Polarization measurements and their perspectives: PVLAS Phase II

Probing Quantum Vacuum and WISP Physics

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Università e INFN - Trieste

Summary

- Physics themes
- Polarization experiments
- Moving on to Phase II
- New possibilities and outlook

Starting Group for PVLAS Phase II

G. Cantatore, M. Karuza, V. Lozza, G. Raiteri - University and INFN Trieste

R. Cimino - INFN LNF Frascati

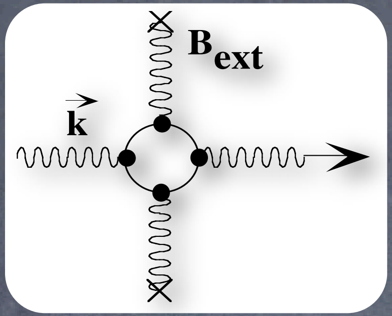
...

Physics themes

- **Basic experimental technique**
  - measure small (1 part in 10^{10} or better) changes in the polarization state of a visible light beam
- **Which physics problems can one attack?**
  - QED effects at low energies
  - WISPs
  - ... (write quickly the White Paper!!!)

QED

- Non linearities in the Maxwell equations predicted by the Heisenberg-Euler effective Lagrangian (1936). Photon-photon scattering in QED

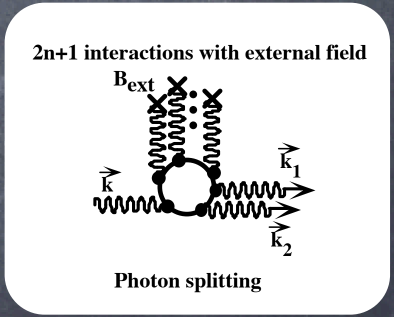


$$\psi = \left(\frac{\pi L}{\lambda}\right)\Delta n = \left(\frac{\pi L}{\lambda}\right)(n_\parallel - n_\perp) = \frac{3\alpha^2 B L \omega}{45 m_e^4}$$

  - 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)

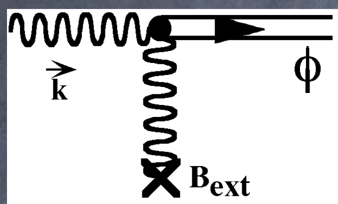
$$\alpha = \left(\frac{\pi L}{\lambda}\right)\Delta\kappa = \left(\frac{\pi L}{\lambda}\right)(\kappa_\parallel - \kappa_\perp) = \left(\frac{L}{2}\right)(0.27)\left(\frac{\omega}{m_e}\right)^5\left(\frac{B}{B_{cr}}\right)^6 \ \mathrm{cm}^{-1}$$



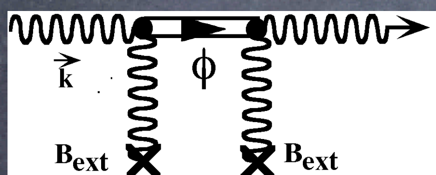
  - Polarization selective absorption. "Detectable" as an apparent rotation of the polarization plane (dichroism) when using a resonant cavity

ALPs, MCPs, ... (WISPs)

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

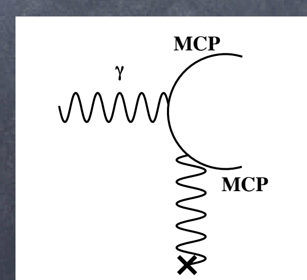


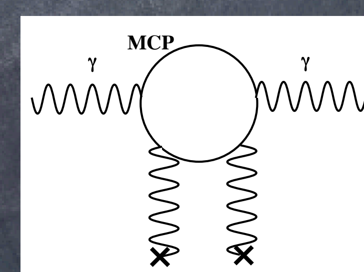
$$\alpha = \frac{B^2\omega^2}{M^2 m^4}\left[\sin\left(\frac{m^2 L}{2\omega}\right)\right]^2$$



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

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





Polarization experiments

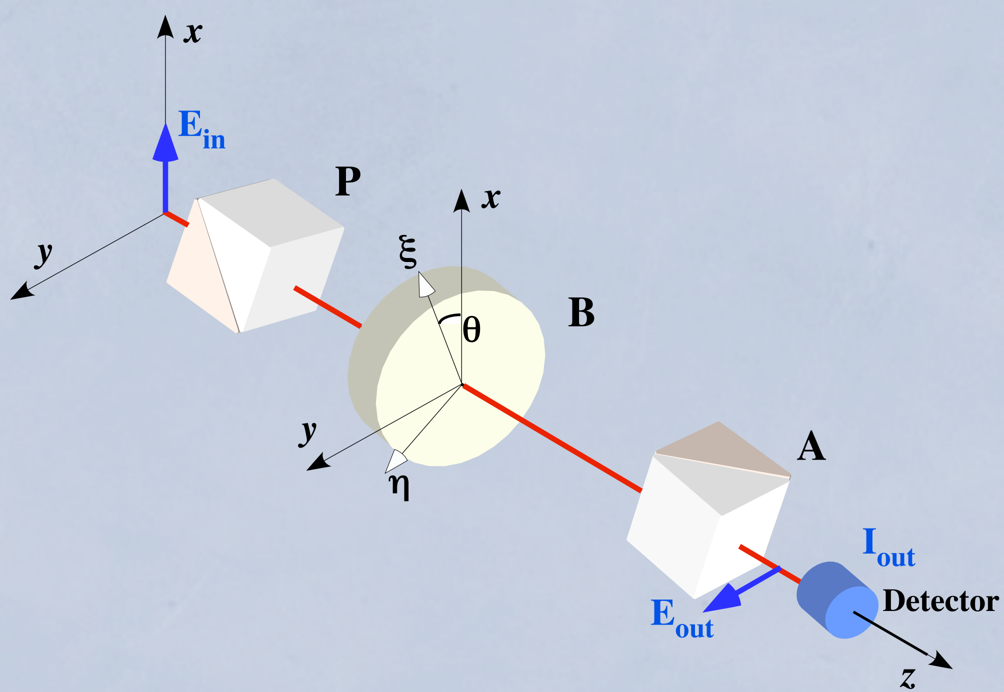
- Original idea: Iacopini and Zavattini at CERN (1979)
- Precursor experiment
  - BFRT (Brookhaven, Fermilab, Rochester, Trieste)
- Current
  - PVLAS (INFN Italy), Q&A (Taiwan)
- Up next
  - BMV (Toulouse) -> nearly completed
  - OSQAR (CERN) -> development stage
- Proposal stage
  - PVLAS Phase II

Common features

- Photon beam probes a magnetic field region
  - low energy (1-2 eV)
  - low flux (1 W continuous at most ->3-6$\cdot10^{18}$ ph/s
- Time-varying effect
- Optical path amplification
- Main problem: noise background

Basic principle of polarization measurements

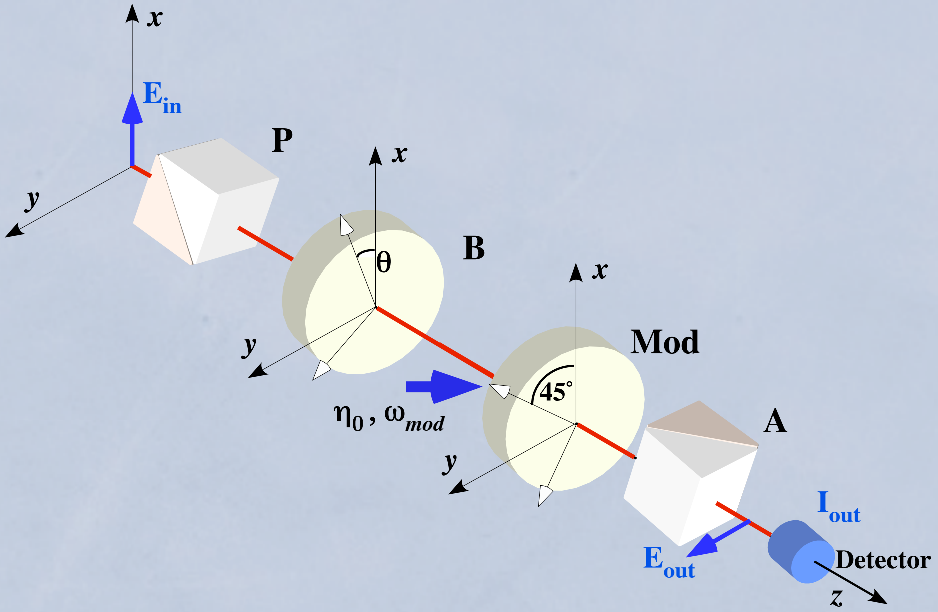
Basic principle of polarization measurements



Static detection

Basic principle of polarization measurements

Homodyne detection



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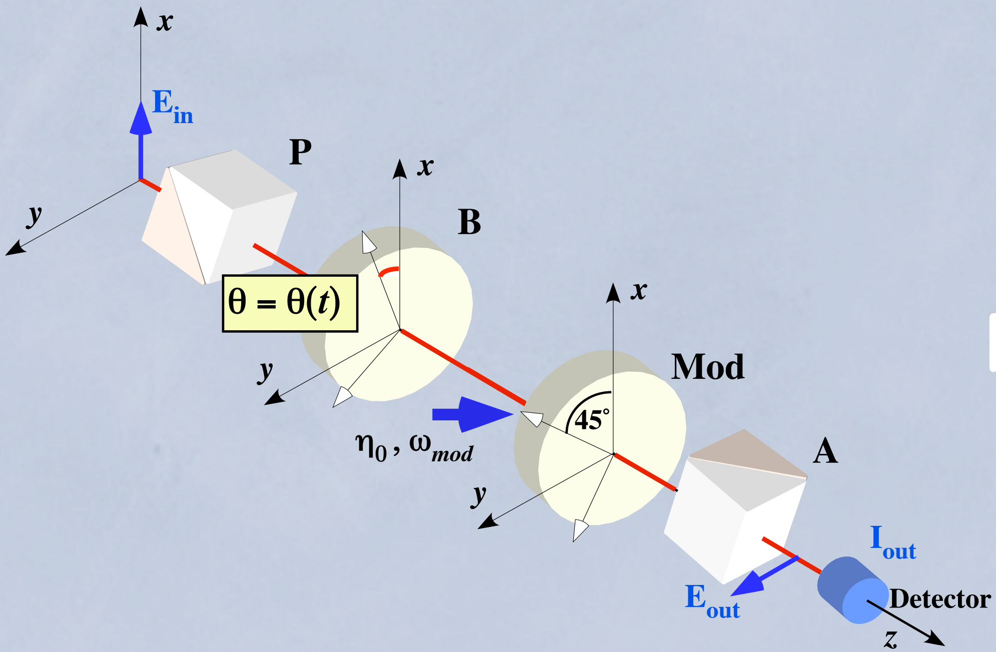
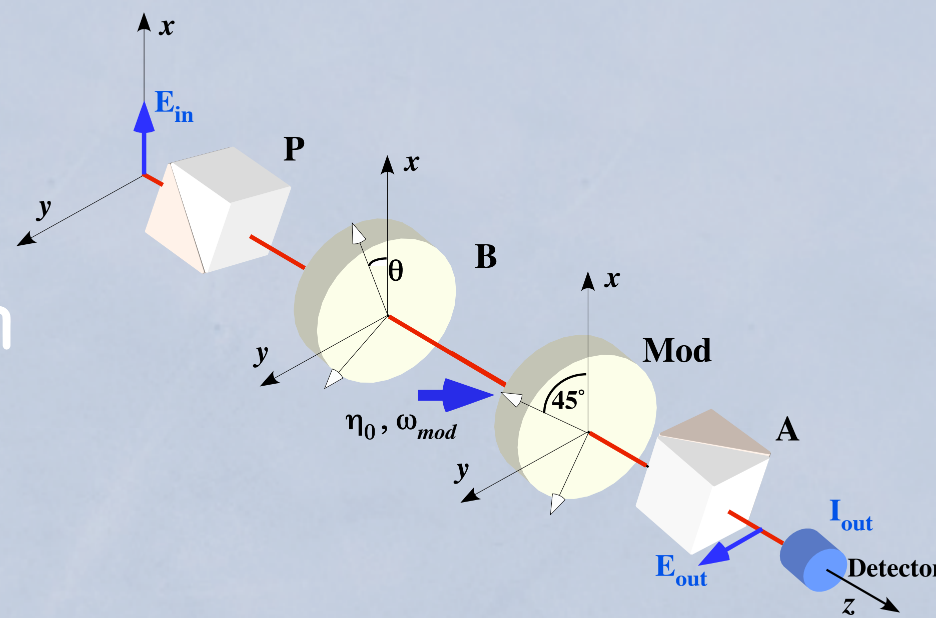


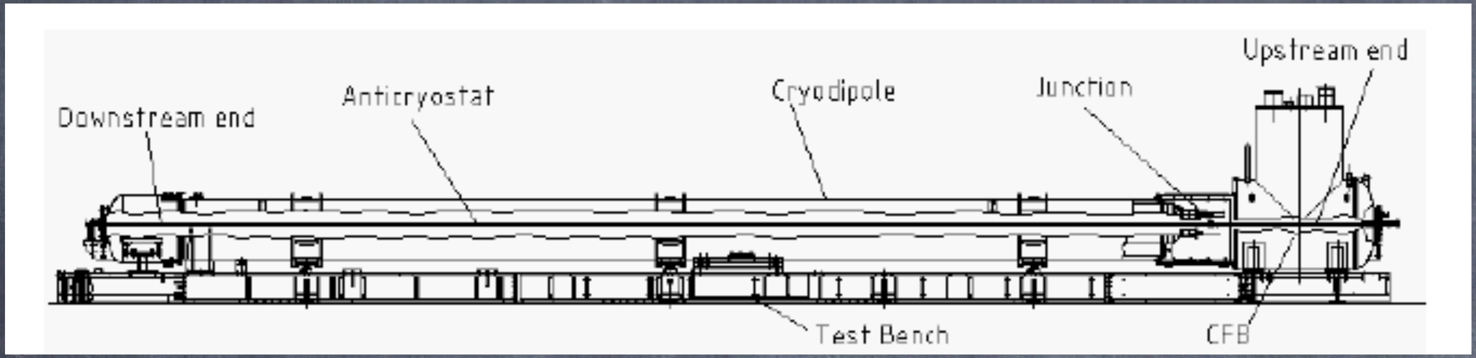
Heterodyne detection



Homodyne detection

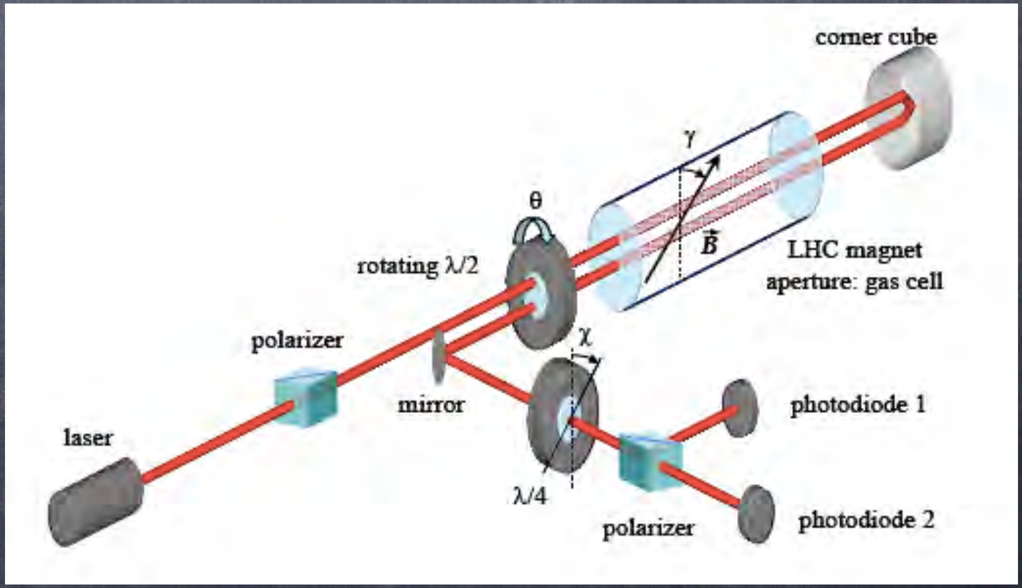
OSQAR

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



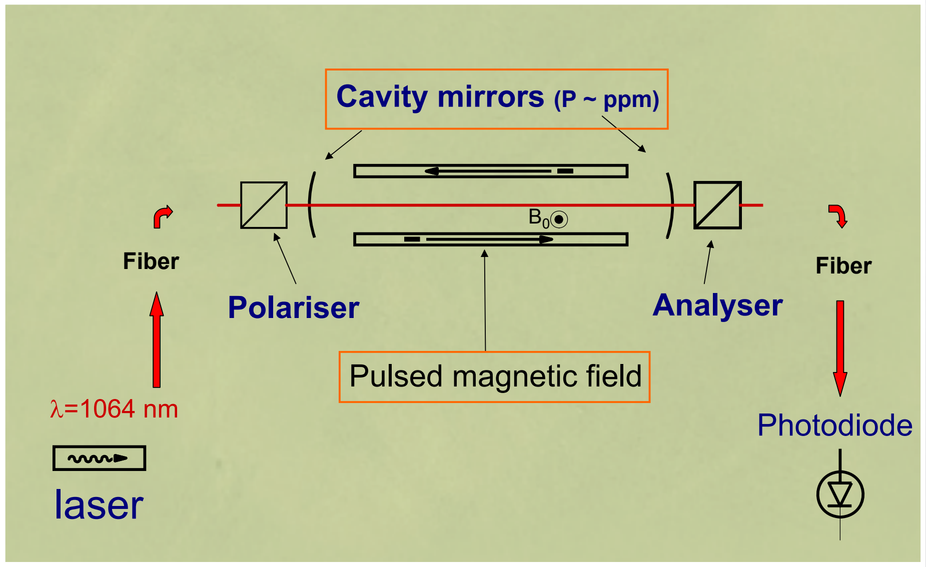
LHC dipoles

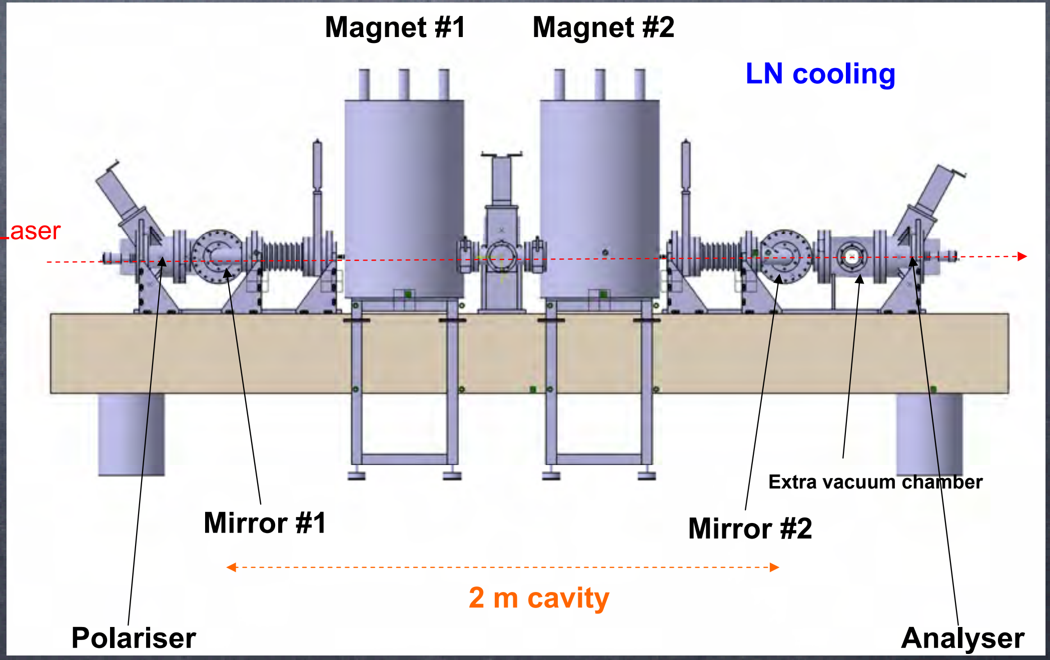
simplified optical setup



BMV

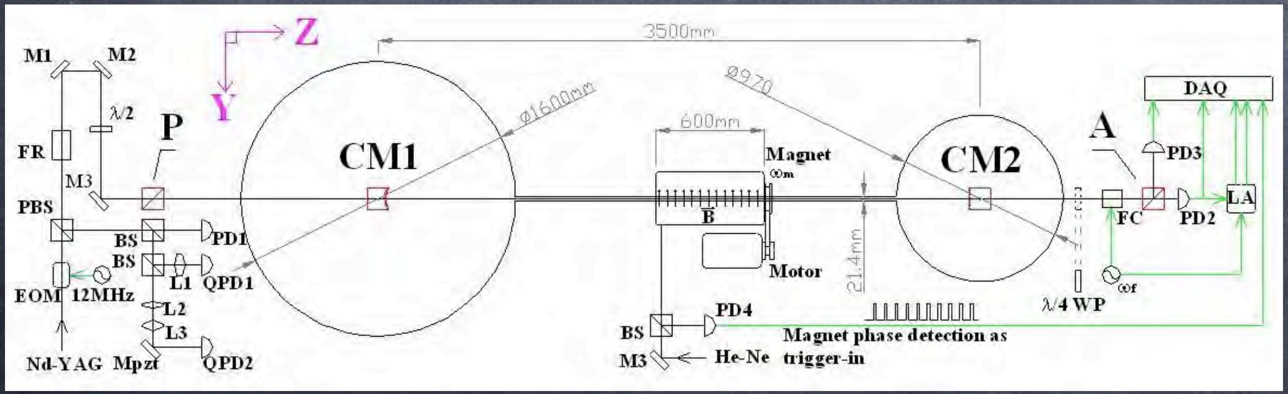
- BMV (Toulouse, C. Rizzo group leader)
  - 1 eV photons, few mW power, pulsed magnetic fields up to 12 T (ms duration), omodyne detection, Fabry-Perot resonator
  - Status: magnets tested, assembly of optics
  - R. Battesti et al., Eur. Phys. J. D 46, 323-333 (2008)





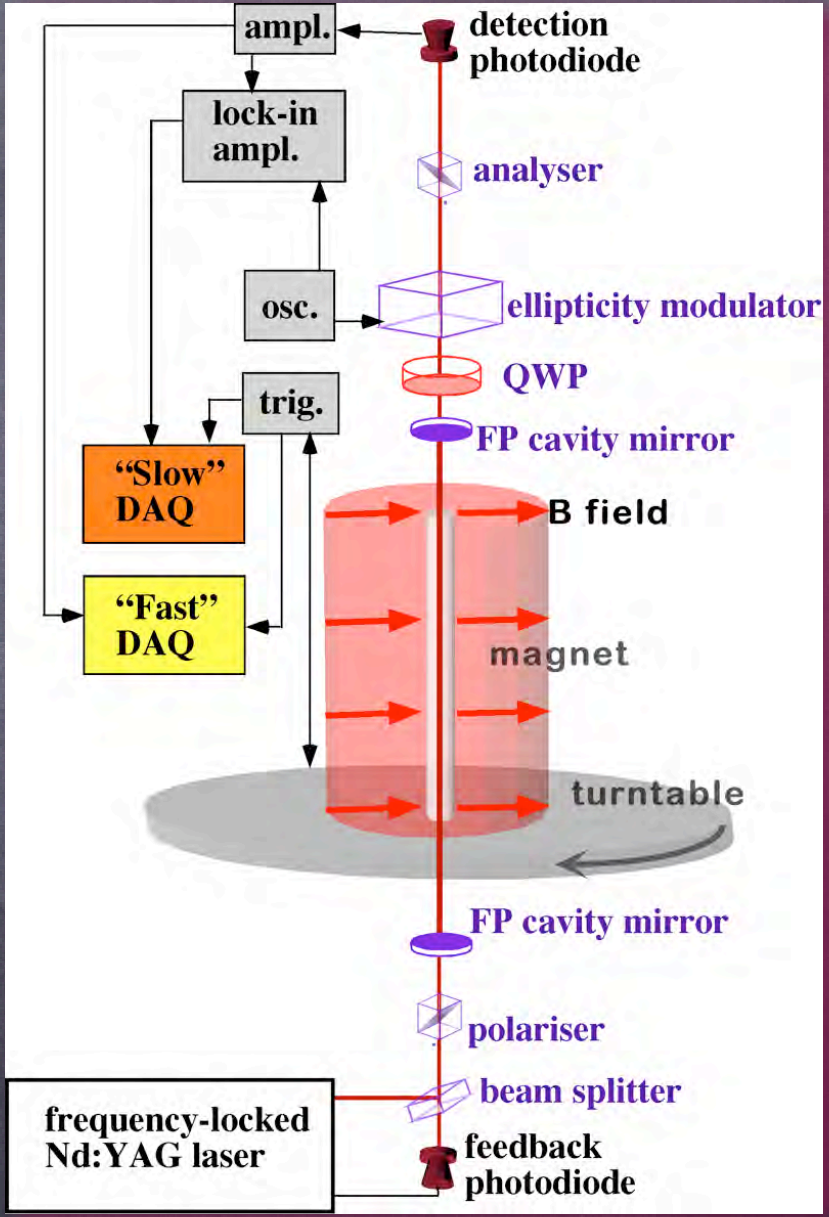
Q&A

- Q&A (Taiwan, W.T. Ni group leader)
  - 1 eV photons, few mW power, rotationg 2.2 T permanent magnet, heterodyne detection, Fabry-Perot resonator
  - Status: active
  - arXiv:hep-ex/0611050



PVLAS

- 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)
  - Recent papers
    - M. Begant et al., arXiv:0805.3036v1
    - E. Zavattini et al., Phys. Rev. D 77, 032006 (2008)
    - E. Zavattini et al., Phys. Rev. Lett. 96, 110406 (2006)



www.ts.infn.it/experiments/pvlas

A one-slide history ...

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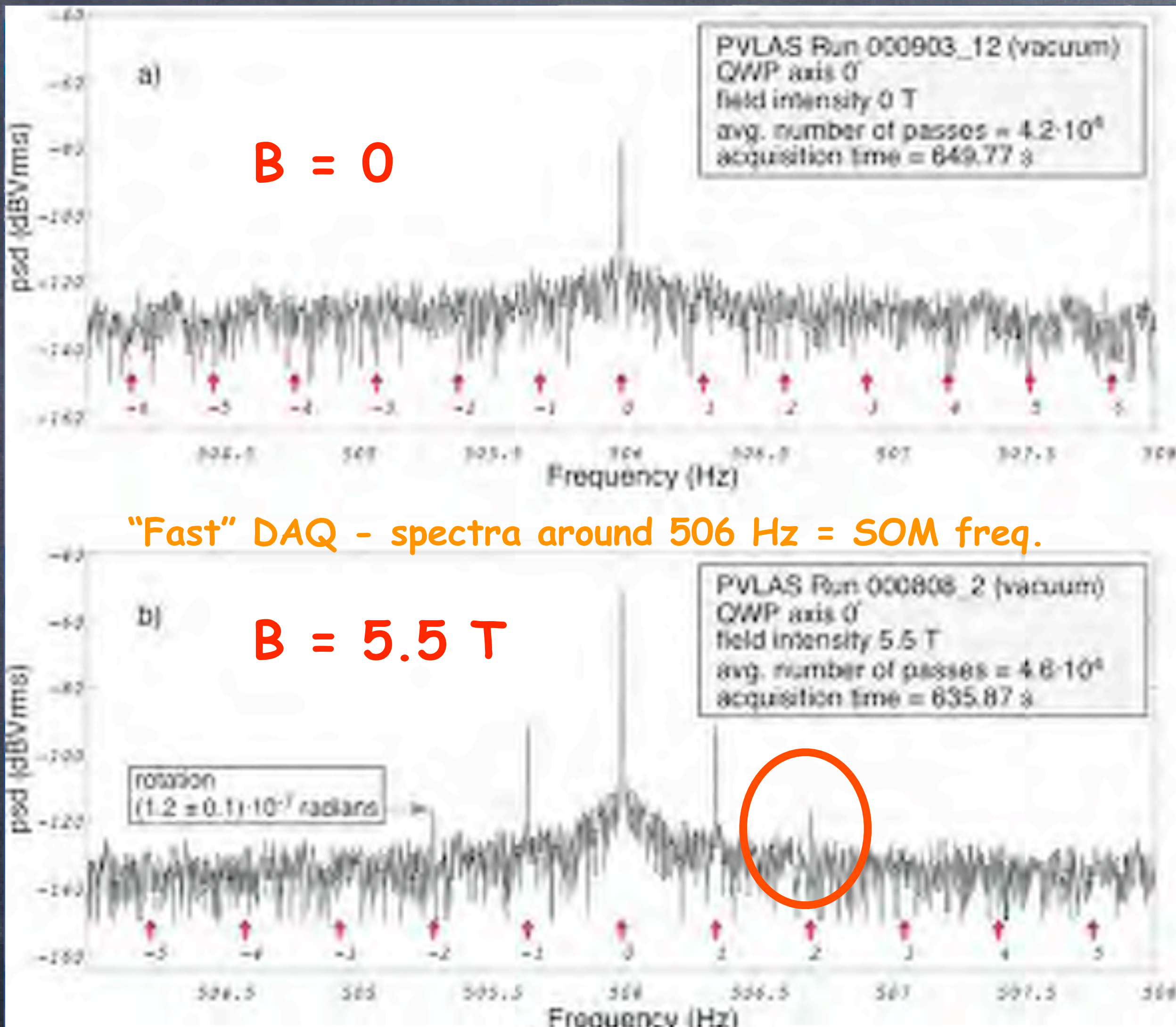
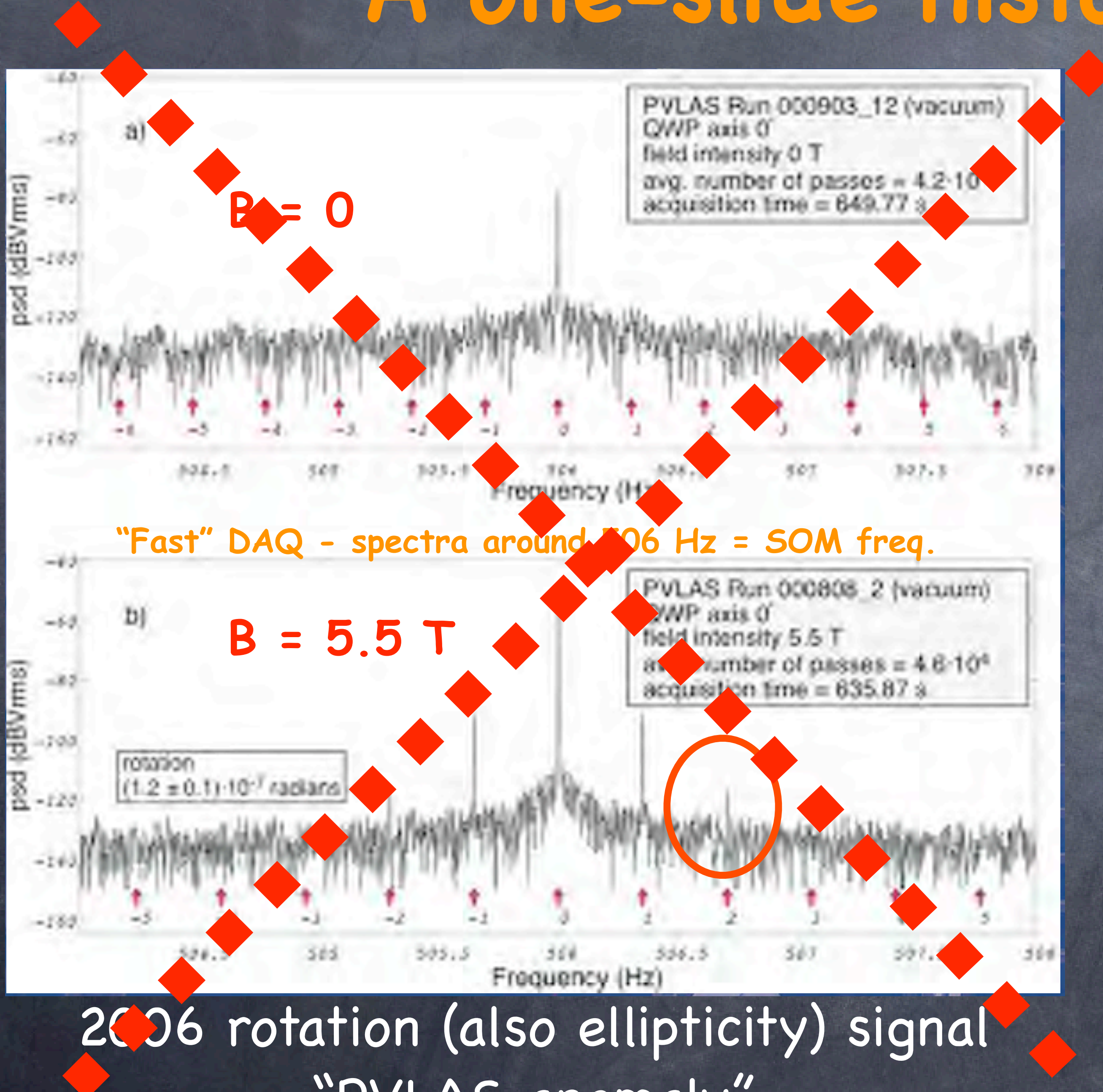


2006 rotation (also ellipticity) signal
"PVLAS anomaly"

A one-slide history ...



2006 rotation (also ellipticity) signal
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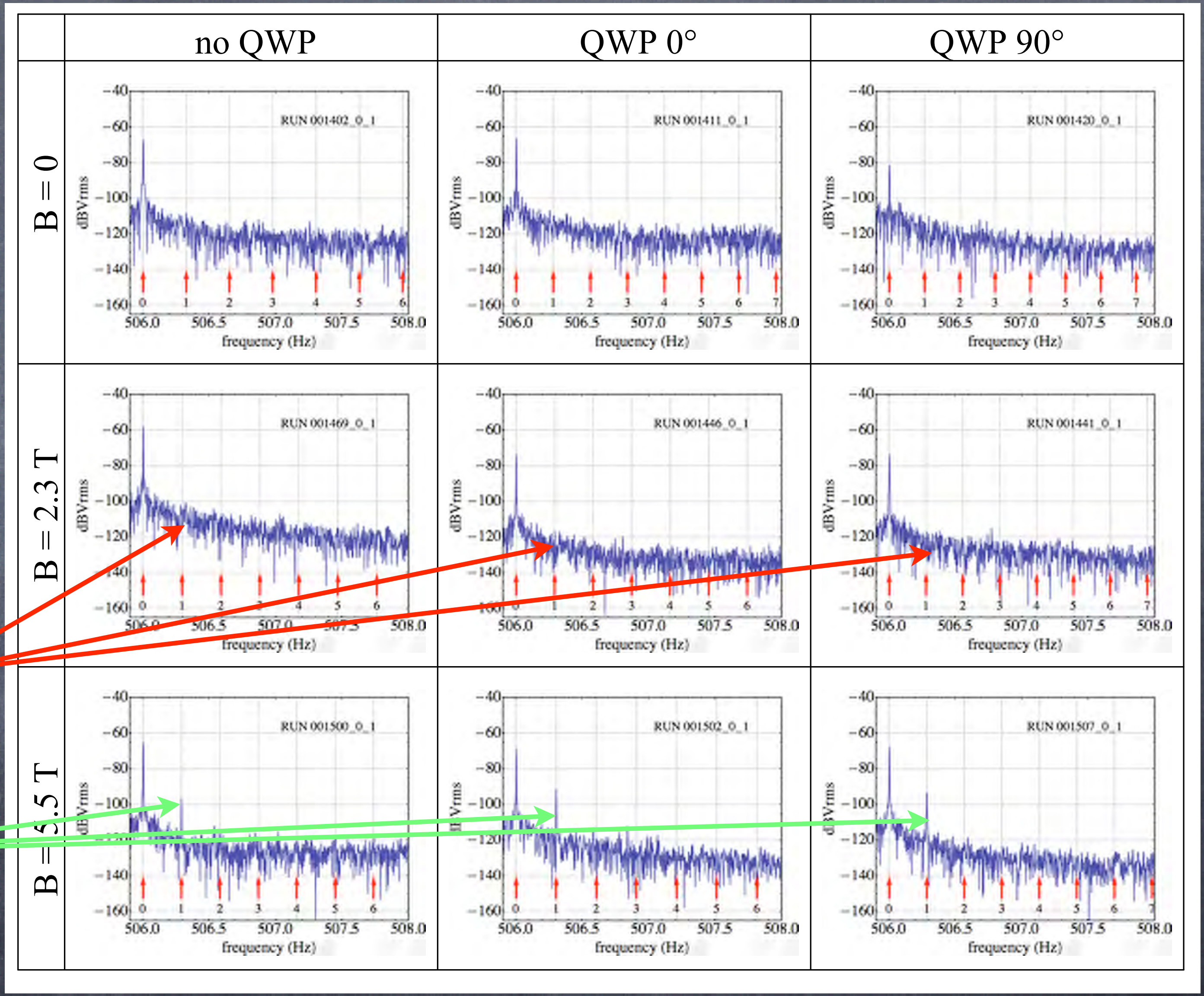
A one-slide history ...

- Apparatus upgraded in 2007
  - signals go away
  - just background or a clear spurious



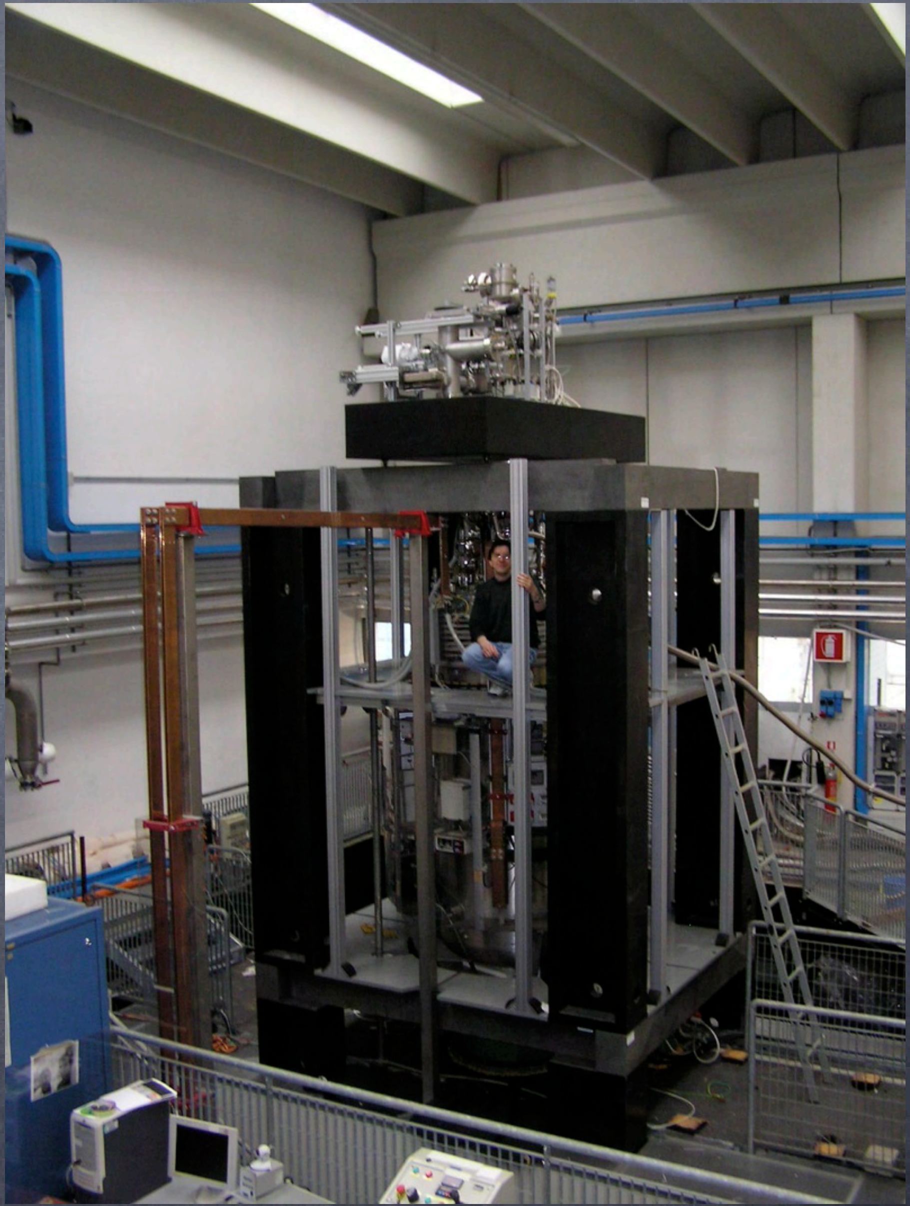
What now?

- Controversial signal disappeared
- Focus must now shift on background noise limiting the sensitivity
- The PVLAS sensitivity in angle (ellipticity or rotation) has never gone below $5 \cdot 10^{-7}$ $1/\sqrt{Hz}$
  - too large!!! -> detecting the 10^{-11} QED ellipticity would take $2.5 \cdot 10^{9}$ s (about 80 years of continuous running -> not even good for retirement!)
- Prime suspect for the "noise barrier" is the granite tower holding the optics

Moving on to Phase II

Phase I mission completed ...

- 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



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A sailor's answer ...

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- If you want to explore here..

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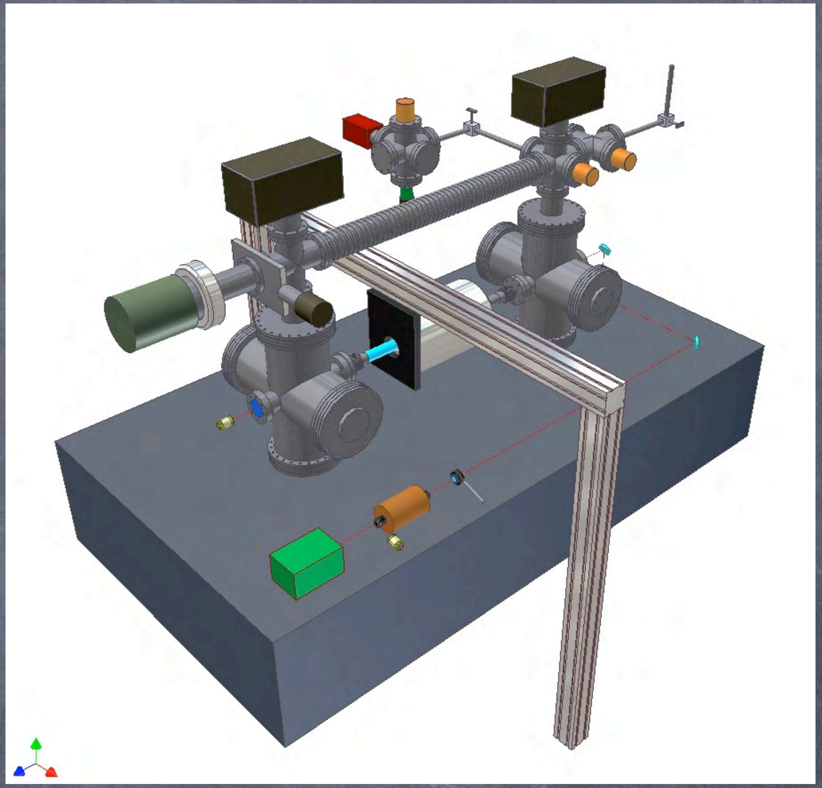
- If you want to explore here..
- You don't want this...

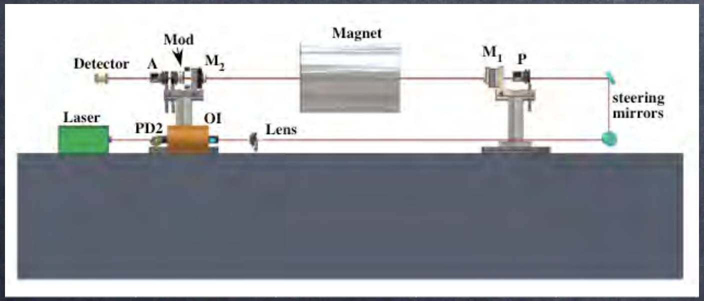
A sailor's answer ...

- If you want to explore here..
- You don't want this...
- You want this!!!

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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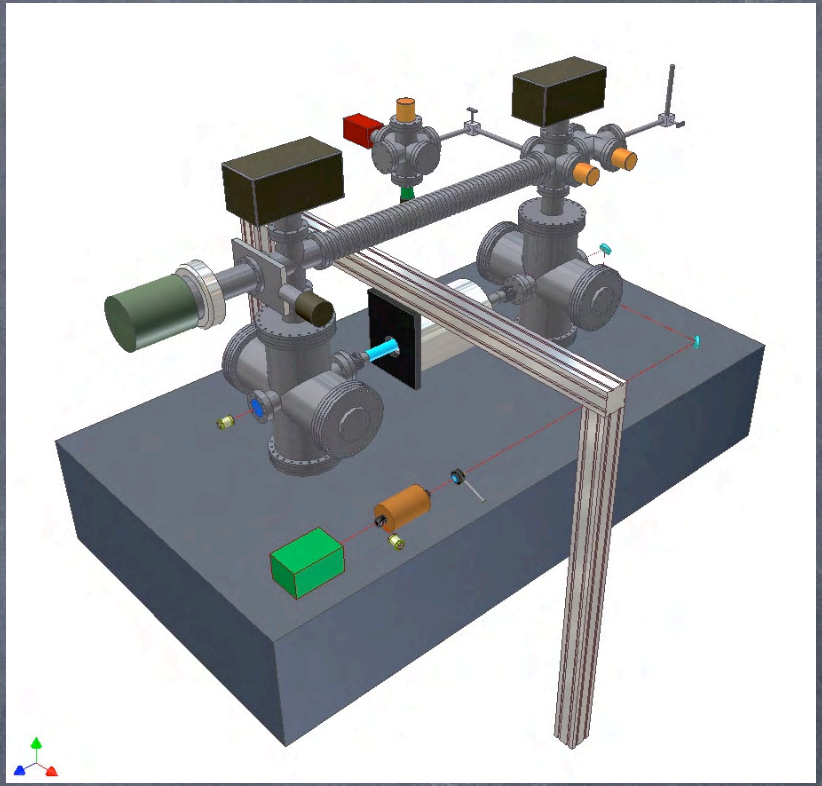

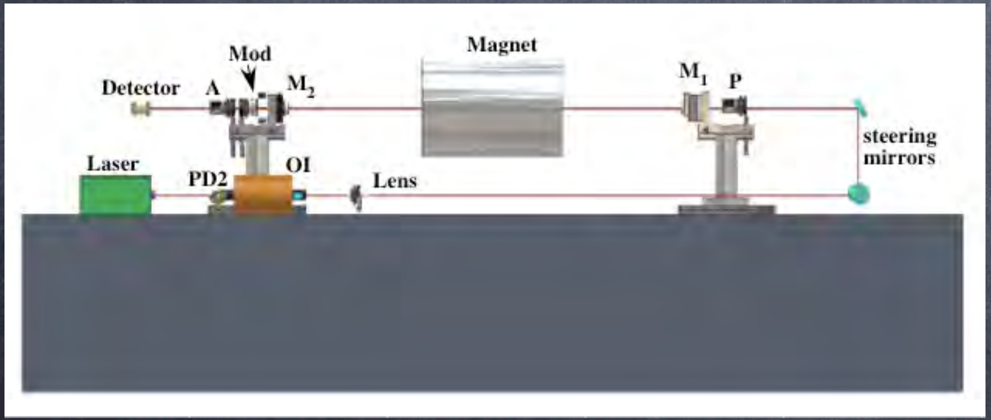

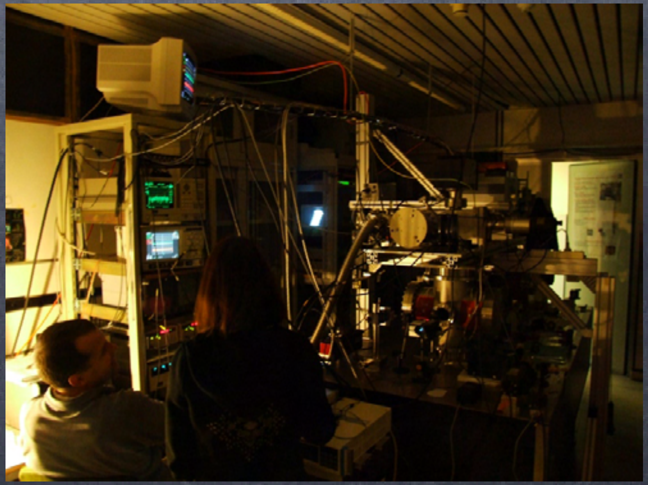

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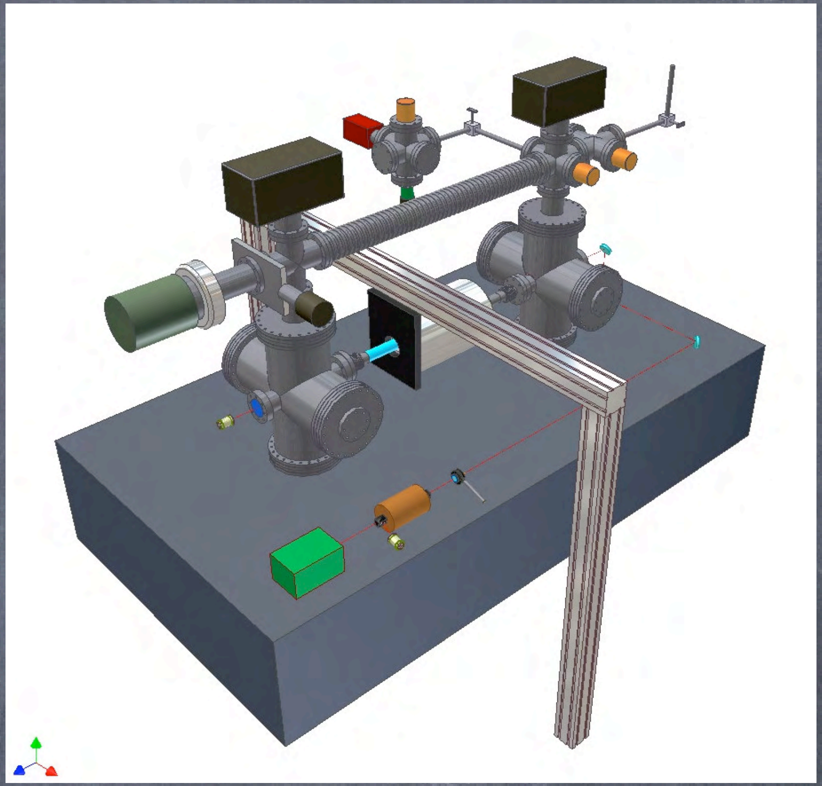
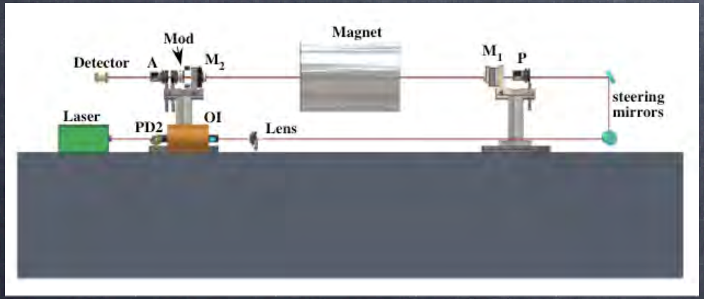
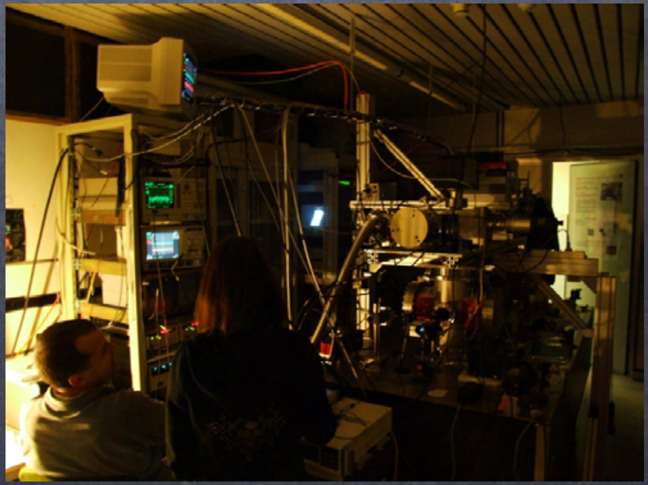
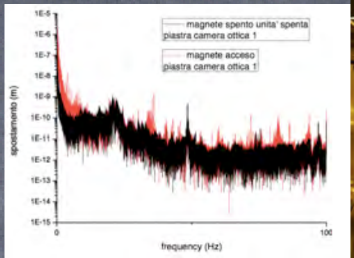


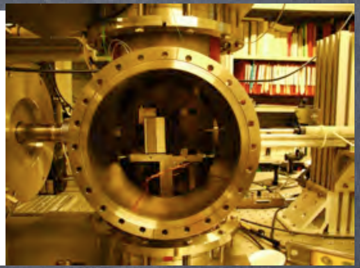


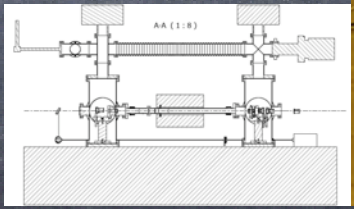


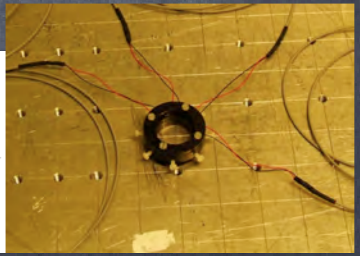
PVLAS Phase II solutions

- Compactify 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
  - well tested vacuum system
  - reduce number of components with new modulation scheme (protype already tested)
- Use rotating permanent magnet









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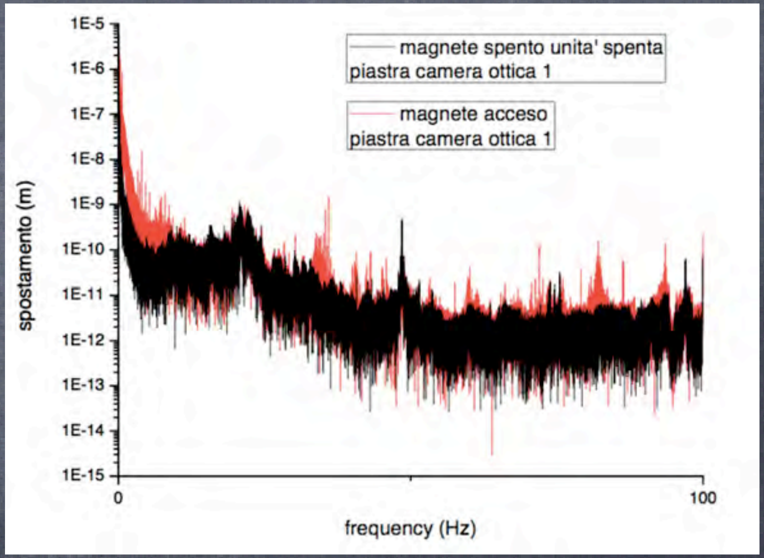

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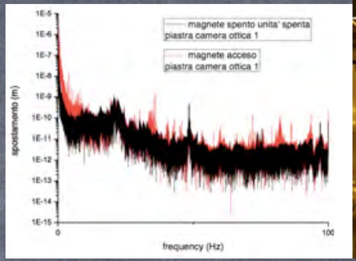

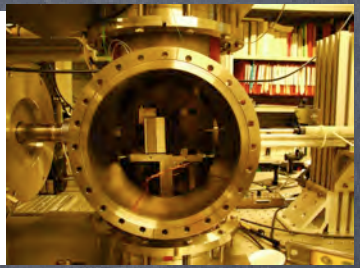

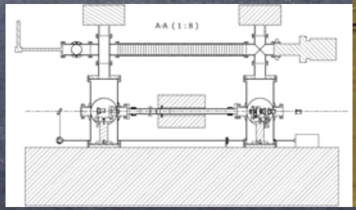

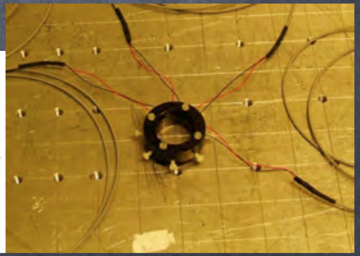

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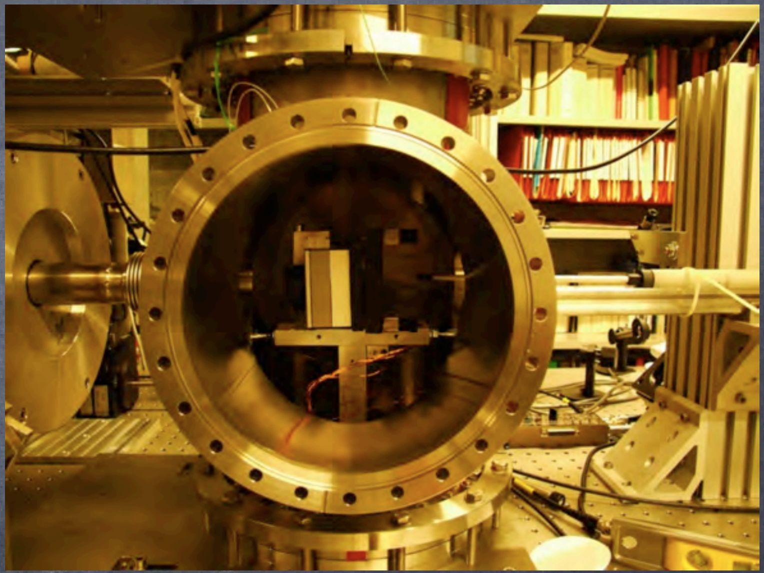

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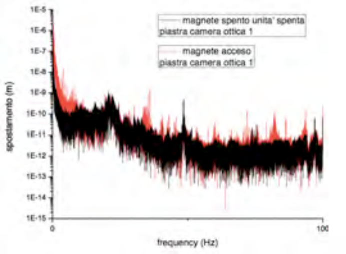

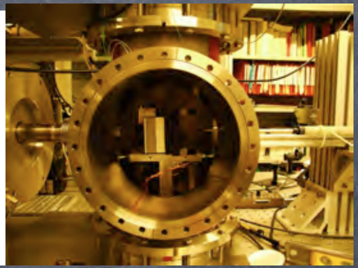

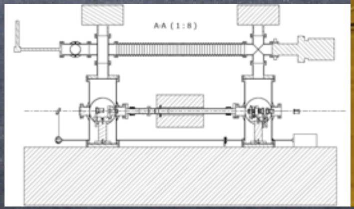

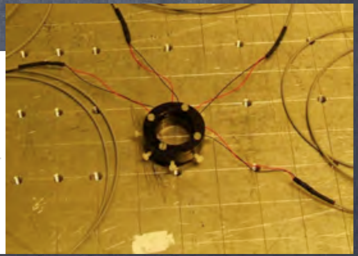

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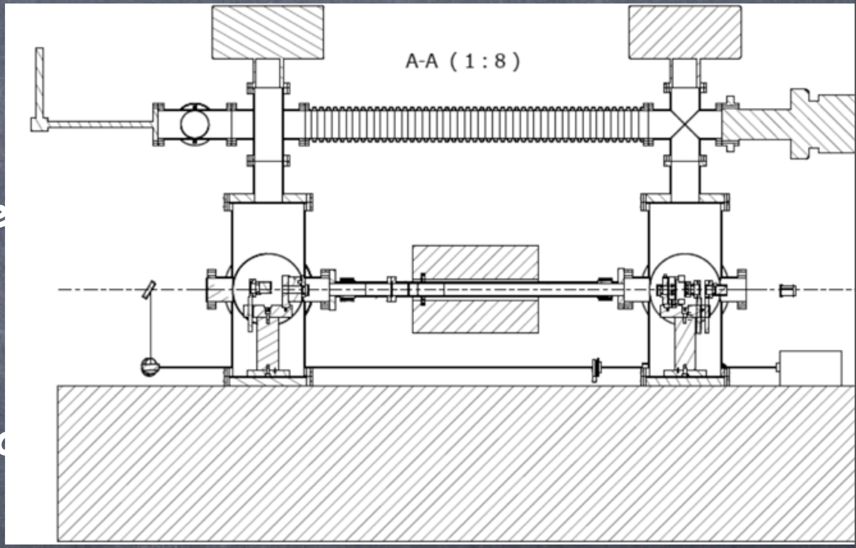

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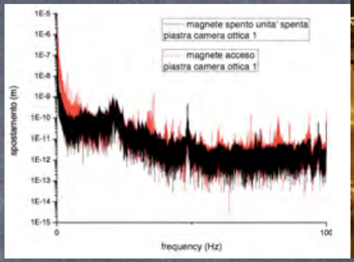

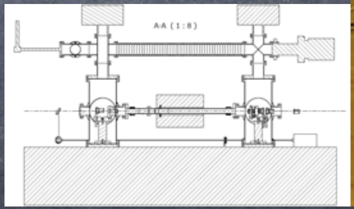

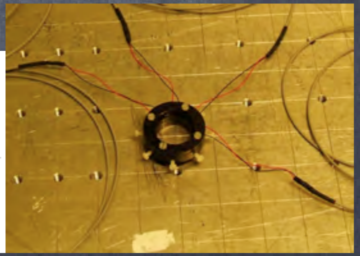

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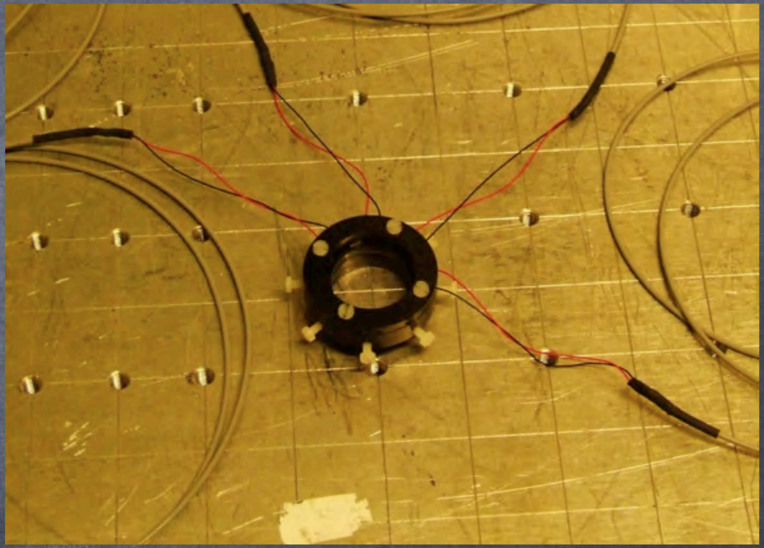

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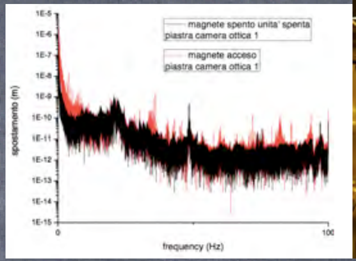
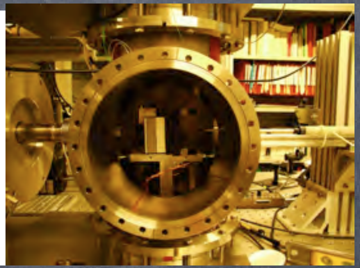
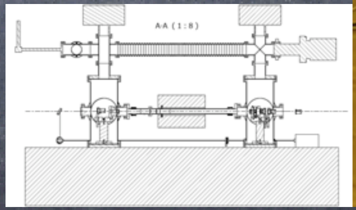
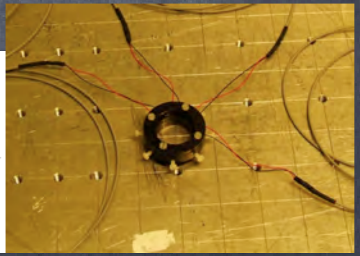




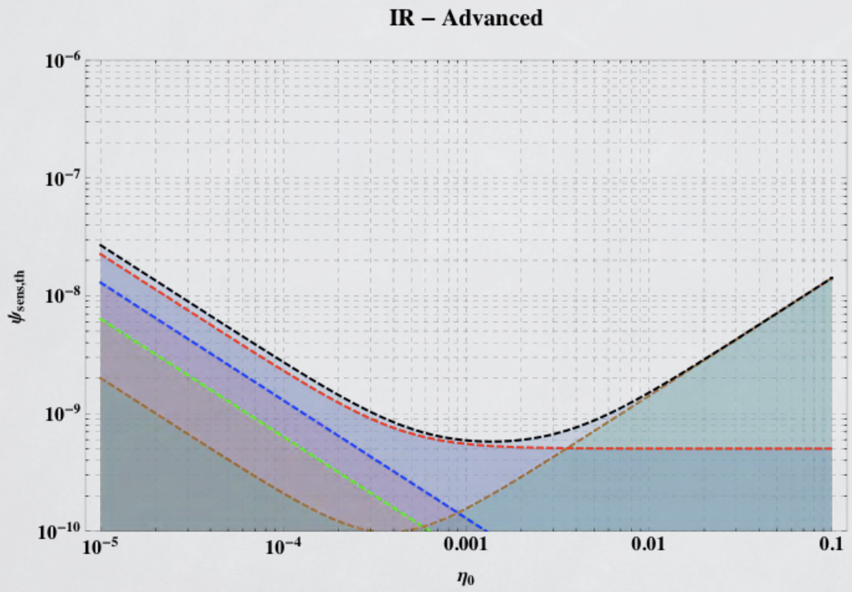


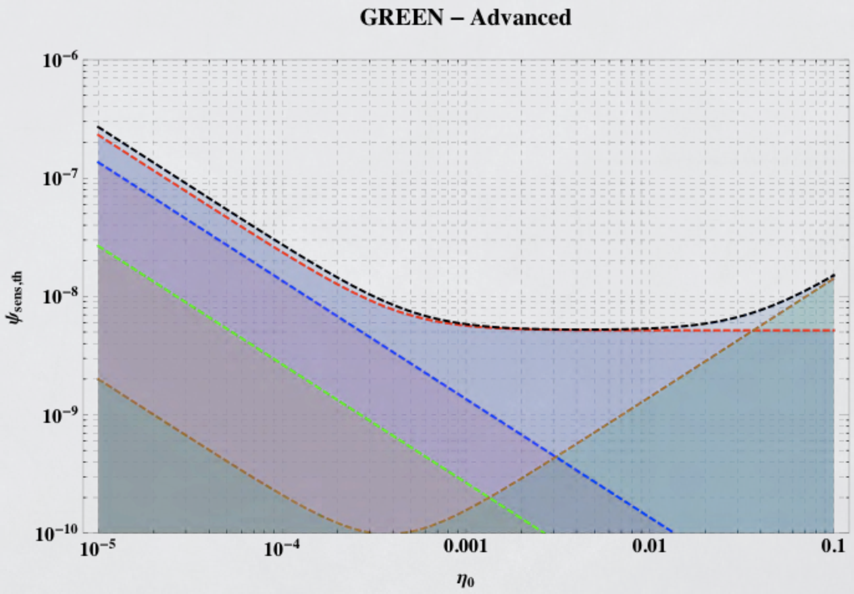


Apparatus parameters

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} $1/\sqrt{\text{Hz}}$	10^{-6} $1/\sqrt{\text{Hz}}$
$\hat{V}_d$	$8 \cdot 10^{-6}$ $\text{V}/\sqrt{\text{Hz}}$	$2 \cdot 10^{-6}$ $\text{V}/\sqrt{\text{Hz}}$

Some noise considerations





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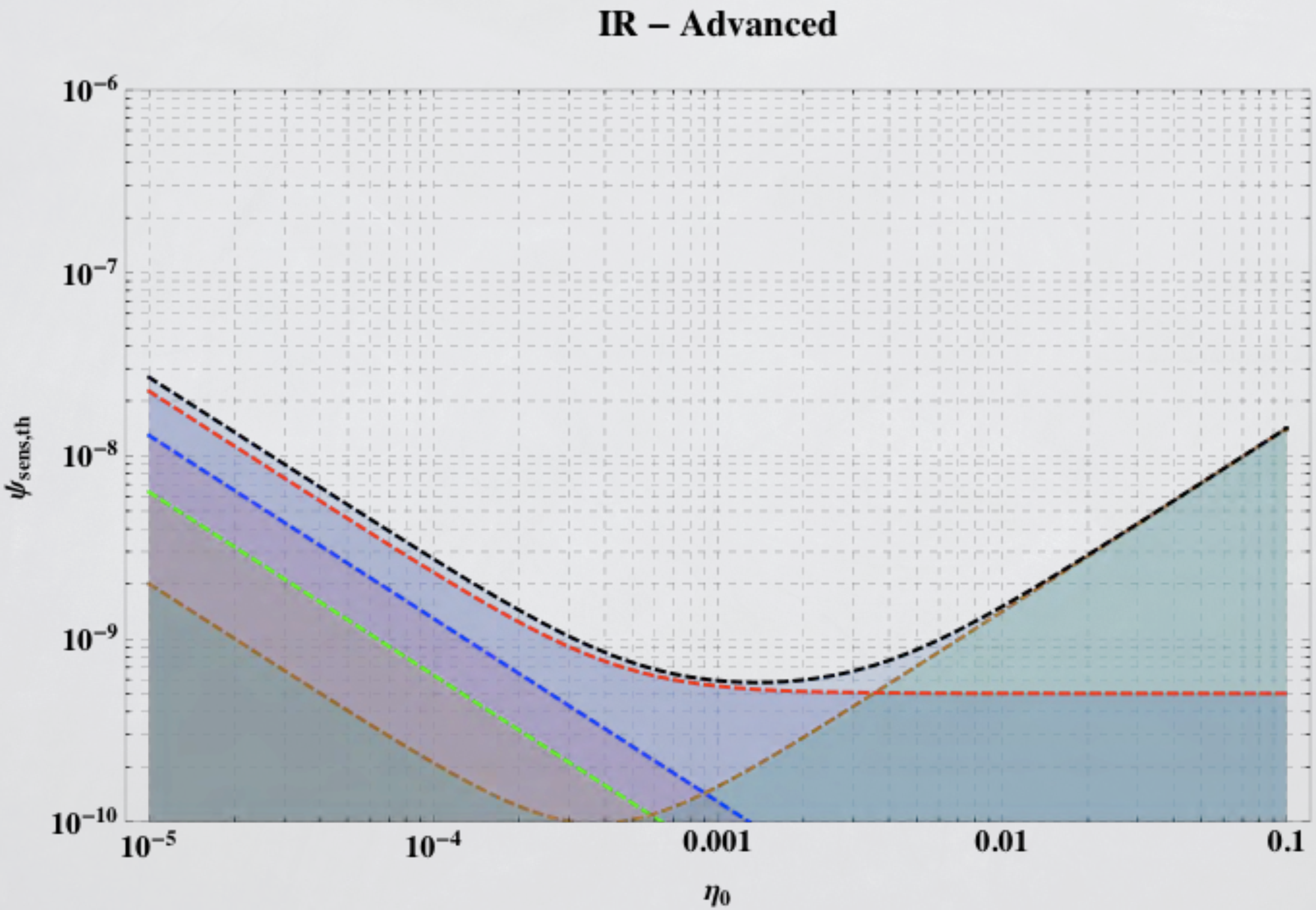

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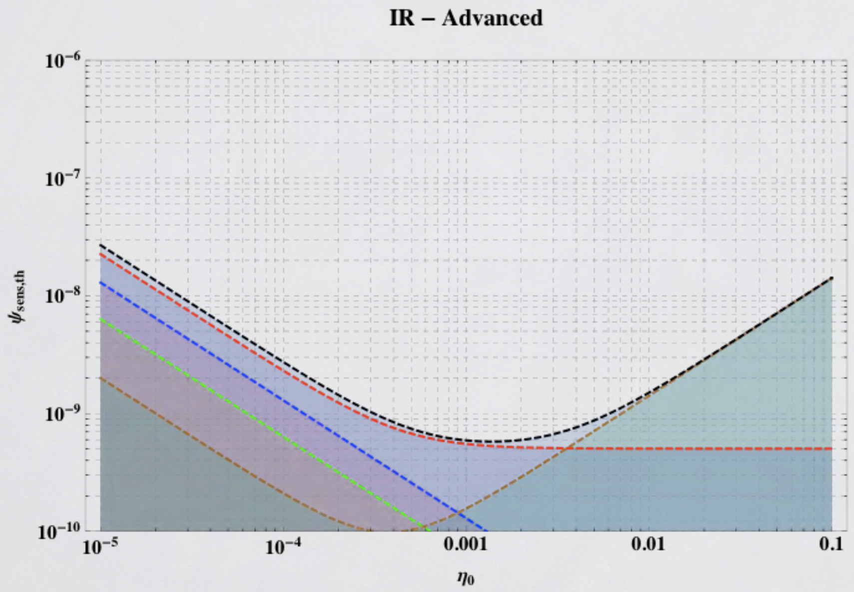

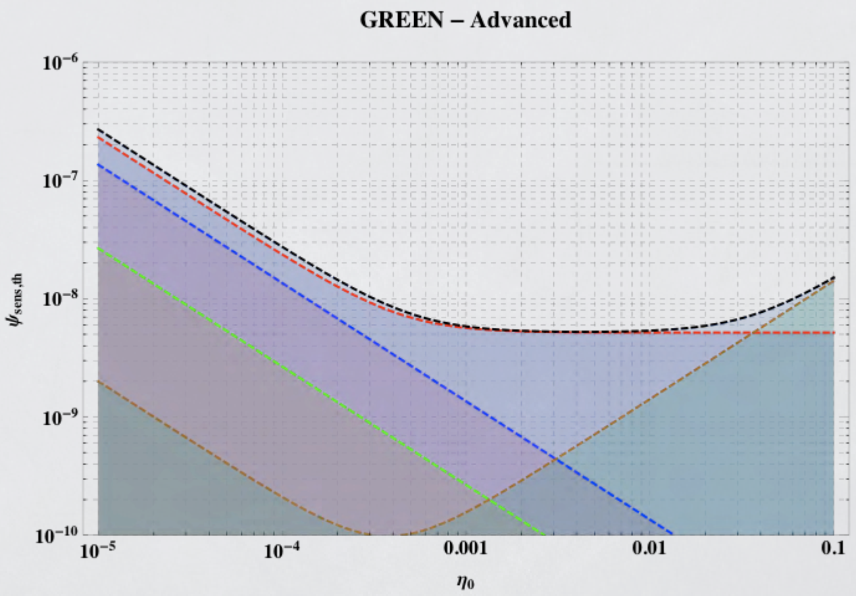

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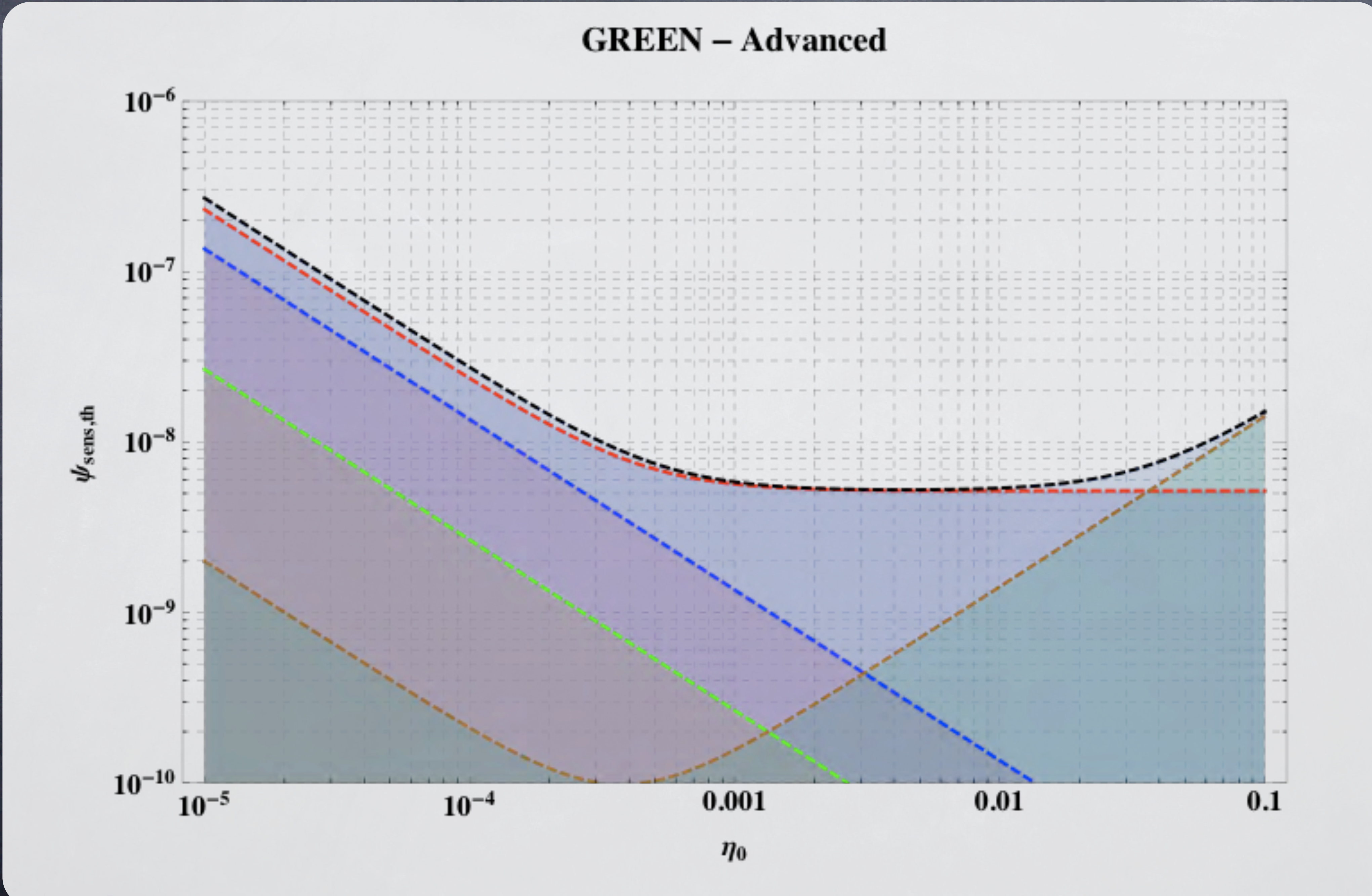

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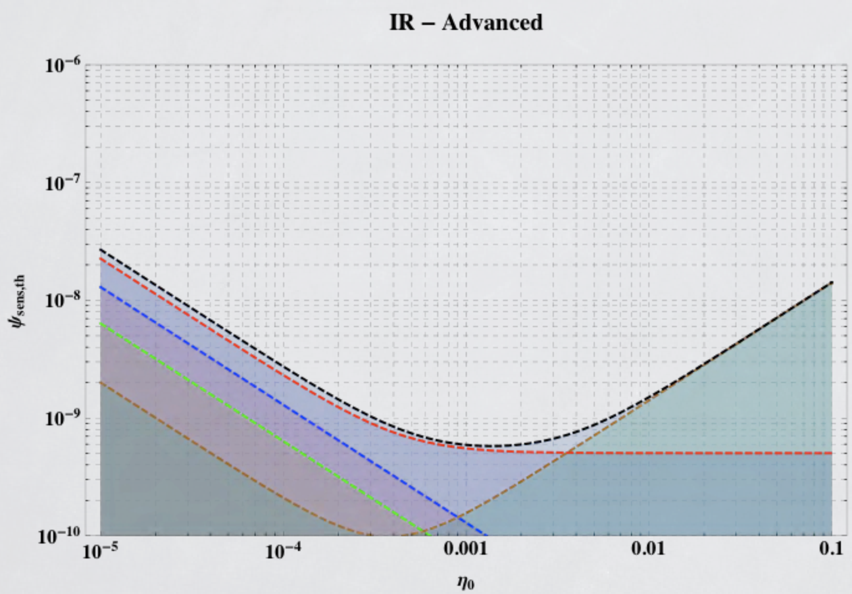

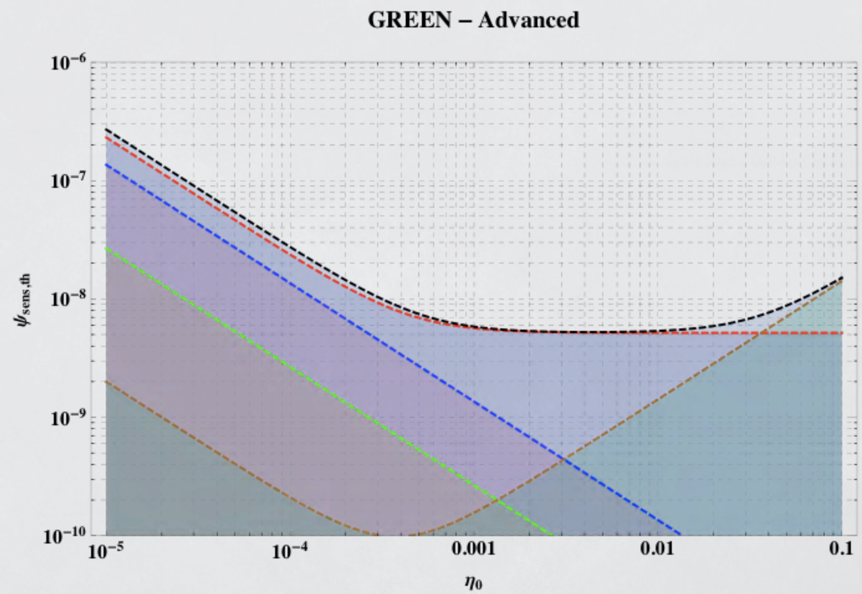

Config.		IR		GREEN		
		Prototype	Advanced	Prototype	Advanced	Adv. power upg.
	Sens. $[1/\sqrt{\text{Hz}}]$	10^{-8}	$6 \cdot 10^{-10}$	10^{-8}	$6 \cdot 10^{-9}$	10^{-9}
	Min. det. angle in 400 std. days	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-13}$	$3 \cdot 10^{-12}$	$1.8 \cdot 10^{-12}$	$3 \cdot 10^{-13}$
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}	$6.1 \cdot 10^{-17}$	$6.1 \cdot 10^{-17}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$	$1.2 \cdot 10^{-16}$
	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}
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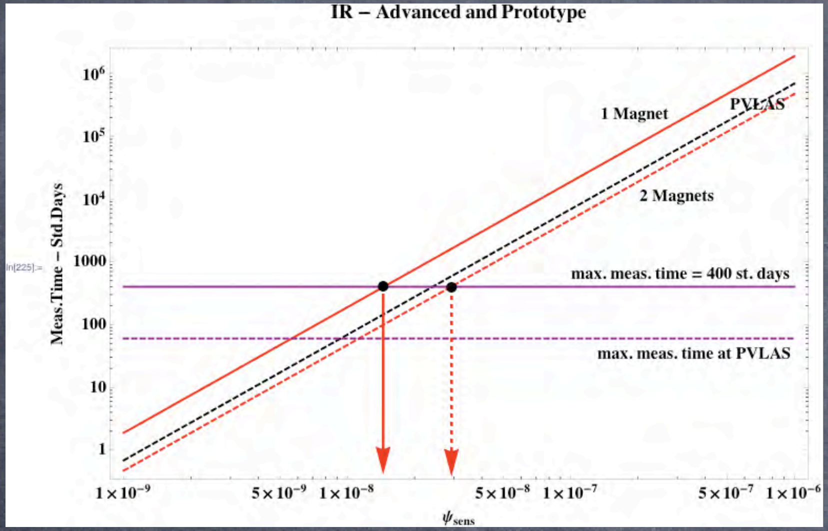
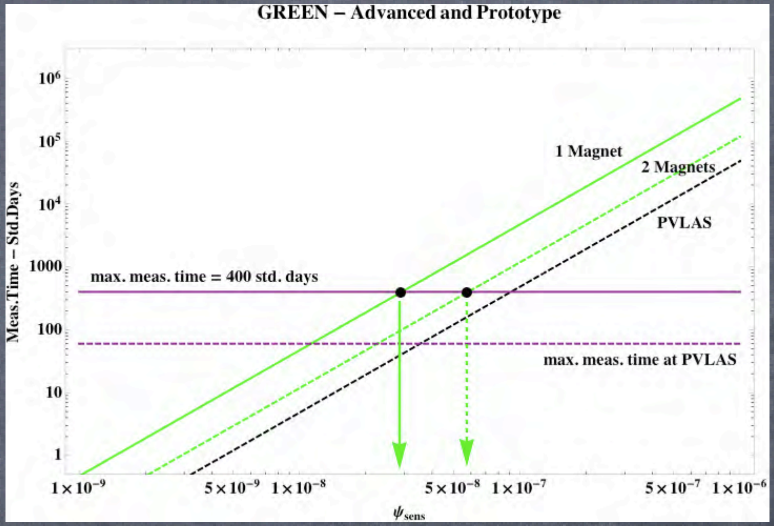
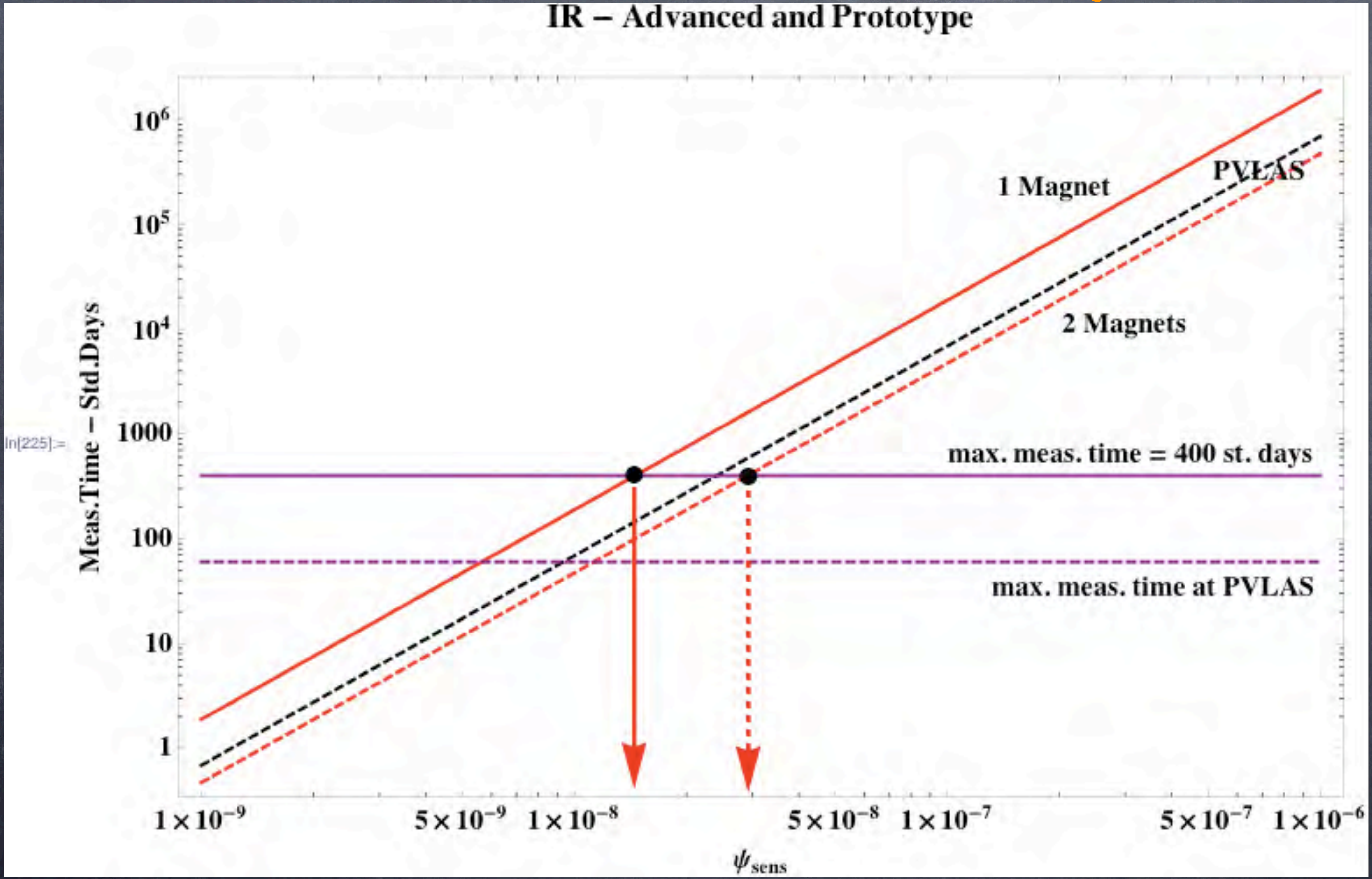
Table IV: Minimum measurement times necessary to detect QED photon-photon scattering for several apparatus configurations.

Measurement times for QED

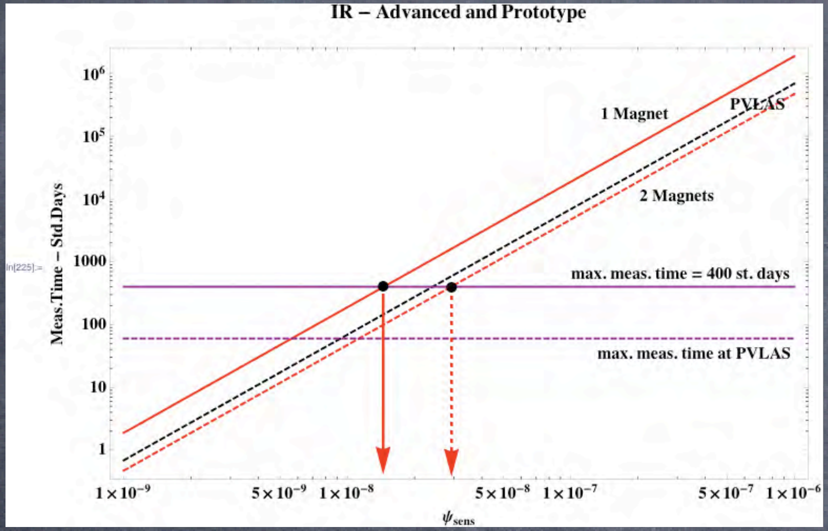


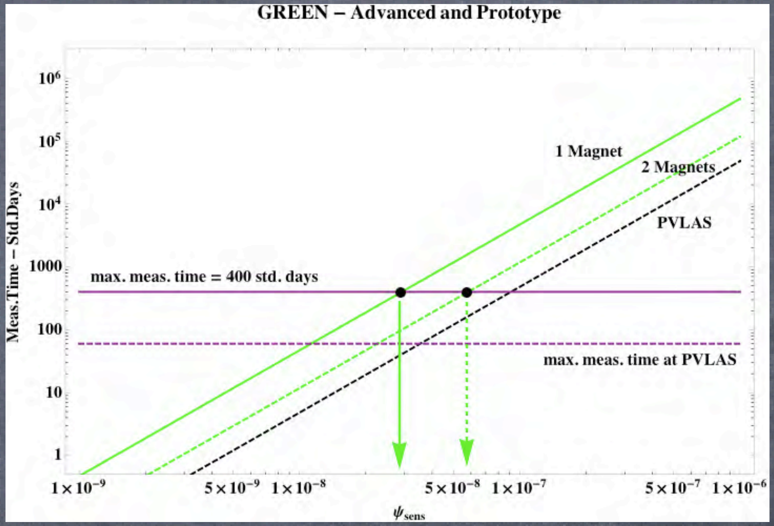


Measurement times for QED



Measurement times for QED





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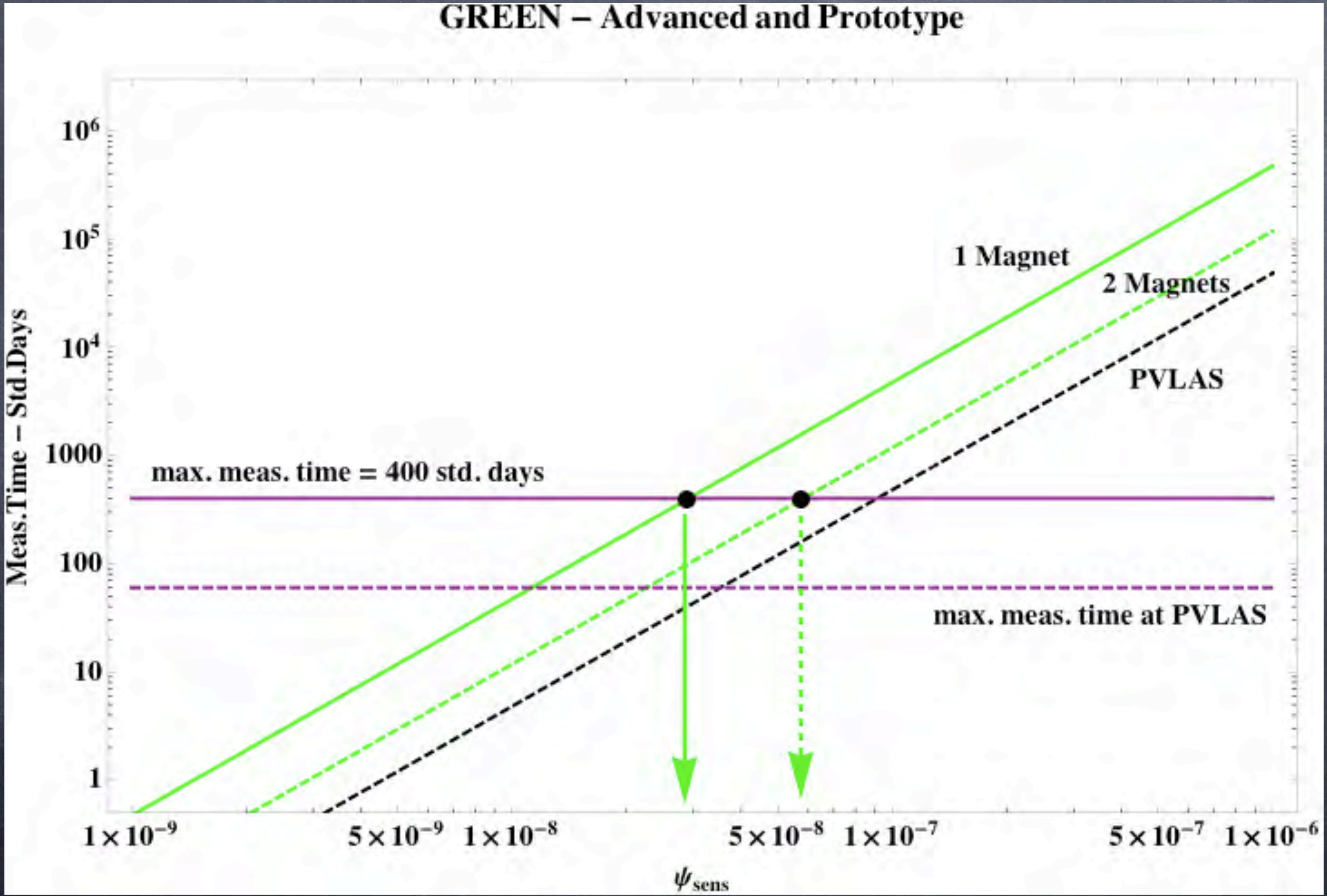
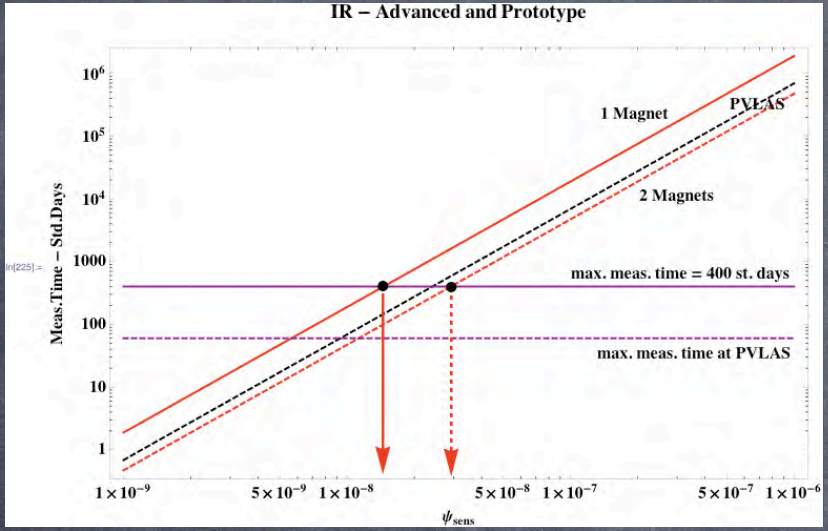
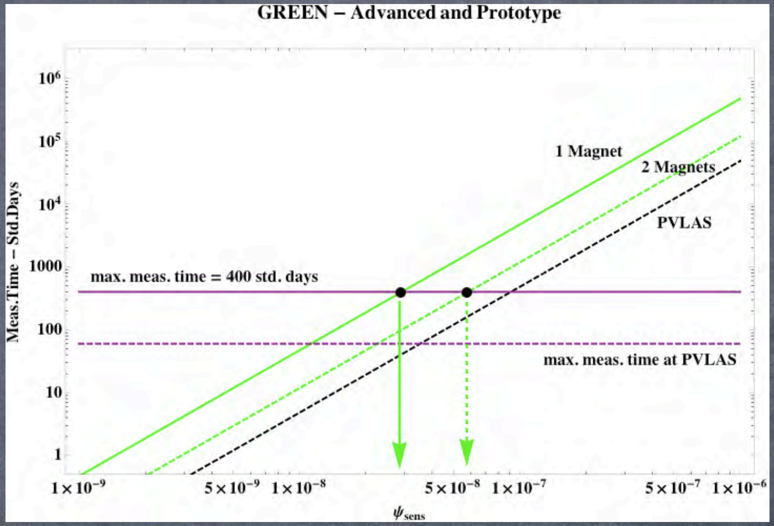
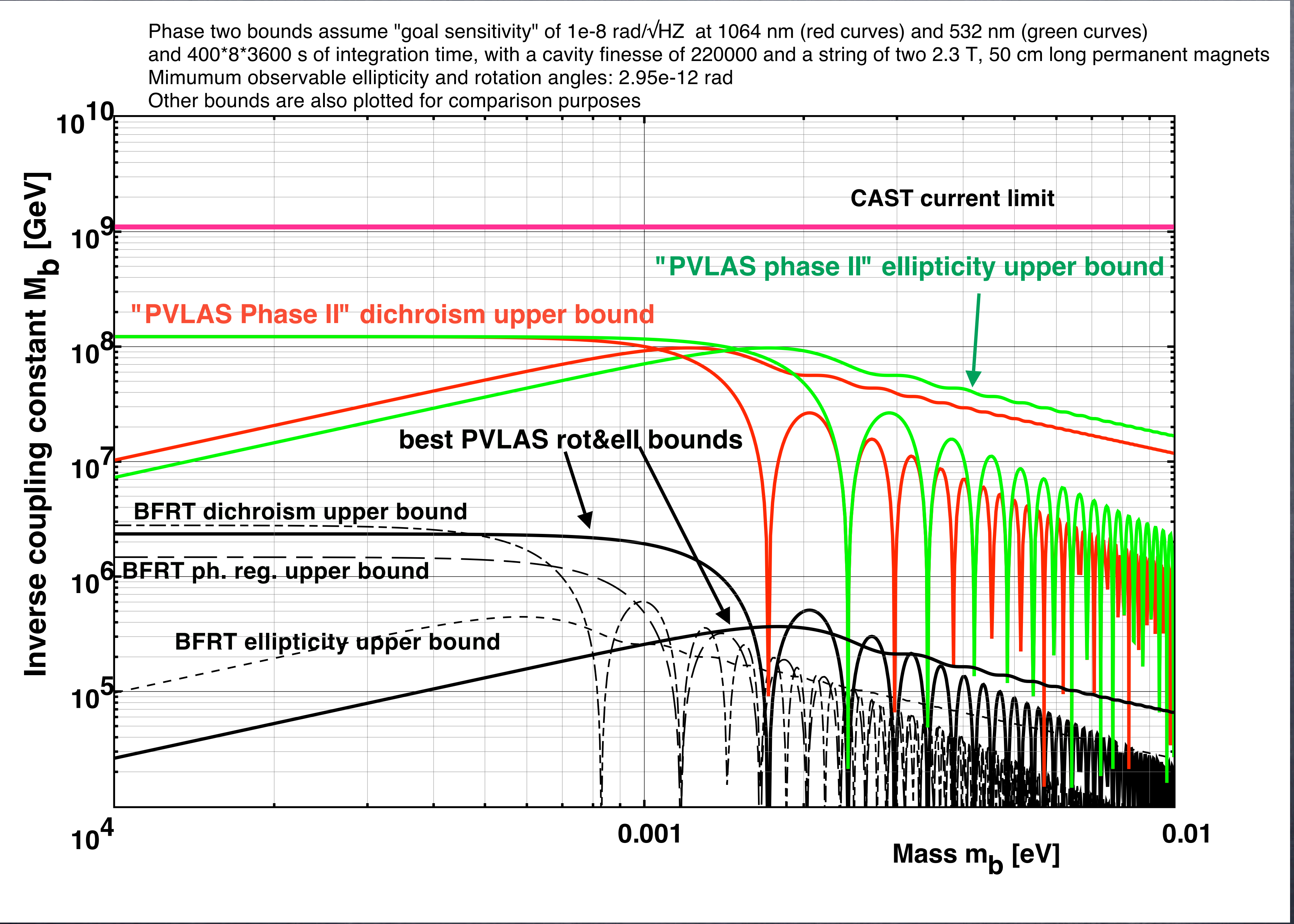


Measurement times for QED





ALP parameter space coverage

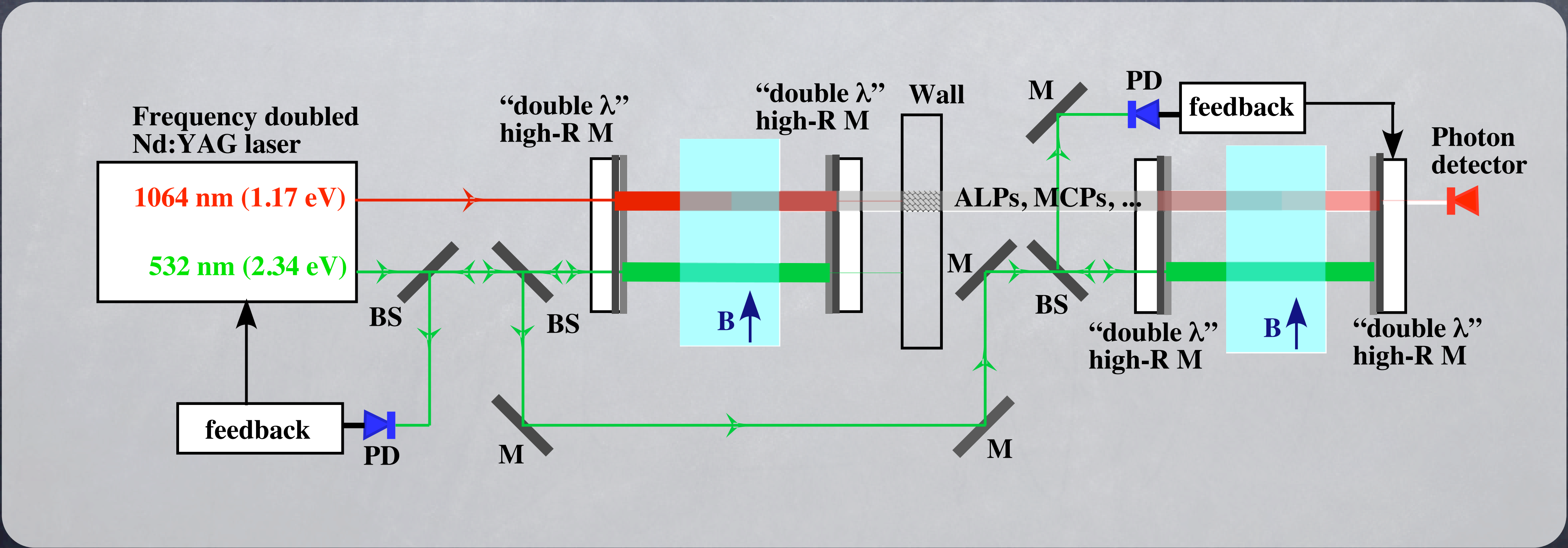


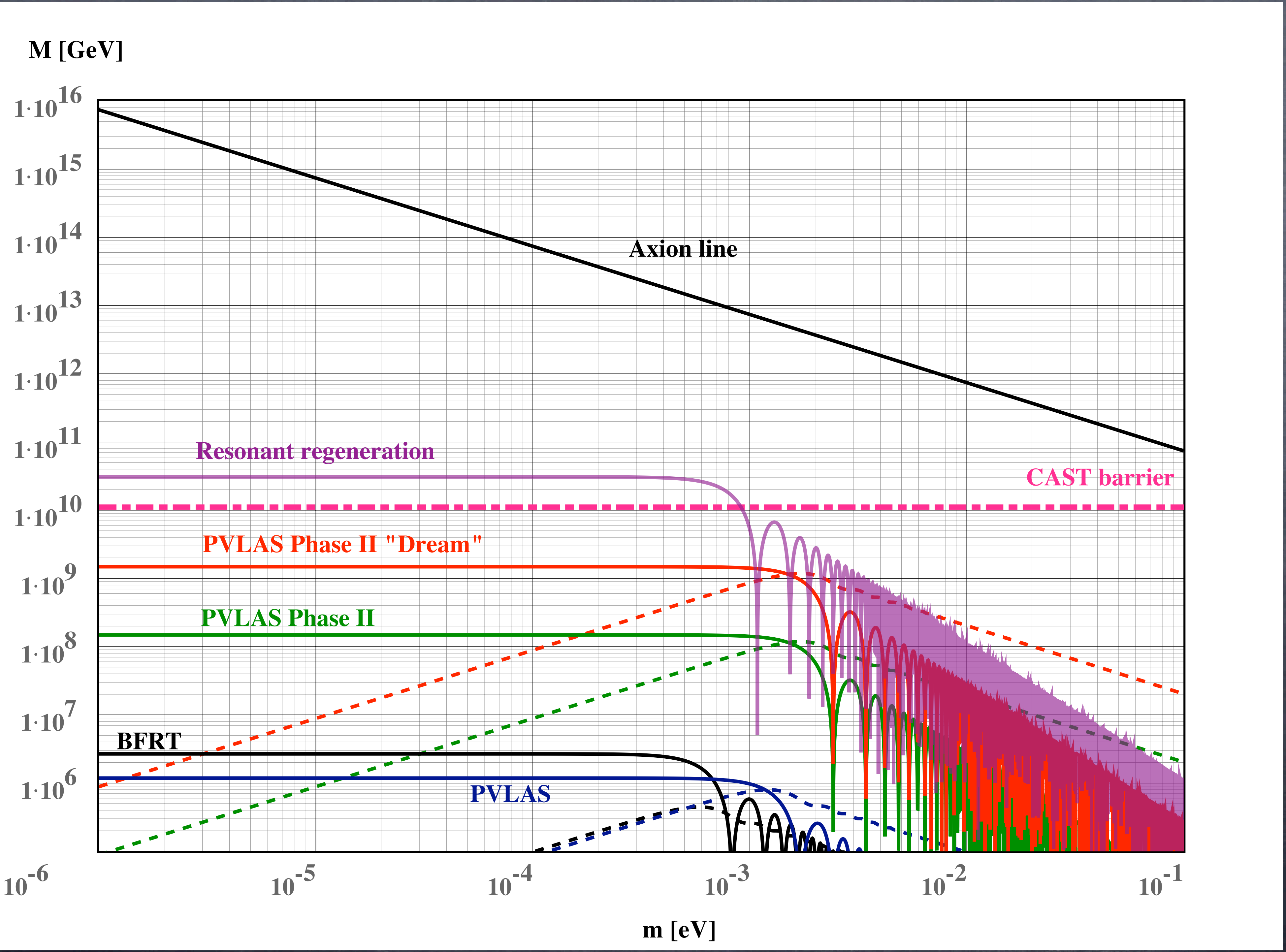
New possibilities

- Resonant regenerneration
- Polarization experiments with "high energy" photon sources

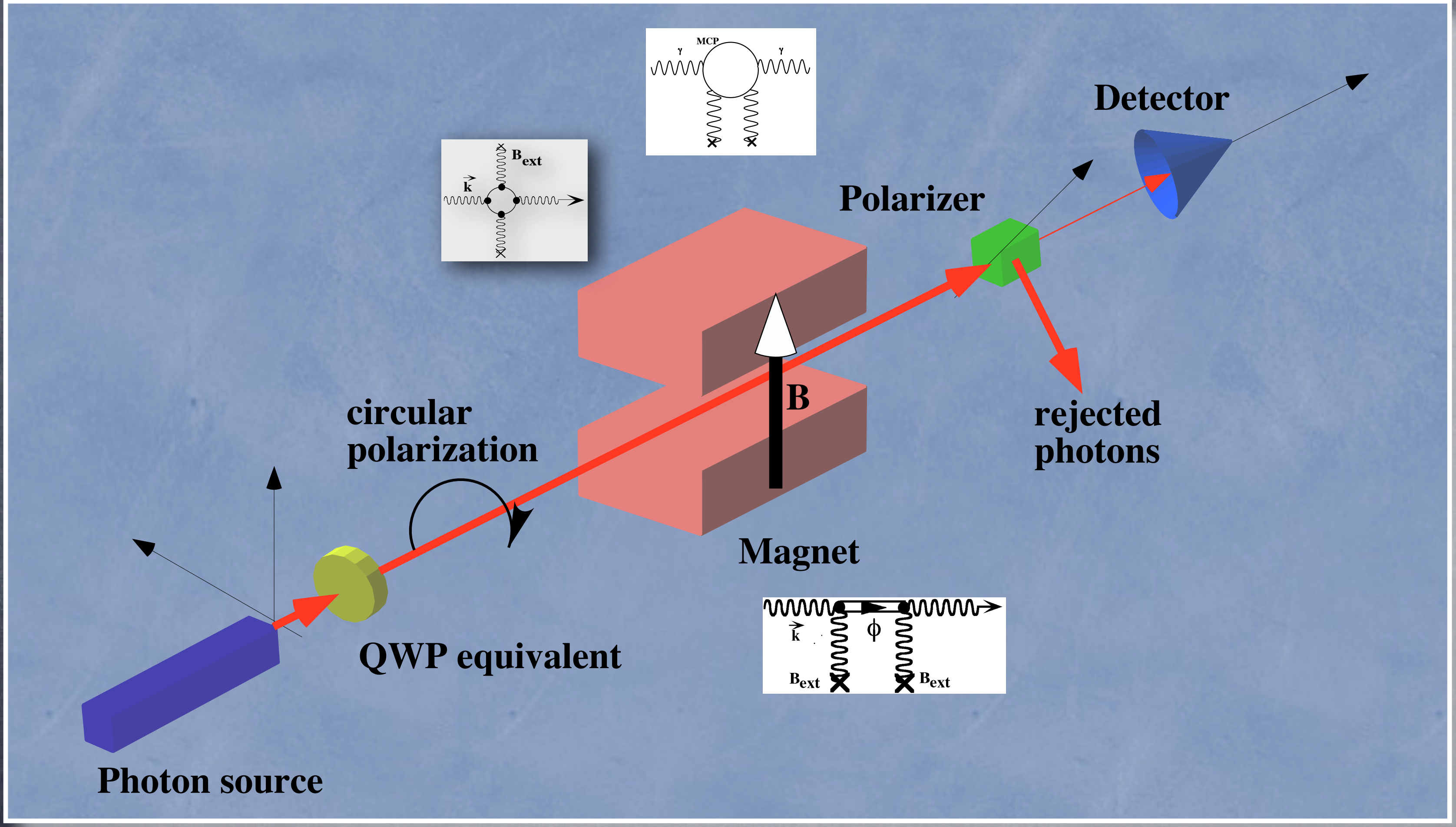
Resonant regeneration

- Following an idea by Sikivie, Tanner and Van Bibber, PRL 98, 172002 (2007)
- Can be implemented with a frequency doubled laNd:YAG laser and two locked identical Fabry-Perot cavities made with double λ mirrors
- Gain of a factor of F^2 in overall rate of regenerated photons




M [GeV]
1·10^16
1·10^15
1·10^14
1·10^13
1·10^12
1·10^11
1·10^10
1·10^9
1·10^8
1·10^7
1·10^6
Axion line
Resonant regeneration
CAST barrier
PVLAS Phase II "Dream"
PVLAS Phase II
BFRT
PVLAS
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
m [eV]

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

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

$$\mathrm{signal} = R_{on} - R_{off} = N_\gamma \frac{(1-\epsilon^2)}{2} sin2\Delta \qquad \mathrm{noise} = \sqrt{N_\gamma \frac{(1+\epsilon^2)}{2}}$$

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

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

Conclusions

- 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!