Exploration of the stratosphere with cosmic-ray muons detected underground

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Exploration of the stratosphere with cosmic-ray muons detected underground

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(LVD Collaboration)

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SUMMARY

- 24-year series of the underground muon flux recorded with the Large Volume Detector (LVD) in the Gran Sasso Laboratory
- Advanced spectral methods: annual and multiannual significant components
- Multiannual components are not present in the effective temperature

  SSA analysis of raw temperature
  at different levels in the atmosphere
- Origin of the multiannual variations

  annual temperature cycle as a function of height

  relationship with the solar activity
- Amplitude of the multiannual variations much larger than expected from temperature
- Short-term (daily to monthly scale) variations
- Gran Sasso area in a larger-scale perspective

Aglietta et al. (The LVD Collaboration), Il Nuovo Cimento A , 1992

INFN Istituto Nazionale di Fisica Nucleare

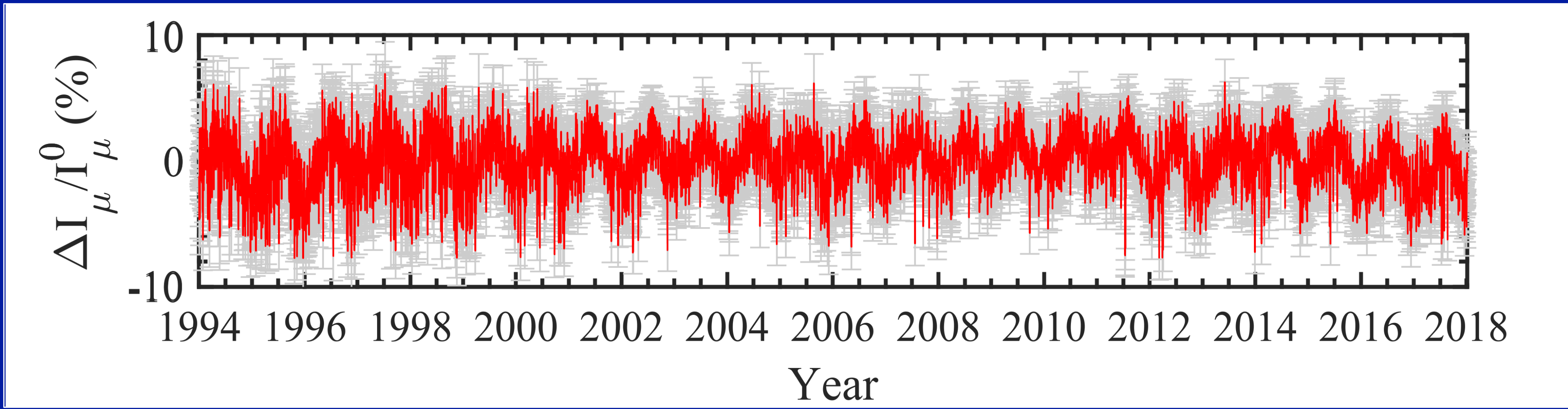
LVD

The Large Volume Detector

- *1000 tons of liquid scintillator*
- *Depth: 1400 m of rock (3600 m.w.e.)*
- *840 counters, each viewed by three PMTs - 3- fold coincidence mode*
- *μ rate ~ 0.1Hz*
- *Energy Threshold: E_H~4 MeV (E_L~0.5 MeV for 1 ms)*
- *50% trigger efficiency at 4 MeV*
- *15% energy resolution at 10 MeV*
- *Timing accuracy 12.5 ns (relative) /100 ns (absolute)*
- *Muon energy threshold: 1.3 TeV*

(~1 muon per million at the sea level can penetrate down to the LNGS depth)

THE DAILY MUON FLUX TIME SERIES …



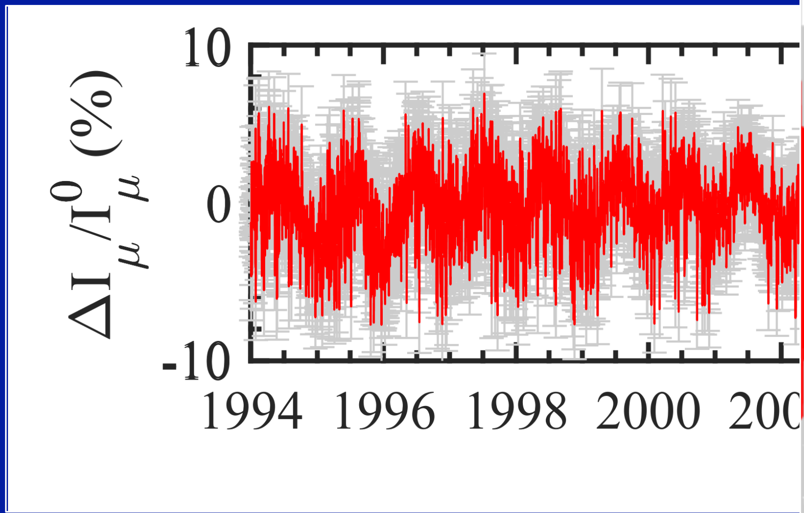
Agafonova et al. (The LVD Collaboration), Phys. Rev. D 2019

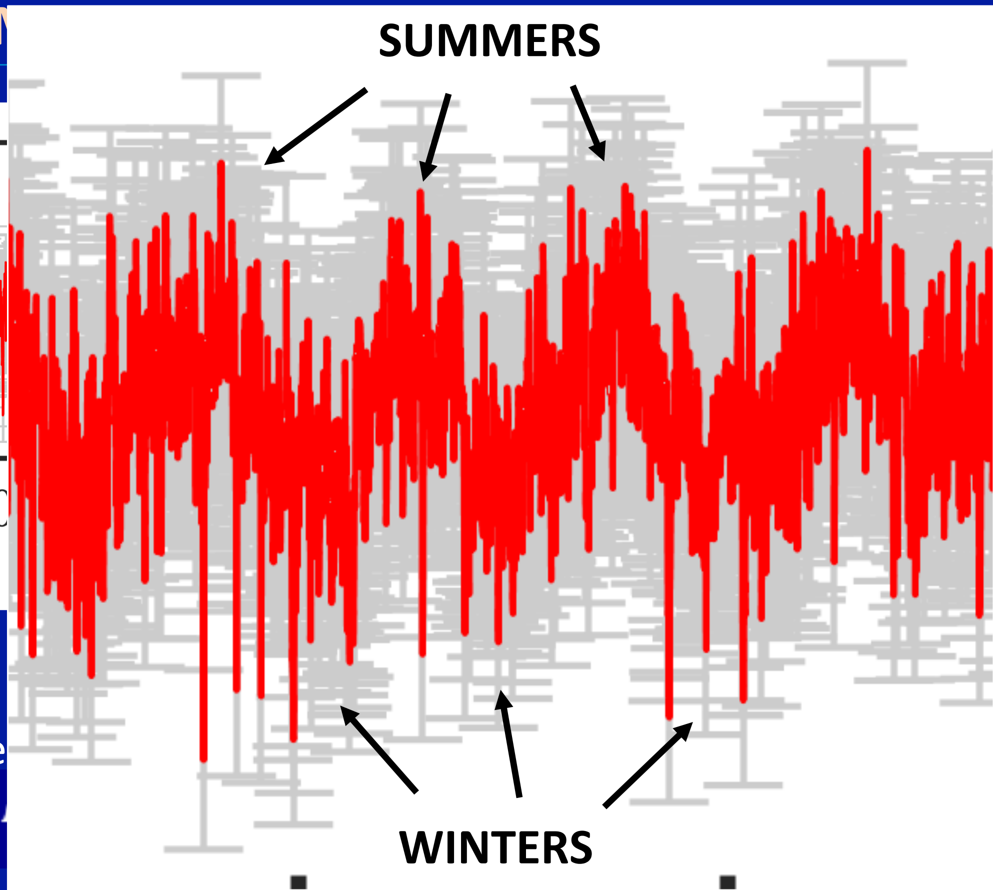
- January 1994 – December 2017 (24 years) – the longest muon flux series
- Relative deviations from the average I_μ^0
- Dominant annual cycle

… AND THE ATMOSPHERIC TEMPERATURE

T ↑ ⇨ ρ_{air} ↓ ⇨ decay probability of mesons ↑ ⇨ Muon flux ↑

THE DAILY M





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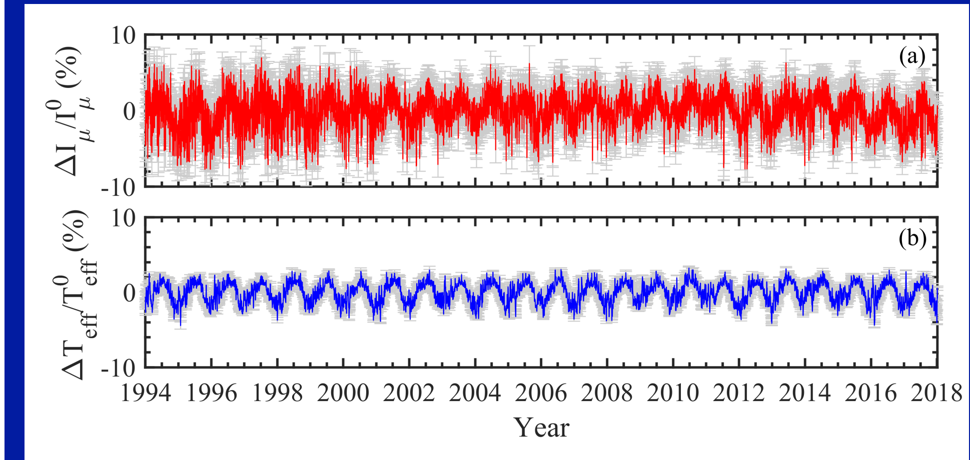
MUON FLUX AND EFFECTIVE TEMPERATURE



To describe the effect of temperature variations on muons production

➡ a weighted temperature average on N layers is conventionally used in this kind of studies:

$$T_{eff} = \frac{\sum_{n=1}^{N} \Delta X_n T(X_n) W(X_n)}{\sum_{n=1}^{N} \Delta X_n W(X_n)}$$

temperature data from the ERA-Interim reanalysis dataset- ECMWF

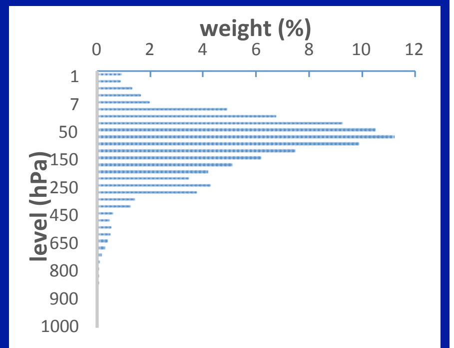
called **EFFECTIVE TEMPERATURE**

T_{eff} : temperature of an ideal isothermal atmosphere that would produce the observed muon intensity

$T(X_n)$

ΔX_n layer thickness

$W(X_n)$ weight



$$\frac{\Delta I_\mu}{I^0_\mu} = \alpha_T \frac{\Delta T_{eff}}{T^0_{eff}} \qquad \alpha_T = 0.94 \pm 0.02$$

r = 0.56 ($p_{value} < 10^{-5}$)

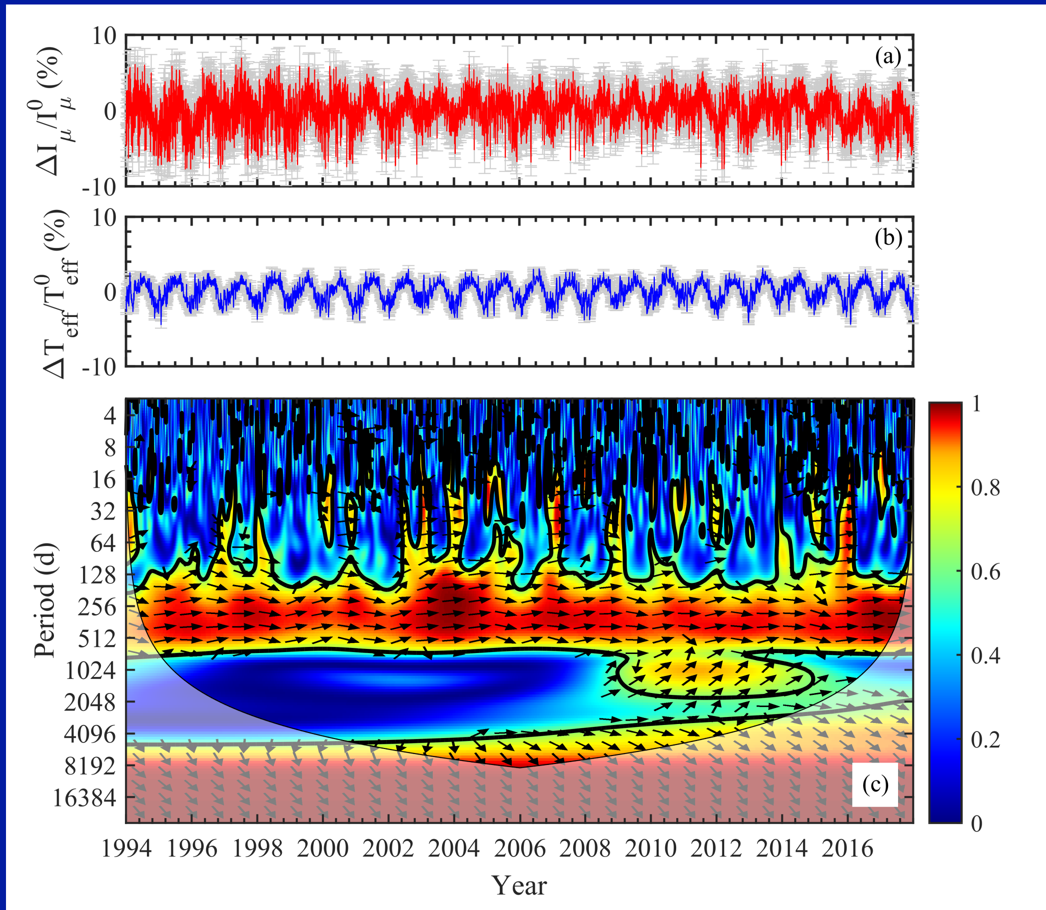
WAVELET TRANSFORM COHERENCE:
a general view of common oscillations from days to decades

HIGH SIGNIFICANT CORRELATION :

- Annual red band (as expected)
- ~ 4 y (from 2008)
- ~ 10 y

Red band lies outside the cone of influence (edge effects)

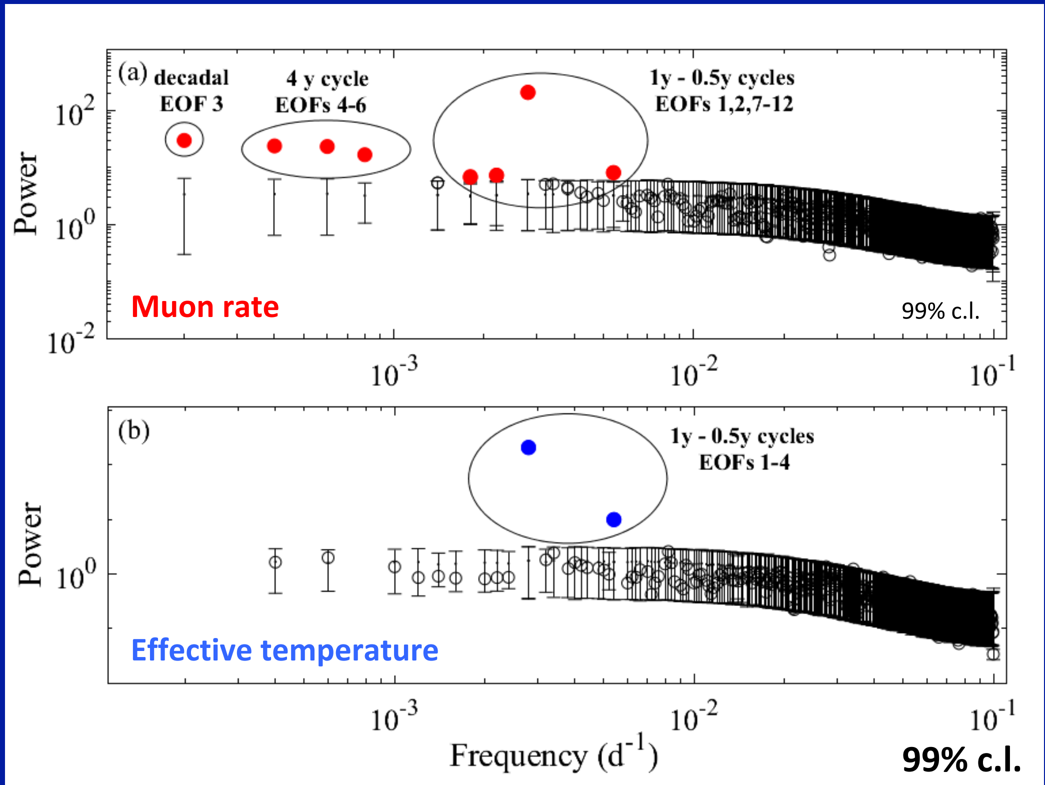
WTC method not suitable for such long-term component



Daily series

95% confidence level

MONTE CARLO - SINGULAR SPECTRUM ANALYSIS (SSA): SIGNIFICANT COMPONENTS



0.5 y (2%)
1 y (44%)
~ 4 y (6.4%)
~ 10 y (3%)

the annual cycle dominates both series

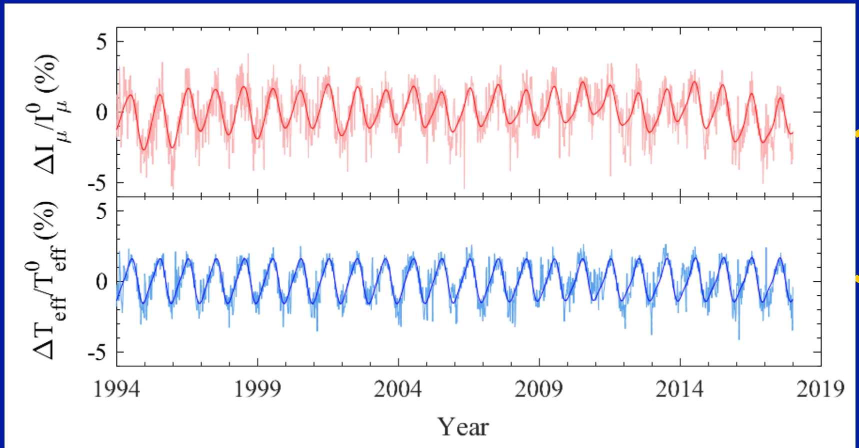
0.5 y (3%)
1 y (68%)

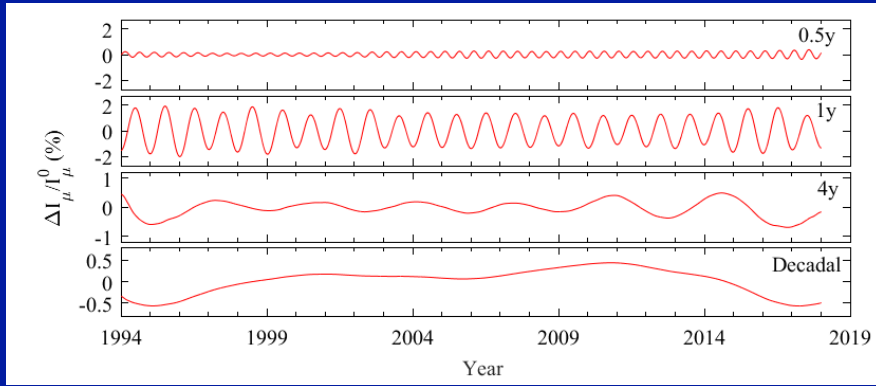
→ the muon flux shows a spectral content richer than the effective temperature

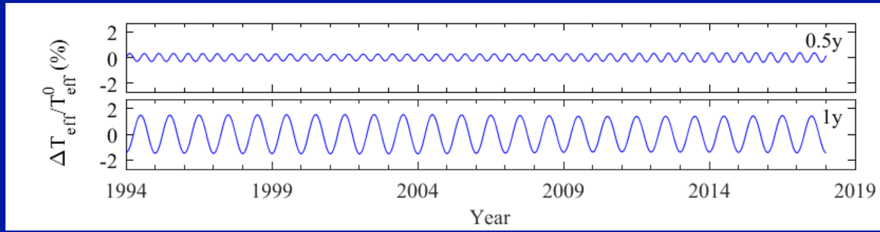
5-days rebinned series

Null hypoth. : AR(1) noise

RECONSTRUCTED SIGNIFICANT COMPONENTS







→ 4y cycle

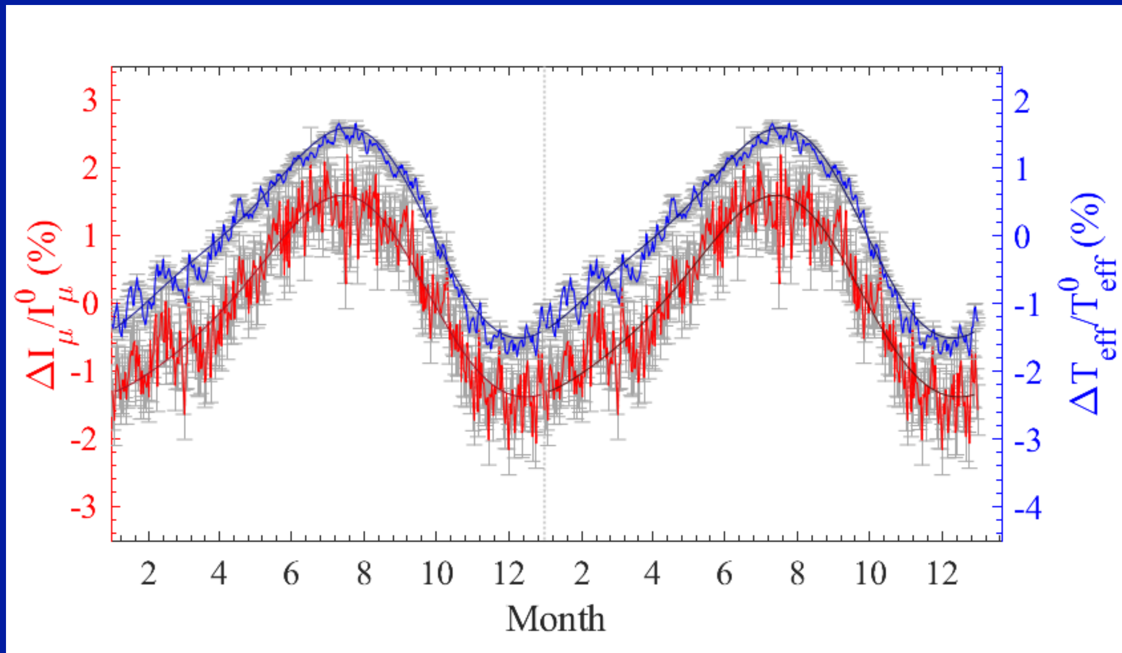
→ decadal variation

Note: the components are not sinusoidal waves!

SEMIANNUAL COMPONENT AND ASYMMETRY OF THE ANNUAL VARIABILITY

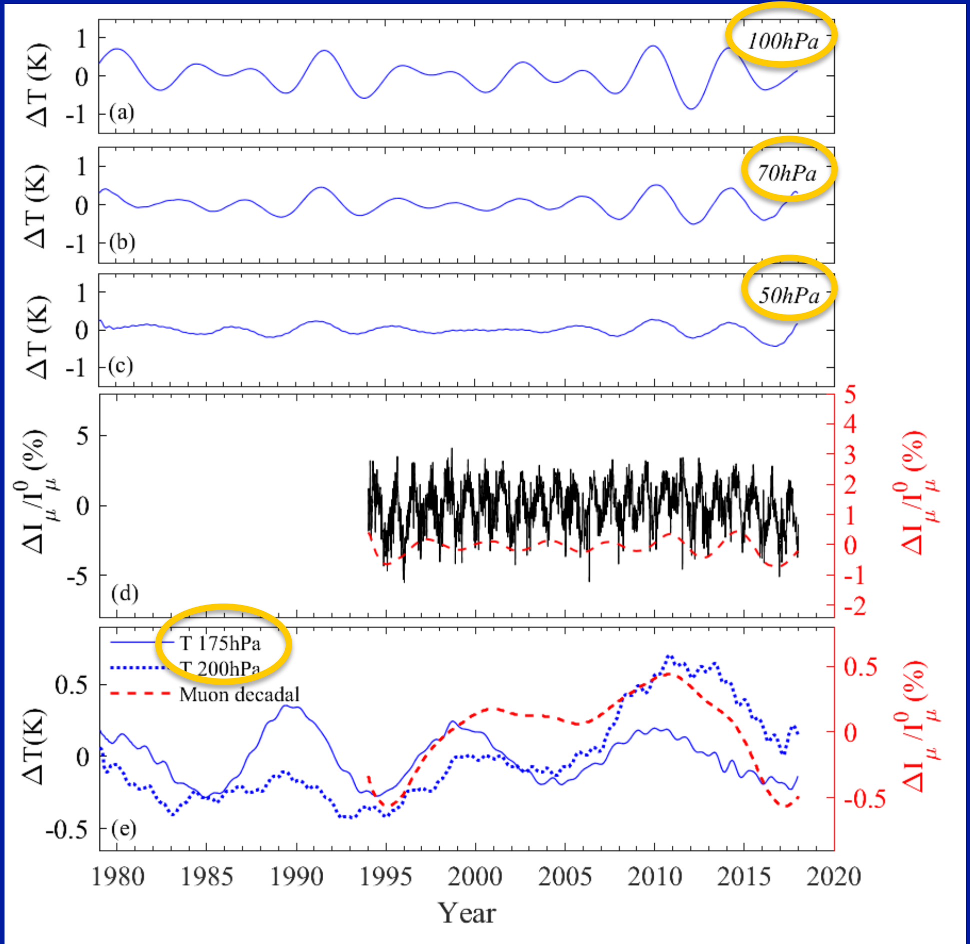
The folding of the 24-y muon flux and effective temperature time series onto a 1-y period reveals an asymmetry of the annual variability

Denoised superposed signals: sum of the annual and semiannual SSA-components



The semiannual component describes the pronounced asymmetry of the annual variability → It is due to sudden warming events which happen in winter

ORIGIN OF THE MULTIANNUAL (decadal and 4-y) COMPONENTS



The variations in the muon flux MUST reflect temperature variations!

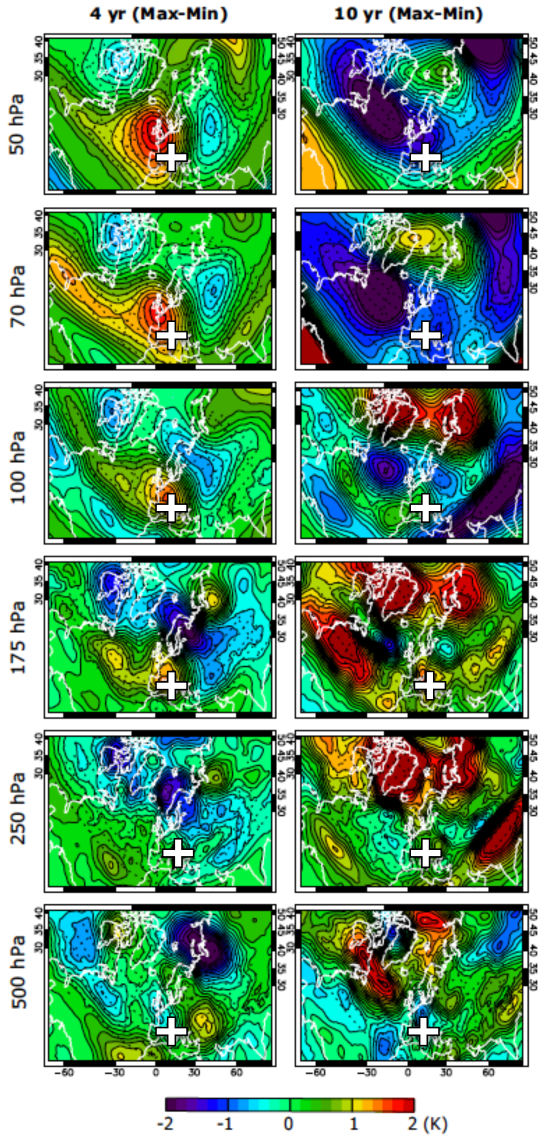
We investigate the origin of the decadal and 4-y components in the muon series by applying the SSA to the raw temperature time series layer by layer (from the ERA-Interim reanalysis dataset- ECMWF)

4 y → **100 hPa** – 70 hPa – 50 hPa

10 y → **175-200 hPa**

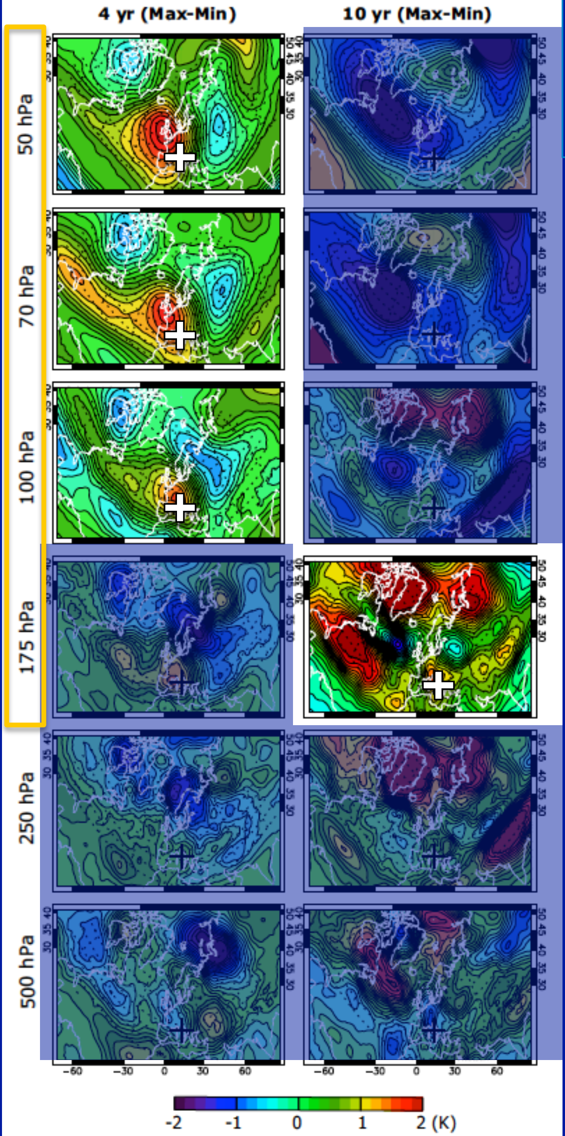
tropopause, low-stratosphere

DECADAL AND 4-Y TEMPERATURE COMPONENTS: LARGE-SCALE PERSPECTIVE



Maps - over the Northern Hemisphere- of the intensity of the 4-y and decadal temperature oscillations at different levels
(differences between periods of maxima and minima)

+ GRAN SASSO LABORATORY



DECADAL AND 4-Y TEMPERATURE COMPONENTS: LARGE-SCALE PERSPECTIVE

→ Maximum intensity is present in the layers suggested by the SSA analysis

4 y → 100 hPa – 70 hPa – 50 hPa

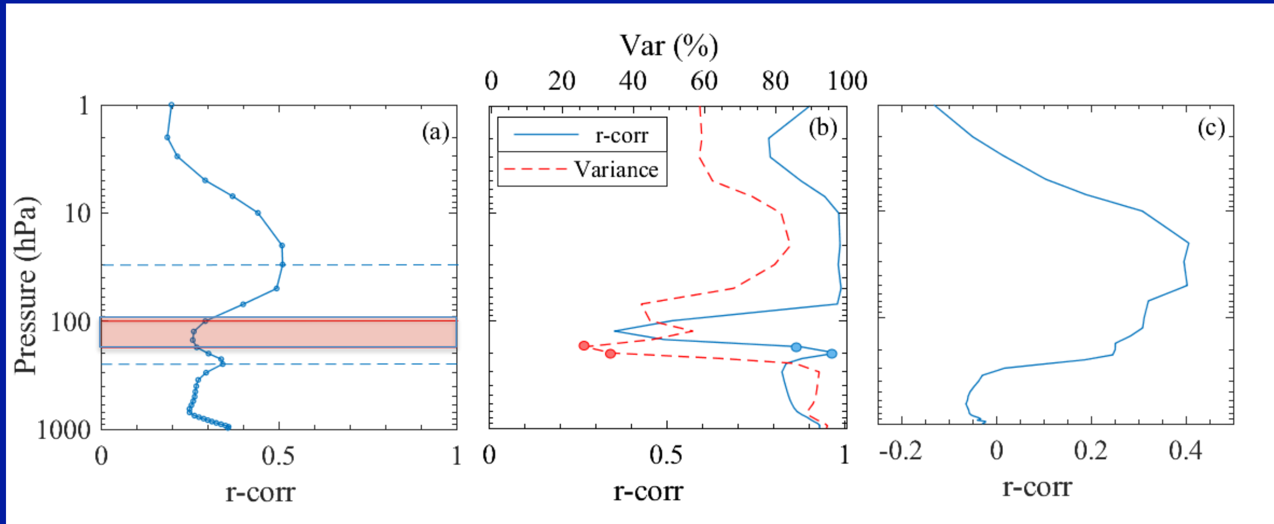
10 y → 175 hPa

→ both cycles are **not local but extended in larger areas** (4-y: Western Europe decadal variation: Northern Hemisphere)

WHY THE 4- AND 10-YEAR CYCLES ARE EVIDENT IN THE TEMPERATURE JUST AT THESE LEVELS (LOWER STRATOSPHERE)

_?_

ATTENUATION OF THE DOMINANT ANNUAL CYCLE



We examine the **correlation coefficients** between the muon series and the temperature series at different levels

(a) local correlation minimum between 100 and 200 hPa (in red) → Multiannual periodicities revealed exactly around this minimum!

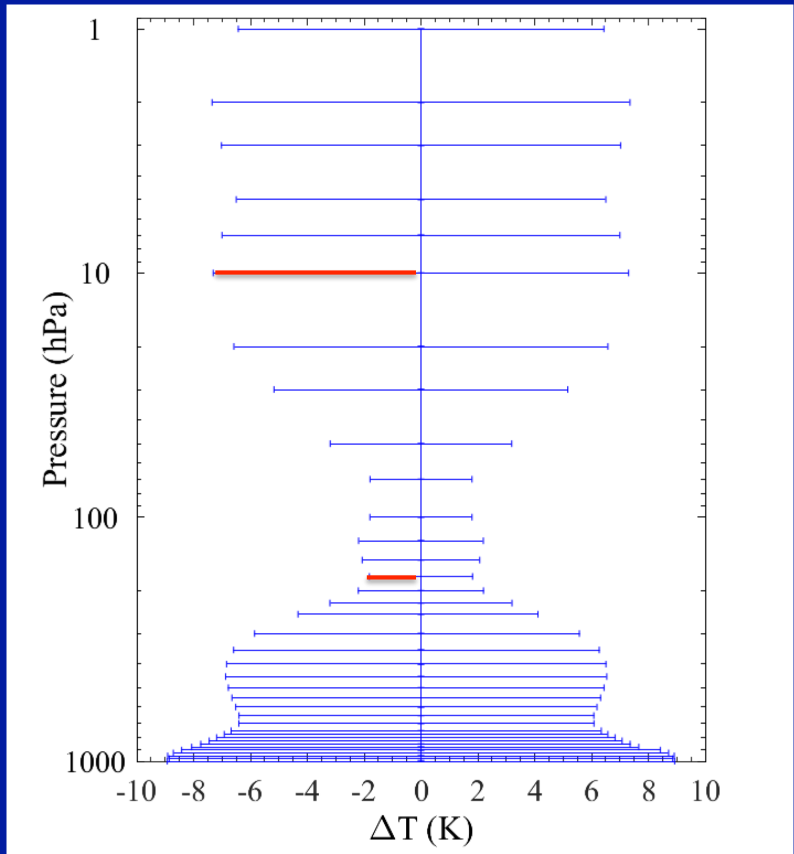
Hyp.: minimum in the correlation is due to to the weakening of the annual cycle → Plausible, because:

(b) minimum variance of the temperature annual component corresponds to these layers (dotted red curve) and

(c) after detrending muon and temperature series with the annual cycle: the correlation minimum disappears

→ **THE MULTIANNUAL CYCLES EMERGE IN THE TEMPERATURE SERIES AT THE LAYERS IN WHICH THE DOMINANT ANNUAL CYCLE IS WEAKER**

AMPLITUDE OF THE ANNUAL CYCLE



The amplitude of the annual cycle decreases by a factor of ~4 from 10 to 100–200 hPa and then increases again below this level

DECADAL MUON COMPONENT AND THE 11-Y SOLAR CYCLE

11-y solar cycle modulates cosmic rays with E < 1 GeV

⇓

muons cannot reach the Gran Sasso Laboratory

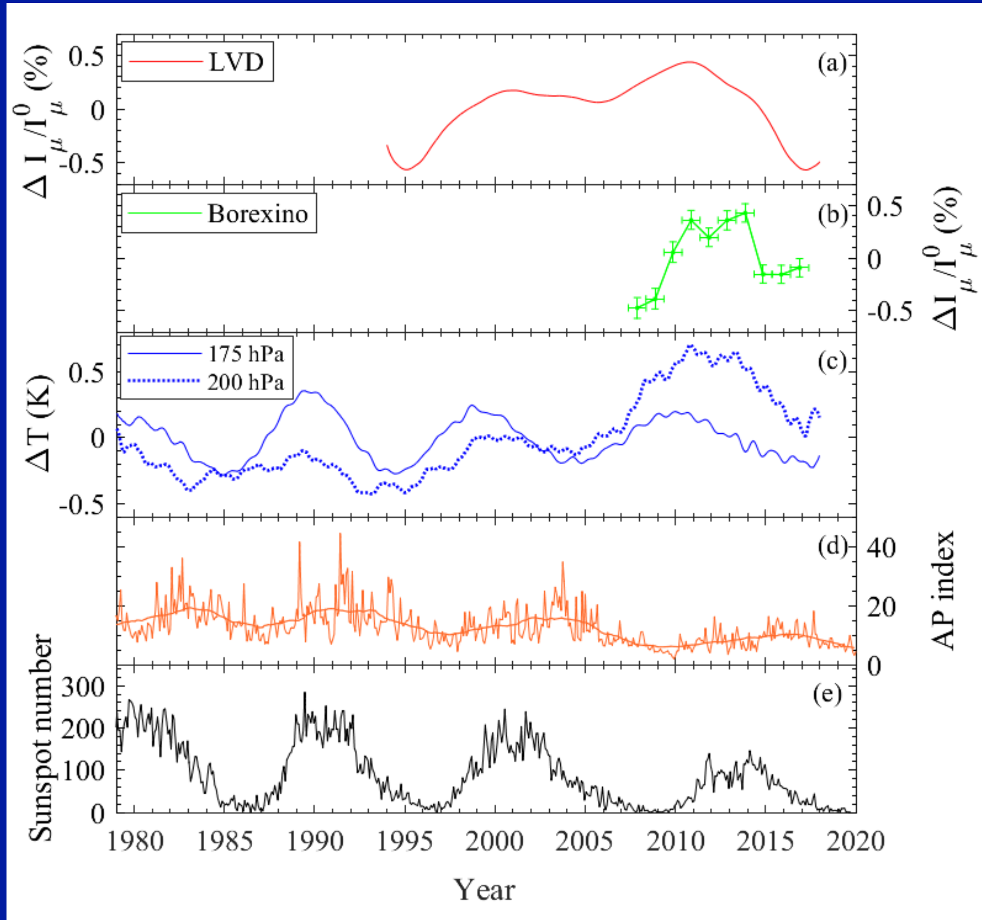
11-y solar cycle

⇓

stratospheric temperature

⇓

muon flux decadal modulation



- Reasonable agreement between decadal muon and temperature components and sunspot number series
- Borexino experiment: 10 y of data decadal modulation consistent with LVD data and in phase with the solar cycle
- Temperature not perfectly in phase with sunspot number series ⟶ terrestrial effects modify the original solar signal (UV absorption by ozone, geomagnetic activity variations, etc.)

AMPLITUDE DISCREPANCY

The amplitude of the multiannual modulations imprinted in the muon series is much larger than that expected from temperature variations

Amplitude of the muon decadal variation: $\frac{\Delta I_\mu}{I_\mu^0} \sim 1\%$ $\frac{\Delta T_{eff}}{T_{eff}^0} \sim 1\%$ ΔT_{eff} = 2.3 K

$T_{eff}^0 = 220.3 \pm 0.5\ \mathrm{K}$

$$\boxed{\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}^0} \qquad \alpha_T = 0.94 \pm 0.02}$$

At the 175–200 hPa levels, the decadal raw temperature variation is of ~ 0.75 K

These layers contribute to the effective temperature for only 9.3% → ΔT_{eff} = 0.07 K

A FACTOR OF ~ 30 LESS THAN EXPECTED!

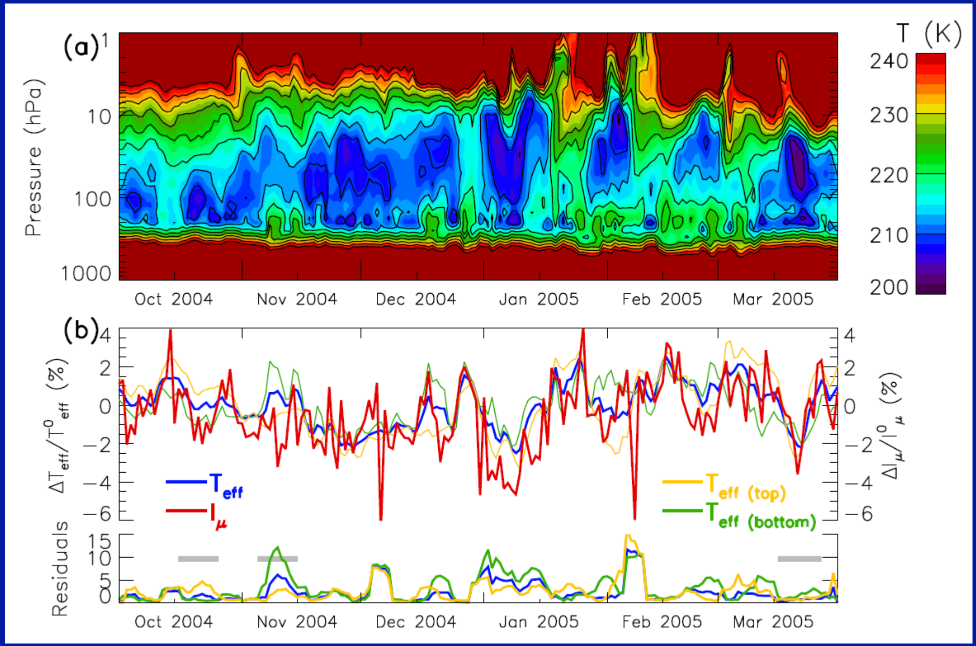
An analogous evaluation for the 4-y components yields a factor of ~ **10**

We suggest that the large discrepancy may be due to acknowledged **difficulties of the adopted temperature reanalysis dataset to represent long-term variability scales**

→ long-term modulations in the raw temperature series and, consequently, in the effective temperature record would result as artificially attenuated (not significant in the T_{eff} spectrum)

SHORT-TERM VARIABILITY

Example of the highly variable winter temperatures
in the LNGS area for the 2004–2005 cold season



- The muon variability reveals short-term (daily) temperature variability during winter

- Also on short time-scale, **muon variability is higher** then that of effective temperature

MAIN RESULTS (CONCLUSIONS)

1. Highly significant multiannual variations in the 24-y long muon flux series measured by LVD

1. The effective temperature is not adequate to explain what the muons see!

2. The amplitude of the long-scale modulations in the muon series is much larger than that expected from raw-temperature variations

MUON FLUX AS A HIGH TIME-RESOLUTION PROXY OF LOWER-STRATOSPHERIC TEMPERATURE