Galactic Magnetic Fields

Andrew Fletcher
Newcastle University

1. What we know: summary of observed properties.
2. How does this compare with dynamo theory?
3. Modelling cosmic ray electron propagation.
4. Magnetic fields in galaxy formation models.

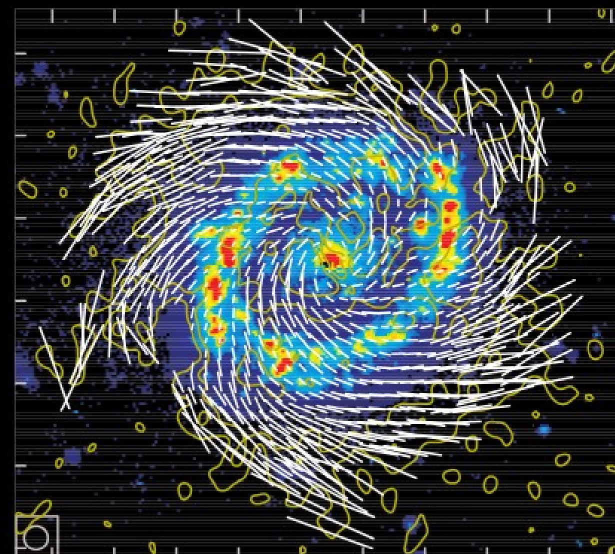
Synchrotron radiation

Total intensity	$I_{\rm syn} \propto B_{\perp}^{(1+\gamma)/2}$	observed
Degree of polarization	$p = p_0 \dfrac{\bar{B}^2}{(\bar{B}^2 + b^2)}$	observed
Polarization angle	$\psi \cdot \bar{B}_{\perp} = 0$	observed
Faraday rotation	$\mathrm{RM} = \dfrac{\Delta\psi}{\Delta(\lambda^2)}$	observed

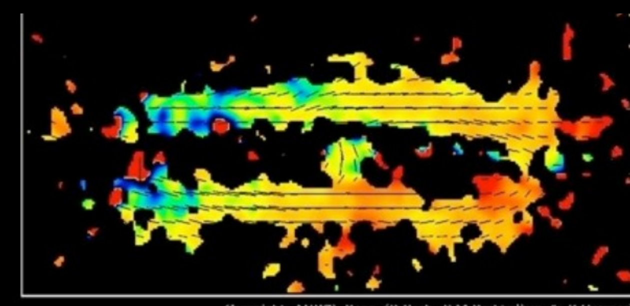
$$R = 0.81 \int_{\rm los} \frac{n_e}{\rm cm^{-3}} \frac{\bar{B}_{\parallel}}{\mu \rm G} \frac{{\rm d}l}{\rm pc} \quad \rm rad\, m^{-2}$$ theoretical

Lots of observations:

Fletcher et al. 2011

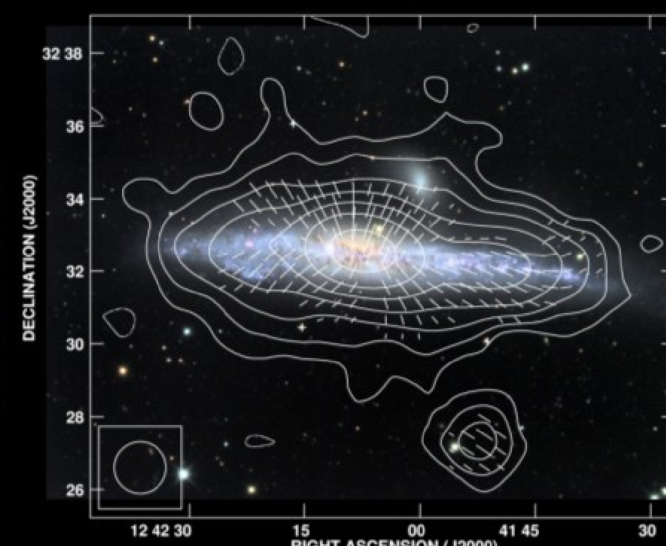


Chyzy & Buta 2007



Berkhuijsen et al. 2003

Krause 2009



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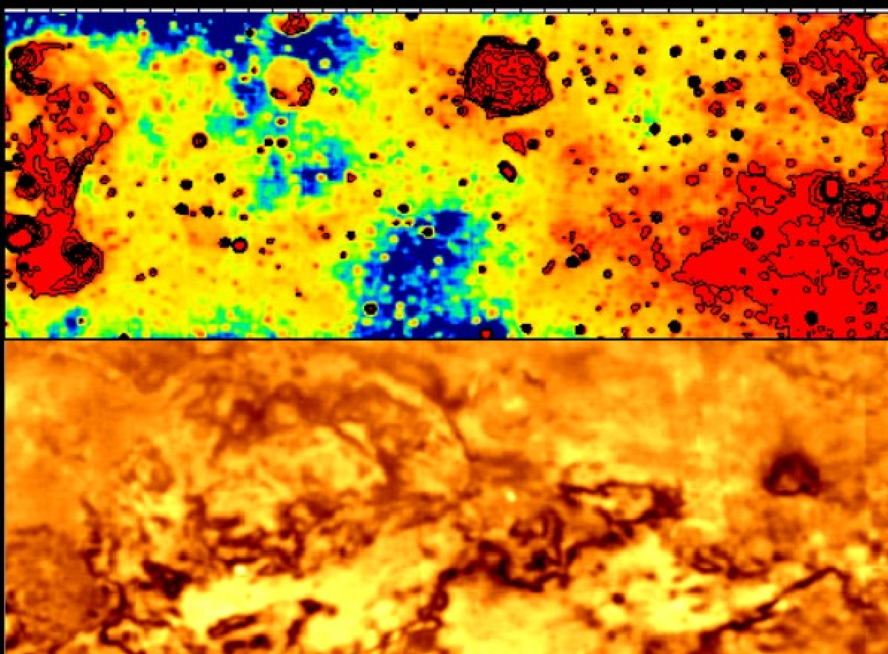
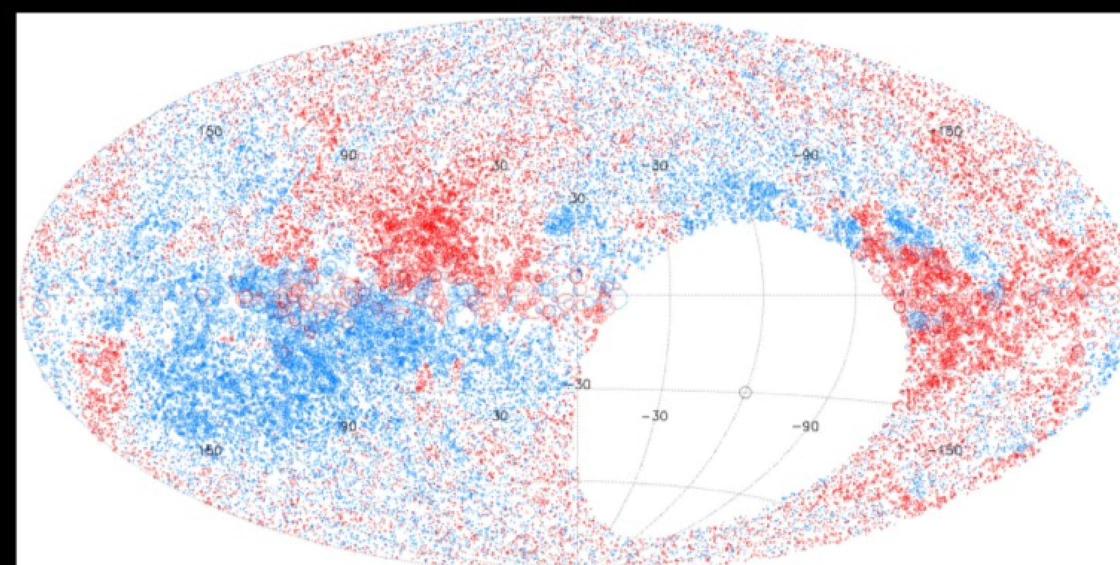
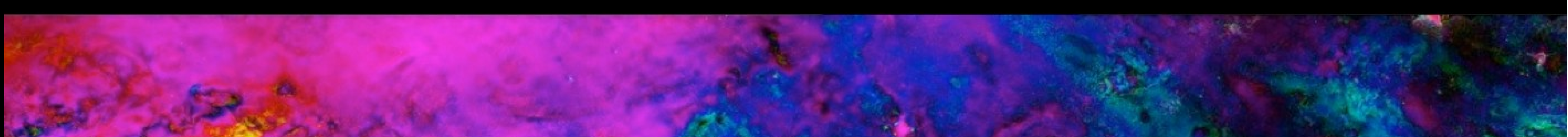


Reich et al. 2004

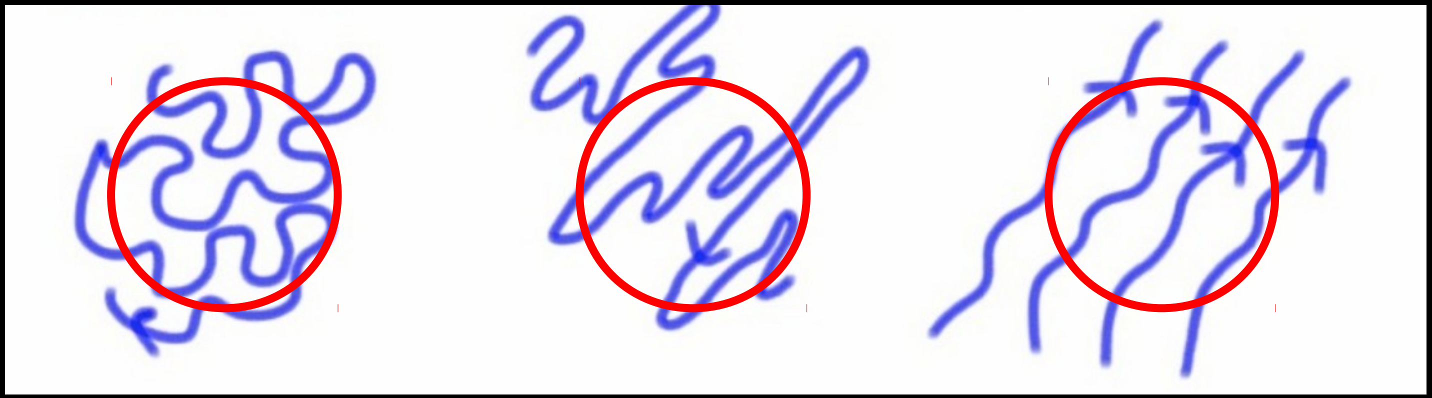
Taylor et al. 2009





Landecker et al. 2010

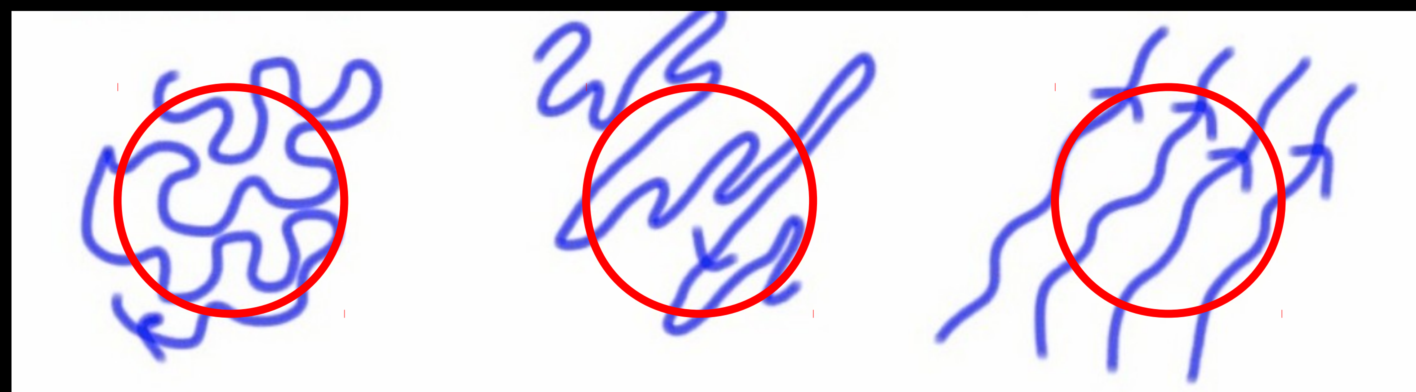
Magnetic Field Components



Synchrotron	Yes	Yes	Yes
Polarisation	No	Yes	Yes
Faraday Rotation	No	No	Yes

Magnetic Field Components

	Random		Ordered
	Isotropic	Anisotropic	Mean



	Isotropic	Anisotropic	Mean
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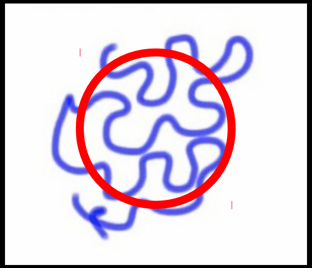
Isotropic random field



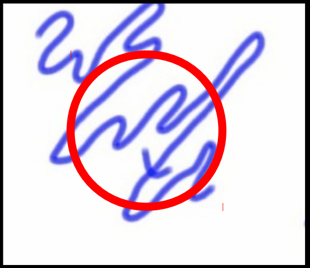
Strength: about $10\mu G$ (~30 galaxies)

Energy density ~ turbulent, thermal, cosmic ray

Correlation length: 50—100pc (Milky Way, LMC, M51)
also Milky Way 2 estimates <20pc

Origin: fluctuation dynamo
or
tangling of mean field
or
both

Anisotropic random field



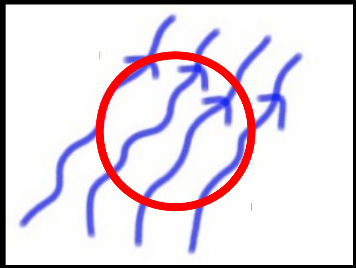
Observed in: Milky Way, M33, M51, NGC1097, NGC1365
(using different methods)

Strength: about $2—4\mu G$ (Milky Way, M51)

Degree of anisotropy: $l_{\parallel} \sim 2l_{\perp}$ (M51)

Origin: shear
or
shock compression
or
intrinsic to MHD turbulence

Mean field



Typical strength: $B \sim b/(1\text{—}3) \sim 4\mu\mathrm{G}$

Spiral field lines: $B_r \sim (0.2\text{—}0.4)\, B_\varphi$ (~20 galaxies)

pitch angle similar to spiral arms (8 galaxies)

Weak vertical field in disc: $B_z \sim 0.1\, B_r$ (Milky Way)

Axisymmetric (8 out of 12 modelled galaxies)

Origin: mean-field dynamo (αω-dynamo of some form)

not a wound-up relic field

Dynamo models for many galaxies

20 galaxies with known magnetic field plus …
gas density, star formation rate, rotation curve.

Test predictions of 3 non-linear αω-dynamo models:
mean-field strength and pitch angle = $\arctan(B_r/B_\varphi)$

1. Equipartition of magnetic & turbulent energies.
2. Balance of Coriolis & Lorentz forces.
3. Magnetic helicity balance

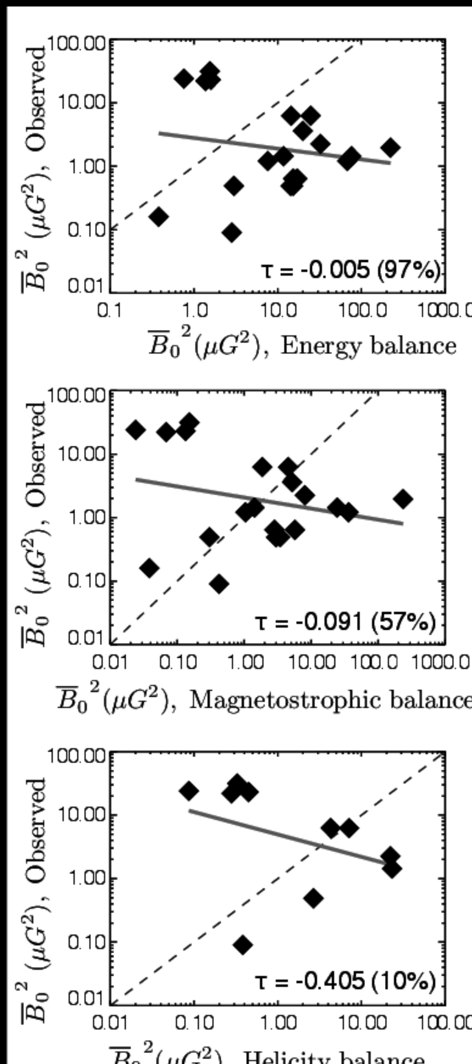
Each mechanism gives $B(\Sigma_{gas}{}^{a}, \mathrm{SFR}^{b}, \Omega^{c}, h^{d}, l^{e}, v^{f})$
and $p(\Sigma_{gas}{}^{a}, \mathrm{SFR}^{b}, \Omega^{c}, h^{d}, l^{e}, v^{f})$

(h = scale height, l = turbulence scale, v = turbulent velocity)

Van Eck, Brown, Shukurov & Fletcher, 2015

Theory vs. Observations

Mean-field strength



Simple model

Coriolis = Lorentz

Helicity balance

Van Eck, Brown, Shukurov & Fletcher, 2015

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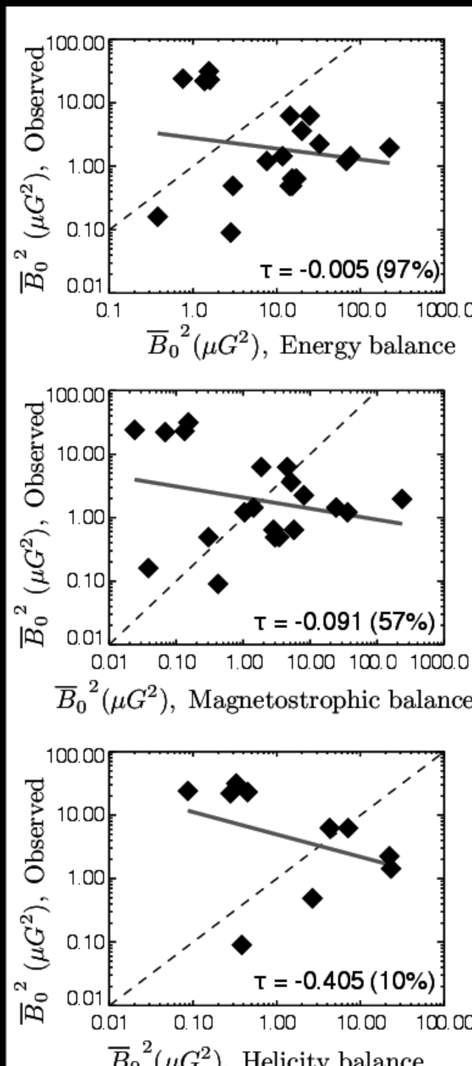
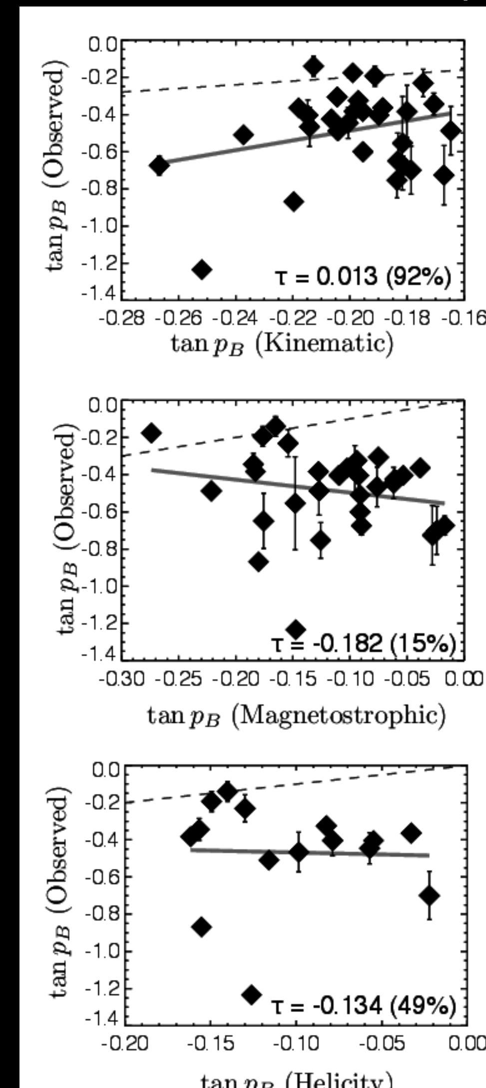


$p = \arctan(B_r / B_\varphi)$



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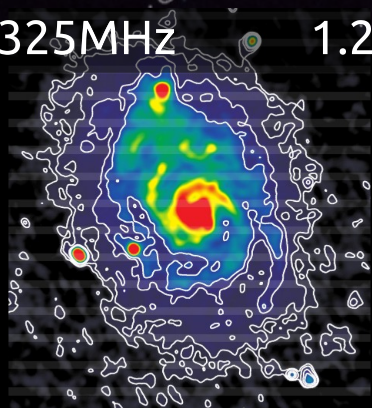
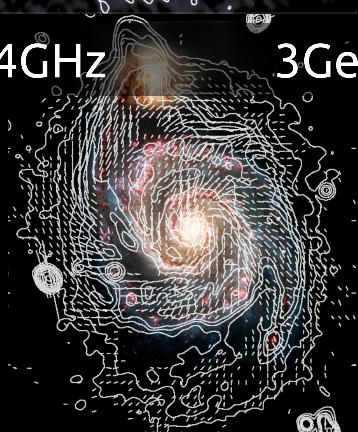
Cosmic ray electrons in M51





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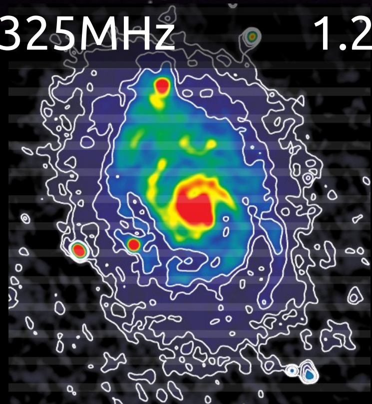
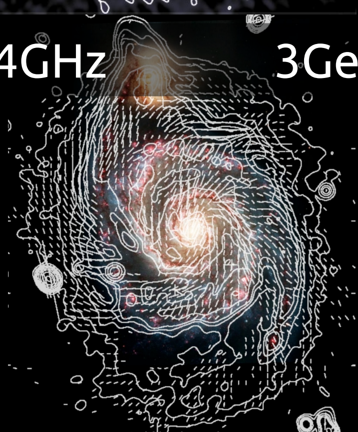
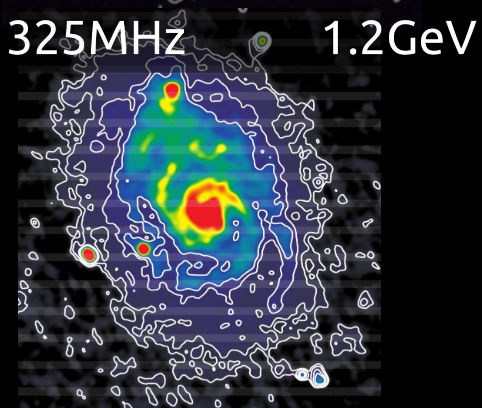
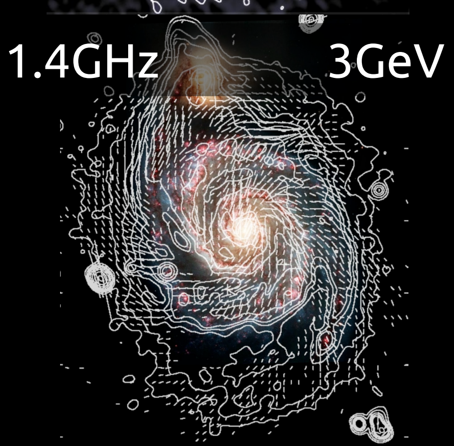




$$\frac{\partial N}{\partial t} = D\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial N}{\partial r}\right) + \frac{\partial}{\partial E}(\beta E^2 N) + Q + \frac{N}{\tau}$$

Cosmic ray electrons in M51





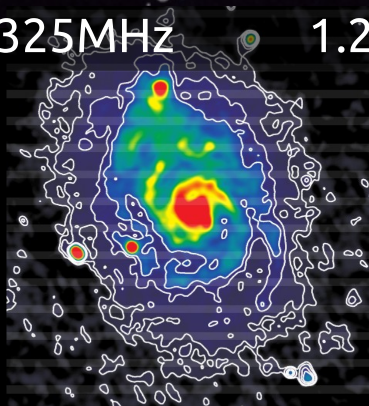
diffusion coefficient

$$\frac{\partial N}{\partial t} = D\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial N}{\partial r}\right) + \frac{\partial}{\partial E}(\beta E^2 N) + Q + \frac{N}{\tau}$$

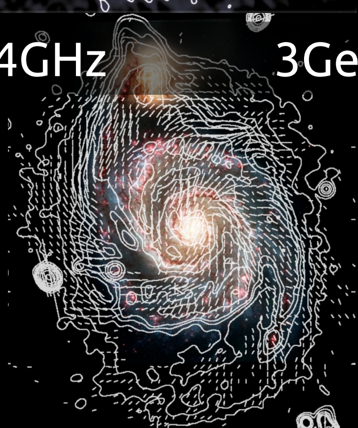
Cosmic ray electrons in M51

151MHz 1GeV

325MHz 1.2GeV



1.4GHz 3GeV



diffusion coefficient

synchrotron & inv. Compton

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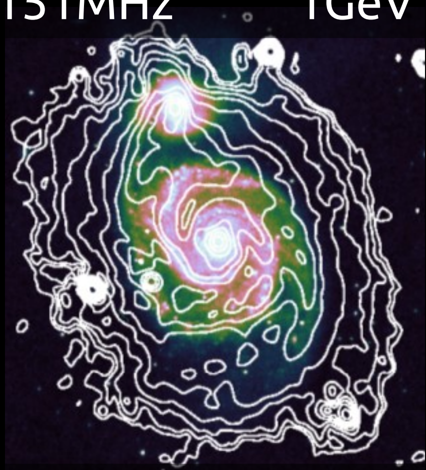

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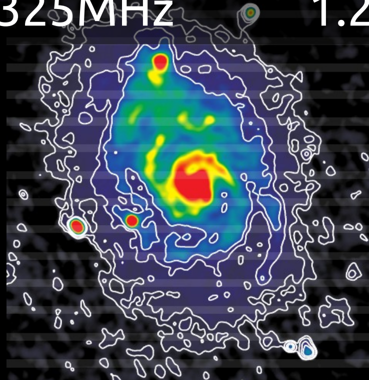

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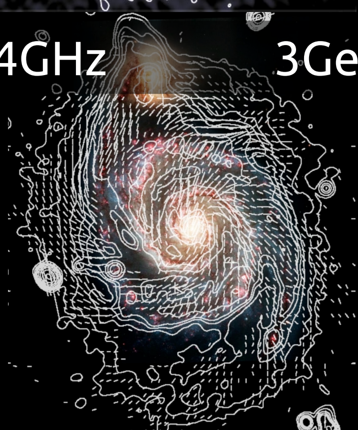

diffusion coefficient

synchrotron & inv. Compton

vertical escape

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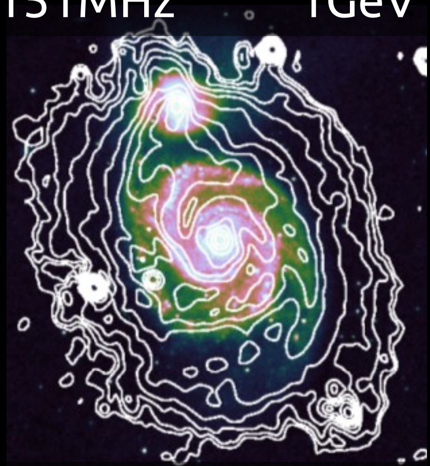

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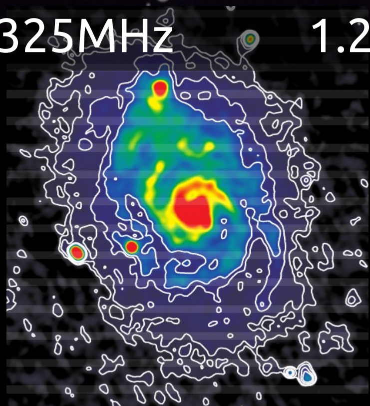

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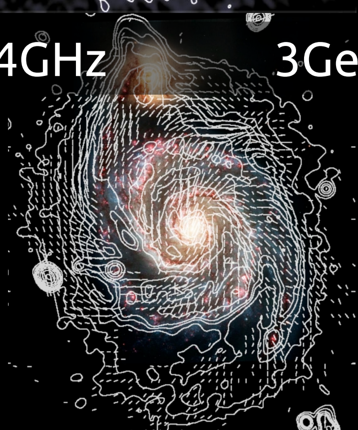

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source of CRE, $Q(r, E)$

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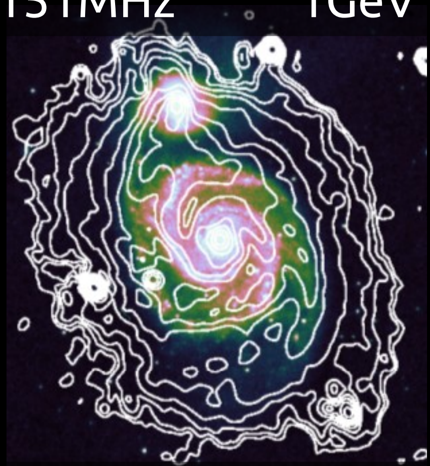

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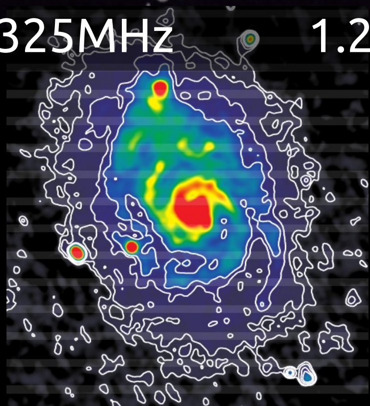

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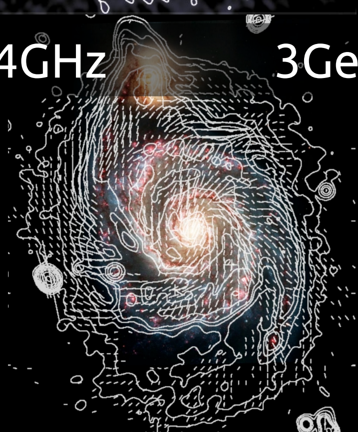

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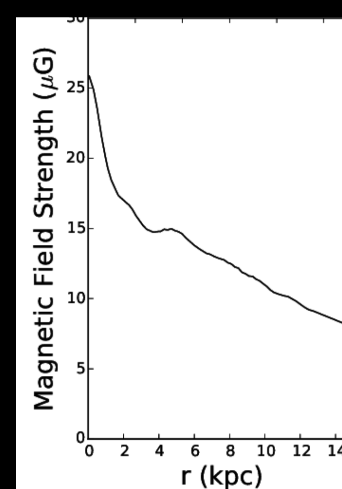
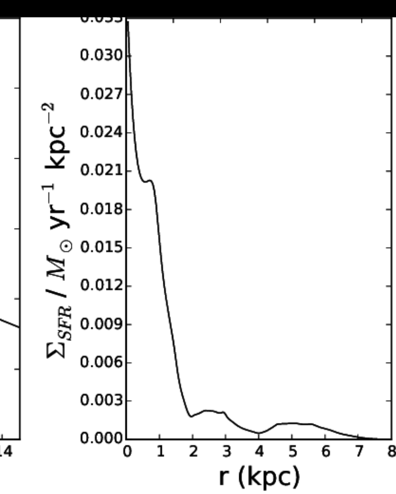
source of CRE, $Q(r, E)$

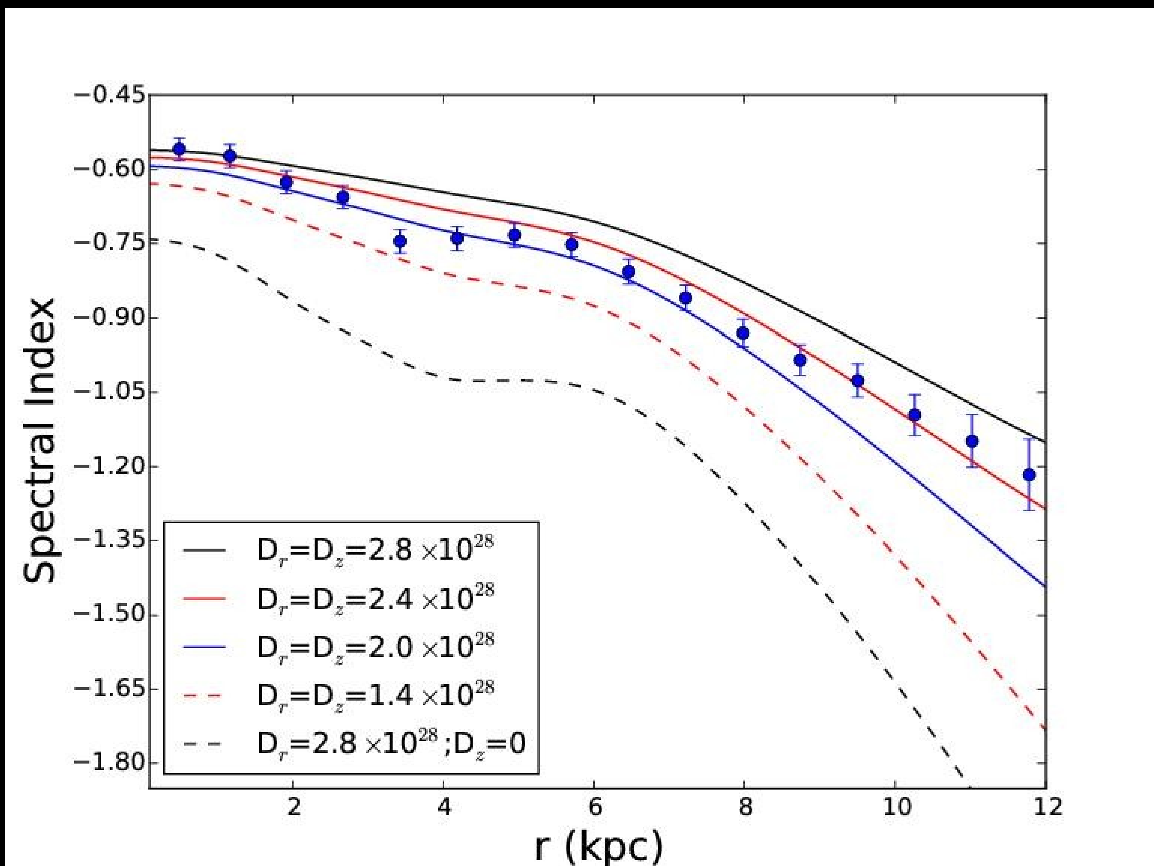
$B(r)$

SFR(r)



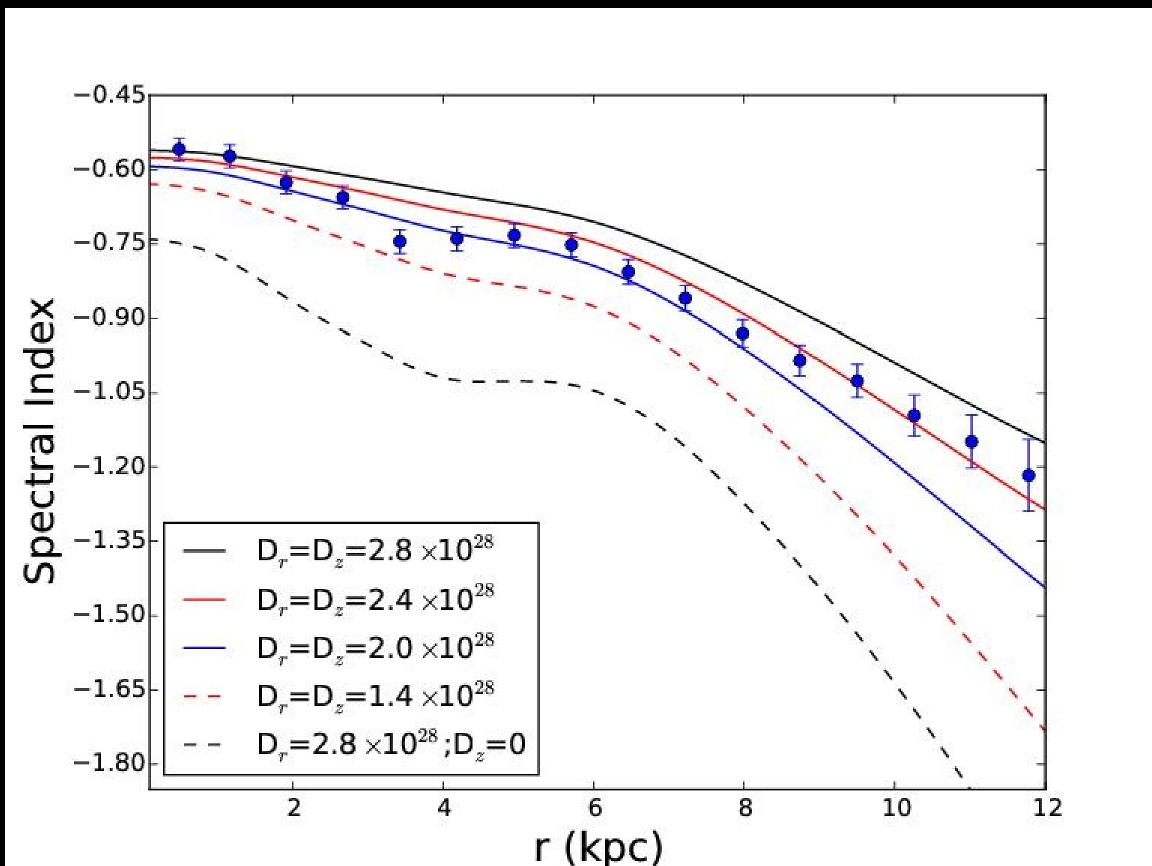


Cosmic ray electrons in M51



Mulcahy, Fletcher, et al. in prep.

Cosmic ray electrons in M51



$$D = 2.4 \pm 0.4 \times 10^{28} \mathrm{cm}^2 \mathrm{s}^{-1}$$

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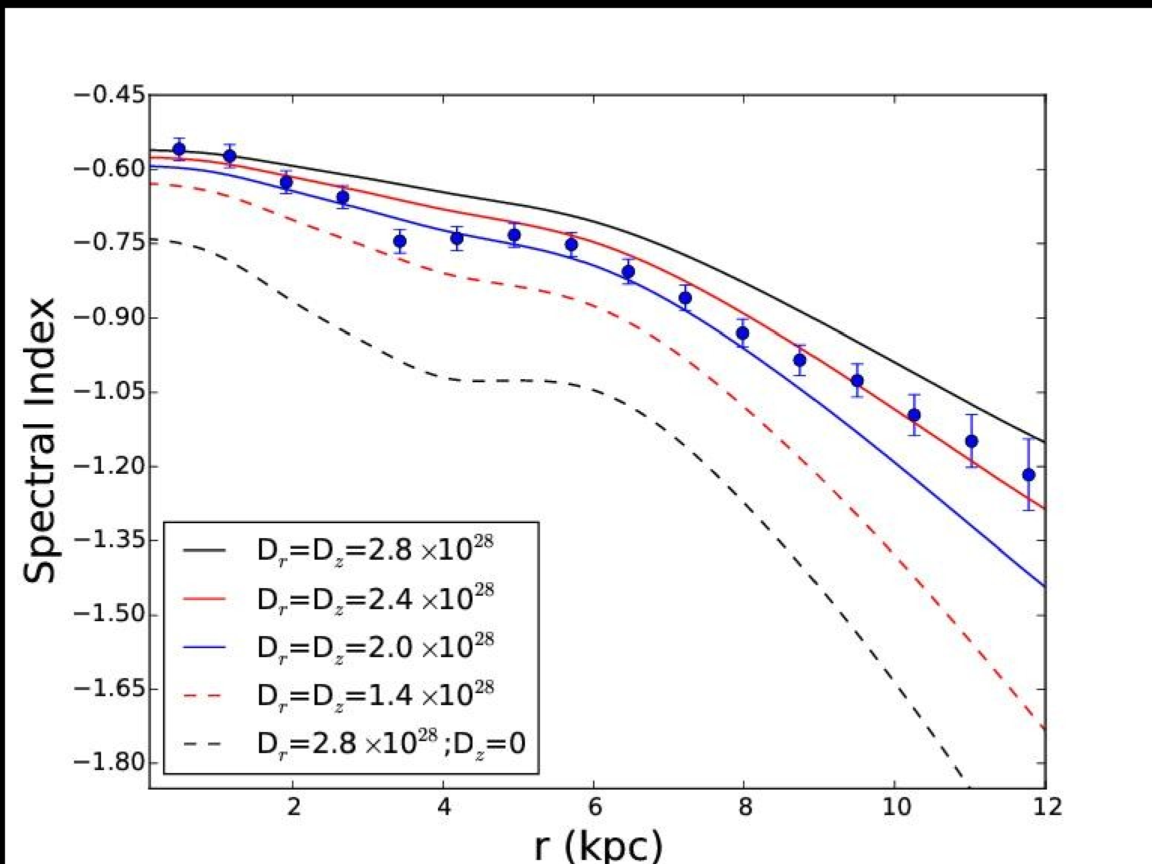
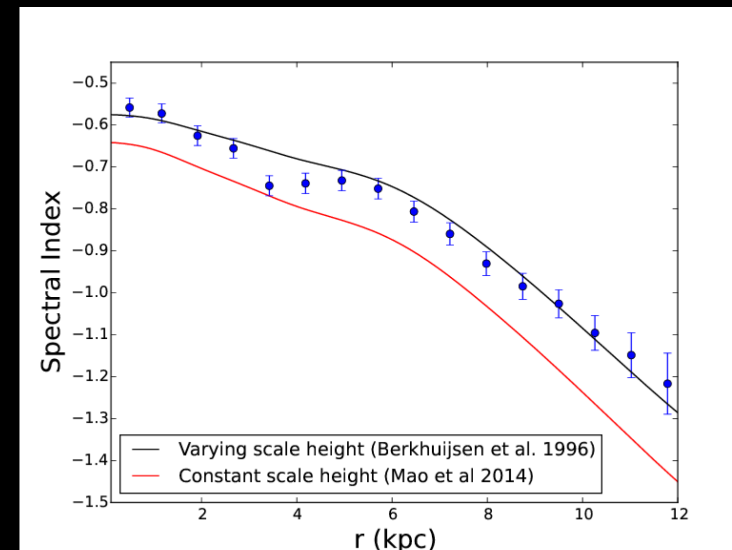
Cosmic ray electrons in M51



$h(r)$, better than h=const



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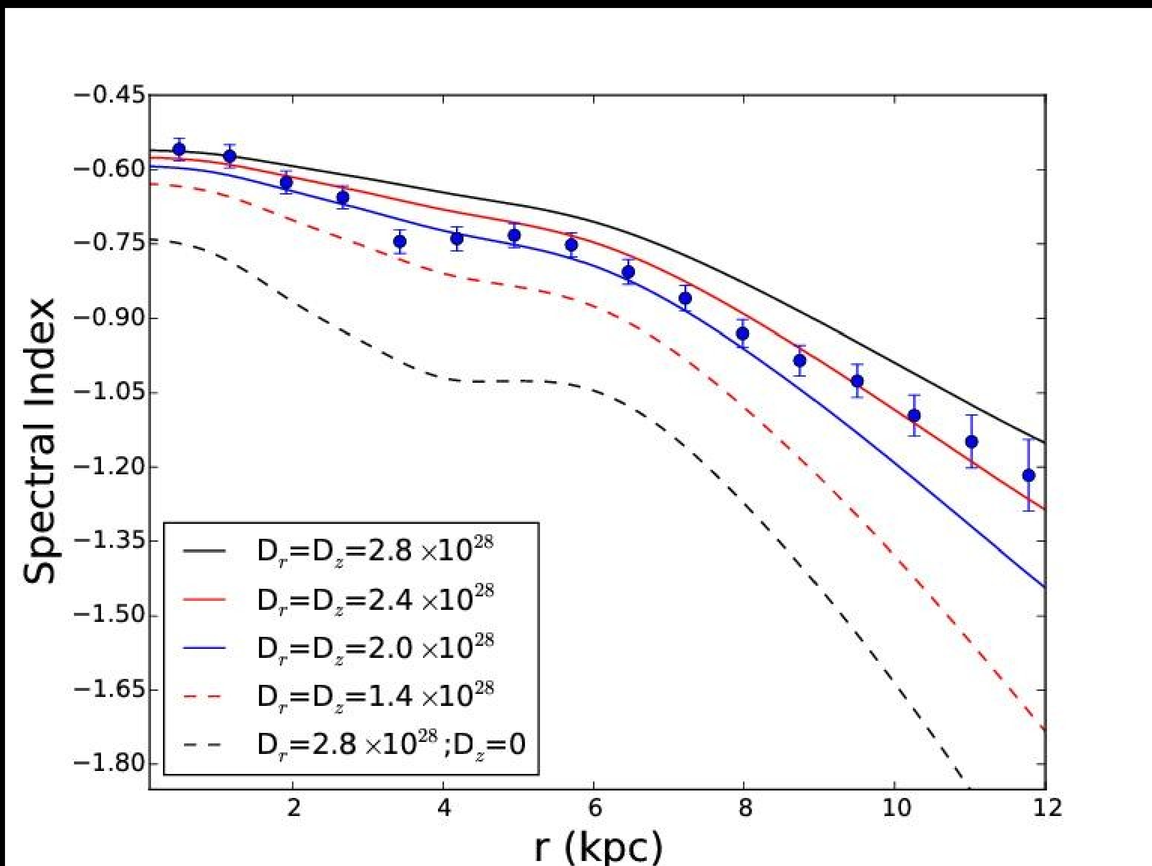

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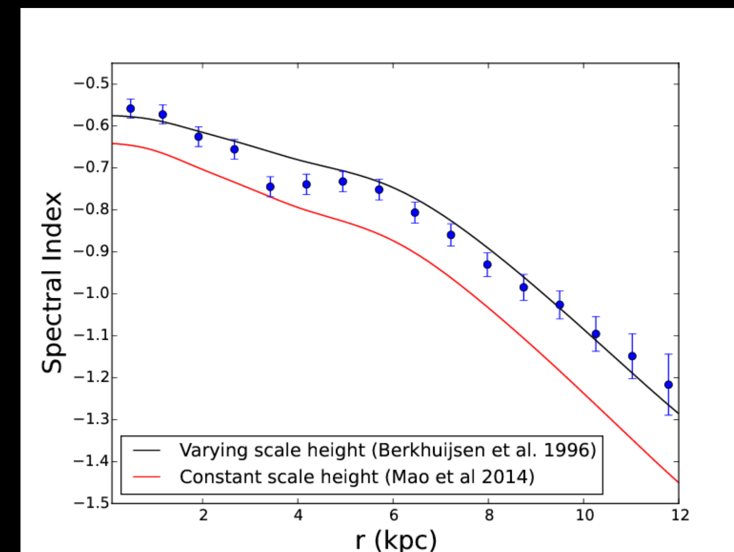
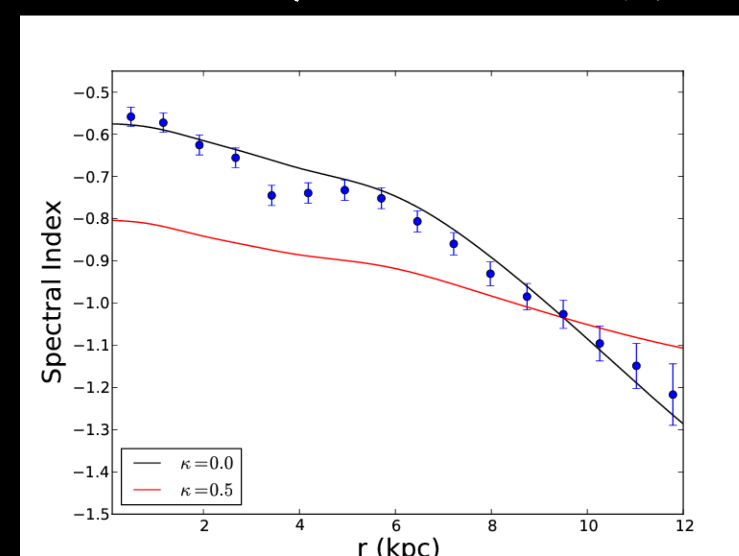


D=const, better than $D(E)$



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B-field & evolving galaxies

GALFORM (Cole et al. 2000)
galaxy formation model:

M_{gas} cold gas mass
M_{star} stellar mass
r_{50} half-mass radius
V_0 circular velocity at r_{50}
SFR star formation rate

… all as functions of time

Rodrigues, Shukurov, Fletcher & Baugh, 2015

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Estimate:

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… and other parameters

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D dynamo number
D_c critical D
B mean magnetic field
b random magnetic field

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B mean magnetic field
b random magnetic field

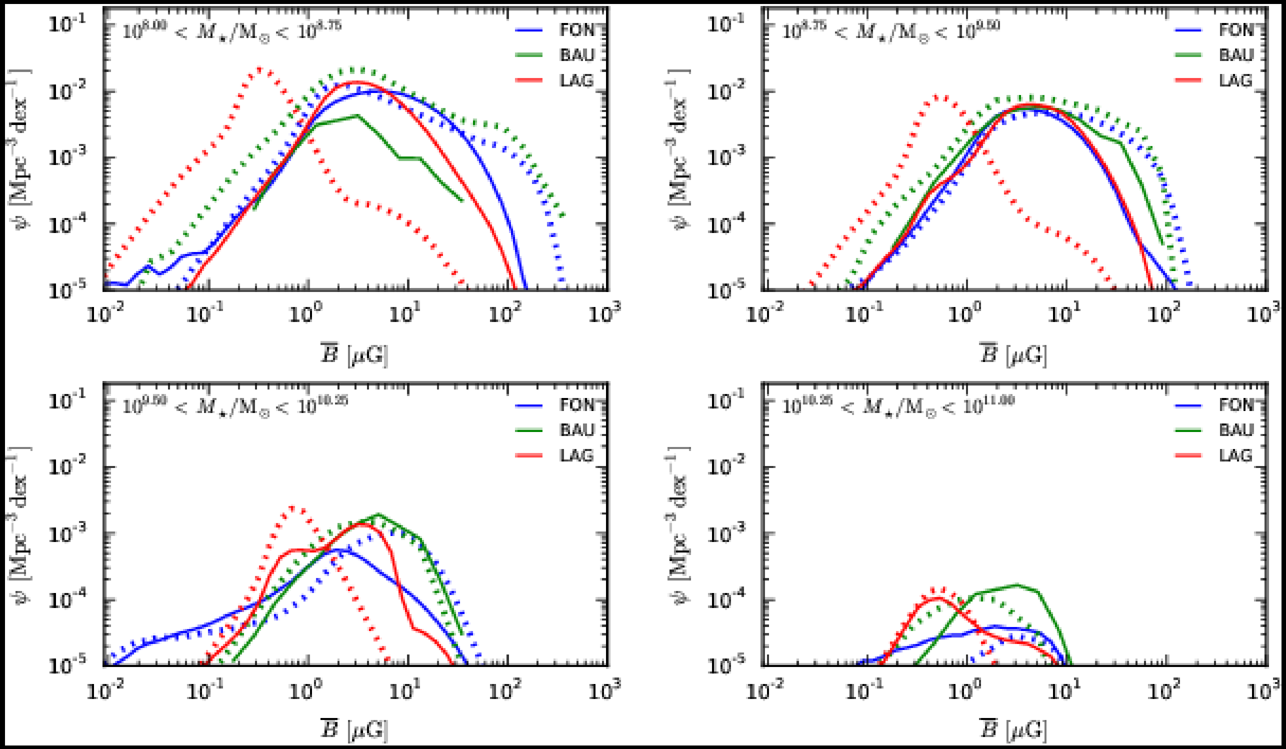
$$B^2 \propto (\rho v_0^2)\left(\frac{D}{D_c} - 1\right) R_u$$

$$D(l_0, v_0, h, S, R_u), \quad D_c(R_u), \quad R_u[SFR(\rho)]$$

Rodrigues, Shukurov, Fletcher & Baugh, 2015

Predicted mean field

PDFs at z=0

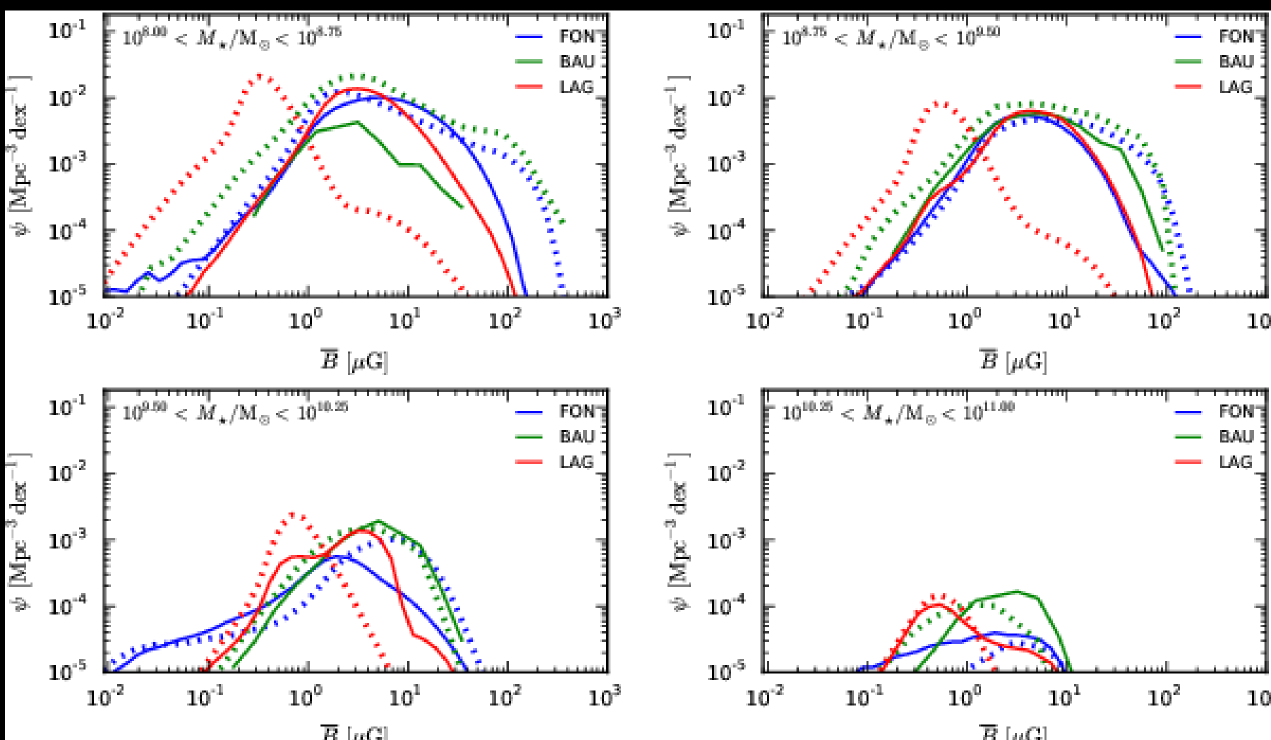


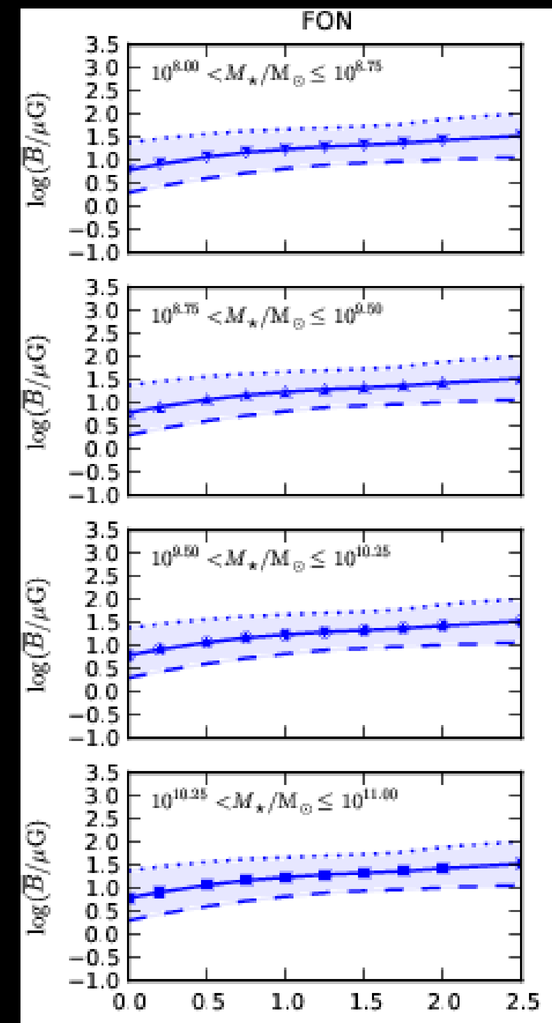
Rodrigues, Shukurov, Fletcher & Baugh, 2015

Predicted mean field

$\log(B)$ vs redshift

PDFs at z=0





Rodrigues, Shukurov, Fletcher & Baugh, 2015

Summary

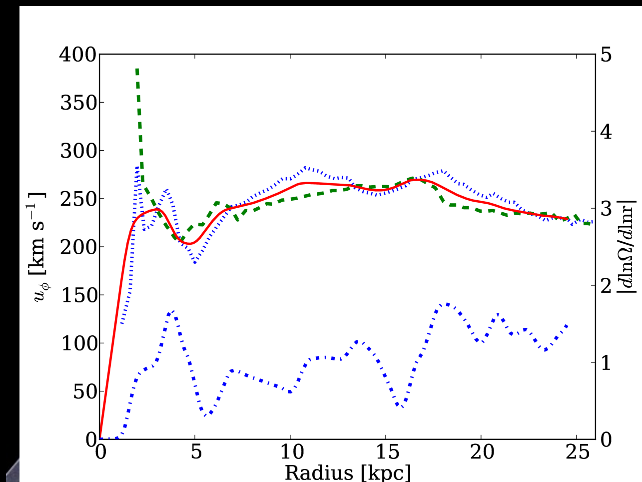
- Know magnetic properties of ~20 disc galaxies.
- Mean-field properties broadly as predicted by $\alpha\omega$-dynamo theory.
- Individual galaxies: $\alpha\omega$-dynamo, constrained by observed parameters, good results.
- Simple dynamo model does not predict B of all galaxies: problem with models or data?
- Low frequency, high resolution observations allow cosmic ray electron propagation to be modelled.
- First steps in coupling galaxy evolution models with dynamo (catalogues of galaxies, not individual).

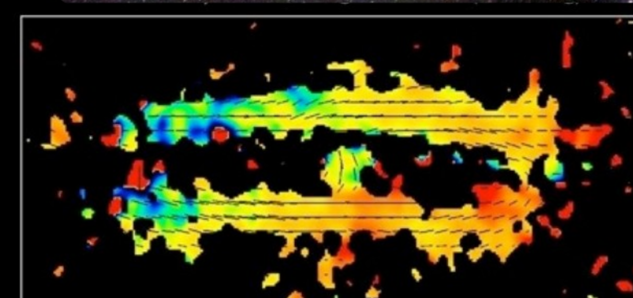
Dynamo model for M31

Non-linear αω-dynamo, outflow from disc removes small-scale magnetic helicity.

Observed: rotation curve,
star formation rate,
gas density,
disc scale height.

Compare to observed mean-field:
radial profile of B
pitch angle = $\arctan(B_r / B_\varphi)$





Copyright: MPIfR Bonn (R.Beck, E.M.Berkhuijsen & P.Hoernes)

Fletcher et al. 2004

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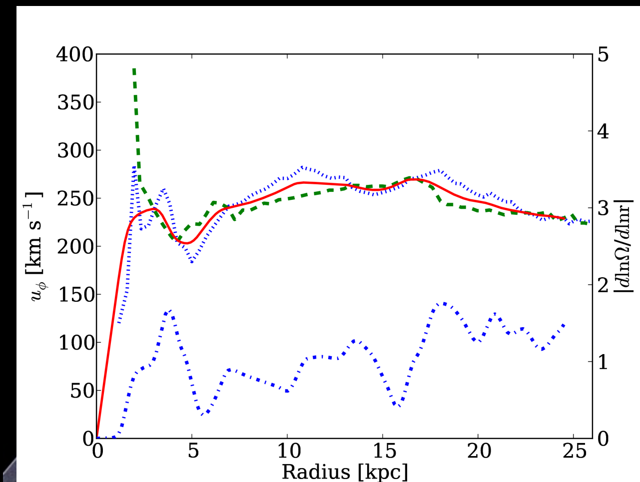
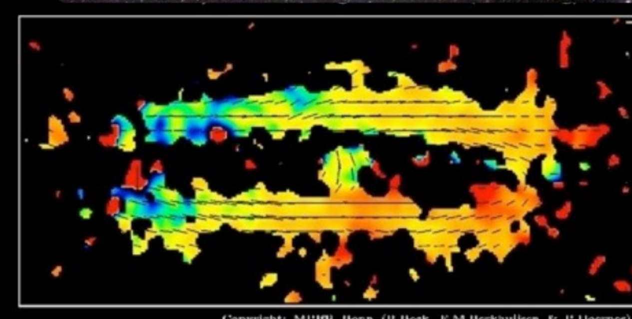
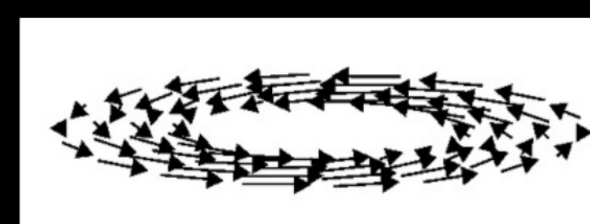
$$\frac{\partial B_r}{\partial t} = -\frac{\partial}{\partial z}[(\alpha_k + \alpha_m)B_\phi] + \eta\frac{\partial^2 B_r}{\partial z^2} - \frac{\partial}{\partial z}(U_z B_r)$$

$$\frac{\partial B_\phi}{\partial t} = SB_r + \eta\frac{\partial^2 B_\phi}{\partial z^2} - \frac{\partial}{\partial z}(U_z B_\phi)$$

$$\frac{\partial \alpha_m}{\partial t} = \cdots - \frac{\partial}{\partial z}(U_z \alpha_m) + \ldots$$



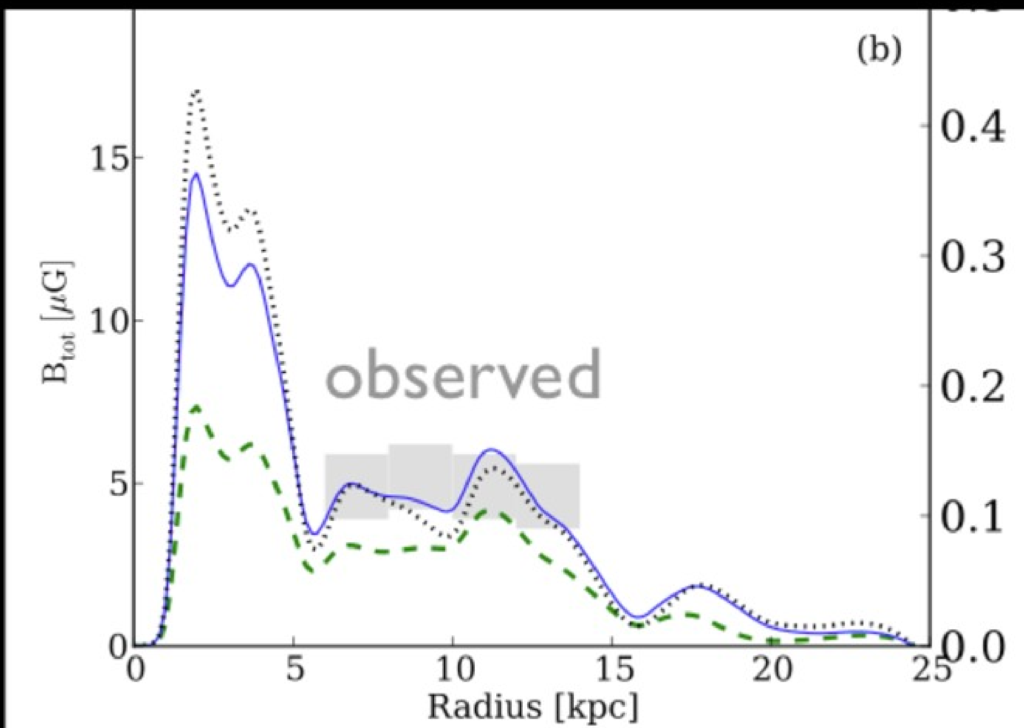




Fletcher et al. 2004

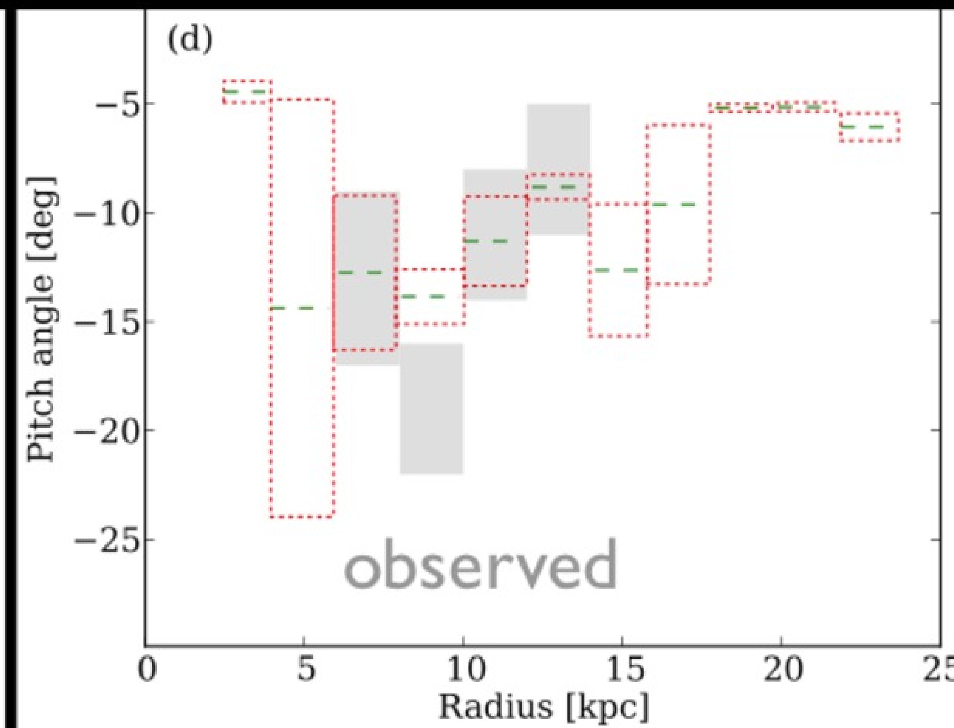
M31 dynamo with outflow

B strength



radius

B pitch angle



radius

Smith PhD Thesis 2012