Galactic dynamos need galactic outflows to survive

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Outline

- Nonlinear dynamo action, magnetic helicity and galactic wind/fountain

- Galactic magnetic field affected by the outflow: magnetic pitch angle

Nonlinear dynamo action, magnetic helicity, and galactic wind/fountain

Magnetic helicity: $\chi = \langle \vec{\mathcal{A}} \cdot \vec{\mathcal{B}} \rangle, \quad \vec{\mathcal{B}} = \nabla \times \vec{\mathcal{A}}$

(conserved in ideal MHD)

$t = 0 \Rightarrow \vec{\mathcal{B}} \approx 0$ (weak seed field)

$\Rightarrow \chi|_{t=0} \approx 0 \Rightarrow \chi|_{\mathrm{now}} \approx 0$

Introduce large- & small-scale magnetic fields

$\vec{\mathcal{B}} = \vec{B} + \vec{b}, \quad \vec{\mathcal{A}} = \vec{A} + \vec{a},$

and the corresponding helicities:

$\chi = \chi_B + \chi_b, \quad \chi_B = \vec{A} \cdot \vec{B}, \quad \chi_b = \vec{a} \cdot \vec{b}$

A mechanical analogy of helicity conservation: twist & writhe of a hose pipe

Twist by 90°

Twist by 180°

$$\chi = \chi_B + \chi_b, \quad \chi_B = \vec{A}\cdot\vec{B}, \quad \chi_b = \vec{a}\cdot\vec{b}$$

- $\chi_B = \langle \vec{A}\cdot\vec{B}\rangle \simeq -LB_rB_\phi \simeq \frac{1}{4}LB^2$,

  for $B_r/B_\phi = -\sin p$, $\quad p = 15^\circ; \quad L \gtrsim 1\,$kpc.

- $\chi_b = \langle \vec{a}\cdot\vec{b}\rangle \simeq -l_d b^2$,

  $l_d \lesssim l \simeq 100\,$pc ($l_d =$ scale of χ_b, $l =$ turbulent scale)

- $\chi = \chi_B + \chi_b = 0 \quad \Rightarrow \quad \dfrac{B^2}{b^2} \simeq \dfrac{4l_d}{L} \simeq 0.4$, **if** $l_d \simeq l$

Catastrophic α-quenching: $\dfrac{B^2}{b^2} \simeq R_m^{-1} \ll 1$ **if** $\dfrac{l_d}{L} \simeq R_m^{-1}$

(R_m =magnetic Reynolds number)

Galactic discs are not closed systems:

galactic winds and fountains

$\Rightarrow$ the "unwanted" magnetic helicity can be removed from the disc

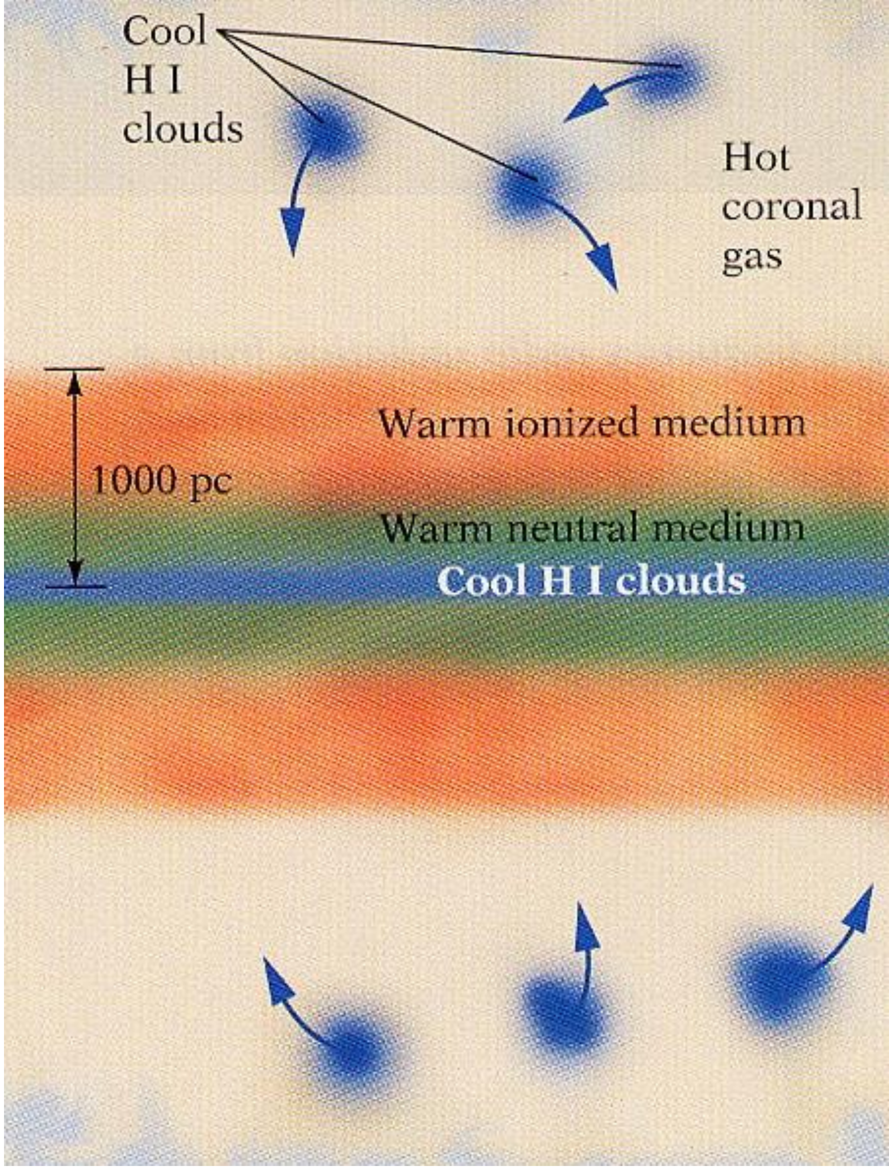
The multi-layered interstellar medium (ISM)

Warmer components of the ISM expand further away from the Galactic midplane: the 10^4 K gas layer is surrounded by a 10^6 K halo.

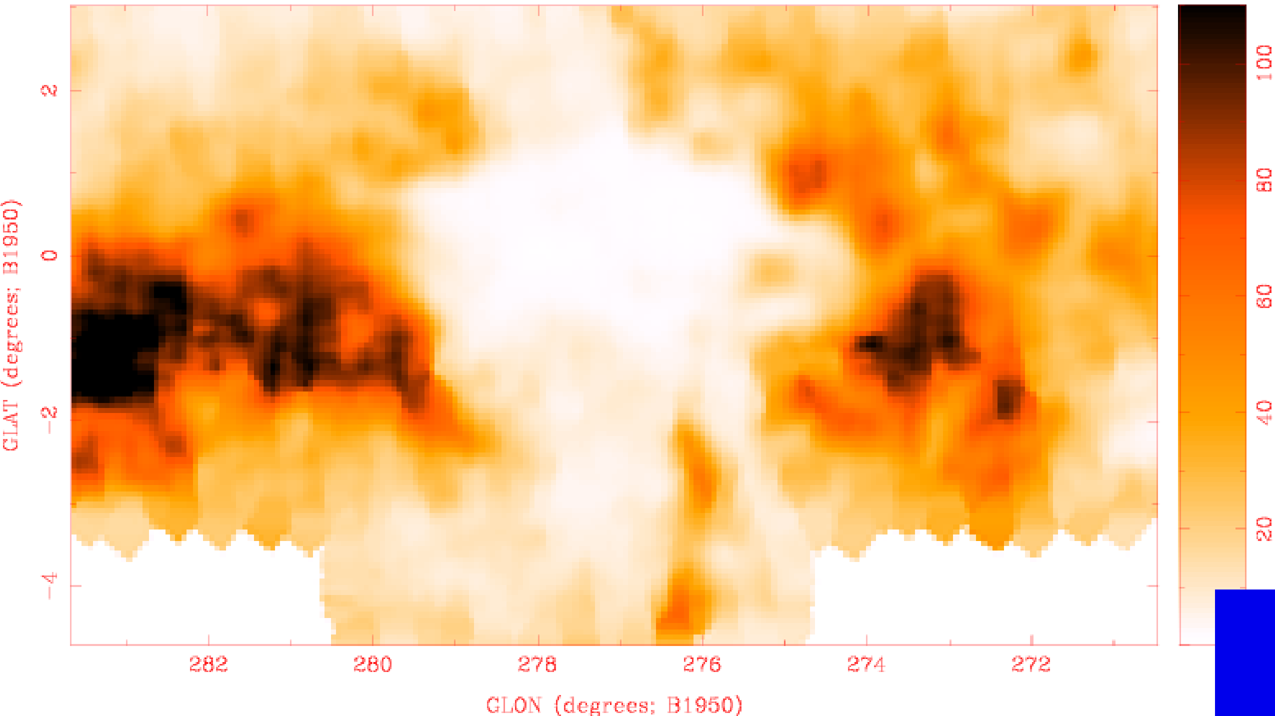
Galactic fountain:

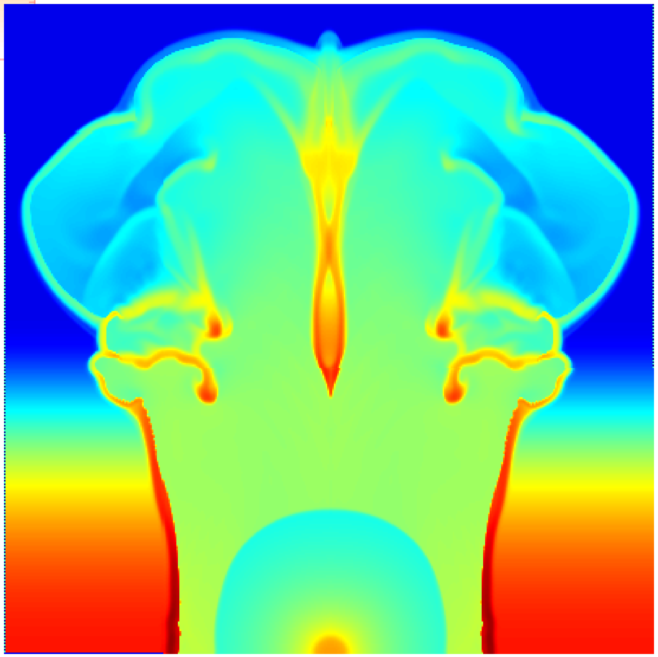
Hot gas rises to the halo, cools, and returns to the disc in $\simeq 10^9$ yr

Galactic wind in star-forming galaxies: hot gas escapes to the intergalactic space



HI shell : hot gas breaking through the gas layer into the halo





Numerical simulation of a supernova exploding in a stratified gas layer (M.-M. Mac Low)

Galactic fountain/wind removes magnetic field from the disc

Hot gas outflow through the disc surface: $V_z = 150\text{–}200$ km/s

Surface filling factor of the hot gas: $f_\mathrm{s} = 0.2\text{–}0.3$

Relative density of the hot gas: $\dfrac{\rho_h}{\langle\rho\rangle} = 10^{-2} - 10^{-3}$

Effective (mass-averaged) advection speed:

$$U_z \simeq f_\mathrm{s}\frac{\rho_h}{\langle\rho\rangle}V_z \simeq 0.1 - 2\,\mathrm{km/s}$$

Helicity balance

(Shukurov et al. A&A 448, L33, 2006)

Random field $\vec{b}$ has finite correlation length $\Rightarrow$ define volume density of linkages of $\vec{b}$:

$\chi \approx H_b$ for $\nabla \cdot \vec{a} = 0$ (Subramanian & Brandenburg , ApJLett, 2006)

Evolution equation:

$$\frac{\partial \chi}{\partial t} + \nabla \cdot \vec{F} = -2\vec{\mathcal{E}} \cdot \vec{B} - 2\eta \overline{\vec{j} \cdot \vec{b}}$$

$\vec{j} = \nabla \times \vec{b}, \quad \vec{J} = \nabla \times \vec{B},$ electric current densities

$\vec{\mathcal{E}} \approx \alpha \vec{B} - \beta \nabla \times \vec{B},$ mean electromotive force

$\vec{F} = \chi \vec{U},$ advective flux.

$\alpha = \alpha_{\rm kinetic} + \alpha_{\rm m}, \qquad \alpha_{\rm m} \simeq \frac{1}{3}\tau k_0^2 \frac{\chi}{\rho}$

$$\frac{\partial \alpha_{\rm m}}{\partial t} = -2\beta k_0^2 \left(\frac{\vec{\mathcal{E}} \cdot \vec{B}}{B_{\rm eq}^2} + \frac{\alpha_{\rm m}}{R_{\rm m}} \right) - \nabla \cdot \left(\alpha_{\rm m} \vec{U} \right)$$

+ mean-field dynamo equations for B_r and B_ϕ

Mean-field dynamo: $$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{U} \times \vec{B} + \alpha \vec{B} - \beta \nabla \times \vec{B}) \, .$$

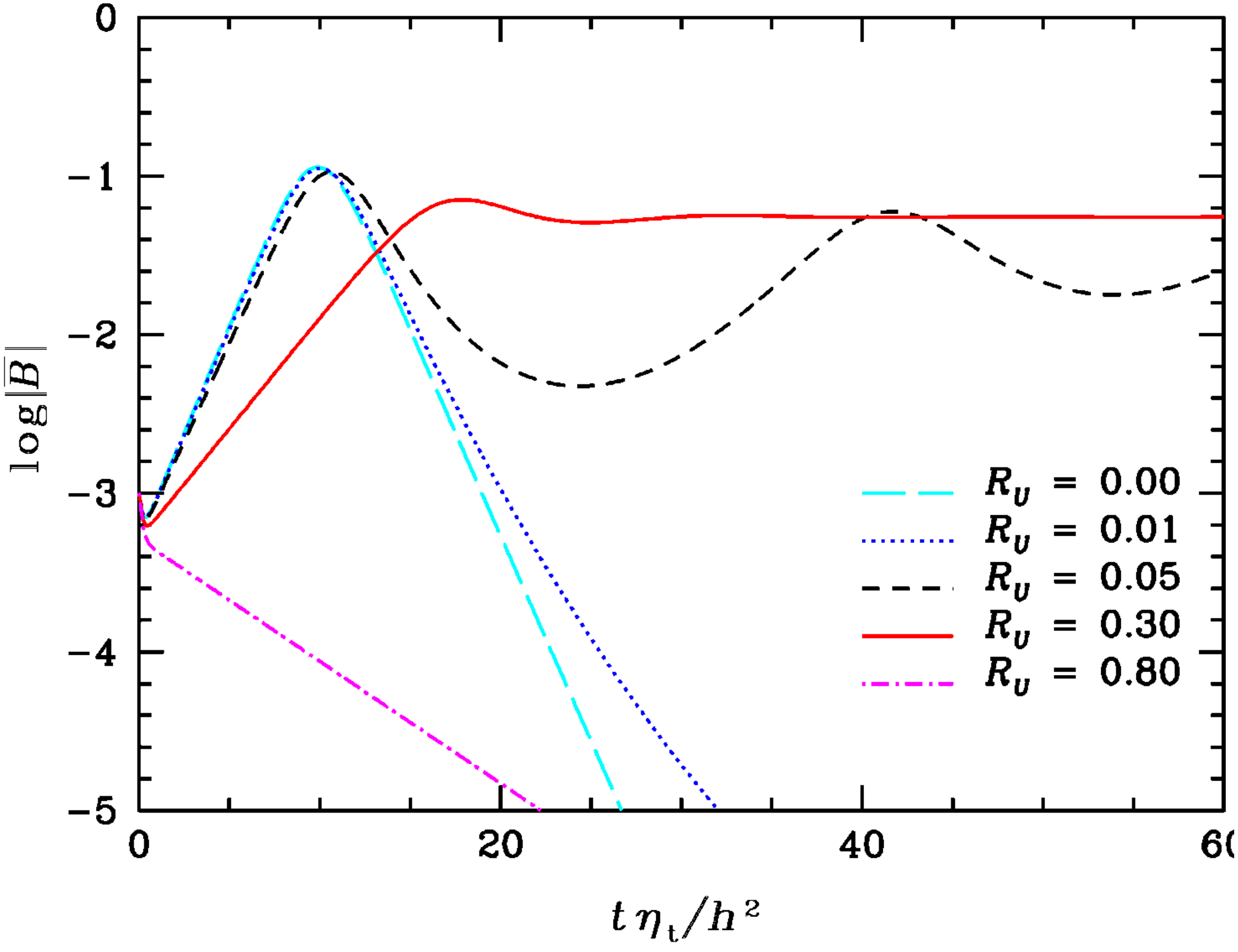
Thin disc $|z| \cdot \quad h$, $\dfrac{\partial}{\partial z} \gg \dfrac{\partial}{\partial r}$, axial symmetry, $\partial/\partial\phi = 0$,
$\vec{U} = (0, r \quad (r), U_z)$, dimensionless equations:

$$\begin{aligned}
\frac{\partial B_r}{\partial t} &= -\frac{\partial}{\partial z}(R_u U_z B_r + R_\alpha \alpha B_\phi) + \frac{\partial^2 B_r}{\partial z^2} \, , \\
\frac{\partial B_\phi}{\partial t} &= R_\omega B_r - R_u \frac{\partial}{\partial z}(U_z B_\phi) + \frac{\partial^2 B_\phi}{\partial z^2} \, , \\
\frac{\partial \alpha_m}{\partial t} &= -C \left(\alpha B^2 - R_\alpha^{-1} \vec{J} \cdot \vec{B} + \frac{\alpha_m}{R_m} \right) - R_u \frac{\partial}{\partial z}(U_z \alpha_m) \, ,
\end{aligned}$$

$$\alpha = \alpha_K + \alpha_m, \quad \alpha_K \simeq \frac{l^2}{h}, \quad C = 2\frac{h^2}{l^2}, \quad \vec{J} \cdot \vec{B} = B_\phi \frac{\partial B_r}{\partial z} - B_r \frac{\partial B_\phi}{\partial z},$$

$$R_\alpha = \frac{\alpha_0 h}{\beta} \, , \quad R_\omega = \frac{(r\partial \quad /\partial r)_0 h^2}{\beta} \, , \quad R_u = \frac{U_{z0} h}{\beta} .$$

Sur, Shukurov & Subramanian (2007): Magnetic field evolution in a galactic disc with helicity advection by the galactic fountain/wind, "no-z" approximation: $\partial/\partial z \to 1/h$, $\partial^2/\partial z^2 \to -1/h^2$



Steady-state large-scale magnetic field (Sur et al., MNRAS 2007) due to helicity advection:

$$B^2 \approx 4\pi\rho v^2 \frac{2}{C}\left(\frac{D}{D_{\rm crit}} - 1\right)\left(R_U + \frac{C}{R_m}\right) \simeq (1\mu{\rm G})^2,$$

$R_U = U_z h/\eta_{\rm turb}$, turbulent Reynolds number of the outflow, $U_z = F({\rm SFR})$,

$C = 2(h/l)^2 \simeq 50$,

$D = R_\alpha R_\omega \simeq -(\quad h/v)^2 \approx -10$, the dynamo number near the Sun,

$D_{\rm crit} \approx -8$, critical dynamo number

Allowing for the anisotropy of interstellar turbulence (Vishniac & Cho 2001)

further enhances the magnetic field, $B \simeq \sqrt{4\pi\rho v^2} \simeq 5\,\mu$G

Dependence of B on SFR, disc-halo connection, winds, galactic evolution, etc.

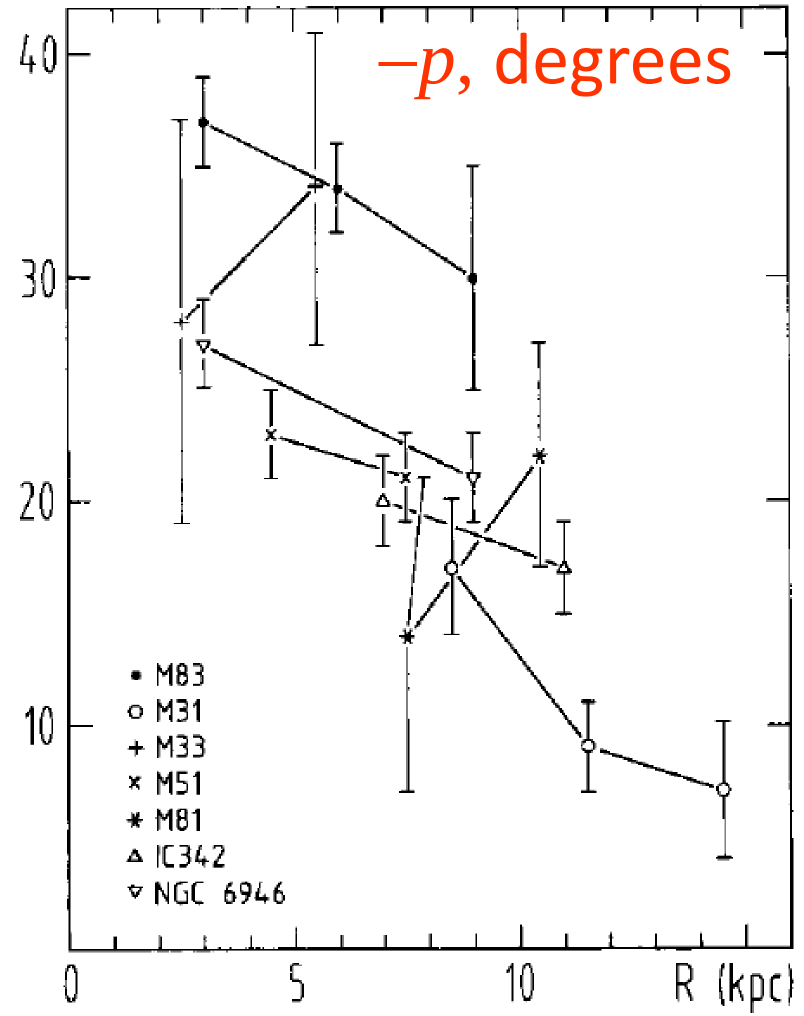
Galactic magnetic field affected by the outflow: magnetic pitch angle

Magnetic pitch angle: $\tan p = \dfrac{B_r}{B_\phi}$

Kinematic dynamo, $\dfrac{\partial \vec{B}}{\partial t} = \gamma \vec{B}$:

$$\tan p \simeq -\sqrt{\frac{R_\alpha}{|R_\omega|}}$$

$p \simeq -(10\text{–}20^\circ)$.



Beck et al., ARAA, 1996

Nonlinear, steady state: $\partial/\partial t = 0$,

α-effect suppressed to its marginal level, $D(\alpha_K + \alpha_m) = D_c$

no-z approximation:

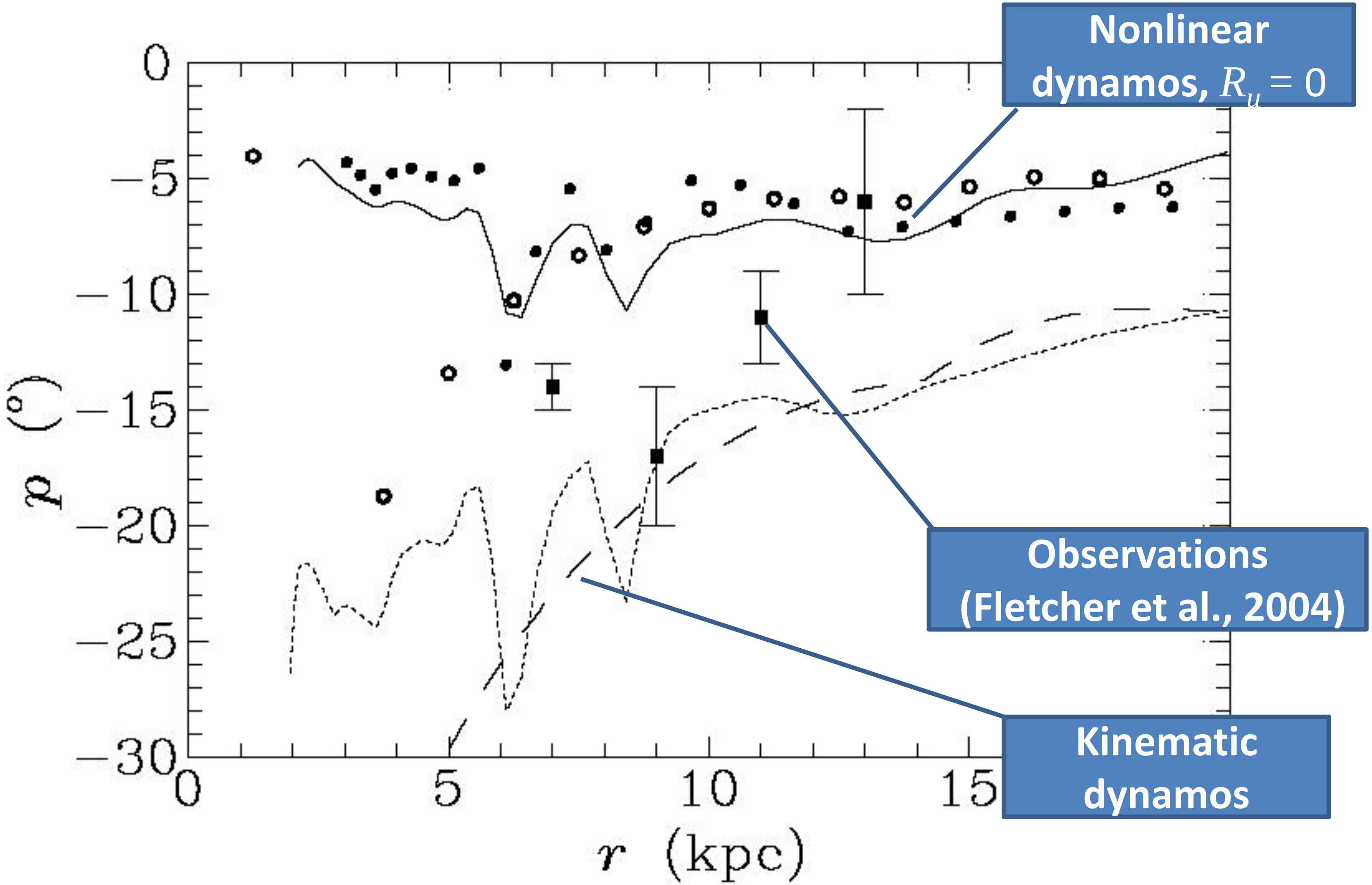
$$0 = -\frac{2}{\pi} R_\alpha \frac{D}{D_c} B_\phi - \left(R_u + \frac{\pi^2}{4} \right) B_r \,,$$

$$0 = R_\omega B_r - \left(R_u + \frac{\pi^2}{4} \right) B_\phi \,.$$

$$\frac{B_r}{B_\phi} = \frac{R_u + \pi^2/4}{R_\omega} \,,$$

$$R_U = 0 \quad \Rightarrow \quad \tan p = \frac{\pi^2}{4R_\omega}, \quad p \simeq -10^\circ$$

Mean-field dynamo models for M31, axial symmetry, $\partial/\partial r$ retained, magnetic pitch angle:

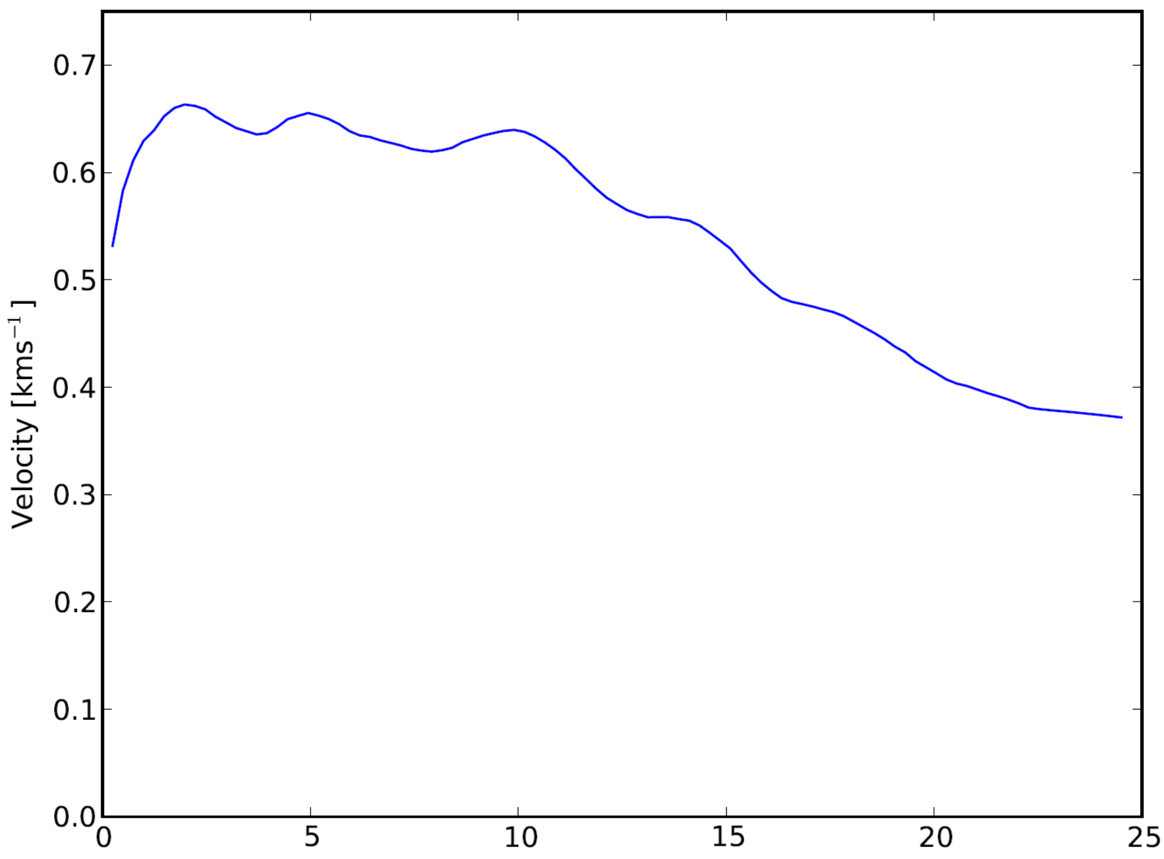


Shukurov, in: Mathematical Aspects of Natural Dynamos, 2006, astro-ph/0411739

Mean-field dynamo model for M31, disc outflow included,

axial symmetry, no-z approximation, $\partial/\partial r$ retained

(Smith, Fletcher & Shukurov, in preparation)



gas density

$\rightarrow$ SFR

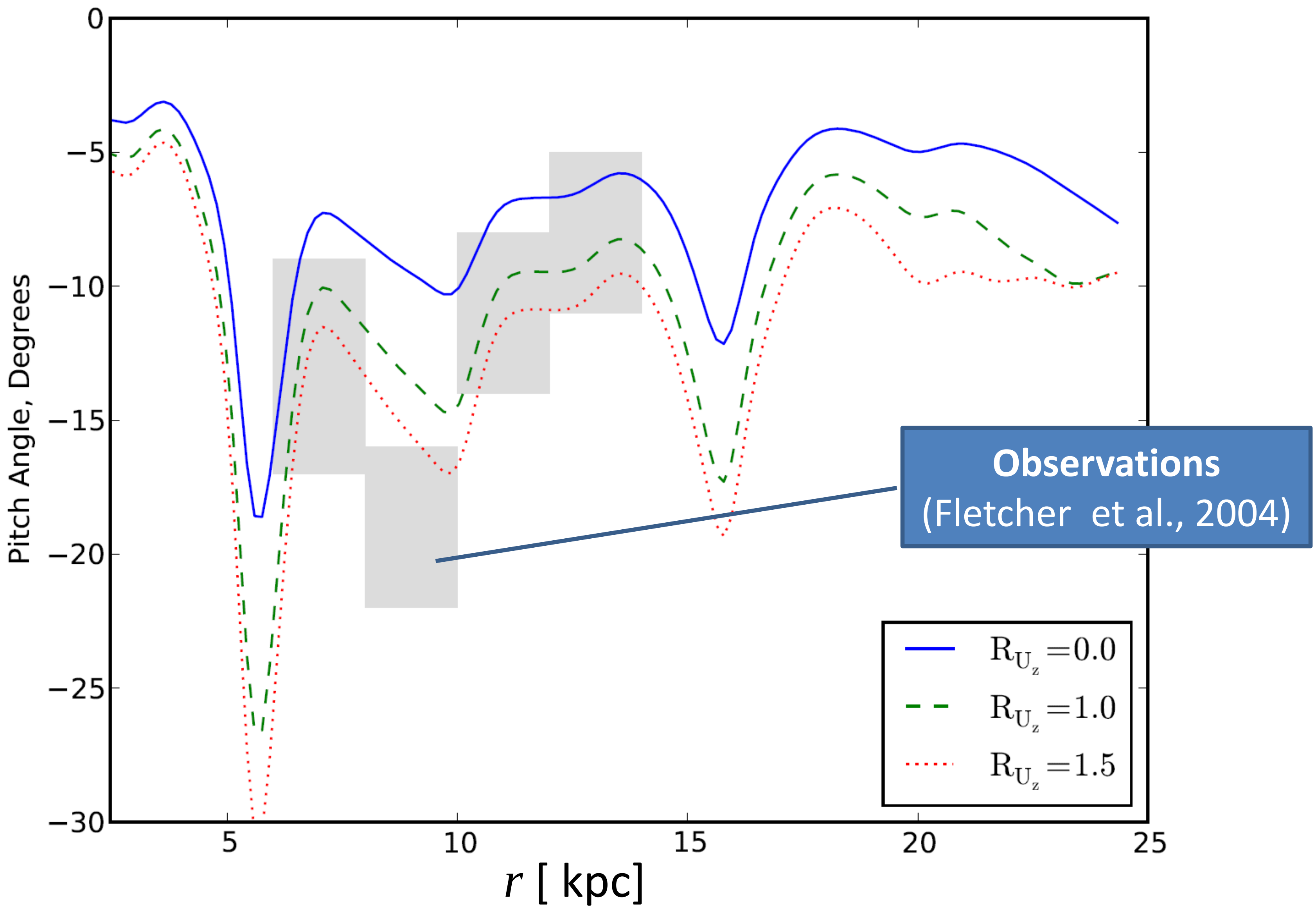
+ gravitational potential

$\rightarrow \quad V_z \propto \langle\rho\rangle^{0.35}$

$\rightarrow$mass-weighted outflow speed

Cf. order of magnitude estimate above: $U_z \simeq f_\mathrm{s}\dfrac{\rho_h}{\langle\rho\rangle}V_z \simeq 0.1 - 2\,\mathrm{km/s}$

Magnetic pitch angle in M31



Conclusions

- Galactic dynamos need galactic-scale outflows to produce significant large-scale magnetic fields.

- Fountains & winds relieve the magnetic helicity constraints for the mean-field dynamo and

- produce magnetic pitch angles comparable to those observed.