Cosmic Magnetism

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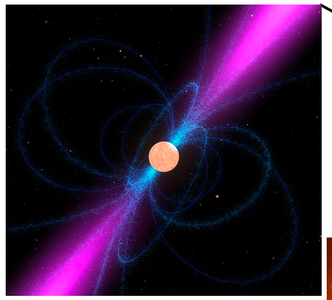
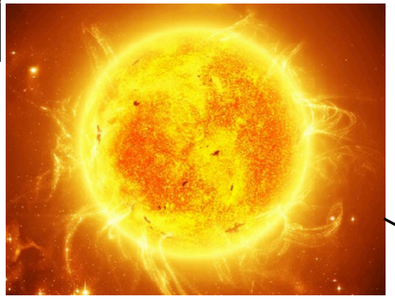
Prevailing Magnetic field in the Universe



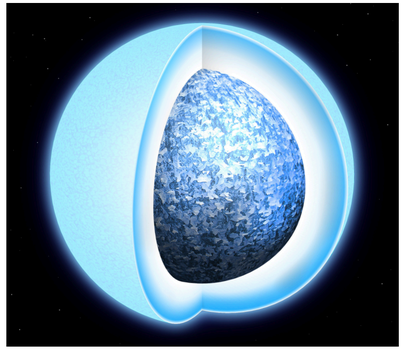
Neutron Stars
~ 10^12 G



Protostars
~ 1 kG

Sun ~ 10 G (poles)

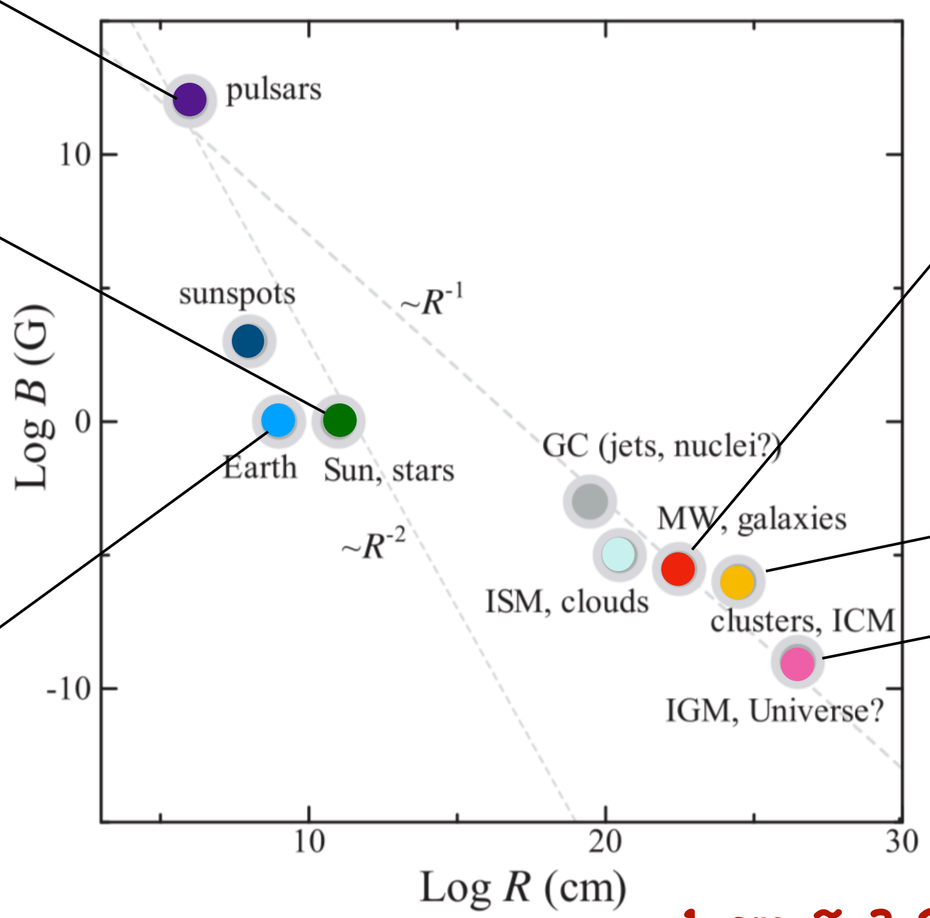
Sunspots ~ 1000 G



White dwarfs
~ 10^6 G

Earth ~ 0.5 G

Akahori et al (2017)



Milky Way ~ 5 uG ; 1 mG (nucleus)

Spiral galaxies ~ 10 uG

Starburst galaxies ~ 50 uG

Interplanetary Space ~ 50 uG

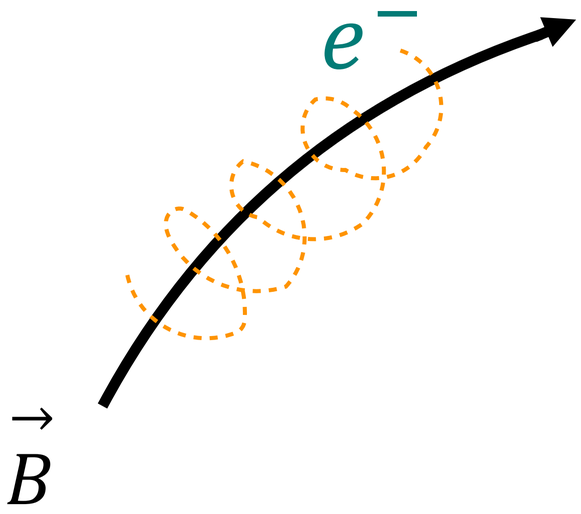
Clusters of galaxies ~ 0.1-1 uG

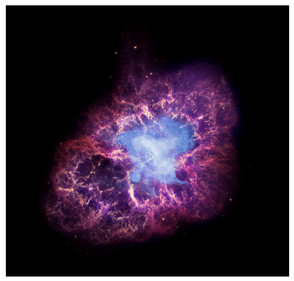
IGM ~ 1E-2 - 1E-3 uG

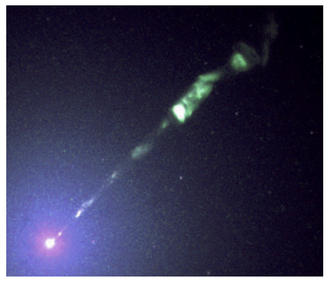
1 cm ~ 3.24E-22 kpc

Measure the Magnetic Field by :

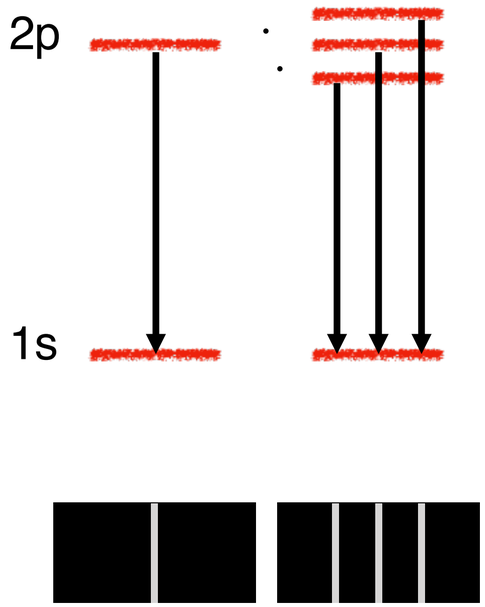
Synchrotron Emission





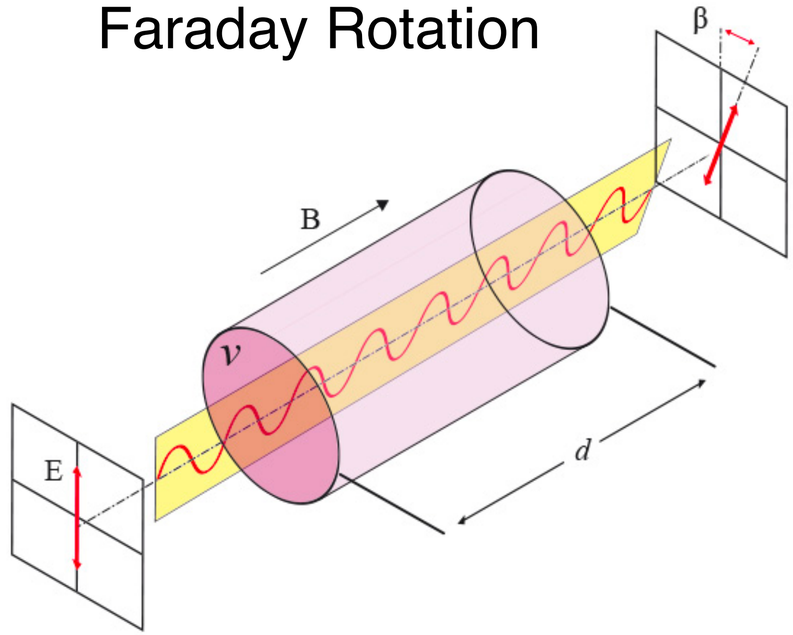


Zeeman Effect



In presence of the magnetic field, the original energy level splits into three due to the different orientation of the electron spin.

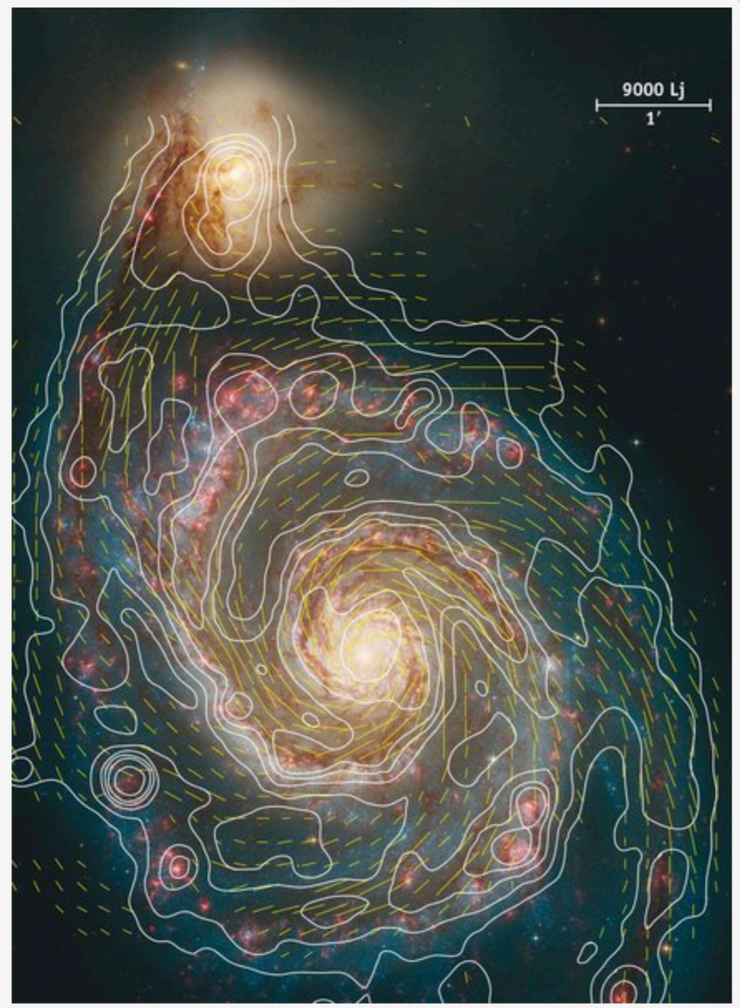
Faraday Rotation



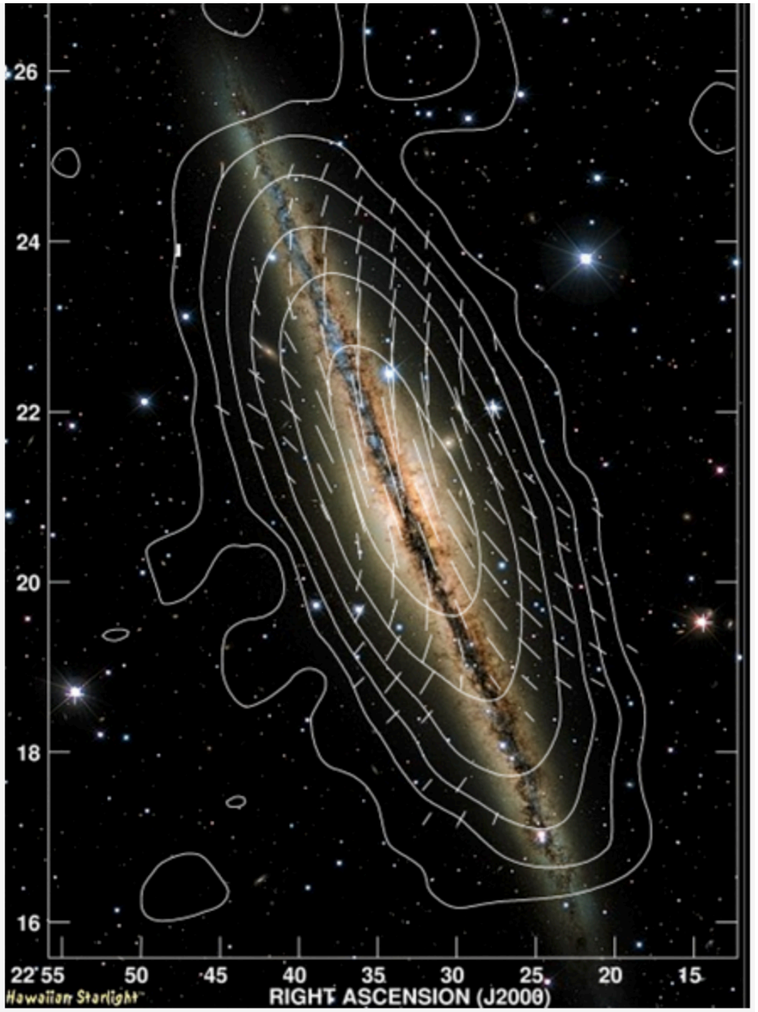
The polarization angle will rotate after passing through the medium with B-field.

In space, use pulsars as the polarized light source

Magnetic Field : Patterns and Orientations

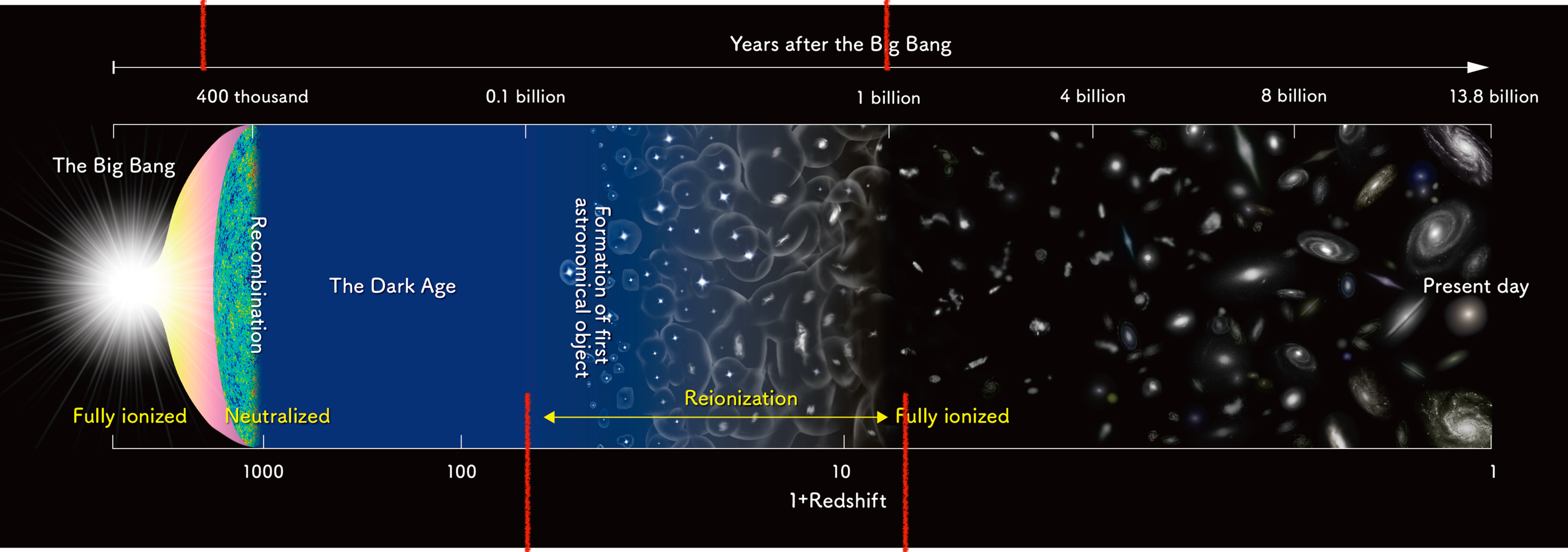


M51 VLA+Effelsberg @ 6 cm
(Fletcher & Beck 2004)



NGC 891 Radio Emission @ 3.6 cm
(Krause, priv.comm)

How is the large scale magnetic field formed ?


Primordial ?
Formed since the era of galaxies and AGNs ?
Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Reionization
Present day
Fully ionized
Neutralized
Fully ionized
1000
100
10
1
1+Redshift
Generated and evolving With early stars and protogalaxies ?

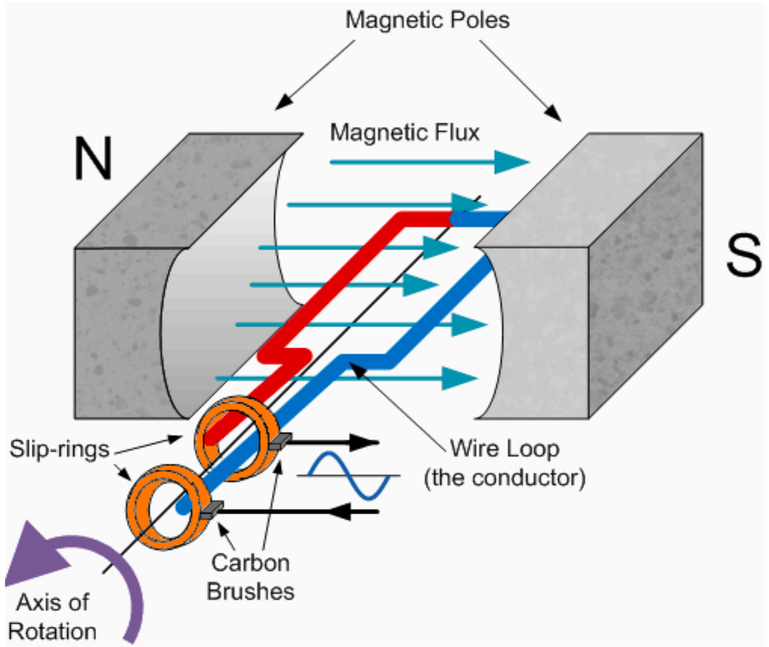
Evidence Against the Primordial Origin (Kulsrud 2008 & Widrow 2012)

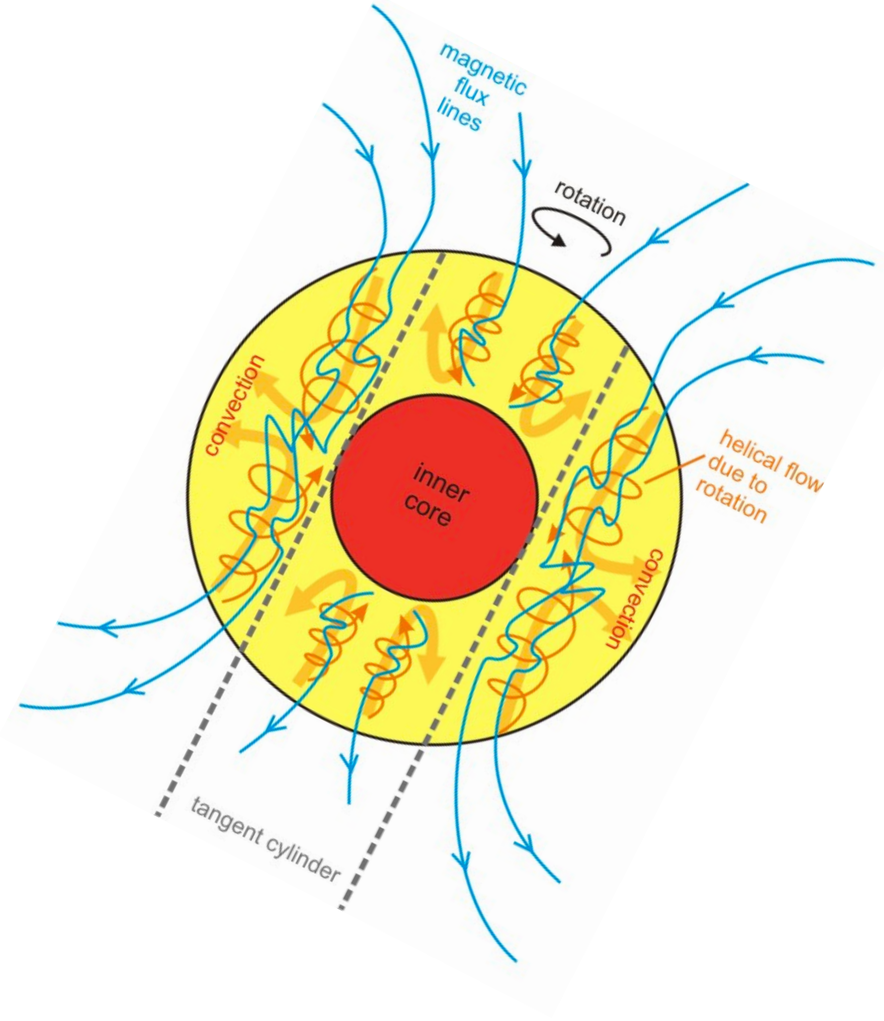
- Quantum fluctuation in electromagnetic field + inflation produced density perturbation
  - Inflation-produced field will be diluted by the expansion to utterly negligible levels

- Plasma physics of the very early universe is only partially known.
  - Any magnetic field generated at a redshift $z > 1E13$ whose present scale is smaller than 1 kpc in the galaxy is undetectable.

- Some observational evidences of the chemical composition of the oldest stars in the galactic halo (Zweibel 2003) may suggest the existence of the pre-galactic magnetic field.
  - However, we still need some mechanism to **keep the magnetic field from resistive decay !**

Dynamo Theory : Magnetic field Generation and Amplification





$$\boldsymbol{E}' = \boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c} = \eta \boldsymbol{j}$$

$$\partial \boldsymbol{B}/\partial t = -c\nabla \times \boldsymbol{E}$$

$$\nabla \times \boldsymbol{B} = 4\pi \boldsymbol{j}/c$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \frac{\eta c^2}{4\pi} \nabla^2 \boldsymbol{B}$$

(Kulsrud 2008)

Dynamo Theory : Magnetic field Generation and Amplification

(Kulsrud 2008, Mean field dynamo theory)

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

$$\boldsymbol{v} = \boldsymbol{U} + \delta \boldsymbol{v} \qquad \boldsymbol{B} = \bar{\boldsymbol{B}} + \delta \boldsymbol{B}$$

Mean motion Random walk

$$\frac{\partial \bar{\boldsymbol{B}}}{\partial t} = \nabla \times (\boldsymbol{U} \times \bar{\boldsymbol{B}}) + \nabla \times (\langle (\delta \boldsymbol{v} \times \delta \boldsymbol{B} \rangle)$$

decorrelation time of the turbulence motion

kinetic helicity / angular twist of the convective cell

$$\alpha = -\frac{\tau}{3} \langle \boldsymbol{v} \cdot \nabla \times \boldsymbol{v} \rangle$$

$$\beta = \frac{\tau}{2} \langle \boldsymbol{v}^2 \rangle$$

turbulent resistivity : not real dissipation, but mixing term of random motion that smooths out the field

- Assuming typical turbulent velocity as the same of the interstellar medium couldn't generate the alpha effective enough to amplify the field

- Much stronger turbulence due to supernova explosion and stellar winds (Ferriere's dynamo theory)

The Problems of the Mean Field Theory

- Vacuum boundary conditions
  - Assuming the diffusion outside of the disc is much larger than that in the disc.
  - Hard to justify the flux removal
- Horizontally homogeneous interstellar medium assumed.
- Require some **seed fields** to function !

Biermann Battery Effect as the Seed Field

The motion of the electron fluids :

Electron-ion frictional force

$$n_e m \frac{d\boldsymbol{v}_e}{dt} = -n_e e(\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \nabla p_e + n_e m \boldsymbol{g} + \boldsymbol{F}_{ei}$$

$$\boldsymbol{E} + \frac{\boldsymbol{v}_e \times \boldsymbol{B}}{c} = -\frac{\nabla p_e}{n_e e}$$

Start with B=0

If n_e is constant

$$\boldsymbol{E} = \frac{\nabla p_e}{-n_e e}$$

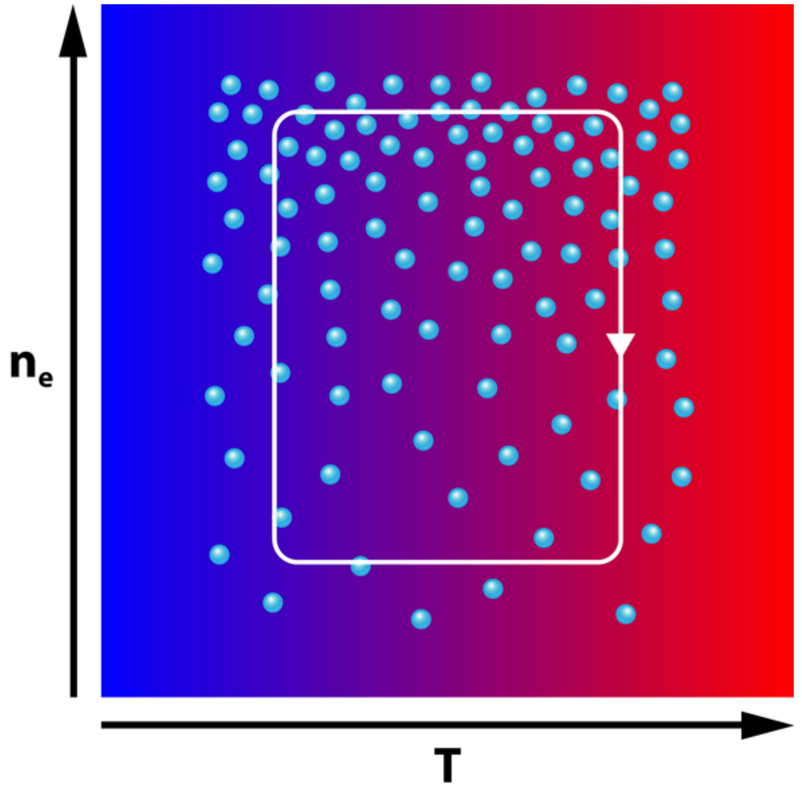
(like a battery without current flowing through)

$$\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{c} = -\frac{M}{e(1+\chi)} \frac{\nabla p}{\rho}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \frac{\nabla p \times \nabla \rho}{\rho^2} \frac{Mc}{e(1+\chi)}$$

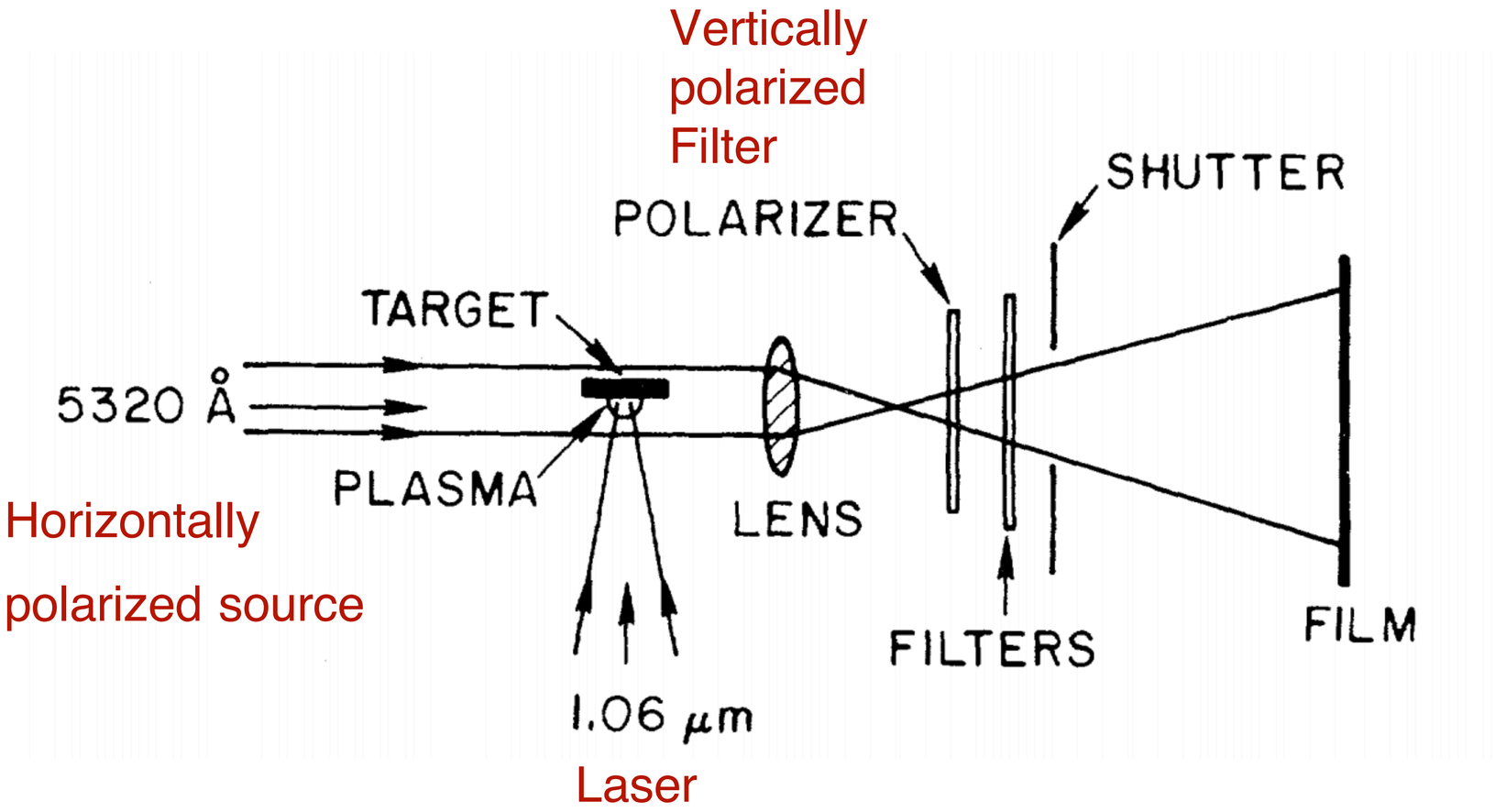
Dynamo term (with helical motion in turbulence)

Battery term



(Zweibel 2013)

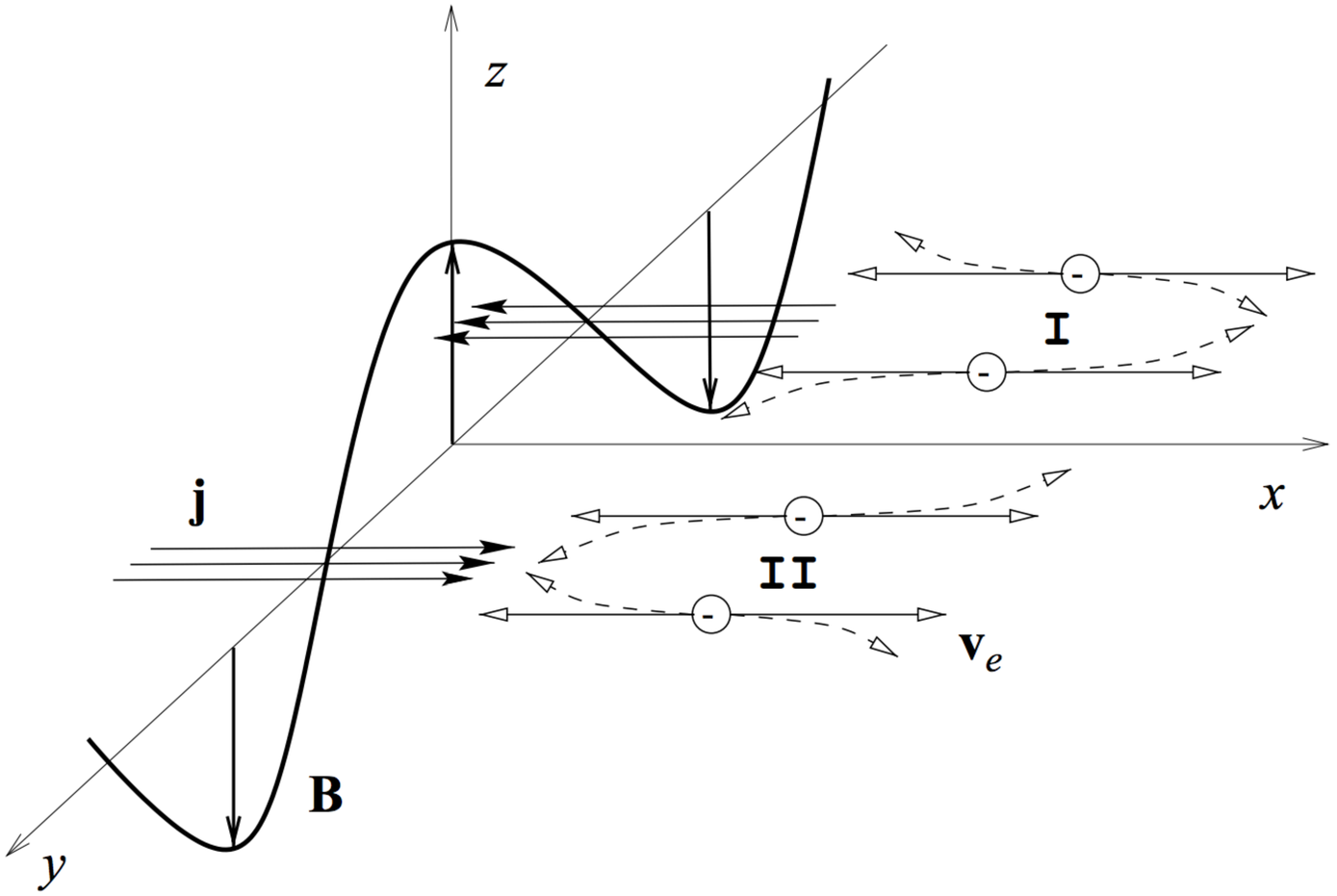
Biermann Battery Effect : Experimental Proof



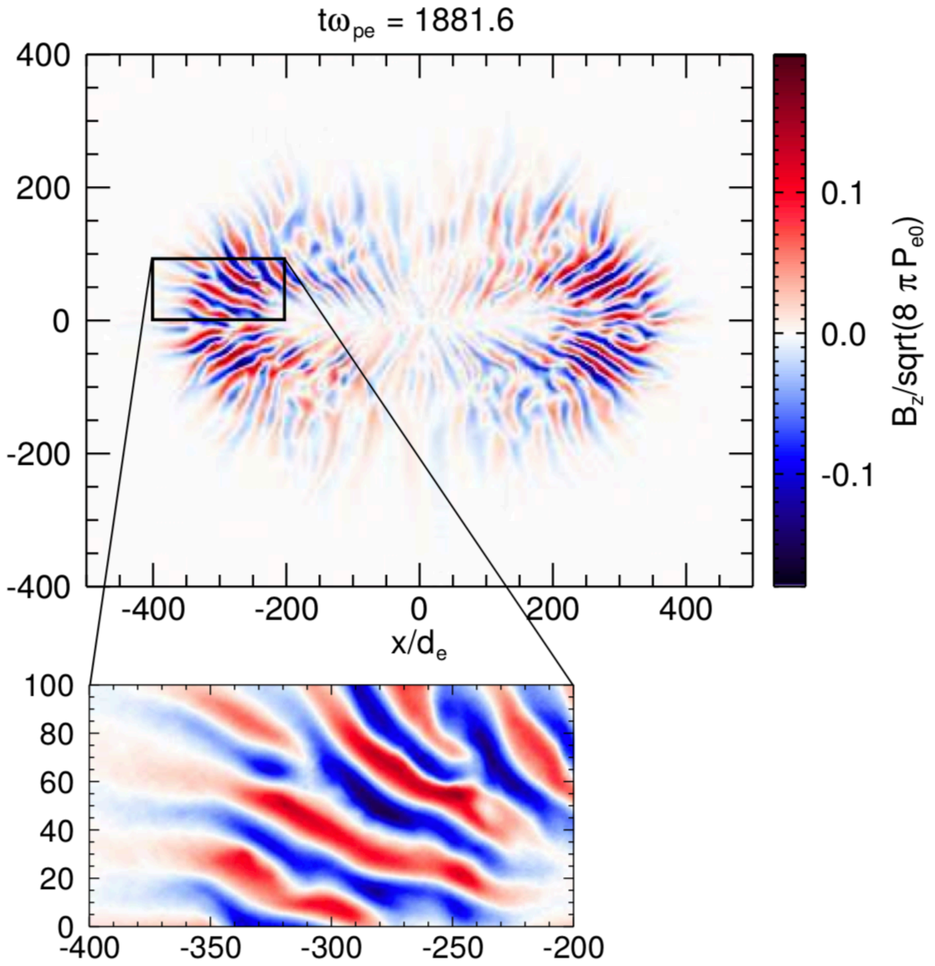
(Stamper & Ripin 1975)

- The first direct observations of the spontaneous megagauss magnetic fields in laser produced plasmas
- The magnetic field is measured by faraday rotation of polarized light
- Biermann Battery creates magnetic field out of absolute zero

Biermann Battery Effect vs. Weibel Instability

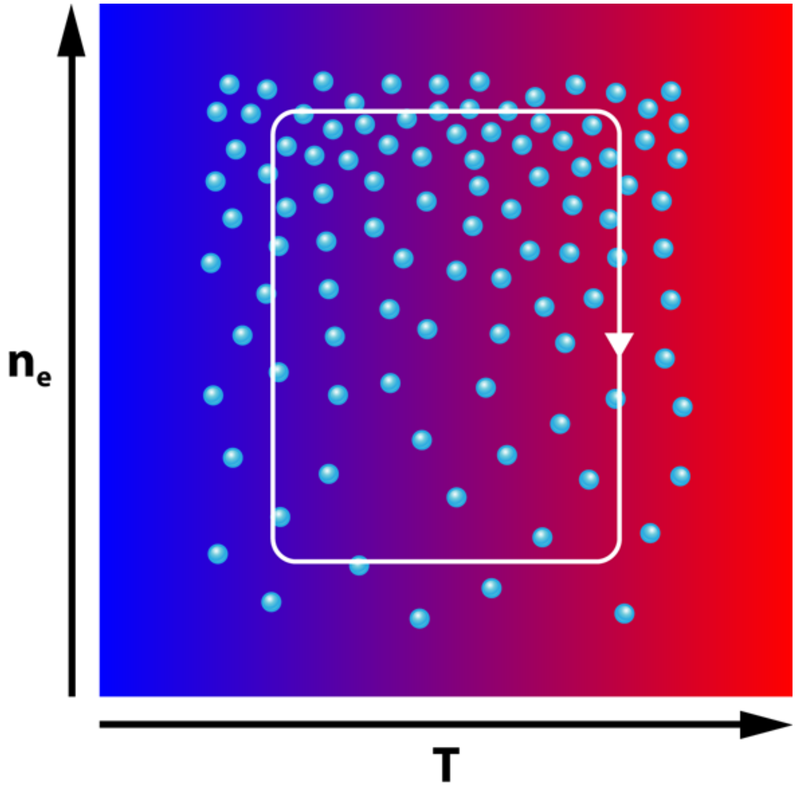


(Medvedev & Loeb, 1999)



(Schoeffler et al, 2016)

Biermann Battery Effect vs. Weibel Instability



Biermann Battery : Fluid Effect

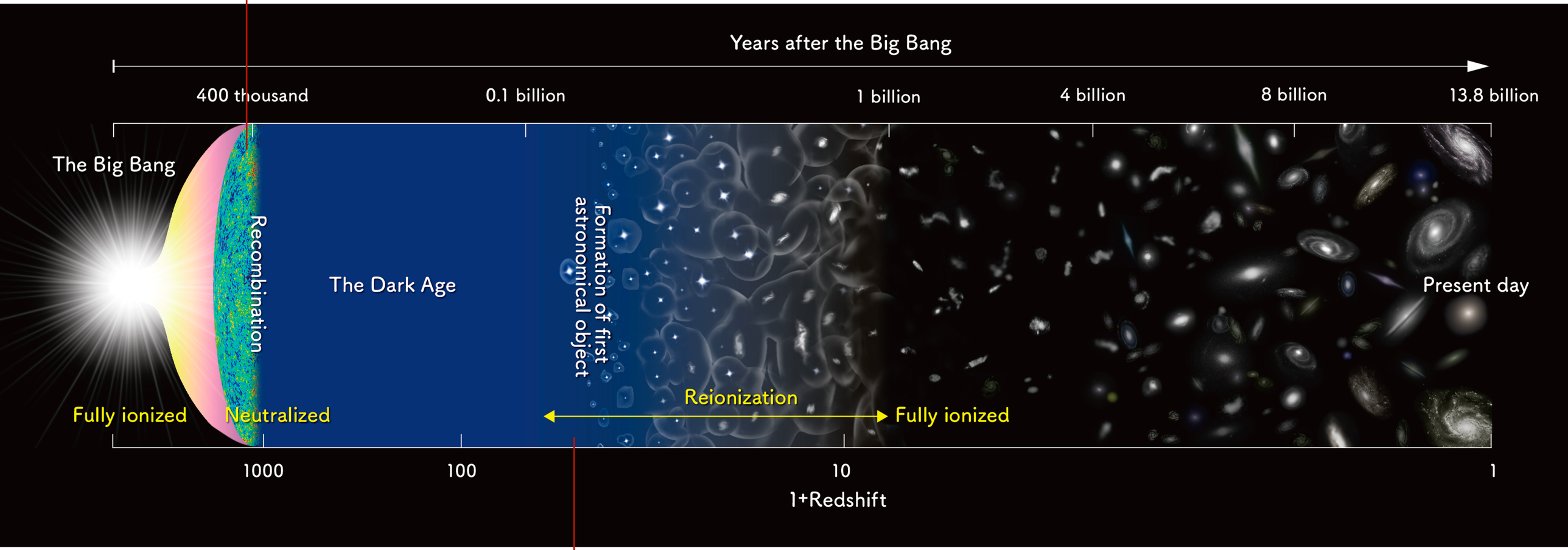
Maxwellian distribution

Weibel Instability : Kinetic Effect unique to plasmas

Highly anisotropic,
usually counter-streaming particles in shock fronts

Biermann Battery Effect : Recent Study

A primordial field could also be generated due to the temperature fluctuation —> 1E-25 ~ 1E-24 G



(Naoz & Narayan, 2013)

From the birth of first stars and quasars,

the Universe is full of ionization fronts —> 1E-20 ~ 1E-18 G

Other Possibilities for Seed Fields :

- From Early Universe (Widrow 2002)

- First-generation stars
  - The weak field generated by the Biermann battery could be amplified by stellar dynamo / Magneto-rotational instability and then spread out through jet, outflow and supernovae explosion (Syrovatskii 1970, Silk & Langer 2006)

- Active Galactic Nuclei
  - Strong magnetic field arise in AGNs.
  - These fields expand adiabatically to fill a “galactic” volume via jets can be on the order of ~ uG (Hoyle 1969)

A Summary View :

Seed fields

Biermann Battery

Jet / outflow / winds

Stellar dynamo

Magneto-rotational instability

Weibel instability

Primordial origin

… …

Amplification

Mean-field dynamo

Turbulent dynamo

Adiabatic compression