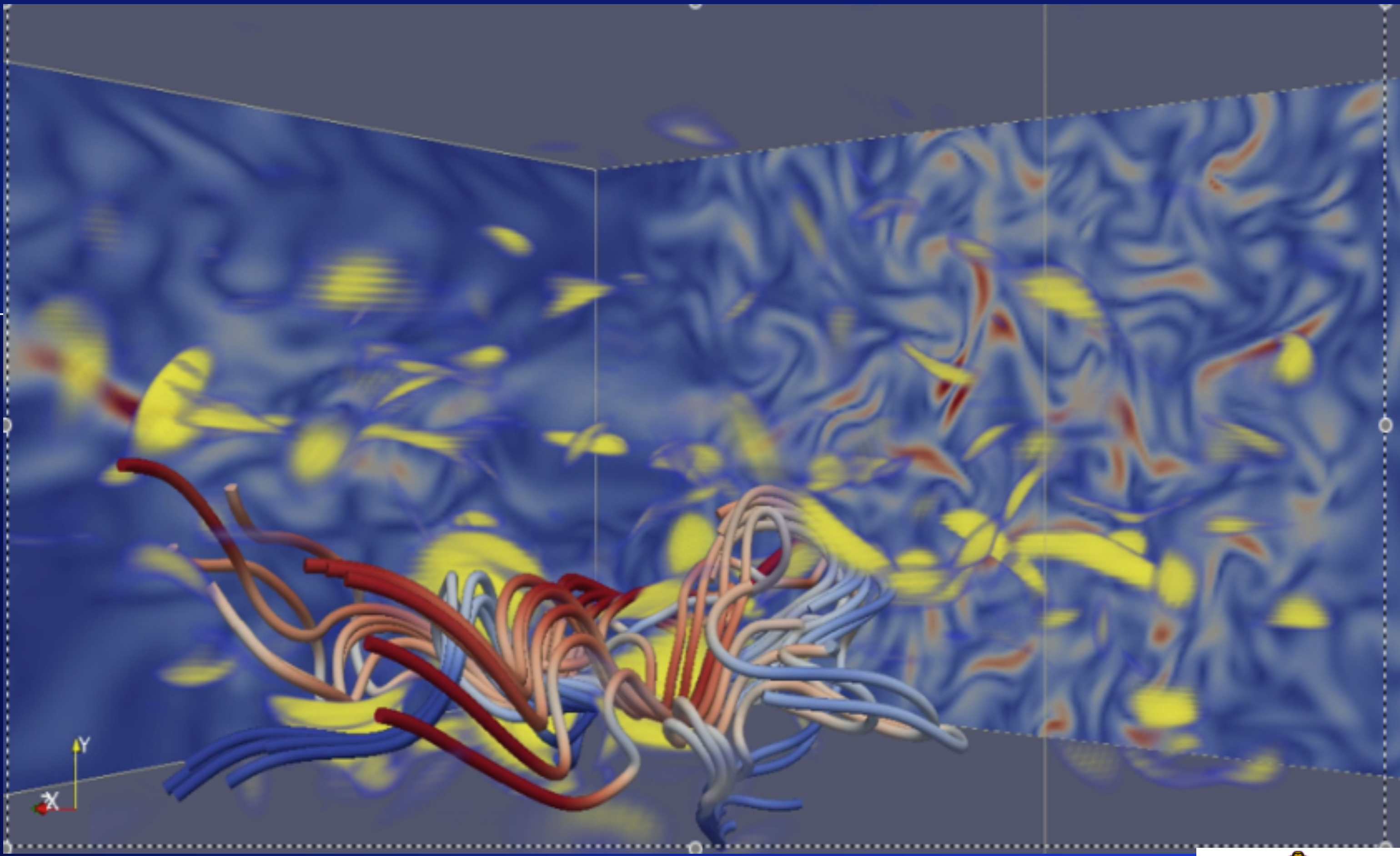
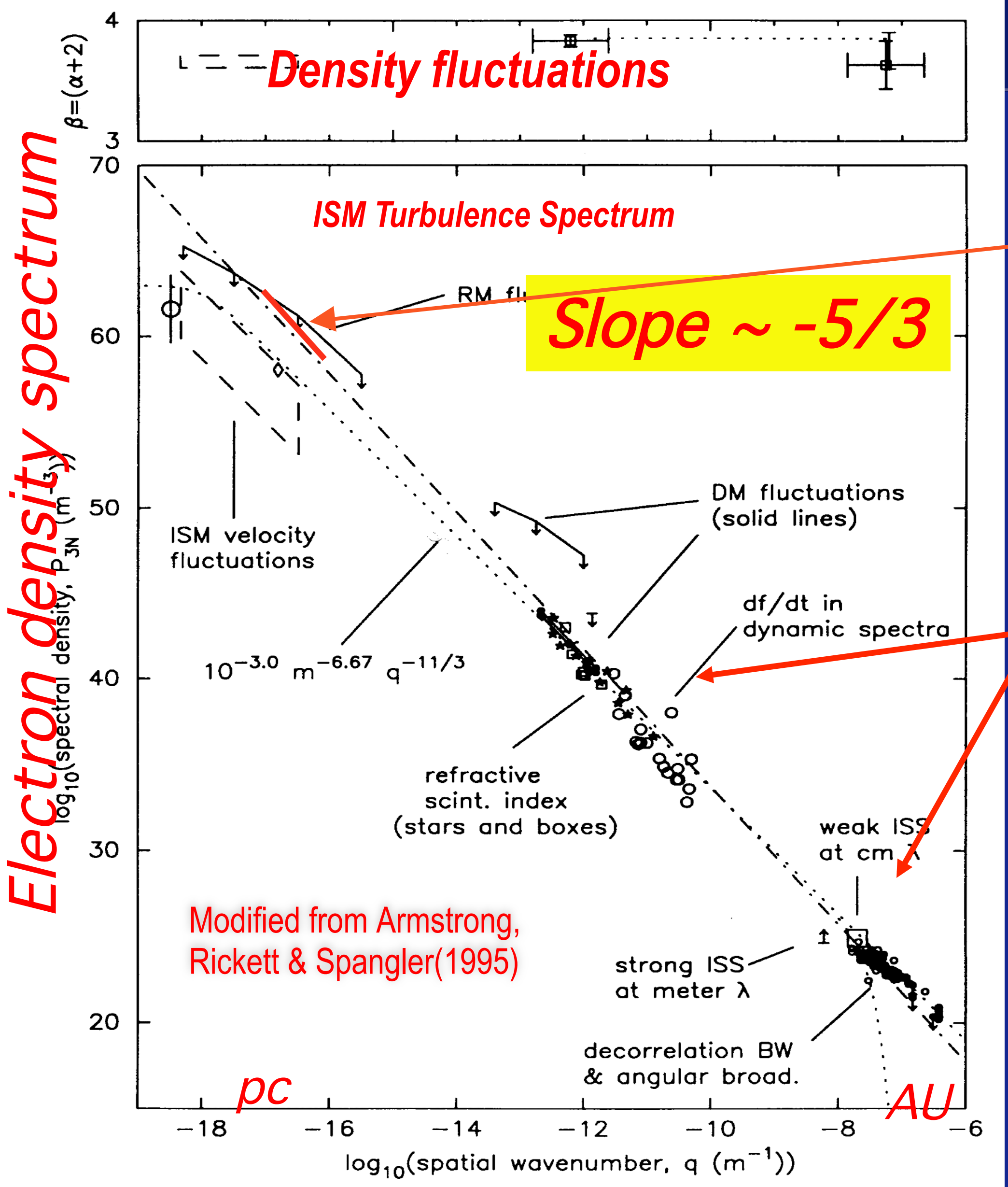
MHD Turbulence Theory and Selected Implications



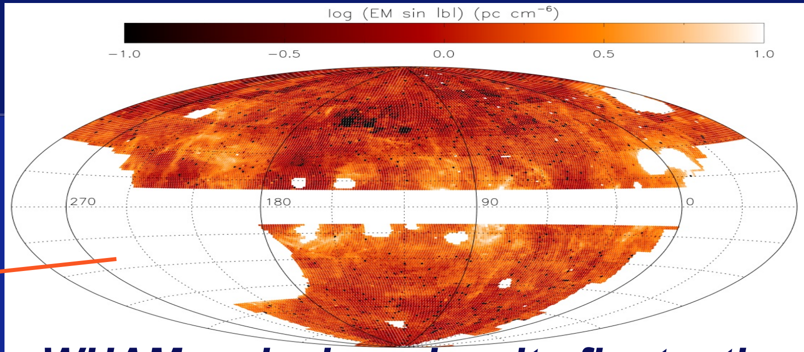
Alex Lazarian (Astronomy, Physics and CMSO)

Special Thanks to G. Eyink, G. Kowal, E. Vishniac

ISM reveals Kolmogorov spectrum of density fluctuations.



Modified from Armstrong, Rickett & Spangler(1995)



WHAM emission: density fluctuation

Chepurnov & Lazarian 2009

Scincillations and scattering

Density fluctuations also extreme scattering and absorption events which can be related to small ionized and neutral structures: SINS

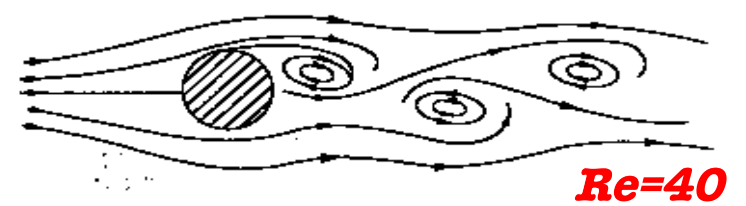
Turbulence is a chaotic order

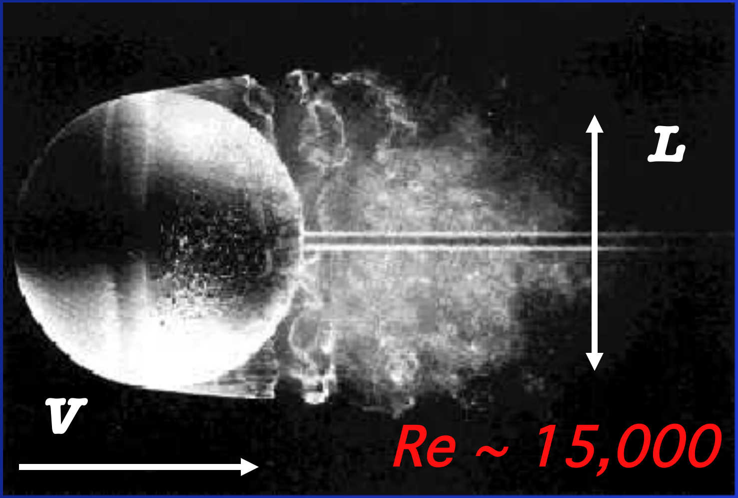
Turbulence = Σ

eddies

Flows get turbulent for large Reynolds numbers

$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$

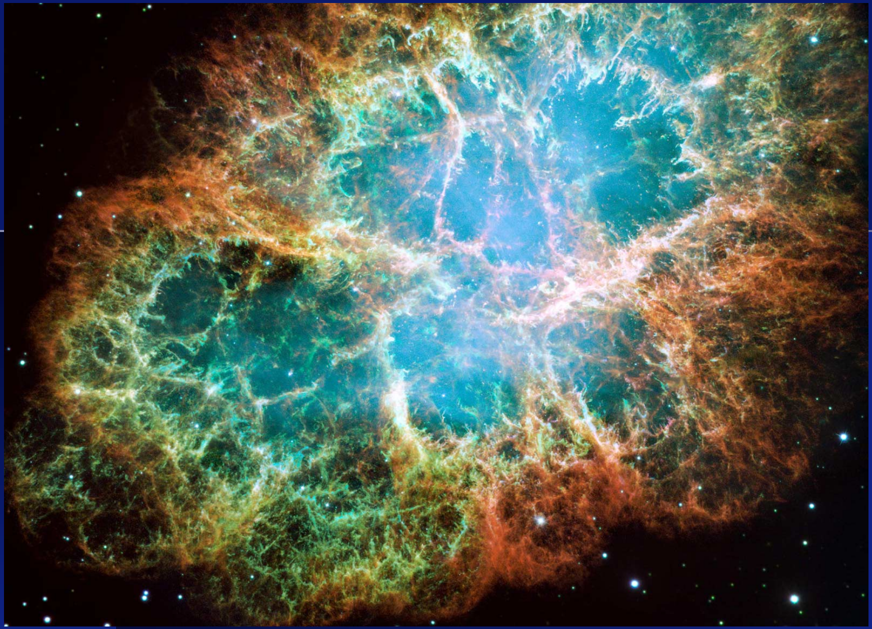




Point for numerical simulations: flows are similar for similar Re. Numerical Re<10^4, while Re of astro flows > 10^{10}

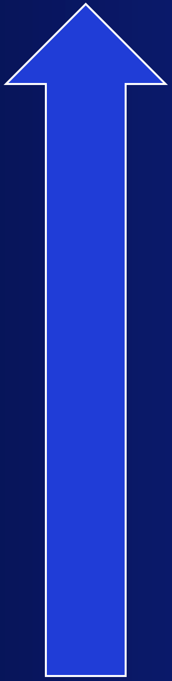
Astrophysical fluids are generically turbulent

$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$



Astrophysical flows have $Re > 10^{10}$.

The studies of reconnection extrapolate from low resolution numerical simulations to very different astrophysical regimes

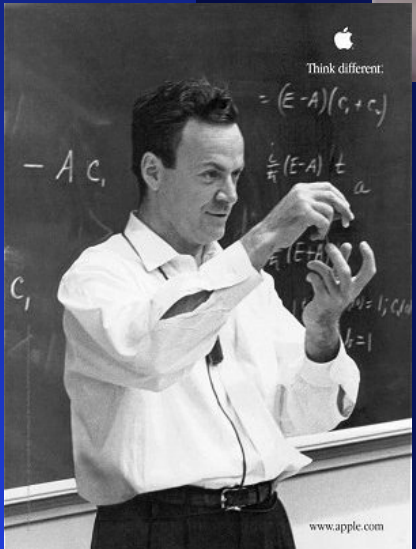


Real world

Numerical simulations

Turbulence is both dynamically and scientifically important

Due to turbulence DC-8 plane lost its engine



“Turbulence is the last great unsolved problem of classical physics”

R. Feynman

Main Points

Basic Properties of MHD turbulence
Turbulence and Reconnection
Reconnection Diffusion and Star Formation

Main Points

Basic F
Turbule
Reconn ation

Main Points

Basic Properties of MHD turbulence

Turbulence and Reconnection

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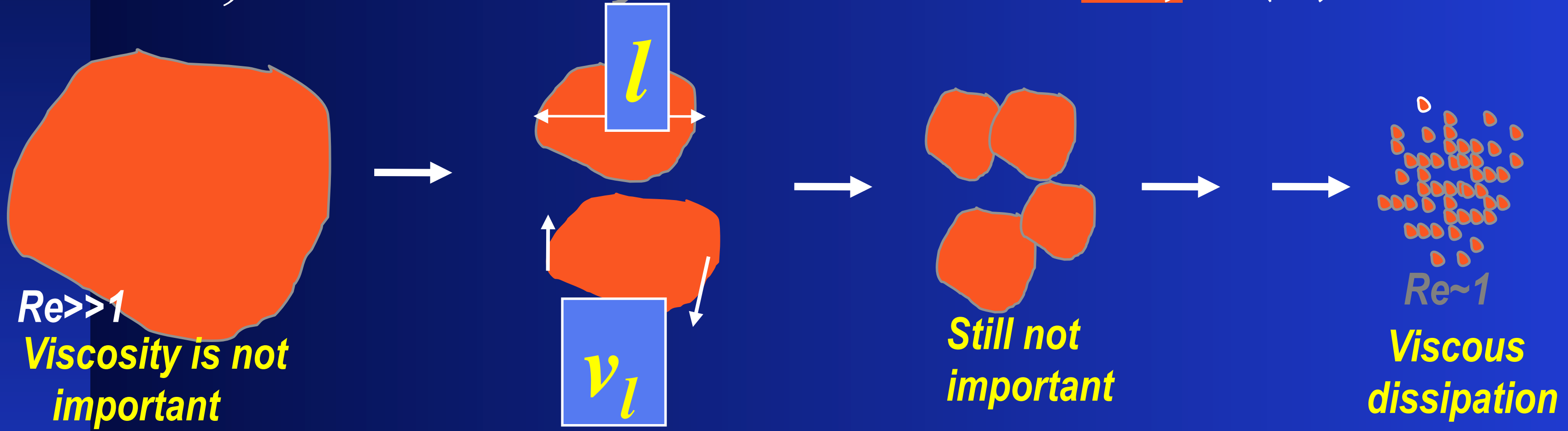
Kolmogorov theory reveals order in chaos for incompressible hydro turbulence

$$\left.\begin{array}{l} \dfrac{V_l^{2}}{t_{cas,l}} = const \\ t_{cas,l} = l/V_l \end{array}\right\} \quad \frac{V_l^{3}}{l} = const, V_l \sim l^{1/3}$$

Or, $E(k) \sim k^{-5/3}$

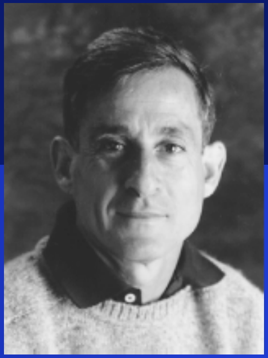


Viscosity is not important

Still not important

Viscous dissipation

Strong MHD turbulence is characterized by a "critical balance".



- Critical balance

$$\frac{l_\perp}{b_{\perp l}} = \frac{l_\parallel}{B_0}$$

- Constancy of energy cascade rate

$$\frac{b_{\perp l}^2}{t_{cas}} = const$$

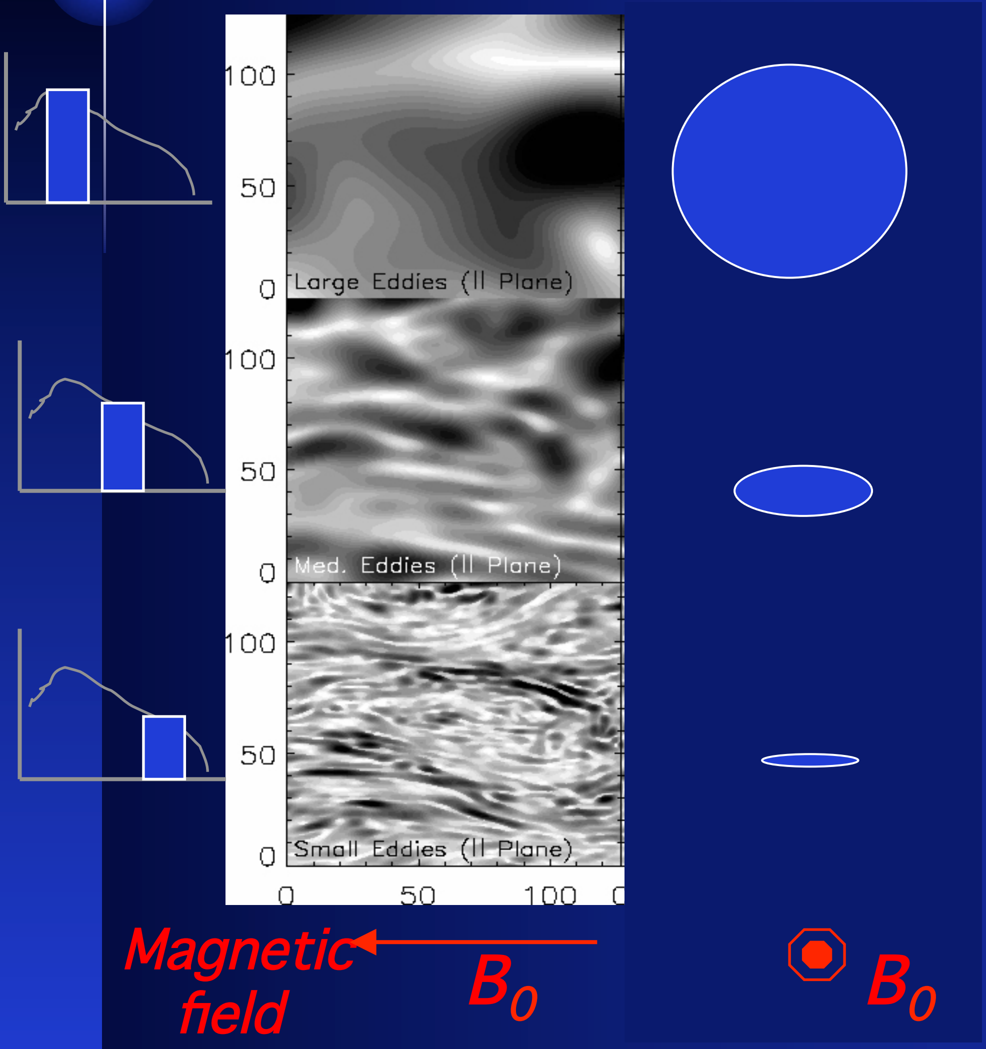
$$\frac{b_{\perp l}^2}{(l_\perp / b_{\perp l})} = const$$

$$\boxed{\begin{array}{c} b_\perp \sim l_\perp^{1/3} \\ \text{Or, } E(k) \sim k^{-5/3} \end{array}}$$

$$\boxed{l_\parallel \sim l_\perp^{2/3}}$$

Goldreich-Sridhar model (1995)

Alfvenic eddies get more and more elongated with the decrease of the scale



Cho, AL & Vishniac 2003

Arguments related to the nature of strong Alfvenic turbulence have faded away recently with GS winning

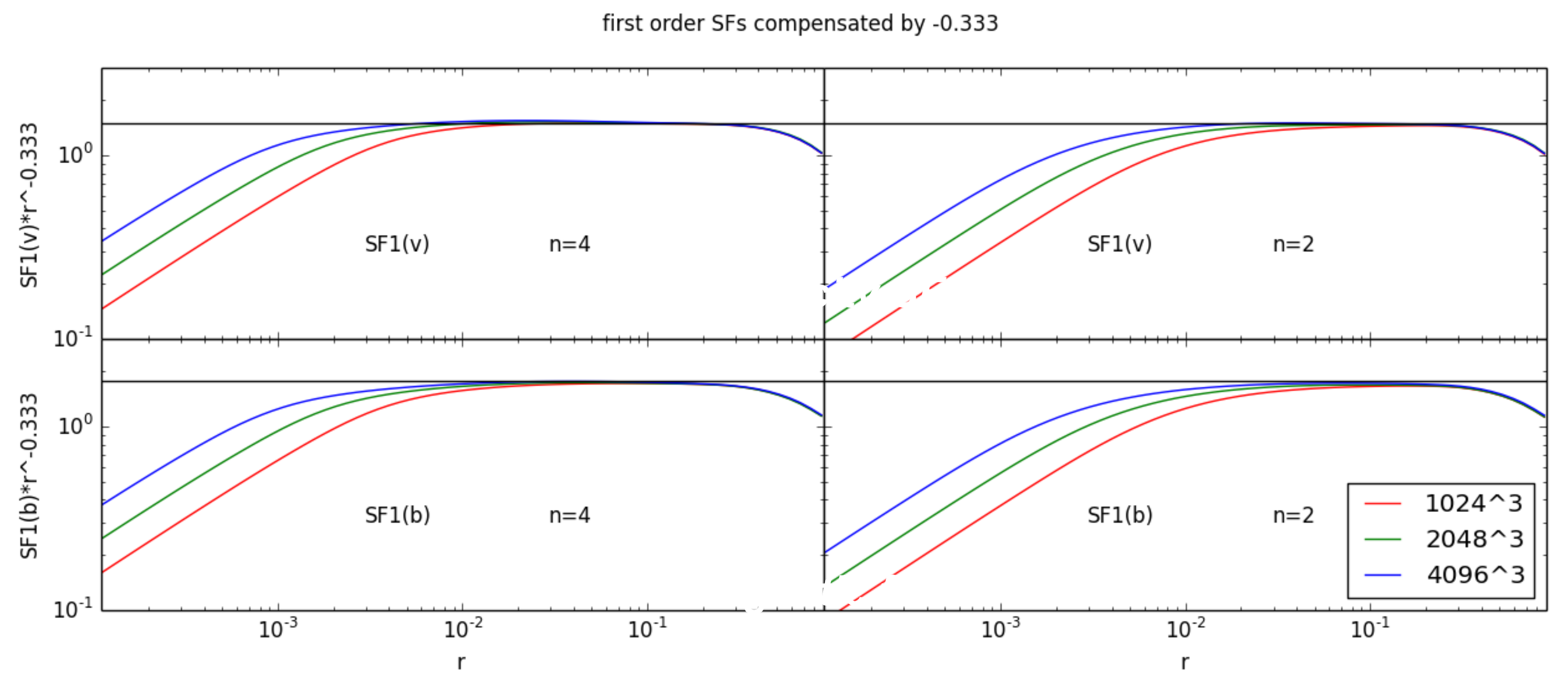
Additional effects related to dynamical alignment (Boldyrev 2005, 2006), polarization (Beresynak & AL 2006), non-locality (Gogoveridze 2007) could potentially change the nature of MHD turbulence

The highest resonance had Boldyrev's work that claimed k$^{-3/2}$ spectrum and $l_{\parallel} \sim l_{\perp}^{1/2}$

However, MHD turbulence is "diffusively local" (Beresnyak & AL) and therefore a larger extend of the bottleneck is expected. Thus the k$^{-3/2}$ is an artifact of the bottleneck and not the real slope.

First order structure functions

Demonstrates $r^{1/3}$ scaling

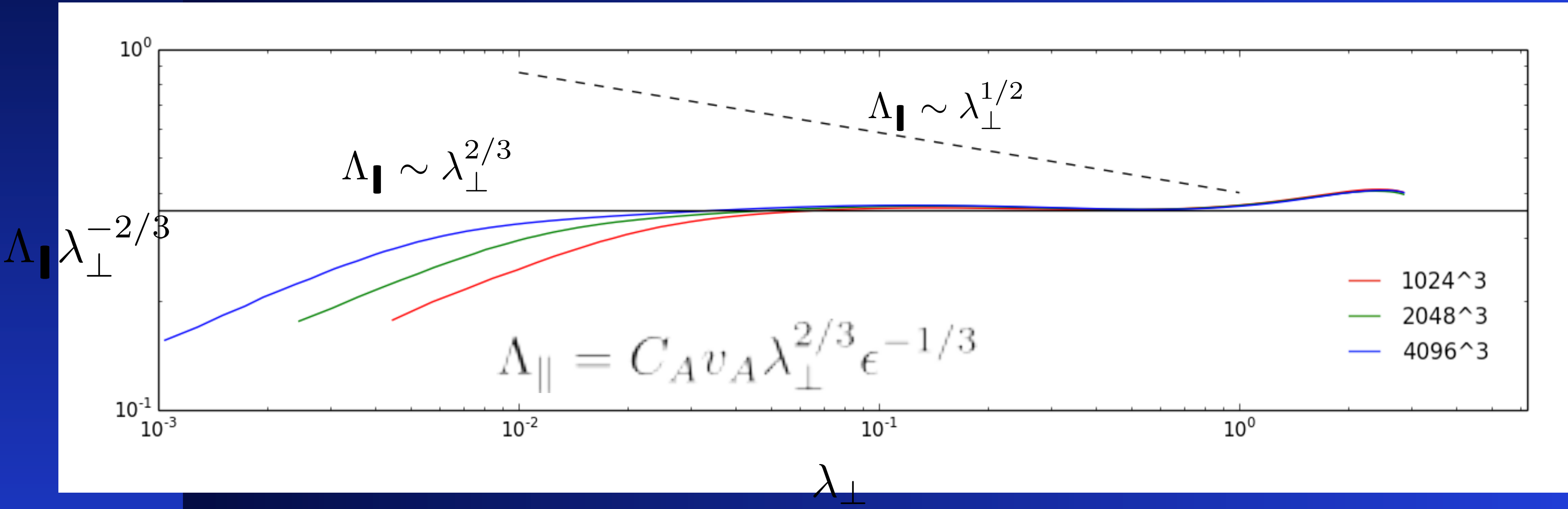


$1024^3, 2048^3, 4096^3$ ***simulations***

Anisotropy in SF

GS95:

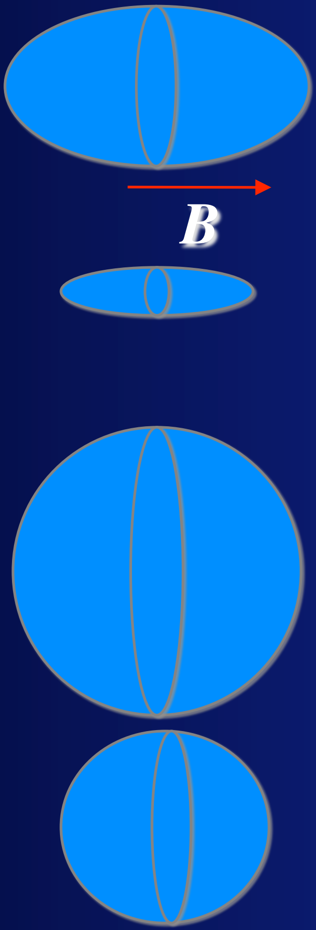
Boldyrev $l_{\|} \sim l_{\perp}^{1/2}$ ***(incompatible with the measurement)***



Credit: Francesca Grifo

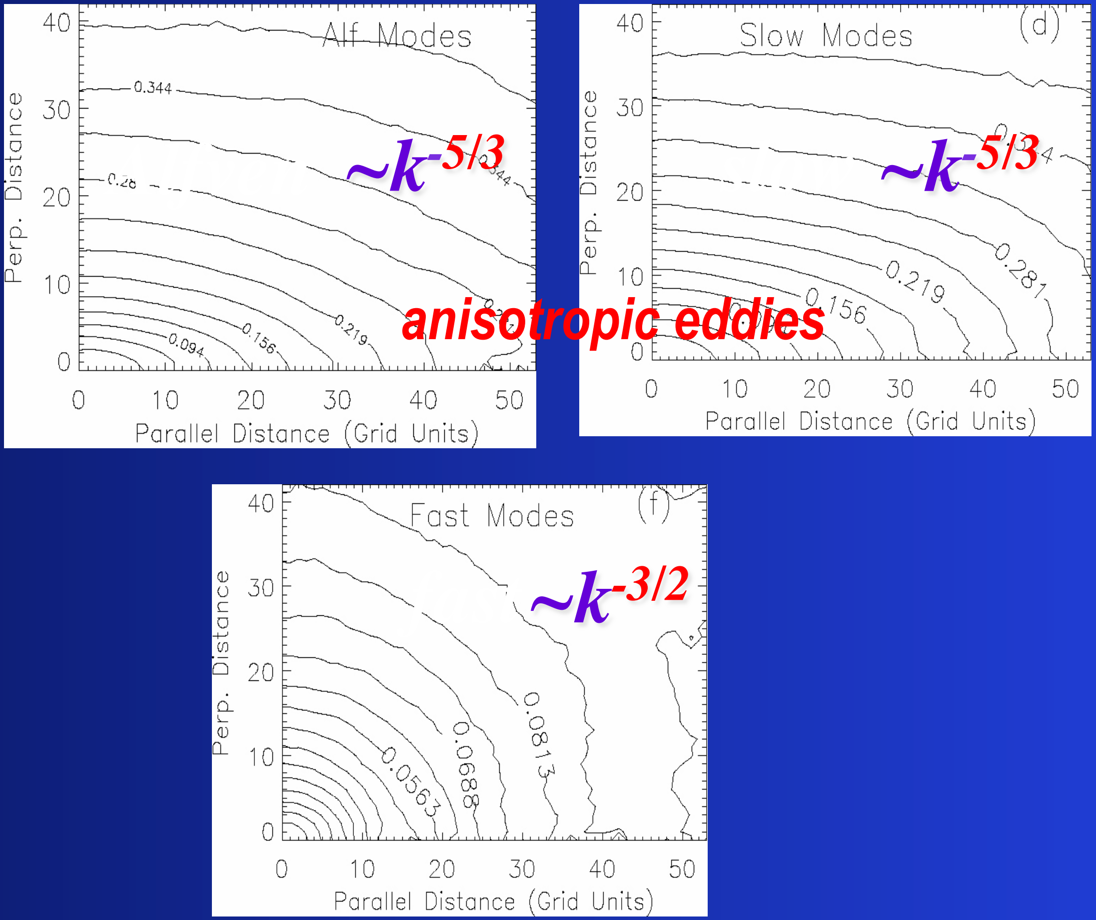
Tested model of MHD turbulence demonstarte anisotropy for Alfvenic and slow modes and isotropy for fast modes

Alfven and slow modes (GS95)

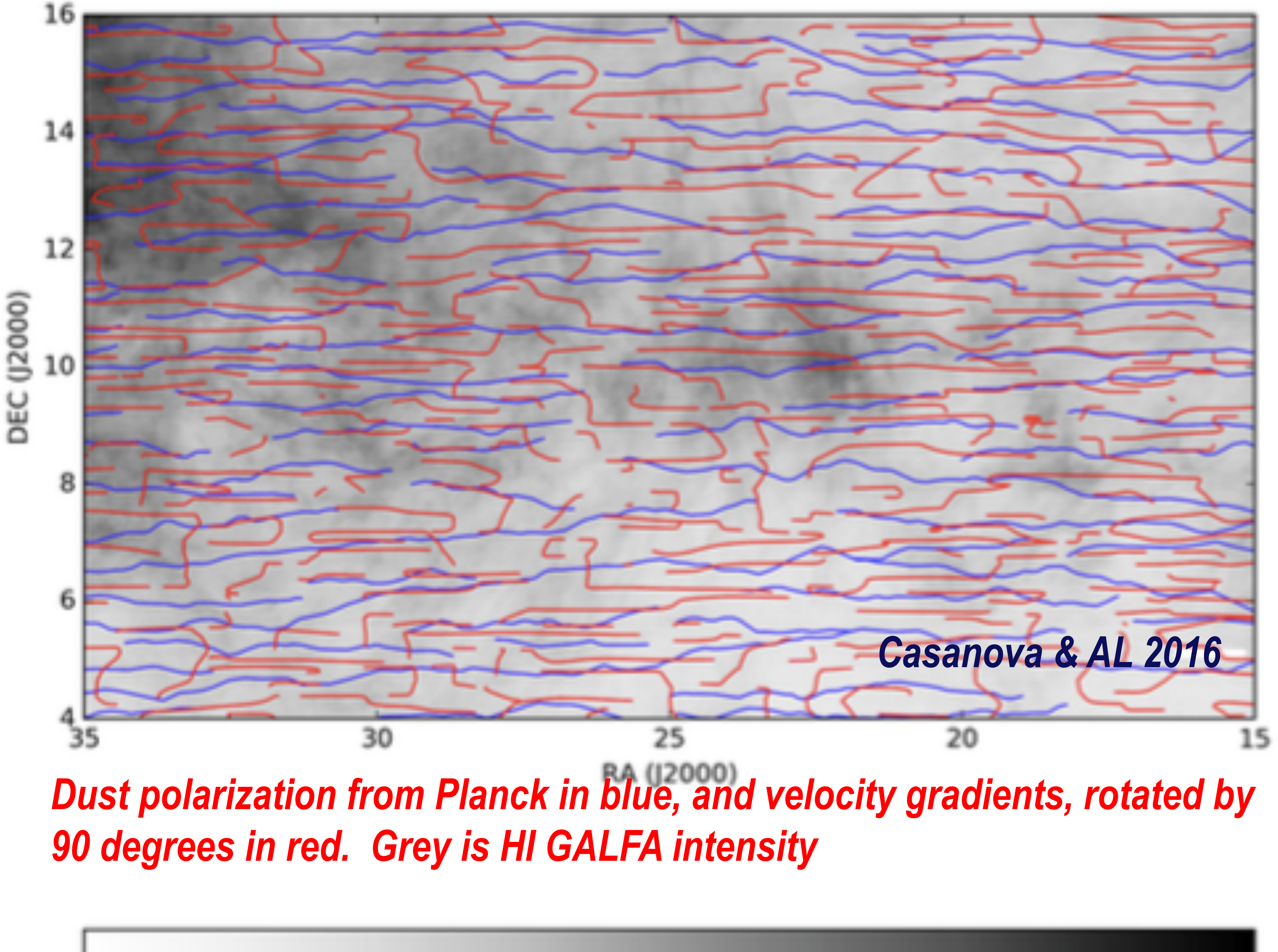


fast modes

Equal velocity correlation contour (Cho & Lazarian 02)



Understanding of turbulence allows developing techninques to study magnetic fields



Casanova & AL 2016

Dust polarization from Planck in blue, and velocity gradients, rotated by 90 degrees in red. Grey is HI GALFA intensity

Main Points

Basic Properties of MHD turbulence

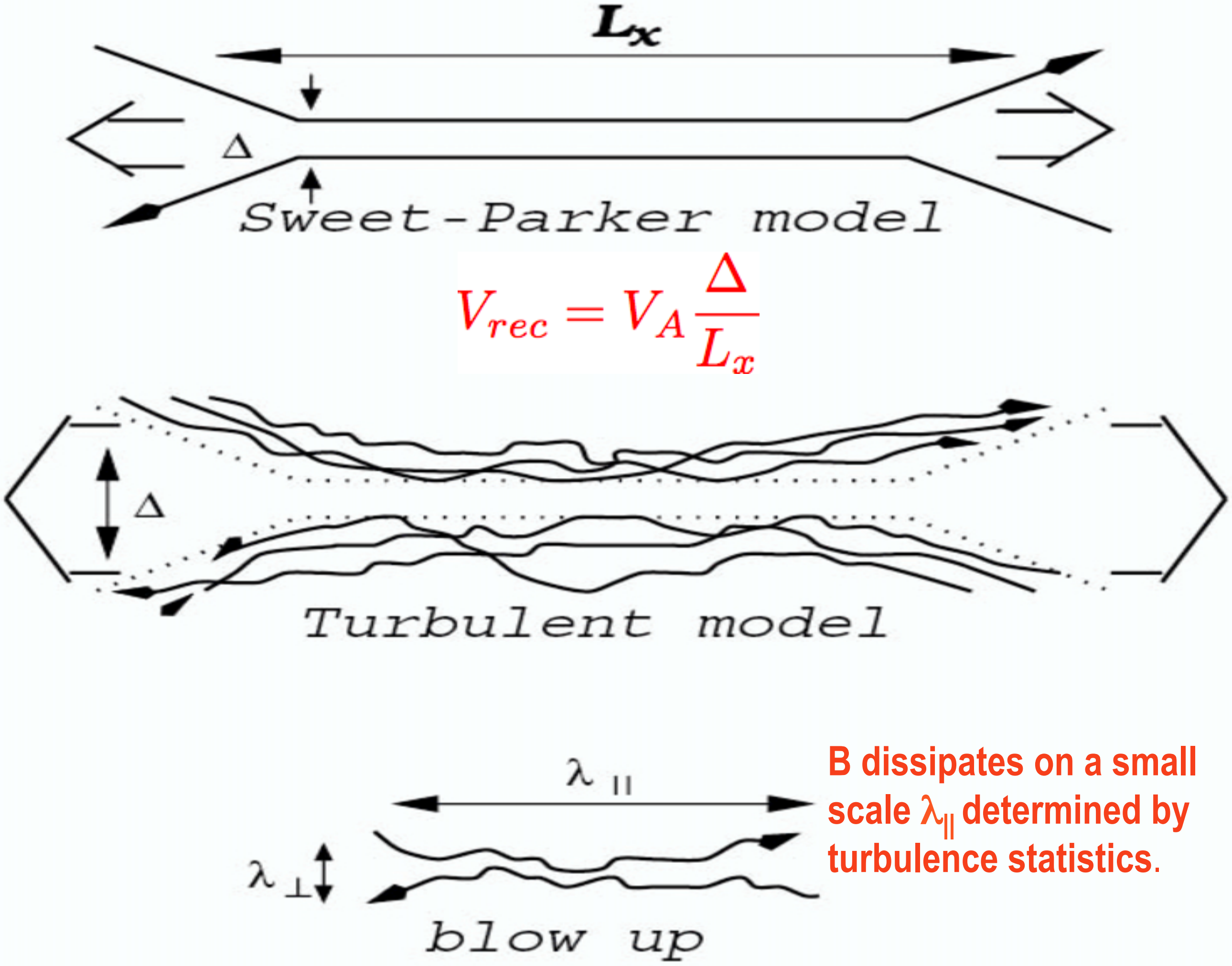
Turbulence and Reconnection

Reconnection Diffusion and Star Formation

LV99 model extends Sweet-Parker model for turbulent astrophysical plasmas and makes reconnection fast

Turbulent reconnection:

Outflow is determined by field wandering.



$$V_{rec} = V_A \frac{\Delta}{L_x}$$

B dissipates on a small scale $\lambda_{||}$ determined by turbulence statistics.

Key element:

$L/\lambda_{||}$ reconnection simultaneous events

AL & Vishniac (1999)

henceforth referred to as LV99

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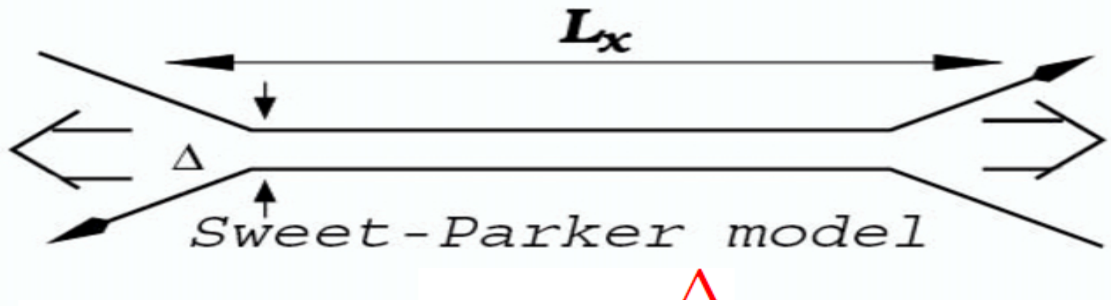

Without turbulence:
molecular diffusion coefficient D ~10^{-5} cm^2/sec
(← It's for small molecules in water.)

→ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !

Key element:

$L/\lambda_{\|}$ reconnection simultaneous events

AL & Vishniac (1999)

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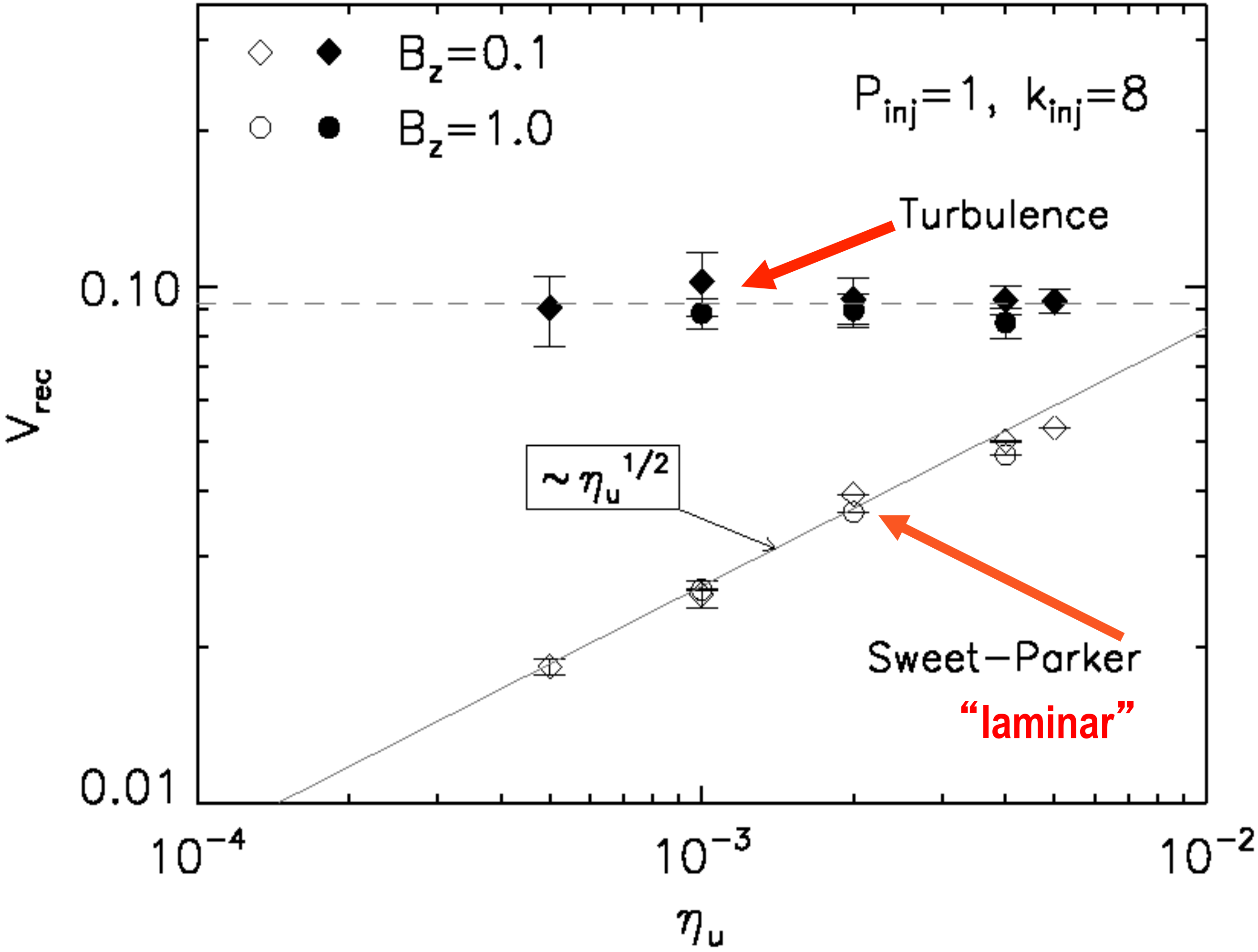
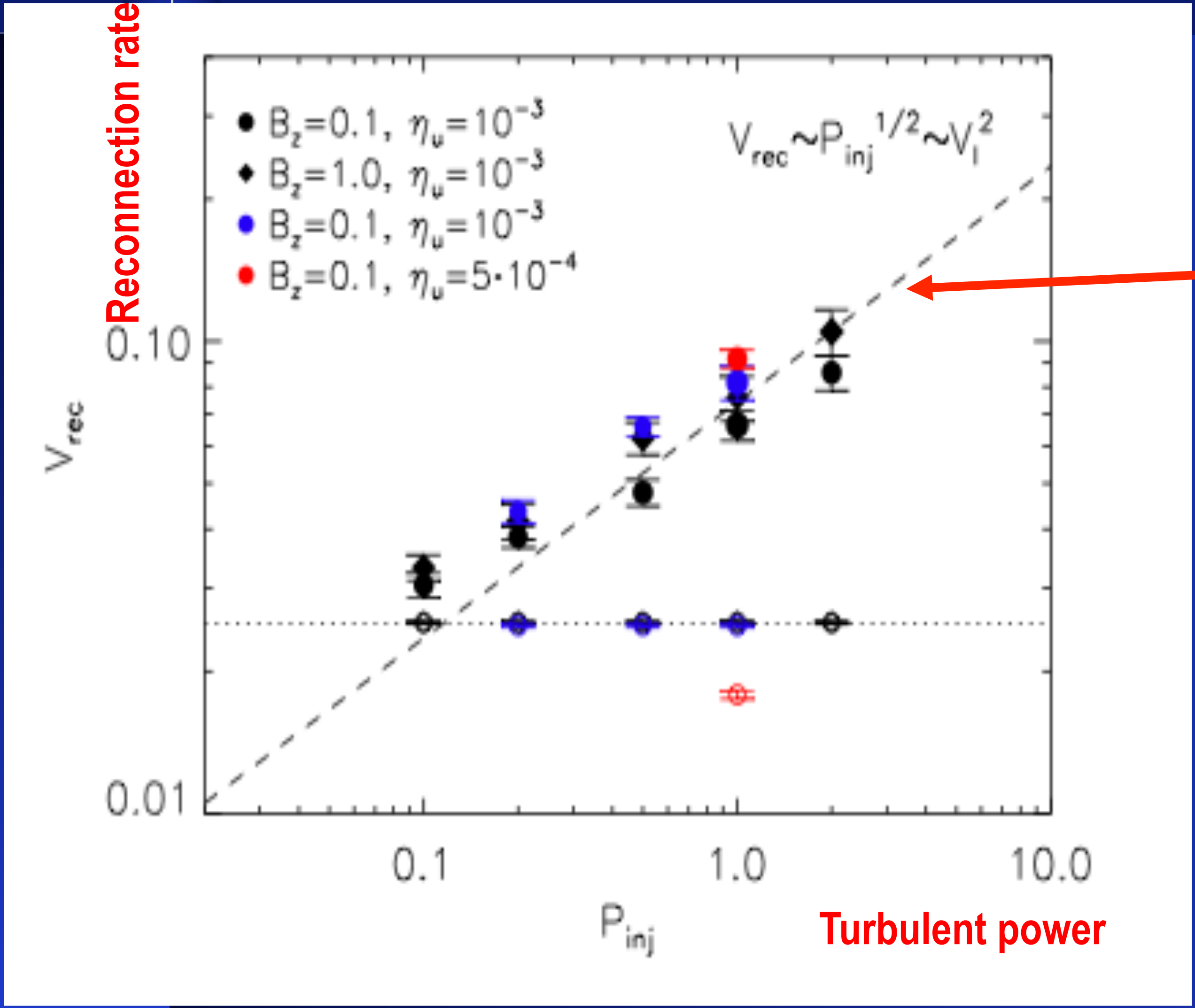
Reconnection is Fast: speed does not depend on Ohmic resistivity!



Lazarian & Vishniac 1999 predicts no dependence on resistivity

Kowal et al. 2009

The reconnection rate increases with input power of turbulence



Reconnection rate

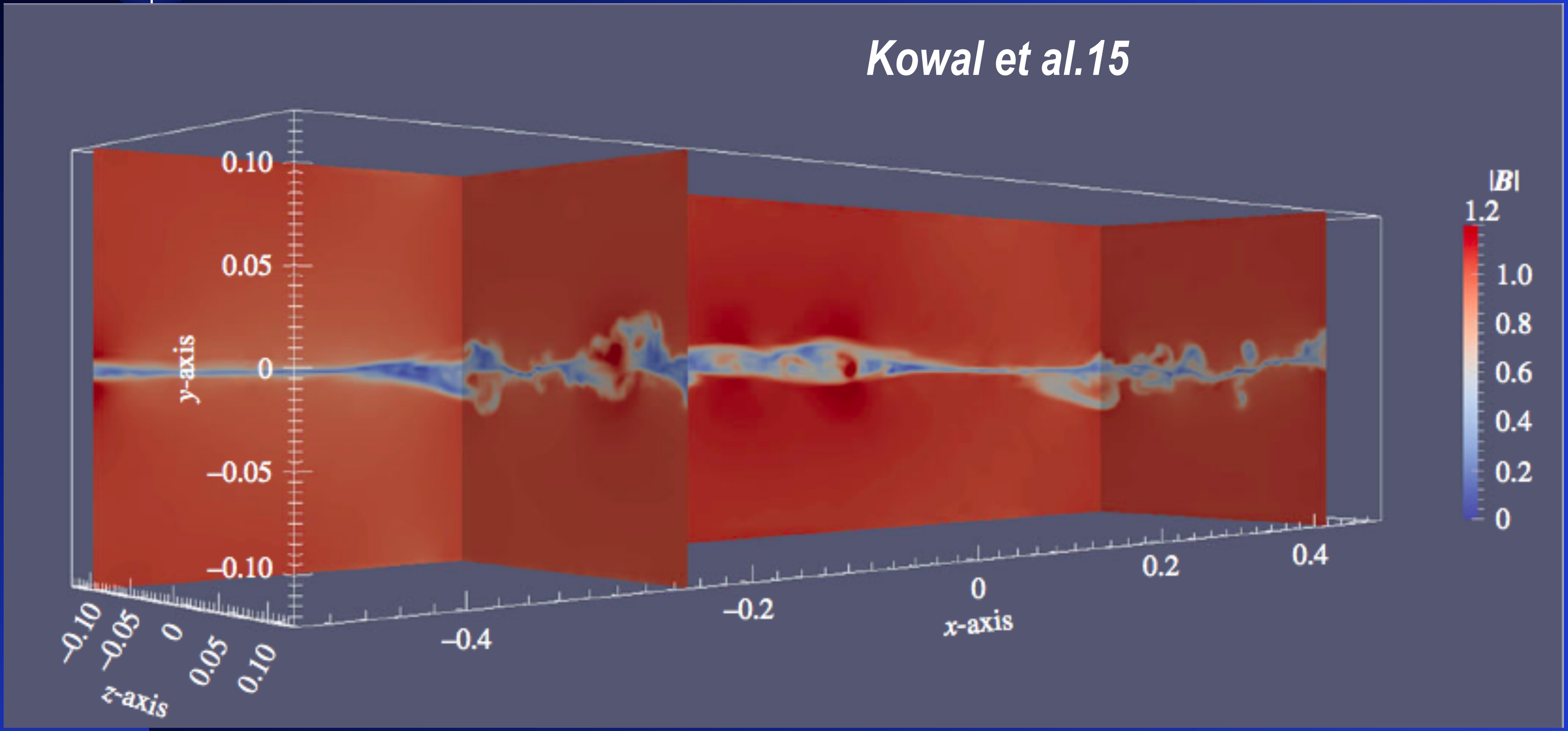
Turbulent power

Lazarian & Vishniac (1999) prediction is $V_{rec} \sim P_{inj}^{1/2}$

Results do not depend on the guide field

Kowal et al. 2012

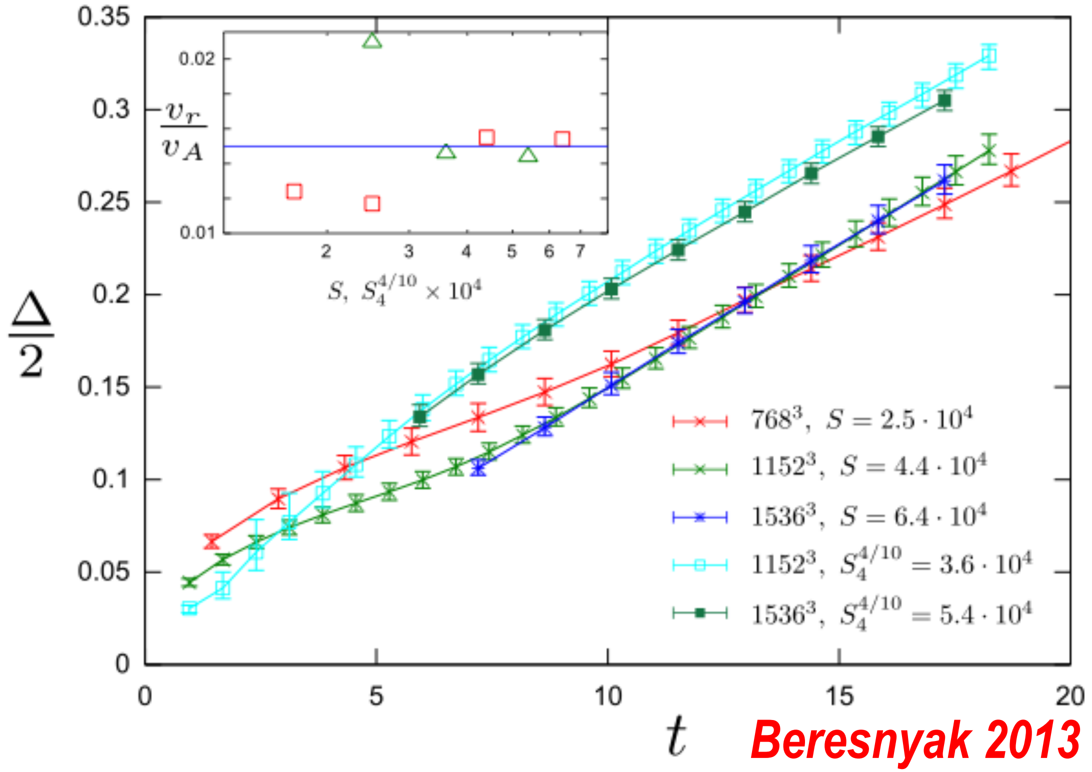
Simulations demonstrate the development of turbulence through Kelvin-Helmholz instability


Kowal et al.15

$$V_\Delta \approx (C_K r_A)^{3/4} V_{Ay} \beta^{1/2}$$

Expected reconnection rate, Ck is Kolmogorov constant, r_A is magnetization

Measurements of the growth of reconnection layer agree with the prediction



Beresnyak 2013

$$V_\Delta \approx (C_K r_A)^{3/4} V_{Ay} \beta^{1/2}$$

$$r_A \approx 1/30, V_\Delta \approx 0.01$$

New measurements in Kowal et al. 2015 agree well with this

$$\frac{d\Delta}{dt} \approx g\beta^{1/2}(C_K r_A)^{3/4} V_{Ay}$$

AL et al. 2015

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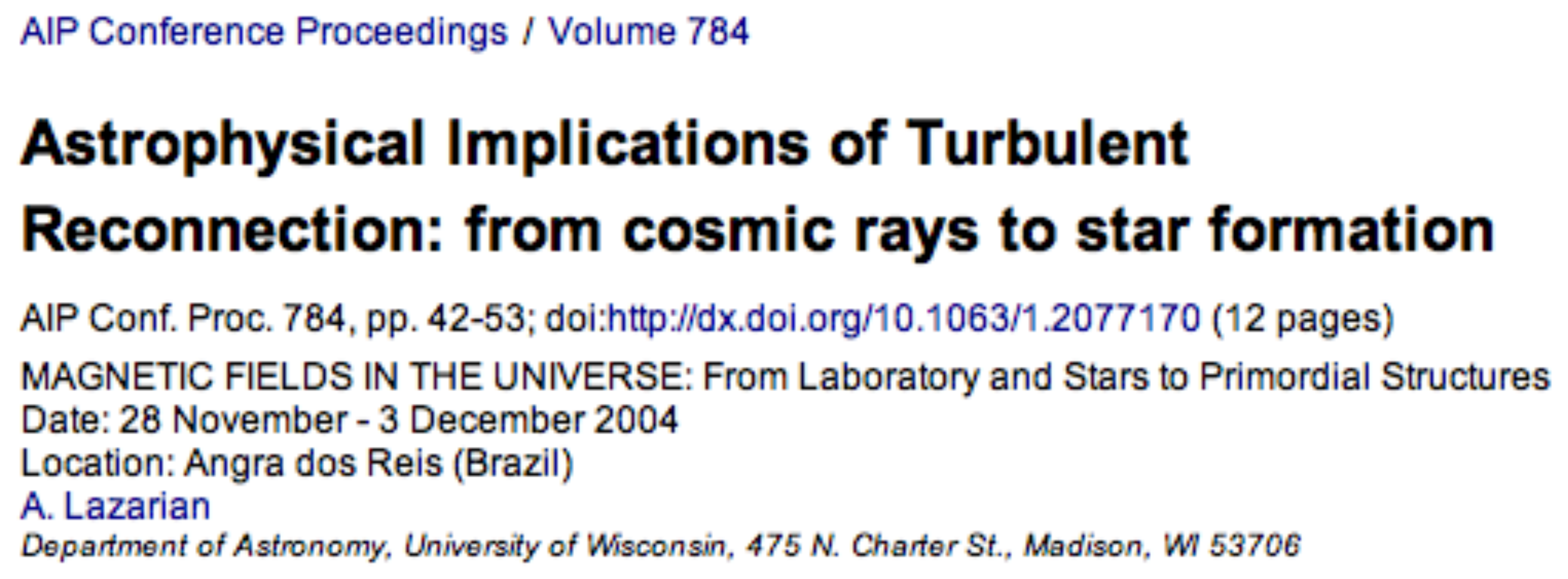
Big Implication: LV99 means that magnetic field in *turbulent fluids* is not frozen in

Hannes Alfven

Instead of flux freezing condition one should consider flux diffusion by turbulent flow. This has dramatic consequences for many areas of astrophysics including star formation!

Violation of magnetic field frozen in condition in turbulent fluids proven in Eyink (2011). The equivalence of this and LV99 approach was demonstrated in Eyink, Lazarian & Vishniac 2011.

Reconnection diffusion is a key process for star formation



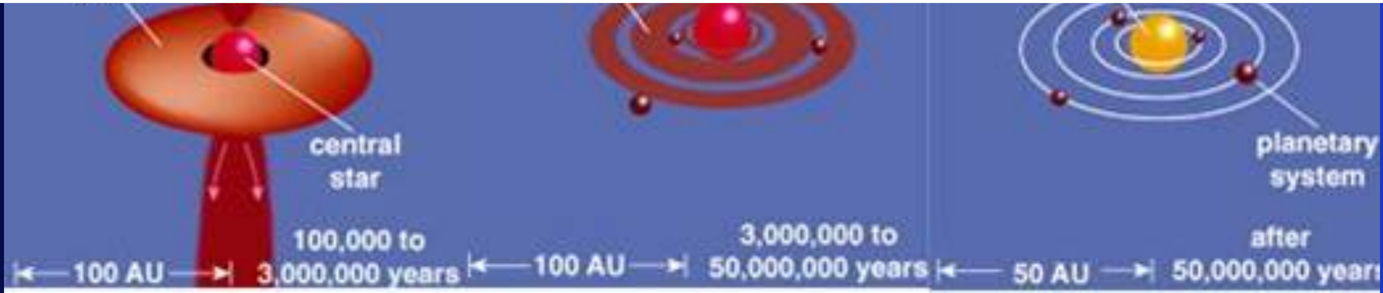
AIP Conference Proceedings / Volume 784

Astrophysical Implications of Turbulent Reconnection: from cosmic rays to star formation

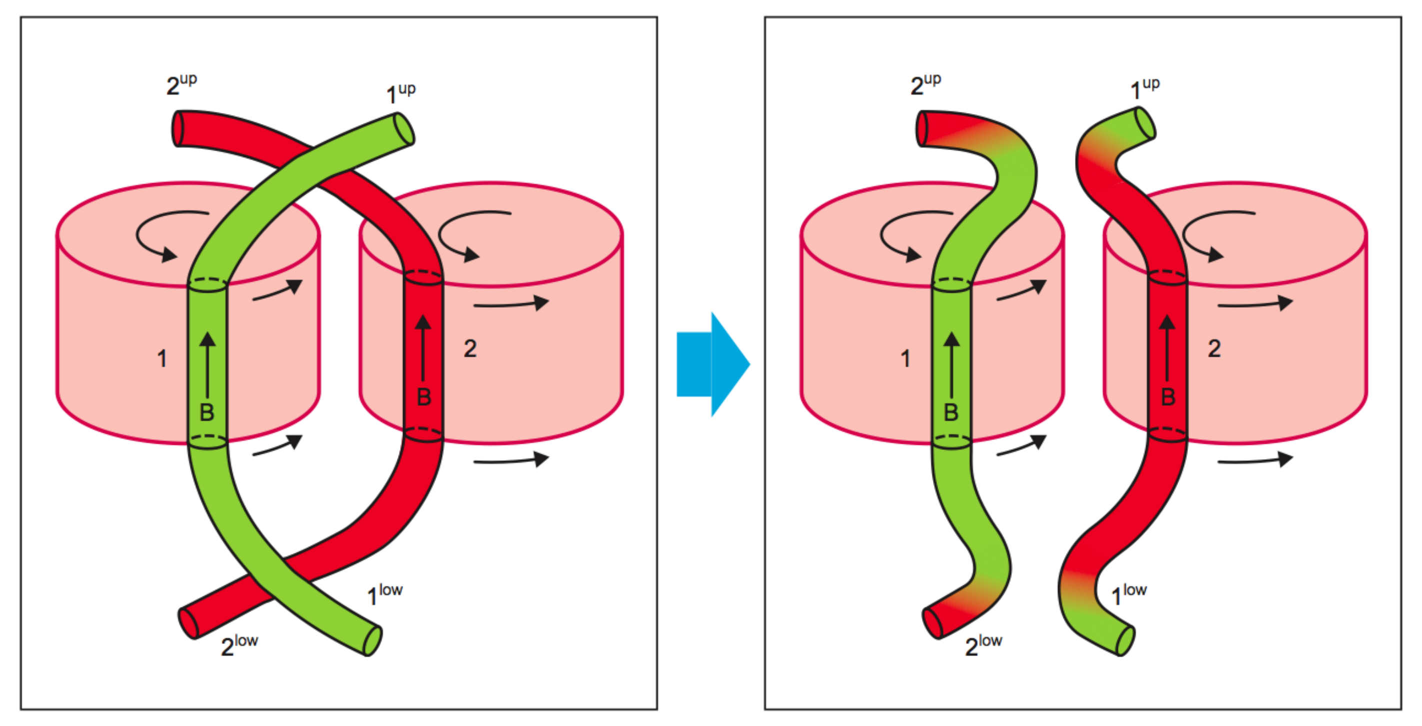
AIP Conf. Proc. 784, pp. 42-53; doi:http://dx.doi.org/10.1063/1.2077170 (12 pages)

MAGNETIC FIELDS IN THE UNIVERSE: From Laboratory and Stars to Primordial Structures
Date: 28 November - 3 December 2004
Location: Angra dos Reis (Brazil)

A. Lazarian
Department of Astronomy, University of Wisconsin, 475 N. Charter St., Madison, WI 53706



Reconnection can provide diffusion with the turbulent diffusion rates



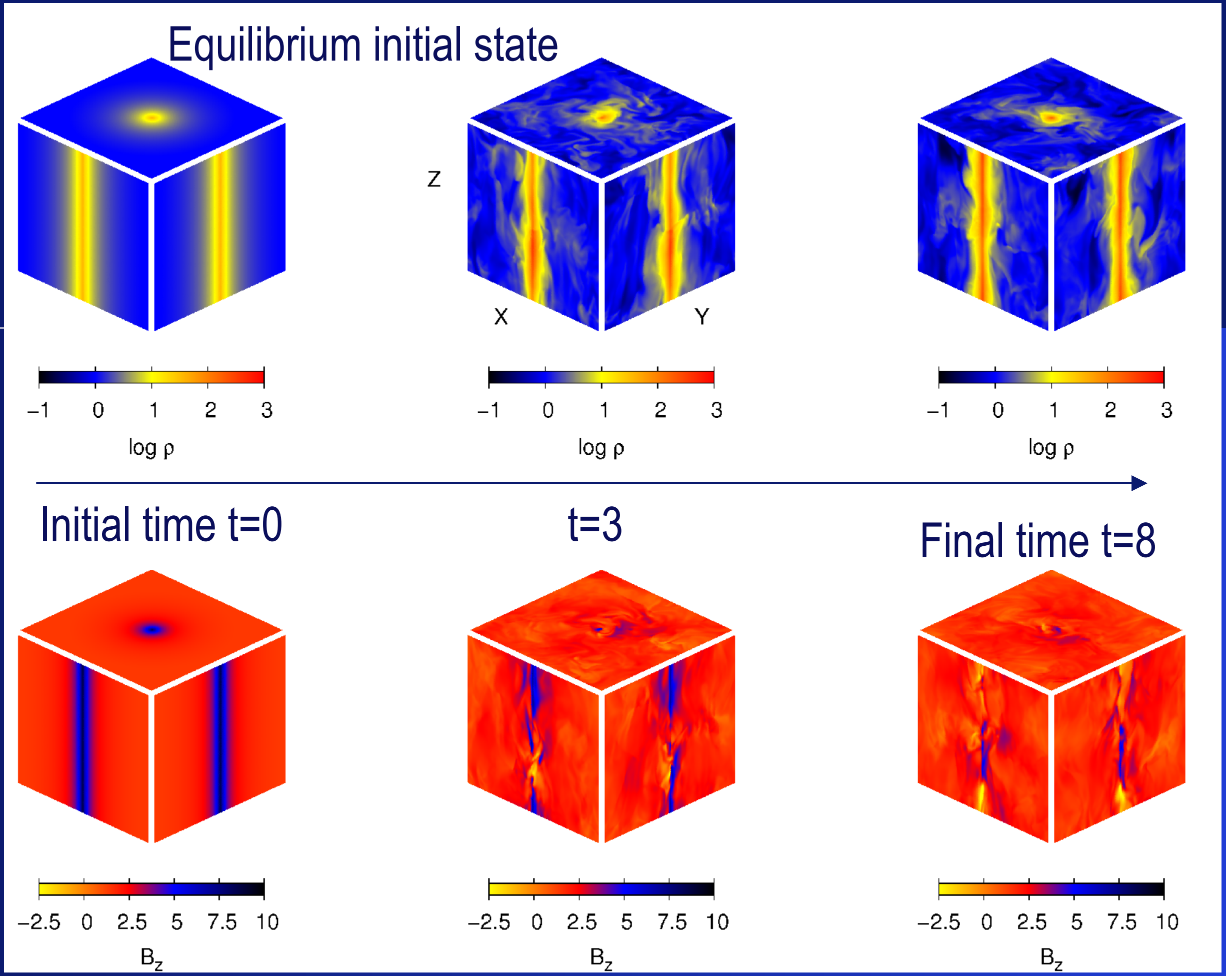
In the presence of weak turbulence and gravity magnetic field diffuses away from the core

Gravitational potential:

$$\Psi(R \leq R_{max}) = -\frac{A}{R + R_*}$$

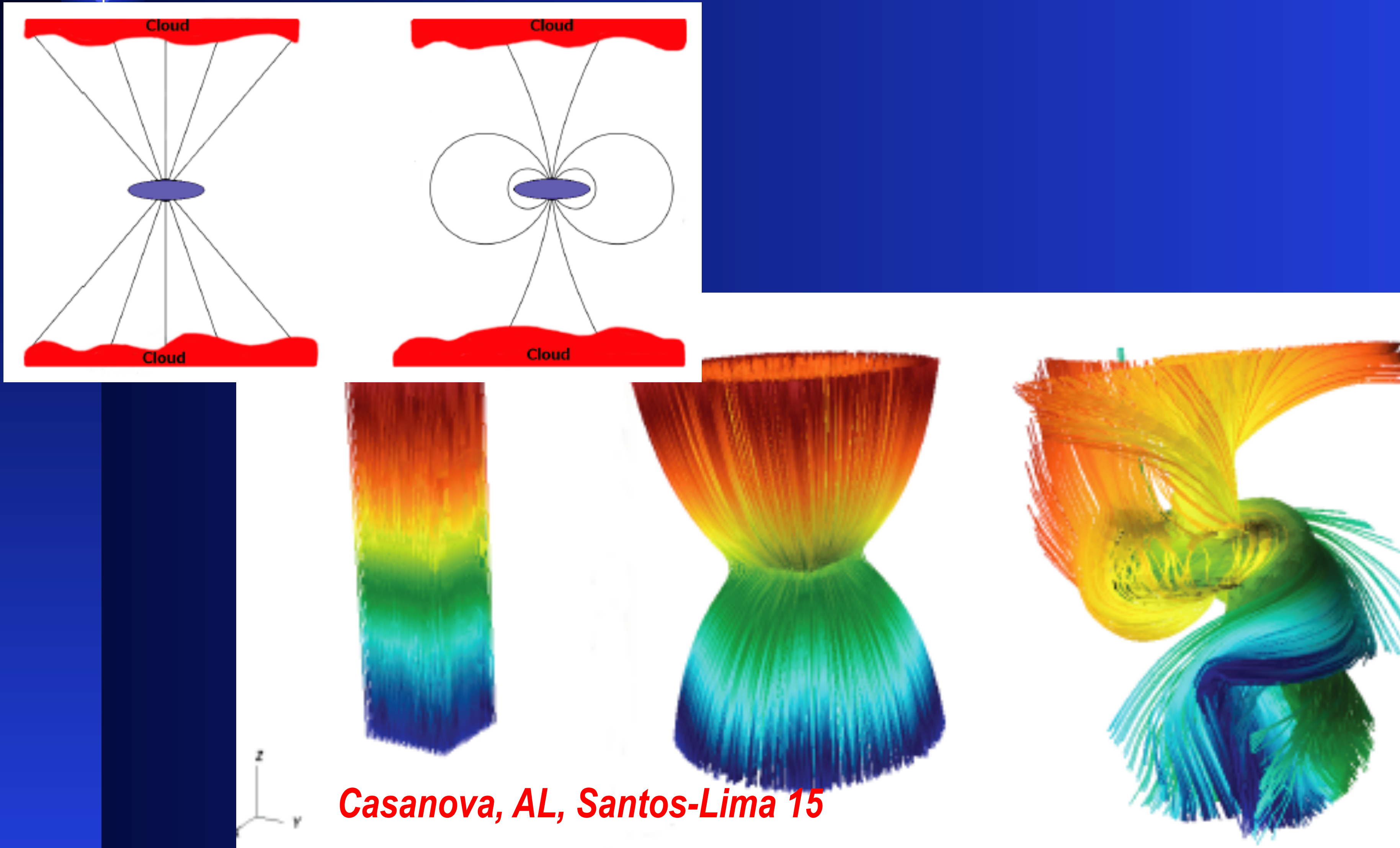
$$\Psi(R > R_{max}) = -\frac{A}{R_{max} + R_*}$$

Santos de Lima et al. 2010



Models starting in equilibrium simulate the evolution of subcritical clouds, while those starting in non-equilibrium reproduce some features of supercritical collapse.

Turbulent Reconnection solves “magnetic braking catastrophe”



Casanova, AL, Santos-Lima 15

Turbulence and fast reconnection are interconnected; astrophysical implications are numerous

MHD turbulence makes reconnection fast

Turbulence

Reconnection

SOFIA
STUDIES
STAR FORMATION

The SOFIA observatory studies astronomical observations at wavelengths between 0.3 and 1000 microns.

www.sofia.usra.edu/Gallery/science/SCI2012_0001.html

Reconnection diffusion and star formation