Electrostatic Considerations in Shock Acceleration

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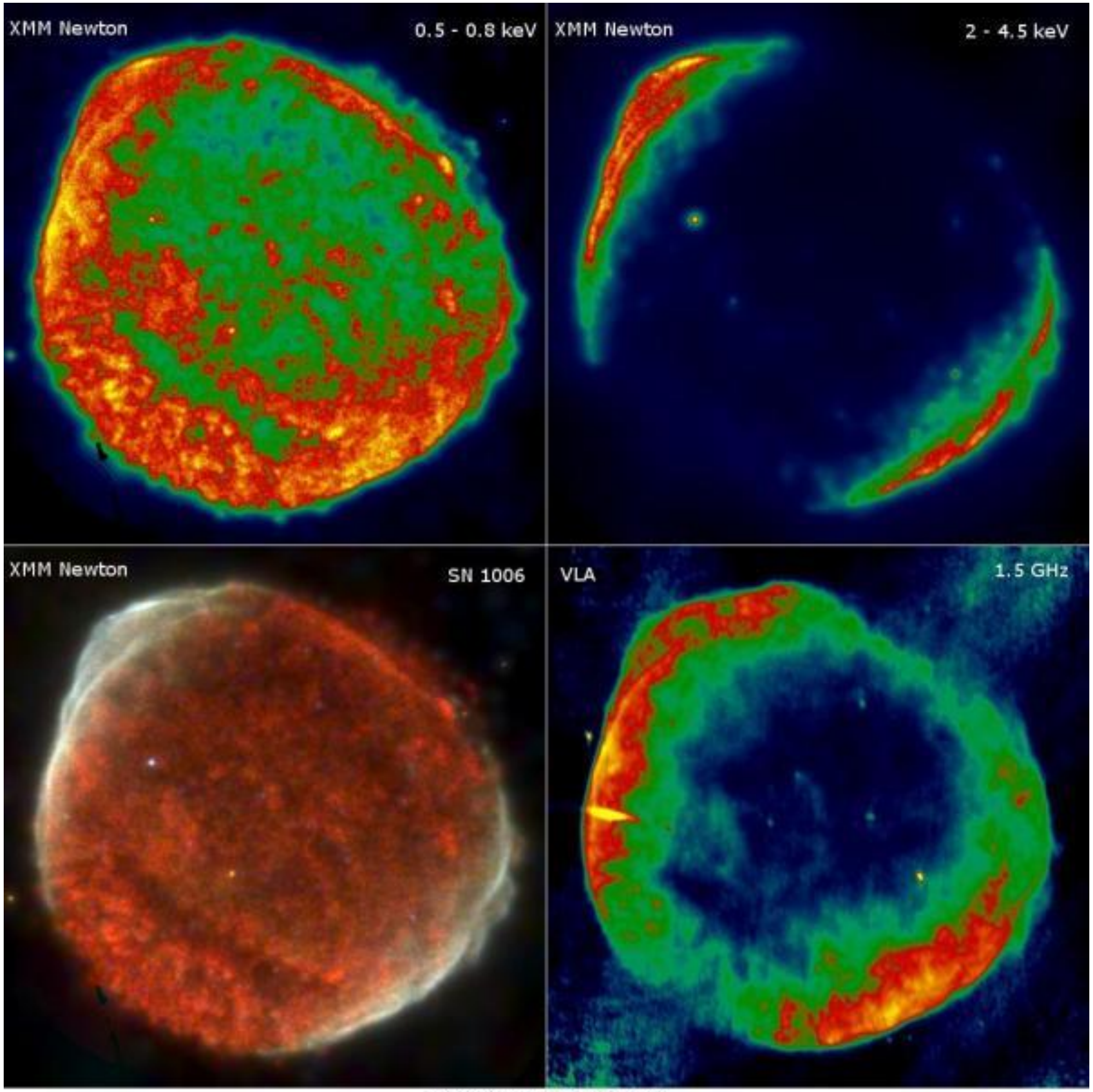
SN 1006

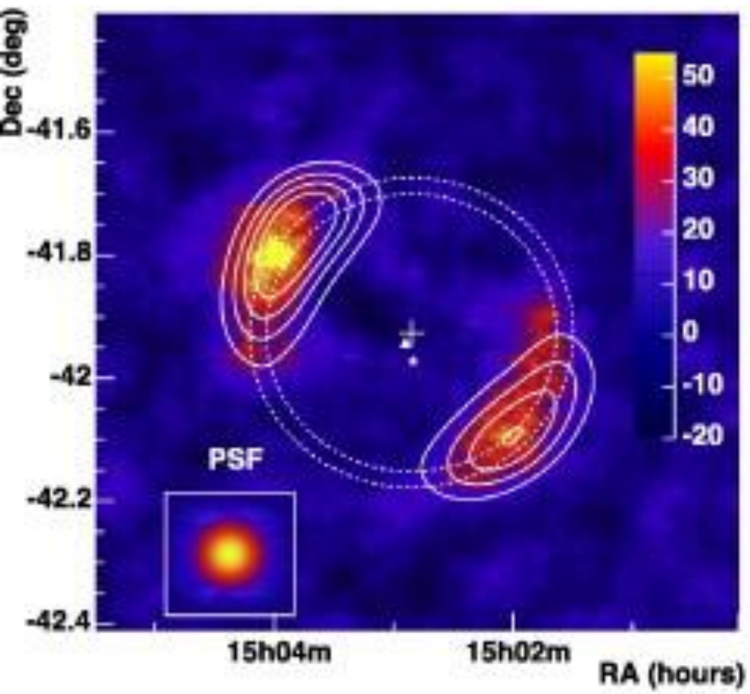


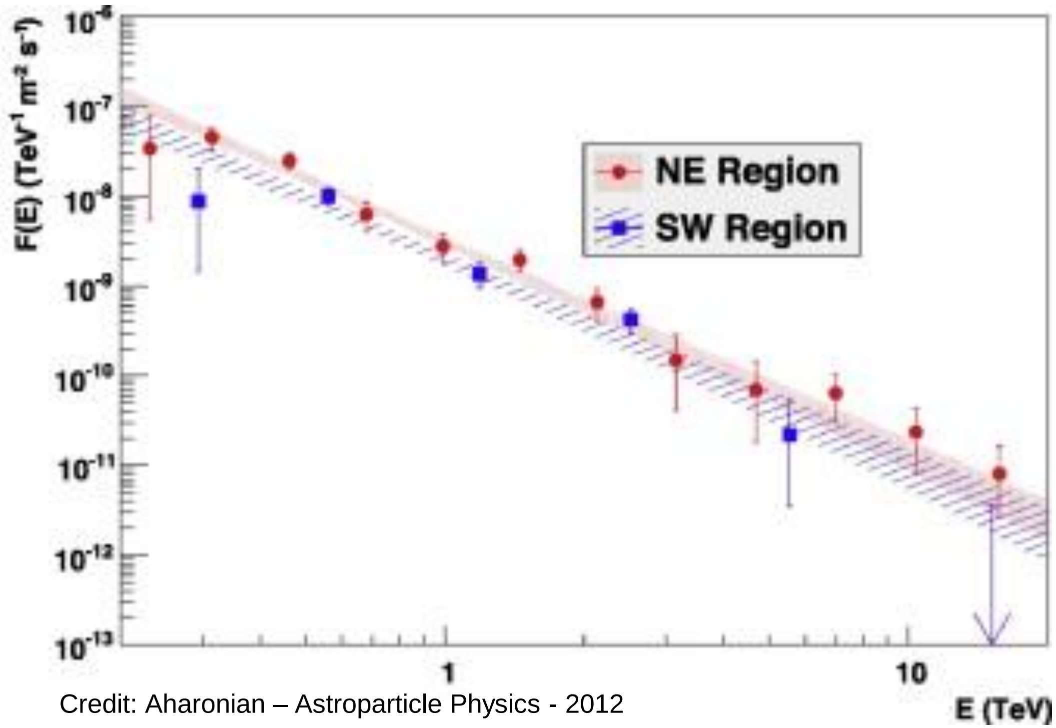
Particle acceleration in SN 1006

Image courtesy of CEA/DSM/DAPNIA/SAp

European Space Agency

SN 1006





Credit: Aharonian – Astroparticle Physics - 2012

- SN 1006 has a high energy nonthermal spectrum in the form of a power-law tail that extends well into gamma rays
- Emission is likely due to radiative processes (synchrotron, IC) from nonthermal electrons accelerated by the expanding SNR shock.

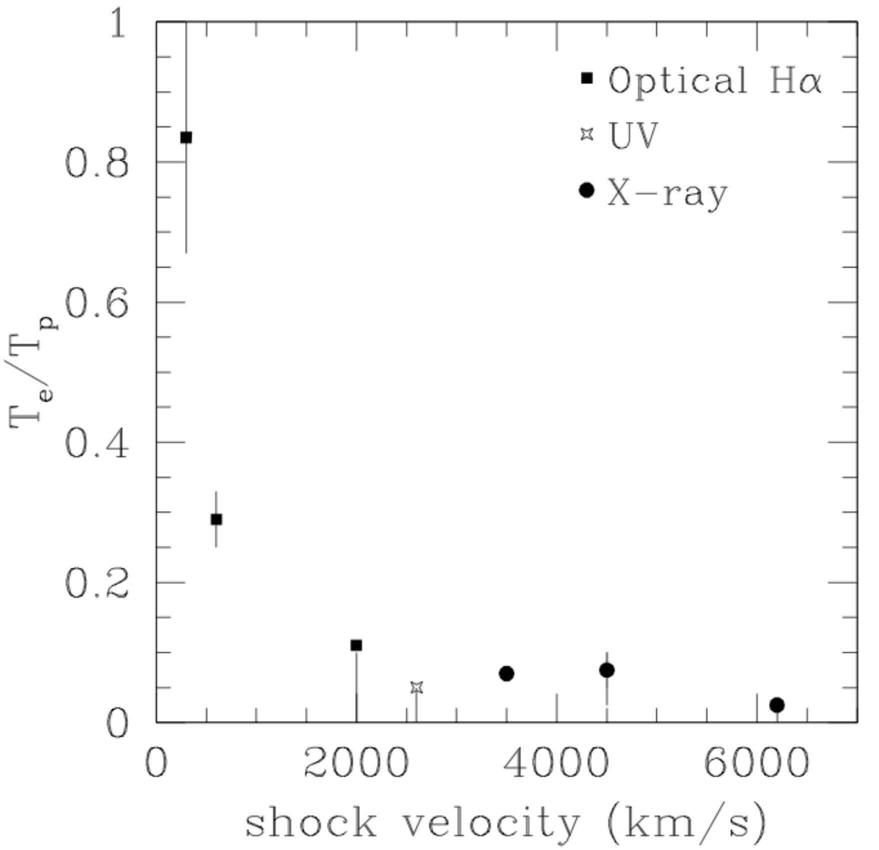
e/p Equilibration in SNRs

- Electrons and protons at the shock front are not in thermal equilibrium
- With ballistic heating, electrons are cooler by the mass ratio

$$kT \approx \beta_1 mc^2, \qquad \frac{T_{p,dn}}{T_{e,dn}} = \frac{m_p}{m_e}$$

- Coulomb heating provides some equilibration
- Non-linear DSA modifies heating
- What else is there?

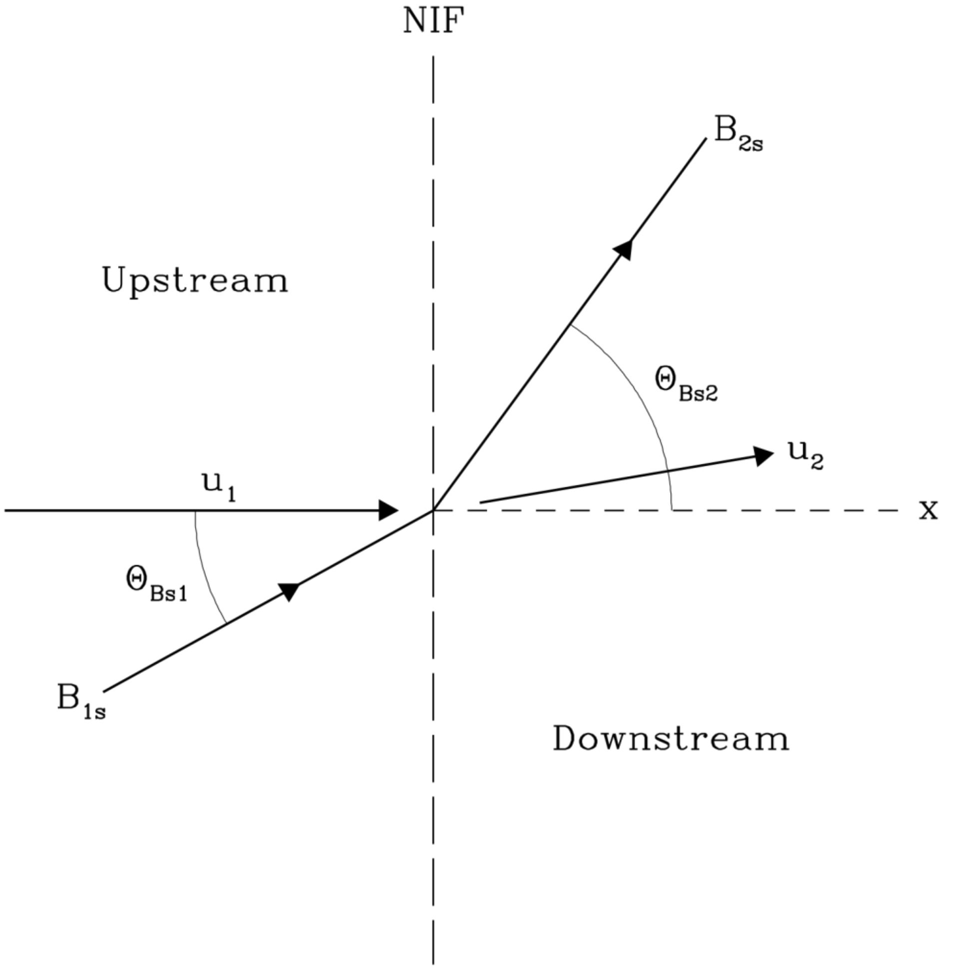
  Shock Layer Electrostatics



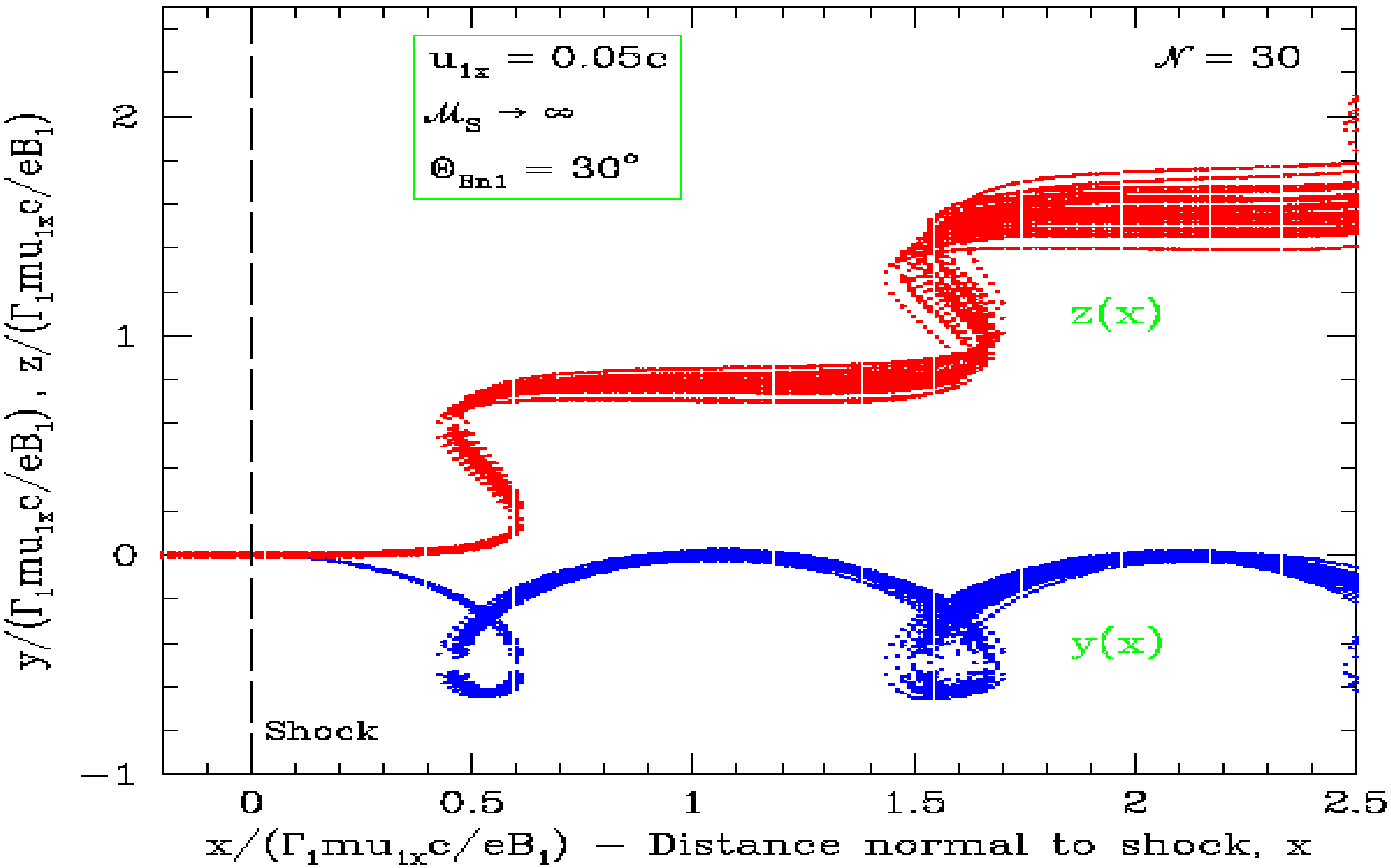
Hwang, U., Decourchelle, A., Holt, S. S., & Petre, R. 2002, ApJ, 581, 1101

Shock Geometry

- We prefer the normal incidence frame (NIF)
- NIF is co-moving with the shock front, which is placed at x=0
- Upstream (supersonic) flow is parallel to the shock normal
- Drift electric fields exist in this frame



Charge Buildup in a Shock Layer

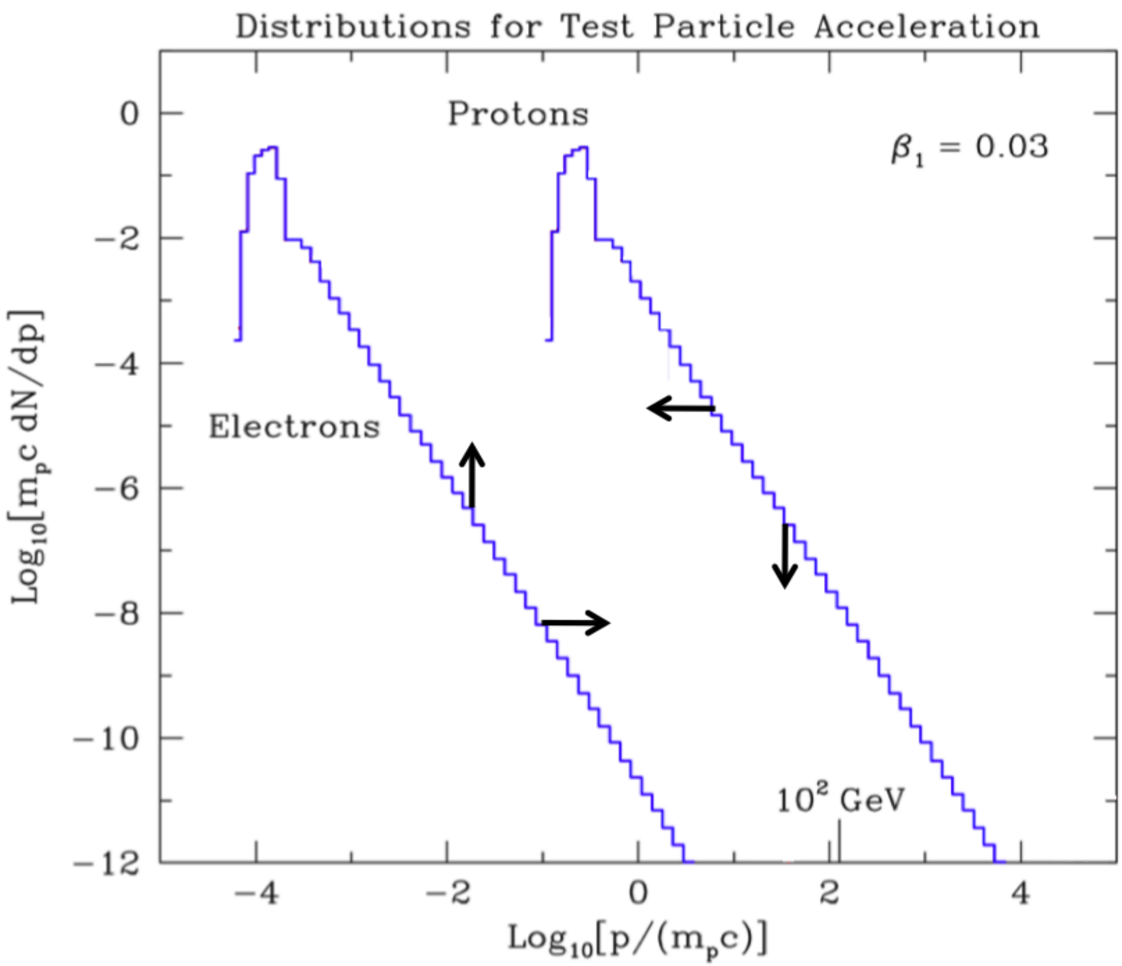


Credit: Baring & Summerlin 2006

- Magnetic field enhancement and kinking causes a coherent gyration
- This leads to an obvious density enhancement near the shock layer
- Different gyroscales for different species

Energy Exchange Expectation

- Partial Equilibration
- Net energy gain for electrons, loss for protons
- Reshaping of distributions
- The shape of these distributions affect predictions of EM & hadronic flux ratios in sources



Monte Carlo Simulation

- A test particle population is followed on its journey through a shock region
- Jump conditions are used to determine the MHD properties (B fields, flow speeds, temps) of a shock
- Diffusive turbulence is treated stochastically
- The resulting particle distributions can be used to calculate the cross-shock electric field
- A new simulation run can be made with the same parameters, only with this electric field superimposed
- This is repeated with the aim of obtaining a self-consistent field profile

Test Particle Evolution

- Particles move through fields and scatter off turbulence
- Field trajectories must now include arbitrary electric field
- Scattering off turbulence is parameterized using a mean free path and modeled as elastic scattering with rigid scatterers co-moving with the flow; small-angle (SAS)

Ellison Jones & Reynolds (1997), Ellison & Double (2004)

$$\lambda_{scatt} = \eta r_g; \quad r_g = \frac{p_\perp c}{qB}$$

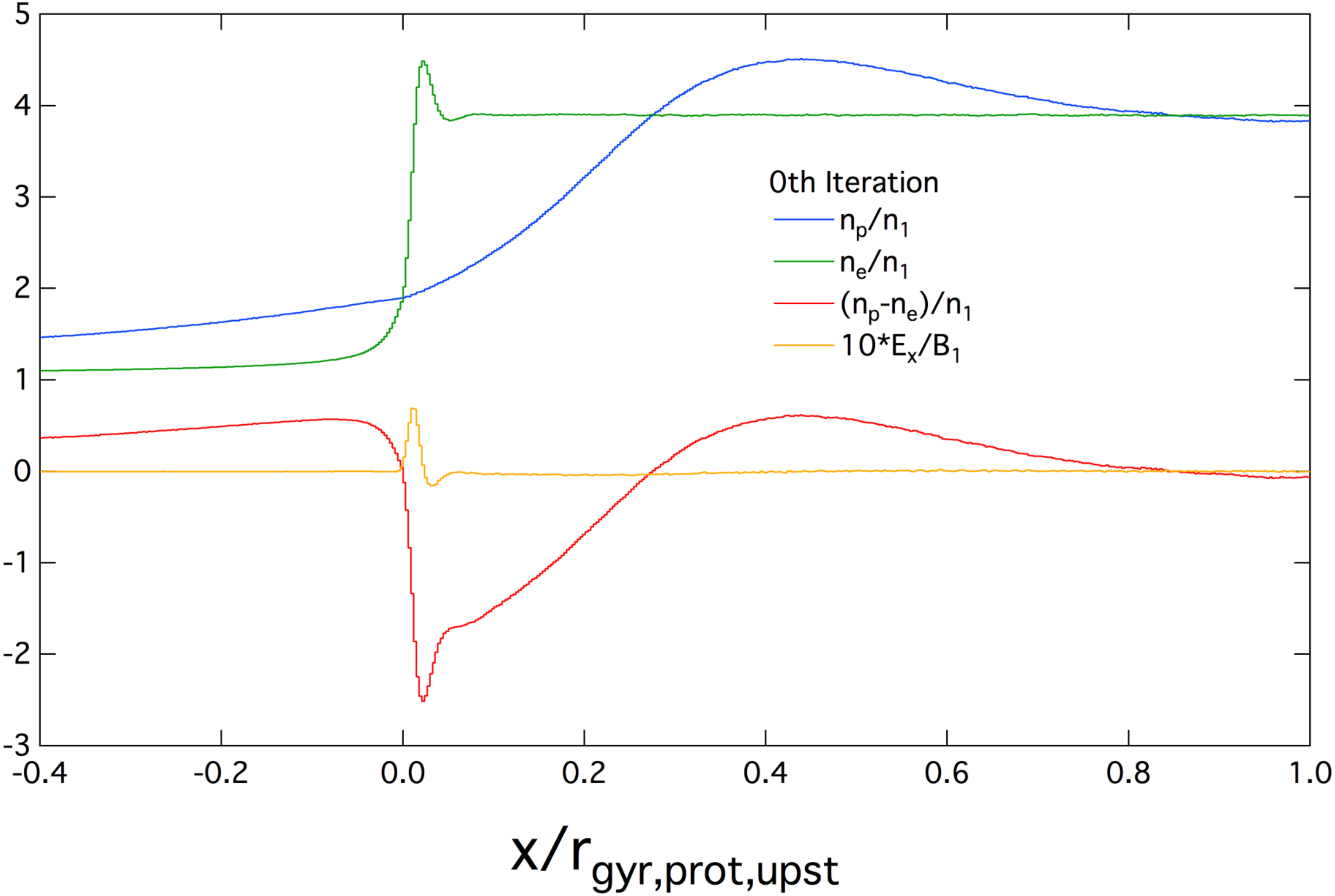
Electrostatics

- Debye screening: mobile charges like to short out electric fields
- Screened Poisson's Equation

$$\left(\nabla^2 - \frac{1}{\lambda^2}\right)\Phi = -4\pi\rho, \quad \lambda \approx \lambda_D = \sqrt{\frac{kT}{4\pi n e^2}}$$

- 1D: $\Phi(x) = 2\pi\lambda \int_{-\infty}^{+\infty} \rho(s) e^{-|x-s|/\lambda} ds$

$$M_S = 10, \quad M_A = 13, \quad u_1 = 0.03c, \quad \lambda = 5r_g, \quad m_e = m_p/20$$



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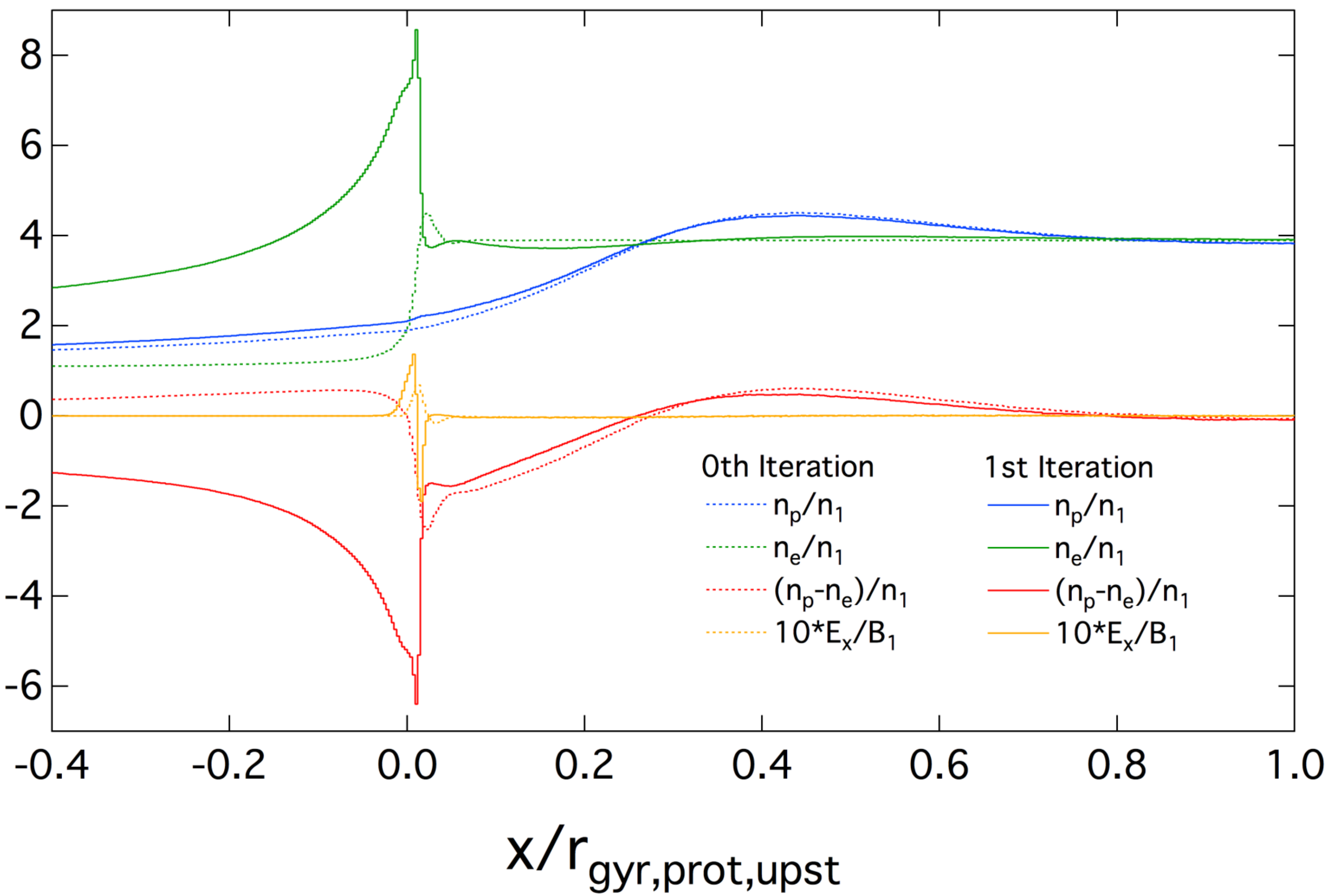

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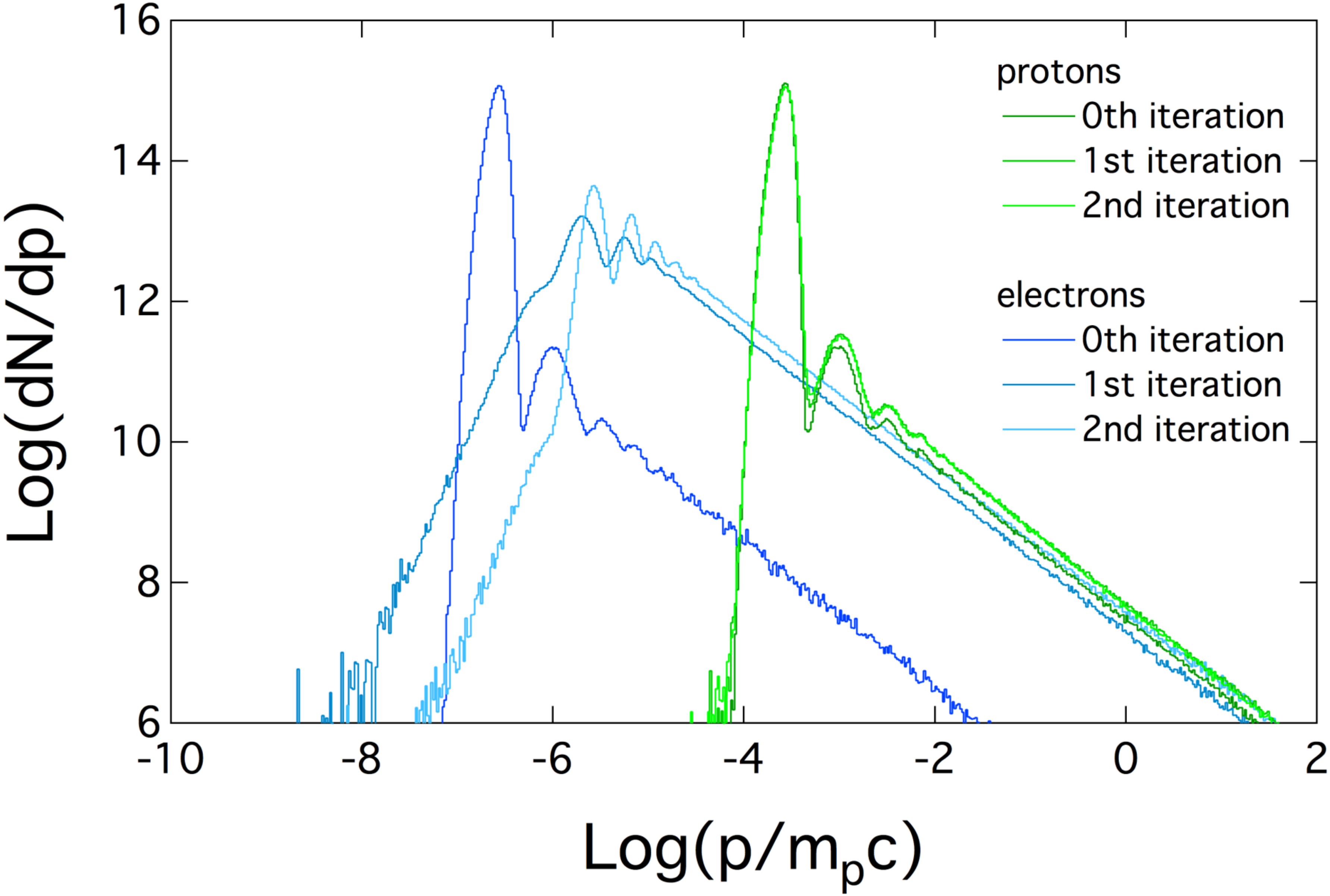

Conclusion

- Cross-shock electrostatic effects are potentially important in predicting e/p equilibration in shock accelerated regions
- The electrons are influenced more due to their low inertia; electron heating by cross shock potentials is profound
- This will alter the ratio of leptonic to hadronic predictions, and has implications for both cosmic ray and neutrino production models

MHD Jump Conditions

- Relates the bulk quantities asymptotically upstream and downstream from a shock

$$\begin{aligned}
(\text{mass}) \quad 0 &= [\rho\vec{u}\cdot\hat{n}]_1^2 \\
(\text{mmtm}) \quad 0 &= \left[\rho\vec{u}(\vec{u}\cdot\hat{n}) + (P + B^2/8\pi)\hat{n} - (\vec{B}\cdot\hat{n}\vec{B})/4\pi\right]_1^2 \\
(\text{energy}) \quad 0 &= \left[\vec{u}\cdot\hat{n}\left(\gamma P/(\gamma-1) + \rho u^2/2 + B^2/4\pi\right) - (\vec{B}\cdot\hat{n})(\vec{B}\cdot\vec{u})/4\pi\right]_1^2 \\
(\text{electric}) \quad 0 &= \left[\hat{n}\times(\vec{u}\times\vec{B})\right]_1^2 \\
(\text{magnetic}) \quad 0 &= \left[\vec{B}\cdot\hat{n}\right]_1^2
\end{aligned}$$