Synthesizing Theory and Observation to Understand Galactic Magnetic Fields

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New Perspectives on Galactic Magnetism
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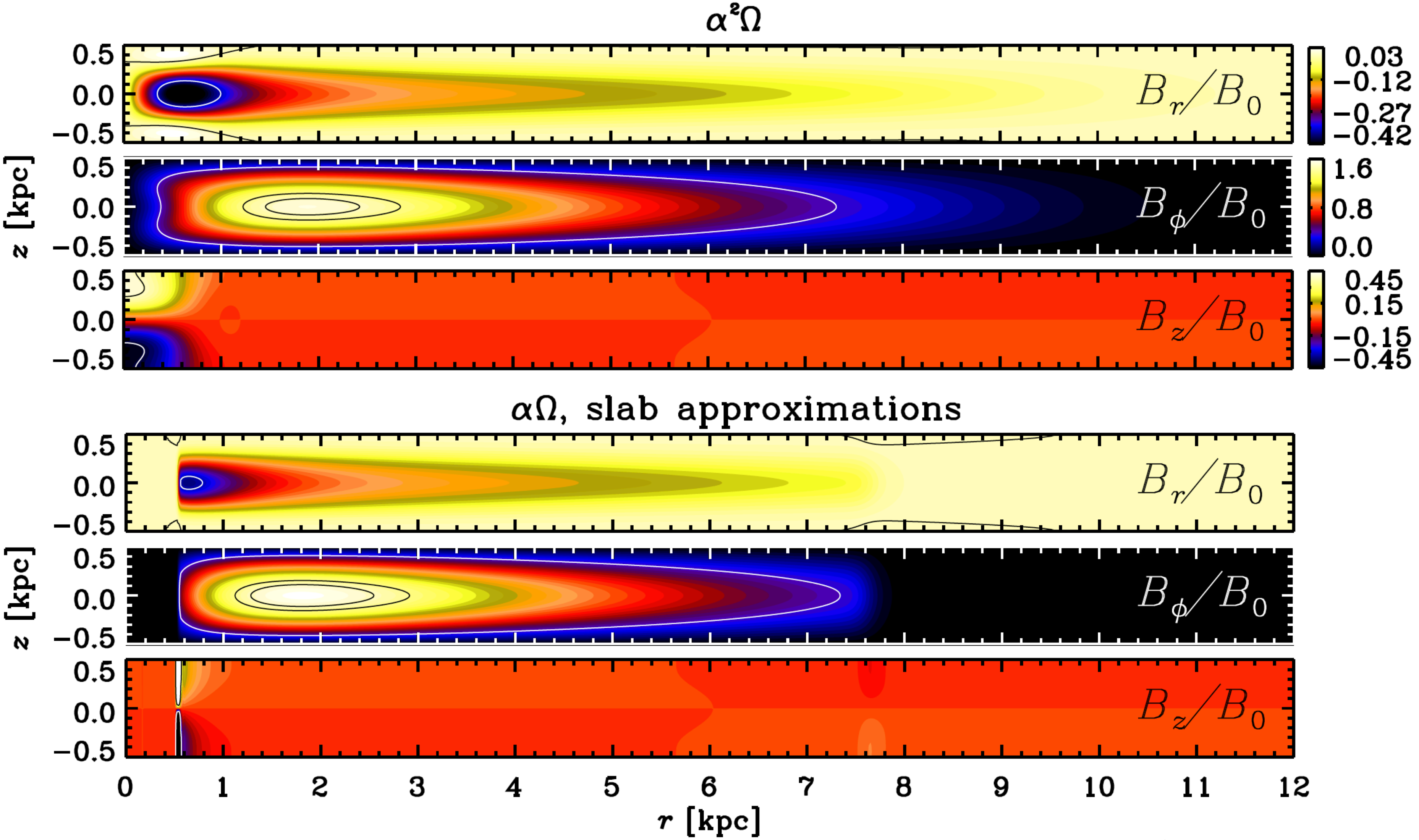
Outline

- Mean-field dynamo models
- Some successes of models vis-à-vis observations
- Constraining dynamo input parameters
- Interplay of small-scale and large-scale dynamos: magnetic Rädler effect
- Caveats in comparing observation and theory

2.5D vs 1.5D saturated solution

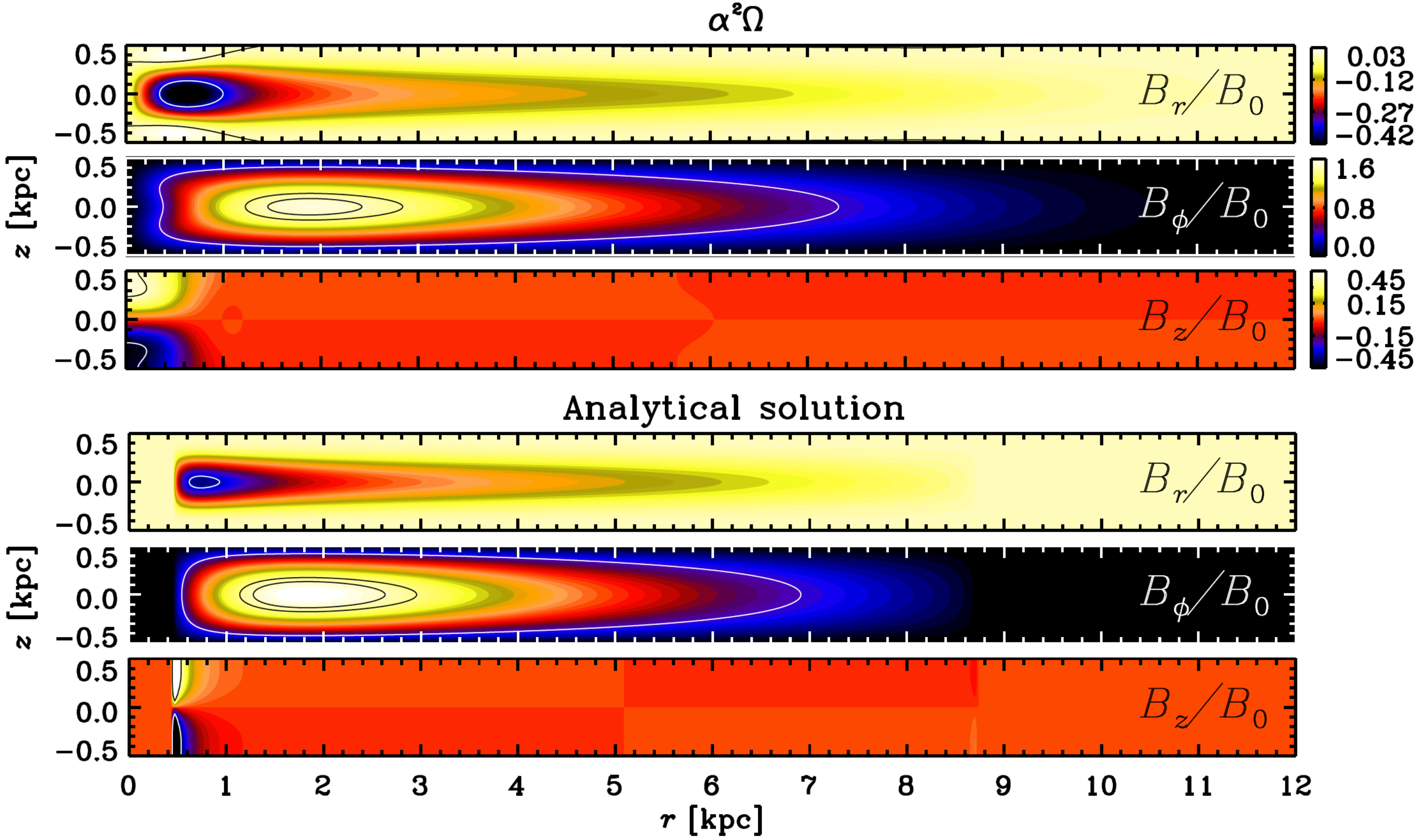


$\alpha^2\Omega$

$\alpha\Omega$, slab approximations

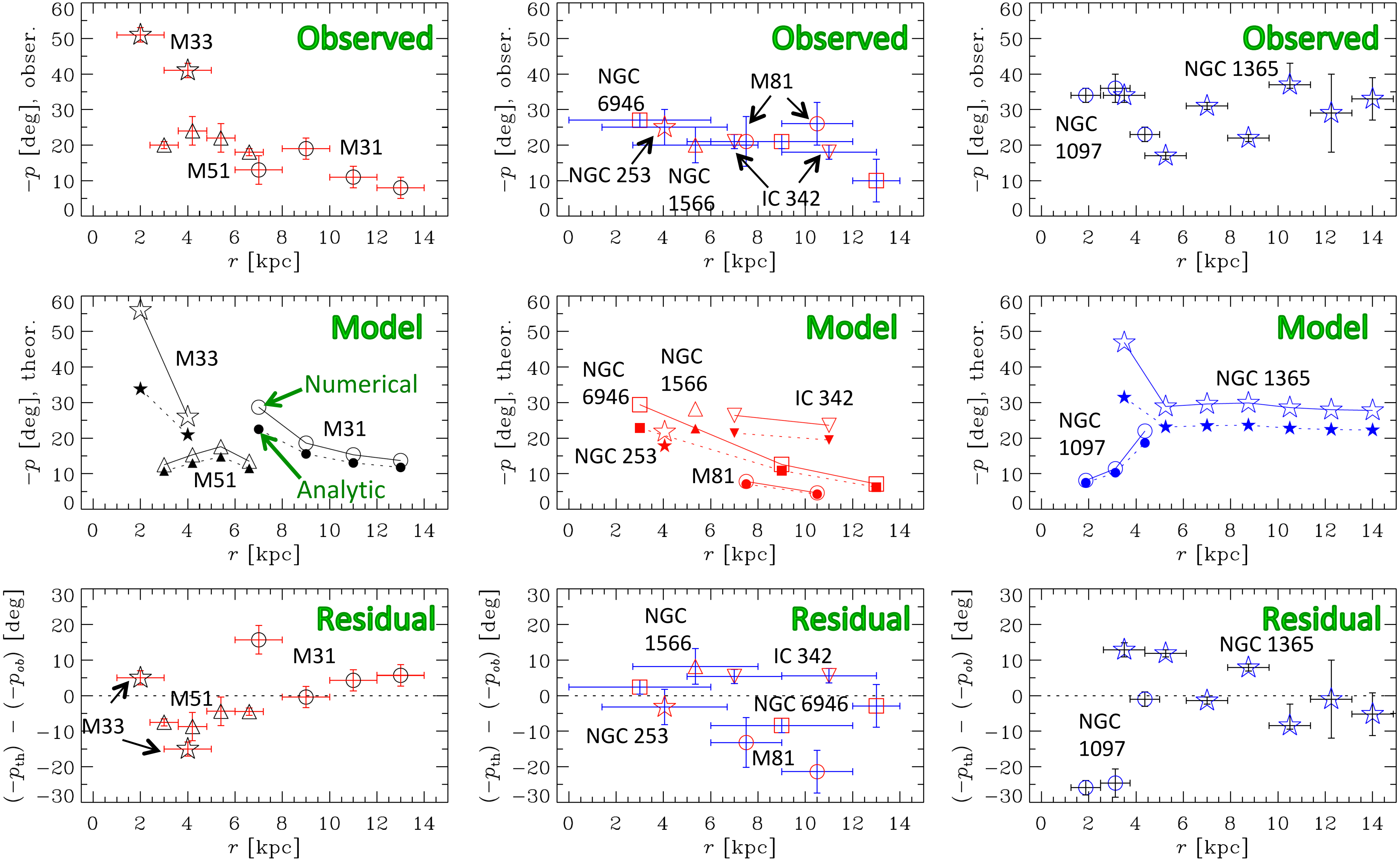
Chamandy 2016

2.5D vs analytic saturated solution



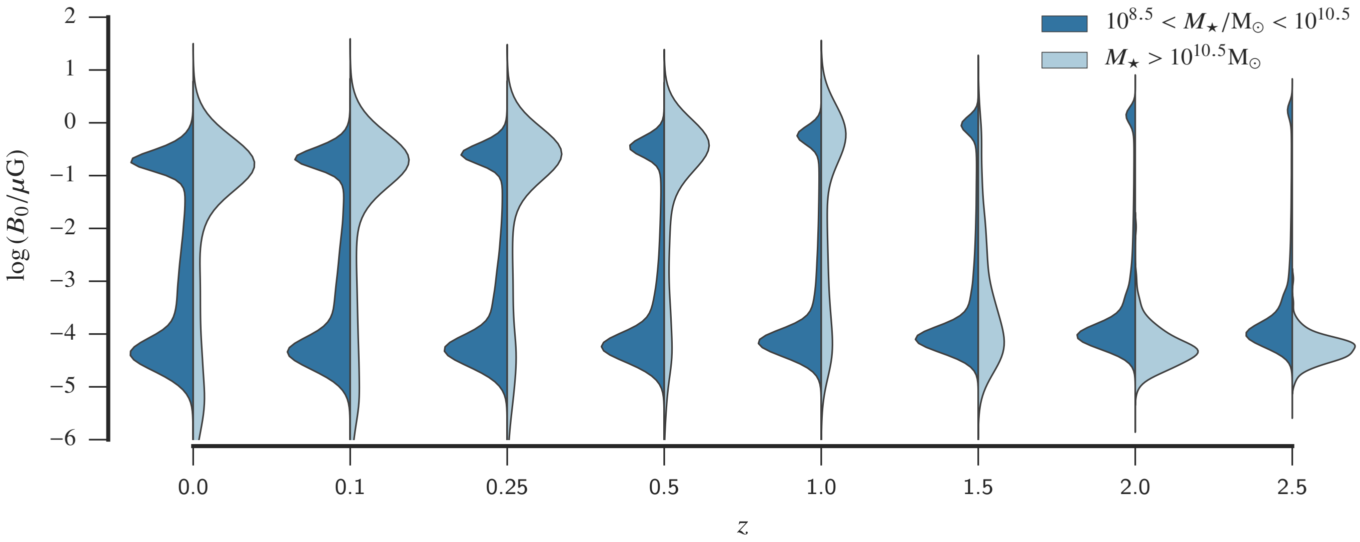
Chamandy 2016

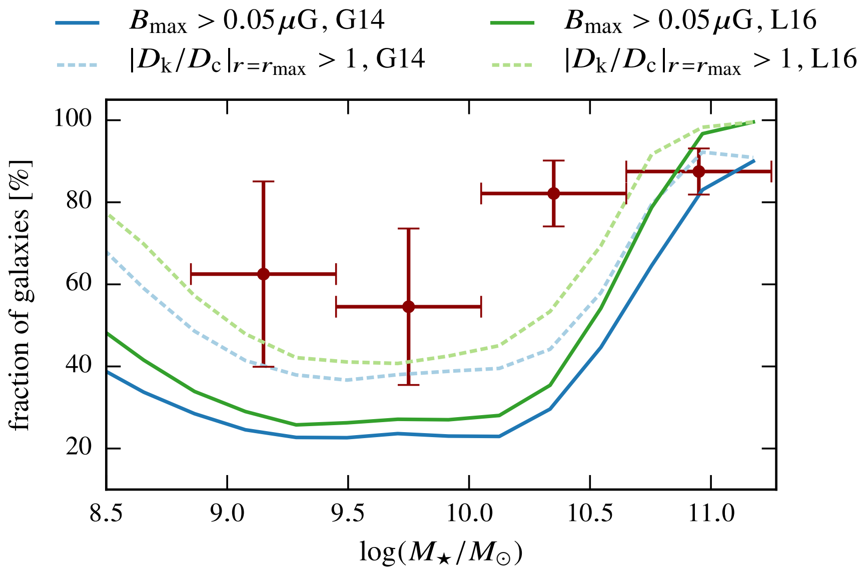
Pitch angle of large-scale field



Chamandy, Shukurov & Taylor 2016

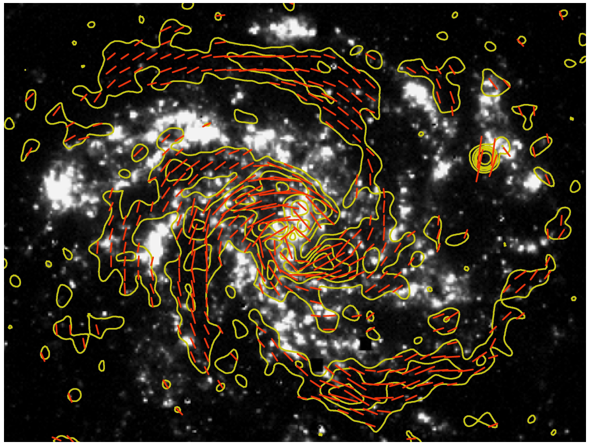
Cosmological evolution

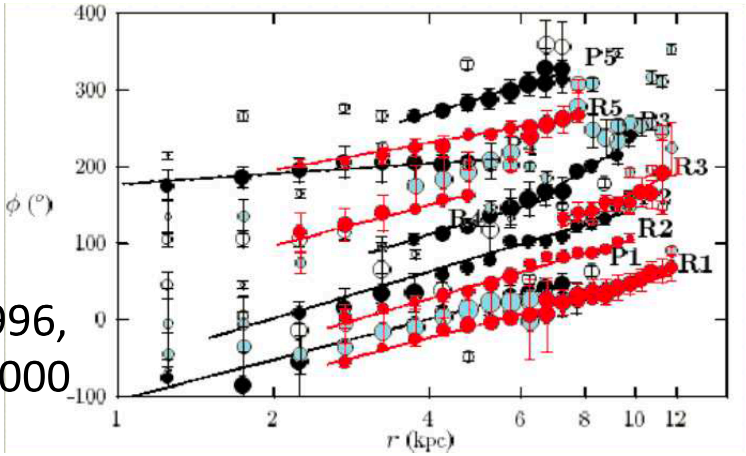




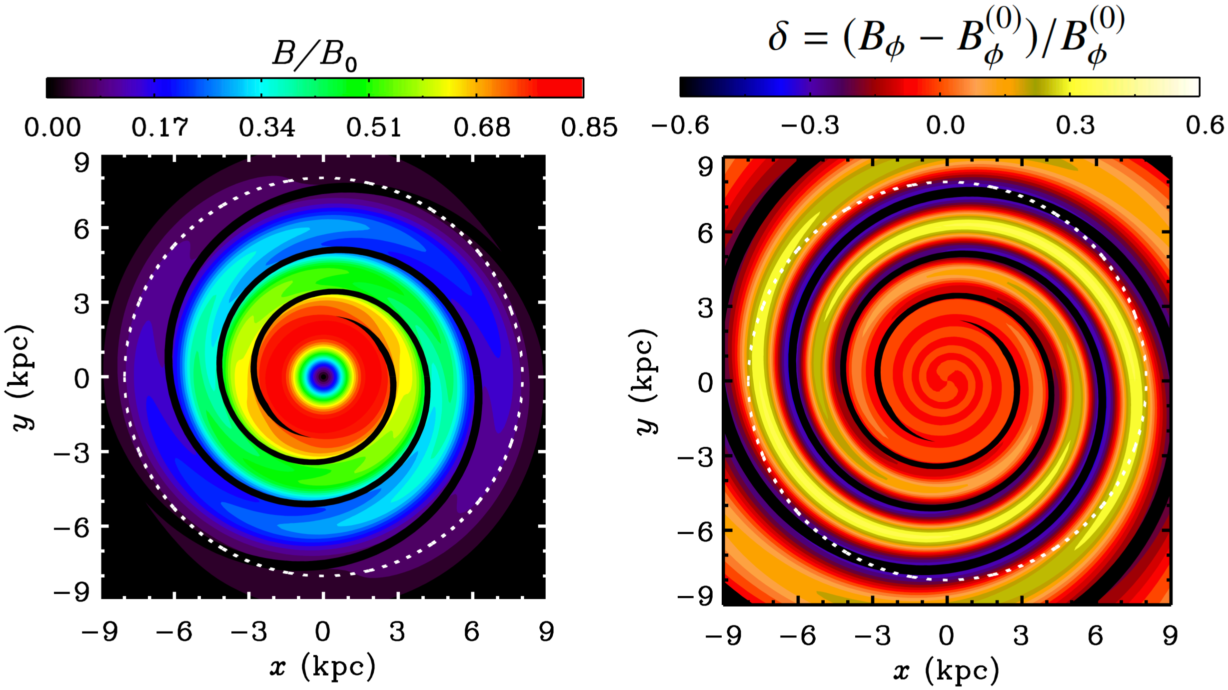
Rodrigues, Chamandy, Shukurov, Baugh & Taylor 2019

Magnetic arms





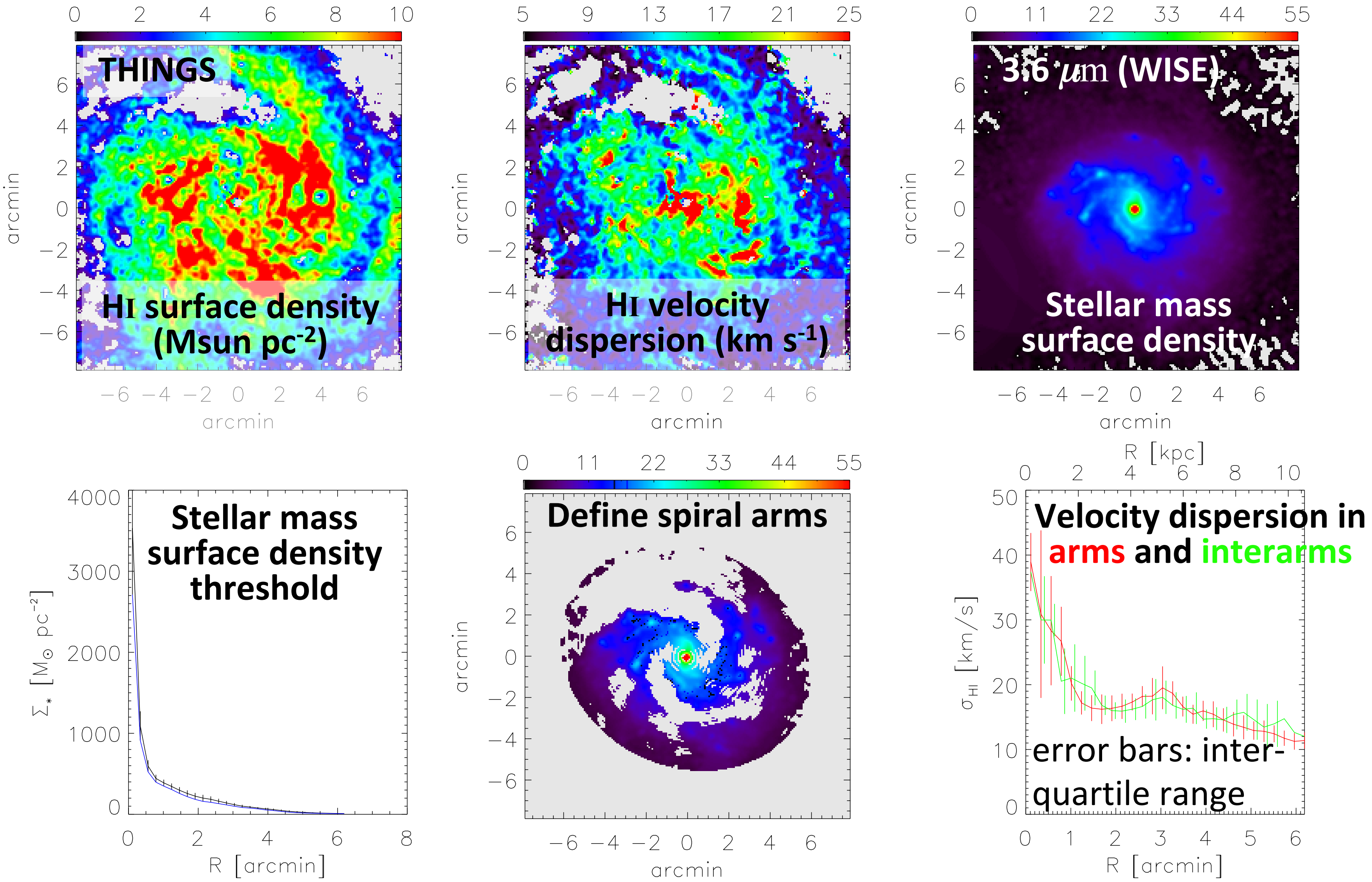
Beck & Hoernes 1996, Beck 2012, Frick+2000



Chamandy, Shukurov & Subramian 2015

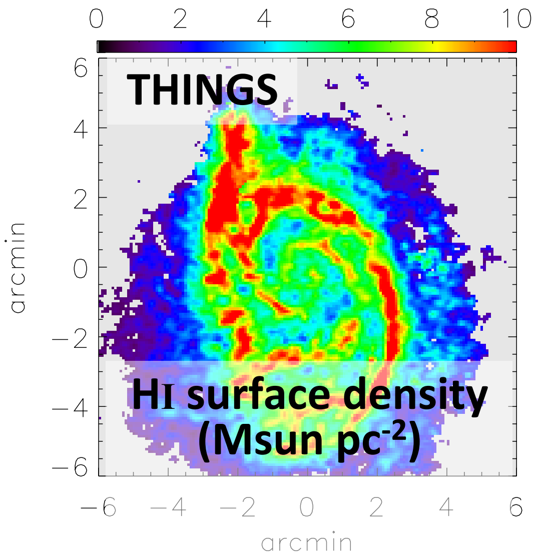
- Depends on nature of spiral structure & evolution
- Need to non-axisymmetrically force the dynamo—but how?
  - spirally modulate U_z?
  - model spiral streaming motions, which affect U_r and U_ϕ?
  - spirally modulate u? (Moss+2015)

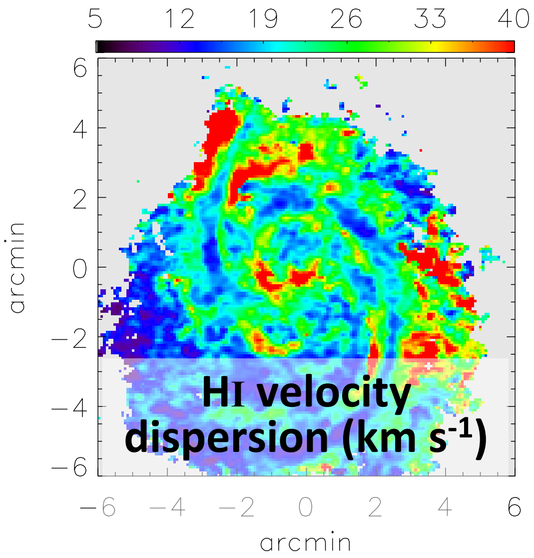
NGC 6946

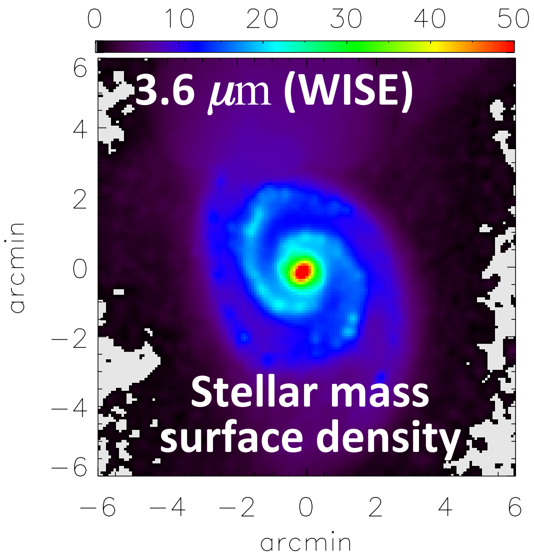


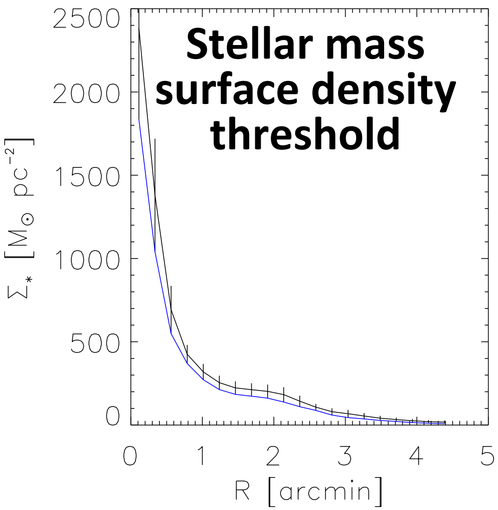
Beck, Chamandy, Elson & Blackman 2019 (to be submitted to *Galaxies*)

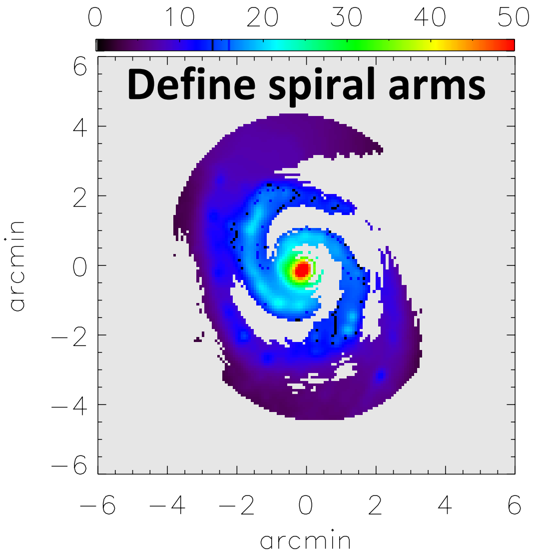
M51 (NGC 5194)

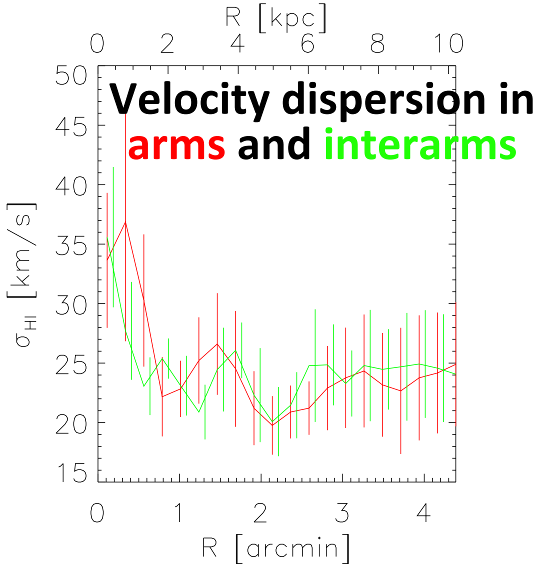






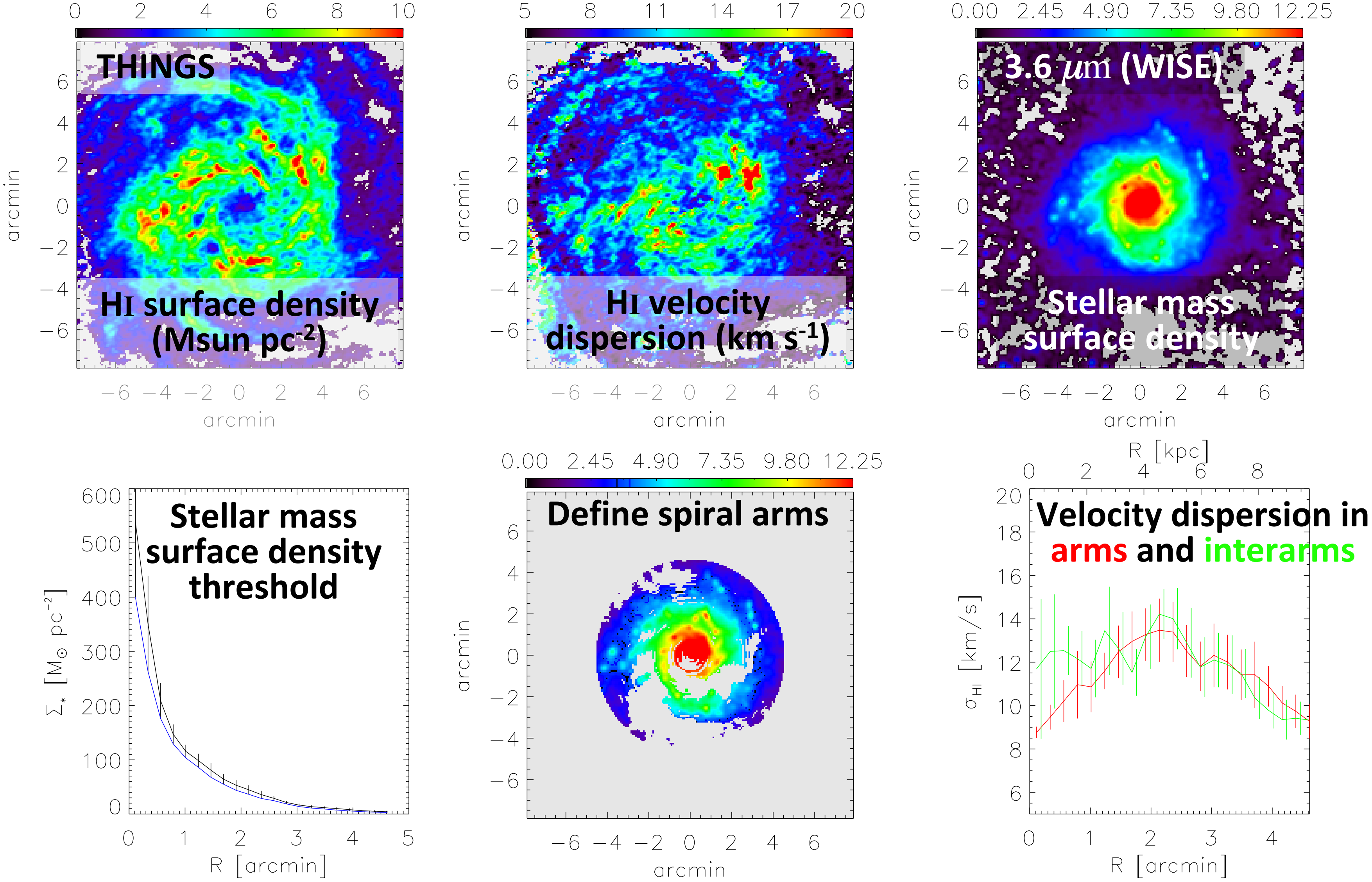






Beck, Chamandy, Elson & Blackman 2019 (to be submitted to *Galaxies*)

M74 (NGC 628)



Beck, Chamandy, Elson & Blackman 2019 (to be submitted to *Galaxies*)

Constraining arm-interarm velocity dispersion

- No evidence for arm-interarm contrast of velocity dispersion in NGC 6946, M51 or M74: difficult to reconcile a difference of >20%.
- Using SFR or HI surface densities to define arms does not yield very different results
- But analysis could still be improved:
  - Separating out thermal component of line broadening
  - Separating “regular” component of HI from “anomolous” component, e.g. by fitting more than one Gaussian to line profile
  - Better definition of arm/interarm regions (e.g. using wavelet analysis)

ISM turbulence parameters

Want dynamo parameters u, τ, l, as functions of "observables":

	Symbol	Unit	Range	Fiducial
Ambient sound speed	c_s	$\mathrm{km\,s^{-1}}$	10–20	10
Ambient gas number density	n	$\mathrm{cm^{-3}}$	0.1–1	0.1
Disk scale height	H	kpc	0.2–1	0.4
Fraction of SNe clustered into OB associations	f_SB	–	0.5–0.75	0.75
SN frequency per unit volume	ν	$\mathrm{kpc^{-3}\,Myr^{-1}}$	50–100	50
Number of SNe residing in a SB	N_SB	–	10^2–10^3	10^2
Fraction of the SB energy that is kinetic energy	η	–	0.05–0.1	0.1
Initial SN energy	E_SN	erg	10^{50}–10^{51}	10^{51}

Estimate of l

$$l_\mathrm{SN} \approx R_\mathrm{SN}(t_\mathrm{s}^\mathrm{SN}) = 142\,\mathrm{pc}\,E_{51}^{16/51} n_{0.1}^{-19/51} c_{10}^{-1/3}$$

$$l_\mathrm{SB} = \min\left[R_\mathrm{SB}(t_\mathrm{s}^\mathrm{SB}), \xi H\right]$$

$$R_\mathrm{SB}(t_\mathrm{s}^\mathrm{SB}) = 0.53\,\mathrm{kpc}\,\eta_{0.1}^{1/3} N_{100}^{1/3} E_{51}^{1/3} n_{0.1}^{-1/3} c_{10}^{-2/3}$$

$$\boxed{l = l_\mathrm{SB}\left\{\frac{1 + (l_\mathrm{SN}/l_\mathrm{SB})\dot{\varepsilon}_\mathrm{SN}/\dot{\varepsilon}_\mathrm{SB}}{1 + \dot{\varepsilon}_\mathrm{SN}/\dot{\varepsilon}_\mathrm{SB}}\right\}}$$

Estimate of u

$$\dot{\varepsilon}^\mathrm{i} = \frac{2\pi}{3}\rho_0 c_\mathrm{s}^2 \nu \left[(1 - f_\mathrm{SB}) l_\mathrm{SN}^3 + \frac{f_\mathrm{SB}}{N_\mathrm{SB}} l_\mathrm{SB}^3\right]$$

$$\dot{\varepsilon}^\mathrm{d} = \frac{\rho_0 u^2}{\tau^\mathrm{e}} = \frac{\rho_0 u^3}{l}$$

$$\dot{\varepsilon}^\mathrm{i} = \dot{\varepsilon}^\mathrm{d}$$

$$\boxed{u = \left[\frac{2\pi}{3} l c_\mathrm{s}^2 \nu \left((1 - f_\mathrm{SB}) l_\mathrm{SN}^3 + \frac{f_\mathrm{SB}}{N_\mathrm{SB}} l_\mathrm{SB}^3\right)\right]^{1/3}}$$

Estimate of τ

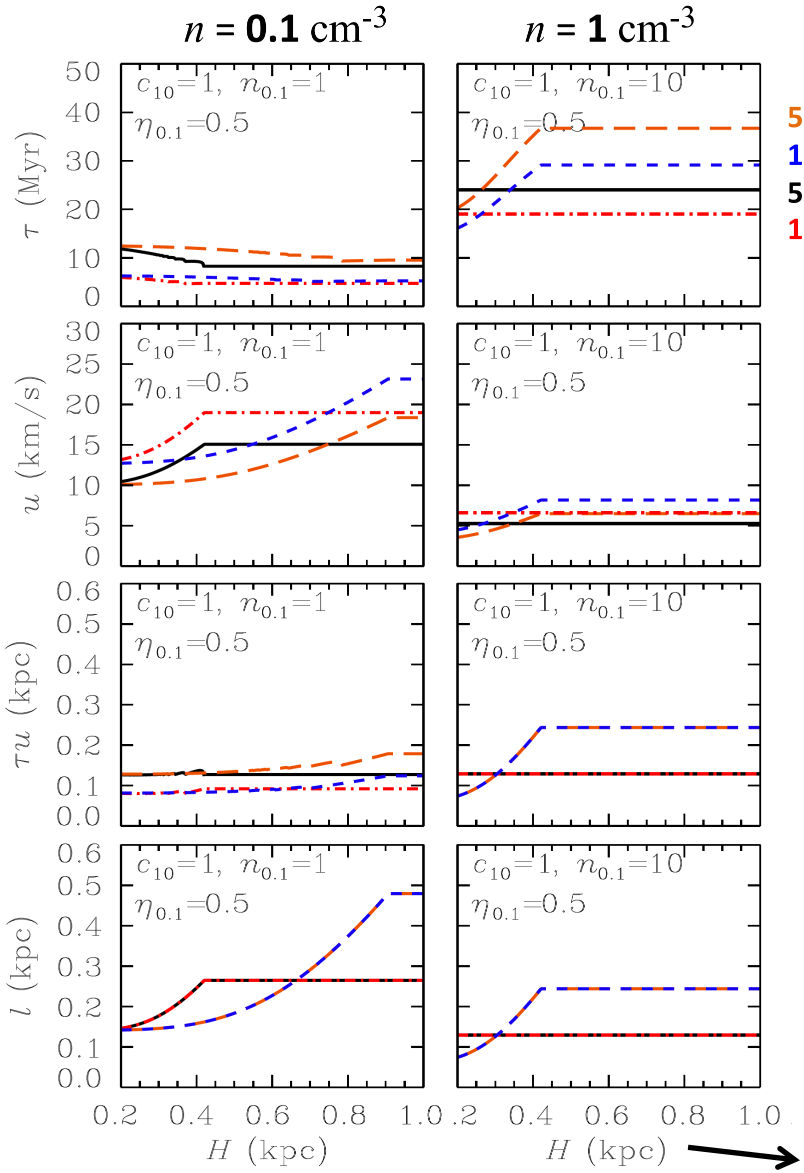
$$\tau^\mathrm{e} = l/u$$

$$\tau^\mathrm{r} = \left(\frac{1}{\tau_\mathrm{SN}^\mathrm{r}} + \frac{1}{\tau_\mathrm{SB}^\mathrm{r}}\right)^{-1}$$

$$\boxed{\tau = \min(\tau^\mathrm{r}, \tau^\mathrm{e})}$$

Chamandy & Shukurov 2019 (to be submitted to *Galaxies*)

ISM turbulence parameters



50 SN kpc^{-3} Myr^{-1} & **1000** SN per SB
100 SN kpc^{-3} Myr^{-1} & **1000** SN per SB
50 SN kpc^{-3} Myr^{-1} & **100** SN per SB
100 SN kpc^{-3} Myr^{-1} & **100** SN per SB

- $\tau \sim$ 5—30 Myr, as expected
- u increases with *SNR* (hence *SFR*) but decreases with n

  → This could help to explain low variation of u between arm and interarm regions, since arms have high n and high *SFR*
- But *SFR* and *n* arm-interarm contrasts still need to be measured!
- SBs are less signficant for small disc scale heights, since they quickly break out
- $l \sim$ a **few ×** 100 pc **but** $\tau u \sim$ 100 pc
- Hence Strouhal number $\neq 1$

→ **Scale height of diffuse gas (Lockman layer)—see Mac Low & McCray 1988**

SS field may affect LS dynamo

- SS dynamo is much faster than LS dynamo, leads to SS field in near-equipartition with turbulent KE while LS dynamo is still in kinematic regime.
- Can LS dynamo operate in the presence of strong magnetic fluctuations?: Yes (Sur+2008, Subramanian+Brandenburg 2014, Bhat+2019).
- But if one allows the turbulent transport coefficients of LS dynamo theory to be anisotropic (owing to LS rotation/shear), new contributions arise that depend, in part, on SS magnetic energy (Rädler+2003, Brandenburg+Subramanian 2005).

MEAN INDUCTION EQUATION

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{U} \times \boldsymbol{B} + \boldsymbol{\mathcal{E}})$$

MEAN ELECTROMOTIVE FORCE

$$\mathcal{E}_i = \alpha_{ij} B_j - \eta_{ij} J_j + (\boldsymbol{\gamma} \times \boldsymbol{B})_i + (\boldsymbol{\delta} \times \boldsymbol{J})_i + \kappa_{ijk} B_{j,k}$$

MEAN ELECTROMOTIVE FORCE IN SLAB GEOMETRY, CYLINDRICAL COORDS

$$\mathcal{E}_r = \alpha B_r + \eta \frac{\partial B_\phi}{\partial z} - \gamma B_\phi - (\delta - \kappa) \frac{\partial B_r}{\partial z}$$

$$\mathcal{E}_\phi = \alpha B_\phi - \eta \frac{\partial B_r}{\partial z} + \gamma B_r - (\delta - \kappa) \frac{\partial B_\phi}{\partial z}$$

UNITS

$\rho = 1$

$\mu_0 = 1$

‘MAGNETIC RÄDLER EFFECT’

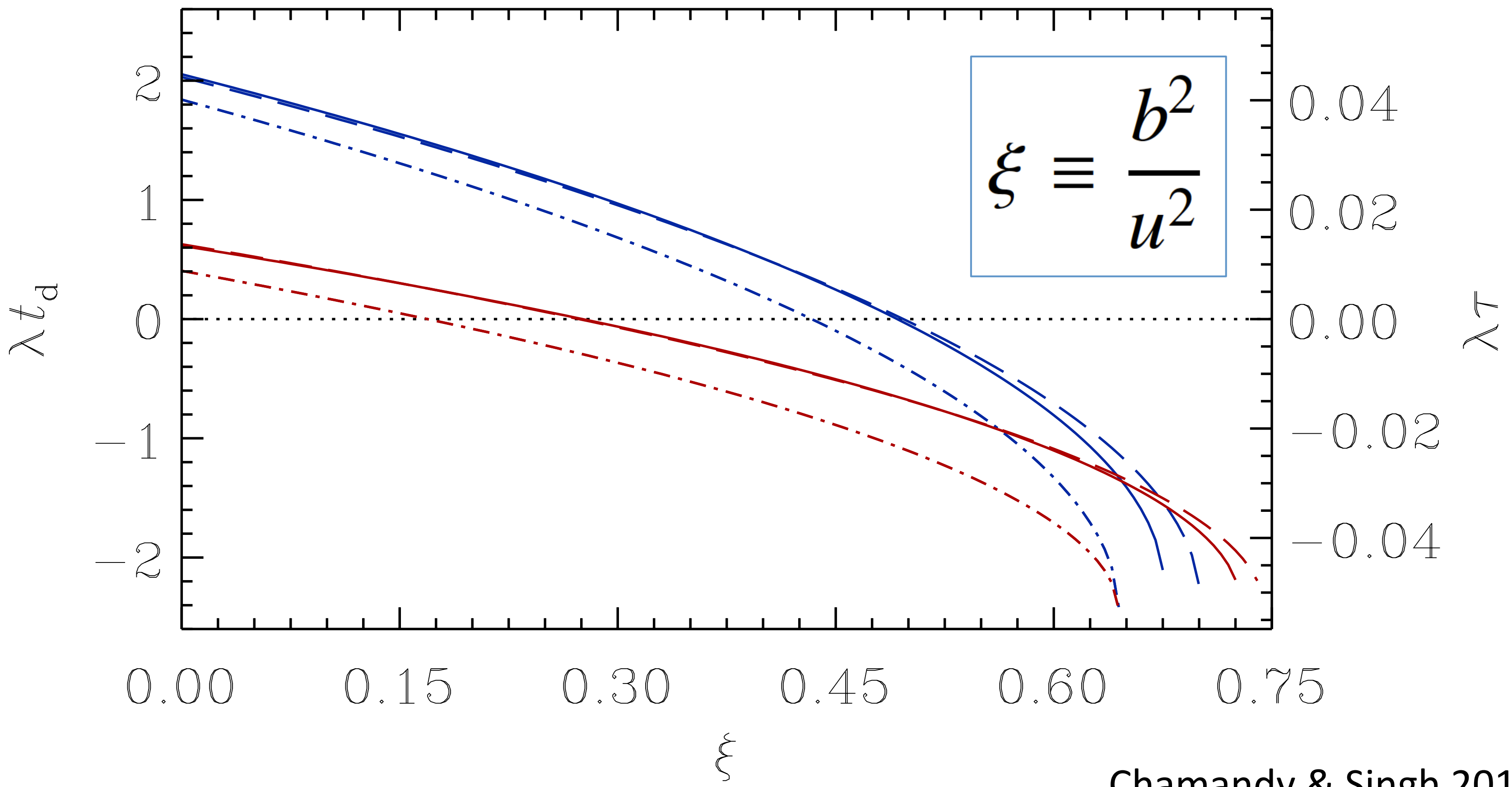
$$\delta = \delta_z = \tfrac{1}{6} \Omega \tau^2 \left(u^2 - b^2 \right),$$

$$\kappa = \kappa_{rrz} = \kappa_{\phi\phi z} = \tfrac{1}{6} \Omega \tau^2 \left(u^2 + \tfrac{7}{5} b^2 \right).$$

$$\boxed{\delta' \equiv \delta - \kappa = -\tfrac{2}{5} \Omega \tau^2 b^2}$$

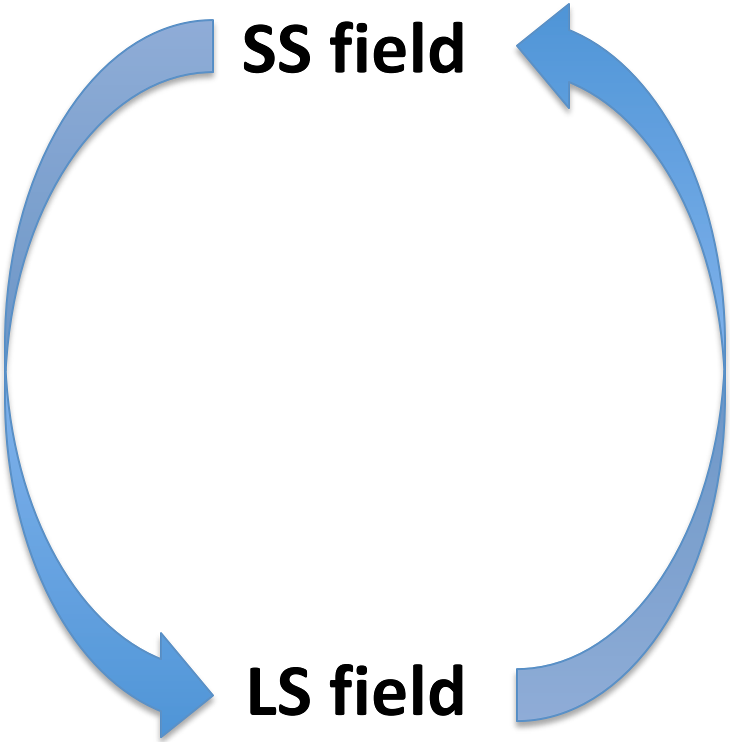
Rädler, Kleeorin & Rogachevskii 2003,
Brandenburg & Subramanian 2005 (Sec. 10),
Chamandy & Singh 2017, 2018

Model	ξ	R_Ω	R_α	$q^{1/2}h/(\tau u)$	$\Omega\tau$	D
A_ξ ●	varied	−14.1	0.92	3.91	0.31	−13.0
B_ξ ●	varied	−21.1	1.38	3.91	0.46	−29.2



Chamandy & Singh 2017

This also leads to a new type of feedback in the non-linear regime



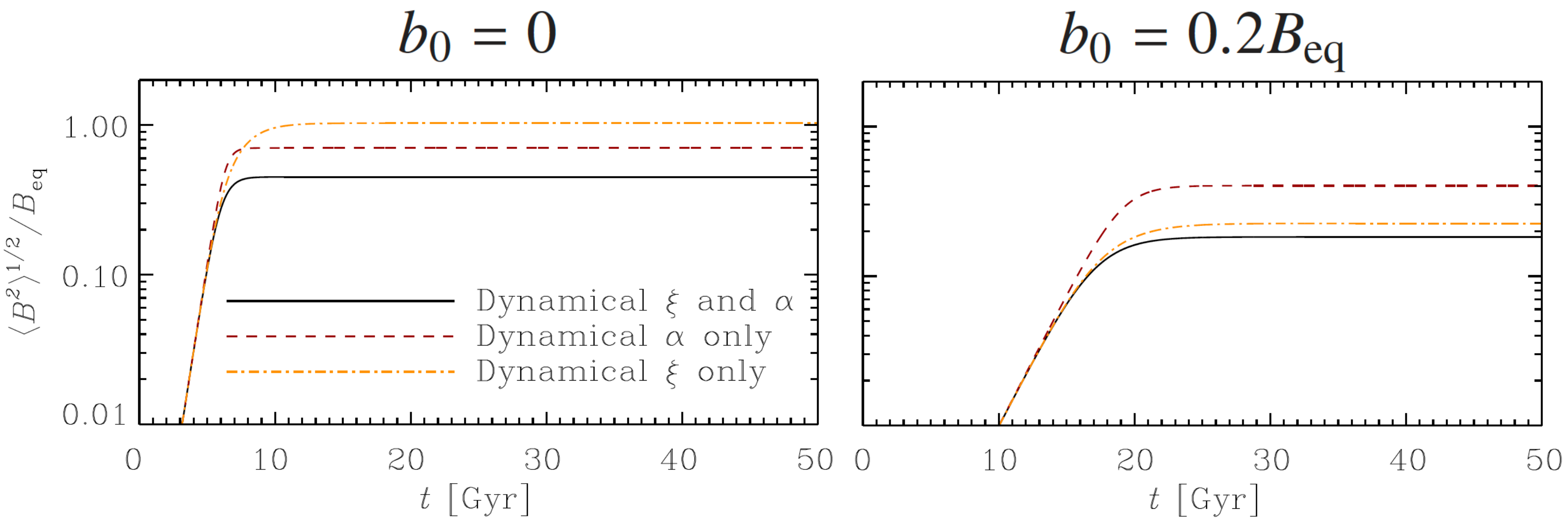
SS field

Magnetic Rädler effect

Turbulent tangling

LS field

This saturation mechanism is competitive with dynamical α quenching for realistic galactic parameter values

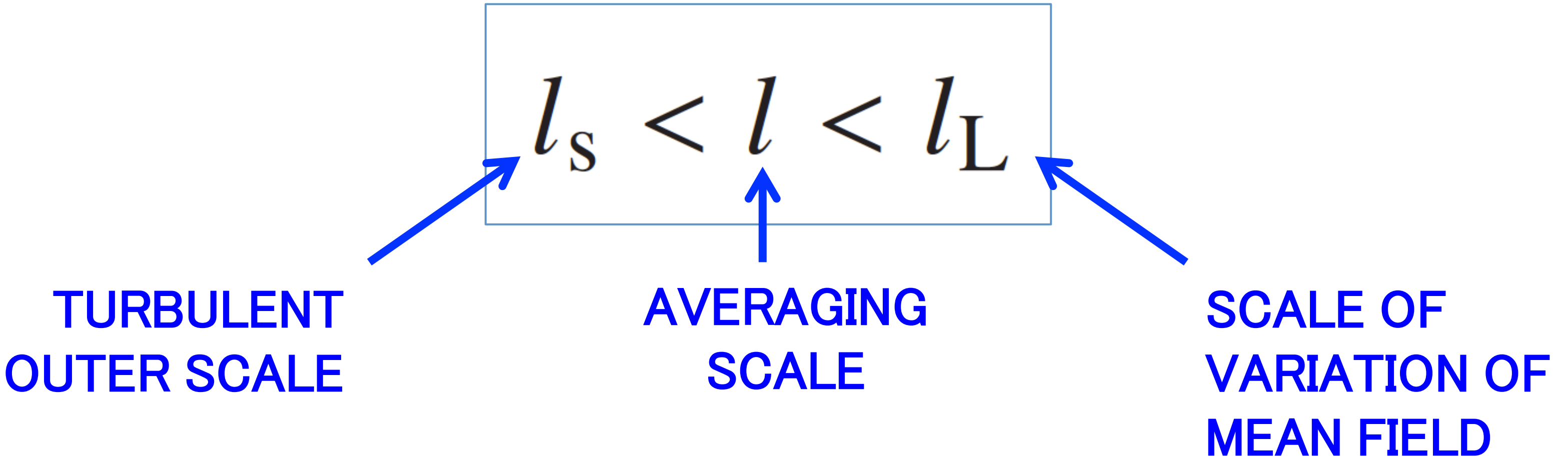


- Effect of anisotropy due to shear not yet included.
- Needs to be explored using direct numerical simulations.
- There are other effects also involving SS magnetic energy and helicity fluxes (Kandu's talk) that need to be explored.

Chamandy & Singh 2018

Direct comparison of models and observations

- Mean-field electrodynamics assumes Reynolds averaging rules
- Formally valid only for $N \to \infty$ ensemble averages
- Observations involve spatial averages
- Finite scale separation so Reynolds rules not satisfied
- If infinite ensemble average is replaced with spatial average, leads to changes in mean-field equations



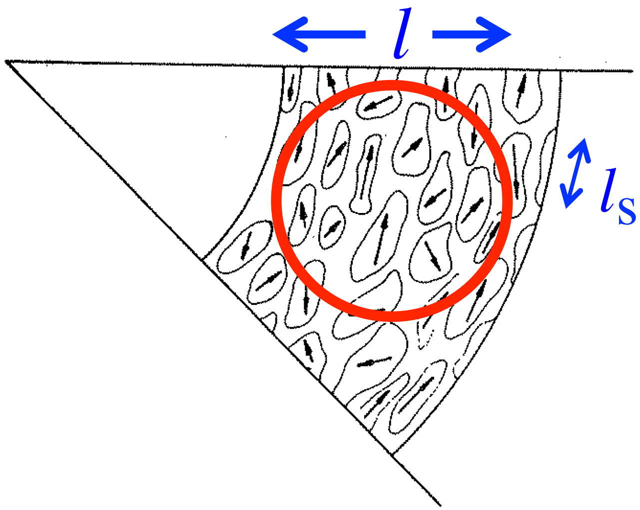
$$\boxed{l_\mathrm{s} < l < l_\mathrm{L}}$$

TURBULENT OUTER SCALE

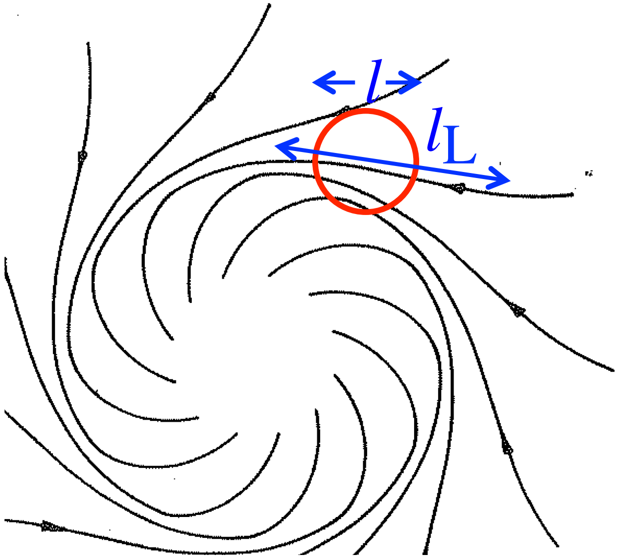
AVERAGING SCALE

SCALE OF VARIATION OF MEAN FIELD

Direct comparison of models and observations



Adapted from Ruzmaikin, Shukurov & Sokoloff 1988



- Spatial mean of fluctuating component is not precisely zero $\sim b/(l/l_S)^{3/2}$
- Leads to random uncertainty in model that must be propagated through to yield uncertainty on theoretical prediction of observed mean (regular) field
- Relevant for seed mean fields

- Spatial average of field is not identical to “actual” (infinite ensemble averaged) mean field because of bending inside the averaging volume (non-locality)
- Leads to systematic error which results in correction terms in the theory of order $(l/l_L)^c$

Zhou, Blackman & Chamandy 2018

Summary

- Mean-field dynamo models are useful tools to study galactic magnetic fields.
- Some success in explaining observations; models are verging on being truly predictive!
- Dynamo input parameters can and must be better constrained using observation and theory (cross-disciplinary!).
- Including anisotropy of the turbulence leads to new terms in large-scale dynamo models that may produce an alternate saturation mechanism that is competitive with alpha quenching.
- Mean-field models should really be based on explicit spatial averaging, ideally averaging that approximates that inherent in observations. Doing this results in a theoretical “uncertainty” owing to the stochastic nature of turbulence.