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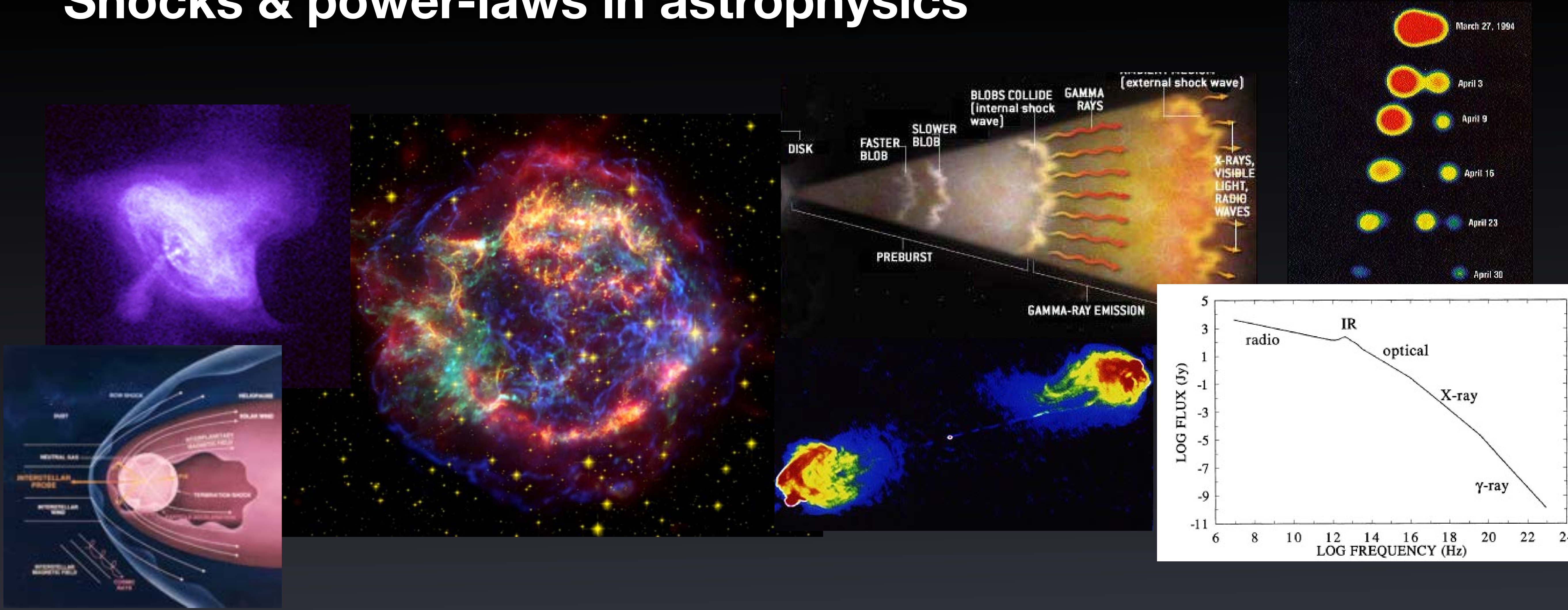
Particle acceleration in shocks: insights from kinetic simulations

Anatoly Spitkovsky, Damiano Caprioli,
Jaehong Park, Ana Pop, Dennis Yi,
Horace Zhang
Princeton University

Shocks & power-laws in astrophysics



Astrophysical shocks are typically collisionless (mfp >> shock scales).

Many astrophysical shocks are inferred to:

1) accelerate particles to power-laws
2) amplify magnetic fields
3) exchange energy between electrons and ions

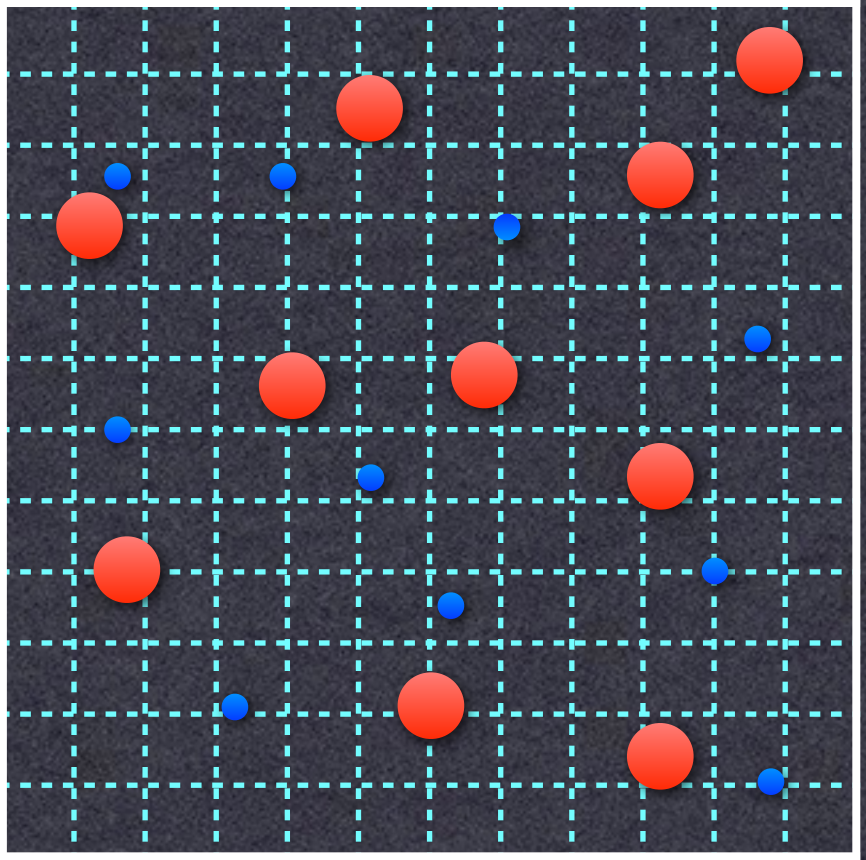
How do they do this? Mechanisms, efficiencies, conditions?…

Collisionless shocks from first principles

- Full particle in cell: TRISTAN-MP code

  (Spitkovsky 2008, Niemiec+2008, Stroman+2009, Amano & Hoshino 2007-2010, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012, Niemiec+2012, Guo+14,...)

  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally expensive!

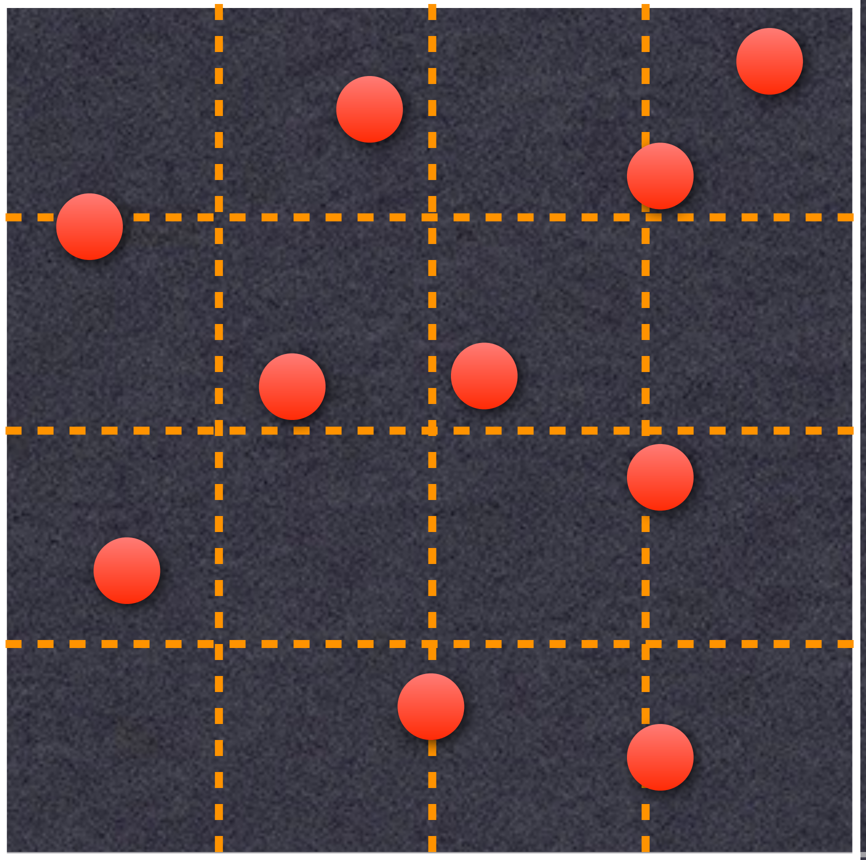


- Hybrid approach: dHybrid code

  Fluid electrons - Kinetic protons

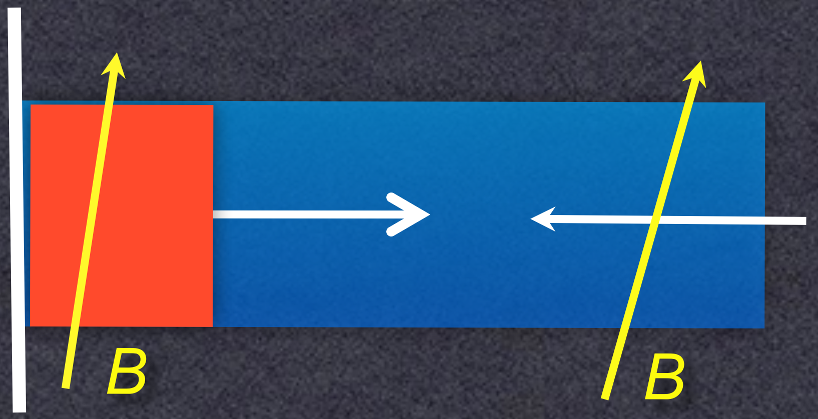
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013, 2014)

  - massless electrons for more macroscopic time/length scales



Survey of Collisionless Shocks

We simulated relativistic and nonrelativistic shocks for a range of upstream B fields and flow compositions, ignoring pre-existing turbulence.



Main findings:

Dependence of shock mechanism on upstream magnetization

Ab-initio particle acceleration in relativistic shocks

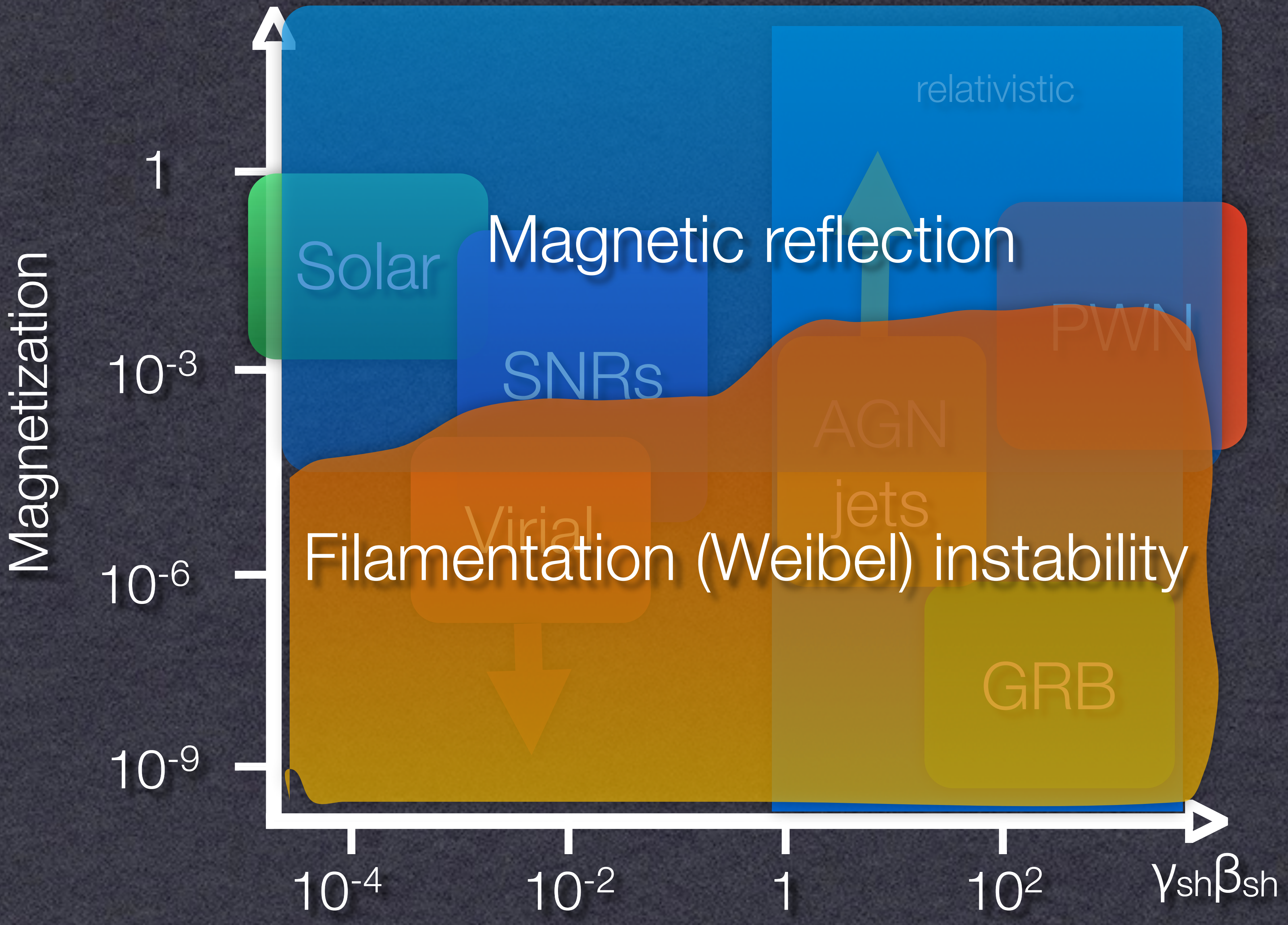
Shock structure and acceleration in non-relativistic shocks

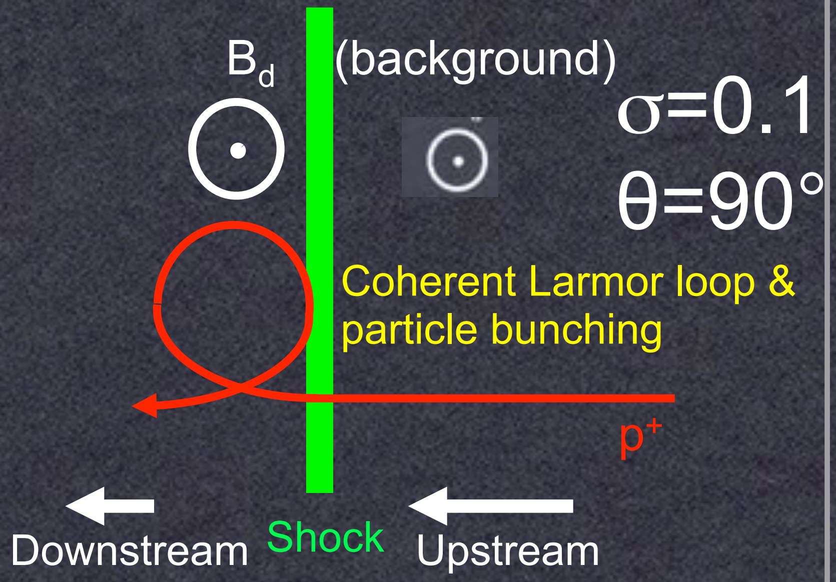
- Ion acceleration vs Mach # in quasipar shocks; DSA; D coeff.
- Evidence for simultaneous e-ion acceleration in parall. shks
- Electron acceleration in quasiperpendicular shocks

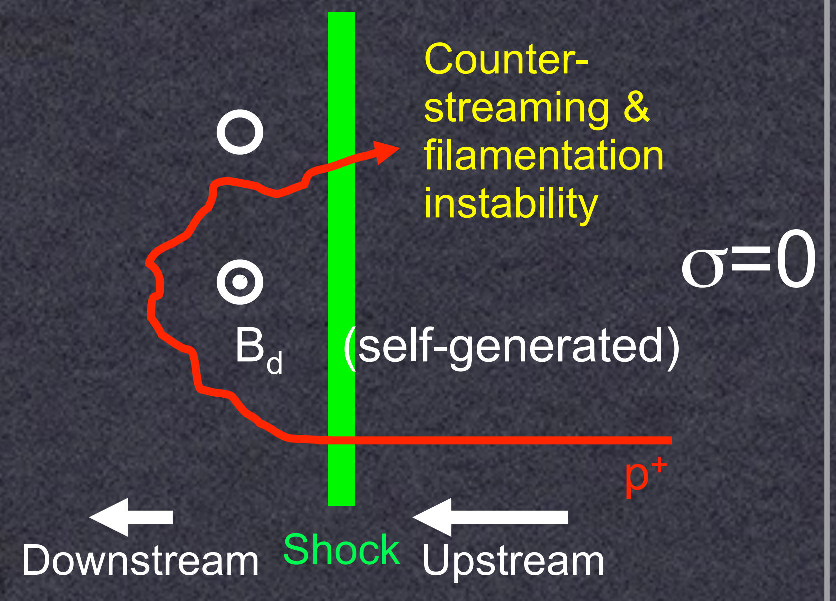
FIeld amplification and CR-induced instabilities

Parameter Space of shocks

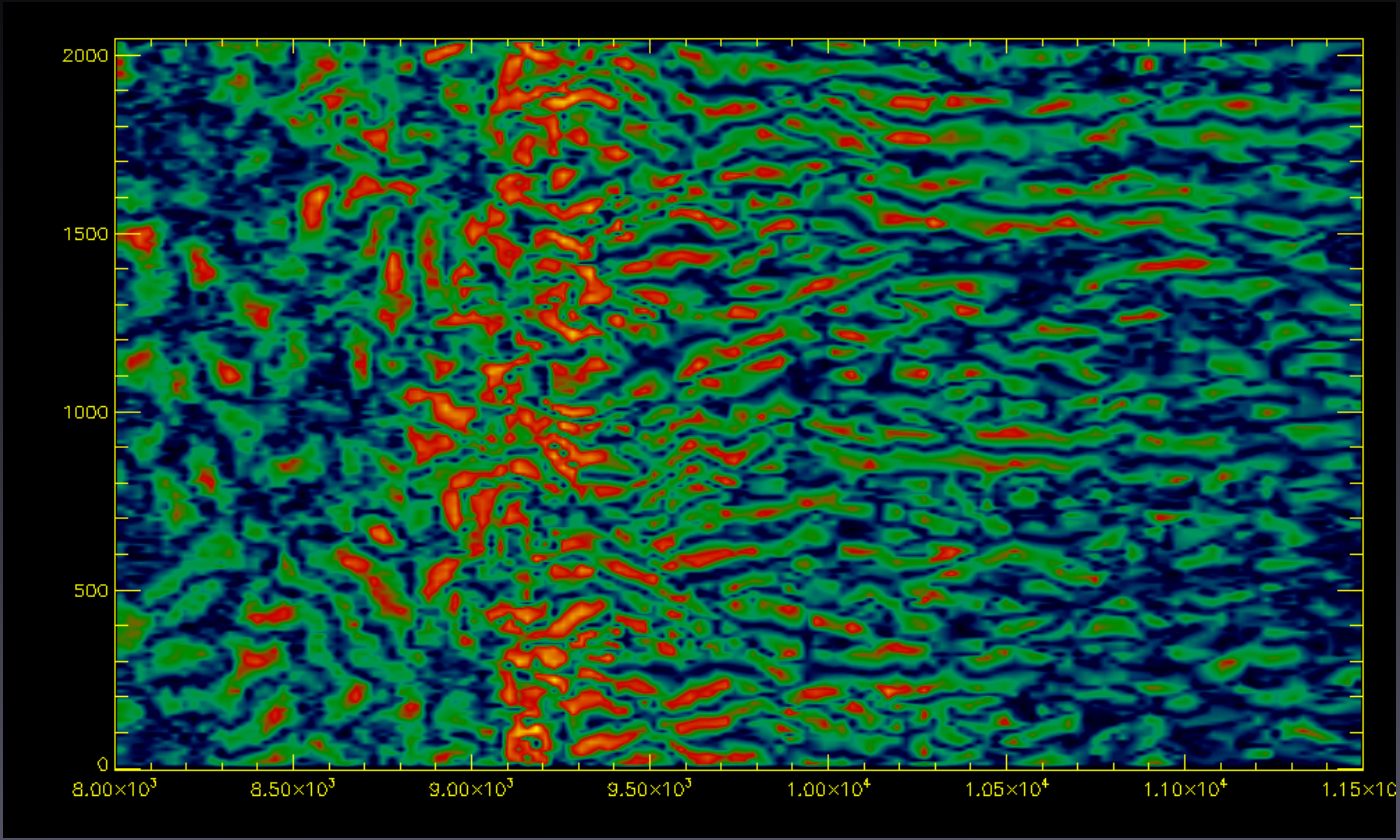
$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$





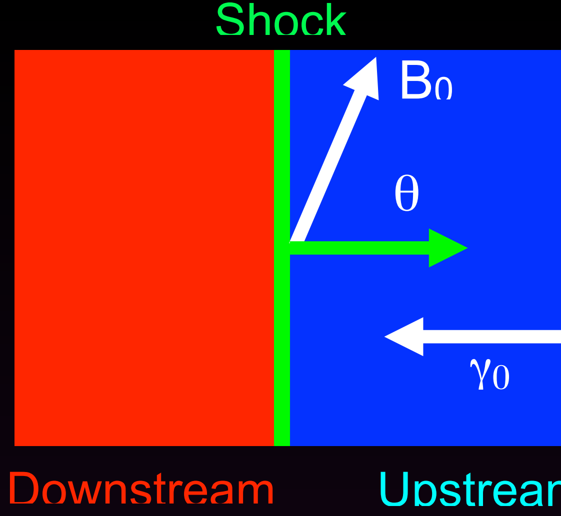


Unmagnetized pair shock: particle trajectories



color: magnetic energy density

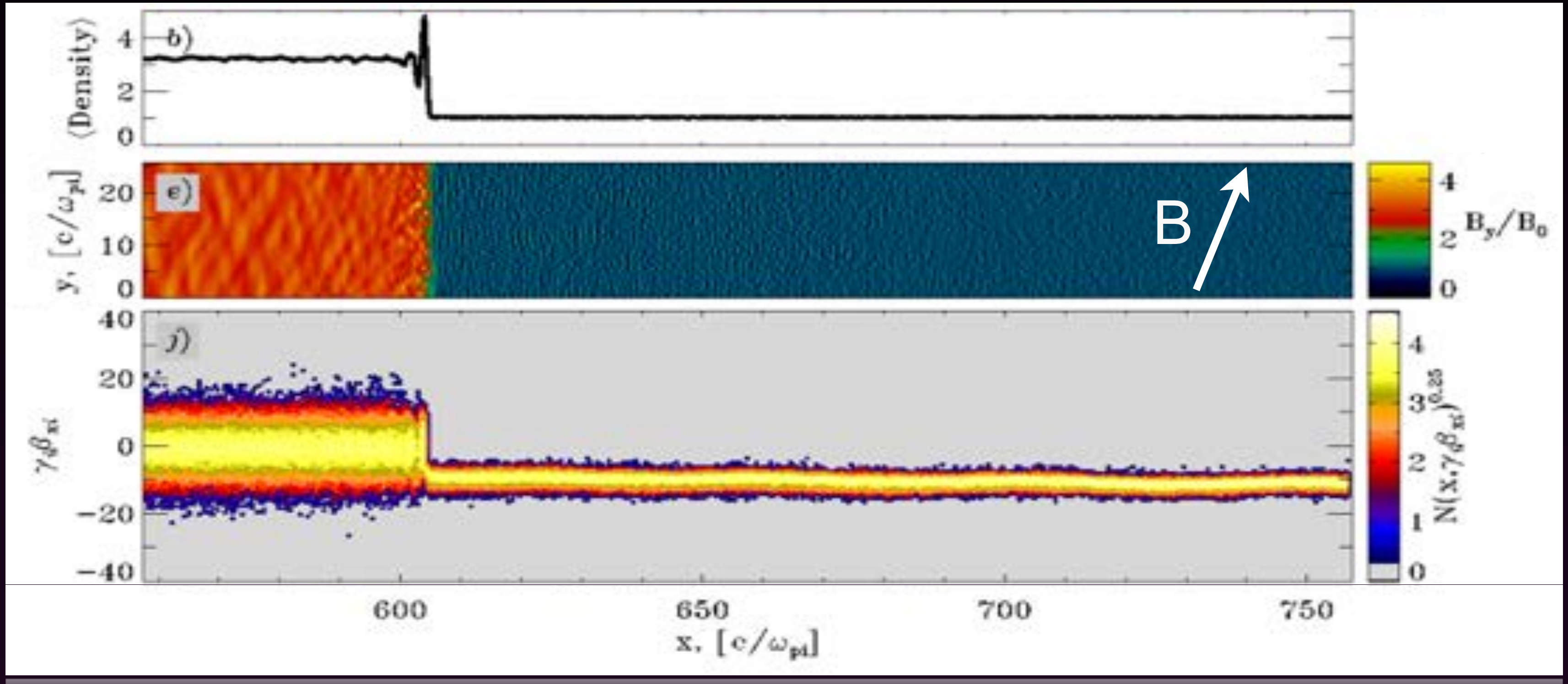
Perpendicular vs parallel shocks



- Quasi-perpendicular shocks: mediated by magnetic reflection

<Density>

$\sigma=0.1$
$\theta=75°$
$\gamma_0=15$
e^--p^+



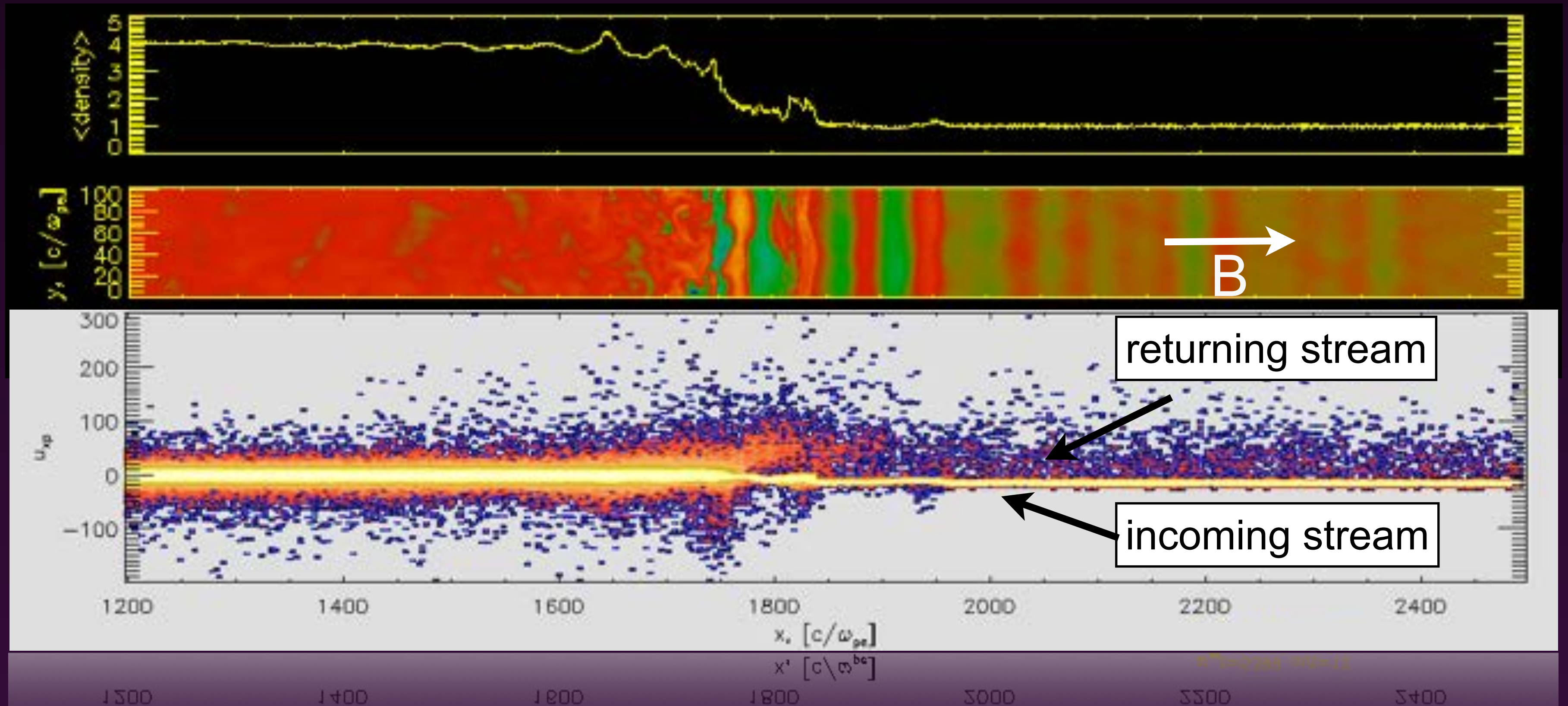
B_y

$\gamma\beta_x$

(Sironi and AS 11)

- Quasi-parallel shocks: instabilities amplify transverse field component

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



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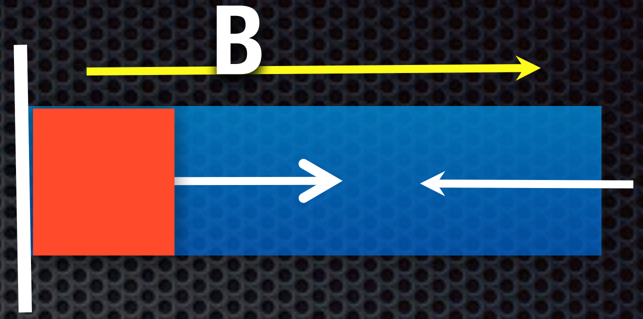
B_y

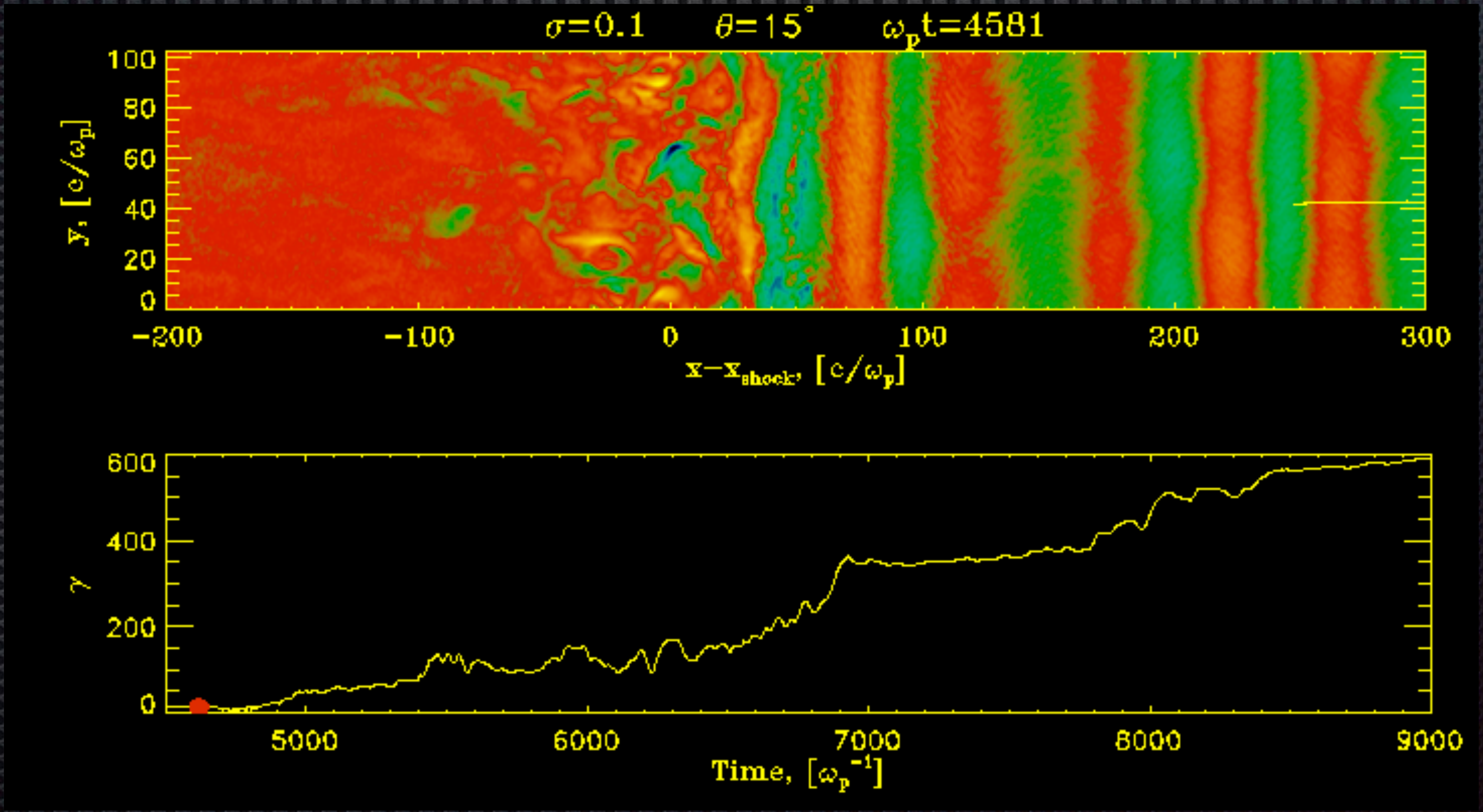
$\gamma\beta_x$

(Sironi & AS 11)

Particle acceleration



Magnetized shock (parallel, e-p): scattering on self-generated upstream waves

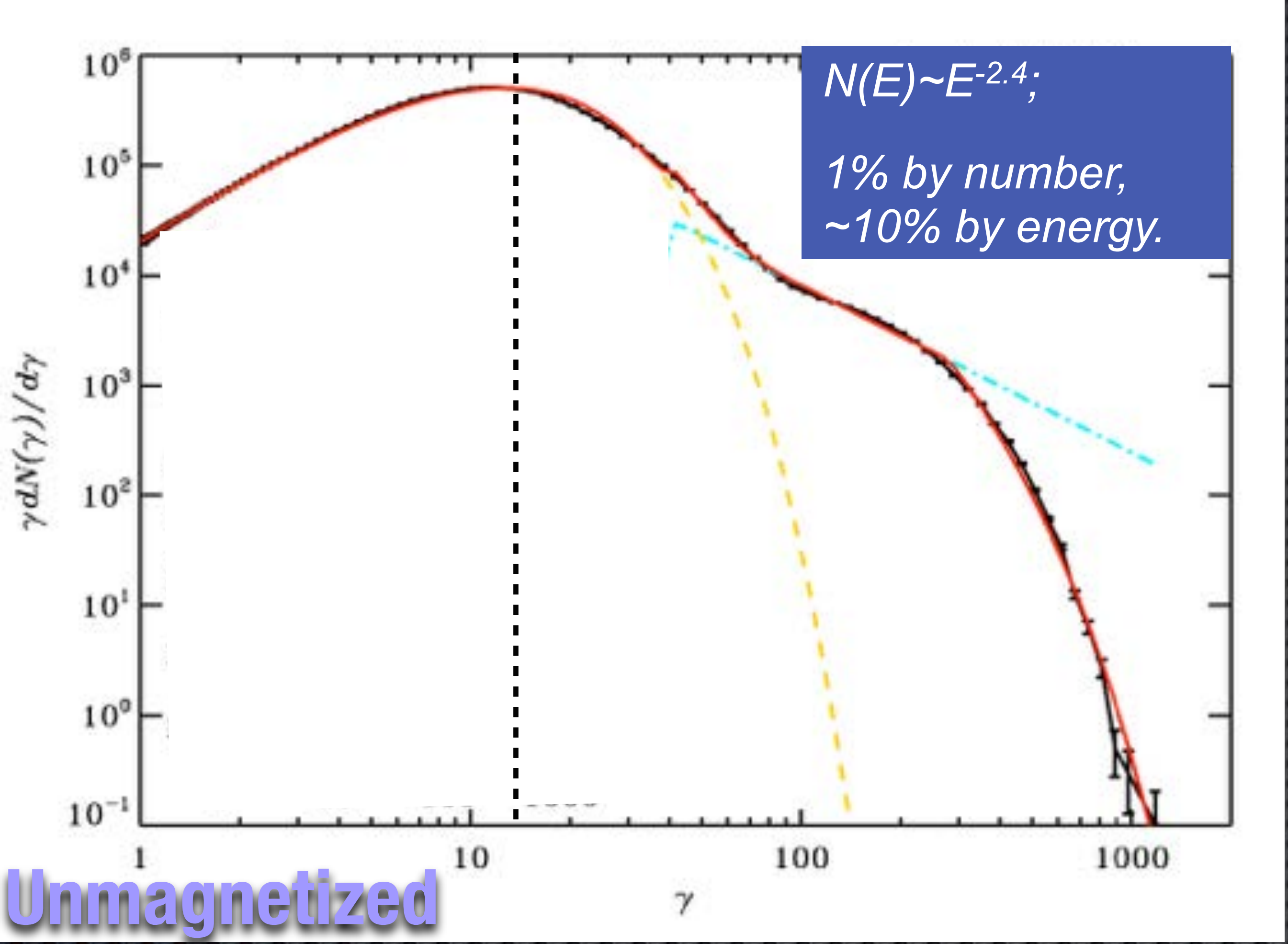


Transverse Magnetic Field

Particle energy

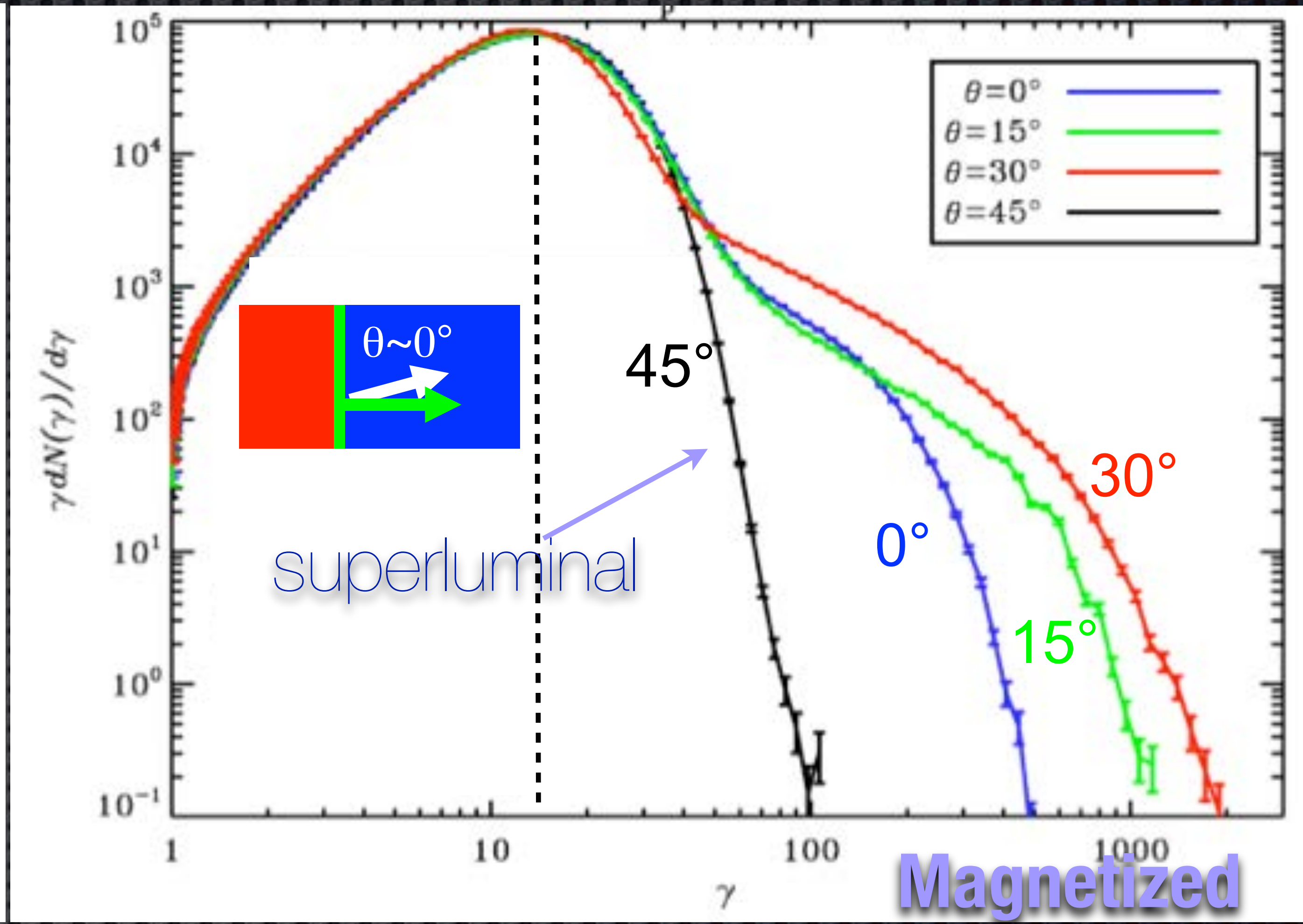
Particle acceleration

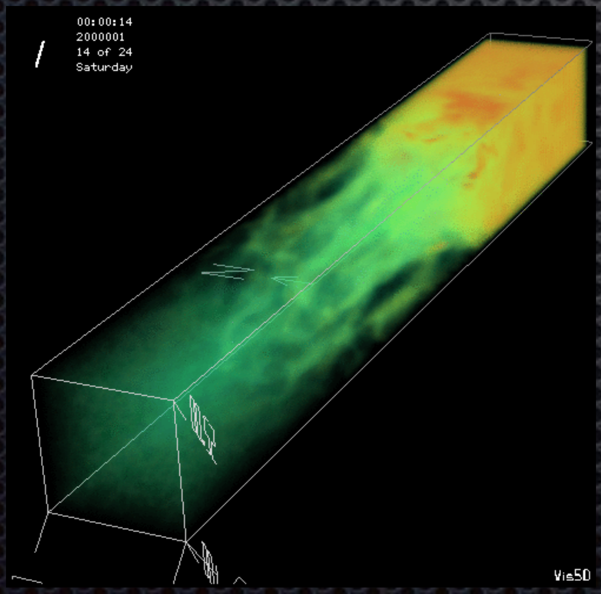
Sironi & AS 09



$N(E) \sim E^{-2.4}$;

1% by number,
~10% by energy.



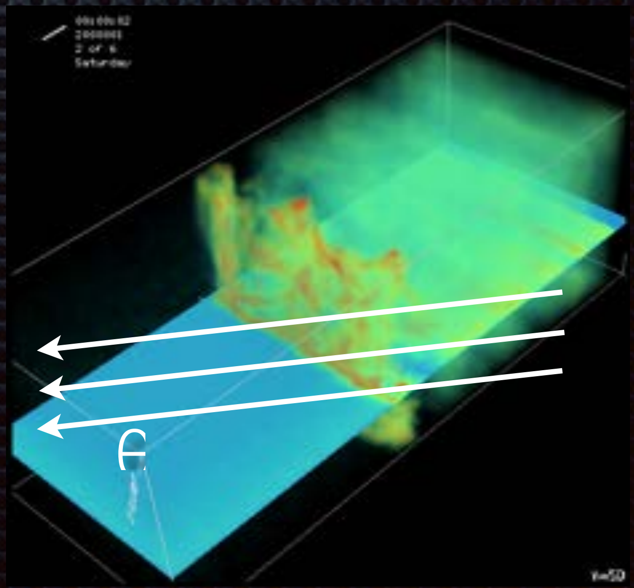


Conditions for acceleration in relativistic shocks:

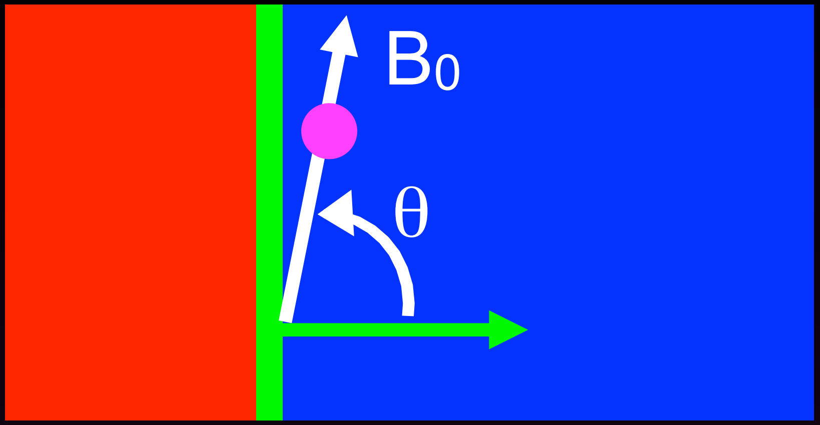
low magnetization of the flow

or quasi-parallel B field (θ<34°/Γ);

electrons & ions behave similarly



Superluminal vs subluminal shocks



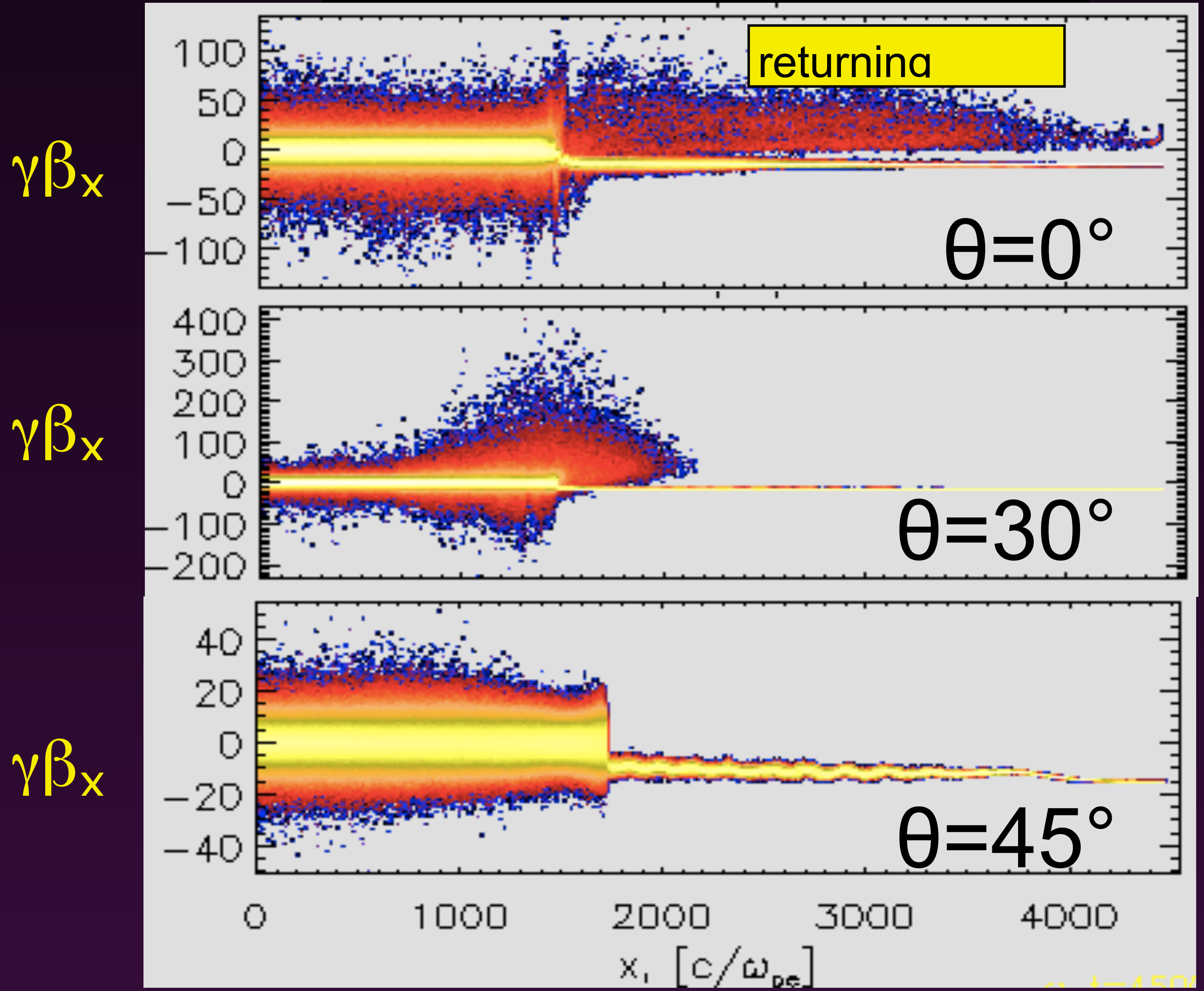
σ is large → particles slide along field lines

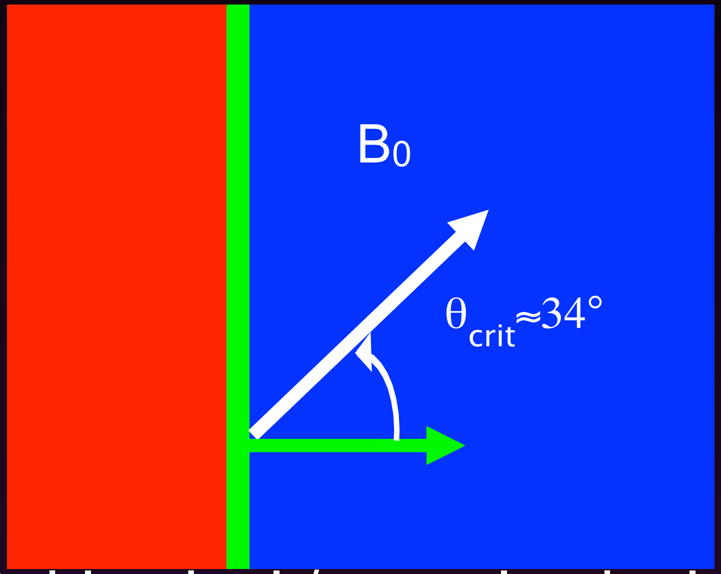
θ is large → particles cannot outrun the shock

unless v>c ("superluminal" shock)

⇒ no returning particles in superluminal shocks

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





Subluminal / superluminal boundary at $\theta\sim 34°$

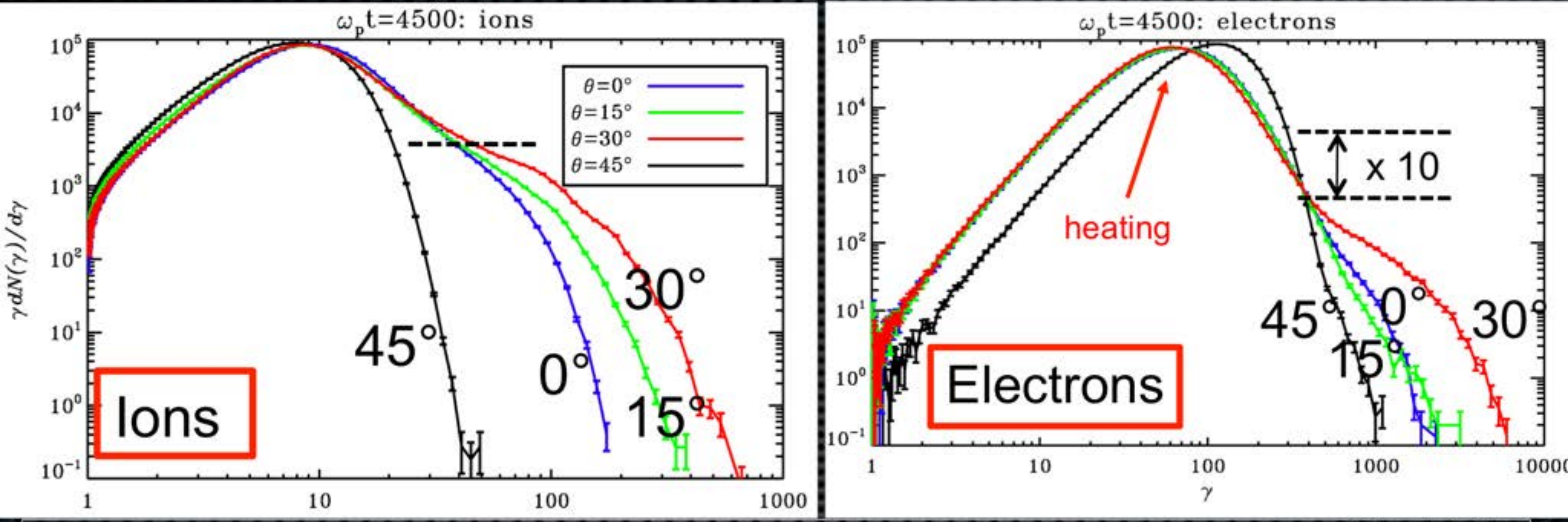
→ Fermi acceleration should be suppressed

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

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

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

Particle acceleration: e-ions



Sironi & AS 11

Relativistic magnetized e-ion shocks:

protons are accelerated for quasi-parallel configurations, up-to 30% of energy in the tail; 5% by number;

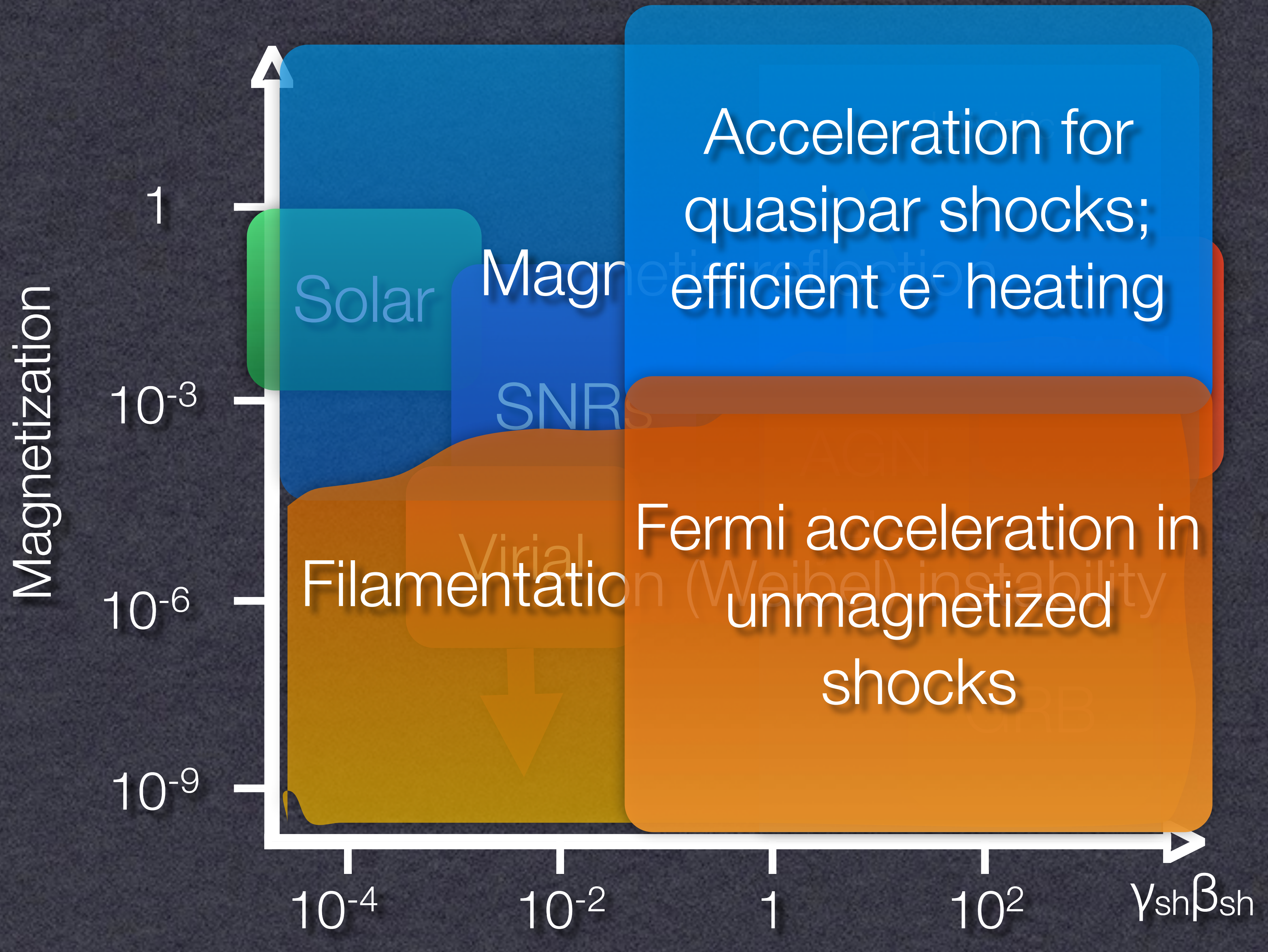
electron acceleration is 5-10 times less efficient;

electrons are strongly heated by ions; hot electrons accelerate well

Relativistic electron-ion shocks behave like pair shocks

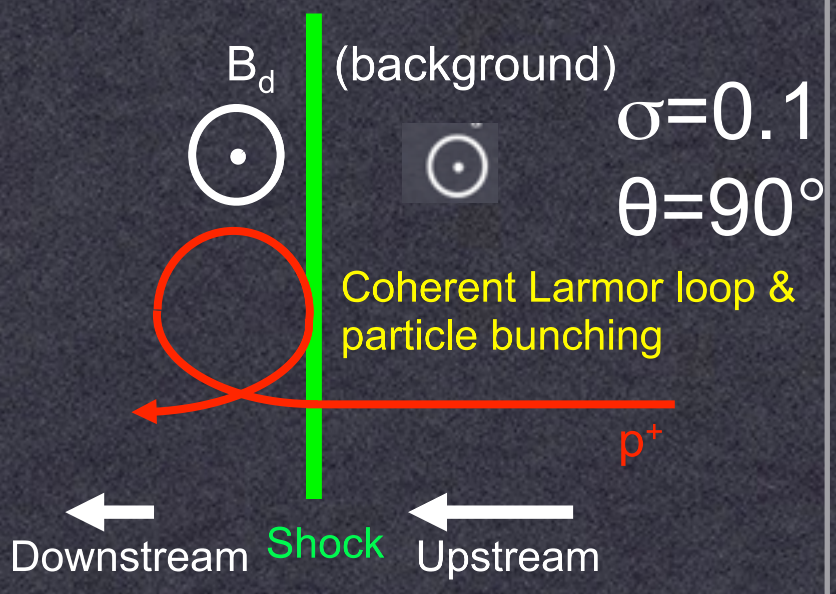
Parameter Space of shocks

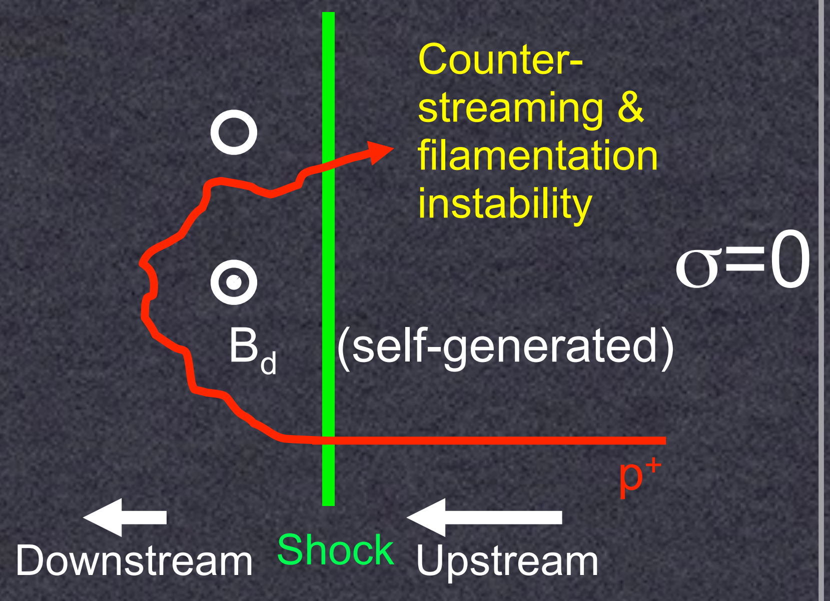
$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2\left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$



Acceleration for quasipar shocks; efficient e^- heating

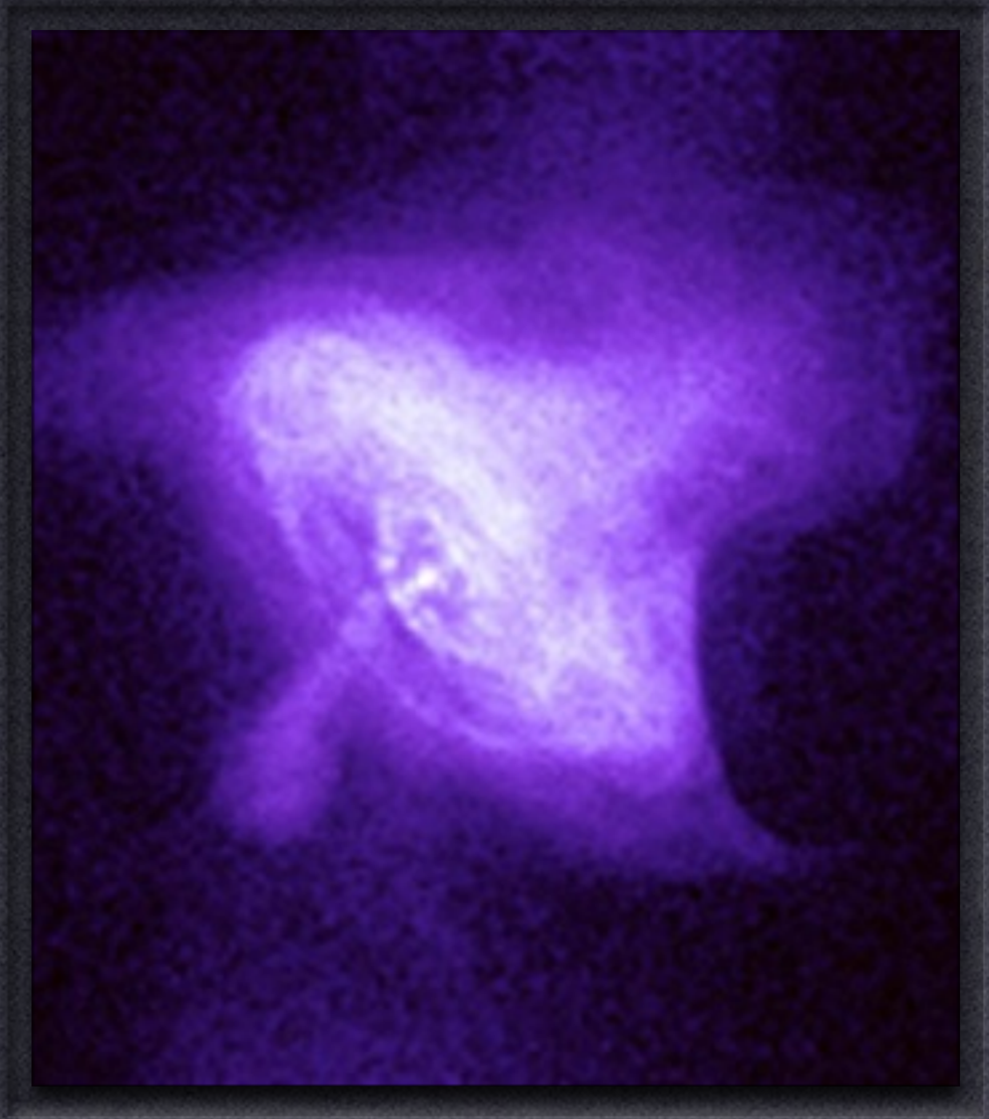
Fermi acceleration in unmagnetized shocks





Astrophysical implications

- Pulsar Wind Nebulae
  - Toroidal magnetic geometry will accelerate particles if field is weak at the shock
  - Implies efficient magnetic dissipation in the wind
  - Low equatorial magnetization -- consistent with PWN morphology
  - Alternative: magnetic dissipation at the shock (reconnection/striped winds)



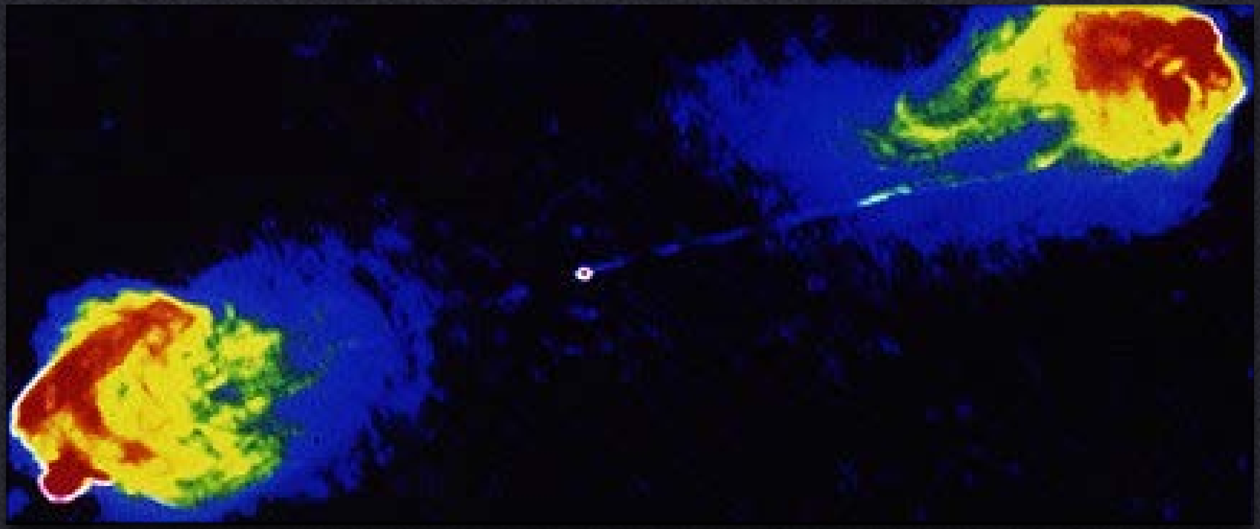
Astrophysical implications

- AGN Jets

  High magnetization toroidal field configuration is disfavored

  Either magnetic field is dissipated in the process of acceleration,

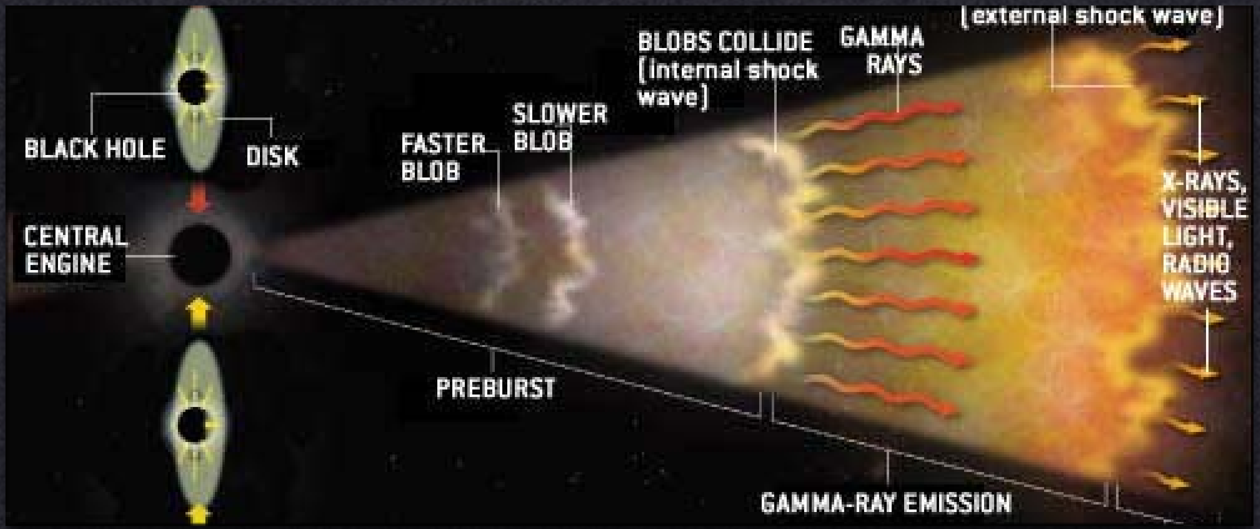
  or field is reoriented to lie along the flow (sheath vs spine flows?)

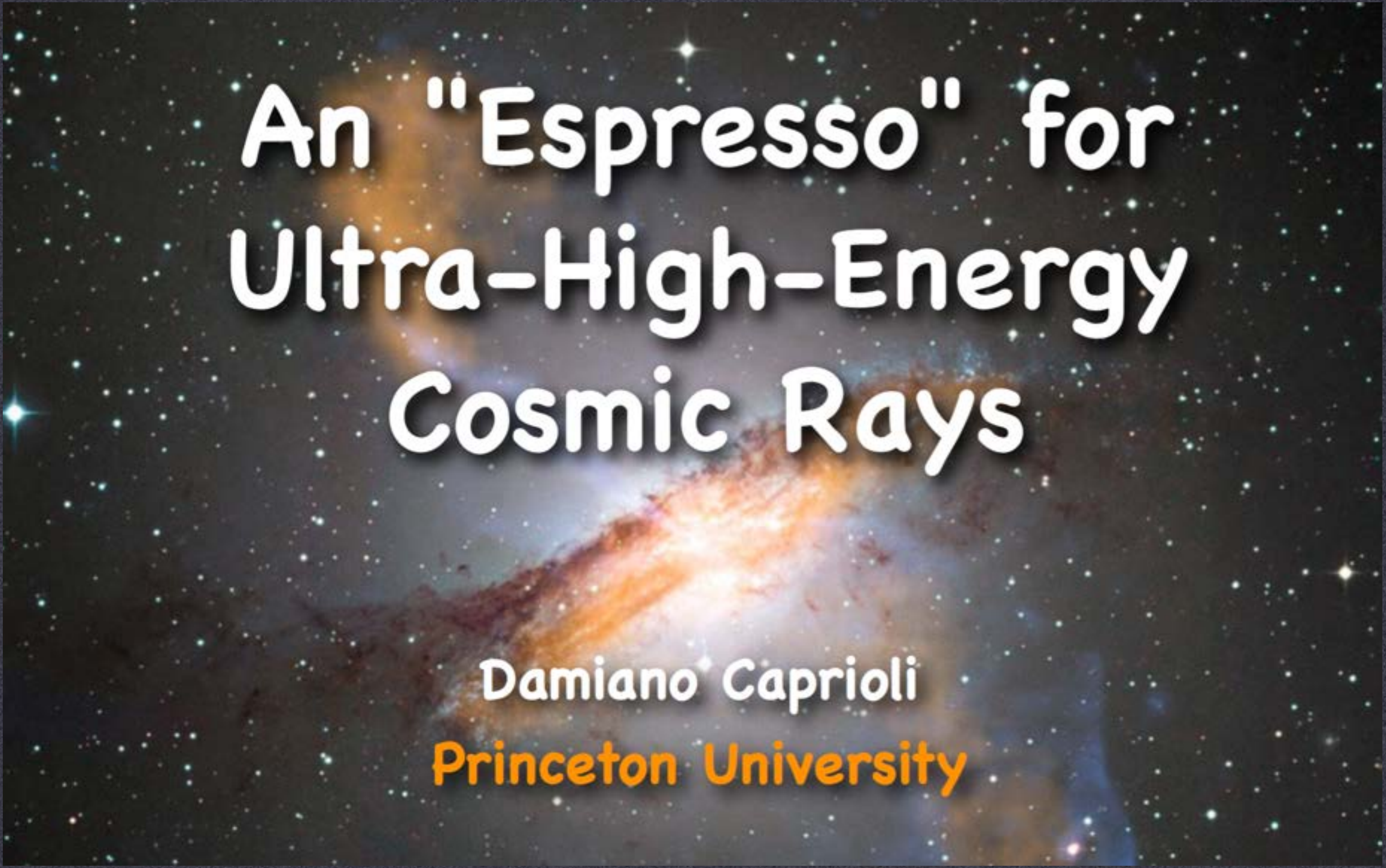


- GRB jets

  Low magnetization external shocks can work; Field survival? GeV emission too early?

  Efficient electron heating explains high energy fraction in electrons





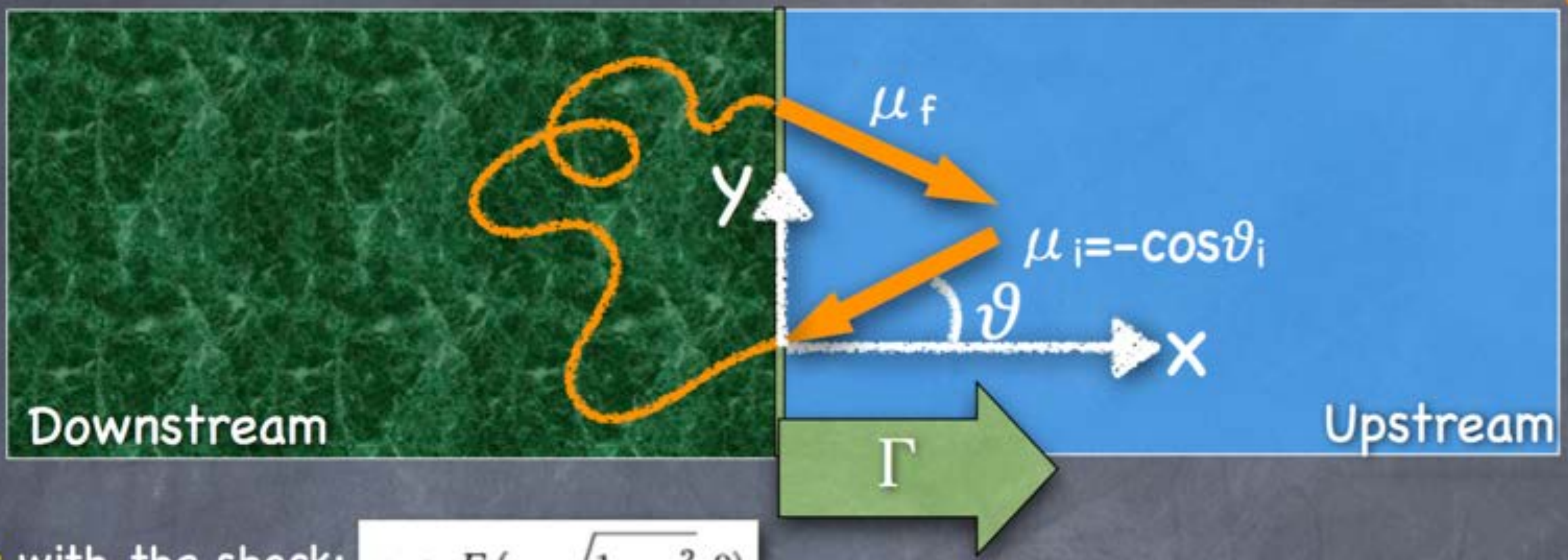
An "Espresso" for Ultra-High-Energy Cosmic Rays

Damiano Caprioli

Princeton University

Caprioli 2015, ApJ, 811, L38

Acceleration at relativistic shocks



Encounter with the shock: $\mathbf{p}_i \simeq E_i(\mu_i, \sqrt{1-\mu_i^2}, 0),$

in the downstream frame:

$$E'_i = \Gamma(E_i - \beta p_{i,x}) = \Gamma E_i(1 - \beta\mu_i),$$

Elastic scattering (gyration):

$$p'_{f,x} \equiv \mu'_f E'_f$$

$$\mu_f = \frac{\mu'_f + \beta}{1 + \beta\mu'_f},$$

Back in the upstream:

$$E_f = \Gamma(E'_f + \beta p'_{f,x}) = \Gamma^2 E_i(1 - \beta\mu_i)(1 + \beta\mu'_f),$$

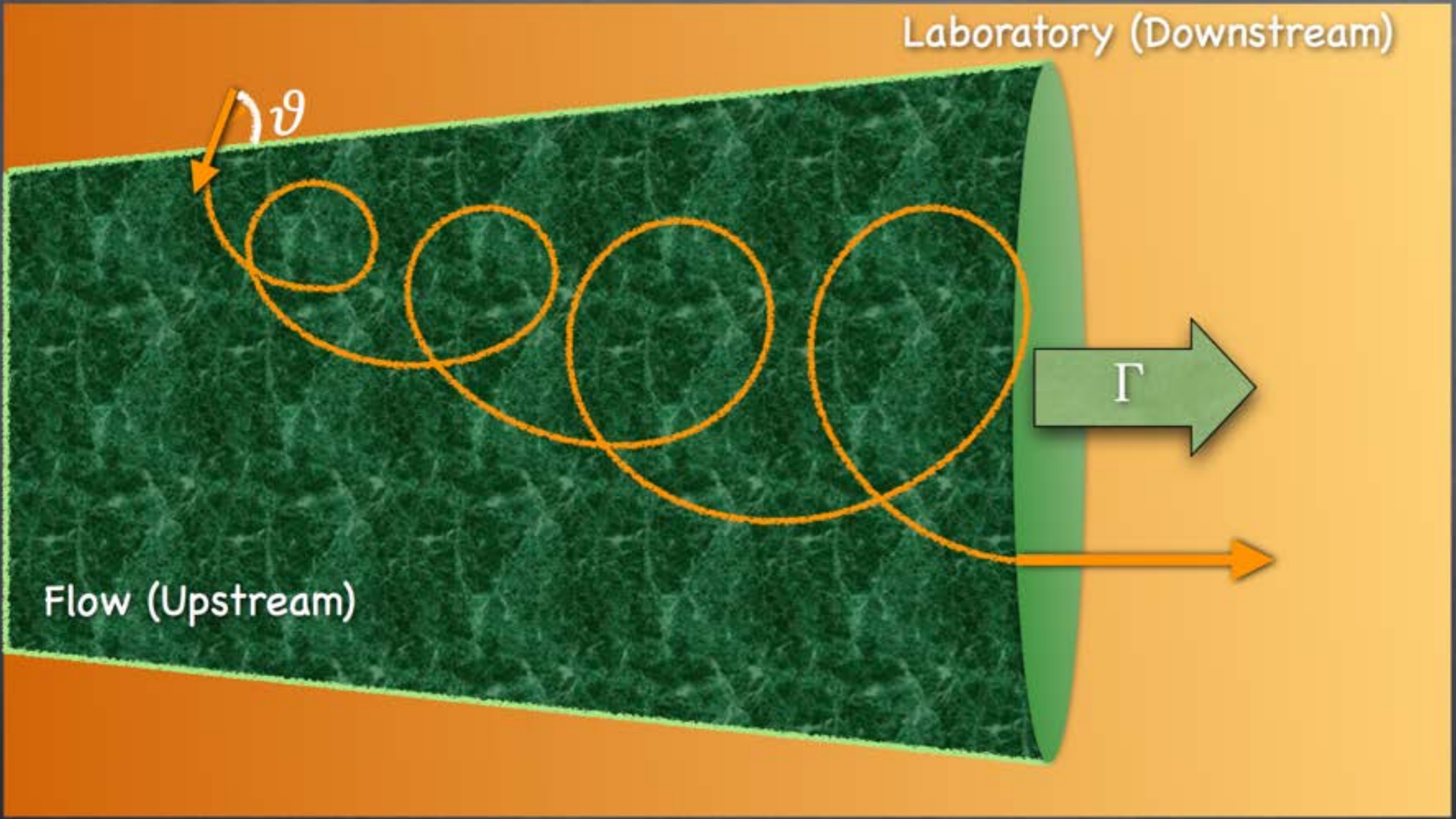
- Energy gain depends on $\mu_f - \mu_i$

First cycle: $E_f \sim \Gamma^2 E_i$

- Following cycles: $E_f \sim 2 E_i$
- CAVEAT: return not guaranteed!

Acceleration in relativistic FLOWS

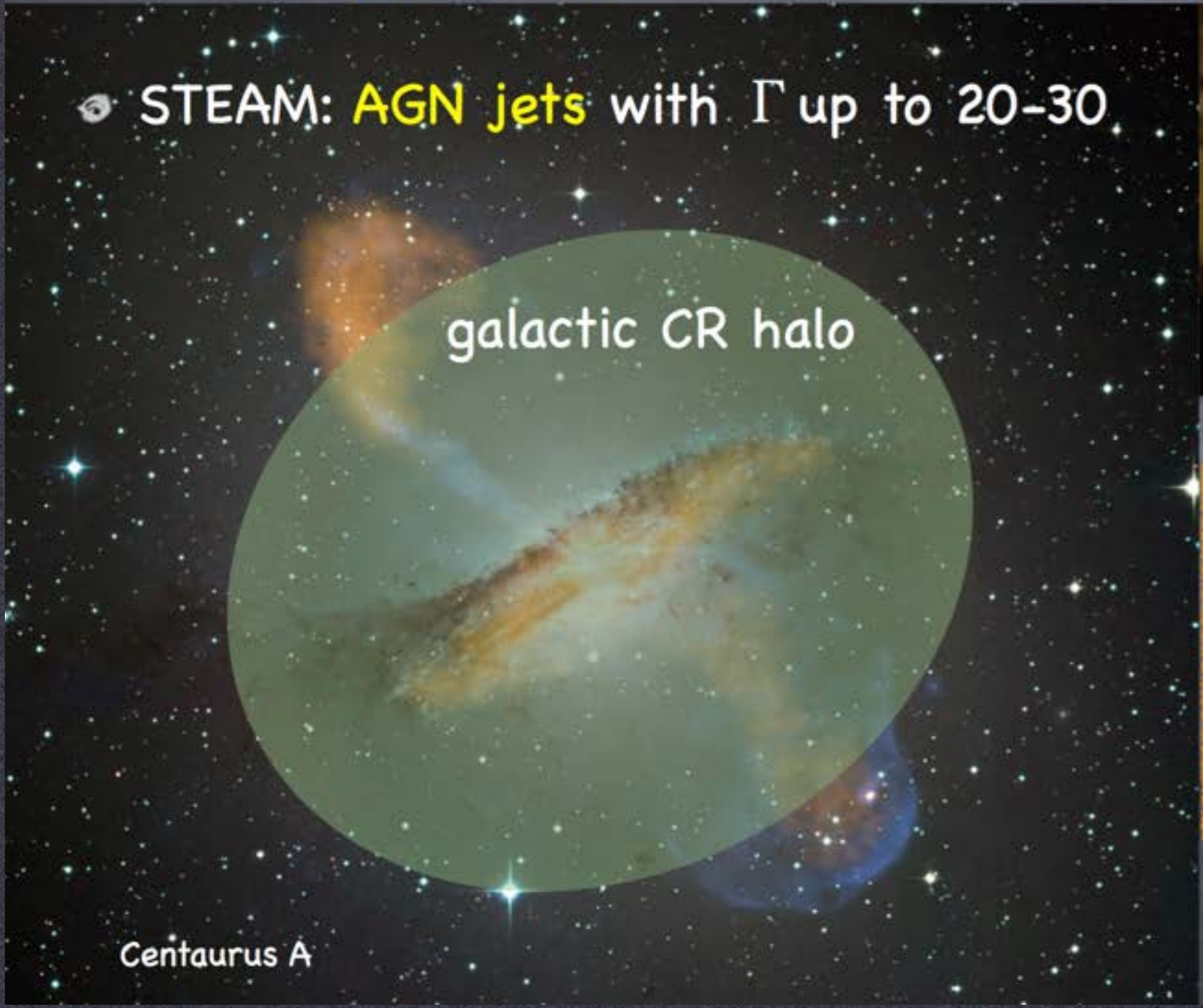
- **Requirement**: interface thickness << gyroradius << typical flow size



- Most trajectories lead to a $\sim\Gamma^2$ energy gain!

An “espresso” for UHECRs

- SEEDS: galactic CRs with energies up to $\sim 3Z\times10^{6}$GeV
- STEAM: AGN jets with Γ up to 20-30



One-shot reacceleration can produce UHECRs up to $E_{max}\sim 2\,\Gamma^{2}\,3Z\times10^{6}$ GeV

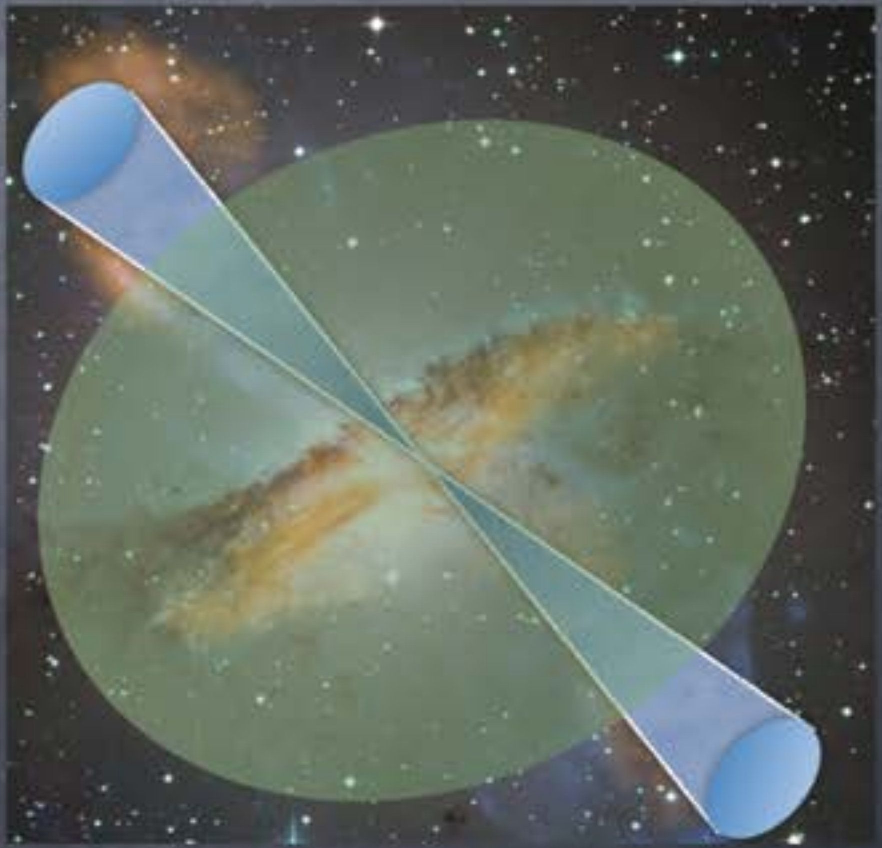
$E_{max}\sim 5Z\times10^{9}$ GeV

UHECRs from AGN jets: constraints

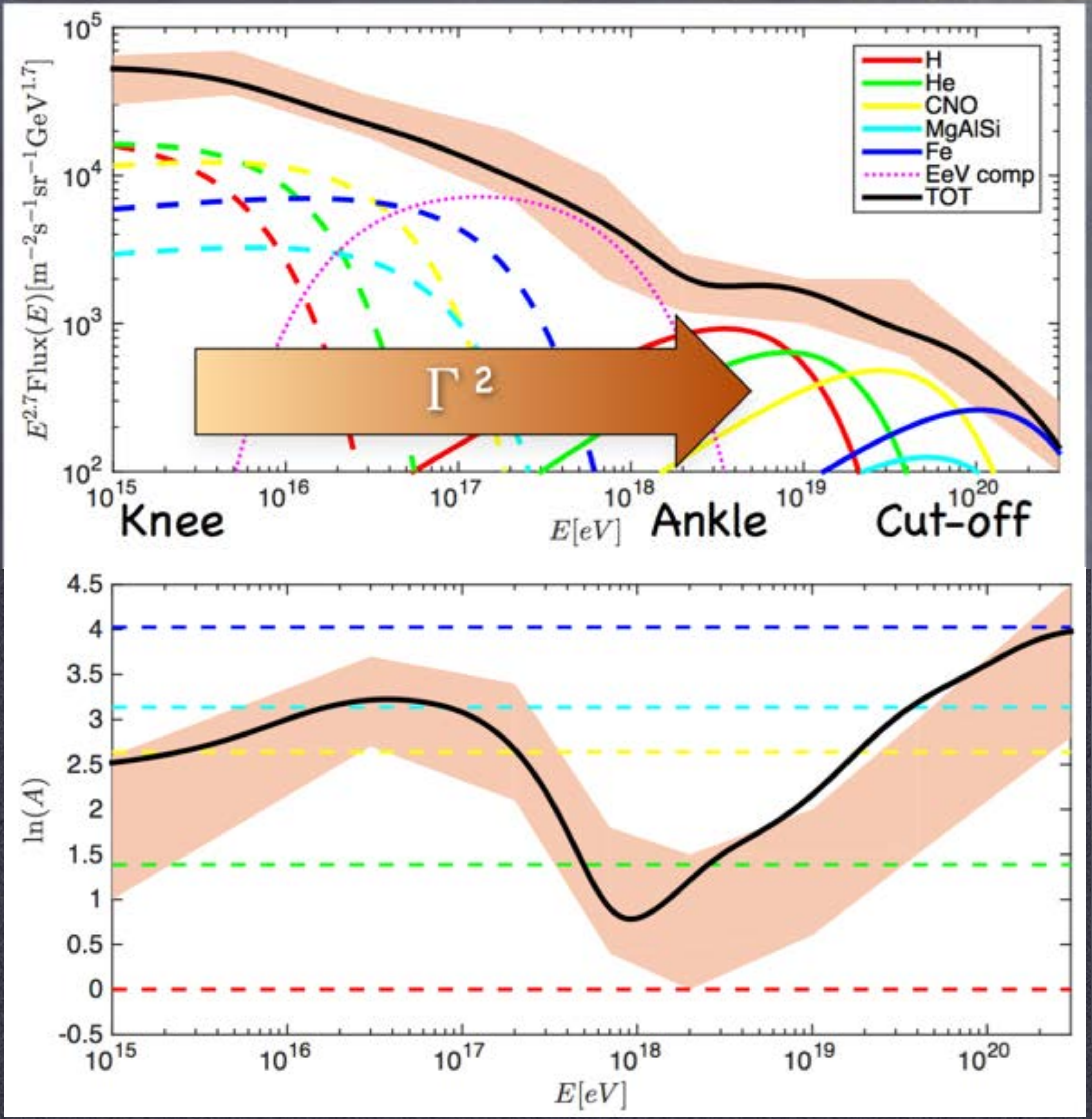
- **Confinement** (Hillas Criterion): $\boxed{B_{\mu\mathrm{G}} D_{\mathrm{kpc}} \gtrsim \frac{4}{Z_{26}} \frac{E_{\max}}{10^{20}\mathrm{eV}}}$ ✓
- **Energetics**: $Q_{\mathrm{UHECR}}(E \gtrsim 10^{18}\mathrm{eV}) \approx 5\mathrm{x}10^{45}\mathrm{erg/Mpc^3/yr}$

  $L_{\mathrm{bol}} \approx 10^{43}$–$10^{45}$erg/s; $N_{\mathrm{AGN}} \approx 10^{-4}/\mathrm{Mpc}^3$

  $Q_{\mathrm{AGN}} \approx$ a few 10^{46}–10^{48}erg/Mpc^3/yr >> Q_{UHECR} ✓
- **Efficiency** depends on:
  - Reacceleration efficiency
  - Jet cross section (angle of a few degrees: $\varepsilon \sim 10^{-1}$–10^{-2})
  - Contributing AGNs
    - Likely radio-loud quasars, blazars, FR-I,...



Galactic CR + UHECR spectrum

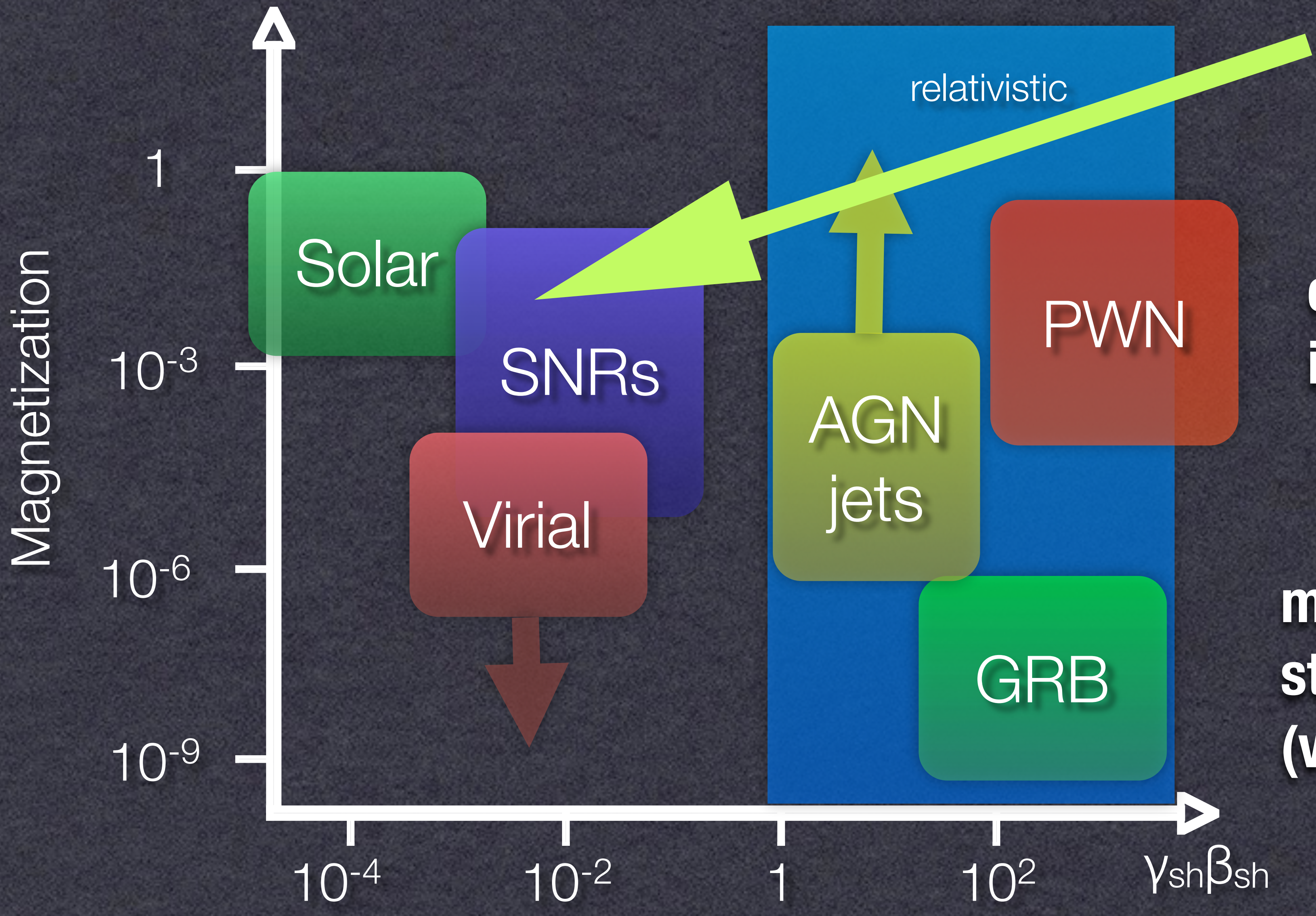


- CR spectral features
- Prediction of UHECR chemical composition!
  - UHECR spectra must be quite flat, ~$E^{-1.5}$

    (Aloisio+13, Gaisser+13, Taylor 14,...)
  - An additional steep/light component must fill the gal-extragal transition
- Different kinds of AGNs?

Parameter Space of shocks

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



nonrelativistic shocks

e and ions are different in non-relativistic case

most of our PIC runs are still mildly relativistic (v/c~0.03-0.1c)

Shock acceleration

Two crucial ingredients:

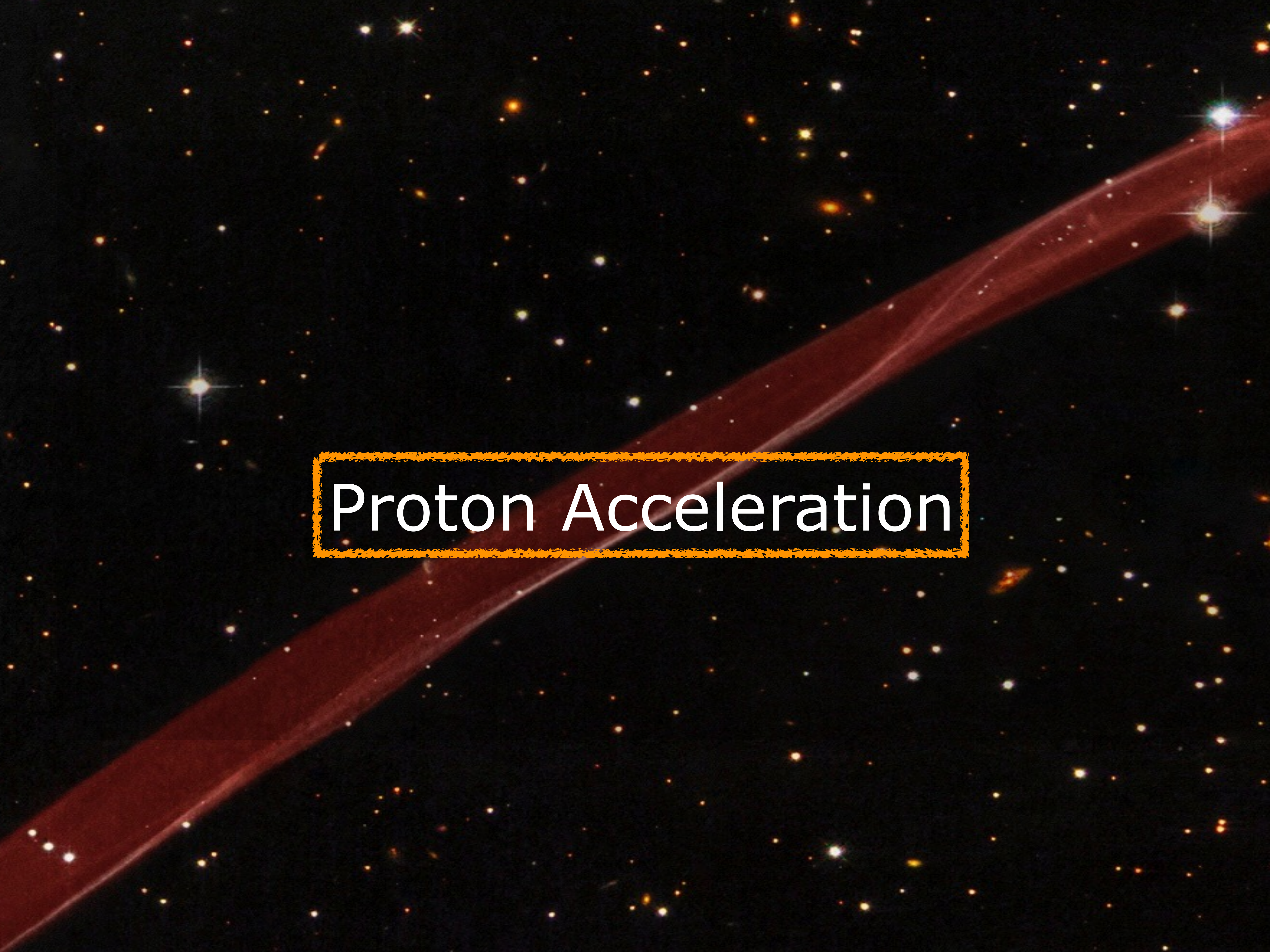
1) ability of a shock to reflect particles back into the upstream (injection)

2) ability of these particles to scatter and return to the shock (pre-existing or generated turbulence)

Generically, parallel shocks are good for ion and electron acceleration, while perpendicular shocks mainly accelerate electrons. *There are many sub-regimes, not fully mapped yet.*

Outline

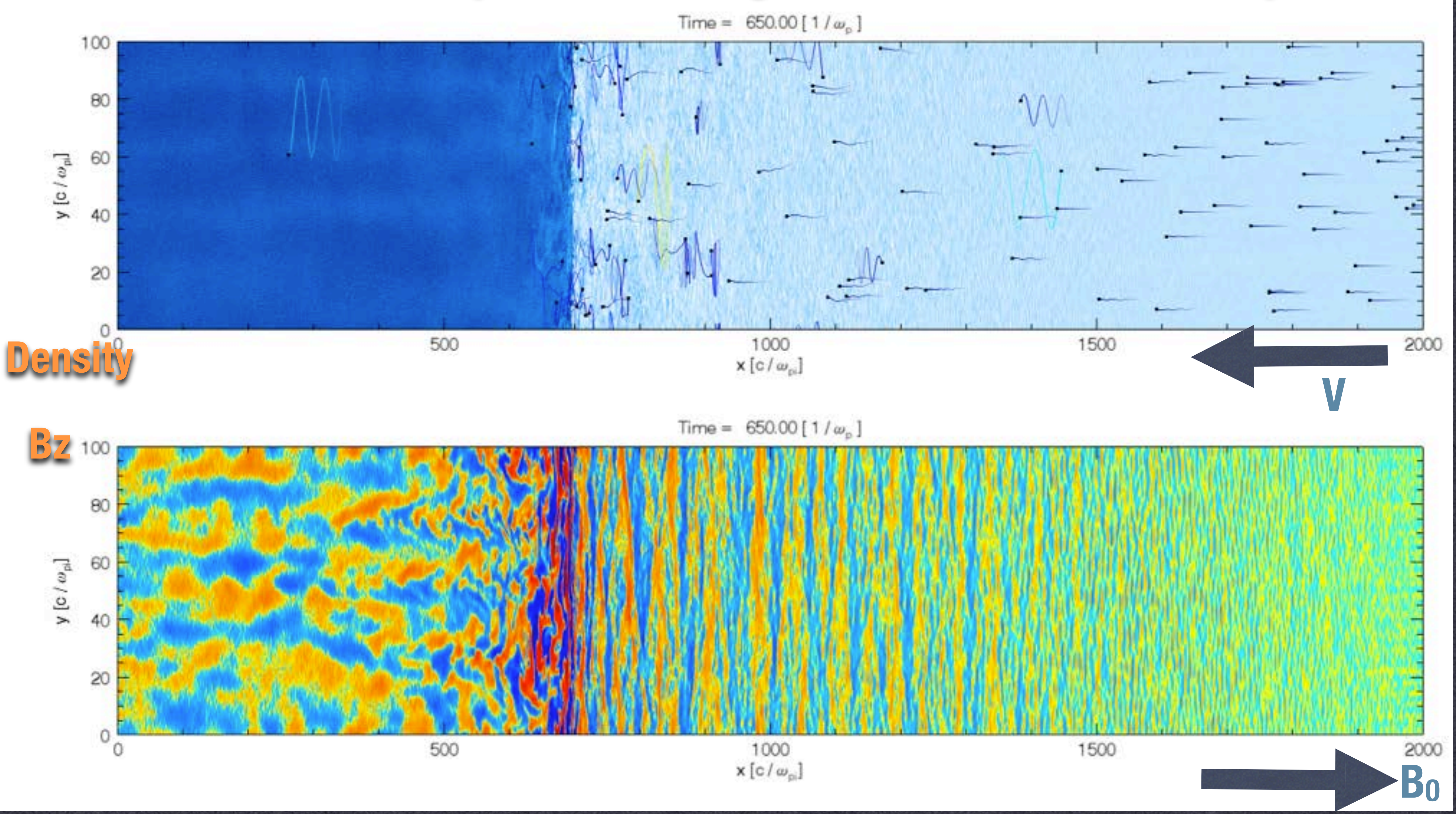
1) Proton injection physics
2) Electron injection physics and proton/electron ratio in CRs
3) Injection of heavy ions
4) Re-acceleration of cosmic rays



Proton Acceleration

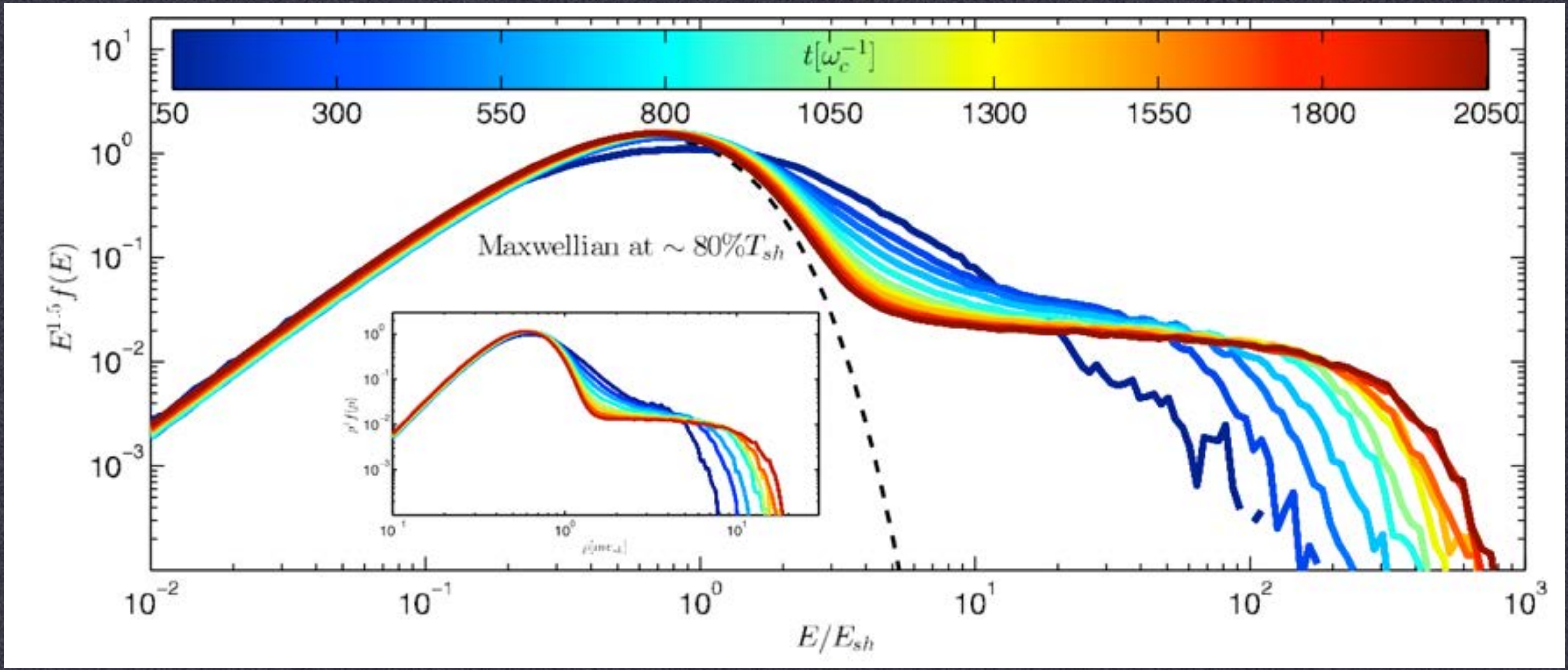
Proton acceleration

M_A=5, parallel shock; hybrid simulation. Quasi-parallel shocks accelerate ions and produce self-generated waves in the upstream.



Proton spectrum

Long term evolution: Diffusive Shock Acceleration spectrum recovered



First-order Fermi acceleration: $f(p) \propto p^{-4}$ $4\pi p^2 f(p)dp = f(E)dE$

$f(E) \propto E^{-2}$ (relativistic) $f(E) \propto E^{-1.5}$ (non-relativistic)

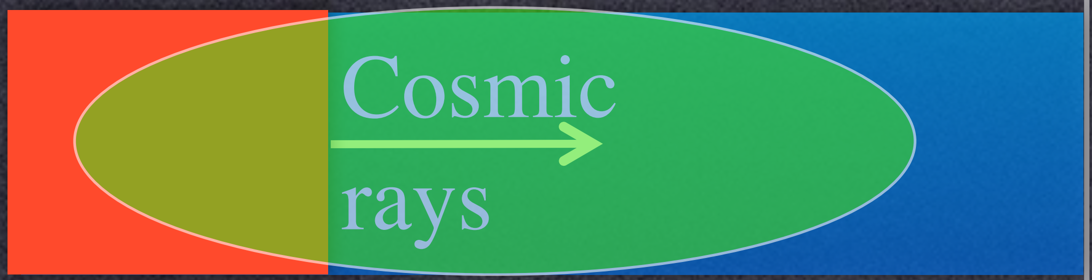
CR backreaction is affecting downstream temperature

Caprioli & Spitkovsky 2014a

Field amplification

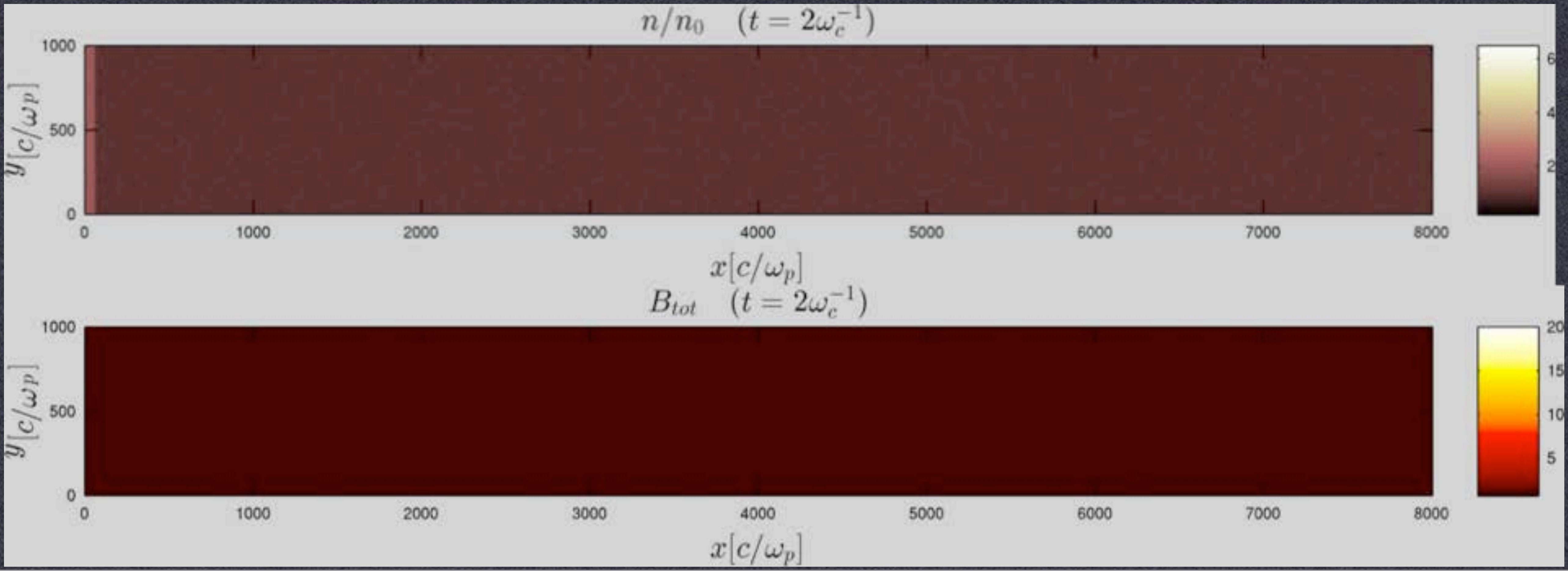
We see evidence of CR effect on upstream.

This will lead to “turbulent” shock with effectively lower Alfvenic Mach number with locally 45 degree inclined fields.

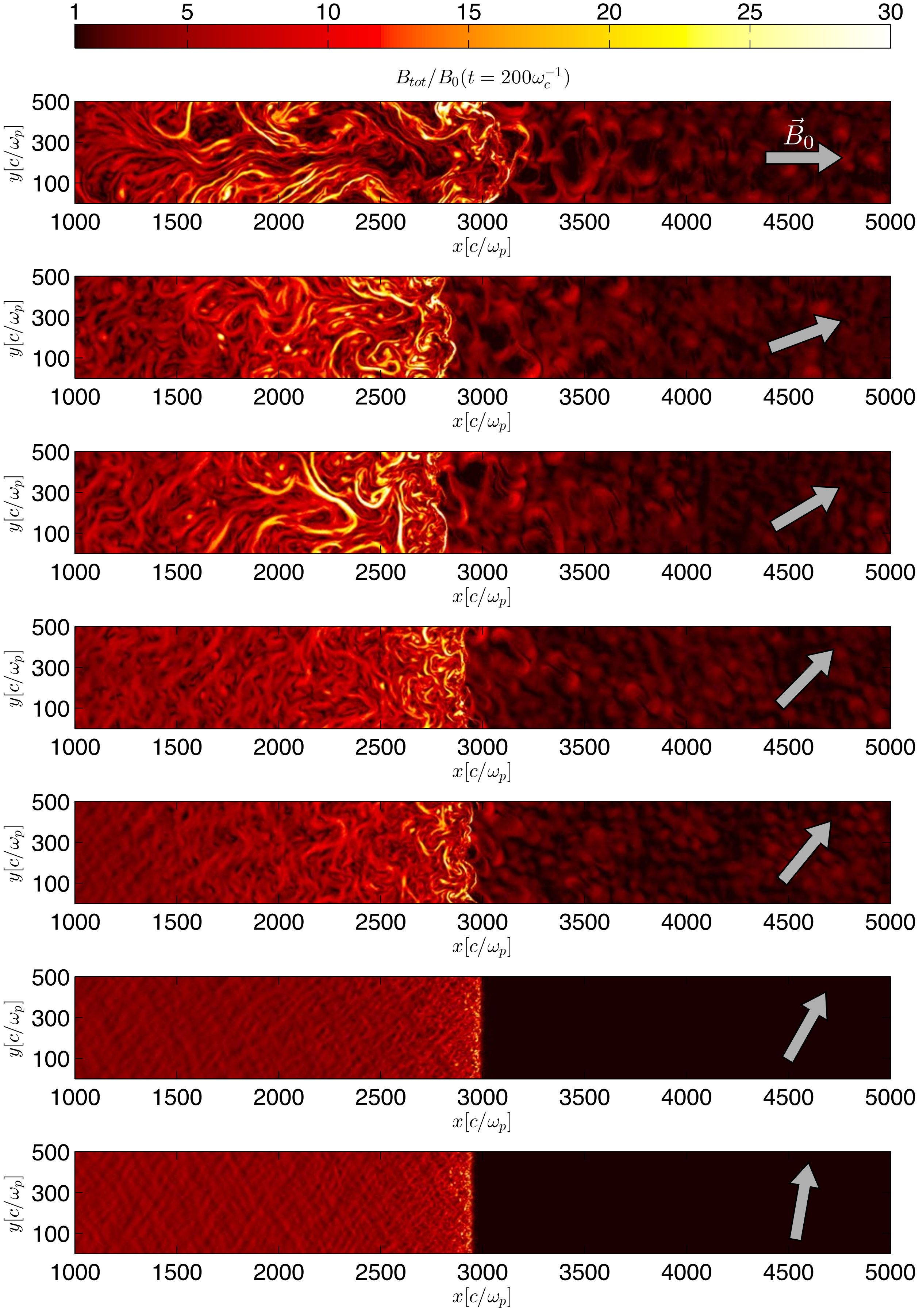


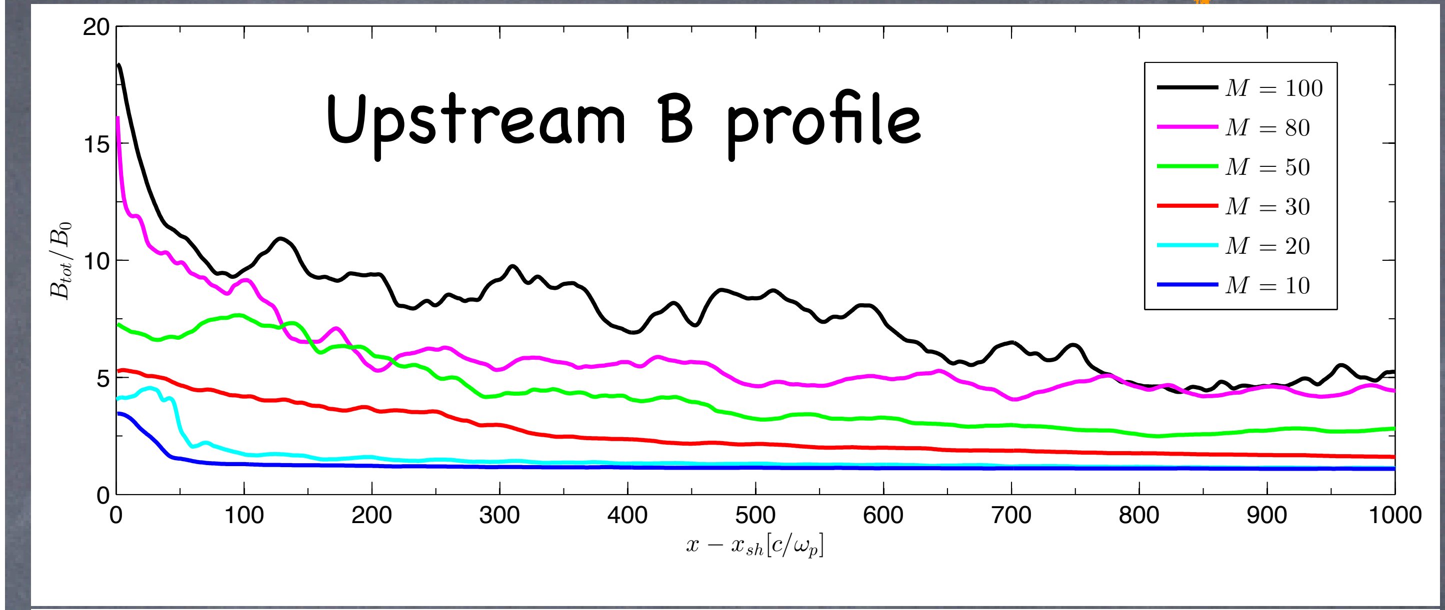
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

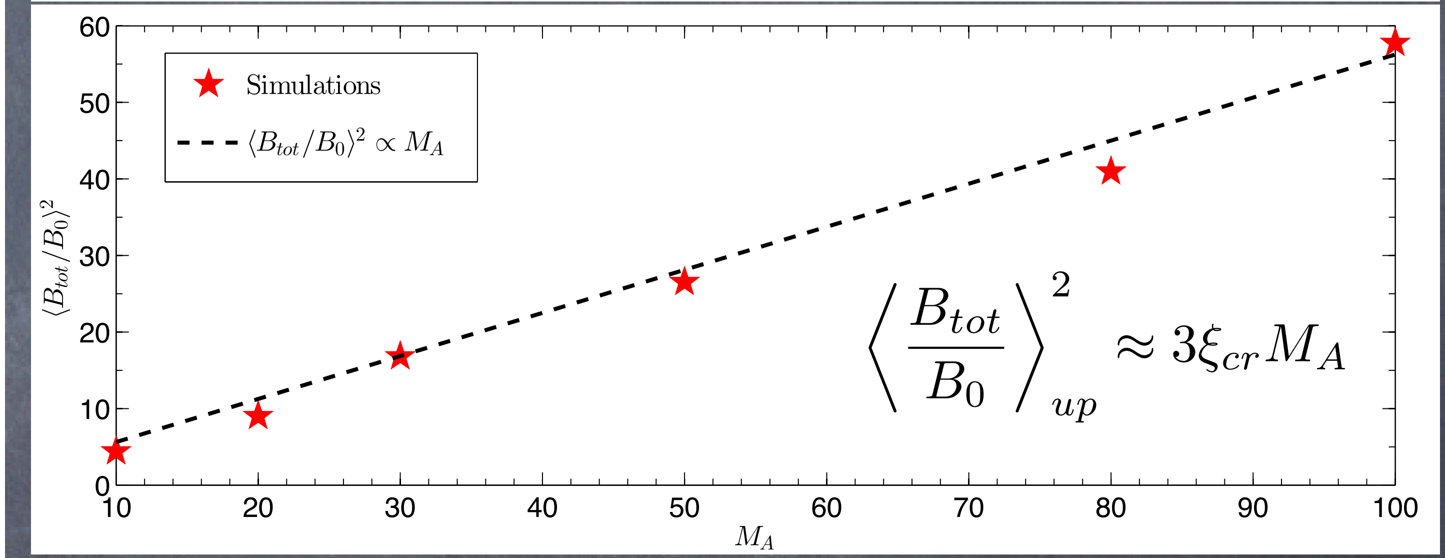
Combination of nonresonant (Bell), resonant, and firehose instabilities + CR filamentation



Dependence of field amplif. on inclination and M





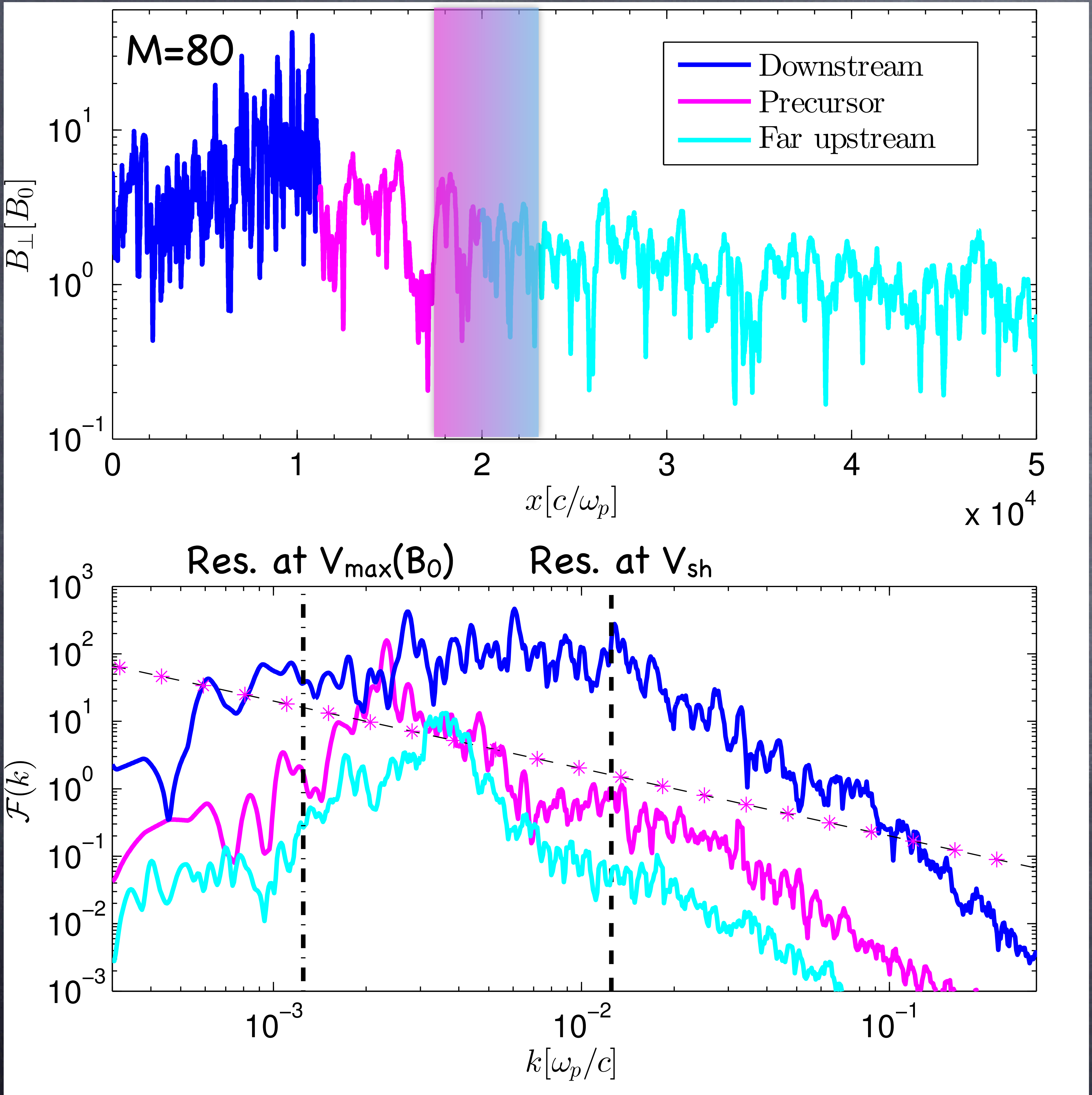


$$\left\langle \frac{B_{tot}}{B_0} \right\rangle_{up}^2 \approx 3\xi_{cr} M_A$$

- In agreement with the prediction of resonant streaming instability

More B-field amplification for stronger shocks!

Magnetic field spectrum, high M_A



- Bell modes (short-wavelength, right-handed) grow faster than resonant
- Far upstream: escaping CRs at $\sim p_{max}$ (Bell)
- For large $b=\delta B/B_0$ $k_{max}(b)\sim k_{max,0}/b^2$
- There exist a b^* such that $k_{max}(b^*)r_L(p_{esc})\sim 1$

Free escape boundary

- Precursor: diffusion + resonant

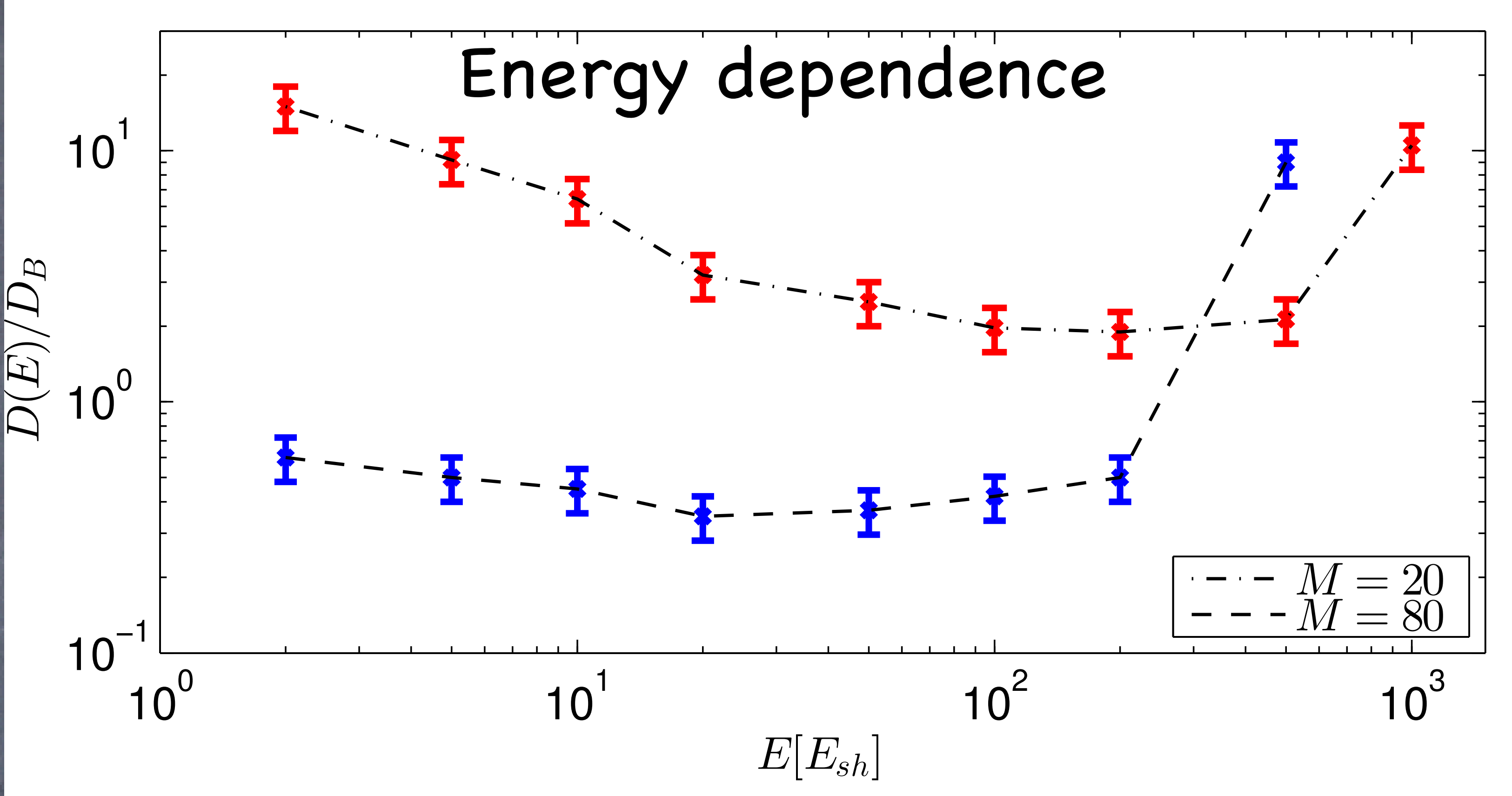
Caprioli & AS, 2014b

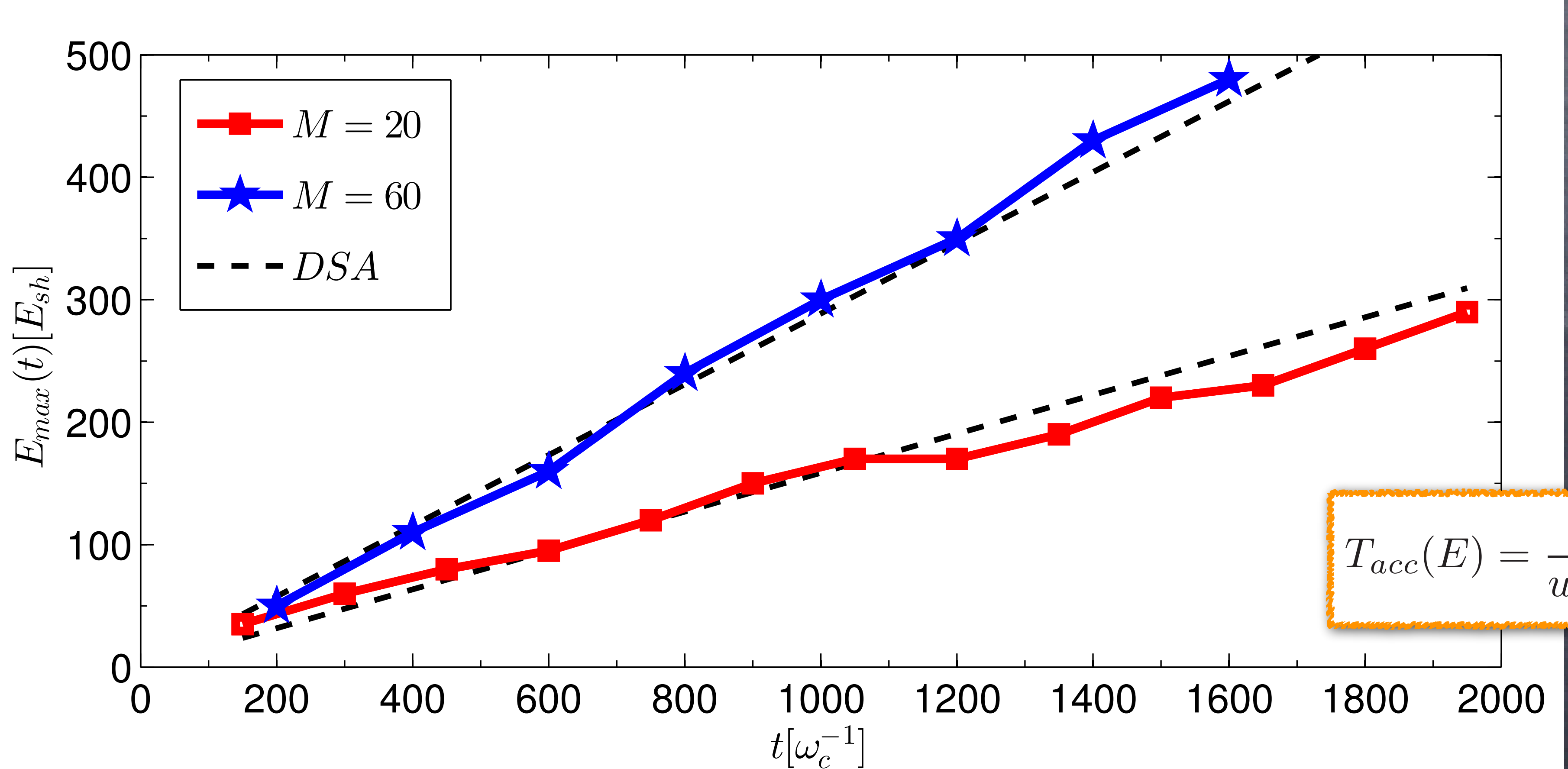
Diffusion coefficient

- Directly measurable in simulations:

$$D(E) \equiv \lim_{t\to\infty} D(E,t) = \lim_{t\to\infty} \sum_{n=1}^{N} \frac{|x_n(t) - x_n(0)|^2}{2tN}.$$

Bohm diffusion in the amplified B


Energy dependence

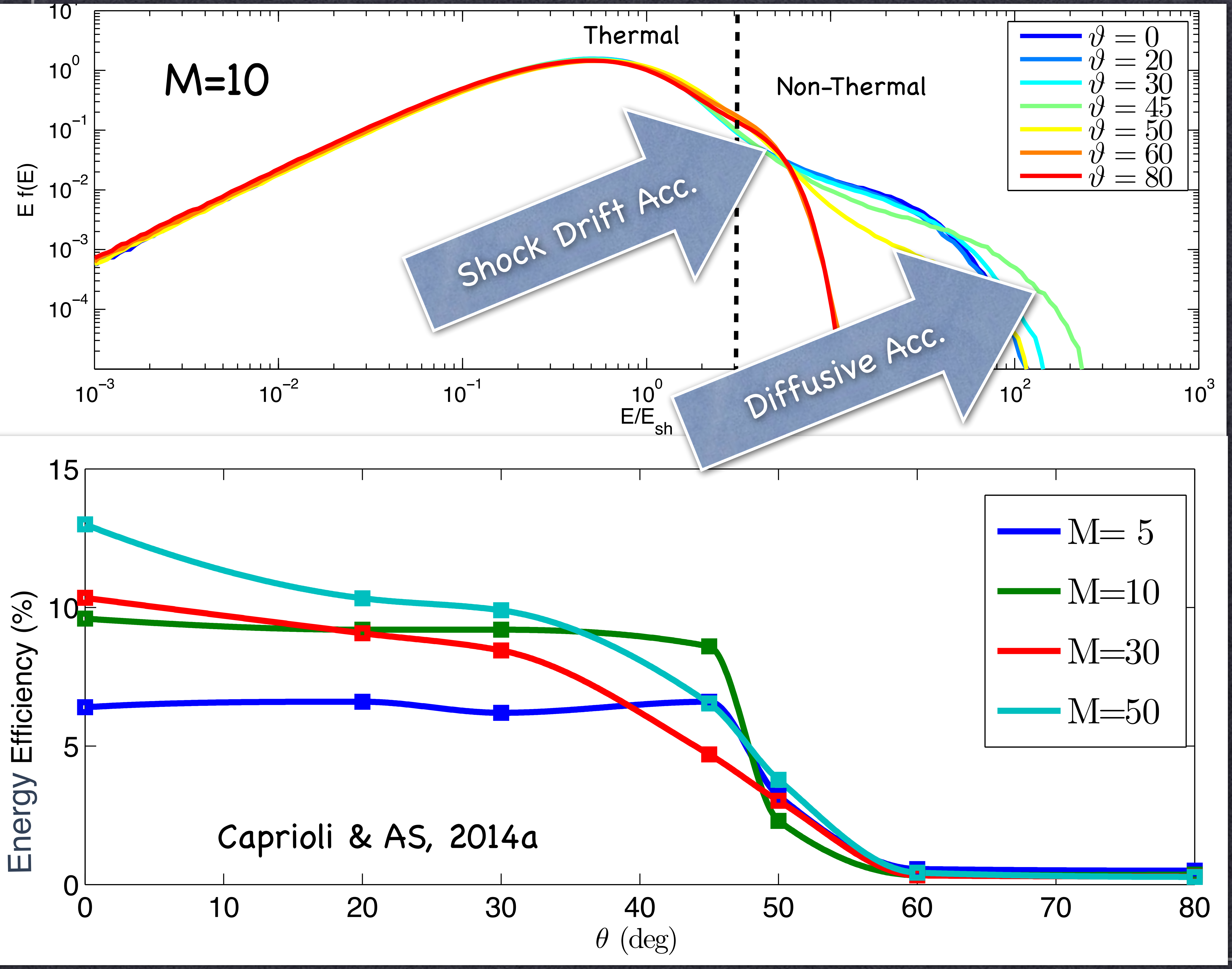


- Evolution of $E_{max}(t)$ according to DSA (e.g., Drury 1983)

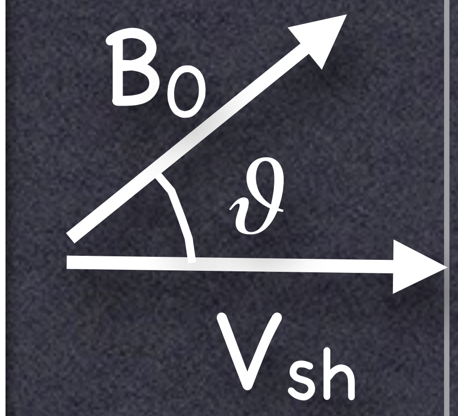
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2-1}\frac{D(E)}{v_{sh}^2}.$$

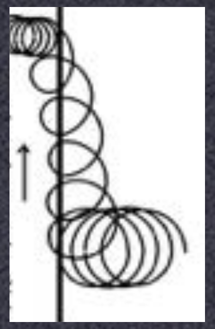
Caprioli & AS, 2014c

Acceleration in parallel vs oblique shocks



Caprioli & AS, 2014a

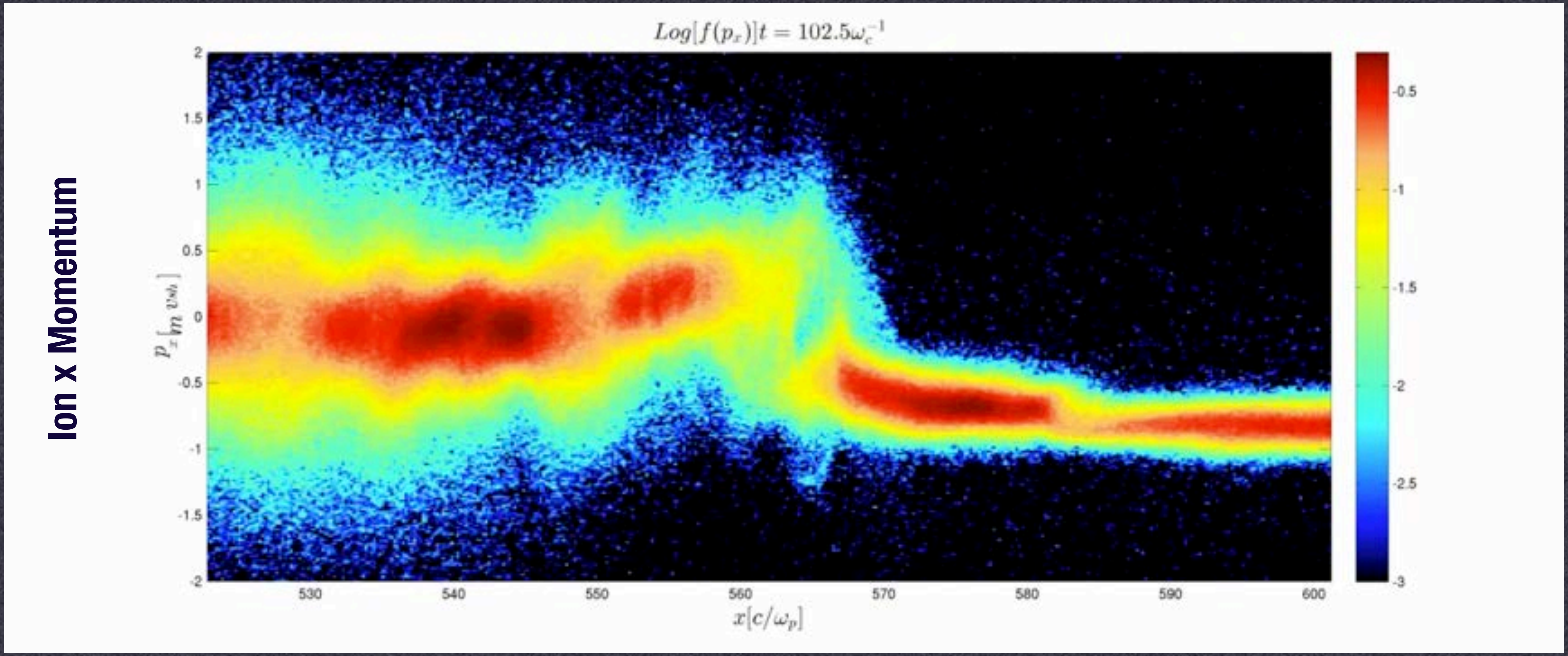




About 1% accelerated protons by number, what is causing that?

Shock structure & injection

Quasiparallel shocks look like intermittent quasiperp shocks



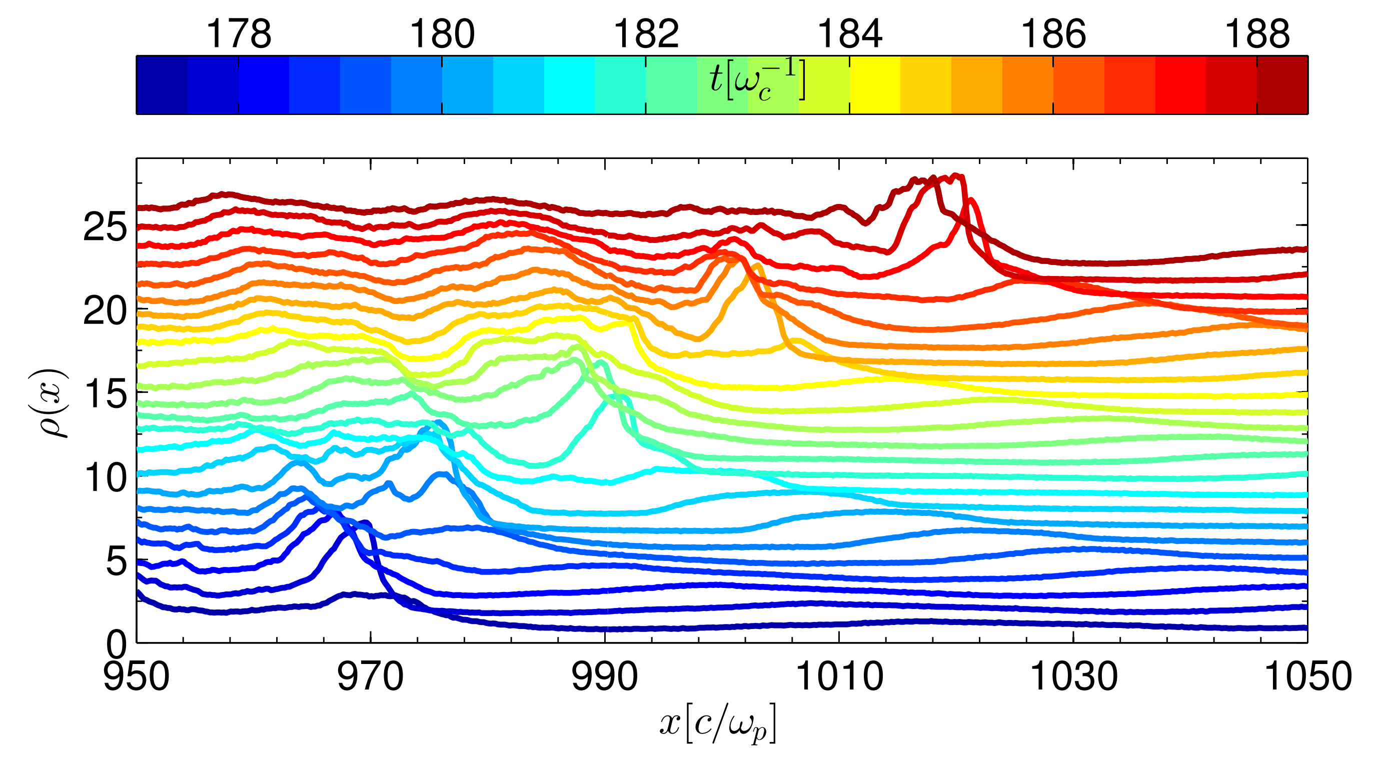
Injection of ions happens on first crossing due to specular reflection from reforming magnetic and electric barrier and shock-drift acceleration.

Multiple cycles in a time-dependent shock structure result in injection into DSA; no “thermal leakage” from downstream.

Ion injection: theory

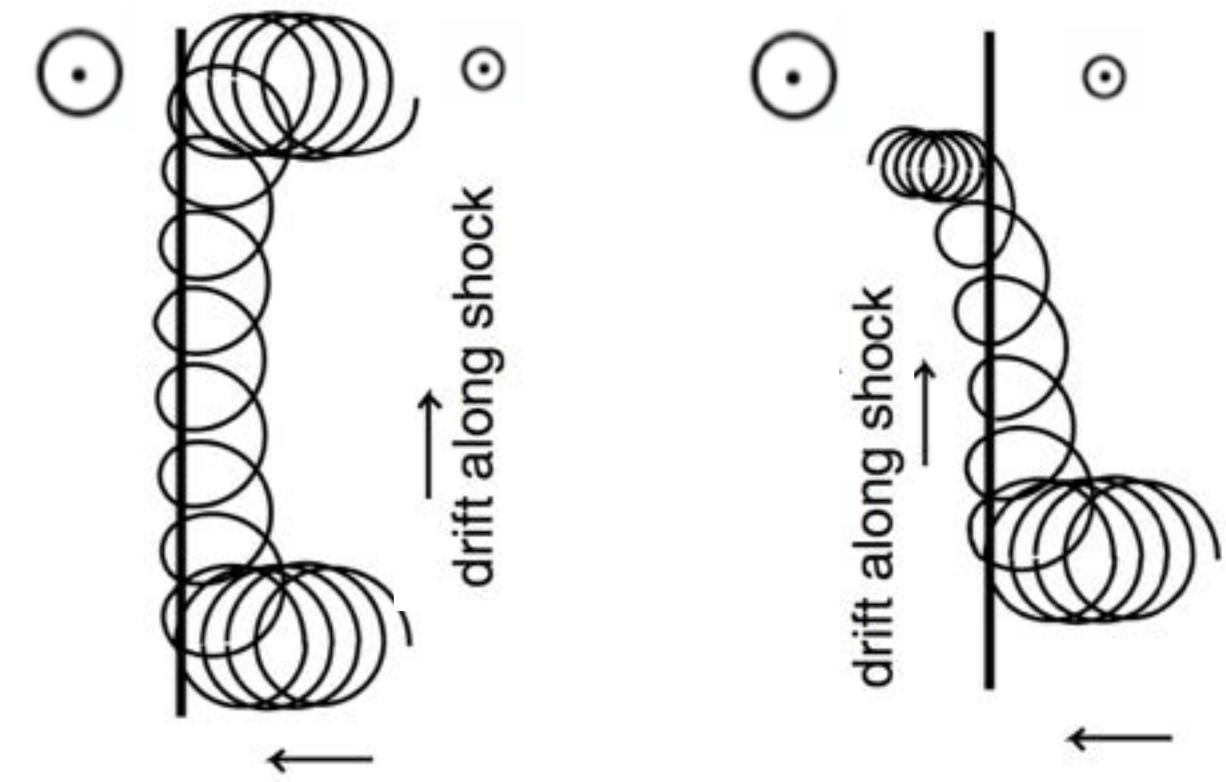
Caprioli, Pop & AS 2015

- Reflection off the shock potential barrier (stationary in the downstream frame)
- For reflection into upstream, particle needs certain minimal energy for given shock inclination;
- Particles first gain energy via shock-drift acceleration (SDA)
- Several cycles are required for higher shock obliquities
- Each cycle is “leaky”, not everyone comes back for more
- Higher obliquities less likely to get injected



Shock-drift acceleration:

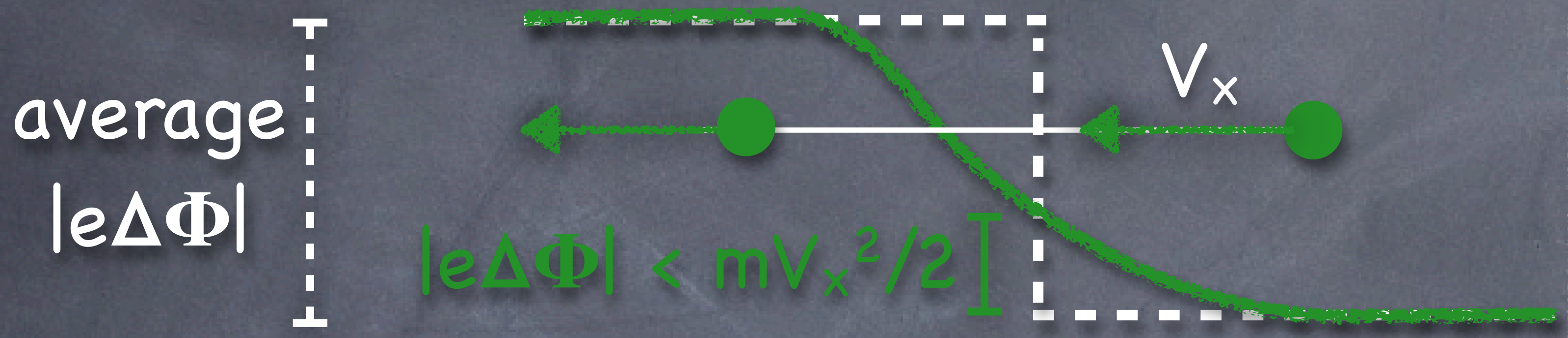
downstream upstream Larger B Smaller B



Path of incoming particle

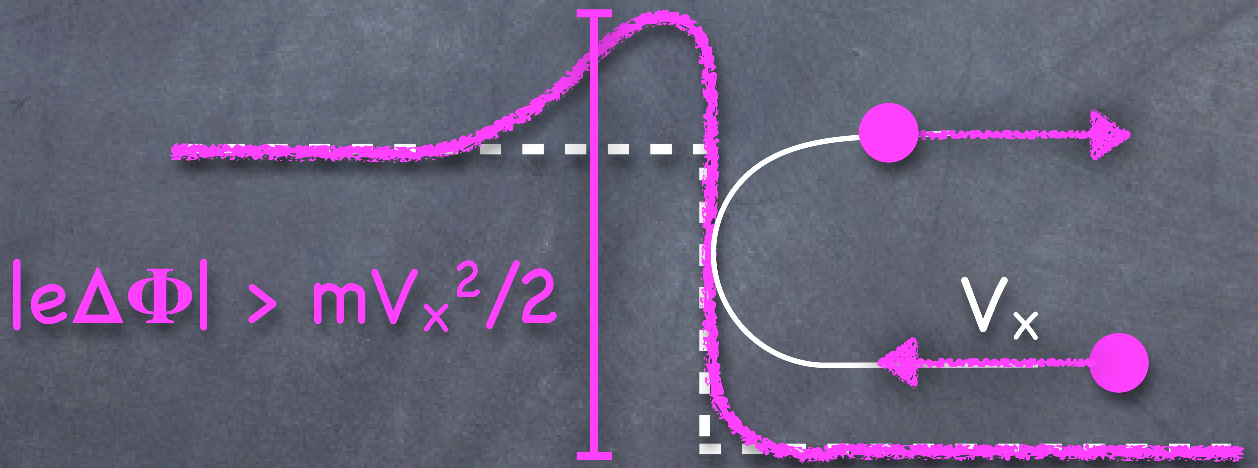
Encounter with the shock barrier

- Low barrier (shock reforming)



Particles are advected downstream, and thermalized

- High barrier (overshoot)



Particles are reflected upstream, and energized via Shock Drift Acc.

- To overrun the shock, proton need a minimum E_{inj}, increasing with ϑ
- Particle fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj}\sim10E_0$, which requires N~3 -> $\eta\sim1\%$

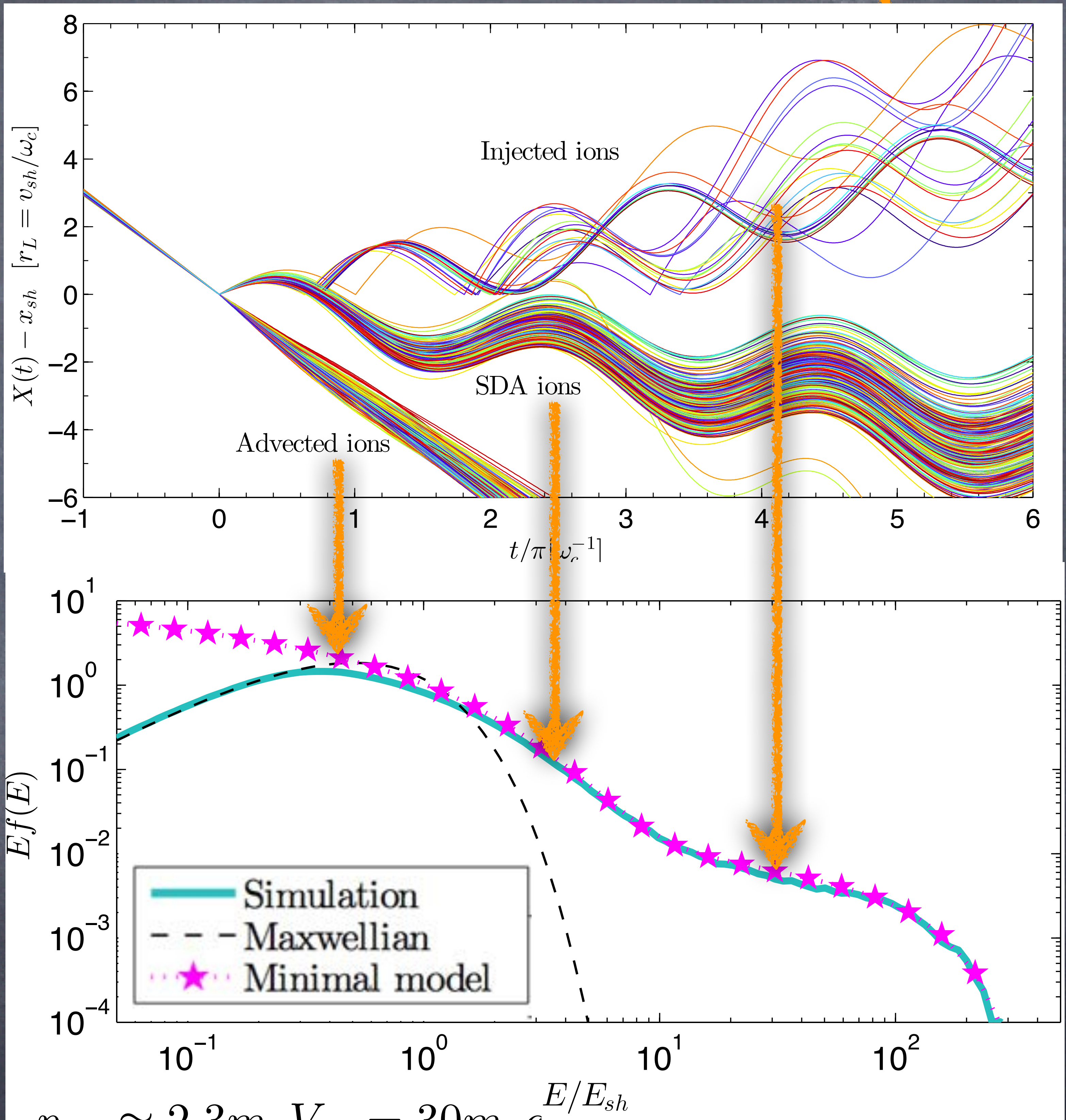
Minimal Model for Ion Injection

- Time-varying potential barrier
  - **High state** (duty cycle 25%)
    -> Reflection
    -> Shock Drift Acceleration
  - **Low-state** -> Thermalization

- Spectrum à la Bell (1978)

$$f(E) \propto E^{-1-\gamma}; \quad \gamma \equiv -\frac{\ln(1-\mathcal{P})}{\ln(1+\mathcal{E})}$$

- P=probability of being advected
- ε =fractional energy gain/cycle



$$p_{\rm inj} \approx 2.3 m_p V_{\rm sh} = 30 m_e c$$

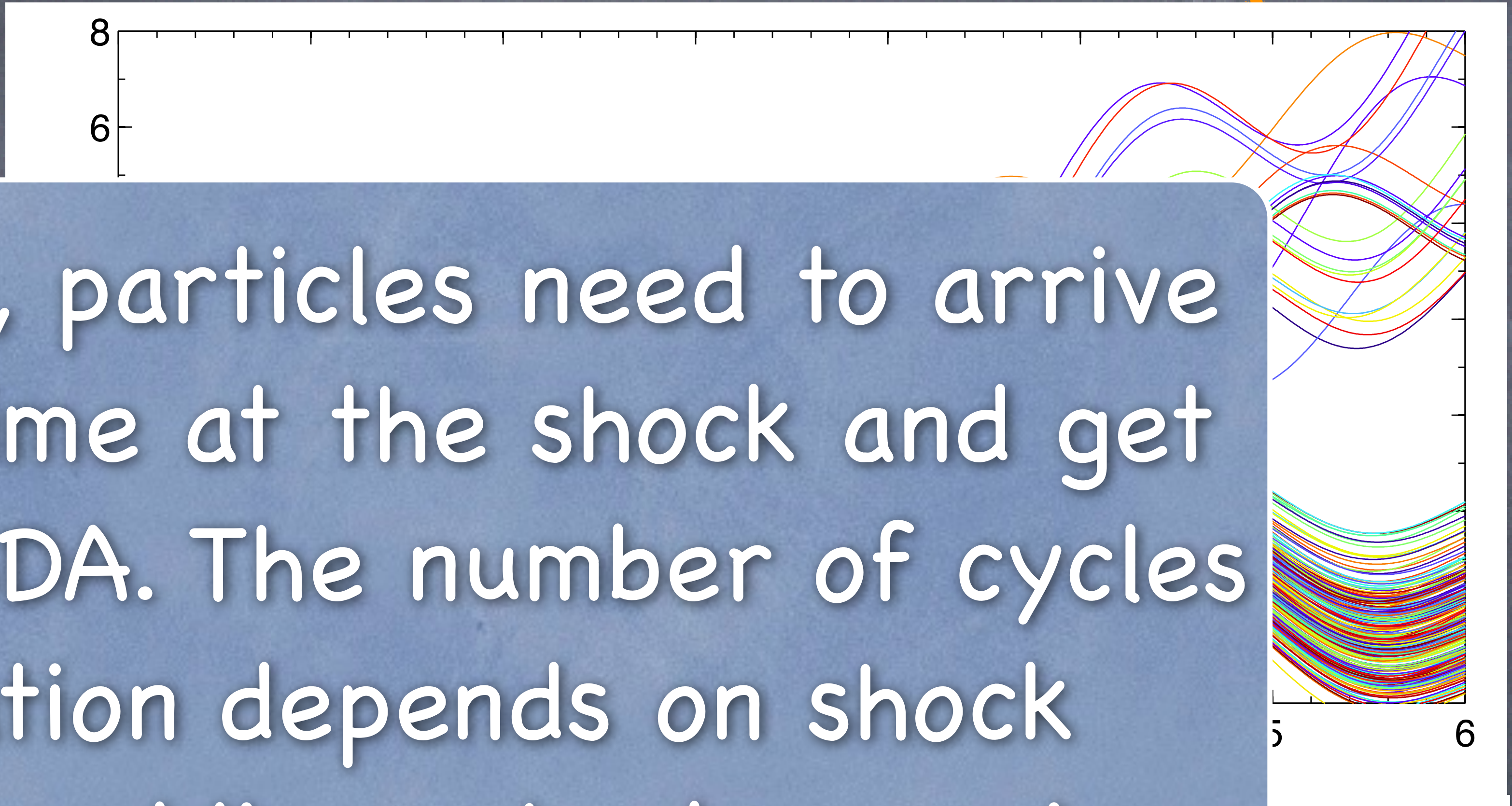
Caprioli, Pop & Spitkovsky, 2015

Minimal Model for Ion Injection

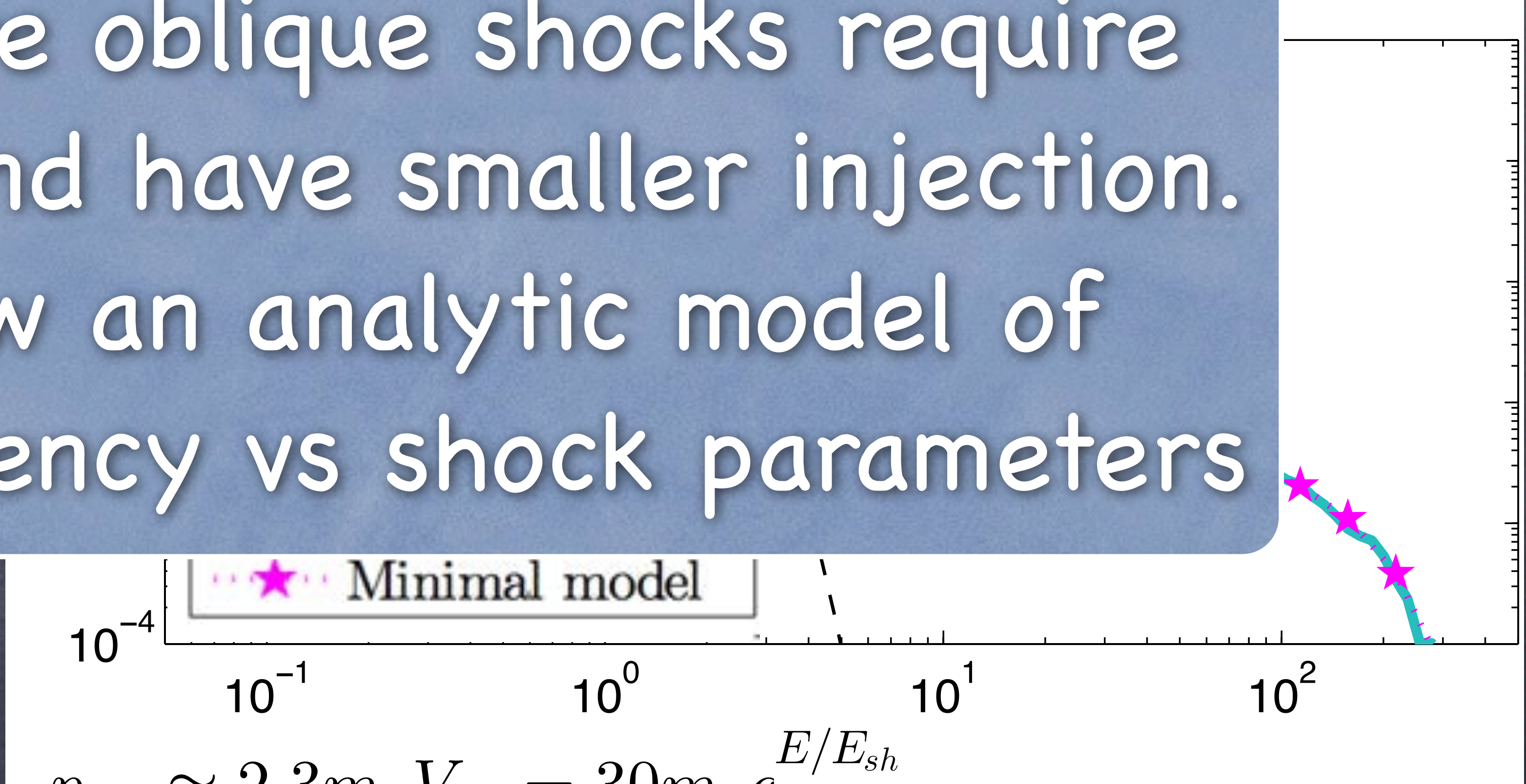
- Time-varying potential barrier
  - High
    -> R
    -> Sl
  - Low-
- Spectru

$f(E) \propto$

- P=proba
- ε =fractional energy gain/cycle



To be injected, particles need to arrive at the right time at the shock and get energized by SDA. The number of cycles of energization depends on shock obliquity. More oblique shocks require more cycles, and have smaller injection. There is now an analytic model of injection efficiency vs shock parameters



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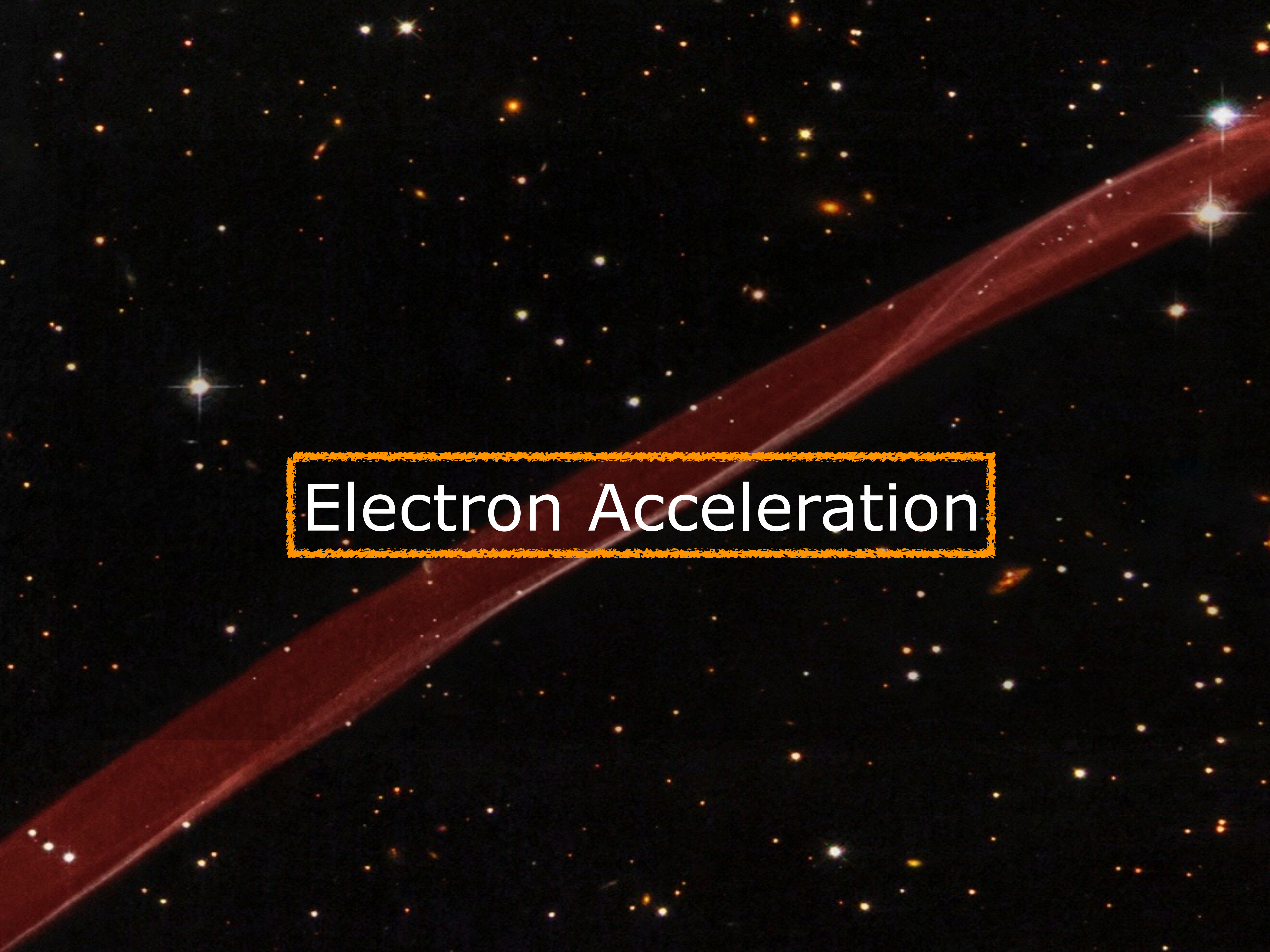
Caprioli, Pop & Spitkovsky, 2015

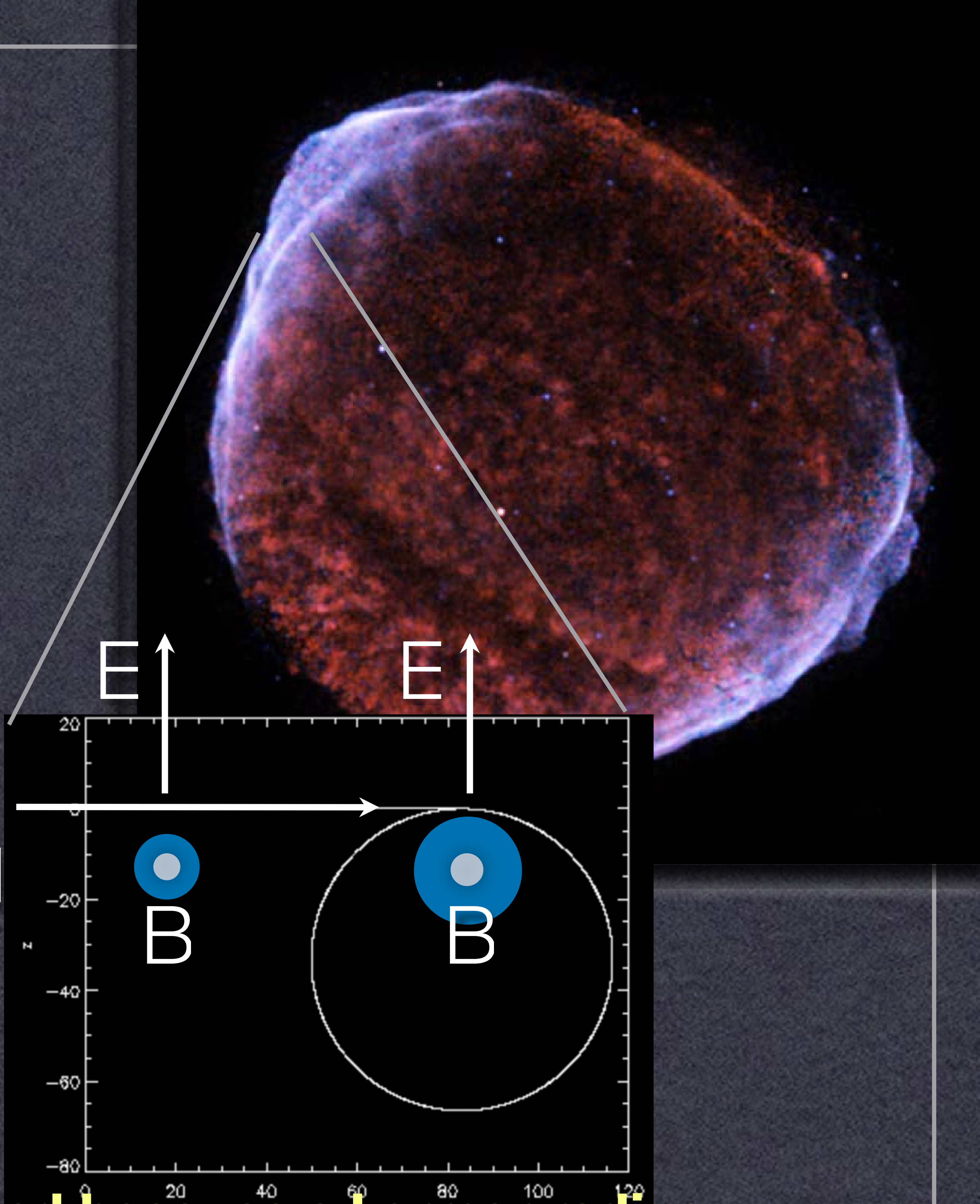


Electron Acceleration

WHAT ACCELERATES ELECTRONS?

Electrons are notorious for being difficult to inject because of the disparity in the Larmor scales with ions.

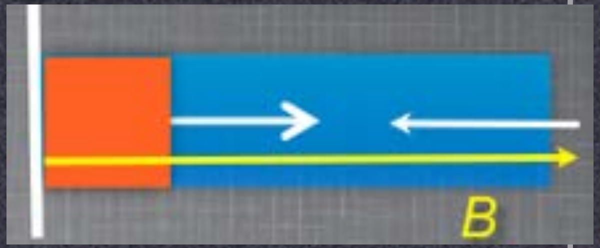
Shock is driven on ion scales, electrons need to be pre-accelerated to be injected. But how?



Typically electron acceleration is suppressed because e Larmor radius is << ion Larmor radius. Need pre-acceleration of electrons.

This means trapping at the shock, and turbulence upstream. Is it self-generated?

Electron acceleration at parallel shocks



Recent evidence of electron acceleration in quasi parallel shocks.
PIC simulation of quasiparallel shock. Very long simulation in 1D.

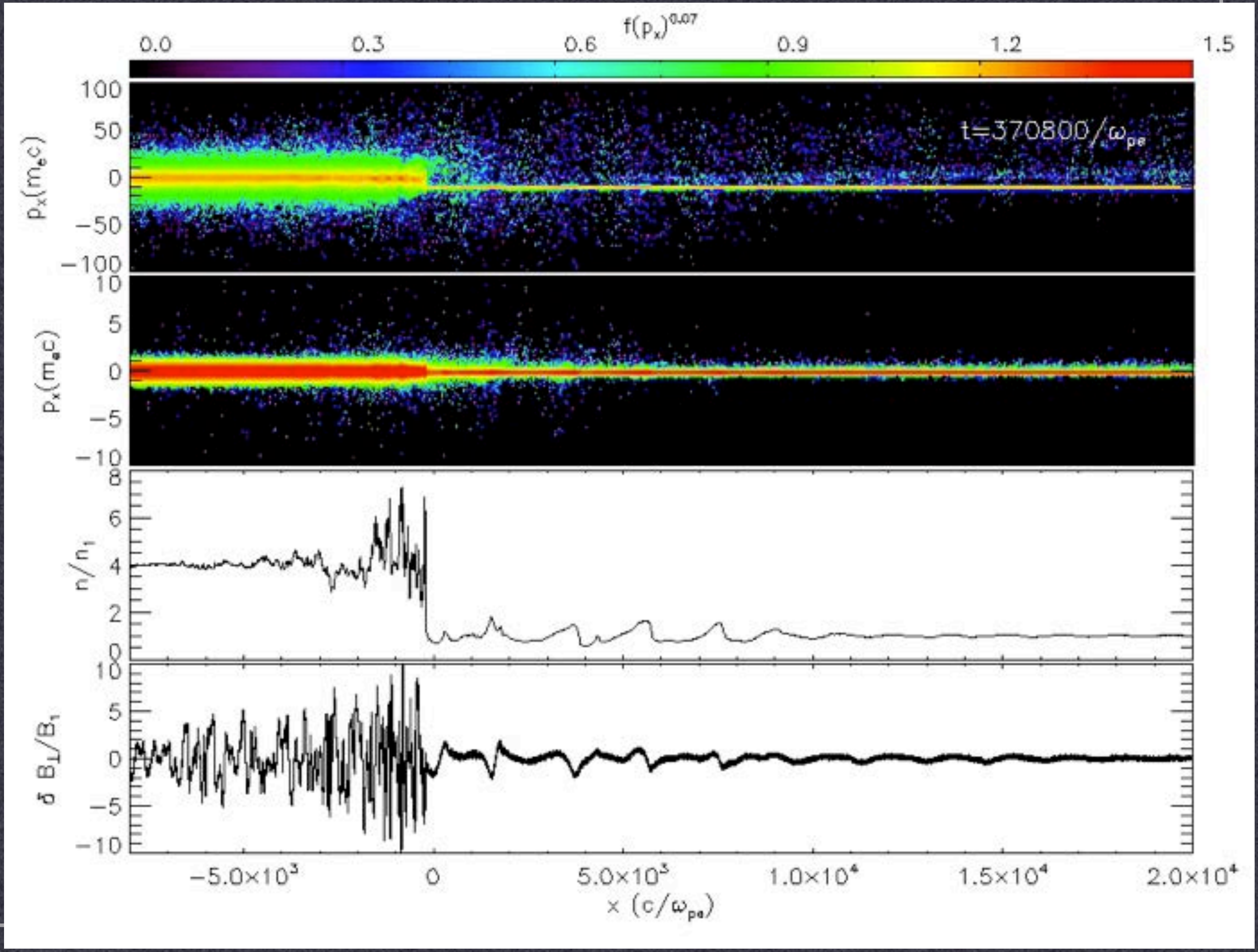
Ion-driven Bell waves drive electron acceleration: correct polarization

Ion phase space

Electron phase space

Density

Transverse Magnetic field



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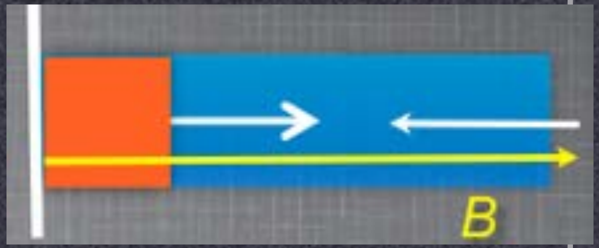
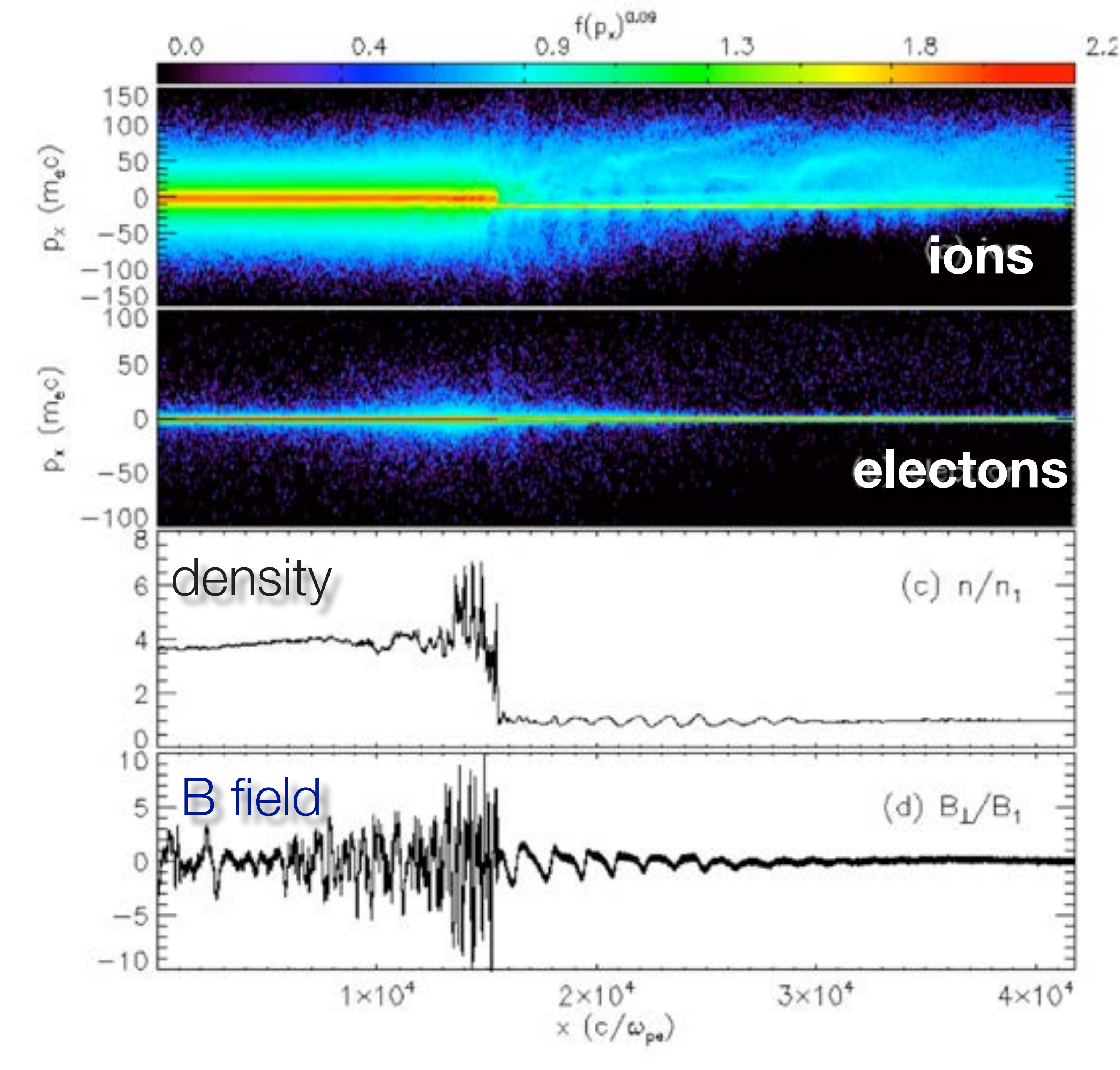
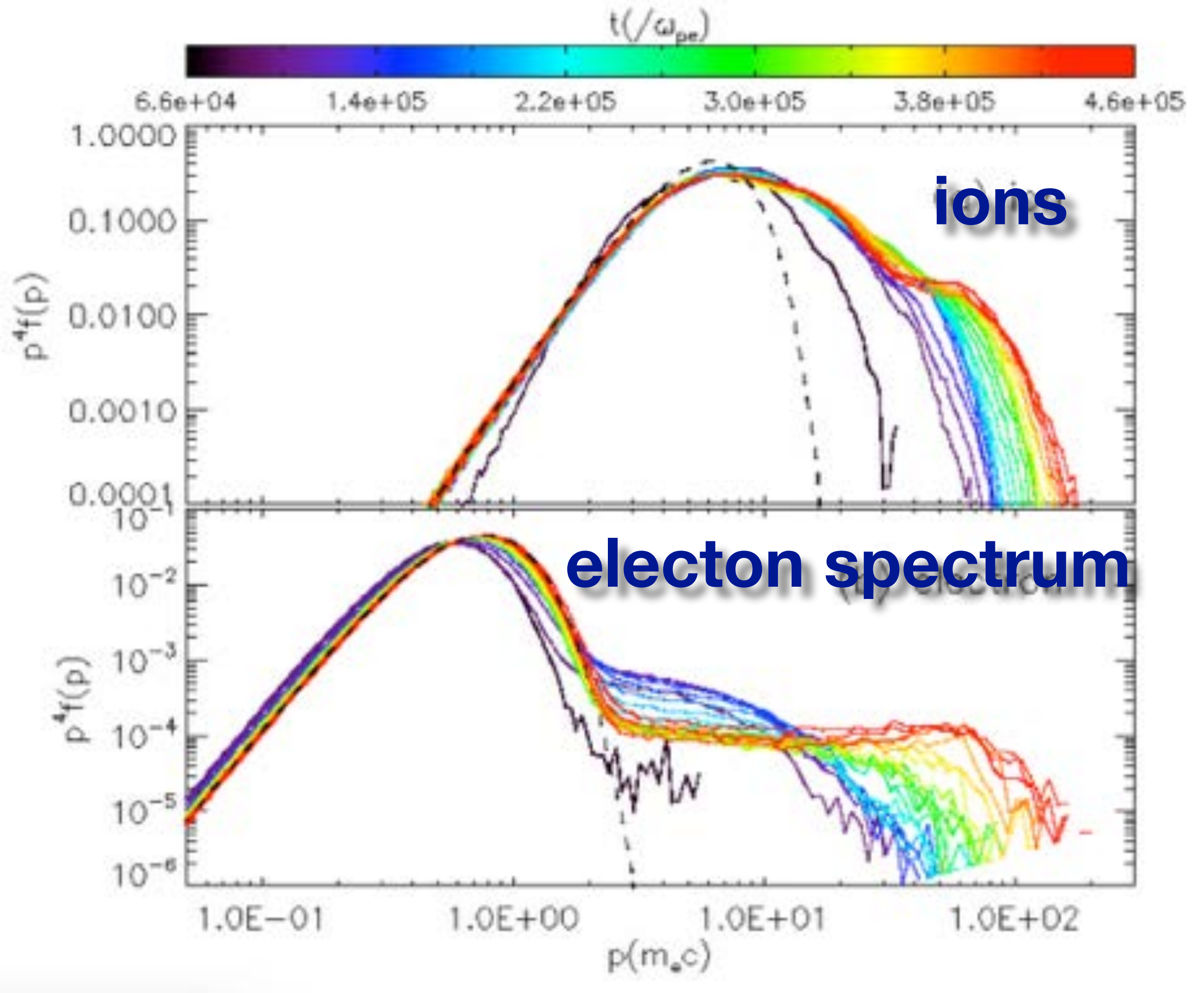


Ion-driven Bell waves drive electron acceleration: correct polarization



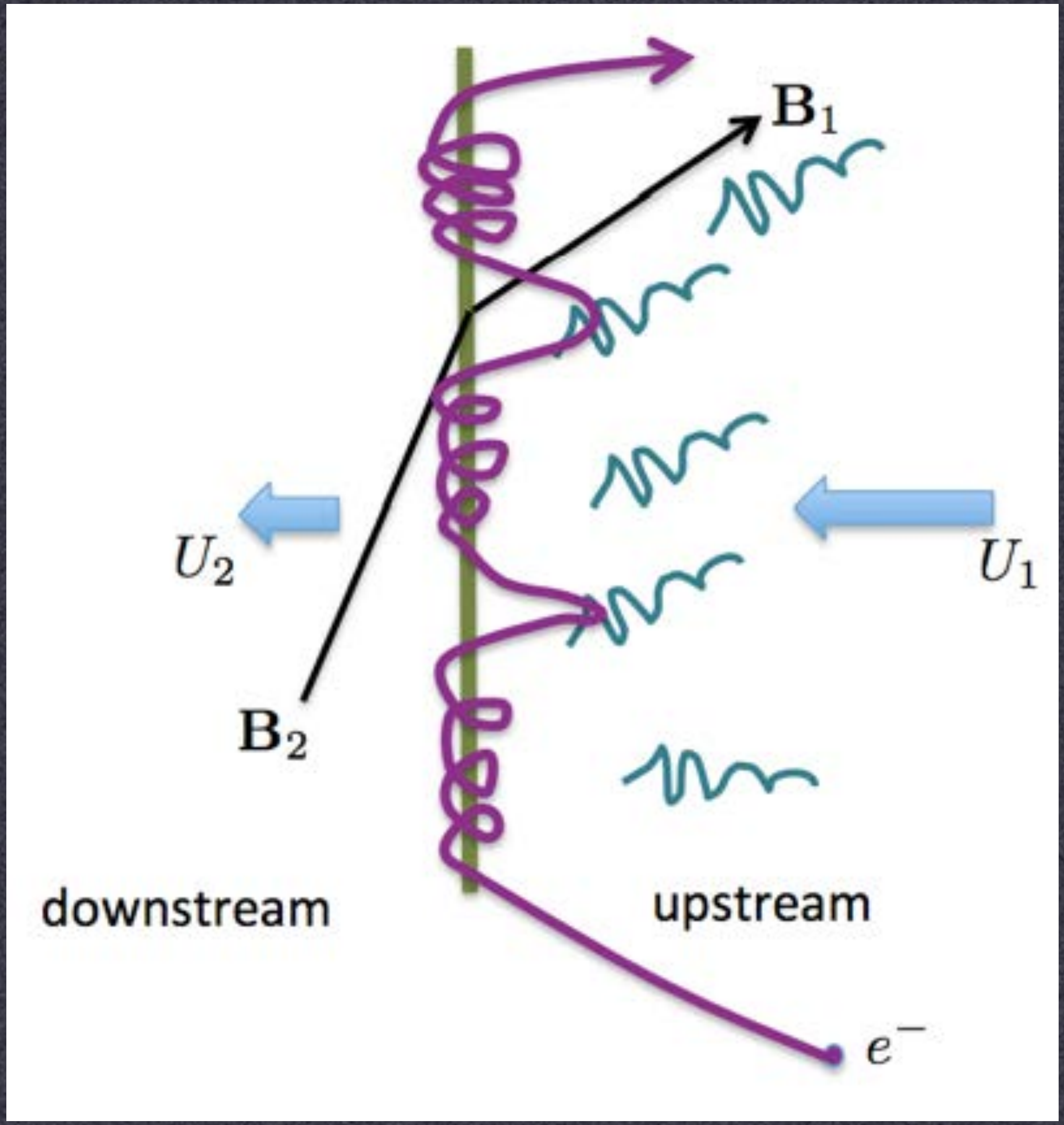


DSA spectrum recovered in _both_ electrons and ions
Electron-proton ratio can be measured!

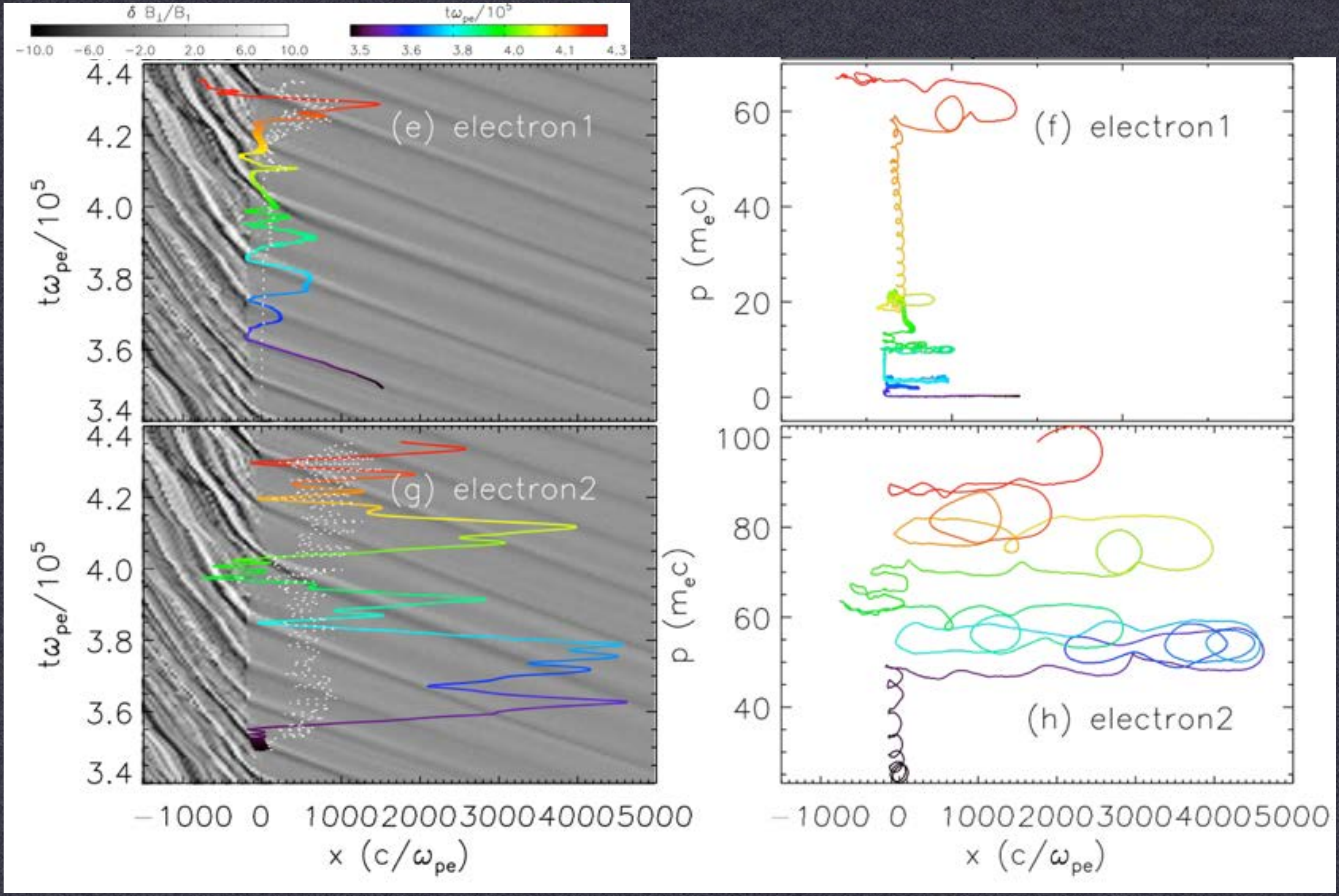
Park, Caprioli, AS (2015)

Electron acceleration at parallel shocks

Multi-cycle shock-drift acceleration, with electrons returning back due to upstream ion-generated waves.



Electron acceleration mechanism: shock drift cycles



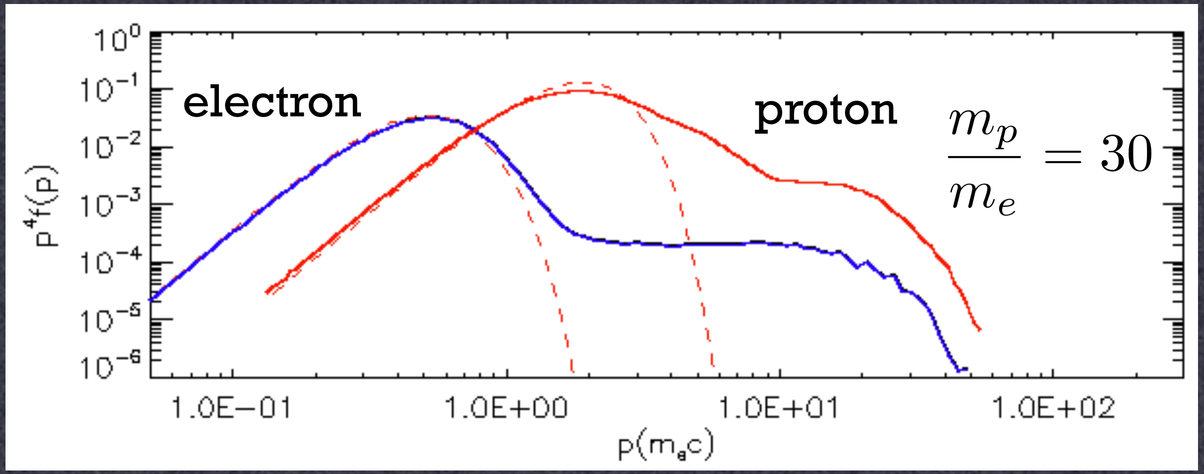
Shock-drift

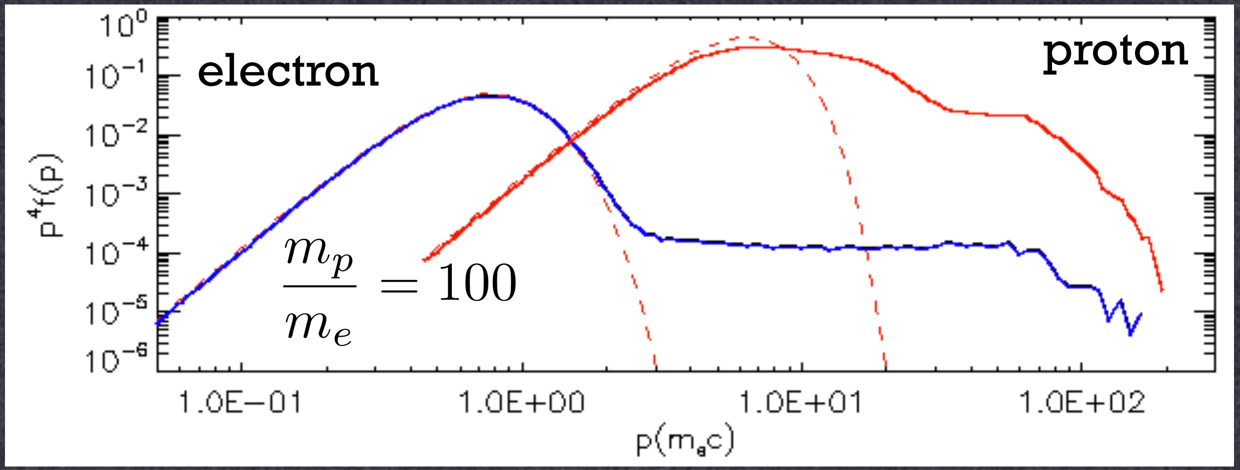
Diffusive

Electron track from PIC simulation.

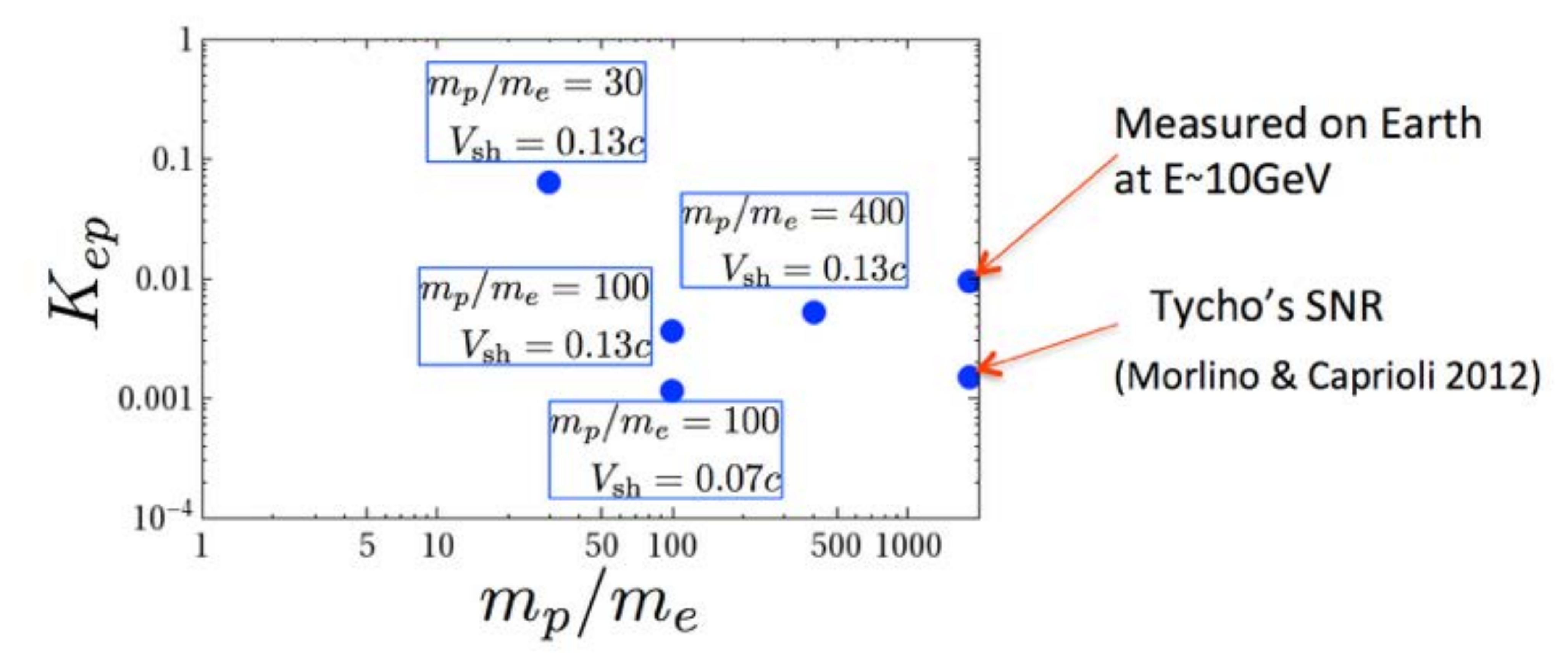
Electron-proton ratio K_{ep}:

Park, Caprioli, AS (2015)





$$K_{\rm ep} \equiv \frac{f_e(p)}{f_p(p)} = \text{const for } p > p_{\rm inj} \quad K_{\rm ep} \approx 3.8 \times 10^{-3} \text{ for } \frac{m_p}{m_e} = 100$$



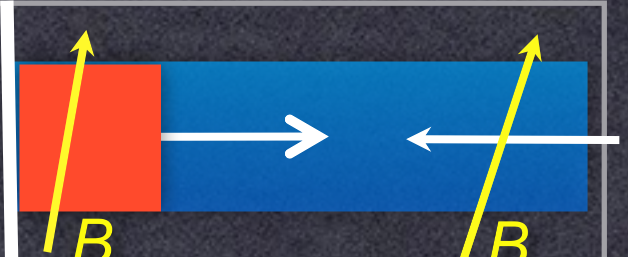
Measured on Earth
at E~10GeV

Tycho's SNR

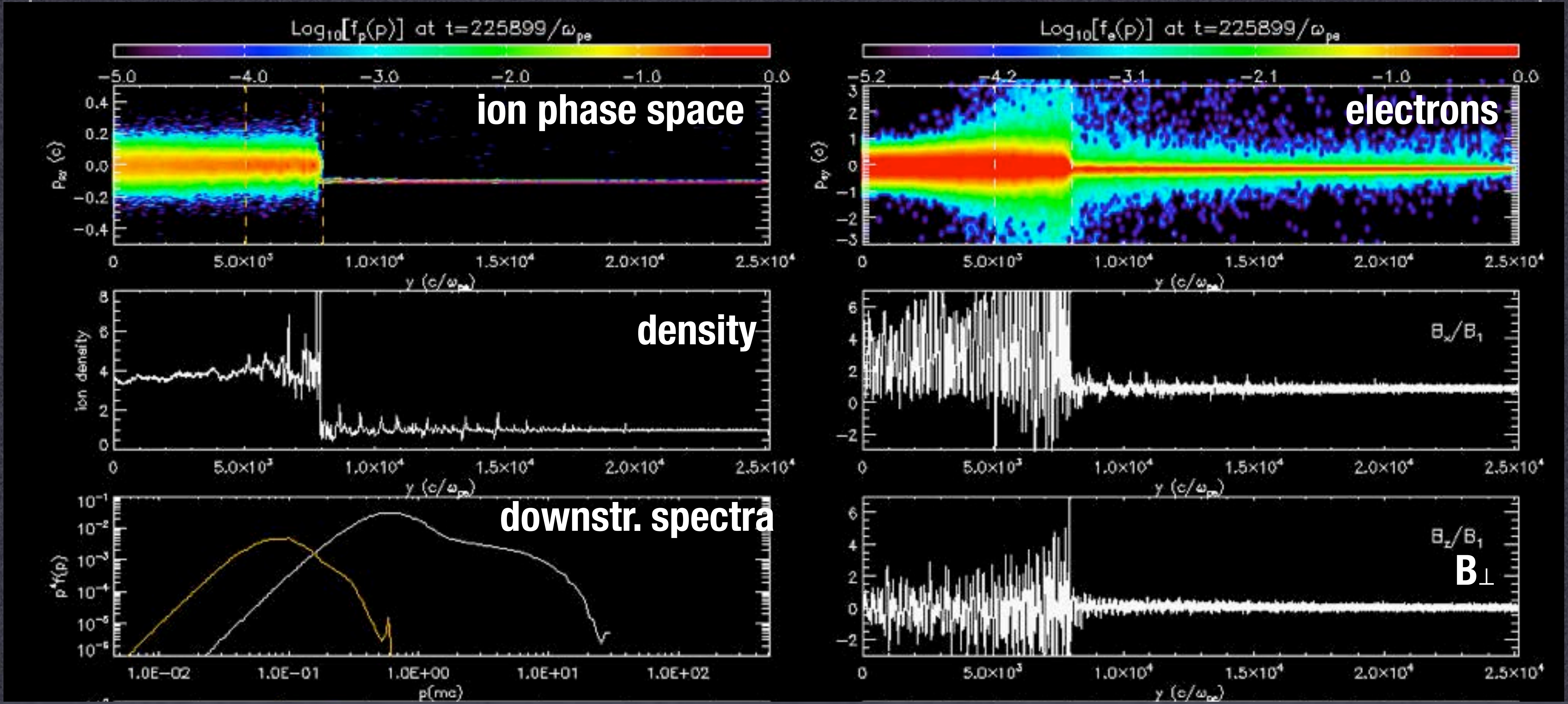
(Morlino & Caprioli 2012)

Electron acceleration at ⊥-shocks

60 degrees shock inclination, mi/me=100, M_A=20;
electron-driven waves upstream



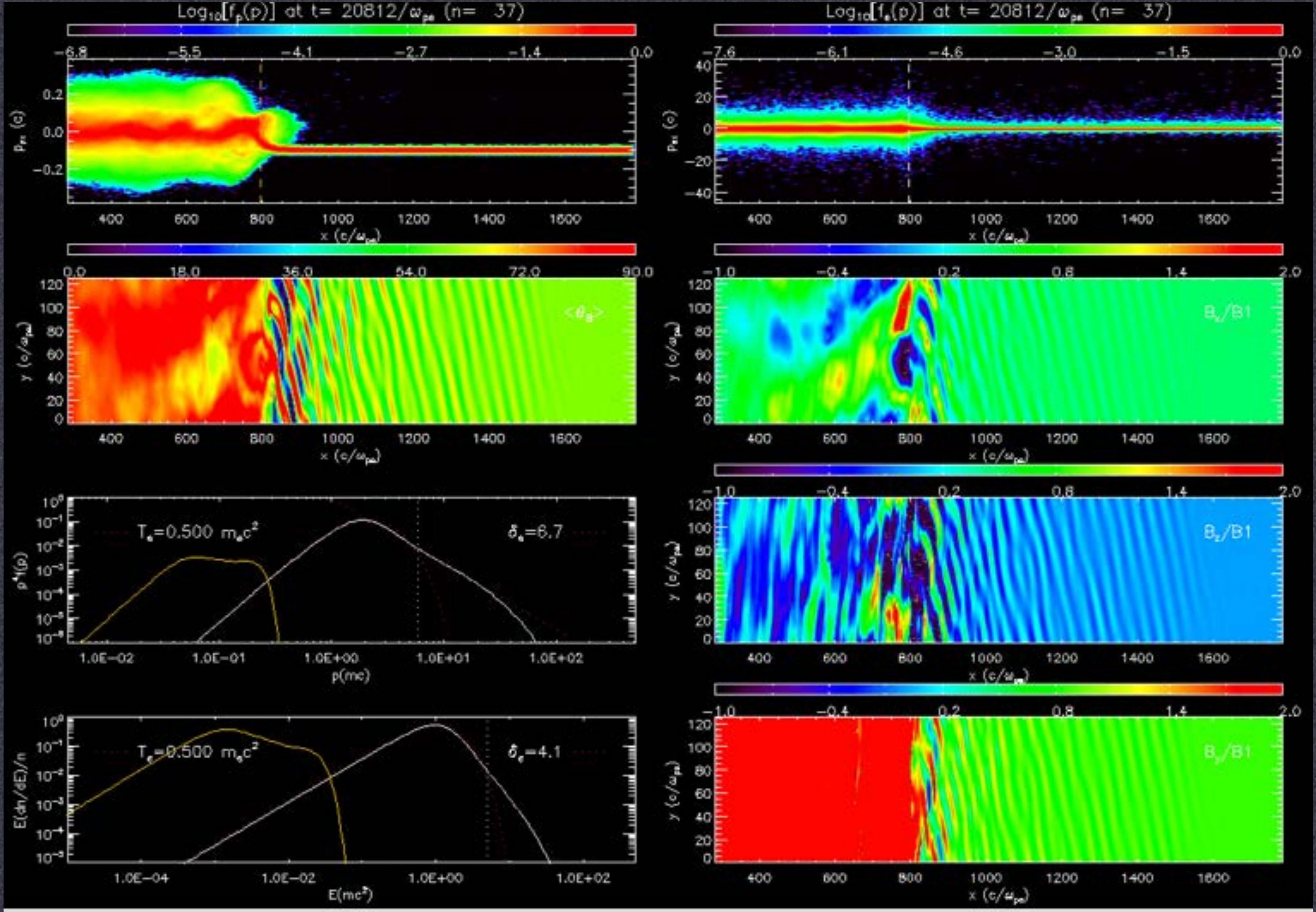
(Caprioli, Park, AS, in prep)



Ions are not injected or accelerated into DSA, while electrons drive their own Bell-type waves. Electrons are reflected from shock due to magnetic mirroring.

Recover DSA electron spectrum, 0.1-4% in energy, <1% by number.

Electron acceleration at ⊥-shocks: 2D



Low-M shocks; Whistler waves in the shock foot for $M_A<m_i/m_e$;

Electron DSA! Large-amplitude Electron-driven modes! Oblique firehose? (Guo+ 2014). Or whistlers?

Shock acceleration: emerging picture

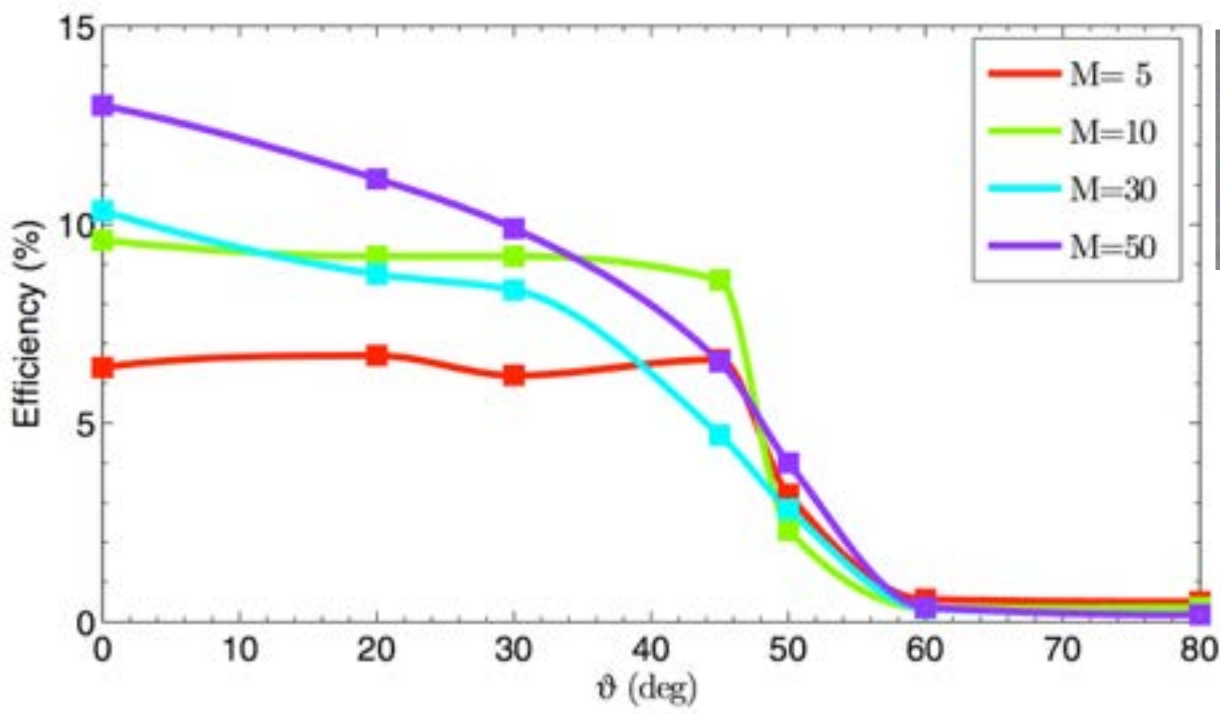
Acceleration in laminar field:

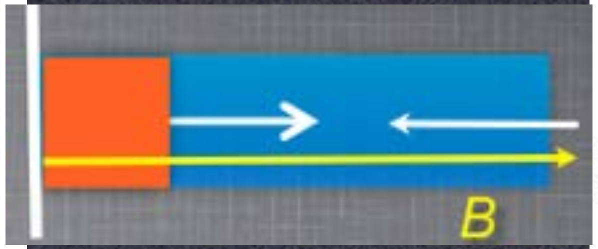
quasi-parallel -- accelerate both ions and electrons

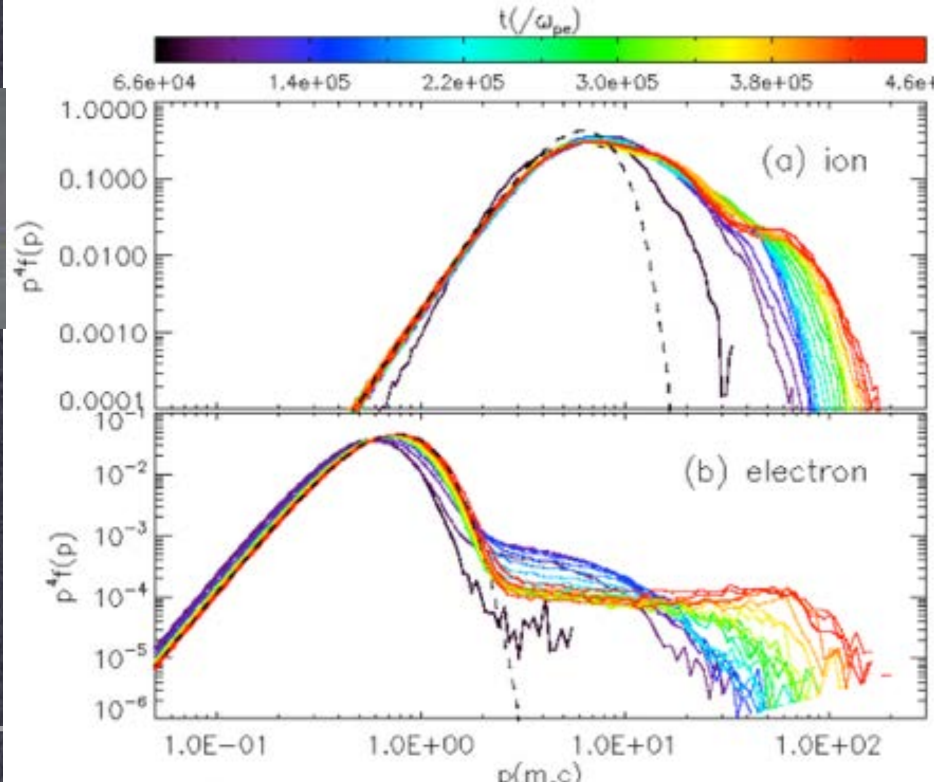
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)

quasi-perpendicular -- accelerate mostly electrons

(Guo, Sironi & Narayan 2014; Caprioli, Park, AS in prep)







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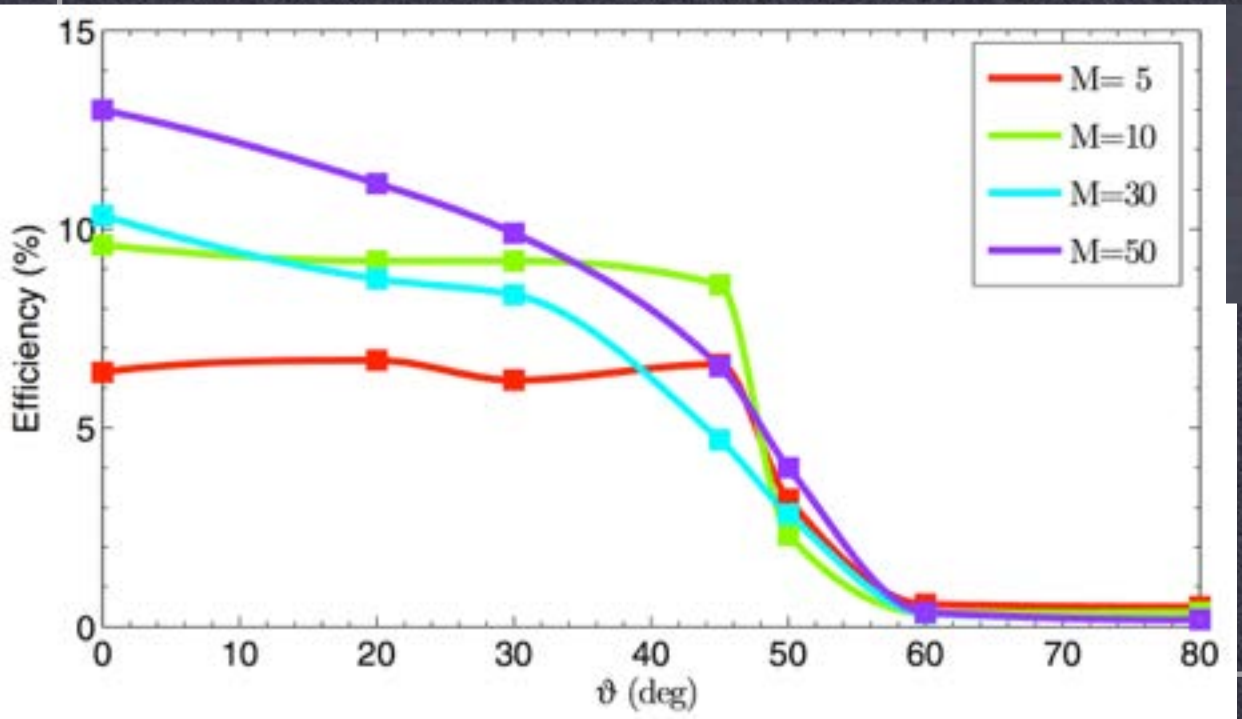
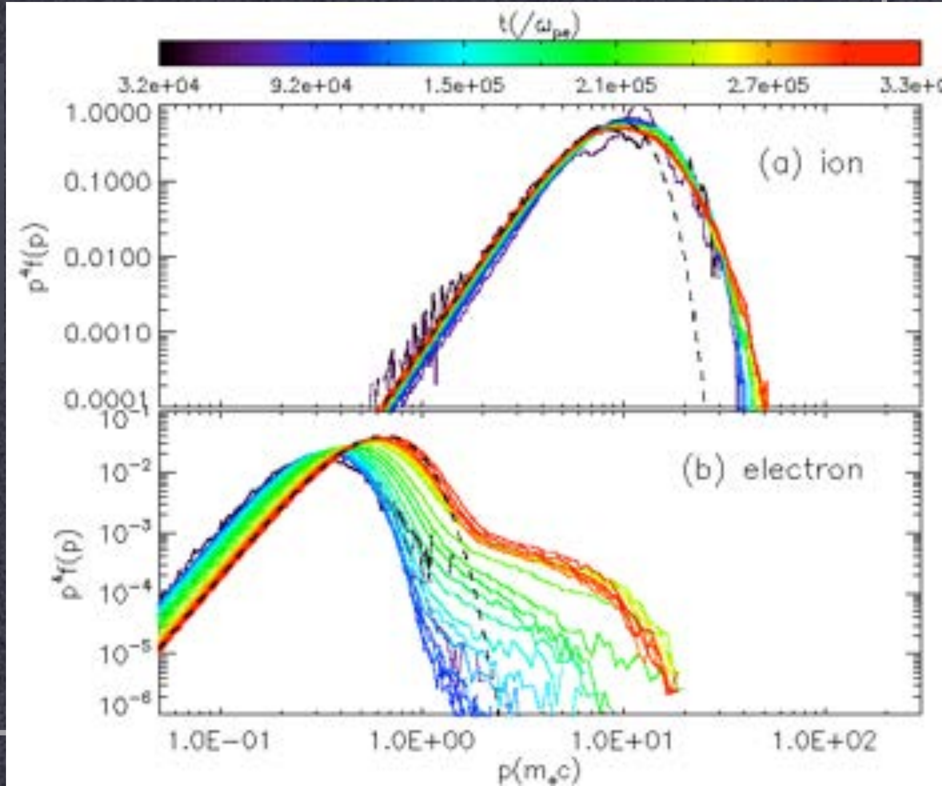
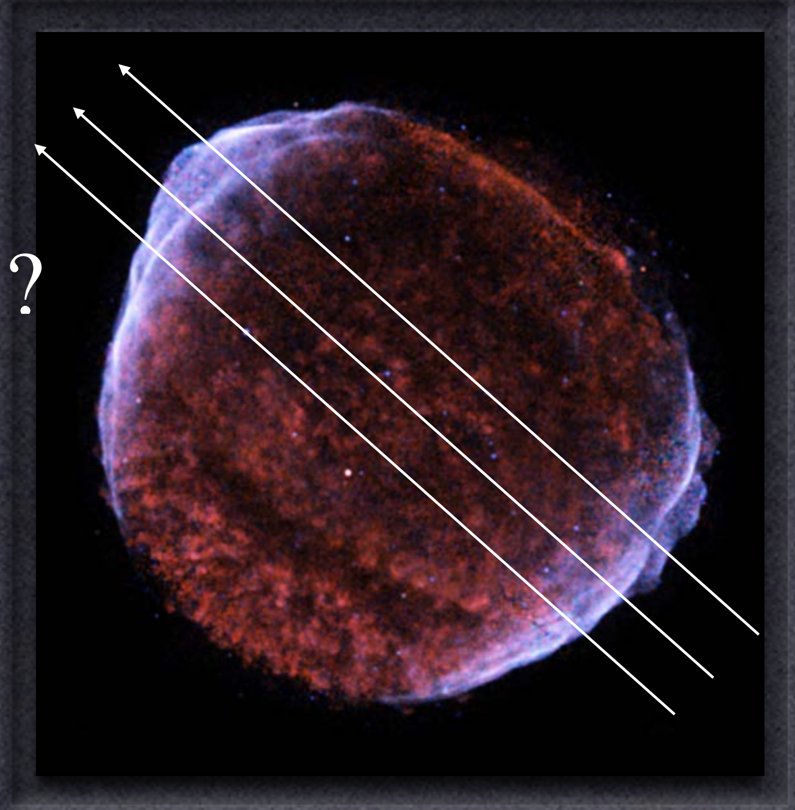




SNR story

Nonthermally-emitting SNRs likely have large scale parallel magnetic field (radial). This leads to CR acceleration and field amplification.



Locally-transverse field enters the shock, and causes electron injection and DSA.

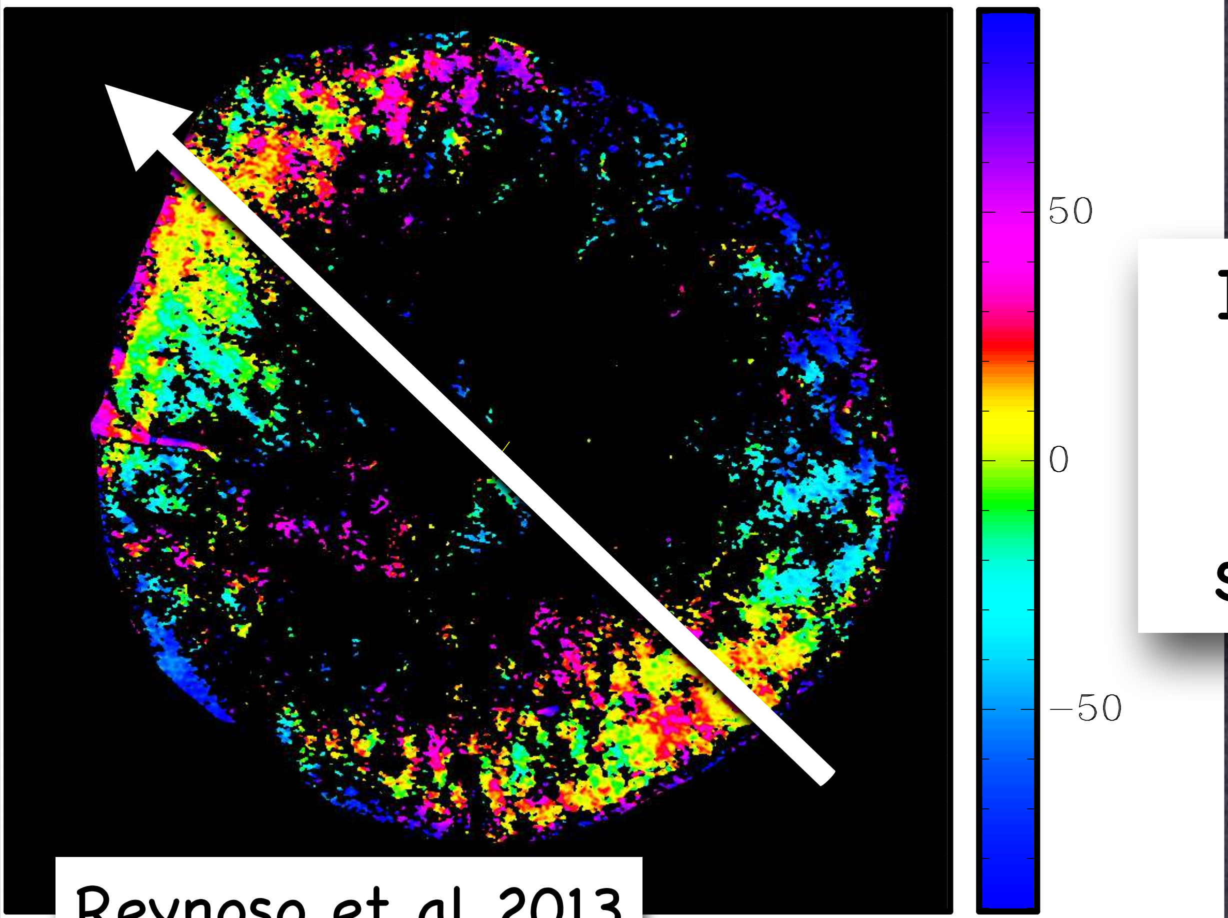
This favors large-scale radial B fields in young SNRs. Polarization in “polar caps” should be small -- field is random

Ab-initio plasma results allow to put constraints on the large-scale picture!

SN1006: a parallel accelerator

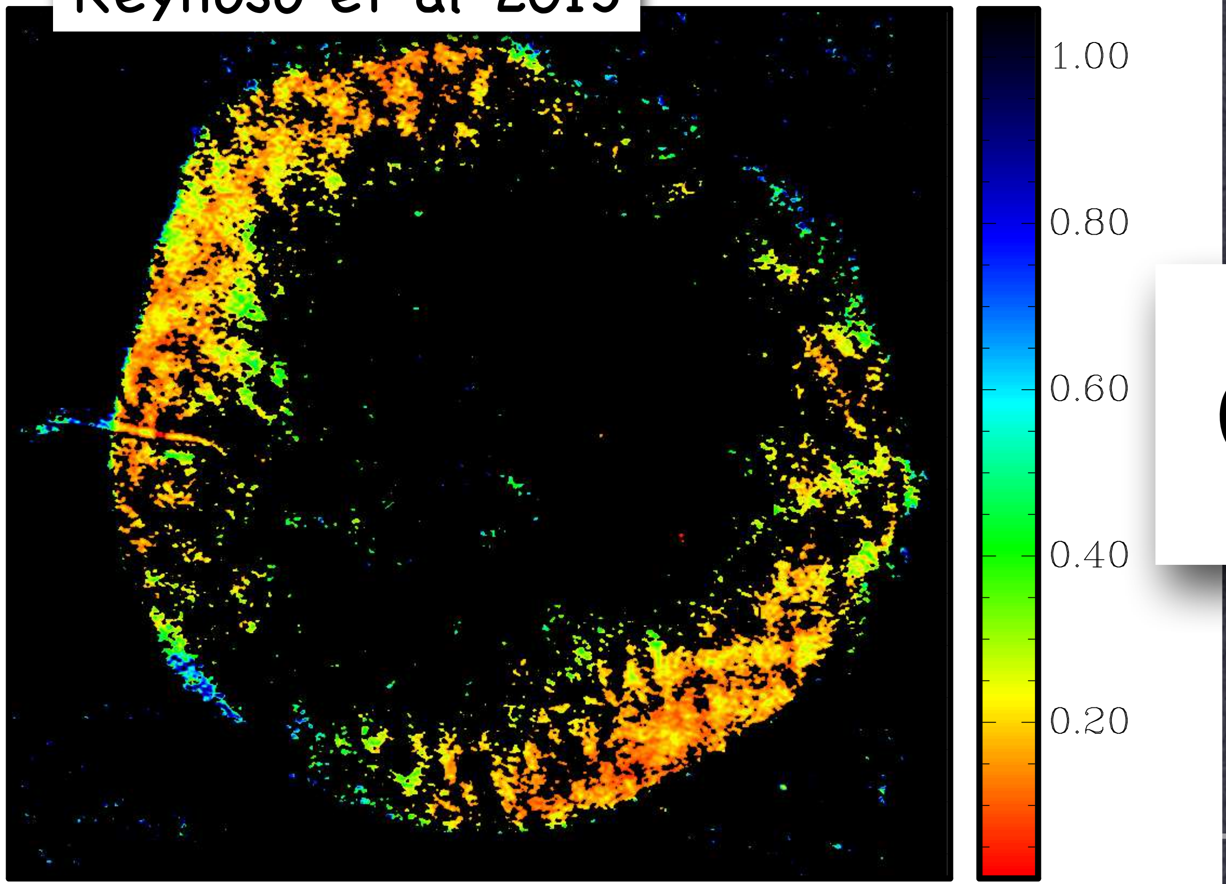
X-ray emission
(red=thermal
white=synchrotron)

Magnetic field amplification and particle acceleration where the shock is parallel

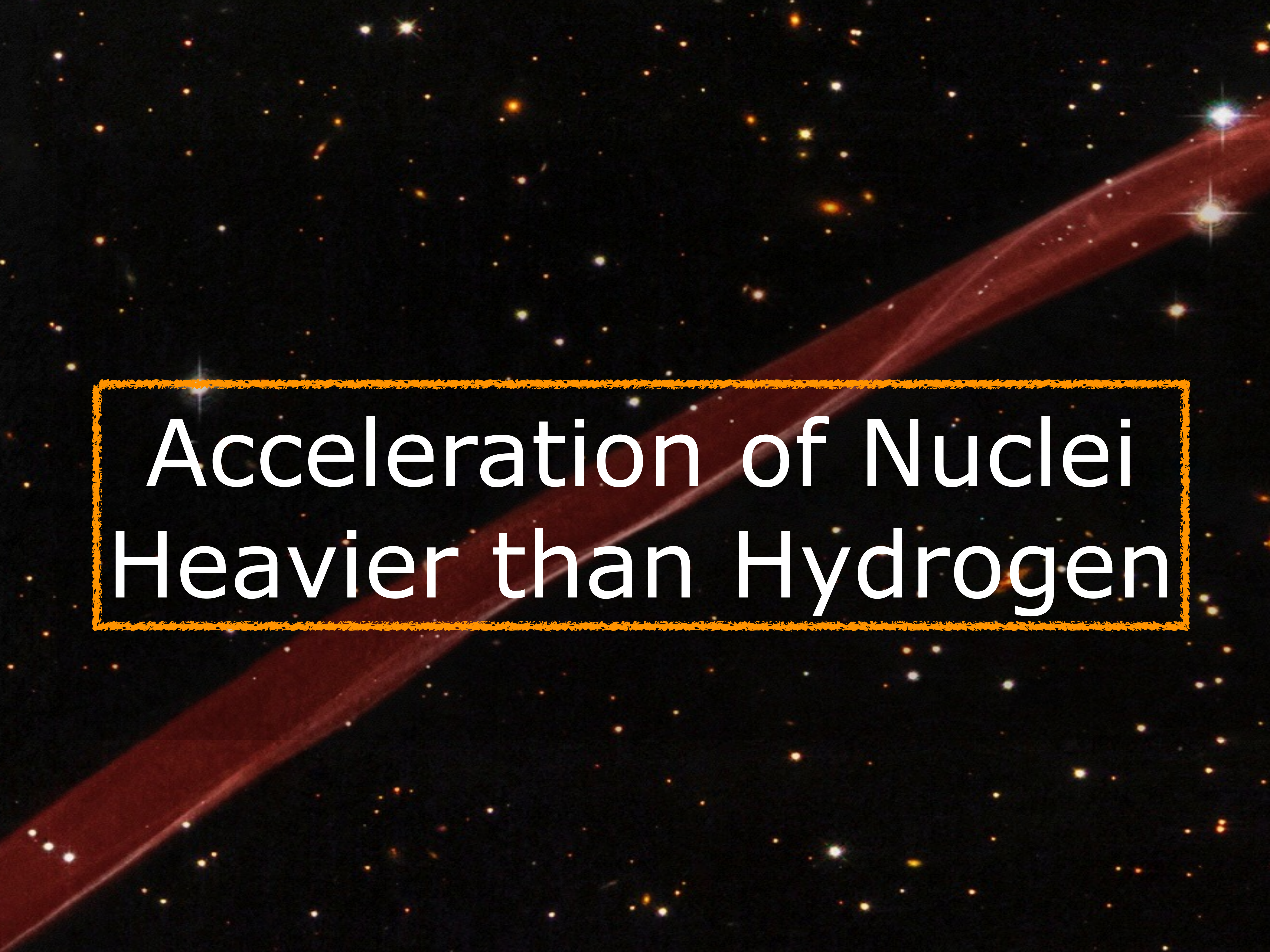


Reynoso et al 2013

Inclination of the B field wrt to the shock normal



Polarization
(low=turbulent
high=ordered)



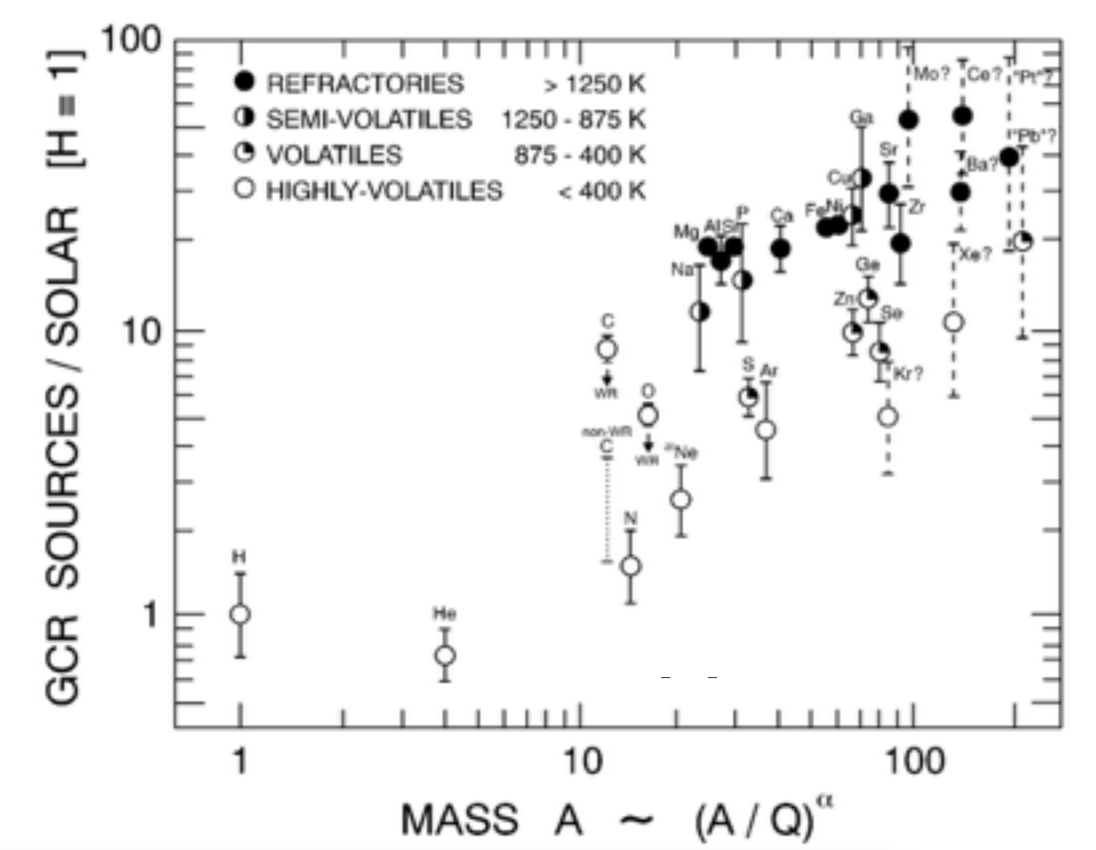
Acceleration of Nuclei Heavier than Hydrogen

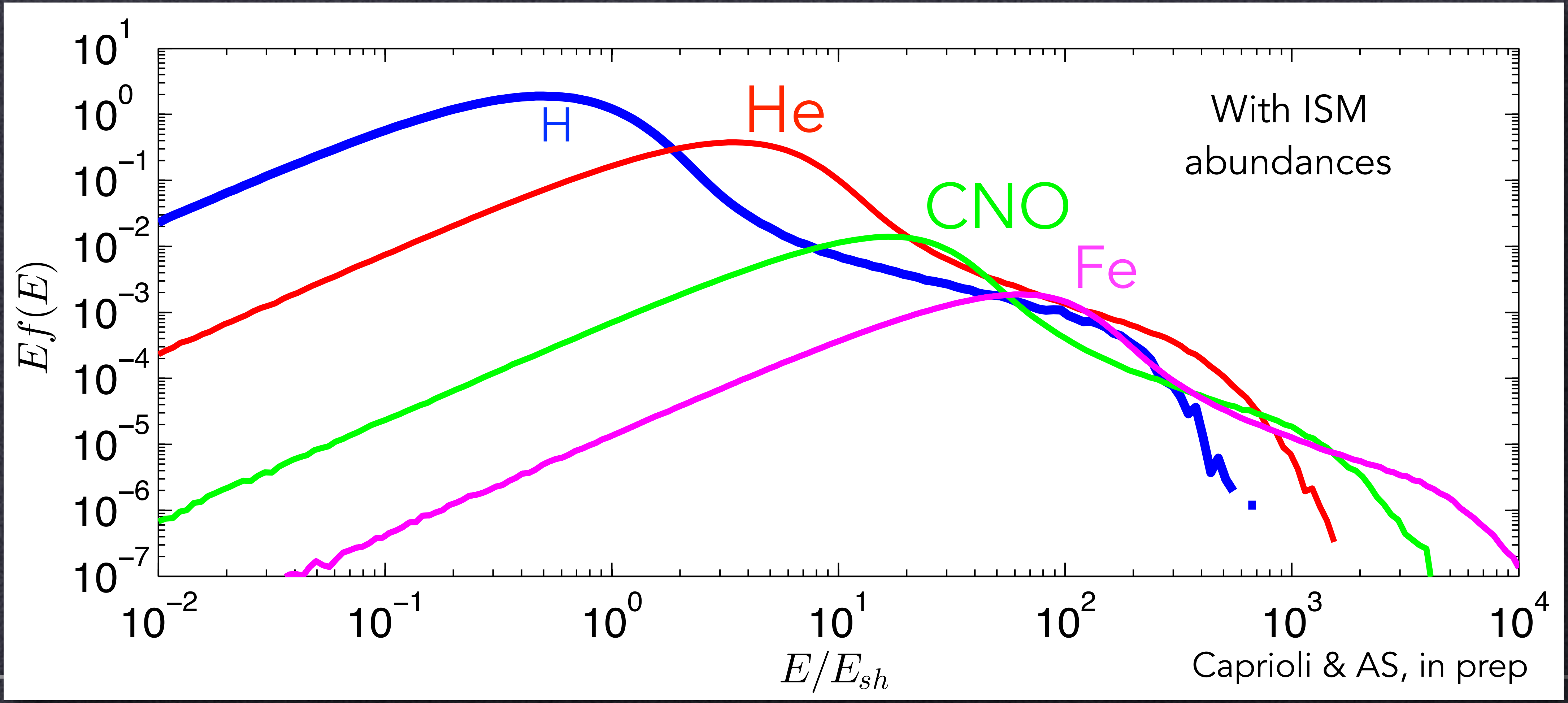
Acceleration of heavy nuclei

Nuclei heavier than H must be injected more efficiently (Meyer et al 97)

Multi-species hybrid simulations.
Max energy is proportional to charge Z;

Most nuclei have A/Z ~ 2. Investigate also A/Z>2 for partially ionized nuclei.



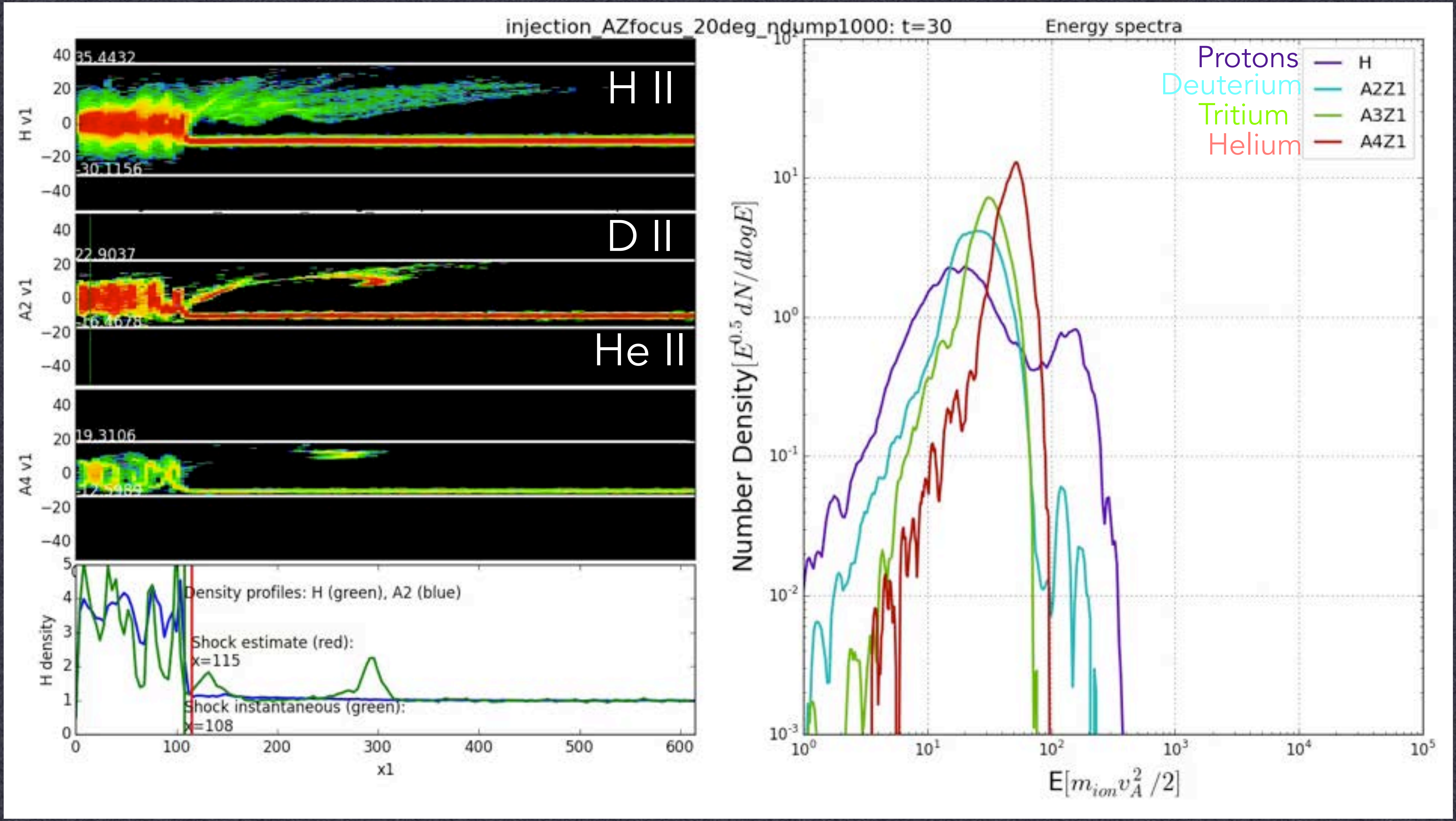


With ISM abundances

Caprioli & AS, in prep

Injection of singly-ionized nuclei

M=10, parallel shock (Caprioli, Yi, AS in prep)



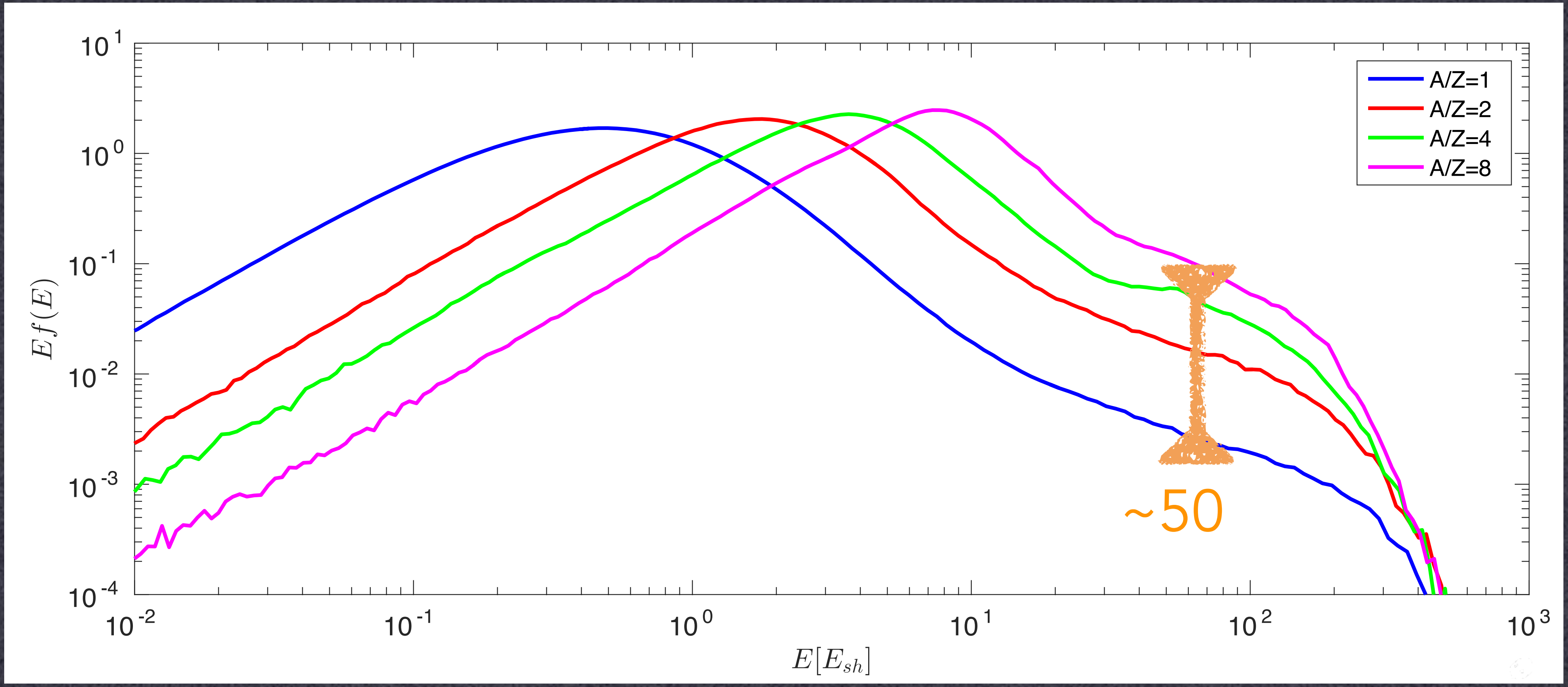
Injection fraction is larger for nuclei with larger A/Z!

Injection of singly-ionized nuclei

In the absence of H-driven turbulence, heavies are thermalized far downstream

With B amplification from H, heavies are thermalized to $kT=A\,mv_{sh}^2/2$, and can recross the shock due to their large larmor radii. More chances to scatter on H fluctuations leads to higher "duty fraction" of the shock for larger A/Z.

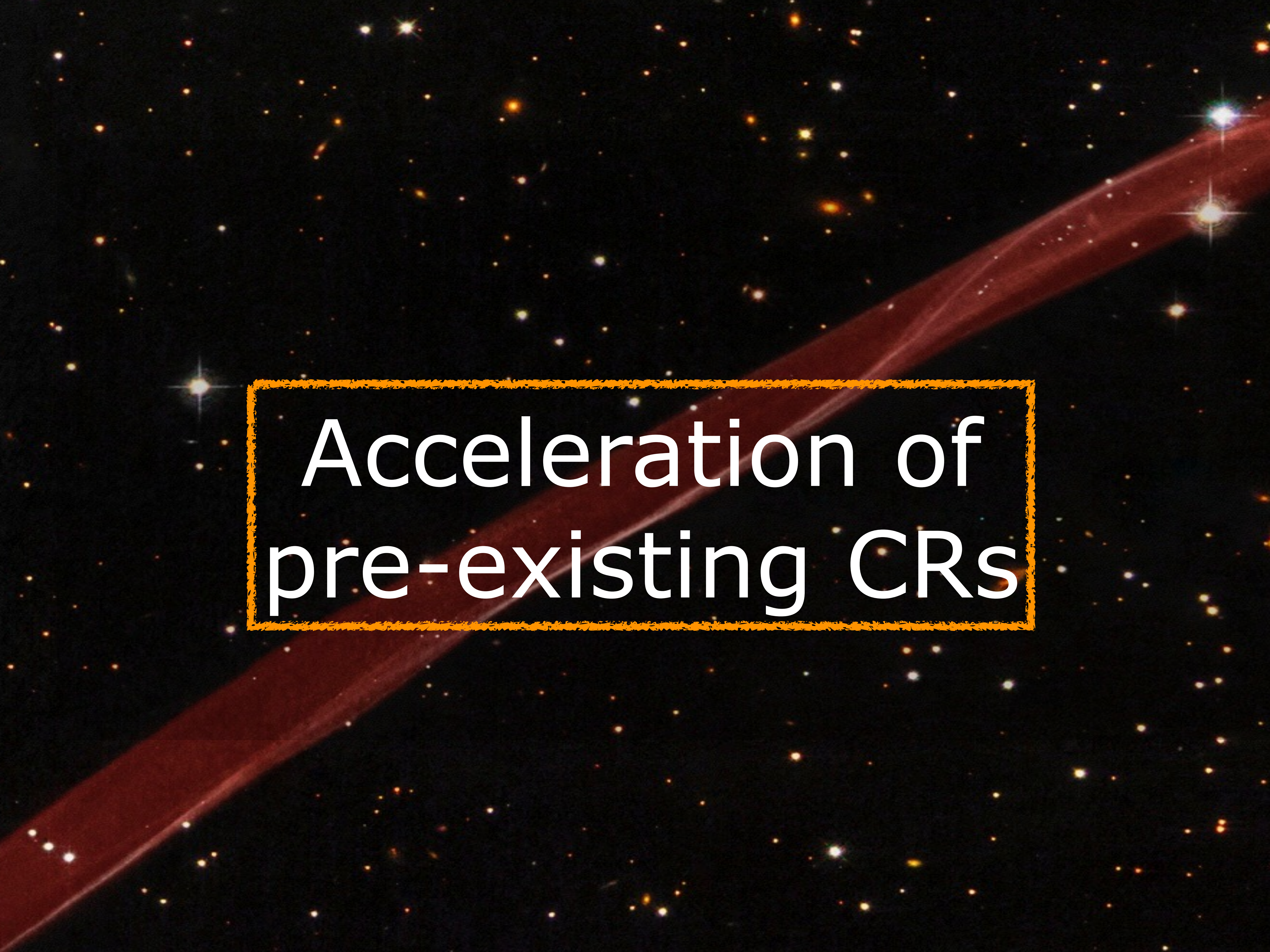
Nuclei enhancement depends on A/Z and Mach number.



Caprioli, Yi, AS in prep

Injection fraction is larger for nuclei with larger A/Z!

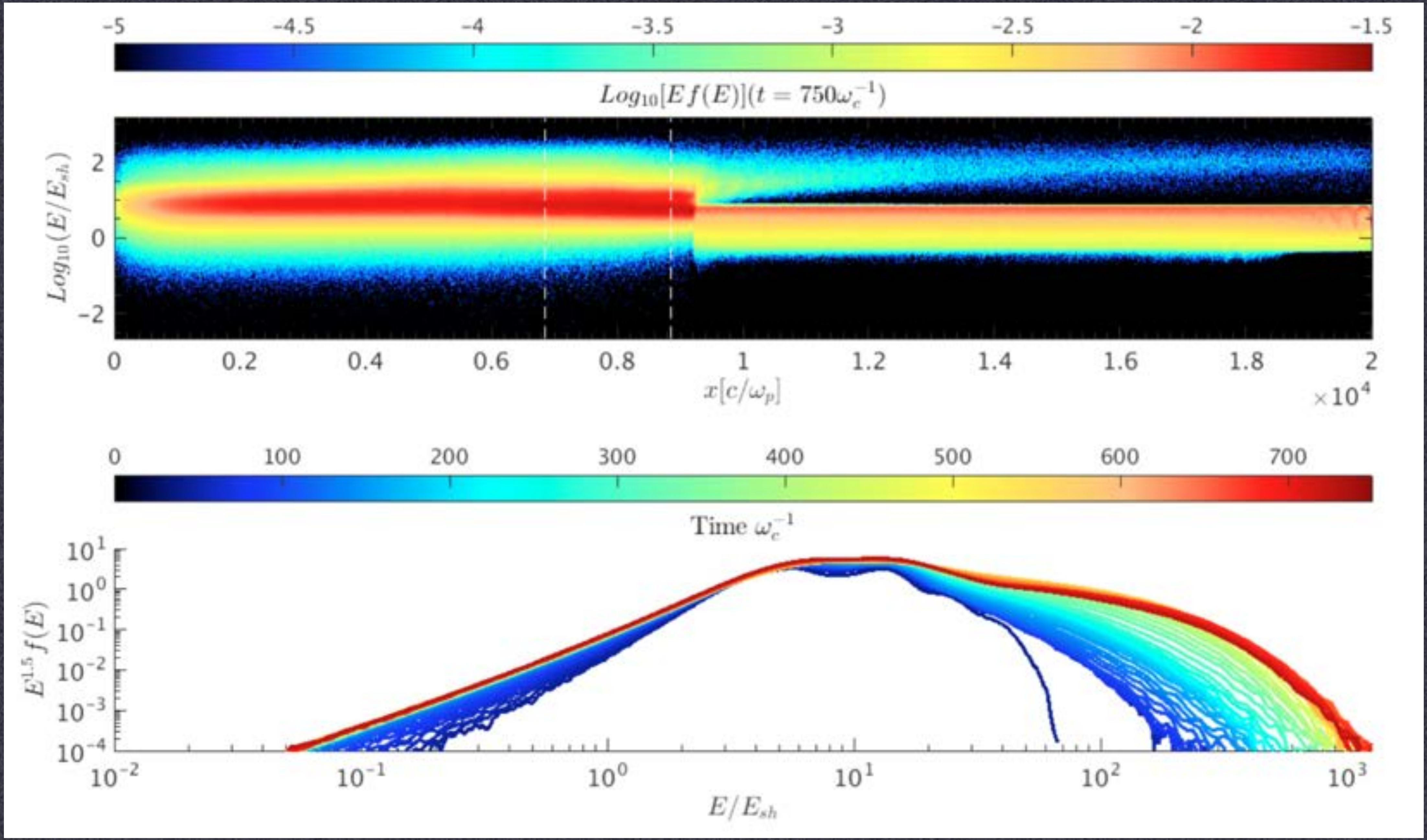
Acceleration of pre-existing CRs



Re-acceleration of pre-existing CRs

Add hot "CR" particles to upstream flow.

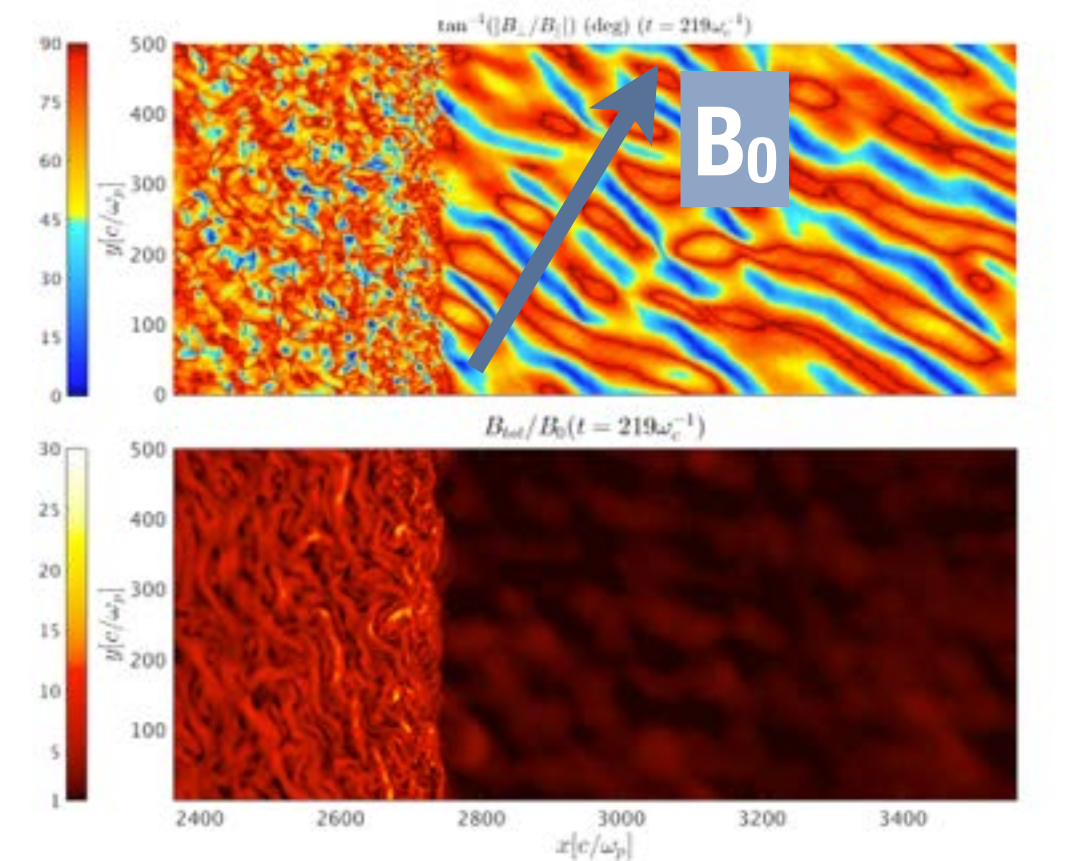
Quasi-perp shock: CRs have large Larmor radii and can recross the shock, accelerate, and be injected into diffusive acceleration process; 10



Turbulence driven by reaccelerated CRs

Escaping CRs drive turbulence

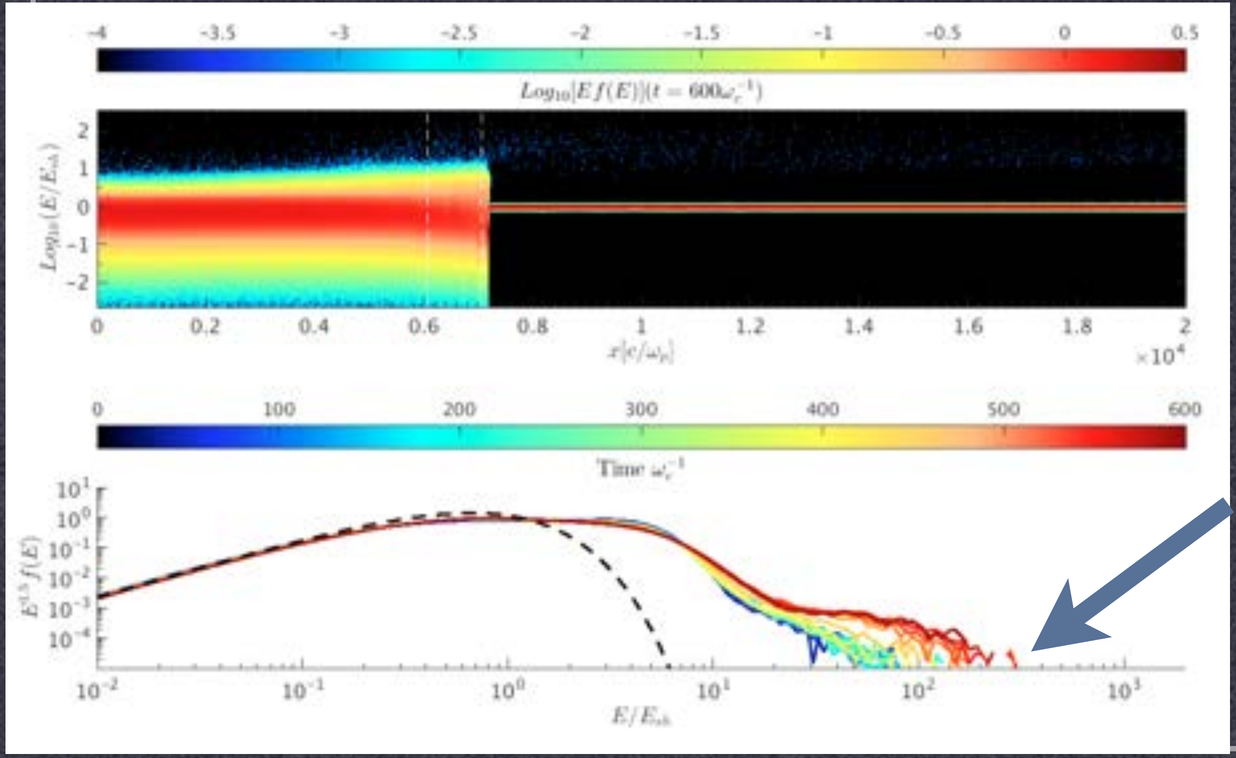
field inclination



Orientation of the field at the shock changes to regions of quasi-parallel, and efficiency of H acceleration increases.

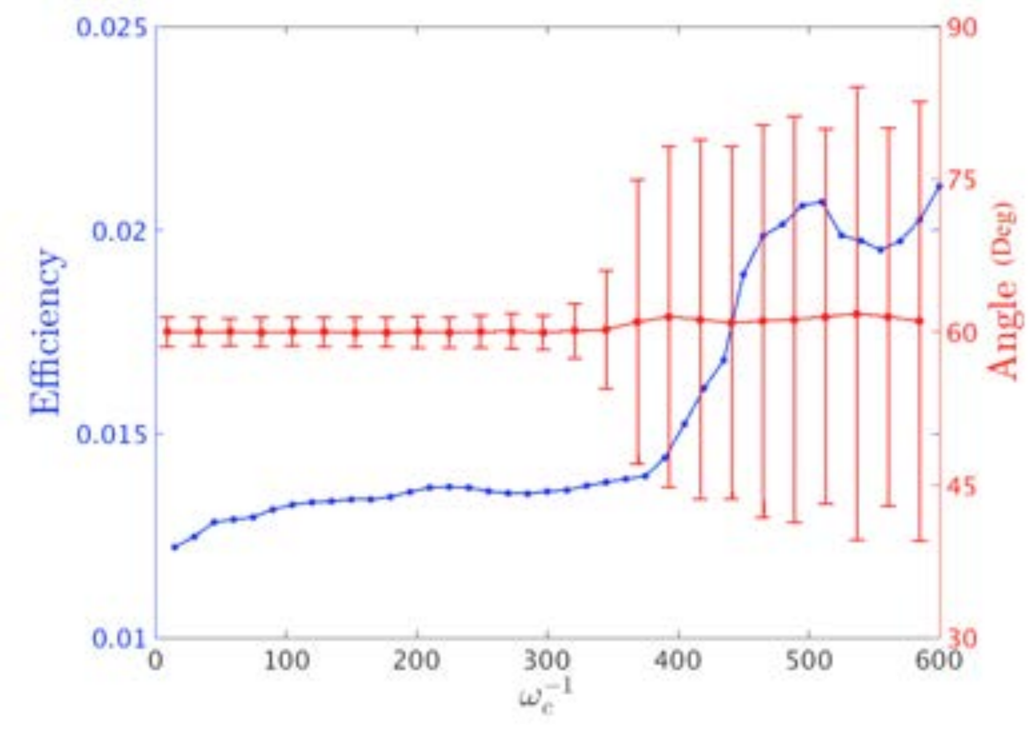
Pre-existing CRs improve local efficiency of the shock!

Growth time in SNR ~10yrs << age.



Proton spectrum

60˚ shock



Conclusions

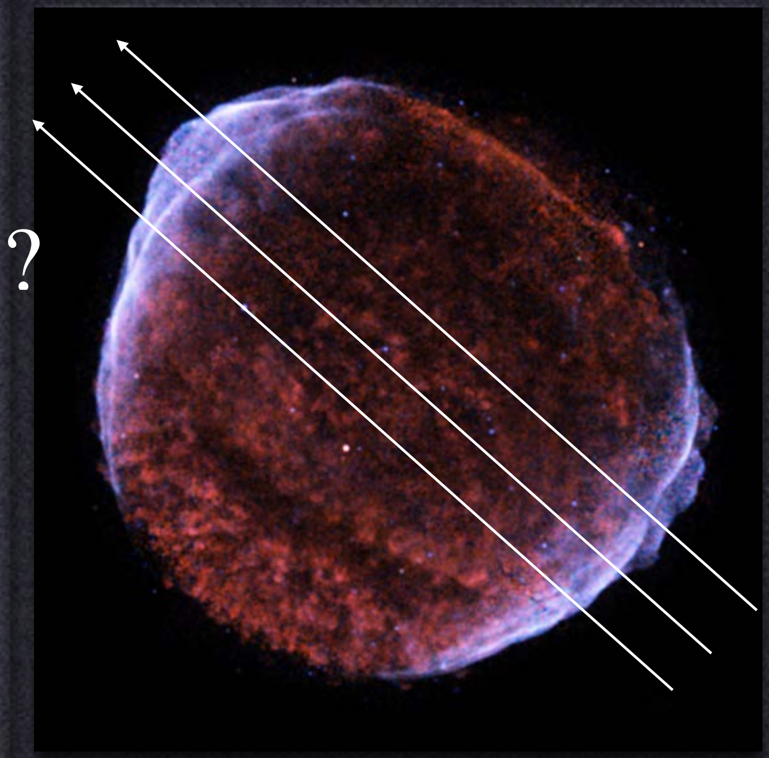
Kinetic simulations allow to calculate particle injection and acceleration from first principles, constraining injection fraction

Magnetization (Mach #) of the shock and B inclination controls the shock structure

Nonrelativistic shocks accelerate ions and electrons in quasi-par if B fields are amplified by CRs. Energy efficiency of ions 10-20%, number ~few percent; K_{ep}~10^{-3}; p^{-4} spectrum

Electrons are accelerated in quasi-perp shocks, energy several percent, number <1%. Fewer ions are accelerated at oblique shocks.

A/Z>2 species are injected more efficiently; CR re-acceleration may be important



Long-term evolution, turbulence & 3D effects need to be explored more: more advanced simulation methods are coming