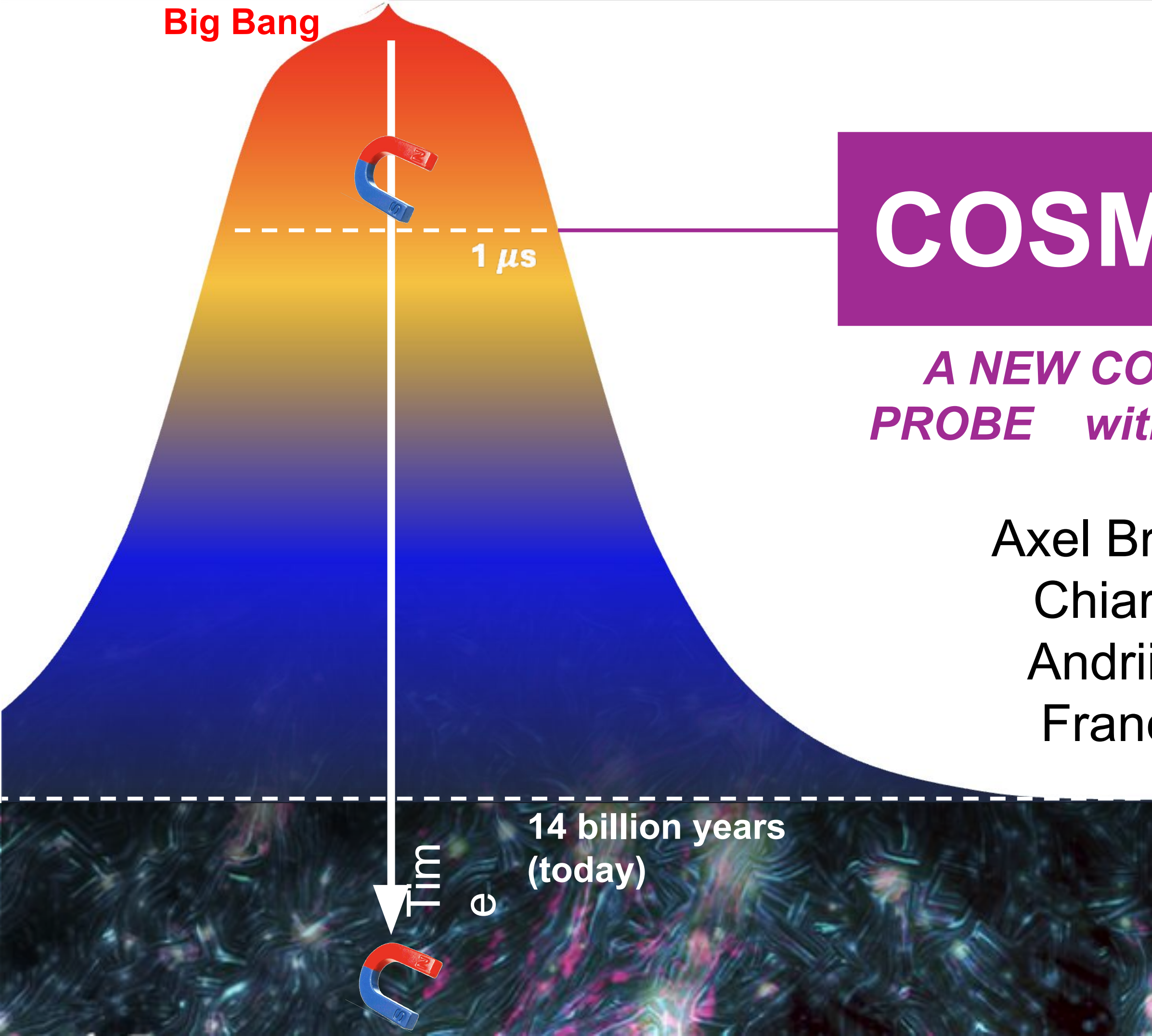
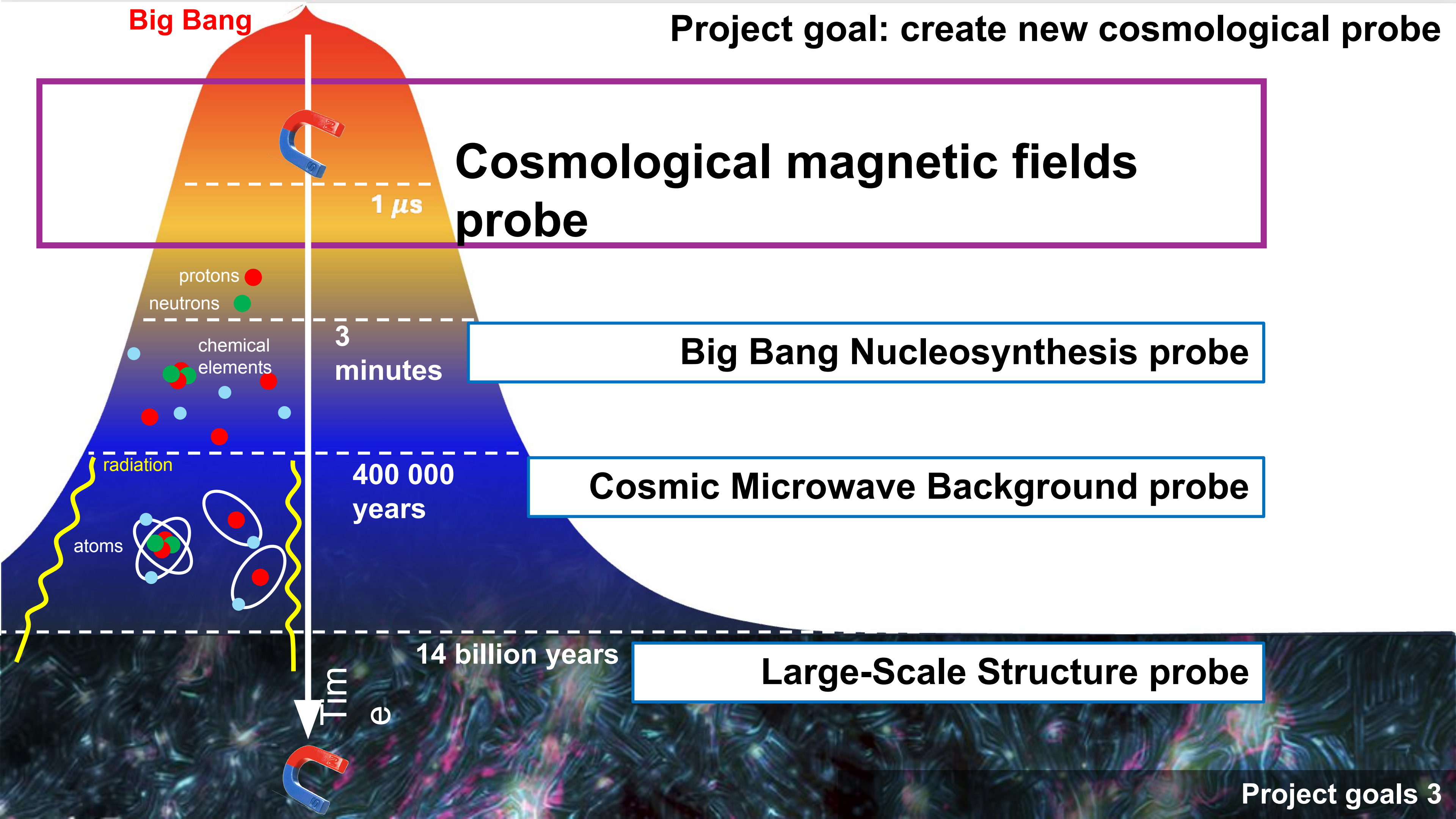


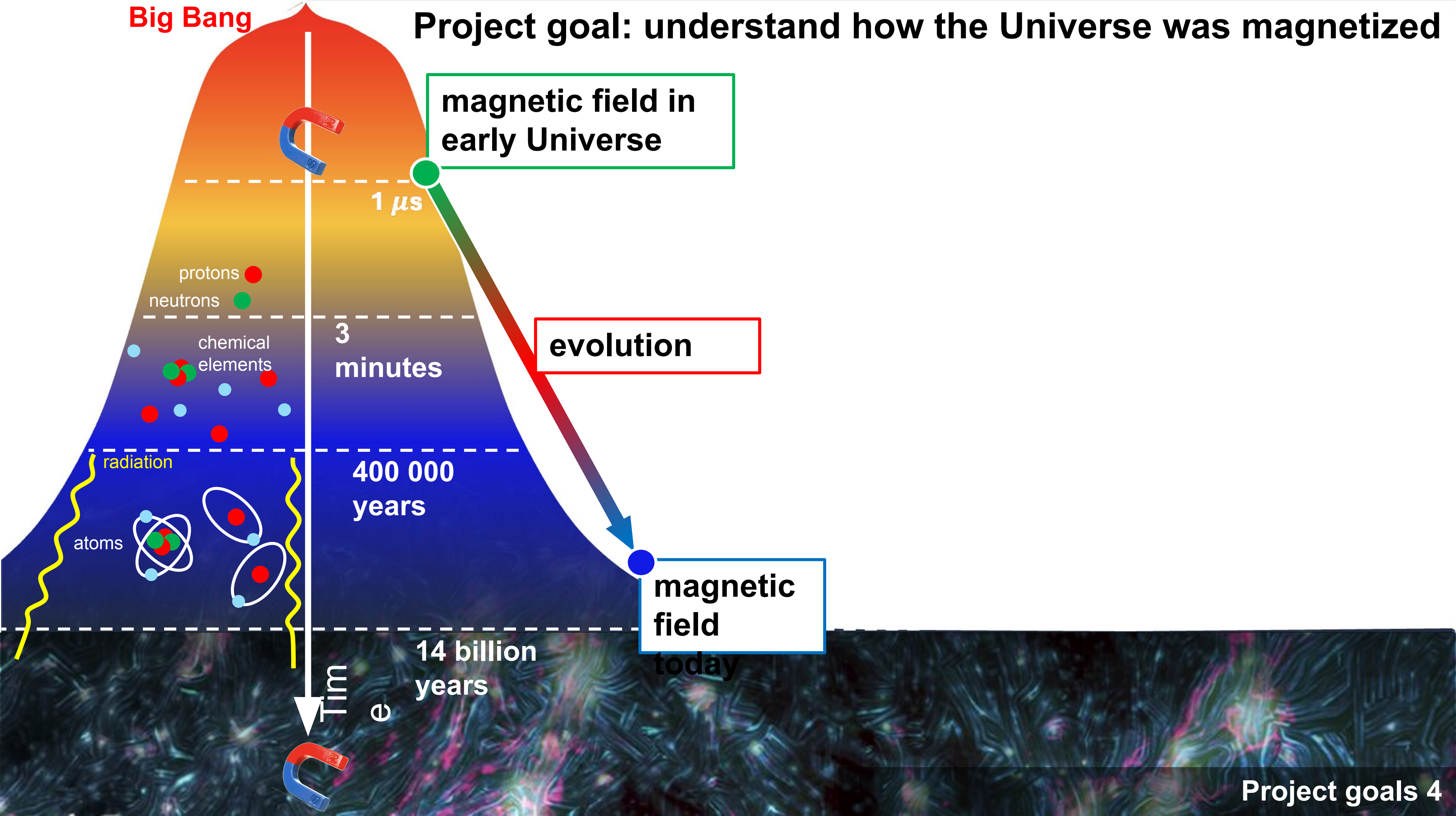
COSMOMAG

A NEW COSMOLOGICAL PROBE with magnetic fields

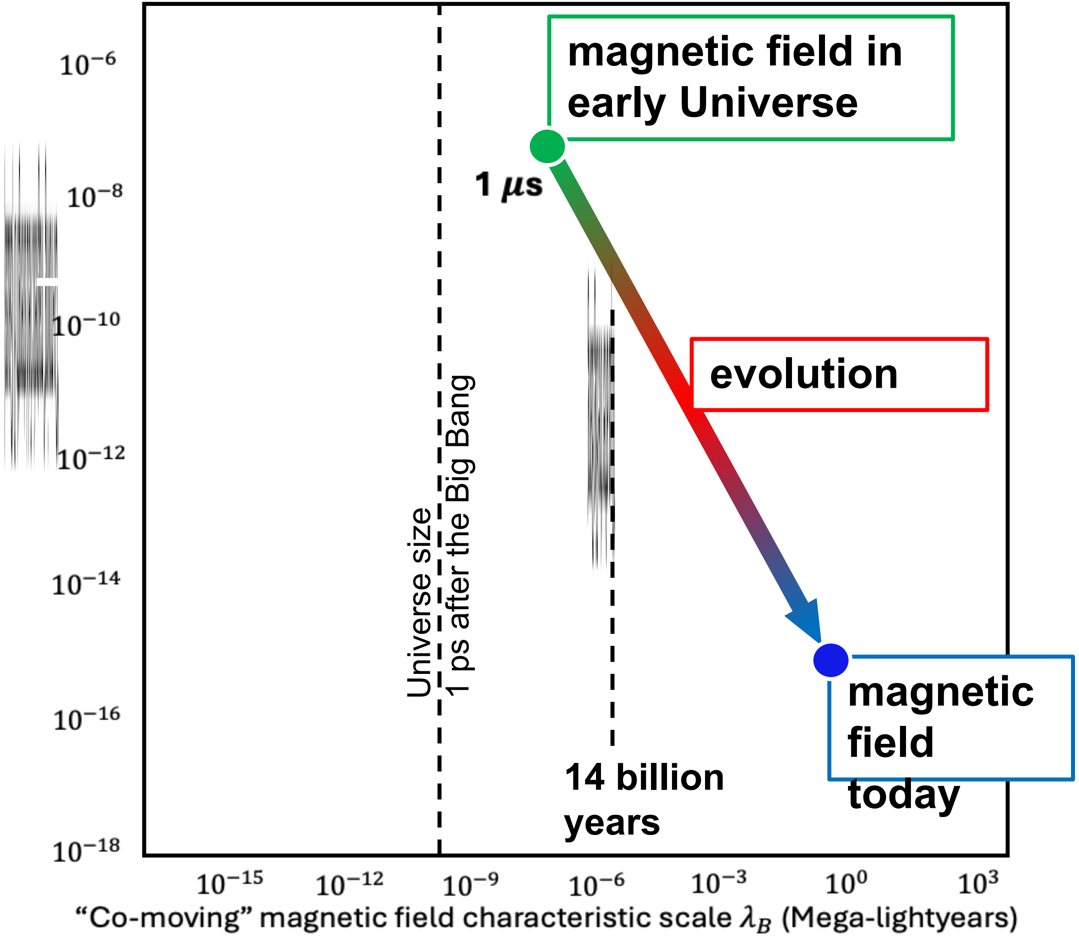
Axel Brandenburg
Chiara Caprini
Andrii Neronov
Franco Vazza


Big Bang
Project goal: create new cosmological probe
Cosmological magnetic fields probe
1 μs
protons
neutrons
chemical elements
3 minutes
Big Bang Nucleosynthesis probe
radiation
atoms
400 000 years
Cosmic Microwave Background probe
14 billion years
Large-Scale Structure probe
Time
Project goals 3

Project goal: understand how the Universe was magnetized



Project goal: nail down cosmological magnetic field evolutionary track

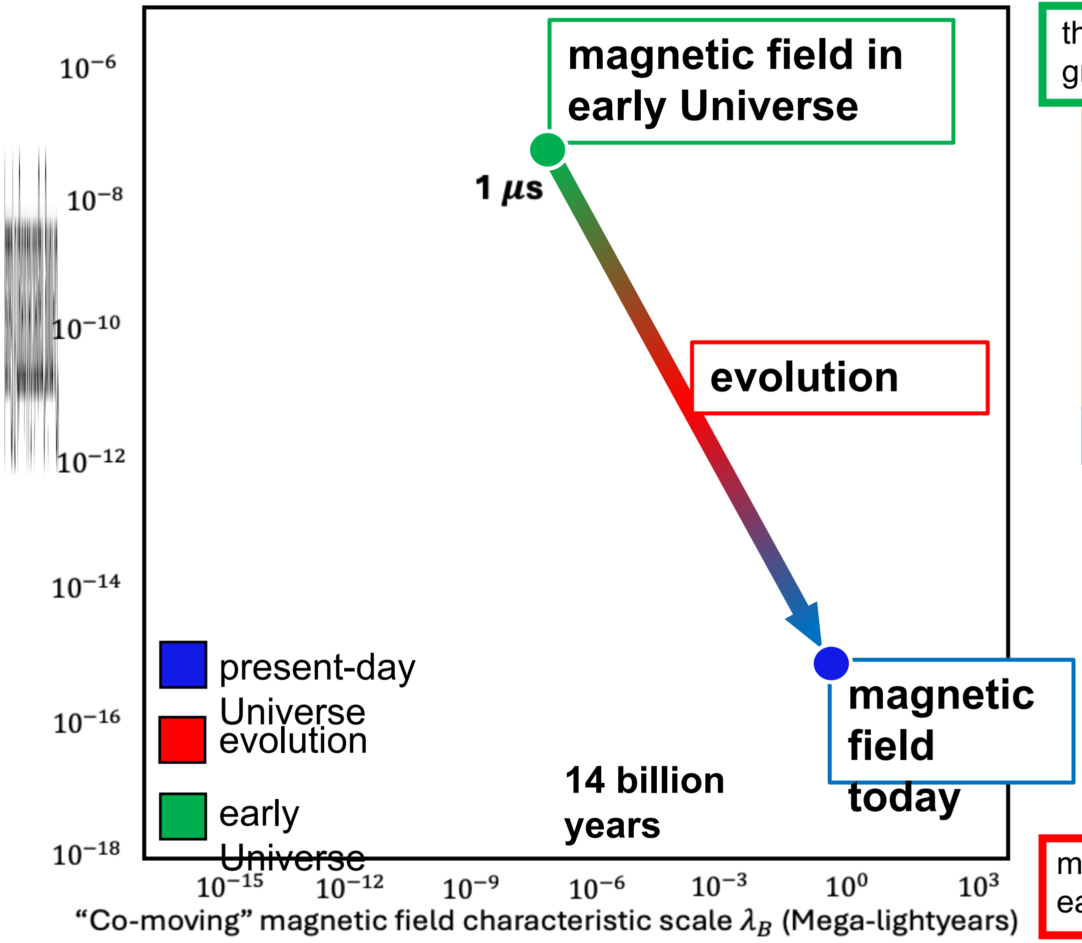


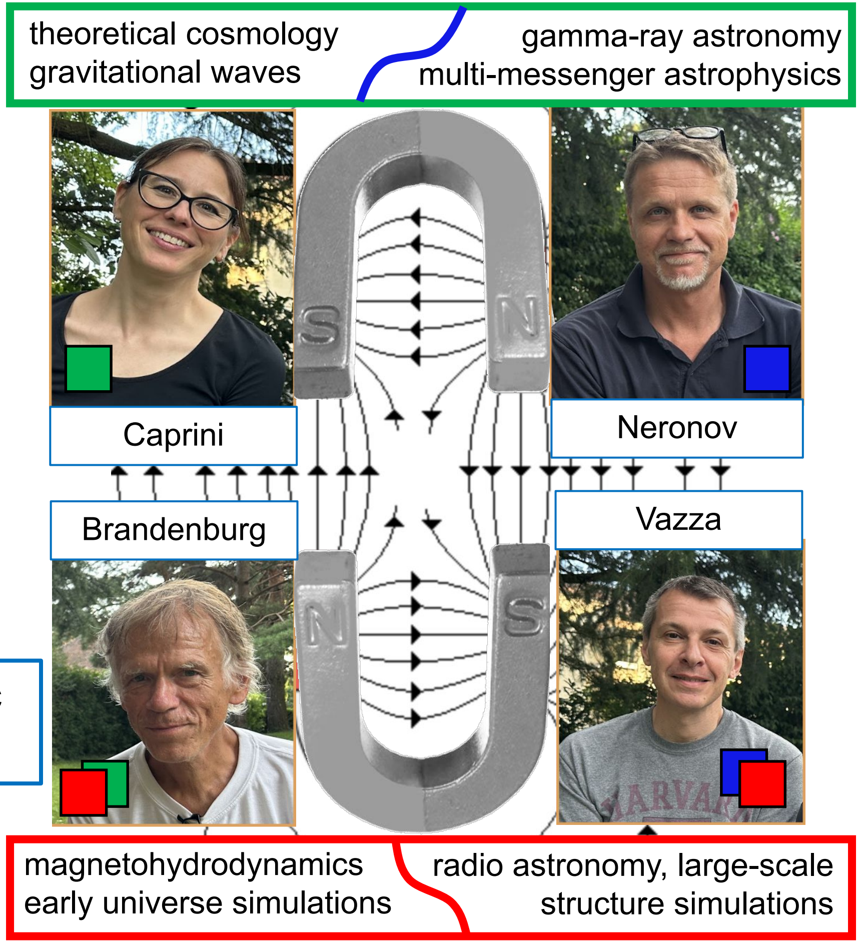
Two magnetic field parameters:

- strength
- length scale

We will measure these parameters.
We will understand how did they evolve.

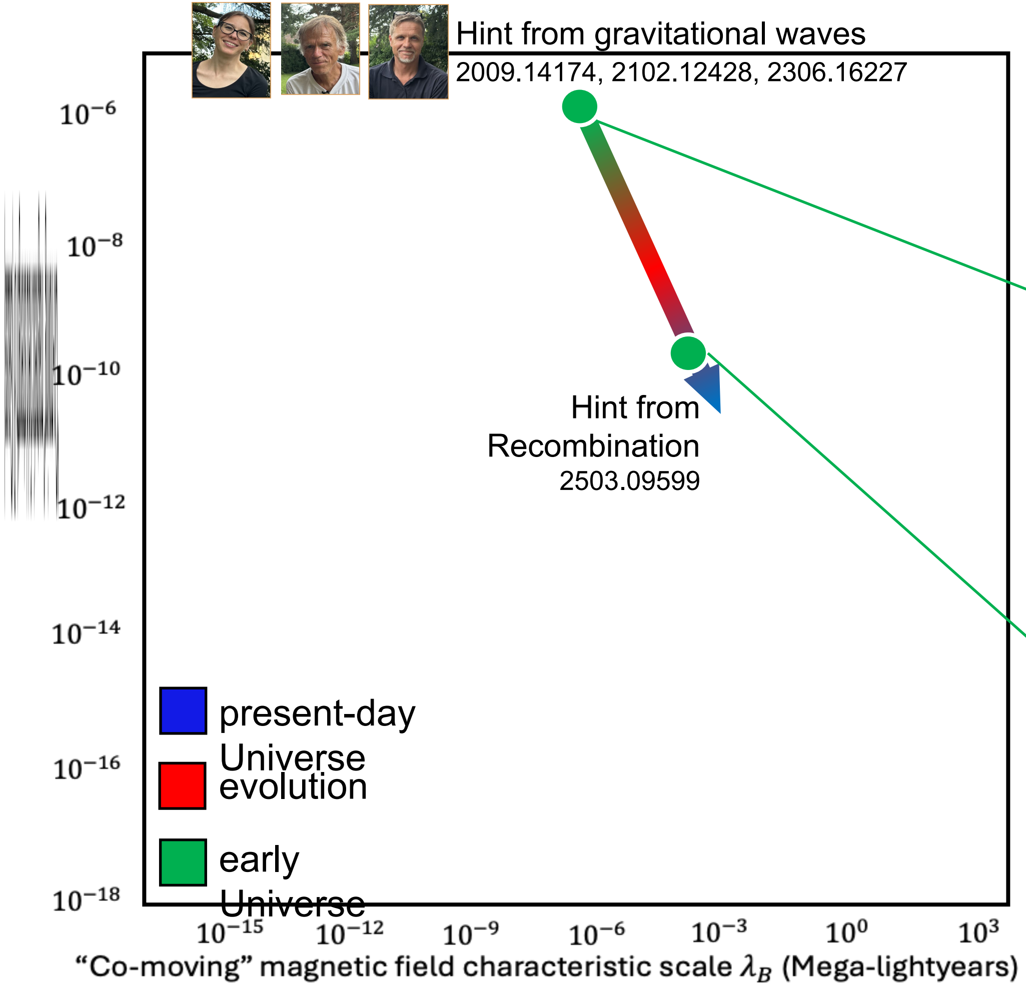
The magnetized team

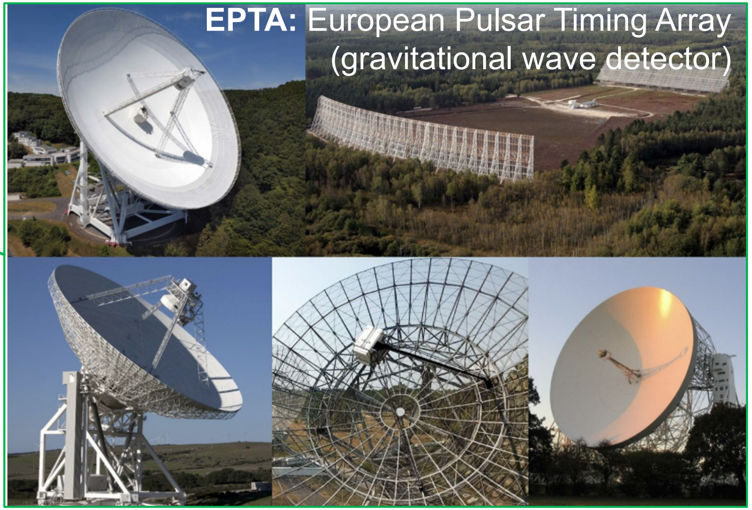


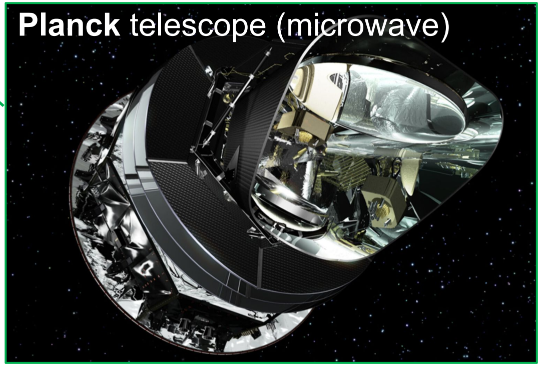


Synergy 6

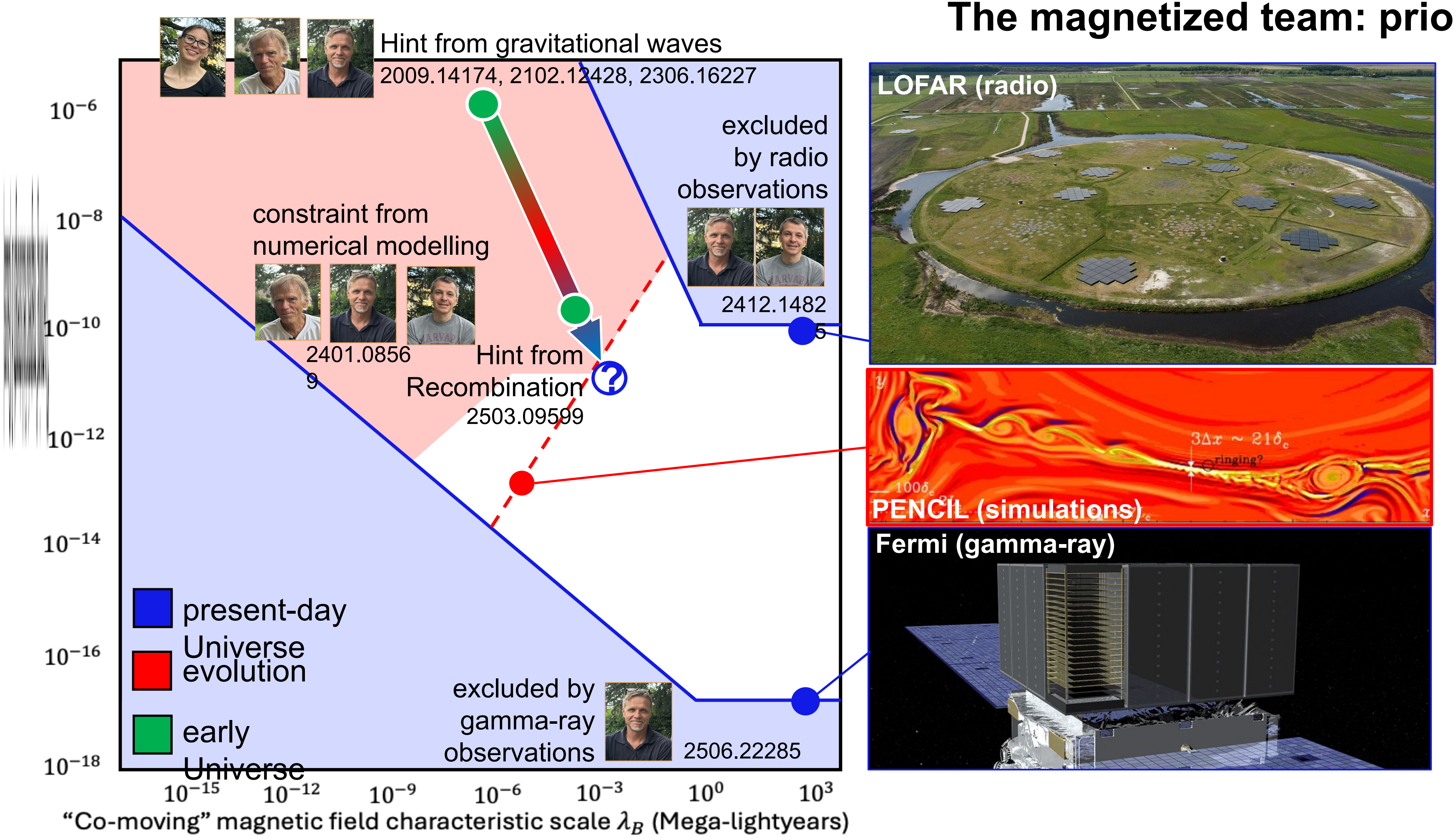
The magnetized team: prior work



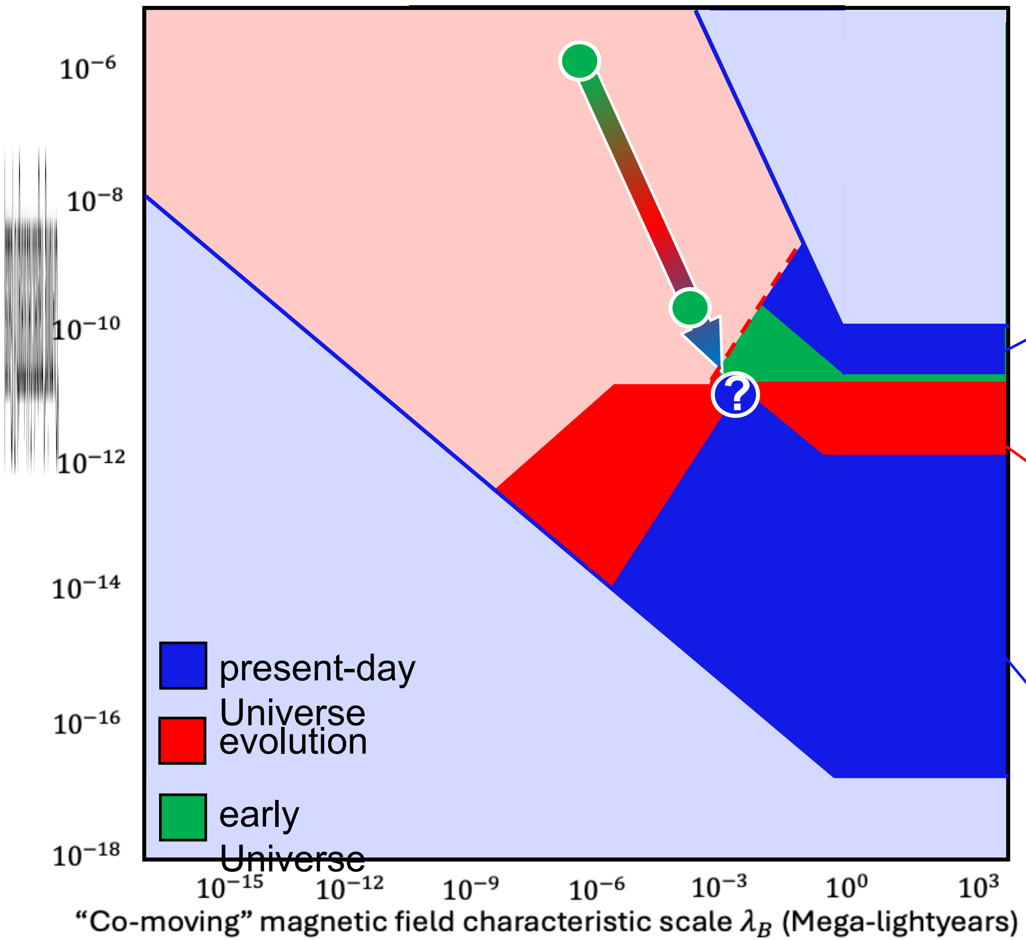


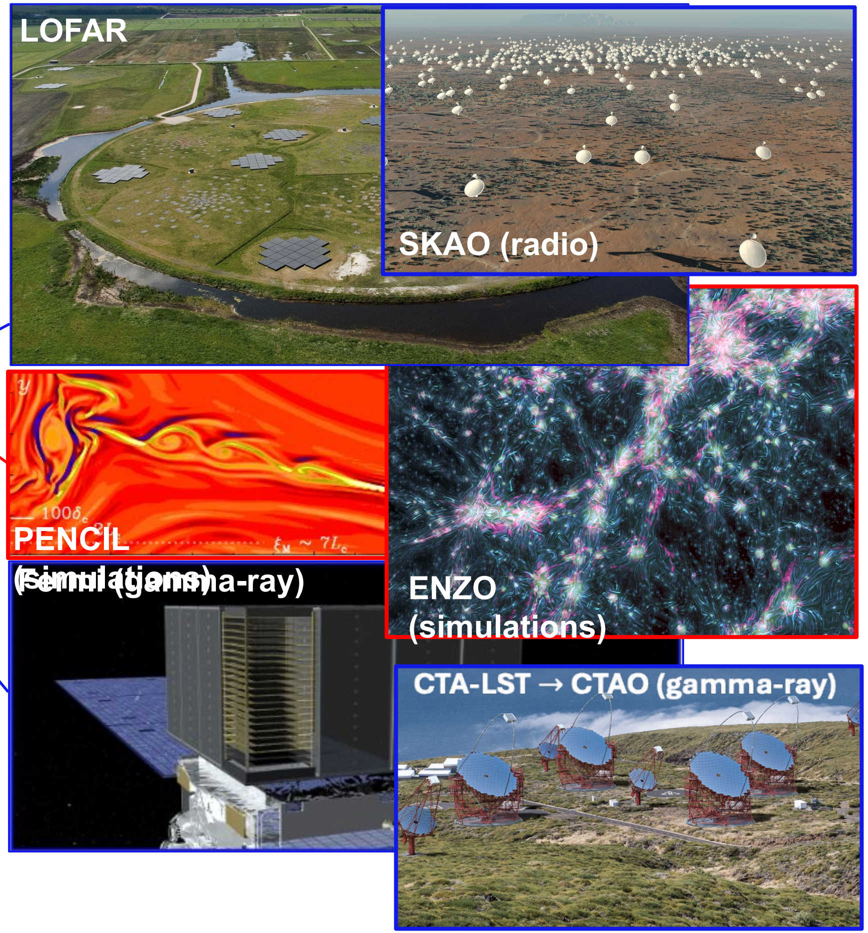


The magnetized team: prior work

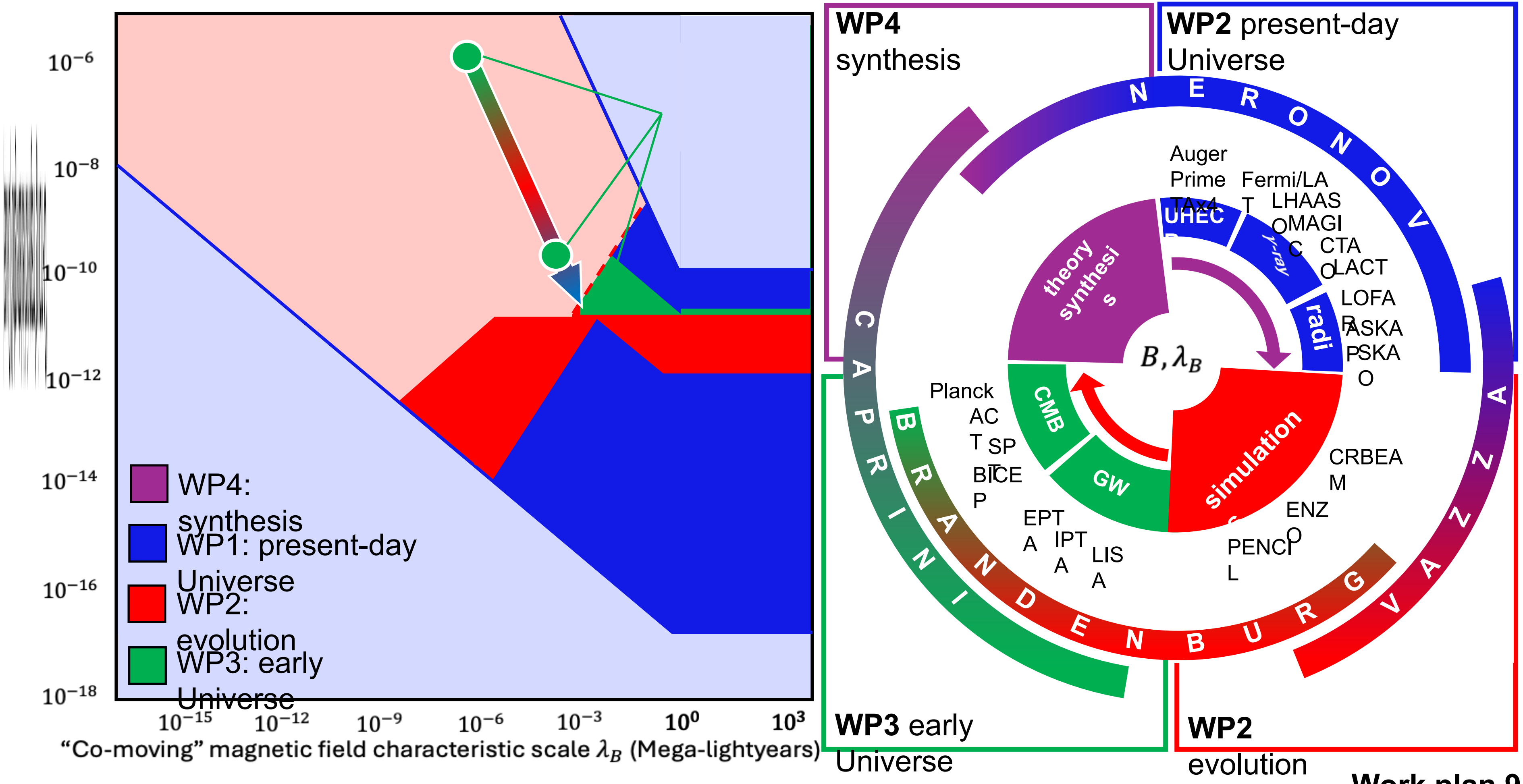


COSMOMAG: explore full cosmological magnetic field parameter space

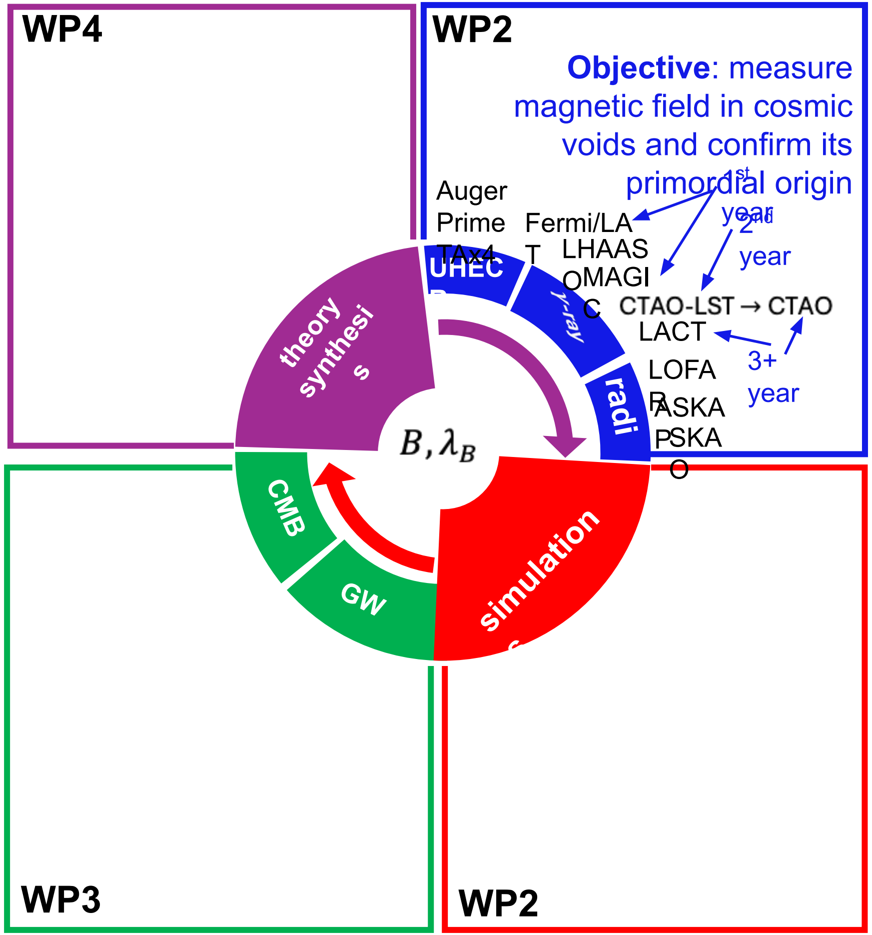




Project organisation

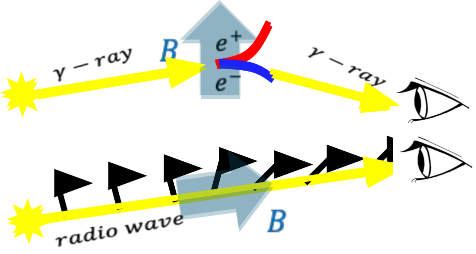


COSMOMAG: explore full cosmological magnetic field parameter space

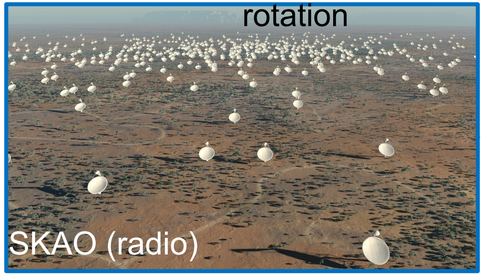


COSMOMAG: explore full cosmological magnetic field parameter space

electromagnetic cascade



Faraday rotation



CTAO

?

SKA O

WP4

WP2

Objective: measure magnetic field in cosmic voids and confirm its primordial origin

Auger Prime

TAx4

Fermi/LAT

LHAASO

MAGIC

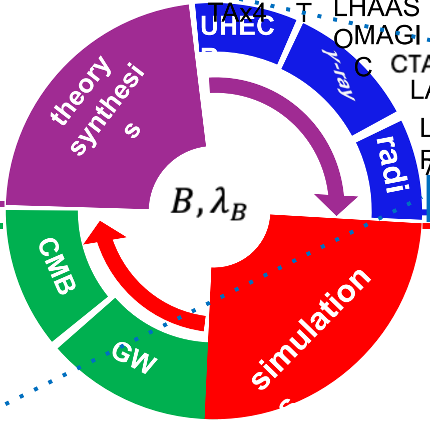
CTAO-LST → CTAO

LACT

LOFAR

ASKAP

SKAO

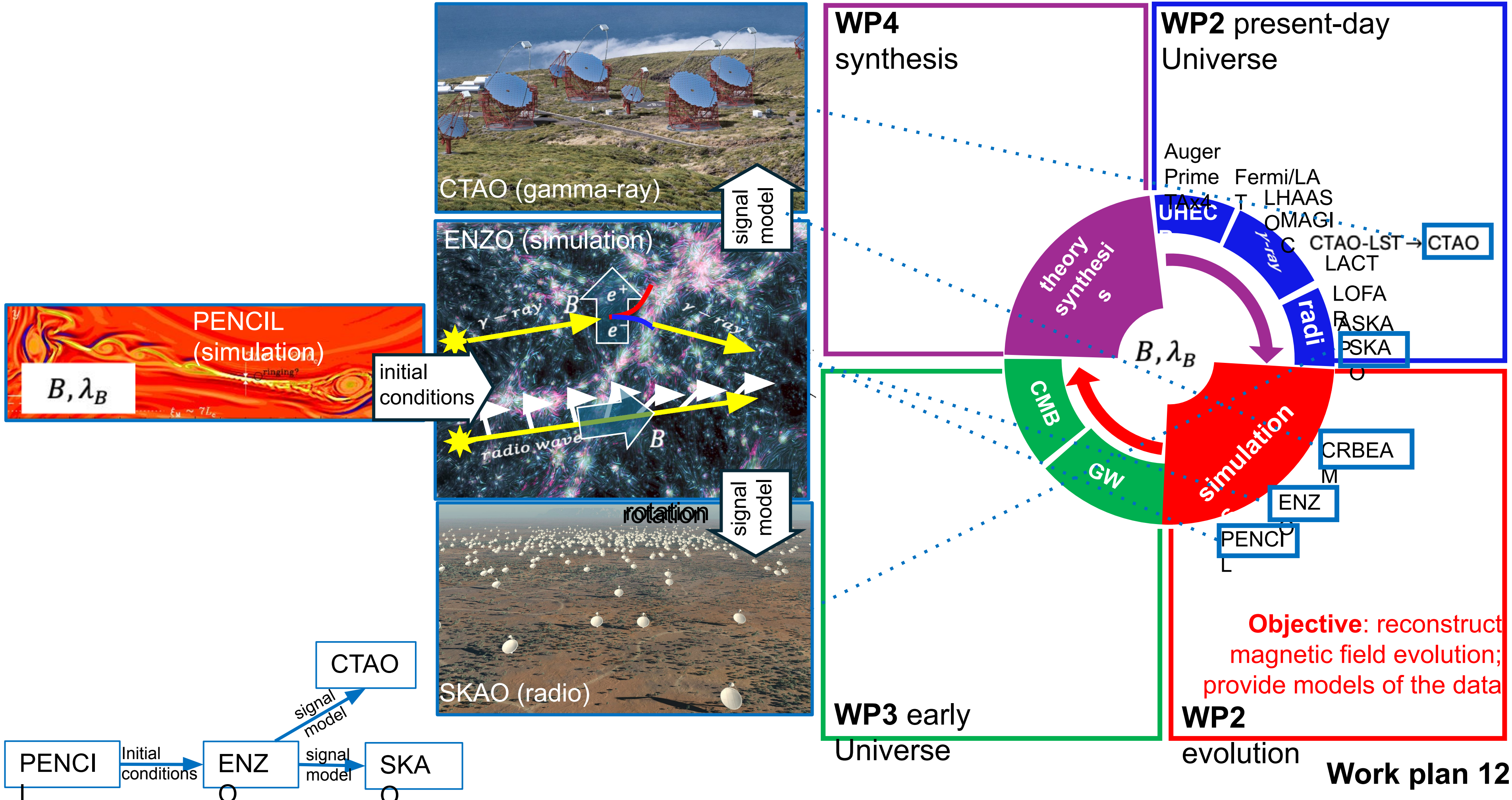


WP3

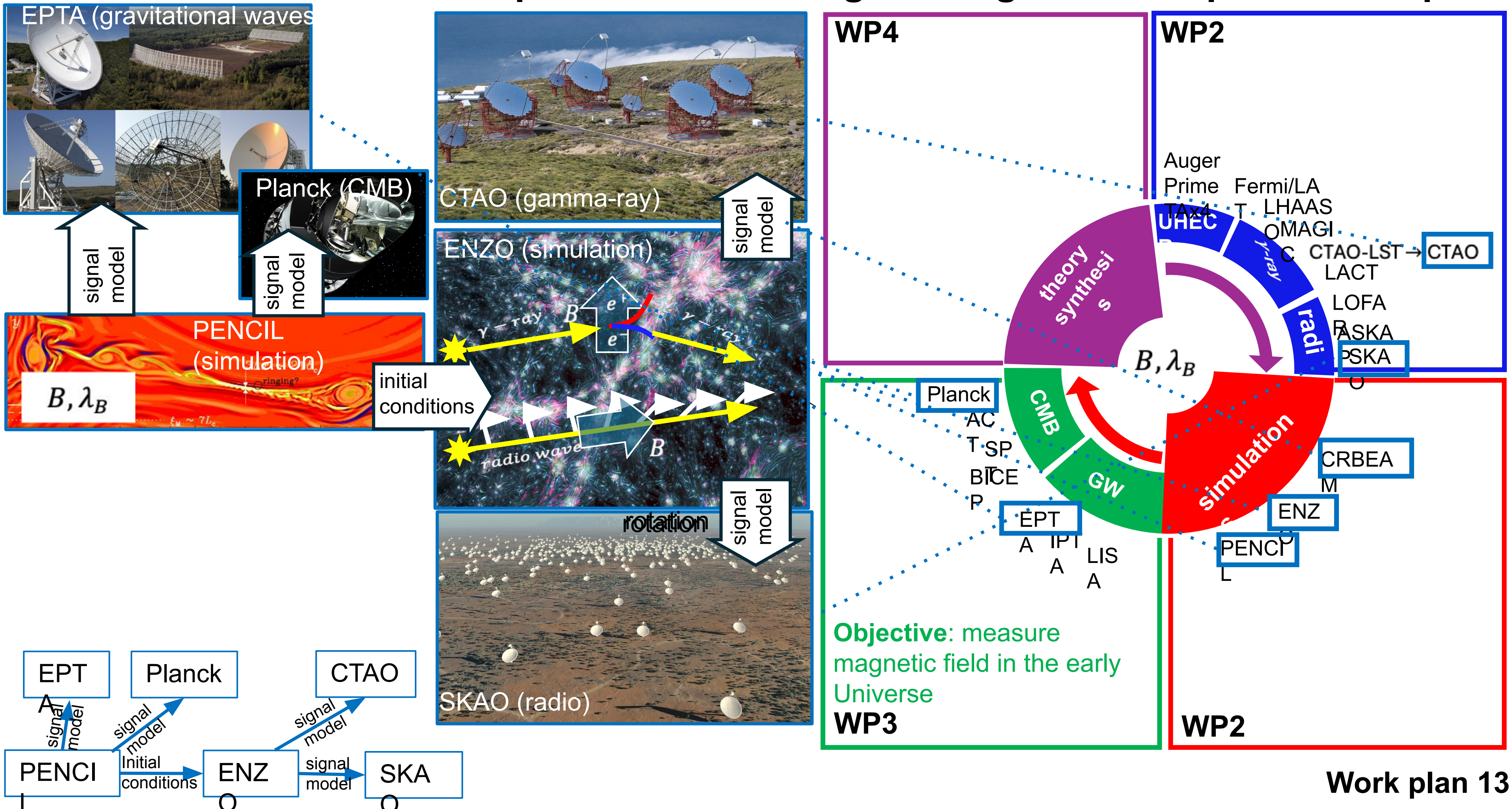
WP2

Work plan 11

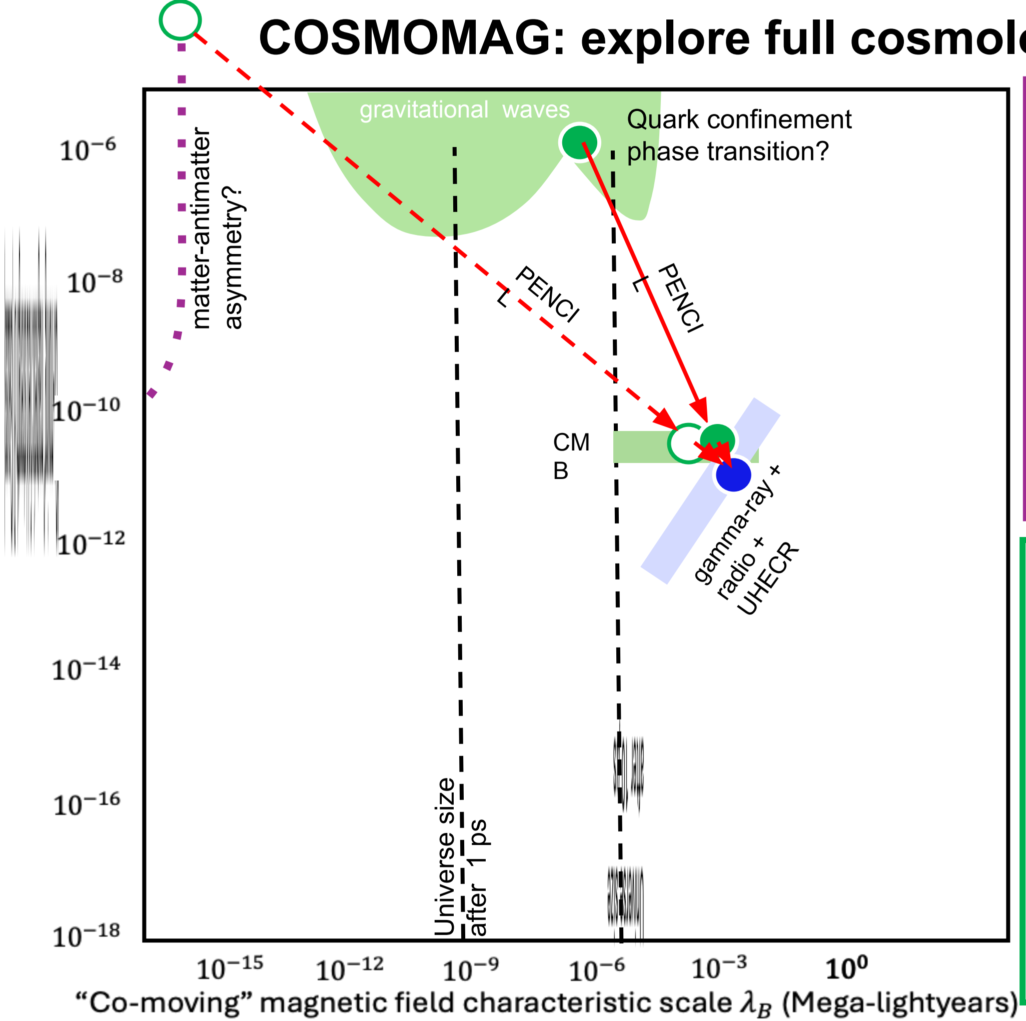
COSMOMAG: explore full cosmological magnetic field parameter space

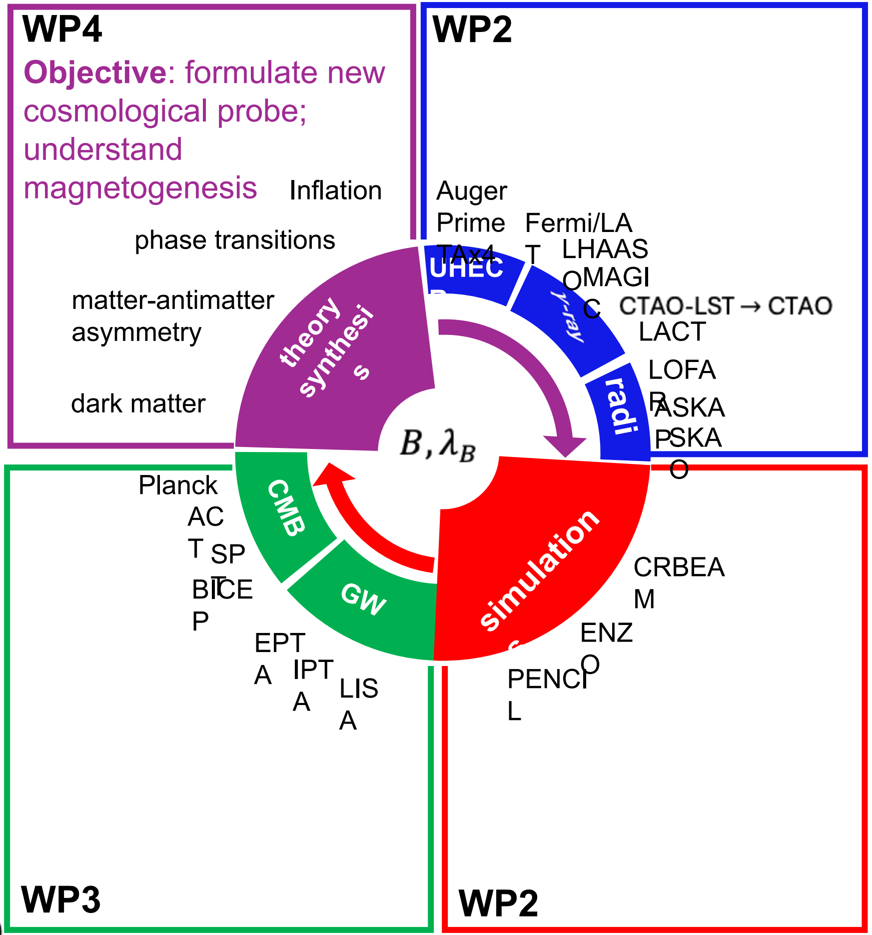


COSMOMAG: explore full cosmological magnetic field parameter space

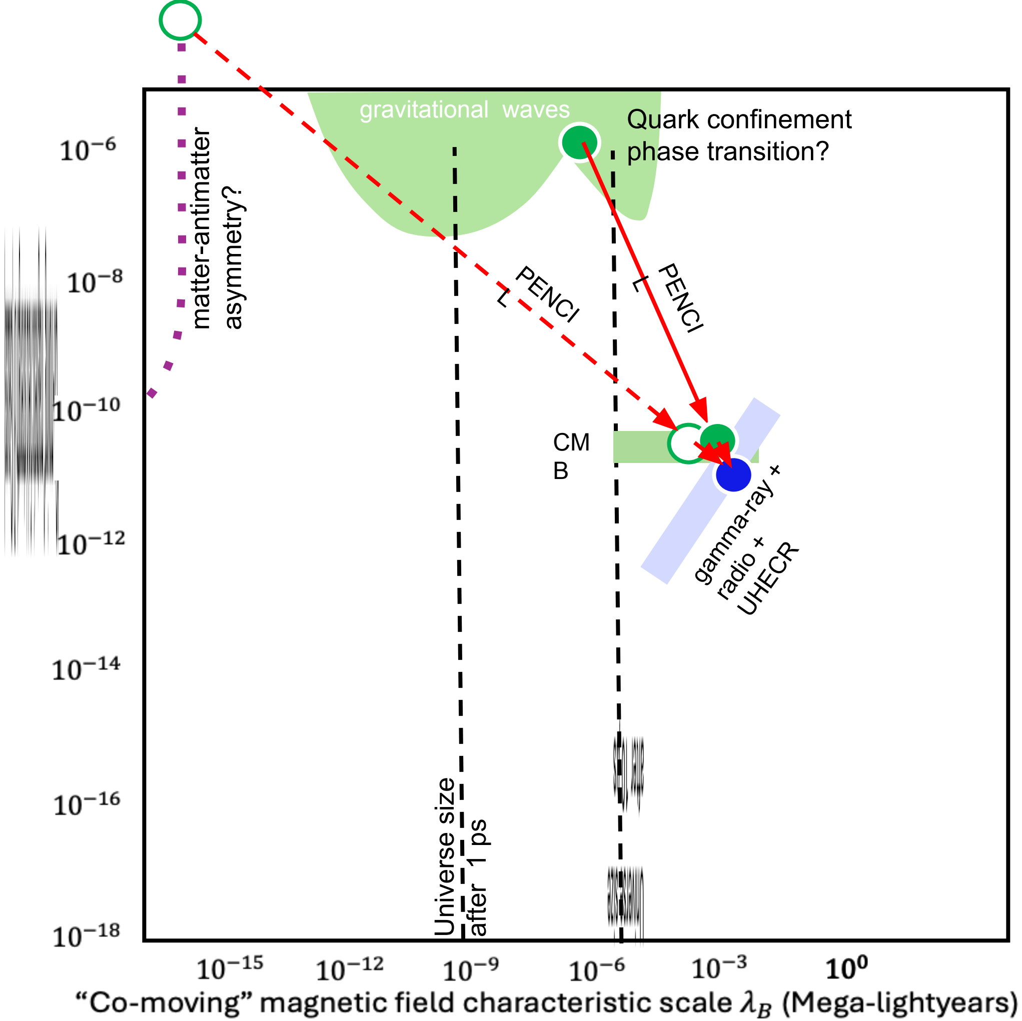


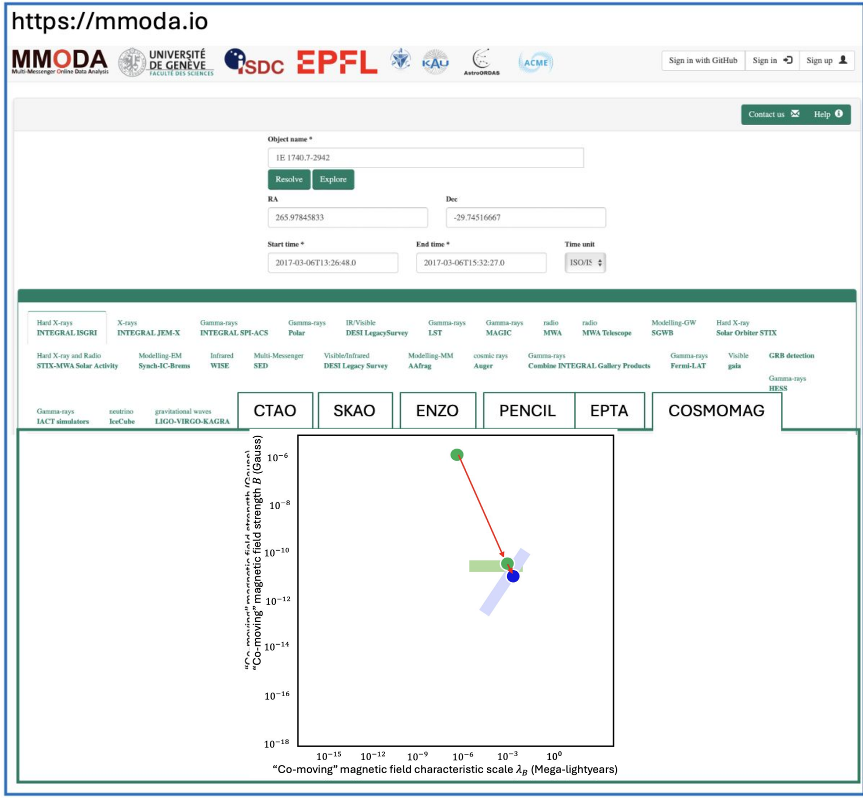
COSMOMAG: explore full cosmological magnetic field parameter space

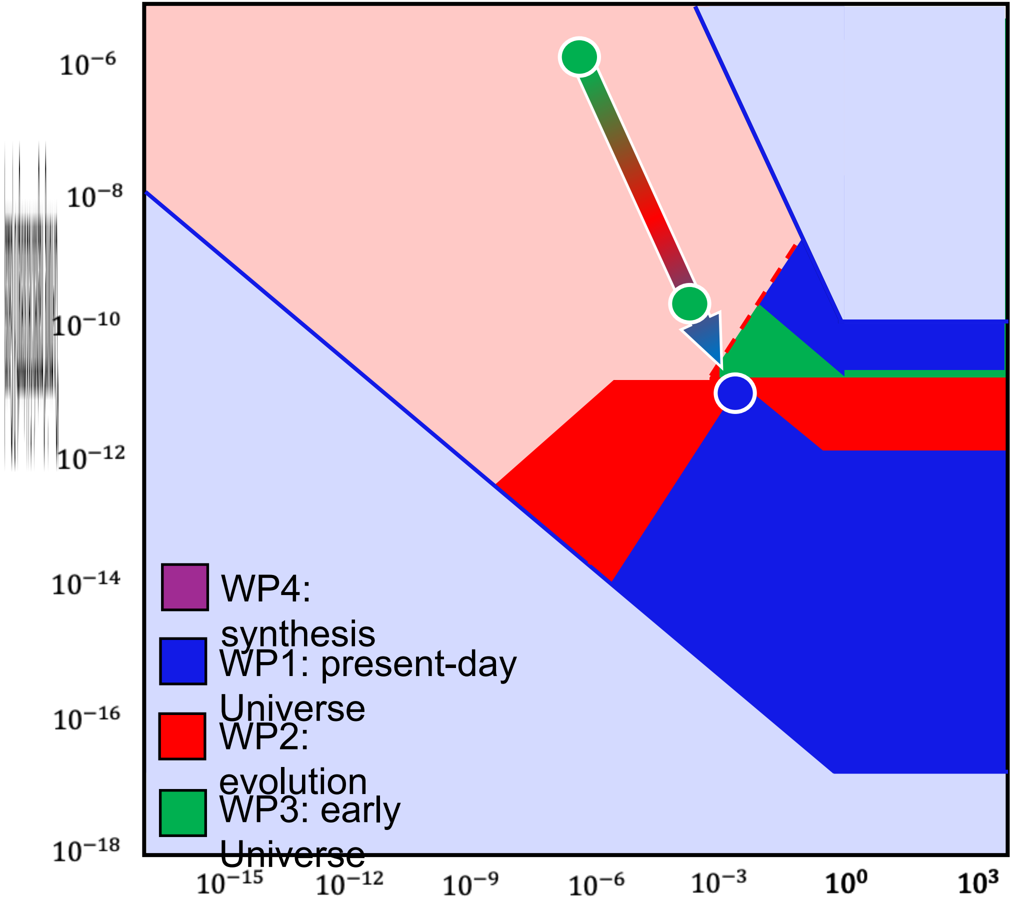




COSMOMAG explorer







COSMOMAG

A NEW COSMOLOGICAL PROBE with magnetic fields

– clarify the origin of cosmic magnetism,

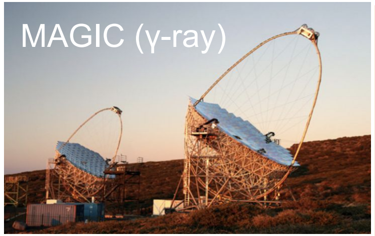
– explore the first microseconds after the Big Bang,

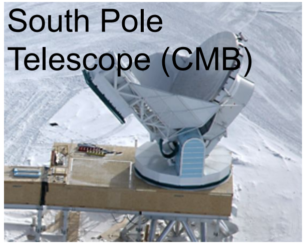
– unveil connection to puzzling processes in the early Universe.

Enabled by new astronomical observatories

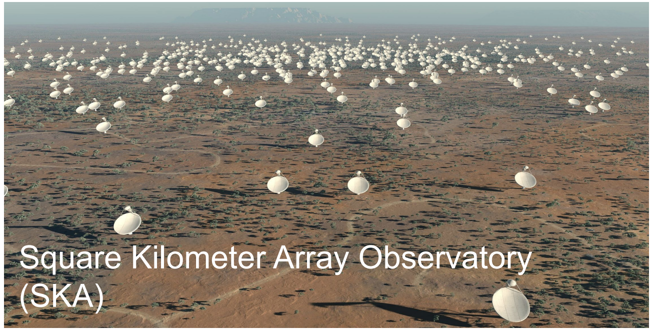
….. and by the synergy of the PI's expertise.

Timelines of telescopes





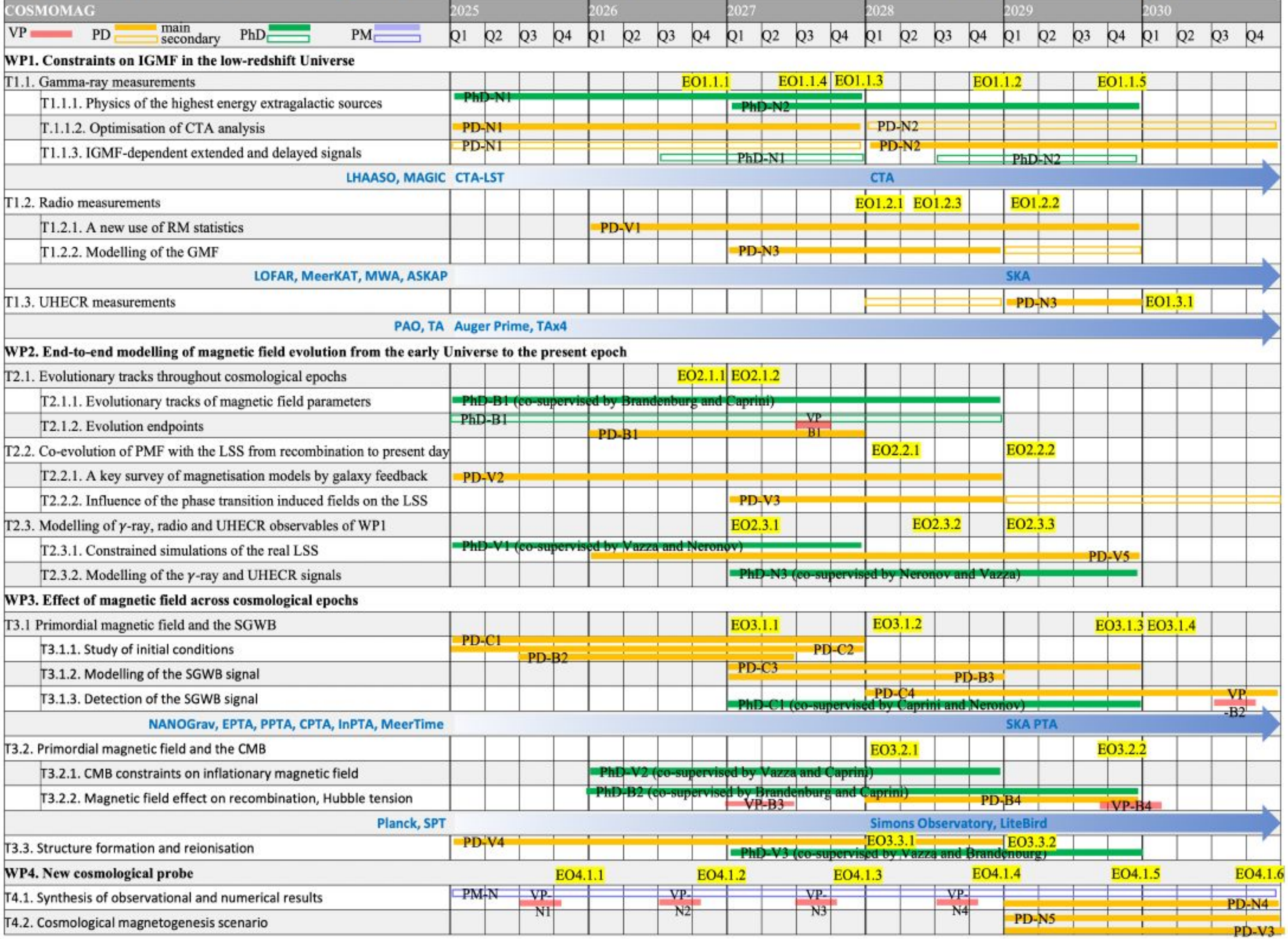
		2025	2026	2027	2028	2029	2030
γ-ray	LHAASO, MAGIC	CTA-LST			CTA		
radio	LOFAR, MeerKAT, MWA, ASKAP					SKA	
UHECR	PAO, TA	Auger Prime, TAx4					
GW	NANOGrav, EPTA, PPTA, CPTA, InPTA, MeerTime					SKA PTA	
CMB	Planck, SPT				Simons Observatory, LiteBird		



Budget

Cost category			Corr. PI	2nd PI	3rd PI	4th PI	Total in Euro
PI name			**Neronov**	**Caprini**	**Vazza**	**Brandenburg**	
Host Institution			**UPC**	**CERN**	**UNIBO**	**UNIST**	
A. Direct personnel costs	P.I.		312 307 €	539 909,16 €	213 480,00 €	449 395,20 €	1 515 092 €
	Senior Staff		0 €	0 €	0 €	0 €	0 €
	Post docs		773 760 €	1 296 000 €	800 000 €	607 360 €	3 477 120 €
	Students		498 220 €	151 200 €	181 800 €	485 888 €	1 317 108 €
	Other		180 000 €	0 €	0 €	0 €	180 000 €
	Total Personnel costs		**1 764 287 €**	**1 987 109 €**	**1 195 280 €**	**1 542 643 €**	**6 489 320 €**
B. Subcontracting costs (No indirect costs)						**0 €**	**0 €**
C. Purchase costs	C.1 Travel and substinence		120 000 €	40 000 €	168 000 €	170 000 €	498 000 €
	C.2 Equipment - including major equipment		0 €	0 €	110 000 €	55 000 €	165 000 €
	C.3 Other goods, works and services	Consumables incl fieldwork and animal costs	10 000 €	10 000 €	10 000 €	10 000 €	40 000 €
		Publications (incl. Open Access fees) and dissemination	5 000 €	5 000 €	5 000 €	5 000 €	20 000 €
		Other additional direct costs	245 000 €	115 000 €	116 000 €	309 829 €	785 829 €
		C3. Total other goods, works and services	260 000 €	130 000 €	131 000 €	324 829 €	845 829 €
	Total purchase costs (C.1+C.2+C.2)		**380 000 €**	**170 000 €**	**409 000 €**	**549 829 €**	**1 508 829 €**
D. Internally invoiced goods and sevices (No indirect costs)							**0 €**
E. Indirect Cost e=25%*(A+C1+C2+C3)			**536071,8**	**539277,29**	**401070**	**523118,05**	**1999537,14**
Total eligible costs			**2 680 359 €**	**2 696 386 €**	**2 005 350 €**	**2 615 590 €**	**9 997 686 €**
Requested EU Contribution			**2 680 359 €**	**2 696 386 €**	**2 005 350 €**	**2 615 590 €**	**9 997 686 €**

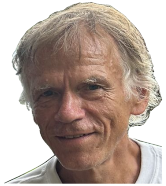
Gantt chart



N=Neronov

C=Caprini

V=Vazza



B=Brandenburg

COSMOMAG objectives (B1)

O1 Perform multi-messenger measurements of intergalactic magnetic fields in different parts of the cosmic web.

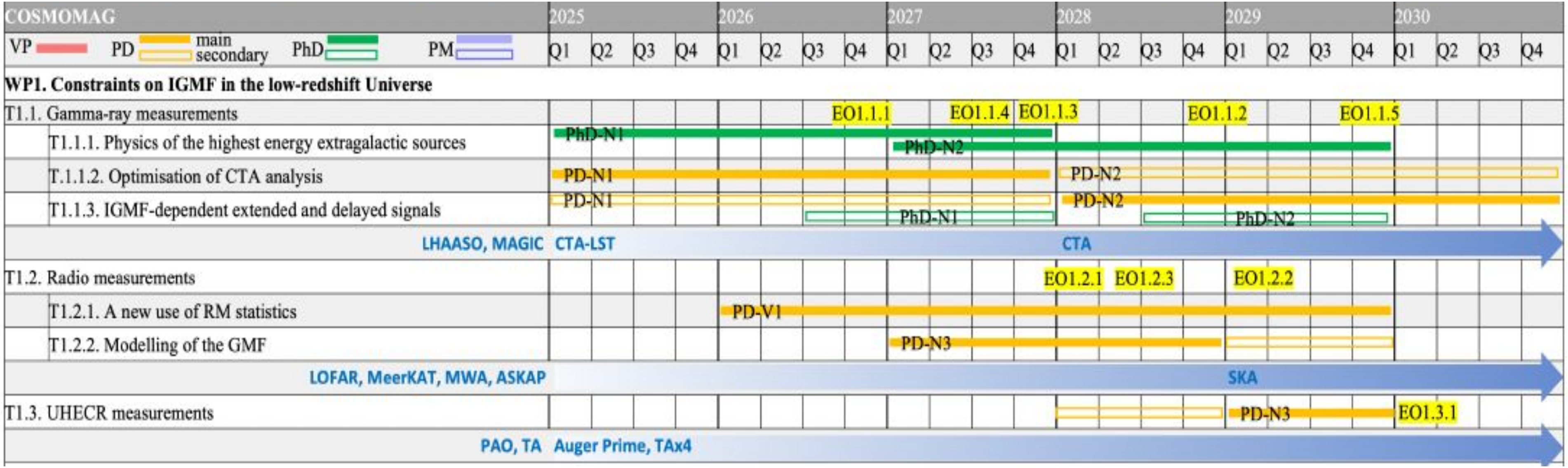
O2 Understand the role of magnetic fields in the structure formation process and probe the cosmological origin of the magnetic field in cosmic voids and filaments.

O3 Establish a relation between the relic magnetic fields and the stochastic gravitational wave background in different frequency ranges, derive constraints on magnetic field during the quark confinement epoch from the stochastic gravitational wave background.

O4 Link the parameters of the relic magnetic field in the present-day Universe to its initial characteristics in the early Universe.

O5 Use multi-messenger observational constraints on the primordial magnetic fields to test theoretical models of cosmological magnetogenesis and constrain Beyond-Standard-Model processes in the early Universe.

WP1: Constraint on intergalactic MFs in the present-day Universe



Workforce: 4PDs, 2PhDs

Risks and mitigations: Operation and data releases of the new observatories may be delayed:

(i) tune our methods using simulated data and

(ii) work with the data and public data products of prototype/pathfinder instruments

WP1: Constraint on intergalactic MFs in the present-day Universe

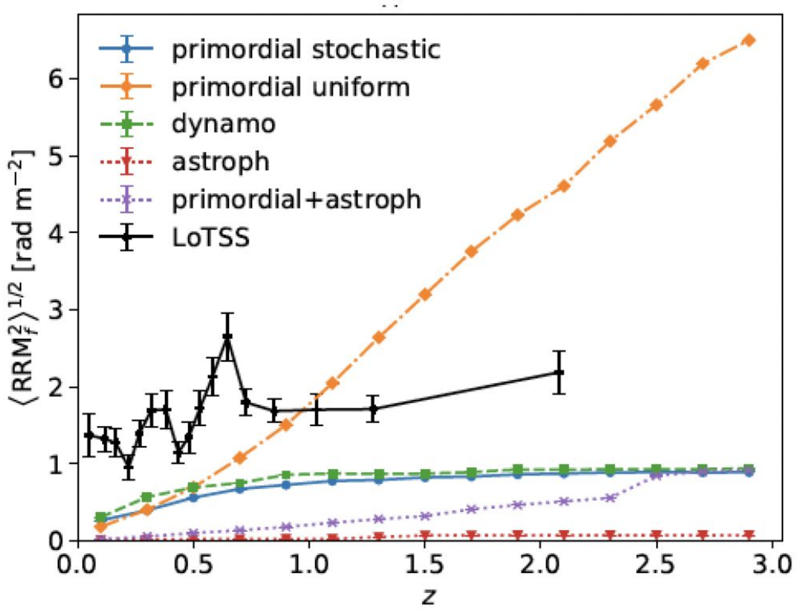


Figure 3: LOFAR observation of the evolution of RM with redshift [18], compared to numerical predictions by different MFs seeding models.

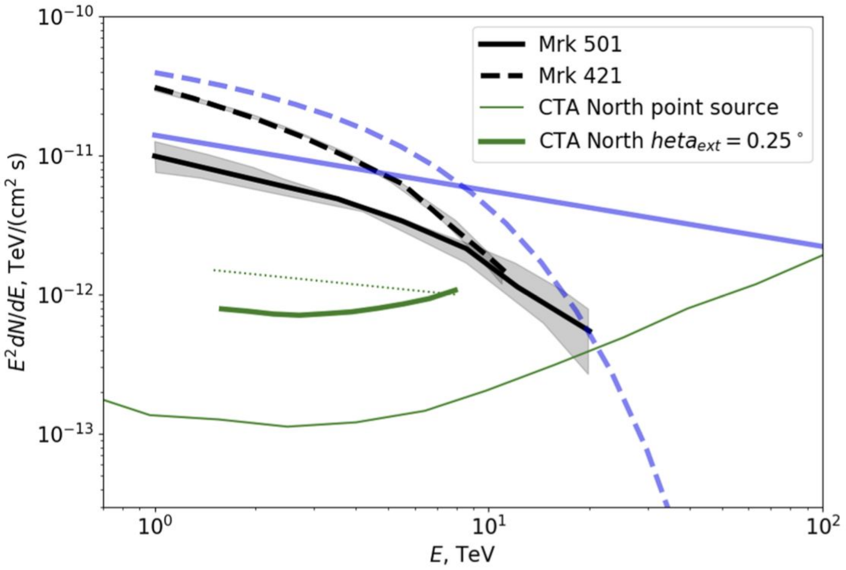
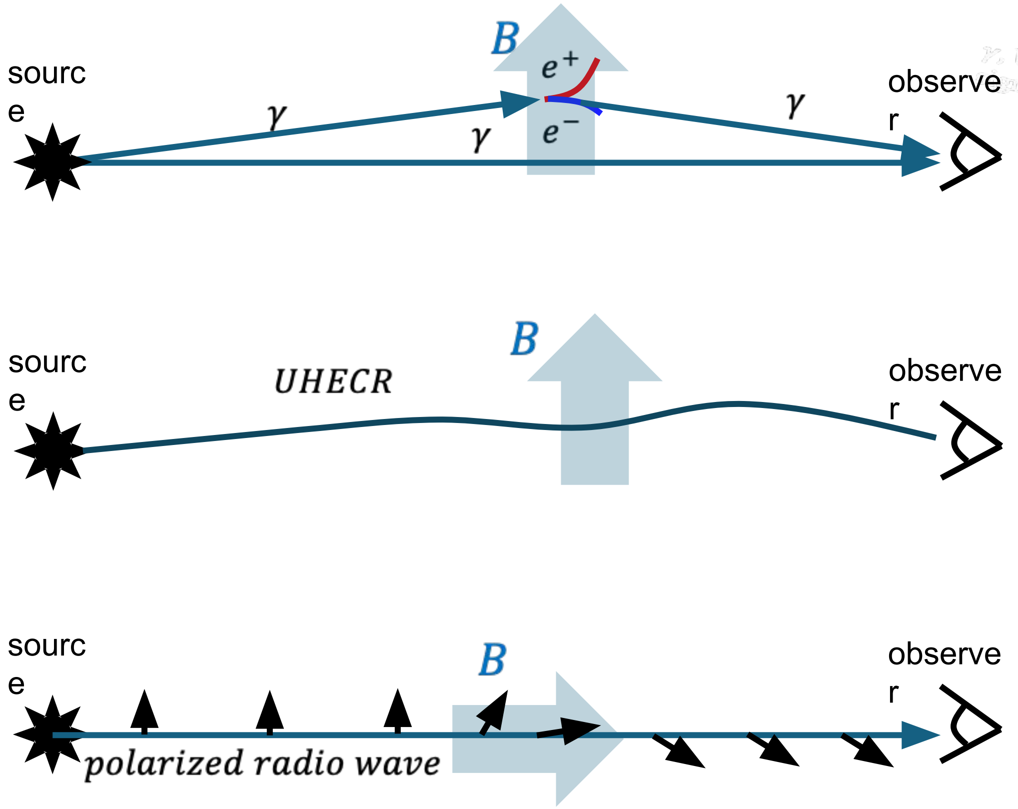


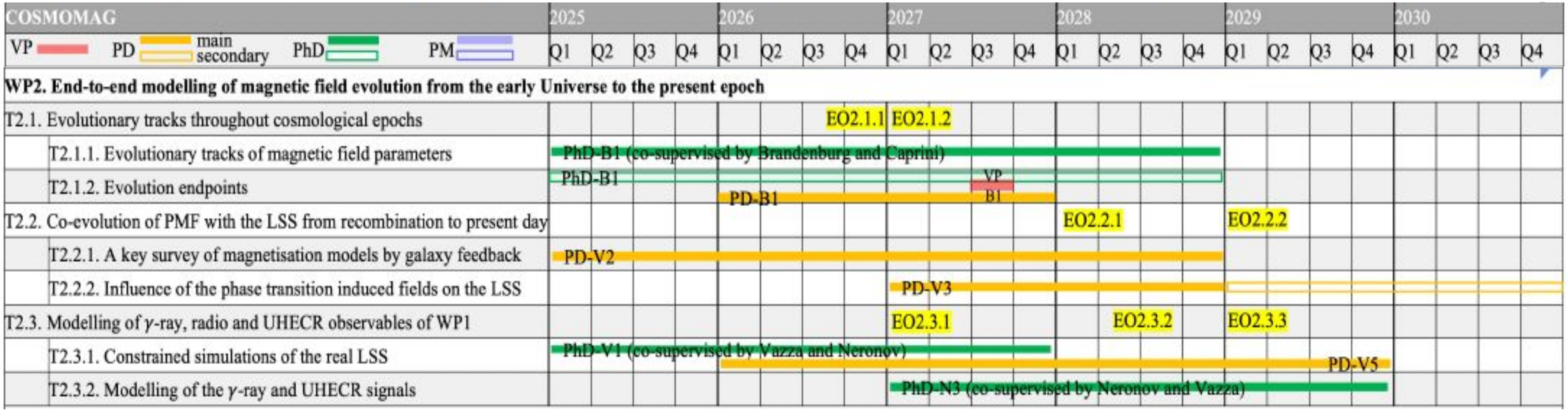
Figure 2: Measured (black) and intrinsic (blue) spectra of the two closest blazars, Mrk 421 and Mrk 501, compared to CTA North sensitivity for point sources (thin green solid line). Green thick line shows the sensitivity for extended emission, green dotted line is the expected secondary flux [169].

WP1: Constraint on intergalactic MFs in the present-day Universe



Name	TeVCat (C.U.)
1ES 1959+650	0.64
Mrk 421	0.3 ✓
Mrk 501	0.3 ✓
1ES 1218+304	0.08
1ES 2344+514	0.07 ✓
1ES 1426+428	0.03
1ES 2037+521	0.03
RGB J0710+591	0.03
RBS 0723	0.025
1ES 1727+502	0.021 ✓
RGB J0152+017	0.02
1ES 0229+200	0.018
1ES 1741+196	0.016
RX J1136.5+6737	0.015
1ES 1440+122	0.01
PGC 2402248	0.01
1ES 0414+009	0.006

WP2: End-to-end modelling of MF evolution from the early Universe to the present



Workforce: 4PDs, 3 PhDs

Risks and mitigations: we would not be able to determine the decay exponent κ or locations of the endpoints *B*, l_B unambiguously for all cosmological epochs:

(i) rely on previous analytical understanding of the evolution, adding the modelling uncertainty of new simulations as systematic error in the synthesis work of WP4.

WP2: End-to-end modelling of MF evolution from the early Universe to the present

h

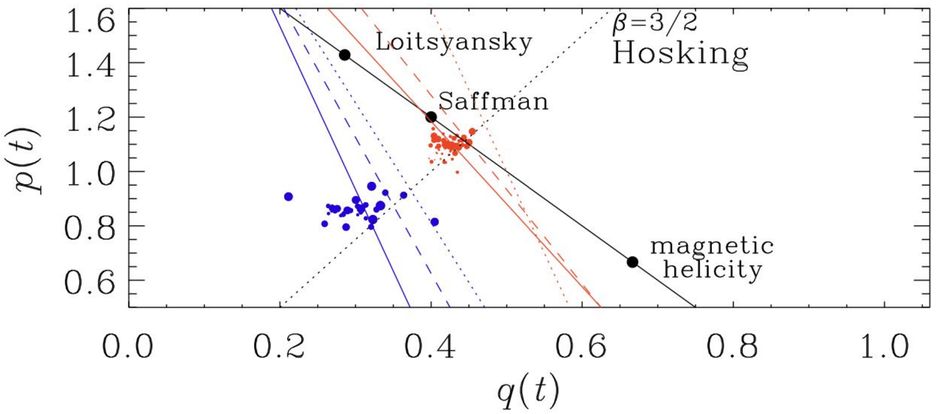


Figure 4: Parametric representation of $p(t)$ (decay exponent of magnetic energy) and $q(t)$ (exponent of the correlation length) adapted from [117] for time-dependent magnetic hyperdiffusion (blue) and ordinary magnetic hyperdiffusion that is constant (red). Symbol sizes increase with time. Dotted, dashed, and solid coloured lines mark different evolutionary tracks.

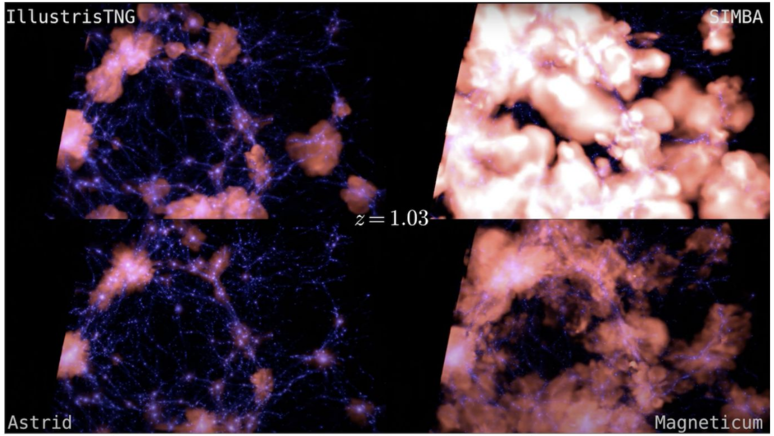
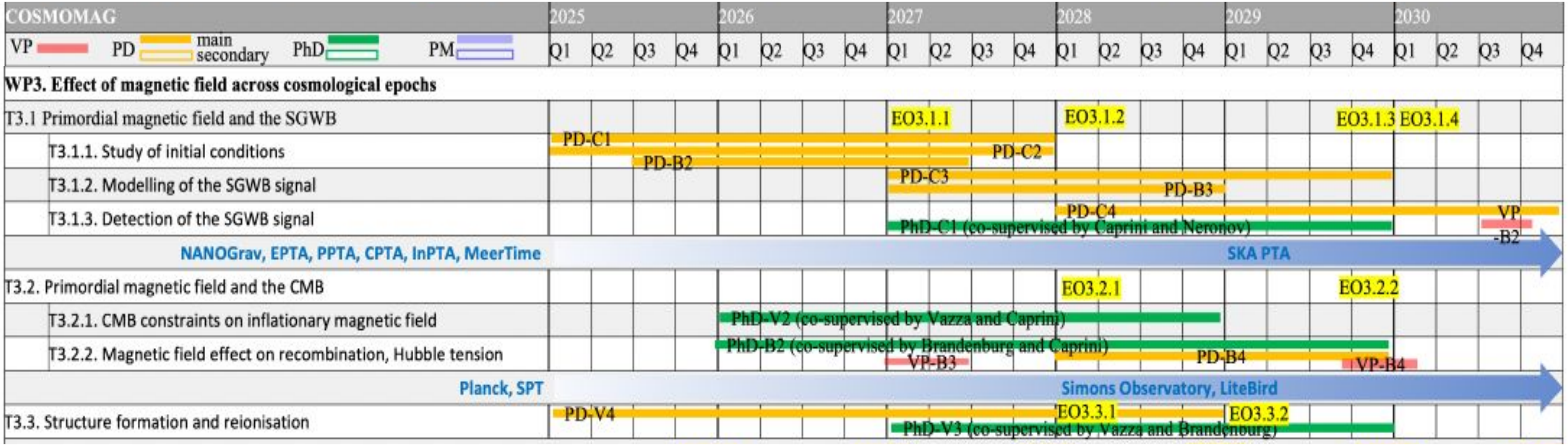


Figure 5: Comparison of feedback models by the Camels project (`https://www.camel-simulations.org/`), showing the projected gas density (blue) and very different distribution of hot gas (red) for the same cosmic volume.

WP3: Observational imprint of magnetic field on past cosmological epochs



Workforce: 8 PDs, 4PhDs

Risks and mitigations: The PTA GW background may be due to supermassive black holes binaries:

(i) consider other generation scenarios at LISA, and/or derive constraints on (instead of measurements of) the early Universe signal component at PTA

WP3: Observational imprint of magnetic field on past cosmological epochs

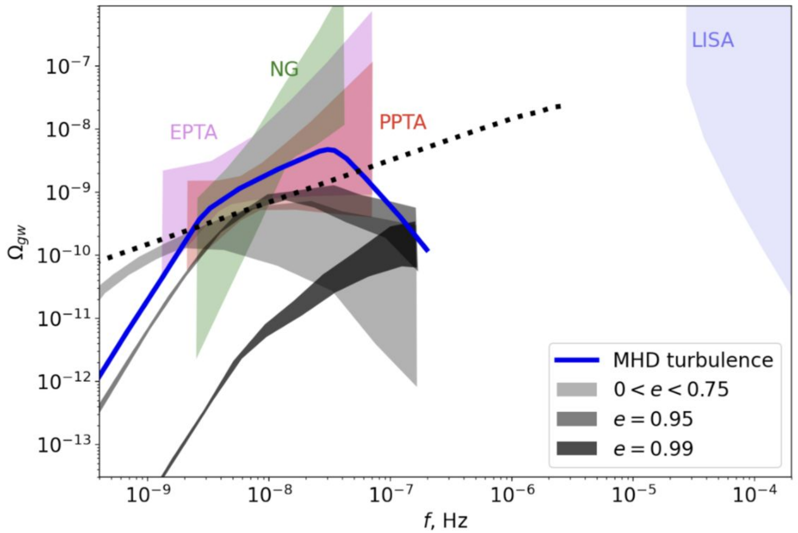


Figure 7: From [101]. The Stochastic GW Background measurement by PTAs in 2021 (green, red, magenta) compared to the predictions of the same signal from a primordial MF at the QCD energy scale (blue) and from supermassive black hole binaries with different orbital eccentricities e (grey).

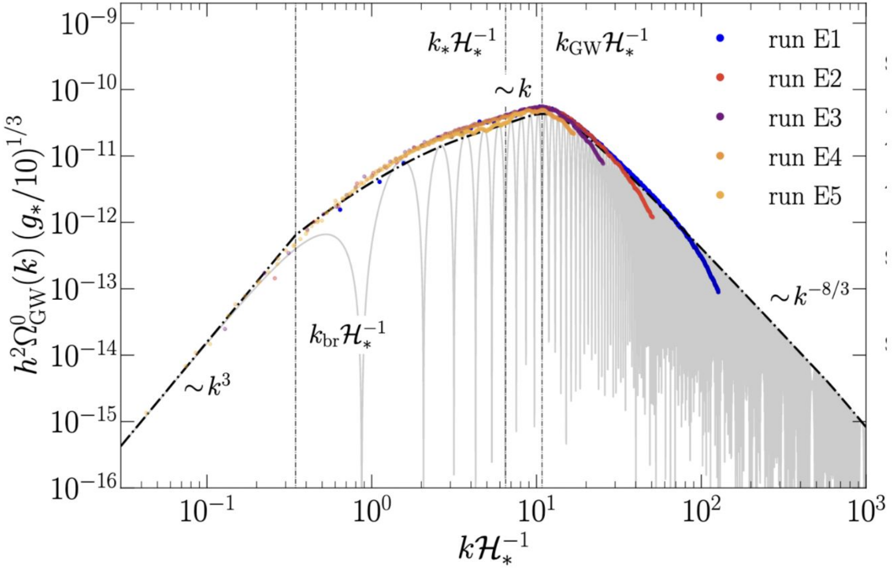
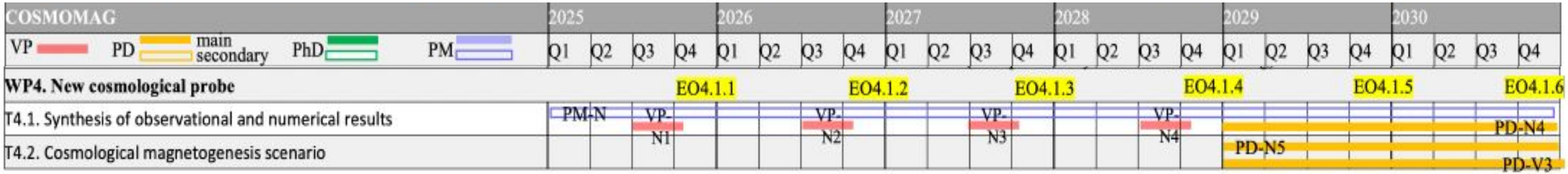


Figure 6: From [101]: The Stochastic GW Background power spectrum from MHD simulations (coloured points) performed with the PENCIL CODE, spanning from super-Hubble scales to wave numbers in the inertial range, compared with a physics-informed analytical fit (dashed-dotted line). The large scale break of the spectrum $k_{\rm br}$ corresponds to the source duration, while the spectral peak corresponds to the MF correlation scale $k_{\rm GW} \sim k_* = 2\pi/l_B$.

WP4: New cosmological probe



Workforce: 3PD

Risks and mitigations: measurements of WP1 and WP3, and the modelling of WP2, give discordant results and no self-consistent picture emerges. It may also be that none of the previously proposed MF generation processes are consistent with the data.

(i) critically asses systematic uncertainties of each measurement, before reporting a new cosmological "tension" providing insight into beyond-Standard-Model phenomena, or possibly multiple cosmological sources of MFs.

WP4: New cosmological probe

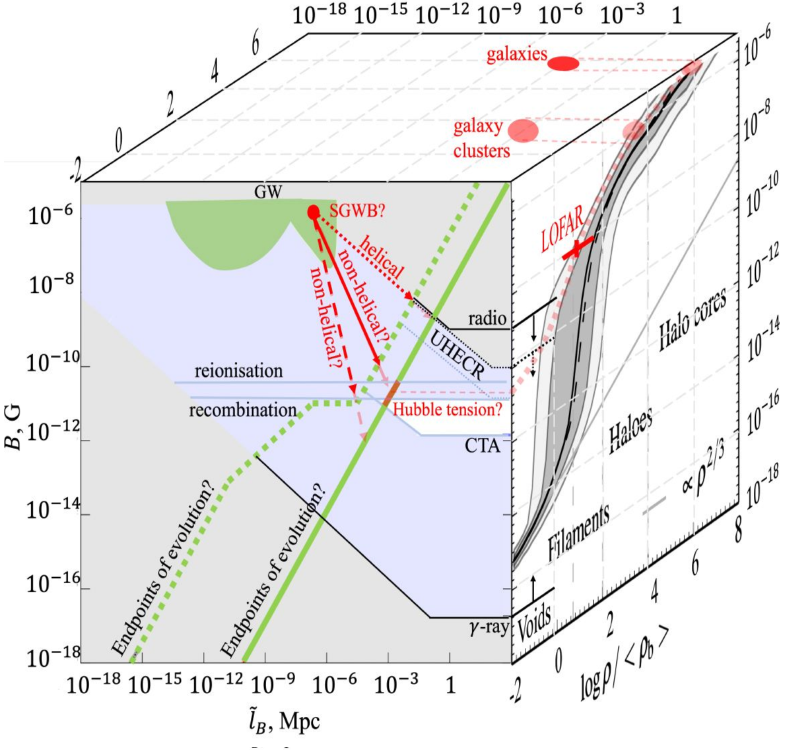
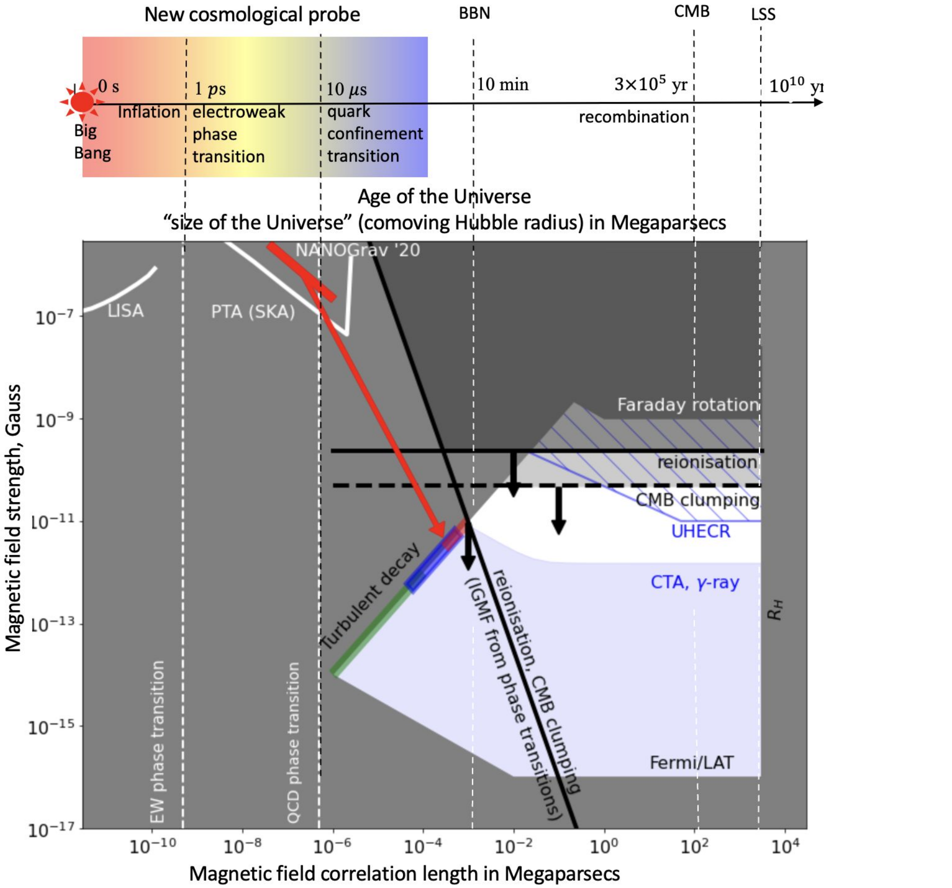
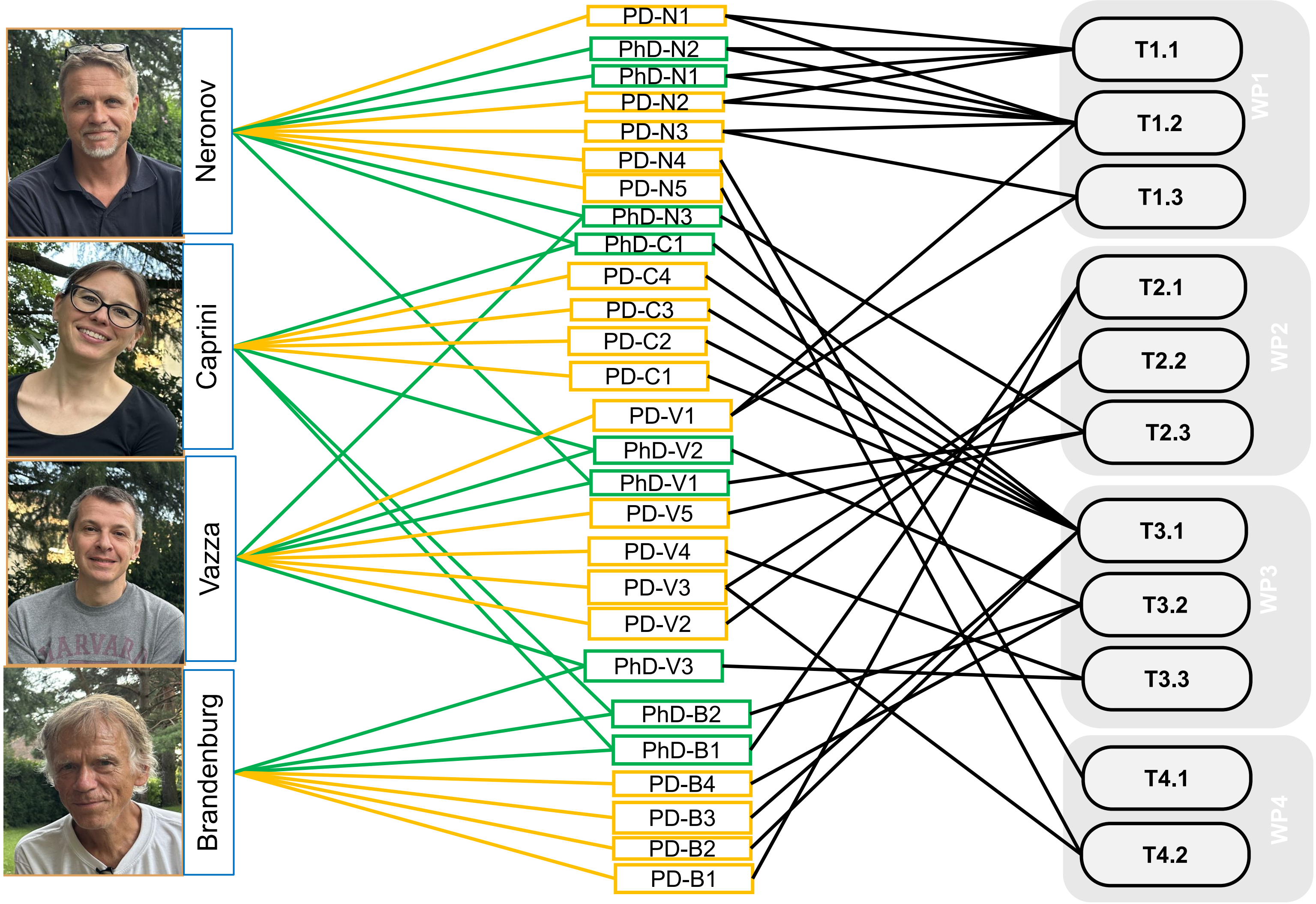


Figure 1: *Front face* of the cube shows observational constraints on the primordial MF strength and correlation length (grey shading) [11]. Green lines show alternative theoretical predictions for the endpoints of the primordial MF evolution [12, 13]. Green regions show the sensitivity reach of GW detectors [11]. Red dot shows an example of initial field parameters consistent with the primordial Stochastic GW Background interpretation of the PTA data [14]. Red arrows show alternative predictions for the evolution of the primordial MF parameters before Recombination [12, 13][15]. The "Hubble tension" interval on the endpoint line shows the observational hint from Ref. [16]. Blue shaded region shows the parameter space that we will explore in COSMOMAG. *Right face* shows numerical calculations of the field strength scaling with the matter overdensity (grey band and black line) [17]. The red cross shows the estimated field strength in the filaments [18]. The red dashed curve shows a possible scaling of the field strength, to be constrained by COSMOMAG. *Top face* shows parameters of MFs in galaxies and galaxy clusters.



Workforce



Neronov
Caprini
Vazza
Brandenburg
PD-N1
PhD-N2
PhD-N1
PD-N2
PD-N3
PD-N4
PD-N5
PhD-N3
PhD-C1
PD-C4
PD-C3
PD-C2
PD-C1
PD-V1
PhD-V2
PhD-V1
PD-V5
PD-V4
PD-V3
PD-V2
PhD-V3
PhD-B2
PhD-B1
PD-B4
PD-B3
PD-B2
PD-B1
WP1
T1.1
T1.2
T1.3
WP2
T2.1
T2.2
T2.3
WP3
T3.1
T3.2
T3.3
WP4
T4.1
T4.2

	Team	Expertise	
APC	**PI:** A. Neronov	γ-ray, UHECR, Simulations, Theory, GW	**Instruments:** Fermi-LAT, MAGIC, CTA, LHAASO, TA, EPTA, LISA, LOFAR, ASKAP, SKA Planck, ACT, SPT, BICEP, LiteBIRD **Codes:** CRBEAM, PENCIL, ENZO
	Members (in-kind): S.Babak, O.Kalashev, Y.Revaz, D. Semikoz		
CERN	**PI:** C. Caprini	GW, Theory, CMB, Simulations	
	Members (in-kind): V.Domcke, A.Roper Pol, U.Wiedermann		
UNIBO	**PI:** F. Vazza	Simulations, Radio, UHECR, CMB	
	Members (in-kind): A. Bonafede, E. Carretti, F. Finelli, D. Paoletti		
UNIST	**PI:** A. Brandenburg	Simulations, MHD, GW	
	Members (in-kind): , K. Bondarenko, O. Ghosh, O. Iarygina, F. Niedermann		

APC Team - 1 PI, 5 Post-Docs, 3 PhDs

PI		2026	2027	2028	2029	2030	2031	work package	activity
PhDN1								WP1	Transients and GRBs with CTA, LHAASO; EBL, delayed emission
PhDN2								WP1	Extreme blazars (CTA, LHAASO), EBL, extended emission
PDN1								WP1	CTA analysis optimization, search for delayed emission
PDN2								WP1	CTA analysis optimization, search for extended emission
PDN3								WP1	Galactic magnetic field, UHECR
PhDN3								WP2 (co-supervision **Vazza**)	Modelling of UHECR and gamma-ray signals (CR beam, ENZO)
PDN4								WP4	Synthesis of observables and modelling of WP1-WP3
PDN5								WP4	Theoretical magnetogenesis models

+4 visiting professors in 2025, 2026, 2027, 2028

CERN Team , 1 PI, 4 Post-Docs, 1 PhD

PI	2025	2026	2027	2028	2029	2030	work package	activity
PDC1							WP3	Study of QCD magnetogenesis
PDC2							WP3	Study of EW and inflationary magnetogenesis
PDC3							WP3	MHD simulations of GW production
PDC4							WP3	Pipelines for SGWB detection with LISA
PhDC1							WP3 (co-supervision **Neronov**)	Pipelines for SGWB detection with PTA

UNIBO Team: 1 PI, 5 Post-Docs, 3 PhDs

PI	2025	2026	2027	2028	2029	2030	work package	activity
PDV1							WP1	radio analysis, LOFAR, ASKAP, SKA
PDV2							WP2	ENZO simulations: feedback testing
PDV3							WP2-WP4	ENZO AMR simulations: magnetic effects on structure formation
PhDV1							WP2 (co-supervision **Neronov**)	ENZO simulations: constrained simulation of Local Universe
PDV5							WP2	ENZO simulations & radio: validation with radio data
PhDV2							WP3 (co-supervision **Caprini**)	CMB constraints and predictions for LiteBird
PhDV3							WP3 (co-supervision **Brandenburg**)	ENZO simulations: reionisation in local Universe
PDV4							WP3	ENZO simulations: magnetic effects on reionisation

UNIST Team, 1 PI, 4 Post-Docs, 2 PhDs

PI	2025	2026	2027	2028	2029	2030	work package	activity
PhDB1							WP2 (w/ **Caprini & Neronov)**	Evolution track and endpoints
PDB1							WP2	endpoints
PDB2							WP3	initial conditions (magnetogenesis mechanisms)
PDB3							WP3	SGWB modeling
PhDB2							WP3 (w/ **Caprini)**	Magnetic field effect on Recombination, Hubble tension, with focus on numerical simulations
PDB4							WP3	magnetic field effect on Recombination and Hubble tension, with focus on magnetic effects on CMB

+4 visiting professors in 2026, 2027, 2028, 2029

Advisory board

- Four senior researchers in the field
- One of them will play the role of ombudsperson
- Meet yearly to
    - monitor development of the project from scientific and managerial sides
    - mitigate unlikely conflicts among the team

Meetings

- Yearly COSMOMAG workshops (synthesis work, challenges, PhD and postdoc training, outreach)
    - 20 kEuro per event
- 2 international PhD schools
    - 50 kEuro per event
- 2 topical conferences open to broad community
    - 50 kEuro per event
- 2nd edition of program “Generation, evolution and observations of cosmological magnetic fields”
    - 100 kEuro for the event (co-funding)