Shocks, Particle Acceleration, and Nonthermal Emission in Supernova Remnants and Pulsar Wind Nebulae

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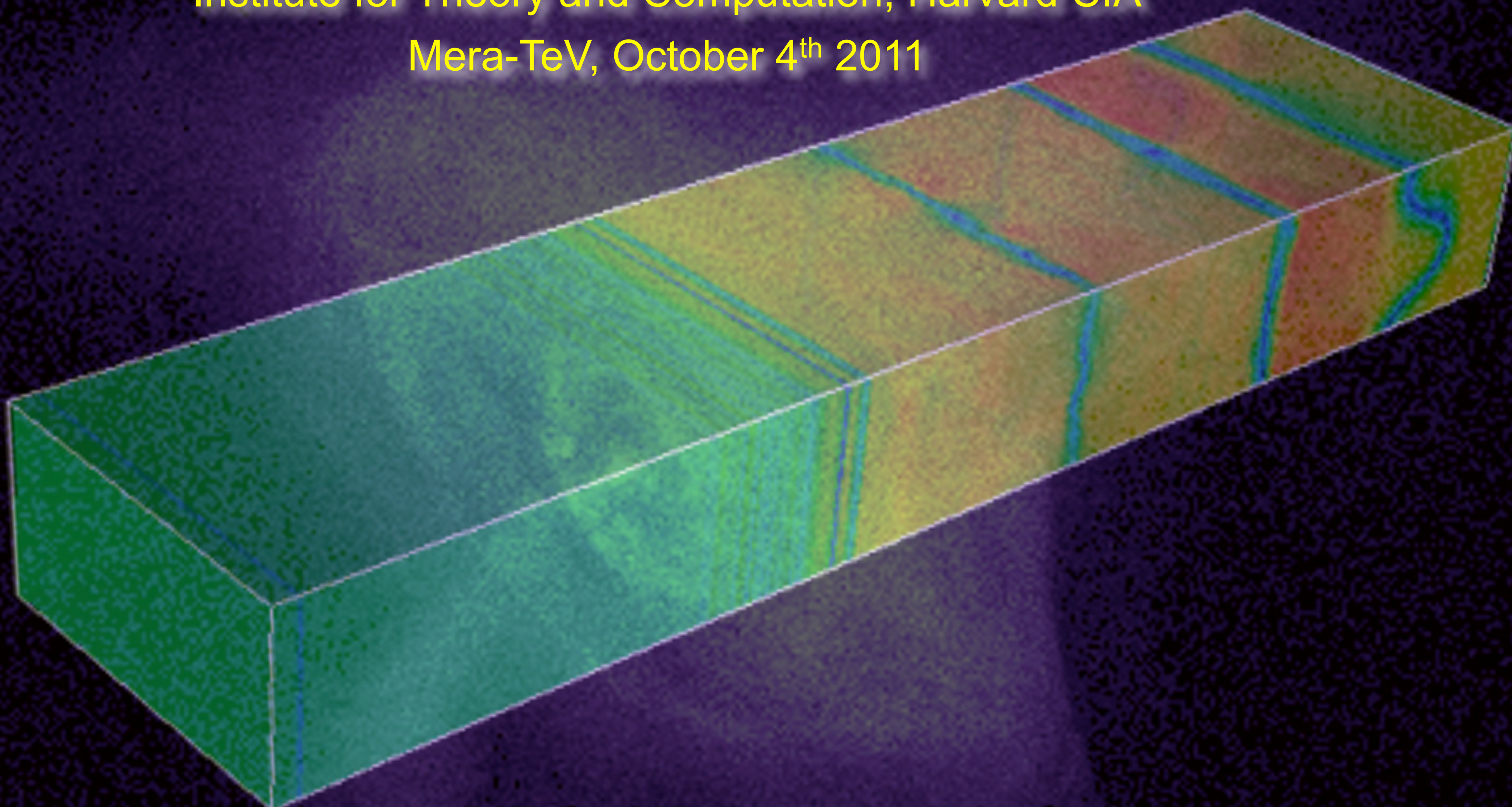


Outline

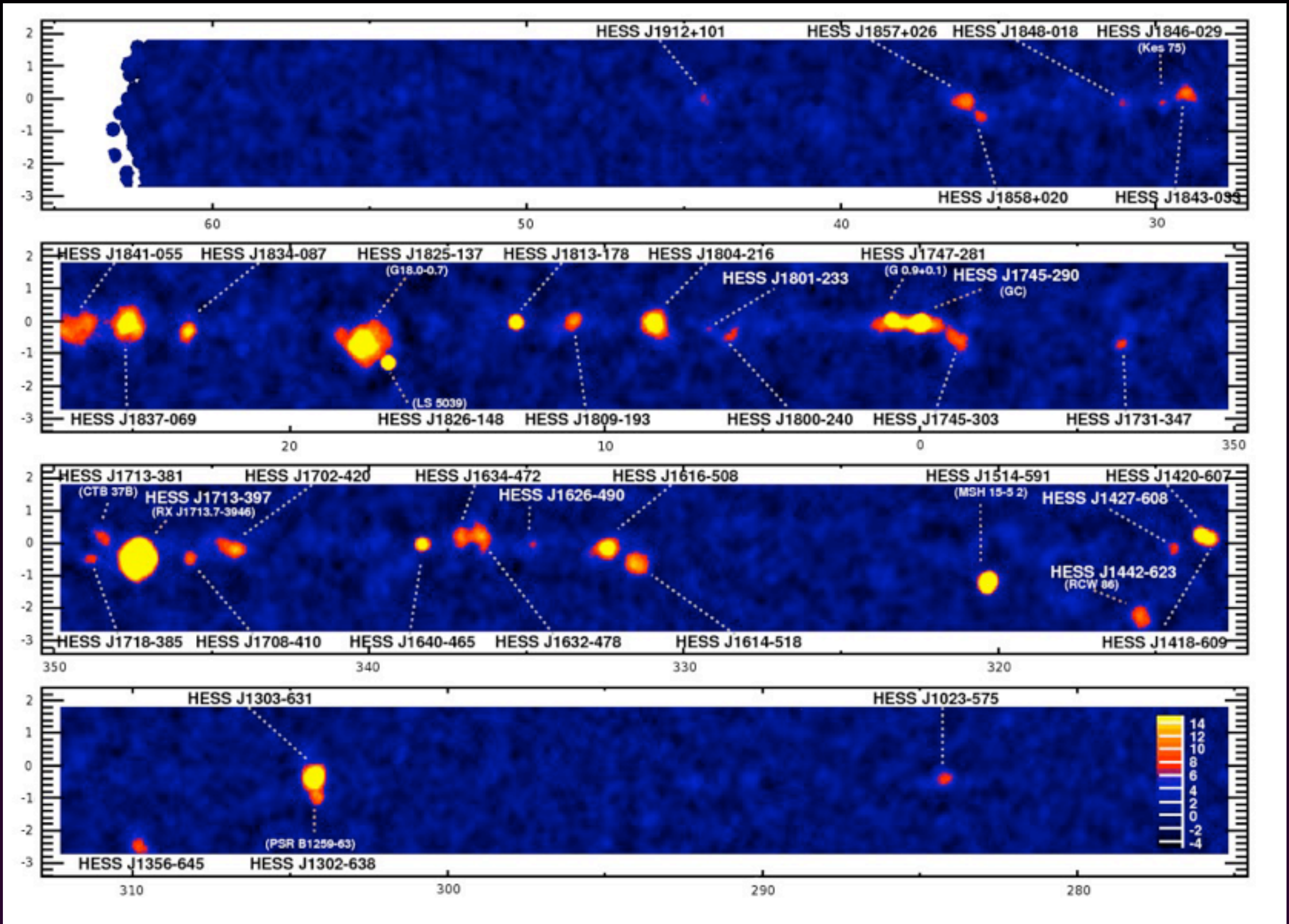
- Phenomenology of Supernova Remnants and Pulsar Wind Nebulae
- TeV emission from SNRs and PWNe
- The role of collisionless shocks in astrophysics
- Particle acceleration in astrophysics: direct vs diffusive acceleration
- Fermi first- and second-order acceleration in astrophysical shocks
- Self-consistent simulations of particle acceleration in shocks

Phenomenology of

Supernova Remnants (SNRs) and

Pulsar Wind Nebulae (PWNe)

The Galactic TeV sky

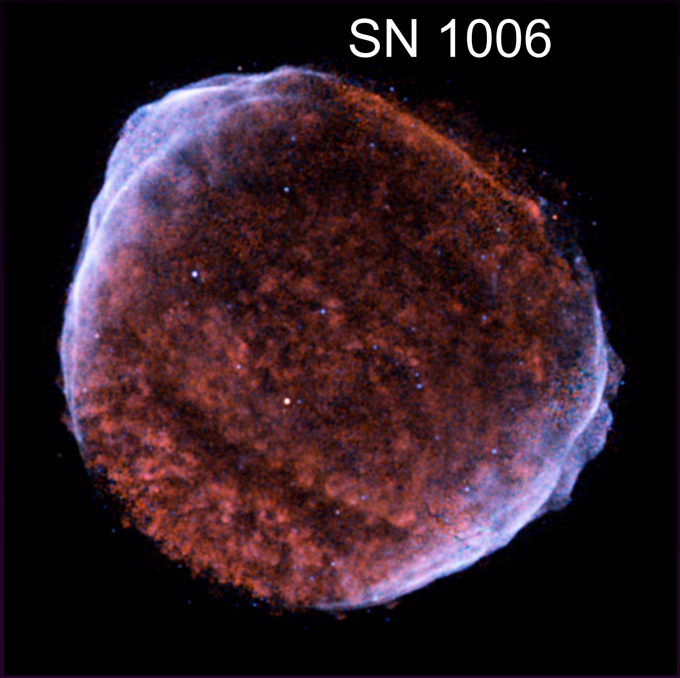


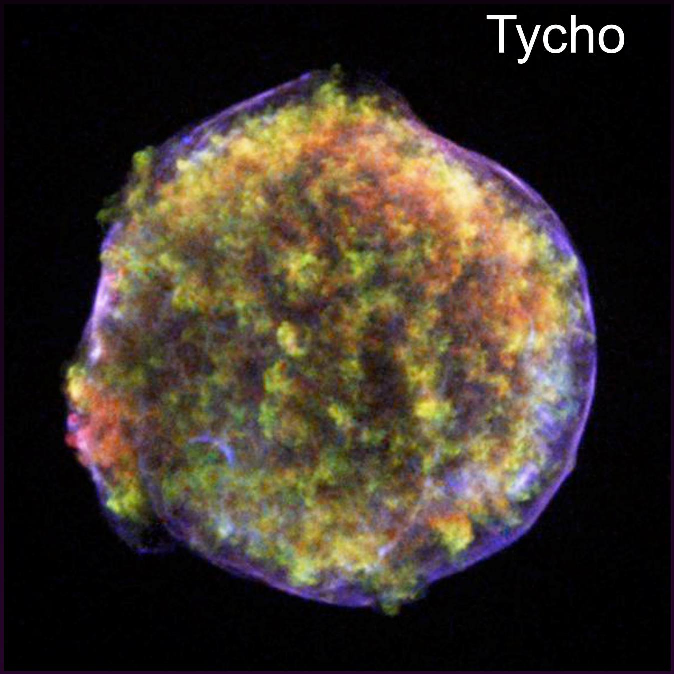
H.E.S.S. Galactic plane survey

Most of the Galactic TeV sources are Supernova Remnants (SNRs) or Pulsar Wind Nebulae (PWNe)

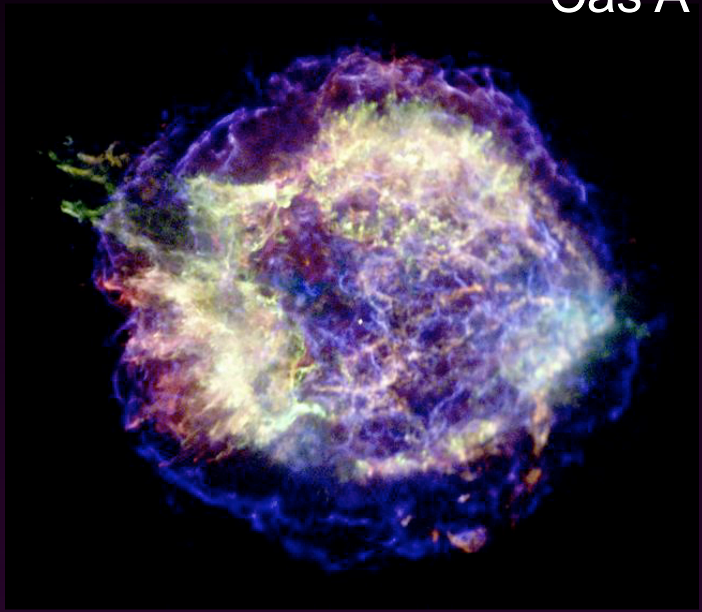
Supernova Remnants

Bright shells resulting from the interaction of stellar ejecta (following a stellar explosion) with the interstellar medium





Cas A



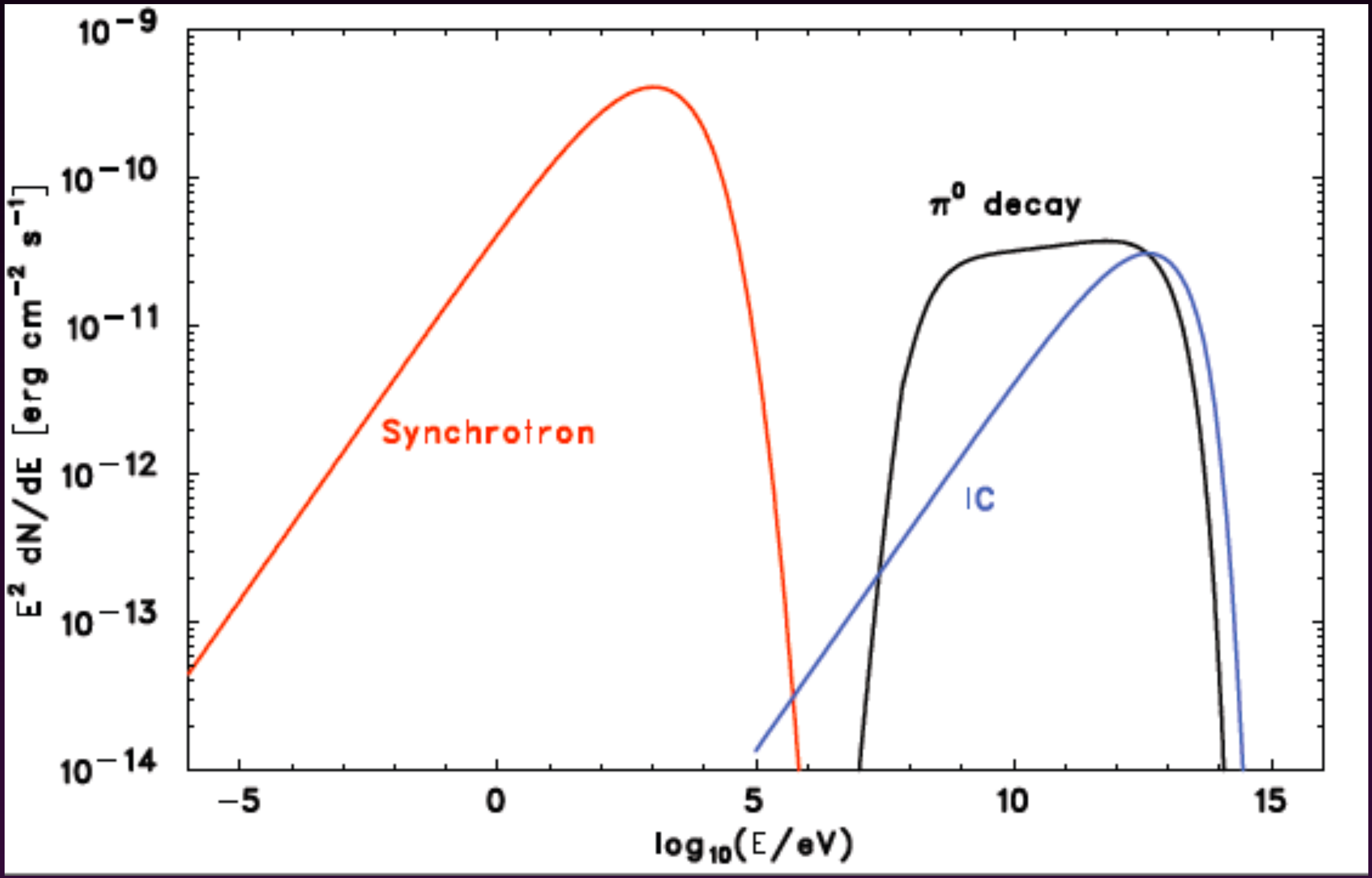
- Optical filaments of thermal emission
- X-ray shell and X-ray rims of nonthermal synchrotron emission

Leptonic vs Hadronic Models

Origin of gamma-ray emission from SRNs is still debated:

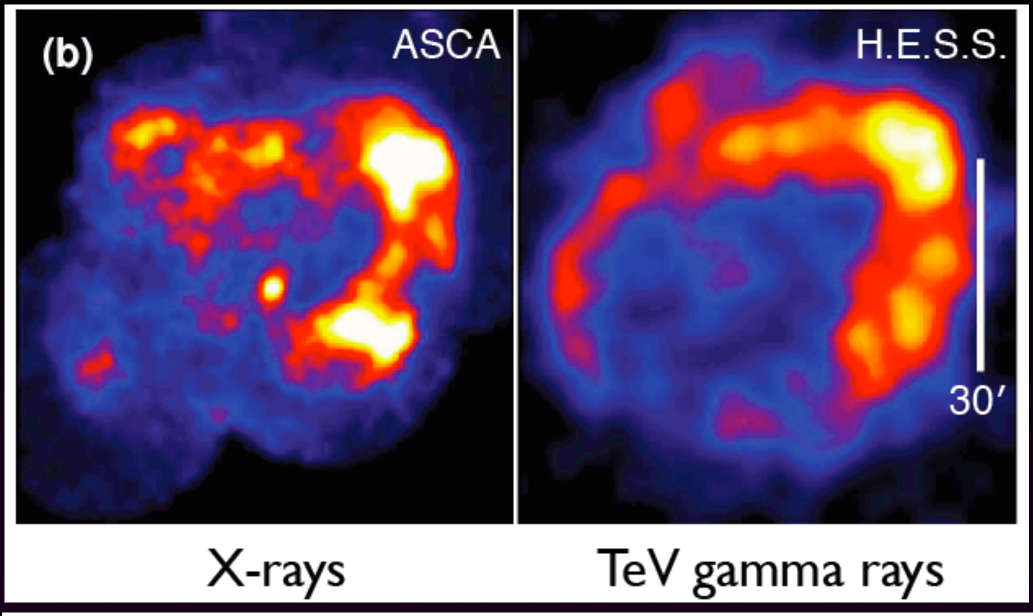
• LEPTONIC: inverse Compton from the same electrons that emit X-ray synchrotron

• HADRONIC: from high-energy protons, whose interaction with the surrounding matter produces π^0, which then decays into two gamma-rays

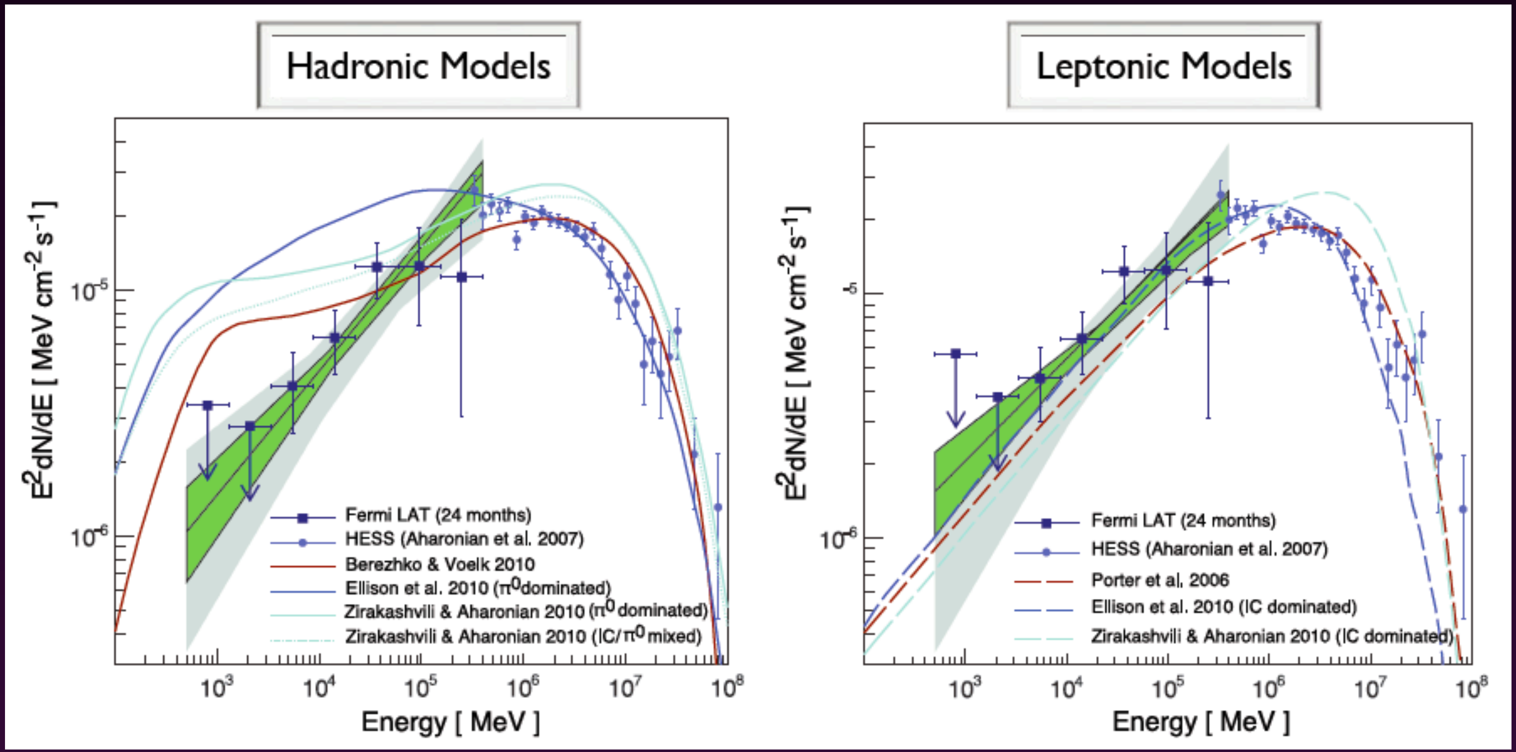


Typical SNR spectrum

RX J1713.7-3946

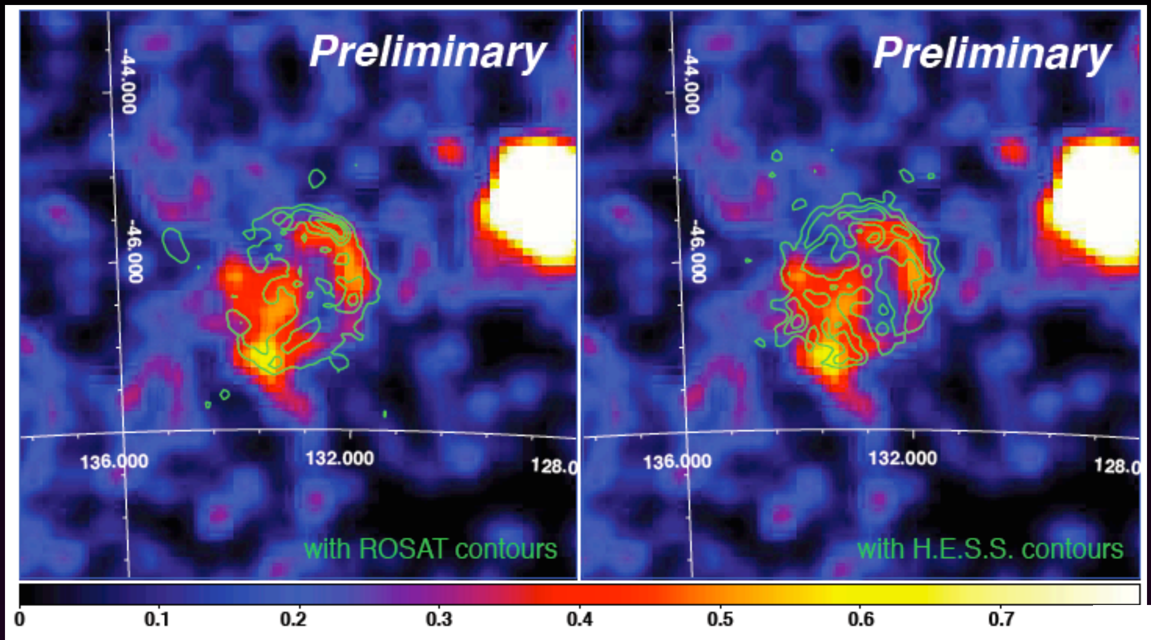


Excellent correlation of nonthermal X-rays with TeV emission → same electron population

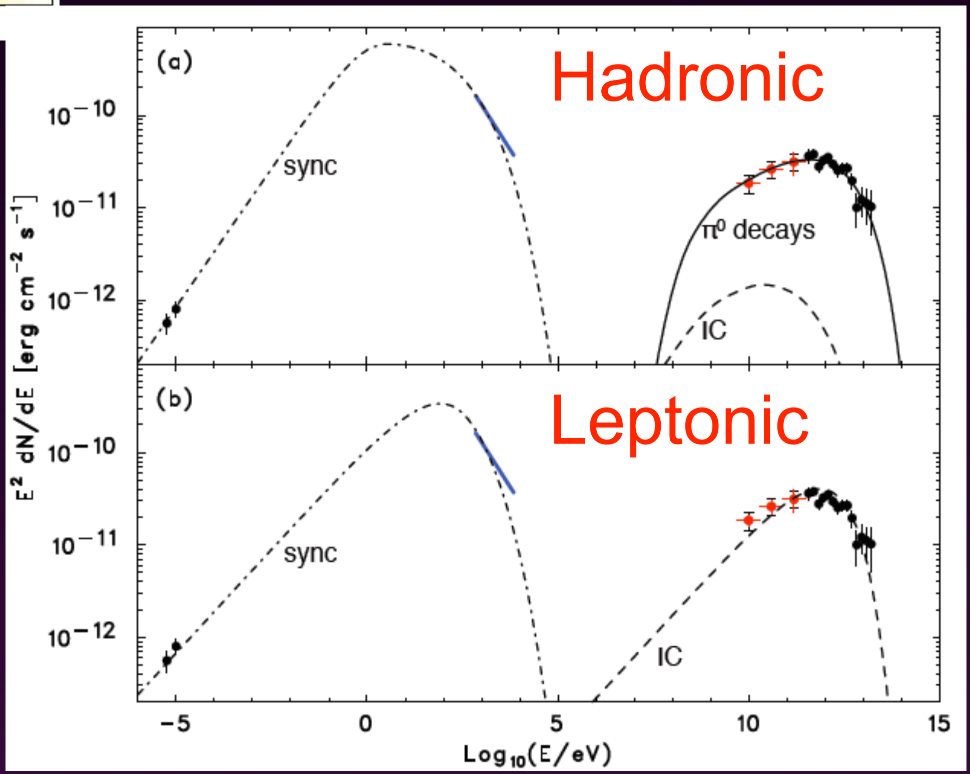


Leptonic models are favored here (thanks to Fermi data)

RX J1713.7-3946

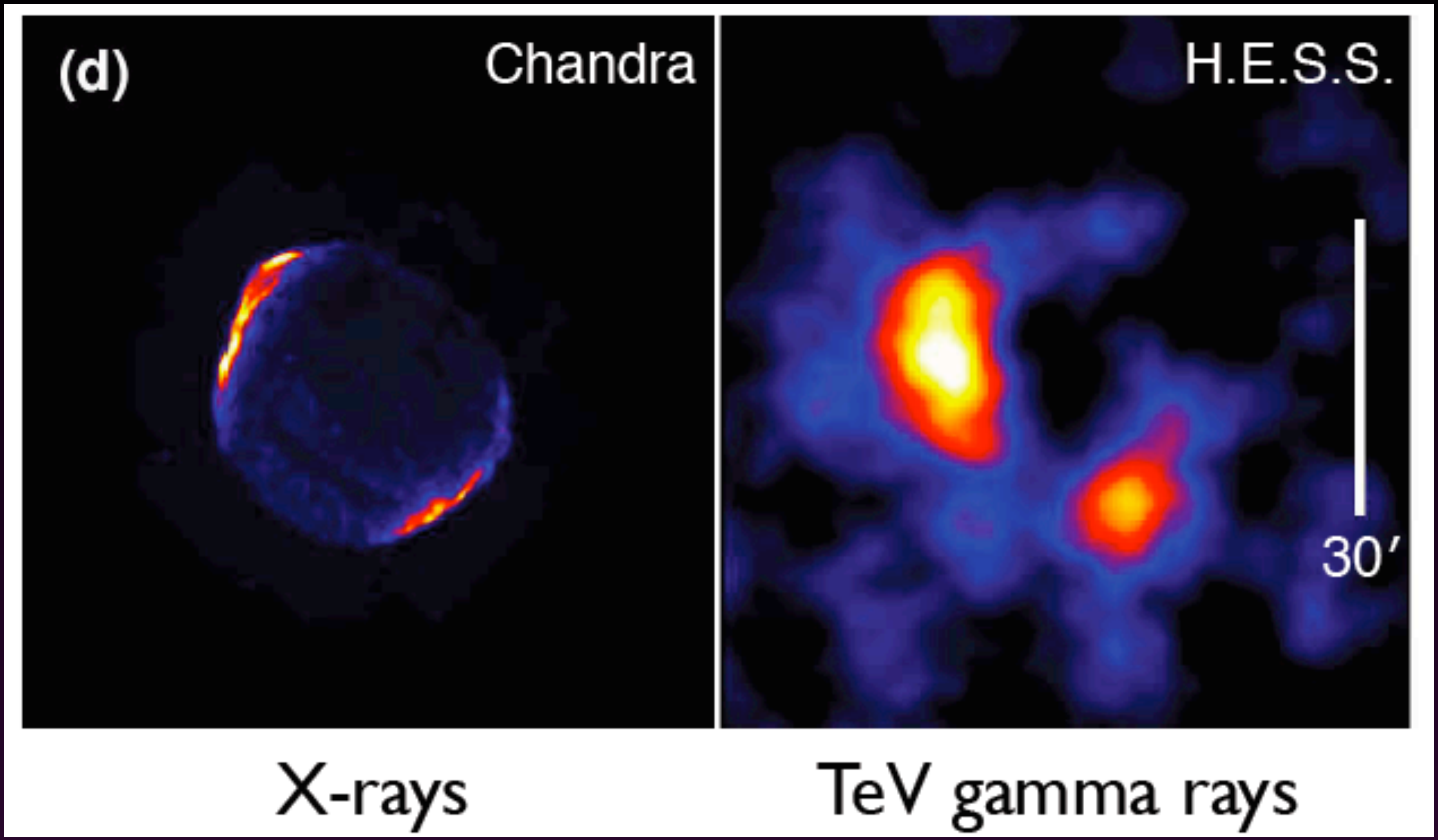


Excellent correlation of nonthermal X-rays emission with gamma-ray (Fermi) and TeV emission



Hadronic models are favored here (thanks to Fermi data)

SN 1006



Excellent correlation of nonthermal X-rays with TeV emission in “polar caps”: if TeV emission is hadronic, electrons and protons need to be accelerated in the same location

Pulsars

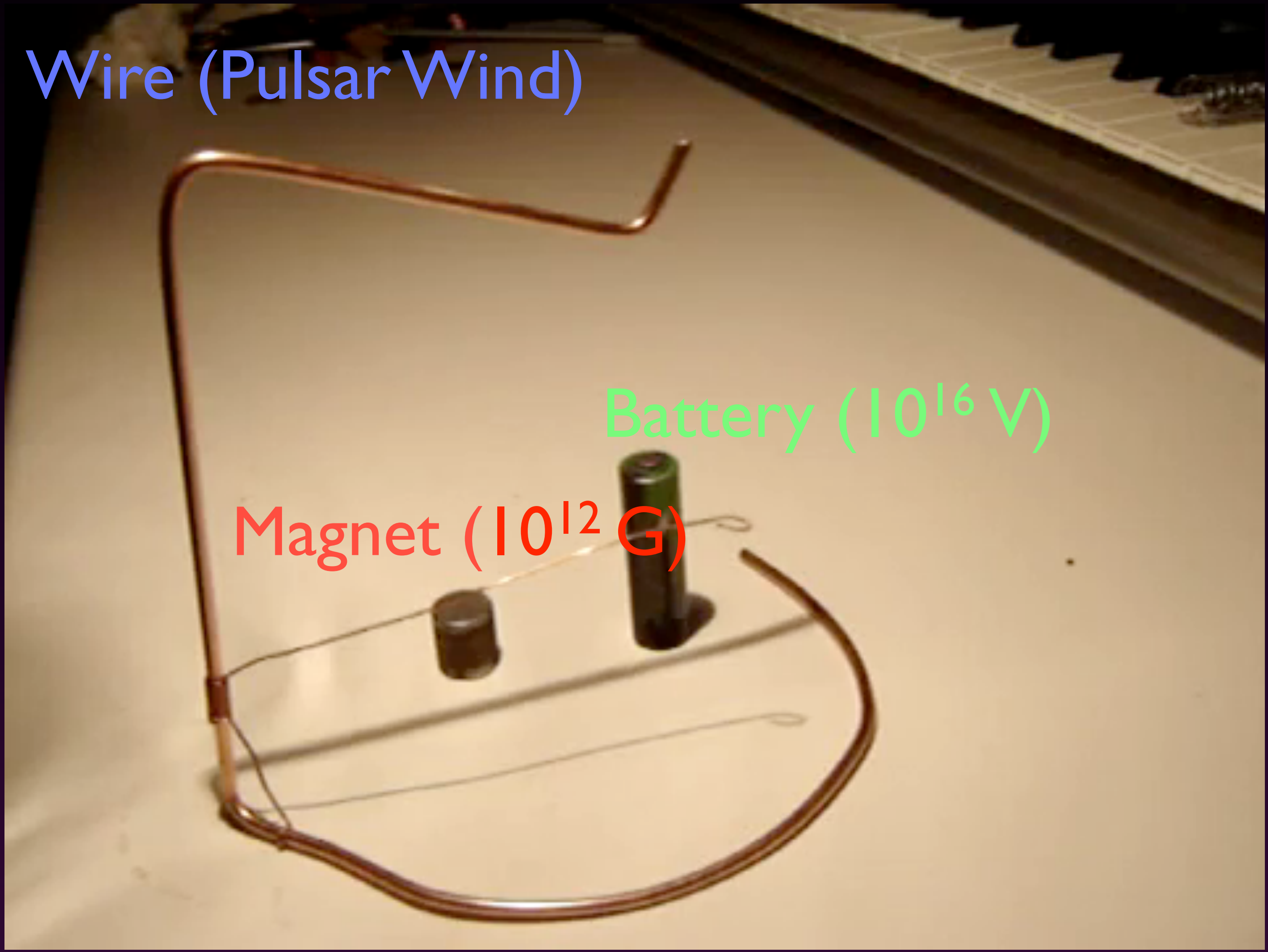
Rotating magnetized neutron stars emitting pulsed radiation

The main energy loss is invisible, but detectable: pulsars lose rotational kinetic energy

Energy loss in radiation is a tiny fraction (0.01-10%) of the spin-down luminosity

Energy loss leaves as a magnetized relativistic wind, the Pulsar Wind

Where does the spin-down energy go?

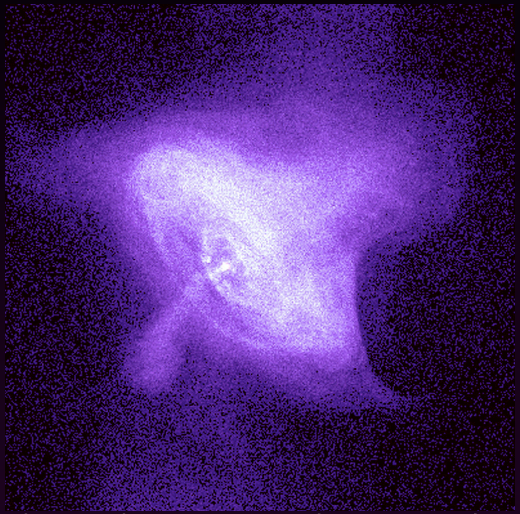


Unipolar inductor

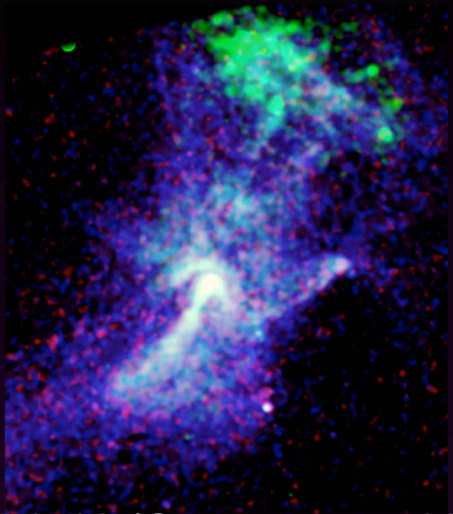
Pulsar Wind Nebulae (PWNe)

Pulsar's rotational energy is ultimately visible as nonthermal nebular emission

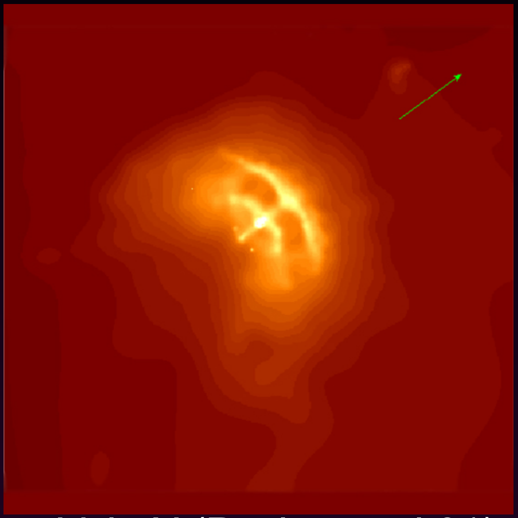
PWNe are calorimeters for Pulsar Winds



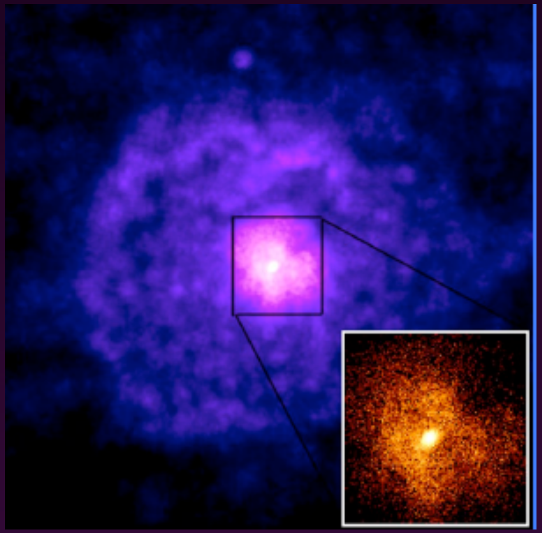
Crab (Weisskopf et al 00)



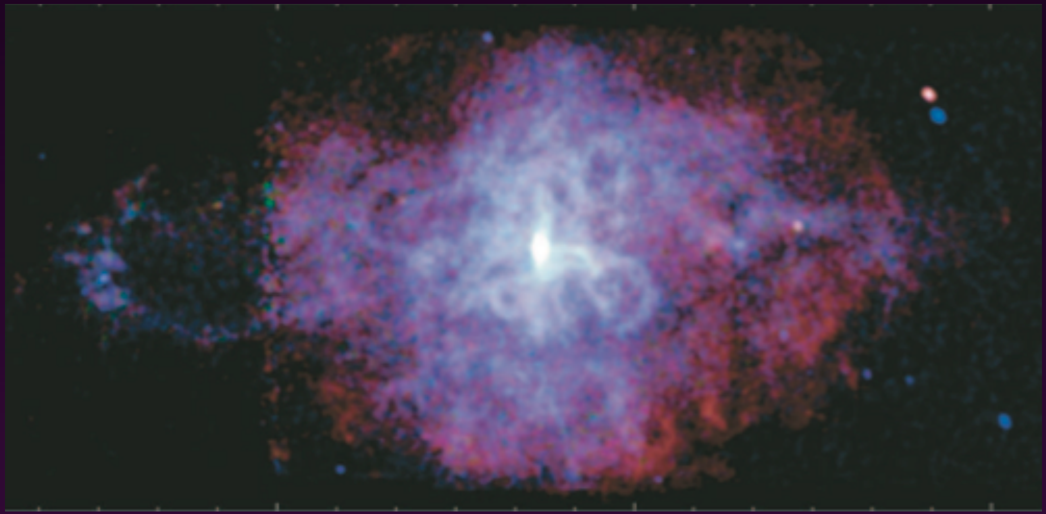
B1509 (Gaensler et al 02)



Vela X (Pavlov et al 01)



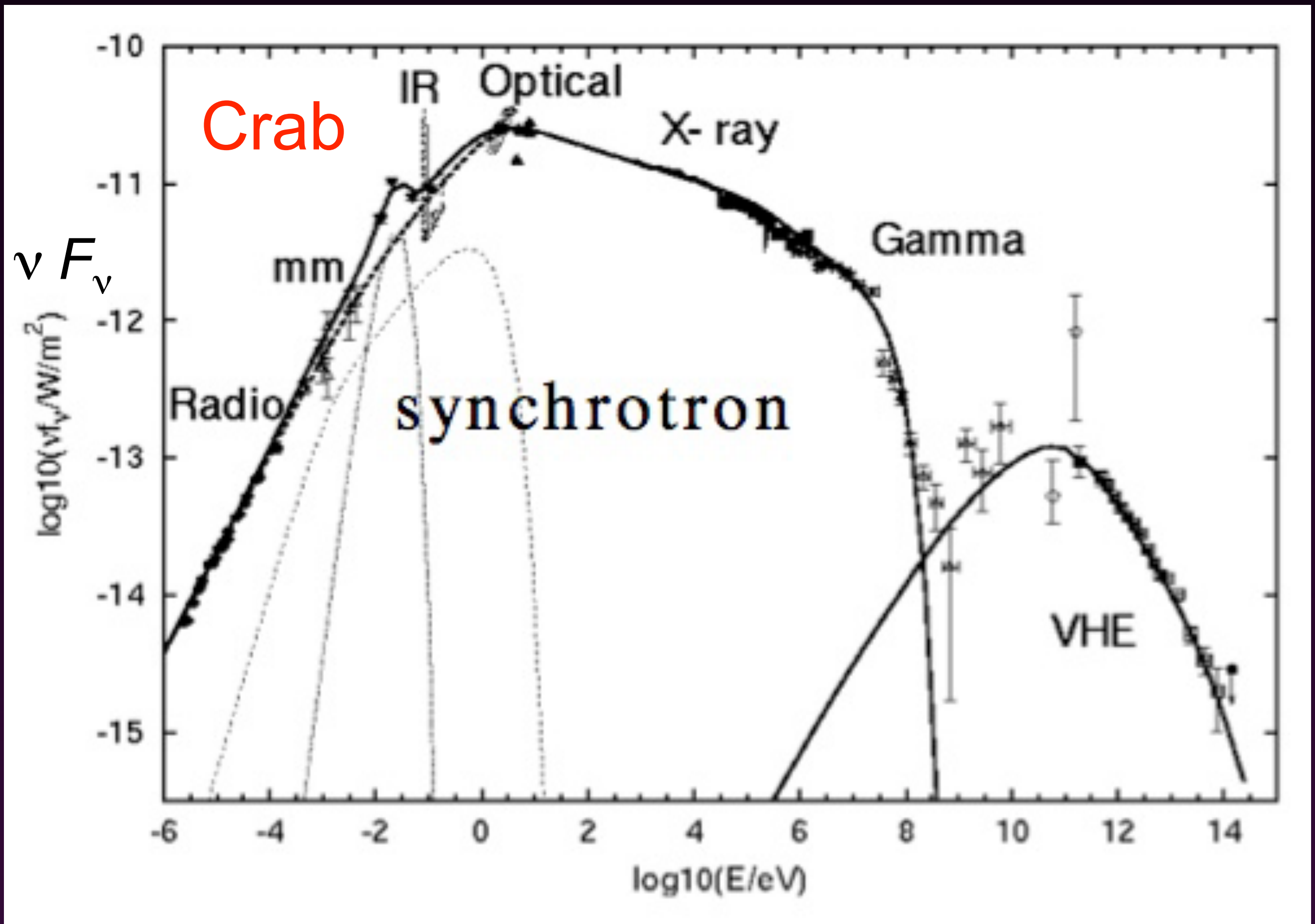
G21.5 (Safi-Harb et al 04)



3C58 (Slane et al 04)

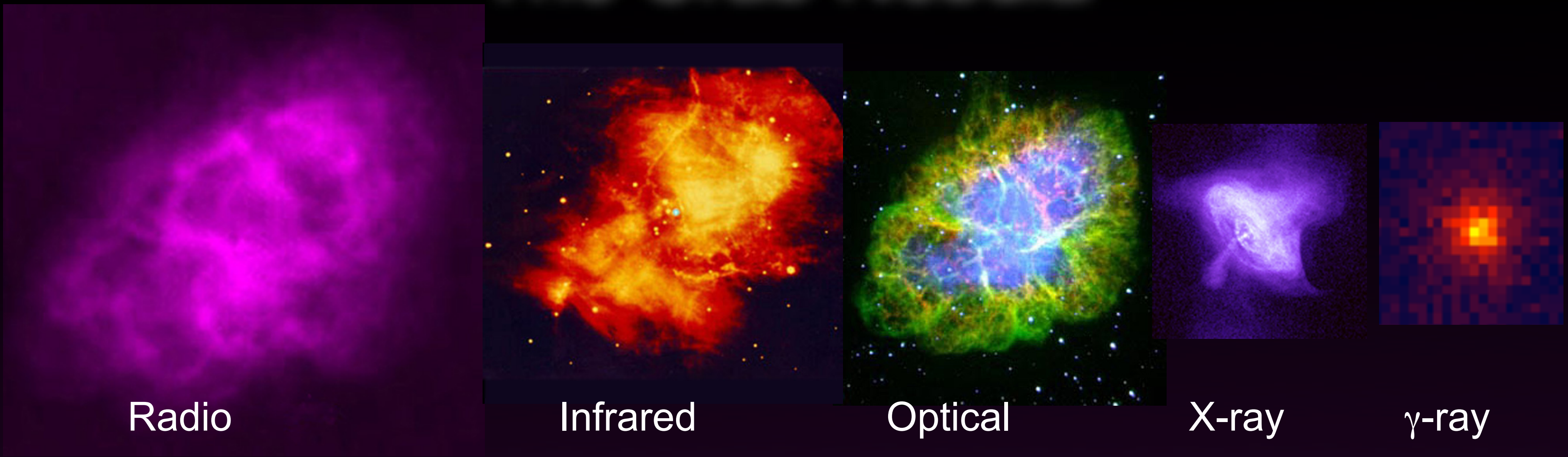
Properties of PWNe

- SNRs with center-filled radio morphology (Pulsar Wind confined by SN shell)
- flat radio spectrum, high degree of linear polarization in radio band
- broad nonthermal spectrum, up to TeV energies; multiple spectral slopes
- low-energy synchrotron + TeV inverse Compton (hadronic origin not likely)



The Crab Nebula has been the standard candle of TeV astronomy since its discovery

The Crab Nebula



Low-energy spectrum explained as synchrotron emission in B~10^{-4} G~10^2 B_{ISM}:

Lifetime: X-rays -- few years. Need energy input!

Crab pulsar: $\dot{E}_{rot} = 5 \times 10^{38} erg/s$ → 10-20% efficiency of conversion to radiation

Nebular shrinkage with energy indicates one accelerating stage, followed by cooling

High-energy spectrum explained as inverse Compton from the same electrons

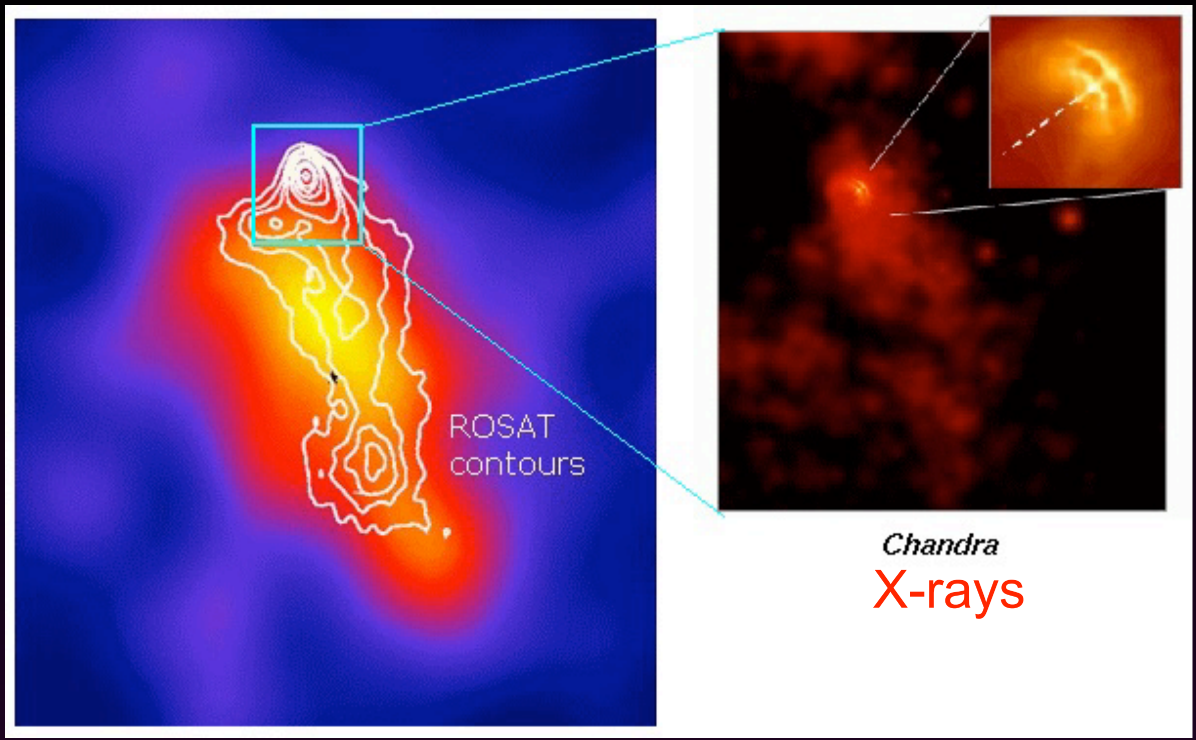
X-ray synchrotron + TeV IC give constraints on B and the particle distribution in PWNe

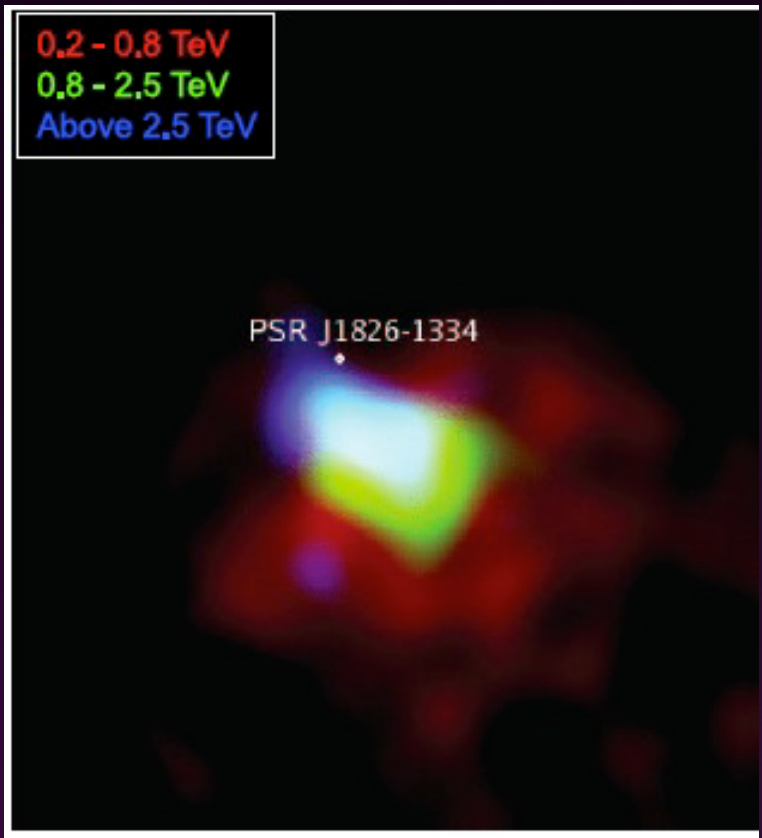
Other TeV PWNe

Vela X:

• TeV emission coincident with one-sided jet

• X-ray nebula (torus+jet) not bright at TeV energies → large B field





HESS J1825-137:

• TeV spectral steepening with distance, consistent with cooling of the emitting electrons

The role of

collisionless shocks

in astrophysics

Shocks for mathematicians

A shock is a discontinuity in some thermodynamical quantities (density, velocity, temperature, pressure)

Hydrodynamic conservation laws

- Mass

$$\frac{\partial \rho}{\partial t} = -\nabla \rho v$$

- Momentum

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v}\right) = -\nabla P$$

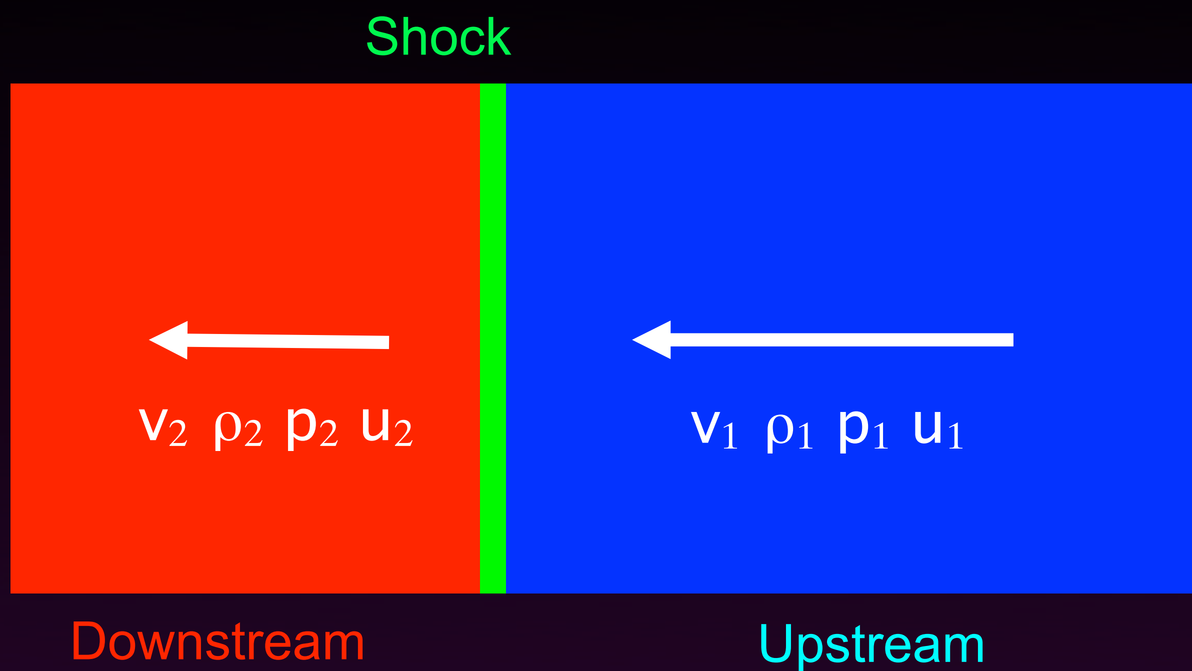
- Energy

$$-\frac{\partial}{\partial t}\left[\frac{1}{2}\rho v^2 + u_{int}\right] = \nabla\left[\left(\frac{1}{2}\rho v^2 + u_{int} + P\right)\vec{v}\right]$$

credit R. Terrier

Jump conditions

The mass, momentum, and energy fluxes are conserved across the shock



In the shock frame : Rankine-Hugoniot jump conditions :

$$\rho_1 v_1 = \rho_2 v_2$$

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_1 v_2^2$$

$$\rho_1 v_1 \left(\frac{v_1^2}{2} + \frac{P_1}{\rho_1} + u_1 \right) = \rho_2 v_2 \left(\frac{v_2^2}{2} + \frac{P_2}{\rho_2} + u_2 \right)$$

credit R. Terrier

Jump conditions

Density, velocity, temperature and pressure jumps are only functions of the adiabatic index of the gas and the shock Mach number

$\gamma = C_p/C_v = 5/3$ (monoat. gas)

$M = v/C_s$

- Density and velocity discontinuity

$$r = \frac{v_1}{v_2} = \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$$

- Pressure discontinuity

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - (\gamma-1)}{\gamma+1}$$

shocks are heating machines

- Temperature discontinuity

$$\frac{T_2}{T_1} = \frac{\left(2\gamma M_1^2 - (\gamma-1)\right)\left((\gamma-1)\gamma M_1^2 + 2\right)}{(\gamma+1)^2 M_1^2}$$

credit R. Terrier

Shock as entropy factories

The **compression ratio** r

- gives the density jump
- For a strong shock : $M_1 \gg 1$, we have :

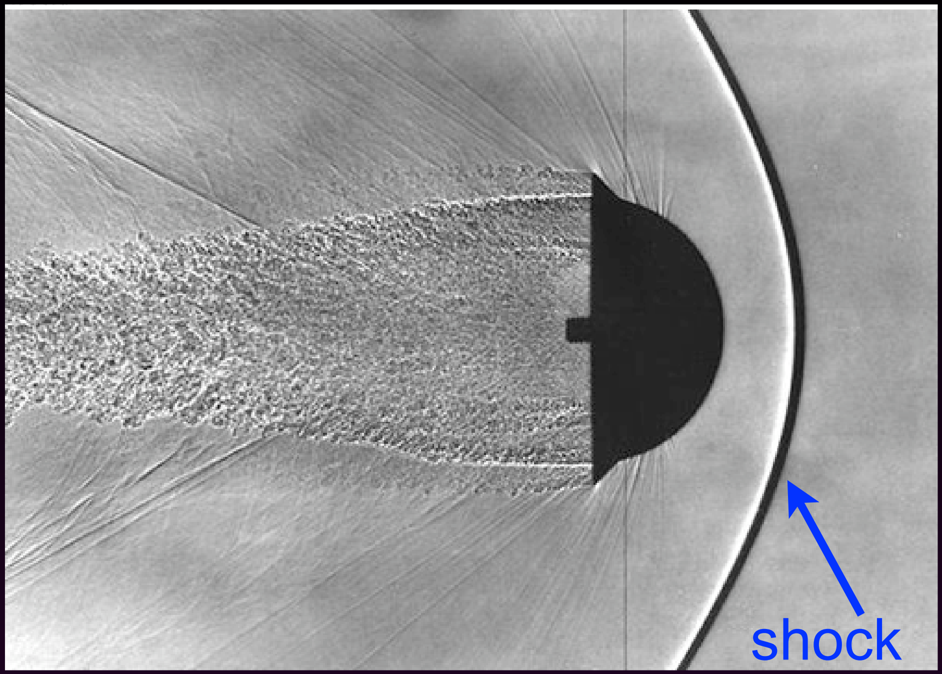
$$r = \frac{\gamma + 1}{\gamma - 1}$$

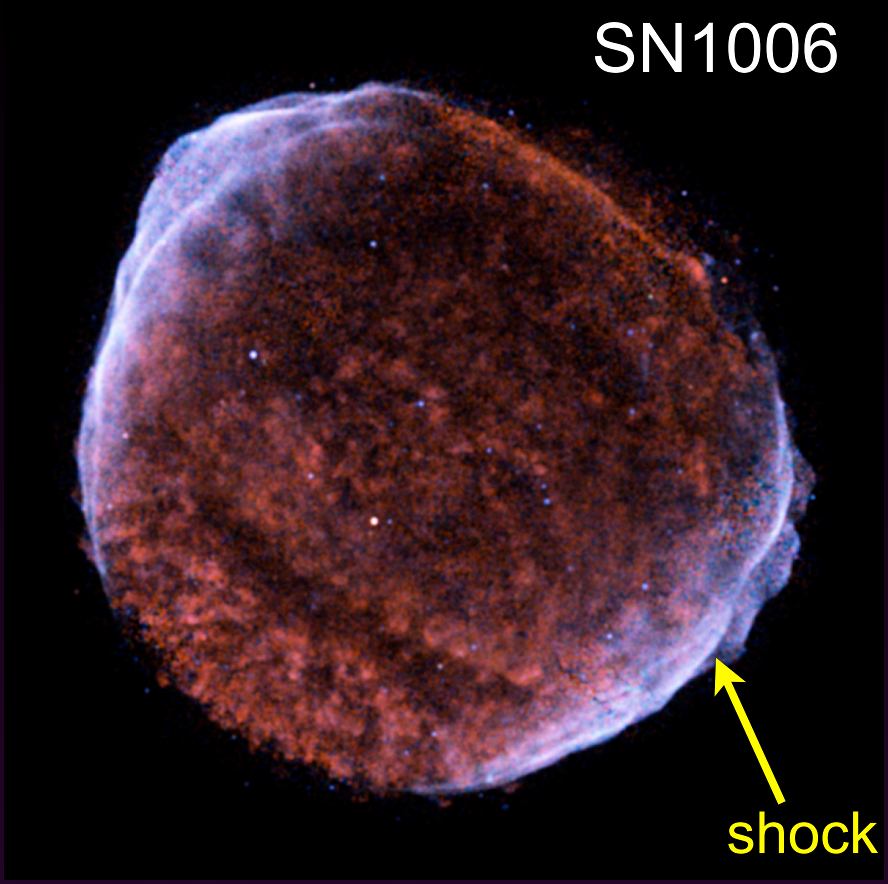
- For a gaz monoatomic gas, $\gamma = 5/3$, therefore : $r = 4$
- Density increases : $\rho_2 = r\rho_1$
- Velocity decreases $v_2 = v_1/r$
- Shock converts bulk energy of upstream medium to thermal energy downstream

credit R. Terrier

What is the mechanism that converts ordered kinetic energy into random motions, thus creating entropy?

Collisional vs collisionless shocks





Astrophysical shocks: mean free path to Coulomb collisions is enormous: 1 kpc in supernova remnants, ~Mpc in galaxy clusters

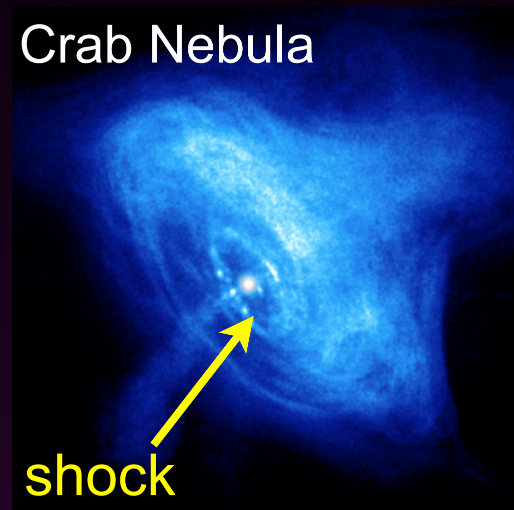
mean free path >> scales of interest

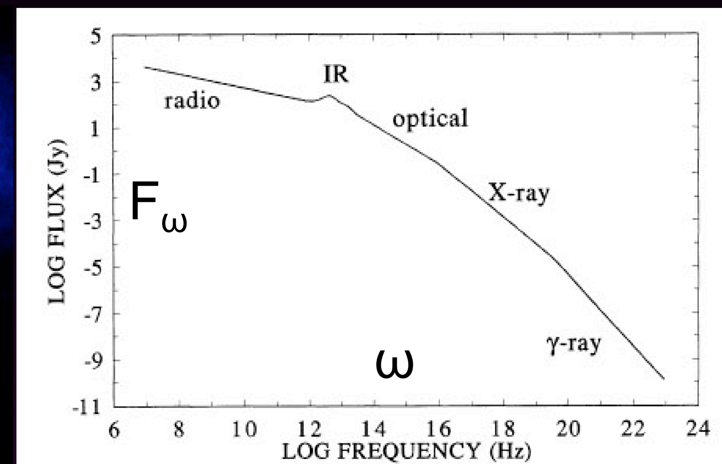
Shocks must be mediated without direct collisions, but through interaction with collective em fields → collisionless shocks

What astrophysical shocks do?

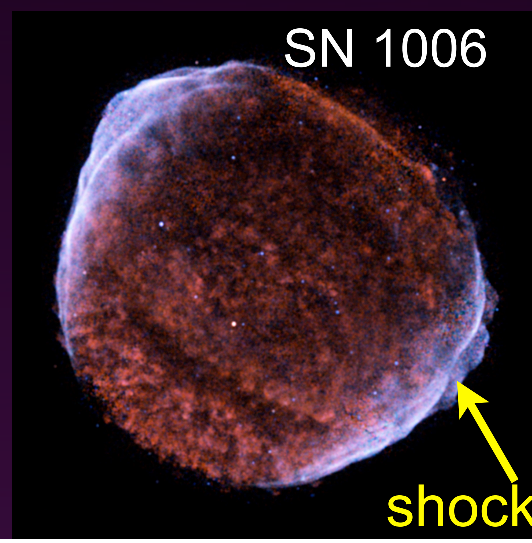
1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between ions and electrons

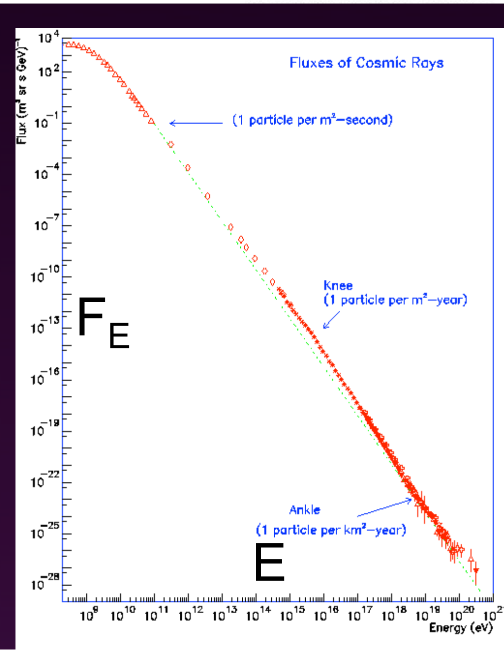
Power-law spectra of synchrotron (or IC) emission are observed from PWNe, SNRs, AGN jets, GRBs
→ Power-law population of accelerated particles is required





SNRs show direct evidence of CR acceleration (shock modification): ~10% of energy in CRs
CRs up to 10^{15}eV thought to be accelerated in SNR shocks





What astrophysical shocks do?

1. accelerate particles
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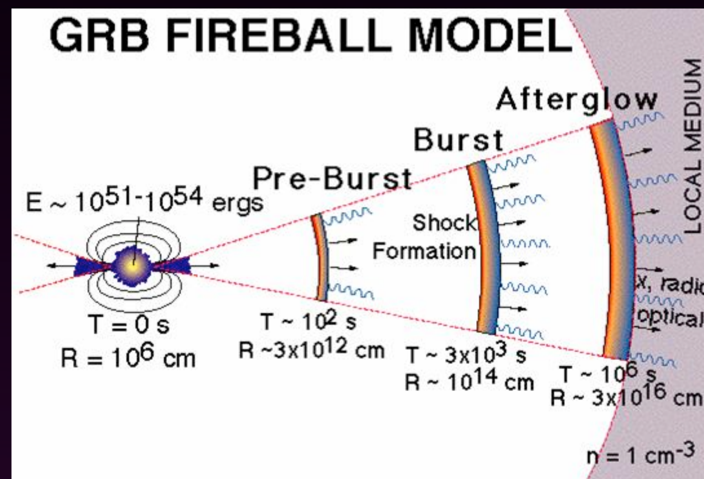
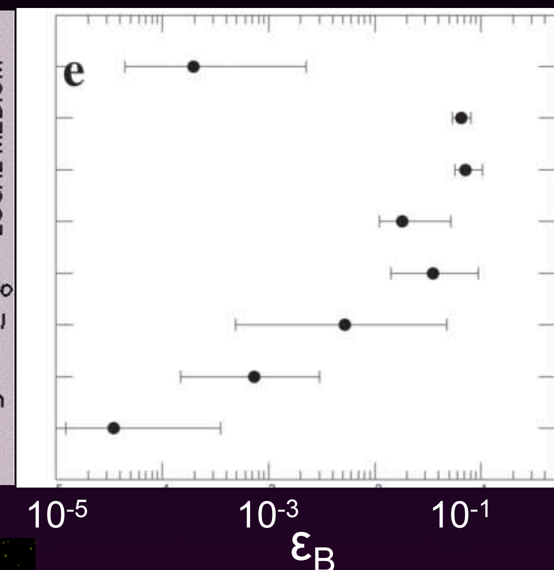
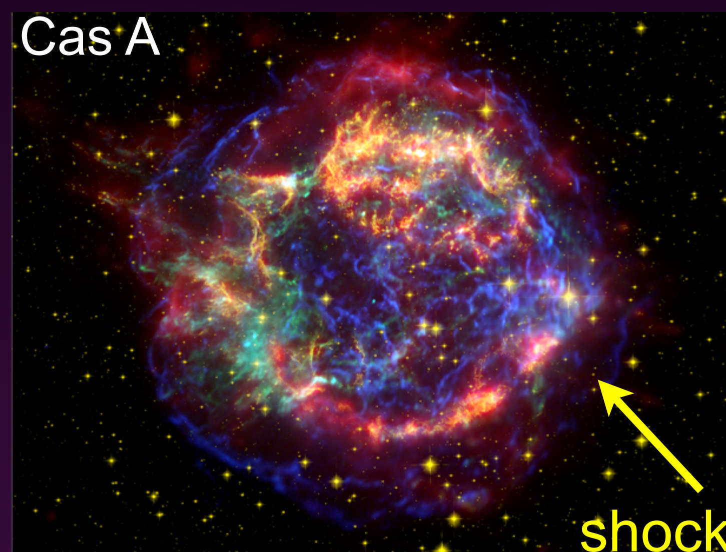
Synchrotron afterglow emission from GRBs implies at least 1% of kinetic energy in magnetic fields around the external shock (Panaitescu & Kumar 2001) >> pre-shock magnetization





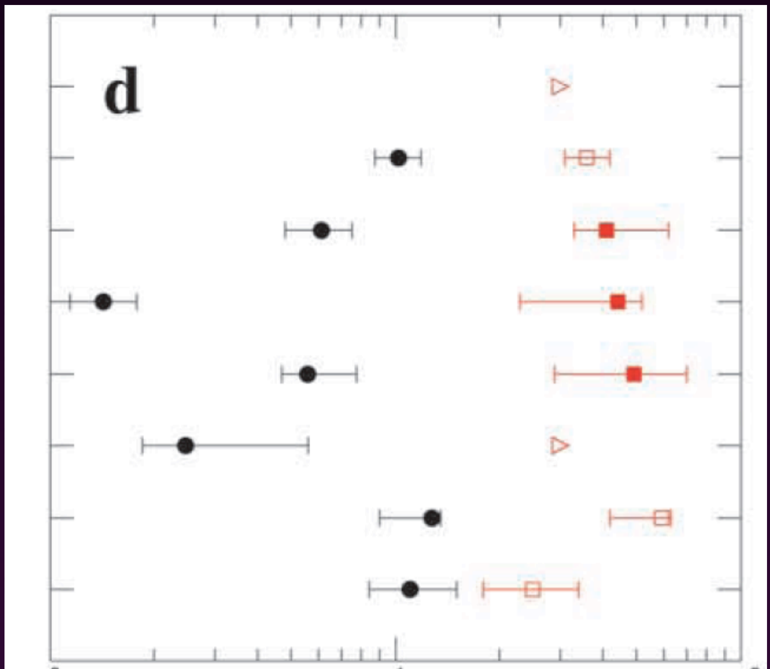
Thinness and variability of synchrotron rims in SNRs imply magnetic fields ~100 μG >> expected from shock compression alone



What astrophysical shocks do?

1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between ions and electrons

GRB afterglow observations suggest ~10% of energy in electrons behind the external shock (Panaitescu & Kumar 2001)

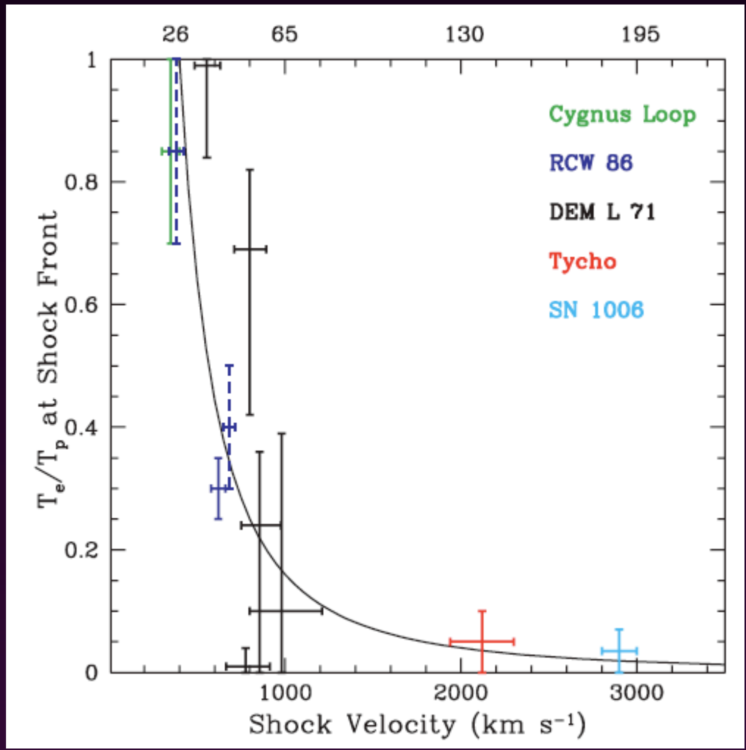


10^{-2} 10^{-1} 10^{0}

ε_e

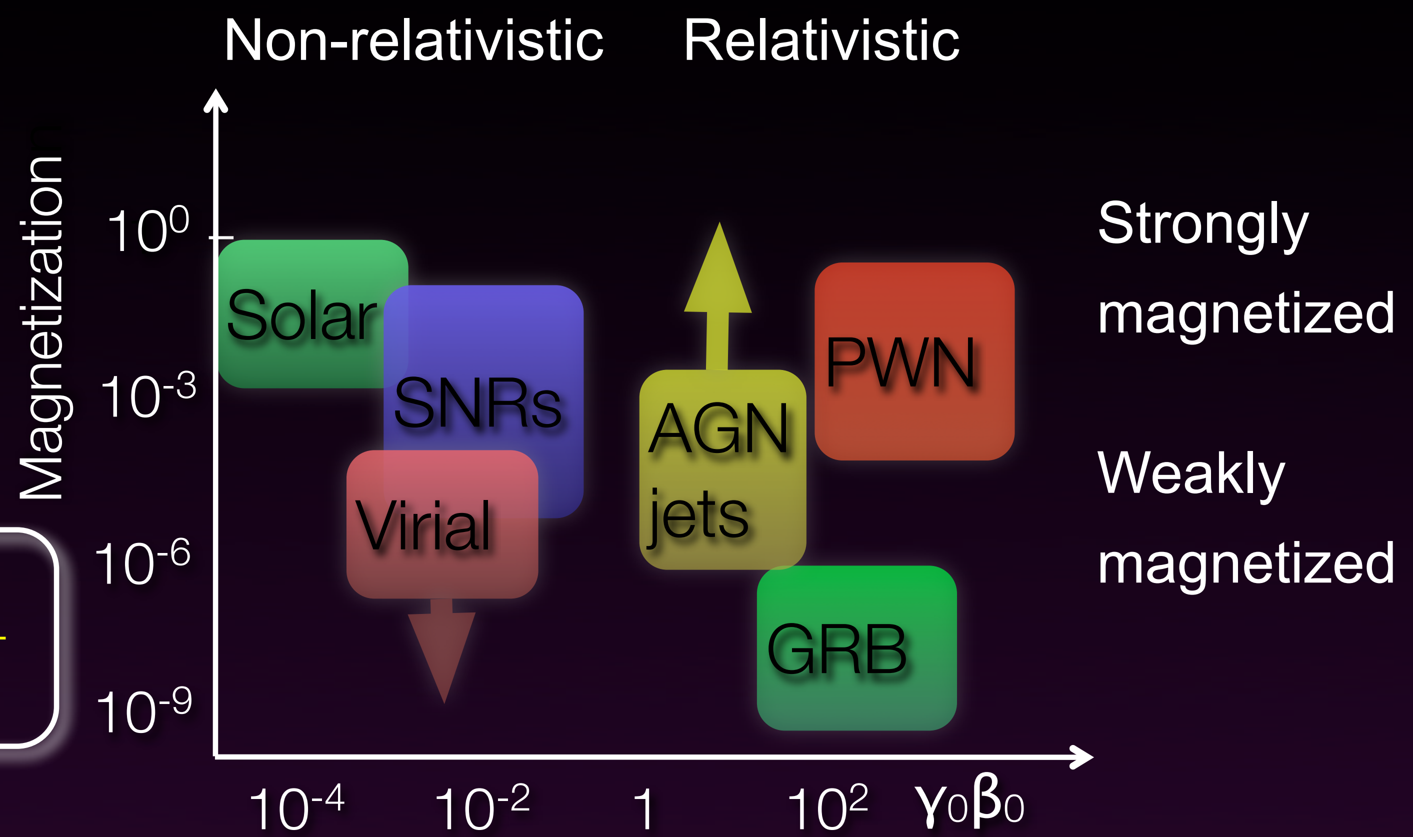
Spectral fits of SNRs (Balmer lines) allow measurements of T_e and T_p, suggesting efficient electron heating (Ghavamian et al 2007)

T_e/T_p

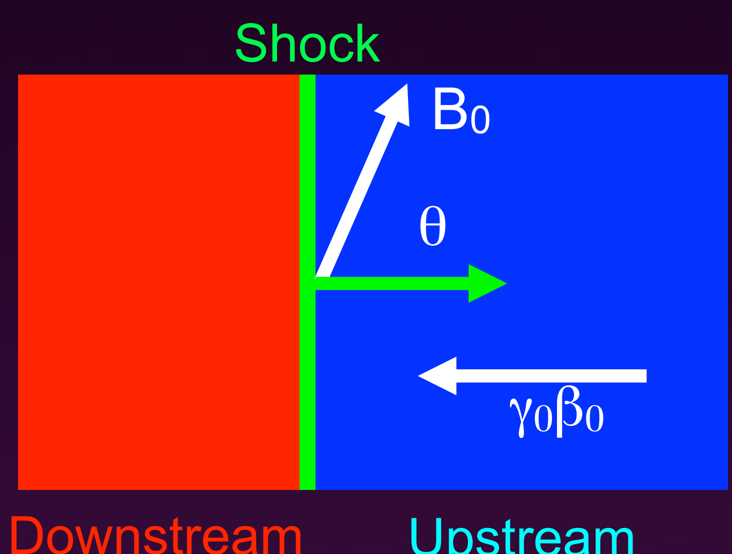


v_{sh}

Parameters of astrophysical shocks



$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$



The pre-shock flow can span a range of parameters:

- Composition (electron-positron or electron-proton)
- Bulk Lorentz factor γ_0 or (dimensionless) bulk velocity β_0
- Magnetization (σ=magnetic/kinetic energy density) and magnetic obliquity (with respect to the shock normal)

Acceleration of particles in astrophysical flows

Direct vs stochastic acceleration

Particle acceleration in astrophysics is governed by electromagnetic fields. But magnetic fields do not make work, so particles are accelerated by electric fields.

What is the origin of the electric fields that accelerate particles?

DIRECT ACCELERATION

- Unipolar inductor
- Magnetic reconnection

STOCHASTIC ACCELERATION

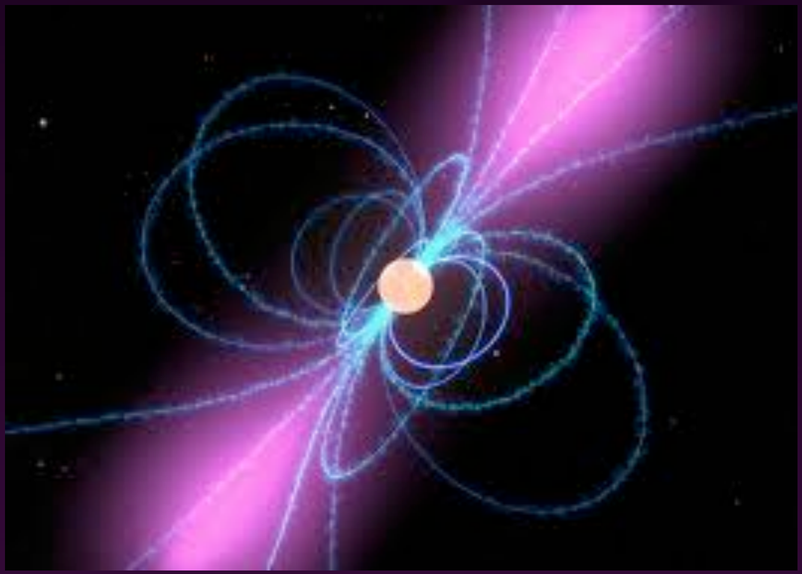
- Second-order Fermi
- First-order Fermi

Direct acceleration

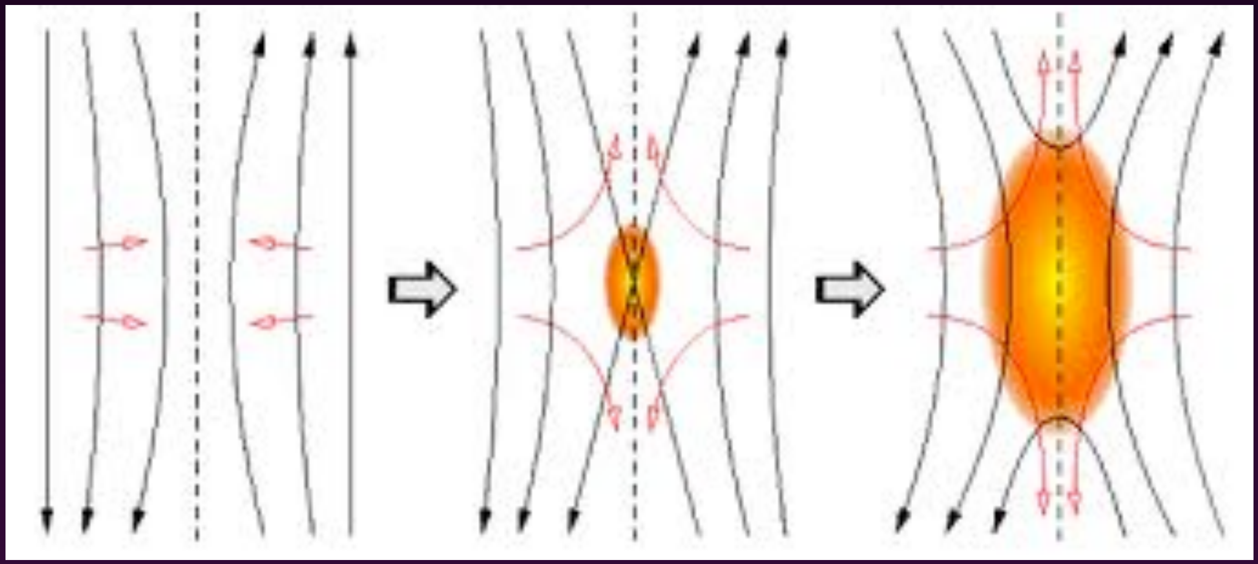
Powered by large-scale net electric fields $\langle E \rangle \neq 0$

BUT: difficulty to create net electric fields in astrophysics, for the high conductivity of astrophysical plasmas. Some exceptions:

Unipolar Inductor

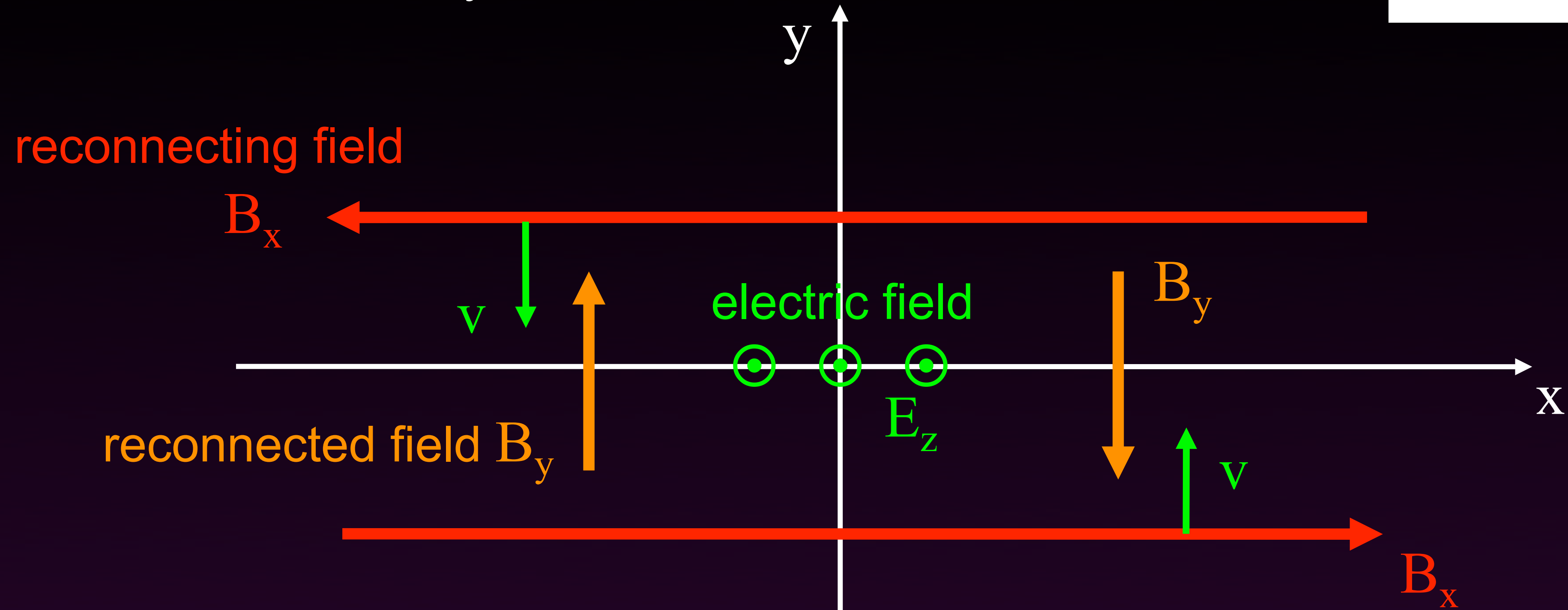


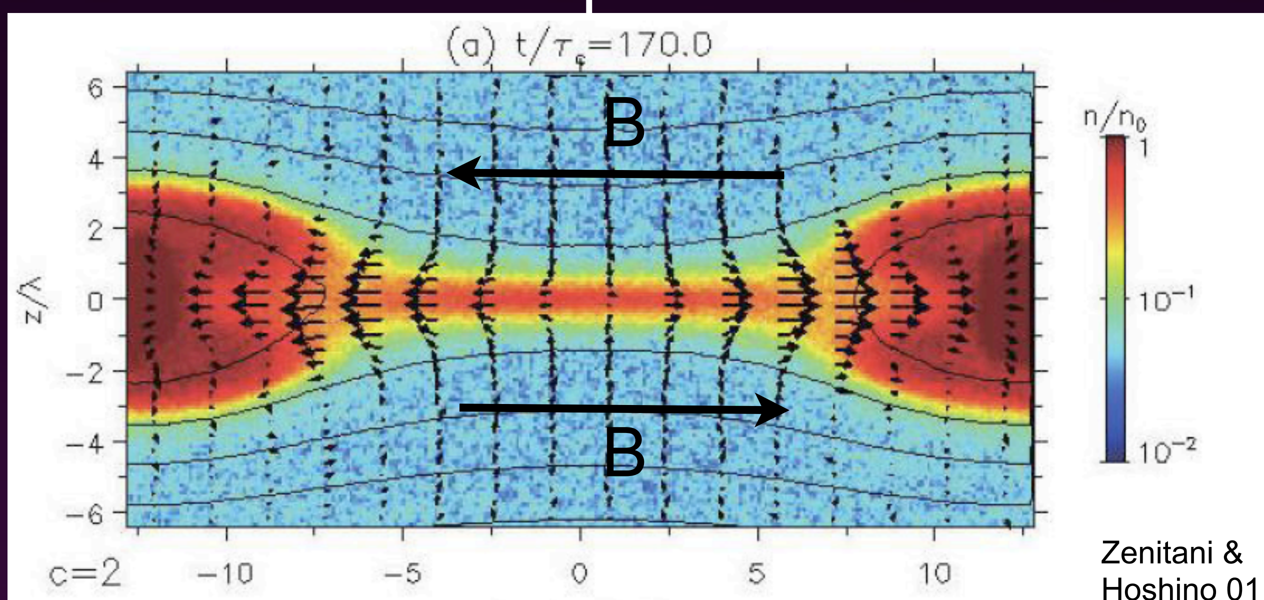
Magnetic Reconnection



Magnetic reconnection

Particle acceleration by the inductive reconnection electric field $E = v \wedge B$



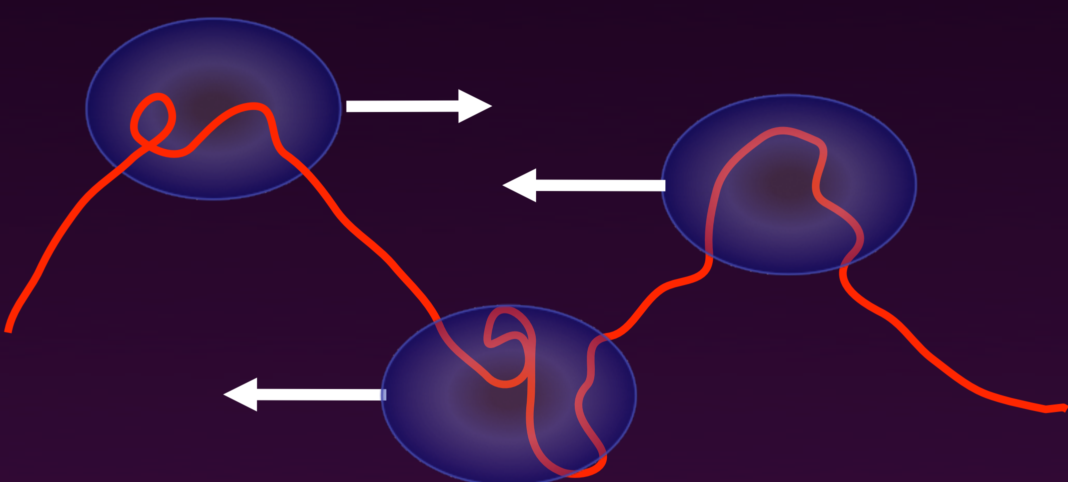


Stochastic acceleration

Powered by small-scale random electric fields $\left\langle \vec{E} \right\rangle = 0 \qquad \left\langle \vec{E}^2 \right\rangle \neq 0$

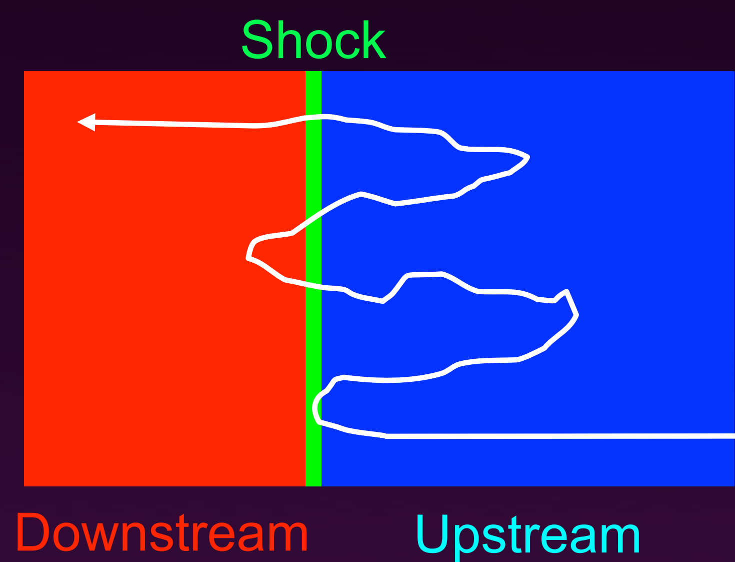
Second-order Fermi

in randomly-moving magnetized clouds



First-order Fermi

at shock fronts

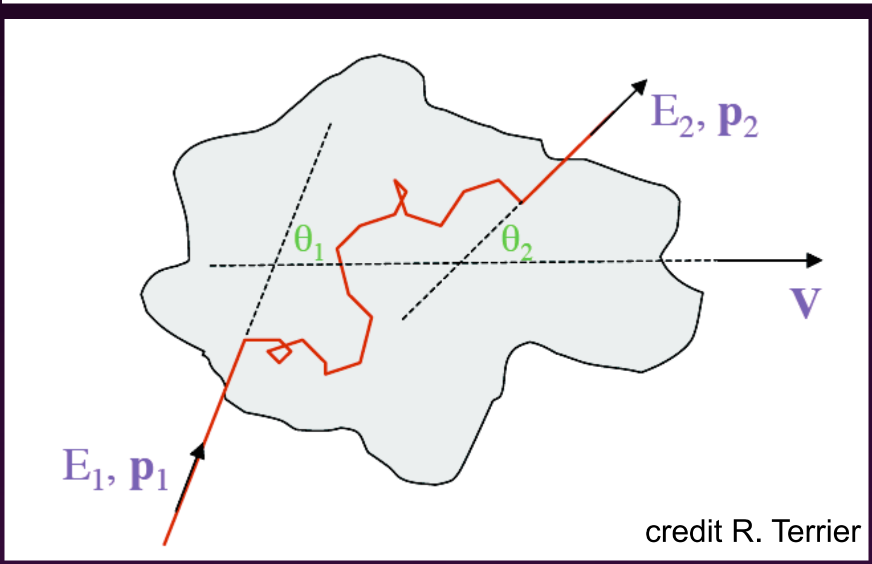


Second-order Fermi: principle

Acceleration mechanism through frame change

Fermi 1949

- Magnetic clouds deflect charged particles
- Magnetic clouds have random motion in ISM
- Deflected particle gains energy in a head-on collision
- Some energy is lost in a rear-end collision
- On average head-on collisions are more probable than read-end collisions → energy gain on average



Interaction of a particle with an interstellar cloud

Second-order Fermi: energy gain

- Writing γ and β Lorentz factor and velocity of the cloud, we have in the cloud frame :

$$E'_{in} = \gamma\,(E_{in} - \beta p_{in} c \cos\theta_{in}) \sim \gamma E_{in}\,(1 - \beta\cos\theta_{in})$$

- The particle direction is randomized in the cloud, then in the lab frame :

$$E_{out} = \gamma E'_{out}\,(1 + \beta\cos\theta'_{out})$$

- Elastic scattering in the cloud, $E'_{in} = E'_{out}$:

$$E_{out} = \gamma^2 E_{in}\,(1 - \beta\cos\theta_{in})\,(1 + \beta\cos\theta'_{out})$$

- Therefore :

$$\frac{\Delta E}{E} = \frac{\beta(\cos\theta'_{out} - \cos\theta_{in}) + \beta^2(1 - \cos\theta_{in}\cos\theta'_{out})}{1 - \beta^2}$$

credit R. Terrier

Second-order Fermi: collision probability

- We now have to find the probabilities of head-on and rear-end collisions By hypothesis the escaping particles are isotropic in the cloud frame $< \cos\theta'_{out} >= 0$
- For a cloud of velocity V, the number of particles incident at θ_{in} is $dN = 2\pi \sin\theta_{in} d\theta_{in}$
- During time δt, the number of particles reaching the cloud is :

$$dN \propto (c - V\cos\theta_{in})\,\delta t$$

FLUX FACTOR

- Therefore :

$$< \cos\theta_{in} >= \frac{\int_{-1}^{1} \cos\theta_{in}\,(c - V\cos\theta_{in})\,d\cos\theta_{in}}{\int_{-1}^{1} (c - V\cos\theta_{in})\,d\cos\theta_{in}}$$

$$= \frac{-2V/3}{2c} = -\frac{\beta}{3}$$

credit R. Terrier

Second-order Fermi: mean energy gain

$$< \frac{\Delta E}{E} >= \frac{\beta(< \cos\theta'_{out} > - < \cos\theta_{in} >)}{1-\beta^2} + \frac{\beta^2(1 - < \cos\theta_{in} >< \cos\theta'_{out}) >}{1-\beta^2} = \frac{4}{3}\frac{\beta^2}{1-\beta^2} \sim \frac{4}{3}\beta^2$$

- Positive energy gain : particle is undergoing an acceleration $\propto$ E
- stochastic : energy gain on average
- second order

credit R. Terrier

Where does the energy gain come from? Where is the electric field?

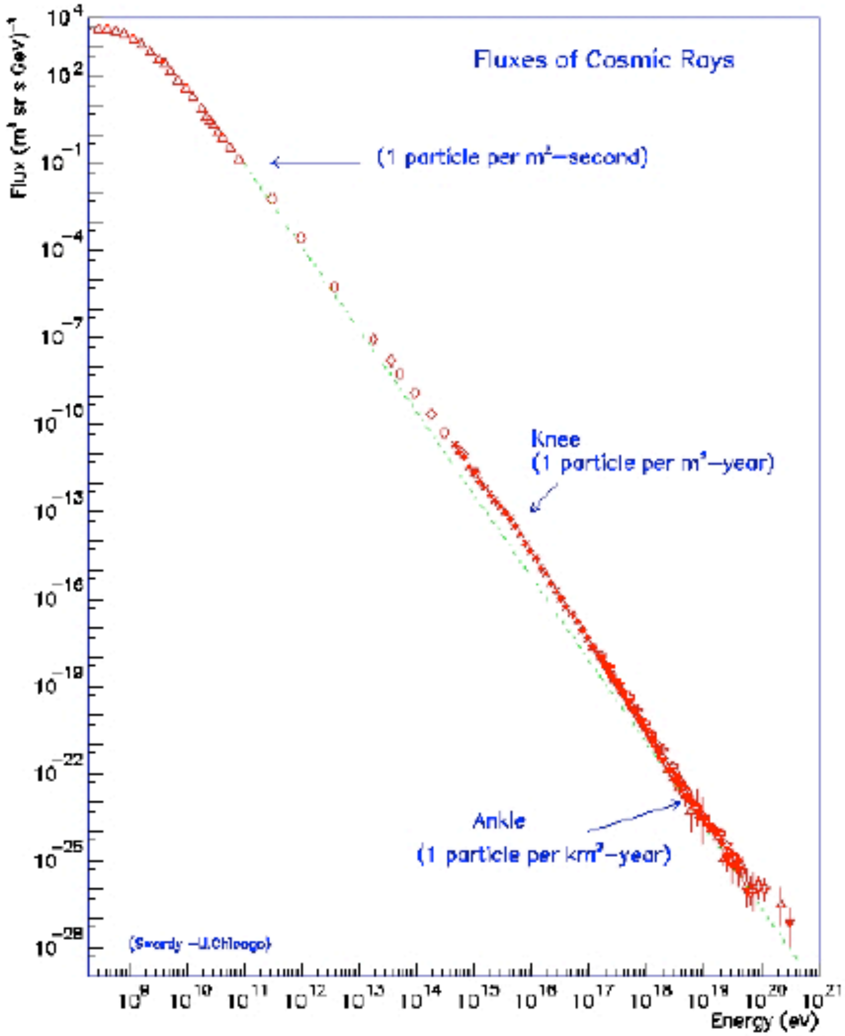
From Lorentz frame transformation $E = v \wedge B$

Second-order Fermi: limitations

- Energy gain is too small. Typical velocities of magnetized clouds in the interstellar medium are V~10 km/s, so $V/c \sim 10^{-4}$
- Acceleration time is too long. For cosmic rays, acceleration time may be longer than escape time from the Galaxy
- Particle injection: it may be problematic to compete with Coulomb losses at low energies
- The power-law spectrum is not universal!

The cosmic ray spectrum

COSMIC RAYS: hadronic particles of cosmic origin detected on Earth



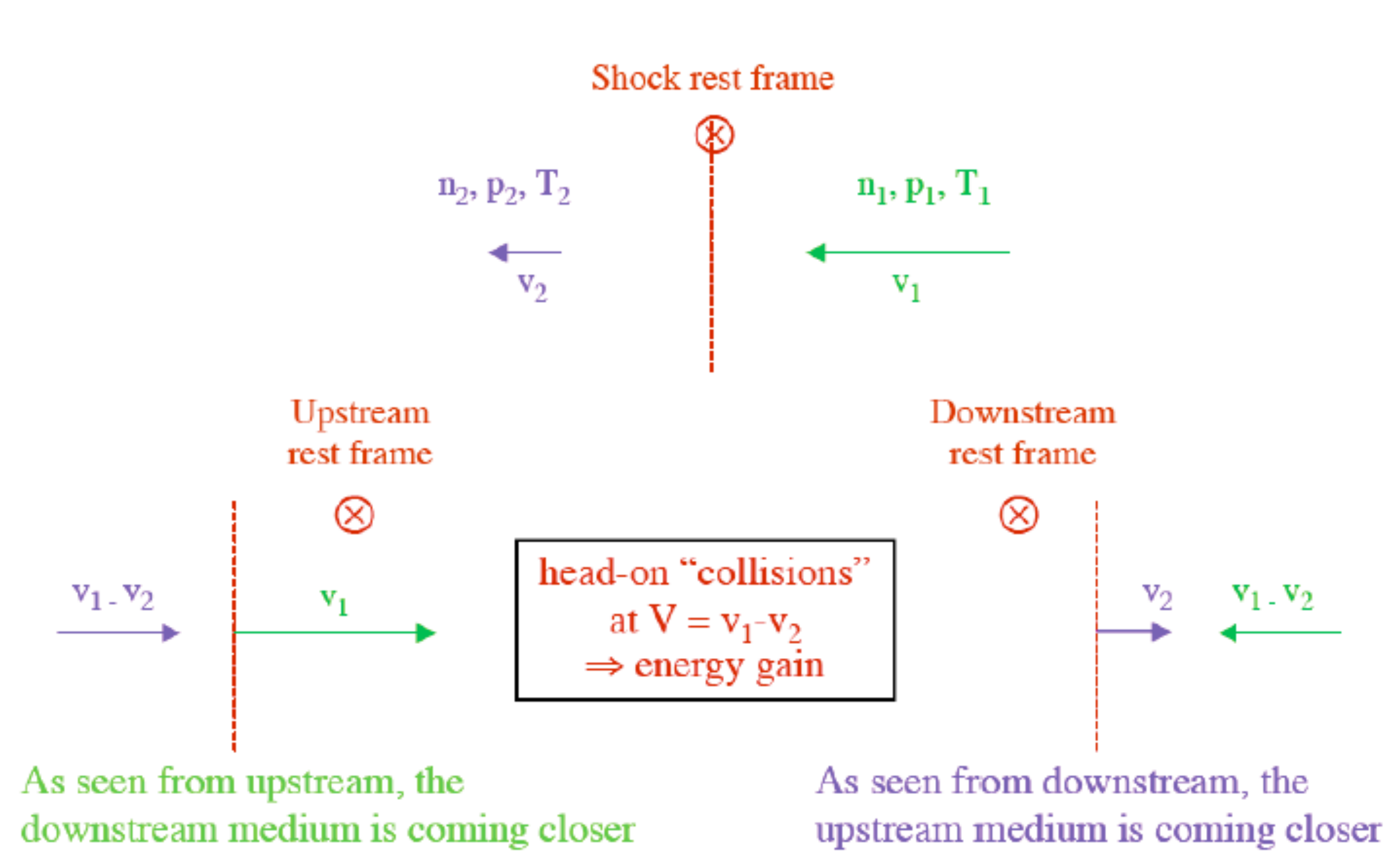
- Power law over 10 magnitudes
- Need an acceleration mechanisms that provides :
- universal power laws
- Maximum energies (e.g. knee 3 10^{15}eV)

credit R. Terrier

First-order Fermi: principle

- Collisions are always head-on : particles gain energy at each shock crossing
- Particles can escape downstream

credit R. Terrier



First-order Fermi: energy gain

Energy gain is computed for a particle crossing the shock back and forth as for 2nd order Fermi

- energy gain per crossing at first order in β :

$$\frac{\Delta E}{E} = \beta(\cos\theta'_{out} - \cos\theta_{in})$$

- Upstream particle distribution is isotropic $\frac{dn(\theta_{in})}{n} = \frac{1}{2}\sin\theta_{in} d\theta_{in}$
- We can compute the average $\cos\theta_{in}$ for particles crossing the shock :

$$\frac{dN}{dSdt} = n_0 c \cos\theta_{in} d\Omega_{in} = \frac{1}{2} n_0 c \cos\theta_{in} \sin\theta_{in} d\theta_{in}$$

FLUX FACTOR

- $$< \cos\theta_{in} >= \frac{\int_{\pi/2}^{\pi} \cos^2\theta_{in} \sin\theta_{in} d\theta_{in}}{\int_{\pi/2}^{\pi} \cos\theta_{in} \sin\theta_{in} d\theta_{in}} = -\frac{2}{3}$$

credit R. Terrier

First-order Fermi: mean energy gain

Same reasoning yields $< \cos\theta_{out} >= \frac{2}{3}$
Therefore at first order in β :

$$< \Delta E >= \frac{4}{3}\beta E = \frac{4}{3}\frac{v_1}{c}\left(1 - \frac{1}{r}\right) E$$

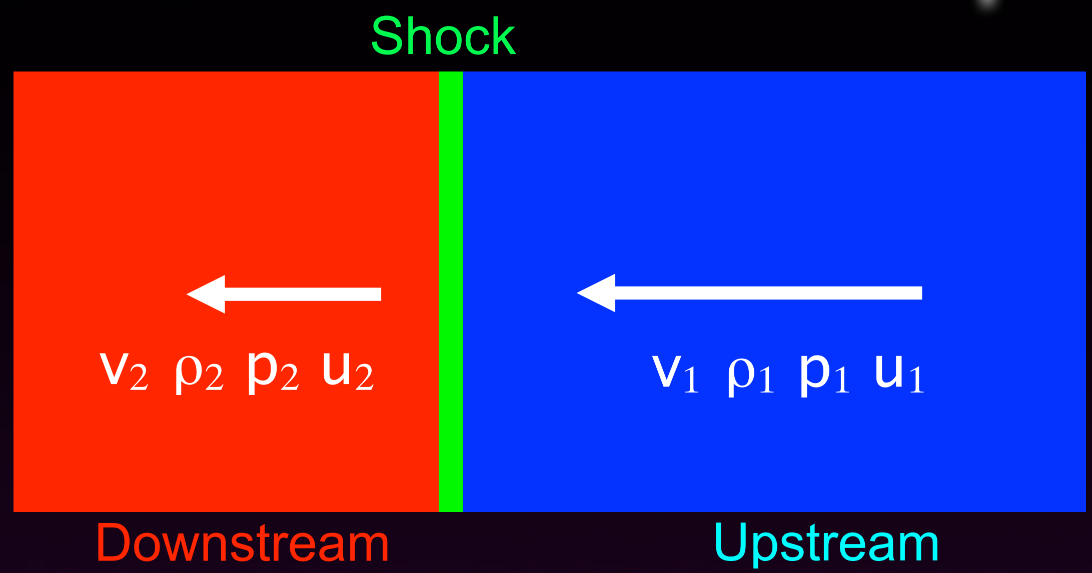
- $\Delta E > 0$: particles accelerate
- $\Delta E = kE$ at each crossing. Therefore after n crossings :

$$E_n = (k+1)^n E_0$$

- $\Delta E / E = v_1 / c$ if $r = 4$.
- First order process

credit R. Terrier

First-order Fermi: escape



Seen from the shock frame :

- Upstream medium is closing in : a particle located upstream has a probability of 1 to cross the shock independent of its energy.
- Downstream medium flowing away from the shock : a particle downstream can be advected far away from the shock. Particles drift at velocity v_2
- There is therefore an escape probability P_{esc} from the acceleration region.
- It does not depend on energy

credit R. Terrier

First-order Fermi: escape

- Flux crossing the shock :

$$\frac{dN_{1\to2}}{dSdt} = \int_{\pi/2}^{\pi} \frac{1}{2} n_0 c \cos\theta \sin\theta d\theta = \frac{n_0 c}{4}$$

- Flux escaping downstream :

$$\frac{dN_{esc}}{dSdt} = n_0 v_2 = n_0 \frac{v_1}{r}$$

- Therefore P_{esc} is really independent on energy :

$$P_{esc} = \frac{N_{esc}}{N_{1\to2}} = \frac{4v_1}{rc}$$

- Therefore if we inject N_0 particles at $t = 0$, there are $N_0(1 - P_{esc})^n$ left during cycle n

credit R. Terrier

First-order Fermi: particle spectrum

- If we inject N_0 particles at $t = 0$, there are $N_0(1 - P_{esc})^n$ left during cycle n
- If minimal injection energy is E_0, $E_n \geq (k+1)^n E_0$, the number of required cycles to produce a particle at E is

$$n = \frac{log(E/E_0)}{log(k+1)}$$

- Therefore

$$N(\geq E) = N_0(1 - P_{esc})^{\frac{log(E/E_0)}{log(k+1)}} = N_0 \left(\frac{E}{E_0}\right)^{\frac{log(1-P_{esc})}{log(k+1)}}$$

- If $V_c \ll c$, we can linearize :

$$\frac{log(1 - P_{esc})}{log(k+1)} \sim -\frac{P_{esc}}{k} = \frac{3}{1-r}$$

credit R. Terrier

First-order Fermi: particle spectrum

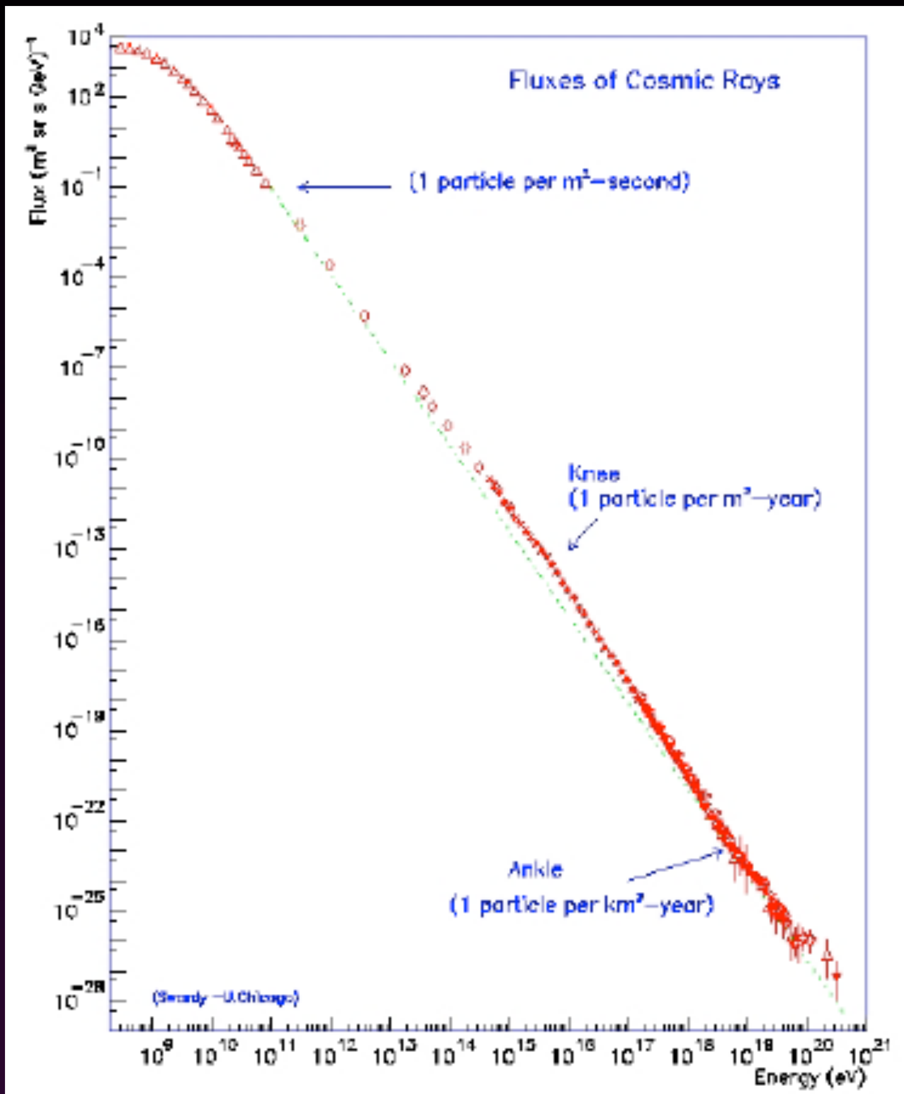
- The differential spectrum is obtained by differentiation since $N(\geq E) = \int N(E)dE$:

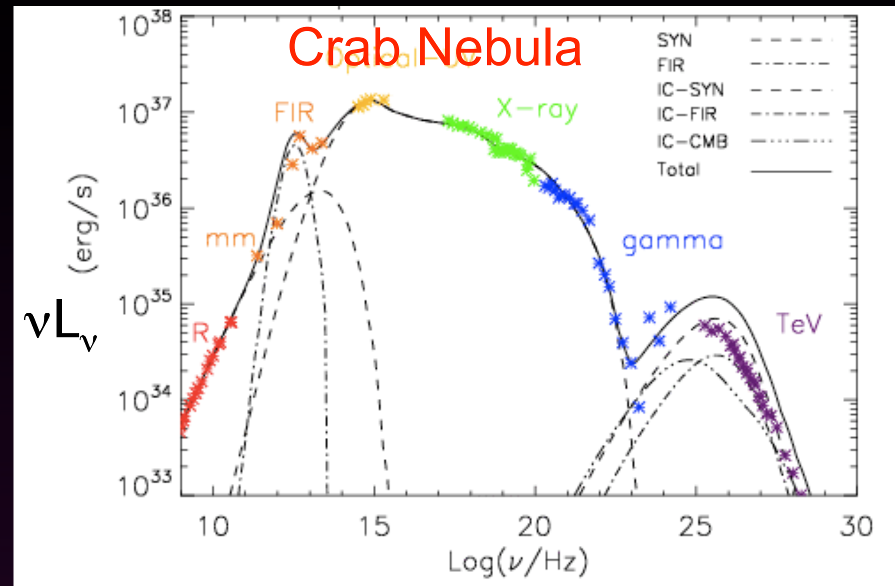
$$N(E) \propto \left(\frac{E}{E_0}\right)^{-\alpha} \quad \text{with} \quad \alpha = \frac{r+2}{r-1}$$

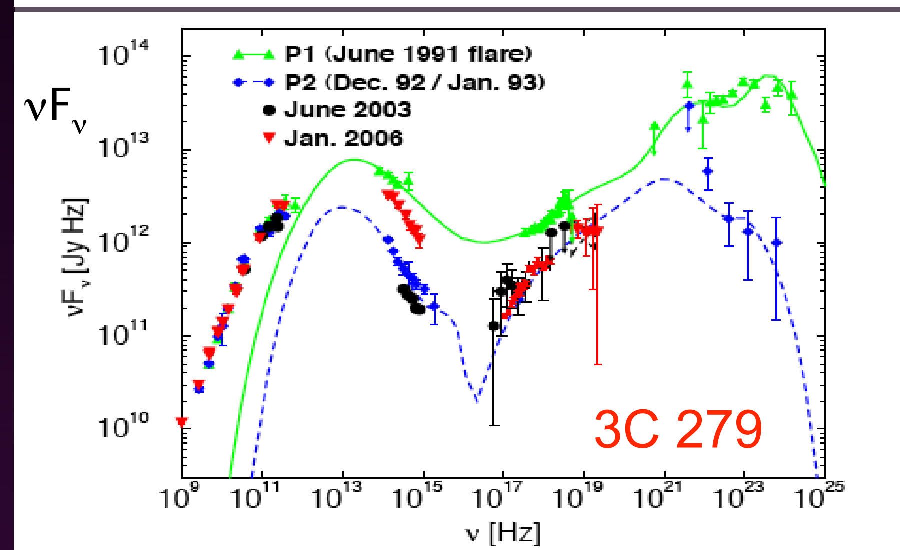
- Diffusive Shock Acceleration produces a power law spectrum
- The spectrum does not depend on V_c, it only depends on r compression ratio
- If $r = 4$ (strong shock) $\alpha = 2$
- **a universal power law !**
- **Efficient acceleration mechanism !**
- E_{max} is limited by several factors :
  - Energy losses (Coulomb, radiative, inelastic collisions)
  - Time : age of the system limits the energy
  - Particle escape (geometry effect)
- Maximal energy depends of system physical conditions

credit R. Terrier

First-order Fermi: successes





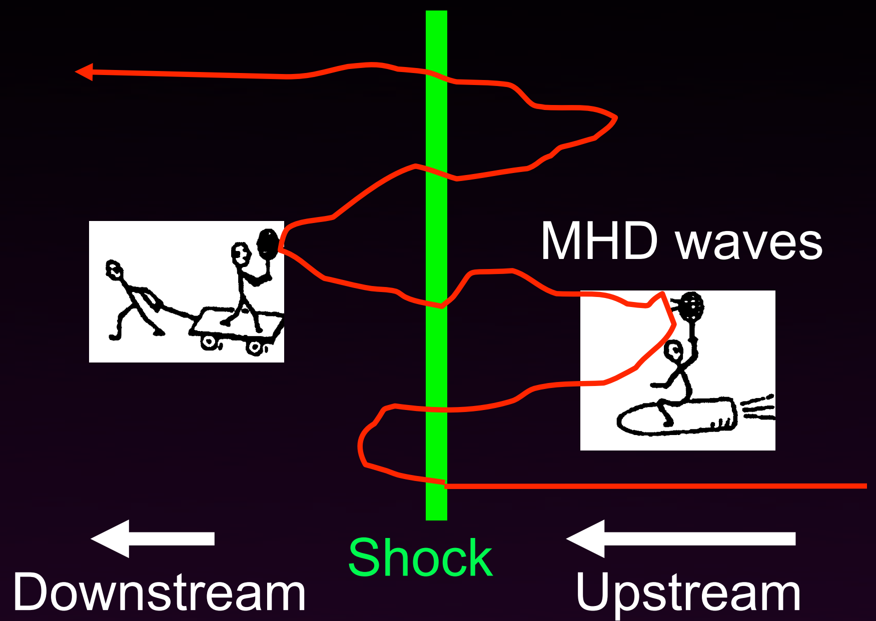


Slope of CRs (+ escape from the Galaxy) in agreement with Fermi

Slope of nonthermal electrons in PWNe, SNRs, blazar jets and gamma-ray bursts generally in agreement with Fermi

First-order Fermi: open questions

• What is scattering the particles? Where does the MHD turbulence come from?



• Under which conditions can the Fermi mechanism operate?

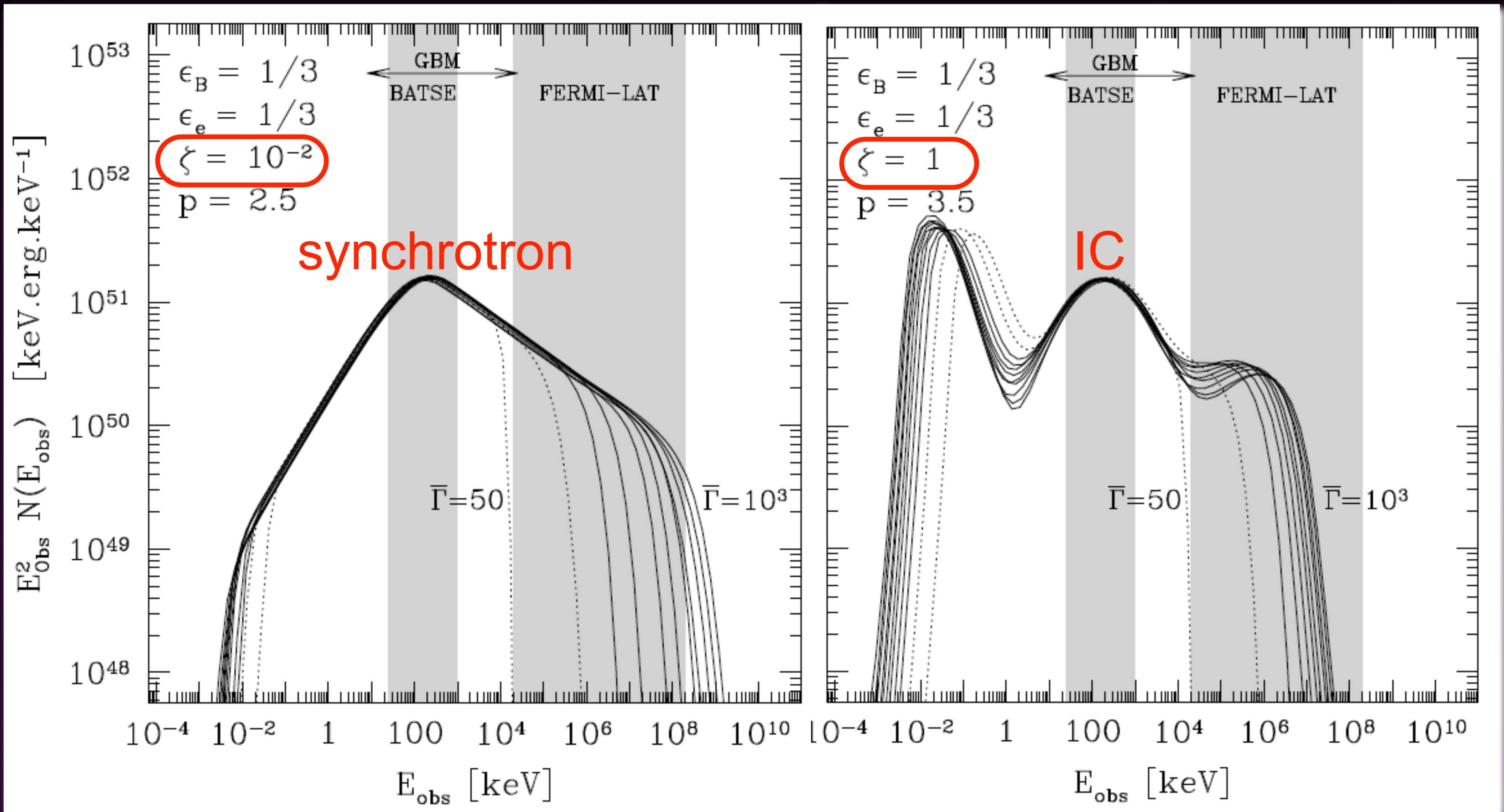
• What is the slope *p* of the nonthermal tail in relativistic shocks, such that

$$\frac{dn}{d\gamma} \propto \gamma^{-p}$$

• How many particles (and energy) does the nonthermal tail contain?

Parameterizing our ignorance

- ζ_e : fraction of electrons in the post-shock nonthermal tail
- ε_e : fraction of flow energy in the electron nonthermal tail
- ε_B : fraction of flow energy in post-shock magnetic fields



(Bosnjak et al 09)

Which values are obtained in real shocks?

Self-consistent simulations of particle acceleration in shocks

The PIC method

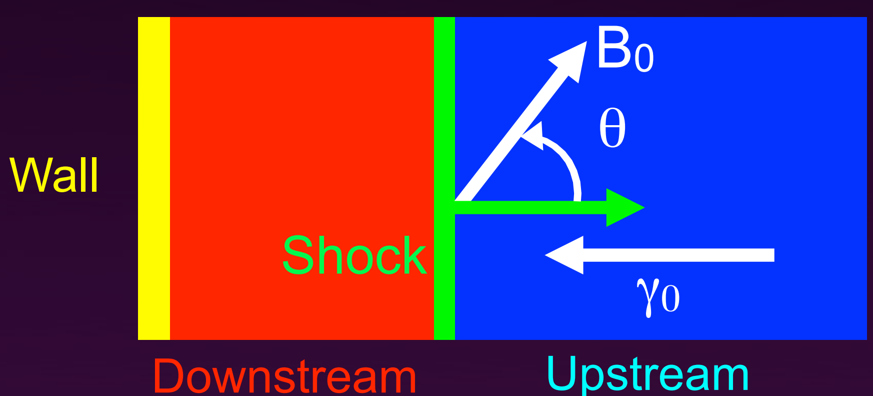
Particle-in-Cell (PIC) method:

1. Particle currents deposited on a grid
2. Electromagnetic fields solved on the grid via Maxwell's equations
3. Lorentz force interpolated to particle locations


No approximations, plasma physics at a fundamental level


Tiny length and time scales need to be resolved ➔ huge simulations, limited time coverage

- Relativistic 3D e.m. PIC code TRISTAN-MP (Buneman 1993, Spitkovsky 2005)
- Incoming flow reflected by a wall, simulations in the downstream frame



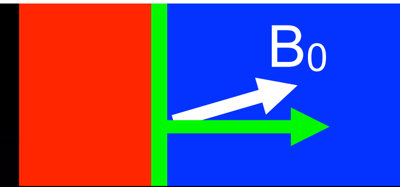
Pre-shock parameters:

composition ($e^- - e^+$ or $e^- - p^+$)

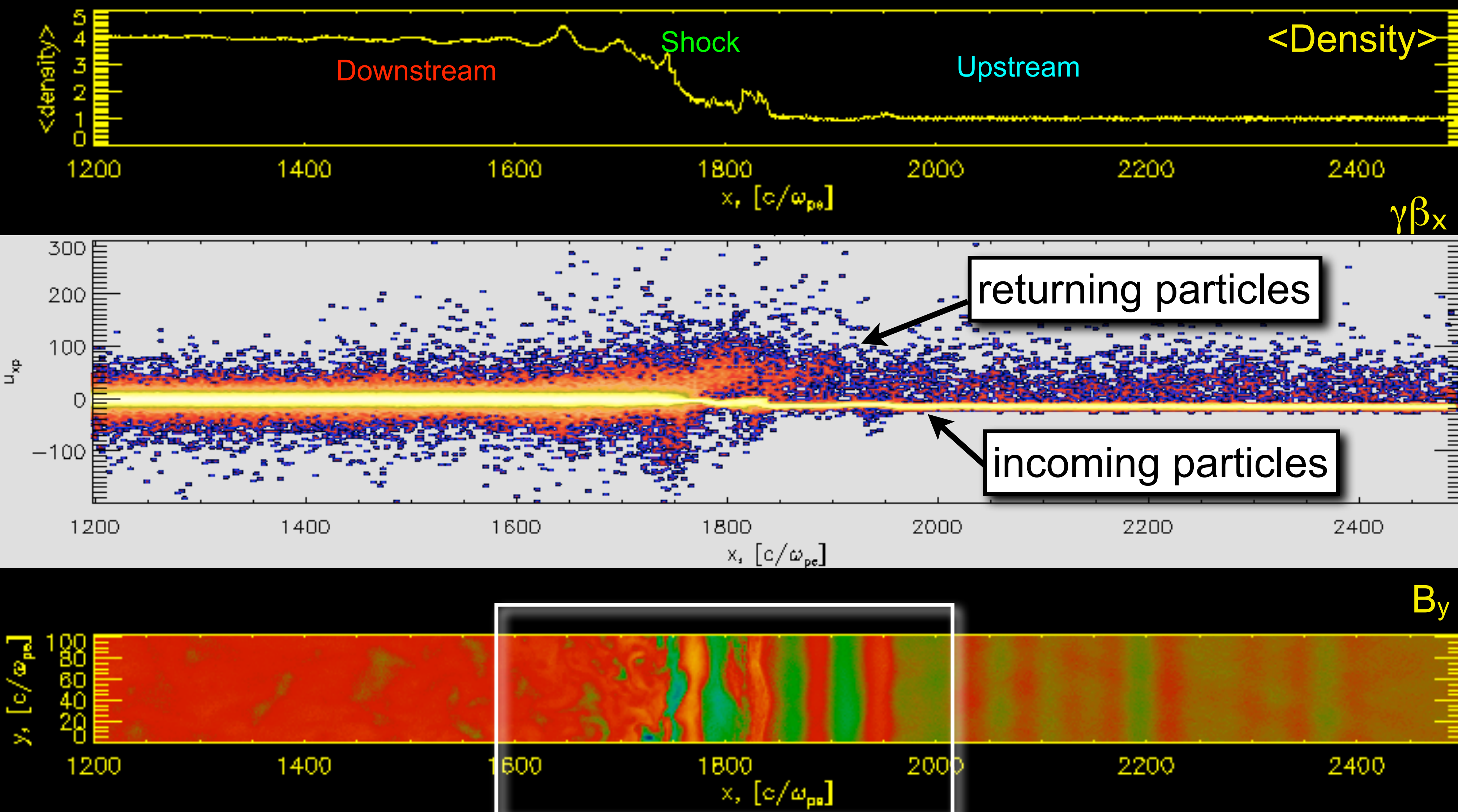
bulk Lorentz factor γ_0

magnetization and obliquity θ $\sigma = \dfrac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$

Relativistic electron-ion shocks



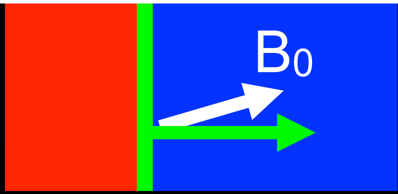
$\sigma=0.1$ $\theta=15°$ $\gamma_0=15$ e^--p^+ shock



(LS and Spitkovsky 11a)

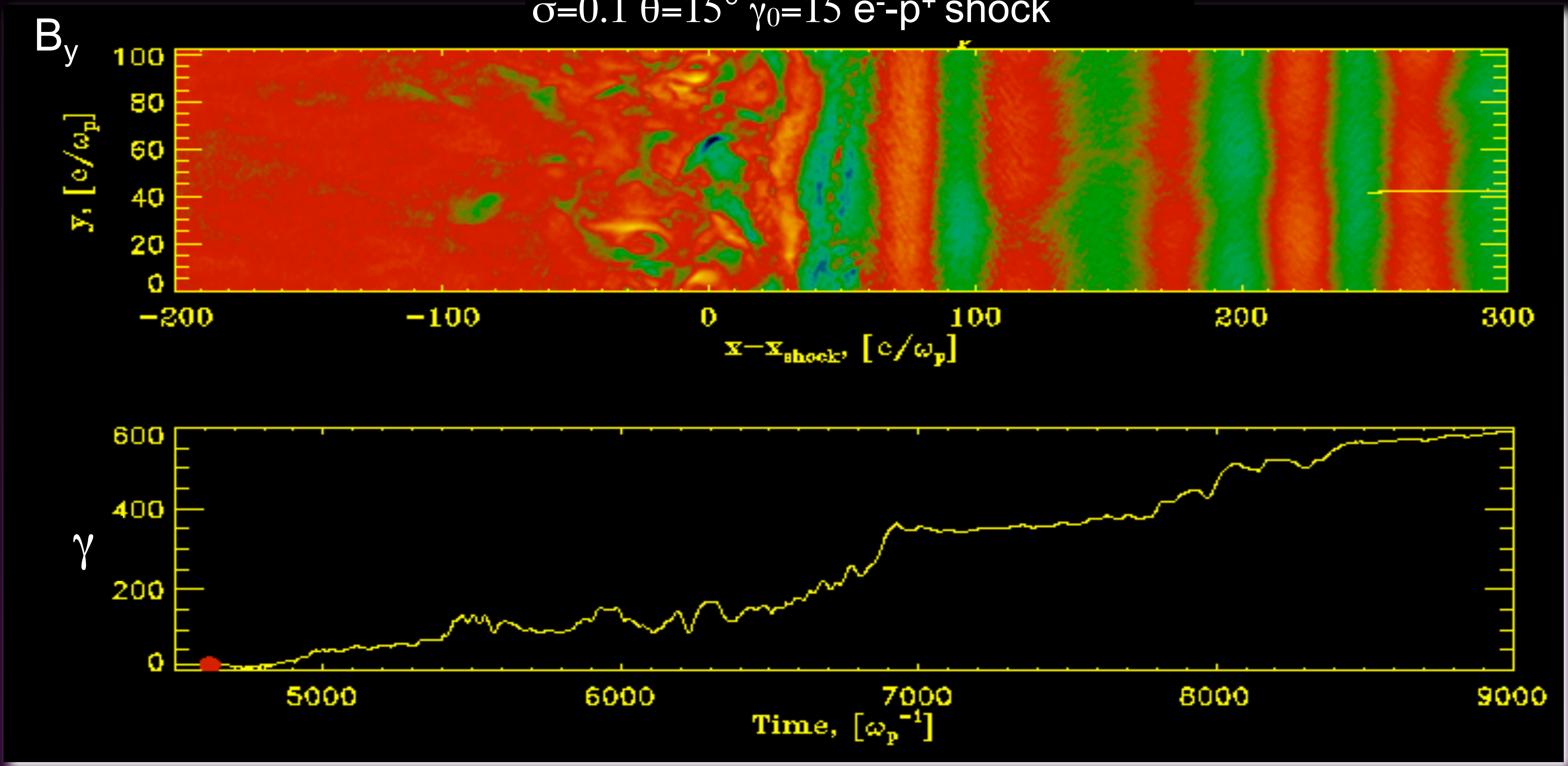
Returning particles → Self-generated turbulence

Ab initio particle acceleration



Self-generated turbulence → Particle acceleration

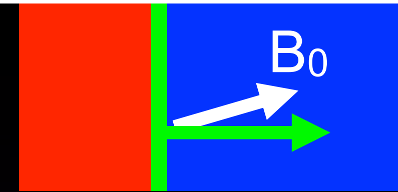
σ=0.1 θ=15° γ_0=15 e^--p^+ shock



(LS and Spitkovsky 11a)

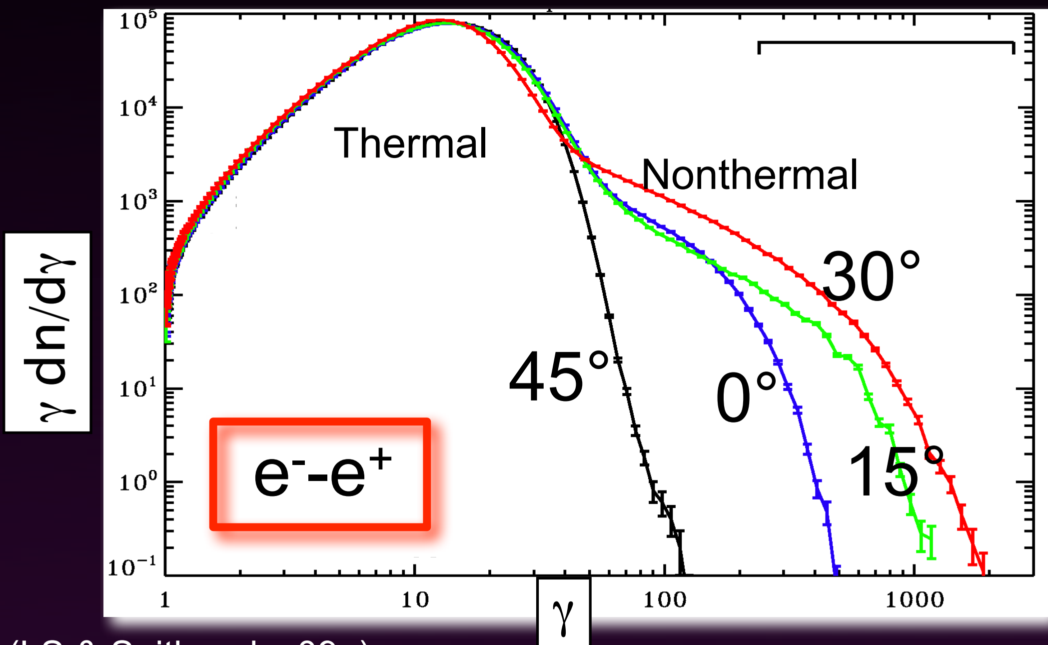
Fermi first-order process from first principles!

Nonthermal spectra from shocks

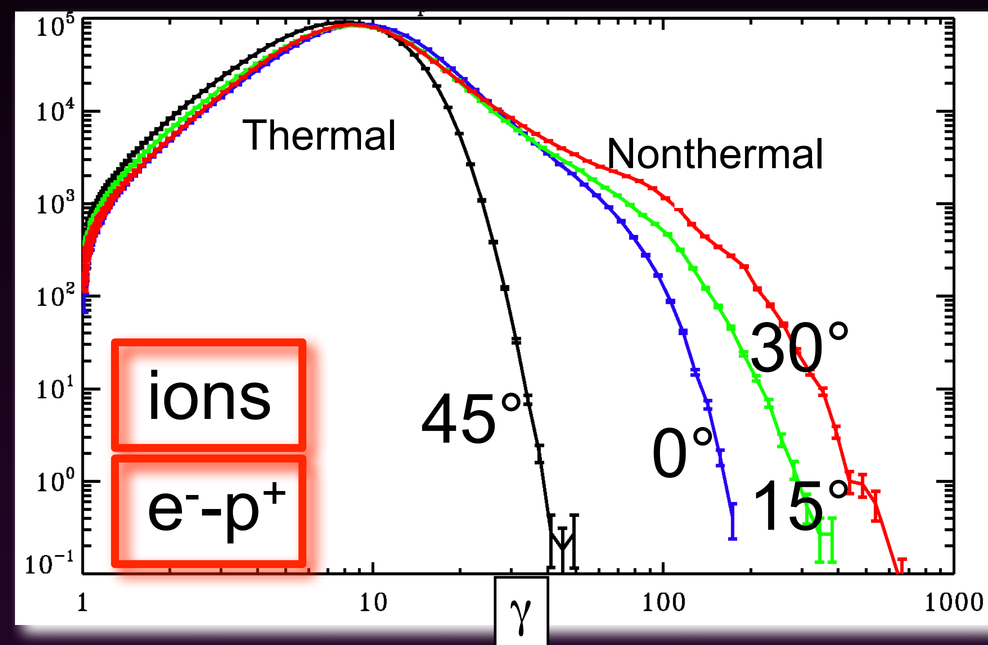


For $\sigma > 10^{-3}$ and $\theta < \theta_{crit} \approx 34°$, the nonthermal tail has slope $p = 2.3 \pm 0.1$ and contains ~1% of particles and ~10% of energy.

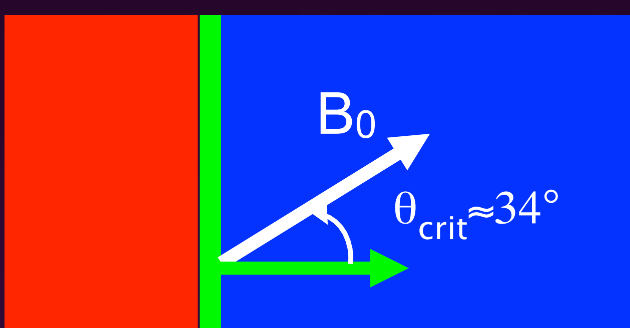
$\sigma = 0.1$ $\gamma_0 = 15$ shock



(LS & Spitkovsky 09a)



(LS & Spitkovsky 11a)



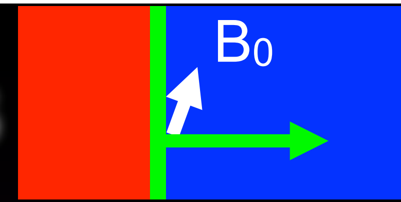
If $\sigma > 10^{-3}$, particle acceleration only for:

$\theta < \theta_{crit} \approx 34°$ (downstream frame)

$\theta' < 34°/\gamma_0 << 1$ (upstream frame)

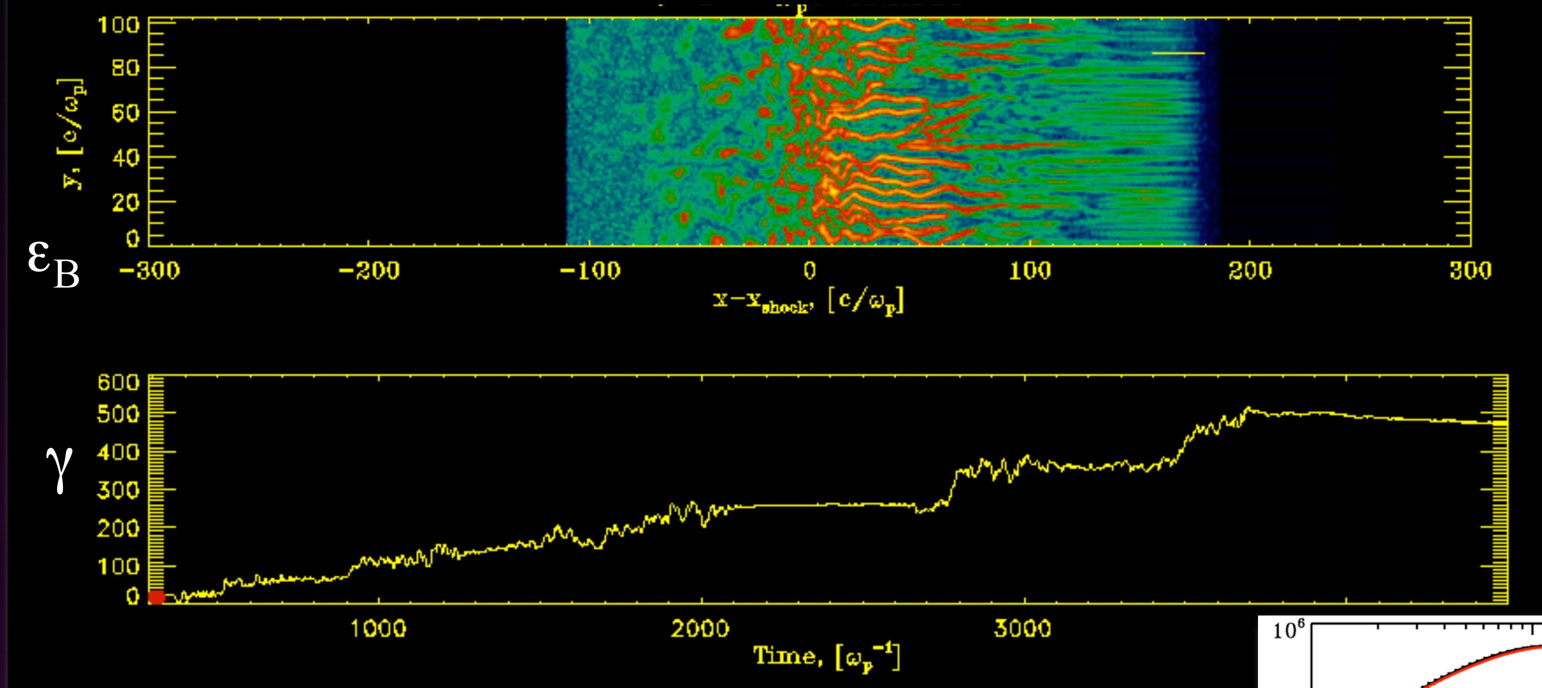
→ Nearly-parallel shocks!

Relativistic electron-positron shocks



For $\sigma<10^{-3}$, shock structure and acceleration properties as in $\sigma=0$ shocks

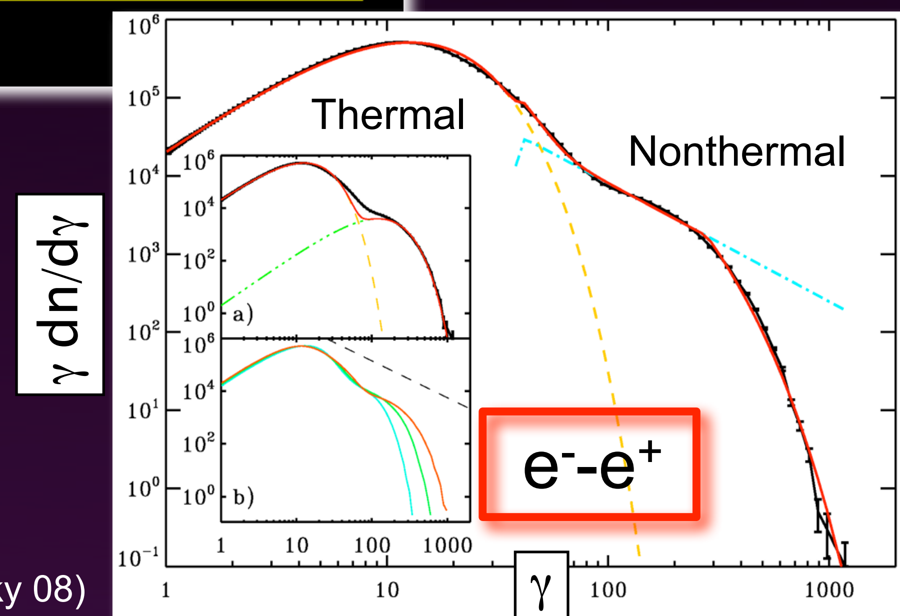
$\sigma=0$ $\gamma_0=15$ e^--e^+ shock



Particle acceleration via the Fermi first-order process in self-generated Weibel turbulence

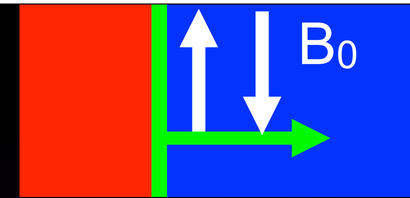
If $\sigma<10^{-3}$, shocks are efficient accelerators

The nonthermal tail has slope $p=2.4\pm0.1$ and contains ~1% of particles and ~10% of energy.



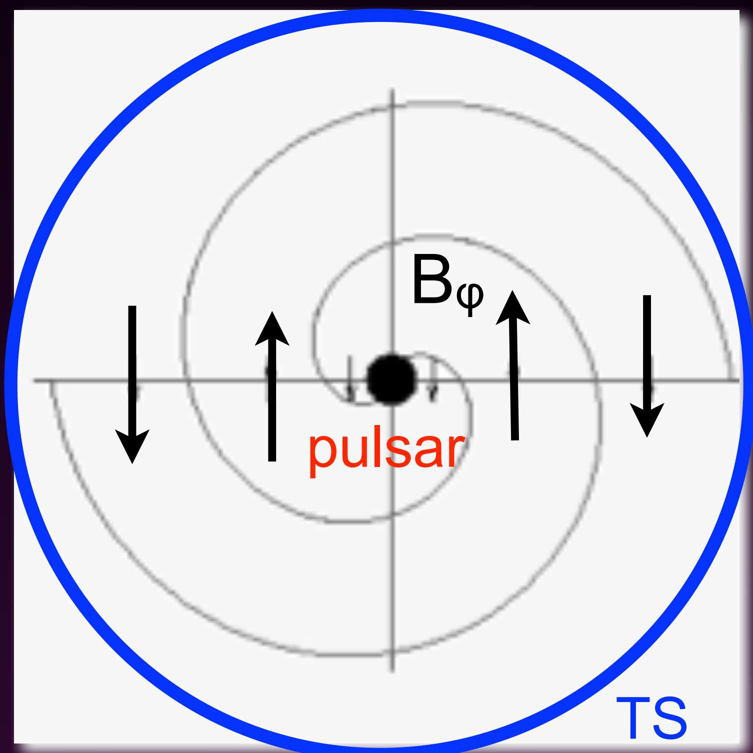
(Spitkovsky 08)

The striped pulsar wind

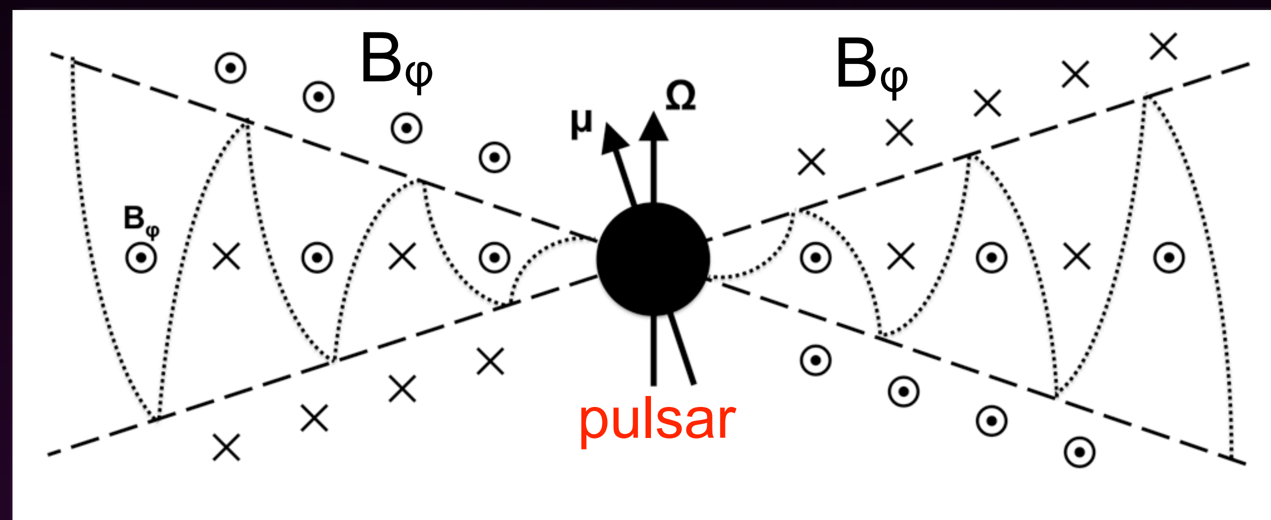


For oblique rotators, the pulsar wind has an equatorial wedge with toroidal stripes of opposite magnetic field polarity, separated by current sheets of hot plasma

Toroidal Structure



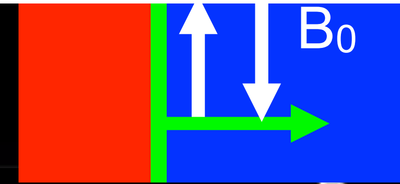
Poloidal Structure



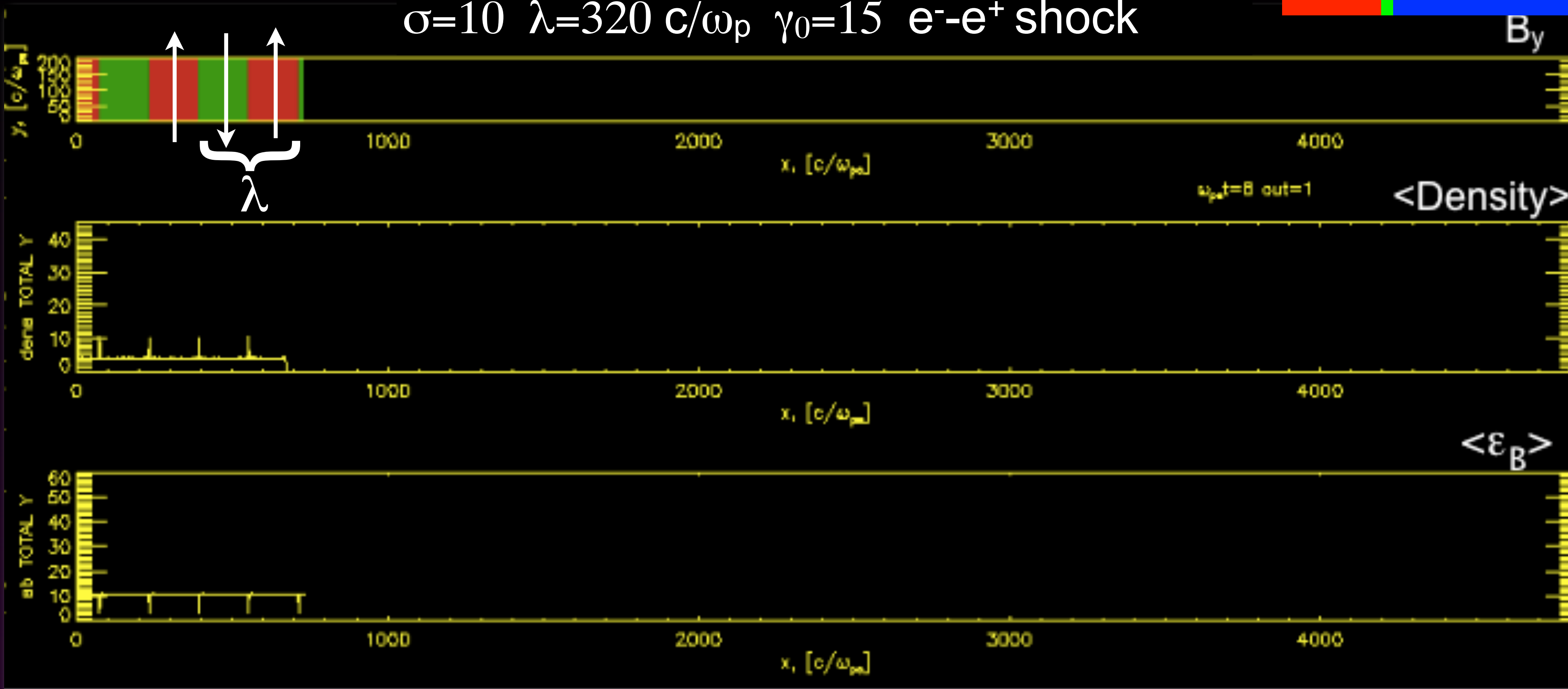
What is the structure of the termination shock if the pre-shock flow is striped?

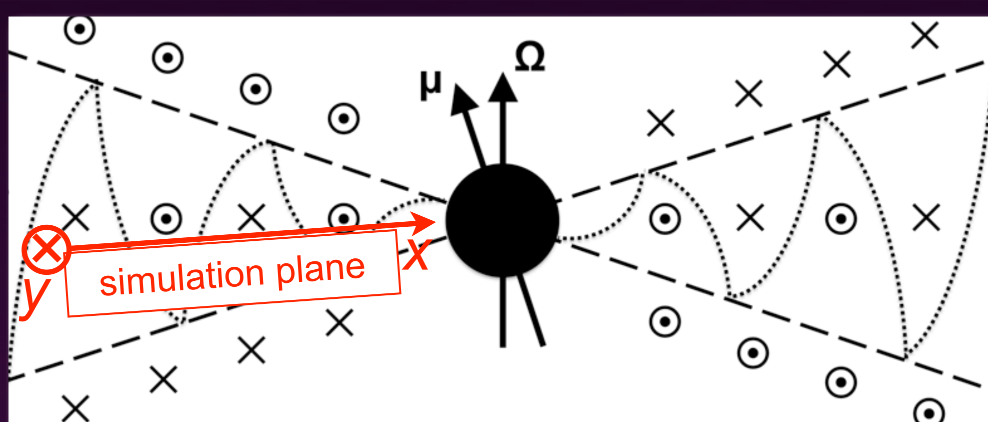
Shock-driven reconnection may produce energetic particles (Lyubarsky 2003)

Shock structure in striped winds

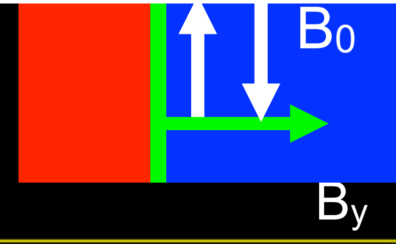


$\sigma=10$ $\lambda=320\ c/\omega_p$ $\gamma_0=15$ e^--e^+ shock

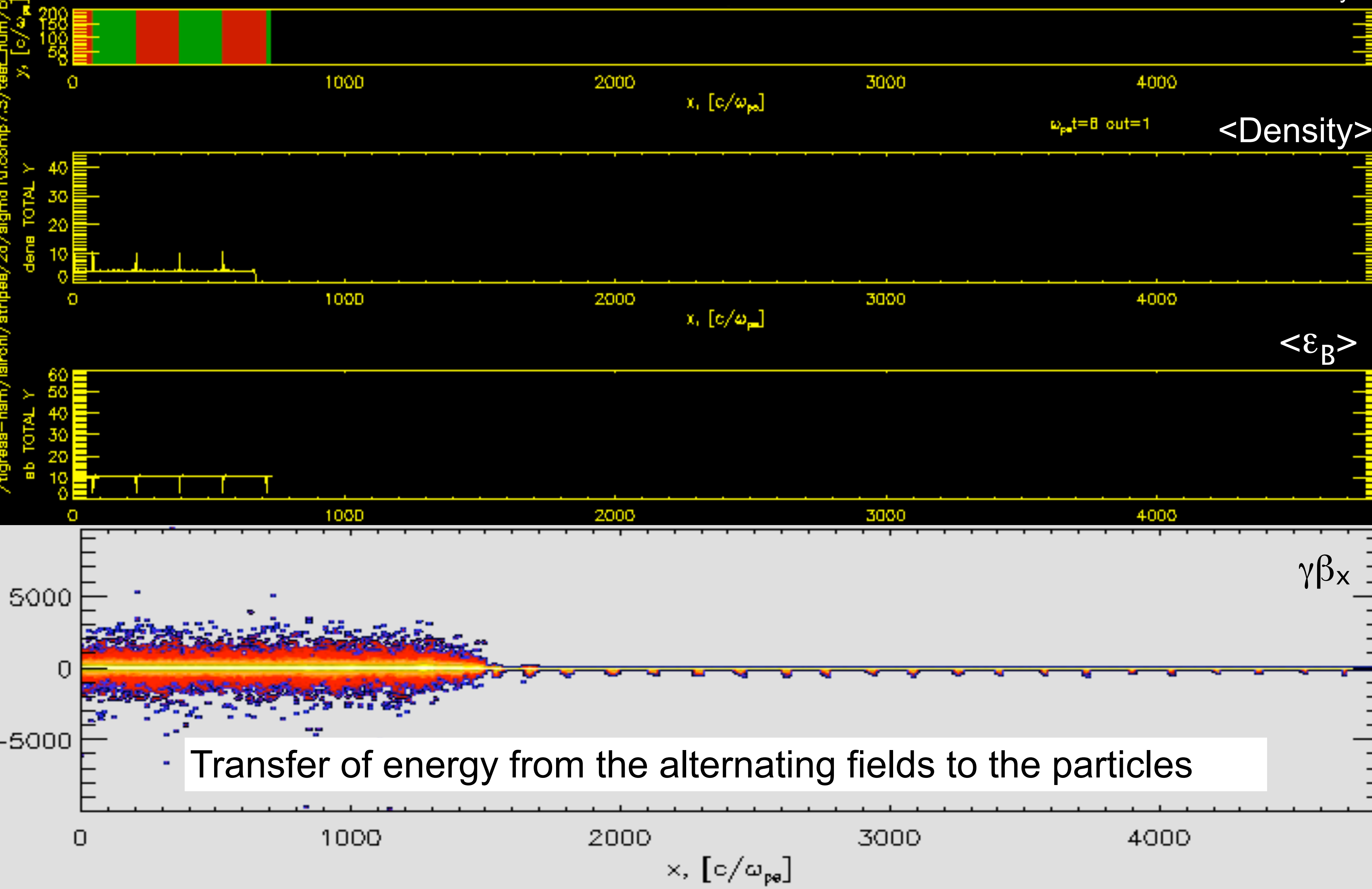




Shock structure in striped winds

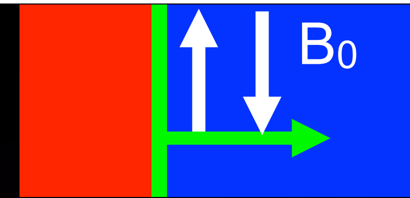


σ=10 λ=320 c/ω_p γ_0=15 e^--e^+ shock

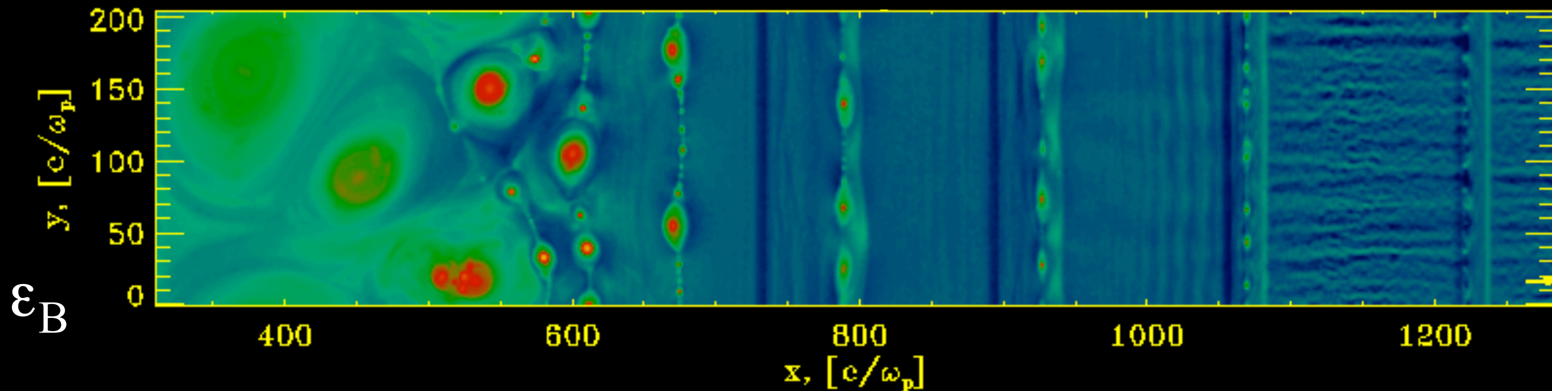


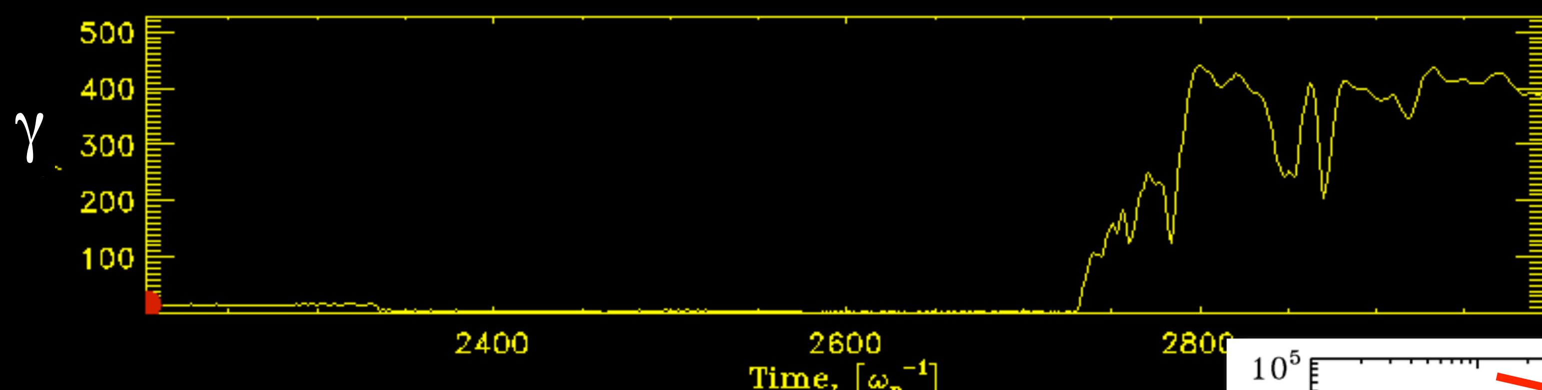
Transfer of energy from the alternating fields to the particles

Striped shocks do accelerate!



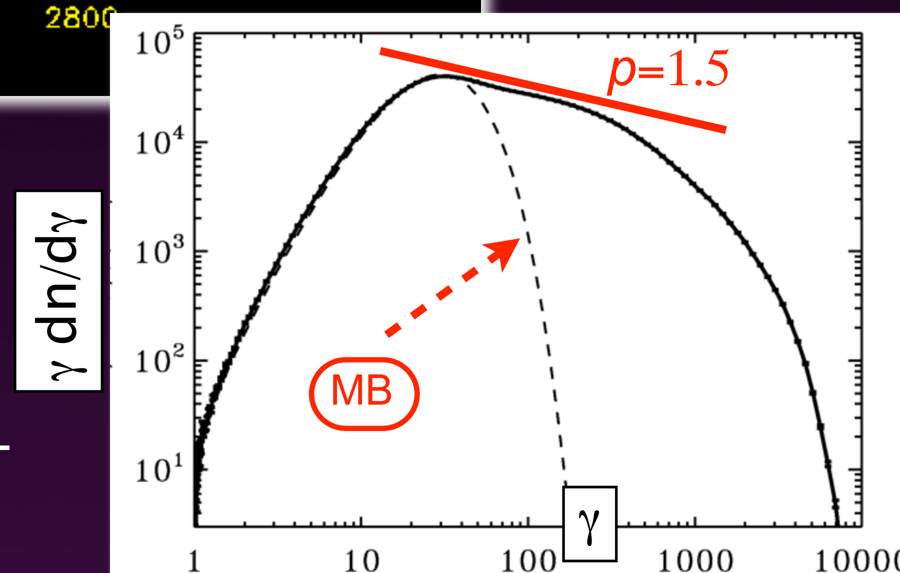
σ=10 λ=320 c/ω_p γ_0=15 e^--e^+ shock





Direct acceleration (non-Fermi process) by the reconnection electric field at X-points

- As a result of complete dissipation of the alternating fields, the average particle Lorentz factor increases from γ_0 up to $\gamma_0\,\sigma$.
- For long stripe wavelengths λ and/or low magnetizations σ, the spectrum is a broad power-law tail with flat slope p~1.5.



Summary

- SNRs and PWNe are the main Galactic sources at TeV energies
- TeV emission is leptonic in PWNe, hadronic or leptonic in SNRs
- TeV + X-ray synchrotron give important clues on the magnetic field and the distribution of emitting particles
- Particle acceleration in astrophysics: direct (magnetic reconnection) vs diffusive (Fermi) acceleration
- Fermi second-order acceleration is not universal and slow
- Fermi first-order acceleration is universal and fast
- Kinetic PIC simulations required to determine from first principles the acceleration efficiency and the acceleration rate