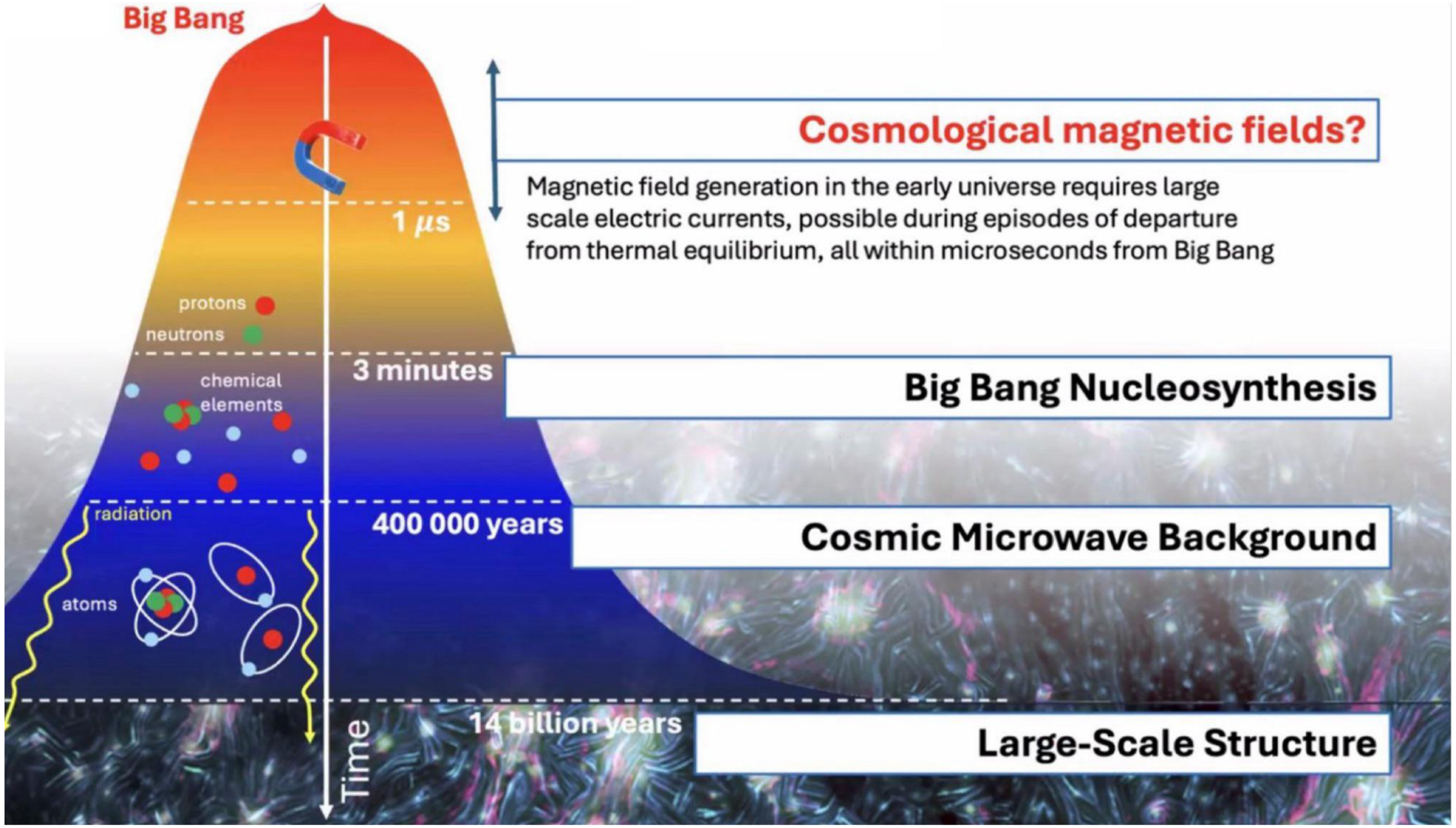
Primordial magnetic fields and relic gravitational waves: messengers of the first microseconds

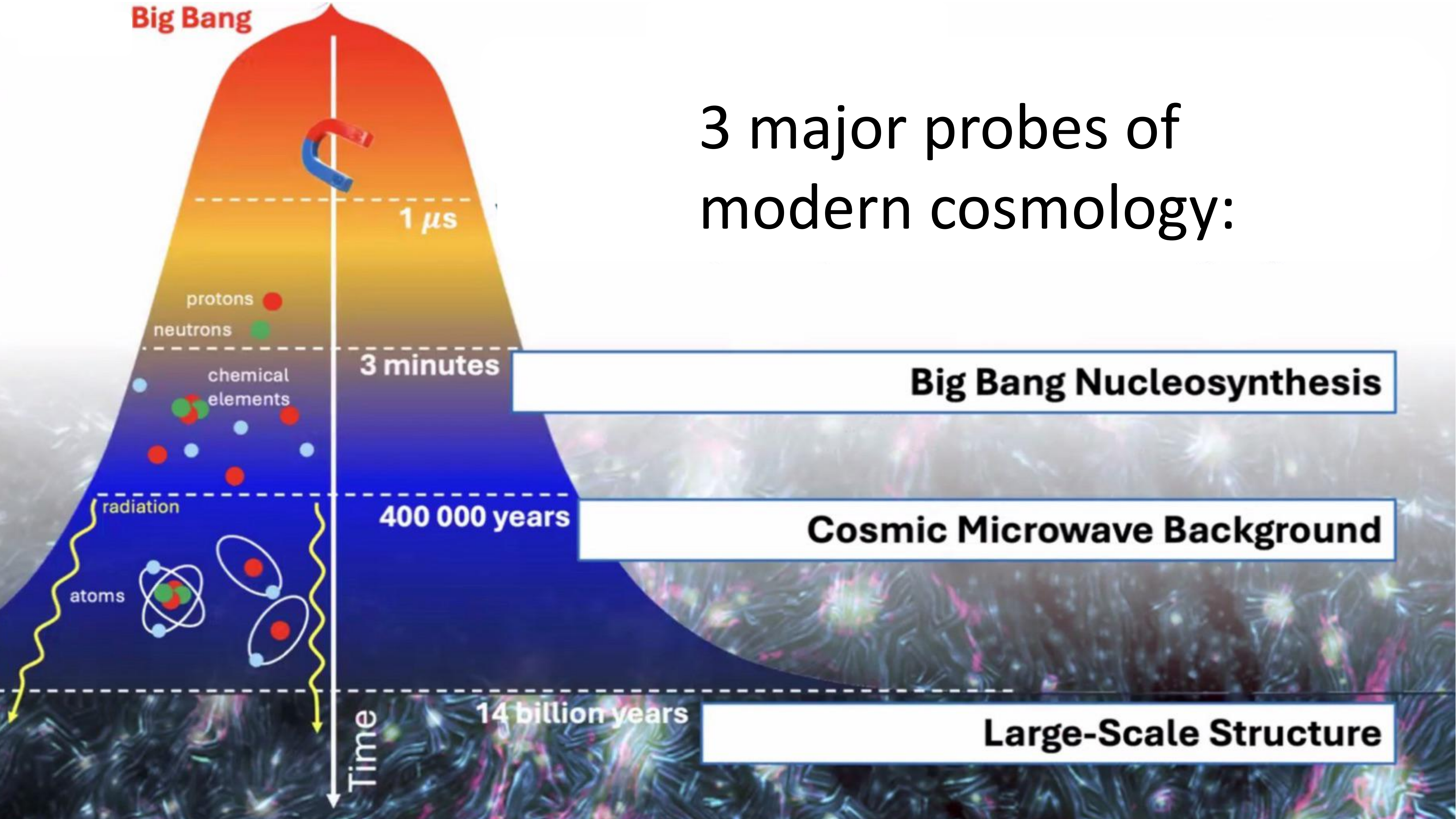


Axel Brandenburg
(Nordita)

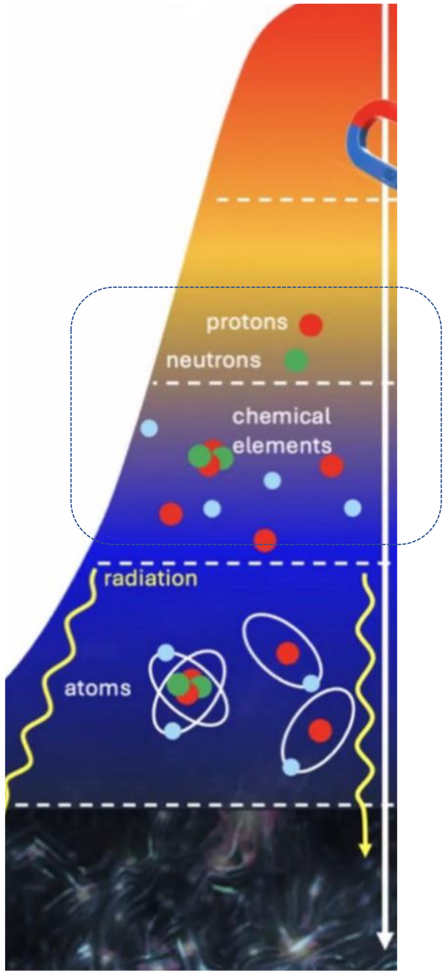
Collaborators: Chiara Caprini (Geneva), Andrii Neronov (Paris/Lausanne), Franco Vazza (Bologna)

- Important physics to be probed:
- Weak and electromagnetic forces decoupled
- Quark confinement (QCD phase transition
- Matter-antimatter asymmetry
- Generation of magnetic fields

3 major probes of modern cosmology:

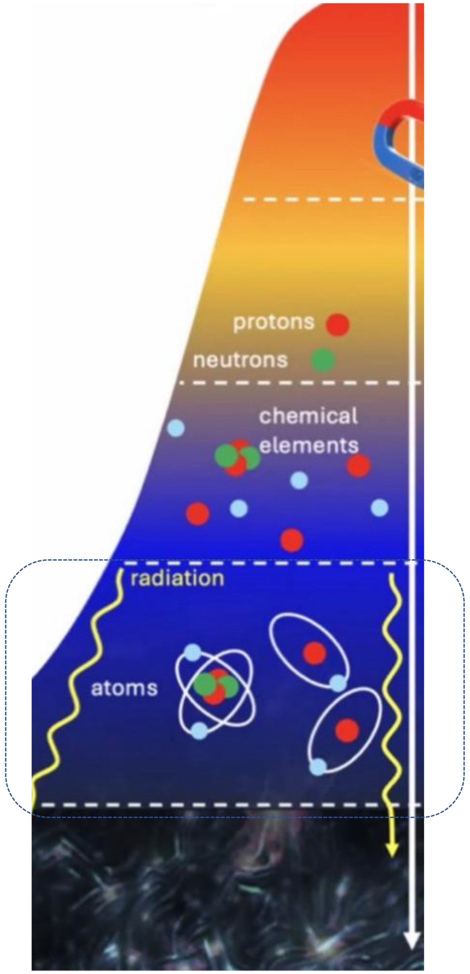


Big Bang Nucleosynthesis



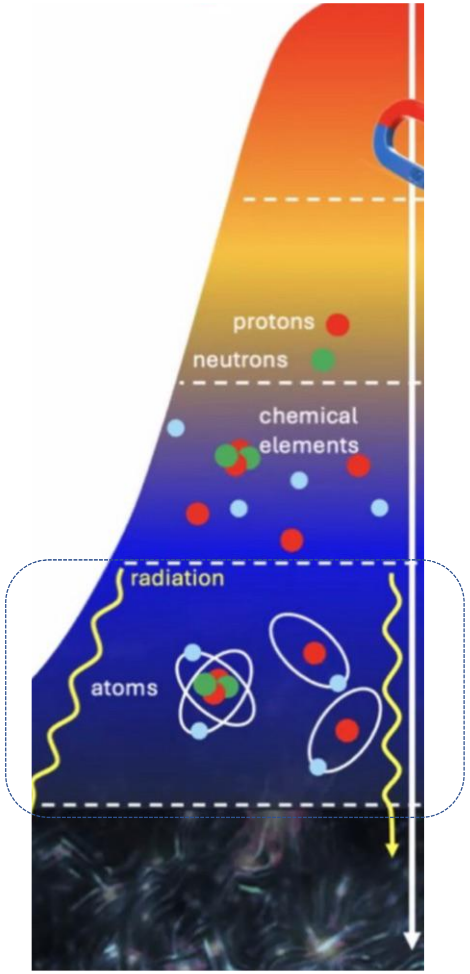
- Abundances of light elements
  - Hydrogen, helium, lithium
  - 75% hydrogen, 25% helium
  - Deuterium, helium-3, helium-4, lithium-7
- Baryon to photon ratio
  - Affects light element production
  - More baryons, more rapid fusion, depleting deuterium; more helium-4
  - Less baryons, preserving more deuterium
  - Ratio measured to be 6.1×10^{-10}
  - Consistent with cosmic microwave background
- Neutrino physics
  - Number of species affects expansion history

Cosmic Microwave Background

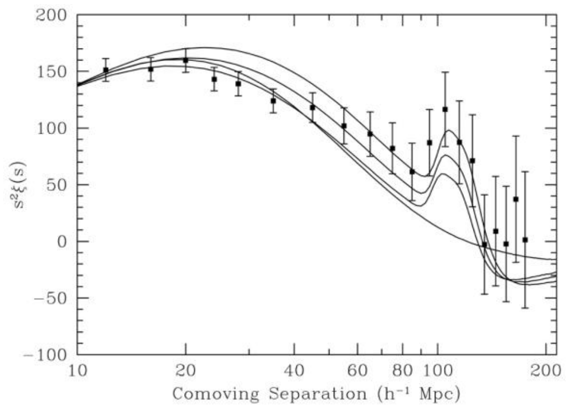


- Composition
  - 5% baryonic matter
  - 26% dark matter
  - 69% dark energy (→ cosmic acceleration)
- Cosmic inflation
  - Tiny temperature fluctuations
  - Large-scale homogeneity
  - Flatness of space
- Age of the universe 13.8 Gyr
  - Expansion history: depends on recombination history
  - Hubble parameter (67 km/s/Mpc) matter content
  - Ω_m=0.31

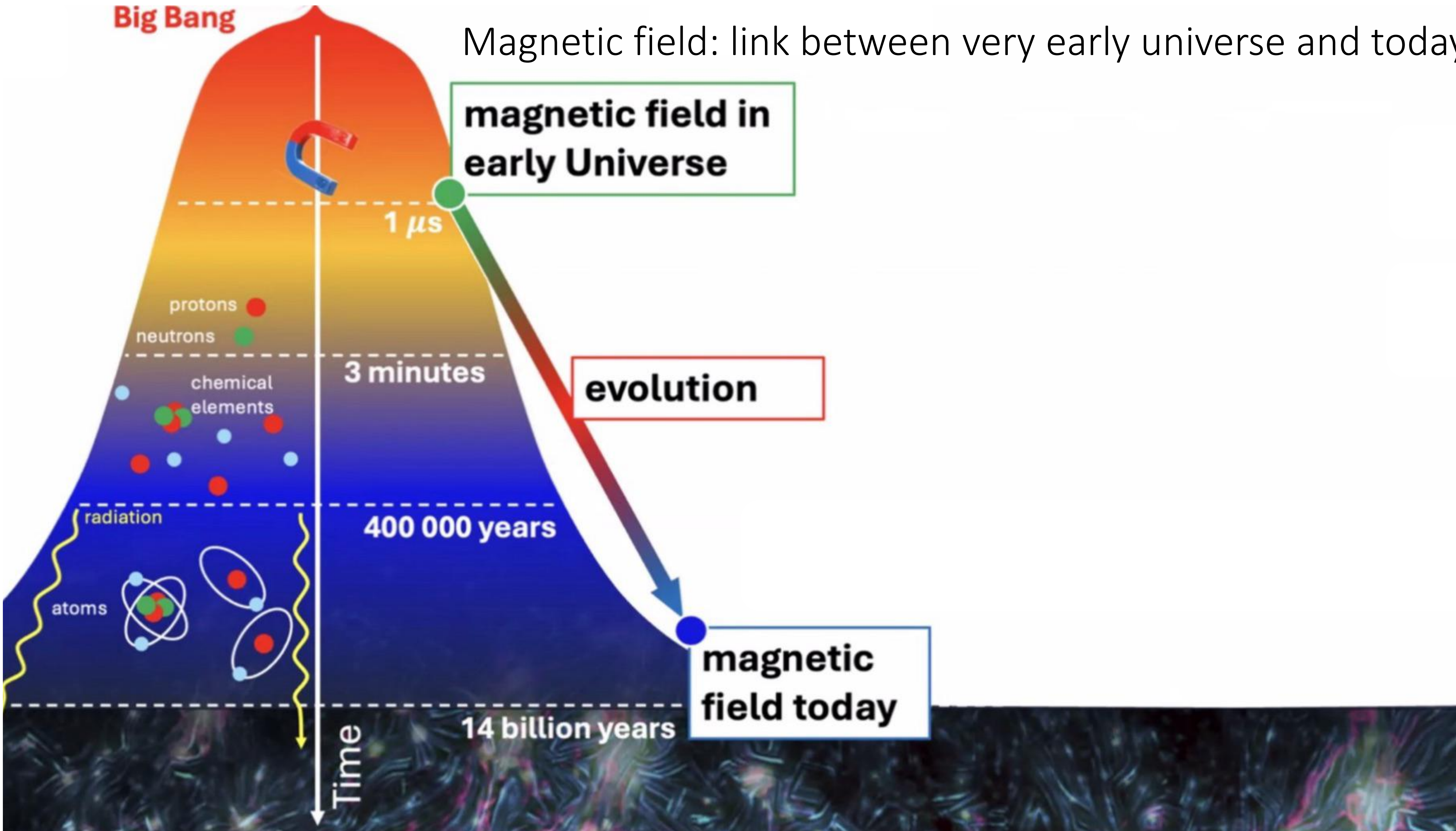
Large-Scale Structure



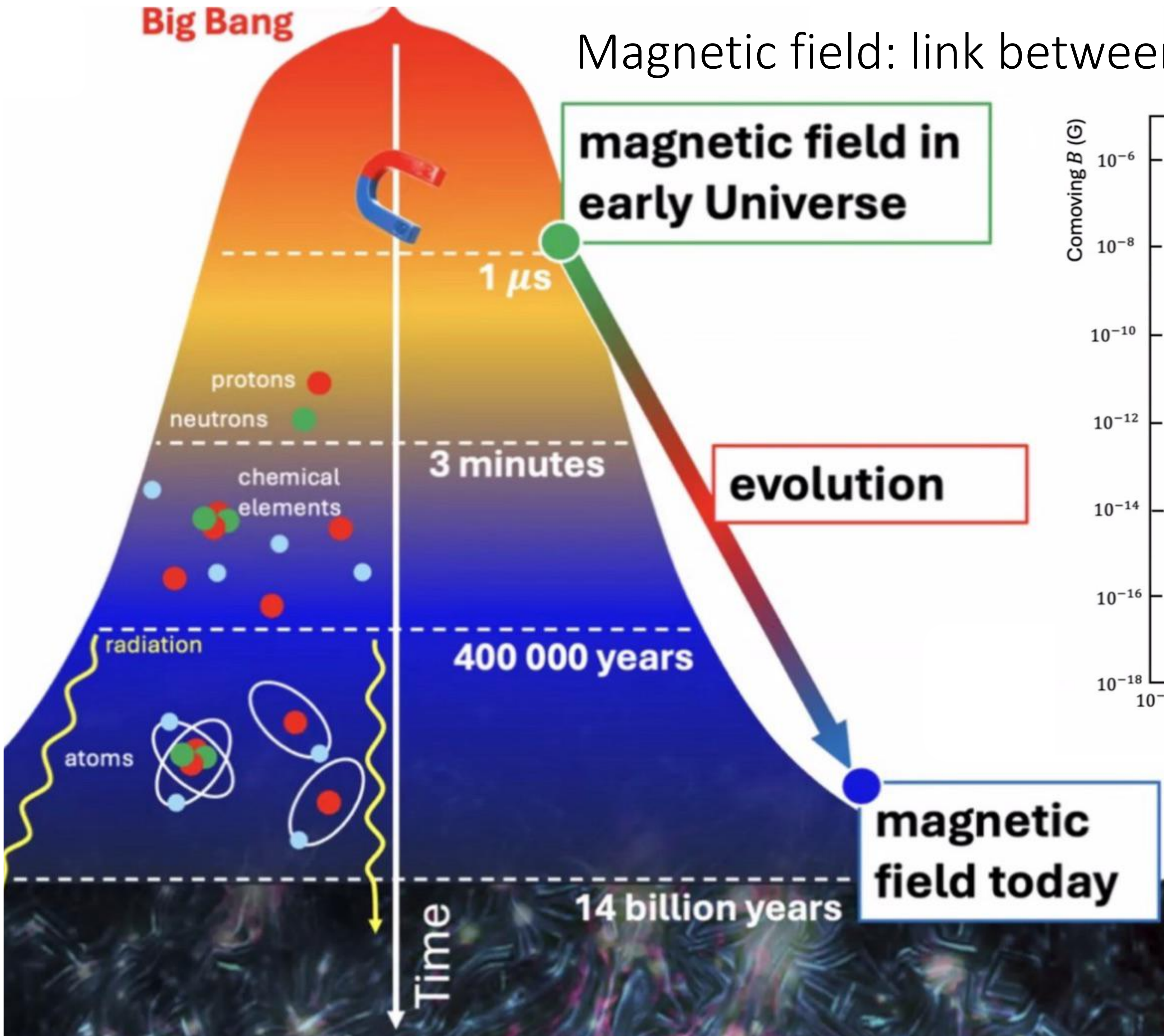
- Dark matter
  - Simulations match expansion history only if dark matter included
- Matter-antimatter asymmetry
  - Matter formed galaxies, instead of annihilating
- Baryon acoustic oscillations
  - Periodic fluctuations in galaxy distributions
  - Cosmic ruler
- Weak lensing surveys
  - Weaker late-time clustering
  - Higher Hubble parameter 73.4 km/s/Mpc
  - Lower Ω_m=0.26

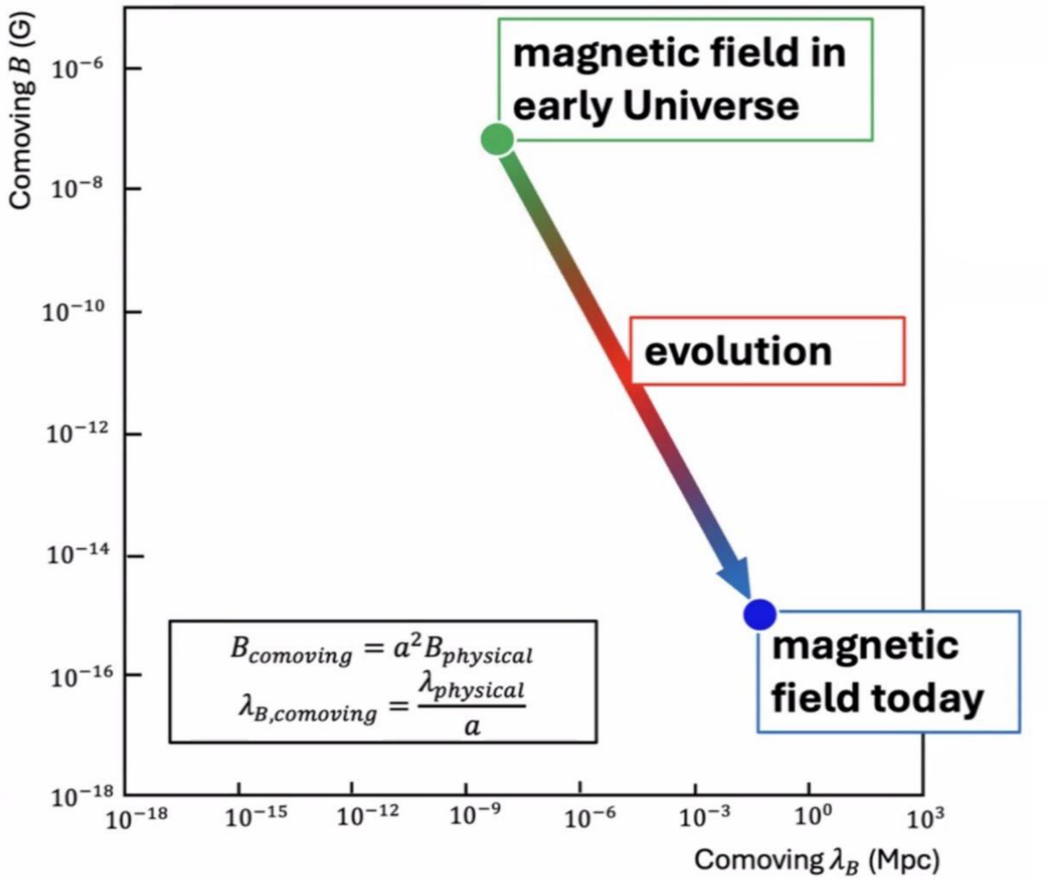


Magnetic field: link between very early universe and today

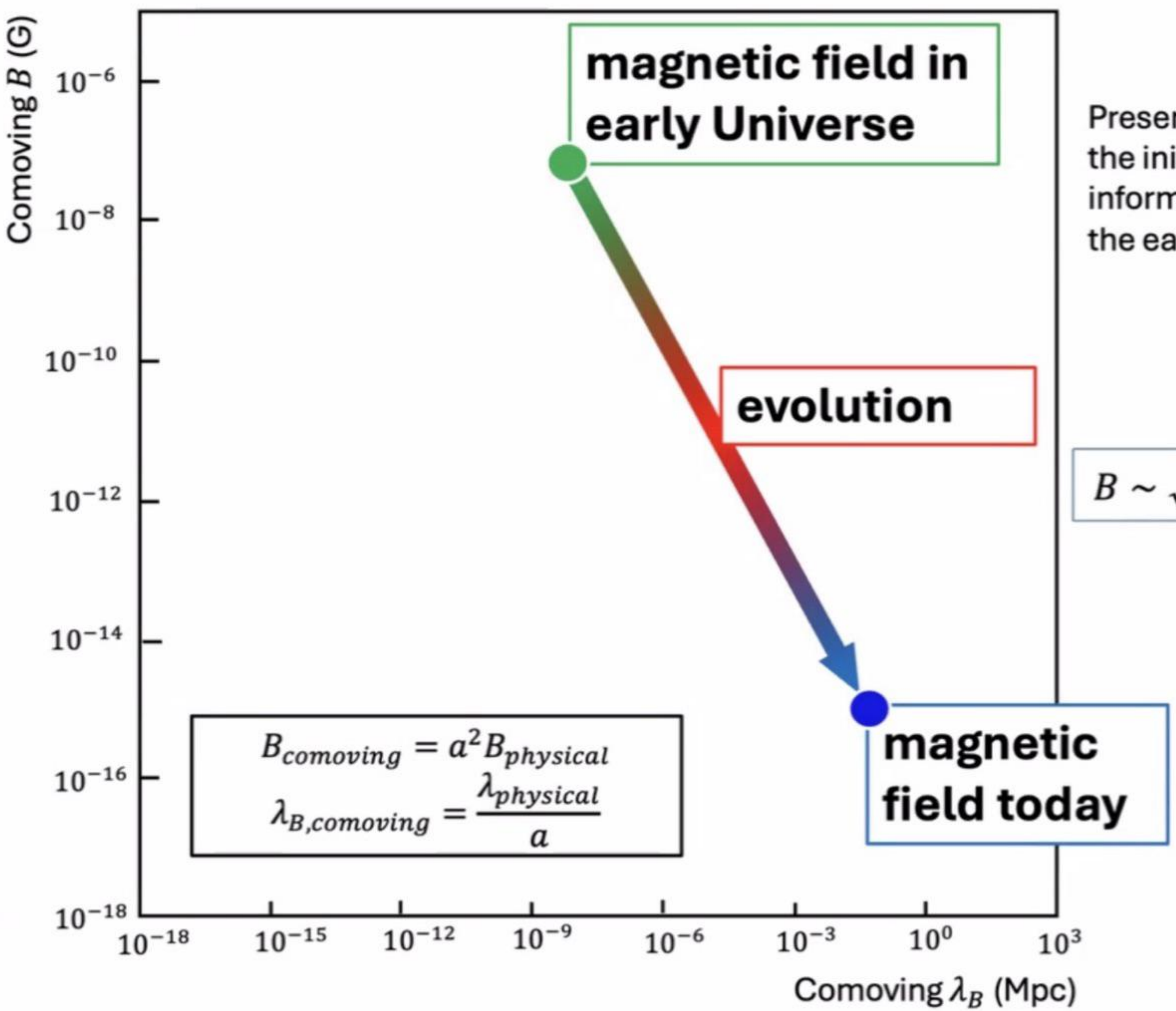


Magnetic field: link between very early universe and toda



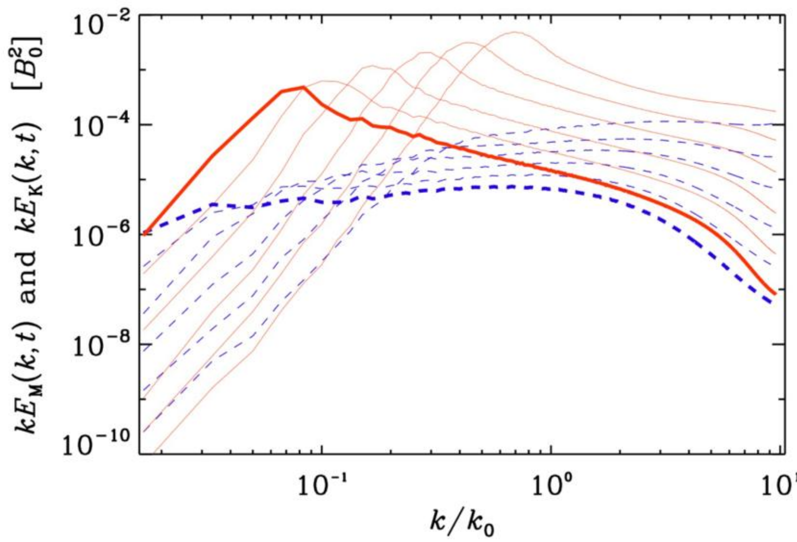


Magnetic field: inversely cascading



Present-day relic magnetic field parameters are related to the initial field characteristics. They potentially provide information on the mechanism of production of the field in the early Universe.

$B \sim \sqrt{2\rho_B}$



- Turbulent decay
  - Magnetic field drives gas motions
  - The velocity stirs up the field further
- But: length scale can increase
  - Energy at large scales (small k) can increase!
  - → Inverse cascade

Comoving horizon scale is small today

$$\lambda_{H_\star} = 5.8 \times 10^{-10}\ \mathrm{Mpc}\left(\frac{100\ \mathrm{GeV}}{T_\star}\right)\left(\frac{100}{g_\star}\right)^{1/6}$$

- Electroweak (EW) energy scale
  - $5.8\mathrm{x}10^{-10}$ Mpc ~ 100 AU
  - Unless inflationary field, sausally generated fields always smaller
- QCD (quark confinement) energy scale (T_*=0.15 GeV, g_*=15)
  - 0.5 pc ~ 100 000 AU

$$f_* = \frac{a_* H_*}{a_0} \simeq (1.8 \times 10^{-8}\ \mathrm{Hz})\left(\frac{g_*}{15}\right)^{1/6}\left(\frac{T_*}{150\ \mathrm{MeV}}\right).$$

- Use GWs to pinpoint starting point of magnetic field evolution
  - End points on a universal line ***B*** vs length scale
  - EW enery scale corresponds to 0.2 mHz

Large-scale magnetic fields from hydromagnetic turbulence in the very early universe

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(Received 1 February 1996)

We investigate hydromagnetic turbulence of primordial magnetic fields using magnetohydrodynamics (MHD) in an expanding universe. We present the basic, covariant MHD equations, find solutions for MHD waves in the early universe, and investigate the equations numerically for random magnetic fields in two spatial dimensions. We find the formation of magnetic structures at larger and larger scales as time goes on. In three dimensions we use a cascade (shell) model that has been rather successful in the study of certain aspects of hydrodynamic turbulence. Using such a model we find that after $\sim 10^9$ times the initial time the scale of the magnetic field fluctuation (in the comoving frame) has increased by 4–5 orders of magnitude as a consequence of an inverse cascade effect (i.e., transfer of energy from smaller to larger scales). Thus *at large scales* primordial magnetic fields are considerably stronger than expected from considerations which do not take into account the effects of MHD turbulence. [S0556-2821(96)02712-9]

Inverse cascade since the 1970s (*driven* turbulence)

J. Fluid Mech. (1975), *vol.* 68, *part* 4, *pp.* 769–778 769
Printed in Great Britain

Possibility of an inverse cascade of magnetic helicity in magnetohydrodynamic turbulence

By U. FRISCH, A. POUQUET,
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J. LÉORAT AND A. MAZURE
Université Paris VII, Observatoire de Meudon, France

J. Fluid Mech. (1976), *vol.* 77, *part* 2, *pp.* 321–354 321
Printed in Great Britain

Strong MHD helical turbulence and the nonlinear dynamo effect

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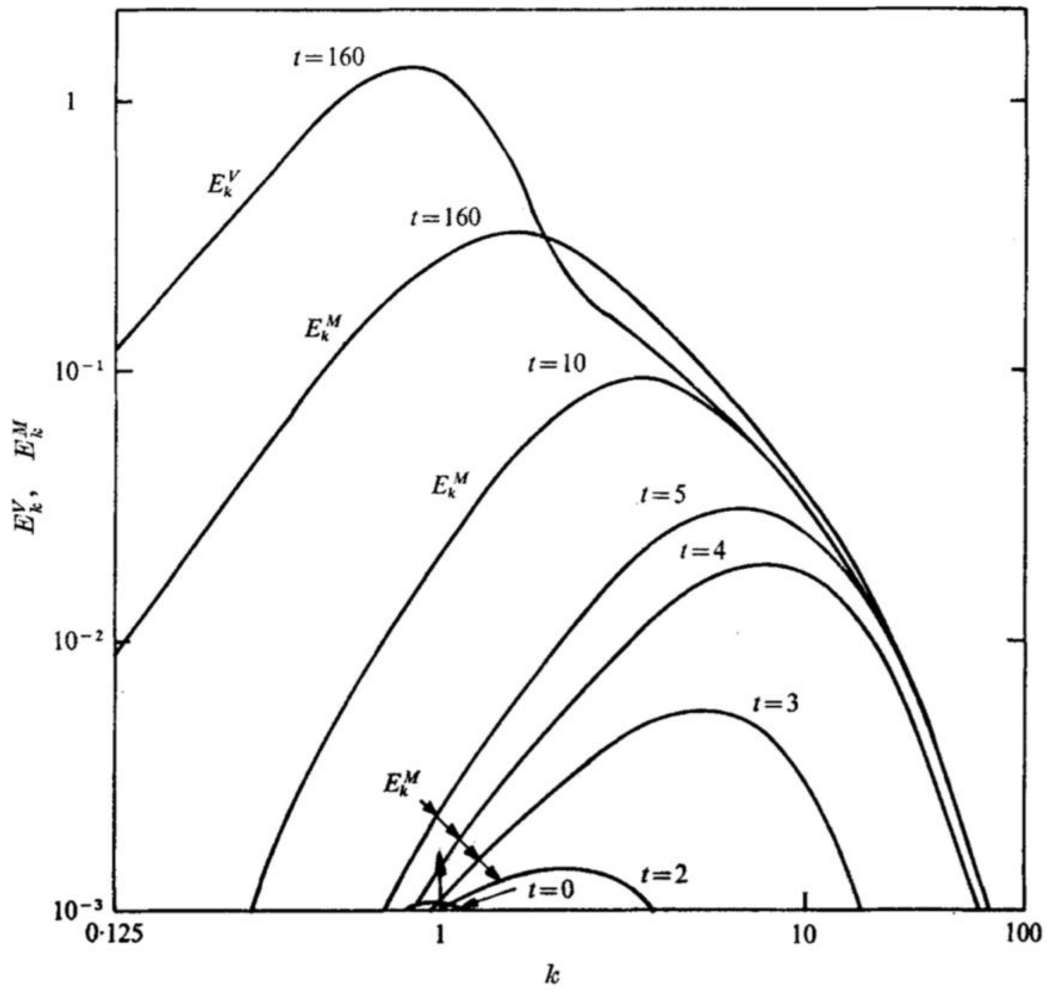
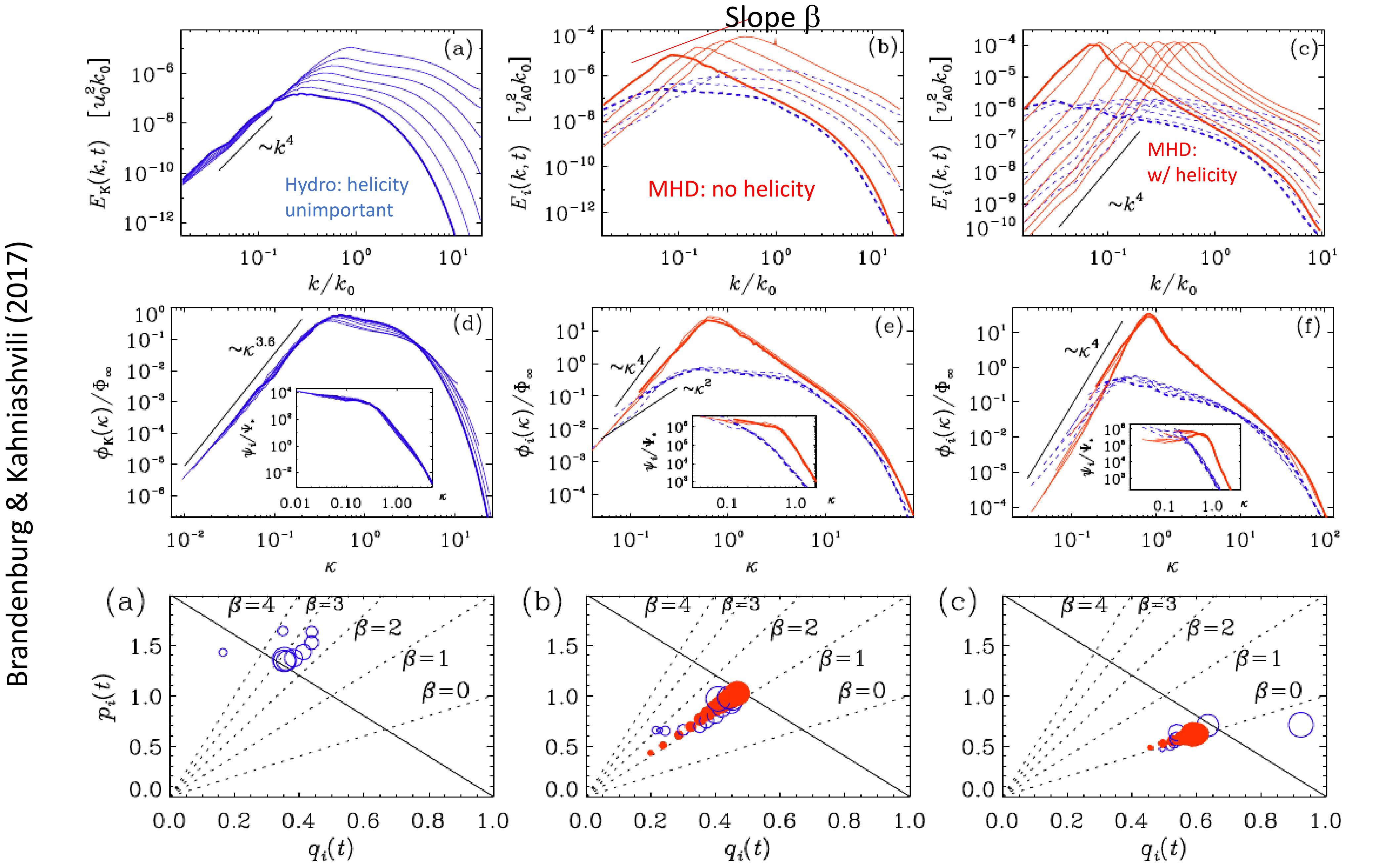


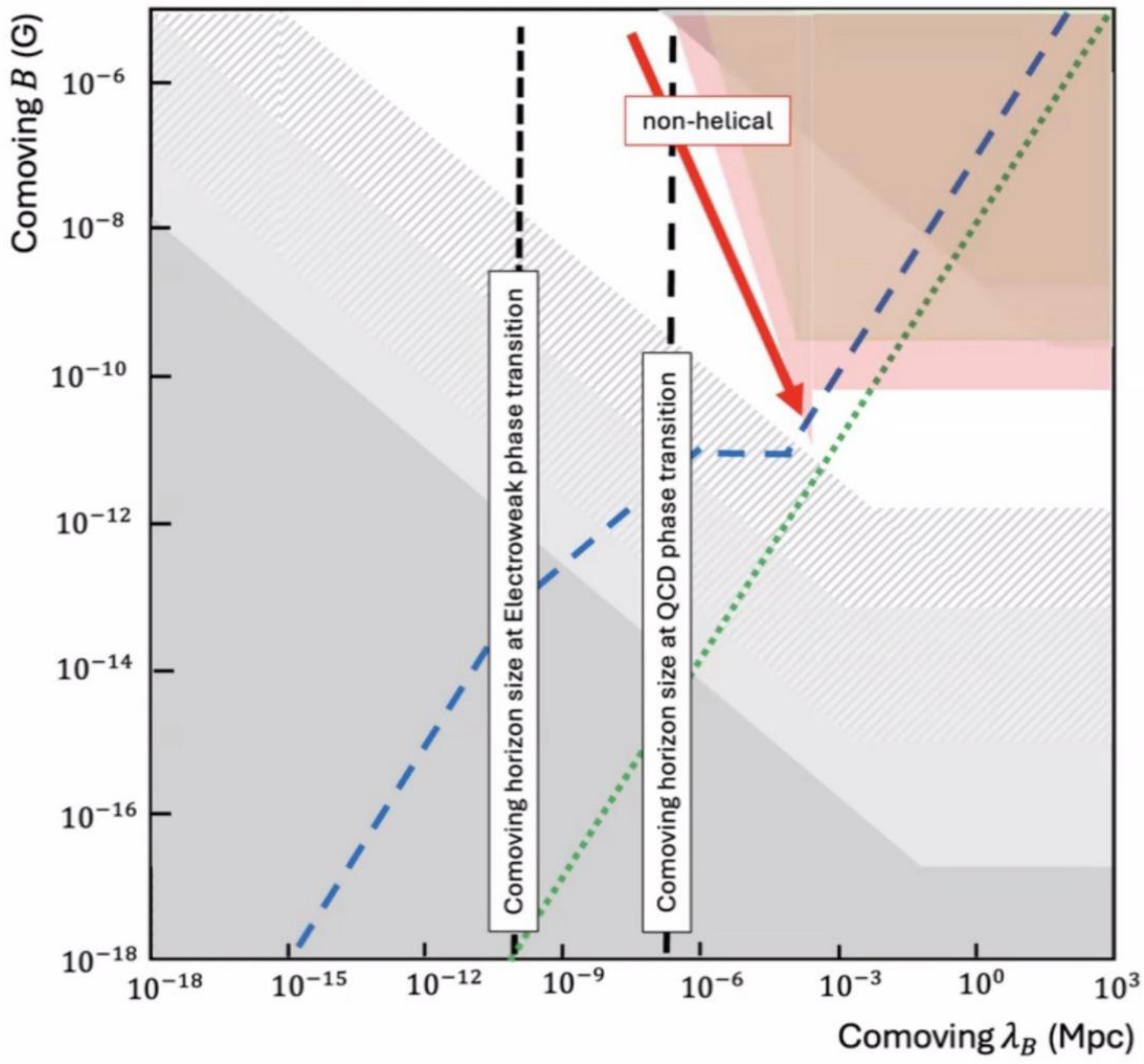
Collapsed spectra and *pq* diagrams

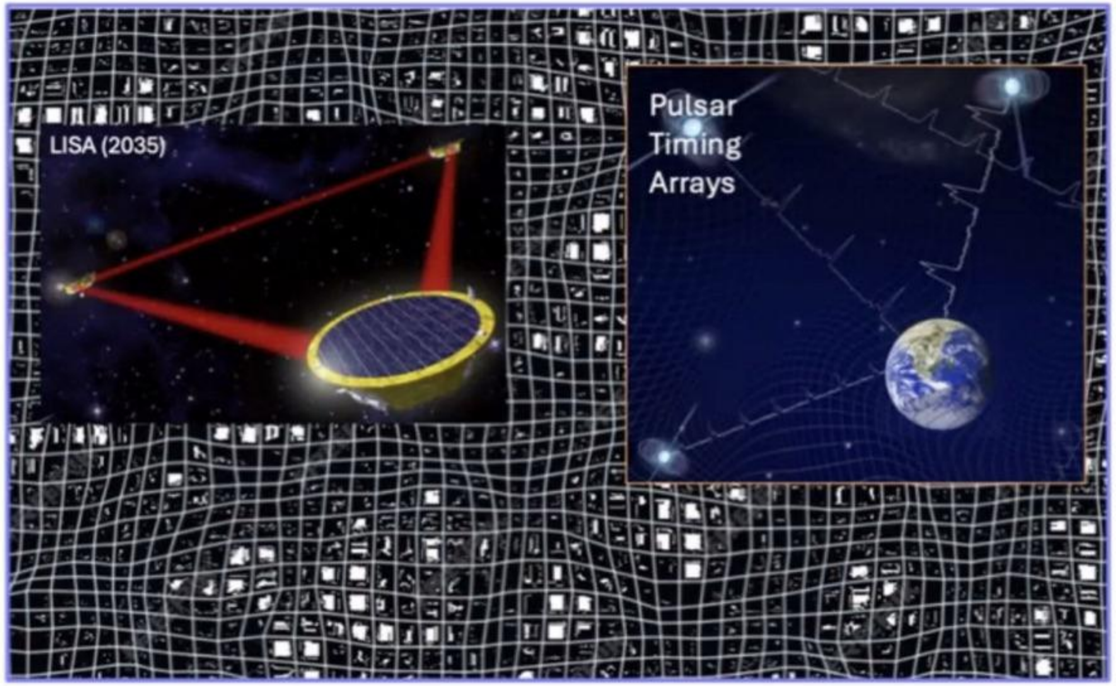
$-p_i(t) = d\ln\mathcal{E}_i/d\ln t, \quad q_i(t) = d\ln\xi_i/d\ln t,$



Explanations for slope β
Exponents *p,q*
(Hosking & Schekochihin 2021+2023)

Magnetic field at the moment of generation: gravitational waves





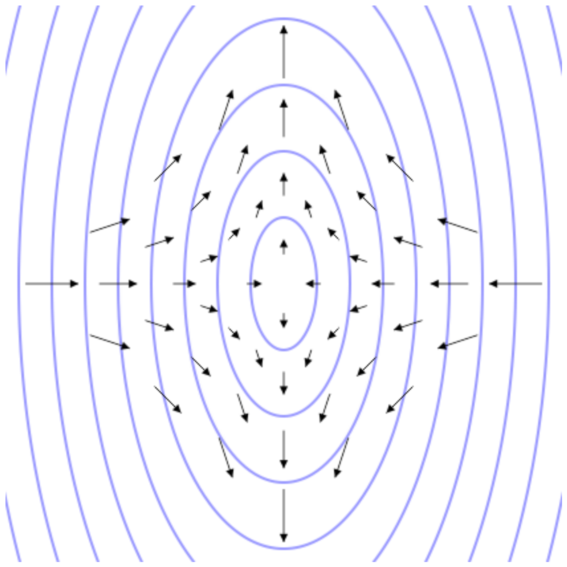
Gravitational wave background

Magnetic field has stress-energy tensor that is a source in the gravitational wave equation.

Magnetic field generates motions of plasma that has stress-energy tensor that is also a source for the gravitational waves

Plasma motions that generate magnetic fields may also source gravitational waves.

Gravitational waves & polarization



traceless-transverse

$$\left(\partial_t^2 + 3H\partial_t - c^2\nabla^2\right) h_{ij}(\boldsymbol{x},t) = \frac{16\pi G}{c^2}\, T_{ij}^{\mathrm{TT}}(\boldsymbol{x},t)$$

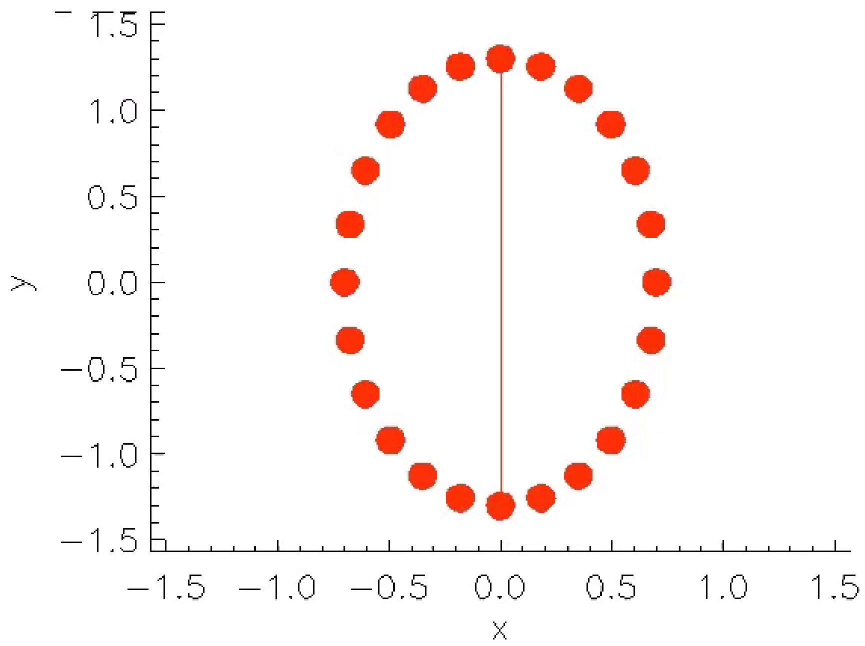
$$T_{ij}(\boldsymbol{x},t) = \left(p/c^2 + \rho\right)\gamma^2 u_i u_j - B_i B_j + (\boldsymbol{B}^2/2 + p)\delta_{ij}$$

Example

$$\boldsymbol{B} = \begin{pmatrix} 0 \\ \sigma \sin kx \\ \cos kx \end{pmatrix} \longrightarrow \nabla \times \boldsymbol{B} = \begin{pmatrix} \partial_x \\ 0 \\ 0 \end{pmatrix} \times \begin{pmatrix} 0 \\ \sin kx \\ \cos kx \end{pmatrix} = k \begin{pmatrix} 0 \\ \sin kx \\ \cos kx \end{pmatrix} = k\boldsymbol{B}$$

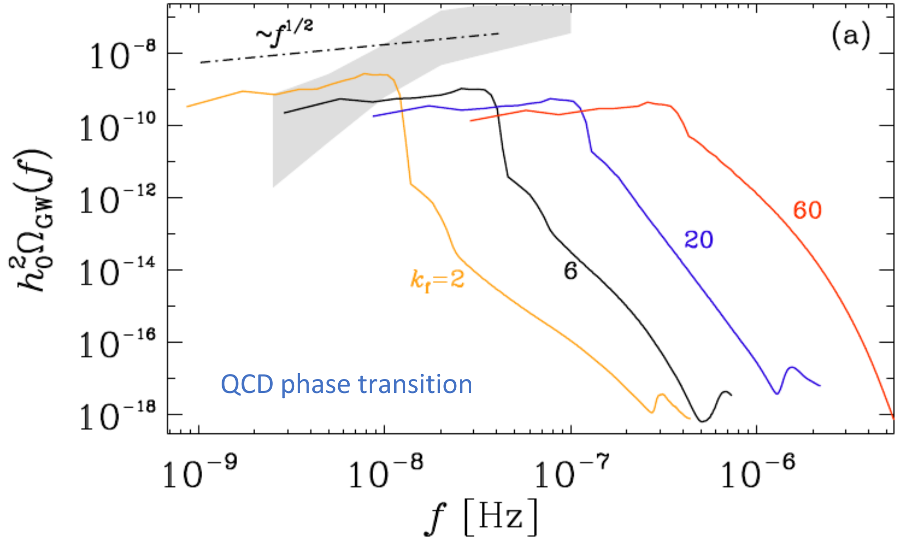
Traceless-transverse

$$T_{ij}(x) = \mathcal{E}_{\mathrm{M}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\cos 2kx & \sigma \sin 2kx \\ 0 & \sigma \sin 2kx & \cos 2kx \end{pmatrix}$$

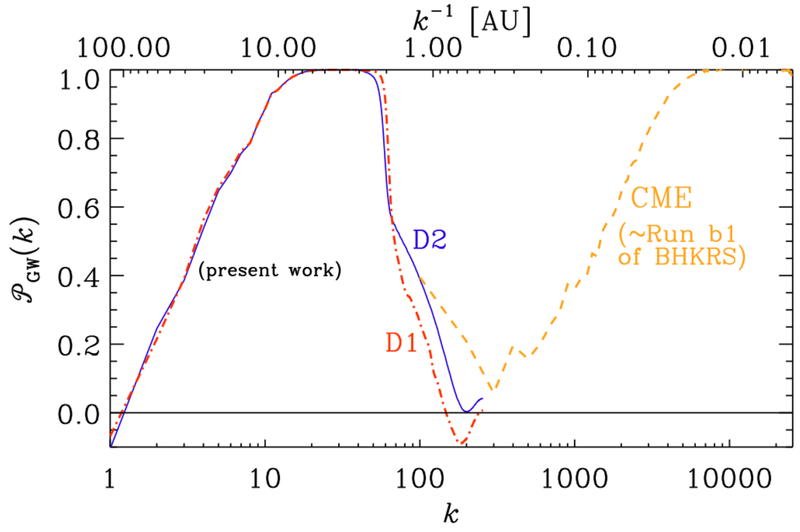


Comparison with Pulsar Timing Arrays

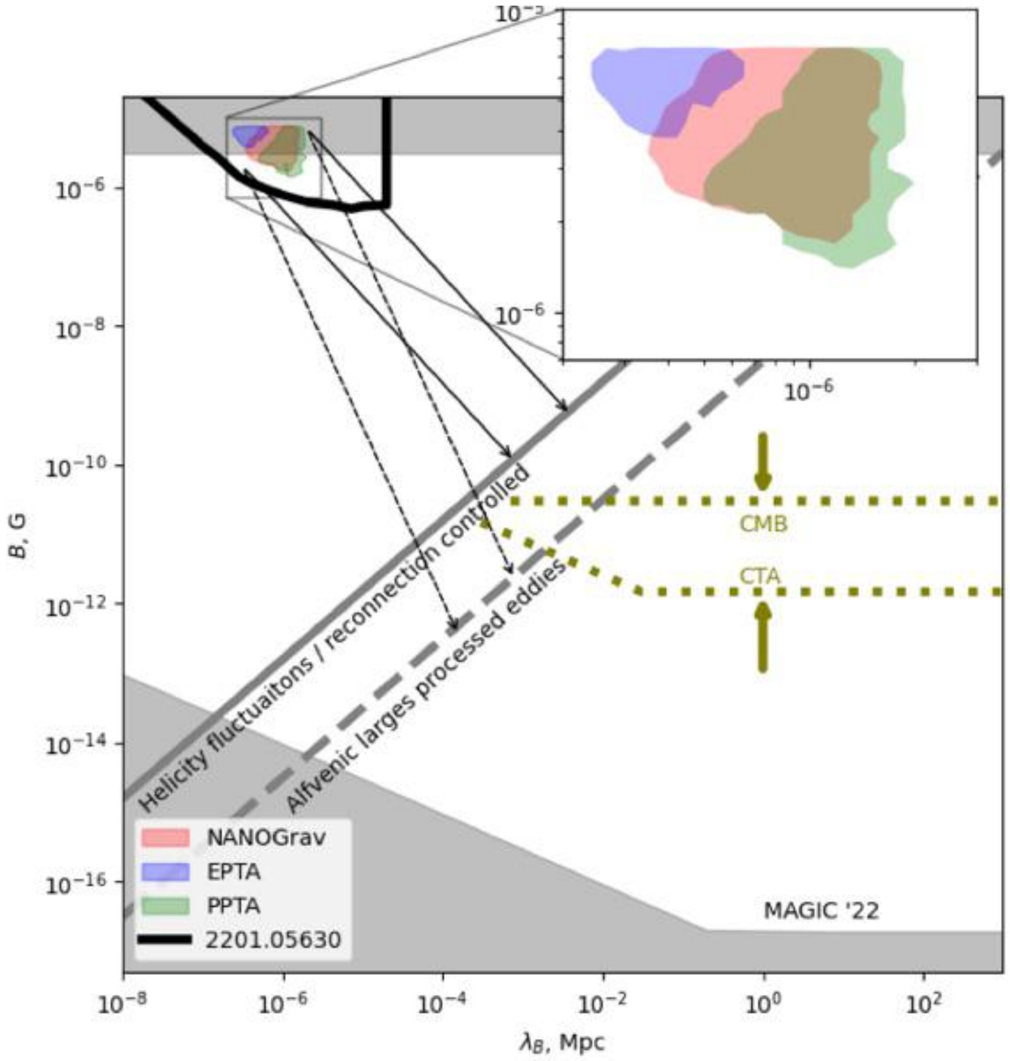
Brandenburg et al (2021)



NANOGrav = North American nHz Obs for GWs

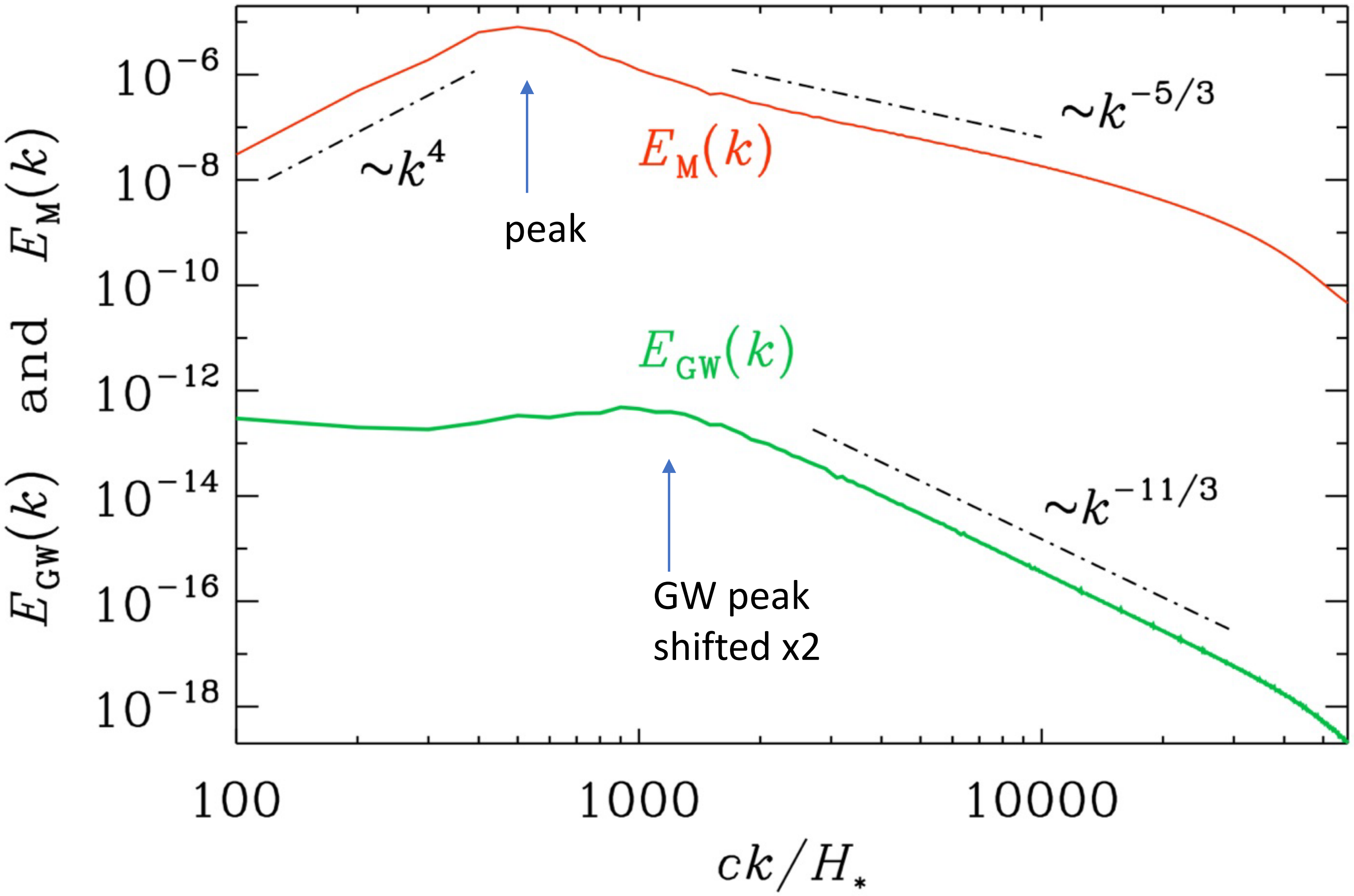


$$\mathcal{P}(k) = \int 2\,\mathrm{Im}\,\tilde{h}_+\tilde{h}_\times^*\,k^2\mathrm{d}\Omega_k \Big/ \int \left(|\tilde{h}_+|^2 + \tilde{h}_\times|^2\right) k^2\mathrm{d}\Omega_k$$



Boyer & Neronov (2024)

Correspondence with (magnetohydrodynamic) turbulence



Roper Pol et al. (2020)

Examples of magnetogenesis in cosmology

(i) Gradients in Higgs field

(ii) Chiral magnetic effect

(electroweak epoch)

(iii) Conformal invariance breaking

(during inflation)

$$F^{\mathrm{em}}_{\mu\nu} \equiv n^a F^a_{\mu\nu} - e^{-1}\eta^{-2} f^{\,a}_{bc}\, \mathrm{D}_\mu \phi^b\, \mathrm{D}_\nu \phi^c$$
$$= \partial_\mu A^{\mathrm{em}}_\nu - \partial_\nu A^{\mathrm{em}}_\mu - e^{-1}\eta^{-2} f^{\,a}_{bc}\, \partial_\mu \phi^b\, \partial_\nu \phi^c\,,$$

The Higgs field is a complex doublet

$$\Phi = \eta \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$\mathbf{B} = \nabla \times \mathcal{A} - i\frac{2\sin\theta_w}{g\eta^2}\nabla\Phi^\dagger \times \nabla\Phi,$$

$$\frac{\partial \boldsymbol{A}}{\partial t} = \frac{c^2}{\sigma}(\mu_5 \boldsymbol{B} - \boldsymbol{\nabla}\times\boldsymbol{B}) + \boldsymbol{u}\times\boldsymbol{B}$$

$$\mu_5 = 24\,\alpha_{\mathrm{em}}\,(n_{\mathrm{L}} - n_{\mathrm{R}})\,(\hbar c/k_{\mathrm{B}}T)^2$$

“Battery” still needed

$$\frac{\partial \mathbf{A}}{\partial t} = \frac{c}{q n_{\mathrm{e}}}\boldsymbol{\nabla} p_{\mathrm{e}},$$

$$f^2 F_{\mu\nu} F^{\mu\nu}$$

$$\tilde{\mathbf{A}}'' + \left(\mathbf{k}^2 - \frac{f''}{f}\right)\tilde{\mathbf{A}} = 0$$

$$f(a) = a^{-\beta}, \quad \text{where } a = (\eta + 1)^2/4$$

Quantum fluctuation

(i) Hypermagnetic fields from Higgs field gradients

Kibble mechanism for electroweak magnetic monopoles and magnetic fields

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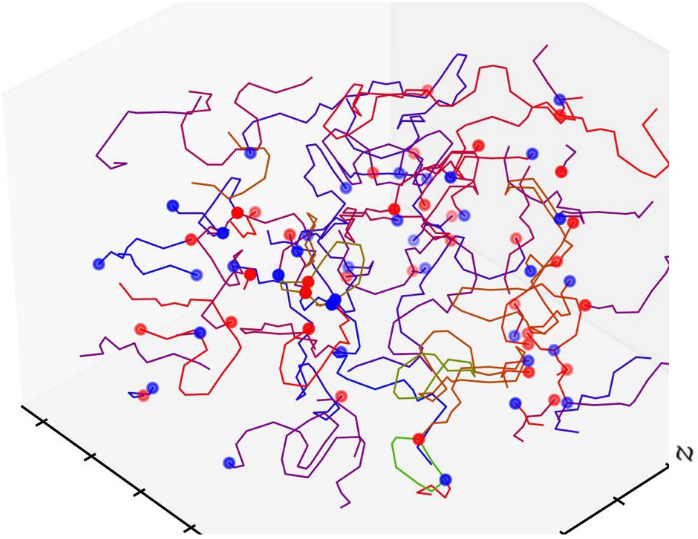
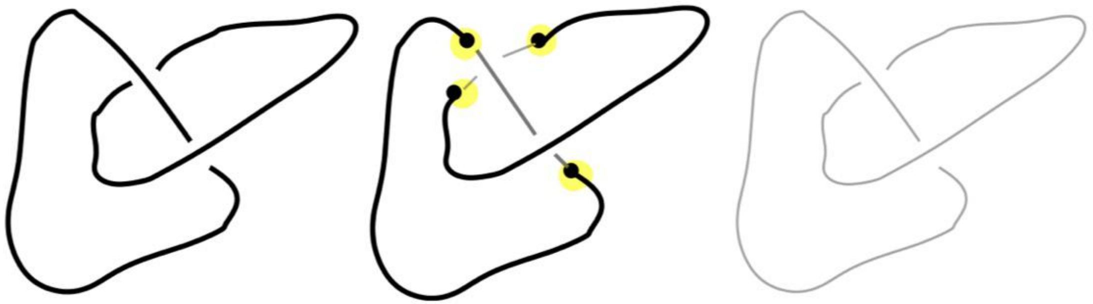
Abstract: The vacuum manifold of the standard electroweak model is a three-sphere when one considers *homogeneous* Higgs field configurations. For inhomogeneous configurations we argue that the vacuum manifold is the Hopf fibered three sphere and that this viewpoint leads to general criteria to detect electroweak monopoles and Z-strings. We extend the Kibble mechanism to study the formation of electroweak monopoles and strings during electroweak symmetry breaking. The distribution of magnetic monopoles produces magnetic fields that have a spectrum $B_\lambda \propto \lambda^{-2}$, where λ is a smearing length scale. Even as the magnetic monopoles annihilate due to the confining Z-strings, the magnetic field evolves with the turbulent plasma and may be relevant for cosmological observations.

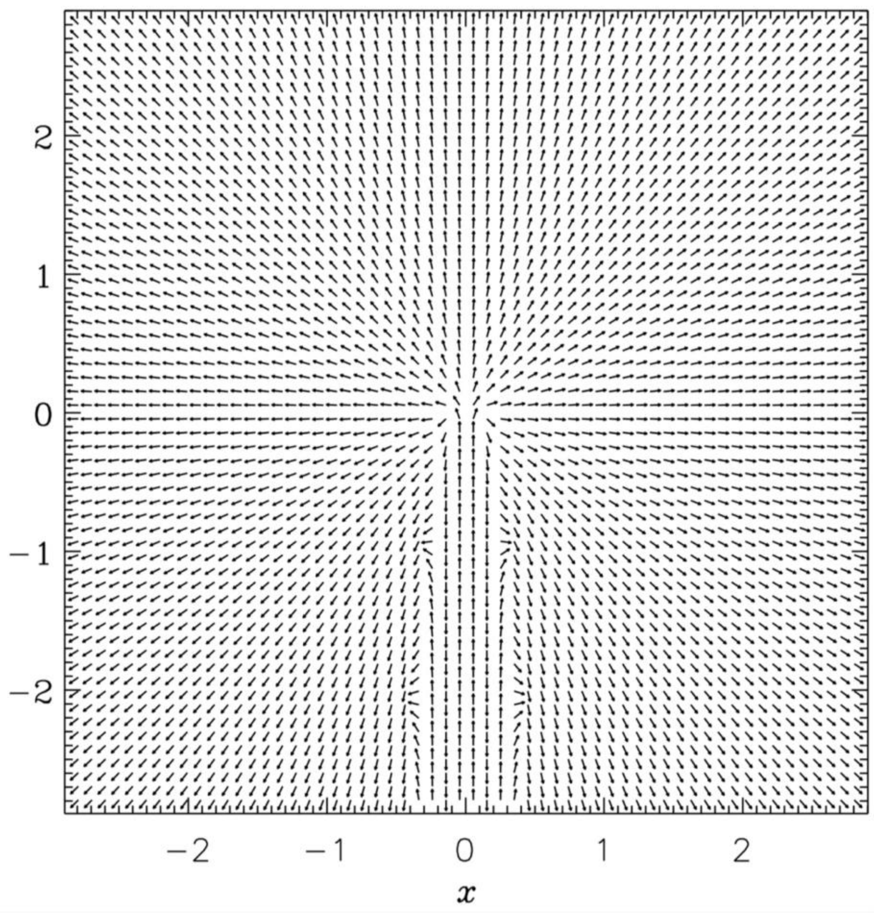
Keywords: Solitons Monopoles and Instantons, Cosmology of Theories beyond the SM, Nonperturbative Effects

ArXiv ePrint: 2108.05357

JHEP01(2022)059



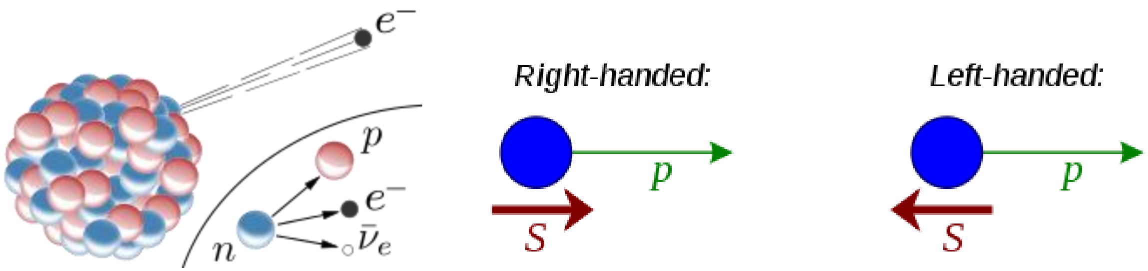




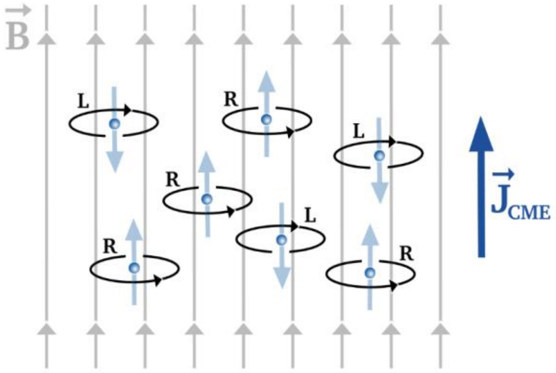
(ii) Chiral magnetic effect: introduces pseudoscalar

- Mathematically identical to α effect in mean-field dynamos
- Comes from chiral chemical potential μ (or μ_5)
- Number differences of left- & right-handed fermions

$$\mu_5 = 24\,\alpha_{\rm em}\,(n_{\rm L} - n_{\rm R})\,(\hbar c/k_{\rm B}T)^2,$$



- In the presence of a magnetic field, particles of opposite charge have momenta
- → electric current
- Self-excited dynamo
- But depletes μ



$$\frac{\partial \boldsymbol{A}}{\partial t} = \eta(\mu \boldsymbol{B} - \boldsymbol{\nabla} \times \boldsymbol{B}) + \boldsymbol{U} \times \boldsymbol{B}$$

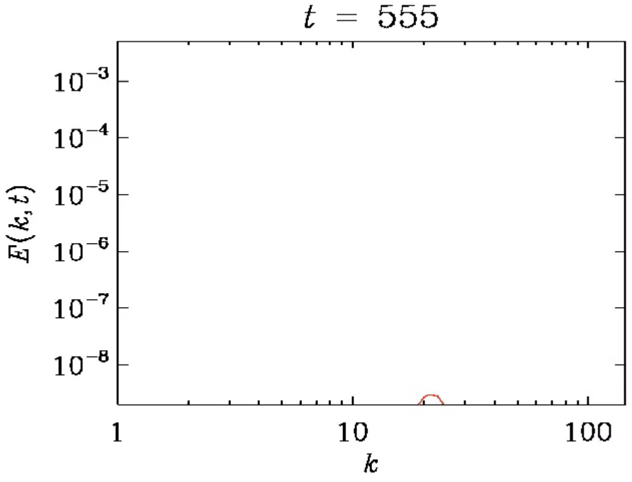
$$\sigma = |\mu k| - \eta k^2$$

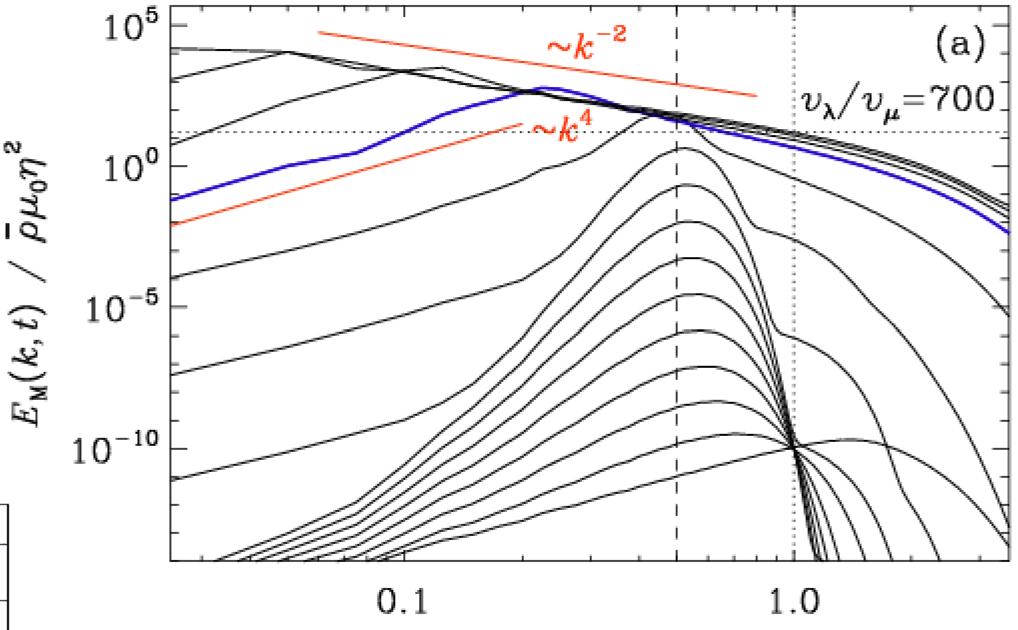
$\boldsymbol{B}$=curl$\boldsymbol{A}$

Discovered originally by Vilenkin (1980); application to magnetogenesis in early Universe by Joyce & Shaposhnikov (1997)

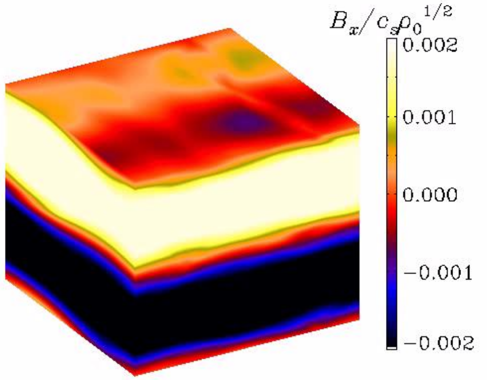
Time dependence from chiral magnetic effect (CME)

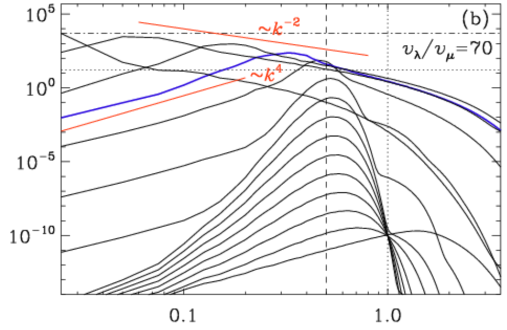
- Exponential growth at one k
- Subsequent inverse cascade
- Always fully helical

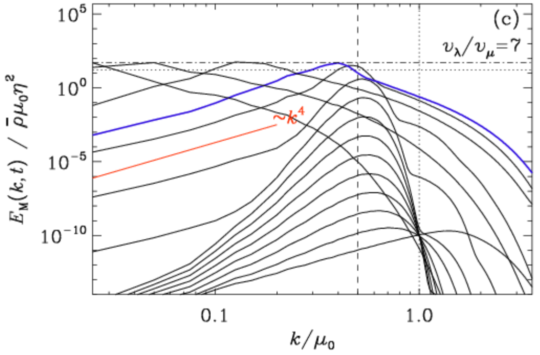


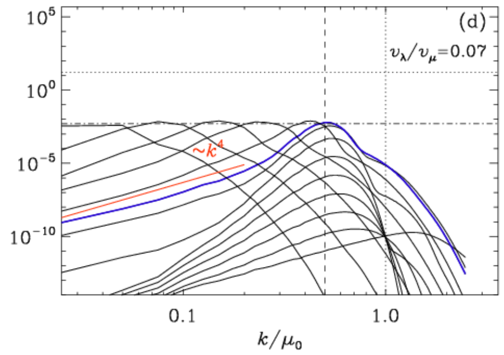


Growth at one wavenumber
Then: saturation caused by initial chemical potential



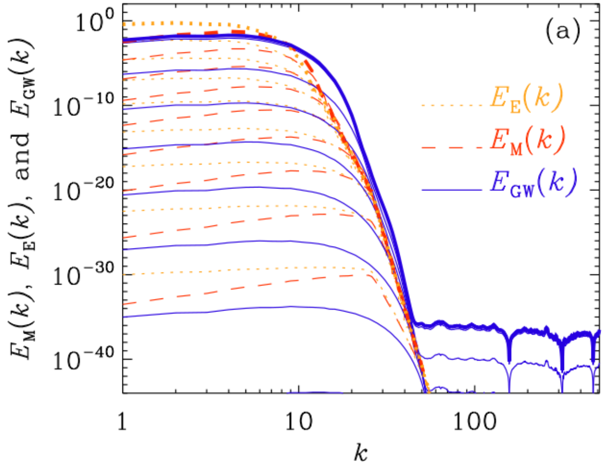






Brandenburg et al. (2017, ApJL 845, L21)

(iii) Inflationary magnetogenesis



- Early Universe Turbulence
  - Source of gravitational waves
  - Information from young universe
- Magnetogenesis
  - Inflation/reheating
  - No particles yet, no conductivity
  - Coupling with electromagn field

$$f^2 F_{\mu\nu} F^{\mu\nu}$$

  - Breaking of conformal invariance
  - Quantum fluct → field stretched

$$\tilde{\mathbf{A}}'' + \left(\mathbf{k}^2 - \frac{f''}{f}\right)\tilde{\mathbf{A}} = 0,$$

$$\tilde{h}''_{+/\times} + \left(\mathbf{k}^2 - \frac{a''}{a}\right)\tilde{h}_{+/\times} = \frac{6}{a}\tilde{T}_{+/\times},$$

$$\iota f^2 F_{\mu\nu} {}^*F^{\mu\nu}$$ Coupling to pseudo-scalar (axion)

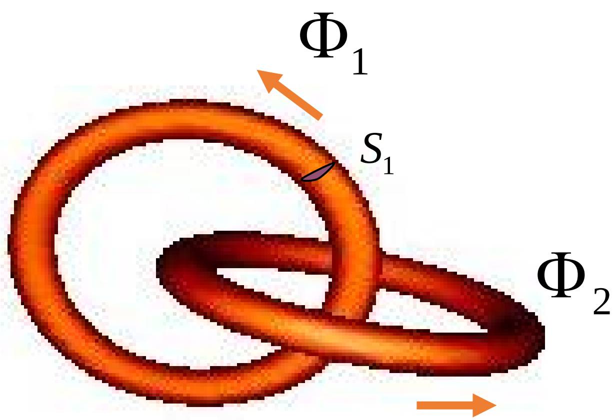
$$f(a) = a^{-\beta}, \quad \text{where } a = (\eta+1)^2/4$$

$$\tilde{A}''_\pm + \left(k^2 \pm 2\iota k \frac{f'}{f} - \frac{f''}{f}\right)\tilde{A}_\pm = 0,$$

$$\frac{f'}{f} = -\frac{2\beta}{\eta+1}, \quad \frac{f''}{f} = \frac{2\beta(2\beta+1)}{(\eta+1)^2}.$$

Brandenburg & Sharma 2106:03857

Magnetic helicity



$$H = \int_V \mathbf{A}\cdot\mathbf{B}\,\mathrm{d}V$$

$$\mathbf{B} = \nabla\times\mathbf{A}$$

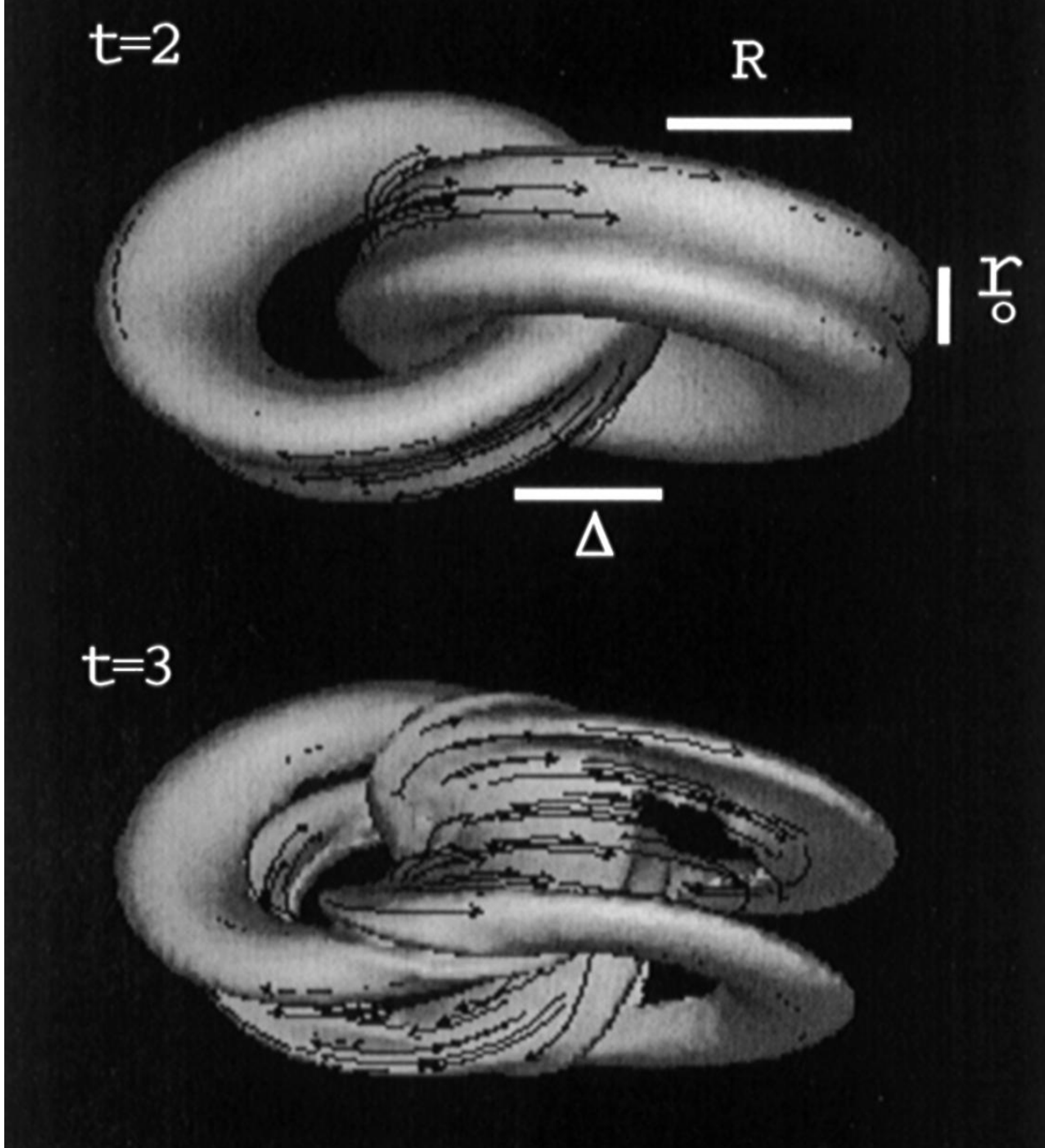
$$H_1 = \int_{L_1} \mathbf{A}\cdot\mathrm{d}\boldsymbol{\ell} \int_{S_1} \mathbf{B}\cdot\mathrm{d}\mathbf{S}$$

$$= \int_{S_2} \nabla\times\mathbf{A}\cdot\mathrm{d}\mathbf{S} = \Phi_2 \qquad = \Phi_1$$

$$H = \pm 2\Phi_1\Phi_2$$

Therefore the unit is Maxwell squared

Kerr & Brandenburg (1999)



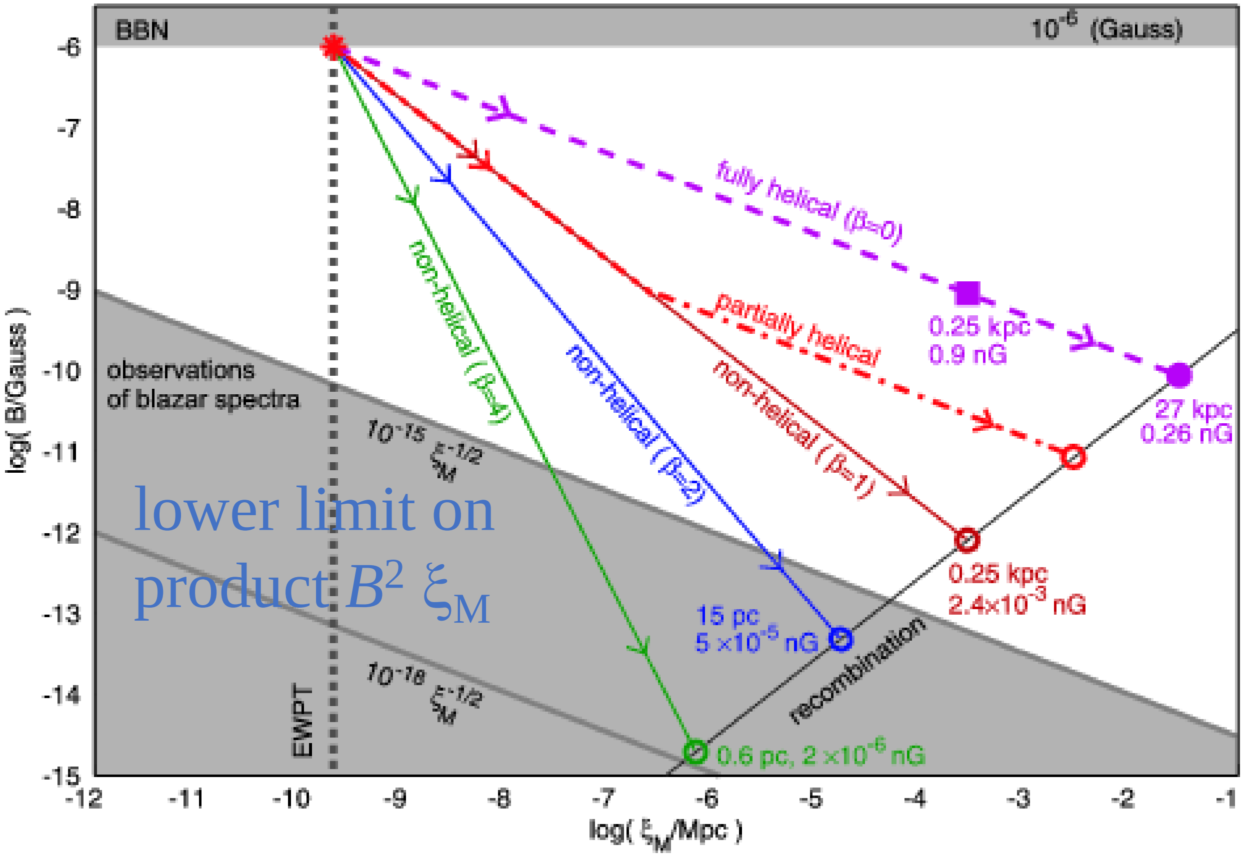
Conservation laws

$\xi_M \sim \langle A.B \rangle\, t^{2/3}$

$\text{cm} \sim (\text{cm}^3/\text{s}^2)\, \text{s}^{2/3}$

Magnetic helicity	$\langle \boldsymbol{A} \cdot \boldsymbol{B} \rangle$	$\text{cm}^3\,\text{s}^{-2}$	$\xi_\text{M}(t) \propto \langle \boldsymbol{A} \cdot \boldsymbol{B} \rangle^{1/3} t^{2/3}$
Anastrophy (2-D)	$\langle A_z^2 \rangle$	$\text{cm}^4\,\text{s}^{-2}$	$\xi_\text{M}(t) \propto \langle A_z^2 \rangle^{1/4} t^{1/2}$
Hosking integral	I_H	$\text{cm}^9\,\text{s}^{-4}$	$\xi_\text{M}(t) \propto I_\text{H}^{1/9} t^{4/9}$
Saffman integral	I_S	$\text{cm}^5\,\text{s}^{-2}$	$\xi_\text{M}(t) \propto I_\text{S}^{1/5} t^{2/5}$
Loitsyansky integral	I_L	$\text{cm}^7\,\text{s}^{-2}$	$\xi_\text{M}(t) \propto I_\text{S}^{1/7} t^{2/7}$

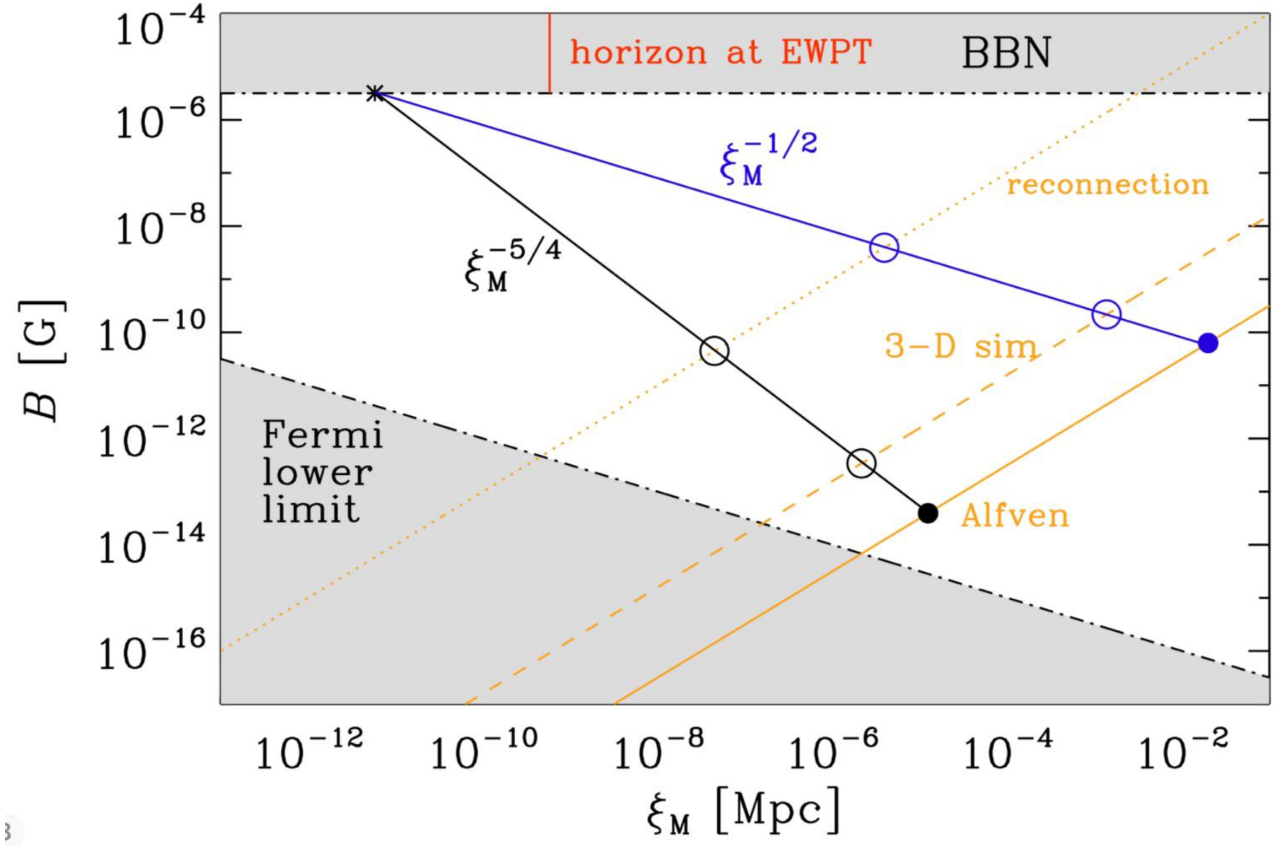
AB, Kahniashvili, ..., Vachaspati (2017)



Magnetic energy dependence
Parametric representation

magnetic energy	$\kappa = p/2q$
$\mathcal{E}_\text{M}(t) \propto \langle \boldsymbol{A} \cdot \boldsymbol{B} \rangle^{2/3} t^{-2/3}$	$\propto \xi_\text{M}^{-1/2}$
$\mathcal{E}_\text{M}(t) \propto \langle A_z^2 \rangle^{1/2} t^{-1}$	$\propto \xi_\text{M}^{-1}$
$\mathcal{E}_\text{M}(t) \propto I_\text{H}^{2/9} t^{-10/9}$	$\propto \xi_\text{M}^{-5/4}$
$\mathcal{E}_\text{M}(t) \propto I_\text{S}^{2/5} t^{-6/5}$	$\propto \xi_\text{M}^{-3/2}$
$\mathcal{E}_\text{M}(t) \propto I_\text{S}^{2/7} t^{-10/7}$	$\propto \xi_\text{M}^{-5/2}$

Resistive slow-down of turbulent decay



- Endpoints under assumption that decay time = Alfven time
- Use: decay time = recombination time
- Possibility: decay time >> Alfven time
- → Premature endpoint of evolution

Resistively controlled primordial magnetic turbulence decay

A. Brandenburg[1,2,3,4,5], A. Neronov[6,7], and F. Vazza[8,9,10]

Relation between decay time

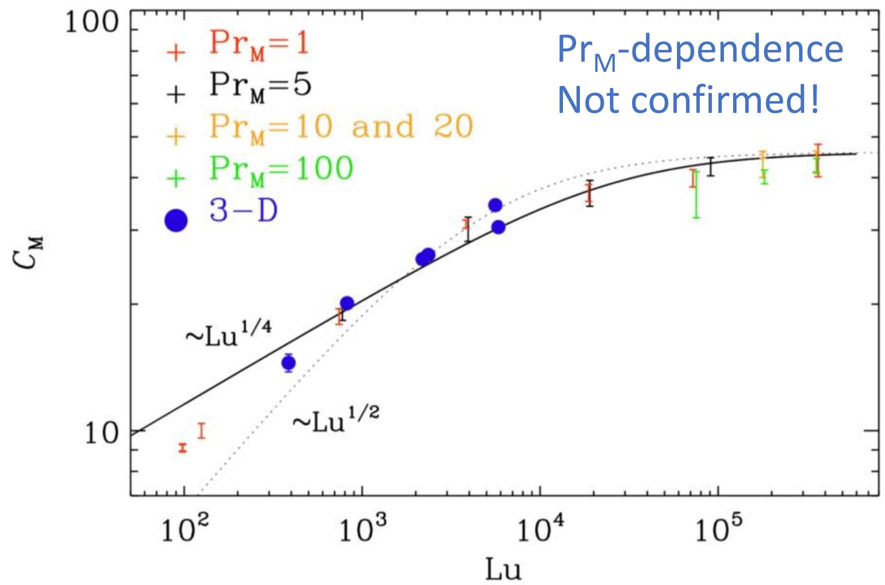
$$\tau^{-1} = -\mathrm{d}\ln\mathcal{E}_\mathrm{M}/\mathrm{d}t$$

and Alfven time

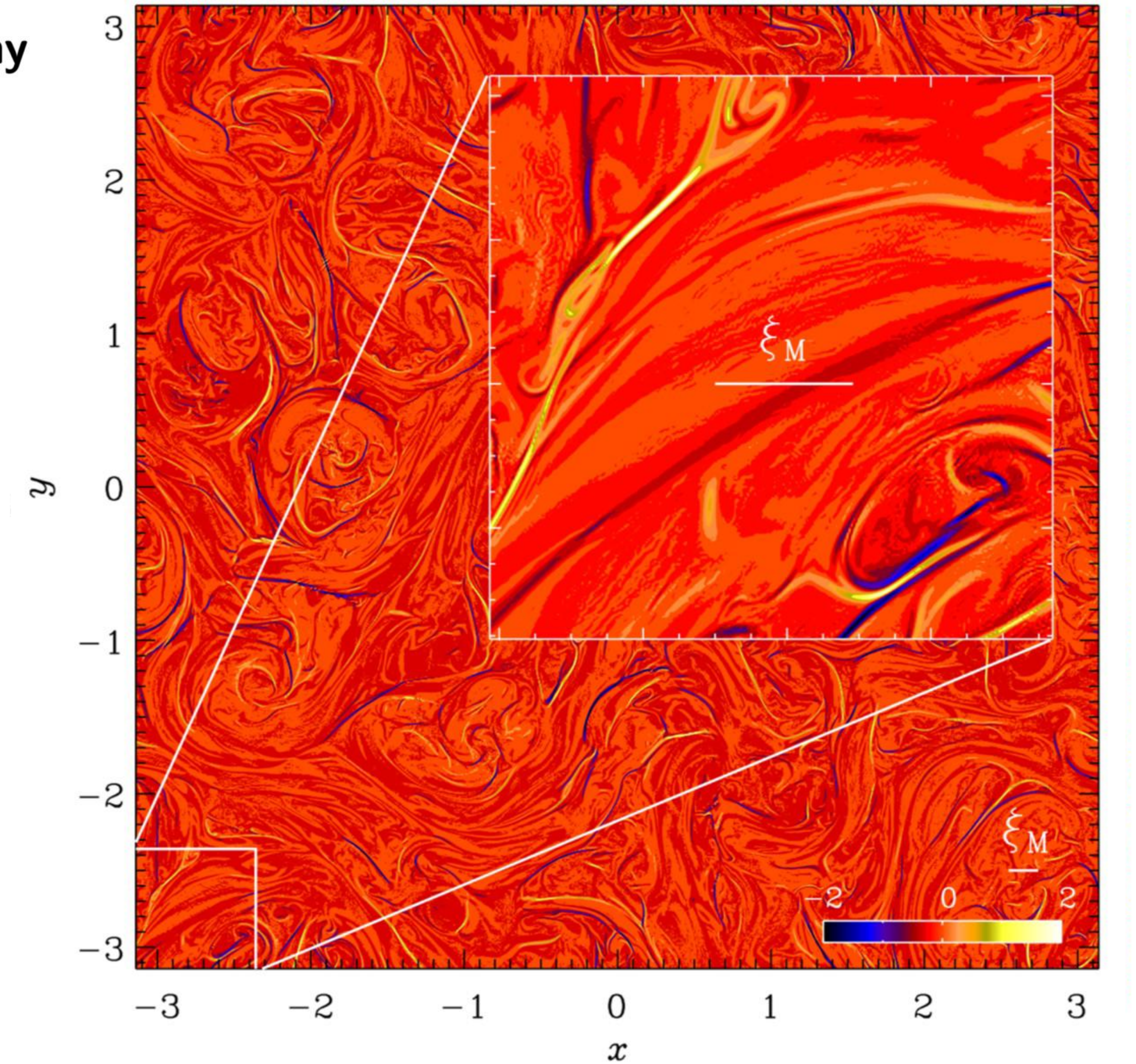
$$\tau_\mathrm{A} = \xi_\mathrm{M}/v_\mathrm{A} \qquad \mathcal{E}_\mathrm{M} = B_\mathrm{rms}^2/2\mu_0 = \rho v_\mathrm{A}^2/2$$

Determine C_M in relation:

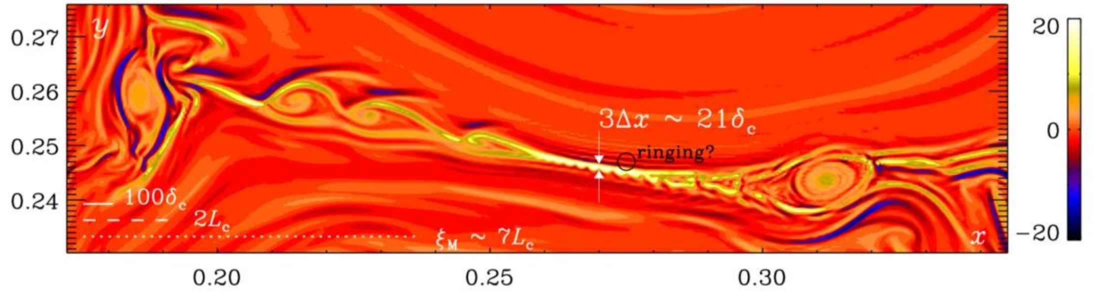
$$\tau = C_\mathrm{M}\xi_\mathrm{M}/v_\mathrm{A}$$



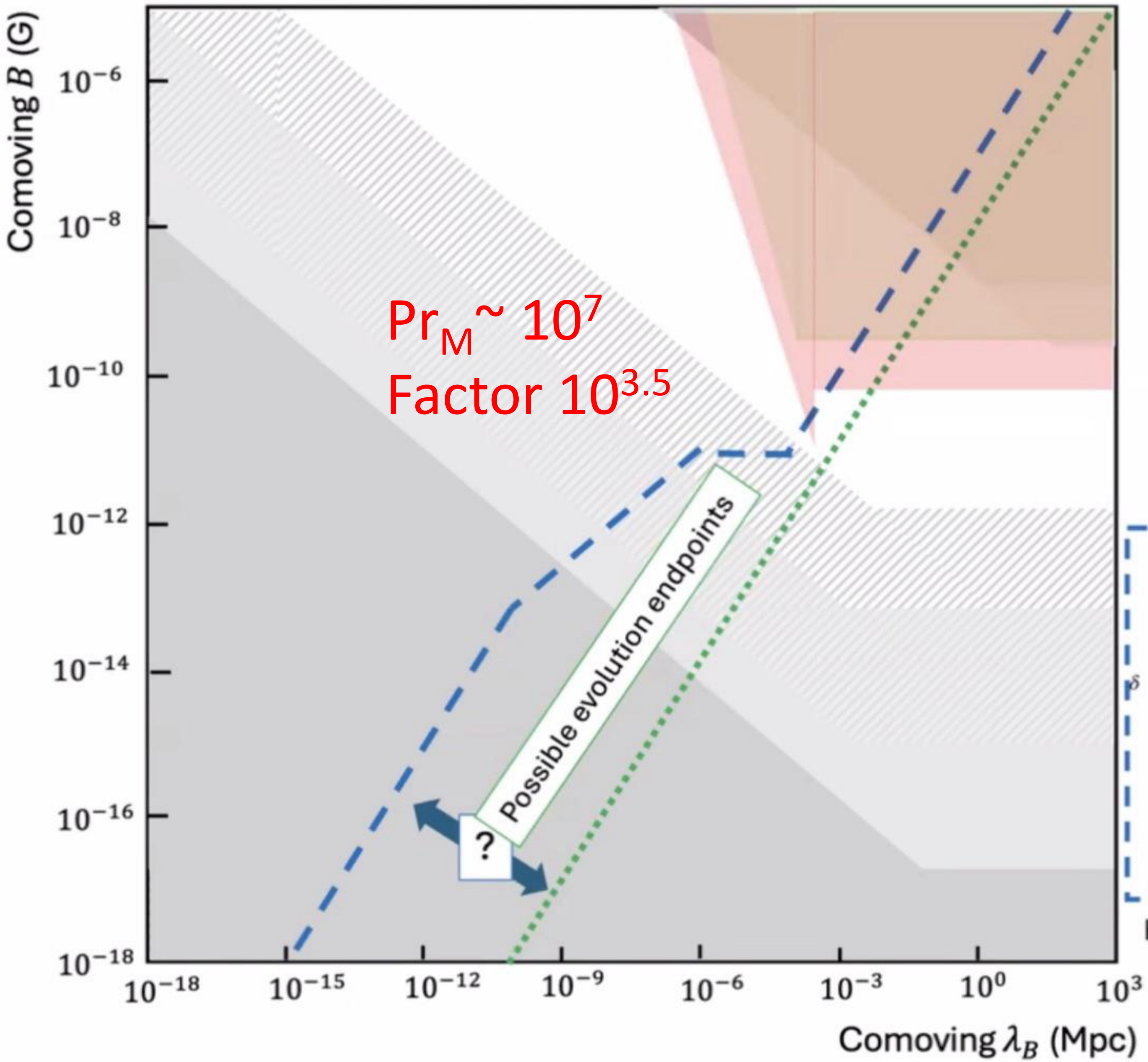
3-D



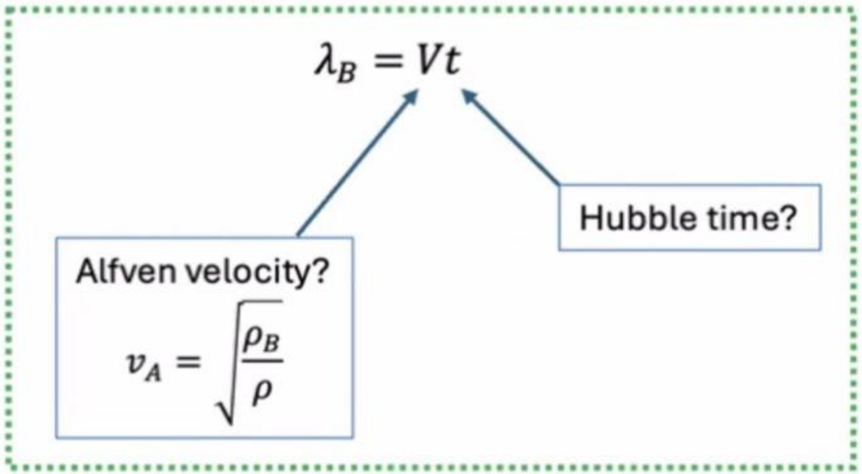
2-D



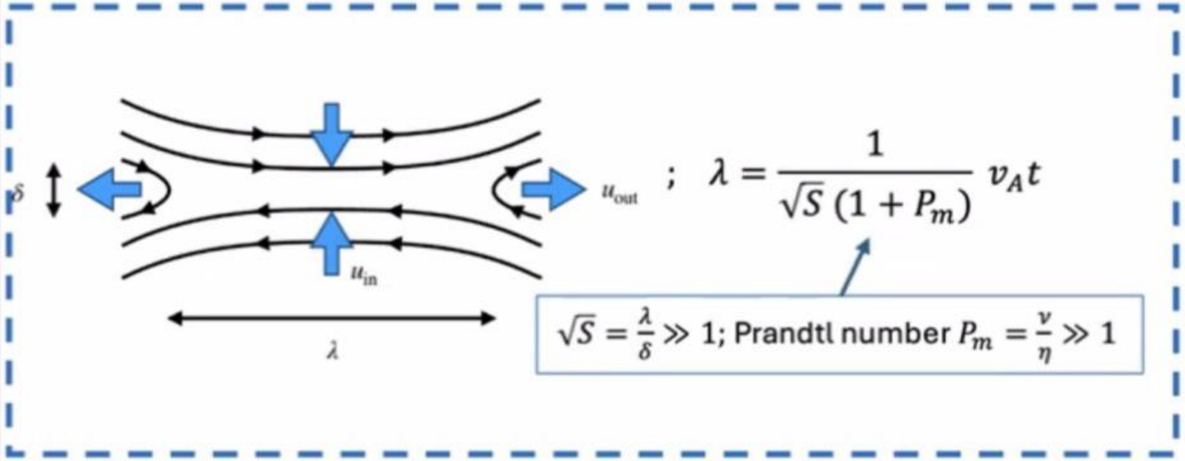
Backtracing of magnetic field evolution



"Largest processed turbulent eddy" concept:



Banerjee, Jedamzik, astro-ph/0410032

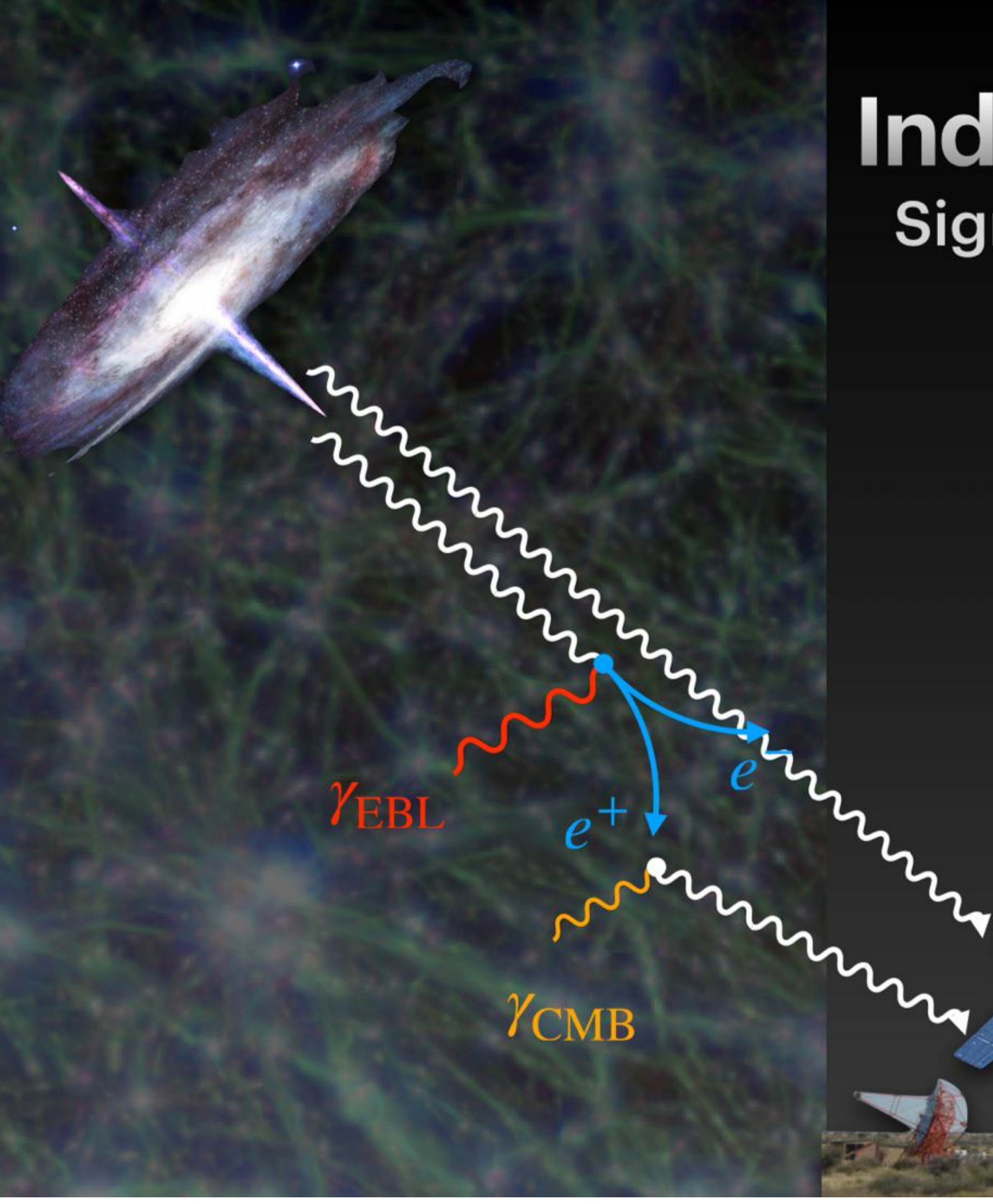


Hosking, Schekochihin, 2203.03573

Structures highly dynamical:
outflow not opposed by viscosity

Indirect detection of the IGMF

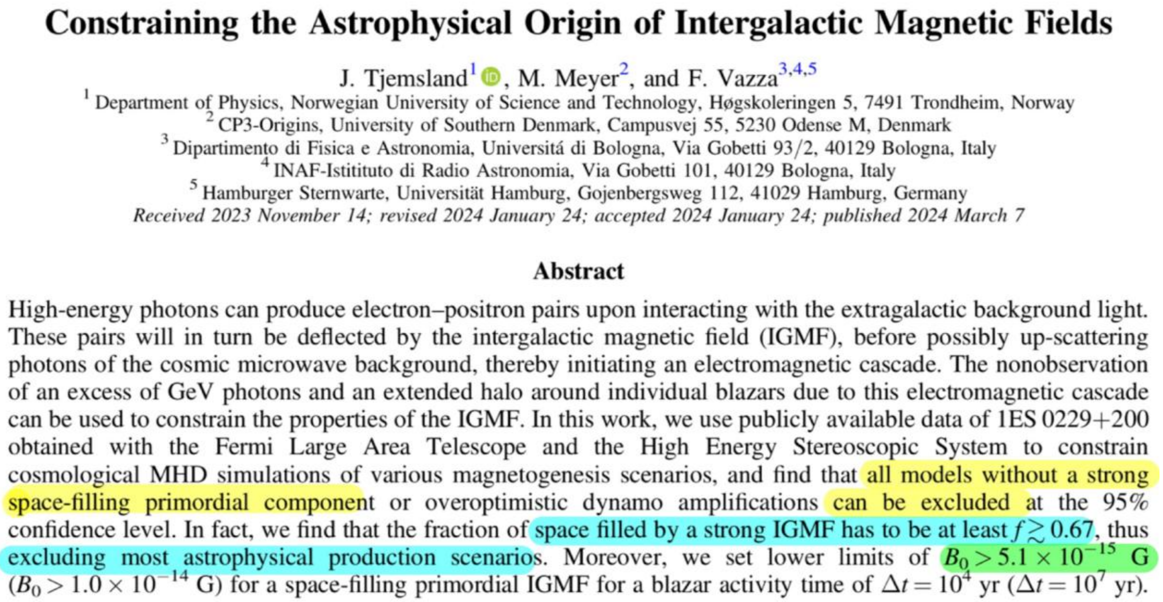
Signatures of an IGMF in γ-ray observations



- Excess ɣ rays at lower energies [e.g. Neronov & Semikoz 2008]
- Extended ɣ-ray halos [Aharonian et al. 1994]
- Time delayed ɣ-ray emission [Plaga 1995]
- Biggest uncertainty: blazar duty cycle [Dermer et al. 2011]

Courtesey: Manuel Meyer

Lower limits from blazar observations



Constraining the Astrophysical Origin of Intergalactic Magnetic Fields

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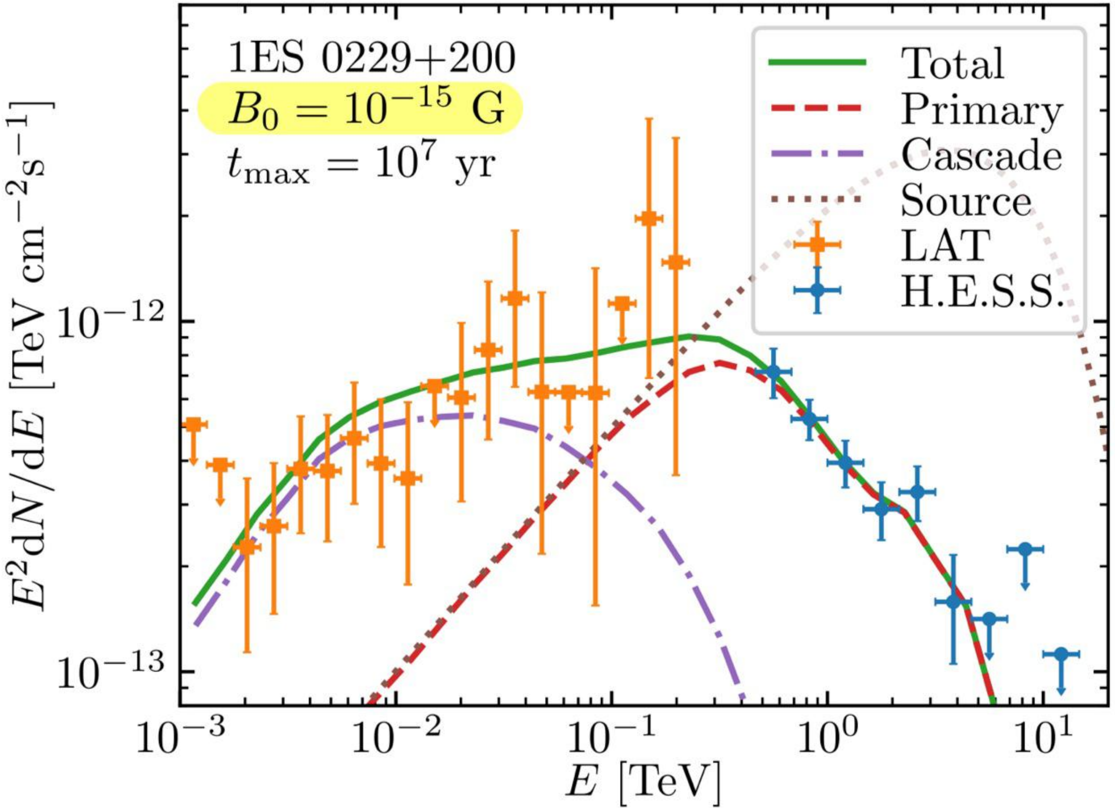
Abstract

High-energy photons can produce electron–positron pairs upon interacting with the extragalactic background light. These pairs will in turn be deflected by the intergalactic magnetic field (IGMF), before possibly up-scattering photons of the cosmic microwave background, thereby initiating an electromagnetic cascade. The nonobservation of an excess of GeV photons and an extended halo around individual blazars due to this electromagnetic cascade can be used to constrain the properties of the IGMF. In this work, we use publicly available data of 1ES 0229+200 obtained with the Fermi Large Area Telescope and the High Energy Stereoscopic System to constrain cosmological MHD simulations of various magnetogenesis scenarios, and find that all models without a strong space-filling primordial component or overoptimistic dynamo amplifications can be excluded at the 95% confidence level. In fact, we find that the fraction of space filled by a strong IGMF has to be at least $f \gtrsim 0.67$, thus excluding most astrophysical production scenarios. Moreover, we set lower limits of $B_0 > 5.1 \times 10^{-15}$ G ($B_0 > 1.0 \times 10^{-14}$ G) for a space-filling primordial IGMF for a blazar activity time of $\Delta t = 10^4$ yr ($\Delta t = 10^7$ yr).

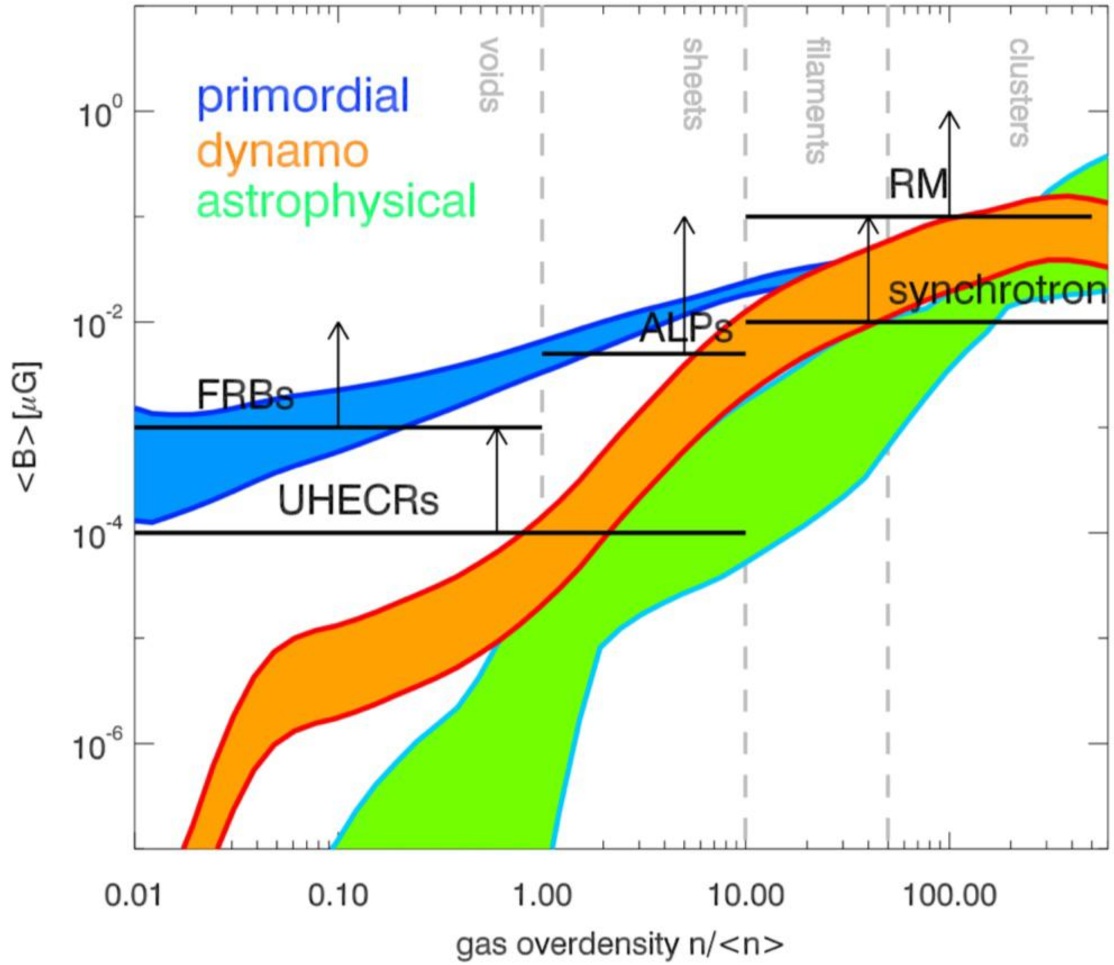


Magnetic fields nearly space-filling (f>0.67) to explain observations

Astrophysical machanisms excluded (too small f)

Similar constraints also from radio observations

Vazza et al. (2017)



- Filaments: compressed magnetic fields?
- Magnetic fields in the low density regions tend not to come from dynamos
- Similar for outflows (astrophysical sources)

Magnetic fields at recombination: Hubble tension

Relieving the Hubble Tension with Primordial Magnetic Fields

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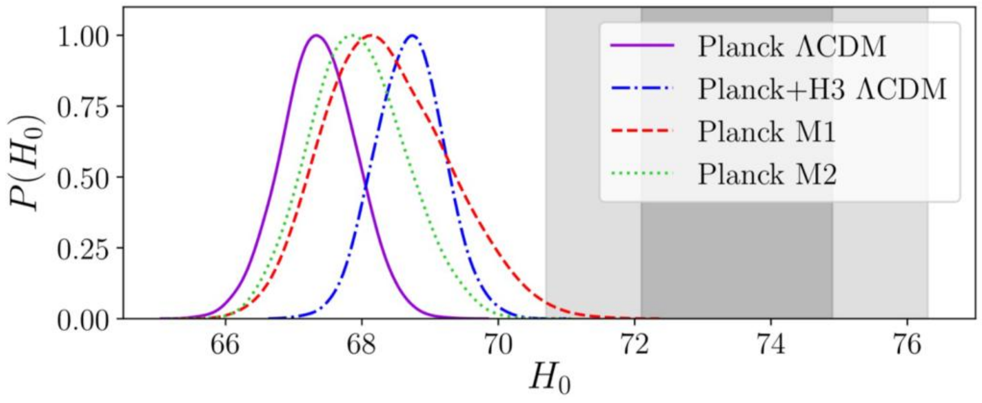
The standard cosmological model determined from the accurate cosmic microwave background measurements made by the Planck satellite implies a value of the Hubble constant H_0 that is 4.2 standard deviations lower than the one determined from type Ia supernovae. The Planck best fit model also predicts higher values of the matter density fraction Ω_m and clustering amplitude S_8 compared to those obtained from the Dark Energy Survey Year 1 data. Here we show that accounting for the enhanced recombination rate due to additional small-scale inhomogeneities in the baryon density may solve both the H_0 and the S_8-Ω_m tensions. The additional baryon inhomogeneities can be induced by primordial magnetic fields present in the plasma prior to recombination. The required field strength to solve the Hubble tension is just what is needed to explain the existence of galactic, cluster, and extragalactic magnetic fields without relying on dynamo amplification. Our results show clear evidence for this effect and motivate further detailed studies of primordial magnetic fields, setting several well-defined targets for future observations.



- Clumping in the baryons
- Sound speed reduced
- Sound horizon lower
- Distance to CMB lower
- D(z)=c/H, so H larger
- Alleviates Hubble tension to low-z universe

Summary:

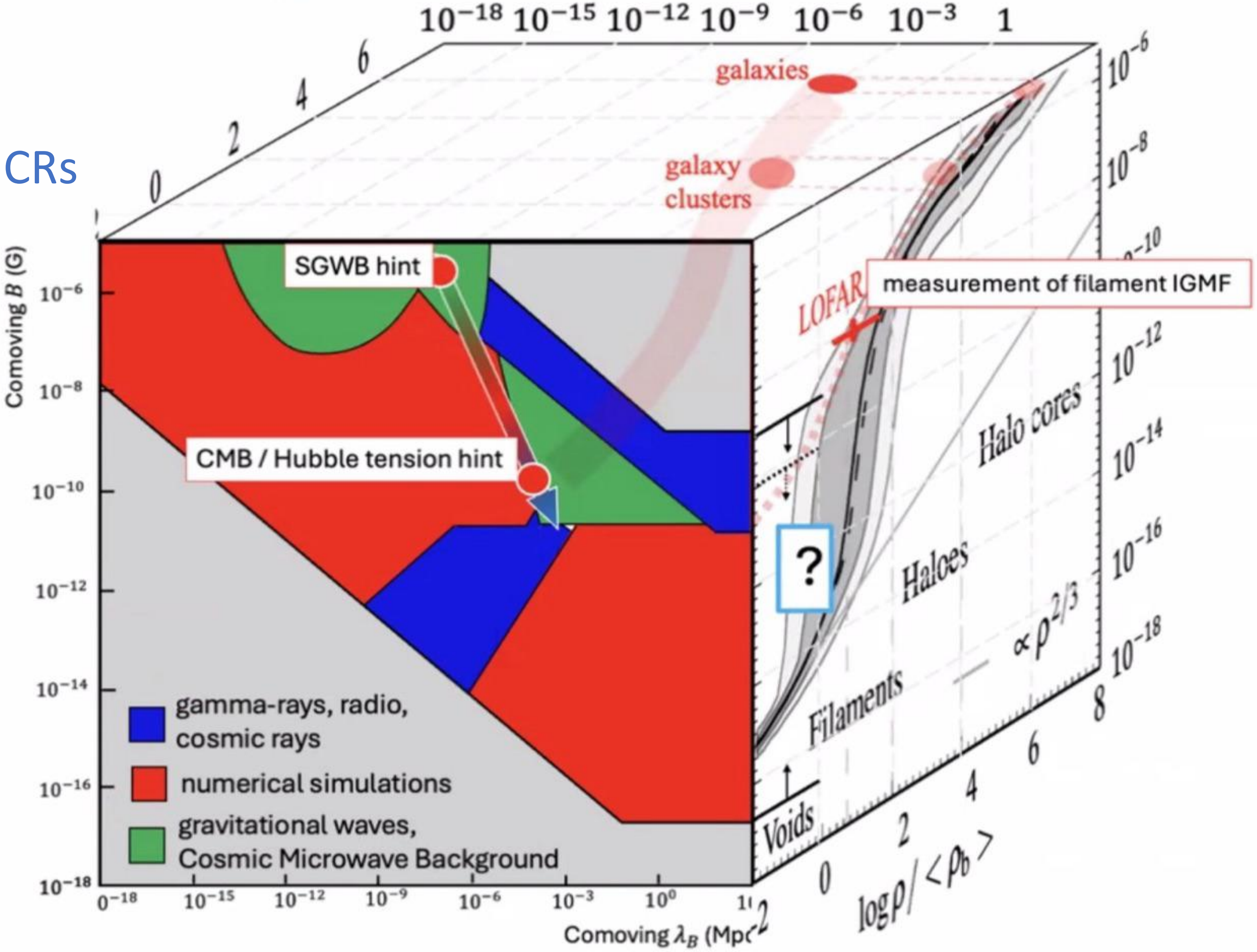
tools are available to explore "full" intergalactic / cosmological magnetic fields parameter space, from the moment of creation to recombination and throughout structure formation up to $z = 0$

Interplay:

Gamma-ray, radio, CRs

GWs, CMB

simulations



Nonlinear Feedback of the Electrostatic Instability on the Blazar-induced Pair Beam and GeV Cascade

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Abstract

Relativistic pair beams produced in the cosmic voids by TeV gamma-rays from blazars are expected to produce a detectable GeV-scale cascade that is missing in the observations. The suppression of this secondary cascade implies either the deflection of the pair beam by intergalactic magnetic fields or, alternatively, an energy loss of the beam due to the beam-plasma instability. Here, we study how the beam-plasma instability feeds back on the beam, using a realistic two-dimensional beam distribution. We find that the instability broadens the beam opening angles significantly without any significant energy loss, thus confirming a recent feedback study on a simplified one-dimensional beam distribution. However, narrowing diffusion feedback of the beam particles with Lorentz factors less than 10^6 might become relevant, even though initially it is negligible. Finally, when considering the continuous creation of TeV pairs, we find that the beam distribution and the wave spectrum reach a new quasi-steady state, in which the scattering of beam particles persists and the beam opening angle may increase by a factor of hundreds. Understanding the implications on the GeV cascade emission requires accounting for inverse-Compton cooling.

Conclusions

- Selfsimilar decay
  - Magnetic helicity plays a role even when it vanishes on average!
  - Hosking integral conserved relevant for early universe
  - Perhaps also for galaxy clusters (after mergers)
- Universe as a whole → primordial (non-astrophysical) fields
  - Decay till recombination: < 0.1 nG fields, 1 kpc scales at best (phase transitions)
  - Larger scales from reheating scenarios
  - If nonhelical: Hosking integral conserved
  - Also applies to fully helical, if balanced by fermion chirality
- Inflationary: large scales, often helical
  - Electric energy → kinetic energy
  - Circularly polarized waves
- What next?
  - Reconnection
  - Rm dependence
  - magnetic helicity fluxes

Note on the Pencil Code

- 2001 started at Summer School
- 2004 First User Meeting
  - Annually since then
- 2016 Steering Committee
- 2020 Special Issue in GAFD
- 2020 Newletter
  - Good references to code updates
- 2020 Office hours
  - Second Thursday of the month
- JOSS=Journal for Open Source Software: code rather than paper

Open code: will one be scooped?
Negative press? Mistakes traced back..

The Pencil Code, a modular MPI code for partial differential equations and particles: multipurpose and multiuser-maintained

The Pencil Code Collaboration[1], Axel Brandenburg[1,2,3], Anders Johansen[4], Philippe A. Bourdin[5,6], Wolfgang Dobler[7], Wladimir Lyra[8], Matthias Rheinhardt[9], Sven Bingert[10], Nils Erland L. Haugen[11,12,1], Antony Mee[13], Frederick Gent[9,14], Natalia Babkovskaia[15], Chao-Chin Yang[16], Tobias Heinemann[17], Boris Dintrans[18], Dhrubaditya Mitra[1], Simon Candelaresi[19], Jörn Warnecke[20], Petri J. Käpylä[21], Andreas Schreiber[15], Piyali Chatterjee[22], Maarit J. Käpylä[9,20], Xiang-Yu Li[1], Jonas Krüger[11,12], Jørgen R. Aarnes[12], Graeme R. Sarson[14], Jeffrey S. Oishi[23], Jennifer Schober[24], Raphaël Plasson[25], Christer Sandin[1], Ewa Karchniwy[12,26], Luiz Felippe S. Rodrigues[14,27], Alexander Hubbard[28], Gustavo Guerrero[29], Andrew Snodin[14], Illa R. Losada[1], Johannes Pekkilä[9], and Chengeng Qian[30]

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Software
- Review
- Repository
- Archive

Editor: Arfon Smith
Reviewers:
- @zingale
- @rtfisher

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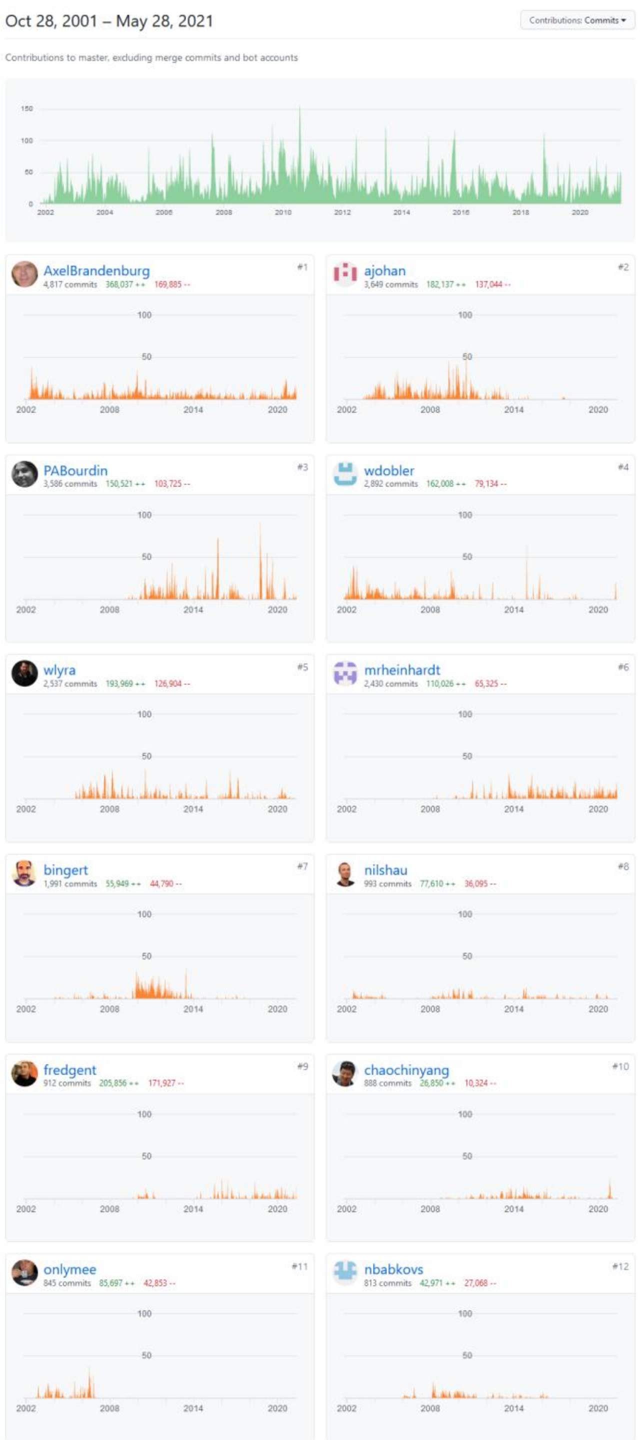
Published: 21 February 2021

Summary

The Pencil Code is a highly modular physics-oriented simulation code that can be adapted to a wide range of applications. It is primarily designed to solve partial differential equations (PDEs) of compressible hydrodynamics and has lots of add-ons ranging from astrophysical magnetohydrodynamics (MHD) (A. Brandenburg & Dobler, 2010) to meteorological cloud microphysics (Li et al., 2017) and engineering applications in combustion (Babkovskaia et al., 2011). Nevertheless, the framework is general and can also be applied to situations not related to hydrodynamics or even PDEs, for example when just the message passing interface or input/output strategies of the code are to be used. The code can also evolve Lagrangian (inertial and noninertial) particles, their coagulation and condensation, as well as their interaction with the fluid. A related module has also been adapted to perform ray tracing

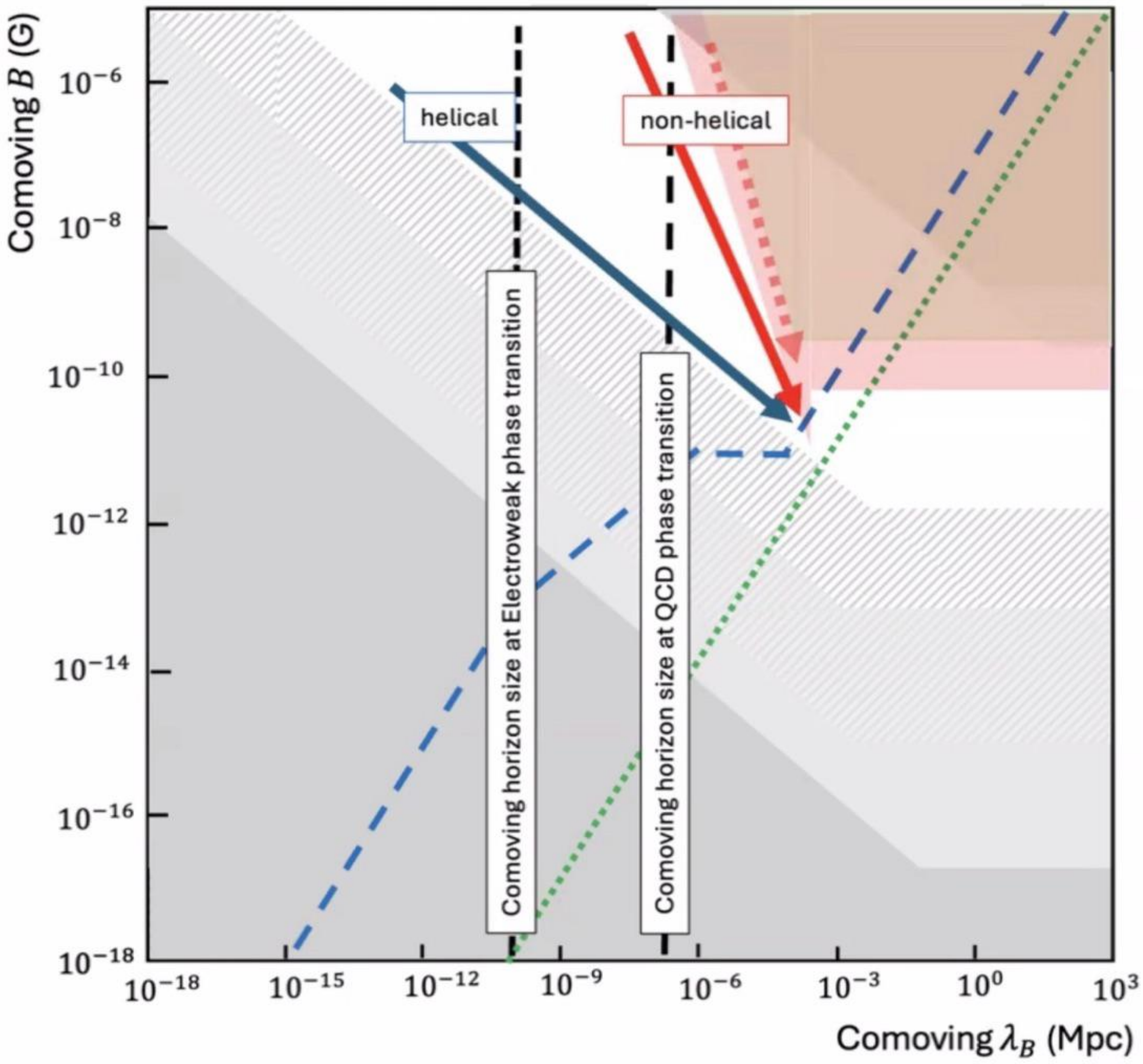
H=37 people have done > 37 commits



Further todos

- Ionization evolution during recombination
  - How important is departure from equilibrium?
  - Can we use Saha equation?
- How are the endpoints affected by this
  - Positive or negative shift?
- Clumping factor
  - Affects sound horizon
  - Hubble tension
- Including dark Matter evolution
  - Selfgravity and particles already in the Pencil Code
  - But nobody used it yet for dark matter modeling

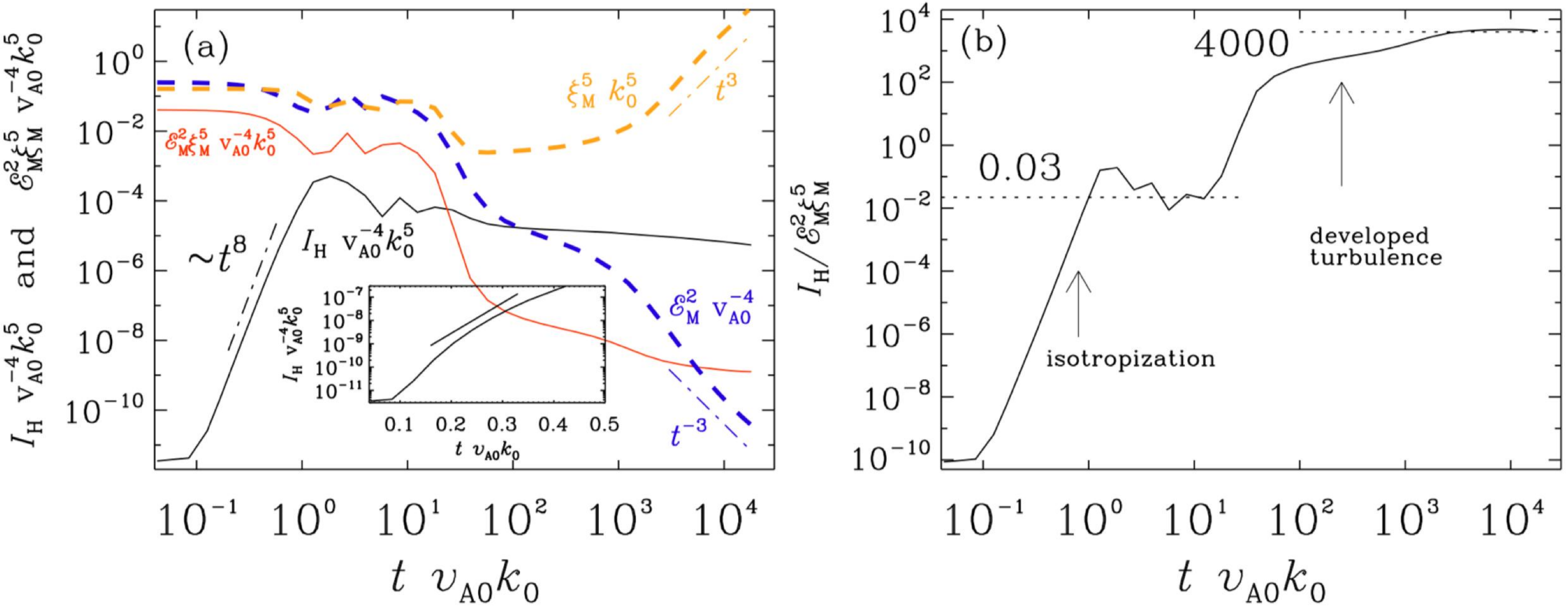
Magnetic field at the moment of generation



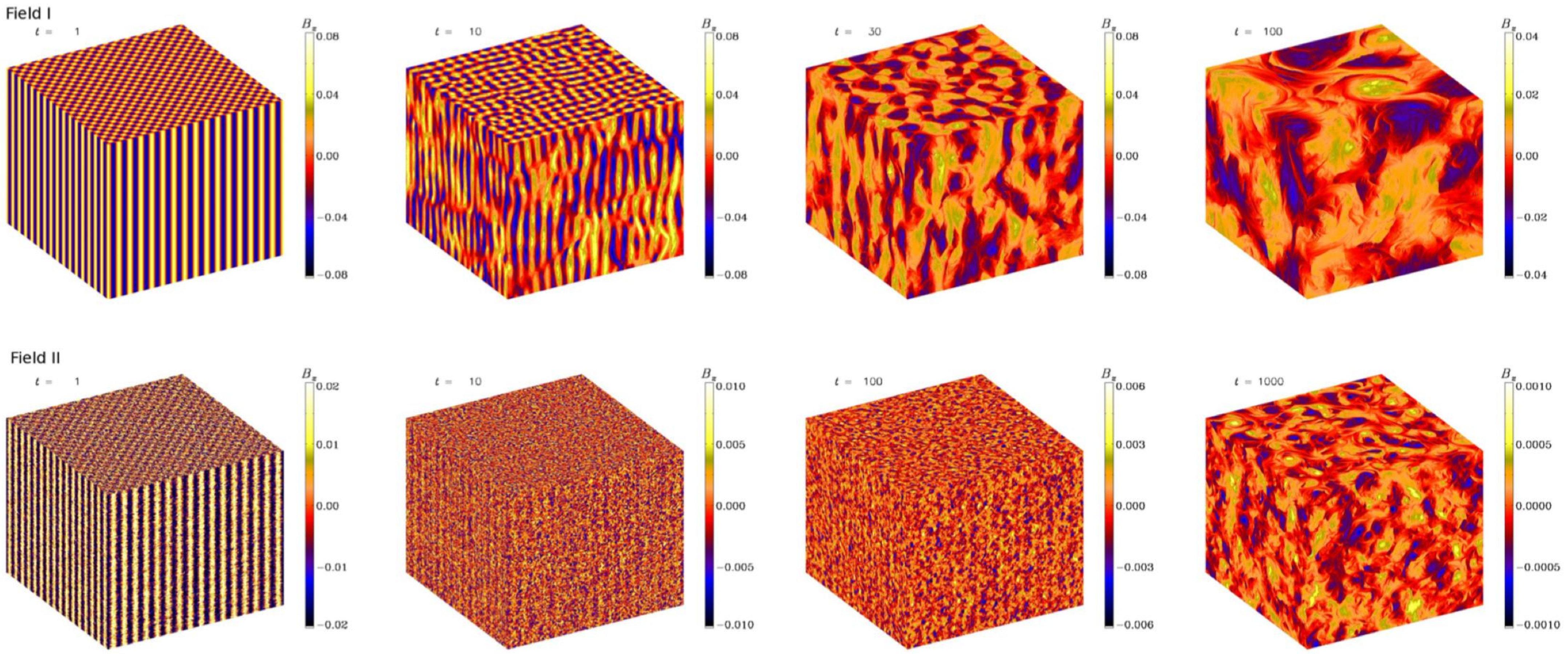
Backtracing the magnetic field trajectory we can guess from which epoch does magnetic field originate.

Example: non-helical magnetic field consistent with the CMB / Hubble tension hint has to originate from the QCD epoch.

Piecewise nonhelical initial field

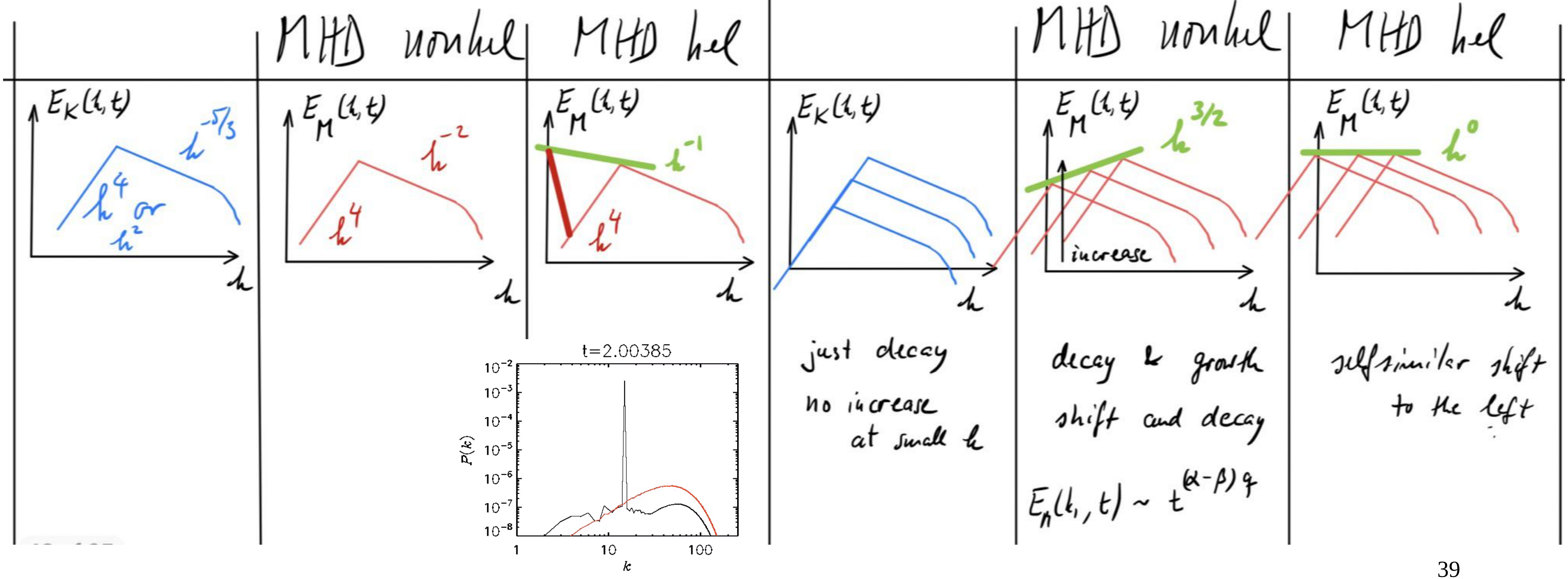


Columnar initial fields

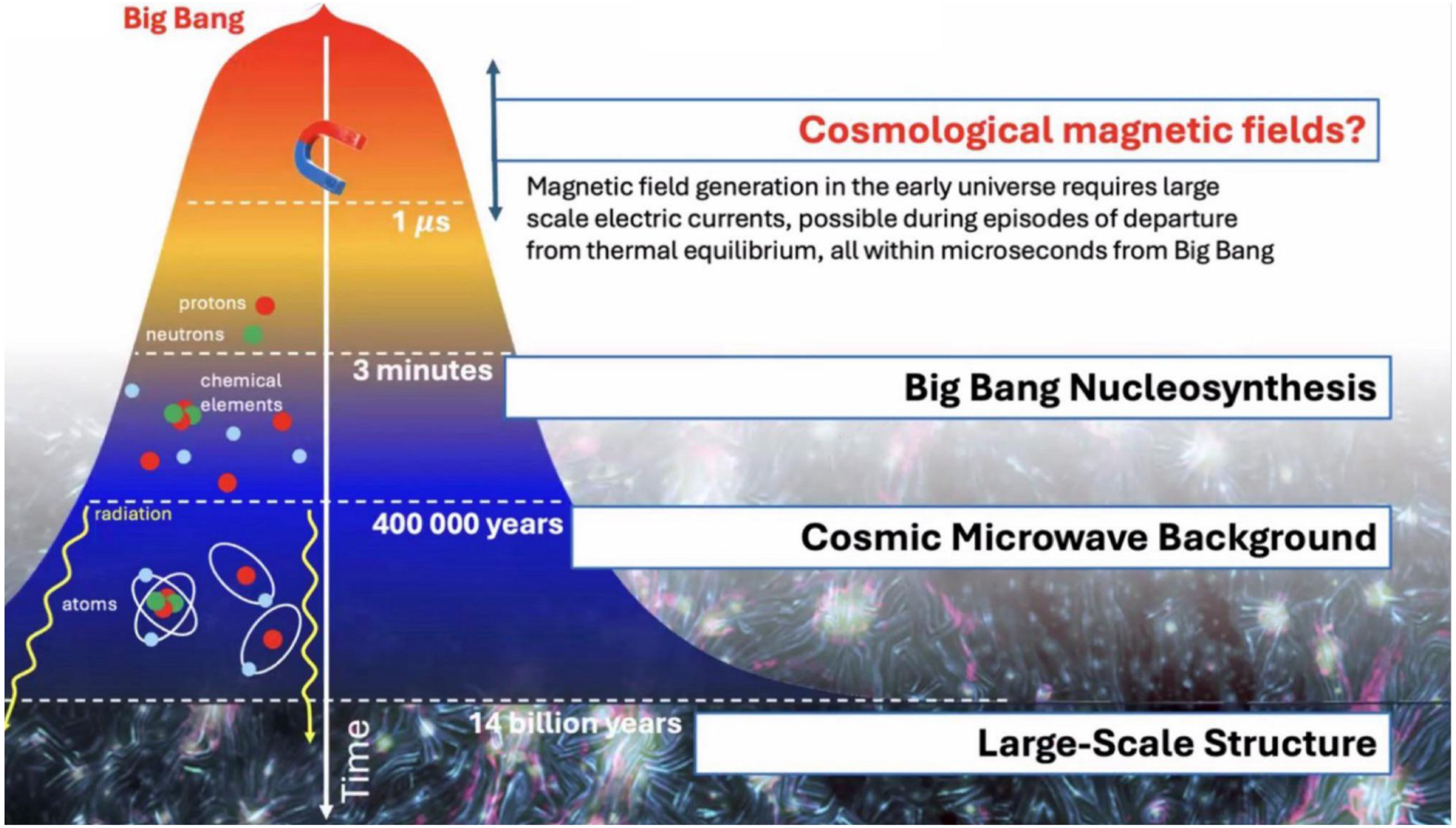


Cascades (periodic box)

forced turbulence | decaying turbulence



Primordial magnetic fields and relic gravitational waves: messengers of the first microseconds



Axel Brandenburg (Nordita)

Collaborators: Chiara Caprini (Geneva) Andrii Neronov (Paris/Lausanne), Franco Vazza (Bologna)

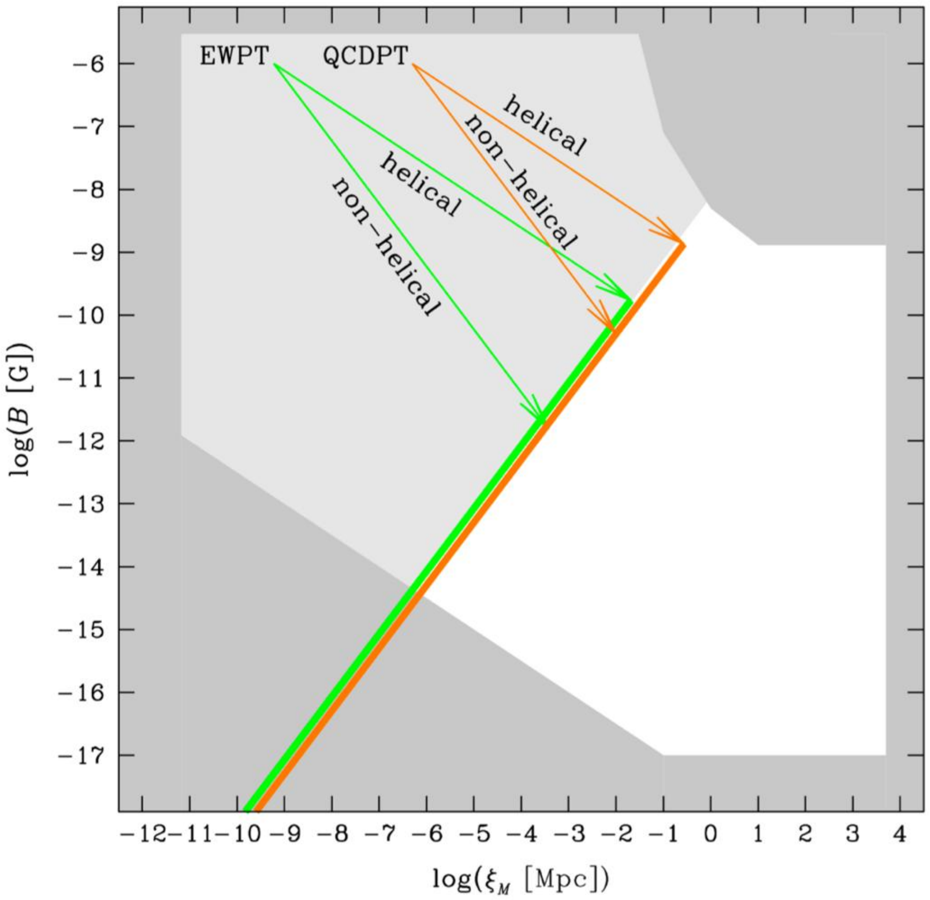
Overview

- Contemporary magnetic fields: dynamo action (kinetic → magnetic energy)
  - Works generically in turbulent flows (allows irreversible foldings of field lines)
  - In stars and galaxies: also large-scale fields (solar 11-yr cycle)
  - Typically in flows with helicity per hemisphere (EMF in direction of B-field: α effect)
  - Alternatively: just small-scale dynamos: probably in galaxy clusters
- Primordial magnetic fields: best contrained in voids (GeV gamma rays)
  - But: also contamination from outflows
- MHD: when electrically conducting (displacement current unimportant)
  - Different during inflation: electromagnetic waves (destabilized at large scales?)
  - Charge-separation almost always unimportant!
- Relic gravitational waves (GWs): they don’t decay
  - Direct probe of turbulence and magnetic fields at time of generation
  - GW spectrum related to turbulence spectrum
  - Circular polarization: related to kinetic and magnetic helicity

Magnetic field evolution

- During radiation-dominated era
  - Possibilities of kinetic energy from phase transitions → dynamo action (but need vorticity)
  - Conversion of chiral chemical potential to magnetic energy (chiral magnetic effect)
  - Higgs field
- Turbulent decay (unless always perfectly uniform)
  - Characterized by a spectral peak (k_{peak}) → generic turbulence spectrum for higher k
  - Turnover time $(u_{\mathrm{rms}}\, k_{\mathrm{peak}})^{-1}$ and/or Alfven time $(v_{\mathrm{A}}\, k_{\mathrm{peak}})^{-1}$ govern speed of decay
  - But possibility of inverse cascade (increase of spectral energy at low k)
  - Most efficient for helical fields (also slower decay)
  - Even nonhelical decay faster than hydrodynamic decay
- Magnetic fields as a probe of the first microsecond of the universe
  - End points on a universal line $\boldsymbol{B}$ vs length scale

Primordial magnetic fields and relic gravitational waves: messengers of the first microseconds



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