Everyprobe,
Everywhere,
All Magnetic Fields at once

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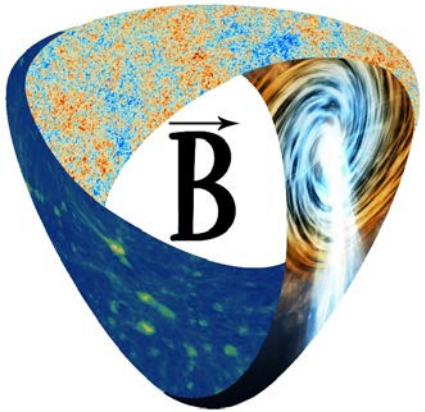
The current INAF side of the magnetic force



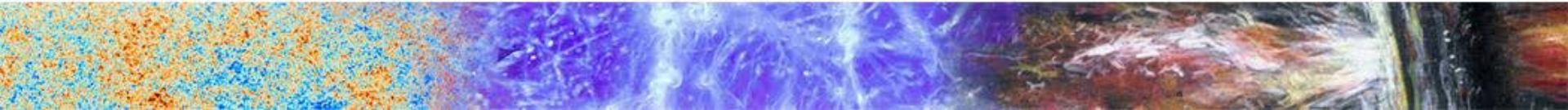
OUR SCOPE

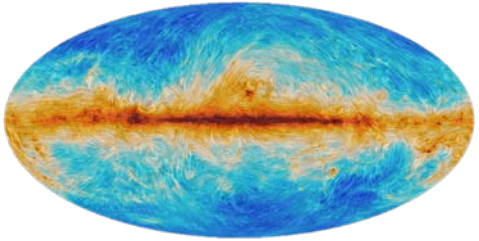
To understand and disclose the entire history of Universe Magnetism from the Big Bang to our days finally discovering the origin of Cosmic Magnetism

To use Universe Magnetism as a probe to investigate the fundamental physics of the Early Universe at energies not reachable by any other probe

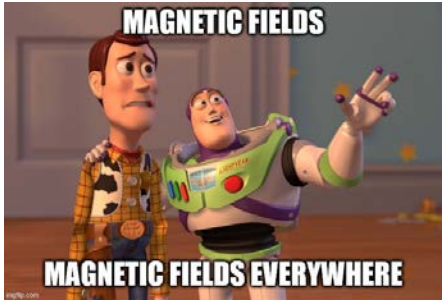
To design the roadmap for the interpretation of the next decade of cosmological and astrophysical MAGNETIC observations

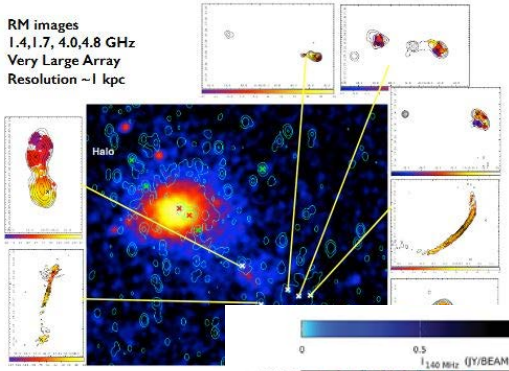
Background Universe image Pablo Carlos Budassi/Wikimedia Commons



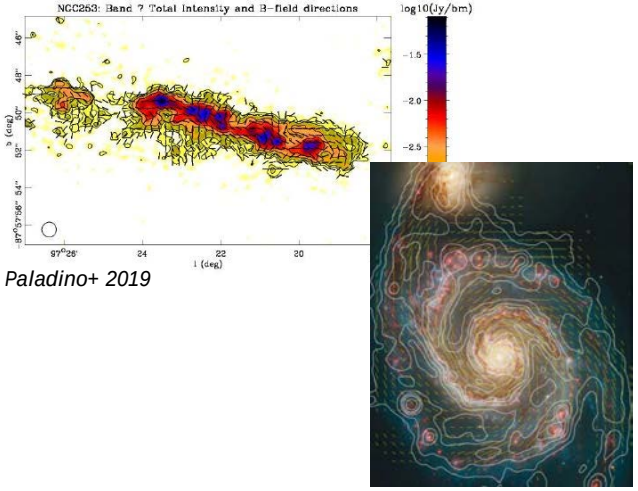


Planck Coll.





Bonafede 2016



Paladino+ 2019

Fletcher+ 2011

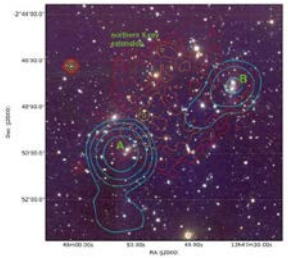


Fig. 8. Overlay of a WHT image of Abell 1612 with the X-ray surface brightness (red-yellow contours) and the total radio emission at 8.35 GHz (blue contours).

Kierdof+ 2017

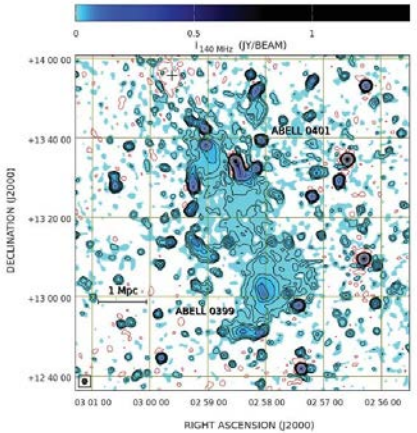
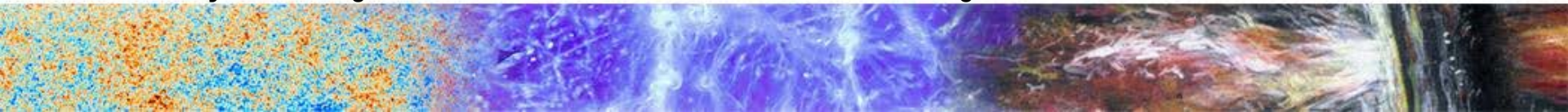


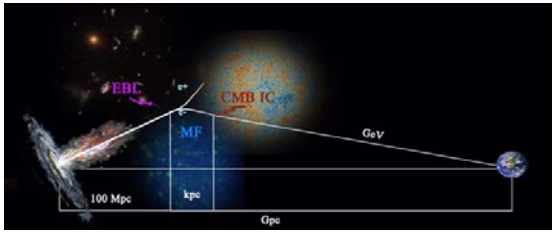
Fig. 1. LOFAR image of the 1.4° × 1.4° region centered on the Abell 0399–Abell 0401 system. Color and contours show the radio emission at 140 MHz with a resolution of 80 arc sec and RMS sensitivity of 1 mJy beam^{-1}. The beam size and shape are indicated by the inset at the bottom left. Contour levels start at 3 mJy beam^{-1} and increase by factors of 2. One negative contour (red) is drawn at −3 mJy beam^{-1}. The black cross (right ascension 02h 59m 38s, declination +13° 54′ 55″, J2000 equinox) indicates the location of a strong radio source that was removed from the image.

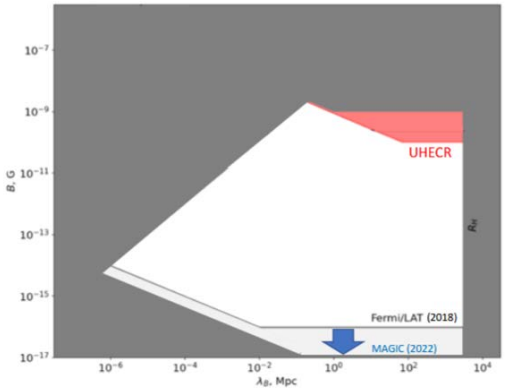
Govoni+ 2019

But in recent years things started to become even more interesting…



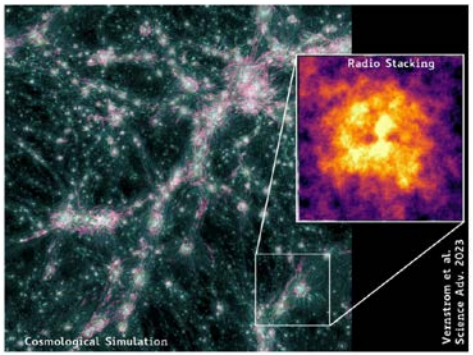
Evidence of the presence of magnetic fields in voids of the LSS through gamma ray observations



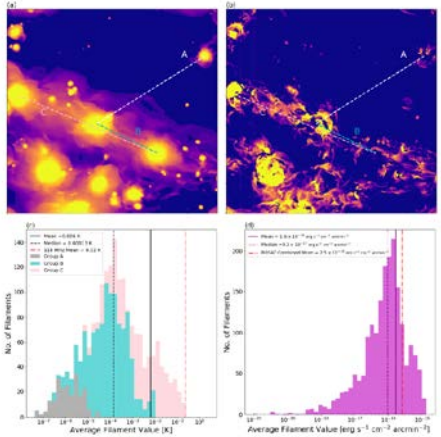


Neronov and Semikoz 2021

Hints of the presence of magnetic fields in filaments of the LSS

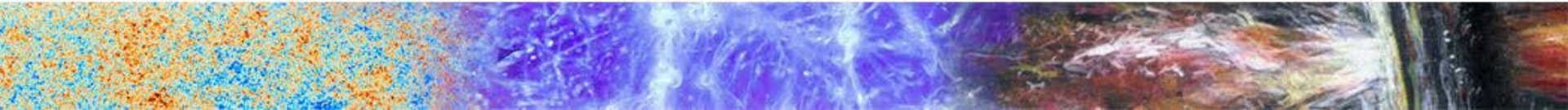


Vernstrom+2023 (Science Adv.)



Vernstrom+2021

Recent data keep pointing more and more to a Cosmic Magnetism relic of Primordial Magnetism: magnetic fields generated in the Early Universe

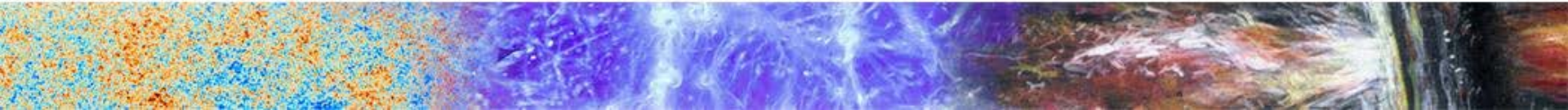


But there is another side of this story to be told

Primordial Magnetic Fields to be generated in the early Universe require peculiar conditions which would imply a fundamental physics in the early Universe very much different from the one we think we know.

From non standard inflation, additional vector, pseudoscalar, whatever, fields; couplings, strange couplings; first order phase transitions (or the secret dream of every astroparticle person)….

Primordial Magnetic Fields represent a unique window into the fundamental physics wonderland (but also a treat for our enthusiast theoretical physicists…)



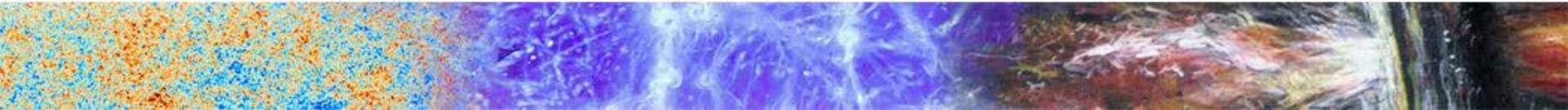
Reconnecting Cosmic and Primordial Magnetism is crucial but how?

There are three main players into this game:

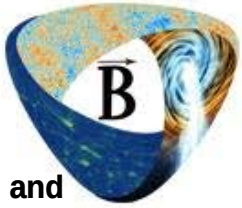
- **Primordial Magnetic Fields and their impact on cosmological probes as Cosmic Microwave Background and Galaxy surveys and the associated constraints we can derive from them**

- **MHD Simulations of structure formation. Evolving initial magnetic fields into the ones we observe today (Challenges: large excursion in dynamical range and many different physical processes to account for)**

- **Observations of current Cosmic Magnetism from radio (LOFAR..SKA) to gamma rays (*Fermi*, MAGIC..CTA).**



Primordial Magnetic Fields and INAF, a story started long time ago



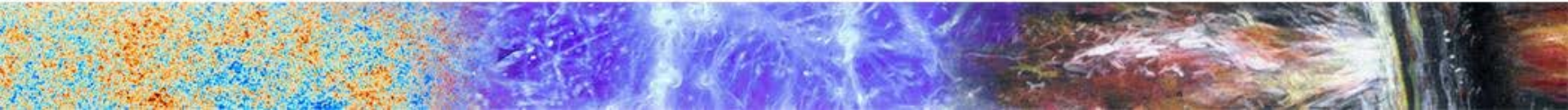
PMF affect all the history of the Universe and cosmological observable. From the Cosmic Microwave Background with the gravitational effect (magnetically induced perturbations), the effect on the thermal and ionization history, Faraday rotation, non-Gaussianities, parity breaking phenomena, to the large scale structure with thermal effects and the effects of magnetically induced perturbations especially on small scales.

INAF is one of the international leaders in the primordial magnetism!

We started in 2007, we are the only ones to have the full analytical and numerical treatments and the codes for all the PMF effects on cosmological probes, ready and graded for future experiments for CMB in developing for galaxy surveys and LSS. ***DP Master Thesis 2007; Finelli+, DP, 2008; DP+ 2009; Caprini, Finelli, DP and Riotto 2009; DP & Finelli 2011; DP PhD Thesis 2011; DP & Finelli 2013; Chluba, DP, Finelli & Rubino Martin 2015; Planck Coll. DP corresponding author 2016; Hutschenreuter+, DP, Vazza, 2018; DP & Finelli 2019; Vazza+, DP, Finelli 2020; DP, Chluba, Finelli & Rubino Martin 2022; LiteBIRD Collaboration, DP corresponding author in preparation -2023, 2024, 2026-.***

In INAF there was the leadership (DP) of the Primordial Magnetic Fields working group in the Planck Collaboration leading to a milestone paper which changed the game for all primordial magnetism studies.

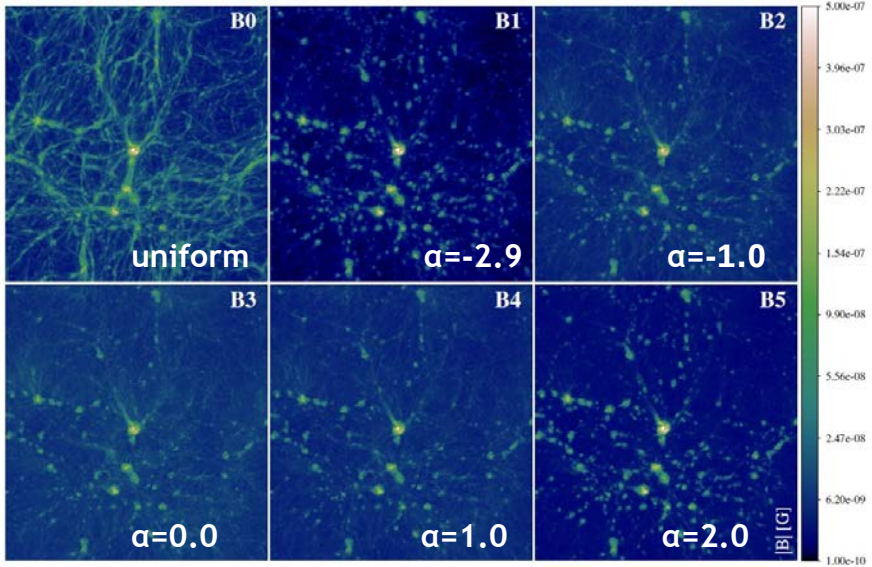
In INAF there is the leader (DP) of the Primordial Magnetic Fields project in the LiteBIRD Collaboration responsible for all the forecasts that will be produced.



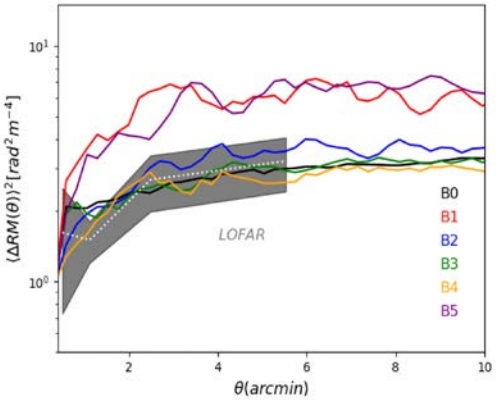
Cosmological MHD Simulations

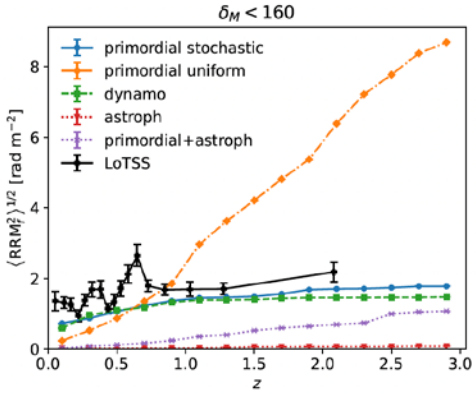
Usually employing initial homogeneous Magnetic Field of around nGauss…(a 1 nGauss homogeneous field would lead to have in the CMB not the axis of evil…but the highway of evil…)

Within our group we performed the first cosmological MHD simulation starting from tangled fields, $P(k) \propto k^{\alpha}$ as constrained by the CMB data – Vazza, Paoletti + 2020,21- also with CINECA HPC facilities

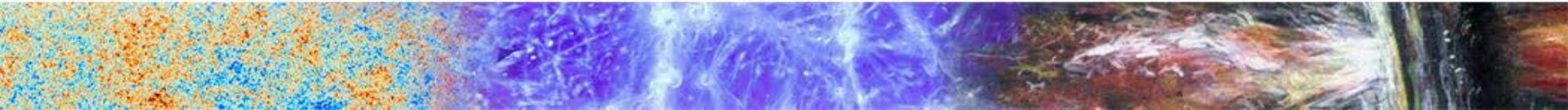


For the first time we can combine CMB constraints with (z<2) radio observations by LOFAR HBA surveys. Uniform primordial field, as well as a few tangled one, are ruled out by extragalactic Faraday Rotation data!





Carretti+22

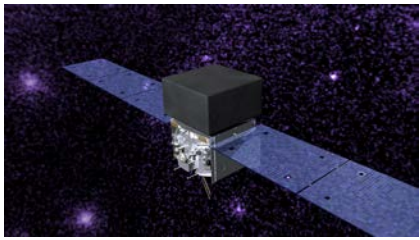


Gamma rays

The search for extended/reprocessed/delayed gamma-ray emission are the only methods providing lower limits to IGMF to date.

Current methods are based on jetted active galaxies observations (*Fermi* below 100 GeV, MAGIC and other IACTs data above 100 GeV).

Very recently, the detection of Gamma Ray Burst (GRB) emission up to the TeV range has opened the possibility of GRB-based IGMF studies - D. Miceli, P. Da Vela, E. Prandini submitted



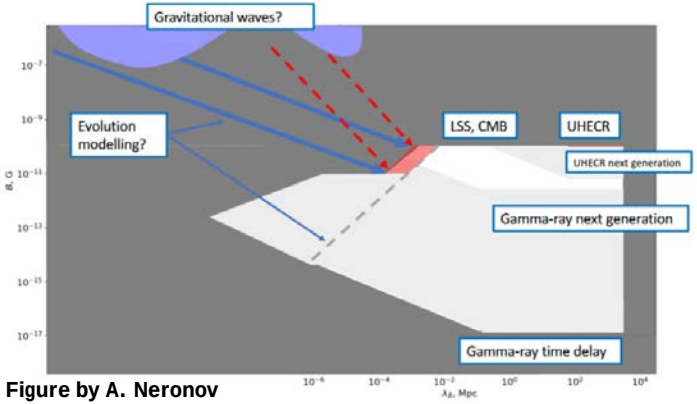
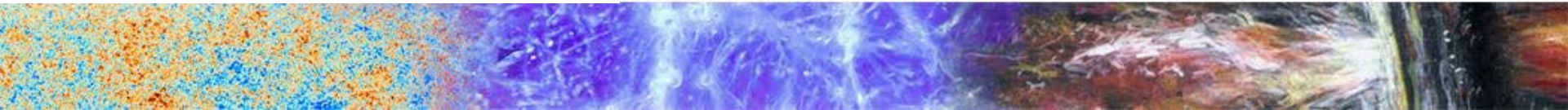


Figure by A. Neronov

Tremendous progresses are expected with next generation of ground based instruments like CTA, towards the detection of IGMF signature in gamma-ray data

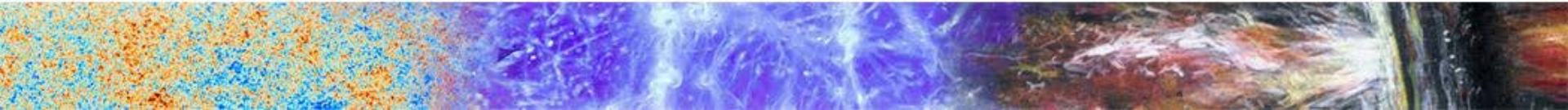


Cosmic Magnetism 2.0
what happens in the next 10 years from an INAF perspective:

- **Early Universe and Cosmological data – strong constraints on Primordial Magnetic Fields:**
  - **CMB: LiteBIRD (plus combination with Stage IV from ground), unprecedented accuracy for CMB polarization where PMF signal is stronger**
  - **LSS: Euclid, Rubin, can reach scales where PMF strongly impact the matter power spectrum**

- **Simulations: improvement thanks to Leonardo (CINECA) and INAF-HPC center, increasing resolution and adding small scale effects. Possibly in the next decade moving towards exascale?**

- **Late Universe and Astrophysical data:**
  - **Radio: LOFAR, MeerKAT, SKA…just to mention the little ones** 😉
  - **Gamma rays: CTA, ASTRI…to stay again on little things** 😉



PMFs THE POTENTIAL NOBEL GRINCH!!!

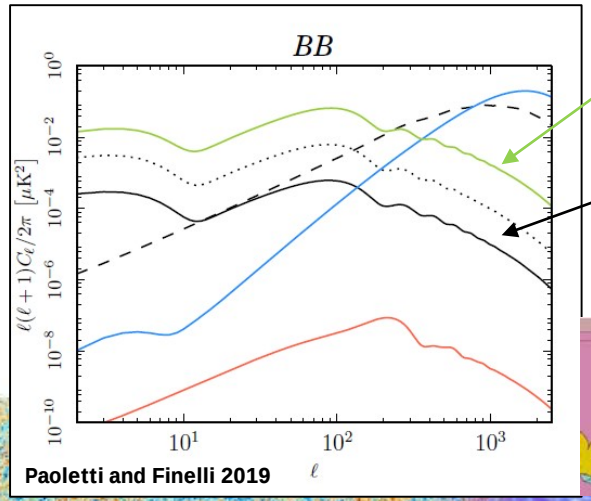
We are facing two possible scenarios for the next decade of CMB experiments:

1. An improvement of the constraining power:

The sensitivities expected are so high that can potentially put in crisis the scenario of primordial relic for the cosmic magnetism (see the lower bounds from voids) for some generation scenarios. Therefore we need to simulate such fields and compare with observations to test this scenario.

2. We have finally a detection beyond any reasonable foreground and systematics of the holy grail of CMB, the B-modes: (and there all hell will get loose)

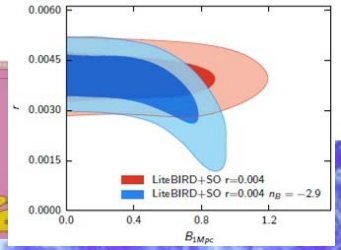
Inflation people will announce the discovery of the long searched inflation signal.. but…



Paoletti and Finelli 2019

These are PMFs

This is your inflation signal



Due to degeneracies the same day we could announce the discovery of PMFs!

Putting together all the efforts we can disentangle the two!

To be fair also stringists may have something to say…

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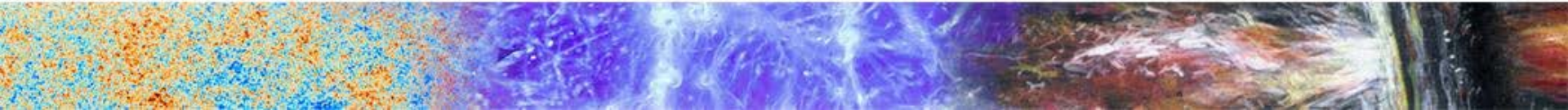
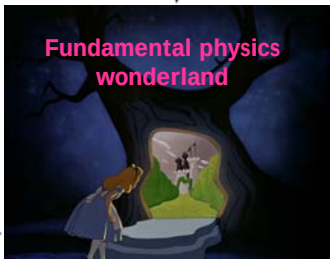
- **Observations of current Cosmic Magnetism from radio (LOFAR..SKA) to gamma rays (*Fermi*, MAGIC..CTA).**

The sum is greater than its single addends.
If you put together the three you have

Everyprobe, Everywhere, All Magnetic Fields at Once

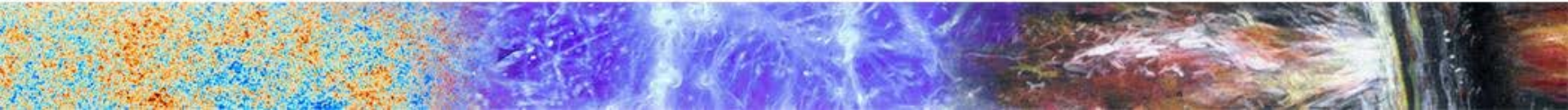


Consider all possible topological PMF configurations, produce the forecasts for future experiments in CMB and LSS

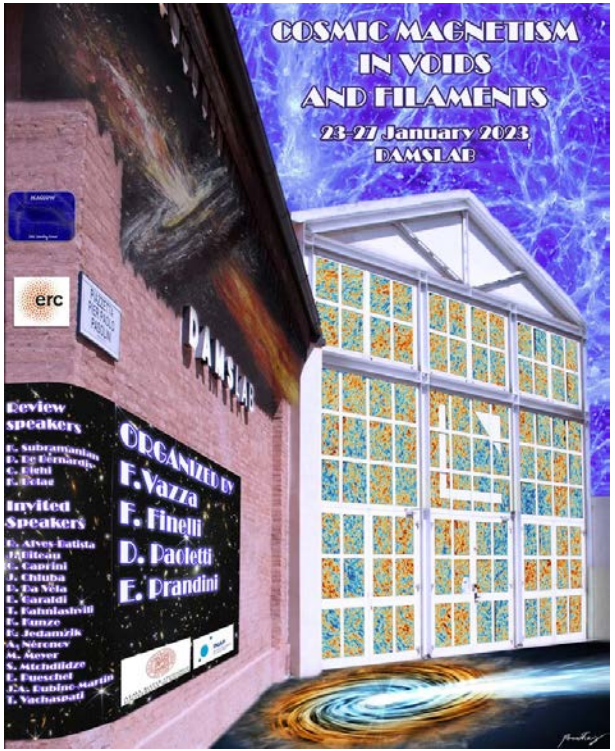


Feed initial conditions both at the level of the PMF and magnetically induced perturbations in full MHD simulations

Compare results of simulations with astrophysical and late time observations, gamma rays, radio and cosmic rays



This is not only an idea….we already started making this getting real



This January we gathered together more or less, between in presence and remotely, the gotha of primordial, cosmic and observational magnetism and most importantly many many young enthusiastic scientists!

This looks to have really Good OMENS!

Part of the planned activities are detailed in the scheda INAF

Good Old Magnetism in the Early uNiverSe

Associated request for mini-grant to keep the collaborations and meetings active

We want to create and keep alive a community devoted not to the single probe or the single aspect of Universal Magnetism but to its whole history from generation to current observations and to understand its implications for the fundamental physics we all think to know