Detecting an infrared photon within an hour

Transition-Edge Detector at ALPS-II

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9th PATRAS Workshop on Axions, WIMPs, and WISPs
Schloss Waldthausen, Mainz Germany
11:15-11:35, June 26th 2013

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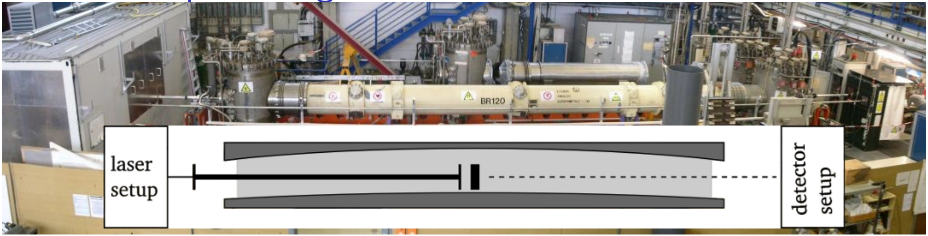
ALPS I – a promising starter



ALPS I experiment at DESY site Hamburg, 2009

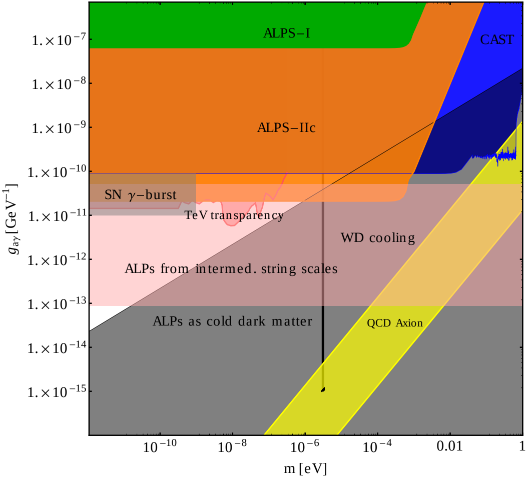
- green laser, production cavity, one HERA magnet
- Piezo-cooled Si-CCD (96% QE at 532 nm) with 1h data/dark frames
  - dark current dominates (10^{-3} e/s) over read-out noise
  - limited by background
- exemplary result:

$\gamma_{\text{in}} \sim 10^{21}\,1/\text{s}$

$\gamma_{\text{meas}} = (2 \pm \mathbf{13}) \times 10^{-3}\,1/\text{s}$

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

ALPS II – lower the limit!



ALPs: $g < \frac{1}{BL}\sqrt[4]{\frac{\gamma_{\rm out}}{\gamma_{\rm in}\times\epsilon}}\frac{1}{F(\ldots)}$

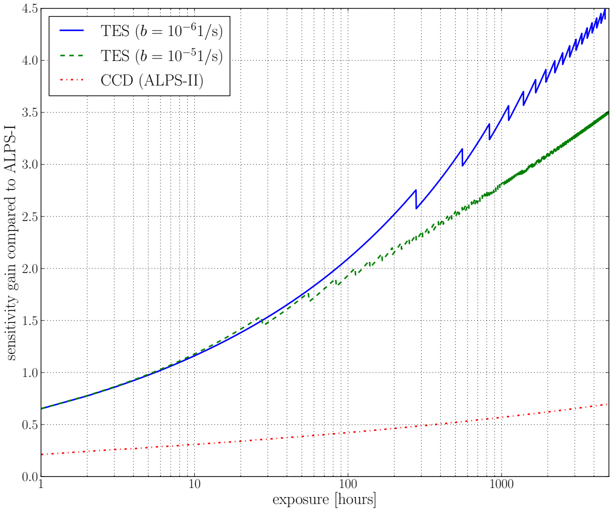
Three steps at ALPS II

- laser power resp. photon flux (**1064 nm**)
- regeneration cavity
- length of experiment (up to 200 m)

Improve sensitivity of detector

- **Challenge:** detection of low rates of single infrared photons ($< 1/\mathrm{h}$)
- **Requirements:** High efficiency and low (dark) noise and background

Detector impact on ALPS II sensitivity



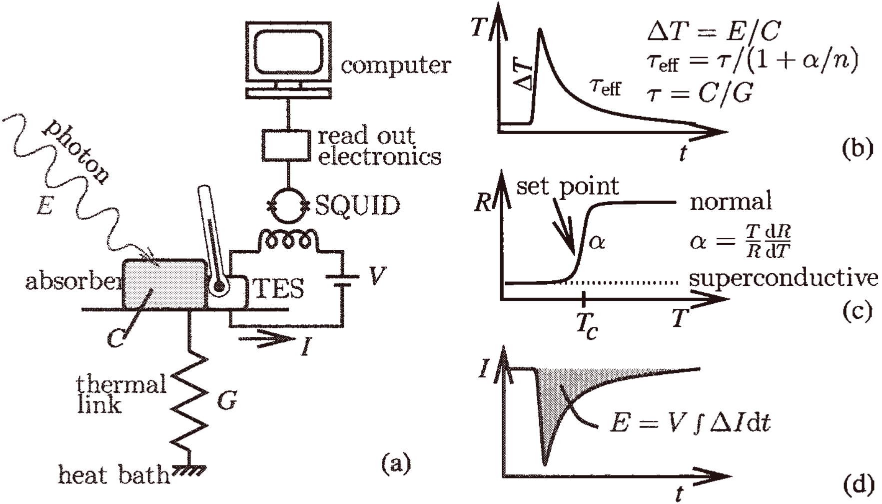
gain = 1

- ALPS I, **532 nm**
- QE = 90%
- 27h exposure
- DC = 0.0012s^{-1}

ALPS II, **1064 nm**

- CCD QE = 1.2%
- TES QE = 75%

Working principle of TES detector



P.A.J. De Korte et. al., *Tes x-ray calorimeter-array for imaging spectroscopy. Proceedings of SPIE, pages 779-789, 2002*

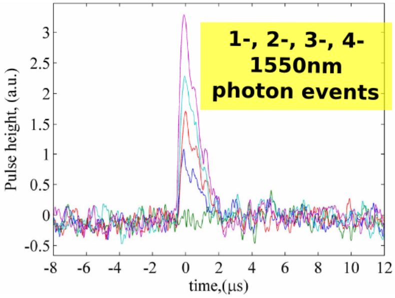
Technical realizations and applications

Some examples:

- Calorimeter: Direct Dark Matter Search (e.g. CRESST II)
- Calorimeter: X-ray & gamma spectroscopy
- Bolometer: mm/sub-mm wave in astronomy
- **Microcalorimeter: single photon counter (near-infrared) for quantum-information (1310/1550 nm)**

This fits to ALPS:

- optical to near-infrared sensitivity
- Time/energy res.: $\sim 1\mu s / \sim 0.1eV$
- Detection efficiency up to 99%
- **No intrinsic dark noise, but th./el. noise and background like black-body photons!**



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

Brief history: TES for ALPS

- before 2011: ALPS with **no** experience in TESs, SQUIDs, mK-cryogenics.
- early 2011: first touch with SQUIDs and „TES photons“ at PTB, Berlin
- mid/end 2011: measurements in Camerino, Italy
  - DR cryostat
  - two low-efficiency TES chips (NIST and INRIM)
  - SQUID array and **electronics, Magnicon**

  → SQUID operation, TES transition, photon event
- mid 2011: meeting the TES community at LTD 14
- end 2012: mK-environment for ALPS: **ADR, Entropy**
- end 2012: exchange with Zeilinger group
- early 2013: characterization of high-efficient TES (each with **PTB 2-stage SQUIDs**)
  - fiber-coupled (glued) AIST (Ti/Au) TES
  - **fiber-coupled (FC) NIST (W) TES**
- now: TES-signals in ALPS lab

PTB

UNICAM Università di Camerino 1336

INFN Istituto Nazionale di Fisica Nucleare

MAGNICON physical research and instrumentation

LTD 14

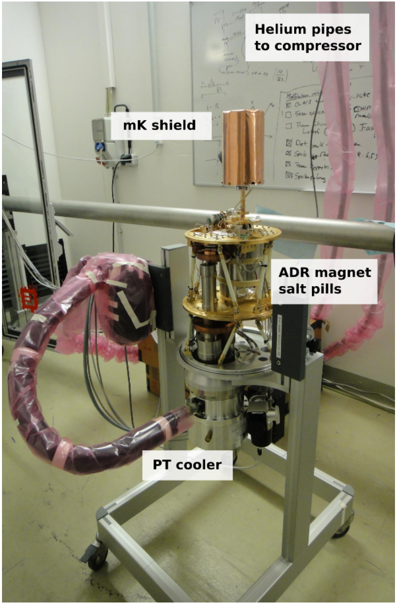
ENTROPY

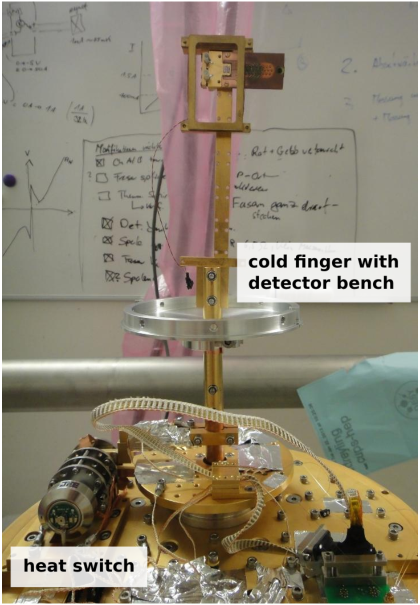
VCQ

AIST

NIST

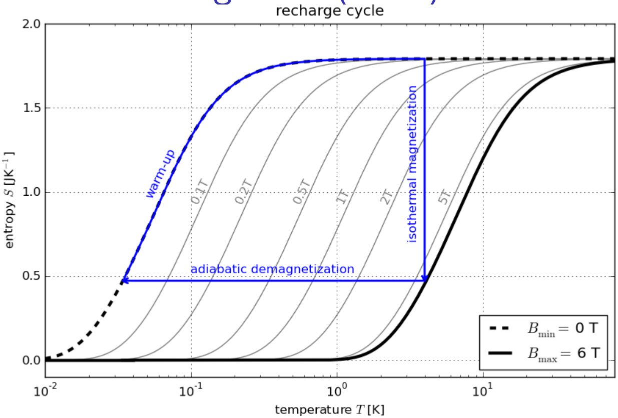
Cryostat for ALPS

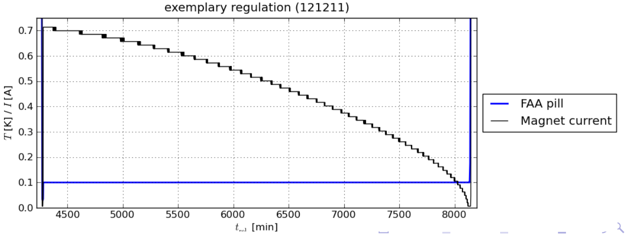




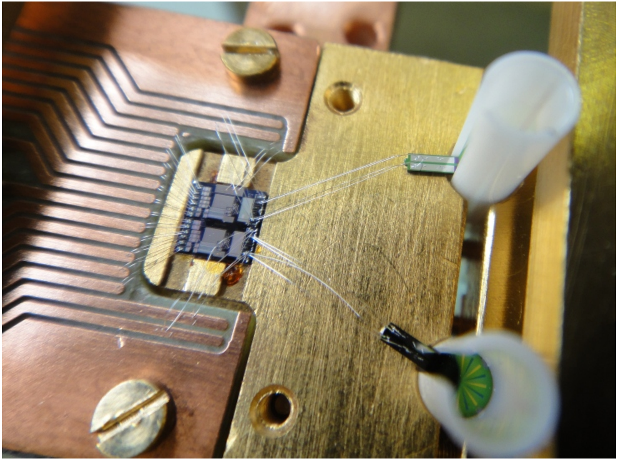
Adiabatic Demagnetization Refrigerator (ADR)

- Pulse-tube cooler: in ~20h to 2.5K
- recharge time 1-2h
- lowest temperature ~30mK
- hold time 24-60h



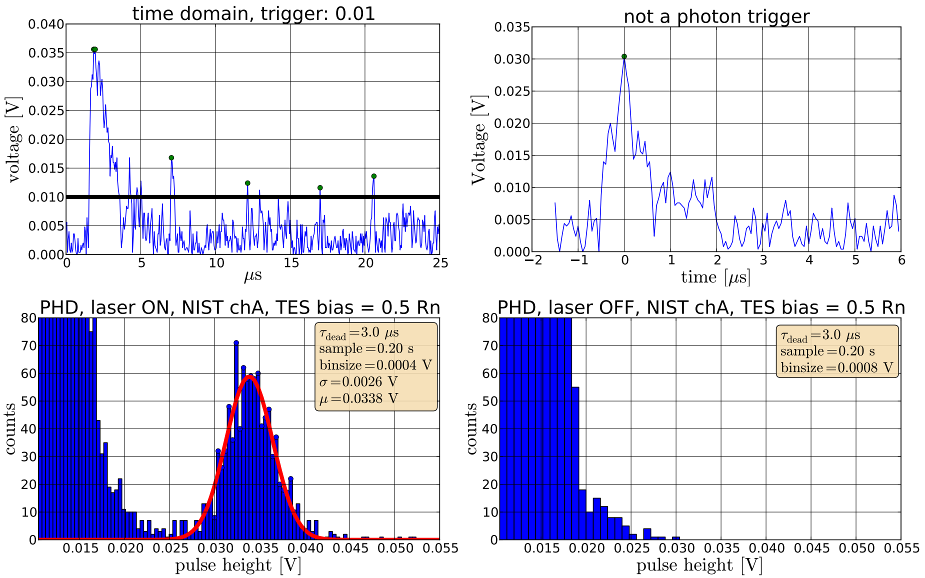


NIST module for ALPS

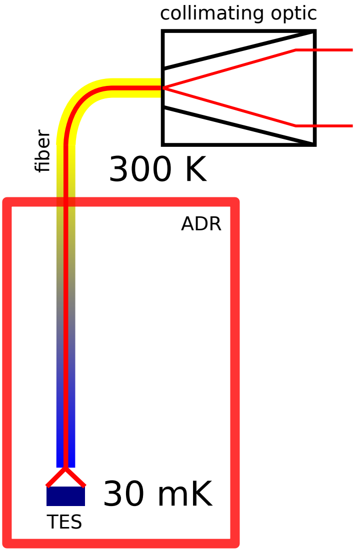


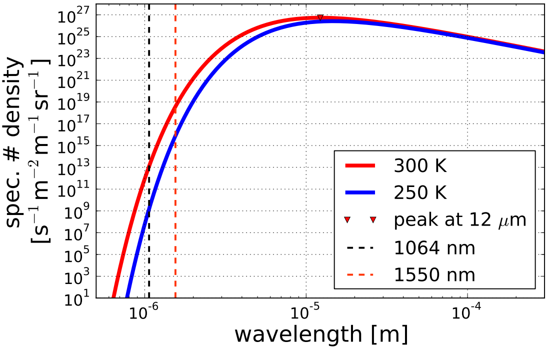
- two channels
- PTB dc 2-stage SQUID
- NIST TES: 25x25μm, W (doped), Tc $\sim$140mK, QE$>$99%
- Coupling: 15-30nH
- Optics: sleeve to connect SM fiber, losses $<$1%

0.2s sample with bad coupled test laser (1066.7nm)



Fiber could see thermal photons...





Conservative estimate:

- At 1064nm within a 200nm band, fiber with MFD=10μm, NA=0.15:

$\rightarrow$ $6.9 \times 10^{-5}\,\mathrm{photons/s}$

Conclusion and Outlook

Conclusion

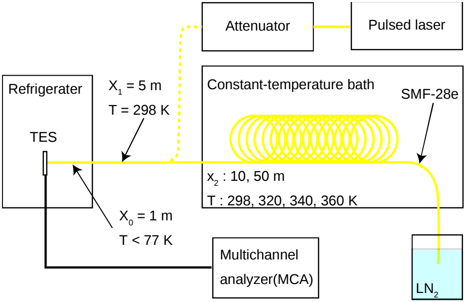
- After a long time TES detector is running in ALPS-IIa lab!!
  - ADR is running
  - SQUID is under control
  - TES sees single photons
- First look at background: quite good!

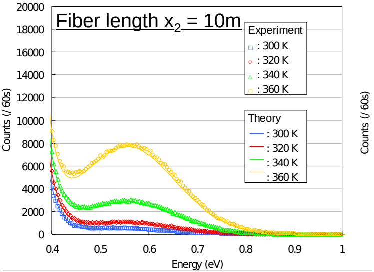
Outlook

- Optimization of SQUID, TES working point
- Optimization of system bandwidth
- (longterm) background measurements
- Data analysis with optimal filter
- Efficient coupling to ALPS-Axion beam

End and Backup

AIST poster: fiber as blackbody

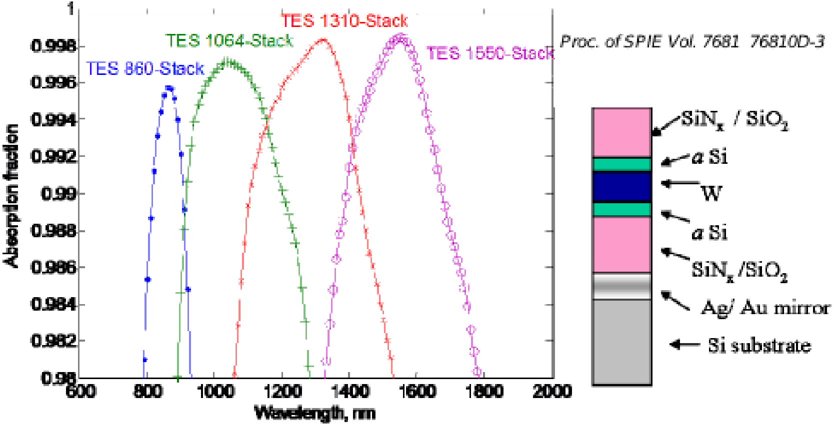




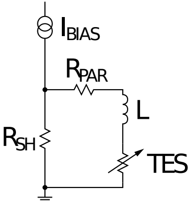
Backup: How can we lower the limit?

- photon rate: $\dot{\gamma}_{\mathrm{meas}} = \dot{\gamma}_{\mathrm{in}} \times P_{\gamma \to \mathrm{WISP} \to \gamma} \times \epsilon$
- conversion probability: $P_{\gamma \to \mathrm{WISP} \to \gamma} \sim (gBL)^4 F(\frac{M^2 L}{4\omega})$
- results in: $g < \frac{1}{BL} \sqrt[4]{\frac{\gamma_{\mathrm{out}}}{\gamma_{\mathrm{in}} \times \epsilon}} \frac{1}{F(\dots)}$

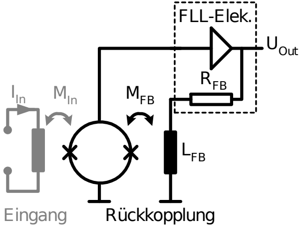
NIST TES simulated light absorption



Concept for TES with SQUID readout



TES input circuit



SQUID Readout scheme

Current divider

$R_{\mathrm{TES}}/R_{\mathrm{SH}} = I_{\mathrm{SH}}/I_{\mathrm{TES}} = I_{\mathrm{BIAS}}/I_{\mathrm{TES}} - 1$

Current noise

$\sqrt{S_I} = 4\,k\,T\,/\,R$

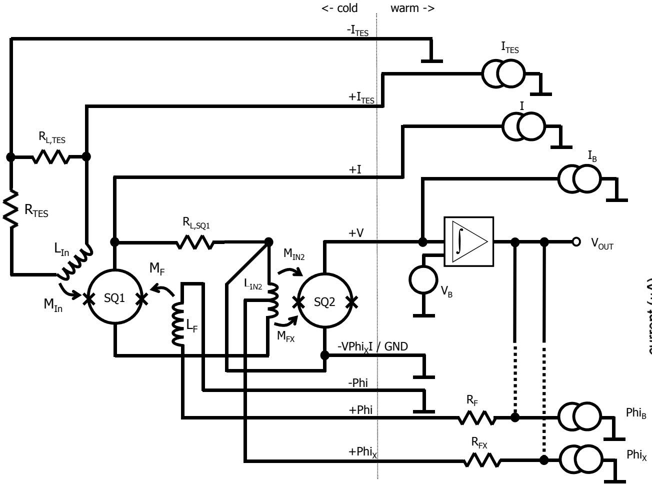
Important formulas

$I_{\mathrm{TES}} = V_{\mathrm{out}} \cdot \frac{M_{\mathrm{in}}^{-1}}{R_{\mathrm{f}}\,M_{\mathrm{f}}^{-1}}$

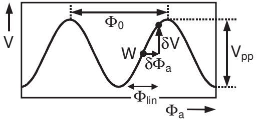
Voltage-biased ($R_{\mathrm{TES}} \gg R_{\mathrm{PAR}} + R_{\mathrm{SH}}$):

$V_{\mathrm{TES}} = I_{\mathrm{BIAS}}\,R_{\mathrm{SH}}$

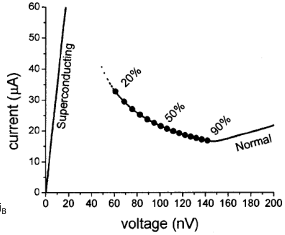
2-stage SQUID with TES input and characteristics



Detailed scheme

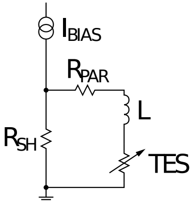


V-Φ-charcteristics (working point)

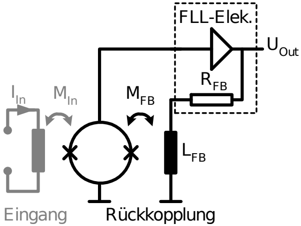


I-V characteristics (working point)

Values



TES input circuit



SQUID Readout scheme

TES AIST specs (Channel A)

meas.: $R_{\rm SH} = 22\,{\rm m}\Omega$

meas.: $R_{\rm TES} = R_{\rm N} = 3.7\,\Omega$

meas.: $T_{\rm C} \sim 303 \ldots 317\,{\rm mK}$

meas.: $R_{\rm PAR} = 7.5\,{\rm m}\Omega$

estim.: $L = 15 \ldots 20\,{\rm nH}$

SQUID specs

datasheet.: $M_{\rm in} = 5.5\,\mu{\rm A}/\phi_0$

working point:

2nd-stage: $I_{\rm b}$, $V_{\rm b}$, ${\rm Phi}_{\rm b}$

1st-stage: I, ${\rm Phi}_{\rm X}$

meas. (at $100{\rm mK}$): $M_{\rm f} = 54.1\,\mu{\rm A}/\phi_0$

(adj.: $R_{\rm f} = 100\,{\rm k}\Omega$)

(adj.: ${\rm GBP} = 7.2\,{\rm GHz}$)