

中間報告2015

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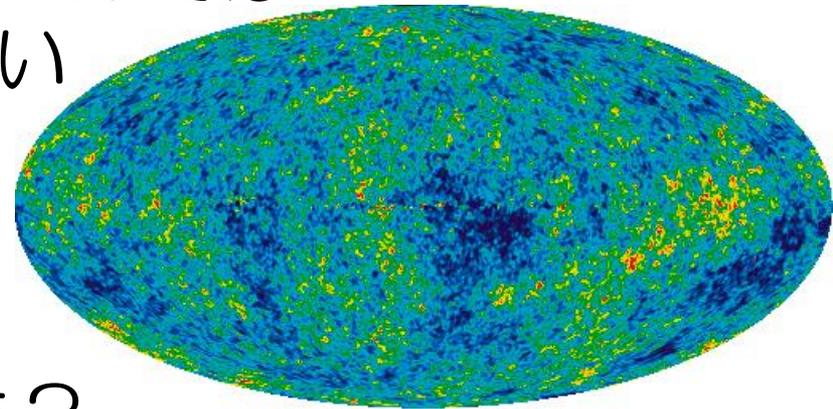
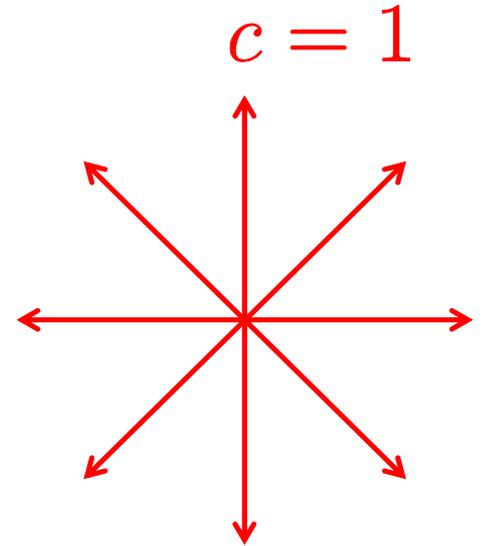
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光速の異方性探査

研究背景

- Lorentz不変性は宇宙の基本的な対称性の一つとして理解されている
- Lorentz不変性が保たれていれば、光速は等方
- Lorentz不変性の破れの示唆
 - 重力と他の相互作用の統一
 - 少なくともPlanckスケールでは我々の物理は正しくない
 - CMBの異方性
 - CMB静止系の存在

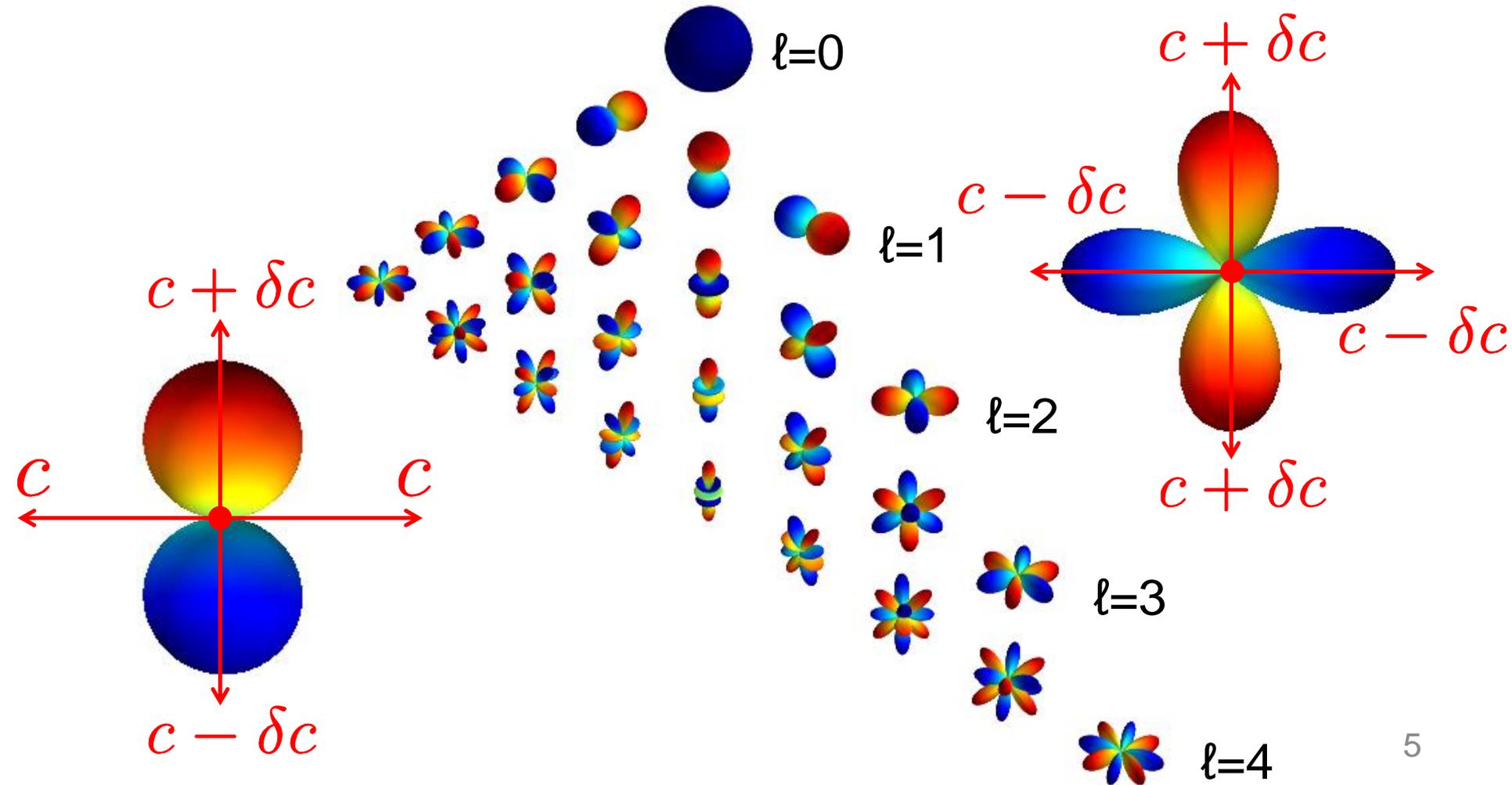


→ 光速の異方性があるかも？

http://en.wikipedia.org/wiki/File:WMAP_2010.png

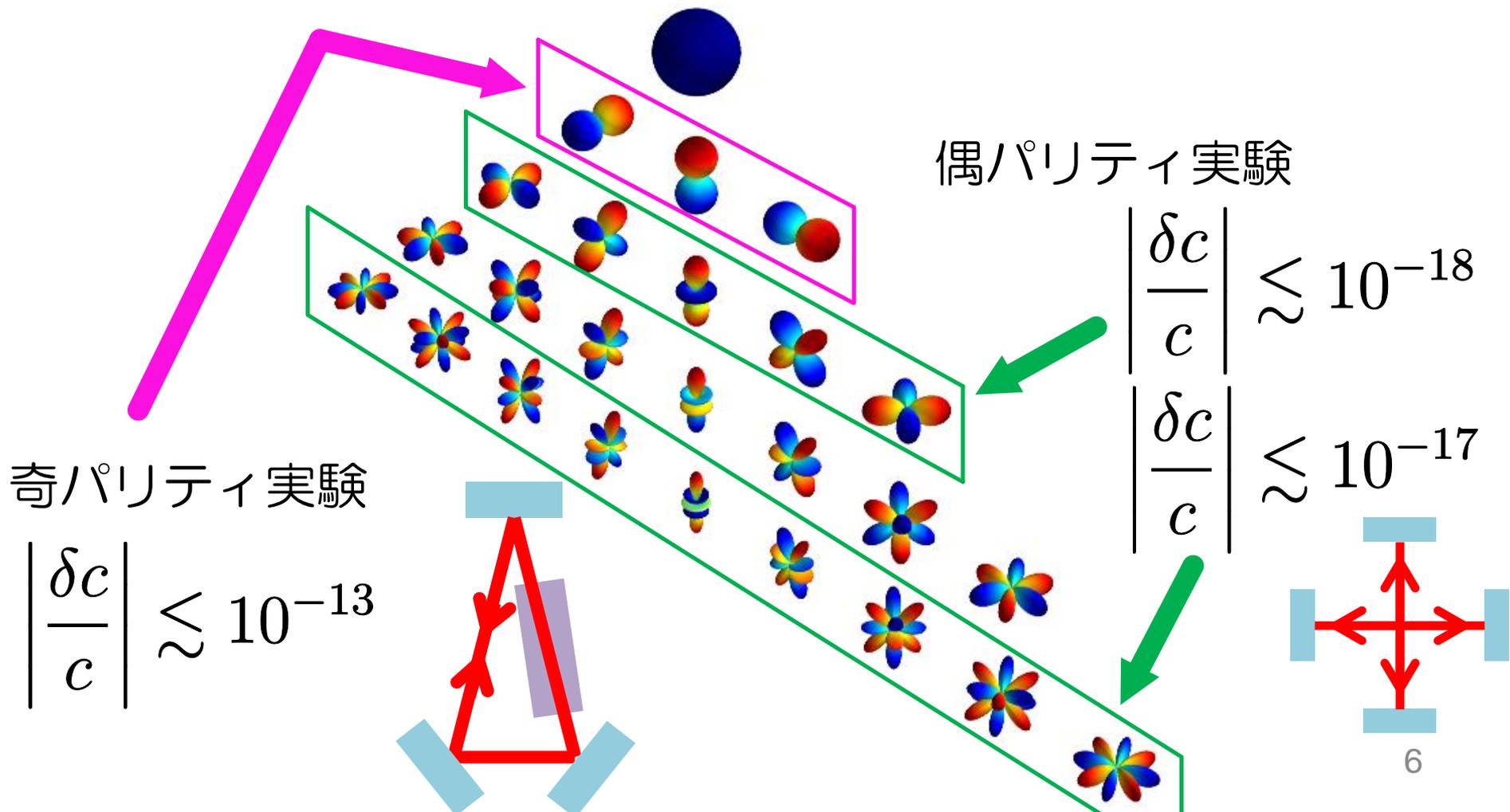
異方性の球面調和関数展開

- 光速の異方性は球面調和関数展開できる
- 次数(ℓ, m)毎に上限値が付いている



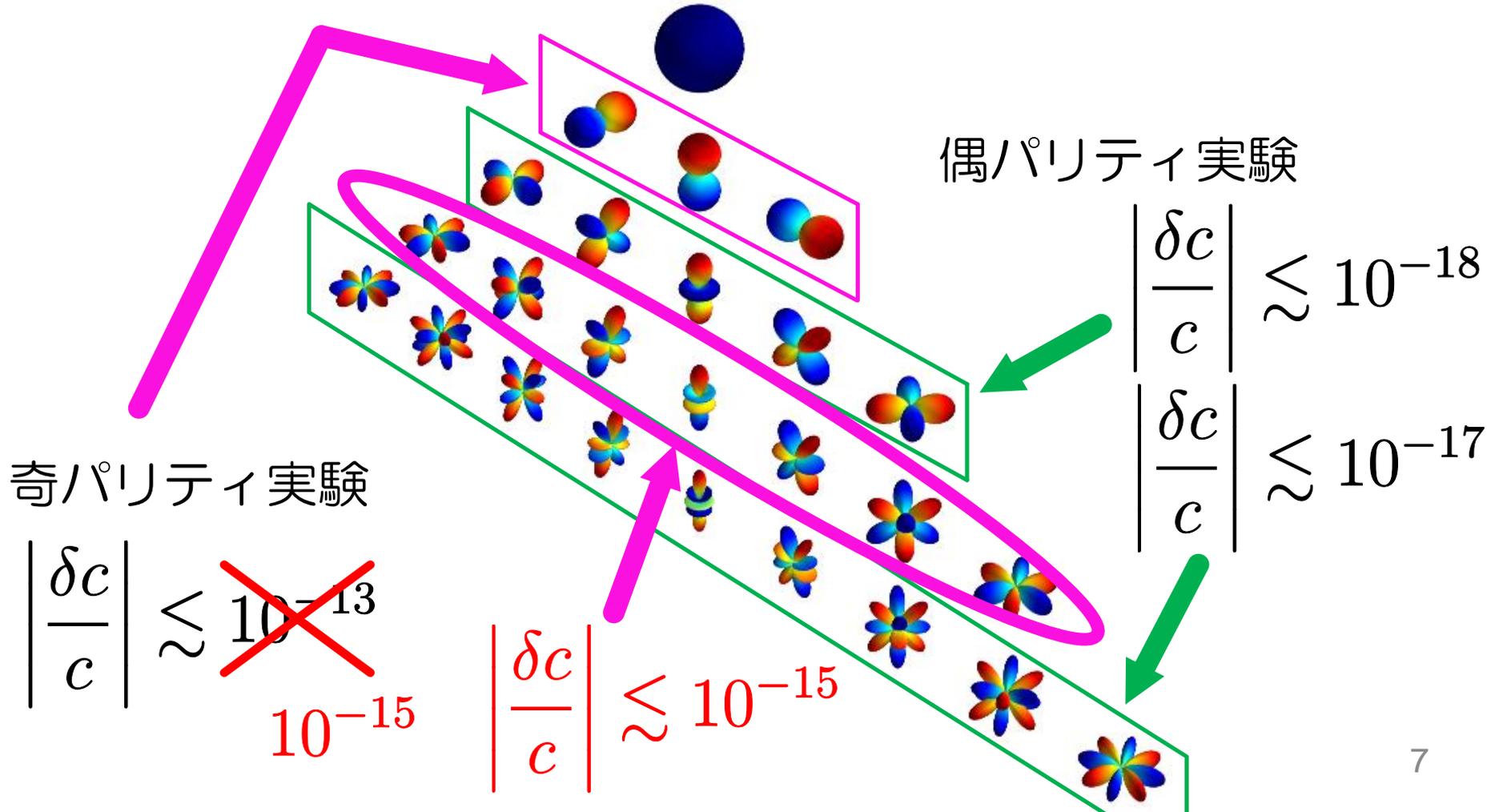
先行研究による上限値

- $\ell=1$ に 10^{-13} レベルの上限値
- $\ell=2$ 、 $\ell=4$ に 10^{-17} レベルの上限値



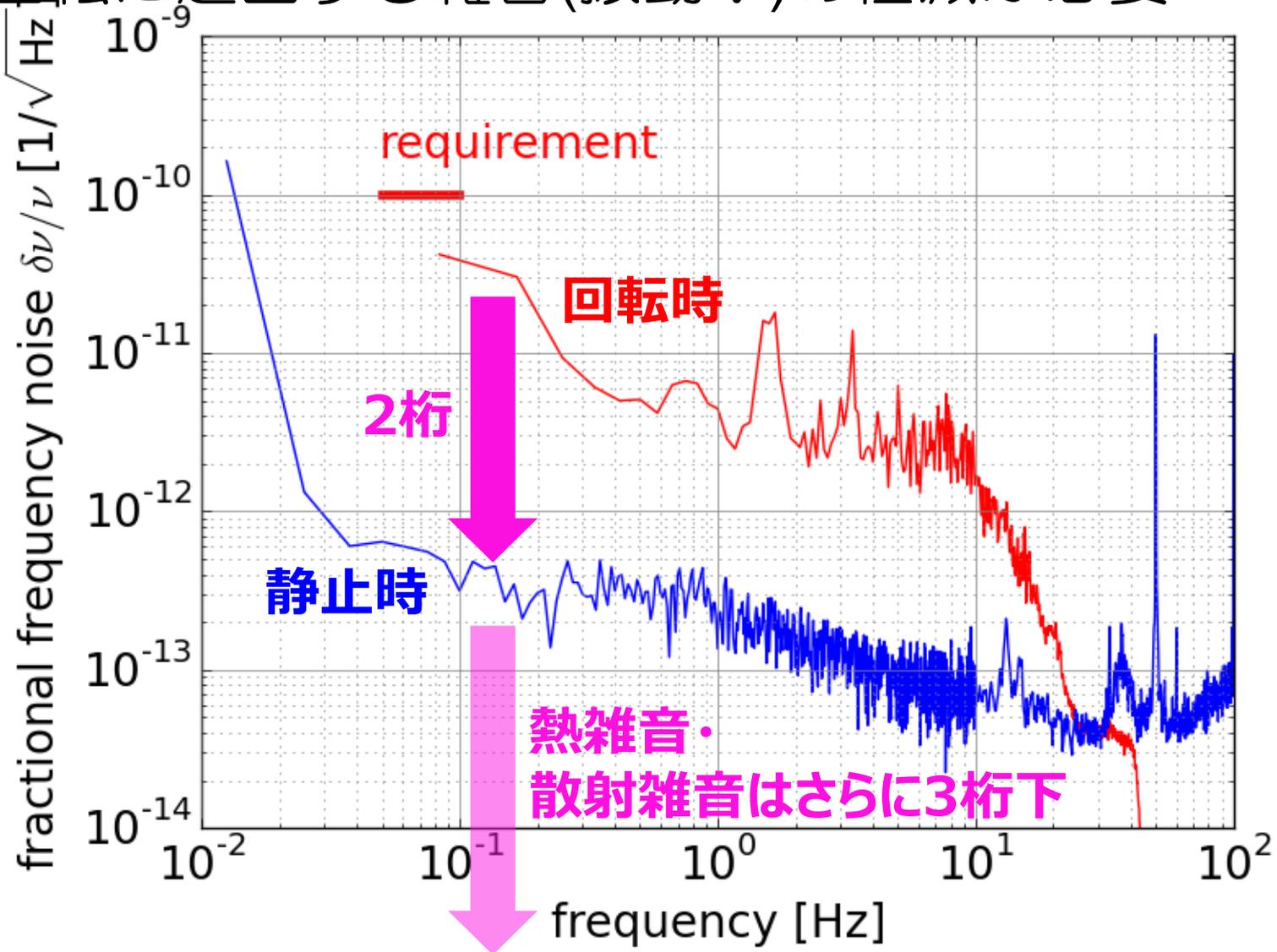
我々による上限値

- $\ell=1$ に 10^{-15} レベルの上限値(2桁更新)
- $\ell=3$ に 10^{-15} レベルの上限値(世界初)



現状の雑音レベル

- 回転に起因する雑音(振動?)の低減が必要



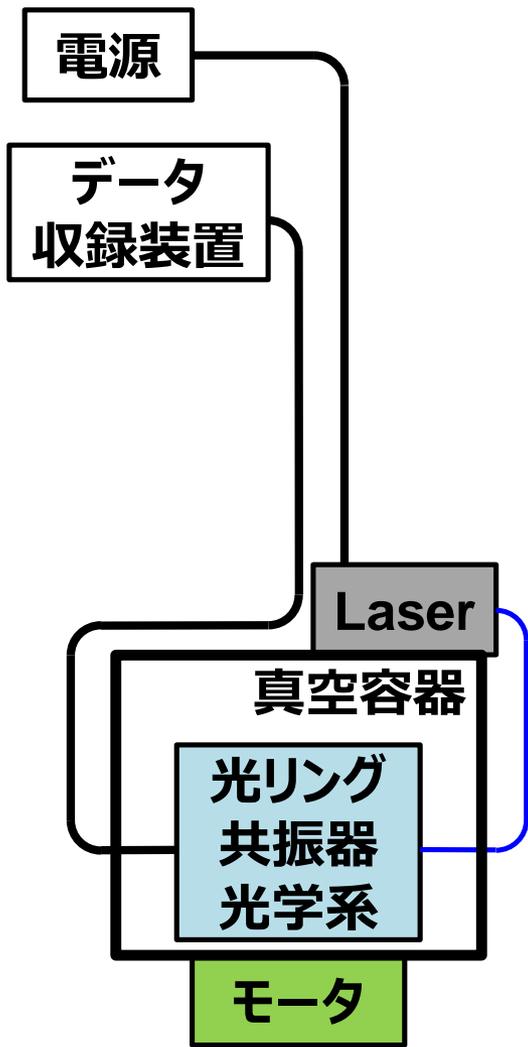
雑音低減の可能性(優先順)

- 信号取得の無線化
連続回転の実現で回転台が安定に
データ解析的にも連続回転の方が有利
1回転毎の解析をしなくてすむ
- 光学系の振動感度低減
ミラーマウント等 → モノリシック光学系

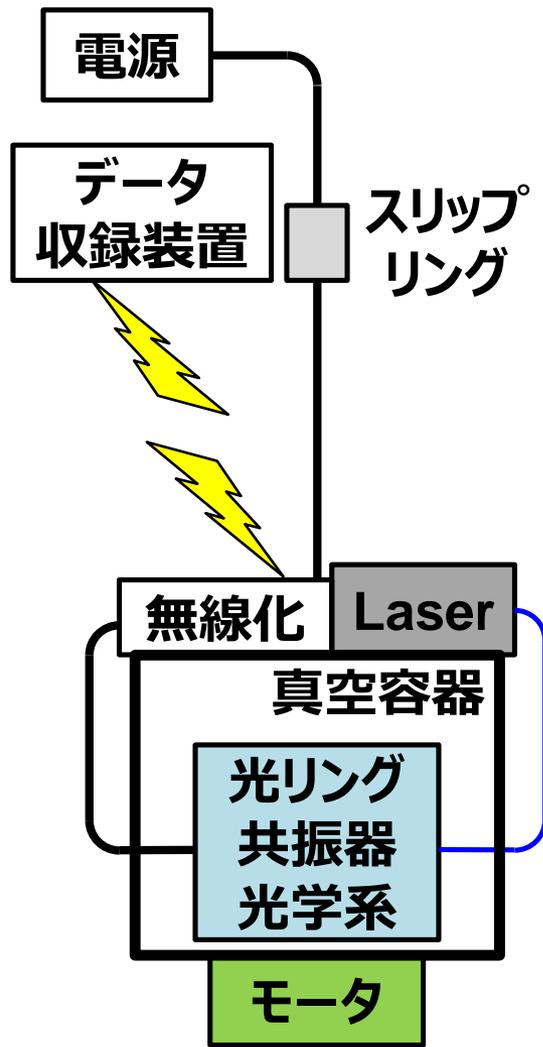


- 高真空による温度安定度の向上
- 懸架による傾き変動低減

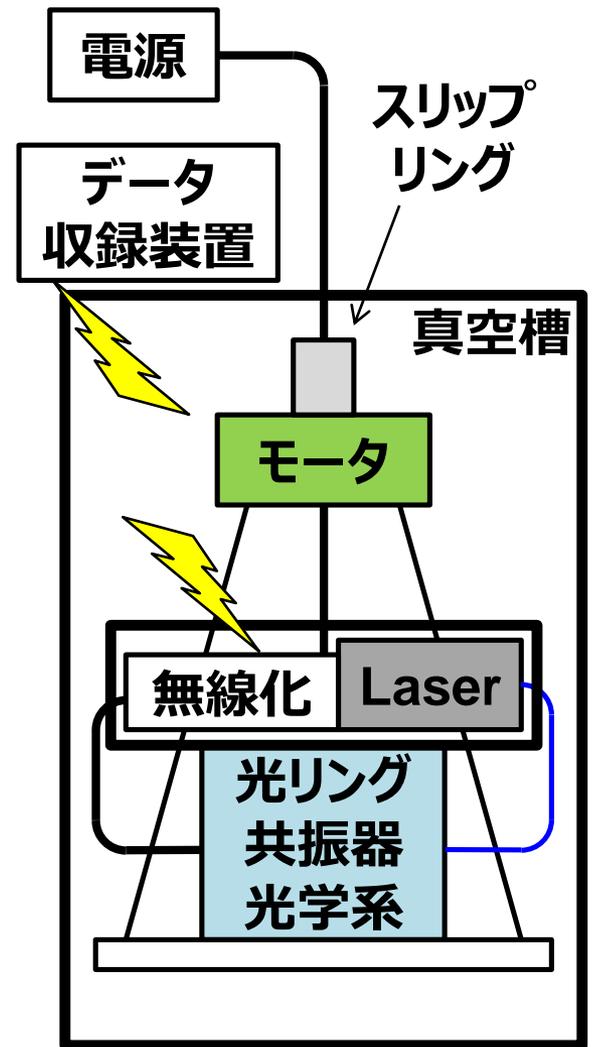
新装置の概念図



2012モデル



2015モデル



2016モデル¹⁰

無線化装置

- 無線化するにはAD変換/DA変換が必要
- UGF 1 kHz実現には100 kHz程度以上のサンプリング周波数が必要(今のところ見つけられてない)
- PD x 4 (s1,p1,s2,p2) エラー信号取得用
INT x 2 強度モニタ用(安定化の可能性も含め)
REFL x 1 反射光モニタ
その他モニタ信号
(回転速度、加速度?)
→ AD変換は 7ch+α 必要
- PZT FB x 1 周波数制御
(INT FB x 1 強度安定化)
→ DA変換は 2ch 必要



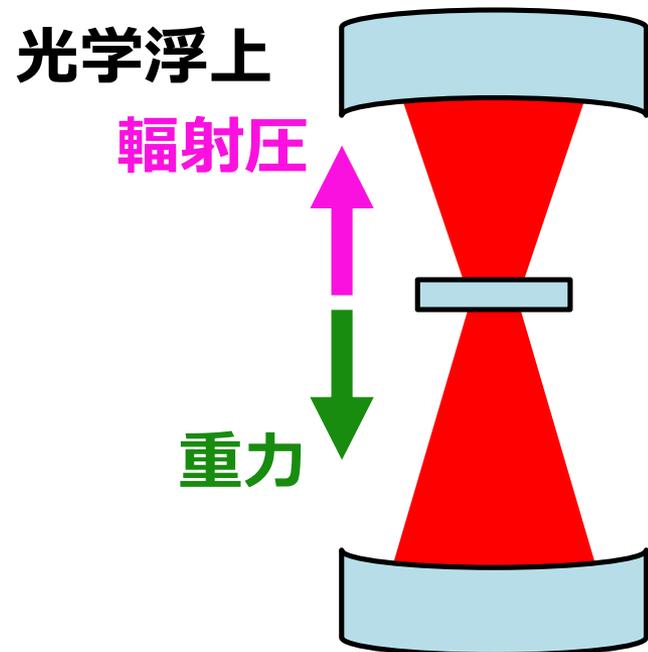
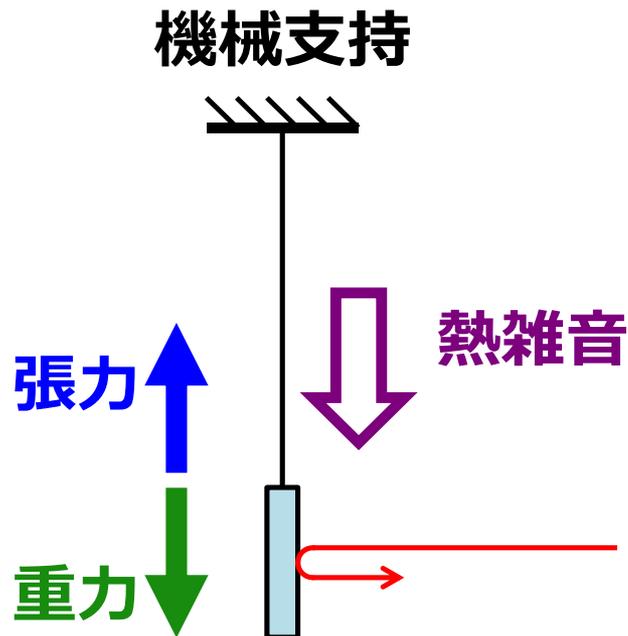
今後の課題と発展性

- モノリシック光学系をどう作るか？
発注か自作か？
共振器のアライメントが取れるか？
まずはミラーマウント等を接着剤で固める？
- 信号取得の無線化は衛星ミッション、回転TOBAにもつながる(電源も電池でやる？)
- 既にある程度のノウハウ(装置、解析)があり、精度向上はほぼ確実にできそう
- 10^{-17} レベルに行けばある程度はすごいが、「物理的な動機付けがあるレベル \equiv プランクスケール」は遠い
- とはいえ極めて重要な基礎研究

光学浮上実験

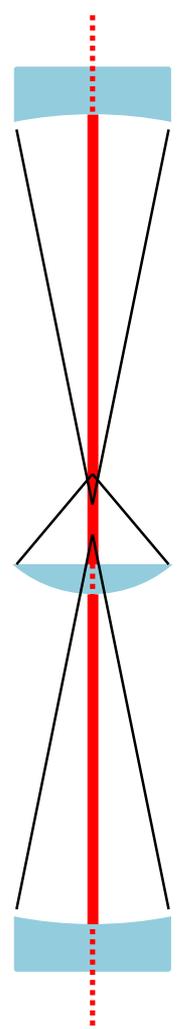
研究背景

- 機械的支持に伴う熱雑音はさまざまな分野で問題
重力波検出器
巨視的な量子測定
微小力の測定(重力、Casimir力、非標準的な力)
- 光輻射圧のみによって鏡を支持することにより、
この問題を解決



これまでの経緯

- 2013年11月 サンドイッチ構成の発見
- 2014年1月 浮上鏡発注
 $\phi=3$ mm、 $t=0.1$ mm、 $RoC=30$ mm、 $R>99.95$ % @1064 nm (~1.6 mg)
- 2014年3月 感度設計の困難性に気がつく
共振器内パワーが鏡の質量で決まってしまう → SQL超えが困難
- 2014年4月 浮上鏡納品
8個注文で7個納品(うち6個はぼろぼろ)
- 2014年10月-2月 ねじれ振り子による基礎実験
有富くん、榎本くん
アクチュエータ改良の必要性



未解決の課題と対策

- 初期アラインメントが困難(かもしれない)
 - 2次の安定性計算を行う
 - まあ、なんとかなるさ
- 微小かつ曲率付きの浮上鏡の製作が困難
 - お金をかければできるかも
 - 別の製作方法の検討
- SQL超えの困難性、応用先をどうするか
 - まずは浮上の実現を目指す
 - 回転の自由度の利用？

振動子による微小力測定

- どのような戦略をとるべきか

- 以下のモデルで考える **地面振動(変位雑音)**

SQL(標準量子限界)

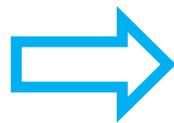
$$x_{\text{SQL}}(\omega) = \sqrt{2\hbar\chi(\omega)}$$

熱雑音(力の雑音)

$$F_{\text{th}} = \sqrt{4k_{\text{B}}T\gamma m}$$

測定したい力

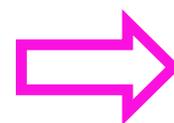
$$F(\omega)$$



$$x_{\text{sh}}(f) = 10^{-7} \text{ m}/\sqrt{\text{Hz}} \left(\frac{1 \text{ Hz}}{f} \right)^2$$

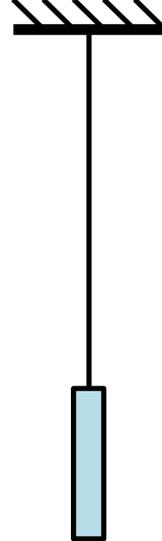
散射雑音(センシング雑音)

$$x_{\text{sh}} = \frac{c}{2\pi} \sqrt{\frac{h}{P_0\nu}}$$



測定する変位

$$x(\omega)$$



Q値

$$Q = \frac{\pi f_0}{\gamma}$$

$$\chi(\omega) \equiv \frac{x(\omega)}{F(\omega)} = \frac{1}{m(\omega^2 - \omega_0^2 - 2i\omega\gamma)}$$

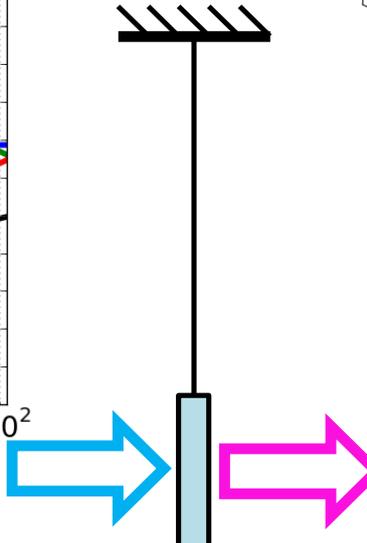
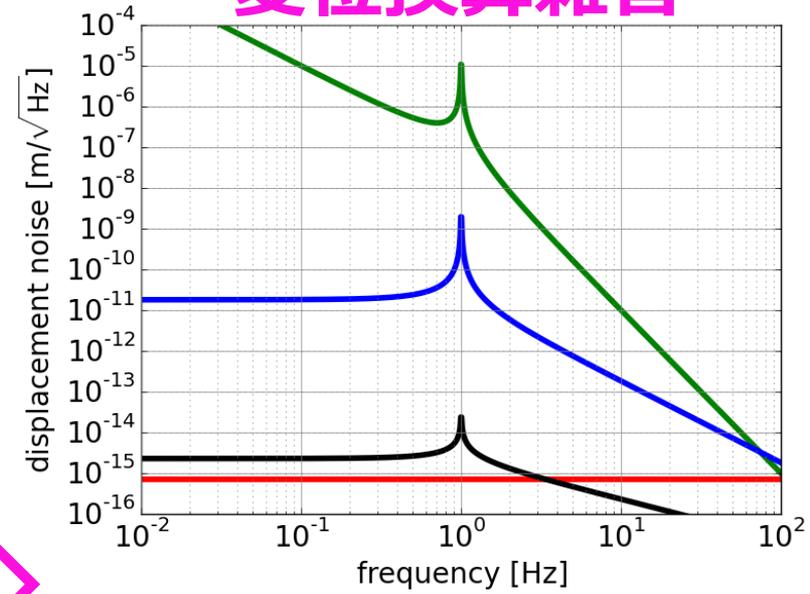
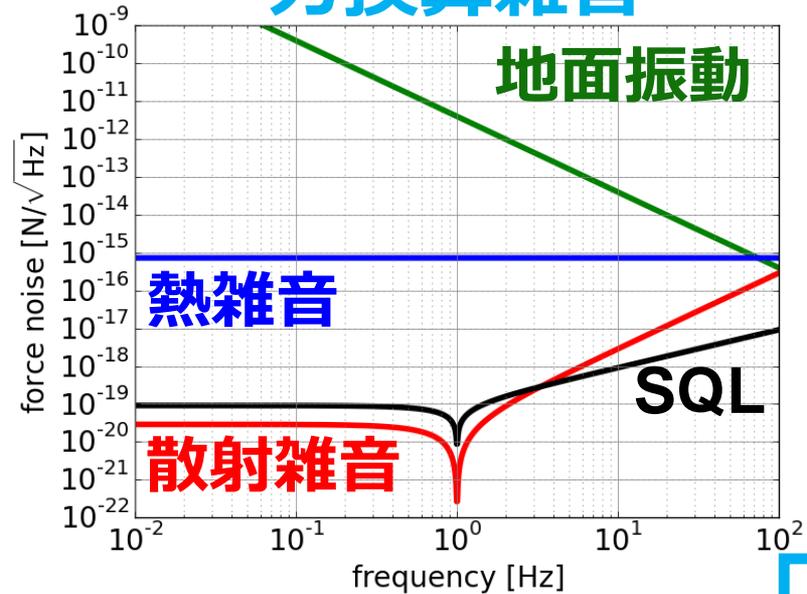
感度の例

- 共振周波数: 1 Hz、質量: 1 mg、 $Q = 1e5$

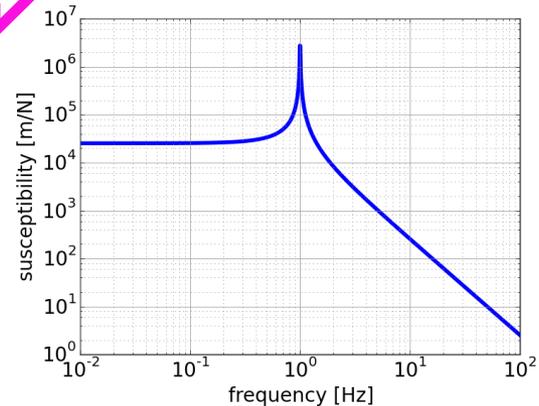
力換算雑音

地面振動

変位換算雑音



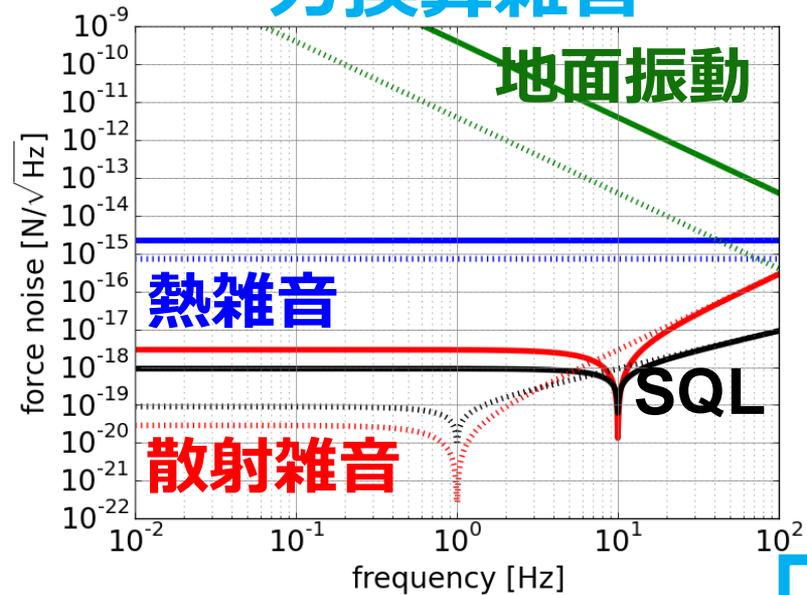
感受率



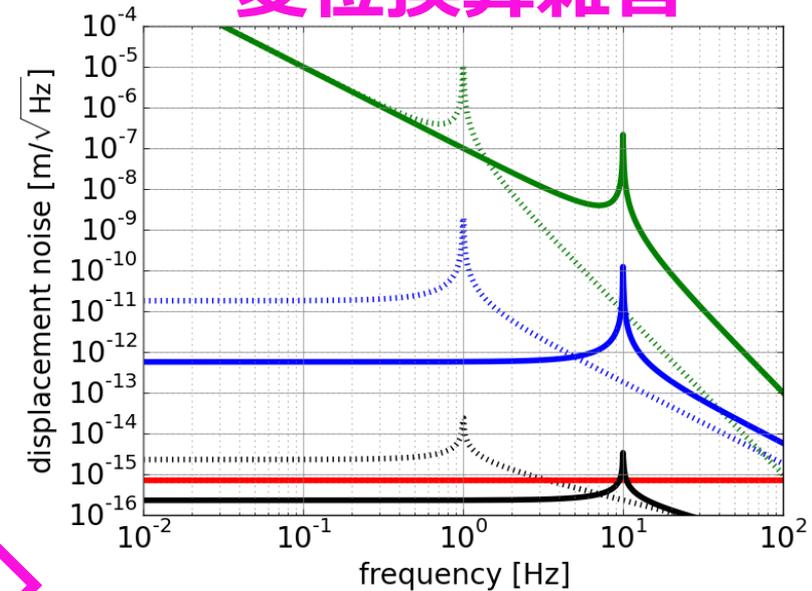
共振周波数を高くする

- 共振周波数: 10 Hz、質量: 1 mg、 $Q = 1e5$

力換算雑音

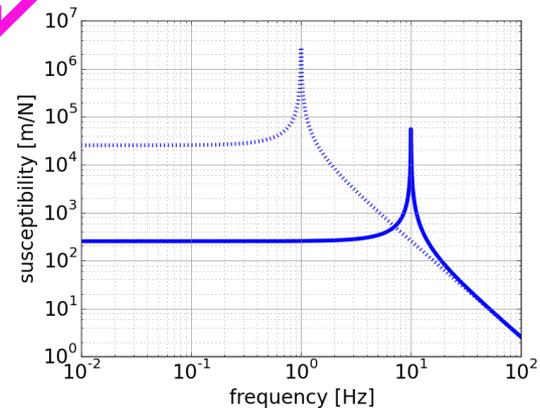


変位換算雑音



- 地面振動と熱雑音で損
- DCでは散射雑音でも損

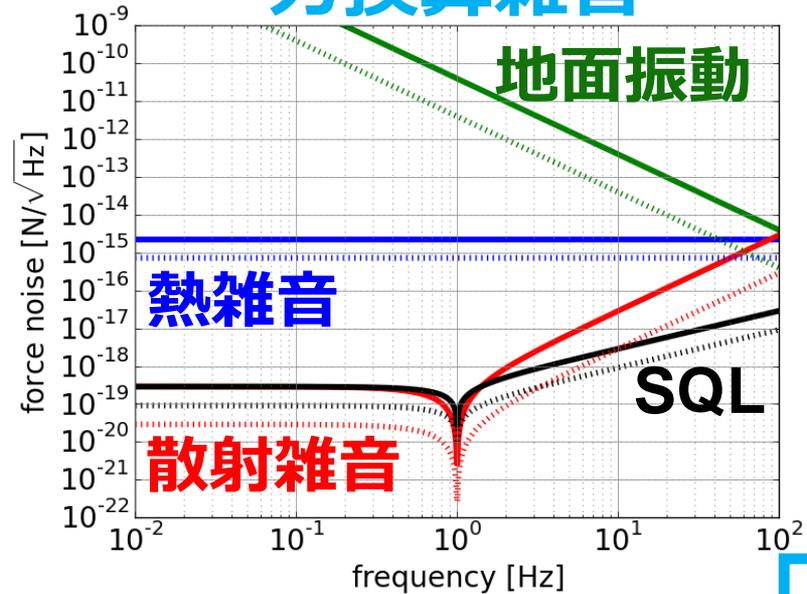
感受率



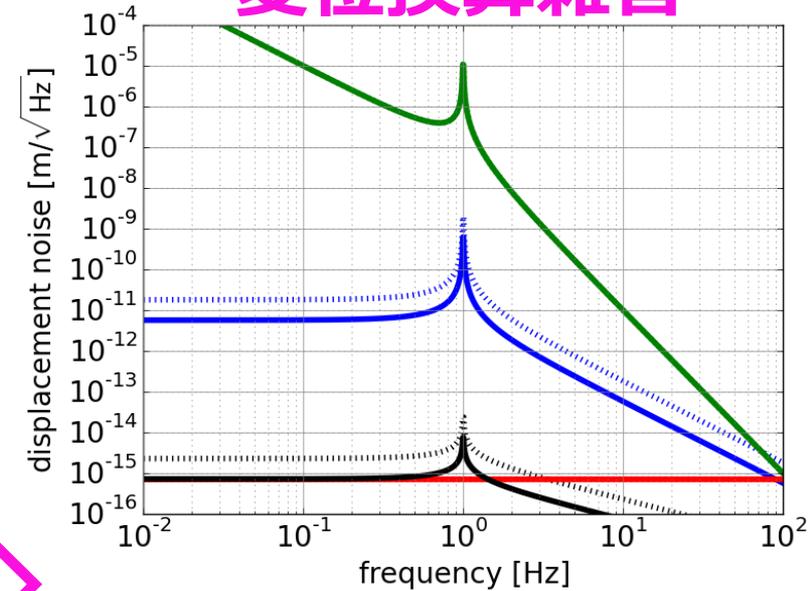
質量を重くする

- 共振周波数: 1 Hz、質量: 10 mg、 $Q = 1e5$

力換算雑音

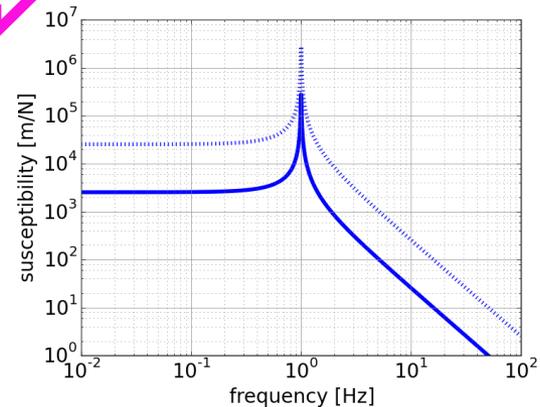


変位換算雑音



- 地面振動、熱雑音、散射雑音すべてで損

感受率



必要となる戦略

- 微小力測定の場合
 - 軽くて共振周波数が低いものほど得
 - 測定帯域が高いほど
 - 地面振動は得(防振もしやすい)
 - 散射雑音は損(共振なら得、DCなら一定)
 - 散射雑音が問題なら共振で
 - そうでないならねじれ振り子でも自由質点領域で微小力を変調させた方がいい
- SQL超えを目指す場合(自由質点領域で)
 - 軽くて共振周波数が低いものほど得
 - 測定帯域が高いほど
 - 地面振動と熱雑音は得
 - 散射雑音は損
- 重力波検出の場合
 - 重くて共振周波数が低いものほど得
 - 散射雑音が問題なら共振で

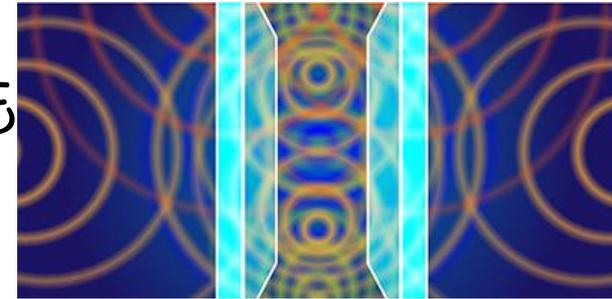
今後の進め方

- 安定性計算についてまとめる
- 応用先について検討する
- これまでは
 - 重くて共振周波数が低い(重力波検出器型)
 - 軽くて共振周波数が高い(カンチレバー等)のパターンが多かったが、光学浮上は
 - 軽くて共振周波数が低いができるはず
- 浮上鏡の評価(曲率、反射率)
- ねじれ振子による基礎実験

面白そうな実験2015

重力カシミール効果

- J. Q. Quach, [PRL 114, 081104 \(2015\)](#)
Featured in Physics
- 重力場の量子化が証明できるかも
- 弱い等価原理の検証



PRL 114, 081104 (2015)

PHYSICAL REVIEW LETTERS

week ending
27 FEBRUARY 2015

Gravitational Casimir Effect

James Q. Quach*

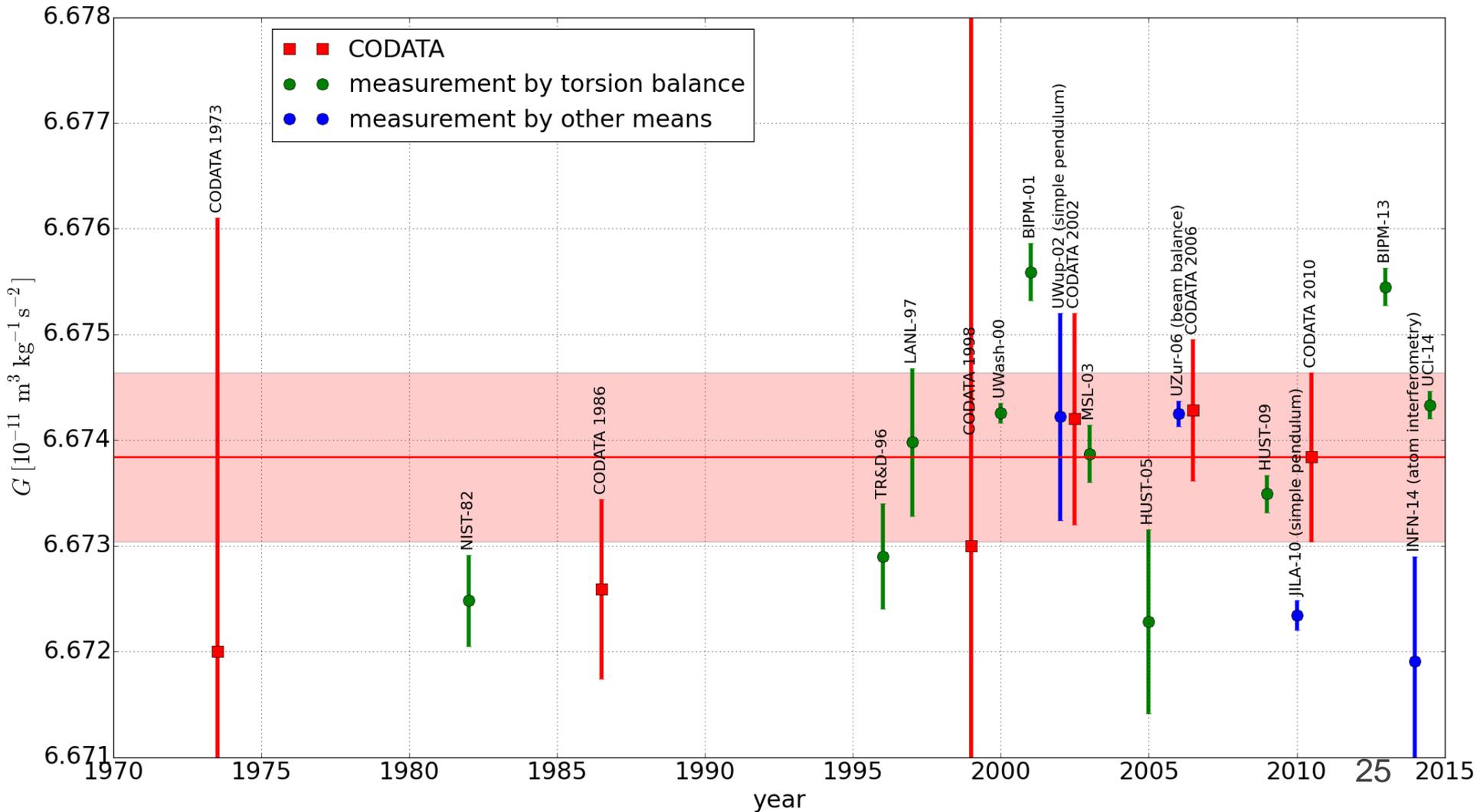
Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan

(Received 25 November 2014; published 25 February 2015)

We derive the gravitonic Casimir effect with nonidealized boundary conditions. This allows the quantification of the gravitonic contribution to the Casimir effect from real bodies. We quantify the meagerness of the gravitonic Casimir effect in ordinary matter. We also quantify the enhanced effect produced by the speculated Heisenberg-Coulomb (HC) effect in superconductors, thereby providing a test for the validity of the HC theory, and, consequently, the existence of gravitons.

万有引力定数の測定

- ばらつきが大きい(10σにおよぶ)



原子干渉計による測定

- G. Rosi+, [Nature 510, 518 \(2014\)](#)
- 現代的な手法の時代が来る？

LETTER

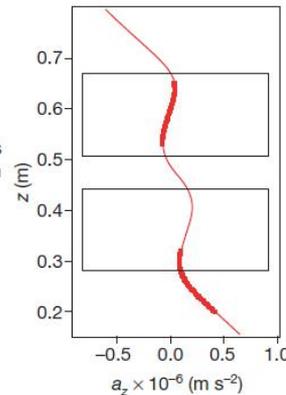
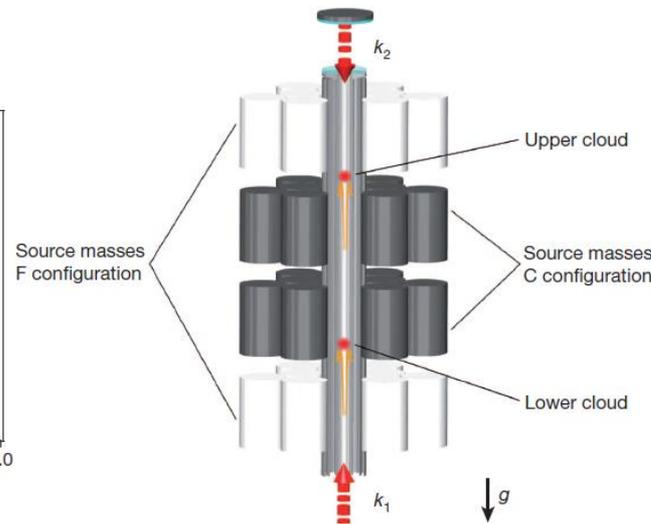
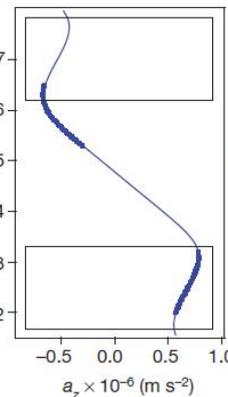
doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi¹, F. Sorrentino¹, L. Cacciapuotì², M. Prevedelli³ & G. M. Tino¹

About 300 experiments have tried to determine the value of the Newtonian gravitational constant, G , so far, but large discrepancies in the results have made it impossible to know its value precisely¹. The weakness of the gravitational interaction and the impossibility of shielding the effects of gravity make it very difficult to measure G while keeping systematic effects under control. Most previous experiments performed were based on the torsion pendulum or torsion balance scheme as in the experiment by Cavendish² in 1798, and in all cases macroscopic masses were used. Here we report the precise determination of G using laser-cooled atoms and quantum interferometry. We obtain the value $G = 6.67191(99) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ with a relative uncertainty of 150 parts per million (the combined standard uncertainty is given in parentheses). Our value differs by 1.5 combined standard deviations from the current recommended value of the Committee on Data for Science and Technology³. A conceptually different experiment such as ours helps to identify the systematic errors that have proved elusive in previous experiments, thus improving the confidence in the value of G . There is no definitive relationship between G and the other fundamental constants, and there is no theoretical prediction for its value, against which to test experimental results. Improving the precision with which we know G has not only a pure metrological interest, but is also important because of the key role that G has in theories of gravitation, cosmology, particle physics and astrophysics and in geophysical models.

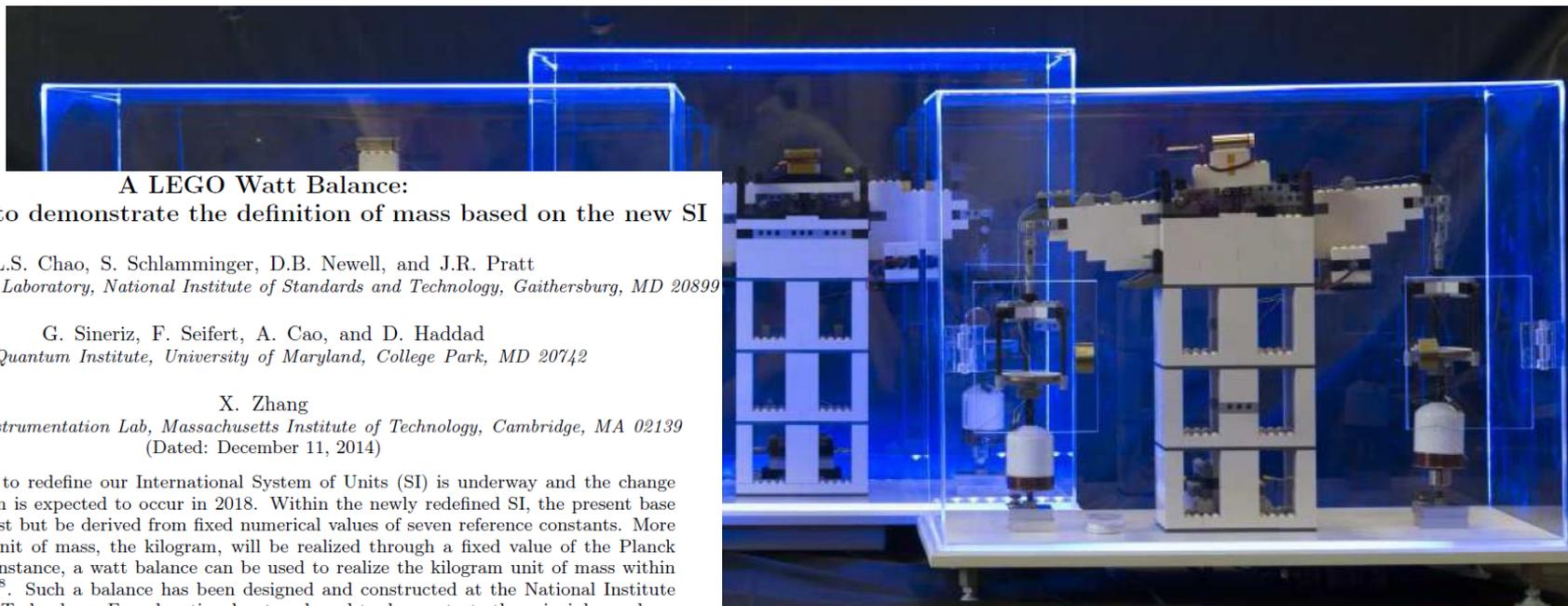
the mo two inte rela due ma: tion red size (E) ^{87}Rb level by $k_2 \approx$ con diff ecti seq



each interferometer provides a direct measurement of the differential acceleration induced by gravity on the two atomic samples. In this way, any spurious acceleration induced by vibrations or seismic noise in the common reference frame identified by the vertical Raman beams is efficiently rejected.

ワットバランス

- ジョセフソン効果と量子ホール効果を使ってプランク定数を測定
→ キログラム原器に変わる質量の定義
- L. S. Chao, [arXiv:1412.1699](https://arxiv.org/abs/1412.1699)
LEGOでできたワットバランス



A LEGO Watt Balance:

An apparatus to demonstrate the definition of mass based on the new SI

L.S. Chao, S. Schlamminger, D.B. Newell, and J.R. Pratt

Physical Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899

G. Sineriz, F. Seifert, A. Cao, and D. Haddad

Joint Quantum Institute, University of Maryland, College Park, MD 20742

X. Zhang

Computational Instrumentation Lab, Massachusetts Institute of Technology, Cambridge, MA 02139

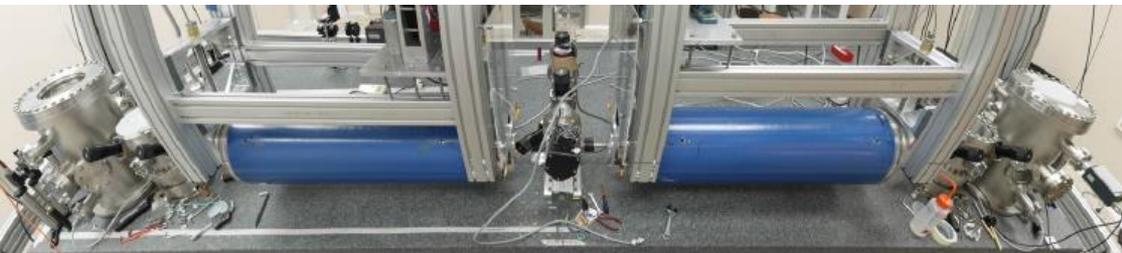
(Dated: December 11, 2014)

A global effort to redefine our International System of Units (SI) is underway and the change to the new system is expected to occur in 2018. Within the newly redefined SI, the present base units will still exist but be derived from fixed numerical values of seven reference constants. More specifically, the unit of mass, the kilogram, will be realized through a fixed value of the Planck constant h . For instance, a watt balance can be used to realize the kilogram unit of mass within a few parts in 10^8 . Such a balance has been designed and constructed at the National Institute of Standards and Technology. For educational outreach and to demonstrate the principle, we have constructed a LEGO tabletop watt balance capable of measuring a gram size mass to 1% relative uncertainty. This article presents the design, construction, and performance of the LEGO watt balance and its ability to determine h .

PVLAS実験

- 磁場により生じる真空の複屈折を測定(光子-光子散乱、アキシオンとの相互作用などからくる)
- F. Della Valle+, [PRD 90, 092003 \(2014\)](#);

[arXiv:1410.4081](#)



New PVLAS model independent limit for the axion coupling to $\gamma\gamma$ for axion masses above 1 meV

F. Della Valle¹, A. Ejlli², U. Gastaldi³, G. Messineo², E. Milotti¹, R. Pengo⁴, L. Piemontese², G. Ruoso⁴, G. Zavattini²

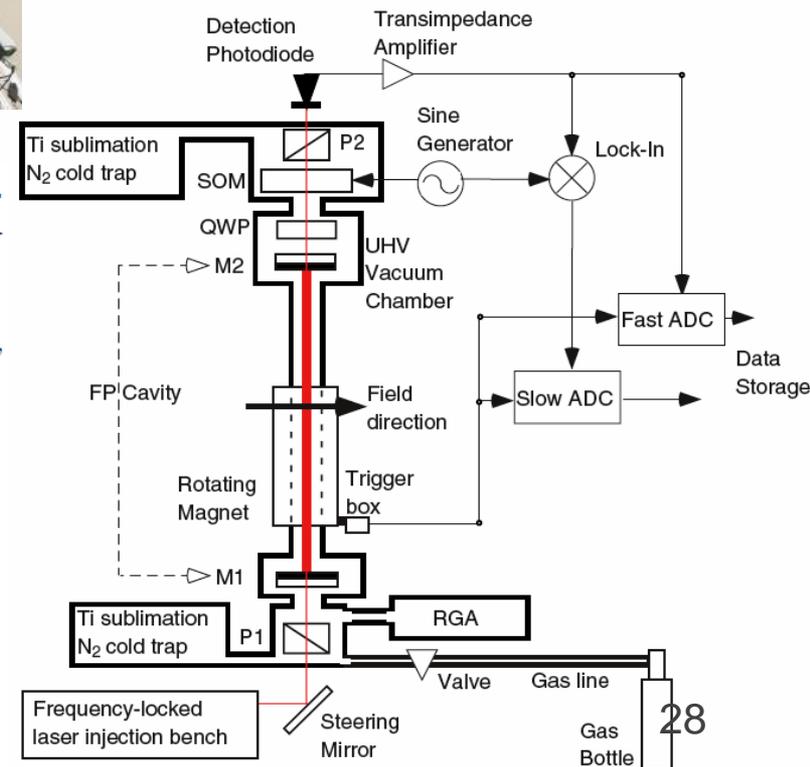
¹ INFN, Sezione di Trieste and Dipartimento di Fisica, Università di Trieste, Italy

² INFN, Sezione di Ferrara and Dipartimento di Fisica, Università di Ferrara, Italy

³ INFN, Sezione di Ferrara, Ferrara, Italy

⁴ INFN, Laboratori Nazionali di Legnaro (PD), Italy

During 2014 the PVLAS experiment has started data taking with a new apparatus installed at the INFN Section of Ferrara, Italy. The main target of the experiment is the observation of magnetic birefringence of vacuum. According to QED, the ellipticity generated by the magnetic birefringence of vacuum in the experimental apparatus is expected to be $\psi^{(QED)} \approx 5 \times 10^{-11}$. No ellipticity signal is present so far with a noise floor $\psi^{(noise)} \approx 2.5 \times 10^{-9}$ after 210 hours of data taking. The resulting ellipticity limit provides the best model independent upper limit on the coupling of axions to $\gamma\gamma$ for axion masses above 10^{-3} eV.



どの光路実験続報

- K. Bartkiewicz+ [PRA 91, 012103 \(2015\)](#)

- TSVFを使わなくても説明できる

- A. Danan+ [PRL 111, 240402 \(2013\)](#)

PHYSICAL REVIEW A 91, 012103 (2015)

One-state vector formalism for the evolution of a quantum state through nested Mach-Zehnder interferometers

Karol Bartkiewicz,^{1,2,*} Antonín Černoš,^{2,†} Dalibor Javůrek,² Karel Lemr,^{2,‡} Jan Soubusta,³ and Jiří Svoboda²

¹Faculty of Physics, Adam Mickiewicz University, PL-61-614 Poznań, Poland

²RCPTM, Joint Laboratory of Optics of Palacký University and Institute of Physics of Academy of Sciences of the Czech Republic, 17. listopadu 12, CZ-771 46 Olomouc, Czech Republic

³Institute of Physics of Academy of Sciences of the Czech Republic, Joint Laboratory of Optics of PU and IP AS CR, 17. listopadu 50A, CZ-772 07 Olomouc, Czech Republic

(Received 30 October 2014; published 12 January 2015)

Linear-optical interferometers play a key role in designing circuits for quantum information processing and quantum communications. Even though nested Mach-Zehnder interferometers appear easy to describe, there are occasions when they provide unintuitive results. This paper explains the results of a highly discussed experiment performed by Danan *et al.* [*Phys. Rev. Lett.* **111**, 240402 (2013).] using a standard approach. We provide a simple and intuitive one-state vector formalism capable of interpreting their experiment. Additionally, we cross-checked our model with a classical-physics-based approach and found that both models are in complete agreement. We argue that the quantity used in the mentioned experiment is not a suitable which-path witness, producing seemingly contrainuitive results. To circumvent this issue, we establish a more reliable which-path witness and show that it yields well-expected outcomes of the experiment.

