Low background, low energy detectors for WISP search experiments

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Summary

- WISPs and photons
- The detector problem
- BaRBE and BaRBE_LT
- Future developments with TES sensors

Photons as WISP search tools

- Two main types of experimental WISP searches are possible
  - Observatories
    - Detect photons from a source carrying the signature of WISP processes happening there
  - Laboratory based
    - Send a beam of photons on a "photon target" and detect WISPs from their "decay" photons

Features common to observatories

- Magnetic field environment to convert WISPs into photons
  - higher fields very desirable
- Very low background photon detectors
  - premium on lowering the background
- Very low rate of expected events
- Physical interpretation relies on cosmological/astrophysical arguments

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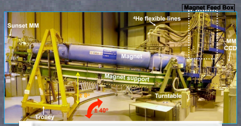
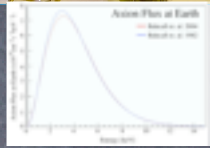
  - 4 X-ray detectors of different types instruments the two bores of the magnet looking for excess photons
  - the wide mass range can be extended to higher masses by inserting gas (4He and 3He) in the bores
- Strengths & Weaknesses
  - wide mass range, good sensitivity (best current wideband experimental bound)
  - integration time limited by swing angle of mount
- Upgrades: lower detector background to increase sensitivity, extend spectral coverage to eV ALPs





Arik et al. Probing eV-scale axions with CAST. Journal of Cosmology and Astroparticle Physics (2009) vol. 2009 pp. 008

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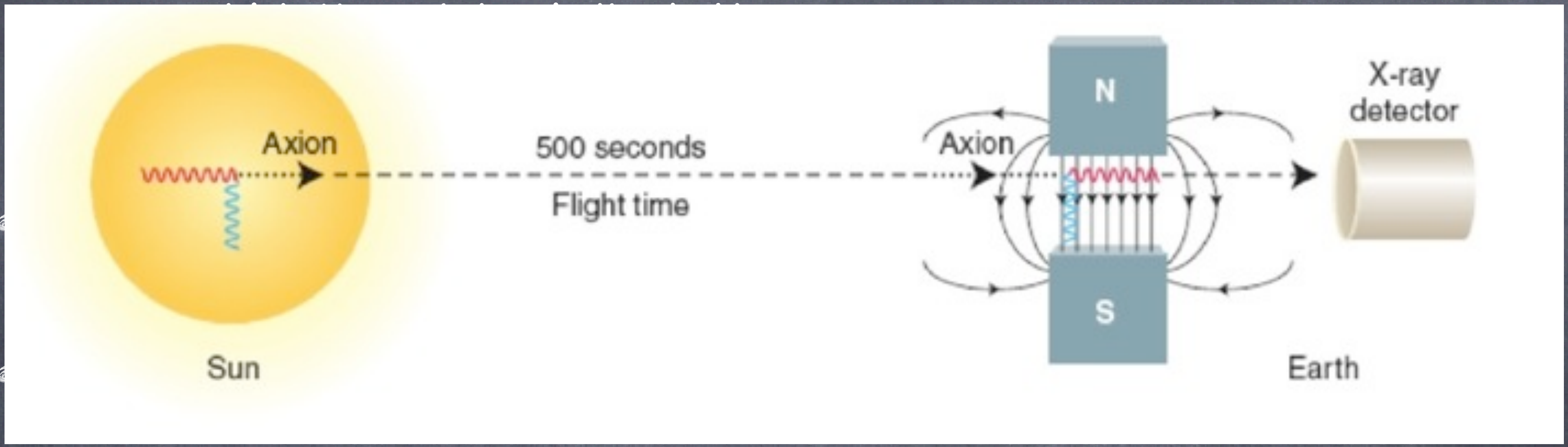

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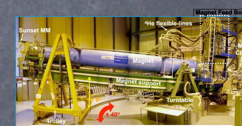

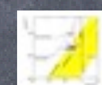

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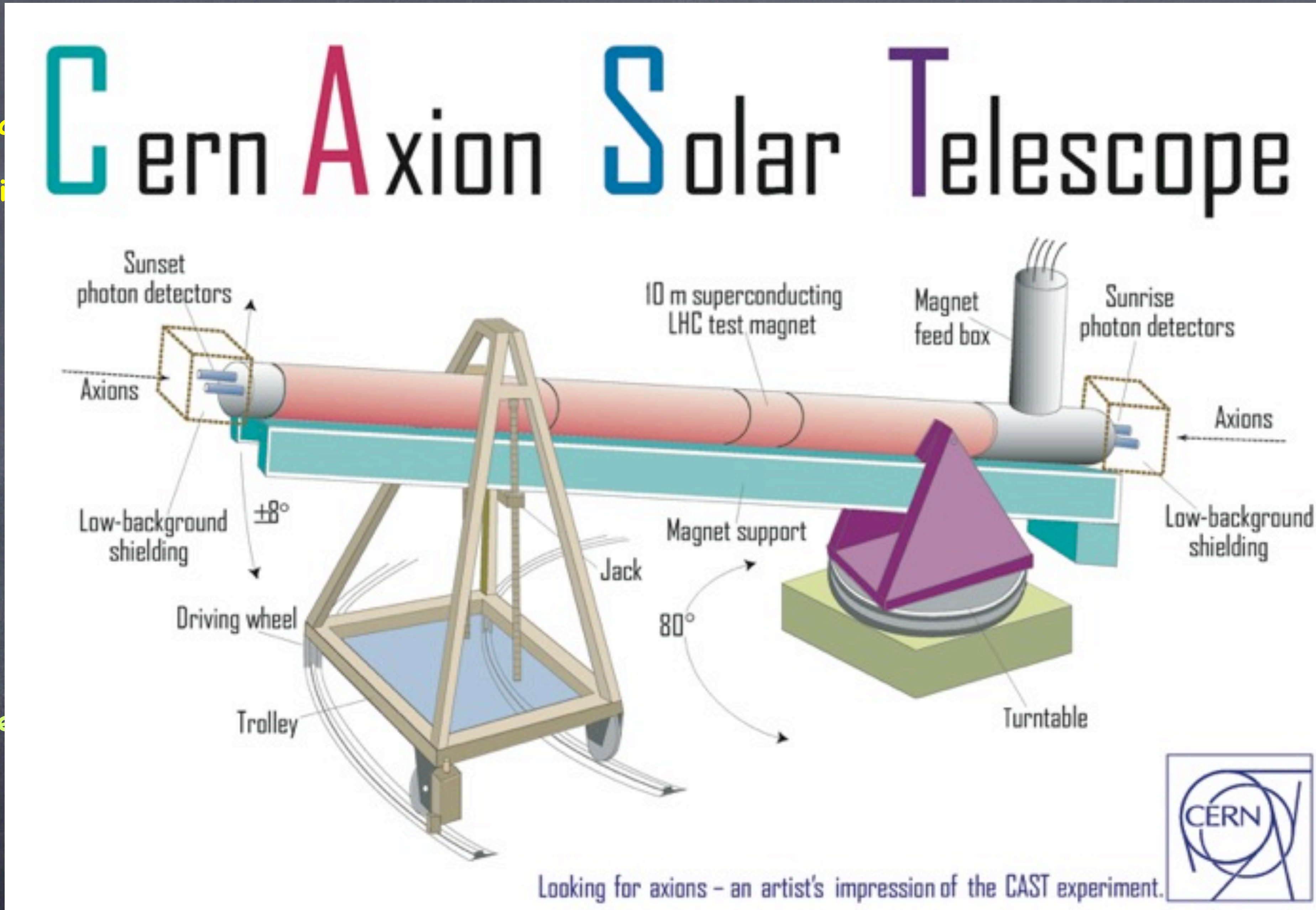

Looking for axions – an artist's impression of the CAST experiment.

- Stre

- **Upgrades: lower detector background to increase sensitivity, extend spectral coverage to eV ALPs**

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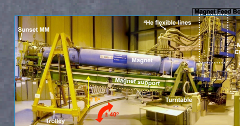

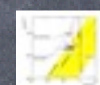

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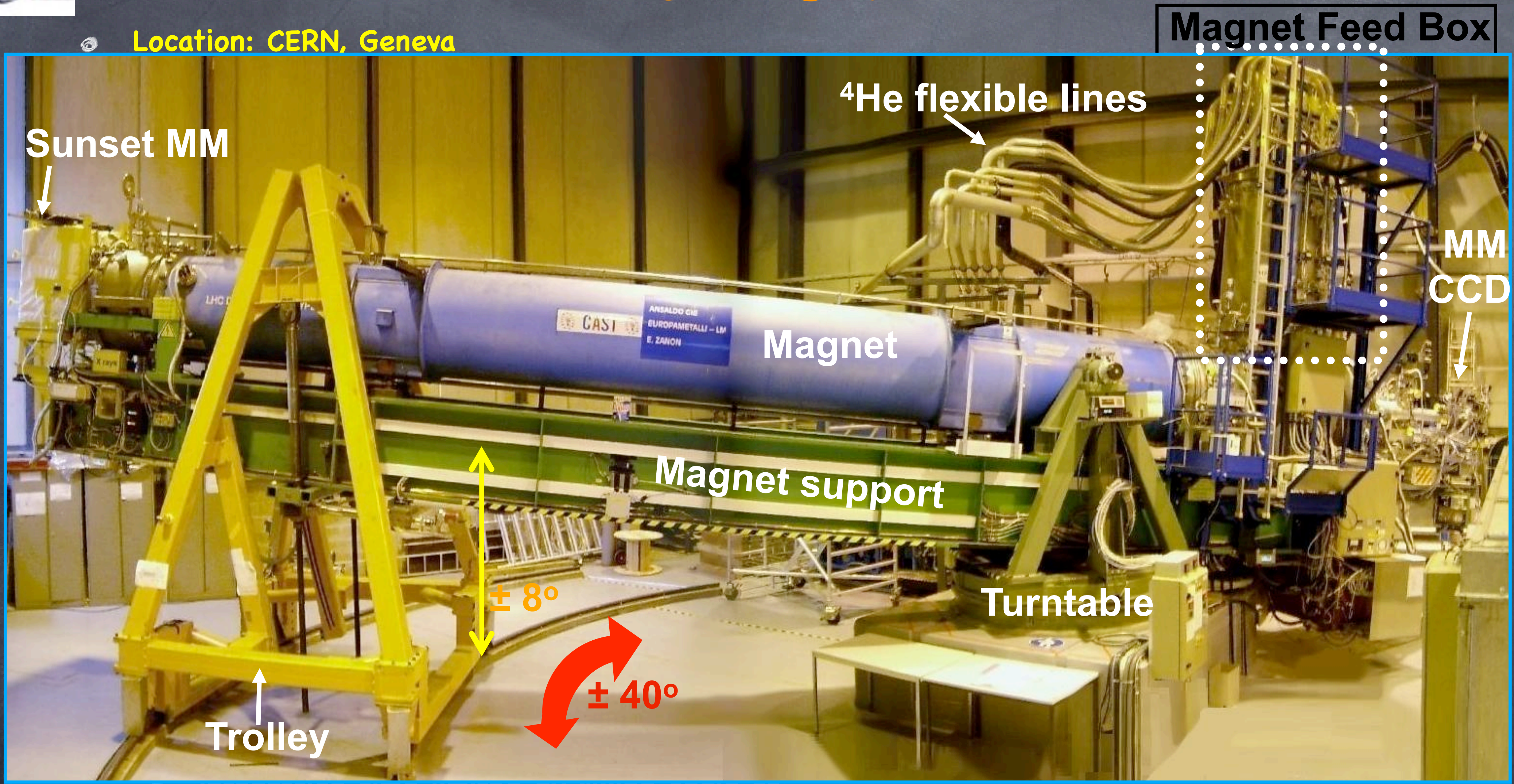

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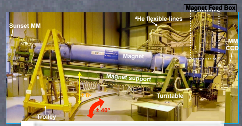

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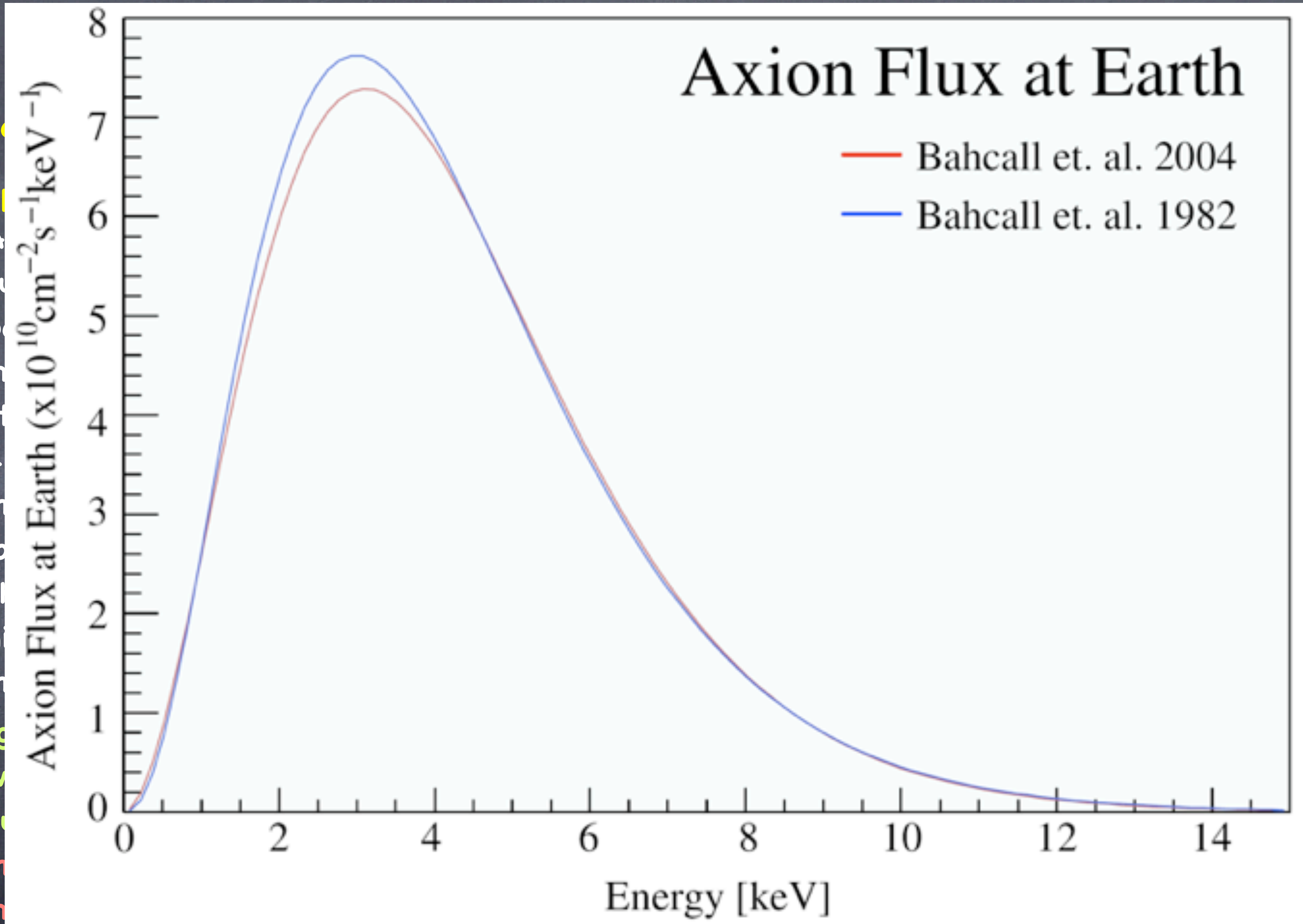

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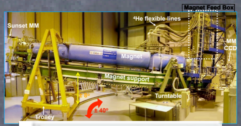

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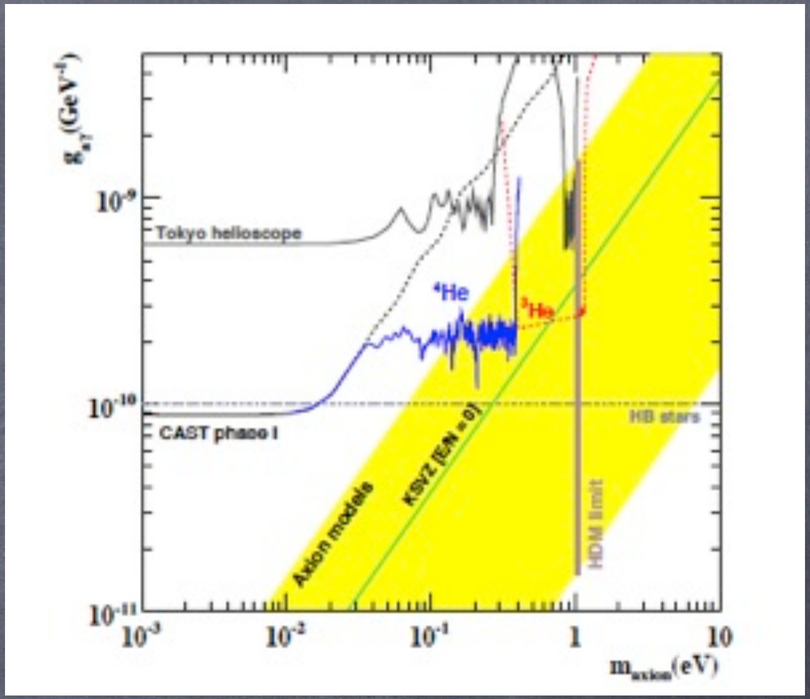

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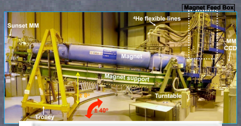

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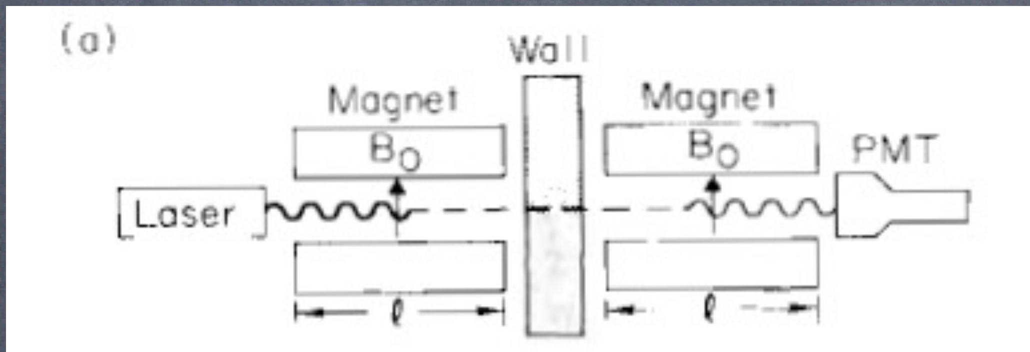
Laboratory searches: photon regeneration

- The "experimentum crucis" to prove beyond reasonable doubt that one has seen ALPs is photon regeneration
- Originally proposed by Van Bibber et al., Phys. Rev. Lett. vol. 59, no. 7, (1987), p 759.



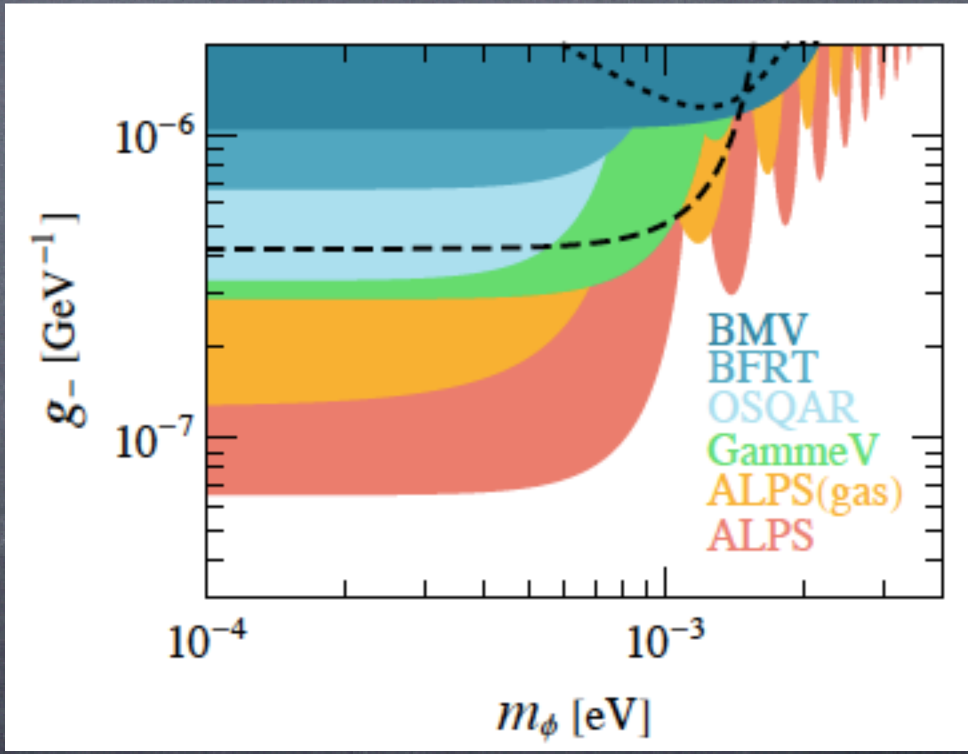
$$p_{0,reg} = \left[\frac{2\omega B_0}{M_a m_a^2} sin \left(\frac{m_a^2 L}{4\omega} \right) \right]^4$$

in vacuum and with $m_a \ll \omega$

- It is poetically known as "light shining through a wall" -> LSW.
- Very difficult, since overall process probability depends on the 4th power of the (ALP-two photons) coupling constant

The ALPS experiment

- Location: DESY - Hamburg
- Basic principle
  - A CW 532 nm laser enters a single magnet split in two chambers by an opaque septum
  - the production chamber is enclosed in a resonant cavity
  - regenerated photons are detected by a CCD sensor
- Strengths & Weaknesses
  - (relatively) short wavelength, resonant enhancement of production probability
  - limited by laser power and detector background
- Upgrades
  - higher laser power
  - higher-finesse resonator
  - resonant regeneration
  - lower background detector

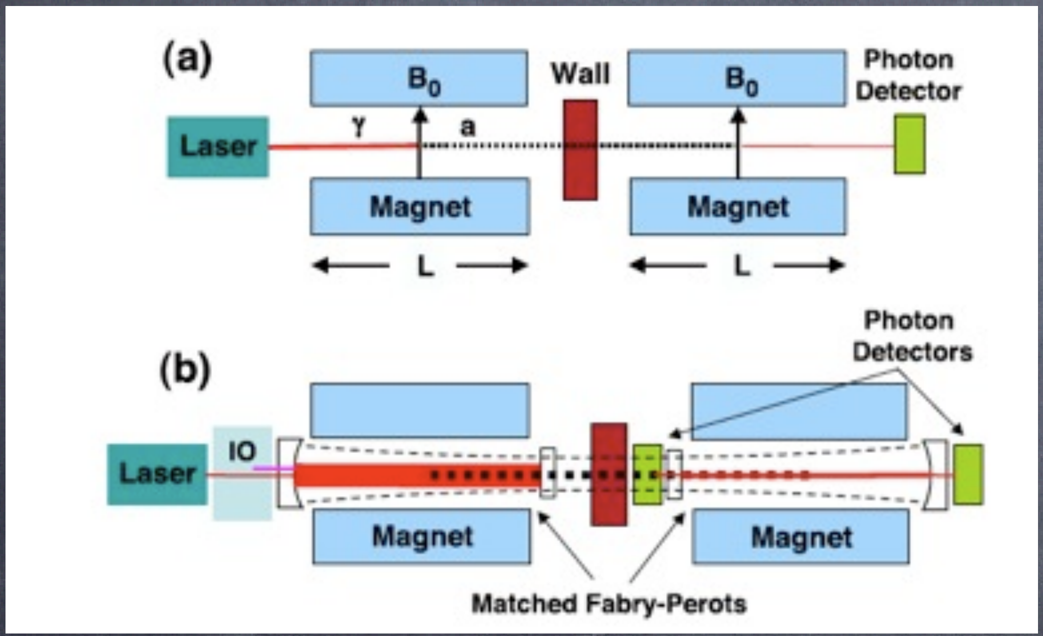


K. Ehret et al., "New ALPS Results on Hidden-Sector Lightweights." arXiv:1004.1313v1

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 and T. Ziegenhagen, Nucl. Phys. B 358, 3(1991)

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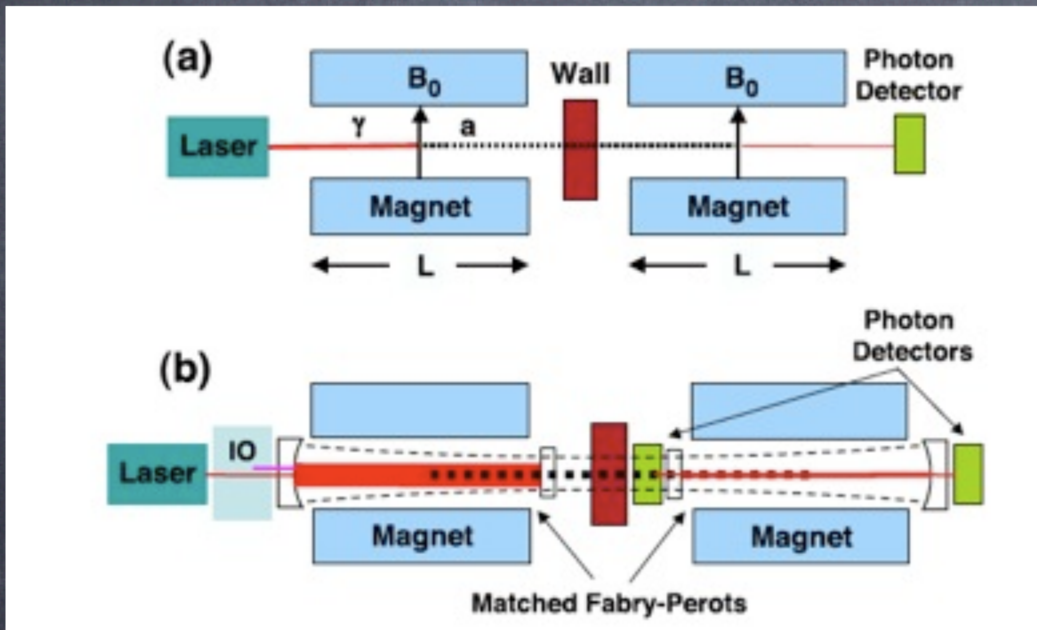

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The challenge(s)

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

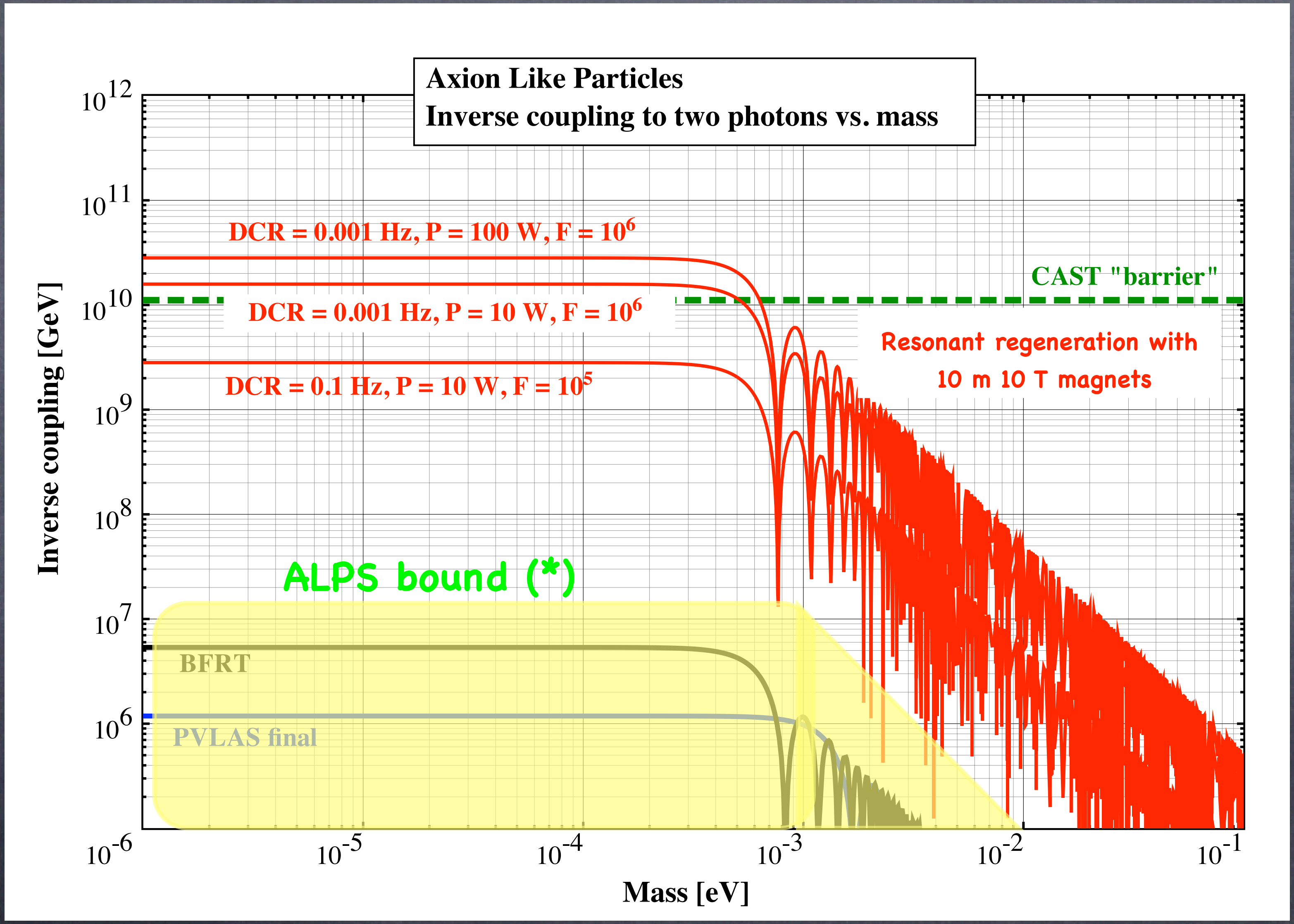
II. Low background detectors

III. High-power laser

IV. Accumulate statistics

The possibilities

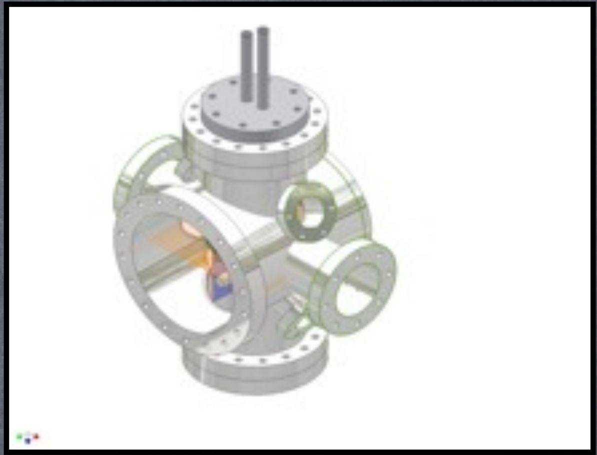
- Reach in the M-m plane



(*) ALPS bound from K. Ehret et al., "New ALPS Results on Hidden-Sector Lightweights." arXiv:1004.1313v1

Challenge II - low background detector

- Common problem of ALP search experiments
- BaRBE experience at CAST for Low Energy Solar axions
  - started with a PMT and an APD (0.35 Hz DCR)
  - moving to LN2-cooled APD



- Resonant regeneration measurements could also begin with a cooled APD (DCR?, maybe 10^{-2} Hz, BaRBE will find out) ... however ....
- Dream detector: a TES (no background!)

BaRBE (Basso Rate Bassa Energia)

University and INFN Trieste

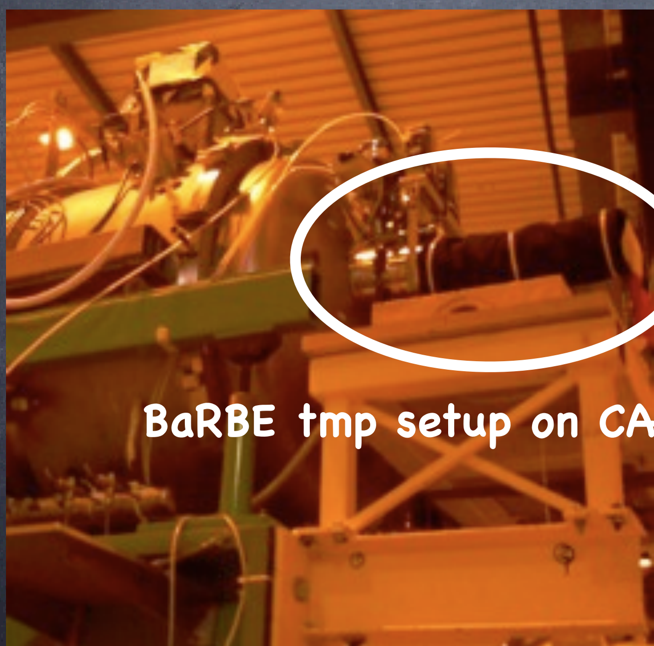
- Goal
  - to develop a low-background detector system capable of single-photon-counting in the 1-10 eV energy range, possibly with spectroscopic capabilities
- Main motivations
  - exploration of the solar ALP spectrum in the 1-10 eV energy range with the CAST experiment at CERN
  - detection of low energy single photons from rare processes such as resonant regeneration at ALPS (possibly in the future with FEL-type sources)

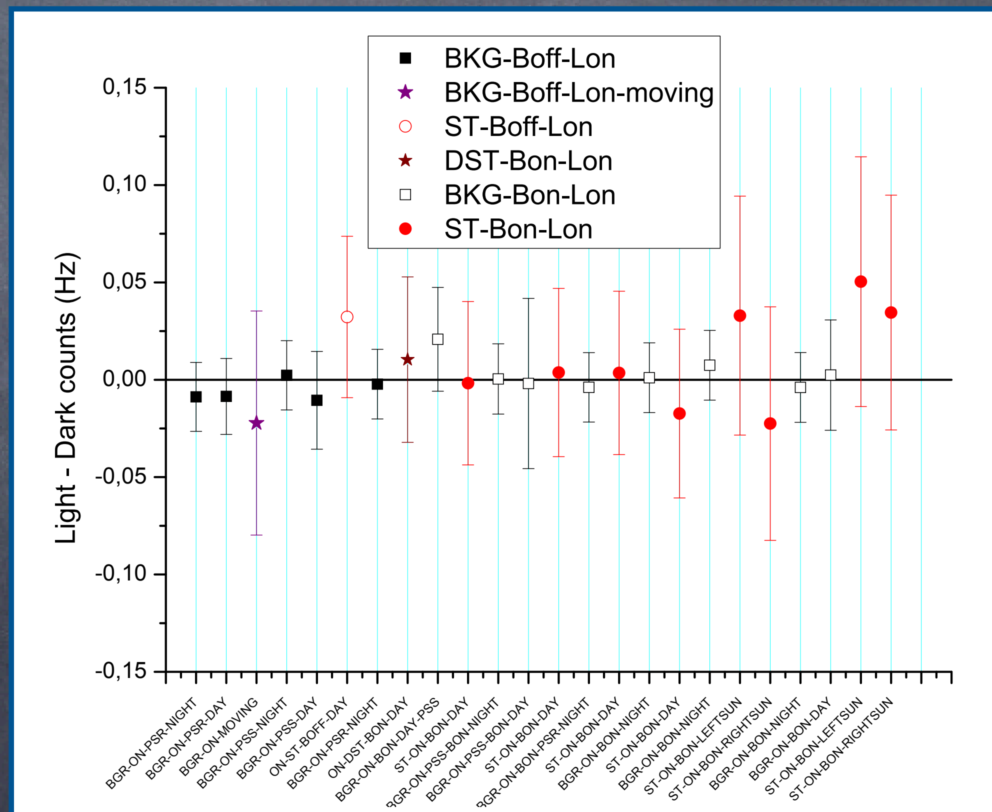
BaRBE experimental activities

- Initial phase (2008-2009)
  - laboratory benchmark tests of "off-the-shelf" detectors (PMT and APD)
  - design and testing of a "beam" coupling system for the detectors to the CAST magnet
  - live sun-tracking measurements at CAST
- Second phase (2009-2010)
  - permanent installation of a low energy photon detector on CAST
  - search for a lower background detector -> start with cooled Avalanche PhotoDiodes

Conclusions from the first BaRBE phase

- It is possible to optically couple a low-background, low-energy photon detector to a "beam" without introducing additional noise sources
- The background measured at CAST for 3-4 eV photons is DCR = 0.35 Hz ± 0.02 Hz for an acquisition time of 30000 s
- No significant excess of signal photons over background has been observed in the 12 solar tracking data sets

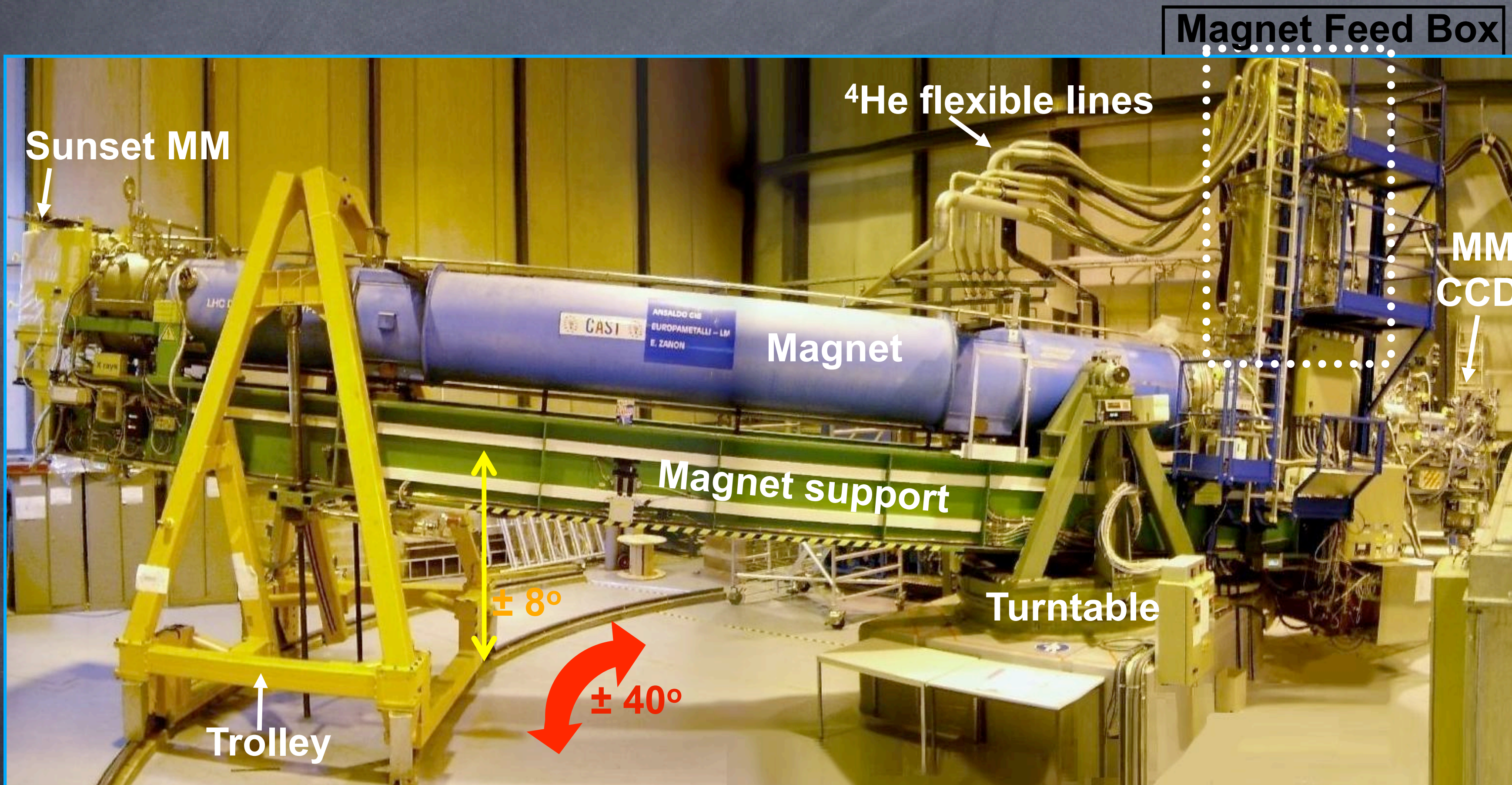




BaRBE second phase (2009-2010)

- Permanent coupling to CAST
  - the original BaRBE system is permanently inserted in the CAST beamline using a semitransparent mirror assembly
- Detector choice
  - further progress depends on finding a lower background detector
  - initial choice falls on a Geiger mode APD (SPAD) cooled at LN2 temperature -> BaRBE_LT (BaRBE Low Temperature) is launched

Permanent coupling to CAST



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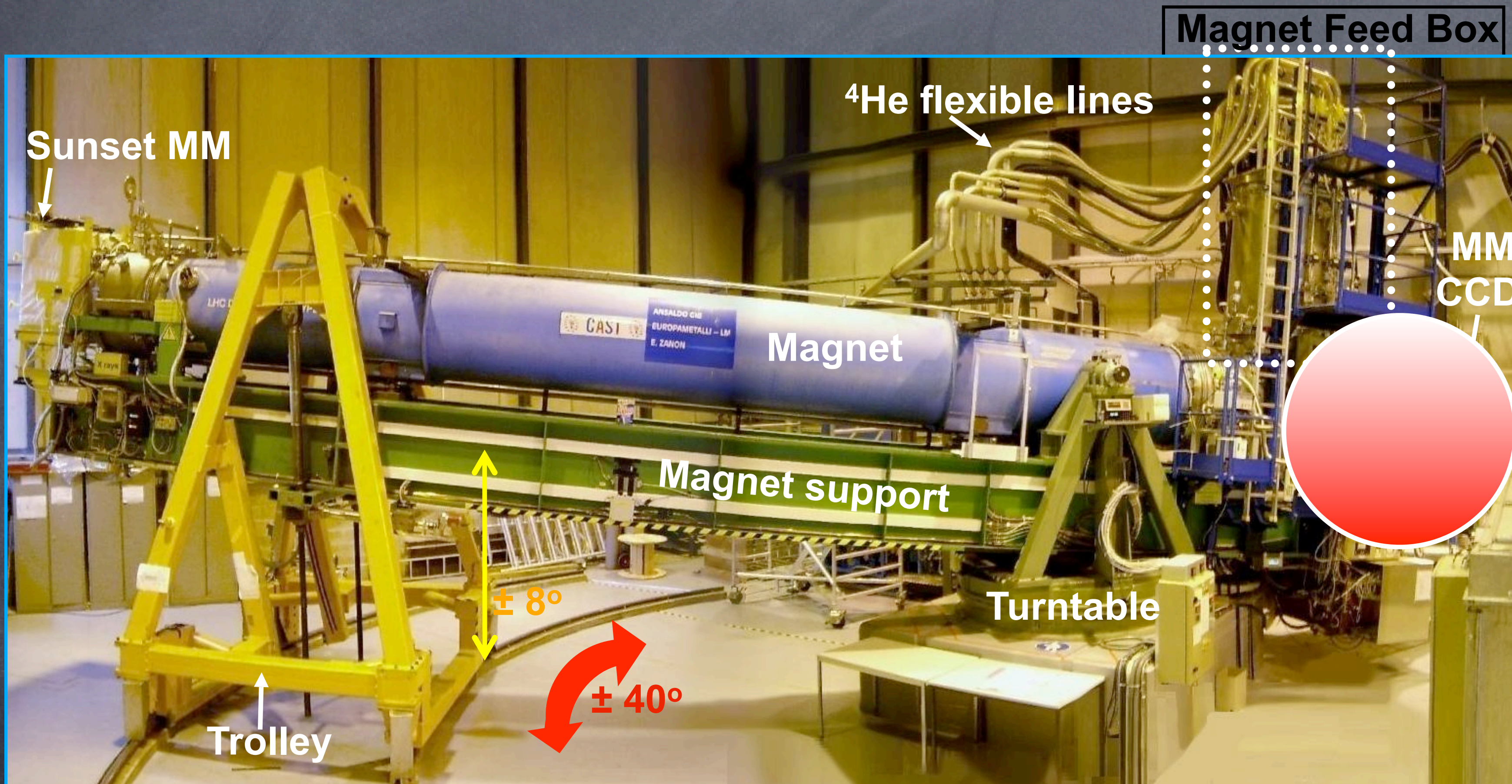

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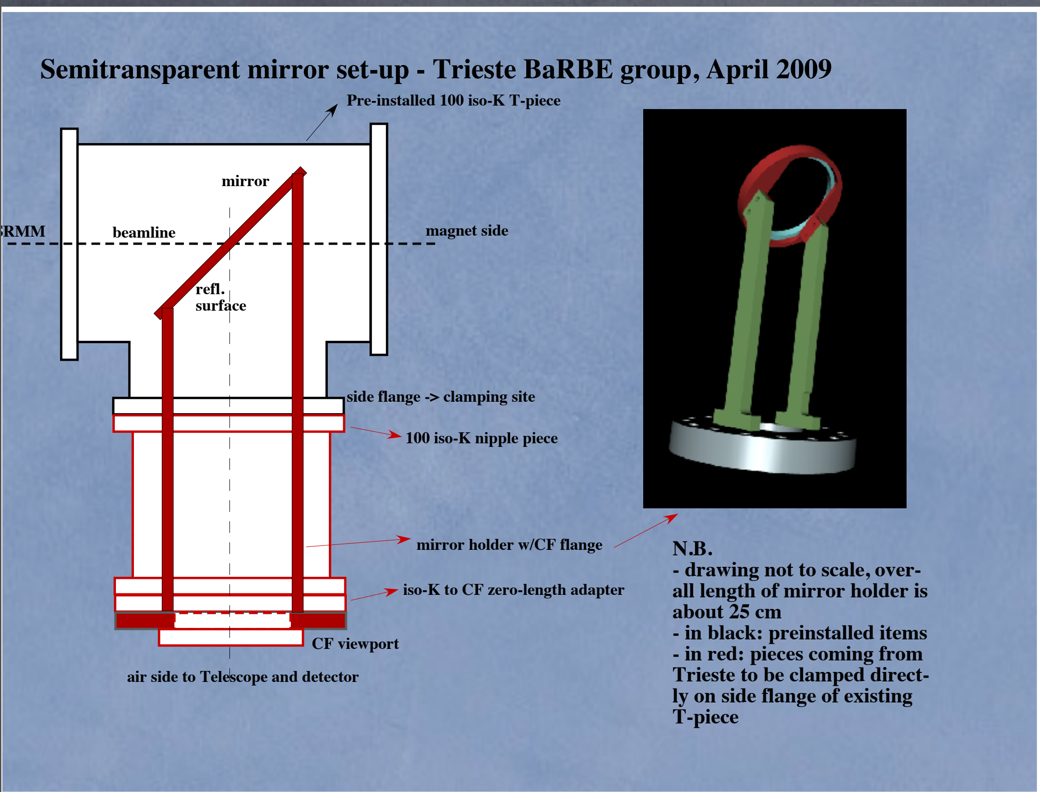

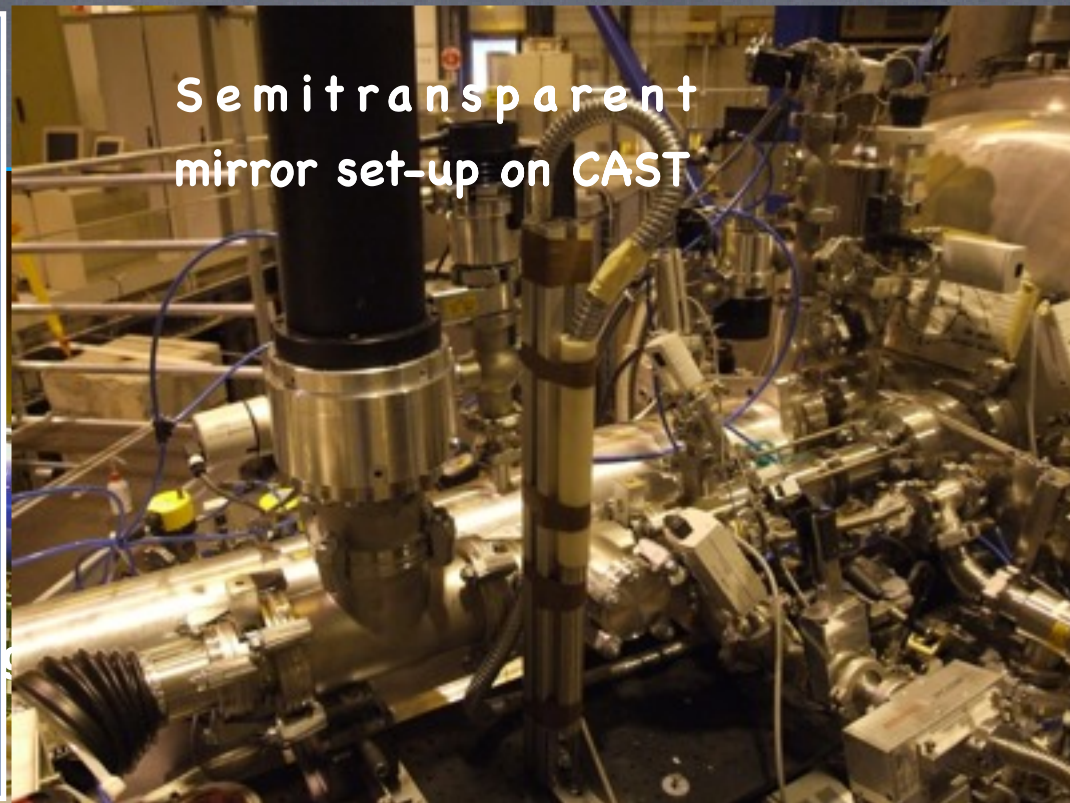

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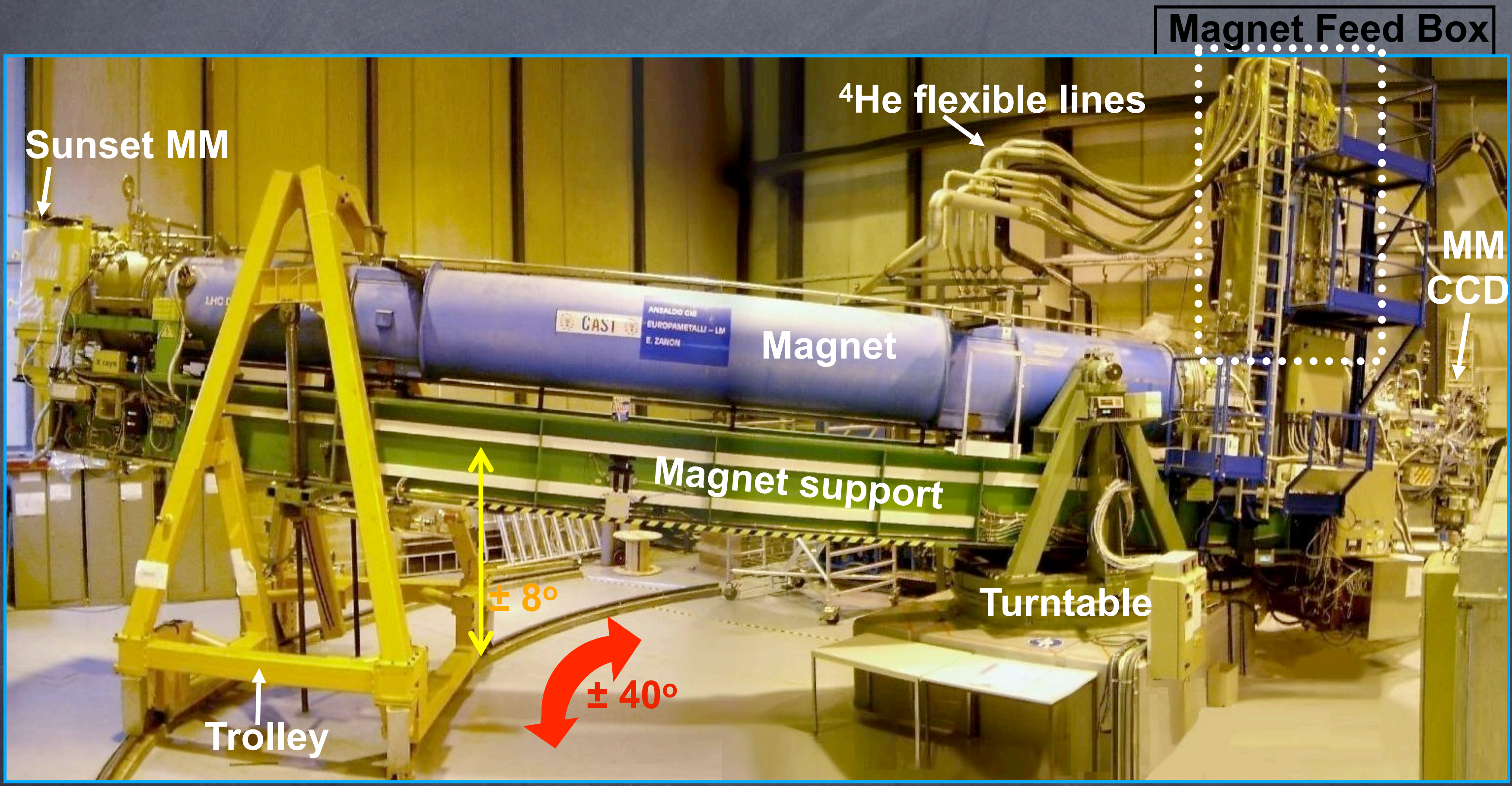

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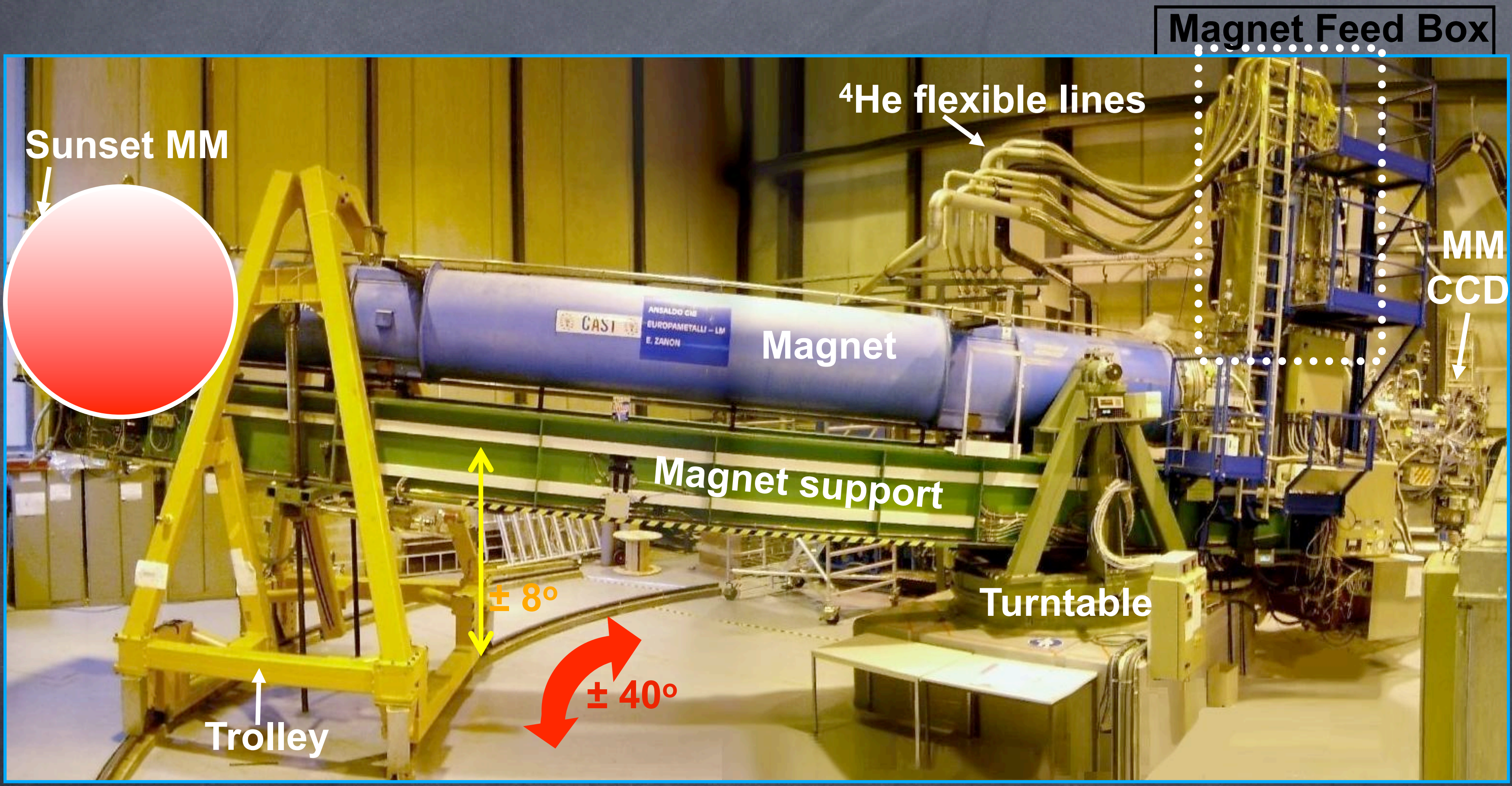

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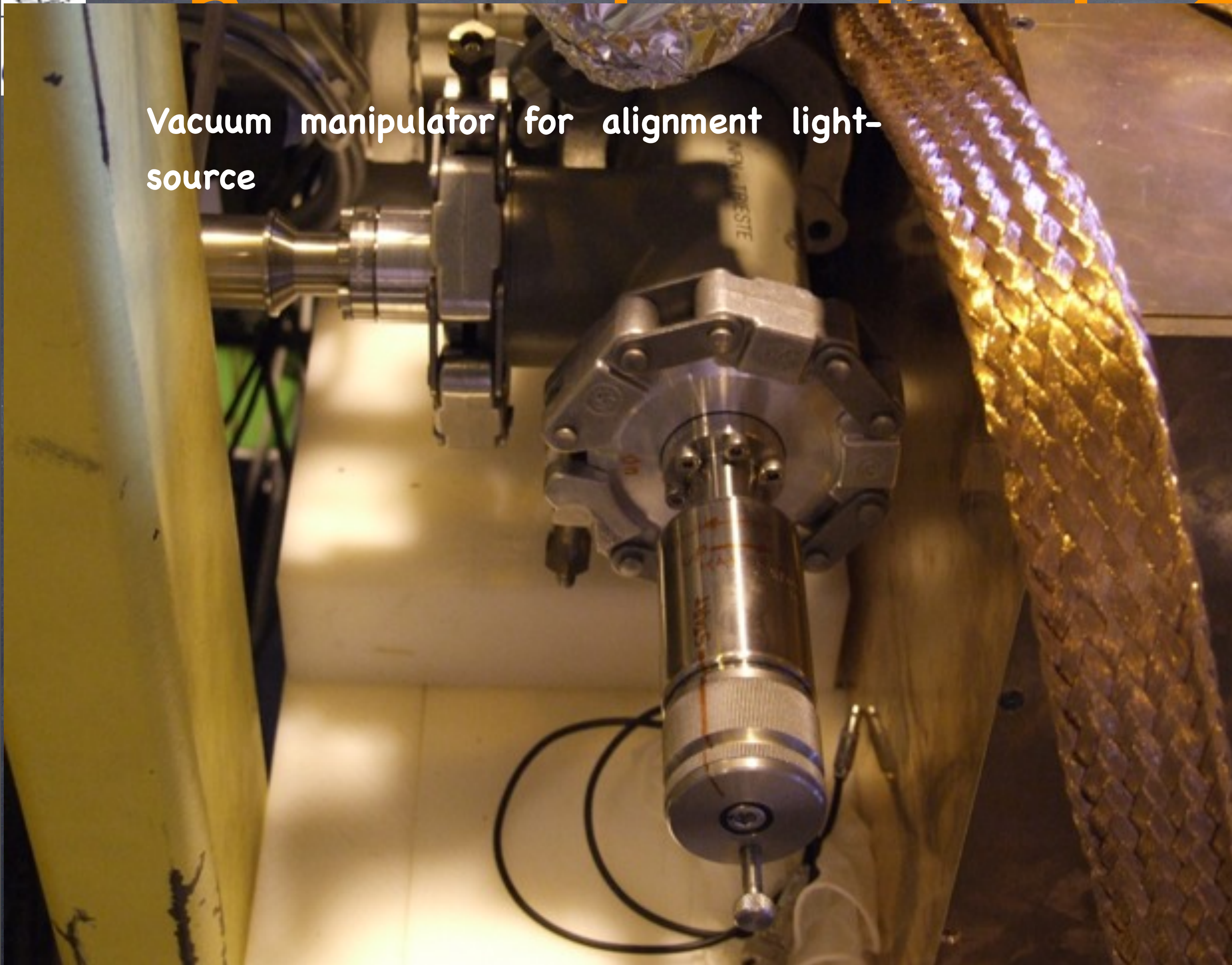
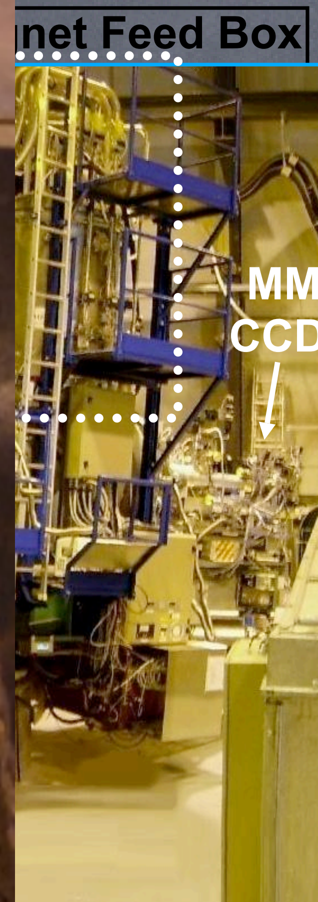


Vacuum manipulator for alignment light-source



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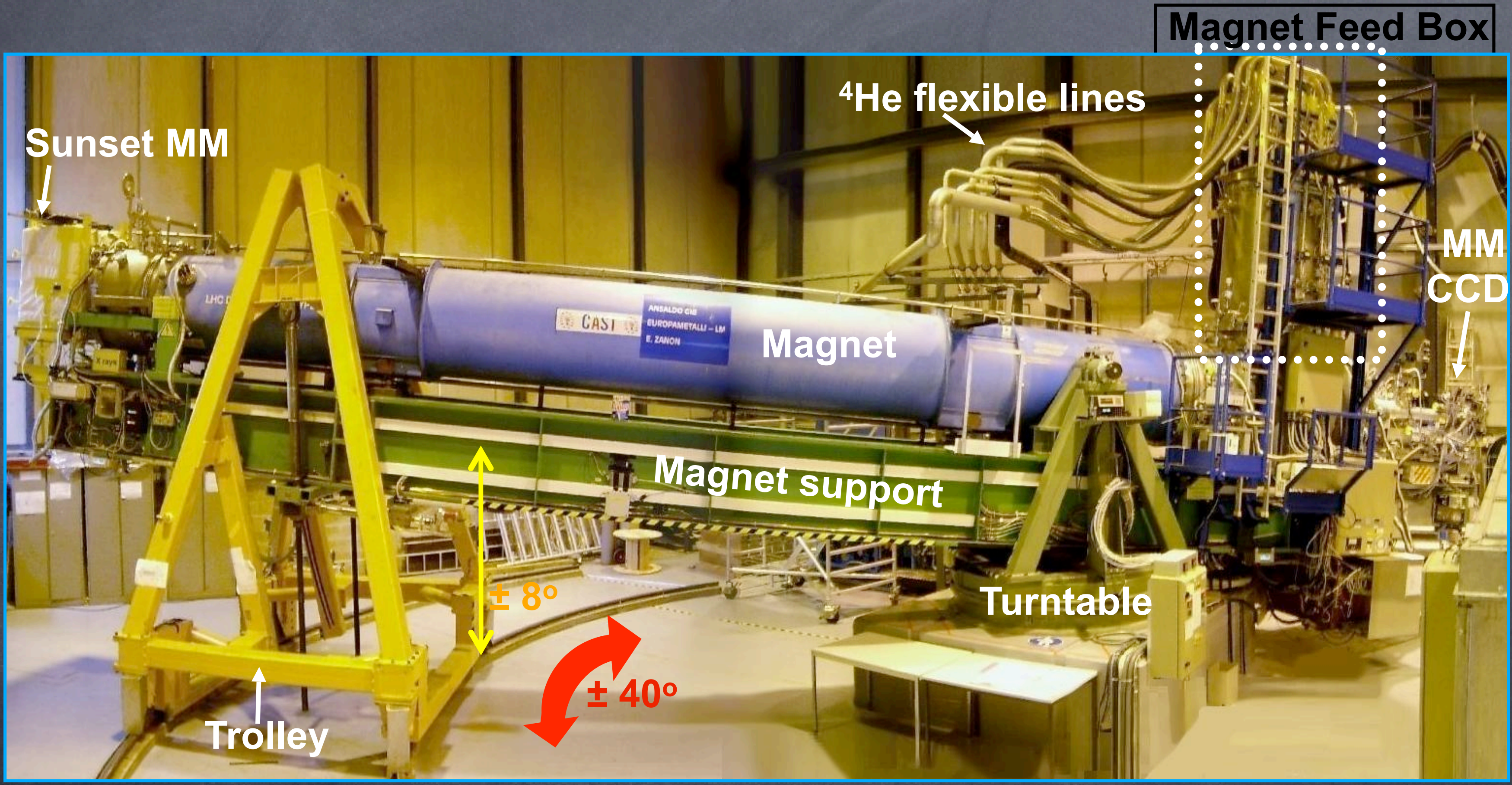
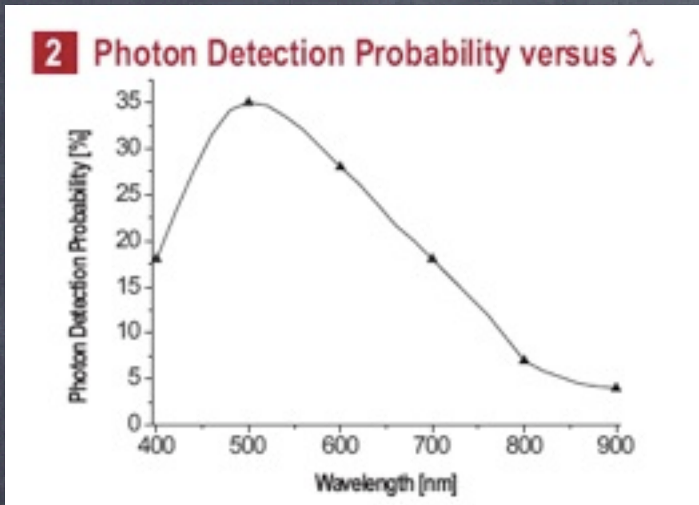
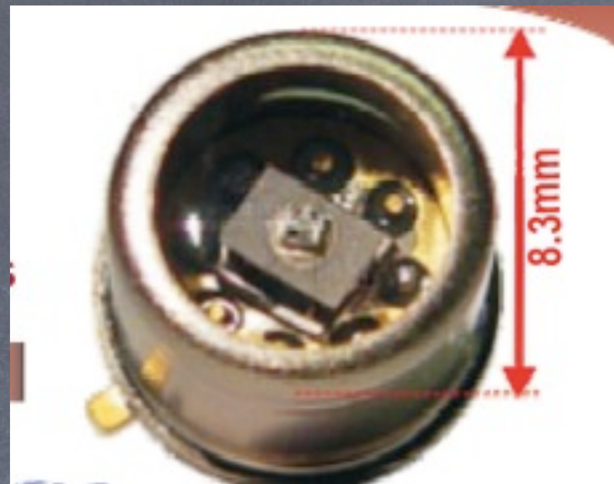
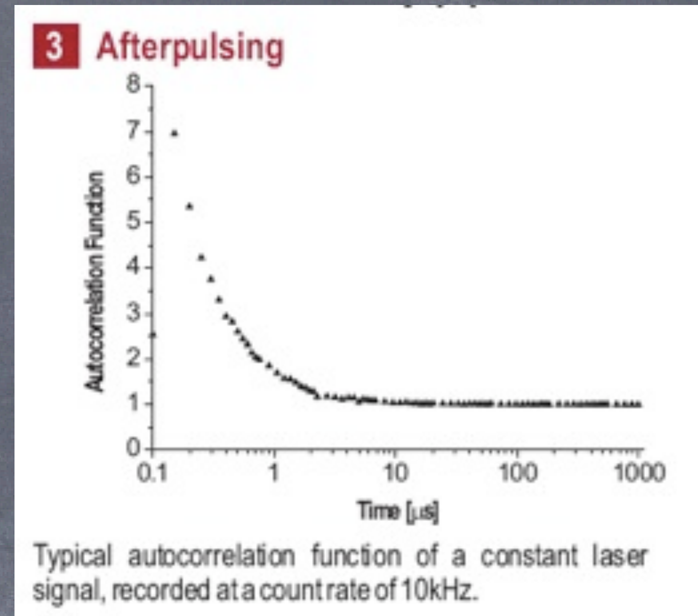


APD detector for BaRBE_LT



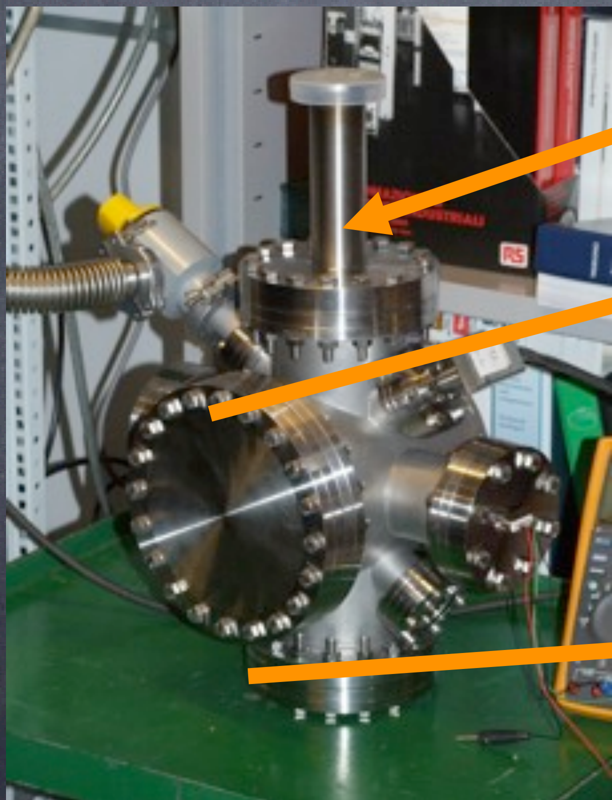




- APD Model id101 made by idQuantique with factory Peltier cooling disabled
- same type of sensor used at 0 °C during the first BaRBE phase (measured DCR = 0.40 Hz)
- the expected increase in the afterpulsing rate when going down in temperature should not be a problem in those applicationa where the rate of expected signal phiotons is low

Liquid-N2 cryostat for BaRBE_LT

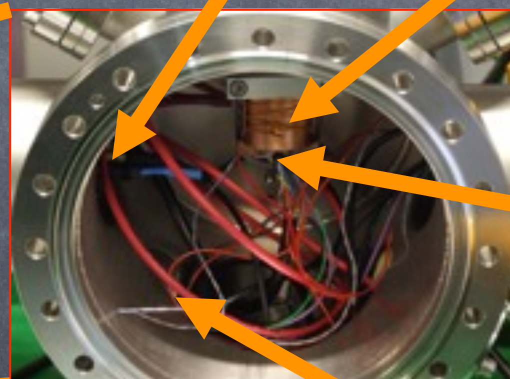
Cryostat for LN2 cooled G-APD



Cold finger

Optical fiber

Copper cold finger with
Detector holder



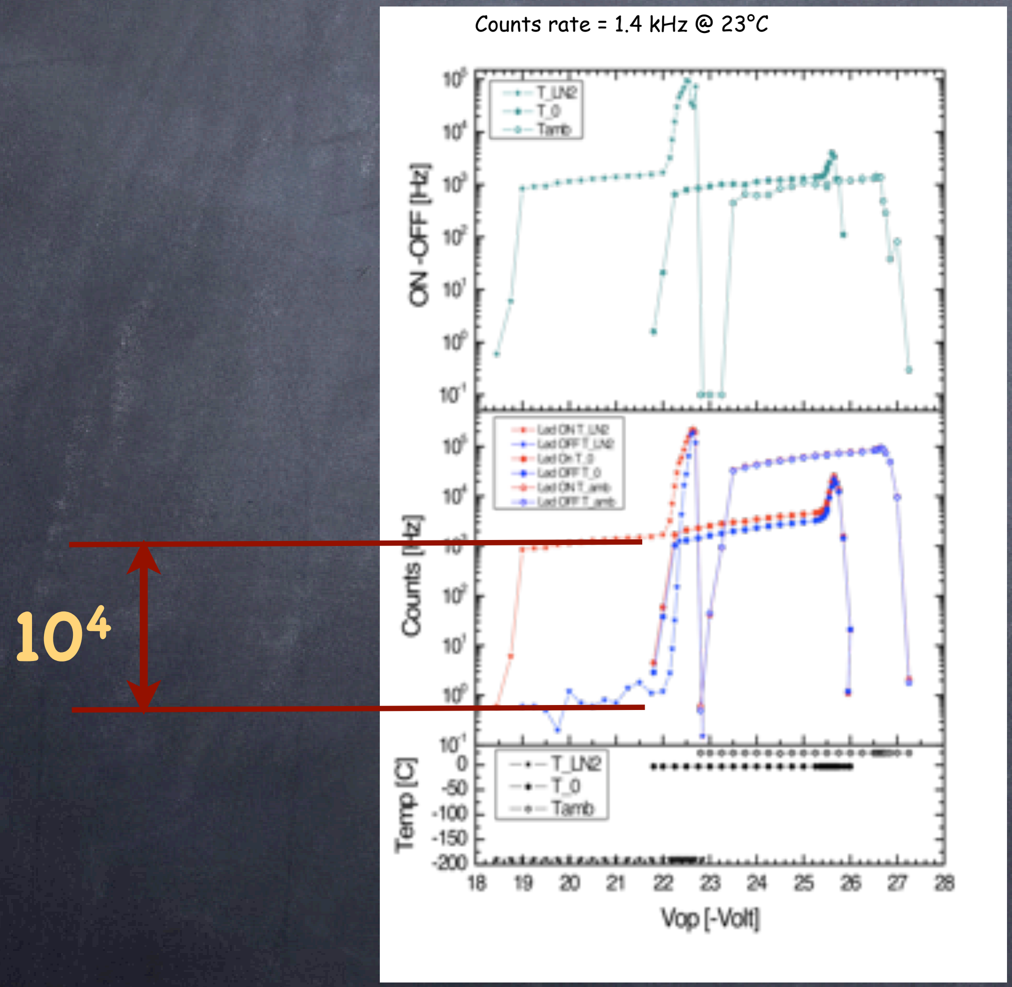
G-APD – idQuantique
DCR @ 23°C = 80 kHz
dia. 50μm

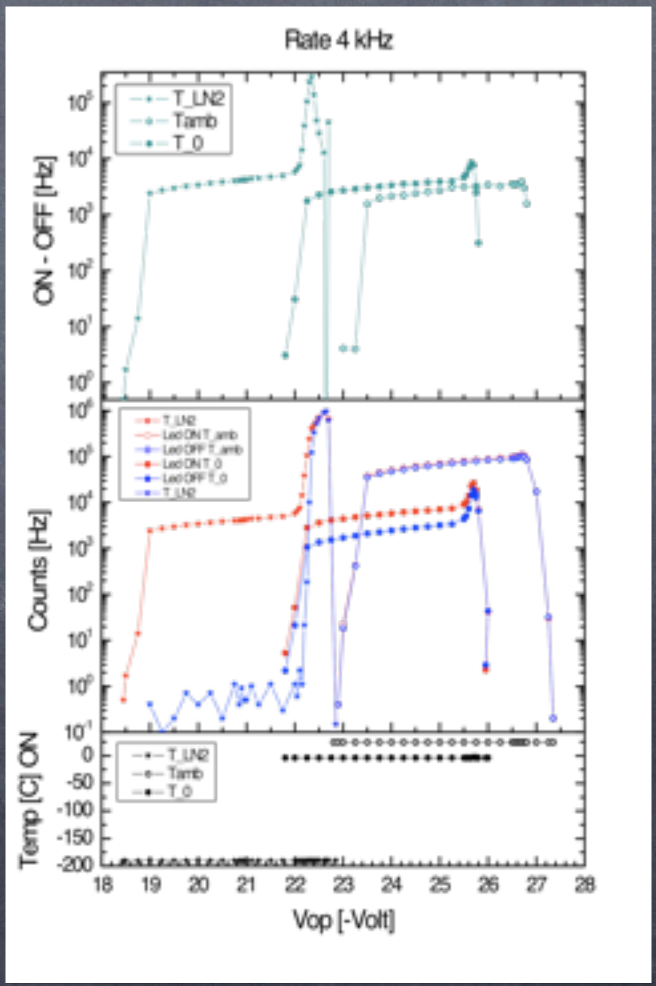
Thermocouple to monitor
cold finger temperature

BaRBE_LT preliminary results

- Test conducted on chips having a room temperature DCR of a few kHz
- A background reduction of a factor 10^4 is observed at low temperature, while the quantum efficiency remains unaffected

(G. Cantatore, M. karuza, V. Lozza and G. Raiteri, "Search for solar Axion Like Particles in the low energy range at CAST.", Nucl. Inst. and Meth. A (2009))





BaRBE_LT: status and beyond...

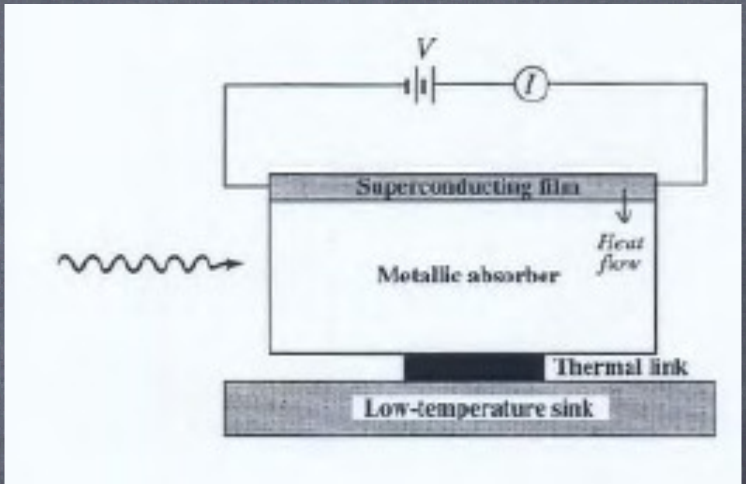
- The goal of developing a prototype of a low-background single-photon-counting system for experiments with a low rate of expected signal photons has been basically attained
- A permanent coupling based on a fiber optic, a telescope and a semitransparent mirror has been installed on CAST; the system includes a light source for alignment purposes
- The preliminary tests at low temperature with APD-type sensors are very encouraging
  - APDs from different manufacturers will be tested at LN2 temperature with active or passive quenching
- New developments -> the recent addition of new collaborators from the University of Camerino with cryogenics expertise opens the way towards the ultimate low background detectors: Transition Edge Sensors

TES based future developments

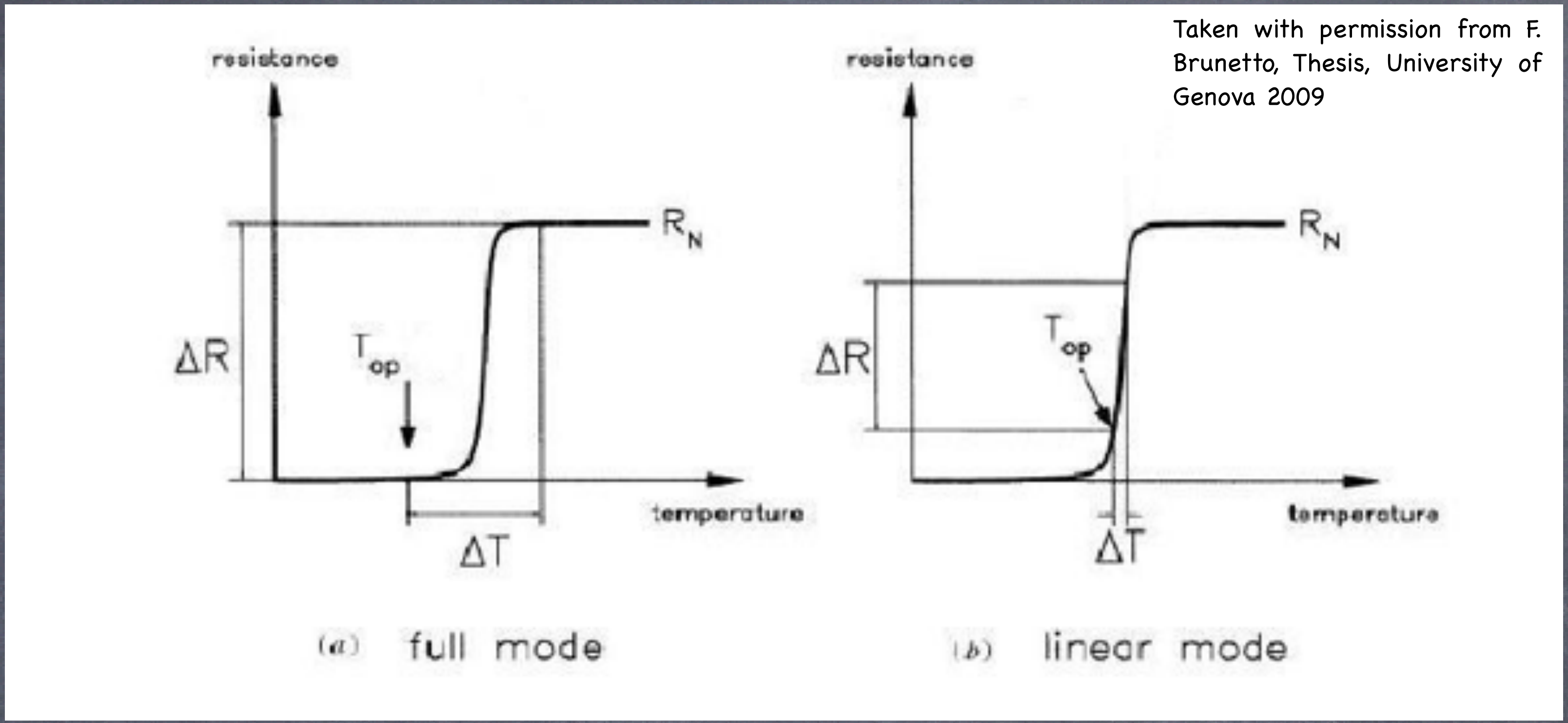
- Transition Edge Sensors (TES) hold the promise of becoming the detectors of choice for WISP searches and many other applications where low background, single-photon counting capability and high energy resolution are required
  - VERY LOW background (< 1 mHz and possibly even lower)
  - single-photon counting capability
  - can be optimized for specific wavelengths in a wide range from < eV up to several keV
- Main drawbacks
  - relatively small active area (typically 100x100 μm^2)
  - need ultracyogenic environment (T around 100 mK)

TES working principle

- Incident energy heats an absorber
- A thin film at the transition temperature between normally-and super-conducting measures the temperature change of the absorber
- The thin film (the actual TES) is biased by a voltage: a change in its resistance is sensed as a change in current with amplitude proportional to the energy deposited in the absorber
- At the end of an event the absorber slowly thermalizes towards an heat-sink



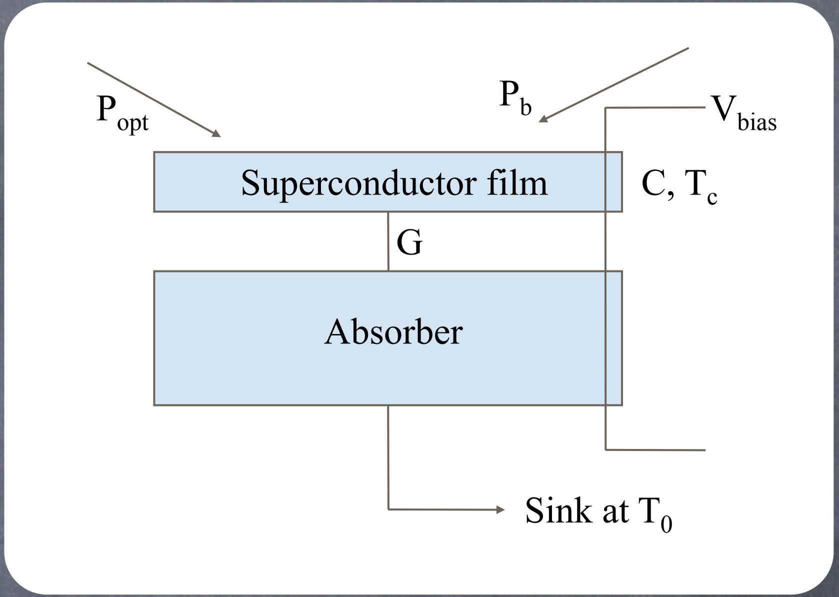
TES transition curve



- In full mode the temperature change ΔT of the absorber is such that the resistance changes fully from zero to normal almost independently of the incdent energy -> equivalent to a Geiger counter
- In linear mode ΔT is proportional to ΔR and therefore to the incident energy -> the detector operates as a calorimeter
- The choice of mode is done by setting the operating temperature T_{op} and by dimensioning the absorber to undergo a certain ΔT in response to a given incident energy

Electro-Thermal Feedback

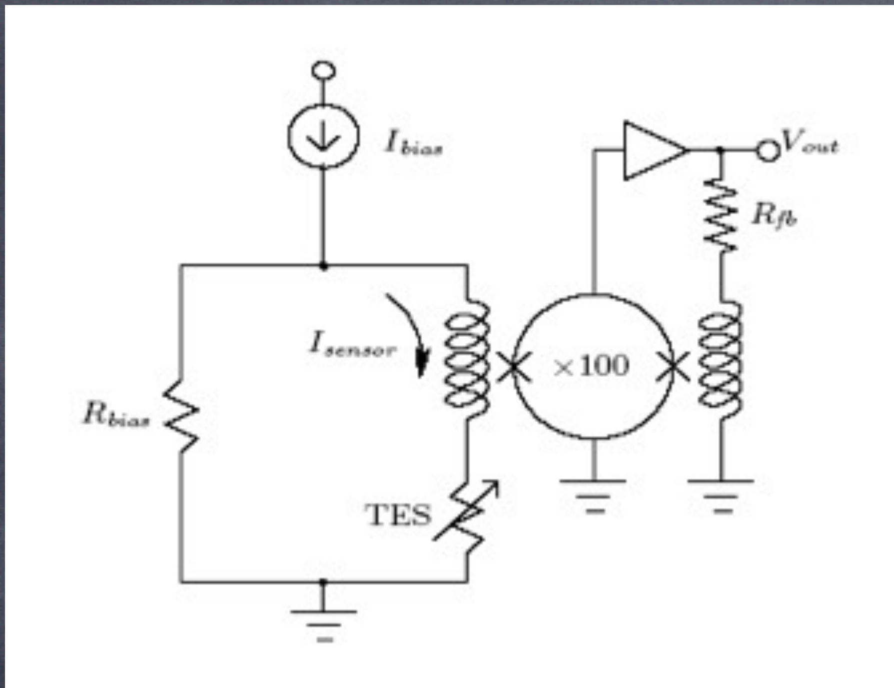
- The power absorbed by the sensor is the sum on the incident radiation power and of the Joule heating power due to the bias $P = P_{opt} + P_b$
- The temperature of the sensor is given by $T = T_0 + C/G$, where C is the thermal capacity and G the thermal conductance
- If the sensor is biased at a constant voltage V, then $P = V^2/R$, therefore
  - increase in T -> increase in R -> decrease in P -> decrease in T -> decrease in R -> increase in P -> increase T -> .....
  - the system reaches stability
- This is called Negative Electro Thermal Feedback (NETF)



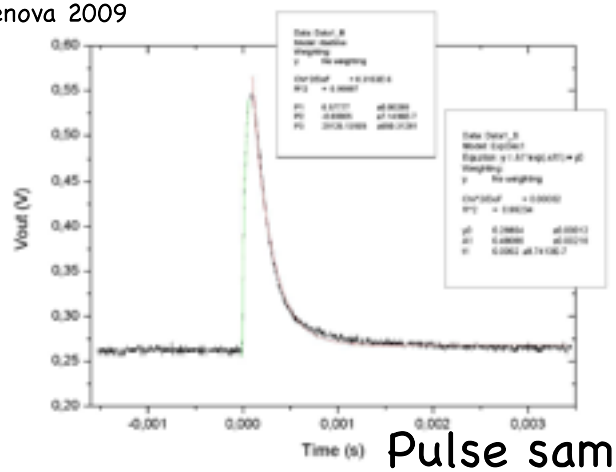
- In a NETF state the heat flow between film and ansborber is kept constant and temperature changes can be read quickly without the need to wait for the absorber to thermalize

Thursday, July 8, 2010

TES voltage bias



Taken with permission from F. Brunetto, Thesis, University of Genova 2009

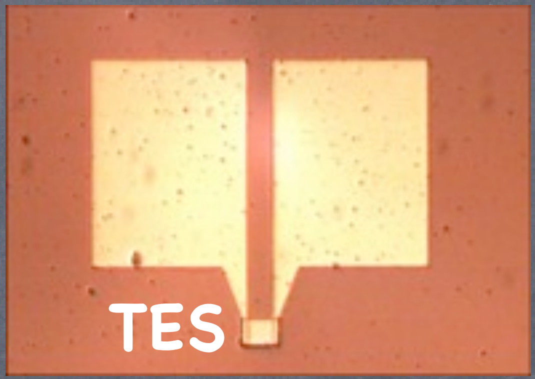


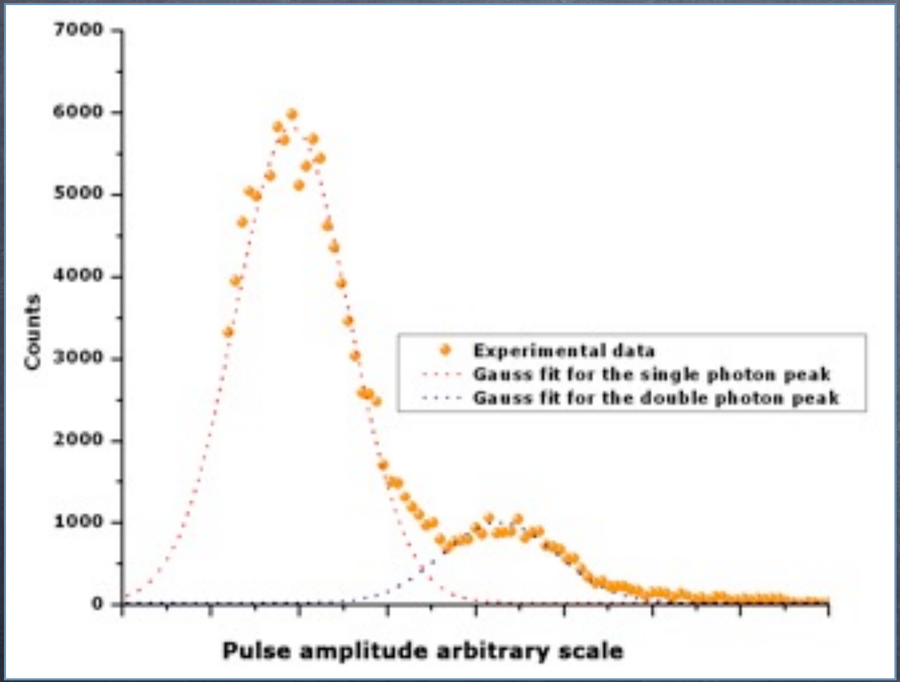
Pulse sample

- The TES is biased by a constant voltage applied in parallel to a shunt resistance R_{bias} (typically < 0.5 Ω)
- When the TES resistance changes in response to an energy deposition event, the current through the sensor decreases and this negative pulse is detected by a SQUID and converted to an output voltage pulse
- The total energy deposited is given by the time-integral of $I_{sensor}(t)$

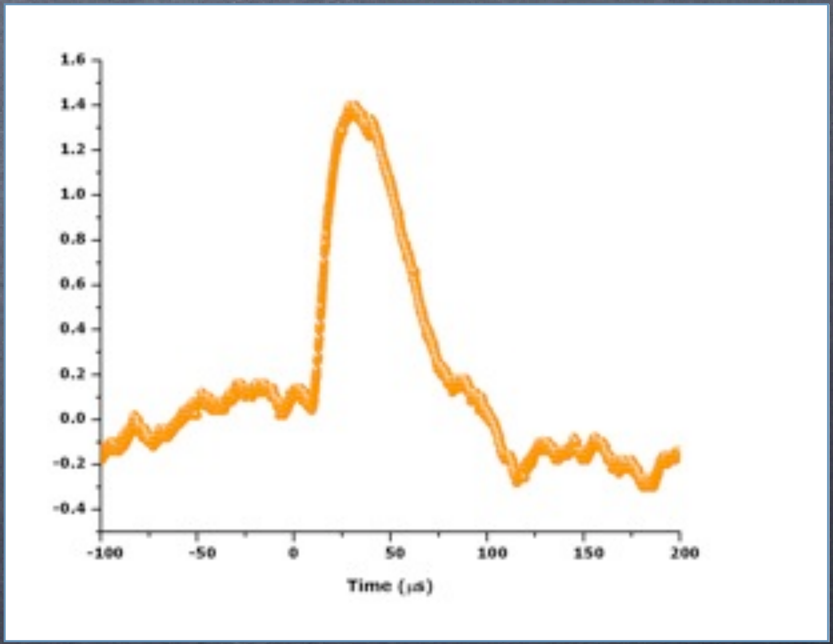
TES prototype preliminary results from INFN-Genova

- Measurements by the INFN-Genova group on a TES prototype detector sensitive at 1-2 eV (from D. Bagliani et al. , Journal of Low Temperature Physics, vol. 151 (1) (2008)pp. 234-238)





Single photon peak



Pulse shape sample

BaRBE_LT plans

- Quickly set up a cooled APD sensor at CAST exploiting the "dual port" capability
- Launch a program Trieste-Camerino and secure funds from INFN to
  - acquire from INFN-Genova TES sensor chips sensitive at 1-10 eV (initially 1-2 eV), mount them in the Camerino dilution refrigerator with SQUID-based electronics and characterize their performance
  - optically couple the sensors with sources and measure both light collection efficiency and detector background over long time periods
  - make the sensors available to laboratory and observatory searches (ALPS and CAST)

Conclusions

- The field of WISP searches is gathering momentum in the US and in Europe as a particle physics program complementary to accelerator searches
- Advanced optics and low background photon detectors sensitive in the low energy range (1-10 eV) are essential components for laboratory-based searches (ALPs) and valuable tools for observatories (CAST)
- TES sensors are poised to become important players in this field and are the ideal detectors for many other applications at several different wavelengths (for instance quantum cryptography, remote sensing and nuclear measurements)
- Mastering TES sensor operation and technology could impact directly on possible discoveries in particle physics and cosmology

The future is in the cold….