Transition-Edge Sensor: A new detector for the ALPS experiment

Contents

- ALPS experiments
  (**A**ny **L**ight **P**article **S**earch)
- Superconducting TES detector
  (**T**ransition-**E**dge **S**ensor)
- Status and plan

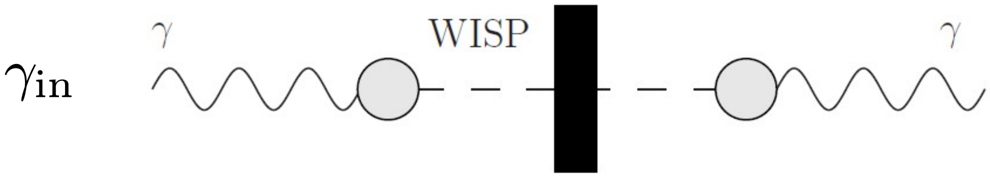
Jan Dreyling-Eschweiler
for ALPS collaboration

IRTG PhD days 2011
Hamburg, 4-5 October 2011

HELMHOLTZ GEMEINSCHAFT · Leibniz Universität Hannover · UHH · PIER · DESY

ALPS is a Light Shining through a Wall experiment

$$P_{\gamma\to\mathrm{WISP}\to\gamma} \sim P^2_{\gamma\to\mathrm{WISP}} \sim (gBL)^4 \frac{\sin^4\left(\frac{M^2L}{4\omega}\right)}{\left(\frac{M^2L}{4\omega}\right)^4}$$

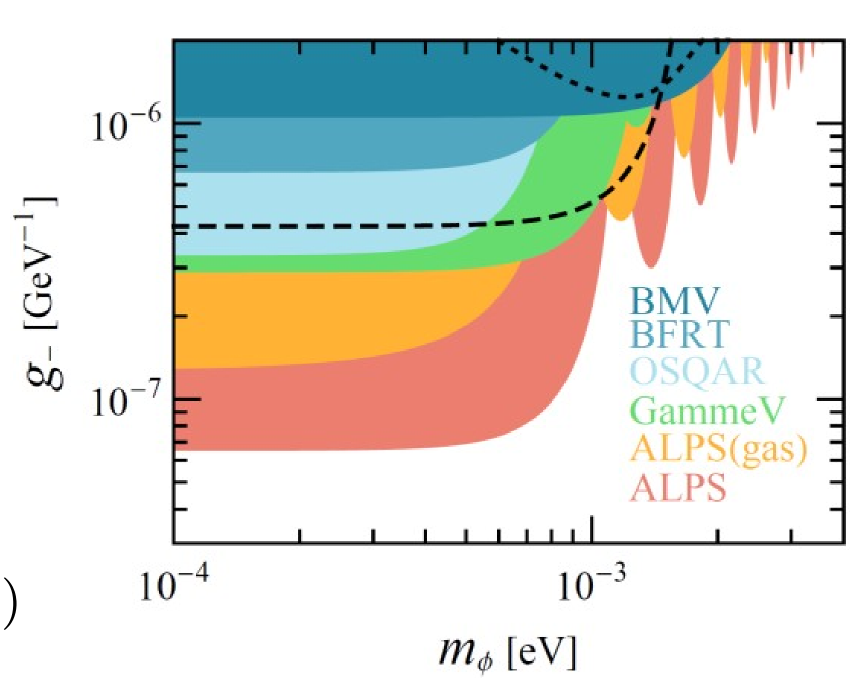


$$\gamma_{\mathrm{meas.}} = \gamma_{\mathrm{in}} \times P_{\gamma\to\mathrm{WISP}\to\gamma} \times \epsilon$$

- ALPS I: 1h data/dark frames with CCD
  - dark current dominates read-out noise
  - limited by background
- Exemplary result from ALPS I:
  - $\gamma_{\mathrm{in}} \sim 10^{21}\,1/\mathrm{s}$
  - $\gamma_{\mathrm{meas.}} = (2 \pm 13) \times 10^{-3}\,1/\mathrm{s}$

  → limit on the rate due to dark current:

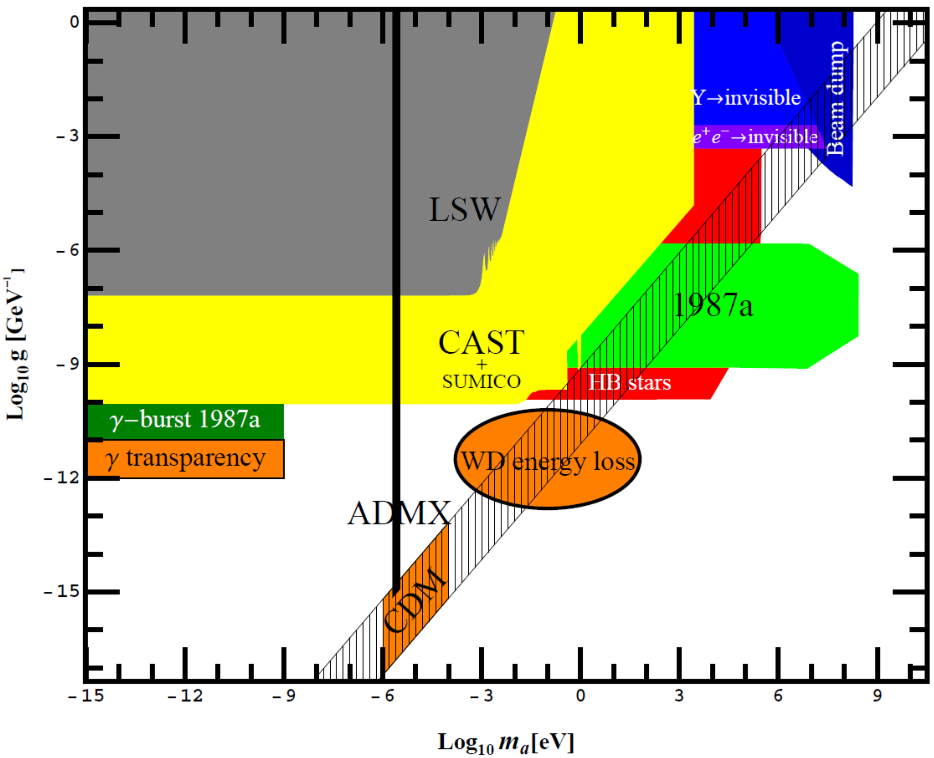
  $$\gamma_{\mathrm{meas.}} < 29 \times 10^{-3}\,1/\mathrm{s} \;\; (95\%\,\mathrm{C.L.})$$

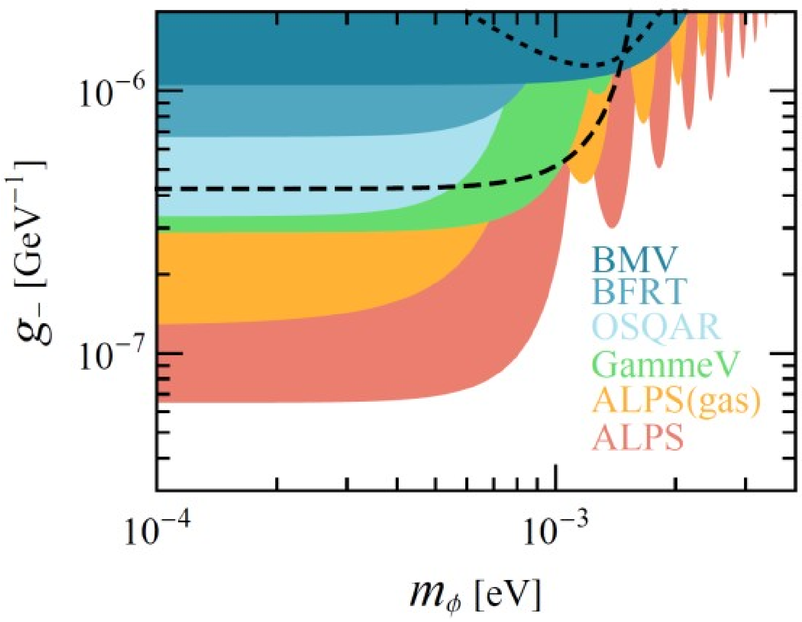


K. Ehret, et al., Physics Letters B 689 (2010) 149

DESY

Exclusion map and limits of ALPS I





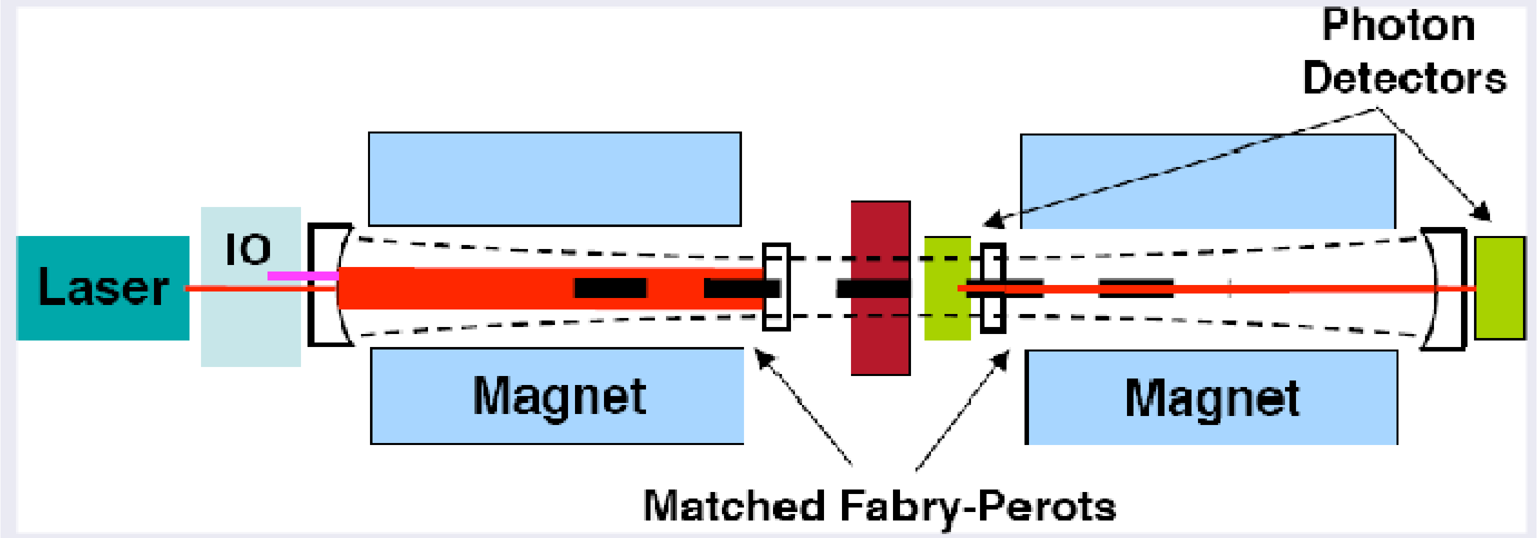
How can we lower the limit?

$$\gamma_{\text{meas.}} = \gamma_{\text{in}} \times P_{\gamma\to\text{WISP}\to\gamma} \times \epsilon$$

$$P_{\gamma\to\text{WISP}\to\gamma} \sim (gBL)^4 F(\frac{M^2 L}{4\omega})$$

$$\Rightarrow \quad g \sim \frac{1}{BL}\sqrt[4]{\frac{\gamma_{\text{meas.}}}{\gamma_{\text{in}} \times \epsilon}}\frac{1}{F(...)}$$

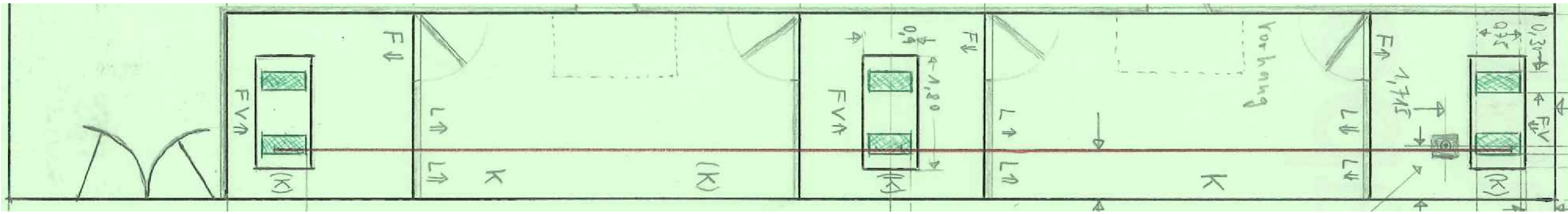
- Increase sensitivity of experiment
  - laser power resp. photon flux (from 532 nm to 1064 nm)
  - length of experiment:
  - regeneration cavity



P. Sikivie. D. Tanner, K. van Bibber: PRL 98:172002, 2007

ALPS II: Go bigger step by step

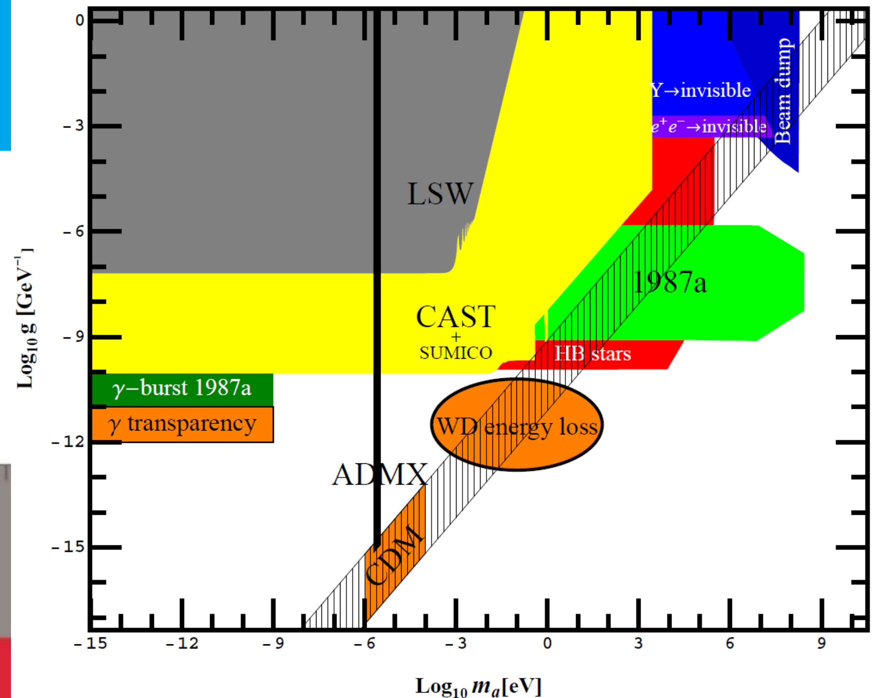
- Hidden photon search and proving the regeneration cavity (end of 2012)
  - New laser lab in HERA-West, 50, room 607: 2 x 10 meter

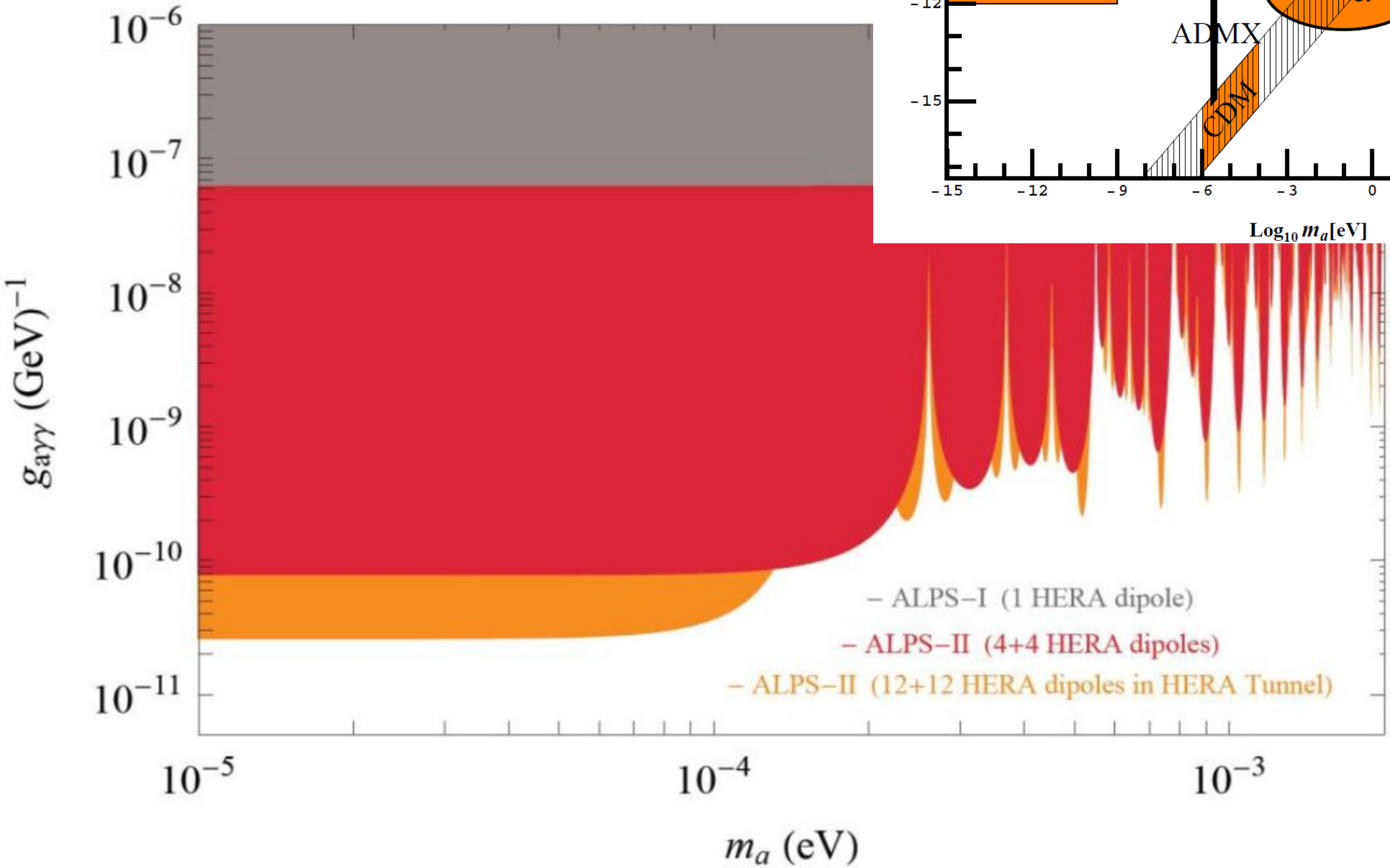


- Hidden Photon search: 2 x 130 meter (in 2014)
- Full experiment: with 12 + 12 straightened HERA dipoles (in 2017)

The ALPS II potential

- for axion-like particles

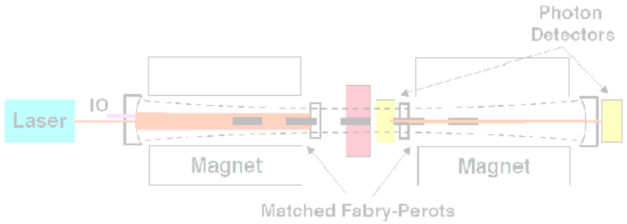




How can we lower the limit?

$$g \sim \frac{1}{BL} \sqrt[4]{\frac{\gamma_{\text{meas.}}}{\gamma_{\text{in}} \times \epsilon}} \frac{1}{F(\ldots)}$$

- Increase sensitivity of experiment
  - laser power resp. photon flux (1064 nm)
  - length of experiment
  - regeneration cavity

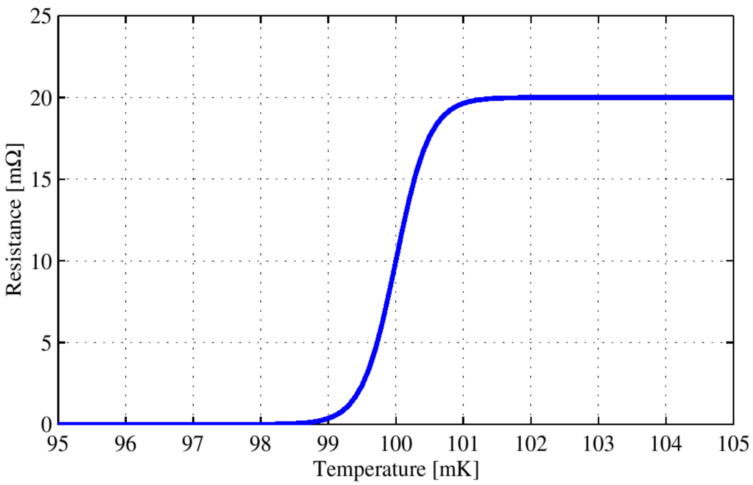


- Improve sensitivity of detector
  - **Challenge:** detection of low rates of single infrared photons (< 1/h)
  - **Requirements**: High efficiency and low (dark) noise and background

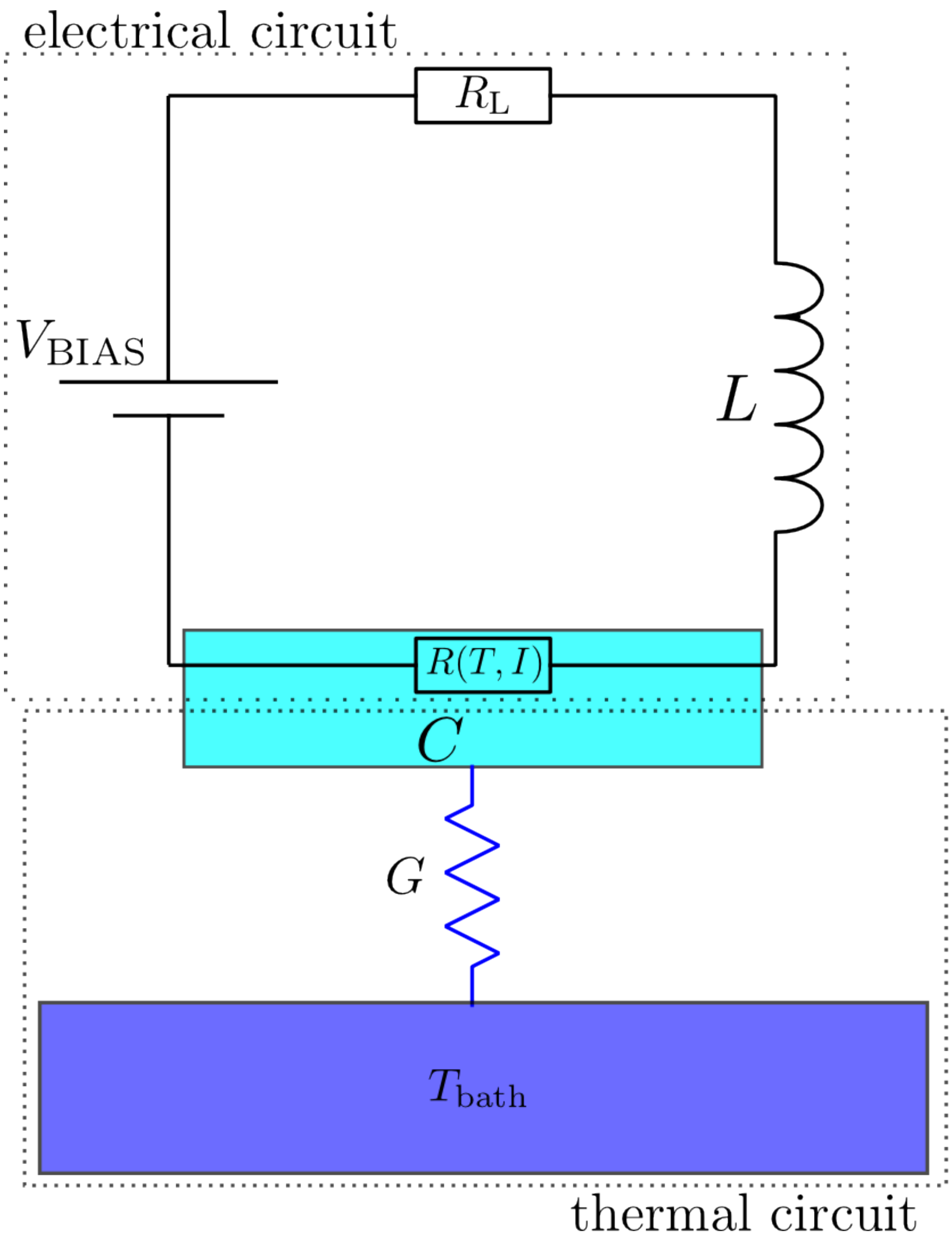
$\longrightarrow$ cryogenic microcalorimeter

Principle of a superconducting Transition-Edge Sensor (TES)

- Time constant of simple calorimeter: $\tau = C/G$
- Sharp superconducting transition: $R(T) \sim T$

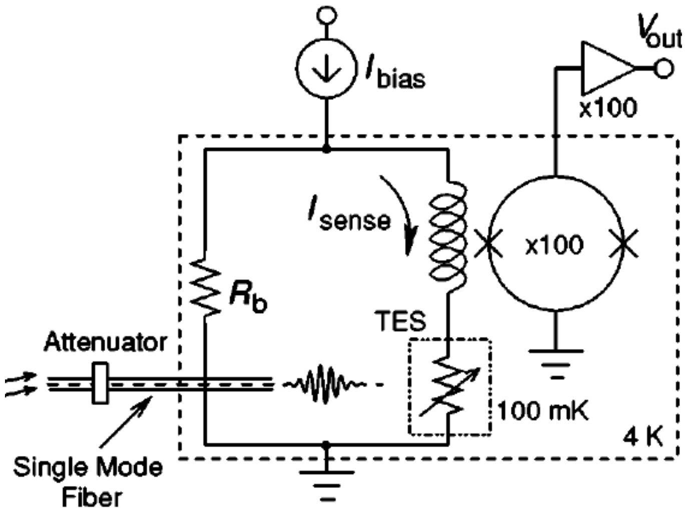


- Stable working point with electrothermal feedback:
  - biased by a constant voltage: $P = V^2/R$

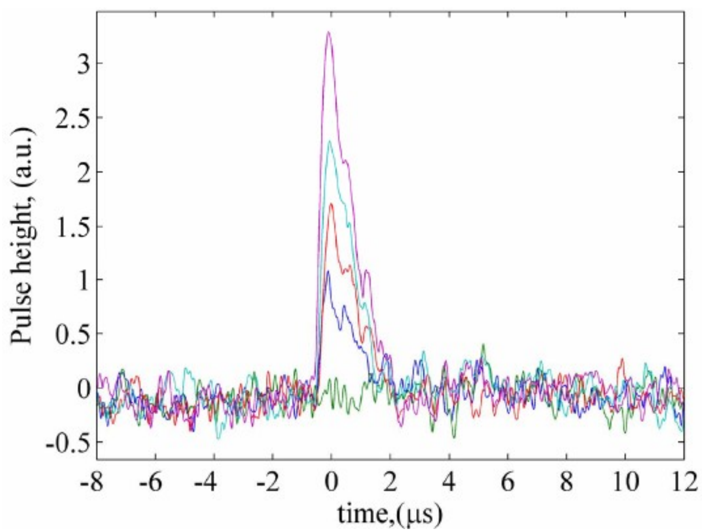


Some technical realizations

- SQUID as current amplifier (**S**upercond. **QU**antum **I**nterference **D**evice)
- Some applications:
  - Direct Dark Matter Search (e.g. CRESST)
  - X-ray & gamma spectroscopy
  - Bolometer in mm/sub-mm wave in astronomy
  - **single photon counter (near-infrared) for quantum-information (1310/1550 nm)**



Miller et al., Appl. Phys. Lett., Vol. 83, 4 (2003)



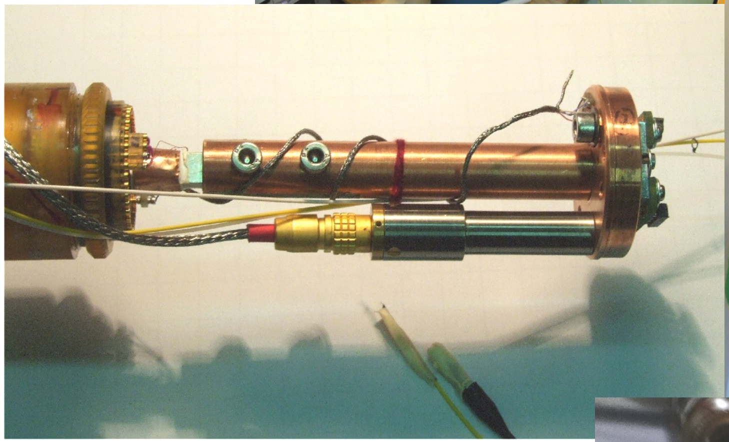
Lita et al., Opt. Express, Vol. 16, 5 (2008)

- Time / energy res.: ~ 1 μs / ~ 0.1 eV
- Detection efficiency up to 99%

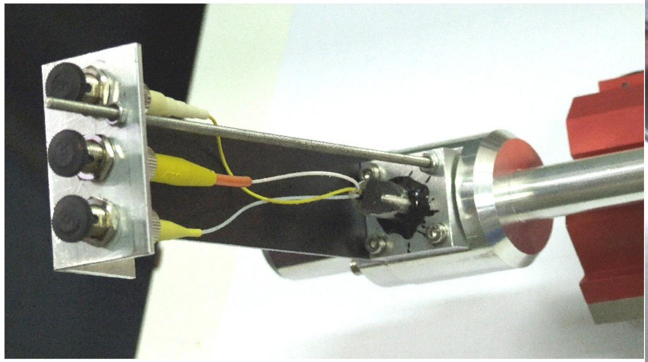
Lita et al., Proc. SPIE 7681, 76810D (2010)

Setup in Camerino, Italy (July 2011)

- *Refrigerator*
  - wet dilution cryostat (Leiden Cryogenics, NL)
- *Amplifier*
  - 16 SQUID array and FLL electronic (Magnicon, HH)

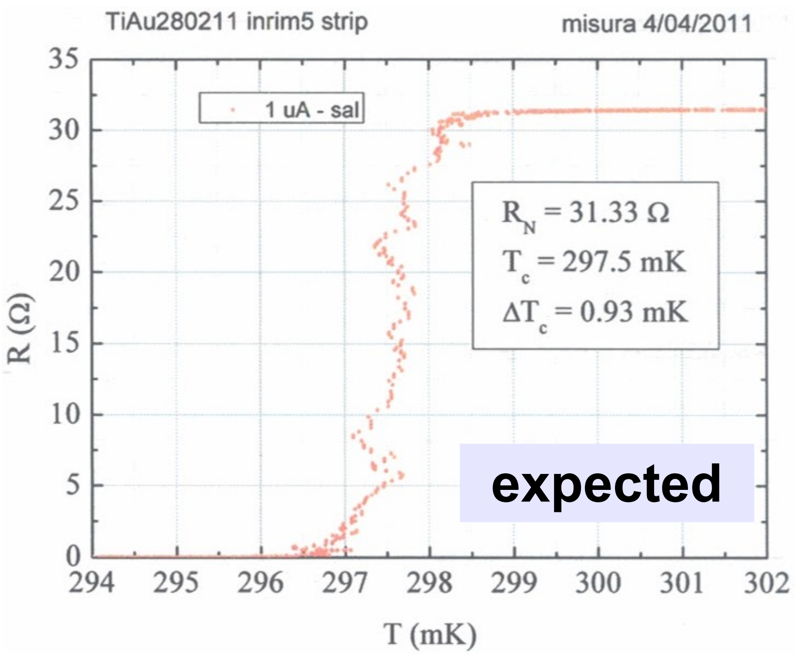


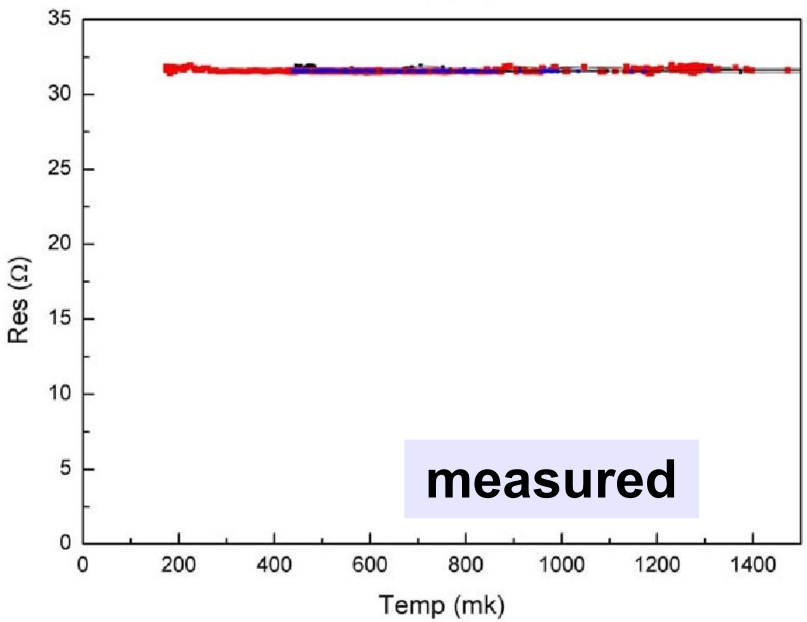
- *Sensor*
  - TiAu-TES (Tc ~300 mK) (INRIM, Turino, Italy)
- *Optics*
  - two SMF (9 µm dia.)
  - one MMF (62.5 µm dia.)
  - fiber coupling



Results of Camerino: First contact to the cryo-world!

- Disadvantage of a dilution cryostat: liquid He (120 l per week)
- SQUID is working, but no transition of TES chip!
- Not sufficient thermal coupling and shielding of 4K radiation
  → Not enough cooling power
- Modified setup and next try in October 2011

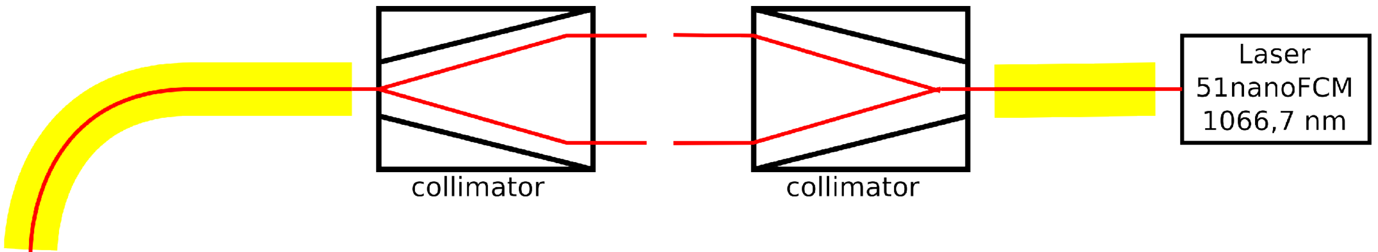


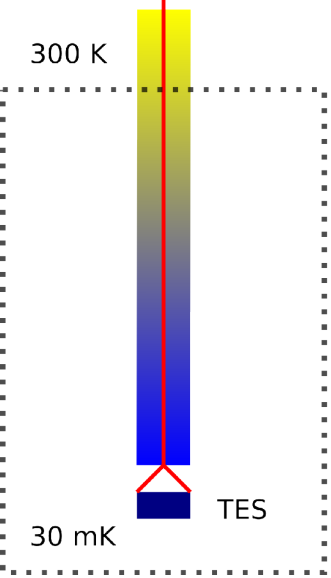


Summary and Outlook

Summary:

- TES detector is a candidate to improve sensitivity of ALPS experiment
- First experience with cryogenic, SQUID, ...





Outlook:

- See a transition in Italy!
- Long term background/noise measurements (for low, low photon rates)
- Optical studies of efficiency of different fiber couplings
- Build up detector in Hamburg for ALPS in mid of 2012 with an adiabatic demagnetization refrigerator (ADR)

The End

- Thanks a lot!

Detailed talk about

the interesting physics of a TES detecor

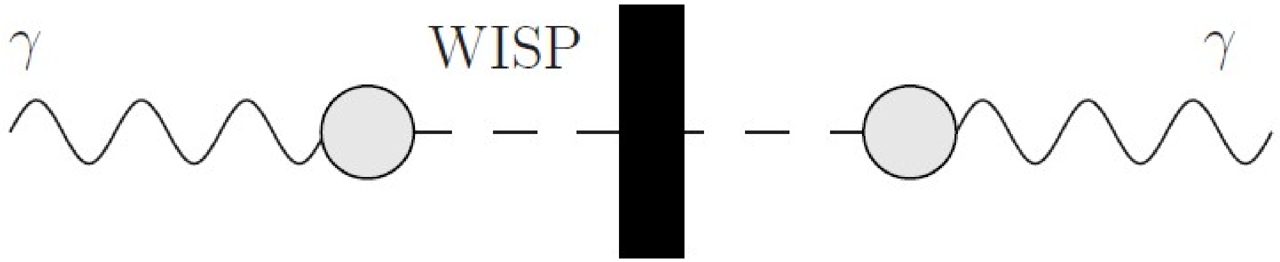
in Students' seminar

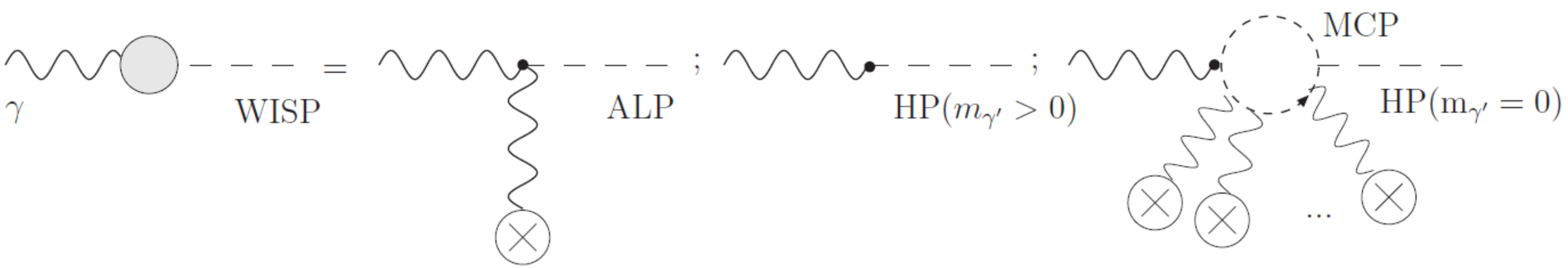
on 3/11/2011 – probably!

- Check out: http://wwwiexp.desy.de/studium/seminare/studsem/wise2011/

Backup

Backup

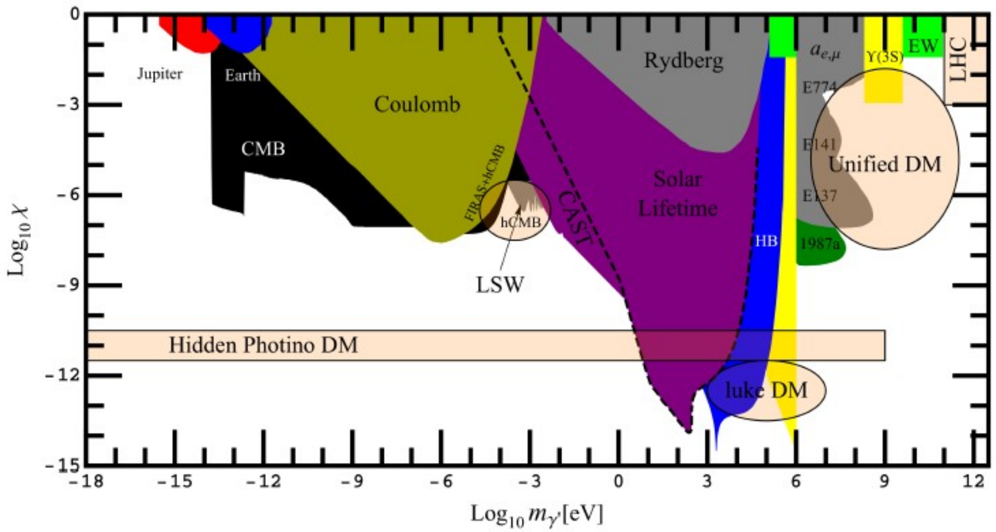


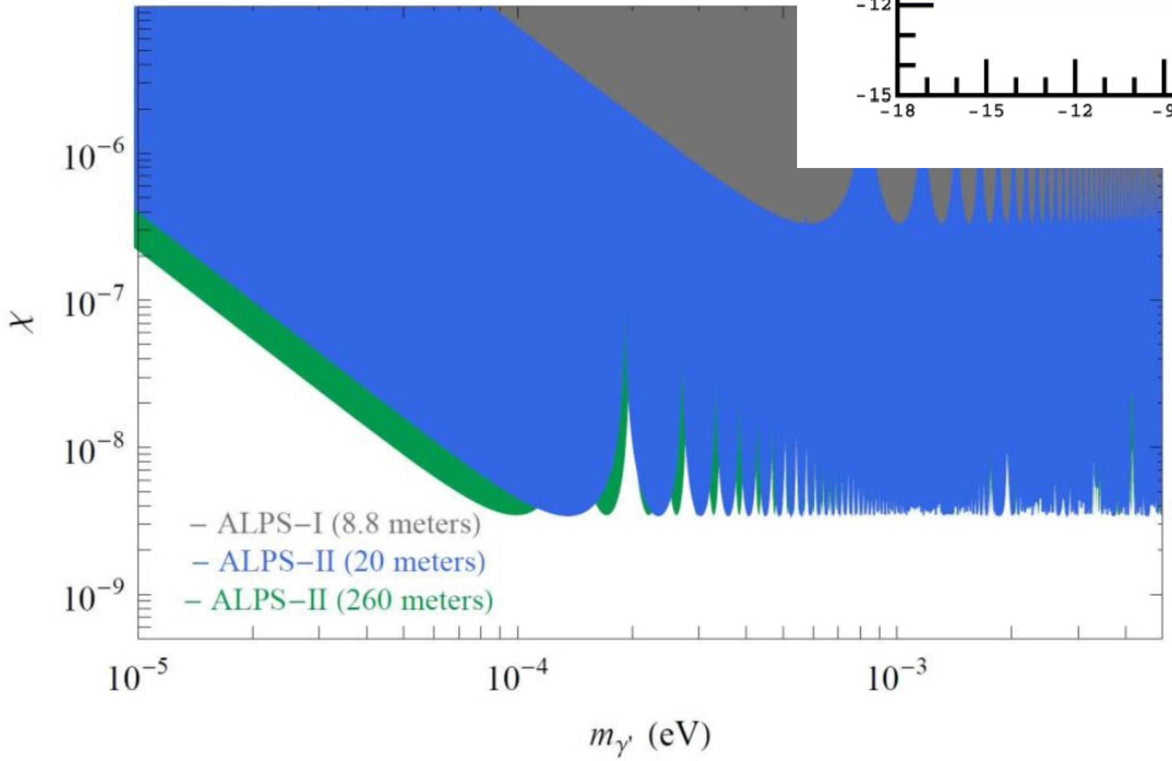


$$P^2_{\gamma\leftrightarrow\mathrm{ALPs}} \sim (gBL)^4 \frac{\sin^4\left(\frac{M^2 L}{4\omega}\right)}{\left(\frac{M^2 L}{4\omega}\right)^4}$$

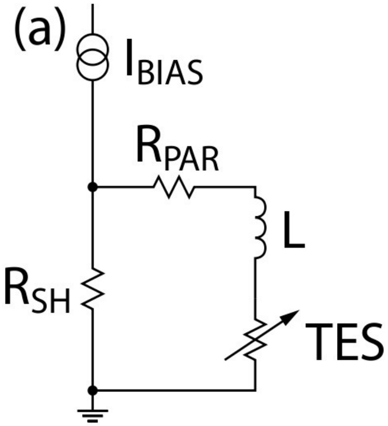
The ALPS II Potential

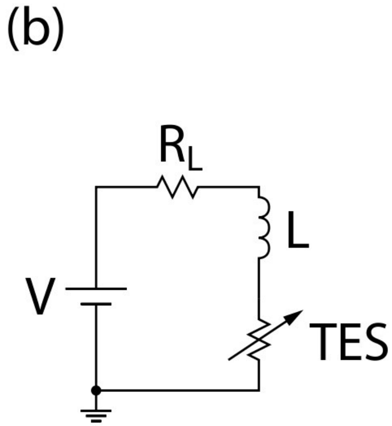
Search for
“hidden photons”:

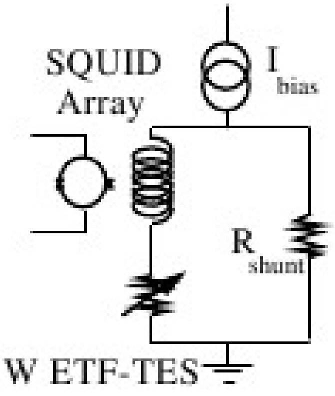


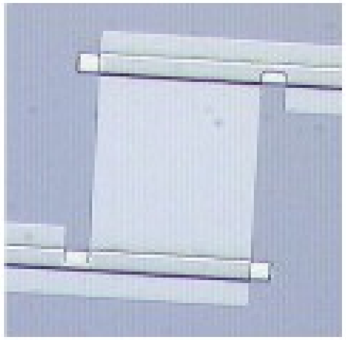


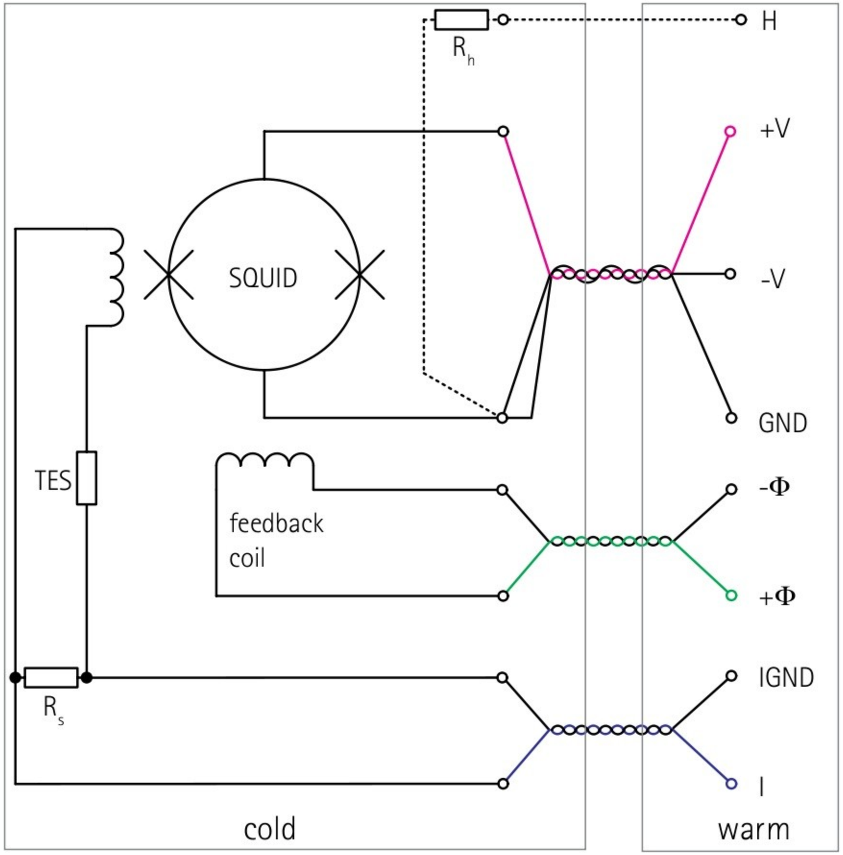
TES input circuit and Thevenin-equivalent representation



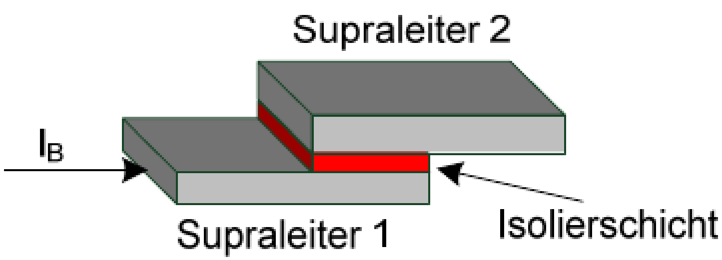






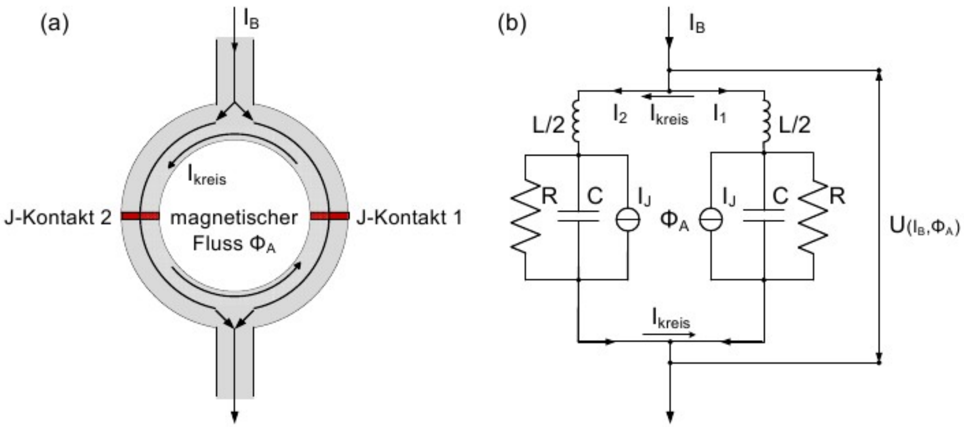


SQUID stuff

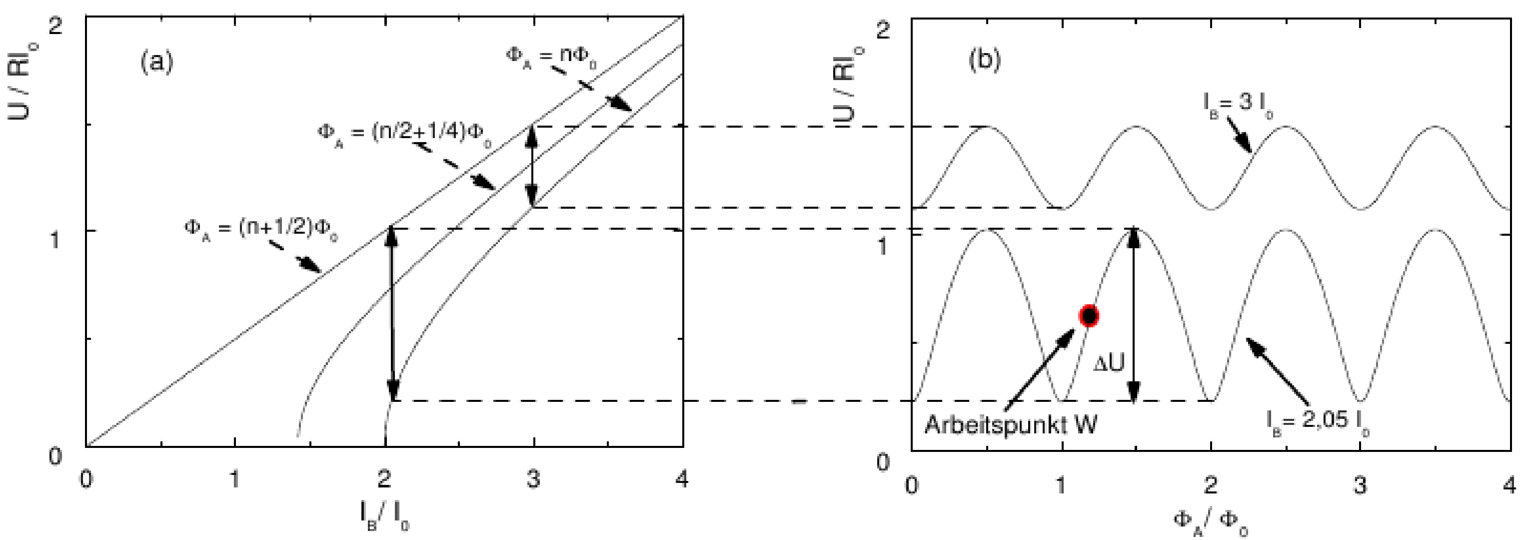


$$I = I_0 \sin\phi \;\; \text{mit} \;\; \phi = \phi_2 - \phi_1$$

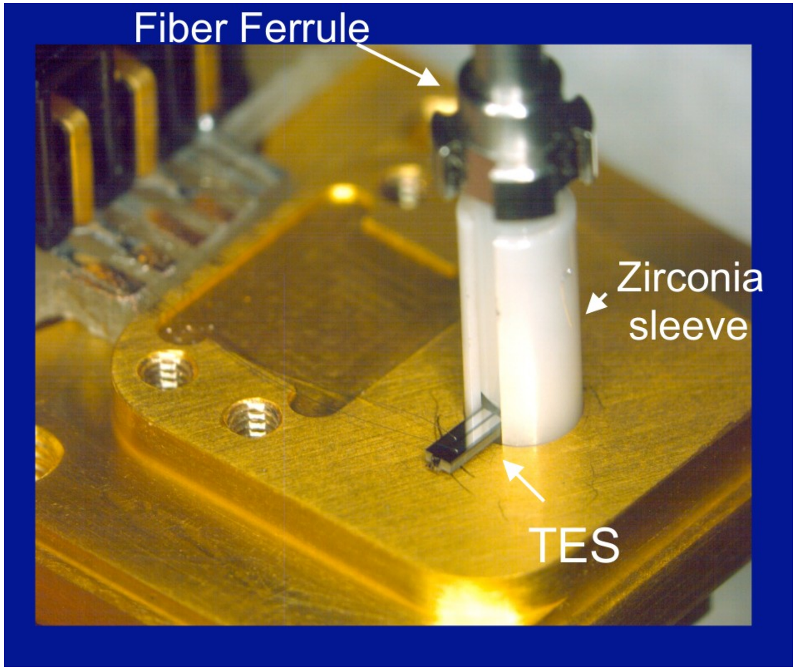
$$\frac{\partial\phi}{\partial t} = \frac{2\pi}{\Phi_0} U$$



$$U = \frac{R}{2}\sqrt{I_B^2 - (2I_0 \cos\pi\frac{\Phi_A}{\Phi_0})^2}$$



Fiber coupling



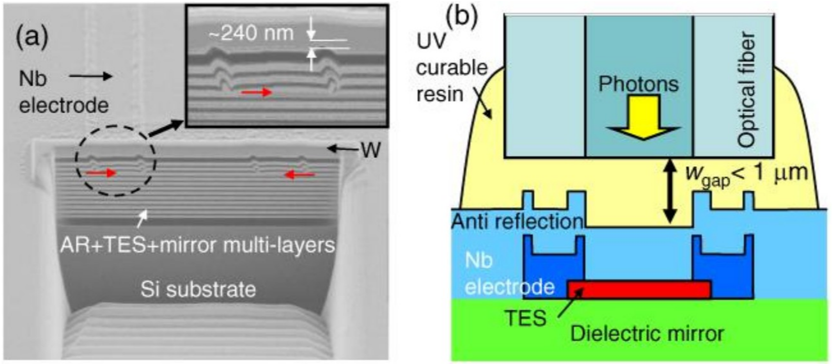
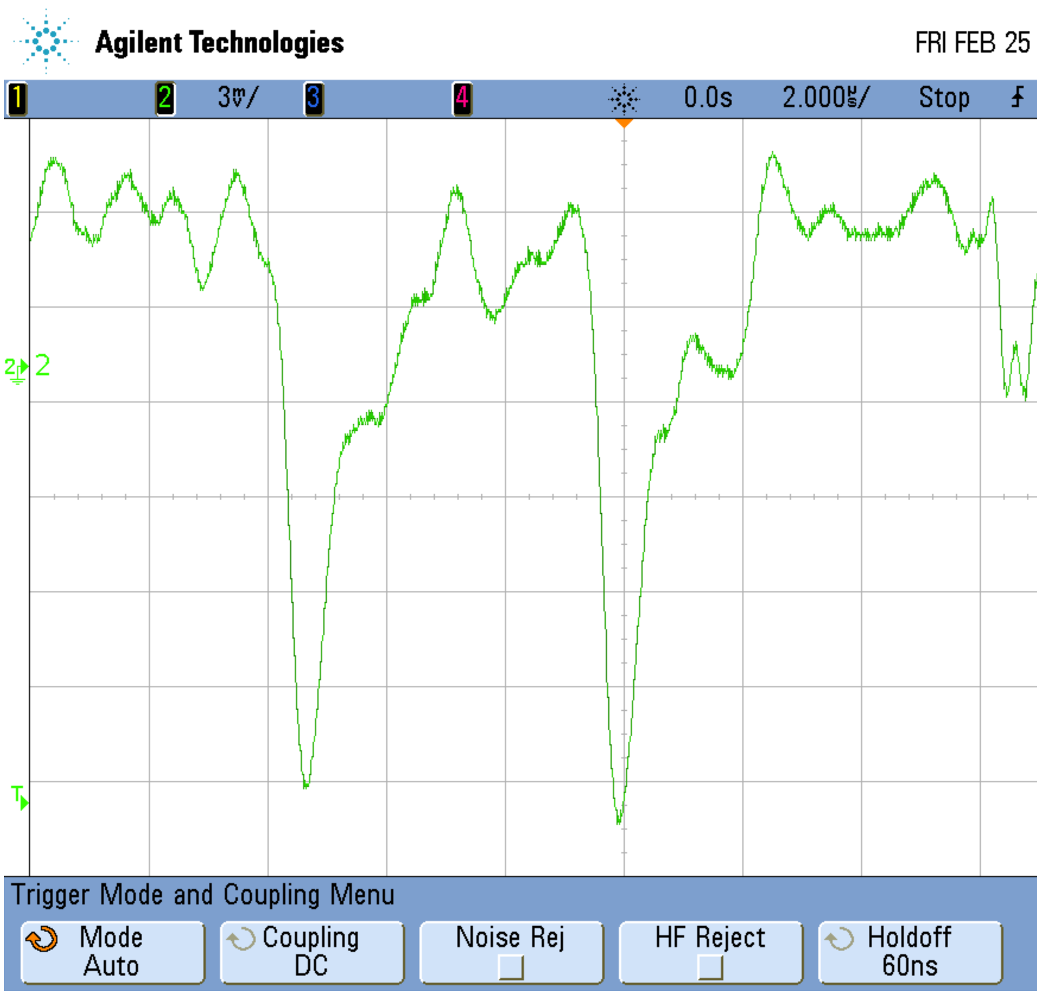


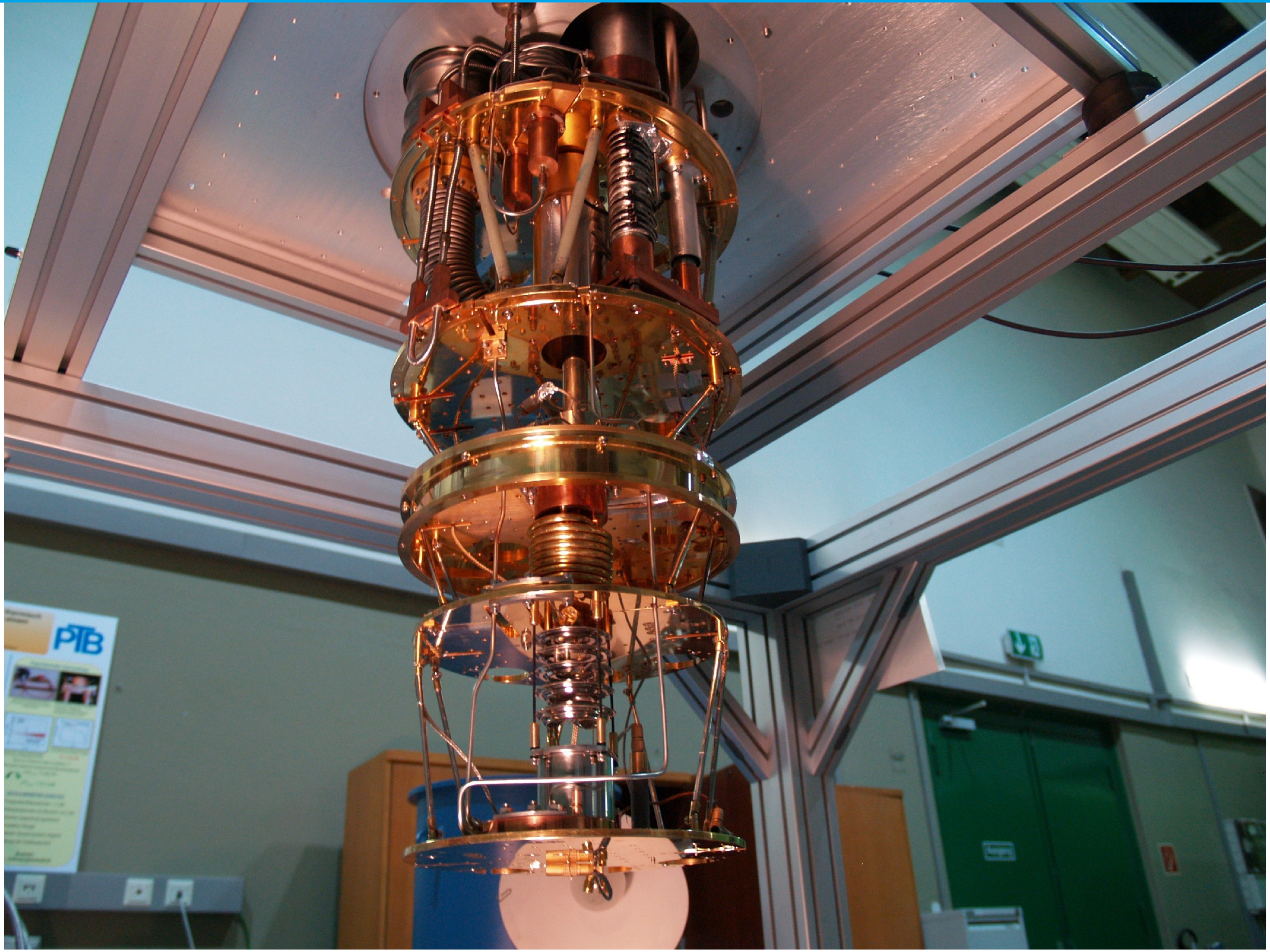
Fig. 1. (a) SEM image of a cross section of an optical TES cavity, produced by focused ion beam milling. The dark and bright layers represent SiO_2 and Ta_2O_5, respectively. The Ti-TES is located between the two red arrows. The upper surface is covered with a tungsten (W) layer as protection against damage by the Ga+ ion beam during milling. The inset is an enlarged view of the contact between the TES and Nb electrodes. (b) Cross-sectional schematic showing the optical-fiber coupling. The fiber is aligned under a microscope using back-side through-chip imaging. A gap with a thickness w_{gap} between the exit end of the fiber and the surface of the antireflection layers is filled with an ultraviolet curable resin.

First learnings and measurements at PTB

- First handling of SQUID operation and readout
  - 16-SQUID series array with a Tungsten TES of NIST (25x25 µm x 20 nm)
- First 'qualitative' measurements with a TES detector at PTB:
  - Determination of parameters (coupling inductances, ...)
  - Noise: $\sqrt{S_{I_{\mathrm{TES}}}} \sim 10\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$ @ 10 kHz
  - Qualitative single photon event from stray light (650 nm)



Inner part of PTB cryostat



The way to TES detector for ALPS

- PAST: Qualitative introduction from PTB in Berlin in spring 2011

- NOW: Own measurement with Italian collaboration in Camerino
  - First try in July: 7 days at mK: no transition!
  - Second try now end of October

- FUTURE: Building up a detector and optimize for ALPS (mid 2012)
  - ***Refrigerator:***
ADR (Entropy): ordered!
  - ***Amplifier:***
SQUID (Magnicon): "ready"
  - ***Sensor:***
high efficiency TES for 1064 nm from AIST or NIST (150k $): checking offers
  - ***Optics:***
studies are in progress