KYUSHU UNIVERSITY 2011
100th Anniversary

銀河磁場の活動性
Various Activities of the Galactic Magnetic Field

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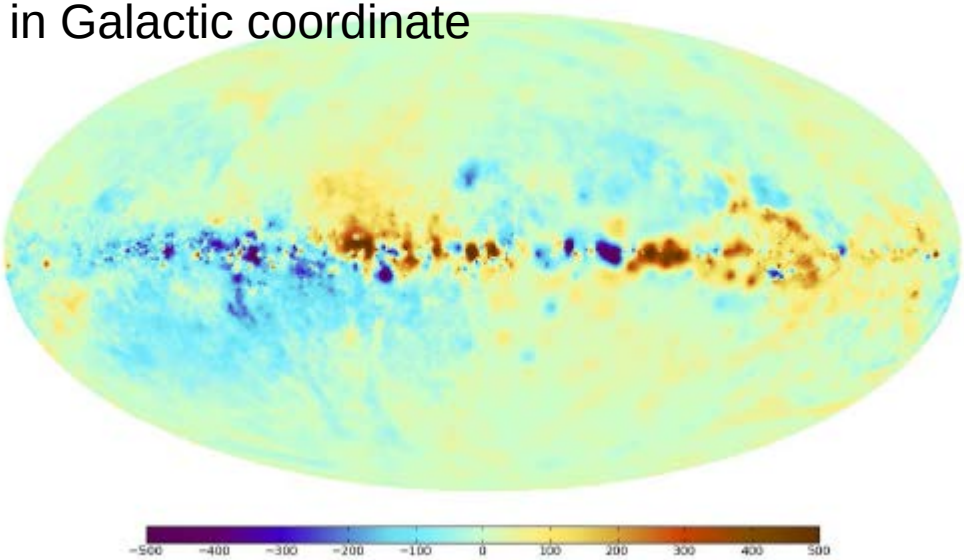
Kakiuchi-san

Magnetic field structure in the Galaxy

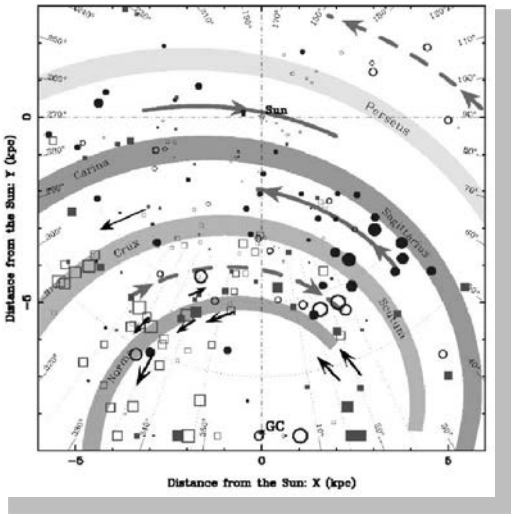
Rotation Measure (RM) $RM = 0.81\int_0^{L(\mathrm{pc})} n \cdot B_{//} dl,\ n[\mathrm{cm}^{-3}],\ B_{//}[\mu\mathrm{G}]$

All sky distribution of the RMs
in Galactic coordinate



Taylor + (2009), Oppermann + (2012)

Reversal of magnetic fields



Han +, ApJL, 570 (2002)

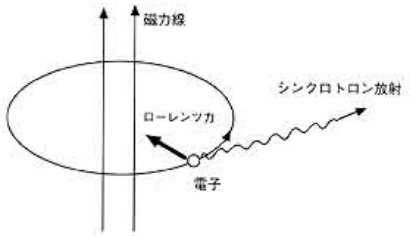
Complex distribution of RM

Mean line of sight magnetic fields: north-positive, south-negative

Direction of the fields change between stellar arms.

How to observe magnetic fields

1. Zeeman-effect --- difficult
2. Synchrotron radiation

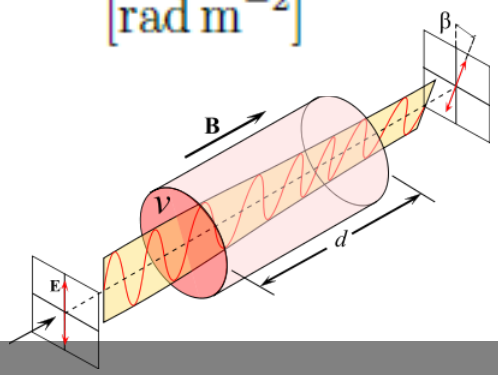


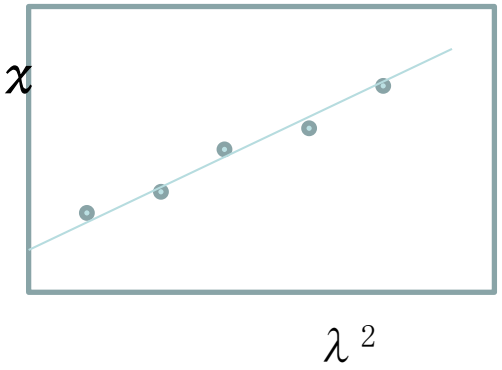
$$I = \int 2G_1(p)j(p)\omega^{(1-p)/2}B_\perp(r)^{(1+p)/2}C(r)dr$$

3. Faraday rotation

$$RM = \frac{e^3}{2\pi m^2 c^4}\int_0^x n_e B_{//}dx$$
$$= 0.81\int_0^x n_e B_{//}dx \qquad [\mathrm{rad\,m^{-2}}]$$

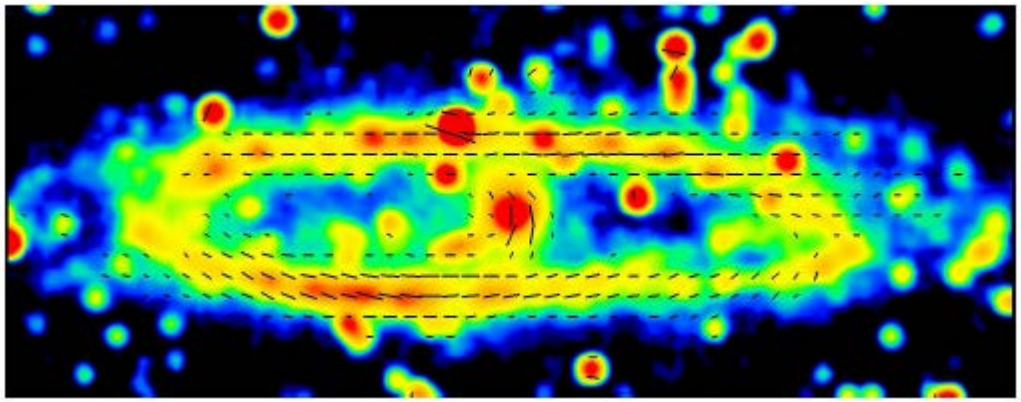
$$\chi = \chi_0 + RM\lambda^2$$



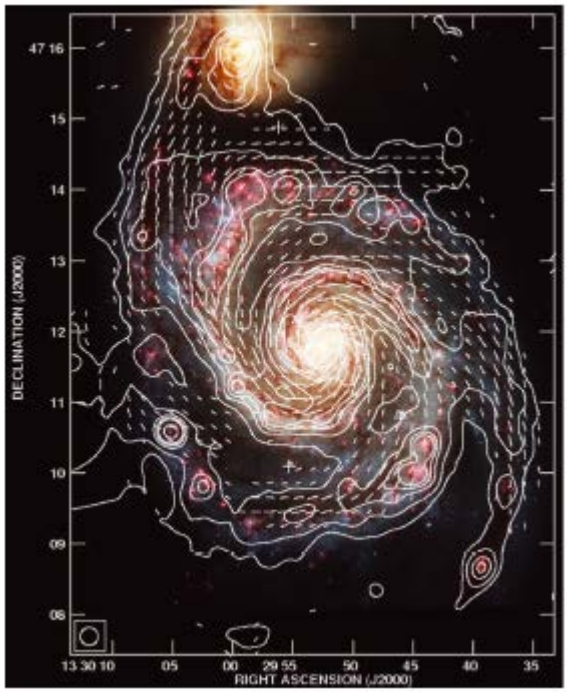


Global Magnetic Fields of extra galaxies

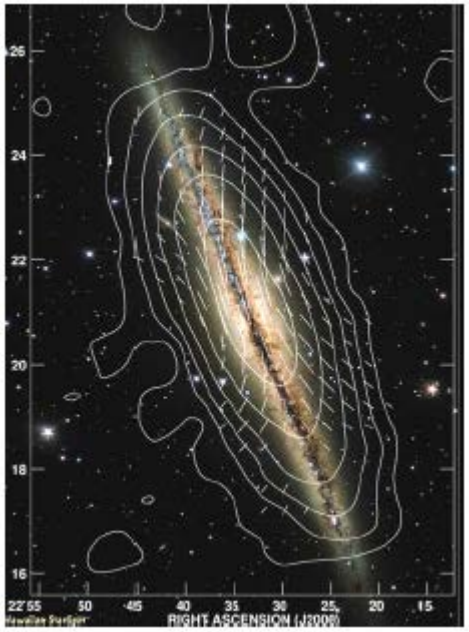
M31 Gießűbel + (2012)



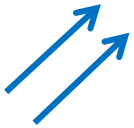
M51 Fletcher + (2011)



NGC891 Krause (2009)



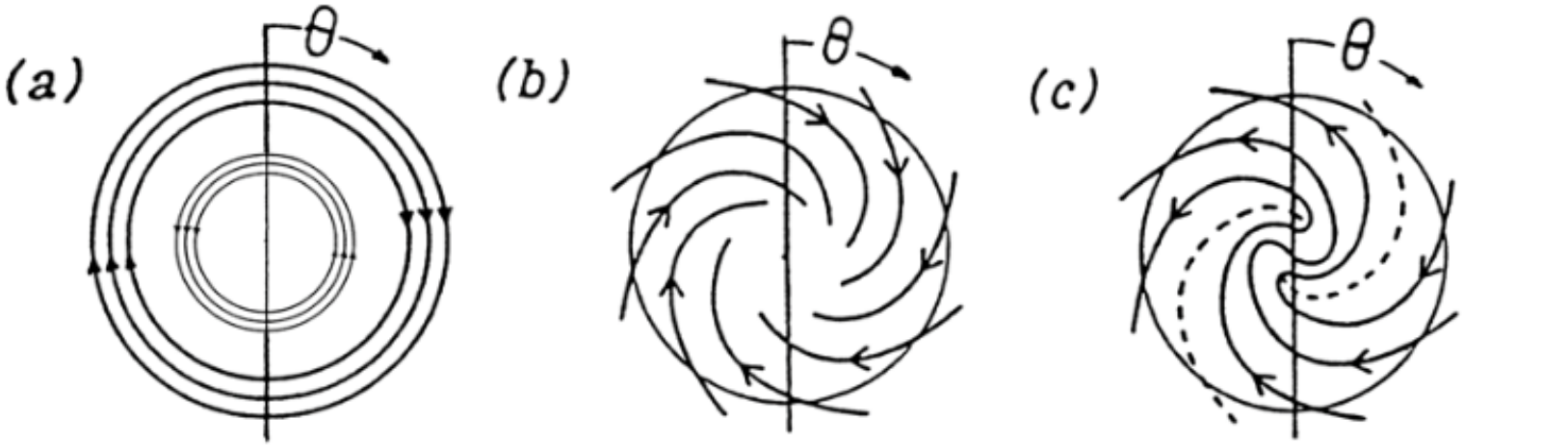
Total Field : 10 – 100 μG
Ordered Field : a few- 10 μG
Regular Field : a few μG



Ordered field

Regular field

Characteristic of Global Magnetic field structure

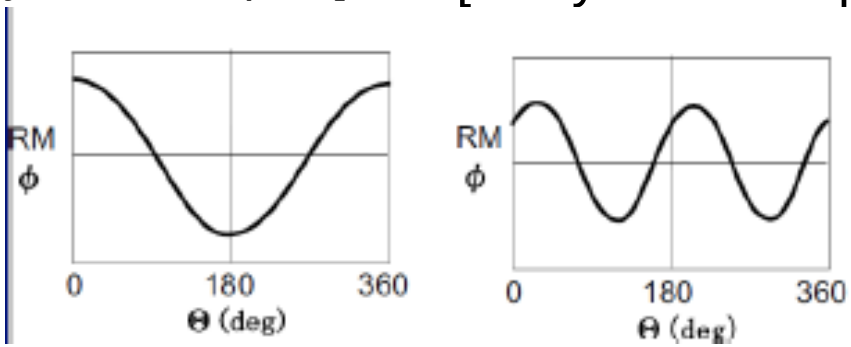


J. L. Han et al 2003

(a) Ring-like

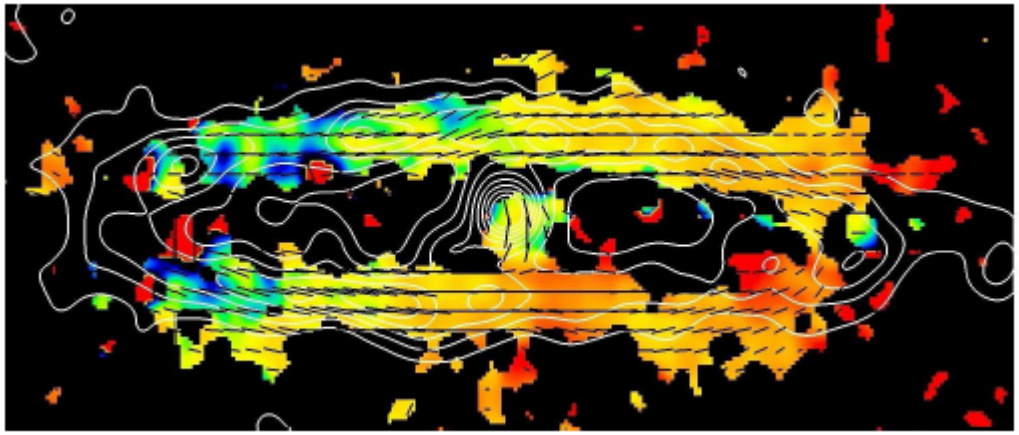
(b) ASS-like
[Axi-Symmetric Spiral]

(c) BSS-like
[Bi-Symmetric Spiral]



3 types of the global magnetic fields (Sofue 1987)

ASS (or Ring-like) Fields



Berkhuijsen et al. (2003)

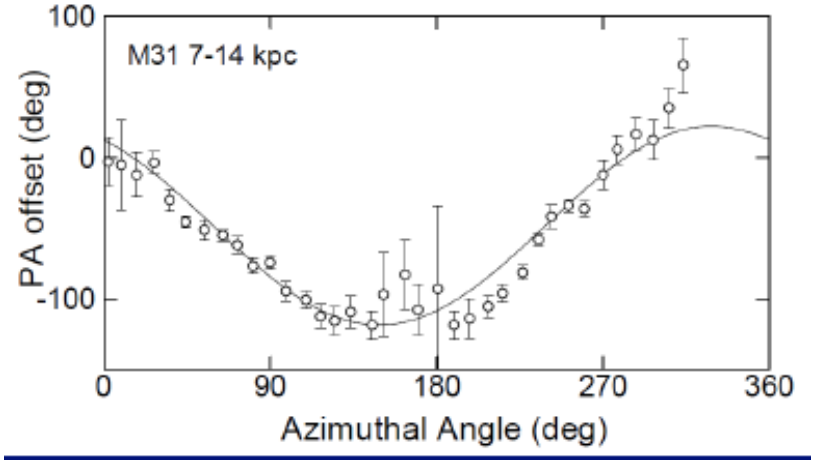
RM distributions indicate ASS-like field.

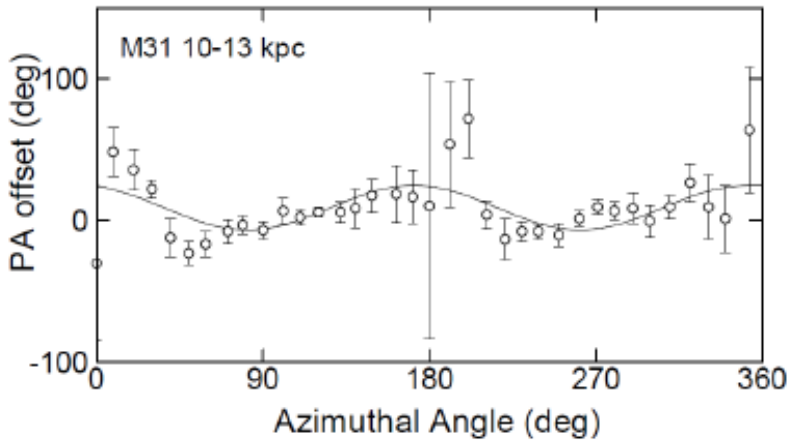
From λ^2-χ relation:

inner region –ASS-like

outer region –BSS-like

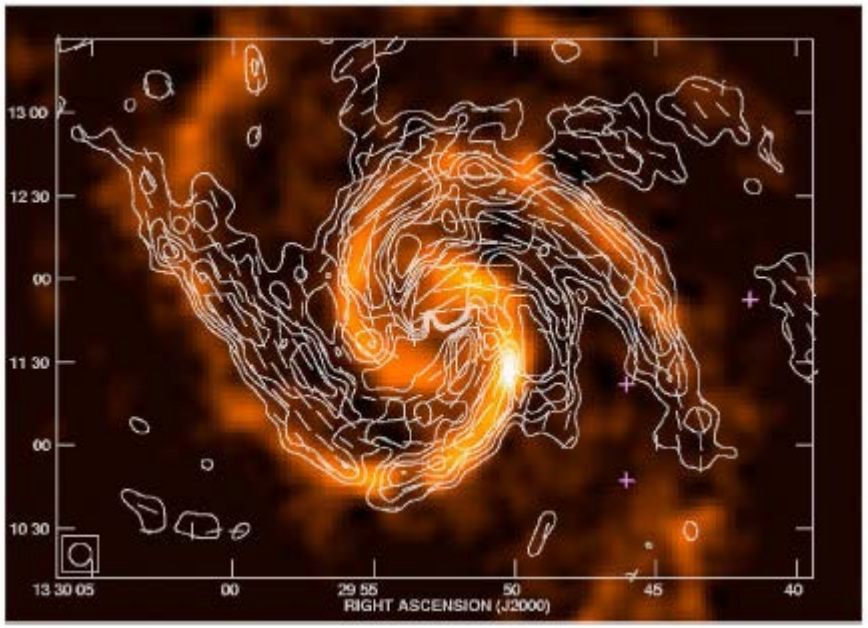
center - Vertical



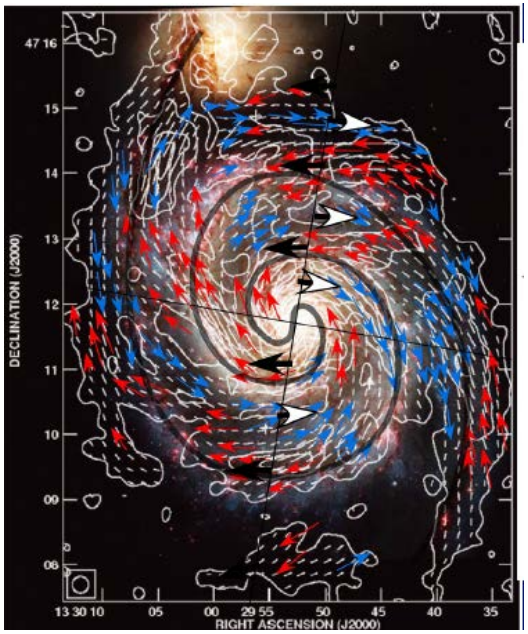


Global magnetic field structure (BSS)

M51 (Fletcher + 2011, Contour: CO line,Helfer + 2003)

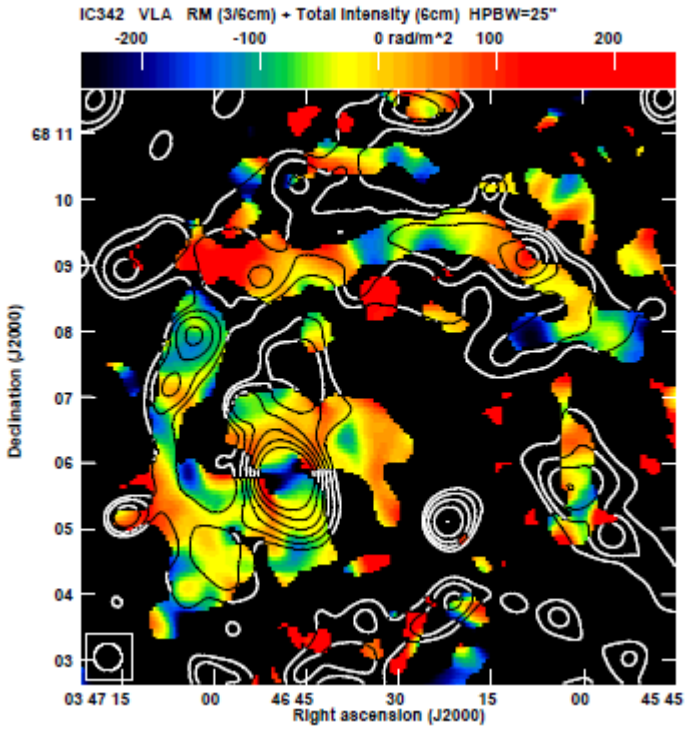


Anraku + (2015)



M51 (cf, M83)
Strong density waves
⇒ Enhanced ordered fields are formed at the inner edges of the spiral arms
Ordered Fields : 10-15μG,
The origin of these magnetic fields are considered by α-Ω dynamo.

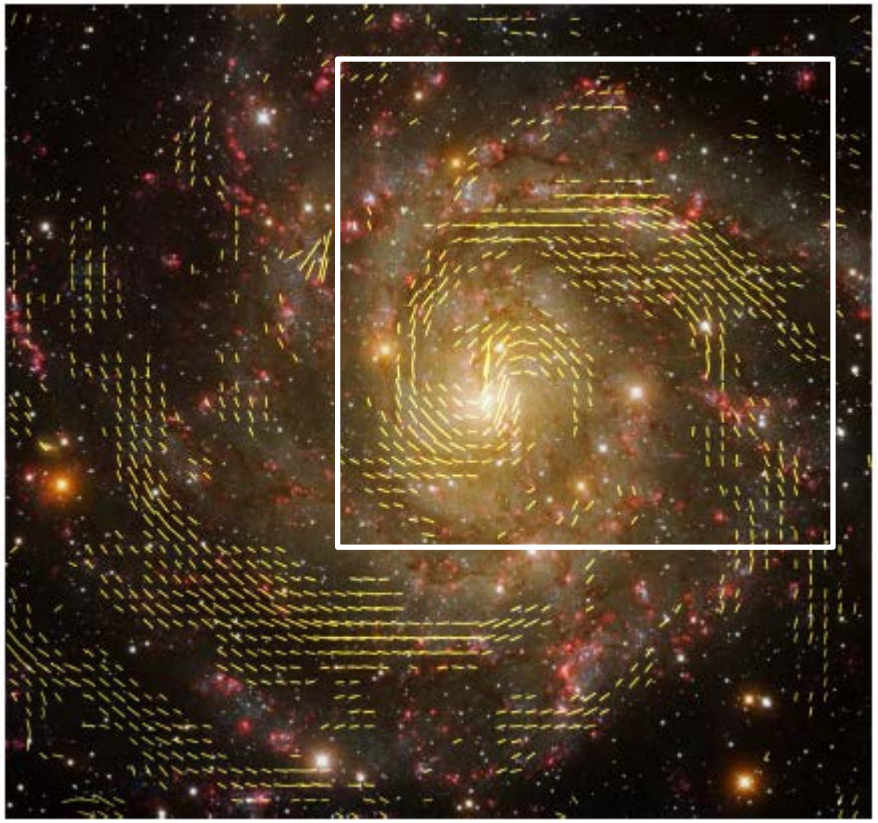
BSS-like Fields without strong density wave



RM of north spiral arm shows periodic pattern.

⇒ The evidence of the magnetic loop.

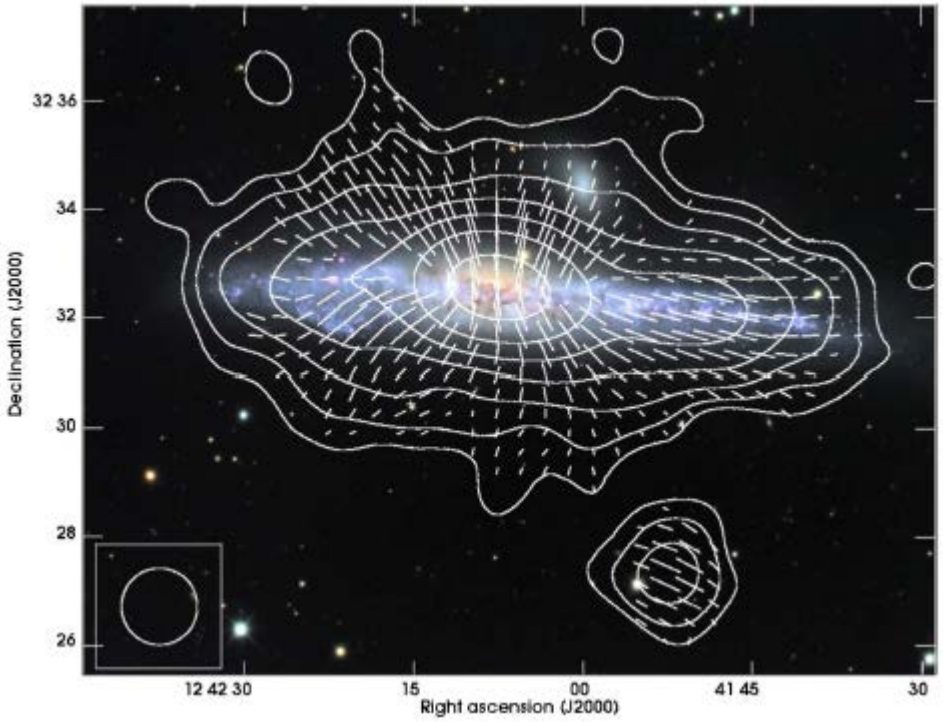
IC342 Beck (2015) MPIfR Bonn



α-Ωynamo is not dominant mechanism.

X-shape field (starburst edge-on galaxy)

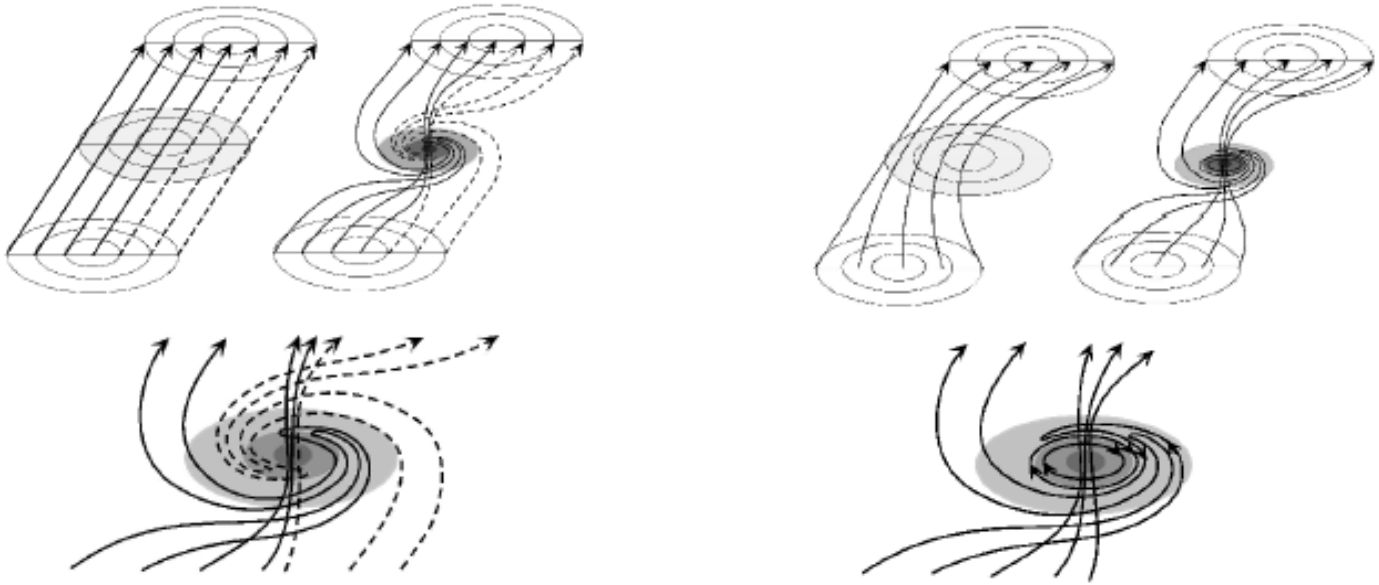
NGC4631



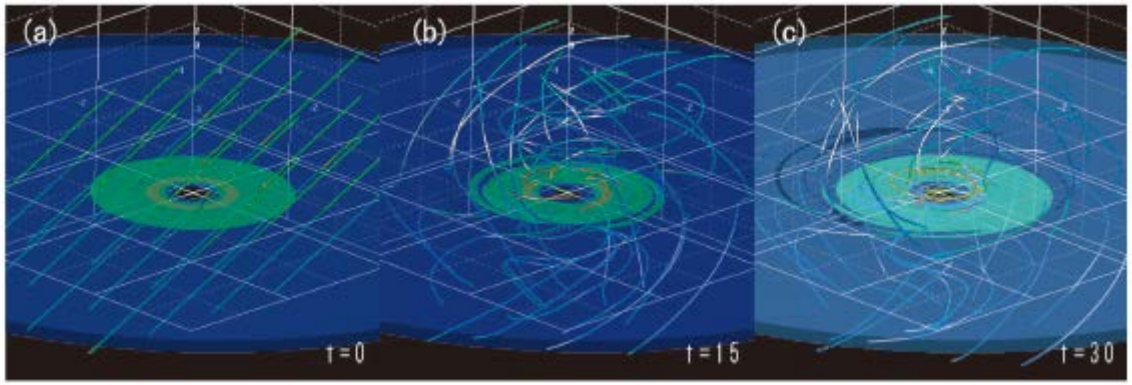
Mora & Krause (2013) MPIfR Bonn

Several edge-on galaxies reveal vertical field components in the halo an X-shaped pattern.
Radio scale height, estimated cosmic-ray lifetimes → outflow speed is 300km/s.

Model of the Global Field structure



Time evolution : θ =45

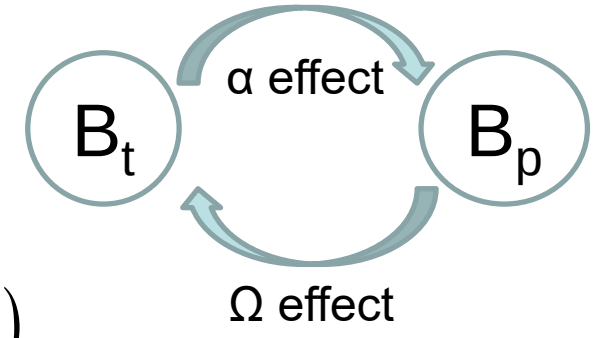


Dynamo theory

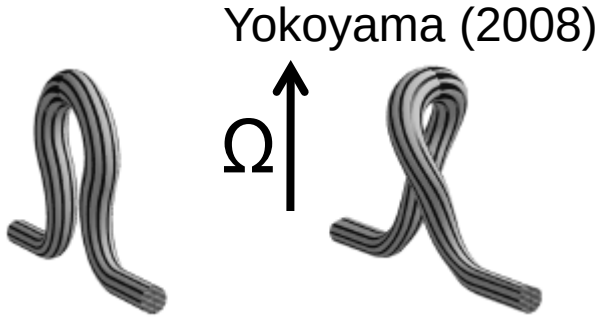
$$V = \overline{V} + v,\ B = \overline{B} + b,\ \overline{X}: \text{ensemble average}$$

$$\frac{\partial \overline{\mathrm{B}}}{\partial \mathrm{t}} = \nabla \times \left(\overline{V} \times \overline{B}\right) + \nabla \times \left(\alpha \overline{B}\right),\ \alpha \overline{B} = \overline{v \times b}$$

$$\overline{V} = V_t, \overline{B} = B_t + B_p \rightarrow \begin{array}{l} \dfrac{\partial \mathrm{B_t}}{\partial \mathrm{t}} = \nabla \times \left(V_t \times B_p\right) + \nabla \times \left(\alpha B_p\right) \\ \dfrac{\partial \mathrm{B_p}}{\partial \mathrm{t}} = +\nabla \times \left(\alpha B_t\right) \end{array}$$



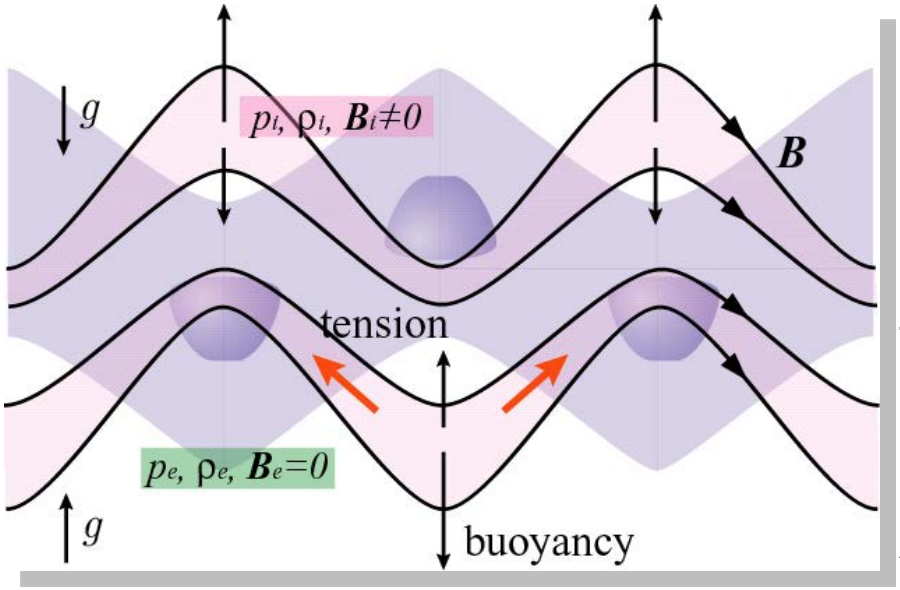
α effect: Coriolis force
Ω effect: differential rotation



Schematic drawing of Coliolis force

Since galactic gaseous disk is the differentially rotating disk, magneto-rotational instability also becomes important. Therefore, we have to include the gas dynamics and back reaction from magnetic fields.

Magnetic Flotation and the Parker instability



if Buoyancy > Magnetic tension

$$(\Delta\rho_i - \Delta\rho_e)g > \frac{B^2}{4\pi r}$$

$\rightarrow$ Magnetic fields rise by buoyancy.

Critical wave length for the instability

$$\lambda > \lambda_c = 4\sqrt{2(1+1/\beta)}H$$

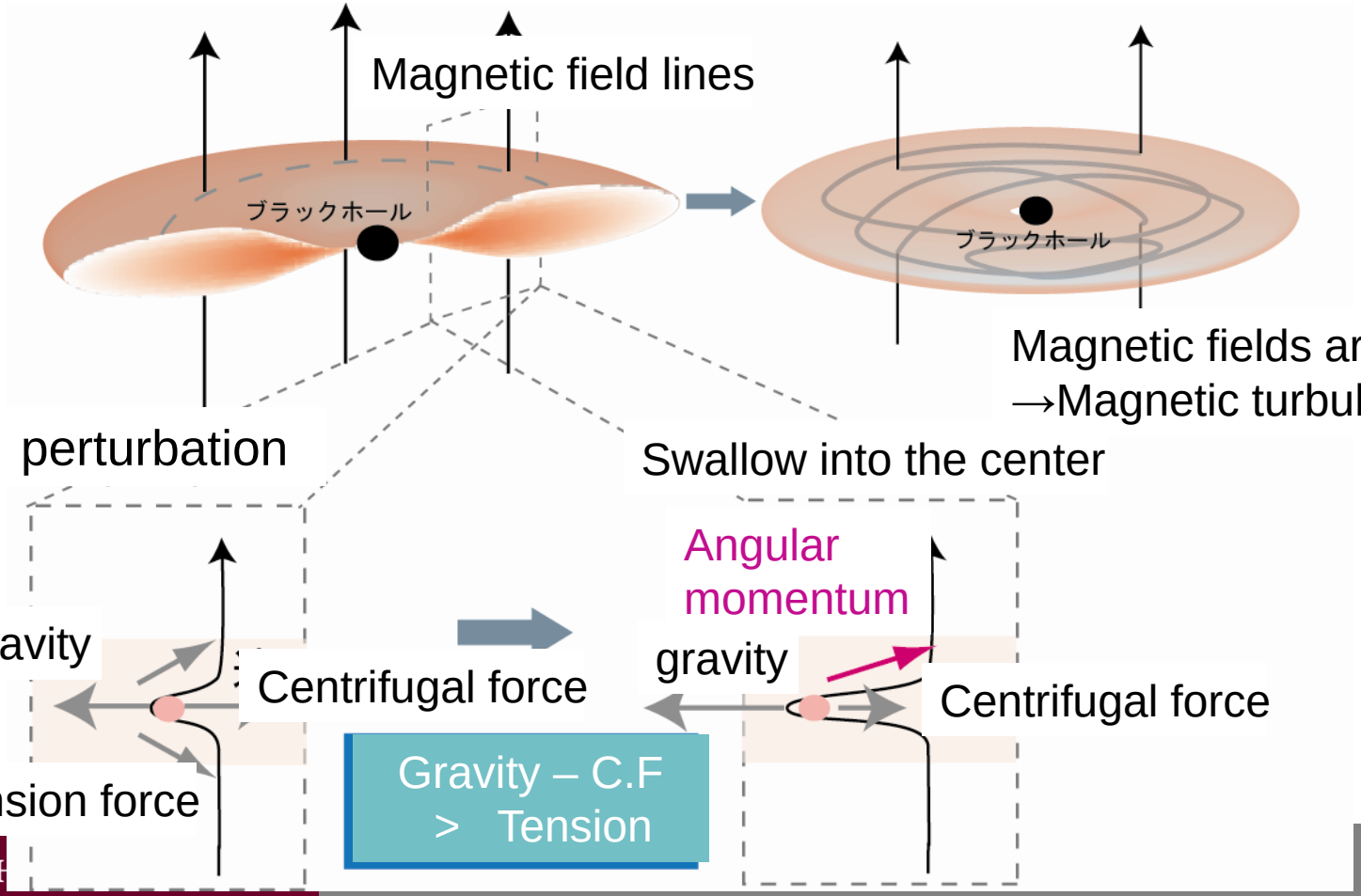
Parker (1966), Matsumoto + (1988)

The most unstable wavelength is about 10 times of the scale height.

Magneto-rotational instability

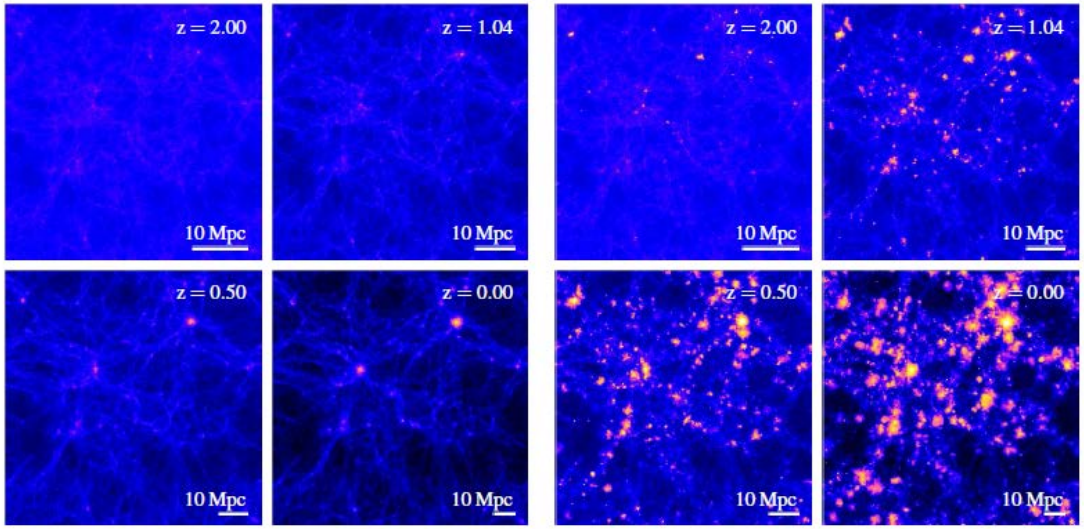
Magnetic stress is the origin of the viscosity

(Velikhov 1959; Chandrasekhar 1960; Bulbus & Hawley 1991)

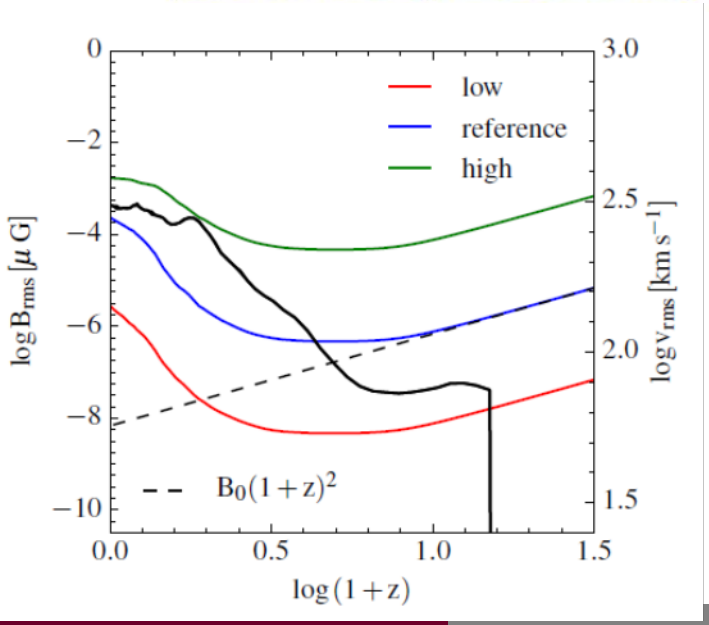


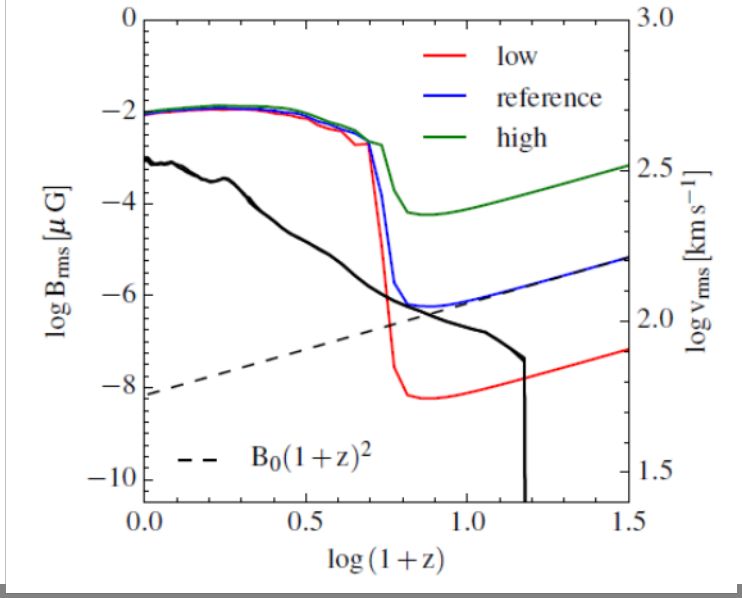
Simulation of cosmological magnetic fields

Adiabatic



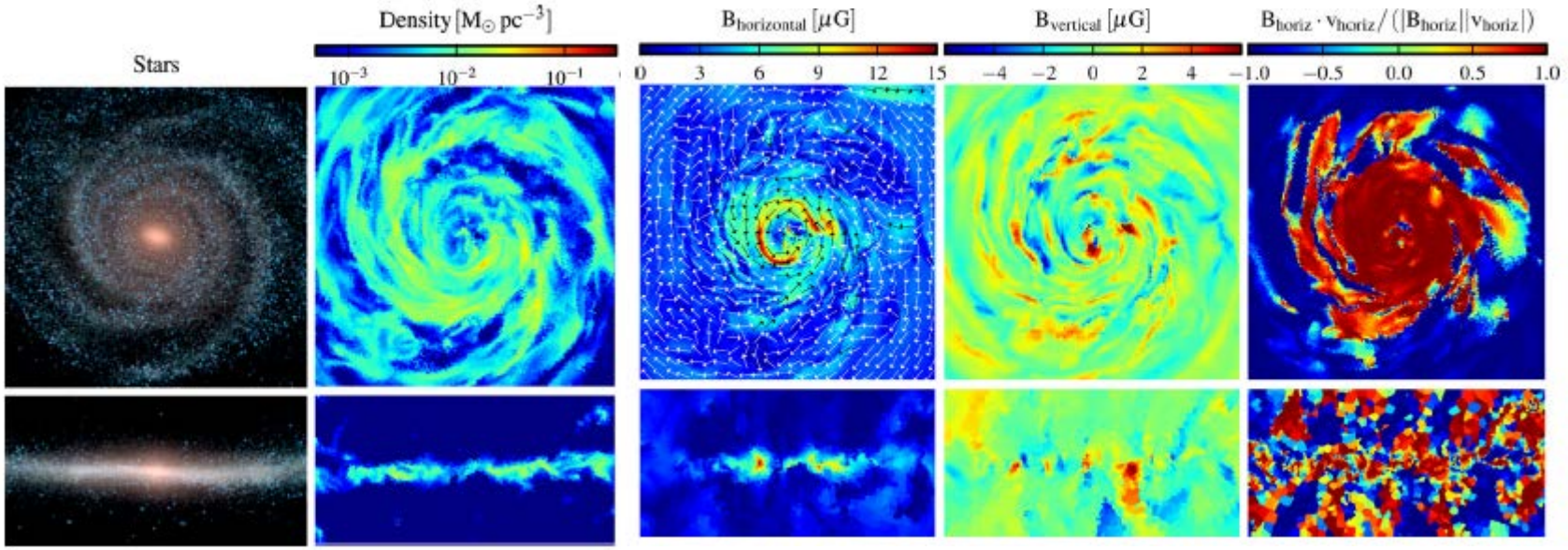
Full physics





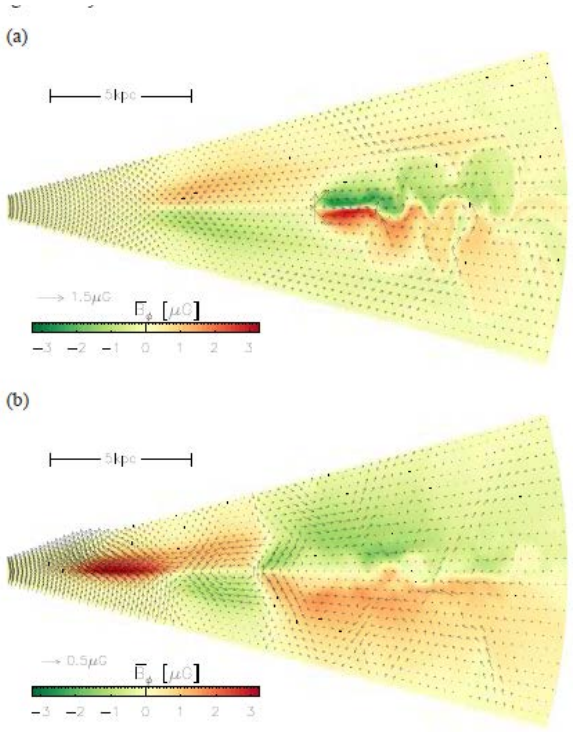
Marinacci et al. (2015)

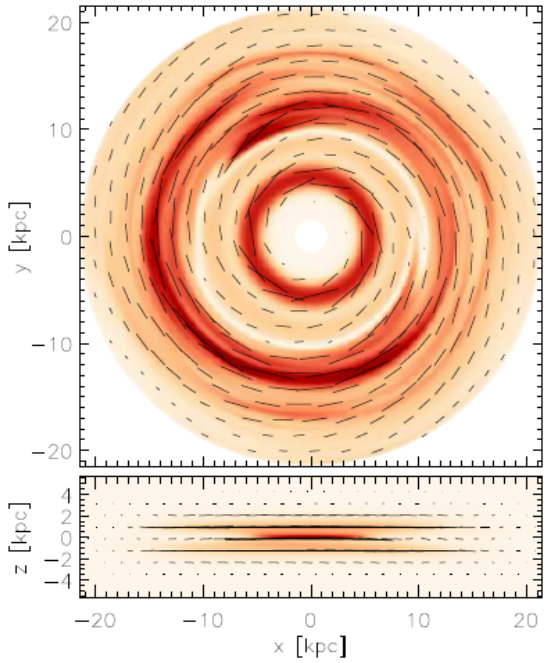
Milkey Way – 1, Pakmor (2015)



Cosmological simulation + moving mesh MHD code (AREPO)
z～127 , random seed field strength is about 10^{-5} μG.
Z～4、turbulent fields are formed
z～2、ordered fields are formed. The strength is about 6 μG.
z～0, E_{mag}/E_{th} ~ 10, E_{mag}/E_{kin} ~ 0.1

Gressel + (2013) Hybrid dynamo model





Both α-Ω dynamo term and MRI are considered.
α-Ω dynamo is stronger fields than MRI case.

Dobbs + (2016)

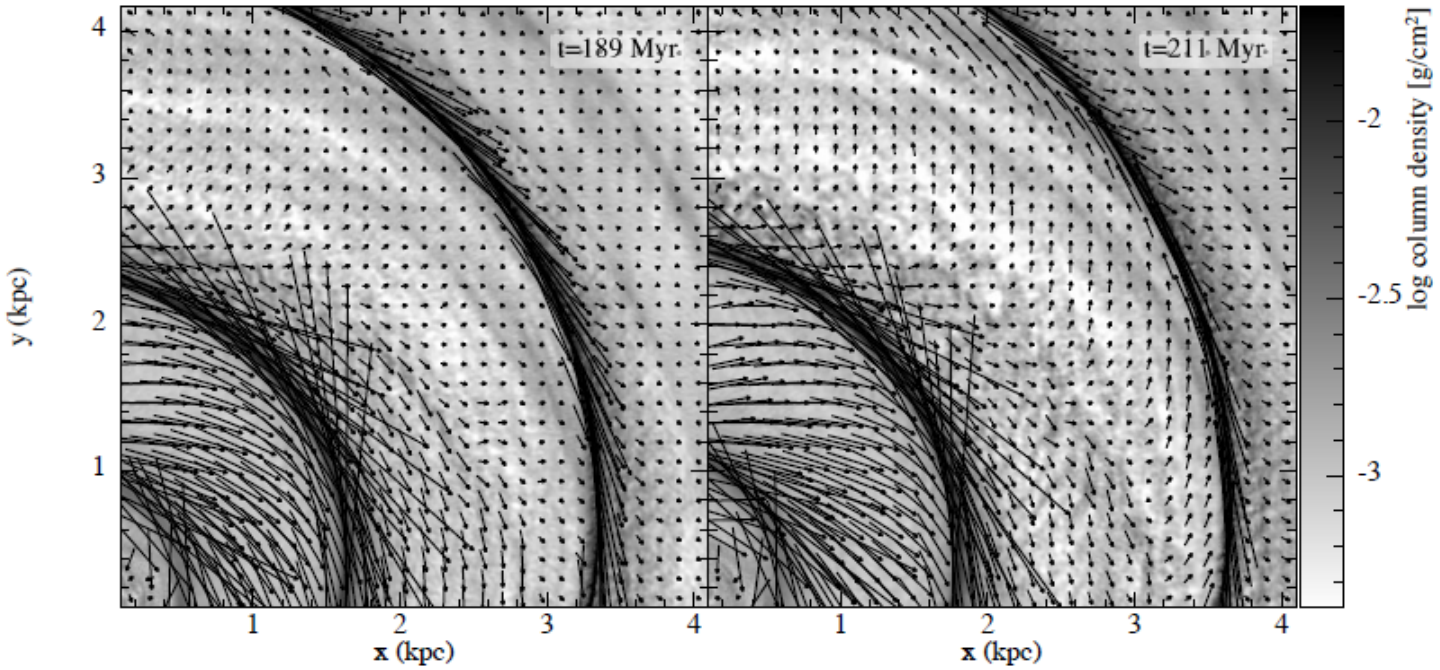


Figure 5. Column density of a section of the disc, shown at times of 189 Myr (left), when a reversal is just starting to occur in the inter arm regions (for $r \gtrsim 2.5$ kpc), and at 211 Myr (right) when the reversal is more clearly established and apparent in the spiral arms. Magnetic field vectors are overplotted on the figures, with the length of each vector indicating the strength of the field.

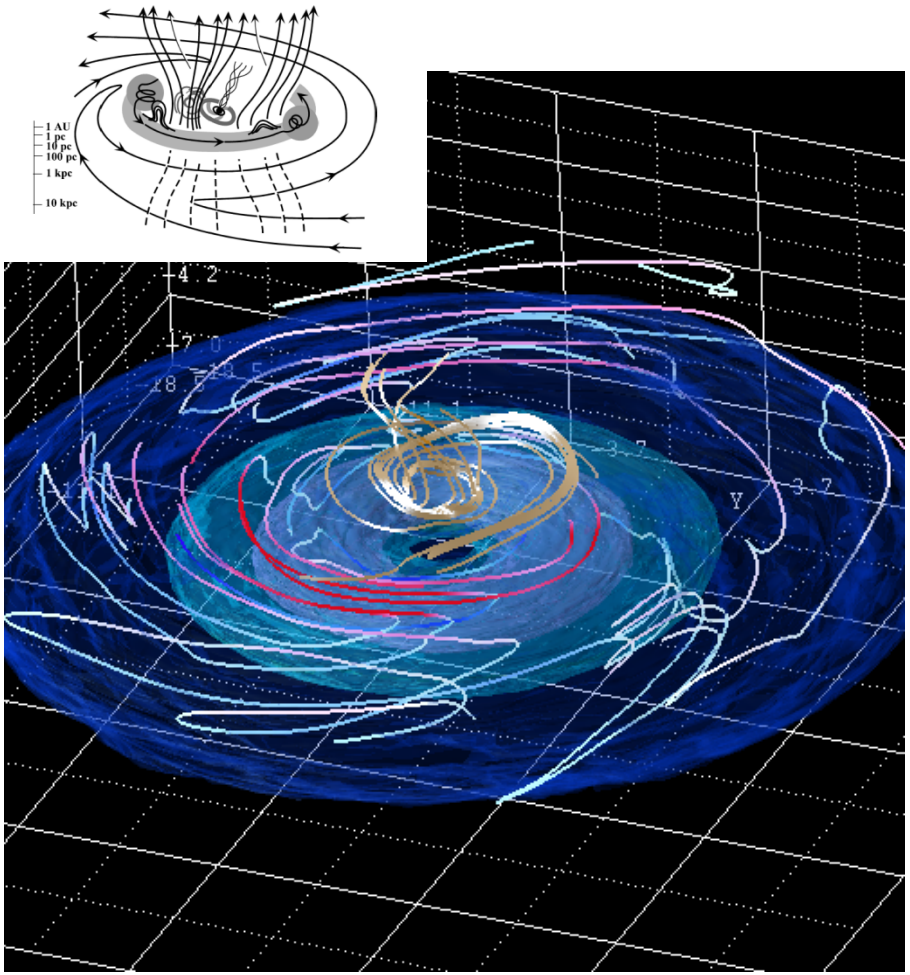
They considered the appearance of reversals of the field with SPHMHD code.

Reversal points: 1. inner Lindblad resonance

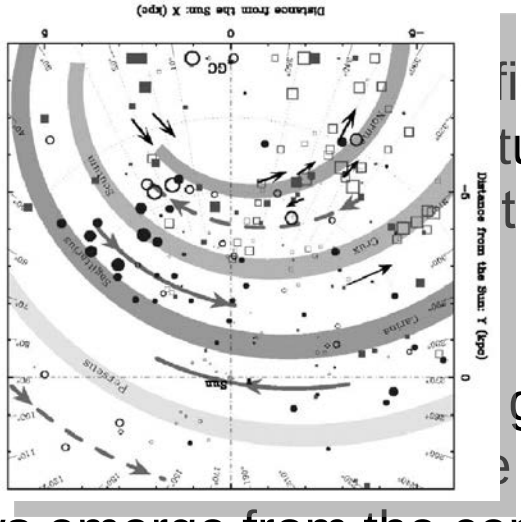
2. Corotation of the spiral arm

Only appears when the spiral potential becomes strong.

MRI –driven model



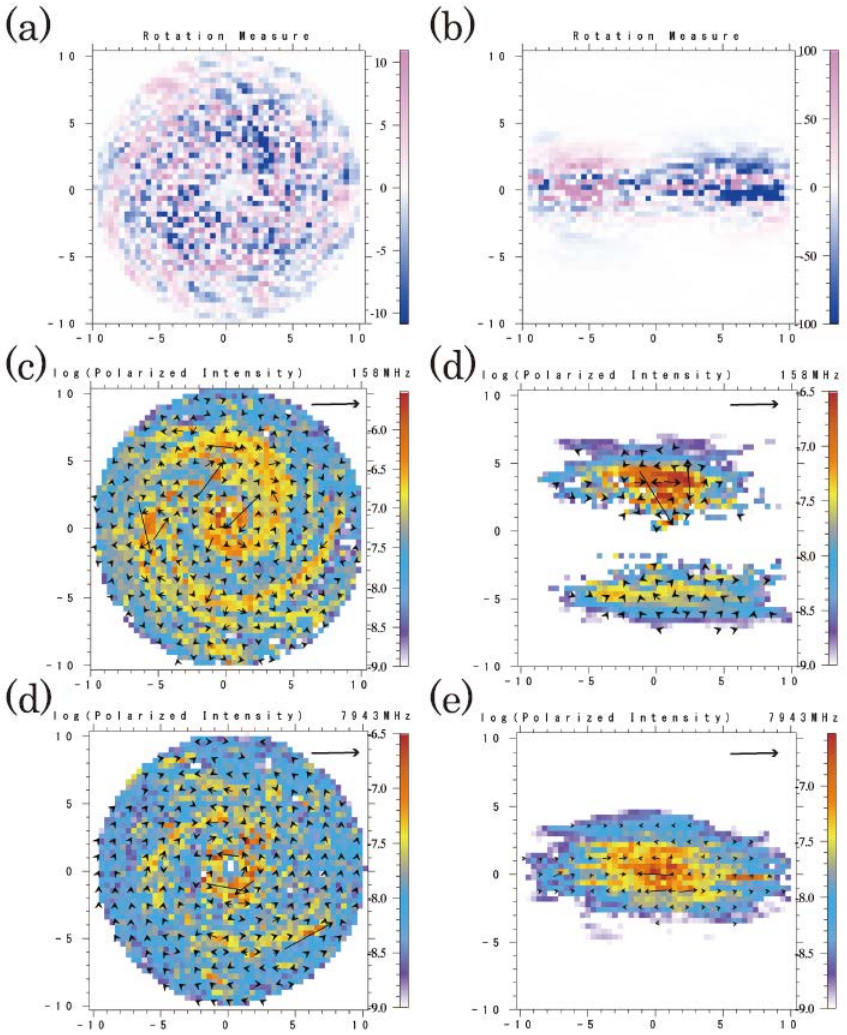
Machdia + 2013

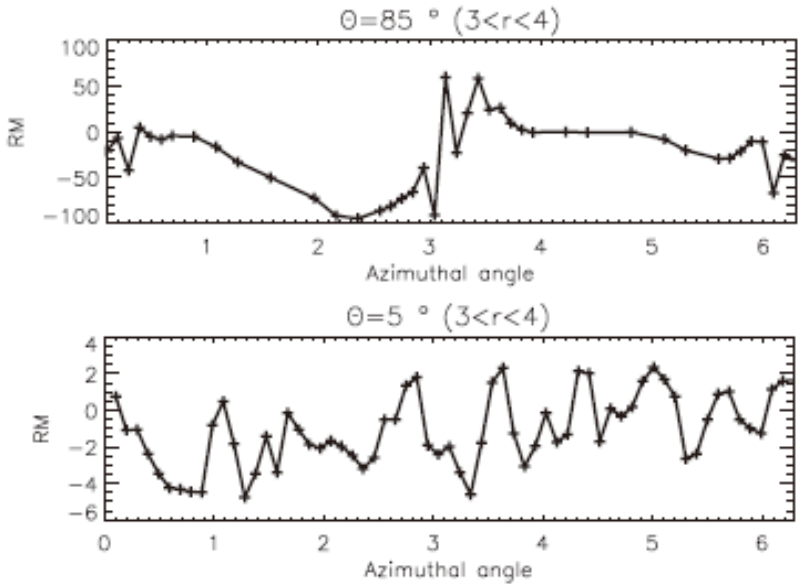


•Initial v fied by MRI, a turbulent.
•Avera t 10 inside t
•When becom gas pressu driven outflows emerge from the central region. This outflows creates a large-scale poloidal magnetic field in the inner most region.

Vertical fields in the Galactic center and toroidal disk fields are natural structure.

RM and Synchrotron Intensity from N.S.

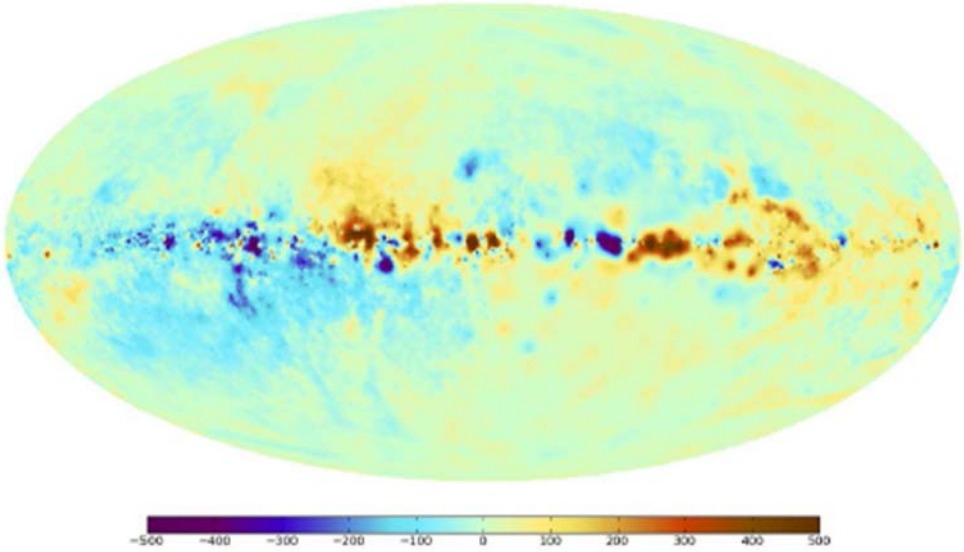


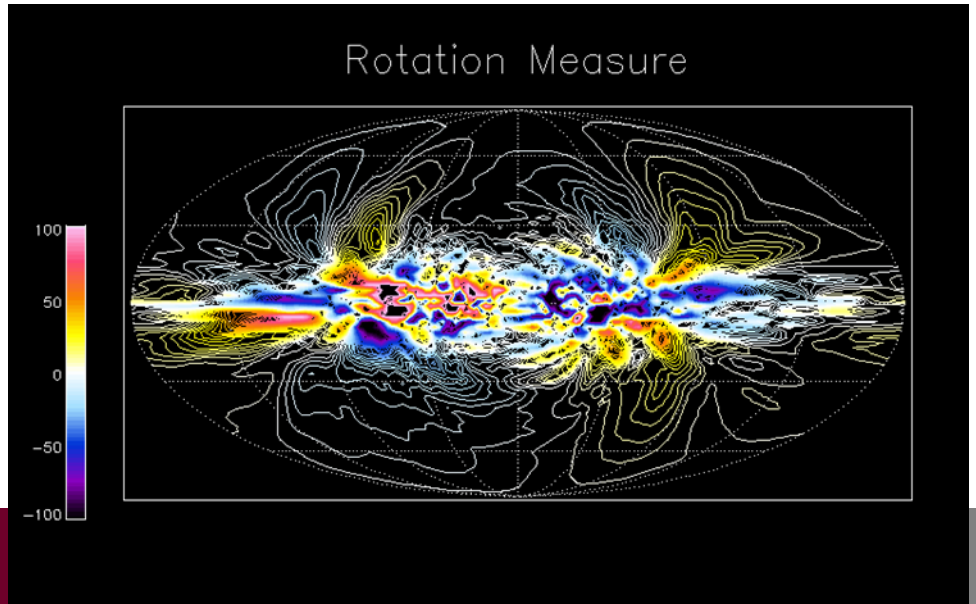


Initial condition – ring shape

Edge-on: ASS – like distribution
Face-on : ?? -- turbulent fields become dominant.

All sky maps of RM





Summary --- global magnetic fields

1. Three-types of global magnetic fields are observed
2. Beautiful spiral arms seem to be related to the spiral density waves.
3. X-shaped feature in edge-on galaxies are coursed to the powerful winds which is made by SN.