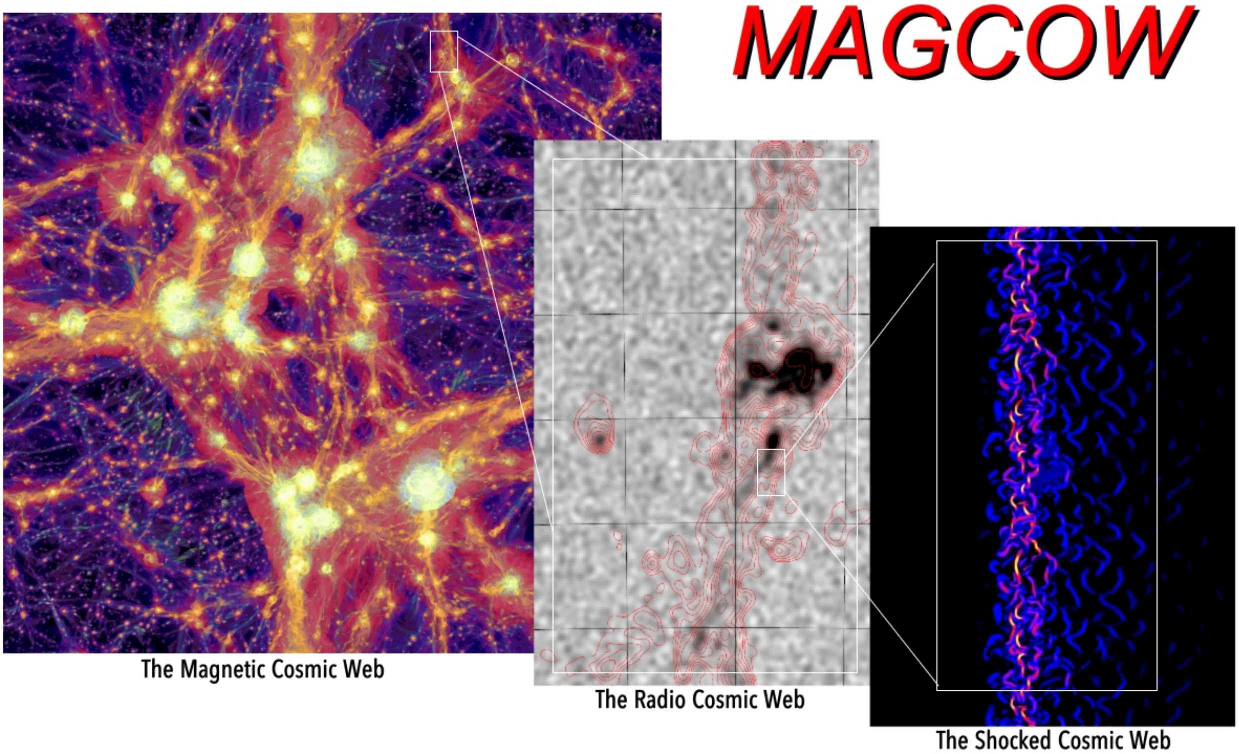
ERC Starting Grant Research proposal (Part B1)

MAGCOW



Principal Investigator: ***Dr. Franco Vazza***
Host institution for the project: ***Universität Hamburg***
Proposal full title: ***The MAGnetic COsmic Web***
Proposal short name: ***MAGCOW***
Proposal duration in months: ***60 months***

Proposal Summary:

On large scales cosmic matter is distributed in a web consistent of clusters, filaments, walls and voids.

While the dark-matter skeleton of the cosmic web is closely traced by galaxies and galaxy clusters, the gaseous distribution has never been directly imaged at any wavelength. This situation might change within the next decade, thanks to the new generation of radio instruments that will survey the sky: LOFAR, MWA, ASKAP and the Square Kilometer Array. Non-thermal components, relativistic particles and magnetic fields are thought to have a spatial distribution that is broader than that of thermal baryons. For this reason, the new generation of radio telescopes should might be able to detect the tip of the iceberg from the rarefied intergalactic medium, provided that magnetic fields are sufficiently amplified in these regions. The detectable signal is expected to be weak and complex because of the contribution from radio galaxies and to the presence of diffuse fore- and backgrounds.

The developments proposed in this ERC proposal are exactly designed to address this complexity, and turn future radio observations into a unique probe of the growth of magnetic fields and of the acceleration of particles. This will be possible through the theoretical exploration of plasmas in extreme conditions with sophisticated numerical simulations. With these simulations I will be able to predict the specific radio signature for the origin of extragalactic fields. This will enable the community to use radio surveys in a quantitative way and to determine the origin of extragalactic magnetism, a longstanding puzzle connected to many open questions of modern astrophysics.

The legacy of this project will be its quantitative representation of non-thermal processes on the largest scales, ultimately going to be fully exploited by the Square Kilometer Array.

Extended Synopsis - SCIENTIFIC MOTIVATION

General problems. 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. While the filamentary distribution of galaxies has been observed by deep optical and infrared survey, the gas locked into filaments and making up to ~ 50% of the total baryonic matter in the Universe remains invisible, (**"missing baryons"** , e.g. Cen & Ostriker 1998). X-ray, ultraviolet OVI, OVII and OVIII lines and the HI Lyman-α line are important tracers of the low density gas with temperatures $\sim10^4$-10^6 K along arbitrary directions where absorbers are (e.g. Richter et al. 2008). Yet the direct imaging of the gaseous cosmic web is missing, hampering our understanding of the cosmic gas flows between galaxies, groups and clusters.

The gas in the filamentary cosmic web affects several important questions of modern astrophysics. First, the thermodynamical properties of this very rarefied phase are largely uncertain: how is this gas kept collisional by collective plasma effects (e.g. Bykov et al. 2008)? Do filaments account for all missing baryons?

Second, the origin of **extragalactic magnetic fields** is unknown. Very different scenarios can account for the observations of magnetic fields in galaxy clusters and high-redshift galaxies (e.g. Widrow et al. 2012). These scenarios make very different predictions for the filamentary cosmic web, which can therefore be used as a unique probe of magnetogenesis (e.g. Vazza et al. 2014b).

Third, the cosmic web is encompassed by **strong shocks**, where cosmic gas gains entropy and becomes enriched with **cosmic rays** (Quilis et al. 1998; Miniati et al. 2000; Ryu et a. 2003). The acceleration efficiency of particles at these shocks is still unknown, and so is the back-reaction of accelerated particles onto magnetic fields (Caprioli & Spitkovski 2014; Guo et al. 2015). Relativistic electrons and magnetic fields will offer the chance of a first imaging of the cosmic web through their **synchrotron radio emission**. This project will enable the next generation of radio surveys to be a unique probe of cosmic magnetism and particle acceleration in the Universe.

The objectives of MAGCOW. Even in the most optimistic scenarios, the detectable radio signal from the cosmic web will be too weak and complex to allow any simple physical interpretation. However, this gap can be solved thanks to the advanced modelling I will develop during the MAGCOW project. Thanks to cosmological simulations of high complexity, **I will predict the observable radio signals implied by alternative magnetisation scenarios,** to be constrained with future radio surveys. At the same time, the acceleration of radio-emitting electrons will be studied across an unprecedented range of scales, by combining cosmological and particle-in-cell simulations of collisionless shocks. This approach will allow me to **relate the synchrotron emission at radio frequencies to the underlying magnetic fields.** This will **constrain the magnetisation history** of cosmic structures better than ever. Thanks to the proposed quantitative approach, even the *non-detections* of radio signals in deep surveys will constrain models with an unprecedented detail.

Uniqueness of MAGCOW. I have a unique expertise in the study of the complex interplay of shocks, turbulence, cosmic ray acceleration and magnetic fields in cosmology. My research work has been recently awarded the prestigious "*Borgia Prize from Accademia dei Lincei"* as best young italian astrophysicist in 2014. Thanks to several successful large programs I got allotted on European supercomputers, I produced and will be analysing some of the best simulations of cosmic rays and magnetic fields in cosmology[1], representing the starting step for MAGCOW. Third, my theoretical work has become increasingly connected to X-ray and radio observations, as tools to falsify models. My latest work is focused on producing realistic radio observations of simulated universes by including the most important ingredients of radio imaging. This is unique in this field and will help me to interpret future observations in detail. I am author and coauthor of successful observation proposals (with JVLA and LOFAR, respectively), aiming at a first detection of intracluster filaments, and I am also part of working groups for future radio surveys (EMU survey with ASKAP and SKA-LOW survey). I pioneered the quantitative prediction of radio imaging of the cosmic web with the SKA, with 3 contributions to the latest "SKA White Book".

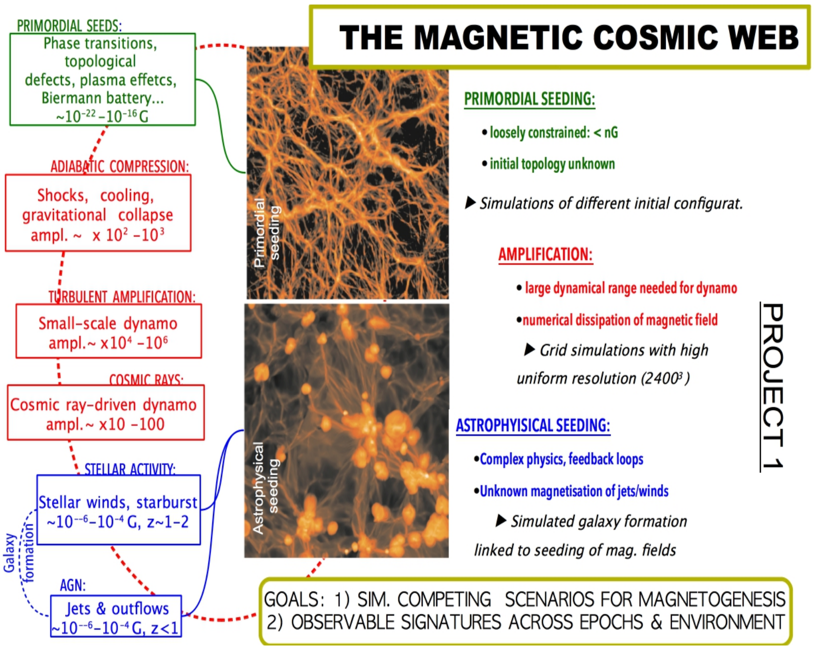
Through the success of this ERC Starting Grant I will be able to turn the above unique advantage points into a strong group focused on the exploration of the cosmic web in radio, and timely deliver groundbreaking results on the origin of magnetic fields and relativistic particles on the largest scales in the Universe.

1st SUB-PROJECT: the magnetic cosmic web

1a. Status Understanding the origin of extragalactic magnetic fields is an unsolved problem. Several competing scenarios have been proposed for the first "seeds" of the fields observed in galaxies and galaxy

1 http://www.cscs.ch/publications/highlights/2014/supercomputer_feels_magnetic_fields_in_the_cosmos/index.html

clusters. Fields up to several B~10 μG can be reached via small-scale dynamo amplification of weak seed fields starting at high redshift (Dolag et al. 2002; Bruggen et al. 2005; Subramanian et al. 2006; Beck et al. 2013).



These fields might come from phase transitions, Biermann battery, resistive mechanisms, plasma fluctuations (e.g. Brandenburg et al. 1996; Miniati & Bell 2011; Schlickeiser 2012; Widrow et al. 2012). However, also the injection of stronger fields by galactic winds, jets and supernovae can produce identical field strengths in clusters (Kronberg et al. 1999; Völk & Atoyan 1999; Xu et al. 2009). On the other hand, outside of dense structures the predictions of these scenarios differ by several orders of magnitude. Producing reliable simulations of extragalactic magnetic fields is still a challenge and the numerical study of cosmic magnetism is mad additionally difficult by the demand on dynamical range. Only for large Reynolds numbers (R_m>>10^2) the timescales for the exponential and following linear growth stages of magnetic fields are realistic (e.g. Beresnyak & Miniati 2015). In recent work I investigated the amplification of primordial magnetic fields in cosmic structures with grid simulations with a very large dynamical range (Vazza et al. 2014b) and this sub-project will expand these preliminary results.

<u>1b. Methods & strategy</u> I will simulate the effects of competing magnetic seeding models onto the largest scales and compare them with multi-wavelength observations. Thanks to a few large allotted computing project at CSCS-ETH (Lugano) I have access to arguably the best simulations of extragalactic magnetic fields, in term of dynamical range and physical complexity[2]. Here I use my original developments to the cosmological grid code ENZO[3] 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. The growth of supermassive black holes, assumed to track AGN accretion disks, with follows the implementation of sink particles by Kim et al. (2011). With my developments I can couple thermal or kinetic AGN feedback (Vazza et al. 2013) to the release of magnetic energy, injecting magnetised dipoles storing ε_B ~1-10%, of the feedback energy. The magnetic seeding from supernovae is also included (e.g. Donnert et al. 2009). In a parameter study, I will test both "radio" (jet) and "quasar" (heat) modes of feedback, by tuning parameters at the resolution of interest. Each model will be benchmarked against 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. radio luminosity function). In this last case, I will make use of the observed relation between the core radio luminosity and the mass accretion rate onto black hole particles to infer the radio emission (e.g. Kording et al. 2006). Moreover, I will 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). I will rely on the magneto-hydrodynamical method of the Dedner cleaning (e.g. Wang & Abel 2009), which is robust and accurate, even if affected by significant numerical dissipation at the smallest scales, which is cured by appropriately increasing the resolution. I will also simulate the acceleration of relativistic electrons by shocks, AGN and star forming regions, expanding my the 2-fluid model (Vazza et al. 2012, 2013, 2014a). The detailed analysis of the properties of cosmic filaments will be performed using the custom-built parallel filament finder recently presented in Gheller, Vazza et al. (2015). The production of these simulations started in September 2015 and will be completed by the middle of 2016.

<u>1c. Results, challenges & timeline</u> All simulated magnetic seeding scenario will produce statistics to enable quantitative testing by incoming radio observations. The main products expected from this subproject are:

- *1st year:* **Strength and topology of magnetic fields** in cluster outskirts and filaments for each competing scenarios. Critical gas density/temperature where the prediction from different scenarios diverges.
- *2nd-3rd years:* **Observable proxies**, such as **synchrotron radio emission** (e.g. Vazza et al. 2015a) and **Faraday Rotation** (e.g. Bonafede, Vazza et al. 2015) that will be used to constrain the level of extragalactic magnetic fields from observations. A PhD student will be recruited to work on the modelling of Faraday

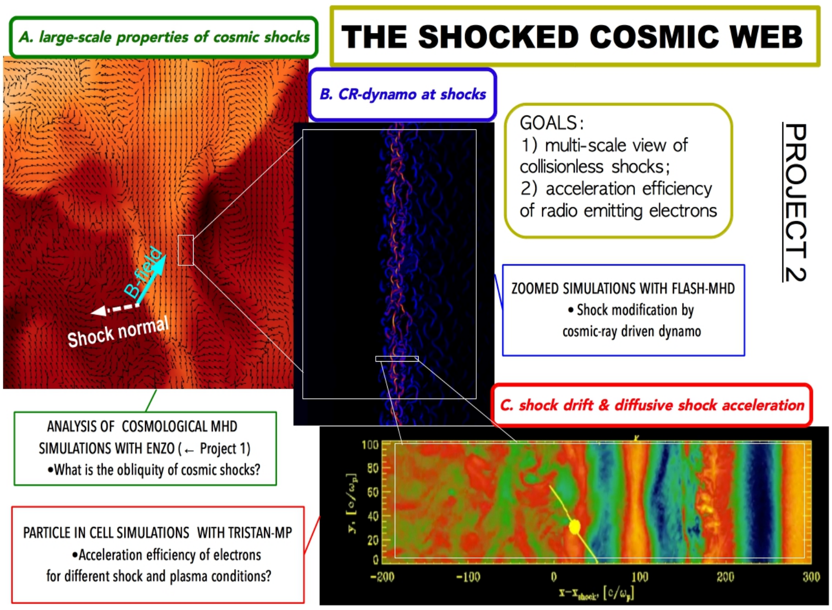
2 http://www.cscs.ch/publications/highlights/2014/supercomputer_feels_magnetic_fields_in_the_cosmos/index.html
3 ENZO is a parallel cosmological grid code largely used in the community, see *enzo-project.org* and Bryan et al. (2014).

Rotation with these large simulations, 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). This is a very relevant tool for the planned high-resolution surveys.

- *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. Tracers will make it possible to follow in detail the ageing of radio emitting particles over time as they are advected into structures.
- *Risk management:* this sub-project ensures timely results and will build on methods already developed in the past. The necessary computing time is already available from allotted projects, or can be obtained from local resources. The high-risk high-gain aspect is represented by the comparison of galactic seeding models to observations, specially at the ~20 kpc scales which will be probed by our runs, requiring the careful tuning of sub-grid parameters for star formation and AGN feedback. This is made non-trivial by the non-linearity of galaxy formation processes. However, my documented numerical expertise, my preliminary results and the large literature available on the topic makes it a very reasonable goal with the time frame of this sub-project.

2nd SUB-PROJECT: the shocked cosmic web

2a. Status The growth of cosmic structure is coupled with the generation of shocks, powered by accretion of gas or by mergers (e.g. Gabici & Blasi 2003; Ryu et al. 2003; Pfrommer et 2006). These collison*less* shocks convert a fraction of the energy of gravitationally accelerated flows into thermal energy, amplification of magnetic fields and possibly into the acceleration of relativistic particles (Bykov et al. 2008). *Radio relic* emission in galaxy clusters shows that particle acceleration is quite efficient at weak merger shocks (Brunetti & Jones 2014). Although these shocks are very different from those observed in supernova remnant and in the heliosphere, they are fairly efficient particle accelerators. The diffusive shock acceleration (DSA) mechanism explains how particles are accelerated to high energies once that the particles are energetic enough (e.g. Kang & Ryu 2013). However, recent studies on radio relics suggests that there the acceleration efficiency of protons and electrons is at odds with the expectations of DSA (Vazza et al. 2014c, 2015c). A powerful method to study collisionless shocks is represented by particle in cell (PIC) simulations, which directly evolve charged macro-particles under the Lorentz force, computed on a grid. Recent PIC simulations describe the complex scenarios in which protons (Caprioli & Spitkovski 2014) and electrons (Guo et al. 2015) gain energy by crossing different regions around shock in $\beta >> 1$ plasmas[4]. However, the dependence of the acceleration mechanisms of electrons and protons on the local plasma conditions and on the shock obliquity, as well as the feedback of accelerated particles onto the shock structure are unexplored territory, specially at this expected low magnetisation level.



2b. Methods & strategy **I will bridge the large scales where cosmic shocks form to the microscopic scales of collisionless shocks where single particles scatter onto MHD waves,** for the first time combining 3 different numerical approaches to get a global view of the process. First, with cosmological ENZO simulations (sub-project 1) I will constrain the typical plasma parameters and obliquity of shocks (defined as the angle between the shock normal and the upstream magnetic field) for competing magnetic seeding scenarios, on scales of $\sim 10^2$ kpc. These scales will represent the initial conditions for following resimulations with the FLASH grid code as in Brüggen (2013, a collaborator of this project). Here I will model the time-dependent evolution of shocks down to a resolution of ~0.1 kpc, studying the interplay between the shock structure and the amplified magnetic fields from cosmic-ray driven dynamo (Downes & Drury 2012; Brüggen 2013). The amount of cosmic ray protons partaking the shock will be constrained by hybrid simulations (e.g. Caprioli & Spitkovski 2014). The FLASH runs will be used to predict how much of the shock surface is predominantly parallel or perpendicular to the upstream magnetic field. The TRISTAN-MP code[5] will finally use the result of FLASH runs to setup the boundary conditions of a large survey of PIC simulations, which will extend the hydro-MHD picture to the collisionless

4 The plasma beta, $\beta=(M/M_A)^2$, is the ratio between the sonic and the Alfvenic Mach numbers, giving the magnetisation of a plasma.

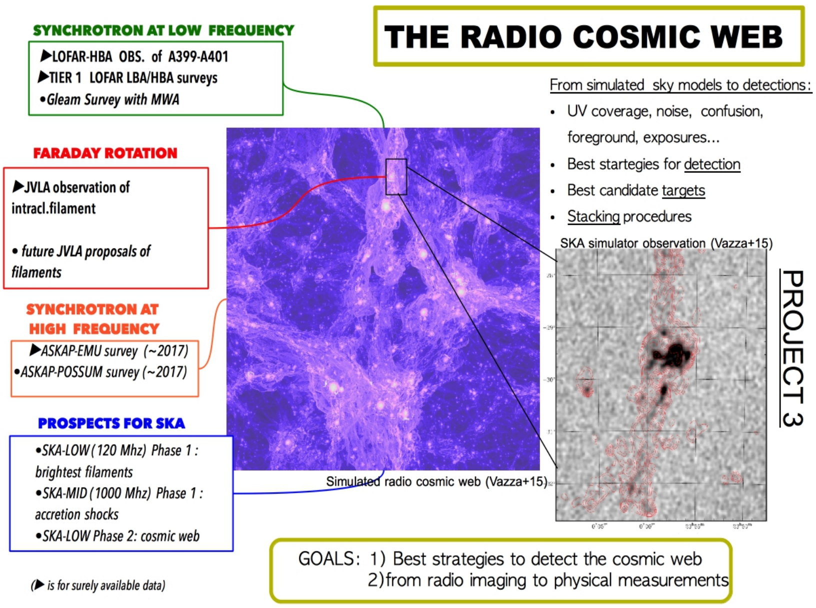
5 Tristan-MP (Spitkovsky 2005) is a parallel version of the TRISTAN code that was optimized for collisionless shocks.

regime of astrophysical shocks. Here I will resolve regions of a few hundredths of the electron gyroradius, i.e. $\sim 10^{-4}$-10^{-3} kpc for ~1nG magnetic fields. These simulations will be tailored to predict the acceleration efficiency of electrons for a realistic range of shock parameters and resulting from different possible mechanisms as shock-drift acceleration (SDA), classic DSA or shock surfing acceleration.

2c. Results, challenges & timeline For the first time cosmological MHD simulations and PIC methods will be combined to give quantitative results on the acceleration of electrons by cosmological shocks.

- *2nd 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 will survey shock parameters with PIC runs. Among the important parameters under scrutiny, 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). 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). A PhD student will be hired to lead this part of the sub-project.
- *Risk management.* Using the real electron to proton mass ratio in PIC runs is still 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. In order to overcome the most critical and technical difficulties related to this sub-project, a collaboration with Lorenzo Sironi (CFA), a world expert on the field, has been established since 2015 and will continue for MAGCOW.

3rd SUB-PROJECT : the radio cosmic web



3a. Status The gas network of the cosmic web has never been observed in radio. Yet the evidence of non-thermal emission in the intracluster medium (e.g. Feretti et al. 2012) 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 (LOFAR, ASKAP, MWA, SKA). If the acceleration of electrons at shocks is at least as significant as in clusters[6] and the the magnetic fields are of a few percent of the thermal gas energy, the synchrotron emission should offer a better chance of first imaging the low-redshift cosmic web. The chances of a successful imaging of the synchrotron cosmic web are higher than using the emission from the HI line, which is instead a better probe of the denser circumgalactic medium at high redshift (e.g. Popping et al. 2015). First rough estimates where given by Keshet et al. (2004) and Brown (2011), while my recent work have pioneered the detailed analysis of radio imaging of the cosmic web with the SKA, LOFAR and other radio telescopes (Vazza et al. 2015a,b). A complementary view on extragalactic fields will be given by Faraday Rotation grids with future radio surveys (e.g. Gaensler et al. 2015), which should get to a statistical detection of the cosmic web (Vacca et al. 2015, Bonafede, Vazza et al. 2015).

3b. Methods & strategy I will produce synthetic radio observations of the cosmic web, with the goal of establishing successful strategies for a first detection of filaments and enabling **quantitative science of the cosmic web with radio observations**. I will employ the modelling obtained in the first two sub-projects to turn radio observations into a tool to measure the strength of magnetic fields and the efficiency of particle acceleration

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6 $\xi_e \sim 10^{-3}$-10^{-5} of the shock kinetic power, e.g. Hoeft & Brüggen (2007); Bonafede et al. (2012); Pinzke et al. (2013); Vazza et al. (2014)

at strong shocks[7], as discussed in Vazza et al. (2015a,b). My modelling will include realistic factors such as galactic foregrounds (e.g. Bonaldi & Brown 2015), the contamination from simulated radio galaxies and clusters (sub-project 1) and all basic steps of radio imaging: finite resolution, sensitivity and sampling of baselines as in Vazza et al. (2015a,b).

3c. Results, challenges & timeline. Thanks to my membership in working groups of future radio surveys (ASKAP, SKA), to my collaborators and through allotted observational proposals with LOFAR and JVLA, I have access to promising data to detect the synchrotron cosmic web. With mock observations I will derive the best combinations of baseline sampling, exposures, frequencies and targets to maximise the chance of detection.

- *3rd year:* **magnetic fields and electron acceleration on the intracluster filaments.** I will have access to the already performed LOFAR-HBA observation of the joint between clusters A399-A401. The P.I. F. Govoni is a collaborator of MAGCOW and my simulations will be used for the interpretation of the cleaned data. I am the P.I. of a 49 hours observation of Faraday Rotation with the JVLA (B-configuration, B/C priority) targeting another likely intracluster filament, which will constrain the **topology and strength of magnetic fields.**
- *4th year:* **volume-averaged constraints on magnetic fields and electron acceleration in low-frequency radio surveys**, LOFAR-Tier1 survey and Gleam survey with MWA, that I will access through collaborators.
- *5th year:* **statistical detection of the radio cosmic web**. I am the PI of a working group for the stacking of filaments and cluster outskirts in the EMU survey with ASKAP (1.4GHz). I am designing the best strategies to co-add fields with high chances of hosting filaments, but with too weak signals to be individually detected. The cross-correlation with other multi-wavelength proxies is crucial and will be derived using mock observations.
- *5th year:* **predictions for the SKA.** The first science is expected in ~2020, at the end of the requested grant.
- *Risk management.* This is manifestly **the most challenging of my sub-projects**. Its success is linked to the successful 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 my JVLA proposal to observe Faraday Rotation from the likely location of an intracluster filament, the non-detection of the signal in a 49h pointing will constrain the primordial field to $B_{seed}<10^{-11}$ G, ~$10-10^2$ better compared to the limits from the CMB (Planck Collab. 2105). 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.

Students, Collaborators & Research Environment

The funding for MAGCOW includes the hiring of 2 PhD students and 2 Post-Doctoral fellow:

- one PhD student will study the observable properties of alternative magnetisation scenarios in sub-project 1;
- one PhD student will focus on PIC simulations of electron and proton acceleration in sub-project 2;
- one Post-Doctoral Fellow will simulate the evolution of electron spectra with tracers in sub-project 1;
- one senior Post-Doctoral expert in radio data reduction and analysis will work on sub-project 3.

MAGCOW will be hosted by the Hamburg Observatory (Universität Hamburg). There I will collaborate with: **Prof. Marcus Brüggen** (particle acceleration), **Junior Prof. Annalisa Bonafede** (radio observations), **Prof. Jochen Liske** (optical/IR surveys), **Dr. Wolfram Schmidt** (numerical methods). Additional collaborators in other institutions will be: **Dr. Claudio Gheller** (CSCS-ETH, Lugano - cosmological simulations); **Dr. Gianfranco Brunetti** (IRA-Bologna, Italy - particle acceleration); **Dr. Chiara Ferrari** (Obsérvatoire de la Còte d'Azur, France - predictions for SKA); **Dr. Shea Brown** (The University of Iowa, US - EMU survey); **Dr. Lorenzo Sironi** (CFA, USA - PIC simulations); **Dr. Federica Govoni** (Cagliari Observatory, Italy - LOFAR observations).

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

Group Member	1st year	2nd year	3rd year	4th year	5th year
Principal Investigator	Simulated magnetic fields in cosmology (sub-project 1). ♣♣♦ ♦				
		Multi-scale 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). ♣♣♣♦		

7 This will constrain $\xi_e \cdot B^2$, where ξ_e is the acceleration efficiency of electrons at shocks and B(<3.2μG) is the magnetic field.

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Section b: Curriculum Vitae

Personal Data:

Born: Vittorio Veneto (TV), Italy, 19/09/1979.
Nationality: Italian.
Present position: Post-Doctoral Fellow of German Science Fundation (DFG)
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Email: franco.vazza@hs.uni-hamburg.de
Home page: http://cosmosimfrazza.myfreesites.net/
Career Breaks: on parental leave for 5.5 months during 2015.

Main topics of research

I am a numerical astrophysicist with experience in the numerical modelling of accretion processes in large-scale structures, including shocks, turbulence, particle acceleration and magnetic fields. My simulations have been used for the physical interpretation of many observed emissions from galaxy clusters in radio waves, X-rays and γ-rays. My recent work focuses on science that will be possible with future big radio surveys.

I have marked in **boldface** the following details of my CV which are more relevant for this ERC proposal.

Formation and Career:

- 22/07/2004: Degree in Astronomy at the University of Padova (mark 105/100), supervisor Prof. G.Tormen - 2004: Research Grant from Department for Information Engineering, University of Padova (4 months, supervisor Prof. G. Tormen)
- 2005: Research Grant from Bologna University (6 months, supervisor Prof. G. Setti)
- 2006: winner of one PhD position at University of Padova (declined).
- 2006-2008: PhD student at the Astronomy Department at Bologna, winner of the INAF grant for PhD in Radio Astronomy (36 months, supervisors Prof.G.Setti an Dott.G.Brunetti).
- 2008: Marco Polo grant from University of Bologna, covering 3 months of research abroad.
- 07/04/2009: Defense and approval of PhD Thesis.
- 2009-2010: Post-Doctoral Fellow at IRA-Bologna (20 months).
- 2010-2012: Post-Doctoral Fellow at Jacobs Univ. Bremen (24 months).
- **1/08/2012 - till present: DFG Post-Doctoral Fellow at Hamburg Observatory.**
- **I have been on parental leave from 10/03/2015 to 09/08/2015 and from 01/09/2015 to 15/09/2015.**

Teaching/education duties:

- 1999-2007: Outreach activity at the Public Observatory in Vittorio Veneto (Italy);
- 2005: High School Teacher (maths and physics) in Vittorio Veneto (Italy); - 2006 - 2010: Outreach activity at the Visitor Centre of Medicina Radio Telescope (Bologna);
- 2003 - till present: coworker of the Italian Astronomical magazine “Le Stelle“, as writer of scientific articles for the general public;
- 2010: Introductory lessons on cosmology and cosmological numerical simulations for PhD students at Jacobs University Bremen (Germany).
- 2011: Teaching at the University of Bologna (Astronomy Department) of a module on ”Non-thermal processes in galaxy clusters”, within the Master Degree course by Dr. F. Brighenti.
- 2011: Coadvisor of PhD Thesis by Thomas Guimbrètiere at Jacobs University Bremen;
- 2013: Supervisor of Bachelor Thesis by Manuel Stubbe at Hamburg University. The thesis focused on the simulated scaling relations of galaxy clusters.
- 2014: Supervisor of Bachelor Thesis by Stefan Hackstein at Hamburg Univiersity. The thesis focused on the propagation of ultra-high cosmic rays in extragalactic magnetic fields.
- **2015-..: Supervisor of Master Thesis by Stefan Hackstein at Hamburg University (ongoing). The thesis focuses on the observational signatures of competing models for extragalactic fields on the propagation of ultra-high energy cosmic rays.**
- **2014-..: Supervisor of PhD Thesis by Denis Wittor at Hamburg University (ongoing). The thesis focuses on the study of particle acceleration in clusters as a function of shock obliquity.**
- **2015-2016: University lectures on "Non-linear growth of structures and numerical cosmology" within the Master Course of Prof. M. Brüggen (6 hours).**

Memberships, commitments and duties:

- 2010-2014: Associated member of National Italian Institute for Astrophysics (INAF).
- 2010-2015: Referee for A&A, ApJ, MNRAS.
- 2011-2015: Referee for CPU allocation time at CINECA (Italy).
- 2010-2015: Associated member of the research unit FOR1254 of DFG.
- **2013-2014: Member of the SKA1-Low Tiger team of SKA1-Low.**
- **2015: Member of 2 working groups (on stacking for clusters and filaments as P.I. and on the cross-correlation with galaxy distribution as collaborator) for the EMU survey with ASKAP.**
- **2015: Member of working groups for the WHIM and galaxy clusters of ATHENA.**
- 2015: Member of the International Astronomical Union.

Successful proposals:

<u>*Computing projects*</u> (as Principal Investigator):

- 2004-2008 : 170 000 allotted CPU hours for 6 regular projects at CINECA (Italy).
- 2009: 400 000 allotted CPU hours as winner of Italian National Key Project at CINECA.
- 2010: 970 000 allotted CPU hours for the PRACE-1IP 7.1 optmiziation call at Julich (Germany).
- 2011: 800 000 allotted CPU hours on JUROPA-Juelich (Germany)
- 2011: 150 000 CPU hours at CINECA.
- 2012: 1 700 000 CPU hours allotted on CURIE (France) for a PRACE proposal
- 2013: 130 000 allotted CPU hours at Juelich (Germany).
- 2013: 1 500 000 CPU hours on FERMI at CINECA (coauthor).
- 2014: 8 000 000 CPU hours on PizDaint @CSCS (Lugano, Switzerland) for the CHRONOS Proposal.
- **2015: 1 200 000 CPU hours allotted on JURECA @ Juelich (Germany).**
- **2015: 32 000 000 CPU hours allotted on PizDaint @ CSCS (Lugano, Switzerland).**

<u>*Observational projects*</u>:

- 2011: X-ray observation of galaxy clusters with XMM, allotted 200ks (P.I. D.Eckert, coauthor).
- 2011: Radio observations of radio relics with GMRT (P.I. A.Bonafede, coauthor).
- 2012: Radio observations of radio halos with JVLA(P.I. A.Bonafede, coauthor).
- 2013: X-ray observations of galaxy clusters with XMM, allotted 330ks (P.I. D. Eckert, coauthor)
- **2014: Radio proposal for LOFAR on intracluster filament (P.I. F. Govoni, coauthor).**
- **2015: ALMA 100GHz observation of El Gordo cluster (P.I. K. Basu, coauthor)**
- **2015: P.I. of allotted JVLA observation of Faraday Rotation from intracluster filaments in B configuration, 49 hours, score 2.4 (priority B & C).**

On-going Grants

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
FOR 1254[8]	DFG	E13-TVL salary	Until 01.06.2016	Post-Doctoral fellow	This will be terminated should the ERC proposal be successful

Pending applications

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
Rita Levi Montalcini	Italian Ministry of	own salary	3 years	applicant	no overlap with ERC research project

8 http://www.astro.uni-bonn.de/~cosmag/index.php . The P.I. presently is a post-doctoral fellow of this research unit.

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
Fellowship	University				
Post-Doc Fellowship	DFG	own salary	3 years	applicant	This will be terminated should the ERC proposal be successful
INAF Permanent Researcher	INAF	own salary	permanent	applicant	no overlap with ERC research project
Professor of Extragalactic Astronomy	University of Potsdam	own salary	permanent	applicant	no overlap with ERC research project
Professor of Extragalactic Astronomy	University of Wien	own salary	permanent	applicant	no overlap with ERC research project

Section c: Early achievements track-record

In my research I have realized unique numerical studies that contributed to a enlarge our understanding of non-thermal processes in the Universe. My research has been awarded the prestigious *Borgia Prize from Accademia dei Lincei*, which I received in Rome on 26th June 2014 at the presence President of the Republic. The following are the main lines of research that I am conducting:

- **The magnetised cosmic web.** *I have produced the largest simulations of cosmological magnetic fields* to date, which are still being used to study the amplification history of magnetic fields in large-scale structures (Vazza et al. 2014, MNRAS). *I have pioneered the study of the synchrotron cosmic web,* by producing mock radio observations to compare with existing and incoming radio surveys (e.g. LOFAR, SKA-LOW and MWA), showing that these can constrain the magnetisation history of the comic web (Vazza et al. 2015 AASKA, Vazza et al. 2015 A&A; Bonafede, Vazza et al. 2015 AASKA).
- **Turbulence in the intracluster medium.** My numerical work on simulating the properties of turbulent motions in the intracluster medium of cluster of galaxies is well known in the community, and I have authored *3 of the 10 most cited papers on "turbulence+galaxy+clusters" on NASA-ADS* (as the first author in 2 cases and the 2nd author in the other). I have established for first the existence of a Kolomogrov-like distribution of motions in the intracluster medium, and delivered to the community algorithms for a better extraction of turbulence in complex data. Recently, I have coauthored a review book chapter on this topic (Brüggen & Vazza 2015 ASSL).
- **Shocks and cosmic ray acceleration.** My main contribution to the field is the *original code implementation to simulate the acceleration and feedback of cosmic rays in grid cosmological simulations* (Vazza et al. 2012, 2013 and 2014 MNRAS). This presently is the only grid method with the capability of simulating diffusive shock acceleration in cosmology using a grid approach, which I extensively used to constrain the (unknown) acceleration efficiency of cosmic ray proton in large-scale structures. With this method I have produced the largest simulations to date with cosmic ray physics.
- **Comparison of numerical methods.** I have directed an important project of numerical comparison among codes used in cosmology (Vazza et al. 2011, MNRAS), which still defines the standard of shock finding in cosmological simulations. I have been recently involved in other comparison of numerical methods, studying the effect of adaptive-mesh refinement on idealized simulations (Schmidt et al. 2014).
- **Radio relic emission in galaxy clusters.** My simulations provided important guidance to understand the energetic, radial distribution and scaling relations of observed *radio emission in clusters ("radio relics"). My latest works highlighted open problems* in understanding the electron (pre)acceleration in relics and the absence of gamma-ray emission from the host clusters, inconsistent with the standard view of diffusive shock acceleration (Vazza & Brüggen 2014 MNRAS; Vazza et al. 2015 MNRAS).
- **The peripheral regions of clusters.** My simulations have been used also to interpret the observed trend of density, temperature, entropy and baryon fraction up to the virial radius of galaxy clusters, obtained by combining ROSAT and PLANCK data (e.g. Eckert, Vazza et al. 2012, A&A; Eckert et al. 2013a,b A&A). The estimate of the clumping factor from simulations is crucial for an unbiased measure of the cluster mass and baryon fraction (Vazza et al. 2013 MNRAS; Eckert et al. 2015 MNRAS).

Although my work is theoretical in several aspects, its impact on the community is documented by my coauthorship to observational papers (10 at the moment, including radio, optical, X-ray and gamma-ray observations), as well as by the number of observational proposals that I coauthored. In 2013, in collaboration with A. Bonafede, I developed an original code for the simulation of Faraday Rotation in synthetic dataset (MiRò), which can be freely downloaded via Web[9].

PUBLICATION LIST

So far I have signed my papers with ~50 researchers working in ~10 different countries.
My personal publication summary, updated to November 2015, reads:

- 38 referred papers in international astronomical journals (23 as the P.I.);
- >1040 citations (>600 for P.I.'s articles);
- h-index of 18 (14 as P.I.'s articles).

Here the 5 publications that I consider most relevant for this grant proposal. They do not represent the list of my most cited. Those including the presence of my PhD supervisor (G. Brunetti) are marked in italic.

9 http://www.hs.uni-hamburg.de/DE/Ins/Per/Vazza/projects/MIRO.html

1. ***VAZZA F**., Brunetti G, Kritsuk A, Wagner R, Gheller C, Norman M (**2009**). Turbulent motions and shocks waves in galaxy clusters simulated with adaptive mesh refinement. ASTRONOMY & ASTROPHYSICS, vol. 504; p. 33-43, ISSN: 0004-6361, doi: 10.1051/0004-6361/200912535* (106 citations, 96 excluding self-citations)
2. ***VAZZA F**., Brunetti G, Gheller C (**2009**). Shock waves in Eulerian cosmological simulations: main properties and acceleration of cosmic rays. MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, vol. 395; p. 1333-1354, ISSN: 0035-8711, doi: 10.1111/j.1365-2966.2009.14691.x* (78 citations, 65 excluding self-citations)
3. **VAZZA F**., Gheller C, Bruggen M (**2014**). Simulations of cosmic rays in large-scale structures: numerical and physical effects. MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, ISSN: 0035-8711, doi: 10.1093/mnras/stu126 (28 citations, 24 excluding self-citations)
4. **VAZZA F**., Bruggen M, Gheller C, Wang P (**2014**). On the amplification of magnetic fields in cosmic filaments and galaxy clusters. MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, ISSN: 0035-8711, doi: 10.1093/mnras/stu1896 (11 citations, 8 excluding self-citations)
5. **VAZZA F**., Ferrari, C., Brüggen, M., Bonafede, A., Gheller, C., Wang, P. (**2015**). Forecasts for th detection of the magnetised cosmic web from cosmological simulations. ASTRONOMY & ASTROPHYSICS, ISSN: 0004-6361, doi: 10.1051/0004-6361/201526228 (2 citations, 2 excluding self-citations)

Invited talks at international conferences:

- 2010: “Non Thermal Phenomena in Colliding Galaxy Clusters”; 15-20, November, France.
- 2012: ”New Horizons in Computational Astrophysics ”, 29-31 January, Davos, Switzerland;
- 2012:”Maison de la Simulation” , 4 April, PRACE conference, Orsay, France;
- 2013: CASPAR meeting, 18-20 September, Hamburg, (Germany);
- 2013: “Towards Exascale Computing” conference, 15-19 September, Ascona, Switzerland;
- 2014: ”High Energy Meeting BOHEME”, 7-9 April, Bologna, Italy;
- **2015 Invited review at Shock acceleration from the solar system to cosmology, Lorenz Centre (Leiden, Nederlands), 5-10 January;**
- **2016 Invited talk at "Exploring the outskirts of galaxy cluster" EWASS, 4-8 July, Athens , Greece.**

Fellowships, Awards & Grants

- 2008: winner of Marco Polo grant from the University of Bologna, for an research experience abroad during the PhD.
- 2009: winner for best contribution contest at “Cosmological Magnetic Field” Conference (31.05-5.06, Ascona, organized by ETH), award in money.
- 2010: winner of a “Taux3” grant from French Government and Scientific Bureau of French Embassy in Italy (declined).
- 09/2010-07/2012: Post-Doc Fellow at Jacobs University Bremen (Germany).
- 2011: winner of money award for “Abstract of best contributed presentation”, Cefalu ́, Italy.
- 08/2012-till present: DFG Post-Doc Fellow at Hamburg Observatory (Germany).
- 2013 Qualified to ”Maıtre de conferences” in France (Section 34)
- **2014 awarded DFG grant for the hiring of 1 PhD student as a PI. The grant covers 3 years of PhD salary and 12,000 Euro of travel/collaboration expenses.**
- **2014 winner of Borgia Prize from Accademia dei Lincei , as ”best italian young astrophysicist” received in Rome at the presence of the President of the Italian Republic (26th June 2014). The prize is assigned only every 4 years and is worth of 10,000 Euro.**