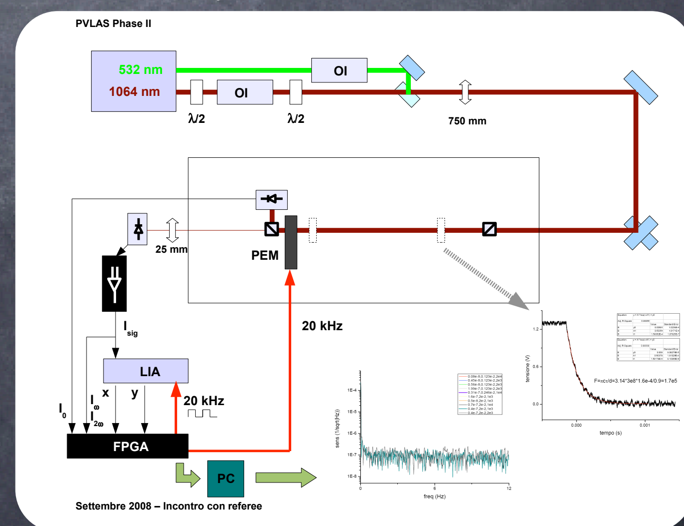
View of the laboratory - INFN Trieste

3D scheme

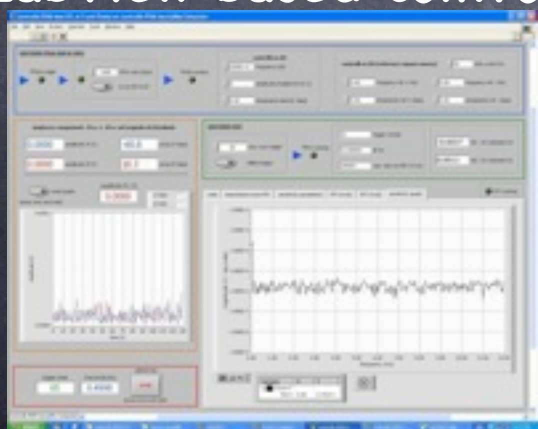


Permanent magnet

optics layout

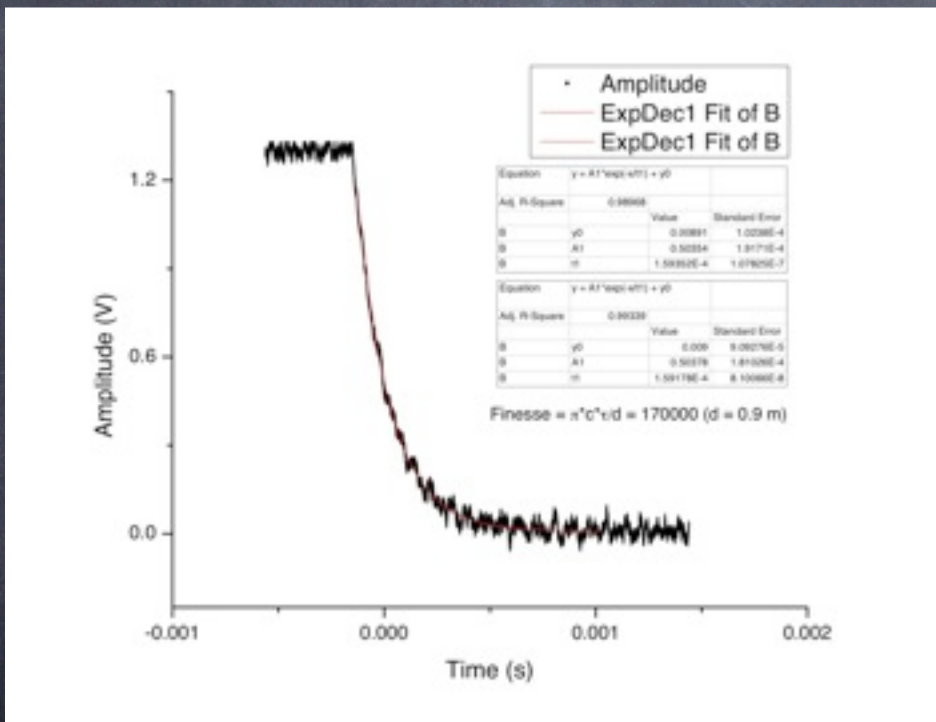


LabView based control



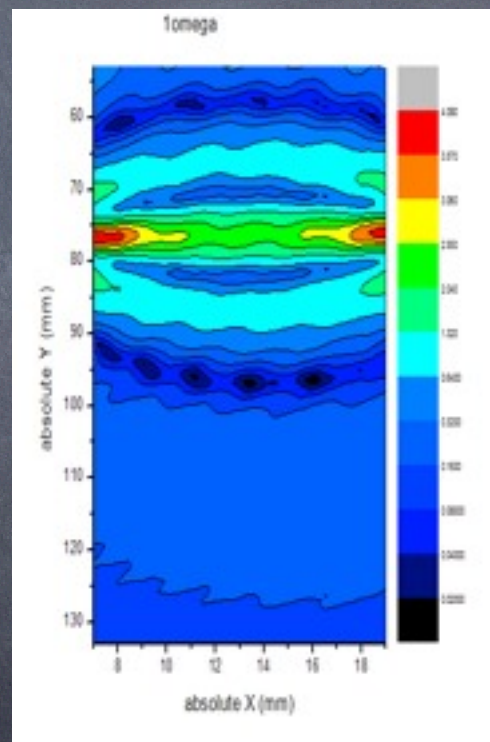
Accomplished tasks I

- Frequency-locking of high finesse Fabry-Perot optical resonator (F ~ 170000, close to design goal)

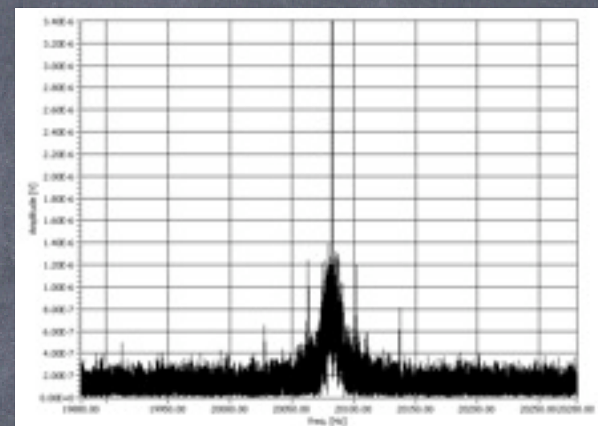


Finesse = 170000

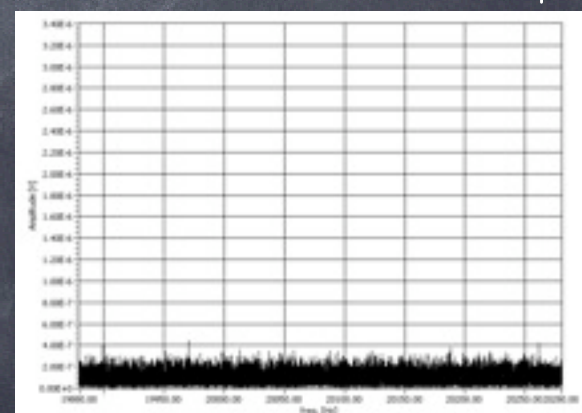
- Characterization of Hinds Instruments PEM I/FS20 photo-elastic modulator
  - highly non-uniform when excited (sine wave excitation)
  - non-uniformity induced excess birefringence noise around the modulation frequency



Birefringence map of PEM modulator crystal



Excess noise around excitation frequency



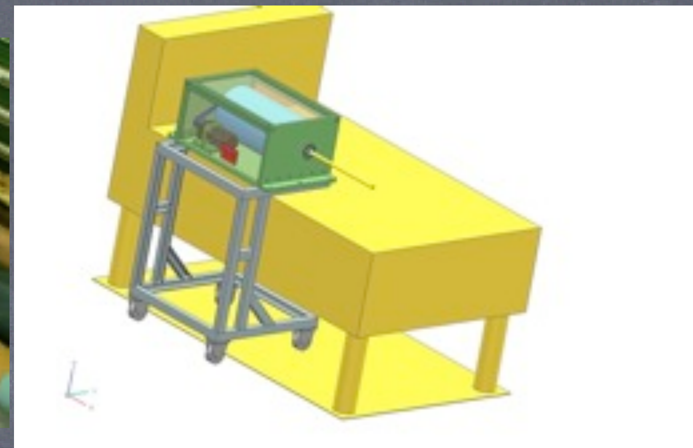
Electronic noise floor

Accomplished tasks II

- Installation of UHV compatible movement stages for optical elements



- Design and contruction of rotating magnet support (final installation in progress)

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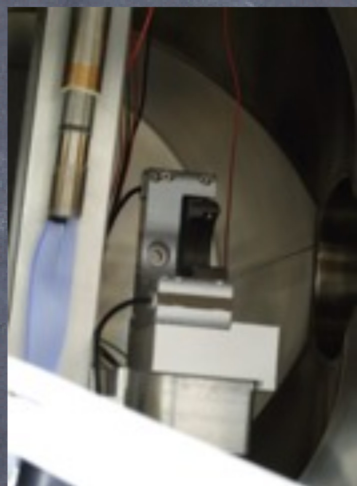


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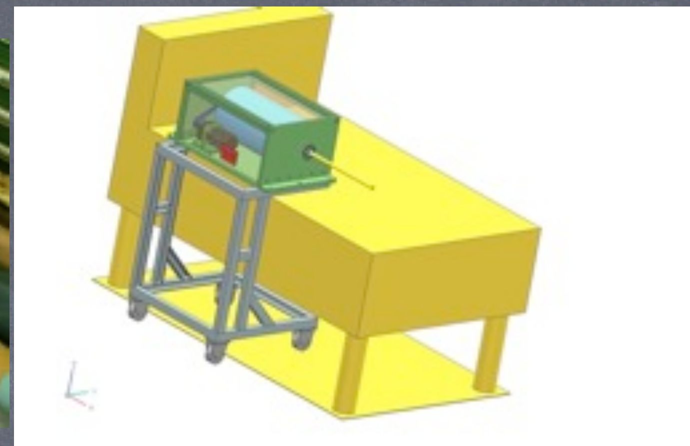
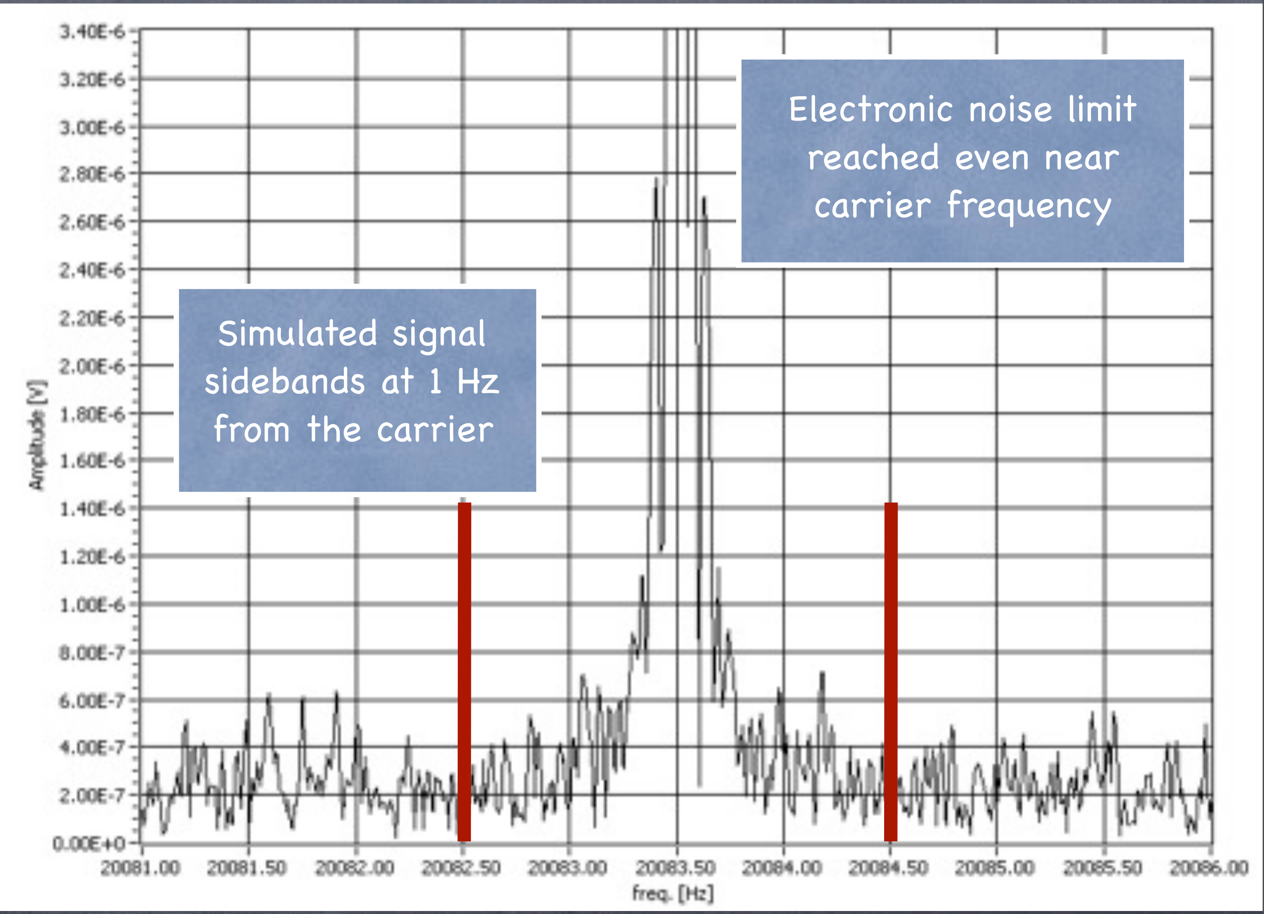


Work in progress

- Construction (completed) and first tests on Mirror Integrated Modulator

- Preliminary sensitivity tests
  - $5 \cdot 10^{-8}$ 1/√Hz (limited by electronic noise)



Conclusions for the first half of 2009

- Major subsystems (Fabry-Perot, DAQ, vacuum, process control) successfully tested
- Design requirements on finesse and sensitivity met or within reach
- Permanent magnet rotating support in final installation phase
- Preliminary tests of MIM modulator prototype

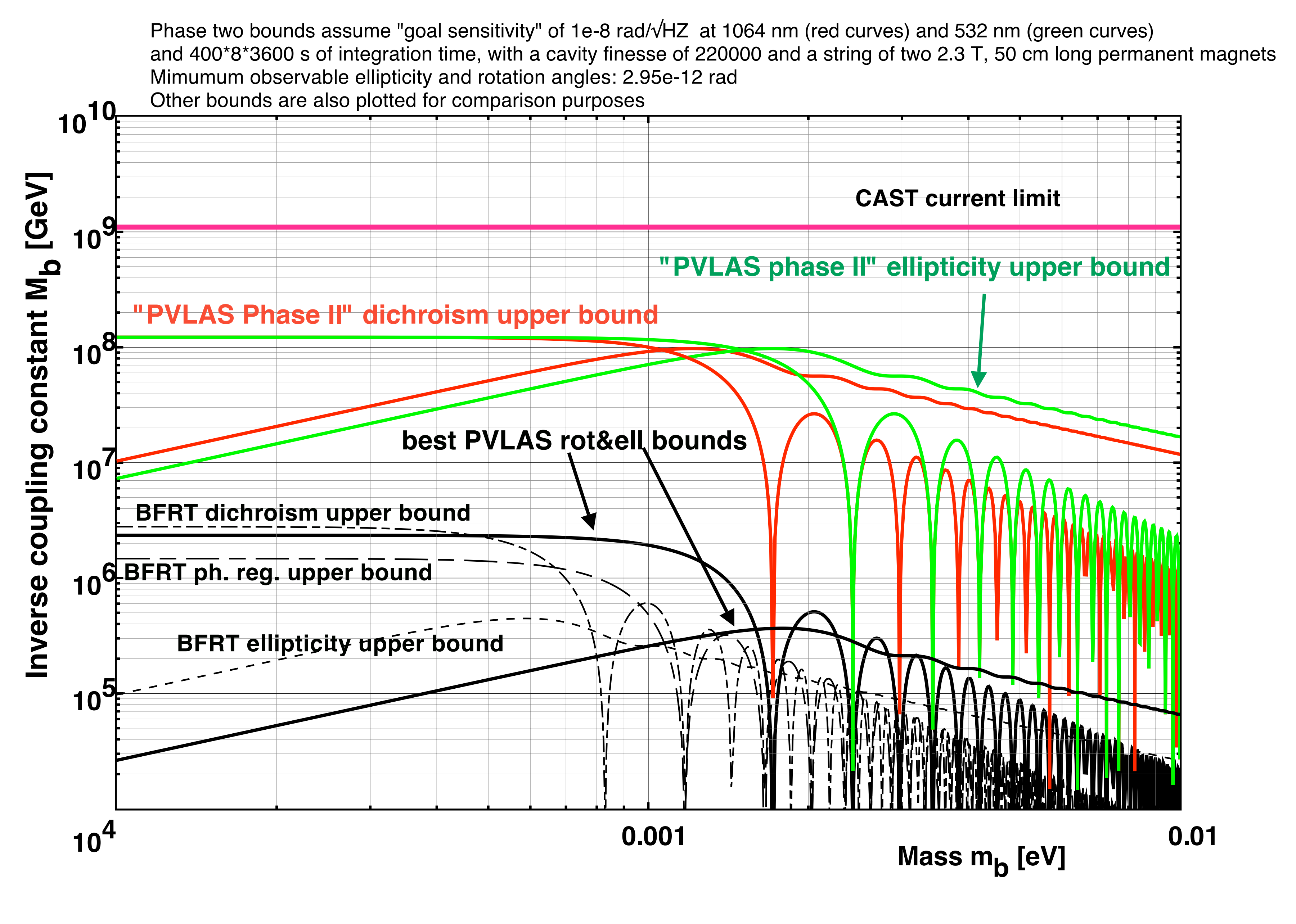
PVLAS Phase II ellipsometer development stages

- Current prototype
  - 900 mW at 1064 nm, 20 mW at 532 nm
  - 1 m long Fabry-Perot with F≈200000
  - 2.3 T, 50 cm long, permanent dipole magnet rotating @7 Hz
  - analog frequency locking, environmental screens
  - Mirror Integrated Modulator (prototype testing stage)
- 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

Config.		IR		GREEN		
		Prototype	Advanced	Prototype	Advanced	Adv. power upg.
	Sens. $[1/\sqrt{Hz}]$	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}	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$
	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.

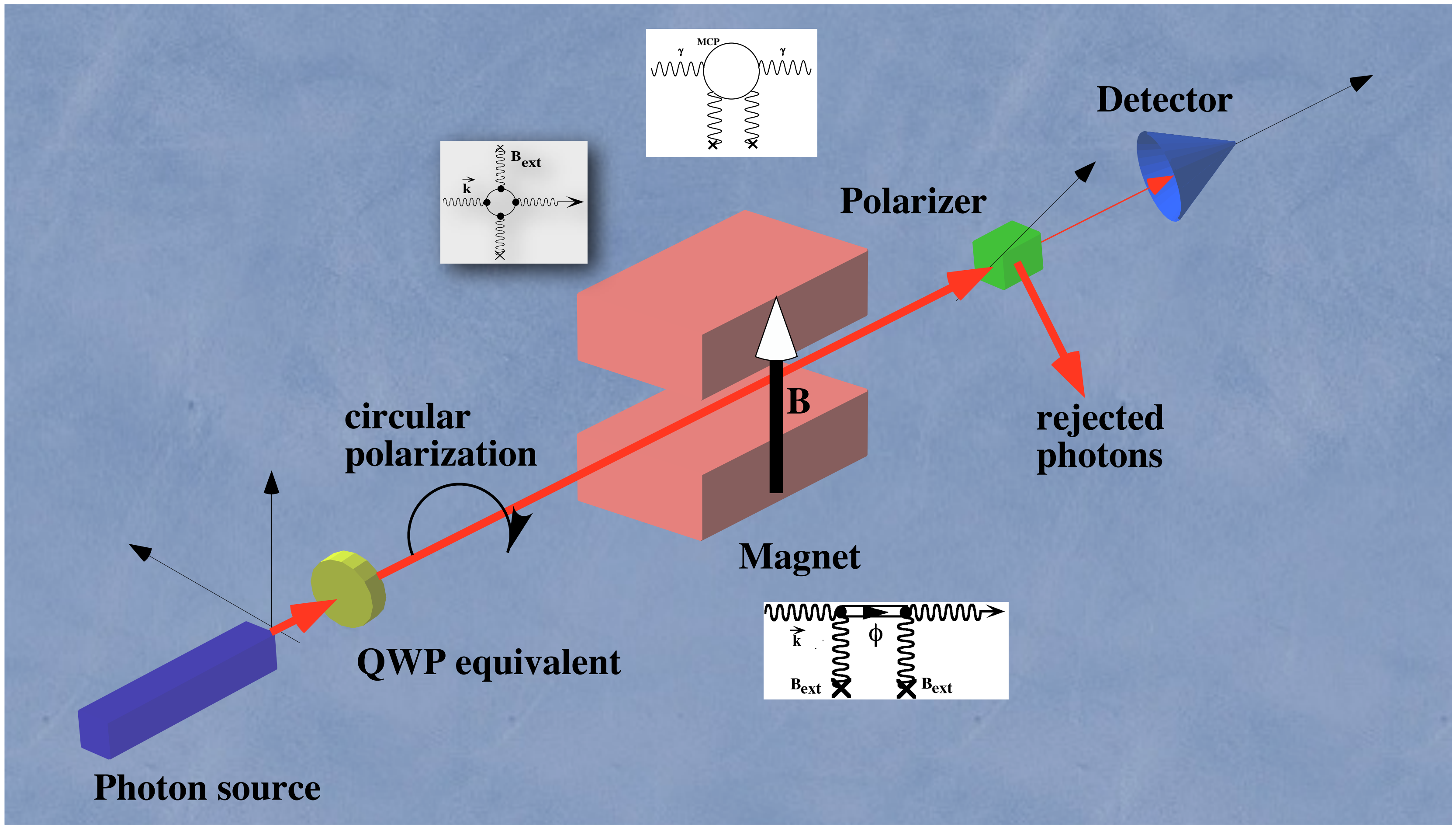
ALP parameter space coverage with polarization measurements



Hopes (and limitations) for the future

- QED effects
  - At low energy (1-2 eV, optical domain), current efforts should be able to achieve dircet detection of photon-photon scattering
  - Polarization experiments with higher energy photon sources (FELs for instance) might be the definitive tool
- WISP physics
  - no hope of reaching the "CAST" barrier with polarization measurements unless fantastic sensitivity is achieved
  - hope -> use expertise gained with Fabry-Perot cavities to implement a reasonant regeneration scheme

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



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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

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

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

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

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

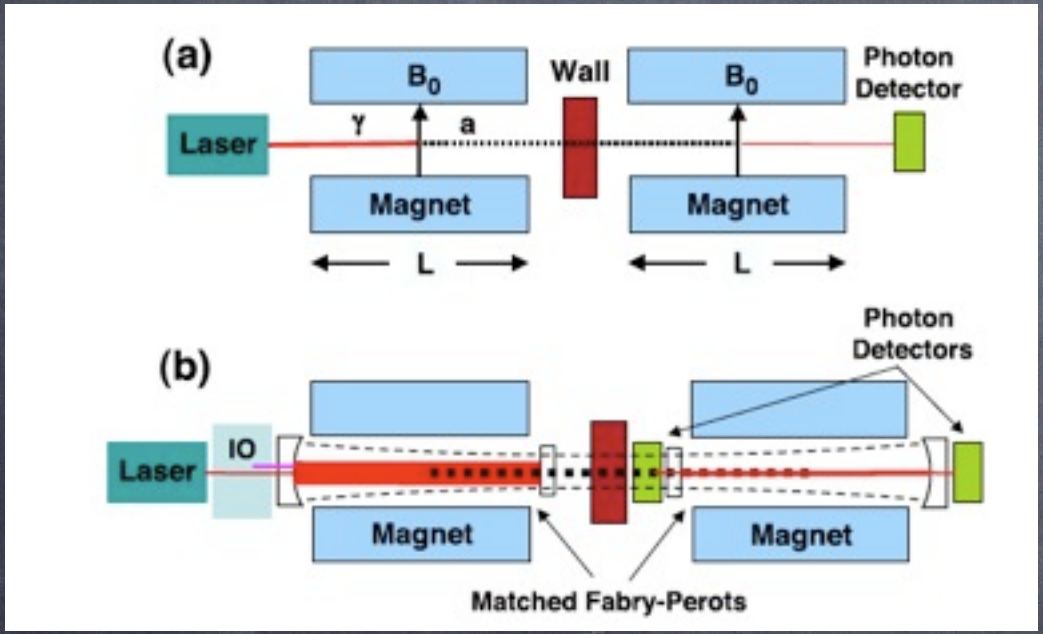
Pro's and con's

- 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

The Next Big Step for ALP detection: 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

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

F. Hoogeveen, T. Ziegenhagen, DESY-90-165, Nucl.Phys.B358

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)

Main challenges for photon regeneration

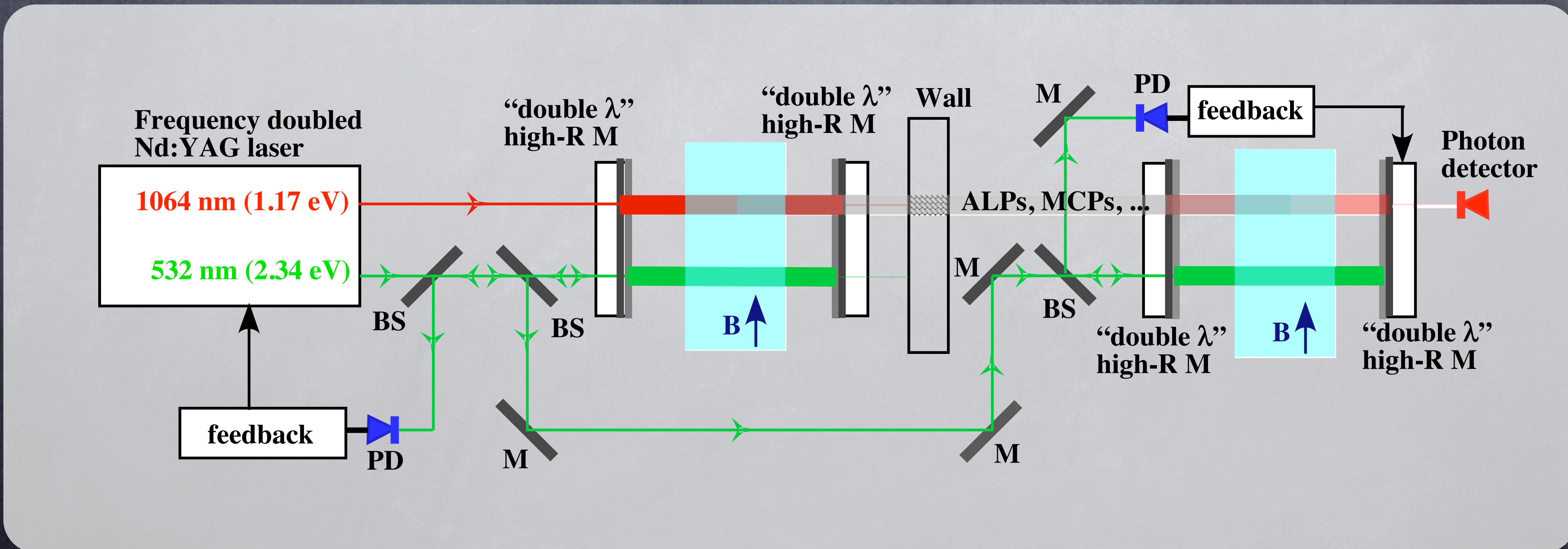
I. Two frequency-locked high finesse Fabry-Perot resonators

II. Low background detectors

III. High-power laser

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



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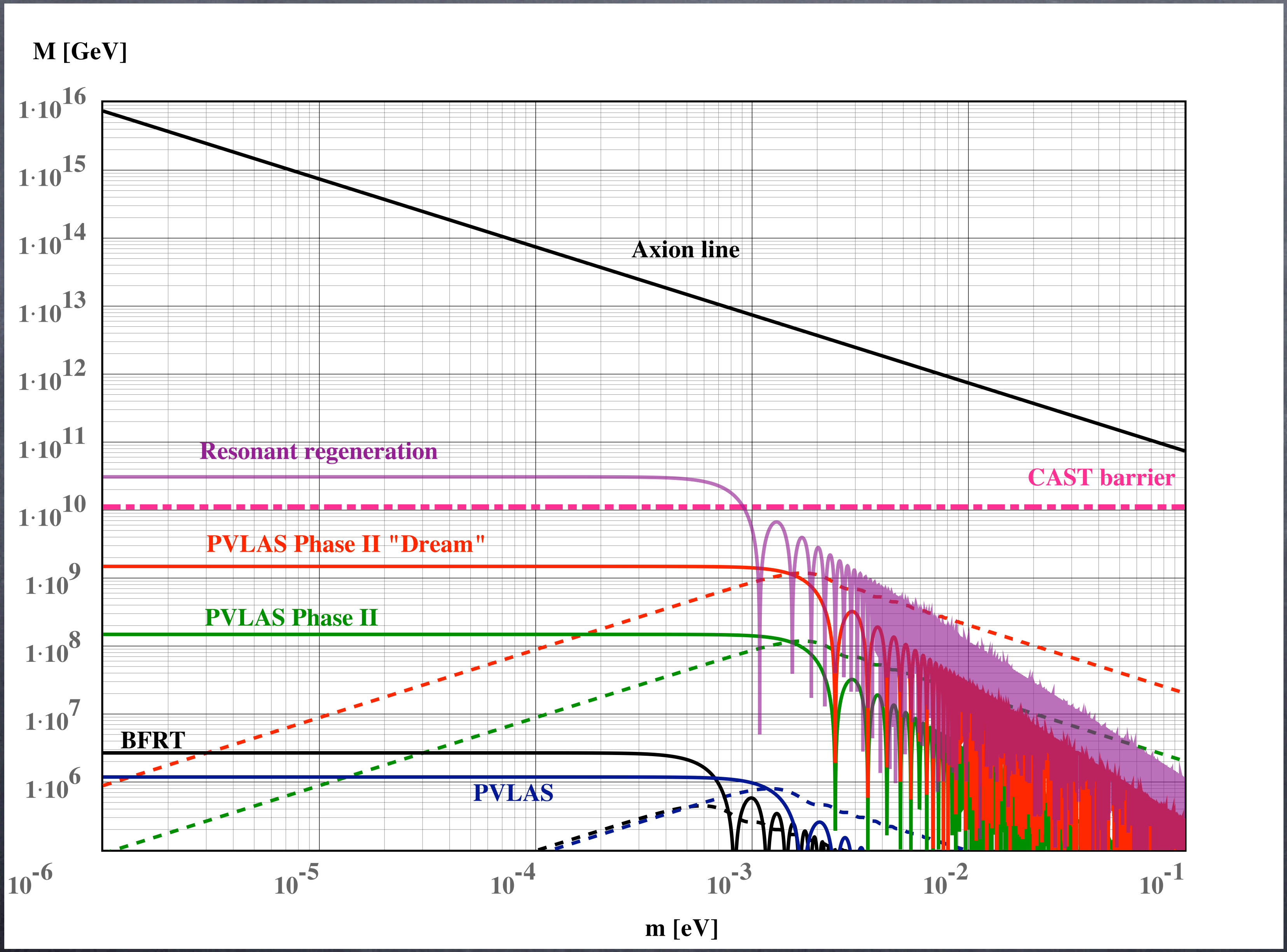
Challenges II-III - Low background detector and high power laser

- **Low background detector at low energy**
  - Common problem of ALP search experiments
  - Experience done within CAST (see talk by M. Karuza)
    - first runs at CAST with a PMT and an APD (reached 0.35 Hz DCR)
    - move to LN2-cooled APD -> first results by BARBE_LT encouraging (background reduction of a factor 104 with respect to normal operating temperature - presented by V. Lozza at Elba 2009)
  - Resonant regeneration measurements can begin with a cooled APD -> Dream detector: a TES (no background!)
- **High-power laser**
  - 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

The reward

- Breaking the CAST barrier



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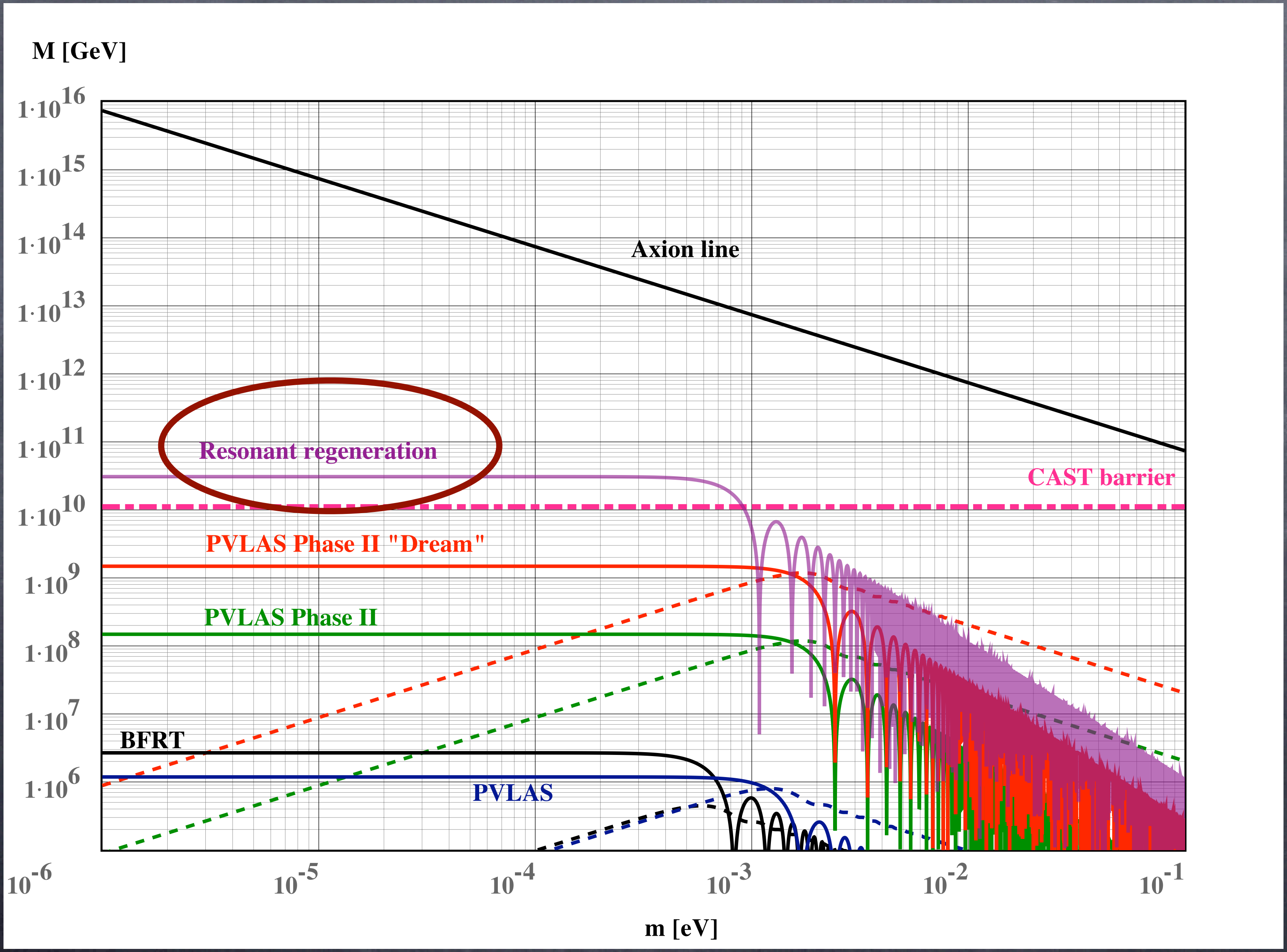

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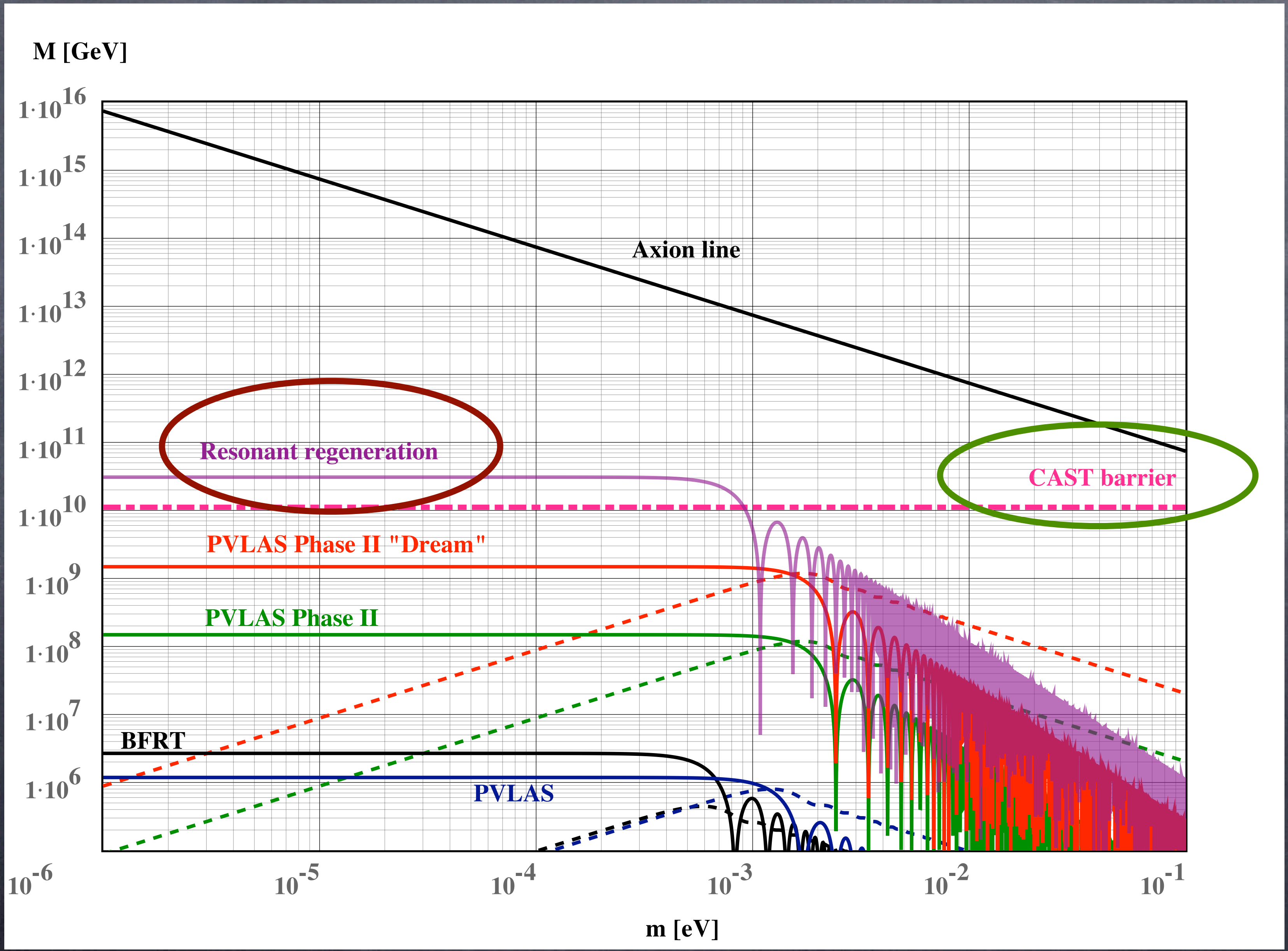
The reward

- Breaking the CAST barrier



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
  - Future -> move up in photon energy starting with FEL sources
- Photon regeneration is the most promising technique to search for ALPs in the laboratory
  - Future -> Resonant Regeneration might propel laboratory experiments over the "CAST barrier"
- Many difficult challenges await us, but that is were the fun is ....

Simple, unauthorized, vacuum experiment...

"Late at night and without permission, Reuben would often enter the nursery and conduct experiments on Vacuum..."

Backup slides