ISM models with SN driven turbulence

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Outline

- ISM simulations with SNE
- Dynamo models until saturation
- SNR dependence
- Explaining the saturation

Introduction

- ISM consists of

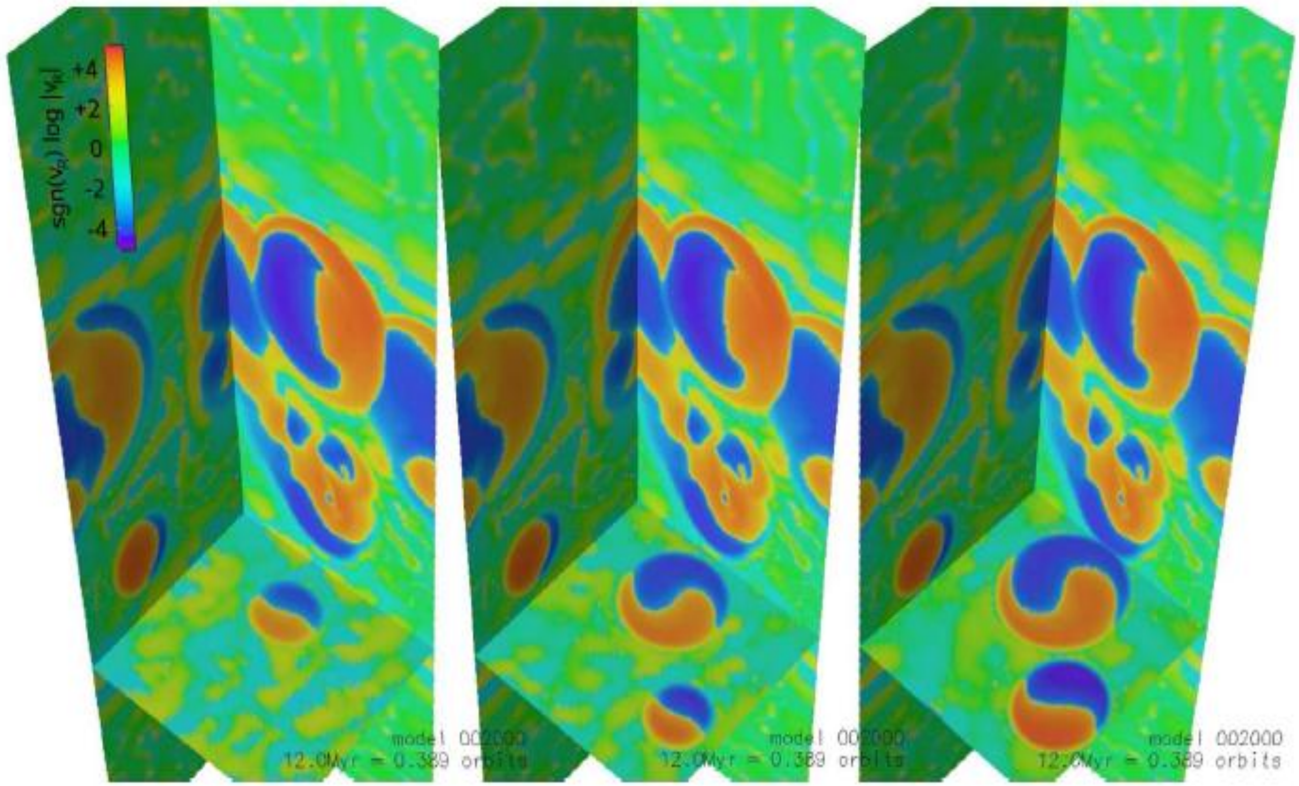
i) Many gaseous phases

ii) Magnetic field (few μG)

iii) Cosmic rays

- Heating and cooling
- ISM turbulence = mainly contributed by SN II (isolated and clustered)
- Energy of SN II explosion : 1.14×10^{51} erg

Simulation box



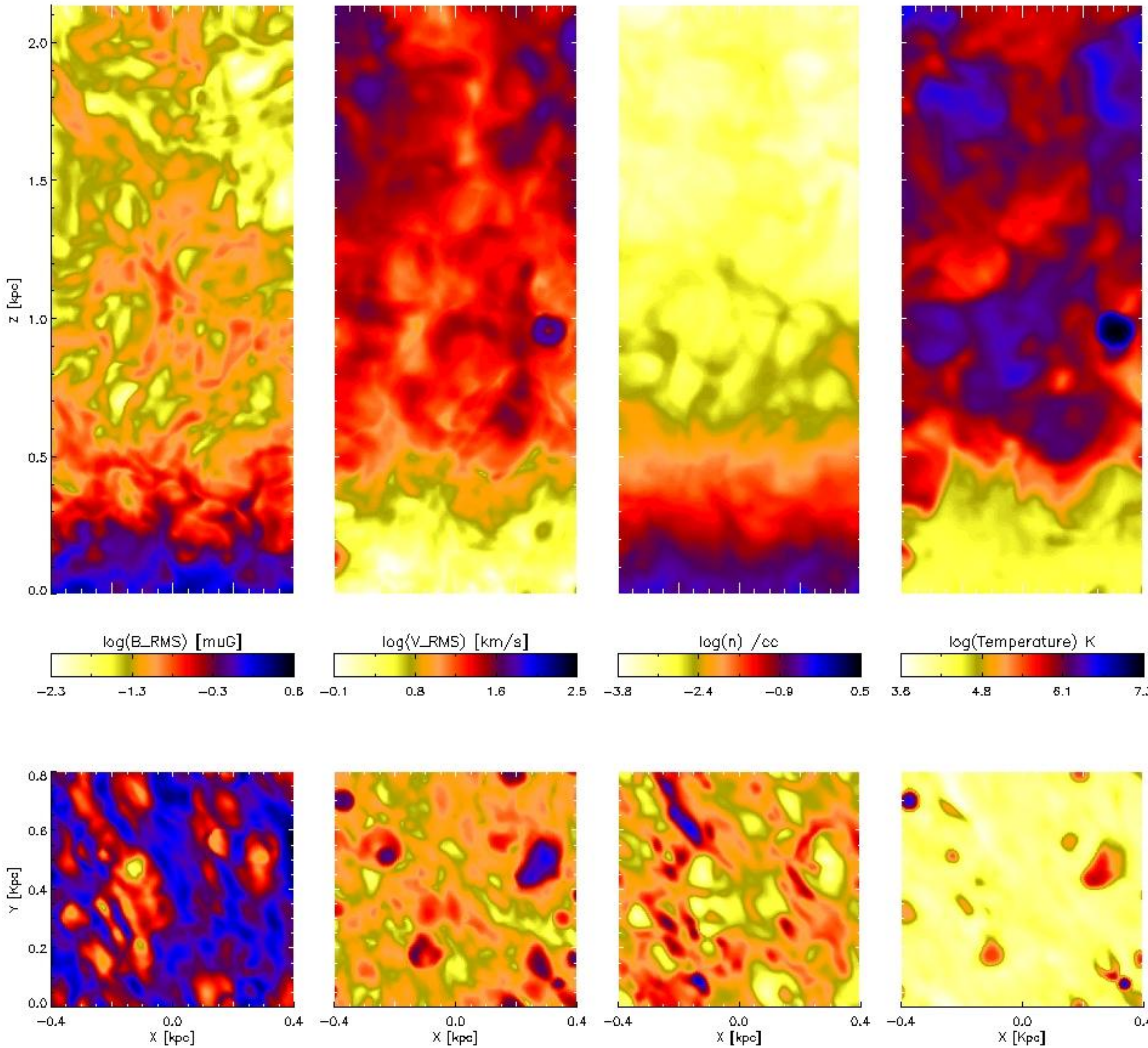
xy plane: 0.8 kpc x 0.8 kpc (96x96 grid cells)

Vertical size z: -2 kpc to 2 kpc (512 grid cells)

Modeling

- Density stratification
- Rotational shear is included (shearing periodic boundary conditions)
- Radiative cooling function
- SN explosions as localized injections of thermal energy
- SN explosions frequency,

$\sigma_{SN\text{-}I} = 4\ \mathrm{myr}^{-1}\ \mathrm{kpc}^{-2}$, $\sigma_{SN\text{-}II} = 30\ \mathrm{myr}^{-1}\ \mathrm{kpc}^{-2}$



Z [kpc]
0.0
0.5
1.0
1.5
2.0
log(B_RMS) [muG]
-2.3 -1.3 -0.3 0.6
log(V_RMS) [km/s]
-0.1 0.8 1.6 2.5
log(n) /cc
-3.8 -2.4 -0.9 0.5
log(Temperature) K
3.6 4.8 6.1 7.3
Y [kpc]
0.0
0.2
0.4
0.6
0.8
-0.4 0.0 0.4
X [kpc]
X [Kpc]

Dependence on the seed fields

- Azimuthal seed fields (Gressel O.)
- Vertical seed fields

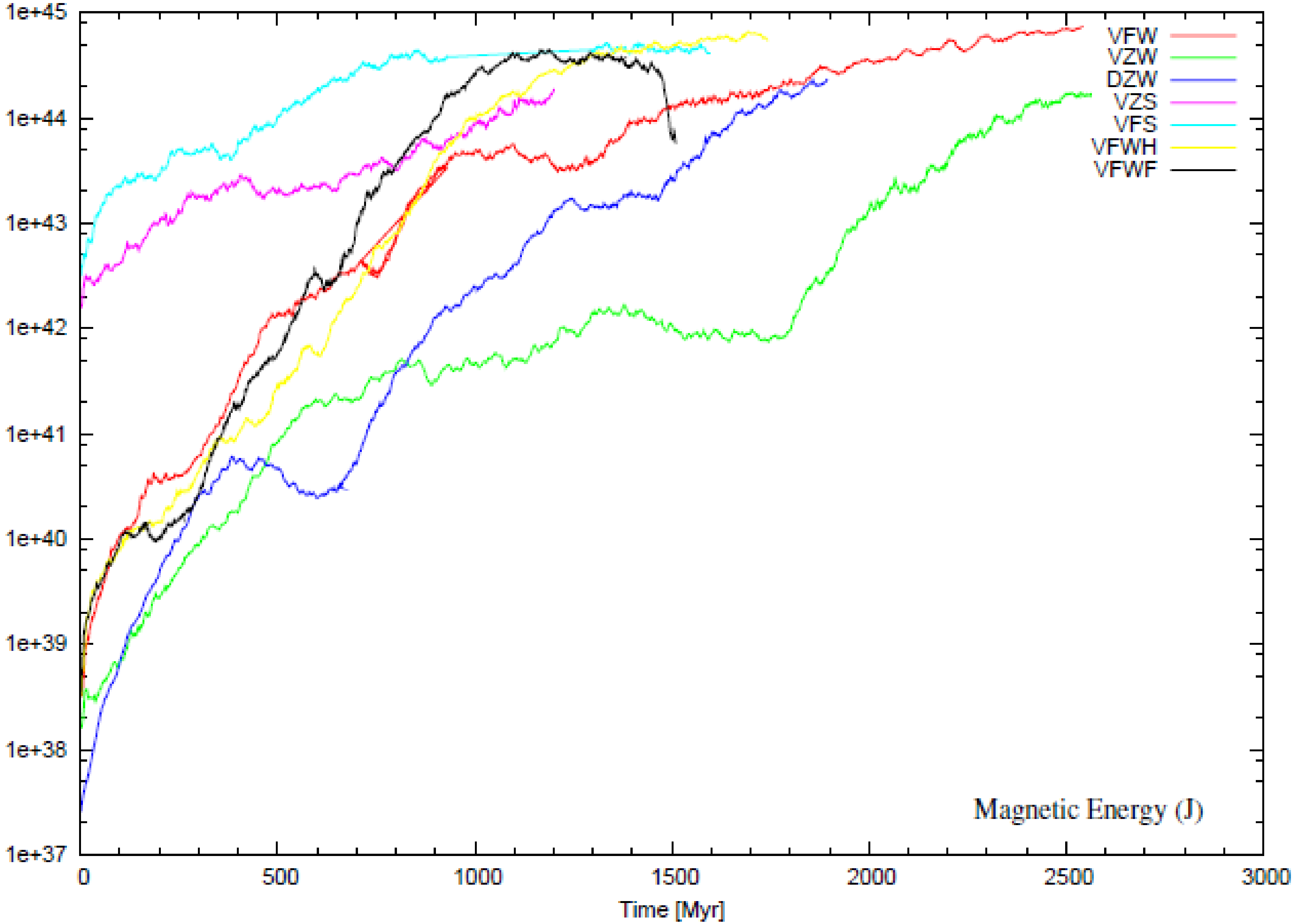
i) With and without flux

ii) Strong and weak initial field strength

IGM magnetic fields < $1e^{-8}$G

- Vertical flux passing through the disk of galaxy
- May influence MRI
- May influence dynamo action

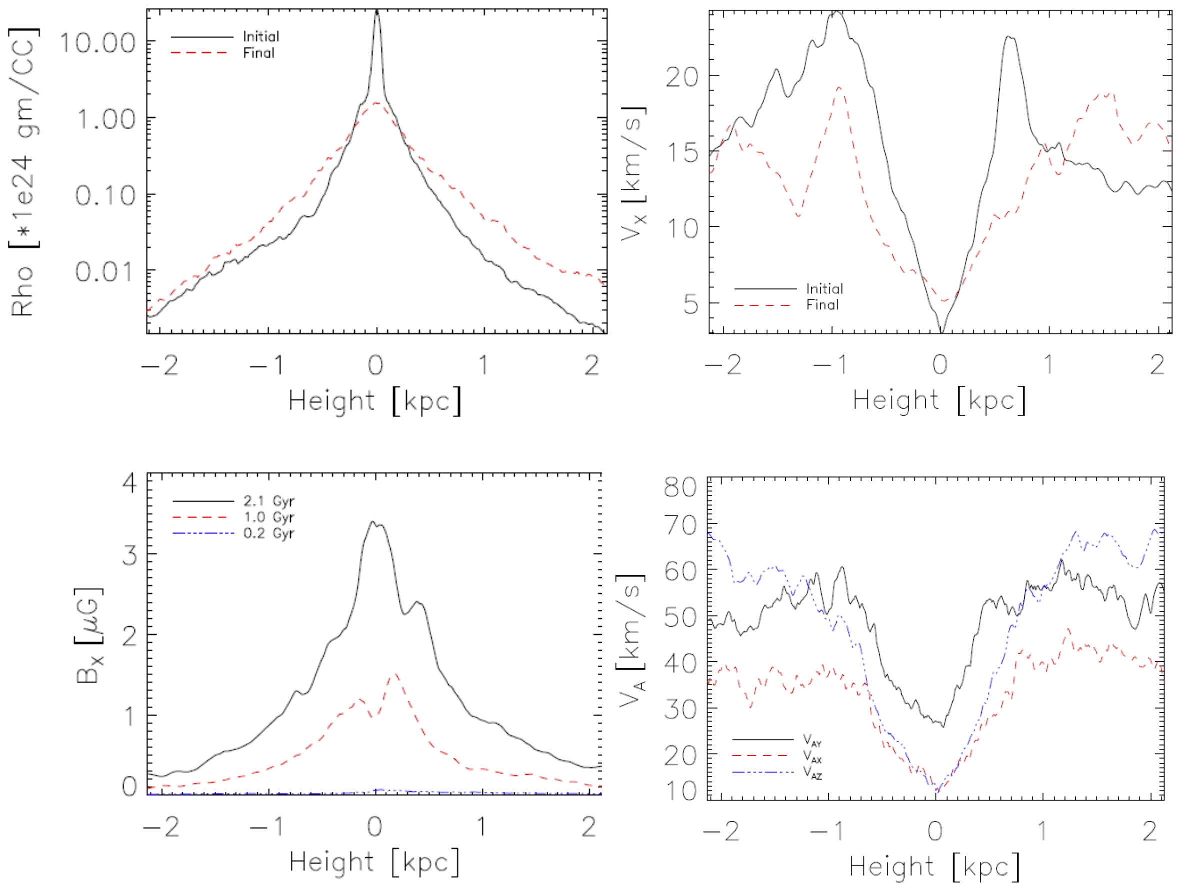
Evolution of magnetic energy



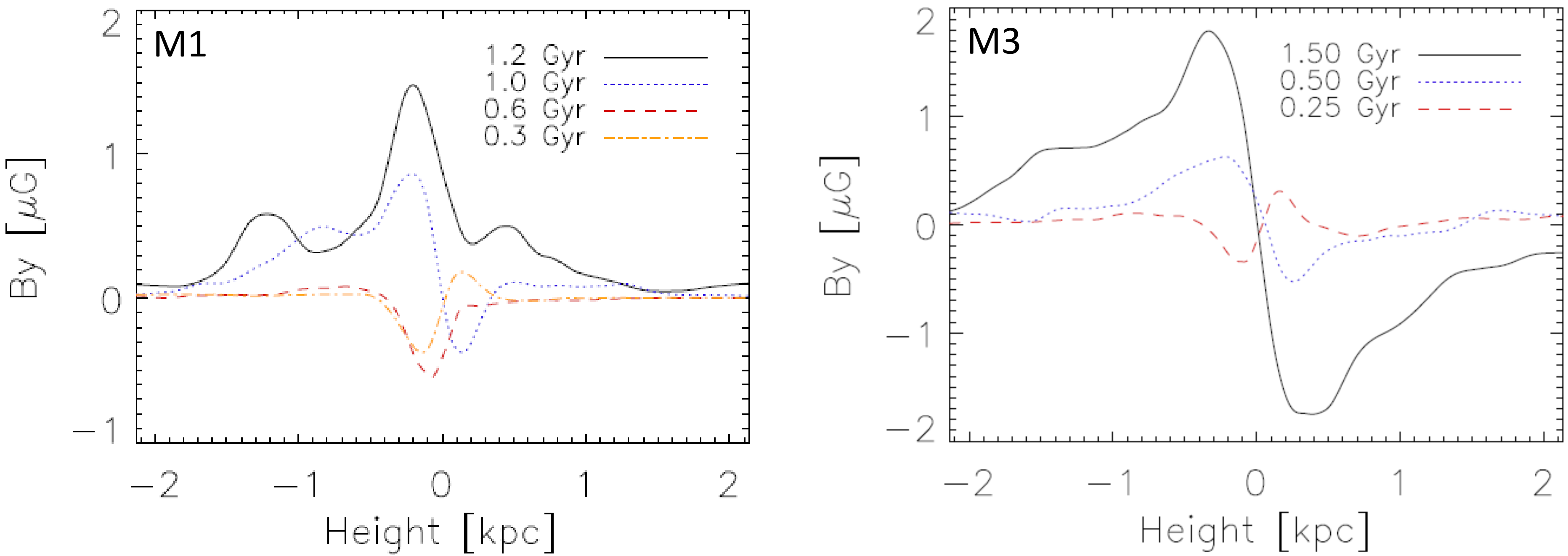
Dependence on the seed fields

- Growth times of E_{MAG} for all models are same in the initial growing region (except the strong field models)
- Strong field vertical flux model is in the over equipartition regime and E_{MAG} Saturated
- Strong field zero flux model still in the growth phase

Properties of the ISM



B Azimuthal evolution

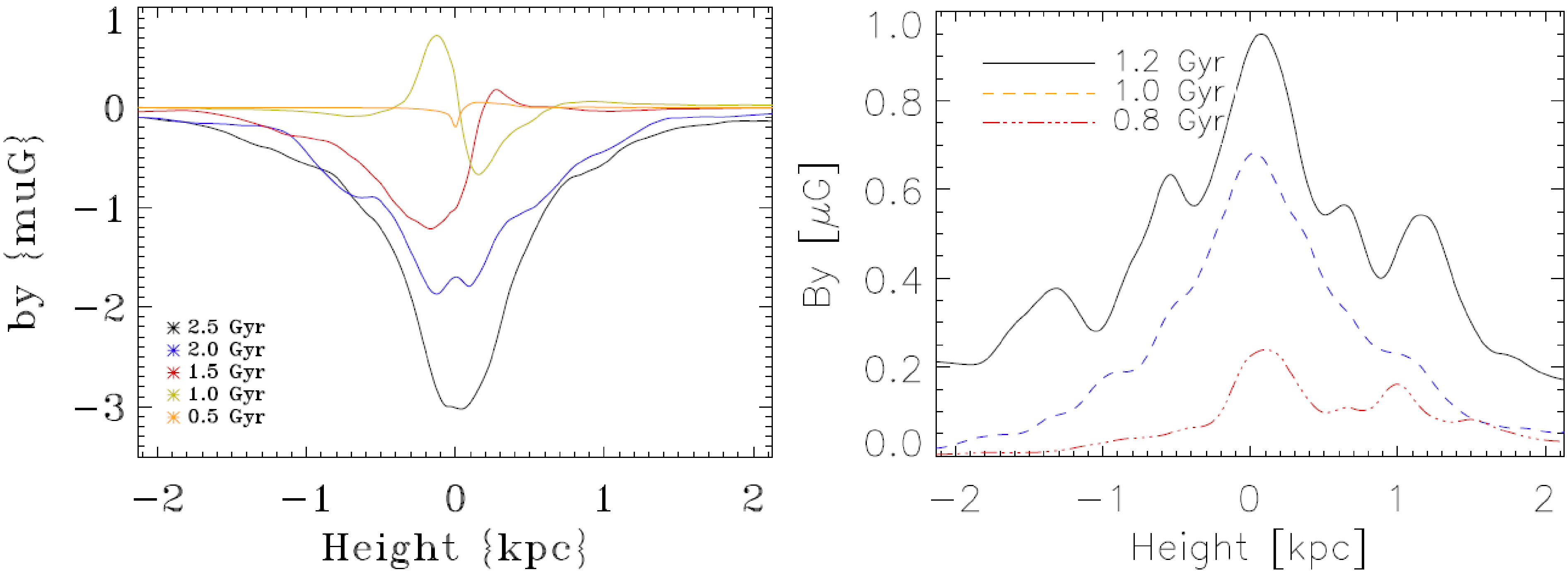


SNR Dependence

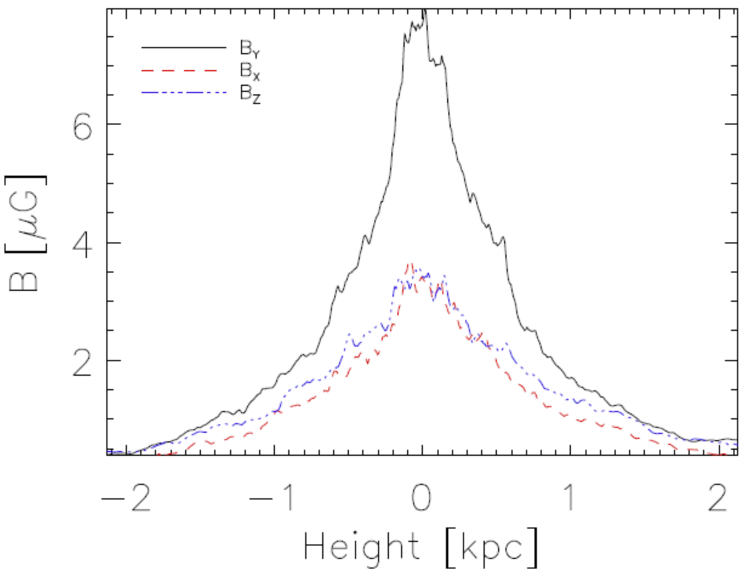
- For week field strength with vertical flux
- Three models with different SNR (calculated until $E_{MAG.}$ saturates)
- Seed field : $B_Z = 1\text{x}10^{-3}$ μG, (Flux 10^{39} μGcm^2)
- Growth times of $E_{MAG.}$ are same in the initial growing phase (200 Myr)
- Total magnetic energy is $4\text{x}10^{51}$ erg for all SNR

	VWQ	VWH	VWF
SNR (%) (times σ)	25%	50%	100%
E_{mag} : E_{kin} (final)	2.3	1.1	0.4

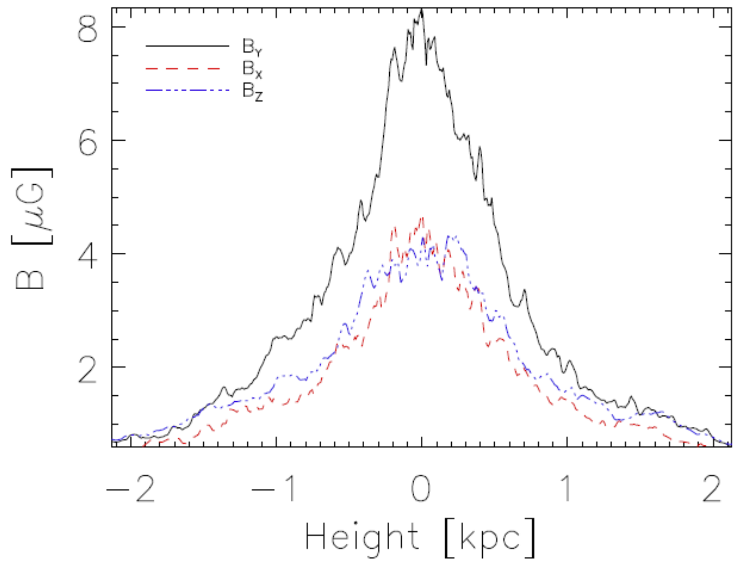
B azimuthal Vs. Z, Profiles evolution



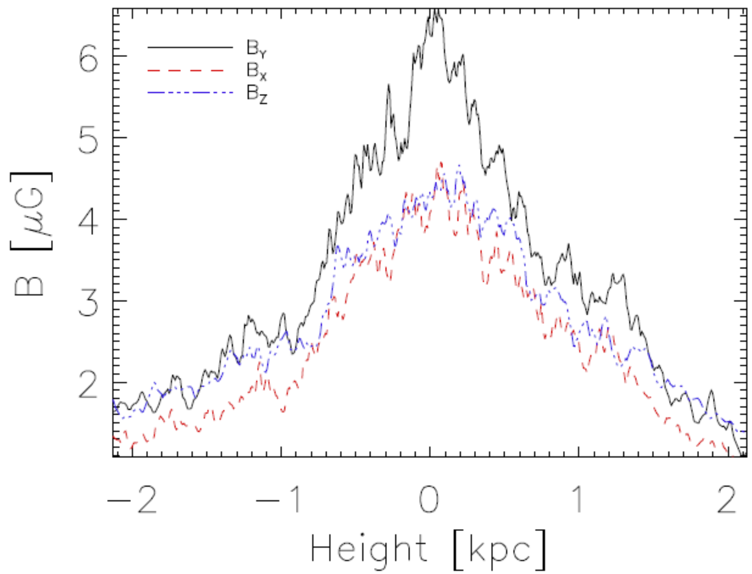
Maximum |B|



B_Y
B_x
B_Z
B [μG]
Height [kpc]



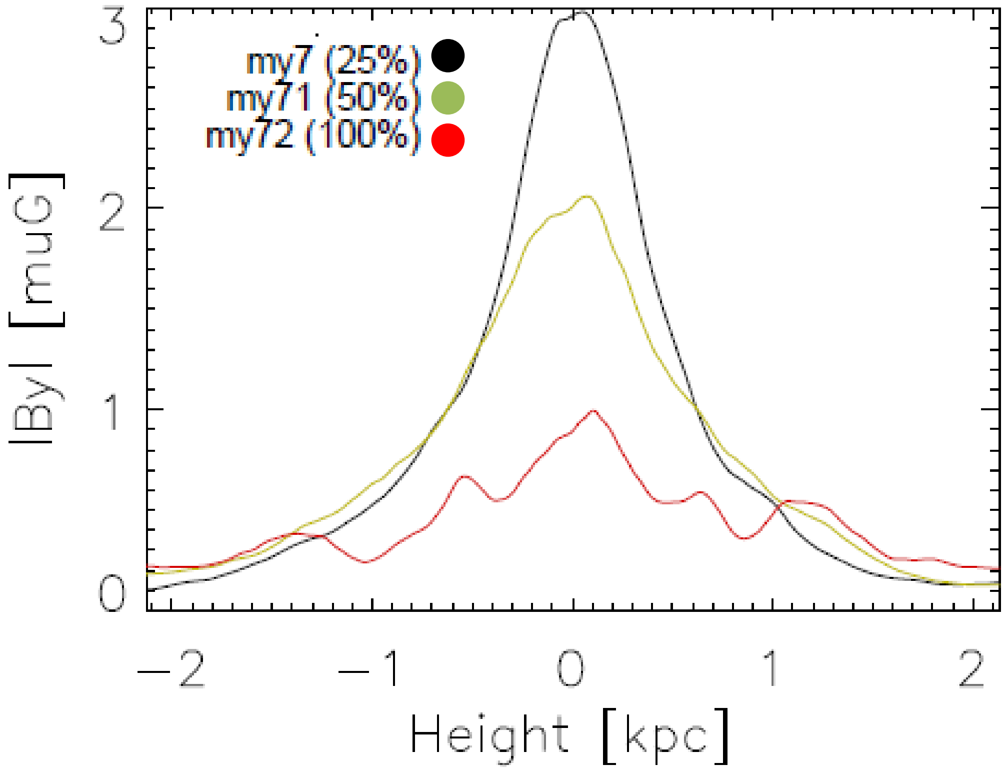
B_Y
B_x
B_Z
B [μG]
Height [kpc]



B_Y
B_x
B_Z
B [μG]
Height [kpc]

B_y Profiles (SNR dependence)

Final field strengths are inversely proportional to SNR



Saturation

Alpha quenching or/and Wind quenching

$$\partial_t \overline{B} = \nabla \times \left(\overline{V} \times \overline{B} \right) + \nabla \times \varepsilon + \eta \nabla^2 \overline{B} \qquad \varepsilon = \overline{\mathrm{v}' \times \mathrm{b}}$$

Correlation

$$\varepsilon_i = \alpha_{ij} \overline{B}_j + \eta_{ijk} \partial_k \overline{B}_j$$

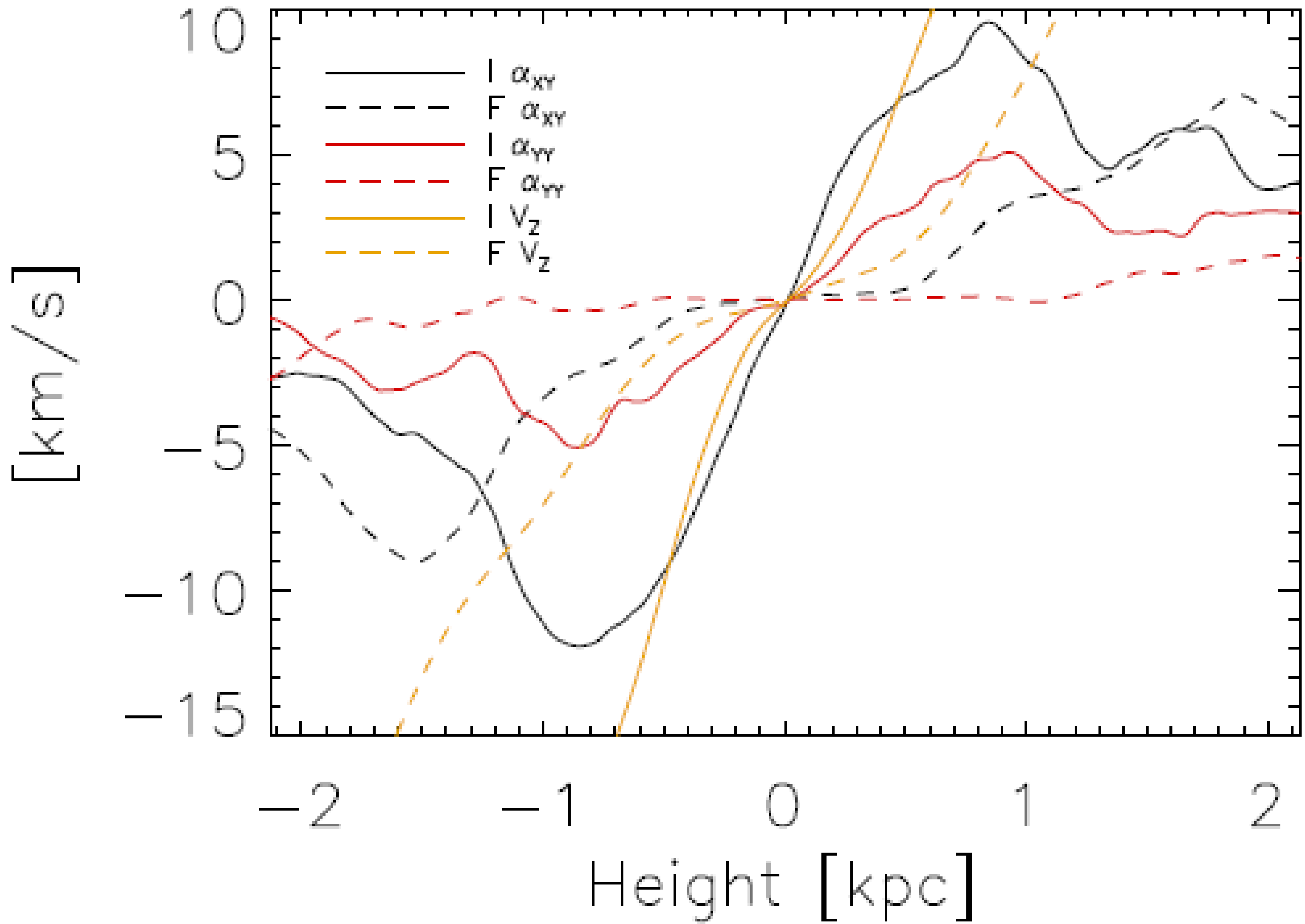
Wind *Pumping* *Alpha* *Turbulent diffusivity*

Differential rotation

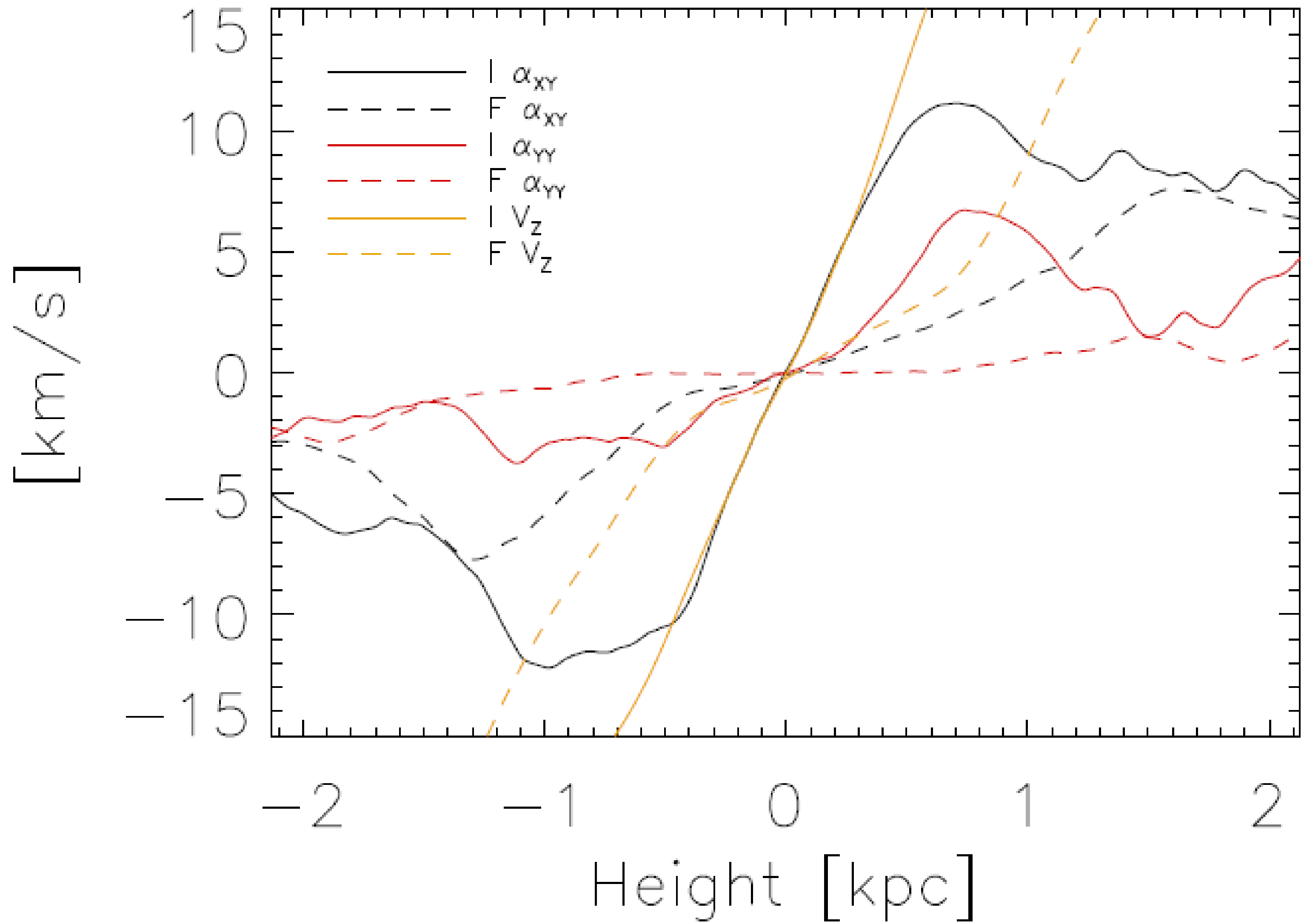
$$\partial_t \overline{B_R} = \partial_z \left[-(\bar{u}_z + \gamma) \overline{B_R} - \alpha_\varphi \overline{B_\varphi} + (\eta_\varphi + \eta) \partial_z \overline{B_R} + \delta \partial_z \overline{B_\varphi} \right]$$

$$\partial_t \overline{B_\varphi} = \partial_z \left[\alpha_R \overline{B_R} - (\bar{u}_z + \gamma) \overline{B_\varphi} - \delta \partial_z \overline{B_R} + (\eta_R + \eta) \partial_z \overline{B_\varphi} \right] - q\Omega \overline{B_R}$$

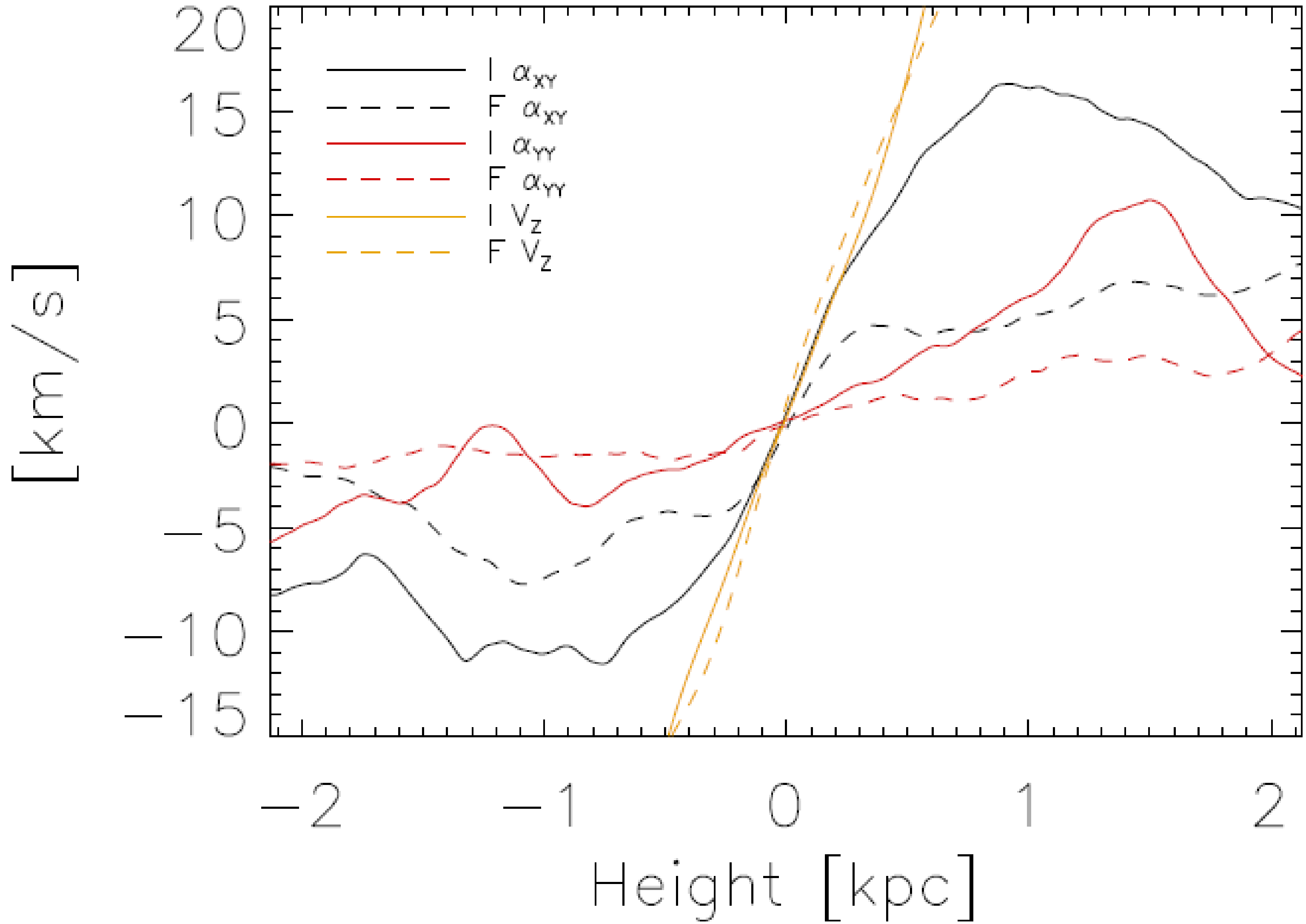
Alpha Quenching (25% SNR)



Alpha Quenching (50% SNR)



Alpha Quenching (100% SNR)

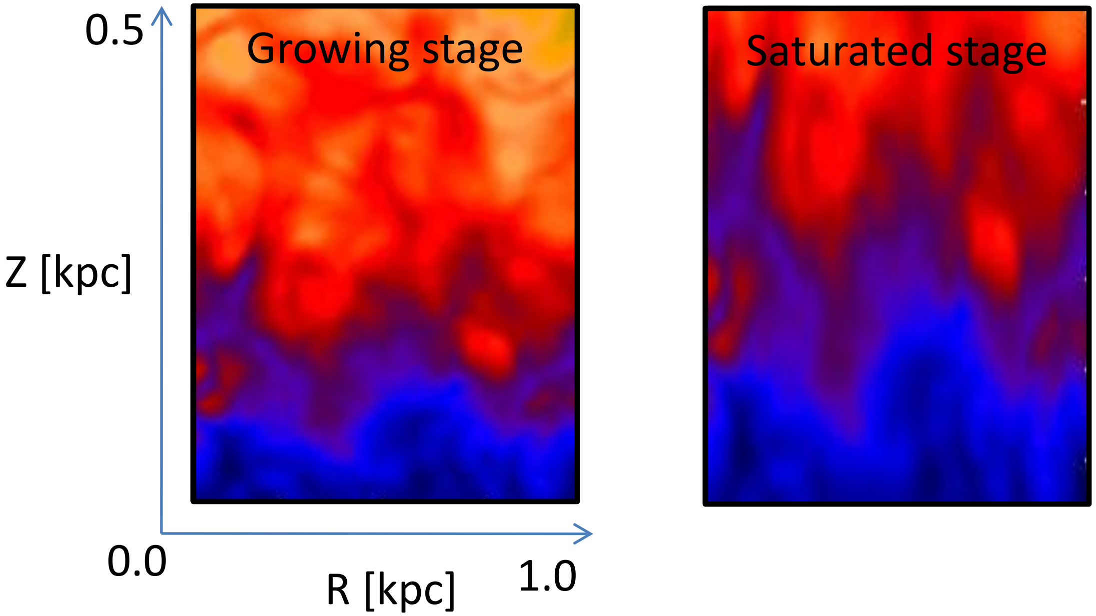


Saturation Process

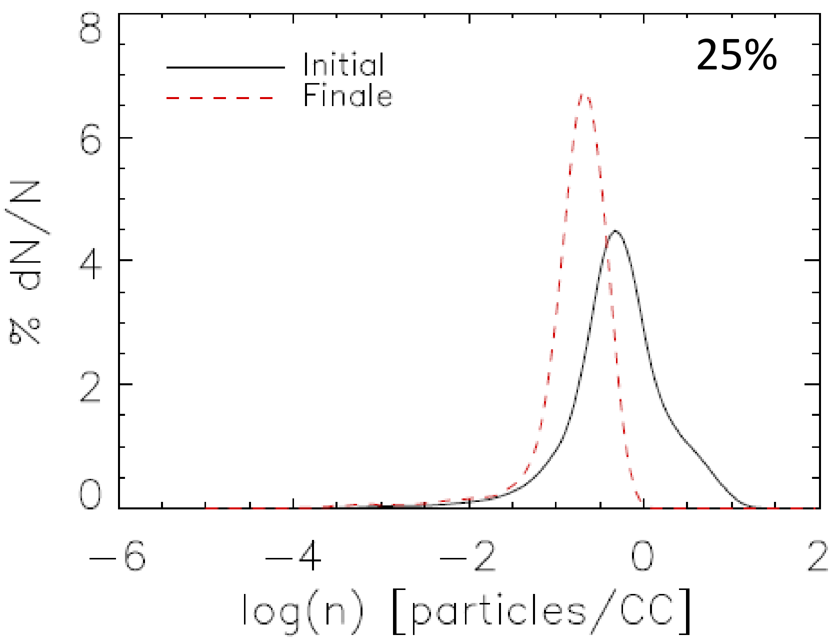
- Magnetic energy gets saturated at equal magnitude for all SNE rates, ($4x10^{51}$ erg)
- Quenching of wind and alpha profile -> dynamo stops
- In the last model with 100% SNR wind did not quench

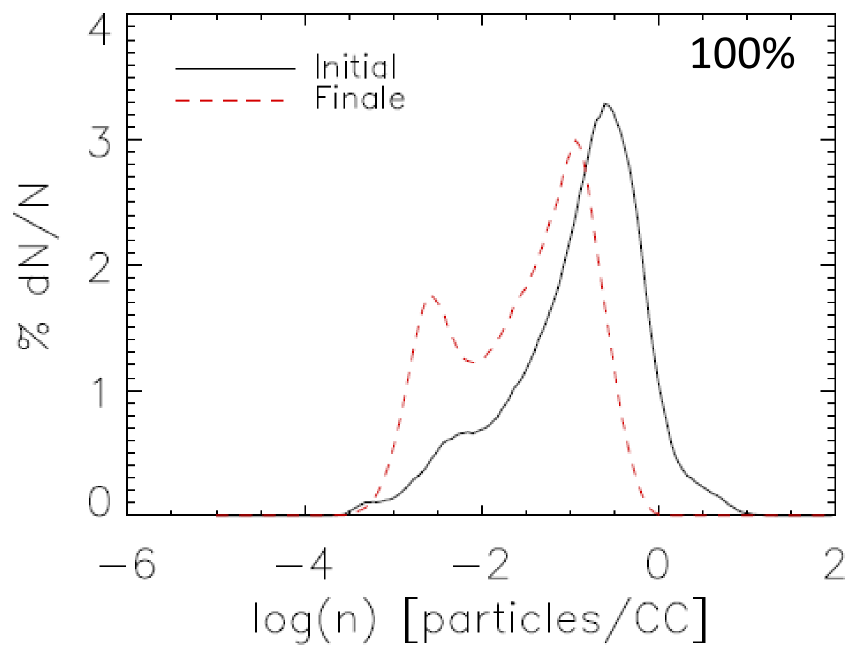
Why?

Mass transport Vs. density distribution



Volume filling fraction (25% & 100% SNR)





May be due to the relatively broader density distribution

Summary

- Magnetic energy saturates at the equal magnitude, irrespective of the seed fields and SNE frequency
- Growth rates are almost equal for all SNR (in the initial growing phase)
- Absolute value of the mean magnetic field decrease with increasing SNR
- $\alpha_{R\varphi}$ and $\alpha_{\varphi\varphi}$ profiles are quenched in the saturated region
- $\alpha_{R\varphi}/\alpha_{\varphi\varphi} = 4$ for all SNR (Elstner D. , Gressel O.)
- Except the 100% SNR model, wind is also quenched in all other models
- Wind may have quenched due to the relatively narrow distributions of density in the mid planes

Outlook

- Models with higher resolution
- Larger box sizes
- Cosmic Rays

Saturated energies

Model	Final energy (erg)	Kinetic energy (erg)
Strong field vertical flux (25%)	4×10^{51}	2×10^{51}
Strong field zero flux (25%)	Growing phase	2×10^{51}
Weak field vertical flux (25%)	4×10^{51}	2×10^{51}
Weak field zero flux (25%)	Growing phase	2×10^{51}
Weak field vertical flux (50%)	4×10^{51}	4×10^{51}
Weak field vertical flux (100%)	4×10^{51}	10×10^{51}
Azimuthal and radial fields (25%)	Growing phase	2×10^{51}

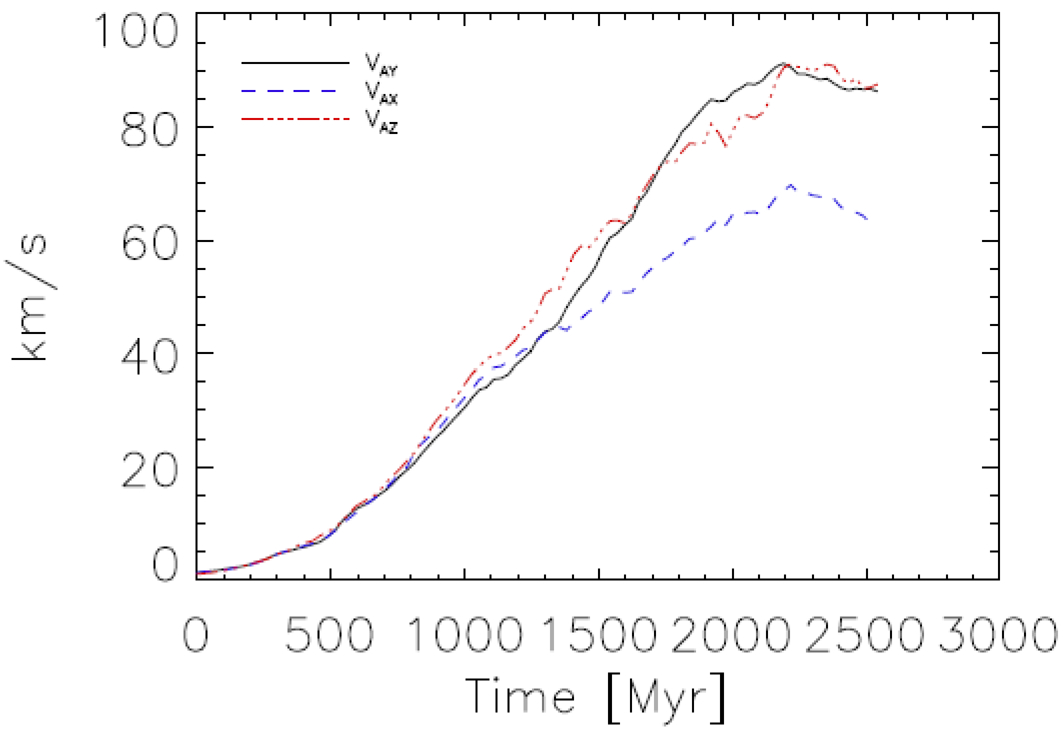
Radiative cooling function

- Modeling of SNE via thermal energy injections
- Necessary to include radiative cooling function
- Adopted as piecewise power law

$$\Lambda(T) = \Lambda_i T^{\beta_i}, \quad \text{for } T_i \leq T < T_{i+1} \,.$$

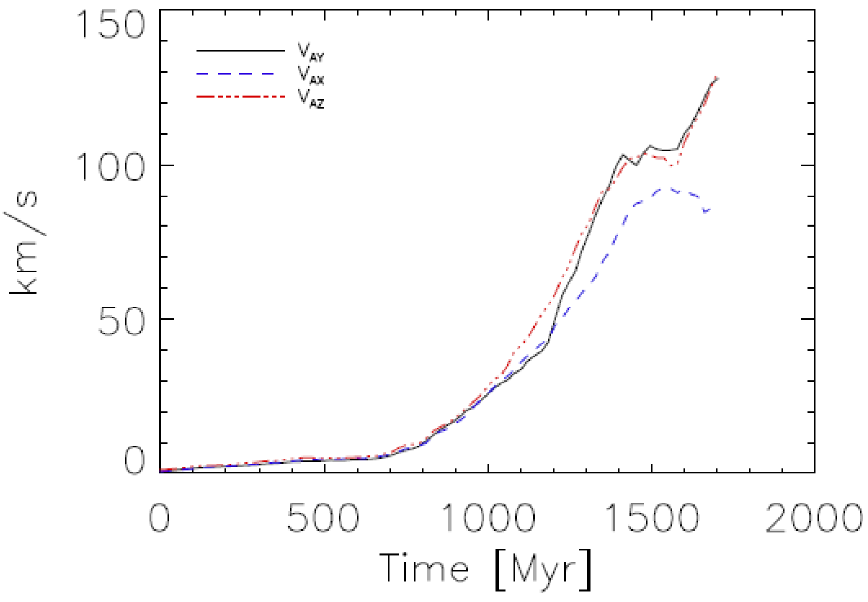
- Thermally unstable range 141K to 6102K

25% SNR

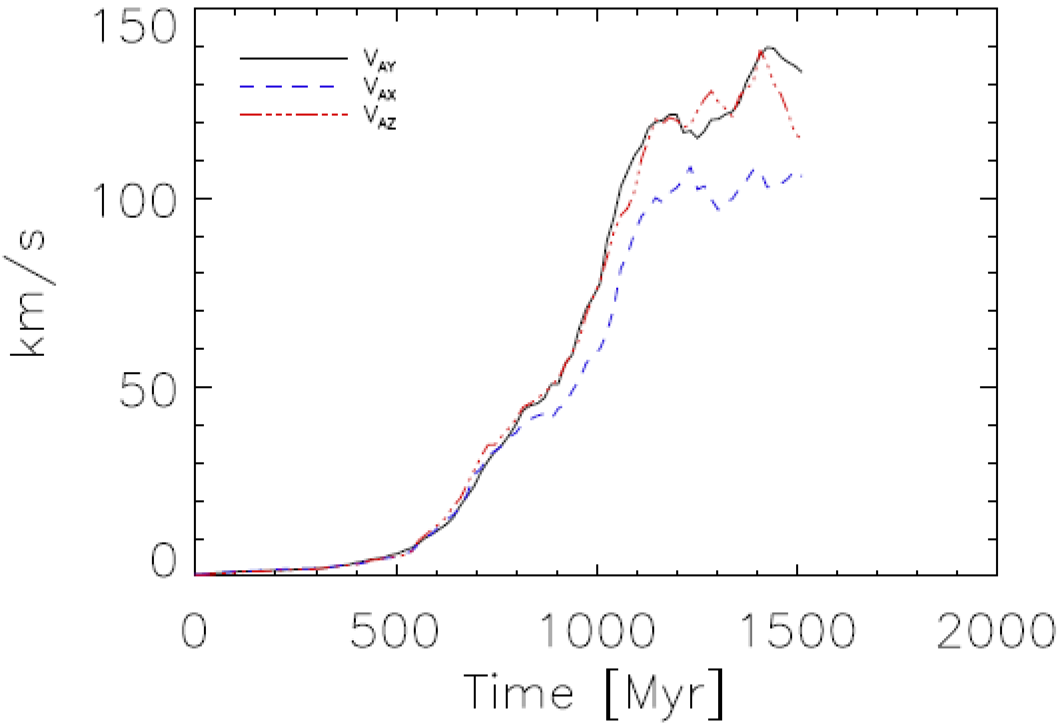


100
80
60
40
20
0
km/s
V_{AY}
V_{AX}
V_{AZ}
0
500
1000
1500
2000
2500
3000
Time [Myr]

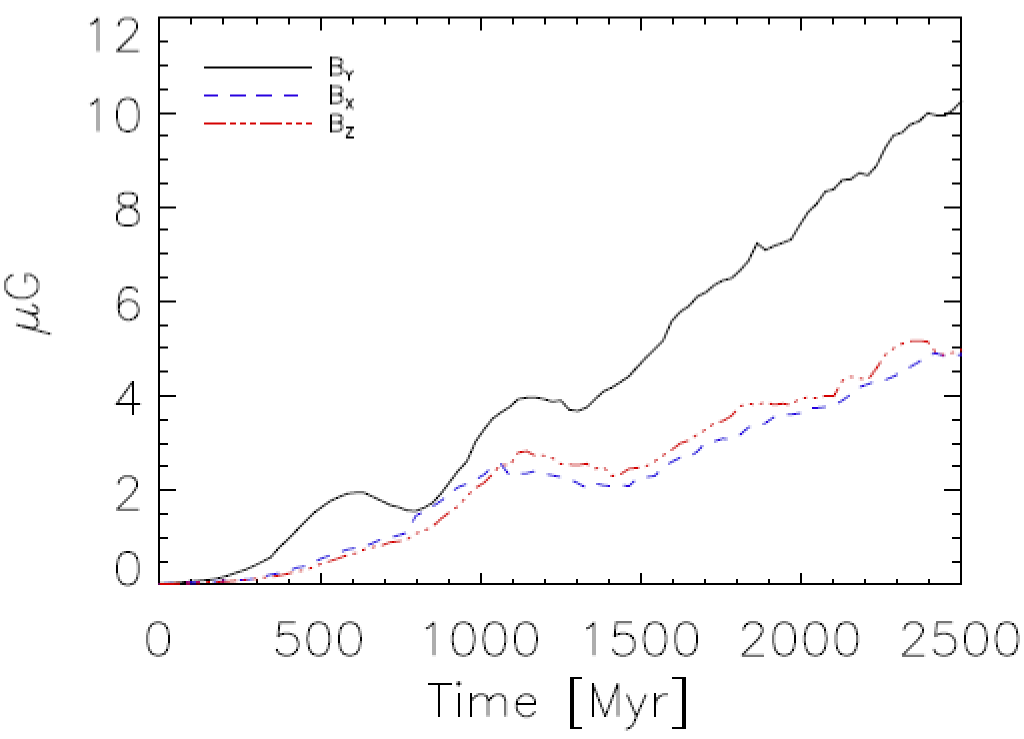
50% SNR



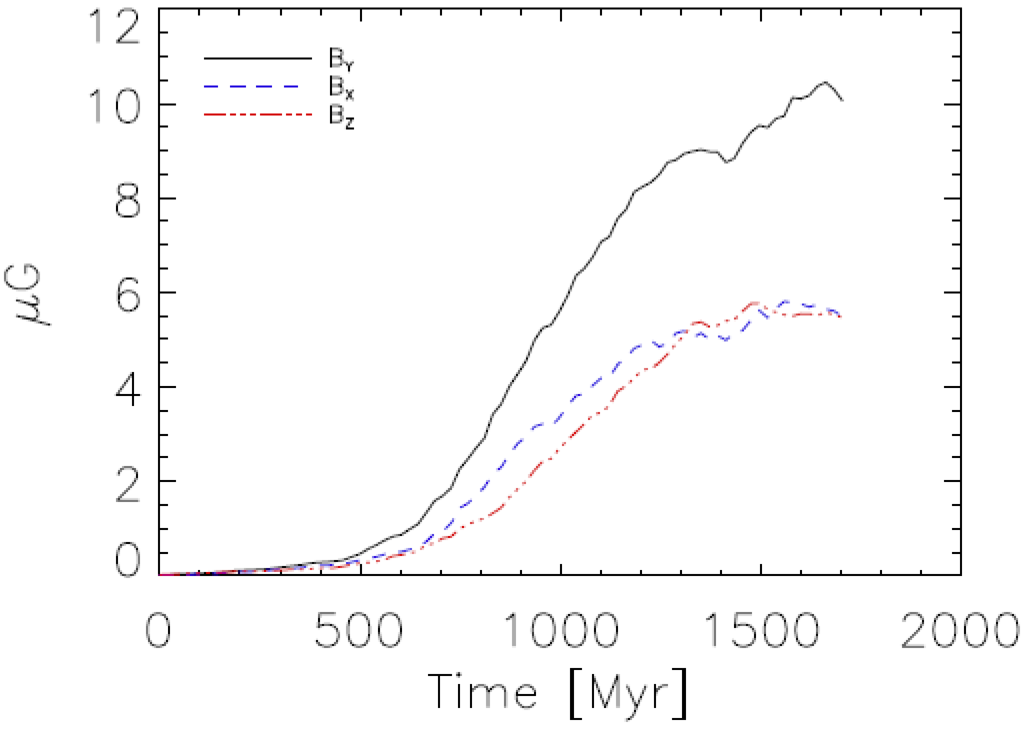
100% SNR



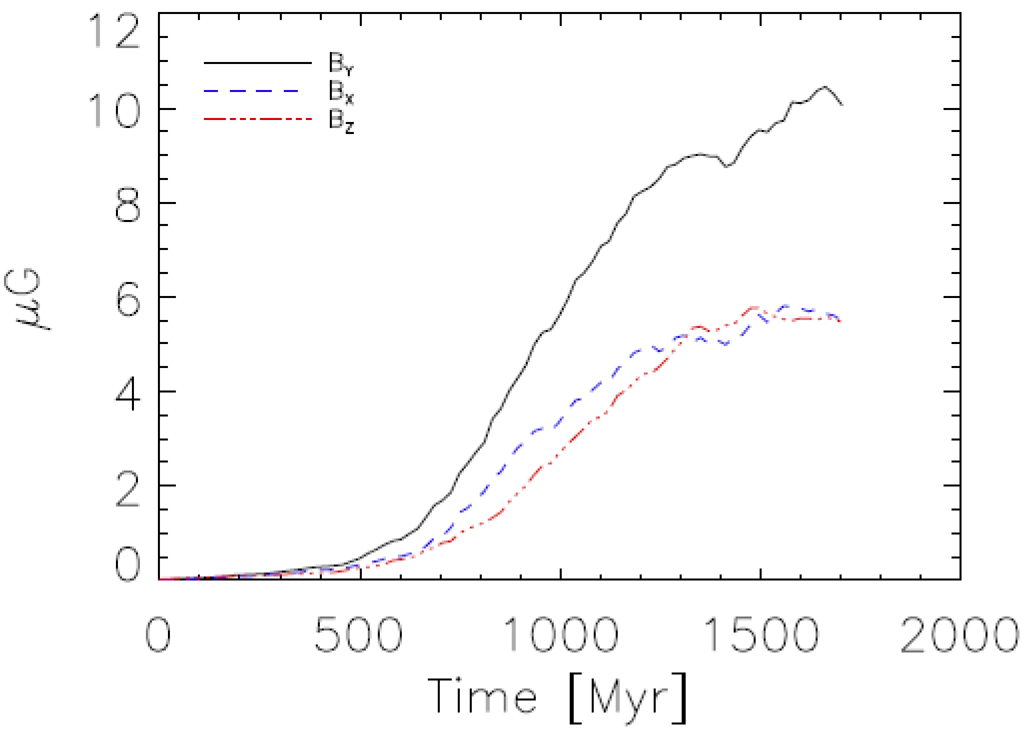
25% SNR



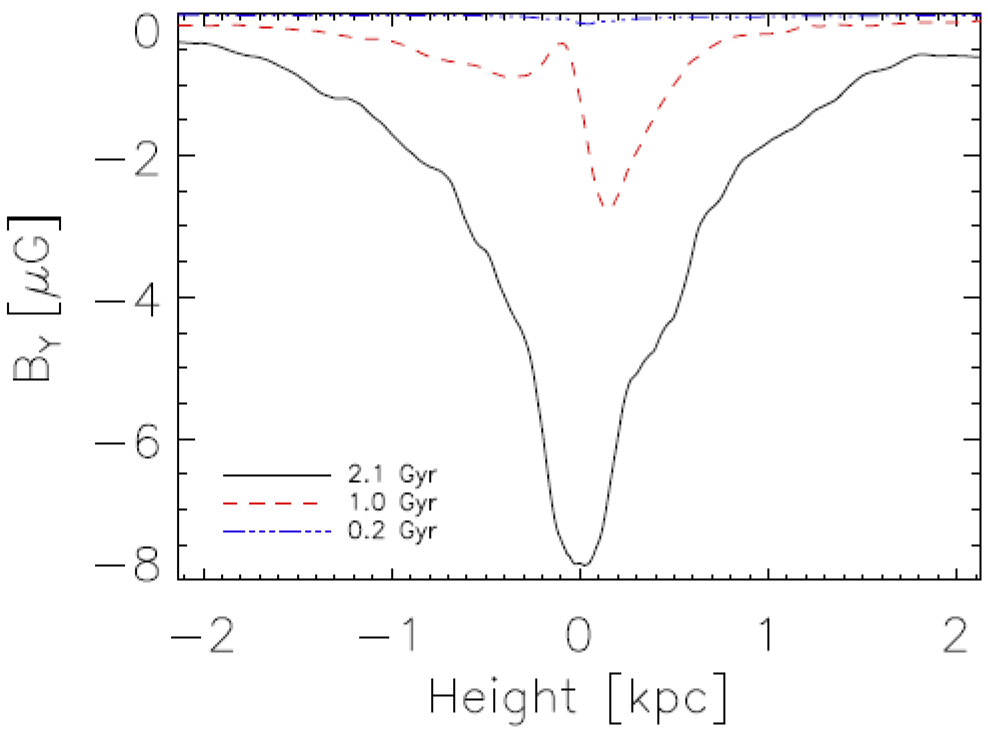
50% SNR



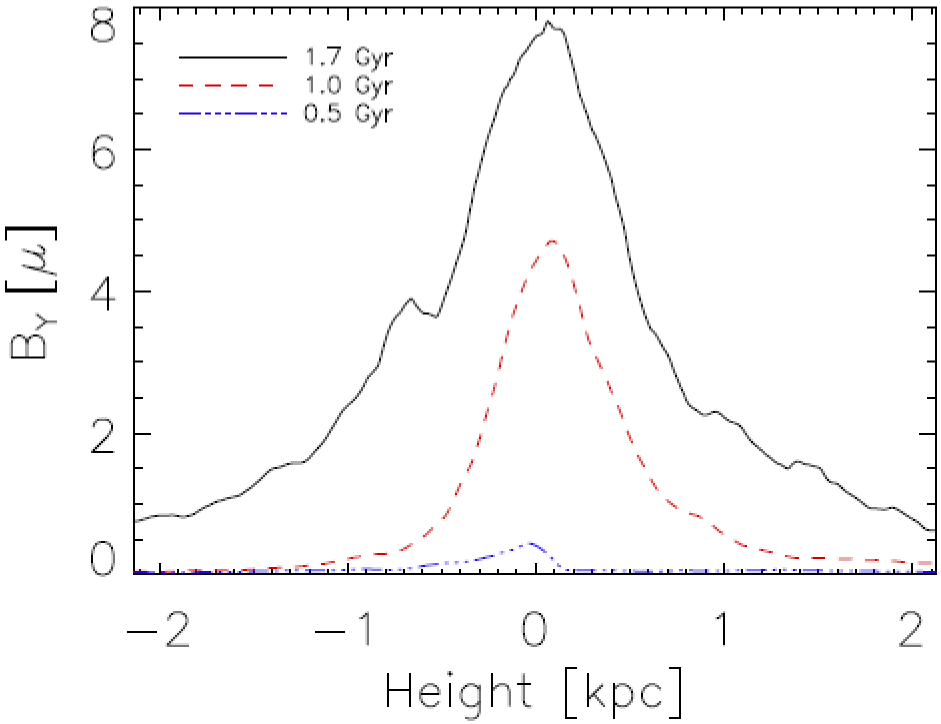
100% SNR



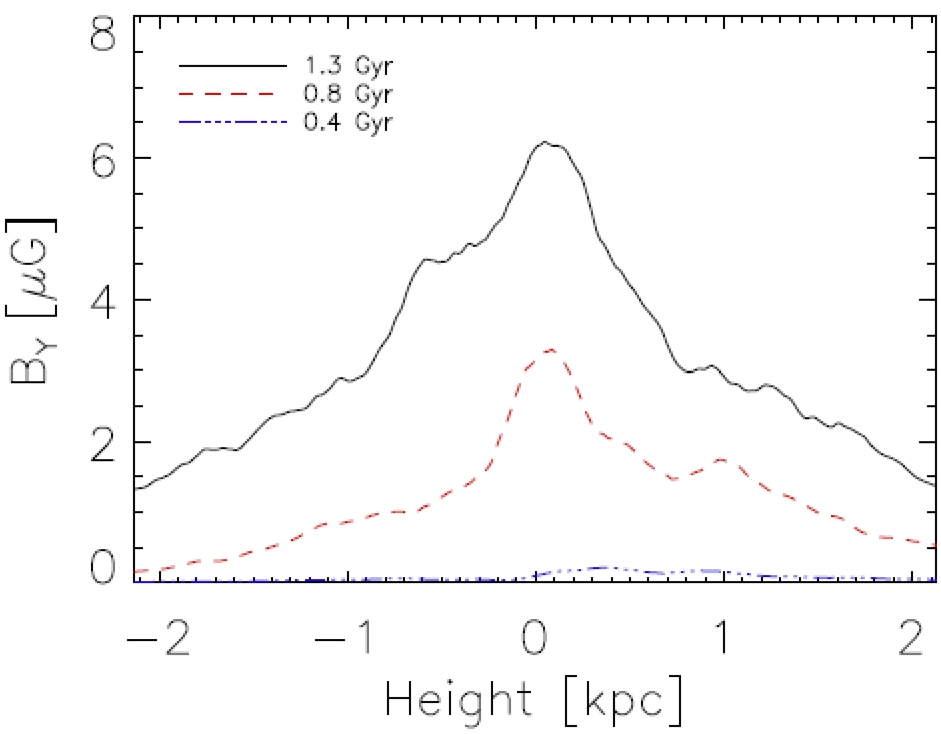
By maximum evolution 25%



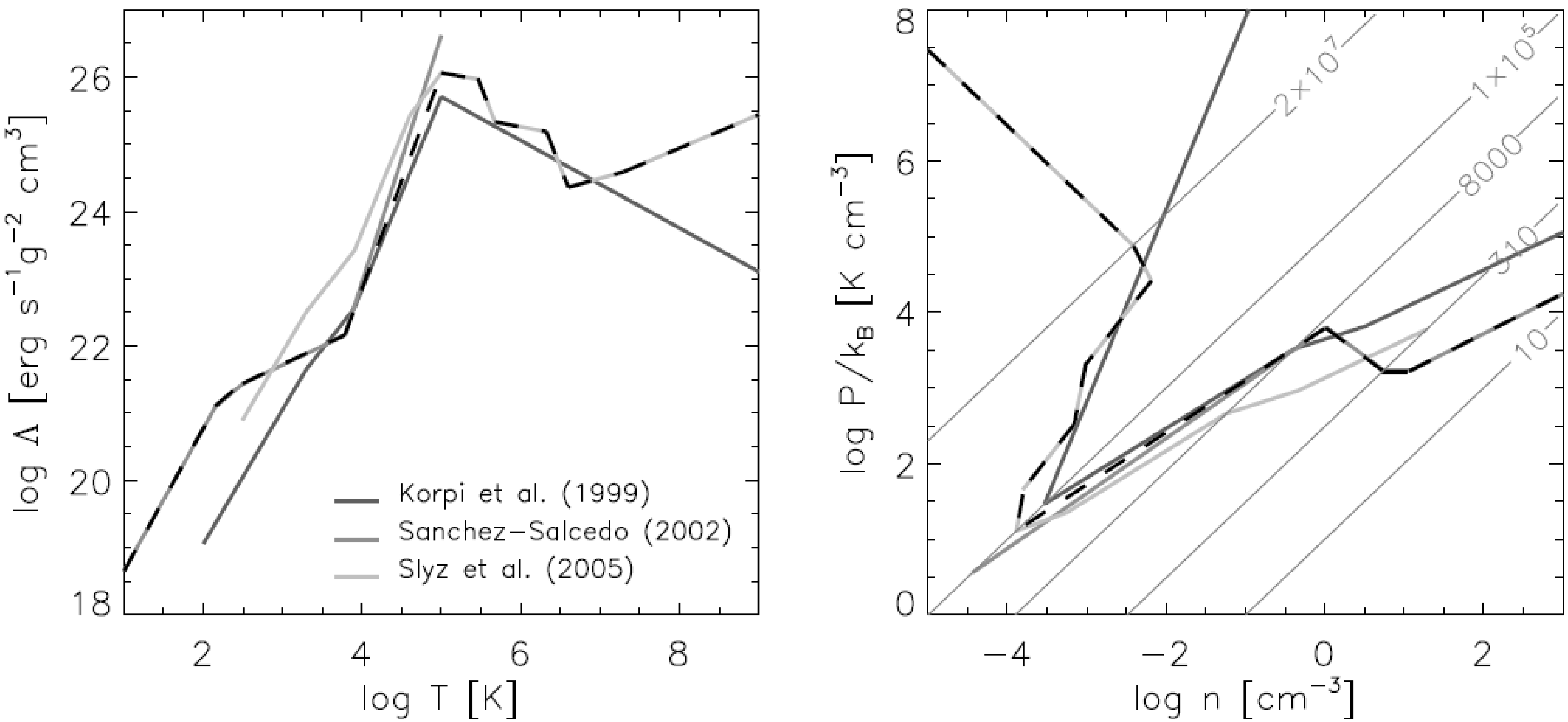
By maximum evolution 50%



By maximum evolution 100%



Equilibrium curve and cooling function



$$\lambda_{\rm F} = 2\pi \left[\frac{\varrho^2 \Lambda}{\kappa T}(1-\beta)\right]^{-1/2}$$

Koyama & Inutsuka (2004)

$\mathrm{Pm} = 2.5$

$\eta = 0.2{\times}10^{25}\,\mathrm{cm^2 s^{-1}}$

$$\Gamma(z) = \Gamma_0 \times \begin{cases} e^{-\frac{z^2}{2z_0\,H_\Gamma}} & \text{if } |z| \le z_0 \\ e^{\frac{z_0}{2H_\Gamma}}\,(e^{-\frac{z}{H_\Gamma}} + 10^{-5}) & \text{otherwise,} \end{cases}$$

$H_\Gamma = 300\,\mathrm{pc}$ and choose $z_0 = H_\Gamma/5$.

$\Gamma_0 = 0.015\,\mathrm{erg\ s^{-1}}$

photoelectric heating and ionising radiation from OB stars.

Joung & Mac Low (2006)

$$\Lambda(T) = \Lambda_i\, T^{\beta_i}$$

T_i [K]	Λ_i [erg $\mathrm{s^{-1}\,g^{-2}\,cm^3\,K^{-\beta_i}}$]	β_i
10	$3.420{\times}10^{16}$	2.12
141	$9.100{\times}10^{18}$	1.00
313	$1.110{\times}10^{20}$	0.56
6102	$1.064{\times}10^{10}$	3.21
10^5	$1.147{\times}10^{27}$	-0.20
$2.88{\times}10^5$	$2.290{\times}10^{42}$	-3.00
$4.73{\times}10^5$	$3.800{\times}10^{26}$	-0.22
$2.11{\times}10^6$	$1.445{\times}10^{44}$	-3.00
$3.98{\times}10^6$	$1.513{\times}10^{22}$	0.33
$2.00{\times}10^7$	$8.706{\times}10^{20}$	0.50

Sánchez-Salcedo, Vázquez-Semadeni & Gazol (2002)

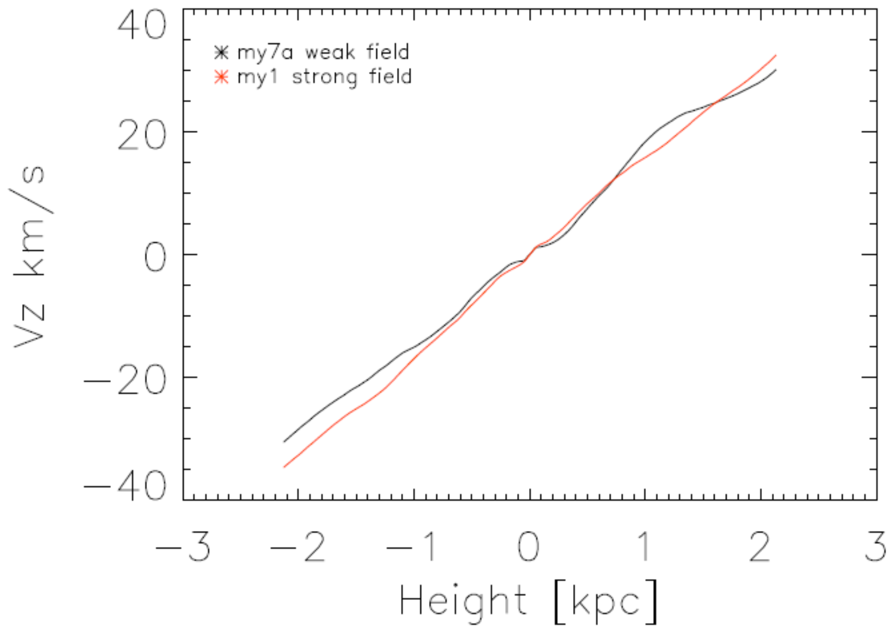
Flux dependence

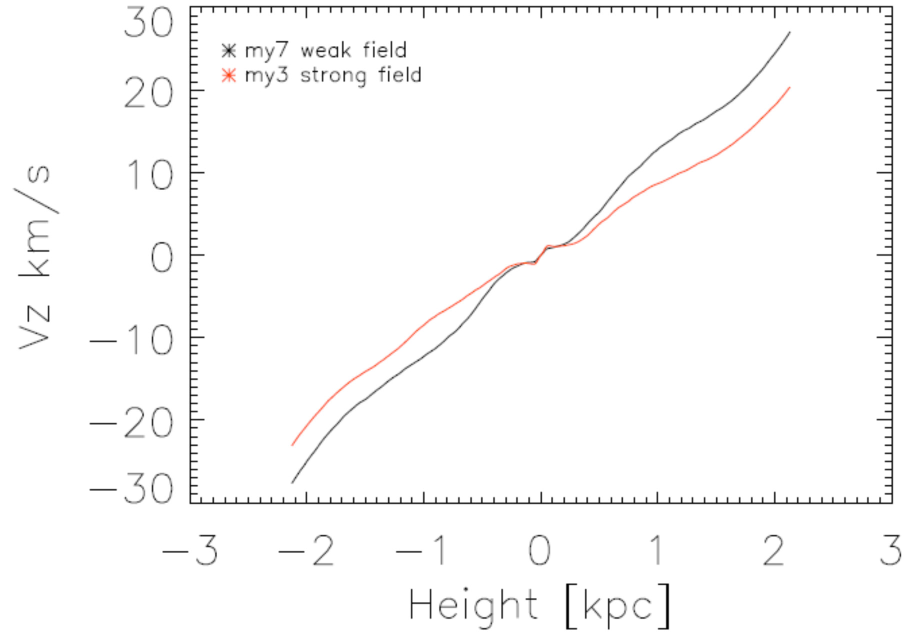
	M1	M3	M7	M7a	Gressel
Time (Gyr)	1.2	1.6	2.5	2.5	1.9
Flux (μGcm^2)	0	10^{41}	10^{39}	0	0
SN rate (%)	25%	25%	25%	25%	25%
B_{seed} (μG)	0.1	0.1	0.001	0.001	0.001 (B_y)
Growth time (Myr)	308	420	200	191	254
E_{mag} : E_{kin} (final)	0.4	1.3	2.3	0.5	0.6
<B> U (μG)	-0.3	-1.8	-1	0.3	0.07
<B> L (μG)	0.9	1.8	-1	0.07	0.3
B_{mean} : B_{rms}	1.5	2	2	2.4	1.7

SNR dependence

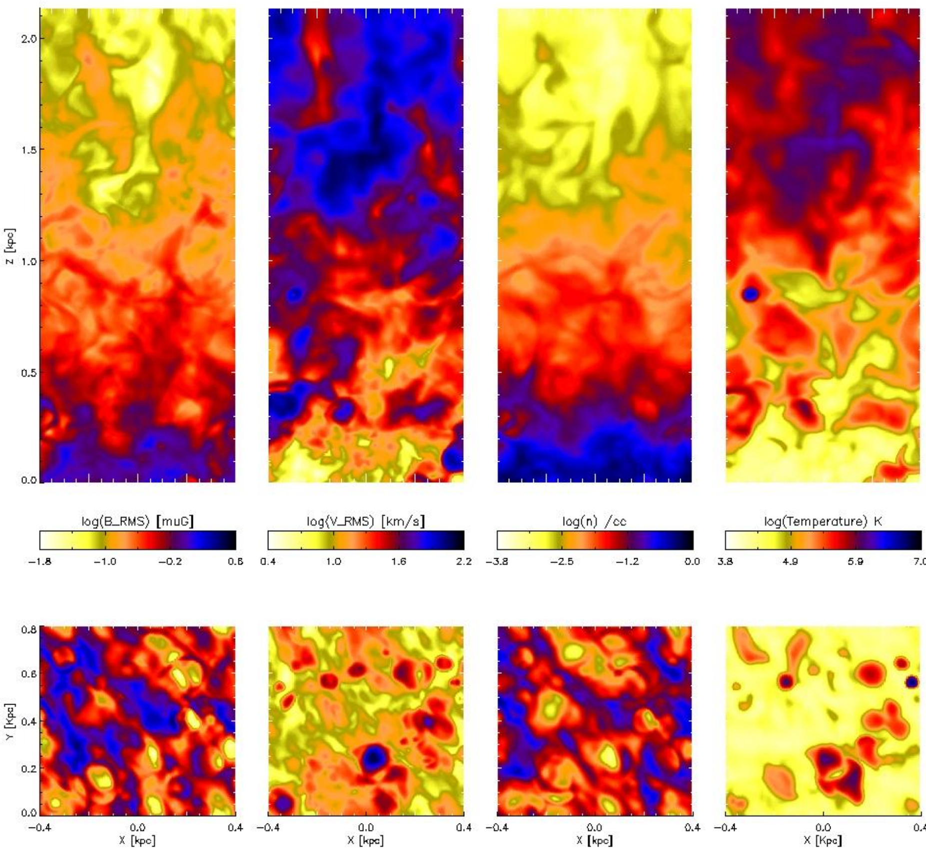
	M7	M71	M72
Time (Gyr)	2.5	1.8	1.5
Flux (μGcm^2)	10^{39}	10^{39}	10^{39}
SN rate (%)	25%	50%	100%
B_{seed} (μG)	0.001	0.001	0.001
Growth time (Myr)	200	190	179
$E_{mag} : E_{kin}$	2.3	1.1	0.4
<B> U (μG)	-1	0.6	0.3
<B> L (μG)	-1	0.6	0.3
$B_{mean} : B_{rms}$	2	1.7	1

Vertical wind

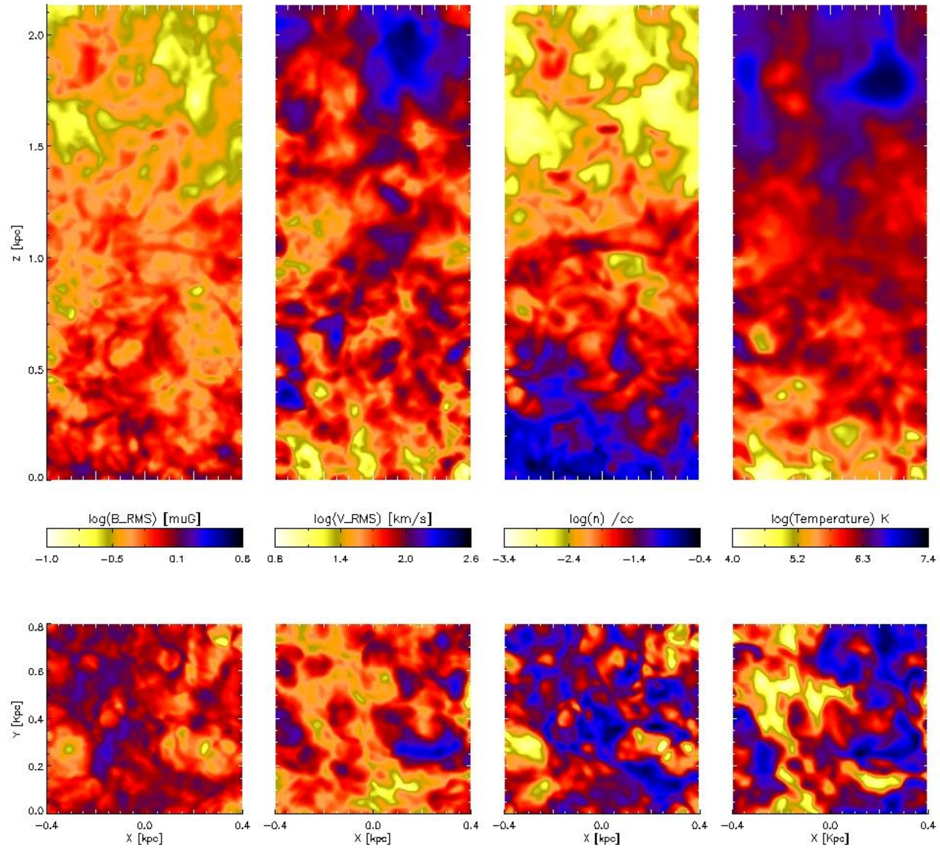




My71

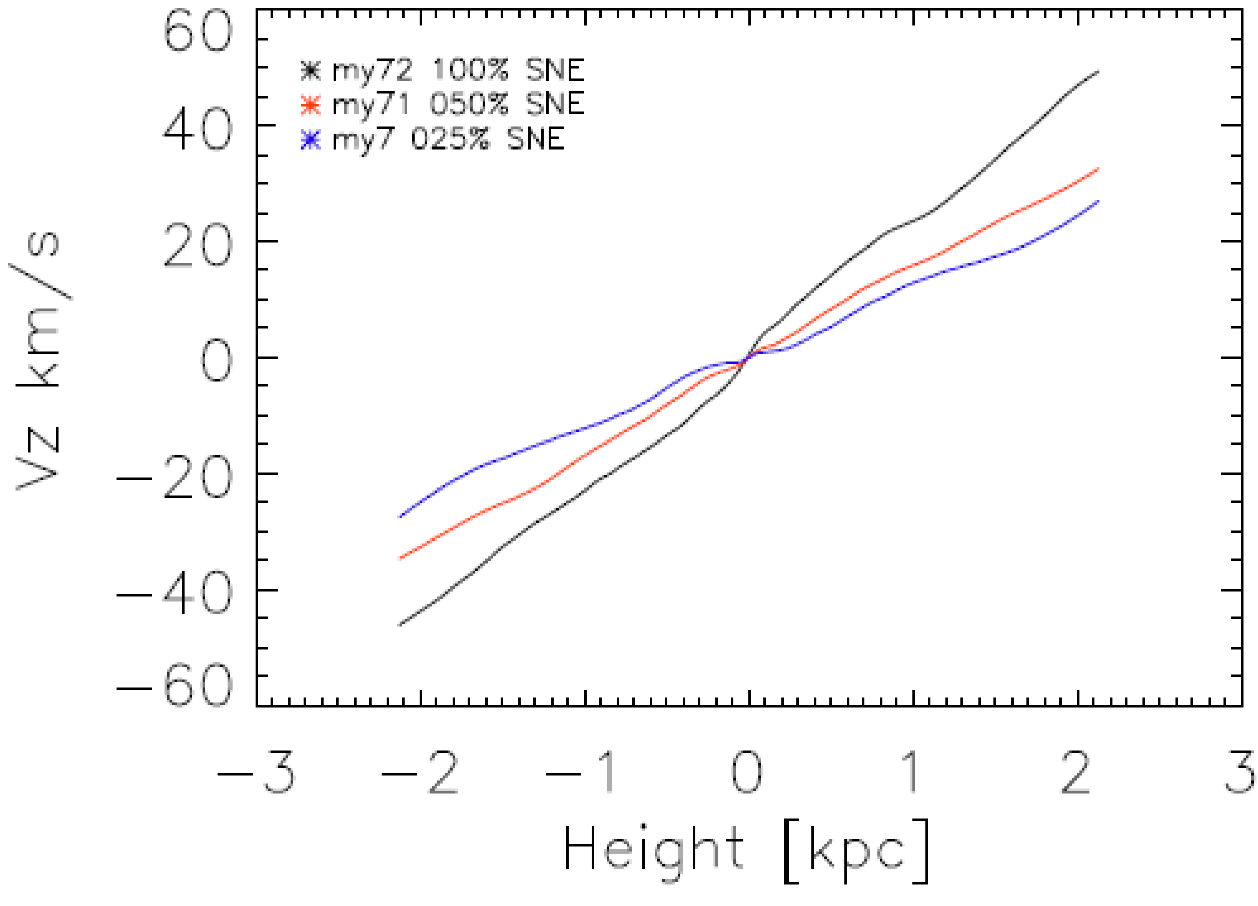

log(B_RMS) [muG]
log(V_RMS) [km/s]
log(n) /cc
log(Temperature) K
Z [kpc]
Y [kpc]
X [kpc]

My72



log(B_RMS) [muG]
log(V_RMS) [km/s]
log(n) /cc
log(Temperature) K
Z [kpc]
Y [kpc]
X [kpc]

Vertical wind (SNR dependence)



Model equations

$$\partial_\tau \rho + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\partial_t (\rho \mathbf{v}) + \nabla \cdot \left[\rho(\mathbf{v} \otimes \mathbf{v}) + p^* - (\mathbf{B} \otimes \mathbf{B})\right] =$$

$$- 2\boldsymbol{\Omega}\rho (\hat{z} \times \mathbf{v}) + 2\boldsymbol{\Omega}^2 \mathrm{q x} \hat{\mathrm{x}} + \boldsymbol{\Omega}\, \mathrm{g}(z) \hat{z} + \nabla \cdot \tau$$

$$\partial_t (e) + \nabla \cdot \left[(e + p^*)\mathbf{v} - (\mathbf{v} \cdot \mathbf{B})\mathbf{B}\right] =$$

$$\begin{aligned} & 2\boldsymbol{\Omega}^2 \mathrm{qx} (\hat{\mathrm{x}} \cdot \mathbf{v}) + \Omega\, \mathrm{g(z)} (\hat{z} \cdot \mathbf{v}) \\ & + \nabla \cdot \left[\mathbf{v} + \eta (\nabla \times \mathbf{B}) + \kappa \nabla \mathrm{T}\right] \\ & + \Gamma_{SN} - \rho^2 \Lambda (\mathrm{T}) + \rho \Gamma (z) \end{aligned}$$

$$\partial_t \mathbf{B} - \nabla \times (\mathbf{v} \times \mathbf{B} - \eta \nabla \times \mathbf{B}) = \bar{0}$$

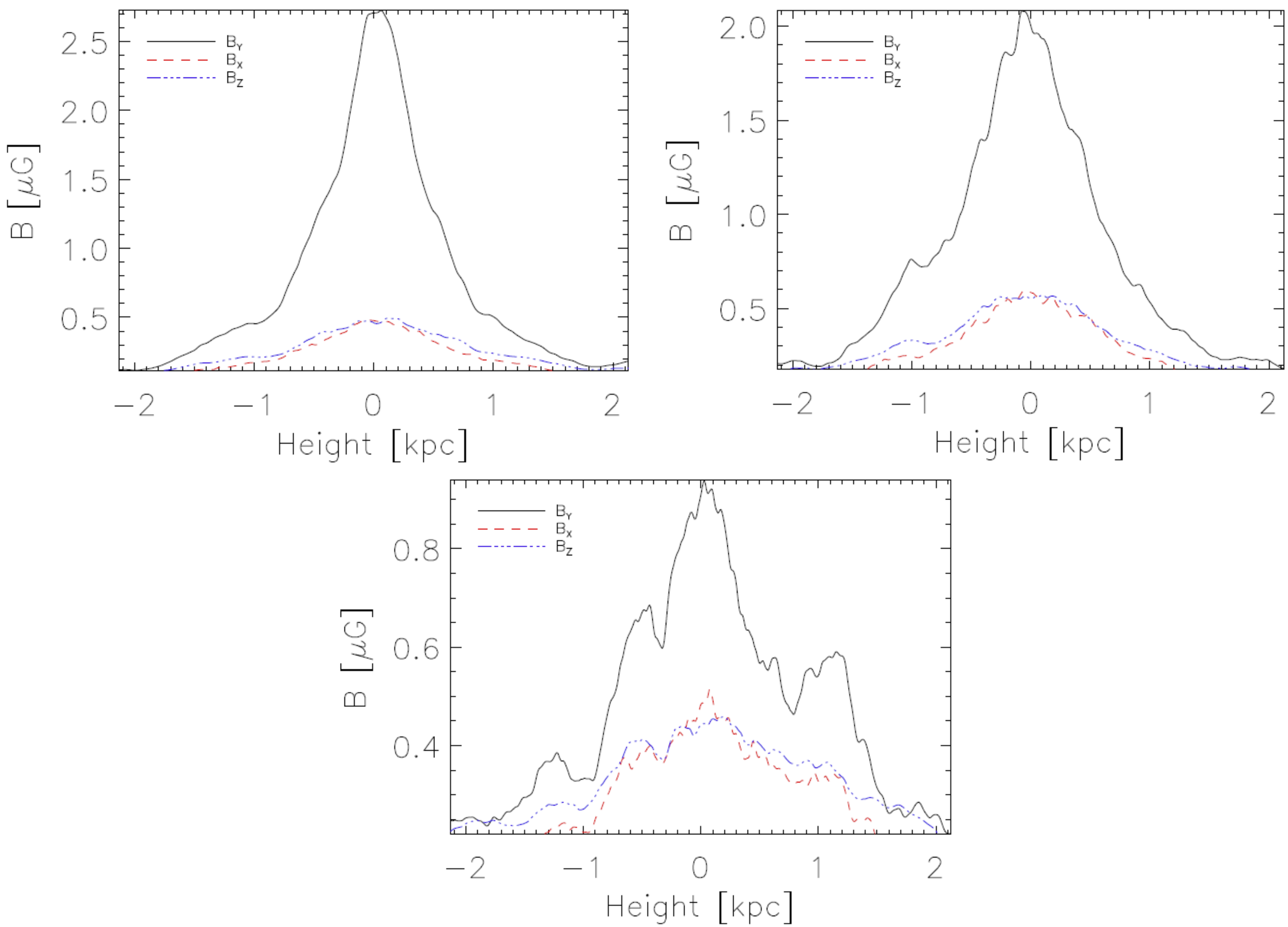
Where, $p^* = p + B^2/2$

Thermal energy, $\varepsilon = e - \rho v^2/2 - B^2/2$

Viscous stress tensor, $\tau = \tilde{\nu}\left[\bar{\nabla}\otimes\bar{v} + (\bar{\nabla}\otimes\bar{v})^T - 2/3\,(\bar{\nabla}\cdot\bar{v})\right]$

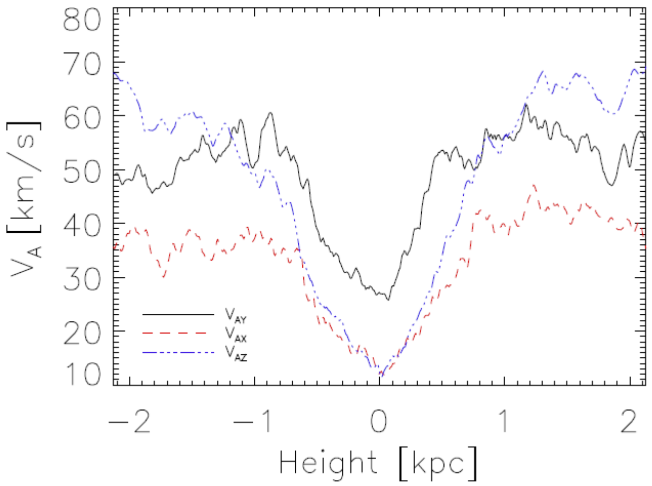
Shear parameter, $q = d\ln\Omega / d\ln R = -1$

Mean |B|

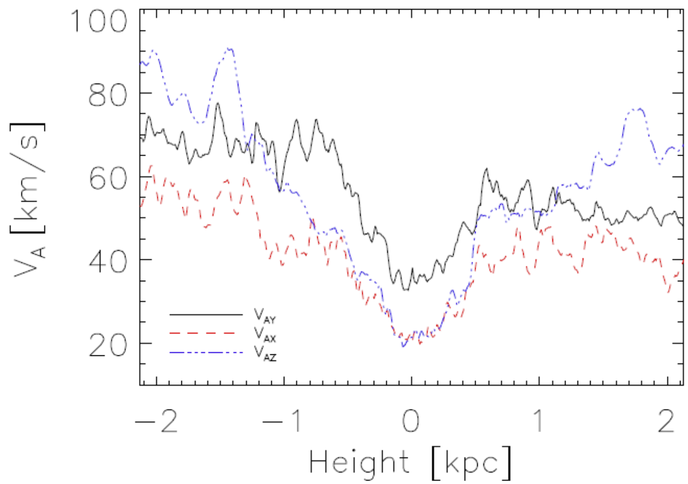


B_Y
B_X
B_Z
2.5
2.0
1.5
1.0
0.5
B [μG]
−2
−1
0
1
2
Height [kpc]
B_Y
B_X
B_Z
2.0
1.5
1.0
0.5
B [μG]
−2
−1
0
1
2
Height [kpc]
B_Y
B_X
B_Z
0.8
0.6
0.4
B [μG]
−2
−1
0
1
2
Height [kpc]

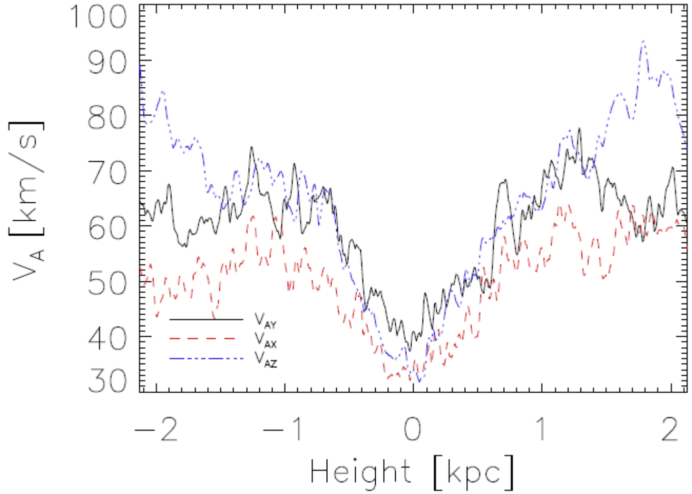
Maximum $|V_A|$



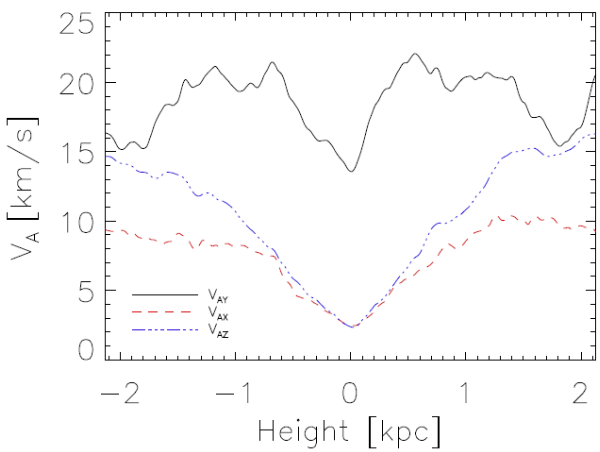
80
70
60
50
40
30
20
10
V_A [km/s]
−2
−1
0
1
2
Height [kpc]
V_{AY}
V_{AX}
V_{AZ}



100
80
60
40
20
V_A [km/s]
−2
−1
0
1
2
Height [kpc]
V_{AY}
V_{AX}
V_{AZ}

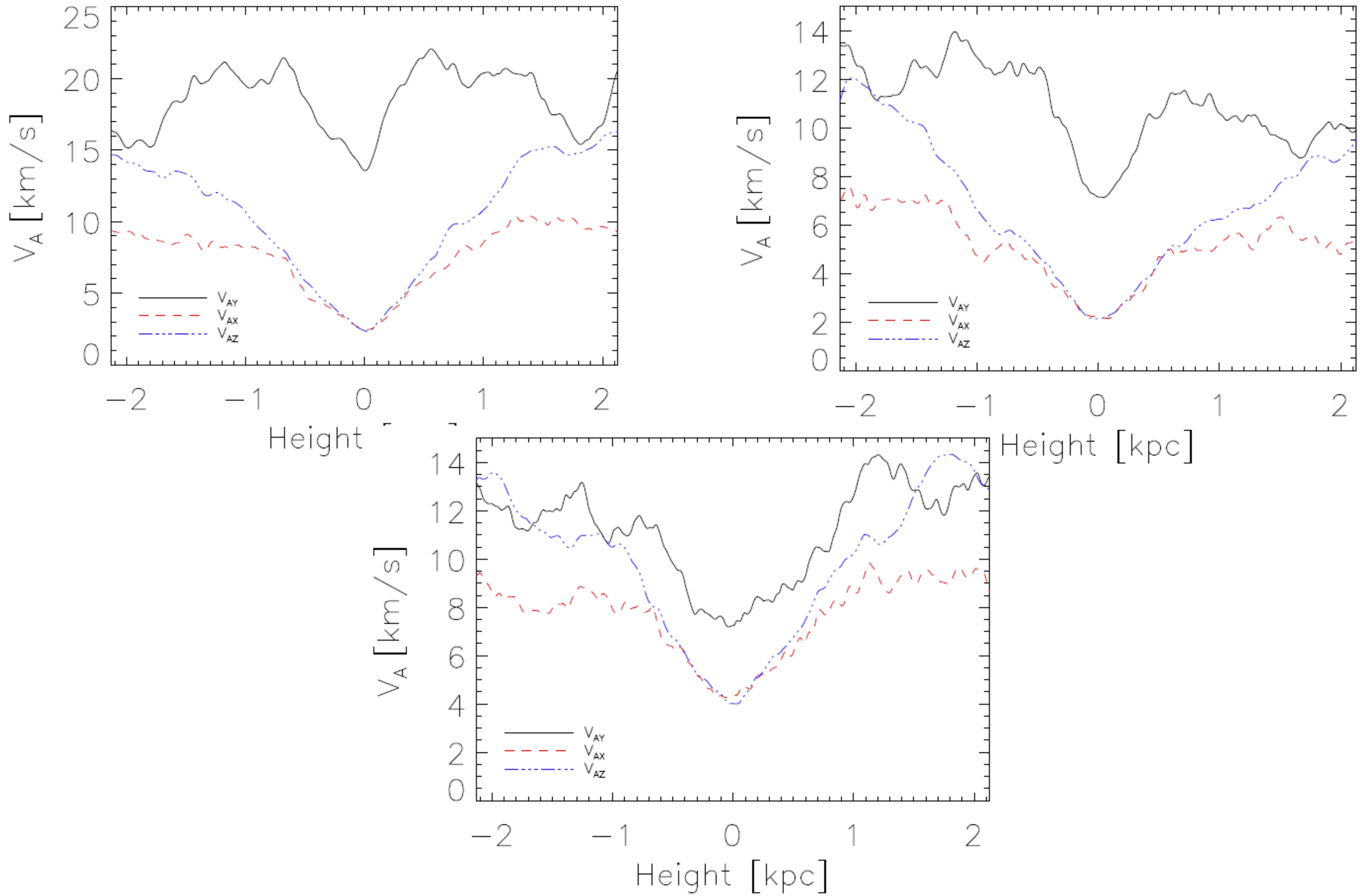


100
90
80
70
60
50
40
30
V_A [km/s]
−2
−1
0
1
2
Height [kpc]
V_{AY}
V_{AX}
V_{AZ}

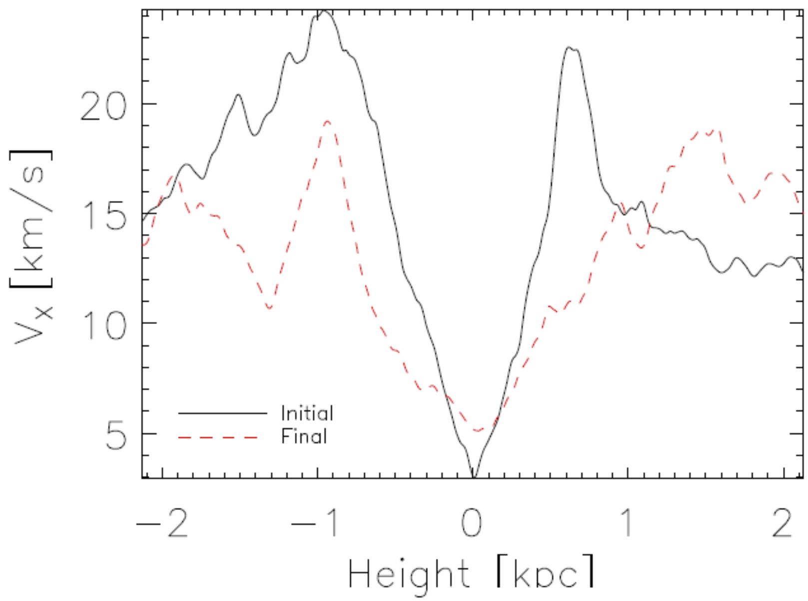


25
20
15
10
5
0
V_A [km/s]
−2
−1
0
1
2
Height [kpc]
V_{AY}
V_{AX}
V_{AZ}

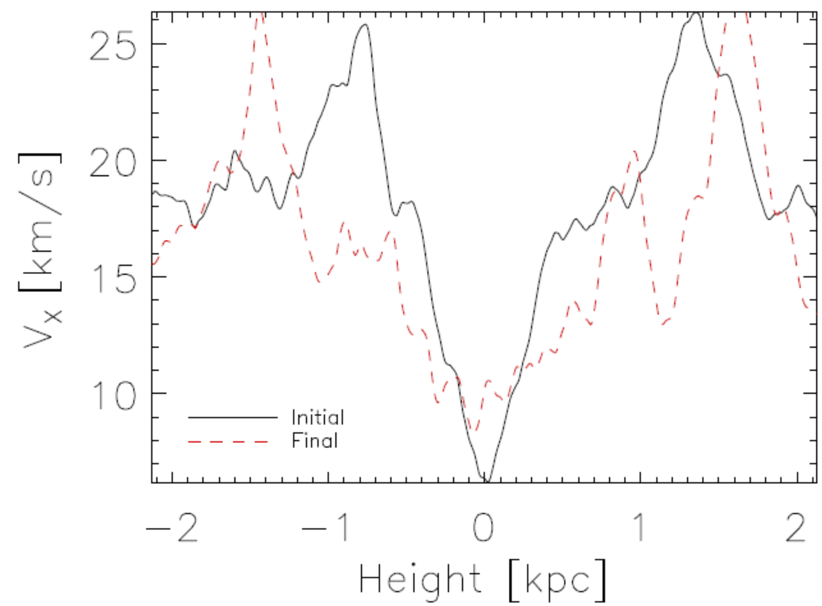
Mean $|V_A|$


25
20
15
10
5
0
V_A [km/s]
V_AY
V_AX
V_AZ
−2
−1
0
1
2
Height
14
12
10
8
6
4
2
0
Height [kpc]

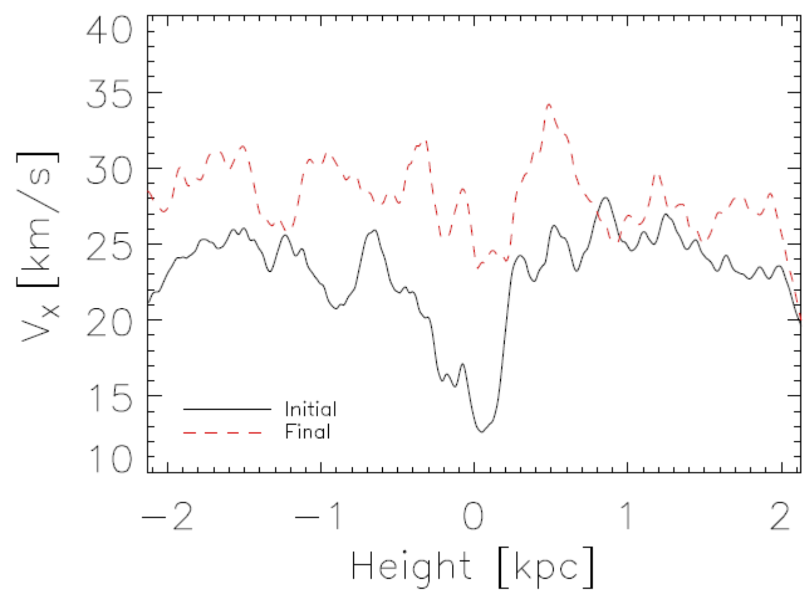
Mean $|V_x|$



20
15
10
5
V_x [km/s]
Initial
Final
−2
−1
0
1
2
Height [kpc]

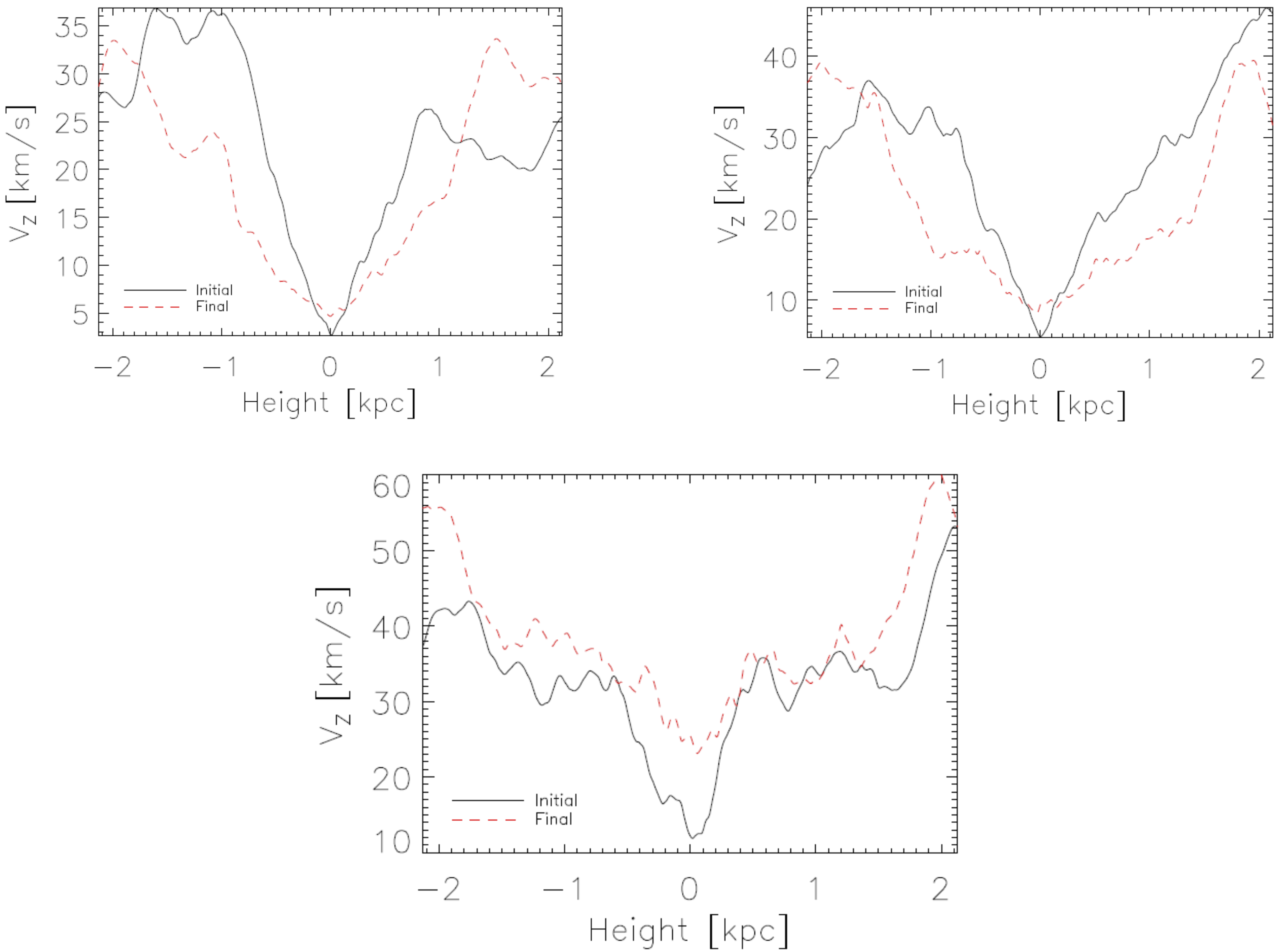


25
20
15
10
V_x [km/s]
Initial
Final
−2
−1
0
1
2
Height [kpc]



40
35
30
25
20
15
10
V_x [km/s]
Initial
Final
−2
−1
0
1
2
Height [kpc]

Mean $|V_Z|$



35
30
25
20
15
10
5
V_Z [km/s]
Initial
Final
−2
−1
0
1
2
Height [kpc]
40
30
20
10
V_Z [km/s]
Initial
Final
−2
−1
0
1
2
Height [kpc]
60
50
40
30
20
10
V_Z [km/s]
Initial
Final
−2
−1
0
1
2
Height [kpc]