CMB and ‘ether-drift’ experiments

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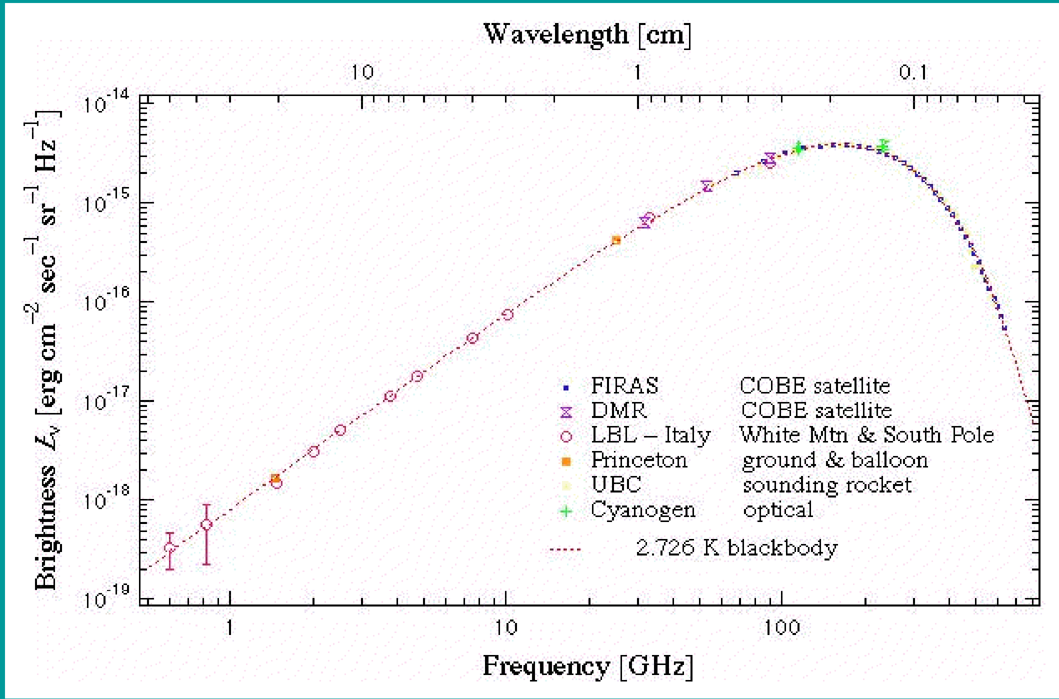
Virtual Institute of Astroparticle Physics, February 19th 2016

References: M.C., A. Pluchino, A. Rapisarda: Europhys. Lett. 113 (2016) 19001 also arXiv:1601.06518; M.C., C. Matheson, A. Pluchino: Eur. Phys. J. Plus, 128 (2013) 78 also arXiv:1302.3508[phys.gen]; M. C., Found. of Phys. 45(2015) 22.

Content

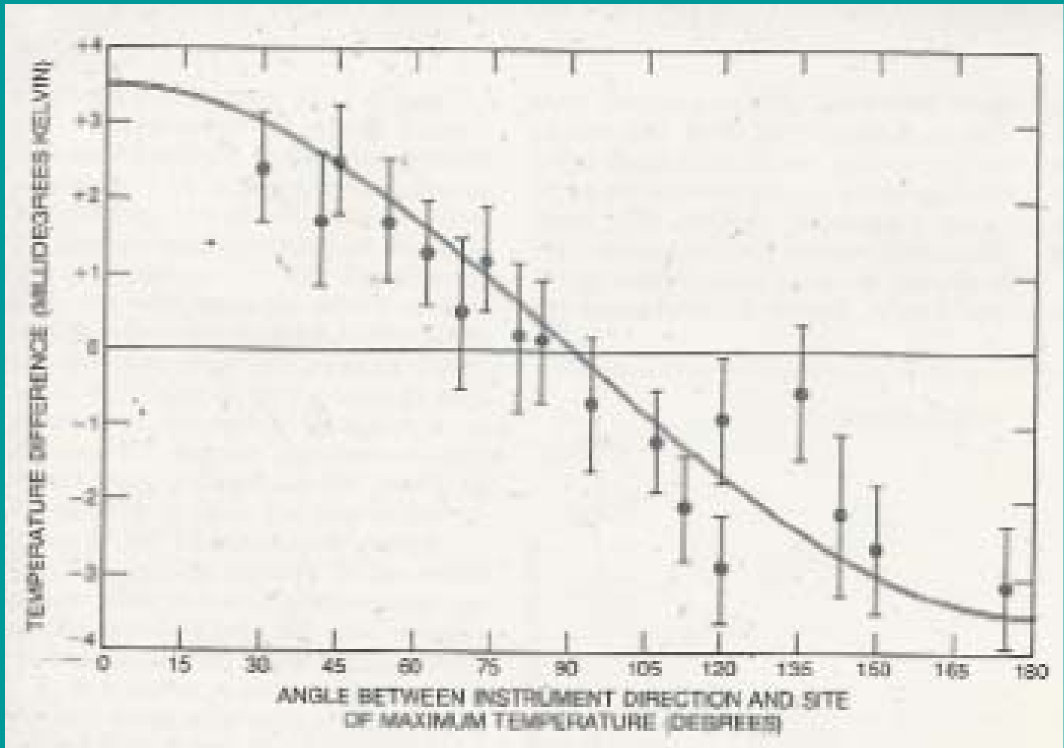
1) Introduction: the CMB and its dipole anisotropy
2) Is it possible to measure the dipole anisotropy in a laboratory?
3) Relevance of the classical ether-drift experiments
4) The first (and most famous) one : Michelson - Morley, 1887
5) The most extensive one : Miller, 1925-1926
6) The most accurate one: Joos, 1930
7) Modern experiments
8) Conclusions and outlook

The CMB spectrum



- The observation of the CMB (Penzias and Wilson 1965) is probably the most important discovery for cosmology
- Years of observations have confirmed its blackbody form to very high accuracy
- Figure taken from: http://spectrum.lbl.gov/www/cobe/cobe.html

The CMB dipole anisotropy



- Soon after the discovery of the CMB, it was pointed out by several authors that it should be possible to observe an anisotropy due to the Earth's motion
- The temperature measurements taken on board of U2 aircrafts at an height of 20 km. From Smoot, Gorenstein and Muller, Phys.Rev.Lett. 39 (1977) 898.

The dipole anisotropy in more detail

- Due to the motion of the observer a blackbody spectrum of temperature $\mathbf{T_0}$ becomes Doppler shifted as (**β=v/c**)

$$T(\theta,\beta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

- Thus, to first order, this gives an angular variation

$$\Delta T(\theta,\beta) \approx T_0\beta\cos\theta$$

- This changes from a “hot pole” (for **cosθ=1**) to a “cold pole” (for **cosθ= -1**) and for this reason is called “dipole” anisotropy
- From such anisotropy, COBE observations have determined the parameters of the Earth’s motion to very high accuracy:

v=369 km/s **right ascension=168 degrees** **declination= -7 degrees**

- This motion corresponds to combine i) the motion of the Solar System within the Galaxy with ii) the motion of our Galaxy (and of the Local Group of galaxies) with a velocity of about 600 km/s toward the “Great Attractor” , a large concentration of matter at about 100 Mpc from us

The dipole anisotropy as an “(a)ether drift”

- From Smoot’s Nobel lecture, one learns that, at the beginning, their research to detect the CMB dipole anisotropy was called “aether –drift” experiment

- This was a natural denomination. In fact, the anisotropy would have detected our drift within the CMB. In this sense, the CMB could be considered some form of (a)ether

- However, due to “the strong prejudice of those good scientists who learned the lesson of the Michelson-Morley experiment and special relativity that there were no preferred frames of reference ”, they had to change the name into

  “new aether-drift experiment”

- Only after this change (and after subtly clarifying the various issues) their research was finally approved

Measuring the CMB dipole in a laboratory?

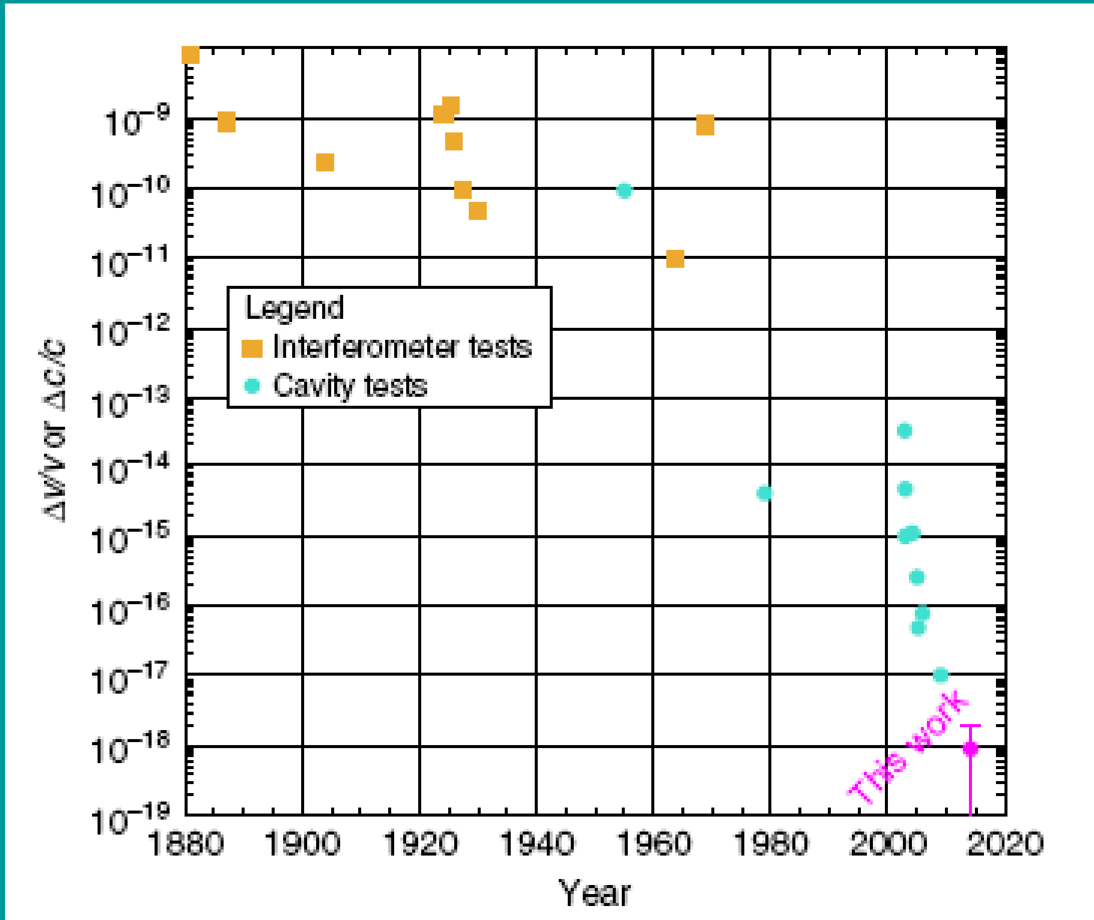
- However, today, after having measured the dipole anisotropy to high accuracy, are there still motivation for that "strong prejudice"?

- An observer moving within the CMB will see different temperatures in different directions. So far, most precise experiments were performed in space (with aircrafts or satellites). However, in principle, apart from possible experimental problems, nothing prevents to observe the same effect with measurements entirely performed inside a laboratory.

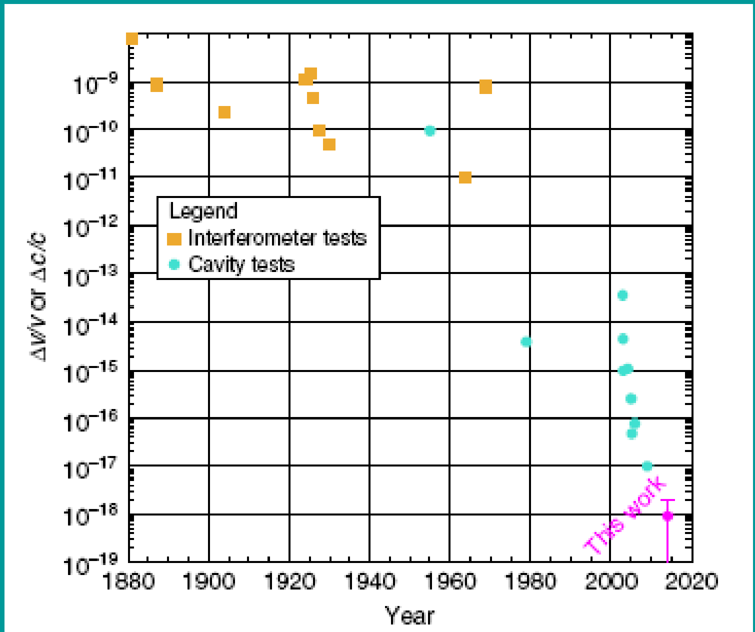
- For instance, a temperature gradient could induce small convective currents in a weakly bound gaseous system and a slight anisotropy of the velocity of light (propagating inside it) which could then be detected with a precise interferometer.

- In this perspective, it becomes natural to look for tiny deviations in the Michelson-Morley type of experiments. After all, periodic temperature differences of a few mK in the air of the optical arms were believed to be responsible for Miller's fringe shifts. This is precisely the order of magnitude expected from the dipole CMB anisotropy.

Standard summary of Michelson-Morley experiments



- Figure from: M. Nagel et al. Nature Comm. **6** (2015) 8174



- First impression: a steady substantial improvement over the original 1887 result

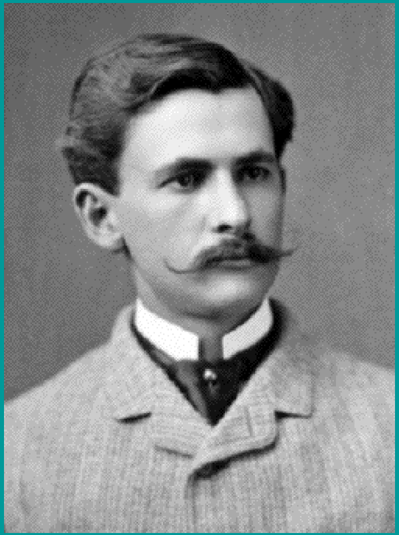
- However, not only technological progress. Experiments were also performed in different media (gases, vacuum or solids) .

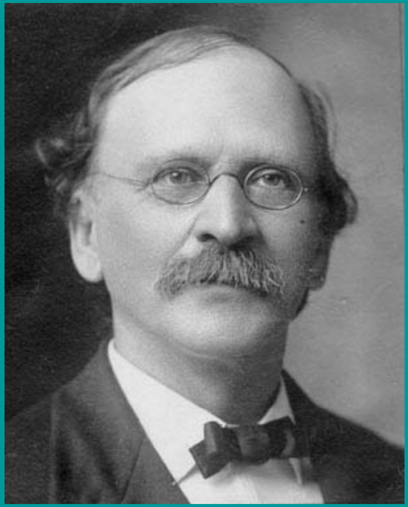
  Could this be important?

- For instance, a universal temperature gradient, conceivably, would affect light propagation in weakly bound gaseous systems more than propagation in solid dielectrics (or in vacuum where there is no matter to act on)

- To understand better the various aspects, one should start from Michelson-Morley where the whole story has begun

1887: Michelson-Morley experiment





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[THIRD SERIES.]

ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether;* by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

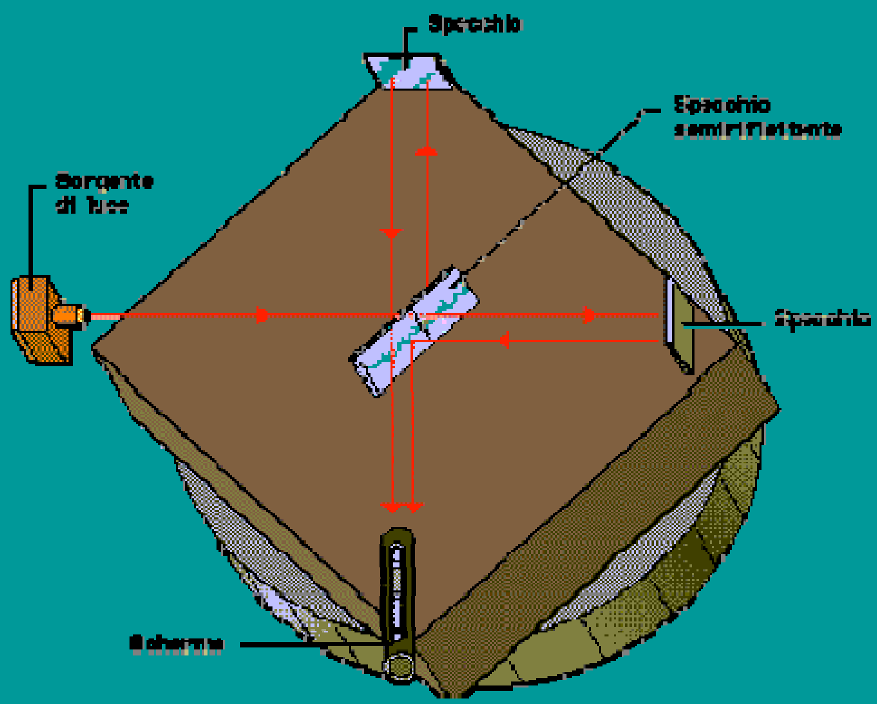
THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

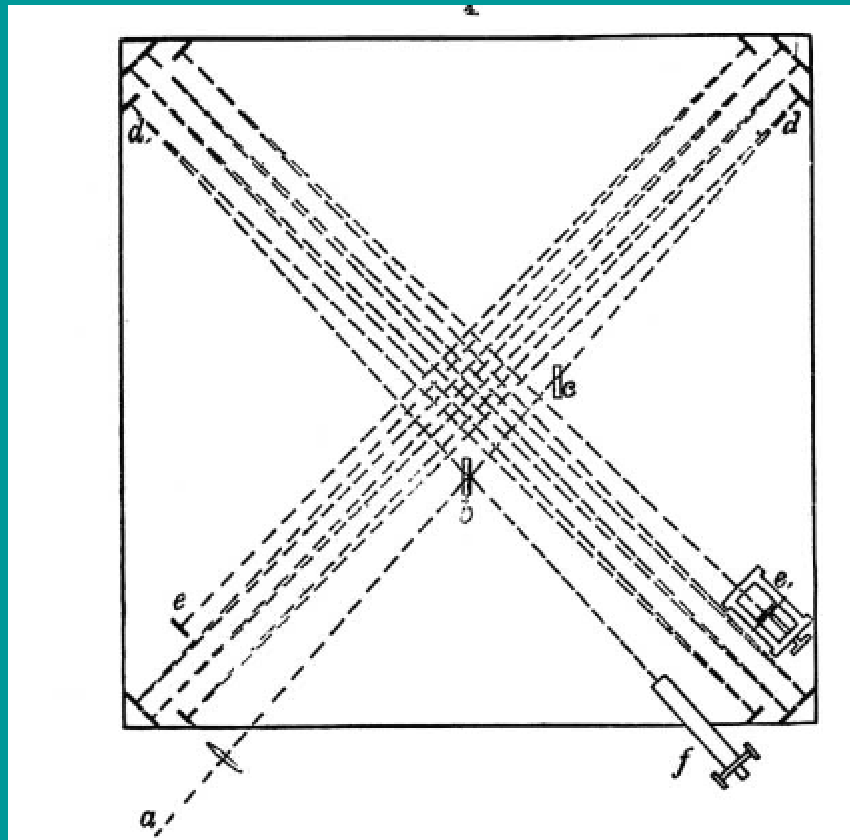
* This research was carried out with the aid of the Bache Fund.

† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

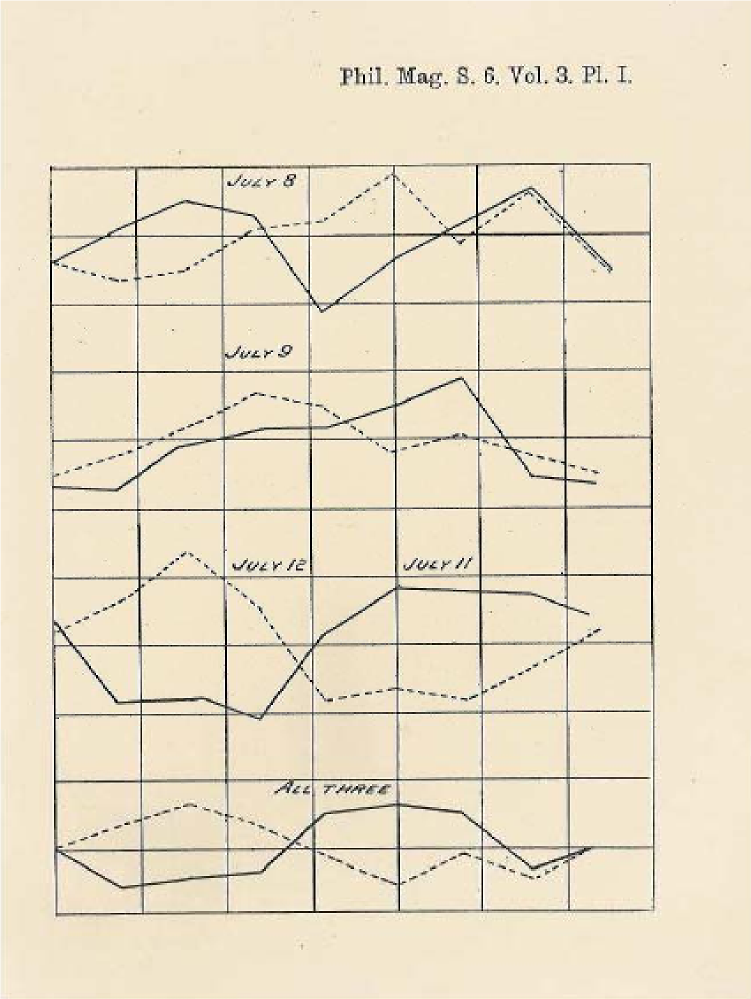
AM. JOUR. SCI.—THIRD SERIES, VOL. XXXIV, No. 203.—NOV., 1887.
22

The apparatus





1902 : Hicks'analysis



- "…the data published by Michelson and Morley, instead of giving a null result show distinct evidence for an effect of the type to be expected "

W. M. Hicks, Phil. Mag.3 (1902) 9

1933 : Miller’s analysis

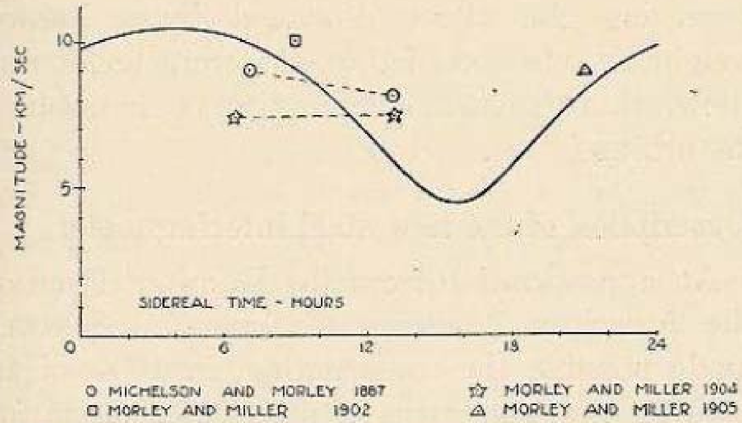


FIG. 4. Velocity of ether drift observed by Michelson and Morley in 1887, and by Morley and Miller in 1902, 1904 and 1905, compared with the velocity obtained by Miller in 1925.

- “The brief series of observations was sufficient to show clearly that the effect did not have the anticipated magnitude. However, and this fact must be emphasized, the indicated effect was not zero .”

- D. C. Miller, Rev. Mod. Phys. 5 (1933) 203

Michelson's interferometer

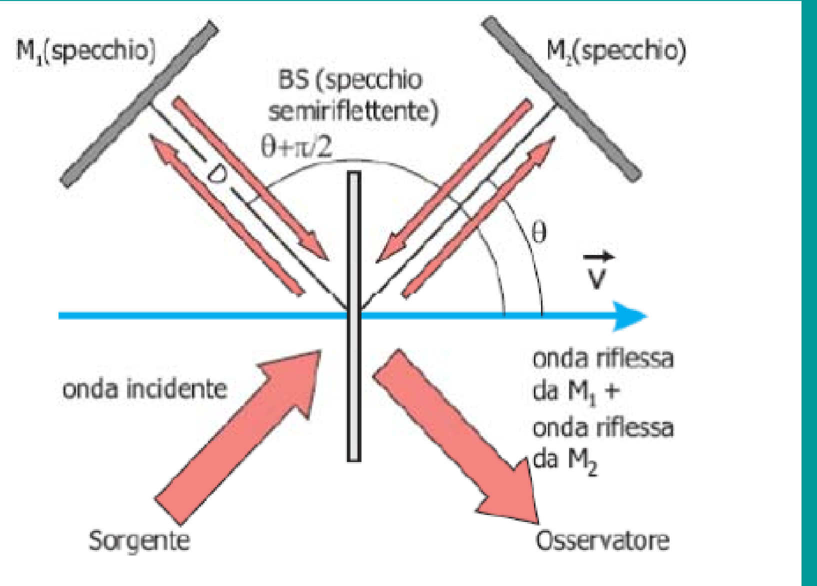


Figure 1: Il tipico schema dell'interferometro di Michelson.

- If the velocity of light changes in different directions, there will be a fringe shift by rotating a Michelson's interferometer.
- The classical formula (see e. g. R. Kennedy Phys. Rev. 47(1935) 965) is a "second harmonic" effect, i.e. periodic in [0,π]

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{class} \approx \frac{D}{\lambda}\frac{v^2}{c^2}\cos 2\theta = A_2^{class}\cos 2\theta$$

- Expected 2nd harmonic amplitude for the orbital velocity of 30 km/s

$$A_2^{class} \approx \frac{D}{\lambda}\frac{v^2}{c^2} \approx 2\cdot 10^7\cdot 10^{-8} \approx 0.2$$

The experimental data

NOON OBSERVATIONS.

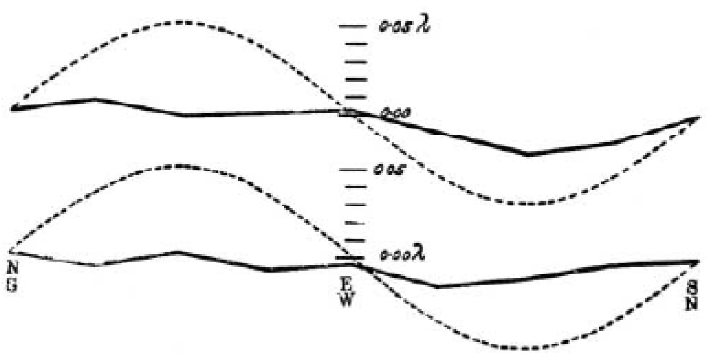
	16.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
July 8.......	44·7	44·0	43·5	39·7	35·2	34·7	34·3	32·5	28·2	26·2	23·8	23·2	20·3	18·7	17·5	16·8	13·7
July 9.......	57·4	57·3	58·2	59·2	58·7	60·2	60·8	62·0	61·5	63·3	65·8	67·3	69·7	70·7	73·0	70·2	72·2
July 11.......	27·3	23·5	22·0	19·3	19·2	19·3	18·7	18·8	16·2	14·3	13·3	12·8	13·3	12·3	10·2	7·3	6·5
Mean.......	43·1	41·6	41·2	39·4	37·7	38·1	37·9	37·8	35·3	34·6	34·3	34·4	34·4	33·9	33·6	31·4	30·8
Mean in w. l.	·862	·832	·824	·788	·754	·762	·758	·756	·706	·692	·686	·688	·688	·678	·672	·628	·616
	·706	·692	·686	·688	·688	·678	·672	·628	·616								
Final mean.	·784	·762	·755	·738	·721	·720	·715	·692	·661								

P. M. OBSERVATIONS.

	16.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
July 8.......	61·2	63·3	63·3	68·2	67·7	69·3	70·3	69·8	69·0	71·3	71·3	70·5	71·2	71·2	70·5	72·5	75·7
July 9.......	26·0	26·0	28·2	29·2	31·5	32·0	31·3	31·7	33·0	35·8	36·5	37·3	38·8	41·0	42·7	43·7	44·0
July 12.......	66·8	66·5	66·0	64·3	62·2	61·0	61·3	59·7	58·2	55·7	53·7	54·7	55·0	58·2	58·5	57·0	56·0
Mean.......	51·3	51·9	52·5	53·9	53·8	54·1	54·3	53·7	53·4	54·3	53·8	54·2	55·0	56·8	57·2	57·7	58·6
Mean in w. l.	1·026	1·038	1·050	1·078	1·076	1·082	1·086	1·074	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172
	1·068	1·086	1·076	1·084	1·100	1·136	1·144	1·154	1·172								
Final mean.	1·047	1·062	1·063	1·081	1·088	1·109	1·115	1·114	1·120								

The results of the observations are expressed graphically in fig. 6. The upper is the curve for the observations at noon, and the lower that for the evening observations. The dotted curves represent *one-eighth* of the theoretical displacements. It seems fair to conclude from the figure that if there is any dis-

6.



placement due to the relative motion of the earth and the luminiferous ether, this cannot be much greater than 0·01 of the distance between the fringes.

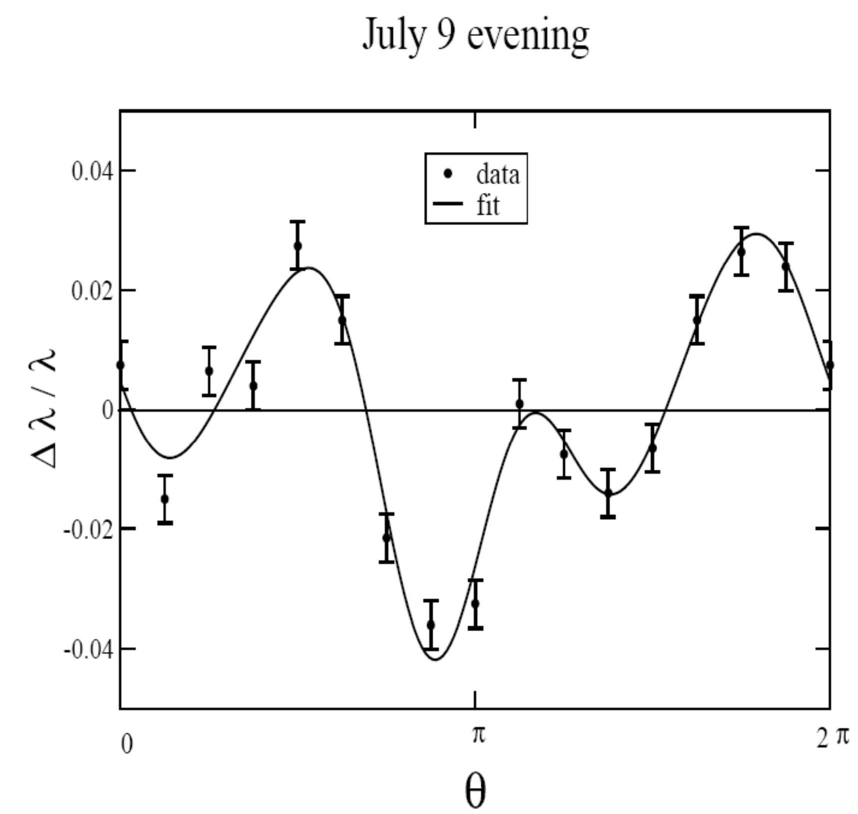
- The classical 2nd harmonic amplitude for 30 km/s is about 0.2 (NOT 0.4). Thus the shown amplitude 0.05 is 1/4 (NOT 1/8) of the expected value.

- "…if there is any displacement …, this cannot much be larger than 0.01 of the distance between the fringes".

Modern re-analysis

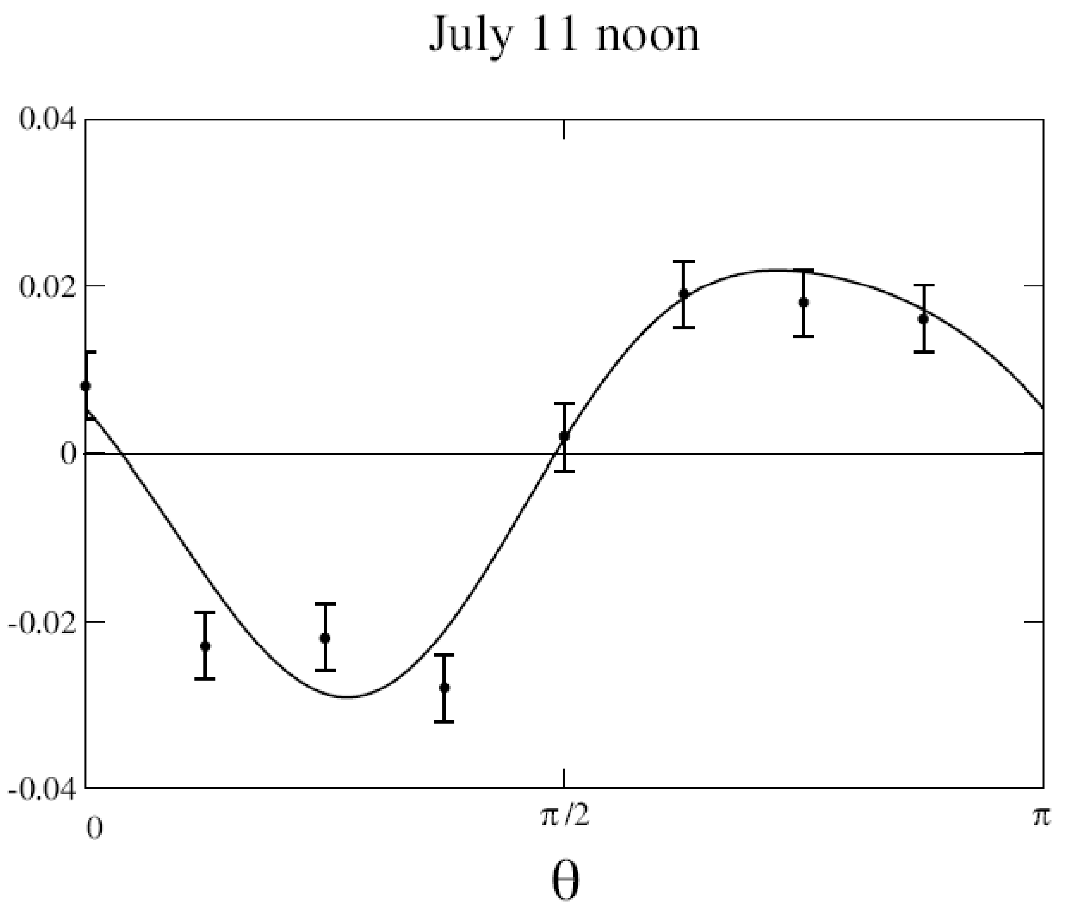
Table 1: *The fringe shifts* $\frac{\Delta\lambda(i)}{\lambda}$ *for all noon (n.) and evening (e.) sessions of the Michelson-Morley experiment.*

i	July 8 (n.)	July 9 (n.)	July 11 (n.)	July 8 (e.)	July 9 (e.)	July 12 (e.)
1	−0.001	+0.018	+0.016	−0.016	+0.007	+0.036
2	+0.024	−0.004	−0.034	+0.008	−0.015	+0.044
3	+0.053	−0.004	−0.038	−0.010	+0.006	+0.047
4	+0.015	−0.003	−0.066	+0.070	+0.004	+0.027
5	−0.036	−0.031	−0.042	+0.041	+0.027	−0.002
6	−0.007	−0.020	−0.014	+0.055	+0.015	−0.012
7	+0.024	−0.025	+0.000	+0.057	−0.022	+0.007
8	+0.026	−0.021	+0.028	+0.029	−0.036	−0.011
9	−0.021	−0.049	+0.002	−0.005	−0.033	−0.028
10	−0.022	−0.032	−0.010	+0.023	+0.001	−0.064
11	−0.031	+0.001	−0.004	+0.005	−0.008	−0.091
12	−0.005	+0.012	+0.012	−0.030	−0.014	−0.057
13	−0.024	+0.041	+0.048	−0.034	−0.007	−0.038
14	−0.017	+0.042	+0.054	−0.052	+0.015	+0.040
15	−0.002	+0.070	+0.038	−0.084	+0.026	+0.059
16	+0.022	−0.005	+0.006	−0.062	+0.024	+0.043



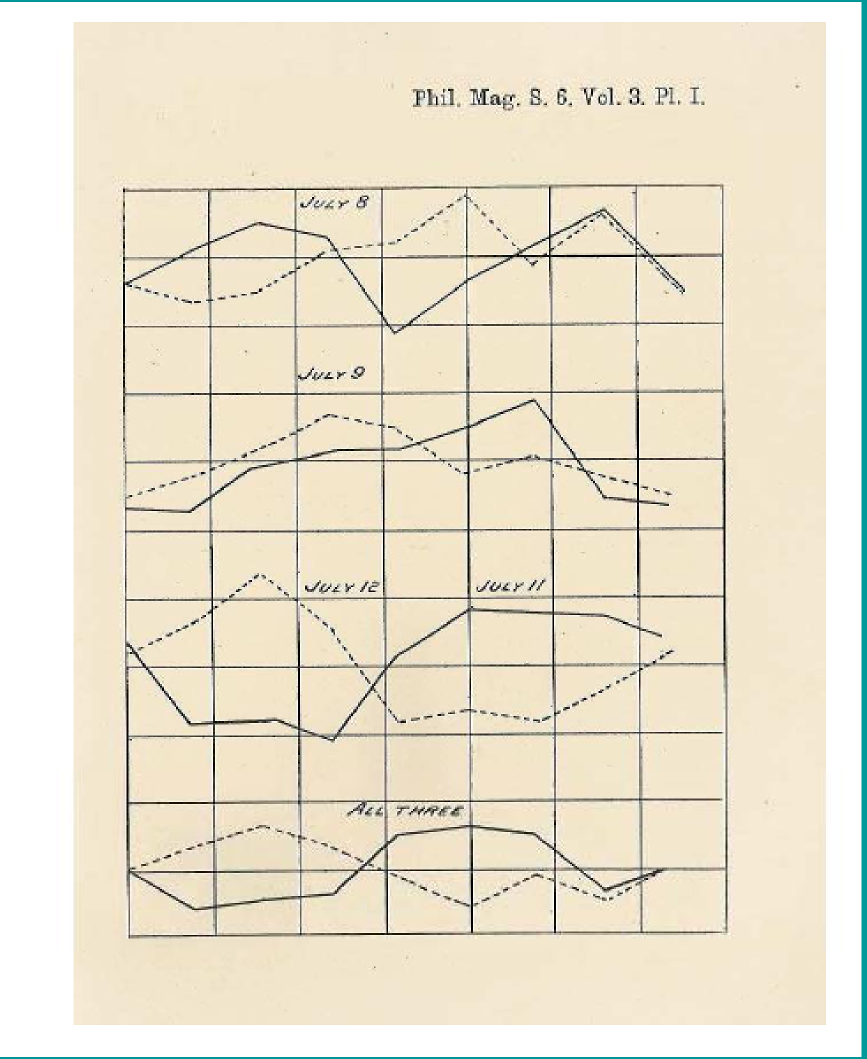
- M. C. and E. Costanzo, Phys. Lett. A333 (2004) 355; N. Cimento 119B (2004) 393

2nd harmonic effect

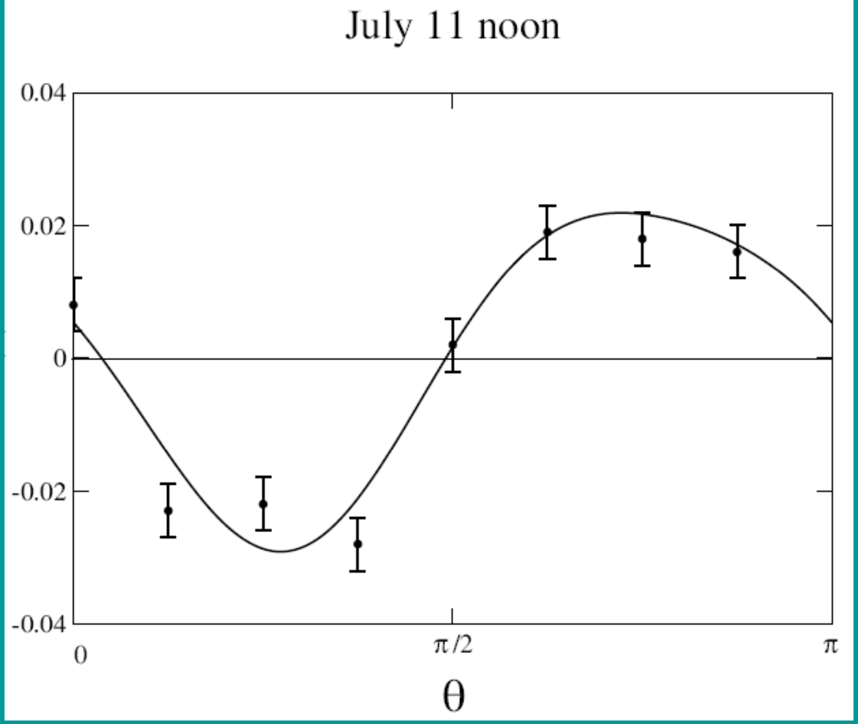


SESSION	A_2^{EXP}
July 8 (noon)	0.010 ± 0.005
July 9 (noon)	0.015 ± 0.005
July 11 (noon)	0.025 ± 0.005
July 8 (evening)	0.014 ± 0.005
July 9 (evening)	0.011 ± 0.005
July 12 (evening)	0.024 ± 0.005

Hicks 1902



- M.C. and E. Costanzo 2004



Classical interpretation of the measurements

SESSION	A_2^{EXP}
July 8 (noon)	0.010 ± 0.005
July 9 (noon)	0.015 ± 0.005
July 11 (noon)	0.025 ± 0.005
July 8 (evening)	0.014 ± 0.005
July 9 (evening)	0.011 ± 0.005
July 12 (evening)	0.024 ± 0.005

- Hicks' analysis shows that one should NOT average directly the fringe shifts due to possible systematic changes of sign induced by the readjustment of the mirrors in the different sessions of consecutive days
- However, one can average the 2nd harmonic amplitudes which are invariant for an overall change of sign of the fringe shifts

- By computing mean and variance of the 6 experimental sessions, one gets

$$A_2^{EXP} = 0.0165 \pm 0.0065$$

- From the relation

$$\frac{A_2^{EXP}}{0.2} \approx \frac{1}{12} \approx \left(\frac{v}{30 km/s}\right)^2$$

one finds a velocity

$$v \approx 8.4^{+1.5}_{-1.7} km/s$$

A fresh look at the ether-drift experiments

- The standard way to look for a preferred reference frame is through an anisotropy of the velocity of light. This could be detected by rotating a Michelson interferometer
- Now, by assuming : i) the existence of a preferred reference frame Σ

  ii) the validity of Lorentz transformations

  any anisotropy in a moving frame S' should vanish **either** when its velocity $v \to 0$ **or** when the velocity of light c_γ coincides with the parameter "**c**" entering Lorentz transformations. For a refractive index $N = 1 + \varepsilon$ one can expand around $\varepsilon = 0$ for small values of the parameter $\beta = v / c$

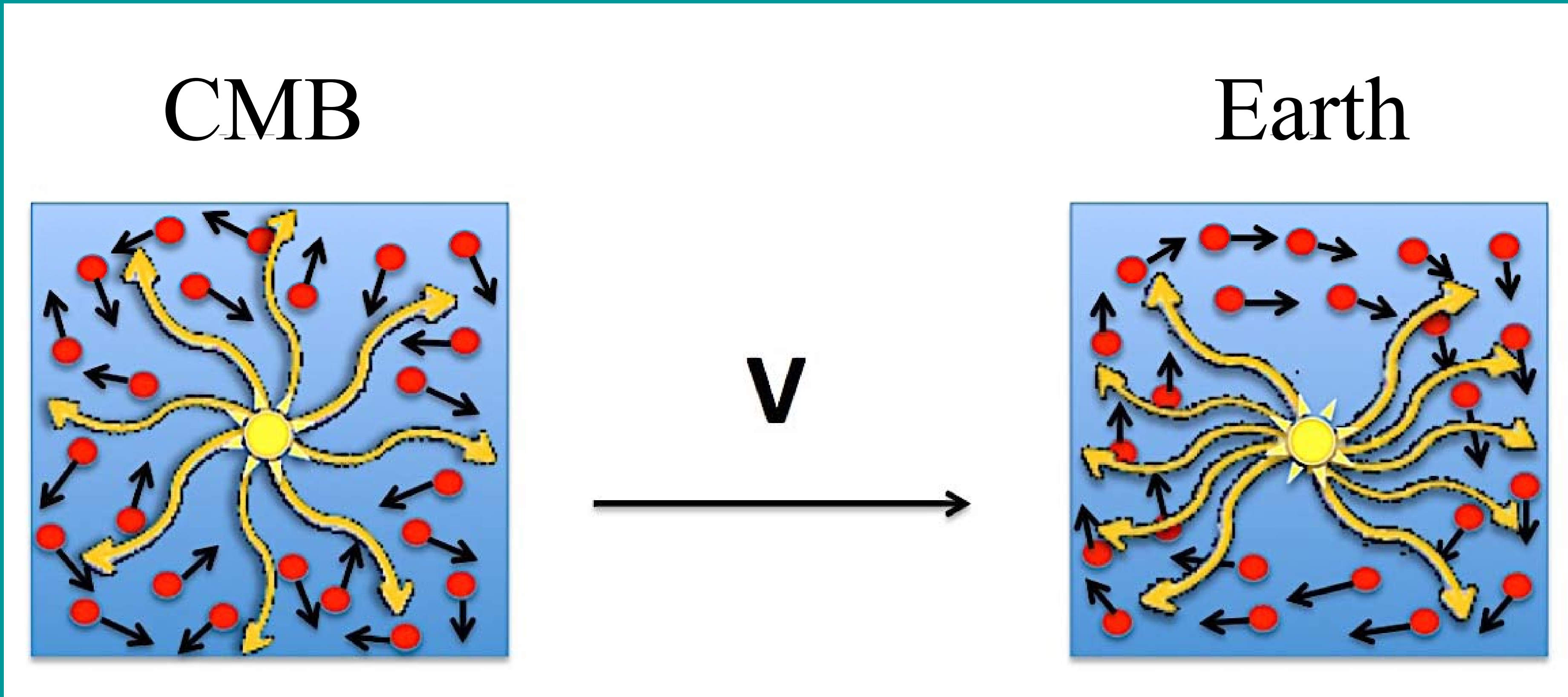
$$c_\gamma(\theta) = \frac{c}{N}\left[1 - \varepsilon\left(\beta F_1(\theta) + \beta^2 F_2(\theta) + ..\right) - \varepsilon^2(...)\right]$$

Thus, from the symmetry properties of the two-way velocity under separate replacements $\beta \to -\beta$ and $\theta \to \pi+\theta$, one finds the general expression

$$\bar{c}_\gamma(\theta) \approx \frac{c}{N}\left[1 - \varepsilon\beta^2 \sum_{k=0}^{\infty} \varsigma_{2k} P_{2k}(\cos\theta)\right]$$

where $P_{2k}(\cos\theta)$ are the Legendre polynomials and ς_{2k} are arbitrary coefficients.
Let us look for a **dynamical** model which could produce this result.

CMB dipole, convective currents in a gas and light anisotropy



Convective currents in a gas

- Convective currents in a gas, of refractive index $\mathbf{N = 1 + \varepsilon}$, induced by the motion of the Earth's frame with respect to a preferred frame, imply the following general expression for the two-way velocity of light (M. C. , C. Matheson and A. Pluchino, EPJ Plus 2013, see also M.C. Found. of Phys. 2015, Appendix 1):

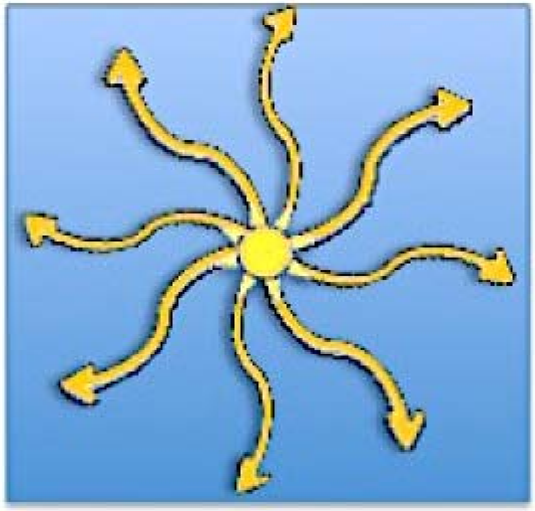
$$\bar{c}_\gamma(\theta) \approx \frac{c}{N}\left[1 - \varepsilon\beta^2 \sum_{k=0}^{\infty} \varsigma_{2k} P_{2k}(\cos\theta)\right]$$

where θ is the angle between light propagation and the Earth's velocity, $\mathbf{P_{2k}(\cos\theta)}$ are the Legendre polynomials and ς_{2k} are coefficients which depend on the type of convective currents established in the gas. **This is exactly the same structure previously obtained from more general arguments**

- Still, there is one more derivation of the $\varepsilon \rightarrow 0$ limit with a preferred frame which uses other symmetry arguments and is a particular case of the previous structure.

Light propagation in an ideal vacuum

CMB



$$\pi_\mu \pi_\nu \eta^{\mu\nu} = 0$$

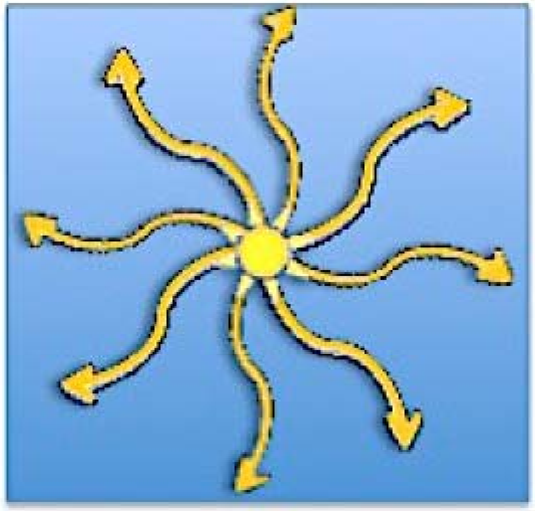
$$\eta^{\mu\nu} = diag(1,-1,-1,-1)$$

$$g^{\mu\nu} = \delta^\mu_\sigma \delta^\nu_\rho \eta^{\sigma\rho} = \eta^{\mu\nu}$$

V

$$g^{\mu\nu} = \Lambda^\mu_\sigma \Lambda^\nu_\rho \eta^{\sigma\rho} = \eta^{\mu\nu}$$

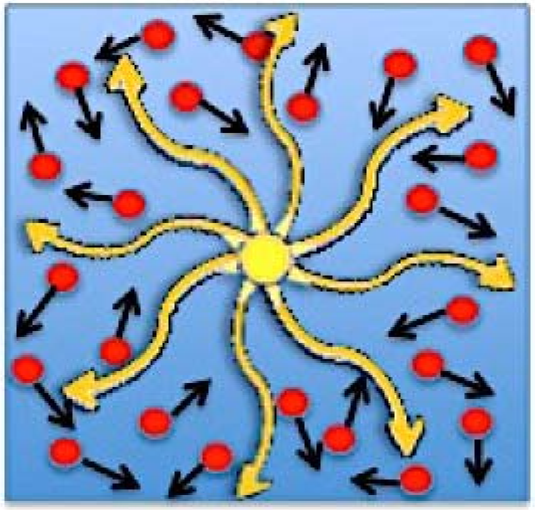
Earth



$$p_\mu p_\nu g^{\mu\nu} = 0$$

Light propagation in a gas

CMB



$$\pi_\mu \pi_\nu \gamma^{\mu\nu} = 0$$

$$\gamma^{\mu\nu} = diag(N^2, -1, -1, -1)$$

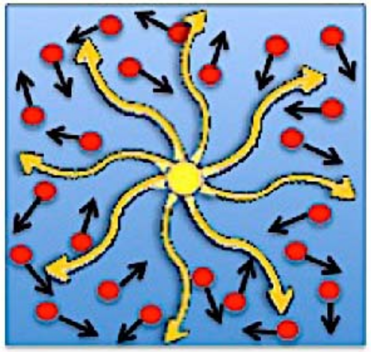
$$\mathbf{N = 1 + \varepsilon}$$

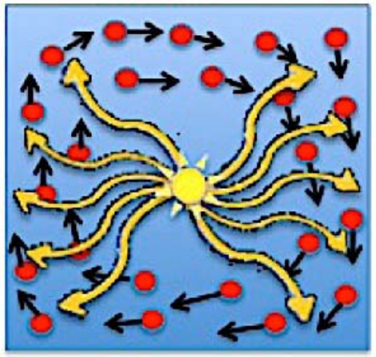
$$\mathbf{g}^{\mu\nu} = \delta^\mu_\sigma \delta^\nu_\rho \gamma^{\sigma\rho} = \gamma^{\mu\nu}$$

V

$$\mathbf{g}^{\mu\nu} = \Lambda^\mu_\sigma \Lambda^\nu_\rho \gamma^{\sigma\rho} \approx \eta^{\mu\nu} + \mathbf{2\varepsilon u}^\mu \mathbf{u}^\nu$$

Earth





$$p_\mu p_\nu g^{\mu\nu} = 0$$

Simple formula for light anisotropy in a gas

- By using Lorentz transformations, to connect the **CMB** to the Earth's frame, one obtains the expression for the two-way velocity of light

$$\bar{c}_\gamma(\theta) \approx \frac{c}{N}\left[1 - \varepsilon\beta^2(2 - \sin^2\theta)\right]$$

- This is a special case of the previous general expression

$$\bar{c}_\gamma(\theta) \approx \frac{c}{N}\left[1 - \varepsilon\beta^2\sum_{k=0}^{\infty}\varsigma_{2k}P_{2k}(\cos\theta)\right]$$

where one sets

$$\varsigma_0 = \frac{4}{3} \qquad \varsigma_2 = \frac{2}{3} \qquad \text{and} \qquad \varsigma_{2k} = 0 \qquad \text{for} \qquad k > 1$$

Analysis of Michelson's interferometer

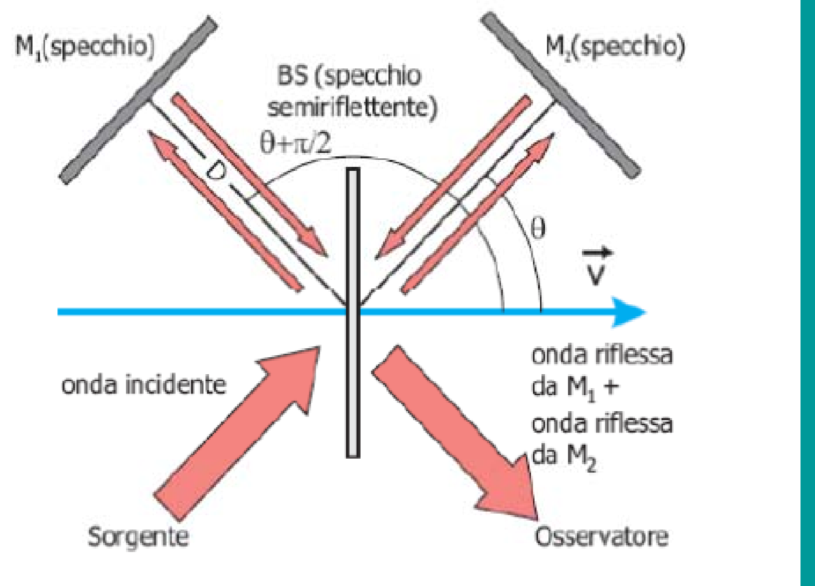


Figure 1: Il tipico schema dell'interferometro di Michelson.

- If the velocity of light is different for different directions, there will be a fringe shift by rotating a Michelson's interferometer. The fringes depend on the time difference $\Delta t(\theta)$

$$\Delta t(\theta) = \frac{2D}{\bar{c}_\gamma(\theta)} - \frac{2D}{\bar{c}_\gamma(\pi/2+\theta)}$$

- In a relativistic formalism one gets

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{rel} = \frac{c\Delta t(\theta)}{N\lambda} \approx \frac{D}{\lambda}\frac{v^2}{c^2}(2\varepsilon)\cos 2\theta$$

- From which, by comparing with the classical result

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{class} \approx \frac{D}{\lambda}\frac{v^2}{c^2}\cos 2\theta$$

there is a re-scaling $\quad v^2 \rightarrow 2\varepsilon v^2 \equiv v^2_{obs}$

The relativistic formula

- In conclusion, in a gas of refractive index **N=1+ ε** one expects a fringe pattern

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{rel} \approx \frac{D}{\lambda}\frac{v_{obs}^2}{c^2}\cos 2\theta$$

where the **observable** velocity depends BOTH on the **kinematical** velocity and the **refractive index** through

$$v_{obs}^2 \approx 2\varepsilon v^2$$

- A 2nd harmonic amplitude which is re-scaled by the tiny factor **2ε**

$$A_2^{rel} \approx \frac{D}{\lambda}\frac{v^2}{c^2}2\varepsilon \approx 2\varepsilon A_2^{class}$$

Example: propagation in air at atmospheric pressure where $N_{air} \approx 1.00029$. In this case, for $v = 300 km/s$ the fringes would be 17 times smaller than those classically expected for $v = 30 km/s$. In gaseous helium where $N_{helium} \approx 1.000035$ the effect would be 140 times smaller !

Alternative interpretation of the data

SESSION	A_2^{EXP}
July 8 (noon)	0.010 ± 0.005
July 9 (noon)	0.015 ± 0.005
July 11 (noon)	0.025 ± 0.005
July 8 (evening)	0.014 ± 0.005
July 9 (evening)	0.011 ± 0.005
July 12 (evening)	0.024 ± 0.005

- The mean and variance of the 6 sessions is $$\mathbf{A_2^{EXP} = 0.0165 \pm 0.0065}$$
- From the relativistic relation $$\frac{A_2^{EXP}}{0.2} \approx \frac{1}{12} \approx 2\varepsilon\left(\frac{v}{30\,\mathrm{km/s}}\right)^2$$

one finds the **observable** velocity $$v_{obs} = \sqrt{2\varepsilon v^2} \approx 8.4^{+1.5}_{-1.7}\,\mathrm{km/s}$$

and the TRUE kinematical value $$v = 349^{+62}_{-70}\,\mathrm{km/s}$$

which agrees well with the average Earth's velocity 369 km/s with respect to the CMB

Important remark: gases vs. solids

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A New Experimental Test of Special Relativity.

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(ricevuto il 23 Gennaio 1969)

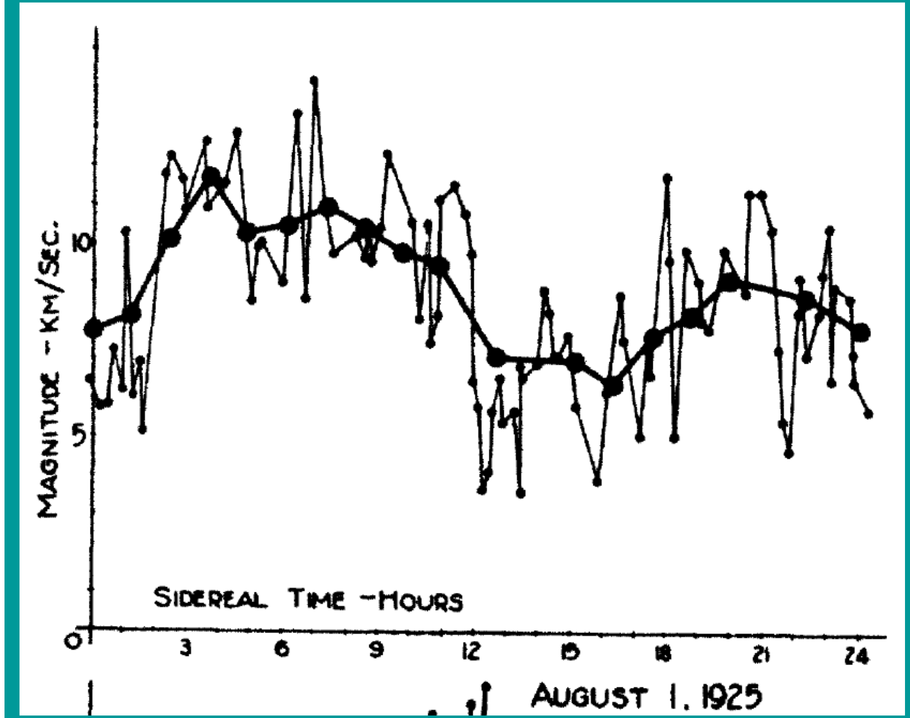
Summary. — Although the special theory of relativity is almost generally accepted as a verified theory, existing experiments cannot distinguish it from a number of other rival theories that assume the existence of a preferred frame of reference (ether), and physical Lorentz contractions. It is shown that the Michelson-Morley experiment, performed in a solid transparent medium, is capable of such a distinction. The negative result of this experiment enhances the experimental basis of special relativity.

The discovery of the cosmic-microwave background radiation ([9]) makes the existence of a preferred reference frame even more of a possibility. In principle this radiation can serve as a reference frame since it should be possible to detect motion through it ([10]). An observer moving through the black-body radiation in space will see different temperatures in different directions. We can define a preferred frame of reference as the frame in which the 3 °K black-body radiation is isotropic.

The Michelson-Morley experiment (MME) did not yield a strictly zero result ([12]). The nonzero result might have been real and due to the fact that the experiment was performed in air and not in vacuum. The effect of the

- Shamir and Fox were aware that the MM experiment could also be consistent with a $\varepsilon(v/c)^2$ light anisotropy for $v \approx 300$ km/s
- Thus they designed a MM experiment in a solid transparent medium (perspex with N=1.5) where the effect of the refractive index would have been enhanced
- This enhancement was not observed. So they concluded that the experimental basis of special relativity was strengthened
- However, with a thermal interpretation of the fringe shifts, the two observed behaviors, in gases and solids, can now be reconciled

Miller's extensive observations 1925-1926



- From D. C. Miller, Rev. Mod. Phys. 5 (1933) 203

- From the re-analysis of Shankland et al. (Rev. Mod. Phys. 27 (1955) 167) it turns out that the average 2nd harmonic of Miller's observation was $A_2^{EXP} \approx 0.044$
- By normalizing this to the classical value

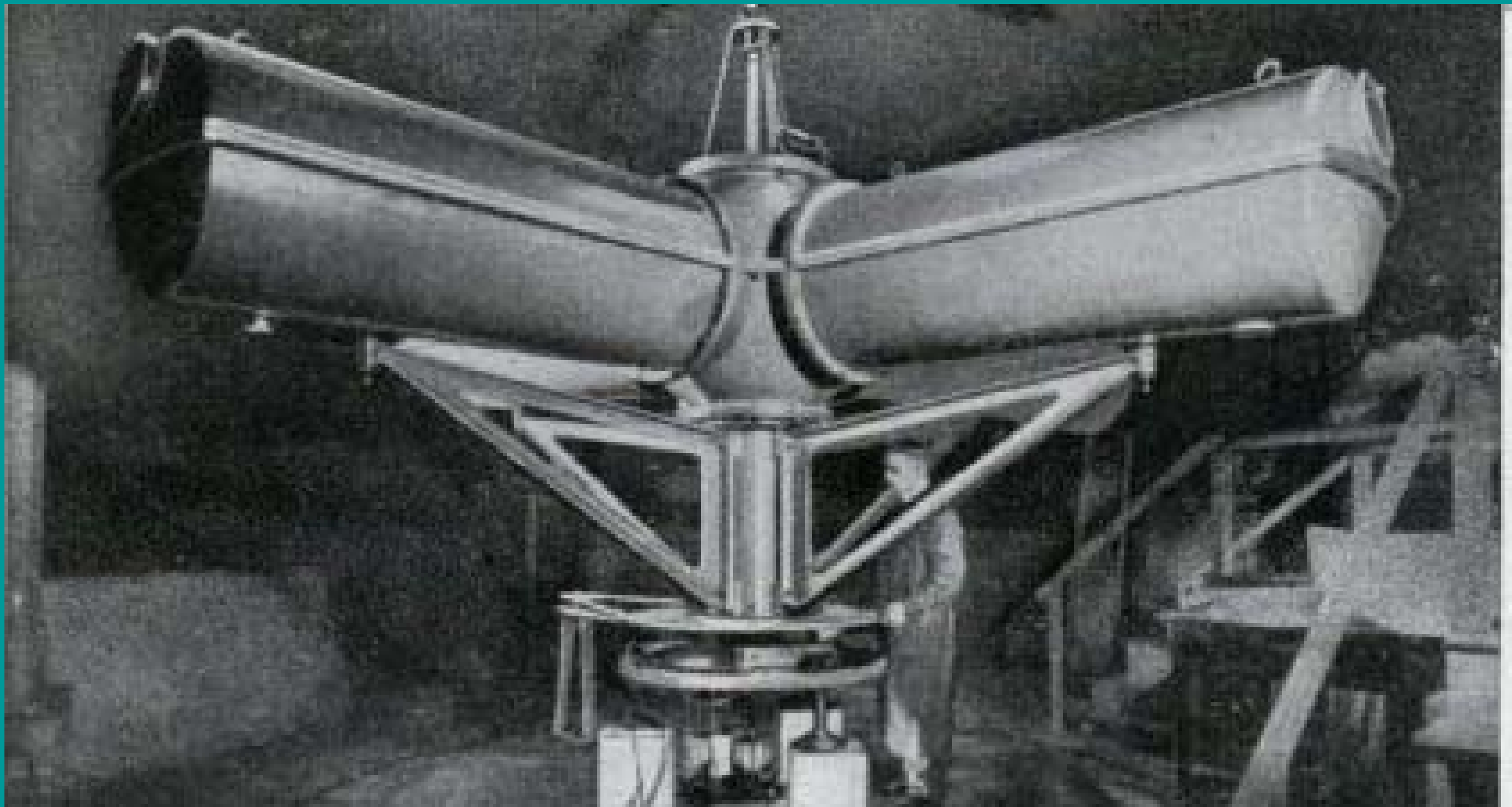
  $A_2^{class} \approx 0.56$ for Miller's apparatus

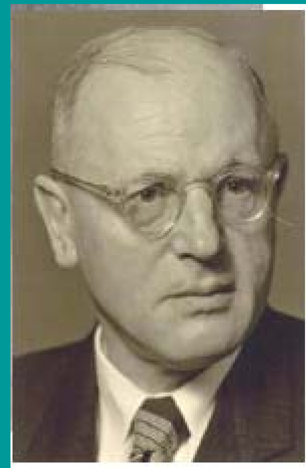
$$\frac{A_2^{EXP}}{A_2^{Class}} \approx \frac{0.044}{0.56} \approx \frac{1}{12} \approx \left(\frac{v_{obs}}{30 km/s} \right)^2$$

Again the average observable velocity is about **8.4 km/s** (and the kinematic **v** about **349 km/s**) as for MM experiment

- Thus, the standard thermal interpretation of Miller's observations is only acceptable if the thermal effects have a **NON-LOCAL** origin

1930: Joos' experiment in Jena





- G. Joos, Ann. Phys. 7 (1930) 385; Naturwiss. 38 (1931) 784

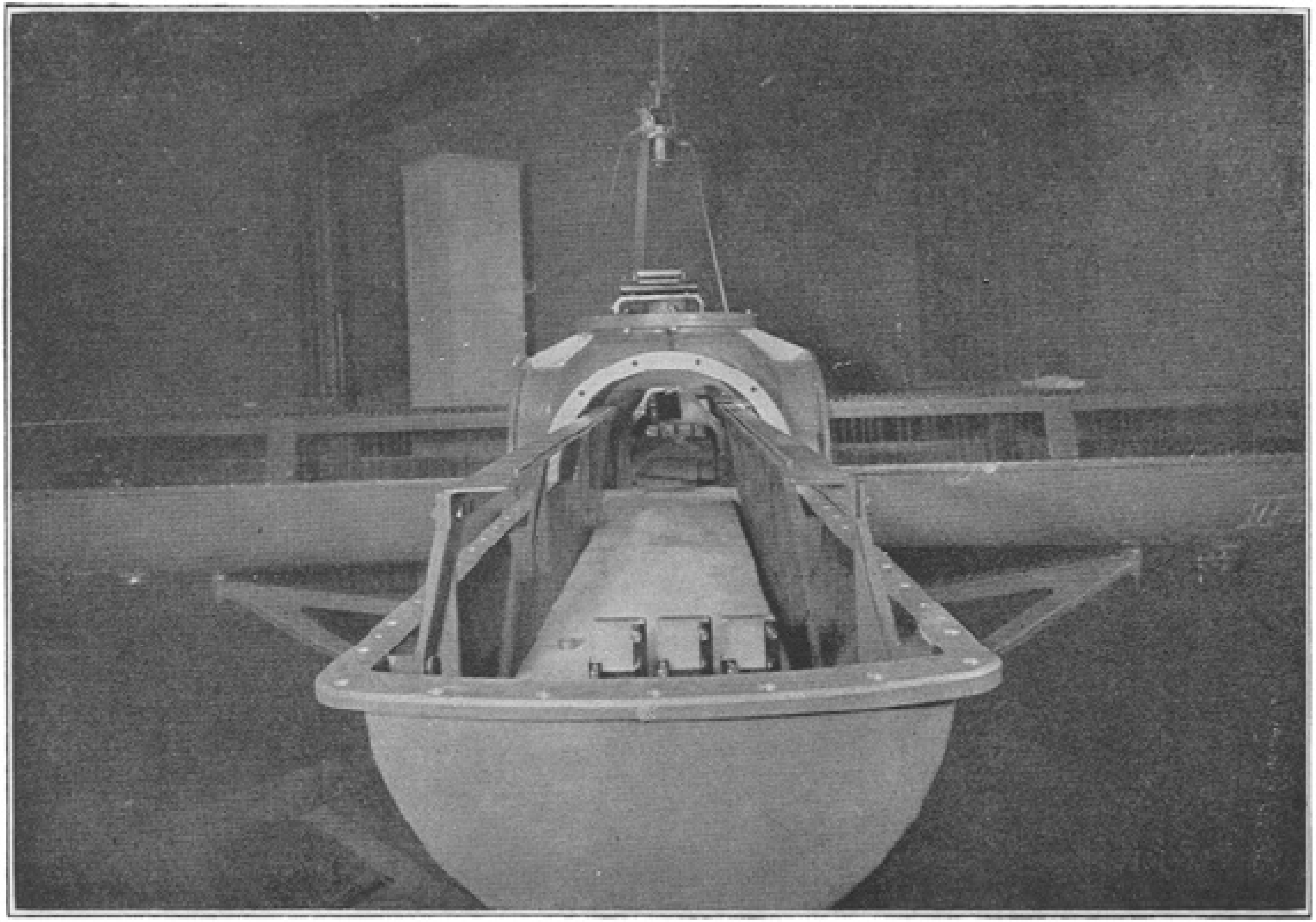


Fig. 5. Lagerung der Optik beim Zeissschen Interferometer.

Joos’ observations

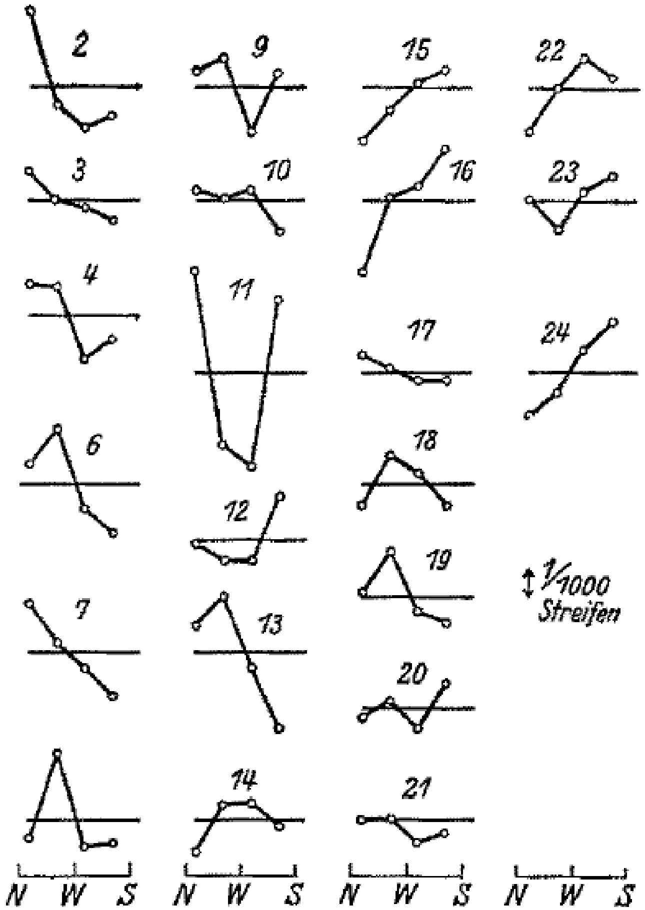
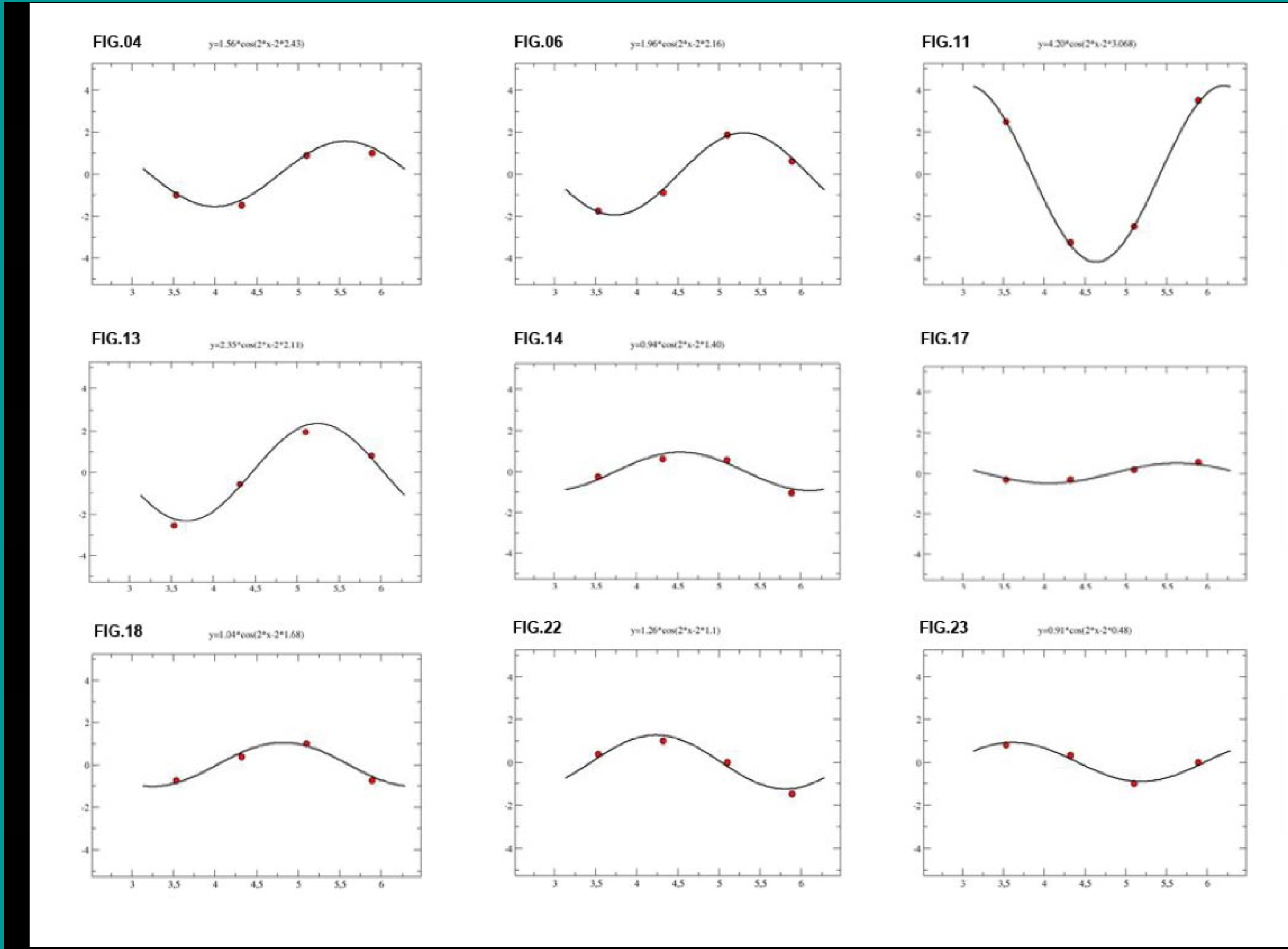


Fig. 8. Verschiebungen in einer über 24 Stunden erstreckten Serie beim Jenaer Versuch.

- Observations performed each hour and registered by photo-camera
- According to L. Swenson, the optical paths were immersed in a helium bath
- The accuracy of Joos’ measurements remains incomparable among the classical experiments (reading errors about $\pm 2 \cdot 10^{-4}$)
- Unfortunately, Joos does not specify the reference angular values of his measurements
- Therefore, one can only extract unambiguously the 2nd harmonic amplitudes (NOT the phases)

2^{nd} harmonic fit to Joos' fringe shifts



Joos' 2nd harmonic amplitudes

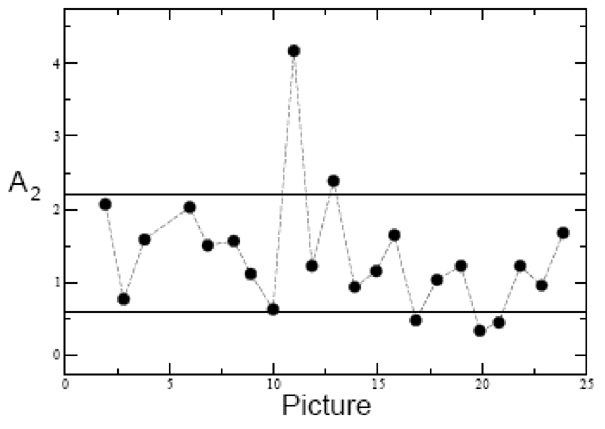


Figure 10: *Joos' 2nd-harmonic amplitudes, in units* 10^{-3}. *The vertical band between the two lines corresponds to the range* $(1.4 \pm 0.8) \cdot 10^{-3}$.

- The simplest model of cosmic motion has 3 parameters

$$(V,\alpha,\gamma)$$

where

$$\mathbf{V = modulus}$$

$$\boldsymbol{\alpha} = \mathbf{right.asc.}$$

$$\boldsymbol{\gamma} = \mathbf{angul.decl.}$$

- A fit to Joos' amplitudes (where for the moment **V** remains free) gives

$$\alpha(\text{fit}-\text{Joos}) = 168^o \pm 30^o \qquad \gamma(\text{fit}-\text{Joos}) = -13^o \pm 14^o$$

- These values are in good agreement with the average CMB parameters

$$\alpha(\text{CMB}) \approx 168^o \qquad \gamma(\text{CMB}) \approx -7^o$$

The projection of the velocity at Jena

- In a relativistic treatment, the velocity extracted from the data depends on the refractive index **N=1+ε** of the gaseous medium . For Joos' experiment one finds

$$\frac{A_2^{rel}}{0.375} = 2\varepsilon\left(\frac{v}{30km/s}\right)^2 \approx 7\cdot 10^{-5}\left(\frac{v}{30km/s}\right)^2$$

- According to Miller, the experiment was performed in a partial vacuum. However, this is by no means clear from Joos' papers
- Instead L. Swenson Jr. reports explicitly that the optical paths were immersed in a helium bath see Journ. Hist. Astron. 1 (1970) 56. In this case, from the experimental mean and variance

$$A_2^{joos} = (1.4 \pm 0.8)\cdot 10^{-3}$$

and for gaseous helium, where $N_{helium} \approx 1.000035$ one would apparently find a kinematical projection

$$v = 217^{+66}_{-79} km/s$$

to compare with the CMB value at Jena

$$v_{CMB}^{Jena} = 330^{+40}_{-70} km/s$$

- Apart from the discrepancy on the average projection, there is a strong difference between the " high " and " low " data (about a factor of 12)

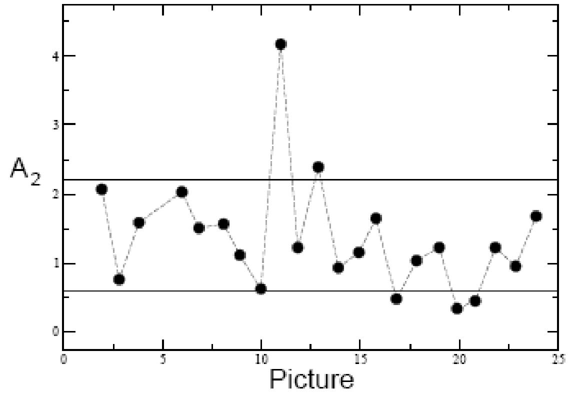


Figure 10: *Joos' 2nd-harmonic amplitudes, in units* 10^{-3}. *The vertical band between the two lines corresponds to the range* $(1.4 \pm 0.8) \cdot 10^{-3}$.

- In a smooth model of the ether-drift values as $v_{CMB}^{Jena} = 330^{+40}_{-70}\,km/s$ would only give a difference by a factor of 2. Thus, by changing the overall normalization, one can reproduce the high data or the low ones but NOT both.
- However, by comparing the chi-square of Joos' amplitudes with those obtained from casual sequences of 22 entries there is difference of an order of magnitude. Therefore, those numbers have a physical meaning

Stochastic nature of the " ether-drift "

- The observed difference between Joos maximal and minimal amplitudes cannot be explained in a smooth model of the ether-drift.
- The idea of a **smooth** phenomenon derives from the simple model of a **fluid in laminar regime**. In this case global and local velocity fields coincide.
- However, differently from a direct measurement of the CMB in space, in a laboratory the effect of the temperature gradient is only indirect. It goes through intermediate steps as in a **fluid in turbulent regime** where global and local velocity fields are only indirectly related.

Velocity field and fringe shifts

- At a given time fringe shifts, in a medium with **N=1+ ε** , depend on a pair $[v(t), \theta_0(t)]$

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{rel} = 2\varepsilon \frac{D}{\lambda}\frac{v^2(t)}{c^2}\cos 2[\theta - \theta_0(t)]$$

- This can be rewritten as

$$\left[\frac{\Delta\lambda(\theta)}{\lambda}\right]_{rel} = 2C(t)\cos 2\theta + 2S(t)\sin 2\theta$$

with

$$C(t) = \frac{D\varepsilon}{\lambda}\frac{v^2(t)}{c^2}\cos 2\theta_0(t) \qquad S(t) = \frac{D\varepsilon}{\lambda}\frac{v^2(t)}{c^2}\sin 2\theta_0(t)$$

- Thus, by introducing the x-y velocity components in the plane of the interferometer

$$v_x(t) = v(t)\cos\theta_0(t) \qquad v_y(t) = v(t)\sin\theta_0(t)$$

- one gets

$$C(t) = \frac{D\varepsilon}{\lambda}\frac{v_x^2(t) - v_y^2(t)}{c^2} \qquad S(t) = \frac{D\varepsilon}{\lambda}\frac{2v_x(t)v_y(t)}{c^2}$$

Stochastic velocity field

- The x-y velocity components can be simulated, in simple model of statistically homogeneous turbulence, by unsteady random Fourier series, see e.g. J. C. Fung et al., J. Fluid Mech. 236 (1992) 281).

$$v_x(t) = \sum_{n=1}^{\infty}\left[x_n(1)\cos\omega_n t + x_n(2)\sin\omega_n t\right] \qquad v_y(t) = \sum_{n=1}^{\infty}\left[y_n(1)\cos\omega_n t + y_n(2)\sin\omega_n t\right]$$

Frequencies are $\omega_n = \dfrac{2n\pi}{T}$ with period $0.1T_{day} \le T \le 10T_{day}$

- The coefficients $x_n(i=1,2)$ and $y_n(i=1,2)$ are random variables with zero mean chosen inside given boundaries $[-\tilde{v}_x(t), \tilde{v}_x(t)]$ and $[-\tilde{v}_y(t), \tilde{v}_y(t)]$ respectively.

- In a uniform probability model their quadratic averages are

$$\left\langle x_n^2(i=1,2)\right\rangle = \frac{\tilde{v}_x^2(t)}{3n^2} \qquad \left\langle y_n^2(i=1,2)\right\rangle = \frac{\tilde{v}_y^2(t)}{3n^2}$$

The amplitude in a stochastic model

- A smooth velocity field $\left(\tilde{v}_x(t), \tilde{v}_y(t)\right)$ produces a 2nd harmonic amplitude

$$A_2^{smooth}(t) \approx \frac{2\varepsilon D}{\lambda}\left(\frac{\tilde{v}_x^2(t) + \tilde{v}_y^2(t)}{c^2}\right)$$

- Instead, in the considered stochastic model, a full statistical average of the amplitude (as for an infinite number of measurements) would give

$$\left\langle A_2 \right\rangle_{stat} = \frac{2\varepsilon D}{\lambda}\left(\frac{\tilde{v}_x^2(t) + \tilde{v}_y^2(t)}{c^2}\right)\sum_{n=1}^{\infty}\frac{1}{3n^2} = \frac{\pi^2}{18}A_2^{smooth}(t)$$

- In this way, in a stochastic model, one gets higher velocity values from the same data

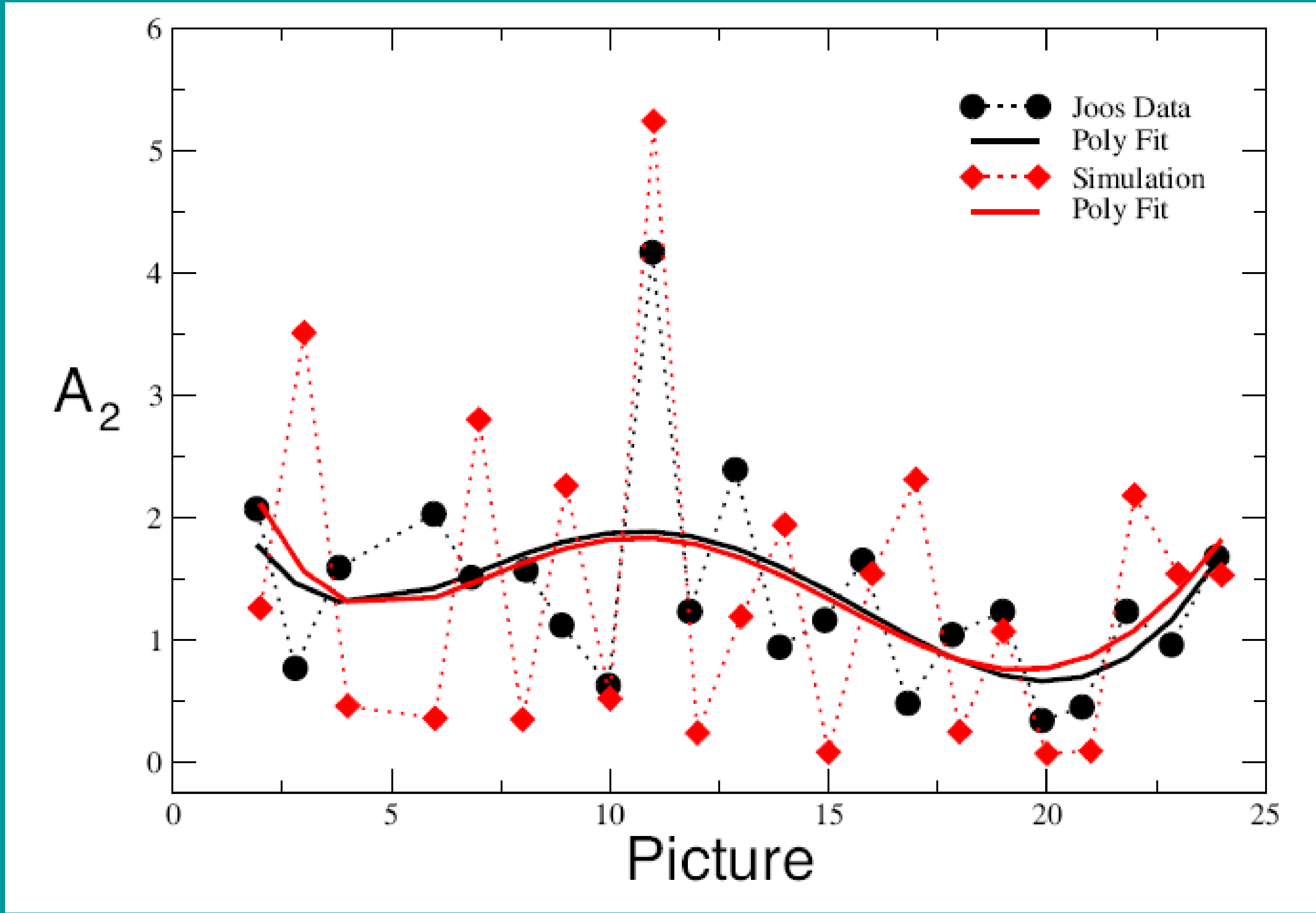
Numerical simulations vs. Joos' amplitudes

- To fix the boundaries $\left(\tilde{v}_x(t), \tilde{v}_y(t)\right)$ of the stochastic velocity components, we have chosen the kinematical parameters which describe the CMB anisotropy

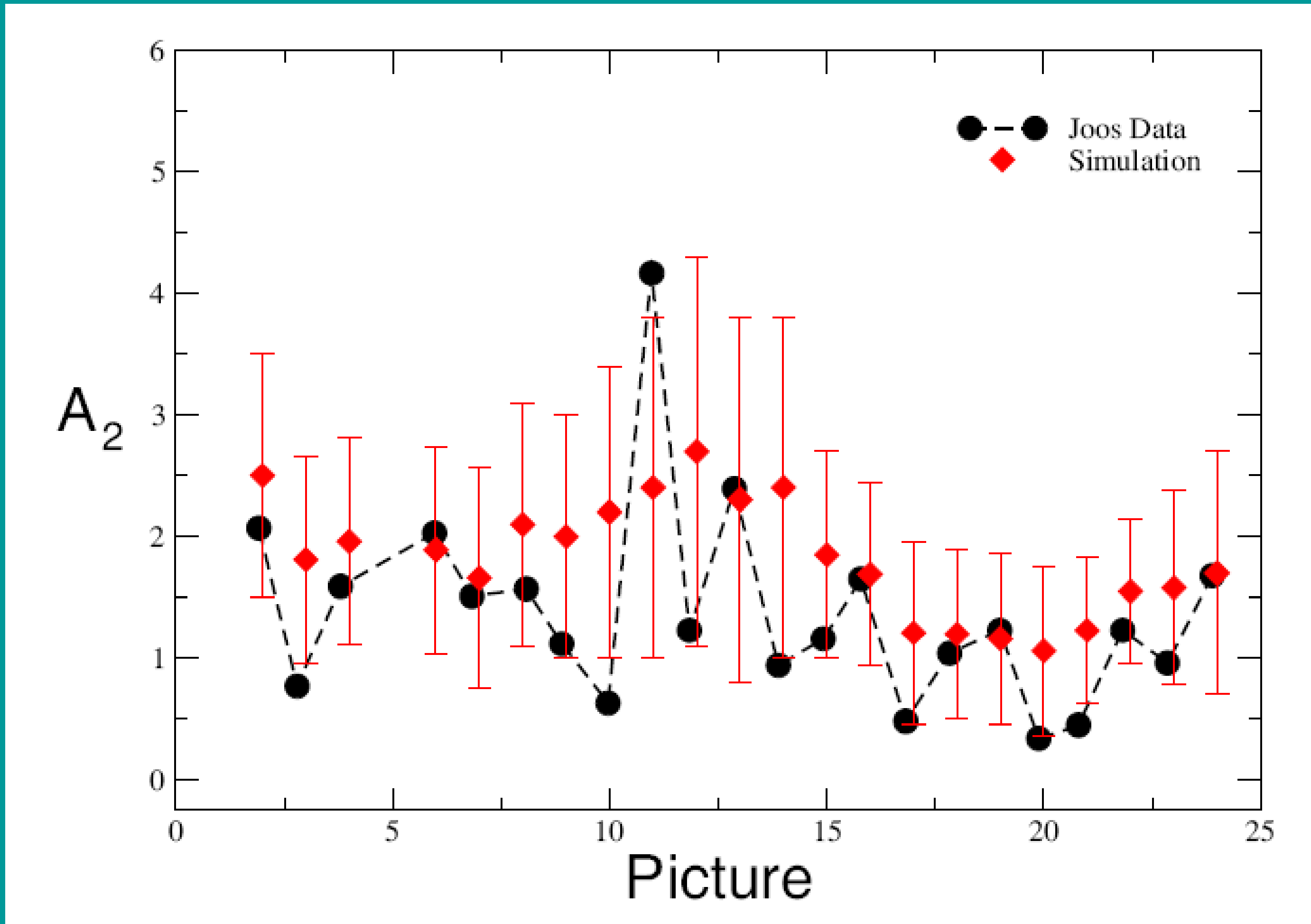
- This corresponds to

$$V_{CMB} = 369 km/s \qquad \alpha_{CMB} = 168^o \qquad \gamma_{CMB} = -6^o$$

- With these values, one can study the dependence on the remaining parameters of the simulation, namely the random sequence and the number of Fourier modes.



- Joos' amplitudes are compared with the result of a **single** simulation for fixed random sequence and fixed number of Fourier modes



- Joos' amplitudes are compared with a **simulation of the averaging process over 10 hypothetical measurements** performed at the same Joos times. Errors take into account the variation of both the random sequence and the number of Fourier modes

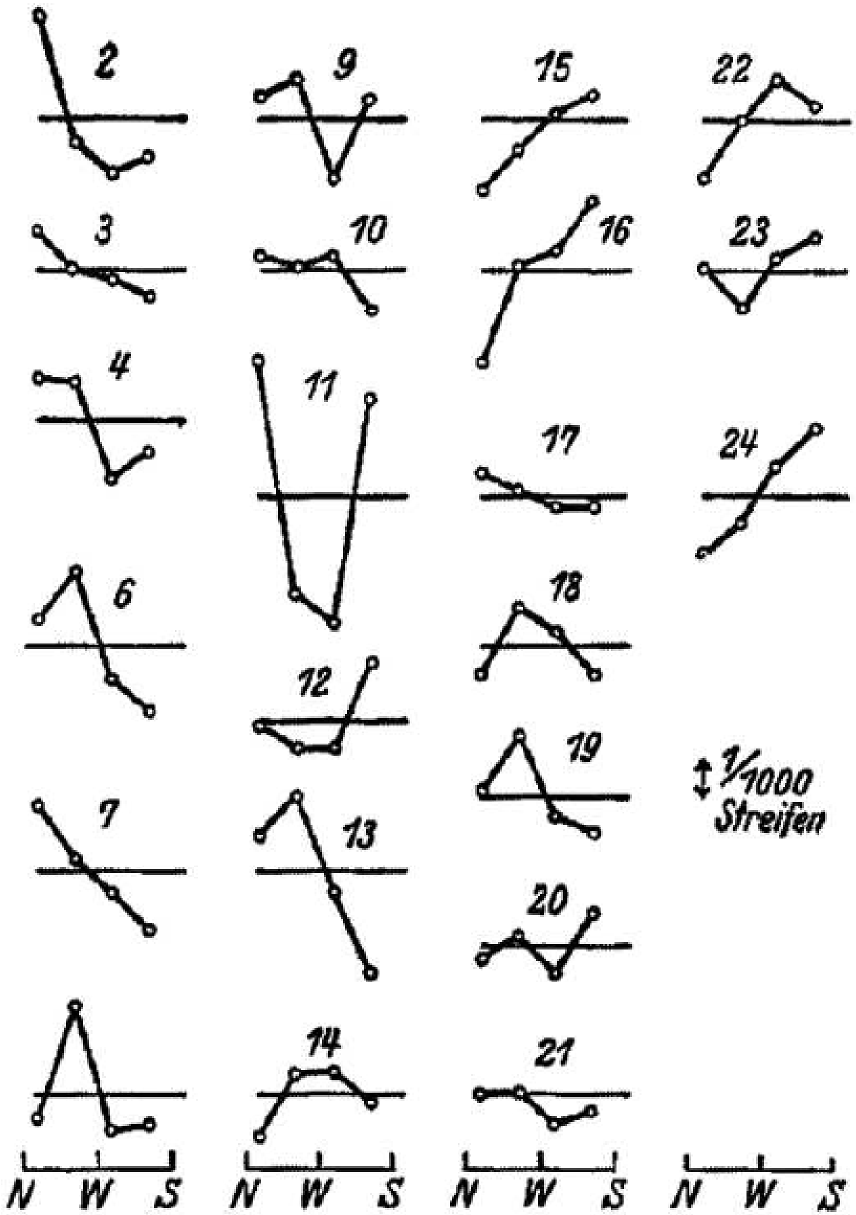
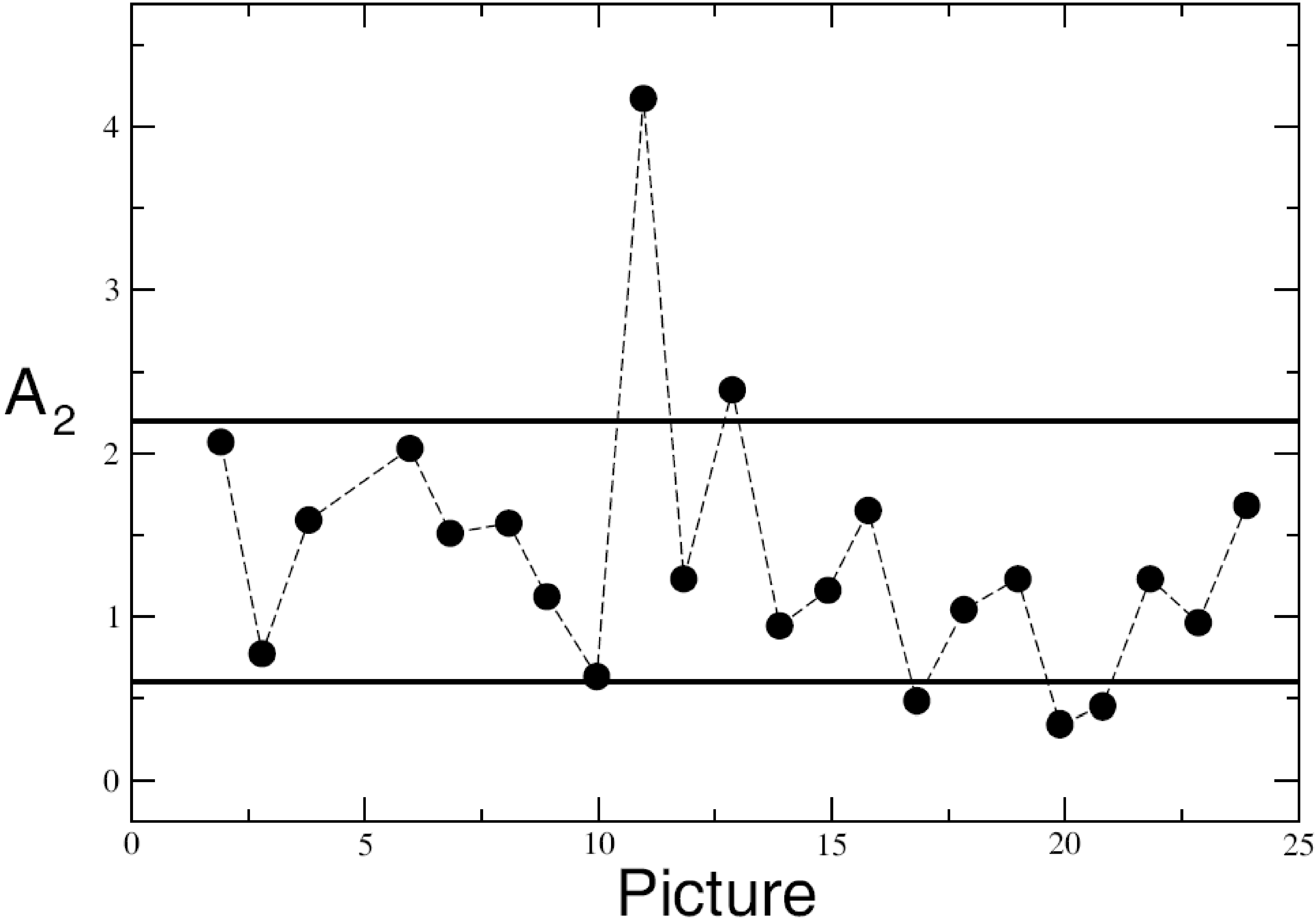


Fig. 8. Verschiebungen in einer über 24 Stunden erstreckten Serie beim Jenaer Versuch.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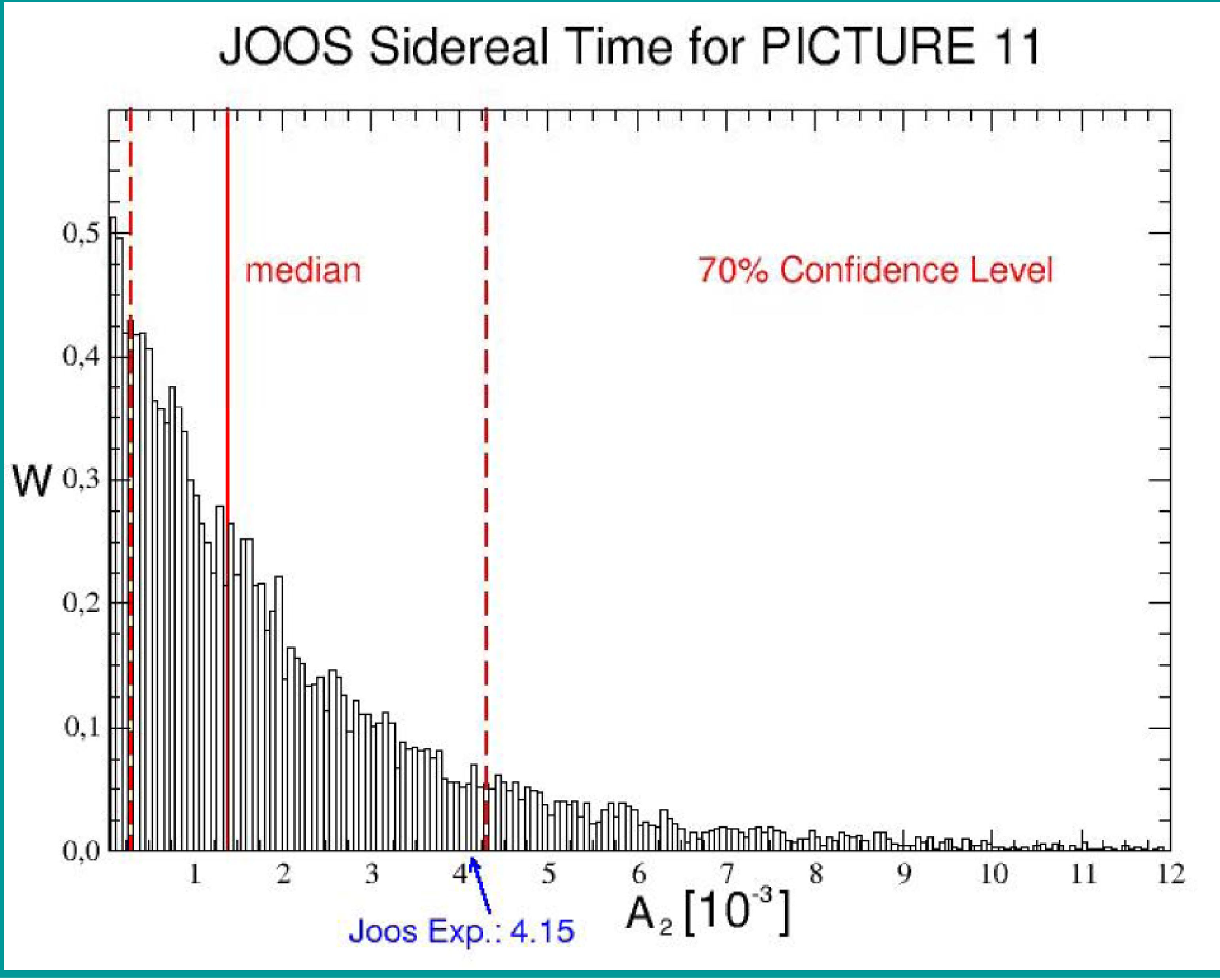
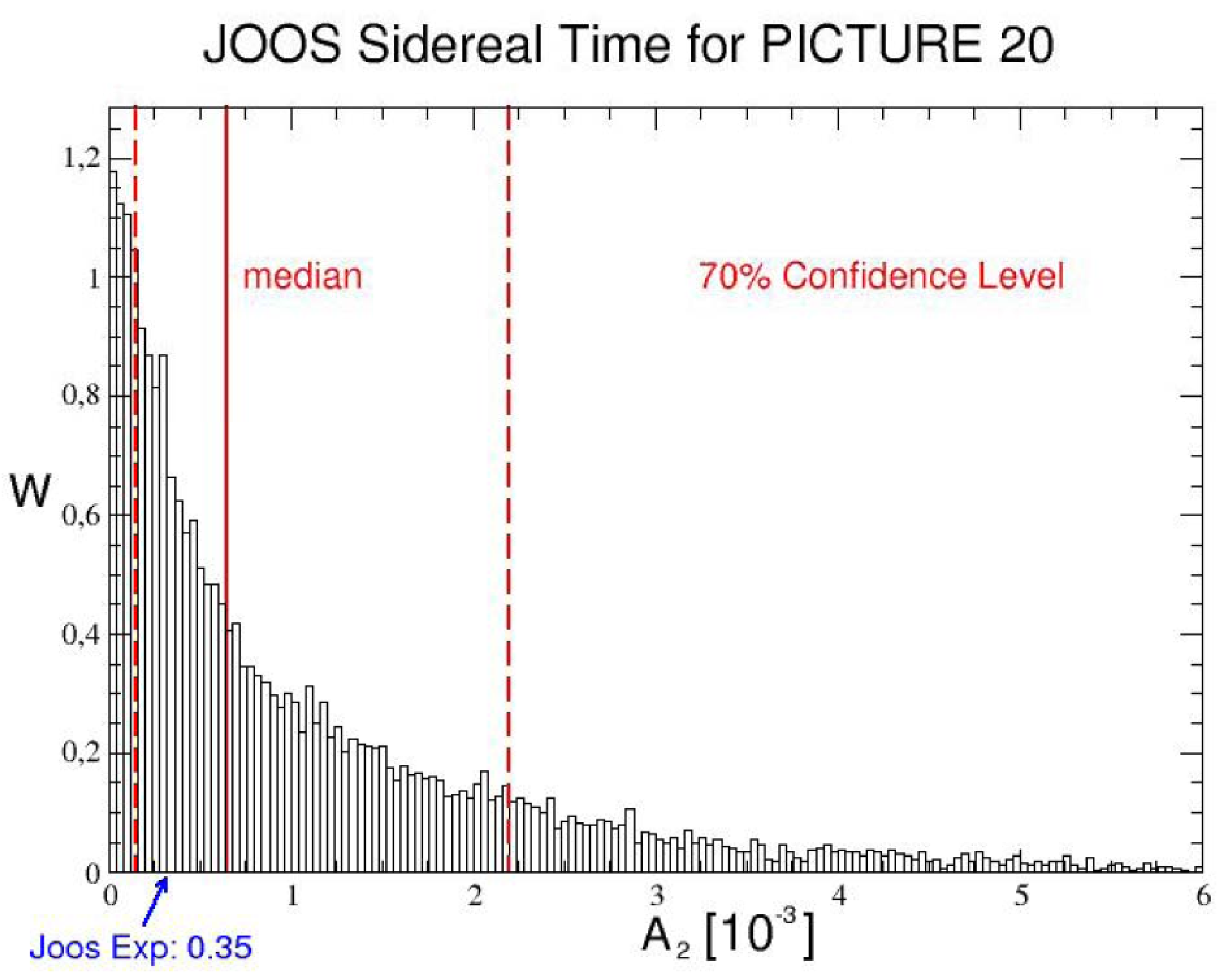
Probability histogram for Joos' picture 11



Probability histogram for Joos' picture 20



- Good agreement between Joos' amplitudes and numerical simulation in which the stochastic fluctuations of the velocity field are controlled by the kinematical parameters associated with the macroscopic Earth's motion with respect to the CMB

- Therefore, in this model, Joos' ether-drift experiment becomes consistent with the range of velocity deduced by direct CMB observations in space

$$\mathbf{v_{CMB}^{Jena} = 330^{+40}_{-70}\,km/s}$$

Summary of the classical experiments

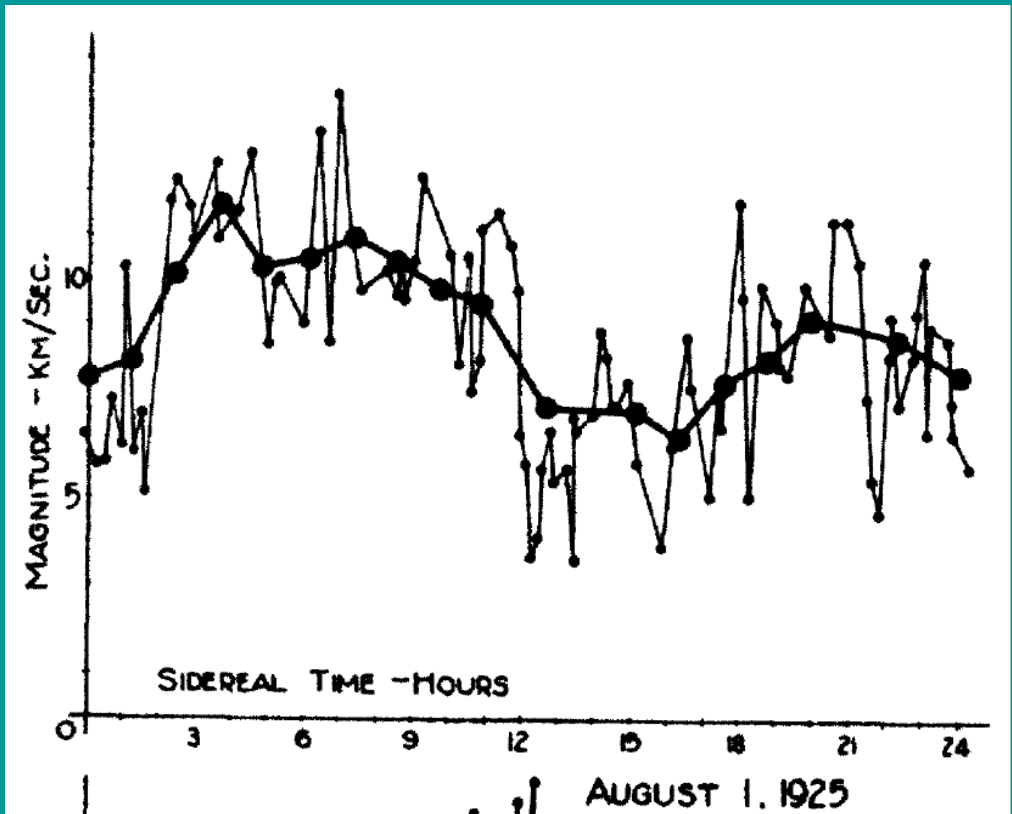
Table 10. The average velocity observed (or the limits placed) by the classical ether-drift experiments in the alternative interpretation of eqs. (24), (29) and (30).

Experiment	Gas in the interferometer	v_{obs}(km/s)	v(km/s)
Michelson-Morley (1887)	air	$8.4^{+1.5}_{-1.7}$	349^{+62}_{-70}
Morley-Miller (1902–1905)	air	8.5 ± 1.5	353 ± 62
Kennedy (1926)	helium	< 5	< 600
Illingworth (1927)	helium	3.1 ± 1.0	370 ± 120
Miller (1925–1926)	air	$8.4^{+1.9}_{-2.5}$	349^{+79}_{-104}
Michelson-Pease-Pearson (1929)	air	$4.5 \pm \ldots$	$185 \pm \ldots$
Joos (1930)	helium	$1.8^{+0.5}_{-0.6}$	330^{+40}_{-70}

[10] Other determinations of less accuracy could also be included, as for the 1881 Michelson experiment in Potsdam [91] or Tomaschek's starlight experiment [92] or the Piccard and Stahel experiment which was first performed in a ballon [93] and later [94] on the summit of Mt. Rigi in Switzerland. These results were summarized in Table I of ref. [68] and by Miller [65]. In the 1881 Potsdam experiment the fringe shifts were in the range 0.002–0.007 to be compared with an expected 2nd-harmonic of 0.02 for 30 km/s. This means observable velocities (9–18) km/s which are comparable and even larger than those of the 1887 experiment. In Tomaschek's starlight experiment, fringe shifts were about 15 times smaller than those classically expected for an Earth's velocity of 30 km/s. This gives $v_{obs} \lesssim 7.7$ km/s or $v \lesssim 320$ km/s. From Piccard and Stahel, in the most refined version of Mt. Rigi, one gets an observable velocity $v_{obs} \lesssim 1.5$ km/s. Since their optical paths were enclosed in an evacuated enclosure, this very low value can easily be reconciled with the typical kinematical velocity $v \sim 300$ km/s of the most accurate experiments in table 10.

A quick look at Miller's and MPP data

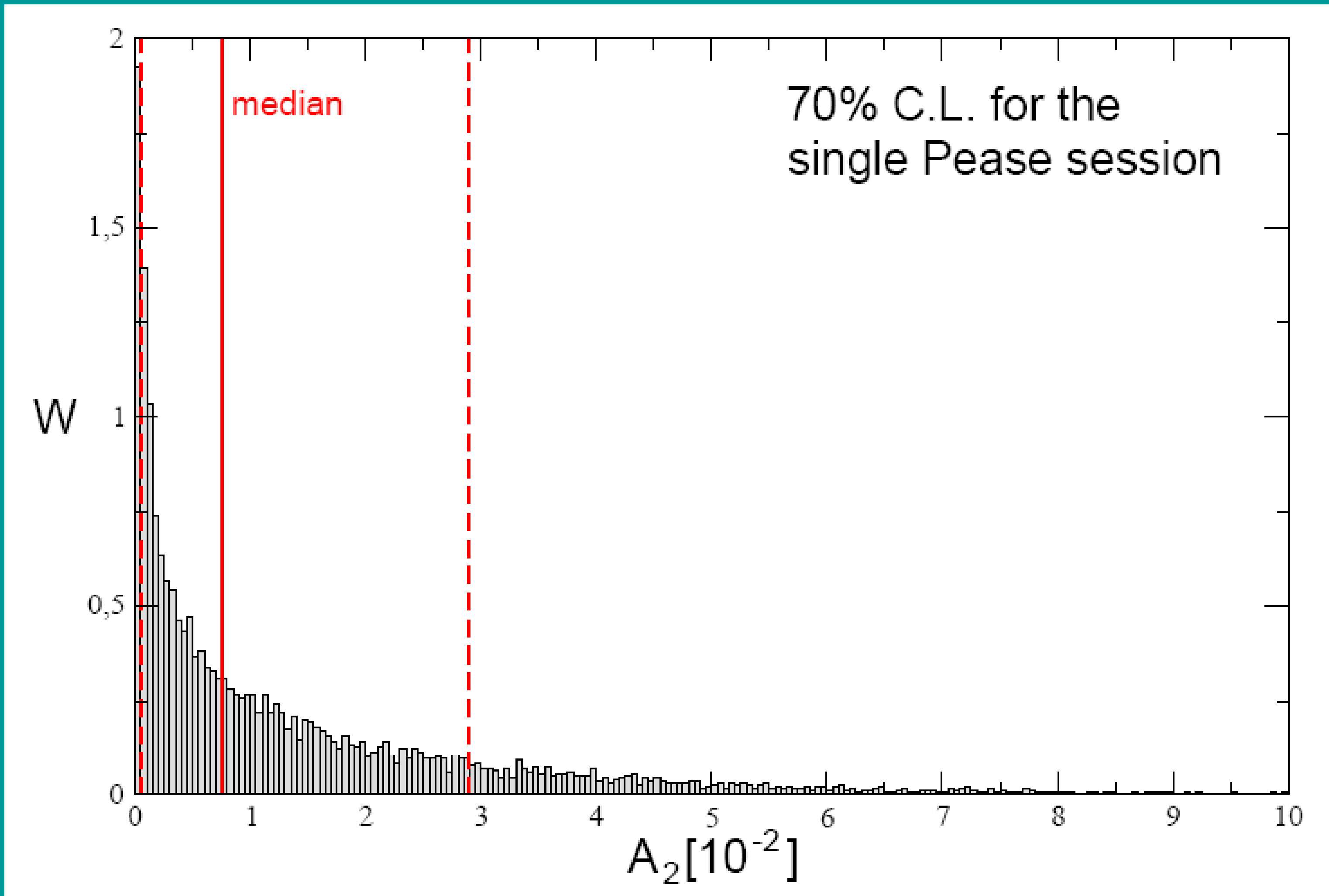
(MPP=Michelson-Pease-Pearson)



- As seen in the figure, Miller's amplitudes for maximal (about 14 km/s) and minimal (about 4 km/s) **observable** velocity differ by a factor of 12, as in Joos' data

- A value of about 4 km/s (or smaller) corresponds to the only known session explicitly reported (by F. Pease) for the MPP experiment. Such low values can easily explained in a stochastic model of the ether-drift

Probability histogram for the only known MPP session



- The median is 0.007 and the 70% CL is between 0.001 e 0.029. This corresponds to observable velocities between 1.8 e 9.4 km/s.

The MIT 1963 experiment

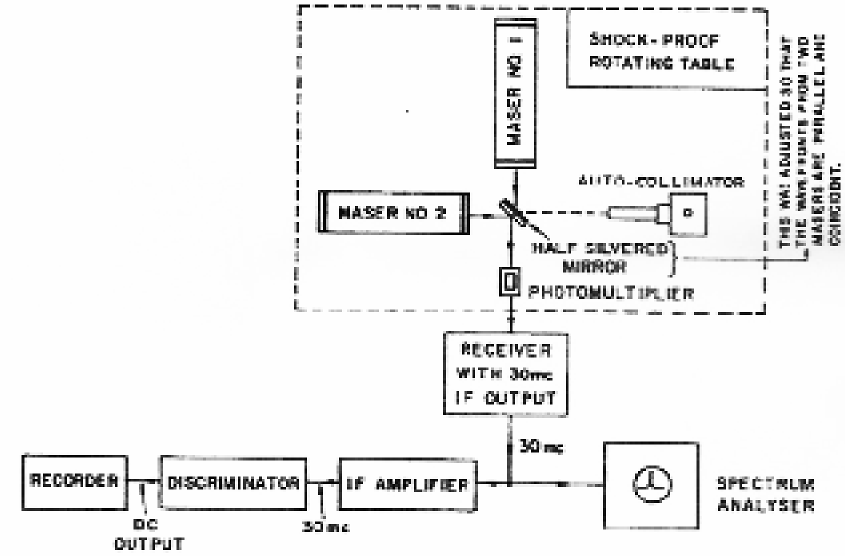


FIG. 1. Schematic diagram for recording the variations in beat frequency between two optical maser oscillators when rotated through 90° in space. Apparatus on the shock-proof rotating table is acoustically isolated from the remaining electronic and recording equipment.

- The apparatus by Jaseja, Javan, Murray and Townes, Phys. Rev.133 (1964) A1221
- Beat signal between due He-Ne masers placed on a rotating table
- With a refractive index **N=1.00004,** the shift expected for $\mathbf{v \approx 320^{+45}_{-60}\, km/s}$ is

$$\langle \Delta\nu \rangle \approx \mathbf{12^{+3}_{-4}\, kHz}$$

- There was however a spurious constant effect of about **271 kHz** (due to magnetostriction). Thus, one can only study the time variation of the signal and compare with the estimate

$$\mathbf{271^{+3}_{-4}\, kHz}$$

Time variations of the signal

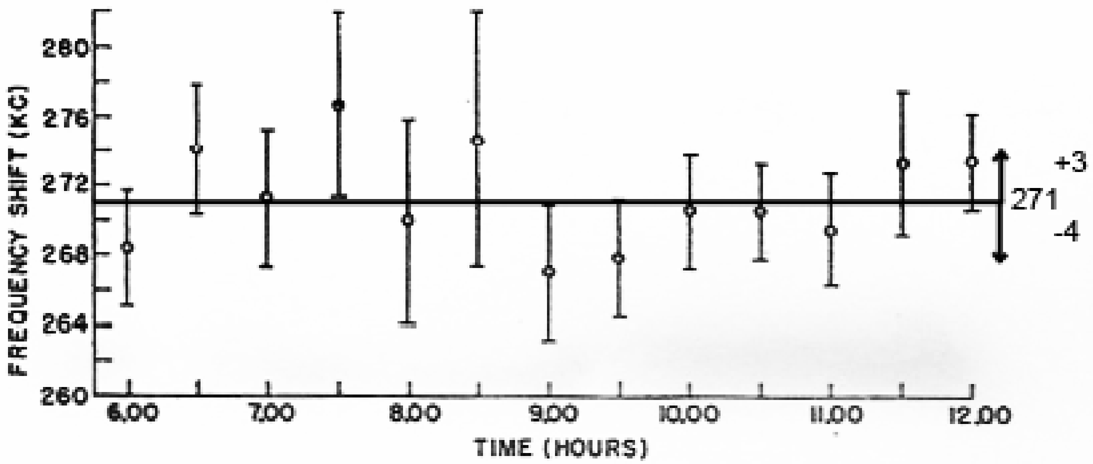


FIG. 3. Plot of relative frequency variation of two masers with 90° rotation as a function of the time of day between 6:00 a.m. and 12:00 noon on 20 January, 1963.

- The data by Jaseja et al. for the time variations of the signal
- The double arrow indicates the maximal time variations expected in the same model used for the classical expts.

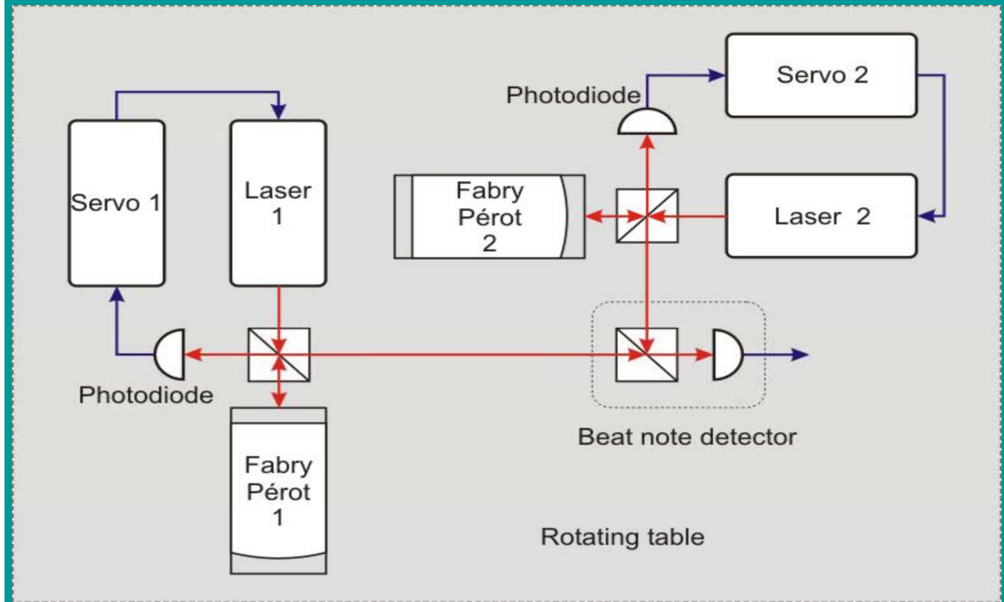
- The data have very large errors. However, they are consistent with the theoretical model adopted for the classical experiments

Check with the modern experiments

- Modern experiments look for an anisotropy of the two-way velocity of light through the relative frequency shift of two lasers stabilized with Fabry-Perot optical cavities (where a high vacuum is made)

$$\frac{\Delta\nu(t)}{\nu_0} = 2S(t)\sin 2\theta + 2C(t)\cos 2\theta$$

$$S(t) \approx \varepsilon \frac{v^2(t)}{c^2}\sin 2\theta_0(t) \qquad C(t) \approx \varepsilon \frac{v^2(t)}{c^2}\cos 2\theta_0(t)$$



- From present data in vacuum, $S(t)$ and $C(t)$ have instantaneous value $O(10^{-15})$

- Instead , by inserting air or gaseous helium in the cavities, one should obtain $O(10^{-9})$ and $O(10^{-10})$ respectively

- This and other tests should be possible with a new generation of dedicated experiments

Conclusions and outlook

- Classical Michelson-Morley experiments **in gaseous systems** have always shown small residuals, usually interpreted as spurious effects, mostly of thermal origin
- Our re-analysis indicates, instead, that these thermal effects have a NON-LOCAL origin. Indeed, when re-analyzed in a relativistic formalism, the typical kinematical Earth's velocities are well consistent with the 370 km/s value obtained from direct observations of the CMB in space. Consistency is also found with the only modern experiment performed in similar conditions (Jaseja et al. MIT, 1963)
- Therefore, this alternative interpretation should be checked with a new generation of dedicated laser interferometers to reproduce the conditions of those early measurements with today's much greater accuracy. These could provide precious complementary information to the direct CMB observations in space
- A non ambiguous confirmation would also imply that all physical systems on the moving Earth (and on any other celestial body) are exposed to an energy flow. This flow is very weak today but was substantially stronger in the past when the temperature of the **Cosmic Background Radiation** was higher. As such, it has represented (and still represents today) a sort of background noise which is independent of any localized source. It is known that such a type of non-equilibrium condition can induce (or could have induced) forms of self-organization in matter. Therefore, our result could also be relevant for those research areas which look for the origin of complexity in nature