TURBULENT AMPLIFICATION OF B-FIELDS AT SHOCKS

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COLLABORATORS

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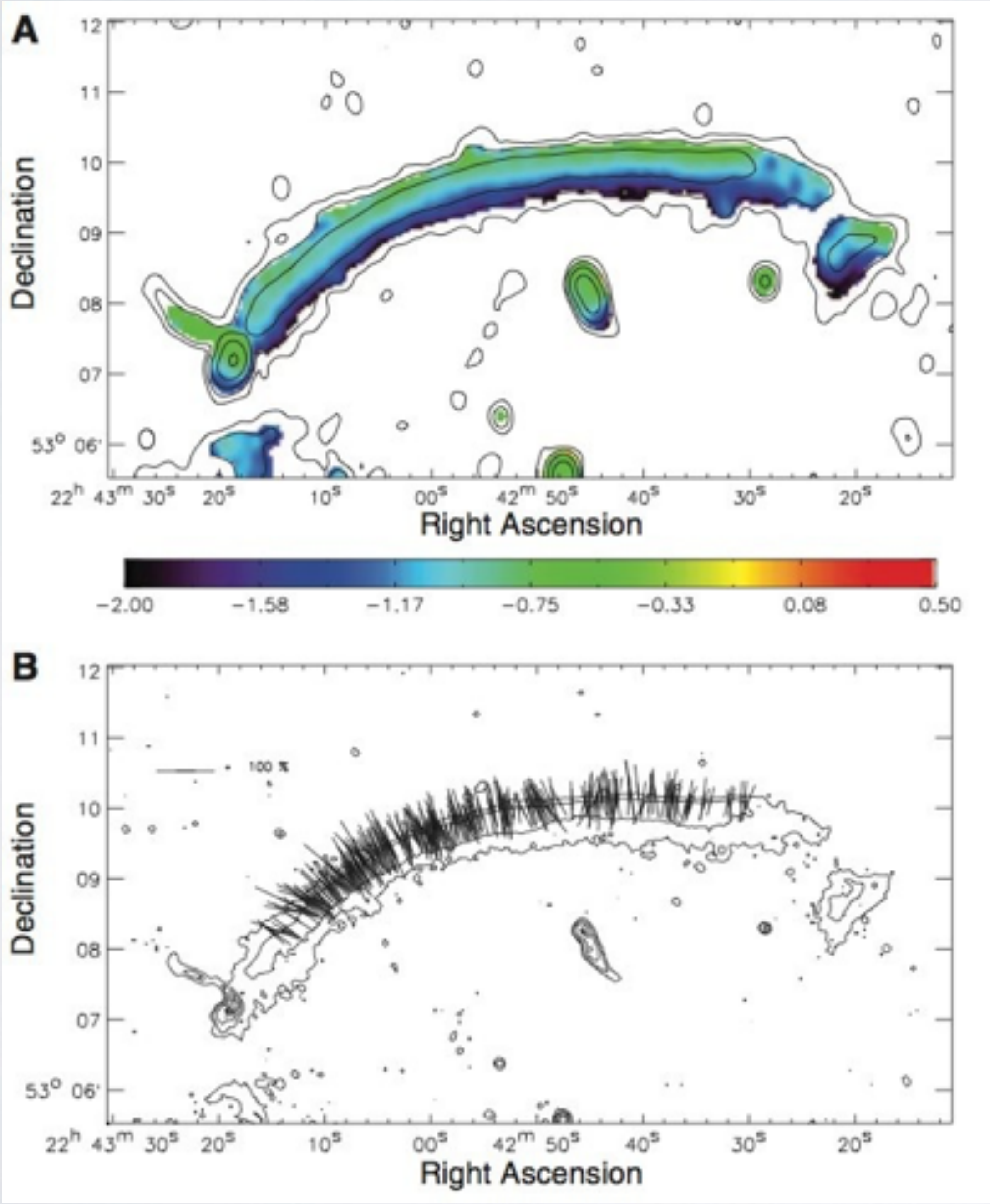
CLUSTER OUTSKIRTS HAVE HIGH B-FIELDS



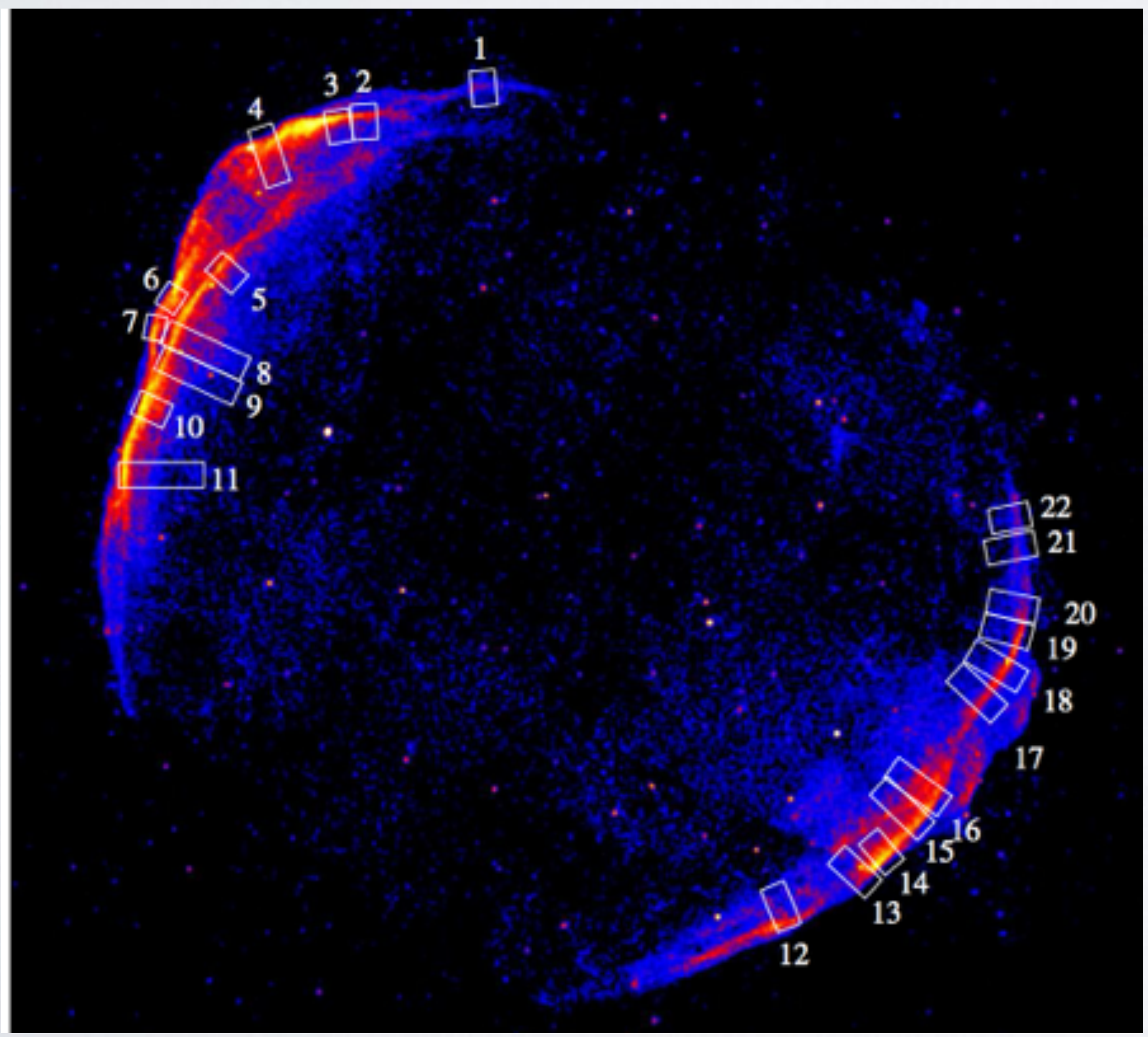
van Weeren et al, 2010

- Radio relics trace shocks in cluster outskirts
- Spectral index: shock Mach number
- Spectral ageing: B-field strength ~ muG
- Polarization: B-field orientation

SUPERNOVA THIN RIMS ALSO HAVE HIGH B-FIELDS…

~100 mu G to 1 milliG in thin rims

High B-fields consistent with what's needed to accelerate CRs



Ressler et al 2014

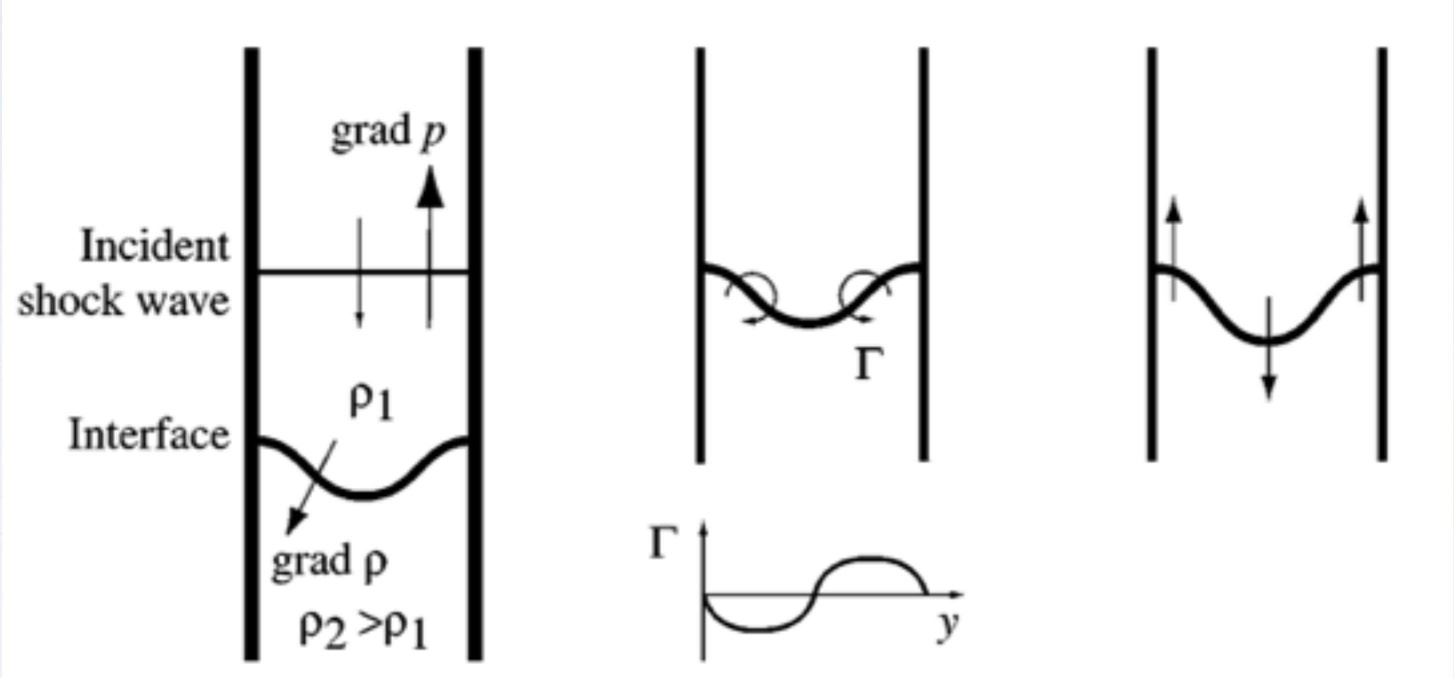
	Mach Number	Initial Magnetic Field	Final Magnetic Field	Postshock Field Line Geometry
Cluster	~3	?	~ 5 μG	tangential
SNR	> 100	~ μG	~ 100 μG	far downstream: radial

WHAT COULD BE RESPONSIBLE?

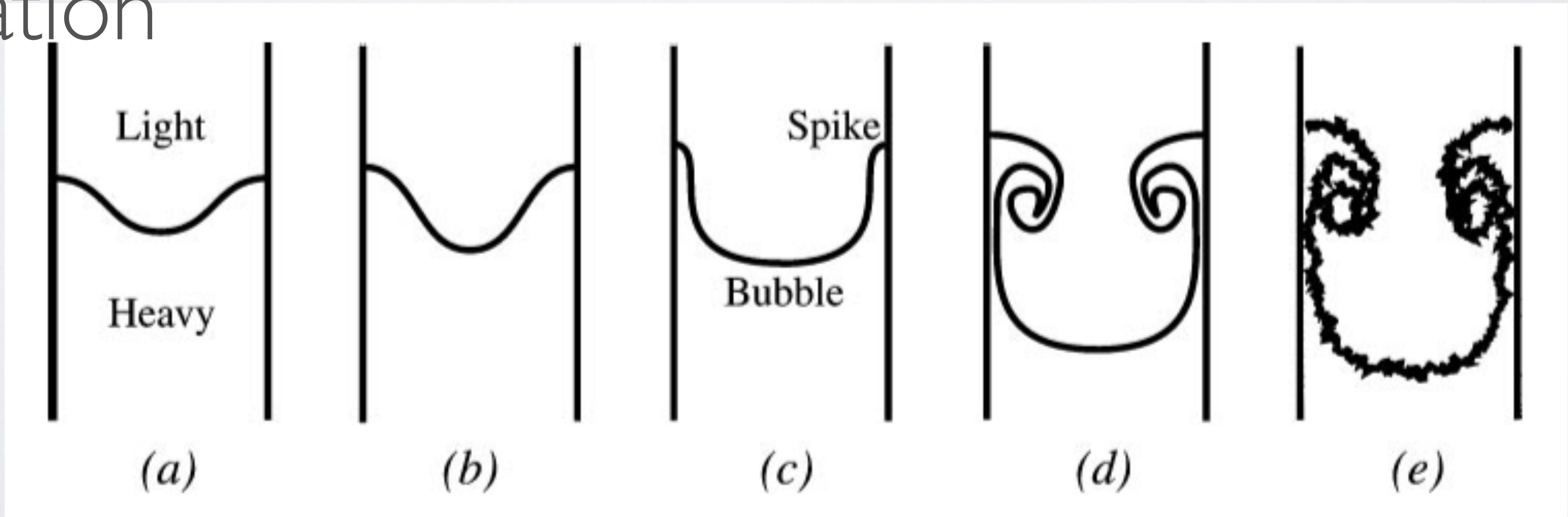
- Compression (amplifies by factor ~2-4 at most)
- Bell instability from cosmic ray streaming
- Shock cloud turbulent dynamo/RMI instability

All 3 processes could be at play

RICHTMYER-MESHKOV INSTABILITY



- Perturbations amplified by baroclinic vorticity generation

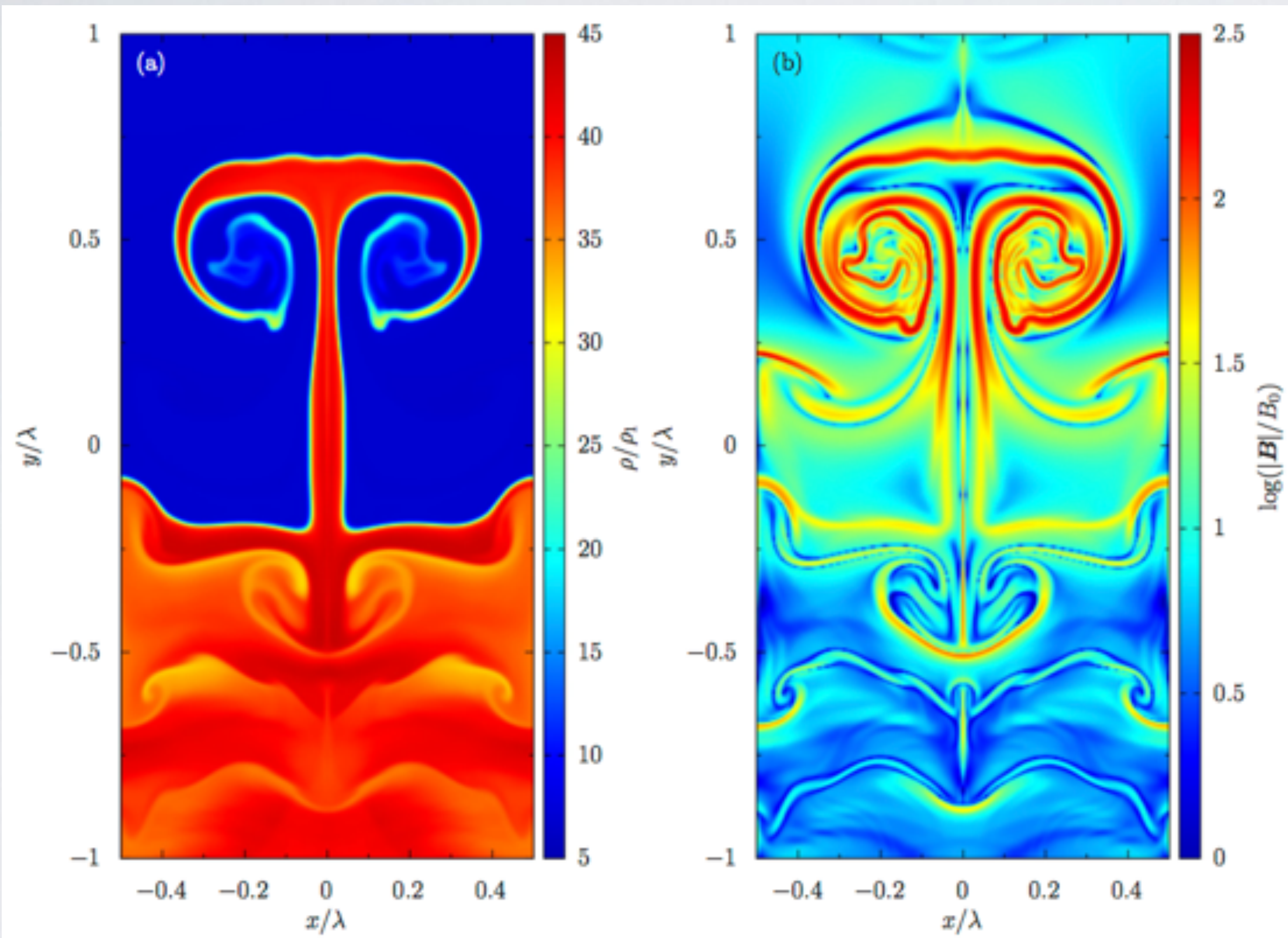


Brouillette 2002

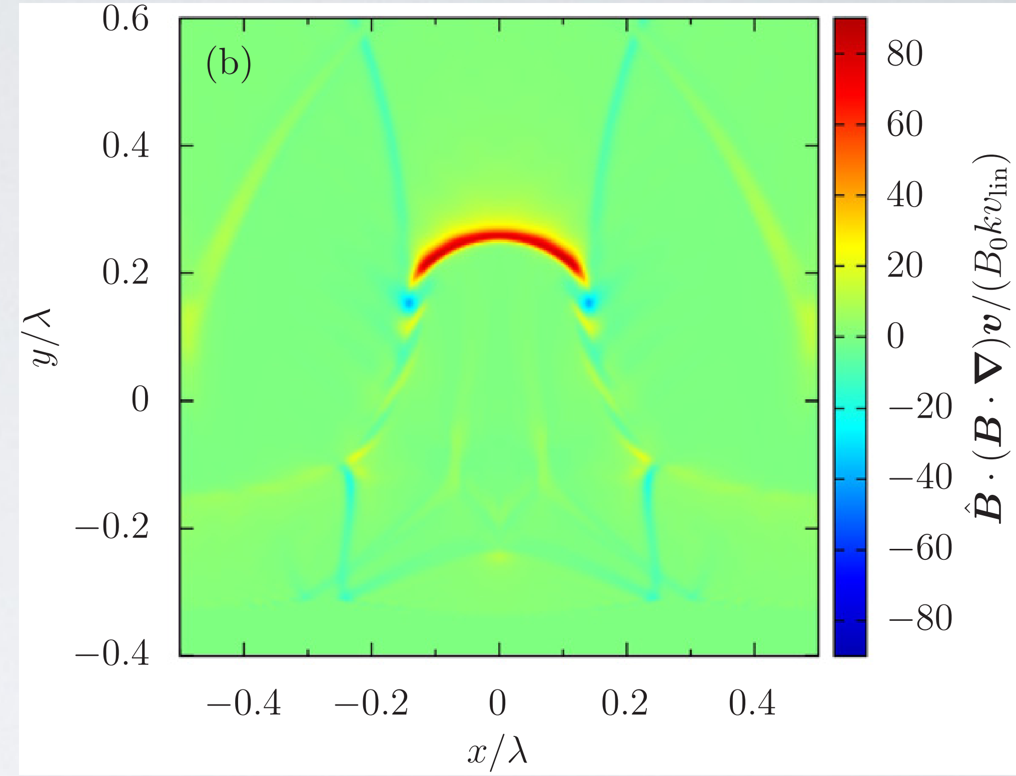
RMI with Magnetic Field

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = -(\boldsymbol{v} \cdot \nabla)\boldsymbol{\omega} + (\boldsymbol{\omega} \cdot \nabla)\boldsymbol{v} - \boldsymbol{\omega}(\nabla \cdot \boldsymbol{v}) + \frac{1}{\rho^2}\nabla\rho \times \nabla\left(p + \frac{\boldsymbol{B}^2}{8\pi}\right) - \frac{1}{\rho^2}\nabla\rho \times \frac{(\boldsymbol{B} \cdot \nabla)\boldsymbol{B}}{4\pi}$$

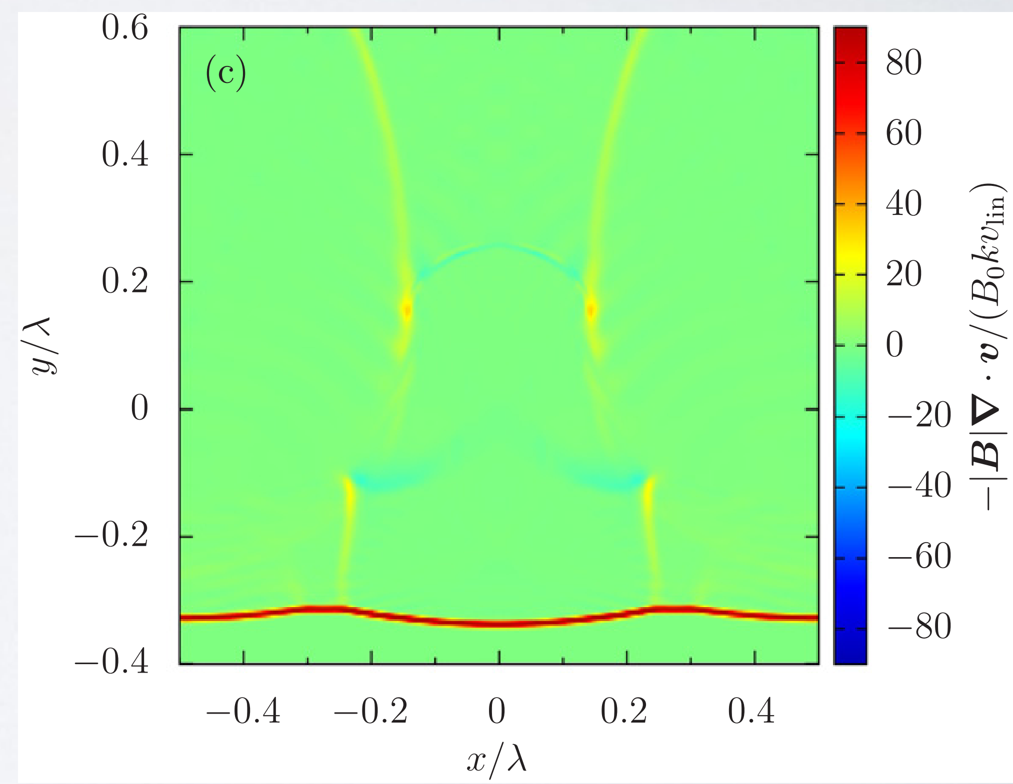
$$\frac{\partial \boldsymbol{B}}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{B} + (\boldsymbol{B} \cdot \boldsymbol{\nabla})\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{\nabla} \cdot \boldsymbol{v})$$



(a)
(b)
y/λ
x/λ
ρ/ρ_l
$\log(|\boldsymbol{B}|/B_0)$
1
0.5
0
−0.5
−1
−0.4
−0.2
0
0.2
0.4
45
40
35
30
25
20
15
10
5
2.5
2
1.5
1
0.5
0



(b)
y/λ
x/λ
$\hat{\boldsymbol{B}}\cdot(\boldsymbol{B}\cdot\nabla)\boldsymbol{v}/(B_0 k v_{\rm lin})$
0.6
0.4
0.2
0
−0.2
−0.4
−0.4
−0.2
0
0.2
0.4
80
60
40
20
0
−20
−40
−60
−80

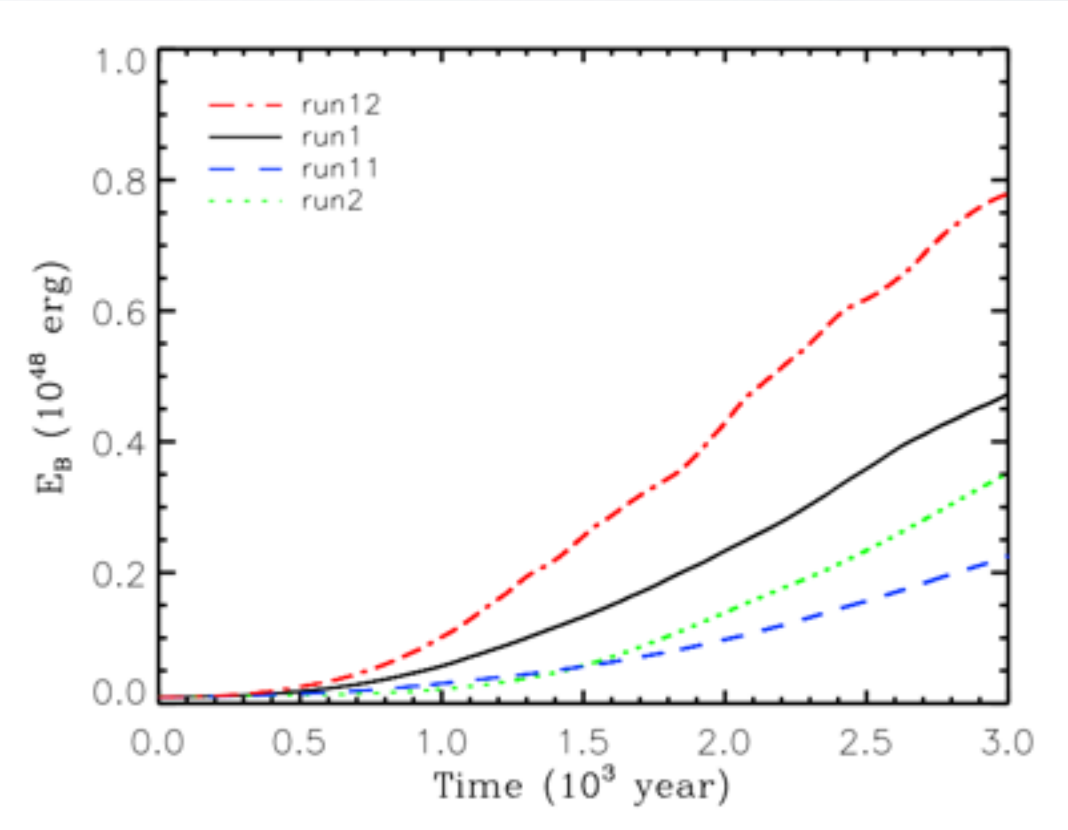


(c)
y/λ
x/λ
$-|\boldsymbol{B}|\nabla\cdot\boldsymbol{v}/(B_0 k v_{\rm lin})$
0.6
0.4
0.2
0
−0.2
−0.4
−0.4
−0.2
0
0.2
0.4
80
60
40
20
0
−20
−40
−60
−80

Sano+, 2012

MOTIVATIONS FOR NEW WORK

- **No simulation work on galaxy cluster/radio relic regime (weaker shocks, higher beta, etc)**
- **NONE of previous studies are numerically converged!** (most do not even carry out convergence tests)
- **We want to build and test a simple physical model** (can we constrain turbulence, gas clumping, B-fields at cluster outskirts?)



Guo et al 2012

MODEL SETUP

Piston driving a shock; inflow/outflow boundary conditions
Mostly 2D sims

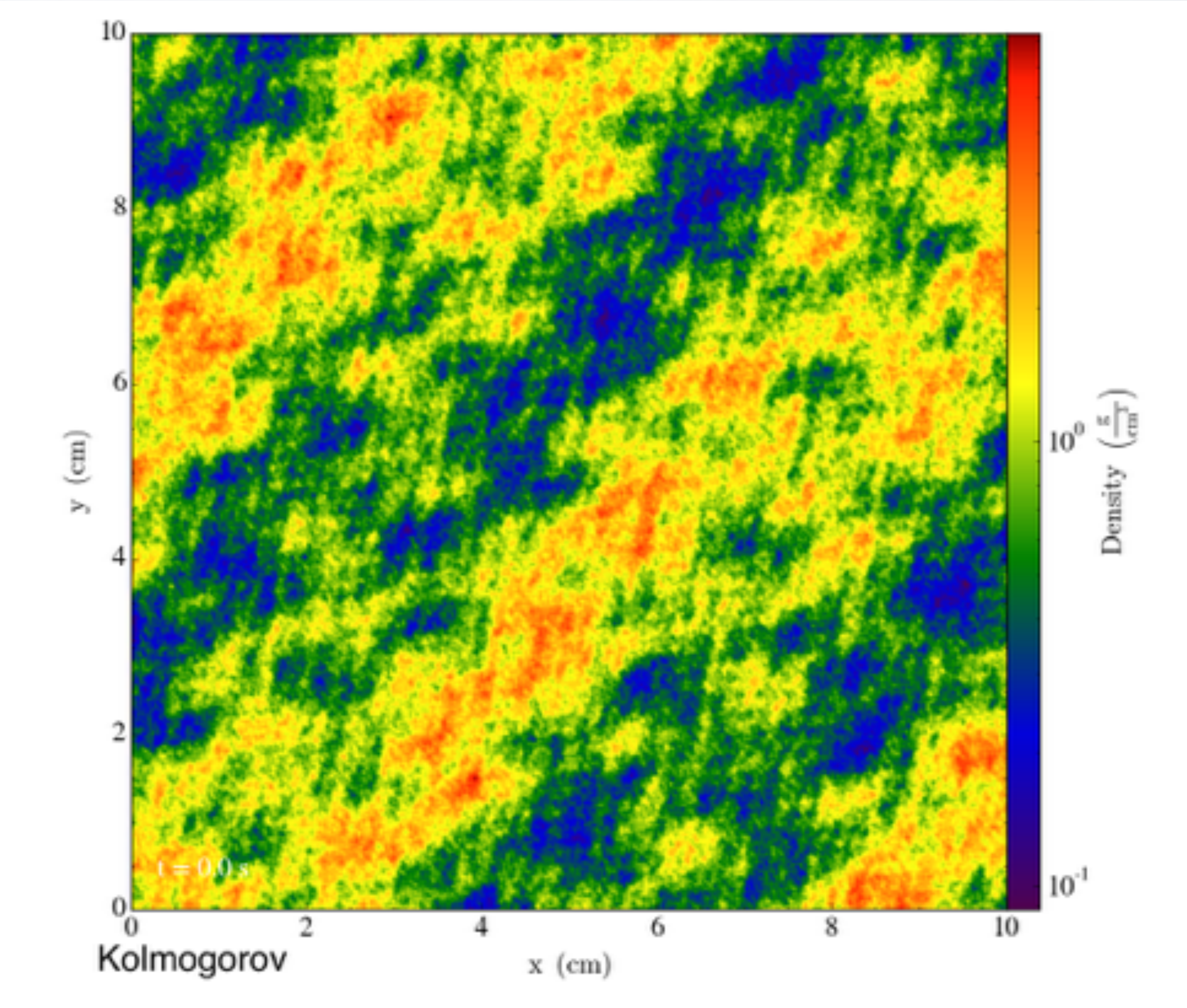
Lognormal density distribution

$$\rho(x, y) = \rho_0 \exp(f_0 + \delta f)$$

$$\delta f(x, y) = \sum_{n=1}^{N} \sqrt{2\pi k_n C \Delta k_n P(k_n)} \times \exp\left[i(k_n \cos\theta_n x + k_n \sin\theta_n y + \phi_n)\right]$$

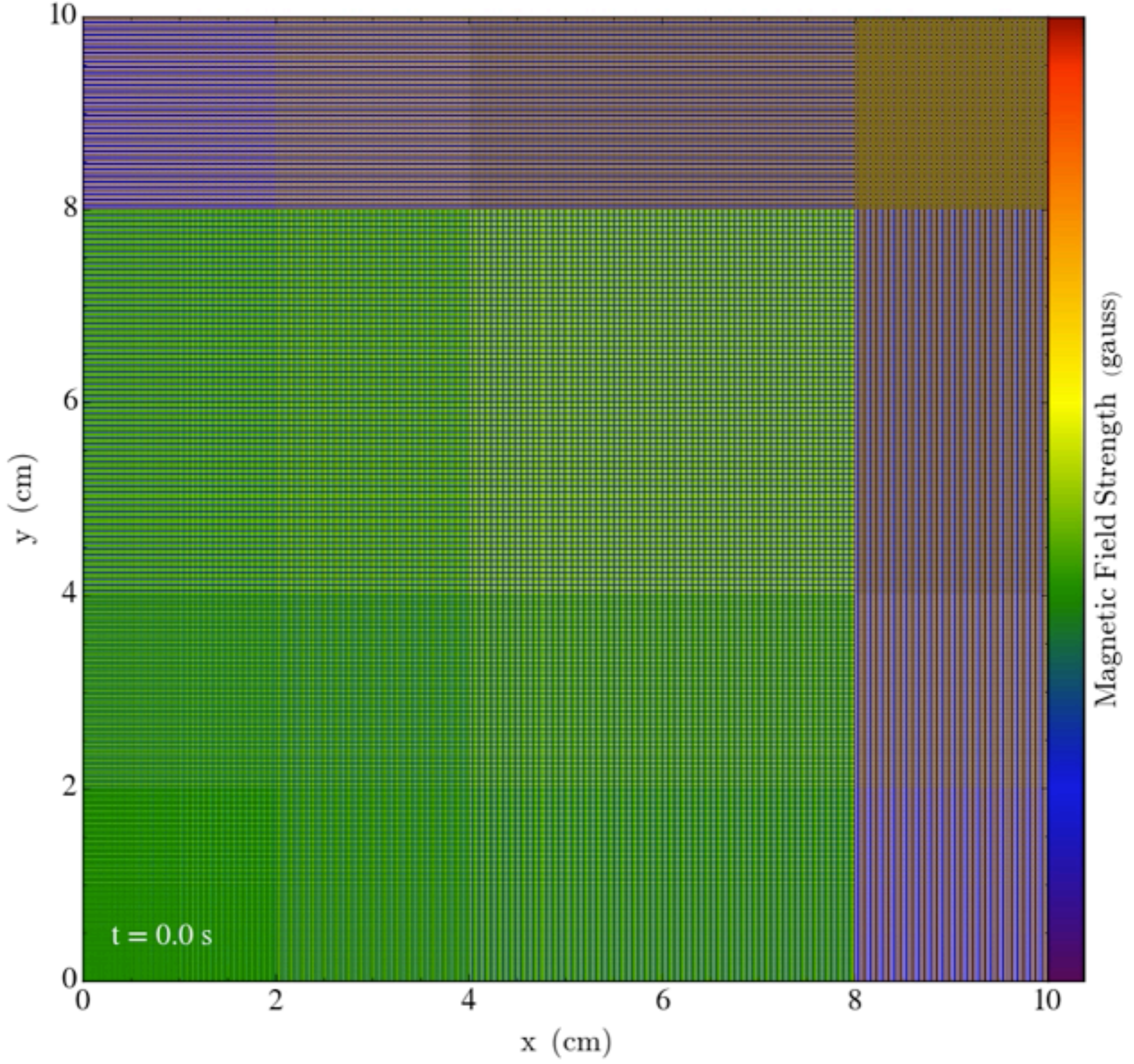
$$P(k) \propto \frac{1}{1 + (kL)^{8/3}}$$

$$\frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \sim 1 - 3$$



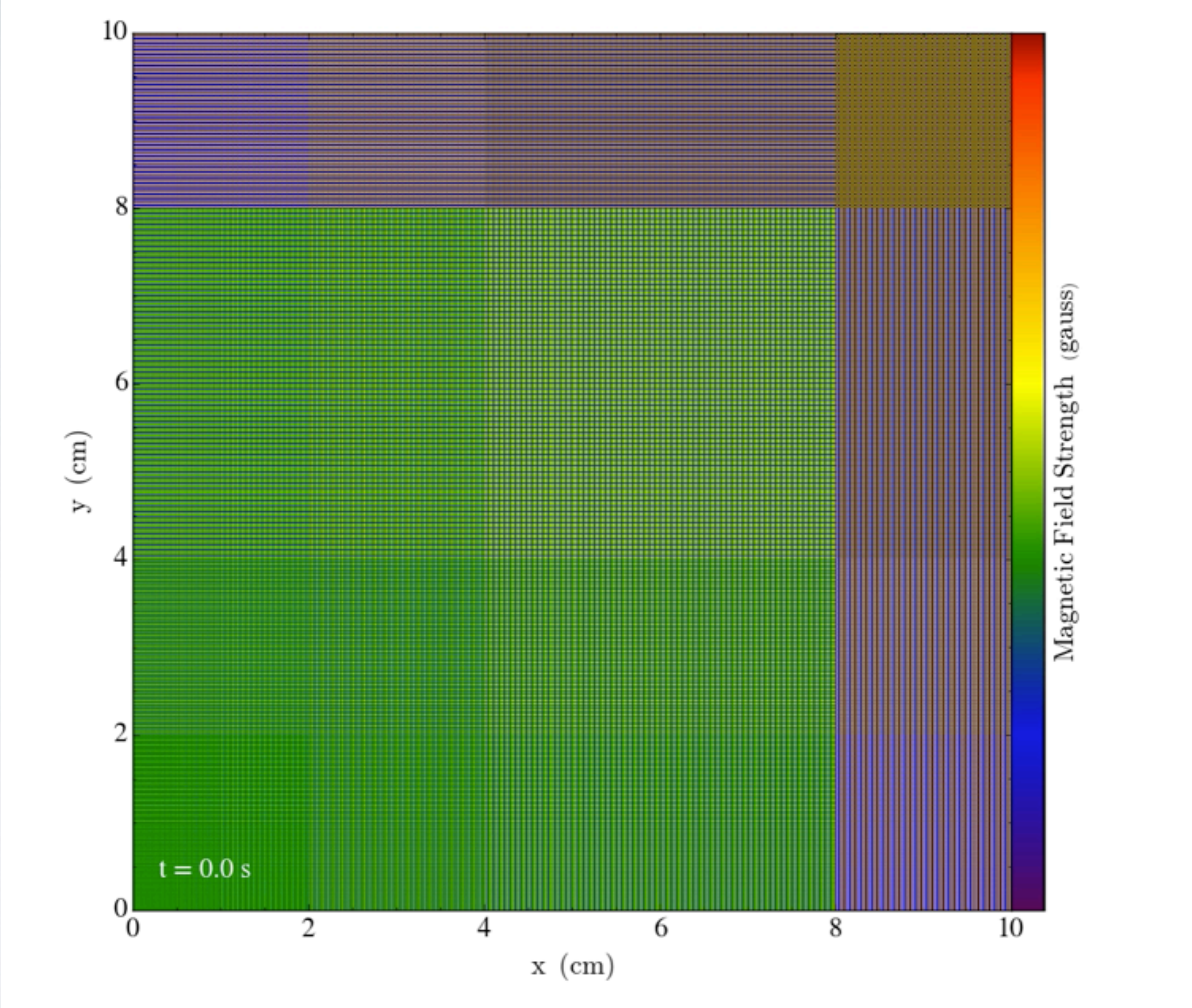
Canonical numbers for radio relic

Clumping Factor	Mach Number	Alfvénic Mach Number	Perturbation Length Scale
$C_X = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2}$ $\sim 1-3$	$\mathcal{M} = \frac{v_{\rm shock}}{c_s}$ ~ 3	$\mathcal{M}_\mathcal{A} = \frac{v_{\rm shock}}{v_{\rm Alfven}}$ ~ 20	inner scale~50 pc outer scale ~10 kpc



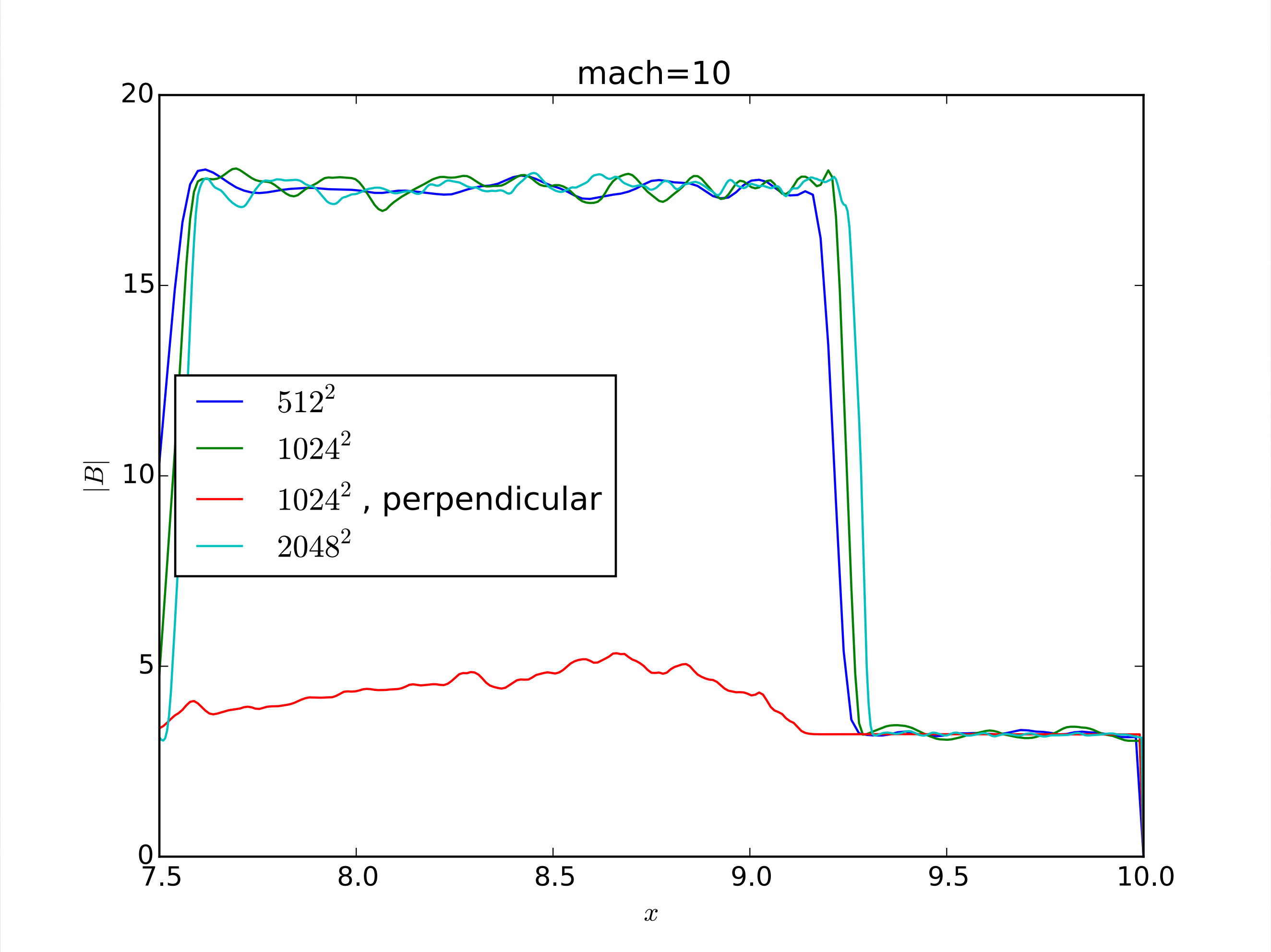
10
8
6
4
2
0
y (cm)
0
2
4
6
8
10
x (cm)
t = 0.0 s
Magnetic Field Strength (gauss)

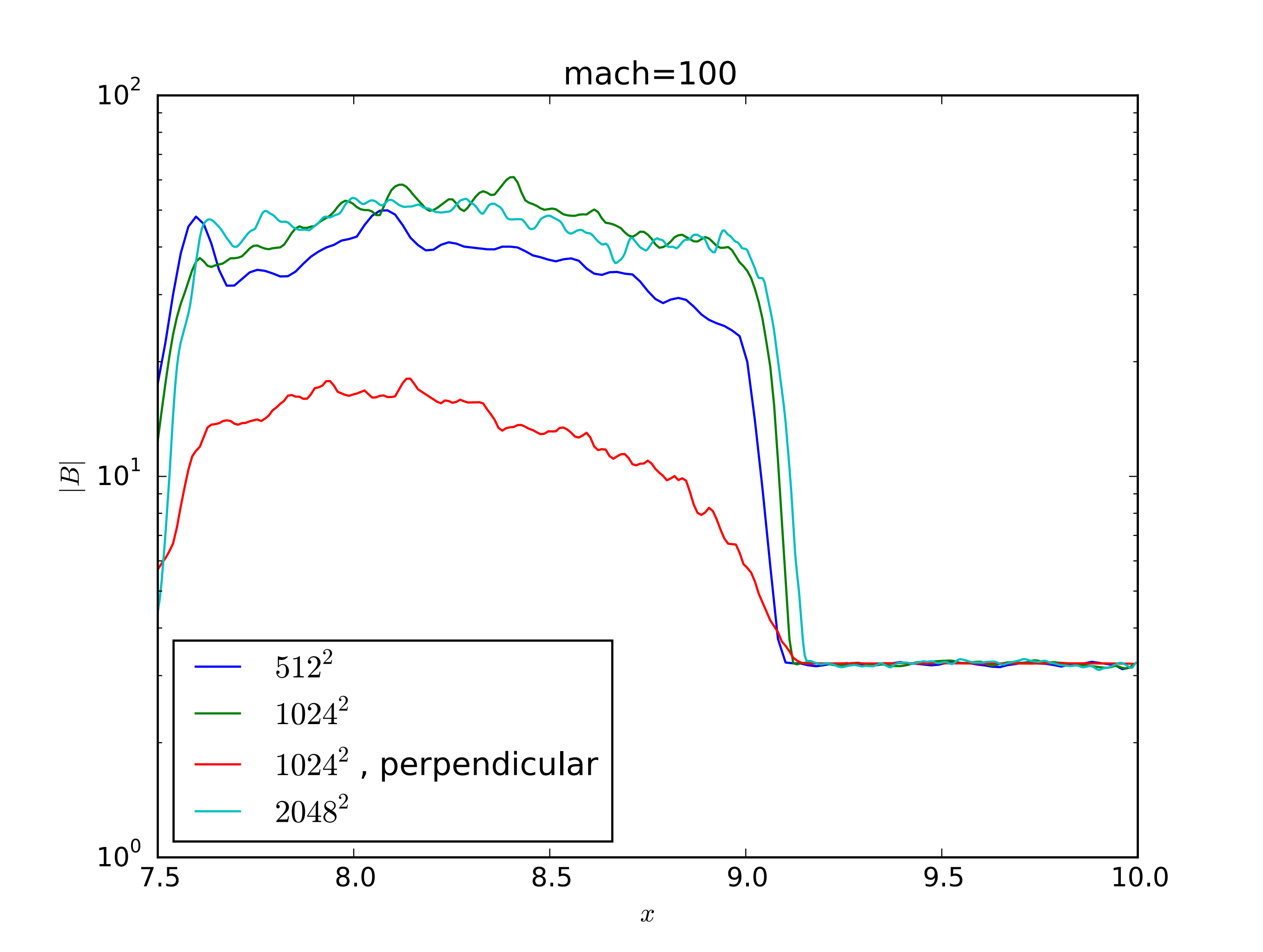
Mach 10



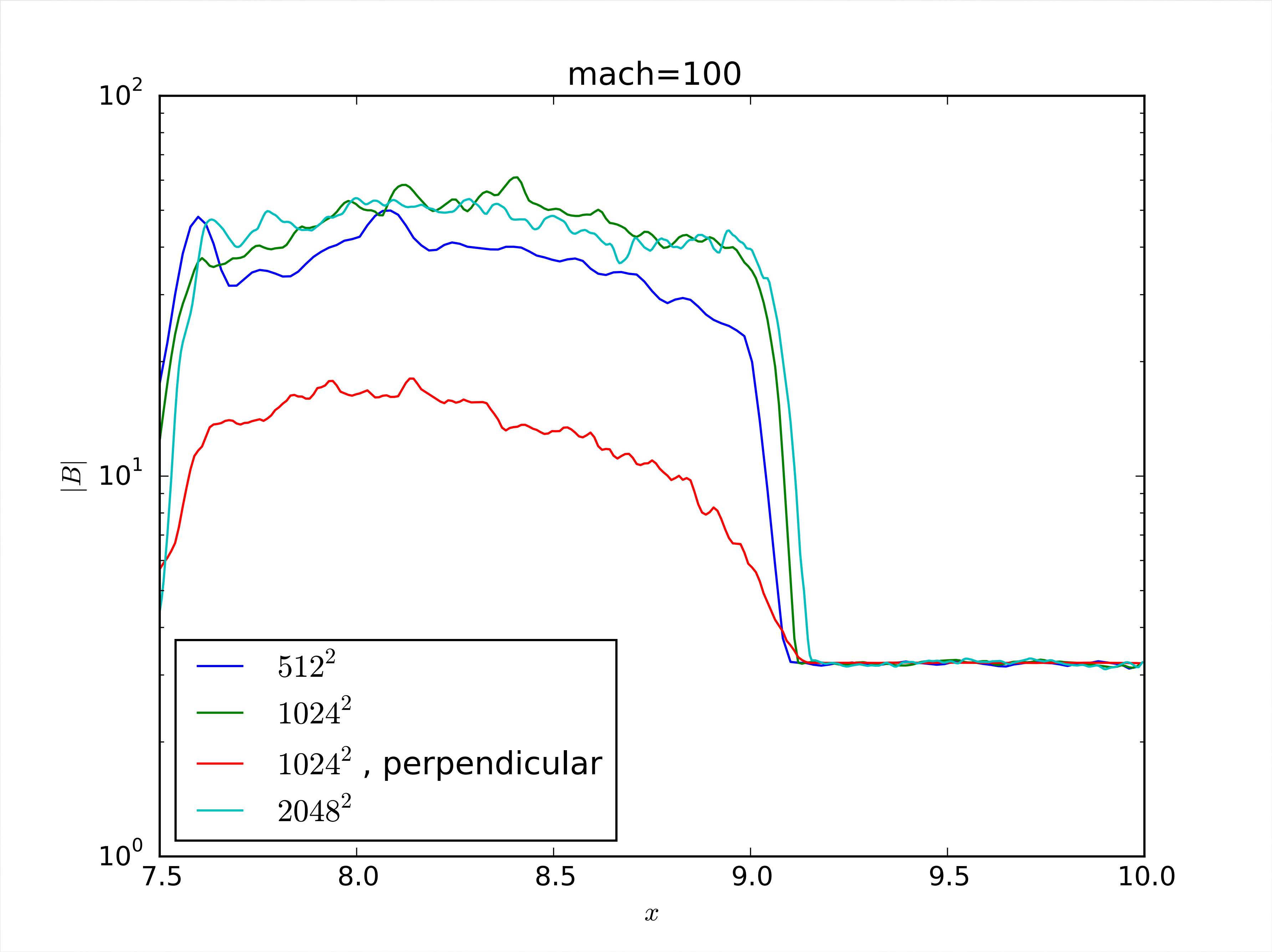
Mach 100

SIMS ARE CONVERGED UP TO M_A~100



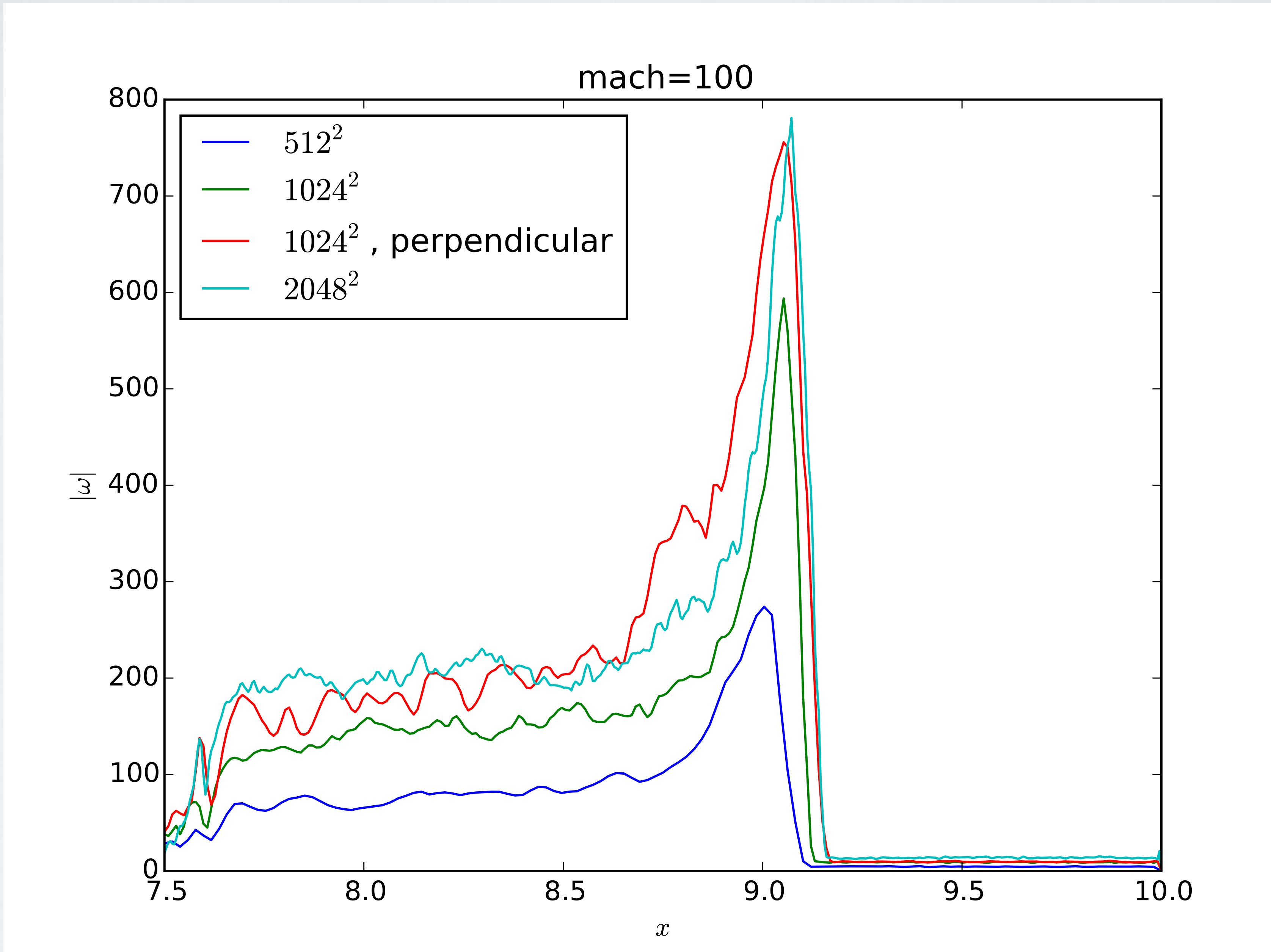


B-FIELD EXPONENTIALLY AMPLIFIES AND SATURATES



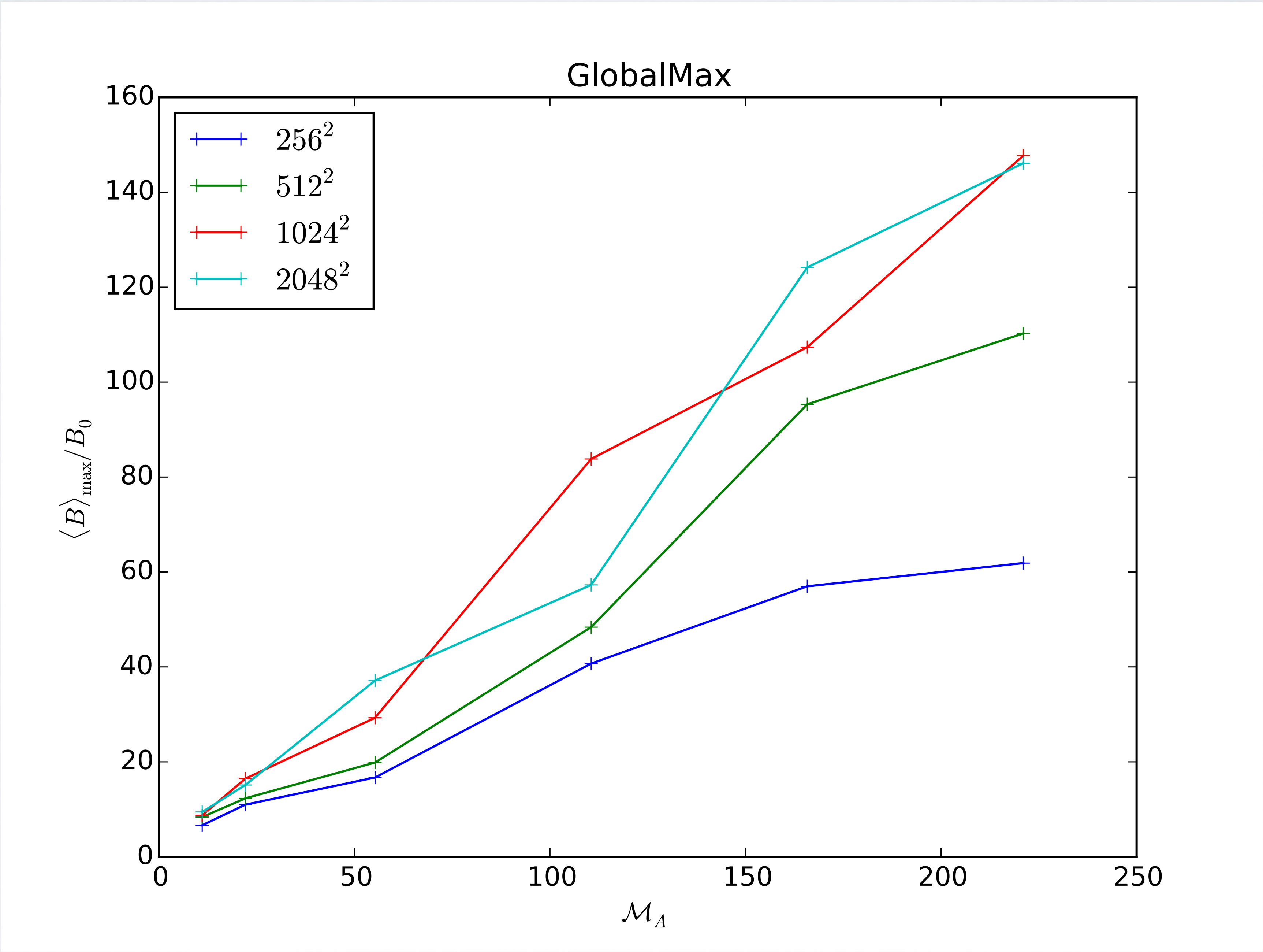
Grows on timescale of peak vorticity $t_{\rm grow} \sim \Omega_{\rm peak}^{-1} \sim L_{\rm min}/v_{\rm shock}$

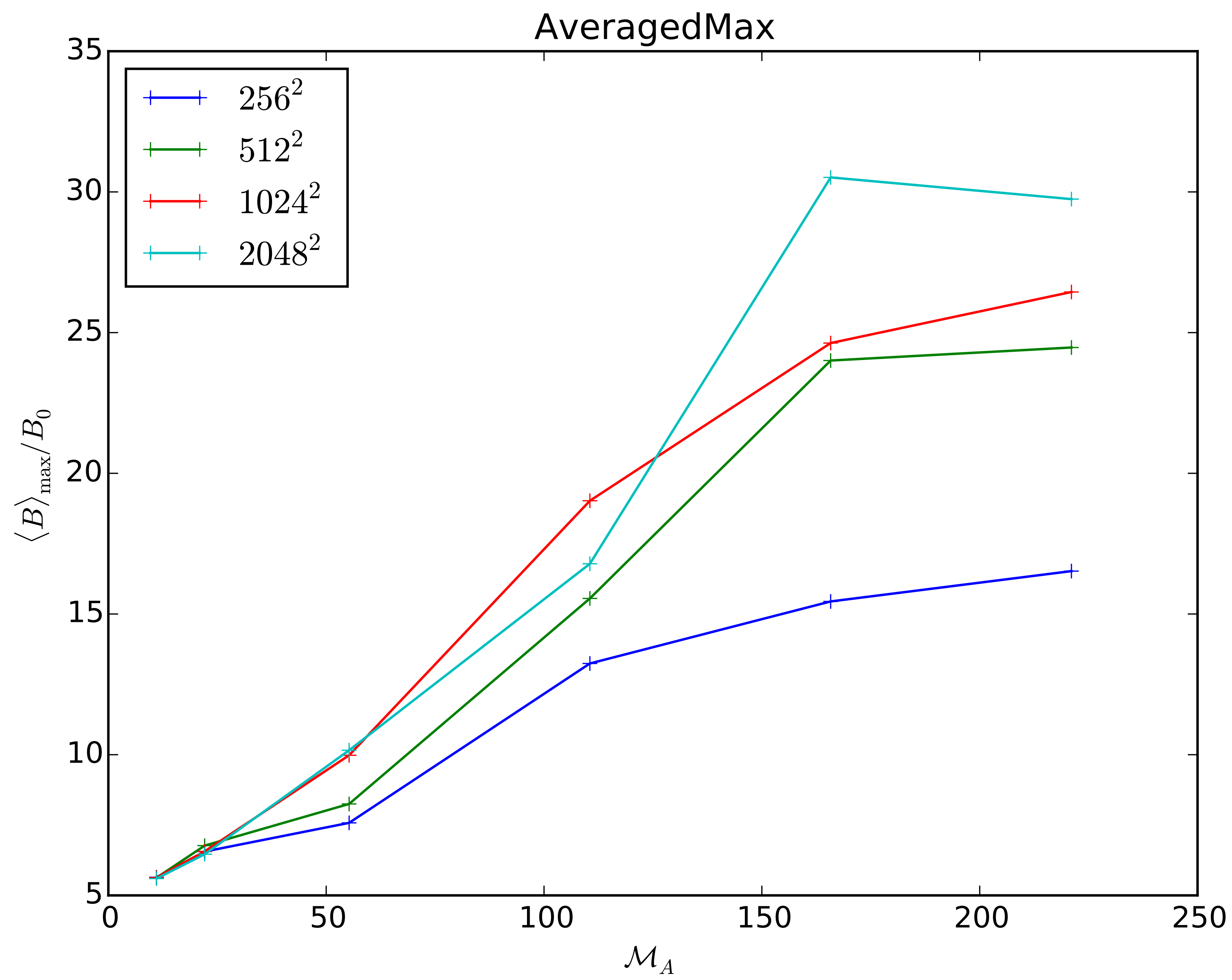
VORTICITY JUMPS SHARPLY AND DECAYS



Peak value $\Omega_{\text{peak}} \sim v_{\text{shock}} / L_{\min}$

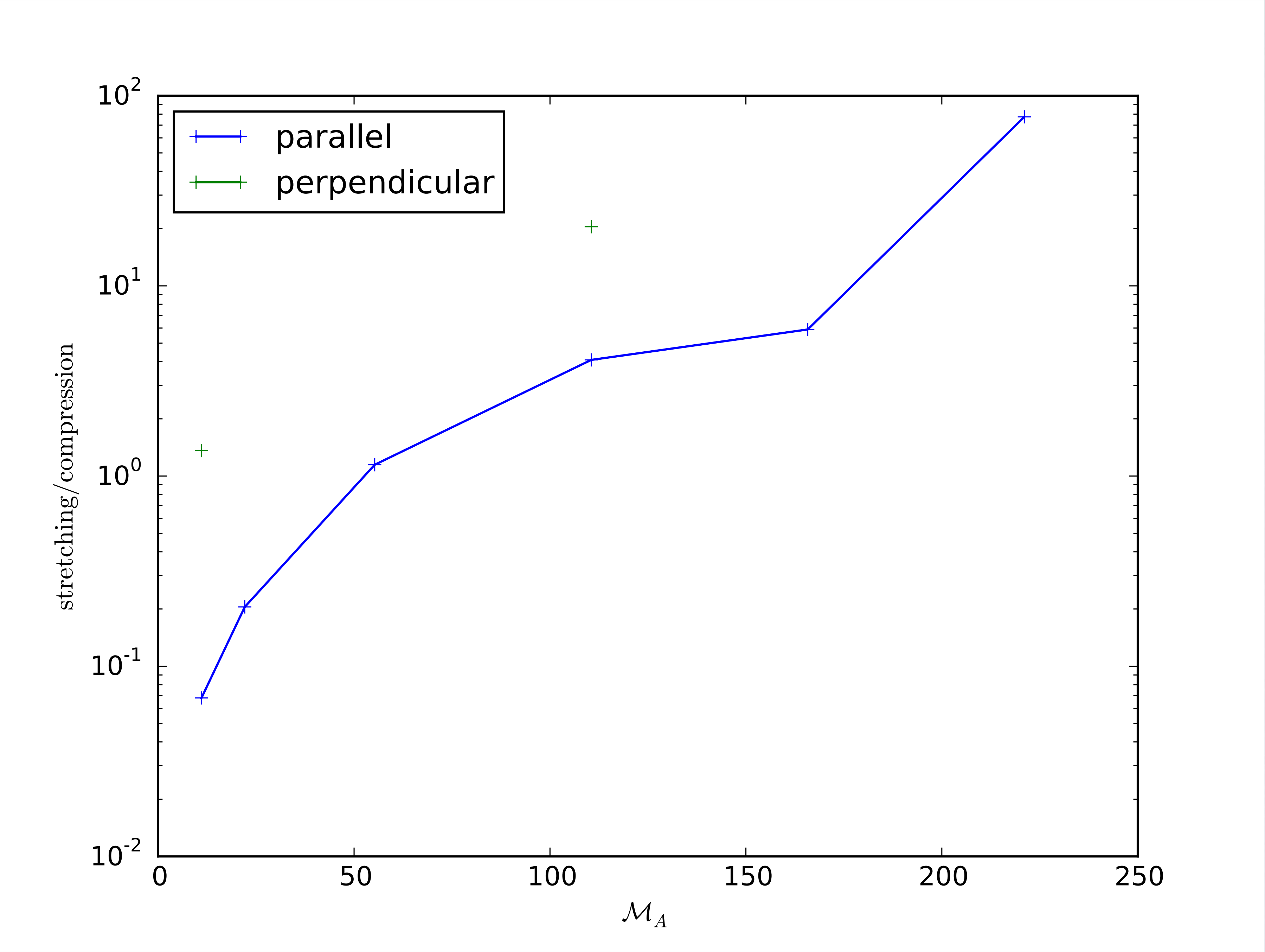
FIELD GROWTH SCALES WITH ALFVEN MACH NUMBER



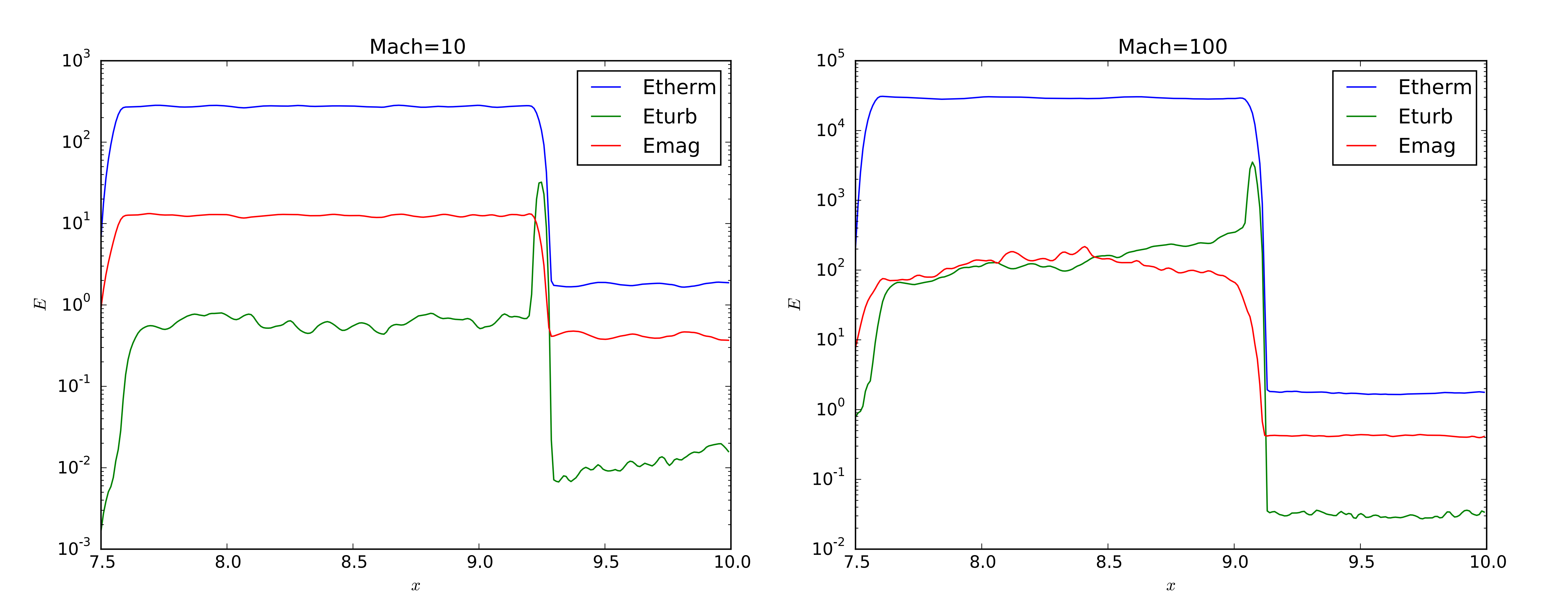


AveragedMax
256^2
512^2
1024^2
2048^2
$\langle B \rangle_{\rm max}/B_0$
$\mathcal{M}_A$
0
50
100
150
200
250
5
10
15
20
25
30
35

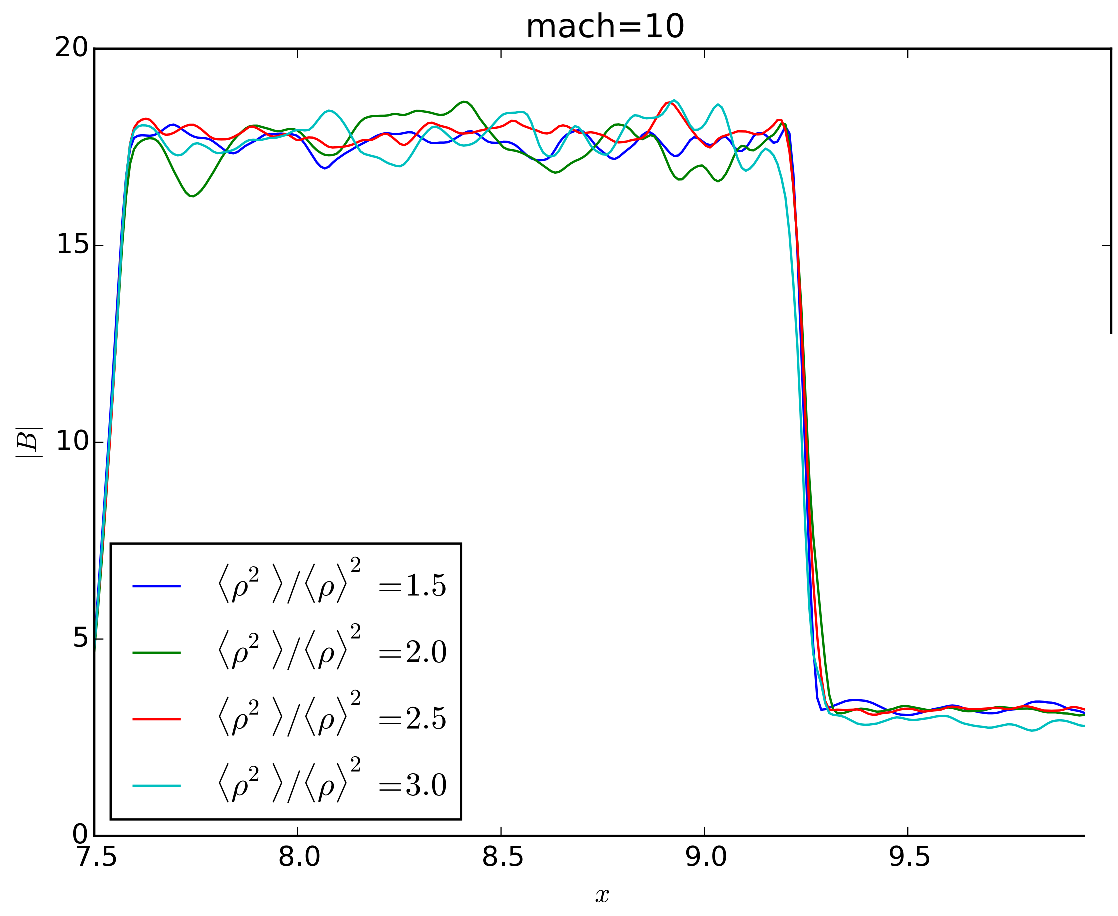
COMPRESSION DOMINATES AT LOW M, STRETCHING AT HIGH M

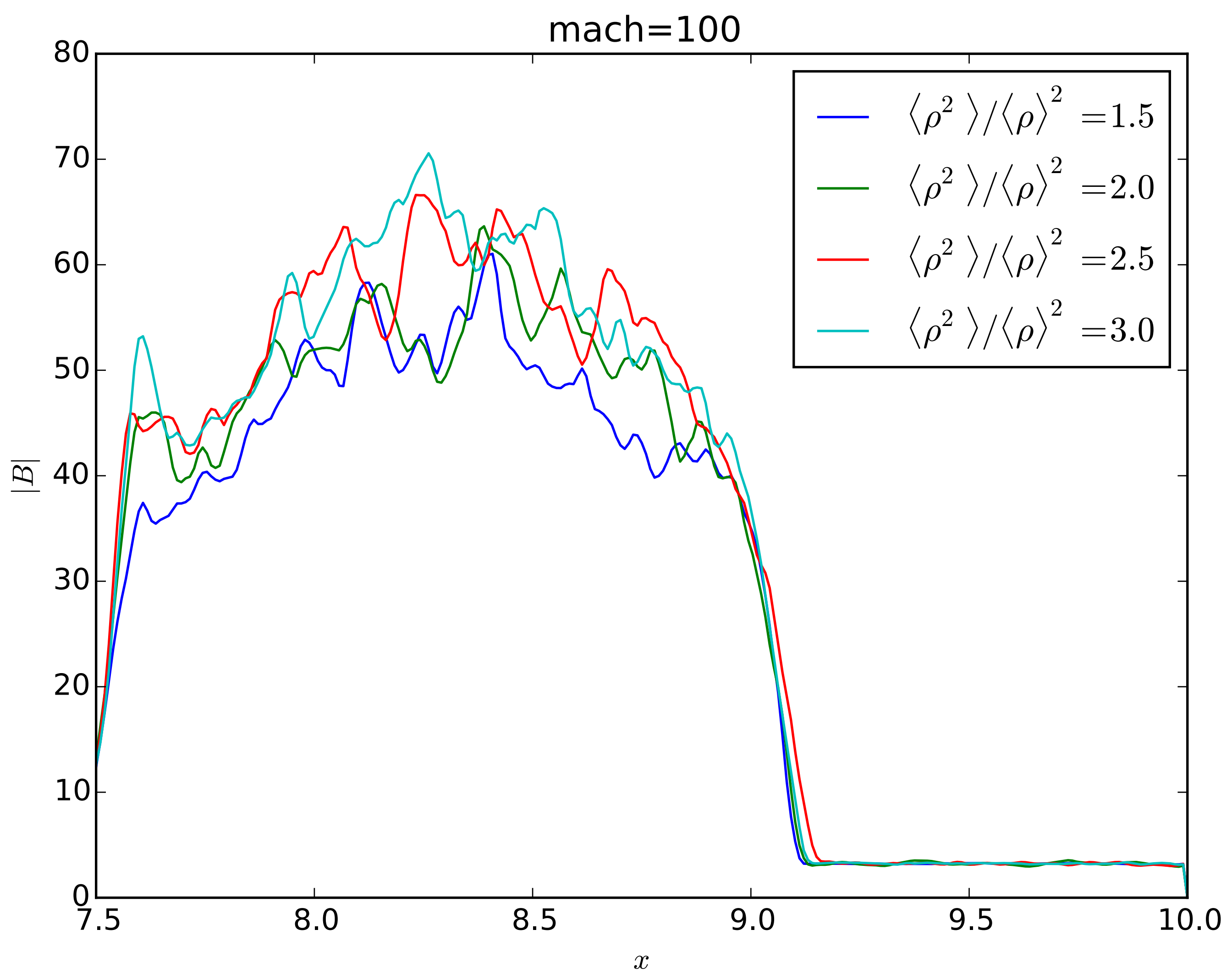


B-FIELDS REACH EQUIPARTITION WITH TURBULENCE AT HIGH MACH NUMBERS

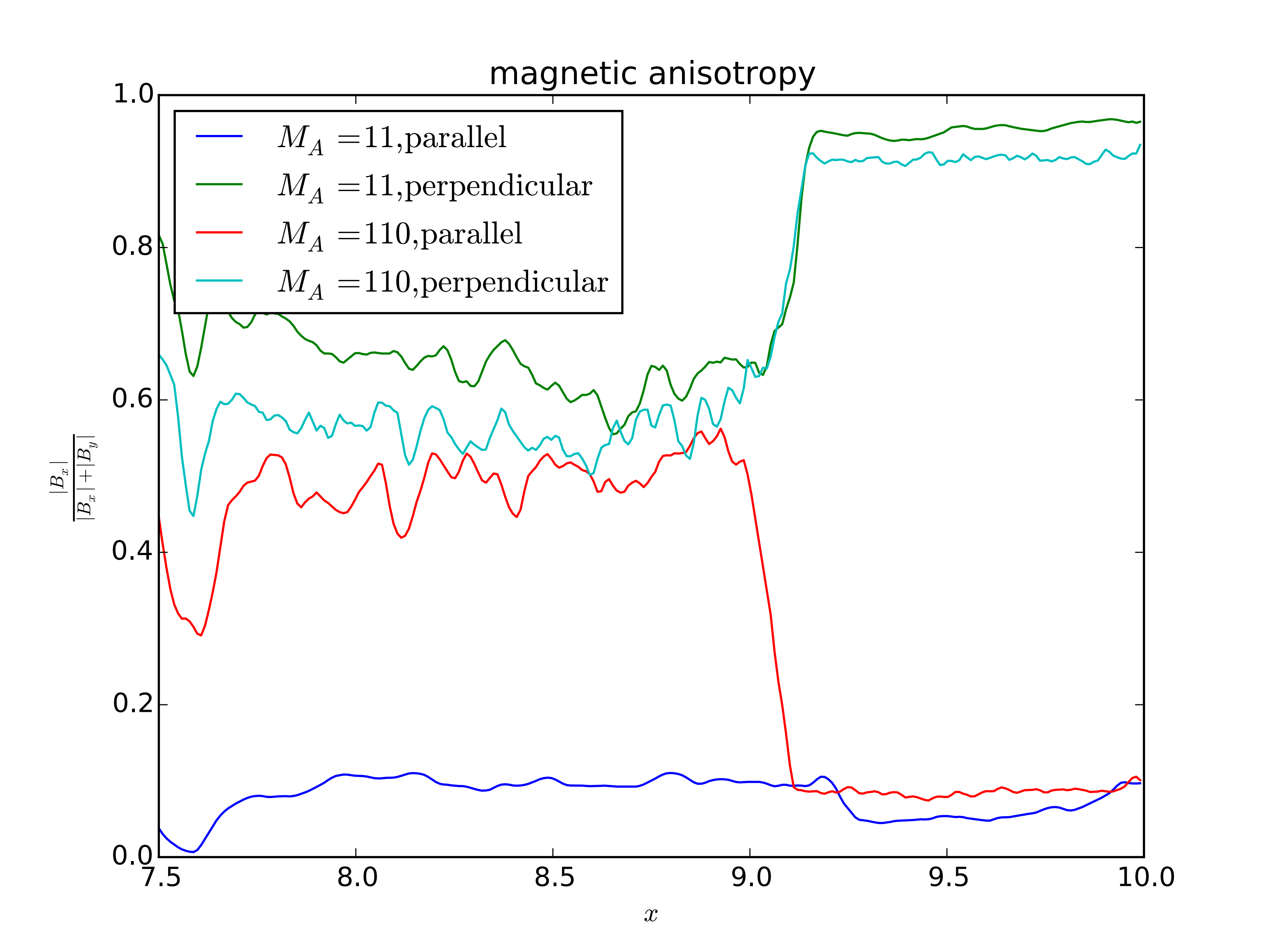


RESULTS FAIRLY INSENSITIVE TO CLUMPING FACTOR



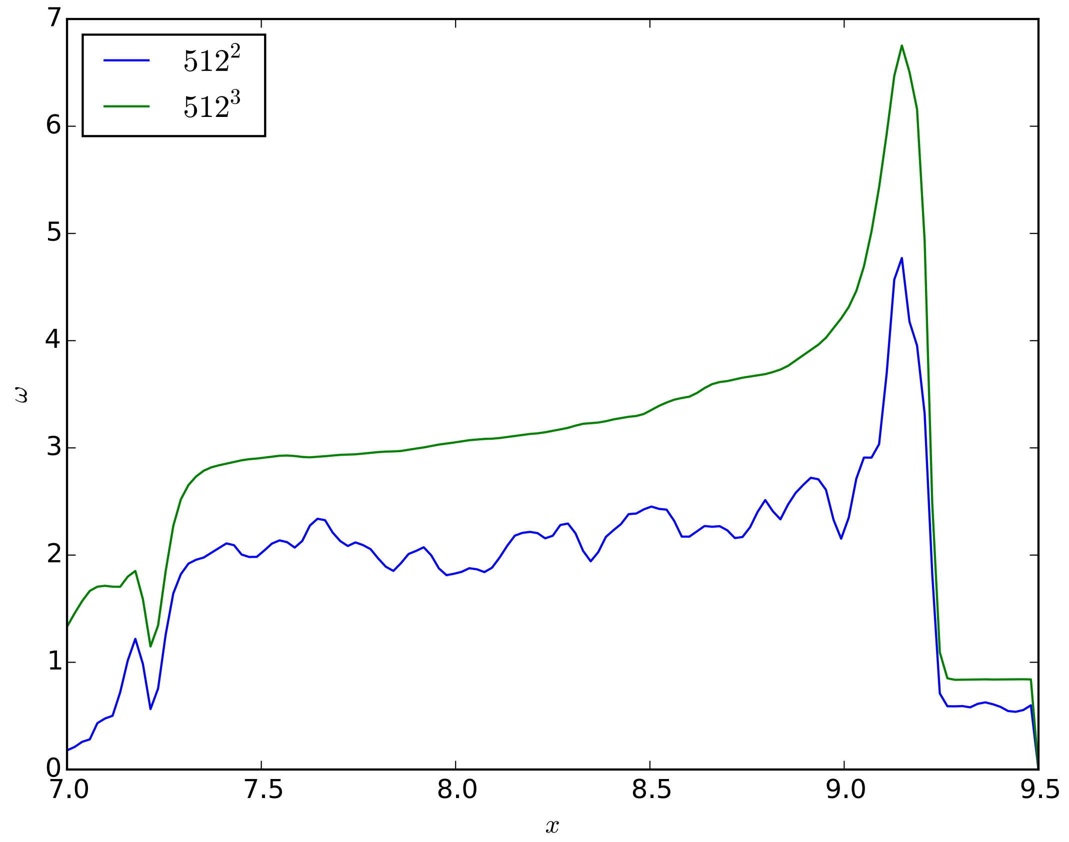


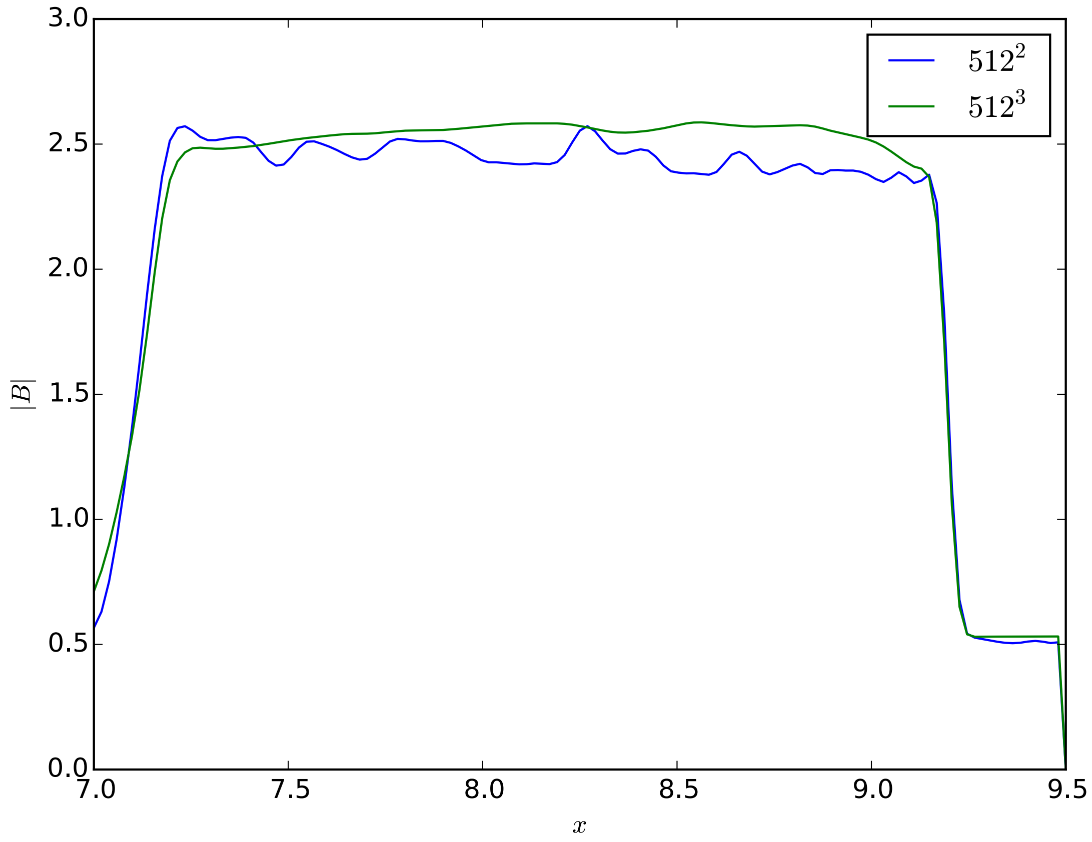
B-FIELDS TANGENTIAL TO SHOCK AT LOW MACH NUMBERS



Becomes isotropic at high Mach numbers

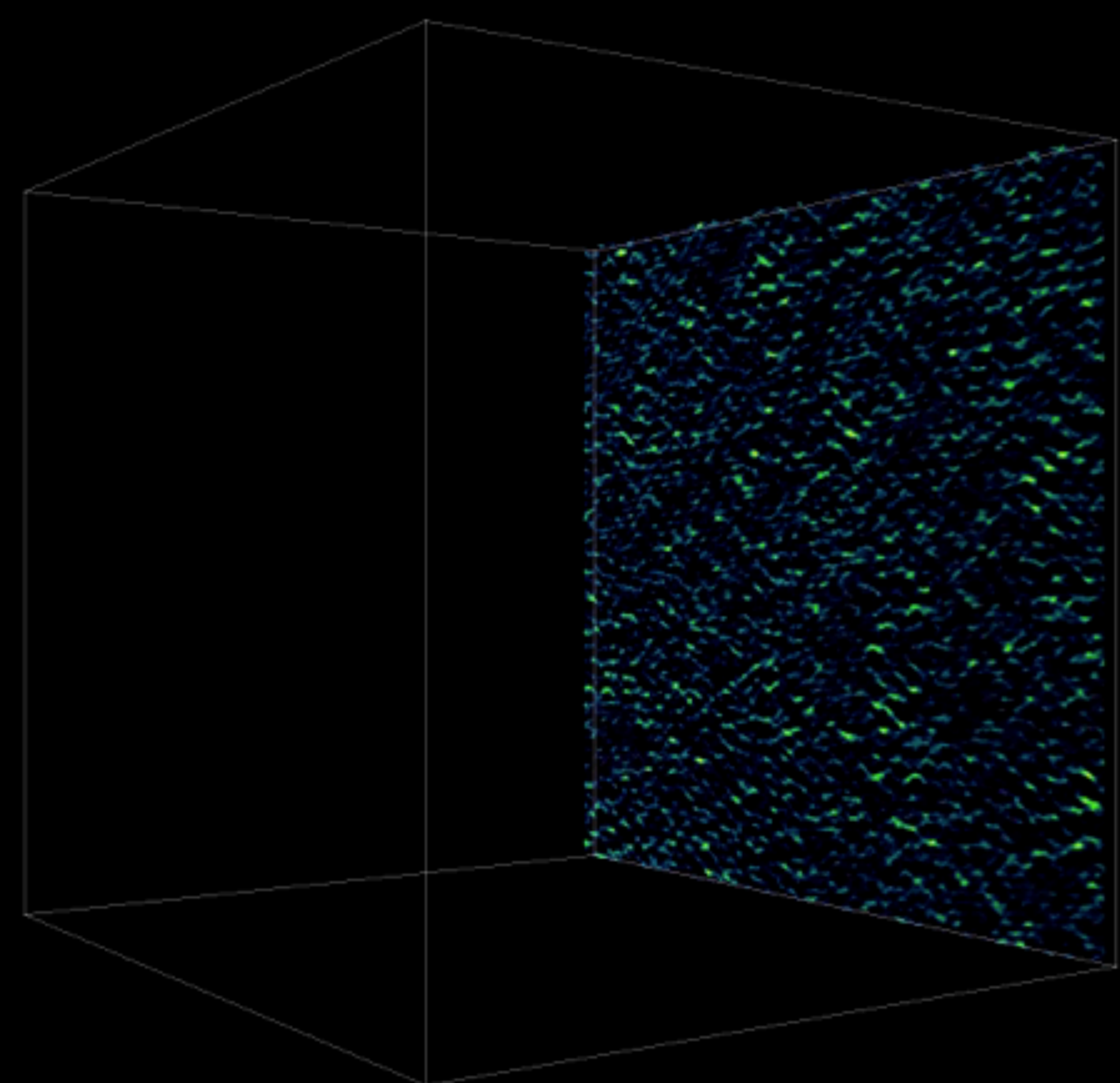
3-D vs. 2-D





* Magnetic fields in 2-D and 3-D converge

3-D Cluster Simulation



BOTTOM LINE

Turbulent dynamo is a nice candidate for supernova, maybe less so for low Mach number radio relics

Can't explain magnetic geometry — compression might be the simplest explanation