

PAPER • OPEN ACCESS

## Recent bounds on graviton mass using galaxy clusters

To cite this article: Shantanu Desai and Sajal Gupta 2020 *J. Phys.: Conf. Ser.* **1468** 012003

View the [article online](#) for updates and enhancements.

### You may also like

- [Cosmological behavior in extended nonlinear massive gravity](#)  
Genly Leon, Joel Saavedra and Emmanuel N Saridakis
- [Probing screening and the graviton mass with gravitational waves](#)  
Scott Perkins and Nicolás Yunes
- [Constraining the range of Yukawa gravity interaction from S2 star orbits II: bounds on graviton mass](#)  
A.F. Zakharov, P. Jovanovi, D. Borca et al.



The Electrochemical Society  
Advancing solid state & electrochemical science & technology

243rd ECS Meeting with SOFC-XVIII

**More than 50 symposia are available!**

Present your research and accelerate science

Boston, MA • May 28 – June 2, 2023

[Learn more and submit!](#)

# Recent bounds on graviton mass using galaxy clusters

**Shantanu Desai**

Dept. of Physics IIT Hyderabad, Kandi Telangana-502285, India

E-mail: [shantanud@iith.ac.in](mailto:shantanud@iith.ac.in)

**Sajal Gupta**

Department of Physical Sciences, IISER-Kolkata, Mohanpur, West Bengal-741246, India

E-mail: [sg15ms084@iiserkol.ac.in](mailto:sg15ms084@iiserkol.ac.in)

**Abstract.** Although galaxy clusters have proved to be wonderful laboratories for testing a plethora of modified gravity theories and other exotic alternatives to  $\Lambda$ CDM, until a few years ago, there was only one paper (from 1974), which obtained a limit on graviton mass (of  $\mathcal{O}(10^{-29})$  eV) with clusters. To rectify this, in the last few years multiple works have obtained different bounds on graviton mass using single cluster data as well as stacking galaxy catalogs. We review these recent limits on graviton mass using galaxy clusters obtained using disparate methods.

## 1. Introduction

Even though General relativity agrees with all observational tests (1; 2; 3), a large number of alternate gravity theories have been proposed after the equations of General Relativity were written down, more than a century ago. The main motivation is to resolve cosmological problems of dark energy, dark matter, baryogenesis, inflation as well as data-driven problems such as Hubble constant tension or  $\sigma_8$  tension (4). Aside from cosmological considerations, another motivation for pursuing modified gravity theories is to address certain conceptual problems such as arrow of time, big-Bang singularity, quantization of gravity etc. (5).

Modified theories of gravity, where graviton is endowed with a non-zero mass have been in vogue, ever since they were first proposed by Pauli and Fierz in 1939 (6). Such theories can resolve problems with dark energy, dark matter, inflation, quantization of gravity etc. In the 1970's, problems with these theories were raised such as vDVZ discontinuity and Boulware-Deser ghosts (6). In the last decade, there has been a breakthrough in these problems, leading to a resurgence of interest in massive gravity theories (7; 8).

A recent review on graviton mass bounds using different observational probes can be found in Refs. (9; 10). There are three different ways to constrain the graviton mass (9). The first method involves looking for a weakening of the gravitational force due to a Yukawa potential. The second constraint comes from looking for fifth force interactions, which arise in massive gravity models. The third type of limit comes from the propagation of gravitational waves, either due to modified dispersion relations or from difference in arrival times between gravitational waves and photons.

The first bound on graviton mass (from the first method) using galaxy clusters was obtained by Goldhaber and Nieto in 1974 (11). Galaxy clusters are the most massive gravitationally collapsed objects in the universe (12), and have proved to be invaluable for testing modified



theories of gravity and other cosmological parameters at the interface of fundamental Physics, such as non-gaussianity and neutrino mass. On the observational front, a large number of new galaxy clusters up to very high redshifts have been discovered in the past two decades courtesy dedicated surveys in Optical, X-ray and microwave (through S-Z effect) from Stage-II and Stage-III dark energy experiments. This will continue into the next decade because of multiple stage IV dark energy experiments such as LSST, Euclid, WFIRST etc. are about to start taking data.

Despite the huge progress on the observational front for galaxy clusters, there was no updated limit on graviton mass from galaxy clusters for the last four decades after Ref. (11). This situation was soon rectified starting in 2018, when new limits on graviton mass with galaxy clusters using latest observational data were presented to supersede the old limit from 1974 (5; 13; 14; 15).

In this paper we provide a succinct review of these updated limits on graviton mass using clusters, along with the first ever limit. We do not discuss limits on graviton mass from Weak Lensing, solar system, gravitational waves or using the black hole in the center of our galaxy. These can be found in recent reviews (9; 10).

## 2. Goldhaber and Nieto limit

Goldhaber and Nieto (11) used the fact that galaxy clusters are bound and the largest clusters known then (from the Holmberg catalog) had sizes of around 580 kpc. According to Bertrand's theorem, only Newtonian gravity gives rise to closed bound orbits. Using the fact that any violations from Newtonian gravity must be valid only at distances greater than the maximum separation between clusters (building on similar ideas earlier on by Hare (16)), a bound on graviton mass was obtained by positing  $e^{-1} \leq \exp(-\mu_g r)$ , where  $\mu_g$  is the inverse of the reduced Compton wavelength. From this, the estimated limit is  $m_g < 1.1 \times 10^{-29}$  eV, or in terms of graviton Compton wavelength is given by  $\lambda_g > 10^{20}$  km. For more than four decades, this was the only bound on graviton mass from clusters and has been widely cited in literature (although not even once in cosmology/galaxy clusters literature). Occasionally, concerns have been raised about this limit because of uncertainties related to dark matter distribution (17). However, this criticism is invalid, since this limit does not make any assumption about the dark matter or any other mass distribution with clusters.

## 3. Recent cluster-based bounds

We now review recent works on obtained a limit on graviton mass using clusters starting from 2018.

### 3.1. Limit from Abell 1689

The Abell 1689 cluster is one of the largest and most massive galaxy cluster located at a redshift of 0.18. In the past decade, a whole slew of X-ray, lensing and SZ observations have provided very precise dynamical mass models for this cluster. This cluster has been a poster child to test a large number of alternate gravity theories and alternatives to  $\Lambda$ CDM (18). From the dynamical mass models for the gas, dark matter and density profile derived in Ref. (18), the acceleration was computed as a function of distance from the center of the cluster for both Newtonian and Yukawa gravity. A  $\chi^2$  residual was constructed between the two accelerations and including the reconstructed errors in acceleration. The 90% c.l. limit on graviton mass was obtained from  $\Delta\chi^2 < 2.71$ . This limit corresponds to  $m_g < 1.37 \times 10^{-29}$  eV or  $\lambda_g > 9.1 \times 10^{19}$  km. More details related to this bound can be found in Ref. (5).

### 3.2. Limits from stacked cluster catalogs

Rana et al (13) considered a catalog of 182 galaxy clusters detected by the ACT-SZ survey as well as a catalog of 50 clusters from the LoCuSS Weak lensing survey. For each cluster,

they calculated the  $\chi^2$  residuals from the difference in Yukawa and Newtonian acceleration for a given cluster mass, followed by summing over all clusters in the survey. The error in the acceleration was obtained from a quadrature sum of the errors in mass and the errors in the Hubble parameter. The upper limit on graviton mass was obtained from this  $\chi^2$  to obtain upper bounds at 68%, 90%, 95% and 99% confidence intervals. The most stringent upper limit obtained from this analysis was from the weak lensing catalog, corresponding to  $m_g < 7.85 \times 10^{30}$  eV or  $\lambda_g > 1.579 \times 10^{20}$  km (13). This same method was applied to the SPT-SZ, Planck-SZ, SDSS-redMaPPer catalog consisting of about 500, 900, and 26000 clusters respectively. The best limit from the SDSS-redMapper catalog, corresponding to a  $m_g < 1.27 \times 10^{-30}$  eV or  $\lambda_g > 9.76 \times 10^{20}$  km (14). Using this same method, the sensitivity of the Euclid cluster catalog would lead a graviton mass bound of about  $10^{-31}$  eV.

### 3.3. Limits from Chandra X-ray catalog

Mostly recently, a catalog of 12 relaxed clusters from the Chandra X-ray sample, for which detailed temperature and density profiles were obtained by Vikhlinin et al (19) was used to bound the graviton mass (15). From the equation of hydrostatic equilibrium in a Yukawa potential, the total Yukawa hydrostatic mass was then estimated. The  $\chi^2$  residual was constructed from the deviations between this Yukawa mass and Newtonian mass and including the errors in the Newtonian mass. Using this method, the best limit was obtained for Abell 2390 corresponding to  $m_g < 3.46 \times 10^{-29}$  eV or  $\lambda_g > 3.58 \times 10^{19}$  km (15). This same method should be applicable to the galaxy clusters from the recently launched eRosita X-ray telescope.

## 4. Conclusions

In this short proceedings, we recapitulate all limits which have been obtained on the graviton mass using galaxy clusters. All these limits assume that in the weak field limit a non-zero graviton mass gives rise to a Yukawa potential. The first ever limit was obtained using the fact that any deviations from Newtonian gravity kick in at length scales greater than 580 kpc (11). Then in 2018, a limit was obtained from the Abell 1689 galaxy cluster using the difference in Yukawa and Newtonian accelerations. This was followed by limits obtained using stacked galaxy cluster catalogs from optical and SZ surveys using similar technique. Finally, a catalog of 12 clusters observed with the Chandra X-ray telescope was used to obtain the most recent limits.

A tabular summary of all these results can be found in Table 1. The best limit comes from the stacked catalog of SDSS redMaPPer clusters, corresponding to a limit of  $m_g < 1.27 \times 10^{-30}$  eV or  $\lambda_g > 9.76 \times 10^{20}$  km (14).

**Table 1.** A summary of various bounds on graviton mass using galaxy clusters. Note that for the Chandra X-ray catalog we only quote the cluster with the most stringent upper limit. All limits are at 90% c.l. except the first one for which no confidence limit was provided.

Reference	Cluster/Catalog	Limit on graviton mass (eV)
Goldhaber and Nieto (11)	Holmberg	$1.1 \times 10^{-29}$
Desai (5)	Abell	$1.37 \times 10^{-29}$
Rana et al (13)	LocuSS (WL)	$7.849 \times 10^{-30}$
Rana et al (13)	ACT (SZ)	$1.05 \times 10^{-29}$
Gupta and Desai (14)	SDSS-RedMaPPer	$1.27 \times 10^{-30}$
Gupta and Desai (14)	SPT (SZ)	$4.73 \times 10^{-30}$
Gupta and Desai (14)	Planck (SZ)	$3 \times 10^{-30}$
Gupta and Desai (15)	Abell 2390	$3.46 \times 10^{-29}$

## References

- [1] Will C M 2014 *Living Reviews in Relativity* **17** 4 (*Preprint* 1403.7377)
- [2] Ishak M 2019 *Living Reviews in Relativity* **22** 1 (*Preprint* 1806.10122)
- [3] Ferreira P G 2019 *Ann. Rev. Astronomy and Astrophysics* **57** 335–374 (*Preprint* 1902.10503)
- [4] Verde L, Treu T and Riess A G 2019 *Nature Astronomy* **3** 891–895 (*Preprint* 1907.10625)
- [5] Desai S 2018 *Physics Letters B* **778** 325–331 (*Preprint* 1708.06502)
- [6] Goldhaber A S and Nieto M M 2010 *Reviews of Modern Physics* **82** 939–979 (*Preprint* 0809.1003)
- [7] de Rham C, Gabadadze G and Tolley A J 2011 *Physical Review Letters* **106** 231101 (*Preprint* 1011.1232)
- [8] de Rham C 2014 *Living Reviews in Relativity* **17** 7 (*Preprint* 1401.4173)
- [9] de Rham C, Deskins J T, Tolley A J and Zhou S Y 2017 *Reviews of Modern Physics* **89** 025004 (*Preprint* 1606.08462)
- [10] Tanabashi M *et al.* (Particle Data Group) 2018 *Phys. Rev.* **D98** 030001
- [11] Goldhaber A S and Nieto M M 1974 *Phys. Rev.* **D9** 1119–1121
- [12] Voit G M 2005 *Reviews of Modern Physics* **77** 207–258 (*Preprint* astro-ph/0410173)
- [13] Rana A, Jain D, Mahajan S and Mukherjee A 2018 *Physics Letters B* **781** 220–226 (*Preprint* 1801.03309)
- [14] Gupta S and Desai S 2018 *Annals of Physics* **399** 85–92 (*Preprint* 1810.00198)
- [15] Gupta S and Desai S 2019 *Classical and Quantum Gravity* **36** 105001 (*Preprint* 1811.09378)
- [16] Hare M G 1973 *Canadian Journal of Physics* **51** 431
- [17] Will C M 1998 *Phys. Rev.* **D57** 2061–2068 (*Preprint* gr-qc/9709011)
- [18] Nieuwenhuizen T M 2017 *Fortsch. Phys.* **65** 1600050 (*Preprint* 1610.01543)
- [19] Vikhlinin A, Kravtsov A, Forman W, Jones C, Markevitch M, Murray S S and Van Speybroeck L 2006 **640** 691–709 (*Preprint* astro-ph/0507092)