On the Origin of Cosmological Magnetic Fields
A short overview*

Jean-Baptiste Durrive

IRAP, Astroplasma meetings, 12 November 2020

B in the Large-Scale Structure of the Universe

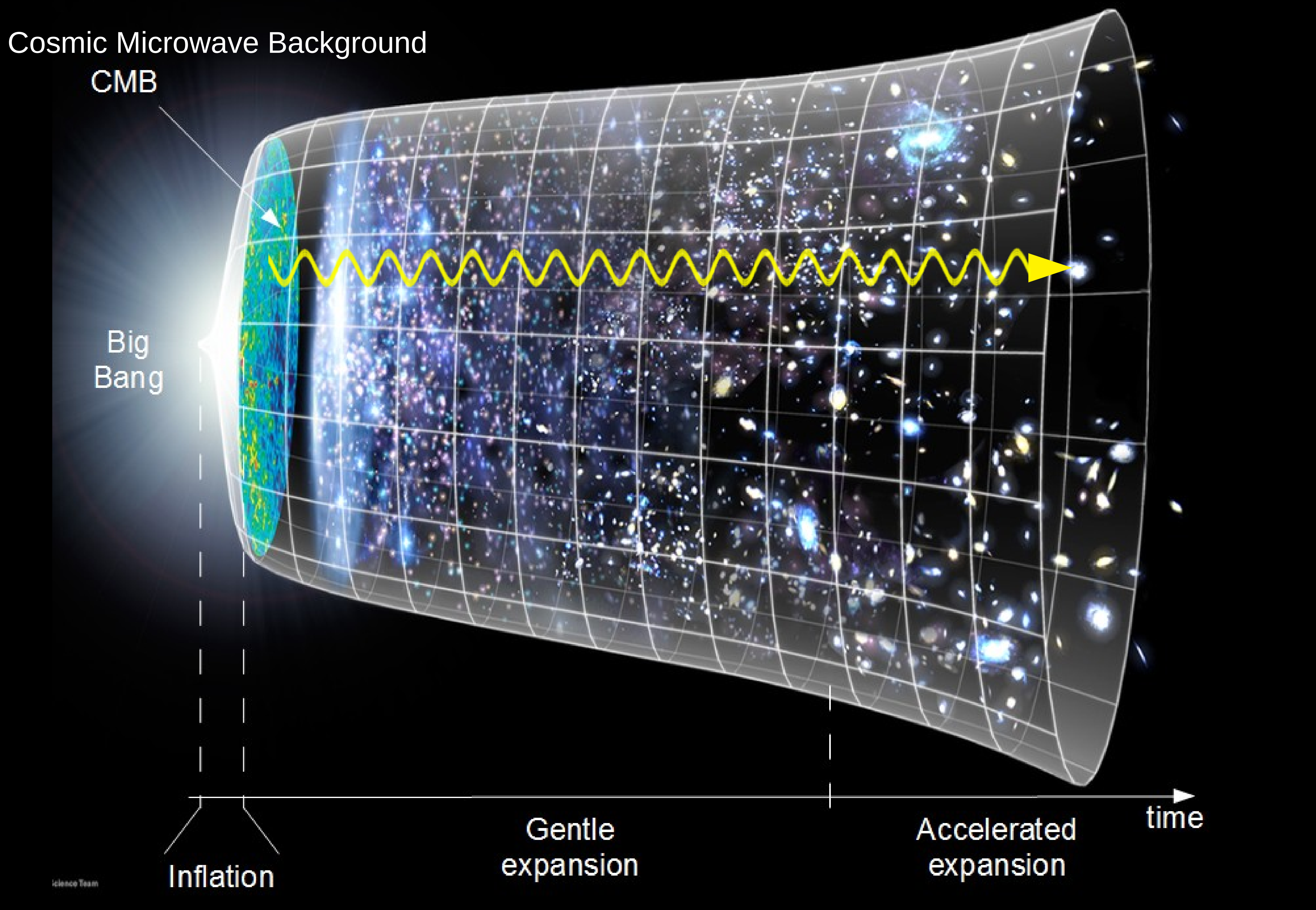
***For full reviews see e.g.**

- **Widrow 2002**
- **Kulsrud & Zweibel 2008**
- **Ryu et al 2012**
- **Widrow et al 2012**
- **Durrer & Neronov 2013**
- **Subramanian, K 2008, 2015**
- **Subramanian, K 2019**

Lots of details on:
- B in General Relativity & Cosmology
- primordial universe B fields
- observational constraints

Short and recent

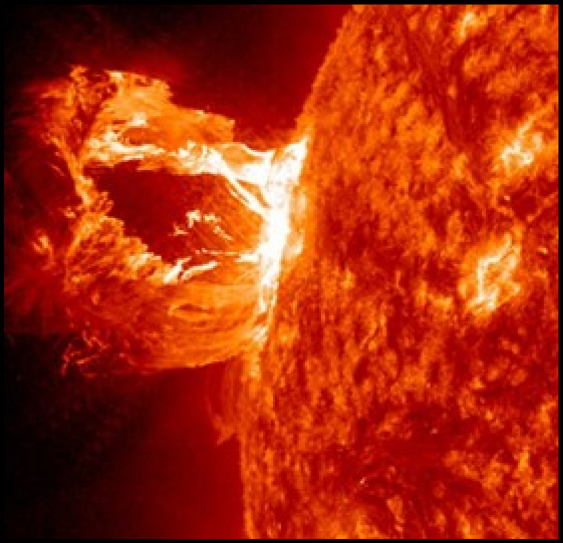
Cosmological context



Magnetic fields & turbulence are ubiquitous in the Universe

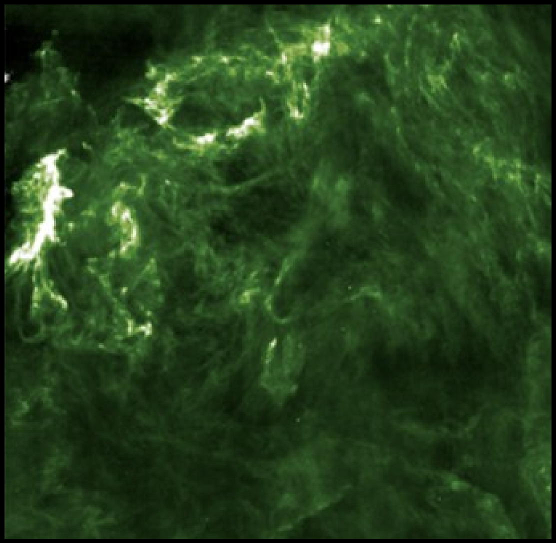
In our galaxy, at all scales

NASA/SDO



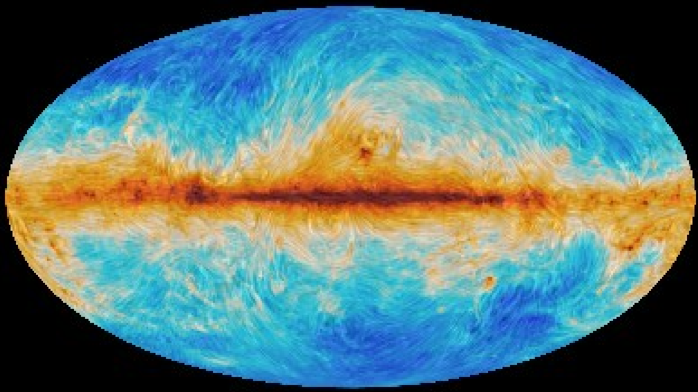
B~kG

Miville-Deschênes+ 2010



B~10 μG

ESA & Planck collab.



B~10 μG

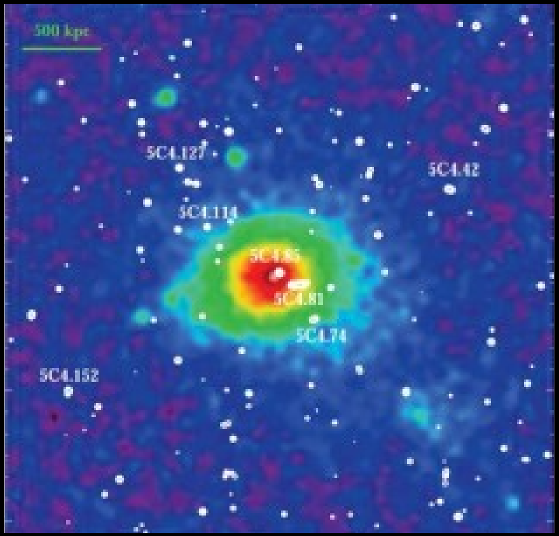
In other galaxies

Fletcher et al., 2011

B~10 μG

In galaxy clusters

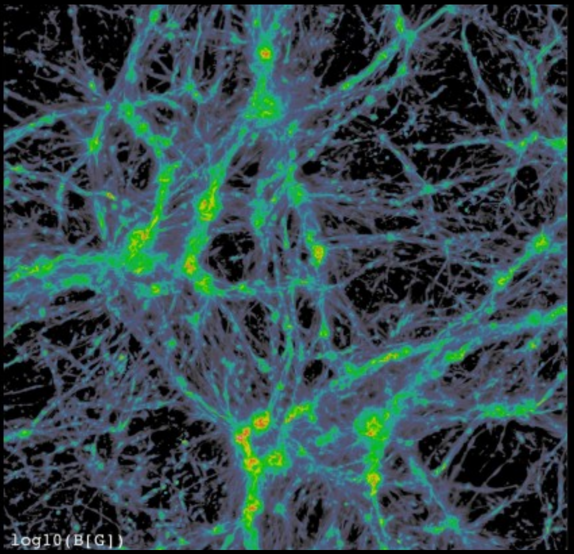
Bonafede et al 2010



B~few μG

In the cosmic web

Vazza et al 2014



B~nG

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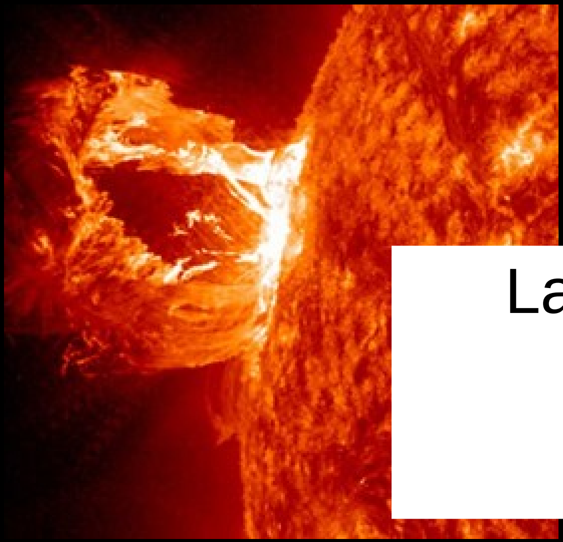
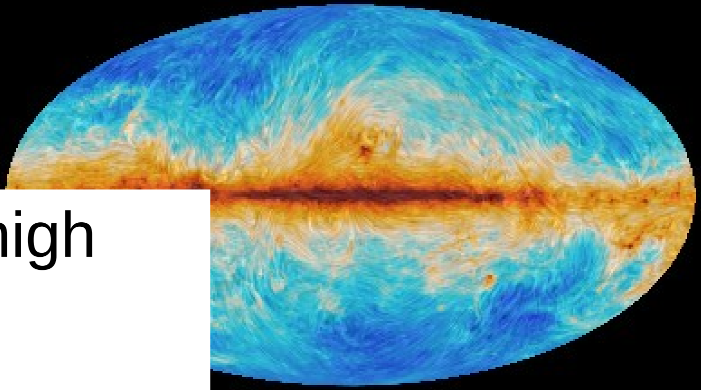


B~kG

Miville-Desc...

B~10 μG

ESA & Pla...



B~10 μG

Large *B* in galaxies even at high redshifts

(84 μG @ z ~ 0.7, Wolfe et al. 2008

~10 μG up to z = 3, Kronberg et al. 2008)

In other galaxies

Fletcher et al., 2011

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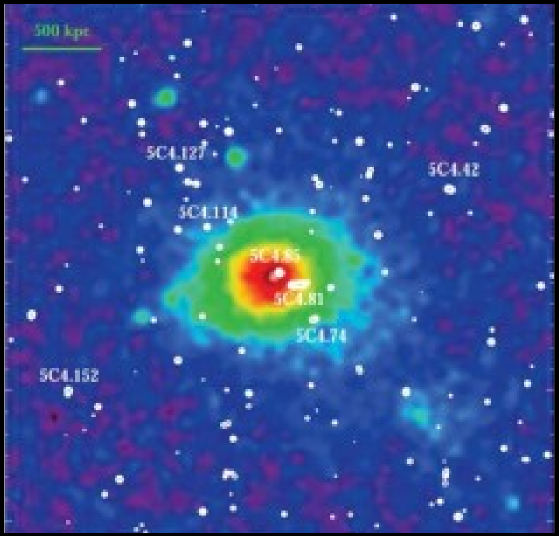

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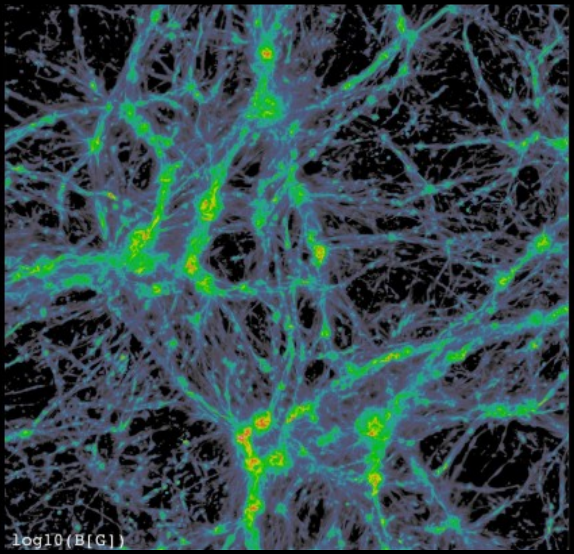

B~nG

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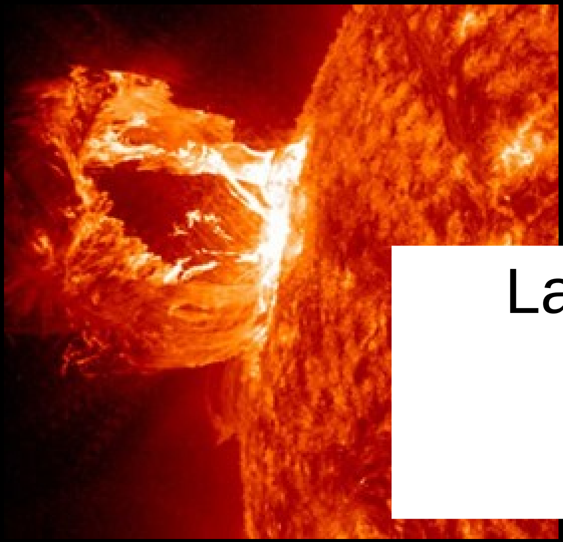

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Miville-Desc... 0

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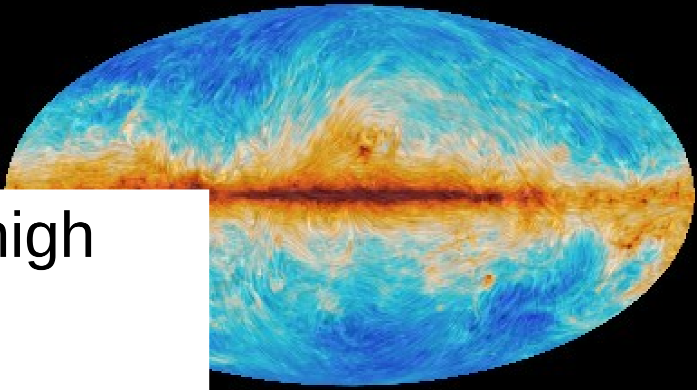

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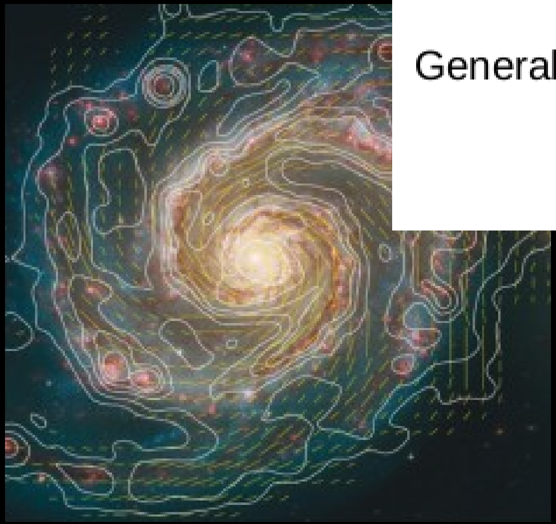

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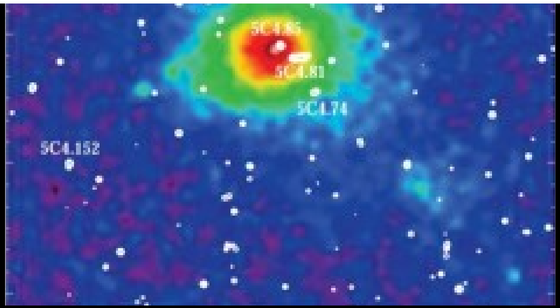

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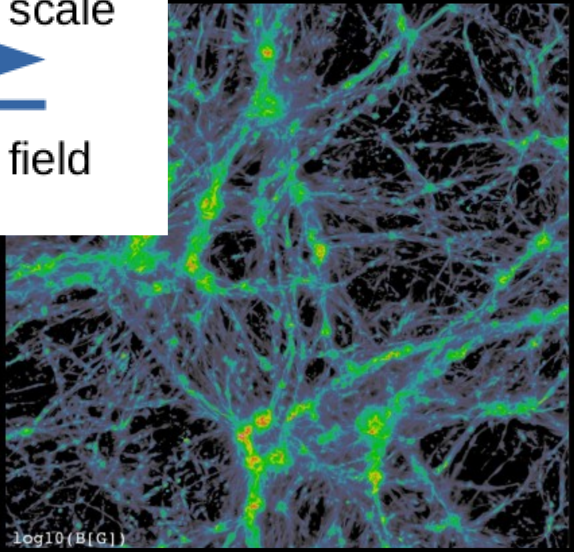
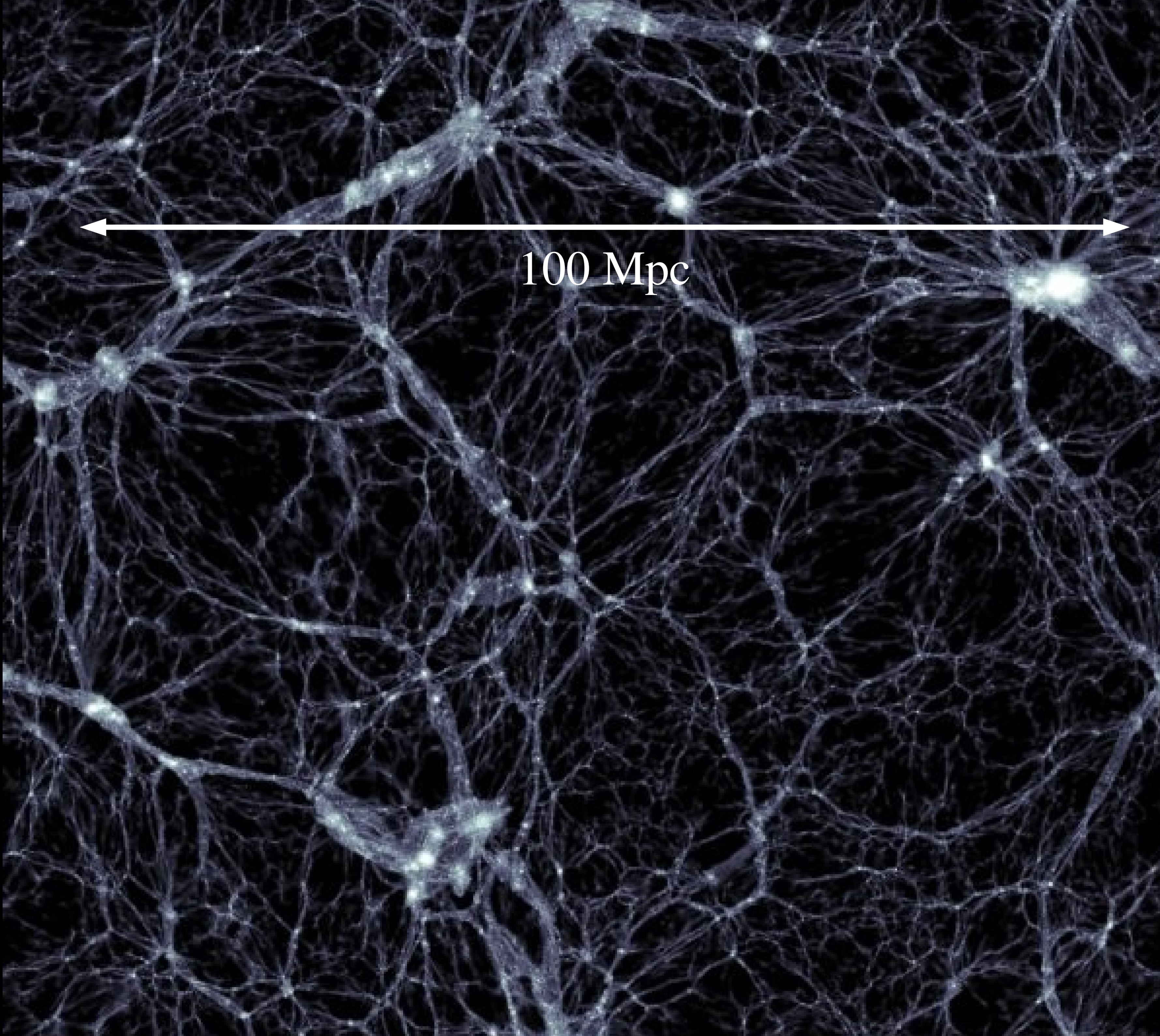


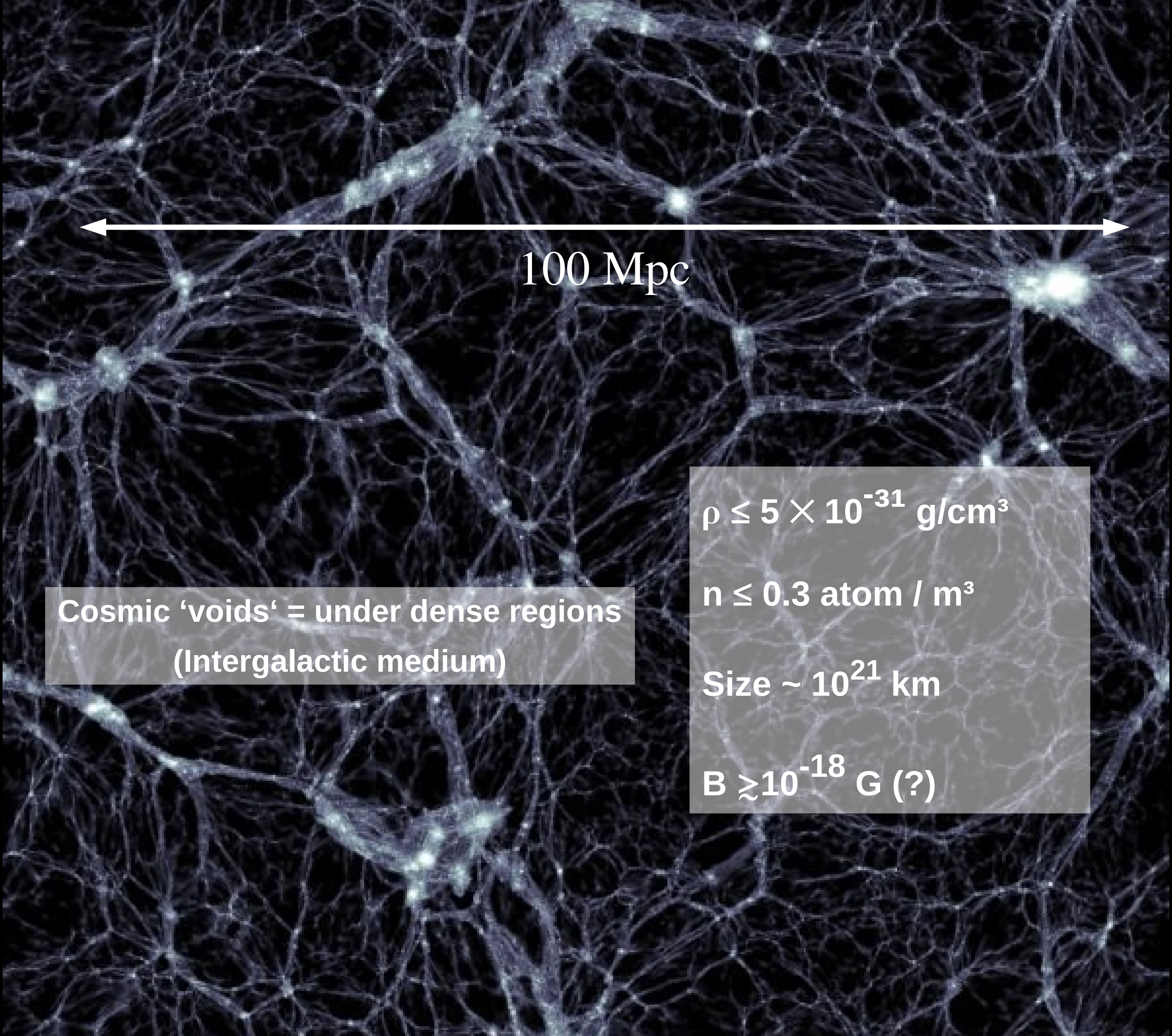
B~nG

Generally:

Small scale →	Large scale
Strong field ←	Weak field



Illustris Simulation, Haider et al (2016)



Illustris Simulation, Haider et al (2016)

Magnetogenesis: General facts

When and how did cosmic magnetic fields appear?

If they appeared with today's strengths, structure formation history would have been totally different from what we observe

→ Current (well accepted) paradigm:

1) **Magnetogenesis**: Generation of weak 'seeds'

2) **Amplified** and reorganized during structure formation
by adiabatic compression ('frozen-in') and **dynamos**
+ maintained by dynamos later on

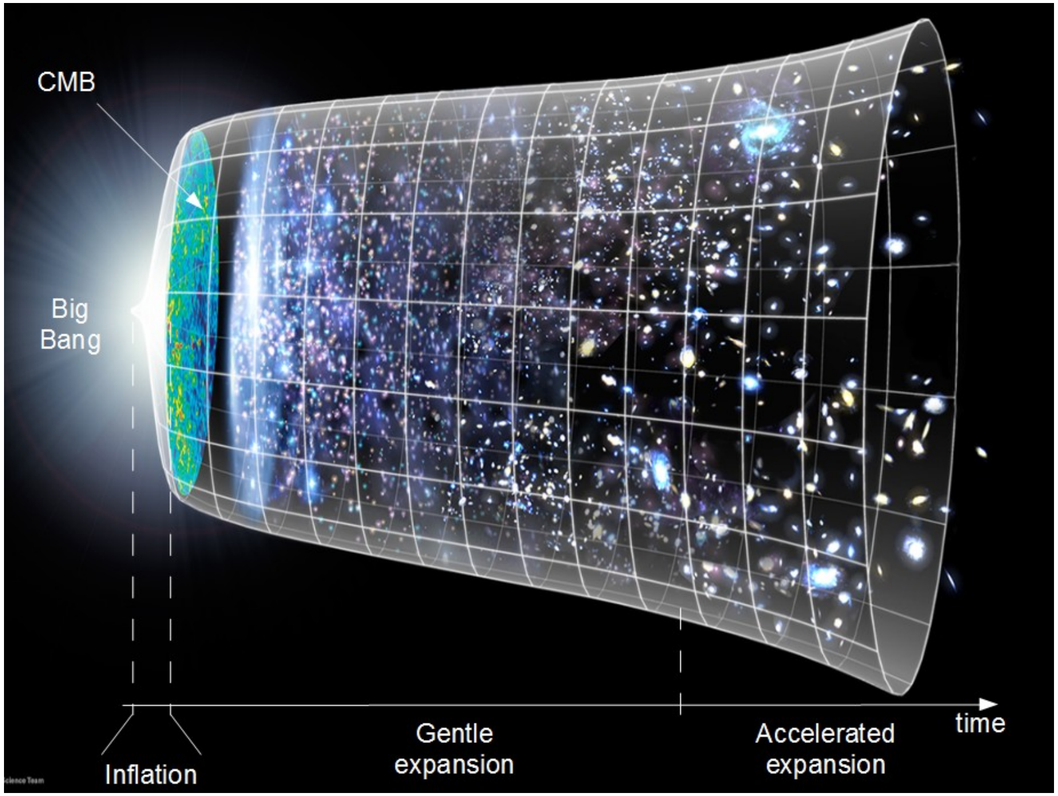
Need ~ 10^{-22} to 10^{-12} G seeds to account for observed μG
e.g. ICM fields (1-40 μG at 1-10 kpc scales)

Turbulence in structures => amplification but then saturation
at levels independent of the initial B properties

=> look at the **intergalactic medium**,
where seeds did not evolve too much
(voids of large scale structure)

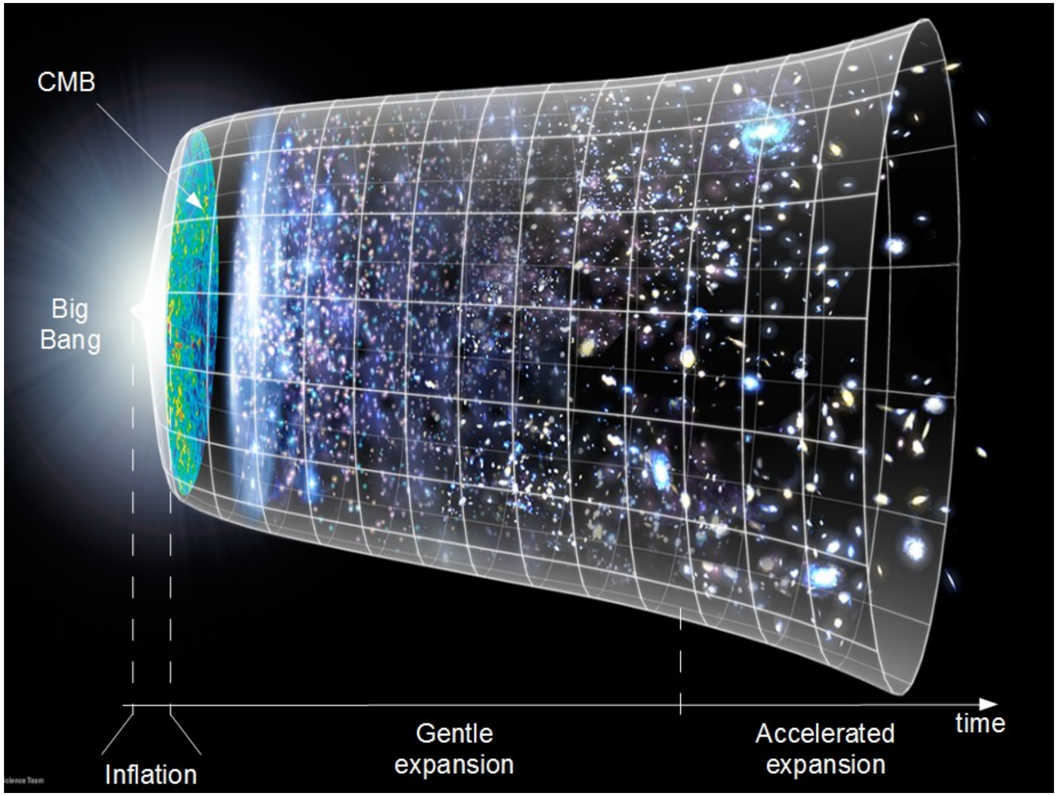
?

B field **generated** early → B **observed** in today's **structured** Universe



→ Need to study the **evolution** of cosmological magnetic fields

B field **generated** early → ? B **observed** in today's **structured** Universe



→ Need to study the **evolution** of cosmological magnetic fields

Major question:
Is ICM turbulence a good-enough dynamo flow?

Magnetic field evolution in Cosmology

How efficient is magnetic diffusion in the cosmological context?

In the diffusive limit (neglect advection & source): $$\frac{1}{t_D} \sim \frac{\eta}{L^2}$$

With L = Hubble radius $$\frac{c}{H_0} \sim 4 \times 10^{18}\ \mathrm{m}$$

And magnetic diffusivity $$\eta \sim 10^{-6}\ \Omega.\mathrm{m}$$

$$t_D \sim \frac{L^2}{\eta} \sim 10^{31}\ \text{years}$$ >> Age of the Universe ~ 10^{10} years!

→ On cosmological scales:
Once B is generated, it not damped by diffusion. It is frozen into matter

Magnetic field evolution in Cosmology

Sphere of plasma of radius r undergoing a uniform and isotropic contraction

mass conservation: $\rho\, r^3 = \text{cst}$

flux conservation through its surface: $B\, r^2 = \text{cst}$

hence $\frac{B}{\rho^{\frac{2}{3}}} = \text{constant}$

In the Standard Model of Cosmology $\rho \propto a^{-3}$

Hence the adiabatic dilution:

$B \propto a^{-2}$ that is $B \propto (1+z)^2$

Note:

Magnetogenesis predict B generation at various epochs in the Universe

→ observational constraints are usually given in terms of their values scaled to today (diluted)

Magnetic field evolution in Cosmology

Flat expanding Universe described by the metric $ds^2 = a^2(t)\left[-dt^2 + \delta_{ij}\, dx^i\, dx^j\right]$

Electromagnetic Lagrangian $L = \frac{1}{4}\sqrt{-g}\, F_{\mu\nu} F^{\mu\nu}$

Durrer & Neronov 2013

Rescaled quantities

$$\tilde{\rho} = a^4 \rho, \qquad \tilde{p} = a^4 p, \qquad \tilde{B}^i = a^2 B^i, \qquad \tilde{E}^i = a^2 E^i, \qquad \tilde{J}^i = a^3 J^i$$

Cosmological MHD equations

$$\frac{\partial \tilde{\rho}}{\partial t} + \nabla\big((\tilde{p} + \tilde{\rho})\mathbf{v}\big) = 0,$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{\mathbf{v}}{(\tilde{\rho} + \tilde{p})} \frac{\partial \tilde{p}}{\partial t} + \frac{\nabla \tilde{p}}{(\tilde{\rho} + \tilde{p})} + \frac{\tilde{\mathbf{B}} \wedge (\nabla \wedge \tilde{\mathbf{B}})}{(\tilde{p} + \tilde{\rho})}$$

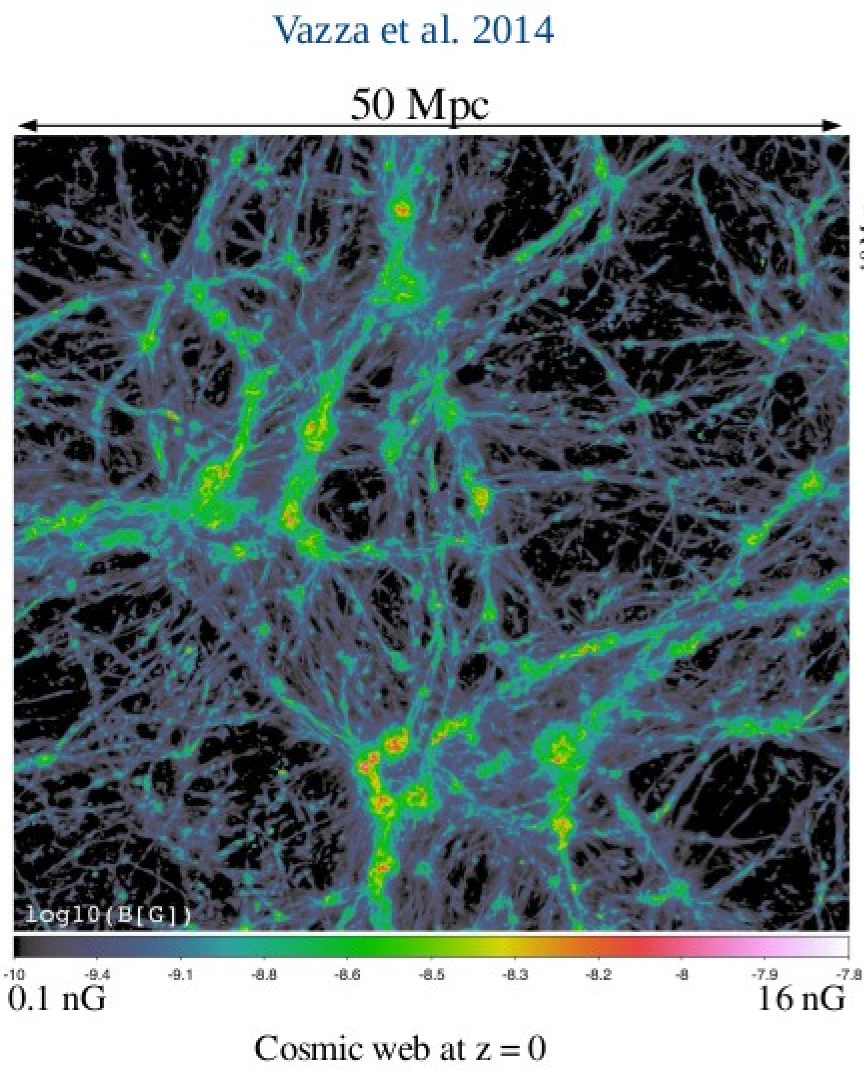
$$= \tilde{\nu}\left(\nabla^2 \mathbf{v} + \frac{1}{3}\nabla(\nabla \cdot \mathbf{v})\right),$$

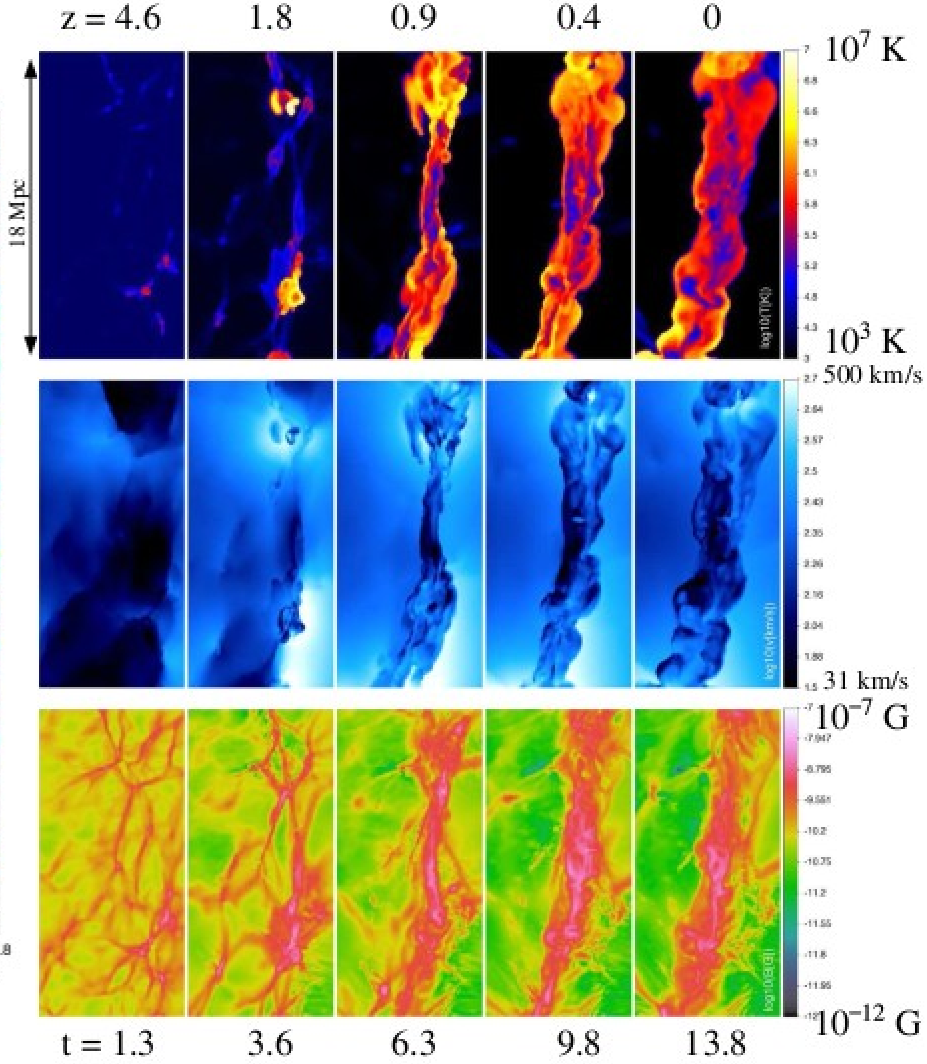
$$\frac{\partial \tilde{\mathbf{B}}}{\partial t} - \nabla \wedge (\mathbf{v} \wedge \tilde{\mathbf{B}}) = \frac{1}{\tilde{\sigma}} \nabla^2 \tilde{\mathbf{B}}.$$

radiation dominated equation of state $\tilde{p} = \tilde{\rho}/3$

shear viscosity, $\tilde{\nu} = \nu/a$ and the conductivity $\tilde{\sigma} = a\sigma$

Numerical simulation of B within intergalactic filaments

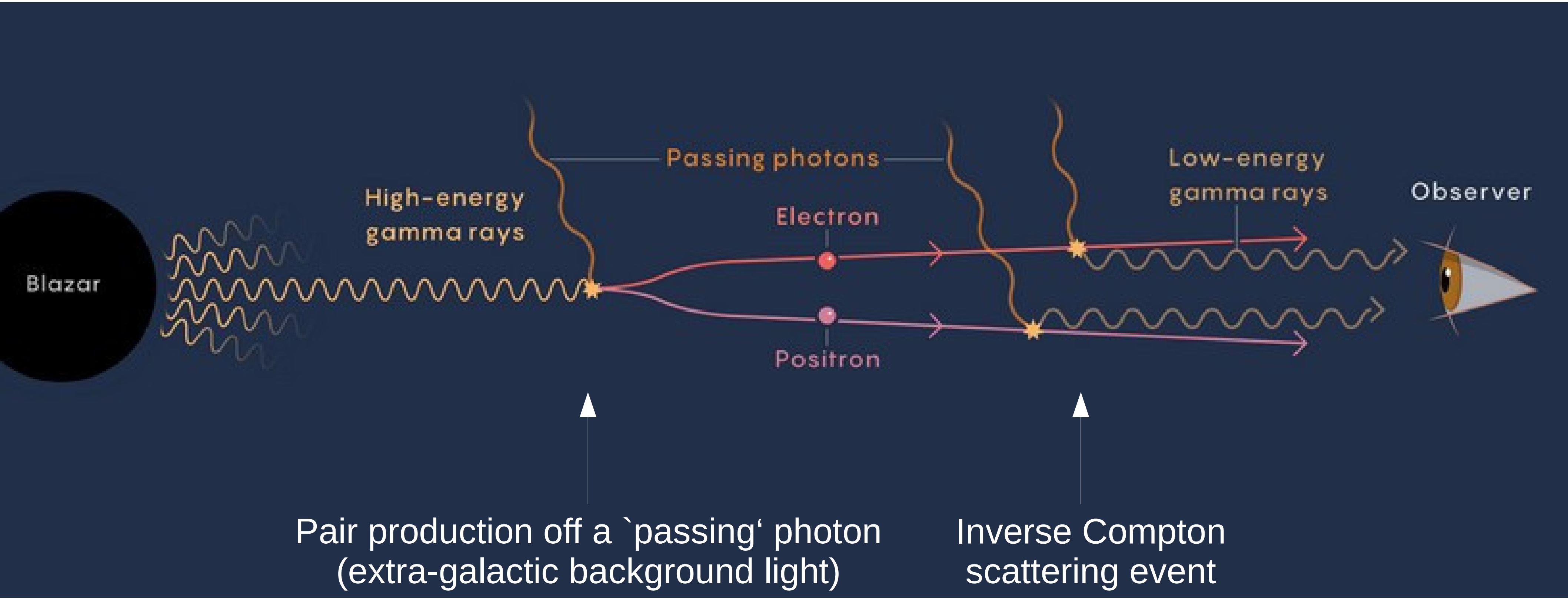




Measuring cosmic B fields

- Synchrotron emission
- Faraday rotation
- Zeeman spectral line splitting

- High energy gamma ray observations of blazars (FERMI satellite & HESS telescopes):



Source: https://www.quantamagazine.org/the-hidden-magnetic-universe-begins-to-come-into-view-20200702/

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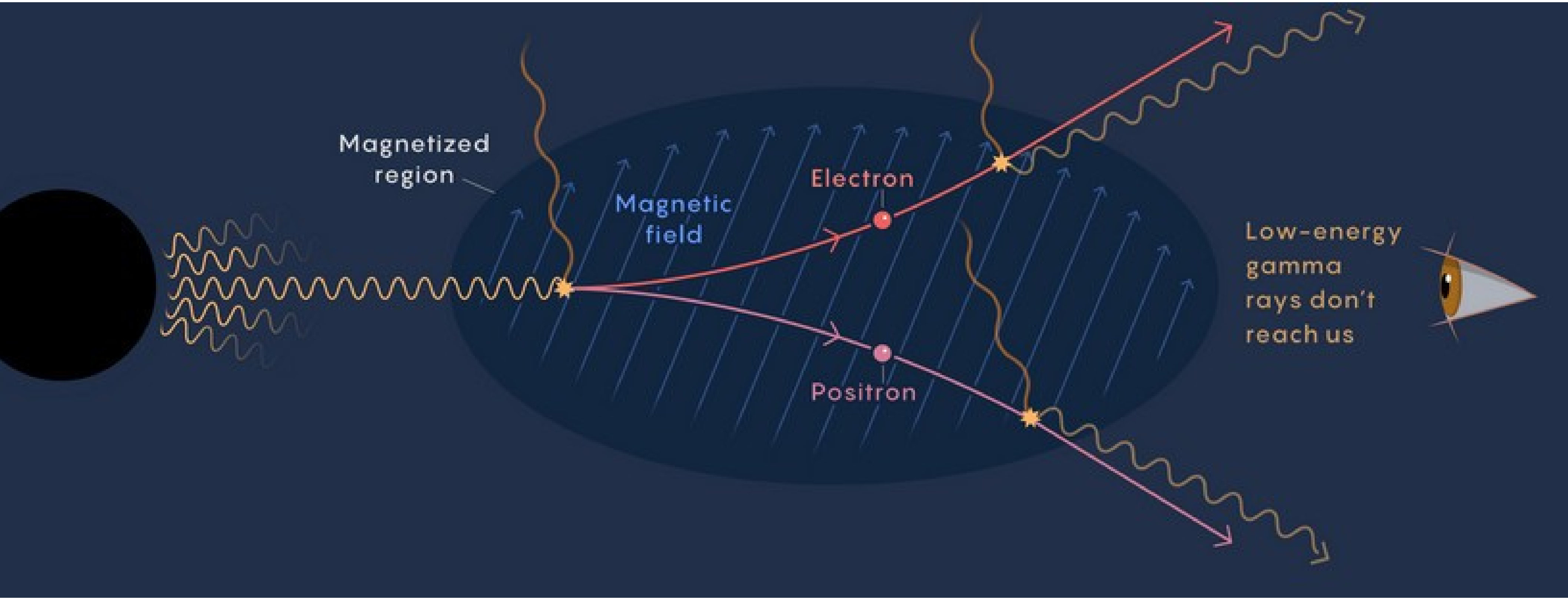

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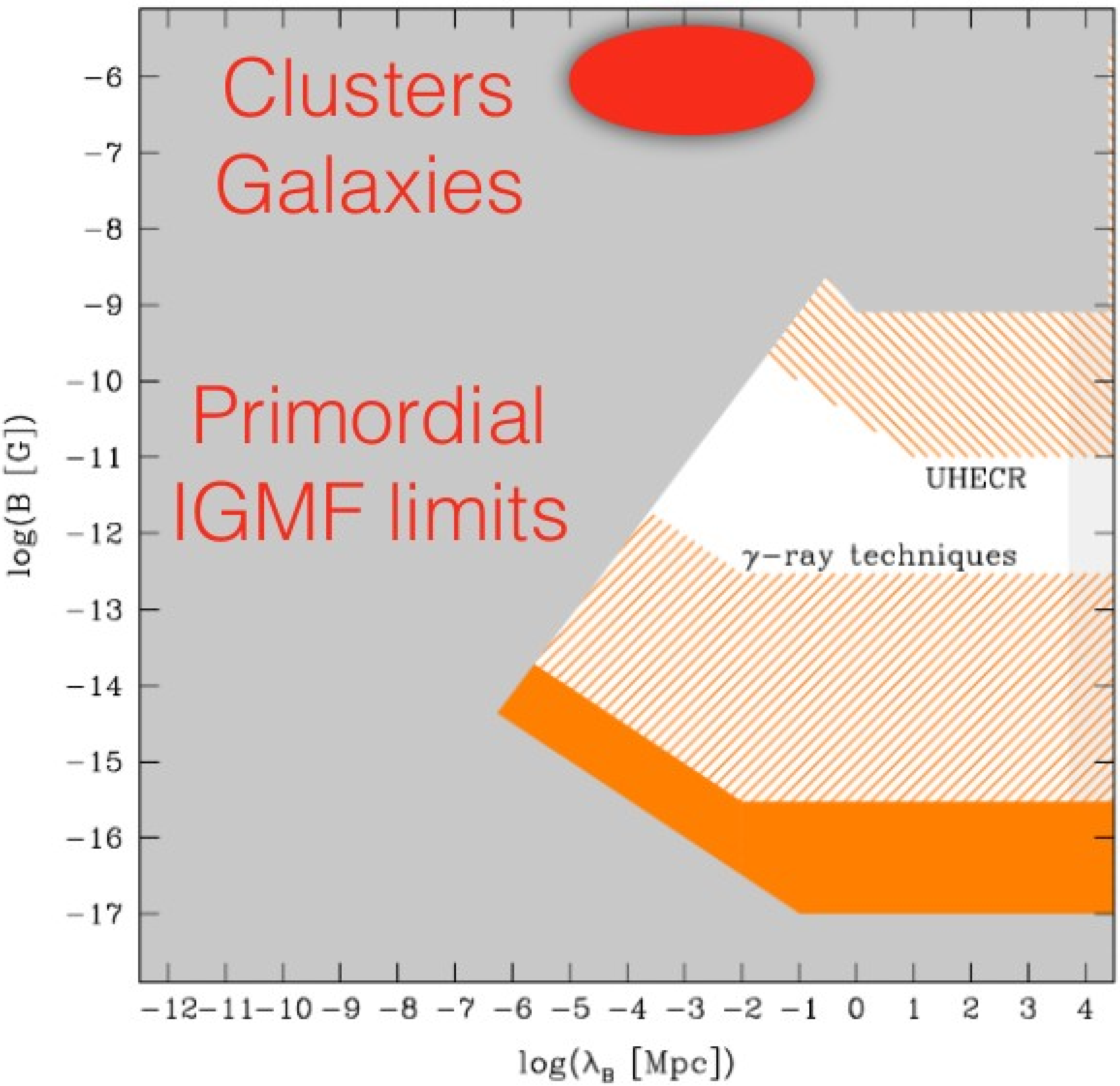
Measuring cosmic B fields

Cosmological magnetic fields, observations:

Durrer & Neronov 2013

Strength of B



Integral scale/correlation length

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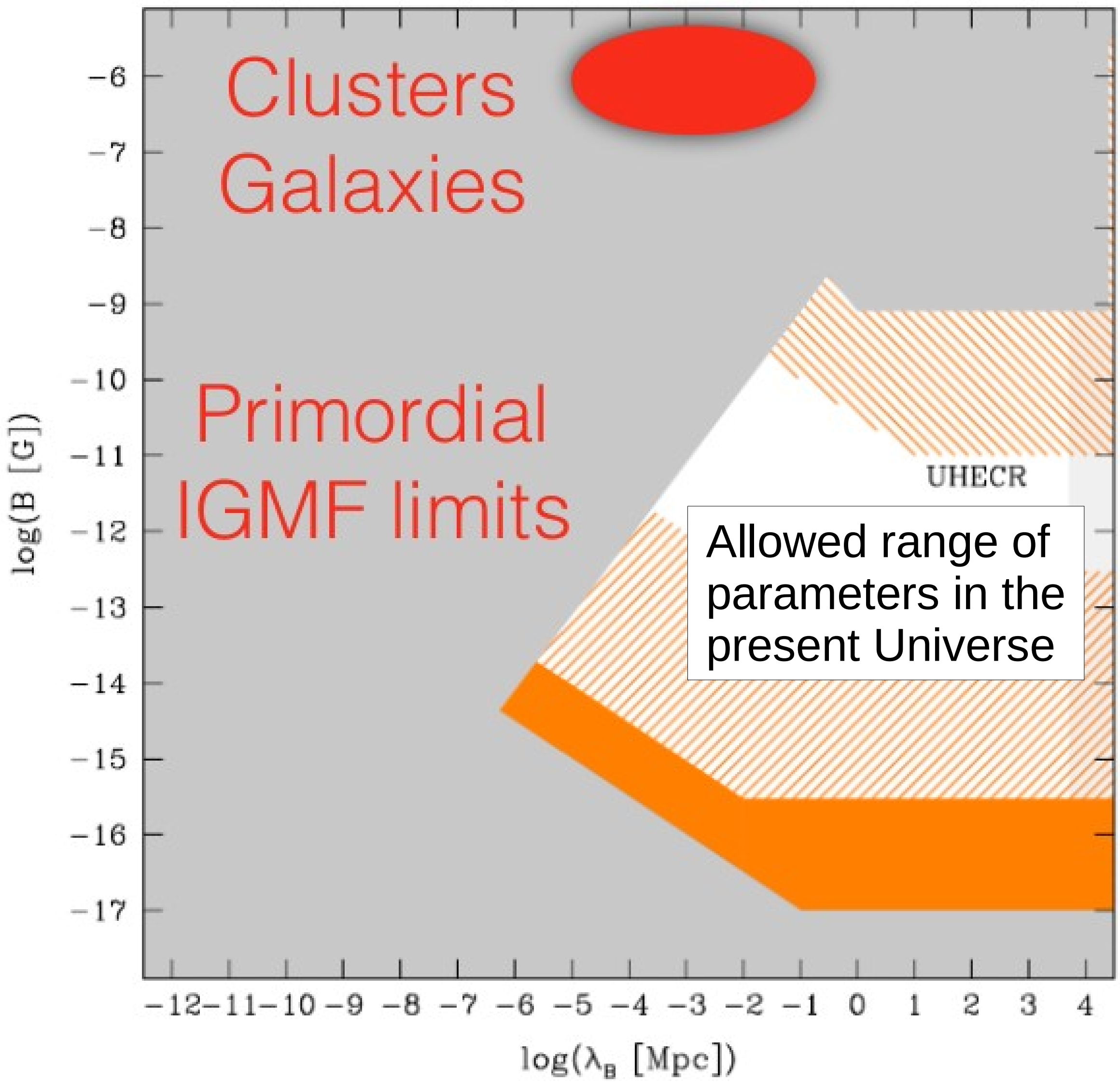

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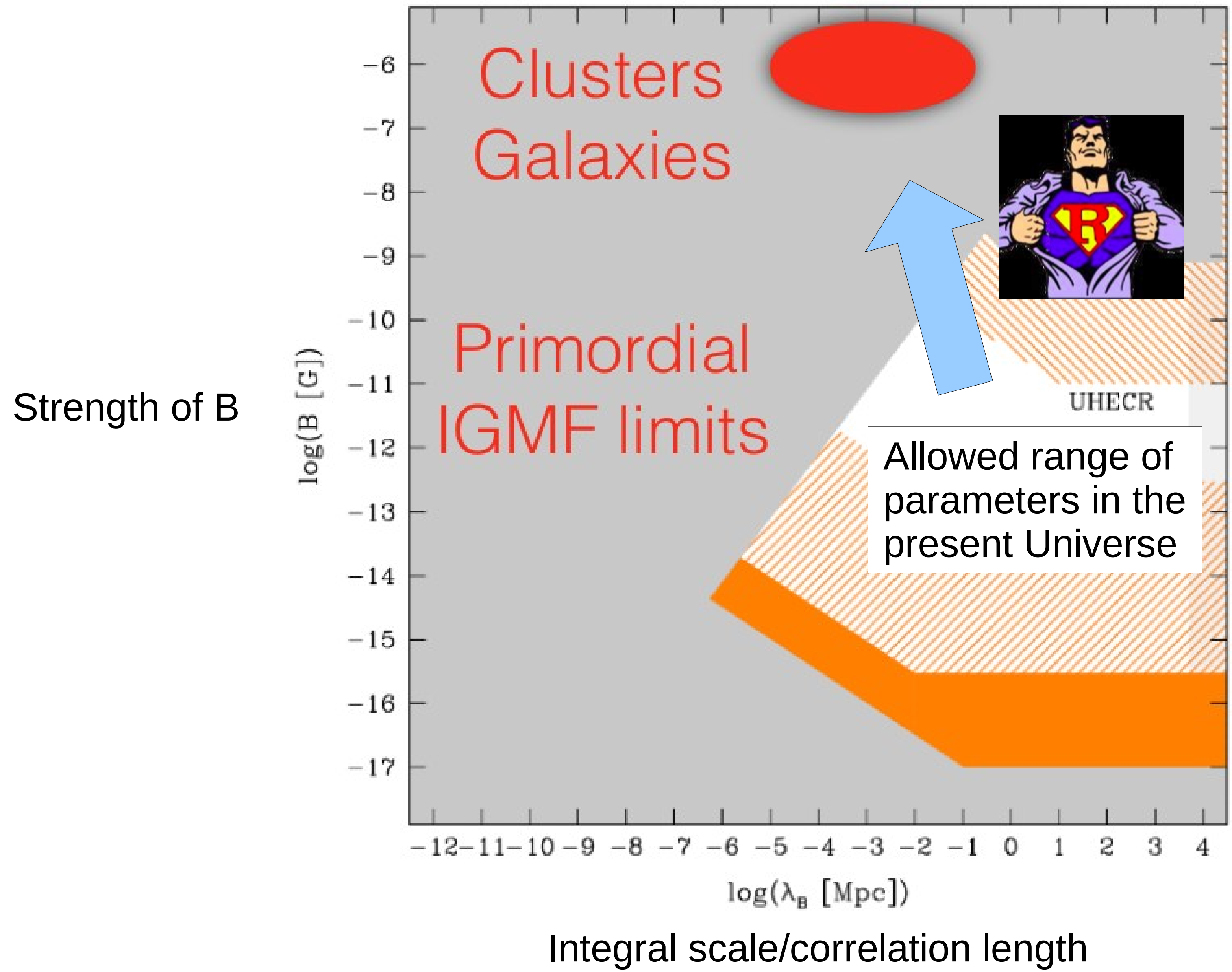

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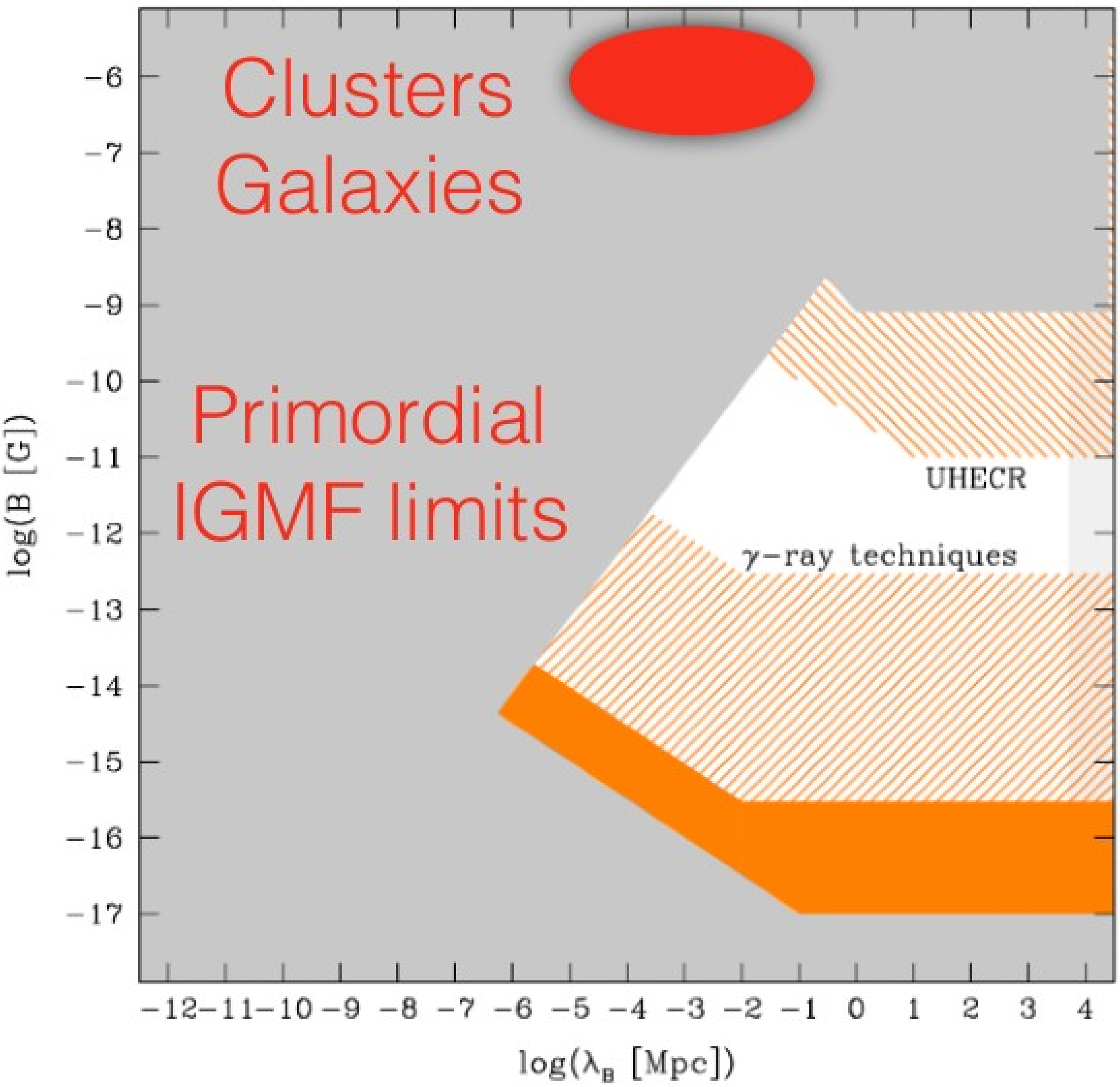
Cosmological magnetic fields, observations: Durrer & Neronov 2013



Measuring cosmic B fields

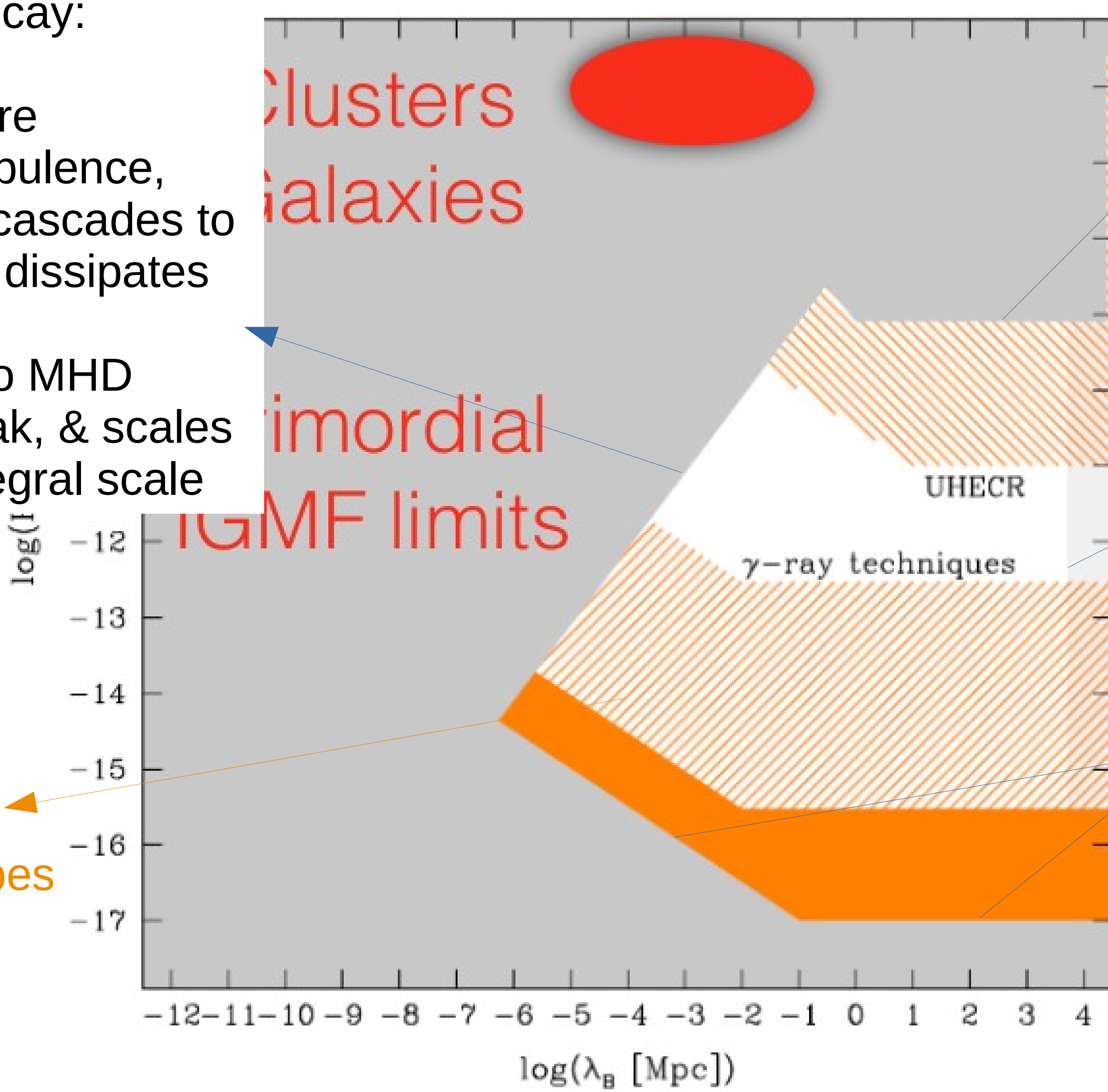
Cosmological magnetic fields, observations:

Durrer & Neronov 2013

Free turbulent decay:

Above: B fields are processed by turbulence, magnetic power cascades to small scales and dissipates

Below: B weak so MHD turbulence is weak, & scales beyond MHD integral scale



CMB anisotropy, Non-gaussianity + Structure formation (Wasserman 1978, Kim et al 1996)

B with λ > H radius would appear cst

High energy gamma rays (Fermi & HESS) (Neronov&Vovk 2010, Taylor et al 2011, Takahashi et al 2011, Chen et al 2015,...)

Next-generation Gamma-ray & UHECR telescopes

Magnetogenesis: Overview of the various mechanisms

Preliminary remark:

Generating B fields basically consists in:

1) a separation of charges

2) creates a rotational electric field $\partial_t \vec{B} = -c\vec{\nabla} \times \vec{E}$

3) which induces a magnetic field

Evolution of B:

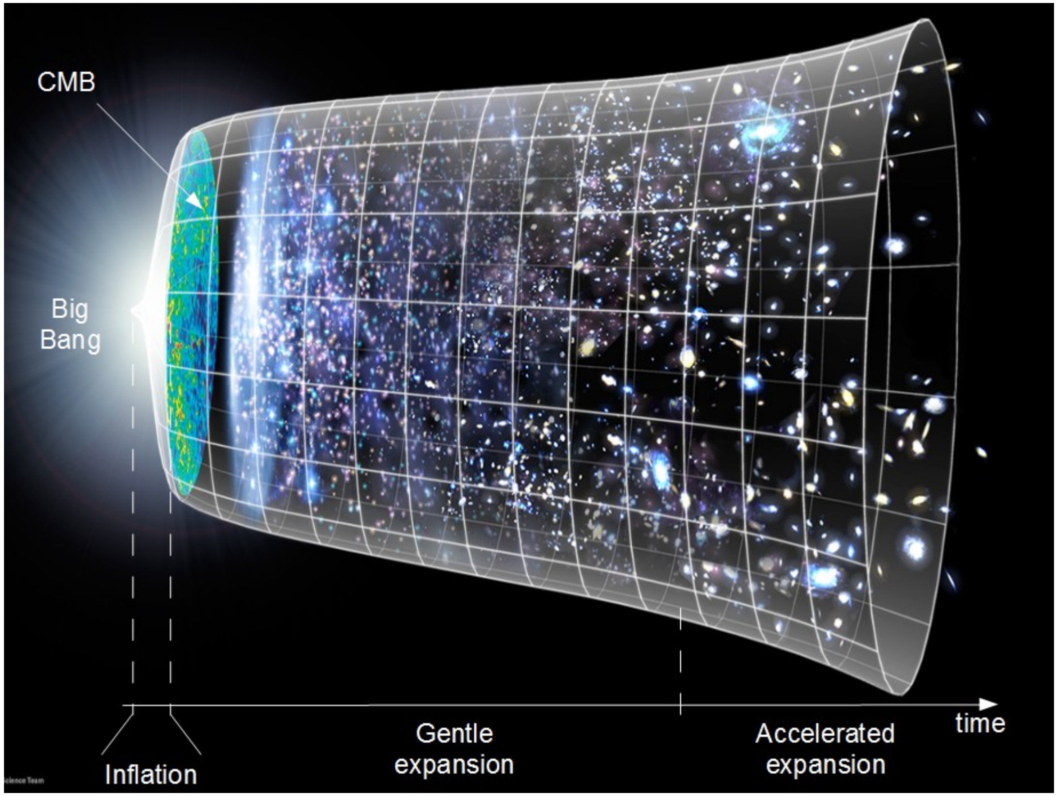
$$\partial_t \vec{B} = \vec{\nabla} \times \left(\vec{v} \times \vec{B}\right) - \vec{\nabla} \times \left(\eta \vec{\nabla} \times \vec{B}\right) - c\vec{\nabla} \times \vec{E}_{\mathrm{s}}$$

advection diffusion source

Origin(s) of magnetic fields

- Numerous mechanisms proposed, but no preferred one so far.
- Several mechanisms most probably happened together
- Two broad classes:

I) **Primordial Universe**
II) **Post recombination**

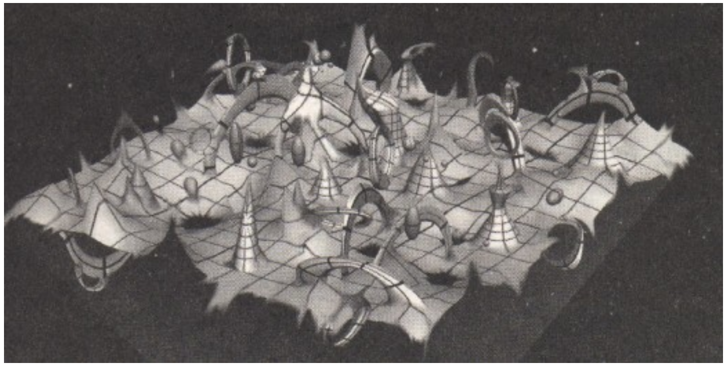


I) Primordial Universe mechanisms

(review: e.g. Widrow et al 2012)

• <u>Inflation:</u>

Current matter density field of the Universe stems from **quantum fluctuations** of the primordial matter fields. How about the quantum fluctuations of the primordial electromagnetic field?



The standard EM action is left invariant under a conformal transformation of the metric: $g^*_{\mu\nu} = \Omega^2 g_{\mu\nu}$

Massless photon => no dimensionful parameter to break the scaling symmetry

The electromagnetic field **does not 'feel' the expansion** of the Universe.

Hence, EM wave fluctuations **cannot be amplified**, so the EM field decays with the expansion as a^{-2}, which is very drastic during inflation => need beyond standard physics

✔ Generation at any scale
✗/✔ Beyond standard physics
✗ Extremely model dependent

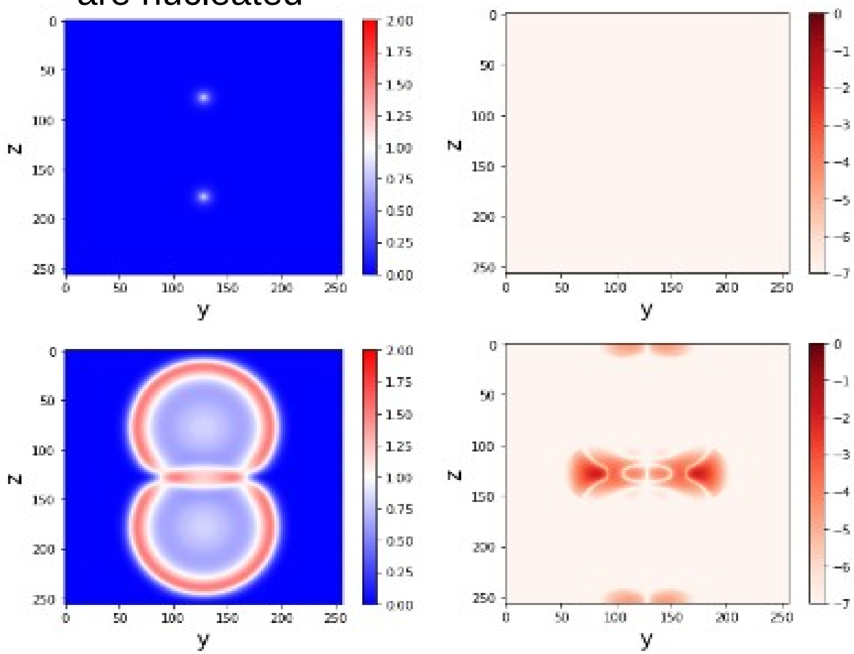
- <u>Phase transitions</u>:

1) At high T, elementary particles are massless. At Tc, W & Z bosons interact with the Higgs field and acquire mass. Weak & EM forces become separate: Electroweak symmetry is broken <u>(t ~ 10^{-12} s)</u>

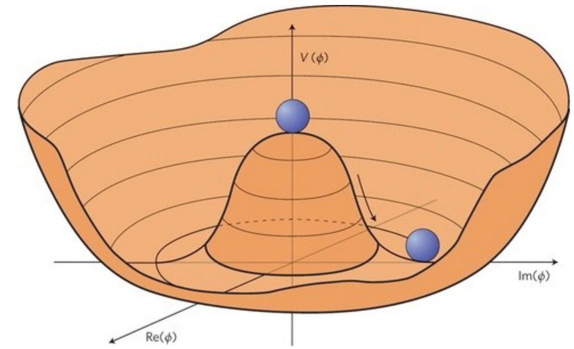
2) when quarks gather into hadrons <u>(t ~ 10^{-5} s)</u>

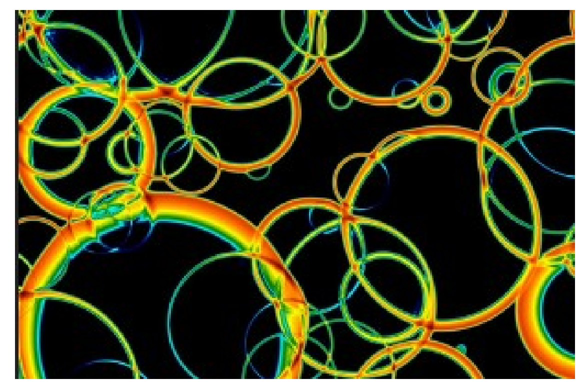
Two bubbles are nucleated

B field



Bubbles grow & collide: B is produced
Vachaspati 2020 arXiv:2010.10525)





B generated with correlation length ~ bubble size ~ fraction of Hubble radius

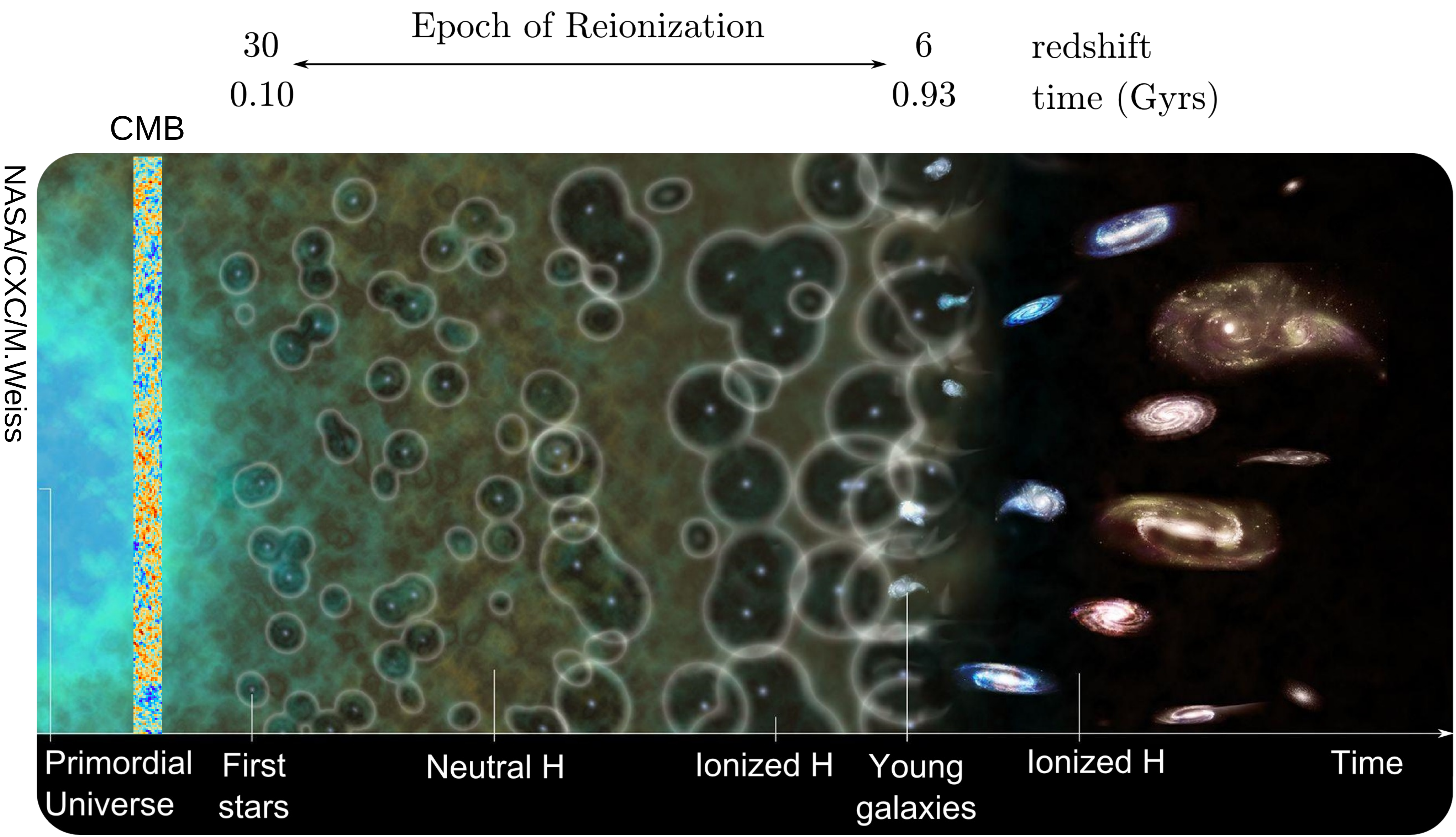
✔ Strong fields
Well understood high energy physics
✗ Scales ~ Hubble radius at early times → **too small**
Unless **inverse cascade** ?
\+ causality constrains the slope of the B power spectrum

- <u>Before and at recombination:</u>

  rotating plasma blobs interacting with background radiation at $z = 1100$, up to $B \sim 5 \times 10^{-24}$ G on Mpc scales
  (Harrison 1970, Fenu et al 2011, Saga et al 2015)

II) Post-recombination mechanisms

Cosmological context (continued)



- <u>Thermal (**Biermann**) battery:</u>

$$\partial_t \vec{B} = \vec{\nabla} \times \left(\vec{v} \times \vec{B}\right) + \frac{c k_B}{e n_e} \vec{\nabla} T_e \times \vec{\nabla} n_e$$

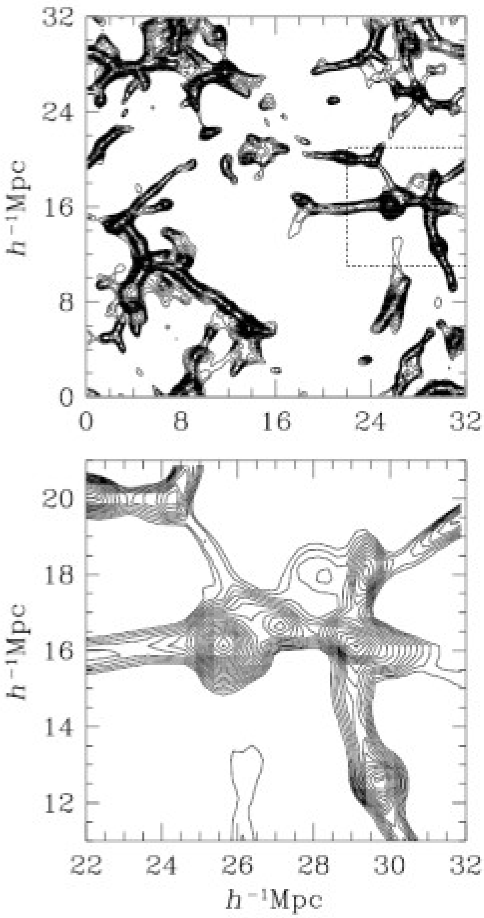
in stars
(Biermann 1950)

from **cosmological shocks** during cosmic web formation
(Pudritz & Silk 1989, Kulsrud et al 1997, Ryu et al 2003)

from propagating **ionization fronts** at EoR in large structures
(Subramanian et al 1994 + Gnedin et al 2000)

→ seed strengths B ~ 10^{-20} to 10^{-18} G on protogalactic scales

Biermann mechanism in cosmology

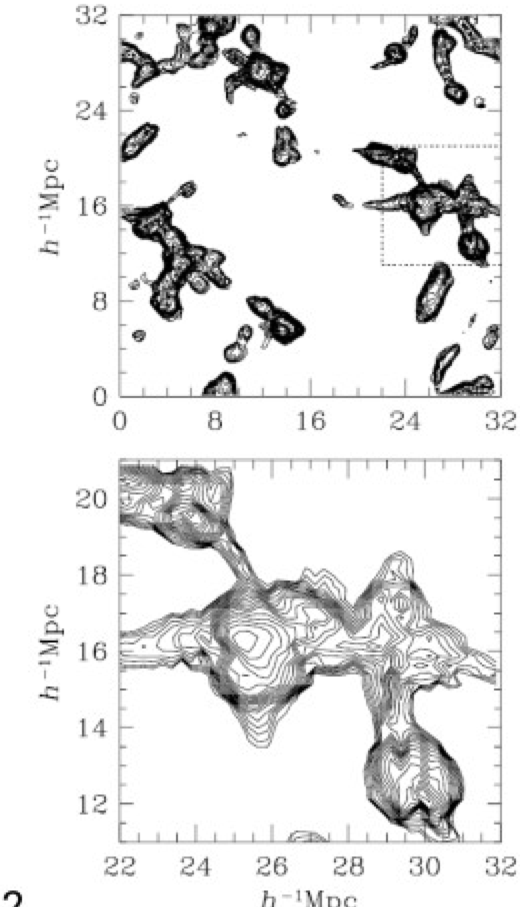


Density
field
0.06 ρ – 6 ρ

Cosmological
shocks during
cosmic web
formation

Kulsrud et al. 1997

snapshots at z ~2



Magnetic field
8×10^{-23} G – 8×10^{-20} G

Propagating ionization fronts at Epoch of Reionization in large structures

$$\partial_t \vec{B} = -\frac{ck_B}{q_e}\frac{\vec{\nabla} n_e \times \vec{\nabla} T_e}{n_e}$$

Subramanian et al. 1994
Gnedin et al. 2000

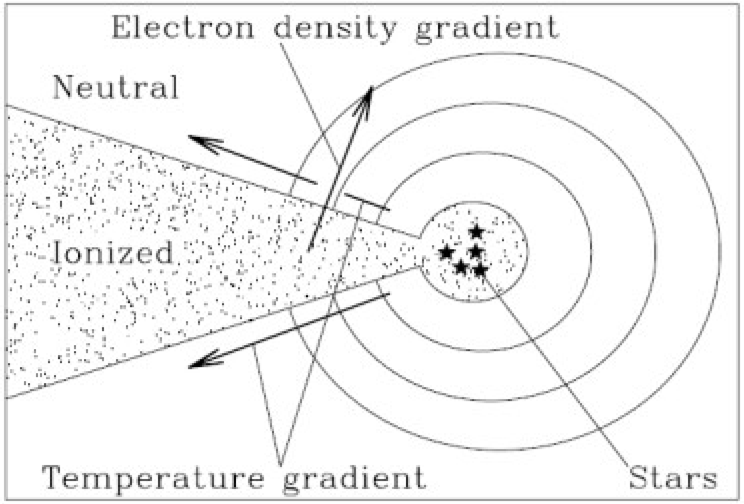


FIG. 6.—Cartoon illustrating the mechanism for generating the primordial magnetic field during the breakthrough of the ionization front from the protogalaxy before the overlap of the H II regions. Enclosed contours show the regions of progressively higher density.

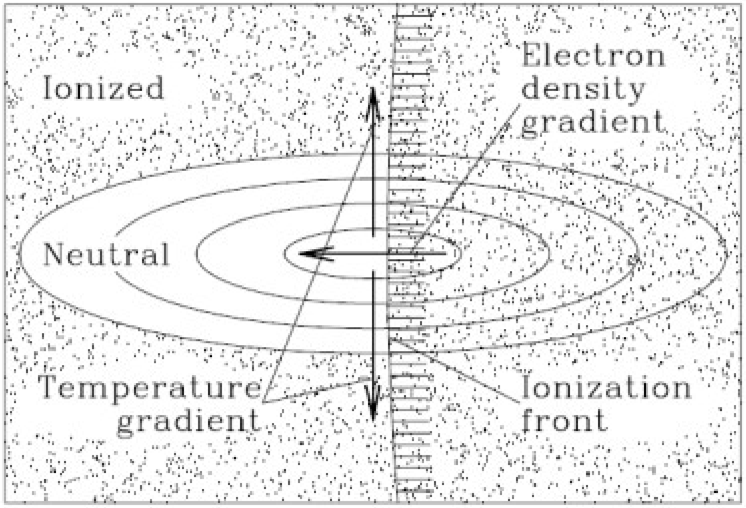


FIG. 8.—Cartoon illustrating the second mechanism for generating the primordial magnetic field during reionization: the ionization front crossing a neutral high-density filament after the epoch of overlap. Enclosed contours show the regions of progressively higher density.

$\boldsymbol{B} \sim 10^{-20} - 10^{-18}$ G @ $L \sim$ a few kpc

Plasma instabilities:

Example: Weibel instability (Weibel 1959)

- Can create high strengths (up to e.g. 10−7 G)
- Only on small kinetic scales
- May occur in large volumes, such as in galaxy cluster shocks (Schlickeiser & Shukla 2003; Medvedev et al. 2006).

Requires some inverse cascade

Fields up to 10−16 G on kpc scales could arise in tens of Myrs, provided fields on smaller scales do not saturate the instability (Ryu et al., 2011)

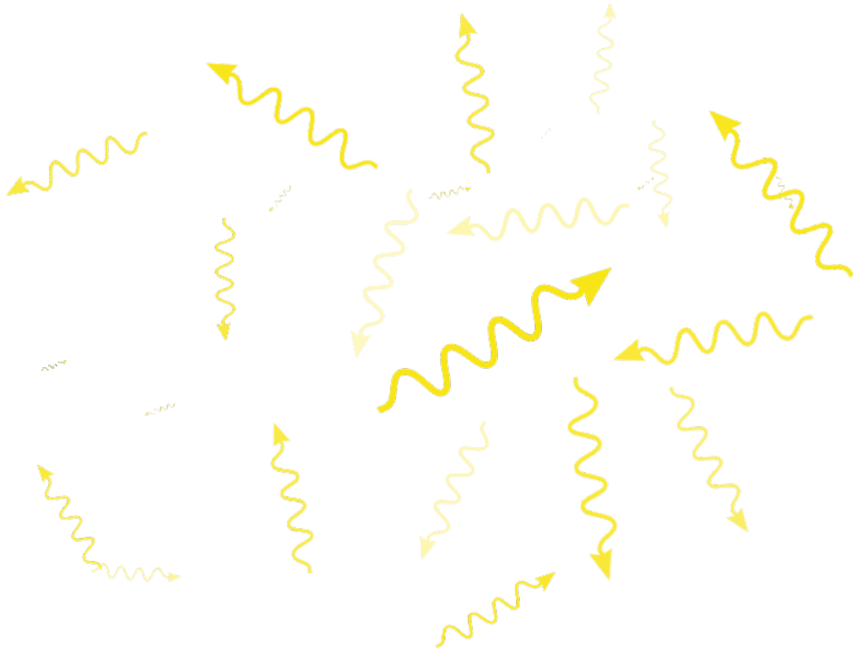
- Radiation:

Thomson scattering:
In protogalaxies (Mishustin & Ruzmaikin 1972, Langer et al 2003, Chuzhoy 2004)

→ typically B ~ 10^{-18} G on protogalactic scales

Photoionization at EoR:
in the IGM (Langer et al 2005, Ando et al 2010, Durrive & Langer 2015, Durrive et al 2017)
around first stars (Silk & Langer 2006, Shiromoto & Susa 2014)

Thermal 'return currents'
Cosmic ray propagation (Miniati & Bell 2011)

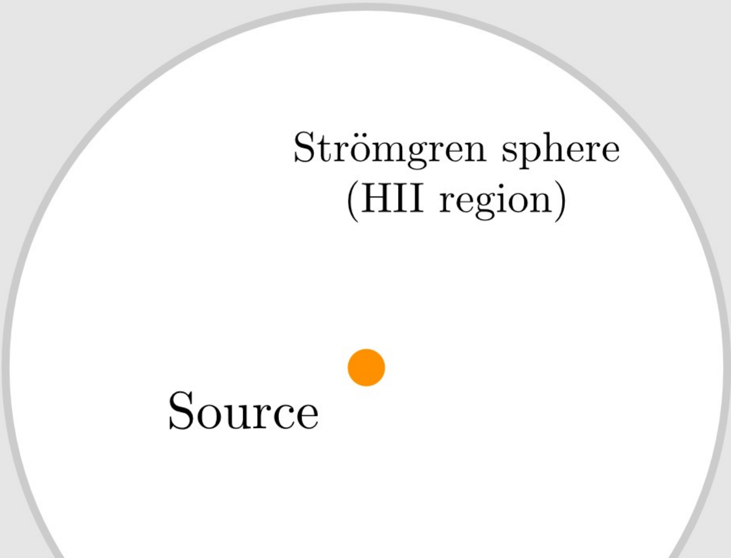



WARNING
Shameful
self-advertizing

Durrive & Langer, MNRAS (2015)

An astrophysical mechanism generating intergalactic magnetic fields at the Epoch of Reionization

Intergalactic medium (Hydrogen)



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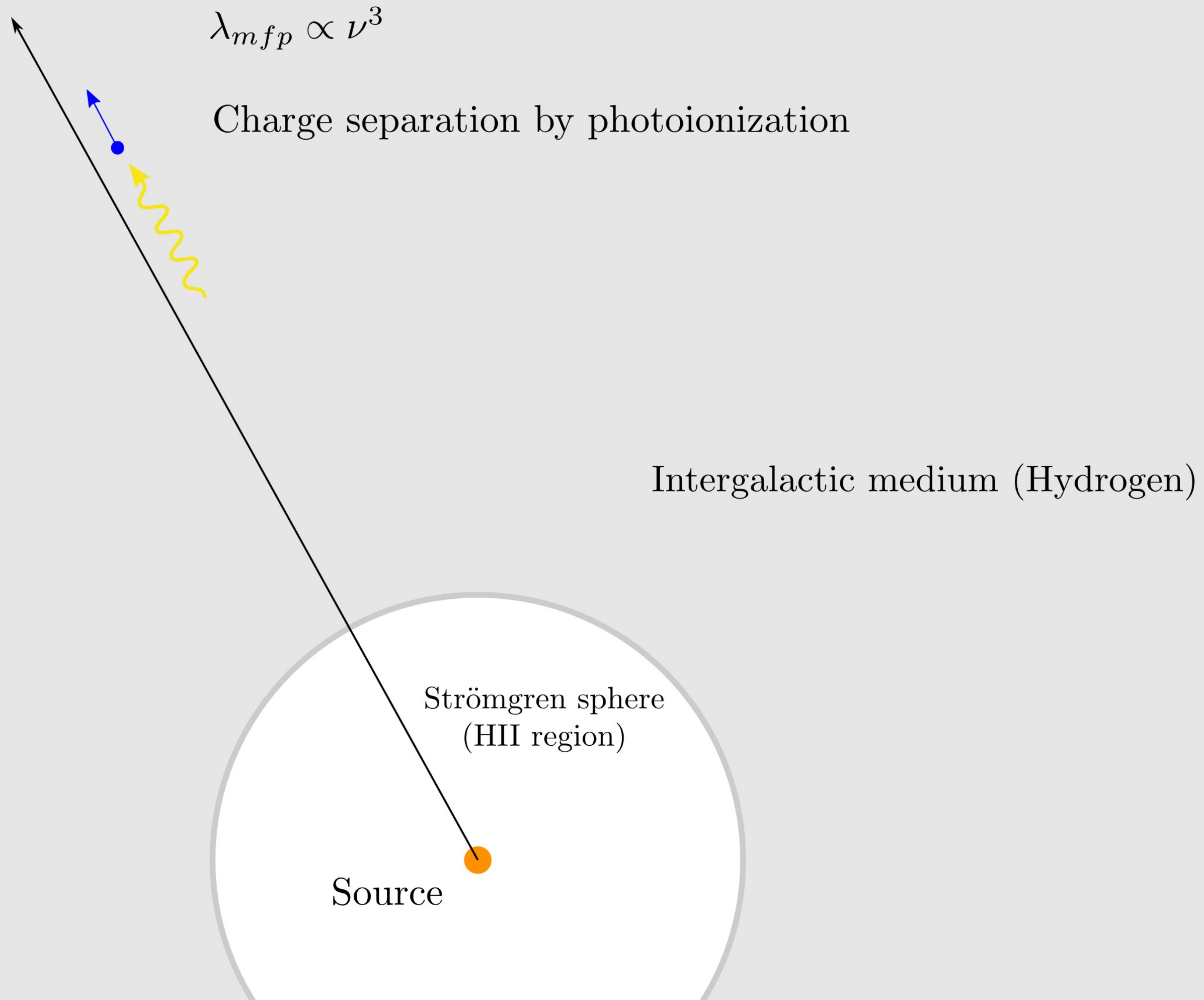

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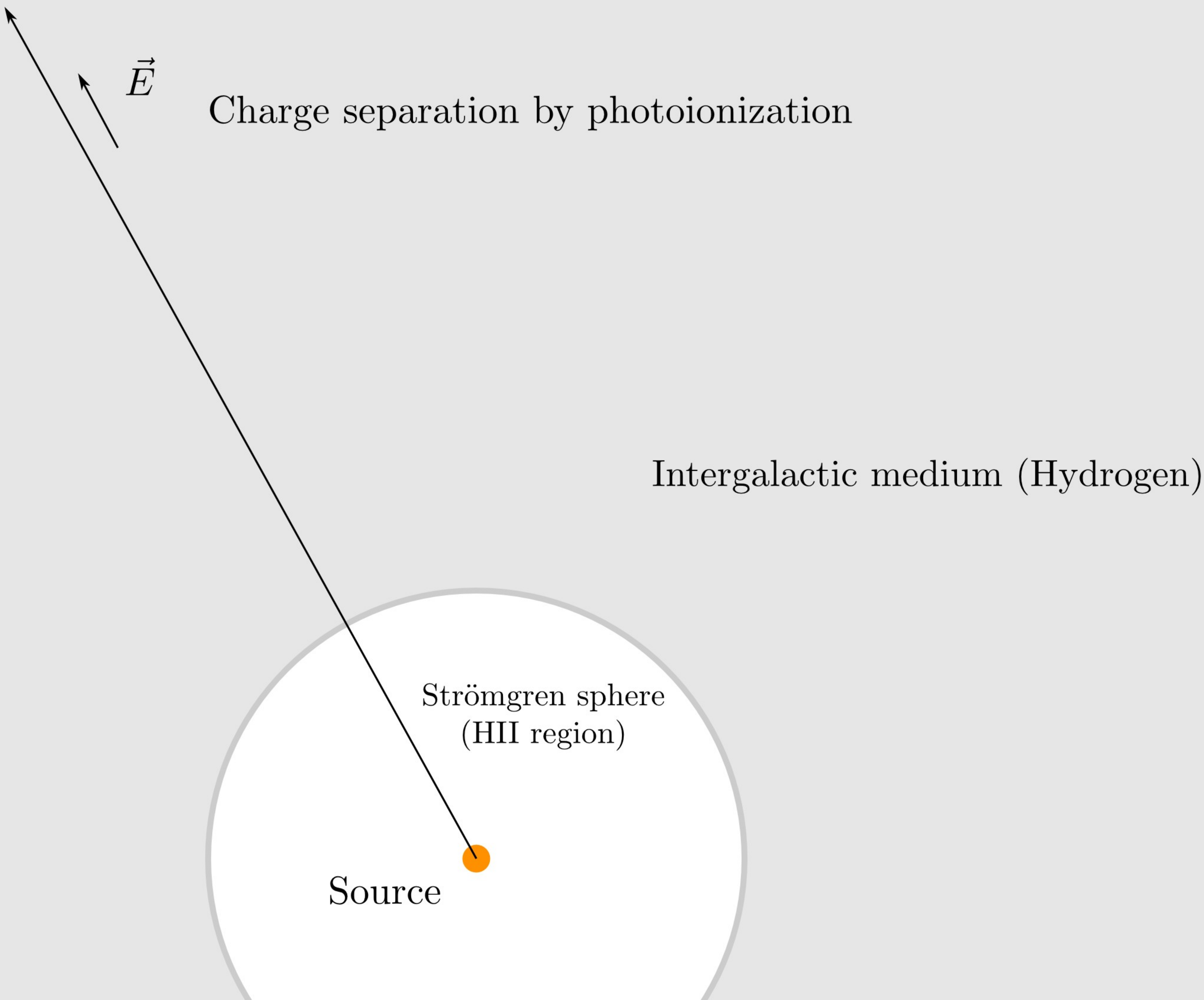
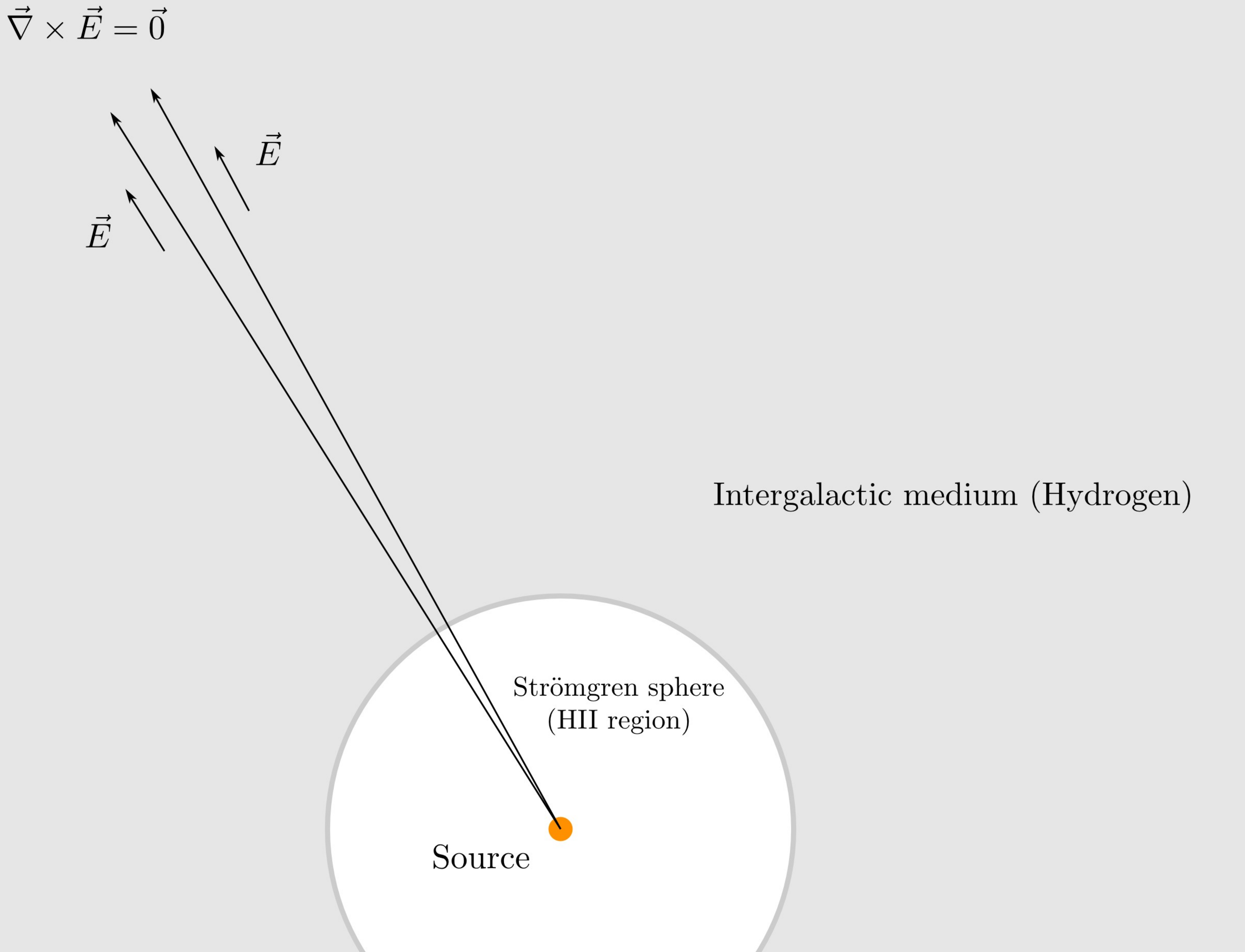
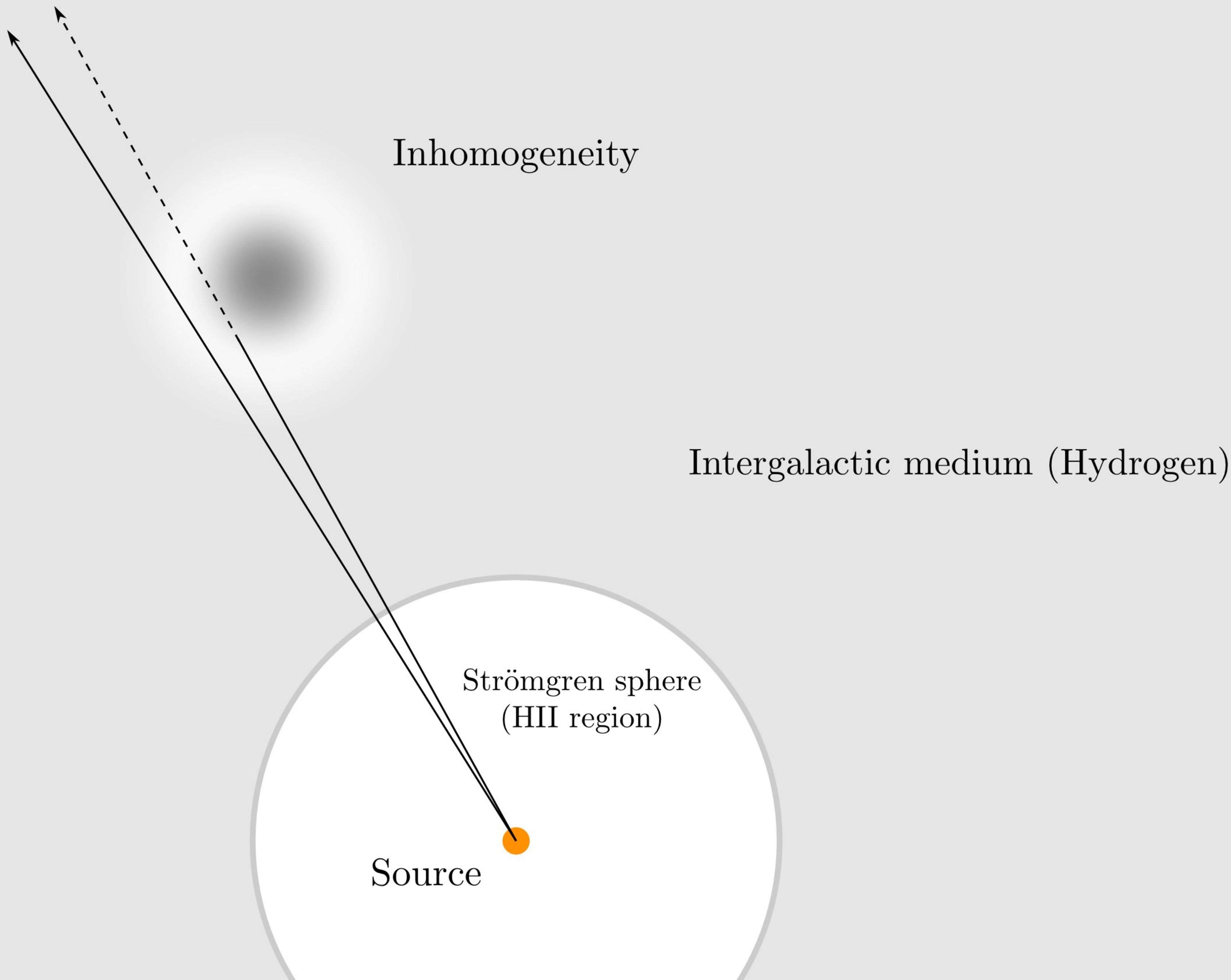
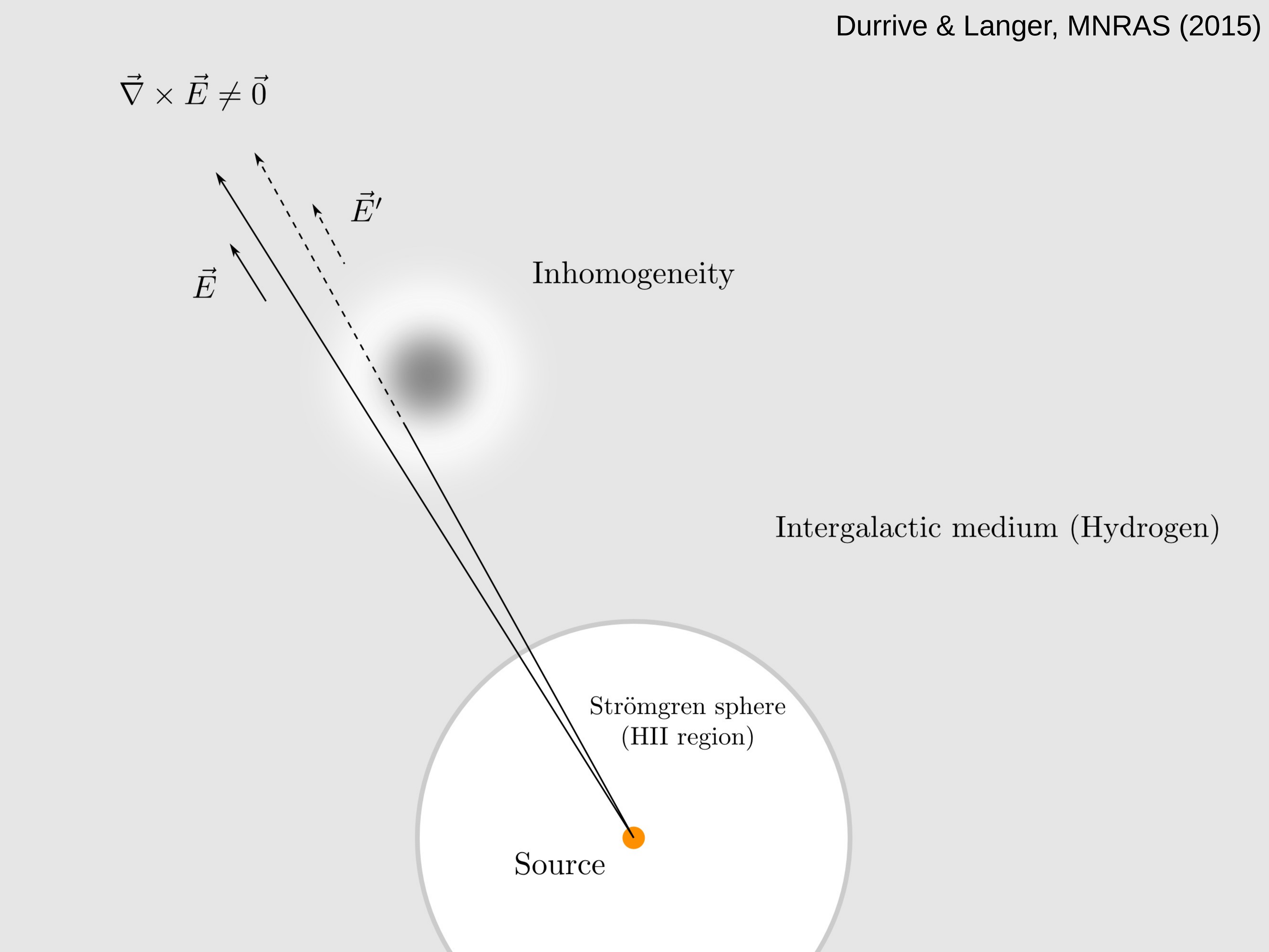


Durrive & Langer, MNRAS (2015)




Inhomogeneity
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


Durrive & Langer, MNRAS (2015)
$\vec{\nabla} \times \vec{E} \neq \vec{0}$
$\vec{E}'$
$\vec{E}$
Inhomogeneity
Intergalactic medium (Hydrogen)
Strömgren sphere
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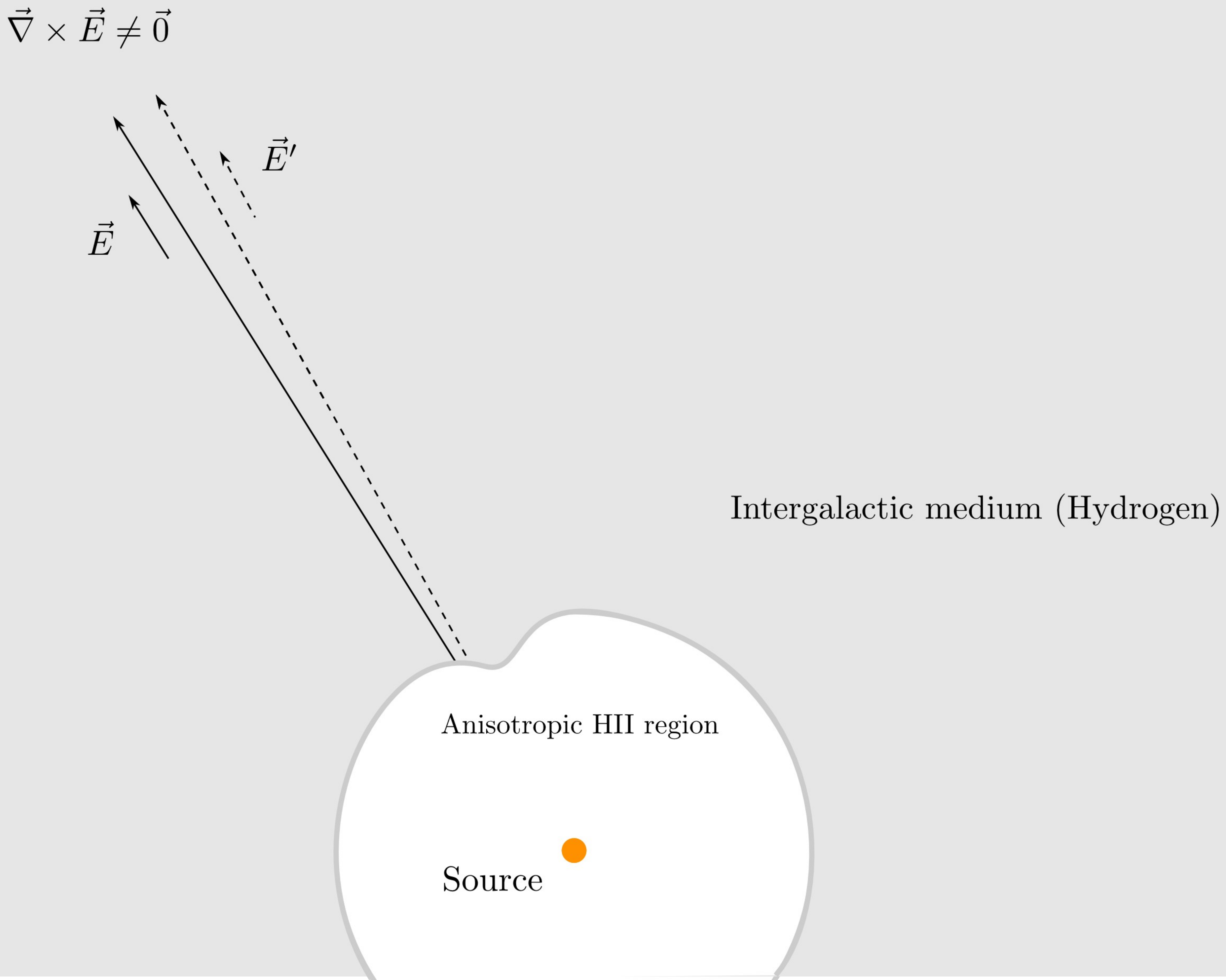
Source

Durrive & Langer, MNRAS (2015)



Durrive & Langer, MNRAS (2015)

Ohm's law reduces to:

Momentum transfer rate
(from photons to electrons)

$$\vec{0} = -en_e\vec{E} - \vec{\nabla}p_e + \dot{\vec{p}}_e$$

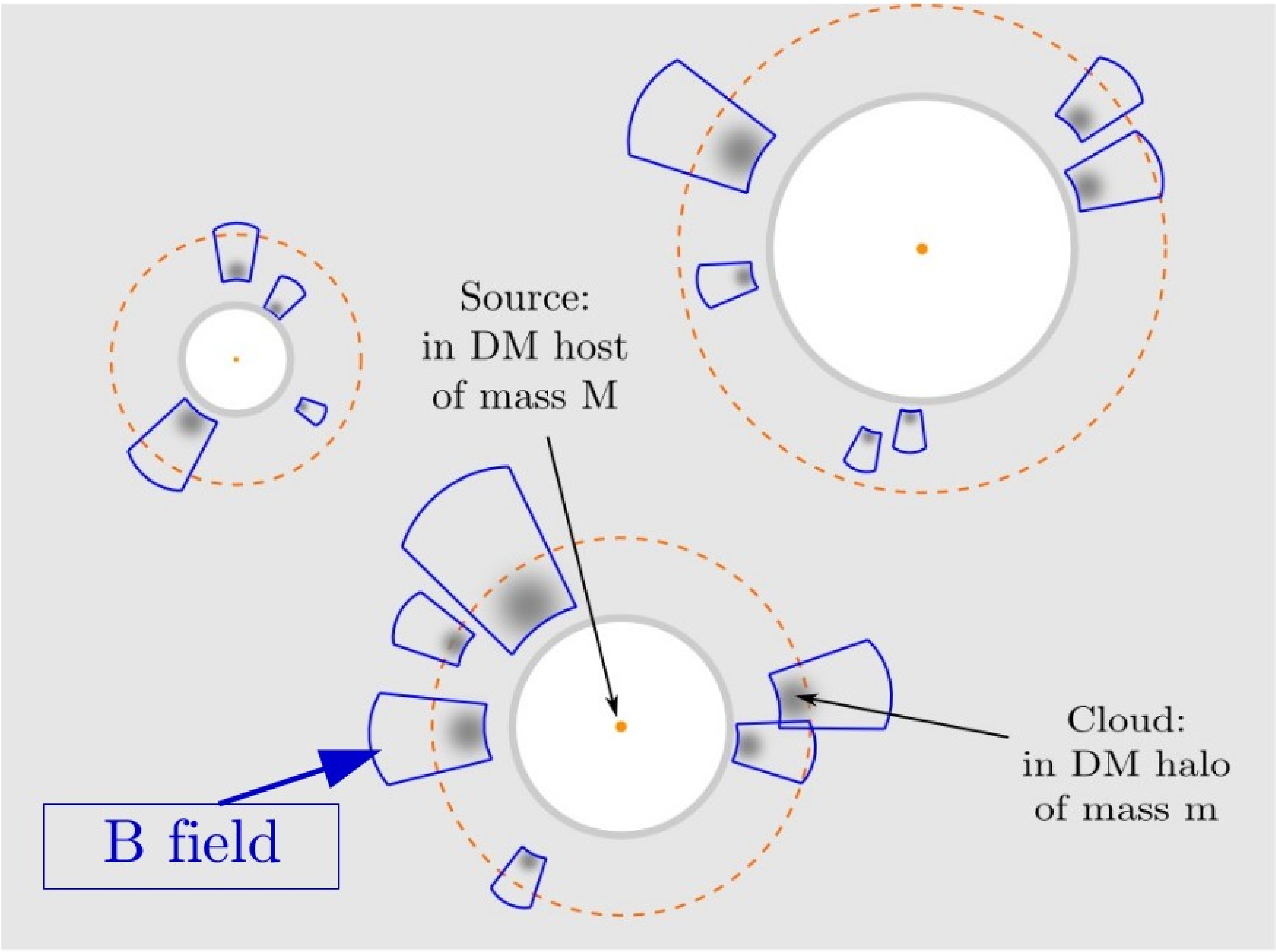
Taking the curl:

$$\partial_t\vec{B} = -\frac{c}{e}\frac{\vec{\nabla}n_e \times \vec{\nabla}p_e}{n_e^2} - \frac{c}{e}\vec{\nabla} \times \frac{\dot{\vec{p}}_e}{n_e}$$

Biermann **Photoionization**

Durrive, Tashiro, Langer, Sugiyama, MNRAS (2017)

In the cosmological context



Our conclusions in 2017

- Astrophysical mechanism, operating for any source, **all along the EoR**

- Strengths possibly comparable to Biermann battery, but on entire intersource scales

  $\Rightarrow$ Contributes to **magnetization of the whole Intergalactic medium**
  interesting for voids
  Needed: Processing by turbulence in cosmic filaments and voids

- Specific spatial configuration: may help discriminate the seeds from other mechanisms

- Directly measurable seeds ?
  → 10^{-19} G fields prior and during EoR (Venumadhav et al 2014)

- Same process in ISM ?

Update in 2020

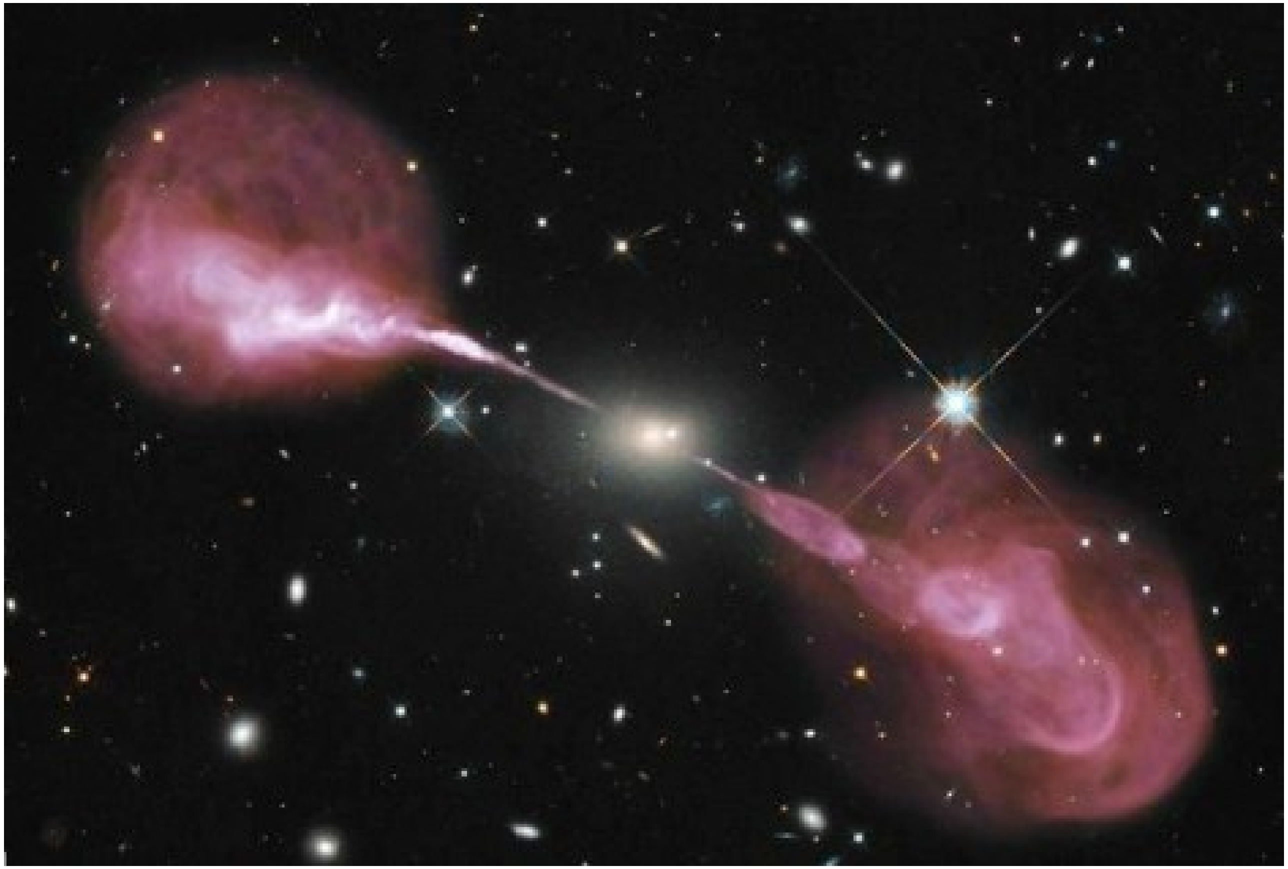
Garaldi et al 2020 (arXiv:2010.09729), they say:

“We have shown for the first time that the seeding scheme recently proposed in Durrive & Langer (2015); Durrive et al. (2017) can magnetise the Universe in realistic scenarios.

However, our results show that the Biermann battery produces geometrically similar but stronger magnetic seed fields, hence being almost always dominant over the Durrive battery.“

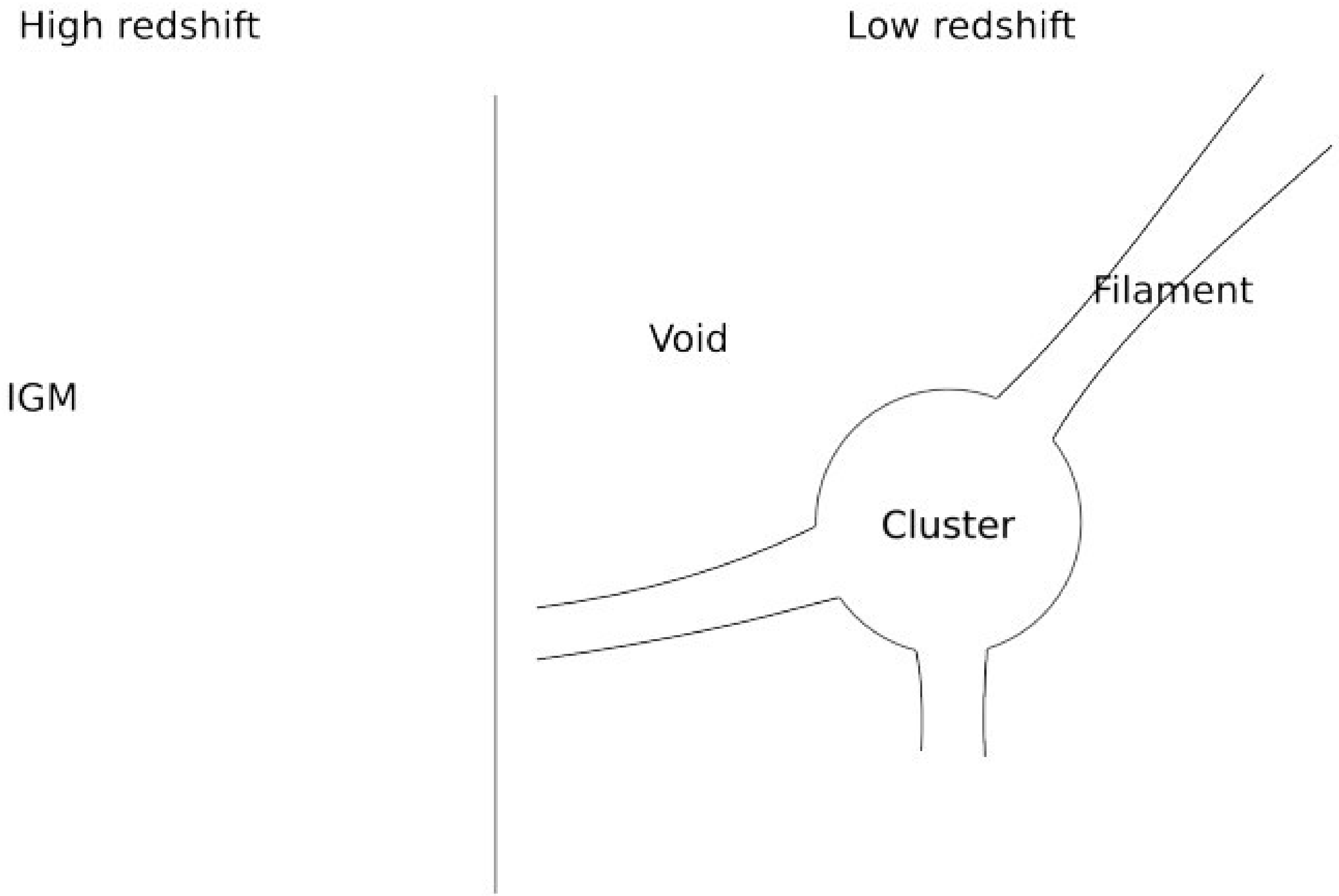
Great to have a numerical implementation! But I have comments & questions about their paper :)

- <u>Outflows:</u>

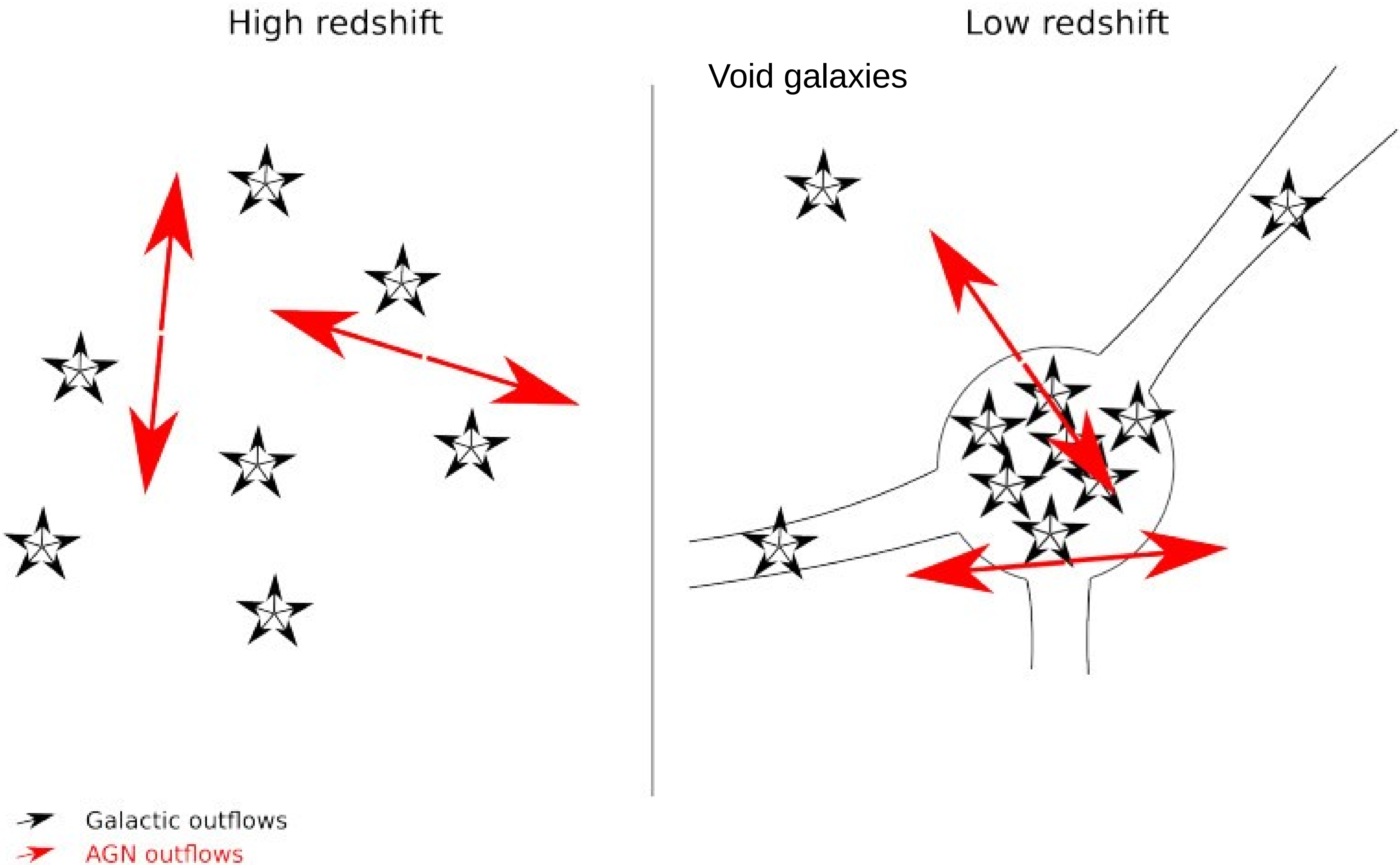


Jets from the supermassive black hole in the core of the Hercules A galaxy

- <u>Outflows:</u>



Outflows:


High redshift
Low redshift
Void galaxies
Galactic outflows
AGN outflows

- <u>Outflows:</u>

Galactic winds from galaxies in clusters

may spread with B ~ 10^{-12} G to 10^{-8} G in most of the IGM
with correlation lengths ~ kpc scales
but strongly dependent on the '**prescriptions**' of galactic winds
(Kronberg et al 1999, Bertone et al 2006, Donnert et al 2009)

Galactic winds from void galaxies (Beck et al 2012)

AGN outflows (Rees 1987, Daly & Loeb 1990, Ensslin et al 1997)

Furlanetto & Loeb 2001: by z ~ 3 some 5-20% of IGM may be 'polluted' by B ~ 10^{-9} G
with correlation lengths ~ Mpc scales (radio lobe size)

In short:

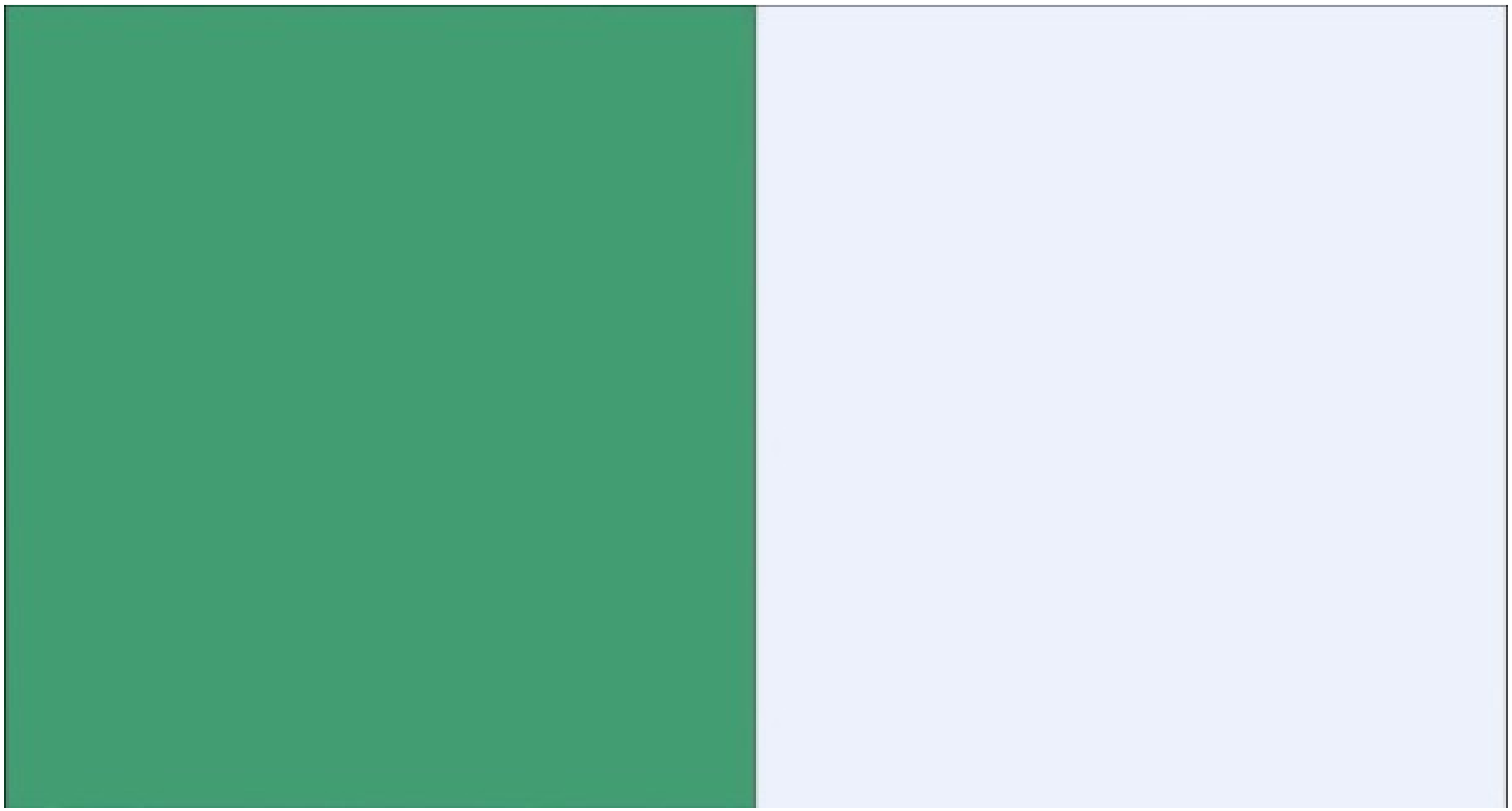
- No definite consensus, not enough constraints yet on efficiency of ejected magnetized matter (clumping of matter, beam focalisation, gravitational potential of host, etc.) and mixing efficiency

- But outflows sure contribute (significantly) to the magnetization of structures and IGM

- Focus on low-density environments such as filaments and voids to infer possible origin

Primordial VS Astrophysical origin

Simulation by F.Vazza



Uniform seed field
(primordial Universe)

Astrophysical outflows

Primordial VS Astrophysical origin

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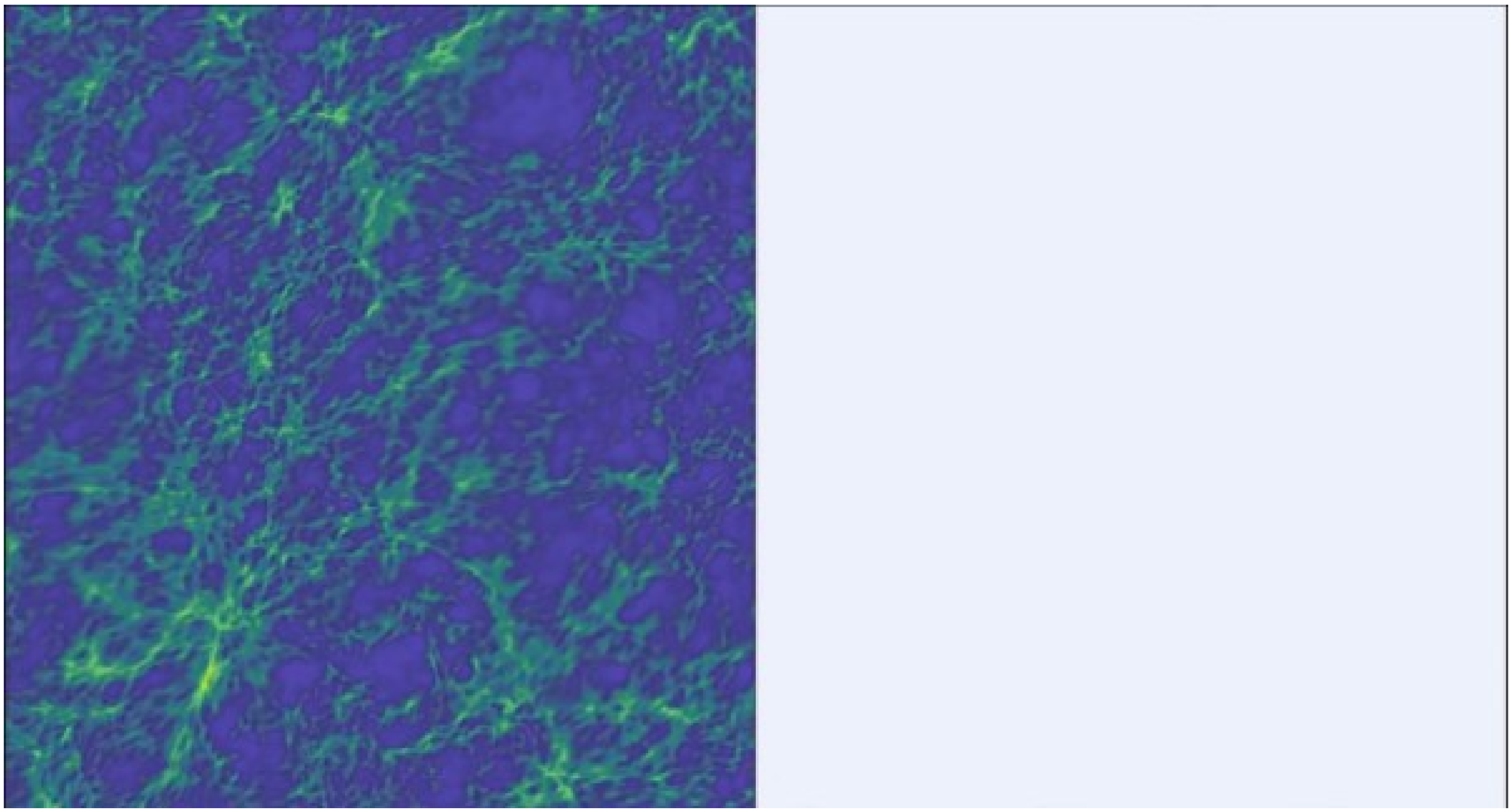

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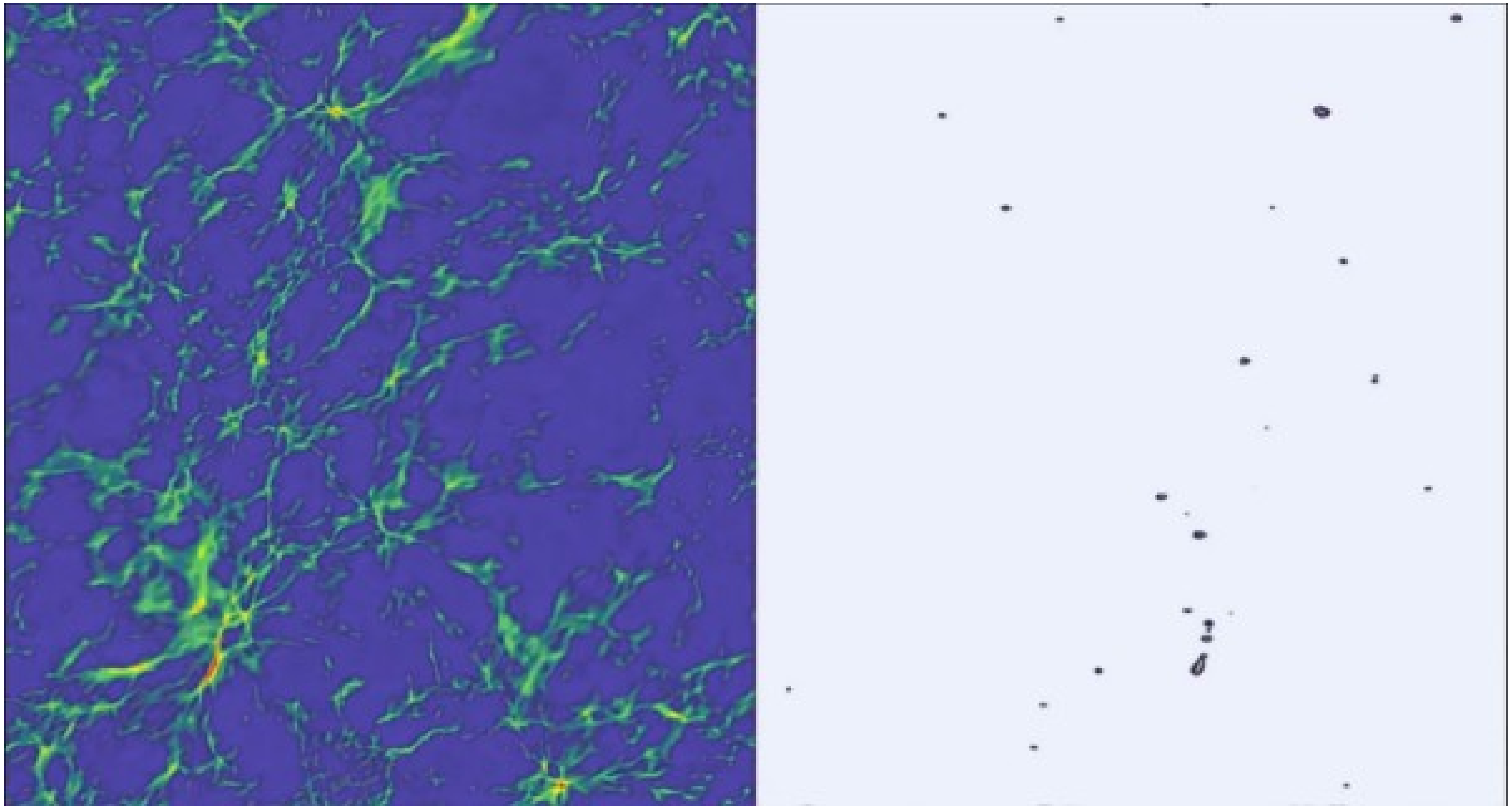

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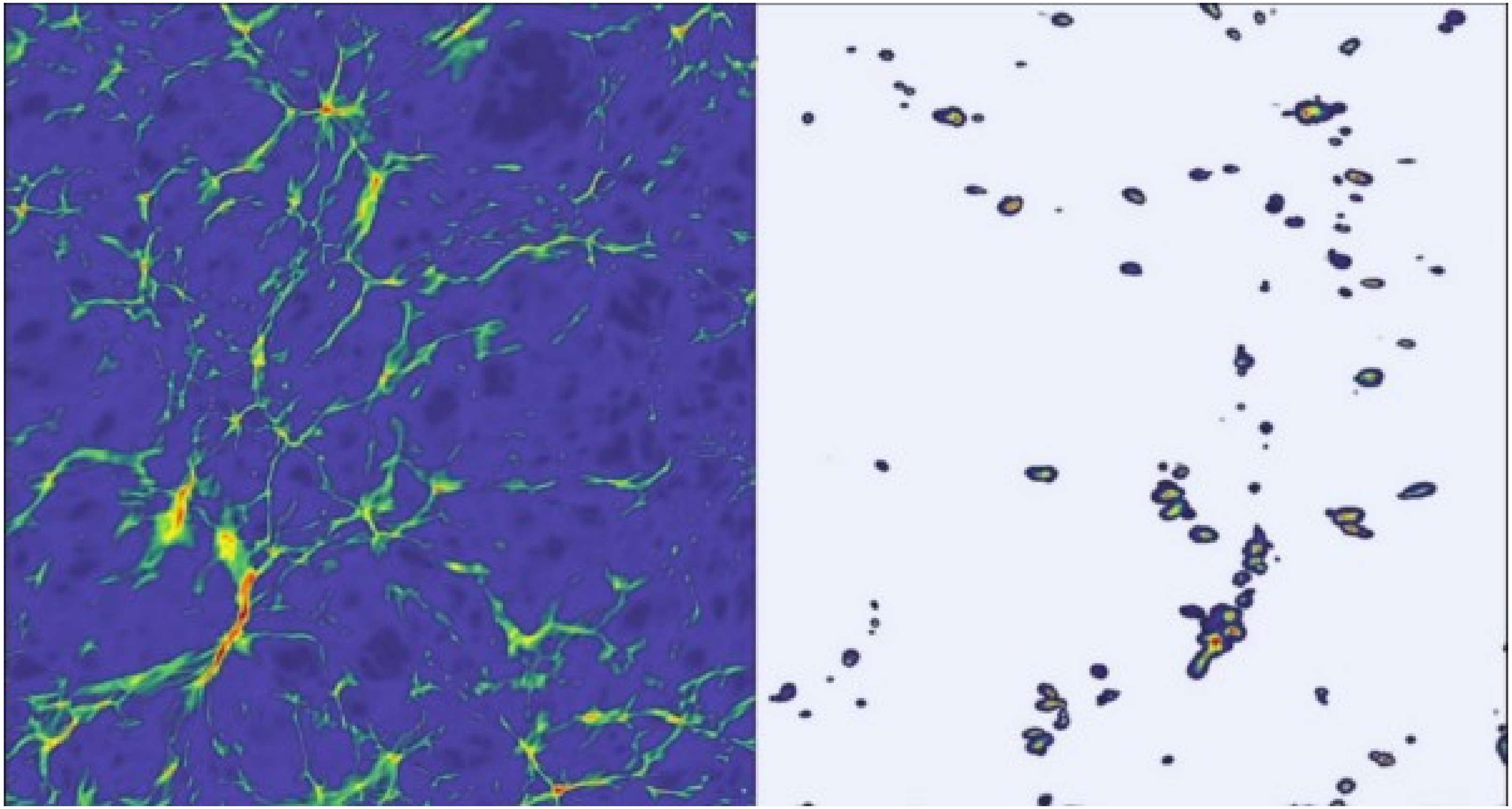

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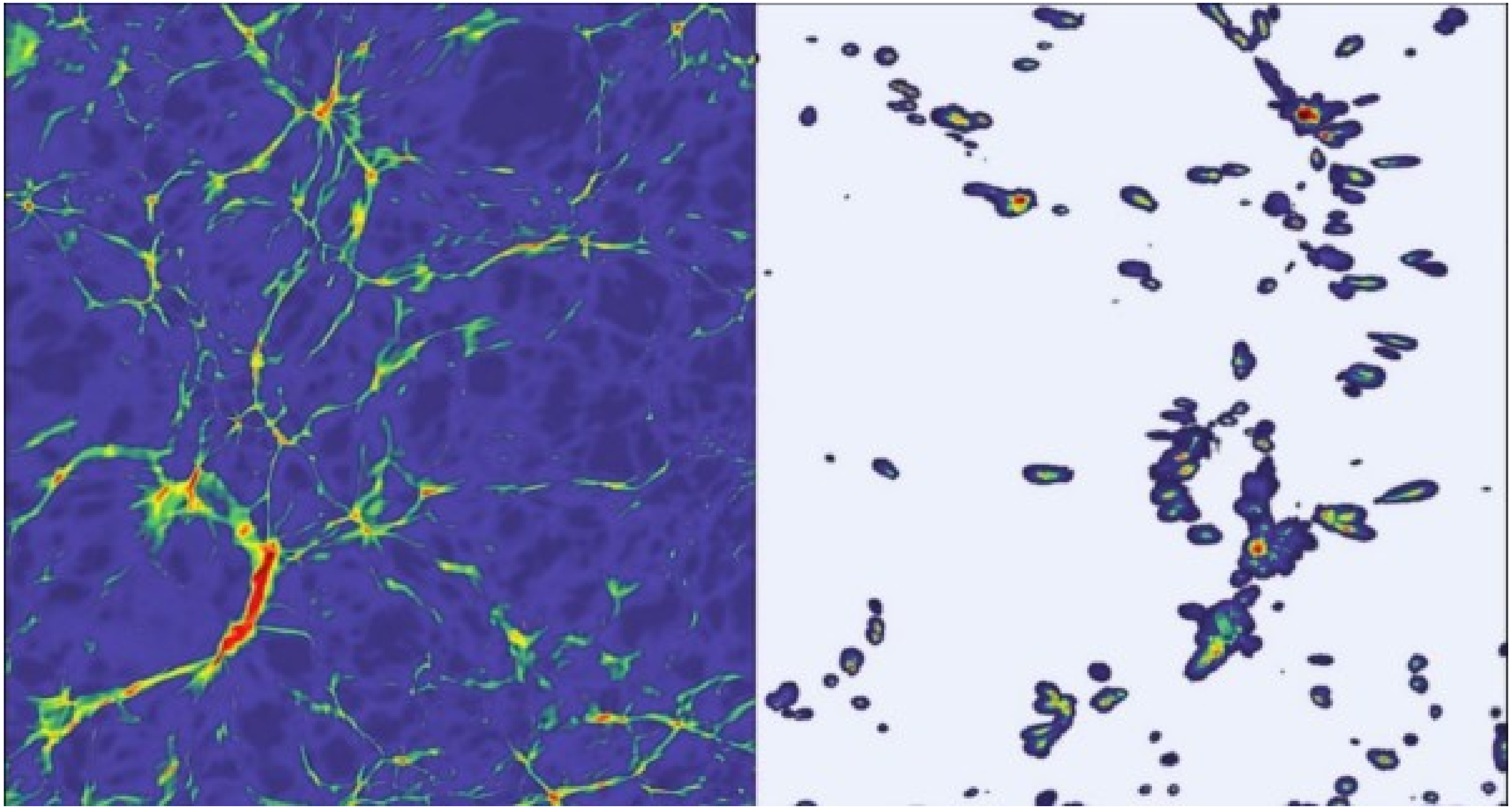

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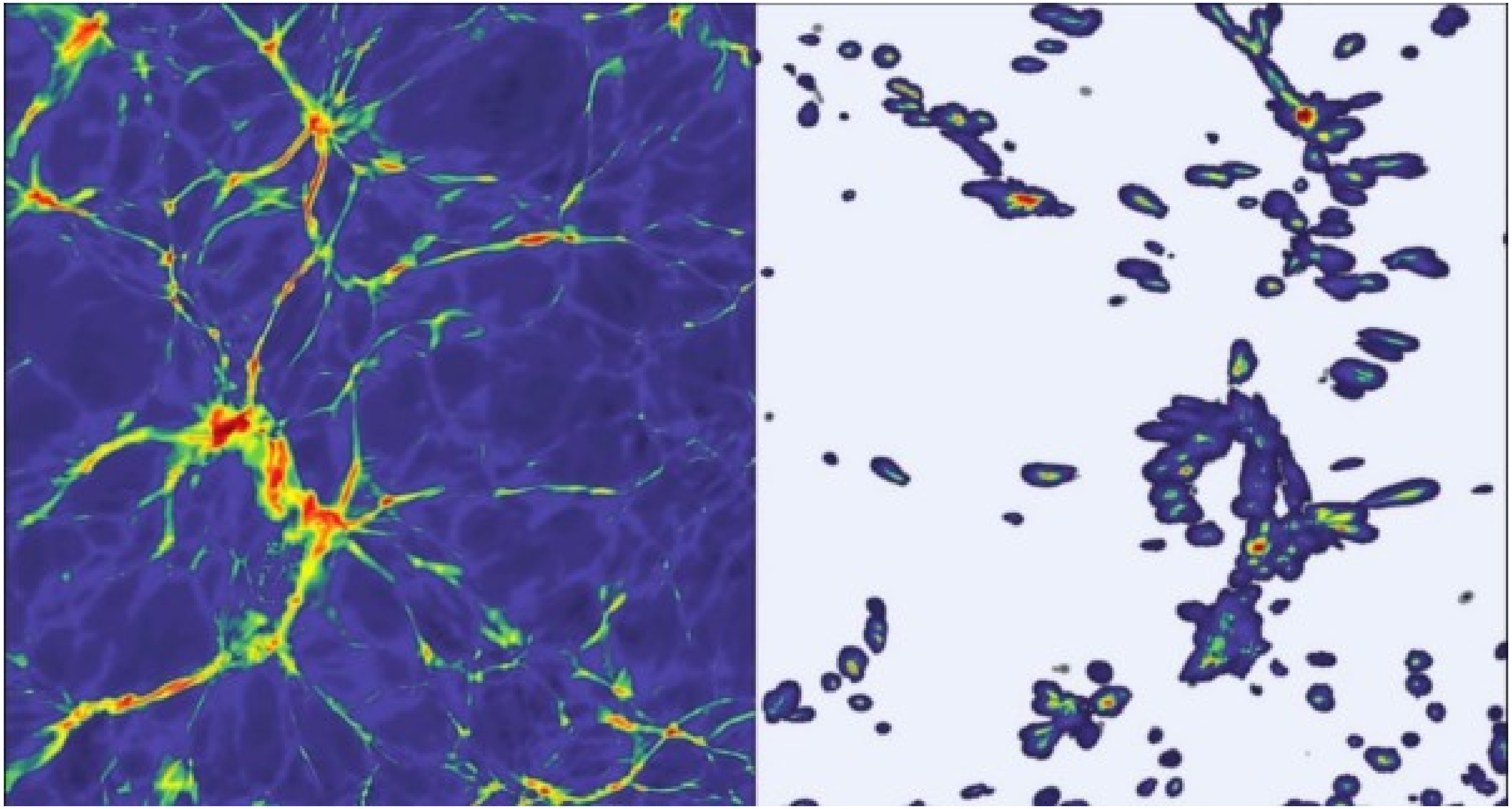

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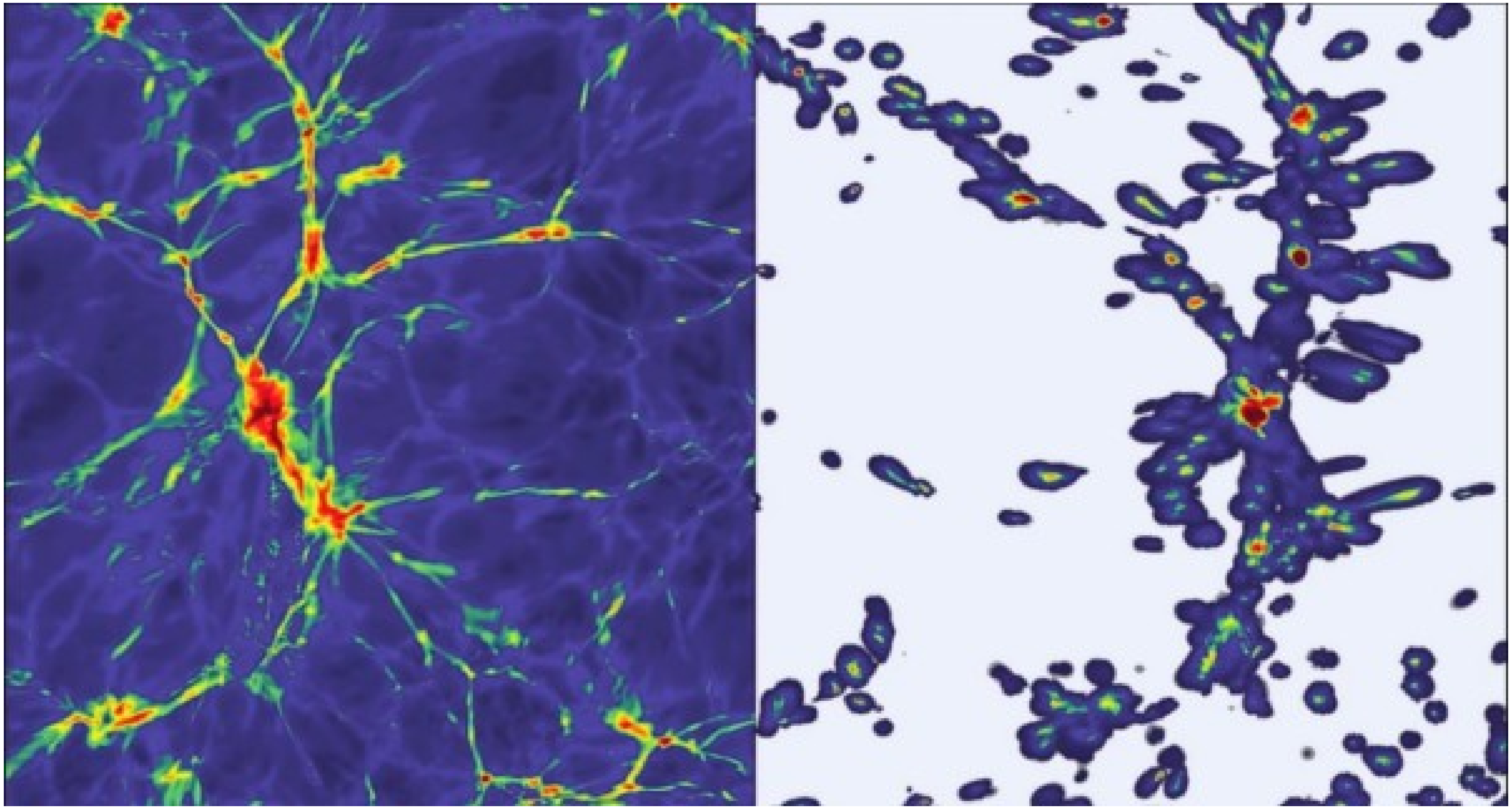

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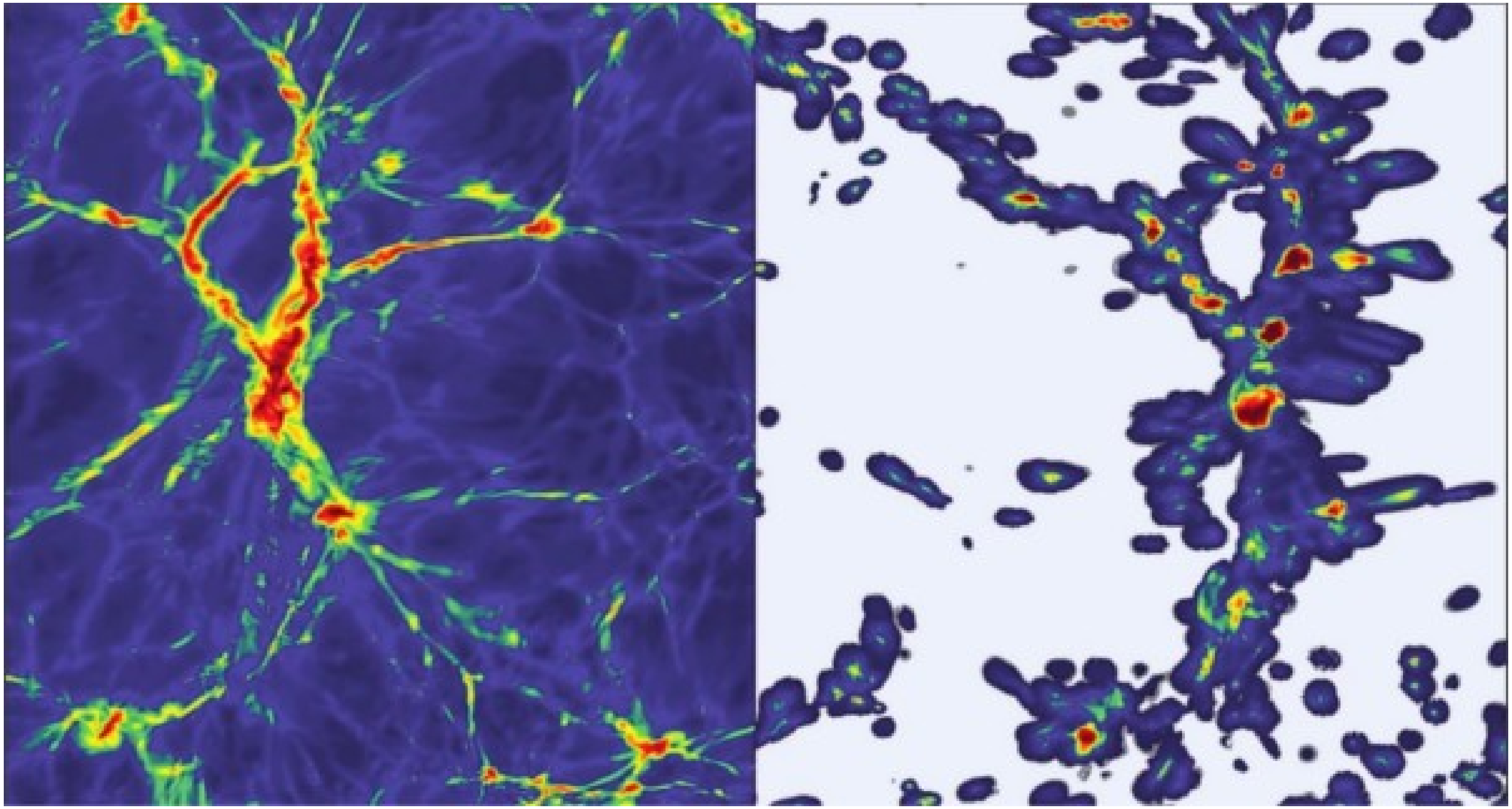
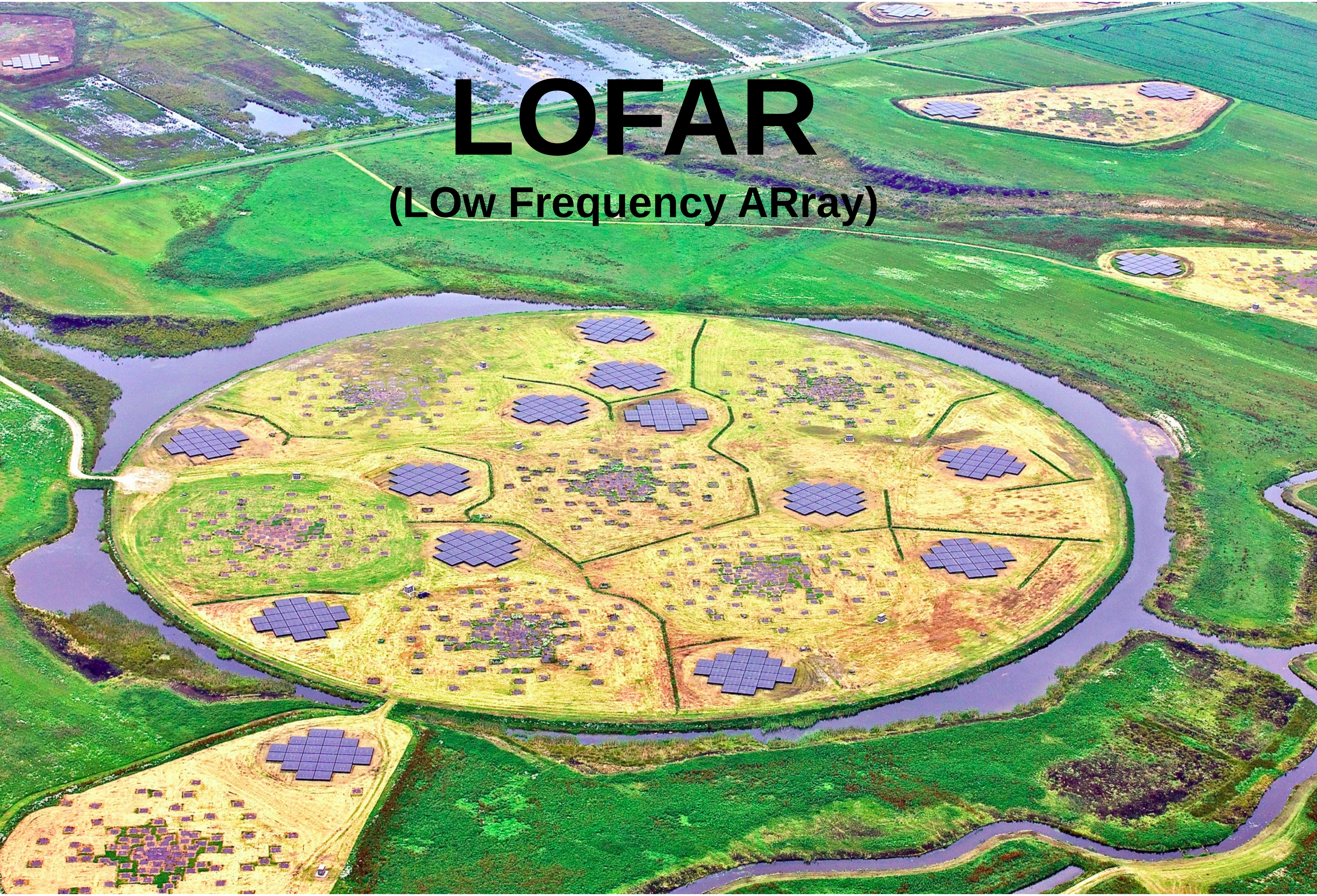


Uniform seed field
(primordial Universe)

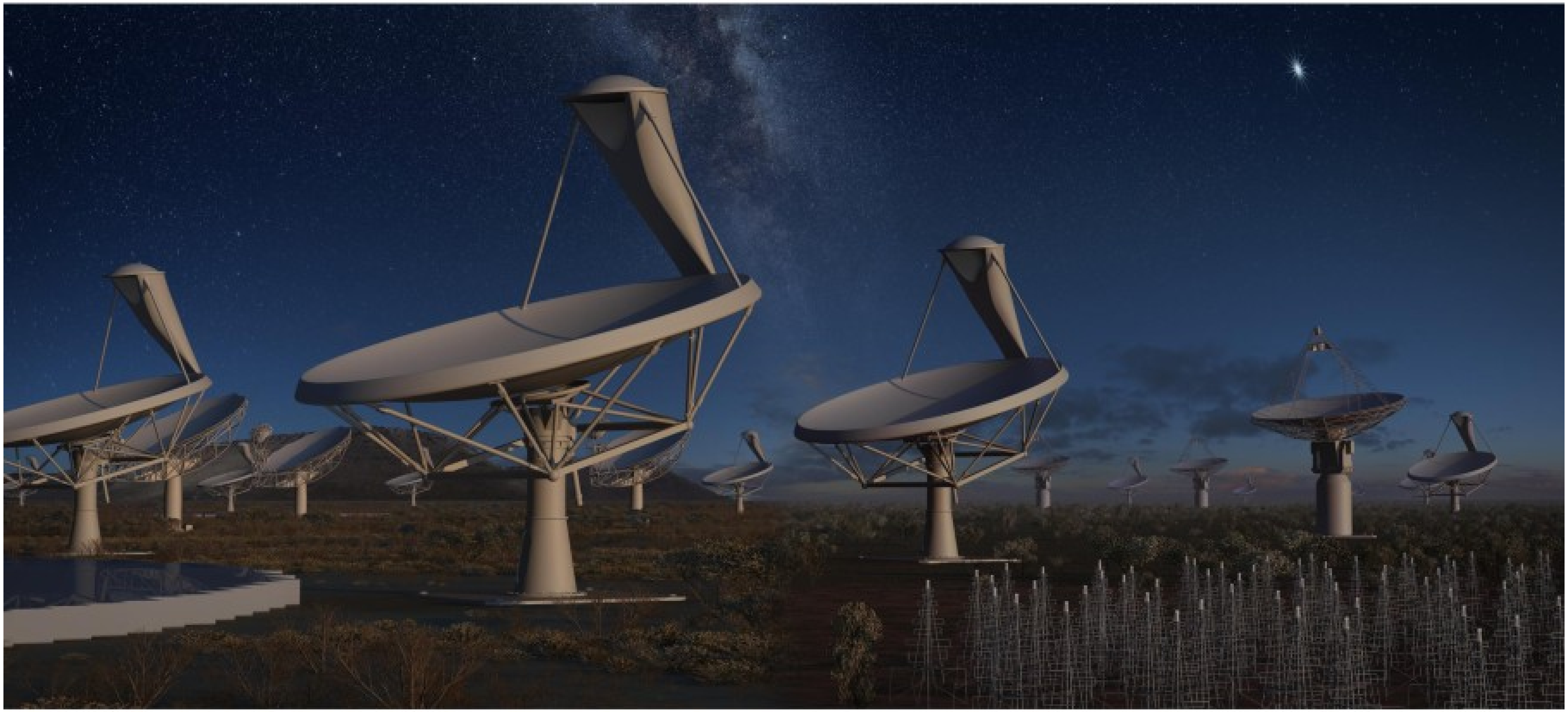
Astrophysical outflows

Radio-telescopes for which cosmic magnetism is one of the ‘Key Science Projects’



Radio-telescopes for which cosmic magnetism is one of the ‘Key Science Projects’

Square Kilometre Array



- Galaxy evolution, cosmology and dark energy
- Strong-field test of gravity using pulsars and back holes
- **The origin and evolution of cosmic magnetism**
- Probing the Cosmic Dawn
- The cradle of life
- Exploration of the unknown

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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.

Conclusion:

Stay tuned, or participate!

Thank you for your attention