Cosmic ray streaming instabilities in the long-wavelength limit

Spectral steepening at oblique shocks

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Outline

- Connecting the source spectrum with the observed CR spectrum on Earth
  - Diffusive shock acceleration
  - Where does the diffusion arise from?
- Theory
  - Growth rate for collision and stress tensor mediated instability
- Long-wavelength regime
- Spectral steepening at oblique shocks

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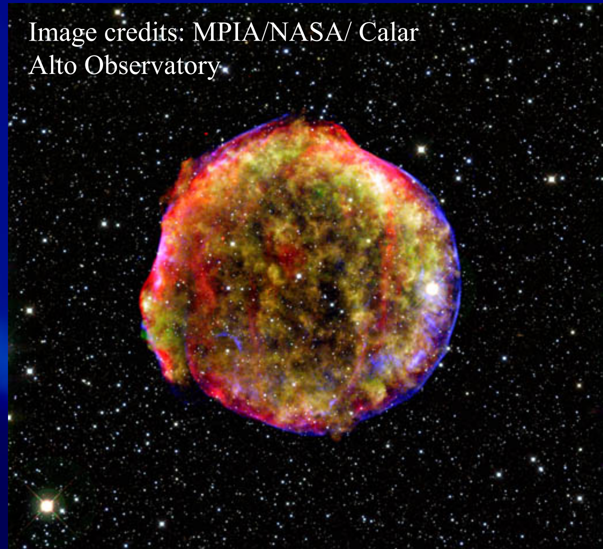

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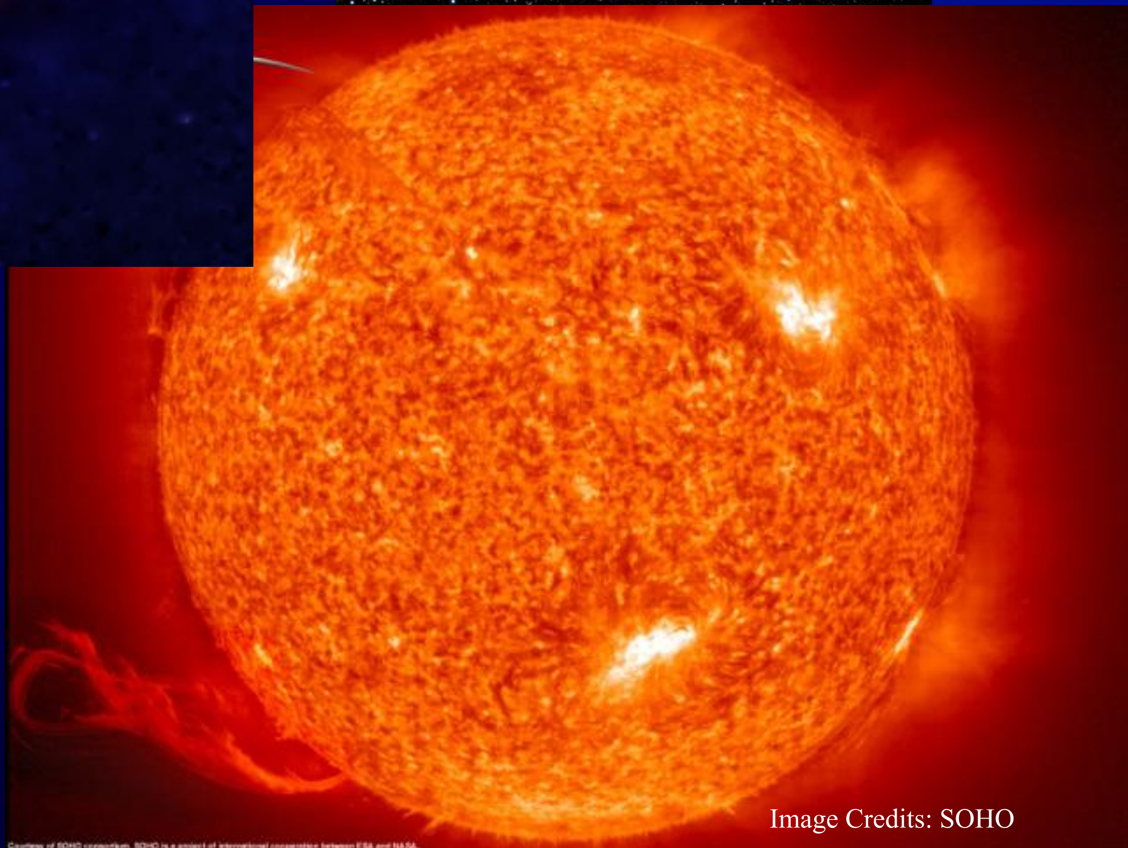

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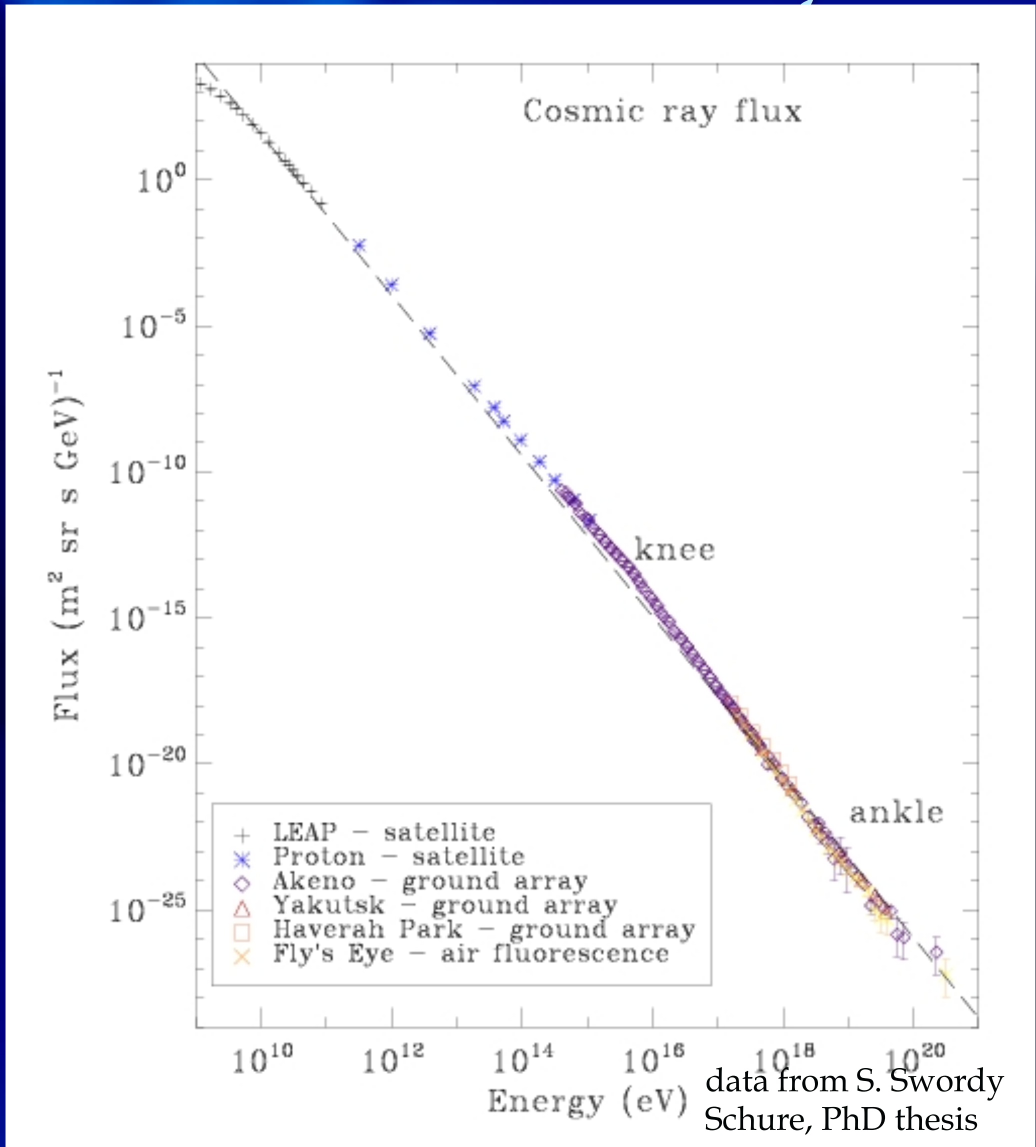
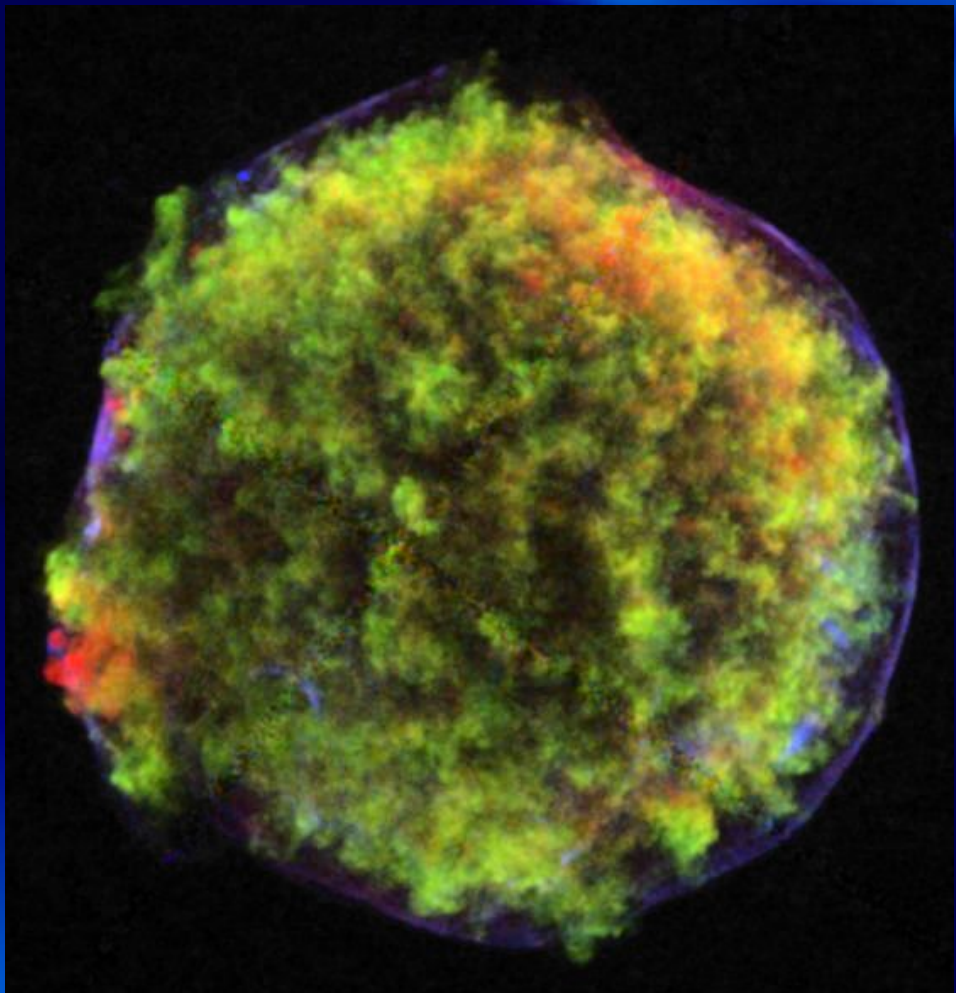
Cosmic Rays



data from S. Swordy
Schure, PhD thesis

Supernova remnants as particle accelerators



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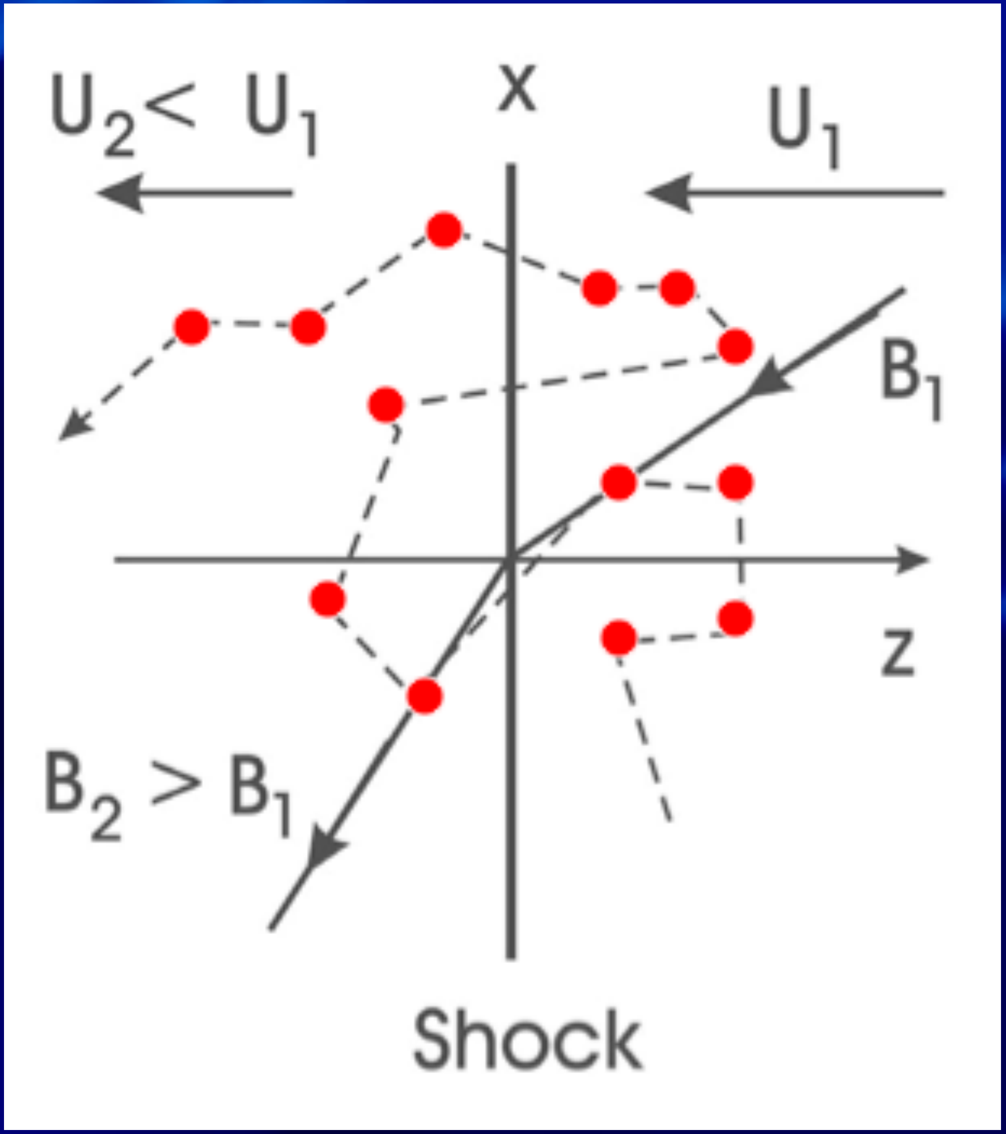
Diffusive shock acceleration



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Confinement in SNR

- Small angle scattering off magnetic field fluctuations
- Scale length fluctuations of same order as gyroradius CRs
- Long wavelength regime: this is what confines the highest energy cosmic rays at a source and determines p_{max}

Cosmic-ray driven instabilities

- Magnetic field amplified by return current
- non-resonant on scale smaller than gyroradius
  - Bell 2004
- resonant with gyroradius
  - Lerche 1967, Kulsrud & Pearce 1969, Wentzel 1974, Skilling 1975
- scales longer than gyroradius
  - Bykov et al 2011
  - Schure & Bell 2011 submitted

$$\partial_t \mathbf{f} + \mathbf{v}\cdot\nabla\mathbf{f} + \frac{q}{m}\left(\mathbf{E}+\frac{\mathbf{v}\times\mathbf{B}}{c}\right)\cdot\nabla_v\mathbf{f} = \nabla_v\cdot(\mathbf{D}\cdot\nabla_v\mathbf{f});$$

$$\begin{aligned}
\partial_t\mathbf{B} &= \nabla\times(\mathbf{u}\times\mathbf{B}) \\
\rho\partial_t\mathbf{u} &= \frac{\mathbf{j}_{th}\times\mathbf{B}}{c} - \nabla P - \nabla\cdot\Pi - \mathbf{F}_R. \\
\mathbf{f} &= f_0 + \frac{f_i v_i}{v} + \frac{f_{ij}v_iv_j}{v^2} + \frac{f_{ijk}v_iv_jv_k}{v^3} + \ldots, \\
v &= \sqrt{\mathbf{v}_x^2+\mathbf{v}_y^2+\mathbf{v}_z^2}
\end{aligned}$$

$$\partial_t\mathbf{f}_y + \frac{q}{mc}(\mathbf{B}_0\times\mathbf{f}_z + \mathbf{B}_z\times\mathbf{f}_{x(0)}) + \nu\mathbf{f}_y + \frac{2}{5}v\partial_x\mathbf{f}_{xy} = 0$$

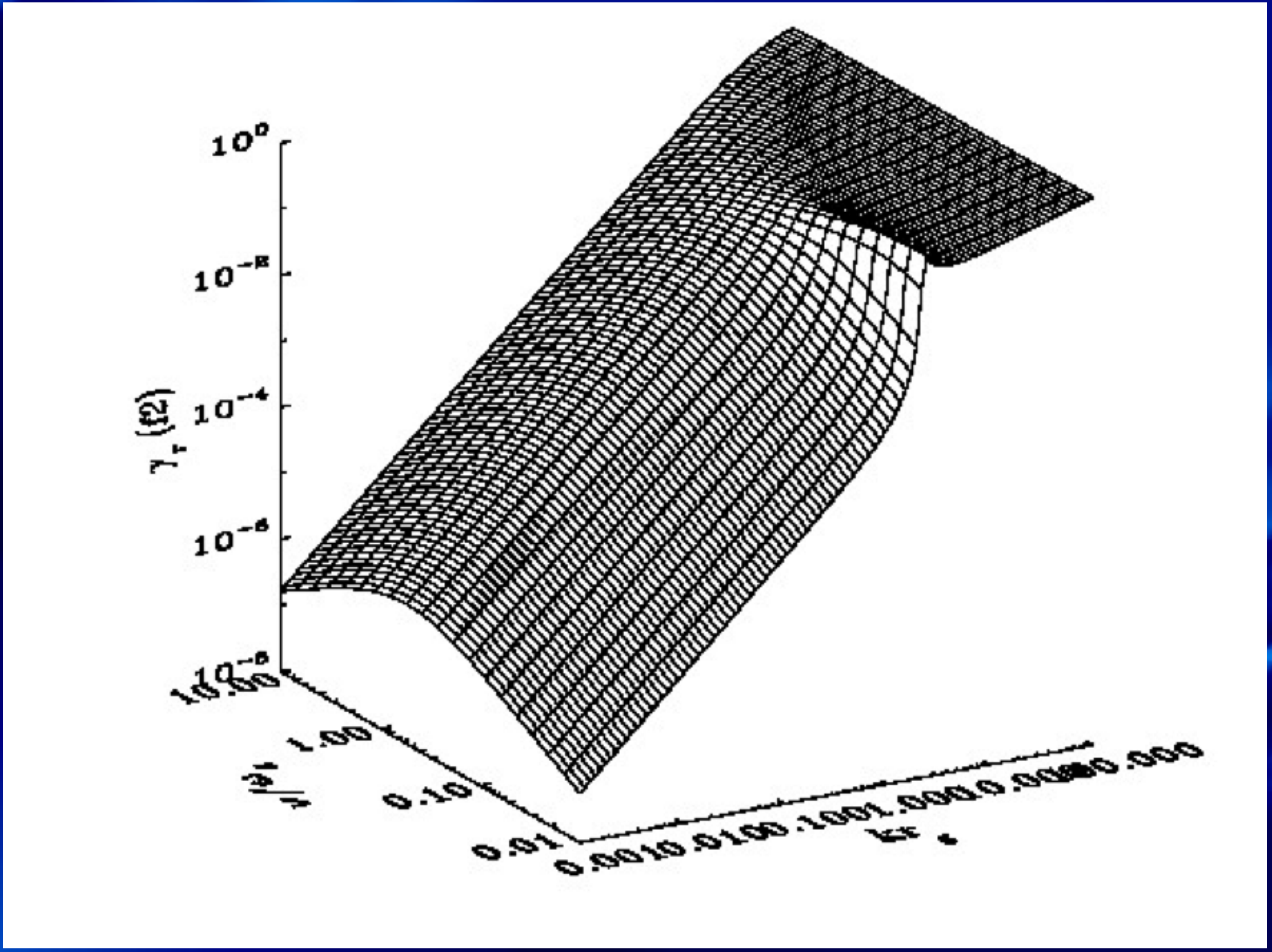
$$\partial_t\mathbf{f}_z + \frac{q}{mc}(\mathbf{B}_0\times\mathbf{f}_y + \mathbf{B}_y\times\mathbf{f}_{x(0)}) + \nu\mathbf{f}_z + \frac{2}{5}v\partial_x\mathbf{f}_{xz} = 0,$$

Dispersion relation

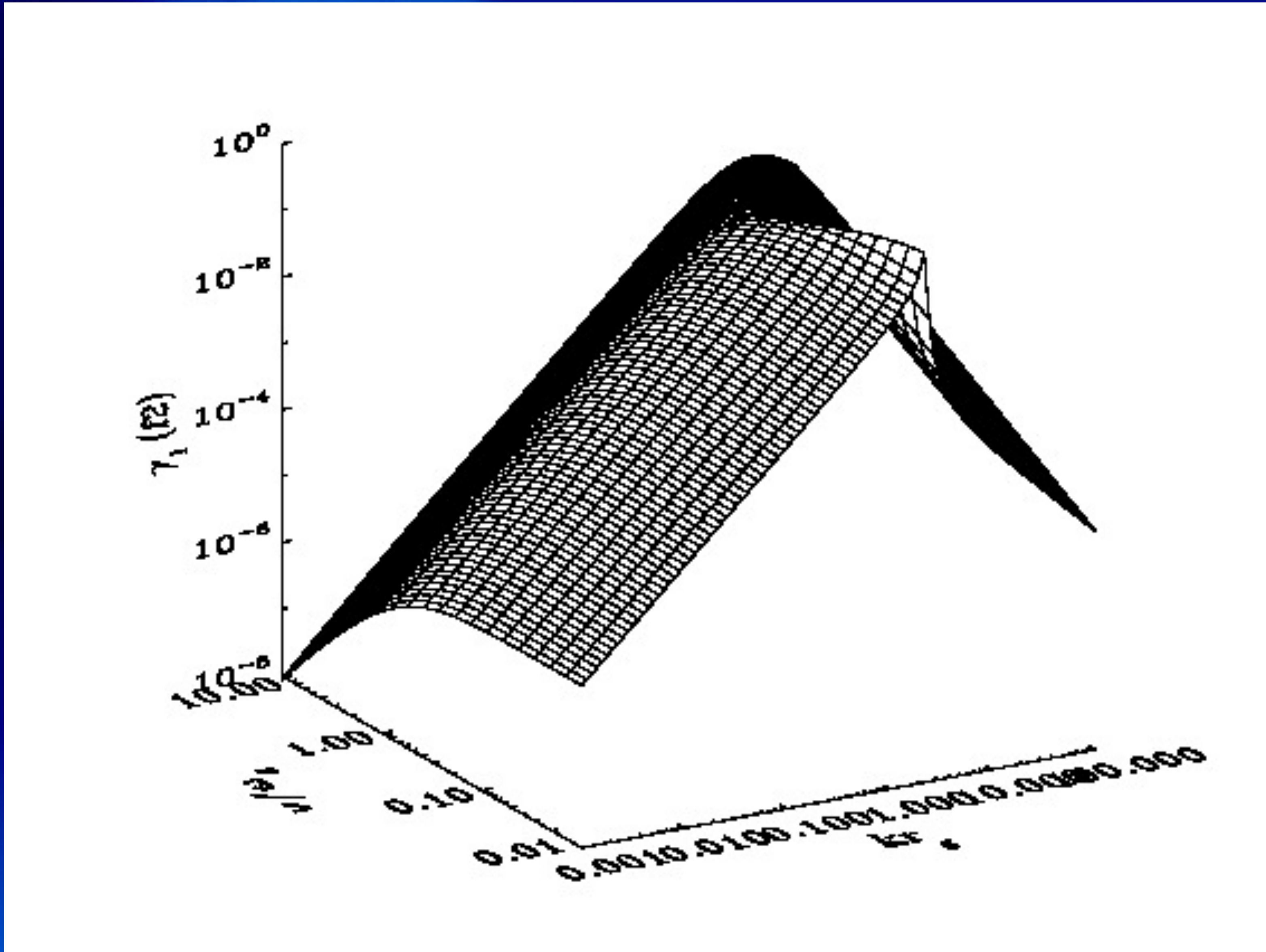
$$\omega^2 = \mp\Omega^2 \left(i\omega - \frac{k^2c^2}{5(3\nu \mp i\omega_g)} \right) \Big/ \left(\nu - i\omega \mp i\omega_g + \frac{k^2c^2}{5(3\nu \mp i\omega_g)} \right)$$

$$\Omega = \sqrt{k j_0 B_0/(\rho c)}$$

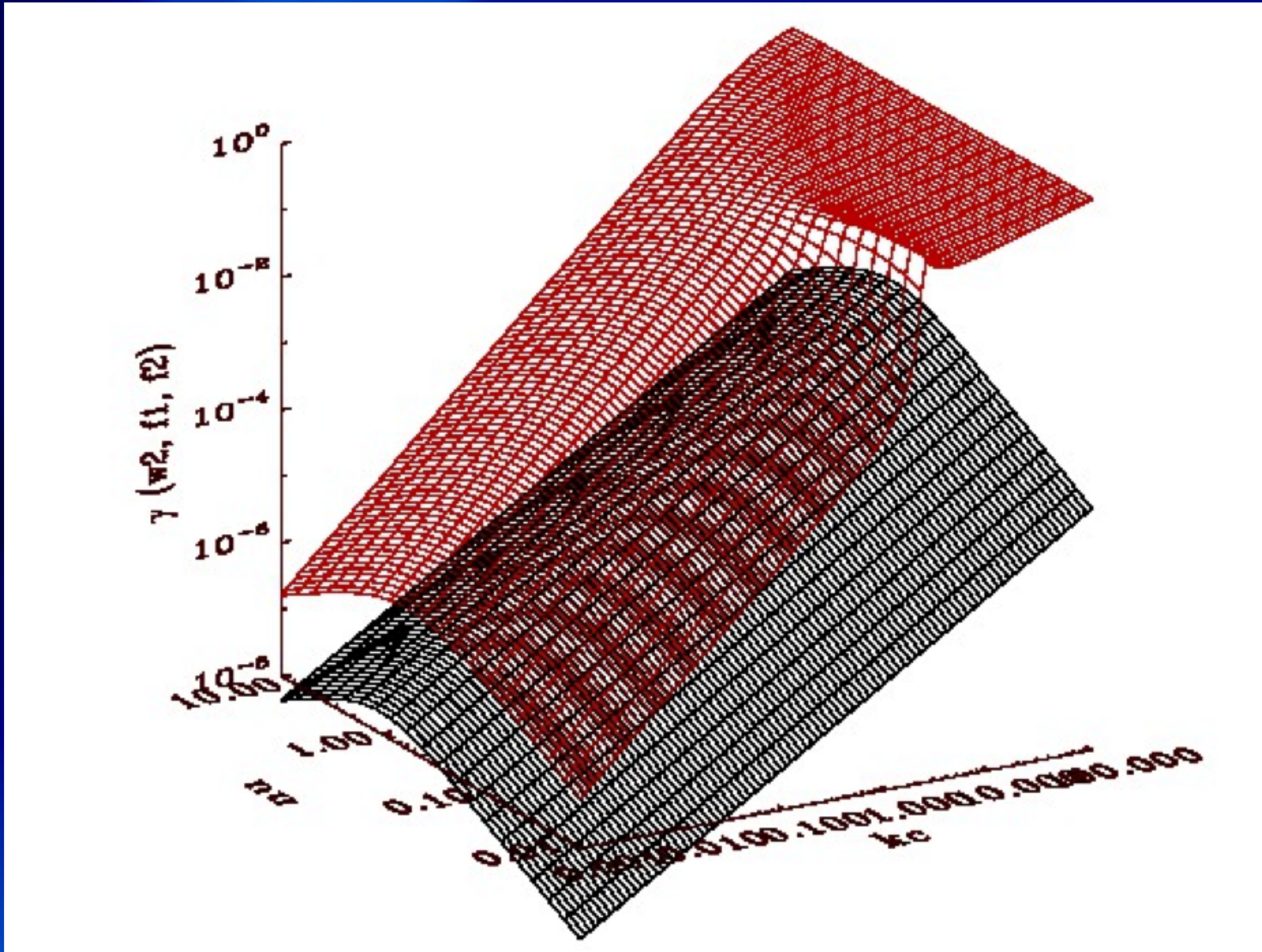
R-H mode



L-H mode

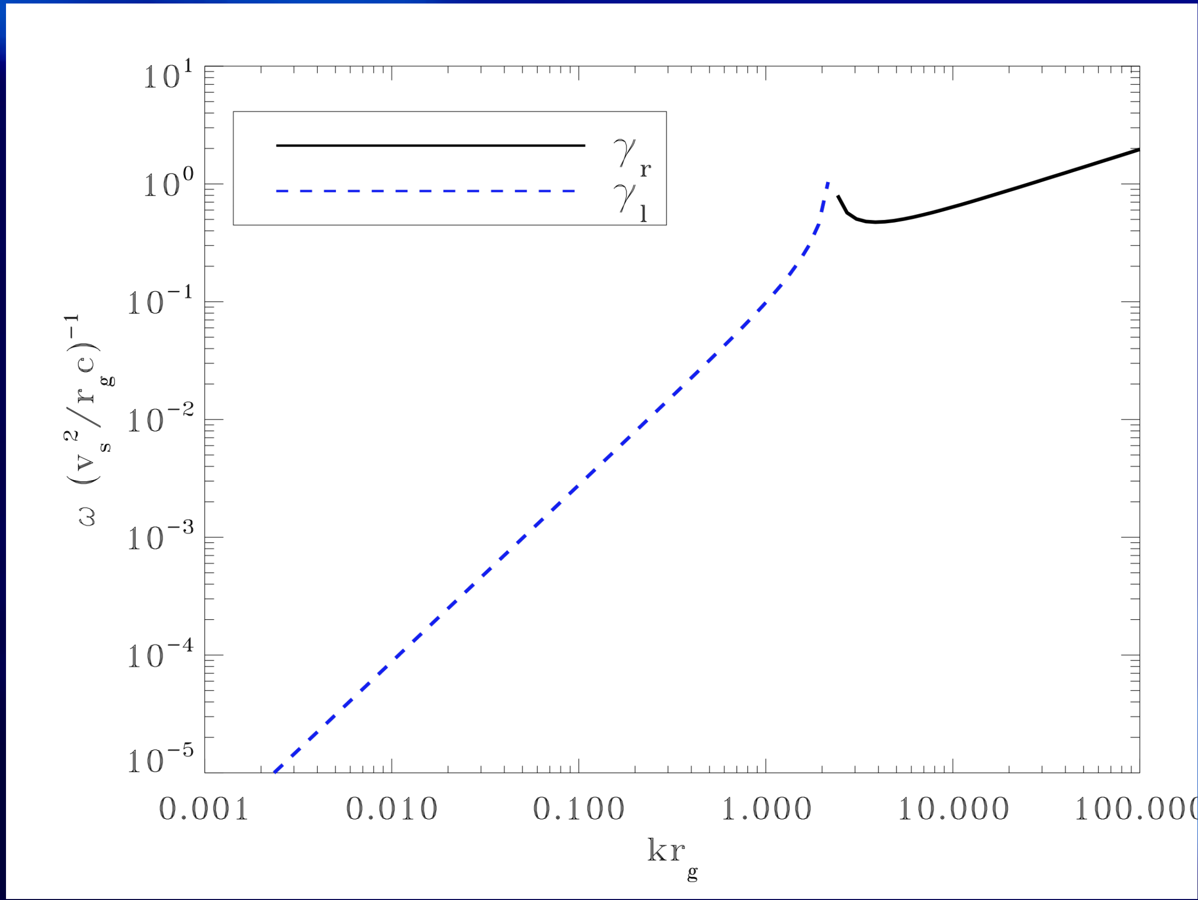


without stress tensor



without collisions, with f_2

- R-H unstable at short wavelengths
- L-H unstable at long wavelengths



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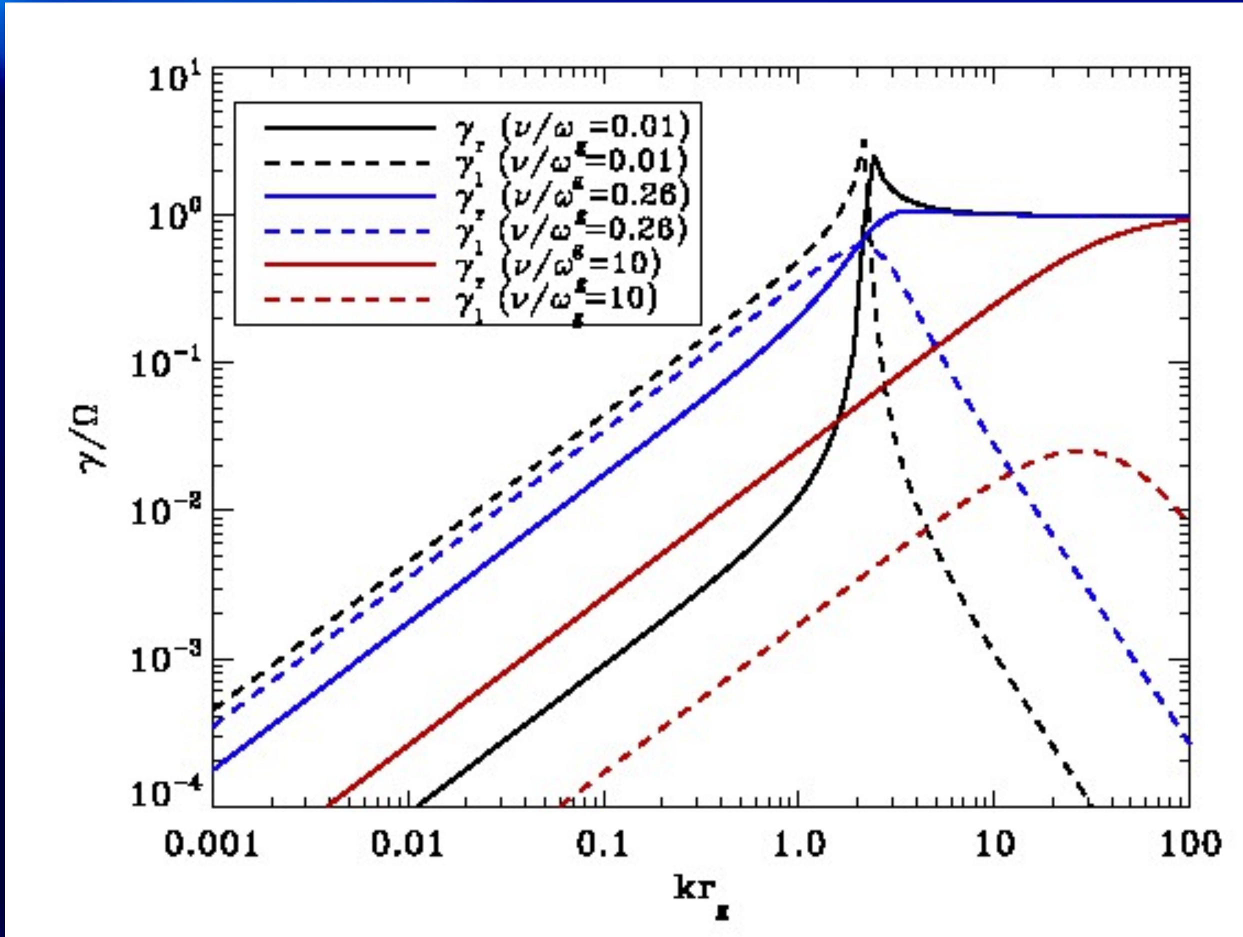
long-wavelength regime

- L-H mode dominant for most values of collisionality
- L-H mode is more efficient in scattering protons



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The long-wavelength instability:

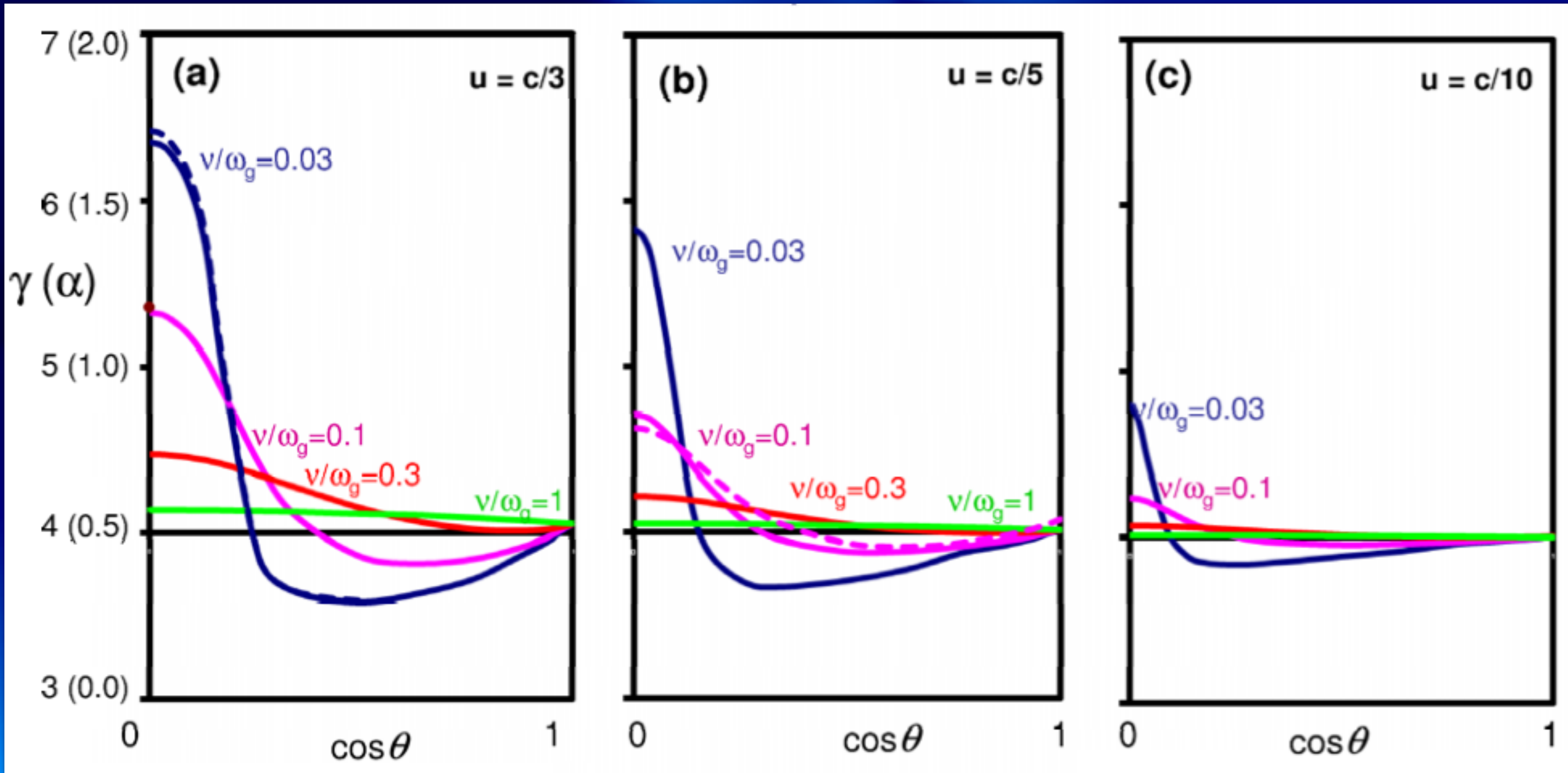
- Driven by cosmic ray current
- Mediated by stress tensor and small-scale collisions
- Left-hand mode (same direction to gyrating protons) dominant on scales longer than resonant wavelength
- Growth rate proportional to $k^{3/2}$

Spectral index steepening

- source spectrum should be around 2.2-2.6
- nonlinear feedback
- NEW: DSA theory in oblique shocks
  - Significant changes in spectrum when shock velocity is high (>10,000 km/s)
  - Steepening for near-perpendicular shock

A.R. Bell, K.M. Schure, B. Reville

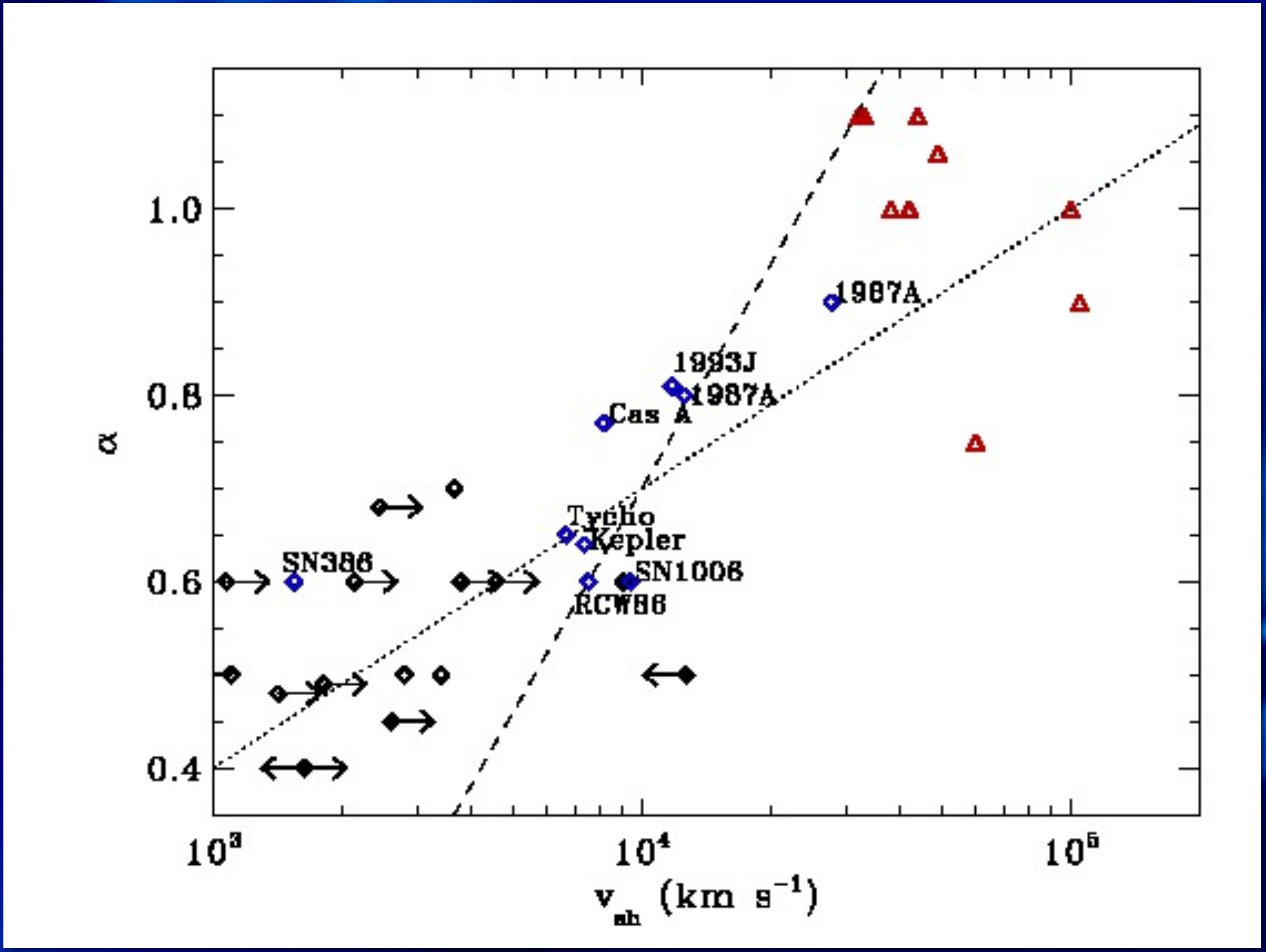
spectral index vs. obliquity angle



Average spectrum

- Depends on obliquity
- For random field orientation: steepening and flattening cancel out
- Magnetic field at high velocity shocks might be preferentially perpendicular due to:
  - stellar magnetic field: Parker spiral
  - magnetic field amplification
- Young SNRs responsible for galactic cosmic rays?

spectral index vs. shock velocity



To conclude

- Confinement of highest energy cosmic rays depends on magnetic field fluctuations with long wavelengths (Schure & Bell)
- Left-hand mode dominant: efficient scatterer

- Spectrum of cosmic rays can be steeper than p=-2 for fast shocks (Bell, Schure & Reville)