Magnetogenesis from cosmological perturbations

Keitaro Takahashi
YITP, Kyoto University
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with
K. Ichiki, H. Hanayama & N. Sugiyama

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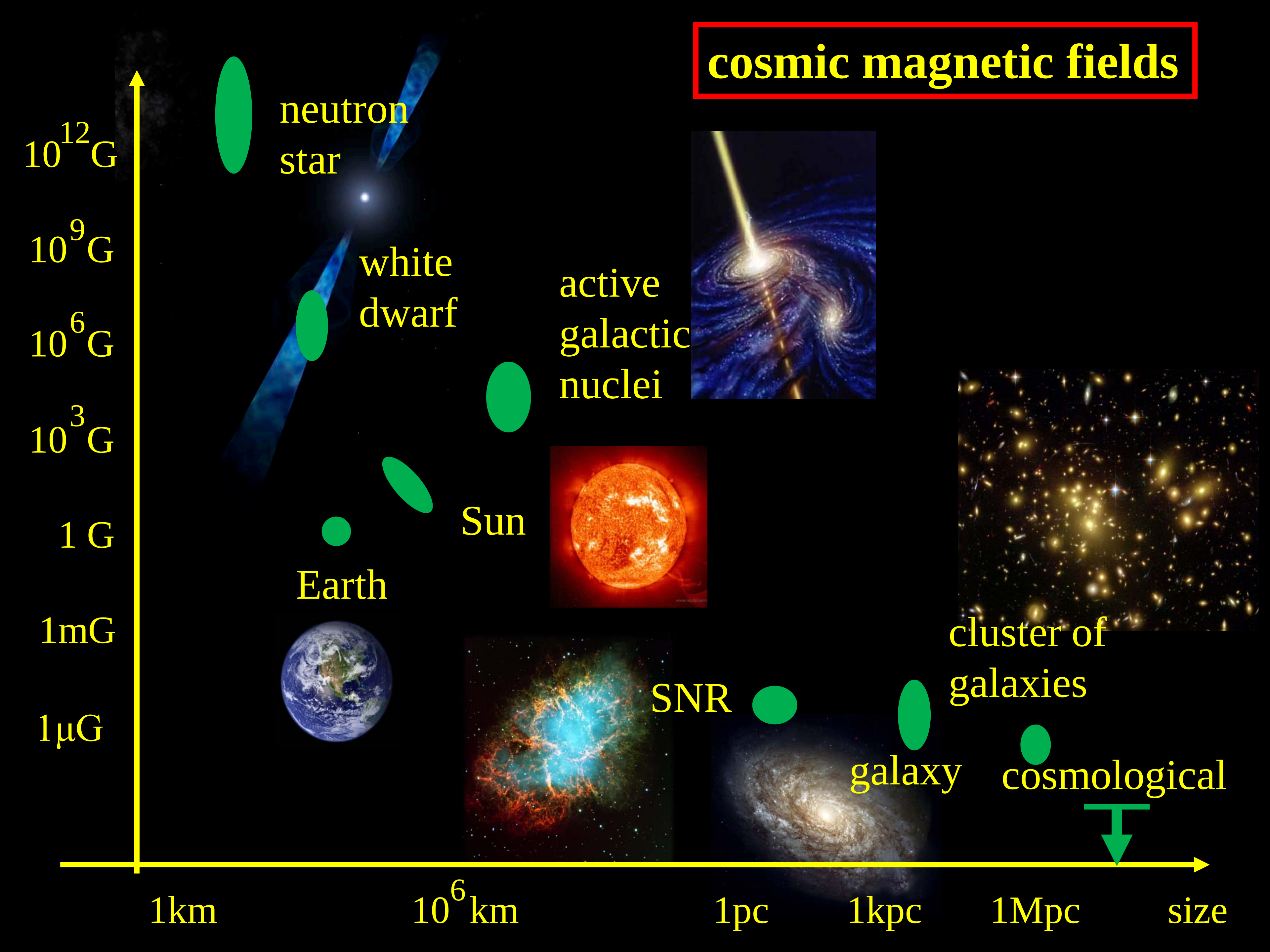
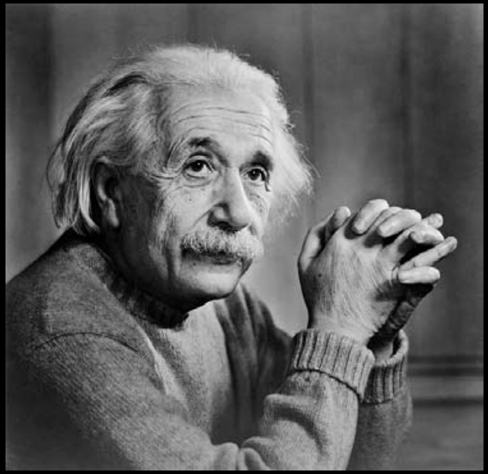
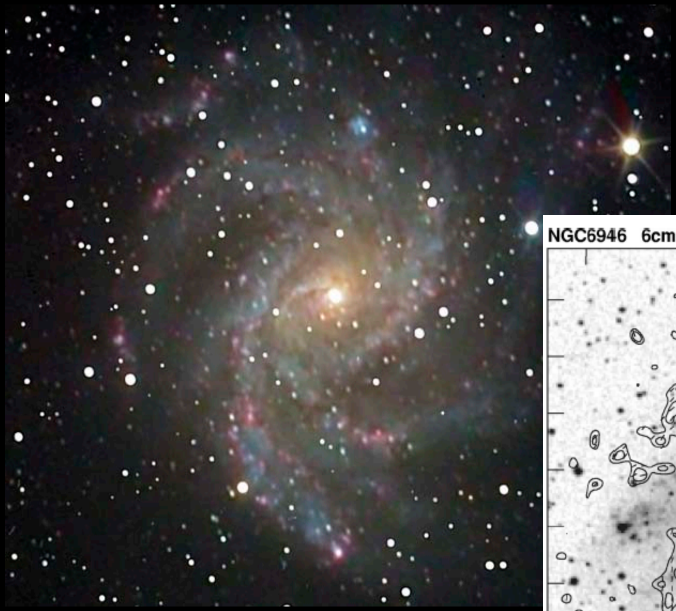

cosmic magnetic fields
10^{12}G
10^{9}G
10^{6}G
10^{3}G
1 G
1mG
1μG
neutron
star
white
dwarf
active
galactic
nuclei
Sun
Earth
SNR
galaxy
cluster of
galaxies
cosmological
1km
10^{6}km
1pc
1kpc
1Mpc
size

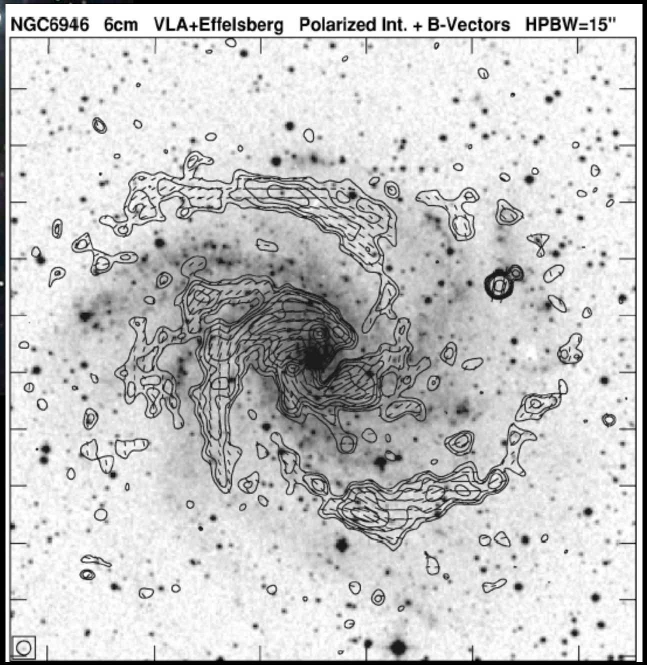


Origin of geomagnetic fields is one of the greatest mystery in modern physics.

→ Origin of magnetic fields of astronomical objects.
Cosmological magnetic fields?



NGC6946



galactic fields ~ 1μG

↑

galactic dynamo

↑

tiny seed fields 10^{-20} G

↑

seed-field generation before galaxy formation

seed-field generation

cosmological

- inflation (Turner & Widrow 1988, Ratra 1992)
- phase transition (Quashnock et al. 1989)

→ unknown high energy physics

astrophysical (Biermann mechanism)

- first star (Hanayama et al. 2005)
- protogalaxy (Davis & Widrow 2000)
- reionization (Gnedin et al. 2000)
- large scale structure (Kulsrud et al. 1997)

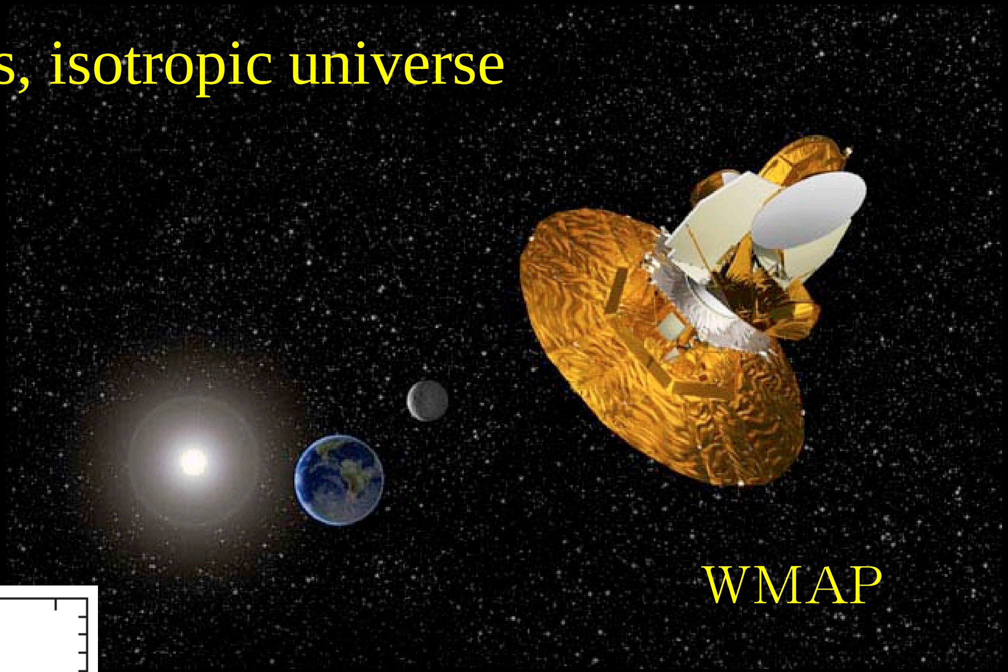
→ not fully understood

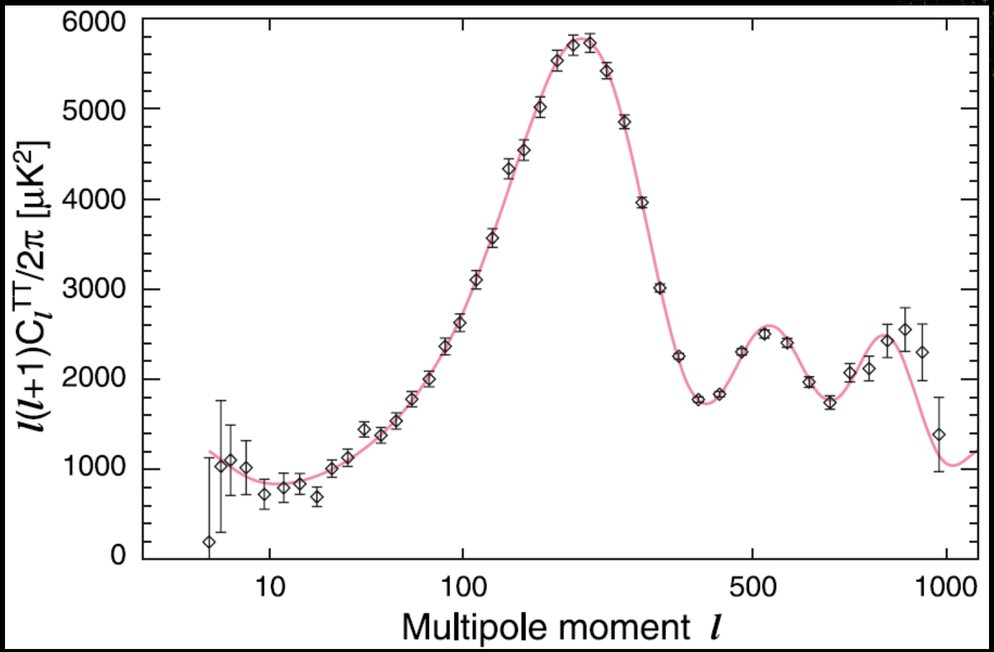
generation from density fluctuations in the early universe
→ based on cosmological perturbation theory

cosmological perturbations

deviation from homogeneous, isotropic universe

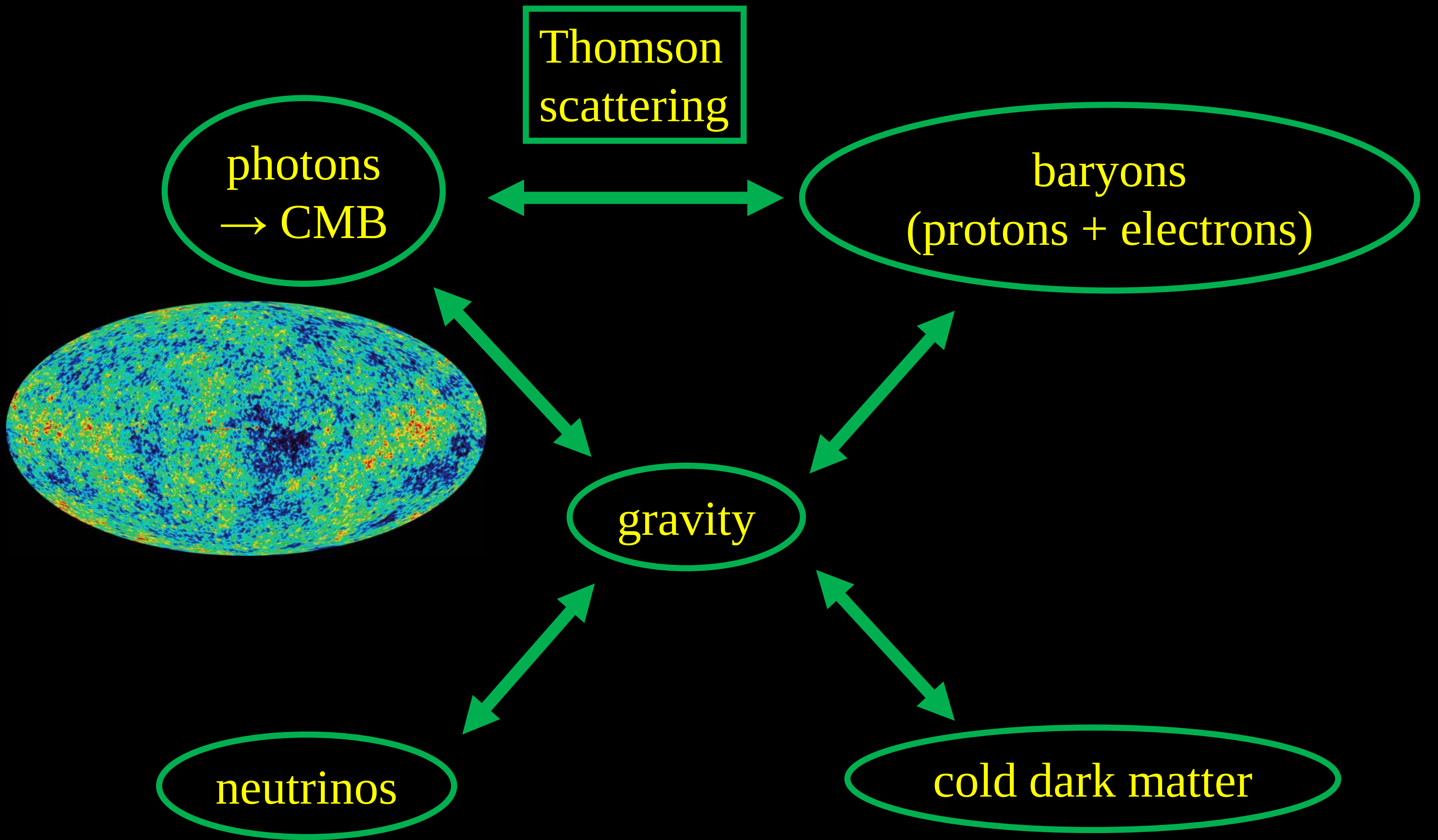
- CMB
  → COBE, WMAP・・・
- galaxy distribution
  → SDSS, 2dF・・・



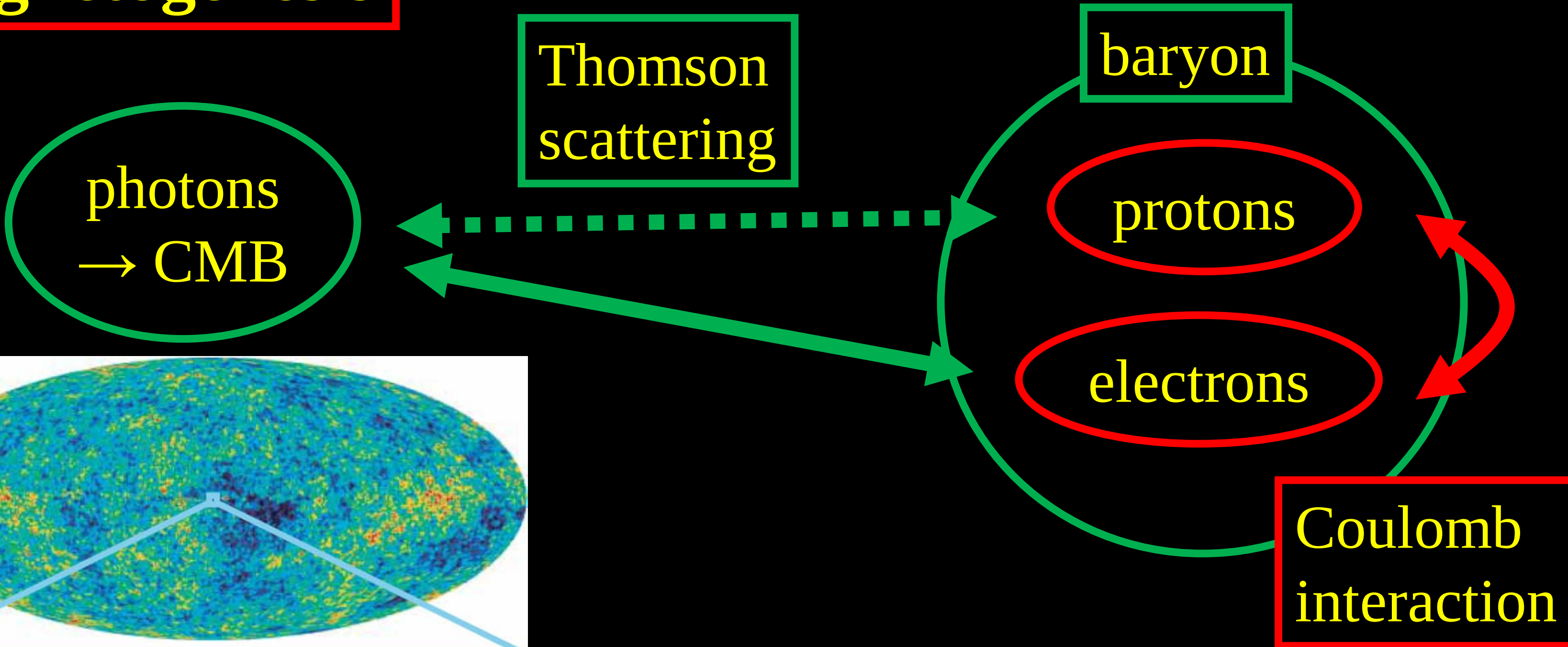


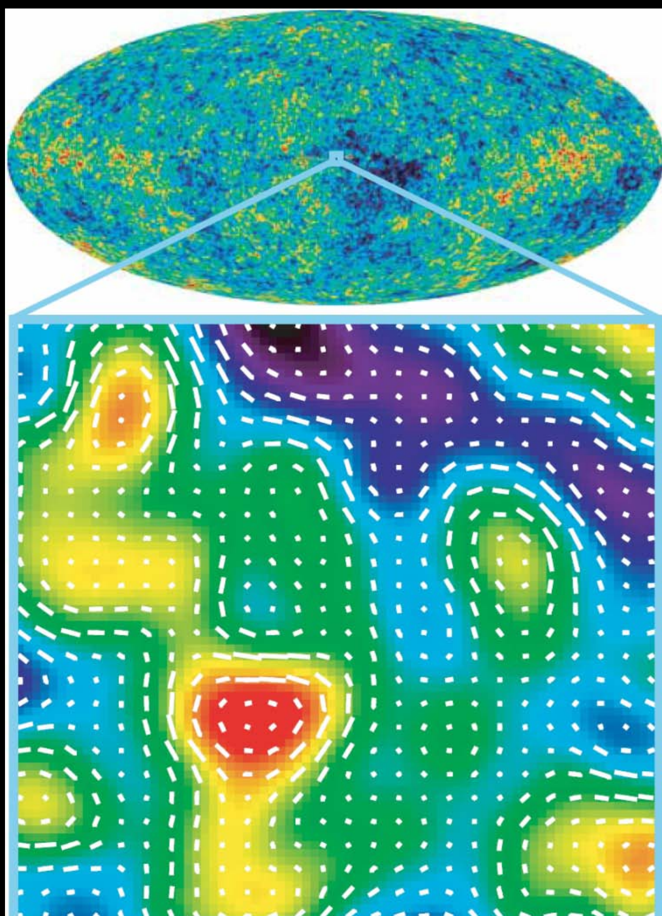
We know the exsistence and basic behavior of cosmological perturbations.

components of the universe



magnetogenesis





Thomson scattering
→ deviation in motion
due to mass difference
→ net electric charge density
and electric current
→ magnetic fields

Extensions to the conventional formalism

What do we need for magnetogenesis?

$$\partial_t \vec{B} = -\nabla \times \vec{E}$$

electric field and its rotation

electric field

- Conventionally, baryons
- Separate treatment of p and e is necessary.

rotational part

- No rotational part at the linear order
- generated by nonlinear effect
  Linear order is sufficient for CMB but insufficient for B.

Two extensions are needed for magnetogenesis.

generalized Ohm's law

EOMs

$$m_p n u_p^\mu u^i_{p;\mu} - e n u_p^\mu F_\mu{}^i = 0,$$

$$m_e n u_e^\mu u^i_{e;\mu} + e n u_e^\mu F_\mu{}^i$$

$$= -\frac{4\sigma_T \rho_\gamma n}{3}\left[(u_e^i - u_\gamma^i) + \frac{1}{8} u_{ej} \Pi_\gamma^{ij}\right]$$

photon pressure

anisotropic stress

generalized Ohm's law

$$u^\mu F^i{}_\mu = -\frac{4\sigma_T \rho_\gamma}{3e}\left[(u_e^i - u_\gamma^i) + \frac{1}{8} u_{ej} \Pi_\gamma^{ij}\right] + \eta\, j$$

$E + v \times B$

resistivity

evolution equation for B

Maxwell equations and Ohm's law

$$
\begin{aligned}
\dot{B}^i &\sim -\epsilon^{ijk} C_{j,k} \\
&\sim \frac{4\sigma_T \overset{(0)}{\rho}_\gamma}{3e}\epsilon^{ijk}\left[\frac{\overset{(1)}{\rho}_{\gamma,k}}{\overset{(0)}{\rho}_\gamma}\left(\overset{(1)}{u}_{ej} - \overset{(1)}{u}_{\gamma j}\right) + \left(\overset{(2)}{u}_{ej,k} - \overset{(2)}{u}_{\gamma j,k}\right)\right. \\
&\quad \left. + \frac{1}{8}\left(\overset{(1)}{u}_{el,k}\overset{(1)}{\Pi}{}^{l}_{\gamma j} + \overset{(1)}{u}_{el}\overset{(1)}{\Pi}{}^{l}_{\gamma j,k}\right)\right]
\end{aligned}
$$

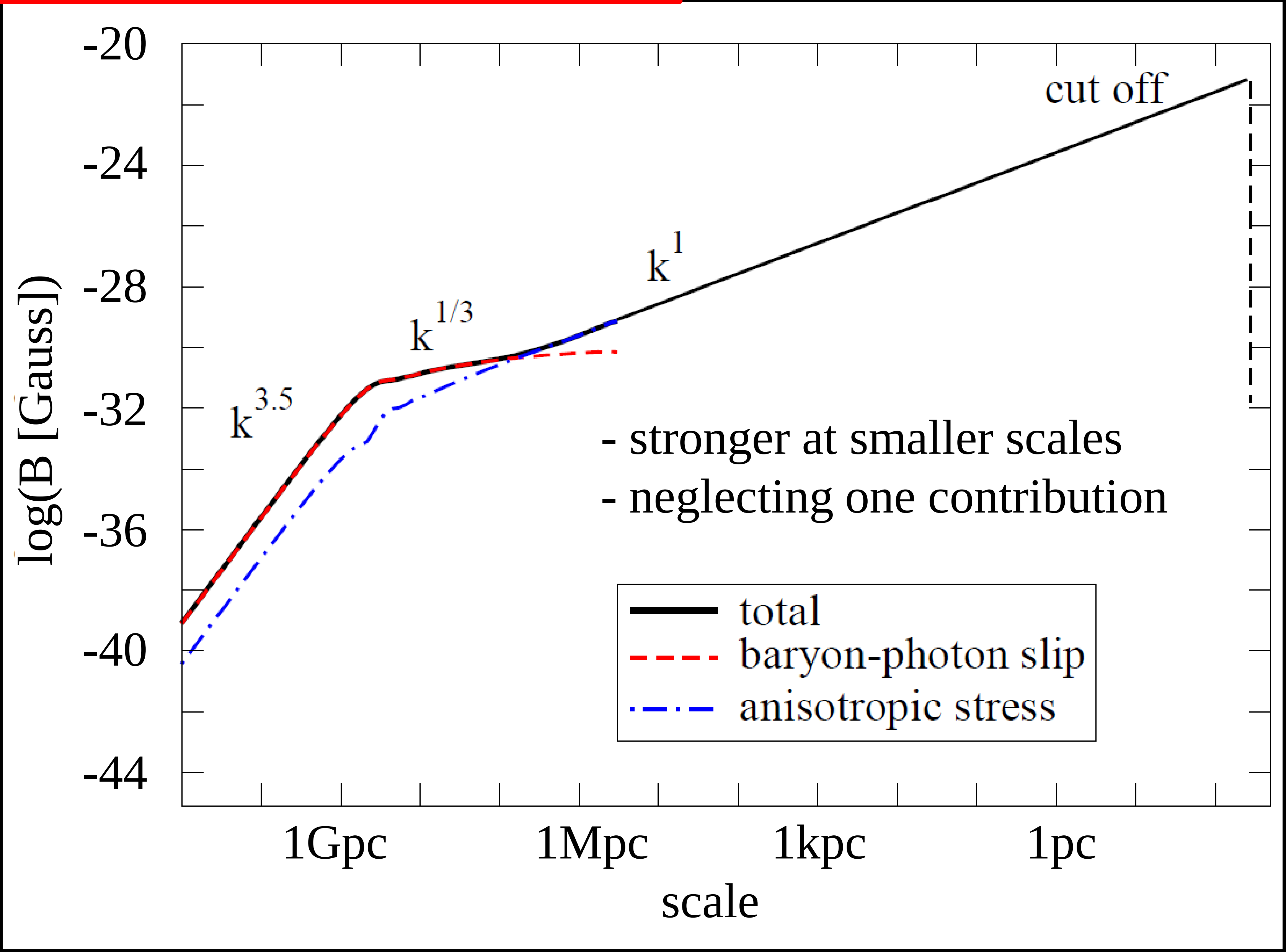
photon pressure

vorticity difference

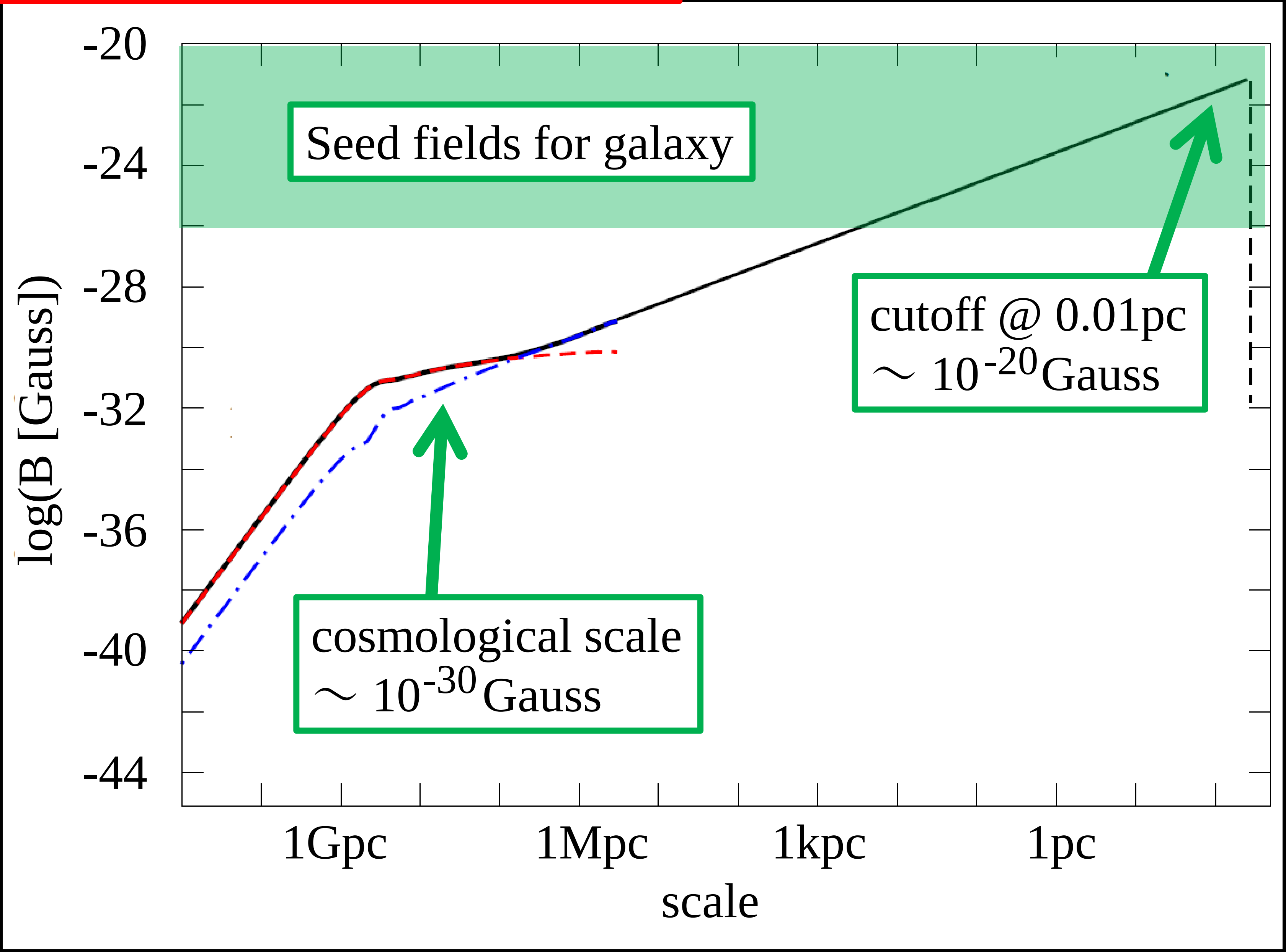
anisotropic stress

B is a time integration of these three source terms.

Spectrum of magnetic fields



Spectrum of magnetic fields



Conclusion

magnetogenesis from cosmological perturbations
in the early universe

* cosmological perturbation theory
  - well understood observationally and theoretically
  - no assumption and new parameter

* extensions to the conventional formalism
  - separate treatment of protons and electrons
  - nonlinear effect

* result
  - the universe is filled with magnetic fields
  - prediction of cosmological magnetic fields
  - seed fields for galactic magnetic fields