Stochastic Particle Acceleration in High Energy Astrophysical Sources

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Collaborators

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Oct. 2008 Krakow, Poland

Outline

I: Observations: Distribution

II: Mechanism: Fermi Acceleration

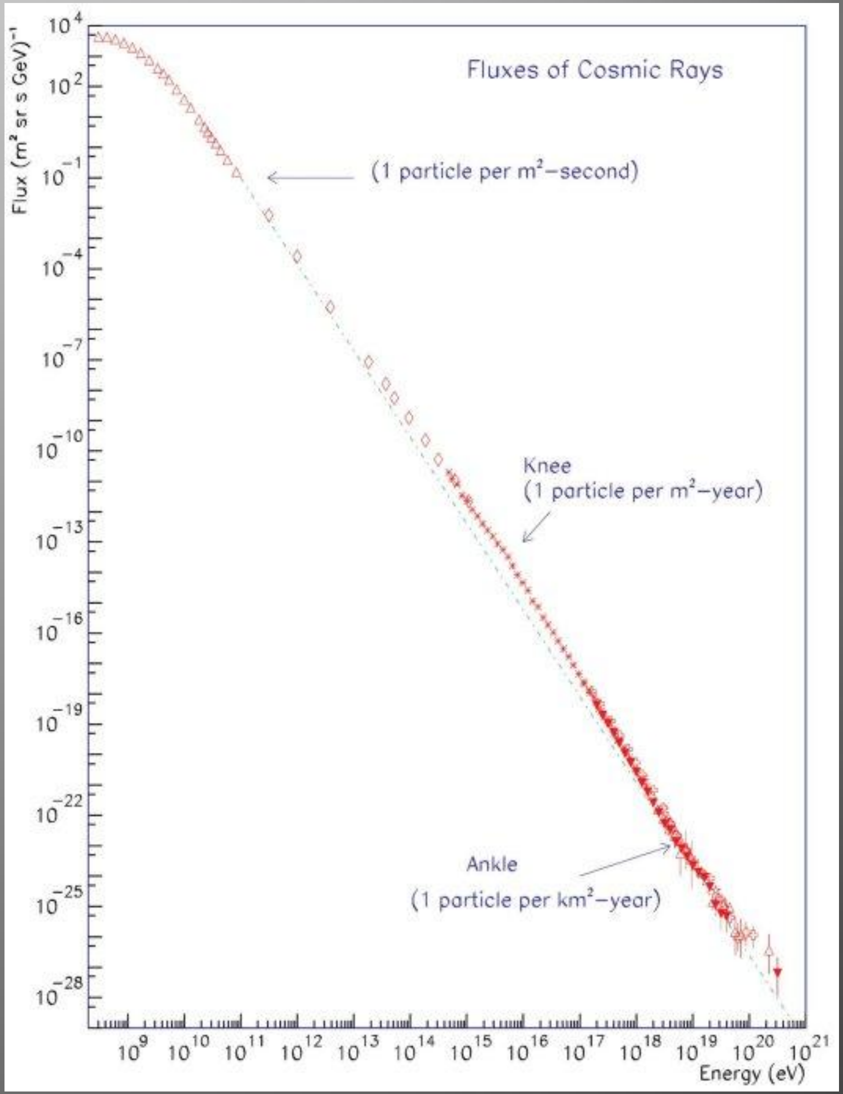
III: Shock Model

IV: Observations: Acceleration Efficiency

V: Stochastic Particle Acceleration Model

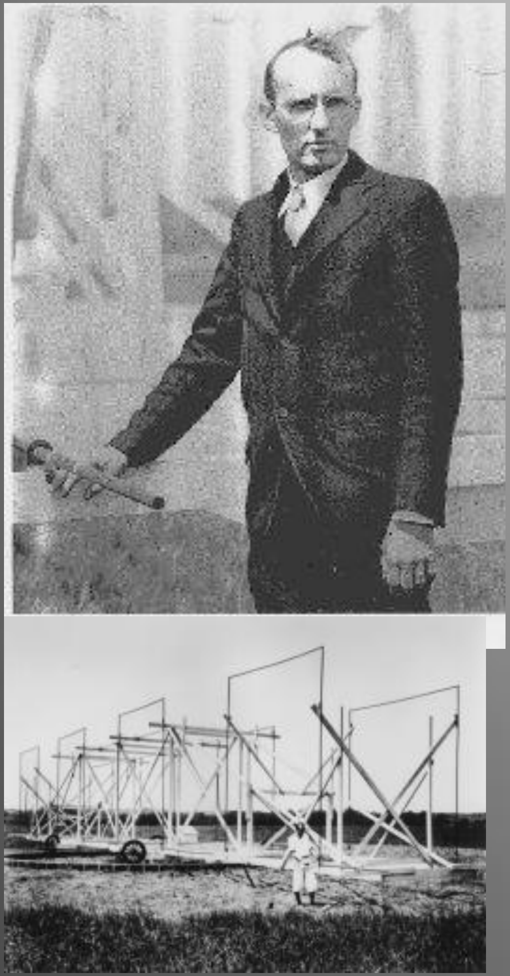
VI: Conclusions

I: Discovery of Cosmic Rays



Victor Franz Hess 1912

I: Birth of Radio Astronomy



Karl Jansky 1933

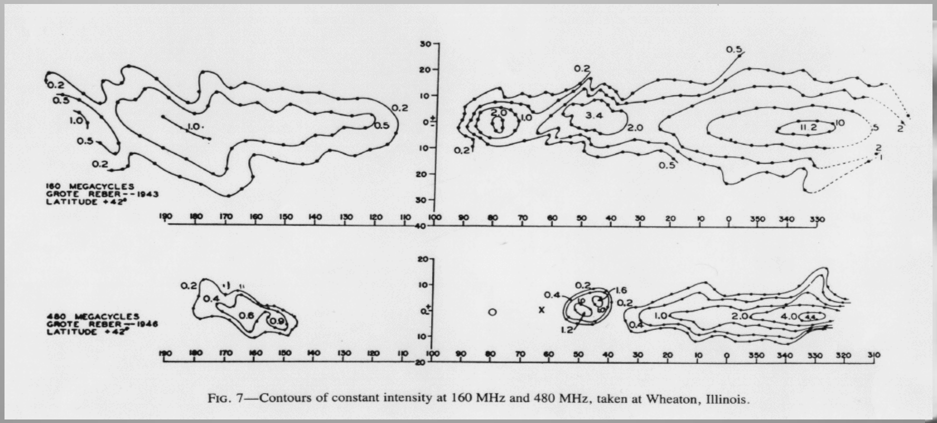
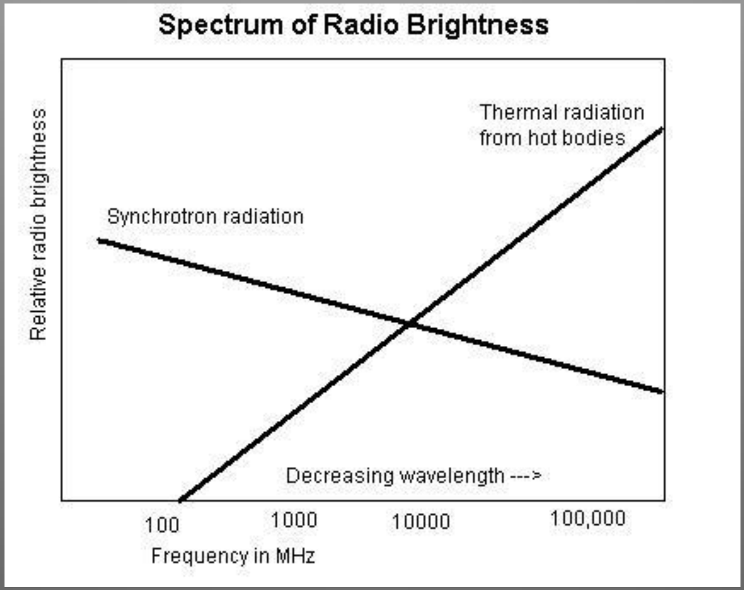
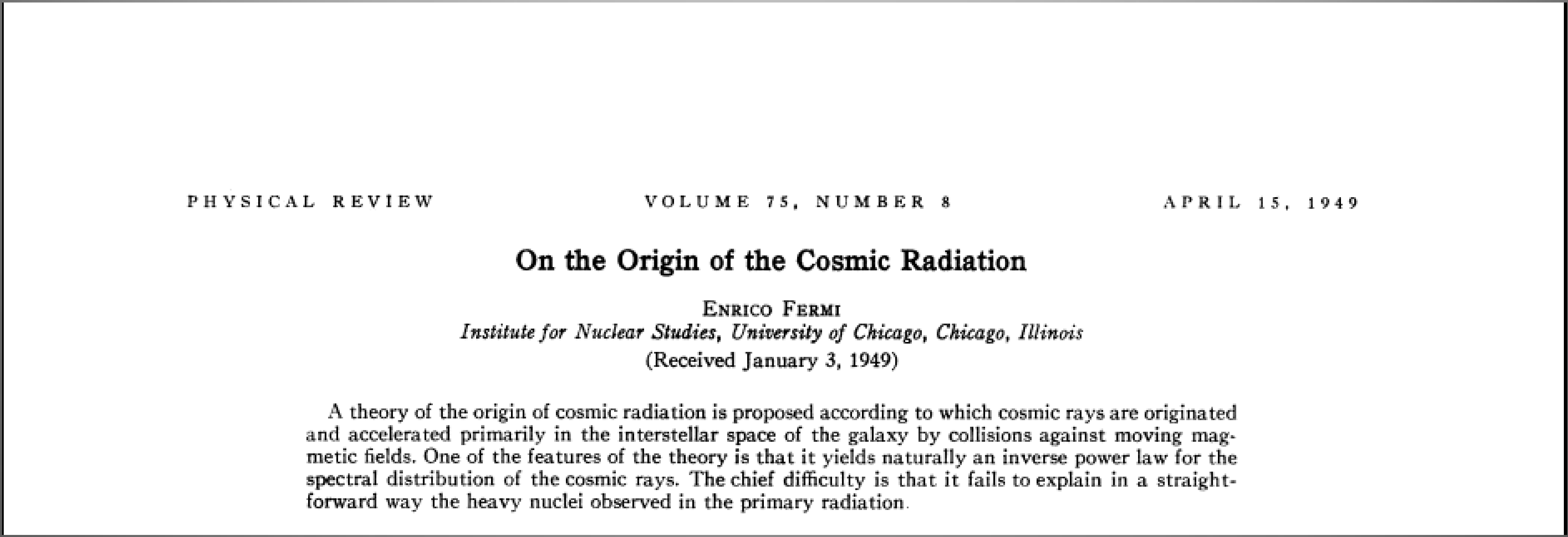


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.



Grote Reber 1944

II: Fermi Mechanism



PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

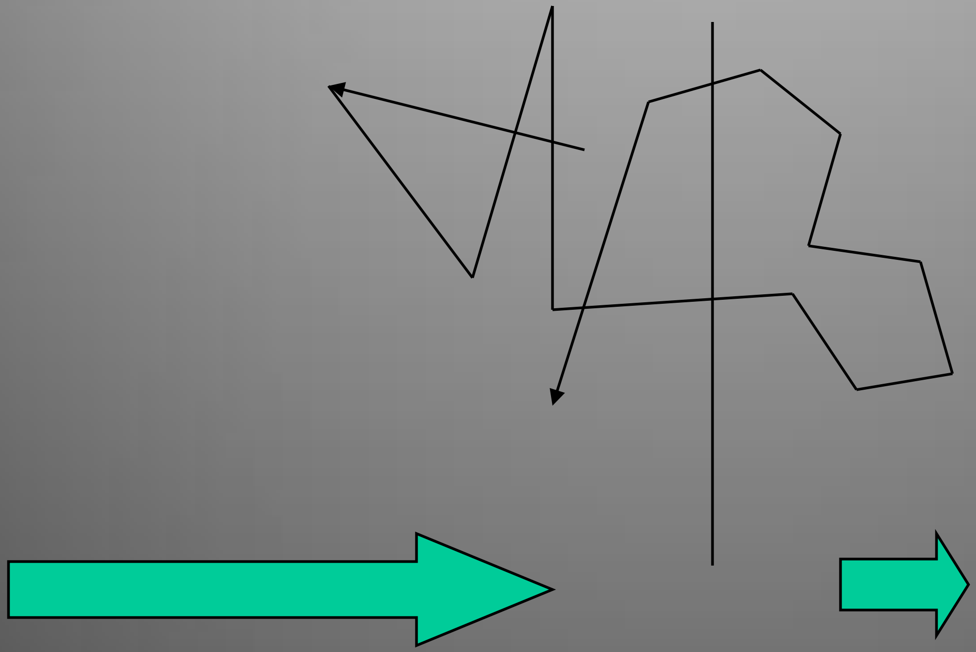
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

Particles interact with Macroscopic objects
Electro-Magnetic Interaction
But not collisional

III: Shock Model

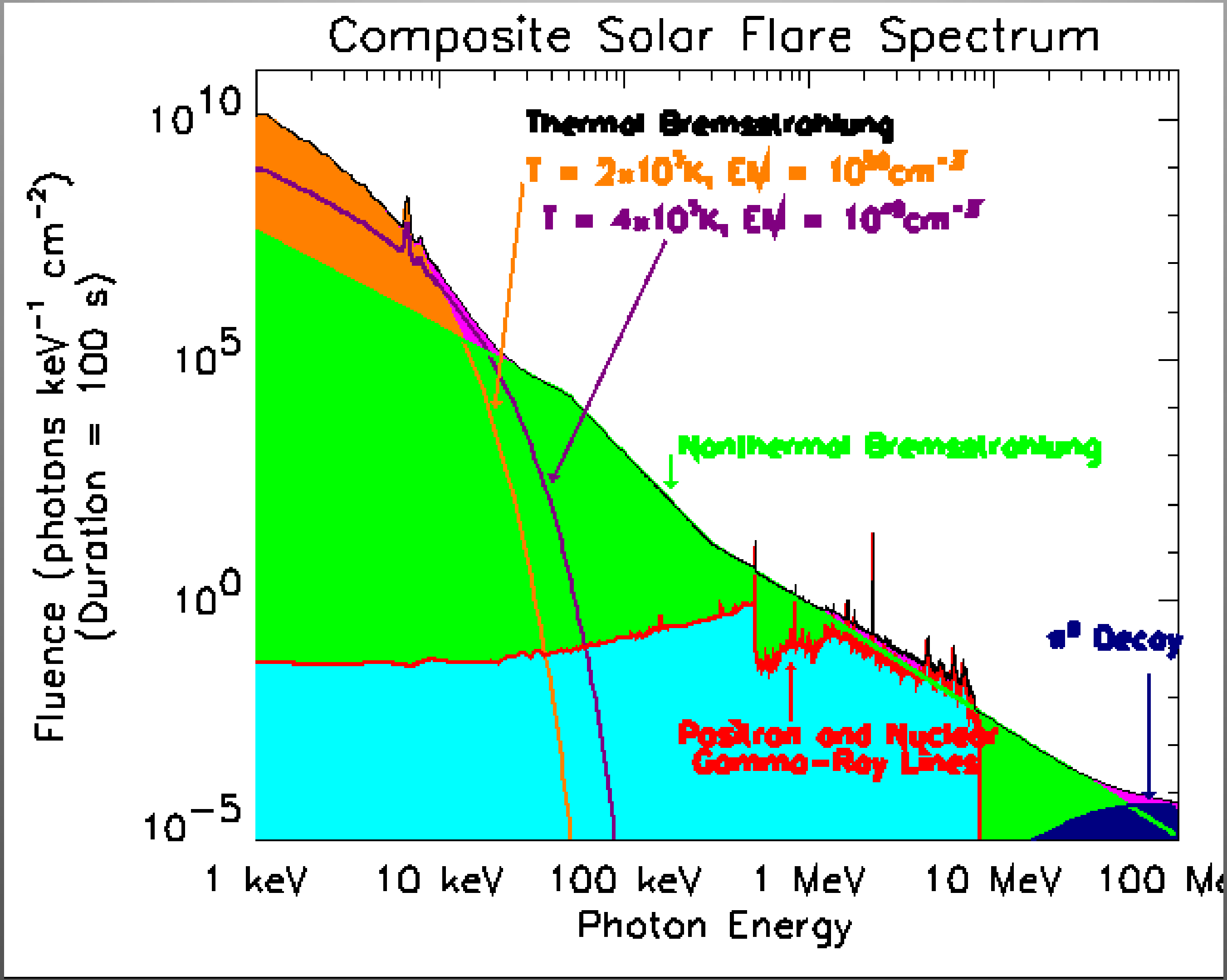


III: Shock Model

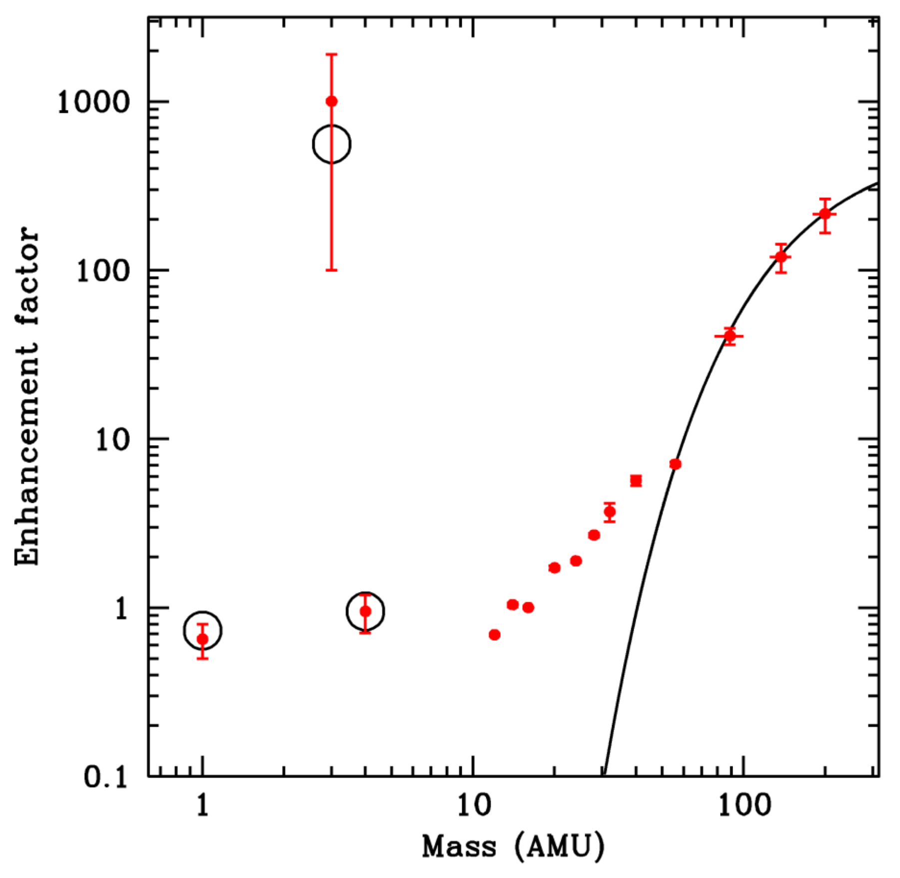
- Scattering Mechanism
- Injection Problem or Particle Acceleration at Low Energy

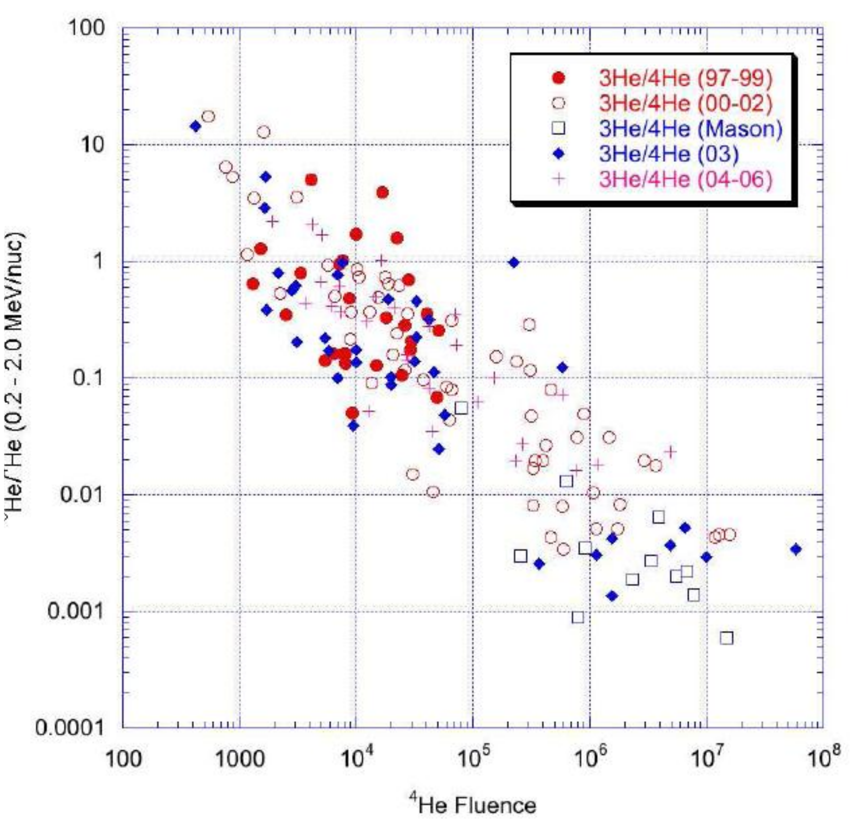
Wave Particle Interactions!!!

IV: Acceleration Efficiency



IV: Solar Energetic Ions





V: Free Energy Dissipation and Turbulence

$$
\begin{aligned}
\frac{d(\rho\mathbf{v})}{dt} + \rho\nabla\mathbf{\Phi} + \rho\mathbf{v}(\nabla\cdot\mathbf{v}) &= \frac{1}{4\pi}(\mathbf{B}\cdot\nabla)\mathbf{B} - \nabla\left(P_{th} + \frac{B^2}{8\pi}\right) \\
&\quad +2\nabla\cdot(\mathbf{S}\rho\nu)\ , \\
\frac{\partial \mathrm{B}}{\partial t} &= \nabla\times(\mathbf{v}\times\mathbf{B}) - \frac{c^2\eta}{4\pi}\nabla\times(\nabla\times\mathbf{B})
\end{aligned}
$$

V: Turbulence Cascade

• Kolmogorov	• Kraichnan
U(L)	V>U
$U^3(L)/L$ = constant	U^4/LV = constant
k~1/L	
$U(k) \sim k^{-1/3}$	$U(k) \sim k^{-1/4}$
$\int E(k)\, dk \sim U^2(k) \sim k^{-2/3}$	$\int E(k)\, dk \sim U^2(k) \sim k^{-1/2}$
$E(k) \sim k^{-5/3}$	$E(k) \sim k^{-3/2}$

V: Diffusion Approximation

Cascade

Damping

$$\frac{\partial \mathcal{W}(\mathbf{k},t)}{\partial t} = \dot{Q}_{\mathcal{W}}(\mathbf{k},t) + \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}\mathcal{W}(\mathbf{k},t)\right] - \Gamma(\mathbf{k})\mathcal{W}(\mathbf{k},t) - \frac{\mathcal{W}(\mathbf{k},t)}{T^{\mathcal{W}}_{\mathrm{esc}}(\mathbf{k})},$$

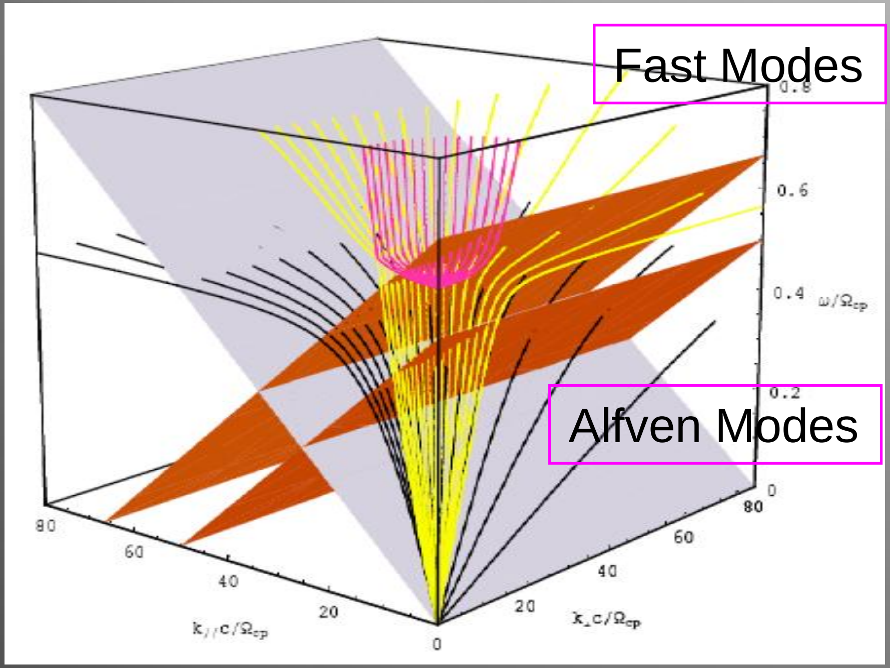
$$D_{ij} = \delta_{ij}\frac{C}{4\pi}k^2\frac{\tau_{NL}^{-2}}{\tau_{NL}^{-1}+\tau_A^{-1}} = \delta_{ij}\frac{C}{4\pi}\frac{\mathcal{W}k^7}{(\mathcal{W}k^3)^{1/2}k+\omega(\mathbf{k})}$$

Suppression of turbulence cascade by wave propagation

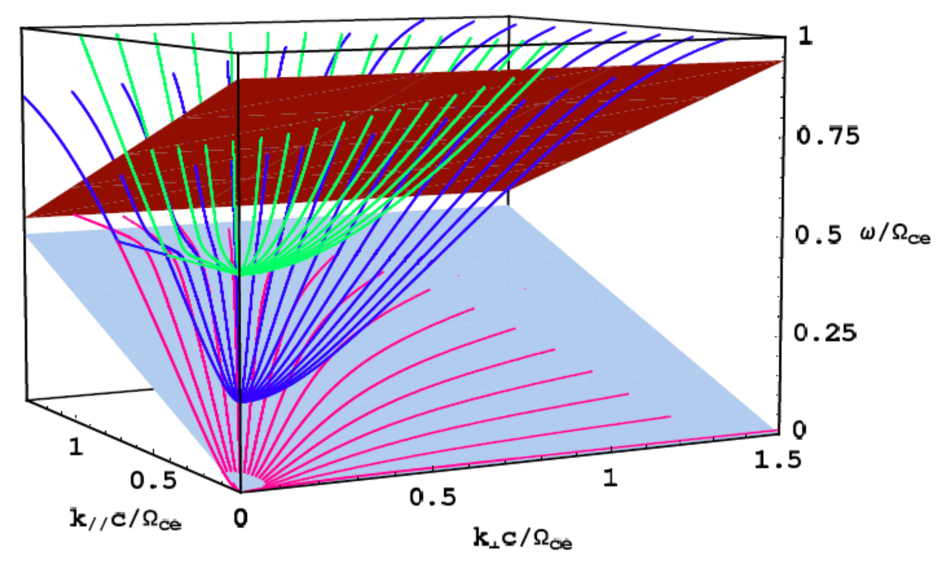
$\int W(k)\, k^2 d\Omega \sim E(k)$

Jiang et al. 2008

V: Dispersion Relation

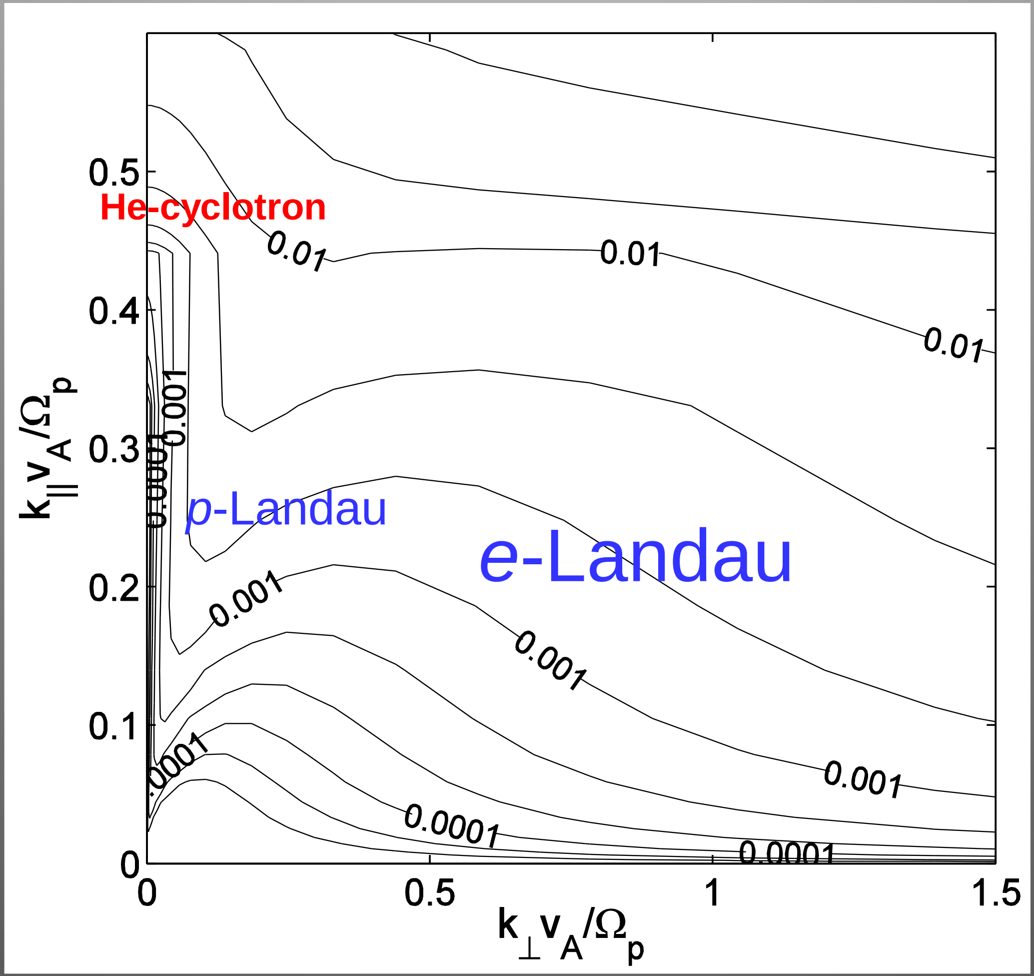

Fast Modes

Alfven Modes

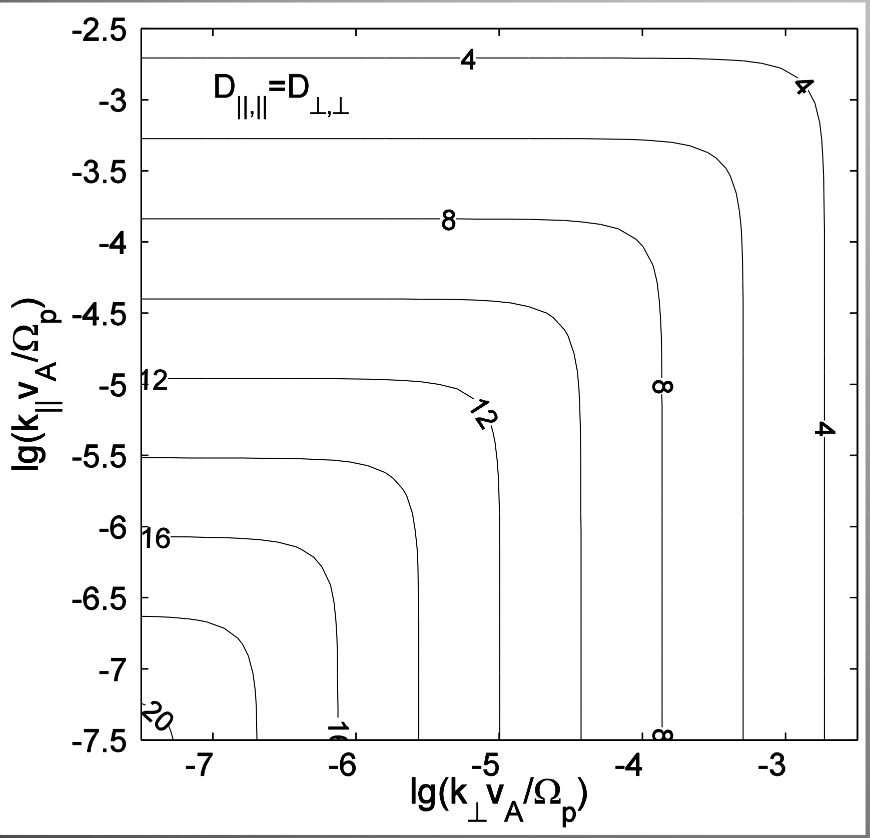


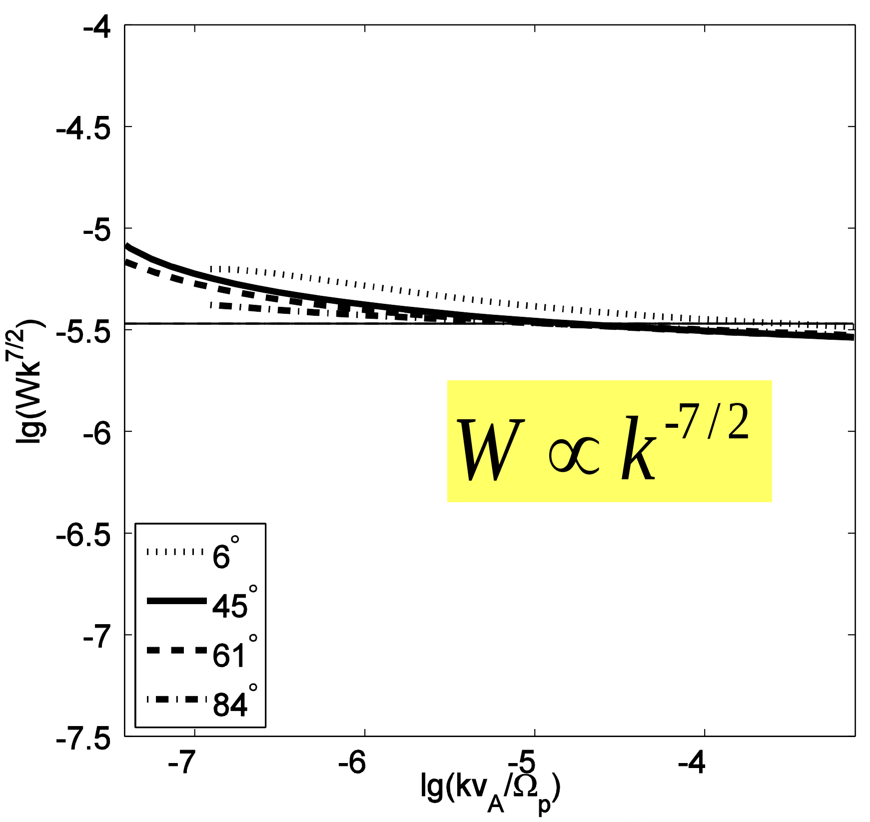
V: Wave Damping

(WHAMP Code)



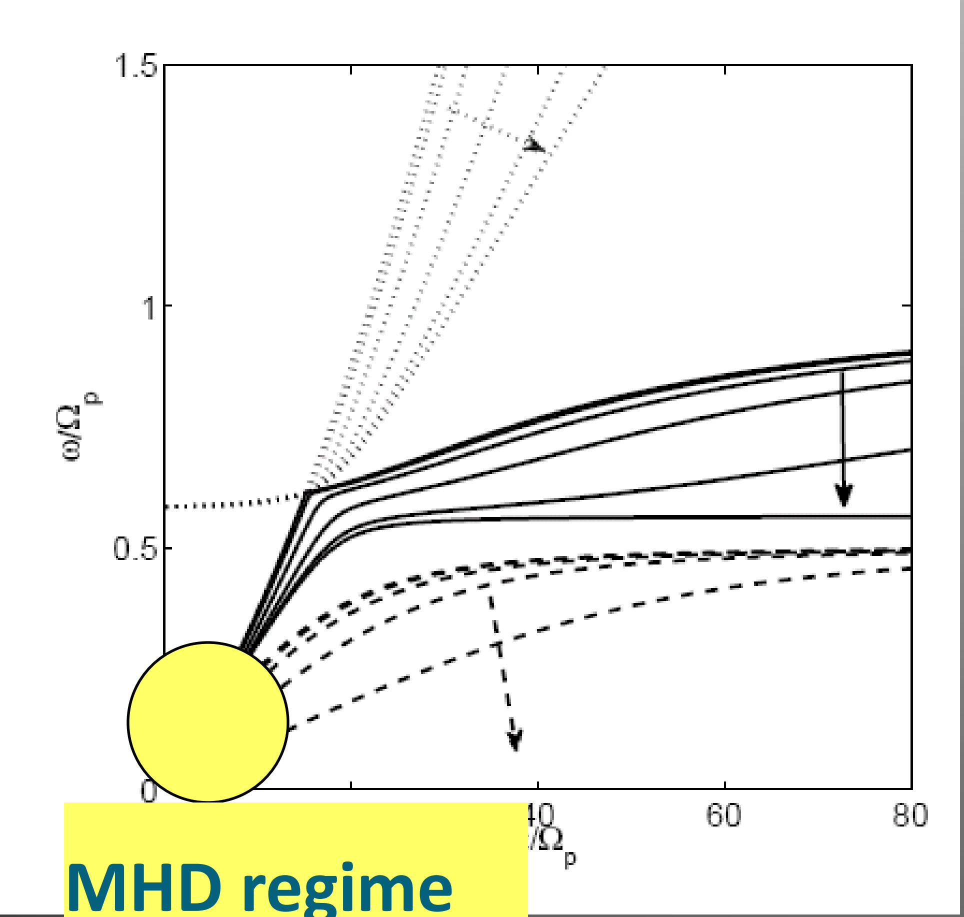
V: Alfven Wave Cascade



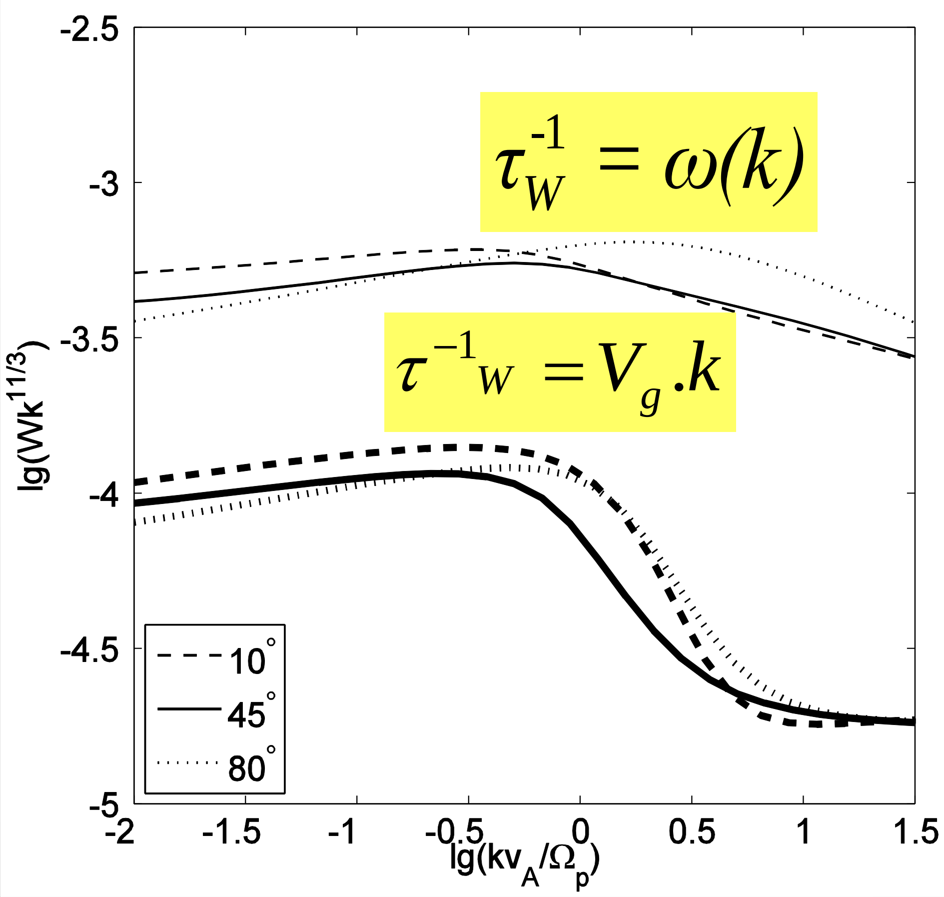


$$W \propto k^{-7/2}$$

V: Turbulence Cascade Dispersive Effects



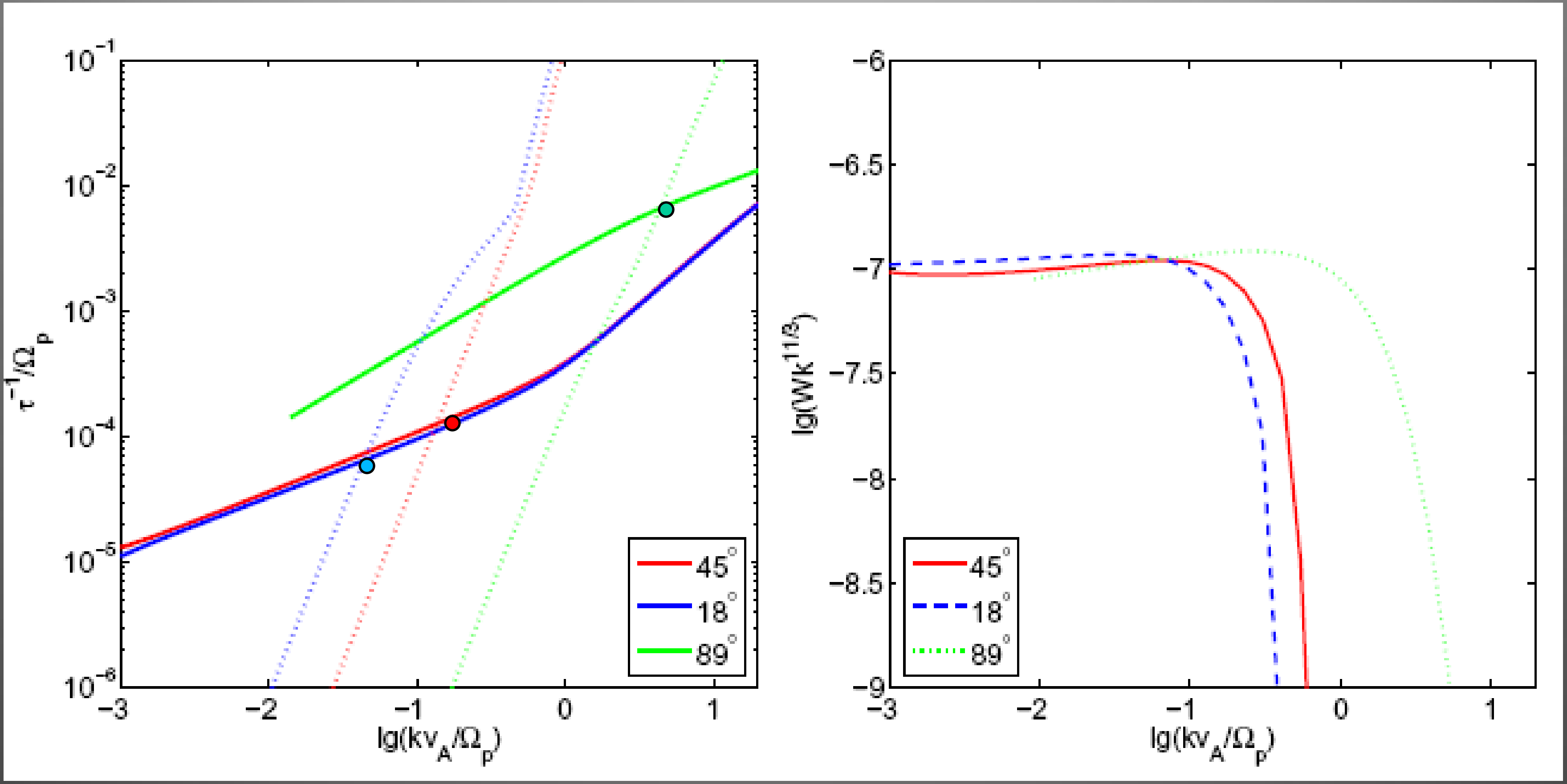
MHD regime



$$\tau_W^{-1} = \omega(k)$$

$$\tau^{-1}{}_W = V_g . k$$

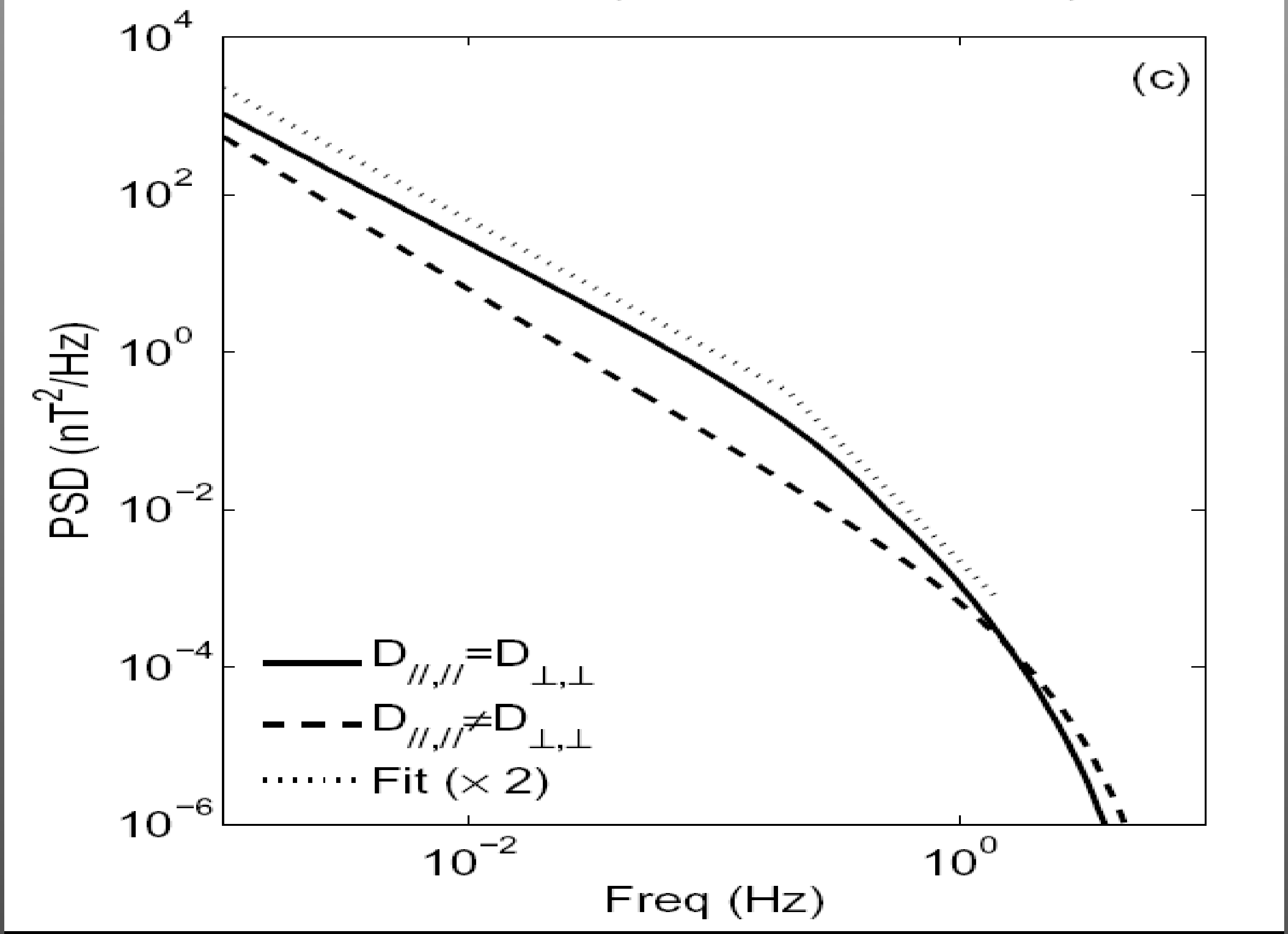
V: Damping Effects



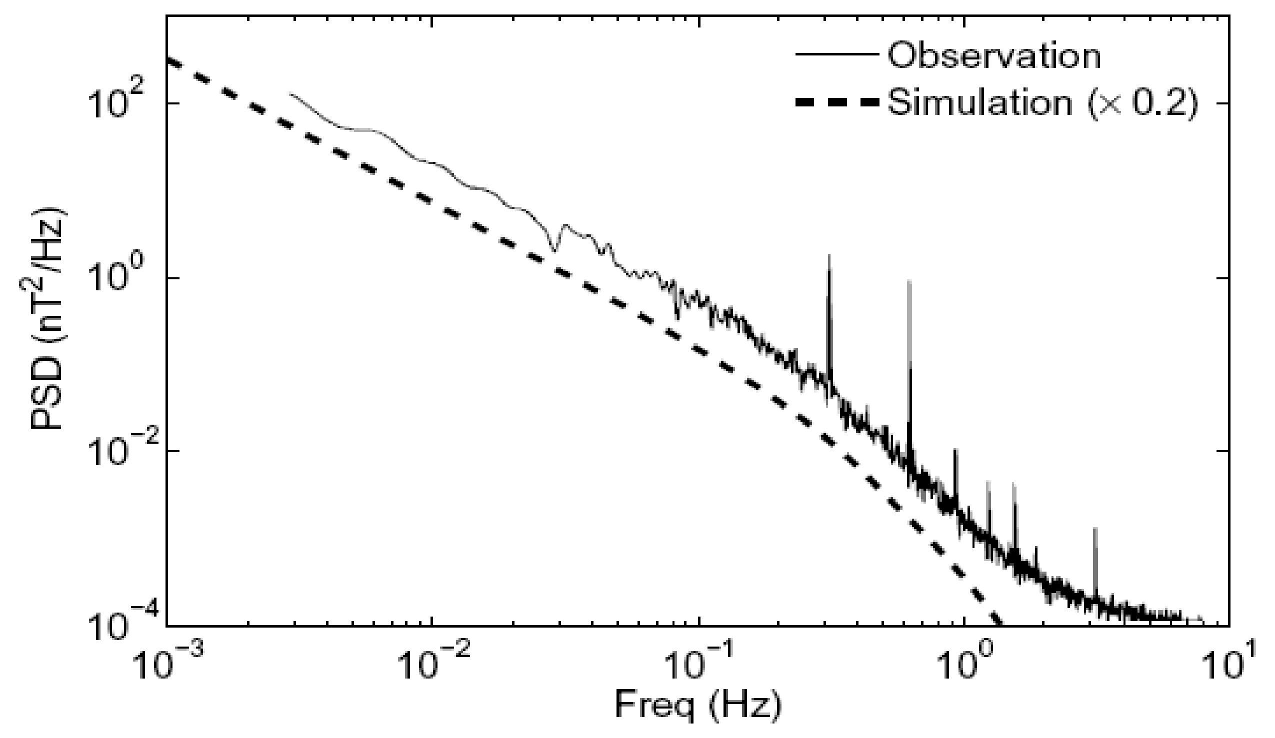
Jiang et al. 2008

V: Turbulence Cascade and Damping

$$P(\nu) = \int \mathcal{W}(\mathbf{k})\delta\left\{\frac{1}{2\pi}\left[\mathbf{k}\cdot\mathbf{V}_{SW} + \omega(\mathbf{k})\right] - \nu\right\} d\mathbf{k}$$



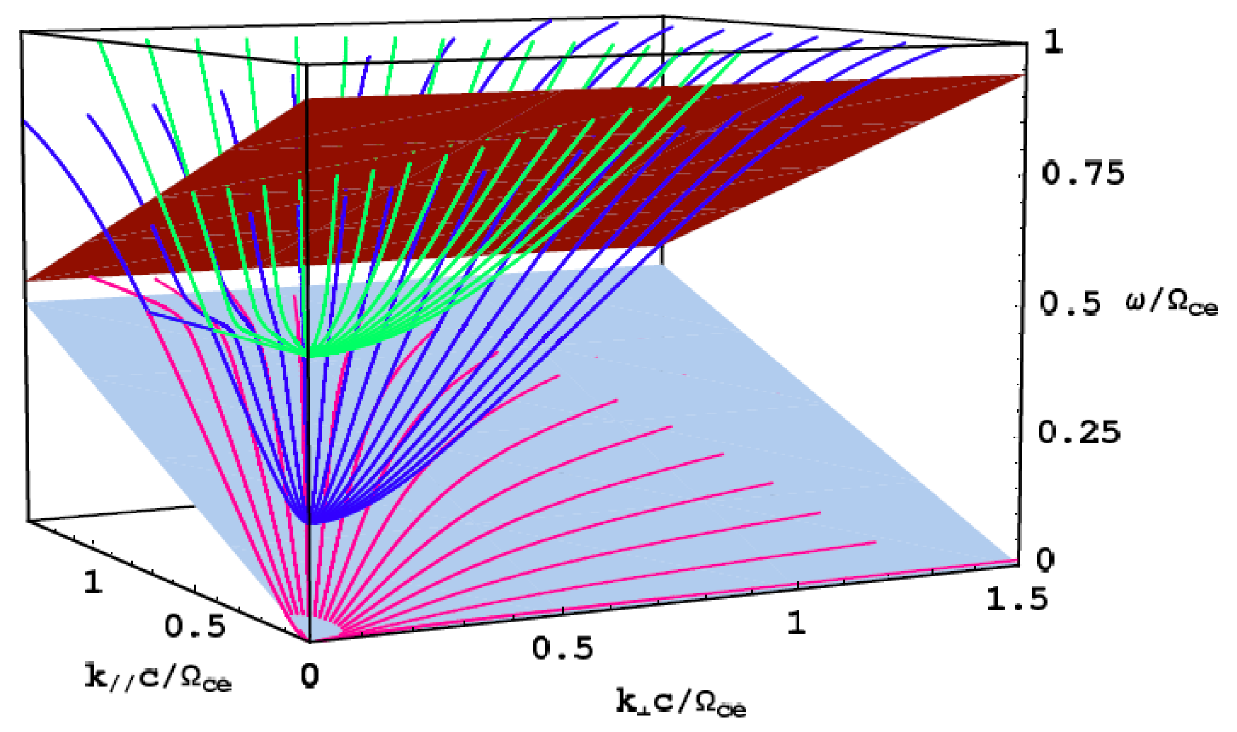
V: Turbulence Cascade and Damping



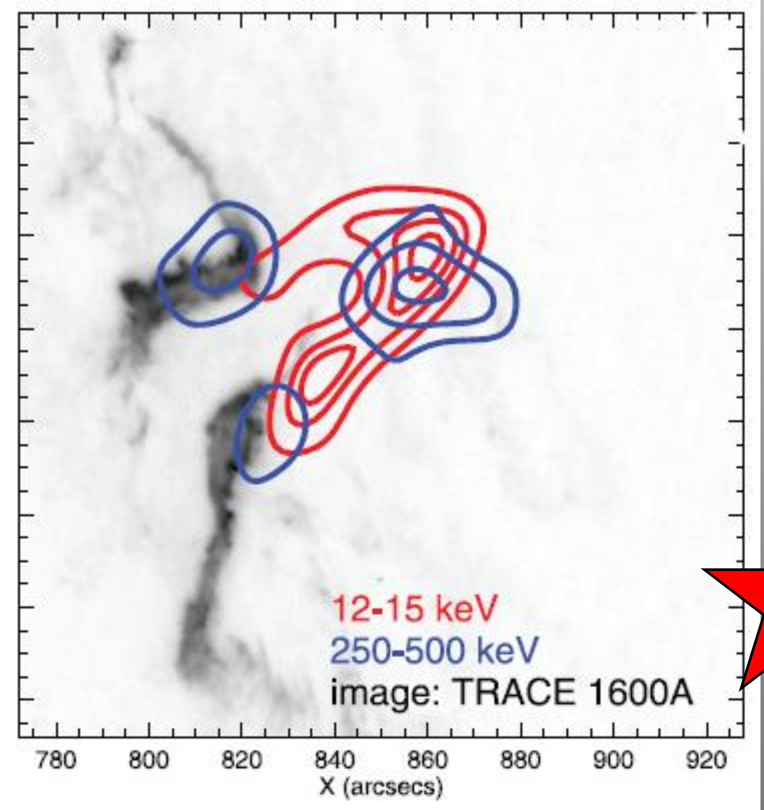
Observation: $\nu_{bf} = 0.235\mathrm{Hz}$ $\gamma_1 = -1.67$, $\gamma_2 = -2.91$ (Leamon et al. 1998)

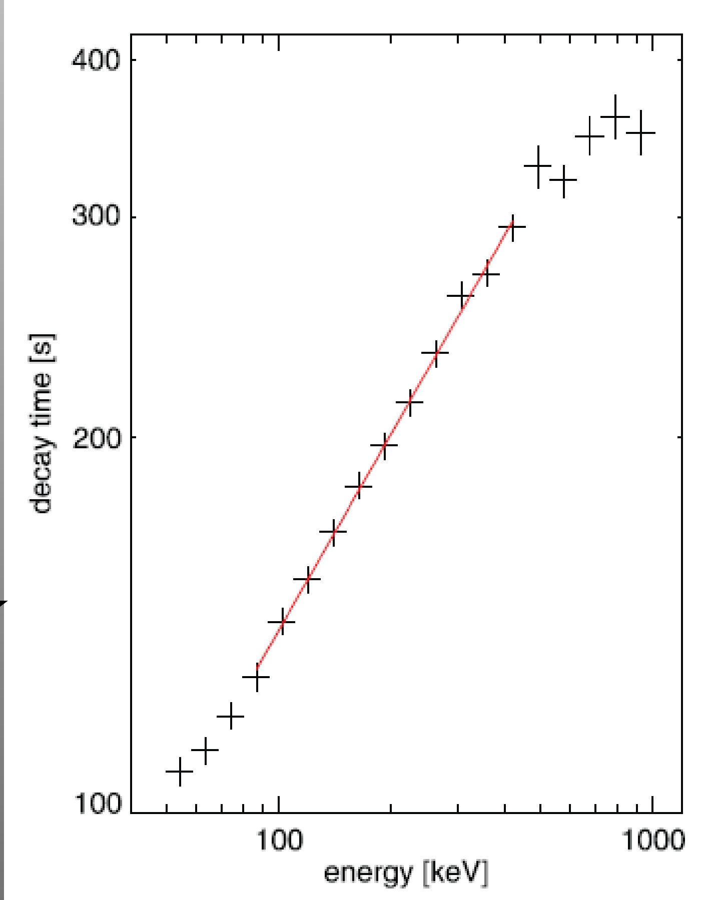
Simulation: $\nu_{bf} = 0.2\mathrm{Hz}$ $\gamma_1 = -1.67$, $\gamma_2 = -2.97$ (Jiang et al. 2008)

V: Dispersion Relation

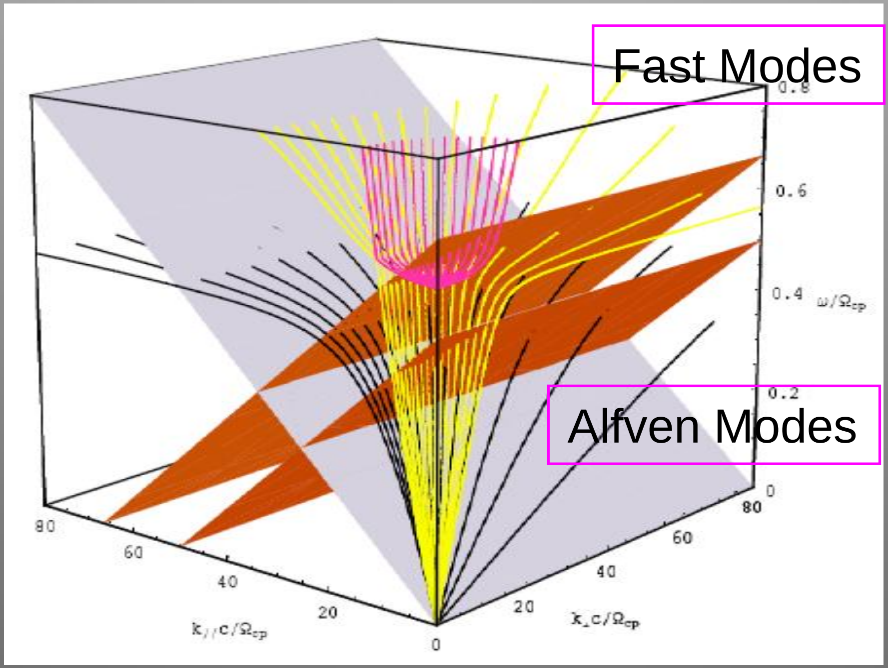


V: Electron-Whistler Resonance





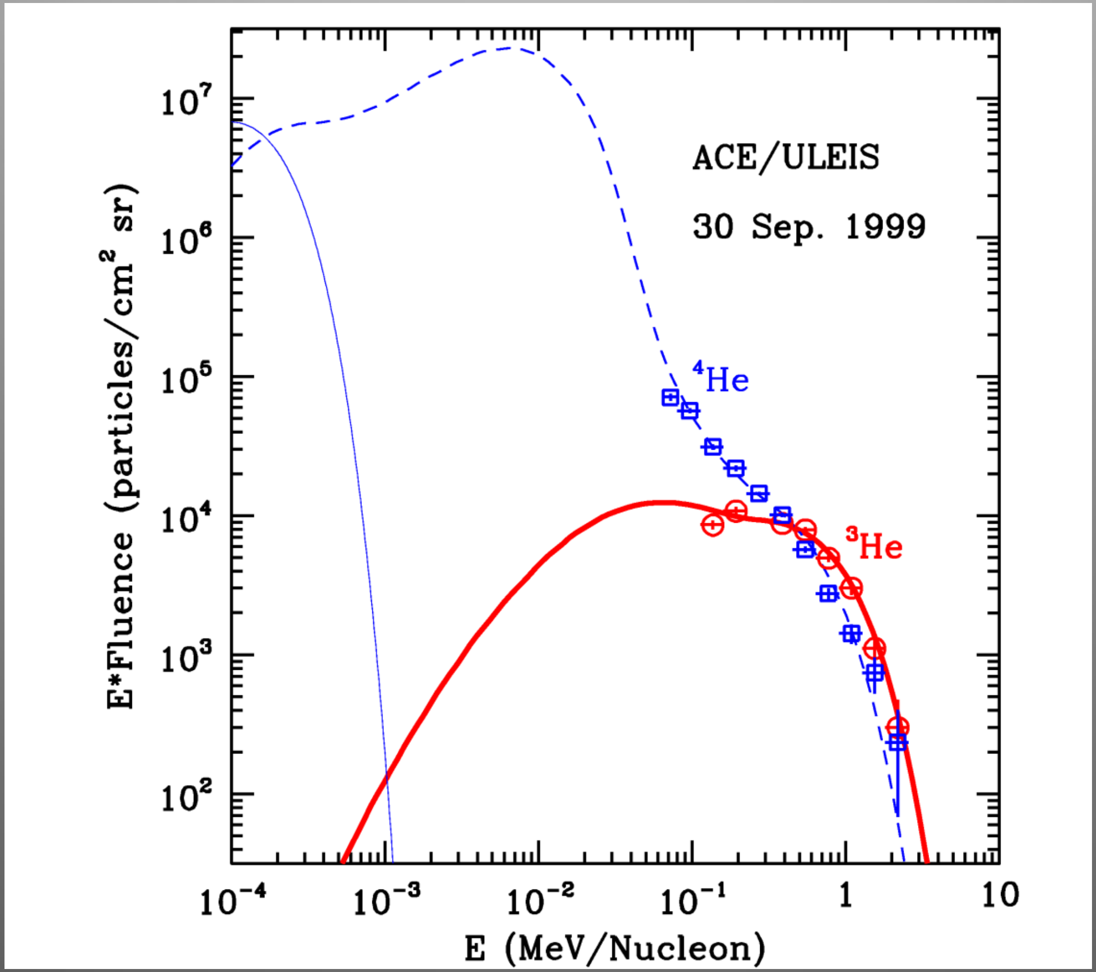
V: Dispersion Relation



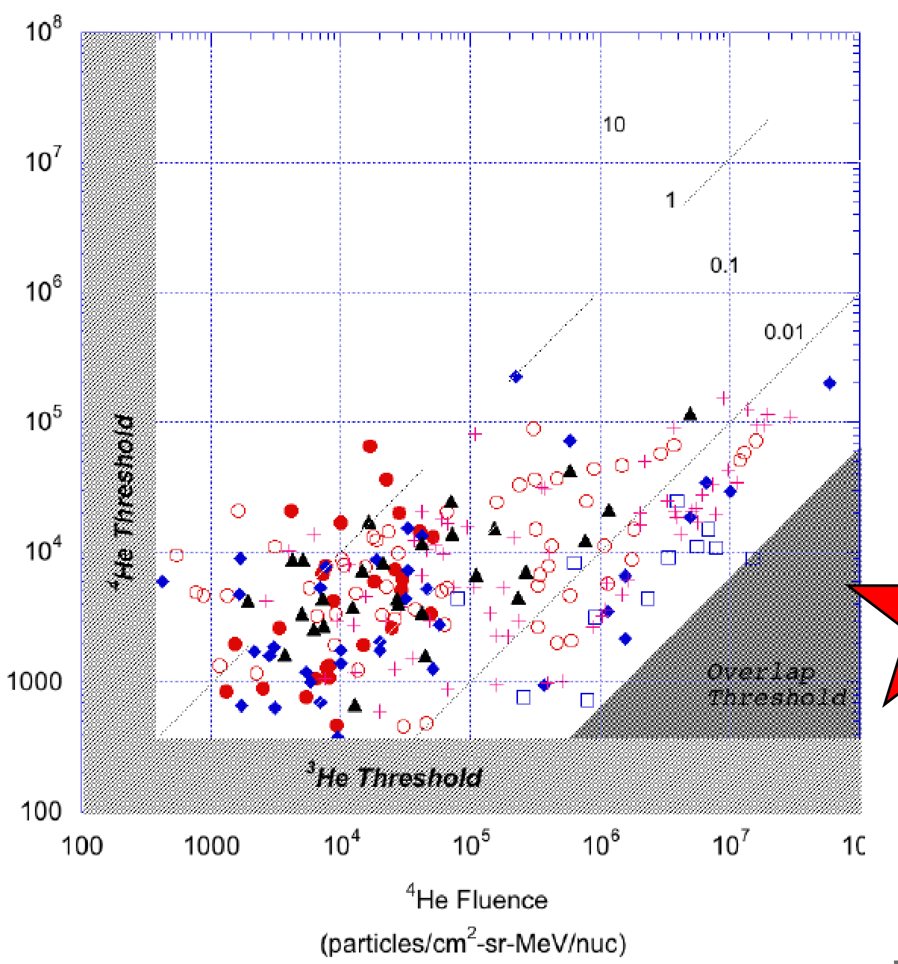
Fast Modes

Alfven Modes

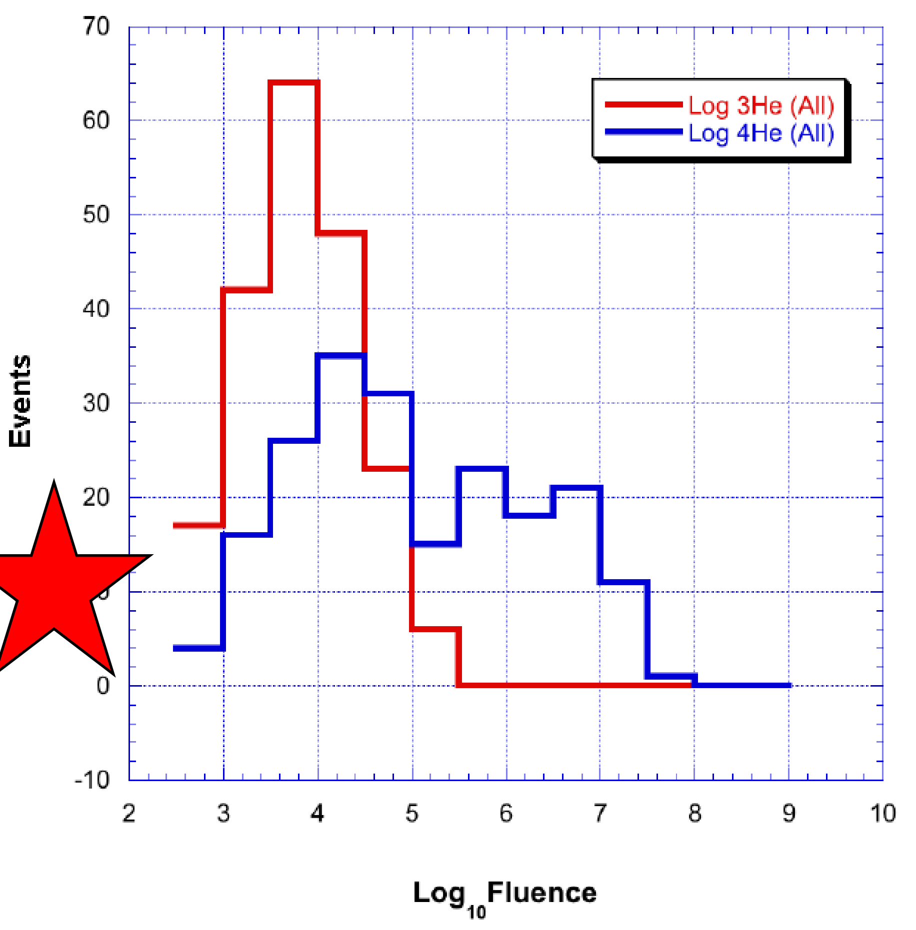
V:3He vs 4He


ACE/ULEIS
30 Sep. 1999
^{4}He
^{3}He
E*Fluence (particles/cm^2 sr)
10^7
10^6
10^5
10^4
10^3
10^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
E (MeV/Nucleon)

V: 3He vs. 4He

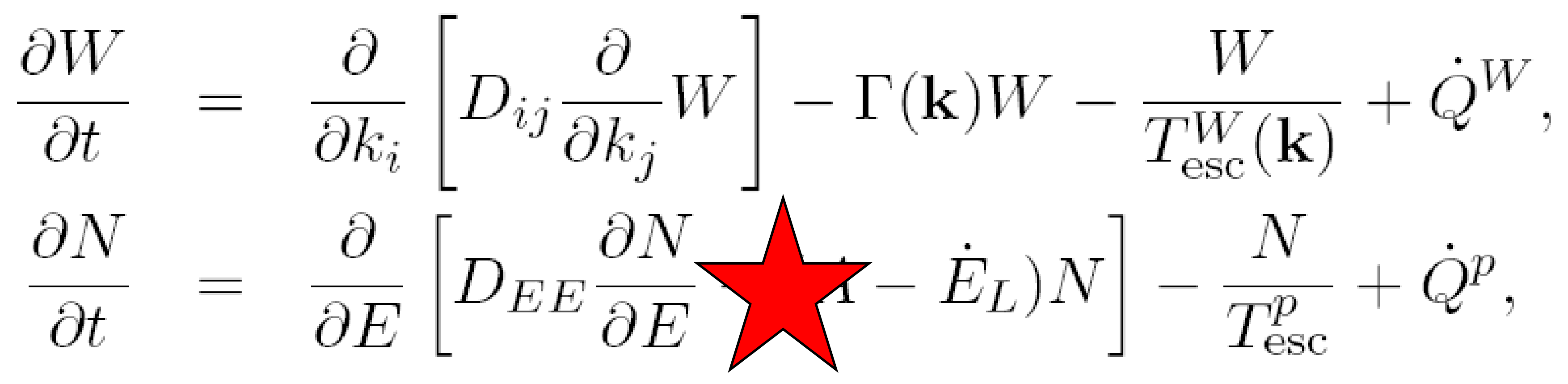


10^8
10^7
10^6
10^5
10^4
1000
100
10
1
0.1
0.01
^{4}He Threshold
Overlap Threshold
^{3}He Threshold
100
1000
10^4
10^5
10^6
10^7
^{4}He Fluence
(particles/cm^2-sr-MeV/nuc)



Events
70
60
50
40
30
20
0
-10
2
3
4
5
6
7
8
9
10
Log 3He (All)
Log 4He (All)
Log$_{10}$Fluence

V: A Complete Treatment of Stochastic Acceleration and Plasma Heating



$$
\begin{aligned}
\frac{\partial W}{\partial t} &= \frac{\partial}{\partial k_i}\left[D_{ij}\frac{\partial}{\partial k_j}W\right] - \Gamma(\mathbf{k})W - \frac{W}{T^W_{\rm esc}(\mathbf{k})} + \dot{Q}^W, \\
\frac{\partial N}{\partial t} &= \frac{\partial}{\partial E}\left[D_{EE}\frac{\partial N}{\partial E} \text{[illegible]} - \dot{E}_L)N\right] - \frac{N}{T^p_{\rm esc}} + \dot{Q}^p,
\end{aligned}
$$

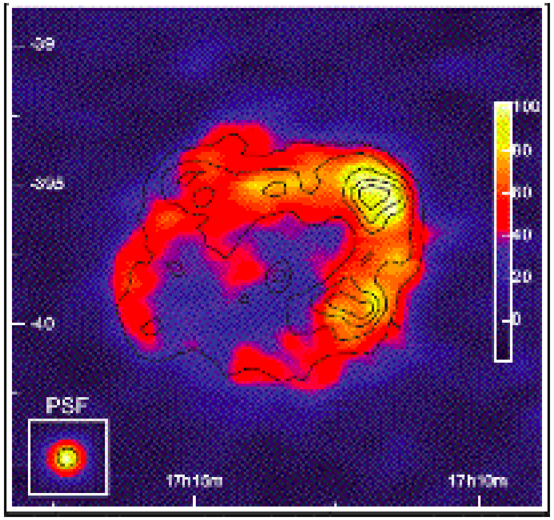
Jiang et al. 2008

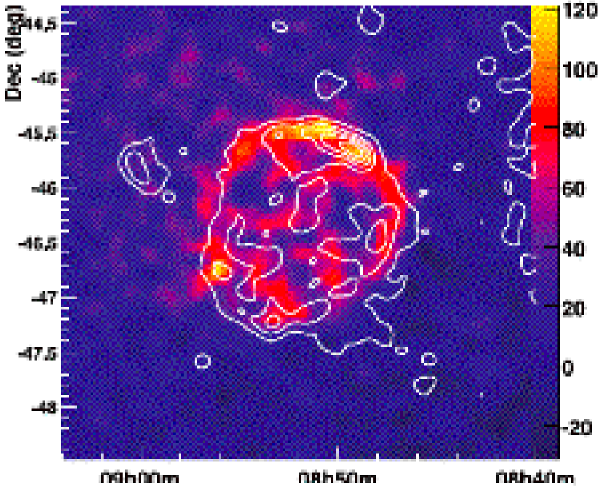
V: A Complete Treatment of Particle Acceleration in Magnetized Dissipative Plasmas

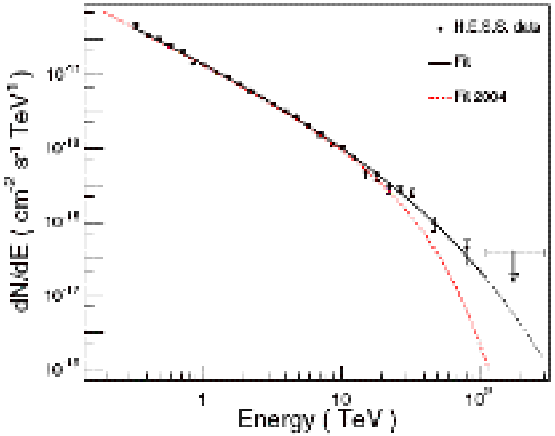
Acceleration by Large Scale Structure
Shock Waves
Electric Fields

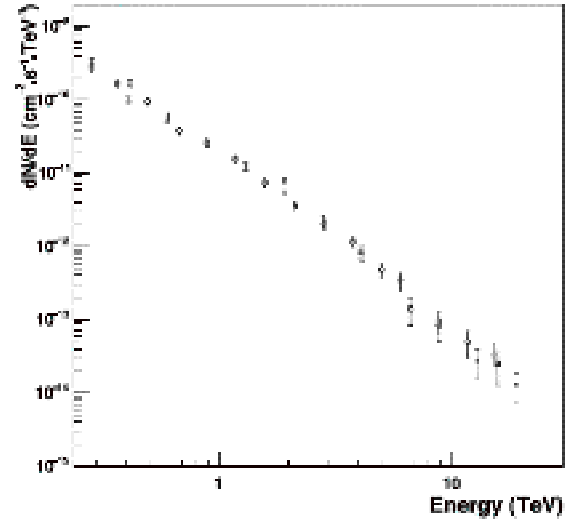
Jiang et al. 2008

Observations



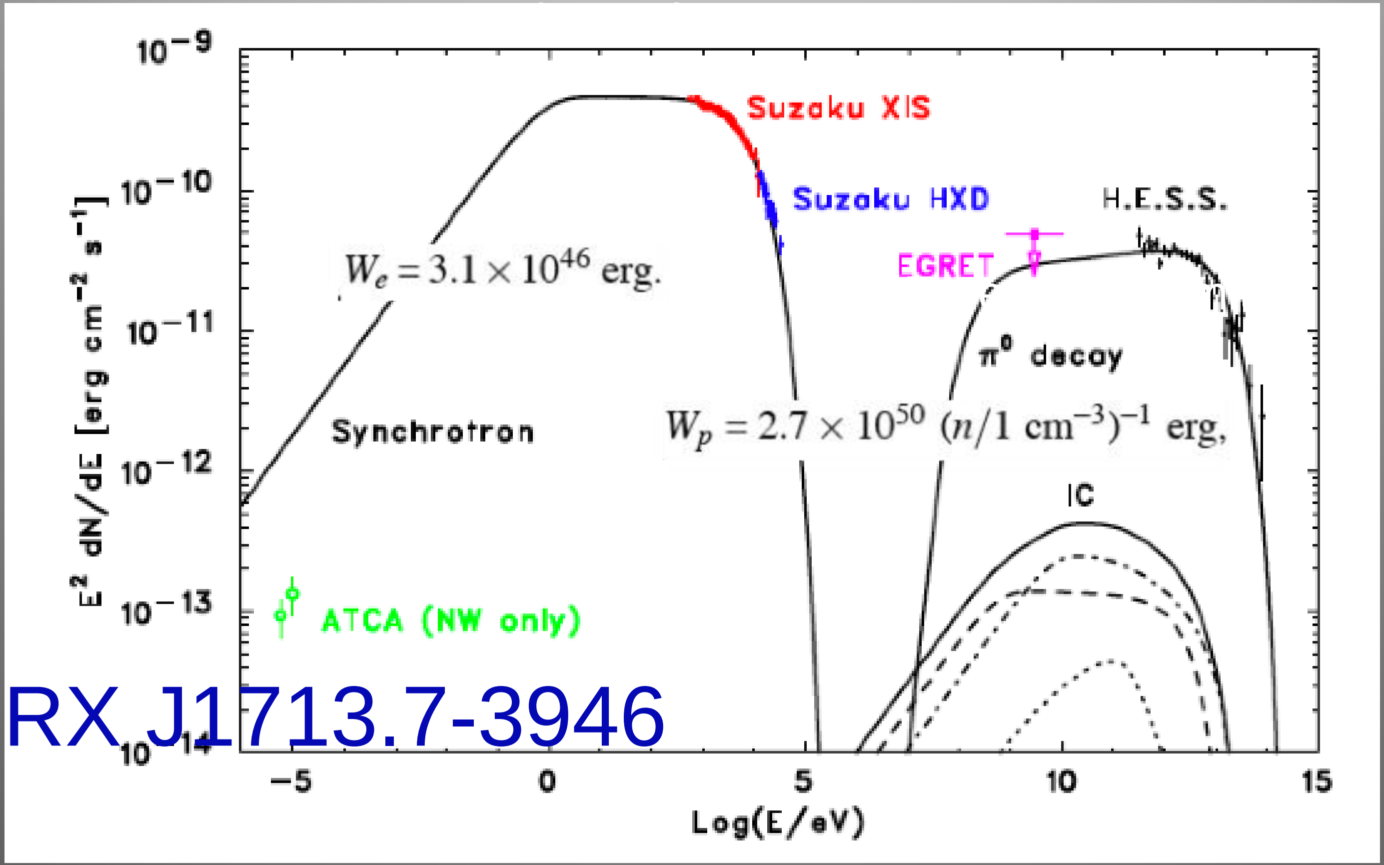






HESS

Challenges to the Hadronic Models



SNR RX J1713.7-3946

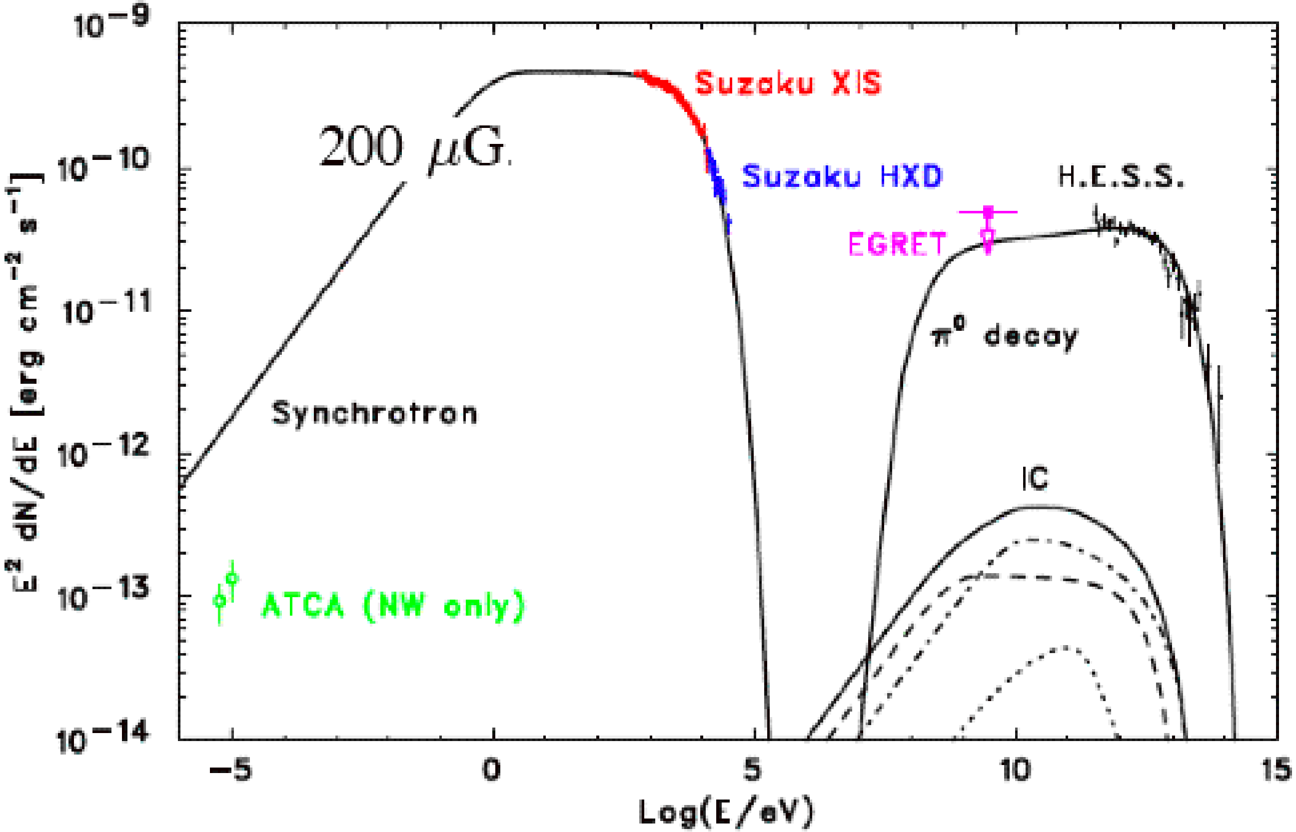
1 Suppression of Electron Acceleration

2 High Energy & 3 Density Requirement

4 Hard Spectrum with $p<2.0$

Tanaka et al.

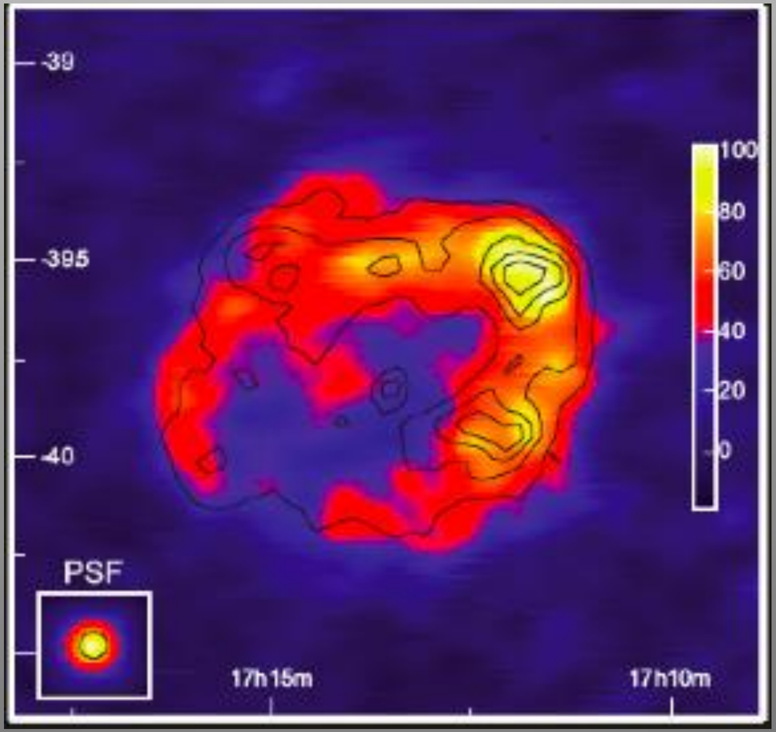
Challenges to the Hadronic Models



5 B Field Amplification

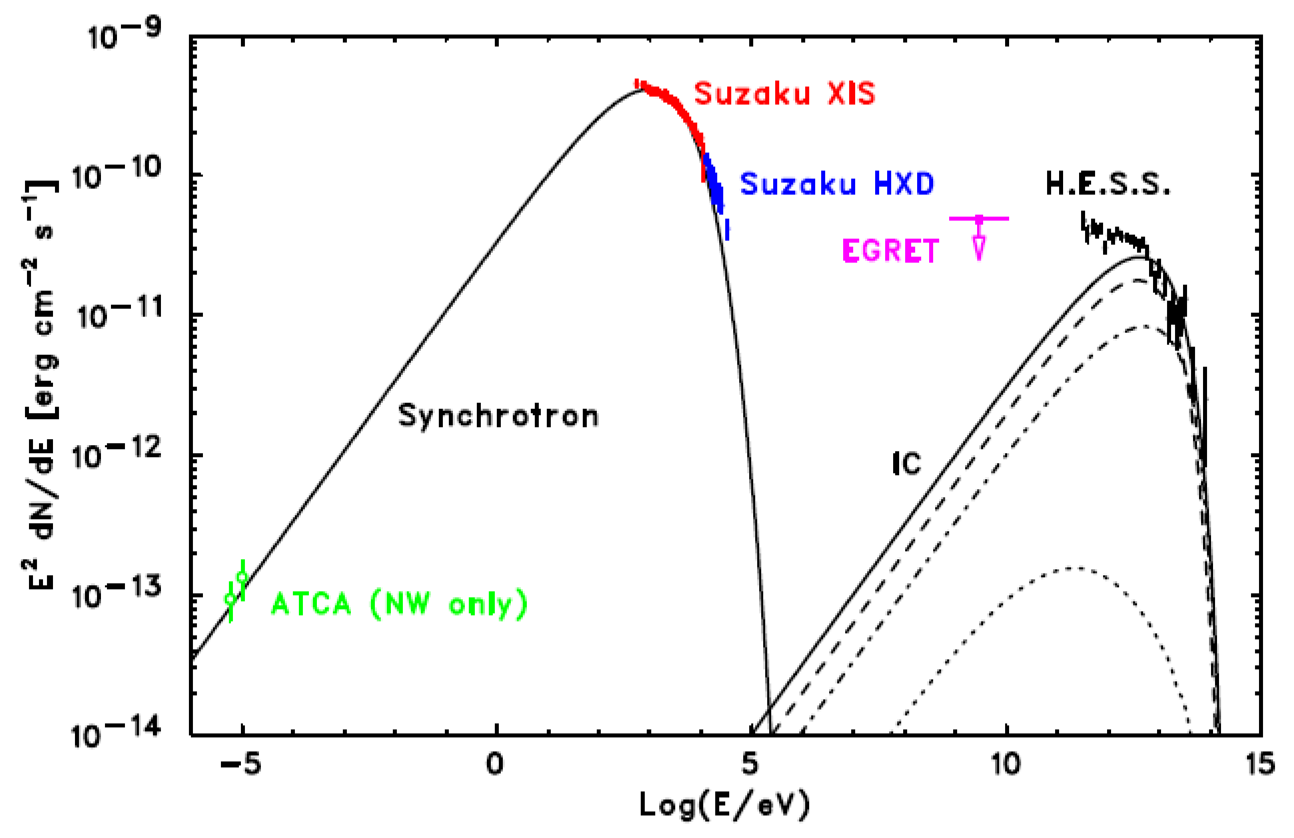
Tanaka et al.

Challenges to the Hadronic Models



6 Lack of Correlation between TeV and Cloud Distribution: Plaga

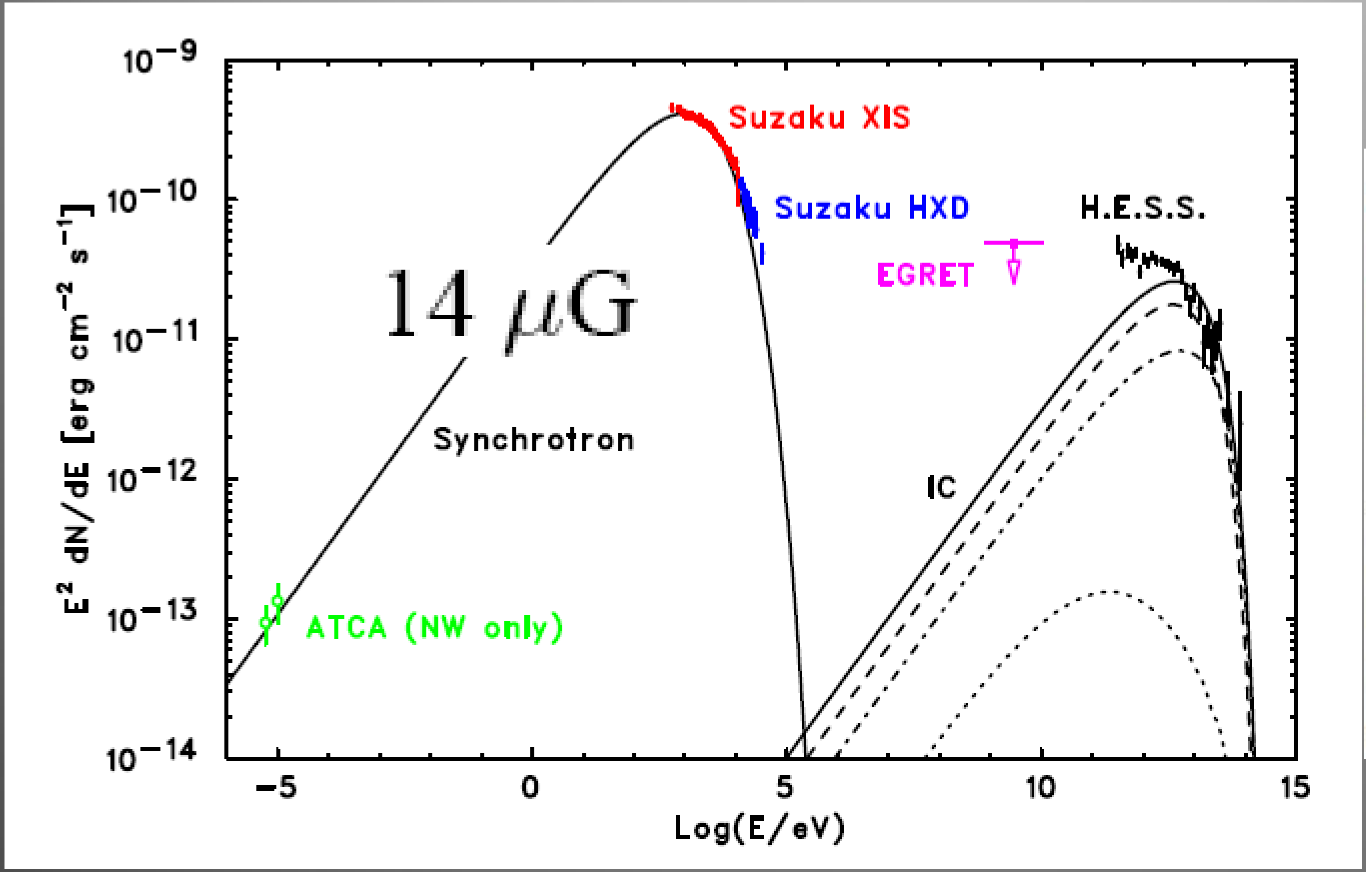
Challenges to the Leptonic Models



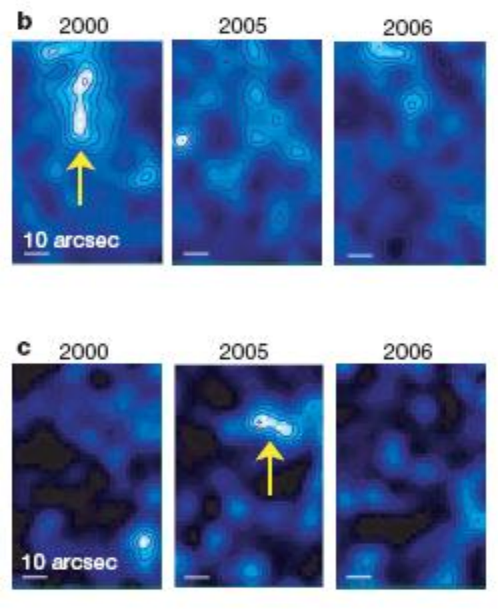
1: TeV spectrum too narrow: Background photon? Porter et al.

Tanaka et al.

Challenges to the Leptonic Models



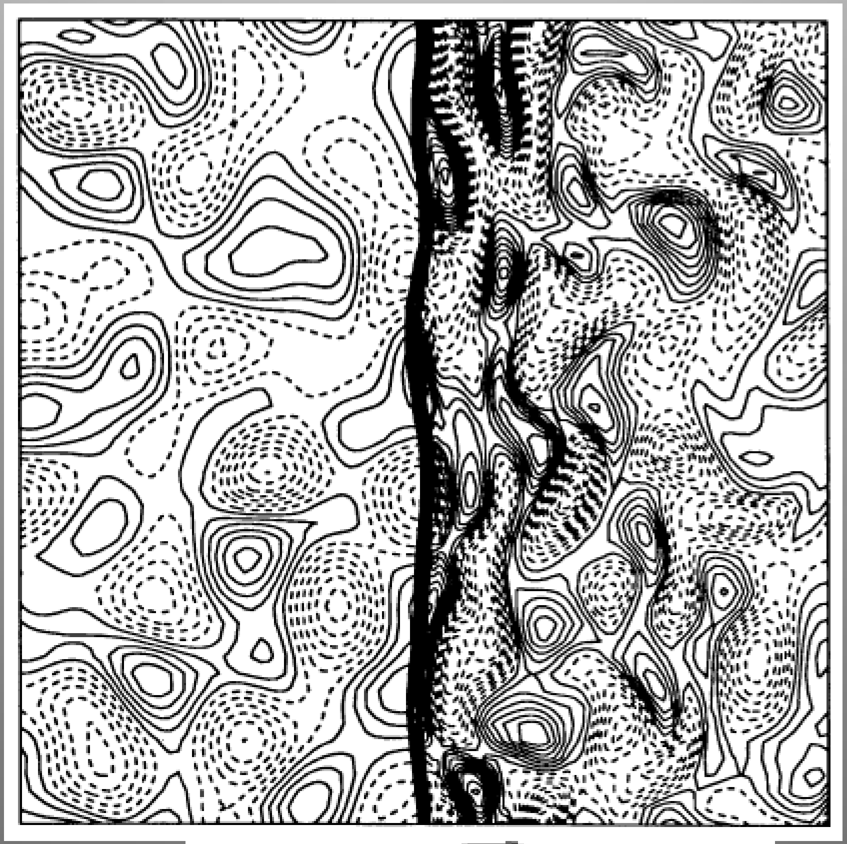
Uchiyama et al. 2007



2: Weak B field: Variability?

Tanaka et al.

A New Paradigm for Collisionless Shocks



$$\vec{\omega} = \vec{\nabla} \times \vec{v}.$$

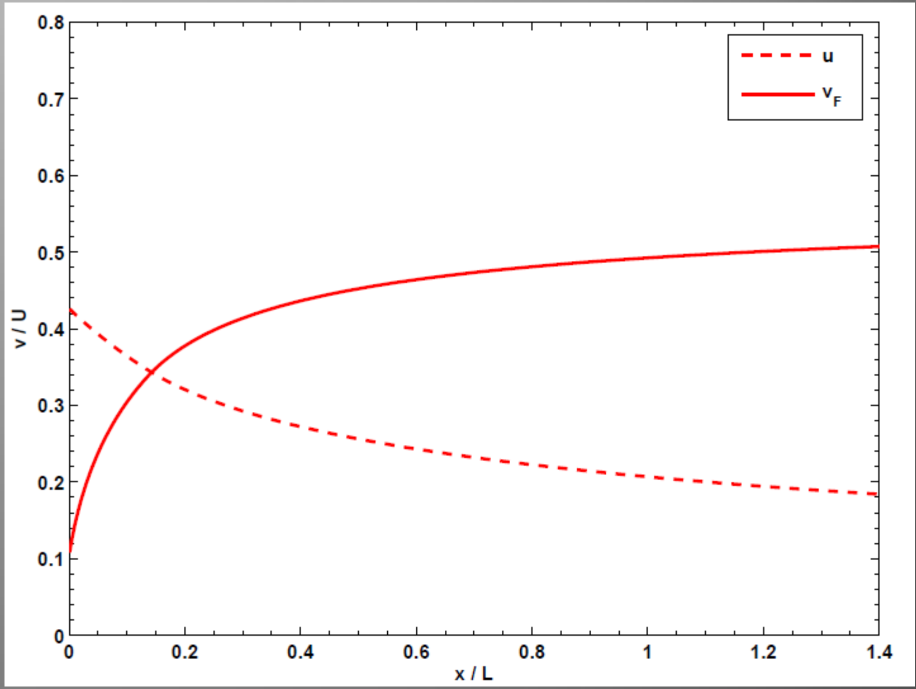
Lee et al. 1994

Speed Profiles in the Downstream

$$U^2 = 5v_S^2 + 5u^2 + 2v_A^2 + U^2/16$$

$$Q = C_1 \rho u^3 / L$$

$$\begin{aligned}
\frac{u(x)}{U} &= \frac{0.25a}{C_1 x/L + a^{1/2}}\,, \\
\frac{v_S(x)}{U} &= \left[\frac{3}{16} - \frac{a^2}{16\left(C_1 x/L + a^{1/2}\right)^2} - \frac{2v_A^2}{5U^2}\right]^{1/2}, \\
\frac{v_F(x)}{U} &= \left[\frac{5}{16} - \frac{5a^2}{48\left(C_1 x/L + a^{1/2}\right)^2} + \frac{v_A^2}{3U^2}\right]^{1/2}.
\end{aligned}$$



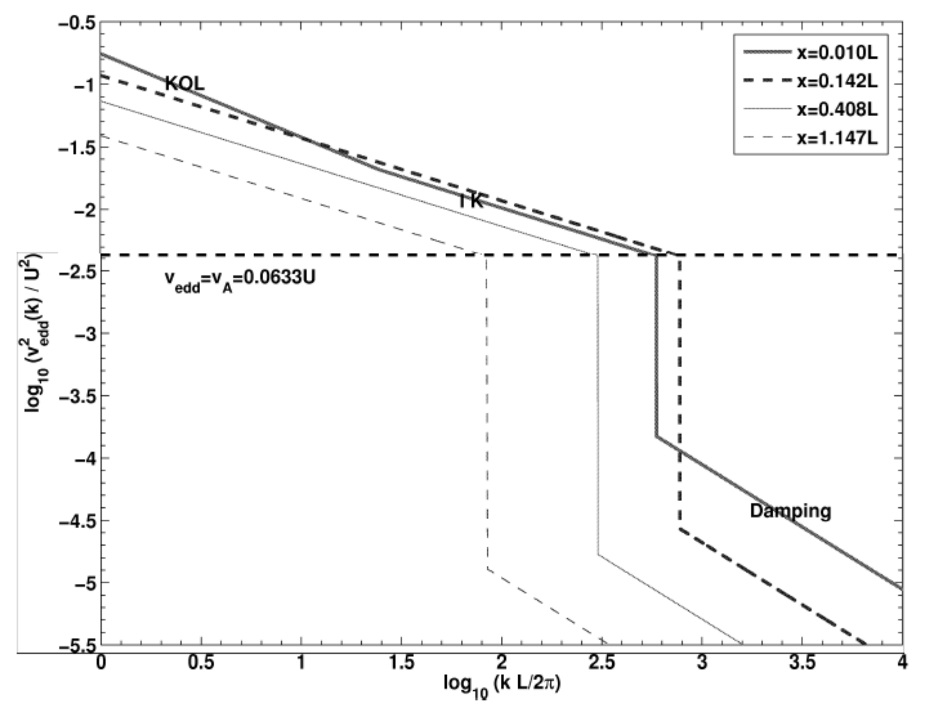
Turbulence spectrum

$$W(k) = (u^2/4\pi)(2\pi/L)^{2/3}k^{-11/3}$$

$$k_t = (u/v_F)^3 k_m$$

$$W(k) = (u^2/4\pi)k_m^{2/3}k_t^{-1/6}k^{-7/2}$$

$$k_d = [u^3 v_F/v_A^4]k_m$$



Electron Acceleration by Fast Mode Waves

$$\Lambda_T(\theta,k) = \frac{(2\pi k_B)^{1/2} k \sin^2\theta}{2(m_e+m_p)\cos\theta}\left[(T_e m_e)^{1/2}\exp\left(-\frac{m_e\omega^2}{2k_B T_e k_{||}^2}\right) + (T_p m_p)^{1/2}\exp\left(-\frac{m_p\omega^2}{2k_B T_p k_{||}^2}\right)\right],$$

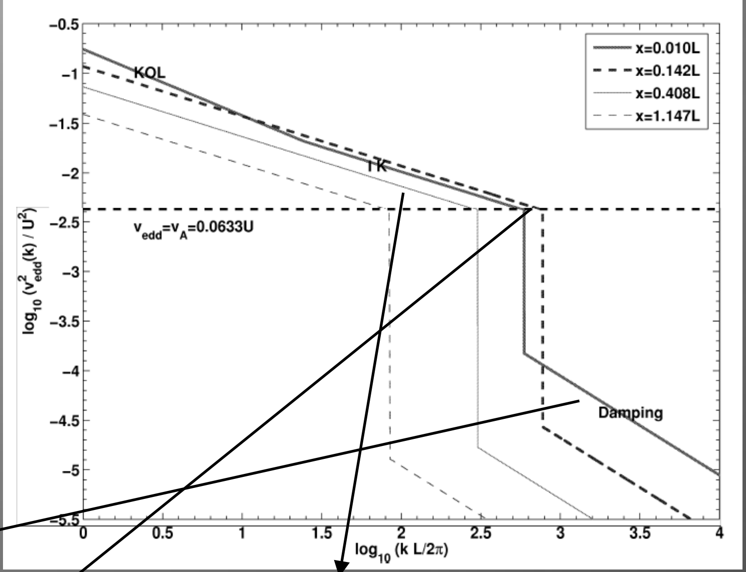
$$\tau_{sc} = 2\pi/ck_d$$

$$\tau_{ac} = (3c^2/v_F^2)\tau_{sc}$$

$$\tau_{esc} = (L^2/4c^2)\tau_{sc}$$

$$p = (9/4+\tau_{ac}/\tau_{esc})^{1/2} - 1/2$$

$$\gamma_c m_e c^2 = 2\pi qB/k_d$$

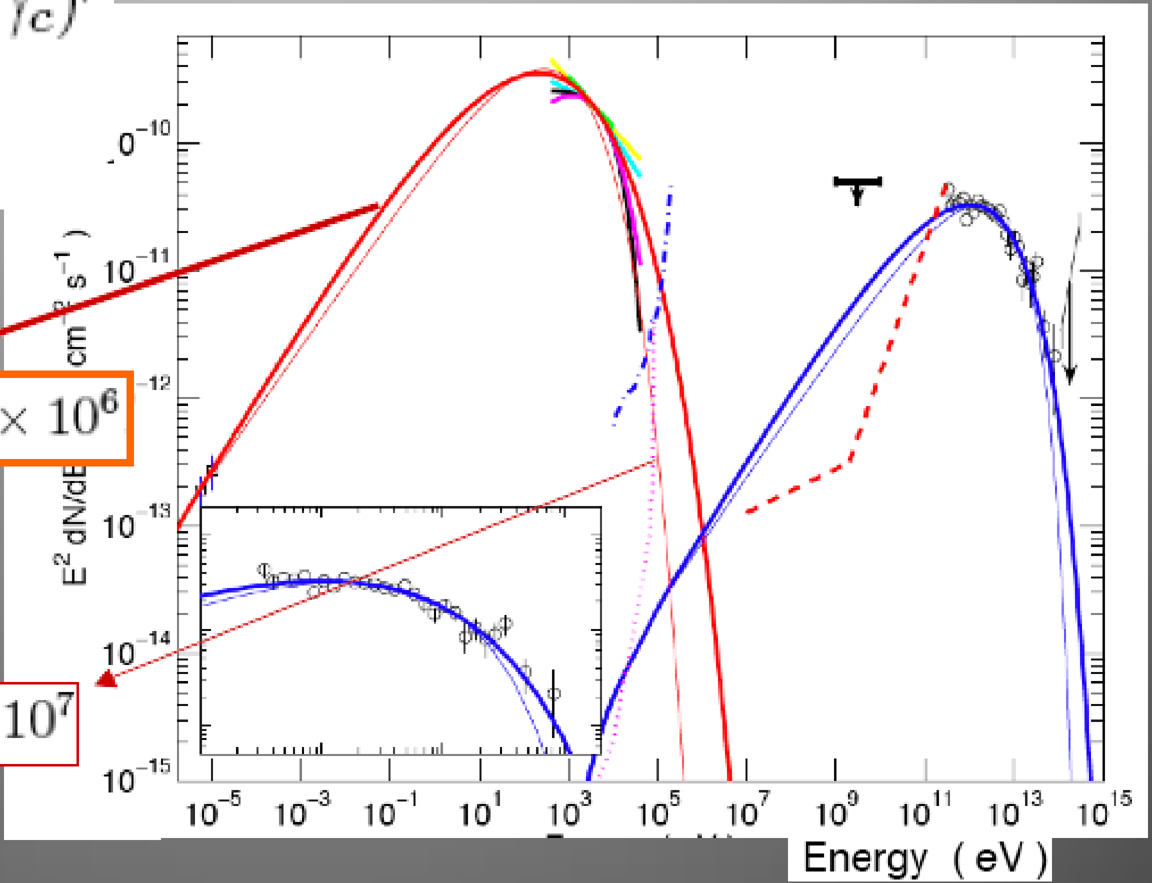


$$f \propto \gamma^{-p}\exp-(\gamma/\gamma_c)^{\beta} \text{ with } \beta = 1/2.$$

Spectral Fit to SNR RX J1713.7-3946

$$f \propto \gamma^{-p} \exp -(\gamma/\gamma_c)^{\beta}$$

$$B = 12.0\ \mu\mathrm{G},$$



$$\beta = 0.5,\ p = 1.85,\ \gamma_c = 7.2 \times 10^6$$

$\beta = 1.0$ $p = 2.0$ $\gamma_c = 4.4 \times 10^7$

The Nature of the SNR Shock

$$\boxed{B = 12.0\ \mu\mathrm{G},}$$

$$\boxed{\gamma_c m_e c^2 = 2\pi q B/k_d}$$

$$2\pi/k_d = \gamma_c m_e c^2/qB = 1.02 \times 10^{15}\ \mathrm{cm}$$

$$\boxed{\tau_{sc} = 2\pi/c k_d}$$

$$\boxed{\tau_{ac} = (3c^2/v_F^2)\tau_{sc}}$$

$$\boxed{\tau_{esc} = (L^2/4c^2)\tau_{sc}}$$

$$\boxed{p = (9/4 + \tau_{ac}/\tau_{esc})^{1/2} - 1/2}$$

$$L = 4.04 \times 10^{17} U_0^{-1}\ \mathrm{cm},$$

Kelvin-Helmholtz Instability?

$$\boxed{k_d = [u^3 v_F/v_A^4]k_m}$$

$$n_e = 1.33 \times 10^{-2} U_0^{-5/2}\ \mathrm{cm}^{-3},$$

No Thermal X-rays

X-ray Variability

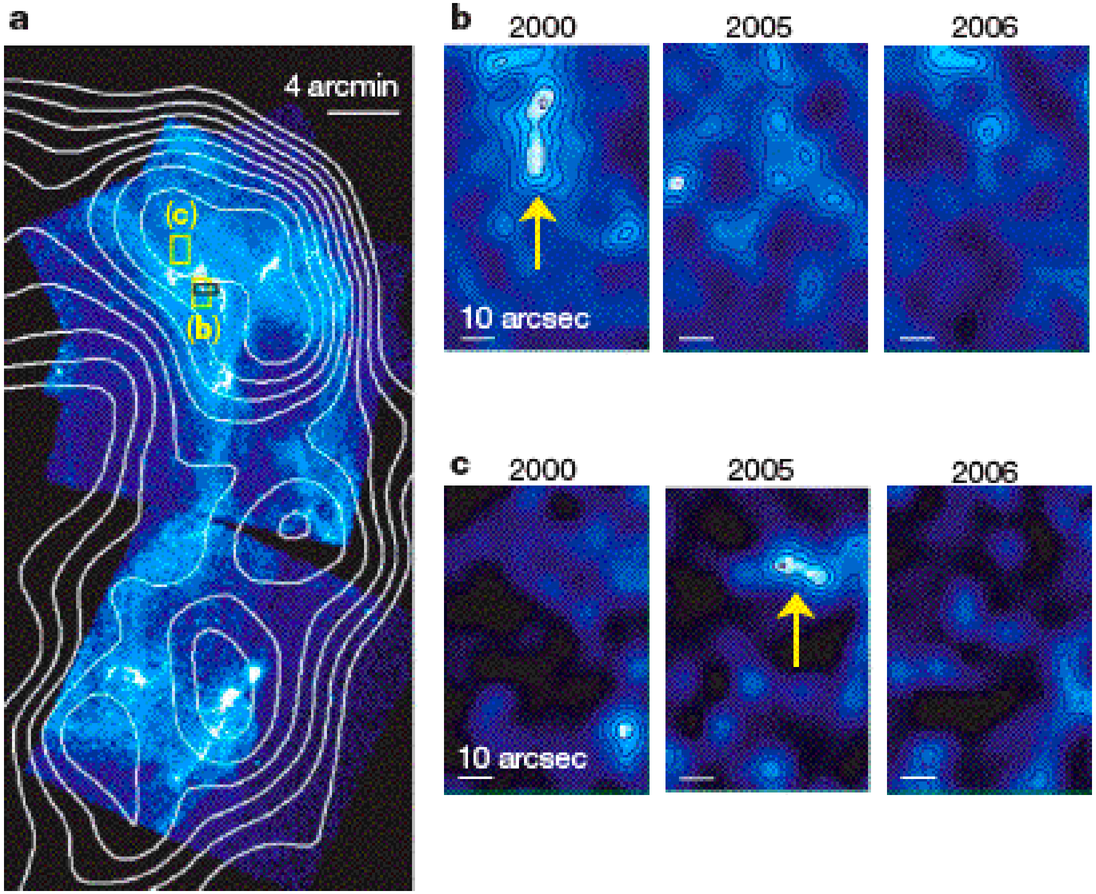
Scattering Mean Free path

$$2\pi/k_d = 1.02 \times 10^{15}\ \mathrm{cm}$$

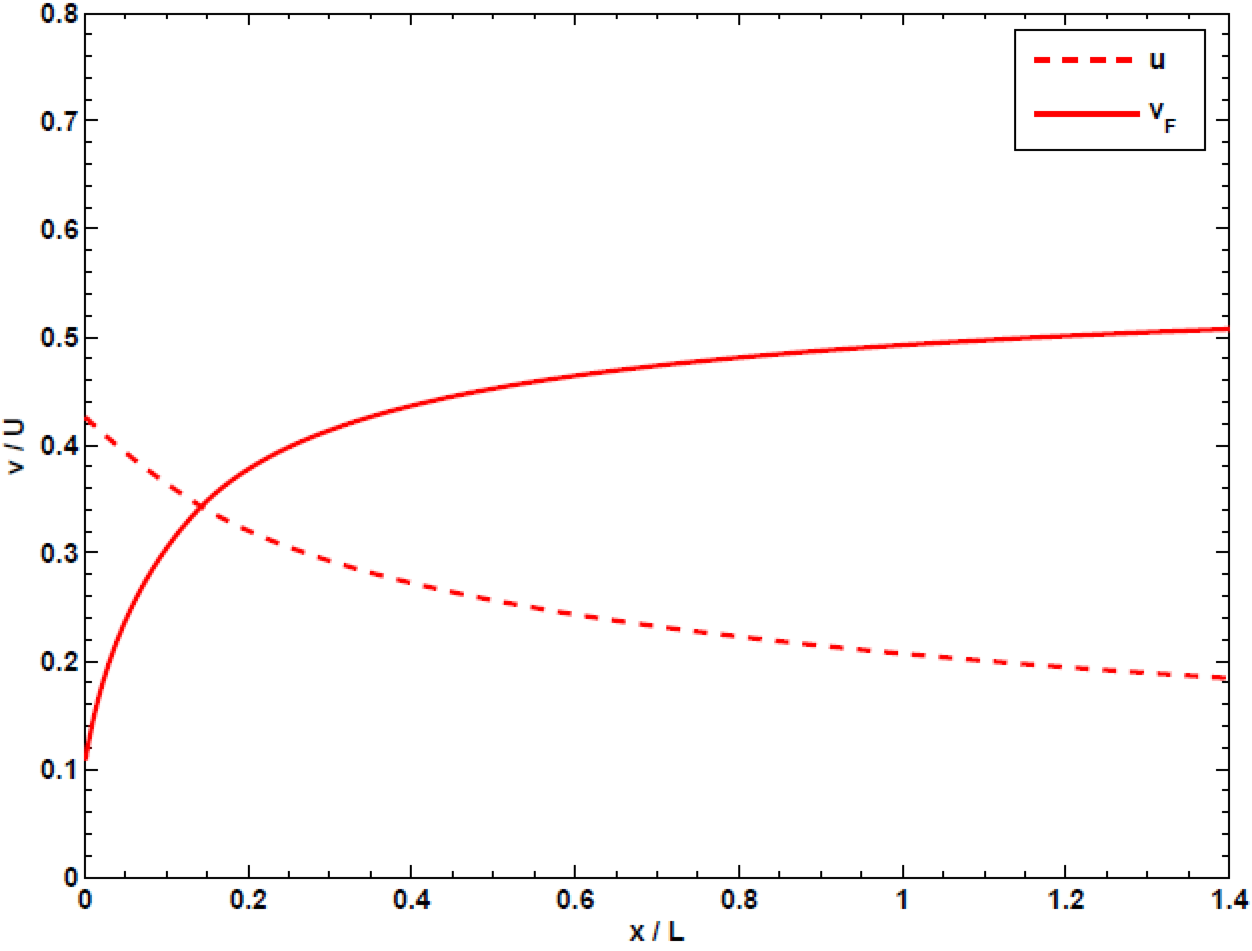
Filament Width

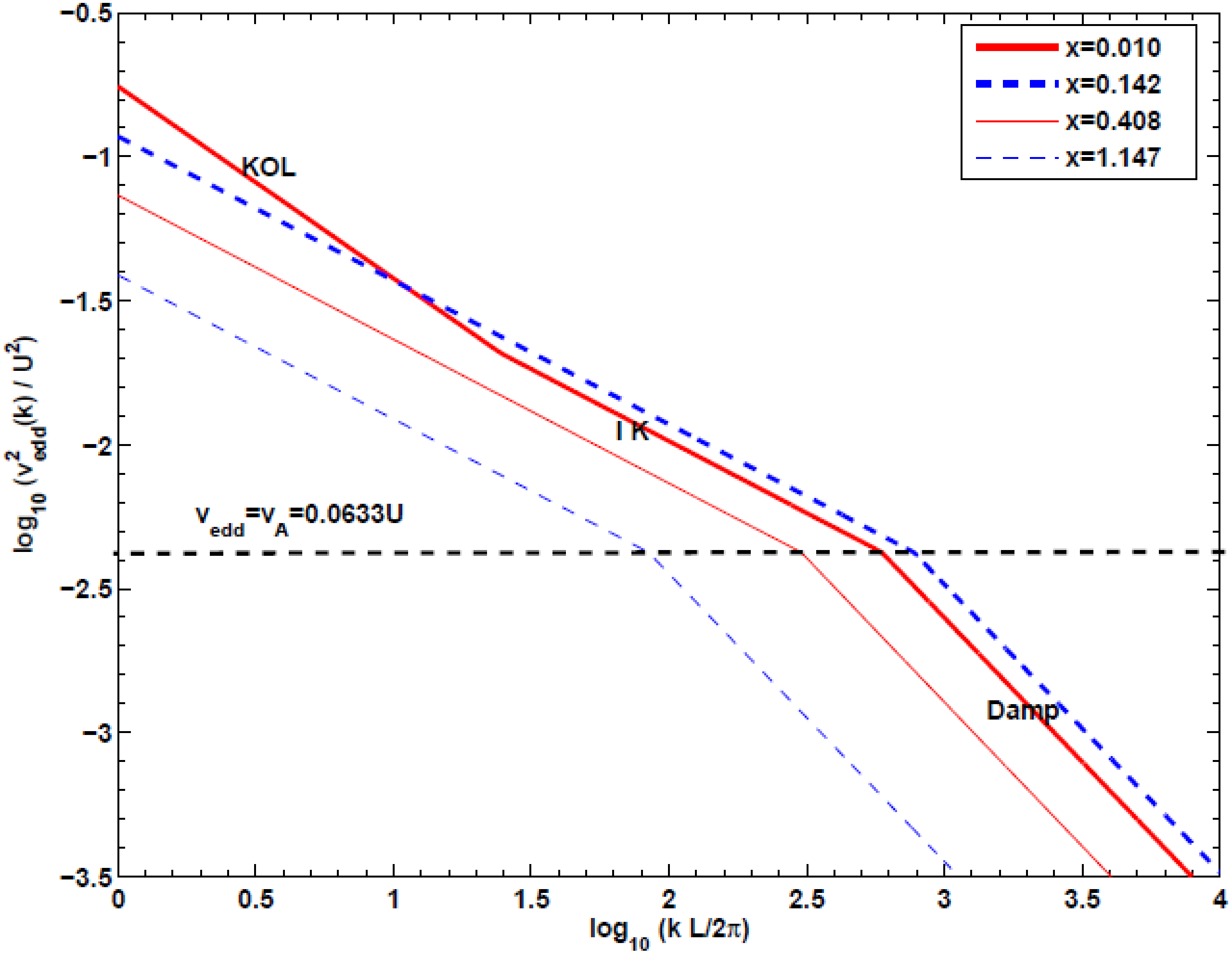
$$w \sim 4''\!.0 \simeq 6.0 \times 10^{16}\ \mathrm{cm},$$

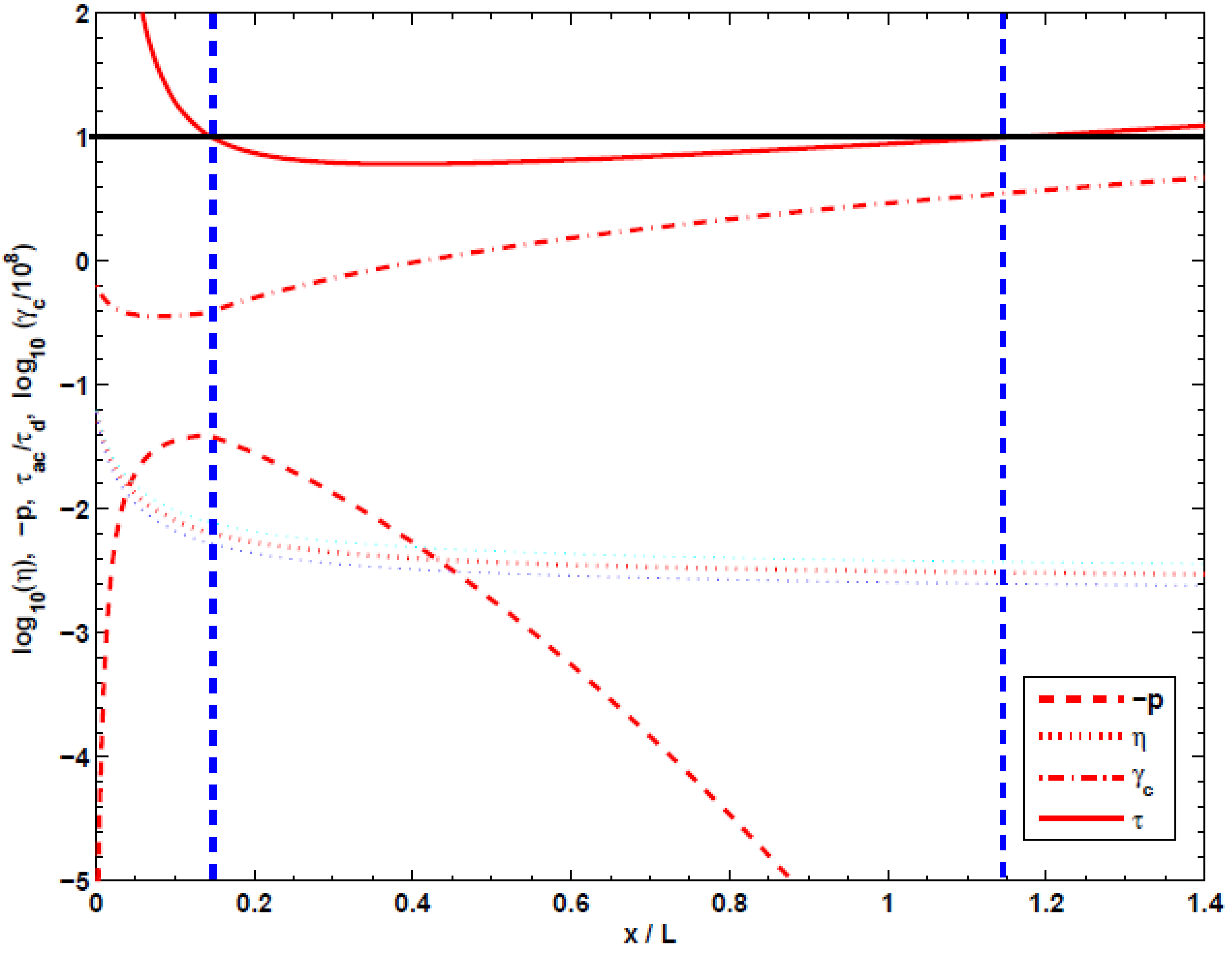
Diffusion Time: 0.93 yr



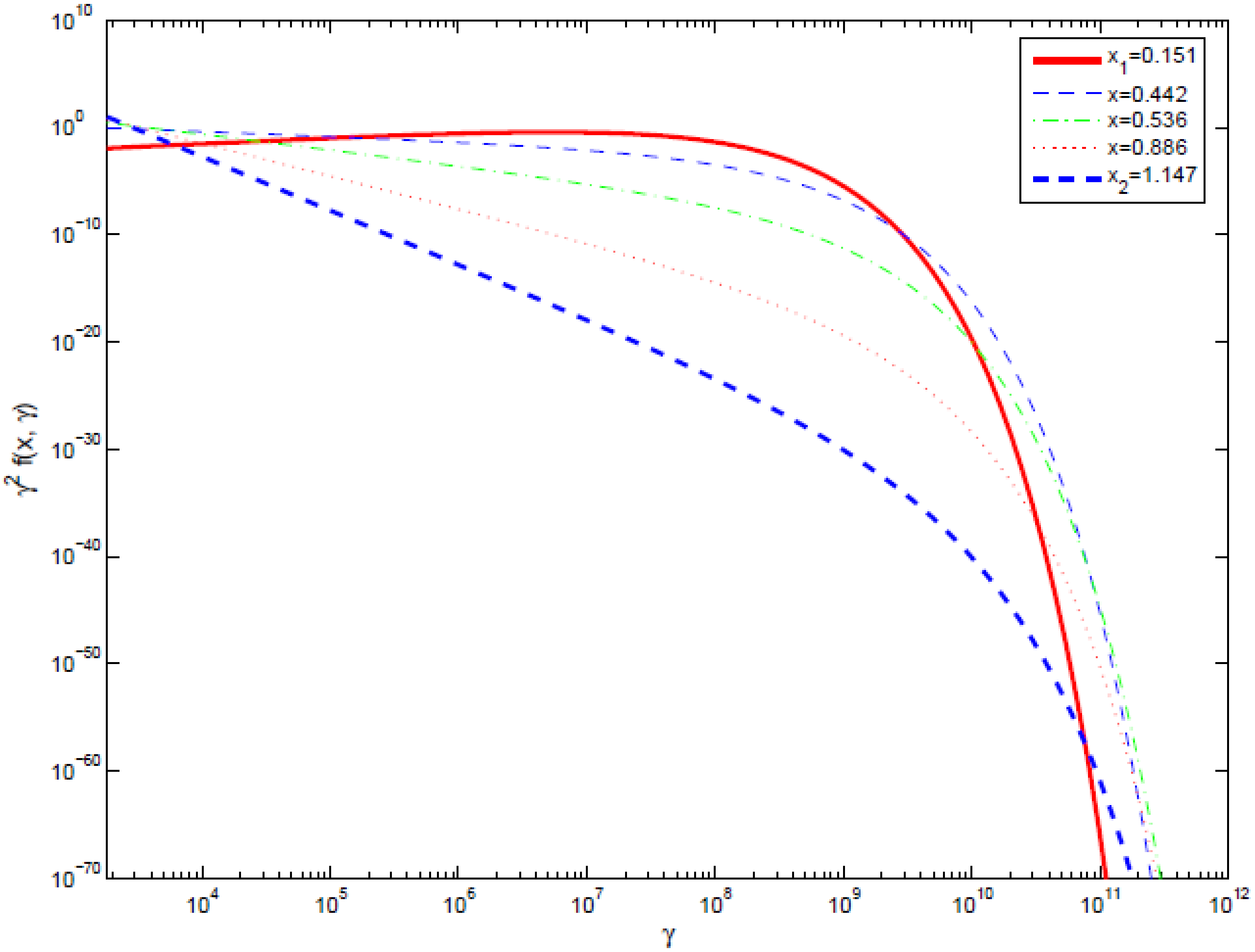
Uchiyama et al. 2007


u
v_F
v / U
x / L
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
0.2
0.4
0.6
0.8
1
1.2
1.4

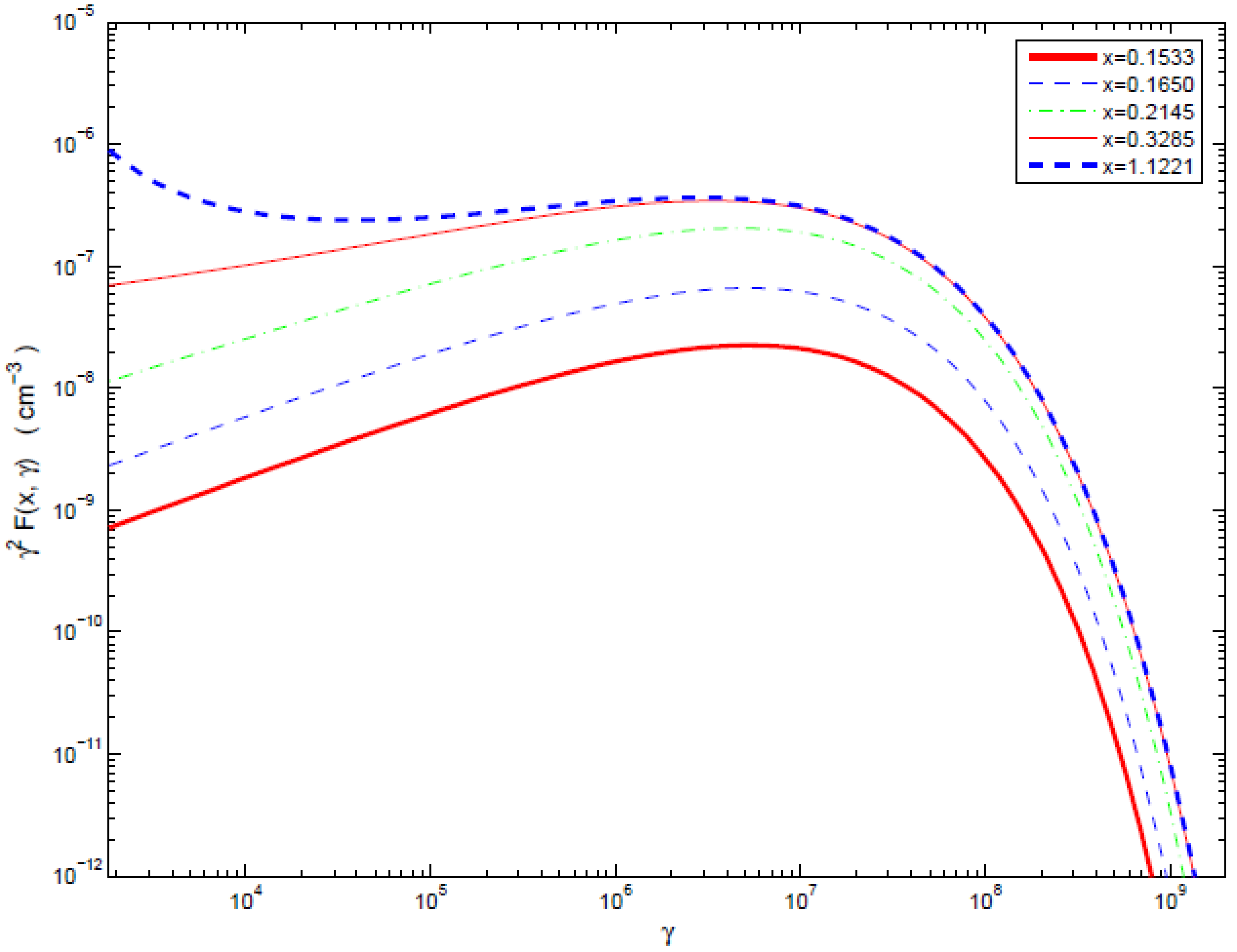

x=0.010
x=0.142
x=0.408
x=1.147
KOL
IK
Damp
$v_{edd}=v_A=0.0633U$
$\log_{10}(v^2_{edd}(k)/U^2)$
$\log_{10}(k L/2\pi)$
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
0
0.5
1
1.5
2
2.5
3
3.5
4

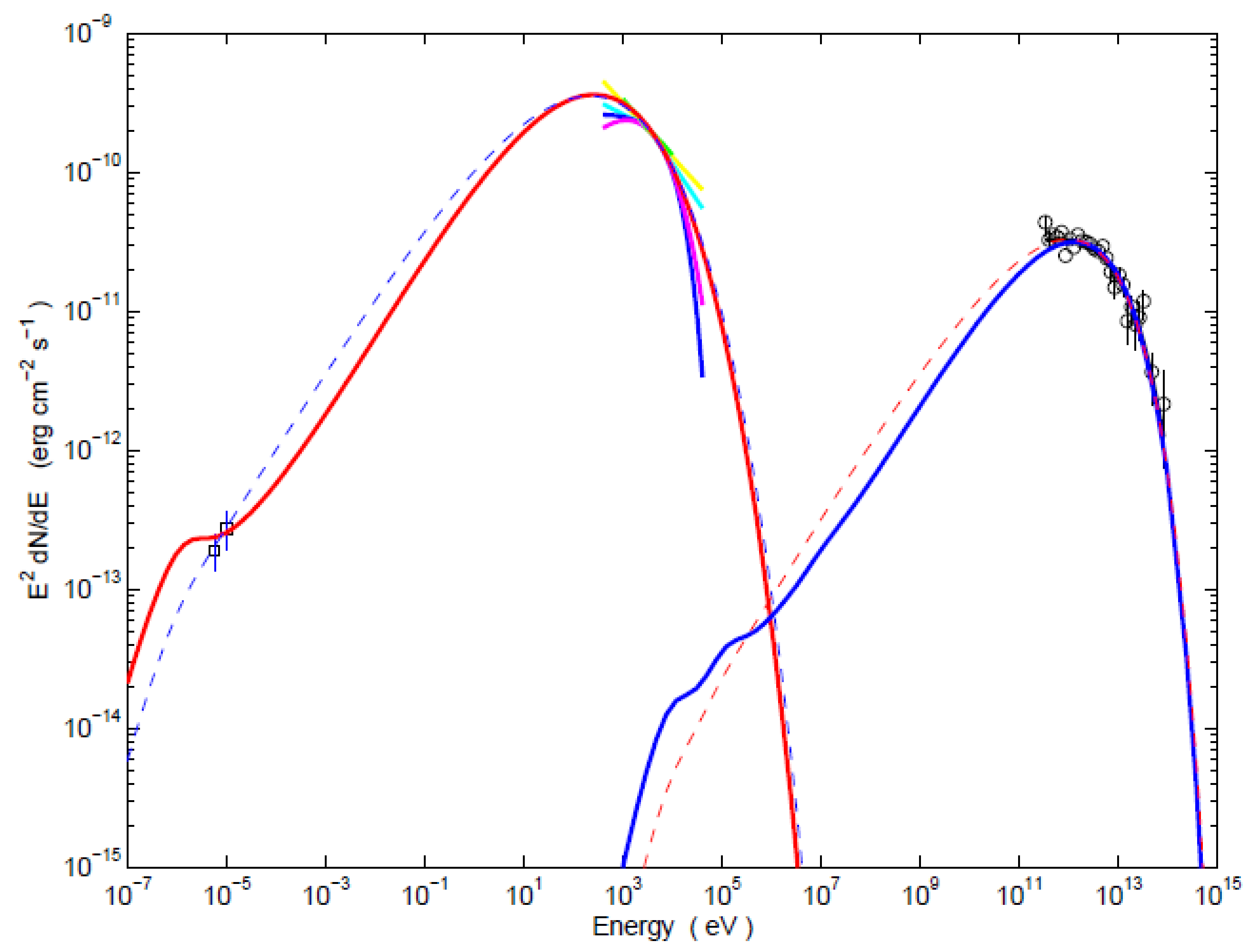


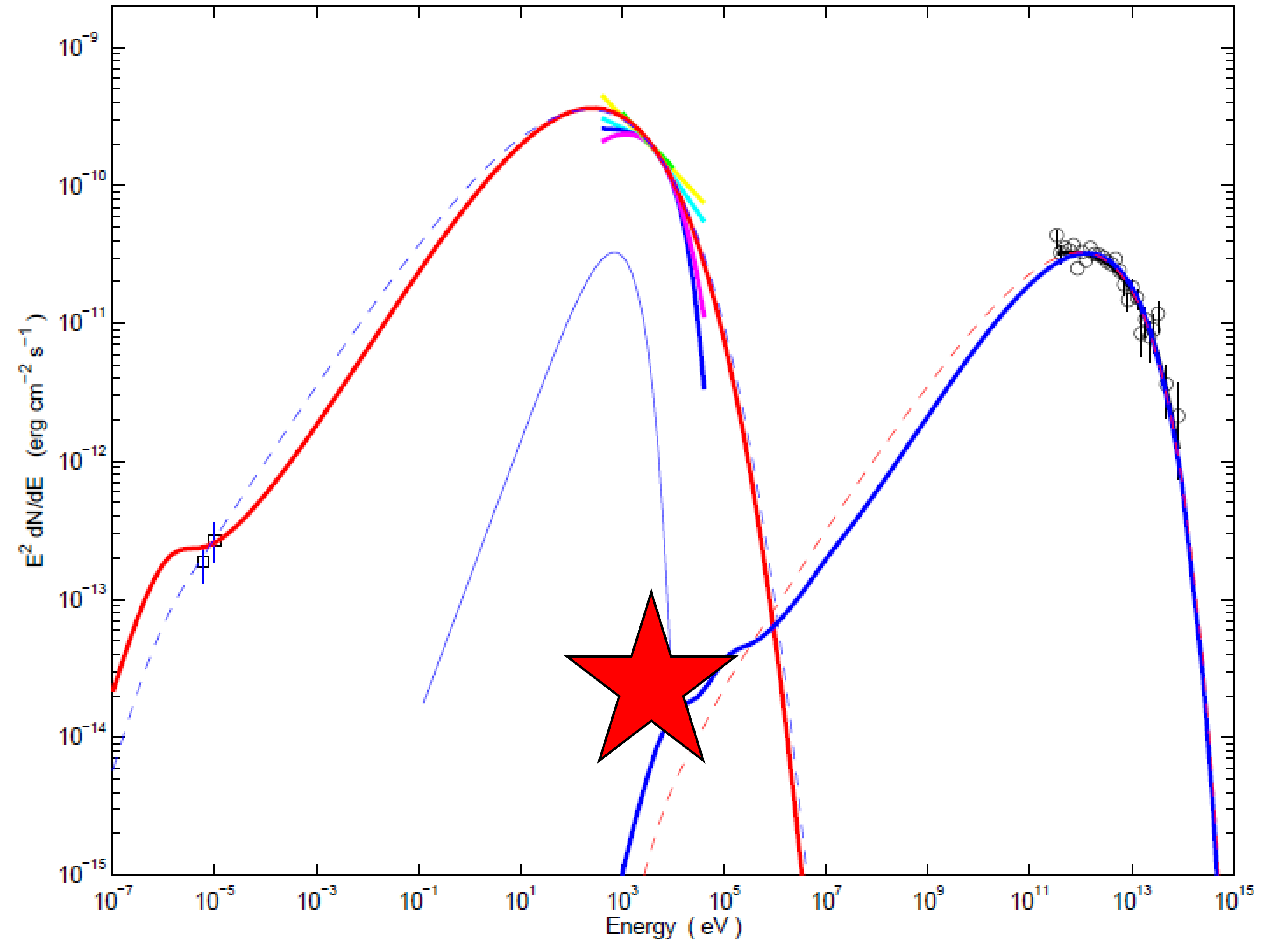
$\log_{10}(\eta)$, $-p$, τ_{ac}/τ_d, $\log_{10}(\gamma_c/10^8)$
x / L
2
1
0
−1
−2
−3
−4
−5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
−p
η
γ_c
τ

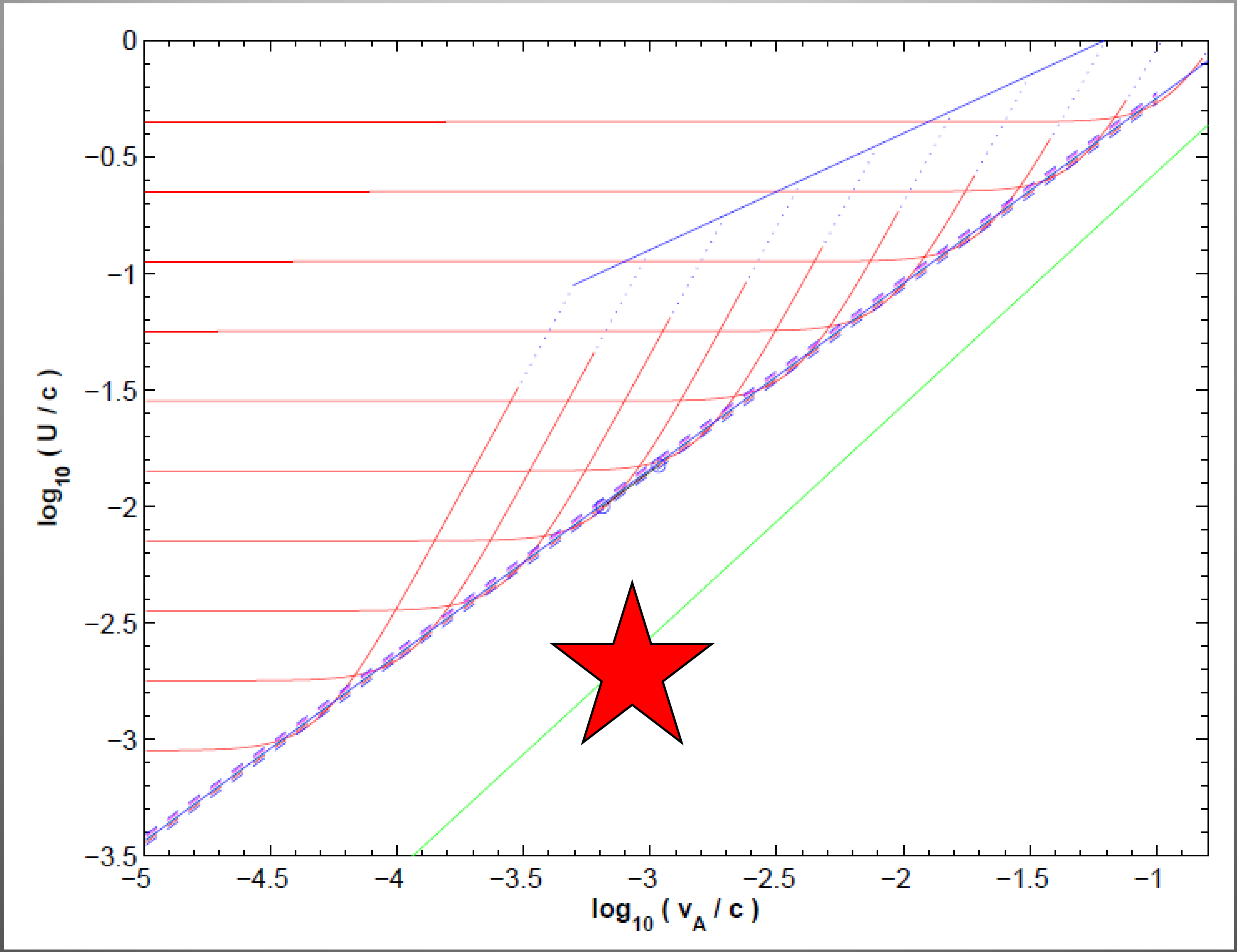


x_1=0.151
x=0.442
x=0.536
x=0.886
x_2=1.147
$\gamma^2 f(x, \gamma)$
γ
10^{10}
10^{0}
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
10^{-70}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}

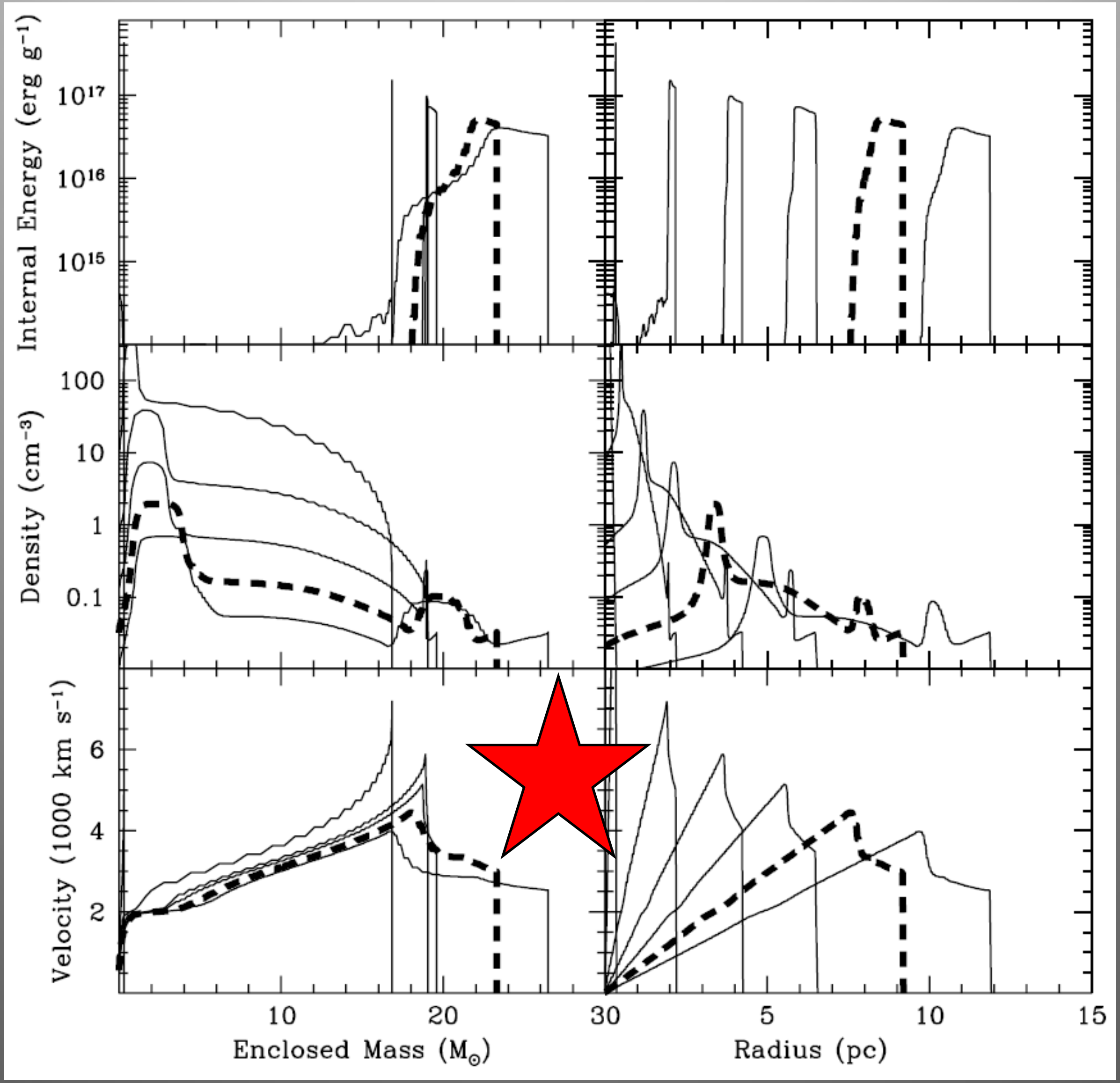

10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$\gamma^2 F(x, \gamma)$ (cm^{-3})
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
γ
x=0.1533
x=0.1650
x=0.2145
x=0.3285
x=1.1221

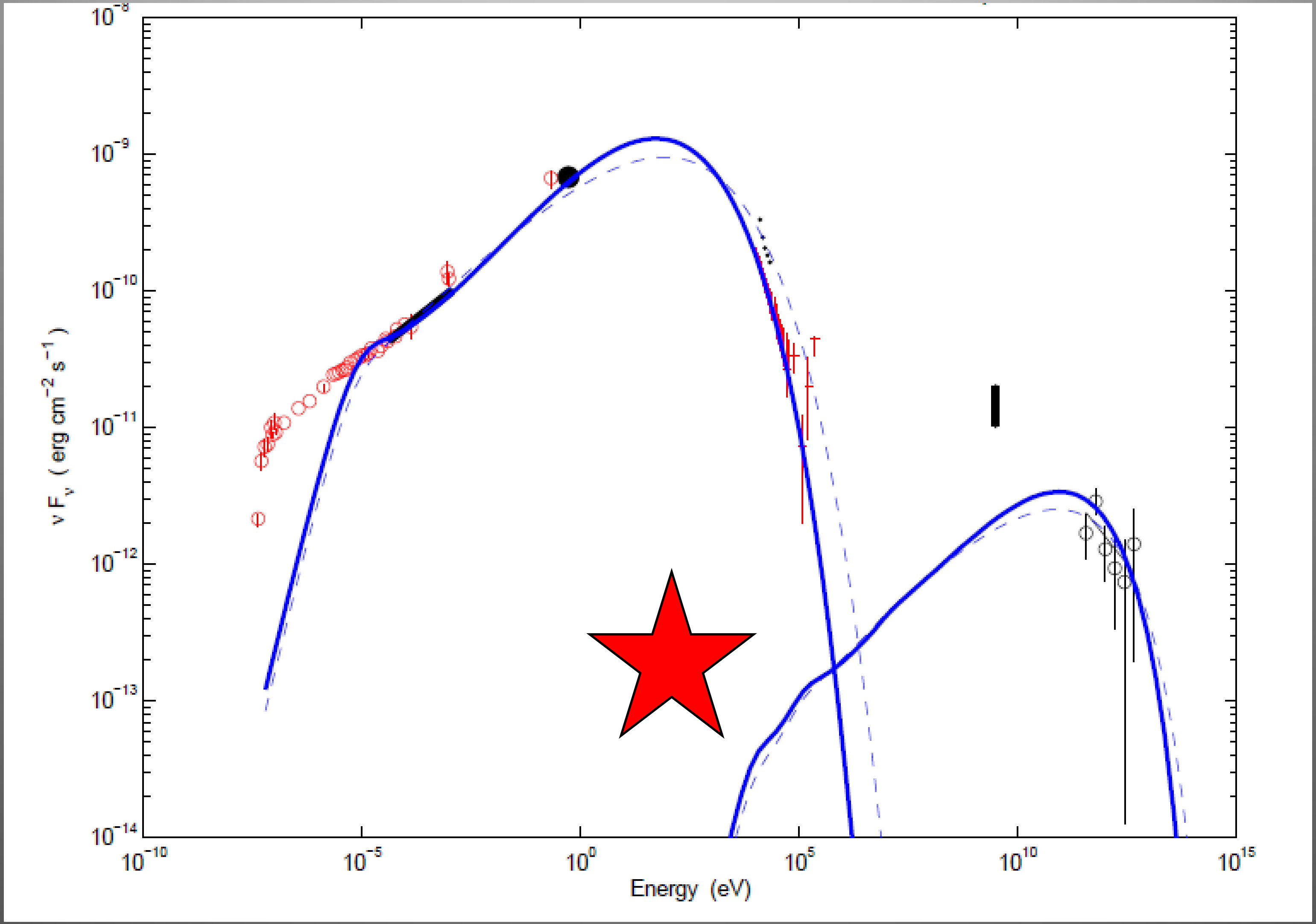

E^2 dN/dE (erg cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
Energy (eV)

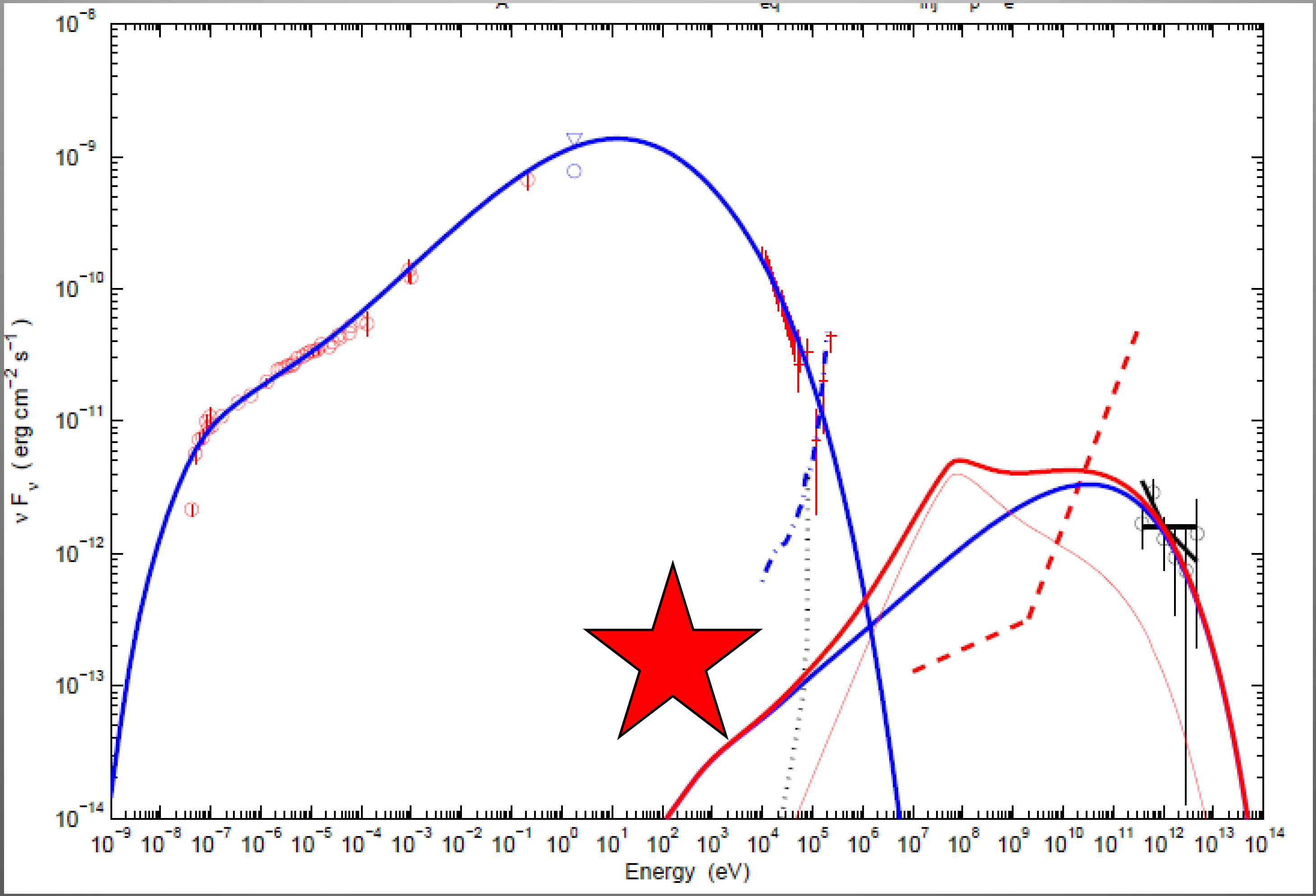

E^2 dN/dE (erg cm^{-2} s^{-1})
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
Energy (eV)



0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−5
−4.5
−4
−3.5
−3
−2.5
−2
−1.5
−1
$\log_{10}$ (U / c)
$\log_{10}$ (v_A / c)


Internal Energy (erg g^{-1})
10^{17}
10^{16}
10^{15}
Density (cm^{-3})
100
10
1
0.1
Velocity (1000 km s^{-1})
6
4
2
10
20
30
Enclosed Mass (M$_\odot$)
0
5
10
15
Radius (pc)


10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
νF_{ν} (erg cm^{-2} s^{-1})
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
Energy (eV)



10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
ν F_ν (erg cm^-2 s^-1)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14
Energy (eV)

VI. Conclusions

Plasma Wave Turbulence is
an important channel for the release of free-energy in high energy astrophysical sources

Stochastic Acceleration by it can lead to a quantitative treatment of plasma heating and acceleration of non-thermal particles