

X-ray Cluster Cosmology

A white paper submitted to the Decadal Survey Committee

Authors: A. Vikhlinin¹, S. Murray¹, R. Gilli², P. Tozzi³, M. Paolillo⁴, N. Brandt⁸, G. Tagliaferri⁹, M. Bautz¹², S. Allen¹³, M. Donahue¹⁴, A. Evrad¹⁵, K. Flanagan¹⁶, P. Rosati⁶, S. Borgani⁵, R. Giacconi¹⁰, M. Weisskopf⁷, A. Ptak¹⁰, D. Alexander¹¹, G. Pareschi⁹, W. Forman¹, C. Jones¹

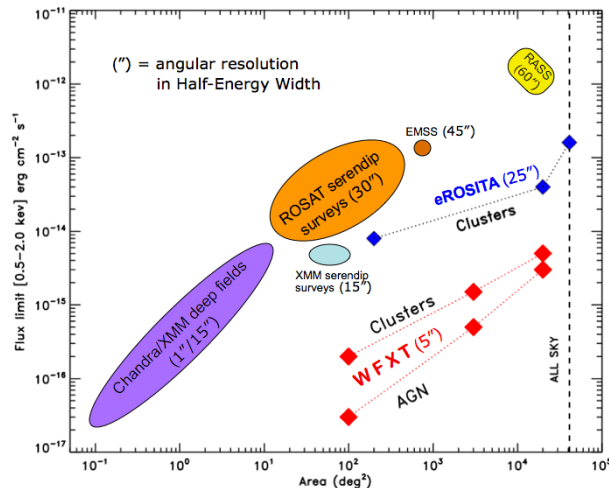
1. Harvard-Smithsonian Center for Astrophysics, Cambridge MA
2. INAF-Osservatorio Astronomico di Bologna, Bologna, Italy
3. INAF-Osservatorio Astronomico di Trieste, Trieste, Italy
4. Università di Napoli, Napoli, Italy
5. University of Trieste, Trieste, Italy
6. European Southern Observatory (ESO), Garching bei Muenchen, Germany
7. NASA Marshall Space Flight Center, Huntsville AL
8. Penn State University, University Park PA
9. INAF-Osservatorio Astronomico di Brera, Milano, Italy
10. The Johns Hopkins University, Baltimore MD
11. University of Durham, Durham, United Kingdom
12. Massachusetts Institute of Technology, Cambridge MA
13. Stanford University, Stanford CA
14. Michigan State University, E. Lansing MI
15. University of Michigan, Ann Arbor MI
16. Space Telescope Science Institute, Baltimore MD

Science Frontier Panels

Primary Panel: Cosmology and Fundamental Physics (GFP)

Secondary panel: Galaxies across Cosmic Time (GCT)

Project emphasized: The Wide-Field X-Ray Telescope (WFXT); <http://wfxt.pha.jhu.edu/>



1 Introduction

Cosmological studies with galaxy clusters, and in the X-ray band in particular, has played an important role in establishing the current cosmological paradigm. Starting with 1990’s, they have consistently indicated low values of Ω_M (both from the baryonic fraction arguments [1] and measurements of the evolution in the cluster number density [2, 3]) and low values of σ_8 [4–6] — a result since confirmed by cosmic microwave background (CMB) studies, cosmic shear, and other experiments [7–11]. Recently, X-ray study of the evolution of the cluster mass function at $z = 0 - 0.8$ have convincingly demonstrated that the growth of cosmic structure has slowed down at $z < 1$ due to the effects of dark energy, and these measurements have been used to improve the determination of the equation state parameter [12]. It is astonishing that these results are still based on samples of ~ 100 clusters derived from old ROSAT surveys (Fig.1). A new, sensitive, X-ray survey should be able to make a quantum leap in the cluster cosmology science.

The main emphasis of a next-generation X-ray survey is to push the discovery space beyond the currently achievable limits in many areas of X-ray astronomy (AGNs, galaxies, X-ray stars, clusters and groups of galaxies, discussed in other white papers [13–15]). We would like to make the same emphasis for cosmology. The survey will provide exceptionally detailed information about the population of galaxy clusters and groups over a very wide range of masses, redshifts, and spatial scales [14]. It would be possible to use these data for the currently discussed cosmological applications such as constraints on the Dark Energy equation of state. However, we would like to push beyond these problems and make large X-ray survey data maximally useful for potential discoveries such as looking for departures from the concordance Λ CDM cosmology.

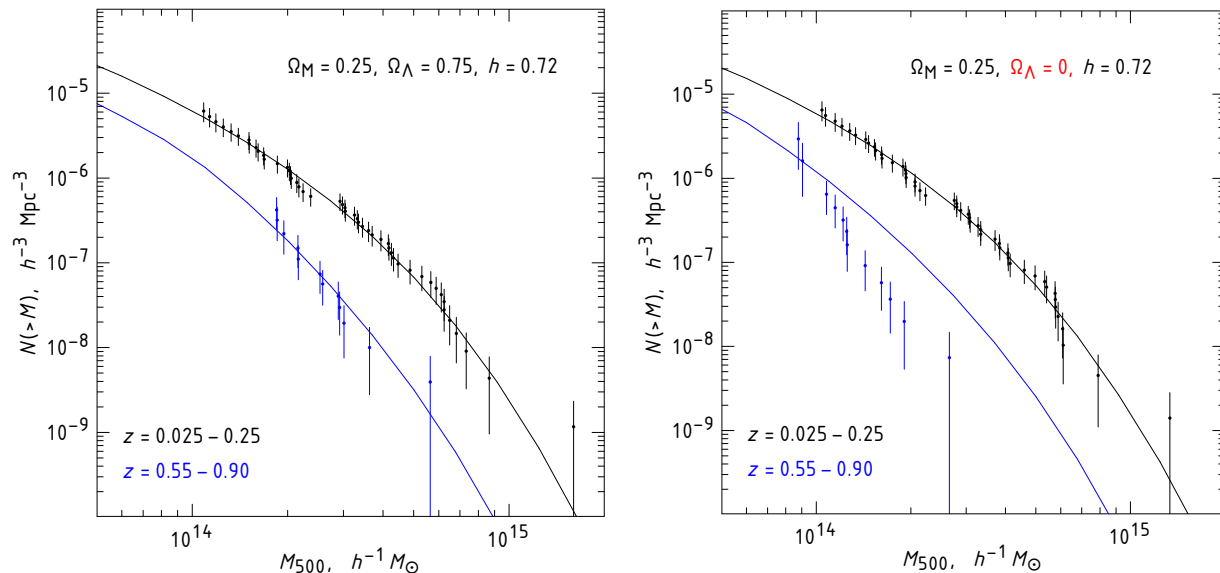


Fig. 1— Illustration of sensitivity of the cluster mass function to the cosmological model. In the left panel, we show the measured mass function and predicted models (with only the overall normalization at $z = 0$ adjusted) computed for a cosmology which is close Concordance Λ CDM. In the right panel, both the data and the models are computed for a cosmology with $\Omega_{\Lambda} = 0$. When the overall model normalization is adjusted to the low- z mass function, the predicted number density of $z > 0.55$ clusters is in strong disagreement with the data, and therefore this combination of Ω_M and Ω_{Λ} can be rejected. Reproduced from [12].

In the X-ray band, there is a huge gap in sensitivity between existing wide-field and deep surveys. The most sensitive wide survey, *ROSAT* All-Sky Survey, is 4.5 orders of magnitude shallower than *Chandra* Deep Fields. The equivalent sensitivity gap in the optical, between SDSS and Hubble Deep Fields, is only a factor of 250. A wide *and* sensitive X-ray survey is long overdue, especially so since all the required technology has long been in place. In this White Paper, we consider cosmological applications of a next-generation X-ray survey. A particular implementation we have in mind is the Wide Field X-ray Telescope (WFXT) mission [16], but the same considerations apply to any experiment meeting the large effective area and high angular resolution across a wide field of view requirements essential for making an “order of magnitude” step in X-ray survey science.

The plan of this White Paper is as follows. First, we outline the use of a large area, sensitive X-ray survey for traditional cosmological tests, and then discuss what aspects of the cluster data can be potentially useful for new discoveries in cosmology. We then briefly discuss the WFXT capabilities for surveys.

2 Traditional cluster cosmology with WFXT

A wide WFXT survey will provide a rich dataset for classical cosmological tests using clusters of galaxies. The number of detected clusters will be so large, that the linear perturbations factor can be derived with 1% uncertainties in each $\Delta z = 0.1$ bin out to $z \simeq 2$ using followup observations with a powerful X-ray telescope (such as IXO) and weak lensing measurements in the optical (the procedure is outlined in the White Paper by Vikhlinin, Allen et al.). The suggested approach starts with clusters selected in a clean survey out to $z = 2$; WFXT-type survey would be the best dataset for this purpose. A subset of the most massive clusters (~ 100 per $\Delta z = 0.1$ bin) will be selected for more detailed observations in the X-ray and optical. X-ray data from a powerful X-ray telescope will be used to measure high-quality total mass proxies such as Y_X [18]; the average weak lensing signal from selected clusters is used to precisely normalize the $Y_X - M_{\text{tot}}$ relation with minimal reliance on theory of cluster formation. A combination of low-scatter X-ray mass proxies and bias-free calibration of M_{tot} by weak lensing leads to $\sim 1\%$ measurements of the perturbation growth factor in each redshift bin (Fig.2). Such a measurement will be extremely useful for improving constraints on the dark energy equation of state from geometric methods, and for testing non-GR models of cosmic acceleration.

The role of WFXT can go well beyond simply providing the initial cluster sample for such an experiment. Uniquely among any other proposed survey missions, WFXT will detect enough photons from clusters with fluxes $f_x > 3 \times 10^{-14}$ erg s $^{-1}$ cm $^{-2}$ so that high-quality proxies for the total cluster mass will be measured. The redshift boundary of this brighter subsample will be around $z = 1$. For $z \lesssim 0.8$, the sensitivity of forthcoming optical surveys such as PanSTARRS will be sufficient to measure the average weak lensing shear and thus to precisely calibrate the proxy vs. mass relations. Therefore, the growth function as a function of z can be measured out to $z = 0.8$ without the need for any additional observations. The growth function which can be derived from the WFXT-only data is illustrated in Fig.2 (blue). In combination with the Planck CMB priors, these data will constrain the growth index, γ [19], to ± 0.042 . This level of accuracy is best appreciated by comparison with projections for the cosmic shear measurements from a dedicated Dark Energy mission (SNAP), $\Delta\gamma = \pm 0.044$ [19].

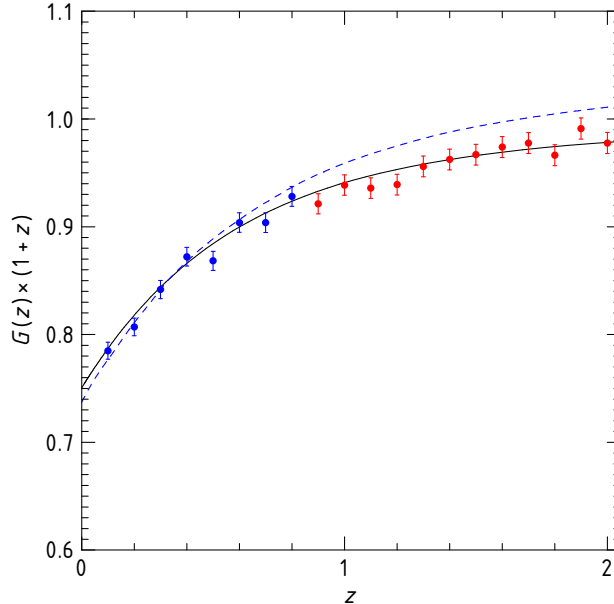


Fig. 2— The normalized growth factor of density perturbations, $G(z)$, constructed from X-ray and weak lensing observations of 2000 clusters detected in sensitive X-ray surveys. The extension of $G(z)$ measurements beyond $z = 2.0$ will be possible only with pointed observations with a powerful X-ray telescope, such as IXO. However, at $z \lesssim 1$, the WFXT will provide sufficient information to carry out this measurement right from the survey data (see text). The growth of structure data are crucial for testing non-GR theories of cosmic acceleration. For example, the dashed line shows the $G(z)$ function predicted for a DGP model with the same expansion history as the quintessence model depicted by the solid curve.

For several hundred clusters at $z \lesssim 0.2$ the WFXT statistics will be sufficient to measure radial temperature profiles of the intracluster gas. These clusters will be a premier, uniform dataset for cross-correlations with the SZ data from Planck or ground-based SZ surveys. The main application of the joint X-ray and SZ analysis is to implement the classical method of determining the absolute distance scale [20].

The WFXT sample of several hundred thousands groups and clusters will provide an independent measurement of the baryonic acoustic oscillations peak in the cluster-cluster power spectrum. This measurement will nicely complement the larger-scale BAO measurements with JDEM and dedicated ground-based galaxy surveys, because observing BAO with cluster-cluster correlation has advantages over the galaxy-galaxy correlation measurements due to simpler modeling of the scale-dependent bias and possibly, of redshift-space distortions. Also, even a simple cross-correlation of the WFXT cluster and group catalog with the sample of luminous red galaxies¹ will go a long way in constraining the LRG bias factor and thus potentially improving the accuracy of the BAO results.

Detailed sampling of the WFXT survey lightcone with galaxy clusters and groups can also be used in cross-correlation with the CMB maps to measure the Integrated Sachs-Wolf effect. Just as with BAO, using clusters as tracers has advantages because of easier modeling of their bias factor compared with normal galaxies or AGNs.

¹ LRGs are usually considered as a prime tool for BAO measurements in the optical surveys; LRGs and WFXT galaxy clusters and groups will have a similar space density.

3 Looking beyond Λ CDM

WFXT will be able to carry out traditional cosmological tests with galaxy clusters as outlined above. However, we believe that a more significant contribution will be made by expanding discovery space, in particular in looking for deviations from the “concordant” Λ CDM cosmological model. WFXT will contribute to this quest by taking the cluster data of the quality and scale unimaginable before.

- Detailed measurements of the mass-dependent power spectrum of groups and clusters, as well as the shape and evolution of the high-mass end of the cluster mass function can be used to search for non-gaussianities in the primordial density fluctuation field [21]. Detecting non-gaussianities would be an extremely important discovery because it opens a window into physics of inflation.

- WFXT will make a detailed determination of the scale, mass, and redshift dependence of the bias factor in the cluster-cluster correlation function. These data will be a prime dataset for testing deviations from General Relativity on large scales.

- A WFXT-type survey will be the first experiment to accurately measure the cluster-cluster correlation function on mildly non-linear scales (~ 1 Mpc)¹. This measurement is also potentially useful for testing departures from GR (e.g., the “chameleon” effect in the $f(R)$ models [22]). Statistics of close neighbors should be also directly linked to the growth rate of clusters. Therefore, comparison of the cluster-cluster correlation at small separations and evolution in the cluster mass function will create an extra level of “redundant” information on the growth of non-linear objects, which can be exploited in testing the Λ CDM paradigm.

- Measuring the cluster-cluster power spectrum over a wide range of spatial scales today, combined with a precise determination of the mass-dependent bias factor, will yield a precise reconstruction of the linear perturbations power spectrum at low redshifts. This can be used to search for signatures of non-zero neutrino mass [23].

- Combining detailed information from number density and clustering of clusters at low redshifts will lead to a very robust local measurement of the amplitude of linear density perturbations (σ_8). A reliable *absolute* measurement of the local value of σ_8 in combination with the CMB measurements from Planck constrains the total growth of perturbations between $z = 1000$ and $z = 0$. Potential applications include searching for effects of early dark energy, or putting tighter constraints on the ratio of tensor and scalar perturbations in the CMB maps.

- Departures from Λ CDM can be searched for by looking at statistics and properties of the rarest objects, such as “Bullet Cluster” [24]. WFXT will dramatically extend the search volume for such objects, especially so because it will provide not only detections but also reasonably detailed X-ray images (1000 – 1500 photons) for virtually every massive cluster in the surveyed lightcone out to $z \simeq 1$.

4 WFXT capabilities for surveys

WFXT is designed to carry out an extremely advanced X-ray survey, which will feature sensitivity limits comparable to *Chandra* and *XMM-Newton* deep surveys and a sky coverage

¹This measurement is hard to do in any other waveband and even in an X-ray survey with poor angular resolution because of problems with separation of close neighbors.

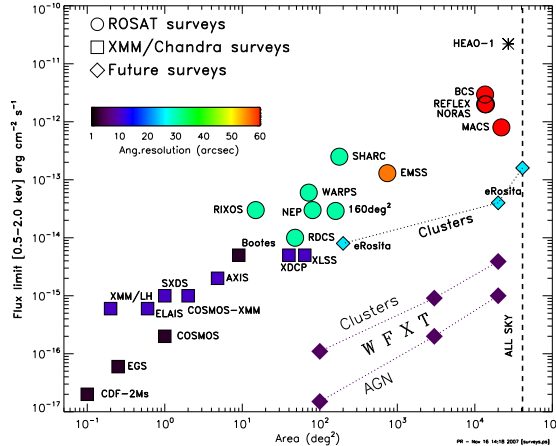


Fig. 3— Comparison of effective areas and sky coverage for various X-ray surveys, past and planned. WFXT provides an unsurpassed combination of sensitivity and areal coverage.

of 10%–25% of the entire sky. The combination of its effective area, field of view, and angular resolution provides unsurpassed capabilities for detection of galaxy clusters and groups over a very broad range in mass and redshift. WFXT design features a total collecting area of X-ray mirrors of 8,000 cm², in combination with an angular resolution of 5'' (half energy width) averaged over the entire wide field of view of 1 deg². The high angular resolution across the field of view is achieved using the well known polynomial perturbation to the standard Wolter-I X-ray telescope optical design [17]. This design distinguishes WFXT from other X-ray survey missions and is critical for classifying faint sources as either point-like or extended. That is, WFXT is the analog to an optical Schmidt telescope, optimized for large area surveys, with an angular resolution over its entire field of view that is sufficient to resolve extended sources and avoid confusion down to the flux limit of the Chandra Deep Fields. The huge grasp of the WFXT will make it possible to carry out, in just a few years, a very sensitive X-ray survey over a very wide area (Fig.3).

The WFXT survey over several thousand square degrees will reach an extended source flux limit of 10⁻¹⁵ erg s⁻¹ cm⁻². At such a low limiting flux, the surface density of extended sources (ranging in mass from rich clusters of galaxies at high redshifts to sub-group objects at low z) is ~ 100 per square degree (extrapolating the *ROSAT* $\log N - \log S$ relation and consistent with the extended source detections by XMM in the COSMOS field). Therefore, a WFXT survey will be guaranteed to provide an enormous sample of clusters and groups, several hundred thousand objects in a surveyed lightcone spanning several thousand square degrees in the sky.

In terms of object detection, such a survey will push the currently achievable limits in both redshift and mass. The upper boundary in redshift for detecting massive galaxy clusters will be beyond $z = 2$, the epoch where the cluster-sized objects first came into the cosmological scene (Fig.4). WFXT will also push the mass limit at low redshifts down to galaxy-sized objects. For example, the “sub-groups” with X-ray luminosities $L_X = 10^{41}$ erg s⁻¹ will be detectable to $z = 0.15$, increasing the search volume for such objects by a factor of 10,000 compared with the *ROSAT* All-Sky Survey and by a factor of 30 compared even with an eRosita all-sky survey. As a result, galaxy clusters, groups, and sub-groups detected by WFXT survey will sample the mass function and the correlation function of the virialized

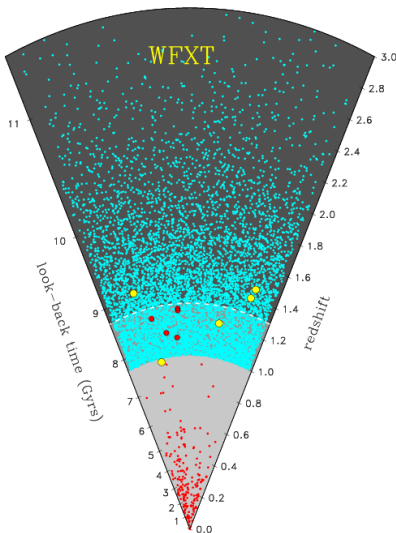


Fig. 4— Look-back time cone of the expected cluster sample from the deep WFXT survey. WFXT will open up a largely unexplored period in cosmic history, back to the epoch when the first protoclusters form and the first virialized structures start glowing in X-rays. For clarity, we show only WFXT clusters at $z > 1$ (blue dots). The red dots indicate clusters found in ROSAT deep surveys out to $z=1.3$; yellow dots indicate distant clusters found with XMM and Chandra and spectroscopically confirmed to date.

objects over an exceptionally broad range of masses, redshifts, and spatial scales.

The WFXT X-ray telescope is so sensitive that it will provide a great deal of detailed information for a large number of sources right from the survey. For example, the clusters with $f_x = 3 \times 10^{-14}$ erg s $^{-1}$ cm $^{-2}$ (around the eRosita detection threshold) — 18,000 such objects in a 5,000 deg 2 survey, with an effective redshift boundary beyond $z = 1$, — will yield 1500 photons each, providing not only substantial information on the X-ray morphology but also to measure the temperature, gas mass and the Y_X parameter [18] with a 10% accuracy. This is the same quality of data that is presently used in the *Chandra* cosmological studies using the cluster mass function [12], only the WFXT experiment will be on a much grander scale, using a factor of 500 larger sample.

Many of the objects yielding 1,500 photons or more will also have detectable iron K-shell emission lines leading to X-ray spectroscopic redshift measurements with $\Delta z \approx 0.01$ [14].

For yet brighter clusters with $f_x = 10^{-12}$ erg s $^{-1}$ cm $^{-2}$, 250 objects in total, WFXT will collect 50,000 photons per object, enough to measure the gas temperature and metallicity profiles with the quality presently accessible only for a handful of best-observed *XMM* and *Chandra* clusters. The size and redshift reach of this sample matches very well the *REFLEX* cluster sample detected in the ROSAT All-Sky survey. However where today we have detections with just a few photons, we would have exceptionally detailed information for each object from the WFXT survey.

5 Summary

Sensitive, wide-area X-ray surveys which would be possible with the WFXT will detect huge samples of virialized objects spanning the mass range from sub-groups to the most massive clusters, and extending in redshift to beyond $z = 2$. These samples will be an excellent dataset for carrying out many traditional cosmological tests using the cluster mass function

and power spectrum. Uniquely, WFXTE will be able not only to detect clusters but also to make detailed X-ray measurements for a large number of clusters and groups right from the survey data. Very high quality measurements of the cluster mass function and spatial correlation over a very wide range of masses, spatial scales, and redshifts, will be useful for expanding the cosmological discovery space, and in particular, in searching for departures from the “concordant” Λ CDM cosmological model. Finding such departures would have far-reaching implications on our understanding of the fundamental physics which governs the Universe

References

- [1] White, S. D. M. et al., 1993, *Nature*, 366, 429
- [2] Eke, V. R. et al., 1998, *MNRAS*, 298, 1145
- [3] Borgani, S. et al., 2001, *ApJ*, 561, 13
- [4] Henry, J. P. & Arnaud, K. A., 1991, *ApJ*, 372, 410
- [5] Reiprich, T. H. & Böhringer, H., 2002, *ApJ*, 567, 716
- [6] Schuecker, P. et al., 2003, *A&A*, 398, 867
- [7] Spergel, D. N. et al., 2007, *ApJS*, 170, 377
- [8] Komatsu, E. et al., 2008, arXiv:0803.0547
- [9] Dunkley, J. et al., 2008, arXiv:0811.4280
- [10] Benjamin, J. et al., 2007, *MNRAS*, 381, 702
- [11] Fu, L. et al., 2008, *A&A*, 479, 9
- [12] Vikhlinin, A. et al., 2008, arXiv:0812.2720
- [13] Murray, S. et al., 2009, The growth and evolution of supermassive black holes, White Paper to Astro2010
- [14] Giacconi, R. et al., 2009, Galaxy clusters and the cosmic cycle of baryons across cosmic times, White Paper to Astro2010
- [15] Ptak, A. et al., 2009, The very local Universe in X-rays, White Paper to Astro2010
- [16] Murray, S. S. et al., 2008, in *SPIE, SPIE Conference Series*, vol. 7011
- [17] Burrows, C. J., Burg, R. & Giacconi, R., 1992, *ApJ*, 392, 760
- [18] Kravtsov, A. V., Vikhlinin, A. & Nagai, D., 2006, *ApJ*, 650, 128
- [19] Huterer, D. & Linder, E. V., 2007, *Phys. Rev. D*, 75, no. 2, 023519
- [20] Bonamente, M. et al., 2006, *ApJ*, 647, 25
- [21] Dalal, N. et al., 2008, *Phys. Rev. D*, 77, no. 12, 123514
- [22] Schmidt, F. et al., 2008, arXiv:0812.0545
- [23] Tegmark, M., 2005, *Physica Scripta Volume T*, 121, 153
- [24] Farrar, G. R. & Rosen, R. A., 2007, *Physical Review Letters*, 98, no. 17, 171302