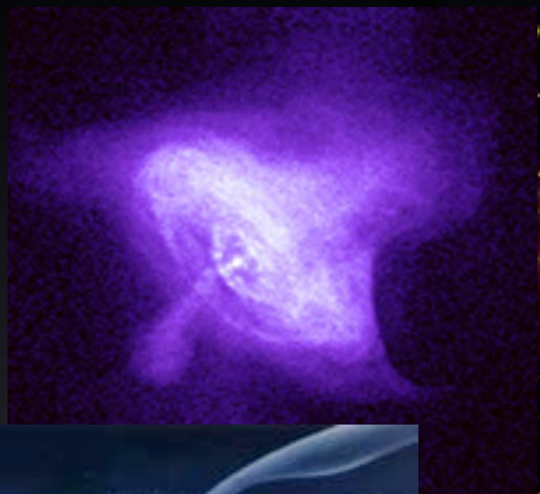
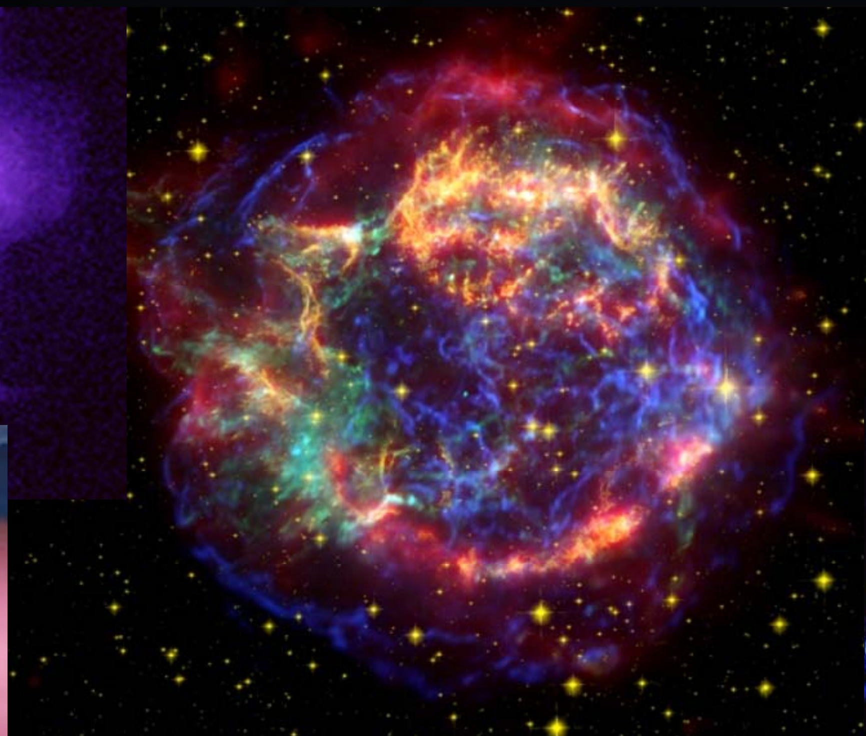
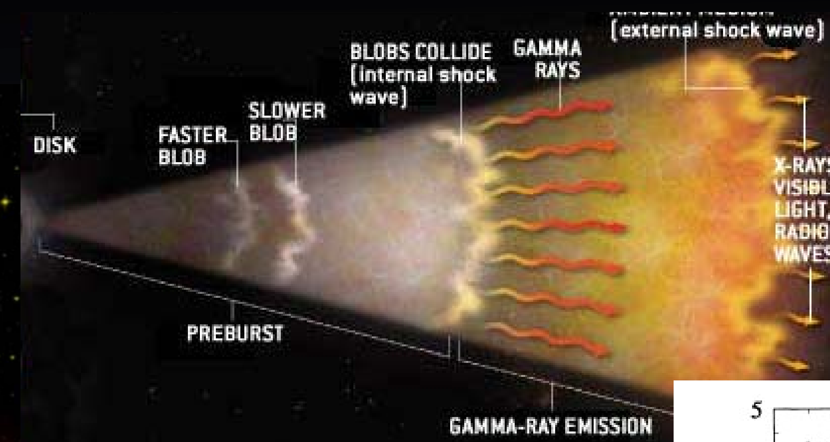
Astrophysical collisionless shocks

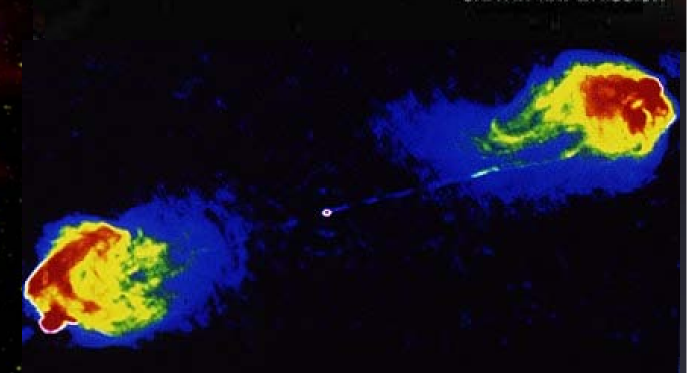
Anatoly Spitkovsky

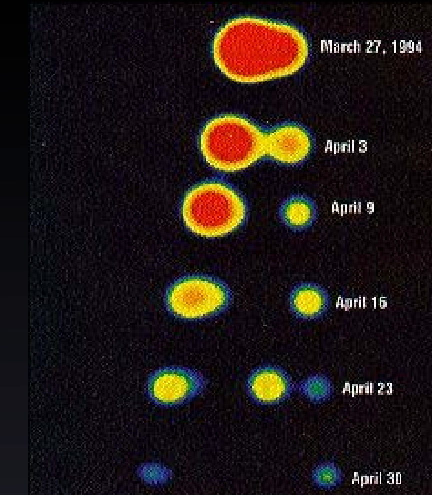
Shocking astrophysics

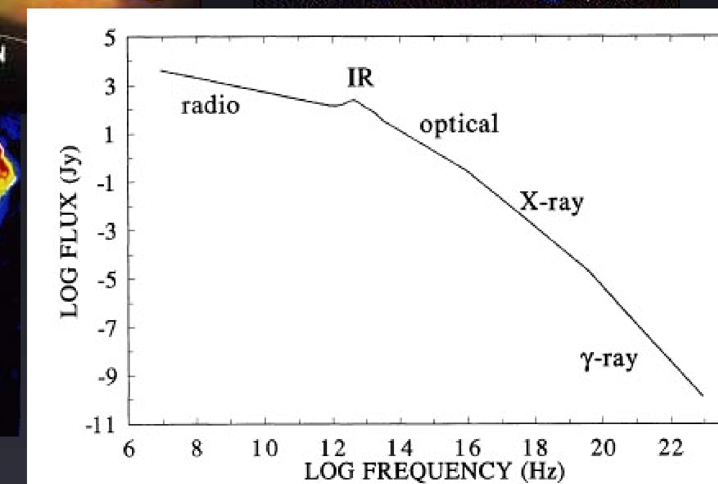


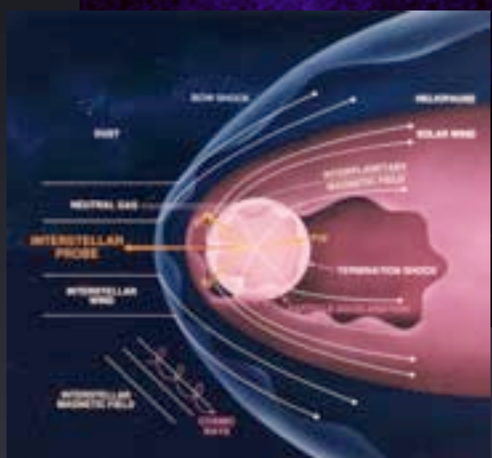












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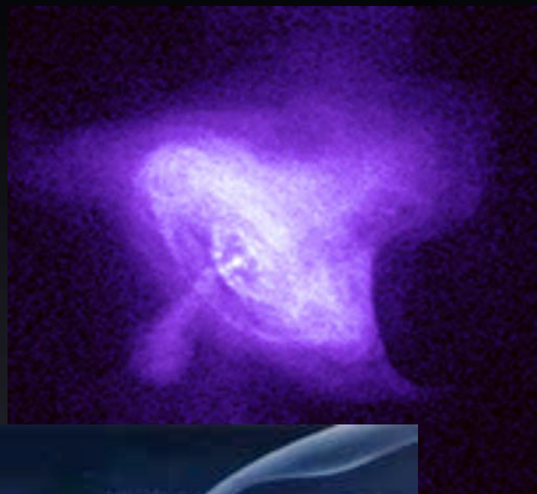
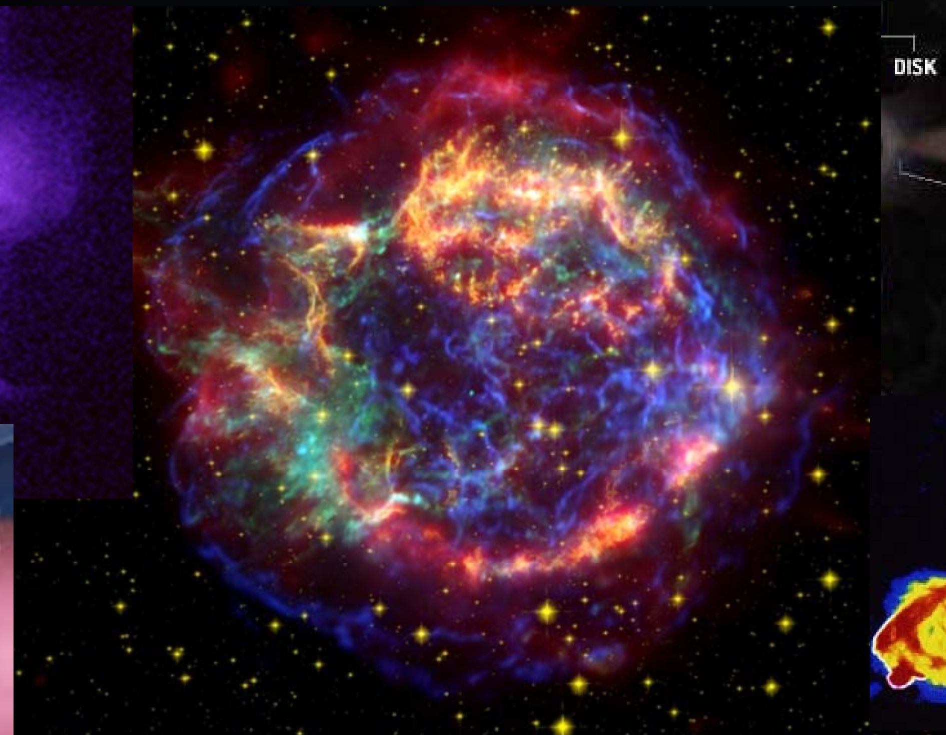
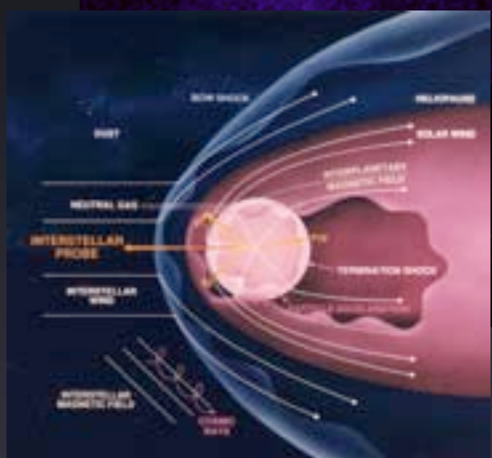
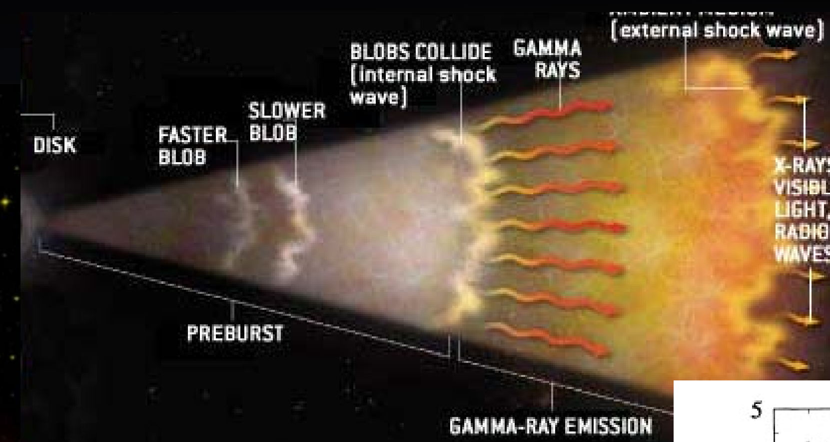
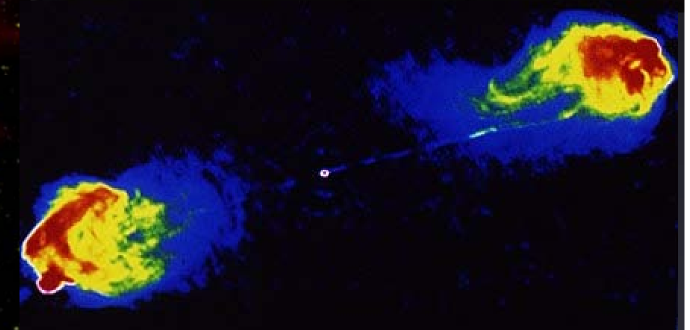
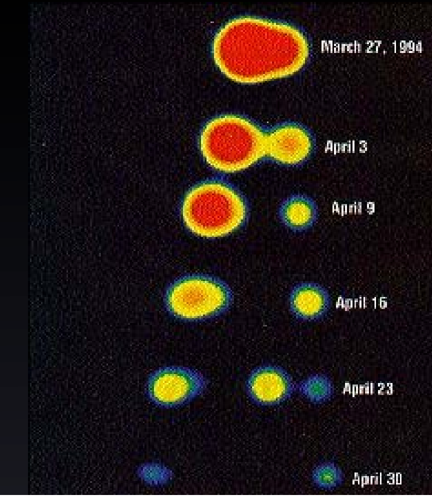
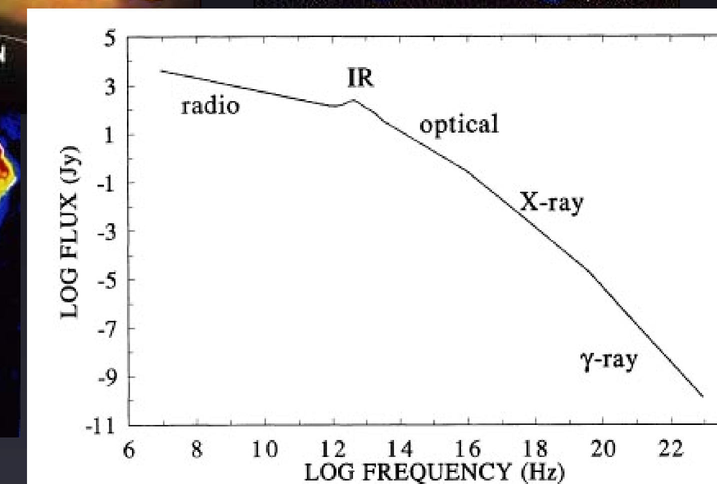







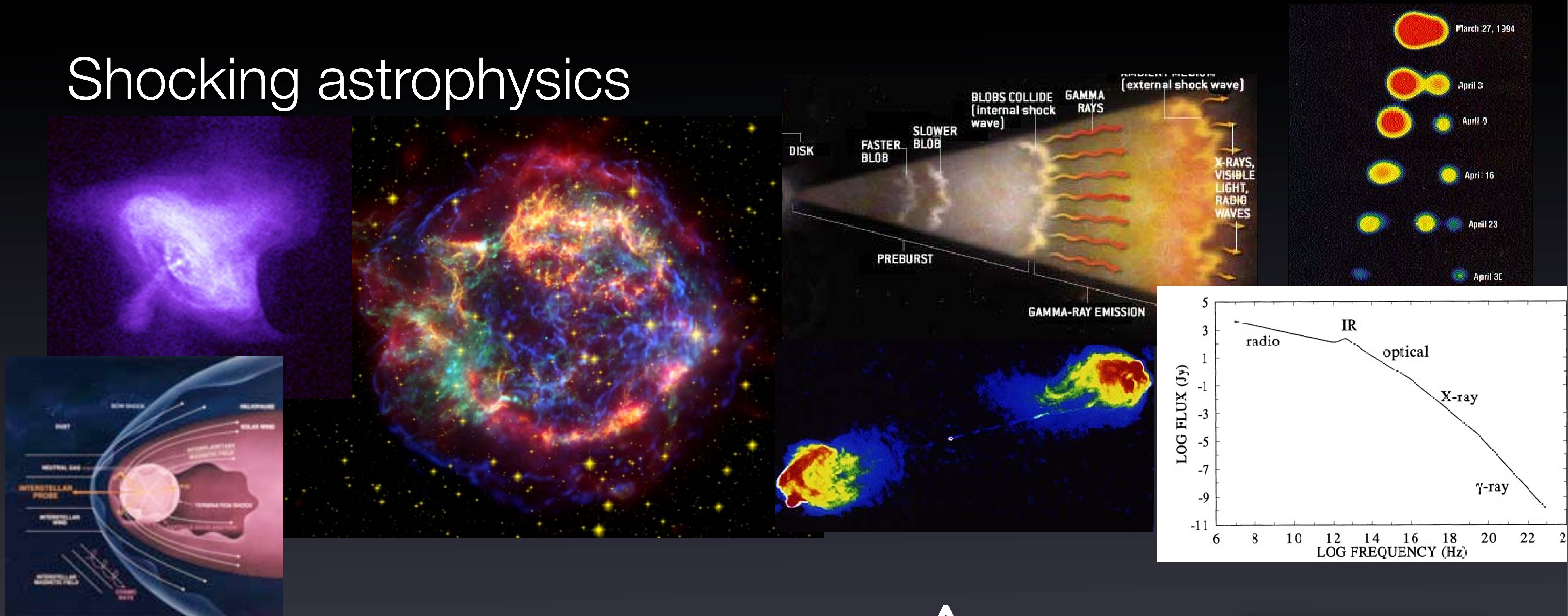
Astrophysical shocks are collisionless

Shocks span a range of parameters:
nonrelativistic to relativistic flows

magnetization (magnetic/kinetic energy ratio)

composition (pairs/e-ions/pairs + ions)

Shocking astrophysics



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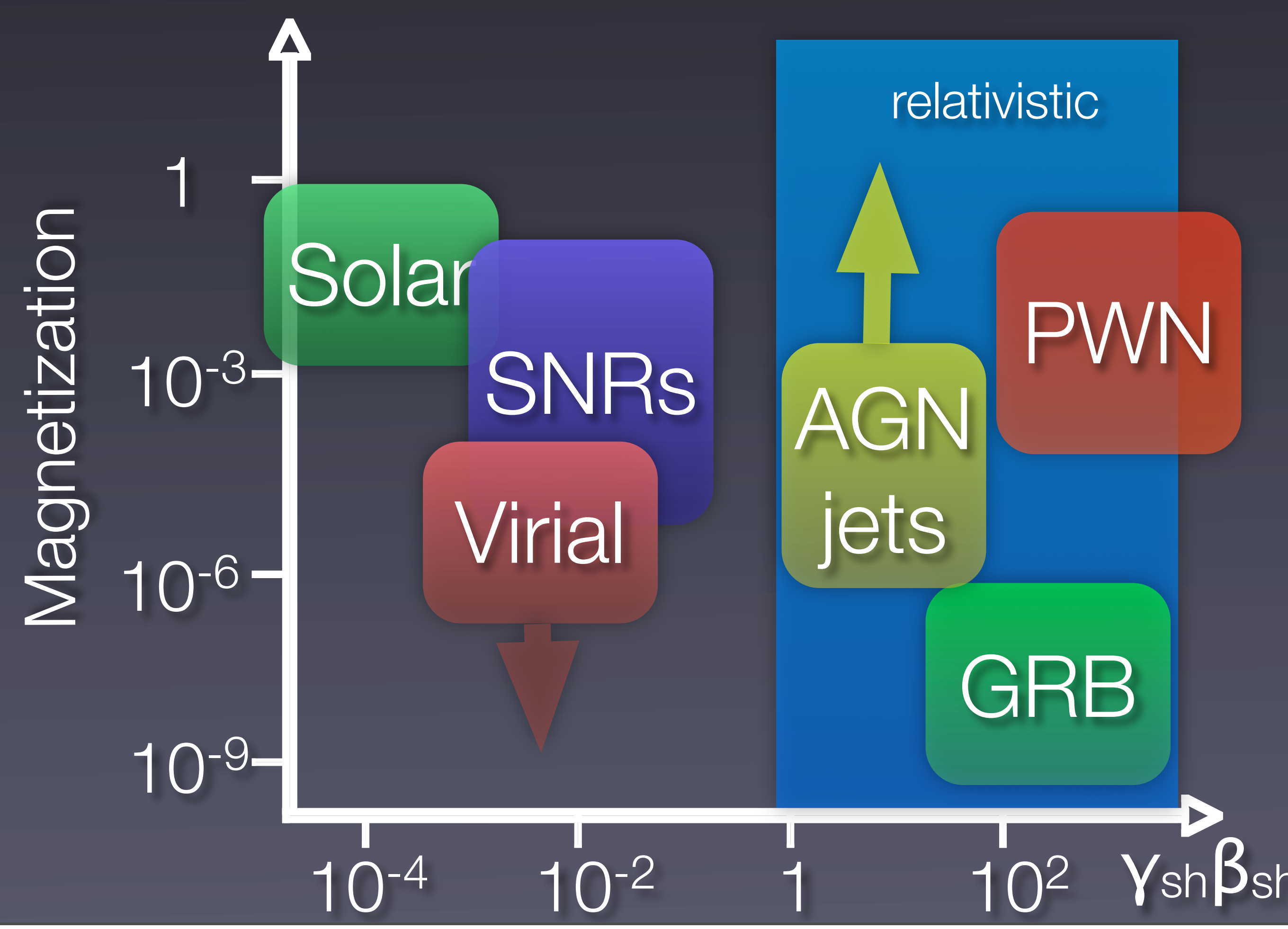

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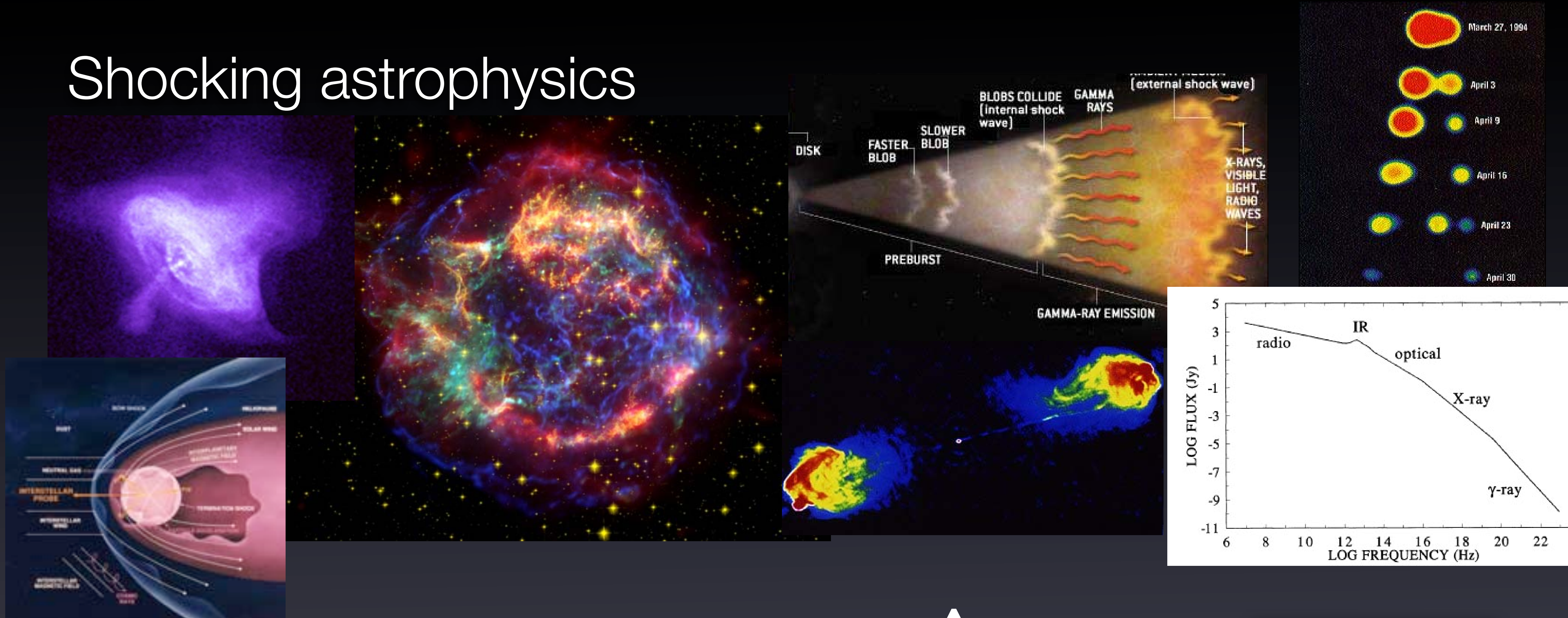

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1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
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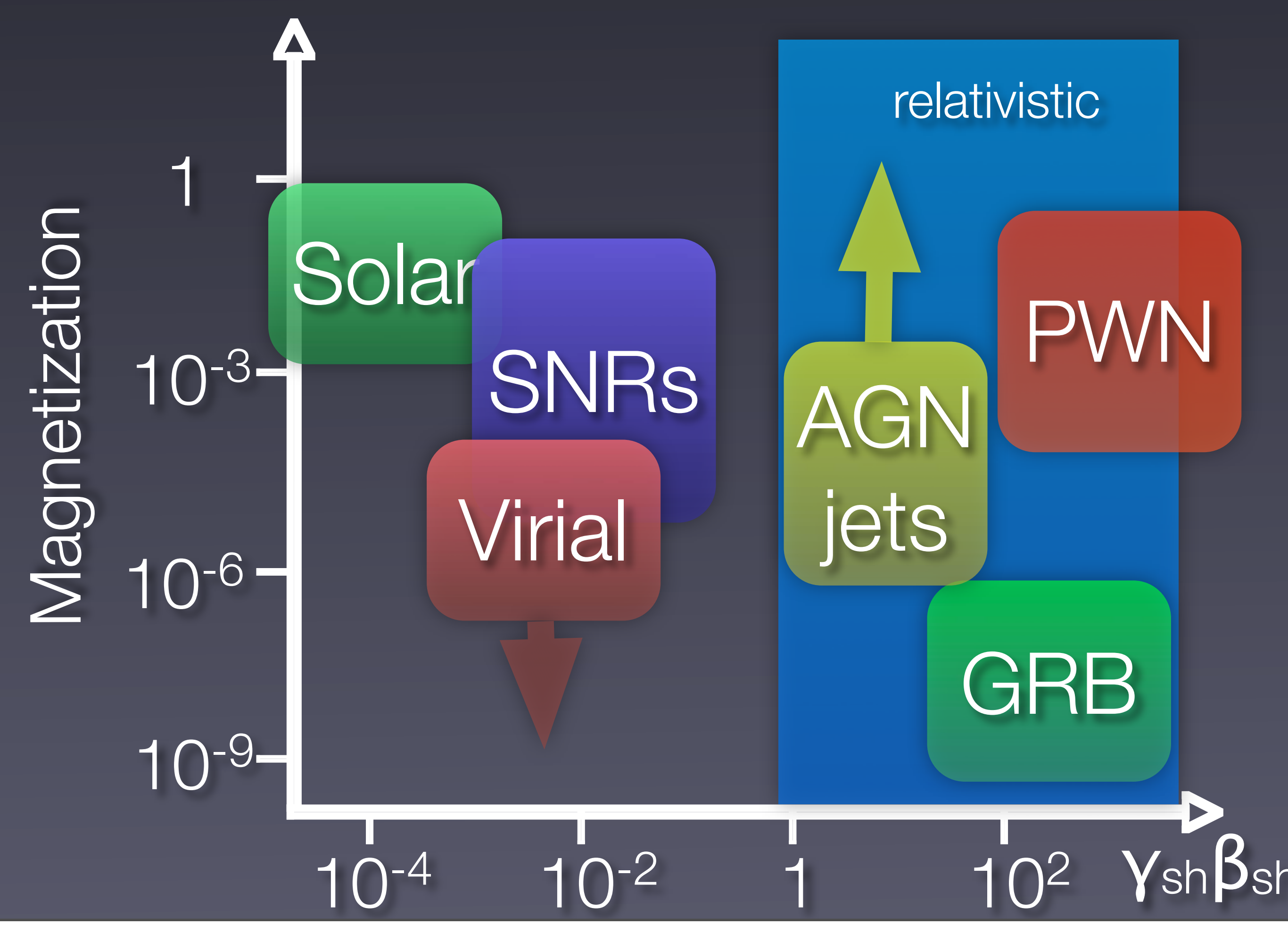

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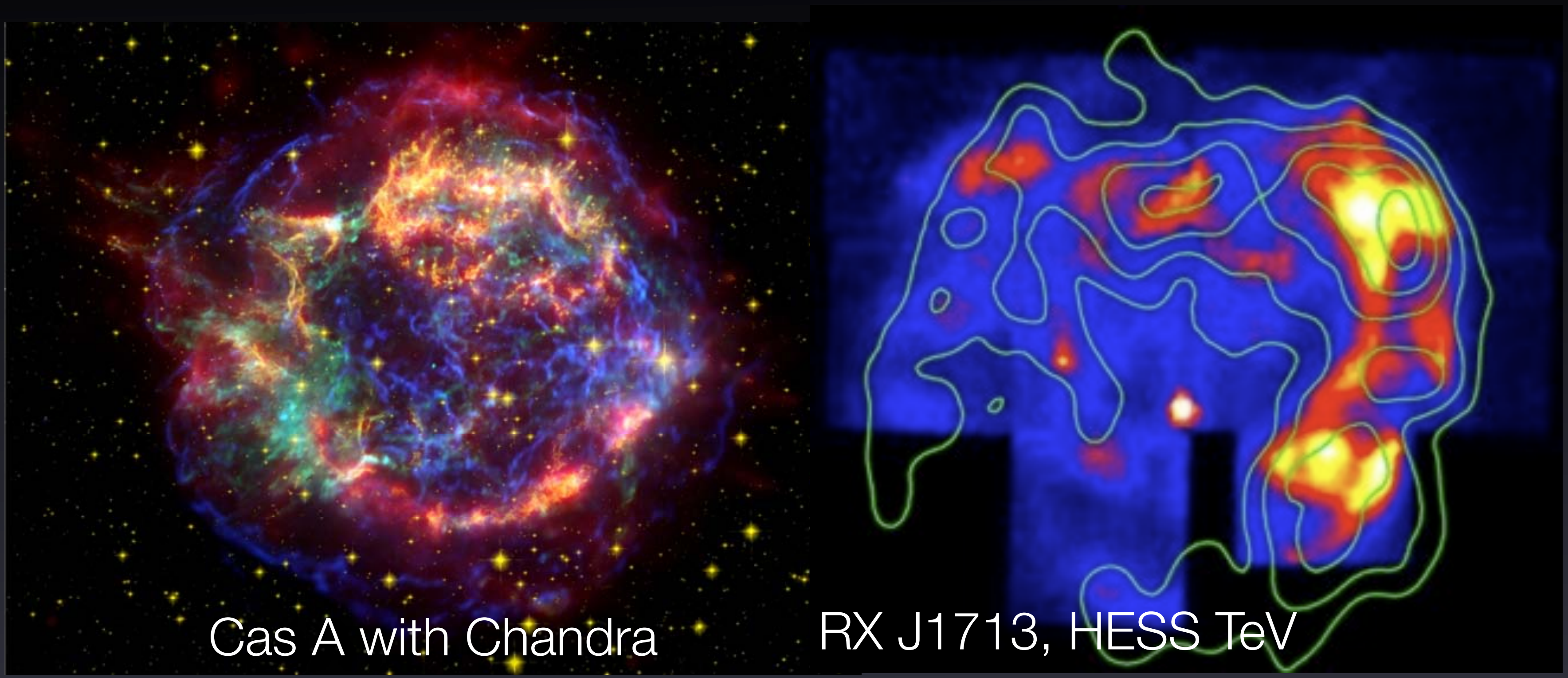

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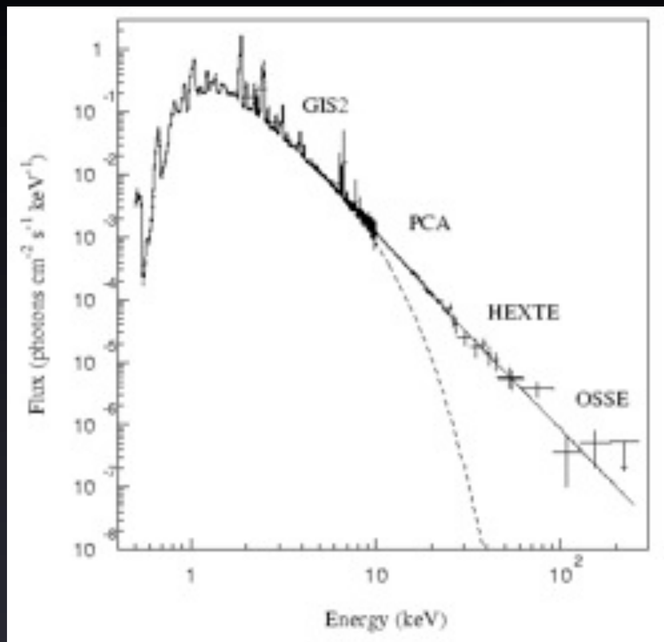
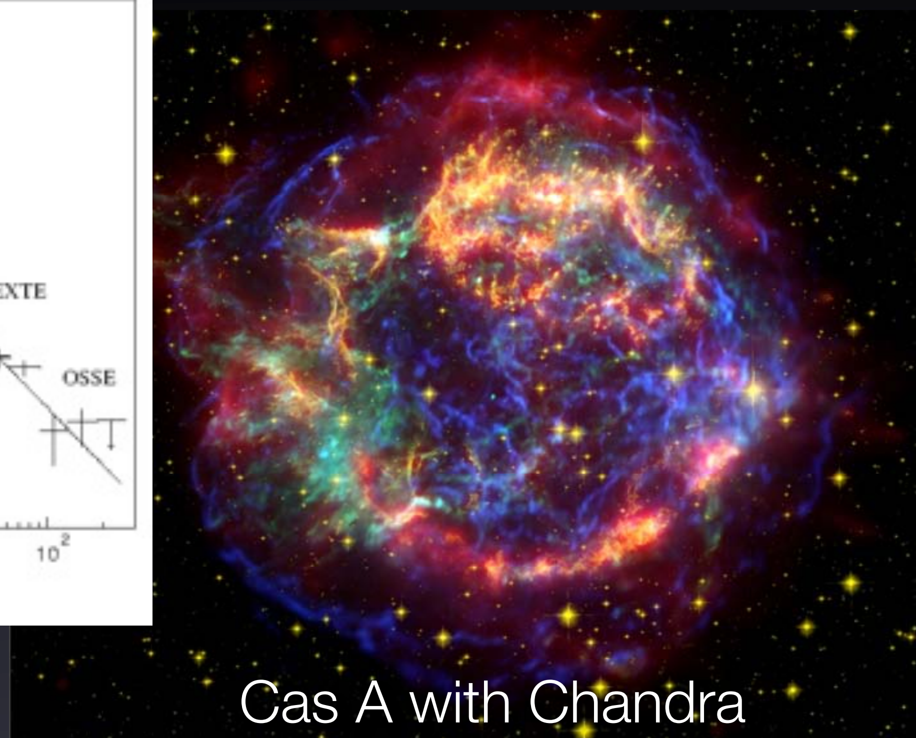
Power law spectra of synchrotron emission are observed in PWNs, SNRs, AGNs, GRBs

Thin synchrotron rims in young SNRs and their TeV emission imply > 10TeV electrons

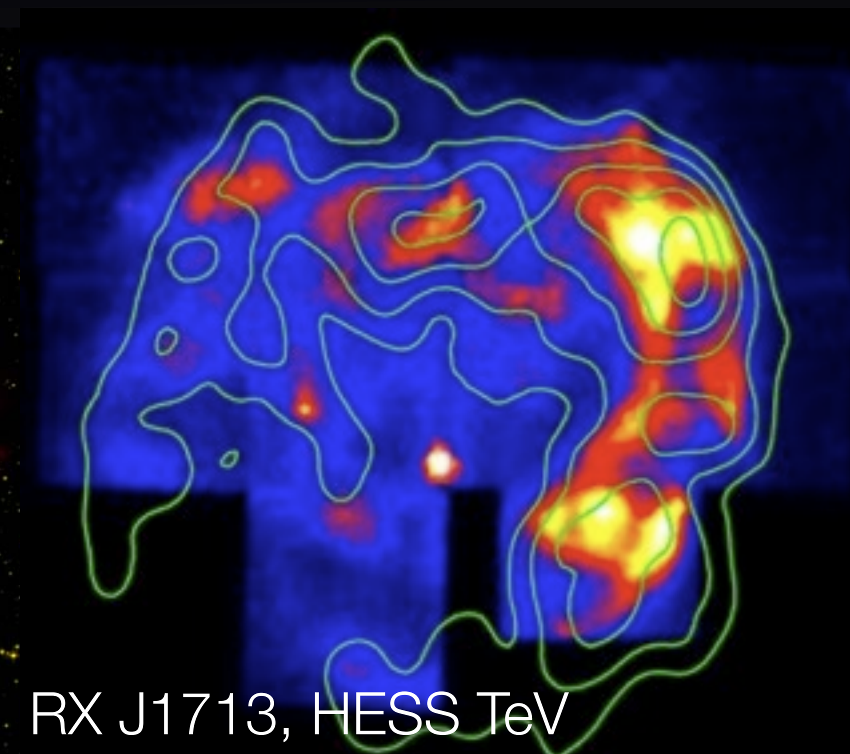
SNRs show direct evidence of CR acceleration (shock modification); ~10% energy in CRs; CRs up to 10^{15}eV thought to come from SNRs.

Shocking astrophysics





Cas A with Chandra



RX J1713, HESS TeV

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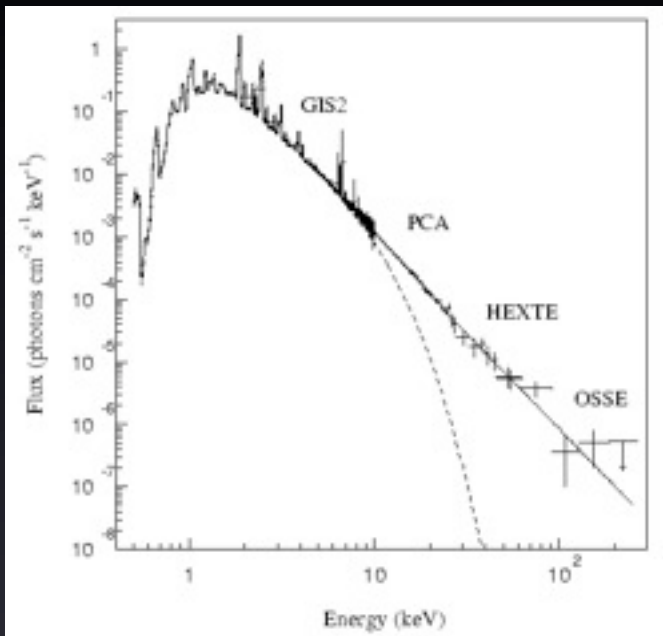

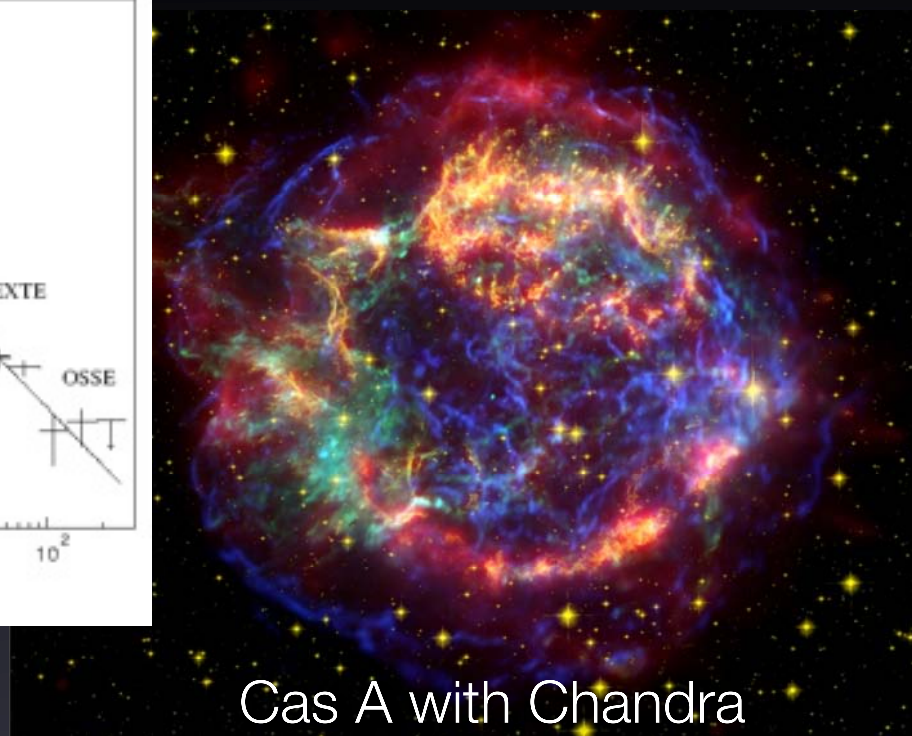
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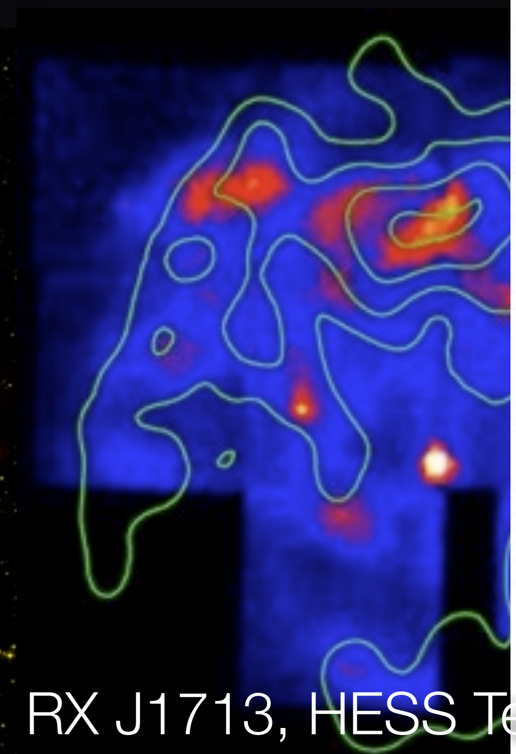
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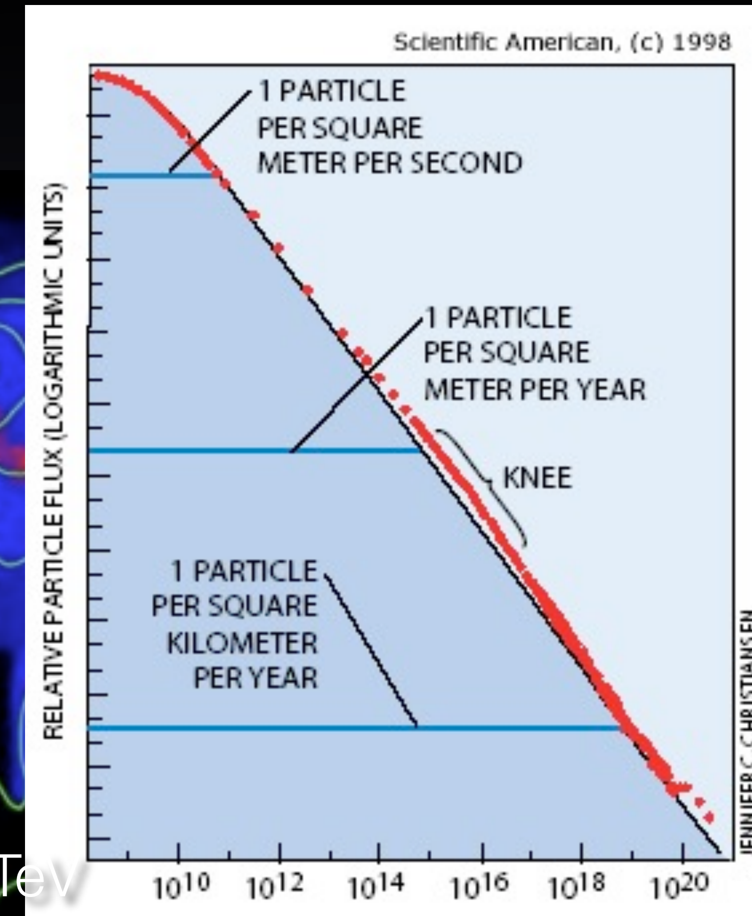

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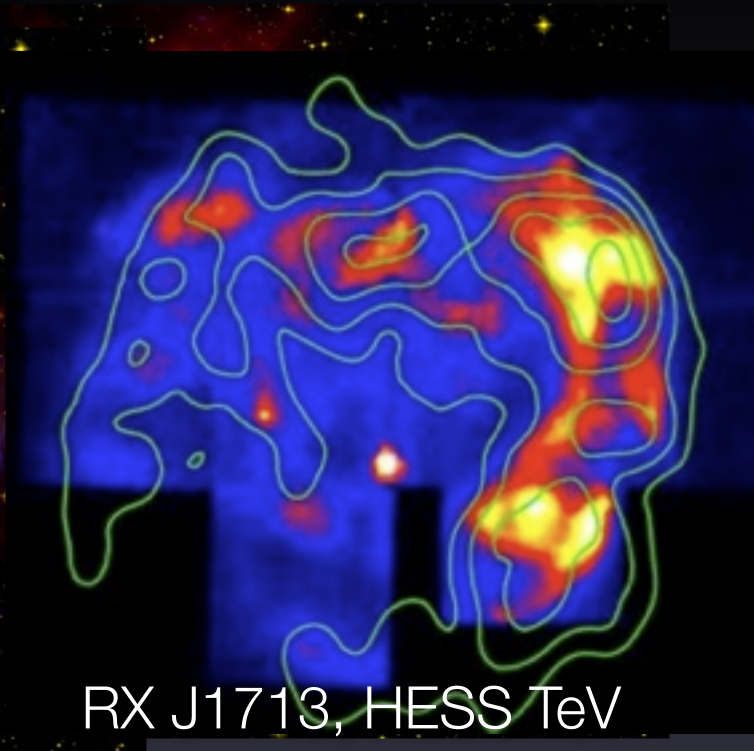

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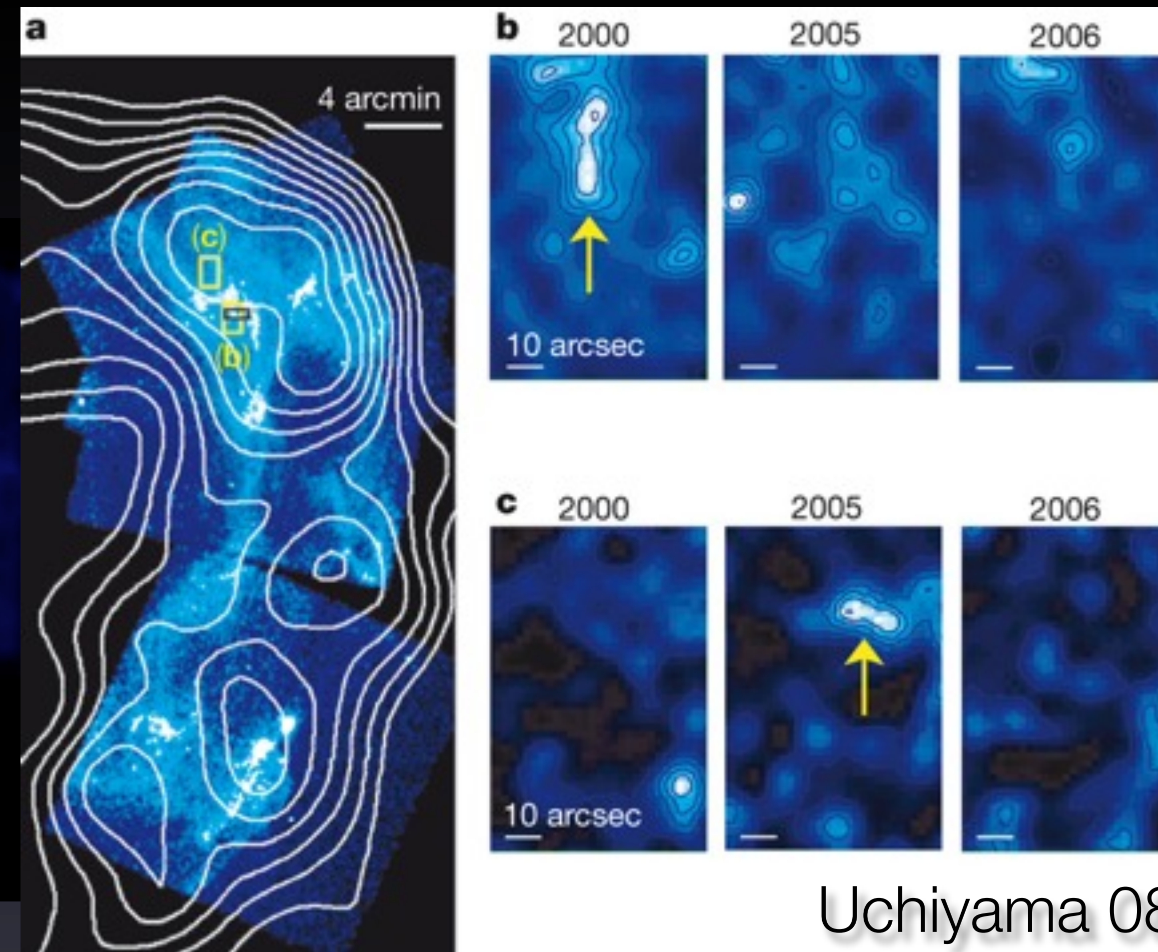

Uchiyama 08

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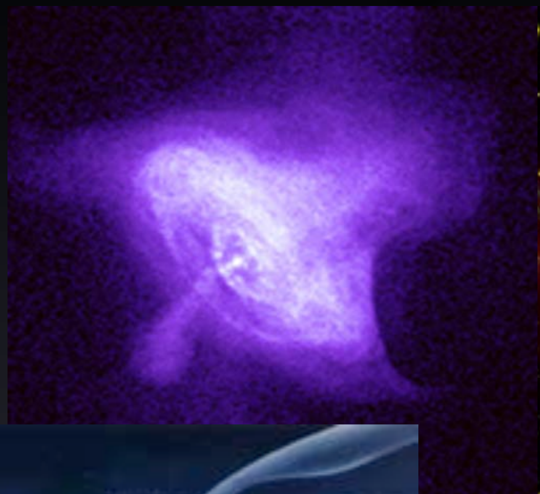
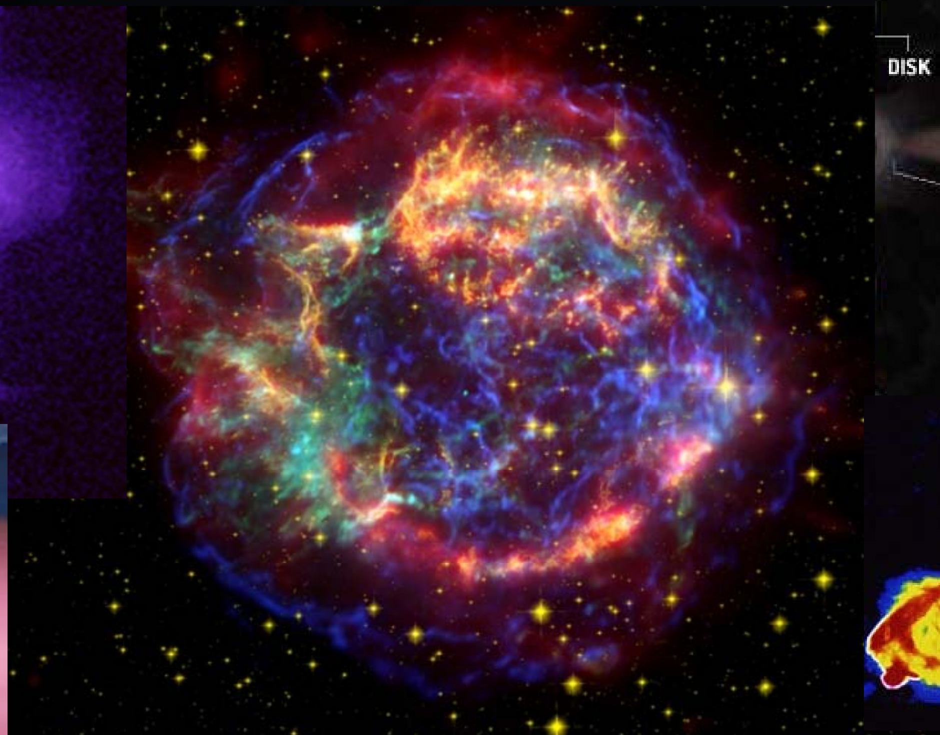
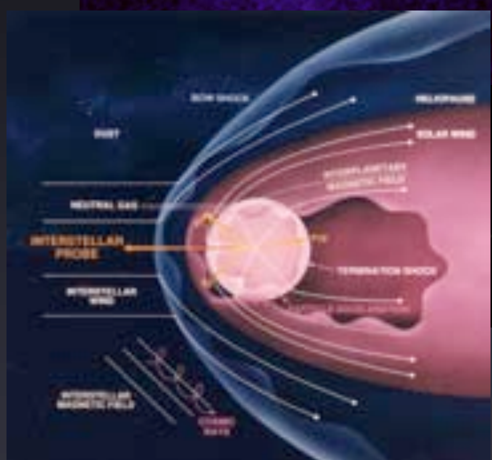
Synchrotron afterglow emission from GRBs implies at least 1% of kinetic energy in the magnetic field after the external shock. Upstream magnetization is essentially zero.

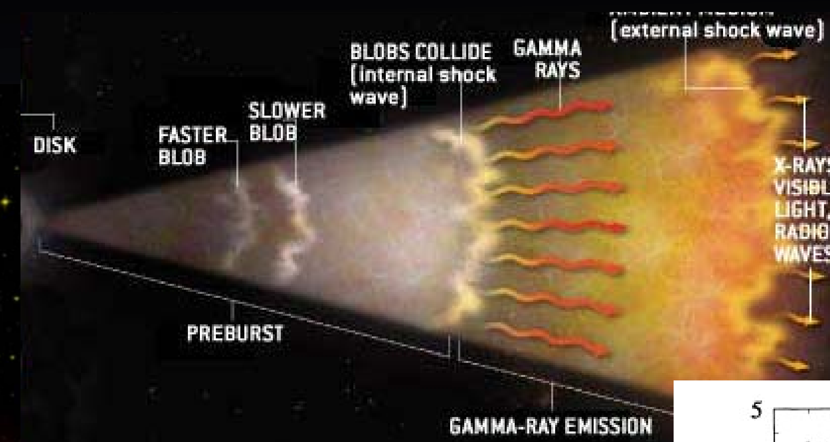
Thinness and variability of synchrotron rims. SNRs imply fast cooling time -- constrains magnetic fields ~100 microG >> than expected from shock compression alone.

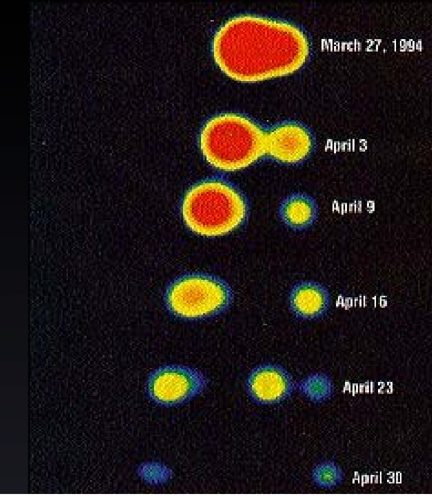
Shocking astrophysics

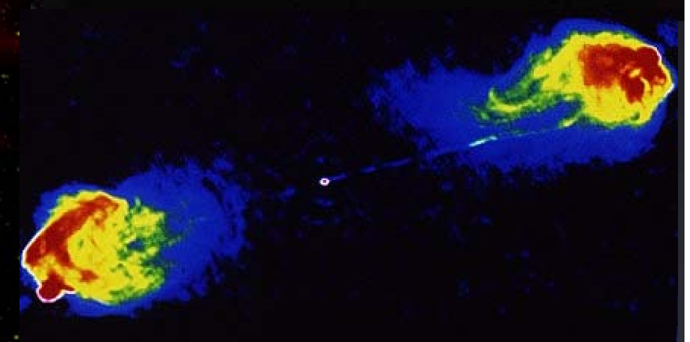


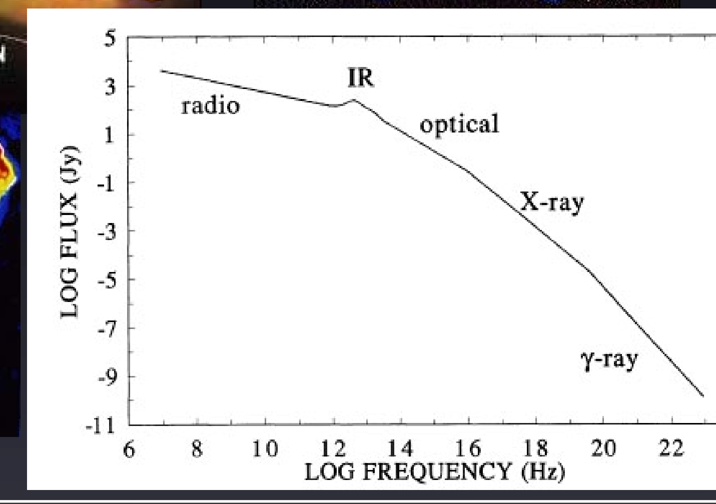












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Shock jump conditions suggest that

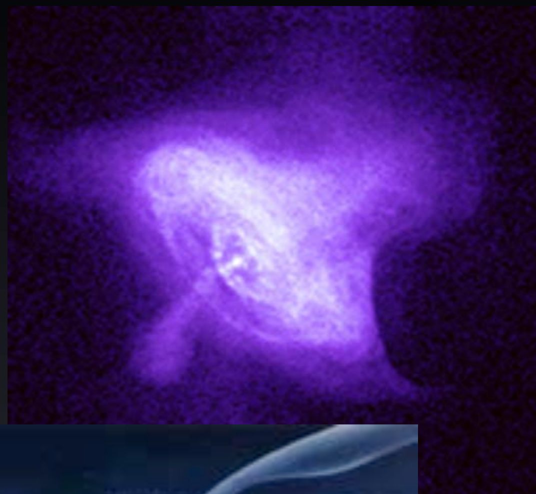
$$kT_{i,e} \sim m_{i,e}\, v_{sh}^2$$

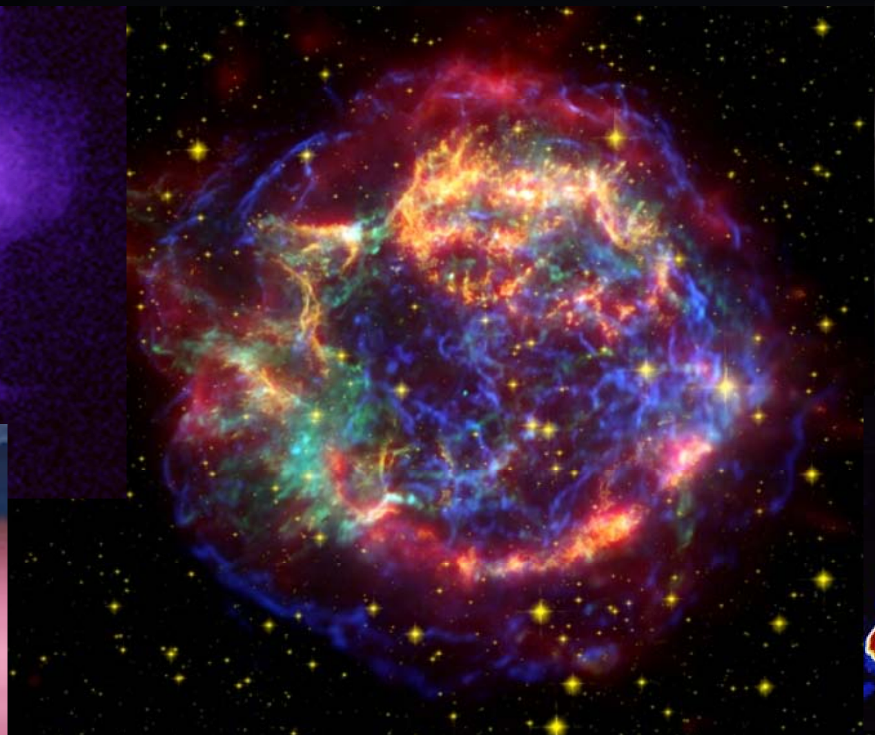
(equilibrate due to collisions or plasma physics)

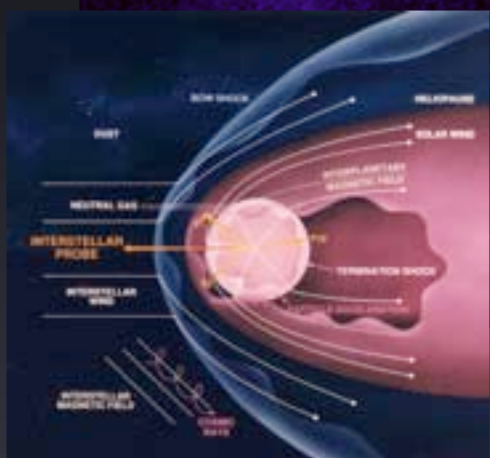
GRB observations suggest large fraction of energy in electrons after relativistic shocks (~10%)

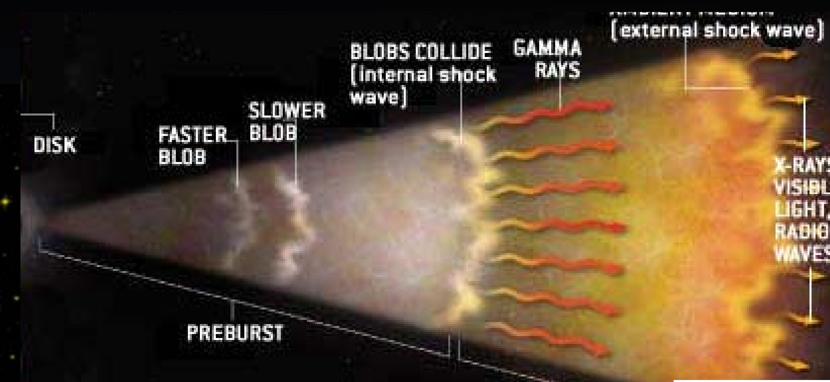
Spectral fits of SNRs (Ballmer lines) allow measurement of T_e and T_i, suggesting velocity-independent electron heating (Ghavamian et al 2007, Heng et al 2008).

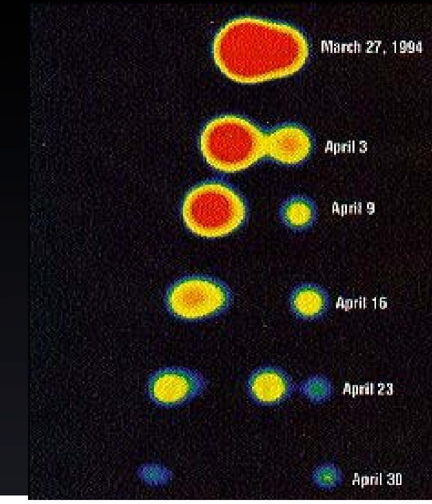
Shocking astrophysics











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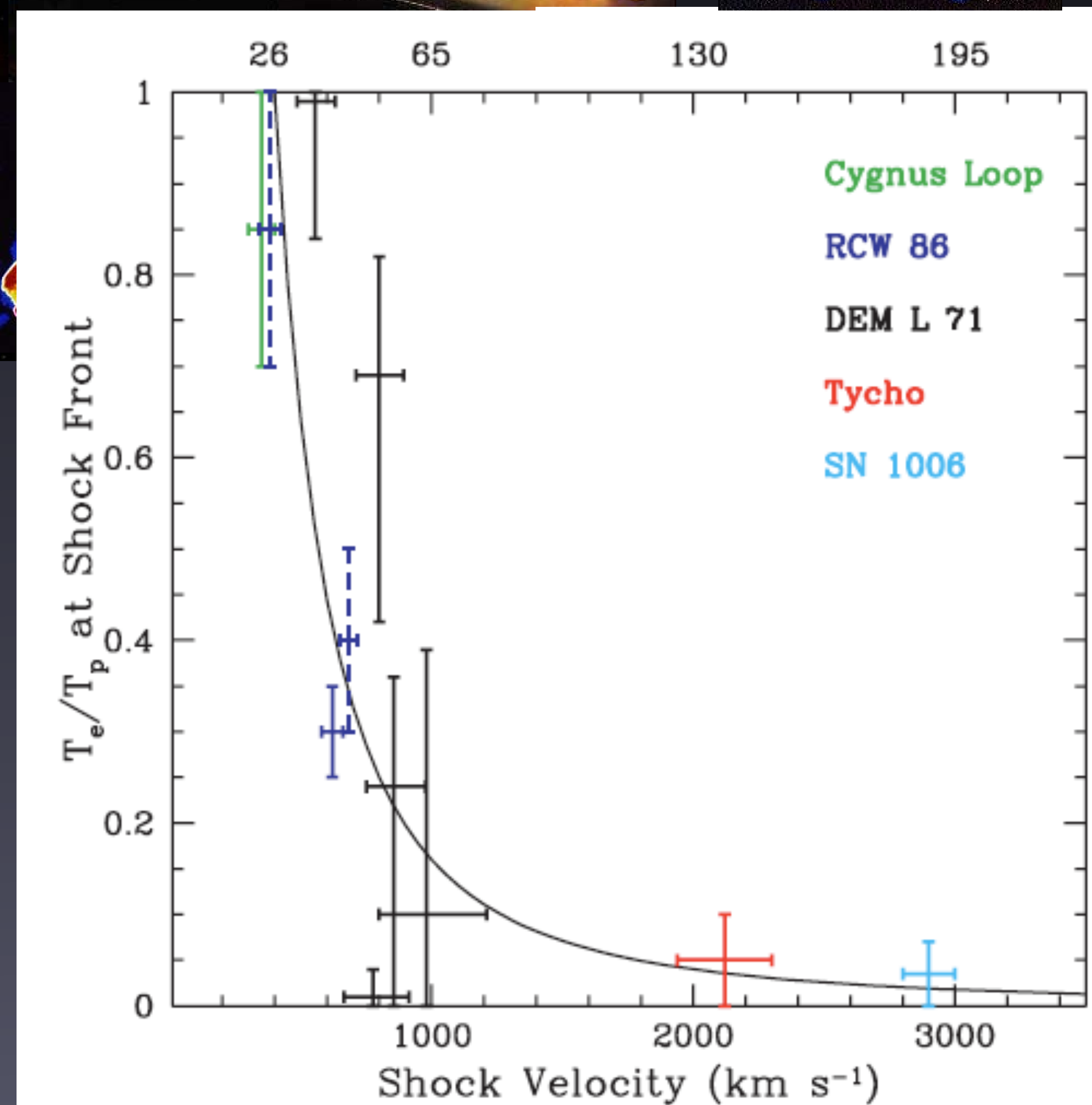
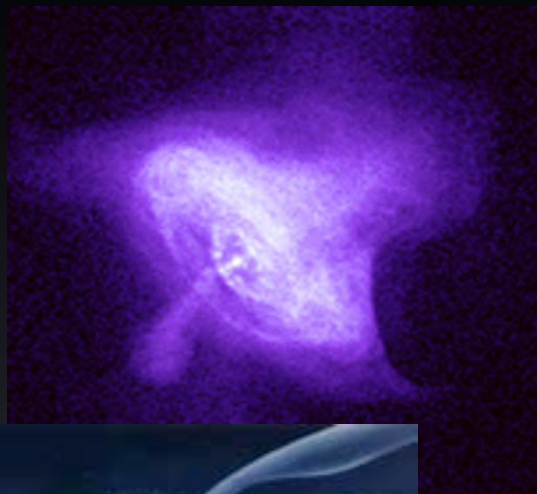
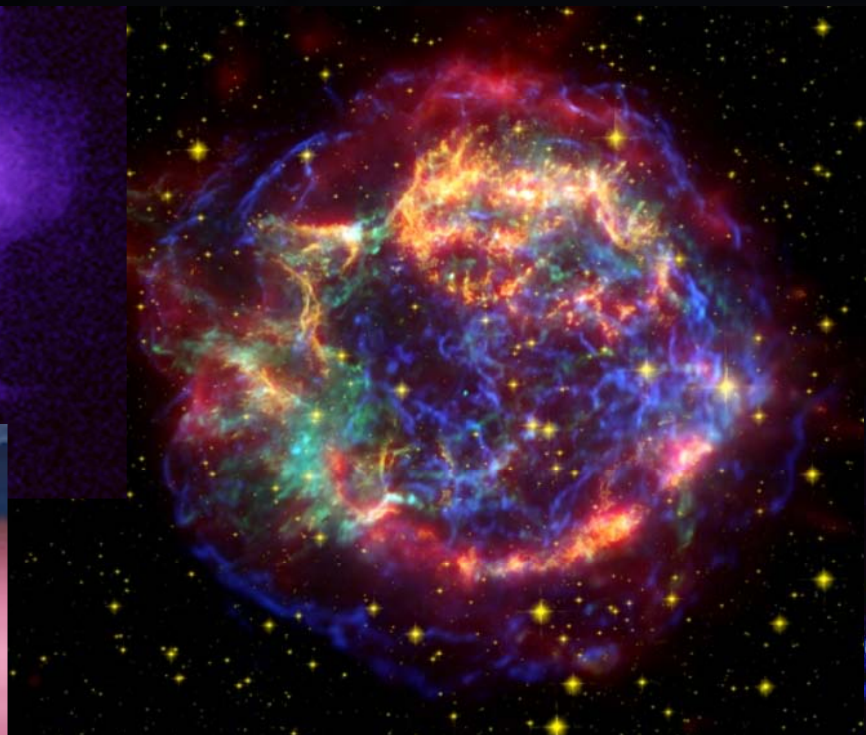
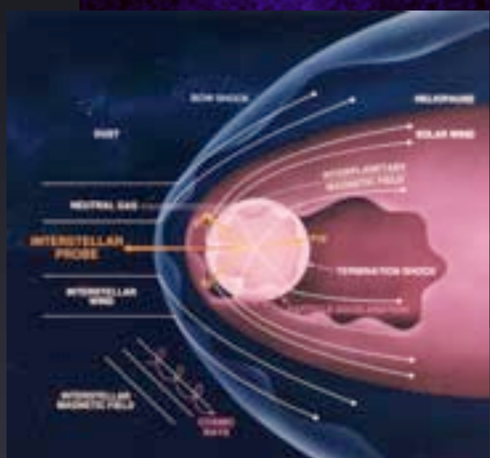


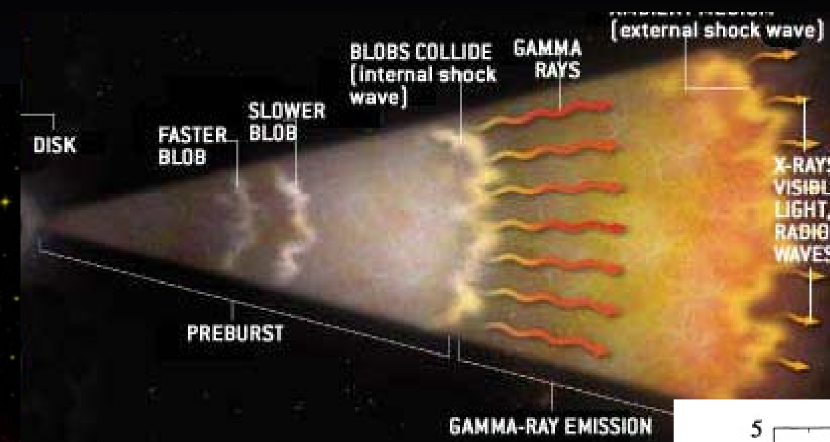
(Ghavamian et al 2007)

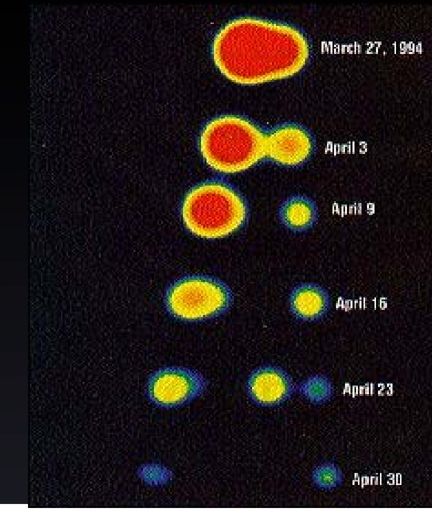
Shocking astrophysics

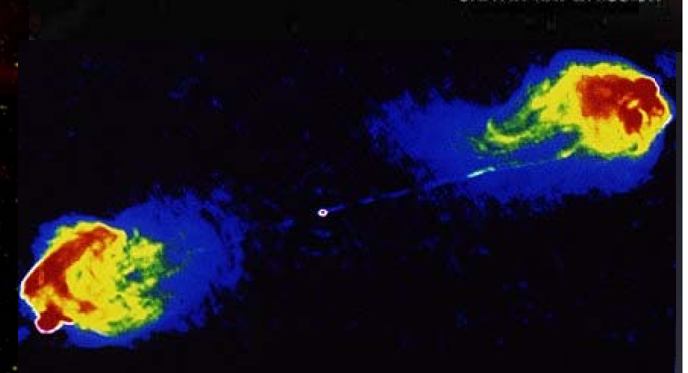


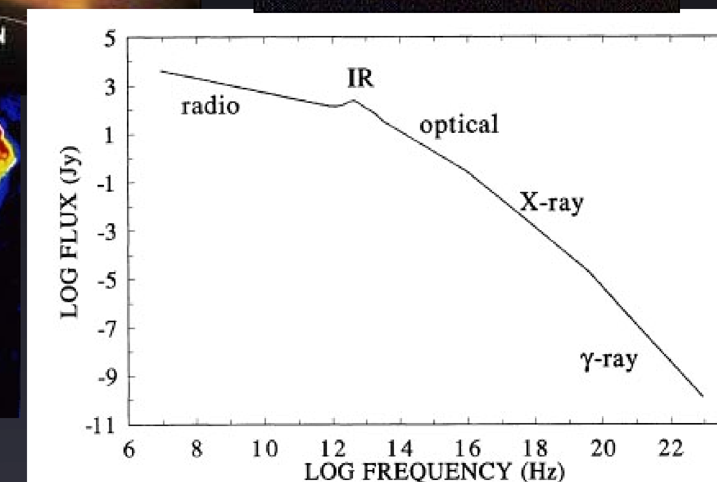












Open issues:

What is the structure of collisionless shocks? Do they exist? How do you collide without collisions?

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Generation of magnetic fields? GRB/SNR shocks, primordial fields?

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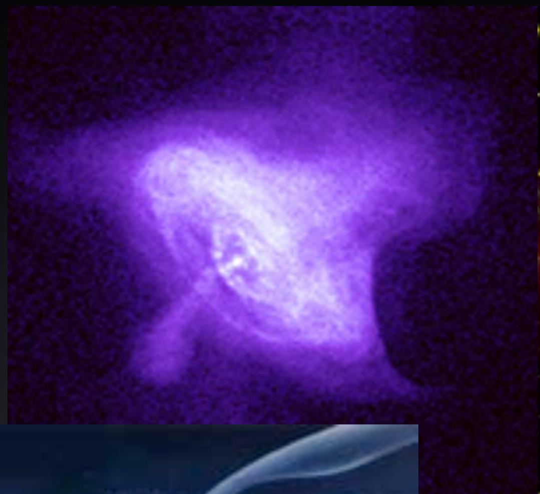

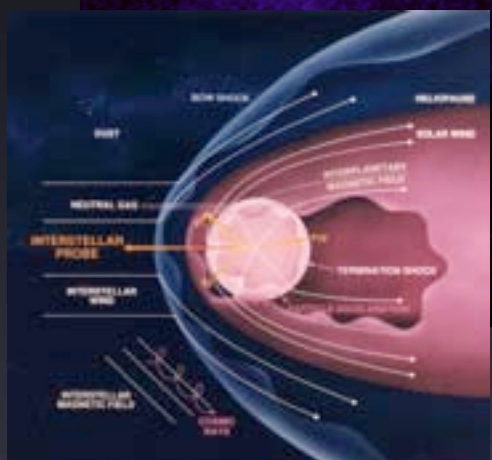

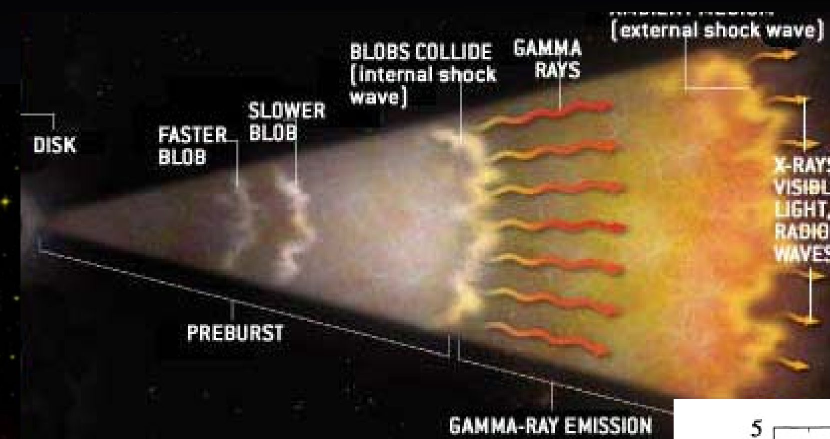

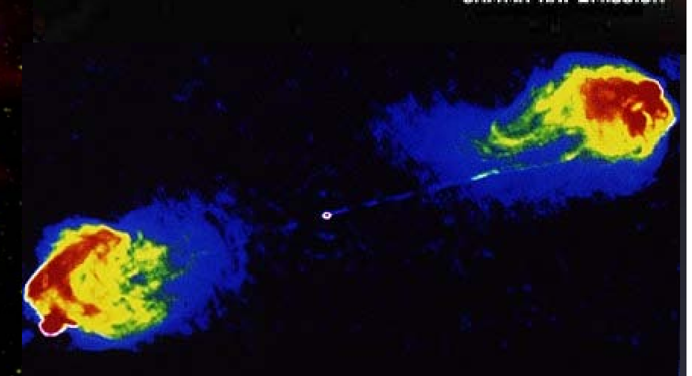

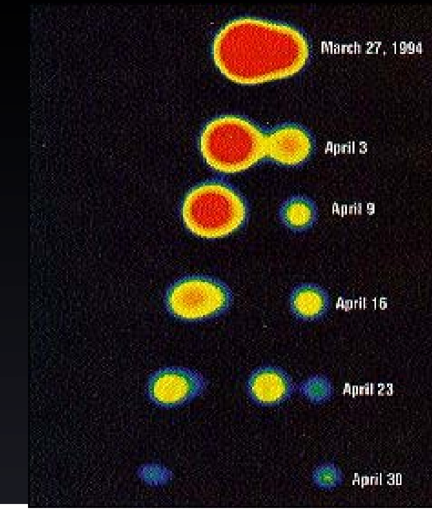

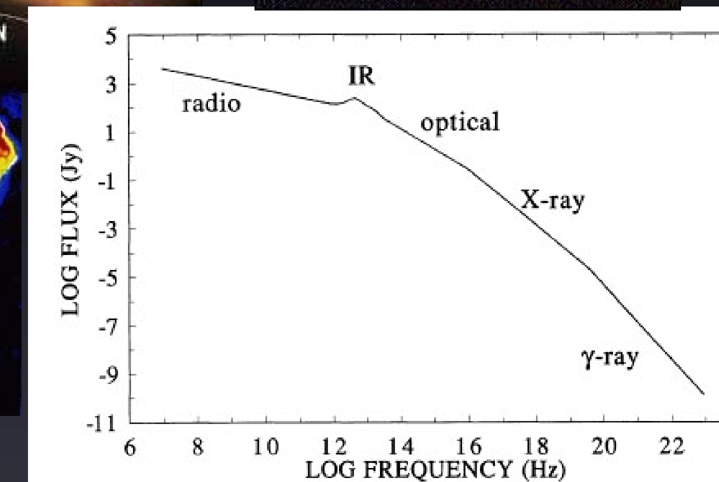

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All are coupled through the structure of turbulence in shocks and acceleration

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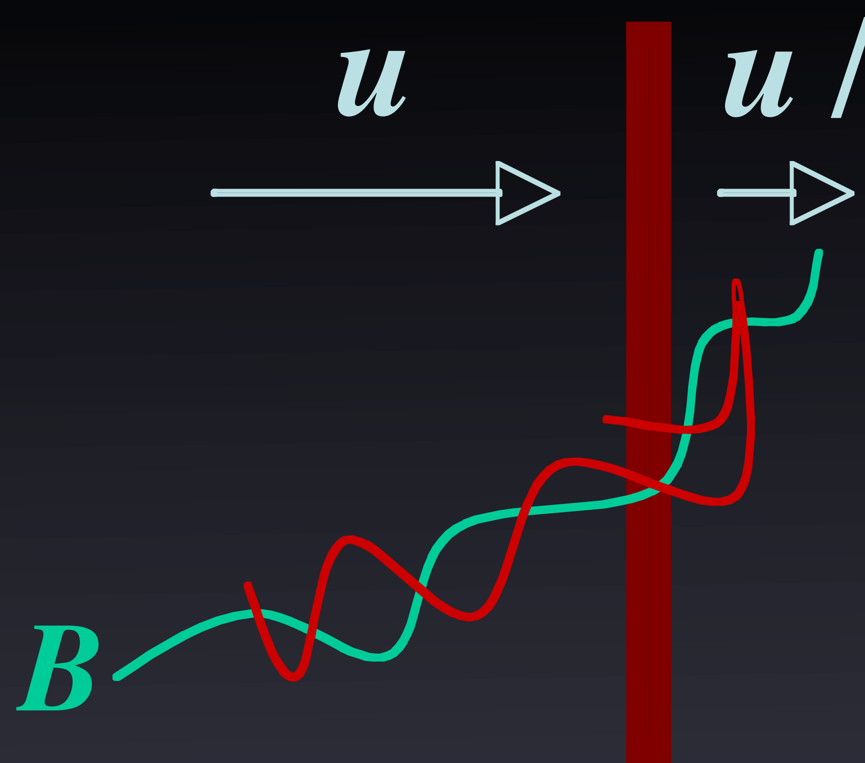

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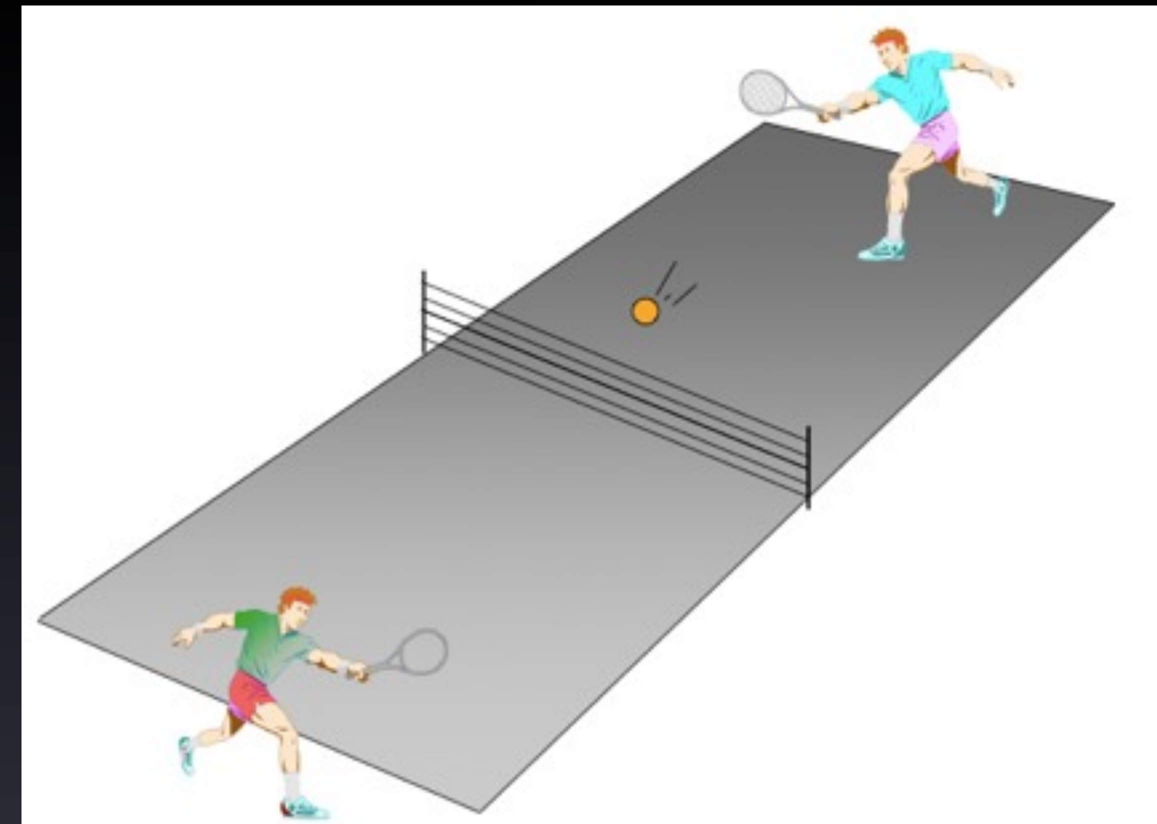
$N(E) \sim N_0\, E^{-K(r)}$



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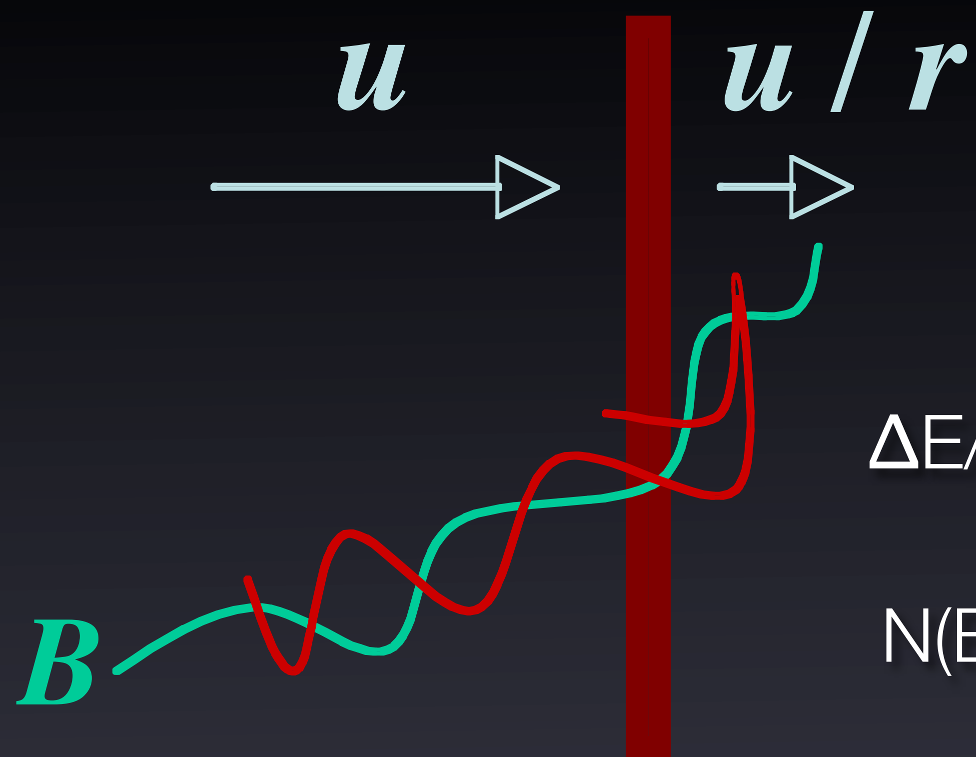

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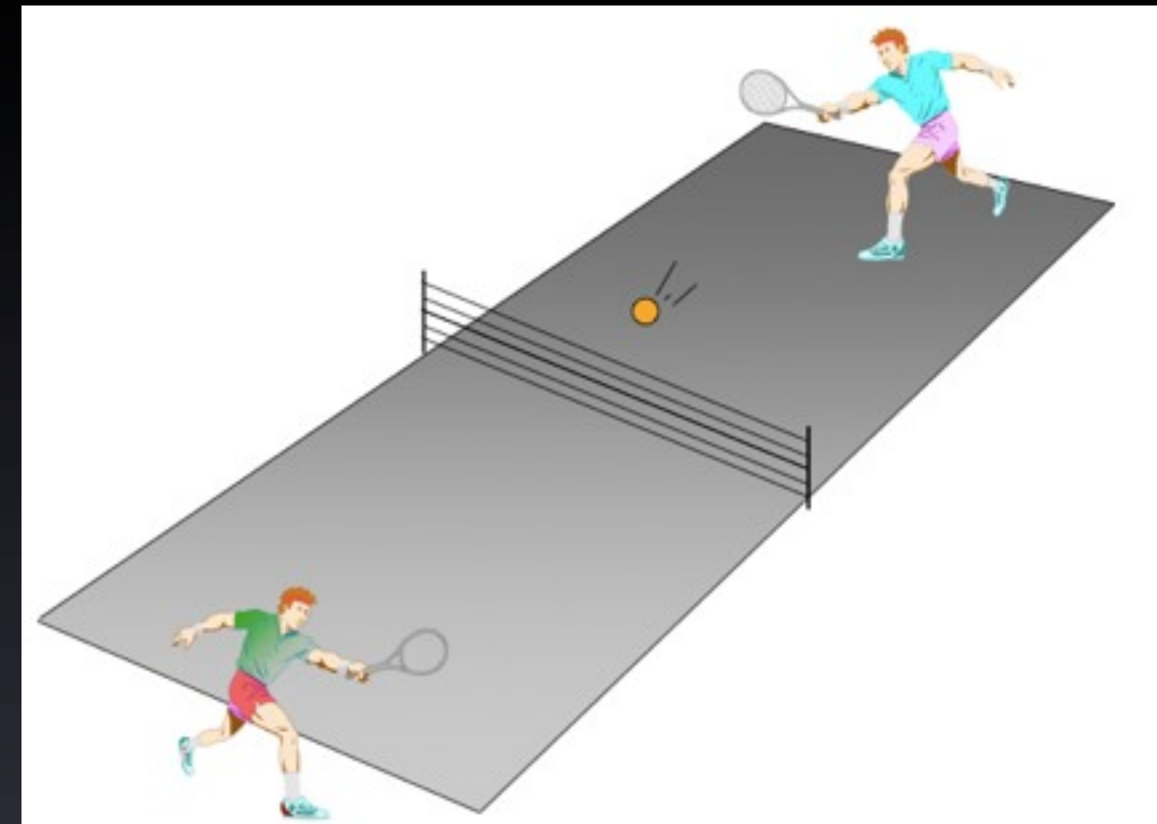

Free energy: converging flows

Acceleration mechanisms:

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  - Diffusive shock acceleration
  - Shock drift acceleration
  - Shock surfing acceleration

- Second order Fermi

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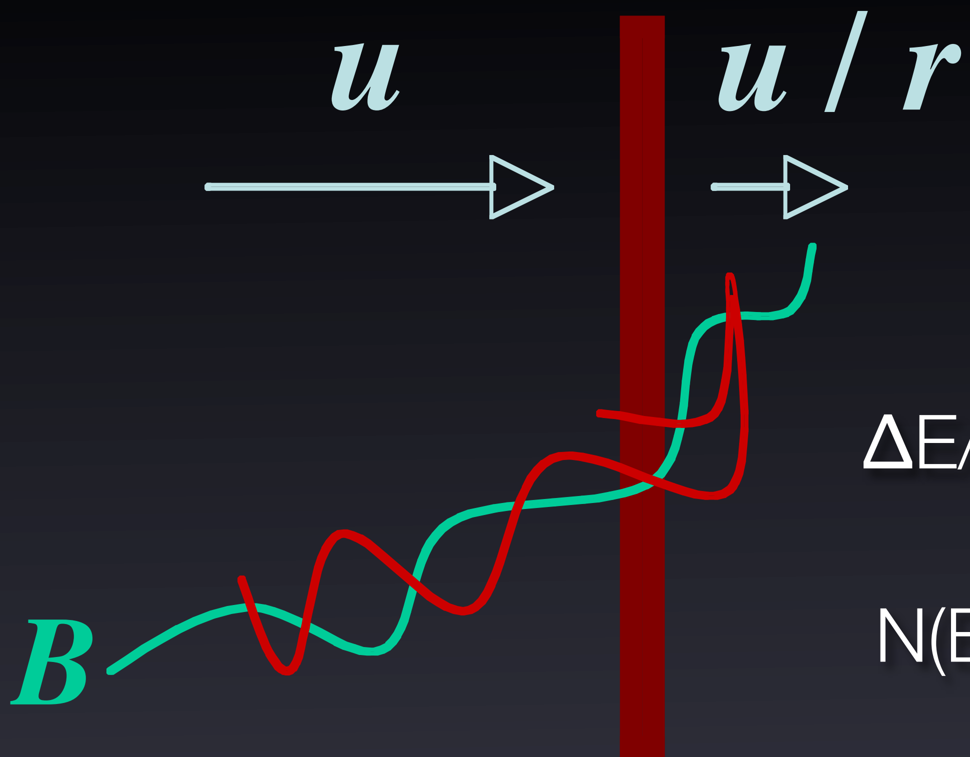

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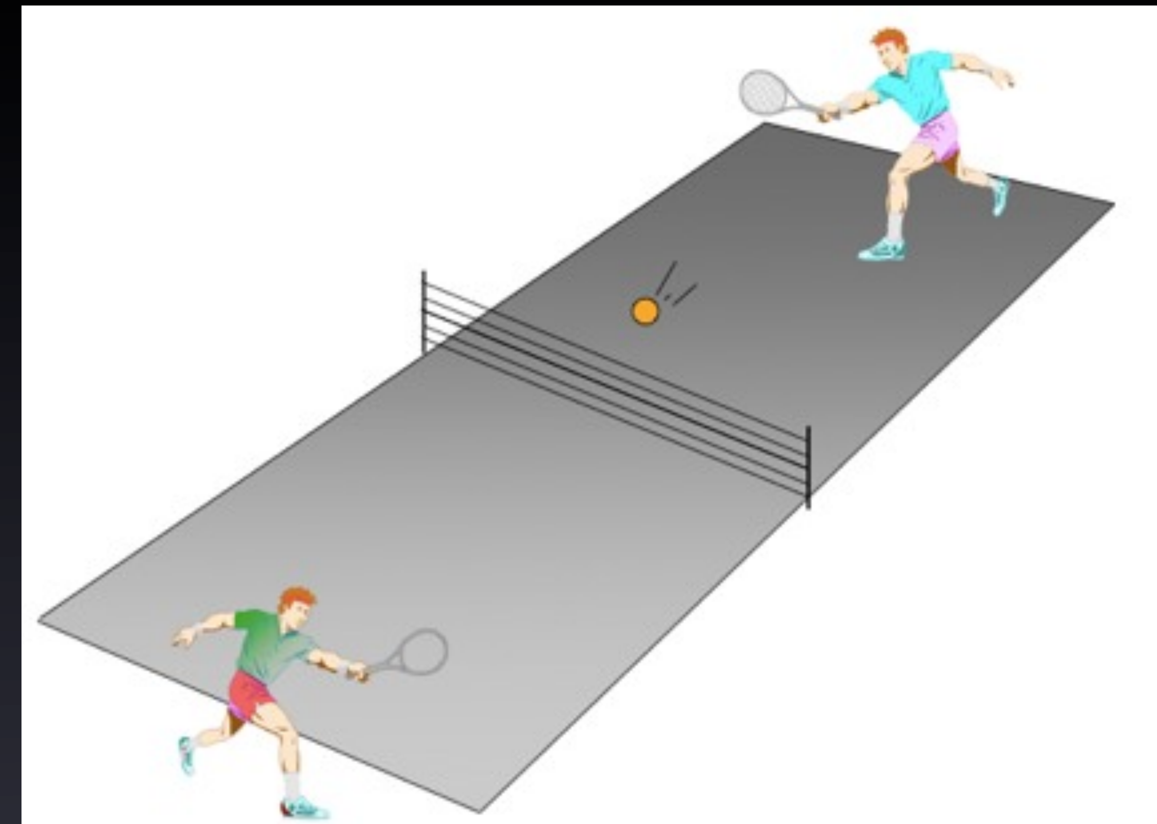

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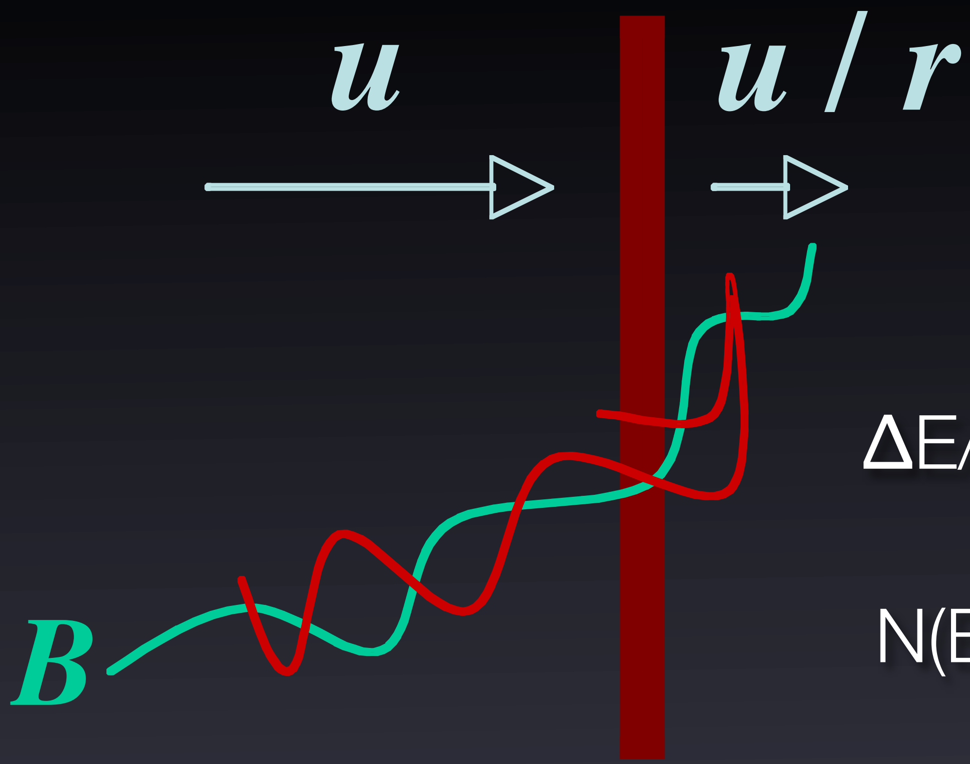

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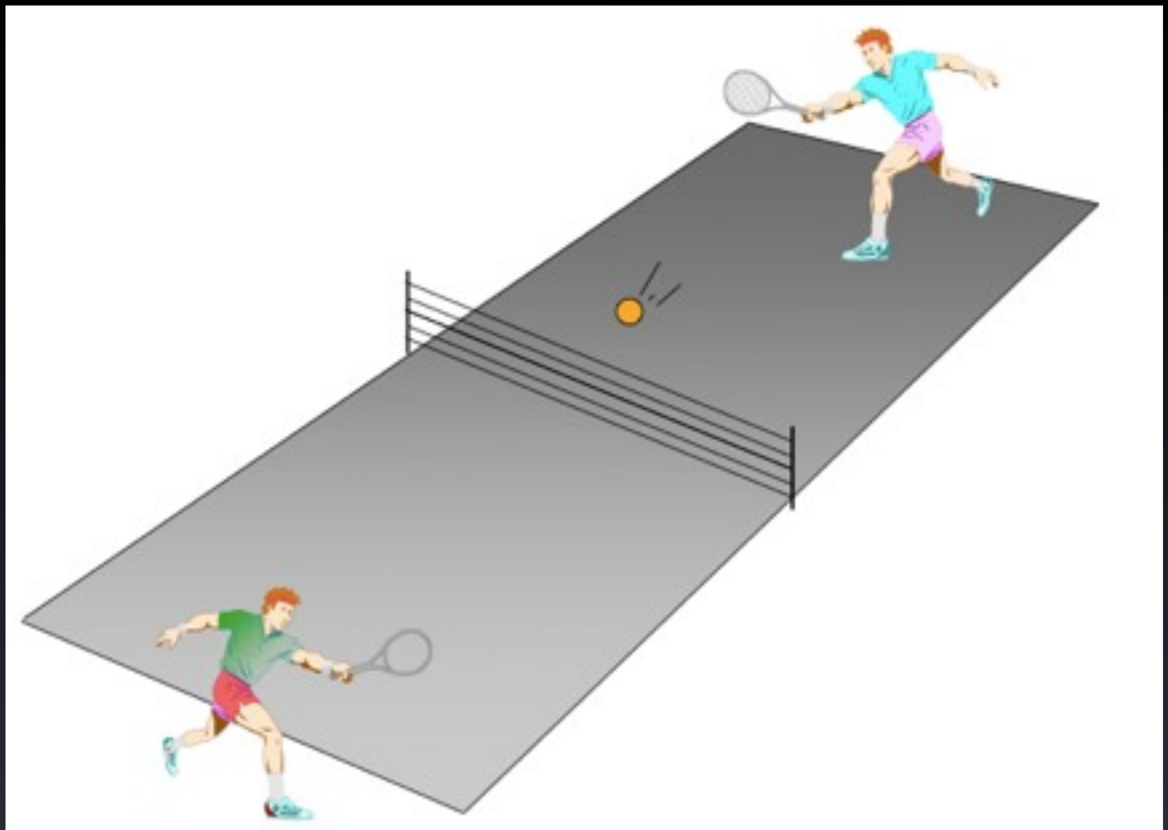

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Requires turbulence for injection into acceleration process and to stay near the shock

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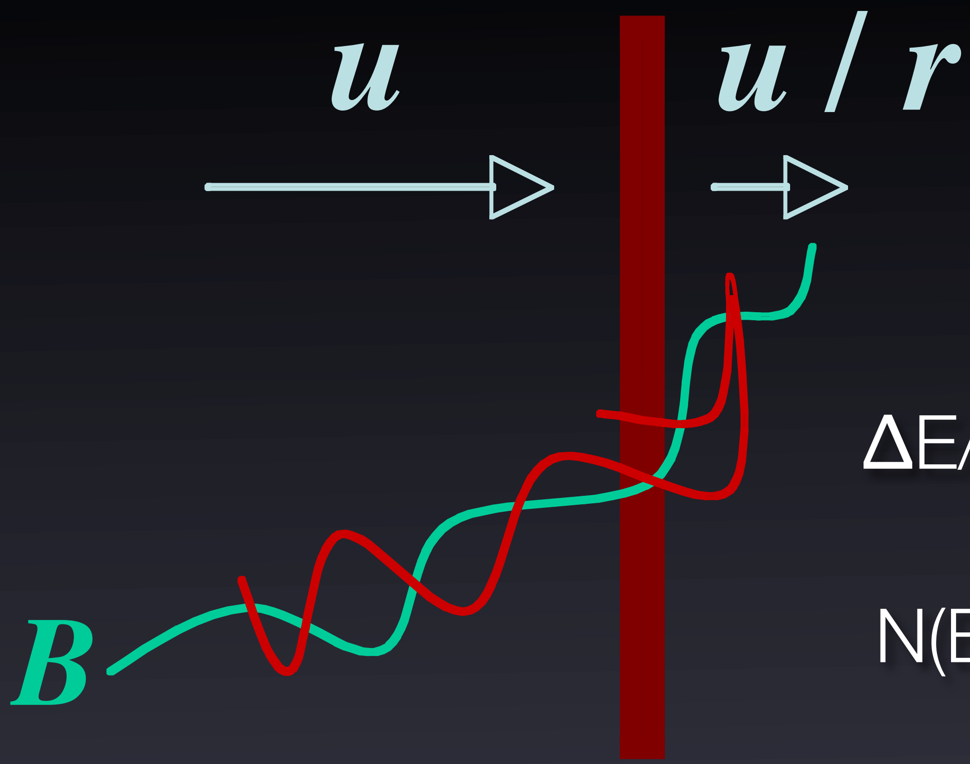

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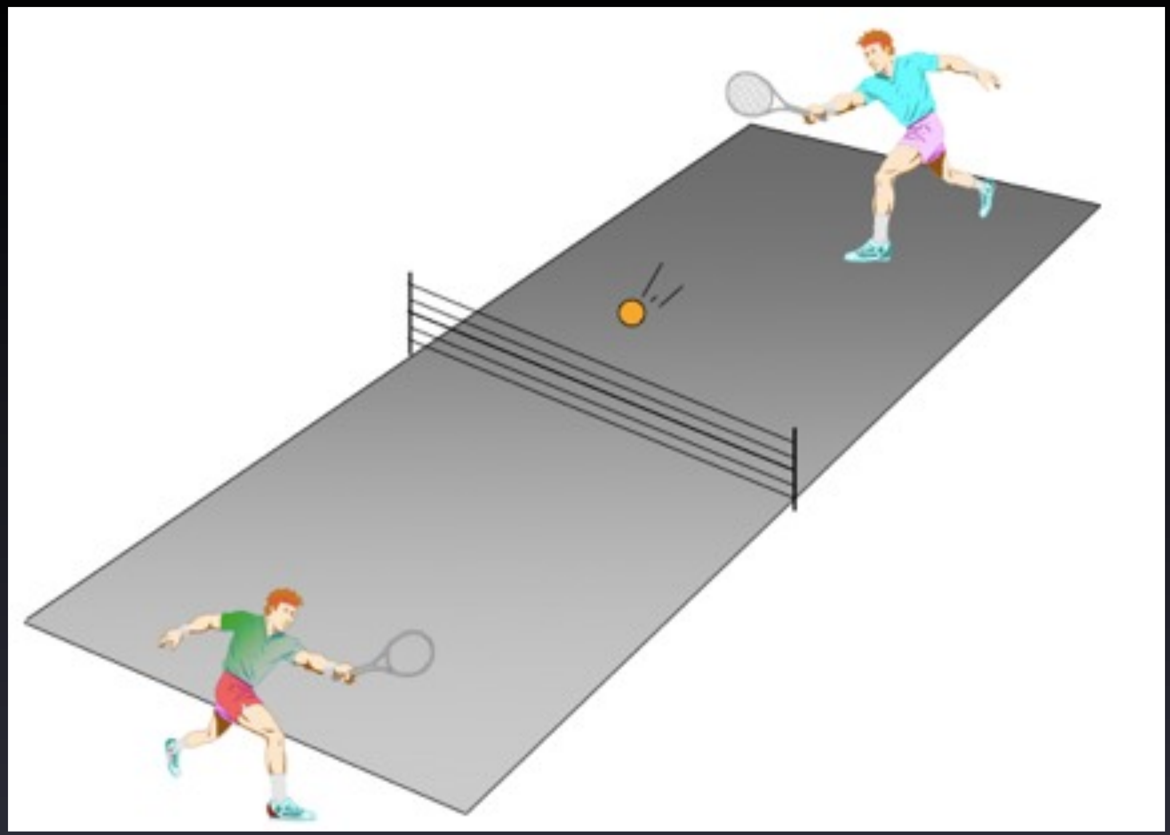


Free energy: converging flows

Acceleration mechanisms:

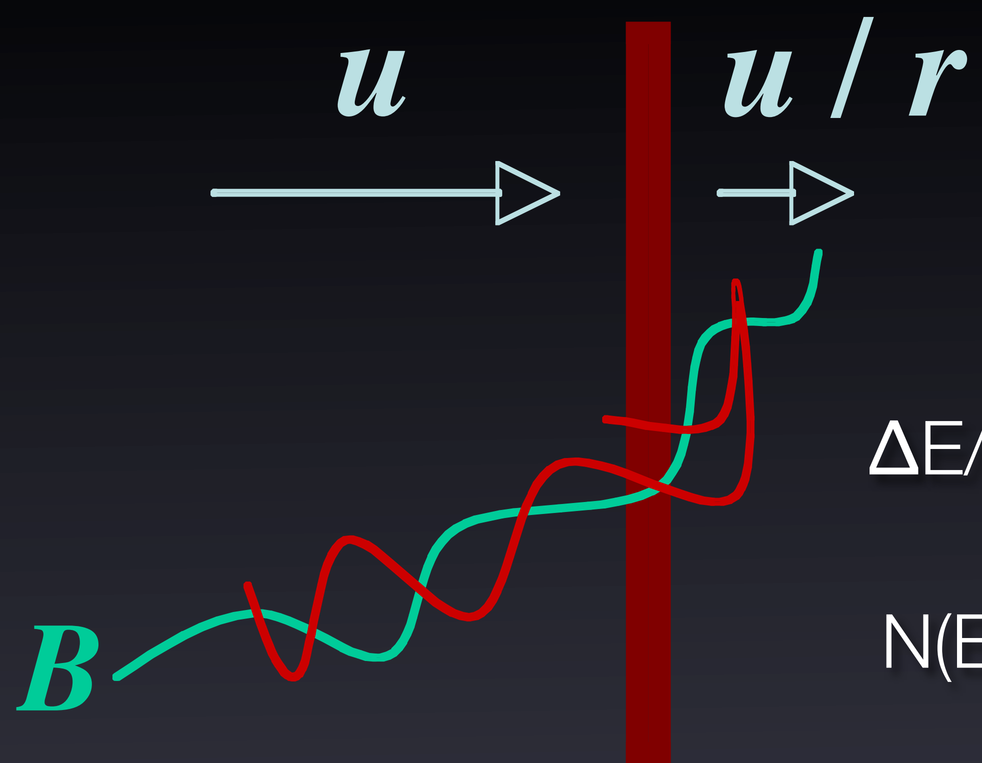
- First order Fermi
  - Diffusive shock acceleration
  - Shock drift acceleration
  - Shock surfing acceleration
- Second order Fermi

Efficient scattering of particles is required. Monte Carlo simulations of rel. shocks show that this implies very high level of turbulence δB/B(Ostrowski et al). Is this realistic? Are there specific conditions?

Requires turbulence for injection into acceleration process and to stay near the shock

Needs spectrum of turbulent motions (waves) downstream.

Particle acceleration:



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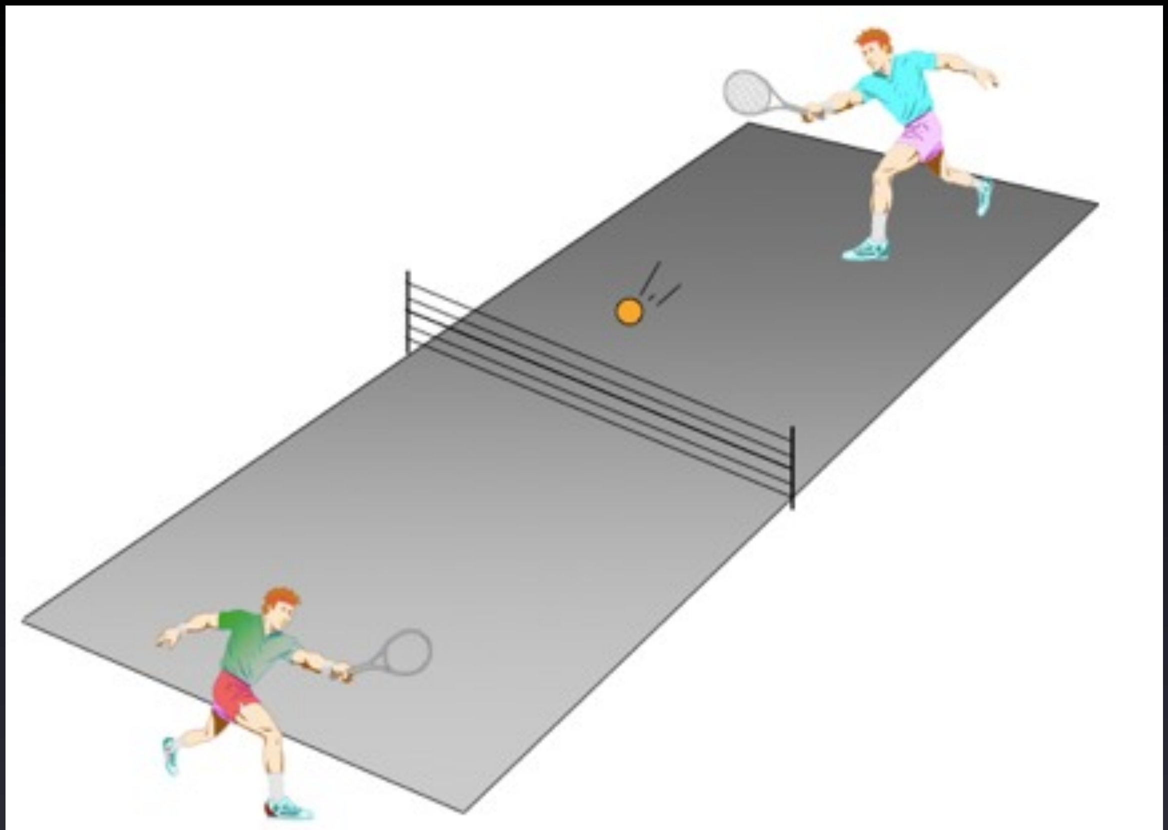

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Requi ...
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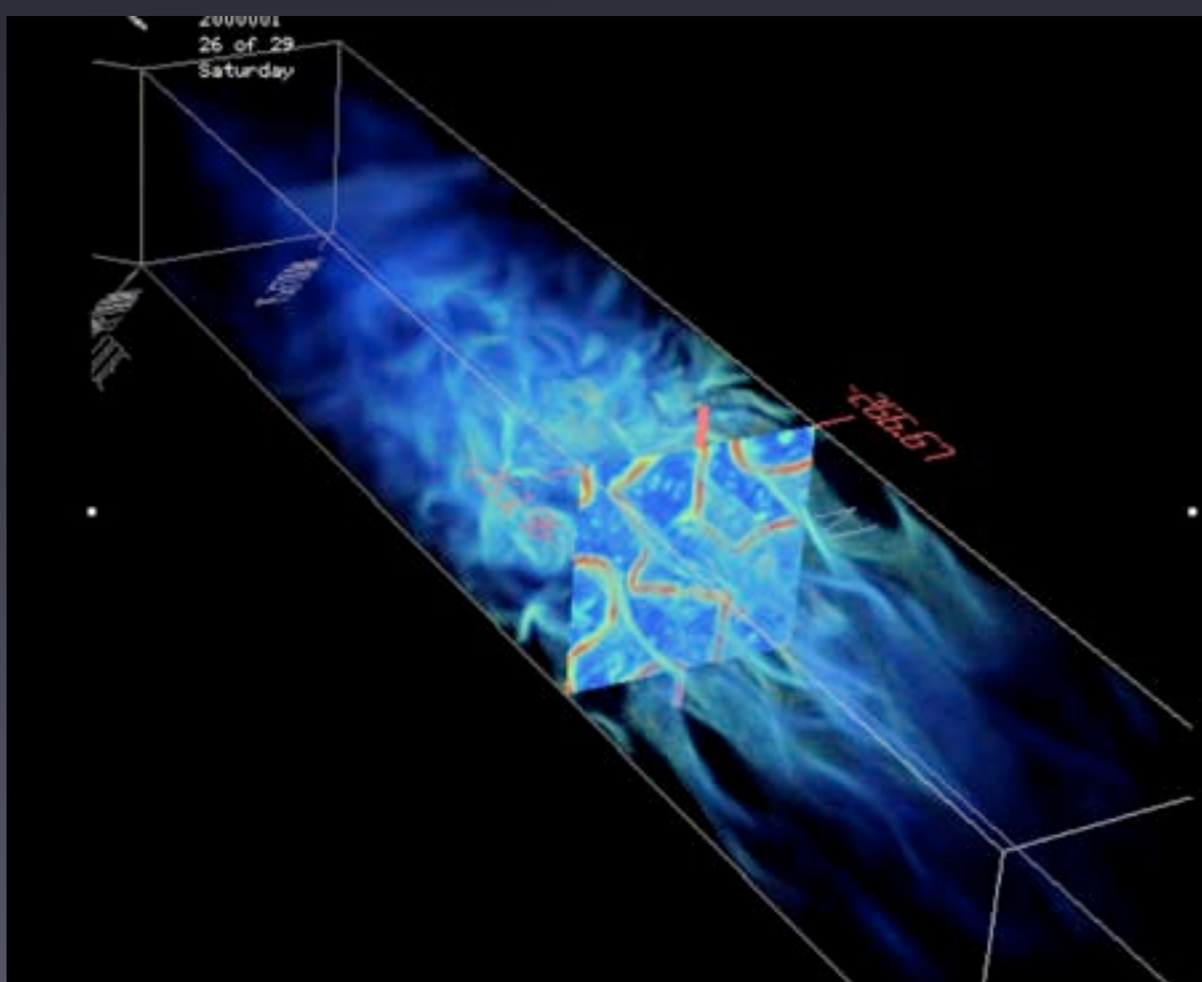
We need to understand the microphysics of collisionless shocks:

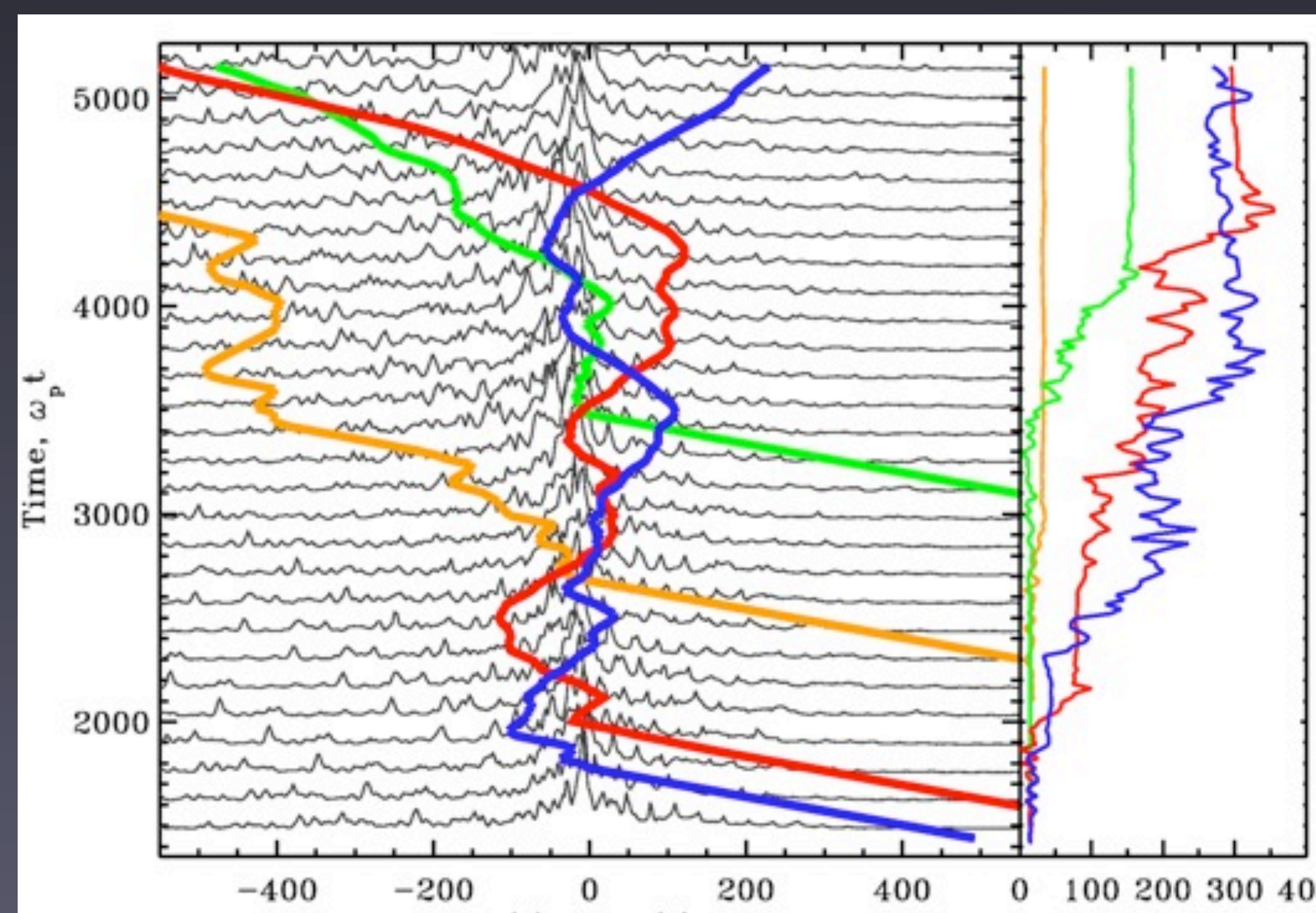
with plasma simulations
with experiments
with space observations

Computer simulations of shocks

Rapid expansion of computer capcity in recent years has allowed the study of collisionless shocks from first principles in multi-dimensions via PIC and hybrid simulations.

Largest simulations 1024x1024x10000, 4e10 particles, or 8000x200000 in 2D. Typical scales 200^2x2000 (c/ω_{pe}). mi/me from 1 to 1000. Run times in 2D 10^4 $1/\omega_{pe}$. Papers by Spitkovsky et al, Silva et al, Nishikawa et al, Hoshino et al. Results are now being confirmed by independent groups.





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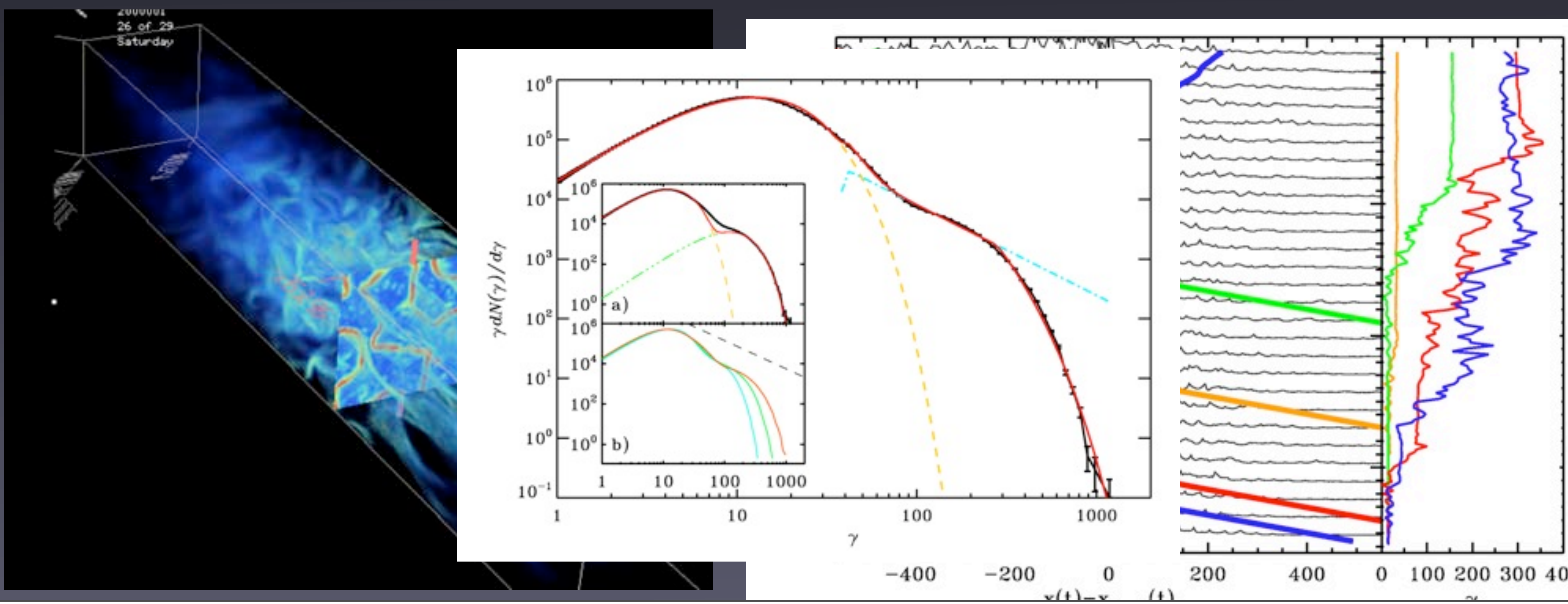

Parameter space of collisionless shocks

Properties of shocks can be grossly characterized by several dimensionless parameters:

Alfven Mach number $M_A = \frac{v}{v_A}$ *Composition* $r = \frac{m_i}{m_e}$ *Sonic Mach number* $M_s = \frac{v}{c_s}$

Magnetization

$$\sigma \equiv \frac{B^2/4\pi}{(\gamma - 1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$

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$$\omega_c = \frac{qB}{\gamma mc}$$

$$\omega_p = \left(\frac{4\pi q^2 n}{\gamma m}\right)^{\frac{1}{2}}$$

Shocking astrophysics

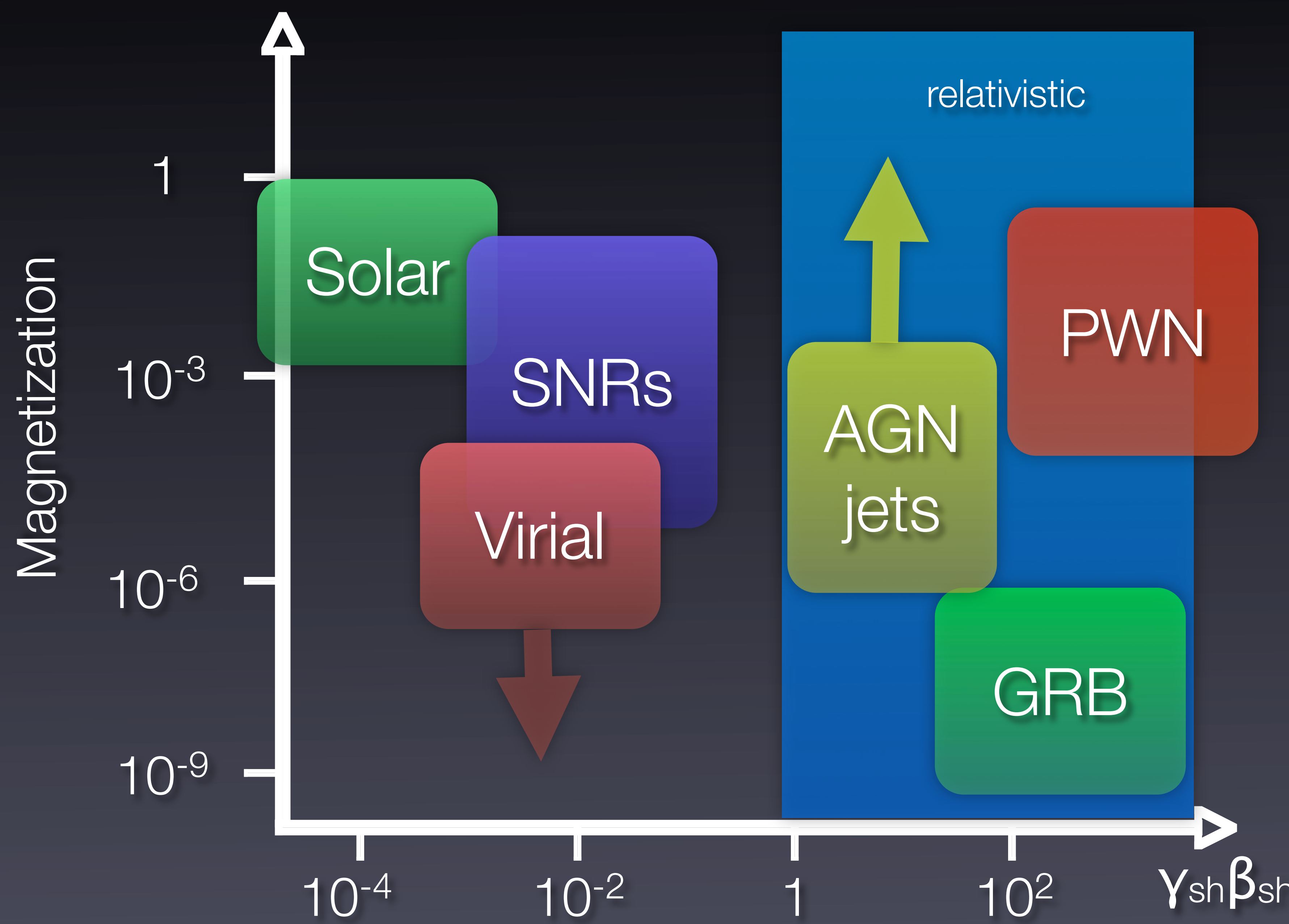
Open issues:

What is the structure of collisionless shocks? Do they exist? How do you collide without collisions?

Particle acceleration -- Fermi mechanism? Other? Efficiency?

Equilibration between ions and electrons?

Generation of magnetic fields? GRB/SNR shocks, primordial fields?



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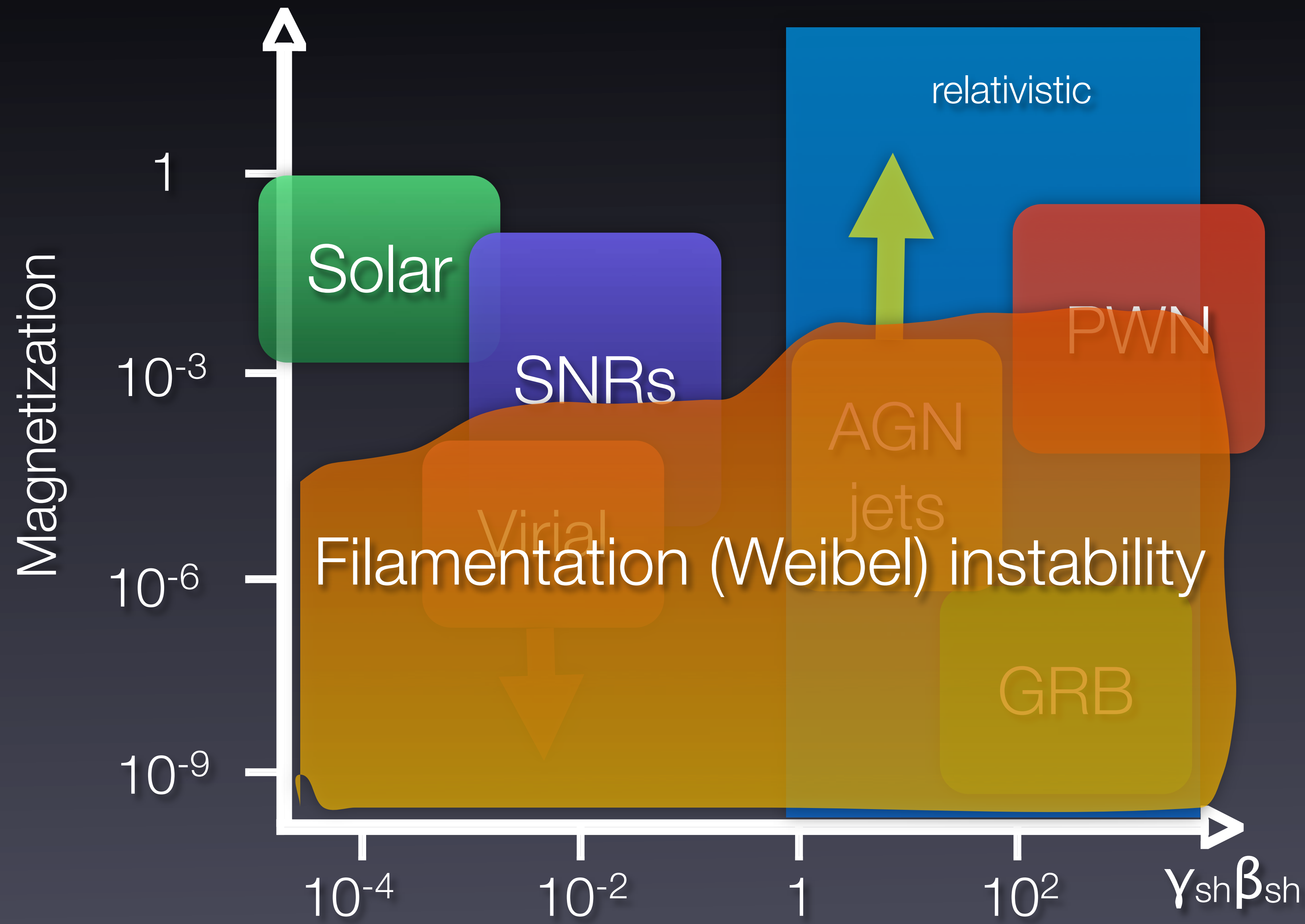

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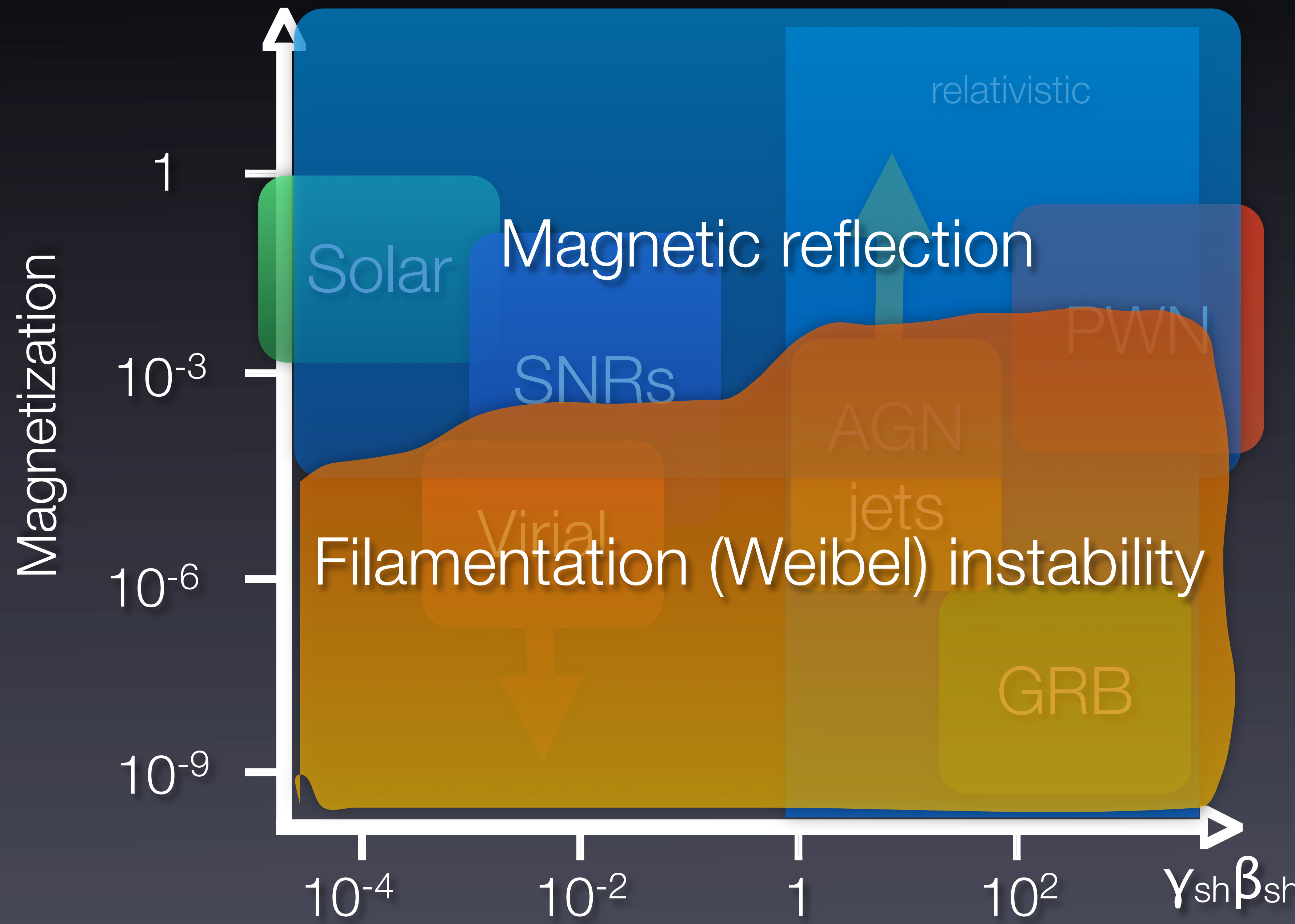
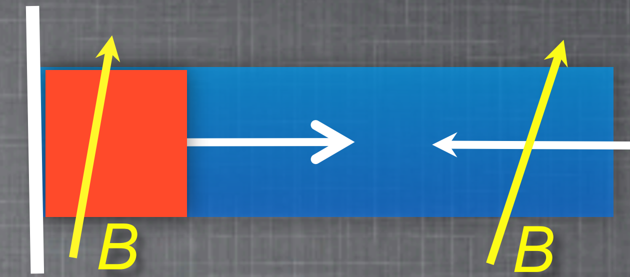


Nonrelativistic shocks: shock structure

mi/me=400, v=18,000km/s, Ma=5, quasi-perp 75° inclination



<Density>

Density

x-p_x ion

B^2

x-p_x e^-

B_z

T_e, T_i

T_e/T_i

Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves.

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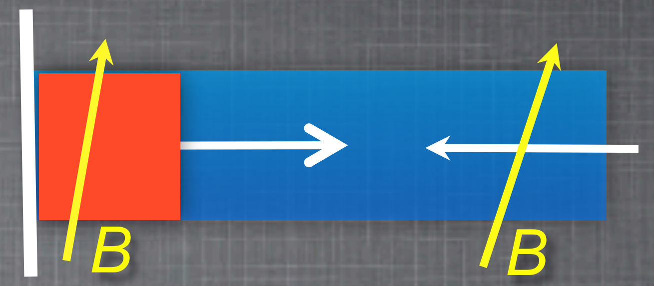
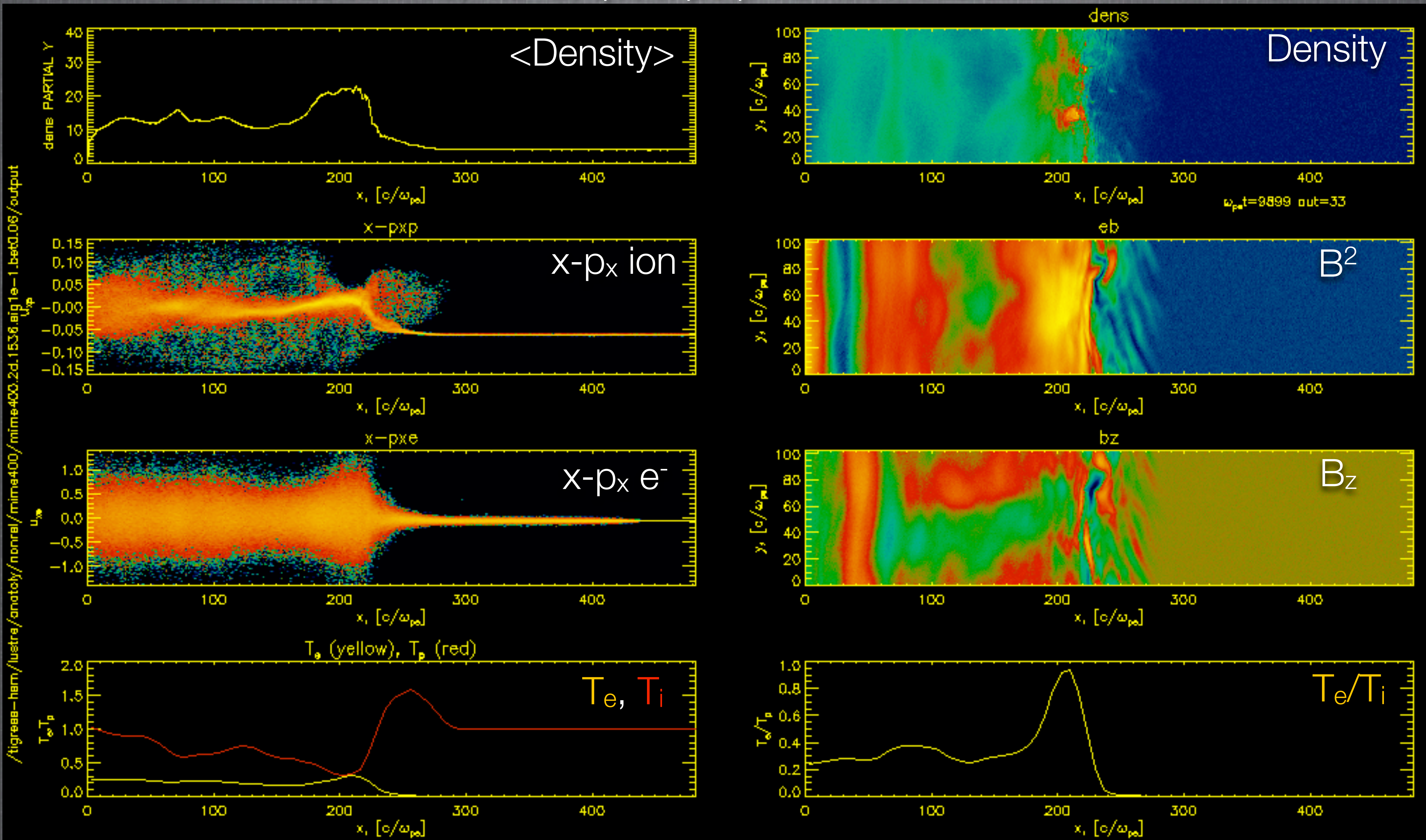
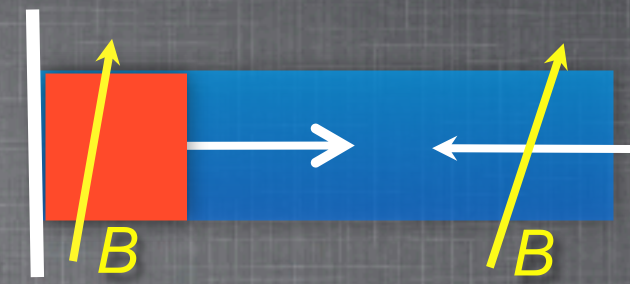


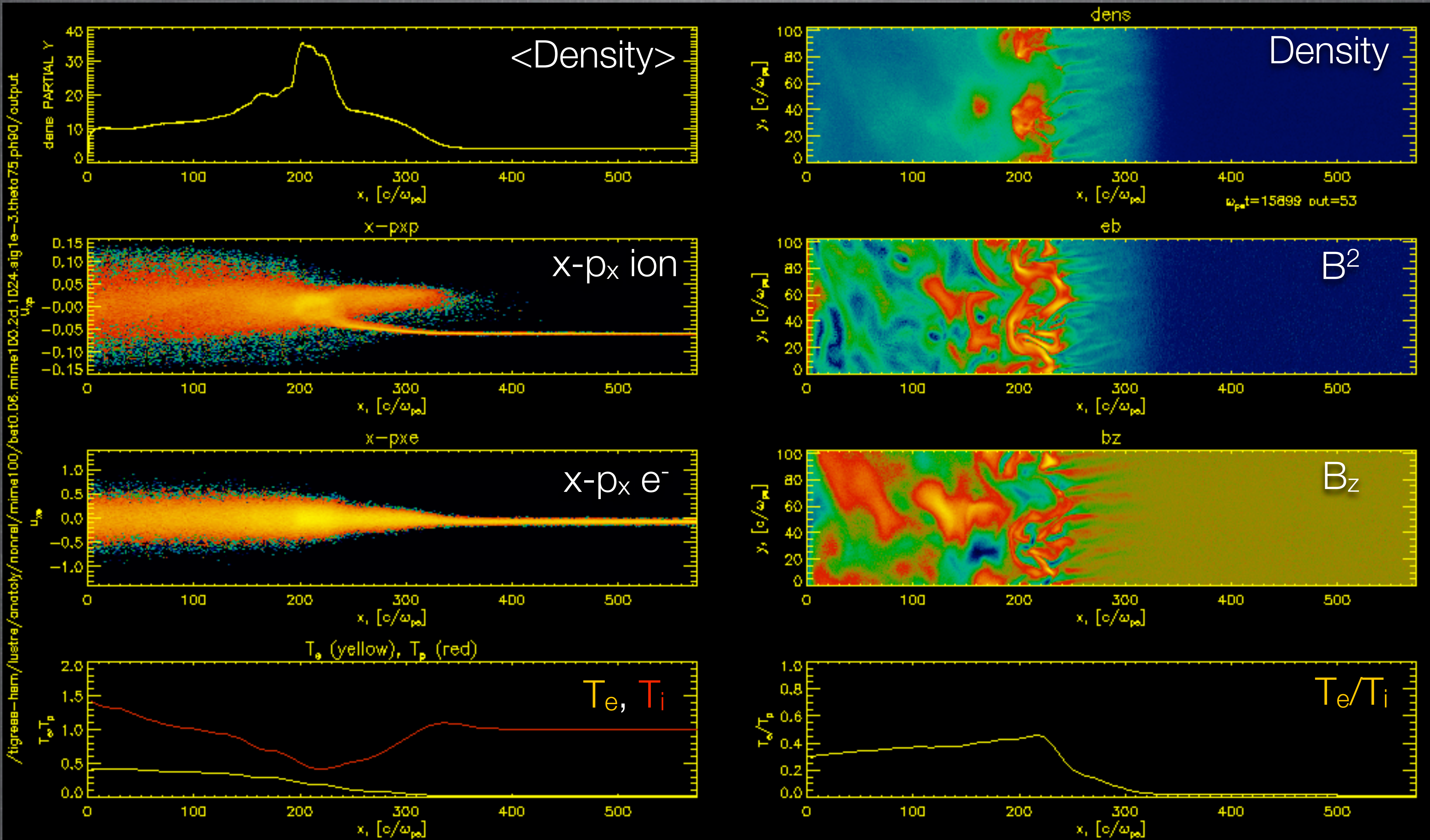


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves.

Nonrelativistic shocks: shock structure

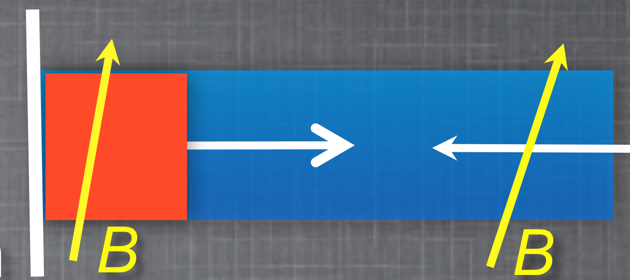
mi/me=100, v=18,000km/s, Ma=45 quasi-perp 75° inclination

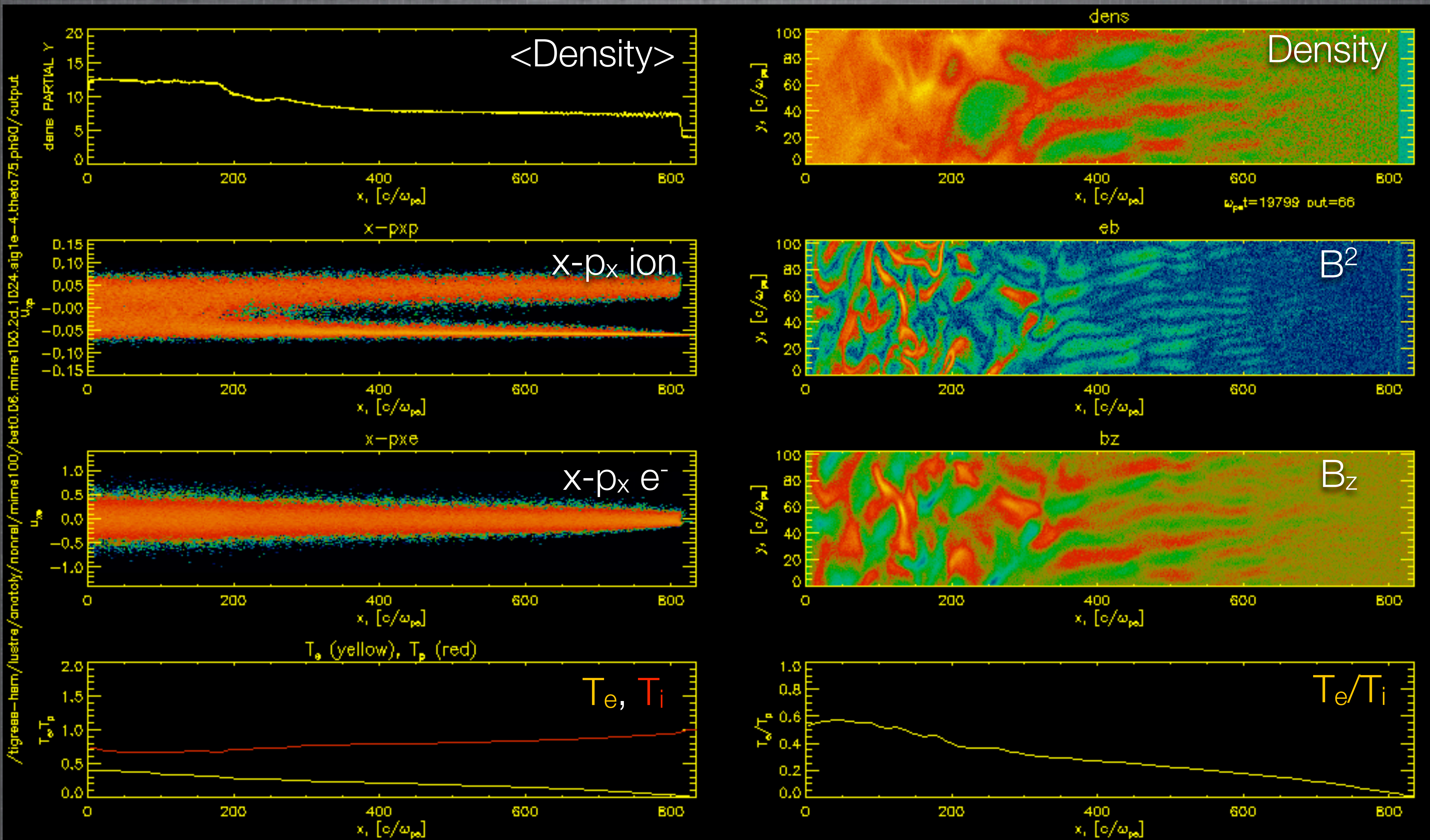




Nonrelativistic shocks: shock structure

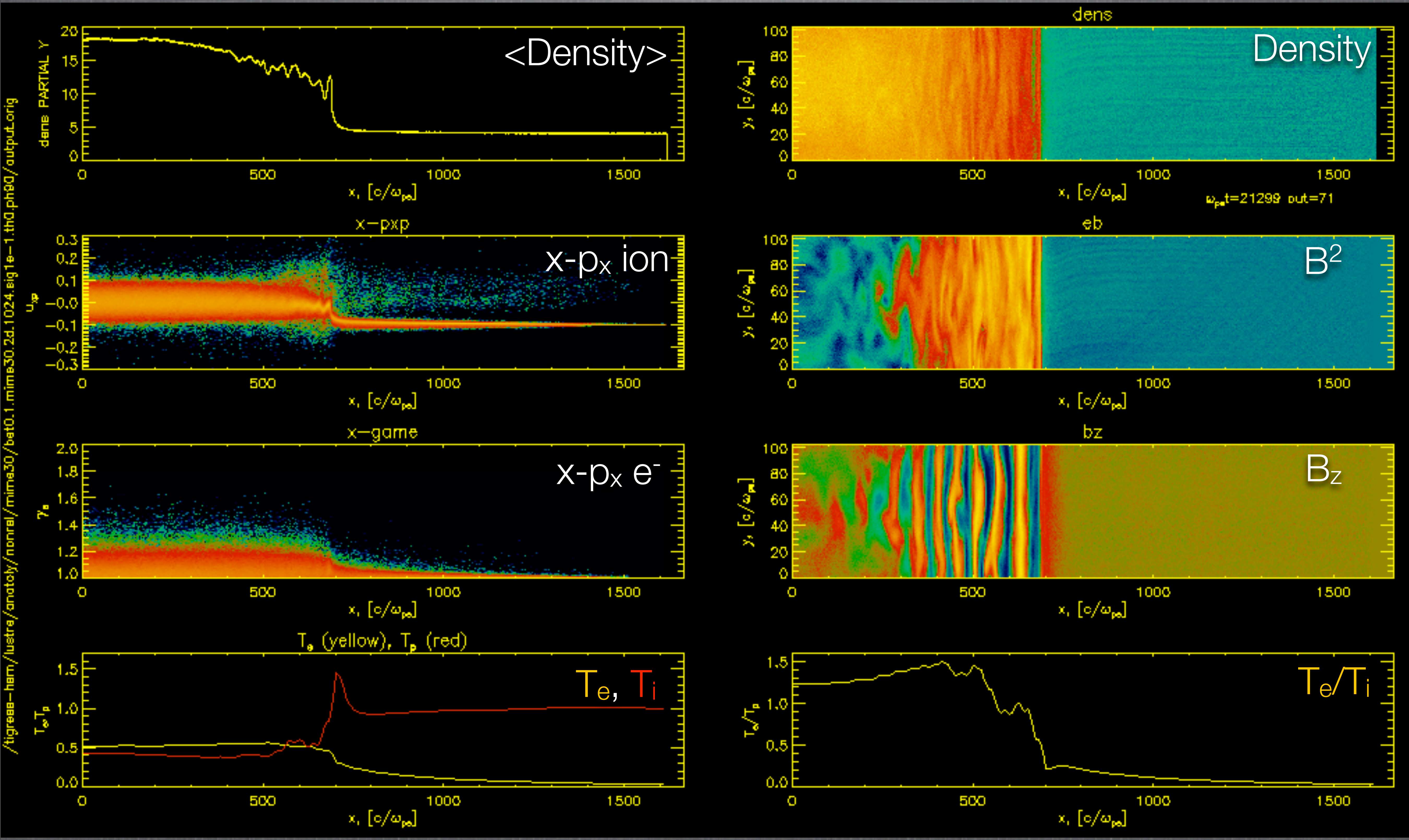
mi/me=100, v=18,000km/s, Ma=140 quasi-perp 75° inclination





Nonrelativistic shocks: quasiparallel shock structure

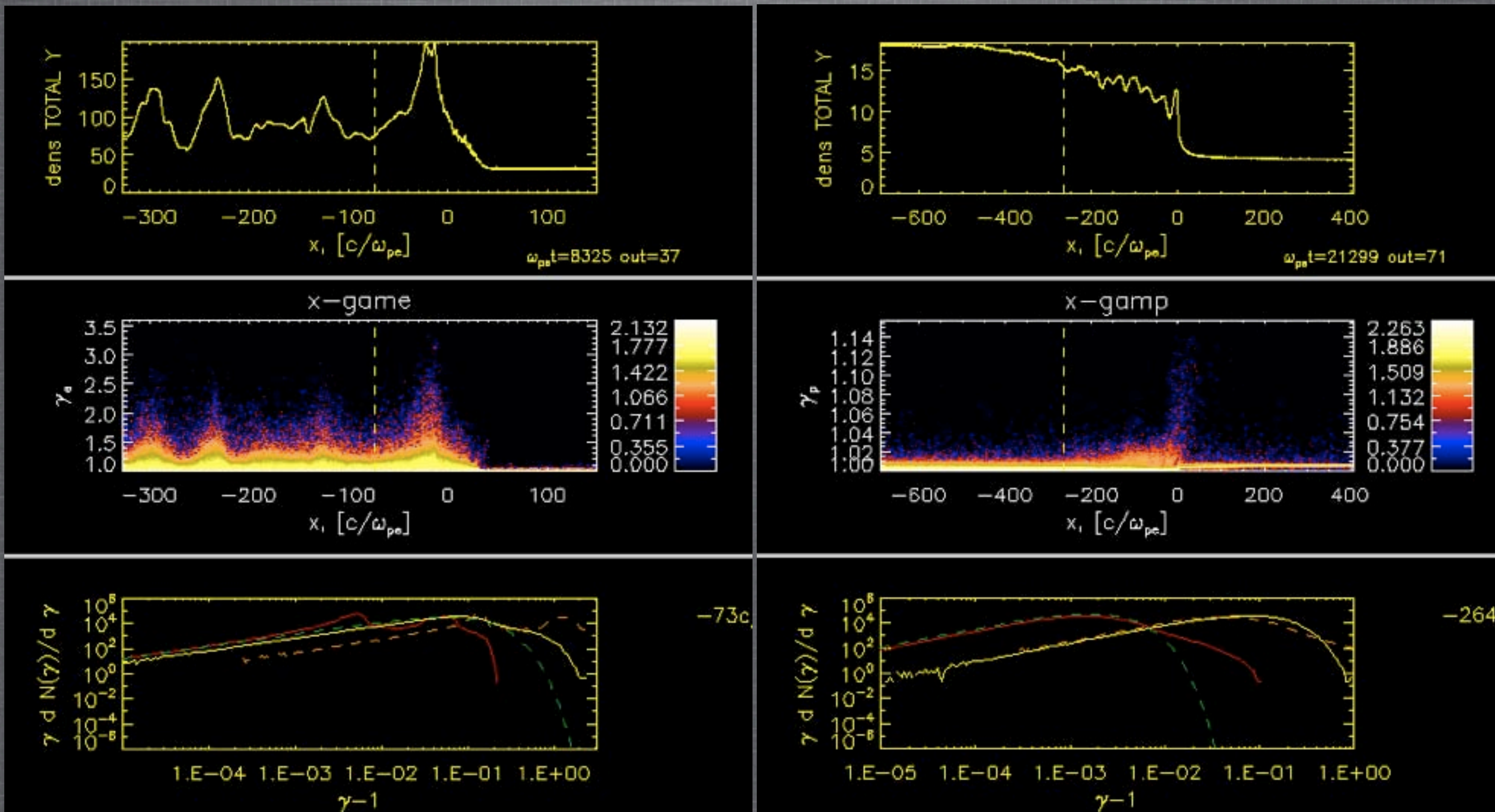
mi/me=30, v=30,000km/s, Ma=5



Nonrelativistic shocks: acceleration

Acceleration of electrons and ions occurs in different regimes!!!

Electrons are accelerated in quasi-perp shocks, ions in quasi-parallel shocks



quasi-perpendicular shock

quasi-parallel shock

B field amplification

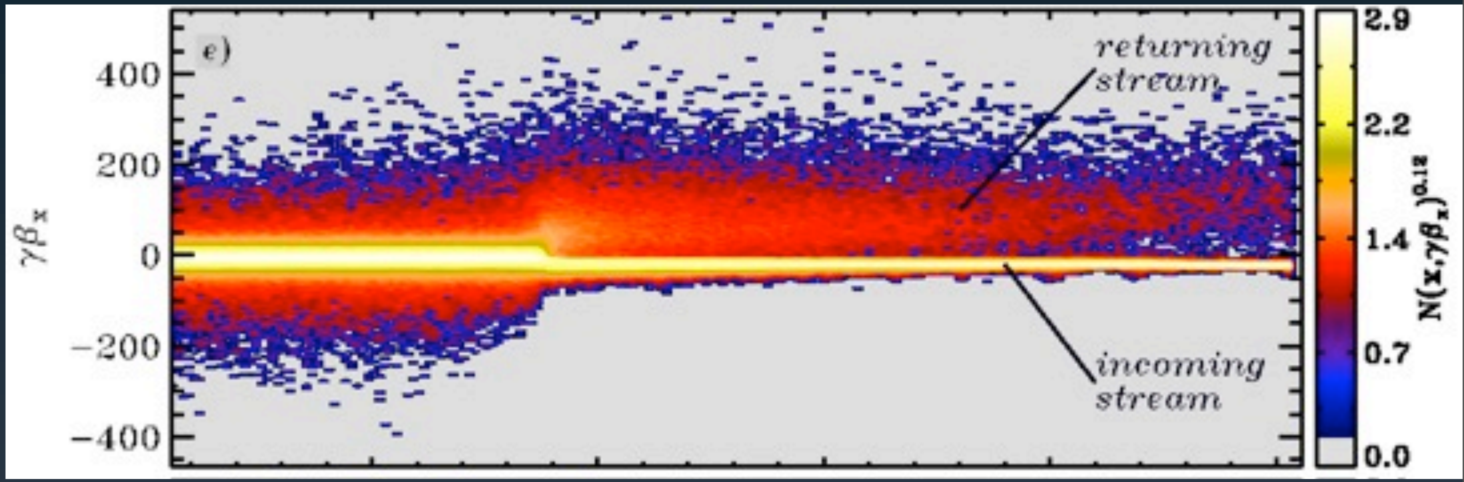
CR accelerating shocks can cause a current of protons to propagate through the upstream. Bell (04, 05) found an MHD instability of CRs flying through magnetized plasma.

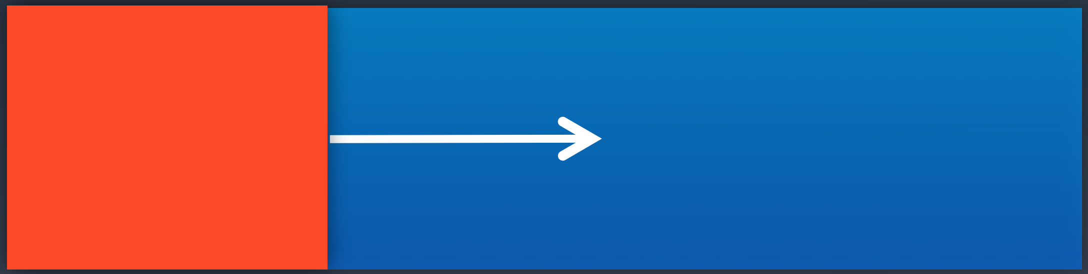
The interaction is nonresonant at wavelength << Larmor radius of CRs.

We simulated this instability with PIC in 2D and 3D (Riquelme and A.S. 09)

Saturation is due to plasma motion ($v_A \sim v_{d,CR}$), or CR deflection; for SNR conditions expect ~10 field increase.

Bell's nonresonant CR instability





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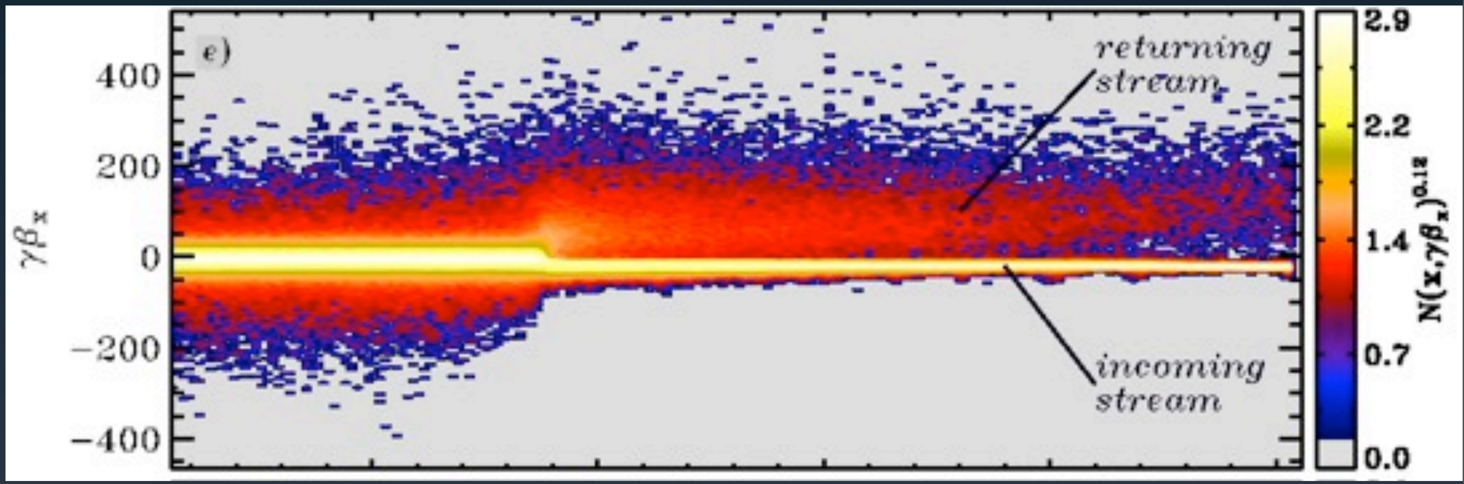

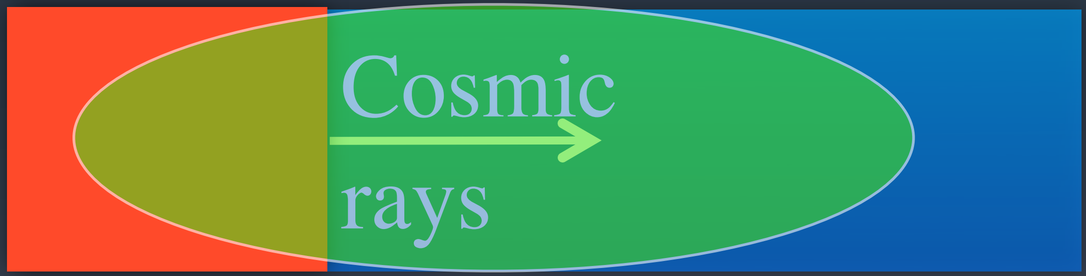

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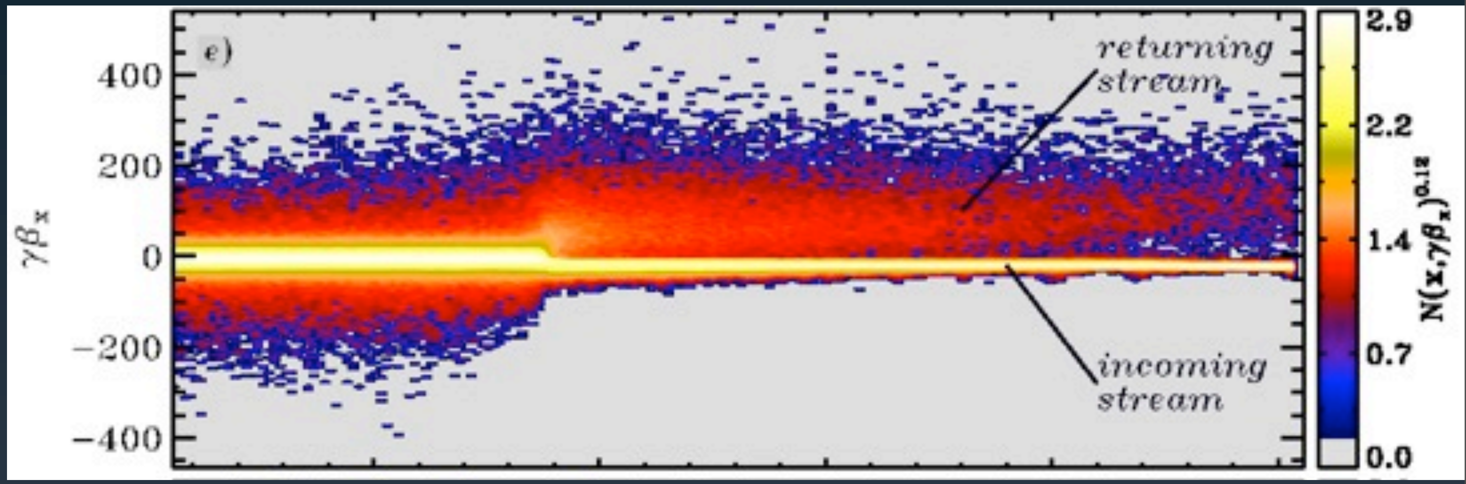

Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

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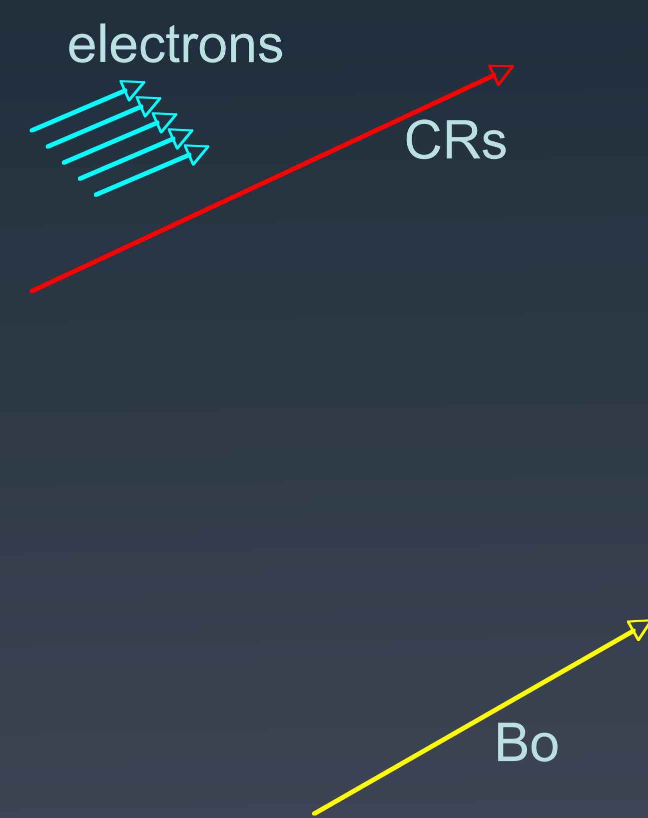

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$$\gamma_{max} = k_{max} V_{Alfven,0}$$

Need magnetized plasma: $\omega_{ci} >> \gamma_{max}$

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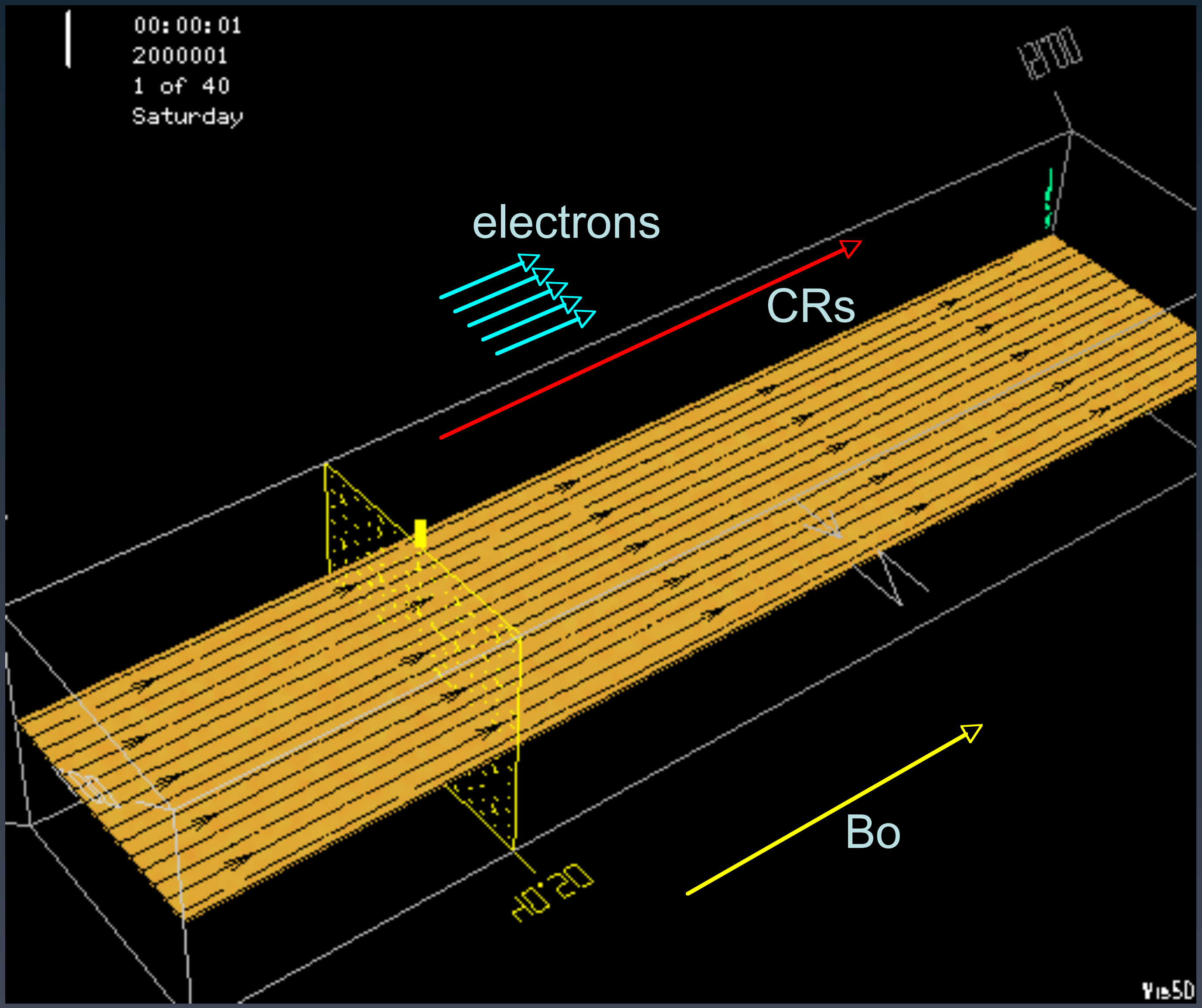

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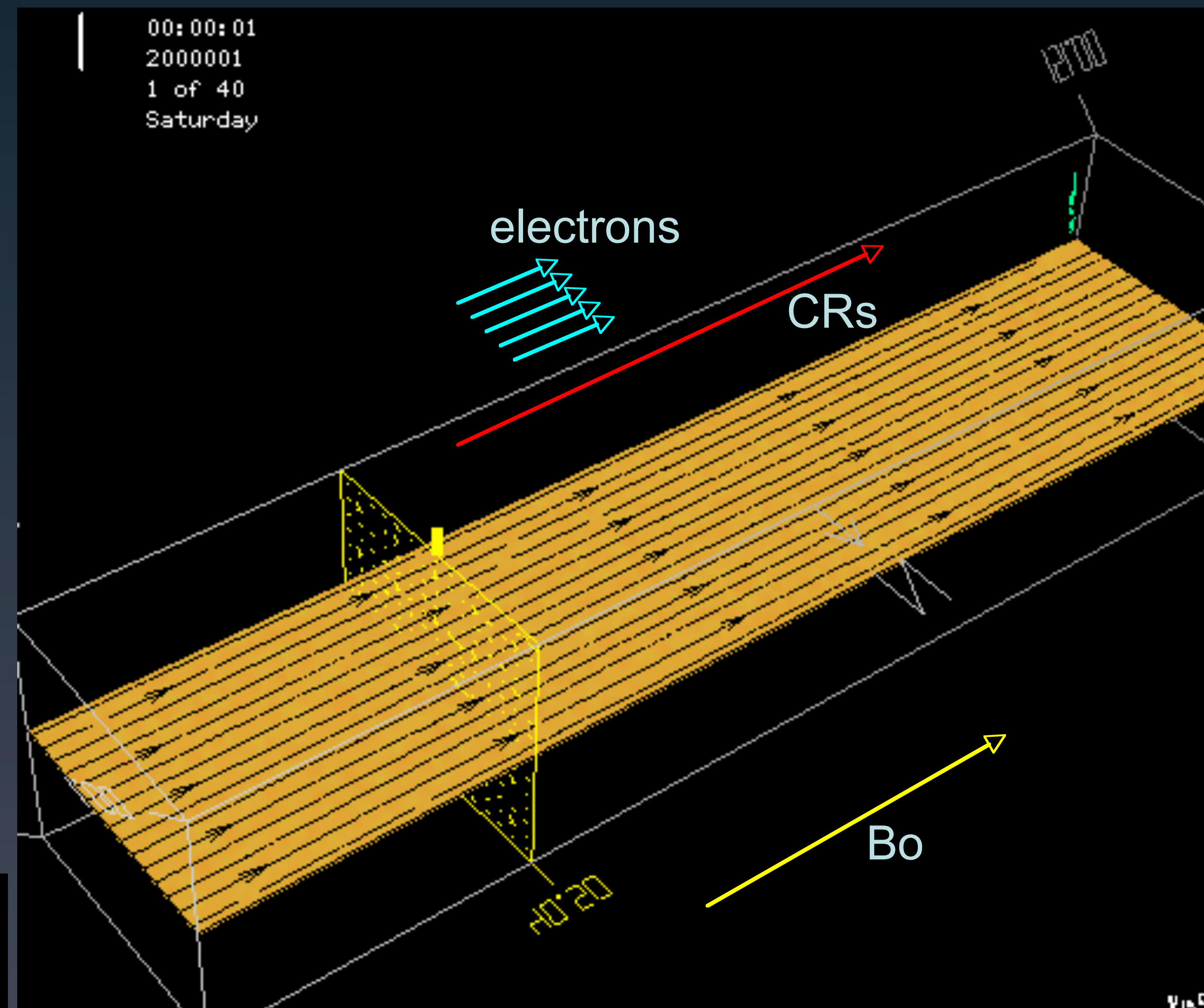

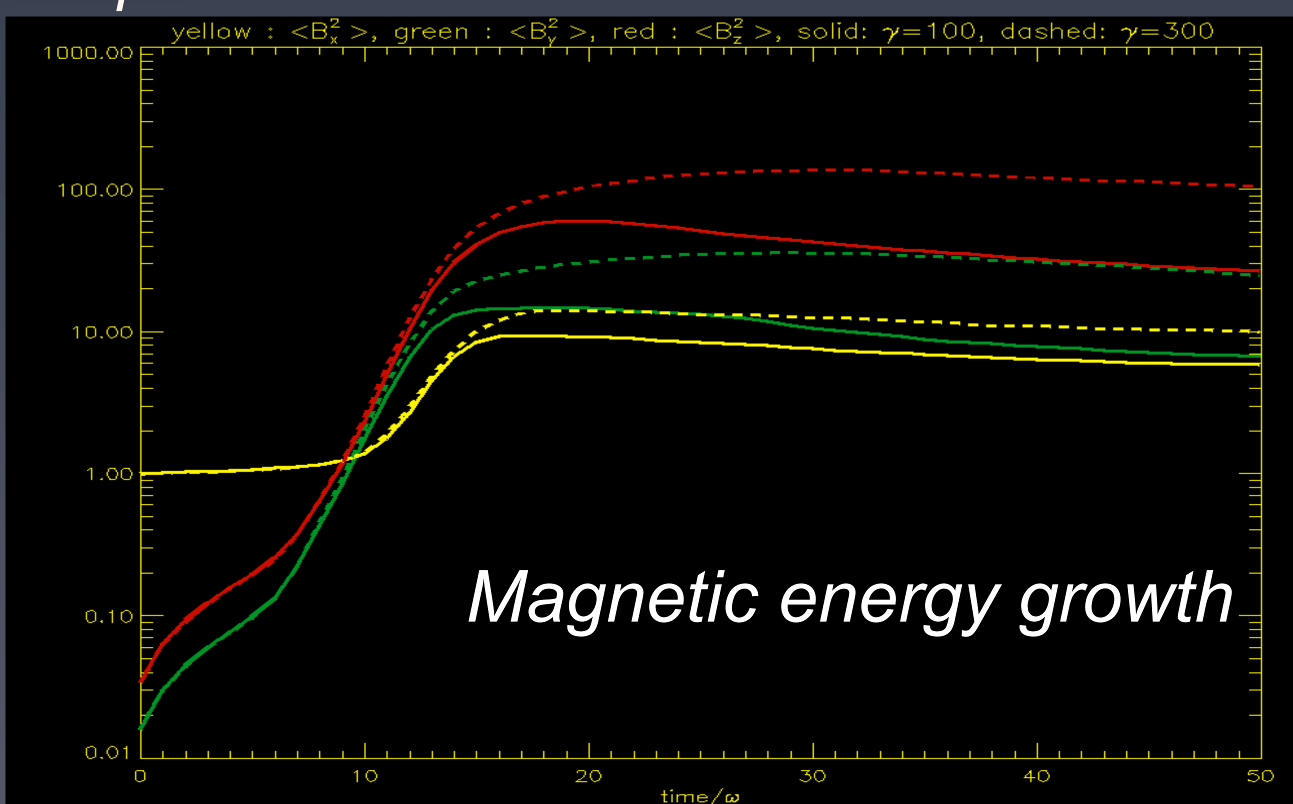

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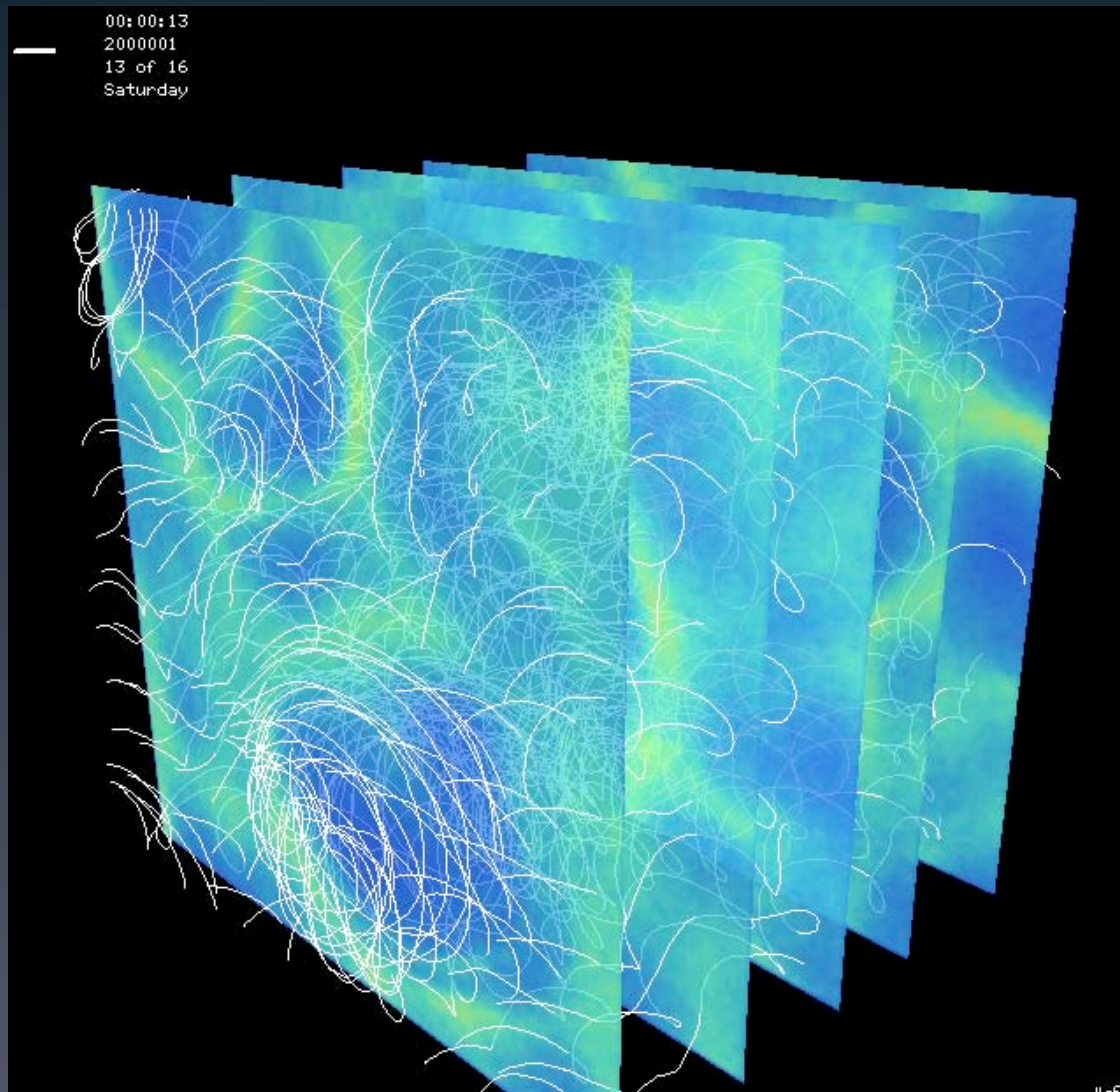
B field amplification: 3D runs

Bell's nonresonant CR instability

(Riquelme and A.S. 2009 ApJ)



Field amplification of ~10 in SNRs can be due to Bell's instability

key unknowns/opportunities

- Acceleration and shock structure as a function of upstream parameters + turbulence
- Field amplification and back-reaction of the shock on the upstream
- Electron heating and energy exchange

With these processes we can constrain astrophysical theories and explain a plethora of observations

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Shocks connect microphysics with large scale astrophysics