Working group on resonant photon regeneration

Axel Lindner, DESY

Vistas in axion physics, April 2012
INT, University of Washington

Working group program

Talks on

- Magnet strings (1)
- Optical cavities (3)
- Microwave cavities (1)
- Polarization studies (1)

… and a lot of interesting discussion!

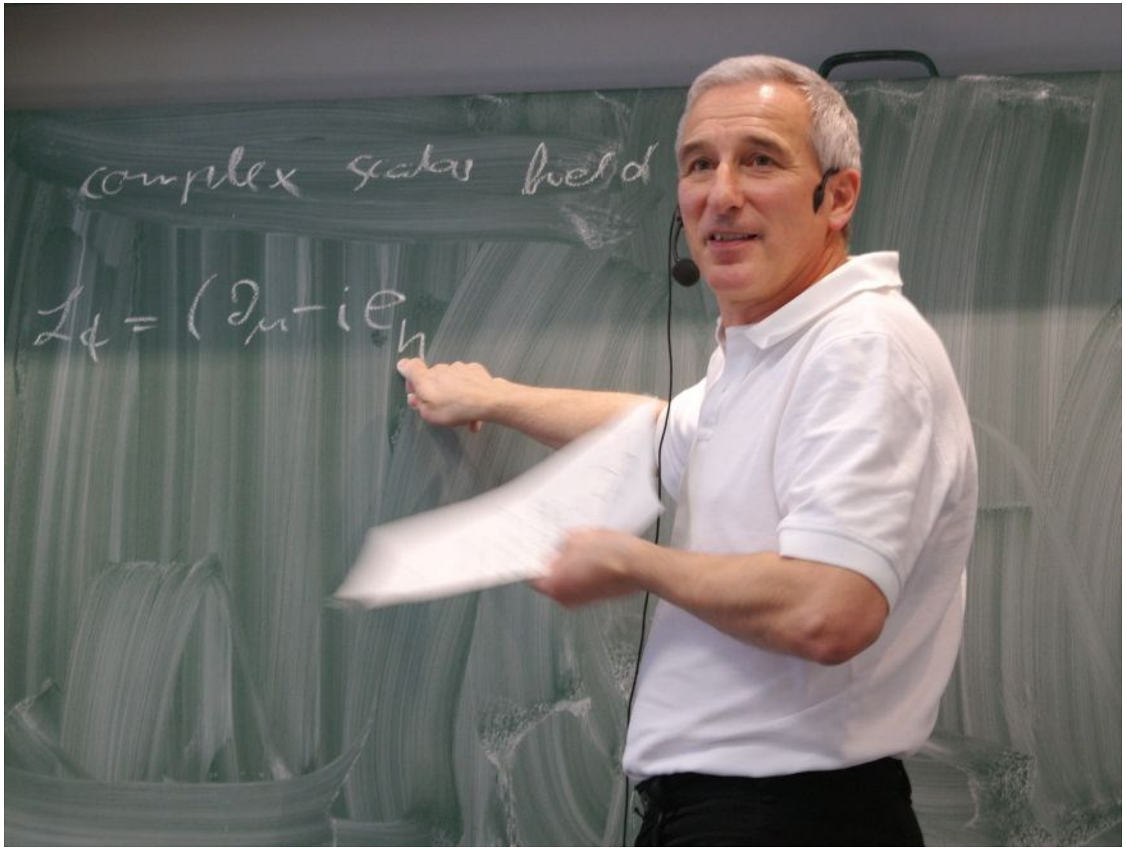
Thanks very much to all who contributed!

Outline

- Motivation for WISP searches in the laboratory
- The potential of light-shining-through-a-wall (LSW)
  - Optical
  - Microwaves
- Polarization measurement
- Summary

Motivation

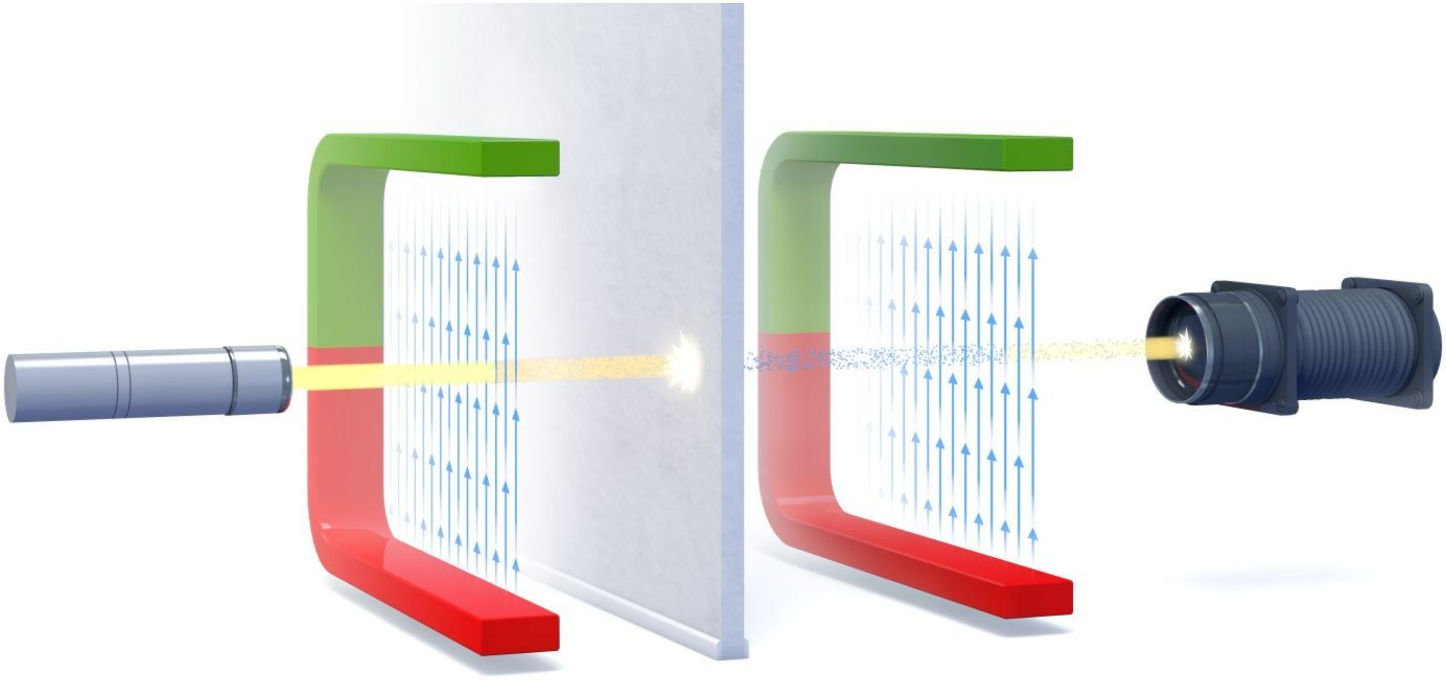
- Andreas will tell …



- Reminder:
  Experiments in the laboratory are much less sensitive to theoretical uncertainties! If no WISPs show up in purely laboratory experiments, there is hardly any excuse.

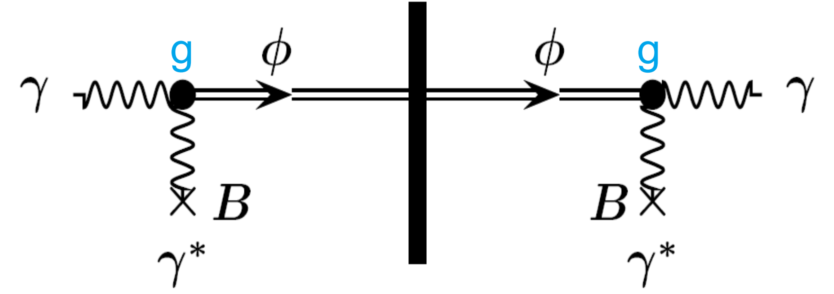
Shining WISPs through walls

- Basic idea: due to their very weak interaction WISPs may traverse any wall opaque to Standard Model constituents (except ν and gravitons).



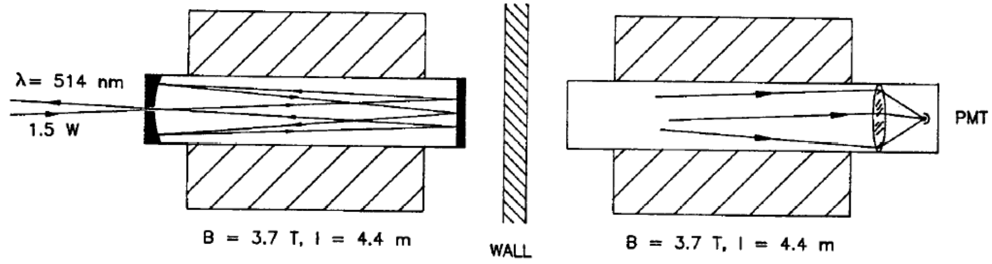
Shining WISPs through walls

“Light-shining-through-a-wall” (LSW)



Okun 1982, Skivie 1983, Ansel‘m 1985, Van Bibber et al. 1987

Note:
$P_{\gamma\to\Phi\to\gamma} \sim (BLg)^4$



G. Ruoso et al.
(BFRT Experiment),
Z. Phys. C 56 (1992) 505

Shining WISPs through walls

"Light-shining-through-a-wall" (LSW)

For ALPs:

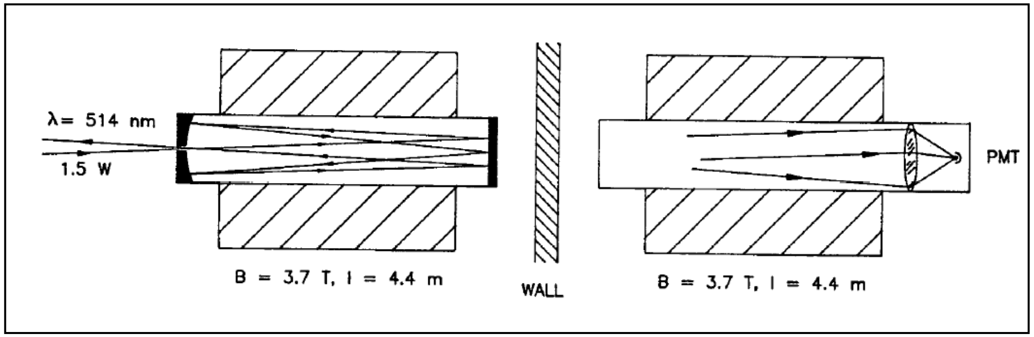
P(B field) / P(beam dump) =

$10^6 \cdot (\mathrm{mm}/\lambda_{abs}) \cdot (B/T)^2 \cdot (L/m)^2$

(A. Ringwald, J. Redondo, arXiv:1011.3741v1 [hep-ph])

Note:

$P_{\gamma \to \Phi \to \gamma} \sim (BLg)^4$



G. Ruoso et al.
(BFRT Experiment),
Z. Phys. C 56 (1992) 505

The challenge of lab experiments

Benchmark: flux of axions: $m_a = 6\ \mu\text{eV}$, $g_\gamma = 10^{-15}\ \text{GeV}^{-1}$

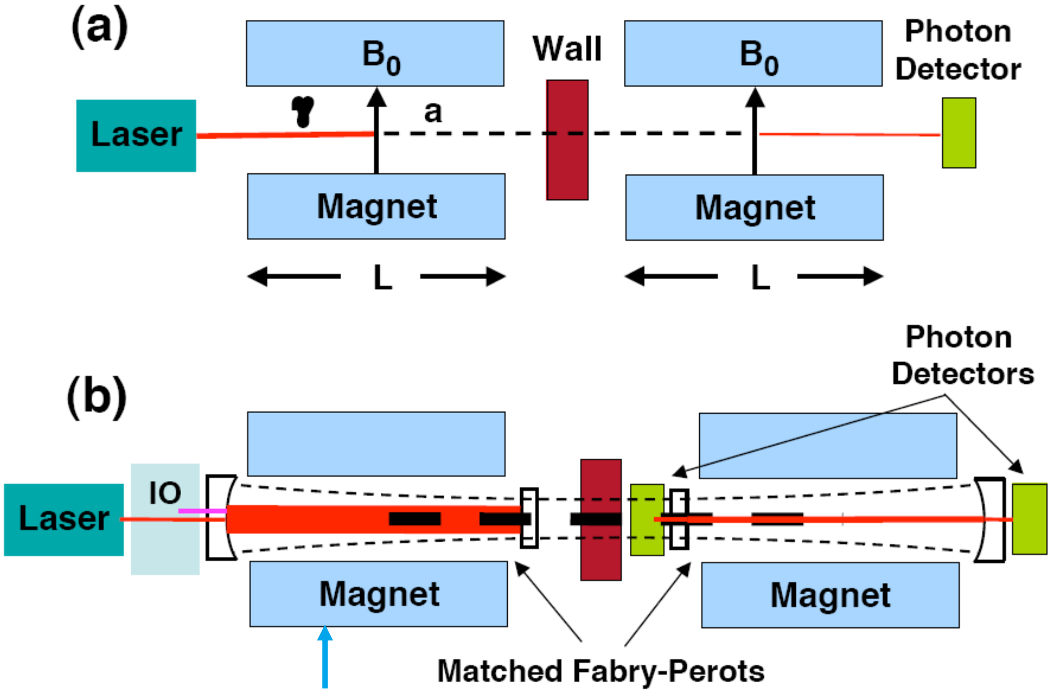
- Reminder: axion-photon conversion does not depend on energy!
- Haloscope:
  flux = $0.3\ \text{GeV/cm}^3 \cdot 200\ \text{km/s} = 6{\cdot}10^{15}\ \text{eV/cm}^2\text{s}$ (= $10\ \text{W/m}^2$!)
  = $2{\cdot}10^{21}$ axions/cm^{2}s
- Helioscopes:
  flux = $4{\cdot}10^{11}$ axions/cm^{2}s $\cdot\ (g_{10})^2$ = 600 axions/s @ CAST with 15cm^2
- LSW (ALPS-I):
  flux = 10^3 axions/s $\cdot\ (g_{10})^2$ = 10^{-7} axions/s

Impossible to probe low mass axions with helioscopes or in the lab.

LSW have to improve in axion production by 10 orders of magnitude to compete with helioscopes!

The regeneration cavity concept

- A cavity behind the wall would boost the reconversion probability of WISPs into photons by its power built-up Q.
  - The WISP beam (the em. component propagating behind the wall) has to have laser-like properties resonanting in the cavity.
  - This is only possible for artifical produced WISPs or WISPs at rest (DM halo).



Realized at ALPS-I

“Resonantly enhanced Axion-Photon Regeneration”
P. Sikivie, D.B. Tanner , Karl van Bibber. *Phys.Rev.Lett.98:172002,2007.*

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

The ALPS-II reach (similar REAPR)

Parameter	Achieved at ALPS-I	Aimed for at ALPS-II	Sensitivity to ALP coupling g	Sensitivity gain compared to ALPS-I
Effective Laser power LP	1 kW	150 kW	$g \sim LP^{-1/4}$	3.5
Rel. photon number flux n	1 (532nm)	2 (1064 nm)	$g \sim n^{-1/4}$	1.2
Magnetic length BL	0.5+0.5 HERA dipole	12+12 HERA dipoles	$g \sim 1/BL$	24.0
Detector Efficiency QE	0.9	0.9	$g \sim QE^{-1/4}$	1.0
Detector Noise DC	0.01 1/s	0.0001 1/s	$g \sim DC^{-1/8}$	1.8
Power built-up in a regeneration cavity PB	1	40,000	$g \sim PB^{-1/4}$	14.1
Total for ALP searches				**2,500**
Total for HP searches				100

The ALPS-II reach (similar REAPR)

Parameter	**Achieved at ALPS-I**	**Aimed for at ALPS-II**	**Sensitivity to ALP coupling g**	**Sensitivity gain compared to ALPS-I**	Gain in effective ALP flux
Effective Laser power LP	1 kW	150 kW	$g \sim LP^{-1/4}$	3.5	150
Rel. photon number flux n	1 (532nm)	2 (1064 nm)	$g \sim n^{-1/4}$	1.2	2
Magnetic length BL	0.5+0.5 HERA dipole	12+12 HERA dipoles	$g \sim 1/BL$	24.0	144
Detector Efficiency QE	0.9	0.9	$g \sim QE^{-1/4}$	1.0	
Detector Noise DC	0.01 1/s	0.0001 1/s	$g \sim DC^{-1/8}$	1.8	
Power built-up in a regeneration cavity PB	1	40,000	$g \sim PB^{-1/4}$	14.1	$4\cdot10^{4}$
Total for ALP searches				**2,500**	**$2\cdot10^{9}$**
Total for HP searches				100	

Four crucial knobs to tune:

- Long magnet strings
- High photon number flux before the wall
- Regeneration cavity behind the wall
- Sensitive and effectively background-free photon detectors

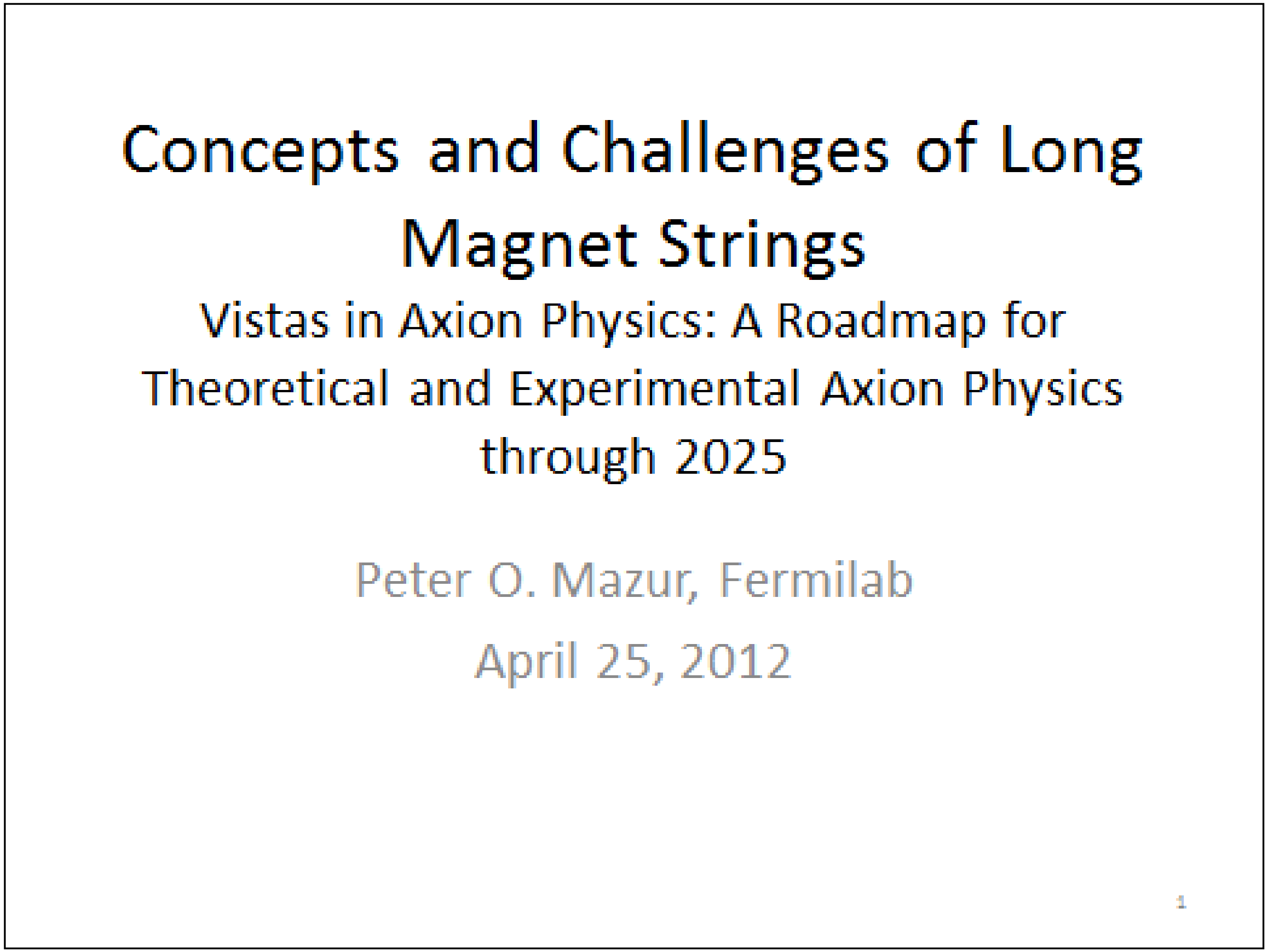
Three crucial knobs discussed here:

- Long magnet strings
- High photon number flux before the wall
- Regeneration cavity behind the wall

not independent!

- Sensitive and effectively background-free photon detectors

Long magnet strings



Concepts and Challenges of Long Magnet Strings

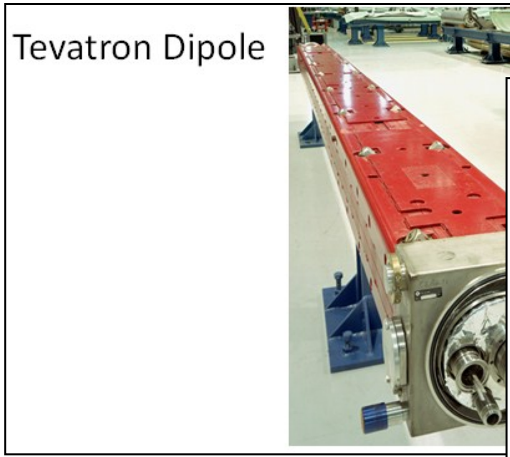
Vistas in Axion Physics: A Roadmap for Theoretical and Experimental Axion Physics through 2025

Peter O. Mazur, Fermilab

April 25, 2012

Long magnet strings

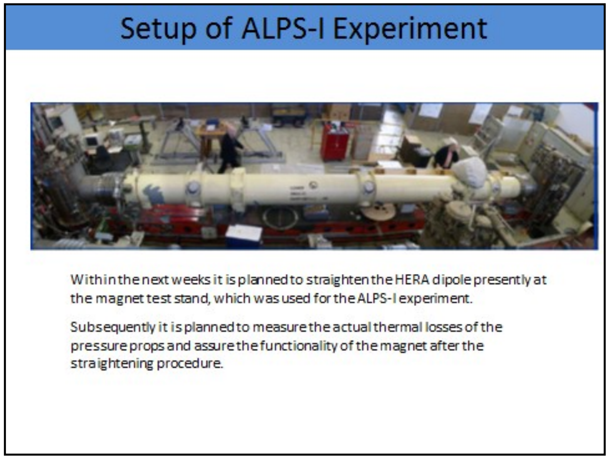
- Many dipoles from particle accelerator wait for a new task!



Tevatron Dipole

Spare Tevatron Dipoles in the Magnet Storage Building

700 More Spare Tevatron Dipoles in the New Underground Magnet Storage Facility



Setup of ALPS-I Experiment

Within the next weeks it is planned to straighten the HERA dipole presently at the magnet test stand, which was used for the ALPS-I experiment.

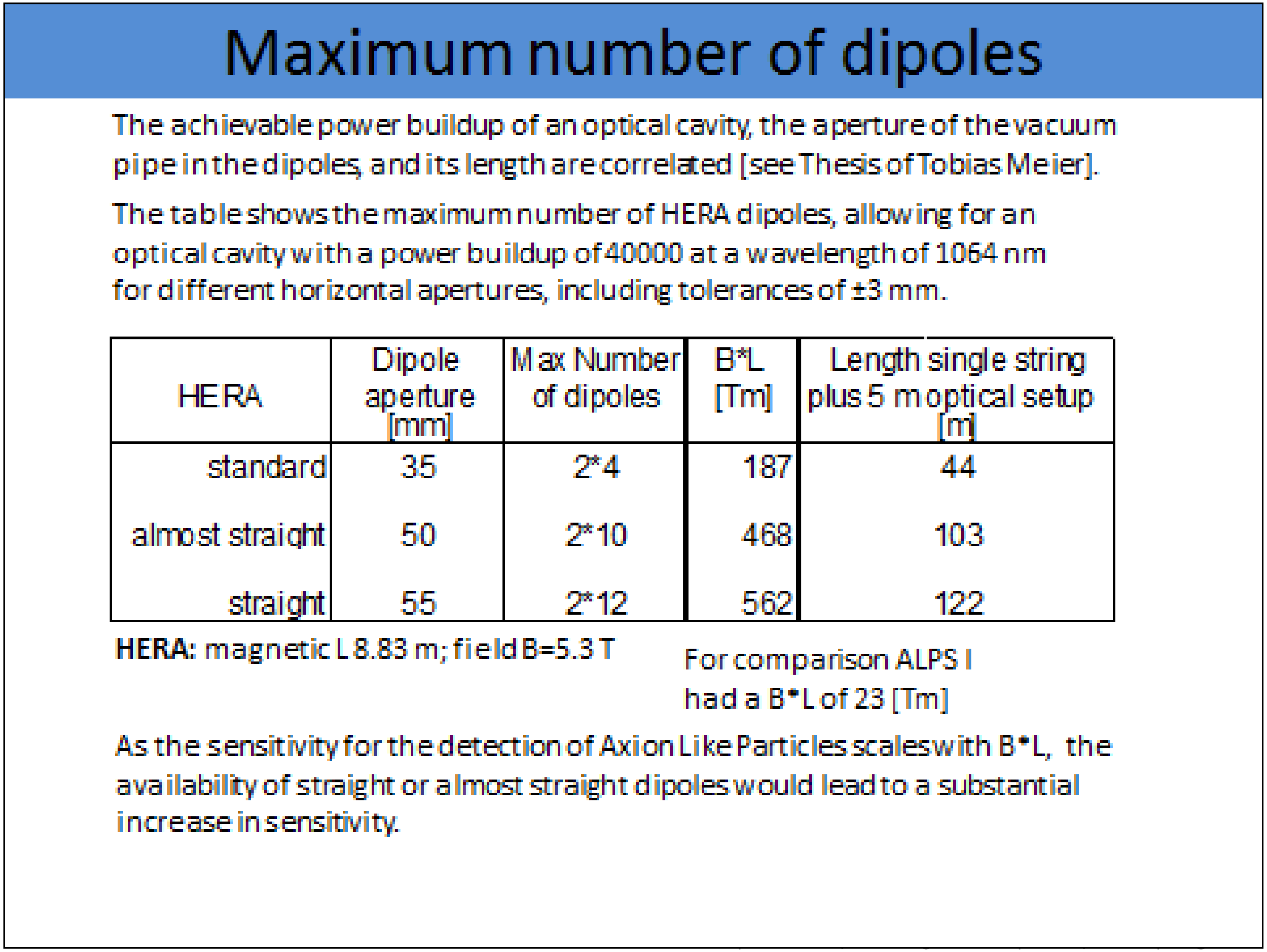
Subsequently it is planned to measure the actual thermal losses of the pressure props and assure the functionality of the magnet after the straightening procedure.

SSC Dipole Magnets

Long magnet strings: figures of merit

- For axions and ALPs: B·L is what counts!
- For existing magnets the maximal B is hardly changeable
  - Only slight increases by improved cryogenics.
  - Within a factor of 2 all accelerator dipoles in question have the same field strength.
- The maximal length is given by the aperture:
  - Clipping losses have to be smaller than other losses in the optical cavities, less than 10^{-4} to 10^{-5}.
  - The maximal length is proportional to $(\text{aperture})^2$!

Crucial: dipole straigthening!



Maximum number of dipoles

The achievable power buildup of an optical cavity, the aperture of the vacuum pipe in the dipoles, and its length are correlated [see Thesis of Tobias Meier].

The table shows the maximum number of HERA dipoles, allowing for an optical cavity with a power buildup of 40000 at a wavelength of 1064 nm for different horizontal apertures, including tolerances of ±3 mm.

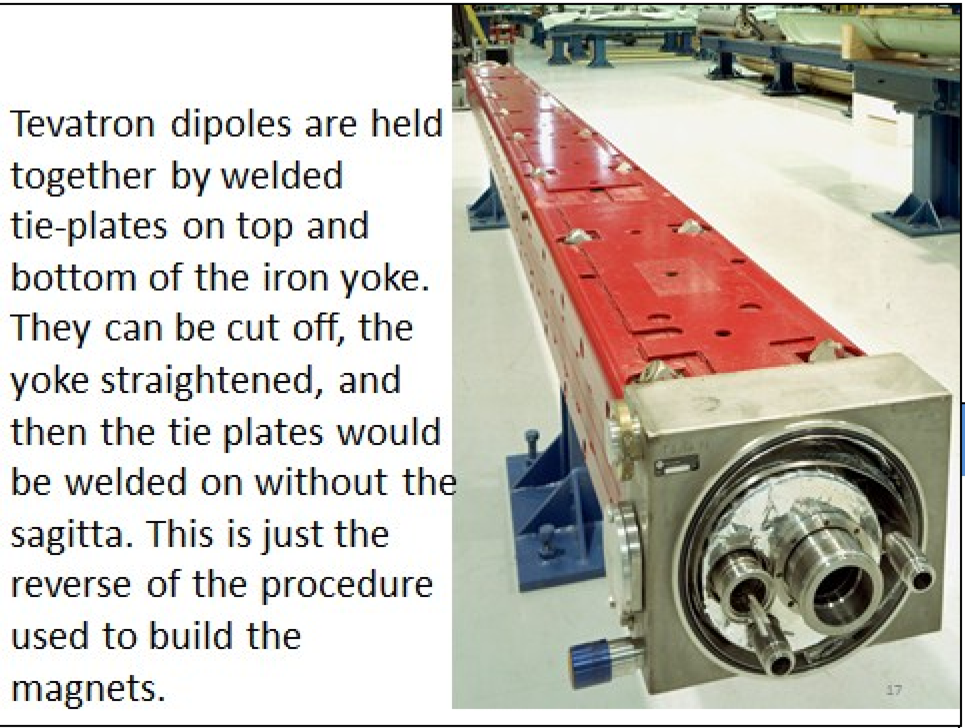
HERA	Dipole aperture [mm]	Max Number of dipoles	B*L [Tm]	Length single string plus 5 m optical setup [m]
standard	35	2*4	187	44
almost straight	50	2*10	468	103
straight	55	2*12	562	122

HERA: magnetic L 8.83 m; field B=5.3 T

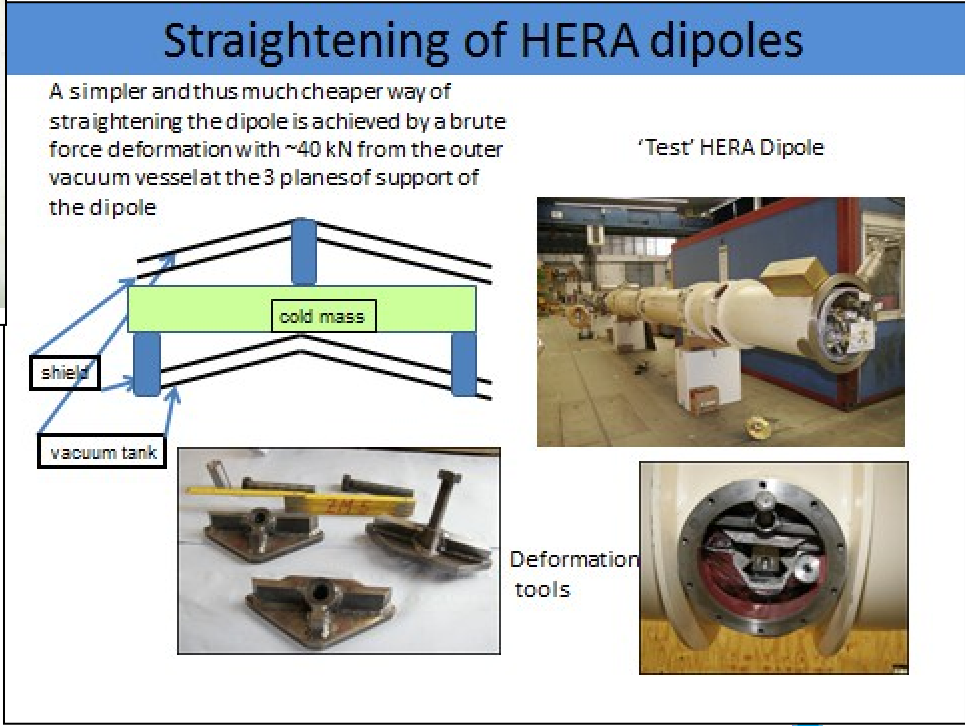
For comparison ALPS I had a B*L of 23 [Tm]

As the sensitivity for the detection of Axion Like Particles scales with B*L, the availability of straight or almost straight dipoles would lead to a substantial increase in sensitivity.

Crucial: dipole straigthening!



Tevatron dipoles are held together by welded tie-plates on top and bottom of the iron yoke. They can be cut off, the yoke straightened, and then the tie plates would be welded on without the sagitta. This is just the reverse of the procedure used to build the magnets.



Straightening of HERA dipoles

A simpler and thus much cheaper way of straightening the dipole is achieved by a brute force deformation with ~40 kN from the outer vacuum vessel at the 3 planes of support of the dipole

'Test' HERA Dipole

Deformation tools

It could work out easily for Tevatron and HERA dipoles!

Long magnet strings

- Strings up to 2·150 m providing more than 2·500 Tm are in reach.
- Infrastructure issues like possible sites, cryogenics, safety issues (quench protection), power supplies and others have been studied and solutions have been found.
- Yearly operation costs amount to a few 100.000 €
(at an existing laboratory).

One could do it now!

- One should start “now” because the re-use of existing magnet relies on the expertise of mature (retired) physicists and engineers!

Long magnet strings 2025ff

- We could benefit from ongoing magnet development for LHC energy upgrades (for example).
- Most promising could be 12 T dipoles with an aperture of 100 mm (by “removing” the HTC superconducting insert boosting the field to 20 T).
- This would allow to quadruplicate the length and nearly duplicate the field strength.

This would allow to boost the sensitivity in ALP-photon coupling by nearly an order of magnitude!

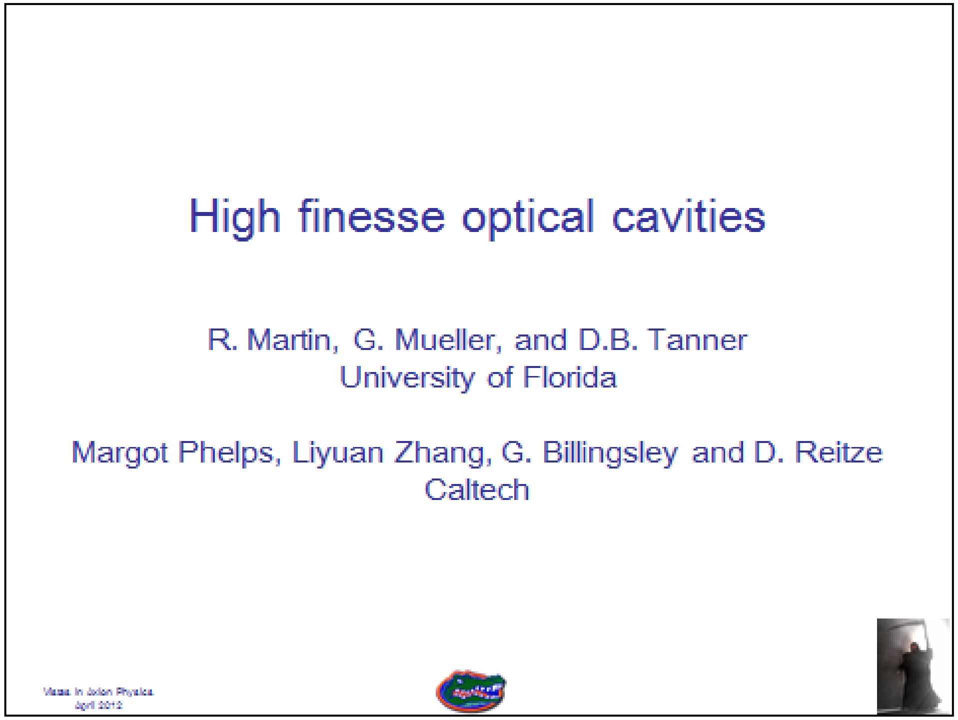
However, this could become costly!

Optics of LSW experiments

Optical design of 'shining light through wall' experiments

Benno Willke
Leibniz Universität Hannover
(member of the ALPS collaboration)

Vistas in Axion Physics: A Roadmap for Theoretical and Experimental Axion Physics through 2025, Seattle, 23-26 April 2012



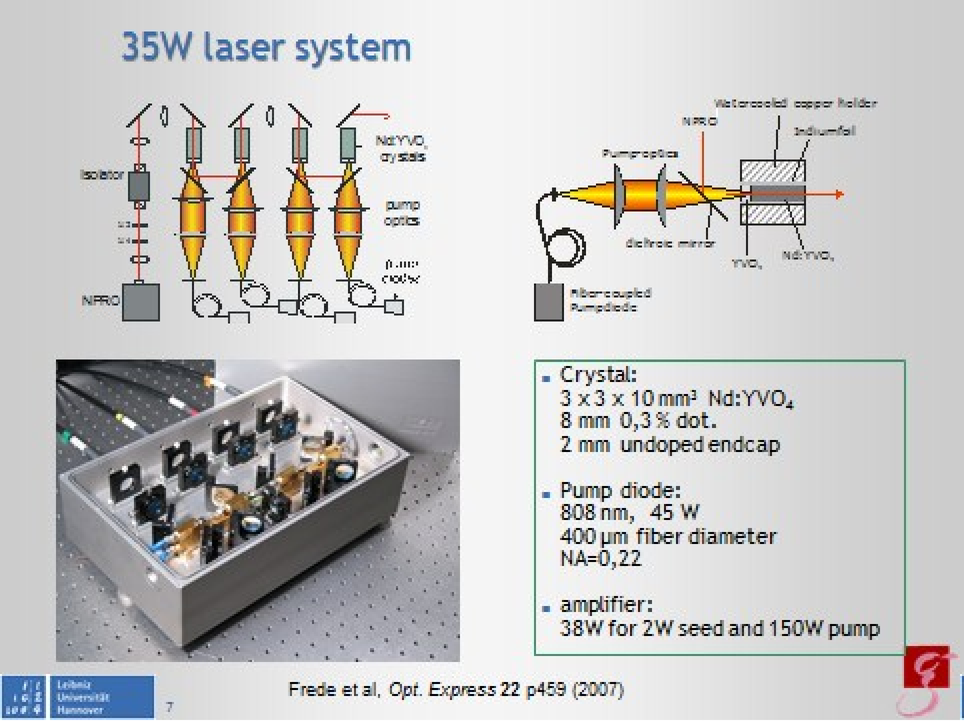
High finesse optical cavities

R. Martin, G. Mueller, and D.B. Tanner
University of Florida

Margot Phelps, Liyuan Zhang, G. Billingsley and D. Reitze
Caltech

Huge leap in sensitivity possible!

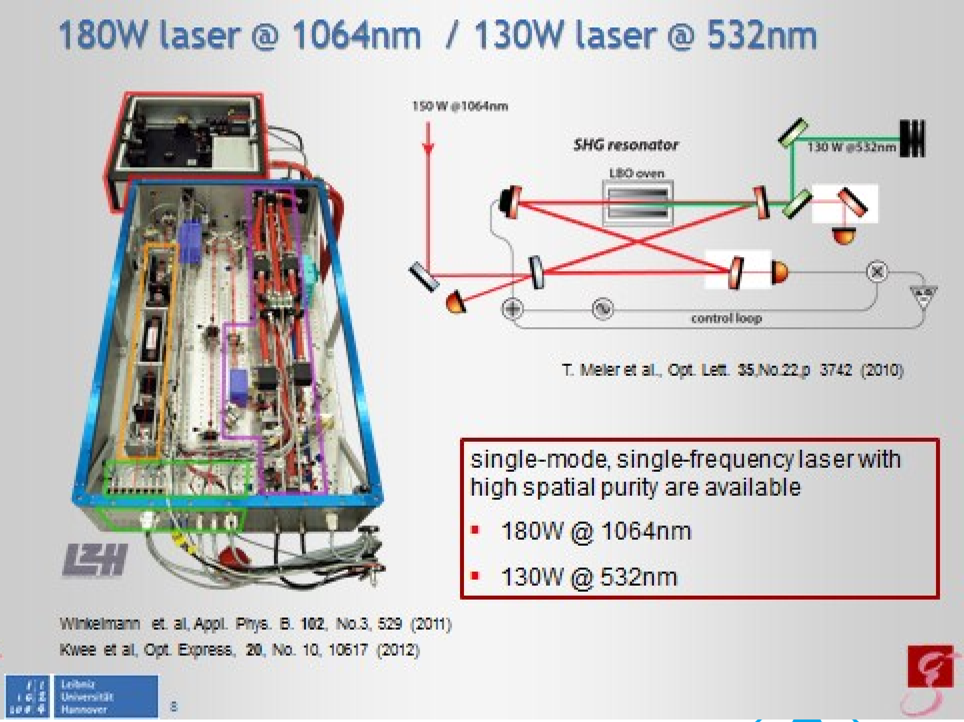
- From GammeV to REAPR:
  the know-how of the gravitational wave interferometer community allows for an increase in the ALP-photon coupling sensitivity by 2 orders of magnitude. Another 2 orders are coming from particle physics.
- Complex laser systems (cw powers!):



35W laser system

- Crystal:
  $3 \times 3 \times 10\ \mathrm{mm}^3$ Nd:YVO$_4$
  8 mm 0,3 % dot.
  2 mm undoped endcap
- Pump diode:
  808 nm, 45 W
  400 µm fiber diameter
  NA=0,22
- amplifier:
  38W for 2W seed and 150W pump

Frede et al, *Opt. Express* 22 p459 (2007)



180W laser @ 1064nm / 130W laser @ 532nm

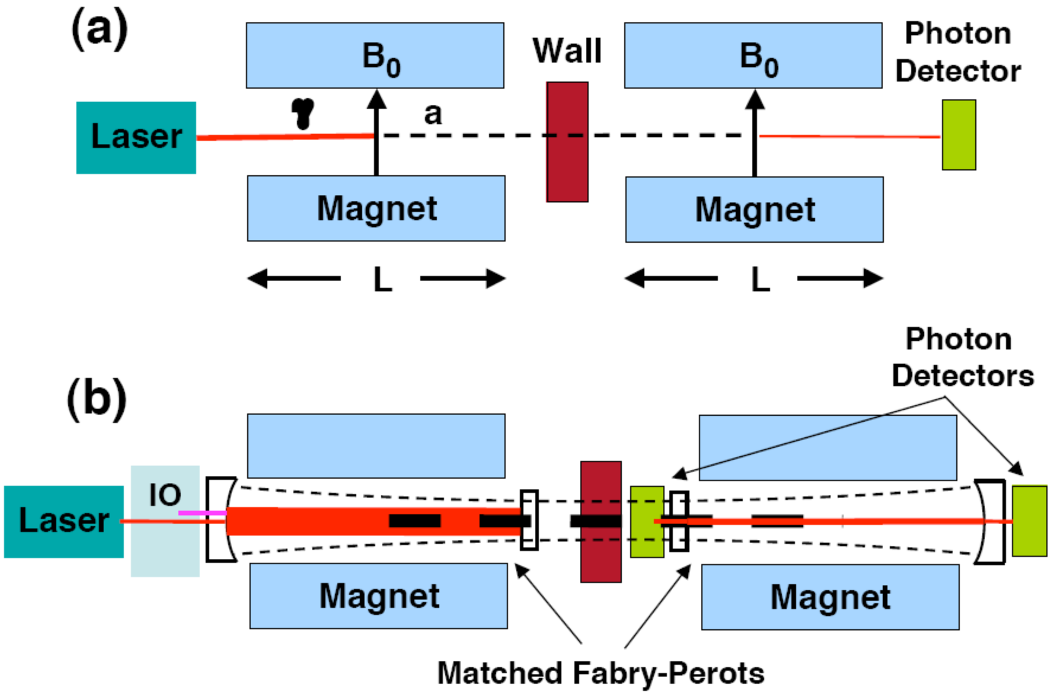
T. Meier et al., Opt. Lett. 35,No.22,p 3742 (2010)

single-mode, single-frequency laser with high spatial purity are available

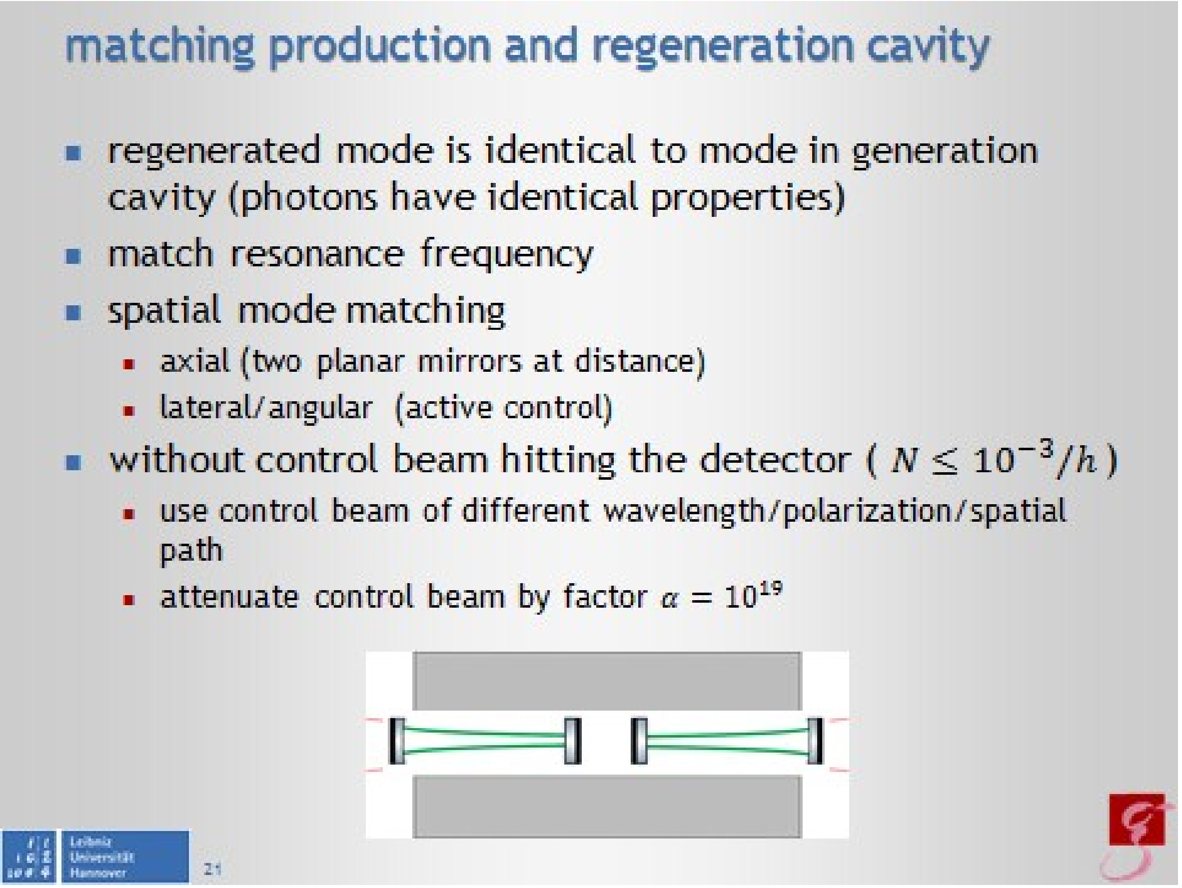
- 180W @ 1064nm
- 130W @ 532nm

Winkelmann et. al, Appl. Phys. B. 102, No.3, 529 (2011)
Kwee et al, Opt. Express, 20, No. 10, 10617 (2012)

The basic idea of the optics setup



The basic idea of the optics setup



matching production and regeneration cavity

- regenerated mode is identical to mode in generation cavity (photons have identical properties)
- match resonance frequency
- spatial mode matching
  - axial (two planar mirrors at distance)
  - lateral/angular (active control)
- without control beam hitting the detector ($N \leq 10^{-3}/h$)
  - use control beam of different wavelength/polarization/spatial path
  - attenuate control beam by factor $\alpha = 10^{19}$

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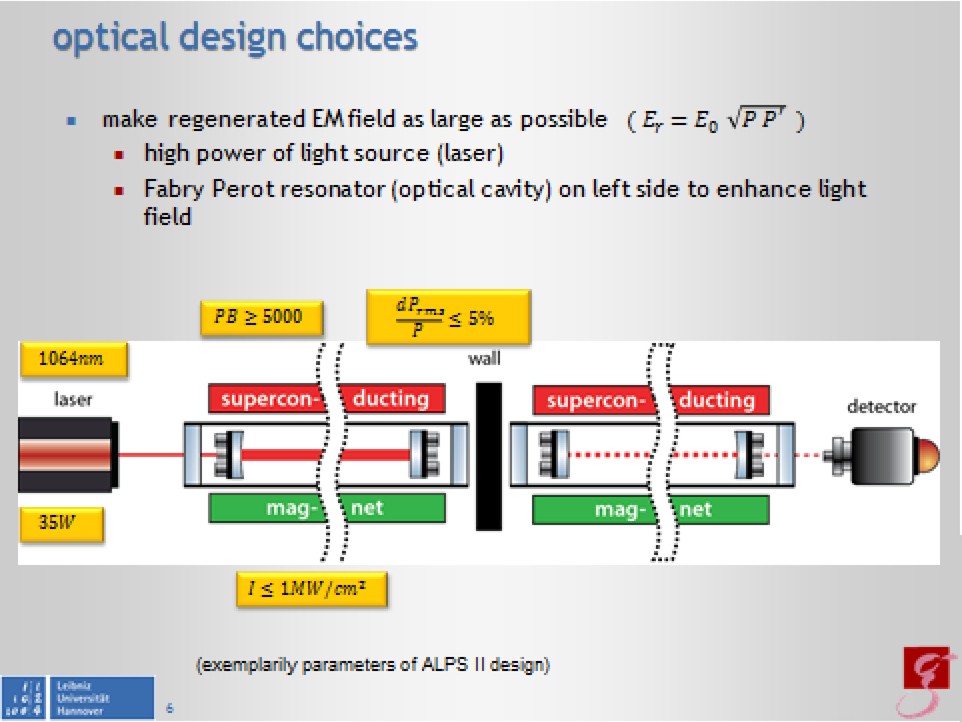
21

- Phase lock and mode matching of both optical cavities required:
  In theory the inner mirrors could be removed to have one large cavity.
- A control beam is required to lock the regeneration cavity, but no photons of this beam should harm the detection of regenerated photons from WISPs!

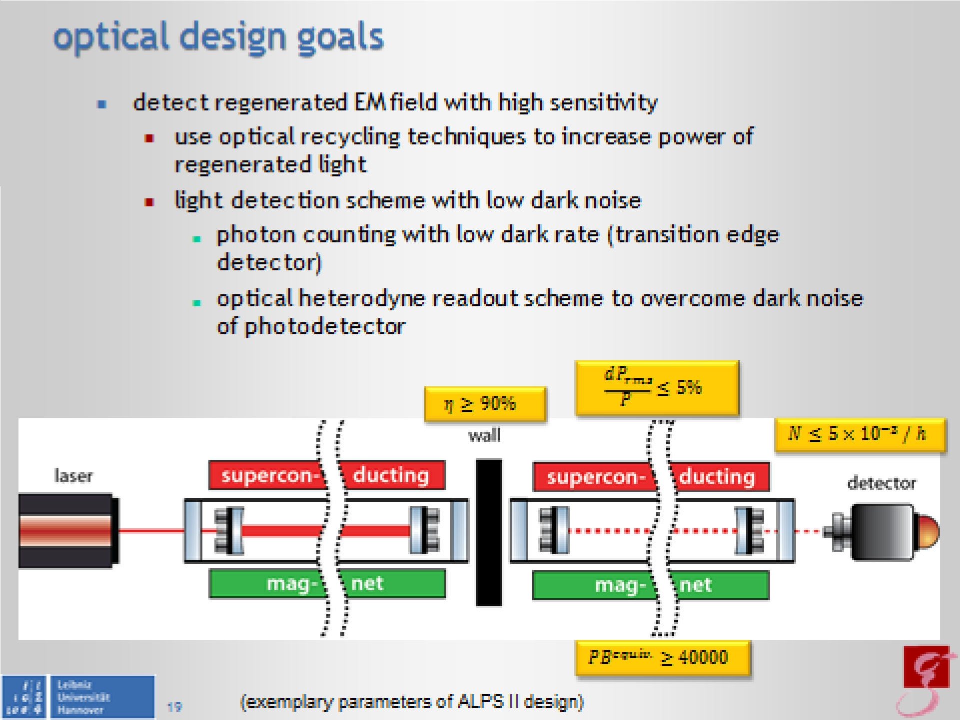
Some design choices



optical design choices

- make regenerated EM field as large as possible ($E_r = E_0\,\sqrt{P\,P'}$)
    - high power of light source (laser)
    - Fabry Perot resonator (optical cavity) on left side to enhance light field

(exemplarily parameters of ALPS II design)

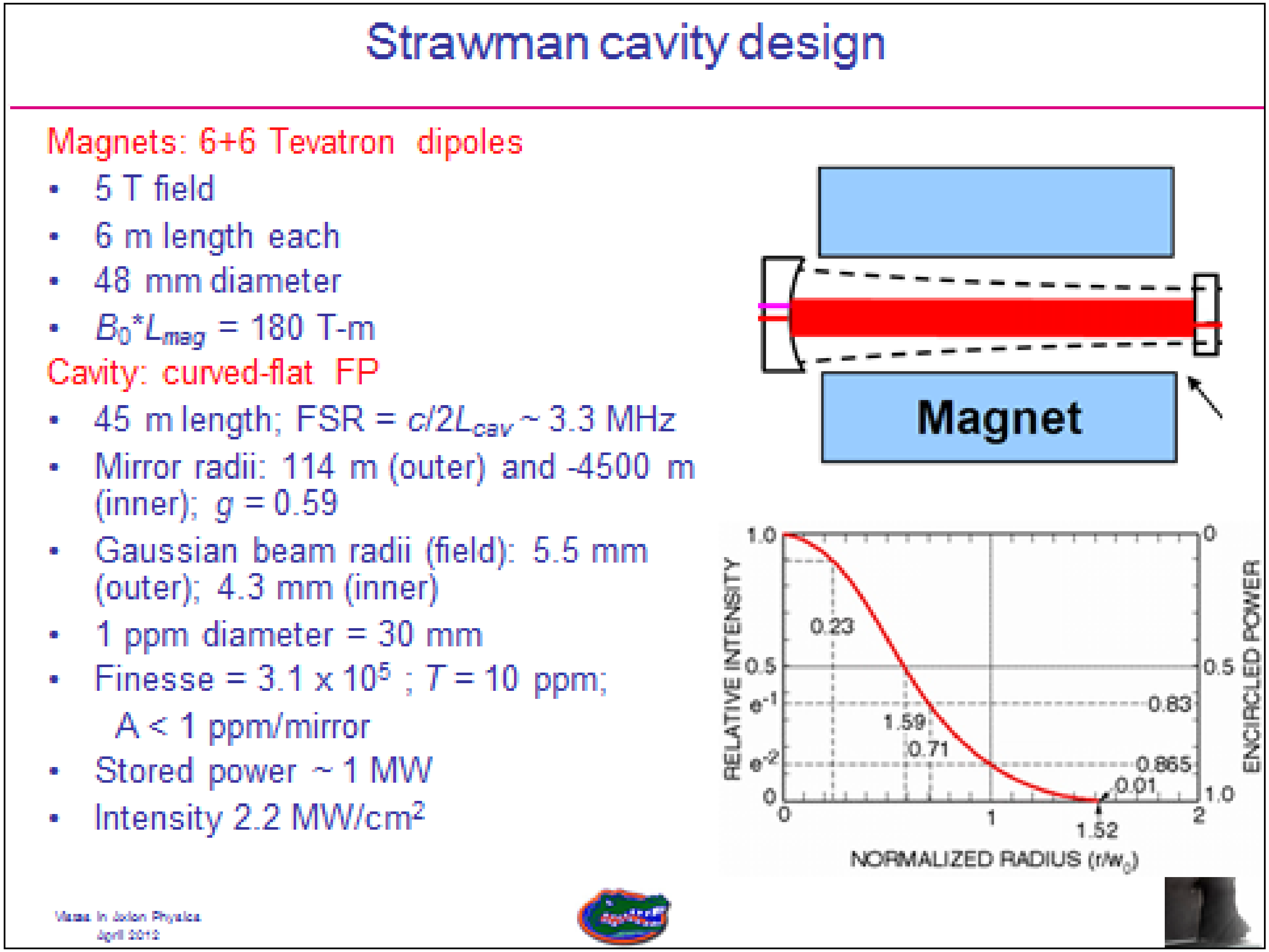


optical design goals

- detect regenerated EM field with high sensitivity
    - use optical recycling techniques to increase power of regenerated light
    - light detection scheme with low dark noise
        - photon counting with low dark rate (transition edge detector)
        - optical heterodyne readout scheme to overcome dark noise of photodetector

(exemplary parameters of ALPS II design)

Some design choices



Strawman cavity design

Magnets: 6+6 Tevatron dipoles

- 5 T field
- 6 m length each
- 48 mm diameter
- $B_0{}^*L_{mag}$ = 180 T-m

Cavity: curved-flat FP

- 45 m length; FSR = $c/2L_{cav}$ ~ 3.3 MHz
- Mirror radii: 114 m (outer) and -4500 m (inner); $g = 0.59$
- Gaussian beam radii (field): 5.5 mm (outer); 4.3 mm (inner)
- 1 ppm diameter = 30 mm
- Finesse = 3.1 x 10^5 ; T = 10 ppm;
  A < 1 ppm/mirror
- Stored power ~ 1 MW
- Intensity 2.2 MW/cm^2

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Two different approaches

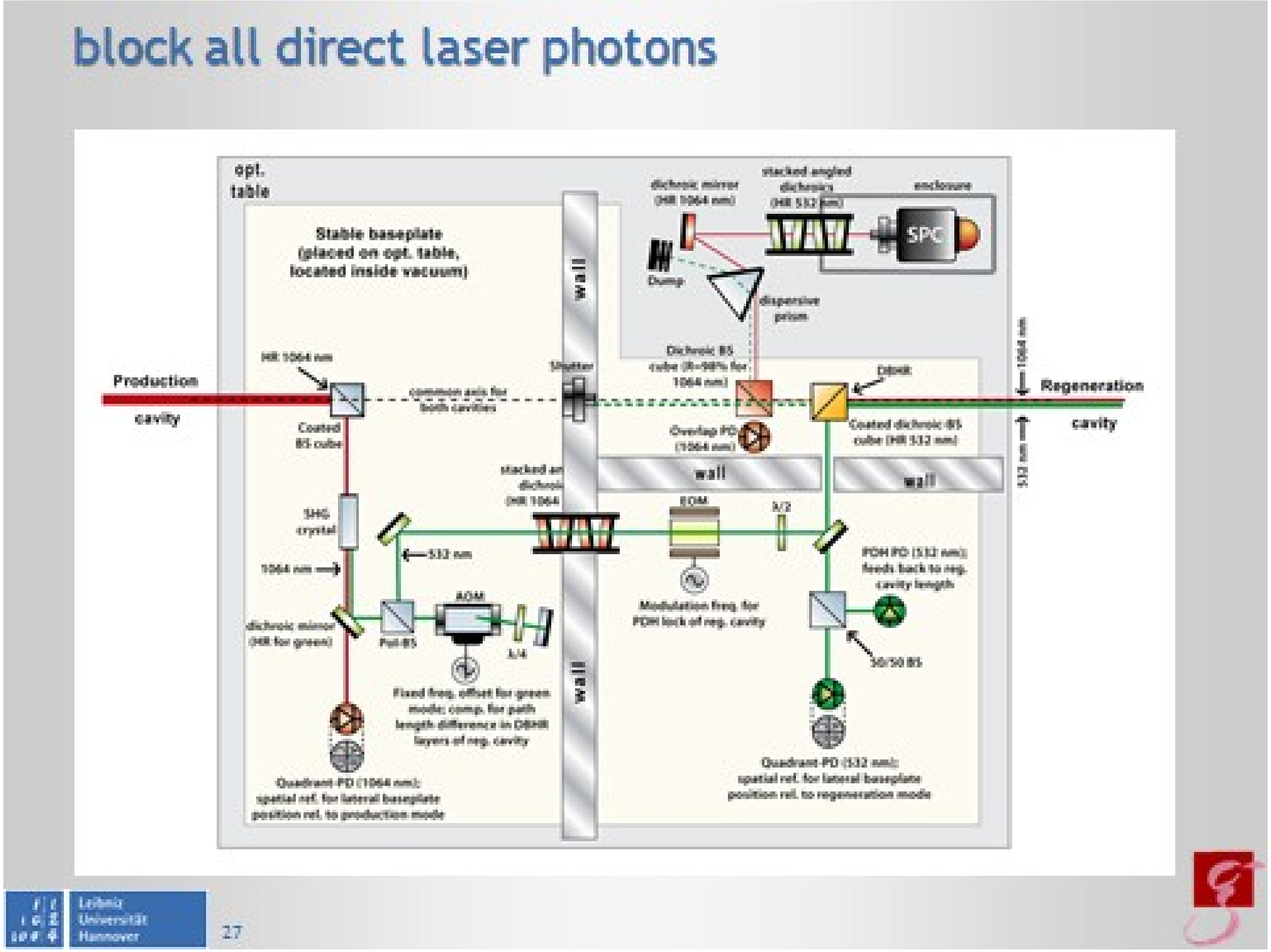
ALPS-II:

- Lock the regeneration cavity with frequency doubled light.
- Shield the photon detector from of this light.
- Count single regenerated photons in a background-free detector

REAPR:

- Lock the regeneration cavity with light shifted by $n \cdot \Delta\lambda$ (free spectral range, few MHz).
- Use heterodyne detection by mixing light used to lock the reg. cavity and reconverted photons.
- In principle detector backgrounds do not matter, look for a beat signal given by $n \cdot \Delta\lambda$.

Two different approaches: ALPS-II



block all direct laser photons

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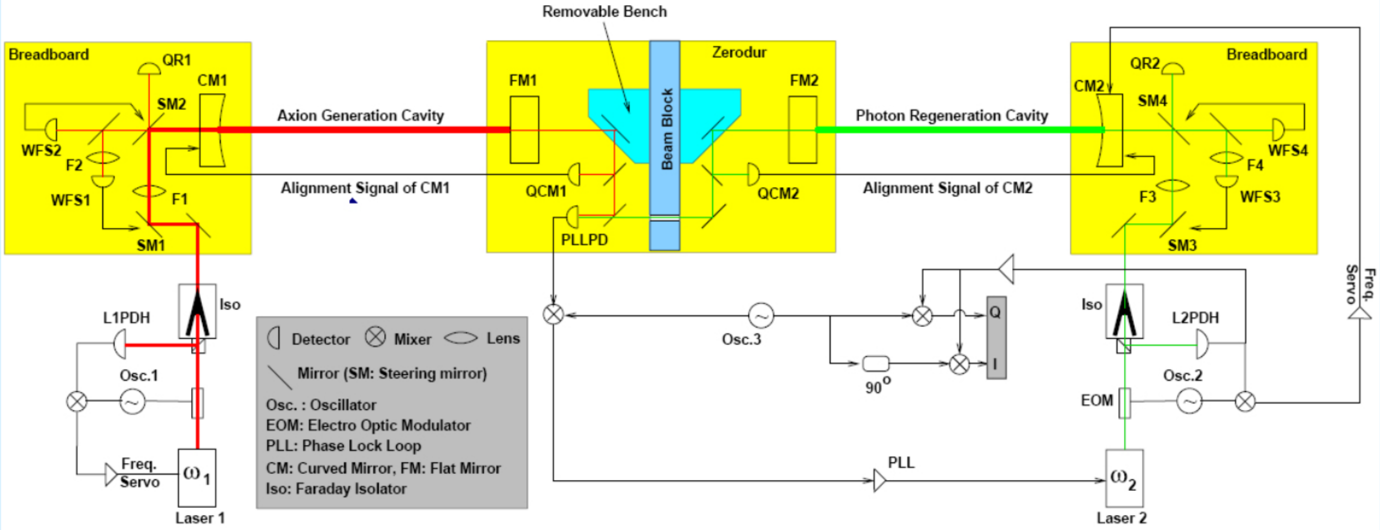
Two different approaches: REAPR

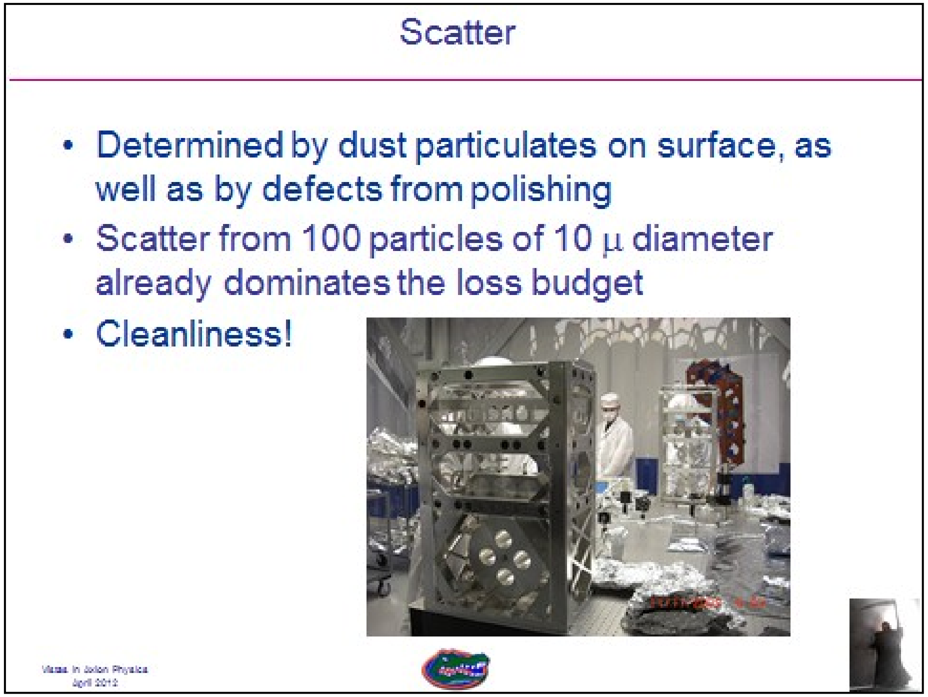
Strawperson optical design



- Use two lasers.
- Laser 1 injects power into generation cavity
- Laser 2 is offset locked to Laser 1
- Offset frequency Ω = integer * FSR of the cavities
- Regeneration cavity is PDH locked to Laser 2
- Laser 2 used to for heterodyne readout of signal in regeneration cavity

G. Mueller (D. Tanner, Univ of FL, DOE Intensity Frontier Workshop)

However, details matter!



Scatter

- Determined by dust particulates on surface, as well as by defects from polishing
- Scatter from 100 particles of 10 μ diameter already dominates the loss budget
- Cleanliness!

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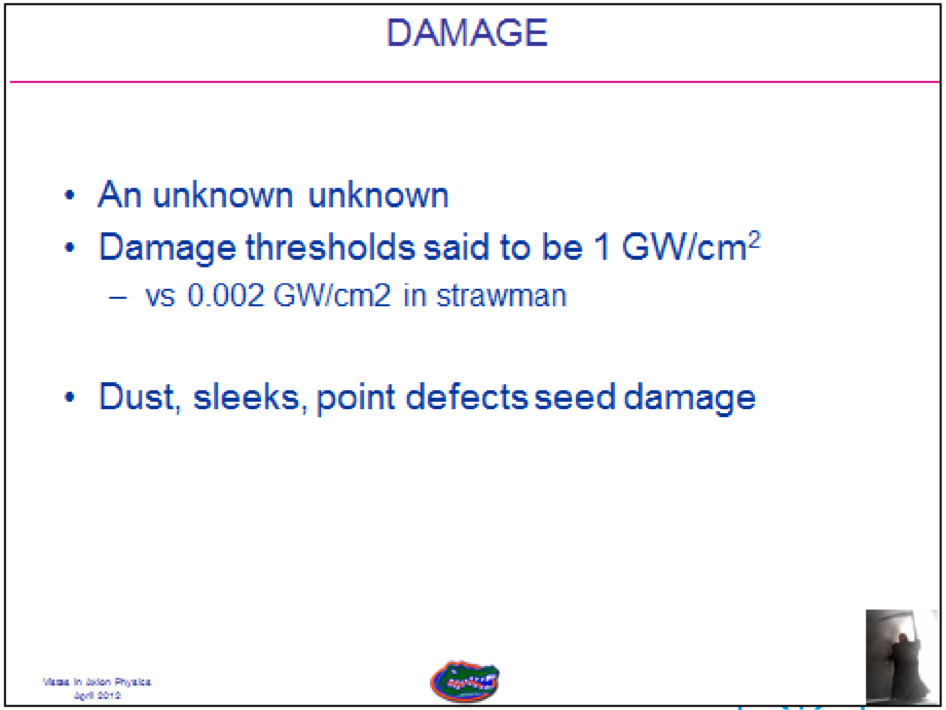

DAMAGE

- An unknown unknown
- Damage thresholds said to be 1 GW/cm^2
  - – vs 0.002 GW/cm2 in strawman
- Dust, sleeks, point defects seed damage

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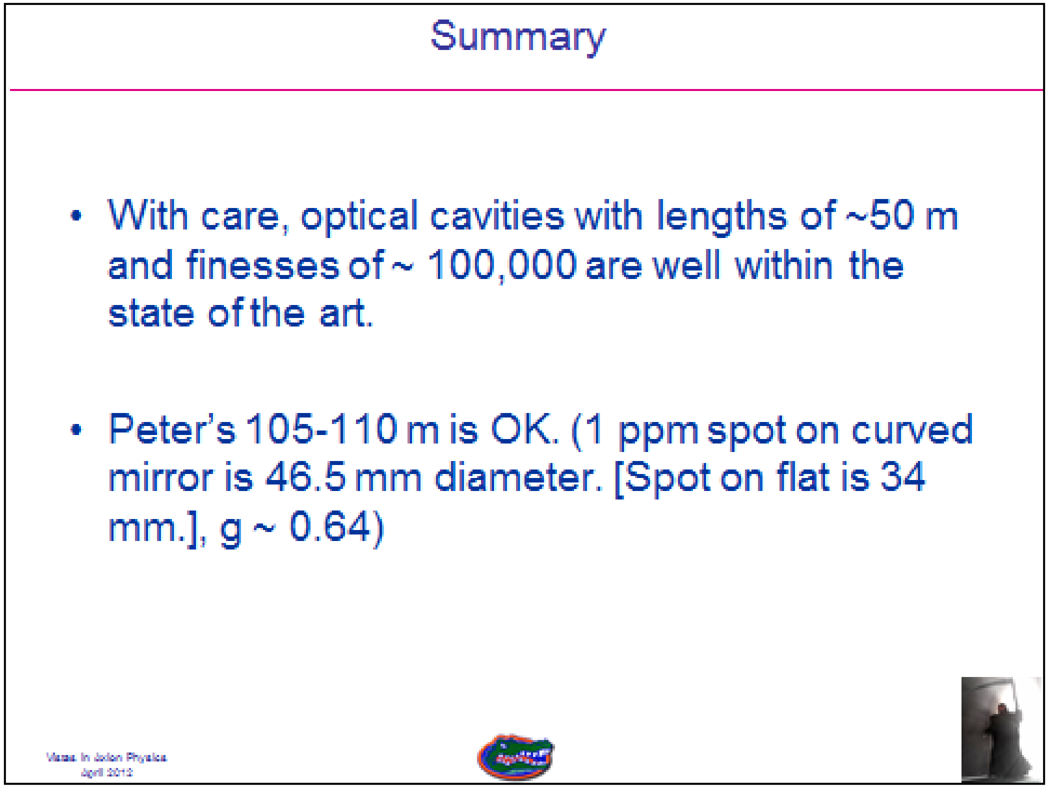
Summary: possible, but not easy!



Summary

- With care, optical cavities with lengths of ~50 m and finesses of ~ 100,000 are well within the state of the art.
- Peter's 105-110 m is OK. (1 ppm spot on curved mirror is 46.5 mm diameter. [Spot on flat is 34 mm.], g ~ 0.64)

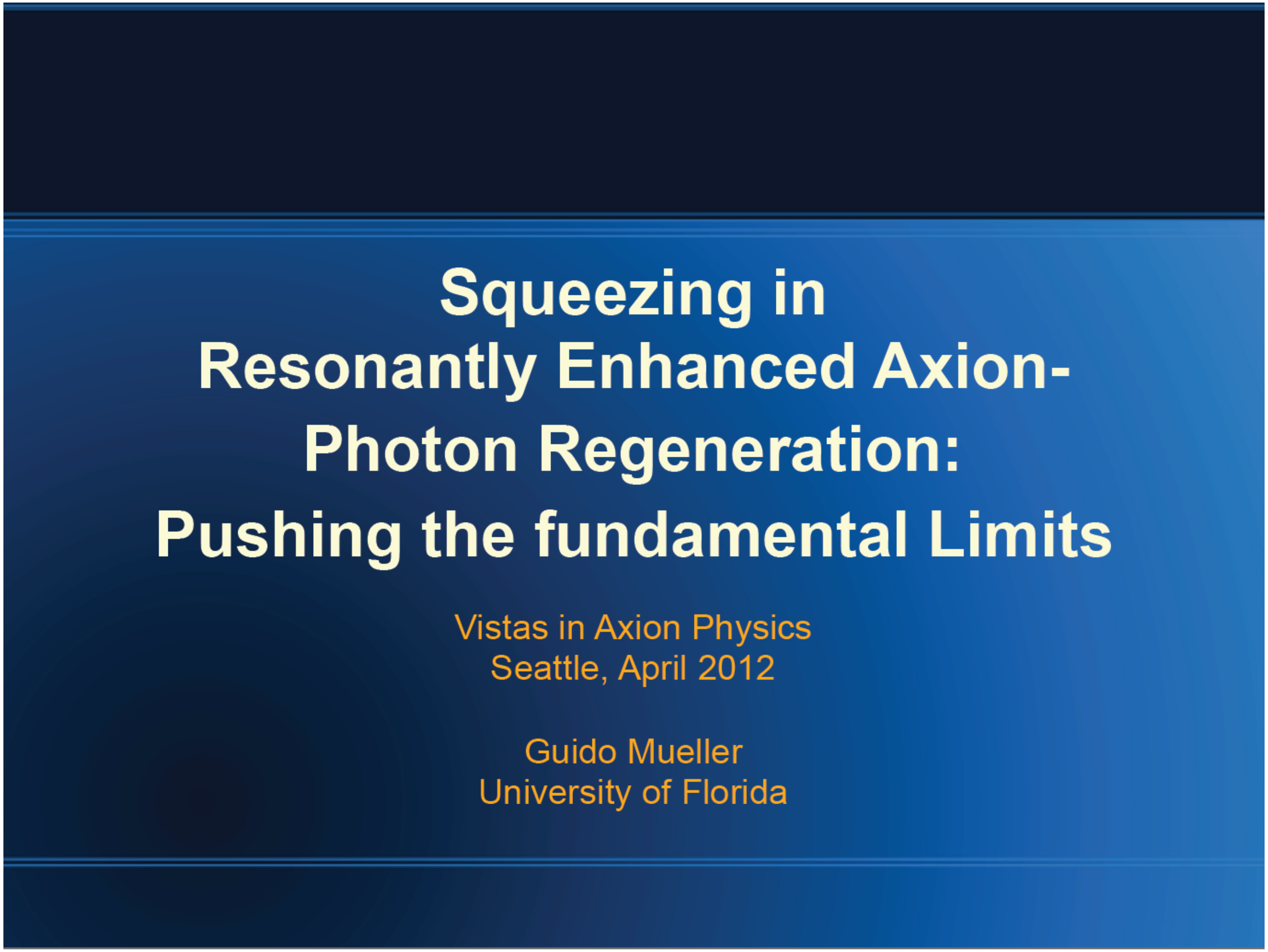
Still some R&D required:

- High power cavities with the targeted finesses do not exist yet.
- Mode matching and phase locking two O(100m) long cavities is still a challenge.

Clear two to three year long R&D programs from table-top to ultimate sizes exist!

Funding might still be an issue …

A new means: squeezed light?



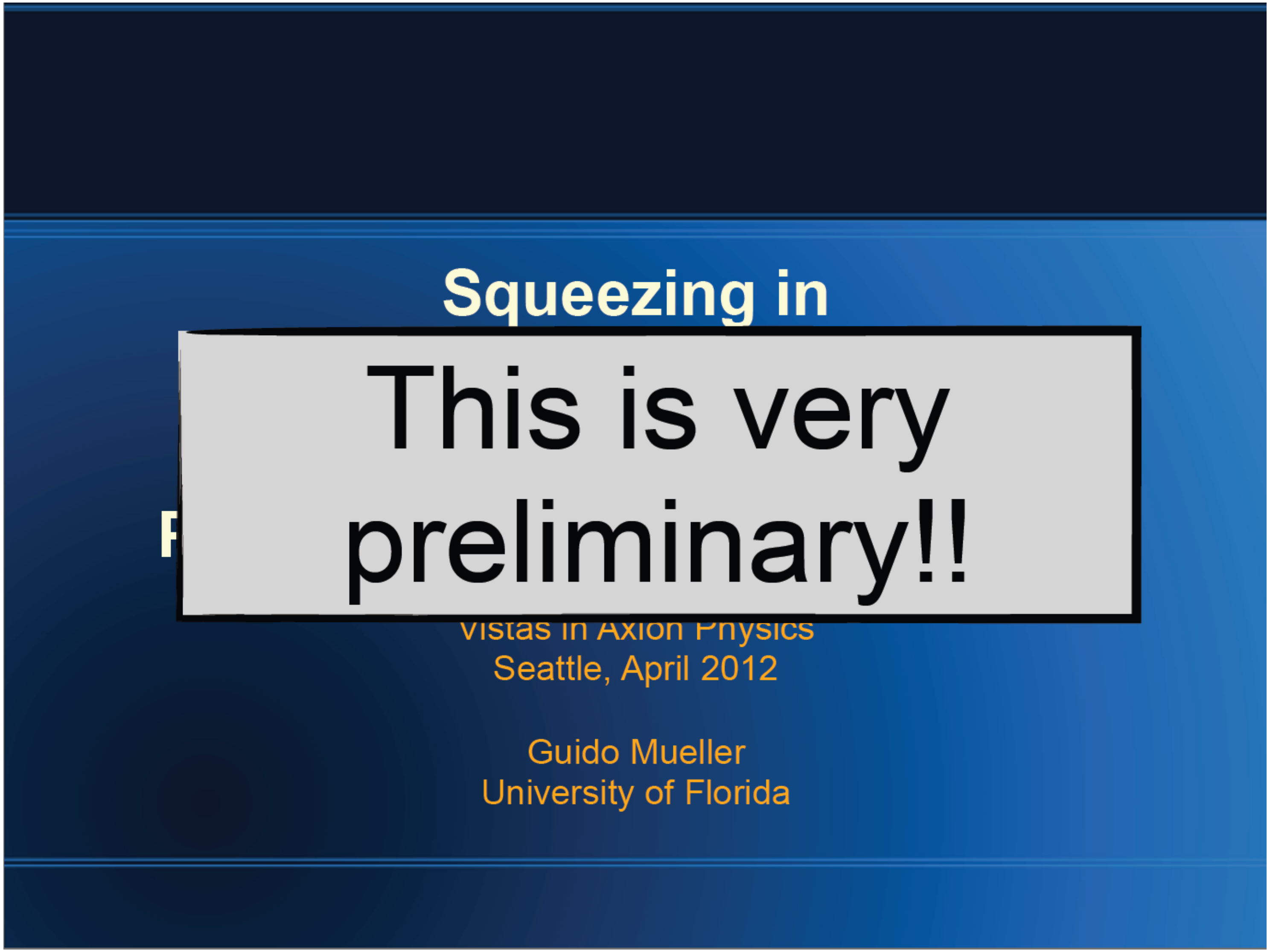
Squeezing in Resonantly Enhanced Axion-Photon Regeneration:

Pushing the fundamental Limits

Vistas in Axion Physics
Seattle, April 2012

Guido Mueller
University of Florida

A new means: squeezed light?



Squeezing in

F

This is very preliminary!!

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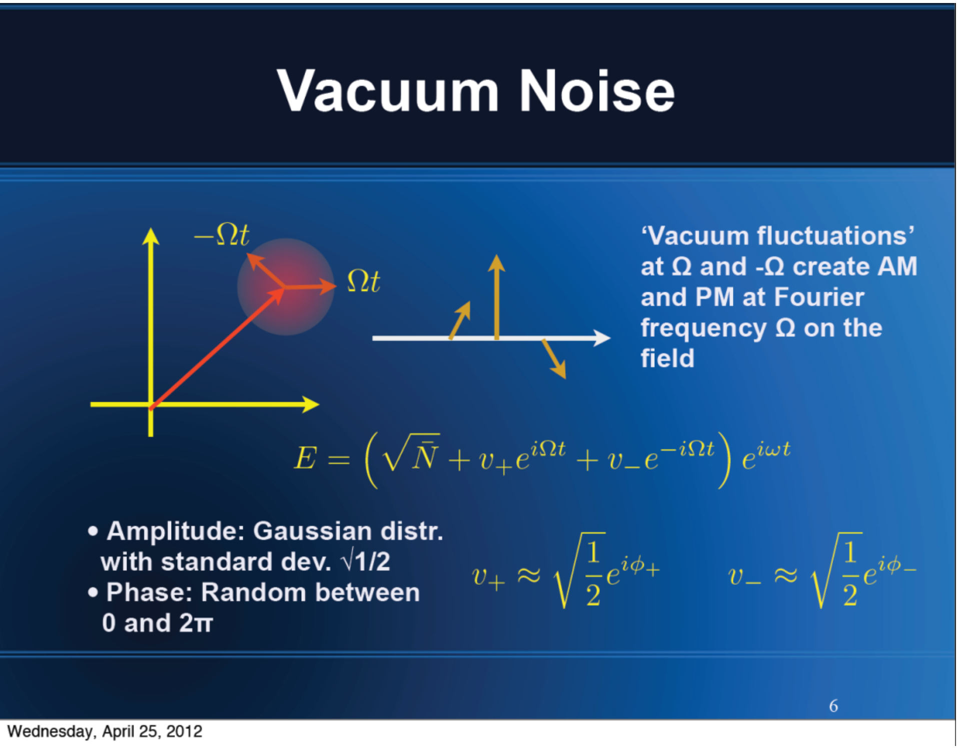
Guido Mueller
University of Florida

Wednesday, April 25, 2012

Squeezed light

- Overcome the barrier of shot noise by squeezing fluctuations from one coordinate into another: correlate statistical noise by nonlinear optics.



Vacuum Noise

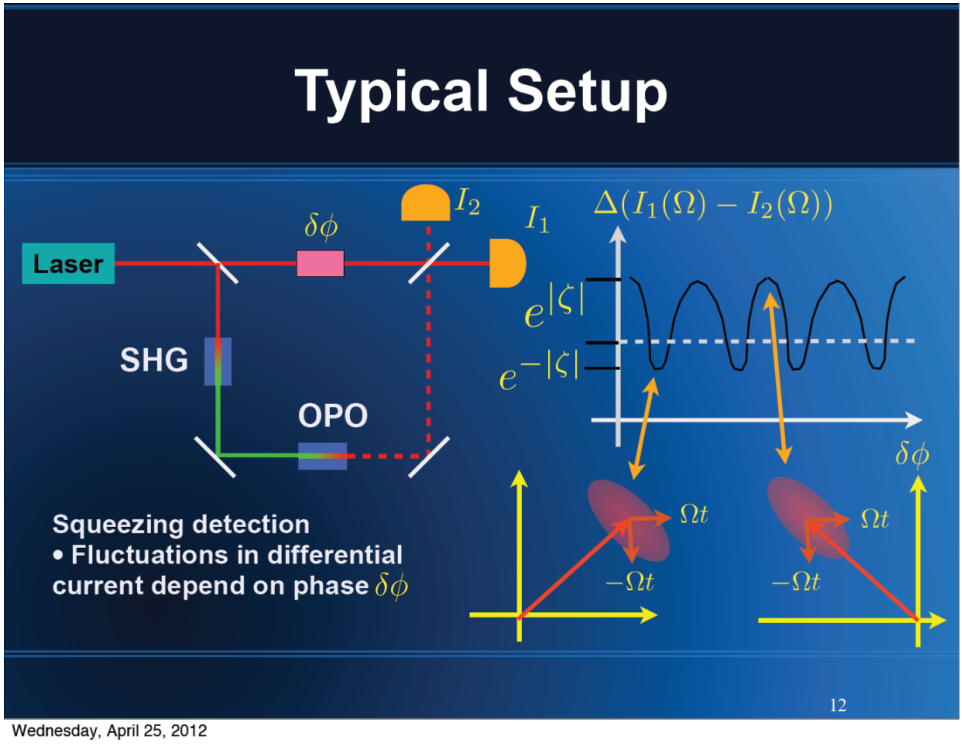
'Vacuum fluctuations' at Ω and -Ω create AM and PM at Fourier frequency Ω on the field

$$E = \left(\sqrt{\bar{N}} + v_+ e^{i\Omega t} + v_- e^{-i\Omega t}\right) e^{i\omega t}$$

- Amplitude: Gaussian distr. with standard dev. √1/2
- Phase: Random between 0 and 2π

$$v_+ \approx \sqrt{\frac{1}{2}} e^{i\phi_+} \qquad v_- \approx \sqrt{\frac{1}{2}} e^{i\phi_-}$$

Wednesday, April 25, 2012



Typical Setup

Squeezing detection

- Fluctuations in differential current depend on phase $\delta\phi$

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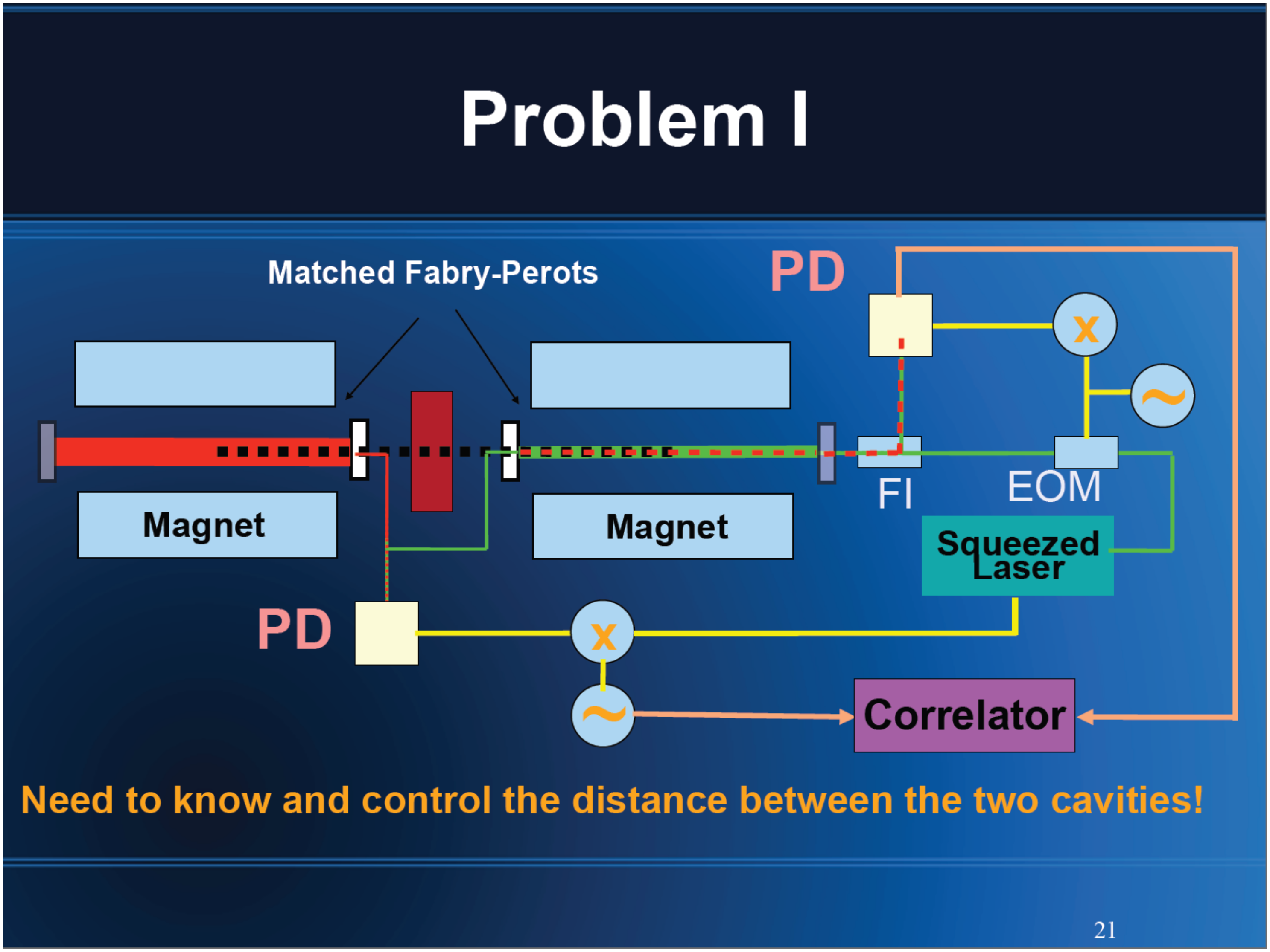
- At LIGO one aims for effectively reducing the shot noise by a factor of 2.

A possible setup …



Problem I

Need to know and control the distance between the two cavities!

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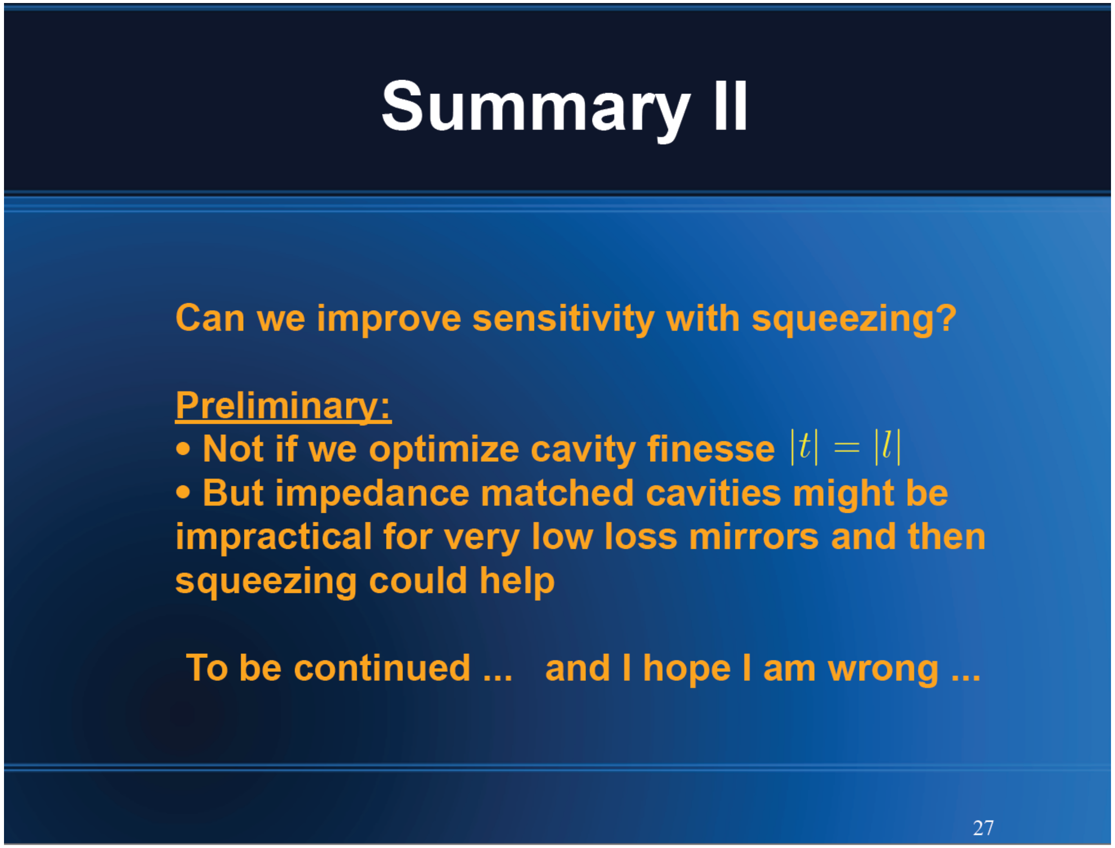
… but fundamental limitations?

- LSW experiments will use impediance matched cavities to optmize tht power built-up.
  Hence the the squeezed light injected into the cavity will not reach the photon detector. Thus the shot noise will not be diminished.



Summary II

Can we improve sensitivity with squeezing?

<u>Preliminary:</u>
- Not if we optimize cavity finesse $|t| = |l|$
- But impedance matched cavities might be impractical for very low loss mirrors and then squeezing could help

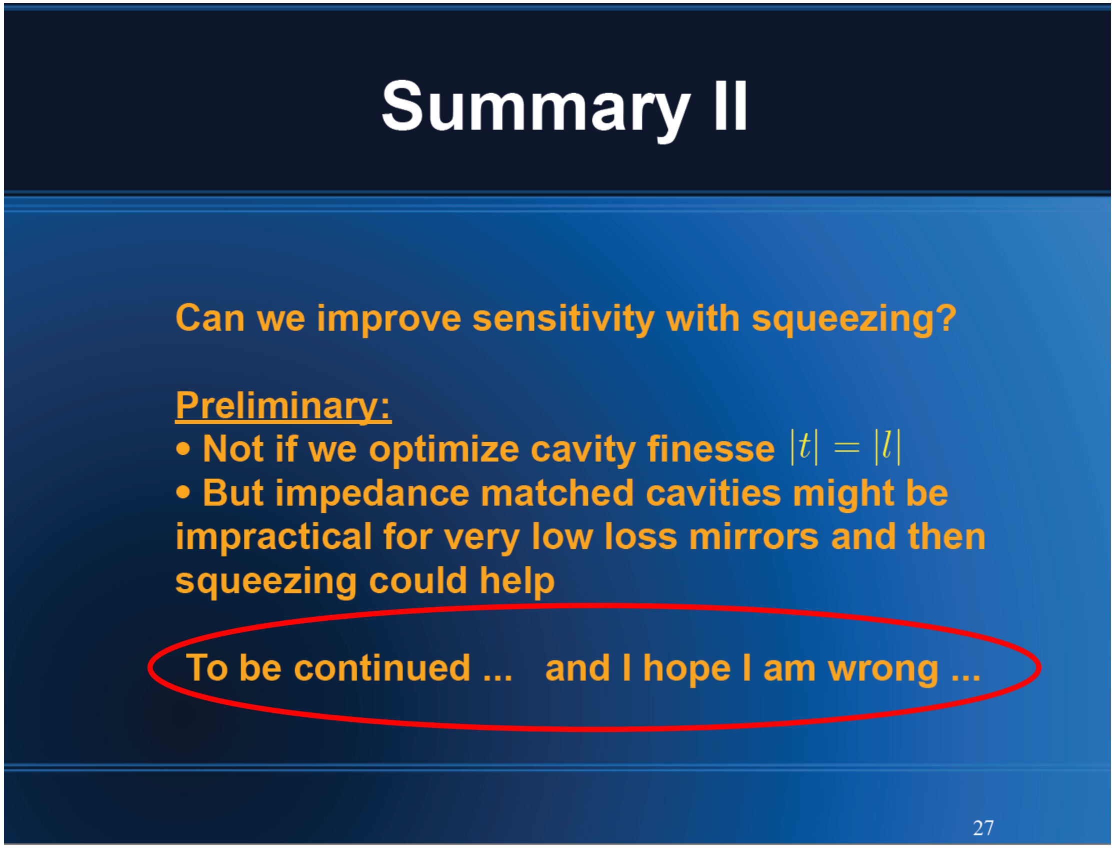
To be continued … and I hope I am wrong …

27

Wednesday, April 25, 2012

… but fundamental limitations?

- LSW experiments will use impediance matched cavities to optmize tht power built-up.
  Hence the the squeezed light injected into the cavity will not reach the photon detector. Thus the shot noise will not be diminished.



Summary II

Can we improve sensitivity with squeezing?

Preliminary:

- **Not if we optimize cavity finesse** $|t| = |l|$
- **But impedance matched cavities might be impractical for very low loss mirrors and then squeezing could help**

To be continued … and I hope I am wrong …

27

Wednesday, April 25, 2012

Microwave photon regeneration

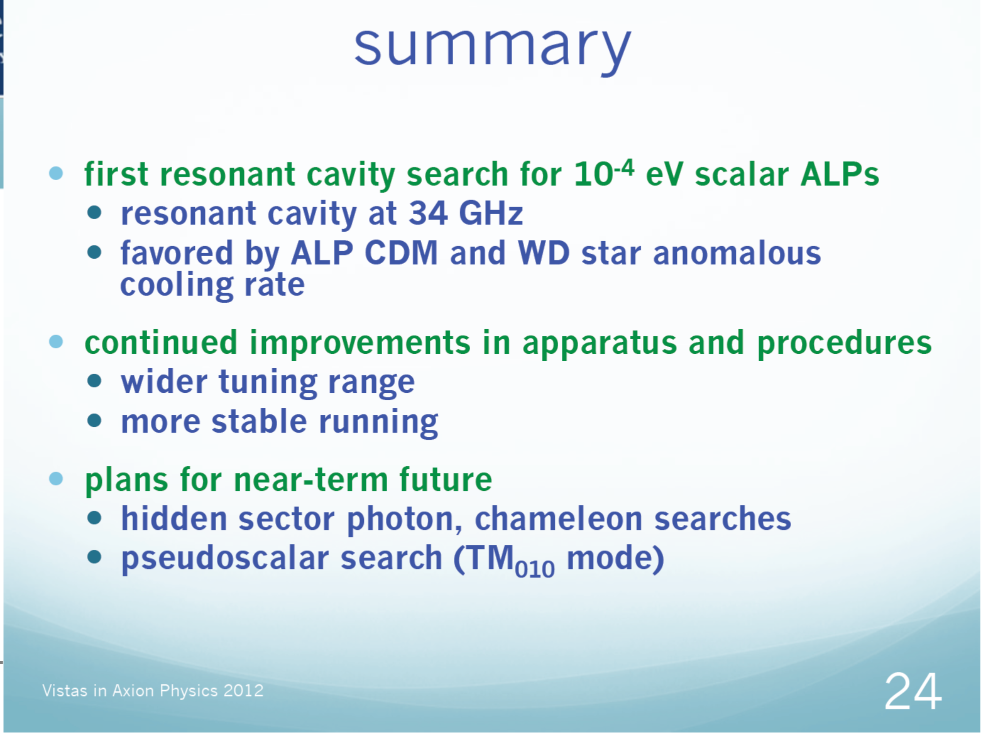
search for a scalar axion-like particle at 10^{-4} eV

P. L. Slocum, O. K. Baker, J. L. Hirshfield,
Y. Jiang, G. Kazakevitch, S. Kazakov,
M. A. LaPointe, A. T. Malagon, A. J. Martin,
S. Shchelkunov, A. Szymkowiak

Yale University

Vistas in Axion Physics 2012

1



summary

- first resonant cavity search for 10^{-4} eV scalar ALPs
  - resonant cavity at 34 GHz
  - favored by ALP CDM and WD star anomalous cooling rate
- continued improvements in apparatus and procedures
  - wider tuning range
  - more stable running
- plans for near-term future
  - hidden sector photon, chameleon searches
  - pseudoscalar search (TM_{010} mode)

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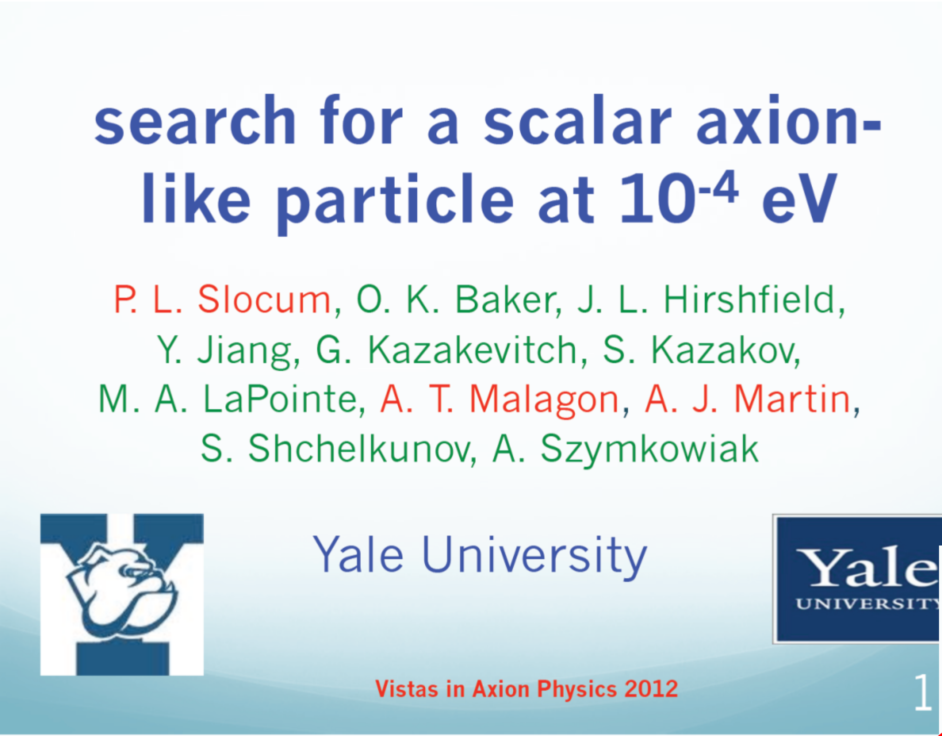
Microwave photon regeneration



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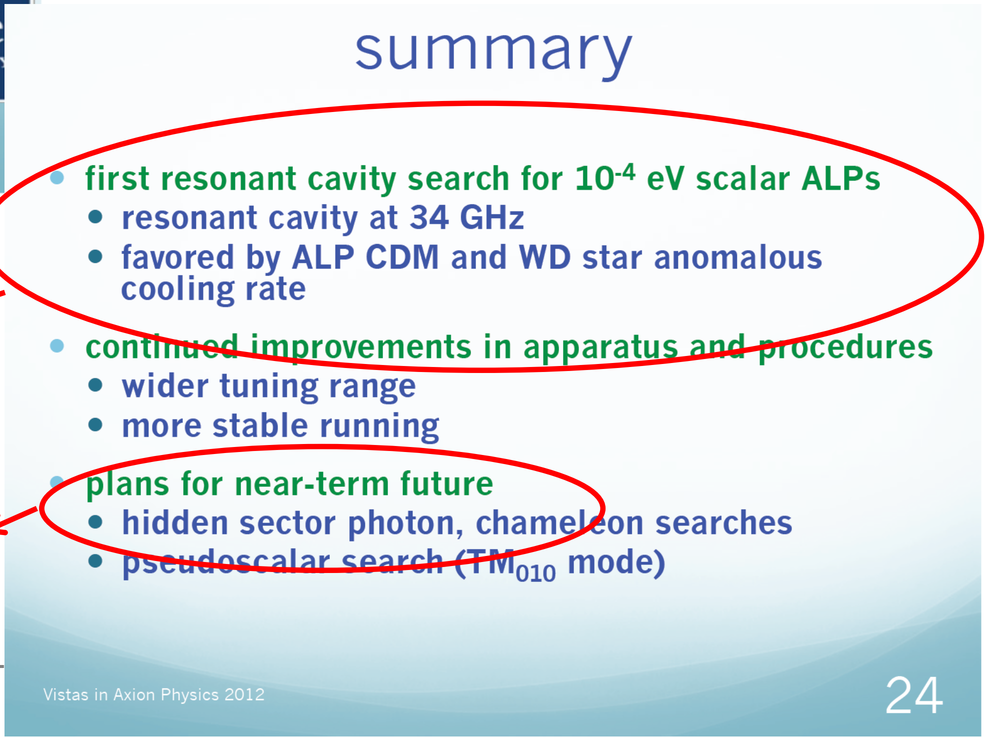
1



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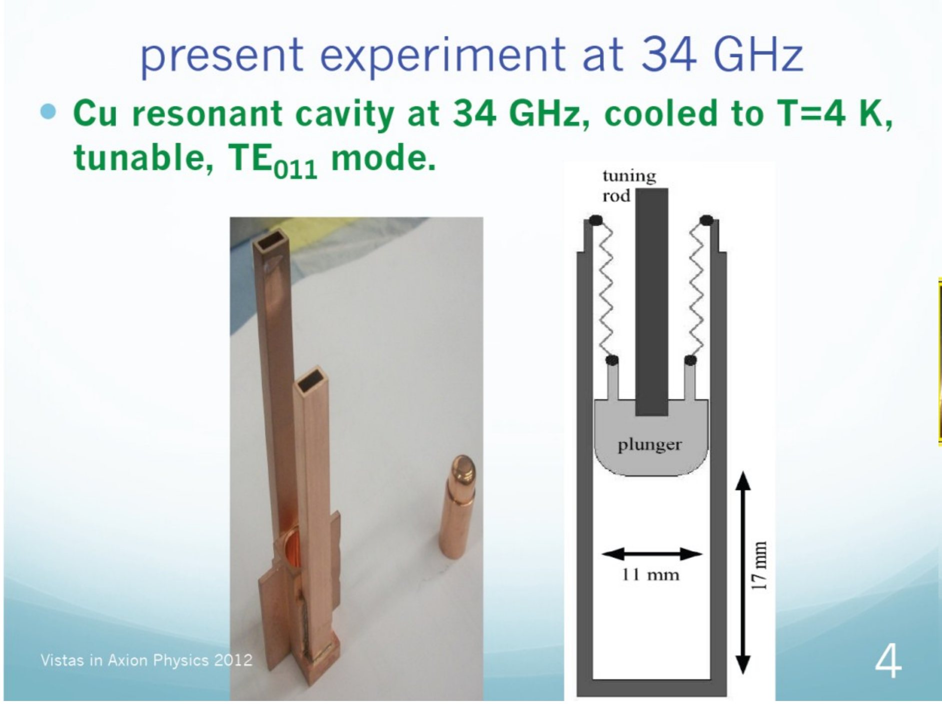
24

Direct dark matter search at high frequencies.

Laboratory LSW.

The instrument



present experiment at 34 GHz

- **Cu resonant cavity at 34 GHz, cooled to T=4 K, tunable, TE_{011} mode.**

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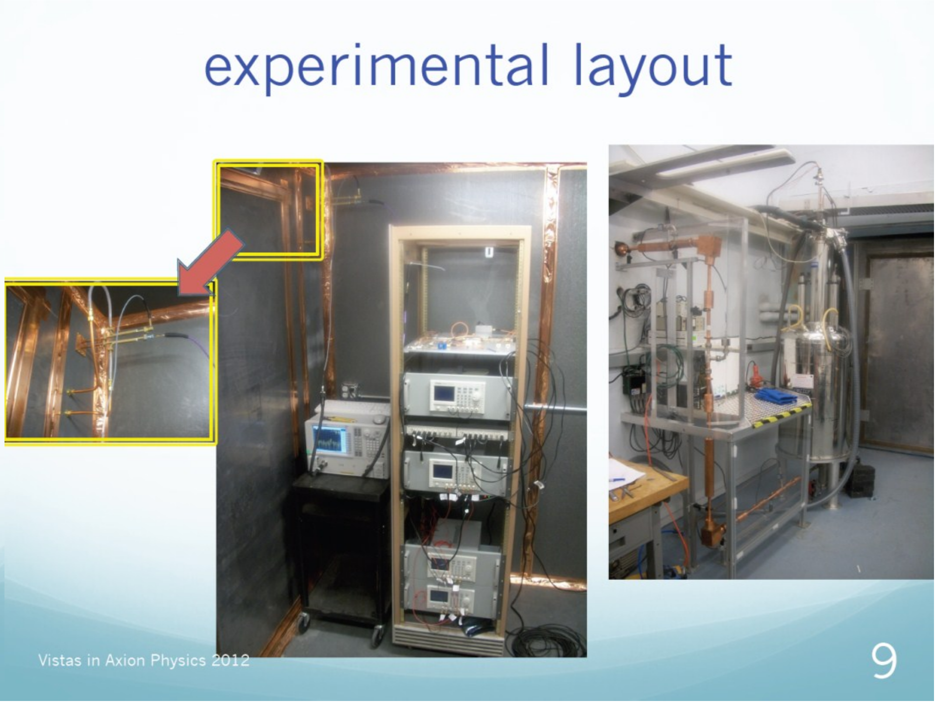

experimental layout

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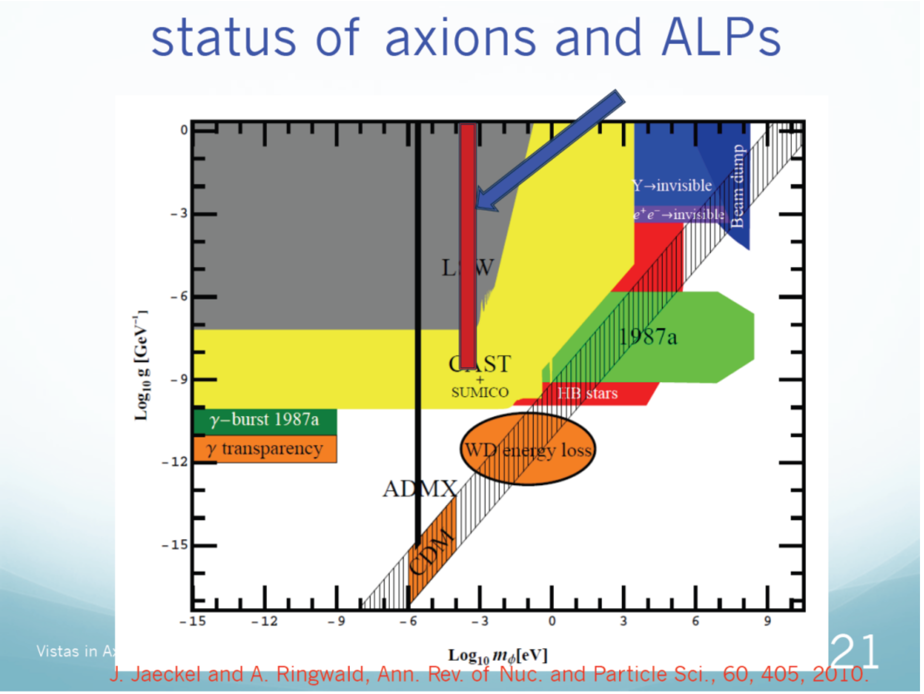
9

- Power sensitivity $2 \cdot 10^{-18}$ W
- Scan range limited by receiver at present, improvements under way.
- At present integration time limited to < 1 min., but effect understood and improvements under way.

Results and next steps



status of axions and ALPs

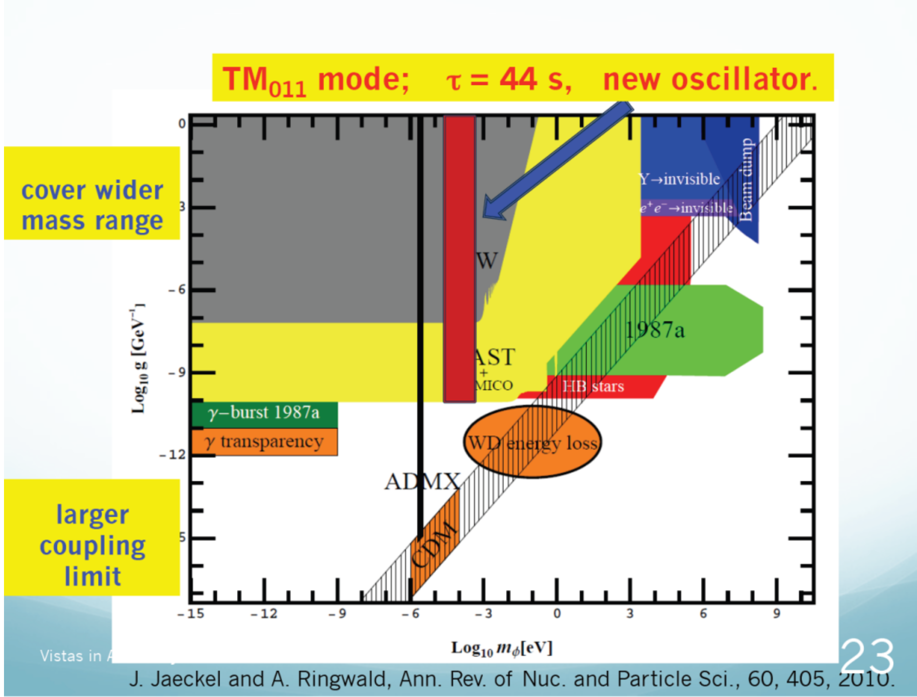
Vistas in A

21

J. Jaeckel and A. Ringwald, Ann. Rev. of Nuc. and Particle Sci., 60, 405, 2010.

Dark matter search:

- Increase sensitivity
- Broaden mass range
- Look also für pseudoscalars



TM$_{011}$ mode; τ = 44 s, new oscillator.

cover wider mass range

larger coupling limit

Vistas in A

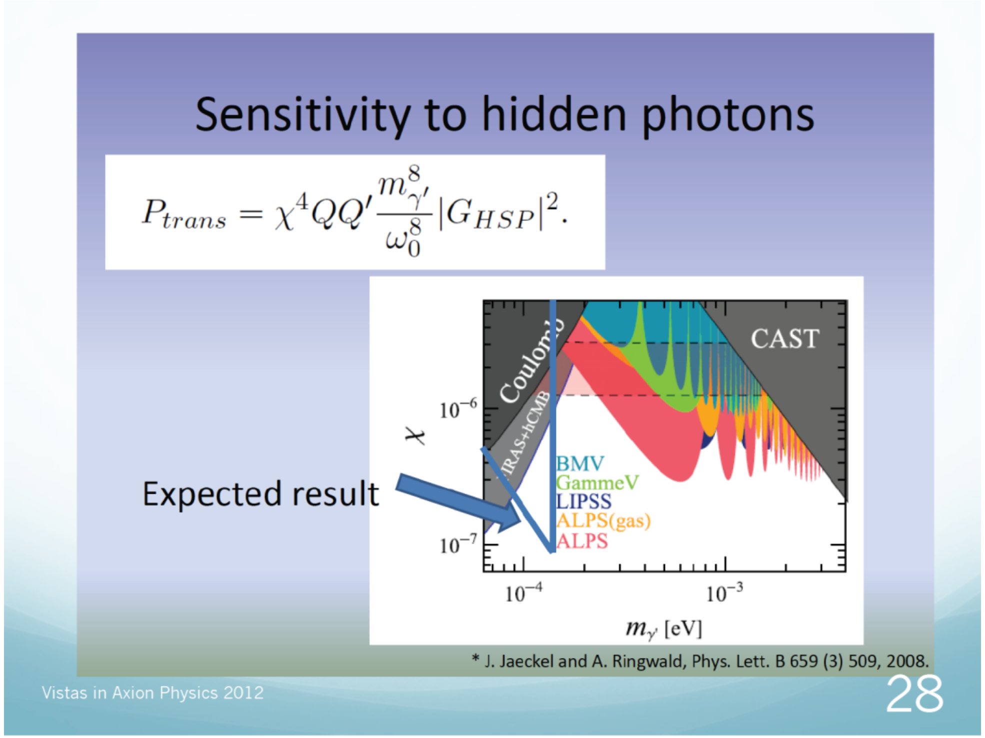
23

J. Jaeckel and A. Ringwald, Ann. Rev. of Nuc. and Particle Sci., 60, 405, 2010.

Results and next steps

LSW with microwaves:

- Exploit potential to search for hidden photons using a strong 34 GHz source at Yale.
- Study options to search also for ALPs.



Sensitivity to hidden photons

$$P_{trans} = \chi^4 QQ' \frac{m_{\gamma'}^8}{\omega_0^8} |G_{HSP}|^2.$$

Expected result

* J. Jaeckel and A. Ringwald, Phys. Lett. B 659 (3) 509, 2008.

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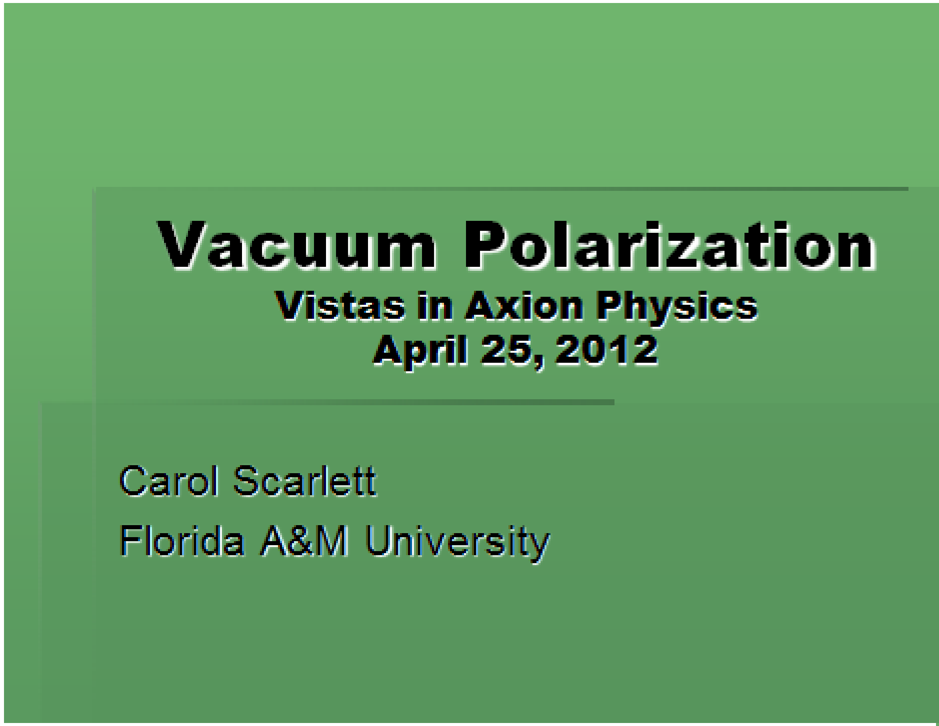
28

Microwave versus optical LSW

- Photon number counts when producing axions.
  - Microwave wins here by a factor 10^6!
- Power counts when detecting regenerated photons.
  - ADMX can detect powers of 10^{-24} W, ALPS-II / REAPR should reach the same level (one photon per day). Optical photons win here by a factor 10^6!
- For microwaves wavelength and dimension of experiments are comparable, hence massive axion and photons do not run out of phase.
  - Microwaves win with sensitivity nearly up to photon energy.
  - Microwaves loose due to much lower photon energy.
- New possibilities due to a “near field” configuration?
  - Wavelength of axions comparable to geometrical dimensions of a RF LSW experiment.

Follow both approaches for the time being?

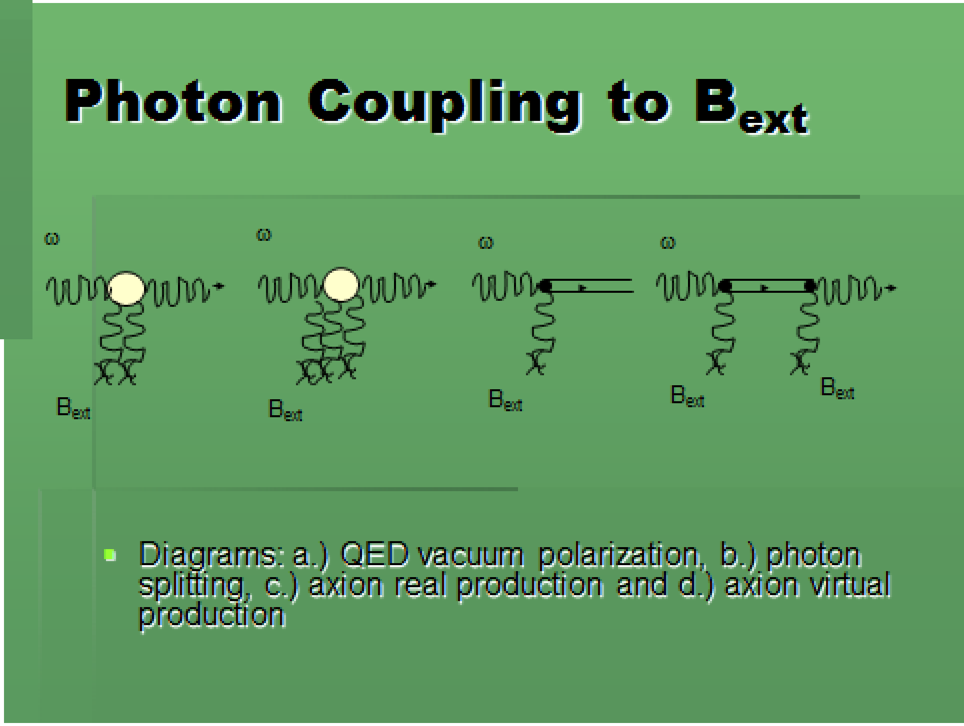
Polarization effects



Vacuum Polarization

Vistas in Axion Physics
April 25, 2012

Carol Scarlett
Florida A&M University



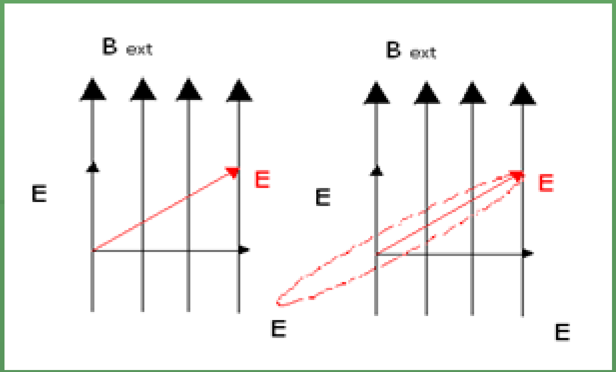
Photon Coupling to B_{ext}

- Diagrams: a.) QED vacuum polarization, b.) photon splitting, c.) axion real production and d.) axion virtual production

Observables

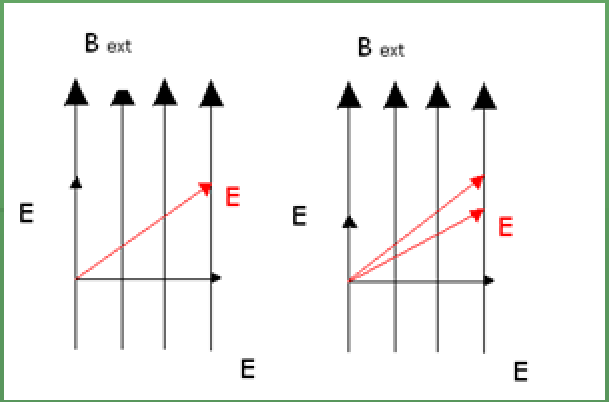
Measurable Effects

- Ellipticity:



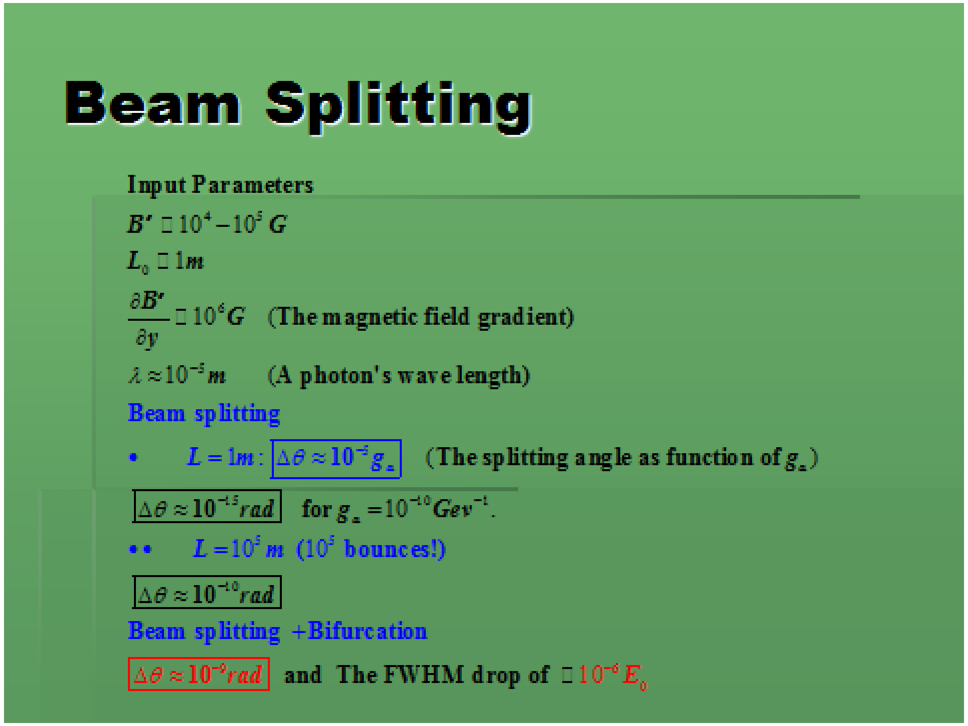
Measurable Effects

- Dichroism:



Polarization effects

- It would be really challenging to improve existing results and to compete with the ongoing BMV (Toulouse) program with pulsed magnets.
- Is the observation of beam splitting in a magnetic field gradient a new viable option?



Beam Splitting

Input Parameters

$B' \square 10^4 - 10^5\ G$

$L_0 \square 1m$

$\frac{\partial B'}{\partial y} \square 10^6 G$ (The magnetic field gradient)

$\lambda \approx 10^{-5} m$ (A photon's wave length)

Beam splitting

- $L = 1m$: $\boxed{\Delta\theta \approx 10^{-5} g_a}$ (The splitting angle as function of g_a)

$\boxed{\Delta\theta \approx 10^{-15} rad}$ for $g_a = 10^{-10} Gev^{-1}$.

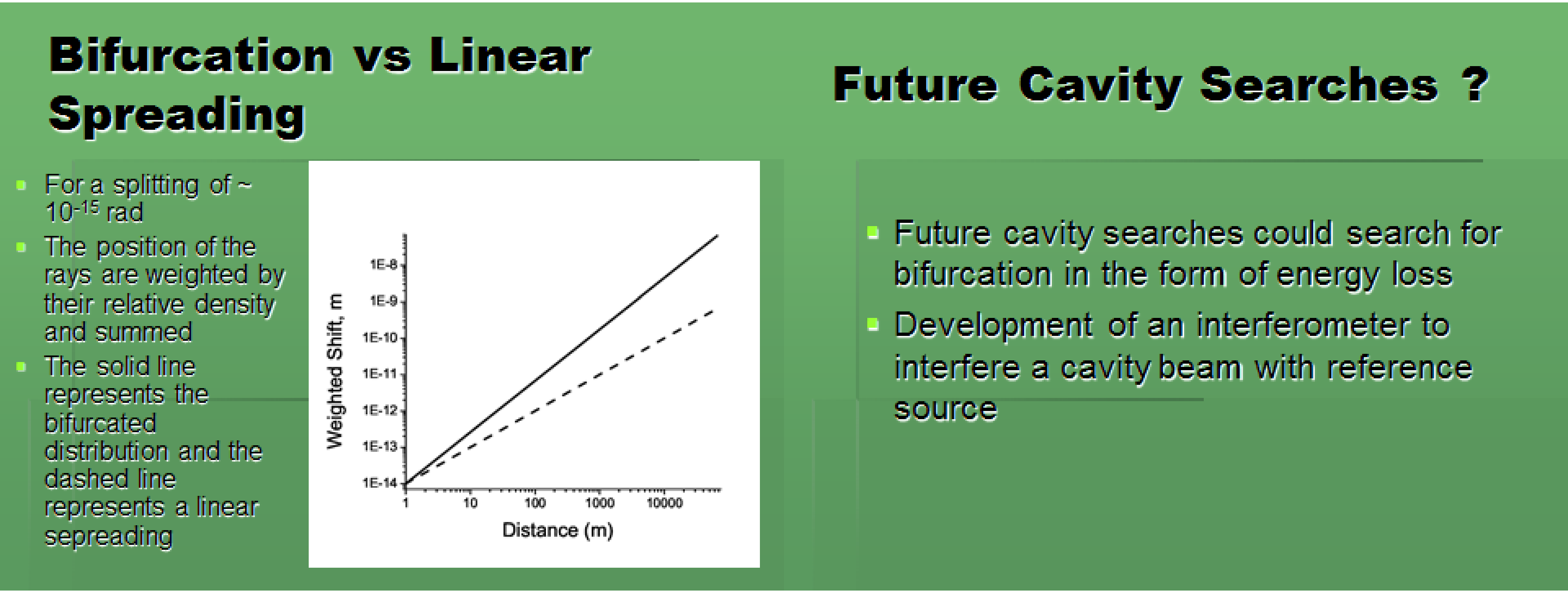
•• $L = 10^5\ m$ (10^5 bounces!)

$\boxed{\Delta\theta \approx 10^{-10} rad}$

Beam splitting +Bifurcation

$\boxed{\Delta\theta \approx 10^{-9} rad}$ and The FWHM drop of $\square 10^{-6} E_0$

A new aspproach?



Bifurcation vs Linear Spreading

- For a splitting of ~ 10^{-15} rad
- The position of the rays are weighted by their relative density and summed
- The solid line represents the bifurcated distribution and the dashed line represents a linear sepreading

Future Cavity Searches ?

- Future cavity searches could search for bifurcation in the form of energy loss
- Development of an interferometer to interfere a cavity beam with reference source

- However, effects are really tiny!
  - Compare 10^{-15} rad to divergence of laser beams.
- Probably still some basic R&D required to judge on possible realizations.

Summary (simplifying things)

- At present light-shining-through-a-wall experiments at optical wavelengths seem to show more potential than microwave experiments.
  - Optical LSW benefit from large magnet strings and laser know-how.
- At present polarization studies can not really compete.

Summary on optical LSW enterprises

- At first generation of experiments aiming for quick returns have been completed successfully.
- A second generation aiming for best use of existing magnets is on its way.
  - Recommendation 1:
    There should be a coordinated effort to investigate the use and potential of HERA, TEVATRON and perhaps LHC dipoles including a site survey for a 200 m scale LSW experiment. A corresponding working group could also foster contacts to magnet R&D going on elsewhere.
  - Recommendation 2:
    ALPS-II and REAPR follow two different approaches for optics and photon detection. Within about two years table top of 10 m scale prototypes should allow for a comparison of both approaches. Proceed with both for the time being!
- More general: LSW experiments follow a road proposed more than two decades ago.
  - Recommendation 3:
    Provide resources (personnel and modest investments) to investigate new possibilities (see Aaron's talk, squeezed light, intra-cavity photon measurements, …)

Summary on optical LSW enterprises

- Exploit the potential of a third generation LSW experiment using infrastructure optimized to its needs.
  - One could profit from ongoing magnet R&D:
    - by 2016 NbTn, 12 T, 55 mmm aperture
    - by 2030 NbTn, 12 T, 100 mm (LHC energy upgrade without inner HTS part).
    This would give an increase in B·L by 12/5 * $(100/55)^2$ = 8
  - Laser / optics:
    it might be possible to increased the circulating laser power in the production cavity power up to 10 to 100 MW (ALPS-II aims for 0.15 MW).
    This requires the development of am injection laser with > 1 kW of power (factor 5 compared to today)
  - With these numbers the sensitivity of a third generation experiment could probe couplings below $g_\gamma = 10^{-12}$ GeV^{-1} !
  - <u>Recommendation 4:</u>
    Exploit the potential of a third generation experiment based on
    - experience with the ongoing R&D at ALPS-II and REAPR
    - results of recommendation 3
    - new theoretical developments and astrophysical data expected soon.