Limits on a gravitational field dependence of the proton–electron mass ratio from H_2 in white dwarf stars*

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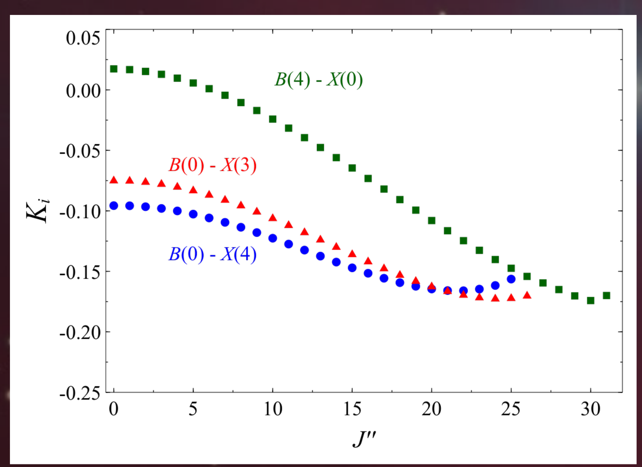
Motivation

- Test of Einstein equivalence principle (EEP)
  "any local non-gravitational measurement of a freely-falling laboratory is independent of the velocity of the laboratory and its location in spacetime"
- EEP implies that fundamental constants do not couple to gravity and do not vary over spacetime
- Modern theories (e.g. String, Loop Quantum Gravity) predict violation of EEP
- Guideposts on Higgs field coupling to gravity?

Sensitivity coefficients to $\frac{\Delta\mu}{\mu}$

$$K_i = \frac{d\ln\lambda_i}{d\ln\mu} = \frac{\mu}{E_B - E_X}\left(\frac{dE_B}{d\mu} - \frac{dE_X}{d\mu}\right)$$

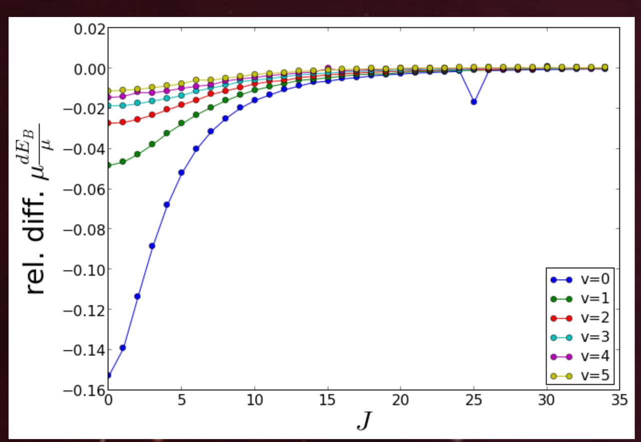


K_i for strong bands in WD spectra, $B(0)-X(3)$ and $B(0)-X(4)$. These are more sensitive than some bands (e.g. $B(4)-X(0)$) observed in quasar absorption systems.

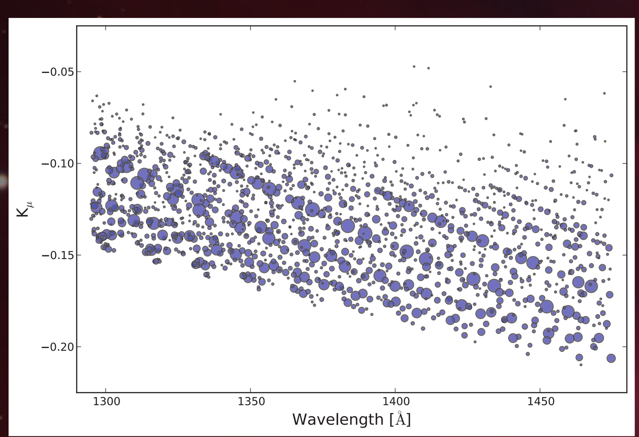
Comparison ab-initio vs. semi-empirical

K_i were calculated using two methods

- *Ab initio*: varied μ in Schroedinger equation to obtain $\frac{dE}{d\mu}$
- Semi-empirical: $\frac{dE}{d\mu}$ extracted from empirical fitting of $\frac{dE}{dv}$, $\frac{dE}{dJ}$



K_i database: H_2 $B-X$



The extensive K_i range and the number of transitions result in a robust analysis of WD spectra. (datapoint size: line intensity)

Phenomenological μ-coupling to gravity

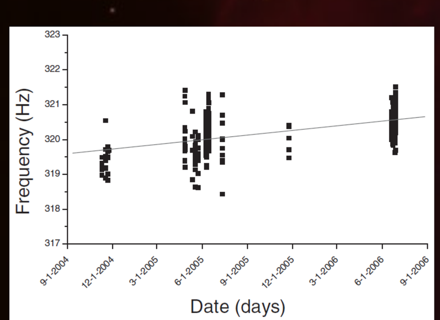
- WD gravitational potential $\phi_{\rm WD} = \frac{GM_{\rm WD}}{R_{\rm WD}c^2} \sim 2\times10^{-4} = 2\times10^4\phi_{\rm earth}$
- μ-coupling to differential potential $\Delta\phi = \phi_{\rm WD} - \phi_{earth}$ may be written as:

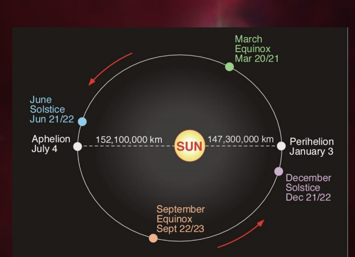
$$\frac{\Delta\mu}{\mu} = k_\mu^{(1)}\Delta\phi + k_\mu^{(2)}(\Delta\phi)^2$$

- leading to lowest-order constraints:

$$|k_\mu^{(1)}| < 0.2 \qquad |k_\mu^{(2)}| < 1\times10^3$$

Comparison to pure lab constraints

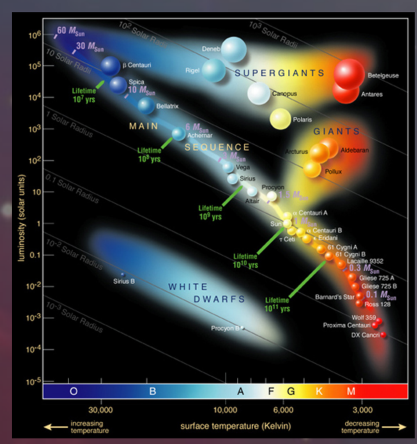


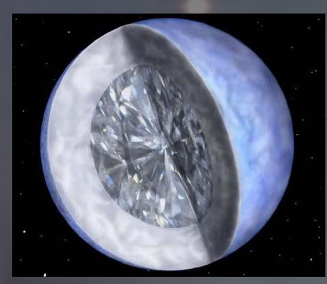


- Earth's elliptical orbit results in $\Delta\phi_{\rm earth} = 3\times10^{-10}$
- $\Delta\mu/\mu < 10^{-13}$ from [5] result in coupling constraints:

$$|k_\mu^{(1)}| < 4\times10^{-4} \qquad |k_\mu^{(2)}| < 1\times10^6$$

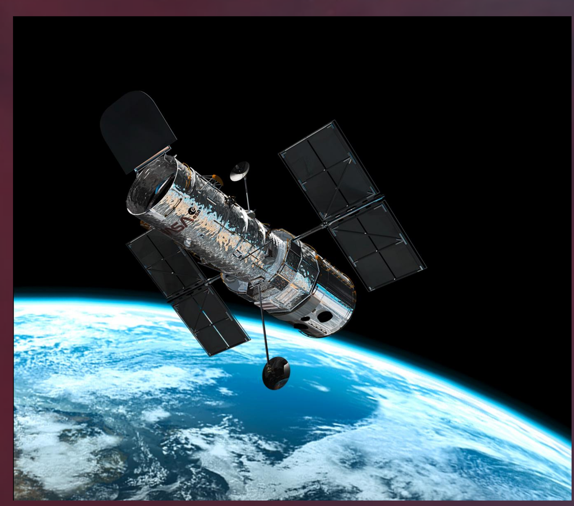
White dwarf stars





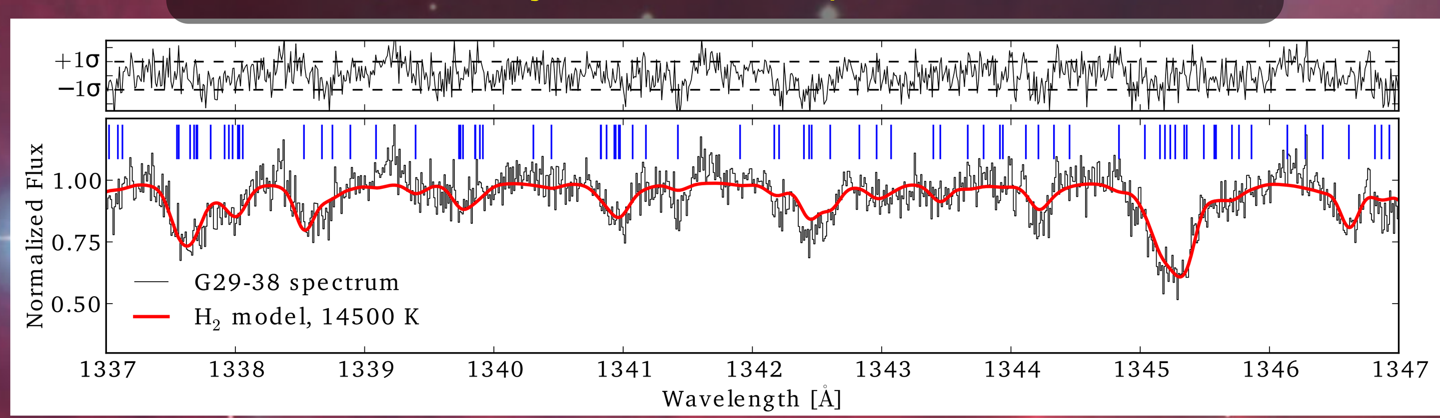
- Electron-degenerate after gravitational collapse
- Mostly made up of carbon and oxygen (may have diamond cores)
- About the size of the earth with about the mass of our sun
- Surface gravity about 10,000 times on earth's surface

Astronomical spectra



- From Cosmic Origins Spectrograph of the Hubble Space Telescope
- Discovery of H_2 in photosphere by Xu *et al.* (2013) [1]
- H_2 lines at $T \sim 13,000$ K in three stars

Analysis of WD spectra



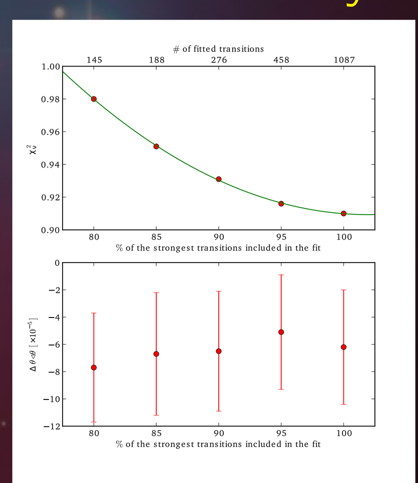
A global value for $\frac{\Delta\mu}{\mu}$ is obtained after fitting H_2 features, in the 1298 – 1444 Å range, using the relation:

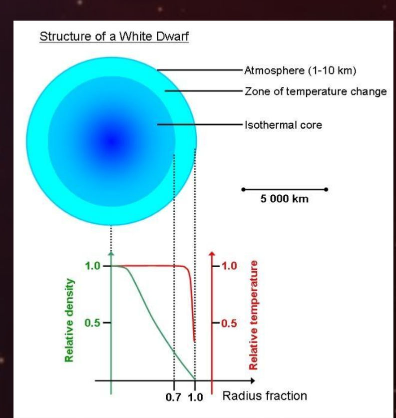
$$\frac{\lambda_i^{\rm WD}}{\lambda_i^0} = (1+z_{\rm WD})\left(1+\frac{\Delta\mu}{\mu}K_i\right)$$

Fitting results

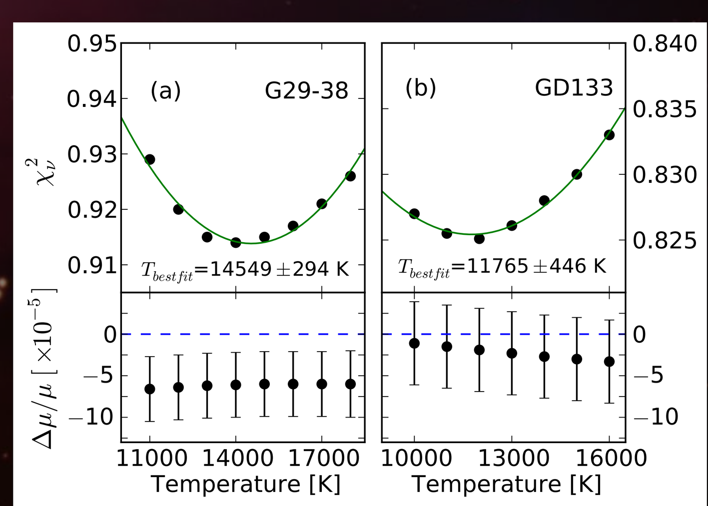
Parameter	GD133	GD29-38
$\log N_{\rm column}$ [cm^{-2}]	15.849 ± 0.007	15.491 ± 0.005
T [K]	11800 ± 450	14500 ± 300
b [km/s]	14.55 ± 0.58	18.65 ± 0.42
z	0.0001820(10)	0.0001360(8)
$\Delta\mu/\mu$	$(-2.7 \pm 4.7)\times10^{-5}$	$(-5.8 \pm 3.8)\times10^{-5}$
$\phi_{\rm WD}$	1.2×10^{-4}	1.9×10^{-4}

Check on systematics





- collision shift estimated to be small
- gravitational redshift also negligible
- effect of temporal intensity pulsations tested
- Stark and Zeeman shifts expected to be low

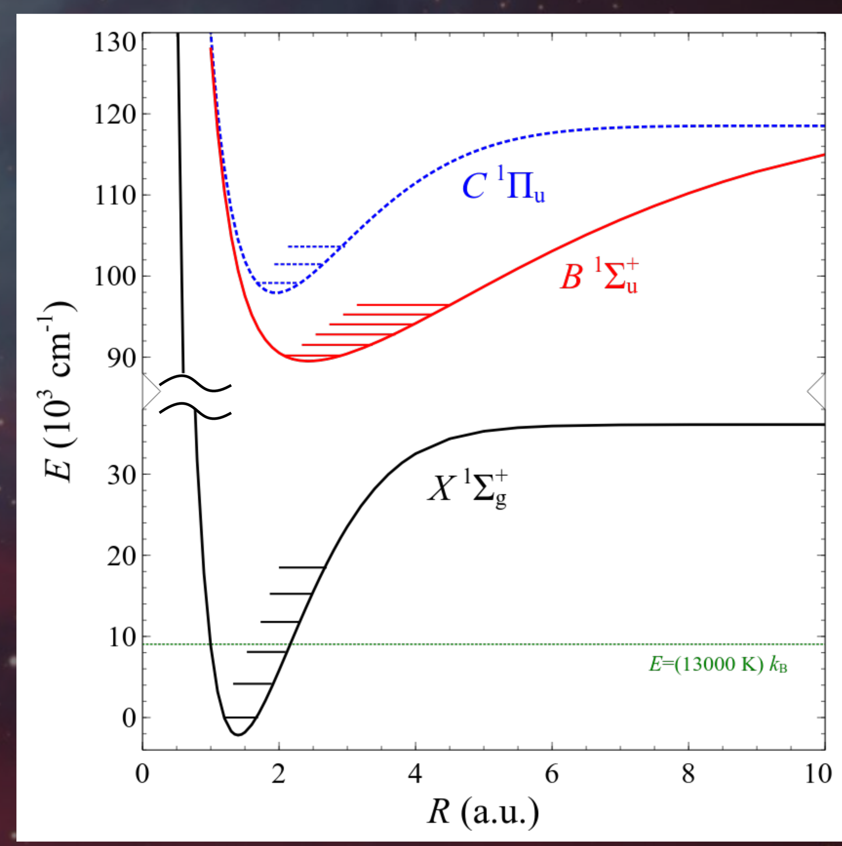


This approach

requires three important ingredients:

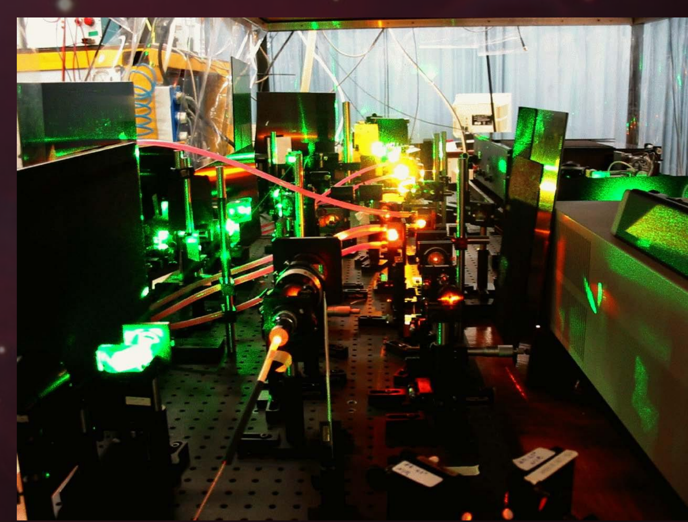
- Accurate white dwarf spectra
- Accurate laboratory spectra
- Transition sensitivity coefficients to $\Delta\mu/\mu$

H_2 potential



- Mostly Lyman ($B^1\Sigma_u^+ - X^1\Sigma_g^+$) transitions observed in WD
- Weaker Werner ($C^1\Pi_u - X^1\Sigma_g^+$) transitions tentatively identified
- Transitions from vibrationally and rotationally excited levels in the ground electronic state X

Lab spectra: λ_i^0 database

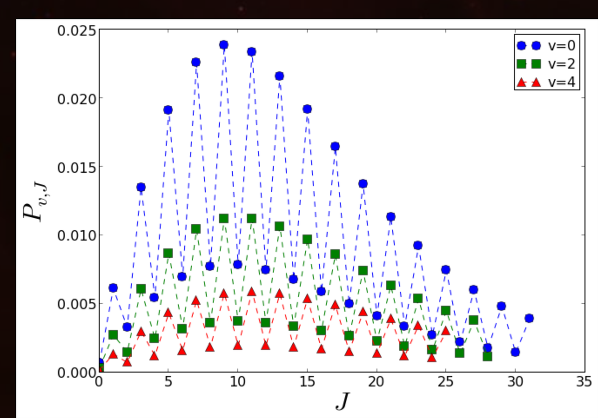


- Low J lines: 10^{-8} uncertainty for laser measurements [2, 3]
- High J lines: 10^{-6} uncertainty level [2, 3, 4]

Thermal population

- $T \sim 13,000$ K: substantial population at $v=4$; peak at $J \sim 9$
- Ortho-para intensity ratio (g_n) also holds

$$P_{v,J}(T) = \frac{g_n(2J+1)e^{\frac{-E_{v,J}}{kT}}}{\sum_{v=0}^{v_{\rm max}}\sum_{J=0}^{J_{\rm max}(v)} g_n(2J+1)e^{\frac{-E_{v,J}}{kT}}}$$



Line intensities

Intensity I_i depends on the population $P_{v'',J''}(T)$ for a temperature T, transition oscillator strengths f^{B-X}, and number of H_2 molecules $N_{\rm column}$

$$I_i = N_{\rm column} f^{BX}_{v',v'',J',J''} P_{v'',J''}(T)$$

Conclusions

- Identification of more than a hundred Lyman transitions in analysis of WD spectra
- Calculation of sensitivity coefficients
- Comparison of white dwarf and lab spectra yield $|\Delta\mu/\mu| < 5\times10^{-5}$
- Limit on $\Delta\mu/\mu$ from white dwarf spectra more constraining for higher-order coupling to gravity

References

*This poster is based on J. Bagdonaite *et al.*, Phys. Rev. Lett., **113**, 123002 (2014); [1] S. Xu *et al.*, Astrophys. J. Lett. **766**, L18 (2013); [2] J. Komasa *et al.*, J. Chem. Theory Comput. 7, 3105 (2011); [3] D. Bailly *et al.*, Mol. Phys. **108**, 827 (2010); [4] H. Abgrall *et al.*, J. Mol. Spectr. **157**, 512 (1993).[5] A. Shelkovnikov *et al.*, Phys. Rev. Lett., **100**, 150801 (2008)