Virgo and the fluctuations of the velocity of light

Maurizio Consoli
Istituto Nazionale di Fisica Nucleare, Sezione di Catania

EGO Observatory, April 15th, 2019

References: M.C. and A. Pluchino: Eur. Phys. J. Plus, 133 (2018) 295, arXiv:1801.03775 [physics.gen-ph]; M. C. and A. Pluchino, "Michelson-Morley Experiments: an Enigma for Physics and the History of Science", World Scientific 2019, ISBN 978-981-3278-18-9

The main point (1/3)

- Modern “ether-drift” expts. measure the frequency shift of two optical resonators.
- Since a few years, they find the same typical magnitude for the short-term fluctuations of the velocity of light (less sensitive to spurious effects) → $\frac{\Delta c_{xy}}{c} \approx 10^{-15}$

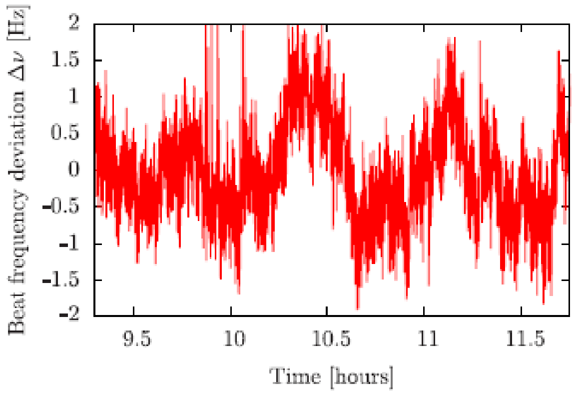
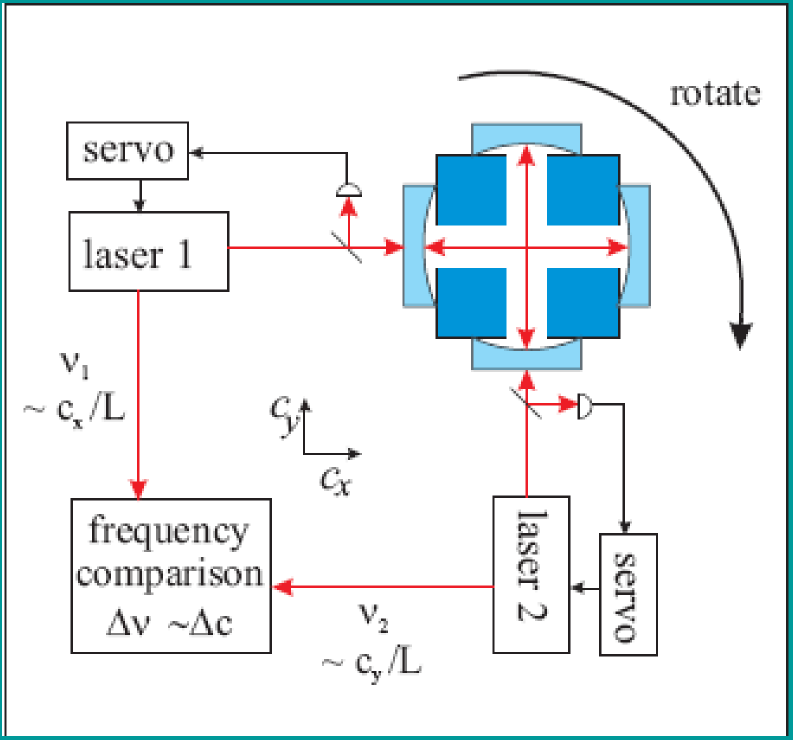


FIG. 4. A 2.5 h time interval of the beat frequency exhibiting a particularly constant drift (39 mHz/s), which was removed before plotting. One frequency reading per second is displayed. The apparatus is rotating.



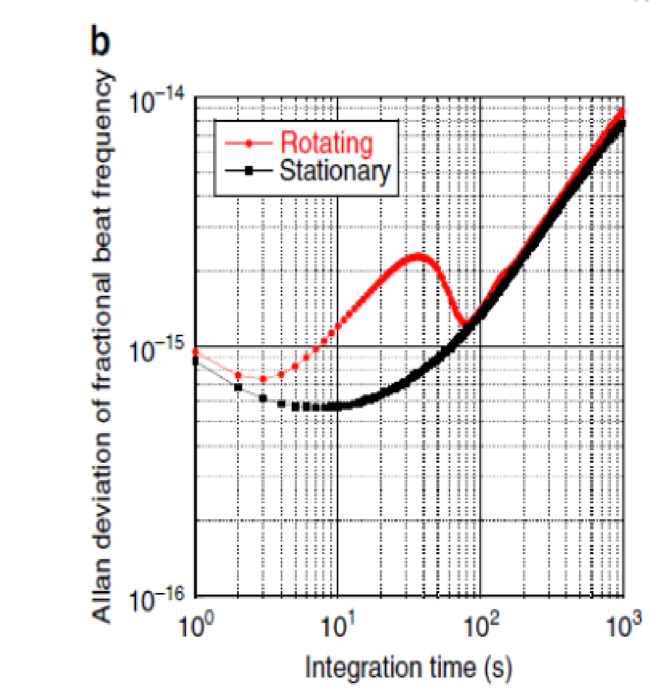
+/- 1 Hz for a laser frequency **ν= 2.82E+14 Hz**

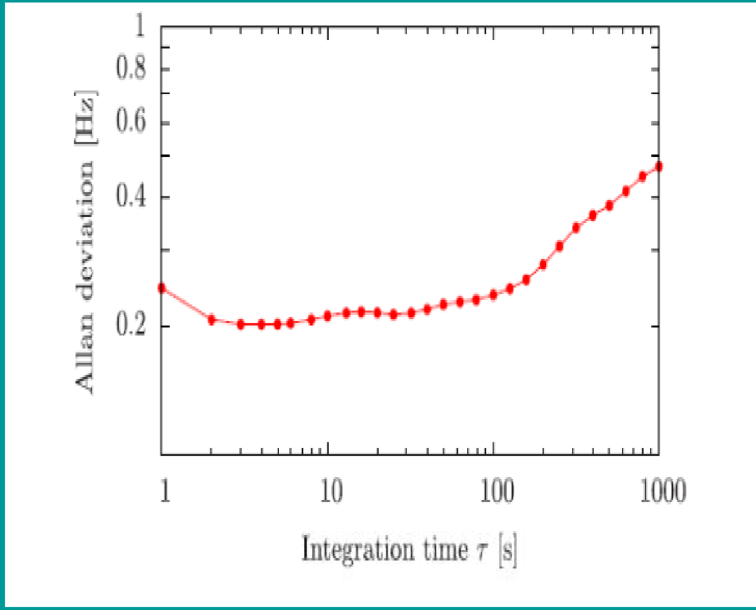
→ **Δc/c ~ +/- 3E-15.**

From Chen et al. PRD 93 (2016) 022003

The main point (2/3)

- The two most precise experiments (Nagel et al. Nature Comm. 6 (2015) 8174 and Chen et al PRD 93 (2016) 022003) find exactly the same fractional spread for an integration time of 1 second : $\sigma(1s) \approx 8.5 \cdot 10^{-16}$





$$\frac{0.24\text{Hz}}{2.8 \cdot 10^{14}\,\text{Hz}} = 8.5 \cdot 10^{-16}$$

- Very different systematics (sapphire cavities, cryogenic vs. vacuum cavities, room temperature)→ unlikely just spurious instrumental noise →Physical interpretation?

The main point (3/3)

- About 10 years ago (M. C. and L. Pappalardo, Gen. Rel. Grav.42(2010) 2585), by extrapolating from the classical Michelson-Morley experiments, we were indeed predicting (for an apparatus placed on the earth surface) **irregular fluctuations of the velocity of light** with the same typical size presently observed

$$\left[\frac{\Delta c_{xy}}{c}\right]_{TH} \approx 10^{-15} \approx \left[\frac{\Delta c_{xy}}{c}\right]_{EXP}$$

- Our most recent numerical simulations give **σ (1s) = (9 +/- 1) E-16** (TH) to be compared with **σ (1s) = 8.5 E-16** (EXP)
- An independent check with a modern Michelson interferometer would require

$$\frac{\Delta c_{xy}}{c} \approx \frac{\Delta L_{xy}}{L} \approx 10^{-15}$$

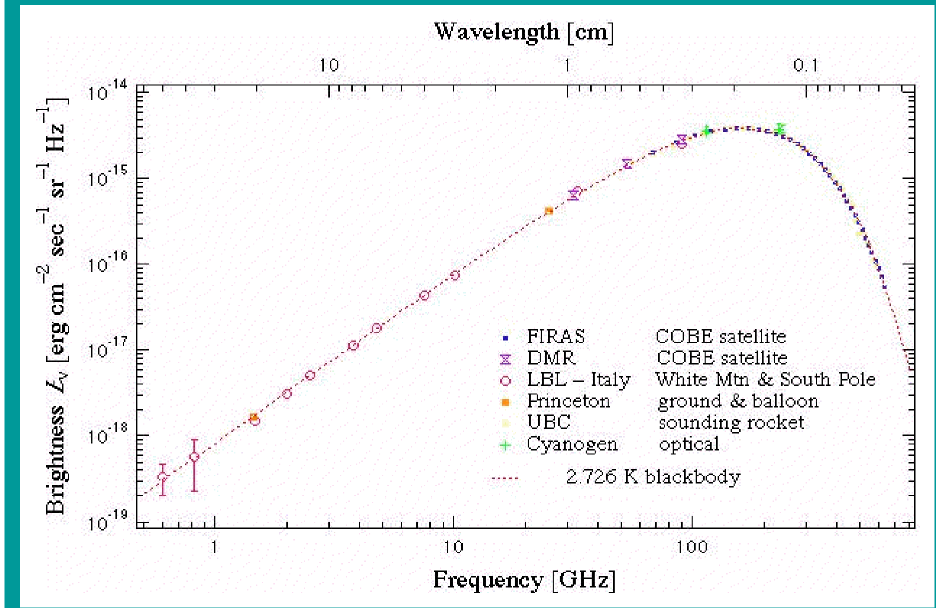
For instance, RMS stability $\Delta L_{xy} \approx 10^{-11}$ **m** and effective path **L ≈ 10 km** (or $\Delta L_{xy} \approx 10^{-10}$ **m** and **L ≈ 100 km …)** → **VIRGO ?**

Motivations and substantial physical implications → Rest of the talk

Summary

1) Unsolved problem: CMB Kinematic Dipole → a fundamental preferred reference frame?
2) Standard answer: try to observe an "ether drift", i.e. to correlate measurements of the velocity of light in laboratory and direct CMB observations with satellites in space
3) Before attempting this comparison, two remarks are in order:
4) **Remark 1**. Ether drift should be unobservable if the velocity of light in the interferometers is the same parameter "**c**" of Lorentz transformations
5) **Remark 2**. Ether drift might be a non-deterministic phenomenon (analogy with local properties of the fluid motion in turbulent flows)
6) From (**1 + 2**) → **Tiny, irregular fluctuations of the velocity of light** which are only correlated INDIRECTLY with the earth cosmic motion
7) Classical experiments (1887-1930) : correlations with CMB? YES
8) Present experiments with optical resonators : correlations with CMB ? YES
9) Traditional criteria for preferred frame OK → Substantial implications
10) Could VIRGO provide a check?

Cosmic Microwave Background



- After the original Penzias and Wilson discovery (1965), precise measurements have confirmed the black-body form of the Cosmic Microwave Background (CMB)

- Today the temperature is 2.725 K and the maximum is at about 2 millimeters (in the microwave region)

Soon after its discovery it was realized that the CMB should exhibit a small anisotropy as a consequence of the earth motion

VOLUME 18, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1967

ISOTROPY AND HOMOGENEITY OF THE UNIVERSE FROM MEASUREMENTS OF THE COSMIC MICROWAVE BACKGROUND*

R. B. Partridge and David T. Wilkinson†
Palmer Physical Laboratory, Princeton, New Jersey
(Received 2 March 1967)

A Dicke radiometer (3.2-cm wavelength) was used to make daily scans near the celestial equator to look for possible anisotropy in the cosmic blackbody radiation. After about one year of intermittent operation we find no 24-h asymmetry with an amplitude greater than ±0.1% (of 3°K). There is, however, a possibly significant 12-h anisotropy with an amplitude of about 0.2%.

PHYSICAL REVIEW VOLUME 174, NUMBER 5 25 OCTOBER 1968

Theory for the Measurement of the Earth's Velocity through the 3°K Cosmic Radiation*

C. V. HEER AND R. H. KOHL
Department of Physics, Ohio State University, Columbus, Ohio 43210
(Received 10 June 1968)

The intensity of radiation for an observer moving through thermal radiation is described by an anisotropic temperature $T(\theta)=T(1+\beta\cos\theta)^{-1}$ or $(h\nu^3/c^2)d\Omega d\nu[\exp h\nu/kT(\theta)-1]^{-1}$, where $\beta=v/c$. Temperature-measuring antennas measure $T(\theta)$. Intensity measurements give an anisotropy between radiation along $\pi+\theta$ and θ of $\beta\cos\theta$ for $(h\nu/kT)\ll 1$ (the same as the temperature anisotropy), and $(h\nu/kT)\beta\cos\theta$ for $(h\nu/kT)\gg 1$. Examples of moving detectors and surfaces in the laboratory and in space are discussed.

The CMB Kinematic Dipole

- For an observer in motion, a black-body spectrum of temperature $\mathbf{T_0}$ is deformed by the Doppler effect (**β=v/c**)

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

- To first order in **(v/c)** there is an angular variation

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

- It changes from a "hot pole" (**cosθ=1**) to a "cold pole" (**cosθ= -1**) and, for this reason, it is called "dipole" anisotropy
- For $\mathbf{T_0}$ = **2.725 K** , measurements by COBE, WMAP, PLANCK have precisely determined the average kinematical parameters of the earth motion
- **v=369 km/s** **Right Ascension = 168 degrees** **declination = -7 degrees**

These parameters correspond to an overall variation

$$\Delta T(\theta) \approx \pm 3.36\,\mathrm{mK}$$

THE CMB DIPOLE: THE MOST RECENT MEASUREMENT AND SOME HISTORY

Charles H. Lineweaver

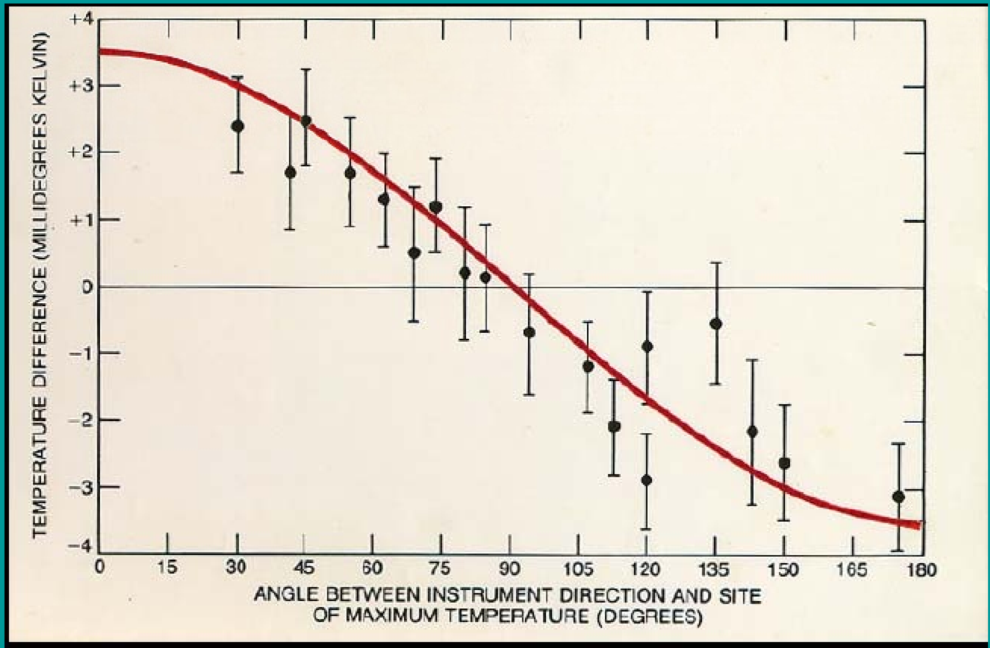
Université Louis Pasteur
Observatoire Astronomique de Strasbourg
11 rue de l'Université, 67000 Strasbourg, France
charley@cdsxb6.u-strasbg.fr

Table 1: CMB Dipole Measurements

#	Reference	Amplitude D(mK)	$\pm\sigma$	Longitude[a] ℓ(deg)	$\pm\sigma$	Latitude[a] b(deg)	$\pm\sigma$	Freq (GHz)
1	Penzias & Wilson(1965)	< 270						4
2	Partridge & Wilkinson(1967)	0.8	2.2					9
3	Wilkinson & Partridge(1969)	1.1	1.6					9
4	Conklin(1969)	1.6	0.8	96	30	85	30	8
5	Boughn et al. (1971)	7.6	11.6					37
6	Henry(1971)	3.3	0.7	270	30	24	25	10
7	Conklin(1972)	> 2.28	0.92	195	30	66	10	8
8	Corey & Wilkinson(1976)	2.4	0.6	306	28	38	20	19
9	Muehler(1976)	2.0	1.8	207		−11		150
10	Smoot et al. (1977)	3.5	0.6	248	15	56	10	33
11	Corey(1978)	3.0	0.7	288	26	43	19	19
12	Gorenstein(1978)	3.60	0.5	229	11	67	8	33
13	Cheng et al. (1979)	2.99	0.34	287	9	61	6	30
14	Smoot & Lubin(1979)	3.1	0.4	250.6	9	63.2	6	33
15	Fabbri et al. (1980)	2.9	0.95	256.7	13.8	57.4	7.7	300
16	Boughn et al. (1981)	3.78	0.30	275.4	3.9	46.8	4.5	46
17	Cheng(1983)	3.8	0.3					30
18	Fixsen et al. (1983)	3.18	0.17	265.7	3.0	47.3	1.5	25
19	Lubin (1983)	3.4	0.2					90
20	Strukov et al. (1984)	2.4	0.5					67
21	Lubin et al. (1985)	3.44	0.17	264.3	1.9	49.2	1.3	90
22	Cottingham(1987)	3.52	0.08	272.2	2.3	49.9	1.5	19
23	Strukov et al. (1987)	3.16	0.07	266.4	2.3	48.5	1.6	67
24	Halpern et al. (1988)	3.4	0.42	289.5	4.1	38.4	4.8	150
25	Meyer et al. (1991)			249.9	4.5	47.7	3.0	170
26	Smoot et al. (1991)	3.3	0.1	265	1	48	1	53
27	Smoot et al. (1992)	3.36	0.1	264.7	0.8	48.2	0.5	53
28	Ganga et al. (1993)			267.0	1.0	49.0	0.7	170
29	Kogut et al. (1993)	3.365	0.027	264.4	0.3	48.4	0.5	53
30	Fixsen et al. (1994)	3.347	0.008	265.6	0.75	48.3	0.5	300
31	Bennett et al. (1994)	3.363	0.024	264.4	0.2	48.1	0.4	53
32	Bennett et al. (1996)	3.353	0.024	264.26	0.33	48.22	0.13	53
33	Fixsen et al. (1996)	3.372	0.005	264.14	0.17	48.26	0.16	300
34	Lineweaver et al. (1996)	3.358	0.023	264.31	0.17	48.05	0.10	53

[a] Galactic coordinates

Measurements with U2 airplanes



- Measurements of the CMB temperature taken on board of a U2 airplane at 20 km of altitude, by Smoot, Gorenstein and Muller, Phys. Rev. Lett. 39 (1977) 898.

The Cosmic Background Radiation and the New Aether Drift

Sensitive instruments have found slight departures from uniformity in the radiation left by the primordial "big bang." The experiment reveals the earth's motion with respect to the universe as a whole

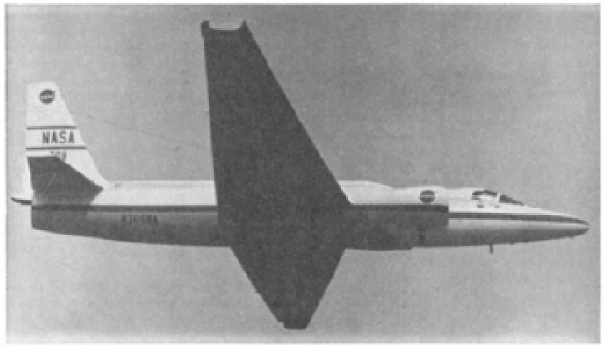
by Richard A. Muller

A curious radiation that bathes the earth almost uniformly from every direction has turned out to be a unique source of information about the nature and history of the universe. The faint radiation was identified 13 years ago during a search for noise sources capable of interfering with satellite communications systems. The "noise" proved to be of cosmic origin and soon became known as the three-degree cosmic black-body radiation because it has the spectral characteristics of a black body, or perfect emitter of radiation, whose temperature is about three degrees Kelvin (three degrees Celsius above absolute zero). Most astrophysicists now believe this microwave radiation was emitted shortly after the "big bang," the cataclysmic explosion in which the universe was created some 15 billion years ago. Not only is it the most ancient signal ever detected; it is also the most distant, coming from well beyond the quasars, the most remote luminous sources known. The three-degree radiation is a background in front of which all astrophysical objects lie.

The observation of the cosmic background radiation is the closest we have come to a direct study of the primordial explosion itself. The very existence of the radiation is the strongest evidence in favor of the big-bang theory. The isotropy of the radiation, that is, the uniformity of the radiation from different directions in space, tells us that the big bang, although it was unimaginably violent, also went quite smoothly. The slight departure from isotropy that has recently been discovered indicates that our galaxy is hurtling through the universe with the surprisingly high velocity of 600 kilometers per second. It is this cosmological velocity that has been called "the new aether drift," in reference to the "aether drift" that A. A. Michelson and E. W. Morley sought unsuccessfully to discover nearly a century ago by measuring the velocity of light over paths rotated at different angles with respect to the earth's motion in space. The three-degree cosmic background radiation provides an all-pervasive radiation "aether" for performing an analogous experiment.

The cosmic background radiation was discovered in 1965 by Arno A. Penzias and Robert W. Wilson of Bell Laboratories; its significance was immediately recognized by Robert H. Dicke and his group at Princeton University. Since then much has been learned about the spectrum of the radiation. Its intensity has now been studied at wavelengths ranging from 30 centimeters down to half a millimeter, confirming the initial conjecture that its spectral curve conforms to that of a black body at a temperature of three degrees K.

One of the most important observations reported by Penzias and Wilson was the constancy of the temperature of the radiation from different directions in space. Their measurements indicated that the temperature varies by less than 10 percent in any direction. Subsequent experiments set even lower limits on the departure from isotropy. Two independent groups have recently carried out measurements sensitive enough to show, however, that the temperature of the radiation is not precisely the same in all directions. One set of experiments was performed at Princeton by David T. Wilkinson and Brian E. Corey, the other set at the Lawrence Berkeley Laboratory of the University of California by a group that included George F. Smoot, Marc V. Gorenstein and me. It is now known that the temperature of the three-degree back-



INSTRUMENT PLATFORM in the new aether-drift experiment was a U-2 aircraft operated by the National Aeronautics and Space Administration. Like the original aether-drift experiment performed nearly a century ago by A. A. Michelson and E. W. Morley, the new experiment was designed to measure the earth's motion with respect to a universal frame of reference, in this case the cosmic background radiation. That radiation, which is equivalent to the radiation emitted by a black body (a perfect radiator) with a temperature of about three degrees Kelvin (three degrees Celsius above absolute zero), is radiation left over from the fireball in which universe was created 15 billion years ago. U-2 has made 10 flights carrying an ultrasensitive microwave receiver designed by the author, George F. Smoot and Marc V. Gorenstein.

CMB dipole: → Fundamental Reference Frame?

- The CMB dipole can be reconstructed (to good approximation) by combining the following forms of **Peculiar Motion** :

  1) Earth revolution around the Sun

  2) Rotation of the Solar System around the galactic center

  3) Motion of the Milky Way toward the center of the Local Group

  4) Motion of the Local Group of galaxies toward the Great Attractor

- **Vanishing CMB dipole** ↔ **switching-off all Peculiar Motions**

  → **Global Rest Frame** (average matter distribution in the Universe)
- CMB dipole could just INDICATE the existence of such global frame of rest (a new representation of the ether) but the cosmic radiation itself would NOT COINCIDE with this form of ether
- As in the old Lorentzian formulation, Lorentz transformations could still remain exact to connect two observers in relative, uniform translational motion but NEW PERSPECTIVE (e.g. the Non-Local aspects of the quantum theory)

VOLUME 68, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1992

Quantum Mechanics, Local Realistic Theories, and Lorentz-Invariant Realistic Theories

Lucien Hardy

Department of Mathematical Sciences, University of Durham, Durham DH1 3LE, England

(Received 22 January 1992)

First, we demonstrate Bell's theorem, without using inequalities, for an experiment with two particles. Then we show that, if we assume realism and we assume that the "elements of reality" corresponding to Lorentz-invariant observables are themselves Lorentz invariant, we can derive a contradiction with quantum mechanics.

PACS numbers: 03.65.Bz

- "Non-locality implies that, at the level of hidden variables, there is faster than light transfer of information. This could lead to the possibility of sending information backward in time giving rise to well known causal paradoxes.
- However, **if there is a special frame of reference then such causal paradoxes are blocked.**
- **One possible candidate for this special frame of reference is the one in which the cosmic background radiation is isotropic.** However, other than the fact that a realistic interpretation of quantum mechanics requires a special frame of reference and the cosmic background radiation provides us with one, there is no readily apparent reason why the two should be linked."

Importance of the “ether-drift” experiments

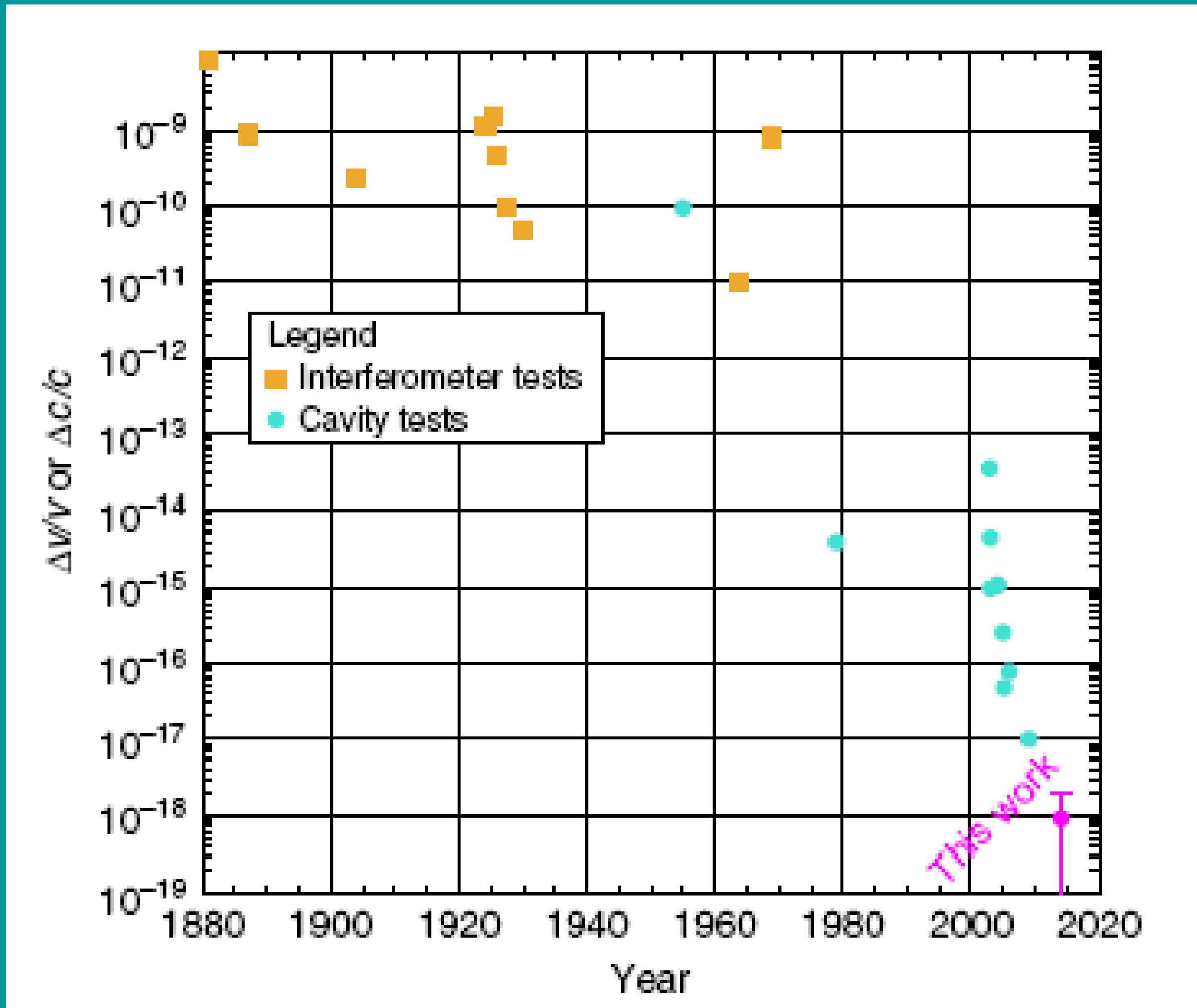
- Questions: does the CMB Dipole indicate a fundamental preferred frame? And how to decide about this basic issue?

- Traditional answer: look at the “ether-drift” experiments

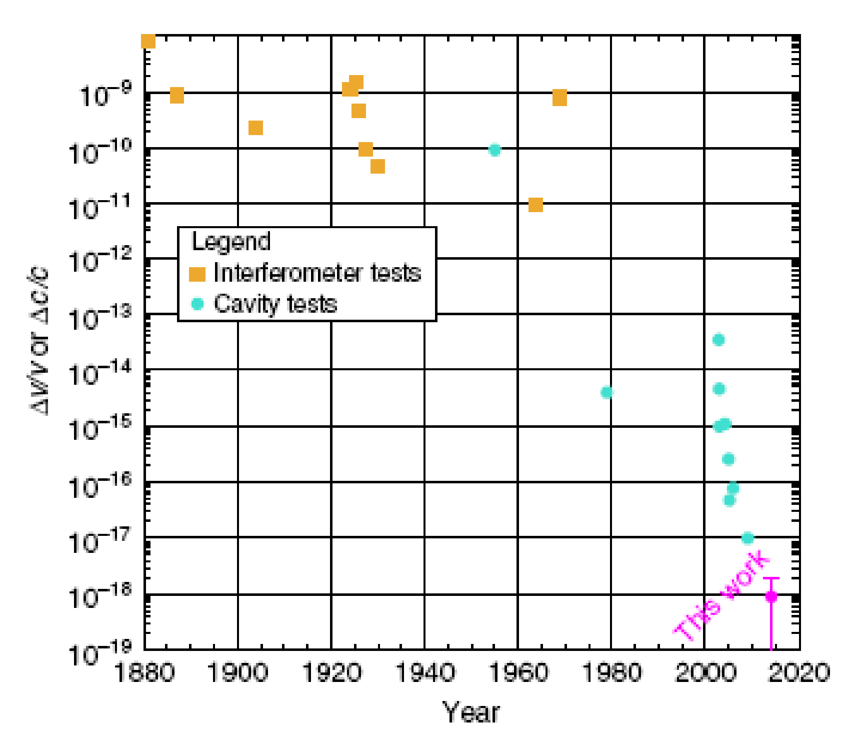
- Namely, the possibility to **correlate small differences Δc_{xy} of the velocity of light measured in laboratory and direct CMB observations** with satellites in space

- Such correlations would represent the “smoking gun” for the long sought fundamental reference frame

Ether-drift experiments: the standard presentation



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



- First impression: steady substantial improvement over the original "classical" measurements
- Traditional view: vanishingly small effects and no correlation with cosmic earth motion
- However: not only technological progress. In classical experiments light was propagating in gaseous media (air or helium at atmospheric pressure)
- Instead, modern experiments are performed in vacuum or solid dielectrics. Is this important?

‘c’ is the speed of light, isn’t it?

George F.R. Ellis*
Department of Mathematics and Applied Mathematics,
University of Cape Town,
Rondebosch 7700, Capetown, South Africa

Jean-Philippe Uzan†
Institut d’Astrophysique de Paris, GRεCO, FRE 2435-CNRS, 98bis boulevard Arago, 75014 Paris, France
Laboratoire de Physique Théorique, CNRS-UMR 8627,
Université Paris Sud, Bâtiment 210, F-91405 Orsay cédex, France
(Dated: October 24, 2018)

- Let us assume that ether drift should become unobservable if the (two-way) velocity of light in the various interferometers $\bar{\mathbf{c}}_\gamma$ coincides with the basic parameter “**c**” entering Lorentz transformations → exact isotropic propagation in this limit
- However, if $\bar{\mathbf{c}}_\gamma \neq \mathbf{c}$, nothing would forbid a small angular difference

$$\Delta\bar{\mathbf{c}}_\theta = \bar{\mathbf{c}}_\gamma(\pi/2+\theta) - \bar{\mathbf{c}}_\gamma(\theta) \neq \mathbf{0}$$

- $\Delta\bar{\mathbf{c}}_\theta \neq \mathbf{0}$ → Fringe shifts in Michelson’s interferometers. Which size?

The two-way velocity of light

- By assuming : i) the existence of a fundamental preferred frame Σ
  ii) the validity of Lorentz transformations

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

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

Therefore , from the symmetry properties of the two-way velocity under replacements $\beta \to -\beta$ and $\theta \to \pi+\theta$, one gets the leading general structure

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

where $P_{2k}(\cos\theta)$ are Legendre polynomials and ς_{2k} arbitrary coefficients. This gives a first estimate

$$\Delta\bar{c}_\theta \approx \varepsilon\beta^2$$ (compare with $(\Delta\bar{c}_\theta)^{class} \approx \beta^2$)

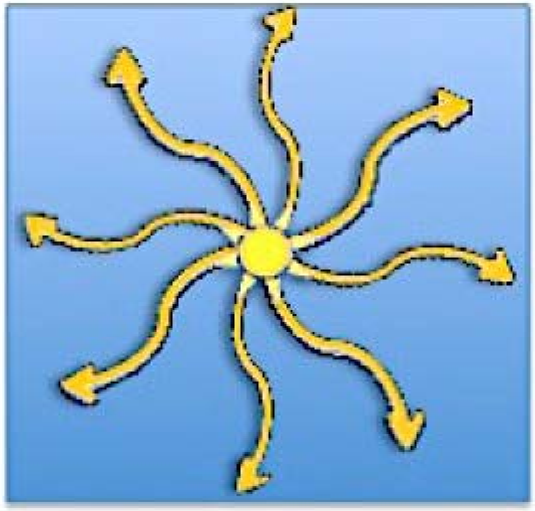
Viable strategy: fitting the data with the first few ς_{2k} as free parameters.

However, one can further sharpen the predictions

Light propagation in a (ideal) vacuum

CMB

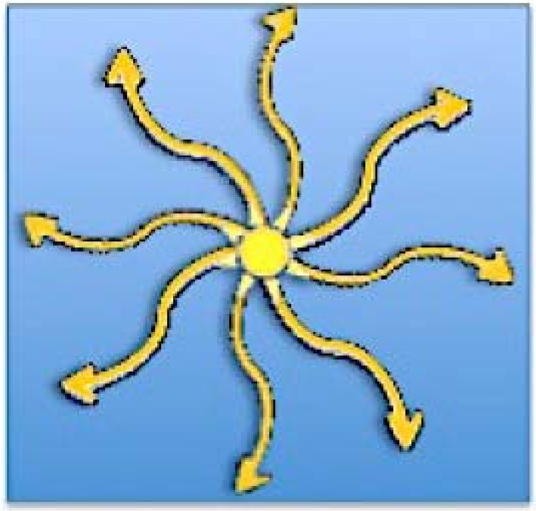
Earth



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

V

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



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

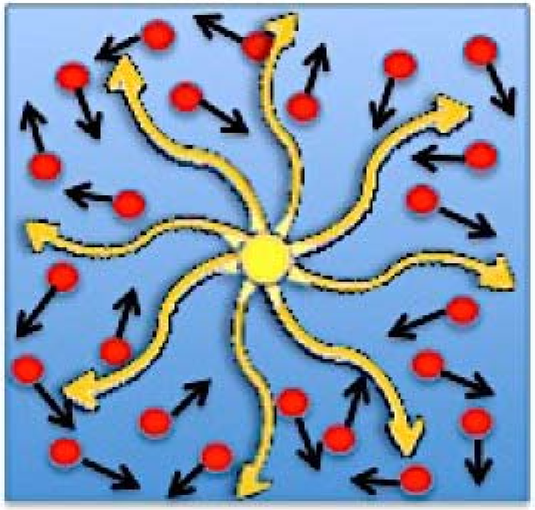
$$\eta^{\mu\nu} = diag(1,-1,-1,-1)$$

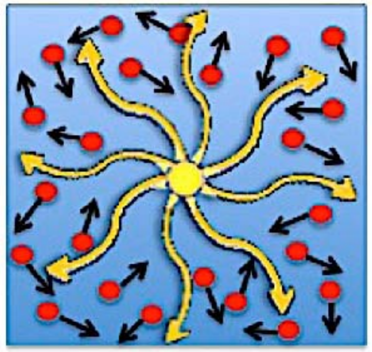
$$p_{\mu}p_{\nu}g^{\mu\nu} = 0$$

Light propagation in a "medium" with **N=1+ε**

Earth

CMB

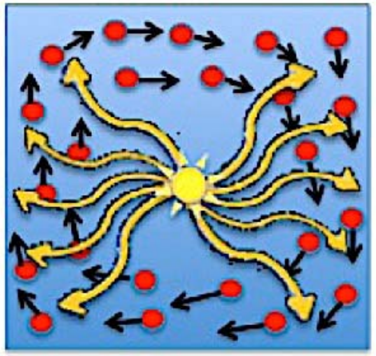




$$g^{\mu\nu} = \delta^{\mu}_{\sigma}\delta^{\nu}_{\rho}\gamma^{\sigma\rho} = \gamma^{\mu\nu} \approx \eta^{\mu\nu} + 2\varepsilon\delta^{\mu}_{0}\delta^{\nu}_{0}$$

V

$$g^{\mu\nu} = \Lambda^{\mu}_{\sigma}\Lambda^{\nu}_{\rho}\gamma^{\sigma\rho} \approx \eta^{\mu\nu} + 2\varepsilon v^{\mu} v^{\nu}$$



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

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

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

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

The modern version of Maxwell's classical calculation

- By using Lorentz transformations one finds the following simple expression for the two-way velocity of light (in the Earth frame)

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

- This is just a particular case of the general structure deduced before

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

where

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

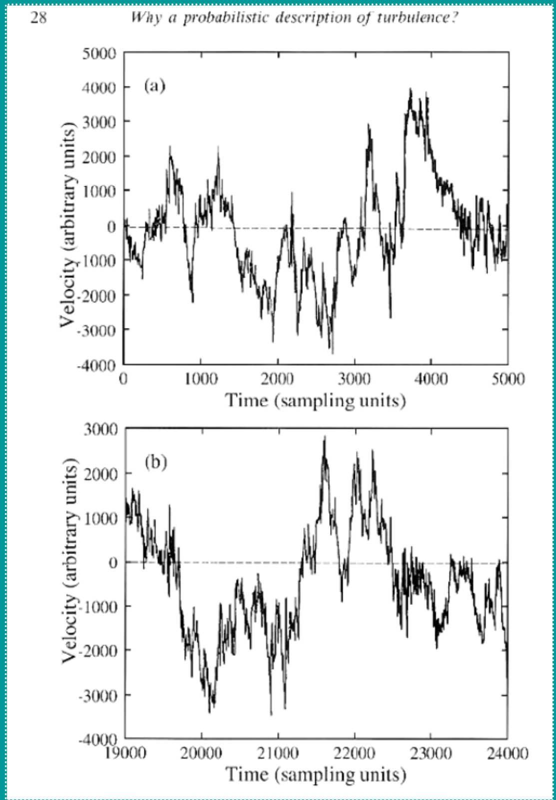
It can be taken as a **modern version of Maxwell's classical calculation**

Physical nature of a hypothetical ether-drift

- Traditionally, ether drift has been assumed to be a purely deterministic phenomenon→ smooth and regular modulations associated with the Earth rotation (and its orbital revolution)
- Thus, for short-time observations (say 1-2 days), only the Earth rotation should be important
- Standard Fourier analysis with just two frequencies: $\omega_{\oplus}$ and $2\omega_{\oplus}$
- Instead the data, of both classical and modern experiments, have always shown a highly irregular nature→ Instantaneous signal of given magnitude has much smaller statistical average
- This has always represented a strong argument to interpret the data as mere instrumental artifacts
- However…

" Ether-drift " experiments : noise or stochastic turbulence?

- Turbulent flow in a wind tunnel (ONERA, from U. Fritsch, Turbulence, Cambridge University Press, 1995).
- This is a **true signal not just noise**



Frequency shift measured by Chen et al. Phys. Rev. D93(2016)022003

So far, **interpreted as noise**

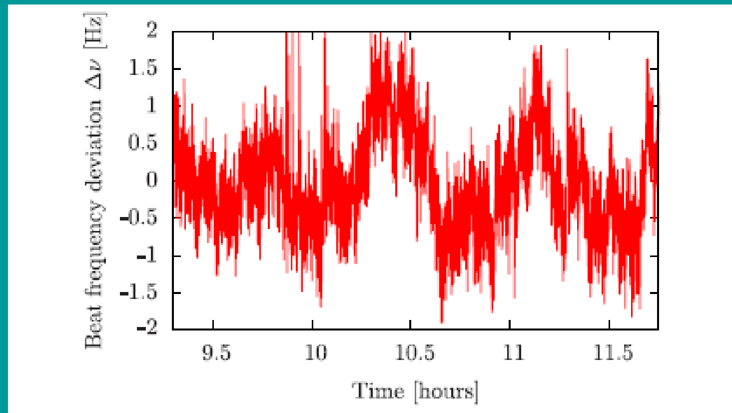


FIG. 4. A 2.5 h time interval of the beat frequency exhibiting a particularly constant drift (39 mHz/s), which was removed before plotting. One frequency reading per second is displayed. The apparatus is rotating.

Laser frequency 2.82E+14 Hz

+/-1 Hz → **Δc/c ~ +/- 3E-15**

" Ether-drift " experiments : noise or stochastic turbulence?

- Power spectrum of the longitudinal component of the wind measured at the Florence Airport, from S. Rizzo and A. Rapisarda, arXiv: [cond. mat./0406684]
- Again this is a **true signal**

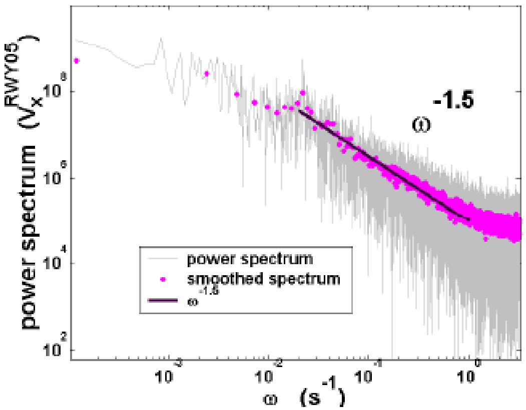
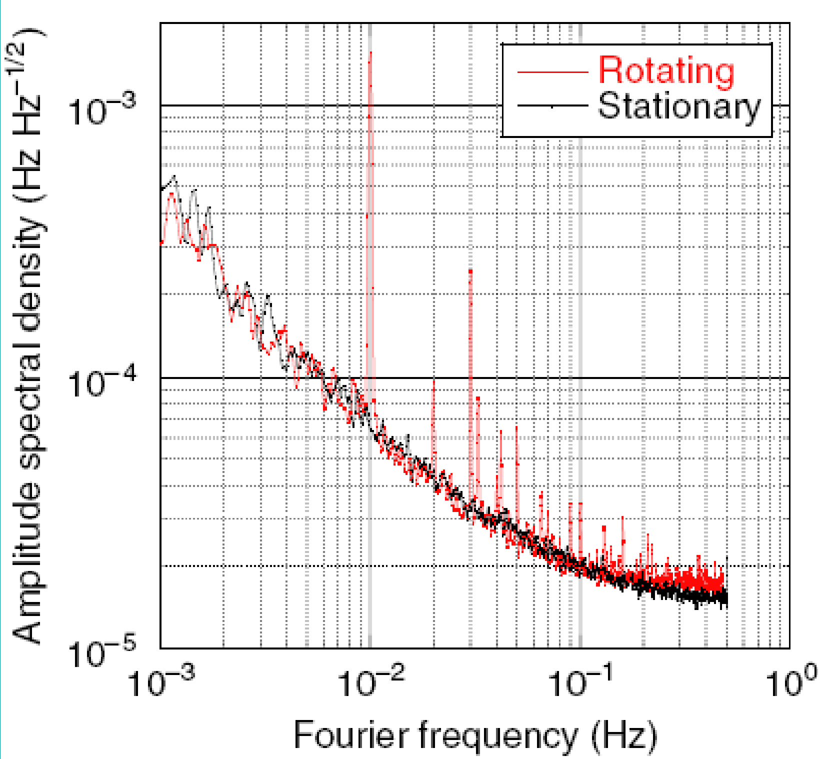


FIGURE 1. Power spectrum of the longitudinal component of the wind, recorded by the RWY05 anemometer. The slope we find is -1.5, slightly smaller than that one predicted by Kolmogorov, i.e. -5/3 [8].

Power spectrum of the frequency shift measured by Nagel et al. Nature Comm. **6** (2015) 8174



Alternative interpretation of the data

- A pure deterministic picture of the signal is equivalent to a model of the “ether” (i.e. the physical vacuum) as some kind of fluid in a state of laminar motion where global and local velocity flows coincide

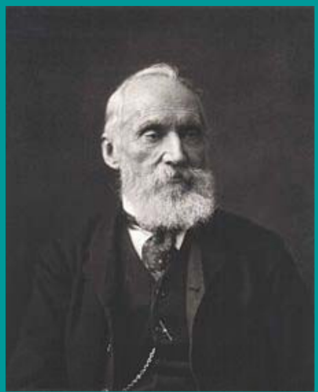
- However, if the physical vacuum is similar to a turbulent fluid…and if turbulence becomes isotropic at small scales…→ THEN a genuine signal would exhibit a very irregular behavior

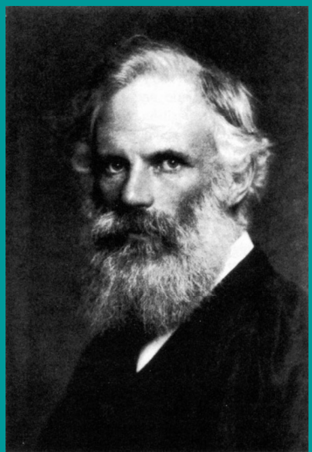
- For instance vector observables, as the fringe shifts, would have vanishing statistical average (for an infinite number of measurements). Yet, there would be a genuine physical signal

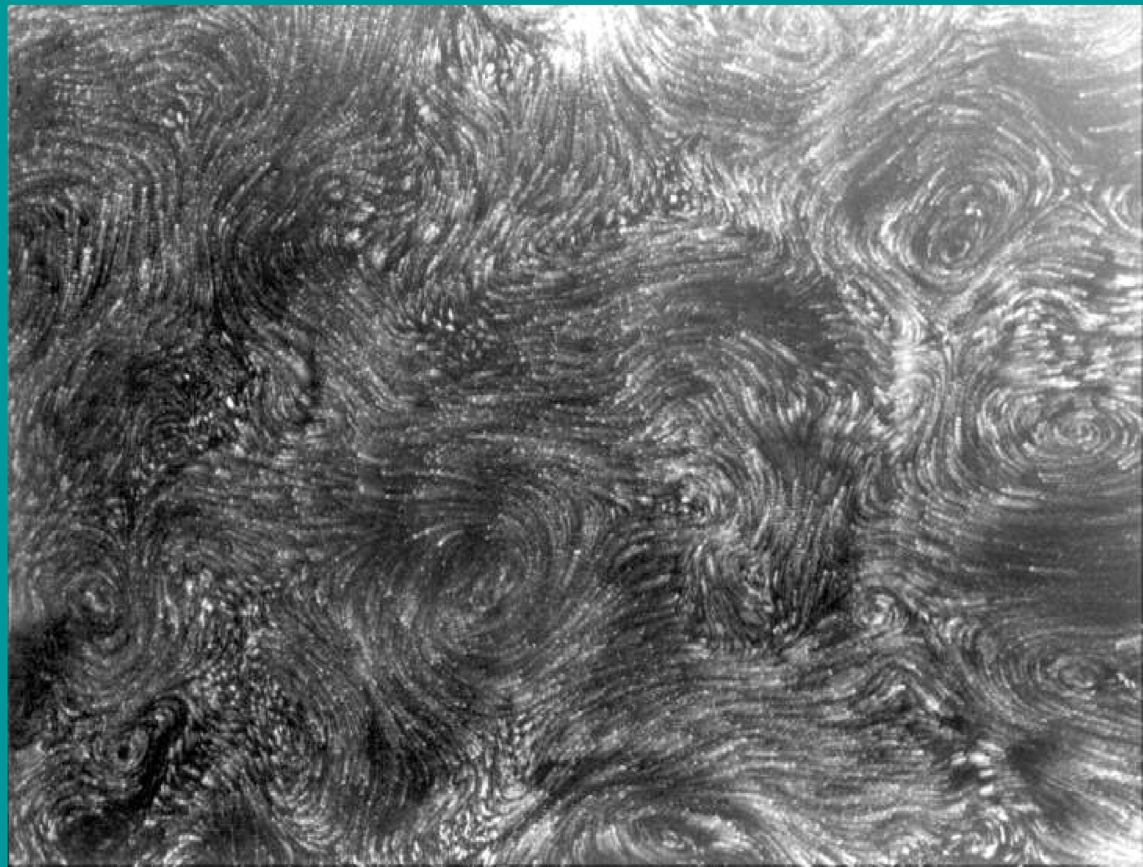
The XIX century ether perspective

At the end of XIX century (for Lord Kelvin , Fitzgerald, Hicks…) the ether was an incompressible turbulent fluid, see e.g. E.T. Whittaker 1955

Maxwell's equations were derived from classical hydrodynamics $\leftrightarrow$ Lorentz invariance as an emergent symmetry







The idea of a turbulent vacuum (1/2)

- In quantum gravity the vacuum is believed to be a form of space-time foam which resembles a turbulent fluid (originally J. A. Wheeler 1957)

- In this picture, repeated measurements of a time interval or of a distance do not produce the same results but fluctuate for fundamental reasons. The frequency of an optical resonator depends on the mirror spacing. Simple models of the fractional length change $\Delta L/L$ lead to flicker noise $S(\nu) \approx \alpha/\nu$ or random walk noise $S(\nu) \approx \beta/\nu^2$ (J. Ng, Mod. Phys. Lett. A18 (2003) 1073). Expts. can place limits on α and β

- More recently, by noticing that the shift vector of general relativity g_{0i} plays the same role of a fluid velocity u_i , the quantum fluctuations of the metric in the holographic model could also be seen as a manifestation of Kolmogorov's scaling laws of velocity in fully developed turbulence (J. Ng and collaborators, Class. Quant. Grav.25 (2008) 225012; Int.J.Mod.Phys.D19 (2010)2311

The idea of a turbulent vacuum (2/2)

- At some deep level the vacuum might be a stochastic medium, similar to a fluid in a turbulent regime→ As in the XIX century perspective, Lorentz symmetry might be an emergent phenomenon

- However, the idea of Lorentz symmetry from an underlying chaotic medium is not peculiar of quantum gravity but is also found in other classical and quantum contexts, see e.g. O. V. Troshkin, Physica A168 (1990) 881; C. D. Froggatt and H. B. Nielsen, The Origin of Symmetry, World Scientific 1991; L. A. Saul, Phys. Lett. A314 (2003) 472; P. Jizba and H. Kleinert Phys. Rev. D82 (2010) 085016…

- The **persistence of this general picture** suggests that this aspect of the vacuum might not be a pure speculative issue but also have phenomenological implications → In our case, **alternative reading of the stochastic signal observed in ether-drift experiments**

Simplest argument: physical vacuum (ether) as a zero-viscosity fluid → infinite Reynolds number→ turbulence

- Informally, viscosity is the quantity that describes the resistance of a fluid to the motion through it of immersed objects

SUPPLEMENTO AL VOLUME VI, SERIE IX DEL NUOVO CIMENTO N. 2, 1949

XIII.

Statistical Hydrodynamics. (*)

L. Onsager

New Haven, Conn.

It is of some interest to note that in principle, turbulent dissipation as described could take place just as readily without the final assistance by viscosity. In the absence of viscosity, the standard proof of the conservation of energy does not apply, because the velocity field does not remain differentiable! In fact it is possible to show that the velocity field in such "ideal" turbulence cannot obey any Lipschitz condition of the form

(26) $$|\vec{v}(\vec{r}' + \vec{r}) - \vec{v}(\vec{r}')| < (\text{const.})\, r^n ,$$

for any order n greater than 1/3; otherwise the energy is conserved. Of course, under the circumstances, the ordinary formulation of the laws of motion in terms of differential equations becomes inadequate and must be replaced by a more general description; for example, the formulation (15) in terms of Fourier series will do. The detailed conservation of energy (17) does not

The Feynman

LECTURES ON

PHYSICS

41–5 The limit of zero viscosity

We would like to point out that none of the flows we have described are anything like the potential flow solution we found in the preceding chapter. This is, at first sight, quite surprising. After all, $\mathfrak{R}$ is proportional to $1/\eta$. So η going to zero is equivalent to $\mathfrak{R}$ going to infinity. And if we take the limit of large $\mathfrak{R}$ in

41–9

Eq. (41.23), we get rid of the right-hand side and get just the equations of the last chapter. Yet, you would find it hard to believe that the highly turbulent flow at $\mathfrak{R} = 10^7$ was approaching the smooth flow computed from the equations of "dry" water. How can it be that as we approach $\mathfrak{R} = \infty$, the flow described by Eq. (41.23) gives a completely different solution from the one we obtained taking $\eta = 0$ to start out with? The answer is very interesting. Note that the right-hand term of Eq. (41.23) has $1/\mathfrak{R}$ times a *second derivative*. It is a higher derivative than any other derivative in the equation. What happens is that although the coefficient $1/\mathfrak{R}$ is small, there are very rapid variations of Ω in the space near the surface. These rapid variations compensate for the small coefficient, and the product *does not go to zero* with increasing $\mathfrak{R}$. The solutions do not approach the limiting case as the coefficient of $\nabla^2\Omega$ goes to zero.

REVIEWS OF MODERN PHYSICS, VOLUME 78, JANUARY 2006

Onsager and the theory of hydrodynamic turbulence

Gregory L. Eyink

Department of Applied Mathematics and Statistics, The Johns Hopkins University, Baltimore, Maryland 21218, USA

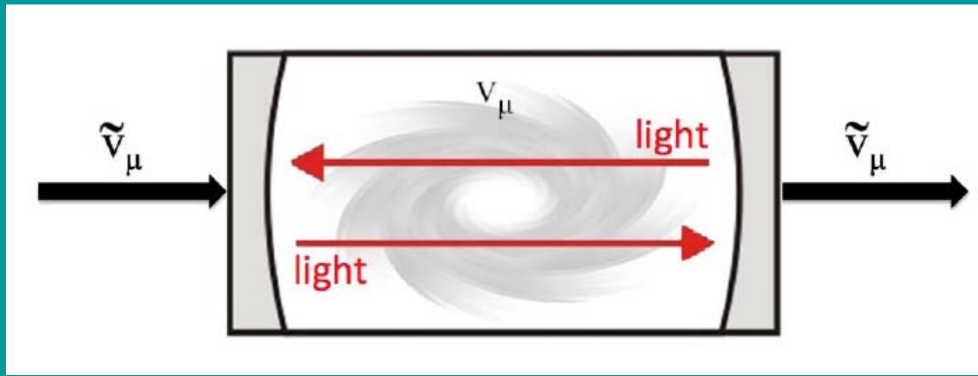
Katepalli R. Sreenivasan

International Center for Theoretical Physics, Trieste, Italy and Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742, USA

(Published 17 January 2006)

flow. In this picture, the turbulent velocity fields in the inviscid limit are continuous, nowhere differentiable functions, similar to ideal Brownian paths. What is

Light propagation in a stochastic vacuum



$\mathbf{v_i(t) \neq \tilde{v}_i(t)}$ but $\mathbf{v_i(t)}$ assumed to be random variable varying within typical limits fixed by the Earth cosmic motion $\mathbf{\tilde{v}_i(t)}$

$$\mathbf{v_i(t) \in \left[-\tilde{v}_i(t), \tilde{v}_i(t)\right]}$$

$$\mathbf{g^{\mu\nu}(t) \approx \eta^{\mu\nu} + 2\varepsilon v^{\mu}(t) v^{\nu}(t)} \qquad \mathbf{p_\mu p_\nu g^{\mu\nu} = 0}$$

Velocity field and light anisotropy

- At any given time "**t**" and at any direction **θ**, light anisotropy has the expression

$$\frac{\Delta\bar{c}_\gamma(\theta,t)}{c} = \varepsilon\frac{v^2(t)}{c^2}\cos 2[\theta-\theta_0(t)]$$

where **v(t)** and $\theta_0(t)$ describe the local velocity field in the relevant plane

$$\frac{\Delta\bar{c}_\gamma(\theta,t)}{c} = 2C(t)\cos 2\theta + 2S(t)\sin 2\theta$$

with

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

- Hence, by introducing the x-y velocity components

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

- one finds

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

Stochastic velocity field

- The x-y velocity components can be simulated in a stochastic model where turbulence becomes isotropic and homogeneous at small scales. This is based on the simple picture of the vacuum as a fluid with vanishing viscosity (or infinite Reynolds number).
- In this case, one can use the **method of random Fourier series** , see e.g. L. Onsager N. Cimento Suppl. 6 (1949) 279; Landau& Lifshitz, Fluid Mechanics; 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 $\omega_n = \frac{2n\pi}{T}$ with period (in our case) $T \approx T_{day}$

- The coefficients $x_n(i=1,2)$ and $y_n(i=1,2)$ are random variables with zero mean within the ranges $[-\tilde{v}_x(t),\tilde{v}_x(t)]$ and $[-\tilde{v}_x(t),\tilde{v}_x(t)]$ respectively. These boundaries are determined by the global flow (Earth cosmic motion)
- In a uniform probability model quadratic averages are

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

where η fixes the power spectrum of the fluctuating components.

Statistically isotropic local velocity field

- In this model statistical averages are

$$\left\langle v_x^2(t)\right\rangle_{stat} = \frac{\tilde{v}_x^2(t)}{3}\sum_{n=1}^{\infty}\frac{1}{n^{2\eta}} = \frac{\tilde{v}_x^2(t)}{3}\zeta_{riemann}(2\eta) \qquad \left\langle v_y^2(t)\right\rangle_{stat} = \frac{\tilde{v}_y^2(t)}{3}\sum_{n=1}^{\infty}\frac{1}{n^{2\eta}} = \frac{\tilde{v}_y^2(t)}{3}\zeta_{riemann}(2\eta)$$

- and $\left\langle v_x(t)v_y(t)\right\rangle_{stat} = 0$

- Therefore $\left\langle 2C(t)\right\rangle_{stat} = \varepsilon\frac{\left\langle v_x^2(t)\right\rangle_{stat} - \left\langle v_y^2(t)\right\rangle_{stat}}{c^2} = \varepsilon\frac{\tilde{v}_x^2(t) - \tilde{v}_y^2(t)}{3c^2}\zeta_{riemann}(2\eta)$

$$\left\langle 2S(t)\right\rangle_{stat} = \varepsilon\left\langle\frac{2v_x(t)v_y(t)}{c^2}\right\rangle_{stat} = 0$$

- If Reynolds number Re → ∞, Kolmogorov theory predicts statistical isotropy and certain scaling laws. By defining $\tilde{v}_x^2(t) + \tilde{v}_y^2(t) = \tilde{v}^2(t)$ the boundaries are $\tilde{v}_x(t) = \tilde{v}_y(t) = \frac{\tilde{v}(t)}{\sqrt{2}}$ so that

$$\left\langle 2S(t)\right\rangle_{stat} = \left\langle 2C(t)\right\rangle_{stat} = 0$$

- and therefore

$$\frac{\left\langle \Delta\bar{c}_\gamma(\theta,t)\right\rangle_{stat}}{c} = \left\langle 2C(t)\right\rangle_{stat}\cos 2\theta + \left\langle 2S(t)\right\rangle_{stat}\sin 2\theta = 0$$

Analysis of a (standard) Michelson's interferometer

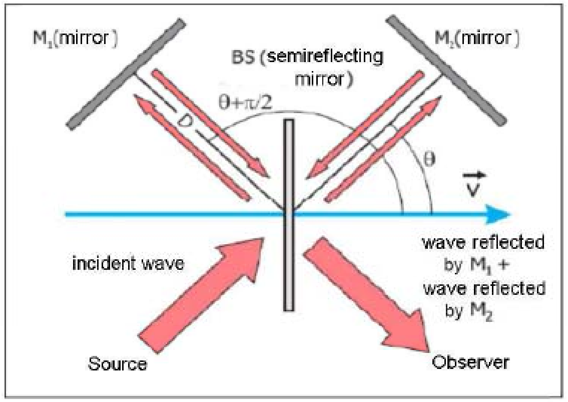


Figure 1: *The typical scheme of Michelson's interferometer.*

Fringe shifts depend on the time difference

$\Delta\tau(\theta,t)$ with

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

so that

$$\frac{\Delta\lambda(\theta,t)}{\lambda}=\frac{2D}{\lambda}\frac{\Delta\bar{c}_\gamma(\theta,t)}{c}\approx\frac{2D}{\lambda}\left[2C(t)\cos 2\theta+2S(t)\sin 2\theta\right]$$

But in a model of isotropic turbulence

$$\left\langle\frac{\Delta\lambda(\theta,t)}{\lambda}\right\rangle_{stat}=\frac{2D}{\lambda}\left[\left\langle 2C(t)\right\rangle_{stat}\cos 2\theta+\left\langle 2S(t)\right\rangle_{stat}\sin 2\theta\right]=0$$

- With such stochastic form of drift, the traditional data taking of a vector average of the fringe shifts (at the same angle and at the same sidereal time) has no sense. The averages would vanish **exactly** for an infinite number of measurements. But, then, how to compare with the old experiments?
- Simple answer: analyze the data in **Amplitude** and **Phase**

Amplitude-Phase analysis of the data

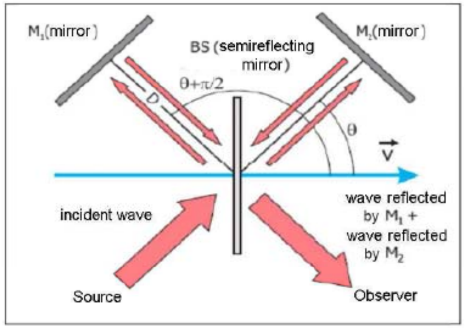


Figure 1: *The typical scheme of Michelson's interferometer.*

$$\frac{\Delta\lambda(\theta,t)}{\lambda}=\frac{2D}{\lambda}\frac{\Delta\bar{c}_\gamma(\theta,t)}{c}\approx\frac{2D}{\lambda}\left[2C(t)\cos 2\theta+2S(t)\sin 2\theta\right]$$

$$\frac{\Delta\lambda(\theta,t)}{\lambda}=A_2(t)\cos 2\left[\theta-\theta_0(t)\right]$$

$$A_2(t)=\frac{2D\varepsilon}{\lambda}\frac{v_x^2(t)+v_y^2(t)}{c^2}$$

$$\left\langle A_2(t)\right\rangle_{stat}=\frac{2D\varepsilon}{\lambda}\frac{\left\langle v_x^2(t)+v_y^2(t)\right\rangle_{stat}}{c^2}=\frac{2D\varepsilon}{\lambda}\frac{\tilde{v}^2(t)}{3c^2}\zeta_{riemann}(2\eta)$$

$$\left\langle A_2(t)\right\rangle_{stat}=\frac{2D\varepsilon}{\lambda}\frac{\tilde{v}^2(t)}{3c^2}\zeta_{riemann}(2)=\frac{D}{\lambda}\frac{\tilde{v}^2(t)}{c^2}2\varepsilon\frac{\pi^2}{18}$$

- **REMARK**: With Kolmogorov scaling , **$\eta=1$** in the Lagrangian description where the point of measurement is a wandering material point in the fluid. Instead **$\eta=5/6$** in the Eulerian description. Predictions would be larger by a factor

$$\frac{\zeta_{riemann}(5/3)}{\zeta_{riemann}(2)}\approx 1.29$$

Comparison with the classical predictions

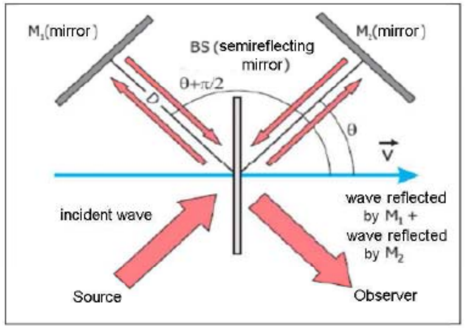


Figure 1: *The typical scheme of Michelson's interferometer.*

$$A_2(t) = \frac{2D\varepsilon}{\lambda}\frac{v_x^2(t)+v_y^2(t)}{c^2}$$

$$\left[A_2(t)\right]_{class} = \frac{D}{\lambda}\frac{\tilde{v}^2(t)}{c^2}$$

$$\left\langle A_2(t)\right\rangle_{stat} == \frac{D}{\lambda}\frac{\tilde{v}^2(t)}{c^2}2\varepsilon\frac{\pi^2}{18} \equiv \frac{D}{\lambda}\frac{\tilde{v}^2_{obs}(t)}{c^2}$$

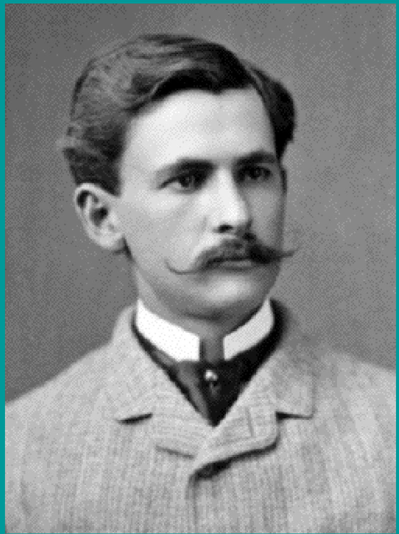
- **Example :** $\tilde{V}$ =**369 km/s** **and** **Expts. in gaseous media**

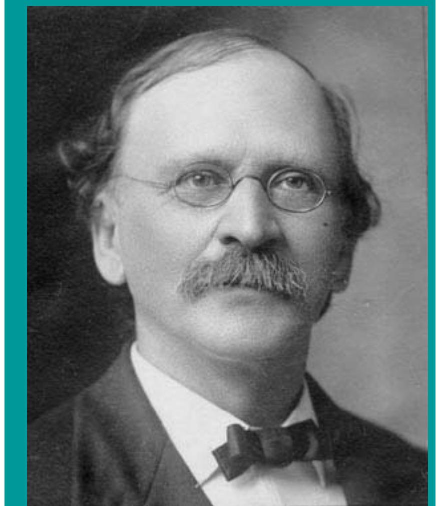
air atm. pressure and room temp. $\varepsilon \approx 0.000278$ → $\tilde{V}_{obs} \approx 6.5$ km/s

helium atm. pressure and room temp. $\varepsilon \approx 0.000033$ → $\tilde{V}_{obs} \approx 2.2$ km/s

Typical fringe shifts are about 20 times smaller or 200 times smaller, respectively, than the classical prediction for the much lower orbital value of 30 km/s !

1887: Michelson-Morley experiment





No. 203. Vol. XXXIV. NOVEMBER, 1887.

Established by BENJAMIN SILLIMAN in 1818.

THE

AMERICAN

JOURNAL OF SCIENCE.

EDITORS

JAMES D. AND EDWARD S. DANA.

ASSOCIATE EDITORS

PROFESSORS ASA GRAY, JOSIAH P. COOKE, AND JOHN TROWBRIDGE, OF CAMBRIDGE,

PROFESSORS H. A. NEWTON AND A. E. VERRILL, OF NEW HAVEN,

PROFESSOR GEORGE F. BARKER, OF PHILADELPHIA.

THIRD SERIES.

VOL. XXXIV.—[WHOLE NUMBER, CXXXIV.]

WITH PLATES II TO IX.

No. 203—NOVEMBER, 1887.

NEW HAVEN, CONN.: J. D. & E. S. DANA.
1887.

TUTTLE, MOREHOUSE & TAYLOR, PRINTERS, 371 STATE STREET.

Six dollars per year (postage prepaid). \$6.40 to foreign subscribers of countries in the Postal Union. Remittances should be made either by money orders, registered letters, or bank checks.

THE

AMERICAN JOURNAL OF SCIENCE.

[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.†

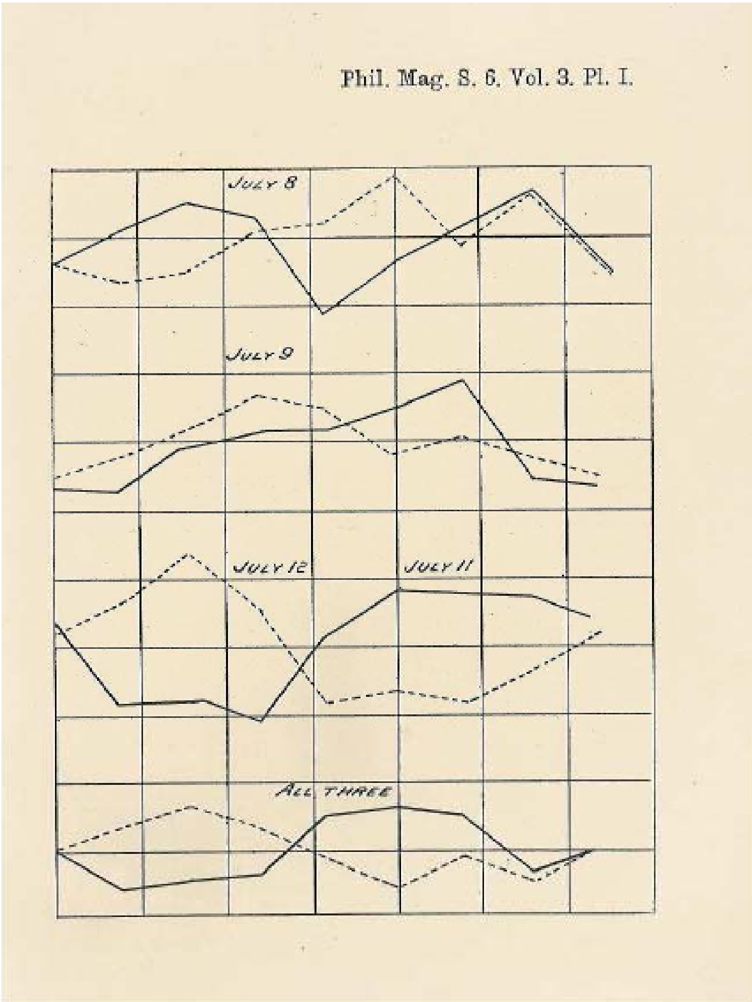
* This research was carried out with the aid of the Bache Fund.
† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the 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

Michelson and Morley—Relative Motion of the **341**

displacement should be $2D\frac{v^2}{V^2}=2D\times10^{-8}$. The distance D was about eleven meters, or 2×10^7 wave-lengths of yellow light; hence the displacement to be expected was 0·4 fringe. The actual displacement was certainly less than the twentieth part of this, and probably less than the fortieth part. But since the displacement is proportional to the square of the velocity, the relative velocity of the earth and the ether is probably less than one sixth the earth's orbital velocity, and certainly less than one-fourth.

1902 : Hicks' analysis of MM data



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

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

1933 : Miller's analysis

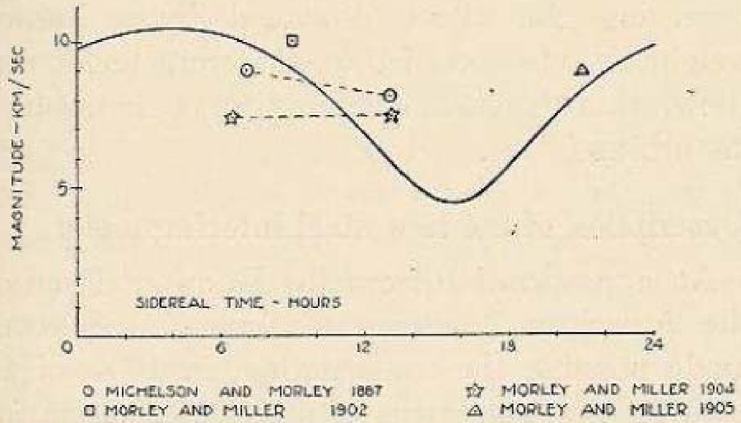
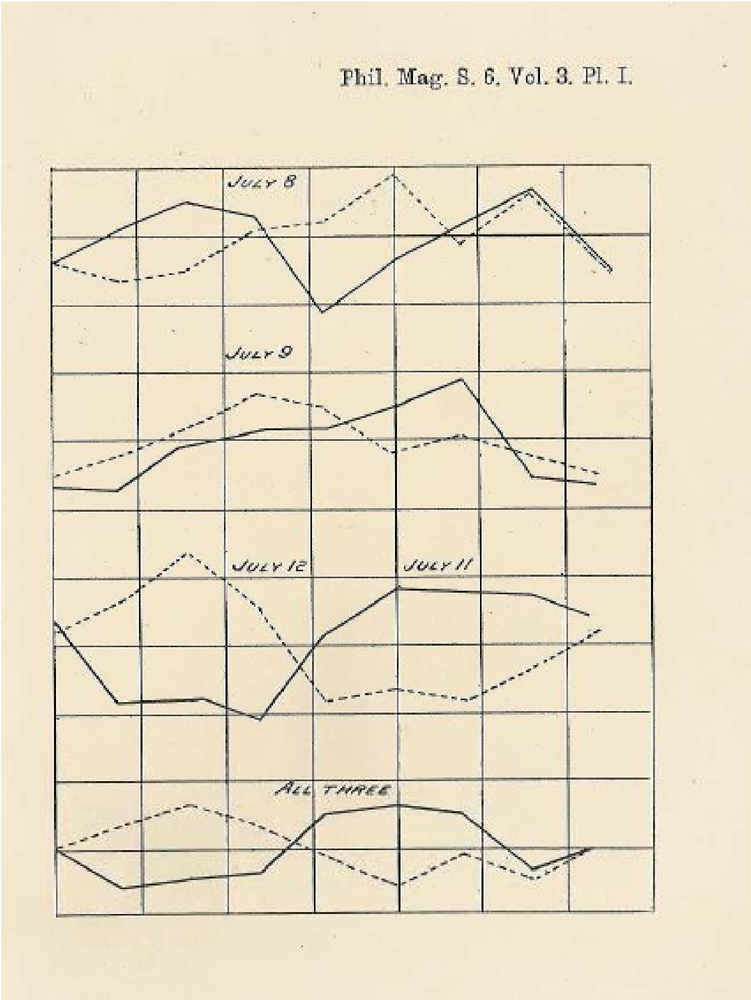


FIG. 4. Velocity of ether drift observed by Michelson and Morley in 1887, and by Morley and Miller in 1902, 1904 and 1905, compared with the velocity obtained by Miller in 1925.

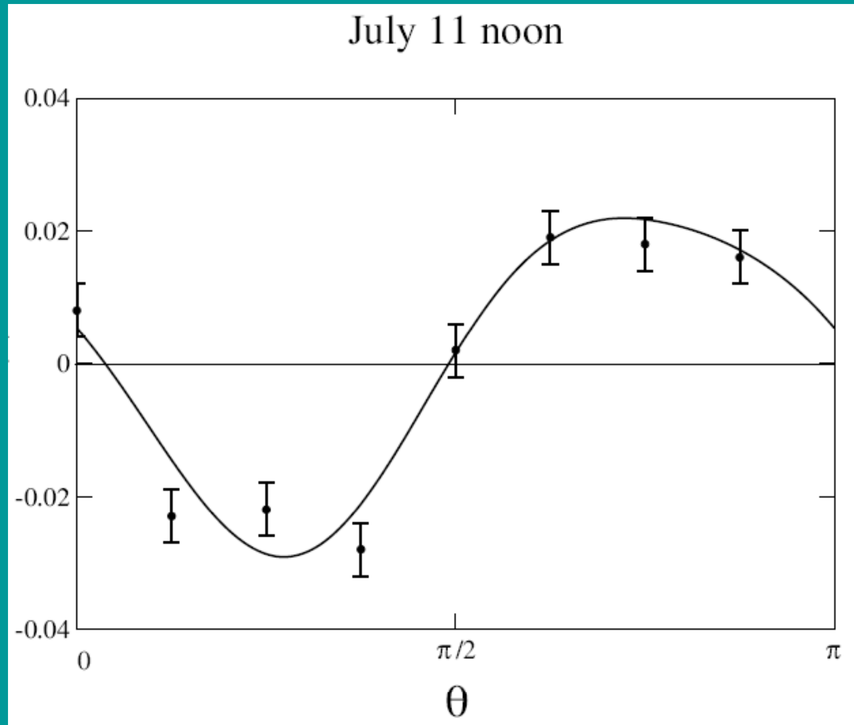
- "The brief series of observations by Michelson and Morley was sufficient to clearly show that the effect had not the expected magnitude. **However**, and this should be emphasized, **the indicated result was not zero** ."

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

Hicks 1902

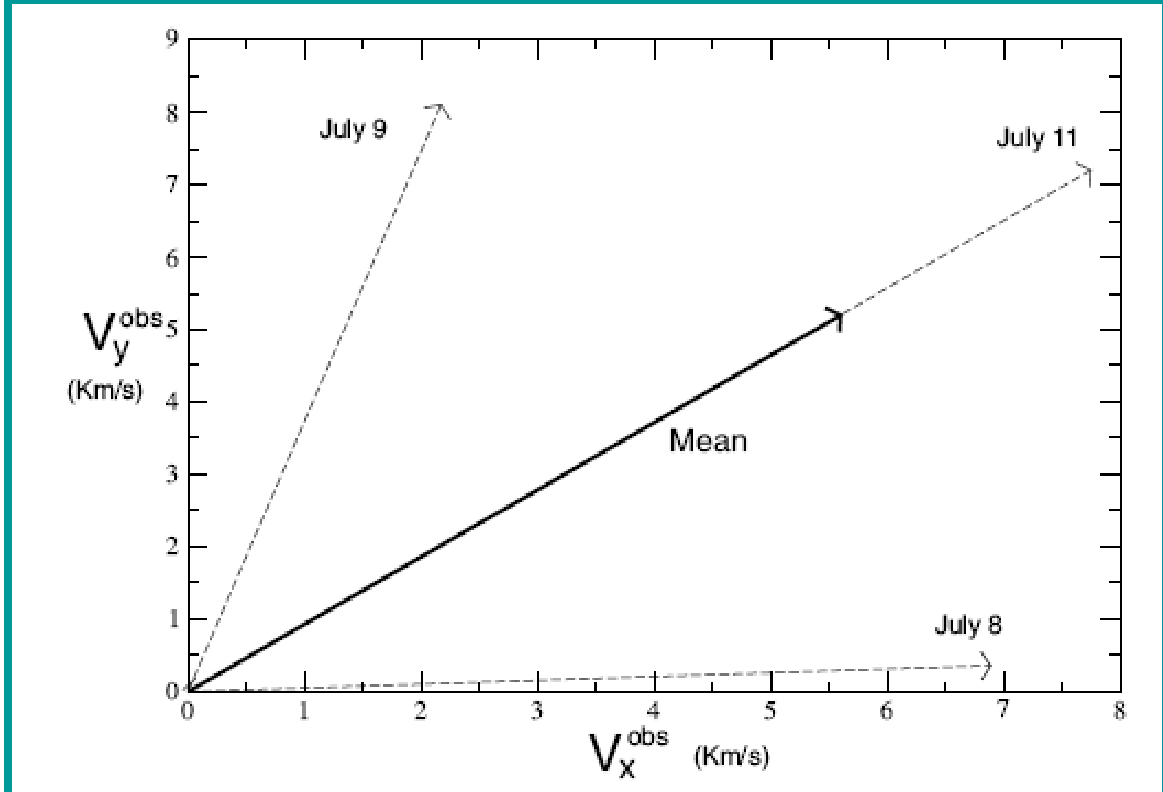


- Second harmonic



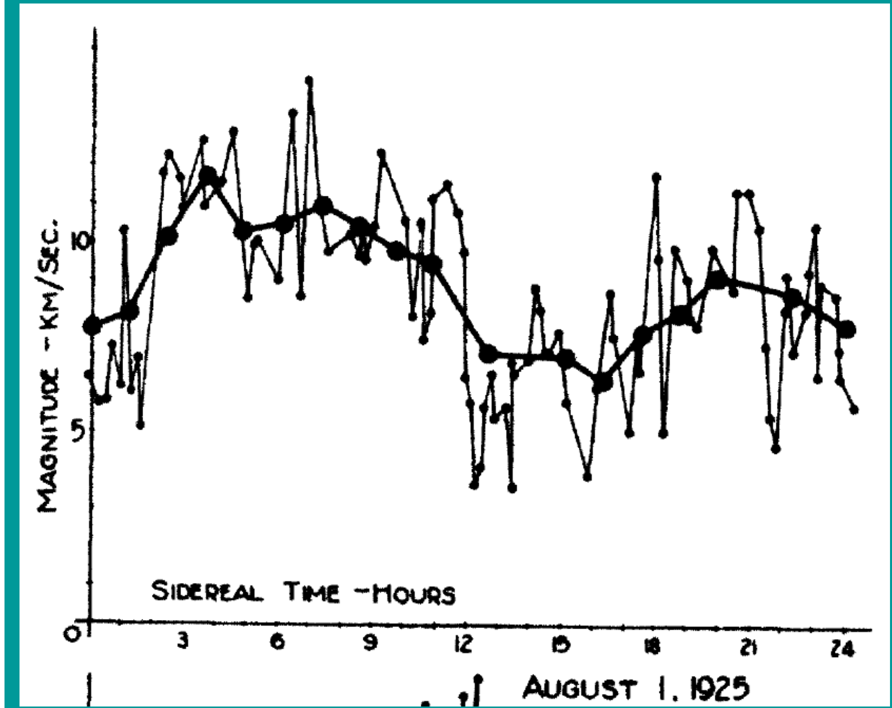
- M.C. and E. Costanzo 2004

Irregular direction of the drift



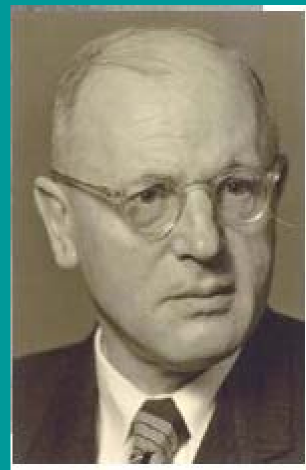
- The velocity vectors for the noon sessions of the MM expt. (typical angular errors +/- 12 degrees)
- Substantial differences among the various sessions

Strong fluctuations in Miller's extensive observations



- The amplitudes are proportional to $\mathbf{v}^2_{\mathbf{obs}}$. Their values at the highest observable velocities (12-13 km/s) are about 10 times bigger than the amplitudes at the minima (4 km/s)
- This aspect cannot be explained in a smooth model of the drift where the ratio depends on the relative size of maximal and minimal daily projections of the Earth velocity and does not exceed a factor of 2
- Same features in Joos' precise measurements
- This aspect could be understood in a stochastic model of the drift

1930: Joos' experiment in Jena



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

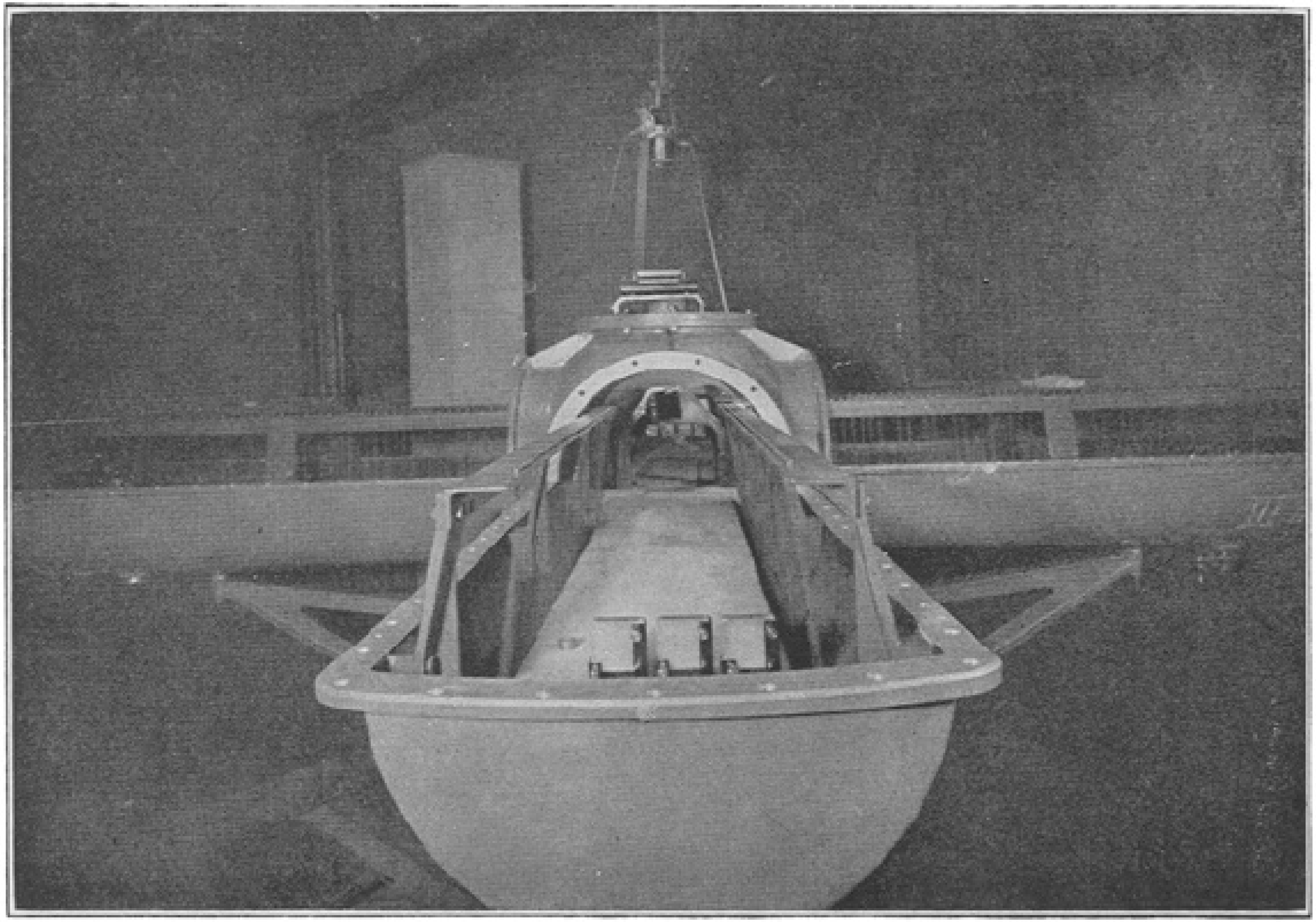


Fig. 5. Lagerung der Optik beim Zeissschen Interferometer.

Joos' data

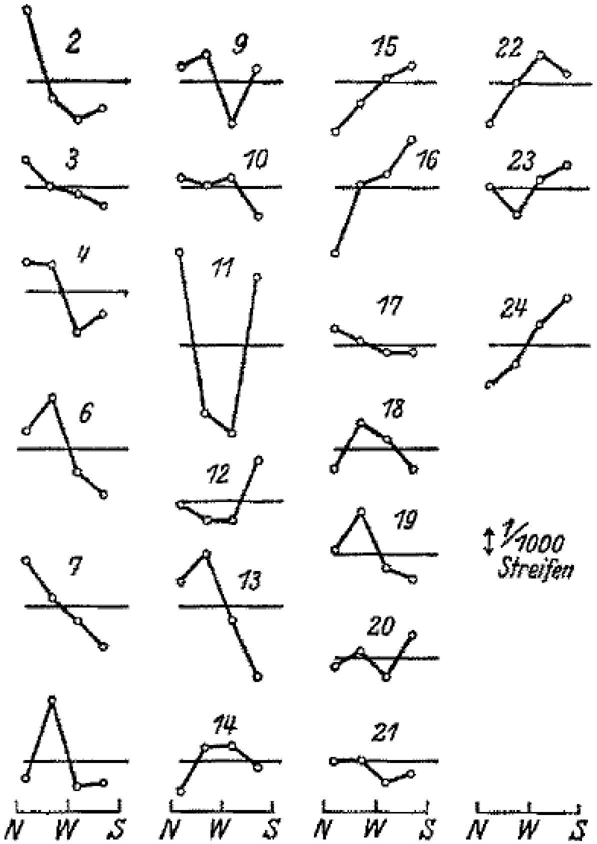
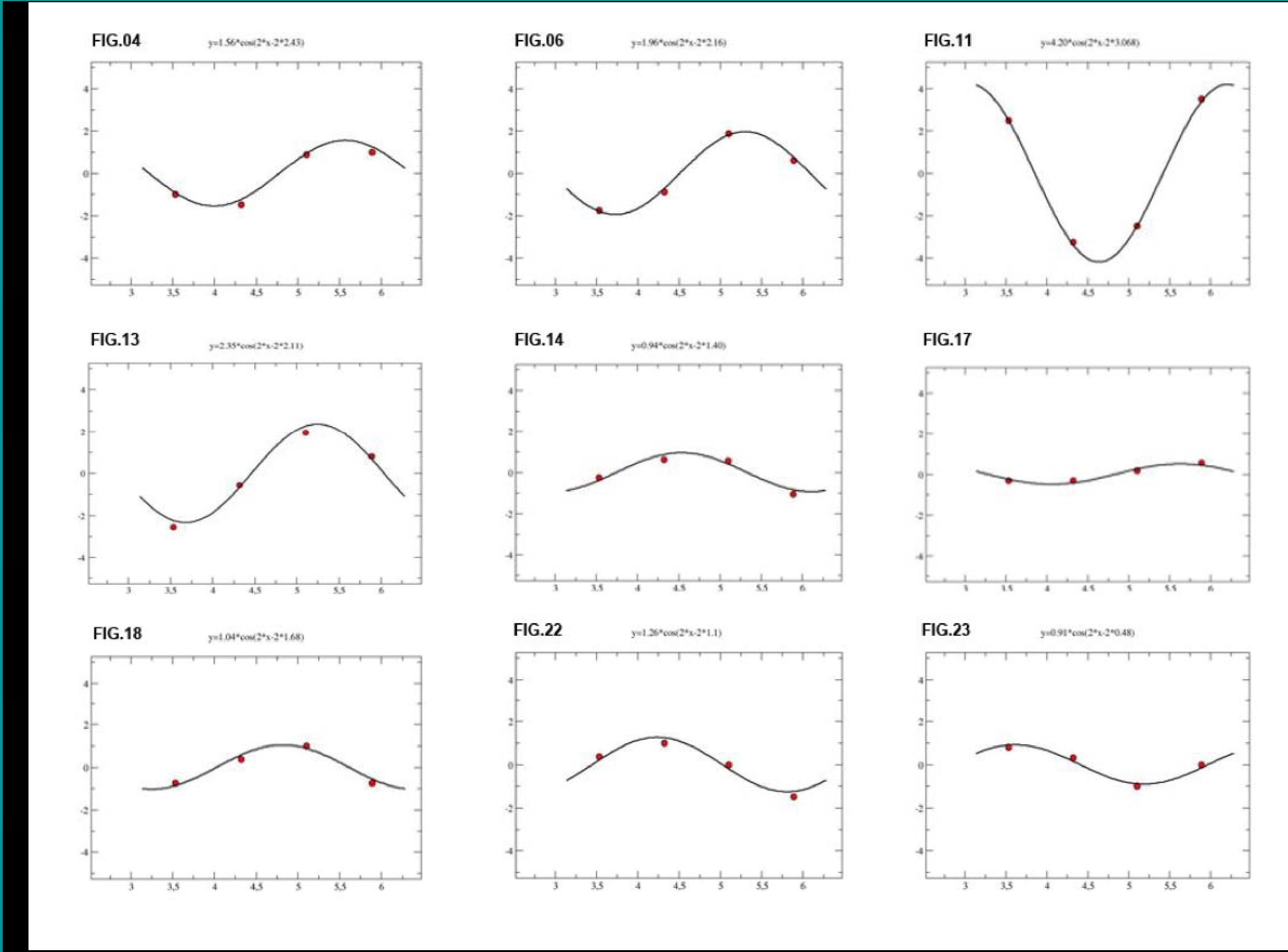


Fig. 8. Verschiebungen in einer über 24 Stunden erstreckten Serie beim Jenaer Versuch.

- Motor-driven rotation system, data collected during all 24 hours and recorded by photo-camera.
- The most accurate classical experiment
- According to Swenson optical paths were placed in a helium bath
- There seems to be a small misalignment (perhaps 17 or 22.5 degrees) between Joos's reference angles and the N, W, S marks
- Only second harmonic amplitudes (and not the phases) can be extracted unambiguously

2^{nd} harmonic fit to Joos' data



- Joos's data are extremely precise, about +/-0.00035
- → Big difference between the lowest data (observations 20 and 21) and high data (about 10σ with observation 11 and 5σ with observations 2, 6 and 13)

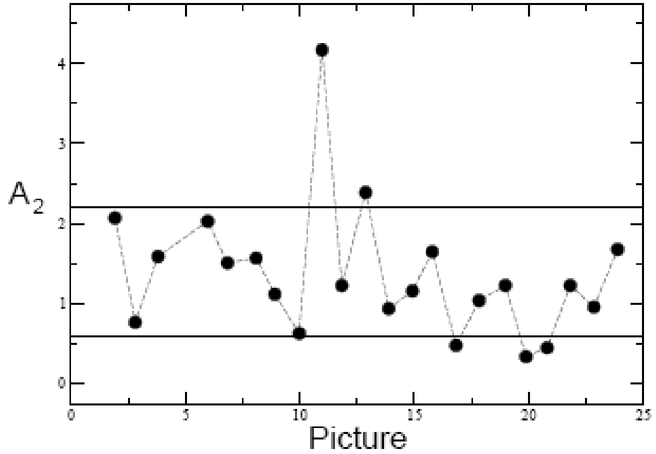
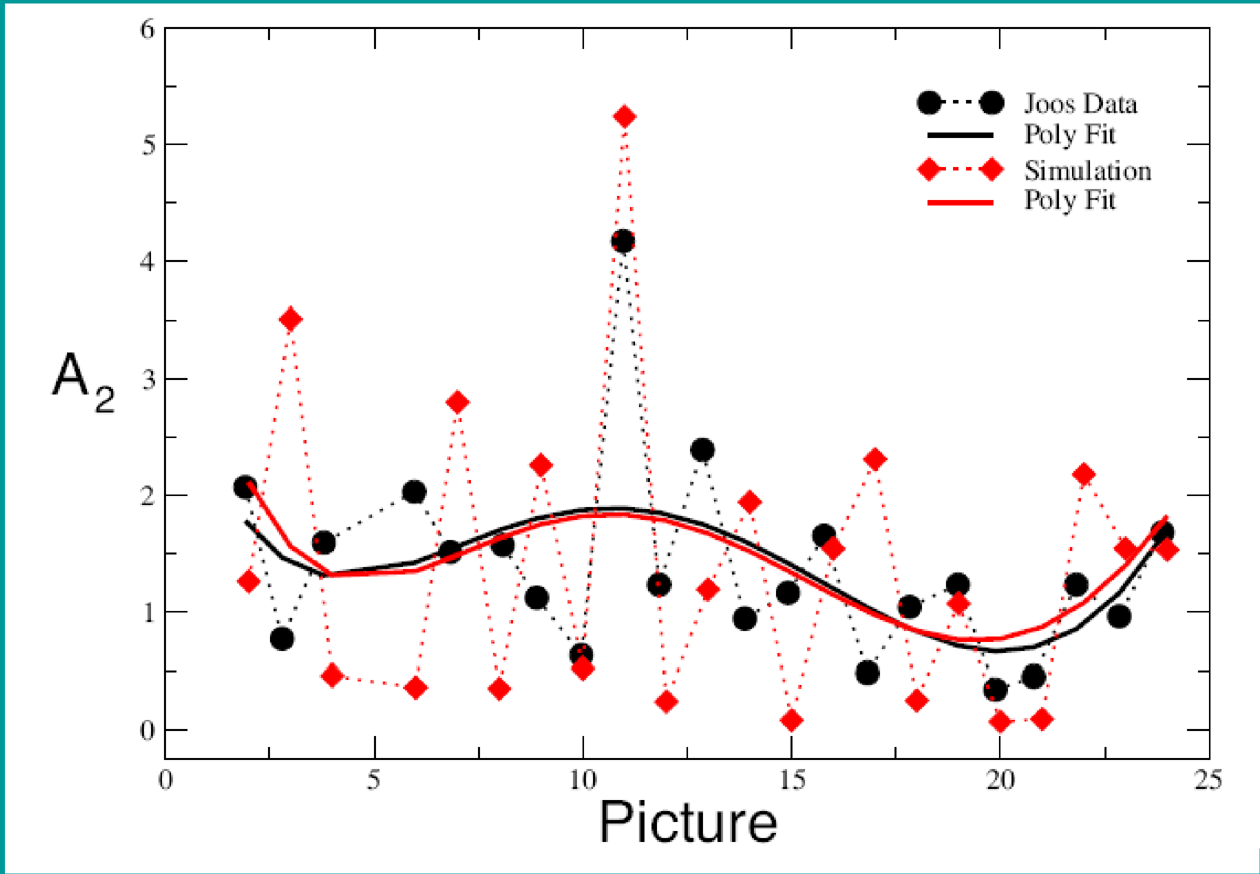


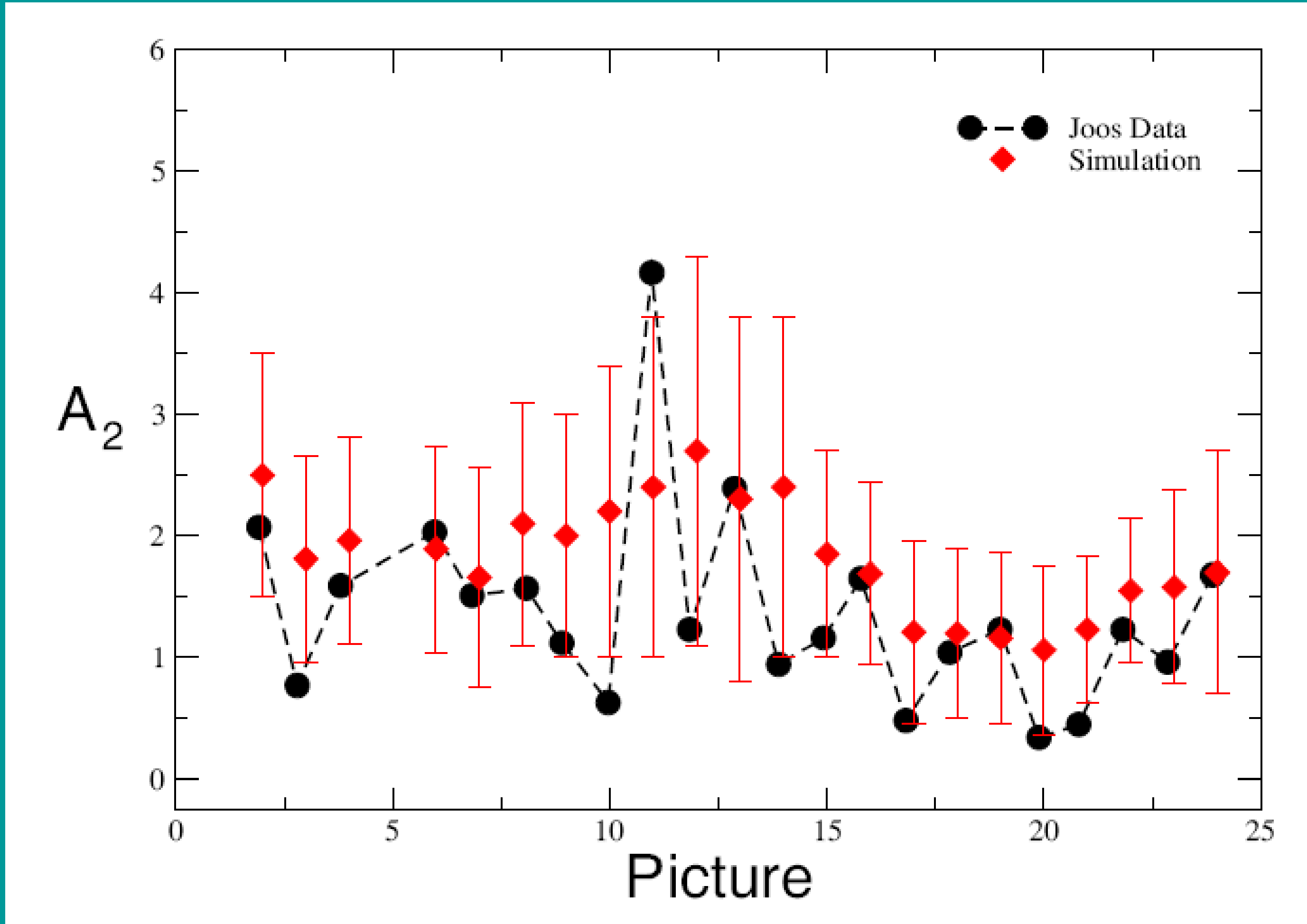
Figure 10: *Joos' 2nd-harmonic amplitudes, in units* 10^{-3}. *The vertical band between the two lines corresponds to the range* $(1.4 \pm 0.8) \cdot 10^{-3}$.

- In a " smooth " model of the drift, the relative magnitude of high and low data is deterministically given by the square of the projections of the earth velocity. For the CMB and Jena $\mathbf{v}_{\mathbf{CMB}}^{\mathbf{Jena}} = \mathbf{330}_{-70}^{+40}\,\mathbf{km/s}$ the ratio is smaller than 2. By changing the overall normalization one cannot reproduce both.
- In a smooth picture of ether drift these data MUST BE instrumental artifacts

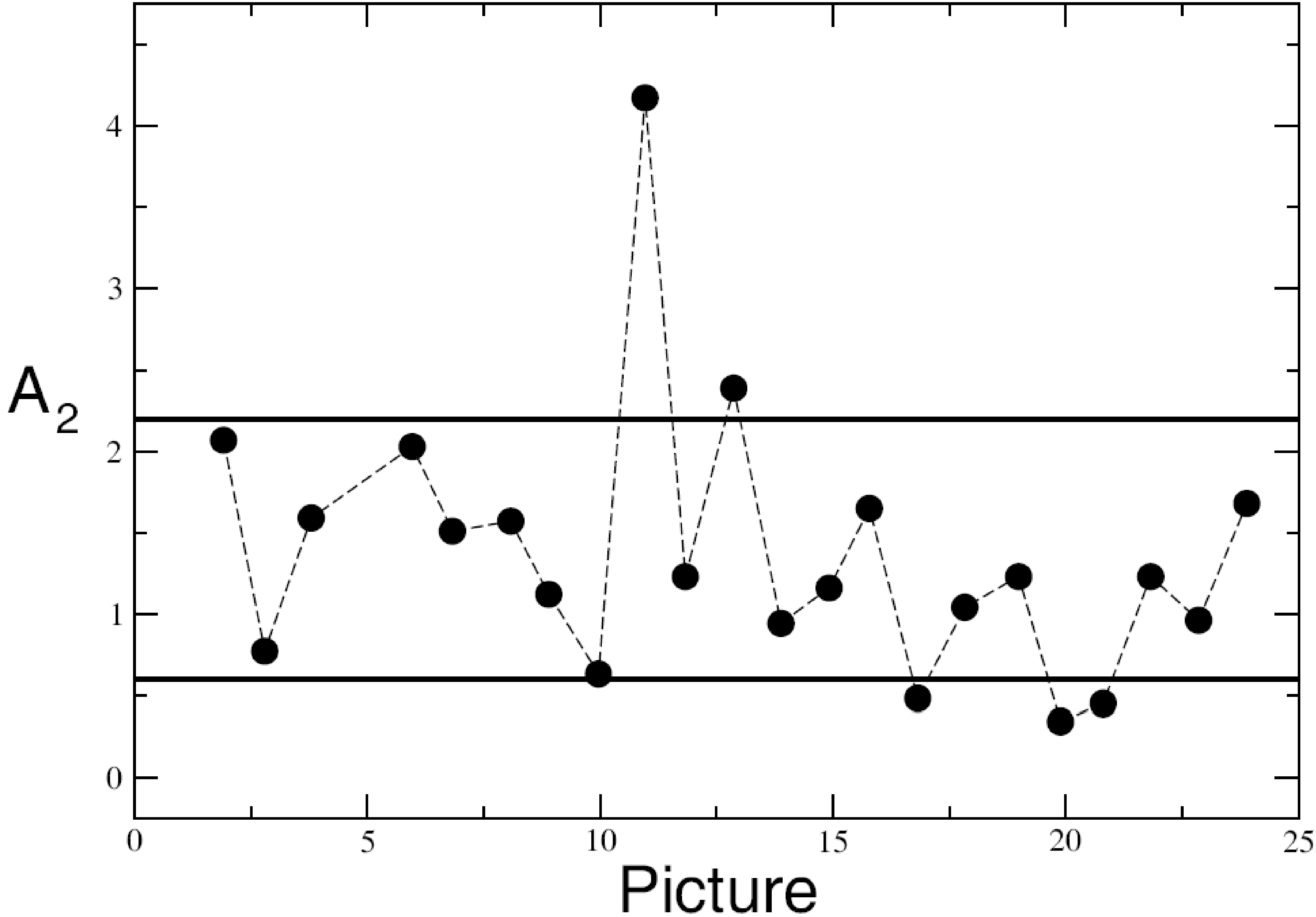
- Comparison between Joos’ measurements and our stochastic model of the drift
- Various statistical tests
- Excellent agreement with the type of cosmic motion indicated by the direct CMB observations



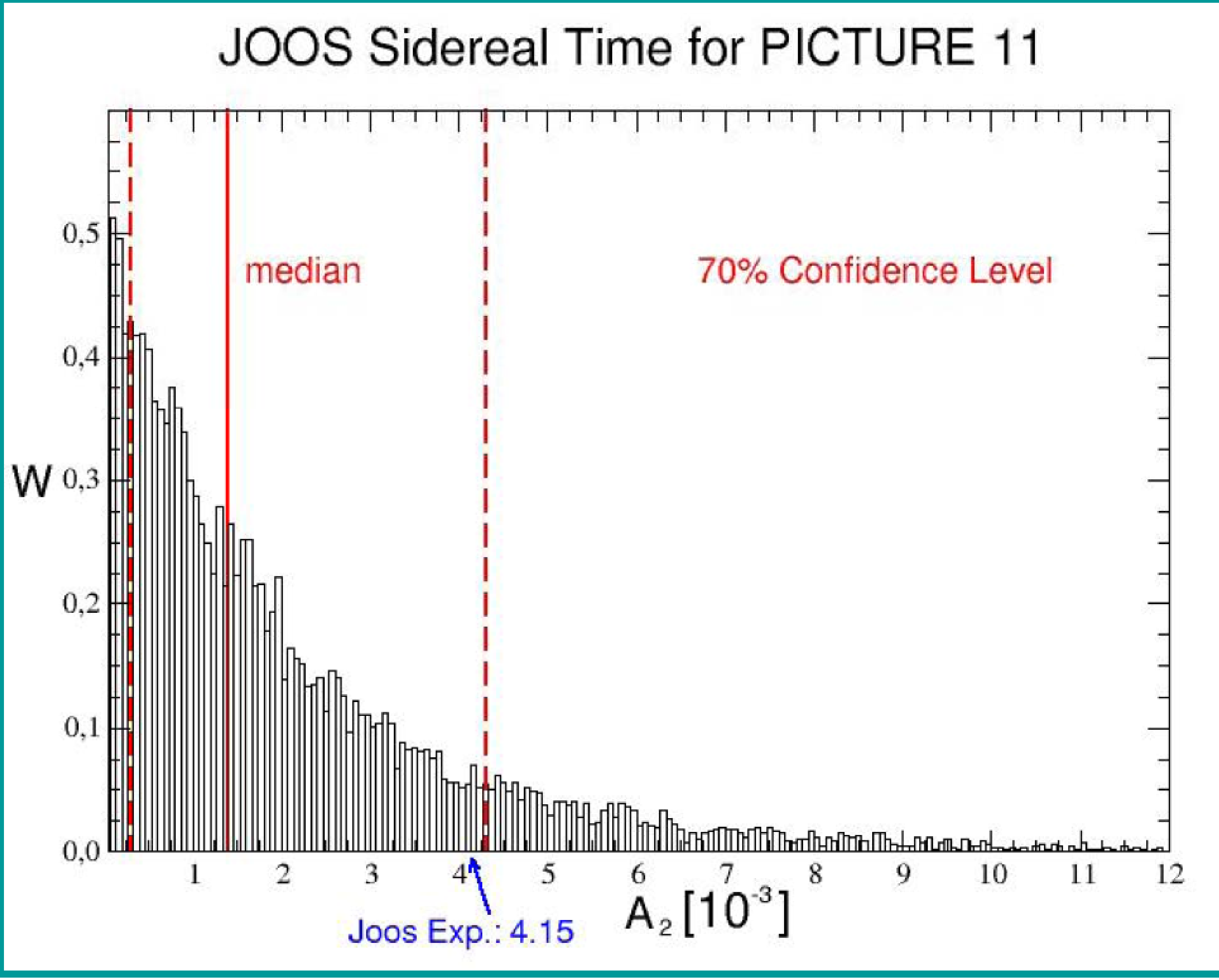
- Joos' amplitudes are compared with the result of a single simulation (for fixed random sequence and fixed number of Fourier modes) with the stochastic velocity field bound by CMB kinematical parameters. Important to get a qualitative impression of the agreement with our model. The smooth curves, as functions of the sidereal times, are fitted to good accuracy by the CMB angular parameters **α (CMB) = 168 Degrees** **γ (CMB) = -7 Degrees**



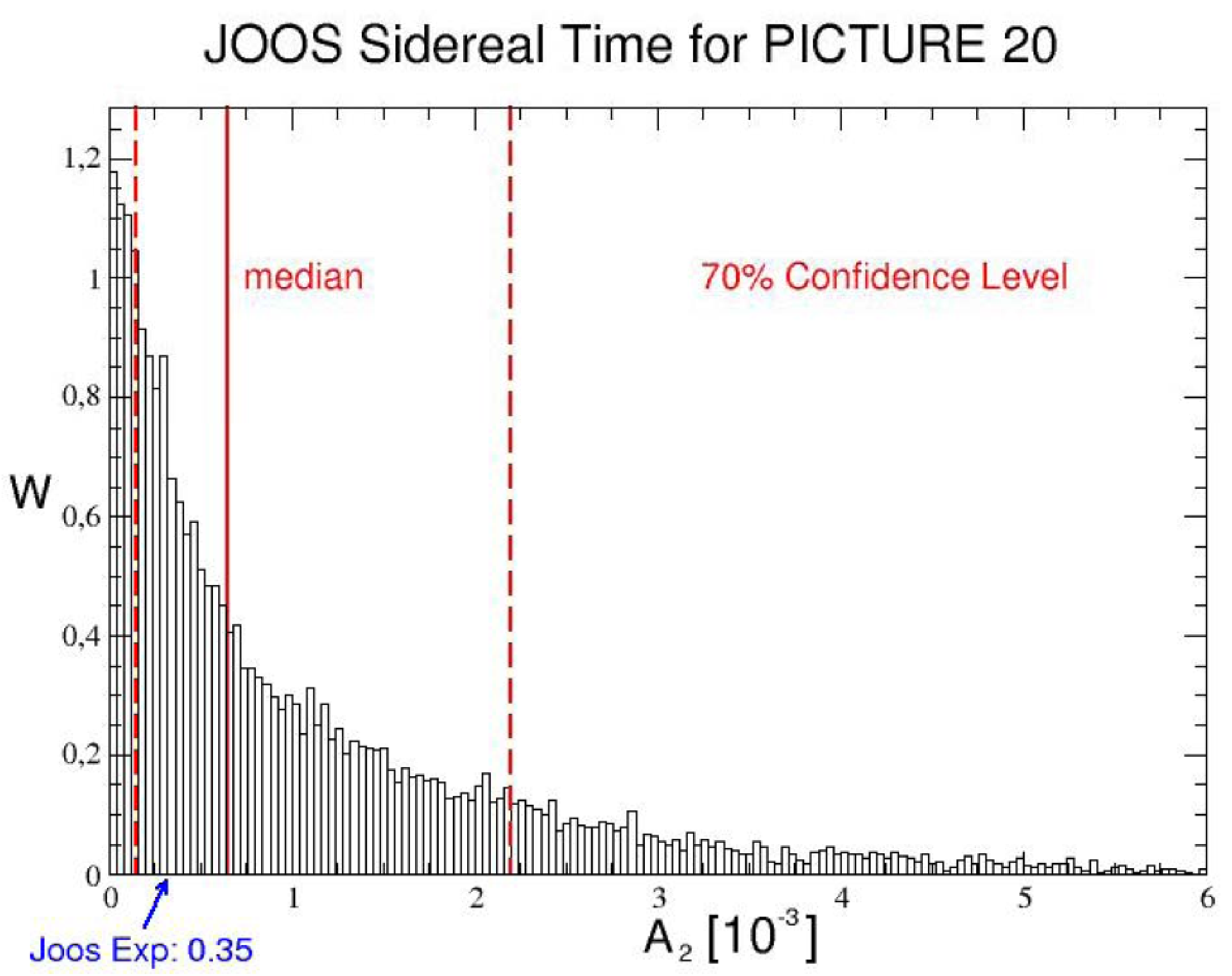
- Joos' amplitudes are compared with a simulation of averaging over 10 hypothetical measurements performed at the same Joos times. Errors take into account the variation of both the random sequence and the number of Fourier modes (for fixed CMB motion)


A2
4
3
2
1
0
0
5
10
15
20
25
Picture

Probability histogram for Joos' figure 11



Probability histogram for Joos' figure 20



Summary of the classical experiments

Table 4: *The average 2nd-harmonic amplitudes observed in the classical ether-drift experiments (as unambiguously attainable from the original data) are compared with the theoretical predictions in our stochastic model of the drift. These are evaluated by using the simple relation with the classical amplitude for 30 km/s,* $\langle A_2^{\rm th}\rangle_{\rm stat} = A_2^{\rm class}\cdot(v/30\ {\rm km/s})^2\cdot(\epsilon\pi^2/9)$*, fixing the CMB value* $v = 369$ *km/s and gas refractivities* $\epsilon_{\rm air} = 2.8\cdot 10^{-4}$ *and* $\epsilon_{\rm helium} = 3.3\cdot 10^{-5}$.

Experiment	gas	$A_2^{\rm class}$	$A_2^{\rm EXP}$	$\langle A_2^{\rm th}\rangle_{\rm stat}$	Pull
Michelson-Morley(1887)	air	0.200	$(1.6 \pm 0.6)\cdot 10^{-2}$	$9.3\cdot 10^{-3}$	1.25
Miller(1925-1926)	air	0.560	$(4.4 \pm 2.2)\cdot 10^{-2}$	$2.6\cdot 10^{-2}$	0.67
Tomaschek (1924)	air	0.150	$(1.0 \pm 0.6)\cdot 10^{-2}$	$7.0\cdot 10^{-3}$	0.26
Illingworth(1927)	helium	0.035	$(2.2 \pm 1.7)\cdot 10^{-4}$	$1.9\cdot 10^{-4}$	0.03
Piccard-Stahel(1928)	air	0.064	$(2.8 \pm 1.5)\cdot 10^{-3}$	$3.0\cdot 10^{-3}$	0.02
Joos(1930)	helium	0.375	$(1.4 \pm 0.8)\cdot 10^{-3}$	$2.0\cdot 10^{-3}$	0.56

(NOTICE: NO FREE PARAMETERS!)

- No doubt: in our stochastic model, there are definite correlations between the classical ether-drift experiments and direct CMB observations

- However, a skeptic would probably argue: “Correlations with the CMB observations? Perhaps... but NOT genuine preferred-frame effects. Instead, these are thermal effects”

New Analysis of the Interferometer Observations of Dayton C. Miller

R. S. Shankland, S. W. McCuskey, F. C. Leone, and G. Kuerti
Case Institute of Technology, Cleveland, Ohio

For nearly thirty years the results of the Michelson-Morley experiment obtained by Dayton C. Miller on Mount Wilson have stood at variance with all other trials of this experiment. As interest in Miller's results has continued to the present time, and since the original data sheets are available to the present writers, it has seemed appropriate that the observations be subjected to a new analysis. It is now shown that the small periodic fringe displacements found by Miller are due in part to statistical fluctuations in the readings of the fringe positions in a very difficult experiment. The remaining systematic effects are ascribed to local temperature conditions. These were much more troublesome at Mount Wilson than those encountered by experimenters elsewhere, including Miller himself in his work done at Case in Cleveland. As interpreted in the present study, Miller's extensive Mount Wilson data contain no effect of the kind predicted by the aether theory and, within the limitations imposed by local disturbances, are entirely consistent with a null result at all epochs during a year.

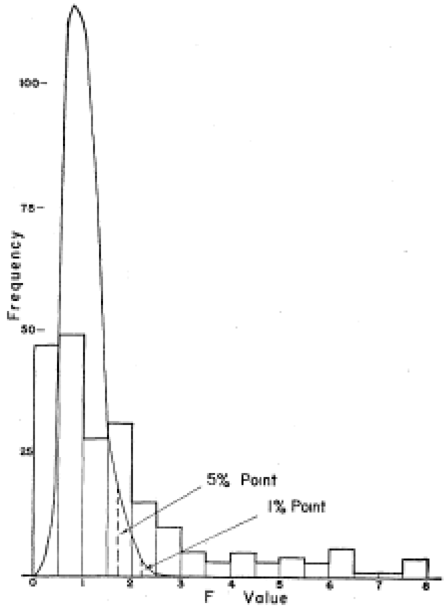


Fig. 1. The distribution of F-values for 216 sets of Mount Wilson data. The smooth theoretical curve is normalized so that the area under this curve is equal to the area of the histogram.

Thus there can be little doubt that statistical fluctuations alone cannot account for the periodic fringe shifts observed by Miller. On the other hand, the presence of a

In what follows, we shall interpret the systematic effects on this basis, but must admit that a direct and general quantitative correlation between amplitude and phase of the observed second harmonic on the one hand and the thermal conditions in the observation hut on the other hand could not be established. The reason for this

temperature differences of the walls. Since periodic temperature variations of only 0.001°C in the air of the optical arms would produce fringe shifts as large as the average effects observed at Mount Wilson,[16] a very

[16] This figure is in agreement with similar estimates made by R. J. Kennedy, Proc. Natl. Acad. Sci. **12**, 621 (1926); and by G. Joos, Phys. Rev. **45**, 114 (1934).

In the ideal-gas approximation, the variation of the refractivity $\epsilon_{\rm gas} = N_{\rm gas} - 1$ with the temperature has the very simple expression

$$-\frac{\partial \epsilon_{\rm gas}}{\partial T} \sim \frac{\epsilon_{\rm gas}}{T} \tag{77}$$

Therefore, a small temperature difference $\Delta T(\theta)$ between the optical arms induces a light anisotropy of typical magnitude

$$\frac{|\Delta \bar{c}_\theta|}{c} \sim |N_{\rm gas}(\theta) - N_{\rm gas}(\pi/2 + \theta)| \sim \frac{\epsilon_{\rm gas}|\Delta T(\theta)|}{T} \tag{78}$$

We can thus extract an experimental temperature difference from the 2nd-harmonic amplitudes A_2 in the fringe shifts

$$\frac{\Delta\lambda(\theta)}{\lambda} \sim \frac{2D}{\lambda}\frac{\Delta \bar{c}_\theta}{c} = A_2 \cos 2\theta \tag{79}$$

$$A_2^{\rm EXP} \sim \frac{2D}{\lambda}\frac{\epsilon_{\rm gas}(T)\Delta T^{\rm EXP}}{T} \tag{80}$$

Table 3: *The average 2nd-harmonic amplitude observed in various classical ether-drift experiments and the resulting temperature difference obtained from Eqs.(75) and (76).*

Experiment	gas	A_2^{EXP}	$\frac{2D}{\lambda}$	ΔT^{EXP}(mK)
Michelson-Morley(1887)	air	$(1.6 \pm 0.6) \cdot 10^{-2}$	$4 \cdot 10^{7}$	0.40 ± 0.15
Miller(1925-1926)	air	$(4.4 \pm 2.2) \cdot 10^{-2}$	$1.12 \cdot 10^{8}$	0.39 ± 0.20
Illingworth(1927)	helium	$(2.2 \pm 1.7) \cdot 10^{-4}$	$7 \cdot 10^{6}$	0.29 ± 0.22
Tomaschek (1924)	air	$(1.0 \pm 0.6) \cdot 10^{-2}$	$3 \cdot 10^{7}$	0.33 ± 0.20
Piccard-Stahel(1928)	air	$(2.8 \pm 1.5) \cdot 10^{-3}$	$1.28 \cdot 10^{7}$	0.22 ± 0.12
Joos(1930)	helium	$(1.4 \pm 0.8) \cdot 10^{-3}$	$7.5 \cdot 10^{7}$	0.17 ± 0.10

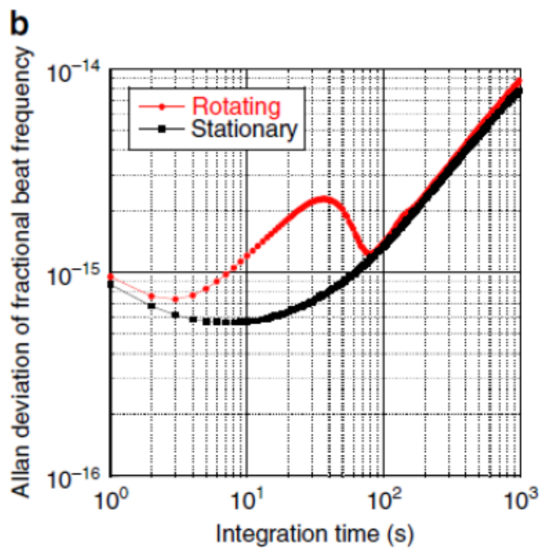
$\langle\Delta T\rangle$ = (0.26 ± 0.06) mK (**non-local** thermal effect)

- Could this **$\langle\Delta T\rangle$** be a "residual" of the CMB dipole **ΔT(CMB) = ± 3.36 mK ?**
- Very weak interactions of the CMB photons with neutral matter → **$\langle\Delta T\rangle$ << ΔT(CMB)**
- Same phenomenology but different from a genuine preferred-frame effect
- How to distinguish the two interpretations?
- Answer: look at ether-drift experiments in vacuum
- In vacuum such a small **$\langle\Delta T\rangle$** should be unobservable

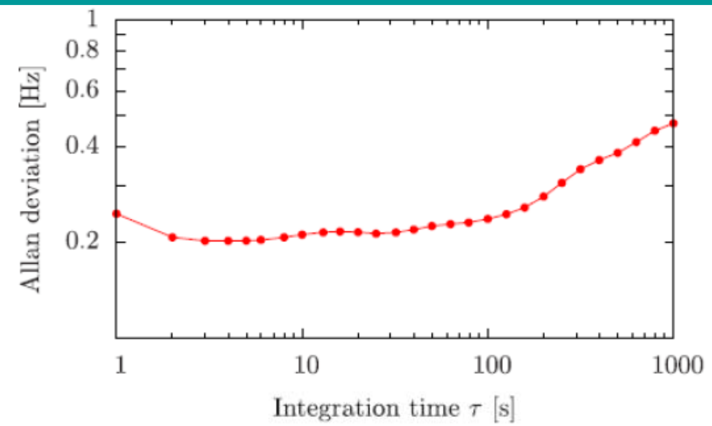
- The thermal interpretation has an important implication:
- Assume that the effects seen in gases are really due to such tiny non-local thermal gradient
- **THEN** one is naturally driven to conclude that **IF** there is a non-zero effect in vacuum, with very precise measurements, **THE SAME** effect should also show up in solid dielectrics
- In a solid, in fact, a tiny **ΔT** of about 0.26 mK would dissipate by thermal conduction without any particle flow and no light anisotropy
- In this way we will return to our starting point: the unexplained agreement between Nagel et al. (sapphire cryogenic) and Chen et al. (vacuum at room temperature)

Two most precise experiments and restrict to the short-term stability

- **Sapphire, cryogenic, EM-wave frequency 1.29 E+10Hz**
- **Vacuum, room temperature, EM-wave frequency 2.818E+14 Hz**



Nagel et al. Nature Comm. 6 (2015) 8174
(sapphire cavities at cryogenic temperature) **σ (1s) = 8.5E-16**



Chen et al. Phys. Rev. D93 (2016) 022003 (vacuum cavities at room temperature)
σ(1s)=0.24 Hz. Note that 0.24 Hz / (2.818E+14 Hz) = 8.5E-16

The very different systematics of the two experiments induce to give a physical meaning to this measured instantaneous signal.

$$\sigma(1s) \approx 8.5E-16$$

A tiny $\varepsilon \approx 10^{-9}$ vacuum refractivity?

- The two experiments have completely different systematics. It is unlikely that such remarkable agreement is just due to spurious instrumental noise

- Instead, with a thermal interpretation of the ENHANCEMENT observed in gases, it could indicate genuine fluctuations of the velocity of light IN VACUUM.

- In fact, from the relation

$$\frac{\Delta \bar{c}_\theta}{c} \approx \varepsilon \frac{v^2}{c^2} \approx 10^{-15}$$

we would deduce that the velocity of light measured in vacuum (on the earth surface) is NOT exactly the same parameter “c” of Lorentz transformations.For an earth velocity $v \approx 300$ km/s, they could differ at the level $\varepsilon \approx 10^{-9}$

- Peculiarity of a tiny $\varepsilon \approx 10^{-9}$ vacuum refractivity

- Observation: such small refractivity is at the limit of the best precision measurements of the speed of light (before the "exactness" assumption)

Journal of Research of the National Bureau of Standards

The Continuity of the Meter: The Redefinition of the Meter and the Speed Of Visible Light

Volume 92 Number 1 January–February 1987

D. A. Jennings, R. E. Drullinger, K. M. Evenson, C. R. Pollock, and J. S. Wells

National Bureau of Standards
Boulder, CO 80303

The product of the frequency and wavelength of the i^{th} hyperfine component of the 11-5, R(127) transition of $^{127}I_2$ yields a value for the speed of visible red light. This value of c, the most accurate ever measured for visible light, agrees with the value defined in the redefinition of the meter within the 3σ error limits of the krypton length standard.

Key words: frequency; laser; meter; speed of light.

Accepted: September 15, 1986

sured frequency of the transition. Since the measurement in 1972 there have been four speed of light measurements [3–6]; two at a wavelength of 3.39 μm and two at a wavelength of 9.31 μm. These measurements have been summarized [7], and the average value for the speed of light is 299 792 458.1 m/s with a fractional uncertainty of $\pm 4 \times 10^{-9}$ (3σ), which is the recognized uncertainty in the realization of the meter from the krypton definition.

Gravitational origin of such $\varepsilon \approx 10^{-9}$ vacuum refractivity?

VSL= Variable Speed of Light

Found Phys (2008) 38: 409–435
DOI 10.1007/s10701-008-9210-8

A Spatially-VSL Gravity Model with 1-PN Limit of GRT

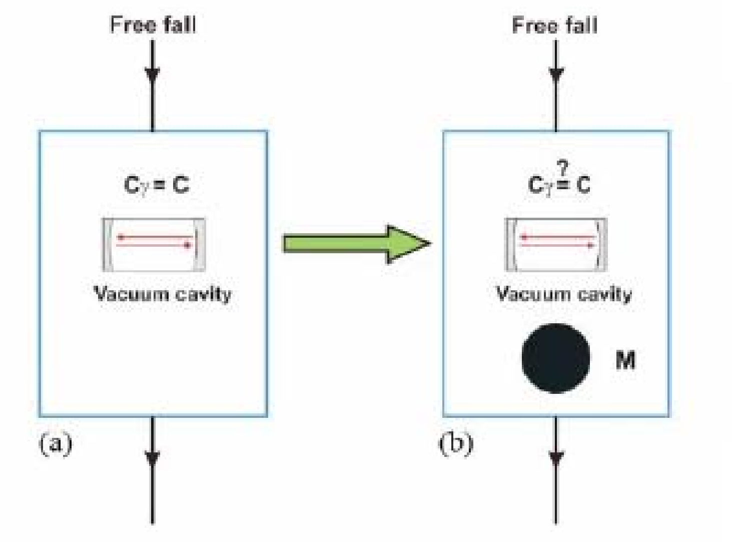
Jan Broekaert

[3] The notion of spatial-VSL is implicitly present in General Relativity Theory, occurring in the coordinate space description of photon dynamics in a gravitational field, as illustrated by following excerpts from the literature: Stephani [81], pp. 197–198, "…interpreted as saying that the three-dimensional space metric has a refractive index caused by the gravitational force …and that the velocity of light v in the gravitational field is decreased according $c = nv$." (where $n = -g_{44}{}^{-1/2}$); Longair [54], p. 453, (17.62), "…the apparent variability of the speed of light in the radial direction according an observer at infinity…in terms of coordinate time t and the distance measure r is" $c(r) = dr/dt = c(1 - 2GM/rc^2)$; Kenyon [49], p. 95, (8.15) and next, "The tangential and radial coordinate velocities are obtained…": $\frac{rd\varphi}{dt} = c\sqrt{Z}$ and $\frac{dr}{dt} = cZ$ "showing that as light approaches the origin its coordinate velocity falls." (here $Z = 1 - 2GM/rc^2$ and φ is the angular variable of the orbital); Will [89], p. 144, (6.14), (6.15), "…post-Newtonian equations for the deviation x_p^j of the photon's path from uniform, straight line motion" $d^2\mathbf{x}_p/dt^2 = (1+\gamma)[\nabla U - 2\mathbf{n}(\mathbf{n}.\nabla U)]$ and $\mathbf{n}.d\mathbf{x}_p/dt = -(1+\gamma)\nabla U$ (where $\gamma = 1$ in GRT and U is minus the Newtonian potential.); Weinberg [88], p. 222, (9.2.5), "…note that the photon speed is …" $|u| = 1 + 2\varphi + O(\bar{v}^3)$; Eddington [34], p. 93, (43.4), "At a distance r_1 from the origin the velocity of light is accordingly" $(1 - m/2r_1)/(1 + m/2r_1)^3$; Moeller [62], pp. 239–240, (69), (69′), (70), "…we see that the velocity of light w depends on the direction of propagation n^i of the signal if $\gamma_i \neq 0$ in the system of coordinates considered…" $w(n^i) = c\sqrt{-g_{44}}/(\gamma_i n^i + 1)$ (where $\gamma_i \equiv g_{i4}/\sqrt{-g_{44}}$); Einstein [43], p. 93, (107), "…velocity of light L is…" $\sqrt{dx_i^2}/dl = 1 - \frac{k}{4\pi}\int \sigma/r dV_0$; Eddington [35], p. 107 and Chap. VI. "…[an] alternative way of viewing this effect on light…[the] velocity of light in the gravitational field is not a constant…[however] if he performed Fizeau's experiment the velocity of light would be exactly the same as that of a terrestrial observer.… It is the coordinate velocity that is here referred to…" and "for light …in radial propagation" $(dr/dt)^2 = \gamma^2$ "…in transversal propagation" $(rd\theta/dt)^2 = \gamma$ (where $\gamma = 1 - 2m/r$); Einstein [38], p. 906, (3), $c = c_0(1 + \Phi/c^2)$ "The principle of constancy of the velocity of light holds good according to this theory on a different form from that which usually underlies the ordinary theory of relativity" (prior to establishing GRT in 1915 Einstein derived half the value of the coordinate velocity of light; leading to half the deflection angle); Einstein [36], following (32)b, p. 461, "…[Eq 32 b], hier tritt aber an die Stelle von c der Wert" $c(1 + \gamma\xi/c^2) = c(1 + \Phi/c^2)$ (where Φ is the gravitational potential, γ is the acceleration—"beschleunigung"—and ξ the coordinate of translation in the accelerated system.)

Looking for a physical interpretation, in the paper by Consoli and Pluchino, EPJ Plus 133 (2018) 295, it is argued that such 10^{-15} instantaneous signal could naturally be understood in terms of a tiny vacuum refractivity (M and R being the earth mass and radius)

$$\varepsilon_v \approx (2G_N M/c^2R) \approx 1.4 \cdot 10^{-9}$$

This would take into account the difference between the physical velocity of light in vacuum c_γ and the parameter c entering Lorentz transformations. The latter refers to the value measured in an *ideal* freely falling frame. However, an apparatus placed on the earth surface is closer to the illustration in panel (b), with M= earth mass, rather than to the idealized situation of panel (a).



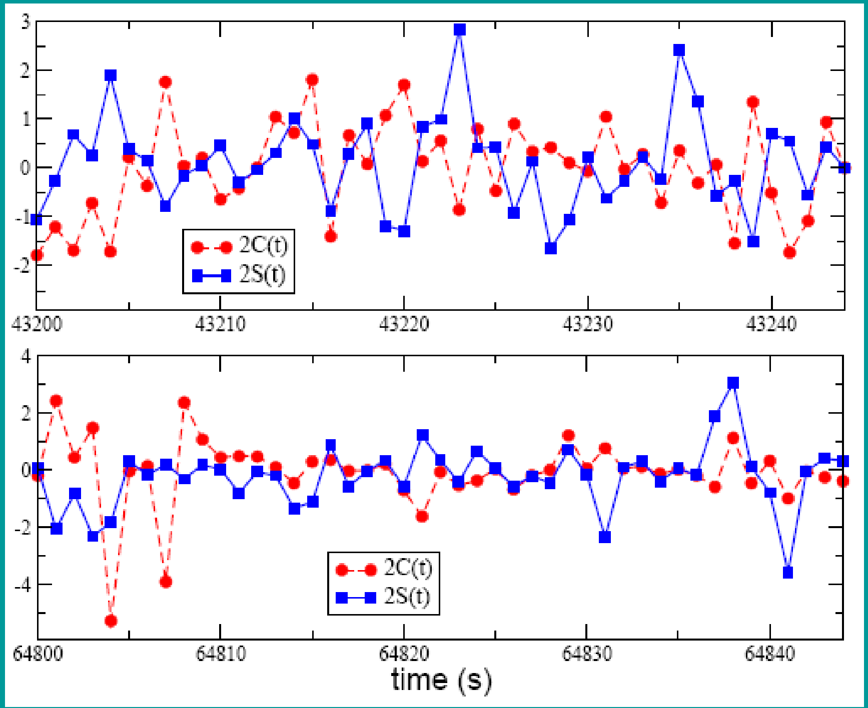
Summarizing:

- 1) in a spatially-VSL scheme, for an apparatus placed on the Earth surface, the physical velocity of light in vacuum would differ from the basic parameter "c" of Lorentz transformation by a tiny vacuum refractivity $\boldsymbol{\varepsilon \approx 10^{-9}}$
- 2) This vacuum refractivity is not DIRECTLY measurable, being comparable to the uncertainty of the best precision measurements performed in the past before assuming standards of measure where "c" has no error
- 3) However, our analysis of the classical experiments suggests that, if there were a preferred reference frame (with the same typical **v≈300 km/s** indicated by the direct CMB observations), we should expect irregular fluctuations of the velocity of light in vacuum at the fractional level $\boldsymbol{10^{-15}}$
- 4) Together with a thermal interpretation of the enhancement observed in gases, this would close the circle and provide a quantitative explanation of the instantaneous signals observed by Chen et al. (in vacuum) and by Nagel et al. (in sapphire)

Simulation of the instantaneous signal

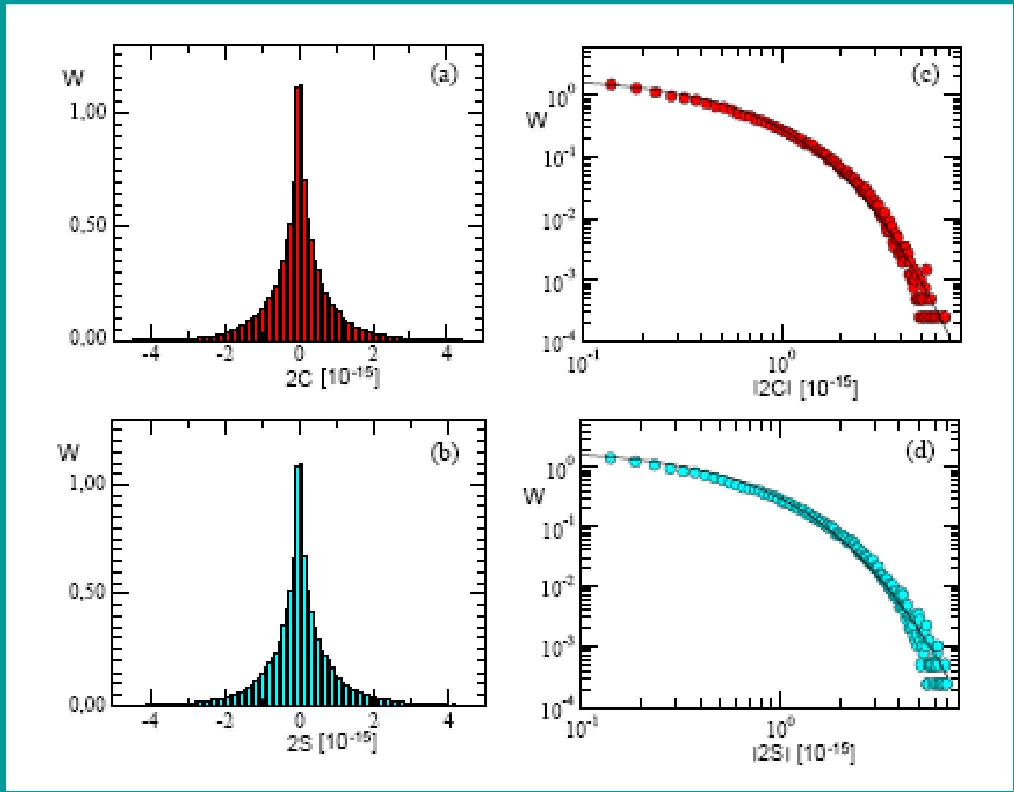
M. C. and A. Pluchino, EPJ Plus 133 (2018) 295

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



- Simulation of the instantaneous signal (units E-15)

Histograms of **2C(t)** and **2S(t)** at steps of 1 second (during one day)



- **σ (2C)= (8.7 +/- 0.8) E-16 ; σ (2S)= (9.6 +/- 0.9) E-16**
- **σ(Δν/ν) = (9 +/- 1)E-16 Simulation**
- **σ (Δν/ν) = 8.5E-16 Experiment**

In our stochastic model:

1) correlations between CMB observations and classical expts.? YES

2) correlations between CMB observations and modern expts.? YES

The traditional requirements for establishing the existence of a Fundamental Preferred Frame are fulfilled

Check with a modern Michelson interferometer

- By extrapolating from the classical Michelson-Morley experiments, we expect short-term fluctuations of the velocity of light of magnitude

$$\left[\frac{\Delta \mathbf{c}_{xy}}{\mathbf{c}}\right]_{TH} \approx \varepsilon_v \frac{\mathbf{v}^2}{\mathbf{c}^2} \approx 10^{-15} \approx \left[\frac{\Delta \mathbf{c}_{xy}}{\mathbf{c}}\right]_{EXP}$$

- An independent check with a modern Michelson interferometer would require

$$\frac{\Delta \mathbf{c}_{xy}}{\mathbf{c}} \approx \frac{\Delta \mathbf{L}_{xy}}{\mathbf{L}} \approx 10^{-15}$$

For instance, RMS stability $\Delta \mathbf{L}_{xy} \approx 10^{-11}$ **m** and effective path **L ≈ 10 km** (or $\Delta \mathbf{L}_{xy} \approx 10^{-10}$ **m** and **L ≈ 100 km …)** → **VIRGO ?**

Conclusions

- In all ether-drift experiments , from Michelson-Morley to the most recent experiments with optical resonators, there are small, irregular residuals traditionally interpreted as mere instrumental artifacts ("null results").
- However, the irregular form of light anisotropy observed in laboratory could also indicate a subtle form of ether-drift, somewhat similar to a turbulent flow where large-scale and small-scale aspects of the fluid motion are only related indirectly.
- By starting from this observation, in a new theoretical scheme, **all data collected so far** (with light propagating in gases, vacuum and solid dielectrics) **show surprising correlations with the direct CMB observations** with satellites in space.
- This opens the possibility of finally linking the CMB to a fundamental preferred frame with substantial implications for the interpretation of non-locality in the quantum theory.
- The importance of the issue would deserve to exploit the unexpressed Virgo potentiality to reveal the same tiny fluctuations of the velocity of light observed in laboratory.