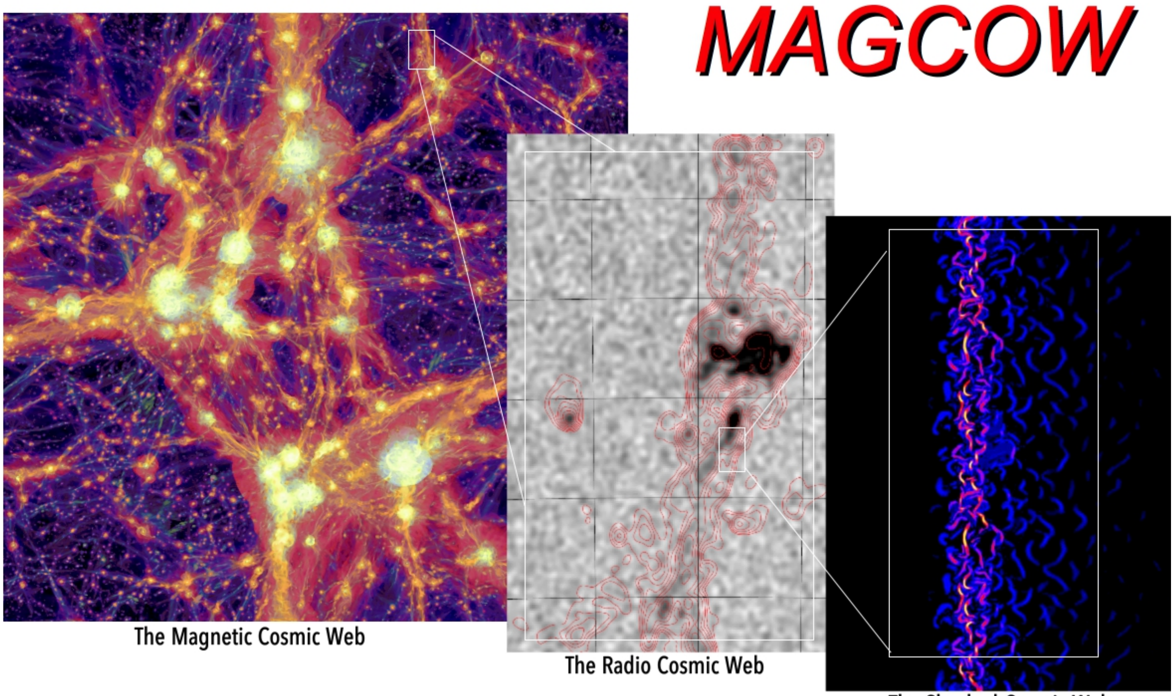
The Magnetised Cosmic Web

MAGCOW



The Magnetic Cosmic Web

The Radio Cosmic Web

The Shocked Cosmic Web

ERC Starting Grant Research Proposal- Part B2

a. State of the art

Our understanding of structure formation in the Universe requires that 90% of the baryonic and dark matter is distributed in a web-like pattern, at the densest knots of which galaxies and galaxy clusters form. The filamentary distribution of galaxies has been observed by deep optical and infrared survey. X-ray, ultraviolet OVI, OVII and OVIII lines and the HI Lyman-α line are important tracers of the low density cosmic web with temperature ~10^4-10^6 K, along arbitrary directions where absorbers are located (e.g. Rauch et al. 1998; Richter et al. 2008). However, the gas locked into filaments and making up to ~ 50% of the total baryonic matter in the Universe, in the form of the warm-hot intergalactic medium (WHIM), has never been imaged ("missing baryons" problem, e.g. Cen & Ostriker 1998, Davè et al. 2001). This situation might change within the next decade, thanks to the new generation of radio instruments (JVLA, LOFAR, MWA, ASKAP and the SKA) which should be able to detect the tip of the iceberg of the emission from synchrotron-emitting electrons in the rarefied **intergalactic medium** (IGM). The radio emission should originate from the strong accretion shocks around structures, where the cosmic gas gains entropy and gets enriched with **cosmic rays** (Quilis et al. 1997; Miniati et al. 2000; Ryu et a. 2003). The acceleration efficiency of particles at these shocks is still unknown, and so is the effect of accelerated particles onto magnetic fields (e.g. Blasi et al. 2004; Caprioli & Spitkovski 2014; Guo et al. 2014).

Intertwined to the physics of the shocked IGM is the the origin and the evolution of **extragalactic magnetic fields.** This is little known and limited to observations of galaxies and of a few galaxy clusters. Crucial information on the first seeding of extragalactic magnetic fields can still reside in the rarefied cosmic web, due to the absence of astrophysical sources of magnetisation there (galaxies, active galactic nuclei).

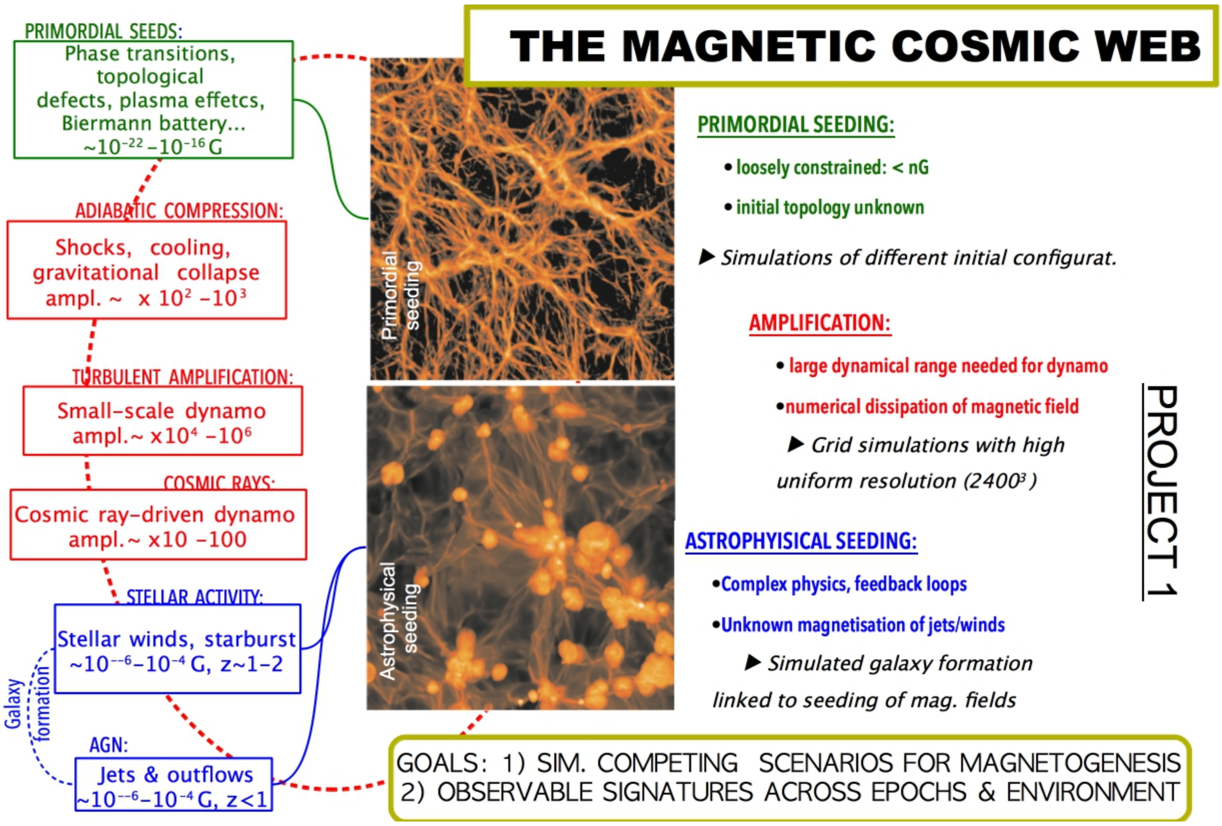
The detection of the **synchrotron cosmic web** will thus offer the chance of a first imaging of the gaseous component of the cosmic web and to shed a new light on all above issues. However, the simple detection of the synchrotron cosmic web will not suffice to solve the above longstanding puzzles, because the signal will likely be too weak and complex to easily allow any simple physical interpretation. For this reason, it is now mandatory to improve our understanding of non-thermal processes at these scales.

My proposed MAGCOW project is designed to provide a timely breakthrough in the study of

magnetism and particle acceleration at cosmological scales. I will model the cosmic web with advanced simulations, that will enable radio observations to become a powerful probe of extragalactic fields. With this quantitative approach, even *non-detections* of radio signal in deep surveys will be used to constrain extragalactic magnetic fields better than ever. Likewise, observations of synchrotron emission at these scales will constrain the physics of particle acceleration in the largest shocks in the Universe. This will advance our description of particle acceleration beyond the current limitations given by extrapolating from supernova remnants, and complementary to the present modelling of cluster shocks.

In summary, the MAGCOW project will tackle the above topics with 3 interconnected sub-projects with **ambitious objectives:**

- the first sub-project, **"The magnetic cosmic web"**, will predict the properties of extragalactic magnetic fields (specially in cluster outskirts and filaments) for several competing scenarios for the origin of extragalactic fields. The output of advanced simulations will be used to identify observable quantities that will lead to discriminate among competing models through radio observations.
- The second sub-project, **"The shocked cosmic web"**, will combine the standard hydro-MHD picture of cosmic shocks with particle-in-cell simulations exploring the collisionless nature of these shocks. I will combine 3 numerical methods to resolve this process from cosmological to microscopic scales, and predict the acceleration efficiency of electrons as a function of shock and plasma parameters.
- The third sub-project, "**The radio cosmic web"**, will study the most efficient strategies to detect the cosmic web within the next decade, exploiting surveys with several radio telescopes: LOFAR, ASKAP, MWA and the Square Kilometer Array.



a1. The magnetic cosmic web

The evolution of cosmic magnetism is still an astrophysical puzzle (*see the schematic view above*). Radio observations provide evidence for magnetic field strengths of up to a few μG in galaxy clusters and up to ~10^2 μG in galaxies (e.g. Ferrari et al. 2008; Feretti et al. 2012; Brunetti & Jones 2014). The theoretical justification for such strong fields is non-trivial, given that the upper limits on the primordial magnetic field at the epoch of the Cosmic Microwave Background are very low (<10^{-10}G, Planck Collab. 2015). The first cosmic seed fields could originate from the very early Universe during inflation and first-order phase transitions. However, the uncertainty on the efficiency of such mechanisms is large, $\sim 10^{-34}$-10^{-10}G (Widrow et al. 2012). Additional processes such as the "Biermann-battery" mechanism, turbulent fluctuations in the inter galactic plasma or resistive mechansims might also provide seed fields in the range $\sim 10^{-19}$-10^{-16} G (e.g. Brandenburg et al. 1996; Gnedin et al. 2000; Miniati & Bell 2011; Schlickeiser 2012). Later on, structure formation can induce a small-scale turbulent dynamo (e.g. Subramanian et al. 2006). The growth of the magnetic fields should first follow an exponential kinematic regime, and second a non-linear growth and stretching of the coherence scales of the magnetic field until the magnetic energy reaches saturation with a fraction of the turbulent forcing (e.g. Schober et al. 2013). Whether or not this scale is reached in a finite amount of time ultimately depends on the age of the system and on the magnetic Reynolds number, R_m (Beresnyak & Miniati 2015).

Other astrophysical processes at lower redshifts ($z<6$) and connected to galaxy evolution can represent a competing mechanism to magnetise the cosmic web. Galactic and stellar activity might steadily release magnetised winds onto the circumgalactic medium (e.g. Kronberg et al. 1999; Völk & Atoyan 1999), while ram pressure stripping of infalling galaxies can further disperse galactic magnetic fields previously amplified via α-Ω dynamo (e.g. Ruszkowski et al. 2014). Finally, powerful jets from active galactic nuclei can strongly magnetise the innermost region of clusters starting from $z\sim2$, and provide additional seeding for the later amplification in merger events (e.g. Xu et al. 2009). The observed Faraday Rotation effect in galaxy clusters provides evidence of diffuse $\sim\mu$G fields with maximum outer scales of ~50 kpc (e.g. Murgia et al. 2004 Bonafede et al. 2010). Cosmological simulations have shown that both scenarios can qualitatively reproduce these observations (e.g. Dolag et al. 2006; Xu et al. 2009; Beck et al. 2013). However, the expectations of these competing scenarios is increasingly different moving outside of virialised structures, where the dynamo amplification is less efficient and some memory of the initial seeding event(s) must be retained (e.g. Vazza et al. 2014; Cho 2014). Different levels of magnetisation in the rarefied cosmic web play a very significant role in the propagation of ultra-high energy cosmic rays, because the Lorentz force deflects the propagation of cosmic rays and hampers the possibility of detecting their sources (e.g. Sigl et al. 2004). Being able to predict the distribution of extragalactic fields will enable even to test promising dark matter candidates, as the axion-like particles which may produce observable oscillations into photons in presence of large-scale magnetic fields ordered on Mpc scales (e.g. Meyer et al. 2014).

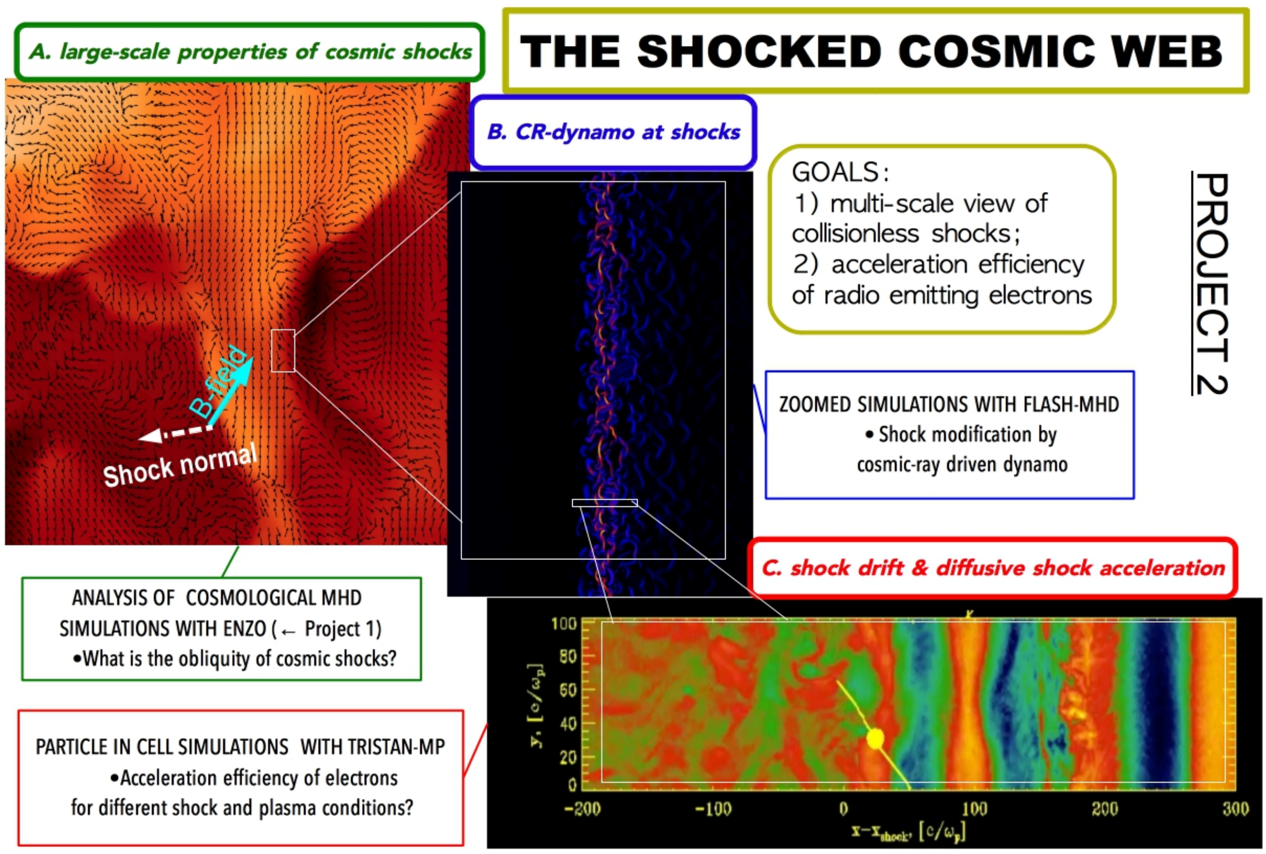
Cosmological simulations have achieved tremendous progresses in describing the basic steps of galaxy formation, even if a complete understanding of the role of epoch and environment in shaping galaxy morphologies is still lacking (e.g. Kauffmann et al. 1997; Springel et al. 2005; Scannapieco et al. 2012, Vogelsberger et al. 2014). On the other hand, relatively little code development has been put into the inclusion of non-thermal energy components in the evolution of large-scale structures. This is partially due to the scarcer observational constraints as well as to the larger physical uncertainties and complexities of the relevant processes to model (e.g. Dolag et al. 2006). High resolution Magneto-hydrodynamical (MHD) simulations of galaxy clusters have been first produced using the smoothed-particle-hydrodynamical approach (e.g. Dolag et al. 2002; Donnert et al. 2009; Beck et al. 2013). Nowadays also grid simulations can reach a large enough resolution to study small-scale amplification in detail, thanks to adaptive mesh refinement (e.g. Brüggen et al. 2005; Dubois & Teyssier 2008; Xu et al. 2009; Ruszkovski et al. 2014). In recent work I investigated the amplification of primordial magnetic fields in cosmic structures with tailored grid simulations (Vazza et al. 2014b) and this first sub-project will build on top of these results, also including sophisticated modelling of magnetic seeding linked to galaxy formation.

a2. The shocked cosmic web

The growth of cosmic structure is interlaced with the generation of shocks at all scales, either powered by accretion of smooth gas or by merger of denser substructures (e.g. Gabici & Blais 2003; Ryu et al. 2003; Pfrommer et 2006; Vazza et al. 2011). Shocks convert a fraction of the energy of gravitationally accelerated flows into thermal energy, amplification of magnetic fields and into the acceleration of relativistic particles. Similar to many other astrophysical shocks (in the solar wind and in supernova remnants, e.g. Blasi 2004), the shocks surrounding large-scale structures are expected to be collision*less*, i.e. Coulomb collisions are not sufficient to provide the viscous dissipation at the shock but rather collective plasma effects are the key ingredient (e.g. Bykov et al. 2008). Specific features of collisionless shocks are that the shock thickness is a few tens of the ion inertial length ($l_p << \lambda_{Coulomb}$), the emergence of a non-Maxwellian distribution of particles, the modification of the shock structure (with the emergence of a precursor pressure jump) due to the escaping of very energetic particles, and the fact that incoming electrons achieve thermal equilibrium with the downstream ions through the mediation of large amplitude non-linear magnetic waves, on a scale larger than the shock thickness. The diffusive shock acceleration (DSA) mechanism can explain how shocked particles are accelerated to relativistic energies, but the mechanism requires the particles to already have sufficient energy to start further acceleration (e.g. Kang & Ryu 2013). Moreover, in presence of accelerating particles the shock structure rearranges itself, by pre-compressing and heating the plasma before the actual shock arrives, and also by amplifying the magnetic fields (e.g. Drury & Downes 2012; Brüggen 2013).

The striking evidence for shocks (e.g. Markevitch & Vikhlinin 2007) and merger-related radio emission in the peripheral regions of clusters ("radio relics", e.g. Feretti et al. 2012; Brunetti & Jones 2014 for recent reviews) makes it extremely likely that a low level of diffuse radio emission is also present in more rarefied regions of the cosmic web, awaiting for discovery. The modelling of radio relics suggests that acceleration efficiency of electrons at merger shocks must be ~10^{-5}-10^{-3} of the incoming kinetic energy flux, in order to explain the observed emission with ~μG fields (Hoeft & Brüggen 2007). However, the acceleration efficiency for M<3 shocks must be much larger than what predicted by DSA, and re-acceleration of pre-existing electrons has been suggested as a possible explanation (e.g. Kang et al. 2012; Pinzke et al. 2013). Finally, my recent modelling of radio and γ-ray data of clusters hosting relics demonstrated that radio-emitting electrons are more accelerated than relativistic protons, completely at odds with DSA (Vazza et al. 2014c,15c). This requires to take into account also other (pre)acceleration mechanisms of cosmic rays in structure formation shocks, like shock-drift acceleration.

A powerful method to study collisionless shocks is represented by particle in cell (PIC) simulations, which essentially evolve a collection of charged macro-particles under the Lorentz force, computed on a grid. The PIC method is the most fundamental way to describe the interplay between charged particles and electromagnetic fields at the basis of non-thermal plasma processes. With this method several groups recently produced promising results on how protons (Caprioli & Spitkovski 2014) and electrons (Guo et al. 2015) gain energy by crossing different regions around the shock. In particular, Guo et al. (2015) found that shock-drift acceleration (SDA) can be an efficient accelerator of electrons at weak cluster shocks (M<5). This possibility would explain the puzzling results I obtained with my recent work on radio relics (Vazza et al. 2014c, 2015c), and opens up unexplored territory to model emission in cosmic shocks. In this sub-project I will combine the standard hydro-MHD approximation of comic shocks to the PIC view of collisionless shocks in the cosmic web, and derive the fundamental parameter of the acceleration efficiency of radio emitting electron at shocks (see Figure below).

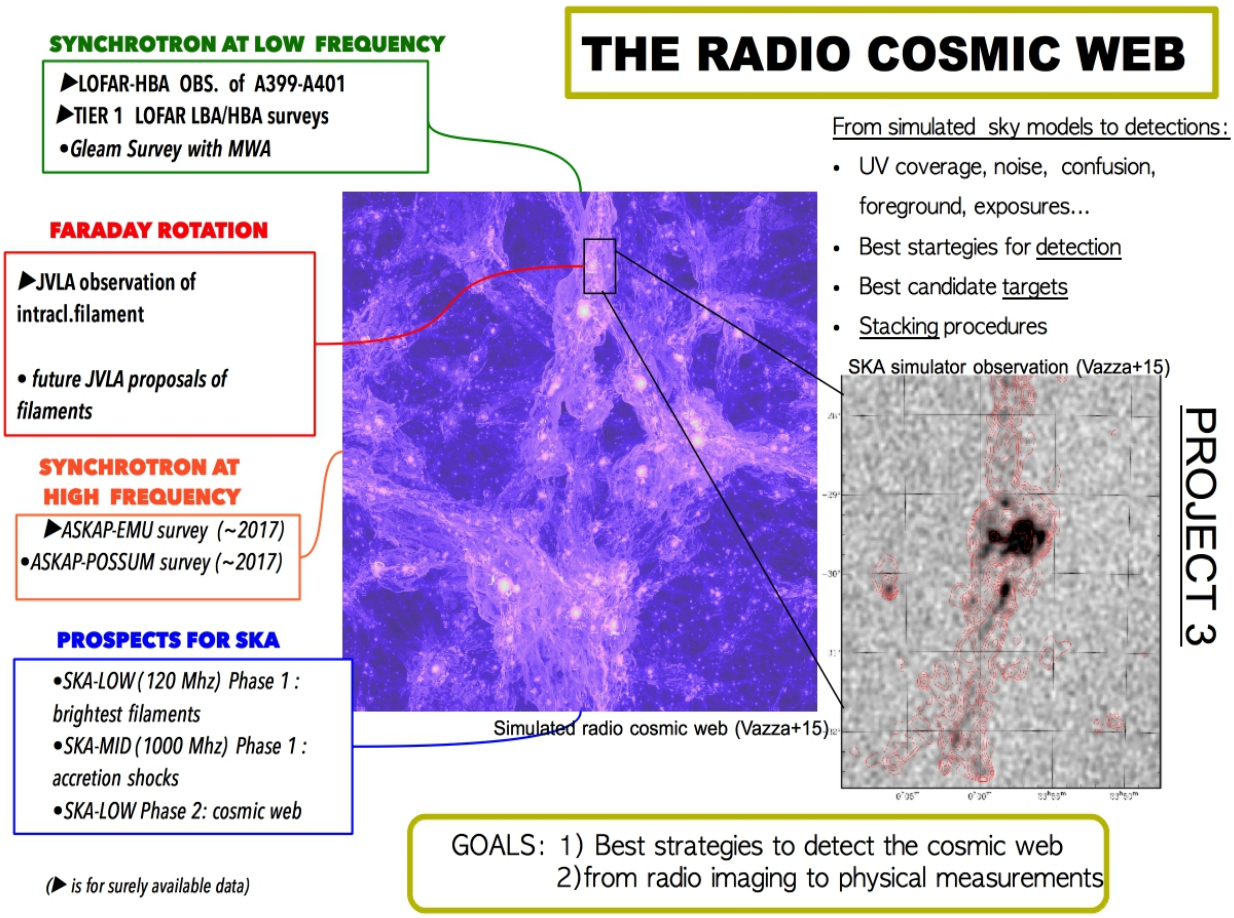


a3.The radio cosmic web

The large-scale network of cosmic baryons has never been observed in radio. However, the evidence of non-thermal emission related to cluster merging activity (e.g. Feretti et al. 2012; Brunetti & Jones 2014) as well as the few tentative detections of radio bridges around clusters (Bagchi et al. 2002; Giovannini et al. 2010; Farnsworth et al. 2013) suggest that the cosmic web might be detectable by incoming high sensitivity radio surveys. In this case, accretion shocks around cosmological filaments may be detected with radio telescopes provided these shocks are efficient enough in accelerating electrons to relativistic energies (e.g. Keshet et al. 2004; Brown 2011).

My recent work has pioneered the detailed analysis of radio imaging of the cosmic web with the SKA, LOFAR and other radio telescopes (Vazza et al. 2015a,b). This showed that the synchrotron emission from shock-accelerated electrons offers a better chance of first imaging the low-redshift cosmic web, compared to other possibilities, like the emission from the HI line, which can better probes the denser IGM at high redshift (e.g. Popping et al. 2015). Using Faraday Rotation we recently found significant magnetisation of a filamentary accretions onto the Coma cluster, up to ~ 2μG (Bonafede, Vazza et al. 2013). Future polarimetric surveys with the SKA will have a chance of a statistical detection of Faraday Rotation from the cosmic web, with rotation measure grids (e.g Akhaori et al. 2014; Vacca et al. 2015; Gaensler et al. 2015).

The next decade thus promises to be a "golden epoch" for radio astronomy, due to the deployment of many revolutionary radio telescopes. While the most powerful of all, the Square Kilometer Array, should deliver first scientific results only from ~2020, a flurry of precious radio observations will be earlier delivered by the its precursors or pathfinders: LOFAR, MWA, ASKAP. Moreover, the augmented capabilities of the Very Large Array after the upgrade with broadband polarimetry (JVLA) will allow deep studies of Faraday Rotation/Synthesis on selected targets. Advanced analysis techniques are being developed to overcome the challenges posed by the wide-ield and multi-frequency nature of next generation of radio data. I am deeply involved in the design of the best observation strategies for SKA and precursors to get to a positive detections of the cosmic web, and this third sub-project of MAGCOW will use connect the results of the other 2 sub-projects to expand and improve my preliminary results on this subject (Vazza et al. 2015a,b).

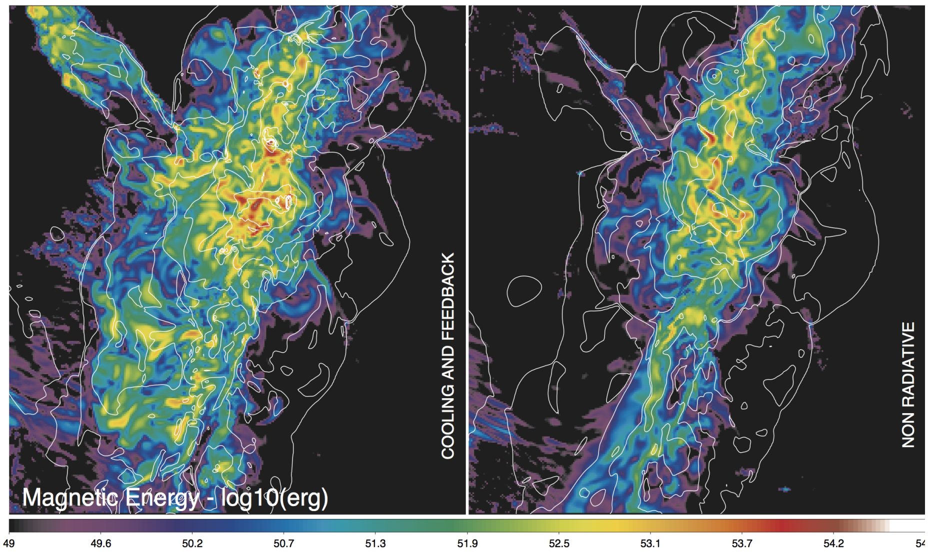


b : Methodology

b1. THE MAGNETIC COSMIC WEB

The simulation of extragalactic magnetic fields requires the use of magneto-hydrodynamical (MHD) simulations, including the effect of compression, small-scale dynamo and localized injection of magnetic field by astrophysical objects as galactic winds or jets from active galactic nuclei. To form a realistic number of massive halos, large simulated volumes are required while to form a dynamo and model all important processes of galaxy formations (such as radiative cooling and the subsequent energy feedback via jets or outflows) the highest possible resolution is necessary.

Thanks to large allotted projects at the Supercomputing centre CSCS-ETH (Lugano) I produced and will be analysing some of the best simulations of extragalactic magnetic fields to date, in term of dynamical range and physical complexity[1]. These simulations features radiative metal-dependent cooling, star formation and growth and feedback from active galactic nuclei, assumed to form around supermassive black holes ($>10^5$ M_o) seeded in the simulation[2]. My original numerical development on the grid code ENZO[3] allow me to simulate the growth of magnetic fields both starting from uniform cosmological seeds and by coupling star forming regions and active galactic nuclei (AGN) to the release of additional magnetic fields. With my developments it is now possible also to couple thermal or kinetic AGN feedback (Vazza et al. 2013) to the release of magnetic energy, e.g. by imposing that a fraction, $\varepsilon_B \sim 1\text{-}10\%$, of the feedback energy is released into magnetised dipoles. The magnetic seeding from supernovae is also included at run-time by coupling the star formation model to the injection of magnetic energy (e.g. Donnert et al. 2009).



In this sub-project I will perform a survey of competing models for the magnetisation of large-scale structures. The different models will be selected on the prior of producing intracluster magnetic fields consistent with observations. The magnetic fields predicted for more rarefied environments will instead be used to predict the observable outcomes of these scenarios, to be falsified by radio observations (sub-project 3). Filaments and cluster outskirts are very volume filling objects of the cosmic web, and given their slower dynamical evolution compared to galaxy clusters and galaxies, they retain memory of the events that injected magnetic fields in the past (Cho 2014). This is also confirmed by numerical tests (Vazza et al. 2014, and also *the Figure above*, showing a 8x10 Mpc^2 region simulated at high resolution), where the turbulent amplification of primordial weal fields (right) is contrasted with the additional seeding by magnetised jets from AGN central to clusters (left). Cluster outskirts and filaments accreting onto the cluster are substantially more magnetised in the jet scenario. On the other hand, the magnetic energy of the innermost cluster regions is very similar in both scenarios. The robust detection of significant magnetic fields in cluster outskirts and filaments will thus inform us about the mechanism(s) that magnetised the innermost large-scale structures.

In this sub-project I will test both "radio" (jet) and "quasar" (heat) modes of feedback. To constrain the tunable parameters of each model I will use for benchmarking the available optical/IR observations (e.g. integrated star formation rate across redshift, stellar mass function), X-ray observations (e.g. scaling relations for clusters and groups) and radio observations (e.g. luminosity function of radio galaxies). I will also test the effects of variations in the initial topology of seed cosmological fields, presently unknown, which can lead to observable effects in outskirts of large-scale structures (e.g. Marinacci et al. 2015). Finally, the acceleration

1 http://www.cscs.ch/publications/highlights/2014/supercomputer_feels_magnetic_fields_in_the_cosmos/index.html
2 These features are presently availabel in the public version of ENZO, see Kim et al. (2011) and Bryan et al. (2014).
3 ENZO is a parallel cosmological grid code largely used in the community, see *enzo-project.org* and Bryan et al. (2014).

and the ageing of electrons injected by shocks, feedback from AGN and star forming regions will be included in ENZO with a passive tracer particles approach, as main topic of a PostDoc (see below). This will expand my previous 2-fluid for cosmic rays (Vazza et al. 2012, 2013, 2014a). The production of these simulations started in September 2015 and will be completed by the middle of 2016.

- ✔ *PhD project number 1.* One PhD student with a numerical profile will be appointed within this first MAGCOW sub-project. She/he will produce realistic mock radio observations of the simulated volumes in this sub-project defining the observable properties of alternative magnetisation scenarios. Computing the Faraday Rotation signal from these large simulations will be one of the main focus of the sub-project, which will include also the combination with semi-analytical algorithms developed in Hamburg in order to increased the dynamical resolution of mock observations (Bonafede, Vazza et al. 2013).
- ✔ *Post Doc Fellow.* One Post-Doctoral Fellow with a strong numerical profile will be appointed for 2 years to study the energy evolution of relativistic electrons injected by shocks waves (as well as AGN) using a Lagrangian tracer approach. This modelling is mandatory to follow the ageing of radio emitting electrons and will allow a better comparison with radio observations also of galaxy clusters.

Executive summary

- I will benchmark the model for galaxy formation (e.g. star formation efficiency and initial mass function, efficiency of thermal/kinetic feedback etc) using available observational proxies. Black hole proxies: star mass versus black hole mass relation in halos. Star formation; integrated star formation rate as a function of redshift. Intracluster medium: X-ray scaling relations of galaxy clusters (mass/temperature, X-ray/temperature and entropy/temperature relations). These steps will test the robustness of our cosmological runs and of the chosen parameters defined at the resolution of the simulation. (1st year)
- For each model leading to intracluster magnetic fields consistent with observations, I will measure the 3D properties (distribution functions, power spectra, etc) across scales and epochs with a particular focus on the filamentary distribution of baryons. The extraction of filament catalogs in the simulated volume will rely on a recently developed ad-hoc parallel filament finder (Gheller, Vazza et al. 2015). (2nd year)
- Observational proxies of competing models: continuum synchrotron emission from shock-accelerated electrons (e.g. Vazza et al. 2015) and Faraday Rotation (e.g. Bonafede et al. 2015). A PhD student will mostly contribute to the analysis of these mechanisms. She/he will also simulate the contribution from radio galaxies and AGN to the synchrotron emission, following empirical relations to link the radio luminosity and the mass accretion rate of simulated black holes, both during the radio quiet and the radio loud phase, based on Kording, Jester & Fender (2008). Combining with the simulated star formation, this will test the radio-infrared relation. (3rd year)
- For each model we will produce projected 2D datasets representing the intrinsic sky model to be further processed for specific instruments. The products of this step will be also shared with the community through the EU-funded EUDAT platform, as already done in preliminary work[4] . (3rd year)

Most challenging aspects of this sub-project.

- *MHD Method.* My method of choice is the Dedner Cleaning scheme, already used for other projects (Vazza et al. 2014). This algorithm is known to be more dissipative than other methods, due to the artificial dampening of small-scale MHD modes in the procedure to enforce $\nabla\cdot B=0$ (Wang et al. 2009). However, it is a very robust scheme and recent comparisons showed that the limitations due to the artificial dampening are alleviated if the spatial resolution is increased (e.g. Kritsuk et al. 2011; Pakmor et al. 2014). My recent work with ENZO showed indeed that for large enough resolution in cosmological simulations the small-scale dynamo regime can be achieved in the simulated intracluster medium (Vazza et al. 2014). On the other hand, the dynamo does not develop in filaments, even at high resolution, consistent with other works (Brüggen et al. 2005; Marinacci et al. 2015). The even larger resolution that will be achieved in my runs will test these trends at unprecedented uniform resolution.
- *Galaxy formation.* The most critical aspect is represented by the benchmarking of galactic seeding models against observations, which is made non trivial by the non-linearity of galaxy formation processes. My preliminary results and the large literature available on the topic makes it very reasonable

4 http://cosmosimfrazza.myfreesites.net/radio-web

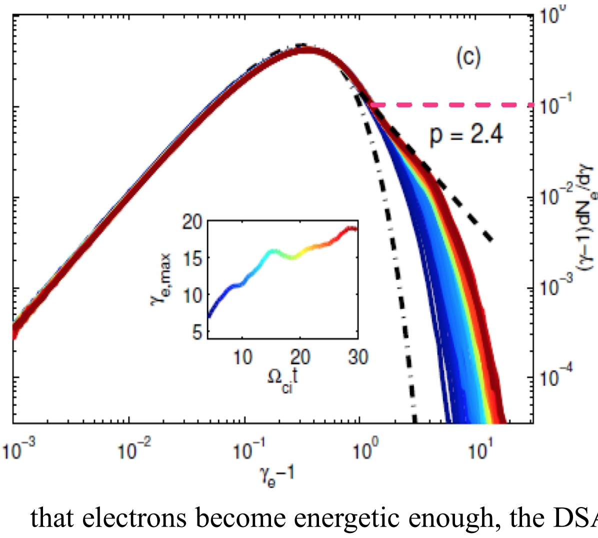
that the proposed simulations will match the observed scaling relations at the scales of interest (~20kpc).

Expected results & Timeline

- *1st year:* **Strength and topology of magnetic fields** in cluster outskirts and filaments for each competing scenarios. Measure of the critical gas density where the prediction from different scenarios diverges. Signature of different prescriptions for primordial seed fields in the rarefied universe at z=0.
- *2nd-3rd years:* **Prediction of the synchrotron radio emission** (based on Vazza et al. 2015a,b) and of the **Faraday Rotation Measurement** (based on Bonafede, Vazza et al. 2015) that will be used to constrain the level of extragalactic magnetic fields from observations (sub-project 3). A PhD student will be recruited to work on the modelling of Faraday Rotation with these large simulations.
- *4th year:* **Spectral evolution of electrons accelerated at accretion shocks.** A Post-Doc will be also hired to work on the implementation of tracers for electron spectra into ENZO.

b2. THE SHOCKED COSMIC WEB

First, through the analysis of our ENZO-MHD simulations (sub-project 1) **I will constrain the typical plasma parameters of IGM shocks** that can be observed in radio, and **I will also constrain the typical magnetic field configuration** (i.e. obliquity between shock normal and magnetic field) on scales of $\sim 10^2$ kpc for competing magnetic field scenarios. Second, with the FLASH[5] grid code (Dubey et al. 2009) I will resimulate the time-dependent evolution of IGM shocks down to a resolution of ~0.1 kpc, and study the **modification of the shock region due to the cosmic ray-driven dynamo**, expected to trigger magnetic field amplification (e.g. Brüggen 2013). These runs will be used to predict the fraction of the shock surface interested by a predominantly parallel or perpendicular field. These configurations will be extrapolated down to the scale of the following PIC simulations with the TRISTAN-MP[6] code. With these runs I will produce **the best predictions ever for the acceleration of relativistic electrons at structure formation shocks**. In this case I will resolve regions of a few hundreds of the electron Larmor gyroradius, $r_{L,e}$, considering a Lorentz factor of $\gamma_L \sim 10^2$ -10^3, i.e. $\sim 10^{-4}$-10^{-3} kpc for magnetic fields of the orders of ~1nG. Resolving the electron plasma scale is essential to describe correctly the generation of electron plasma instabilities, which likely control the injection of electrons into the acceleration process. On the other hand, the shock structure is controlled by the ion Larmor radius, $r_{L,i}$. Covering the electron scale and also the shock evolution over hunderds of proton $r_{L,i}$ is a challenge, and PIC methods has to use a reduced electron to proton mass ratio (~1/100) and calibrate the results to the real ratio with 2D runs. Under these approximation, Guo et al. showed that shock-drift acceleration in M<10 shocks is an efficient way of energizing electrons, up to a Lorentz factor of $\gamma \sim 10$-10^2 (*see left Figure, taken from Guo et al. 2015*). Following the development of the relativistic power-law at higher energy is unfeasible given the limits of the timescales and domain covered by PIC runs. However, once that electrons become energetic enough, the DSA theory can be used to predict the fully developed spectrum, while the injection efficiency can be directly measured in the simulation, at the transition between the supra-thermal and the power-law distribution (indicated by the horizontal pink line in the Figure).



- ✔ *PhD Project number 2.* One PhD student with a numerical profile will be appointed during this sub-project. She/he will produce PIC simulations with Tristan-MP and include these results into ENZO with sub-grid modelling. One of the main goal of this PhD project is to compute the the acceleration efficiency of electrons as a function of the shock parameters, ξ_e(M,M_A,B,obliquity). This will be a major step forward, that any following numerical modelling of cluster radio emission will likely adopt. At present, ξ_e is only assumed to be a function of the Mach number and has unknown normalisation (e.g. Hoeft & Brüggen 2007) and this improvement will be a major breakthrough for the modelling of

5 http://flash.uchicago.edu/site/flashcode/

6 Tristan-MP (Spitkovsky 2005) s a parallel version of the publicl ode TRISTAN , optimized for studying collisionless shocks.

electron acceleration in cosmological simulations.

Executive summary

- Analysis of cosmological MHD runs (sub-project 1) to predict the obliquity of shocks as a function of environment, redshift and magnetic seeding scenario. The goal is to produce numerically accurate predictions for a scale of ~10-100 kpc, and existing runs will be complemented with resolution studies of single objects using AMR. The estimated CPU time for this is modest (~10^5 hours). (2nd year)
- FLASH runs with grid fixed resolution, using the obliquity parameters derived above as initial conditions. I aim at directly simulating scales from ~10 kpc do ~10^2pc, including MHD with the Constrained Transport method and isotropic cosmic ray diffusion (as in Brüggen 2013).I will also add an initial perturbation pattern of density and magnetic field fluctuations in the upstream, extrapolating below the unresolved scales of the cosmological run. Each FLASH run will continue until convergence in the temporal evolution of post-shock quantities (e.g. magnetisation and magnetic field topology) is found, typically ~50 Myr. Previous work suggested that the basic details of the shock modification by cosmic-ray driven turbulence can be captured in 2D, allowing a faster testing of scenarios (Brüggen 2013; Drury & Downers 2012). The estimated CPU time is significant (~10^6 hours), but is available at the University of Hamburg (with the Hummel Intel Cluster, featuring ~10^3 computing cores). (3rd year)
- We will run large PIC simulation with TRISTAN-MP in order to follow the acceleration of protons and electrons starting from the suggested shock configuration of the previous FLASH runs. I will evolve each configuration for ~50 ω_{ci} (where $\omega_{ci}=v_s/r_{L,i}$ is the proton Larmor gyration period), when the formation of a tail of relativistic electrons should form via SDA. Here I will estimate the injection efficiency of each shock configuration, and extrapolate the total energy of the accelerated population for later times, based on DSA. TRISTAN-MP is MPI parallelised, has been shown to scale well up to several thousands of cores and allows a dynamically adjustable domain size, so the size of the computational box can grow in time along the shock normal as the system evolves. In this sub-project I will explore the effects of the initial obliquity of the shock and of the Alfvènic Mach number, for a total of ~ 20 runs in 3D. For typical domains of 10000x512x512 cells (and a twice as large number of electron/protons) the estimated CPU time is of the order of ~300,000 core hours, for a total of ~$6\cdot10^7$ hours, for which an European Supercomputing centre will be necessary. My high rate of success in obtaining large computing allocation in the past ensures that this will not be an issue for the sub-project. (3rd-4th year)

Most challenging aspects of this sub-project

- Using the real electron to proton mass ratio in PIC runs is challenging, as well as covering a large enough domain to self-consistently develop a power-law at relativistic energies. Following Guo et al. (2015) I will perform convergence test in 2D with reduced mass ratios (~1/100) in order to calibrate the results to the real mass ratio. The PIC runs will then be used to predict the injection efficiency of electrons for a range of shocks. As soon as electrons get accelerated via SDA beyond a few thermal momenta, the DSA theory will be used to predict the final accelerated population. **A collaboration with Lorenzo Sironi (CFA), a world expert on PIC simulations, has been established for MAGCOW.** His contribution will help in the most technical parts of PIC simulations.
- The application of the hydro-MHD picture of the IGM at large scales is reasonable, but must be considered with care. In the classic collisional regime dominated by Coulomb collision, the hydro picture is not appropriate for scales $<\lambda_{Coulomb}$. For the typical IGM (T~10^6K and n~10^{-5} part/cm^3) this is a few kpc, much smaller than the maximum resolution of my cosmological ENZO runs (20kpc) but larger than the resolution of FLASH runs (0.1 kpc). At these scales, also a significant difference in the kinetic temperature of ions and electrons is expected (e.g. Bykov et al. 2008). However, the situation is different in collision*less* shocks, where the thickness of the shocks is expected to be ~10-10^2 of the plasma skin depth depending on the shock obliquity, i.e. orders of magnitude below the resolution of FLASH runs. My PIC runs will exactly resolve the scales where the electrons and protons react to the collective plasma effects at the shock transition, will naturally account for the effect of anisotropic thermal motions of ions and electrons, and will serve to map these effects back at the macroscopic level.

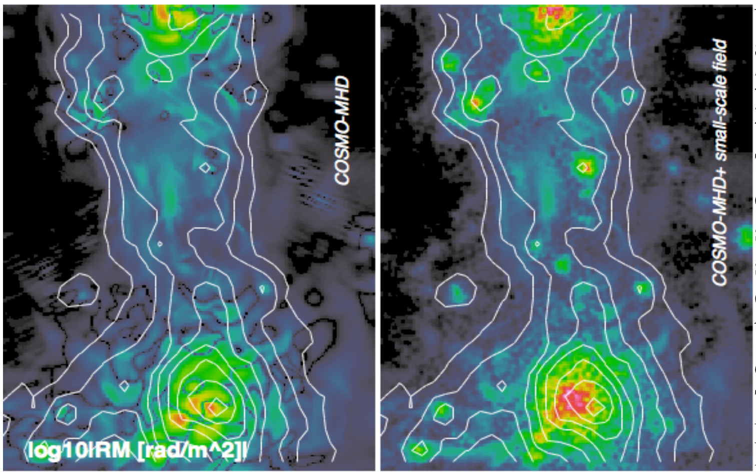
Expected results & Timeline

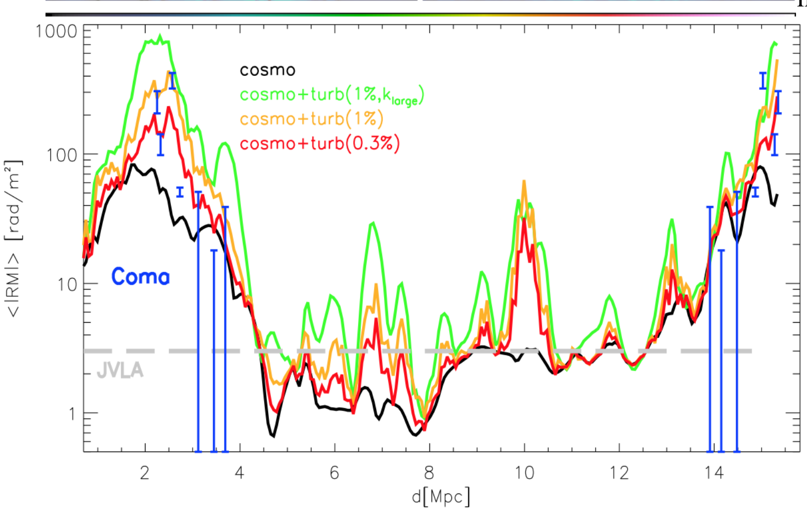
- *3rd year:* **the obliquity of accretion shocks as a function of environment**. I will constrain both the obliquity at scales observable through polarised radio emission (~1-10kpc) and at the "microscopic" scales involved in the acceleration of electrons. Only ENZO and FLASH runs will be necessary here.

- *3rd year:* **the acceleration efficiency of relativistic electrons in the cosmic web.** This sub-project requires the successful completion of the survey of shock parameters with PIC runs, which present some challenges (see above). Among the important parameters that I will survey, it will be important to assess the dependence of the results on M_A. This can be quite large for accretion shocks, producing shocks mediated by filamentation (Weibel) instabilities, a currently unexplored regime.
- *4rd year:* **a new subgrid model for the acceleration of electrons**. The combination of the previous results will give the acceleration efficiency of electrons as a function of the shock parameters,ξ_e(M,M_A,B,obliquity). A PhD student will be hired to lead this part of the sub-project.

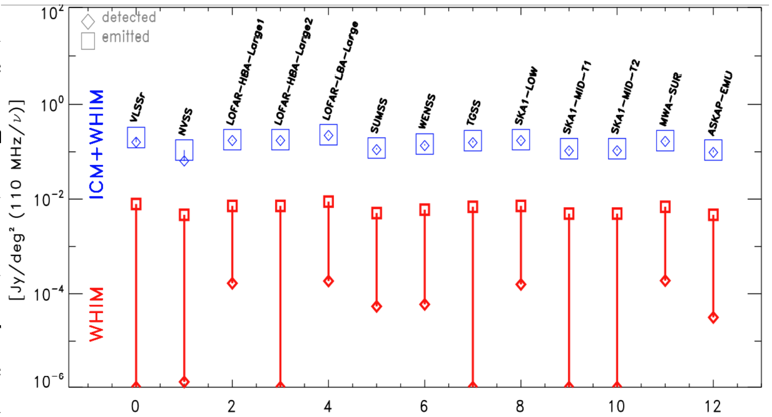
b3. THE RADIO COSMIC WEB

I will simulate radio imaging of the cosmic web and enable quantitative science with incoming radio observations. I will generate mock radio observations for two important goals: a) suggesting successful strategies to get to a first detection of filaments; b) establishing quantitative methods to measure physical conditions of extragalactic magnetic fields and particle acceleration in radio. Simple extrapolations from the scale of clusters presently have little predictive power in the IGM, given the large differences in the degree of magnetisation and in the plasma parameters. Instead, my new simulations will suggest quantitative procedures to invert complex radio signals into physical measurements. An analogy can be made with "radio relics" (e.g. Feretti et al. 2012), where only through detailed modelling it is now possible to use radio observations as a probe of particle acceleration in clusters (e.g. Hoeft & Brüggen 2007; Pinzke et al. 2013; Vazza & Brüggen 2014; Brunetti & Jones 2014).





The level of detected emission from filaments can constrain the combination of magnetic field strength and electron acceleration efficiency at strong shocks (Vazza et al. 2015 a,b). Complementary to this, Faraday Rotation can be used to infer the amplification properties and distributions of scales of IGM magnetic fields. The *left Figures* show preliminary work on Faraday Rotation Measure (FRM) from an intracluster filament that will be targeted for my allotted JVLA proposal. The top panels show the FRM for a ~10 Mpc filament, predicted by MHD simulations (left) or with the additional contribution from small-scale turbulent motions, added using our MiRò code (Bonafede, Vazza et al. 2013,2015). The lower figure shows the radial trend of FRM along the filament, for a few variations of the strength of small-scale turbulent motions. This JVLA observation will probe the FRM down to a few rad/m^2, and this will probe the fluctuating magnetic field down to a level of ~0.1% of the thermal gas energy. In case of no-detection of FRM region, I will be able to limit the primordial seed magnetic field down to $<10^{-11}$ G, ~10-100 lower than the present constraints (Planck Collab. 2015). This will be possible because, given the density structure of the filament (also calibrated with X-ray data) a lack of detection will limit the maximum allowed magnetic field amplification in the target. At the same time, a non-detection will also limit maximum seed magnetic field, if the magnetic field lines in the filament have only been subject to gas compression.



For observations targeting at the synchrotron emission from shock-accelerated electrons, the expectations are that the cosmic web will be detectable only via long targeted exposures, or via stacking techniques. The chance of detecting shocks in filaments is maximum at low frequency, due to the better sampling of large scale emission (i.e. on ~1 degree for structures at ≈100 Mpc). Instruments working at >1000 GHz are instead more disadvantaged due to the lack of short baselines. The *Figure on the right* shows the results of my preliminary simulations of mock radio surveys with different instruments (taken from Vazza et al. 2015b). The vertical lines in the Figure connect the intrinsic simulated emission (big symbols) with the *detectable* emission once that observational filters are applied to each survey (small symbols). While the bulk emission from the intracluster medium (ICM) can be detected by all surveys, the large scale emission from the WHIM can be efficiently detected only by deep surveys with LOFAR, SKA1-LOW and MWA (and to a lesser extend, with ASKAP). In first approximation, the detected emission from the WHIM in large volumes will constrain $\xi_e B^2$, i.e. the combination of the electron acceleration efficiency at strong shocks and the (downstream) magnetic field of the WHIM. However, in the future various contaminants (e.g. radio galaxies, cluster emission) must be carefully removed and the complex simulations produced in sub-projecs 1/2 will serve to this task. The proposed modelling is mandatory to understand the best strategy for the stacking of the weak signal from filaments at this high frequency and understand the amplitude of $\xi_e B^2$ that the stacking can constrain. To better understand the observational procedure in real cases, I am involved as P.I. of the working group for the stacking of filaments and clusters for the EMU survey with ASKAP, using simulated filaments to study the best procedure to get to a statistical detection of the shocked cosmic gas.

- ✔ <u>*Post-Doctoral Fellow.*</u> A senior Post-Doctoral fellow with a consolidated experience in radio observations and data analysis will work on this sub-project for 3 years. She/he is expected to collaborate on new radio proposals and to perform the analysis of available or new radio data.

<u>**Executive summary**</u>

I will simulate observations with several instruments/configurations and measure the performances of alternative approaches to detect signal from the shocked gas in filaments (i.e. long targeted exposures, shallow surveys and stacking of multiple fields). Here is the detailed list of observations I will focus on, approximately in the predicted chronological order:

- **LOFAR-HBA** observation (already taken) of the joint between two clusters already detected through the SZ-effect (P.I. F. Govoni). As a collaborator of the proposal I can access the data to model the electron acceleration and magnetic fields at the filament. During this funding period I will propose for the observation of other promising targets in the next observing calls with LOFAR HBA.
- **Jansky Very Large Array** observation (proposal accepted) of Faraday Rotation from a ~ 13 Mpc region between two massive clusters. I am the P.I. of this proposal targeting 7 fields for a total of 49 hours. These observations (B/C priority) should be taken in 2016, and other promising targets with intracluster filaments will be proposed in next JVLA calls for observing time.
- **LOFAR-LBA and HBA surveys.** The surveys are ongoing and through my network of collaborators I have guaranteed access to the first calibrated data of LOFAR surveys. The Tier 1 and Tier 2 surveys should be delivered by the half of this granting period (~ 2019).
- **Murchison Widefield Array-GLEAM** survey at 73-231 MHz. This 2-year survey with shallow resolution (120") might be able to detect significant emission from filaments. I am collaborating with E. Lenc inside MWA for a proper extraction of the signal using mock observations.
- **Australian Square Kilometre Array Pathfinder-**EMU surveys at 1.4 GHz. The project includes a first survey with a reduced ASKAP configuration (start in early 2016) reaching ~ 25μJy/beam for ~1000

square degrees, also including polarisation information (POSSUM project). The Full Survey Science is expected to be completed in 2017. I am the P.I. of a working group for the stacking of filaments and clusters for the EMU survey, and a collaborator for the cross-correlation with galaxies. The modelling by numerical simulations is mandatory to design strategies for the stacking of the weak signal from filaments at this high frequency and extract physical information from this.

- **The Square Kilometer Array.** I participated the "Continuum" working group for the SKA-LOW and first explored the chances of detecting the cosmic web with the SKA, both in continuum or polarised intensity. However, the early science from the surveys with SKA1-LOW (~120 MHz) and SKA1-MID (~1 GHz) is expected in ~2020, e.g. towards the end of the requested granting period.
- **Multi-wavelength data:** the combination with X-ray, optical and IR catalogs which is important to refine the choice of candidates and to assess the baryon-to-radio bias of the galaxy distributions. These catalog includes: the Gama survey (access through J. Liske), the multi-wavelength Arches catalog, and the X-ray catalog of eROSITA sources (~2017, access ensured through the Hamburg Observatory).

Most challenging aspects of this sub-project.

- This is manifestly **the most challenging of my sub-projects**. Its success is mostly linked to the detection of the synchrotron cosmic web, which is not granted. The expected signal is weak in most scenarios, and only through a careful modelling of the specific response of each observation it will be possible to infer the magnetisation level of the gas. However, due to the quantitative use of simulations even *non-detections* will give unprecedented deep constraints on primordial fields and on acceleration efficiency. Based on the preliminary work for the accepted JVLA proposal on the Faraday Rotation from a possible intracluster filament, even the non-detection of Farady Rotation after 7h of exposure of each of my target fields will constrain the primordial field to $B_{seed}<10^{-11}$ G, which is ~10-10^2 better compared to the current limits from the CMB. Similarly, a combined limit $\xi_e B^2 < 0.001 \cdot (10nG)^2$ will be obtained from a non detection in the stacking of filaments and cluster outskirts with the EMU survey.

Expected results & Timeline

- *3rd year:* **constraints on magnetic field strength and topology in selected intracluster filaments.** The combination of the LOFAR-HBA observation of the SZ filament between clusters A399-A401 and my the accepted JVLA proposal for the observation of Faraday Rotation from an other intracluster filament will give unprecedented data to limit the magnetic field strength in the WHIM on filaments with sizes ~3-10 Mpc, thanks to the techniques developed during MAGCOW.
- *4th year:* **volume-averaged constraints on magnetic fields and electron acceleration in low-frequency radio surveys.** The analysis of the first clean data from the LOFAR-Tier1 survey and from the Gleam survey with MWA will enable to constrain the average $\xi_e B^2$ in IGM shocks.
- *5th year:* **statistical detection accretion shocks**. The stacking of filaments and cluster outskirts in the EMU survey with ASKAP (1.4GHz) aims at the detecting the signal from co-added accretion shocks in nearby structures, with a separate procedure for galaxy clusters and filaments. This will be feasible already with the early science of the EMU survey (~2017). Following from sub-project 2, the stacking will give unprecedented detail on the acceleration efficiency of electrons at accretion shocks.
- *5th year:* **predictions for the SKA.** The first science is expected only in ~2020, close to the end of the requested funding period for MAGCOW. The big efforts to bring the modelling of extragalactic radio astronomy to a higher level of complexity within MAGCOW will surely represent an important legacy for the modelling of future SKA data.

c. RESOURCES

Personal The MAGCOW project will consist of 4 members: the P.I. Dr. Franco Vazza, 2 PhD students, 1 senior Post-Doctoral Fellow and one Standard Post-Doctoral Fellow.

The selection of PhD and Post-Doc candidates will be performed based on an Equal Opportunity basis, and advertised internationally through public astronomical job registers. Each of the PhD student will focus on a specific astrophysical problem concerning non-thermal phenomena in large-scale structures, with a very close connection to relevant observational problems and available data. The basic numerical methods and analysis tool will be common to all sub-projects in order to allow the quick sharing of important developments within the group. Each candidate will produce independent scientific codes and will be fully responsible for her/his own line of investigation, thus enhancing her/his possibility of being recognized by the scientific community as leader in the topic. I plan to hire a **2 new PhD students in the first 2 years** (one each of first 2 years), who will obtain her/his PhD from Hamburg University.

The selection of Post-Doc Fellows will happen during the 1st year of funding. The first Post-Doc Fellow is expected to have already expertise in numerics, particularly in grid simulations and MHD methods. She/he will focus on the modelling of the energy evolution of electrons using passive tracer particles, starting from methods already developed in the past by the P.I. The position will last 2 years.

The second Post-Doc Fellow is expected to have a strong profile in radio astronomy and good expertise in the reduction of low-frequency data (e.g. LOFAR). She/he will dedicate to the analysis of radio observations available to the group, and collaborate to new proposals of observing time on LOFAR, JVLA and GMRT. This position will last 3 years.

The salaries of each member as computed as follows: <u>75,000E/year</u> for the P.I. and the Senior Post-Doc; <u>68,000E/year</u> for the Post-Doc ; <u>45,000E/year</u> for the 2 PhD students.

Suggested GANTT chart for the timeline of activities of MAGCOW. ♣=expected 1st author paper; ♦=expected coauthored paper.

Group Member	1st year	2nd year	3rd year	4th year	5th year
Principal Investigator	Simulated extragalactic mag. fields (sub-project 1). ♣♣♦ ♦				
		Simulations of collisionless shocks: ENZO, FLASH & TRISTAN-MP (sub-project 2).♦♦♣			
			Radio observations of the cosmic web (sub-project 3).♦♦♦♣		
PhD Student #1	Observational signatures of alternative magnetisation scenarios in extragalactic radio observations (sub-project 1). ♣♣♦				
PhD Student #2		Subgrid modelling of electron acceleration in cosmological simulations based on PIC results (sub-project 2). ♣♣♦			
Post-Doc Fellow		Spectral energy evolution of electrons with tracers (sub-project 1). ♣♣			
Senior Post-Doc			Radio observations and new proposals (sub-project 3). ♣♣♣♦		

<u>Costs</u> (a schematic view is given on the next page)

• *<u>Equipment.</u>* I will need a large efficient data-storage device for my numerical simulations. An estimated storage capacity of at least 200 Tb is necessary to store and share all data produced in the various sub-projects. to To ensure the portability of these data and enhancing the chance of sharing with international collaborators, the best option seems to be a Cloud Storage service, through which the data will be stored via web and migrated through the Gigabit Ethernet network. This web-based solution cuts off fixed electricity costs, has no and depreciation rate and allows an incremental billing of the used resources The most competitive solution is at present the Google Cloud Platform[7]. The expected costs in a scenario of an approximately linear increase of the necessary storage (200 Tb in total) is computed in <u>24,700 E.</u> I also request a laptop for every participant of MACGOW, to allow working remotely during visits and for making presentations at conferences and workshops. The best choice is the MacBook Air with 256GB of storage, which currently costs 1011 E[8], for a total of <u>5,055E.</u>

•*<u>Travels.</u>* The participation in international conferences is an important step in the dissemination of my results, and to establish new collaborations. Only very few international conferences are announced up to now for the period 2017/2021. I estimate an average cost 1500E for each conference , and consider 2 conferences/year for each member of the MAGCOW group (for a total of <u>48,000 E</u> for whole duration of the project). This project is a collaborative effort, and regular visits to the external collaborators of the Programme are anticipated (about 1 week for each visit, for a total budget of 1000 E/person per year, for a total of <u>16,000 E</u>). I will also invite collaborators to visit the host institution to strengthen the collaboration within the group, forecasting the need of 2 visits/year during the whole extent of the MAGCOW group (estimated cost of 800E/visit, for a total of <u>8,000E</u>). A period (about 2 months) of cooperation in a research institution external to the Hamburg Observatory will definitely represent an important experience of scientific growth for each PhD student of the group, who will have the chance of closely collaborating with other experts of the fields. I require funding for the 100% of the estimated costs of each of the 2 periods

7 https://cloud.google.com/storage/pricing#pricing-examples
8 http://www.apple.com/shop/buy-mac/macbook-air

abroad for the PhD students and consider a budget of 2000E for each of 2 planned long staying in external host institutions, for a total of 4,000E.

•*Publications.* I can estimate an overall budget of ~15,000 E for the full duration of the project, in order to cover the average cost for publication of my results in the Open Access mode provided by several astrophysical journals (e.g. A&A, MNRAS, New Astronomy etc.). The present cost for the OA mode goes from 400E(A&A) to 2000E(MNRAS). The number of total publications is estimated in at least 13 with members of the sub-project as 1st author (see table above), plus several other with external collaborators.

•*Dissemination.* I plan to organize at least 2 workshops with Germany and 1 international conference during the funding period, in order best disseminate my results as well as to promote collaborations with other researchers in the field. A total expense of 35,000E (5000 for each workshop and 25 000 for the conference) is estimated to cover most of the local costs (e.g. invited speakers, communication etc).

•*Other costs.* A gross estimate of 5,000 E is estimated to cover most of the catering costs for the planned workshops and conferences (e.g. coffee breaks, drinks). Additional 6,000E is the estimated cost of the audits the the University of Hamburg requires for European Project accessing a large budget (the audits will be performed by a subcontractor of the University).

Cost Category			**Total in Euro**
Direct Costs	**Personnel**	PI	375 000
		Senior Staff	
		Postdocs (senior)	225 000
		Postdocs	136 000
		Students	270 000
		Other	
	i. Total Direct costs for Personnel (in Euro)		1 006 000
	Travel		76 000
	Equipment (cloud storage and laptops)		29 755
	Other goods and services	Consumables	
		Publications (including Open Access fees), etc.	15 000
		Other: dissemination (workshops & conferences organised by the group, catering)	40 000
		Audit by University	6000
	ii. Total Other Direct Costs (in Euro)		166 755
A – Total Direct Costs (i + ii) (in Euro)			1 172 755
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)			293 188
C1 – Subcontracting Costs (no overheads) (in Euro)			0
C2 – Other Direct Costs with no overheads (in Euro)			
Total Estimated Eligible Costs (A + B + C) (in Euro)			**1 465 943**
Total Requested EU Contribution (in Euro)			**1 465 943**

•The P.I. dedicates to the project over the period of the grant: 90%

•The P.I. will spend 100% of working time in an EU Member State or Associated Country during the period of the grant.

Research Environment

Host institution – Hamburg Observatory (Germany)

The MAGCOW group will be hosted by the **Hamburg Observatory (Germany)**, which is ideal for the planned activities and tasks of the project, given its multidisciplinary topic of research, very good connection with technological and computational resources in the local and national-scale environment. The Hamburg Observatory is part of the University of Hamburg and has strong national (e.g. through DFG-founded Research Unit, i.e. *FOR 1254*[9], and The Collaborative Research Center *676*[10], DESY) and international collaborations (participation in LOFAR, eRosita, Gama).

Several scientific group at the Observatory are involved in activities which are strongly connected with the goals of the MAGCOW group: the Extragalactic Group led by Prof. M. Brüggen (theoretical and observational modelling of non-thermal processes in galaxy clusters, radio observations); the Star Formation and MHD group by Prof. R.Banerjee (MHD simulation of star formation processes, amplification of primordial magnetic fields); the Radio Astronomy group led by Dr. A. Bonafede (Junior Professor); the extragalactic group by Prof. J. Liske; the Stars & Exoplanets group led by Prof. J. Schmidt (X-ray astronomy and eRosita). Also the The Astroparticle Physics groups led by Prof.G.Sigl and Prof.D.Horns at the Institute for Theoretical Physics (University of Hamburg) are concerned with the very related and complementary topics of the origin and propagation of Ultra High-energy Cosmic Rays. The collaboration with Prof. Sigl's groups (propagation of UHECR with CRPropa[11], developed and maintained by the same group) and Prof. Horns'group (observational signatures of cosmic rays and perspectives from CTA[12]) has already started and is expected to expand in the next future.
In addition, the Hamburg Observatory operates an international LOFAR station, which ensures observational guaranteed time for future projects. Prof. M. Brüggen is a core member of the KSP Surveys, which brings privileged access to all the survey data, and this will enable a timely access to the scientific results to this large radio project also in the future. Several other researchers employed by the Hamburg Observatory are deeply involved in the LOFAR collaboration as well, and I expect them to provide precious support to the most observationally-related topics of MAGCOW.

Collaborators

At Hamburg University:

- **Prof. Marcus Brüggen** (shock particle acceleration, FLASH simulations sub-projects 1/2)
- **Junior Prof. Annalisa Bonafede** (radio observations, modelling of Faraday Rotation, sub-proj. 1/3.)
- **Prof. Jochen Liske** (synergy with optical/IR surveys, sub-project 3)
- **Dr. Wolfram Schmidt** (magnetic fields in cosmological simulations, sub-project 1).

In other institutions:

- **Dr. Claudio Gheller (**CSCS-ETH, Lugano - cosmological simulations, sub-project 1/2);
- **Dr. Gianfranco Brunetti** (IRA-Bologna, Italy - non-thermal mechanisms, sub-project 1/2);
- **Dr. Lorenzo Sironi** (CFA-Harvard, US - Particle In Cell simulations of cosmic shocks, sub-proj.2);
- **Dr. Chiara Ferrari** (Obsérvatoire de la Còte d'Azur, France - predictions for SKA, sub-proj. 3);
- **Dr. Shea Brown** (The University of Iowa, US - EMU survey, stacking sub-project 3);
- **Dr. Federica Govoni** (Cagliari Observatory, Italy - LOFAR observations, sub-project.3).

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9 http://www.astro.uni-bonn.de/~cosmag/index.php
10 http://wwwiexp.desy.de/sfb676/
11 https://crpropa.desy.de/Main_Page
12 http://www.cta-observatory.org/

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