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Can MOND explain the data scattering of "big *G*" ?

Norbert Klein
Imperial College London
Department of Materials
https://www.imperial.ac.uk/people/n.klein/publications.html

This work is currently unfunded and represents my dedicated "hobby" activity

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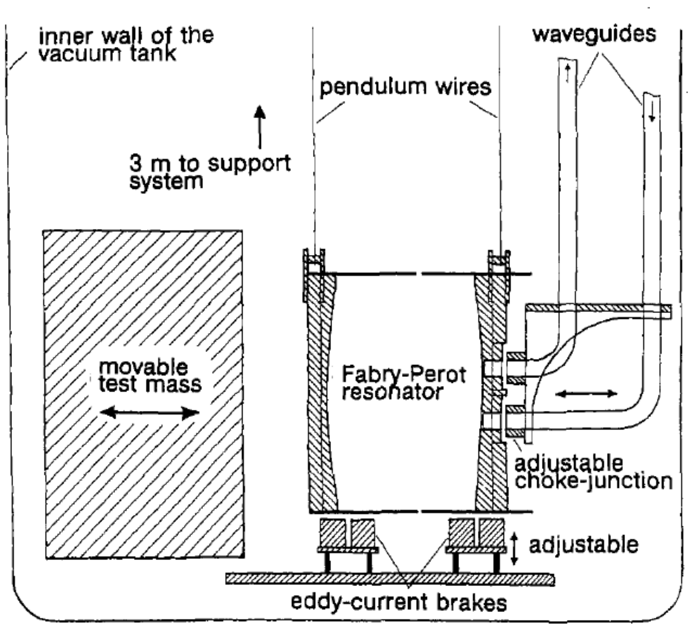
1985-1987: *my early days contribution to experimental gravity research*

A New method for testing Newton's gravitational law



from, J. Schurr, N. Klein, H. Meyer, H. Piel, H. Walesch et al., Metrologia ***28****, 397 (1991)*

2014: *Reincarnation of my engagement was triggered by my undergraduate teacher for Particle Physics* ***Prof Hinrich Meyer***

Hinrich's team is running an improved pendulum *G* experiment in a retired underground particle detector lab at DESY in Germany

Gen Relativ Gravit (2012) 44:2537–2545
DOI 10.1007/s10714-012-1411-y

RESEARCH ARTICLE

Test of the law of gravitation at small accelerations

H. Meyer · E. Lohrmann · S. Schubert · W. Bartel · A. Glazov · B. Löhr · C. Niebuhr · E. Wünsch · L. Jönsson · G. Kempf

OUTLINE

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- Introduction to the MOND phenomenology
- The MOND pendulum at small accelerations
- MOND analysis of Cavendish-type G experiments
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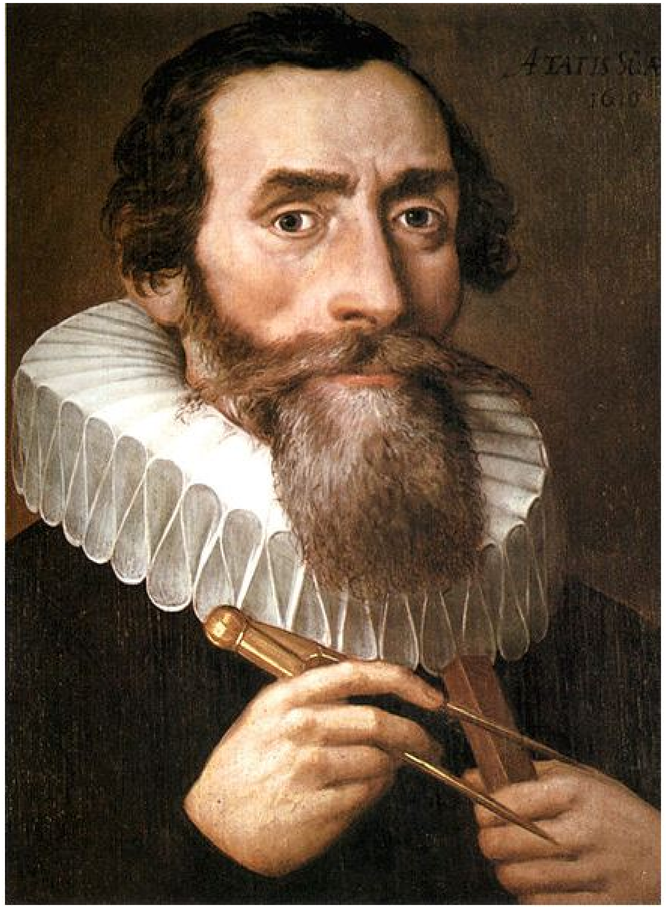
Phenomenological laws of celestial dynamics



Johannes Kepler, 1571-1630

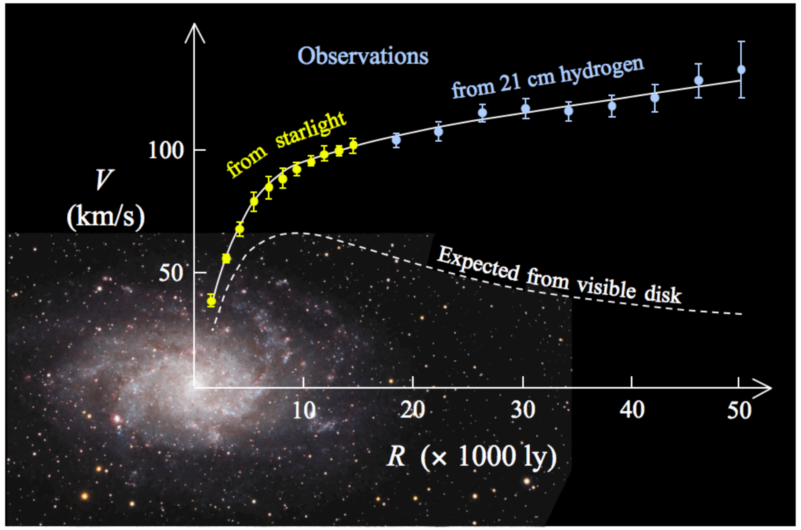
solar systems

Mordehai “Moti” Milgrom, born 1946

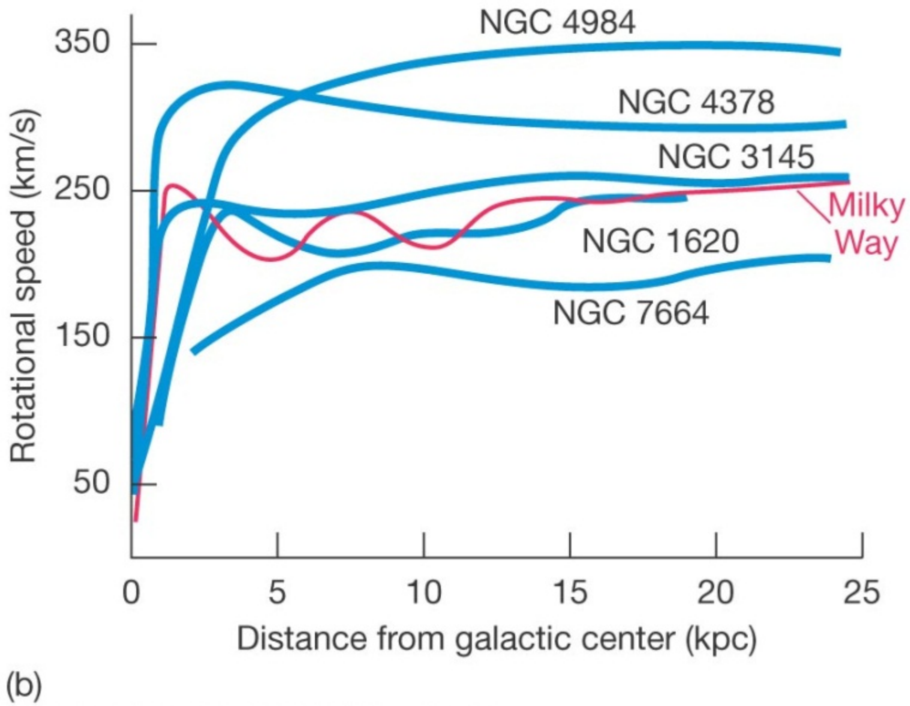
galaxies

The mystery of flat galaxy rotation curves

Imperial College London



Data are from: E. Corbelli, P. Salucci (2000). "The extended rotation curve and the dark matter halo of M33". *Monthly Notices of the Royal Astronomical Society* **311** (2): 441–447. arXiv:astro-ph/9909252. Bibcode:2000MNRAS.311..441C. doi: 10.1046/j.1365-8711.2000.03075.x..



Newton:

$$\frac{v^2}{r} = G\frac{M}{r^2} \Rightarrow v \propto \sqrt{\frac{1}{r}}$$

Flat rotation curves:

$$\frac{v^2}{r} \propto \frac{1}{r} \Rightarrow v = const$$

Flat rotation curves suggest a 1/*r* law for the gravitational field at low accelerations !

The mystery of flat galaxy rotation curves

Experimental evidence: the transition to the flat regime occurs at a certain value of the gravitational field and is ***not*** related to a length scale.

How to bring an **acceleration scale** a_0 into the equation for flat rotation curves ?

$$\frac{v^2}{r} = \frac{\sqrt{G a_0 M}}{r} \Rightarrow v^4 = G a_0 M = const$$

The Baryonic Tully-Fisher relation: hallmark for MOND

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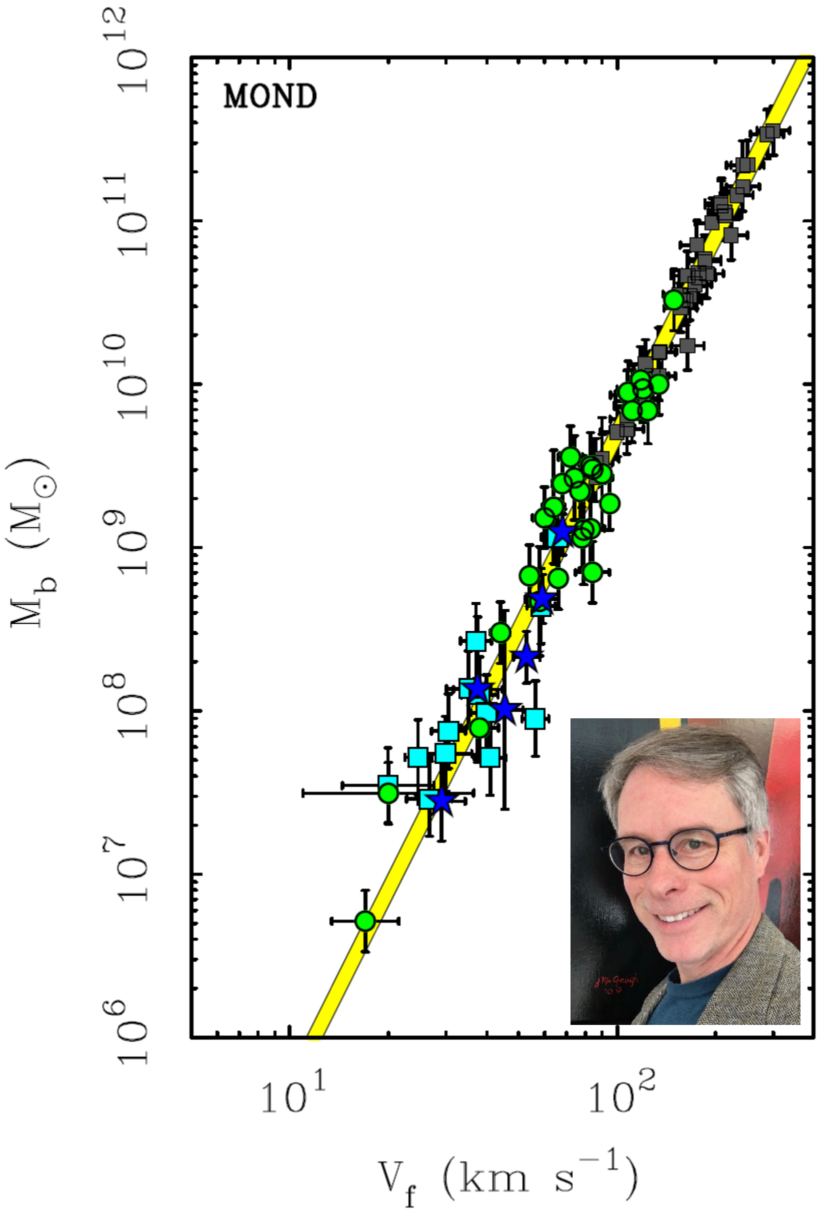

- In the **flat regime** of galaxy rotation curves, the baryonic mass is proportional to the **fourth power of the rotation velocity**
  my notation: Milgrom/McGaugh's first law

- The fit of $v^4 = G a_0 M$ yields
  $a_0 = (1.2 \pm 0.2) \cdot 10^{-10}$ m/s^2
  for the **fundamental MOND acceleration parameter**
  my notation: Milgrom/McGaugh's second law

from S. McGaugh, The Astronomical Journal 143, 40 (2012): baryonic mass vs rotation velocity for the flat regime of galaxy rotation curves
(squares: gas rich, circles: star rich)
yellow: MOND fit 1σ range

Modified Newtonian Dynamics (MOND)

fundamental parameter of MOND theory:

$$a_0=(1.2 \pm 0.2)\cdot 10^{-10}\ \mathrm{m/s^2}$$

- The **MOND acceleration** a_0 is a turning point which marks a **gradual transition** from a $1/r^2$ law (Newtonian regime $a >> a_0$) to a $1/r$ law (deep MOND regime $a << a_0$).
- The **smoothness of the transition** is determined by an **interpolation function, which needs to obey the Newtonian- and deep-MOND limits**
- The numerical value of the **MOND acceleration** is of the order of the **Hubble constant** multiplied by $c \Rightarrow$ numerical coincidence or key to the physics behind MOND ?

$a_0 \approx cH_0/6$ $\quad$ $H_0=67.80 \pm 0.77$ km/s/Mpc $\approx 2.2\cdot 10^{-18}\ \mathrm{s^{-1}}$

↑ Planck Mission

Modified Newtonian Dynamics (MOND)

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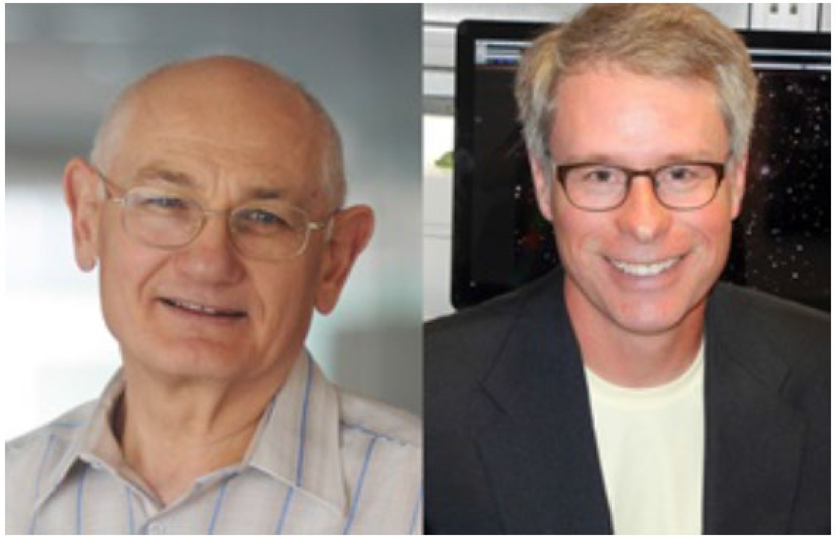
DISCOVER magazine

FROM THE JULY/AUGUST 2015 ISSUE

Dark Matter Deniers

Exploring a blasphemous alternative to one of modern physics' most vexing enigmas.

By Steve Nadis | Thursday, May 28, 2015

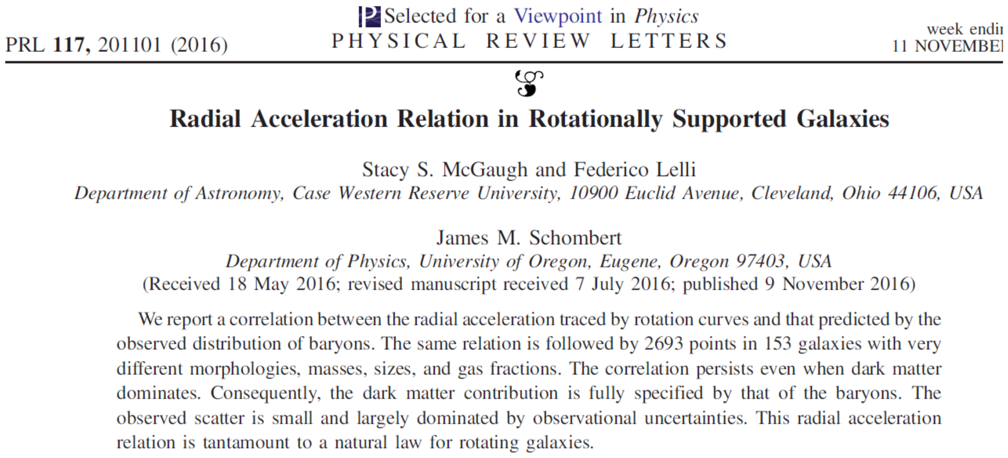


Mordehai Milgrom (left) and Stacy McGaugh

Milgrom: Weizmann Institute of Science; McGaugh: Case Western Reserve University

Transition region: the universal radial acceleration relation

Imperial College London


Selected for a Viewpoint in Physics

PRL 117, 201101 (2016) PHYSICAL REVIEW LETTERS week endi[ng] 11 NOVEMBE[R]

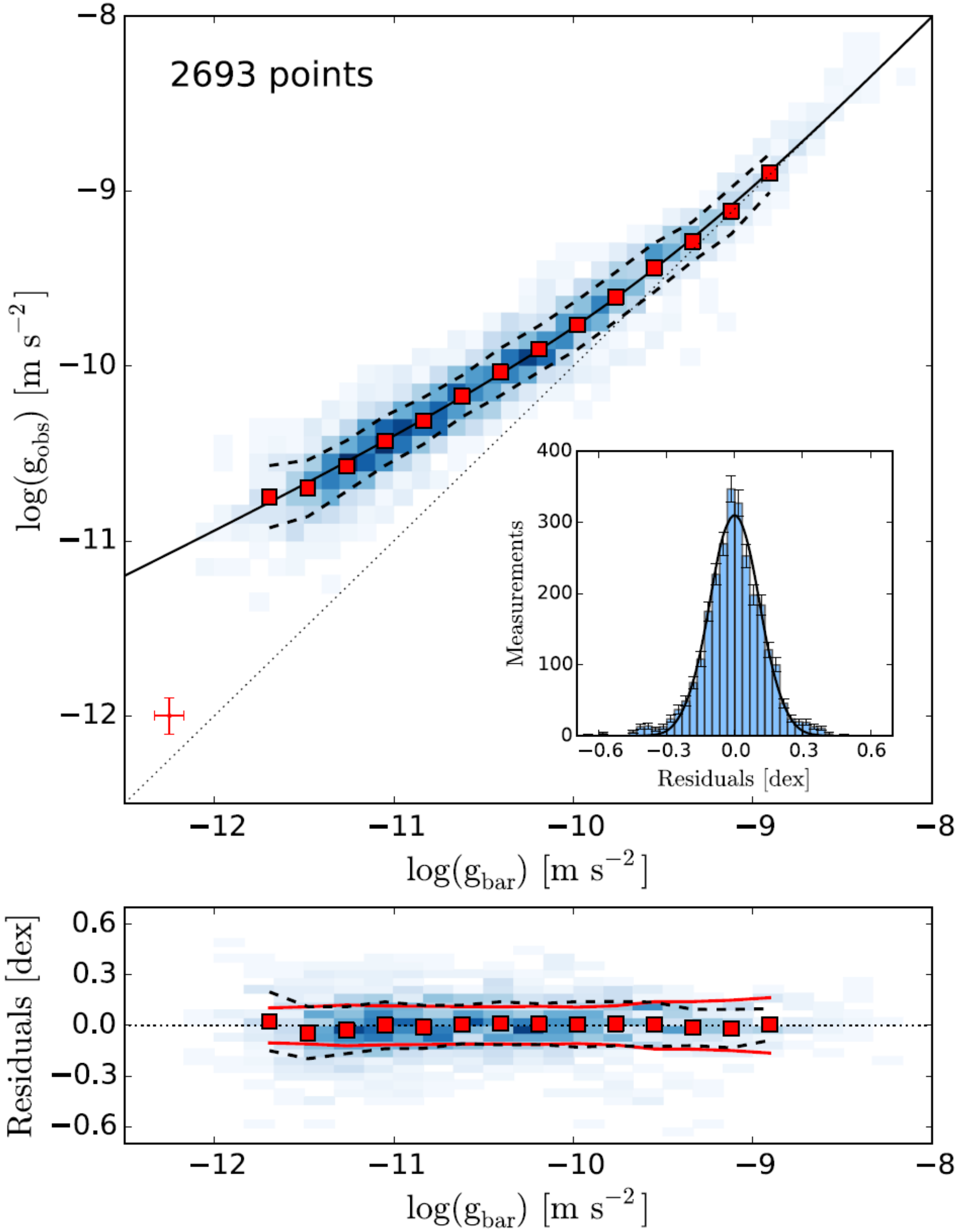
Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, Ohio 44106, USA

James M. Schombert
Department of Physics, University of Oregon, Eugene, Oregon 97403, USA

(Received 18 May 2016; revised manuscript received 7 July 2016; published 9 November 2016)

We report a correlation between the radial acceleration traced by rotation curves and that predicted by the observed distribution of baryons. The same relation is followed by 2693 points in 153 galaxies with very different morphologies, masses, sizes, and gas fractions. The correlation persists even when dark matter dominates. Consequently, the dark matter contribution is fully specified by that of the baryons. The observed scatter is small and largely dominated by observational uncertainties. This radial acceleration relation is tantamount to a natural law for rotating galaxies.



One universal law for (almost ?) all galaxies

my notation: Milgrom/McGaugh's third law

Options for fits to the RAR, which are consistent with the deep MOND and Newtonian limits

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$$g_{MOND} = g_{Newton} \cdot f(|g_{Newton}| / a_0)$$

MOND corrected, i.e. observed acceleration

Newtonian, i.e estimated from baryonic mass according to Newton's law

MOND interpolation function

4 popular choices for *f*

$$f_{\text{MONDsimple}}\left(|a_N| / a_0\right) = \left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{a_0}{|a_N|}}\right]$$

$$f_{\text{MONDstandard}}\left(|a_N| / a_0\right) = \sqrt{\frac{1}{2} + \frac{1}{2}\sqrt{1 + \left(\frac{2a_0}{|a_N|}\right)^2}}$$

$$f_{\text{McGaugh}}\left(|a_N| / a_0\right) = \frac{1}{1 - \exp\left(-\sqrt{|a_N| / a_0}\right)}$$

$$f_{\text{Klein}}\left(|a_N| / a_0\right) = \left[1 + \left(\frac{a_0}{|a_N|}\right)^{\beta}\right]^{\frac{1}{2\beta}}$$

β: fit parameter

MOND effects in our solar system ?

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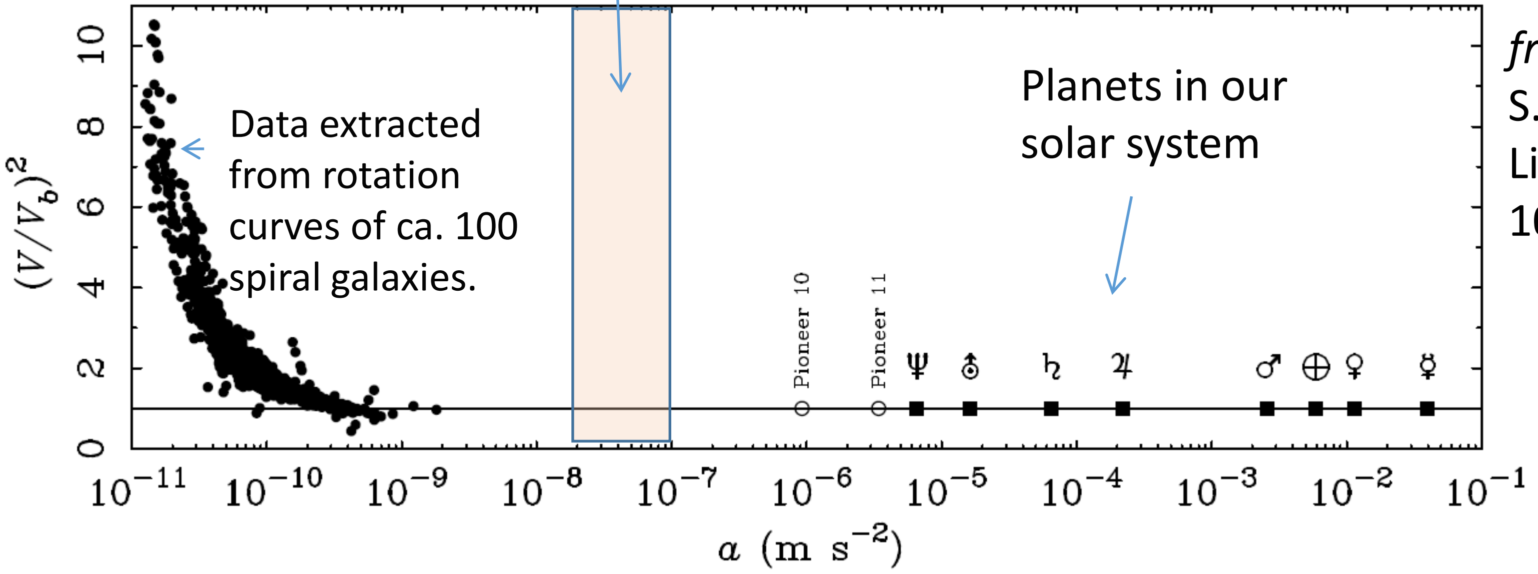
Operational range
of Cavendish G experiments



from B. Famaey and S. McGaugh, Living Rev. Relativity **15**, 10 (2012)

M = 1 kg @ 1m distance:
a = 6.67· 10^{-11} m/s^2

***but*: what about the background field of the earth g = 9.81 m/s^2 ?**

MOND interpretations: the role of the background field

According to Newton's second law the motion of a mass *m* in a gravitational field *g* may be modified in two different ways:

1: modification of the Newtonian gravitational field g_N:

$$m_i \frac{d^2\vec{x}(t)}{dt^2} = \vec{F}_{G,N} f(|\vec{g}_N| / a_0) = m_g g_N f(|\vec{g}_N| / a_0)$$

m_i: inertial mass
m_g: gravitational mass

2: modification of the inertial mass *m*:

$$\frac{m_i}{f(|\vec{g}_N| / a_0)} \frac{d^2\vec{x}(t)}{dt^2} = \vec{F}_{G,N} = m_g \vec{g}_N$$

1 and 2 are identical in case of g_N being the gravitational field from one point mass only.
How about case of a pendulum ?

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Nonrelativistic MOND field theory [AQUAL]

MOND effects are implemented by replacing the **Poisson equation** for the gravitational potential ϕ generated by a given mass distribution ρ by a **modified non-linear Poison equation**:

Newton

$$\vec{\nabla}\Phi_{Newton} = 4\pi\rho G$$

$$\vec{g}_N = -\vec{\nabla}\Phi_{Newton}$$

MOND AQUAL (quadratic Lagrangian)

$$\vec{\nabla}\cdot\left[\mu\left(\left|\vec{\nabla}\Phi_{MOND}\right|/a_0\right)\vec{\nabla}\Phi_{MOND}\right] = 4\pi\rho G, \qquad \vec{g}_{MOND} = -\vec{\nabla}\Phi_{MOND}$$

$$\mu_{\text{MONDsimple}}(x) = \frac{1}{1+x}$$

$$\mu_{\text{MONDstandard}}(x) = \frac{1}{\sqrt{1+x^2}}$$

$f_{\text{MONDsimple}}$ and $f_{\text{MOND standard}}$ are obtained by solving the modified Poison equation for one point mass

- AQUAL excludes the observation of MOND effects on earth and within the solar system, because the magnitude of the **total gravitational field** is used in the argument of the interpolation function μ. This leads to the so-called **external field effect** in MOND.

- Relativistic generalization of AQUAL was unsuccessful.

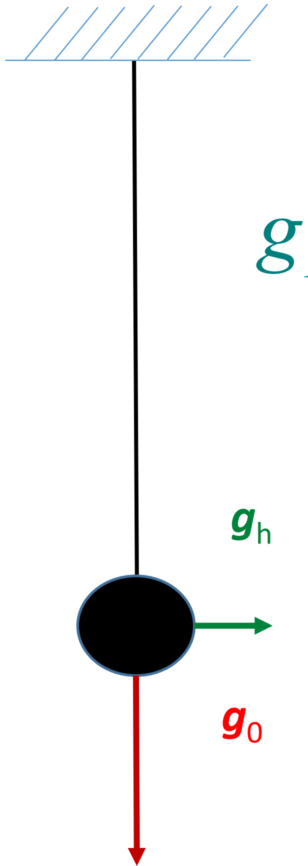
AQUAL: J.D. Bekenstein, M. Milgrom, Astrophys. J. **286**, 7 (1984)

MOND modified inertia interpretation

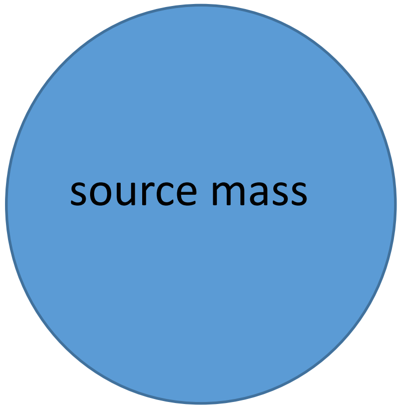
In MOND inertia the magnitude of the **component of the gravitational field which leads to an accelerated motion** should be MOND corrected. In case of a pendulum mass this **excludes the gravitational field of the earth**.

This should enable the observation of MOND effects for a pendulum at extremely small amplitudes !

Since the source masses are moved around, consequently the pendulum body moves $\Rightarrow$ $\boldsymbol{g}_{\text{Newton,h}}$ is time dependent. **Therefore any meaningful MOND analysis must include dynamical effects**



$$g_{MOND,h} = g_{Newton,h} \cdot f(|g_{Newton,h}| / a_0)$$



Experimental constraints related to Newton's second law

Imperial College London

PRL **98,** 150801 (2007) PHYSICAL REVIEW LETTERS week ending 13 APRIL 2007

Laboratory Test of Newton's Second Law for Small Accelerations

J. H. Gundlach, S. Schlamminger, C. D. Spitzer, and K.-Y. Choi
Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, Washington 98195, USA

B. A. Woodahl
Physics Department, Indiana University-Purdue University, Indianapolis, Indiana 46202, USA

J. J. Coy
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E. Fischbach
Physics Department, Purdue University, West Lafayette, Indiana 47907, USA

(Received 12 February 2007; published 13 April 2007)

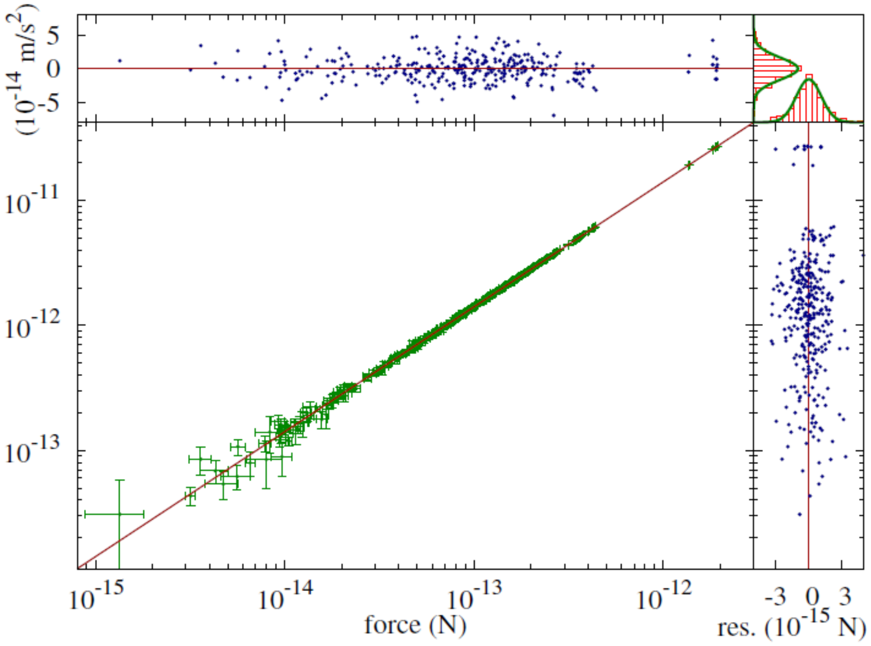


FIG. 2 (color online). The measured force versus the measured acceleration. The solid line is the best fit for acceleration, a being exactly proportional to force F. Our data agree very well with the curve. The insets on the right and top of the main graph give the residuals of the data to the fitted line.

verification of Newton's second law for small accelerations towards $a=a_0/1000$ by **amplitude-frequency measurements** of a free oscillating torsion pendulum. Here the restoring torque originates from the elastic properties of the fibre, which is electromagnetic $\Rightarrow$

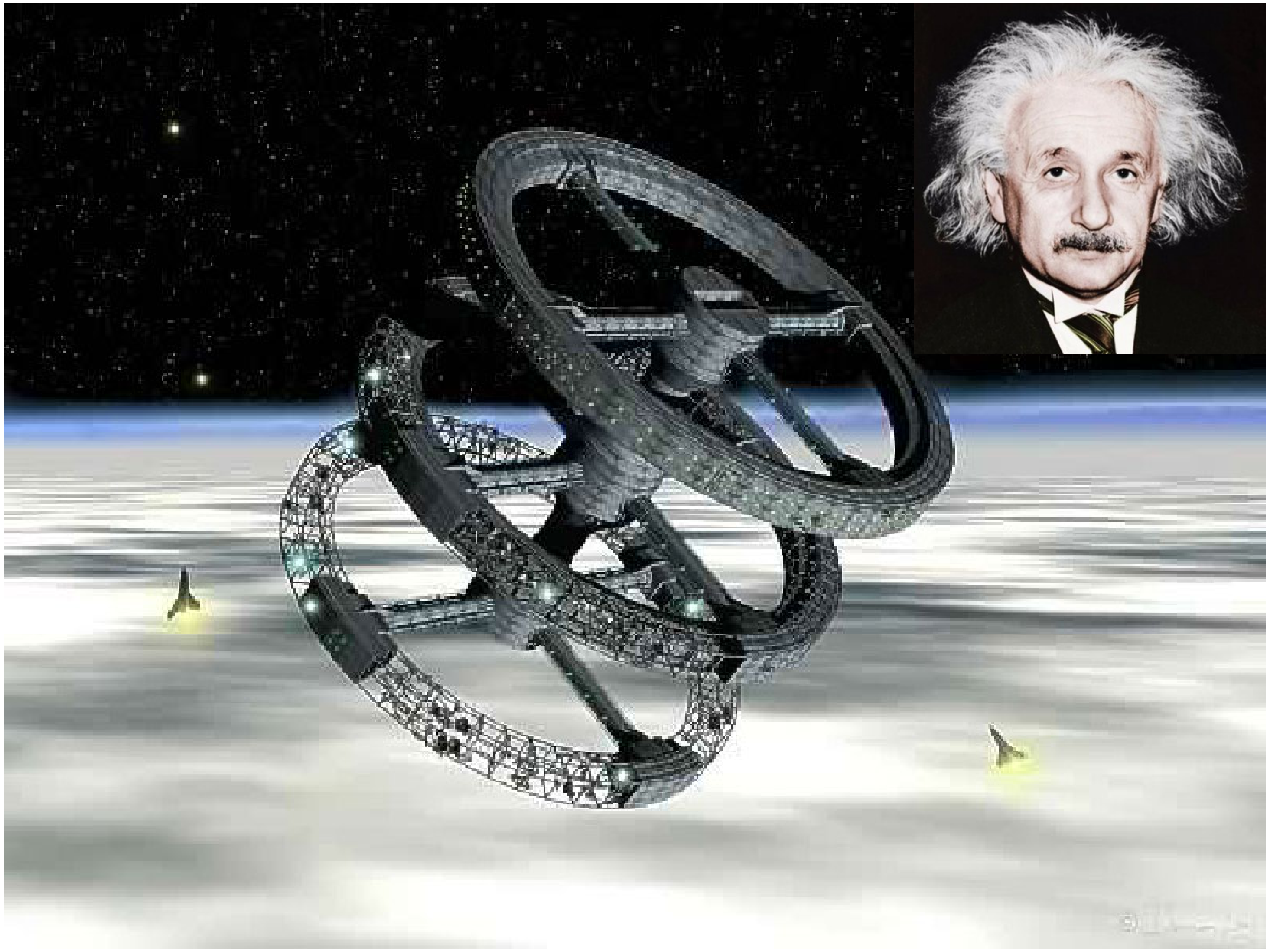
Basic equation for the MOND correction of Cavendish experiments

$$\frac{d^2\vec{x}(t)}{dt^2} = (\vec{g}_{N,h} + \vec{a}_c) f(|\vec{g}_{N,h} + \vec{a}_c| / a_0) + \frac{\vec{F}_{EM}}{m}$$

Working hypothesis of my analysis

- MOND corrections are determined by the magnitude of the horizontal gravitational field component g_N and by accelerated motions due to constraining forces a_c (for example centripetal acceleration in case of pendulum rotation). According to GR, a centripetal acceleration contributes to the gravitational force
- Electromagnetic forces are not MOND corrected.

SPACESHIP WITH ARTIFICAL GRAVITY



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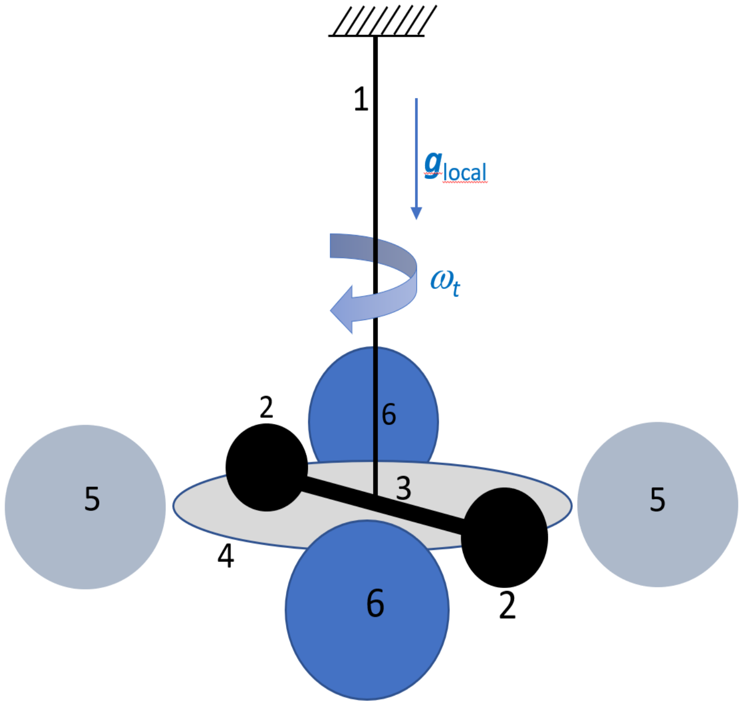
Cavendish experiments: simple and genius



Henry Cavendish, 1731-1810

(1) Suspended torsion wire or torsion strip

(2) Test masses

(3) Rigid massless bar

(4) 2D approximate inertial frame of reference

(5) Source masses position 1

(6) Source masses position 2

- Extremely small spring constant of torsion mode leads to very high sensitivity
- Very weak excitation of torsion mode by seismic motion of the pendulum suspension point

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

rsta.royalsocietypublishing.org

The Newtonian constant of gravitation—a constant too difficult to measure? An introduction

Terry Quinn[1,†] and Clive Speake[2]

from Phil. Trans. R. Soc. A **372**: 20140253 (2014)

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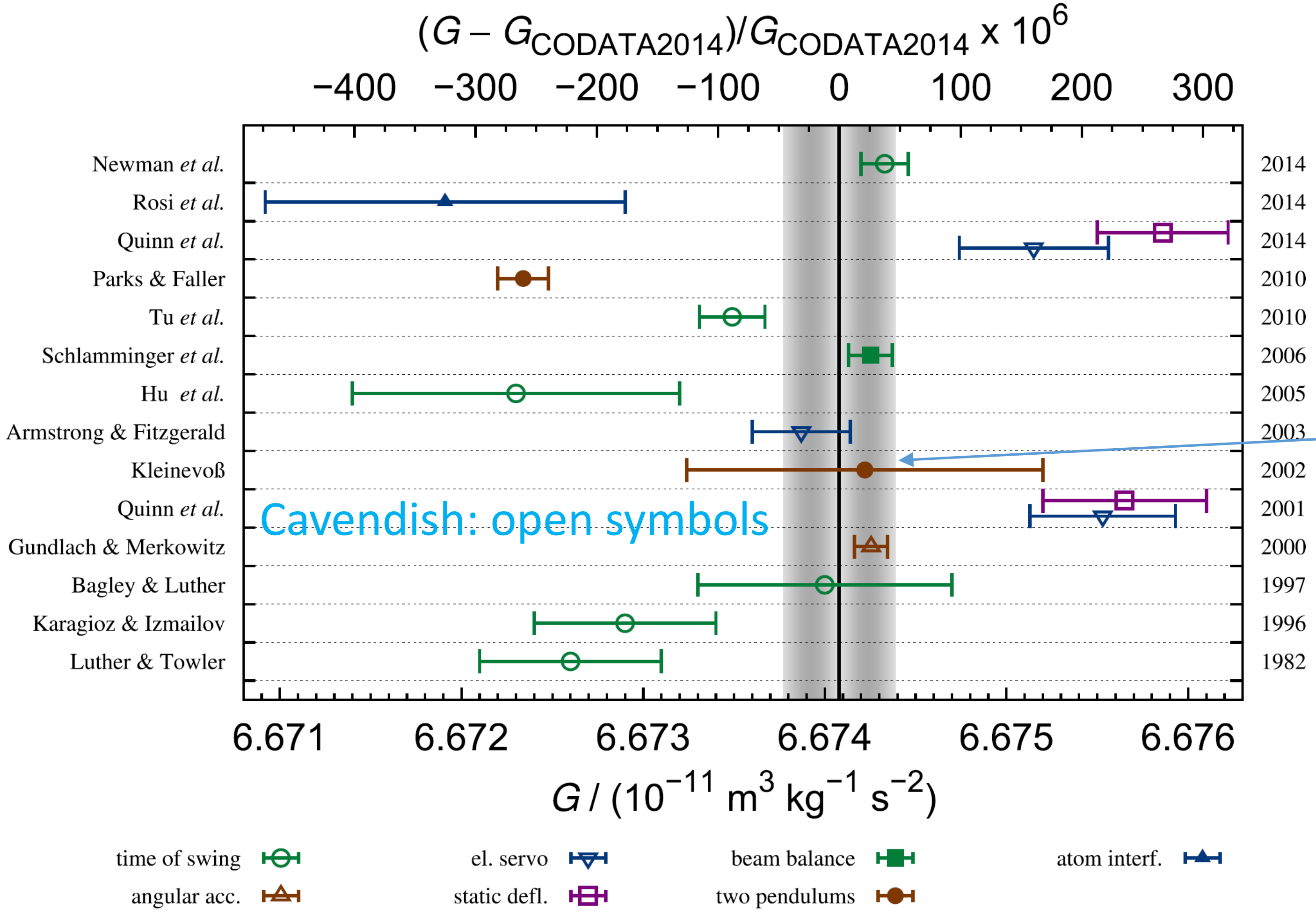
"big G" state-of-art 2017



from C. Rothleitner, S. Schlamminger, Review of Scientific Instruments **88**, 111101 (2017)

my PhD pendulum experiment

This is a real challenge and deserves a proper explanation

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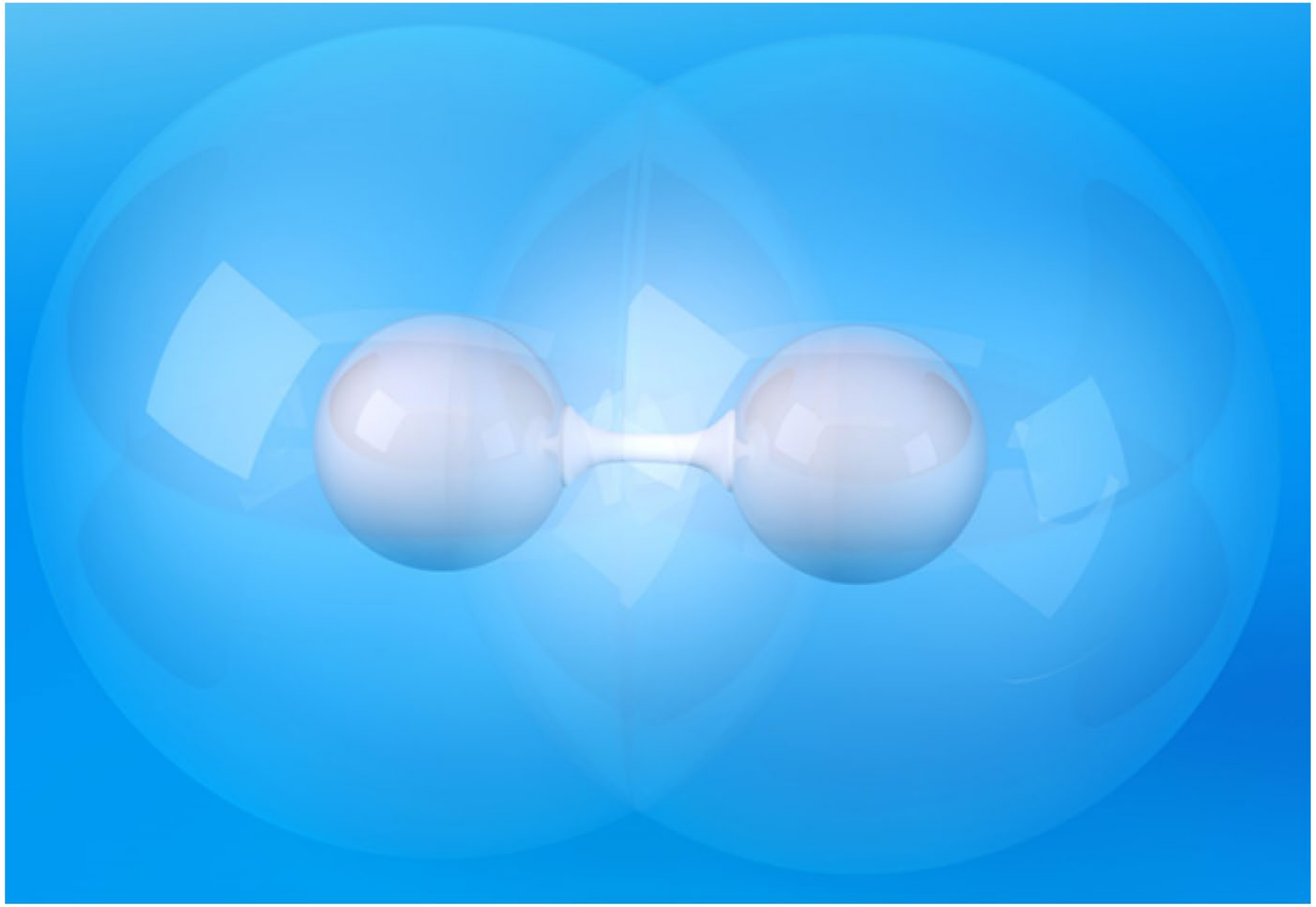
physicsworld

GRAVITY | RESEARCH UPDATE

Gravitational-constant mystery deepens with new precision measurements

30 Aug 2018 Hamish Johnston



Mutual attraction: why is it so difficult to pin down the gravitational constant? (Courtesy: iStock/FrankRamspott)

Cavendish "big G" state-of-art Dec. 2018

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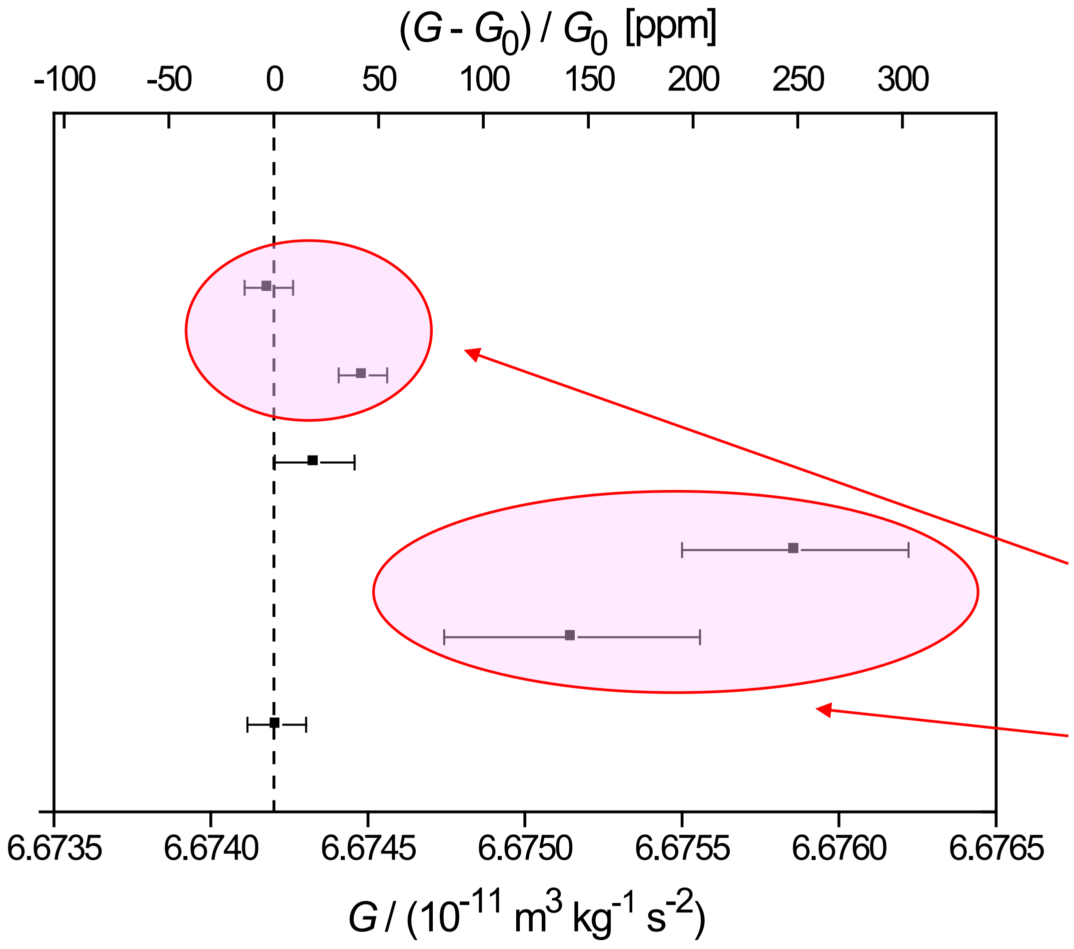


Measurements of the gravitational constant using two independent methods

Qing Li[1,8], Chao Xue[2,3,8], Jian-Ping Liu[1,8], Jun-Fei Wu[1,8], Shan-Qing Yang[1*], Cheng-Gang Shao[1*], Li-Di Quan[4], Wen-Hai Tan[1], Liang-Cheng Tu[1,2], Qi Liu[2,3], Hao Xu[1], Lin-Xia Liu[5], Qing-Lan Wang[6], Zhong-Kun Hu[1], Ze-Bing Zhou[1], Peng-Shun Luo[1], Shu-Chao Wu[1], Vadim Milyukov[7] & Jun Luo[1,2,3*]

The Newtonian gravitational constant, *G*, is one of the most fundamental constants of nature, but we still do not have an accurate value for it. Despite two centuries of experimental effort, the value of *G* remains the least precisely known of the fundamental constants. A discrepancy of up to 0.05 per cent in recent determinations of *G* suggests that there may be undiscovered systematic errors in the various existing methods. One way to resolve this issue is to measure *G* using a number of methods that are unlikely to involve the same systematic effects. Here we report two independent determinations of *G* using torsion pendulum experiments with the time-of-swing method and the angular-acceleration-feedback method. We obtain *G* values of 6.674184×10^{-11} and 6.674484×10^{-11} cubic metres per kilogram per second squared, with relative standard uncertainties of 11.64 and 11.61 parts per million, respectively. These values have the smallest uncertainties reported until now, and both agree with the latest recommended value within two standard deviations.

Q. Li et al., Nature **560**, 582 (2018)

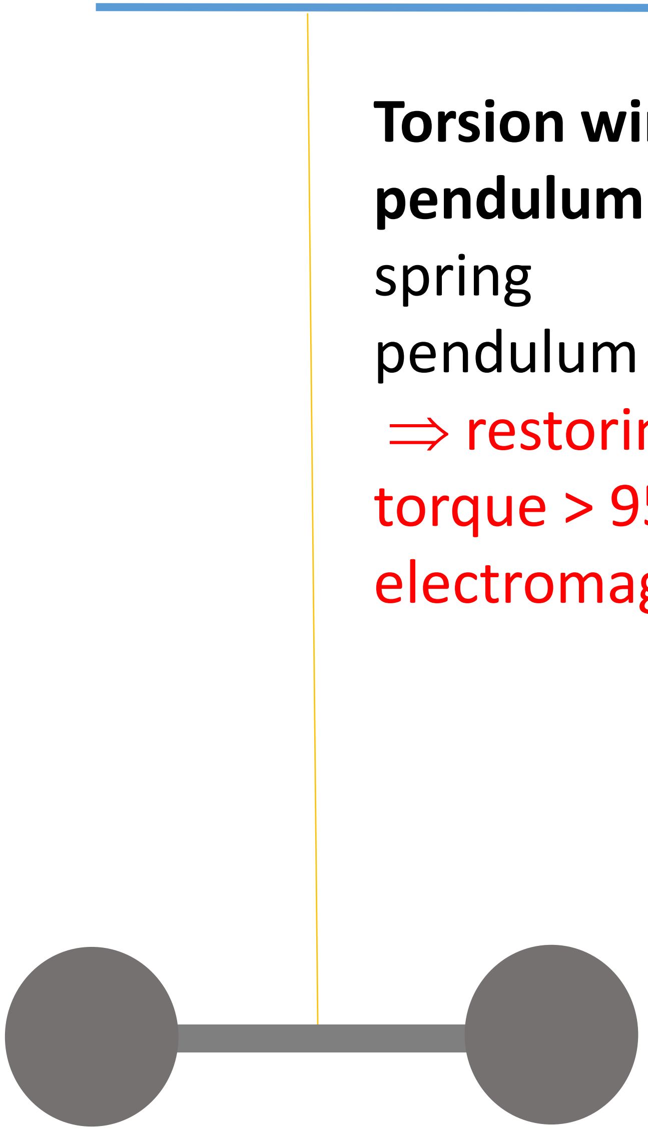
HUST (Huazhong University of Science and Technology)

T. Quinn et al., Trans . R. Soc. A **372**, 20140032 (2014)

BIPM = Bureau International des Poids et Mesures

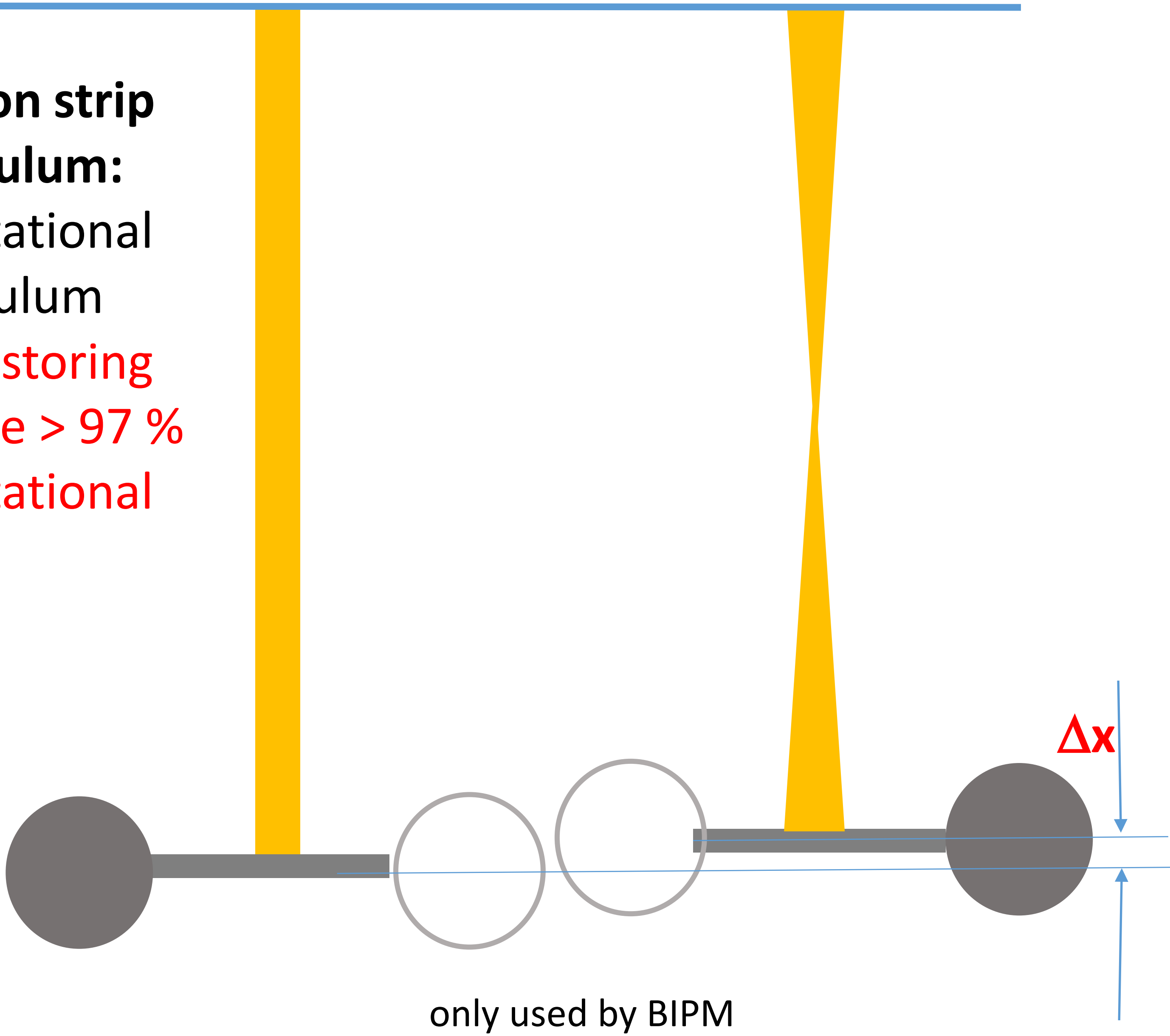
Measurements with 2 independent methods represent ideal test case for MOND, because explanation by systematic errors is much more unlikely !

Torsion pendulum: two versions with huge implications for MOND



Torsion wire pendulum:
spring pendulum
$\Rightarrow$ restoring torque > 95 % electromagnetic

used by everyone else except BIPM



Torsion strip pendulum:
gravitational pendulum
$\Rightarrow$ restoring torque > 97 % gravitational

only used by BIPM

Linear pendulum equivalent of a Cavendish experiment: static deflection or Cavendish mode

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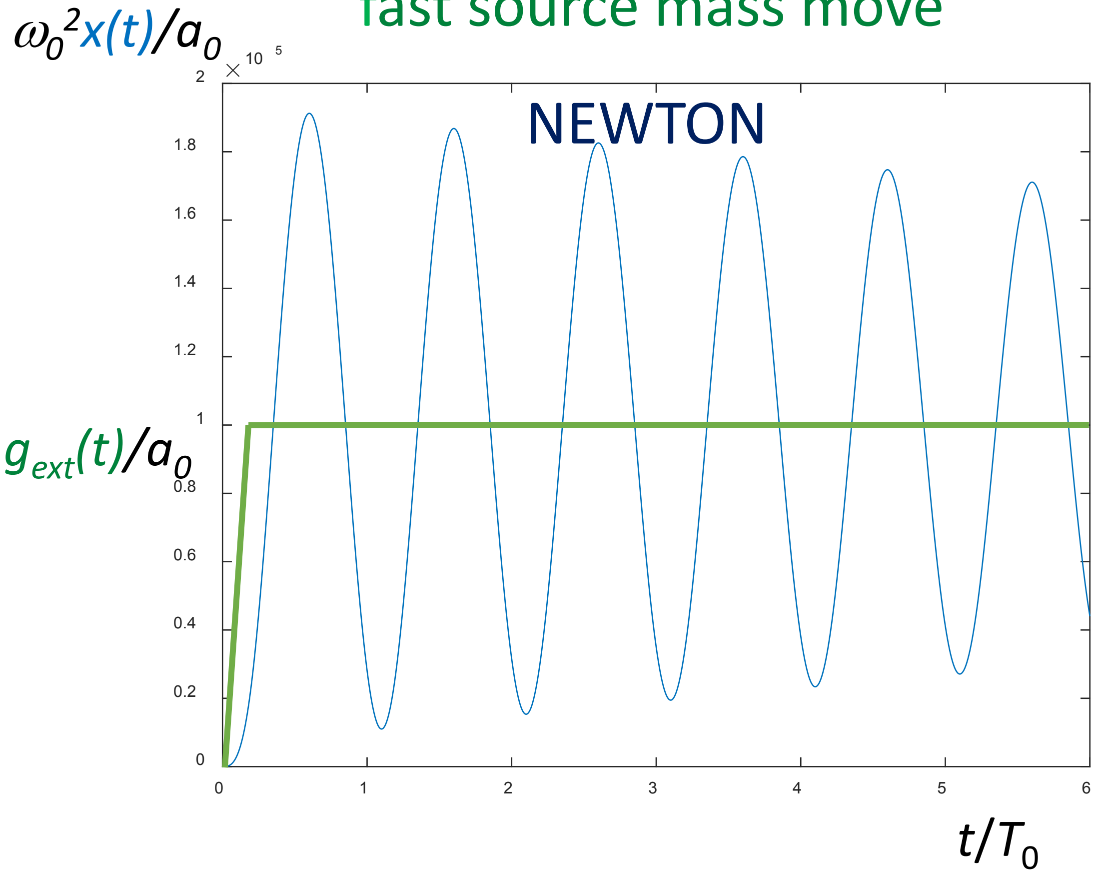
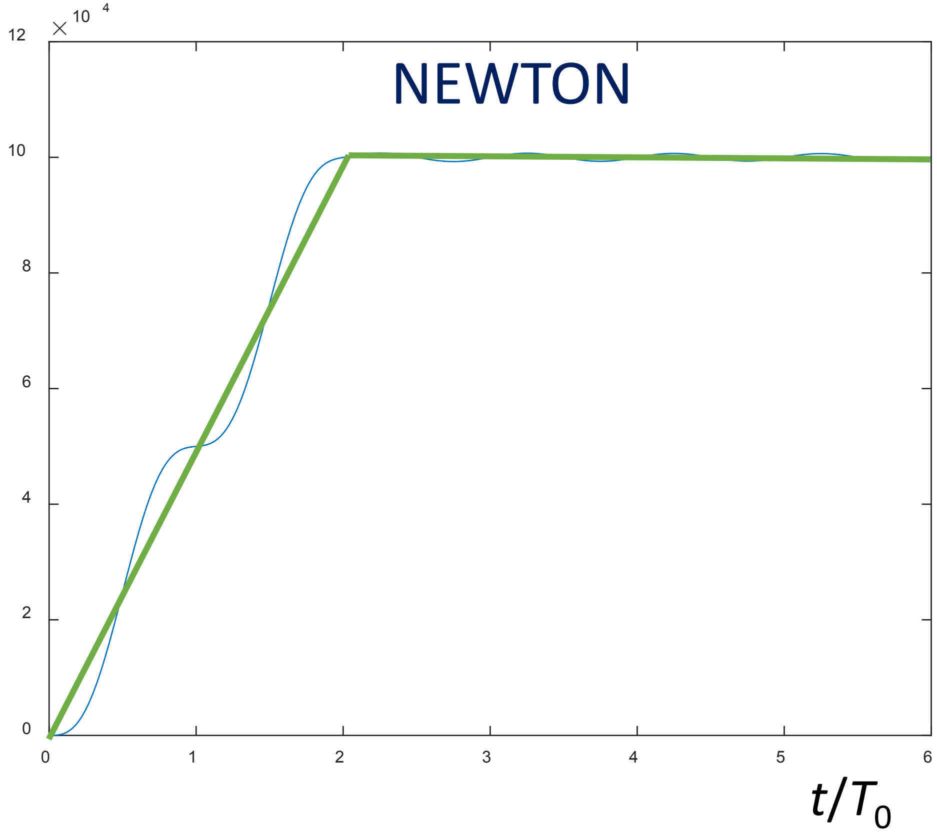
fast source mass move



slow source mass move



$$\ddot{x}(t) + \omega_0^{\;2} x(t) + \frac{\omega_0}{Q}\dot{x}(t) = g_{ext}(t)$$

pendulum oscillates around new equilibrium position

MOND simulations for Cavendish operation mode at $g_{ext}=a_0$

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pendulum with mixed EM / G restoring force:

$$\chi = \frac{\kappa_{em}}{\kappa_g + \kappa_{em}}$$

$\chi = 0$: pure gravitational

$\chi = 1$: pure electromagnetic

$$\ddot{x}(t) = \left[g_{ext}(t) - \omega_0^{\,2}(1-\chi)x(t) \right] \cdot f\left(\left| g_{ext}(t) - \omega_0^{\,2}(1-\chi)x(t) \right| / a_0 \right) - \omega_0^{\,2}\chi x(t) - \frac{\omega_0}{Q}\dot{x}(t)$$

gravitational term: MOND corrected

EM term: not MOND corrected

Results of MOND pendulum simulation: comparison of gravitational and spring pendulum at $g_{N,ext}=a_0$

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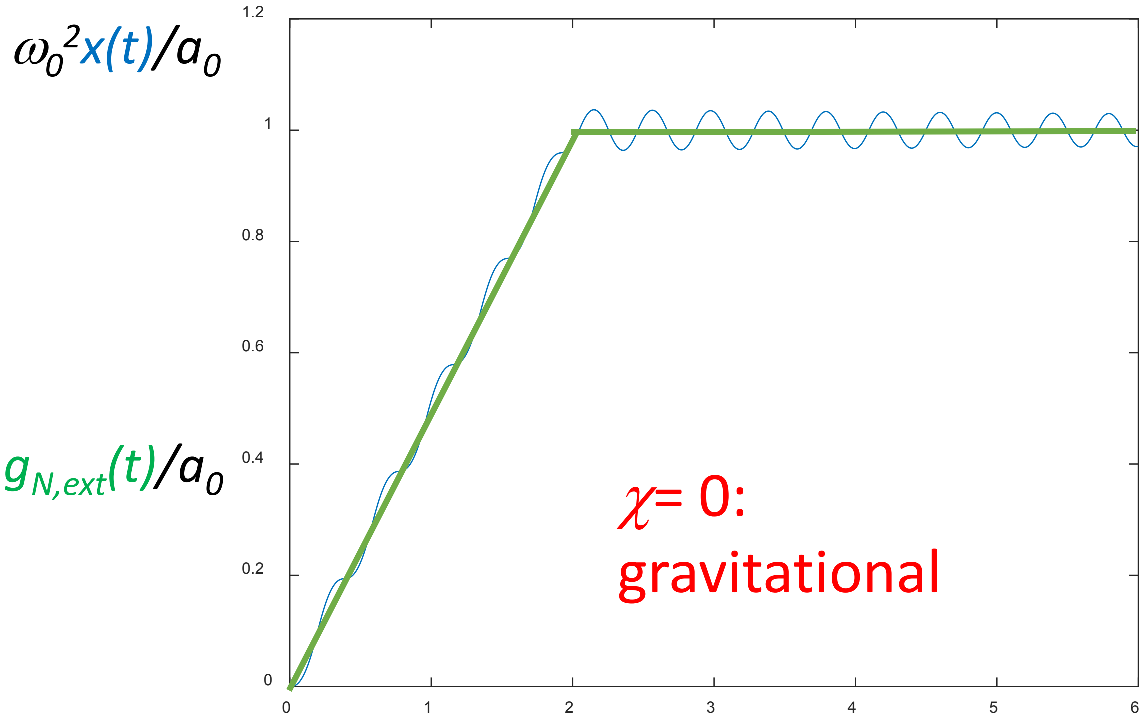
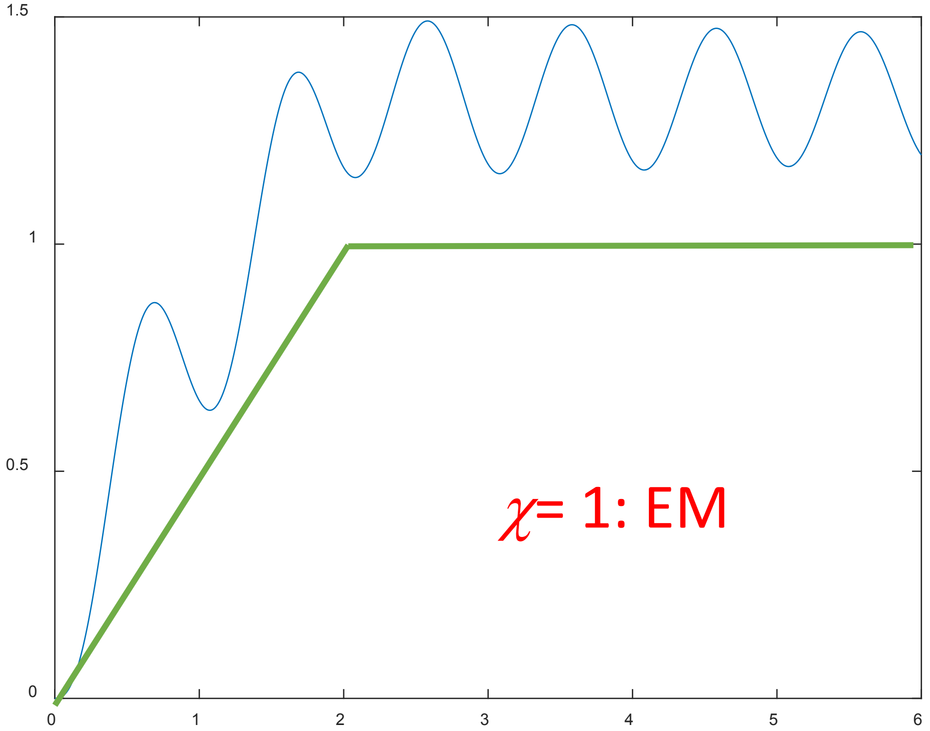
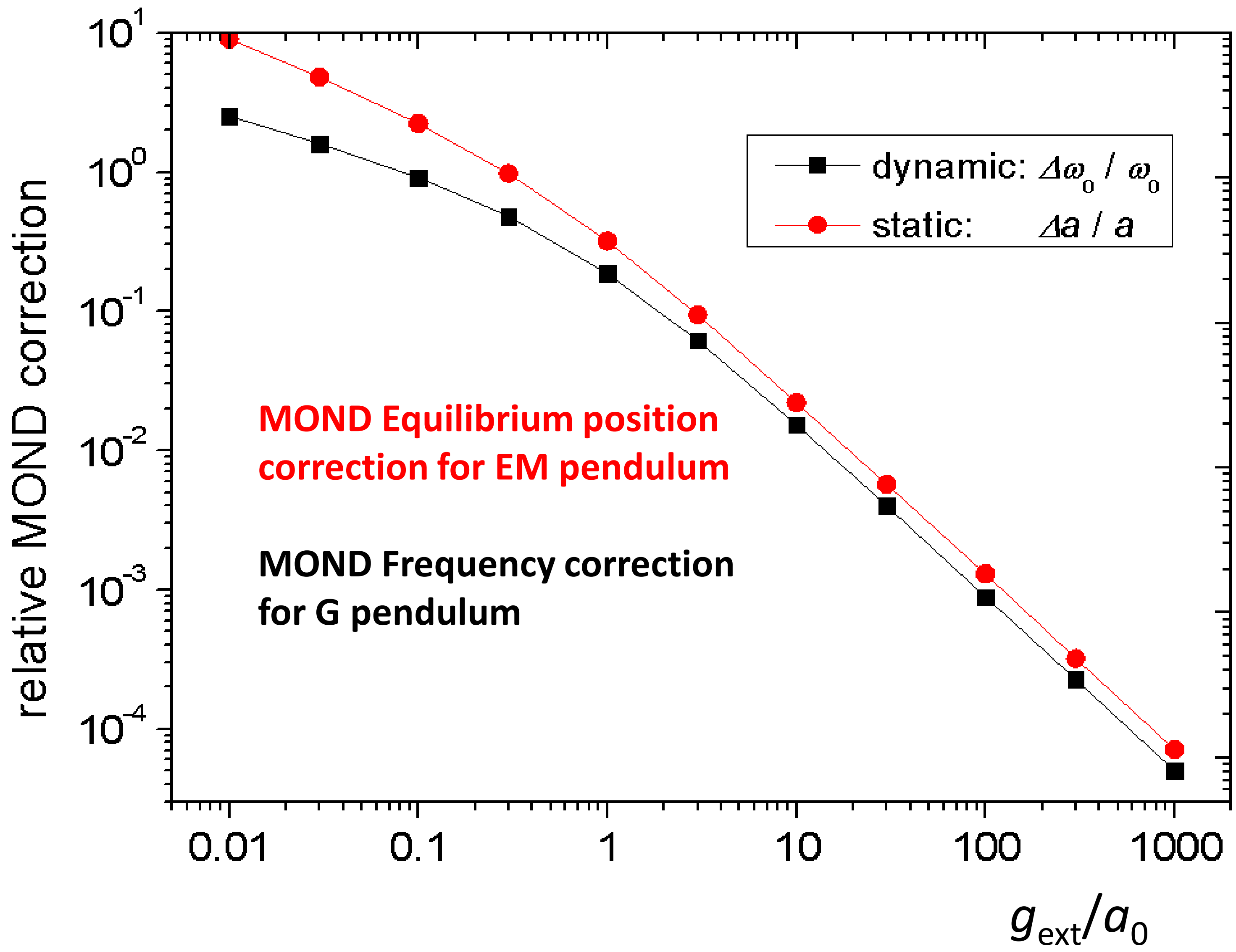




MOND increases pendulum frequency

MOND increases pendulum deflection

Dynamic MOND response of gravitational and spring pendulum for different excitation fields



$$f_{\text{Klein}}\left(|a_N|/a_0\right) = \left[1 + \left(\frac{a_0}{|a_N|}\right)^{\beta}\right]^{\frac{1}{2\beta}}$$

$\beta = 1.3$

Qualitative response independent of interpolation function

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MOND corrections for the BIPM experiment

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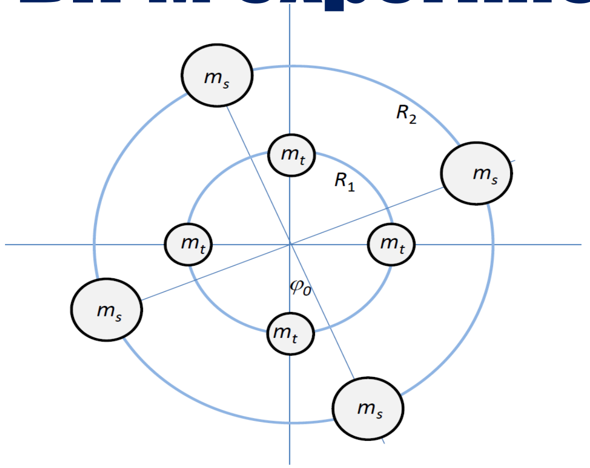

T. Quinn et al., Trans . R. Soc. A **372**, 20140032 (2014)

Static deflection (SD) : measured deflection angle θ *not* affected by MOND. , but the calculation of the corresponding torque requires precise knowledge of the "spring" constant κ_g, which is determined by the resonant frequency of the pendulum ω_p.

$$torque = \kappa_g \cdot \theta \propto \omega_p^{\,2} \cdot \theta \Rightarrow$$

$$\frac{\Delta G_{SD}}{G} = \frac{torque_{SD,MOND}}{torque_{SD,Newton}} = 2\left(\frac{\omega_{p,MOND} - \omega_{p,Newton}}{\omega_{p,Newton}}\right)$$

$>$

Electrostatic servo (ES) : torque by gravitational field of source masses balanced by an electric field from a capacitor (zero deflection) $\Rightarrow$ no restoring pendulum force $\Rightarrow$

Only the external torque by the gravitational acceleration of source masses is MOND corrected:

$$\frac{\Delta G_{ES}}{G} = \frac{torque_{ES,MOND}}{torque_{ES,Newton}} = \frac{g_{ext,MOND} - g_{ext,Newton}}{g_{ext,Newton}}$$

Cavendish "big G" state-of-art Dec. 2018

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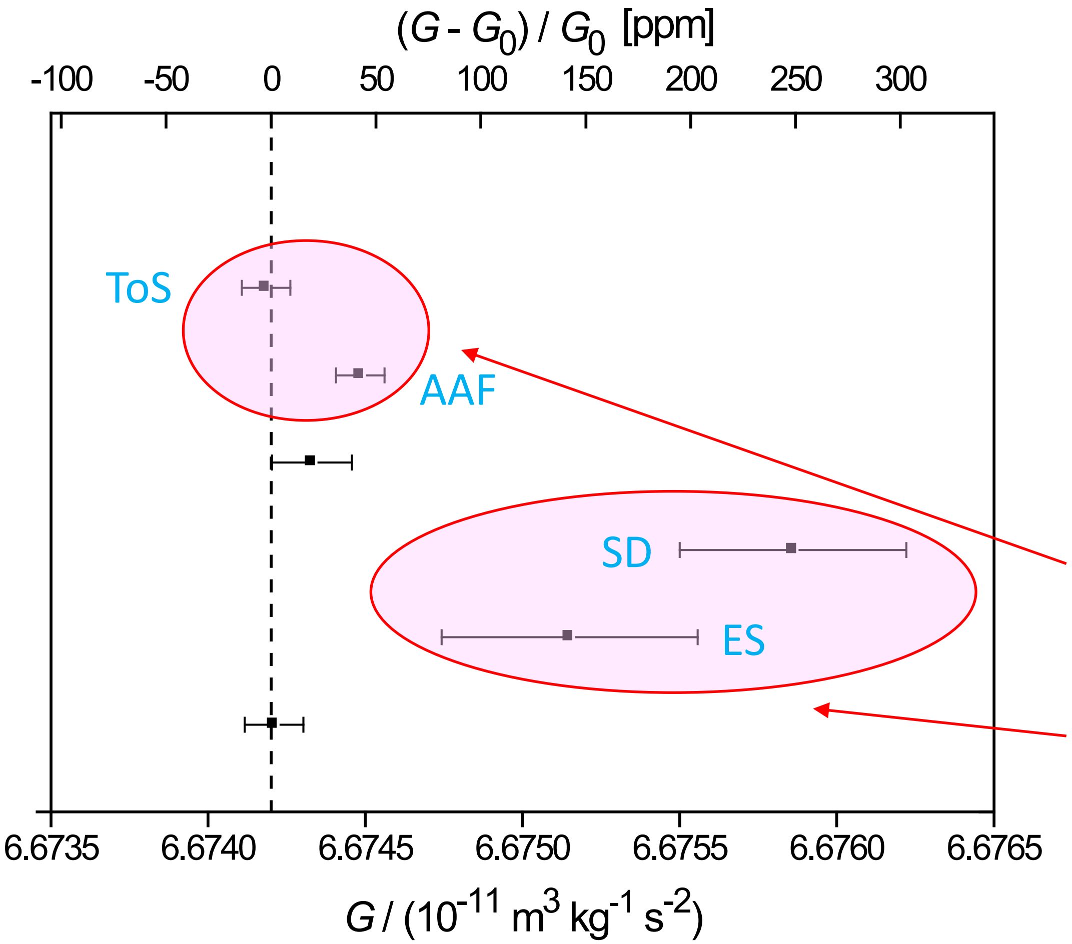

Measurements of the gravitational constant using two independent methods

Qing Li[1,8], Chao Xue[2,3,8], Jian-Ping Liu[1,8], Jun-Fei Wu[1,8], Shan-Qing Yang[1]*, Cheng-Gang Shao[1]*, Li-Di Quan[4], Wen-Hai Tan[1], Liang-Cheng Tu[1,2], Qi Liu[2,3], Hao Xu[1], Lin-Xia Liu[5], Qing-Lan Wang[6], Zhong-Kun Hu[1], Ze-Bing Zhou[1], Peng-Shun Luo[1], Shu-Chao Wu[1], Vadim Milyukov[7] & Jun Luo[1,2,3]*

The Newtonian gravitational constant, *G*, is one of the most fundamental constants of nature, but we still do not have an accurate value for it. Despite two centuries of experimental effort, the value of *G* remains the least precisely known of the fundamental constants. A discrepancy of up to 0.05 per cent in recent determinations of *G* suggests that there may be undiscovered systematic errors in the various existing methods. One way to resolve this issue is to measure *G* using a number of methods that are unlikely to involve the same systematic effects. Here we report two independent determinations of *G* using torsion pendulum experiments with the time-of-swing method and the angular-acceleration-feedback method. We obtain *G* values of 6.674184×10^{-11} and 6.674484×10^{-11} cubic metres per kilogram per second squared, with relative standard uncertainties of 11.64 and 11.61 parts per million, respectively. These values have the smallest uncertainties reported until now, and both agree with the latest recommended value within two standard deviations.

Q. Li et al., Nature **560**, 582 (2018)

T. Quinn et al., Trans . R. Soc. A **372**, 20140032 (2014)

MOND corrections for the HUST experiment

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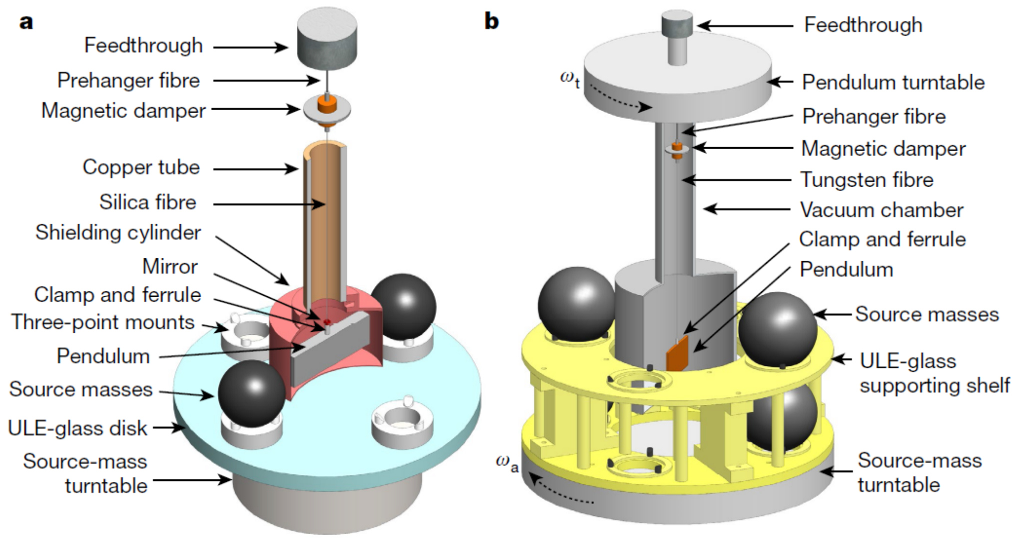

Q. Li et al.,
Nature **560**, 582 (2018)

Time-of- Swing (ToS) : the pendulum oscillates a small amplitudes. In the "near" position of source masses a small component (1-2%) of the gravitational restoring torque adds to the spring torque of the fibre.

far position: $\kappa_{far} = \kappa_{em}$

near position: $\kappa_{near} = \kappa_{em} + \kappa_g \Rightarrow$

$$G \propto \kappa_g = \kappa_{near} - \kappa_{far} \propto \omega_{p,near}^2 - \omega_{p,far}^2$$

No MOND correction of pendulum frequency because the pendulum is still 98% electromagnetic

Angular acceleration feedback (AAF) : source-mass induced pendulum oscillation compensated by pendulum turntable motion $\Rightarrow$ MOND correction like for ES

But: rotation of turntable $\omega_c \approx$ mrad/s adds **centripetal acceleration** of ca. 10^{-7} m/s^2, which **defines the magnitude of MOND correction**

MOND frequency correction of a "mixed" pendulum at $g_{ext}=a_0$

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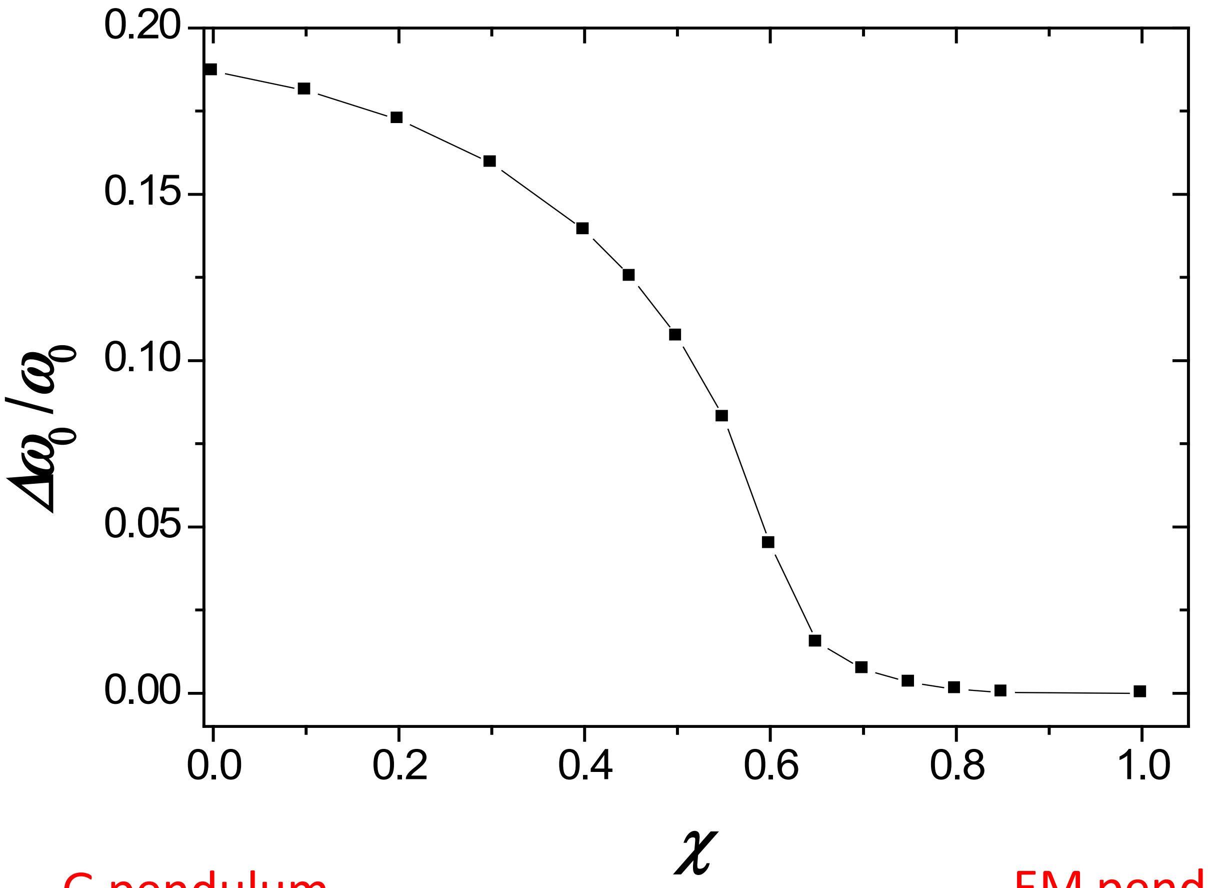
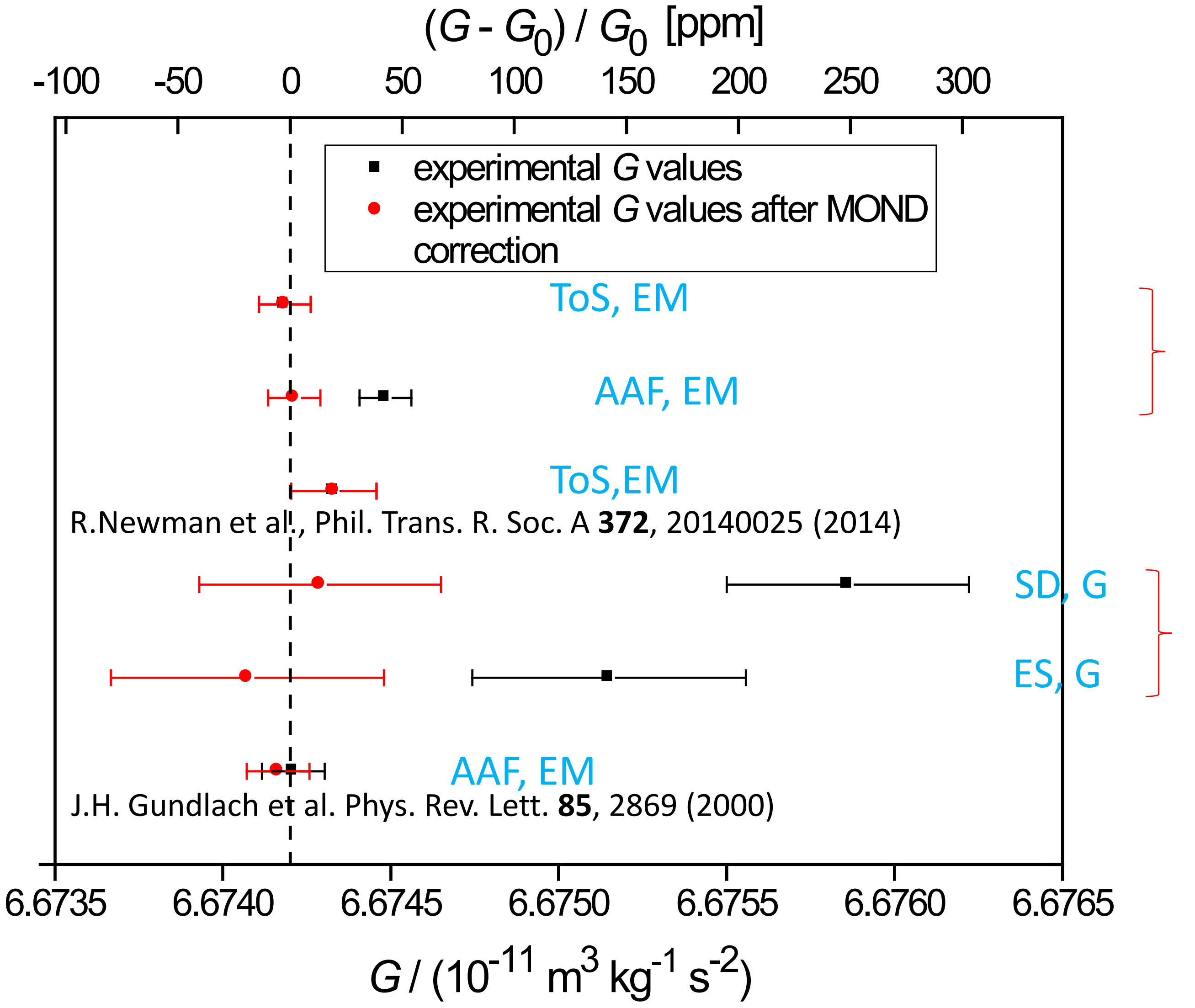


G pendulum

EM pendulum

MOND frequency corrections occur only in case of a large fraction of gravitational restoring force (about > 80 % g-pendulum)

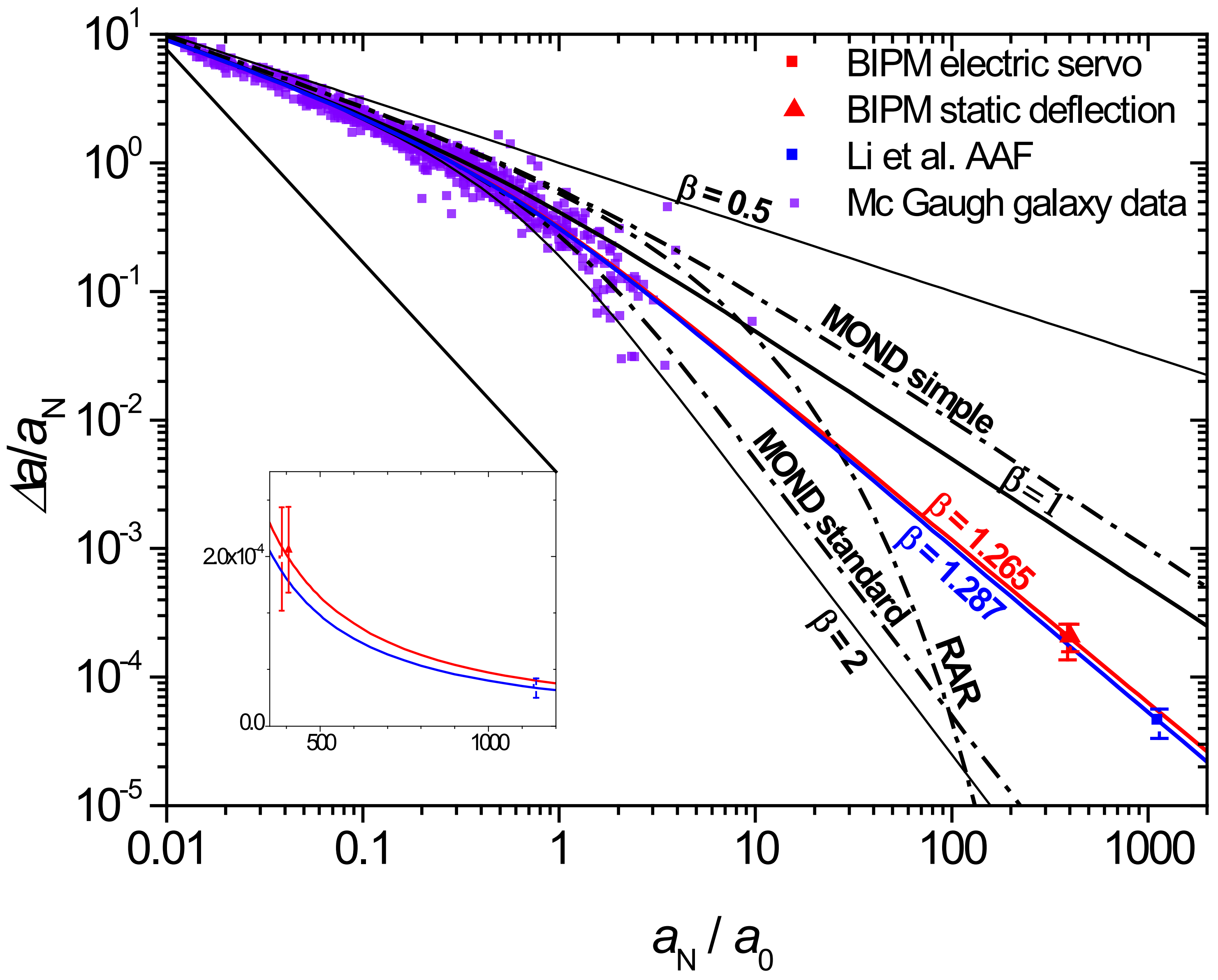
MOND solves the "big G" conundrum



$$f_{\text{Klein}}\left(\left|a_N\right|/a_0\right)=\left[1+\left(\frac{a_0}{\left|a_N\right|}\right)^{\beta}\right]^{\frac{1}{2\beta}}$$

MOND corrected G data are consistent with $G = 6.6742\cdot 10^{-11}\ \text{m}^3\text{kg}^{-1}\text{s}^{-2}$ with just 14 ppm standard deviation with one fit parameter $\beta = 1.30$

Comparison of Cavendish MOND corrections with galaxy rotation curves



- The selected interpolation function with $\beta \approx 1.3$ fits G and galaxy data

- More data points are needed to fill the large gap between the galactic and Cavendish acceleration range.

OUTLINE

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- Introduction to the MOND phenomenology
- The MOND pendulum at small accelerations
- MOND analysis of Cavendish-type G experiments
- What can we learn about the Physics behind MOND ?
- Conclusion

What can we learn about the physics behind MOND from this new experimental evidence ?

- A general MOND inertia modification can be ruled out

- AQUAL non – relativistic MOND modified Poisson field equation can be ruled out

- MOND effects are controlled by the strength of the local gravitational field component in the direction of motion and by enforced accelerated motion

$\Rightarrow$ General Relativity is basis for any reasonable explanation of the Physics behind MOND

$\Rightarrow$ MOND effects are controlled by small deviations from flat space time in the 2D plane of pendulum motion

The physics behind: Einstein's lift at a_0

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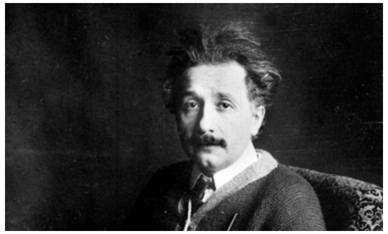

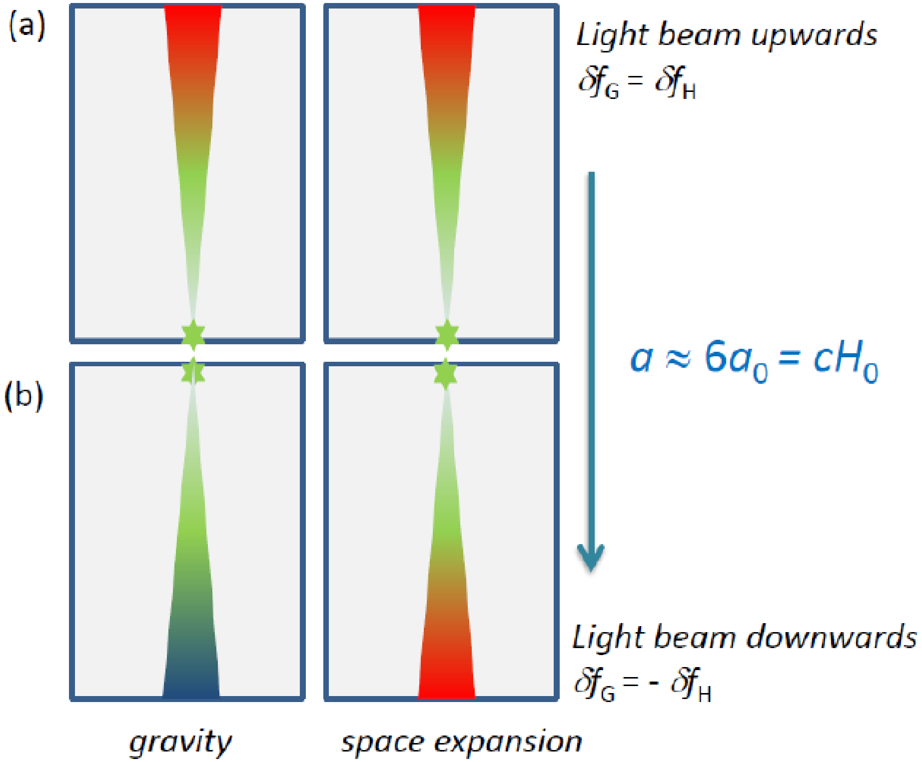

a) Light source on the floor (-)

b) Light source at the ceiling (+)

Combined gravitational / cosmological red/blueshift

$$\frac{\delta f}{f_0} = \frac{\delta f_H}{f_0} \pm \frac{\delta f_G}{f_0} = -\frac{H_0 h}{c} \mp \frac{a_N h}{c^2} \approx -\frac{h}{c^2} a_N \left(\frac{6a_0}{a_N} \pm 1 \right)$$

$\Rightarrow$ Cosmological and gravitational redshift are of the same order of magnitude at $a \approx a_0$

from N.Klein, arXiv:1504.07622 **[gr-qc]**

Mc Vittie's metric: a point mass inside an expanding flat universe

$$ds^2 = \left[\frac{1-\frac{Gm}{2rc^2a(t)}}{1+\frac{Gm}{2rc^2a(t)}}\right]^2 c^2dt^2 - \left[1+\frac{Gm}{2rc^2a(t)}\right]^4 a^2(t)(dr^2+r^2d\Omega^2) \approx$$

$$\left(1-\frac{Gm}{rc^2}\right)c^2dt^2 - \left(1+2H_0t+\frac{2Gm}{rc^2}\right)(dr^2+r^2d\Omega^2)$$

extrapolates between Schwarzschild metric on a small scale and FLRW metric on a large scale

For a recent review see Carrera und Giulini, Rev. Mod. Phys. 82 (2010) 169

assuming $a(t) = \exp(H_0 t) \approx 1 + H_0 t$

- As an example, a mass of 1 kg has a gravitational field of a_0 at a distance of 0.87 m. The corresponding metric element is as small as 1 ± 10^{-27} . This is smaller than the background of gravitational waves and quantum effects may play a role ?!

- Quantum fluctuations of the space-time metric may have an influence on solutions of the geodesic equation, which describes the motion of an object in a space time metric.

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Conclusion

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- Cavendish G experiments were analysed in the framework of MOND taking into account pendulum and source mass dynamics.

- The results revealed great consistency between *G* results measured by different operation modes of recent Cavendish experiments.

- The MOND corrected *G* values from Cavendish experiments published over the last ten years were found to be consistent with $G = 6.6742 \cdot 10^{-11}\ m^3kg^{-1}s^{-2}$ within a standard deviation of 14 ppm.

- The amount of MOND corrections were found to be consistent with the universal acceleration relation of galaxy rotation curves employing one distinct MOND interpolation function.

- Future pendulum experiments should be designed to enable high precision measurements at the galactic acceleration scale a_0.

- MOND effect may be controlled by the magnitude of tiny deviations from flat space time, which are small enough at a_0 to be affected by subtle quantum effects.

THANK YOU FOR LISTENING

paper on arXiv

arXiv:1901.02604 [gr-qc]