Title: When the table-top experiments need the ultracryogenic tons dimension: a personal/experimental remarks

Date: Aug 25, 2017 11:00 AM

URL: http://pirsa.org/17080037

Abstract:

Who I am:

1) 2000-2016 cryogenic responsible of AURIGA and after retirement of Cerdonio PI (2011-2016)
2) 2009-NOW responsible of Dilution Refrigerator of Cuore (Double Beta Decay  experiment)

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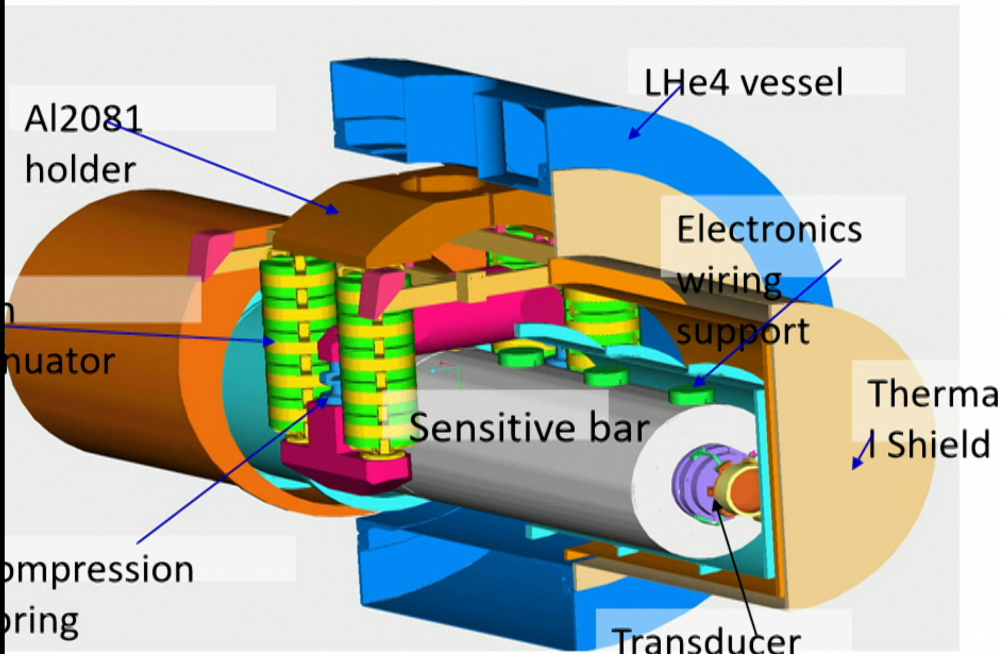

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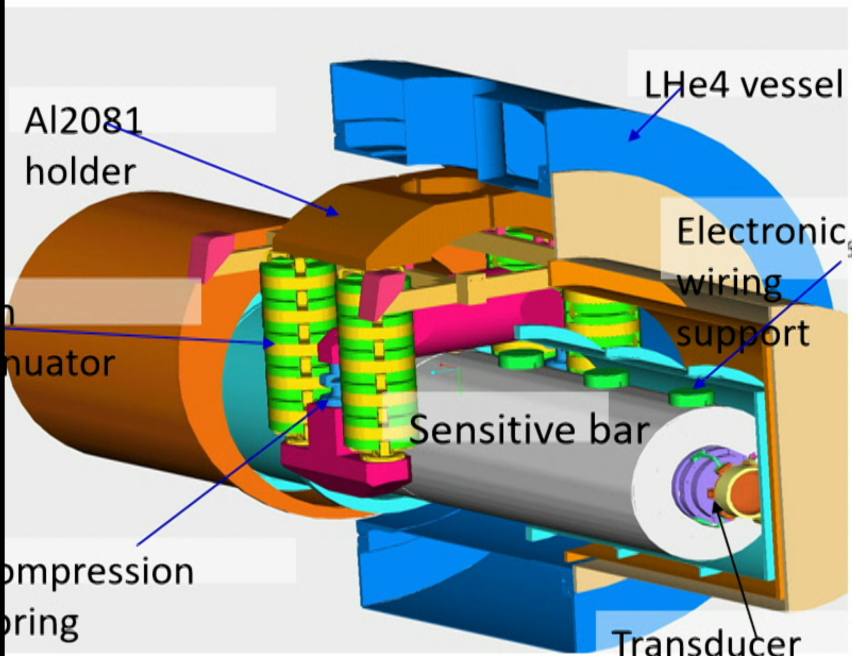


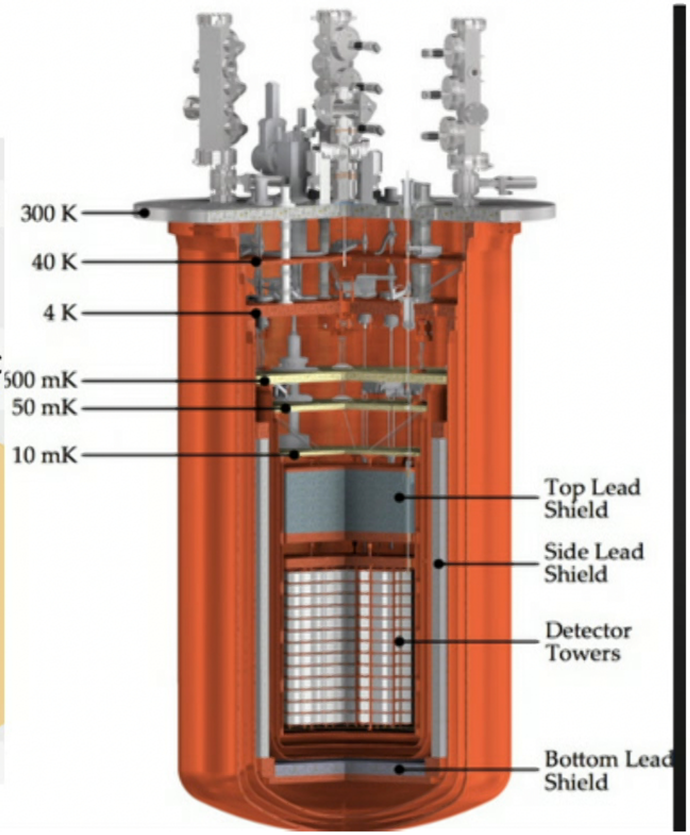

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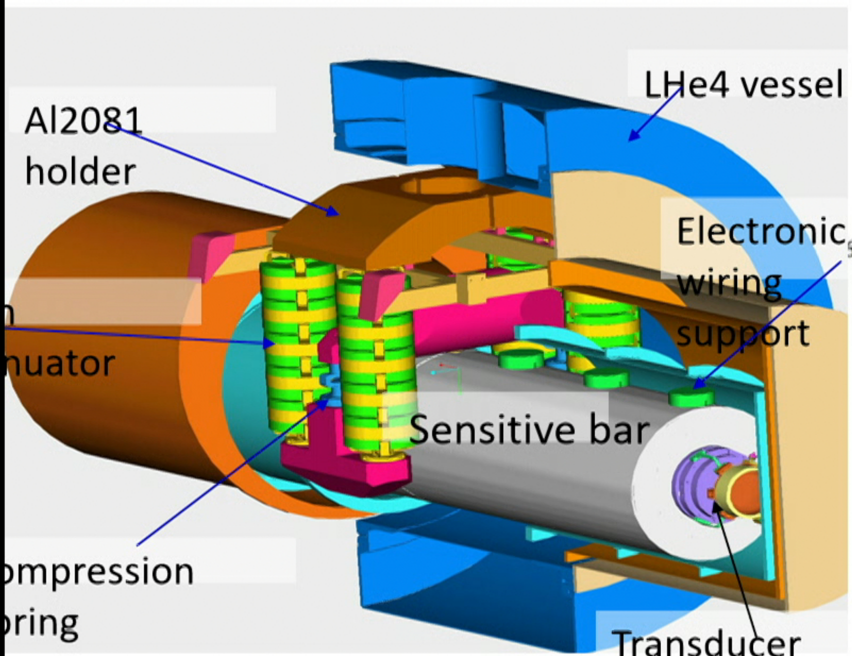
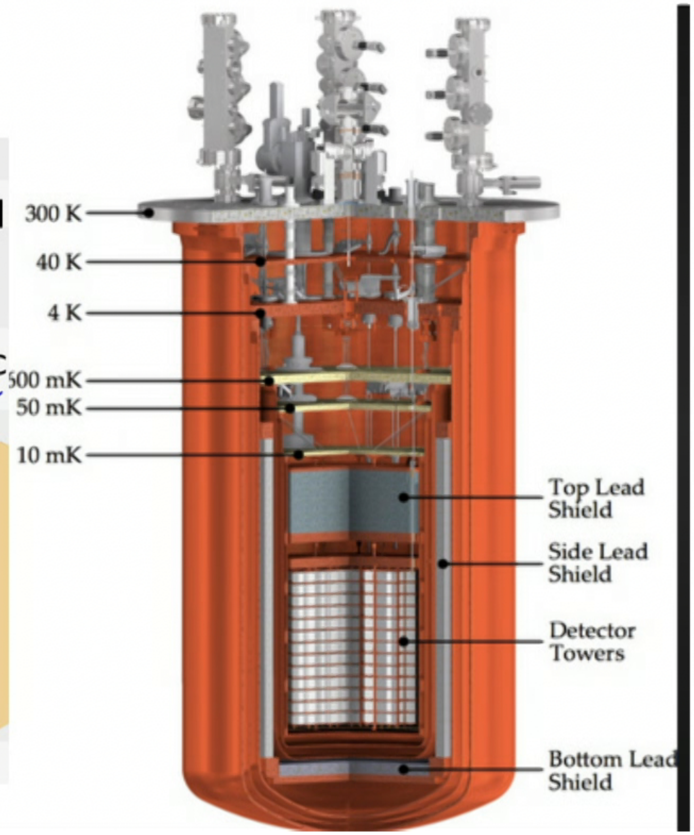
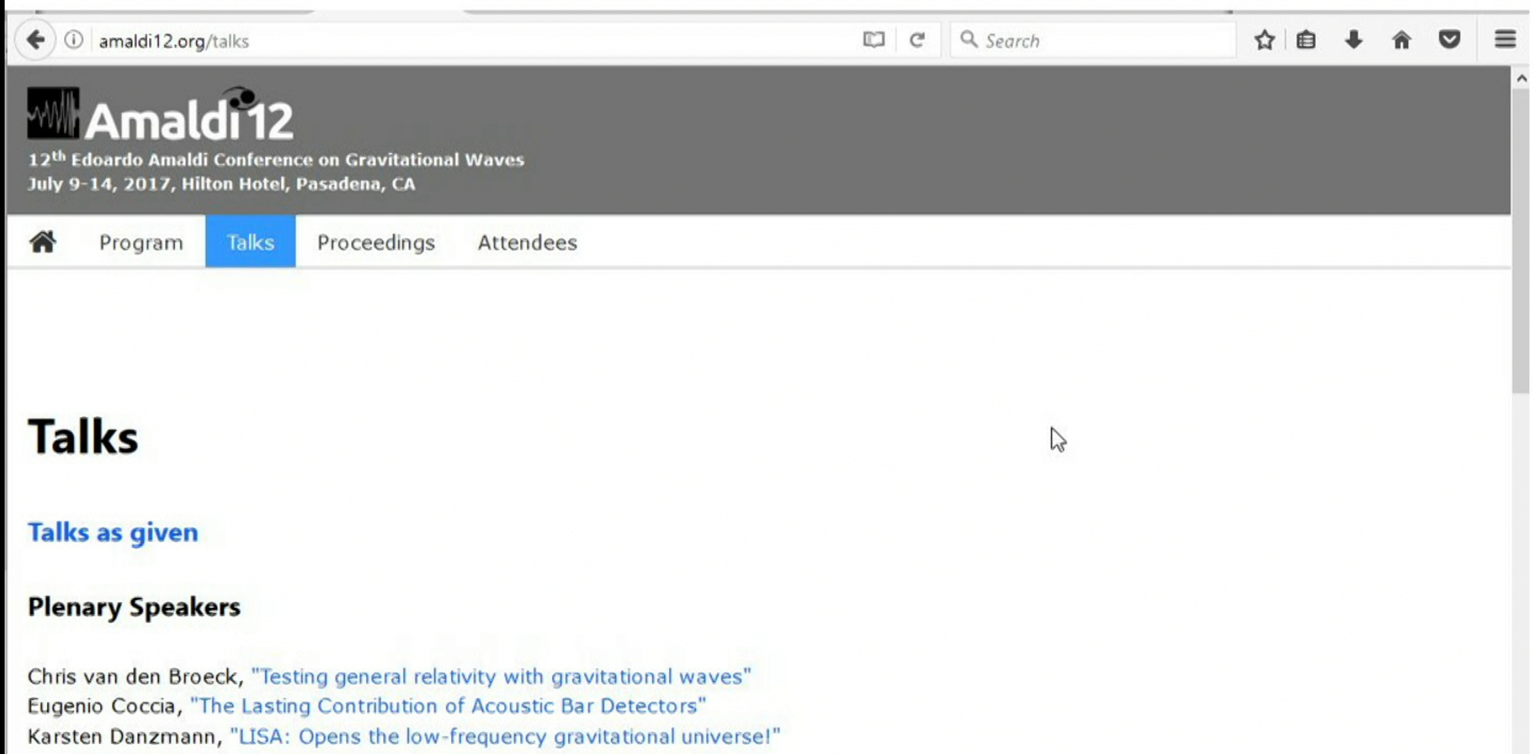
**NOT Exactly Table-Top experiments**



## To know some historical aspects of acustic GW detectors watch the slides of this Coccia's talk



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amaldi12.org/talks

**Amaldi12**

12th Edoardo Amaldi Conference on Gravitational Waves
July 9-14, 2017, Hilton Hotel, Pasadena, CA

Program | Talks | Proceedings | Attendees

## Talks

**Talks as given**

### Plenary Speakers

Chris van den Broeck, "Testing general relativity with gravitational waves"
Eugenio Coccia, "The Lasting Contribution of Acoustic Bar Detectors"
Karsten Danzmann, "LISA: Opens the low-frequency gravitational universe!"

# UltraCryogenic tons Apparatus evolution

**AURIGA** **CUORE**

# UltraCryogenic tons Apparatus evolution

| | AURIGA | | CUORE |
|---|---|---|---|
| Tbase (work point) | 65(200) | mK | 7(16) |

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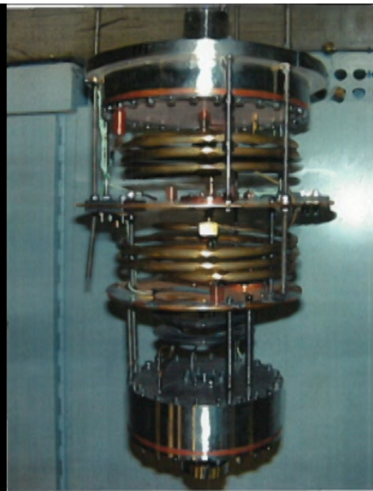

# ryogenic tons A lution

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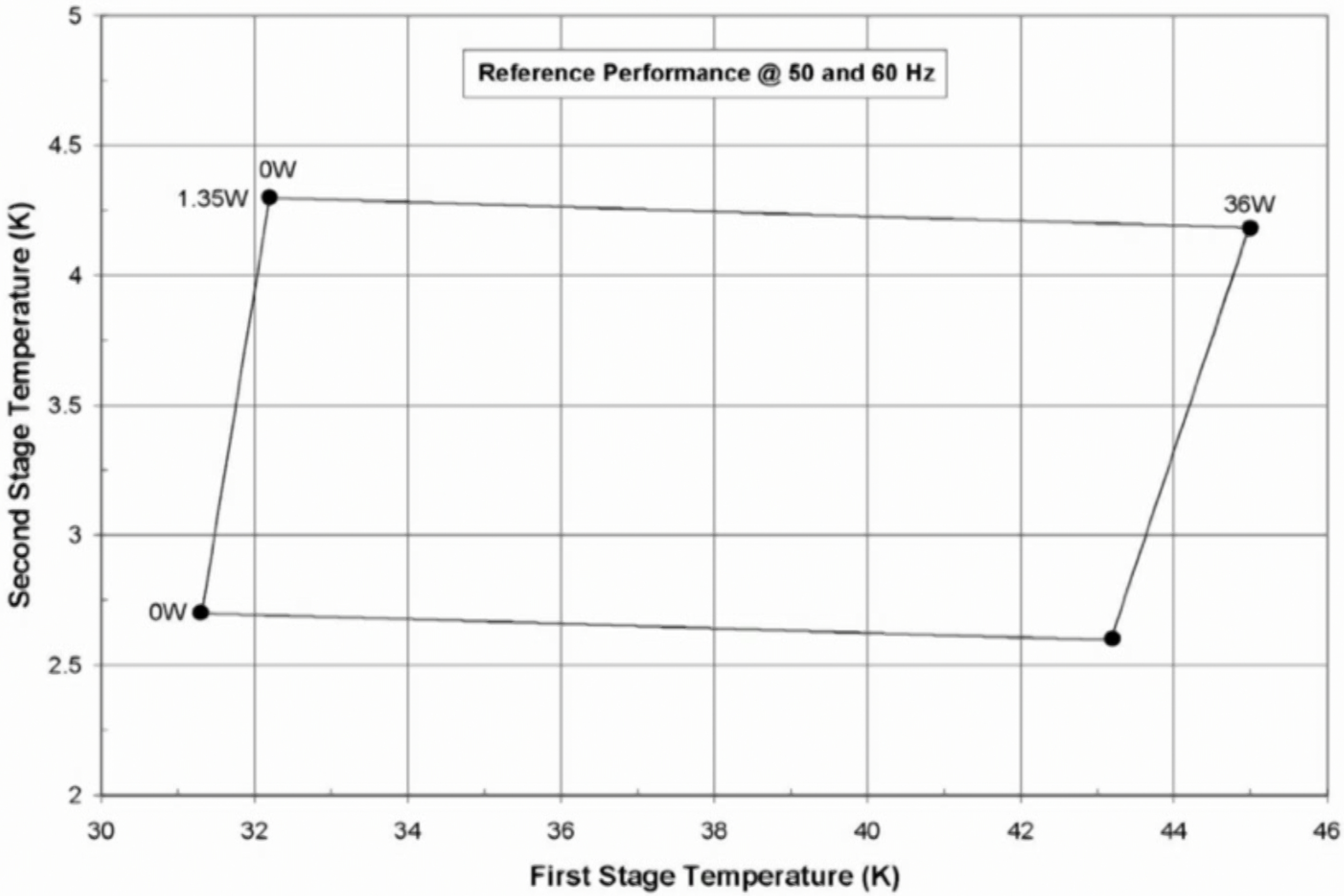
PT tech: true revolution
Isoenthalpic Process, not reversable



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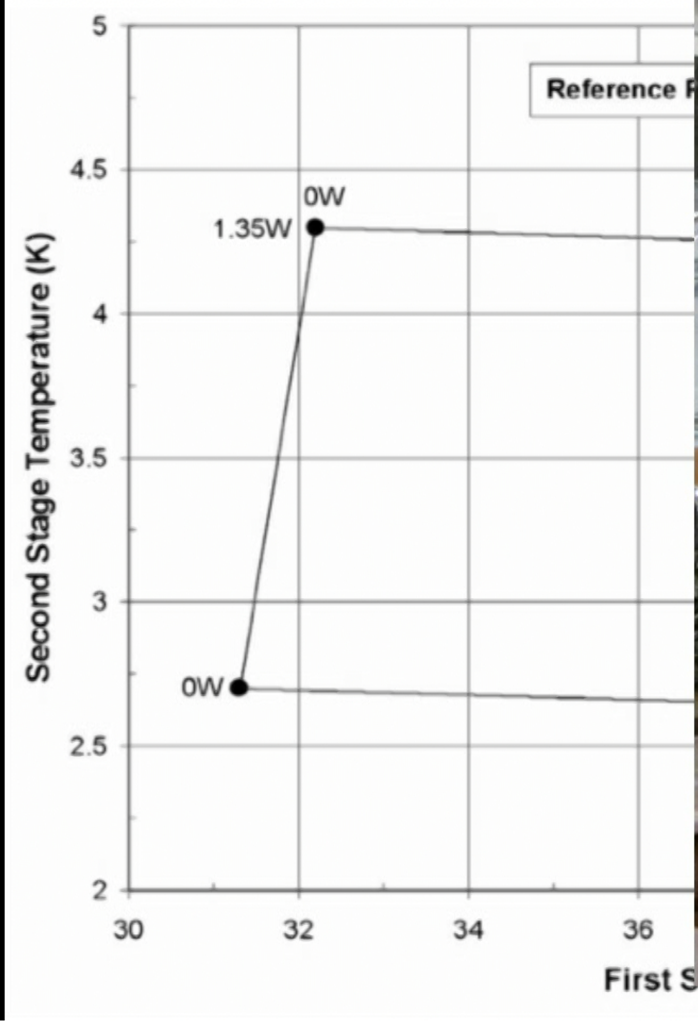
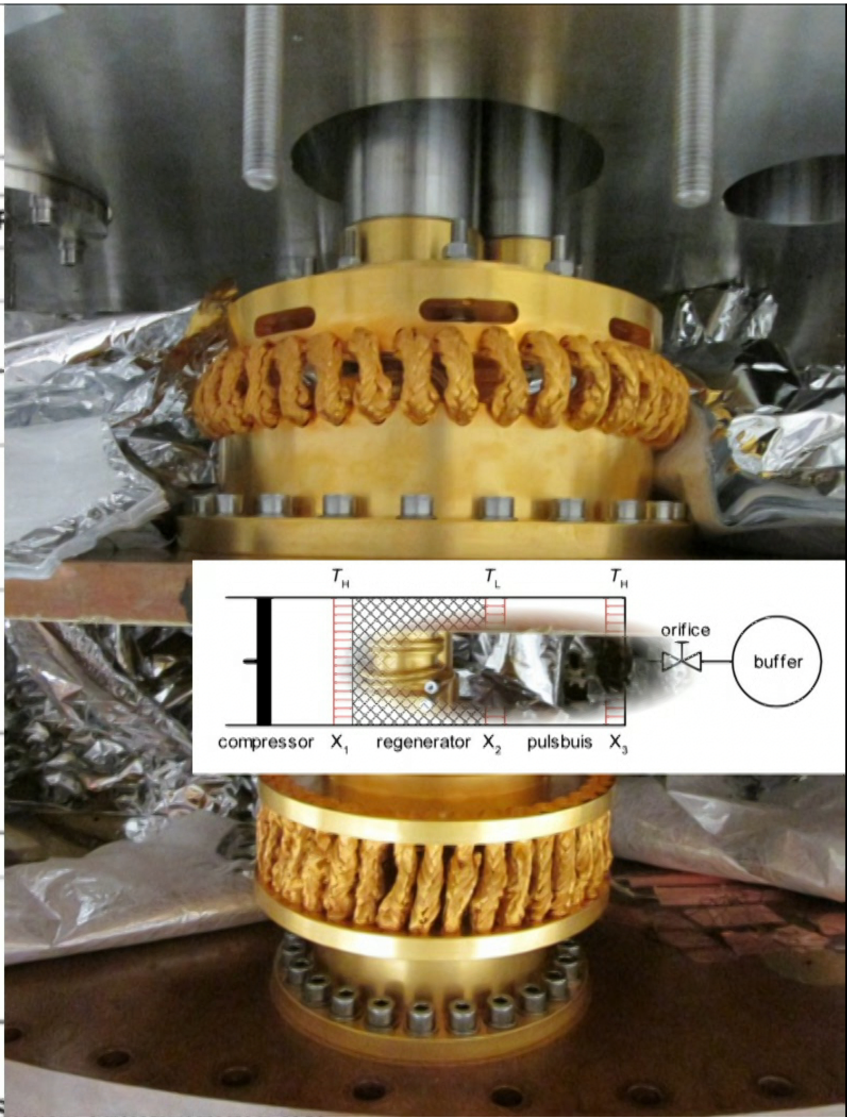
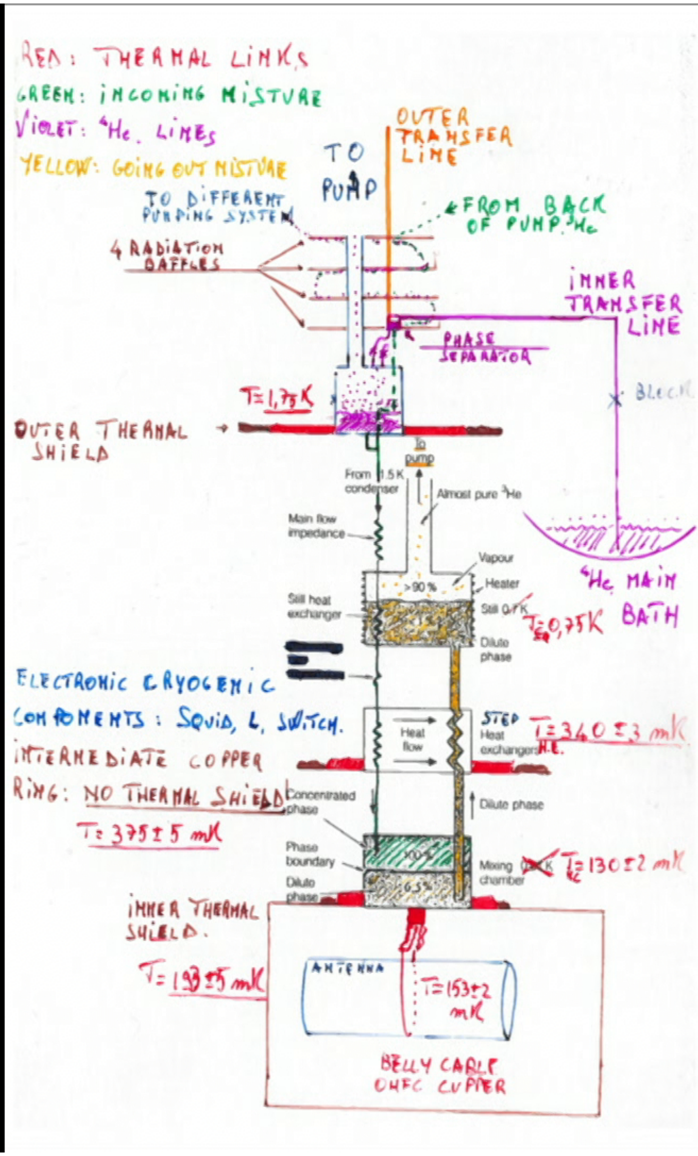
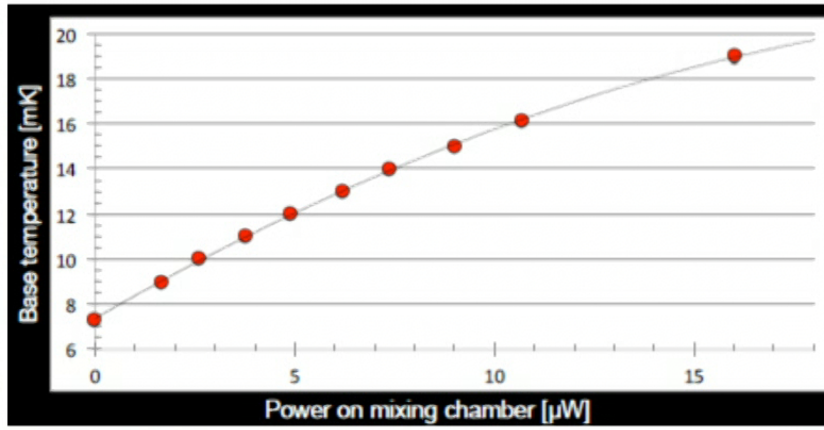



RED: THERMAL LINKS
GREEN: INCOMING MISTURE
VIOLET: 4He LINES
YELLOW: GOING OUT MISTURE
TO DIFFERENT PUMPING SYSTEM
TO PUMP
OUTER TRANSFER LINE
FROM BACK OF PUMP 4He
4 RADIATION BAFFLES
INNER TRANSFER LINE
PHASE SEPARATOR
T=1,75K
OUTER THERMAL SHIELD
To pump
From 1.5 K condenser
Almost pure 3He
Main flow impedance
Vapour
Heater
>90 %
Still heat exchanger
Still 0.7 K
Dilute phase
4He MAIN BATH
T=0,75K
ELECTRONIC CRYOGENIC COMPONENTS: SQUID, L, SWITCH.
INTERMEDIATE COPPER RING: NO THERMAL SHIELD
Heat flow
STEP Heat exchanger
T=340±3 mK
Concentrated phase
Dilute phase
T=375±5 mK
Phase boundary
Dilute phase
Mixing chamber
T=130±2 mK
INNER THERMAL SHIELD.
ANTENNA
T=153±2 mK
BELLY CABLE OHFC COPPER


Base temperature [mK]
20
18
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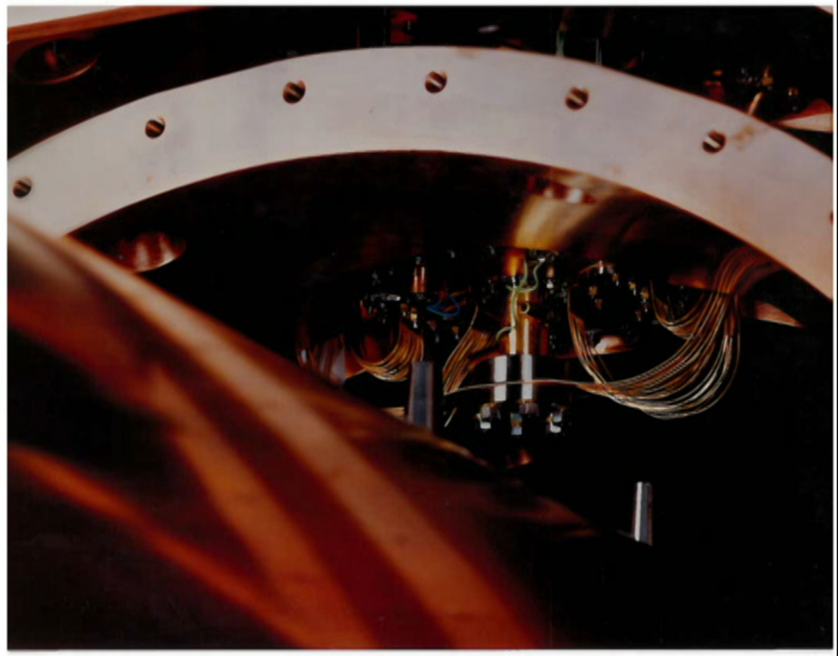
15
Power on mixing chamber [μW]



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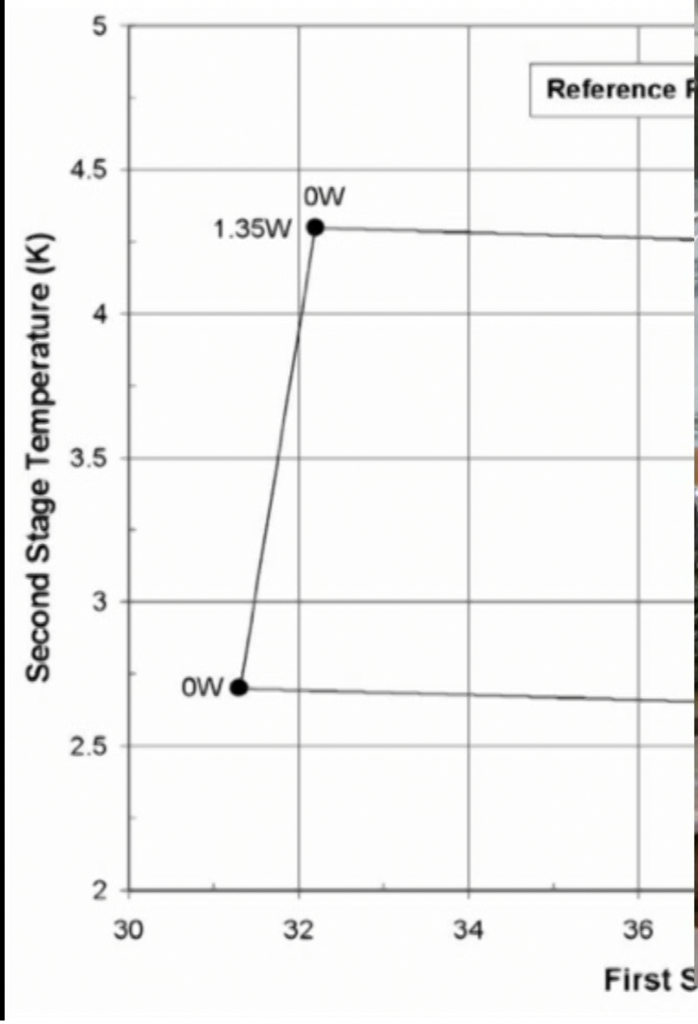


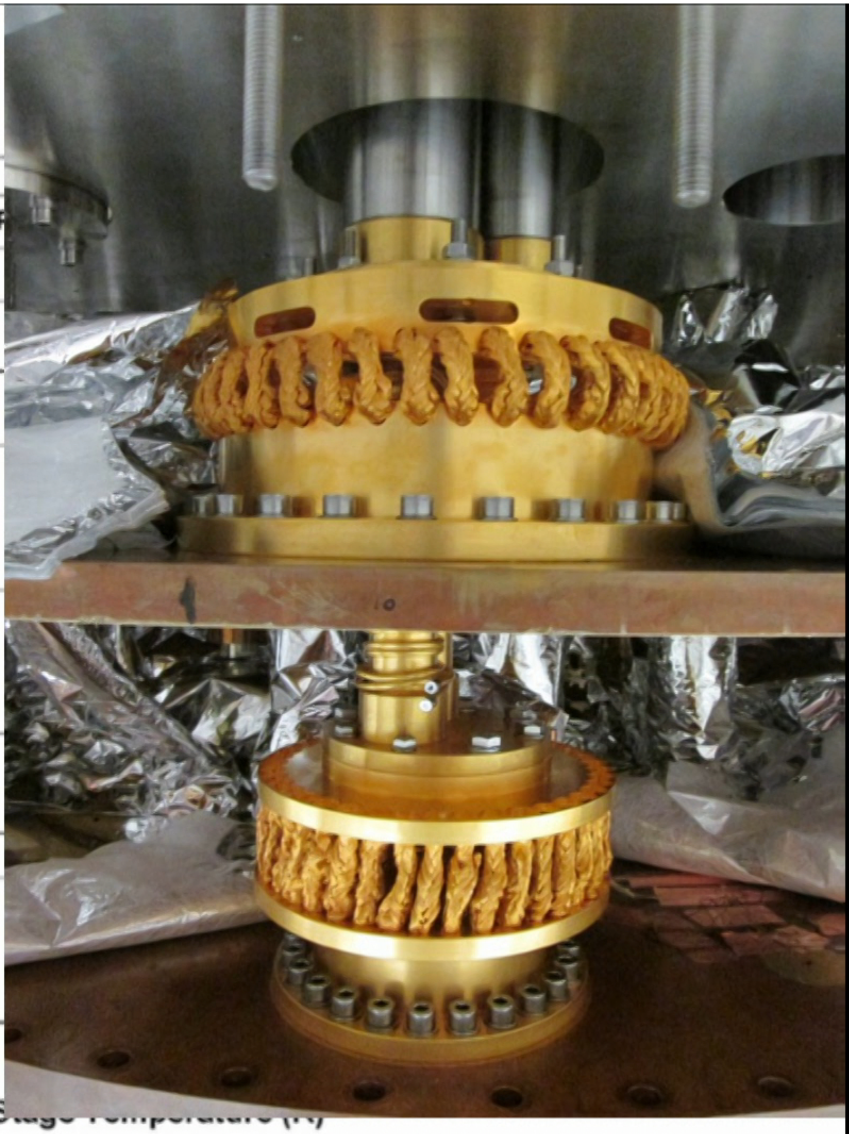

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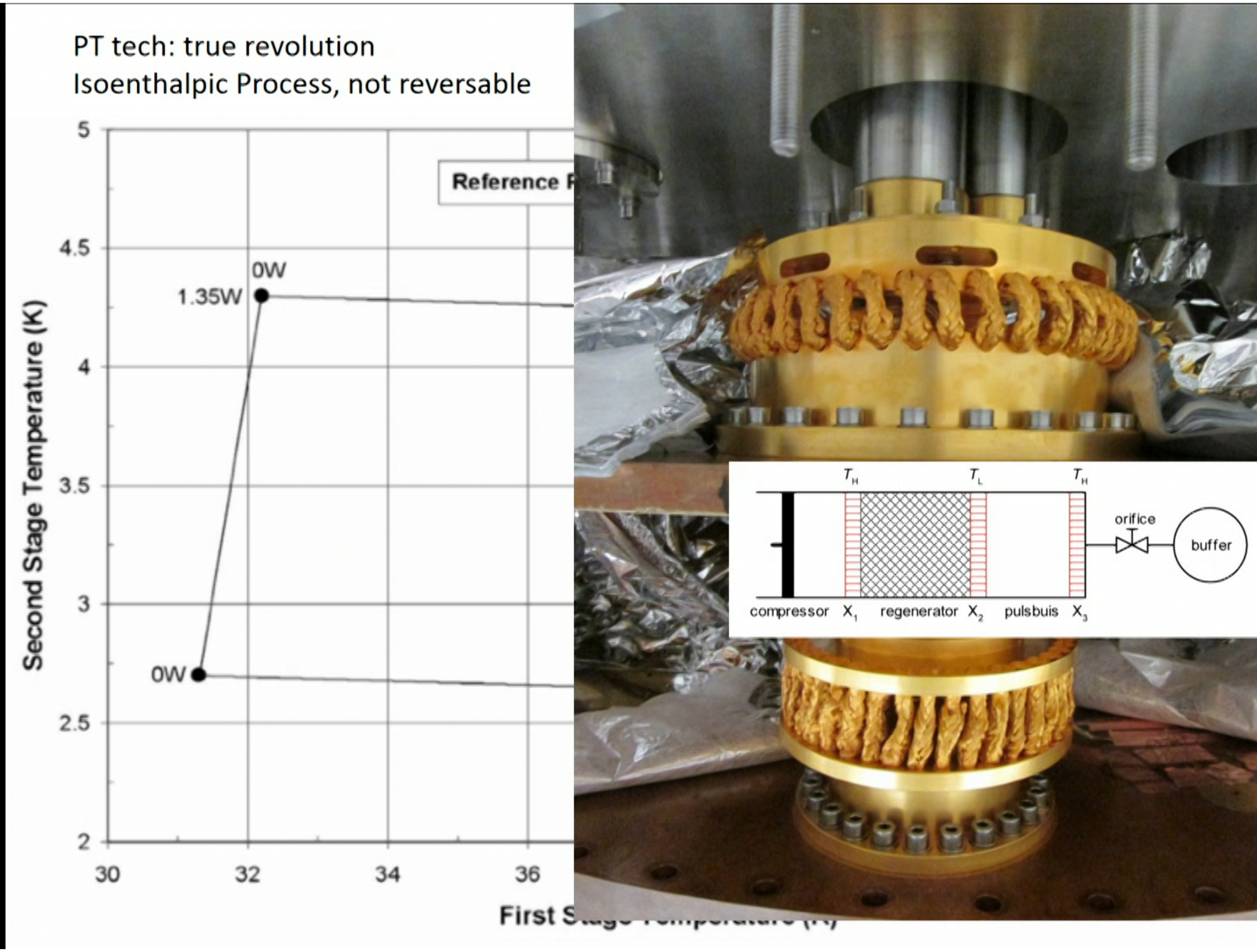

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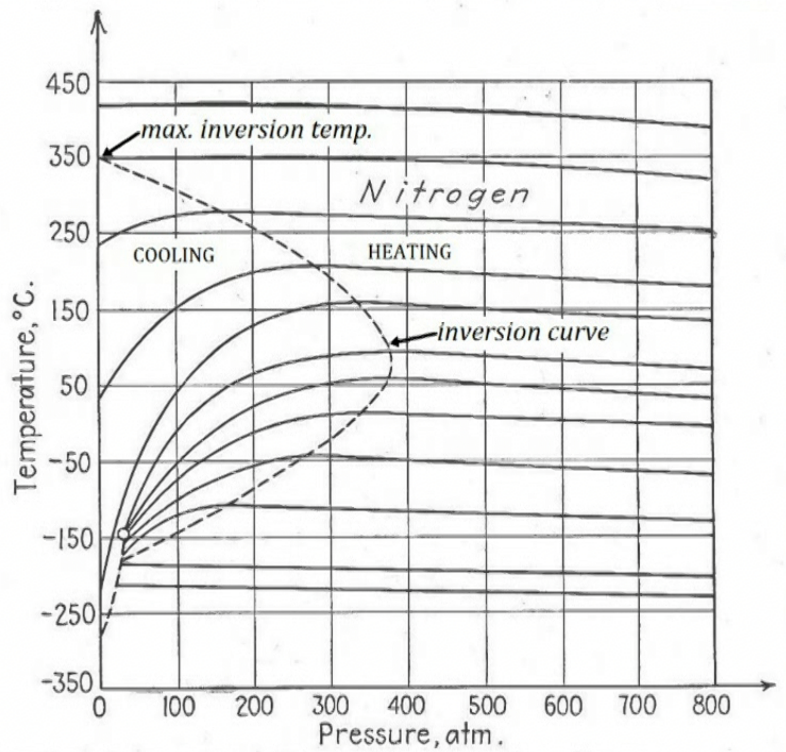
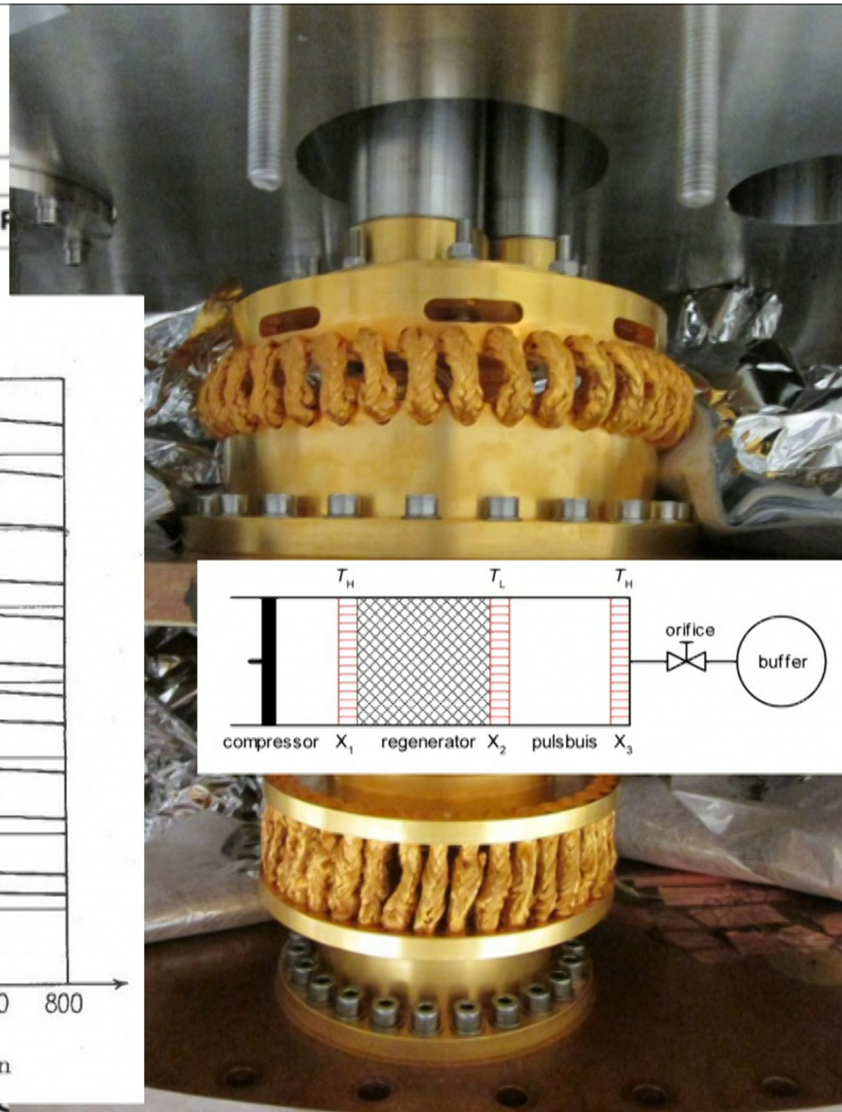
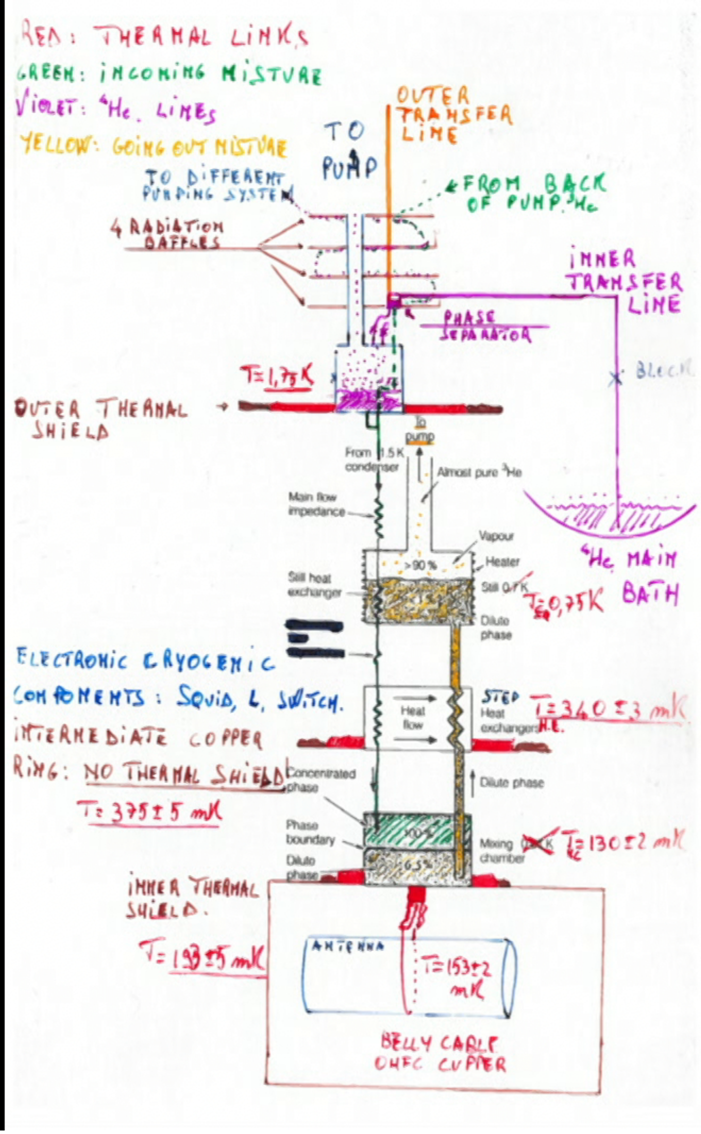


Isenthalpic curves and inversion curve for nitrogen

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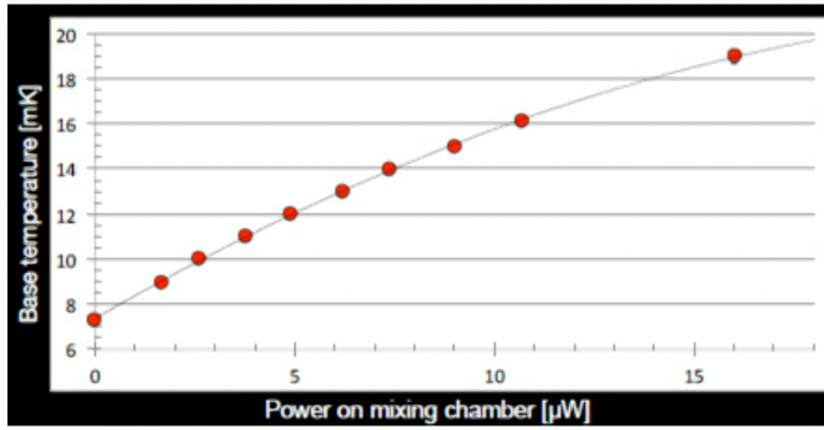
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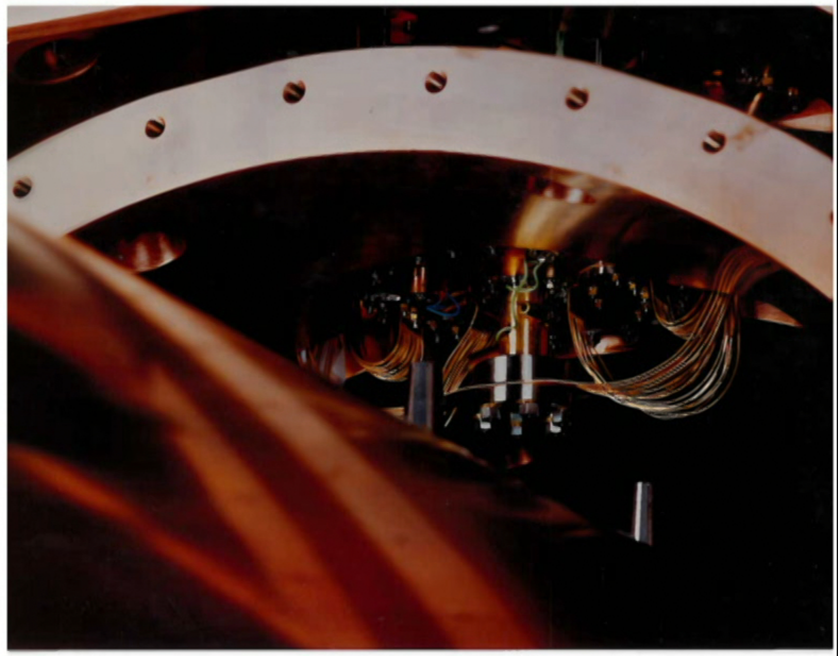

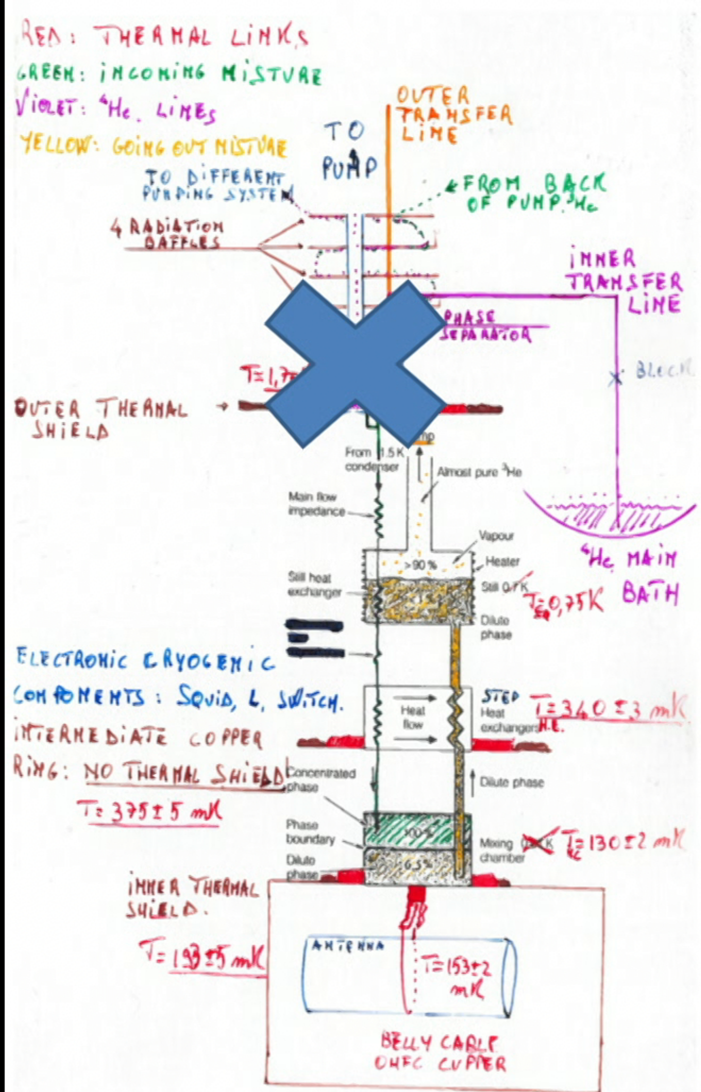
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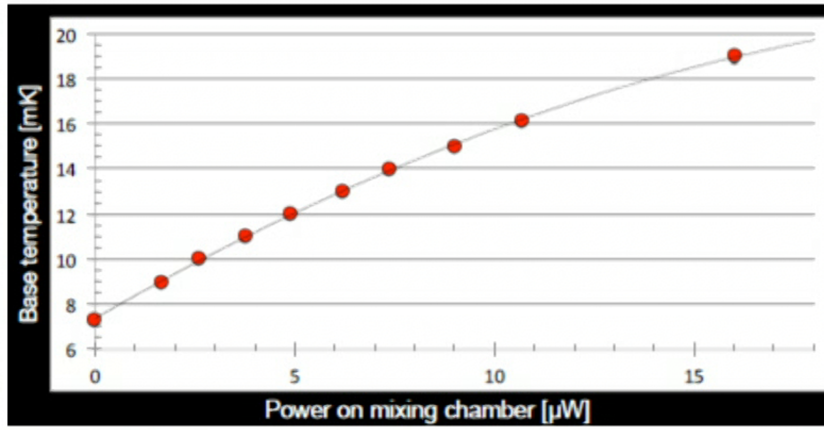
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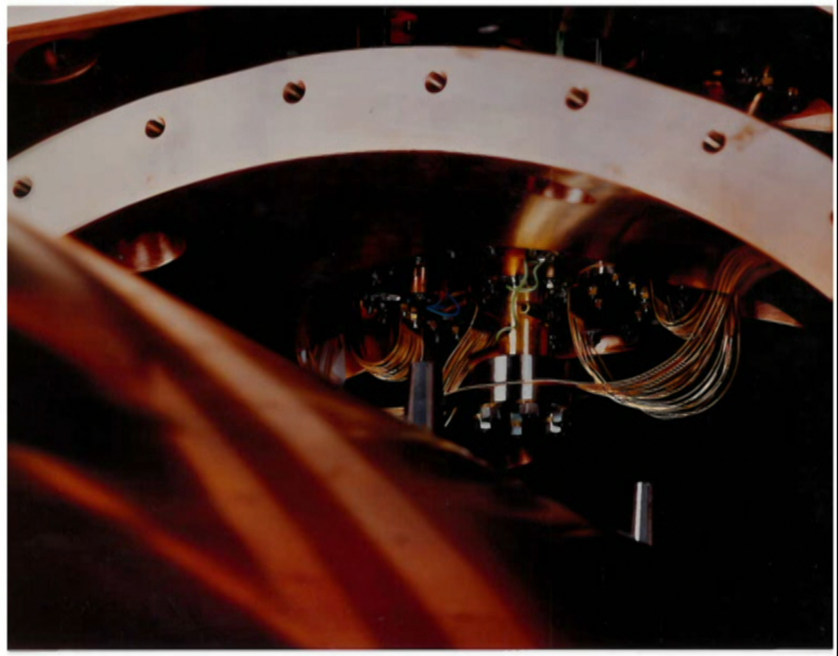
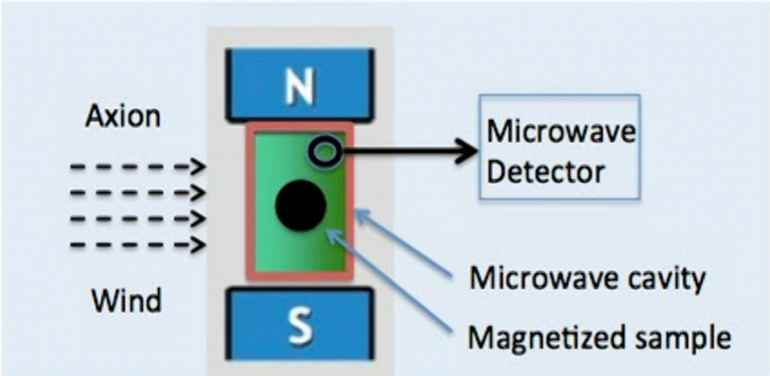


# 5 STORIES

| | | |
|---|---|---|
| 1. QUAX (QCD axion) | Table Top Exp | Just started |
| 2. Moduli vs AURIGA | Particles Data Book | Just done |
| 3. Cuore | Double Beta Decay Exp | Data Taking |
| 4. Planck length | 2012(Nature Physics) | Hard to explain |
| 5. Feedback Cooling | 2008 (PRL) | Emotional |

# The QUAX (QUest for AXion) Exp.

- **Due to the motion of the solar system** in the galaxy, the axion DM cloud acts as an **effective RF magnetic field on electron spin** via **electron-axion coupling**
- This field excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal
- **The interaction with axion field produces a variation of magnetization which is in principle measurable**




**The effective magnetic field associated with the axion wind**

$$B_a = \frac{g_p}{2e}\left(\frac{n_a h}{m_a c}\right)^{1/2} m_a v_E$$

$$B_a = 2.0 \cdot 10^{-22} \left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \;\; \mathrm{T},$$

$$\frac{\omega_a}{2\pi} = 48 \left(\frac{m_a}{200\,\mu\mathrm{eV}}\right) \;\; \mathrm{GHz},$$

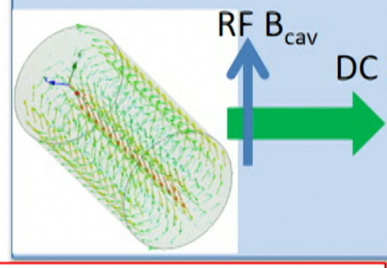
- R. Barbieri et al., *Searching for galactic axions through magnetized media: The QUAX proposal* Phys. Dark Univ. **15,** 135 - 141 (2017)

# QUAX: Axion induced rf emission

A **volume $V_s$ of magnetized material, strong coupled in a microwave resonant cavity,** will absorb energy from the axion wind and **re-emit as rf power**

**With magnetizing field**
**B0 = 1.7 T => 48 GHz**

**Resonant cavity**
**ωc, τc, Vc**




**YIG sphere (Ferrimagnet)**
**ωL = γ B0 , τ2, Vs**

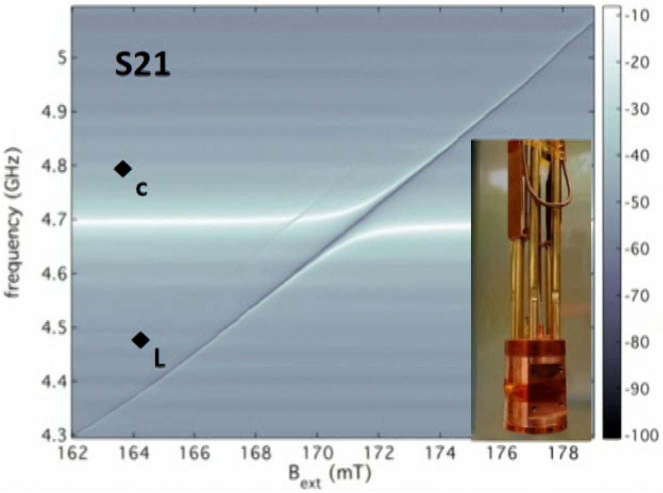
$$P_{\rm out} = \frac{P_{\rm in}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu{\rm eV}}\right)^3 \left(\frac{V_s}{100\ {\rm cm}^3}\right) \left(\frac{n_S}{2 \cdot 10^{28}/{\rm m}^3}\right) \left(\frac{\tau_{\rm min}}{2\,\mu{\rm s}}\right)\ {\rm W}$$

**R & D in progress**

**Niobium Cavity**

T = 300K
$f_c$ = 13.964 GHz
$Q_0$ = 5.0*10^3

T = 4.2K
$f_c$ = 13.960 GHz
$Q_0$ = 5.0*10^5



# QUAX needs 100mK

This is a WET DR
With 1 Kpot and
Liquid Helium reservoir

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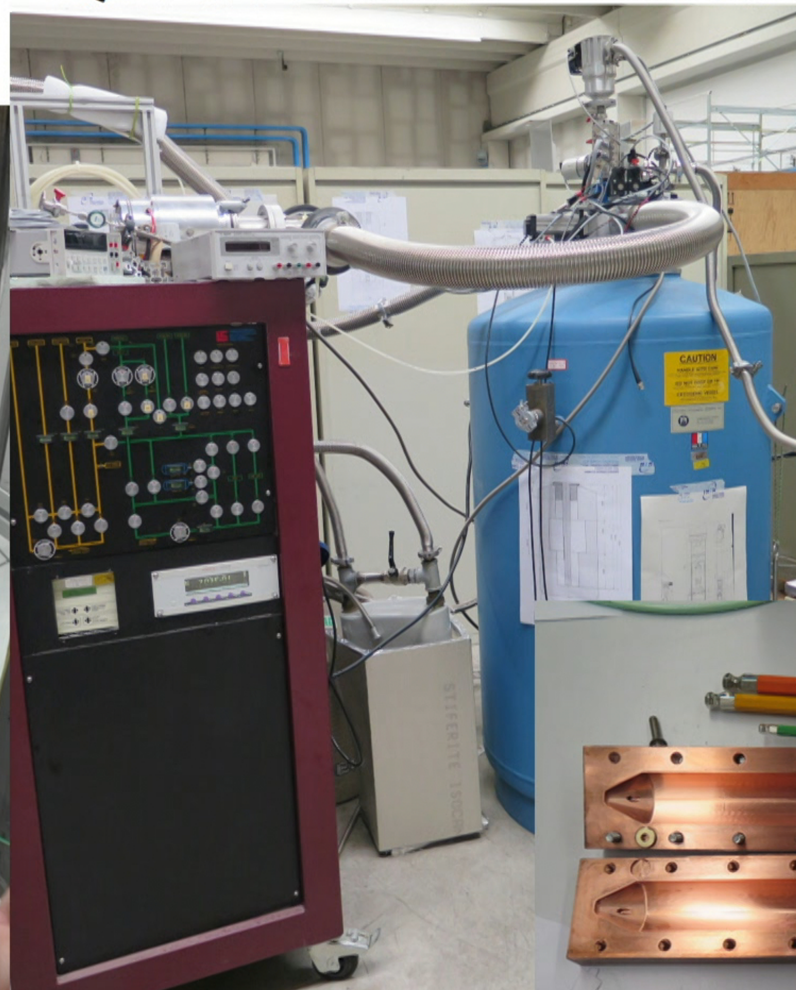

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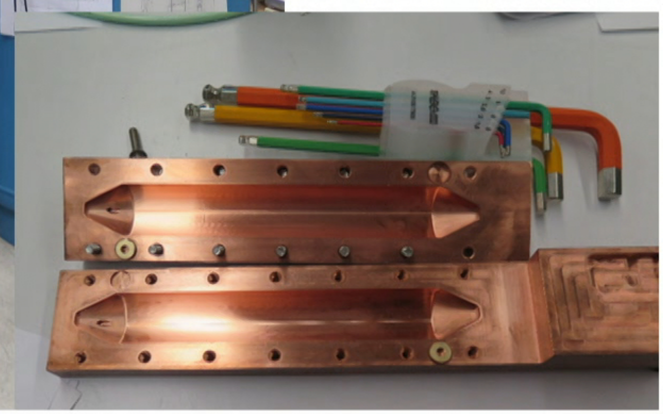

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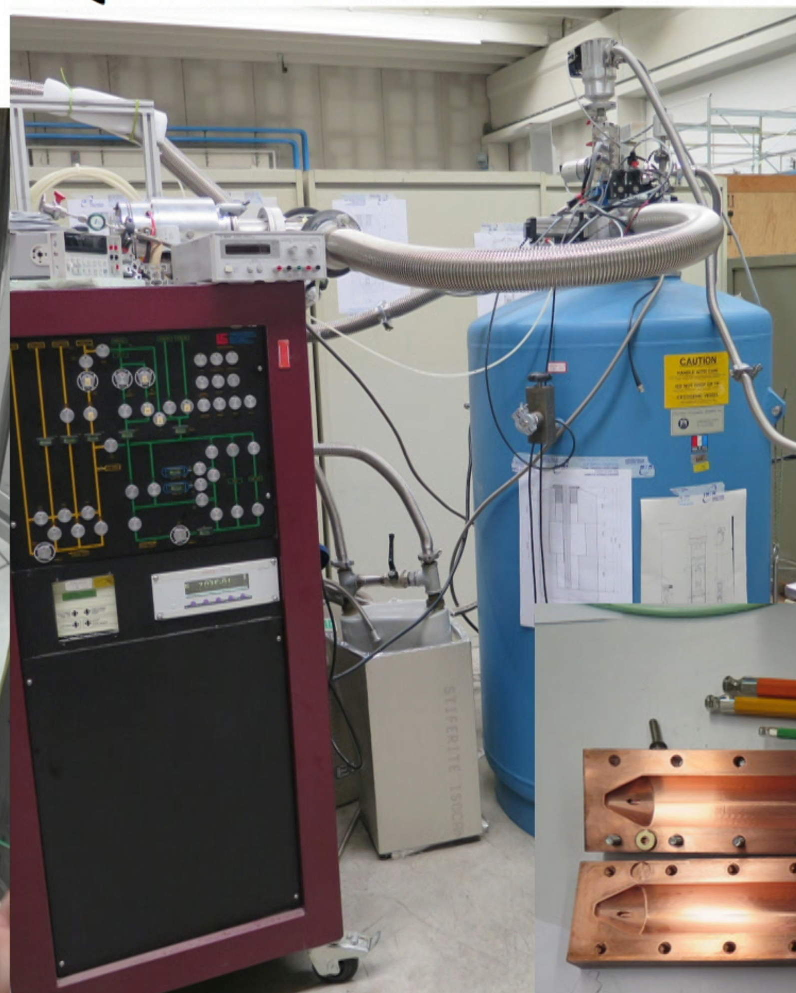
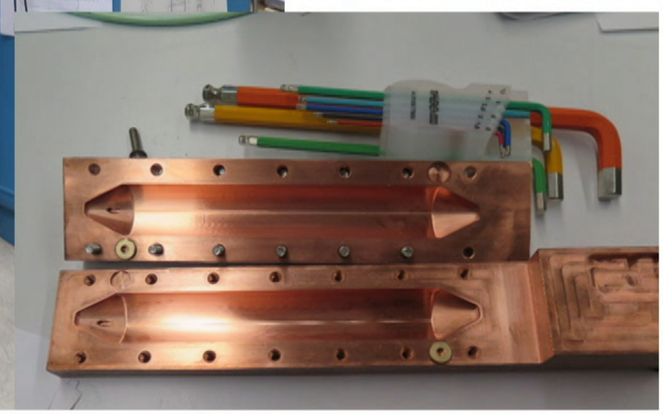


Base T= 19 mK
> 50μW @ 100mK
OK!
My CURRENT
Table Top Experiment
☺

This is a WET DR
With 1 Kpot and
Liquid Helium reservoir



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PRL **118,** 021302 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

## Search for an Ultralight Scalar Dark Matter Candidate with the AURIGA Detector

Antonio Branca,[1] Michele Bonaldi,[2,3] Massimo Cerdonio,[1] Livia Conti,[1] Paolo Falferi,[3,4] Francesco Marin,[5,6,7] Renato Mezzena,[3,8] Antonello Ortolan,[9] Giovanni A. Prodi,[3,8] Luca Taffarello,[1] Gabriele Vedovato,[1] Andrea Vinante,[4] Stefano Vitale,[3,8] and Jean-Pierre Zendri[1]

[1]*INFN, Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy*
[2]*Institute of Materials for Electronics and Magnetism, Nanoscience-Trento-FBK Division, I-38123 Trento, Italy*
[3]*TIFPA—INFN, c/o Dipartimento di Fisica, Universitá di Trento, Via Sommarive 14, 38123 Povo, Trento, Italy*
[4]*Istituto di Fotonica e Nanotecnologie, CNR—Fondazione Bruno Kessler, I-38123 Povo, Trento, Italy*
[5]*Dipartimento di Fisica e Astronomia, Universitá di Firenze, Via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy*
[6]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Firenze, Via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy*
[7]*European Laboratory for Non-Linear Spectroscopy (LENS), Via Carrara 1, I-50019 Sesto Fiorentino (FI), Italy*
[8]*Dipartimento di Fisica, Universitá di Trento, I-38123 Povo, Trento, Italy*
[9]*INFN—Laboratori Nazionali di Legnaro, I-35020 Legnaro (PD), Italy*

(Received 28 July 2016; published 12 January 2017)

A search for a new scalar field, called moduli, has been performed using the cryogenic resonant-mass AURIGA detector. Predicted by string theory, moduli may provide a significant contribution to the dark matter (DM) component of our Universe. If this is the case, the interaction of ordinary matter with the local DM moduli, forming the Galaxy halo, will cause an oscillation of solid bodies with a frequency corresponding to the mass of moduli. In the sensitive band of AURIGA, some 100 Hz at around 1 kHz, the expected signal, with $Q = \triangle f/f \sim 10^6$, is a narrow peak, $\triangle f \sim 1$ mHz. Here the detector strain sensitivity is $h_s \sim 2 \times 10^{-21}\ \mathrm{Hz}^{-1/2}$, within a factor of 2. These numbers translate to upper limits at 95% C.L. on the moduli coupling to ordinary matter $(d_e + d_{m_e}) \lesssim 10^{-5}$ around masses $m_\phi = 3.6 \times 10^{-12}$ eV, for the standard DM halo model with $\rho_{\mathrm{DM}} = 0.3\ \mathrm{GeV/cm^3}$.

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PRL **118**, 021302 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

**Search for an Ultralight Scalar Dark Matter Candidate with the AURIGA Detector**

Anton ... larin,[5,6,7]

[2]I ... Italy
[3]T ... Italy
[5]D ... , Italy
[6]Istitu ... FI), Italy
[7]E ... Italy

3/9/2017 18:06 Page

## Axions ($A^0$) and Other Very Light Bosons, Searches for

NODE=S029

### Search for Relic Invisible Axions

NODE=S029AXI

Limits are for $[G_{A\gamma\gamma}/m_{A^0}]^2 \rho_A$ where $G_{A\gamma\gamma}$ denotes the axion two-photon coupling, $L_{\text{int}} = -\frac{G_{A\gamma\gamma}}{4}\phi_A F_{\mu\nu}\tilde{F}^{\mu\nu} = G_{A\gamma\gamma}\phi_A \mathbf{E}\cdot\mathbf{B}$, and $\rho_A$ is the axion energy density near the earth.

NODE=S029AXI

• • • We do not use the following data for averages, fits, limits, etc. • • •

NODE=S029AXI

| | VALUE | CL% | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|---|---|
| YOUR DATA | | | [1] BRANCA | 17 AURG | $m_{S^0} = 3.5$–$3.9\ \mu$eV |
| | $<3 \times 10^{-42}$ | 90 | [2] BRUBAKER | 17 | $m_{A^0} = 23.55$–$24.0\ \mu$eV |
| | $<8.6 \times 10^{-42}$ | 90 | [3] HOSKINS | 16 ADMX | $m_{A^0} = 3.36$–$3.52$ or $3.55$–$3.69\ \mu$eV |
| | | | [4] BECK | 13 | $m_{A^0} = 0.11$ meV |
| | $<3.5 \times 10^{-43}$ | | [5] HOSKINS | 11 ADMX | $m_{A^0} = 3.3$–$3.69 \times 10^{-6}$ eV |
| | $<2.9 \times 10^{-43}$ | 90 | [6] ASZTALOS | 10 ADMX | $m_{A^0} = 3.34$–$3.53 \times 10^{-6}$ eV |
| | $<1.9 \times 10^{-43}$ | 97.7 | [7] DUFFY | 06 ADMX | $m_{A^0} = 1.98$–$2.17 \times 10^{-6}$ eV |
| | $<5.5 \times 10^{-43}$ | 90 | [8] ASZTALOS | 04 ADMX | $m_{A^0} = 1.9$–$3.3 \times 10^{-6}$ eV |
| | | | [9] KIM | 98 THEO | |
| | $<2 \times 10^{-41}$ | | [10] HAGMANN | 90 CNTR | $m_{A^0} = (5.4$–$5.9)10^{-6}$ eV |
| | $<1.3 \times 10^{-42}$ | 95 | [11] WUENSCH | 89 CNTR | $m_{A^0} = (4.5$–$10.2)10^{-6}$ eV |
| | $<2 \times 10^{-41}$ | 95 | [11] WUENSCH | 89 CNTR | $m_{A^0} = (11.3$–$16.3)10^{-6}$ eV |

OCCUR=2

YOUR NOTE [1] BRANCA 17 look for modulations of the fine-structure constant and the electron mass due to moduli dark matter by using the cryogenic resonant-mass AURIGA detector. The limit on the assumed diatonic coupling implies $G_{S\gamma\gamma} < 4.4 \times 10^{-25}$ GeV$^{-1}$. See Fig. 5 for mass-dependent limits.

NODE=S029AXI;LINKAGE=H

# Light Dark Matter

- moduli ($\phi$): scalar fields from string theory;
- mass values, $m_\phi$, model dependent;
- good dark matter (DM) candidate: standard DM model assumed with $\rho_{DM} = 300\, MeV/cm^3$;
  - heavier than $m_\phi \simeq 10^{-22}\, eV$;
  - classical wave description: lighter than $m_\phi \simeq 0.1\, eV$:

$$\phi(\mathbf{x}, t) = \phi_0 cos(m_\phi t - m_\phi \mathbf{v} \cdot \mathbf{x}) + O(\mathbf{v}^2)$$

**Reference**: A. Arvanitaki, S. Dimopoulos, K. V. Tilburg, Phys. Rev. Lett. 116, 031102 (2016);

## Light Dark Matter

Interaction of moduli with ordinary matter:

$$\mathcal{L} \supset \sqrt{4\pi \mathrm{G_N}}\phi \left[ d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} \right]$$

effects of moduli can be absorbed by the fine structure constant ($\alpha$) and electron mass ($m_e$):

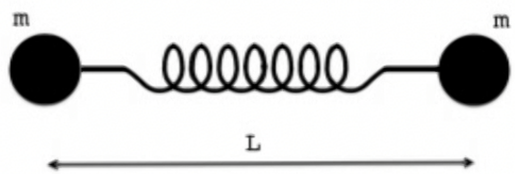
$$\alpha(\mathbf{x}, t) = \alpha(1 + d_e \sqrt{4\pi G_N}\phi(\mathbf{x}, t))$$

$$m_e(\mathbf{x}, t) = m_e(1 + d_e \sqrt{4\pi G_N}\phi(\mathbf{x}, t))$$

**Consequence**: oscillation of the atom's size ($a_0 = 1/\alpha m_e$) in matter:

$$h \equiv \frac{\delta a_0}{a_0} = -(d_e + d_{m_e})\sqrt{4\pi G_N}\phi(\mathbf{x}, t)$$

## Effects on an oscillator




The equation of motion is given by:

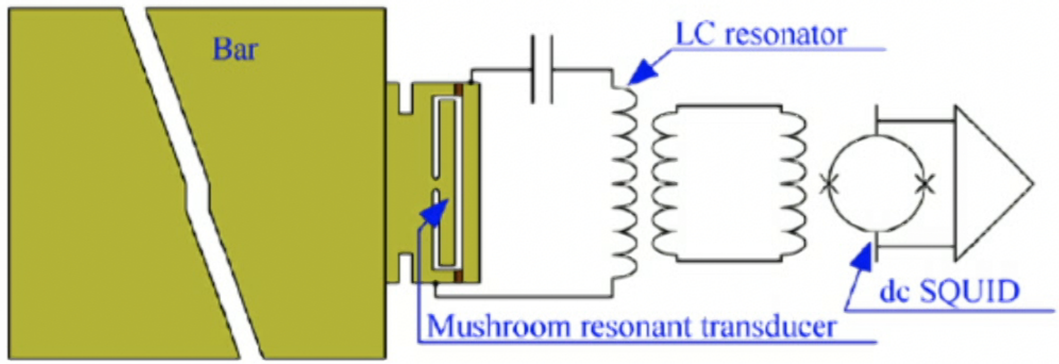
$$\ddot{x} + \frac{\omega}{Q}\dot{x} + \omega^2(x - L) = F_{ext} + F_{th}$$

Rewriting: $\xi = x - L$ (displacement) $\Rightarrow$ $\ddot{x} = \ddot{\xi} + \delta L = \ddot{\xi} + \ddot{h}L$:

$$\ddot{\xi} + \frac{\omega}{Q}\dot{\xi} + \omega^2\xi = -\ddot{h}L + F_{ext} + F_{th}$$

similar to the one of gravitational wave antenna subject to GW tidal force.

# AURIGA detector: read-out scheme

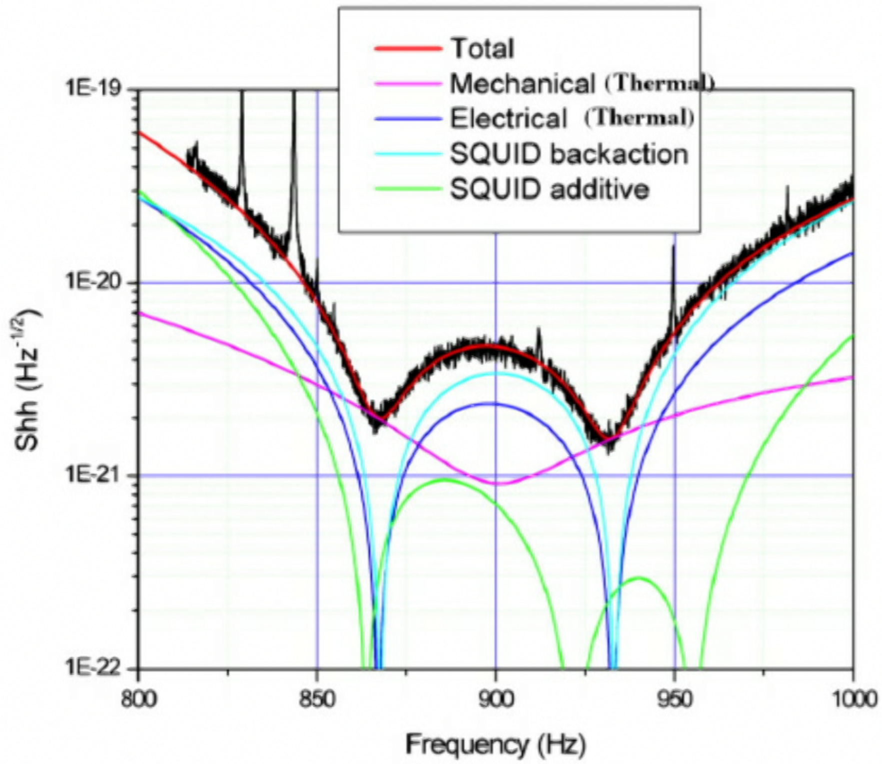



**System components**: 3 coupled resonators (nearly same $f_R \sim 900\ Hz$):

1. cylindrical bar (aluminium alloy);
2. mashroom-shaped resonator;
3. electrical LC circuit;

Operated at cryogenic temperature: $T = 4.5\,K$;

# AURIGA detector: sensitivity




- detector in thermal equilibrium: its fluctuations are described by the Fluctuation-Dissipation theorem
- sensitivity (set by thermal noise) within factor 2:

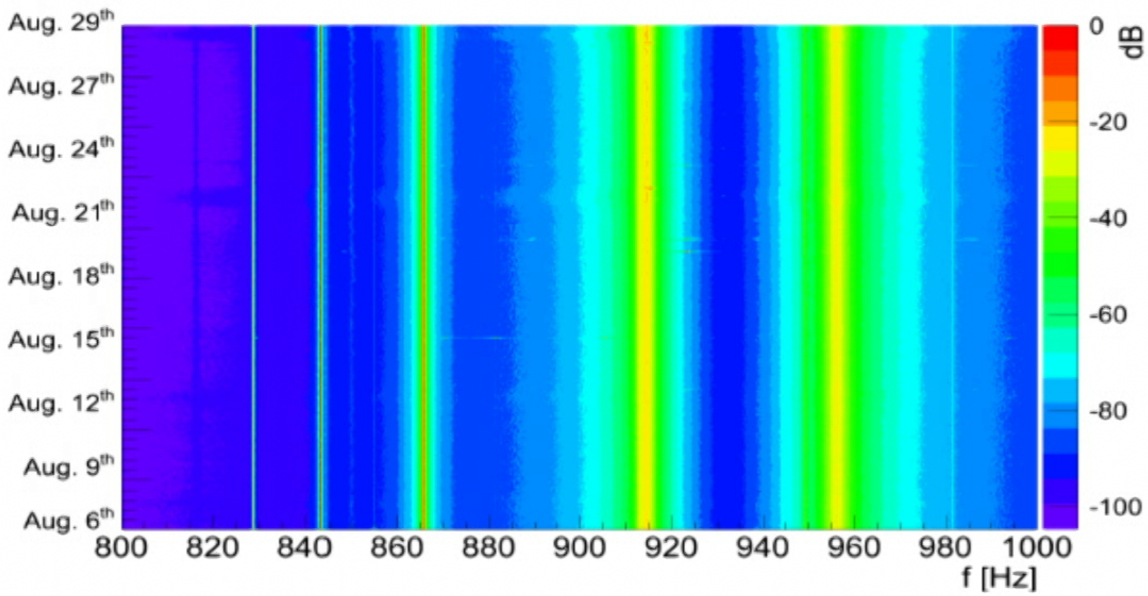
$$h \simeq 2 \cdot 10^{-21} \, 1/\sqrt{Hz}$$

over a bandwidth of:

$$\Delta f \simeq 100 \, Hz$$

## Dataset and data quality

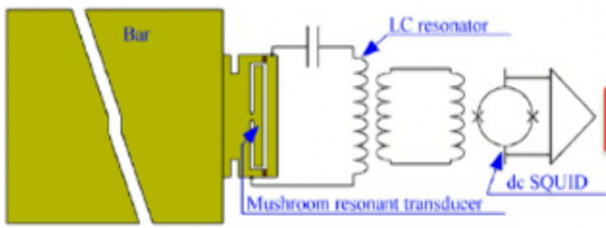
Dataset considered for analysis: August 2015 data. Time-frequency view:




- stable detector conditions: constant mode frequency and shape;
- energetic background events (spikes at fixed time): cut-off by RMS requirement (86% detector duty-cicle);

# Analysis Workflow

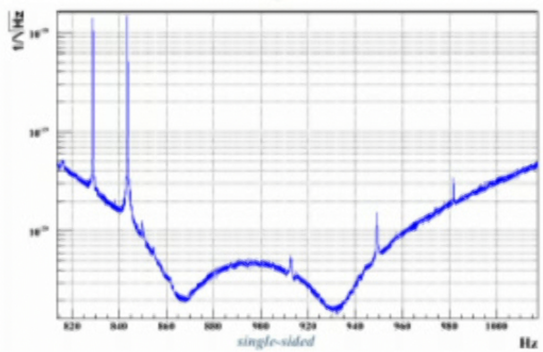
**AURIGA DETECTOR**




READOUT

**OUTPUT (time-domain)**


Power Spectrum (FFT) + Transfer Function

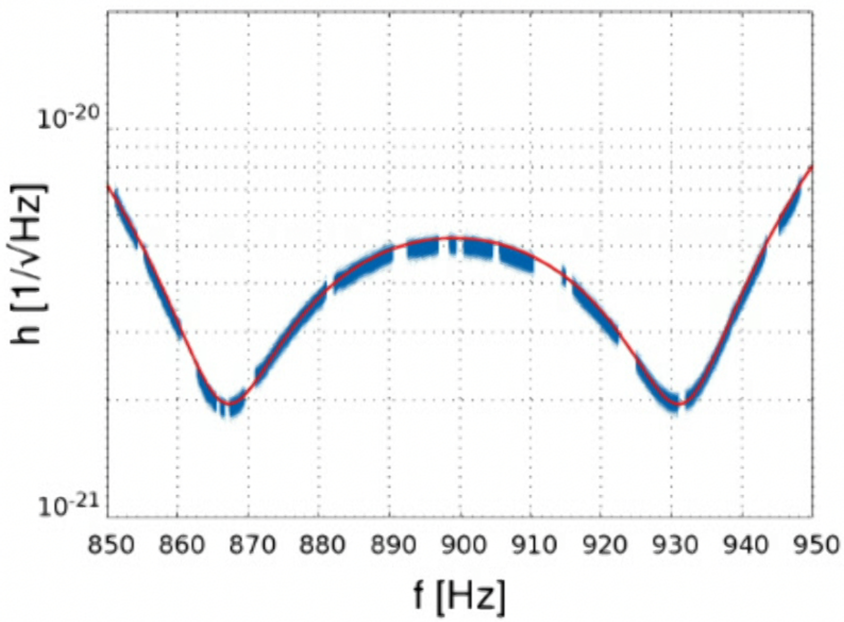



**Measured strain of the AURIGA bar:**

- thermal noise of a system in thermodynamic equilibrium;

# Measured PWS

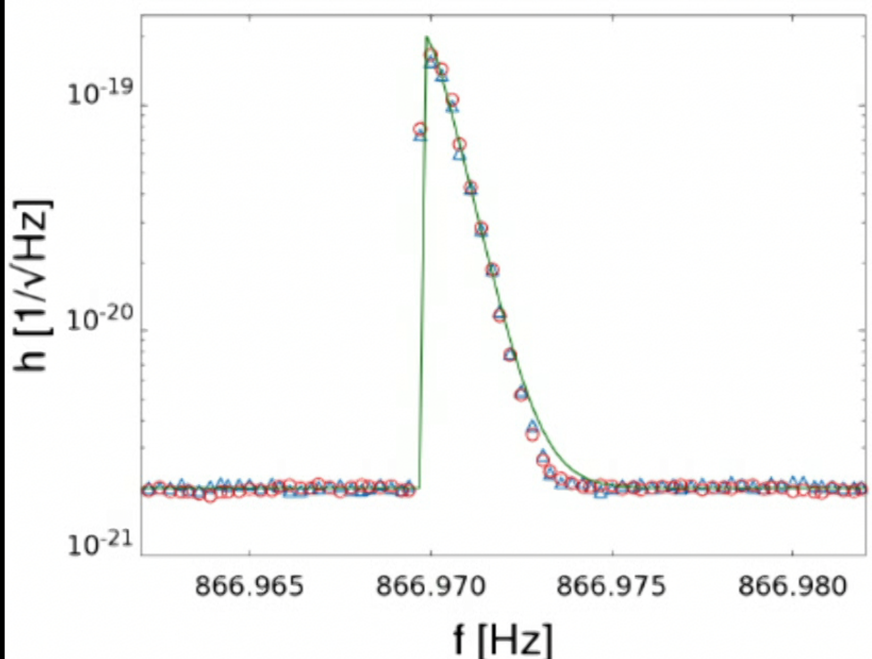
Spectrum of the measured bar relative deformation compared to theory prediction:




- one-sided power spectrum;
- from $N = 400$ averaged power spectrums;
- good agreement with prediction ($\sigma_{Th} \sim 5 - 10\,\%$);
- spurious peaks discarded;

# Test: signal injection

Comparison: full simulation vs signal injection




| Signal parameters | |
|---|---|
| $f_\phi$ $[Hz]$ | $(d_{m_e} + d_e)$ |
| $\sim 867$ | $5 \cdot 10^{-4}$ |

- signal well reconstructed;
- no reduction due to RMS cut;

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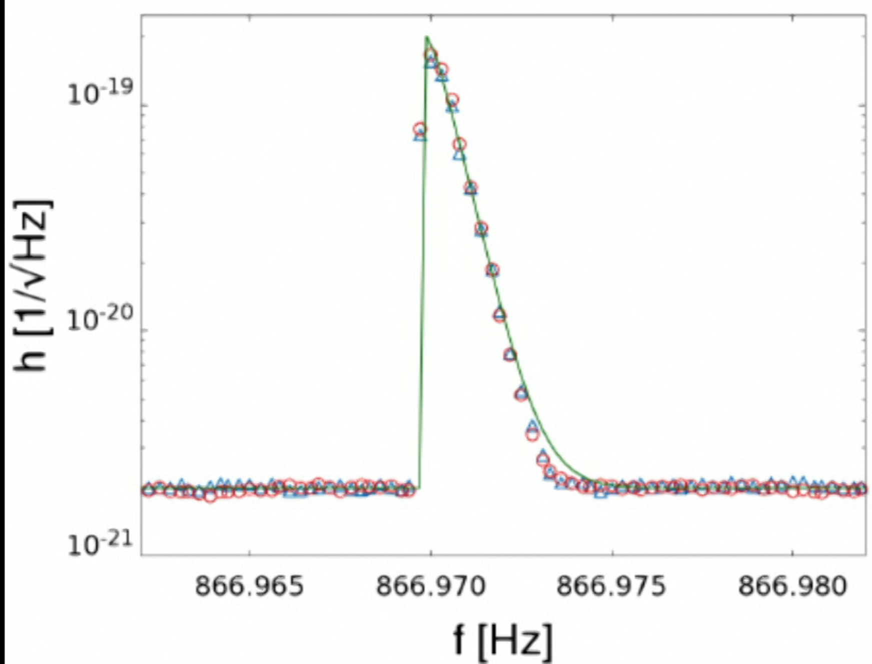


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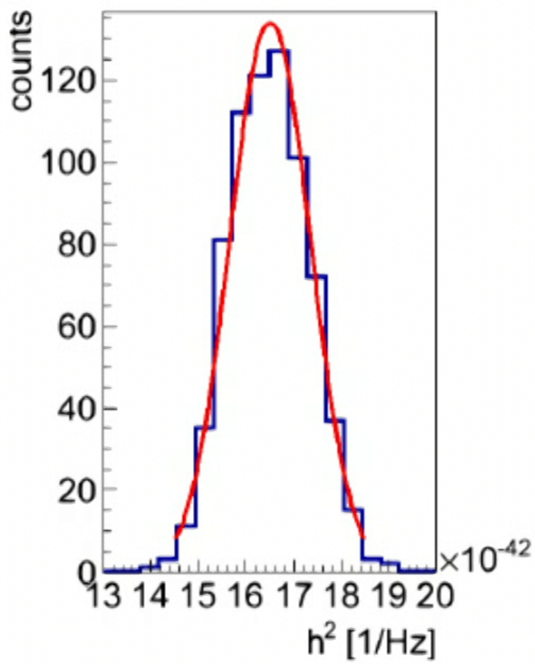
# Statistical analysis

Bins' spectrum statistic

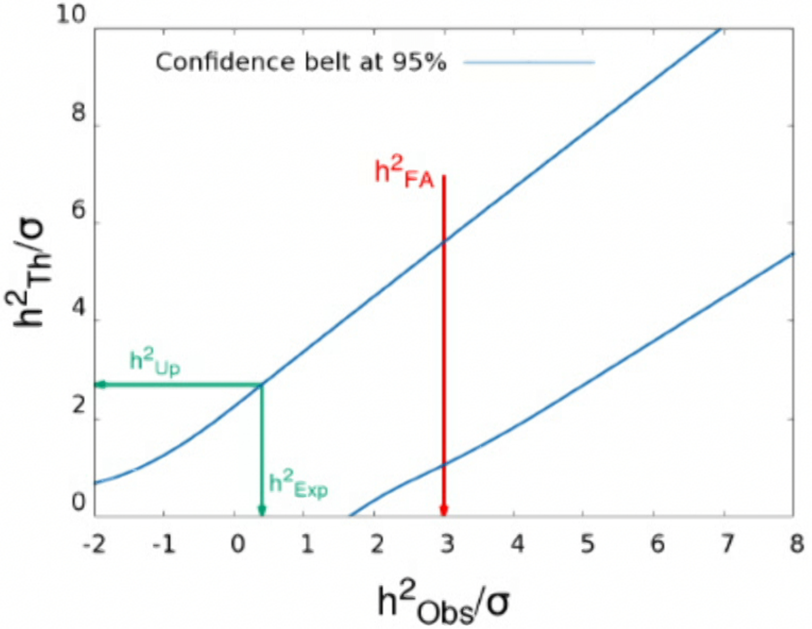



| $f$ [$Hz$] | $\langle h^2 \rangle$ [$\frac{1}{Hz}$] | $\sigma_{h^2}$ [$\frac{1}{Hz}$] | $\chi^2/ndf$ |
|---|---|---|---|
| 857 | $1.65 \cdot 10^{-41}$ | $1.11 \cdot 10^{-42}$ | 6.3/5 |

- gaussian PDF describing bin statistics;
- PDF is used to build the confidence belt in the parameter space $(h^2_{obs}, h^2_{Th})$;

# Confidence belt

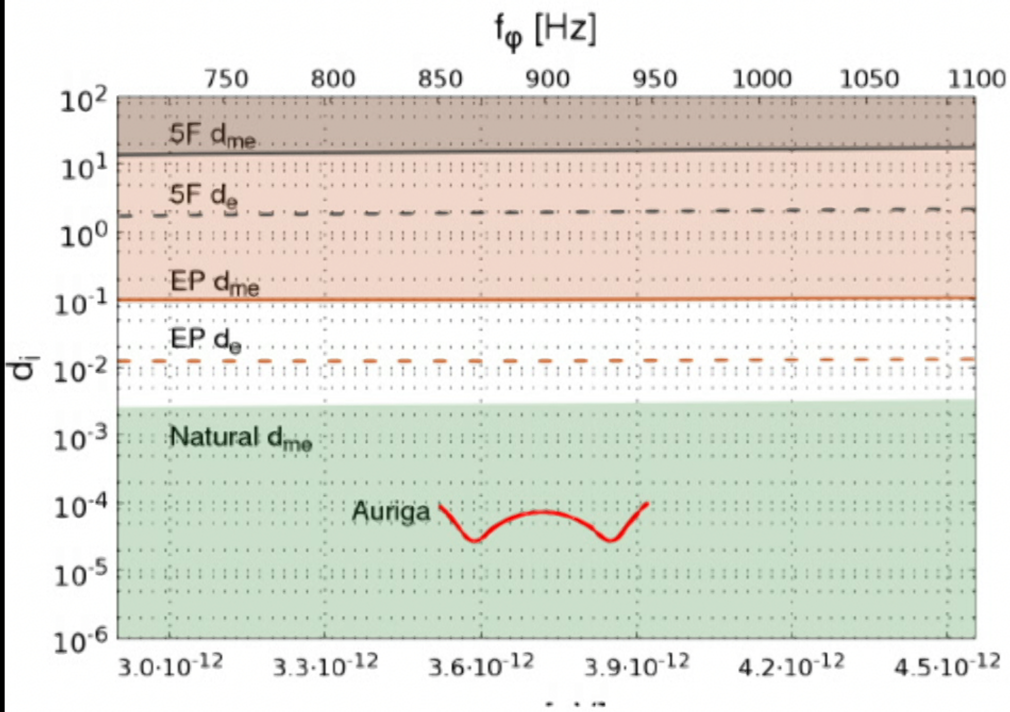
**Reference**: G. J. Feldman, R. D. Cousin, Phys. Rev. D 57, 3873-38891 (1998).




- $h^2_{FA}$: false alarm probability threshold of $3\sigma$ from background only hypothesis;
- $h^2_{Exp}$: observed value (for a given bin);
- $h^2_{Up}$: upper limit corresponding to experimental value;

## Upper Limits

Upper limits on $h$ interpreted as upper limit on the DM couplings to ordinary matter: $h_0 \simeq 1.5 \cdot 10^{-16}(d_{m_e} + d_e)/\left(\frac{1}{3} f_\phi \langle v^2 \rangle\right)^{\frac{3}{2}} f_\phi$

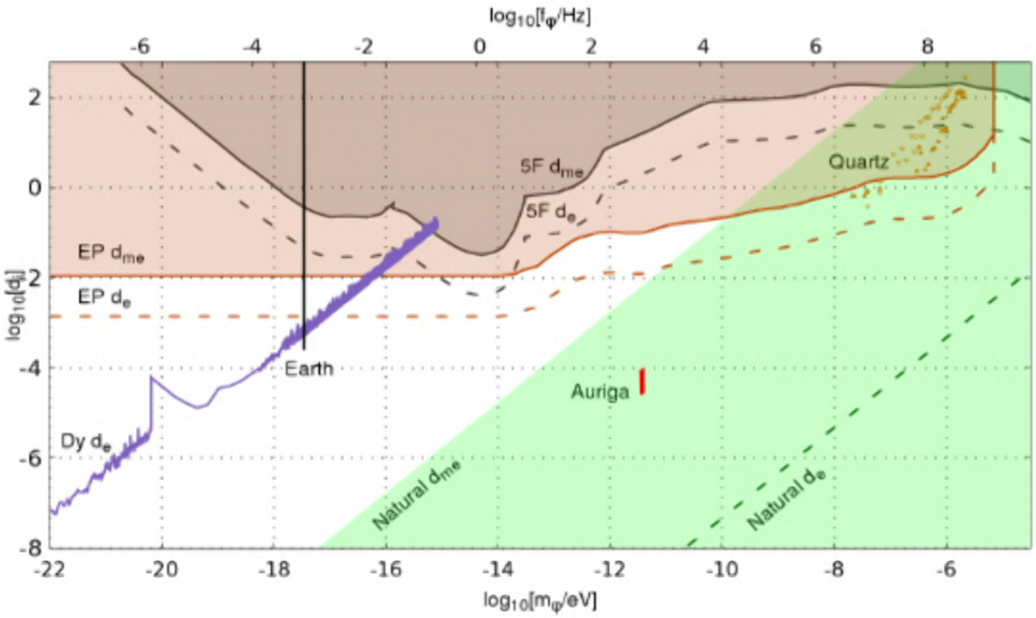



- reached sensitivity on DM couplings: $d_i \simeq 10^{-4}$;
- bandwidth sensitivity: $\Delta f \simeq 100\ Hz$

**FIRST TIME EVER!**

# Upper Limits: wider view

Comparison with other experiments:




From: A. Arvanitaki, S. Dimopoulos, K. V. Tilburg, Phys. Rev. Lett. 116, 031102 (2016)

- Natural: natural parameter space (theory);
- 5F and EP: fifth force and equivalence principle tests;
- Dy: sensitivity of atomic spectroscopy in dysprosium;
- Earth: low frequency terrestrial seismology;
- Quartz: sensitivity of piezoelectric quartz resonators;

# Conclusions

Search for light Dark Matter with AURIGA resonant-mass cryogenic detector:

- light dark matter effects on ordinary matter: microscopic changes of bodies size;
- effects exploited to search for effects on AURIGA detector;
- good sensitivity reached: upper limits on Dark Matter coupling in a physical interesting region of parameter space;

# Cuore is:

## CUORE
(Cryogenic Underground Observatory for Rare Events)

Primary goal: search for $0\nu\beta\beta$ decay in $^{130}Te$

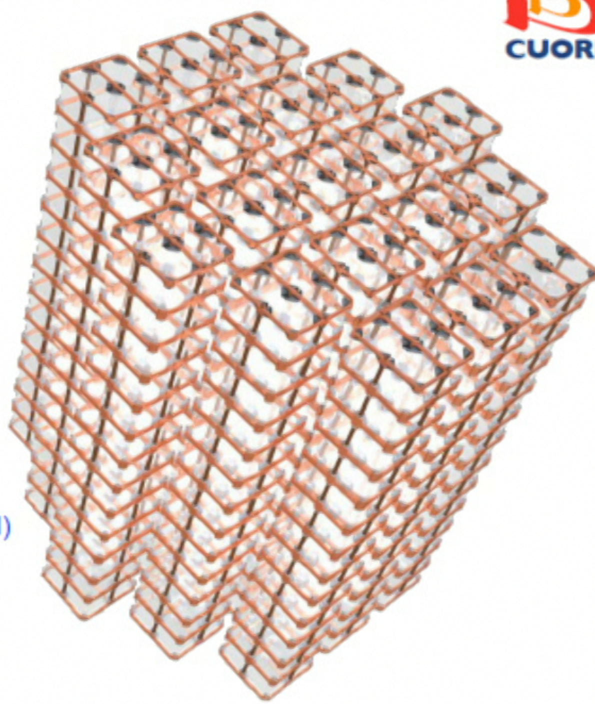
Closely packed array of 988 $TeO_2$ crystals arranged in 19 towers

$^{130}Te$:
- large transition energy: $Q_{\beta\beta}$ ($^{130}Te$) 2527.5 keV
- highest natural isotopic abundance (33.8%)

CUORE design parameters:
- mass of $TeO_2$: **742 kg** (206 kg of $^{130}Te$ )
- low background aim: **$10^{-2}$ c/(keV·kg·yr)**
- energy resolution: **5 keV** FWHM in the Region Of Interest (ROI)
- high granularity
- deep underground location
- strict radio-purity controls on materials and assembly

CUORE projected sensitivity (5 years, 90% C.L.):

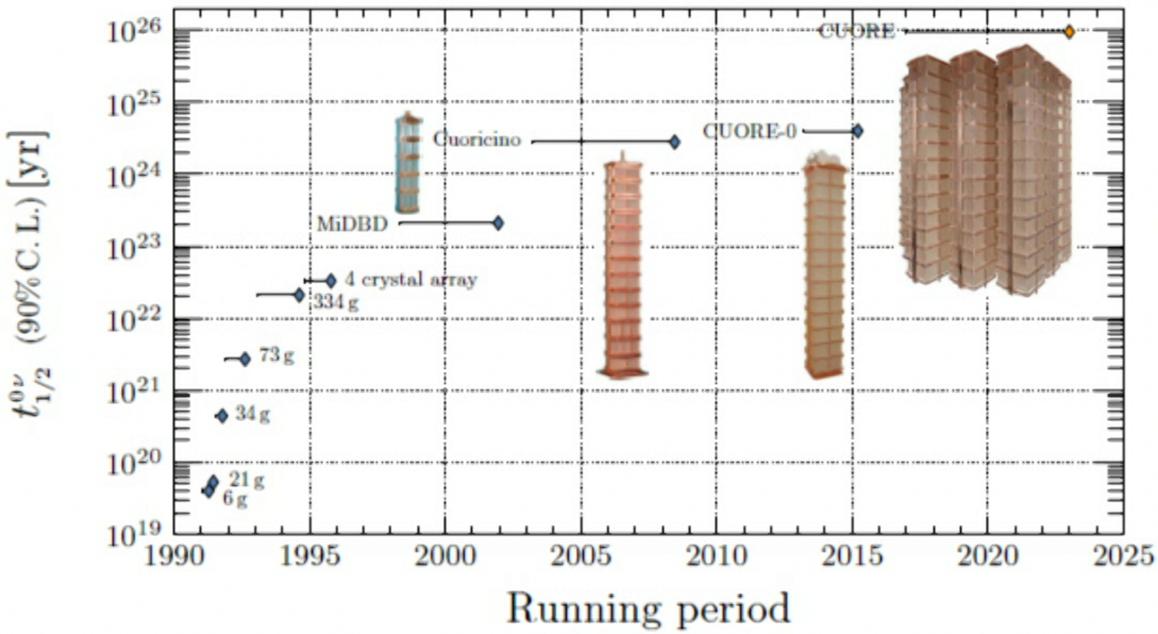
**$T_{1/2} > 9 \times 10^{25}$ yr**



Oliviero Cremonesi - July 28, 2017 - TAUP 2017 - Sudbury

# a Very long story for a mature technology:

## $TeO_2$ arrays

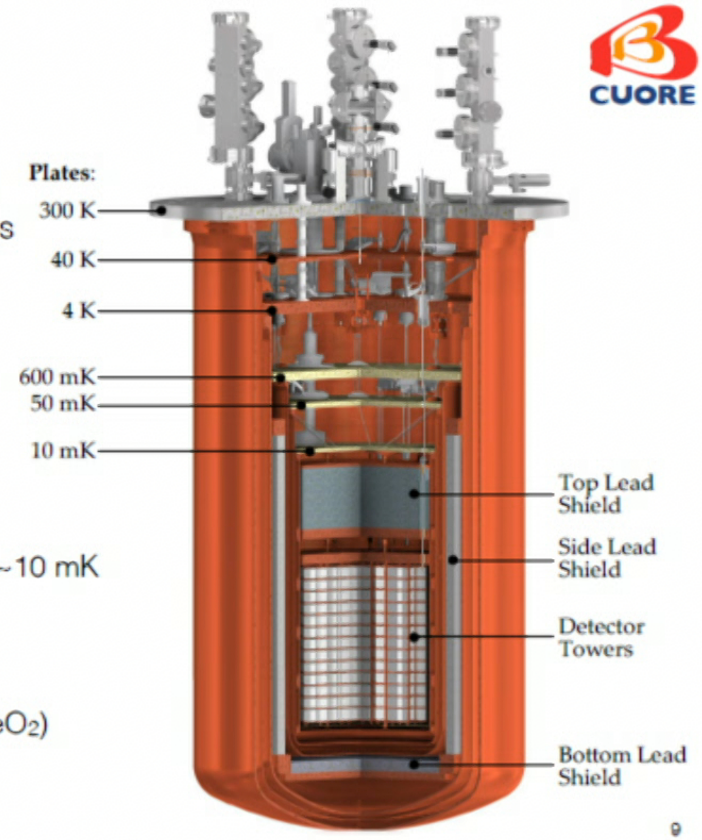



CUORE is the latest evolution of a long series of $TeO_2$ detectors which included two large demonstrators:

- Cuoricino
- CUORE-0

# The CUORE cryostat

- Designed to cool down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- Low background environment




- Cryogen-free cryostat
- Fast Cooling System ($^4$He gas) down to ~50K
- 5 pulse tubes cryocooler down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 3 μW @ 10mK
- Cryostat total mass ~30 tons
- Mass to be cooled < 4K: ~15 tons
- Mass to be cooled < 50 mK: ~3 tons (Pb, Cu and $TeO_2$)

# Cryogenic system commissioning

CUORE

In February 2016 we completed the last test cool-down at full load:

- everything but the CUORE detector
- small test detector ("mini-tower")

Excellent performance of the cryogenic system:

- base temperature below 7 mK
- stable operation

Important information on the noise sources and abatement

Successful deployment of the calibration sources at base temperature

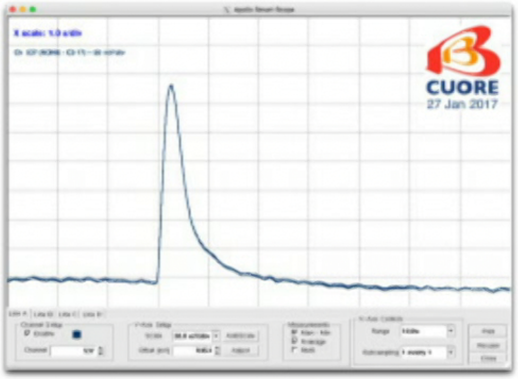
**Ready for the detector installation**

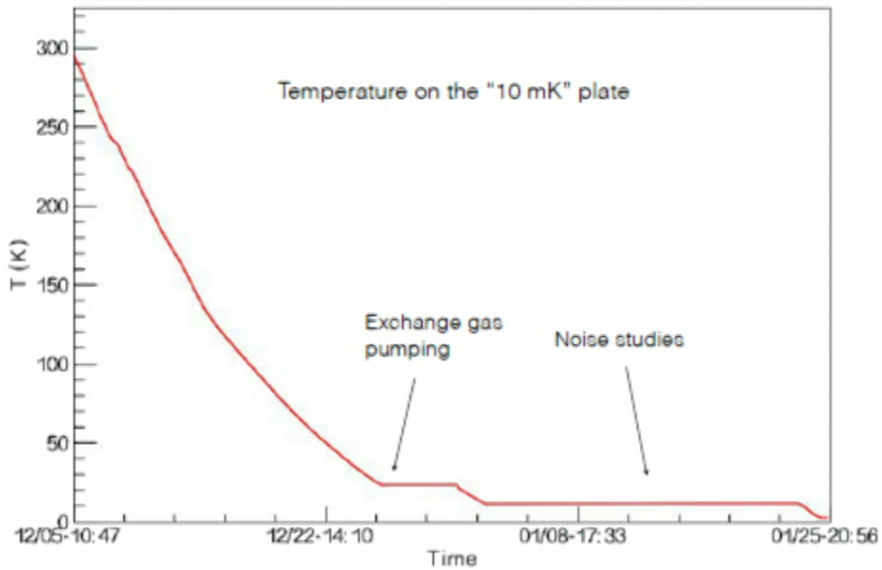

# Detector cool down

Started at the beginning of December 2016:

- reached a stable base temperature of ~7 mK on Jan 27, 2017
- lowest observed temperature: 6.7 mK

- observed first detector pulses just after the cool down without any optimization



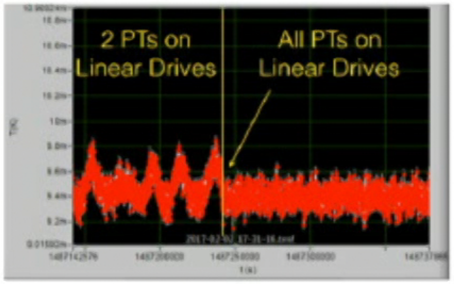



# Detector pre-operation

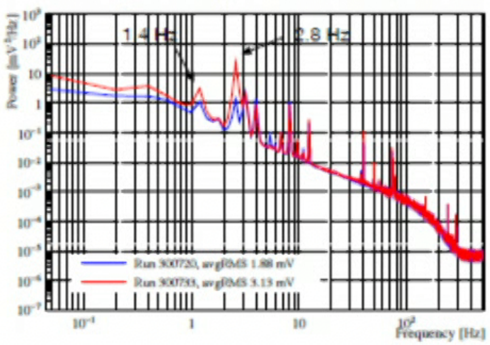
After the successful cool-down we faced the challenge to operate a thousand bolometers in a completely new system.

A long list of tests and activities
- DAQ and front-end electronics optimization
- Detector working points
  - Select representative subset
  - Load curves (to select optimal working points)
  - Temperature scan for the best operating conditions
- Noise reduction
- Linear drives to control the pulse tube (PT) motor-heads
- Monitor and control the relative phase shifts between different PT's using pressure sensors installed on the PT lines
- Impressive results both in terms of temperature stabilisation and noise abatement

End of March 2017:
- Closed first optimisation phase
- Ready to start calibrations and science runs
- Selected working temperature: 15 mK

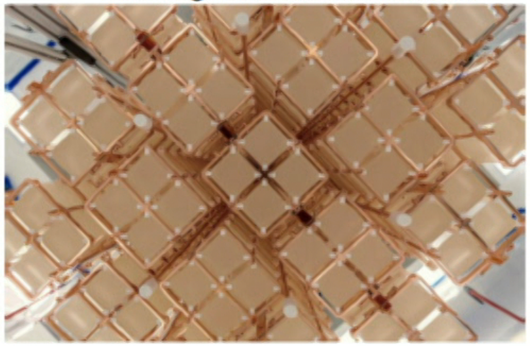



Average Noise Power Spectrum: ch. 142 runs 300720, 300733



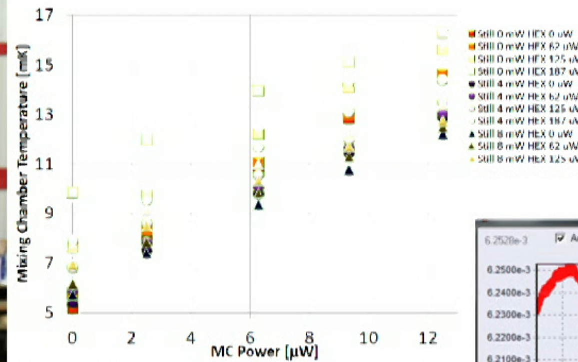
# Conclusions

- The cryostat is working spectacularly well.
- With 3 weeks of physics data we have accumulated higher exposure than CUORE-0/ Cuoricino and surpassed their limit.
  - Total exposure: 38.1 kg·y
  - Invaluable operational experience
  - Important information on detector performance, noise, resolutions, background levels
- Further improvement possible:
  - A detector optimization campaign is underway, focused on improving the resolution through noise reduction.



- Developed and debugged physics tools, stress-tested end-to-end data processing with quality appropriate for science results
- Background rates are consistent with the background model
- More to come

# CUORE dilution refrigerator





Characterized in 2013 in the test cryostat @ LNGS

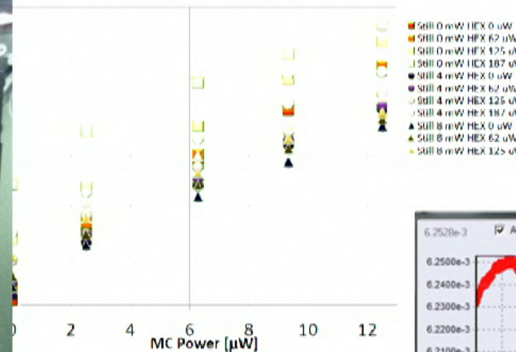
$T_{meas}$ = 4.95 mK (versus 5 mK)

$W_{meas}$ = 9.5 µW (versus 5 µW) @ 12 mK

T stability (over one day) = about 0.1 mK

some issues on the variable impendances

# CUORE
# ilution refrigerator





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ne issues on the variable impendances

When we require high cooling power in the intermediate temperature we use the DU (Dilution Unit) like a "tractor", **High Power**!
HIGH cooling Power in the all stages @ similar T

Still Temperate high, huge flow > 8mmol/s, probably we reach 10mmol/s without the 1 K pot stage, 2 or 3 PT works in parallel

## The worlds biggest tractor - Challenger MT975

| | |
|---|---|
| Displacement | 7.4 liters |
| Power | 570 HP |
| Torque | 2800 Nm |
| @ rpm | 1300 |

When we require lower than possible base temperature we use the DU like a "sportive car", High speed!
Better heat exchange in all the different stages!

Still Temperature 0.5K, low flow < 1mmol/s, only He3 and less than possible to avoid heating because of the incoming mixture in the MC. Probably it is enough 1 PT

## Ferrari 599 GTO the faster commercial car, no prototype

| | |
|---|---|
| **Displacement** | **6 liters** |
| **Power** | **670 HP** |
| **Torque** | **620 Nm** |
| **@ rpm** | **6500** |

Record speed 335 km/h
Acceleration 0-100km/h 3.35 s

It was necessary to realize a flexible DU able to work at the best in between this two so different working points and without the 1Kpot stage!
posted to FarmPhoto.com
To mix this 2 different vehicles in principle produce a "monster", a kind of Frankenstein, but in ultracryogenic world "we can do it"

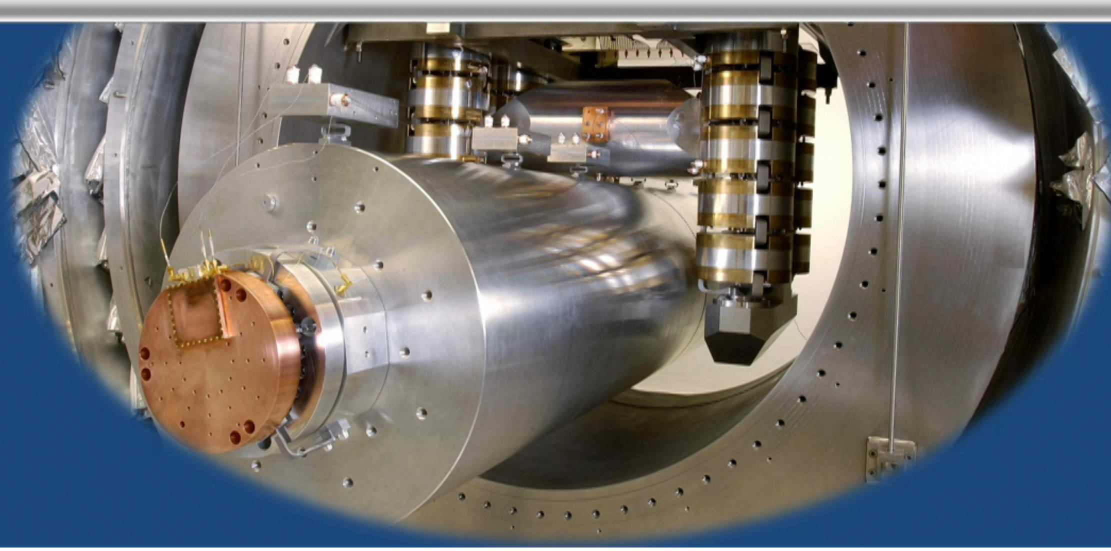
nature physics

LETTERS

PUBLISHED ONLINE: 16 DECEMBER 2012 | DOI: 10.1038/NPHYS2503

# Gravitational bar detectors set limits to Planck-scale physics on macroscopic variables

Francesco Marin[1,2,3]★, Francesco Marino[3,4], Michele Bonaldi[5,6], Massimo Cerdonio[7], Livia Conti[7], Paolo Falferi[6,8], Renato Mezzena[6,9], Antonello Ortolan[10], Giovanni A. Prodi[6,9], Luca Taffarello[7], Gabriele Vedovato[7], Andrea Vinante[8,11] and Jean-Pierre Zendri[7]



INFN Istituto Nazionale di Fisica Nucleare

## Phenomenological quantum gravity

- General 'observation': we cannot determine a position with an accuracy better than the Planck length $L_P = \sqrt{hG/c^3} = 1.6\ 10^{-35}$ m

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→ **AURIGA is a good candidate**

# GUP and harmonic oscillator ground state

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta_0 \left(\frac{\Delta p}{M_p c}\right)^2\right)$$

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$$x=\sqrt{\frac{\hbar}{m\omega_0}}\,X$$
$$p=\sqrt{\hbar m\omega_0}\,P$$

$$H=\frac{\hbar\omega_0}{2}\left(X^2+P^2\right)$$

$$\Delta X \Delta P \geq \frac{1}{2}\left(1+\beta\left(\Delta P\right)^2\right)$$

$$\beta=\beta_0\,\frac{\hbar m\omega_0}{M_p^2c^2}$$

$$<X>=<P>=0$$

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$$x = \sqrt{\frac{\hbar}{m\omega_0}}\,X$$
$$p = \sqrt{\hbar m\omega_0}\,P$$

$$H = \frac{\hbar\omega_0}{2}\left(X^2+P^2\right)$$
$$\Delta X \Delta P \geq \frac{1}{2}\left(1+\beta\,(\Delta P)^2\right)$$
$$\beta = \beta_0\,\frac{\hbar m\omega_0}{M_p^2 c^2}$$

$$< X > = < P > = 0$$

$$E > \frac{\hbar\omega_0}{2}\left[\left(1+\frac{\beta^2}{4}\right)(\Delta P)^2 + \frac{1}{4(\Delta P)^2} + \frac{\beta}{2}\right]$$

$$E_{min} = \frac{\hbar\omega_0}{2}\left[\sqrt{1+\frac{\beta^2}{4}}+\frac{\beta}{2}\right] \simeq \frac{\hbar\omega_0}{2}\beta$$

# AURIGA minimal energy

$$M_{red} = M/2 = 1.1 \times 10^3 \text{ kg}$$

$$\omega_0 = 900 Hz$$

$$E_{exp} = 1.3 \times 10^{-26} \text{ J}$$

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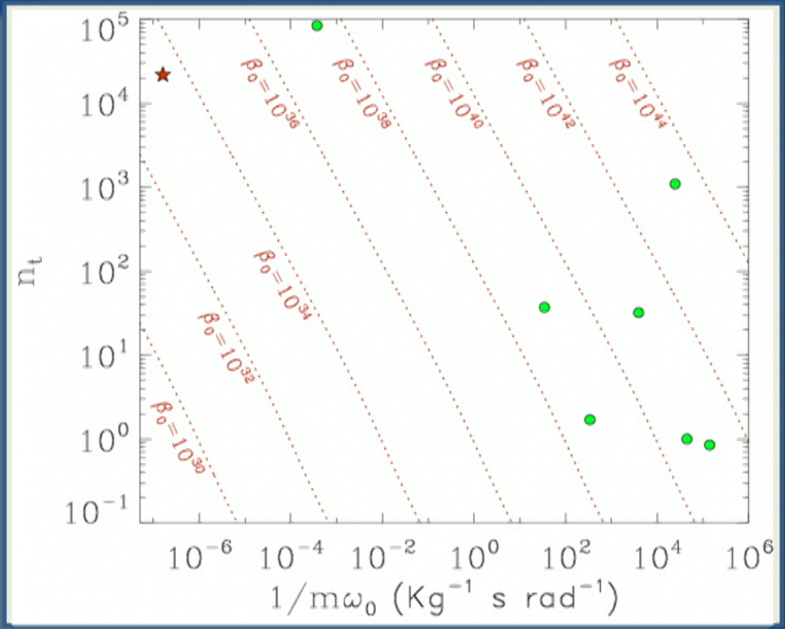

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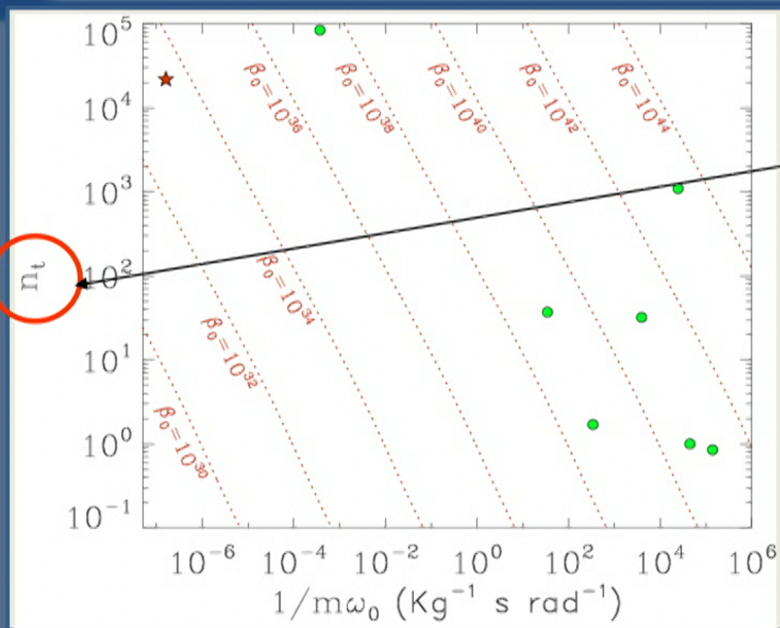



$$E_{exp} = \hbar\omega_0 (1/2 + n_t)$$

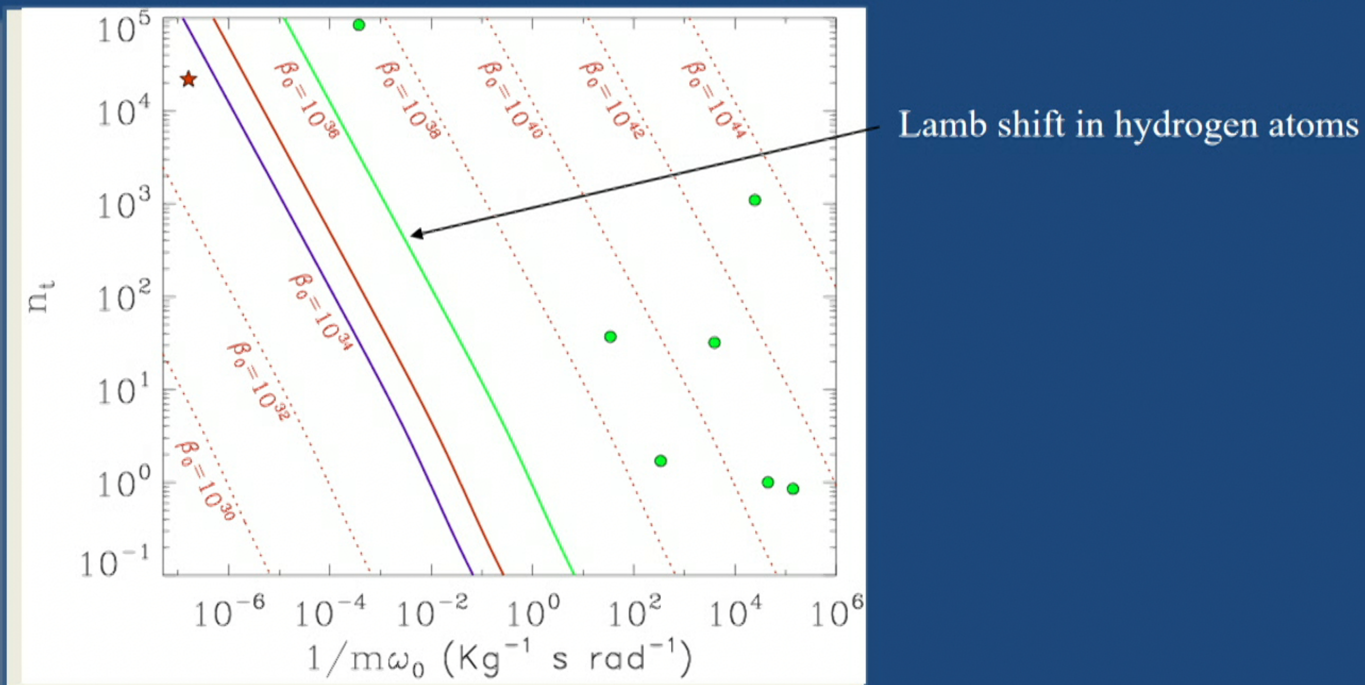
$$n_t = \frac{1}{e^{\frac{\hbar\omega_0}{k_B T_{eff}}} - 1}$$

# Modified commutator

GUP can be associated to a deformed canonical commutator

$$[x,p] = i\hbar\left(1+\beta_0\left(\frac{p}{M_p c}\right)^2\right)$$

Planck scale modifications of the energy spectrum of quantum systems



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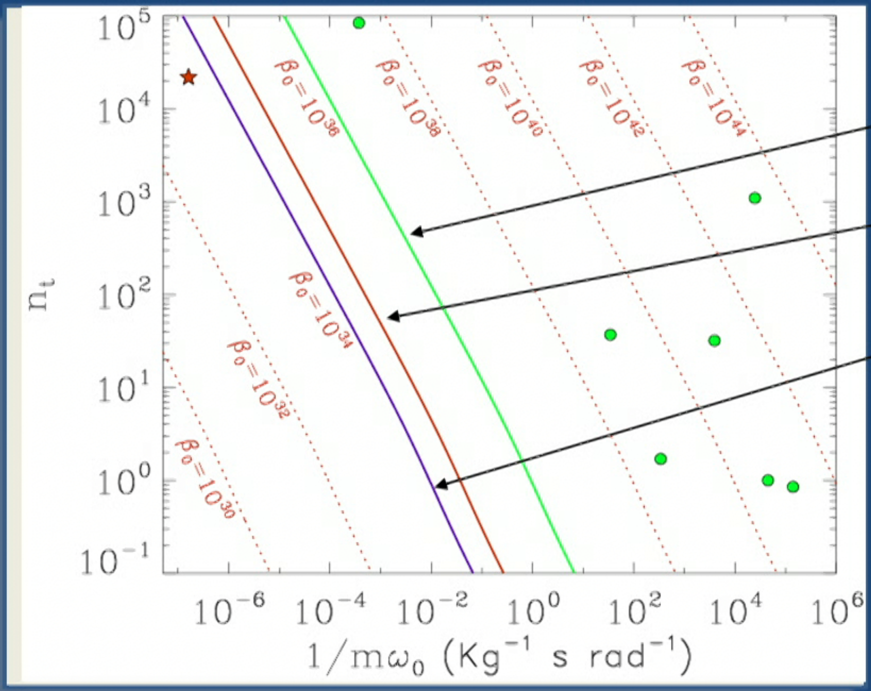


Lamb shift in hydrogen atoms

1S-2S level energy difference in hydrogen

Lack of observed deviations from theory at the electroweak scale

# Conclusions and follow-up

*Various effective models incorporate quantum gravitational effects that are, in principle, experimentally testable (modifications of QM...)*

*A macroscopic mechanical oscillator really behaves as quantum oscillator (recent experimental verification in cooled micro-oscillators)*

*The link between these models and an underlying fundamental theory of quantum gravity is unclear*

*The description of macroscopic objects in the framework of quantum gravity models is still lacking*

# AURIGA re-interpreted

AURIGA is not the "coolest" oscillator, but is the most motionless

$$X_{rms} = (kT/m\omega^2)^{1/2} = (E_{exp}/m\omega^2)^{1/2} \approx 6 \times 10^{-19}\ \text{m}$$

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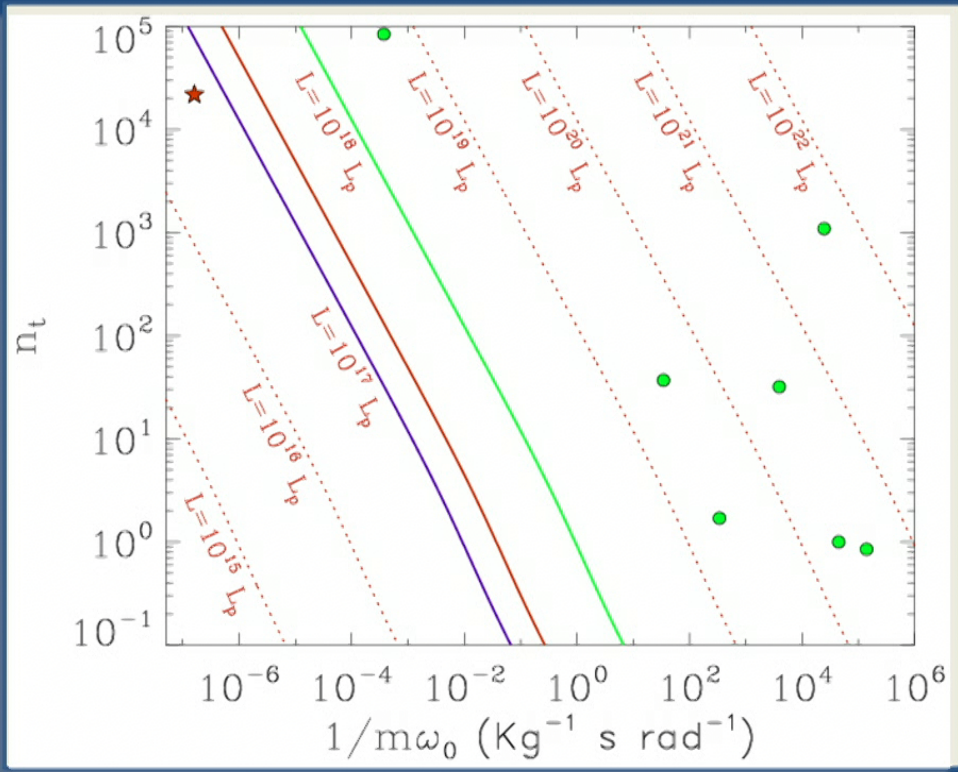
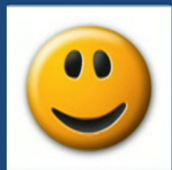



$$L = \sqrt{\beta_0} L_p$$

# Conclusions and follow-up



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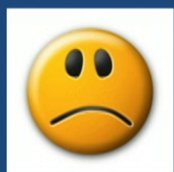

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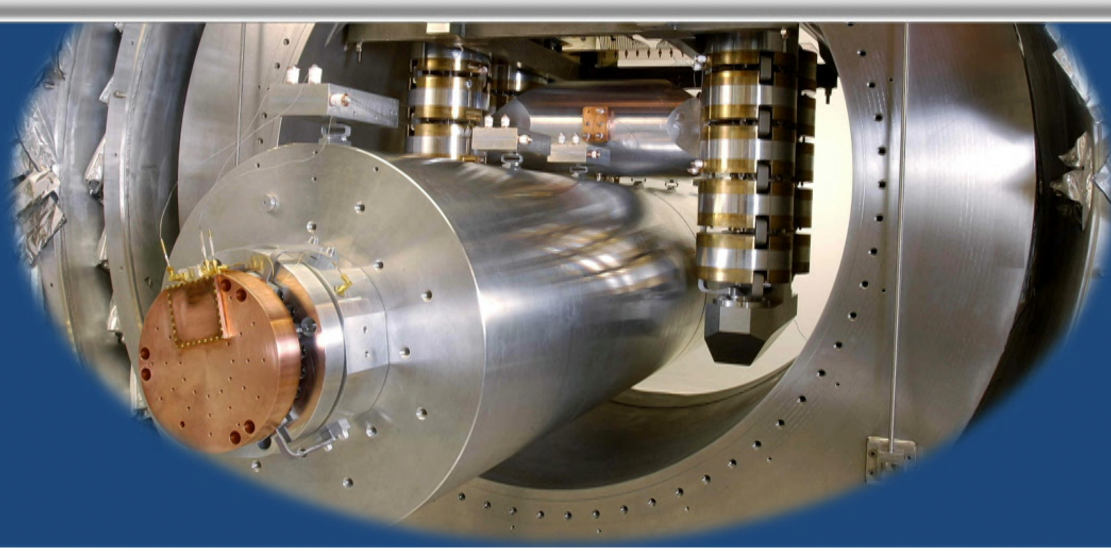
nature physics

LETTERS

PUBLISHED ONLINE: 16 DECEMBER 2012 | DOI: 10.1038/NPHYS2503

# Gravitational bar detectors set limits to Planck-scale physics on macroscopic variables

Francesco Marin[1,2,3]★, Francesco Marino[3,4], Michele Bonaldi[5,6], Massimo Cerdonio[7], Livia Conti[7], Paolo Falferi[6,8], Renato Mezzena[6,9], Antonello Ortolan[10], Giovanni A. Prodi[6,9], Luca Taffarello[7], Gabriele Vedovato[7], Andrea Vinante[8,11] and Jean-Pierre Zendri[7]



INFN Istituto Nazionale di Fisica Nucleare

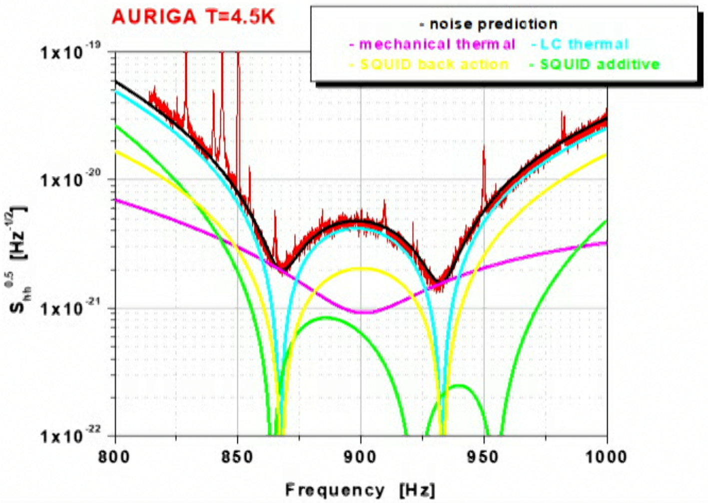
Antenna **U**ltracriogenica **R**isonante per l'**I**ndagine **G**ravitazionale **A**stronomica

## AURIGA

1989-2016

- Strain sensitivity $2\ 10^{-21} < S_{hh} < 10^{-20}\ Hz^{-1/2}$ over 100 Hz band (FWHM ~ 26 Hz)
- Burst Sensitivity $h_{rss} \sim 10^{-20}\ Hz^{-1/2}$
- Duty-cycle ~ 96 %
- ~ 20 outliers/day at SNR>6

**Complete control of the internal sources of noise: fluctuation/dissipation theorem holds**



Auriga was BIG

## Auriga was BIG

# Auriga was BIG



INFN
AURIGA run II: upgrades
AURIGA

# AURIGA run II: upgrades

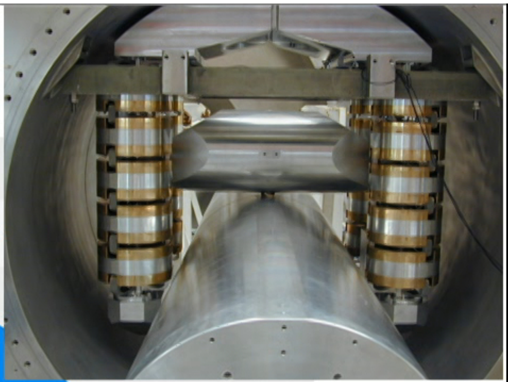

❖ new mechanical suspensions: attenuation > 360 dB at 1 kHz FEM modelled

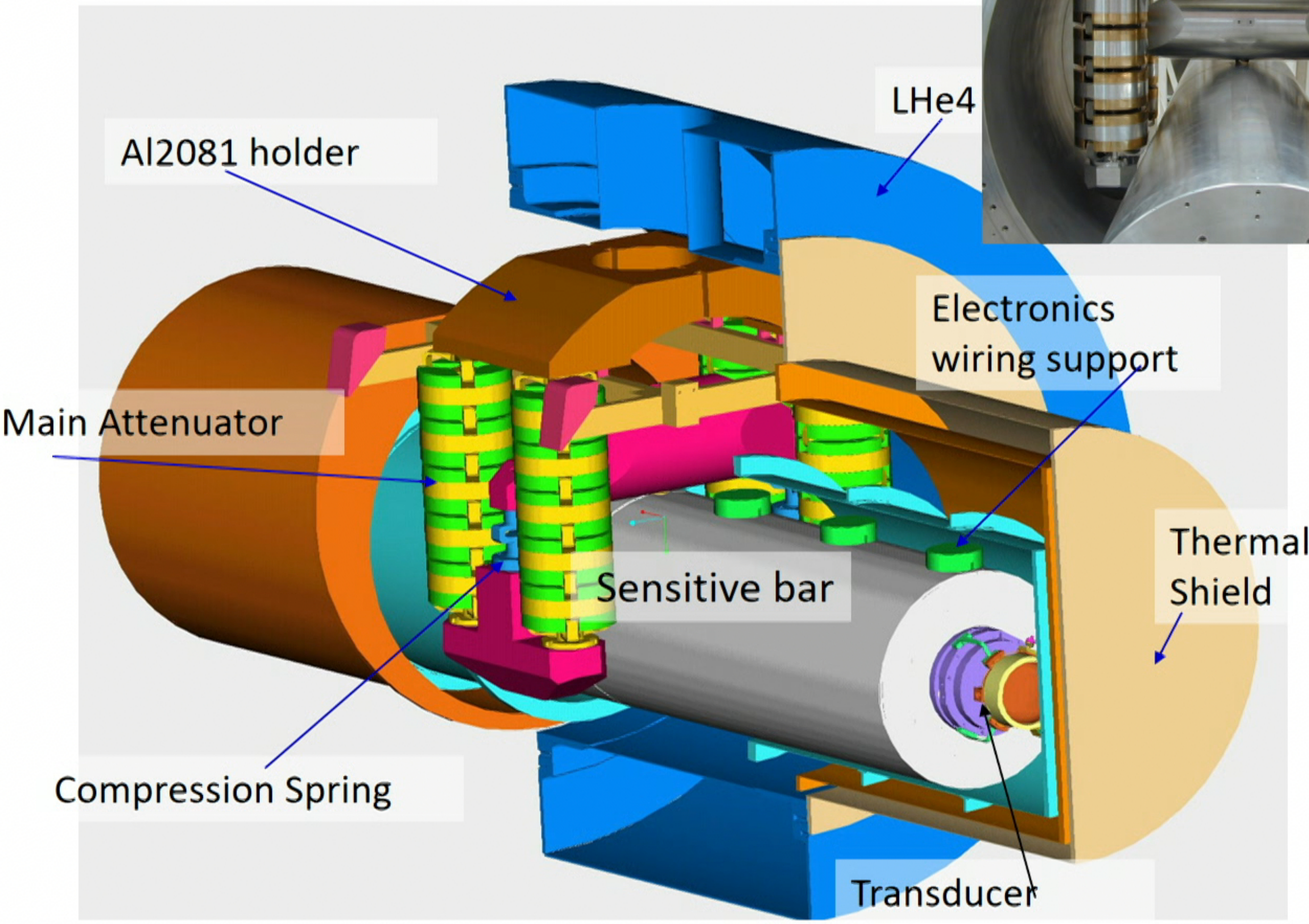
❖ three resonant modes operation: two mechanical modes one electrical

# AURIGA run II: upgrades

- new mechanical suspensions: attenuation > 360 dB at 1 kHz FEM modelled
- three resonant modes operation: two mechanical modes one electrical

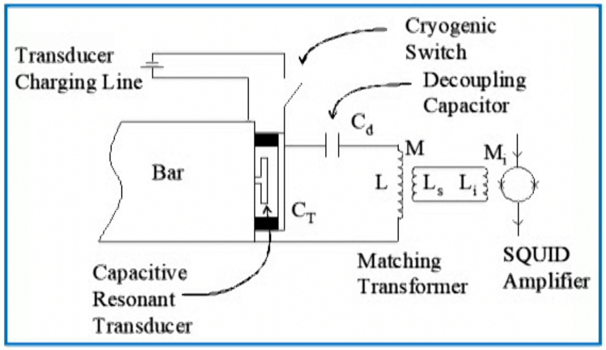
# AURIGA II run *(fall 2003)*

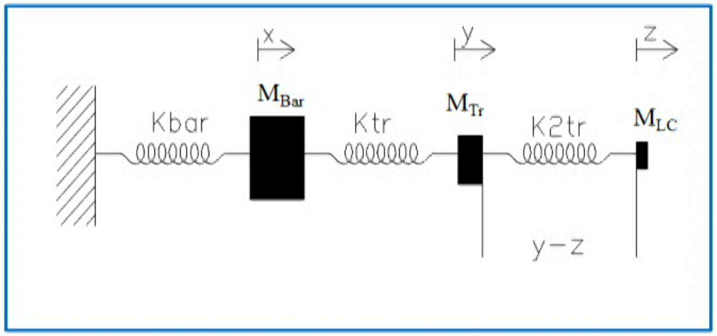





WP1 Cascina January 24-25 2005

# AURIGA 3-mode: Breaking the bandwidth limit



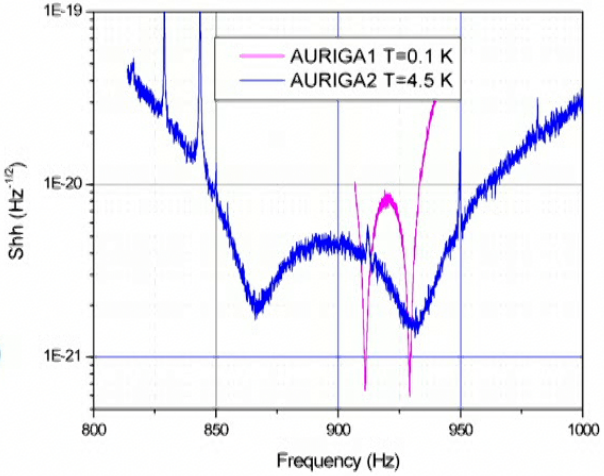

Electrical LC mode tuned to Bar & Transducer mechanical modes

LC Behaves as a lighter mechanical mode
Increases coupling to readout

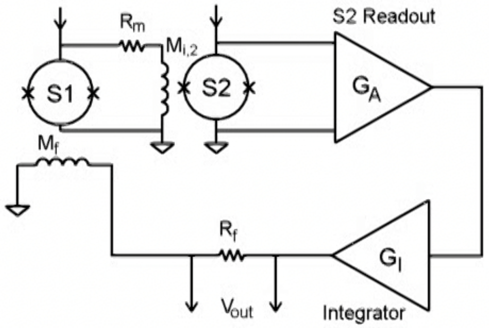
CRUCIAL REQUIREMENTS ACHIEVED IN TRENTO

1) High electrical Q $Q_{el} \sim Q_{mech} \sim 10^6$
2) Thermal noise

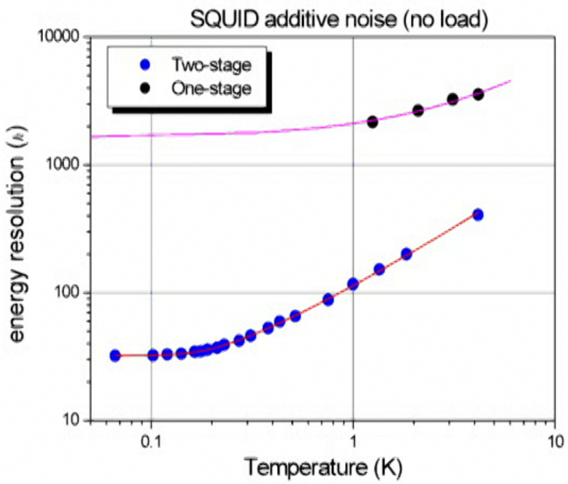
Bandwidth enlarged: $\Delta\nu$=26 Hz (1st run $\Delta\nu \cong$1 Hz)
Sensitivity improved: $T_{eff}$=320 μK @4.5K
(1st run $T_{eff}$>1mK @0.2K)



# The two-stage SQUID breakthrough

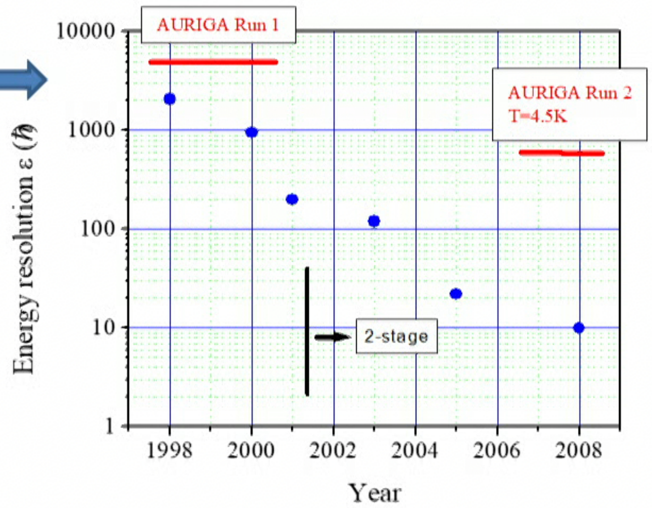


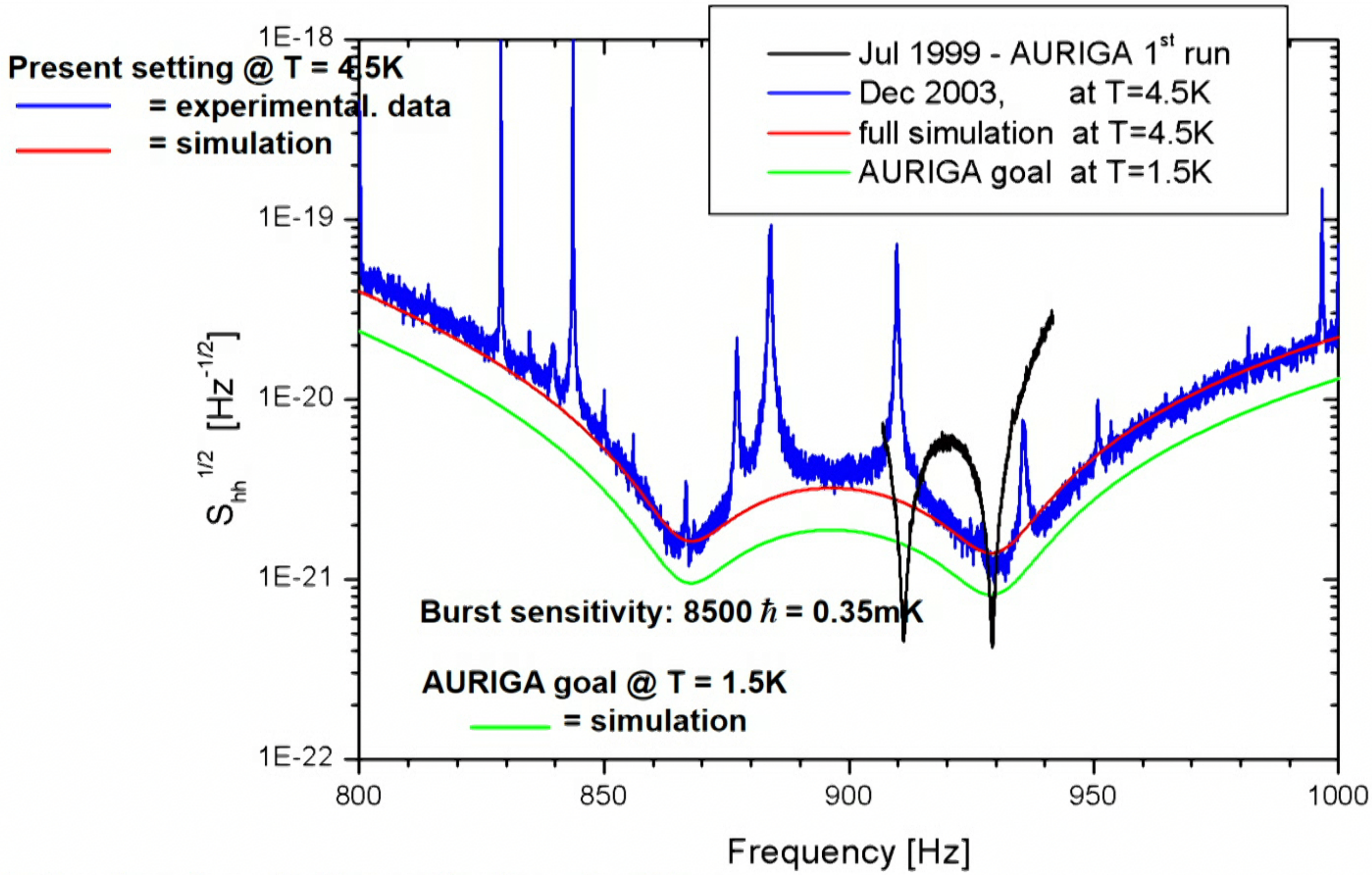

Using a second SQUID as preamplifier
suppresses electronics noise!




Trend of NOISE ENERGY (include back-action)
of SQUIDs developed in TRENTO
(P. Falferi, R. Mezzena, A. Vinante)

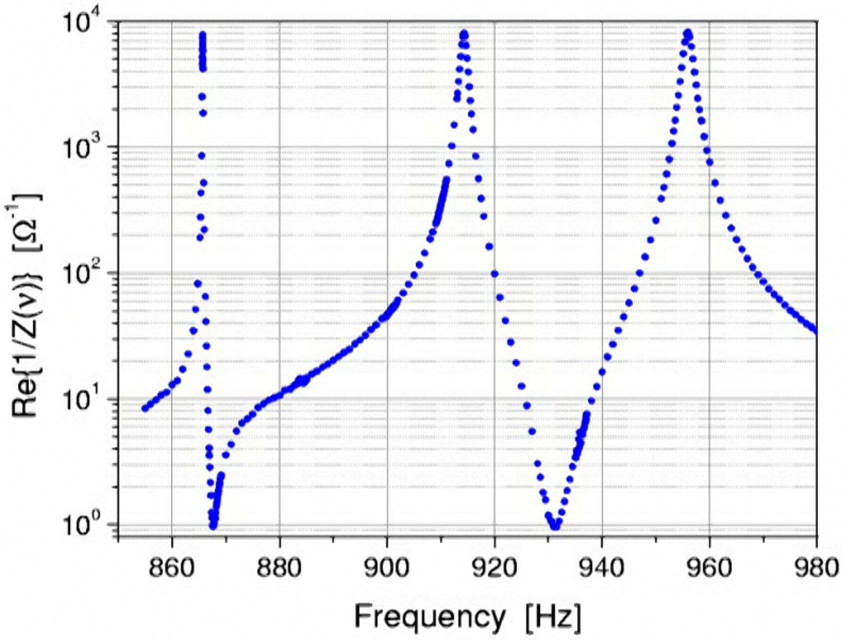
Demonstrated improvement
well beyond current AURIGA level
(but would need 100 mK operation !)






what we have learn in diagnostic phase to address
the spurious features in the noise spectra

The thermal behaviour of the modes is estimates by the measurement of the real part of the input impedence to the SQUID a 4.5 K




865.68 Hz

$$Q_{scarico} = 1.15 \cdot 10^6$$
$$Q_{carico} = 1.15 \cdot 10^6$$

914.14 Hz

$$Q_{scarico} = 5 \cdot 10^6$$
$$Q_{carico} = 0.74 \cdot 10^6$$

955.63 Hz

$$Q_{scarico} = 0.45 \cdot 10^6$$
$$Q_{carico} = 0.75 \cdot 10^6$$

$$Q_{cold-damped} \; \square \; 1000 - 400$$

Not evident lost of charge

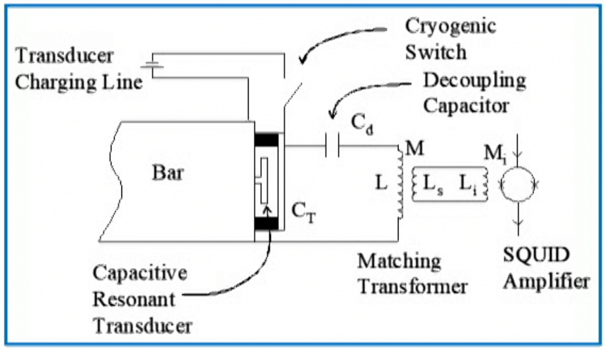
T= 4.5 K

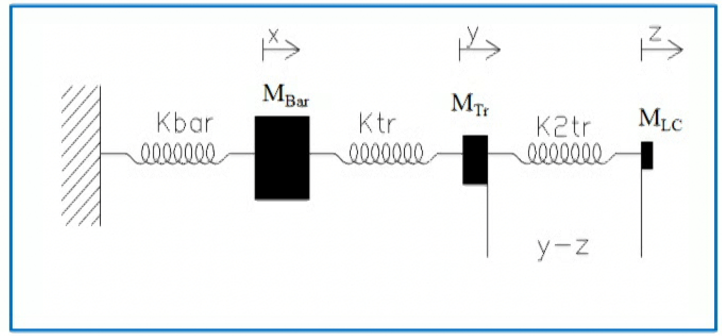
E bias=7.5 MV/m

Monocromatic excitation

Very long operation

# AURIGA 3-mode: Breaking the bandwidth limit

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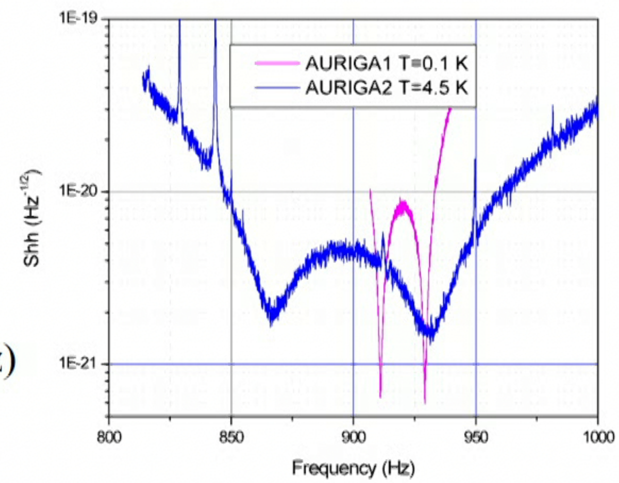
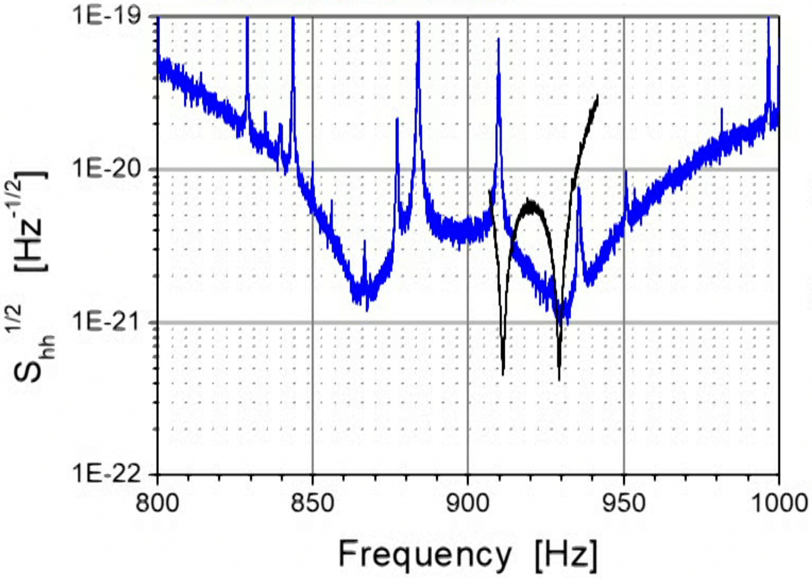


# $S_{hh}$ sensitivity (1)

INFN

AURIGA

**initial operation at 4.5 K started on Dec. 24th 2003**

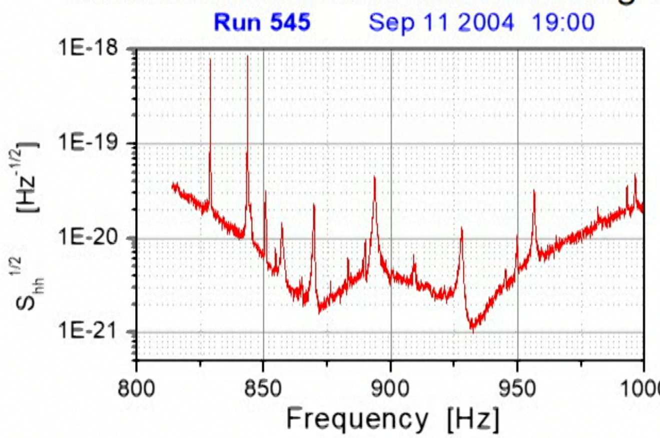


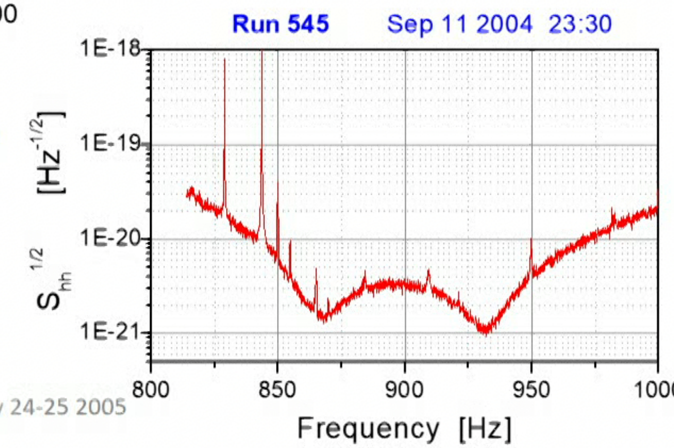

**unmodeled spurious noise peaks** within the sensitivity bandwidth

- not related to the dynamical linear response of the detector
- non gaussian statistics
- related to mechanical external disturbances

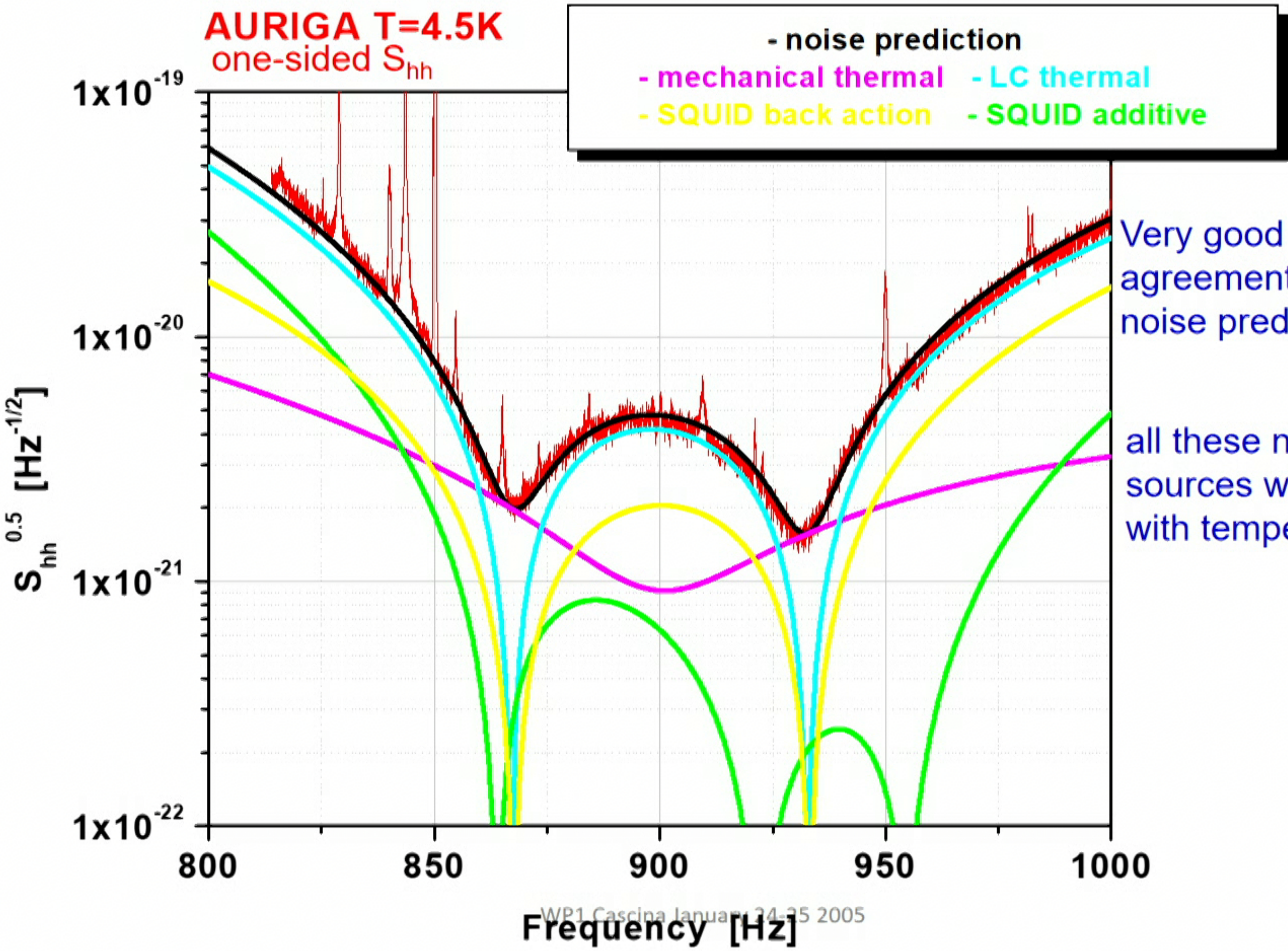
**up-conversion of low frequency noise**

… months of diagnostic measurements and noise hunting …



## $S_{hh}$ sensitivity (2)



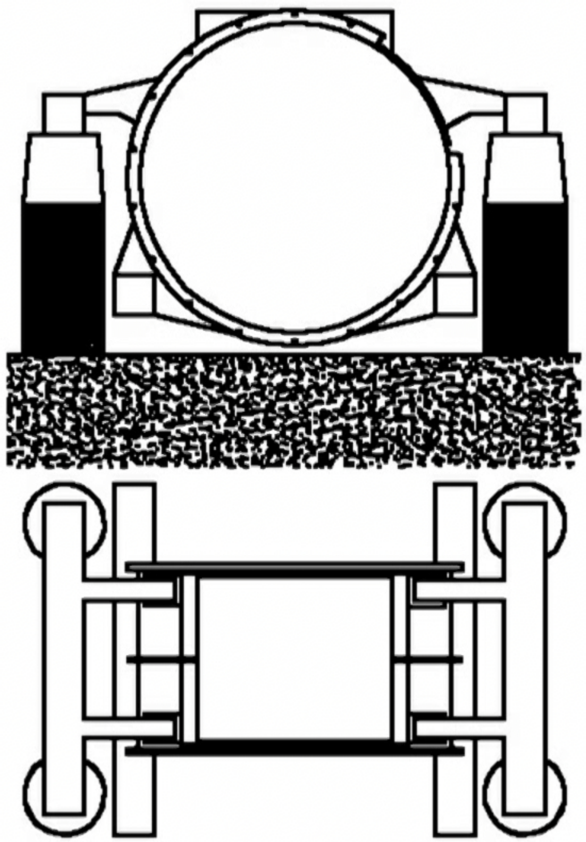

Very good agreement with noise predictions

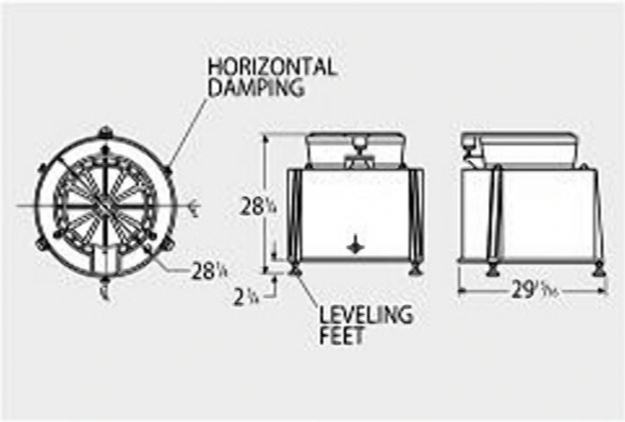
all these noise sources will scale with temperature

WP1 Cascina January 24-25 2005

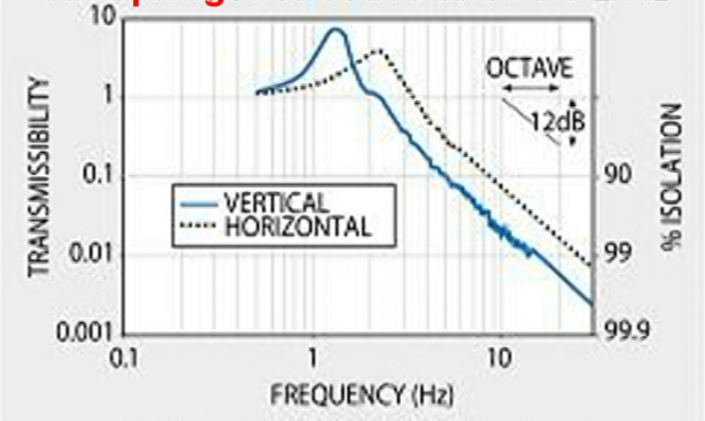
# Seismic isolation up-grade

## external suspensions low frequency with vibrational damping






**Air springs: effective above 1-2 Hz**



# Metal-arc welding on cryostat while keeping liquid helium in

"wings" to support Auriga above the center of mass of the cryostat

## Step 2: integration of low frequency suspensions (May 19th)

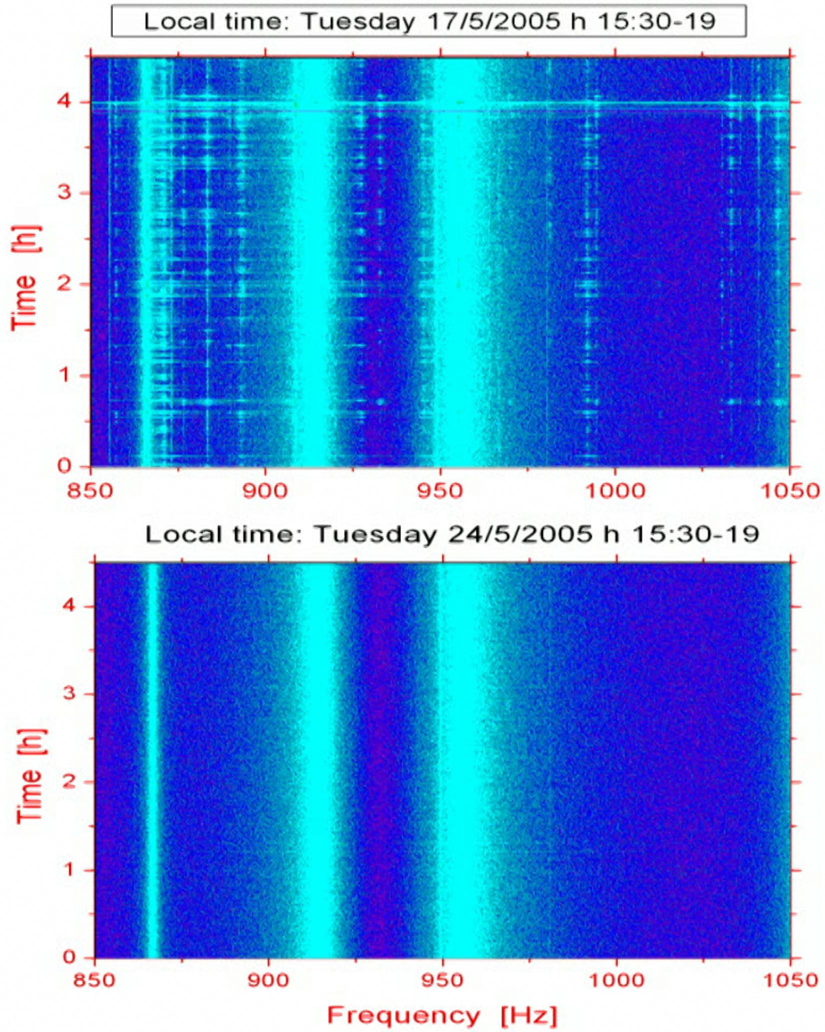
**Final configuration**

Ferroconcrete Pillar

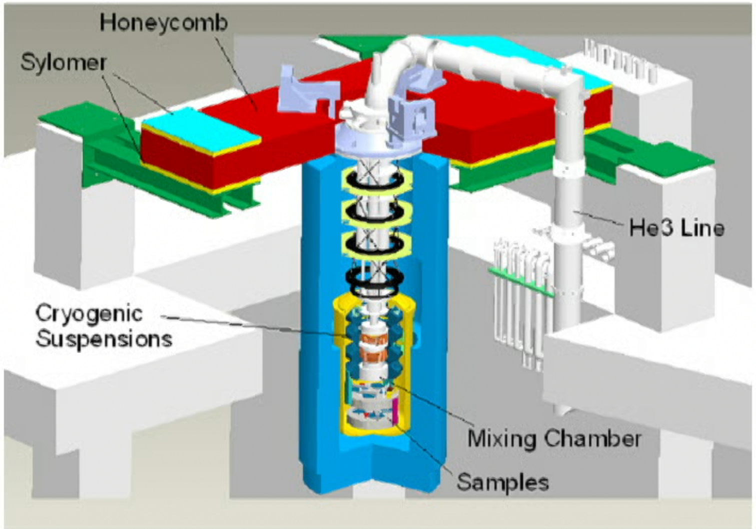
# Last breakthrough:
# achieved 98% Duty Cycle
(May 2005)

"Before the up-grade"

"After the up-grade"



# Test Facility

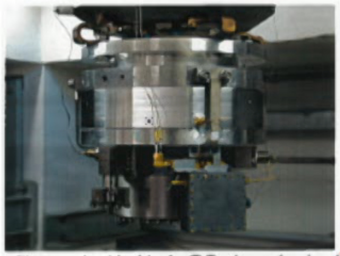


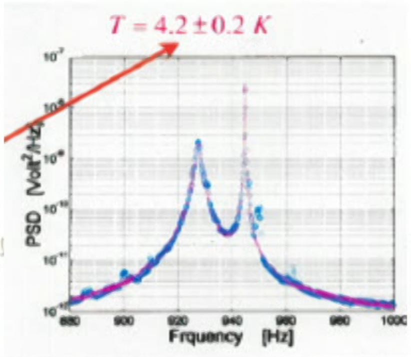

- Heater line to stabilize temperature point.
- Piezoelectric actuator (shaker) to excite sample normal modes.
- Internal high vacuum chamber (down to 1E-7 mbar scale).

**TEMPERATURE MEASUREMENTS RANGE:**
- **2-300 K – Liquid $He^4$ a/o Liquid $N_2$ bath**
- **100mK-2K - dilution refrigerator**

- Cryogenic suspensions 180 db at ~1kHz at 4K (possibility of thermal noise measurement).
- Dilution refrigerator (1mW at 100 mK).
- ~0.04m³ ~50kg available payload: room for more samples in a single run (for example, five samples in last run).
- One optical window.

Shaker

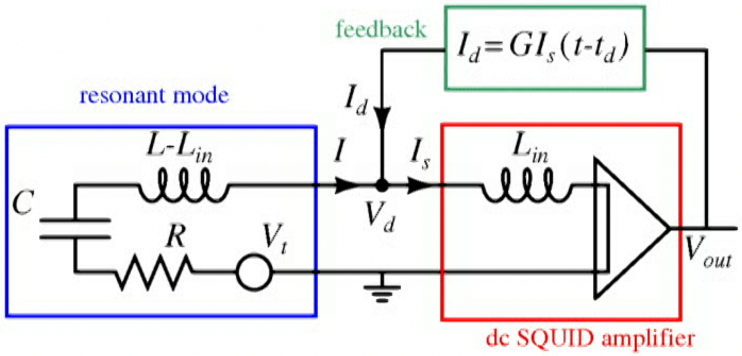


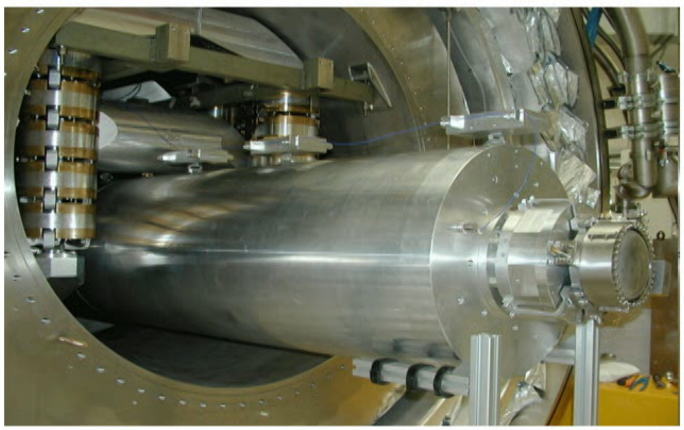


## We measure the noisy position of an oscillator and feed back a force proportional to its velocity, equivalent to an additional damping.

**Standard scheme, now considered to reduce the thermal vibration noise and allow the observation of quantum effects.**

**We applied the technique on the Gravitational Wave detector AURIGA (INFN):**
**3-ton resonant bar cooled to 4.6 K and very well isolated.**



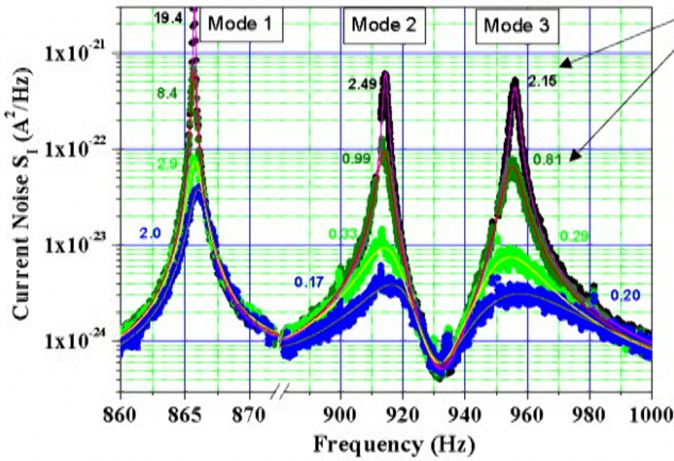



**The resulting Langevin equation does not satisfies the Einstein relation:**

$$L\frac{dI_s(t)}{dt} + I_s(t)\left[R + R_d\right] + \frac{q_s(t)}{C} = \sqrt{2k_B T_0 R}\,\Gamma(t)$$

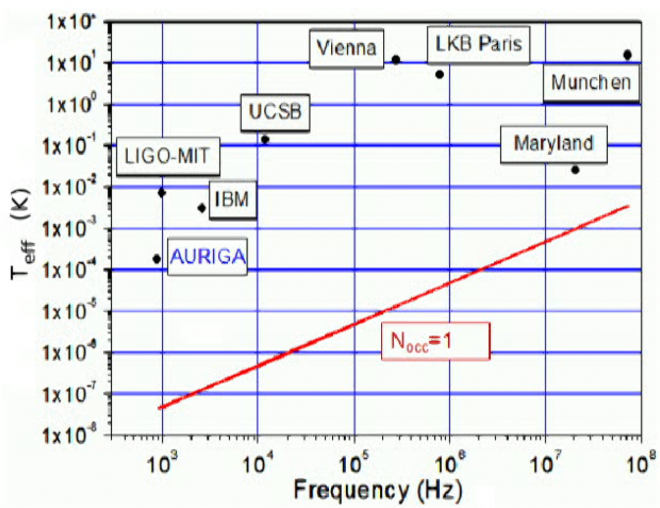
**the additional damping calms down the oscilla**
**BUT**
**the thermal driving force remains the same**

# "Top ten 2008" AIP-APS




$T_{eff}$ [mK]

At increasing feedback gain, the 3 modes of the detector reduce their vibration amplitude.
The equivalent temperature of the vibration was reduced down to $T_{eff}$=0.17 mK.




Far from the world record in terms of occupation number

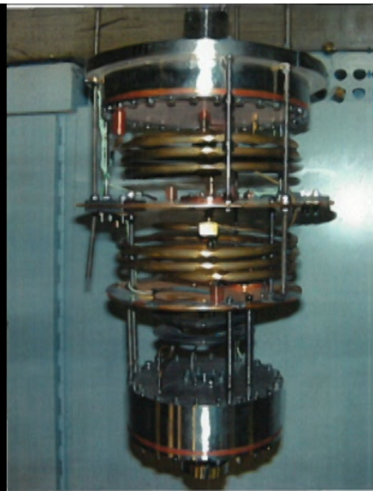
but

quite a remarkable result given the size of the system!

A.Vinante at al.
PRL 101, 033601 (2008);
Viewpoint: Physics 1, 3 (2008);
Selected as one of the "Top ten physics stories of the year 2008" by the American Institute of Physics and the American Physical Society.

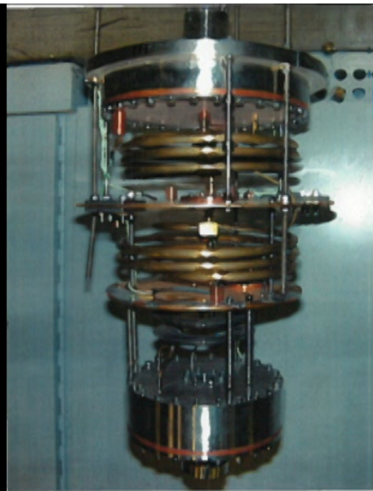
# UltraCryogenic tons Apparatus

| | AURIGA | | CUORE |
|---|---|---|---|
| Tbase (work point) | 65(200) | mK | 7(16) |



# ltraCryogenic tons Apparatus

| | AURIGA | | CUORE |
|---|---|---|---|
| | 65(200) | mK | 7(16) |
| Precooling mixture | 1 Kpot | | Pulse Tube |
| Wiring | 20 | cables | 6000 |
| Weigth below 4 K | 6 | t | 16 |
| Ultimate Thermal links | OFHC | annealed and golded copper (RRR) | NOSV |



# ltraCryogenic t … s

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|---|---|---|---|
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