Magnetic fields in the intergalactic medium

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Overview

Link to the previous lecture: what happens to gamma-rays from blazars when they leave the source?

Gamma-ray induced cascades in the intergalactic space

Influence of magnetic fields in the voids of Large Scale Structure

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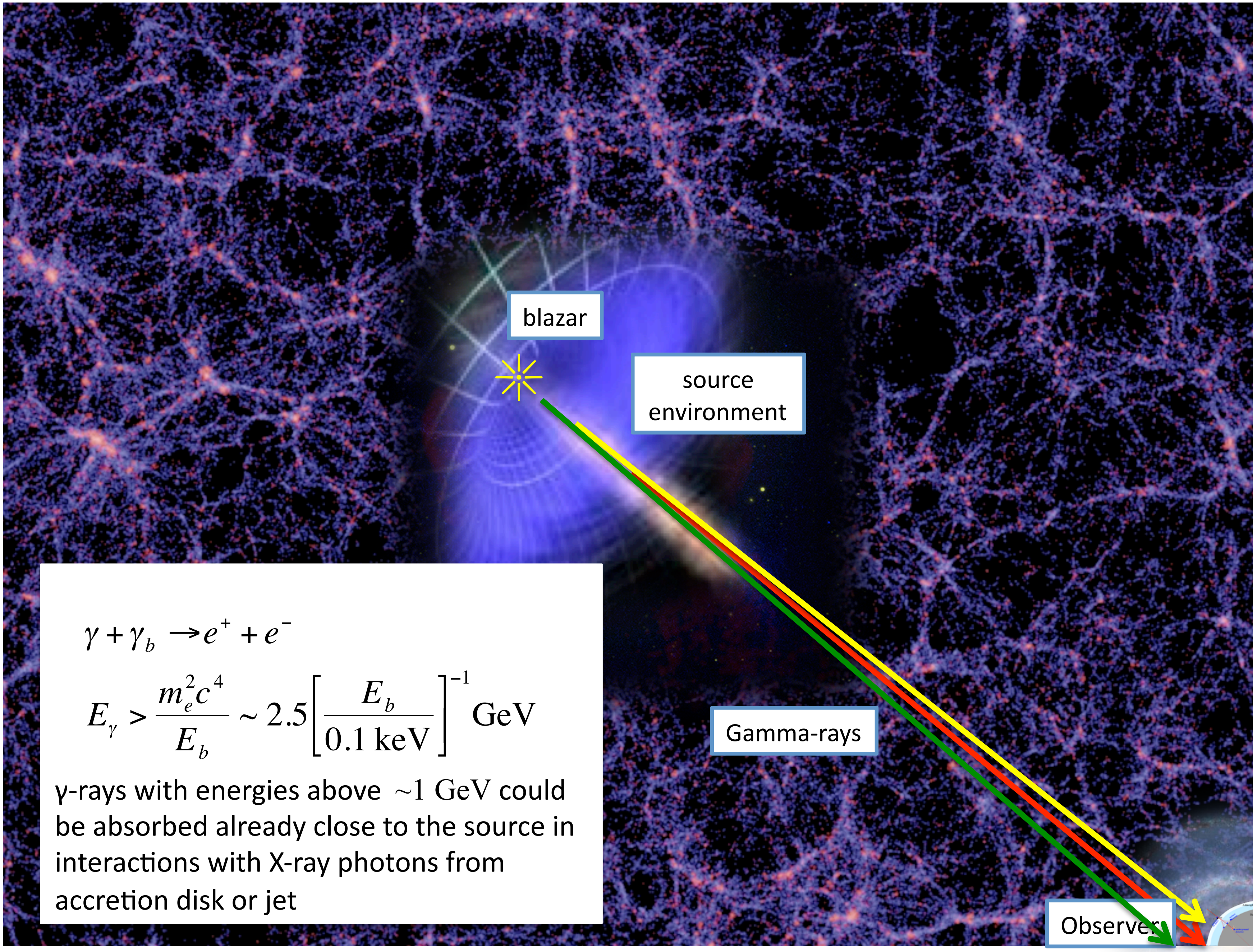
What do we want to know about magnetic fields in the Universe?

- Problem of the origin of magnetic fields
- Cosmological and astrophysical models of the origin of "seed" fields
- "Seed" magnetic fields in the intergalactic medium

Observational constraints on magnetic fields in the intergalactic medium

New observational constraints from gamma-ray observations by Fermi telescope.

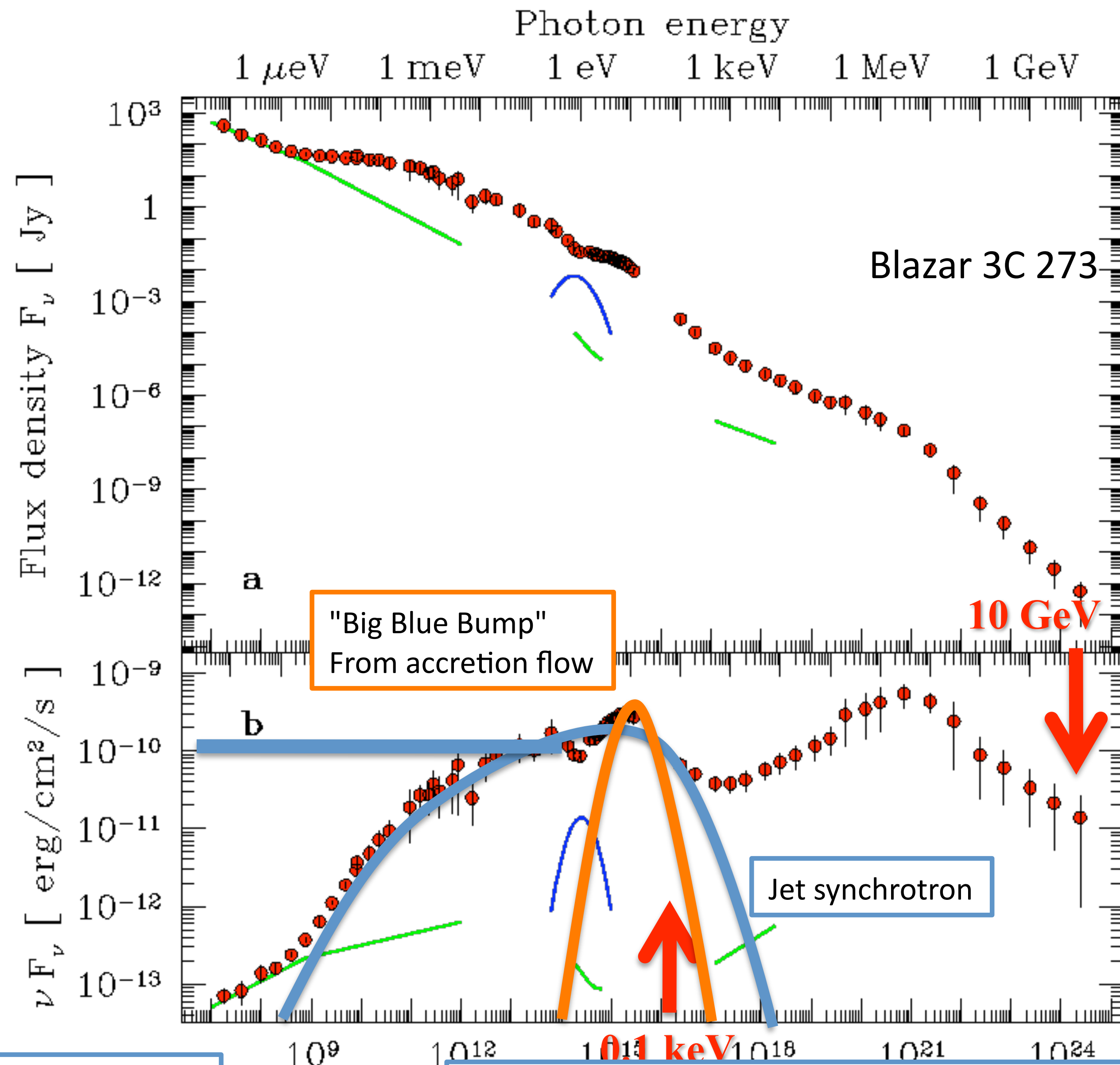
Gamma-ray propagation from the source



$$\gamma + \gamma_b \rightarrow e^+ + e^-$$

$$E_\gamma > \frac{m_e^2 c^4}{E_b} \sim 2.5 \left[\frac{E_b}{0.1\ \mathrm{keV}} \right]^{-1} \mathrm{GeV}$$

γ-rays with energies above ~ 1 GeV could be absorbed already close to the source in interactions with X-ray photons from accretion disk or jet



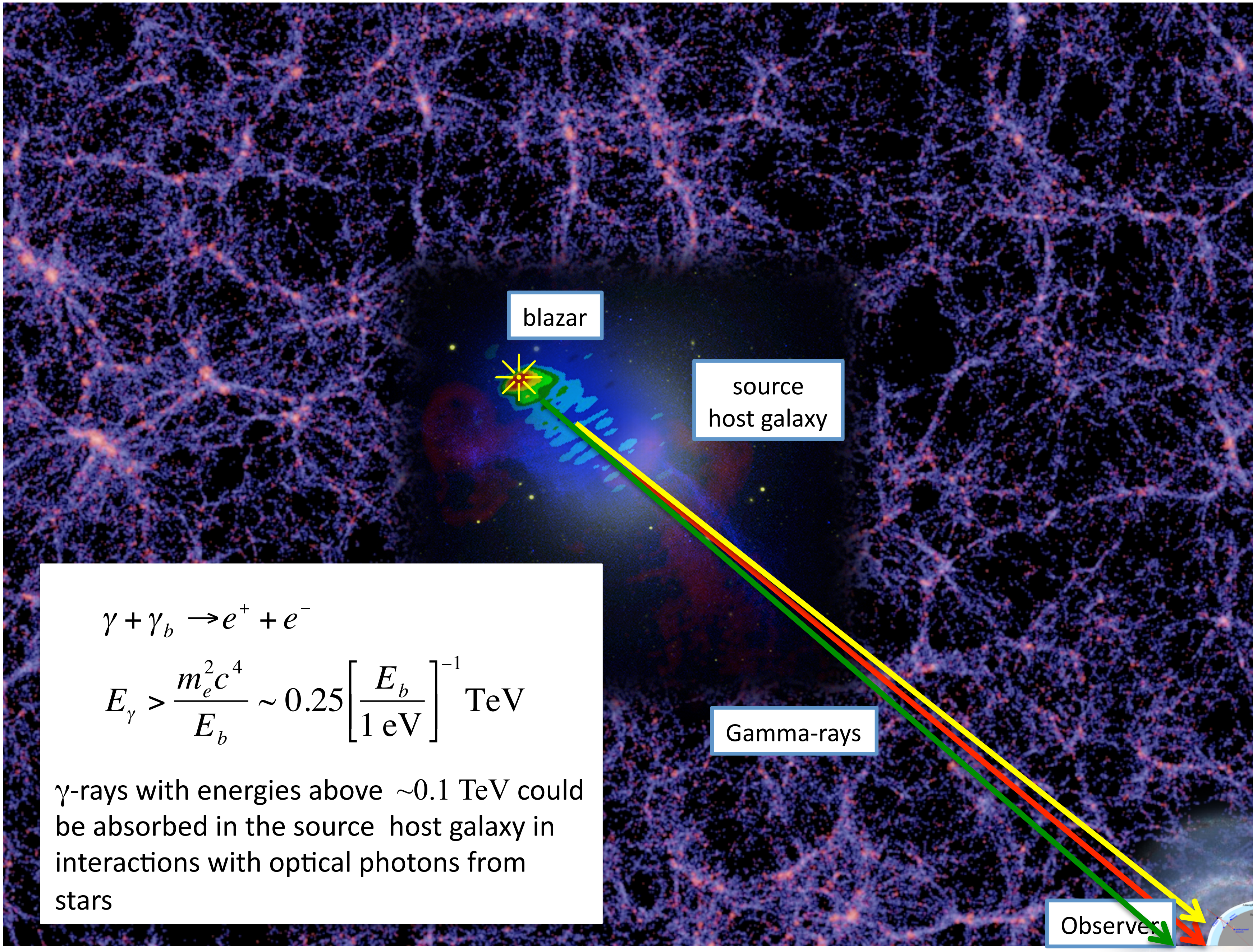
$$\sigma_{\gamma\gamma} \approx 10^{-25}\ \mathrm{cm}^2$$

$$D_\gamma = \frac{1}{\sigma_{\gamma\gamma} n_{EBL}} \approx 0.3 \left[\frac{E_\gamma}{10\ \mathrm{GeV}}\right]^{-1} \mathrm{pc}$$

$$n_b \approx 10^7 \left[\frac{\nu F_\nu}{10\ \mathrm{erg/(s\ cm^2)}}\right]\left[\frac{E}{0.1\ \mathrm{keV}}\right]^{-1}\left[\frac{D}{1\ \mathrm{Gpc}}\right]^{2}\left[\frac{R}{1\ \mathrm{pc}}\right]^{-2} \mathrm{cm}^{-3}$$

$1\ \mathrm{pc} = 3\times10^{18}\ \mathrm{cm}$

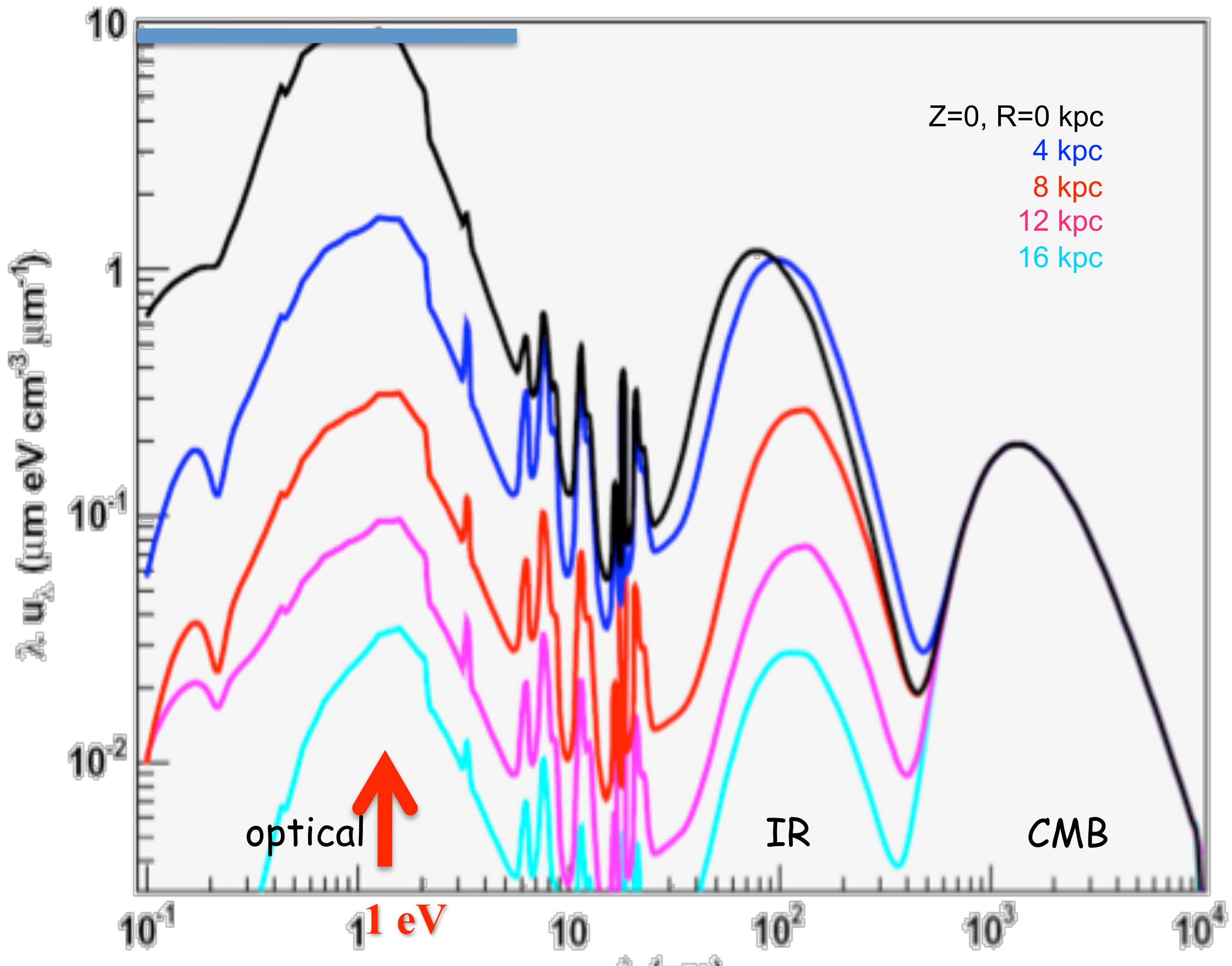
Gamma-ray propagation from the source



$$\gamma + \gamma_b \rightarrow e^+ + e^-$$

$$E_\gamma > \frac{m_e^2 c^4}{E_b} \sim 0.25 \left[\frac{E_b}{1\ \mathrm{eV}} \right]^{-1} \mathrm{TeV}$$

γ-rays with energies above ~ 0.1 TeV could be absorbed in the source host galaxy in interactions with optical photons from stars



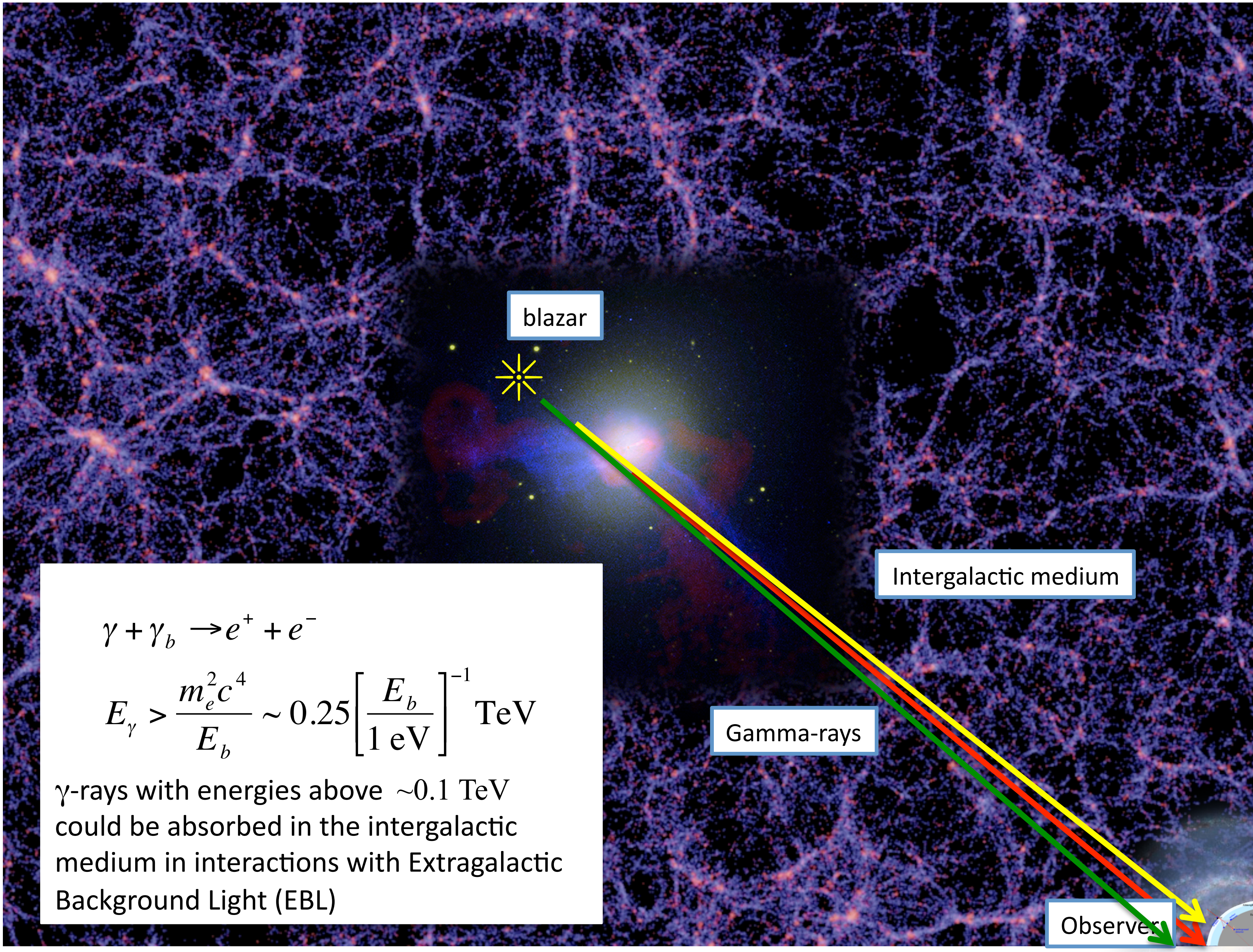
$$\sigma_{\gamma\gamma} \approx 10^{-25}\ \text{cm}^2$$

$$n_b \approx 10\left[\frac{\lambda u_\lambda}{10\ \text{eV cm}^{-3}}\right]\left[\frac{E}{1\ \text{eV}}\right]^{-1} \text{cm}^{-3}$$

$$D_\gamma = \frac{1}{\sigma_{\gamma\gamma} n_{EBL}} \approx 300\left[\frac{E_\gamma}{1\ \text{TeV}}\right]^{-1} \text{kpc}$$

... compare with the size of a galaxy

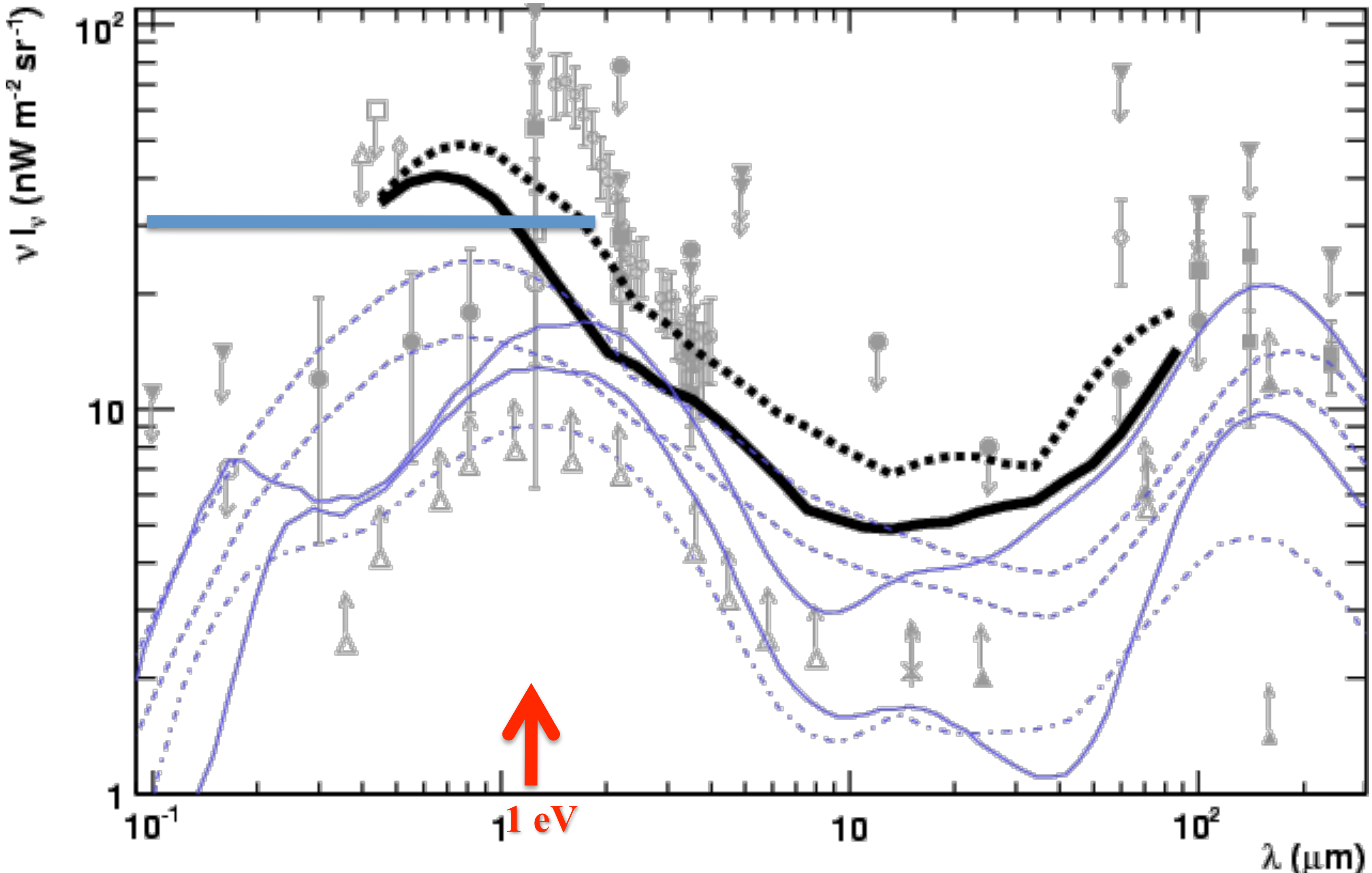
Gamma-ray propagation from the source



$$\gamma + \gamma_b \rightarrow e^+ + e^-$$

$$E_\gamma > \frac{m_e^2 c^4}{E_b} \sim 0.25 \left[\frac{E_b}{1\ \mathrm{eV}} \right]^{-1} \mathrm{TeV}$$

γ-rays with energies above ~ 0.1 TeV could be absorbed in the intergalactic medium in interactions with Extragalactic Background Light (EBL)

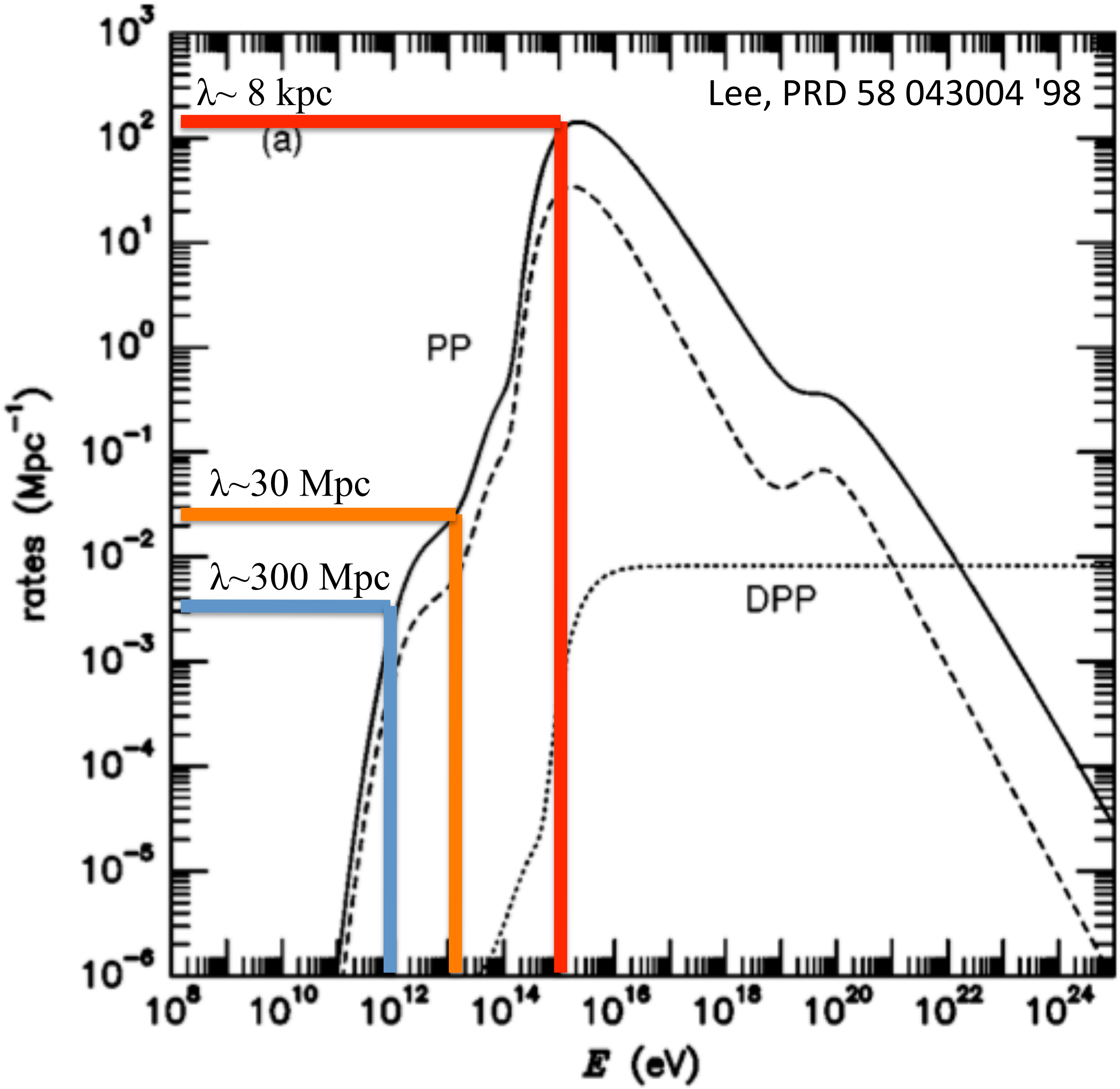


$$\sigma_{\gamma\gamma} \approx 10^{-25}\ \mathrm{cm}^2$$

$$n_{EBL} \approx 10^{-2}\left[\frac{\nu I_\nu}{10\ \mathrm{nW\ m^2\ sr}}\right]\left[\frac{E}{1\ \mathrm{eV}}\right]^{-1}\ \mathrm{cm}^{-3}$$

$$D_\gamma = \frac{1}{\sigma_{\gamma\gamma} n_{EBL}} \approx 300\left[\frac{E_\gamma}{1\ \mathrm{TeV}}\right]^{-1}\ \mathrm{Mpc}$$

… compare with distance to gamma-ray source



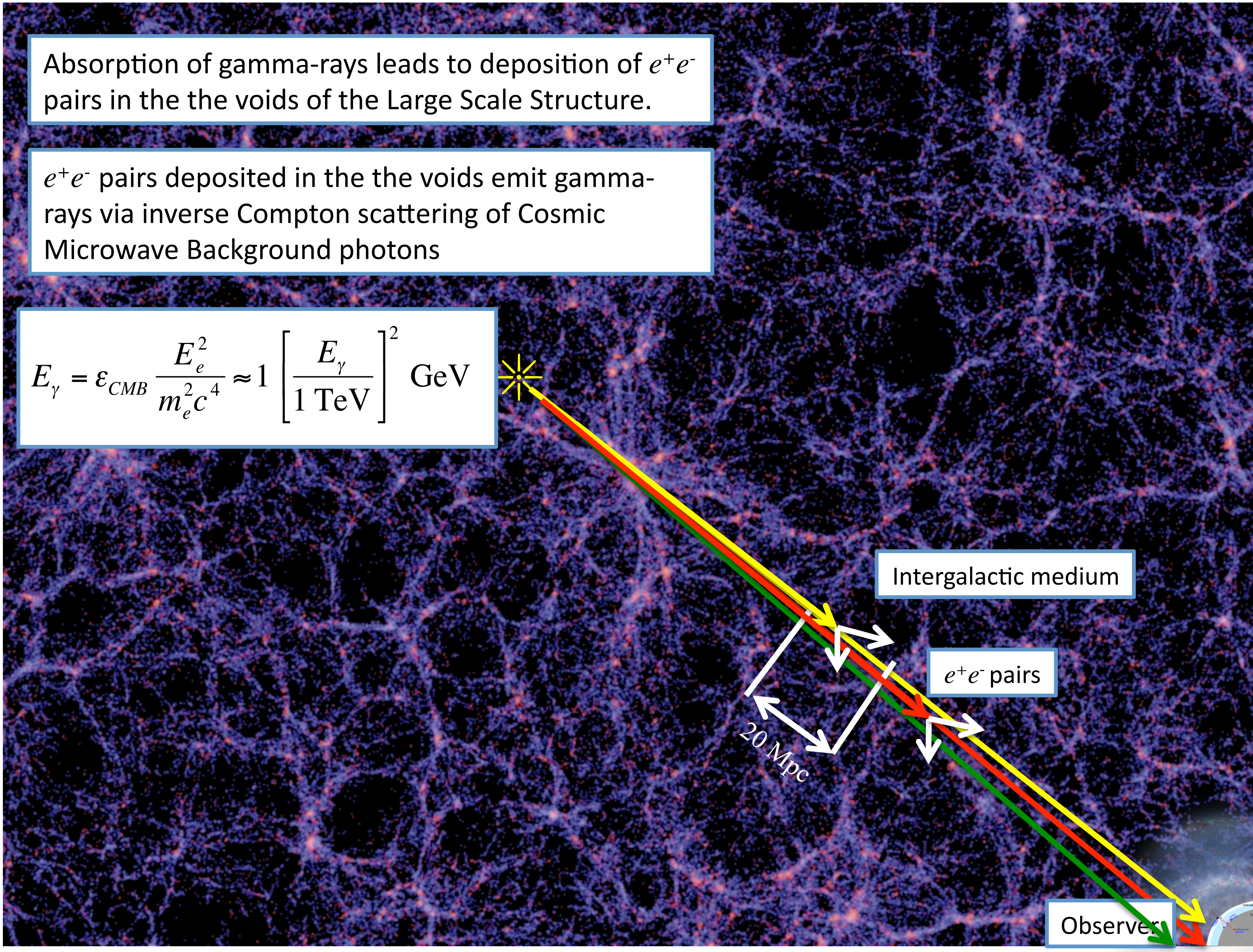
λ~ 8 kpc
Lee, PRD 58 043004 '98
(a)
PP
λ~30 Mpc
λ~300 Mpc
DPP
rates (Mpc^{-1})
E (eV)

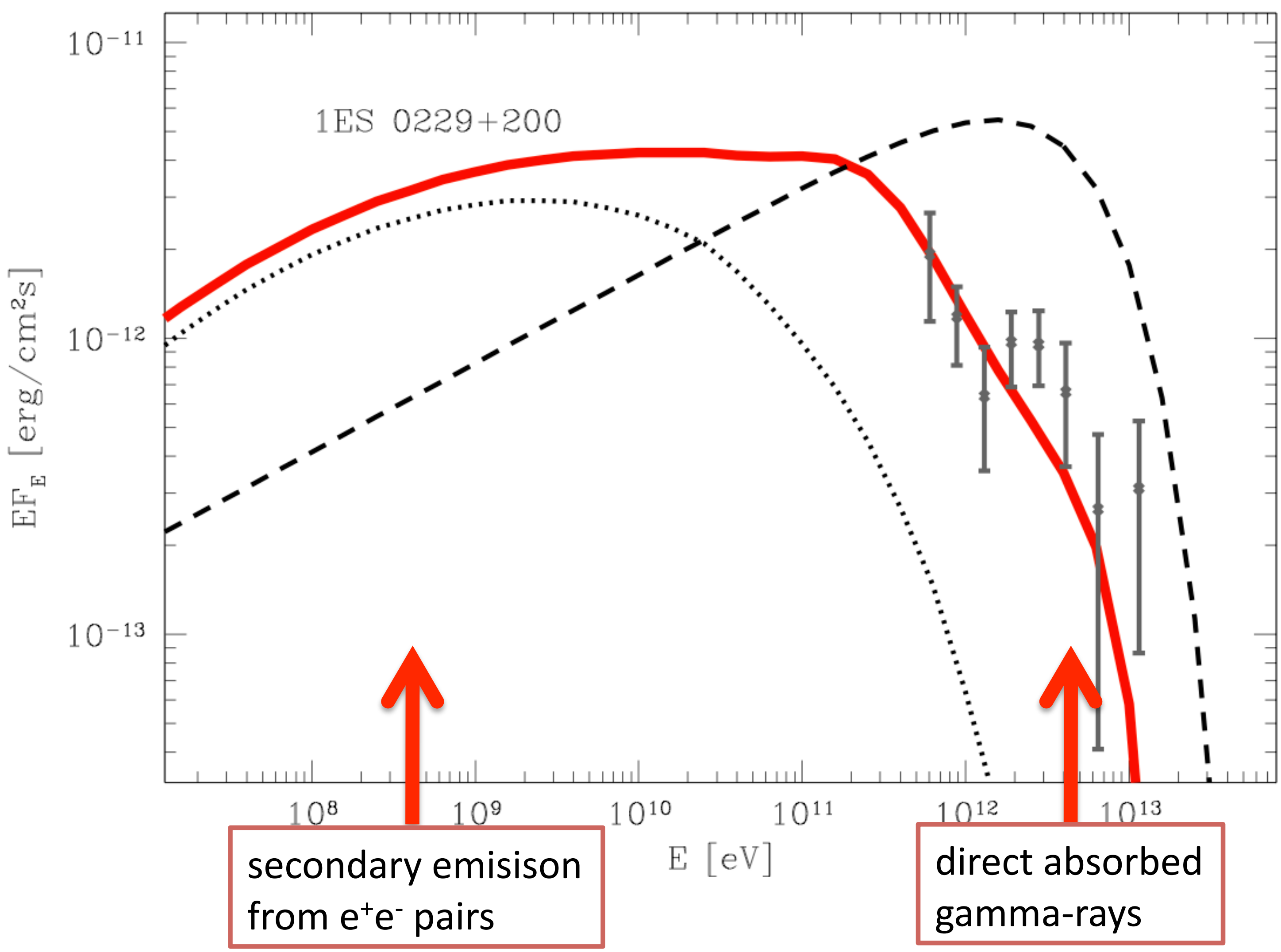
Gamma-ray propagation from the source

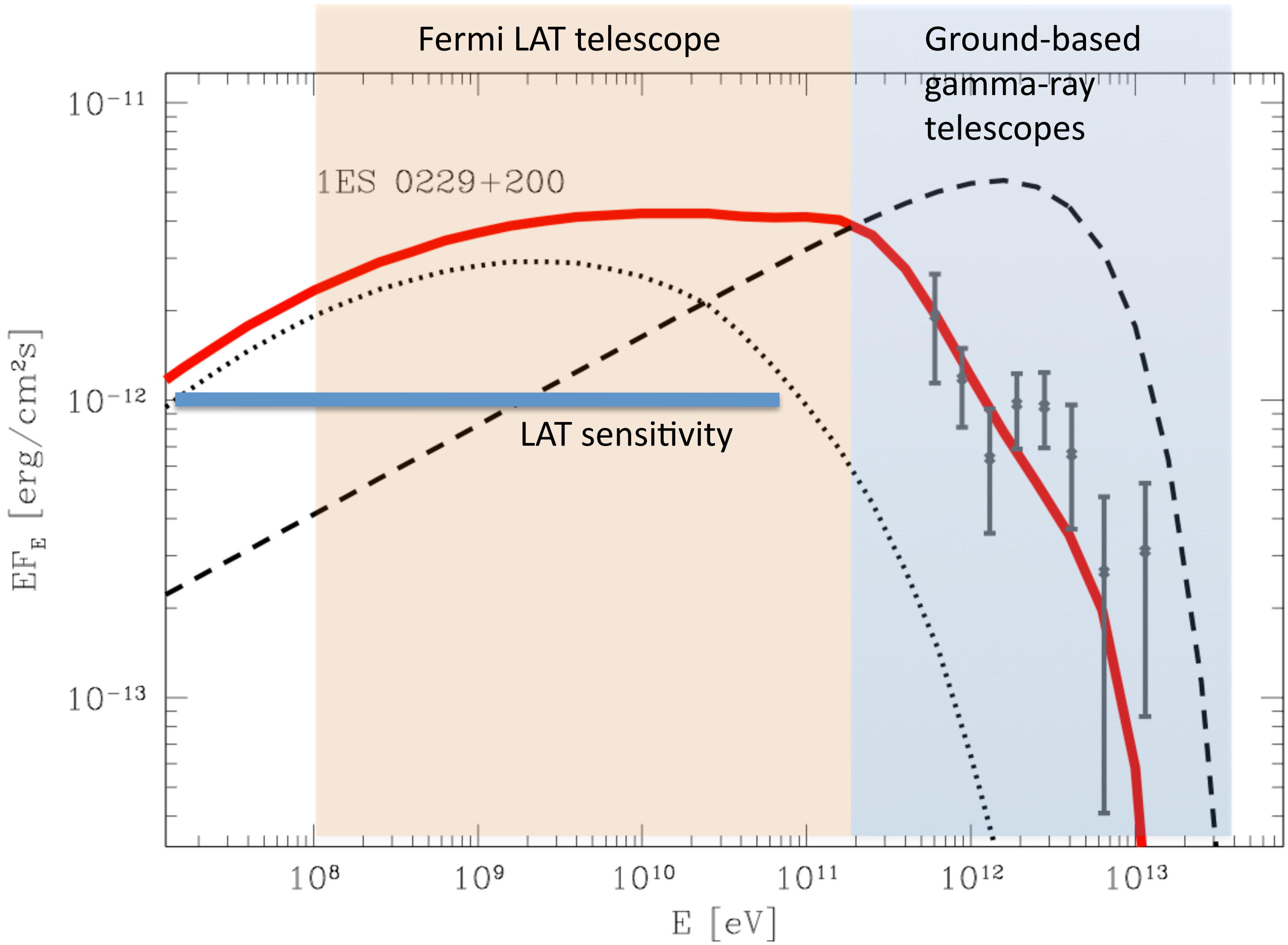
Absorption of gamma-rays leads to deposition of e^+e^- pairs in the the voids of the Large Scale Structure.

e^+e^- pairs deposited in the the voids emit gamma-rays via inverse Compton scattering of Cosmic Microwave Background photons

$$E_\gamma = \varepsilon_{CMB} \frac{E_e^2}{m_e^2 c^4} \approx 1 \left[\frac{E_\gamma}{1 \text{ TeV}} \right]^2 \text{ GeV}$$

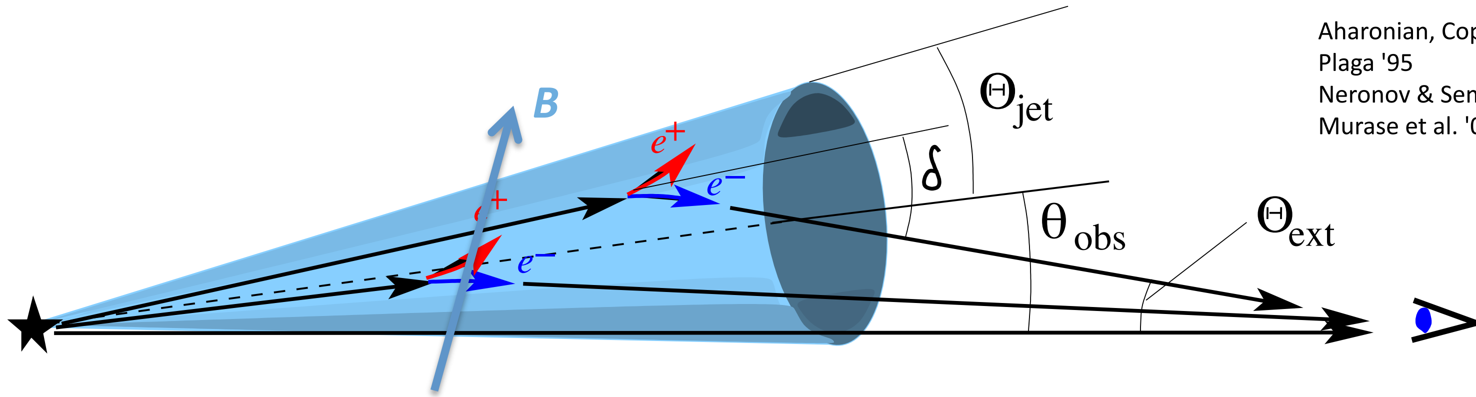



1ES 0229+200
10^{-11}
10^{-12}
10^{-13}
EF_E [erg/cm^{2}s]
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
E [eV]
secondary emisison from e^+e^- pairs
direct absorbed gamma-rays



Gamma-ray emission from e^+e^- pairs in the voids of Large Scale Structure is potentially observable, either as a "secondary" component of spectra of individual sources, or as a component of extragalactic diffuse gamma-ray emission.

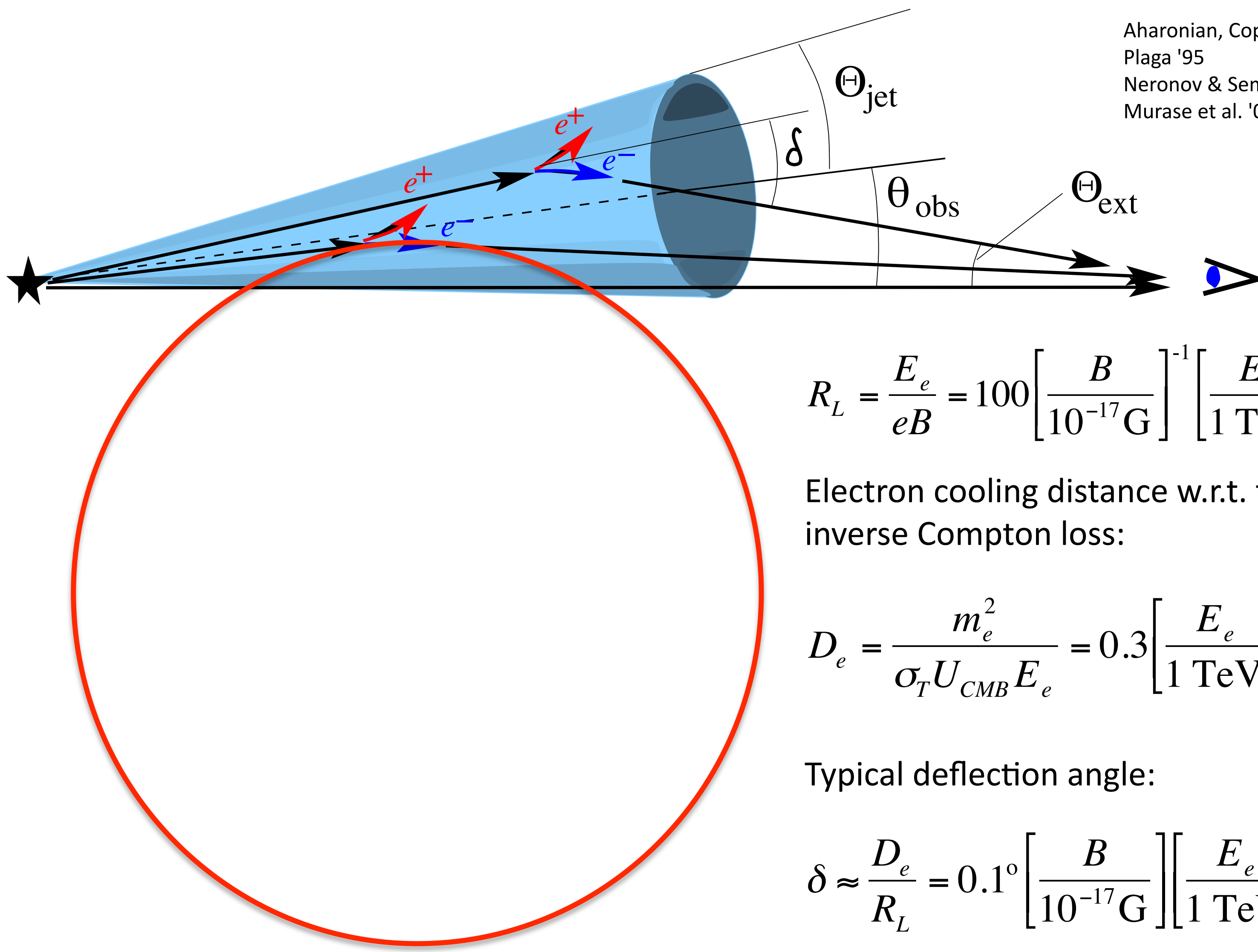
Magnetic fields in intergalactic medium



Aharonian, Coppi & Voelk '94
Plaga '95
Neronov & Semikoz '07, '09
Murase et al. '08

Magnetic field, if present in the voids of Large Scale Structure, deflects e^+e^- pairs so that secondary gamma-rays do not come from the same direction as the primary gamma-rays

Magnetic fields in intergalactic medium



Aharonian, Coppi & Voelk '94
Plaga '95
Neronov & Semikoz '07, '09
Murase et al. '08

$$R_L = \frac{E_e}{eB} = 100\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]^{-1}\left[\frac{E_e}{1\ \mathrm{TeV}}\right]\ \mathrm{Mpc}$$

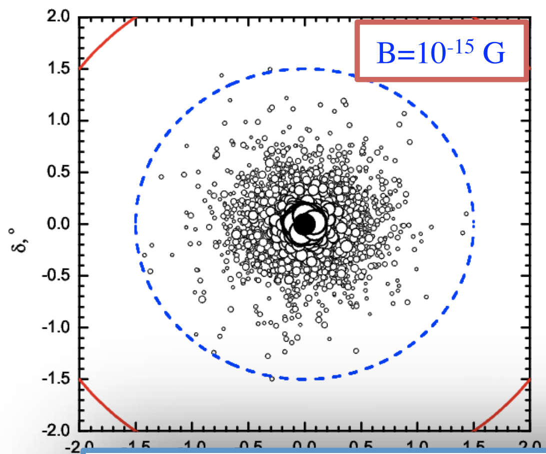
Electron cooling distance w.r.t. the inverse Compton loss:

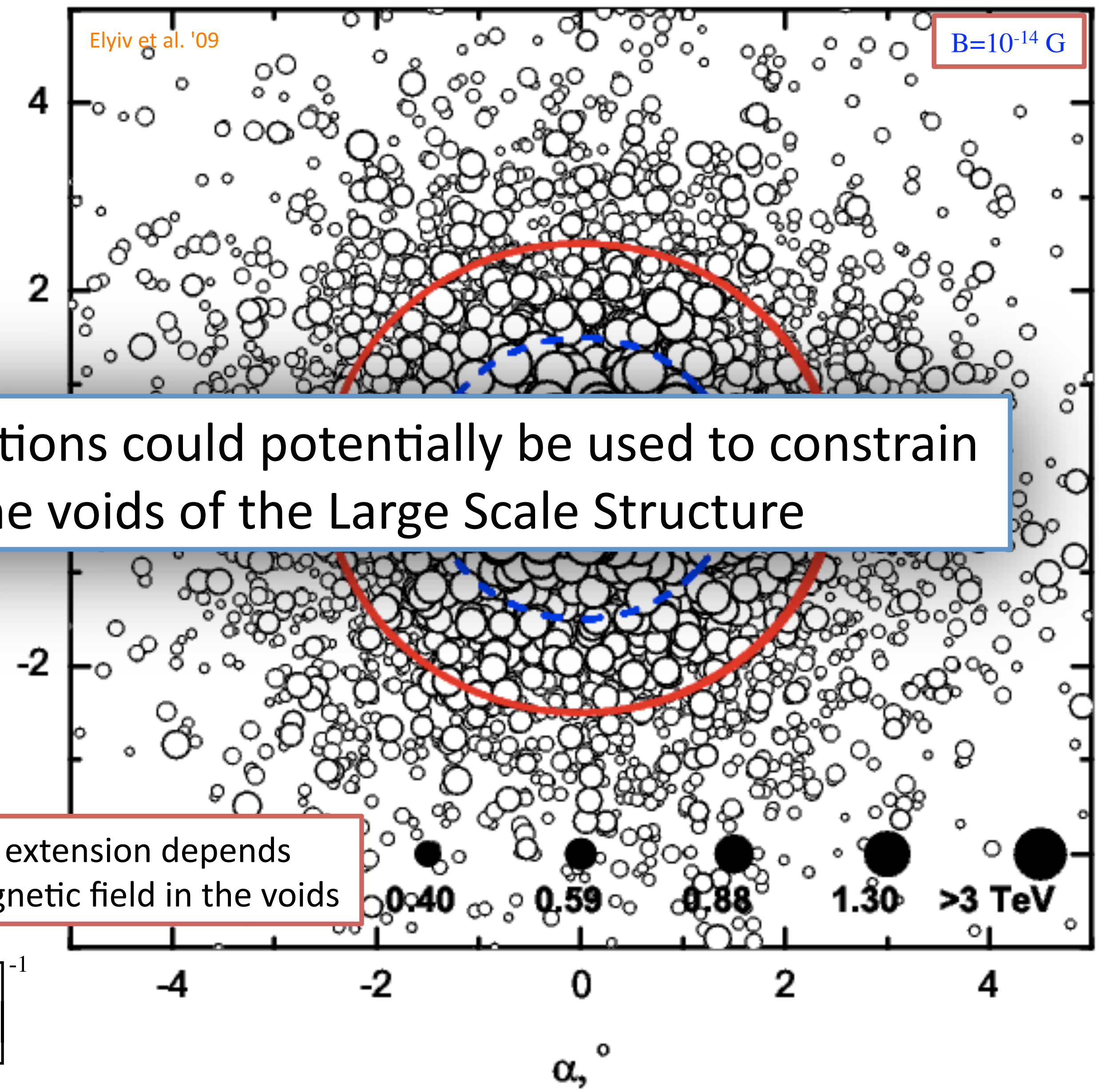
$$D_e = \frac{m_e^2}{\sigma_T U_{CMB} E_e} = 0.3\left[\frac{E_e}{1\ \mathrm{TeV}}\right]^{-1}\ \mathrm{Mpc}$$

Typical deflection angle:

$$\delta \approx \frac{D_e}{R_L} = 0.1^{\circ}\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]\left[\frac{E_e}{1\ \mathrm{TeV}}\right]^{-2}$$

Spatial structure of secondary emission





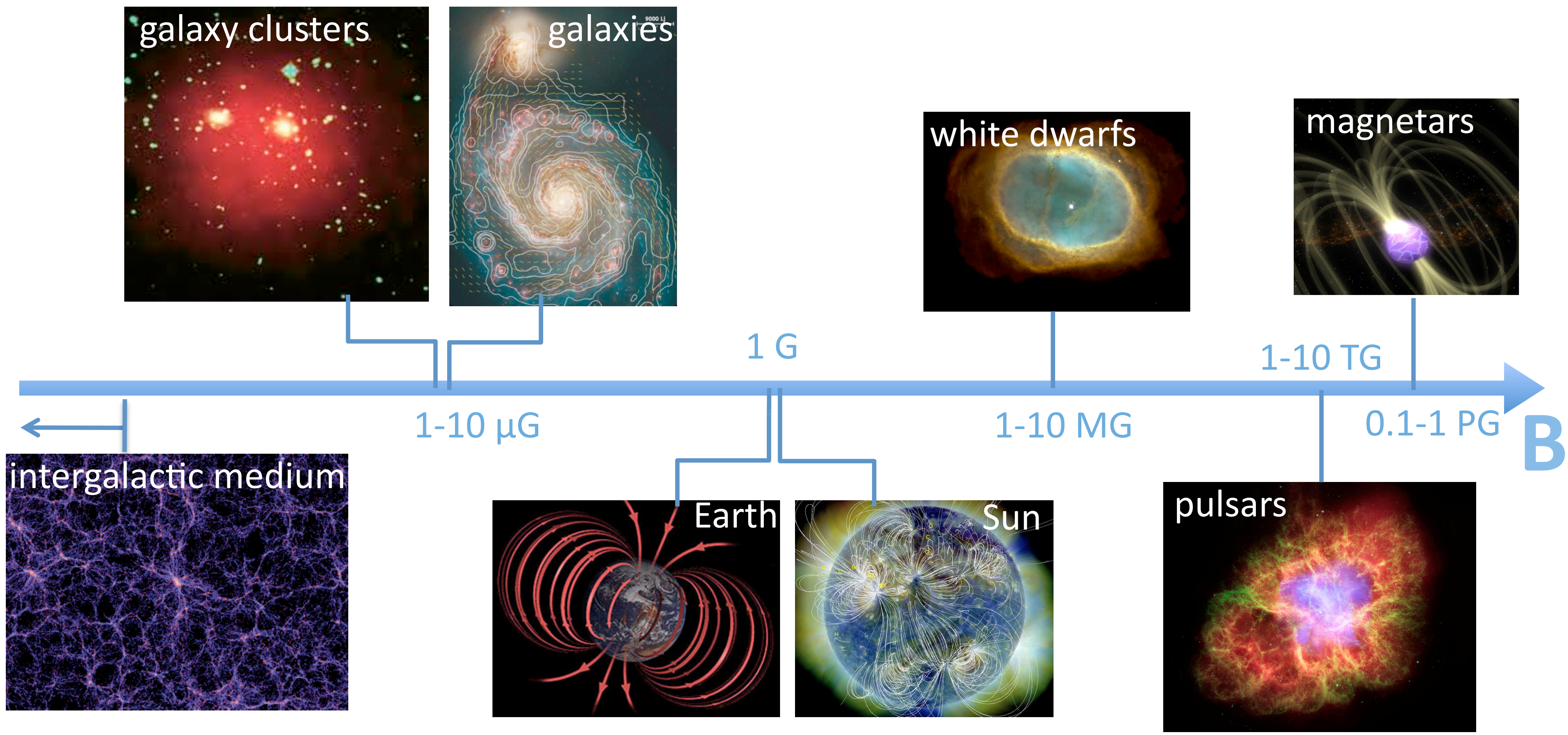
Gamma ray observations could potentially be used to constrain Magnetic fields in the voids of the Large Scale Structure

optical depth for gamma-rays $\tau = D/\lambda_{\gamma\gamma}$

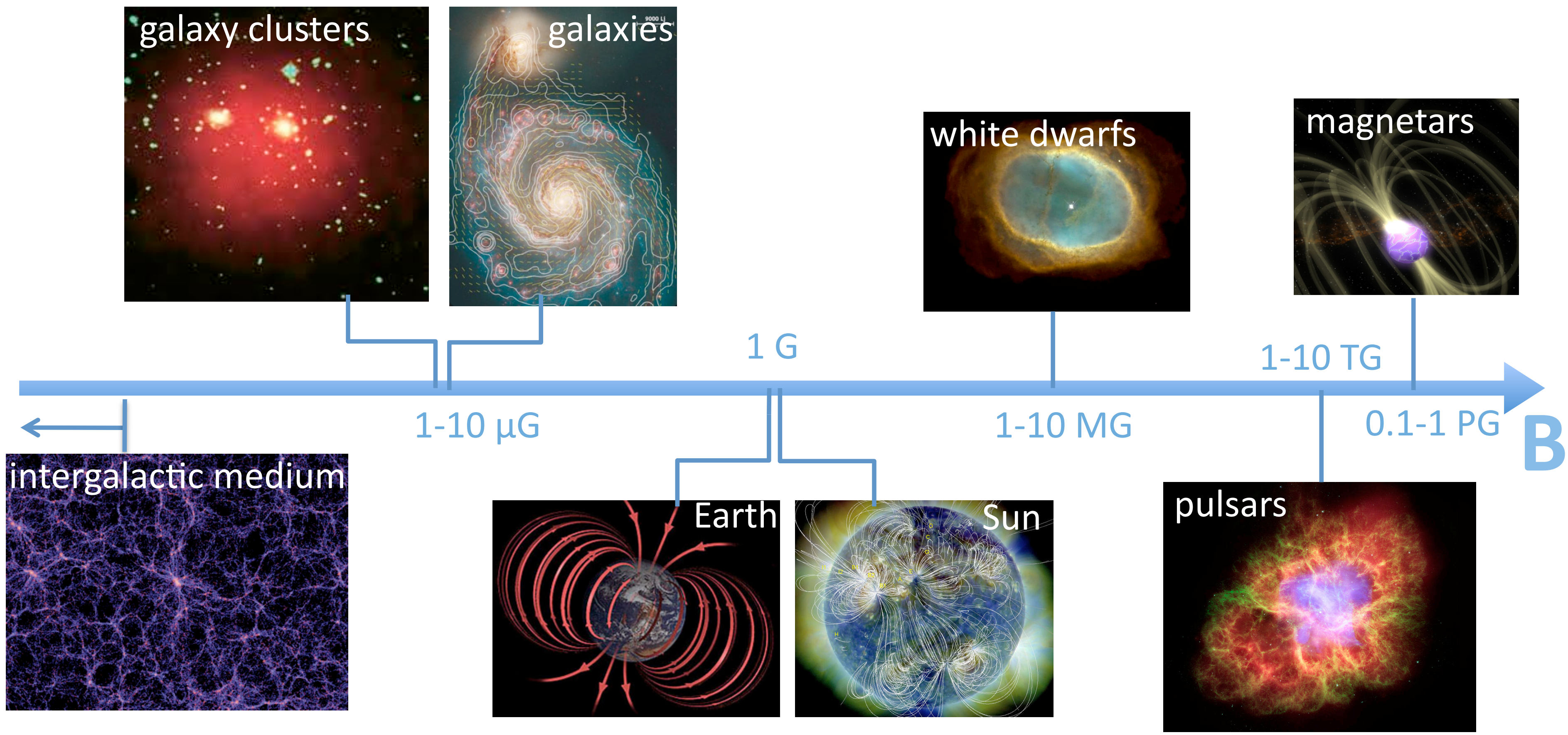
Source extension depends on magnetic field in the voids

$$\Theta \approx \frac{\delta}{\tau_0} = 0.4^\circ \frac{1}{\tau}\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]\left[\frac{E_\gamma}{1\,\mathrm{GeV}}\right]^{-1}$$

Magnetic fields in the Universe



Origin of magnetic fields



Induction equaiton for magnetic field in conducting medium (*Longair Eq. (11.45)*):

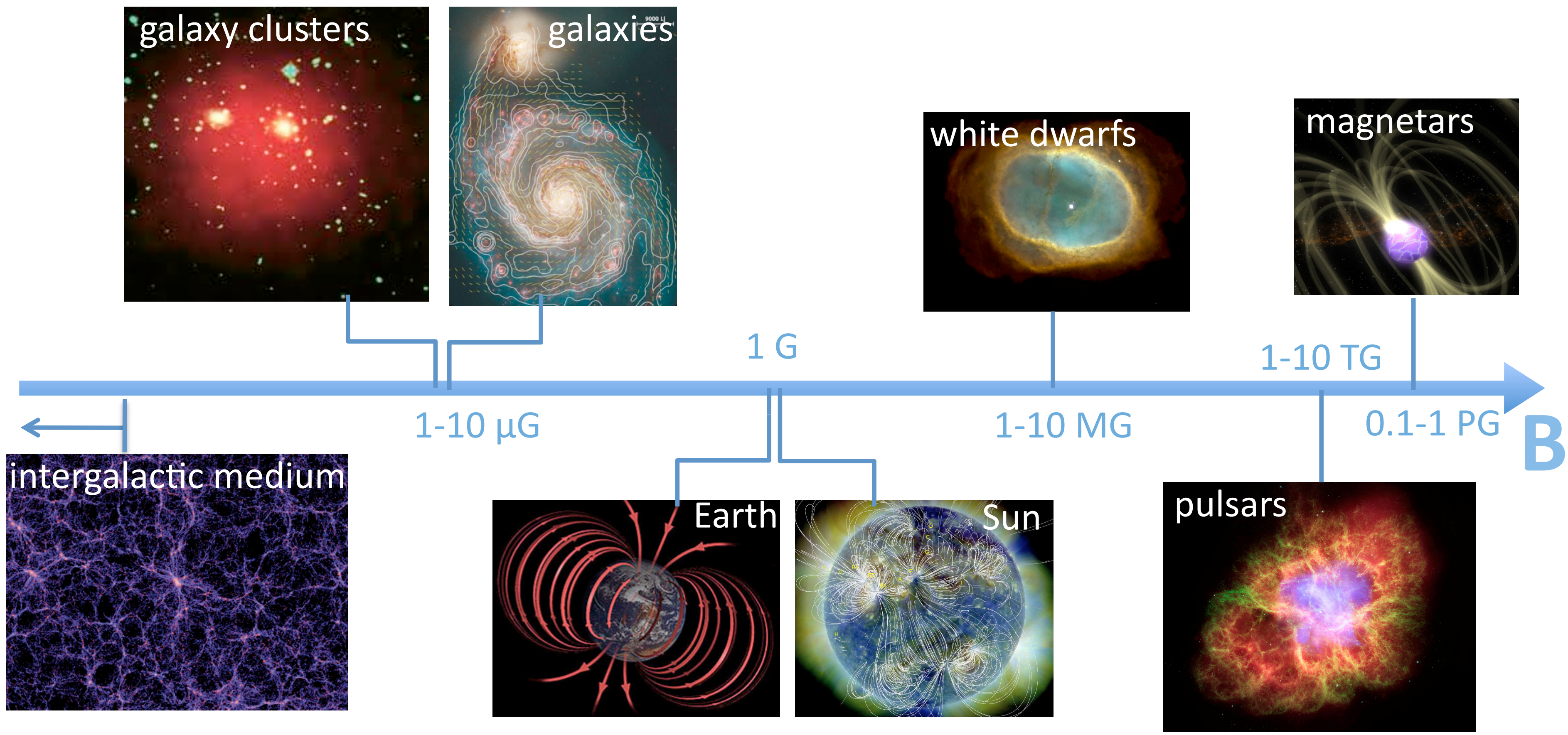
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \frac{1}{\sigma}\nabla^2 \vec{B}$$

Magnetic flux freezing

Magnetic field
Resistive diffusion

conductivity

Origin of magnetic fields

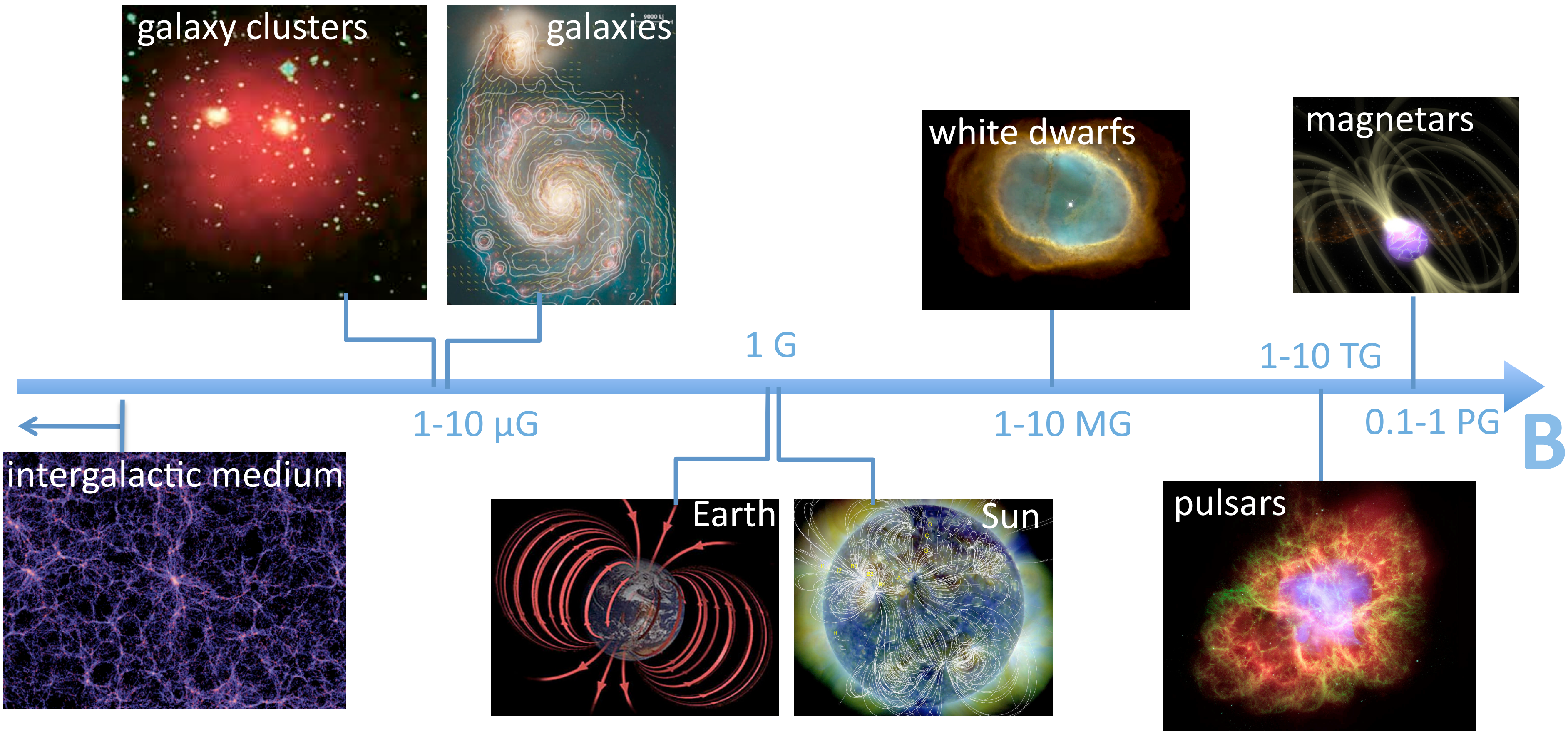


Induction equation for magnetic field in conducting medium (*Longair Eq. (11.45)*):

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

In a plasma with infinite conductivity magnetic field adjusts to the motion of the plasma so that magnetic flux is "frozen in" the plasma, $\Phi \sim BL^2 \sim const.$

Origin of magnetic fields

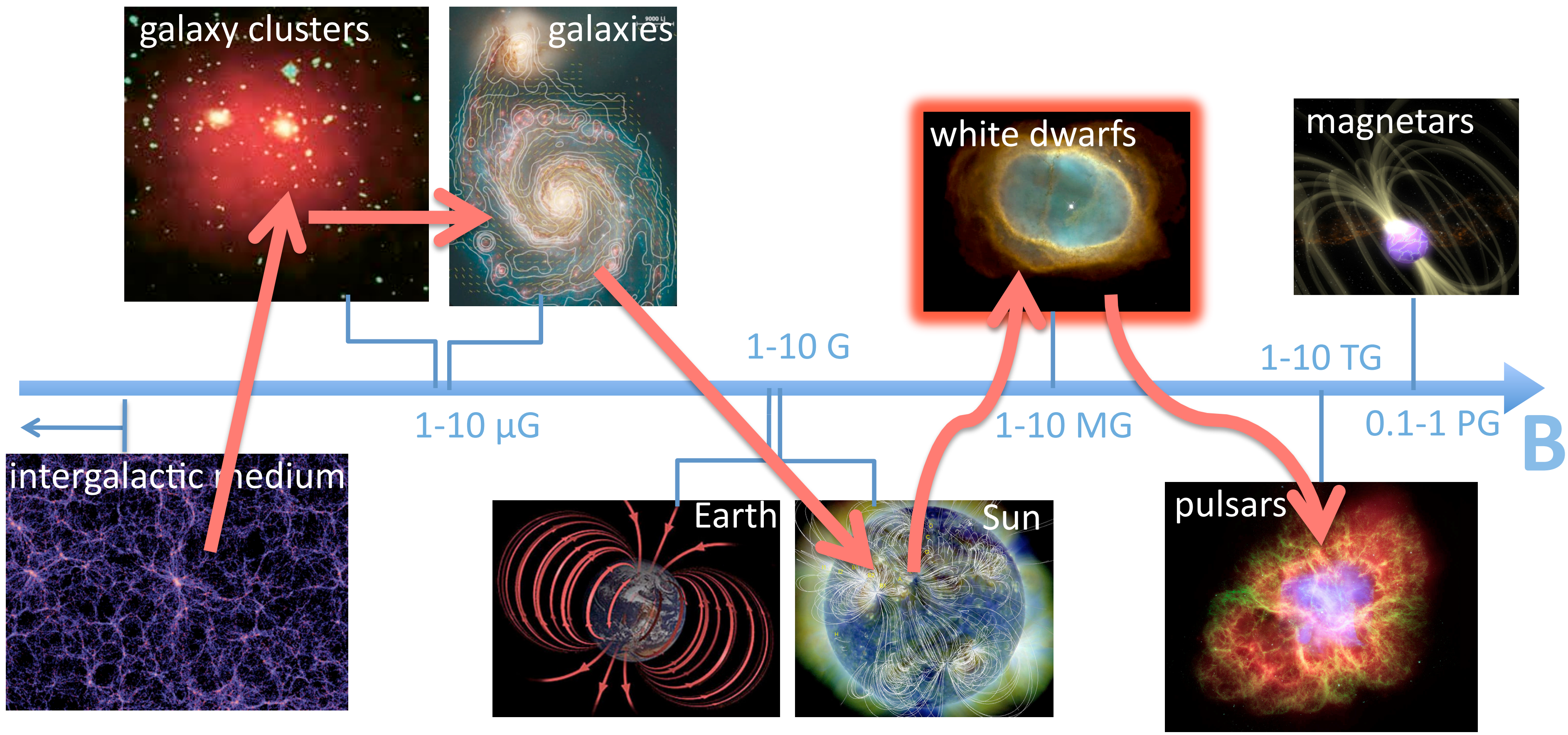


Induction equation for magnetic field in conducting medium (*Longair Eq. (11.45)*):

$$\frac{\partial \vec{B}}{\partial t} = \frac{1}{\sigma}\nabla^2 \vec{B}$$

In a plasma with finite conductivity magnetic field is dissipated on the time scale $\tau_{diff} \sim \sigma L^2$.

Origin of magnetic fields



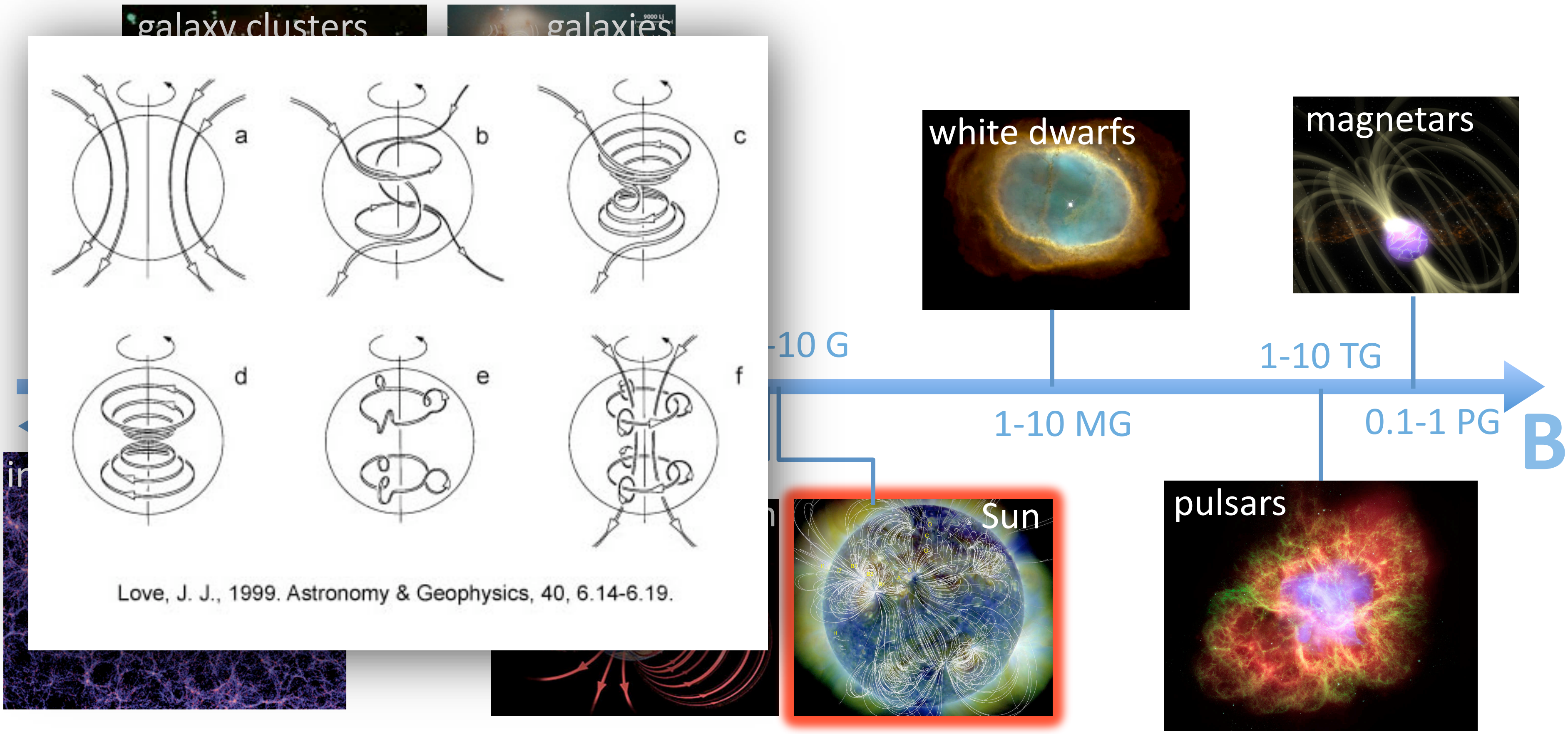
Magnetic flux conservation: $\Phi = BL^2 \sim \text{const}$

Sun: $L_* \sim 10^{11}$ cm, $L_* \sim 1$ G → white dwarf: $L \sim 10^{-3} R_*$, $B \sim 10^6 B_*$

Contraction leads to the **amplification** of magnetic field.

Similar effect might take place on the scales of galaxies and galaxy clusters.

Origin of magnetic fields



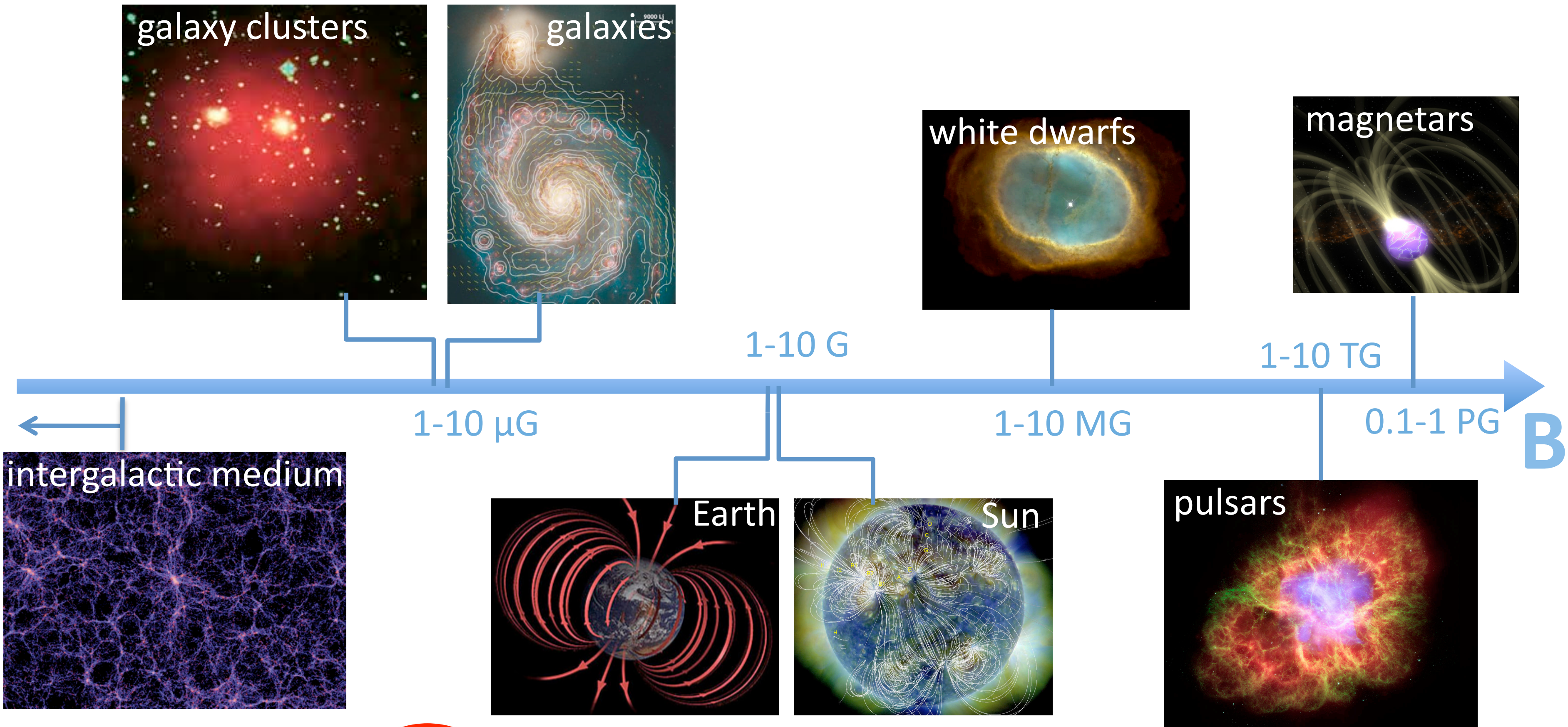
Magnetic diffusion: $\tau \sim \sigma L^2$

Sun: $L_* \sim 10^{11}$ cm, $\sigma_* \sim T^{3/2}/(e^2 m_e^{1/2}) \sim 10^{-9}$ s/cm^2 (plasma conductivity) ➔ $\tau \sim 10^4$ yr

Resistive diffusion leads to the **decay** of magnetic field.

Magnetic field in stars could be continuously re-generated via α-ω dynamo mechanism

Origin of magnetic fields



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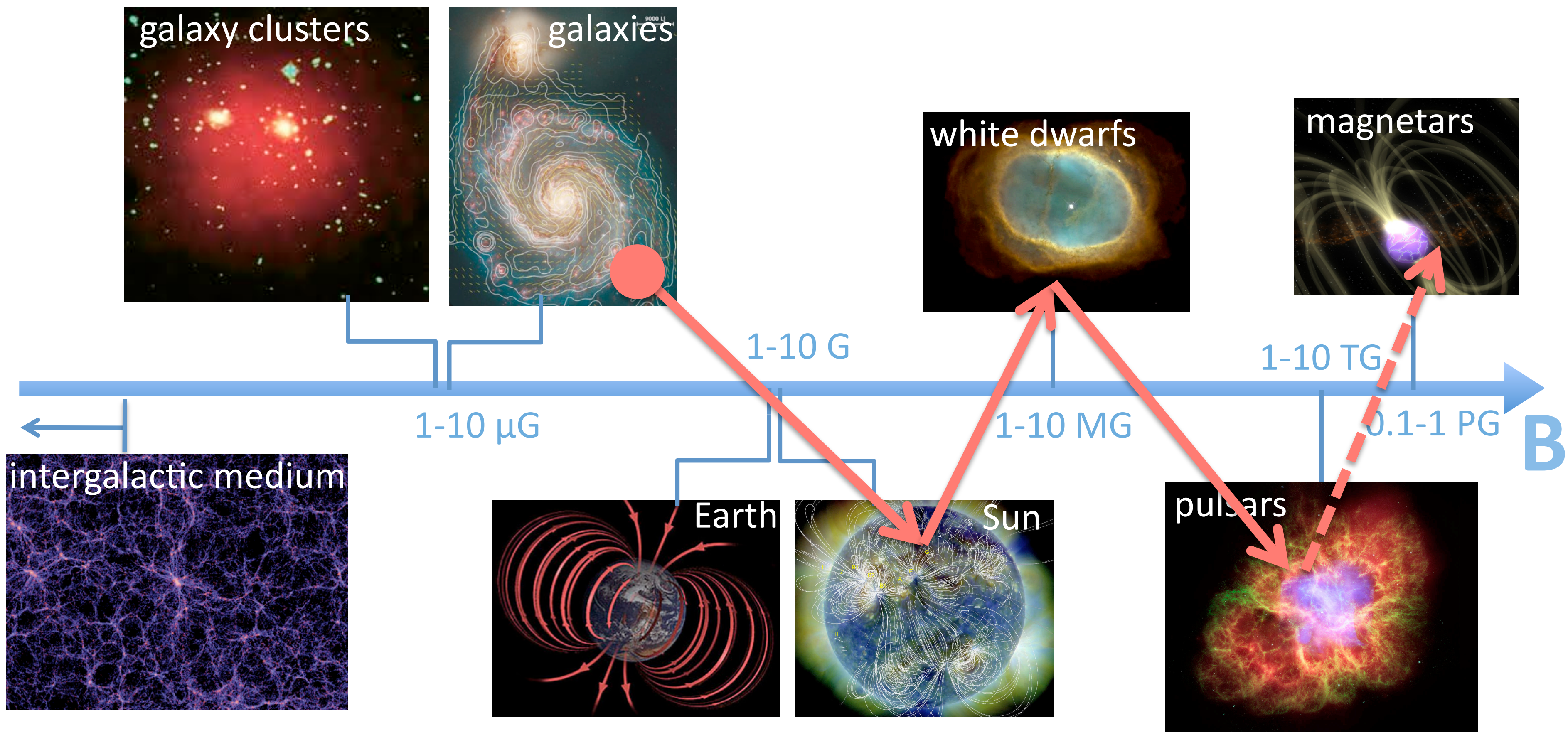
Resistive diffusion leads to the **decay** of magnetic field.

Magnetic field in stars could be continuously re-generated via α-ω dynamo mechanism

Resistive diffusion is not important on large length scales (galaxies, galaxy clusters).

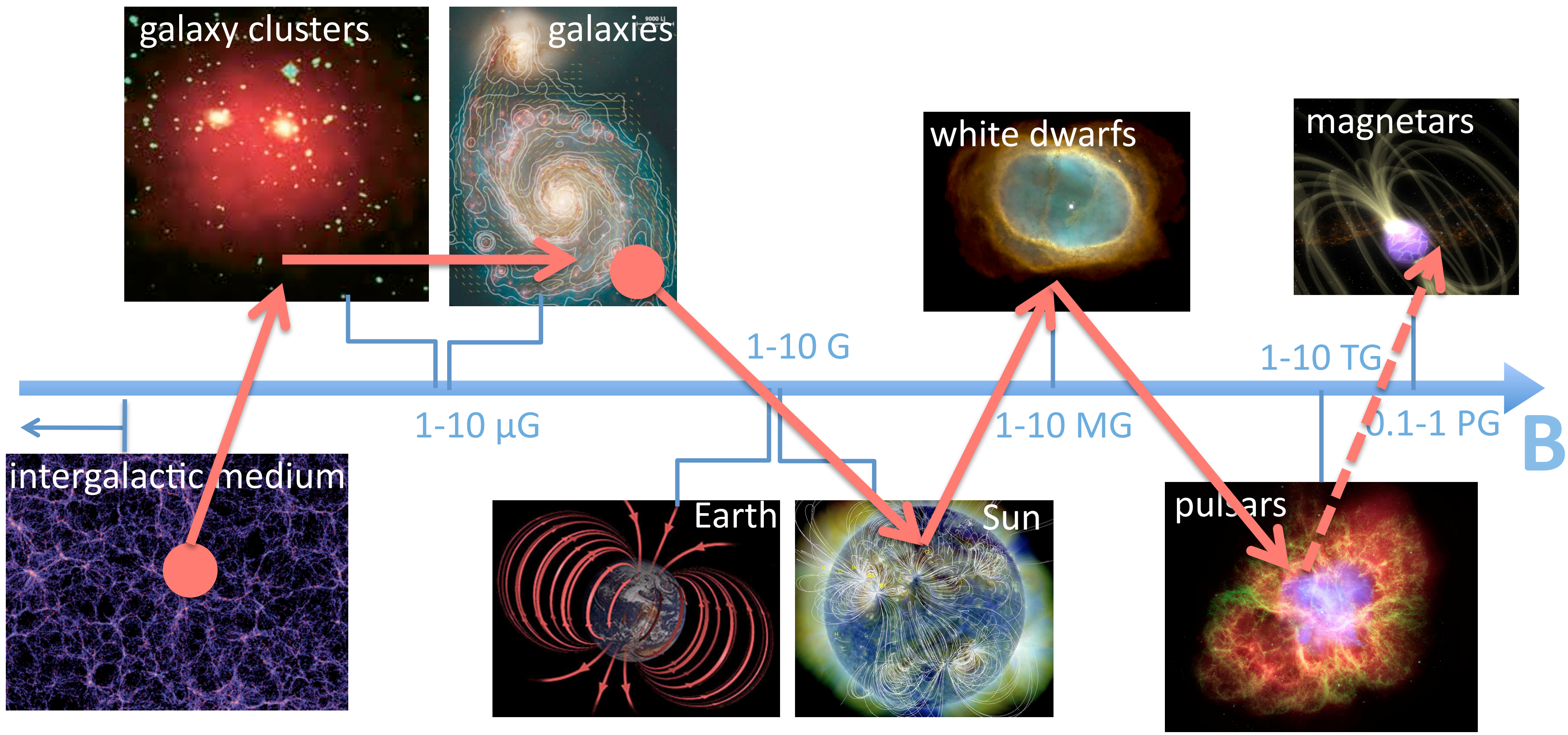
Cosmic "magnetogenesis" scenario



Magnetic fields on the scales of galaxies and galaxy clusters would not be destroyed once they are created.

Magnetic fields in stars (and planets) might be produced via amplification of pre-existing galactic magnetic fields

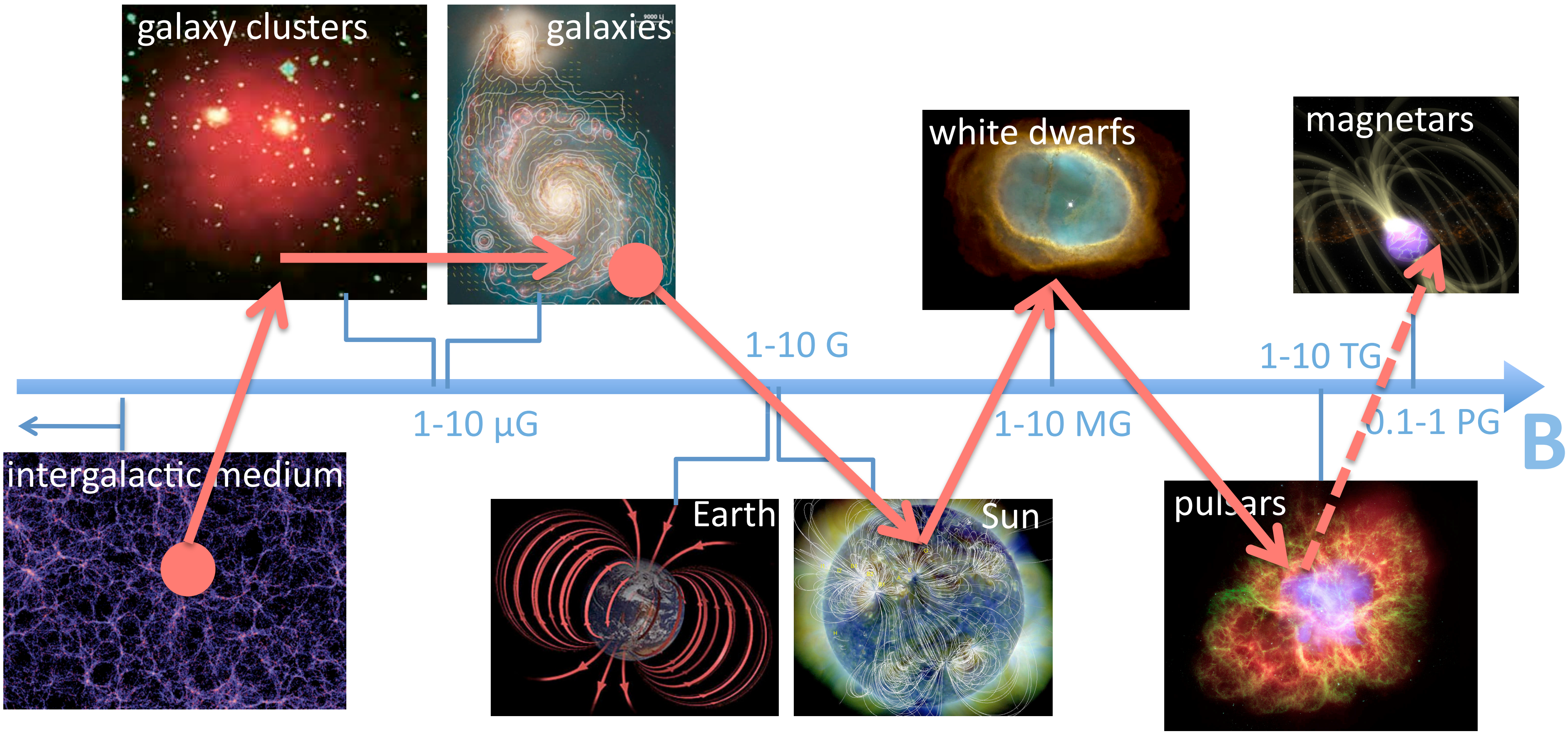
Cosmic "magnetogenesis" scenario



Magnetic fields on the in galaxies and galaxy clusters could, in turn, be produced by amplification of pre-existing magnetic fields in the intergalactic medium

Magnetic fields in the intergalactic medium are, in turn, produced by .... ?

Problems of cosmic magnetogenesis

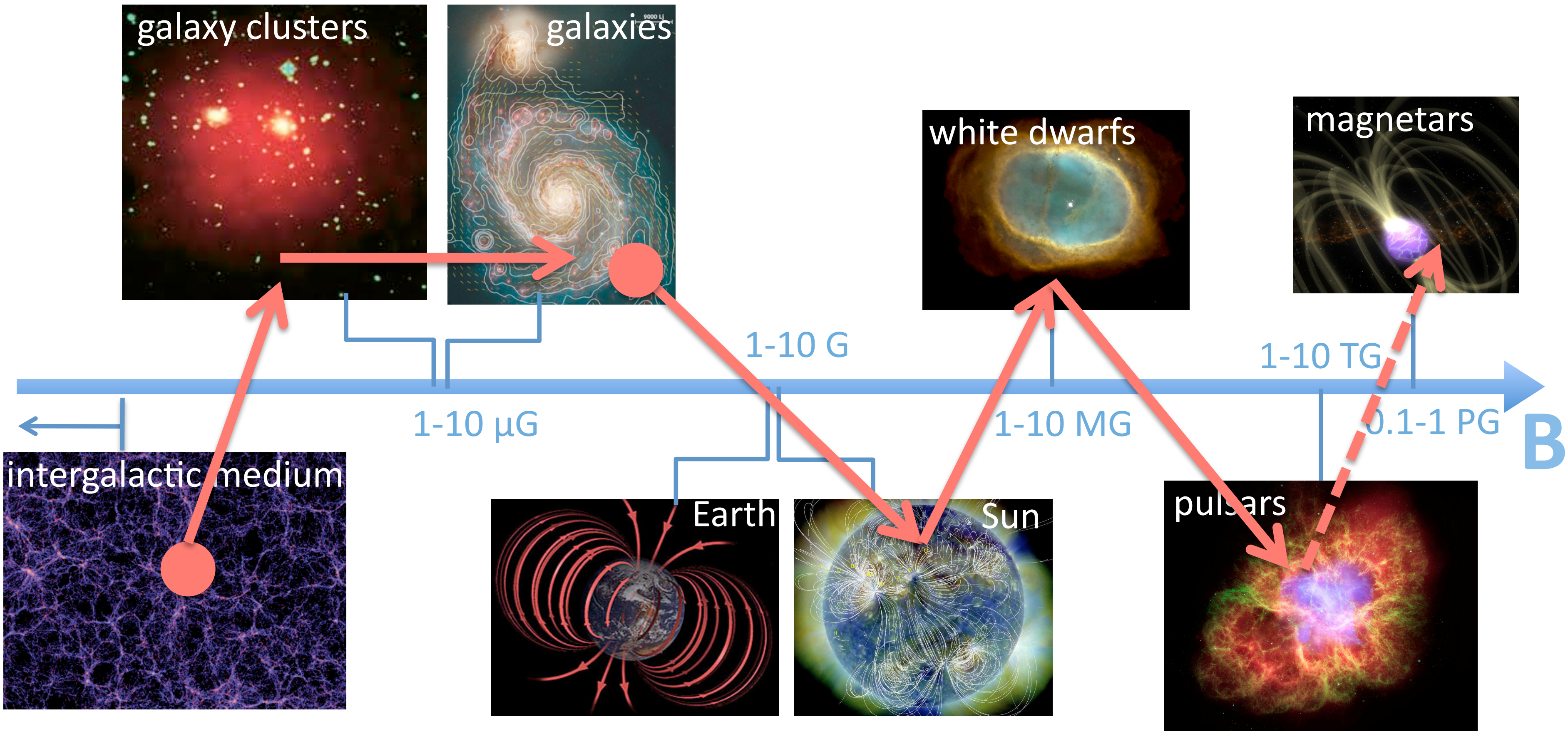


If galaxy and cluster magnetic fields are produced via flux-conserving compression of pre-existing magnetic fields, strength of magnetic fields in them should be different:

$\Phi \sim B_0\, L_0^2 \sim BL^2 \sim$const:
$(L/L_0) \sim 10^6$ in galaxies while $(L/L_0) \sim 10^3$ in clusters

How could clusters and galaxies have comparable magnetic fields?

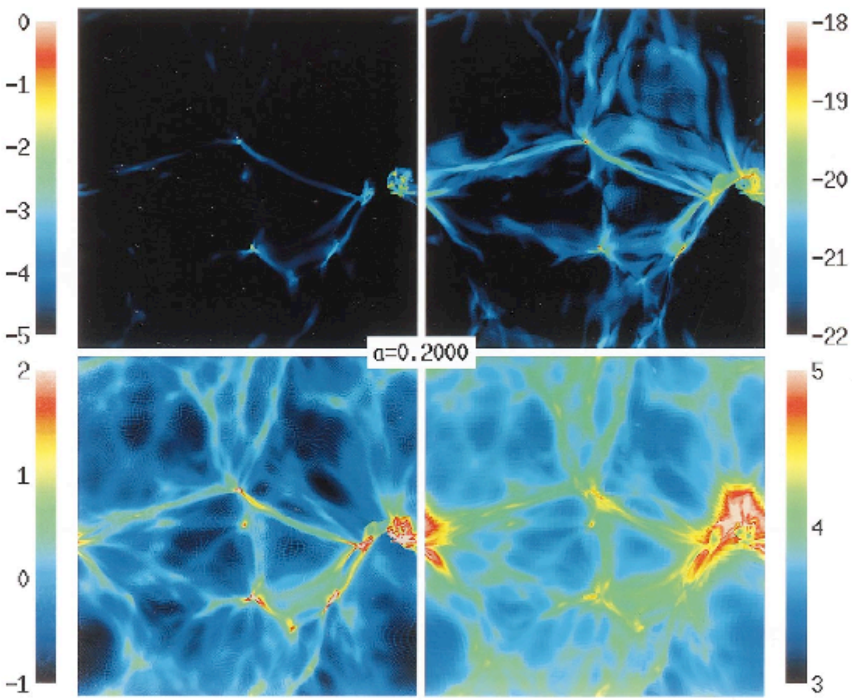
Problems of cosmic magnetogenesis



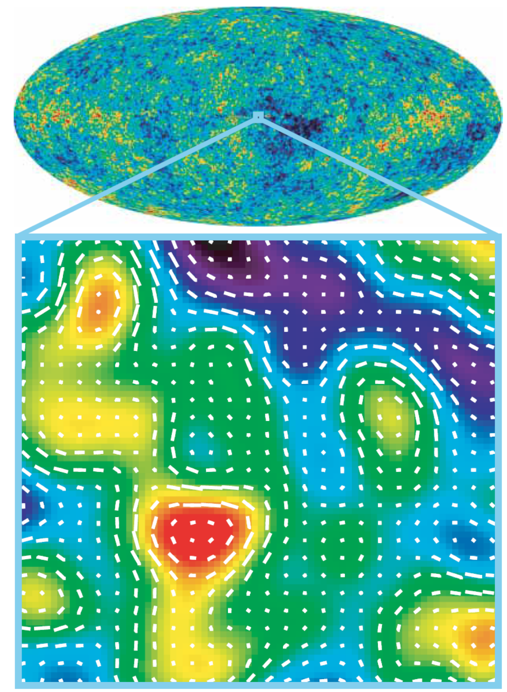
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \frac{1}{\sigma} \nabla^2 \vec{B}$$

$B=0$ is a solution of induction equation..... Where do the initial fields for amplification come from?

Origin of "seed" magnetic fields



Gnedin et al. '00

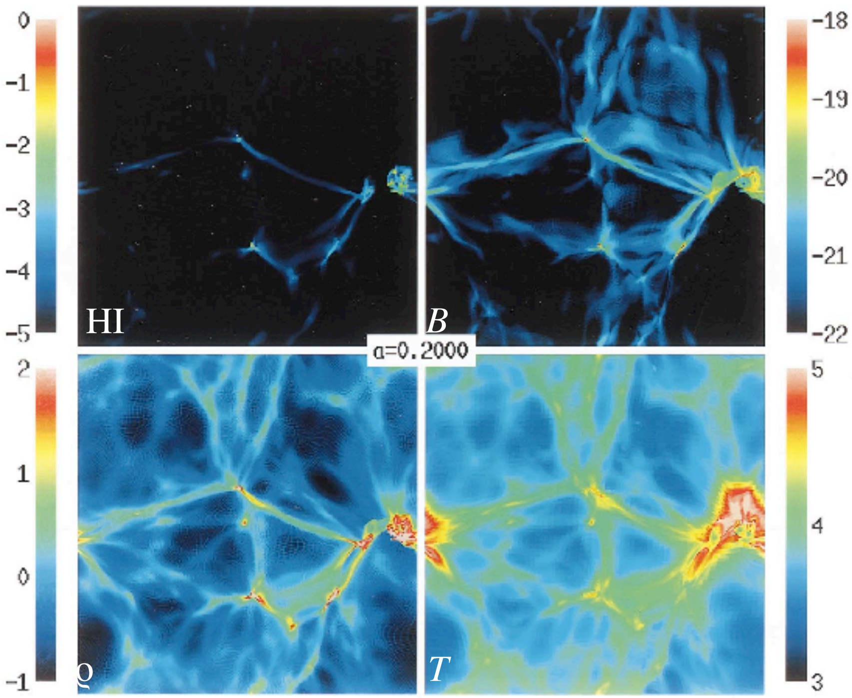


Takahashi et al. '06

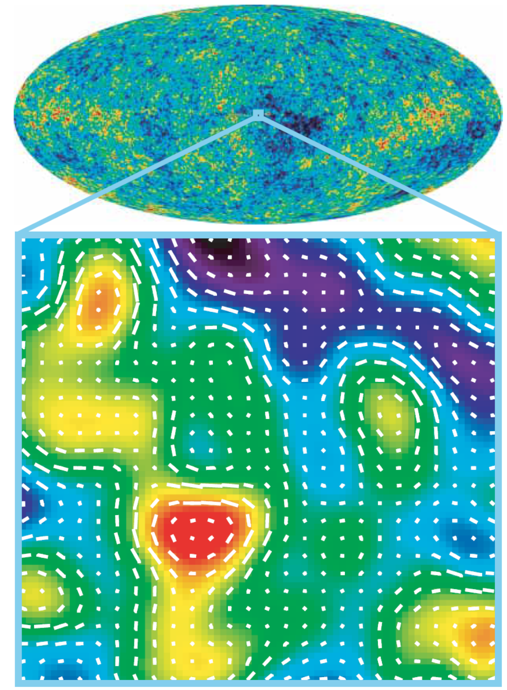
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \frac{1}{\sigma} \nabla^2 \vec{B}$$

A "Biermann battery" source term appears in the induction equation in certain situations in which the difference of inertia of electrons and protons in the plasma is important.

Origin of "seed" magnetic fields



Gnedin et al. '00



Takahashi et al. '06

"**Astrophysical**" scenaria: seed magnetic fields are generated via "Bierman battery" mechanism during structure formation

"**Cosmological**" scenaria assume that the same type of mechanism is working at the moments of phase transitions in the Early Universe

Measurement of the "seed" fields which possibly might exist in the unamplified form in the voids of the Large Scale Structure might provide strong constraints on the possible models of the origin of magnetic fields in the Universe.

Measurement of "seed" fields?

Weak magnetic fields in the intergalactic medium (IGM) are difficult to measure (not enough matter to trace the fields…)

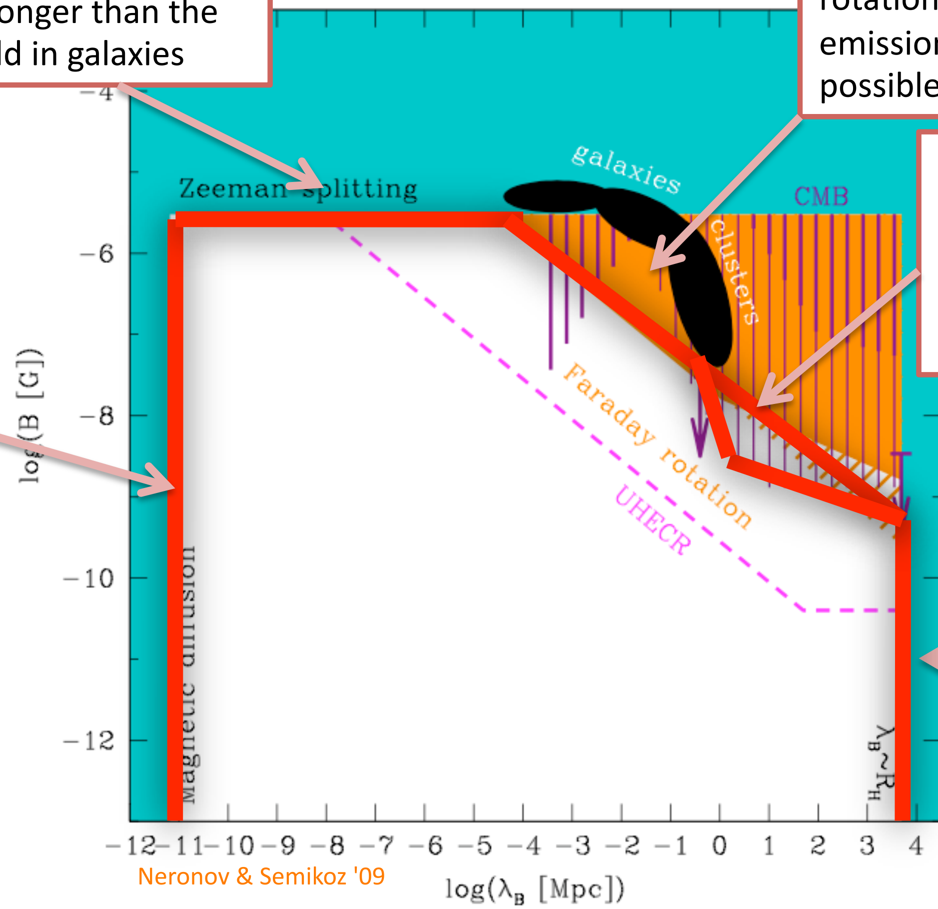
Magnetic field in the IGM is not stronger than the field in galaxies

Non-observation of Faraday rotation of polarized radio emission from quasars limits possible magnetic fields in IGM

Non-observation of magnetic field induced features in the anisotropy of CMB limits magnetic fields produced before Recombinaiton

Resistive decay removes short-correlation length fields in $T<10$ Gyr

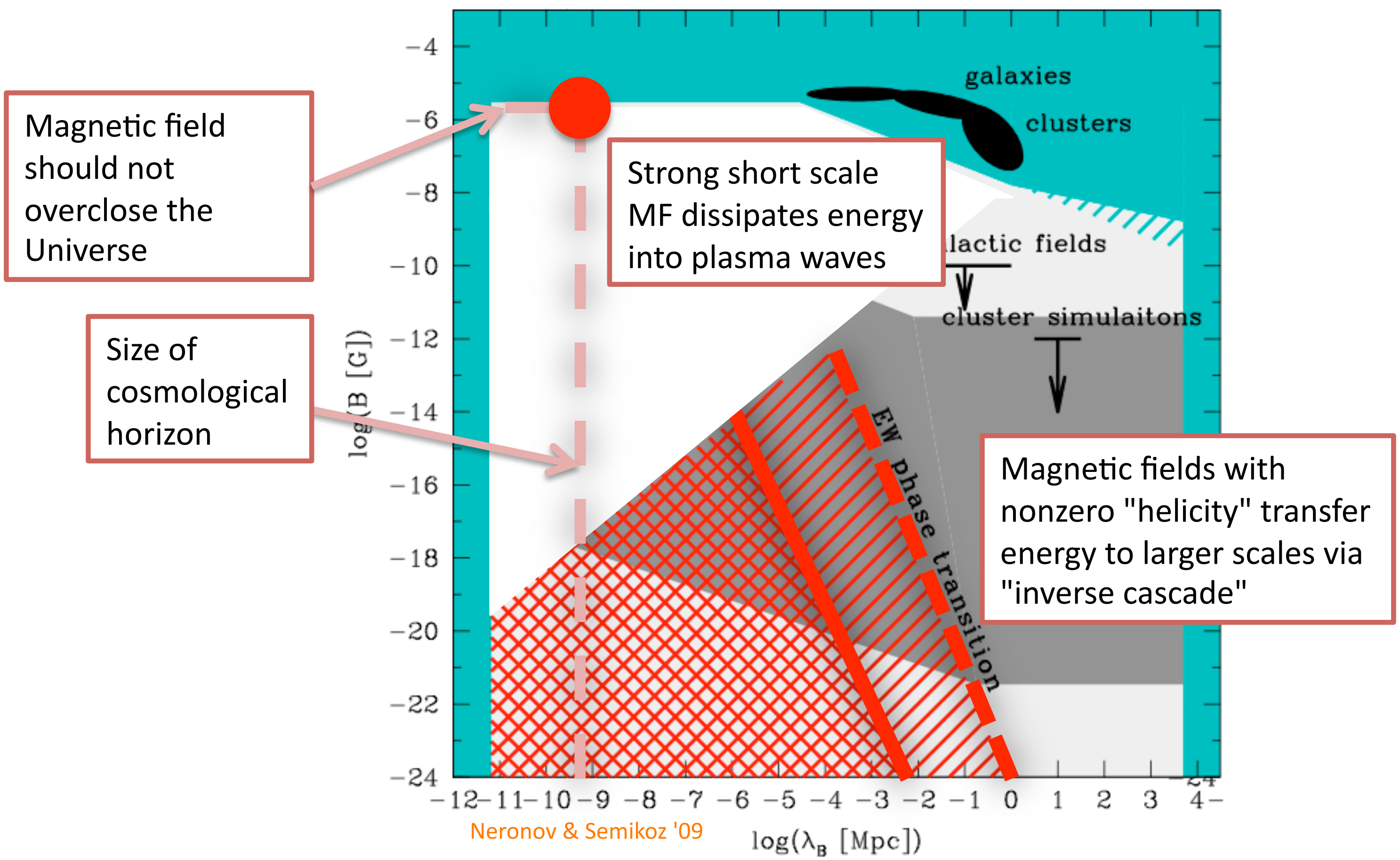
Magnetic field homogeneity scale can, in principle, be comparable to the size of the Universe



Neronov & Semikoz '09

Cosmological models for the seed fields

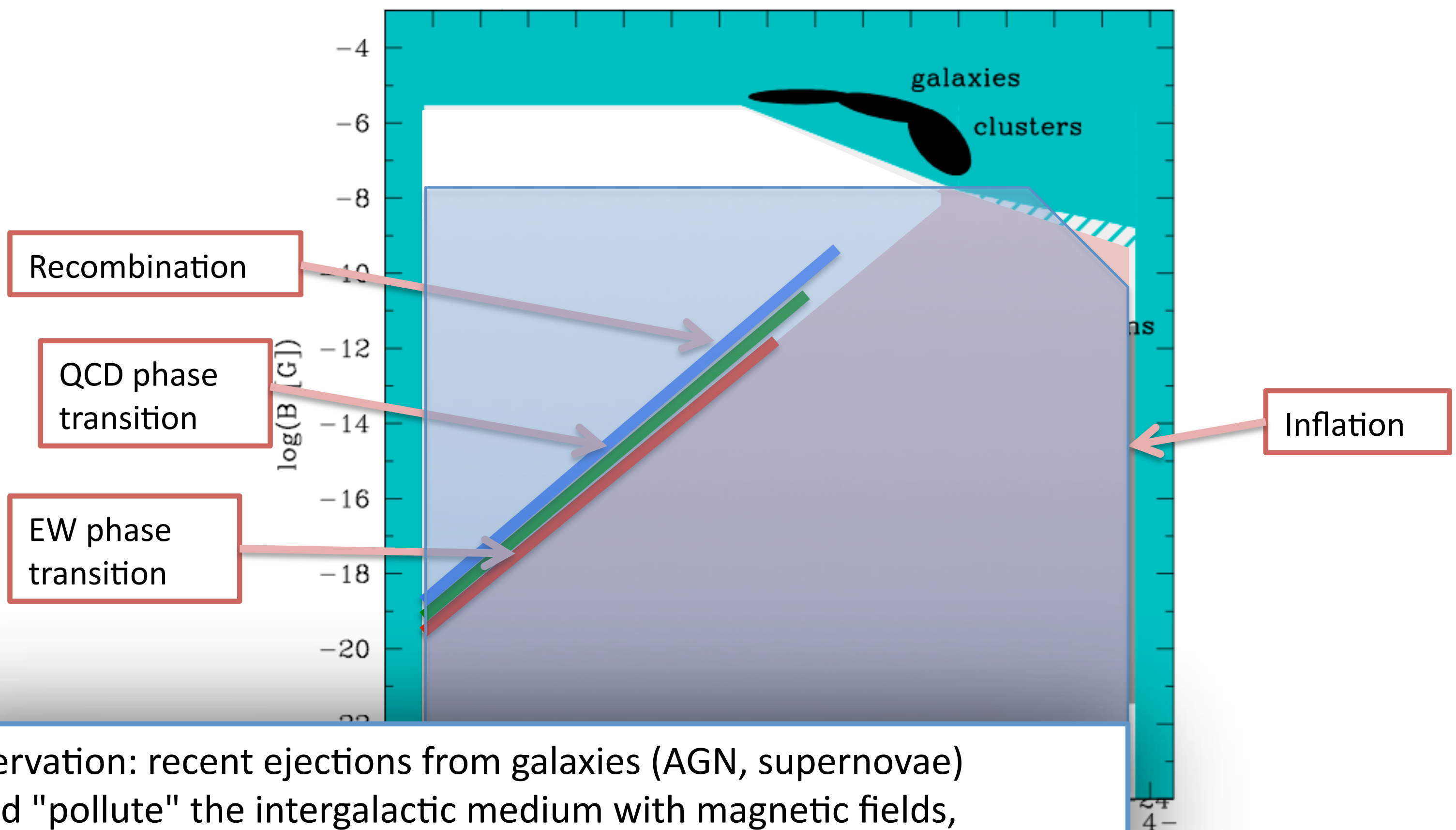
Magnetic fields could be produced at the moments of phase transitions in the Early Universe.



Cosmological models for the seed fields

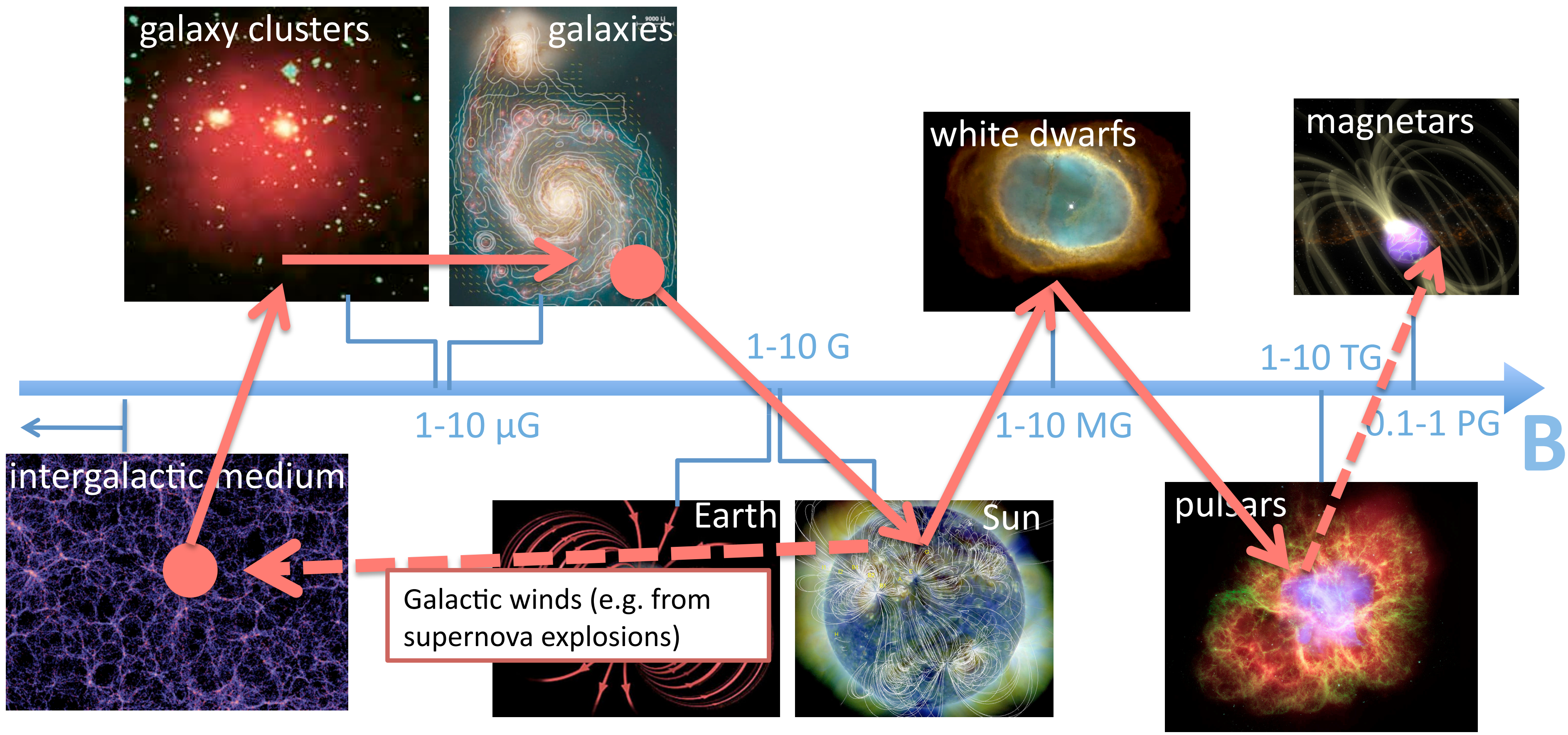
Magnetic fields could be produced at the moments of phase transitions in the Early Universe.

Measurement of parameters of magnetic fields in the intergalactic medium might provide a clue about their origin

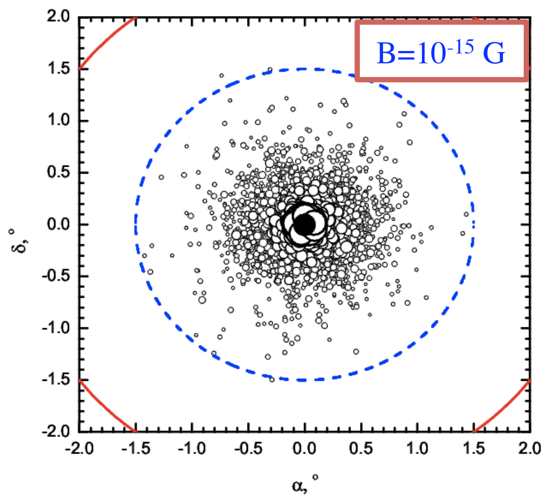


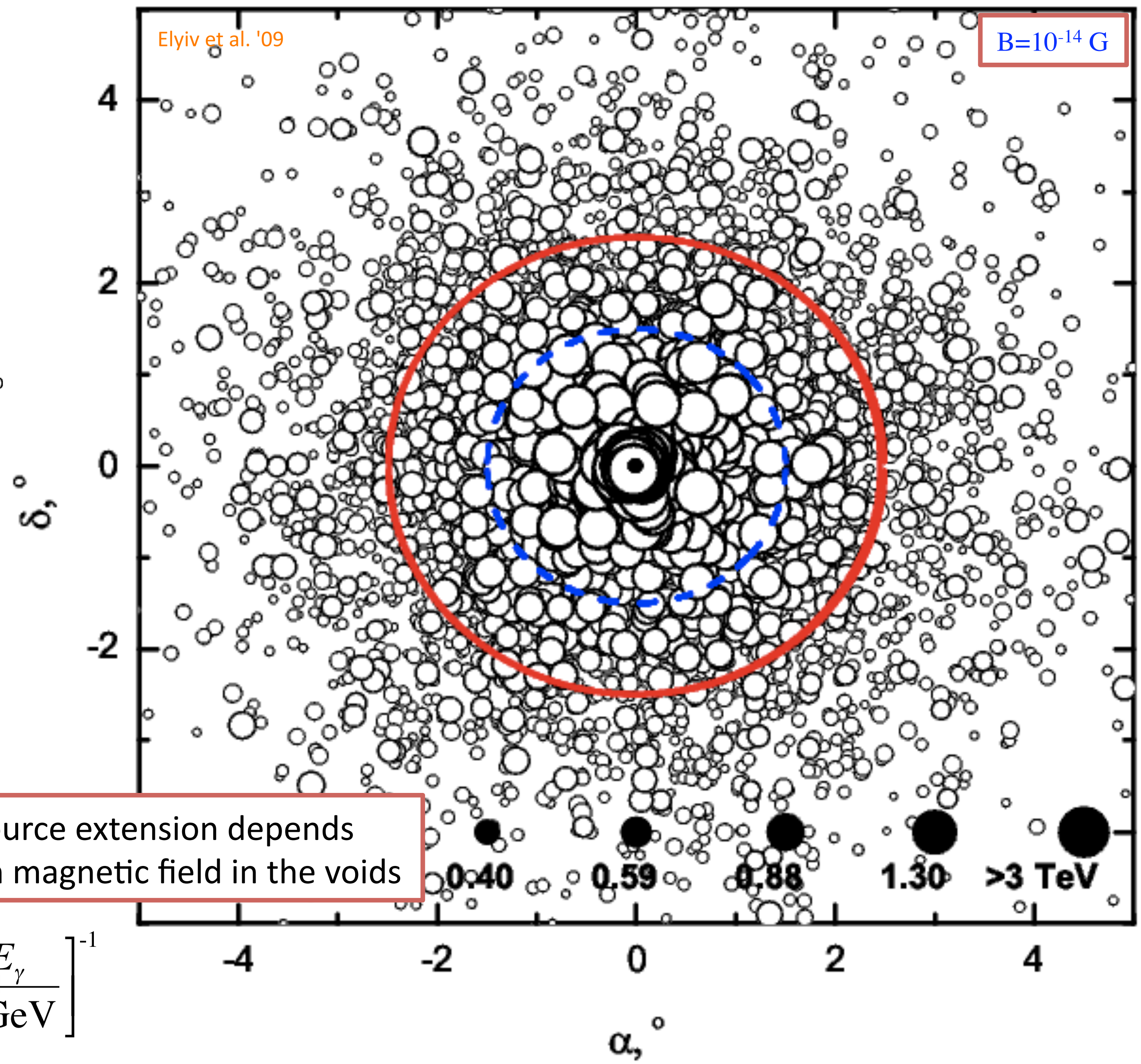
Reservation: recent ejections from galaxies (AGN, supernovae) could "pollute" the intergalactic medium with magnetic fields, Which are much stronger than the initial seed fields

Problems of cosmic "magnetogenesis"



Measurement of magnetic fields in IGM



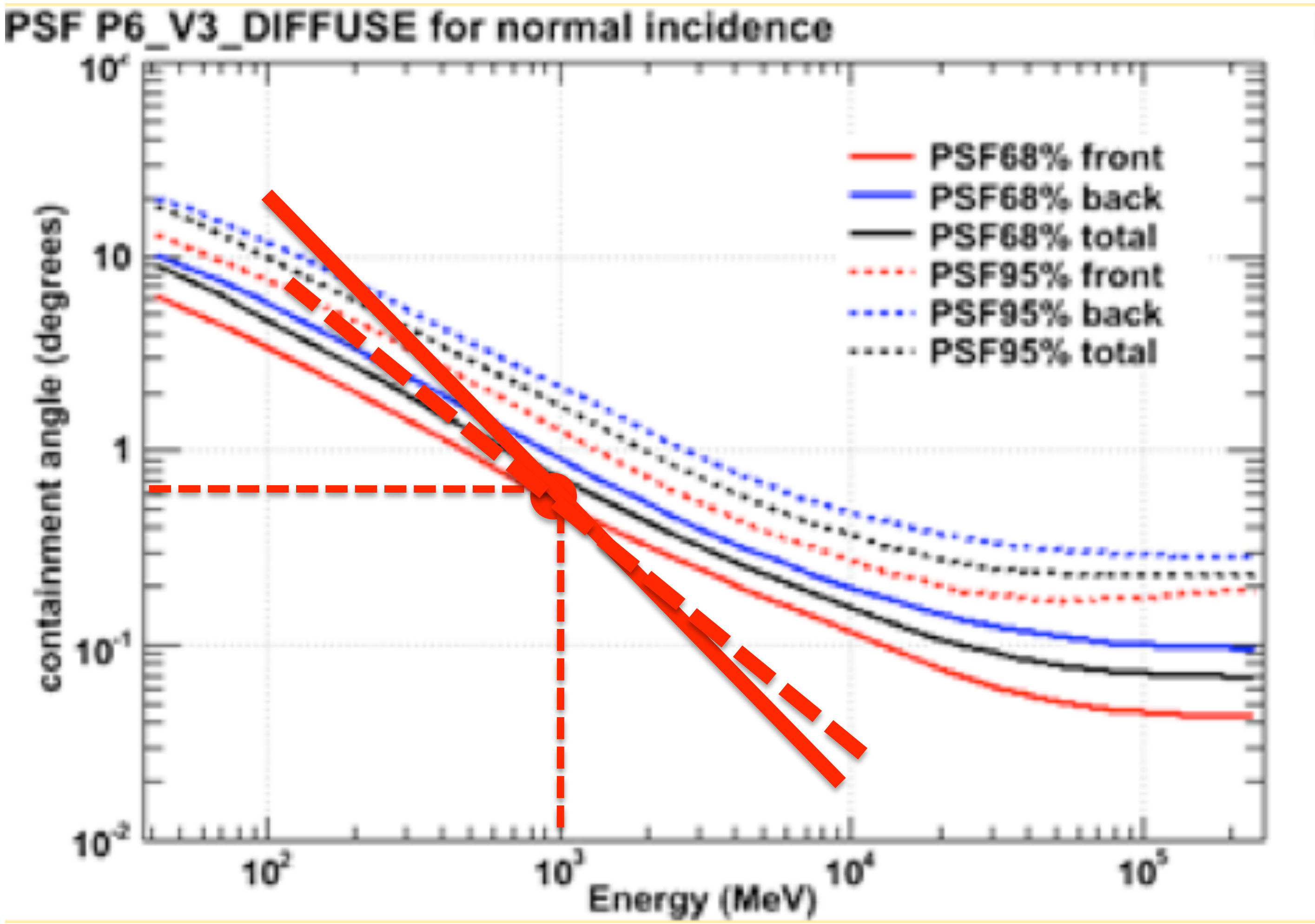


optical depth for gamma-rays $\tau = D/\lambda_{\gamma\gamma}$

Source extension depends on magnetic field in the voids

$$\Theta \approx \frac{\delta}{\tau_0} = 0.4^\circ \frac{1}{\tau}\left[\frac{B}{10^{-17}\,\mathrm{G}}\right]\left[\frac{E_\gamma}{1\,\mathrm{GeV}}\right]^{-1}$$

Measurement of magnetic fields with Fermi



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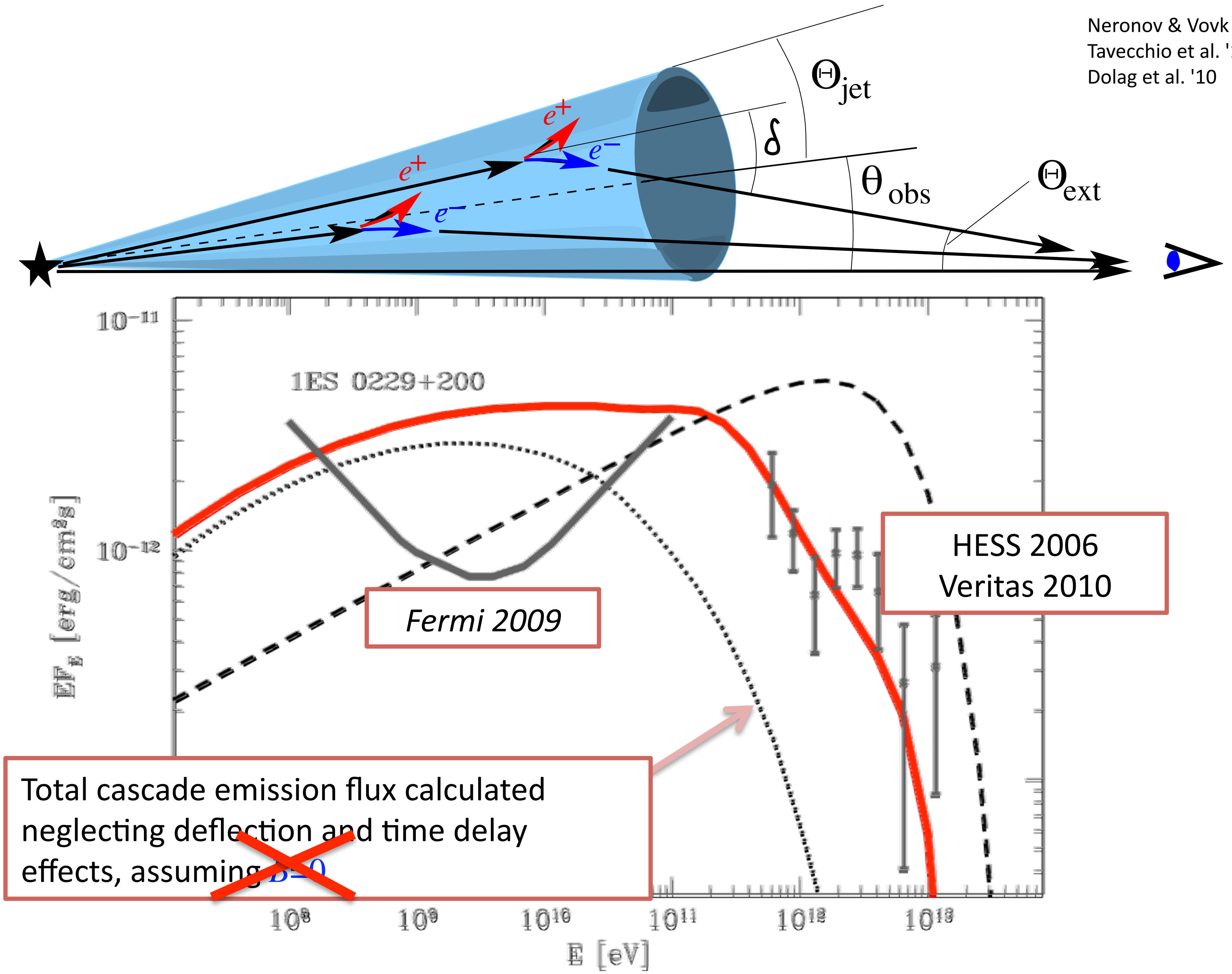
Fermi observations of extended emission from the cascade emission are sensitive to magnetic fields in the range $B \geq 10^{-17}$ G

Measurement of magnetic fields with Fermi

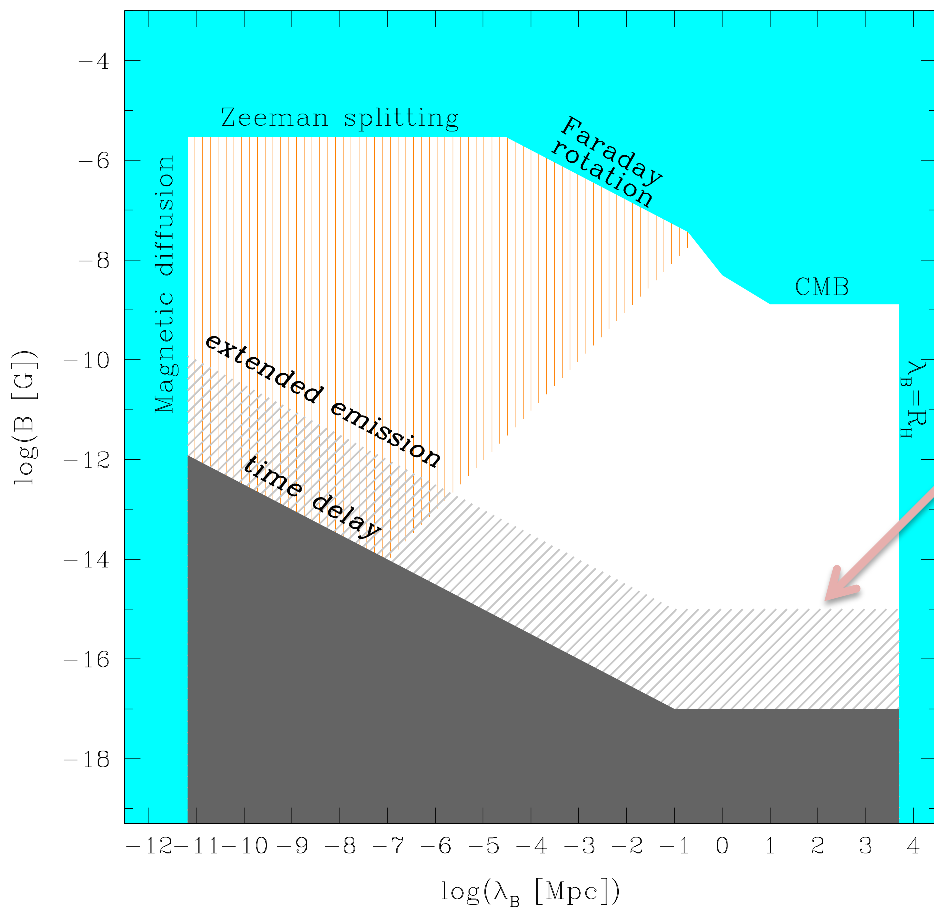
Neronov & Vovk '10
Tavecchio et al. '10
Dolag et al. '10



Lower bound on magnetic fields in IGM

Fermi upper bound on the cascade flux is inconsistent with assumption of negligible magnetic fields along the line of sight

Gamma-ray data could be used to derive a **lower bound** on magnetic field in the intergalactic medium

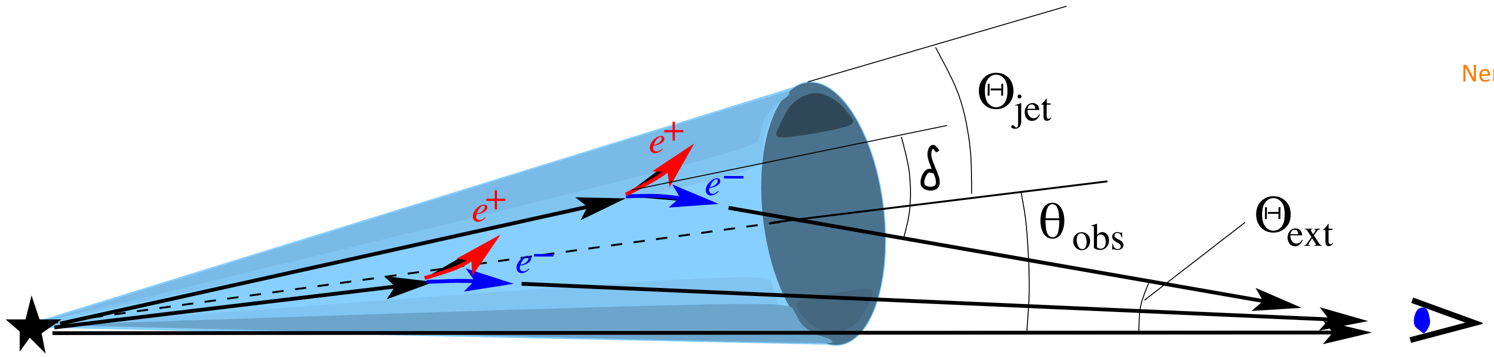


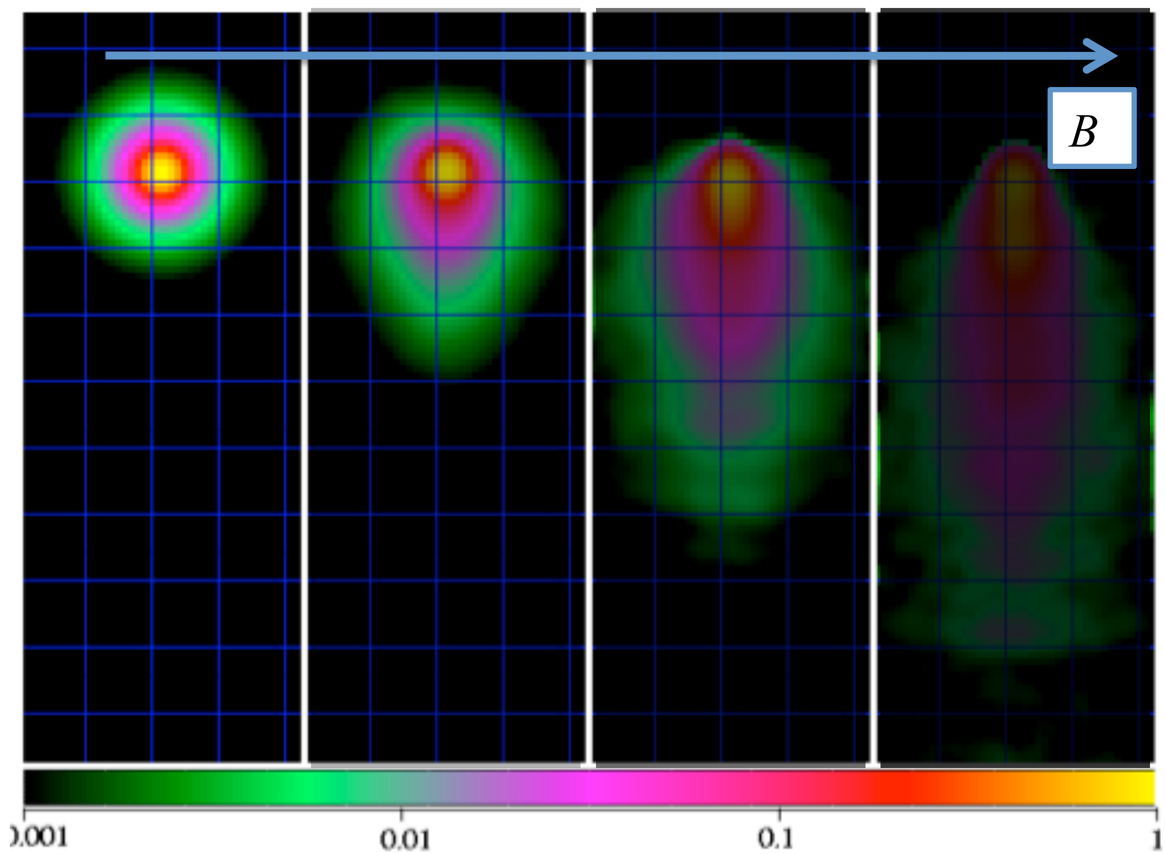
Extension of the cascade source is larger than point-spread function of Fermi telescope

Neronov & Vovk '10
Tavecchio et al. '10
Dolag et al. '10

Detectability of extended emission

Neronov et al. '10





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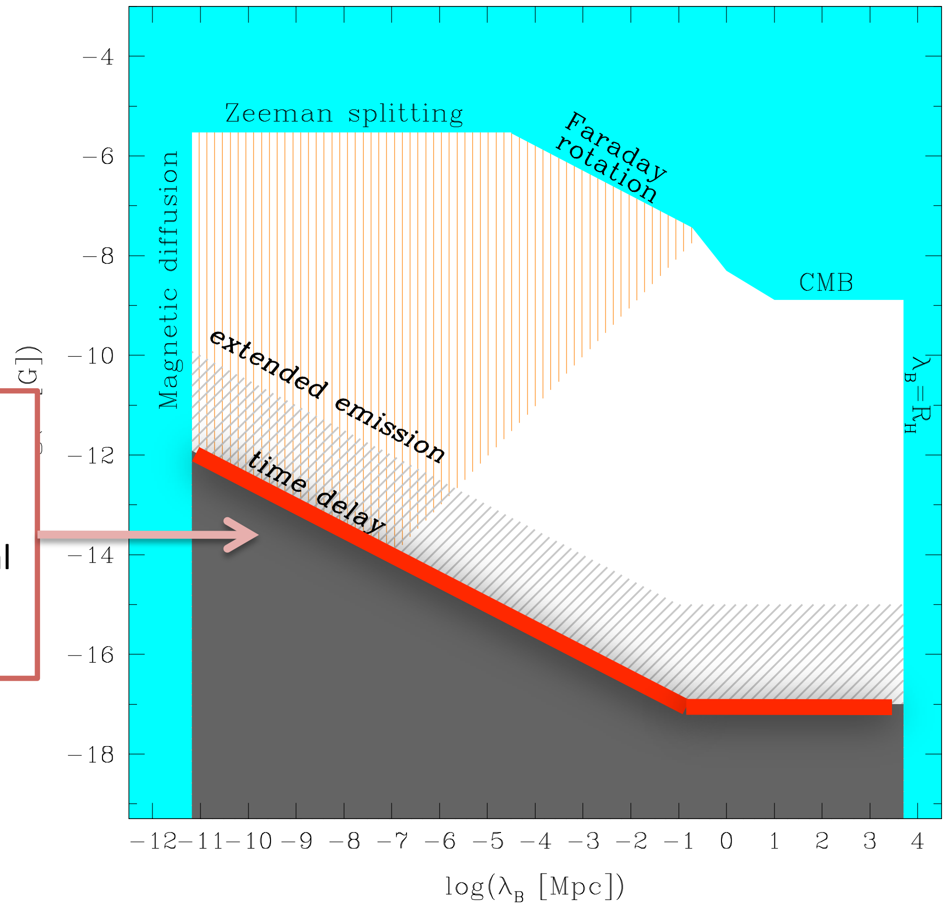
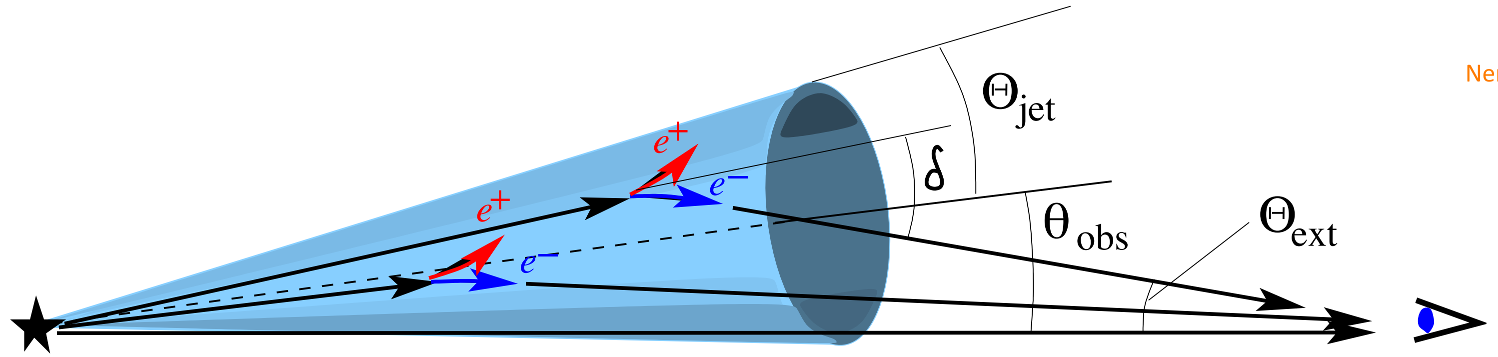


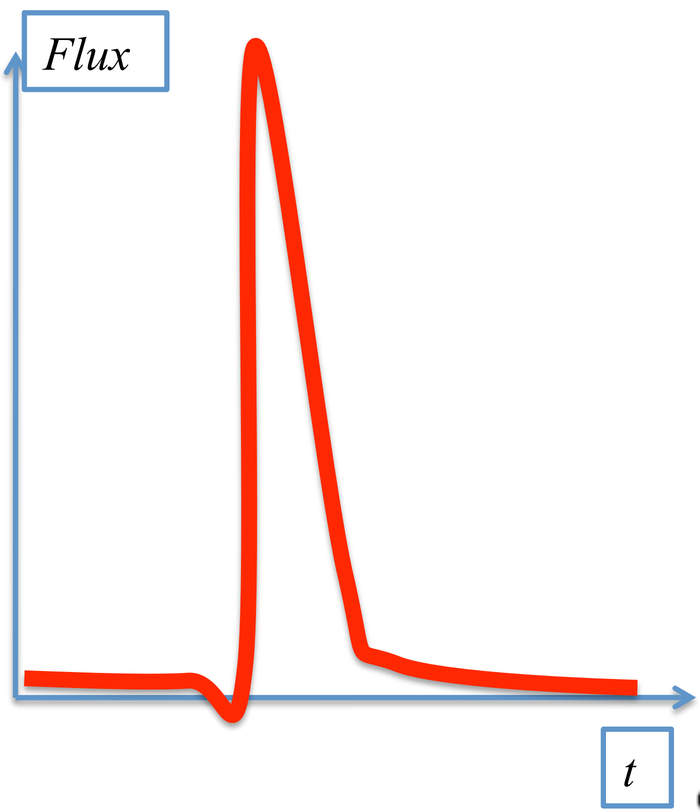
Time delay of the cascade source is larger than assumed source activity period (= several years of gamma-ray observations)

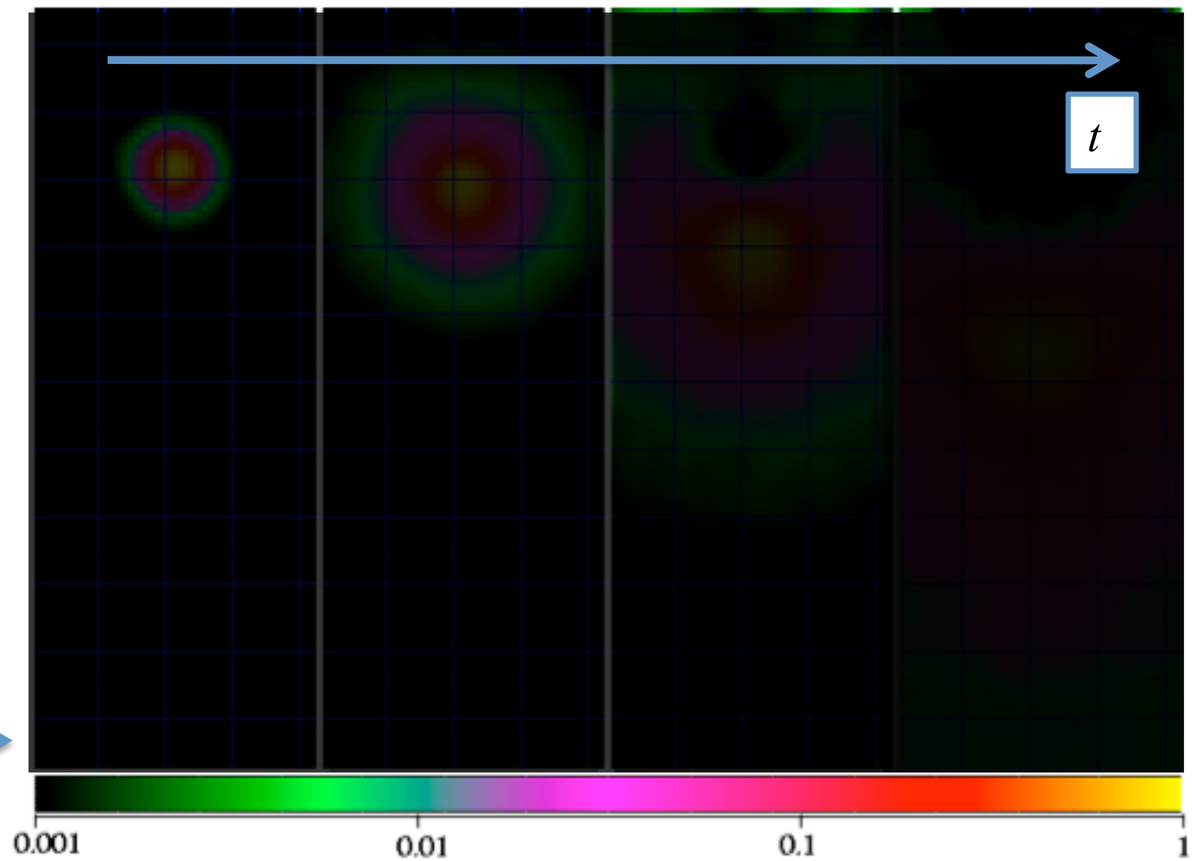
Dermer et al. '10
Taylor, Vovk, Neronov '10

Detectability of time-delayed emission

Neronov et al. '10



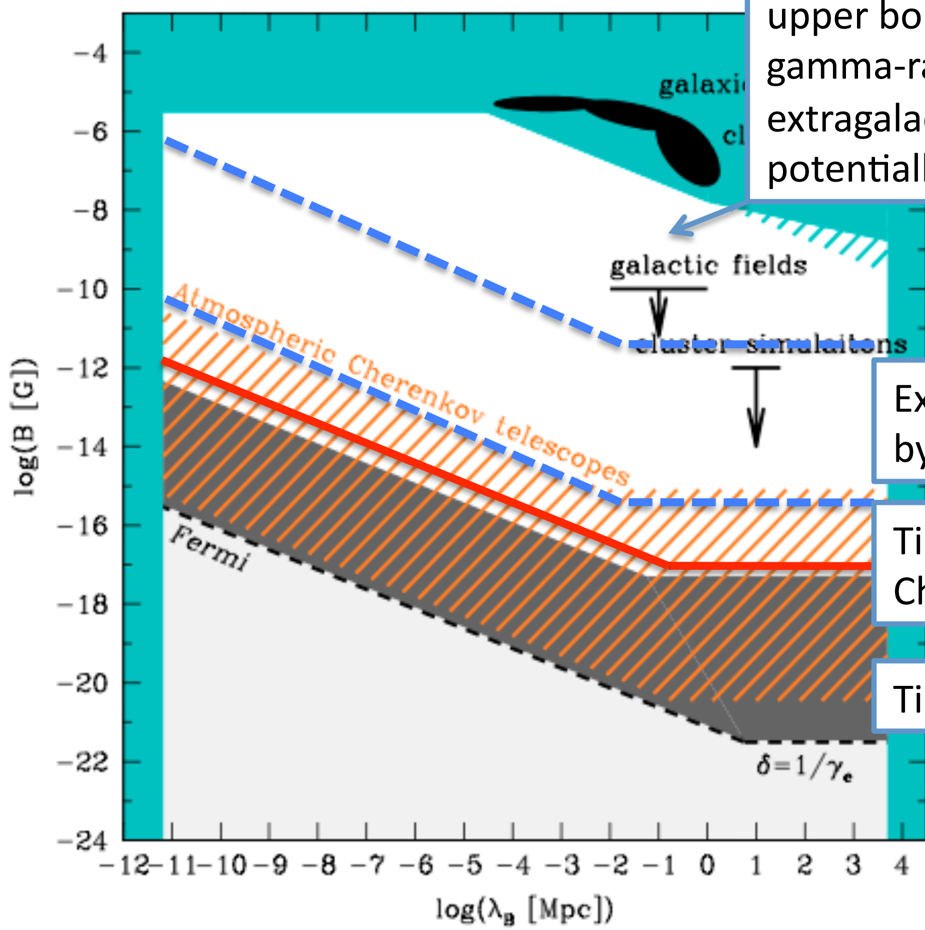




Measurement of magnetic fields in IGM?

Deeper exposure with Fermi might finally lead to detection of extended emission around extragalactic TeV sources, if magnetic field in IGM is close to the derived lower bound.

Stronger magnetic fields could be probed by ground-based gamma-ray telescopes, able to search for extended emission or time delay at higher energies.



Magnetic fields close to the existing upper bounds lead to isotropized gamma-ray halos around extragalactic sources. This effect is potentially also detectable.

Extended emission measurable by Cherenkov telescopes

Time delay measurable by Cherenkov telescopes

Time delay measurable by LAT

Summary

Absorption of TeV gamma-rays in intergalactic space and subsequent re-emission of gamma-rays by e^+e^- pairs leads to appearance of extended and time delayed gamma-ray emission around extragalactic very-high-energy gamma-ray sources.

This emission could be detectable by Fermi and/or ground-based Cherenkov gamma-ray telescopes.

Detection of inverse Compton emission from e^+e^- pairs deposited in the intergalactic medium would provide information on the strength of magnetic field in the voids of Large Scale structure.

Information on the properties of magnetic fields in intergalactic medium is important in the context of the problem of origin of magnetic fields in the Universe.

Non-detection of secondary emission from e^+e^- pairs by Fermi imposes a lower bound on the strength of magnetic field in the intergalactic medium at the level of $\sim 10^{-17}$ G if the signal is suppressed because of the time delay of the secondary emission and $\sim 10^{-16}$ G if suppression is due to the large extension of the secondary source.

Future observations (deeper exposures or more sensitive telescopes) will probe most of the range of possible magnetic field strengths in the intergalactic medium.