Copenhagen
August 18, 2022

On the Acceleration Efficiency of Low-Mach Number Shocks

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WHEN/WHERE: From Helio to Cosmological Scales

HELIOSPHERIC

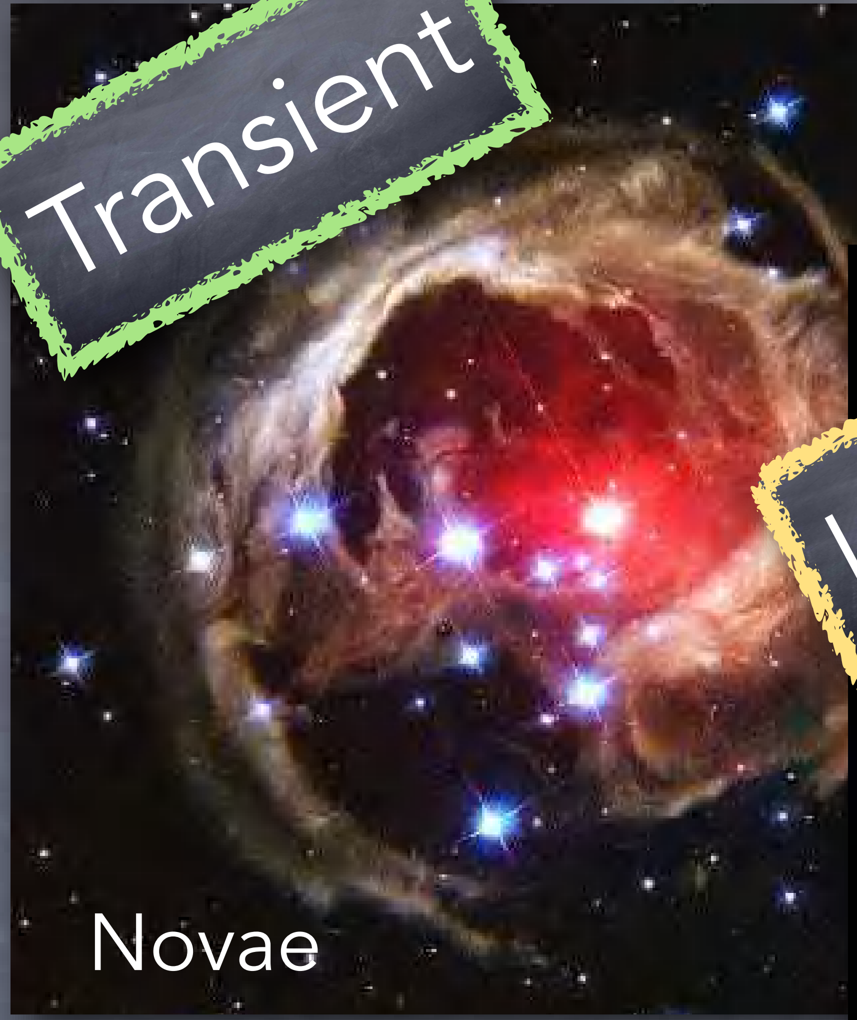

In situ

Earth's bow shock


Transient

Solar flares and helio shocks

GALACTIC


Transient

Novae

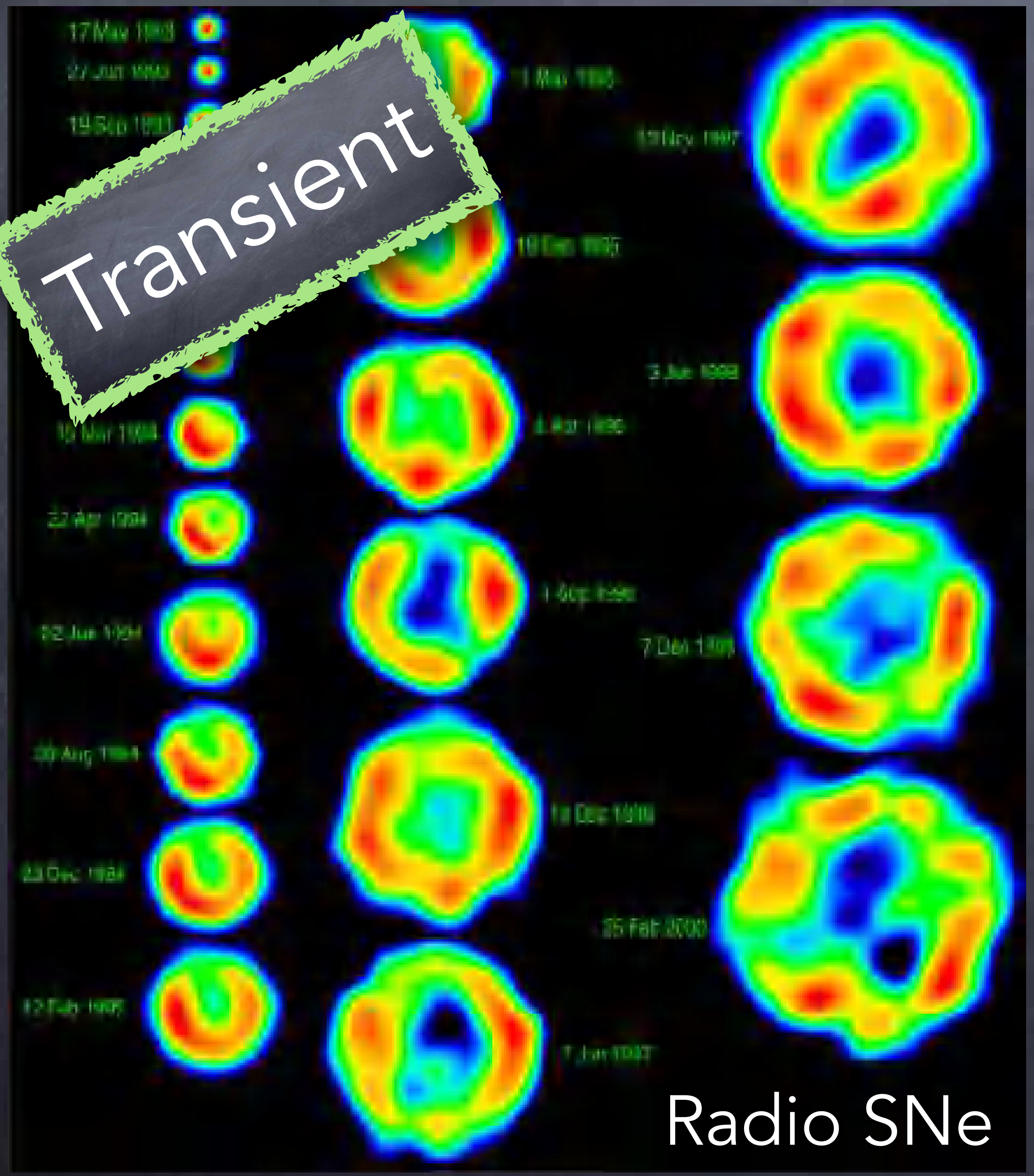

Long-lived

Supernova remnants


Flaring

Pulsars and PWNe

EXTRA-GALACTIC


Transient

Radio SNe


Flaring

AGN jets/lobes


Long-lived

AGN Winds

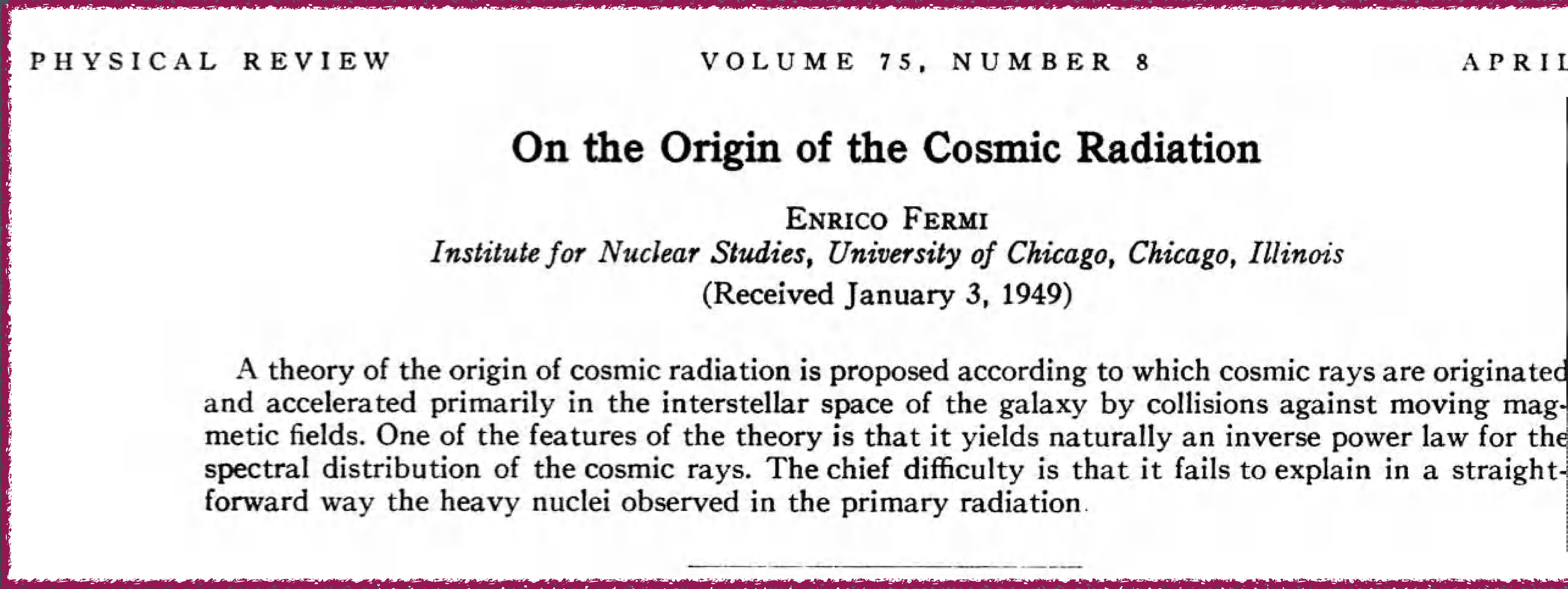

Long-lived

Galaxy clusters

A universal acceleration mechanism

- Fermi mechanism (Fermi, 1949): random elastic collisions lead to energy gain

rd+78)



PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

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(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

- DSA produces power-laws $N(p) \propto 4\pi p^2 p^{-\alpha}$, depending on the compression ratio $R = \rho_d/\rho_u$ only.

$$\boxed{R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}}$$

  - For strong shocks (Mach number $M_s = V_{sh}/c_s \gg 1$): $R = 4$ and $\alpha = 4$

A *Universal* Acceleration Mechanism

- Bell 1978: Let's start with N_0 particles with energy E_0, and a process where at each iteration
  - G is the energy gain and P is the probability of remaining in the accelerator
- After k steps: we have $N_k = P^k N_0$ particles with energy $E_k = G^k E_0$, i.e.,:

$$\frac{dN_k}{dE} = N_0 \left(\frac{E_k}{E_0}\right)^{-q_E}; \quad q_E = 1 - \frac{\log P}{\log G}$$

$$G \simeq 1 + \frac{4}{3}\frac{u_1 - u_2}{c}$$

$$P \simeq 1 - \frac{4u_2}{c}$$

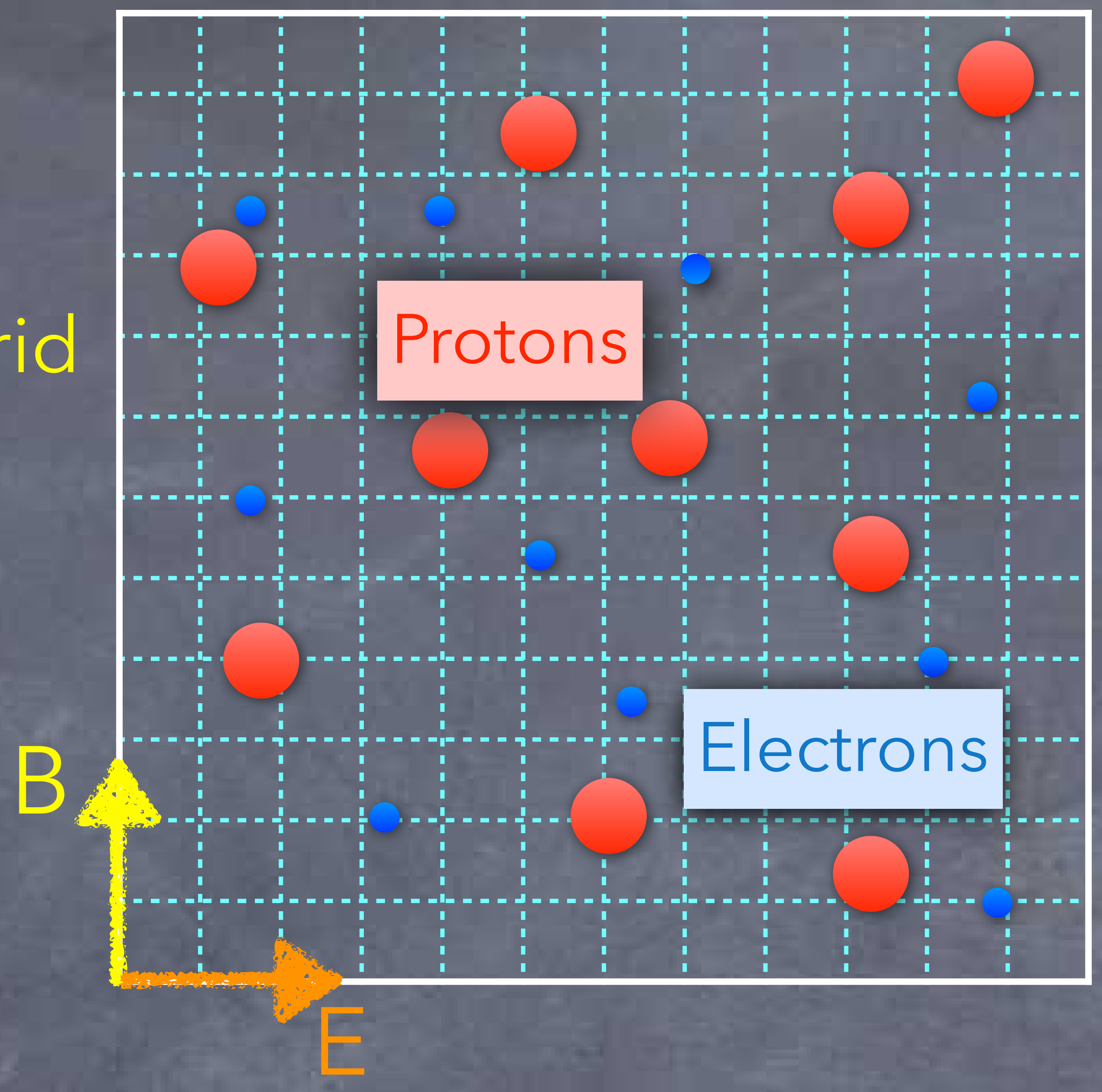
$$q_E \simeq \frac{R+2}{R-1}; \quad R = \frac{u_1}{u_2}$$

- DSA returns energy power-law $f(E) \propto E^{-q_E}$, function of the compression ratio R only.
  - In momentum (relativistically covariant), $f(p) \propto 4\pi p^2 p^{-q}$, with $q = \dfrac{3R}{R-1}$
- For any strong shock: Mach number $M = \dfrac{v_{sh}}{c_s} \gg 1 \rightarrow R = 4$ and spectra are $f(p) \propto p^{-4}$ or

$$f(E) \propto E^{-2} \text{ (for relativistic particles)}$$

Astroplasmas from first principles

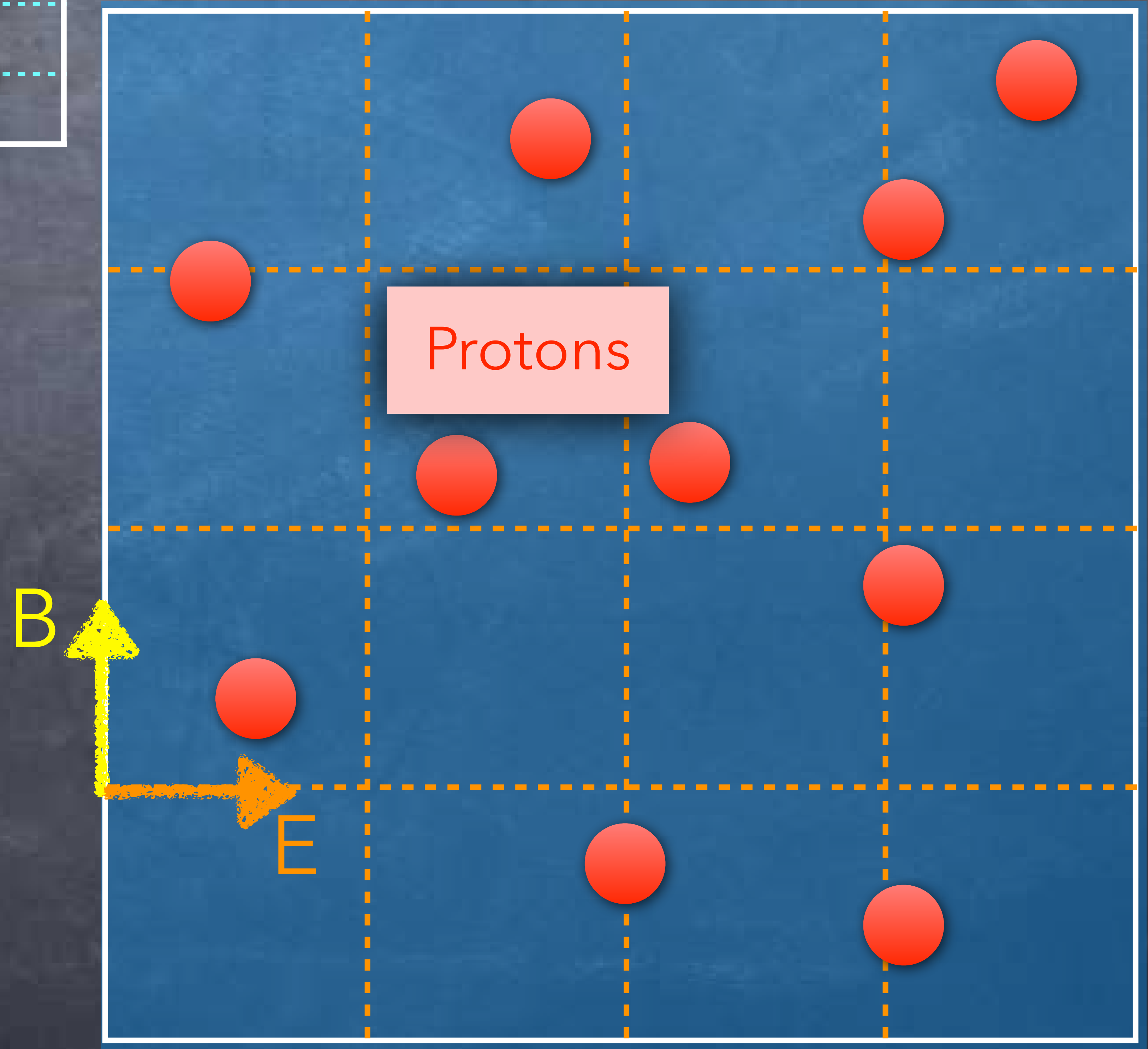
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



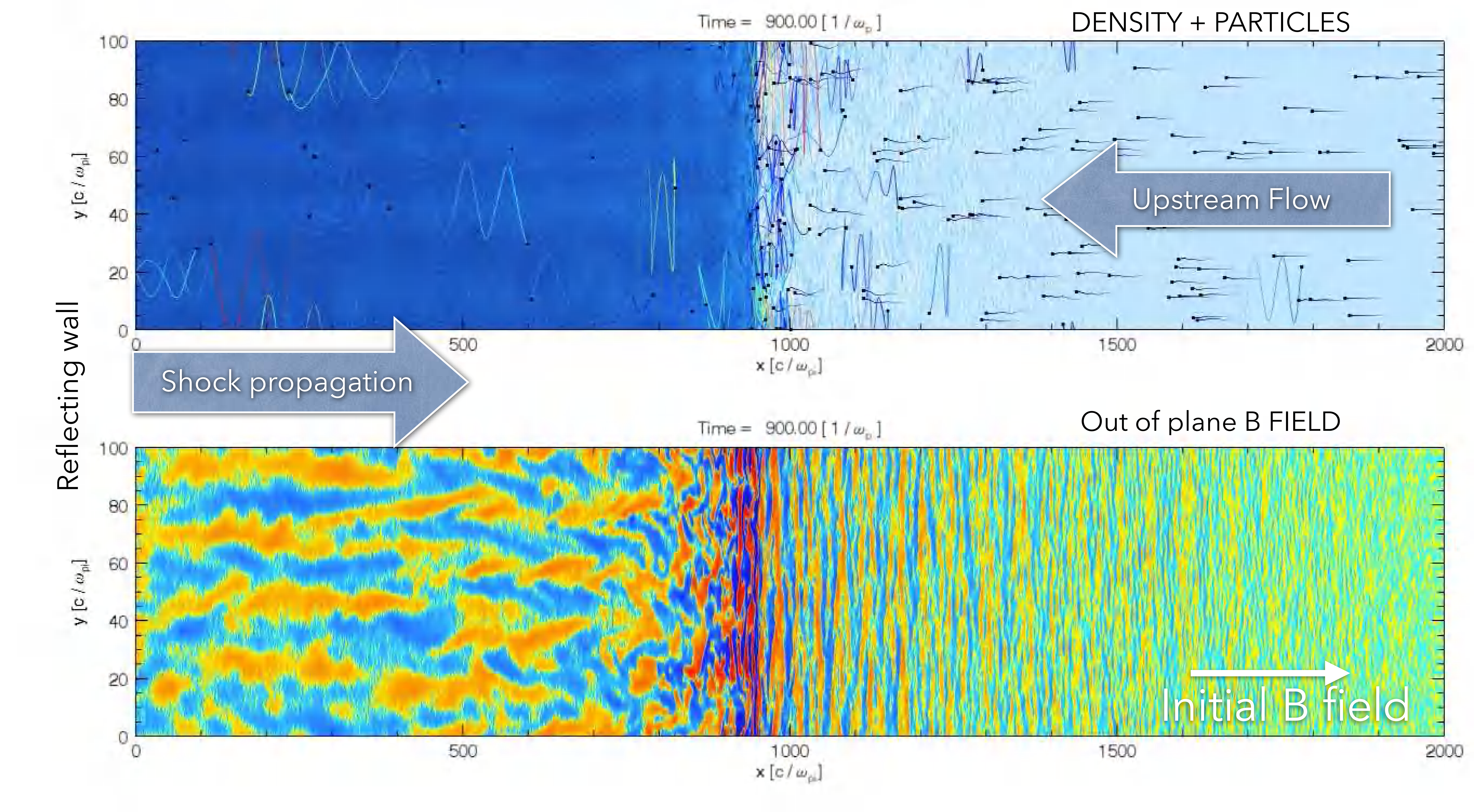
- Hybrid approach: Fluid electrons - Kinetic protons

  (Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015, Haggerty & DC 2019-2022)

  - massless electrons for more macroscopical time/length scales



Hybrid Simulations of Collisionless Shocks

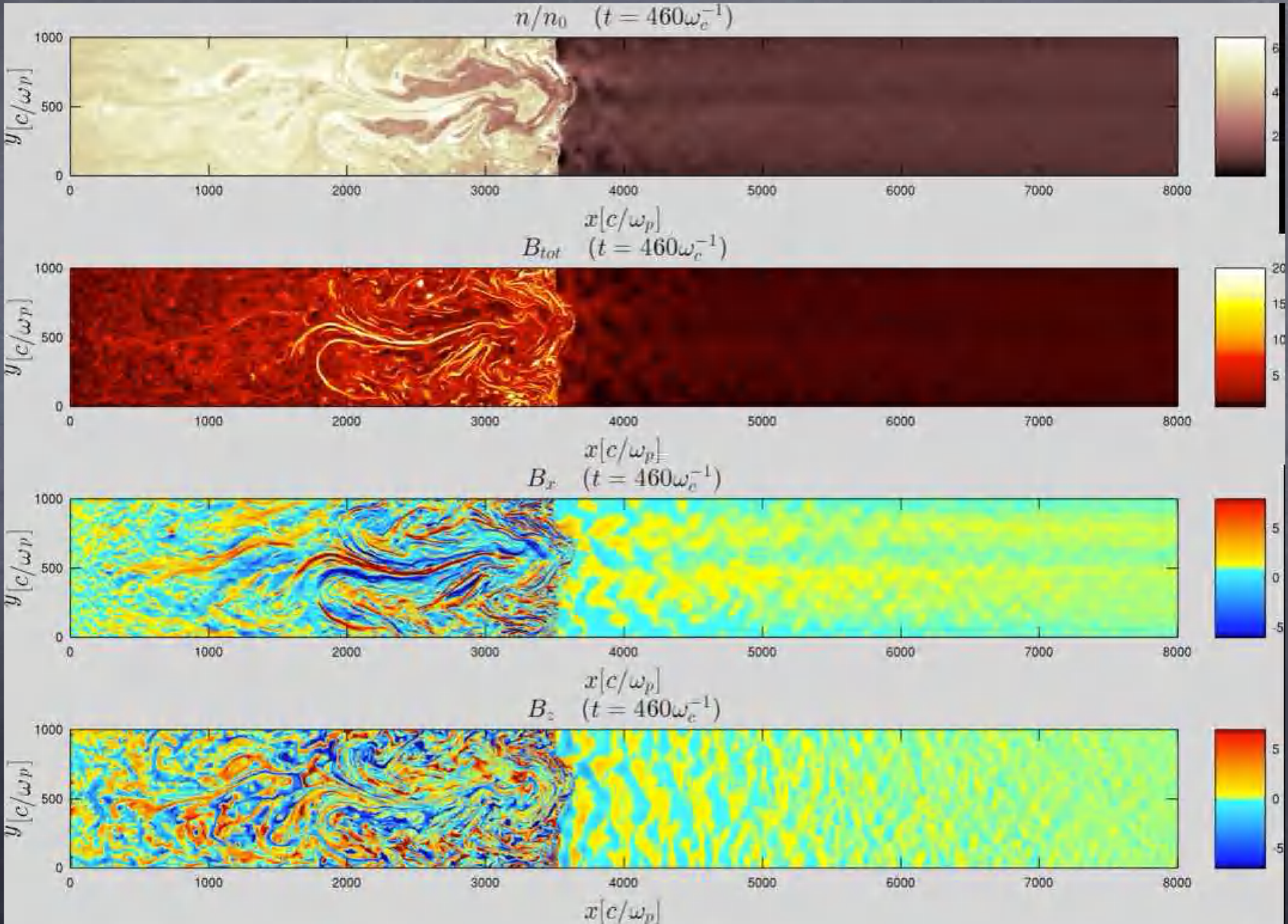


dHybrid code (Gargaté+07; Caprioli-Spitkovsky13-18), now ***dHybridR*** (+relativity; Haggerty & Caprioli 2019)

CR-driven Magnetic-Field Amplification

Initial B field

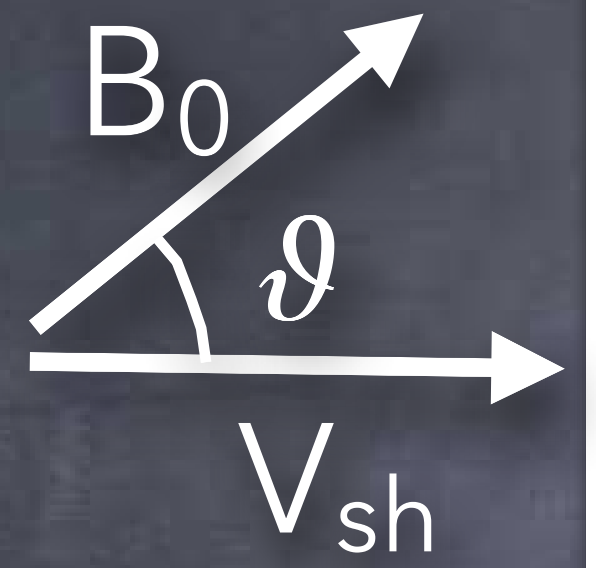
$M_s = M_A = 30$

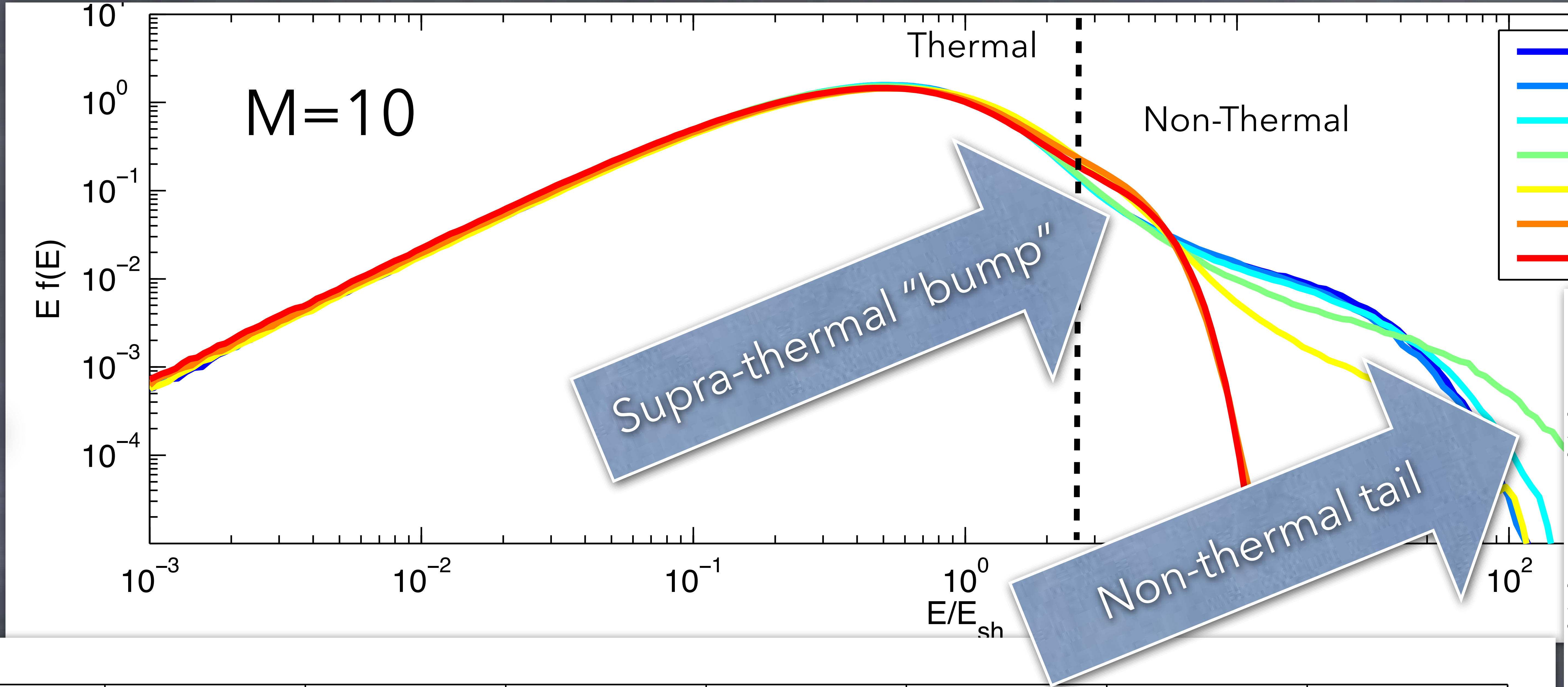


DC & Spitkovsky, 2013

Parallel vs Oblique shocks

Shock inclination

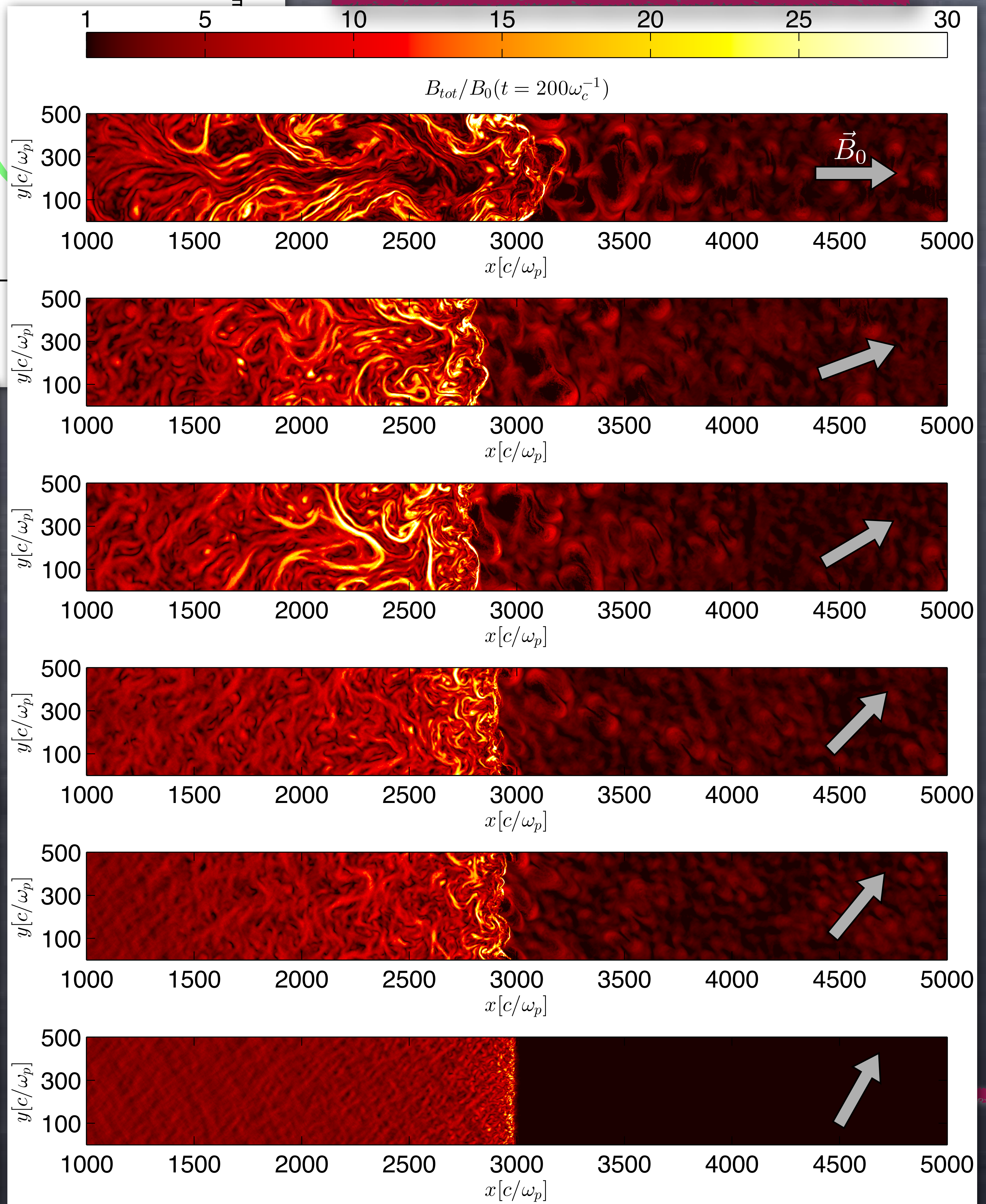


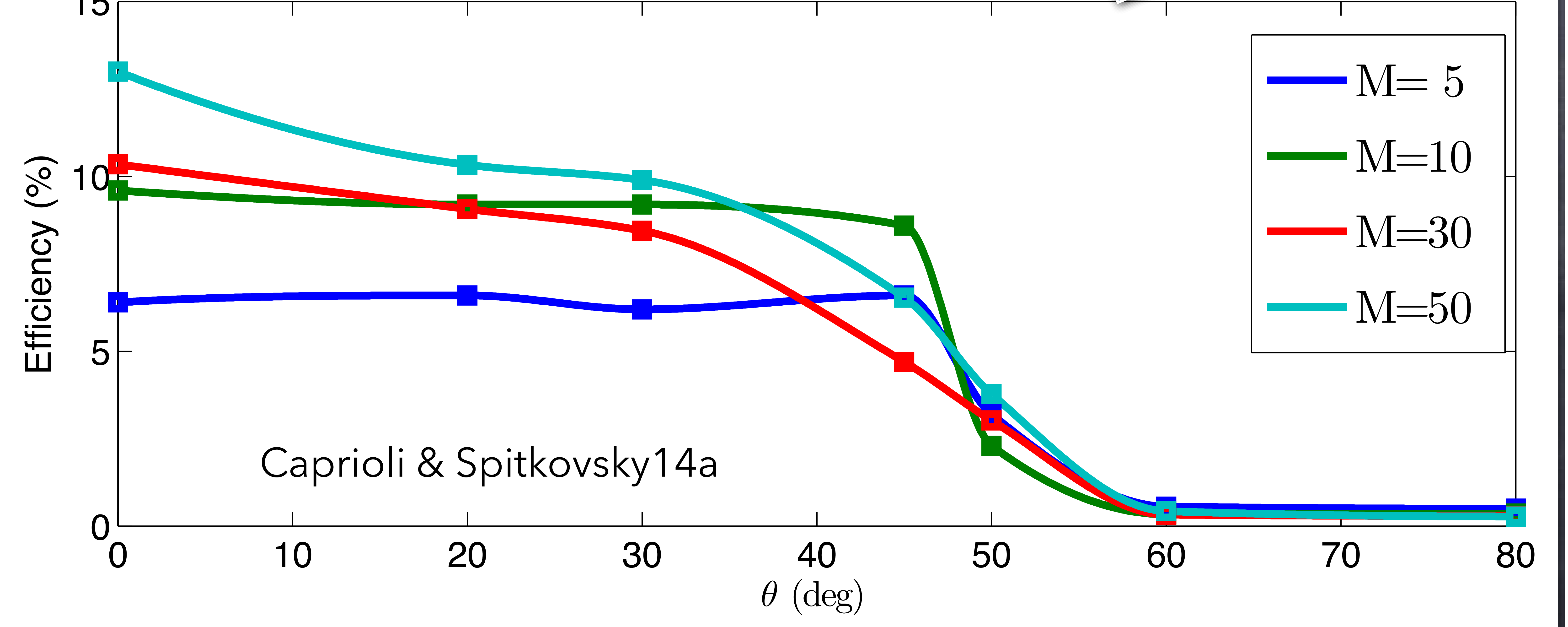


Supra-thermal "bump"

Non-thermal tail

Ion acceleration correlates with B-field amplification

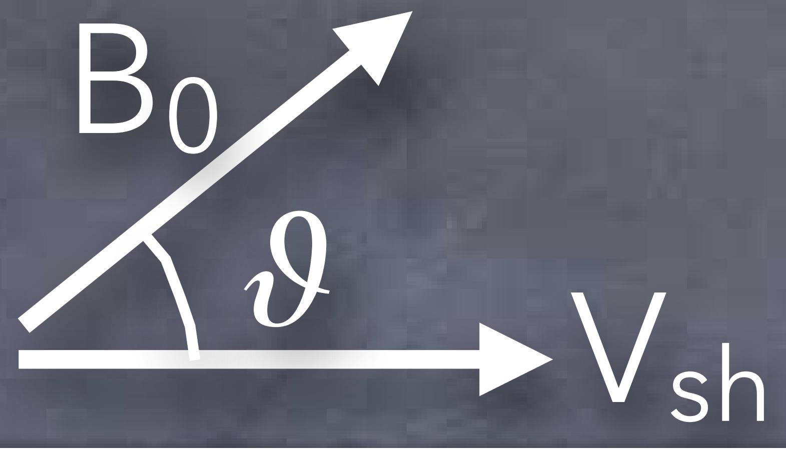


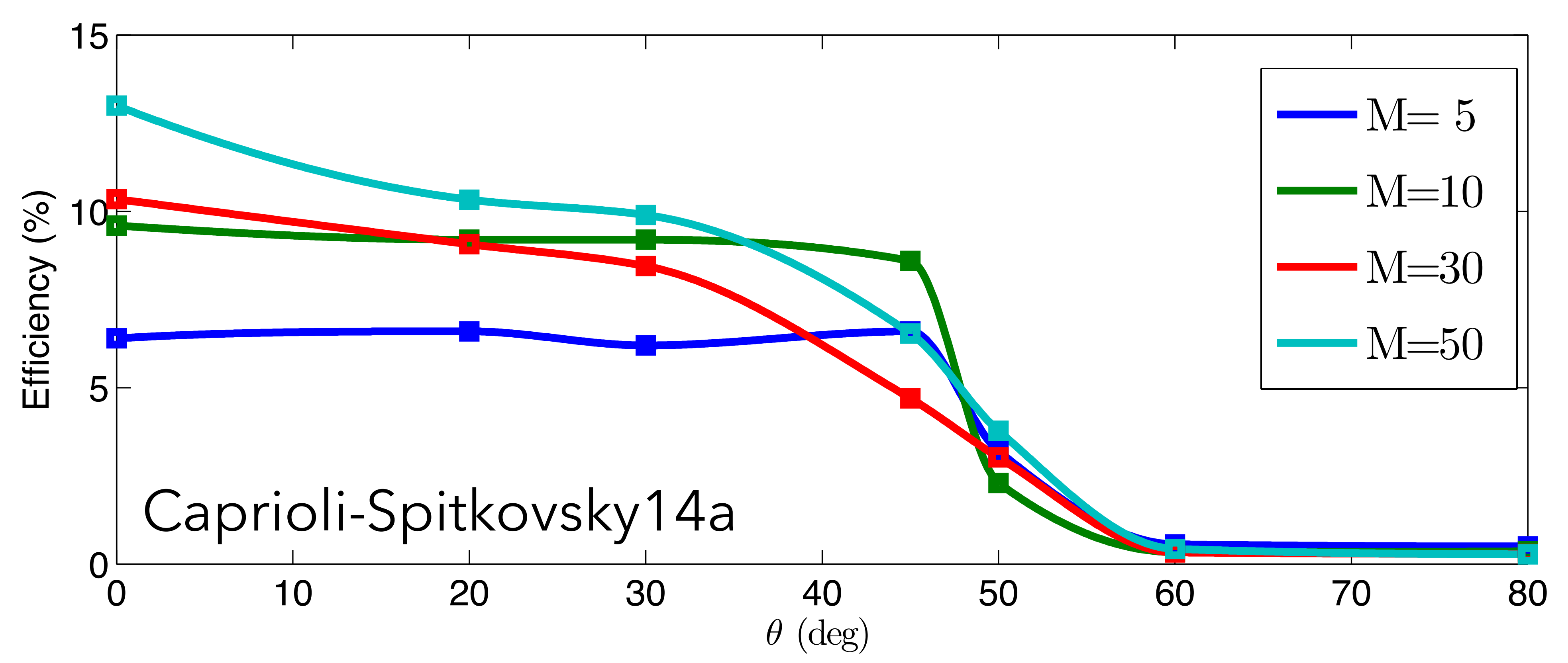


Caprioli & Spitkovsky14a

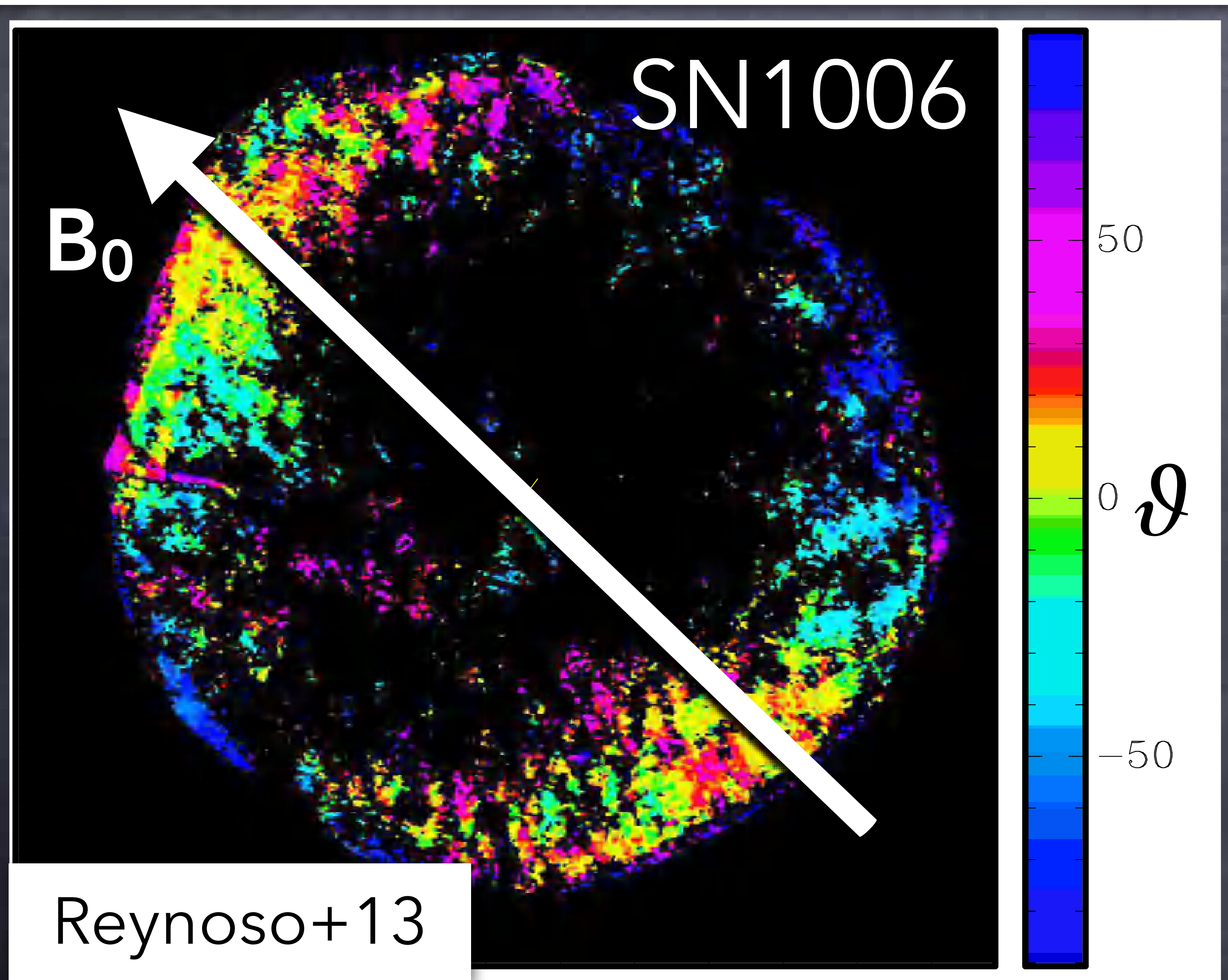
DSA Efficiency

Acceleration depends on the shock inclination



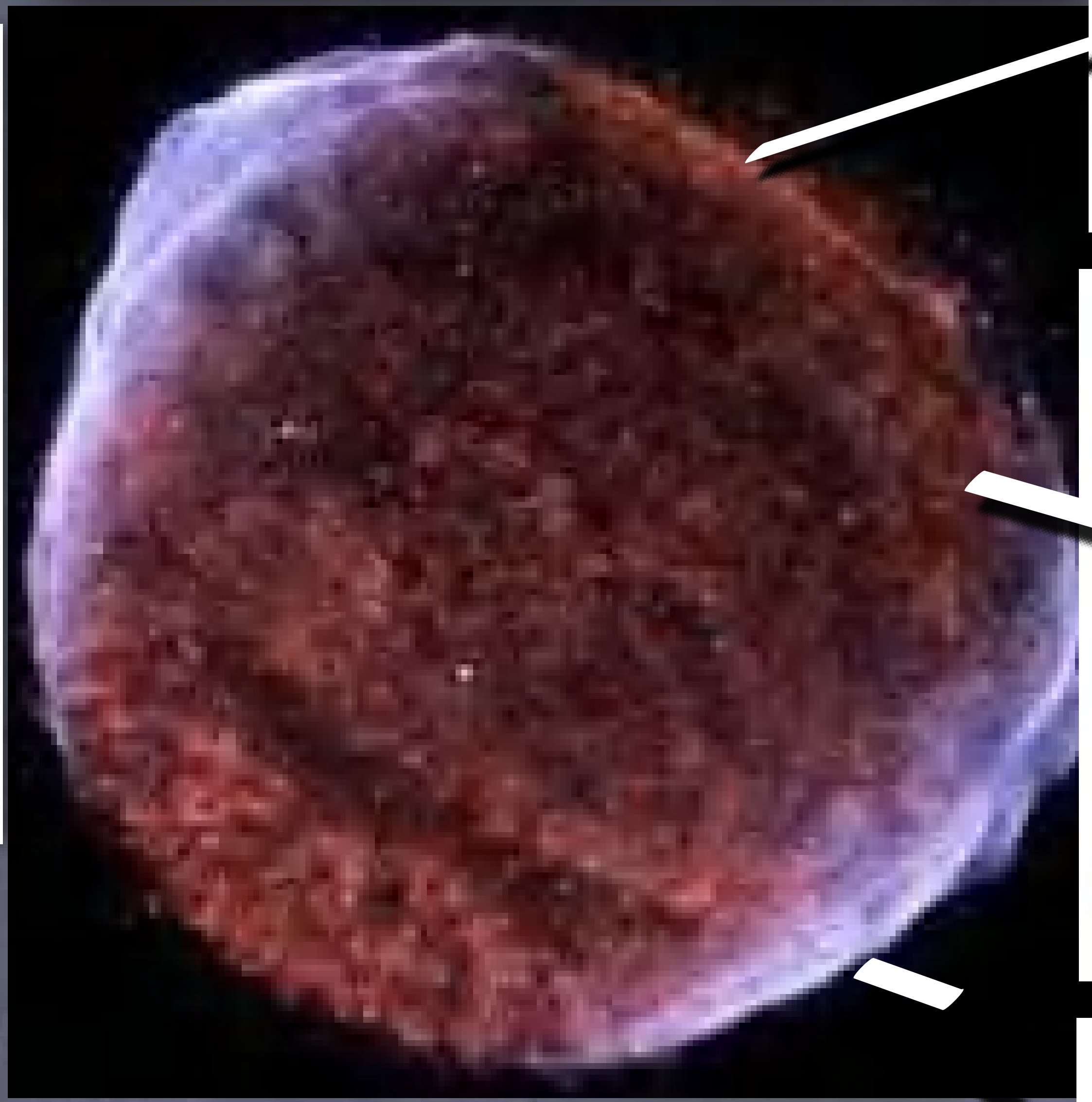


Caprioli-Spitkovsky14a



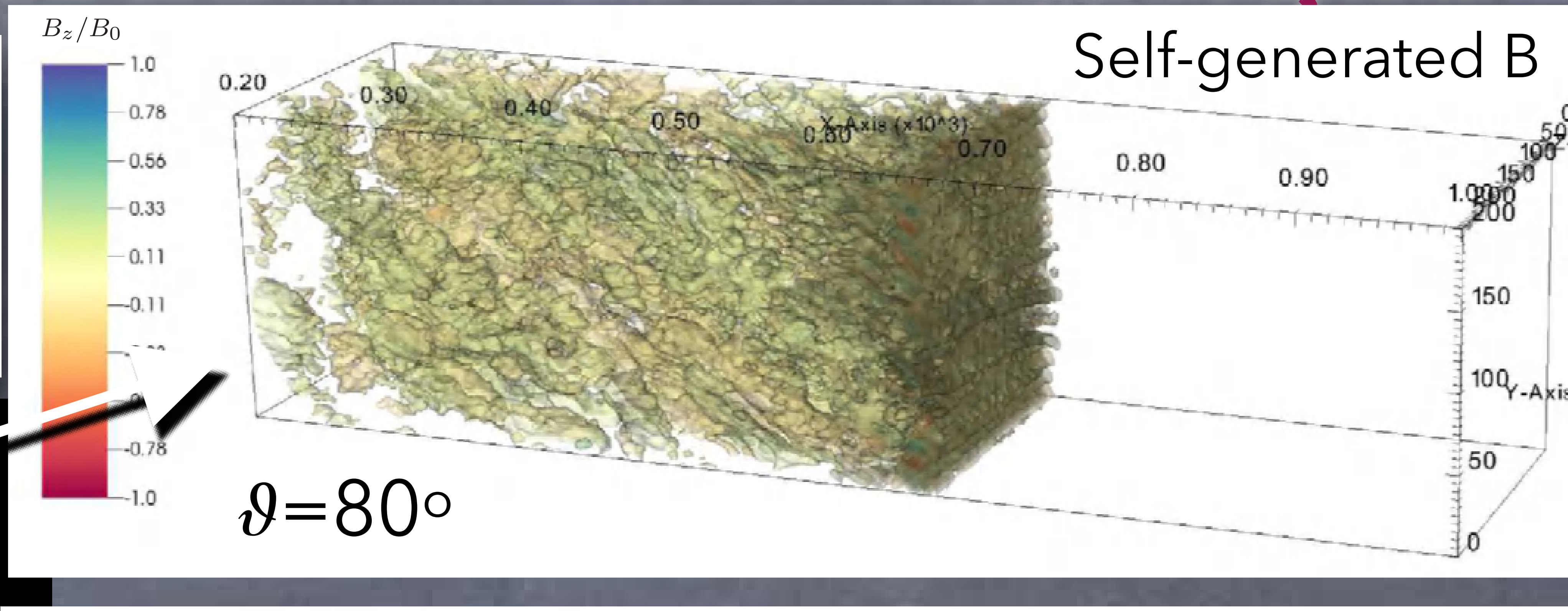
Reynoso+13

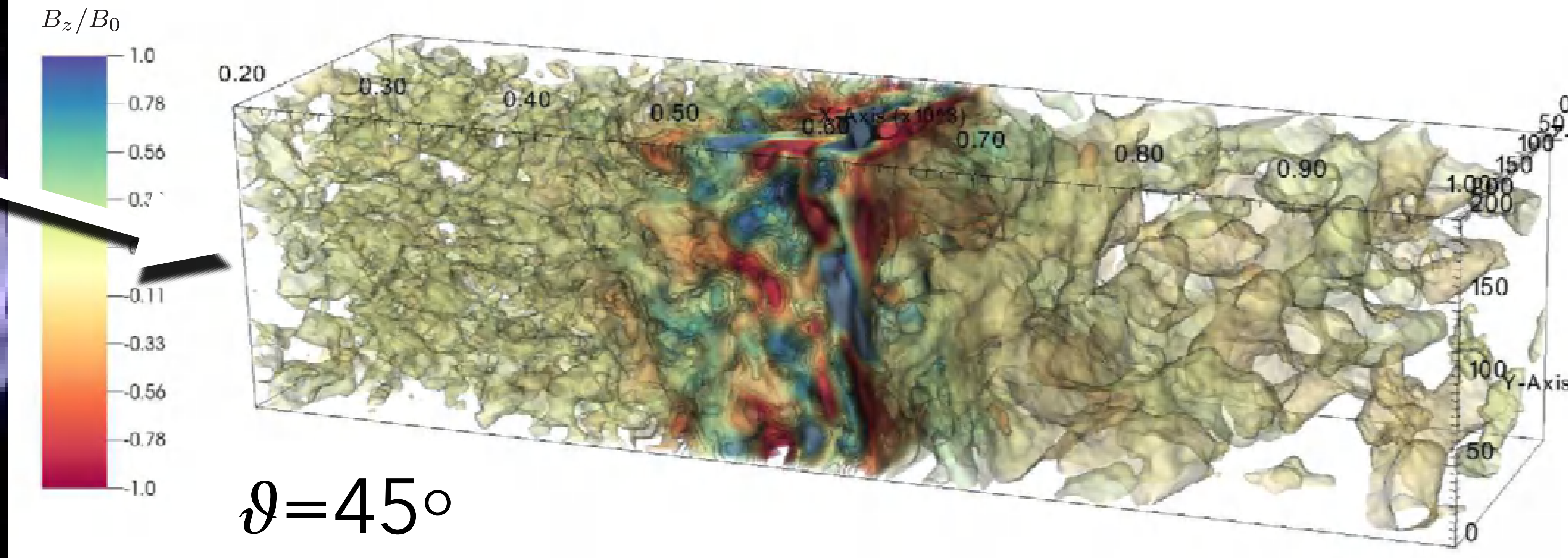
X-ray emission:
red=thermal
white=synchrotron

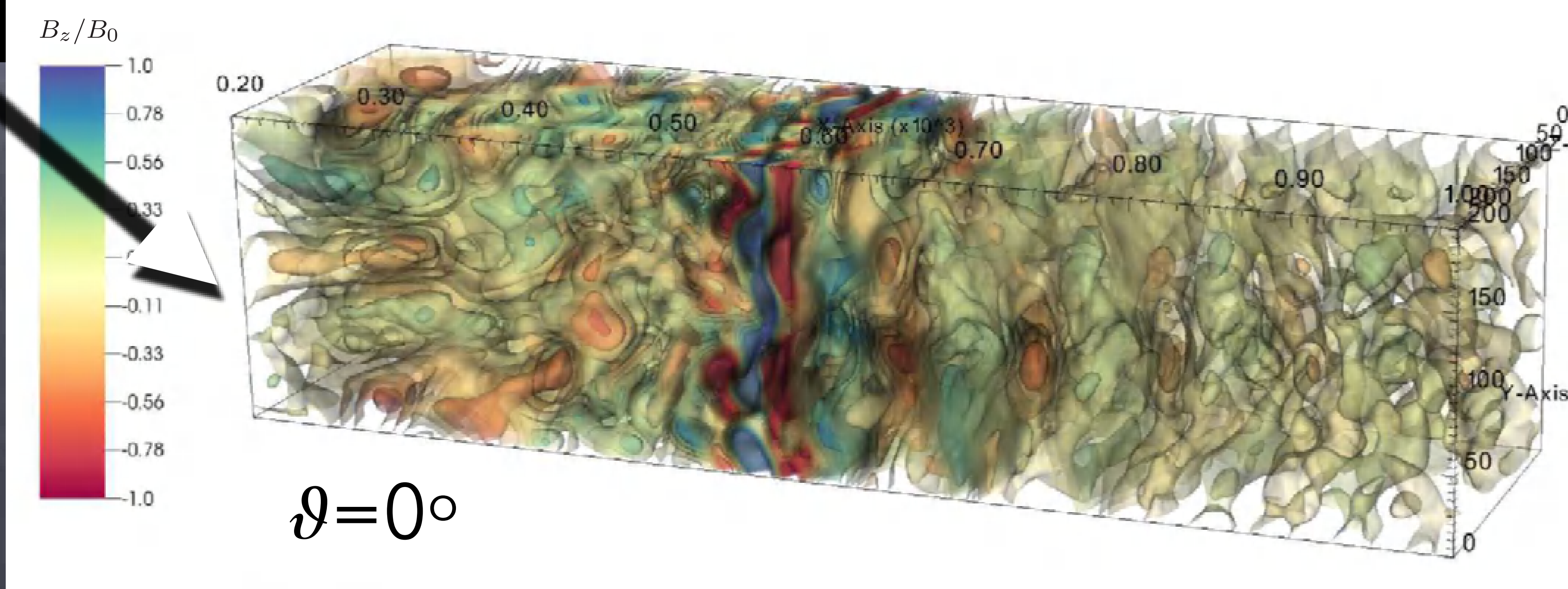


B amplification and ion acceleration where the shock is parallel

Self-generated B



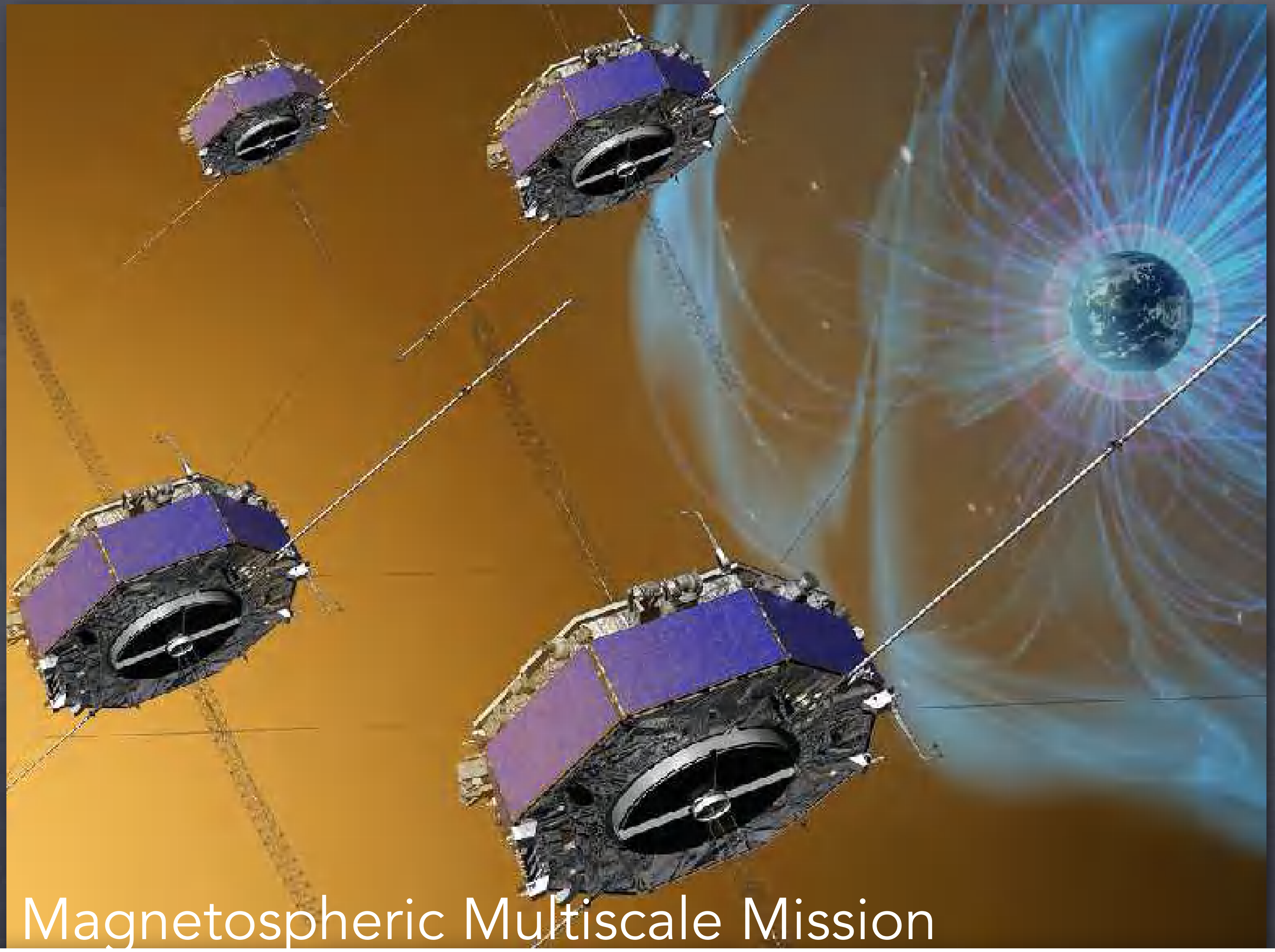


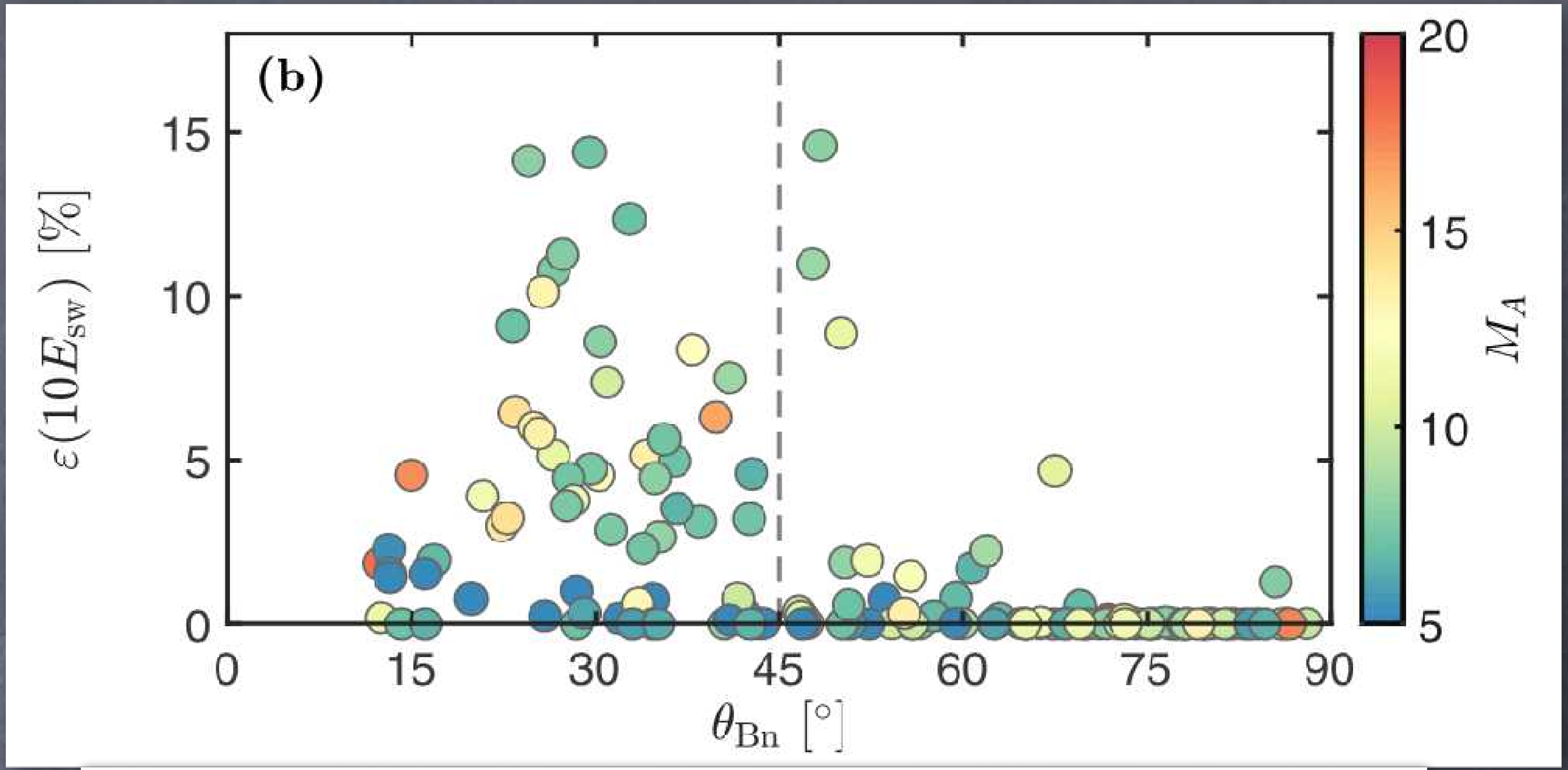


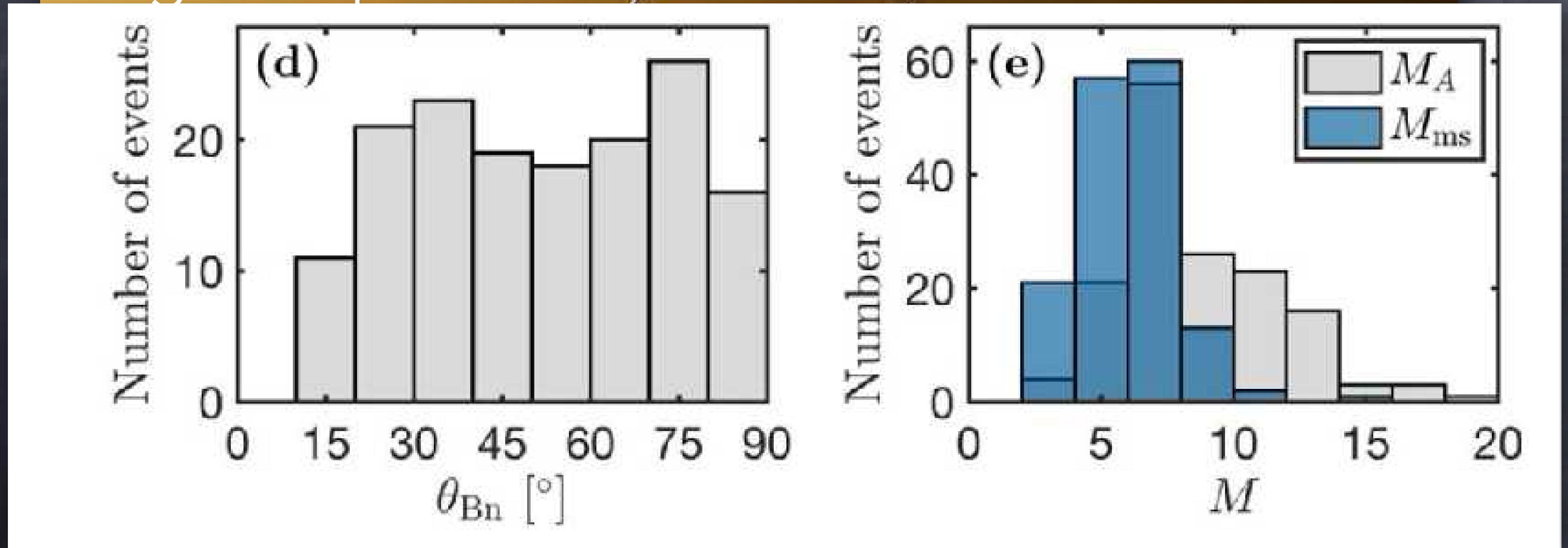
Caprioli-Spitkovsky14a,b,c

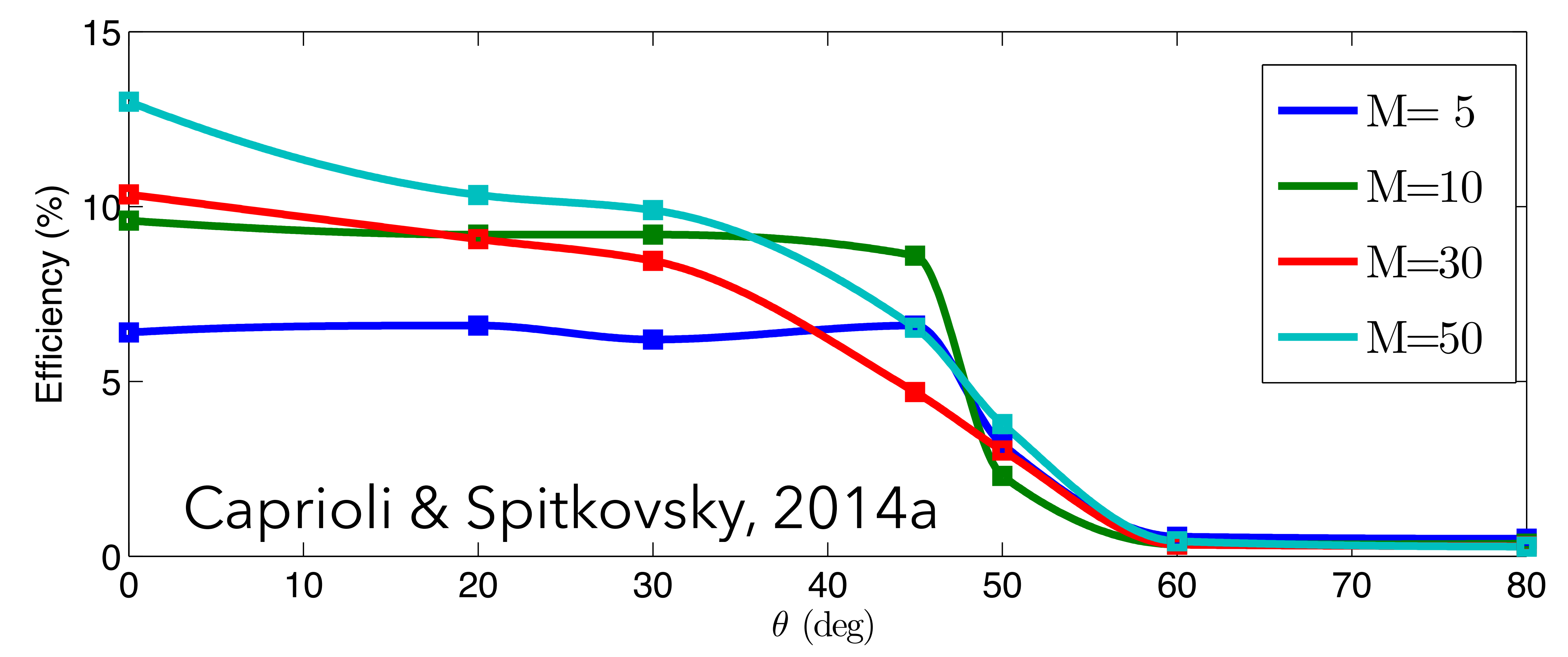
Ion DSA at the Earth Bow Shock

- MMS confirms that DSA is efficient at quasi-parallel shocks (Johlander+21)


Magnetospheric Multiscale Mission



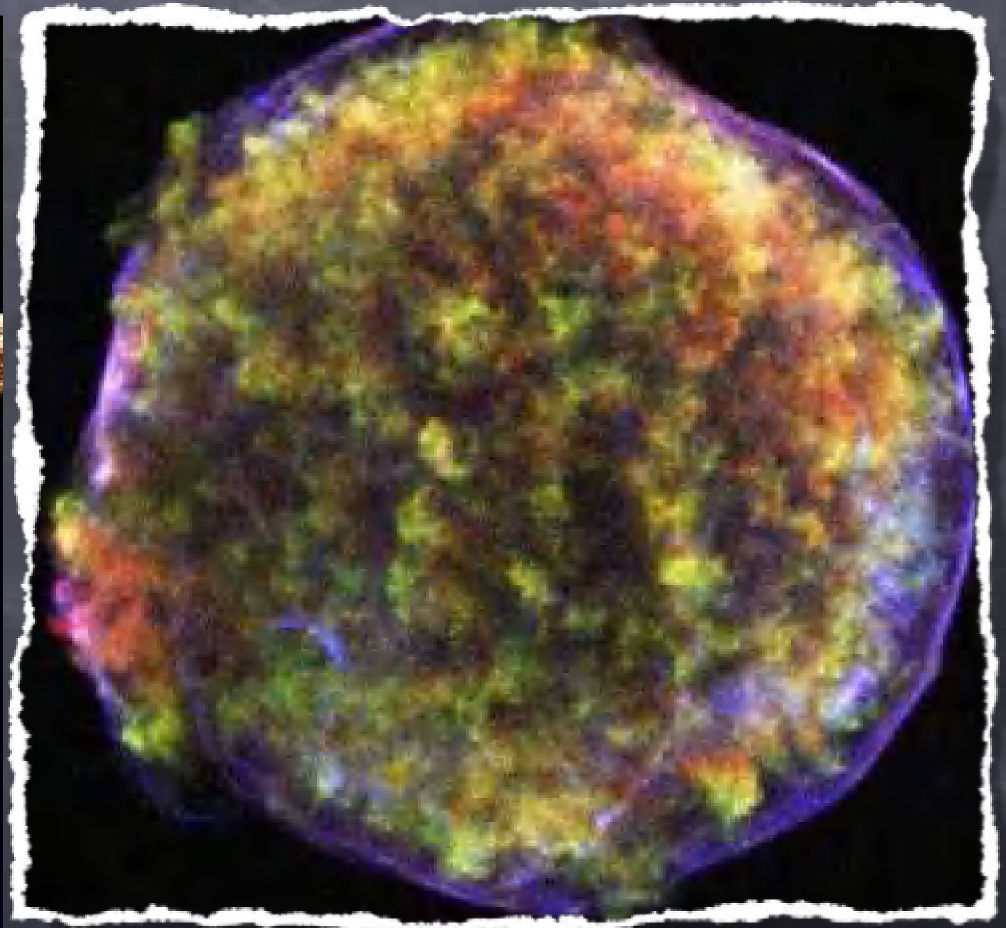




Caprioli & Spitkovsky, 2014a

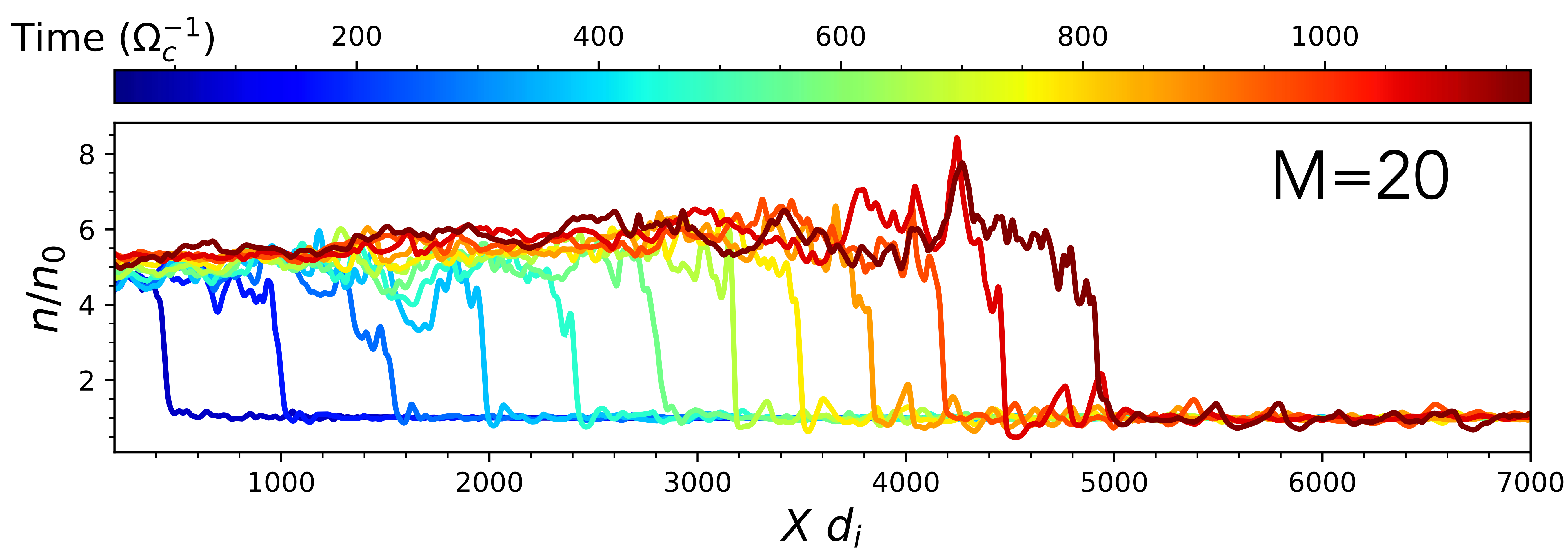
Theory vs Observations

- **Efficient DSA** (Drury 1983, Jones & Ellison 1991, Malkov & Drury 2001,…) should return:
  - Compression ratios $R > 4$;
  - CR spectra flatter than p^{-4} (flatter than E^{-2} for relativistic particles)
- **Observations**, instead, point to significantly steeper spectra:
  - Hadronic γ-rays from historical and middle-age SNRs: $q \sim 4.3 - 4.7$ (e.g., Caprioli11,12; Aharonian+19);
  - Synchrotron emission from radio SNe: $q \sim 5$ (e.g., Chevalier & Fransson06, Bell+11, Margutti+18, …);
  - Propagation of Galactic CRs suggests source spectra with $q \sim 4.3 - 4.4$ (e.g., Blasi-Amato11a,b; Evoli+19).



CR-modified Shocks: Enhanced compression!

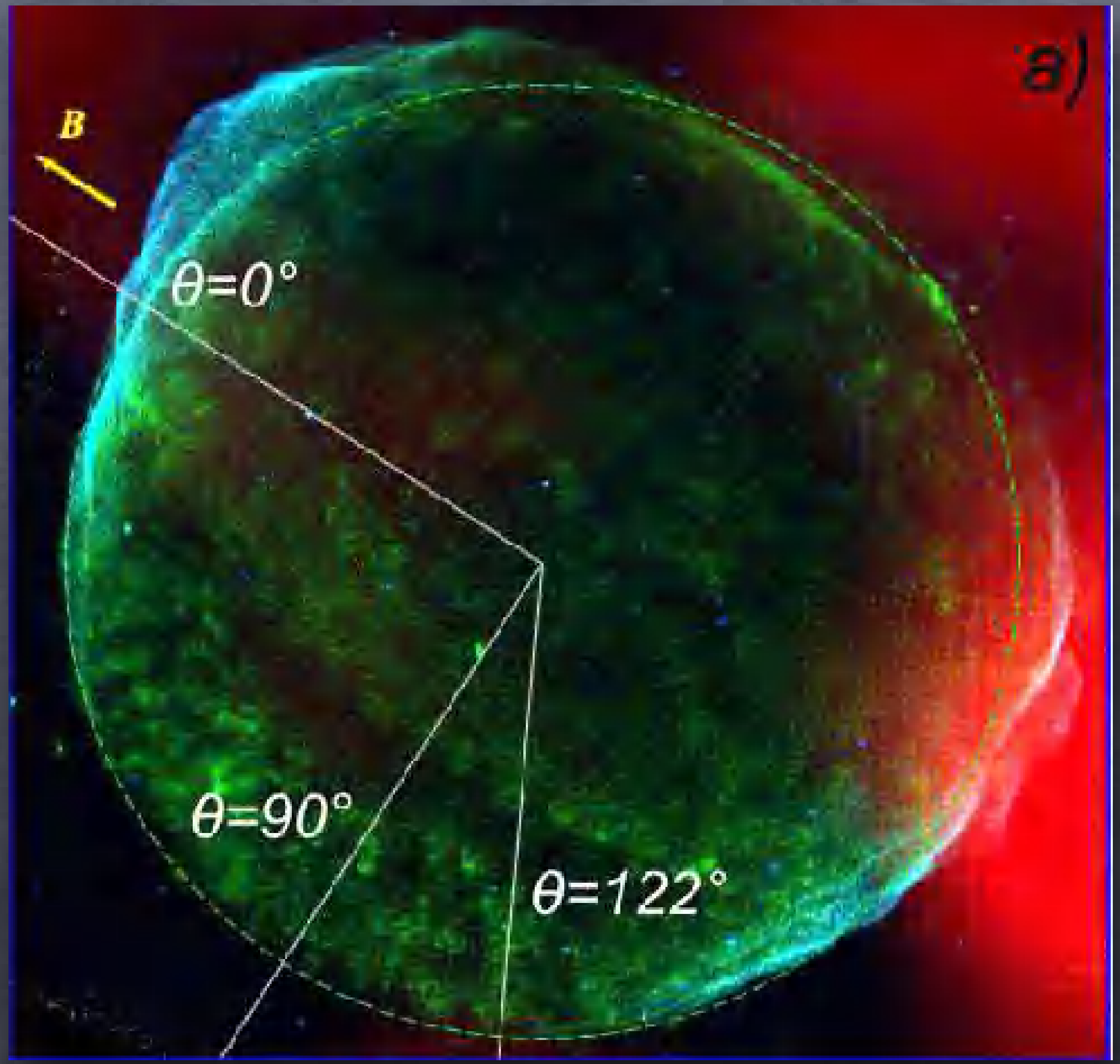
- Hybrid simulations (Haggerty & Caprioli20)
  - Q-par shocks: ion acceleration efficient
  - *R* increases with time, up to ~ 6

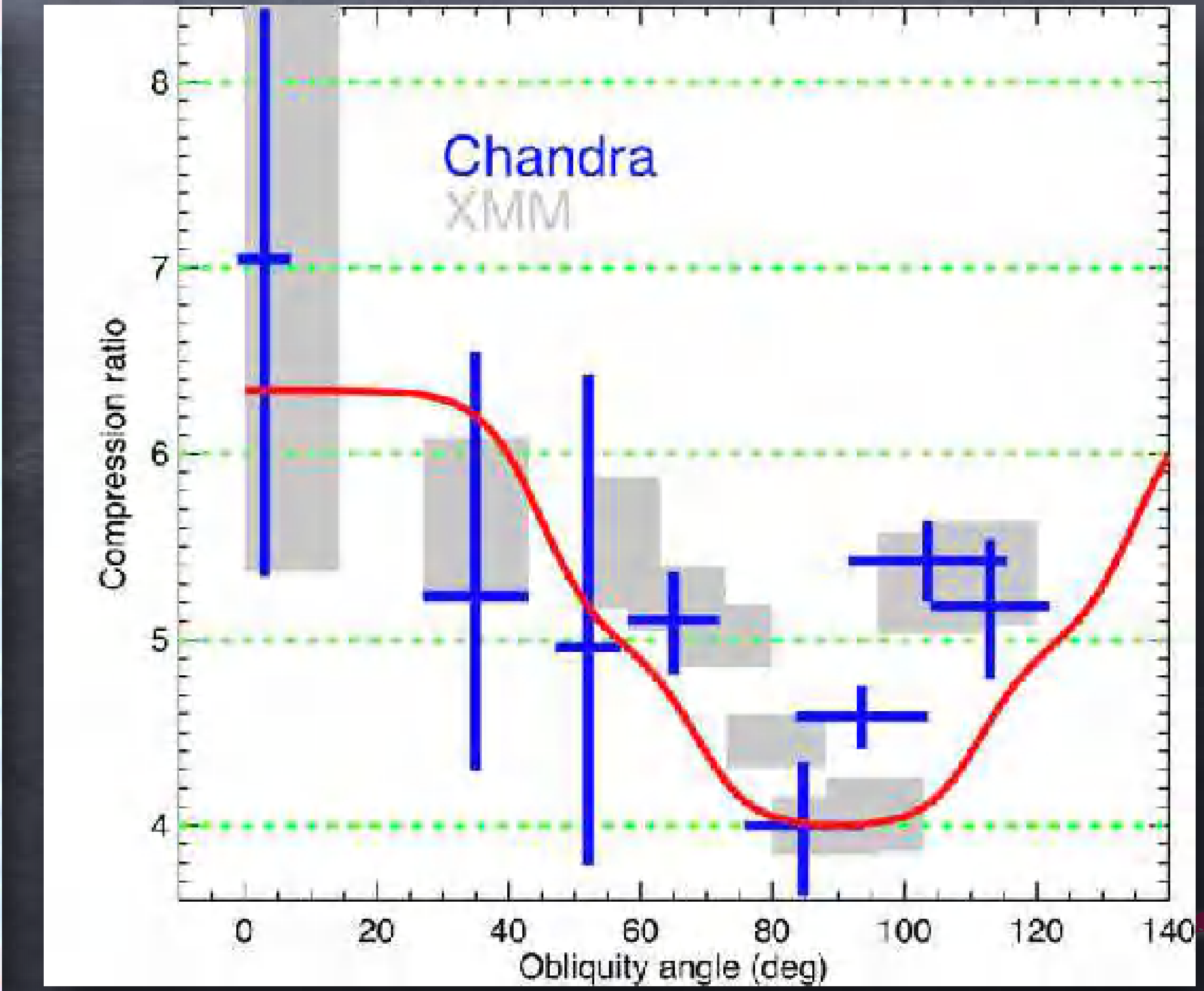


- In SN1006: $R \sim 4-7$, modulated with the azimuth/shock inclination (Giuffrida+22, NatCom)
- However,
  - if $R \simeq 7 \rightarrow q_{\text{expected}} \simeq 3.5$
  - From radio to γ-ray observations:

$$q_{\text{inferred}} \simeq 4.3$$

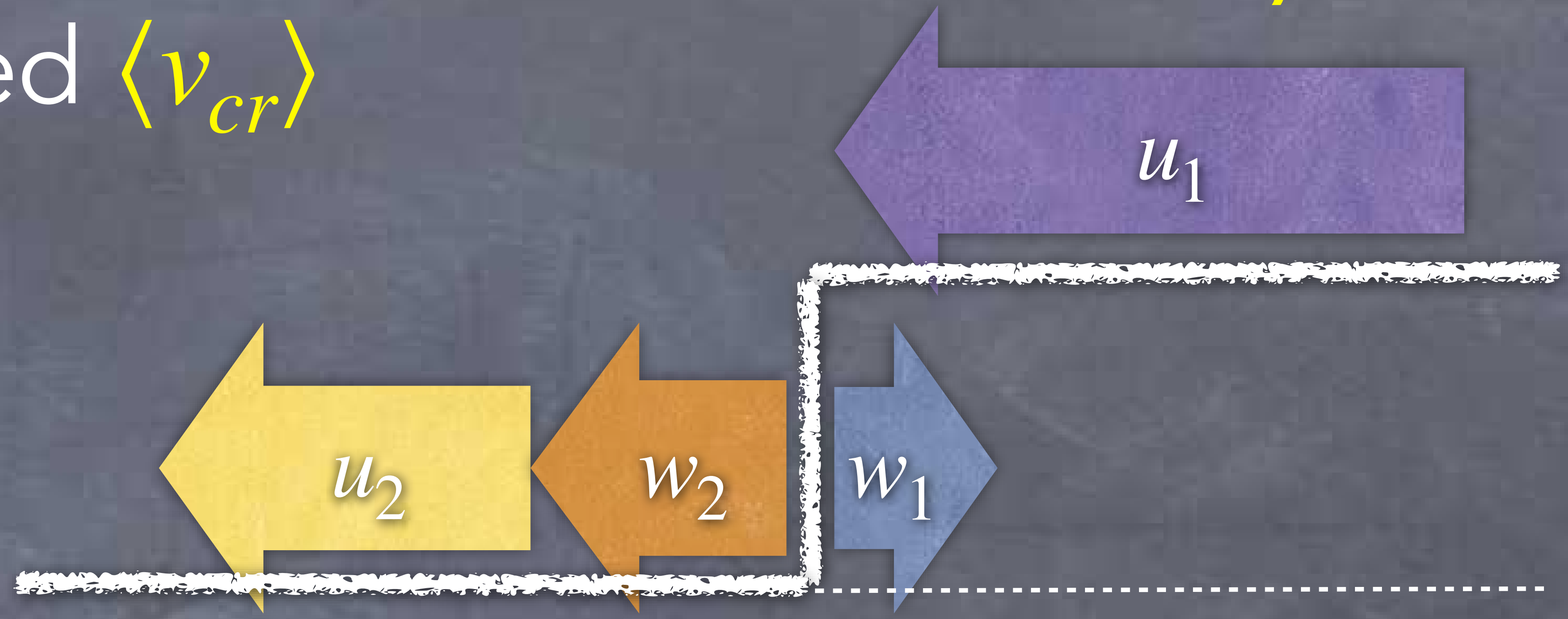
A challenge to DSA theory!

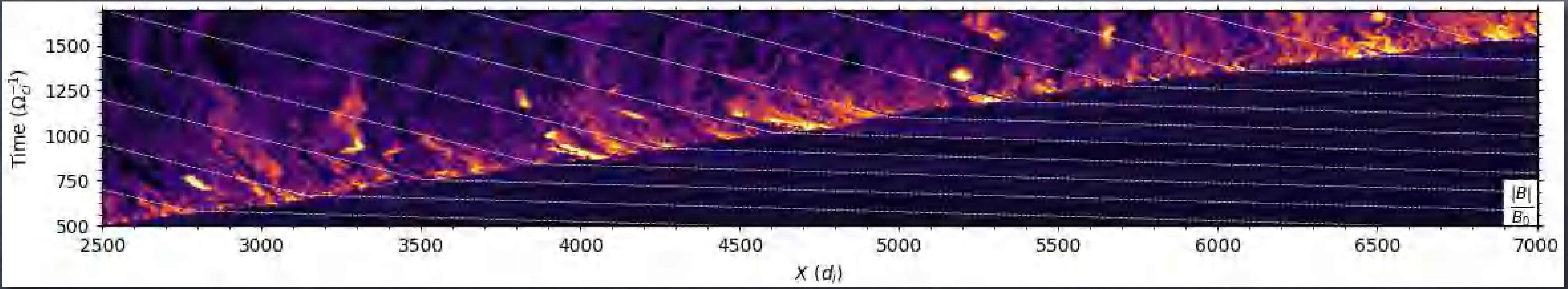




The Role of Amplified Magnetic Fields

- CRs feel an effective compression $R_{cr} = \frac{u_1 + w_1}{u_2 + w_2}$; $w = \text{wave speed} \approx v_A = \frac{B}{4\pi\rho}$
- We can measure both w and the effective CR speed $\langle v_{cr} \rangle$
  - Upstream: $w_1 \simeq -v_{A,1}(\delta B_1) \ll u_1$
  - Downstream: $\langle v_{cr} \rangle \simeq w_2 \simeq +v_{A,2}(\delta B_2) \equiv \alpha\ u_2$



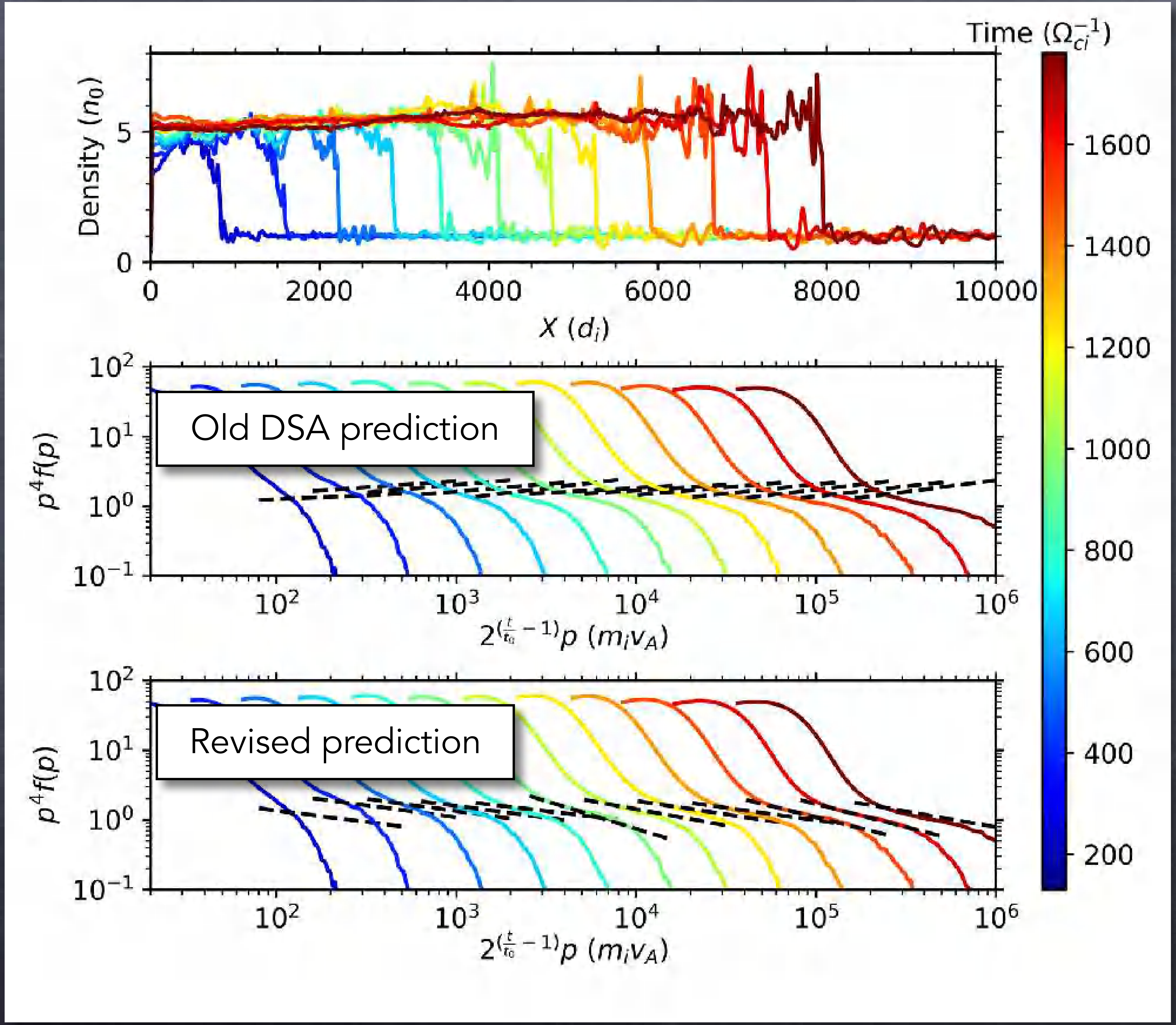


Haggerty-Caprioli20

- B fields (and hence CRs) drift downstream with respect to the thermal gas
  - First evidence of the formation of a *postcursor*
  - CRs *feel* a compression ratio *smaller* than the gas

$$R_{cr} \simeq \frac{u_1}{u_2(1+\alpha)} < R_{gas}$$

A Revised Theory of Diffusive Shock Acceleration



Caprioli, Haggerty & Blasi 2020

- With the effective compression felt by CRs

$$q = \frac{3R_{cr}}{R_{cr} - 1} = \frac{3R_{gas}}{R_{gas} - 1 - \alpha} > q_{DSA}$$

- CRs feel $R_{cr} < R_{gas}$: the power-law index is *not universal, but depends on the (CR-produced) B field*

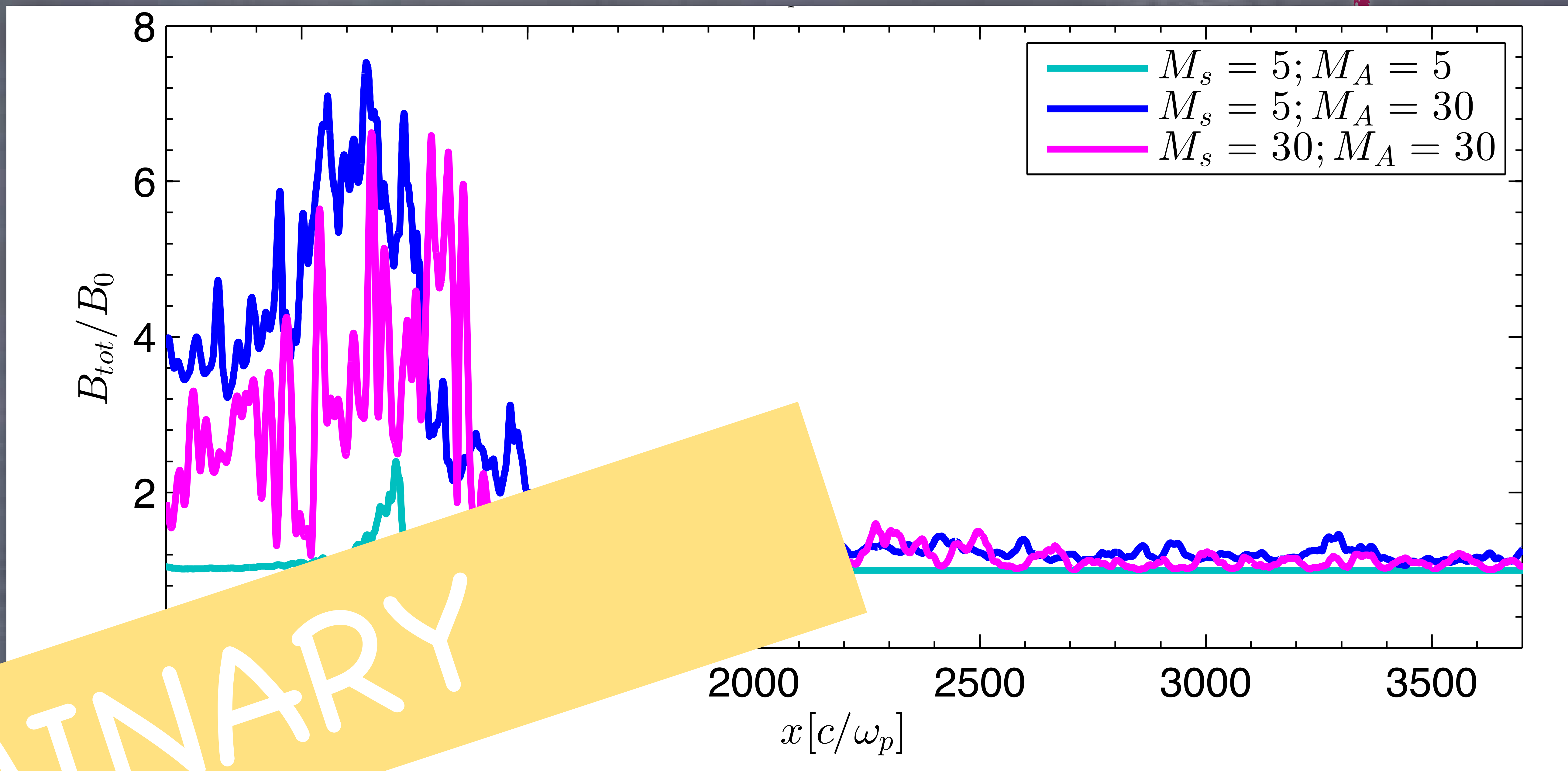
- *Ab-initio* explanation for the steep spectra observed in SNRs
  - Works also for SN1006!

More towards ICM shocks

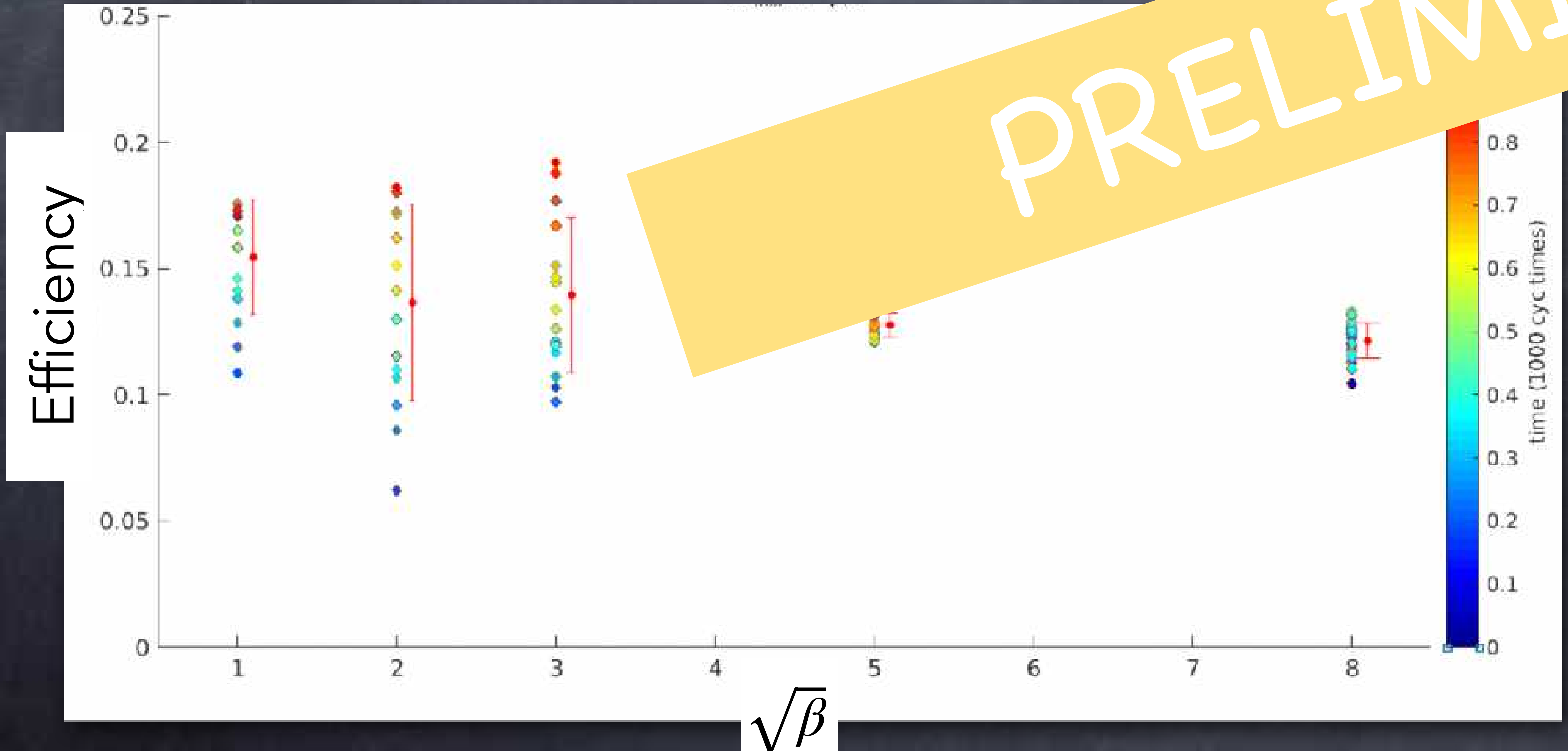
Shocks in high-β plasmas

- The sonic Mach # M_s controls shock dynamics (R) and CR spectrum
- The Alfvènic Mach # M_A controls magnetic field amplification

Magnetic fields are amplified also in high-β plasmas!



PRELIMINARY



- Shocks with low M and high β

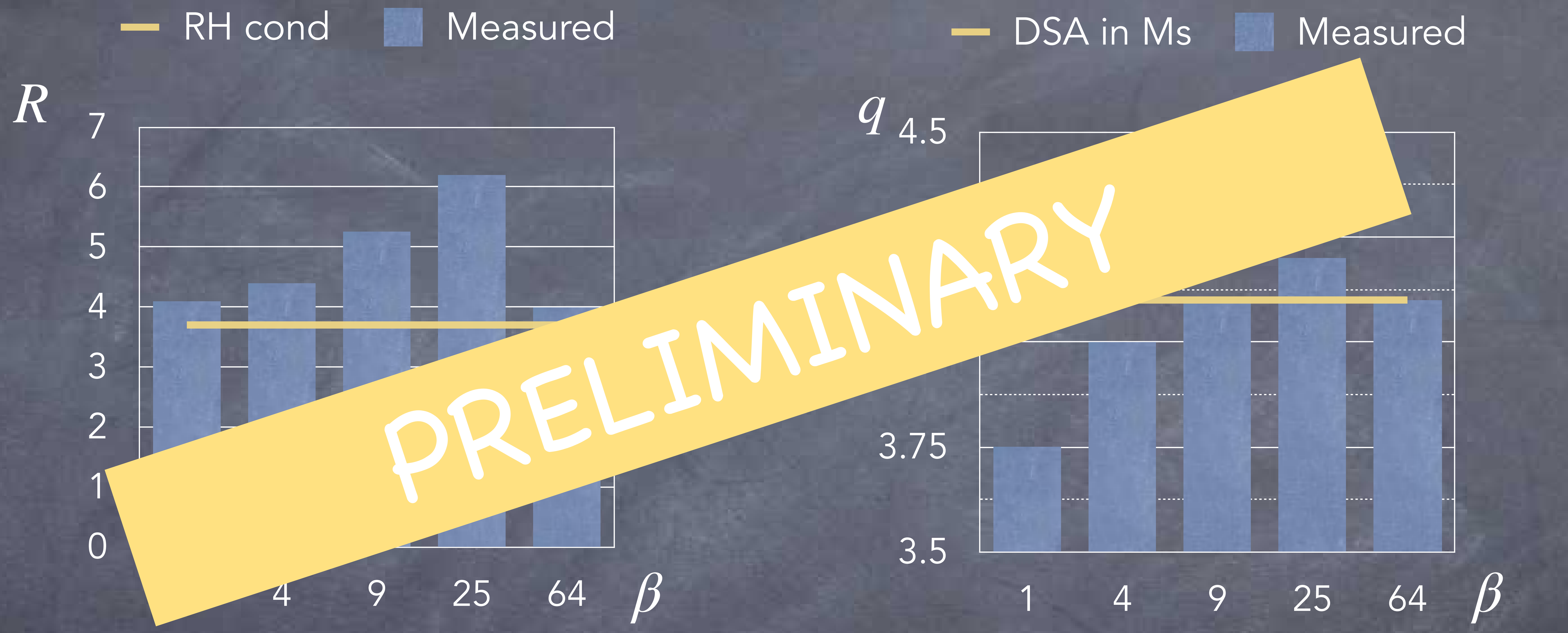
  (with UChicago undergrad Mayur Sharma)

  - Efficiency still $\sim 10\,\%$ for q-par $M = 5$, independent of $\beta \lesssim 100$

in prog.

NLDSA in high-β shocks

- Q-par shocks with $M = 5$ and different β

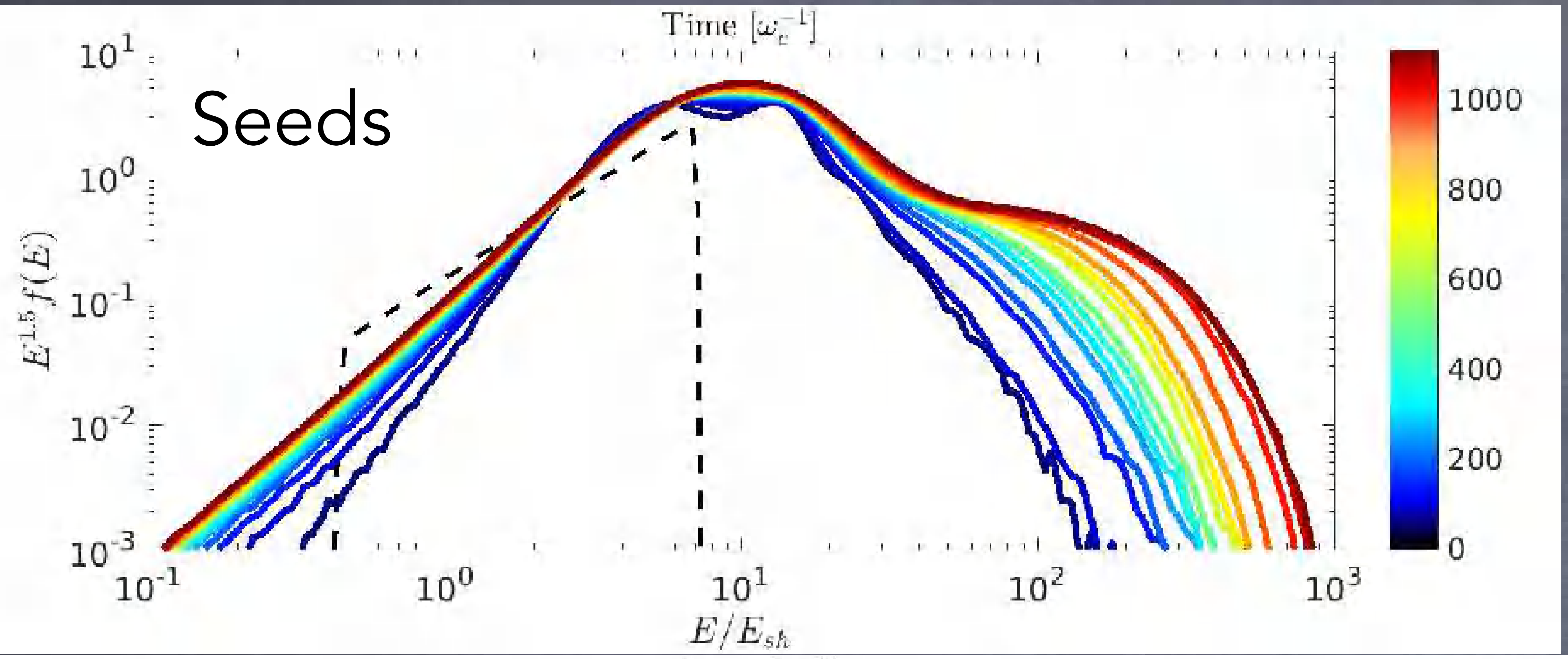


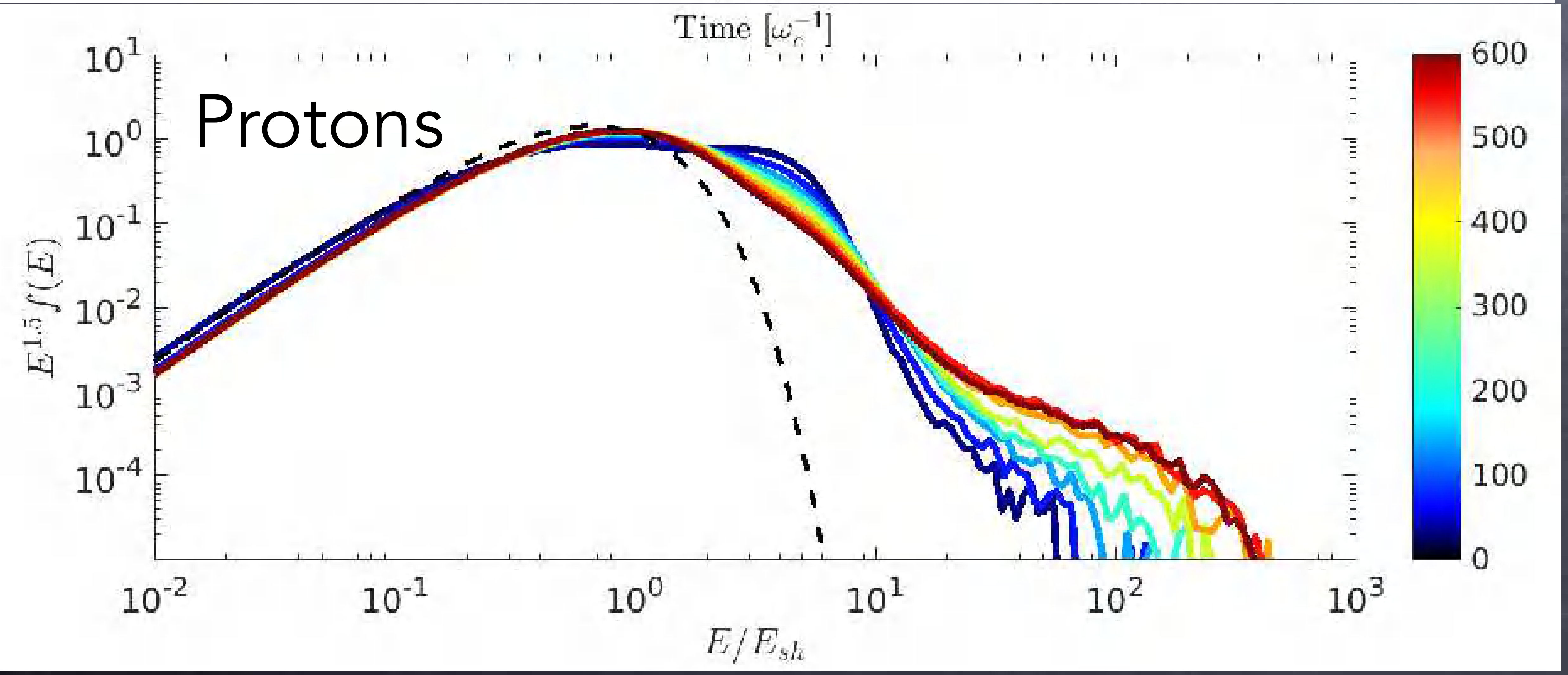
- While R always increases, slope remains closer to DSA prediction
  - Enhanced compression makes spectra *flatter*, while postcursor makes spectra *steeper*
- Modification correlates with B amplification:
  - *Larger* β (smaller M_A) means *larger B*, until β is so large that B damping kicks in

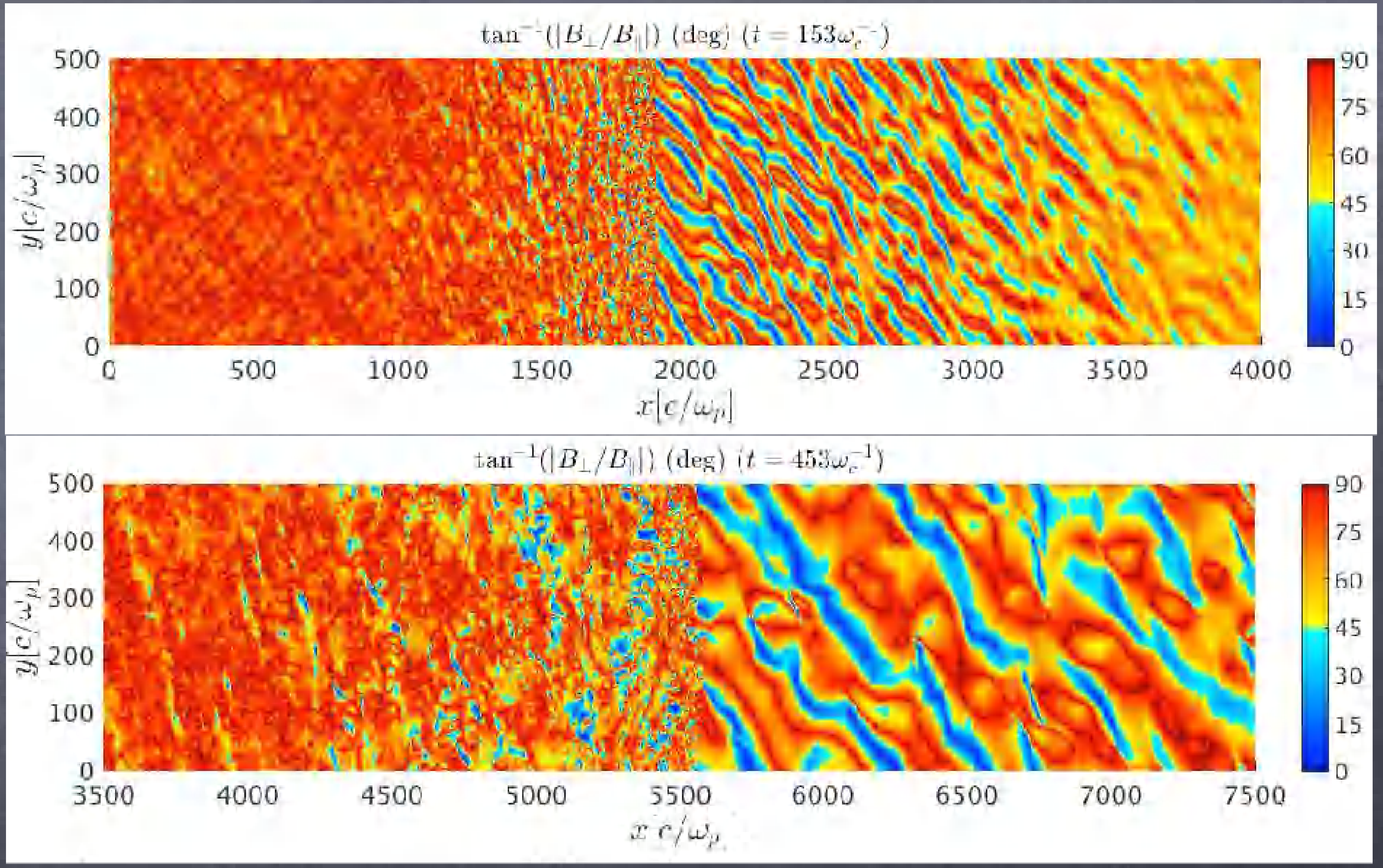
What if there are already energetic particles (seeds)?

Diffusive Shock Re-Acceleration

- $\vartheta=60°$ shock with *isotropic* seeds with $E_{CR}=3E_{sh}$; $n_{CR}=0.01$ (DC, Zhang, Spitkovsky, 2018)
  - Seeds are effectively reflected at the shock, amplify the upstream B, and undergo DSA: DSRA!

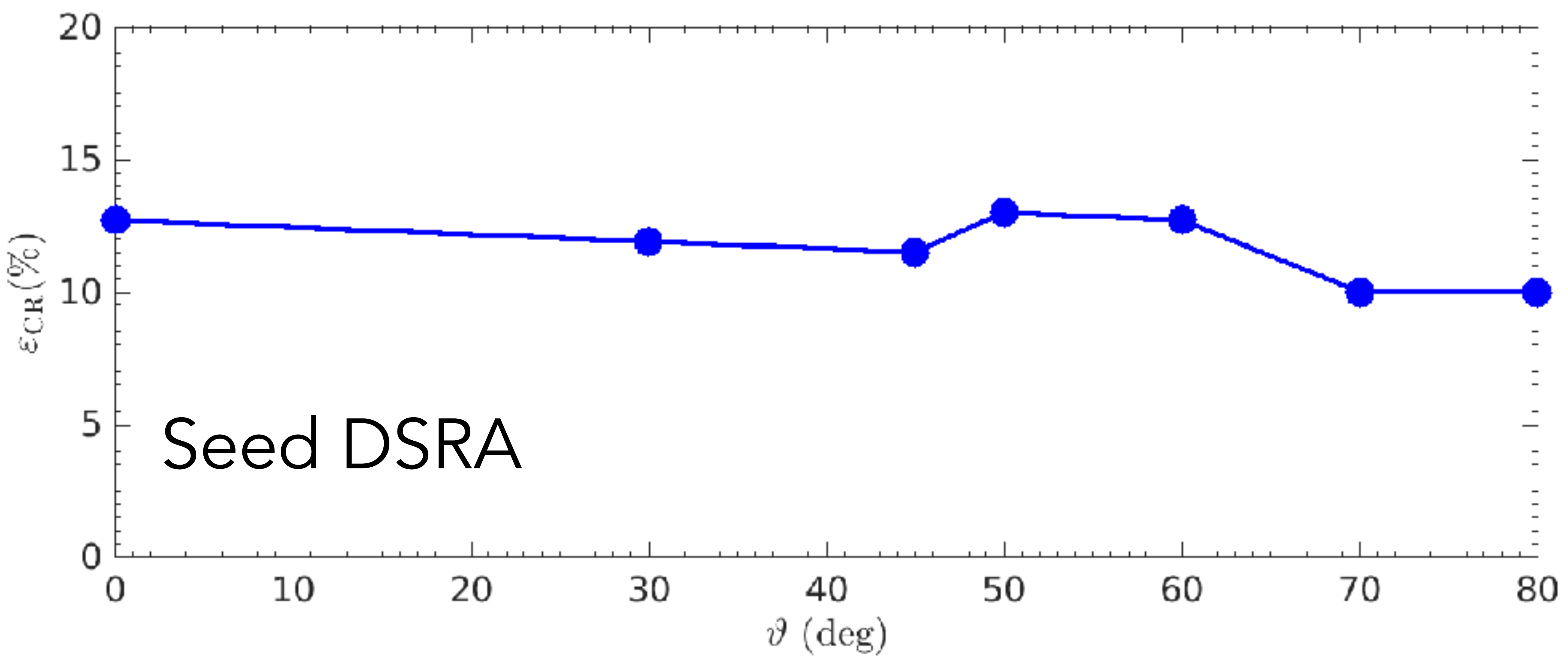


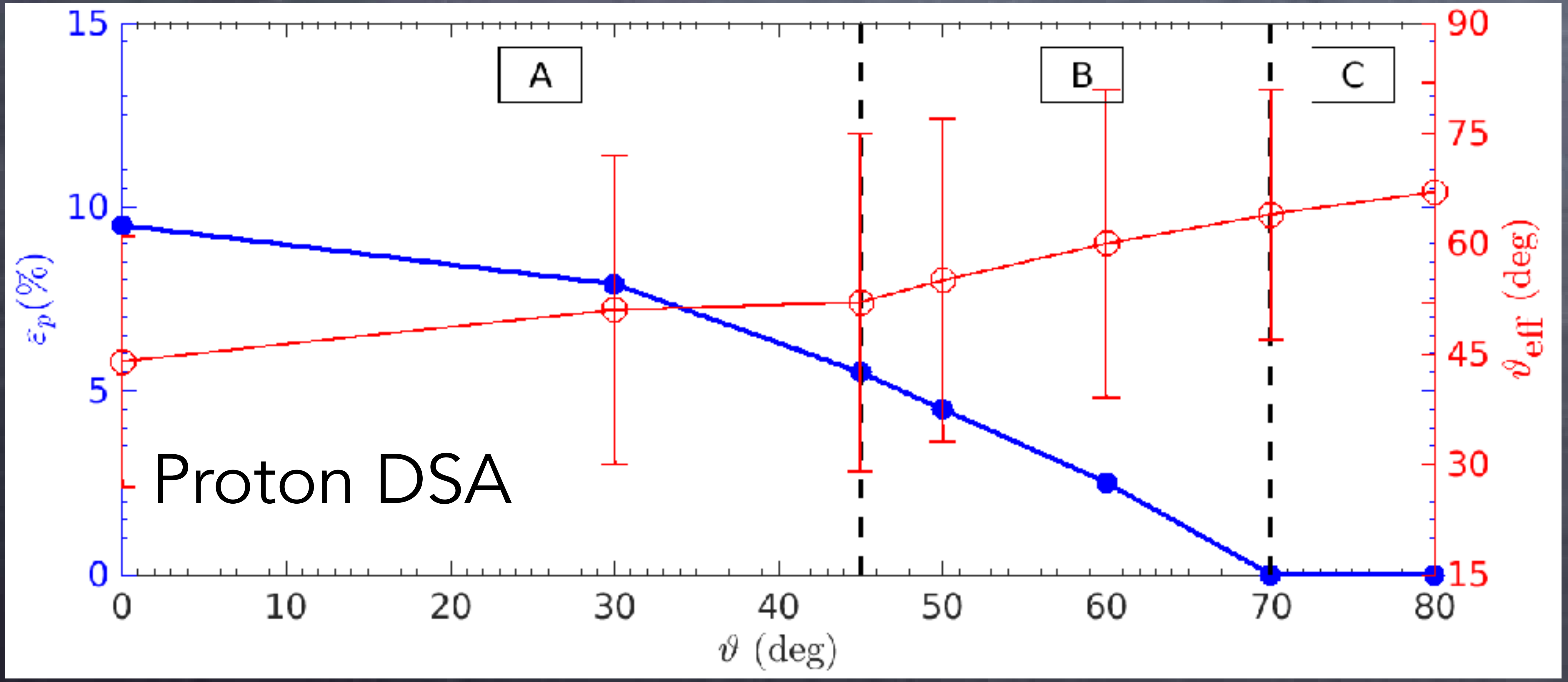




B-amplification opens up quasi-parallel patches at the shock where protons can be injected

DSRA & DSA Efficiencies



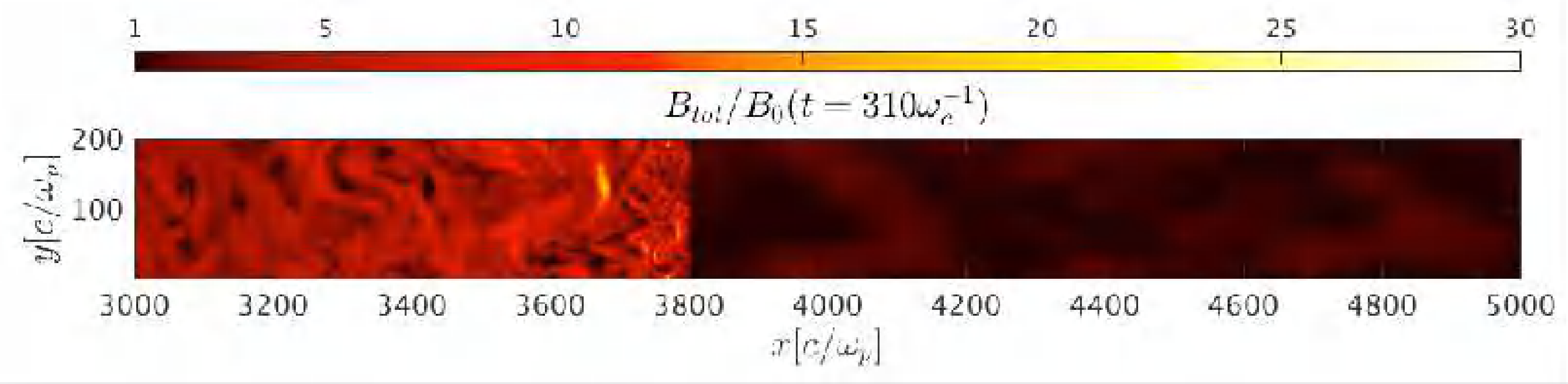


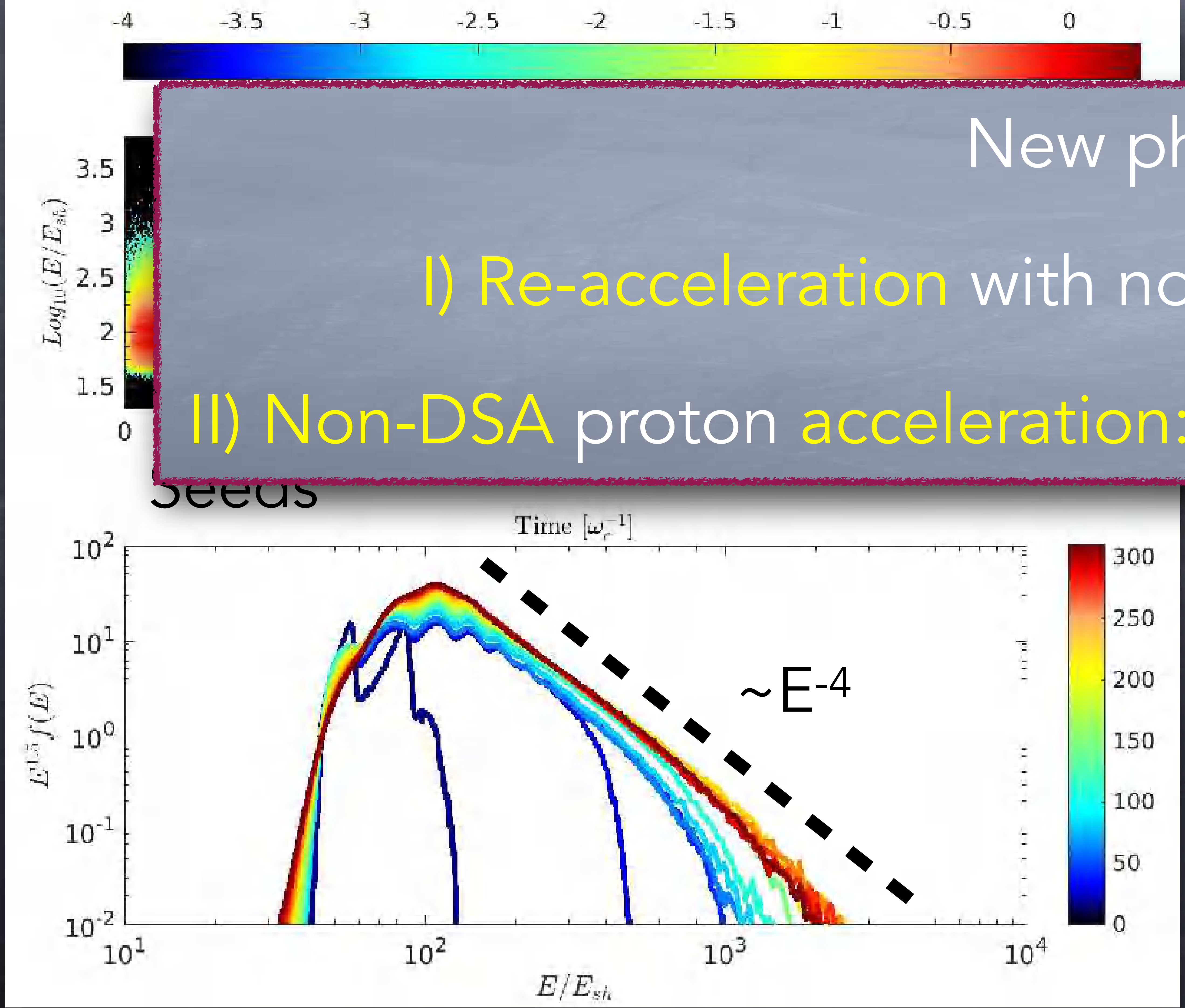
Caprioli+18

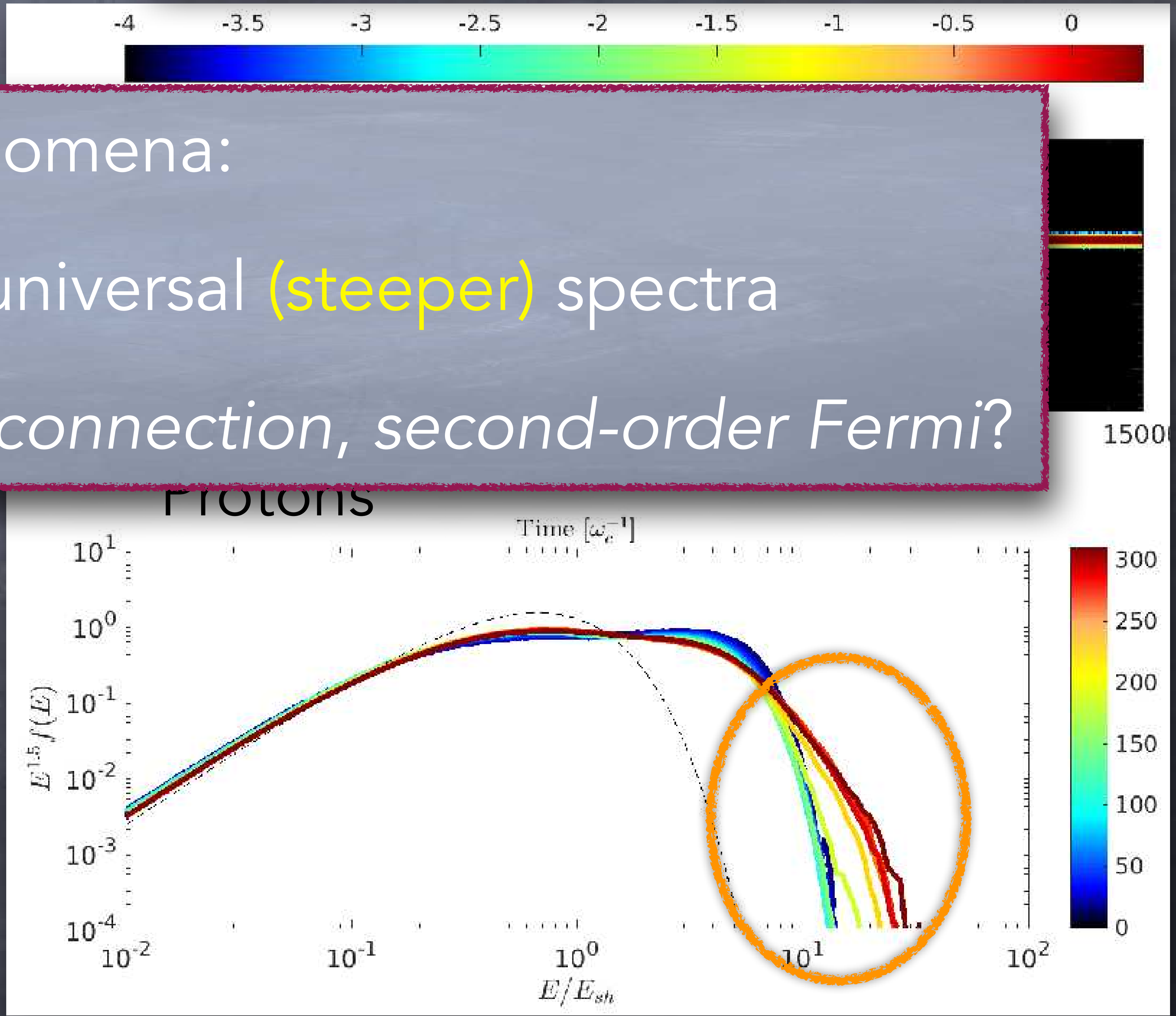
- Seed DSRA independent of ϑ, about 4x the initial CR energy density
  - *Absolute* efficiency depends on seed energy density
- Also electrons can be reaccelerated!
- A ($\vartheta<45^\circ$): Same proton efficiency
- B ($45^\circ<\vartheta<70^\circ$): Boosted to few %
- C ($\vartheta>70^\circ$): No proton DSA

Quasi-Perpendicular SEEDED Shocks

- ϑ=80° quasi-perp shock with seeds $E_{CR}=3E_{sh}$
  - Seeds diffuse but their spectrum is steeper than DSA
  - Non-thermal protons only downstream







New phenomena:

I) Re-acceleration with non-universal (steeper) spectra

II) Non-DSA proton acceleration: *reconnection, second-order Fermi*?

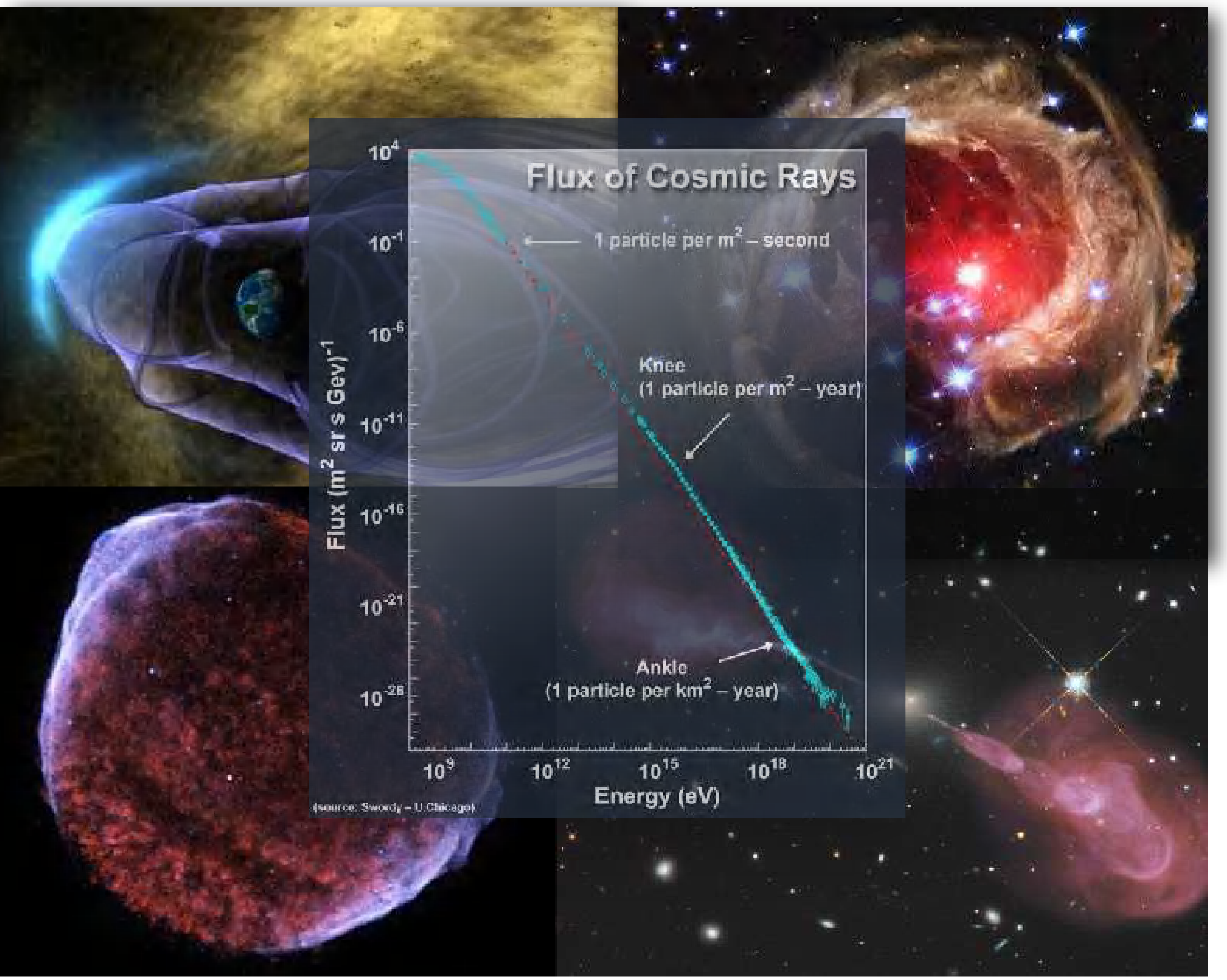
TAKE-AWAY MESSAGES

- Ion DSA is efficient at quasi-parallel shocks
- Non-linear DSA is important; spectra are **non-universal** and **depend on B**
  - Ion DSA efficiency almost independent of β, $\sim 10\,\%$ for $M_s \gtrsim 3$
- Reacceleration (DSRA) can be important at oblique shocks
  - Non-DSA acceleration at quasi-perpendicular shocks

TO DO LIST

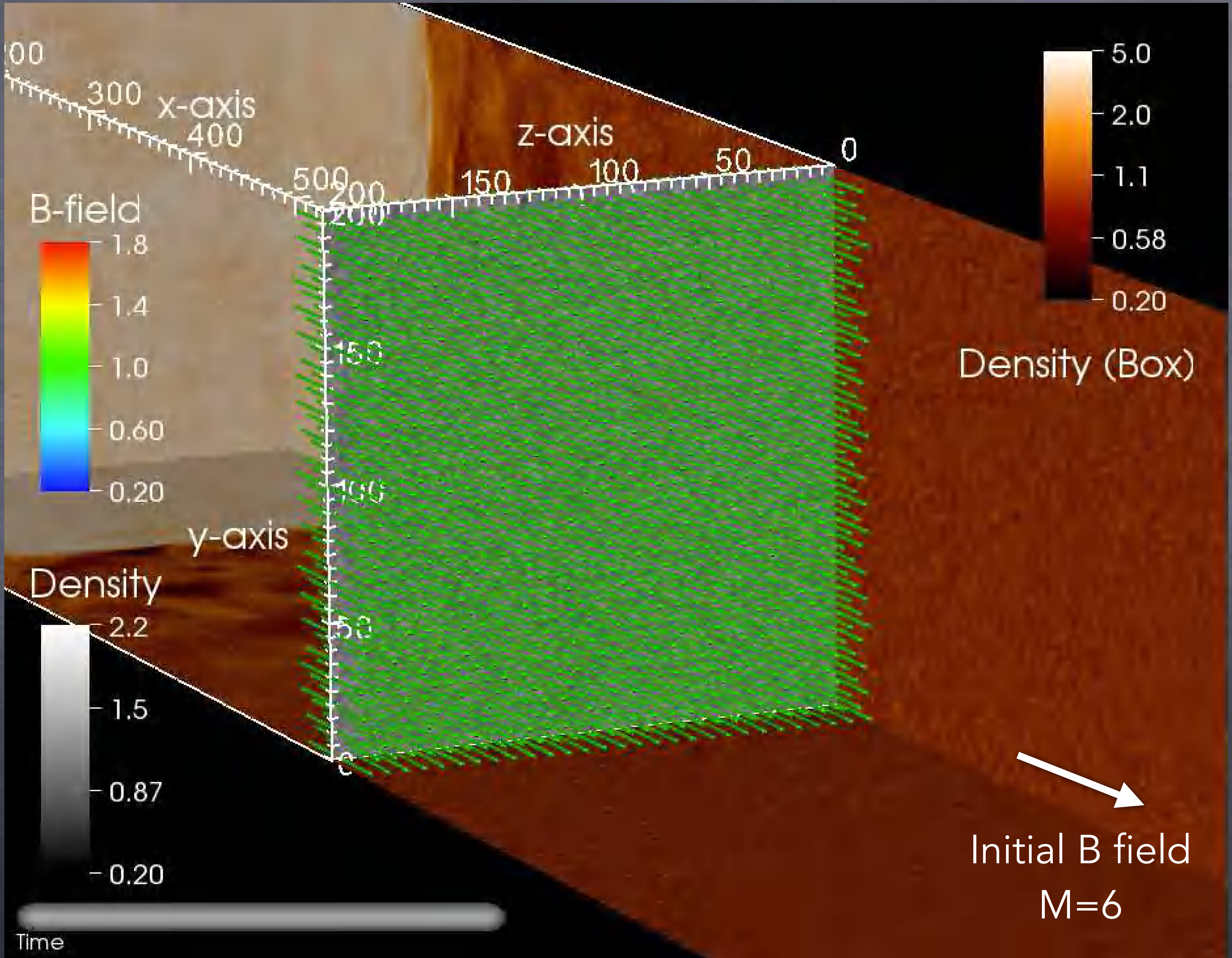
- Shocks with $M_s \lesssim 3$
- Electron injection and DSA; it may exhibit different trends with ϑ, β, M_s
  (Guo+14, Park+15, Xu+20, Shalaby+20, Bohdan+20-22, Morris+22, Gupta & Caprioli in prog…)

MFA and DIFFUSION



(source: Swordy – U.Chicago)

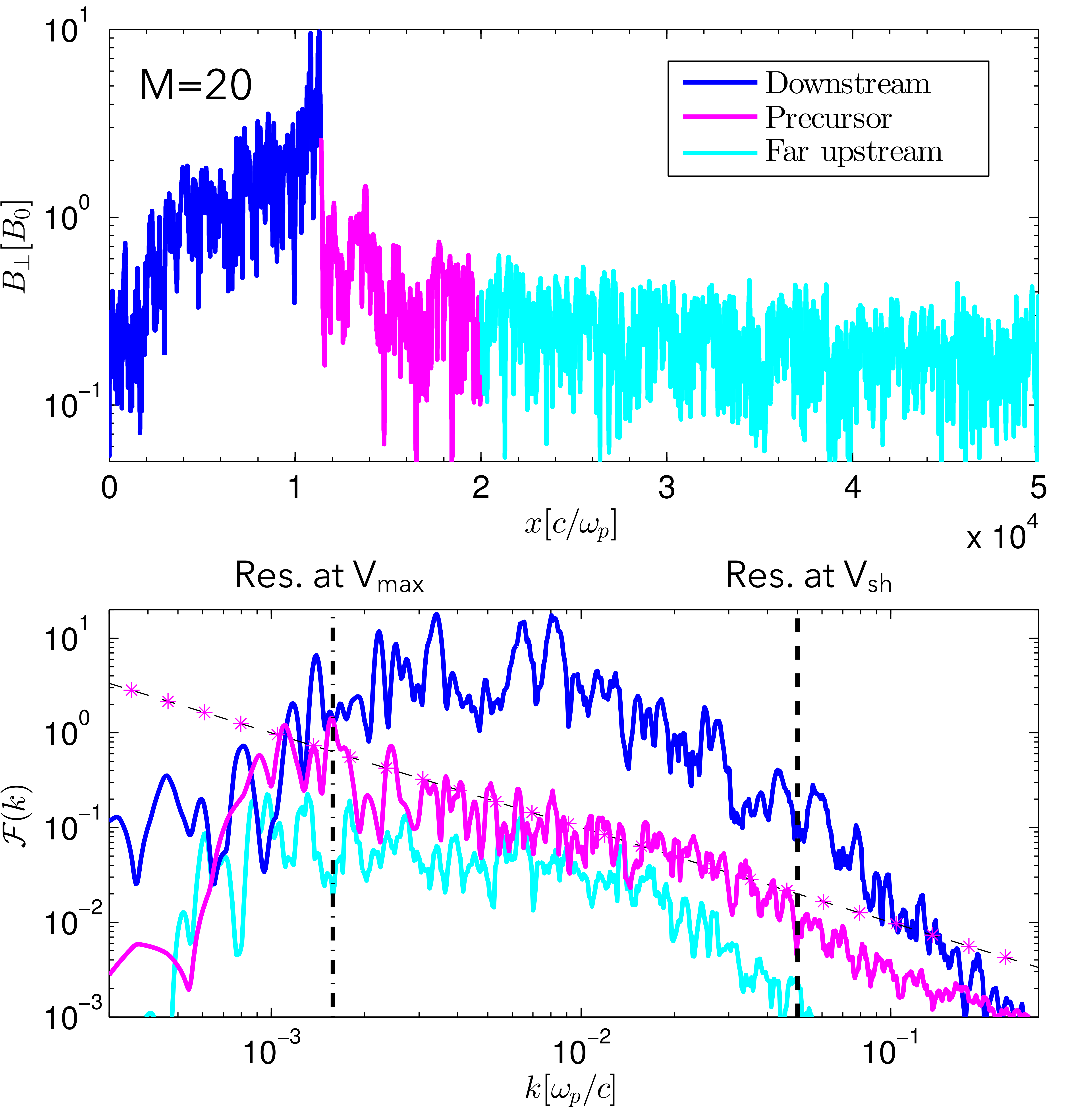
3D simulations of a parallel shock



Initial B field
M=6

DC & Spitkovsky, 2014a

Magnetic field spectrum



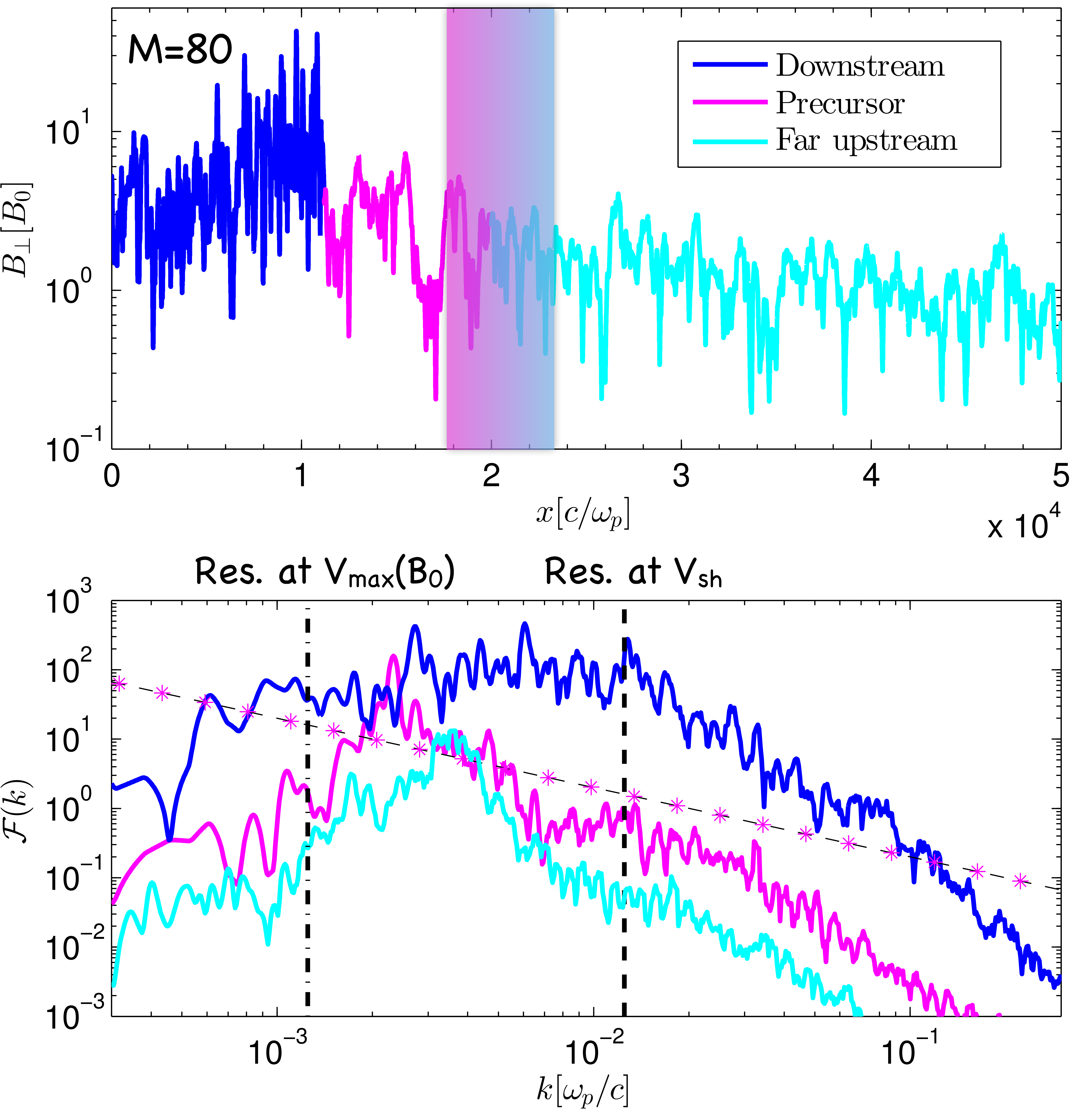
Magnetic energy density per unit logarithmic band-width, F(k)

$$\boxed{\frac{B_\perp^2}{8\pi} = \frac{B_0^2}{8\pi}\int_{k_{min}}^{k_{max}} \frac{dk}{k}\mathcal{F}(k)}$$

- F(k)∝k^{-1} for $\omega_c/V_{max} < k < \omega_c/V_{sh}$
- Turbulence self-generated by a spectrum $\propto p^{-4}$

DC & Spitkovsky, 2014b

Magnetic field spectrum, high M_A



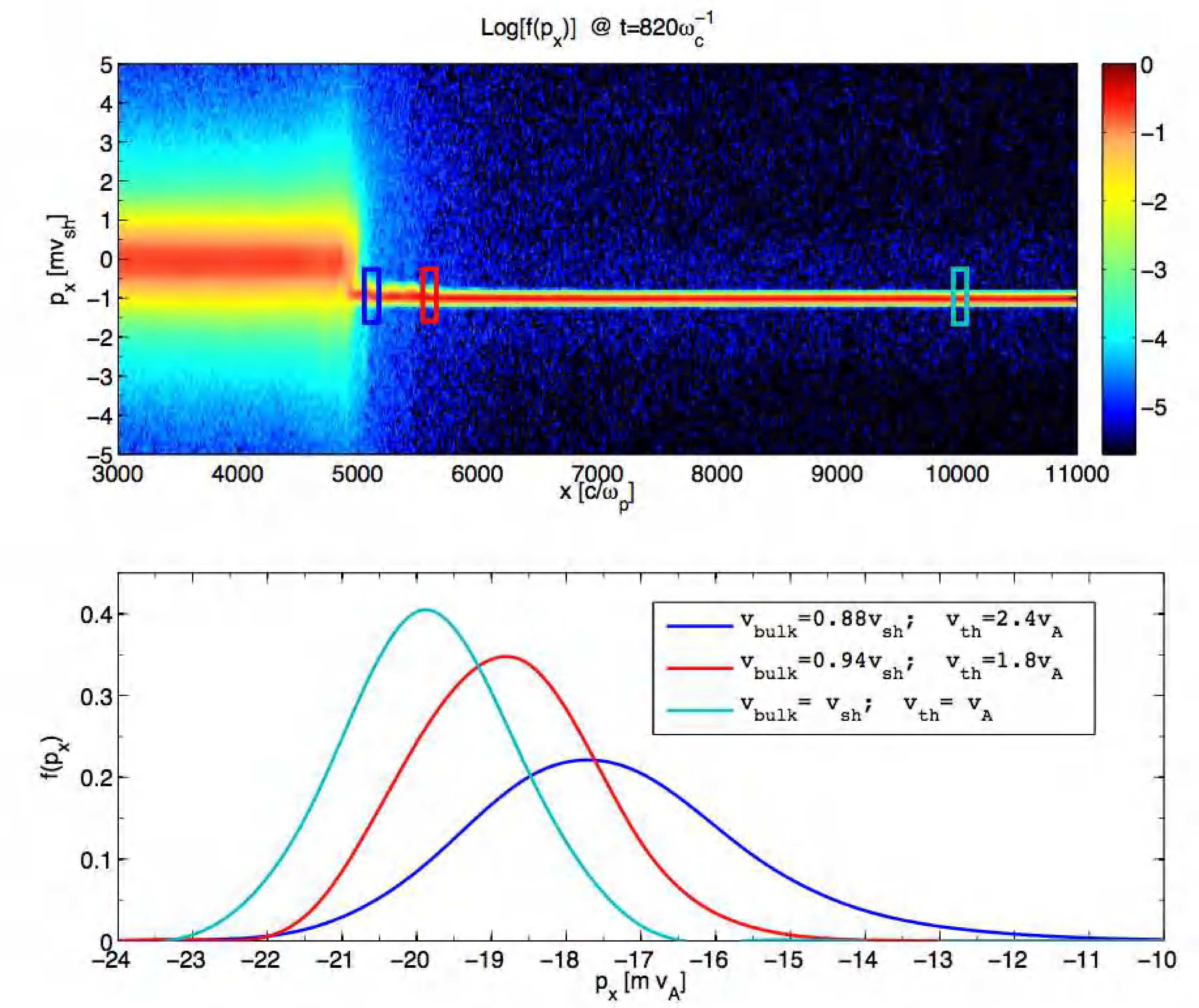
- Bell modes (short-wavelength, right-handed) grow faster than resonant
- Far upstream: escaping CRs at ~p_{max} (Bell)
- For large $b=\delta B/B_0$ $k_{max}(b) \sim k_{max,0}/b^2$
- There exist a b^* such that $k_{max}(b^*)r_L(p_{esc}) \sim 1$

Free escape boundary

- Precursor: diffusion + resonant

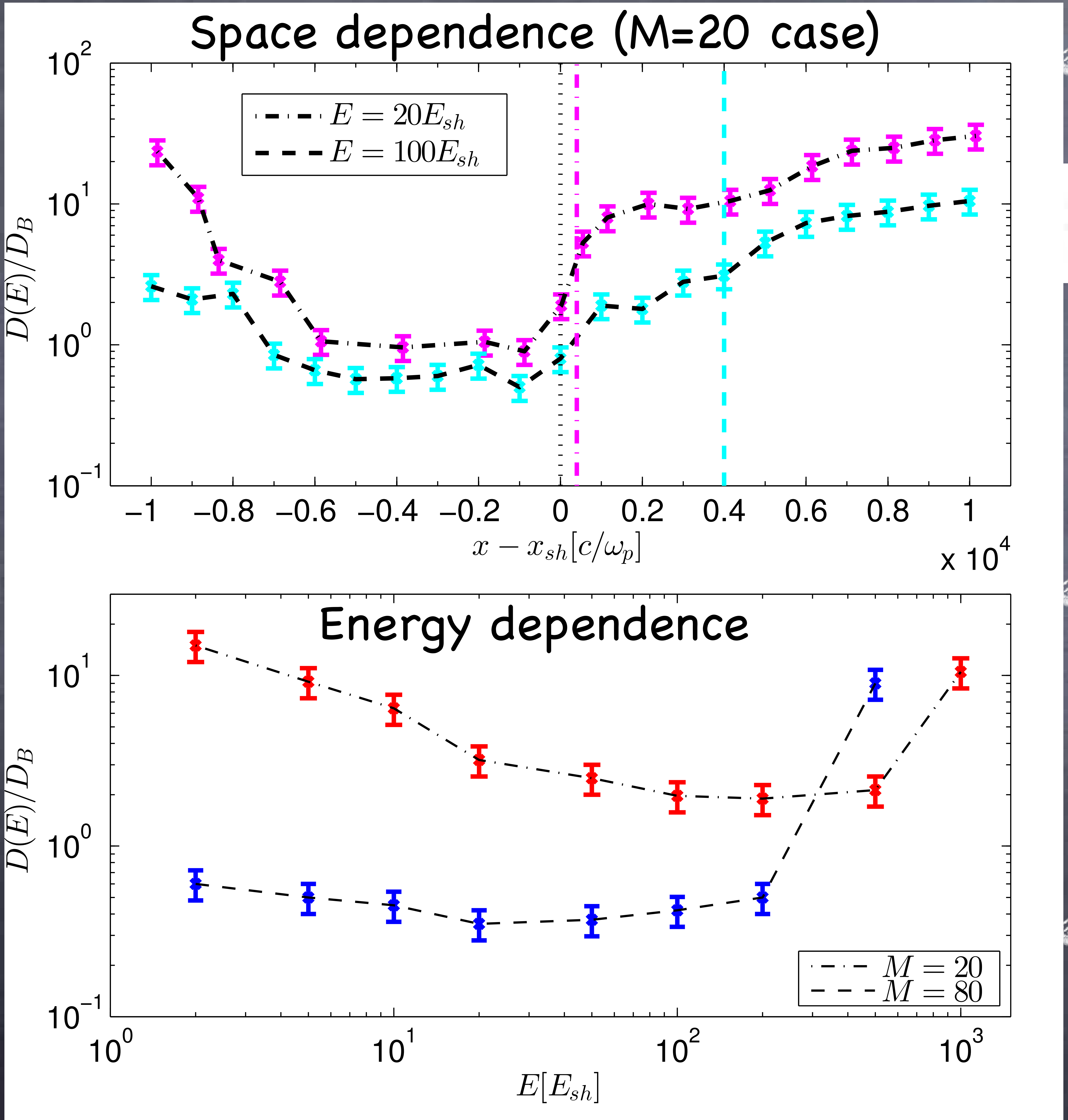
DC & Spitkovsky, 2014b

CR-induced precursor



- Upstream fluid is slowed down & heated up
- Magnetic and thermal pressure remain in equipartition
- Non-adiabatic heating

Diffusion coefficient



- Directly measured in simulations

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

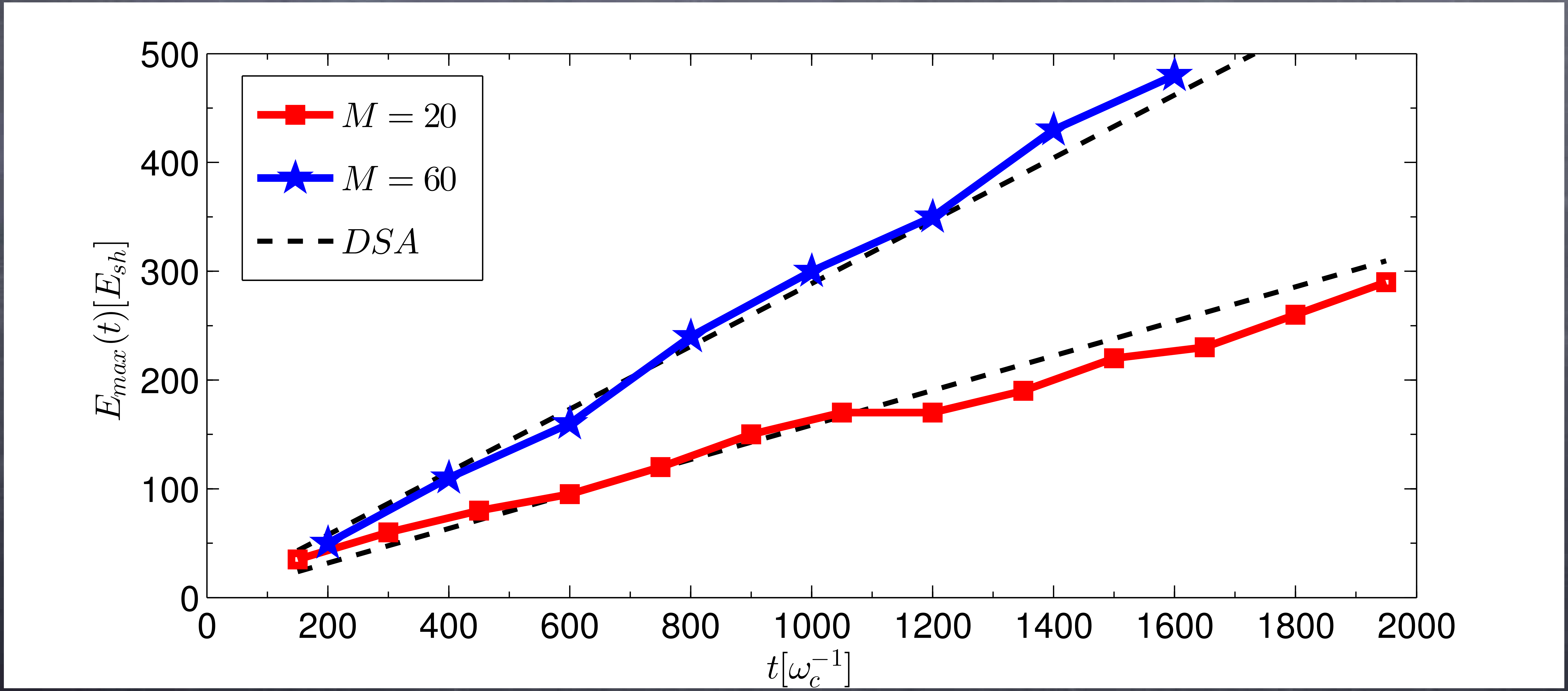
Bohm diffusion
in the amplified B

- D enhancement larger
  - near the shock
  - below E_{max}
- Suppression depends on M (B amplification)

Time evolution of E_{max}

- Evolution of $E_{max}(t)$ according to DSA (Drury 1983, Blasi et al. 2007)

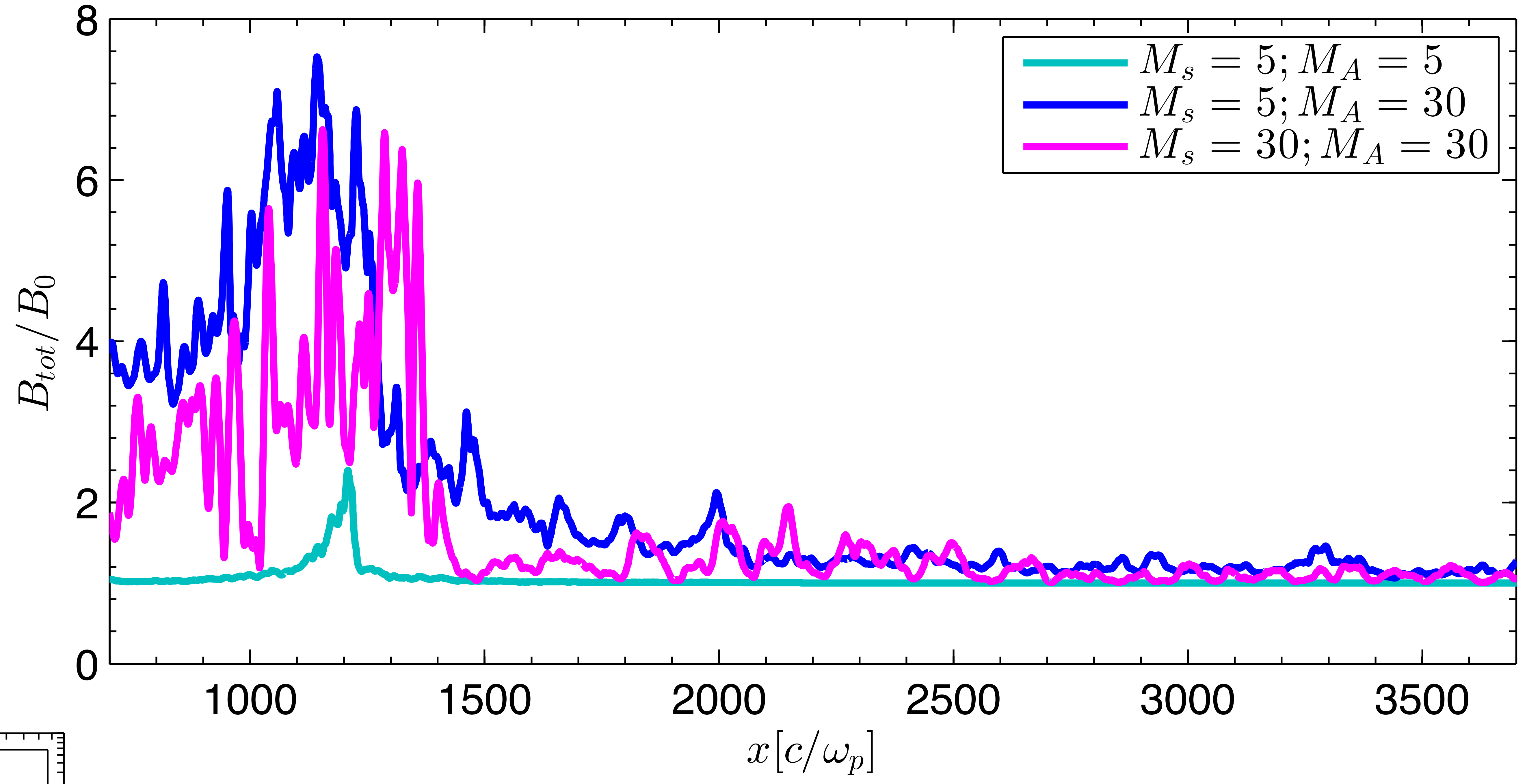
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2-1}\frac{D(E)}{v_{sh}^2}.$$



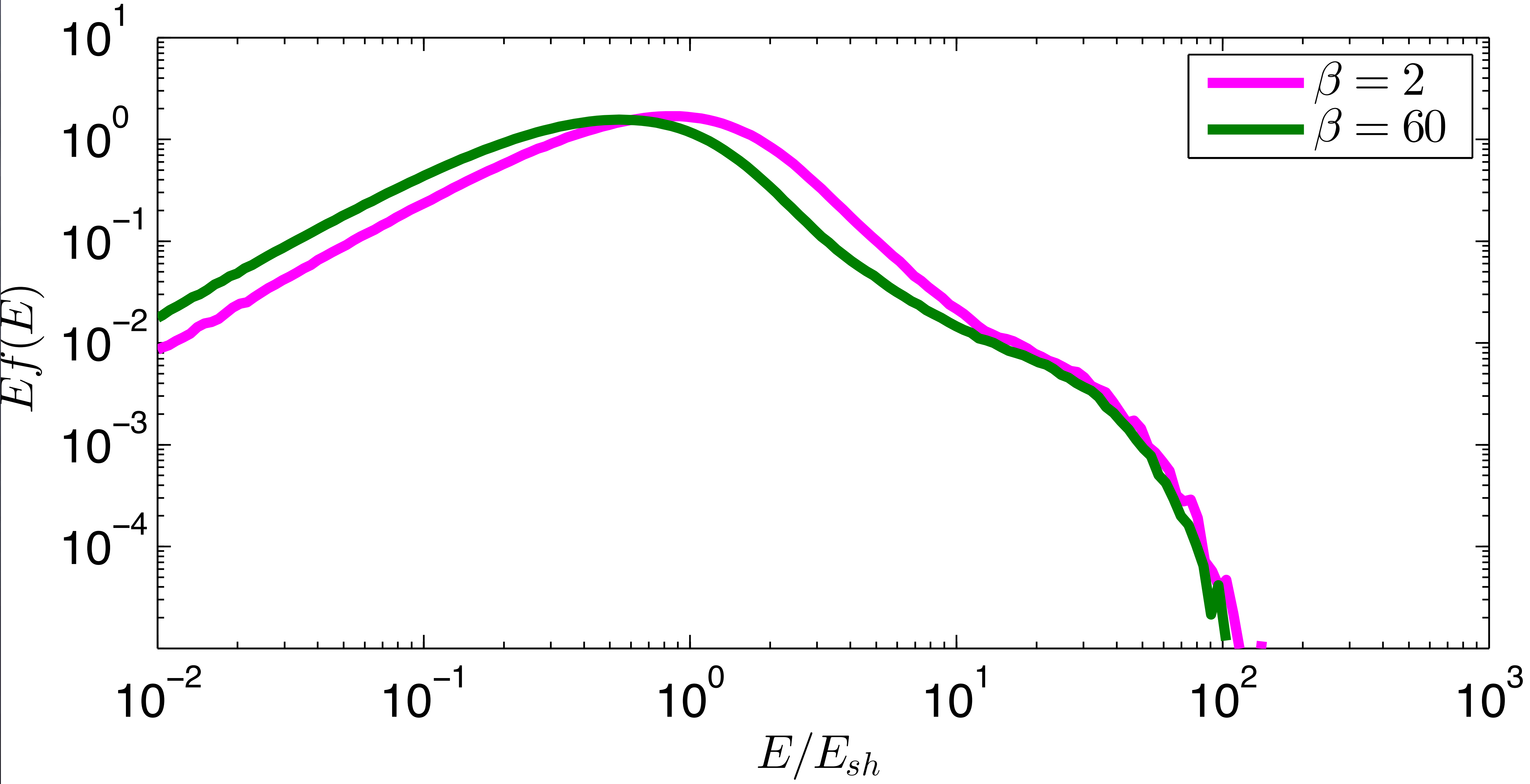
DC & Spitkovsky, 2014c

High-β plasmas

- The Alfvènic Mach # M_A controls magnetic field amplification
- The sonic Mach # M_s controls shock dynamics and CR spectrum



Magnetic fields are amplified also in high-β plasmas!



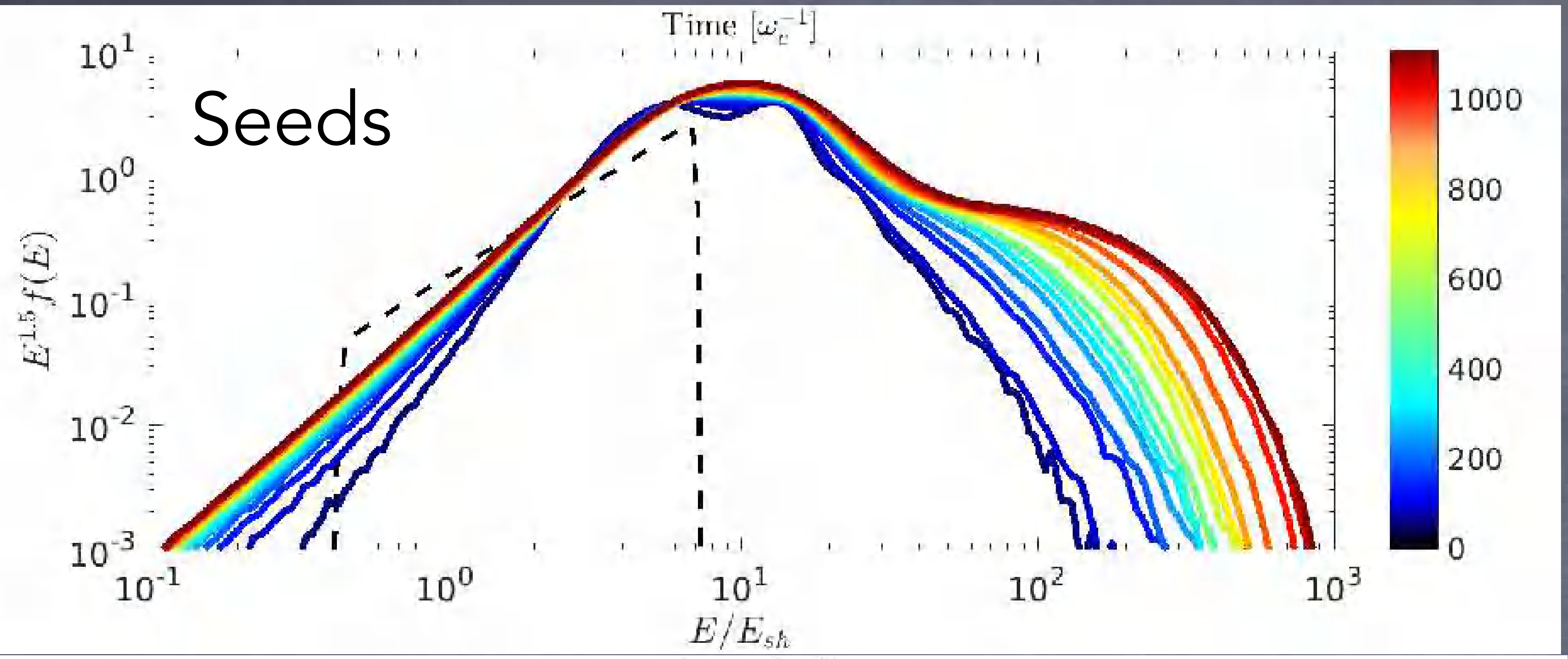
CR spectra agree with DSA prediction (steeper than p^{-4} for r<4)

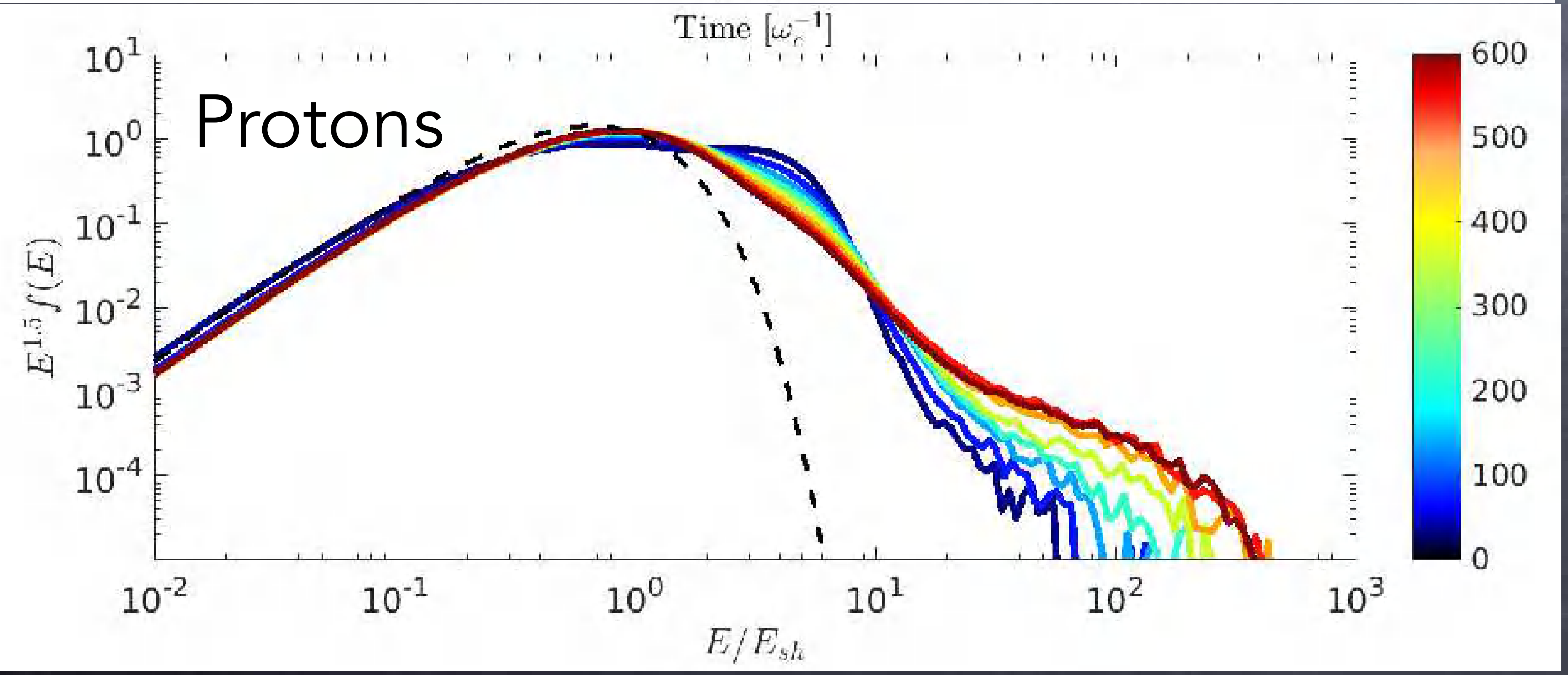
SEEDS

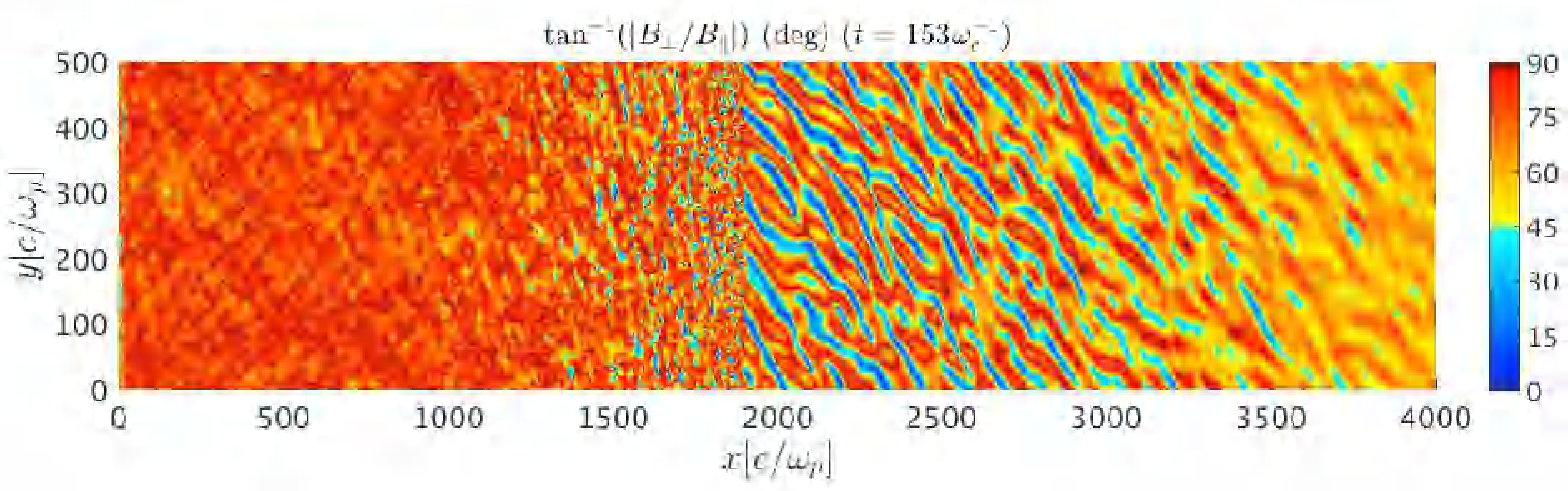
What if there are already energetic particles (seeds)?

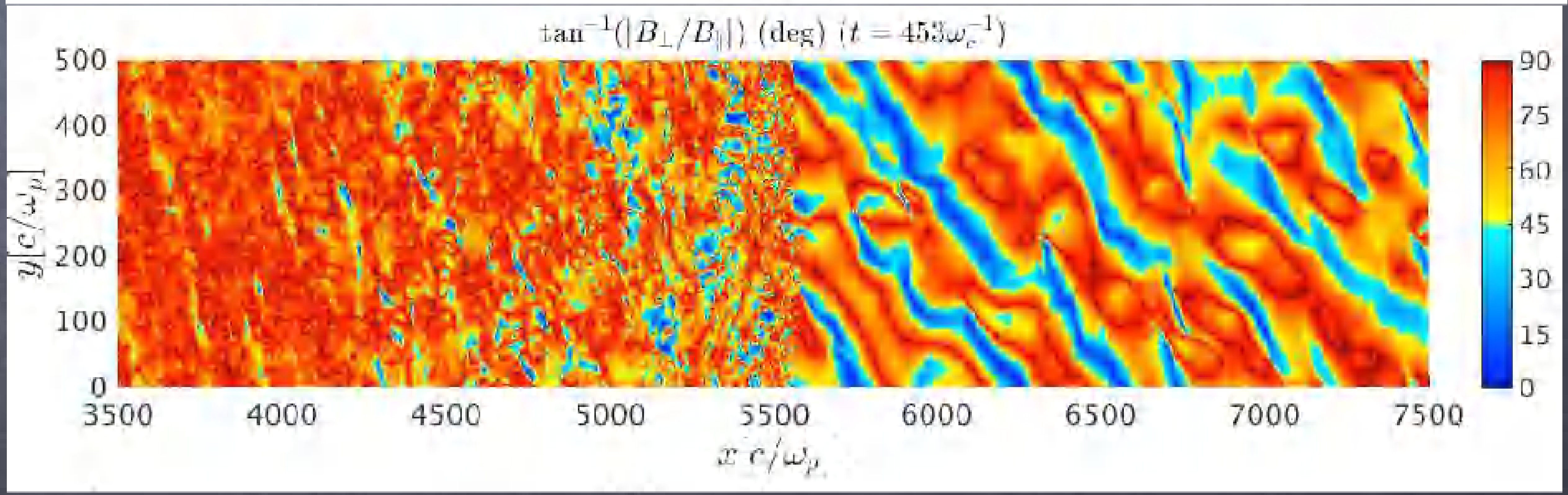
Diffusive Shock Re-Acceleration

- $\vartheta=60^\circ$ shock with *isotropic* seeds with $E_{CR}=3E_{sh}$; $n_{CR}=0.01$ (DC, Zhang, Spitkovsky, 2018)
  - Seeds are effectively reflected at the shock, amplify the upstream B, and undergo DSRA: DSRA!



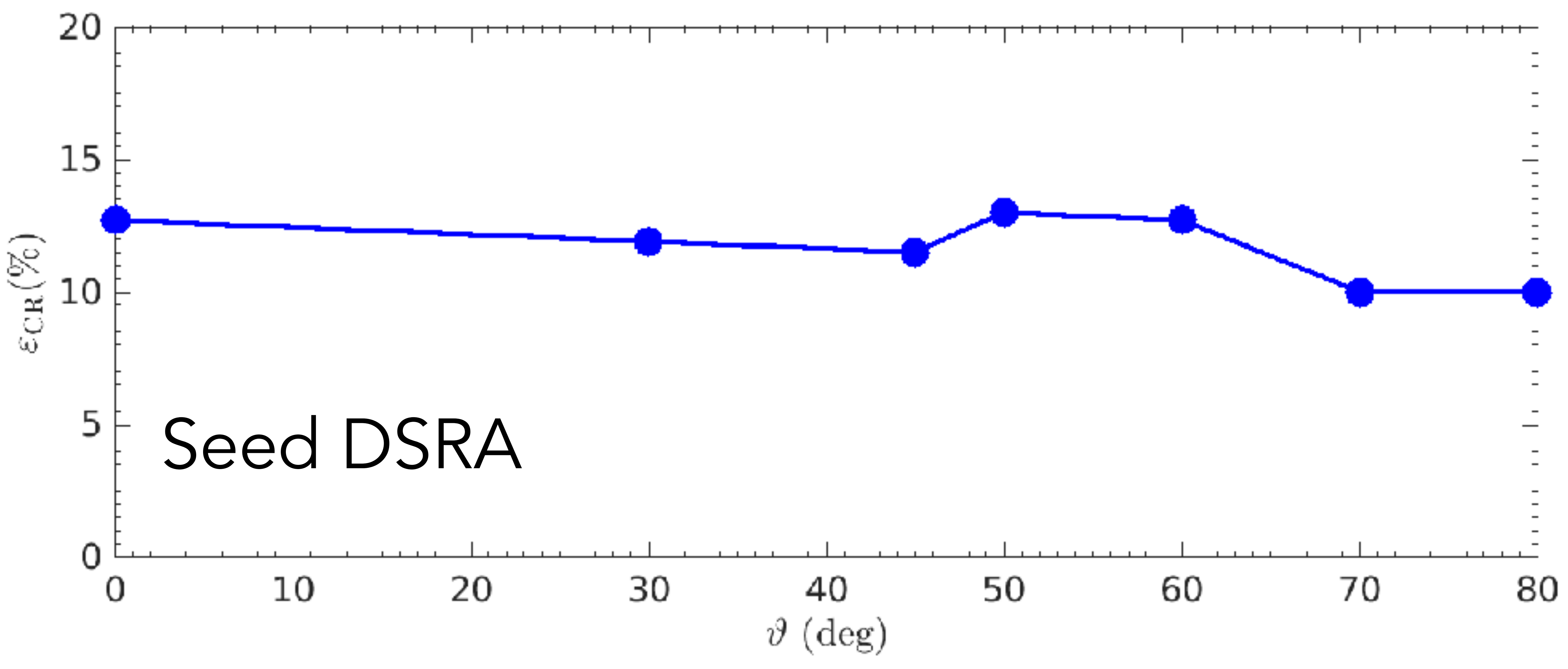


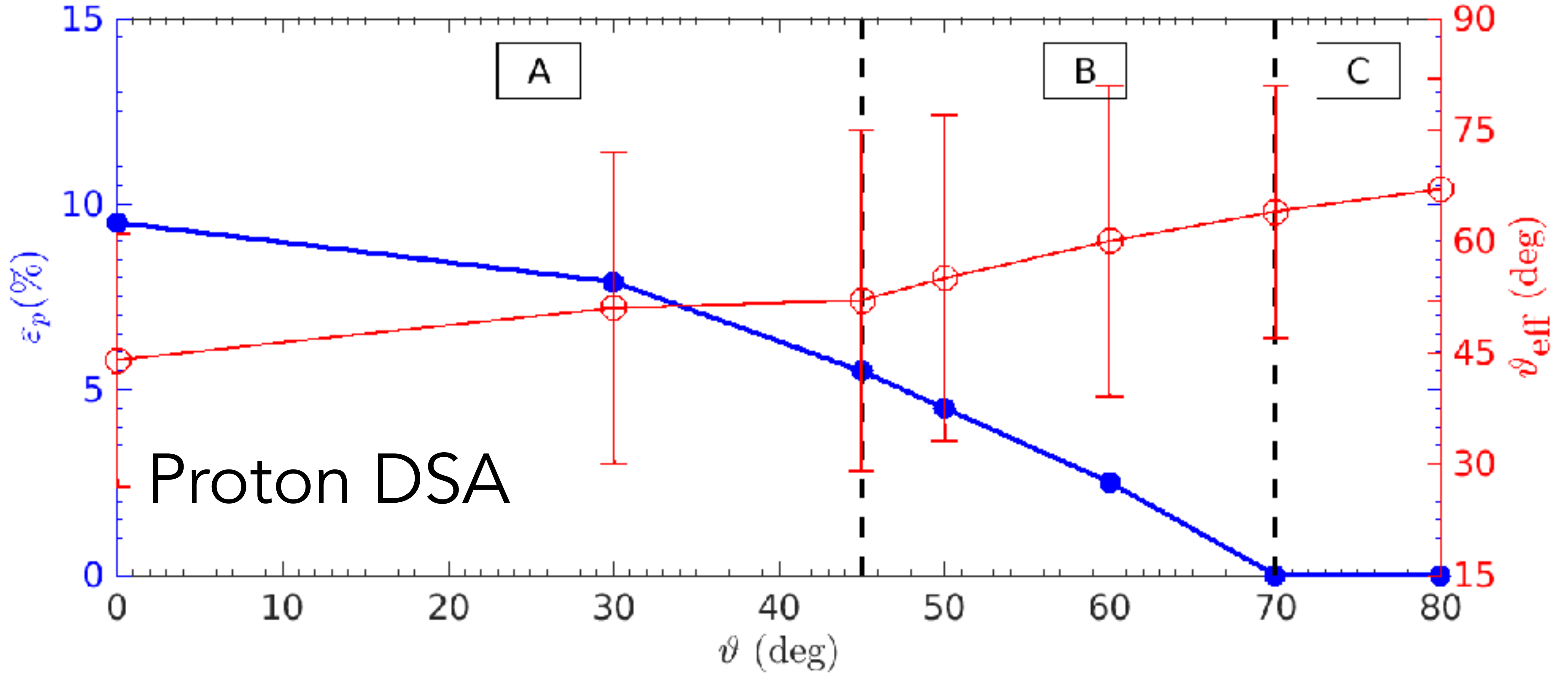




B-amplification opens up quasi-parallel patches at the shock where protons can be injected

Efficiency



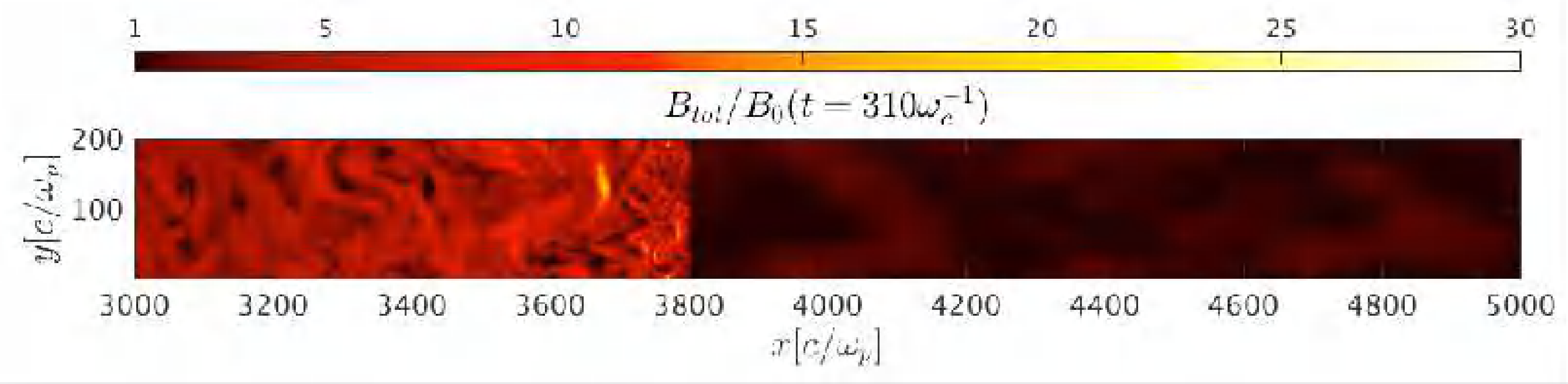


- Seed DSRA independent of ϑ, about 4x the initial CR energy density
  - *Absolute* efficiency depends on seed energy density
- Also electrons can be reaccelerated!

- A (ϑ<45°): Same proton efficiency
- B (45°<ϑ<70°): Boosted to few %
- C (ϑ>70°): No proton DSA

Quasi-Perpendicular SEEDED Shocks

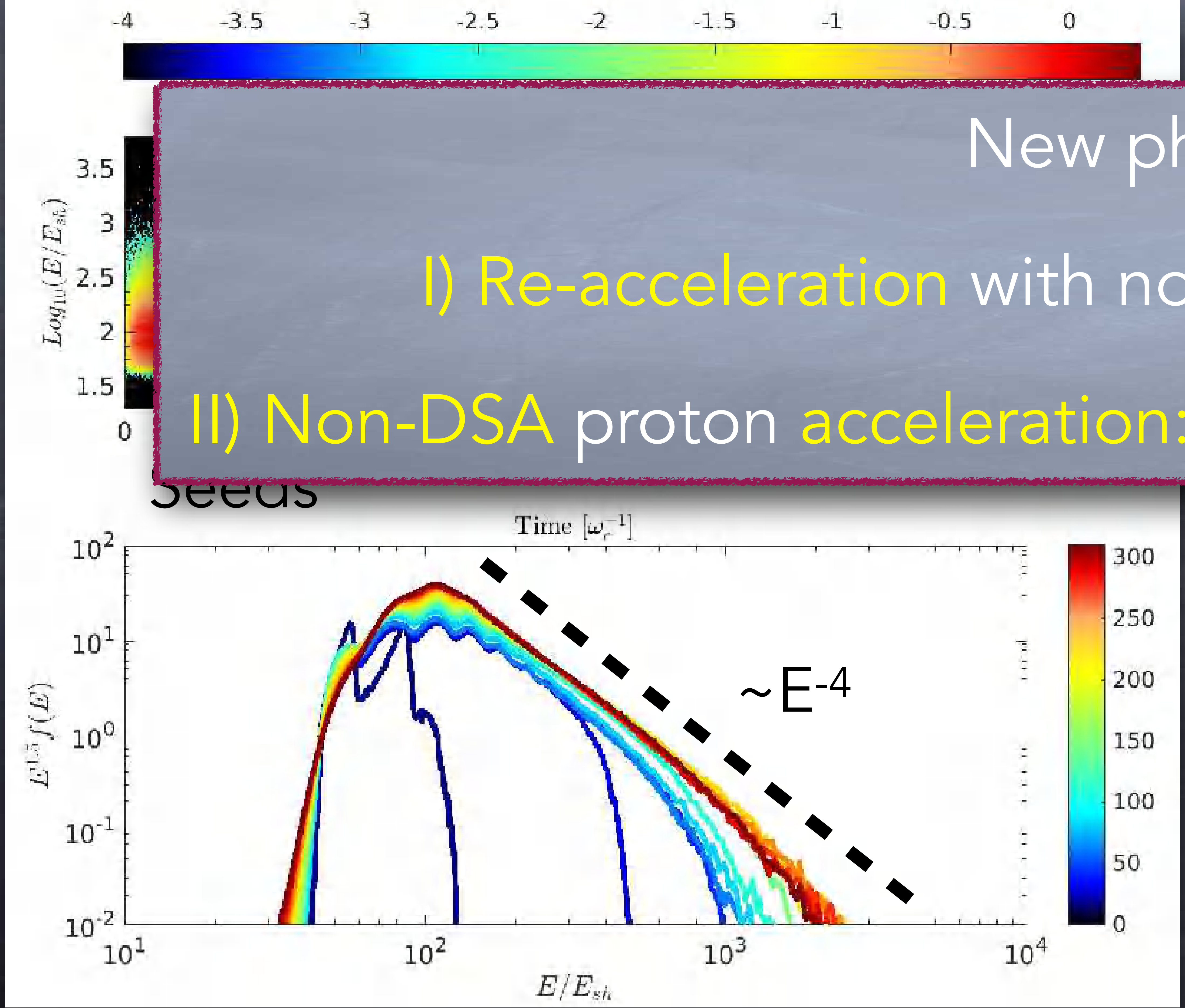
- $\vartheta=80^\circ$ quasi-perp shock with seeds $E_{CR}=3E_{sh}$
  - Seeds diffuse but their spectrum is steeper than DSA
  - Non-thermal protons only downstream



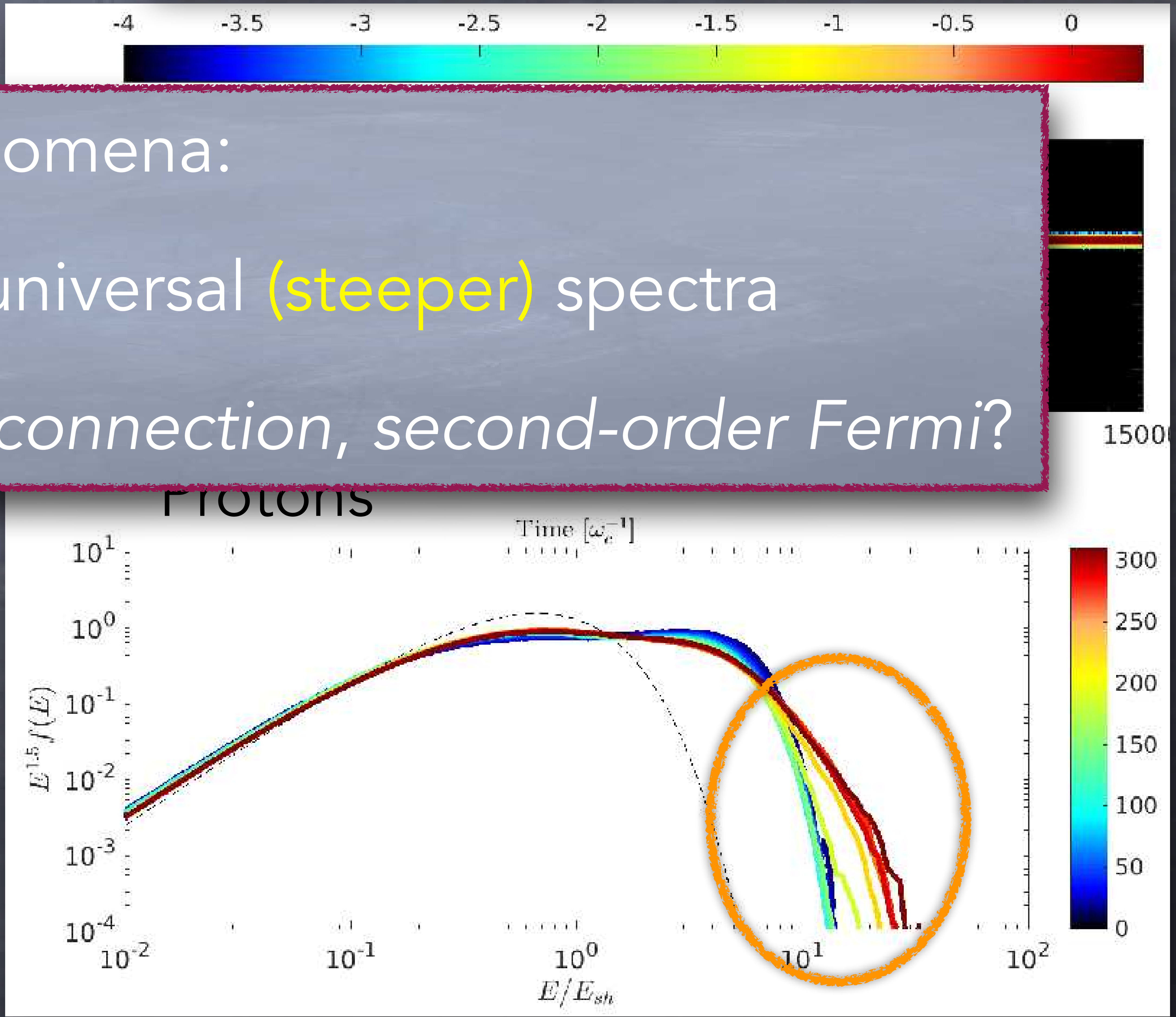
New phenomena:

I) Re-acceleration with non-universal (steeper) spectra

II) Non-DSA proton acceleration: *reconnection, second-order Fermi*?

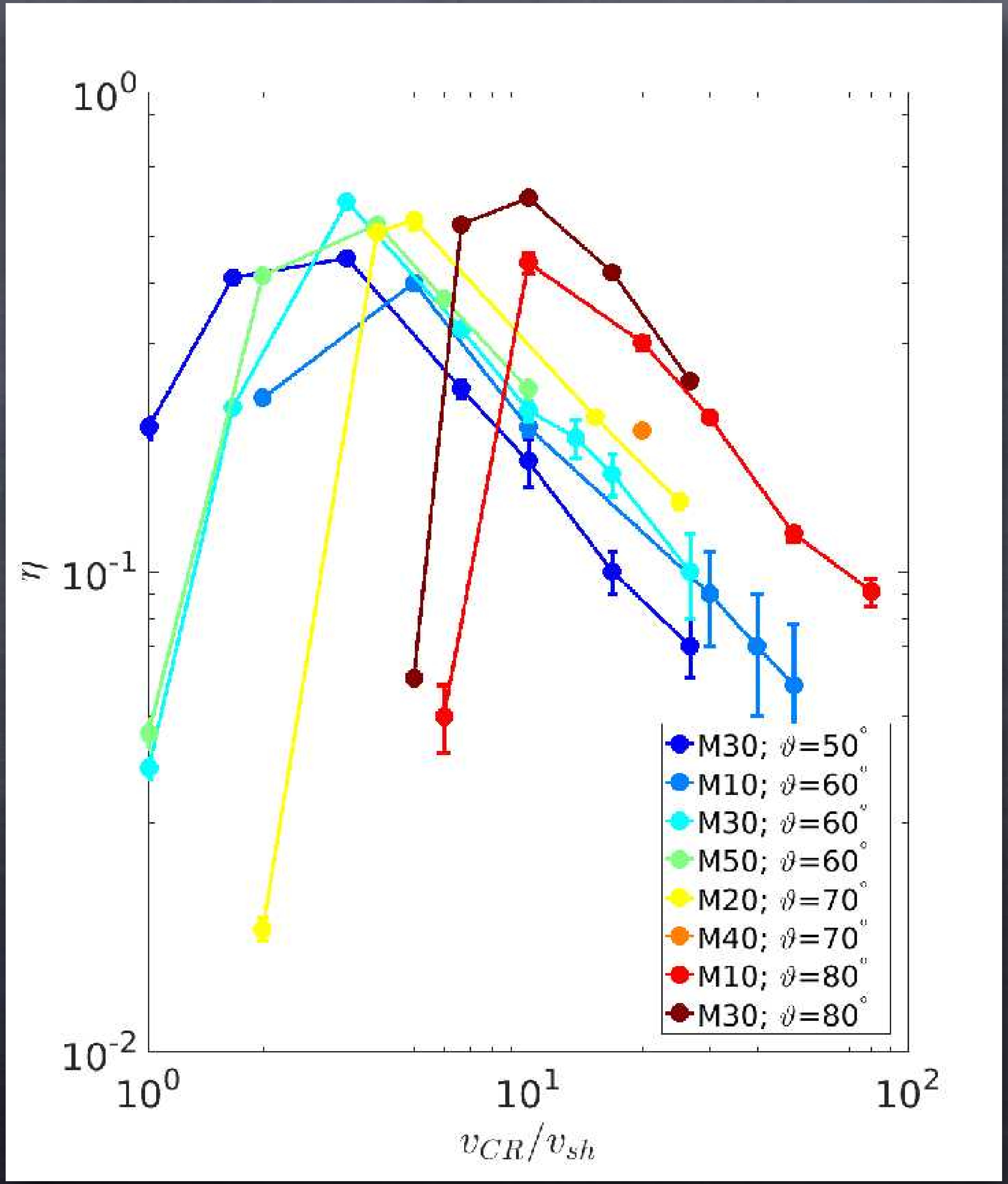


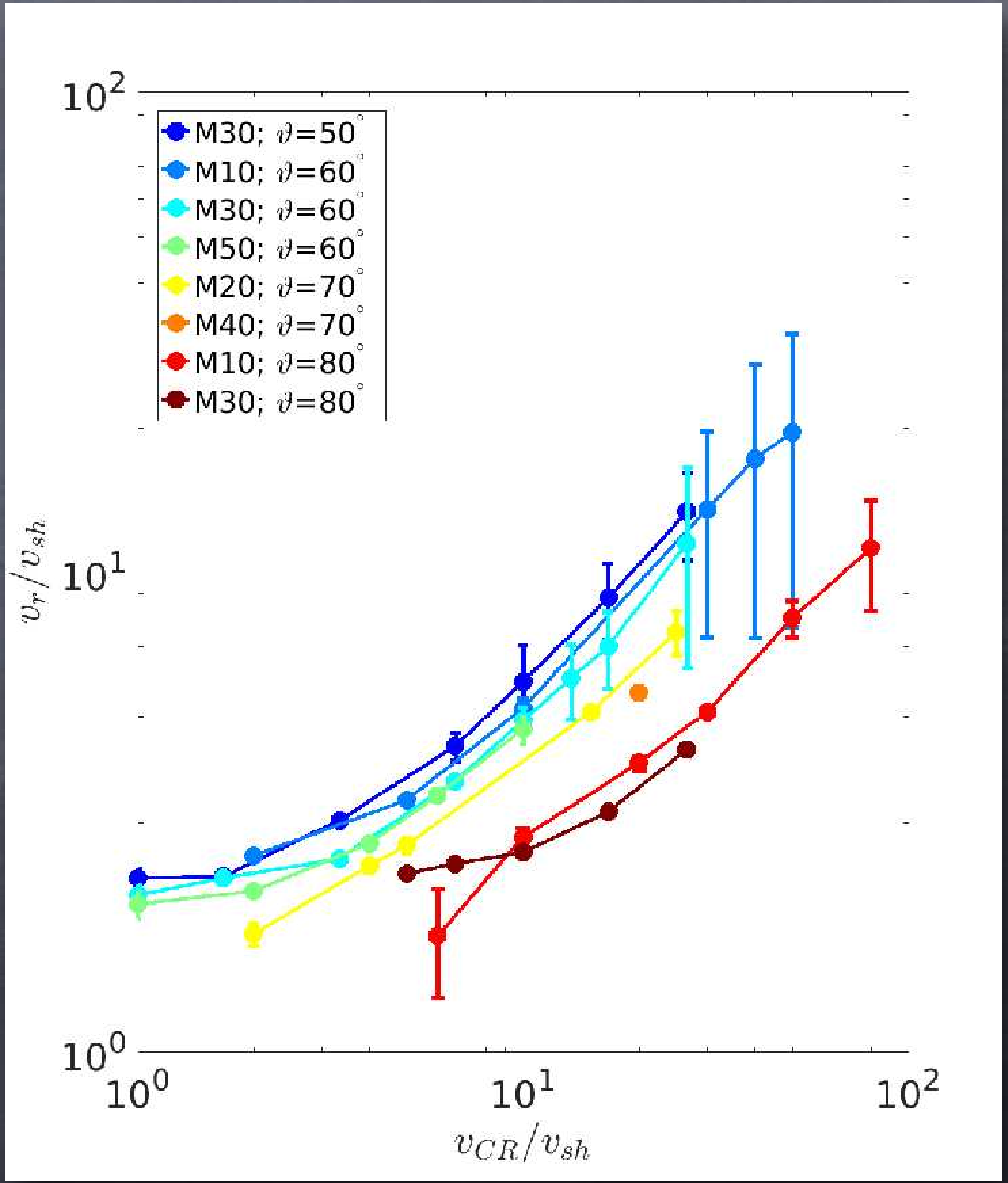
$\sim E^{-4}$



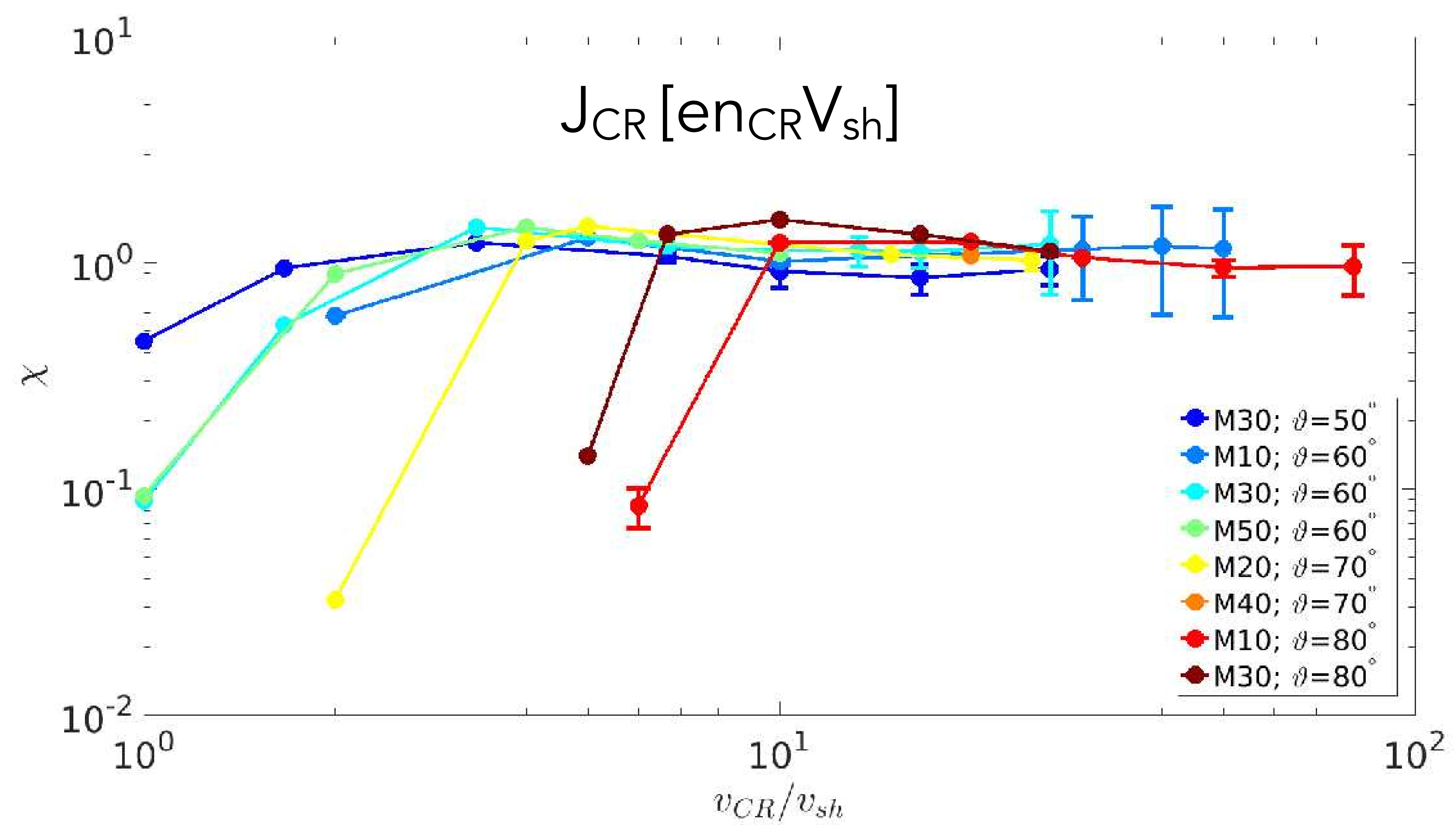
The Current in Reflected CRs

- Depends on the fraction of reflected seeds, η, and their speed, v_r





A *Universal* Current in Reflected CRs



- η and v_r "magically" balance their dependence on ϑ and M exactly:

$$J_{CR} = e n_{CR} V_{sh}$$

- Easy explanation: CRs tend to become isotropic at the shock, *in the shock frame*: they become anisotropic *in the upstream frame*
- For SNRs and Galactic CRs:

$$T_{stream\ inst} \sim 10\mathrm{yr}$$

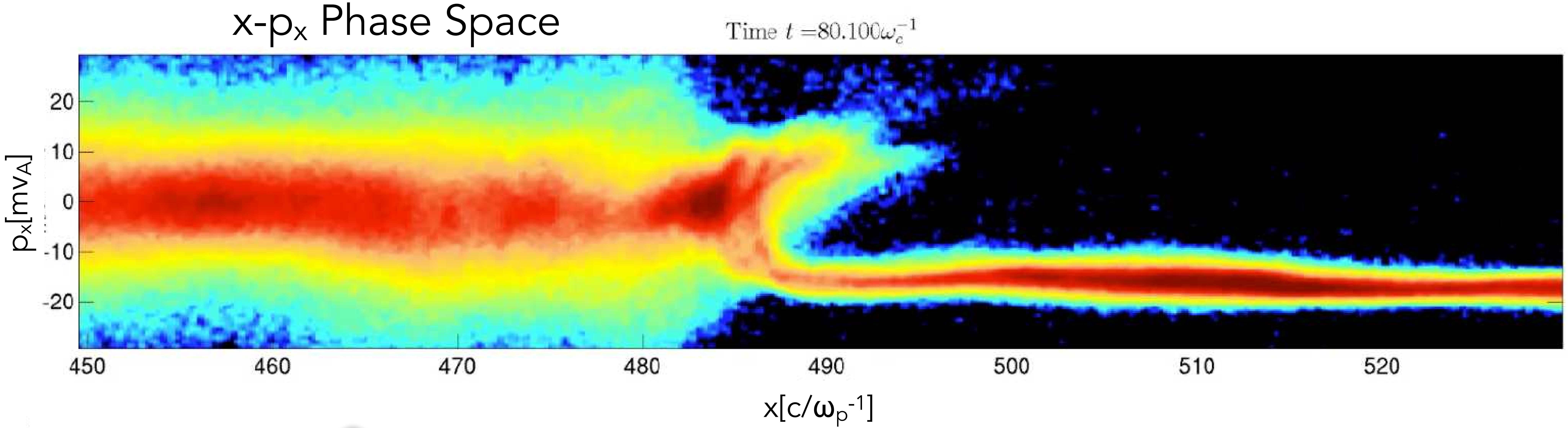
Minimum level of B-amplification for shocks in the ISM

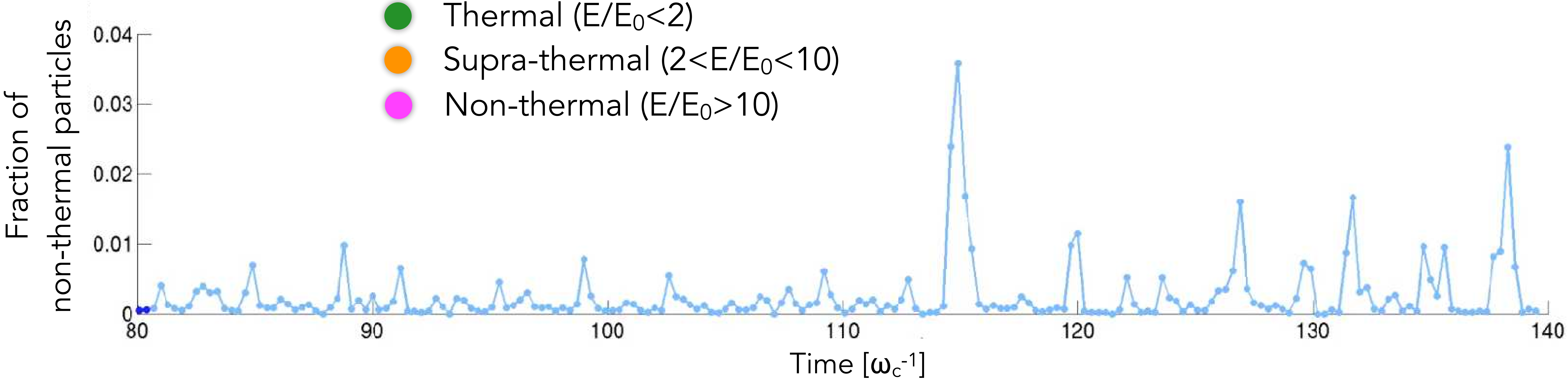
INJECTION

Particle Injection - Simulations

DC, Pop & Spitkovsky, 2015

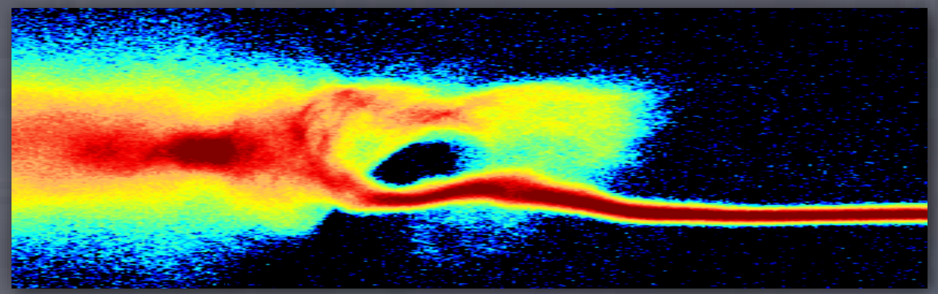
x-p_x Phase Space

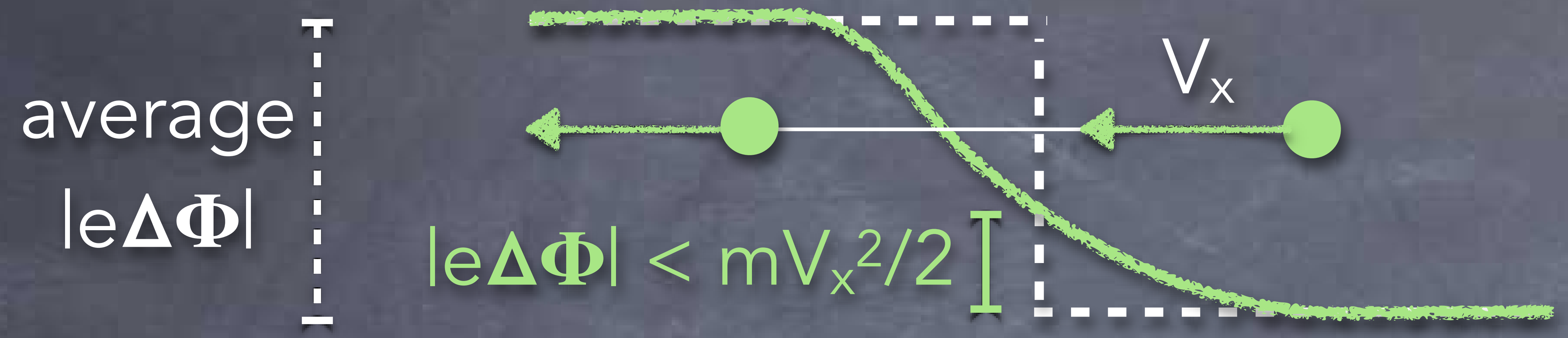




Encounter with the shock barrier

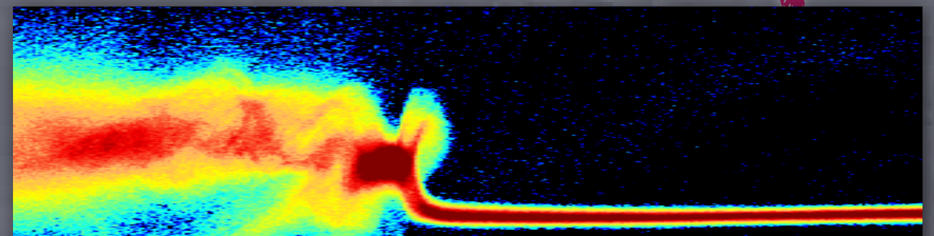
- Low barrier (reformation)





Ions advected downstream, and thermalized

- High barrier (overshoot)



Ions reflected upstream, and energized via Shock Drift Acceleration

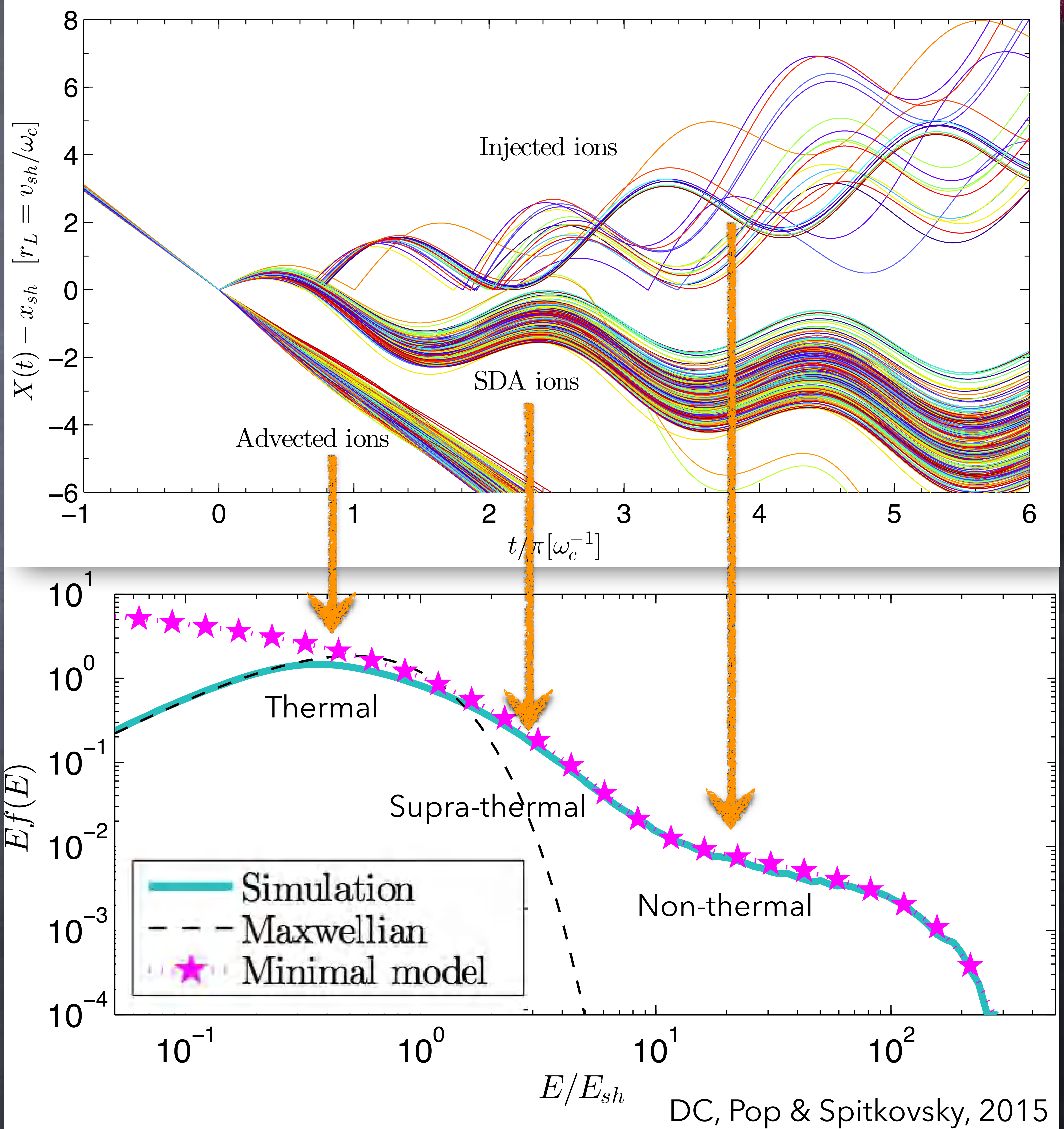
- To overrun the shock, ions need a minimum E_{inj}, increasing with ϑ (DC, Pop & Spitkovsky 15)
  - Ion fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj} \sim 10E_0$, which requires N~3 -> $\eta \sim 1\%$
  - For $\vartheta>45^\circ$, $E_{inj}>10E_0$, hence N>3 and $\eta << 1\%$

Minimal Model for Ion Injection

- Time-varying potential barrier
    - **High state** (duty cycle ~25%)
        - Reflection + SDA
    - **Low-state** (~75%)
        - Thermalization
- Spectrum à la Bell (1978)

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

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

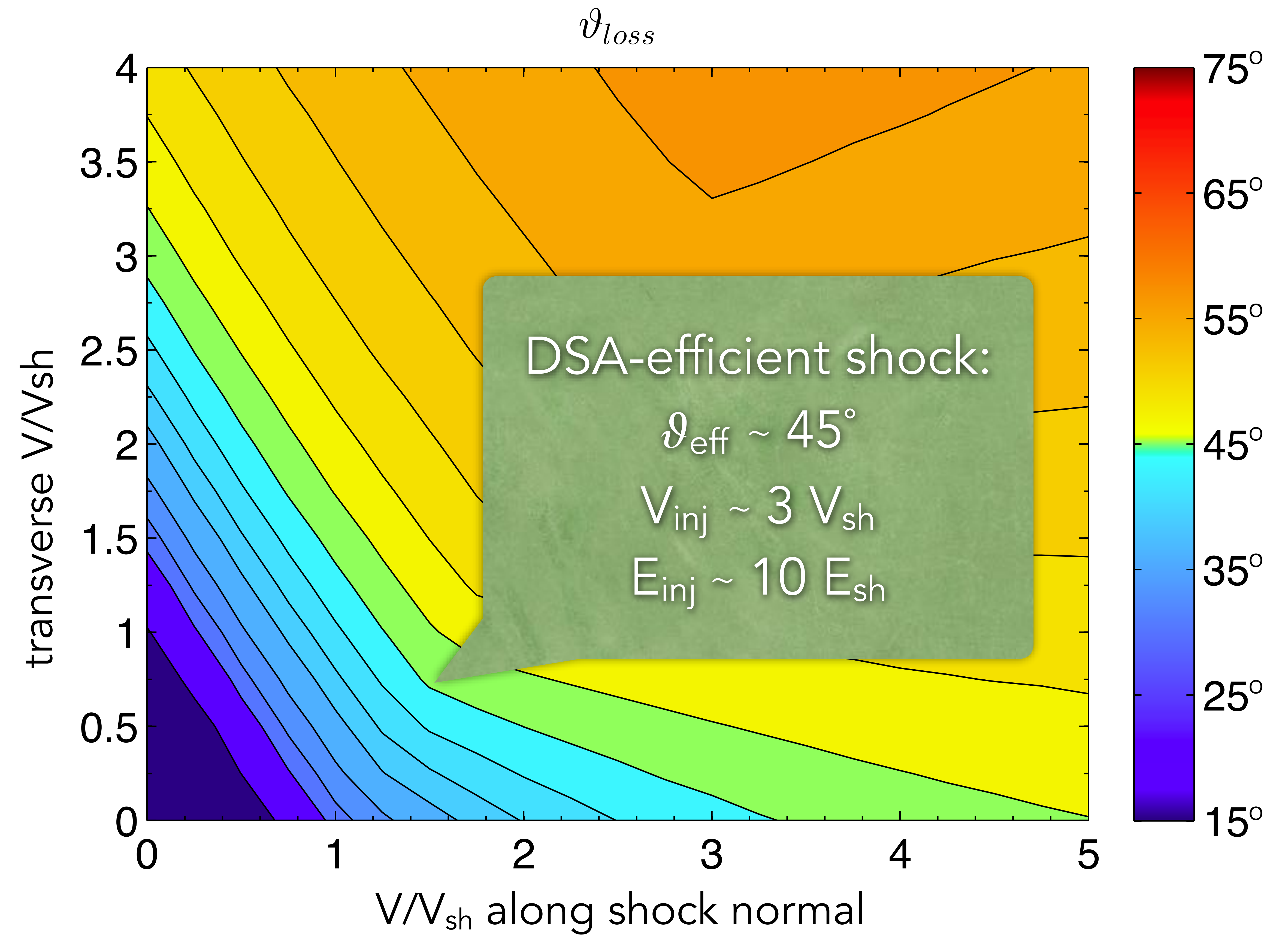


DC, Pop & Spitkovsky, 2015

Ion Injection - Theory

- Ion fate determined by
  - barrier duty-cycle (~25%)
  - pre-reflection V
  - shock inclination
- If $\vartheta<\vartheta_{\rm loss}$, ions escape upstream, and are injected into DSA
- Otherwise, they experience SDA, return to the shock (with larger V), and may be either reflected or advected
  - After N SDA cycles, only a fraction $\eta \sim 0.25^N$ survives
  - For $\vartheta_{\rm eff} \sim 45^\circ$, N~3 -> $\eta \sim 1\%$

Max ϑ allowing reflection upstream



DSA-efficient shock:

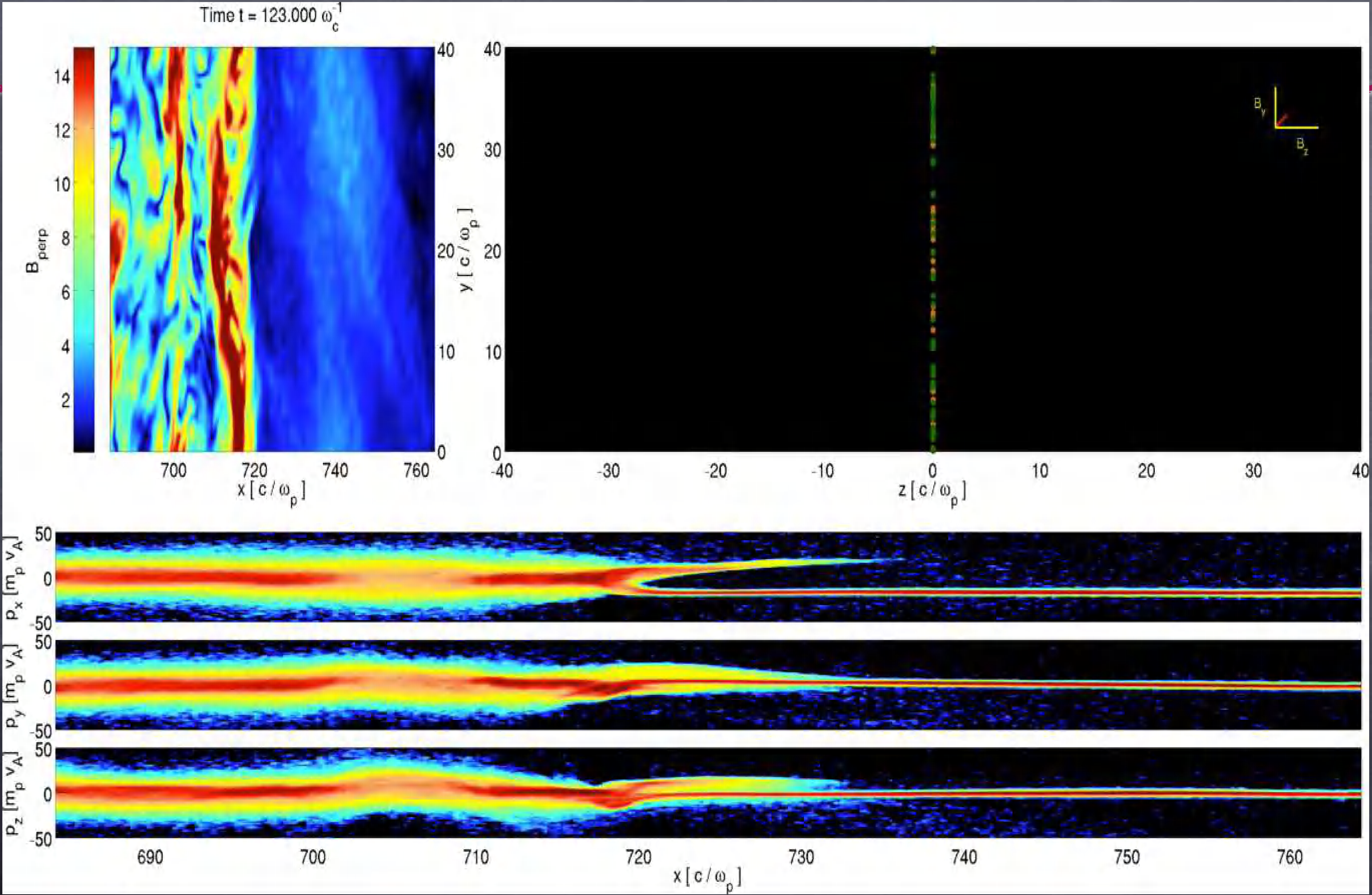
$\vartheta_{\rm eff} \sim 45^\circ$

$V_{\rm inj} \sim 3\ V_{\rm sh}$

$E_{\rm inj} \sim 10\ E_{\rm sh}$

DC, Pop & Spitkovsky, 2015

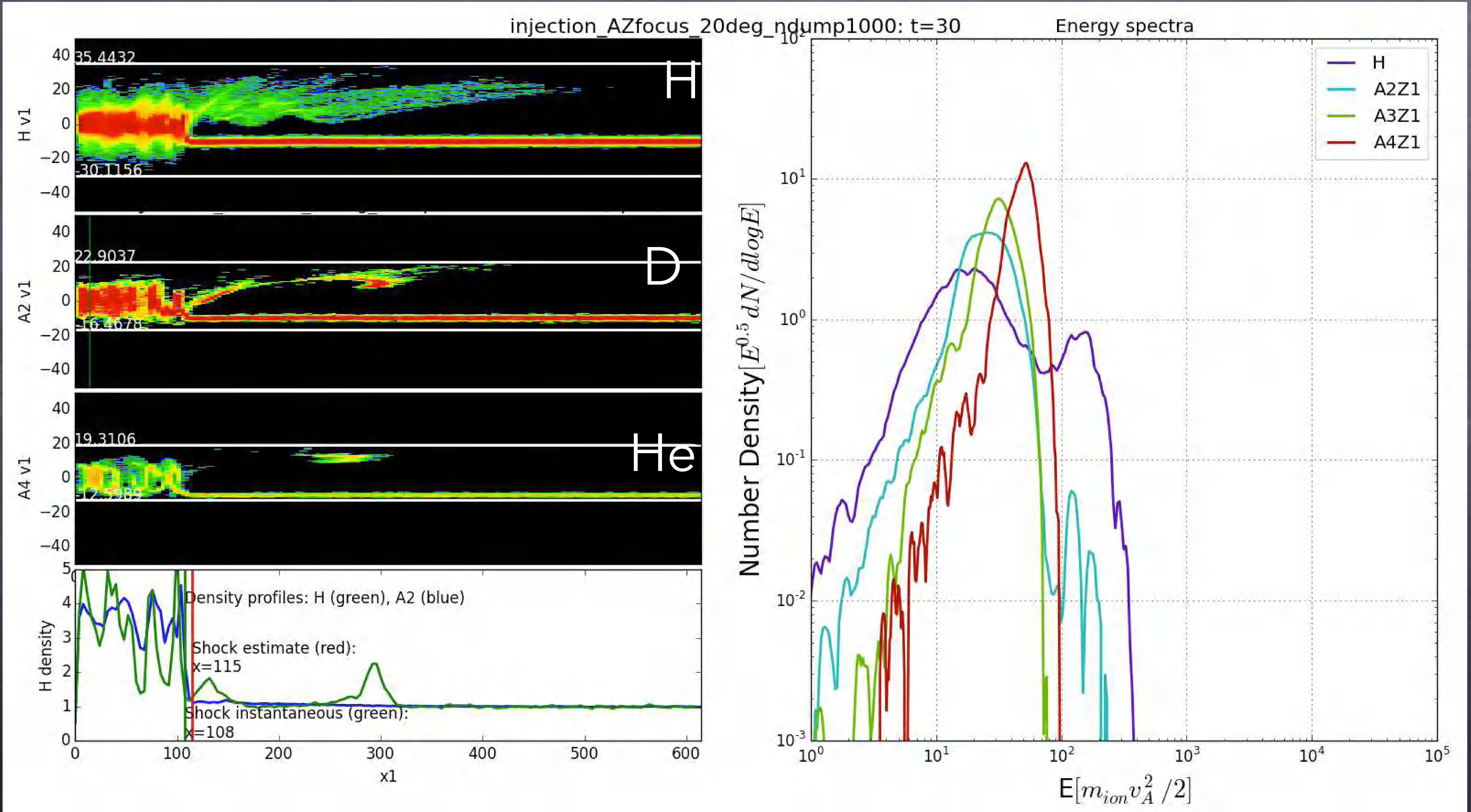
$E_{\rm inj}$ is larger at oblique shocks: injection requires more SDA cycles, and fewer particles can achieve $E_{\rm inj}$


Time t = 123.000 ω_c^-1
B_perp
14
12
10
8
6
4
2
700
720
740
760
x [c / ω_p]
y [c / ω_p]
40
30
20
10
0
B_y
B_z
-40
-30
-20
-10
0
10
20
30
40
z [c / ω_p]
p_x [m_p v_A]
p_y [m_p v_A]
p_z [m_p v_A]
50
0
-50
690
700
710
720
730
740
750
760
x [c / ω_p]

NUCLEI

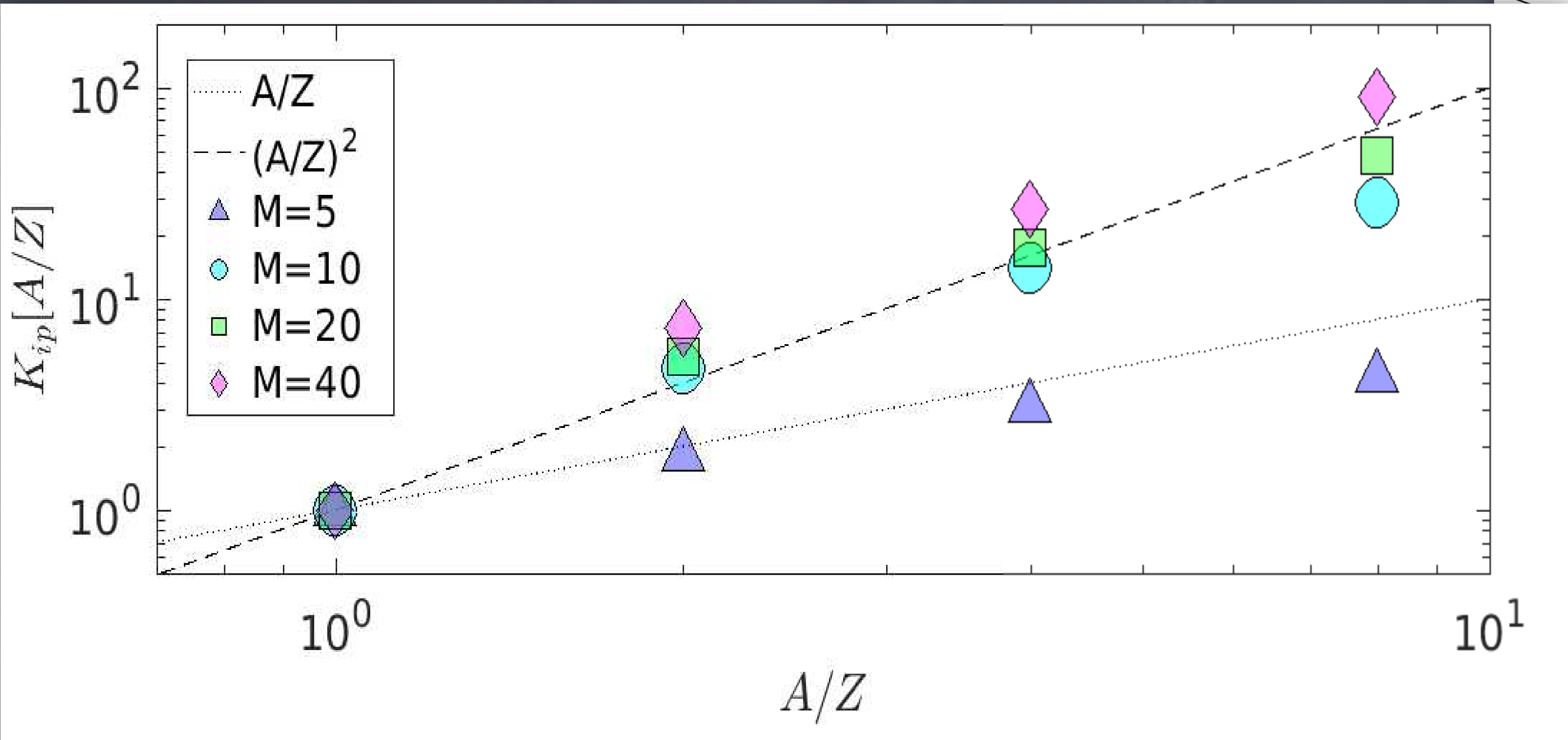
Hybrid Simulations

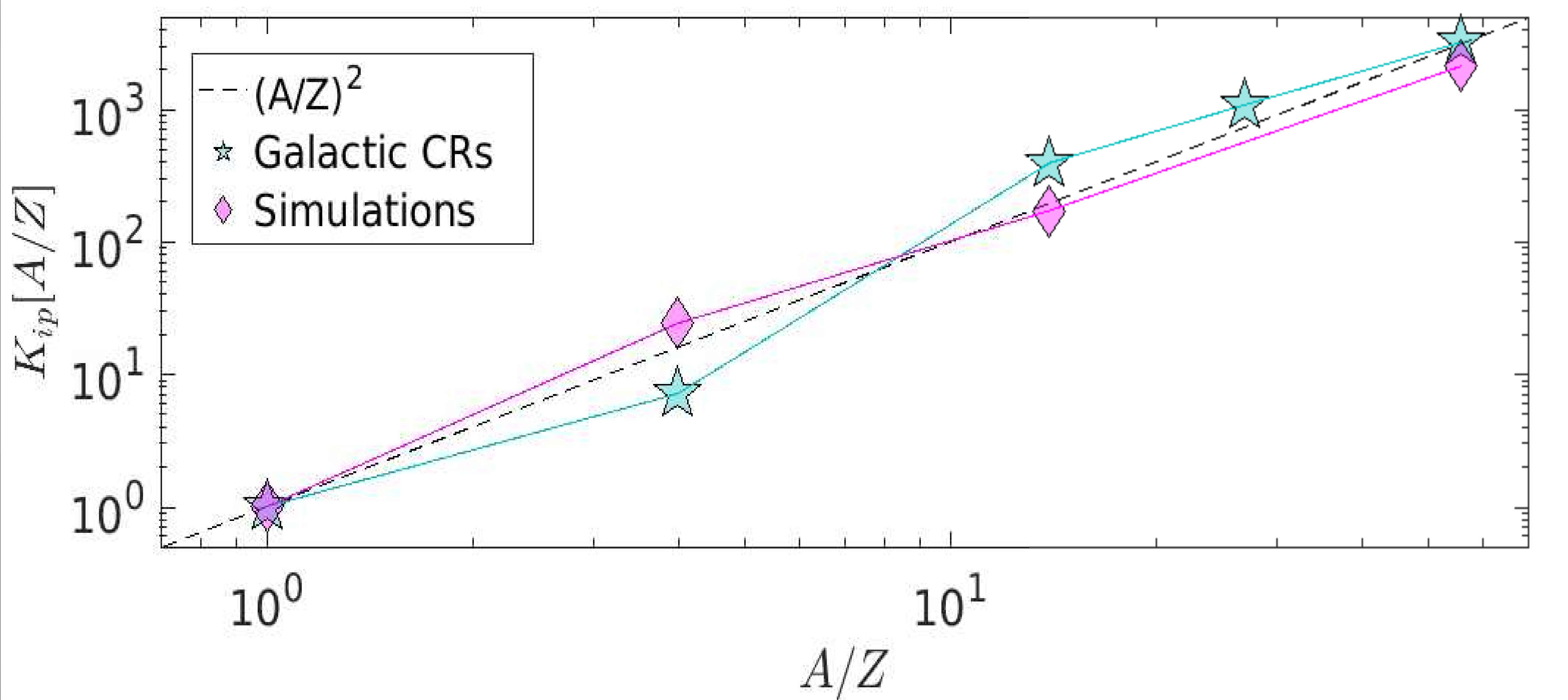
- M=10, parallel shock, with singly-ionized nuclei (DC, Yi, Spitkovsky 2017)

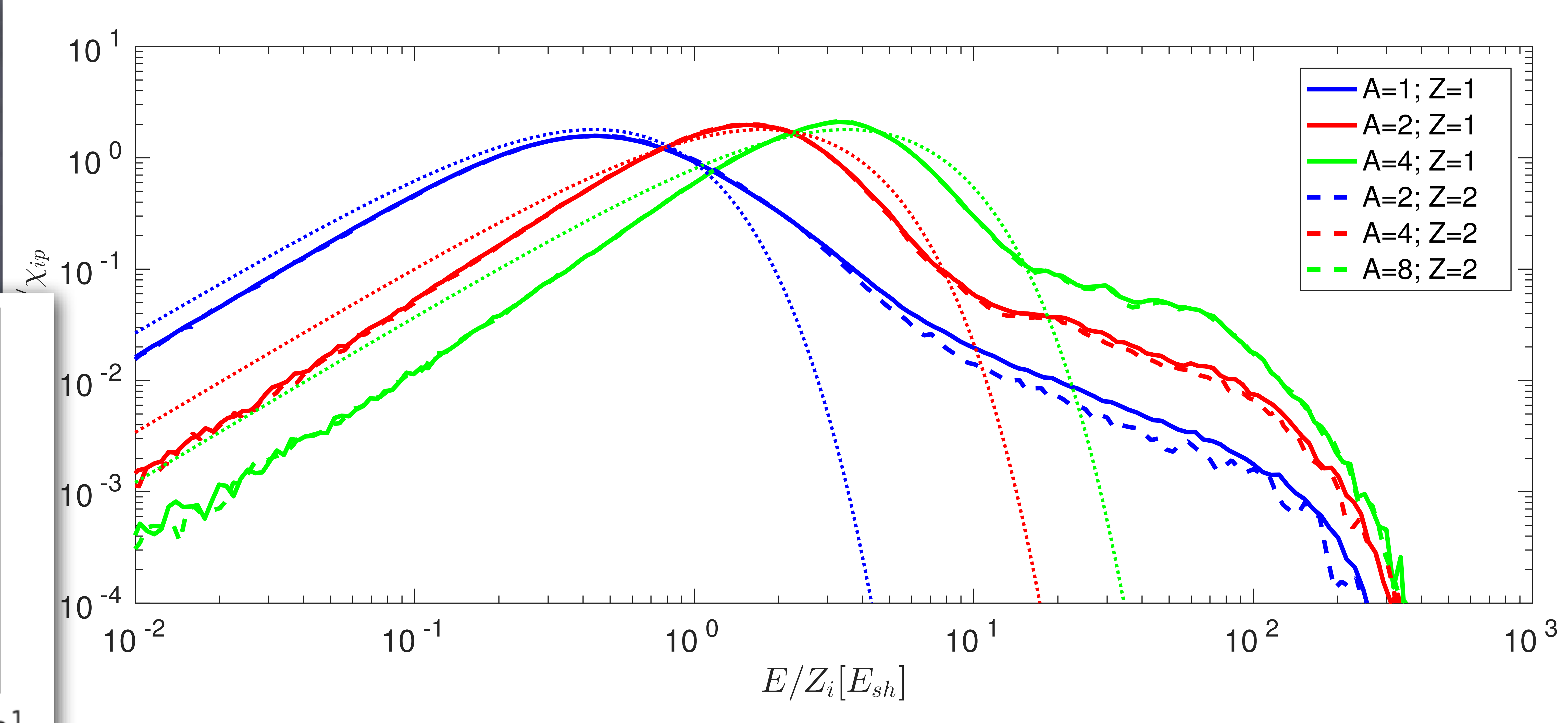


Hybrid Simulations with Heavy Ions

- Quasi-parallel shock, M=20
  Ion DSA when proton DSA!



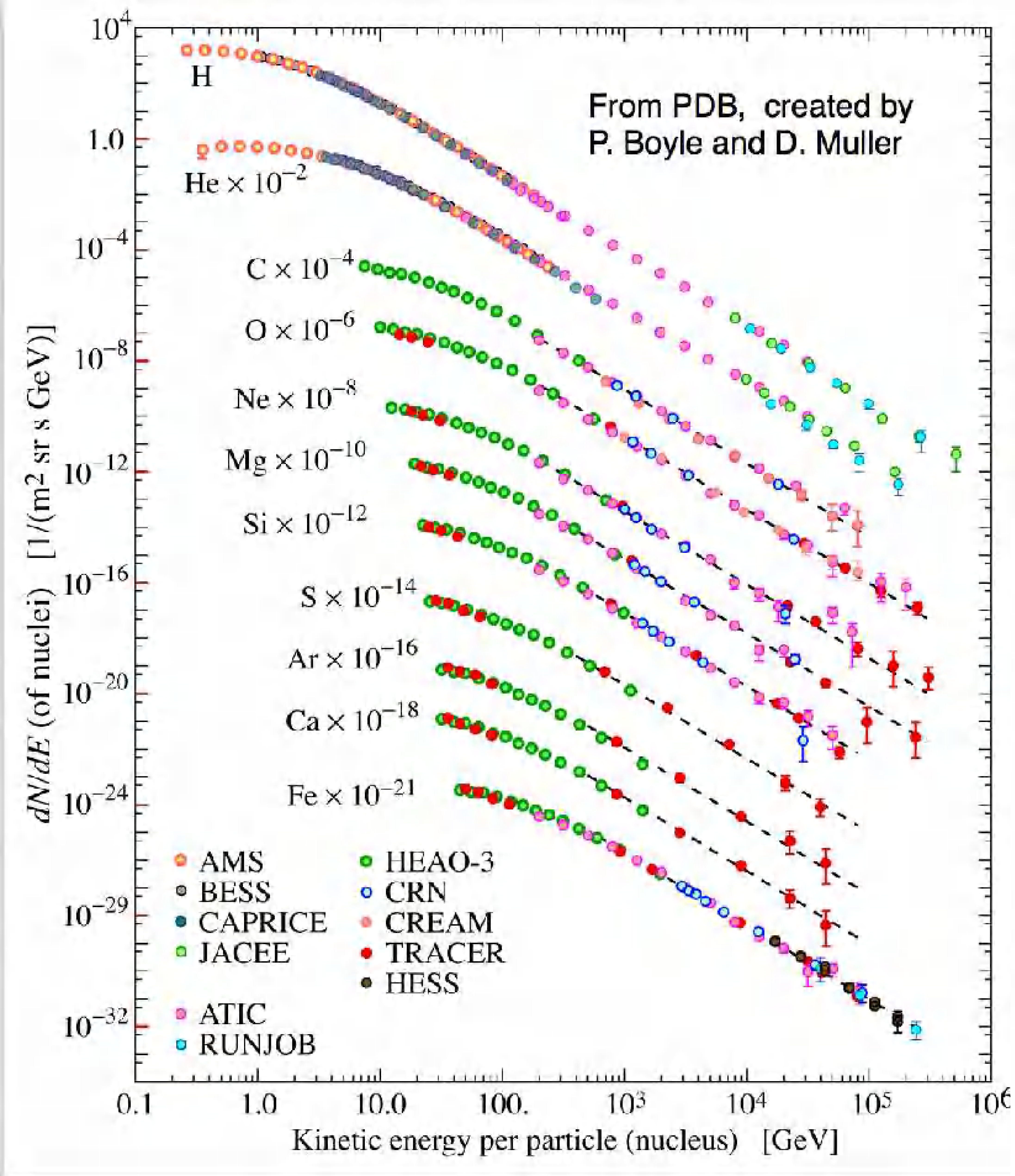


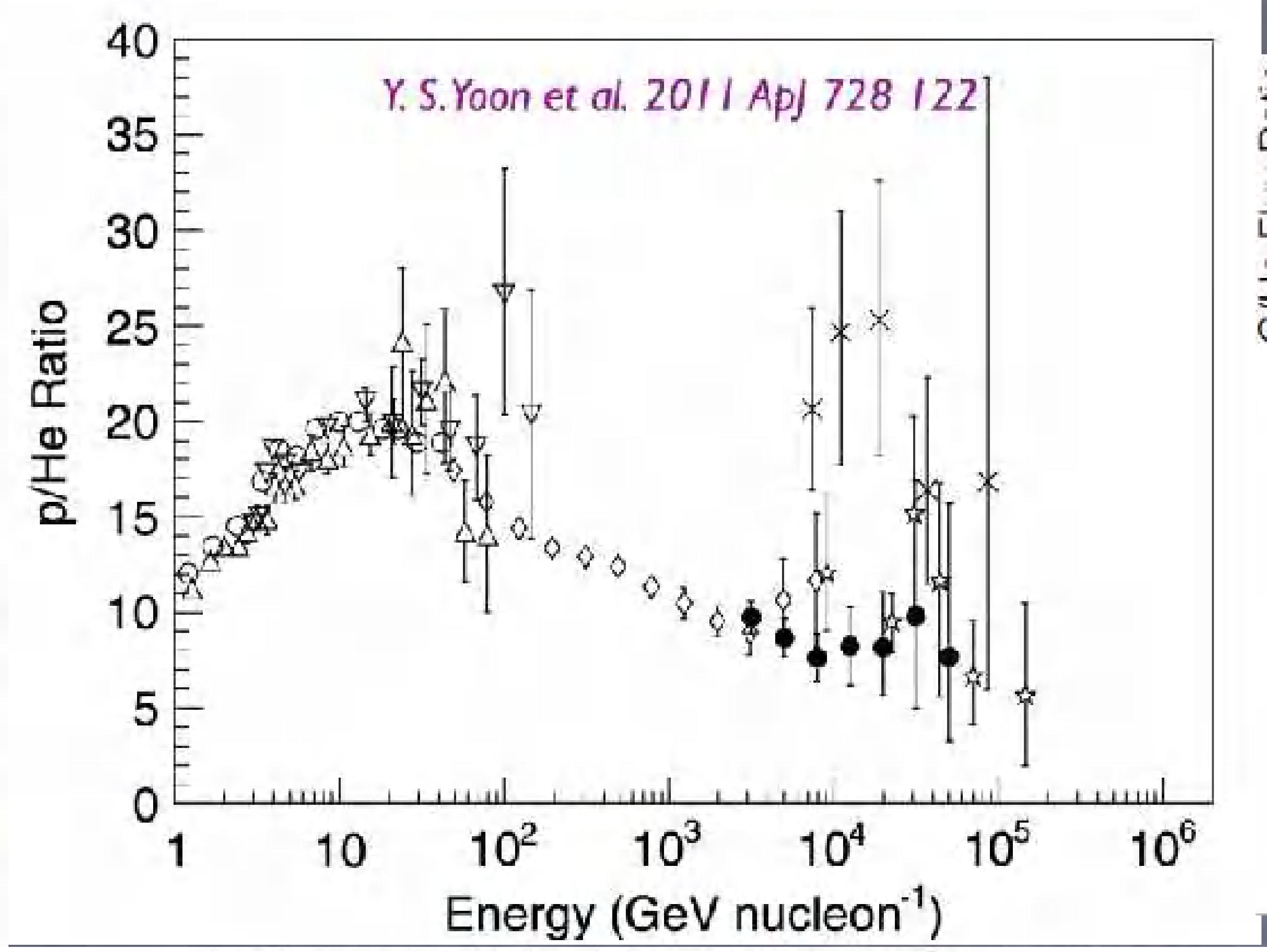


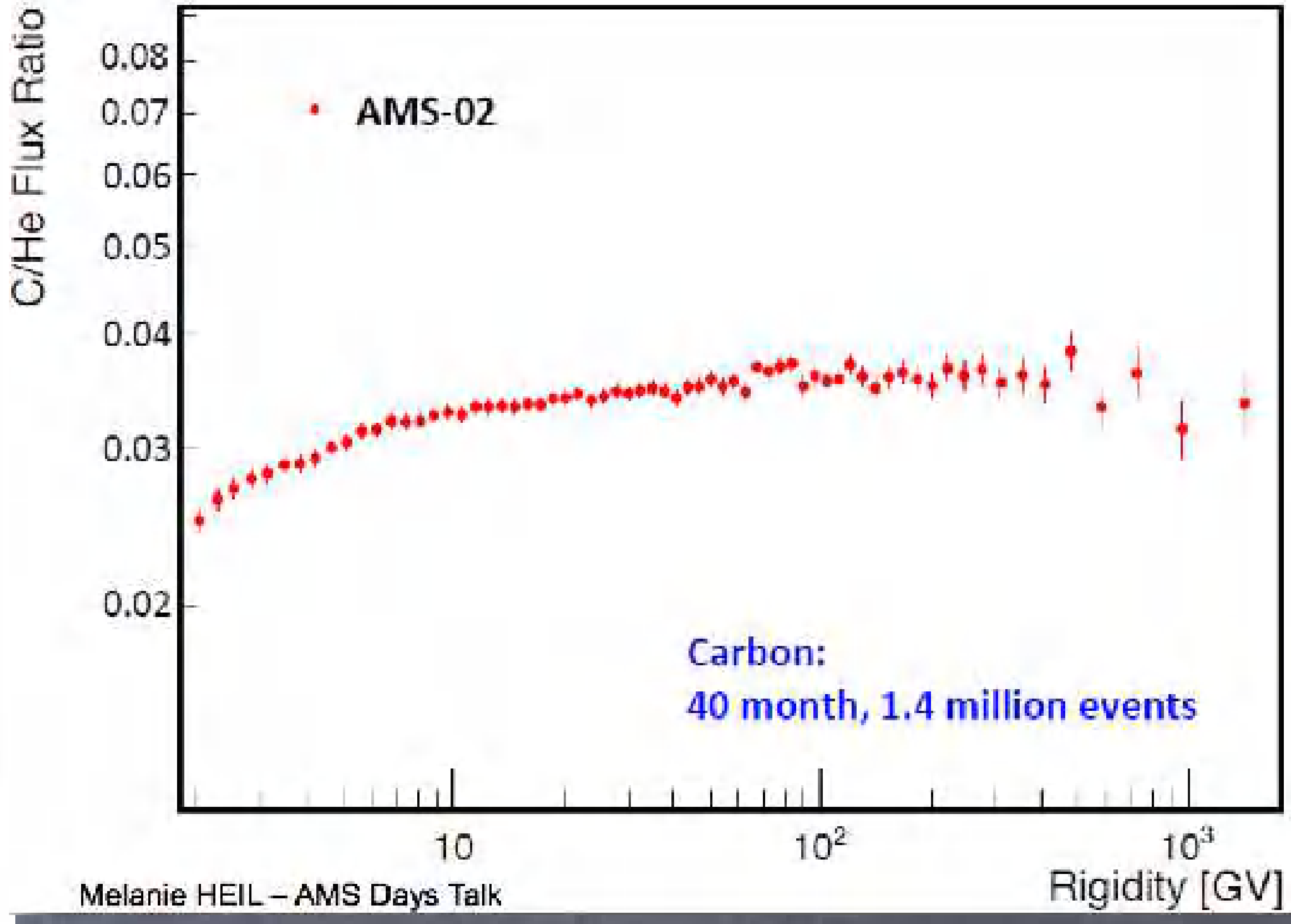
DC, Yi & Spitkovsky, 2017

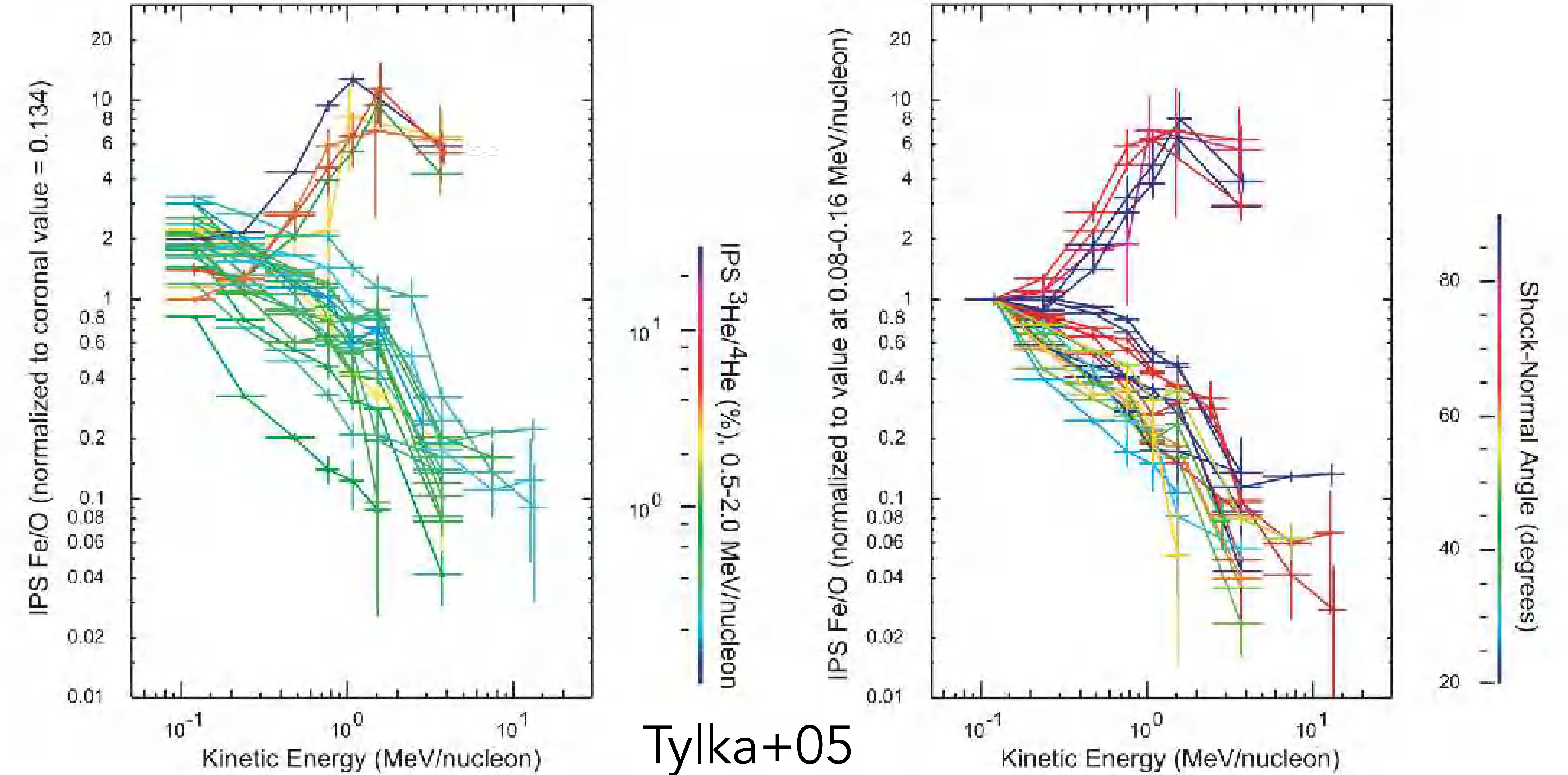
- Post-shock T_i scales with A_i
- $E_{max,i}$ scales with Z_i
- The tail normalization scales with $(A_i/Z_i)^2$
  - Explains CR chemical enhancements!

Anomalous Abundances in CRs and SEPs





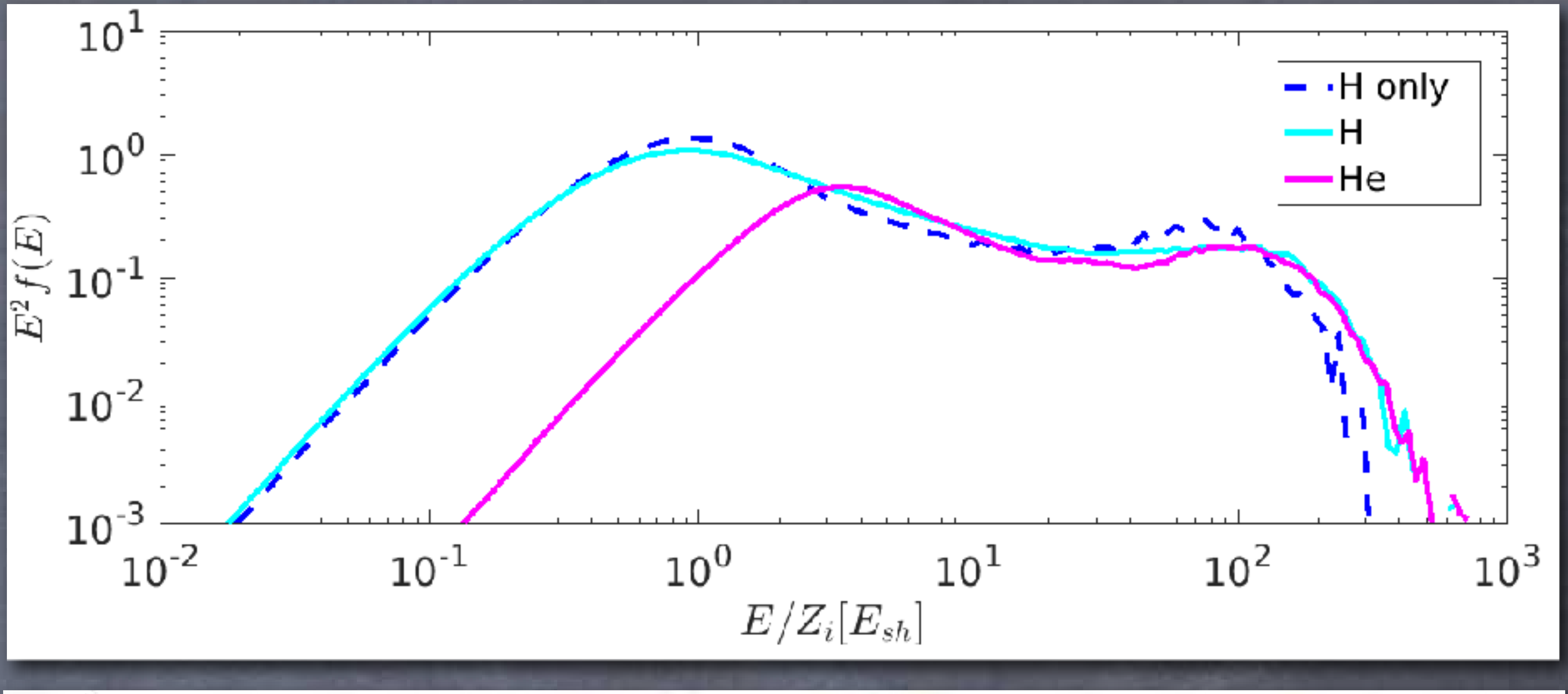


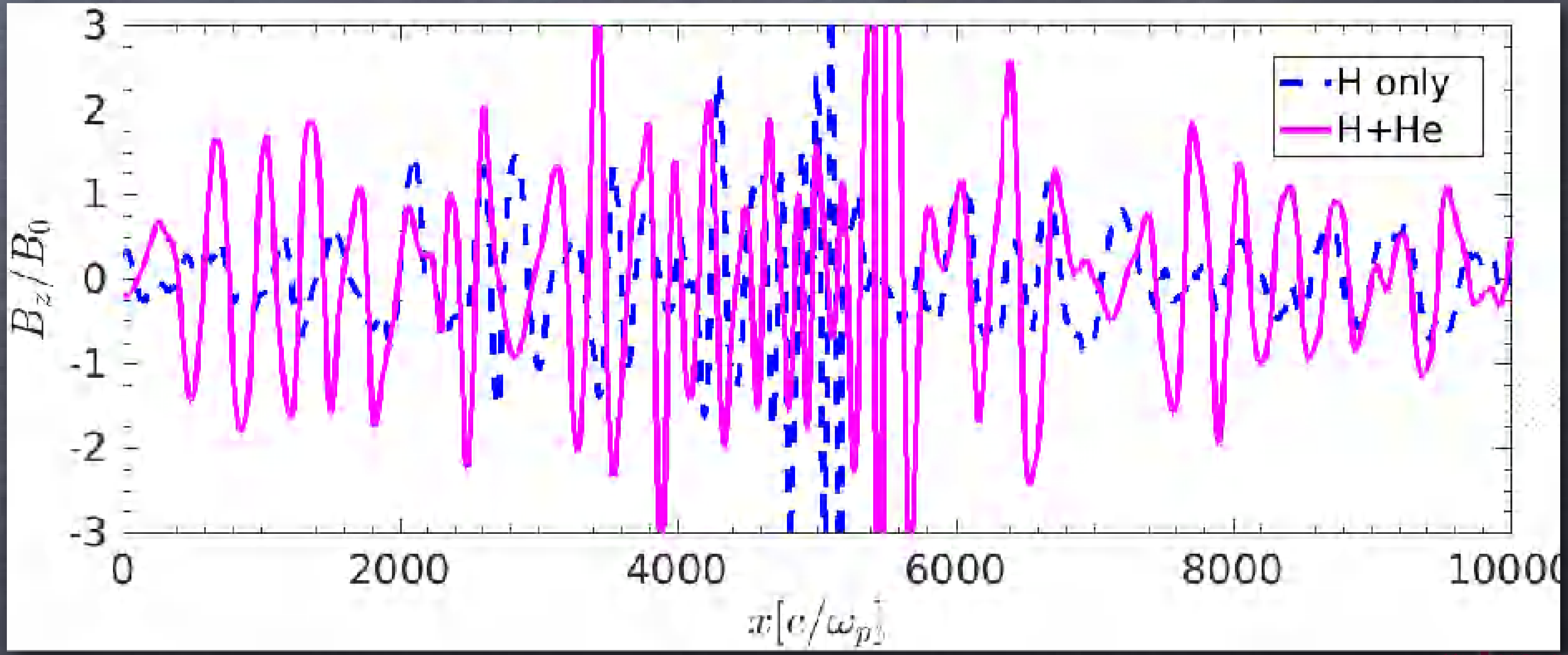


Tylka+05

Helium is *not* test-particle!

- With cosmological He abundance ~10% (DC & Roussi, in prog)
  - He acceleration efficiency ~15% (as H)
    - *Total* efficiency ~30%
    - Increases shock modification
  - He can drive waves as much as H
    - E_{max} 2x larger for both species
- Hadronic gamma-ray emission can be boosted by a factor ~5 (DC et al, 2011)





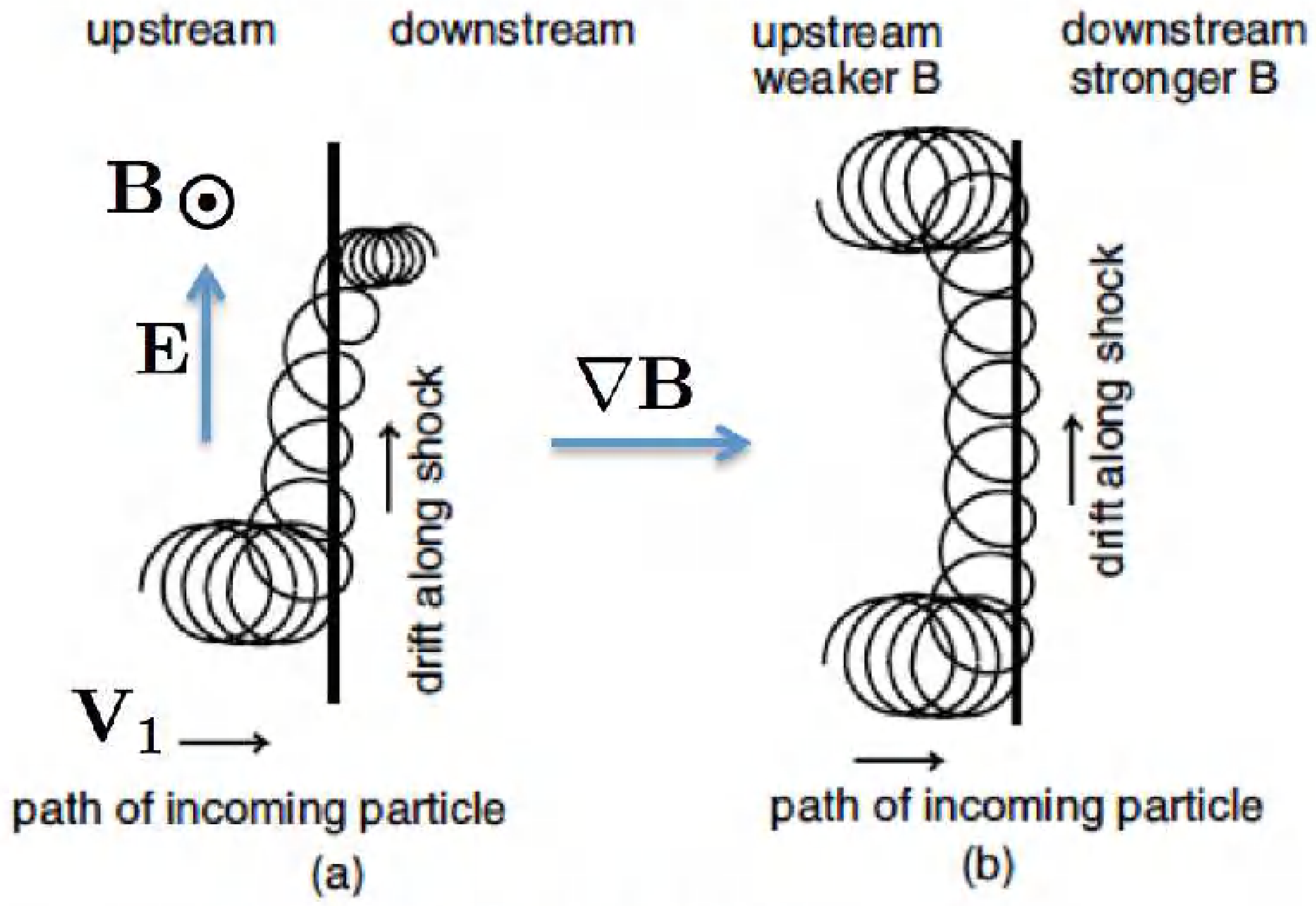
ELECTRONS

Ion vs Electron Injection

- Ions injected by specular reflection
  - Their magnetic moment $W_\perp = p_\perp^2/B$ is not conserved: the shock is evolving on their gyro-time!
- Electrons cannot be reflected by the shock potential barrier, but conserve their $W_\perp$
  - ∇B-drift + shock drift acceleration

$$\mathbf{v}_{\nabla B} = \frac{W_\perp}{qB}\frac{\mathbf{B}\times\nabla B}{B^2} \qquad \mathbf{E} = -\mathbf{V}_1/c\times\mathbf{B}$$

  - Electron injection requires oblique shocks!
    - How can we have simultaneous acceleration of ions and electrons?



cartoon: Ball & Melrose 2001

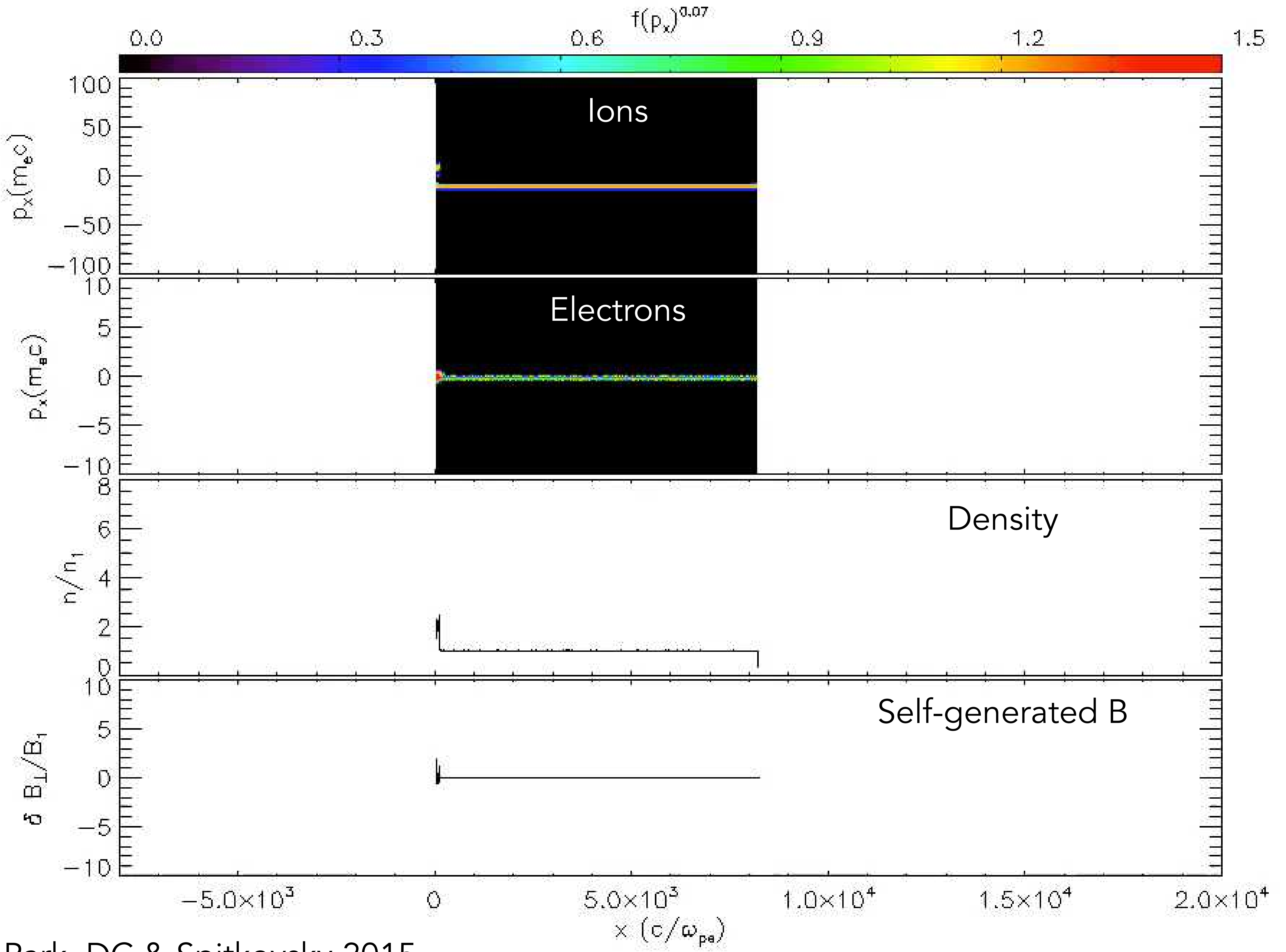
Reflection condition: $\theta_p > \theta_{\rm crit}$

$$\theta_p = \angle(\mathbf{v}, \mathbf{B_1})$$

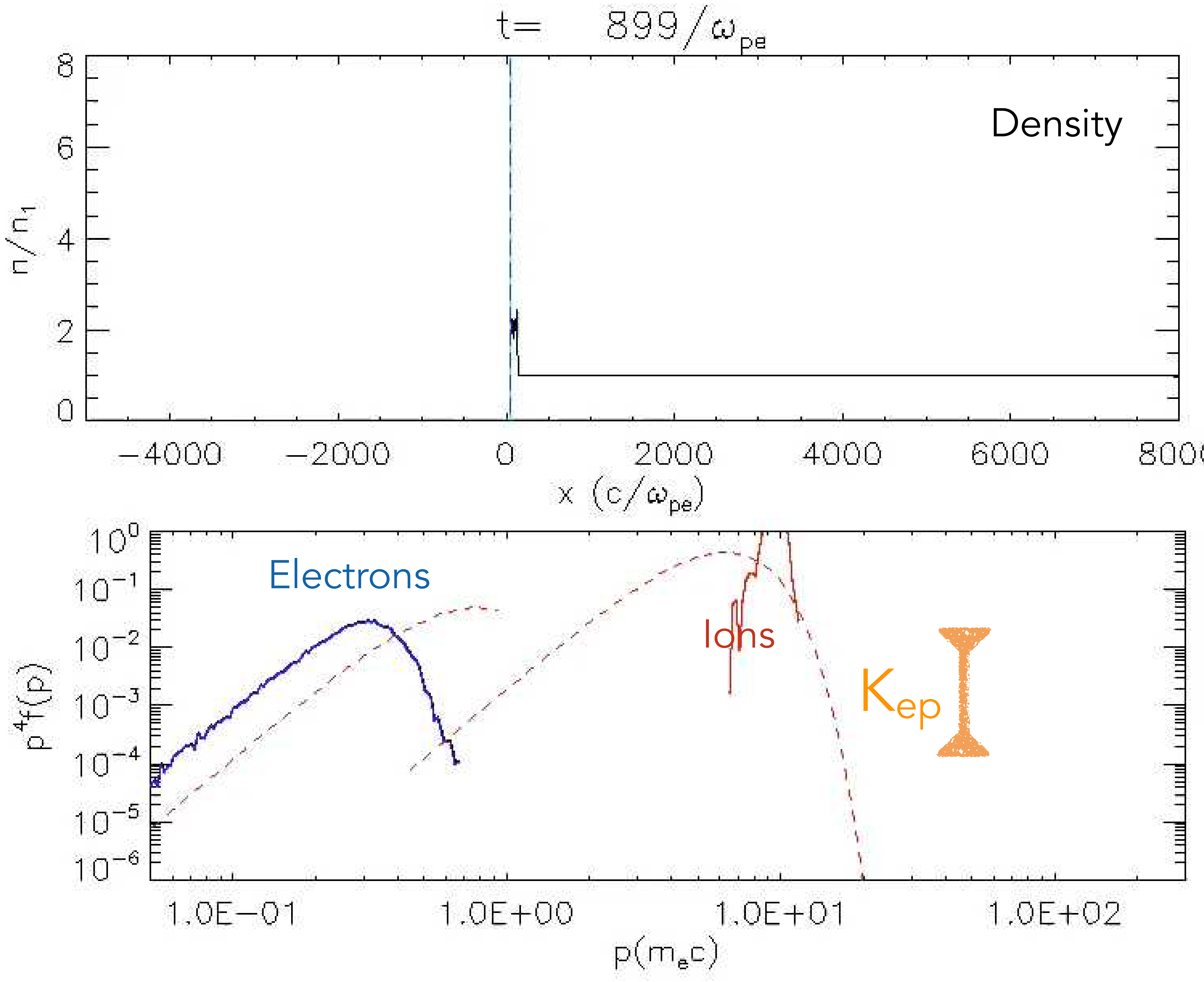
$$\theta_{\rm crit} = \sin^{-1}\sqrt{B_1/B_2}$$

Electron Acceleration

- Full PIC simulations (Tristan-MP code) M=20, V_{sh}=0.1c, quasi-parallel (ϑ=30°) 1D shock



Park, DC & Spitkovsky 2015



Electron/proton ratio K_{ep}~0.01

More on electron acceleration

- PIC simulations of oblique shocks (ϑ=60°) (DC, Spitkovsky, in prep.)

- DSA electron spectra!
- a few % in energy
- <~1% in number
- Stay tuned for scalings with M, β, V_{sh},…

SUPER-HYBRID

Meso-scales: Super-Hybrid

- MHD (Athena) + kinetic ions
- Prescription for injection (DC, Pop & Spitkovsky, 2015)
- Allows to go to larger Mach numbers and scales

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}_g) = 0 \,,$$

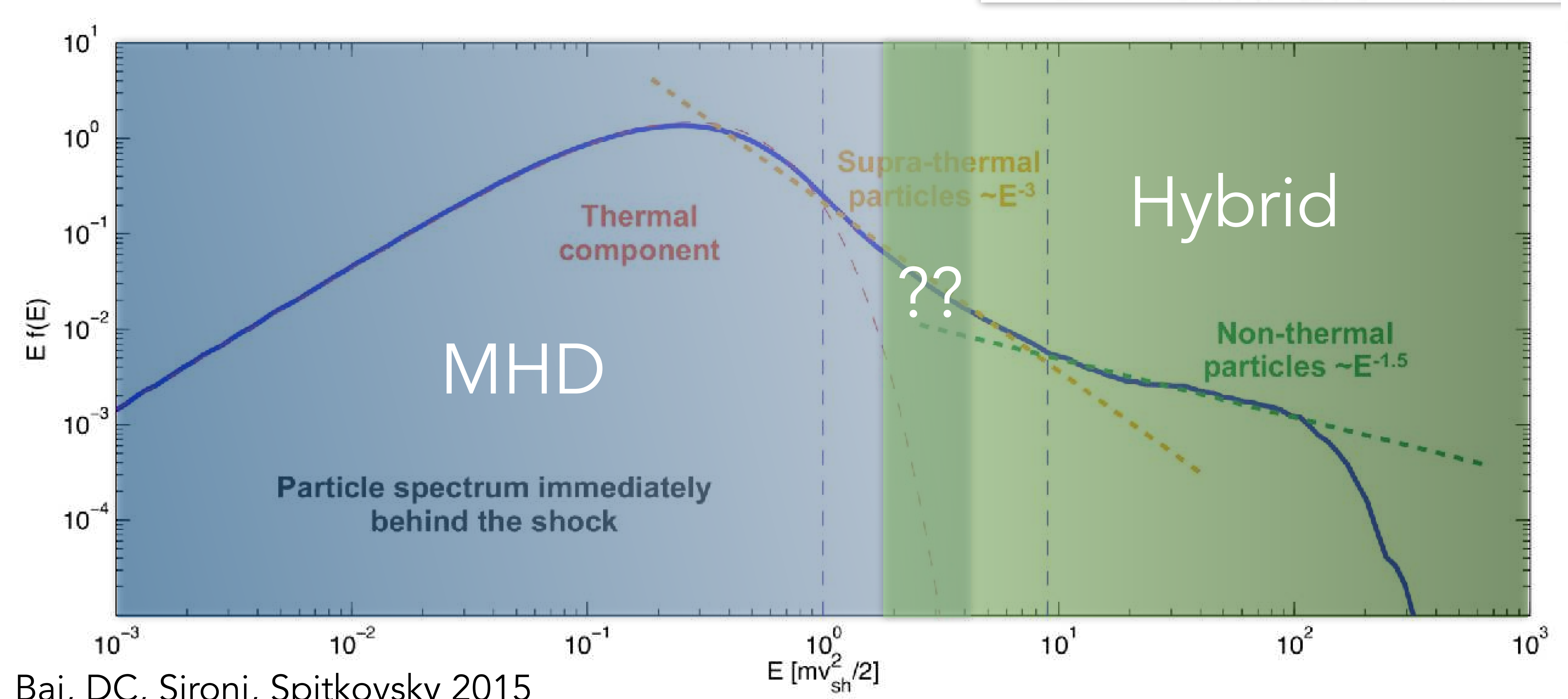
$$\frac{\partial \rho \boldsymbol{v}_g}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v}_g^T \boldsymbol{v}_g - \frac{\boldsymbol{B}^T \boldsymbol{B}}{4\pi} + P_g^* \mathsf{I}\right) \qquad \boldsymbol{\mathcal{E}}_0 \equiv -\frac{\boldsymbol{v}_g}{c} \times \boldsymbol{B}$$

$$= -(1-R)(n_{\rm CR}\boldsymbol{\mathcal{E}}_0 + \boldsymbol{J}_{\rm CR} \times \boldsymbol{B}/c) = -\boldsymbol{F}_{\rm CR} \,,$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P^*)\boldsymbol{v}_g - \frac{(\boldsymbol{B}\cdot\boldsymbol{v}_g)\boldsymbol{B}}{4\pi} + \frac{c}{4\pi}(\boldsymbol{\mathcal{E}} - \boldsymbol{\mathcal{E}}_0) \times \boldsymbol{B}\right]$$

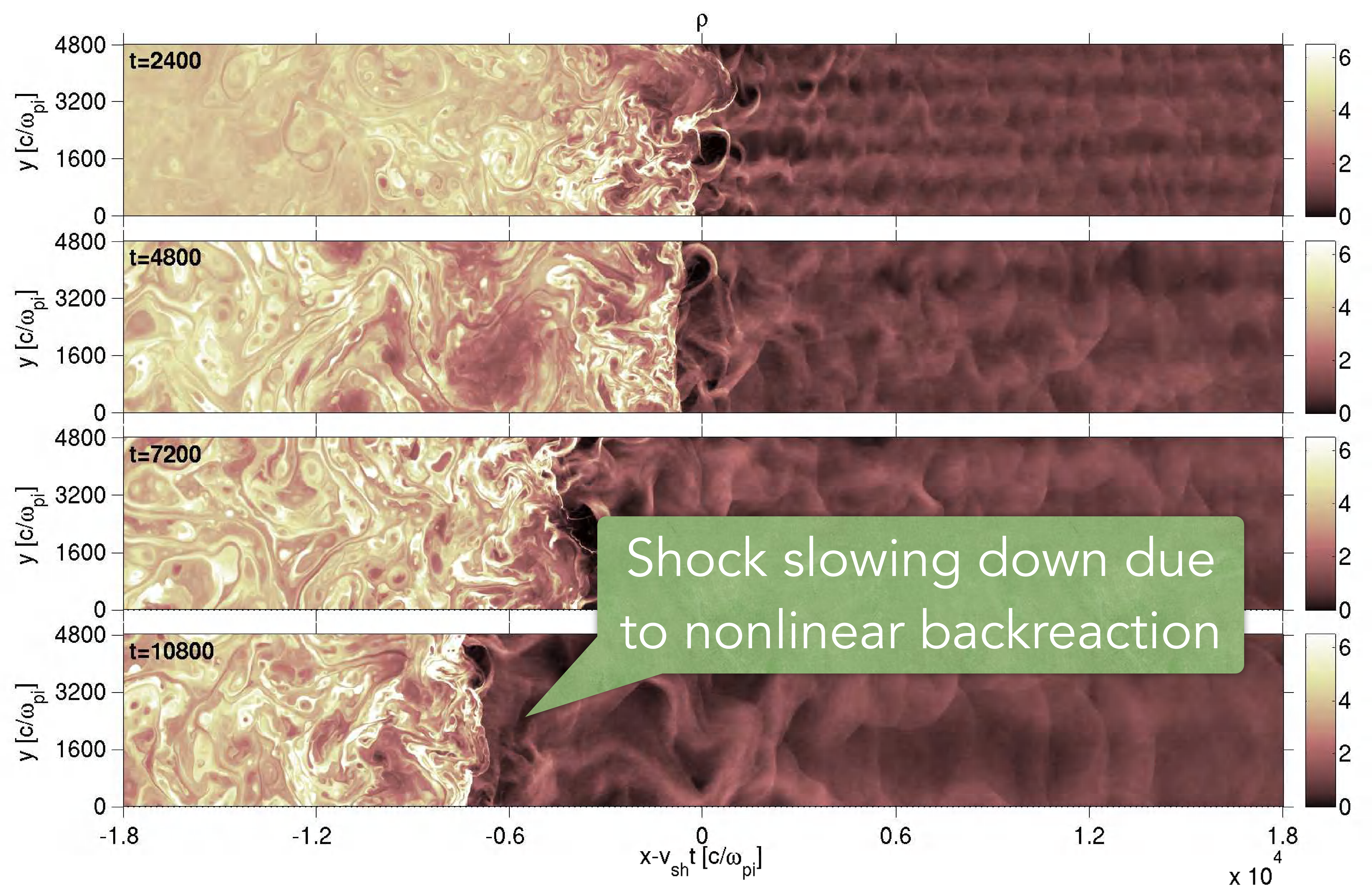
$$= -(1-R)\boldsymbol{J}_{\rm CR} \cdot \boldsymbol{\mathcal{E}}_0 = -\boldsymbol{u}_{\rm CR} \cdot \boldsymbol{F}_{\rm CR} \,,$$

$$R \equiv \frac{n_{\rm CR}}{|n_e|} = \frac{n_{\rm CR}}{n_i + n_{\rm CR}}$$



Bai, DC, Sironi, Spitkovsky 2015

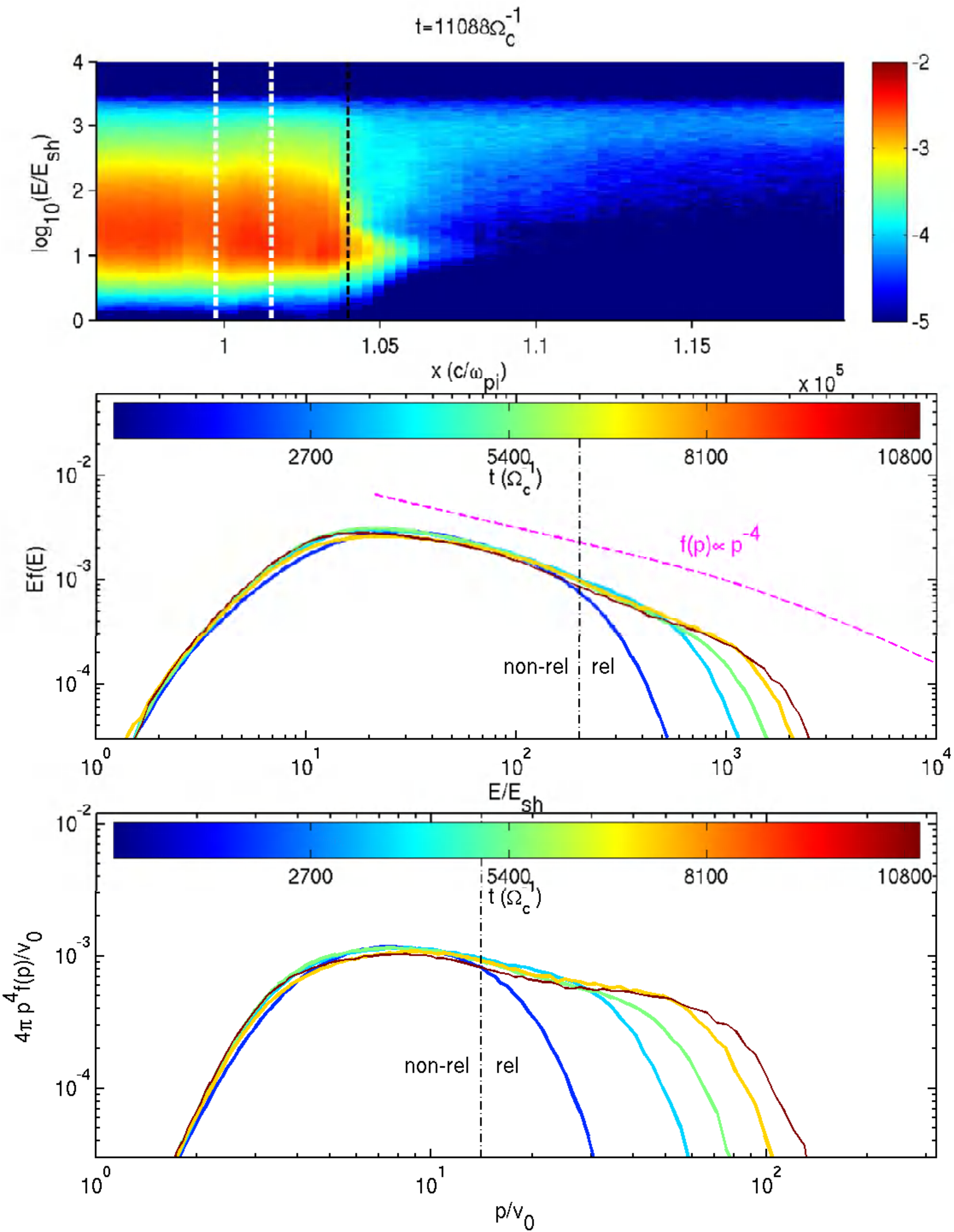
Long-Term Evolution

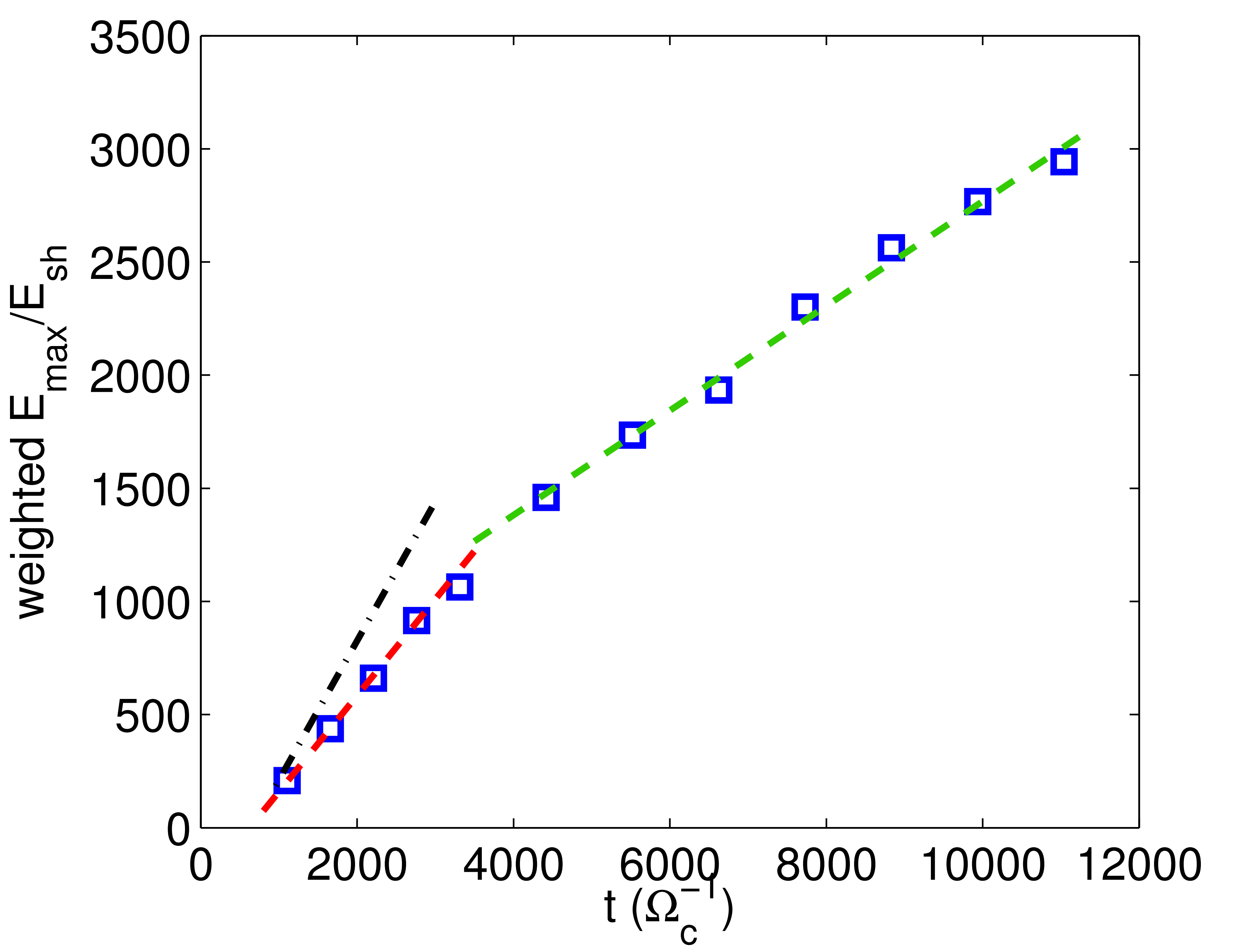


Shock slowing down due to nonlinear backreaction

Bai, DC, Sironi, Spitkovsky 2015

Nonrelativistic - relativistic transition

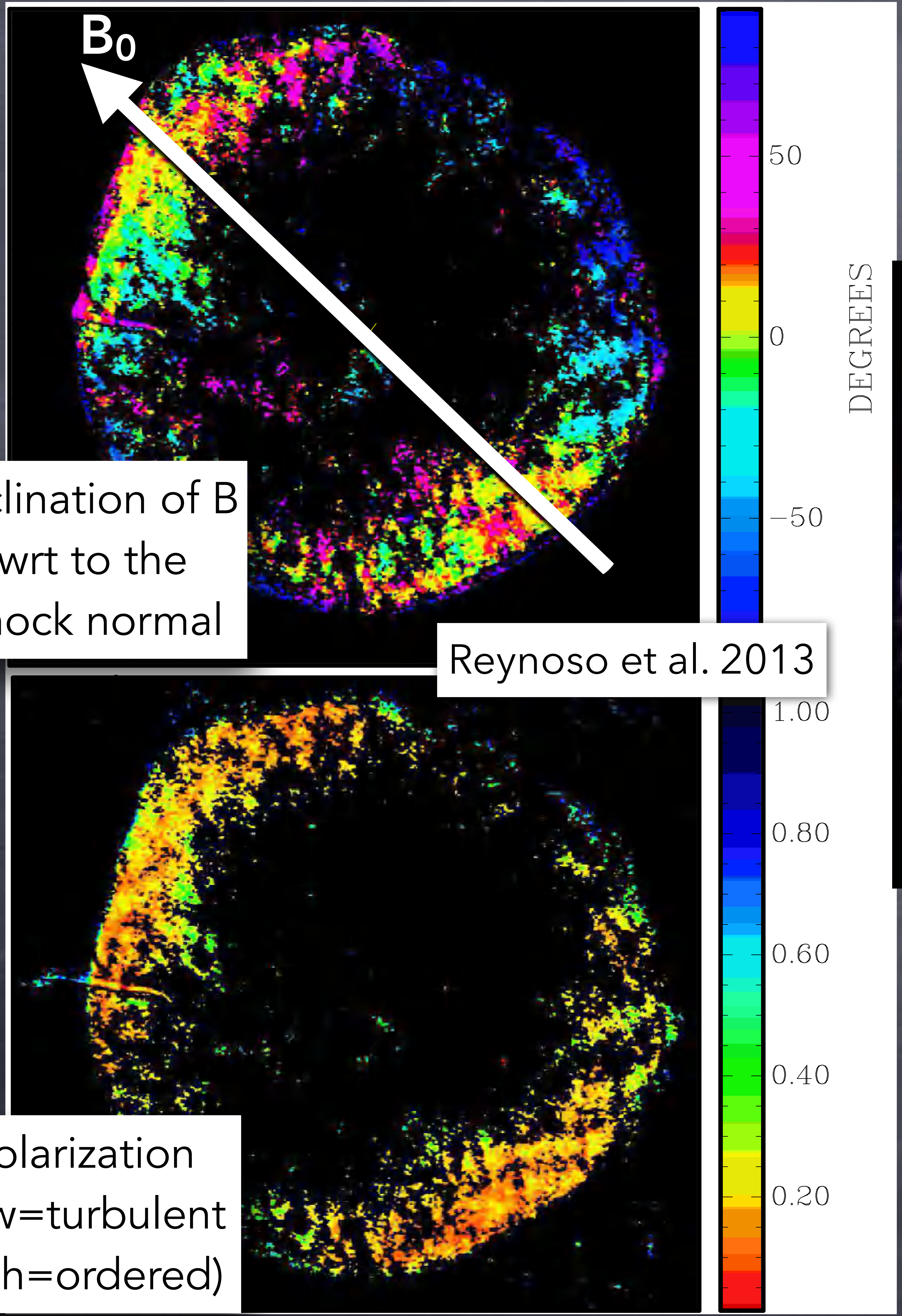




- Rather smooth spectral transition
- E_{max} increases slower in the relativistic regime

PHENOM.

SN 1006: a parallel accelerator



Inclination of B wrt to the shock normal

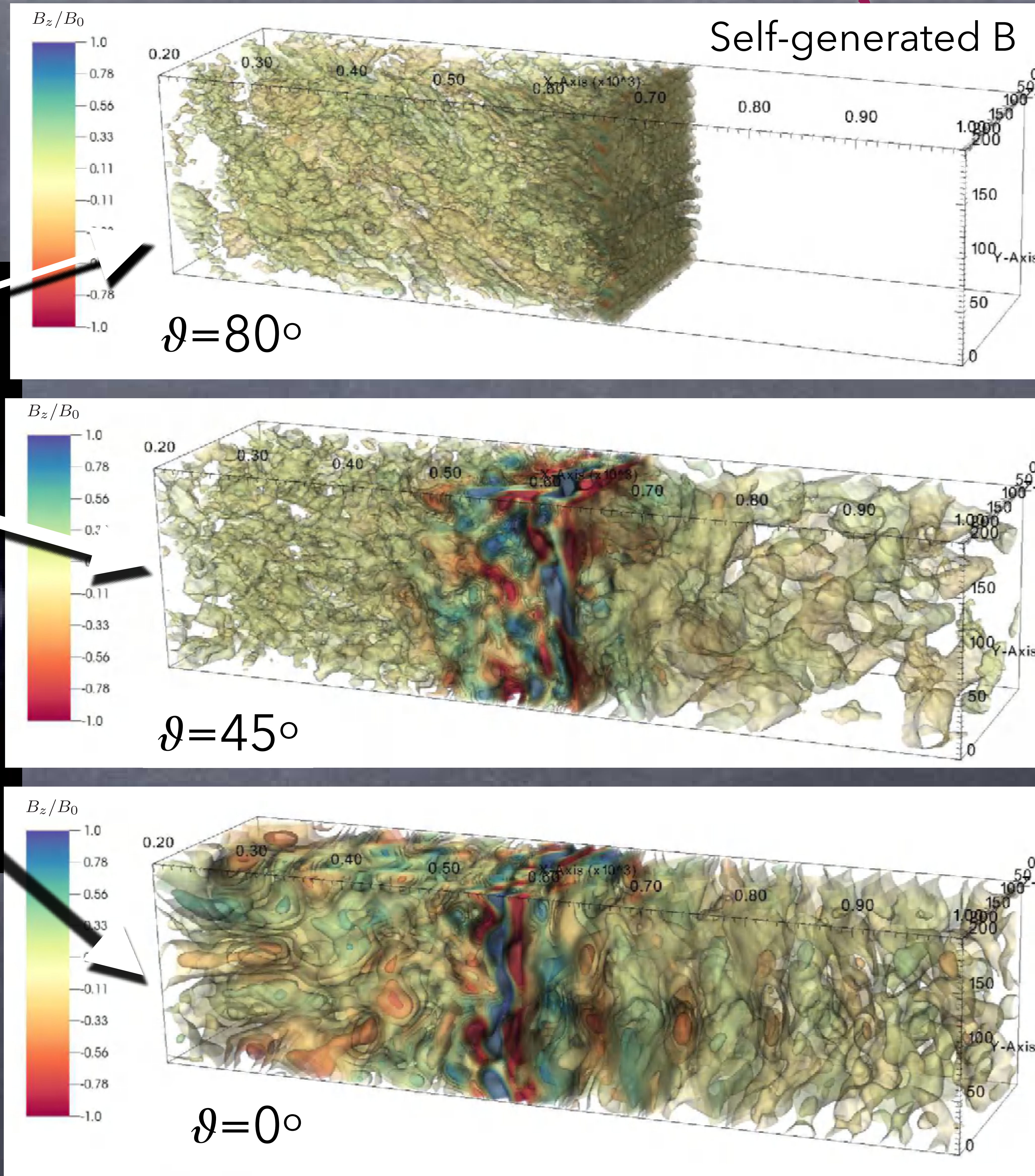
Reynoso et al. 2013

Polarization (low=turbulent high=ordered)

X-ray emission:
red=thermal
white=synchrotron

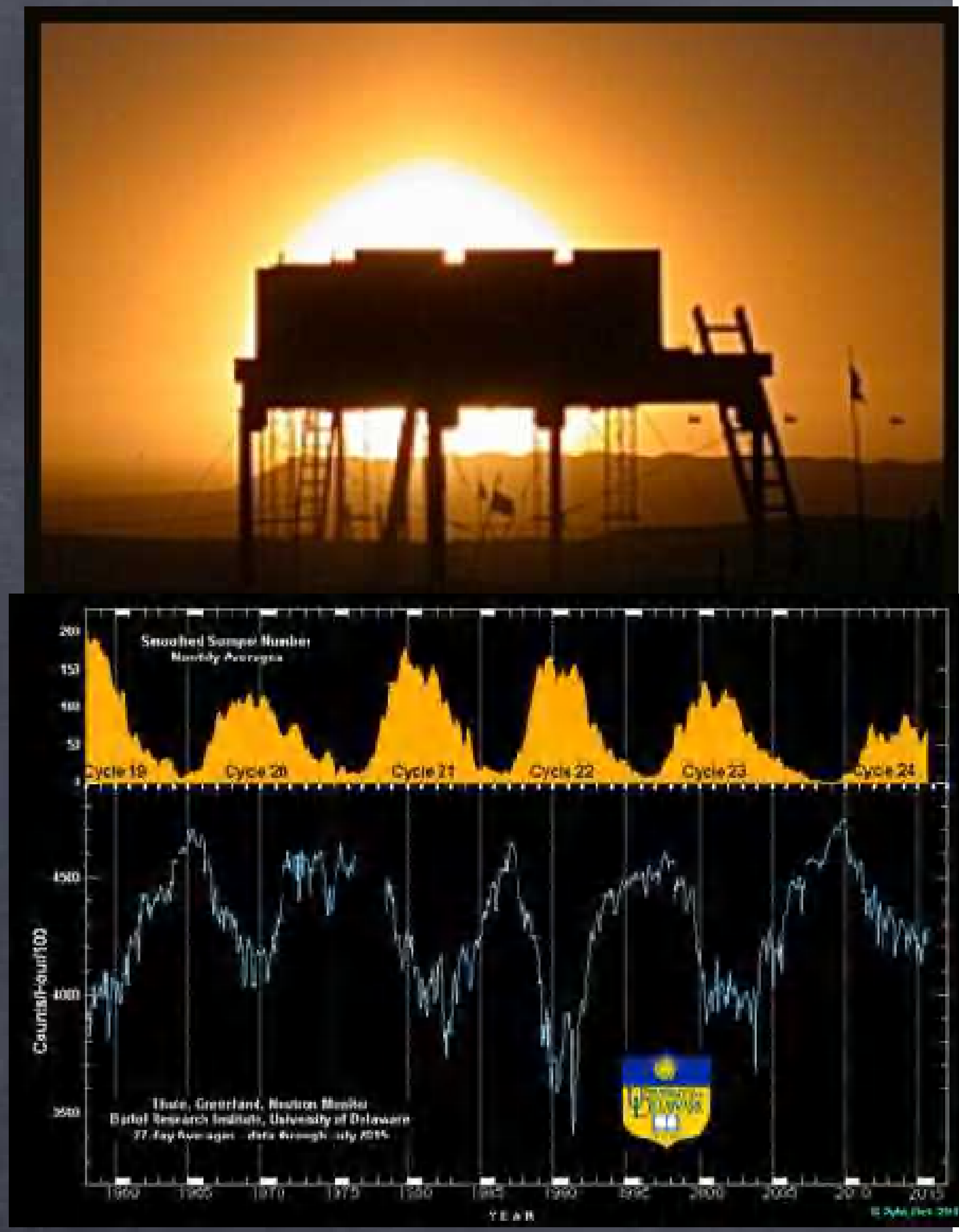
B amplification and ion acceleration where the shock is parallel

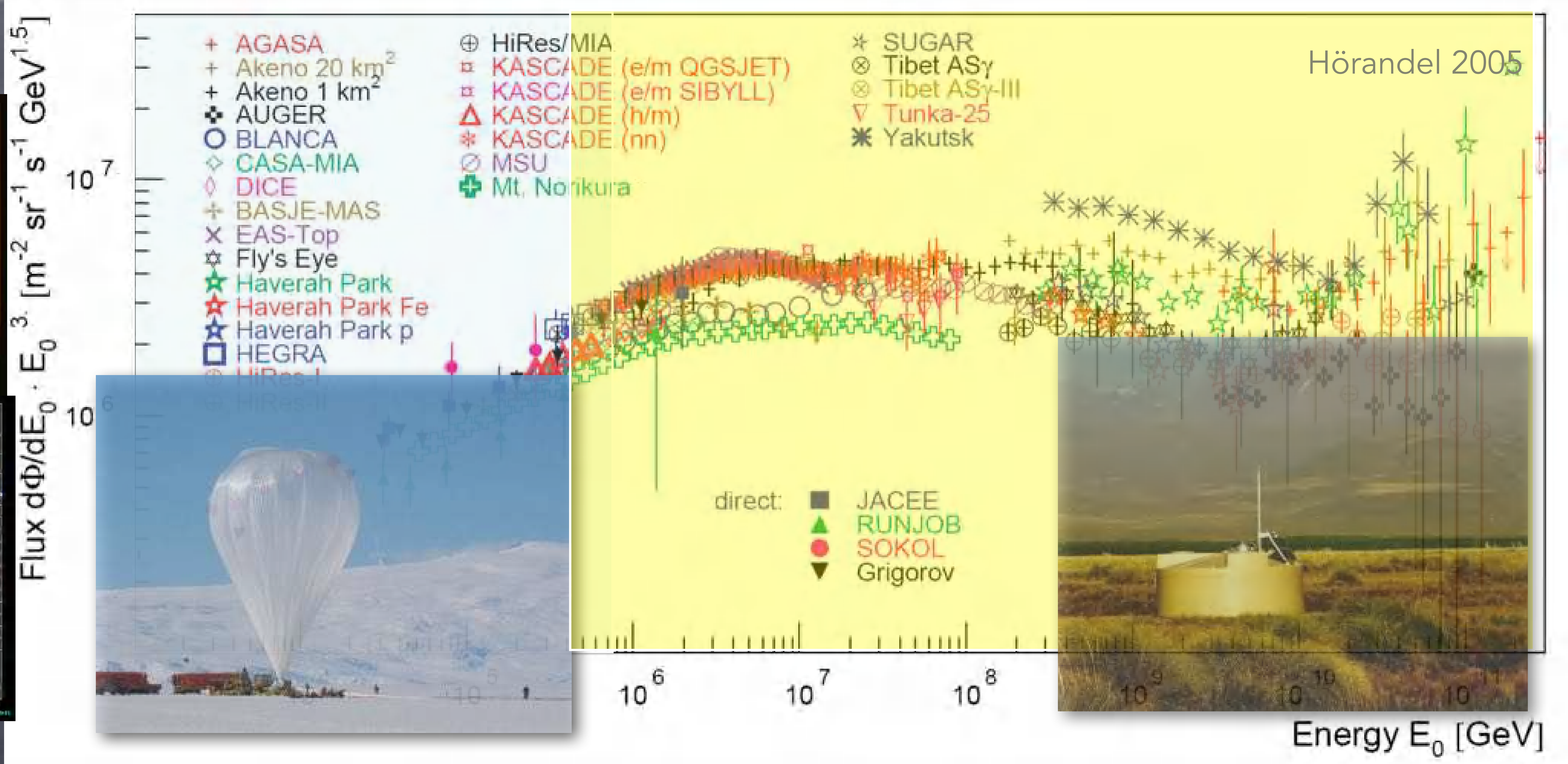
Self-generated B



DC & Spitkovsky, 2014a

Cosmic ray flux at Earth

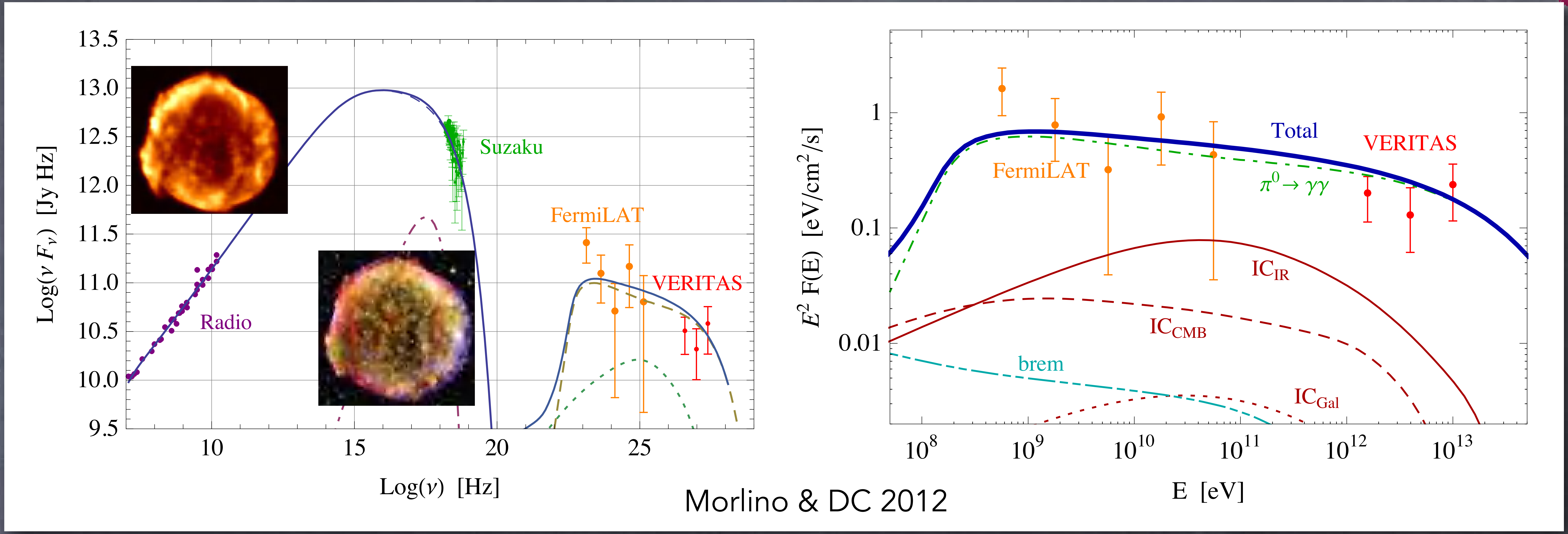




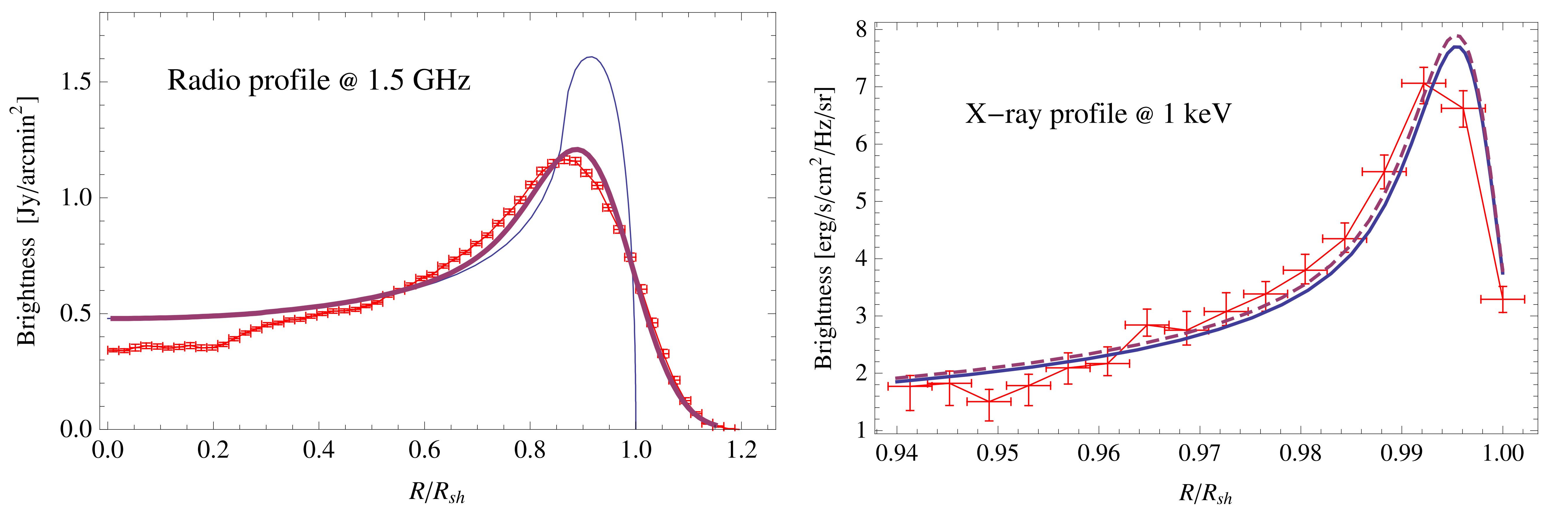
- Below ~10 GeV: solar modulation observed via neutron monitors
- Below ~1 PeV: satellites and balloons
- Above: ground-based arrays, fluorescence telescopes for extensive air showers

Tycho: the smoking gun for hadron acceleration

Type Ia SN
Age=444yr
Distance~3kpc



Morlino & DC 2012

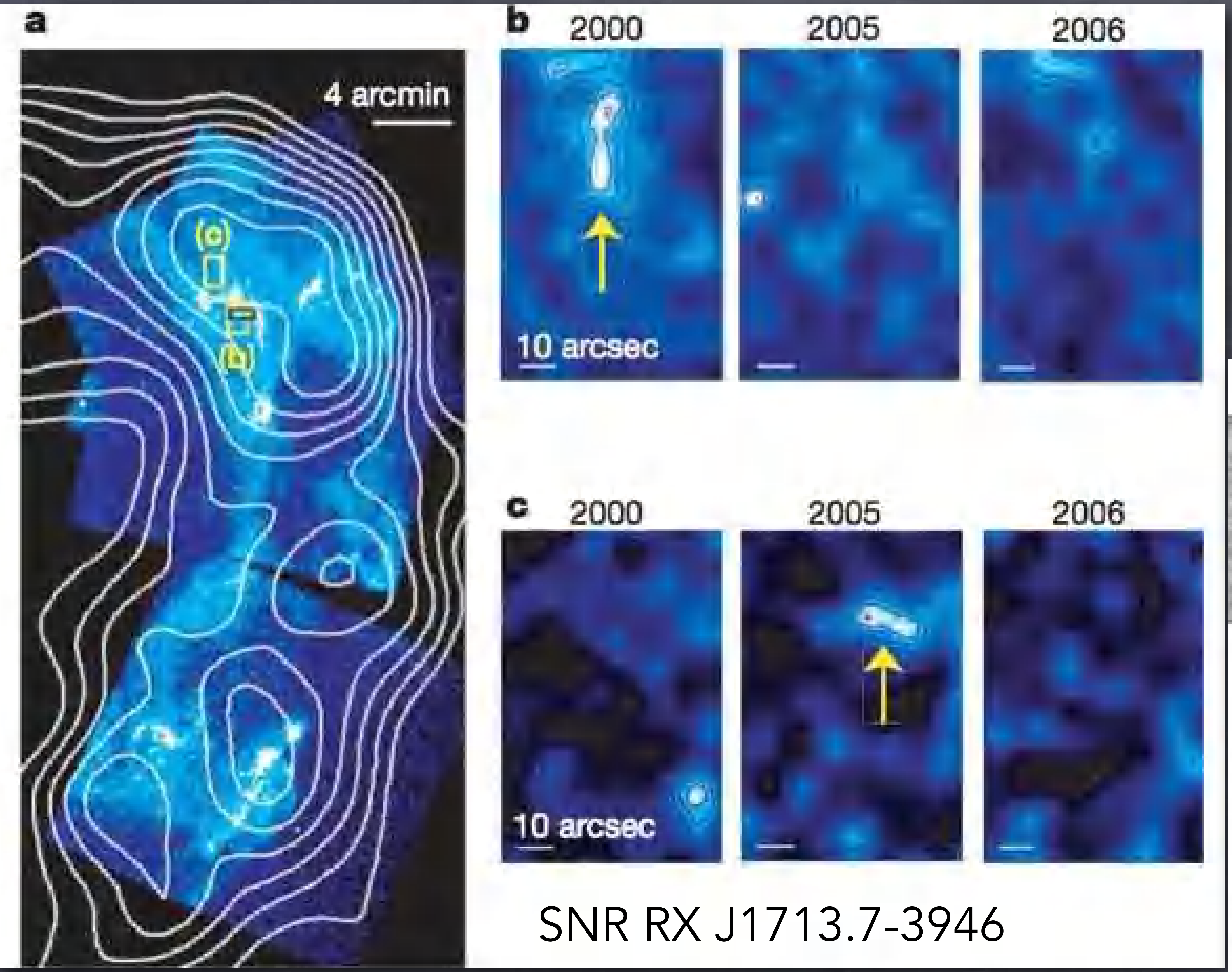


- Spectra from semi-analytical CRAFT
- Acceleration efficiency. ~10%
- Protons up to ~0.5 PeV

- Only two free parameters: electron/proton ratio and injection (now constrained with PIC!)

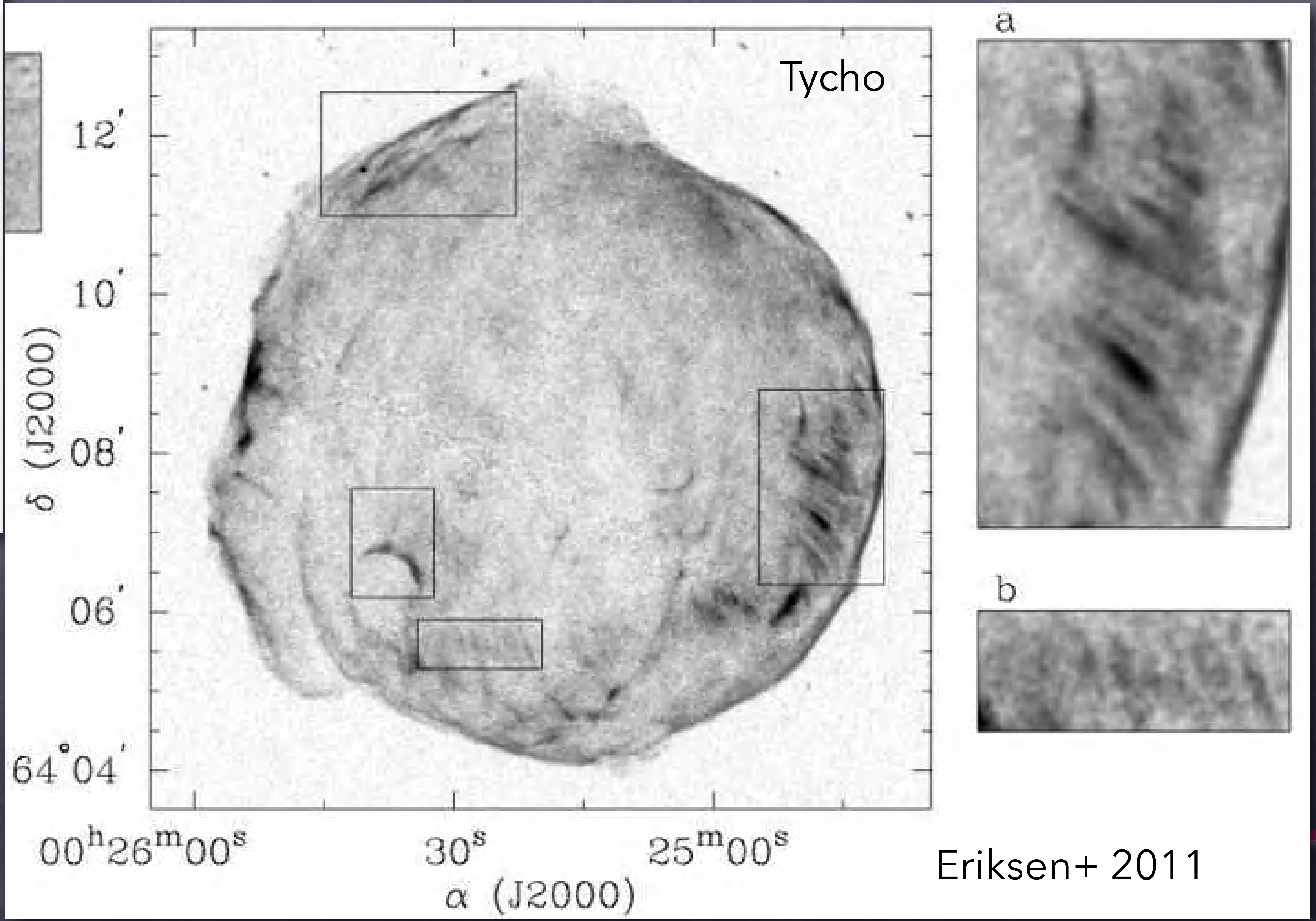
X-ray observations of young SNRs

- Rapidly-variable knots with δB/B~100
- Radial filaments with ~ gyroradius spacing



SNR RX J1713.7-3946

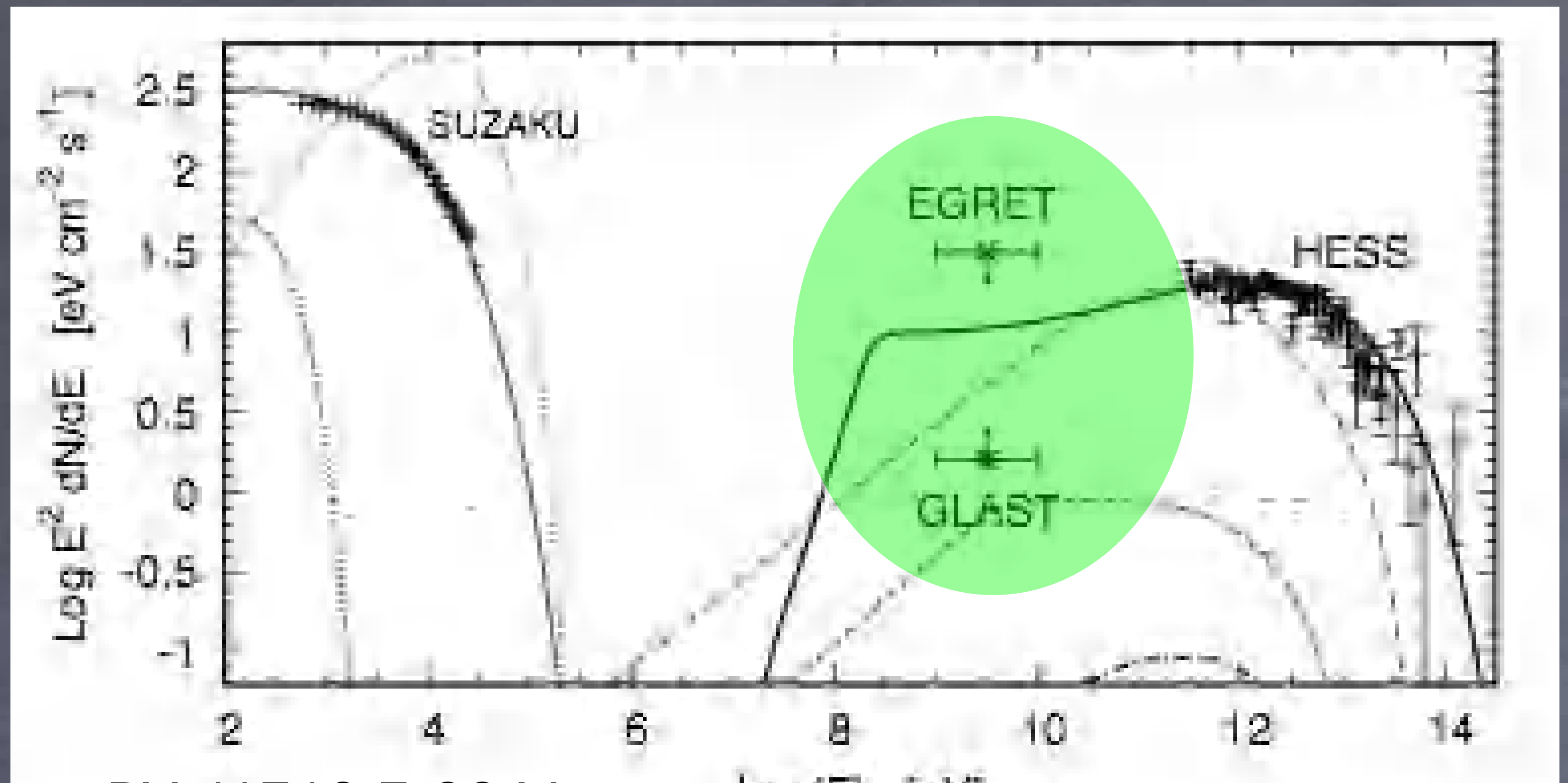
Uchiyama+ 2007



Eriksen+ 2011

Direct evidence: γ-rays from SNRs

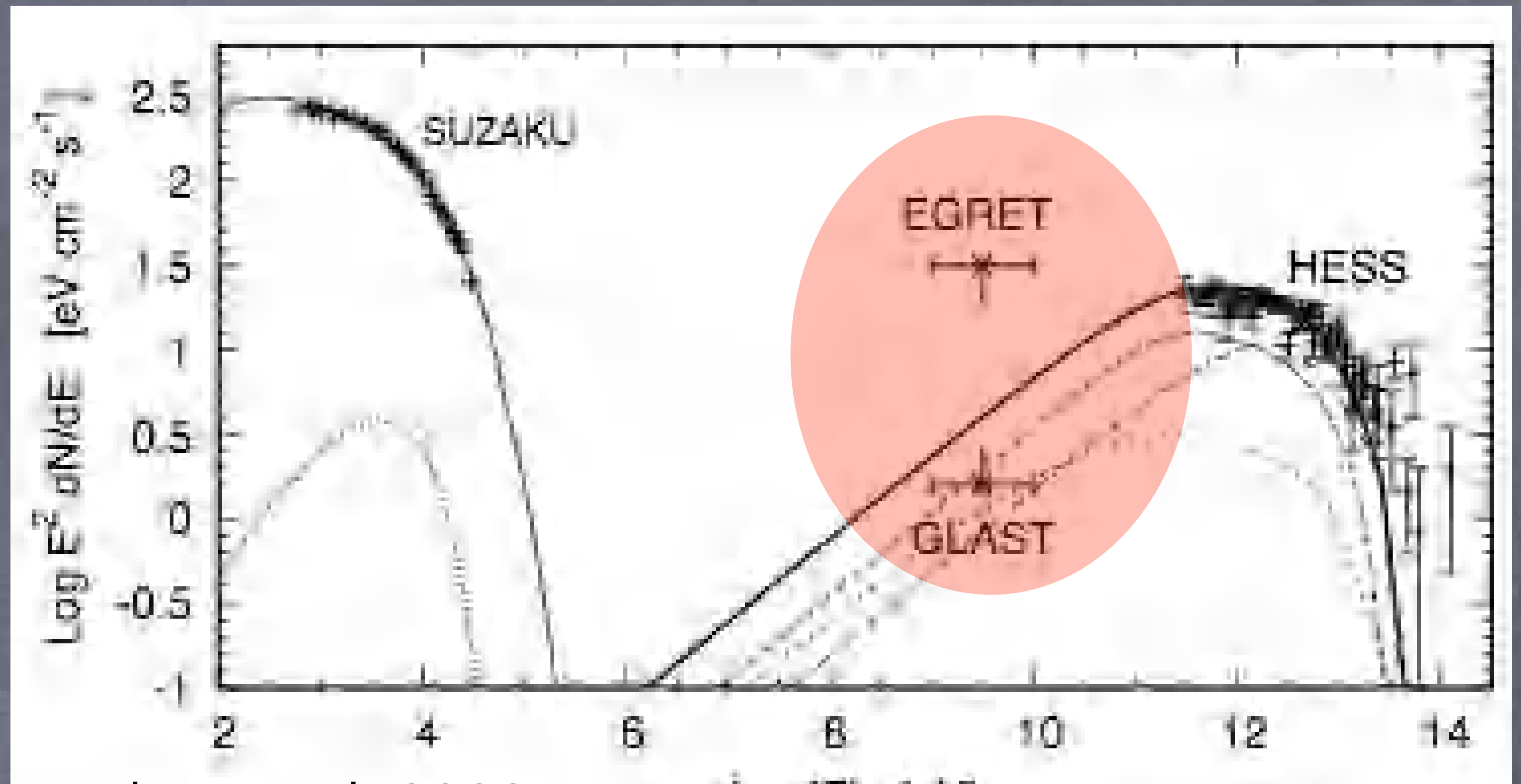
HADRONIC (π_0 decay)



RX J1713.7-3946

γ-ray spectrum parallel to the proton one (~E^{-2})

LEPTONIC (Inverse Compton)



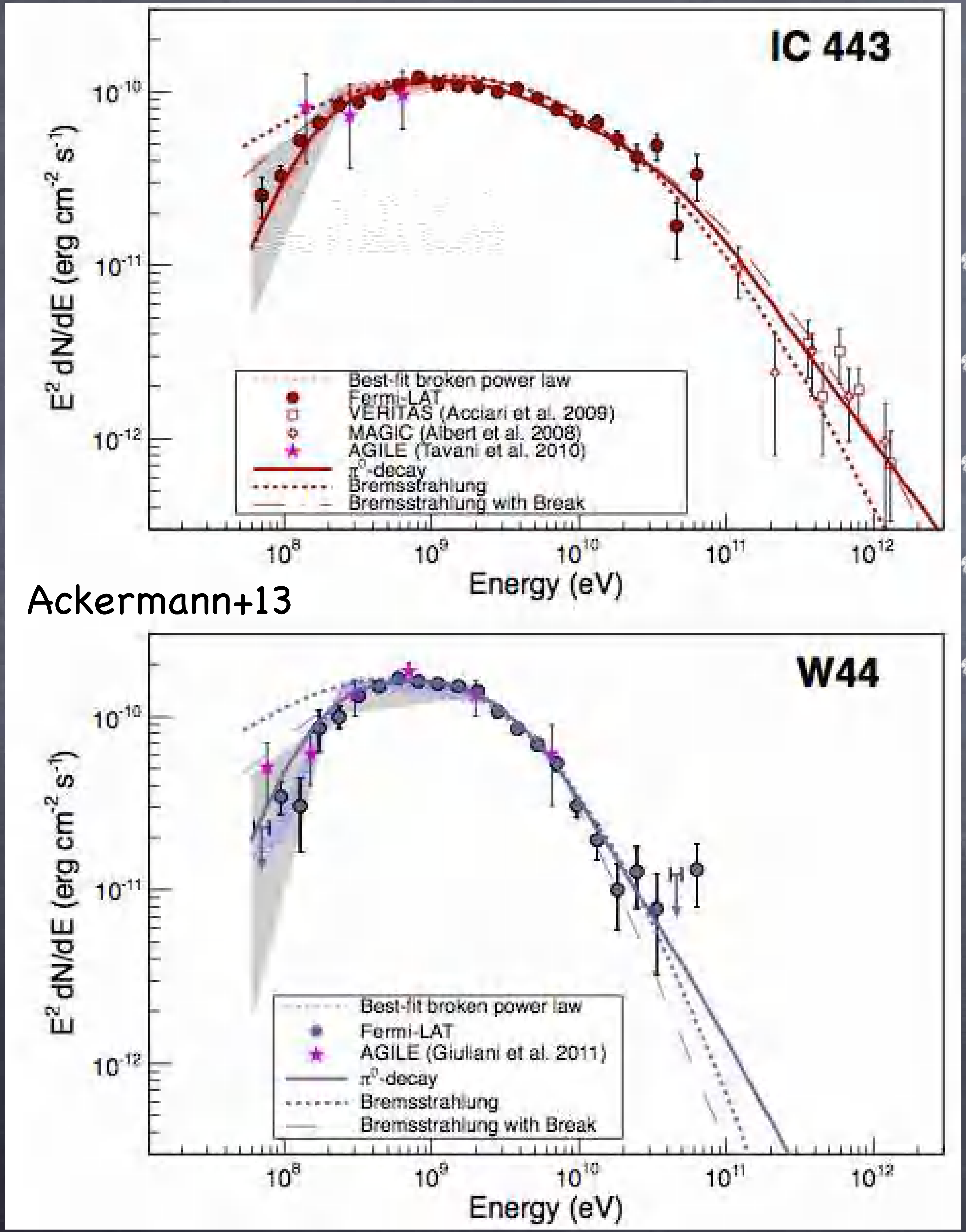
Morlino et al. 2009

γ-ray spectrum flatter than the proton (electron) one (~E$^{-1.5}$)

- Location: gas-/photon-rich environments -> hadronic/leptonic emission

Spectral variety is (typically) environmental!

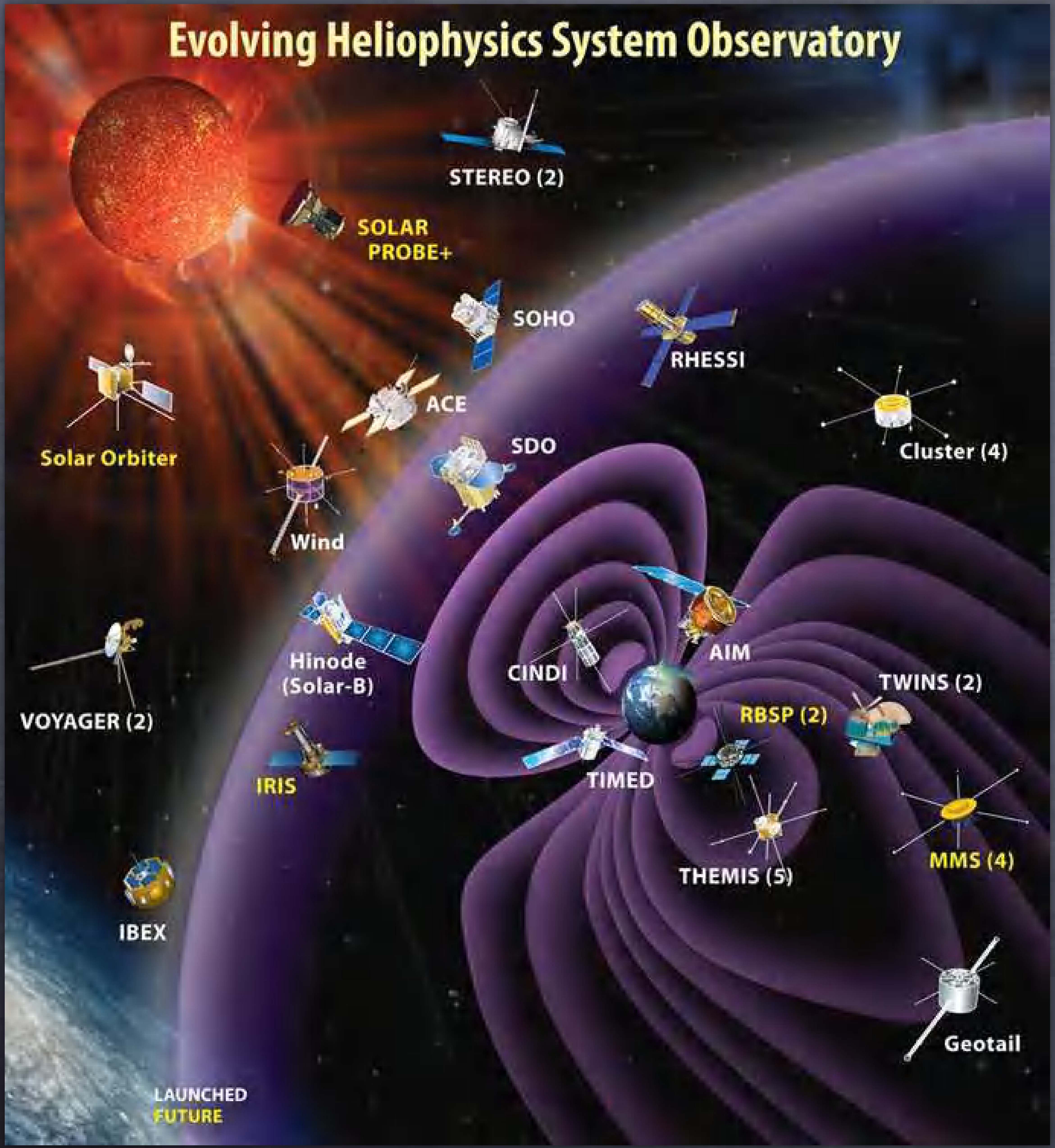
Hadronic emission from molecular clouds



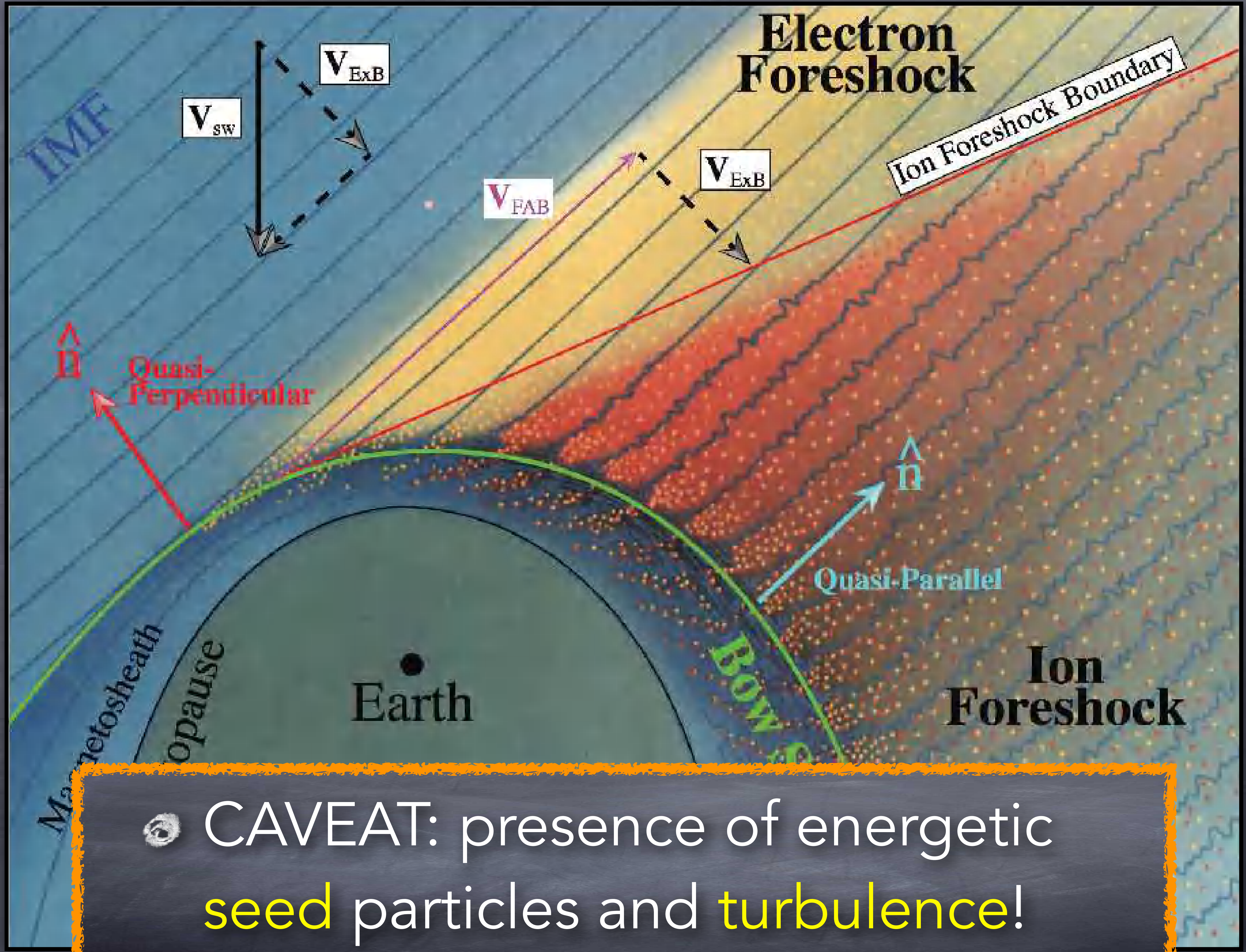
Ackermann+13

- Overabundance of “targets”
- Overabundance of “bullets”?
- SNR, or diffuse CRs?
- Very steep spectra (E^{-3})!!
- The Physics of shock propagating in partially-neutral plasmas is non-trivial!

A Bridge with Heliophysics



- In-situ measurements with spacecraft
- Earth's bow shock (also Venus', Saturn's,…)

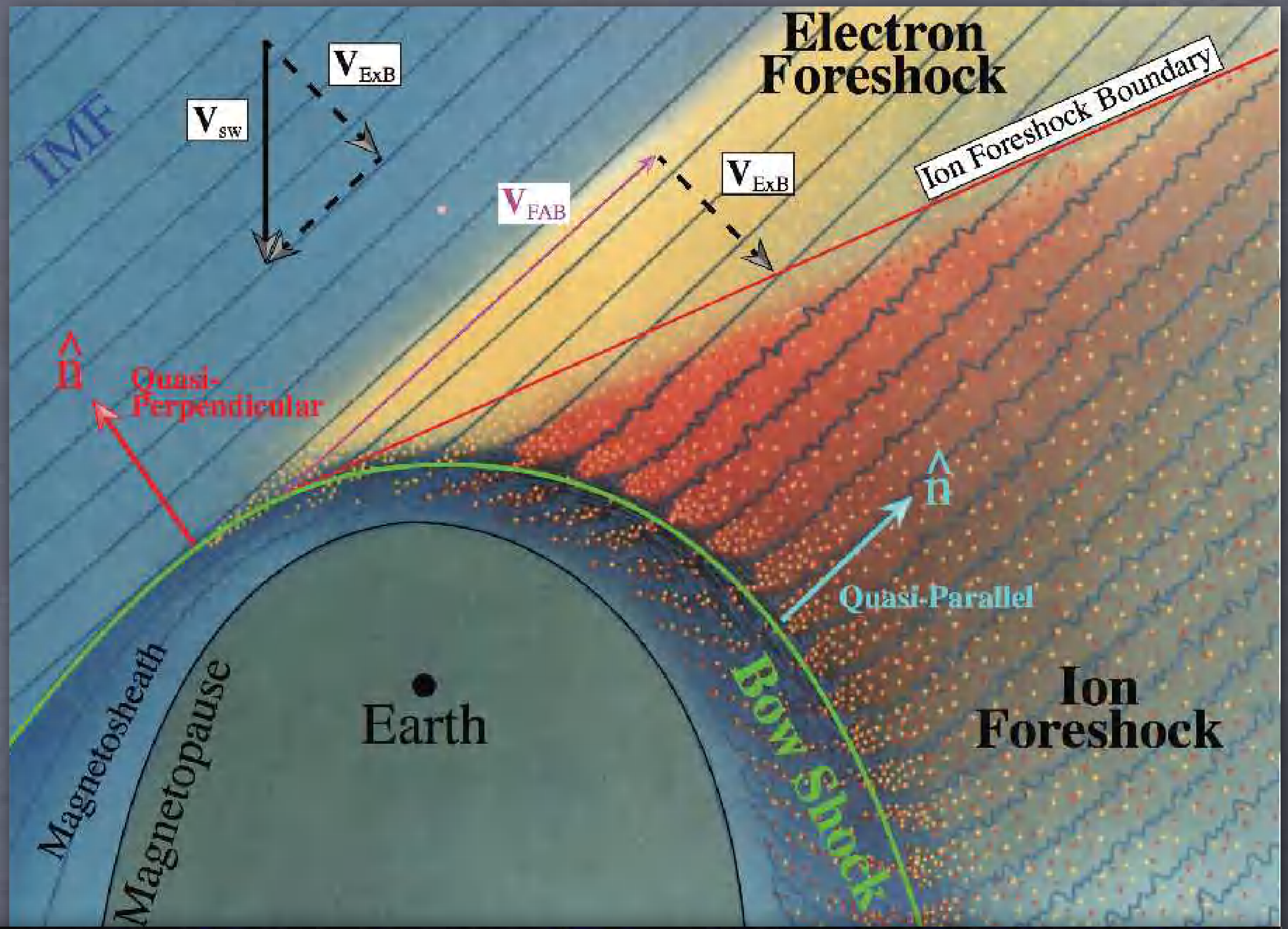


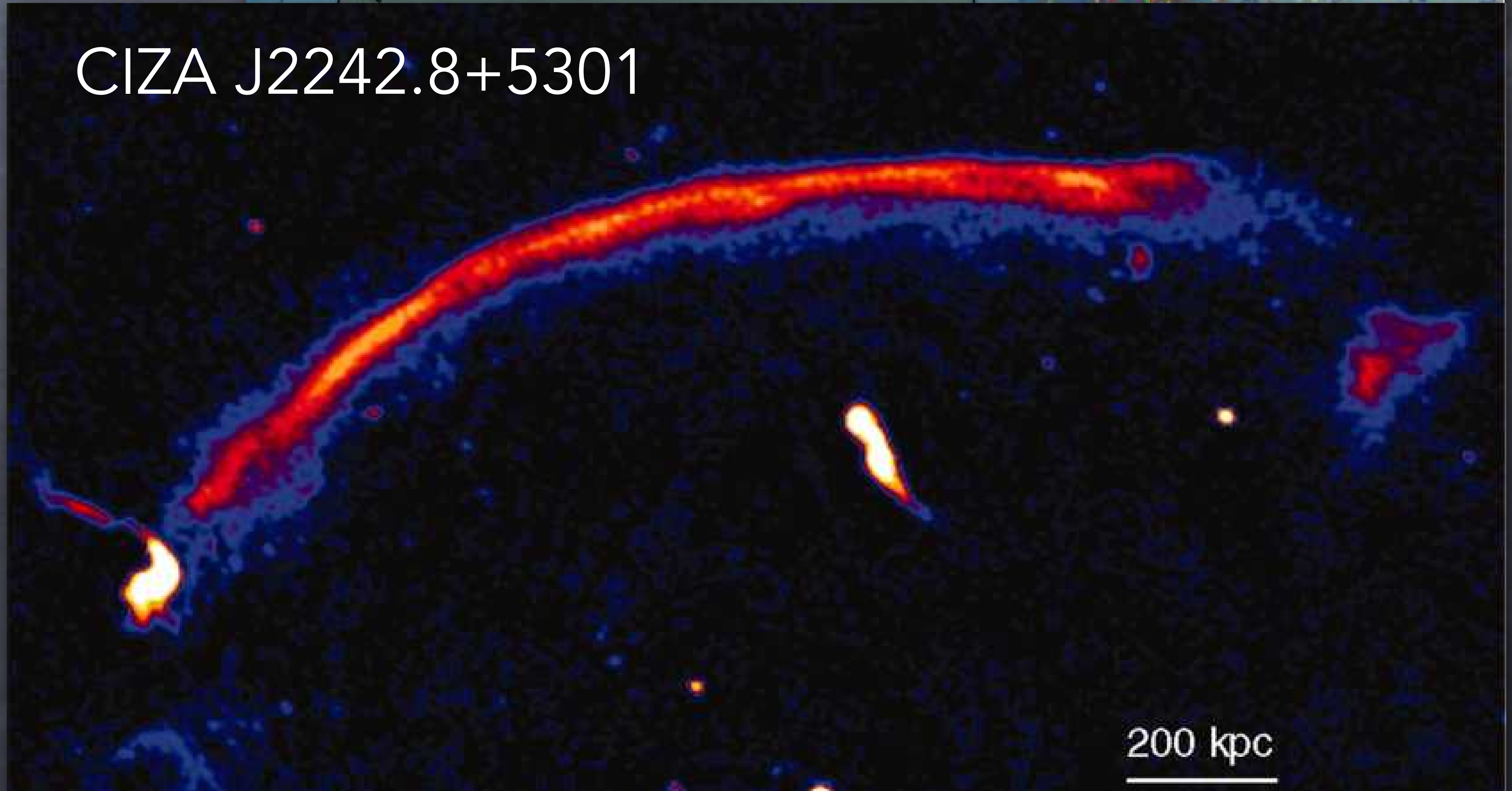
- CAVEAT: presence of energetic seed particles and turbulence!

Electron vs Ion acceleration

- Planetary bow shocks
  - Earth, Venus, Saturn,…
- In situ measurements: Geotail, Polar, SoHO, WIND, Cassini, THEMIS, Cluster, STEREO, ACE,…

- Radio relics in galaxy clusters
- Extended polarized structures
- Fermi-LAT limits on γ-ray emission: constraint on e/p ratio





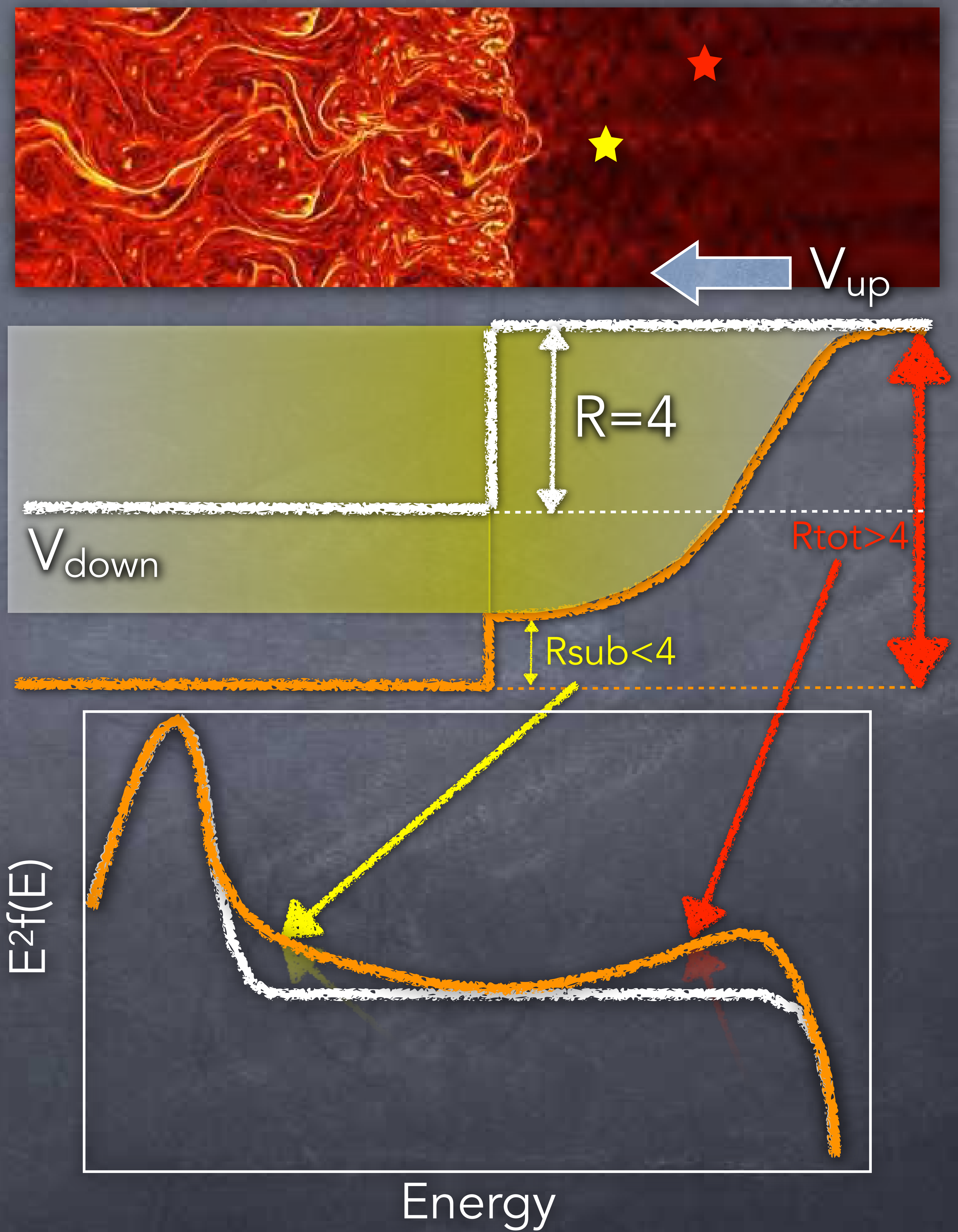
NLDSA

Non-Linear Diffusive Shock Acceleration

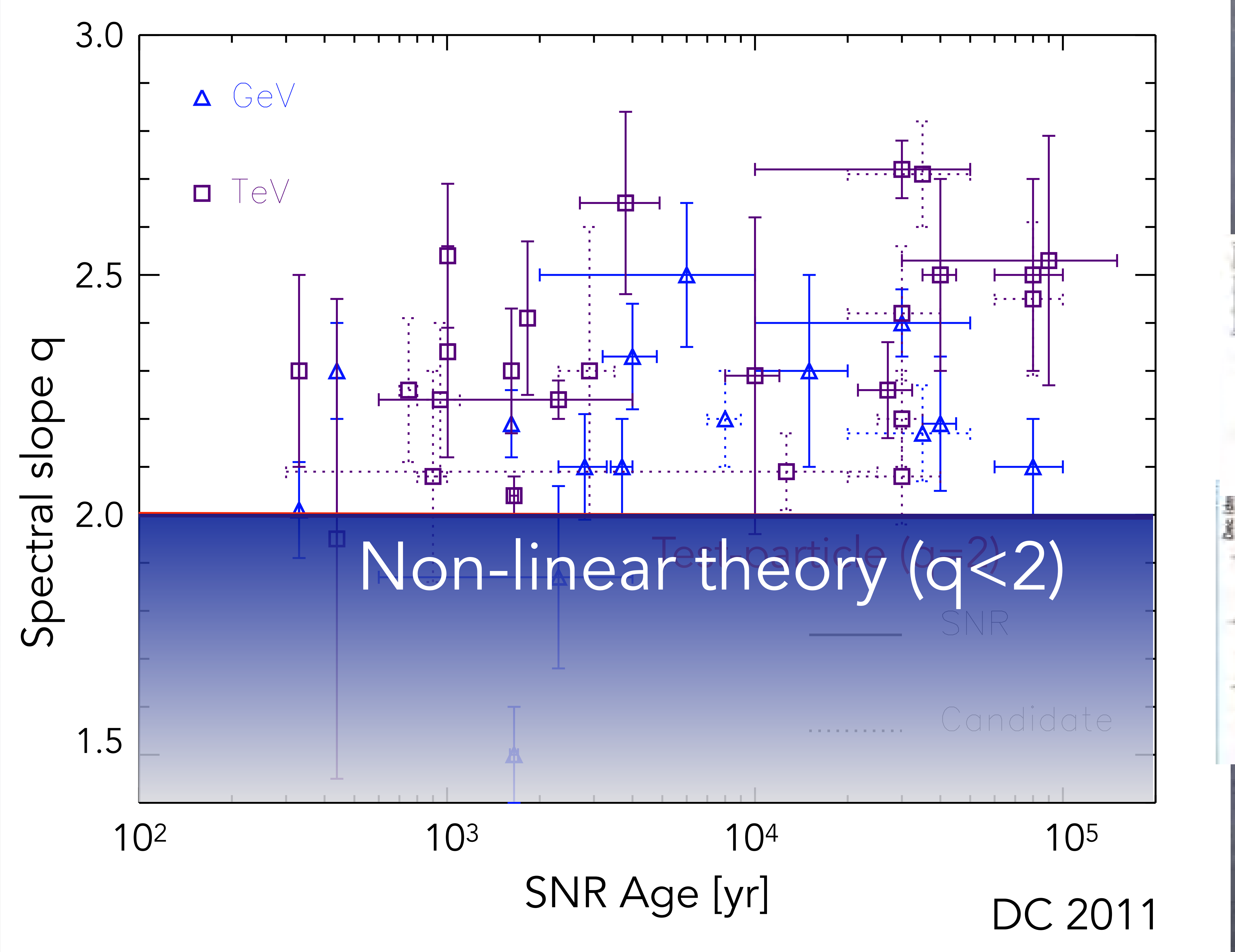
- The spectral index depends only on the compression ratio

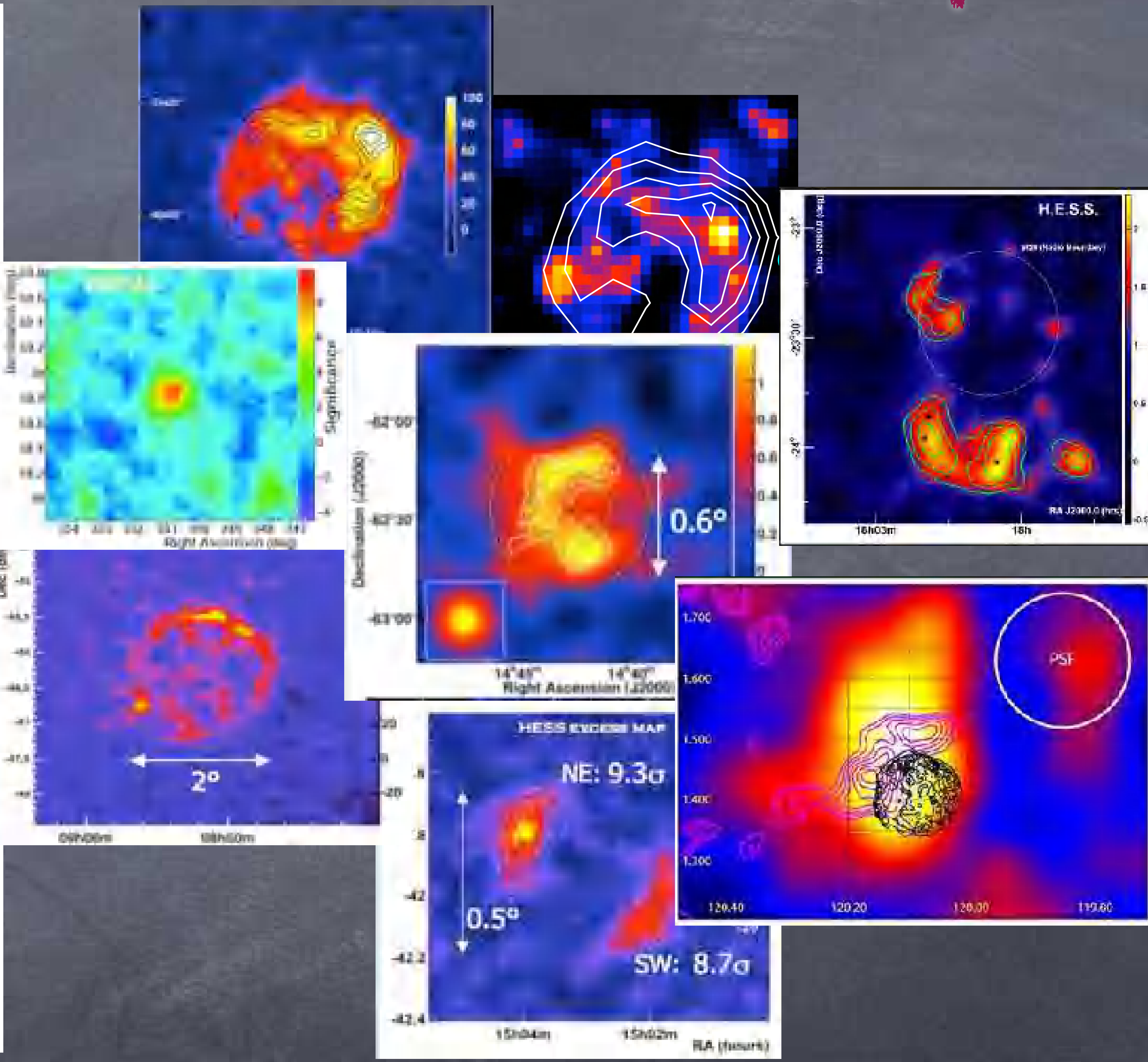
$$q = \frac{R+2}{R-1}; \quad R = \frac{\gamma+1}{\gamma-1};$$

- The CR pressure makes the adiabatic index smaller (R becomes larger)
- Particles "feel" different compression ratios: spectra become concave
- If acceleration is efficient, at energies >1 GeV: $q < 2$ (flat spectra!)



With Fermi, HESS, VERITAS, MAGIC, HAWC,...

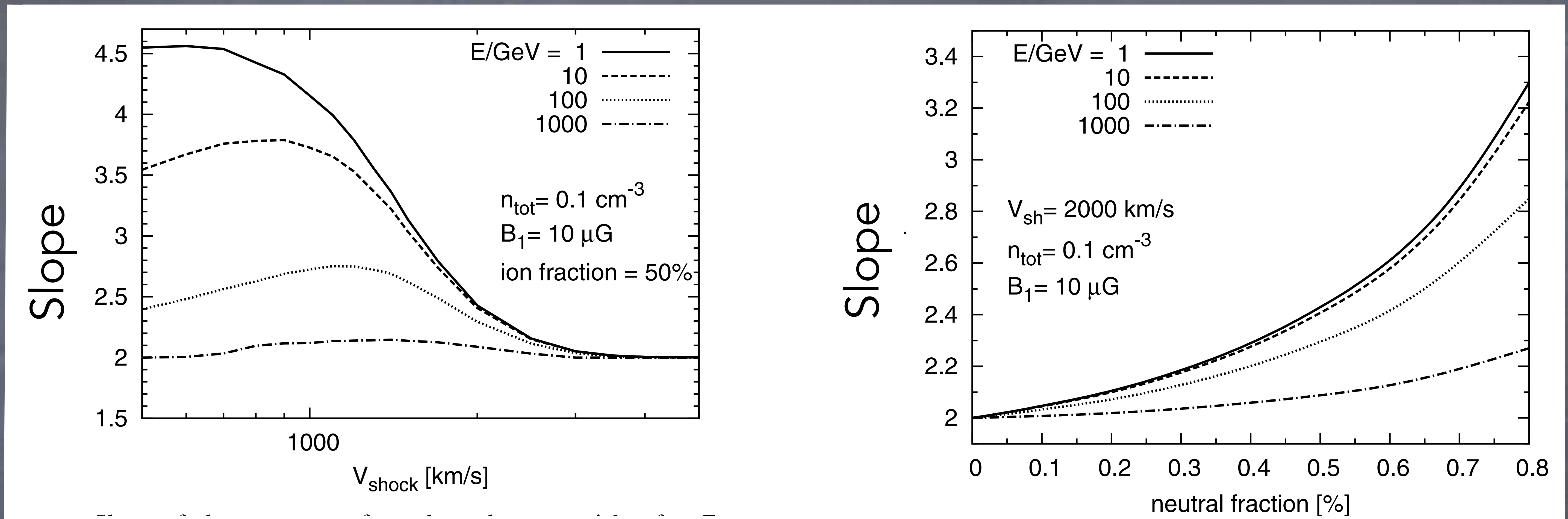




- Evidence of ion acceleration: spectra too steep to be leptonic...
- ...and to be consistent with non-linear DSA theory:
    - Efficient acceleration implies spectra flatter than E^{-2} (Jones & Ellison 1991, Malkov & Drury 2001)

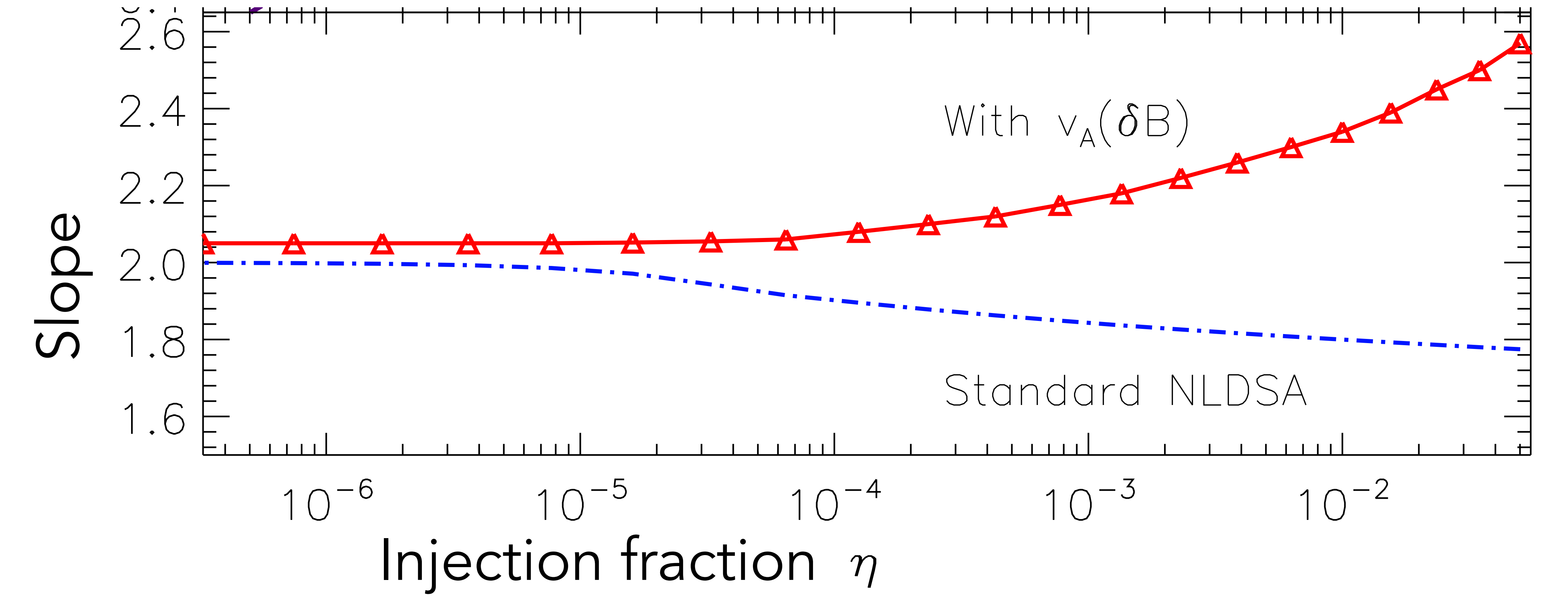
The challenge of producing steep spectra

- Shocks in **partially-neutral media** (Blasi et al. 2012; Morlino et al. 2013; Ohira 2014)
    - **Charge-exchange** may induce a **neutral return flux** that makes the shock weaker
    - **Balmer lines** provide unique test of CR acceleration efficiency (Helder et al. 2009; Raymond et al 2010; Morlino et al. 2014)



- **Magnetic feedback** (Bell 1978; Zirakashvili & Ptuskin 2008; DC et al. 2009; DC 2012,…)
    - Large velocity of scattering centers ($v_A \sim \delta B$) leads to an effective R<4, which in turns implies q>2

$$\boxed{R \quad \simeq \frac{up - \quad A,up}{down}}$$

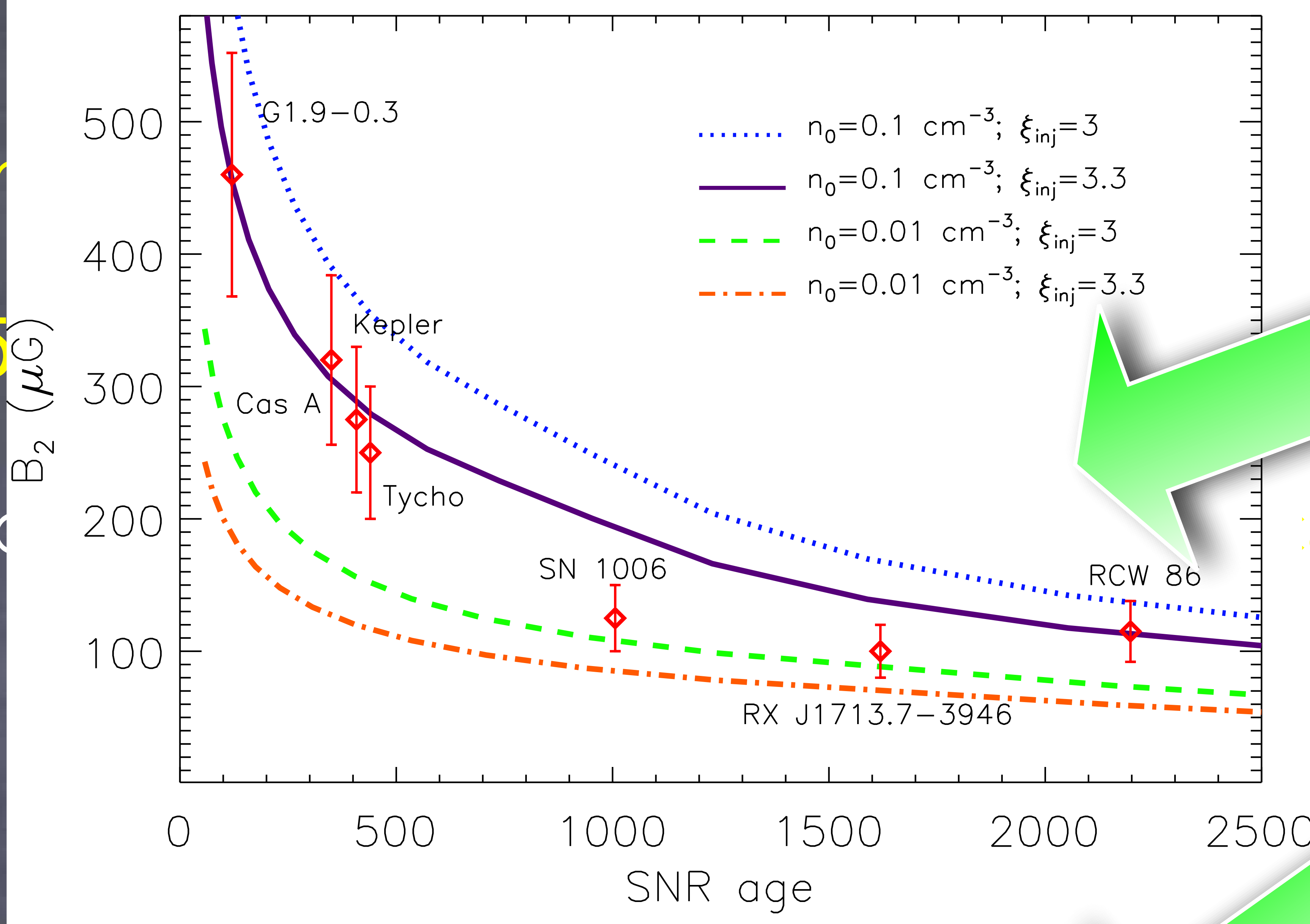


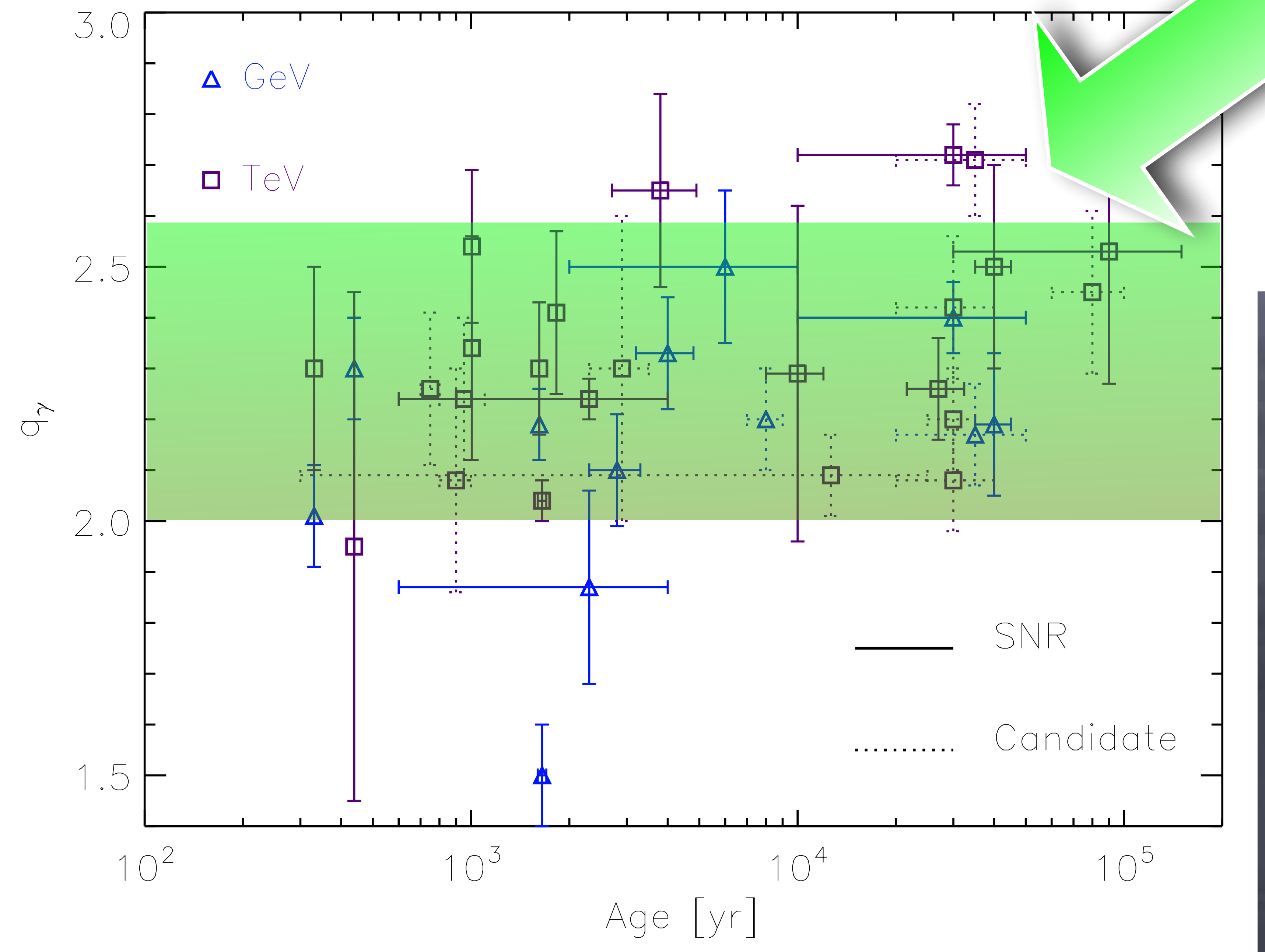
- **Oblique shocks/modified diffusion** (Kirk et al. 1996; Morlino et al. 2007; Bell et al. 2011, …)

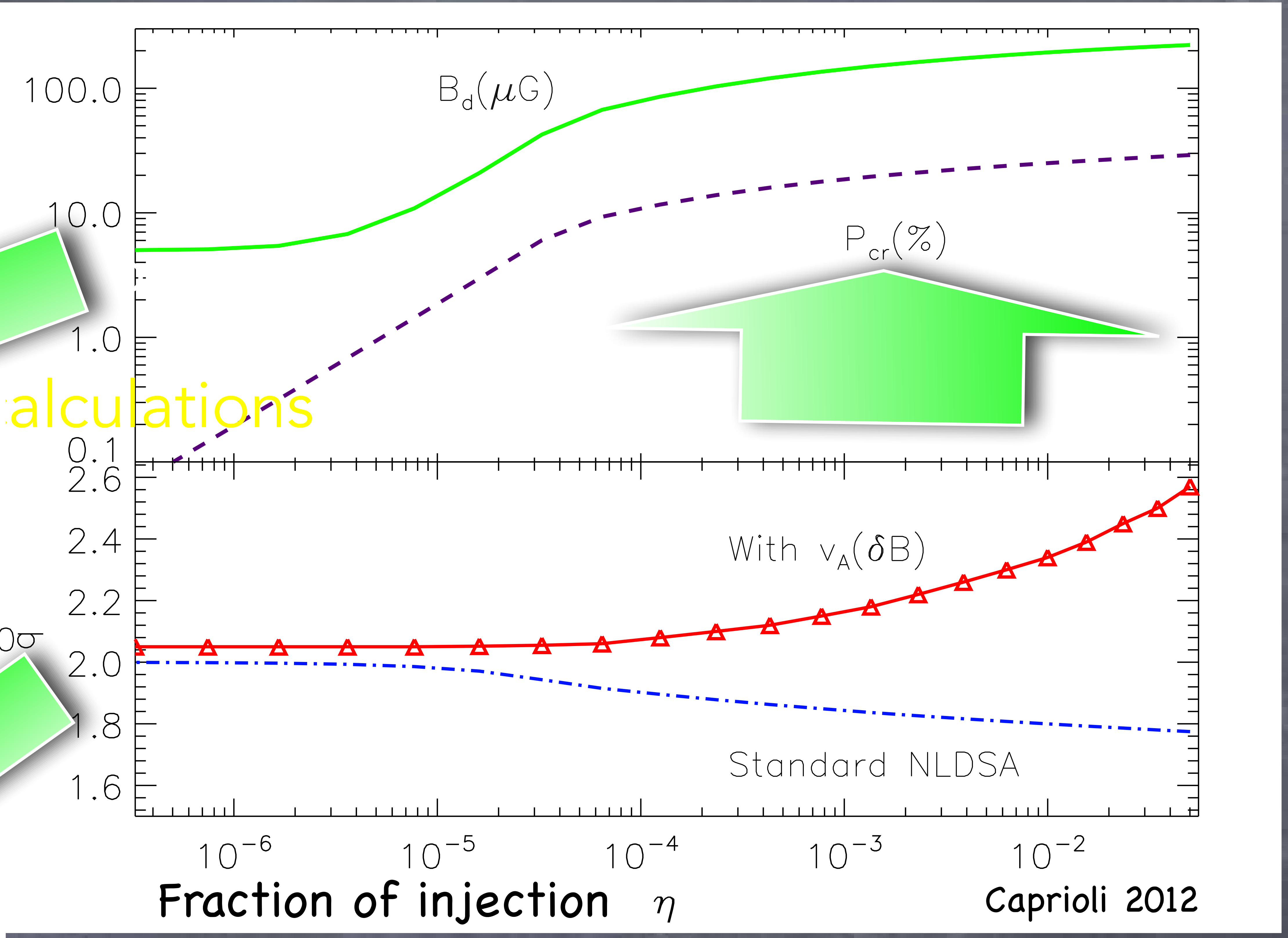
Acceleration Efficiency

- Saturation
- With V_A(δ
- Need to b

alculations

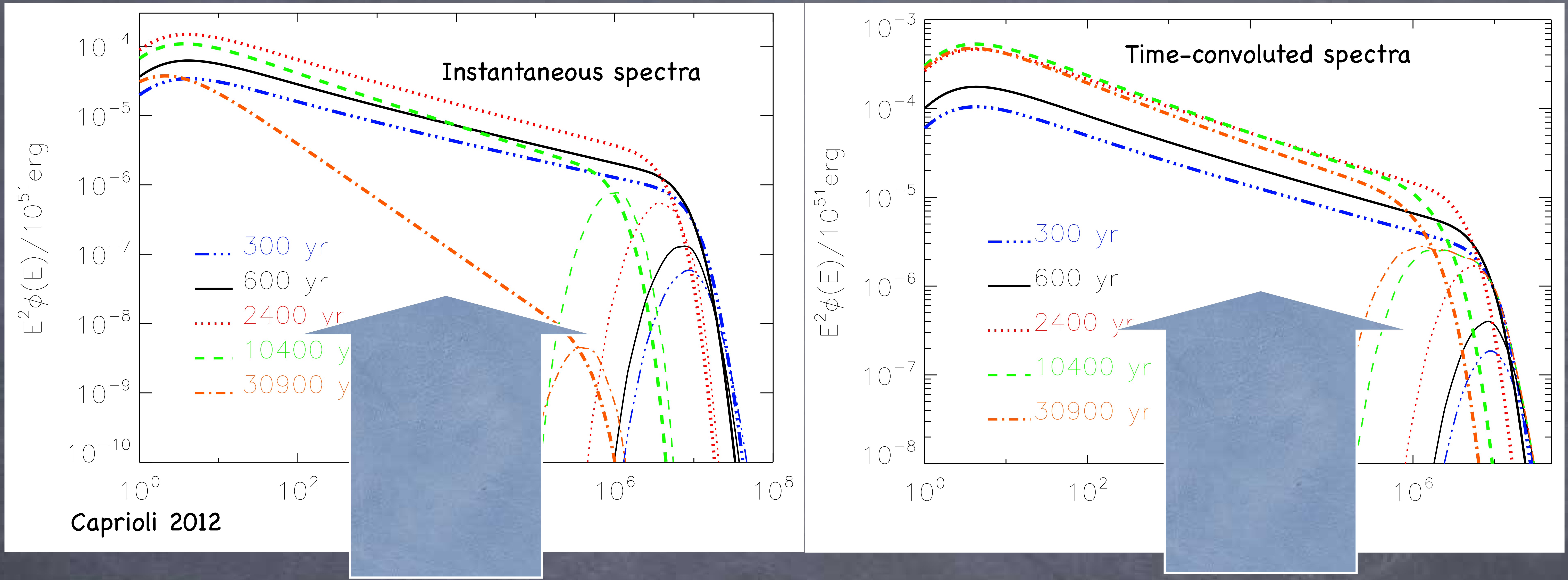






SNR spectra

- The velocity of the scattering centers in $\delta B/B \gg 1$ leads to steep spectra



Caprioli 2012

Relevant for gamma-ray emission

Relevant for the GCR spectrum

The **total CR spectrum** injected by a SNR has roughly the slope of the instantaneous spectrum at **the beginning of the Sedov stage**

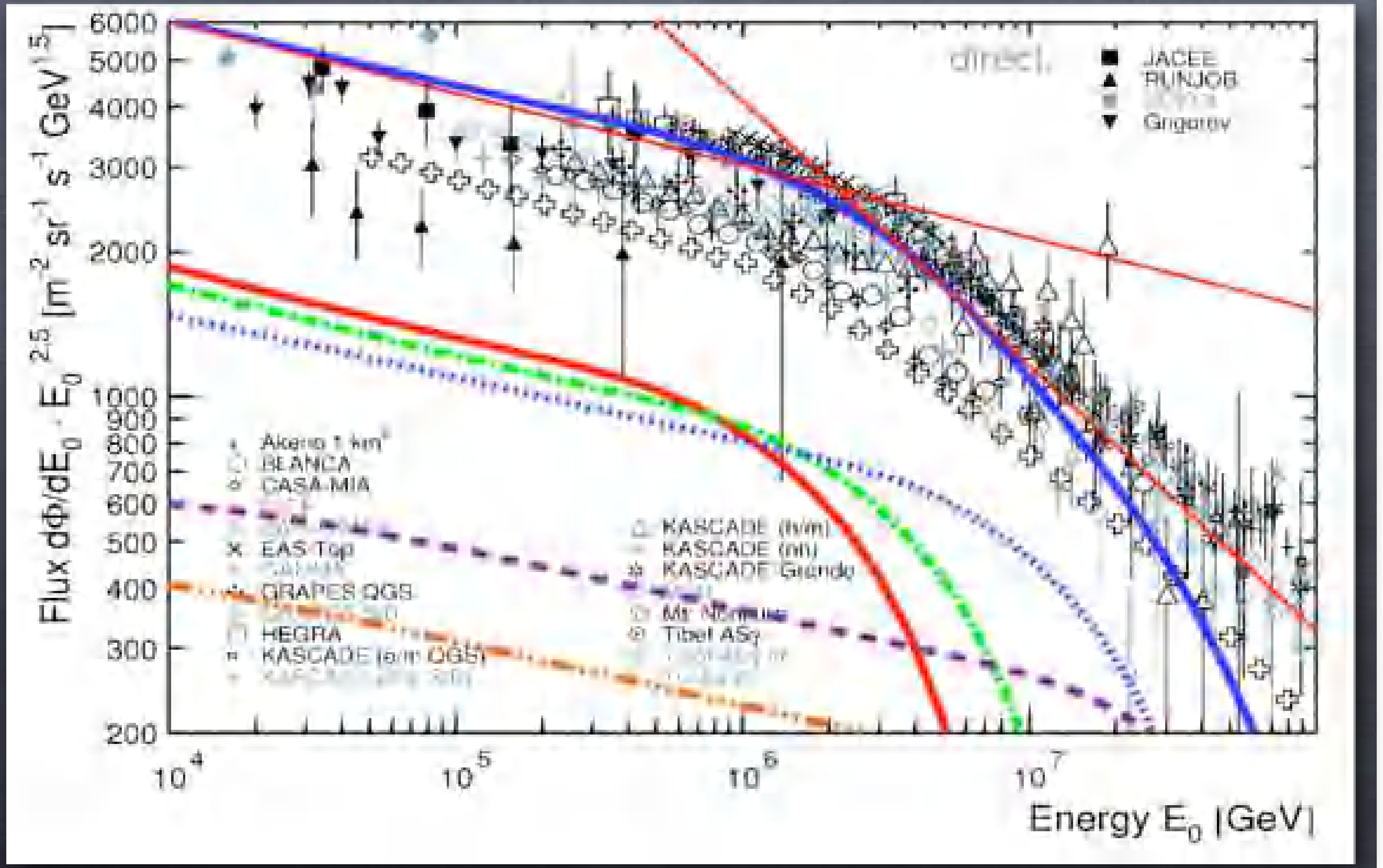
Acceleration of CR nuclei in SNRs

- CR chemical abundances at injection tuned to fit the observed ones (Blümer et al. 2009)
- Correction for propagation in the Galaxy

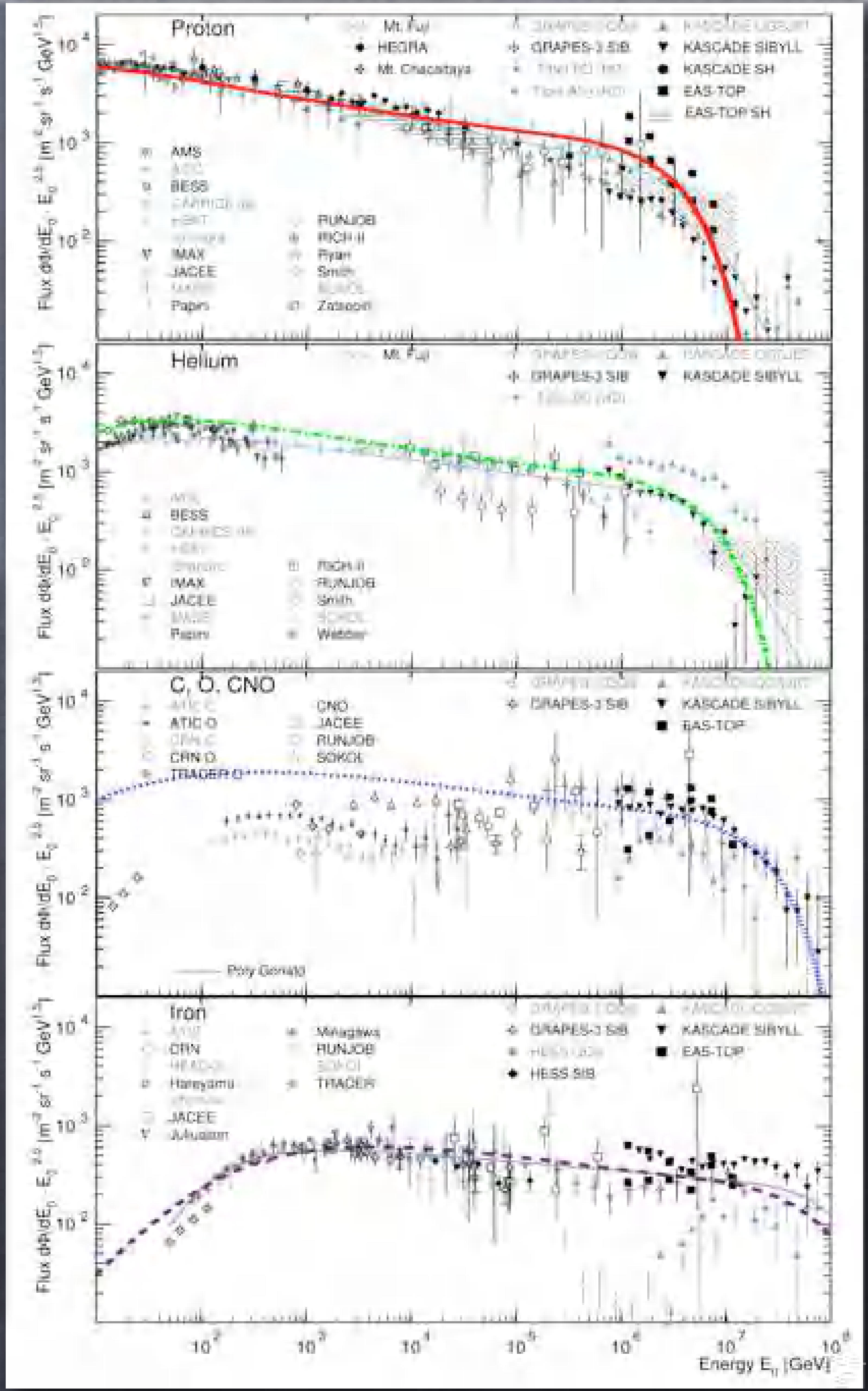
$$\phi_{Earth}(E) = \frac{\eta_{SN} N_{SNR}(E)\tau_{esc}(E)}{4\pi R_{Gal}^2}$$

$$\tau_{esc}(E) = 15\,Myr\left(\frac{1}{Z}\frac{E}{10GeV}\right)^{-0.55} \quad ; \quad \eta_{SN} = \frac{3}{100\,yr}$$

- Possible to fit spectra and the knee feature



DC, Blasi, Amato 2011



From accelerated particles to CRs

- Ejecta dominated stage:
  - Magnetic turbulence and E_{max} increase with time
- Sedov-Taylor stage (around 500-1000yr):
  - The shock velocity an the δB decrease
  - particles with $E_{max}(t)$ cannot be confined any longer and escape the system

- Let F_{esc} be the escaping fraction. During the adiabatic Sedov stage $R_{sh} \sim t^{2/5}$

$$d\varepsilon(t) = F_{esc}(t)\frac{1}{2}\rho V_{sh}^3(t)4\pi R_{sh}^2 dt$$

$$d\varepsilon(E) = N_{esc}(E)EdE$$

$$\Longrightarrow$$

$$N_{esc}(E) \propto E^{-2}t^{5\nu-2}F_{esc}(t)$$

$$R_{sh}(t) \propto t^{\nu}$$

$$\Longrightarrow$$

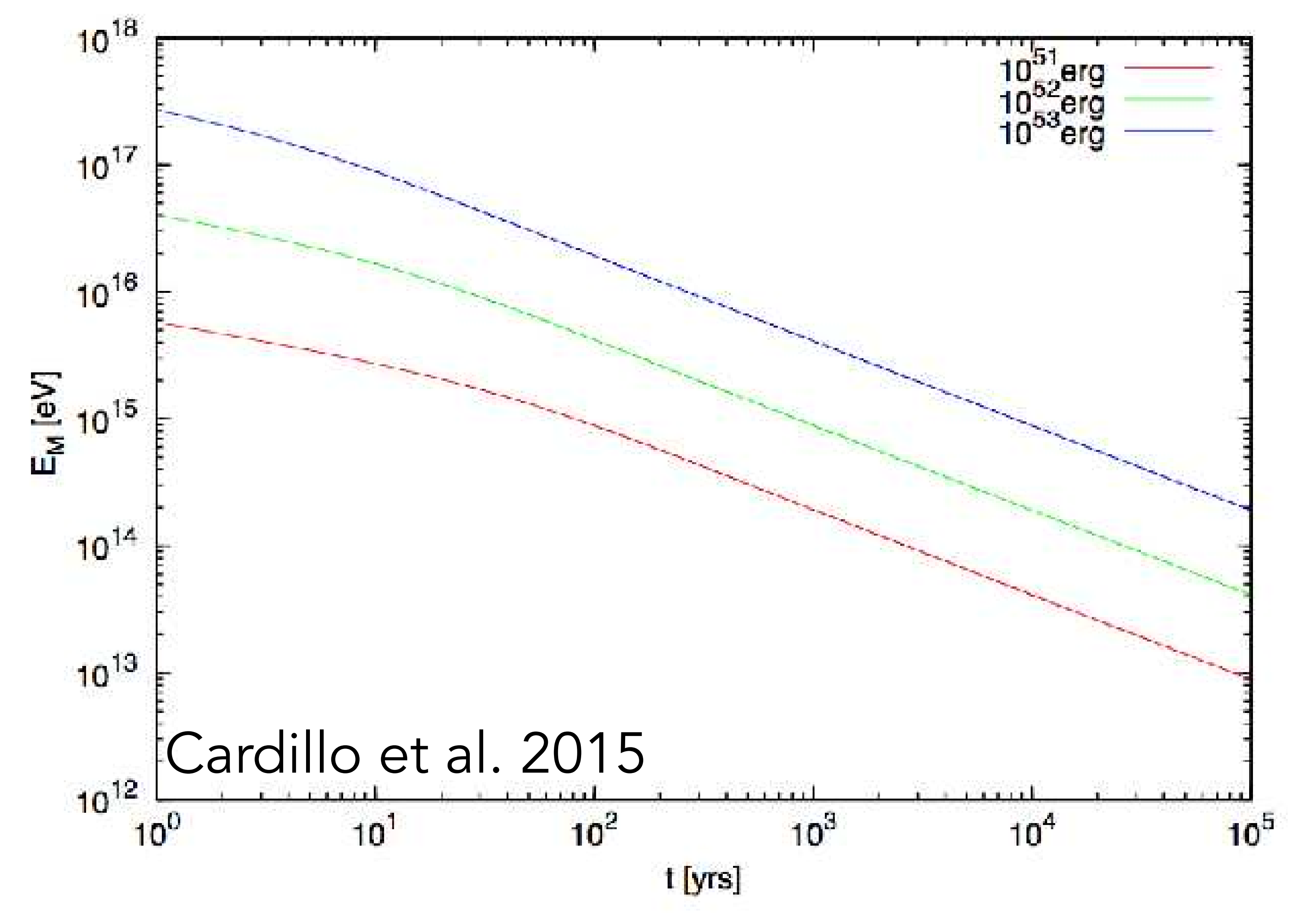
$$\boxed{N_{esc} \propto E^{-2}}$$

The released spectrum is the convolution over time of 2 contributions:
Escape from upstream + Relic advected CRs

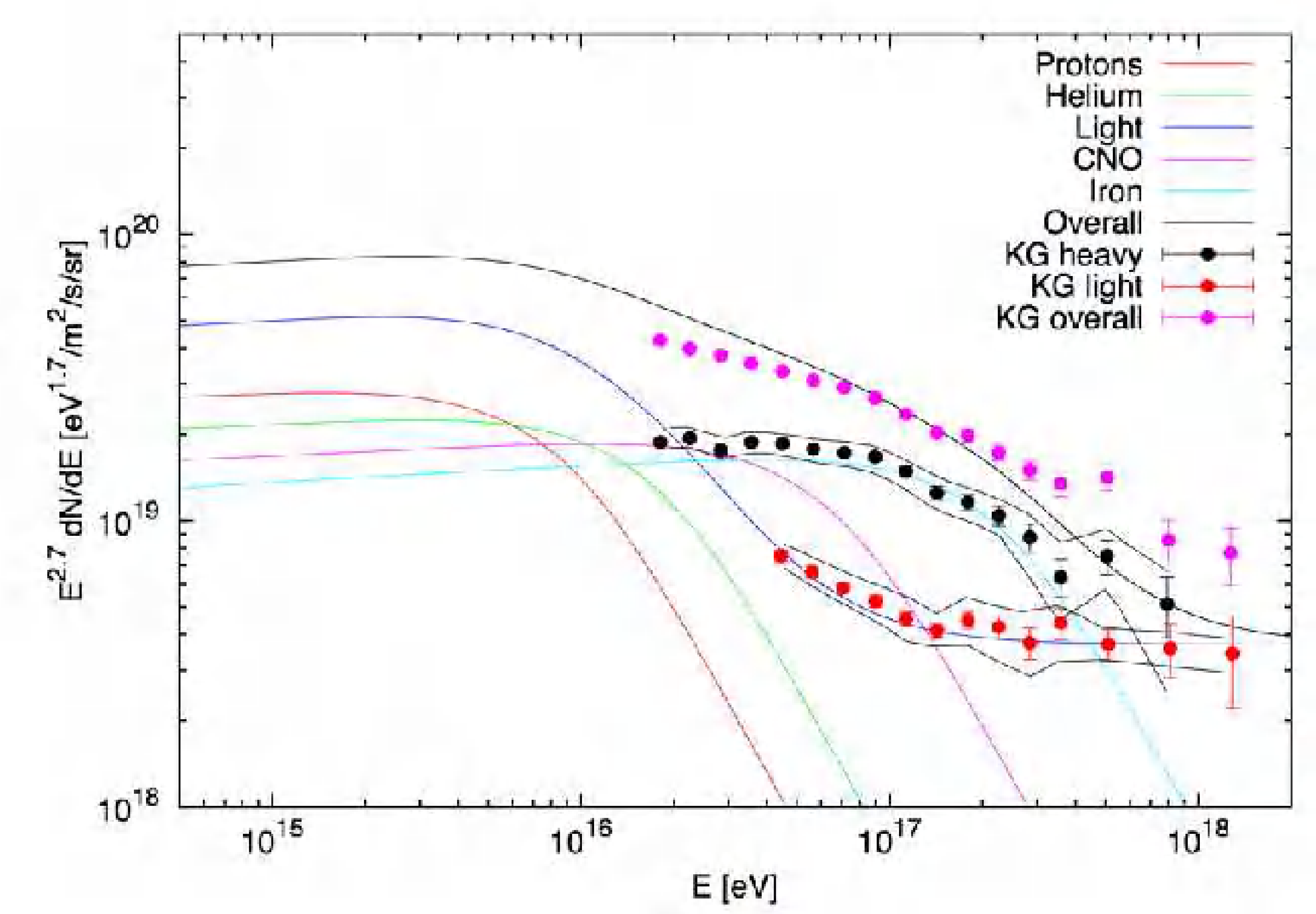
Caprioli, Amato & Blasi 2010a

Escape from PeVatrons

- The released spectrum is likely a convolution over instantaneous (monochromatic) spectra (Ptuskin & Zirakashvili 2005; DC et al. 2009, 2010; Bell et al. 2013; Cardillo et al. 2015)
  - The CR power-law may reflect the self-similar SNR evolution, rather than acceleration!
  - Escaping CRs illuminate molecular clouds (e.g., Gabici et al. 2007,2009; Castro & Slane 2010,…)
- Acceleration rate depends on B amplification (via Bell's instability)
  - multi-PeV achieved for $T_{SNR}<100$ yr in type-II SNe (Bell et al. 2013; Schure & Bell 2013; Cardillo et al. 2015)



Cardillo et al. 2015



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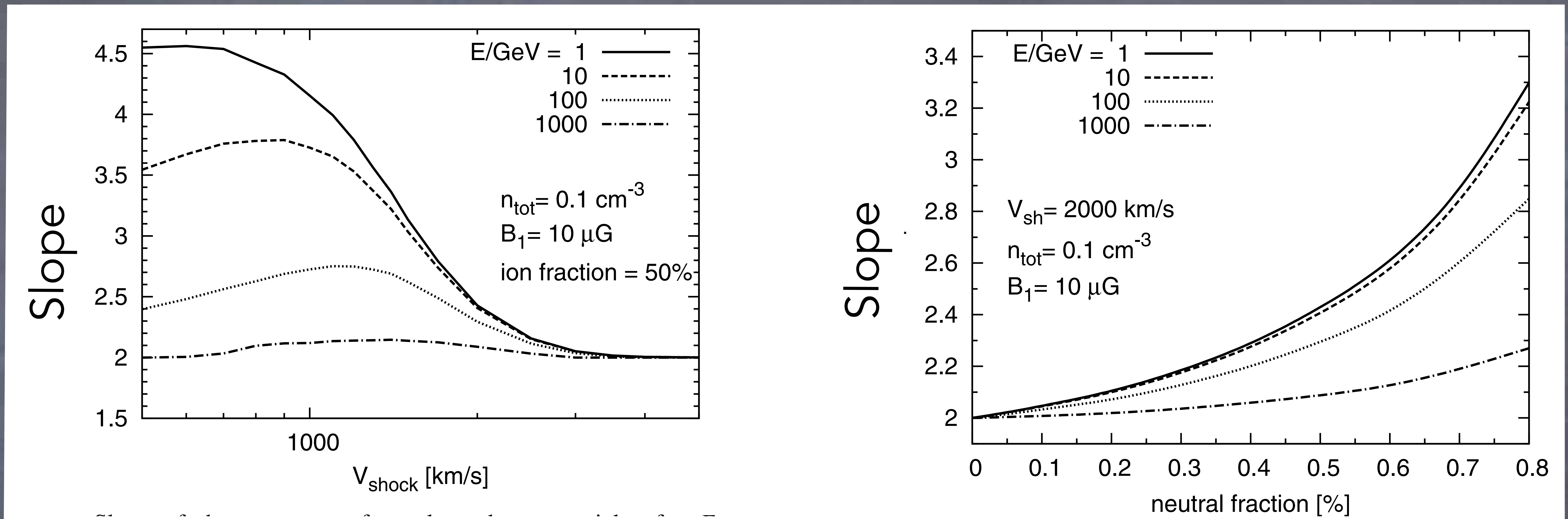

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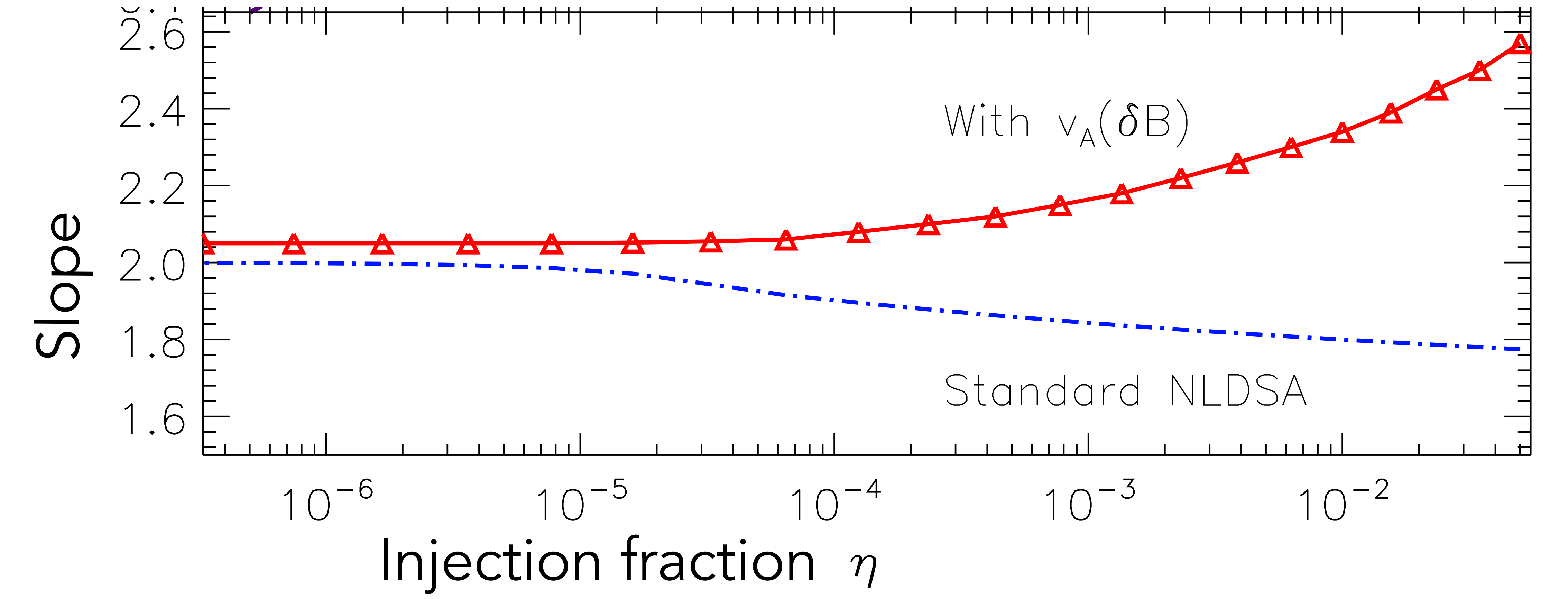
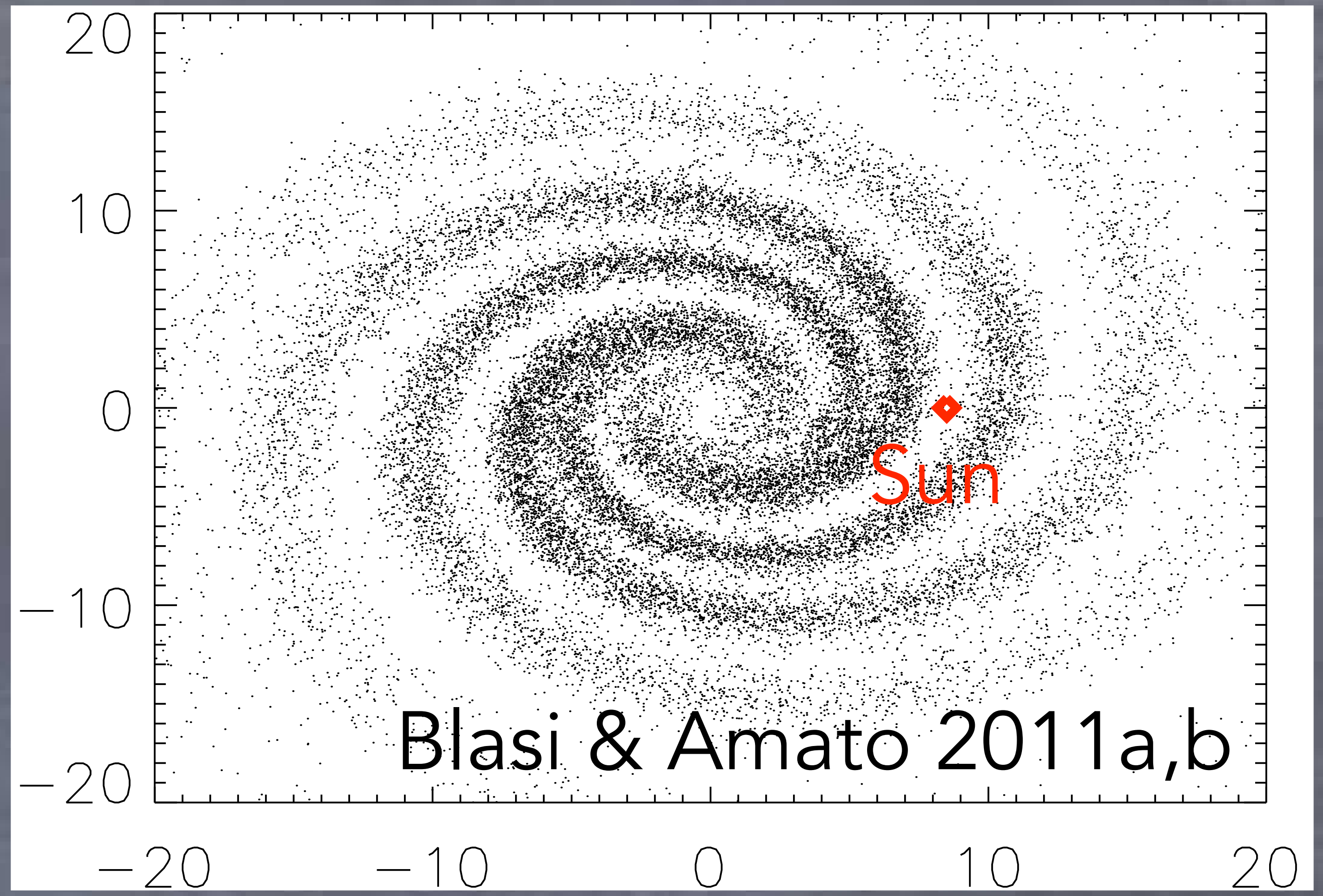


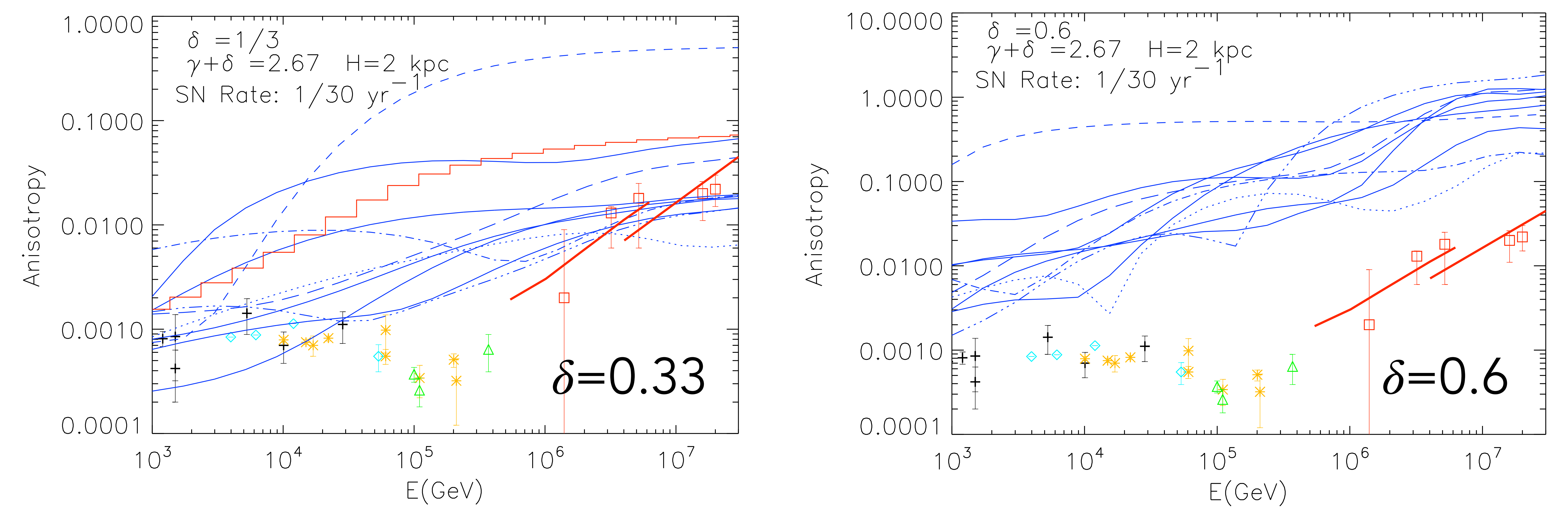
- Oblique shocks/modified diffusion (Kirk et al. 1996; Morlino et al. 2007; Bell et al. 2011, …)

Steep spectra preferred by propagation, too

- Monte Carlo simulations of SNRs + CR transport
- Injection spectrum: $\sim E^{-\gamma}$
- Residence time in the Galaxy: $\sim E^{-\delta}$
  - Constraint: $\delta+\gamma\sim 2.7$



Blasi & Amato 2011a,b



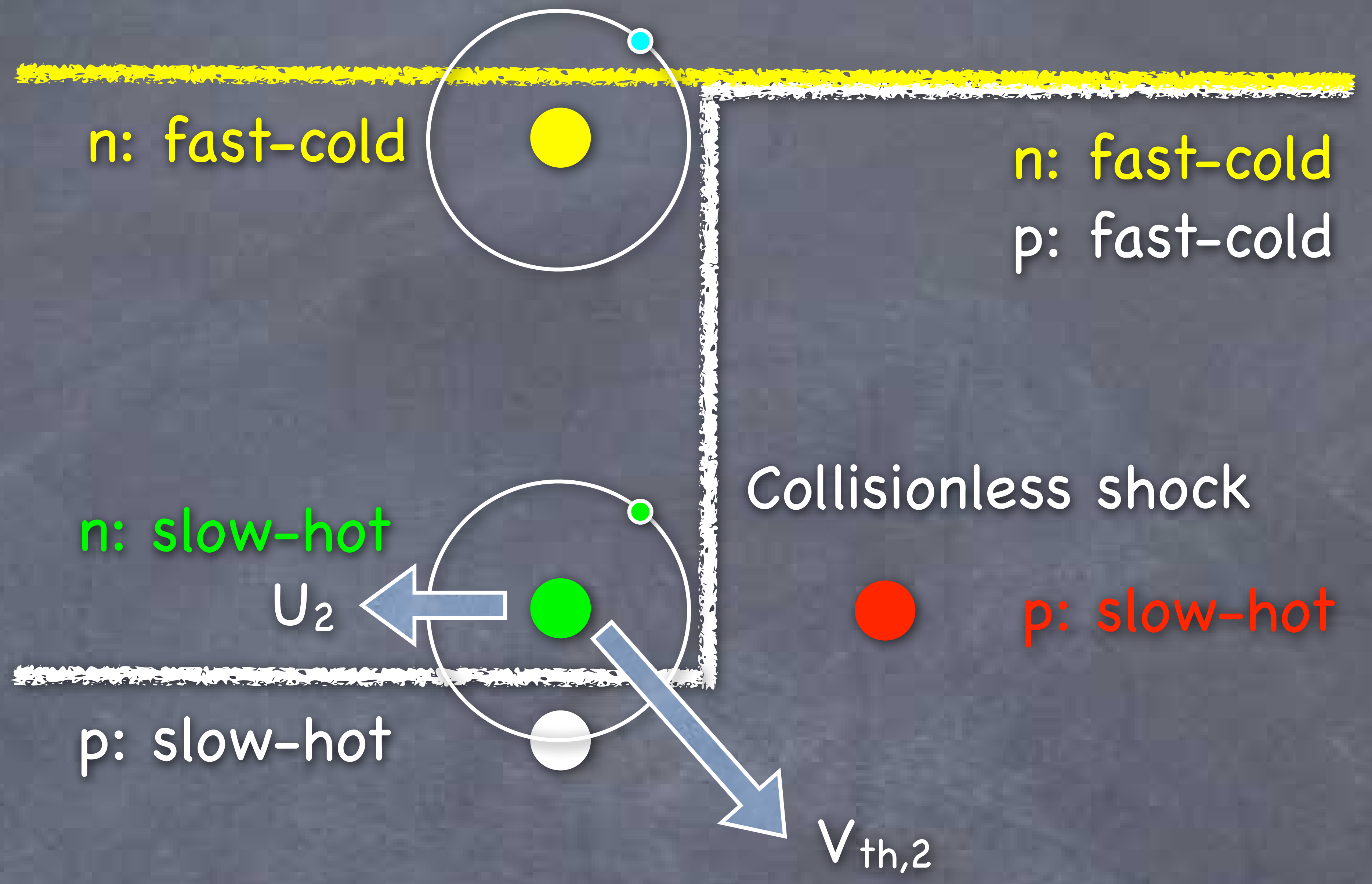
- $\delta=0.33$ is preferred since it returns:
  - more universal CR spectra
  - less anisotropy

Also in this case, an injection slope of $\gamma=2.7-0.33\sim 2.35$ is required

NEUTRALS

Shocks into partially ionized media

- Charge-exchange between neutrals and ions can transfer energy from downstream to upstream!
- Efficient heating implies smaller Mach numbers



n: fast-cold

n: fast-cold
p: fast-cold

Collisionless shock

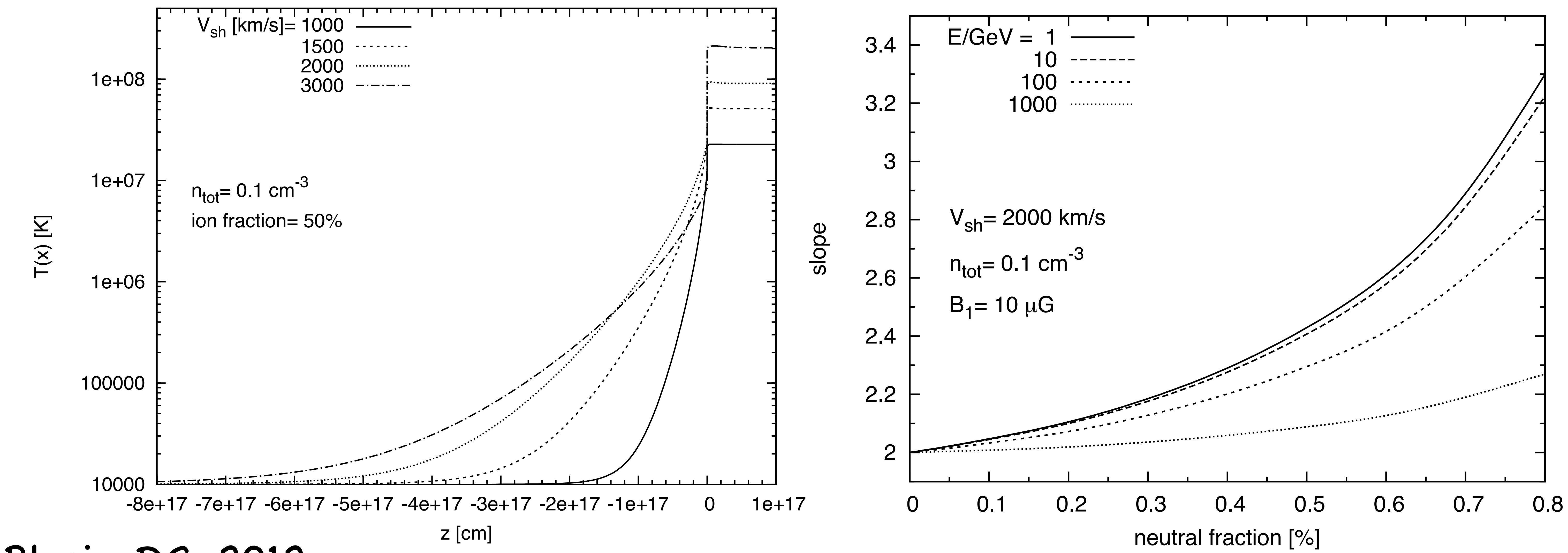
n: slow-hot

U_2

p: slow-hot

p: slow-hot

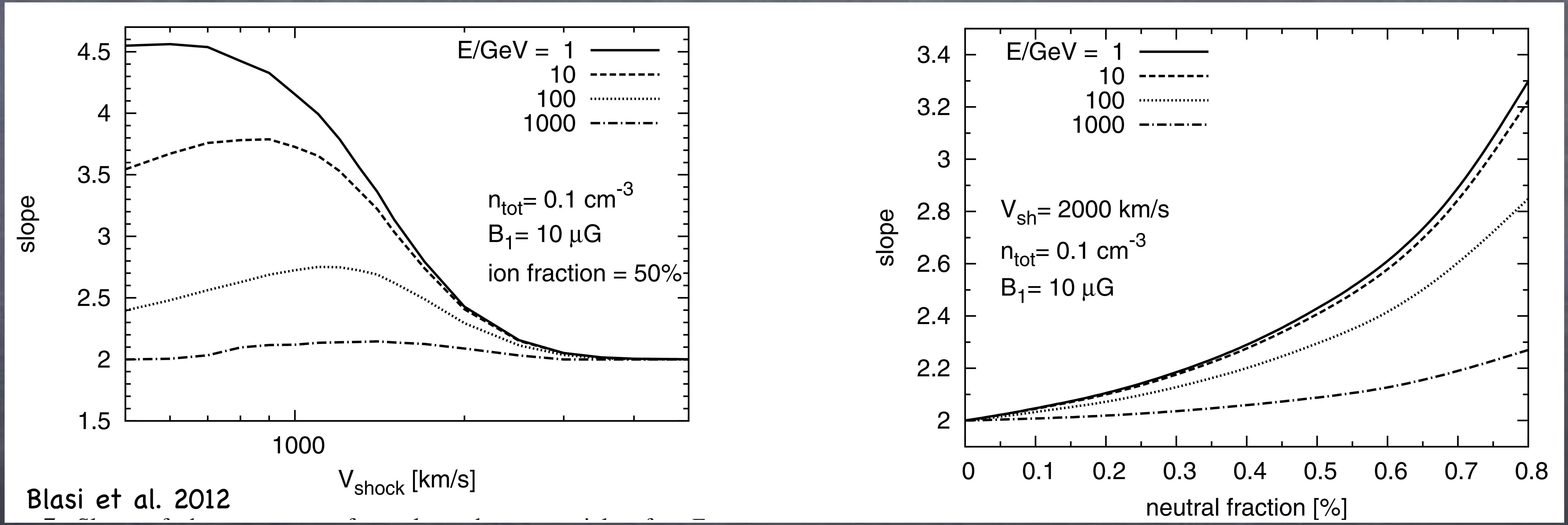
$V_{th,2}$



Blasi,...DC, 2012

Acceleration at Balmer shocks

- A neutral-induced precursor makes the effective compression ratio smaller than 4 (Blasi et al. 2012, Morlino et al. 2012, 2013,...)
- Steep spectra, up to what energy?
  - Charge-exchange scale vs CR diffusion scale



Blasi et al. 2012

- For V_{sh}>3000km/s ionization dominates over CE

MULTI-SCALES

Multi-Scale Approach to Shock Acceleration

Micro

Meso

Space-Physics

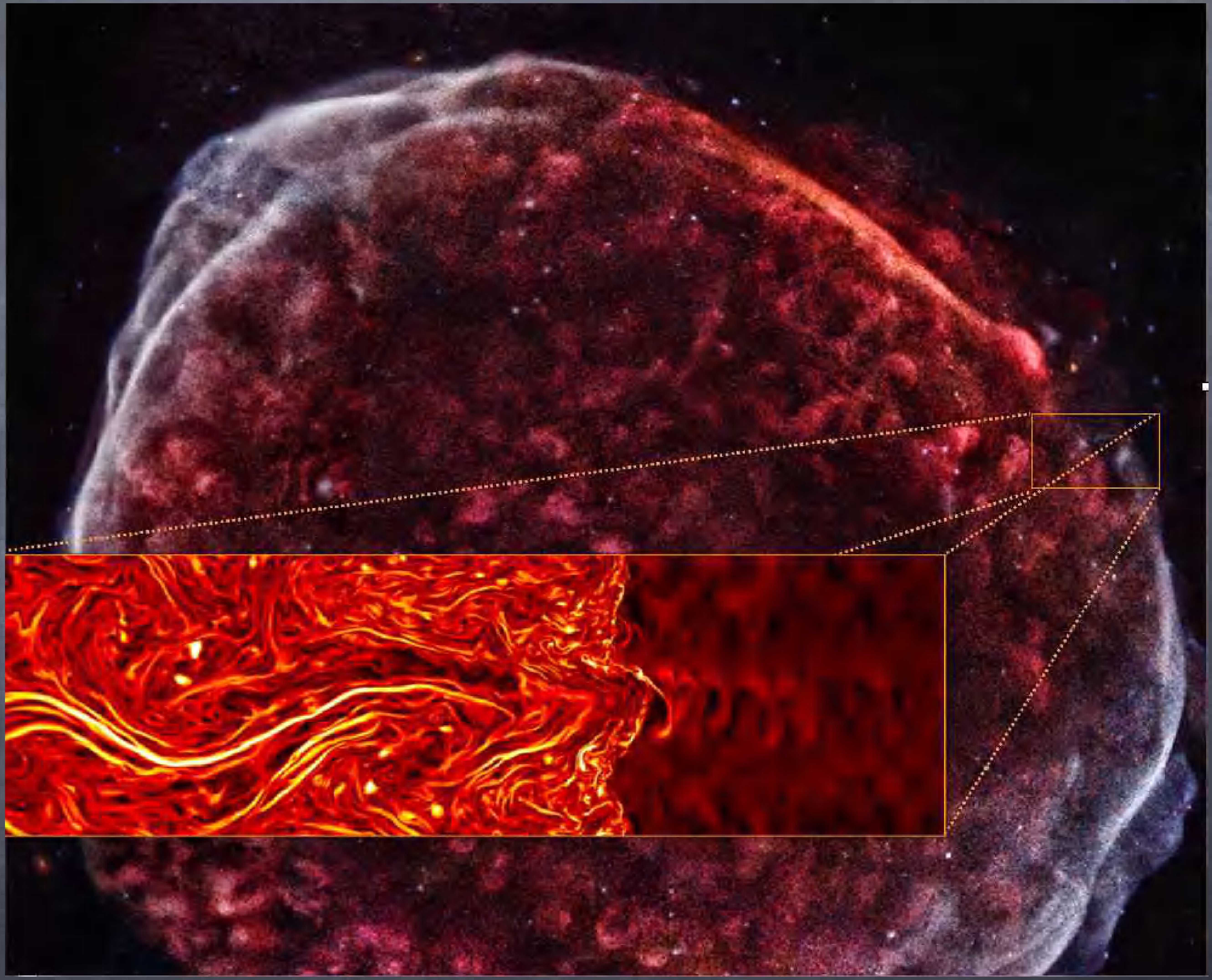
Astro

PIC Simulations
electron + ion dynamics

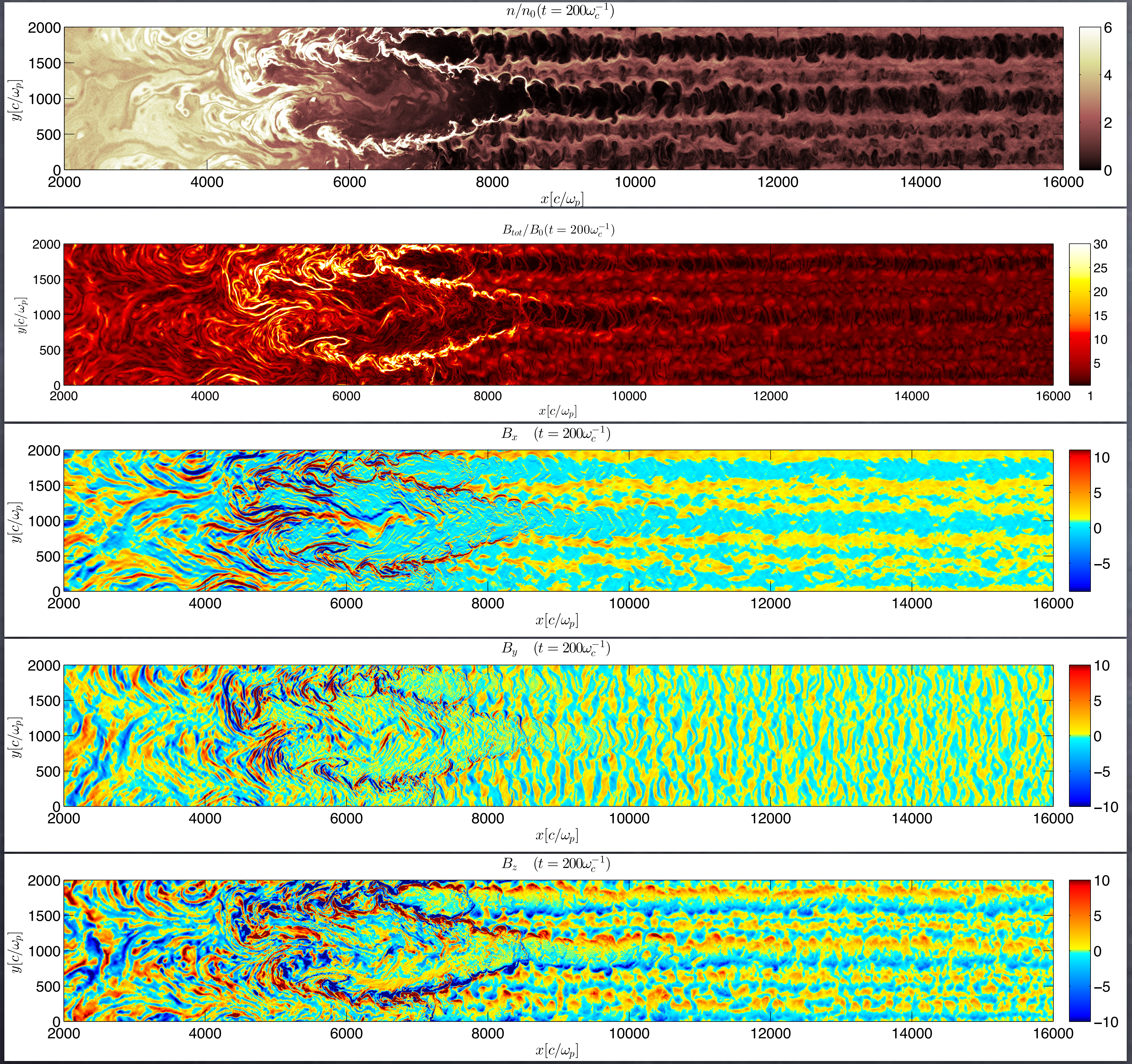
Hybrid: ion dynamics,
magnetic field amplification

Super-Hybrid (MHD+hybrid)
Large/long scales
High-Mach numbers
(Bai et al. 2015)

Semi-Analytical
CRAFT = Cosmic Ray Analytical Fast Tool
(DC et al, in prog.)



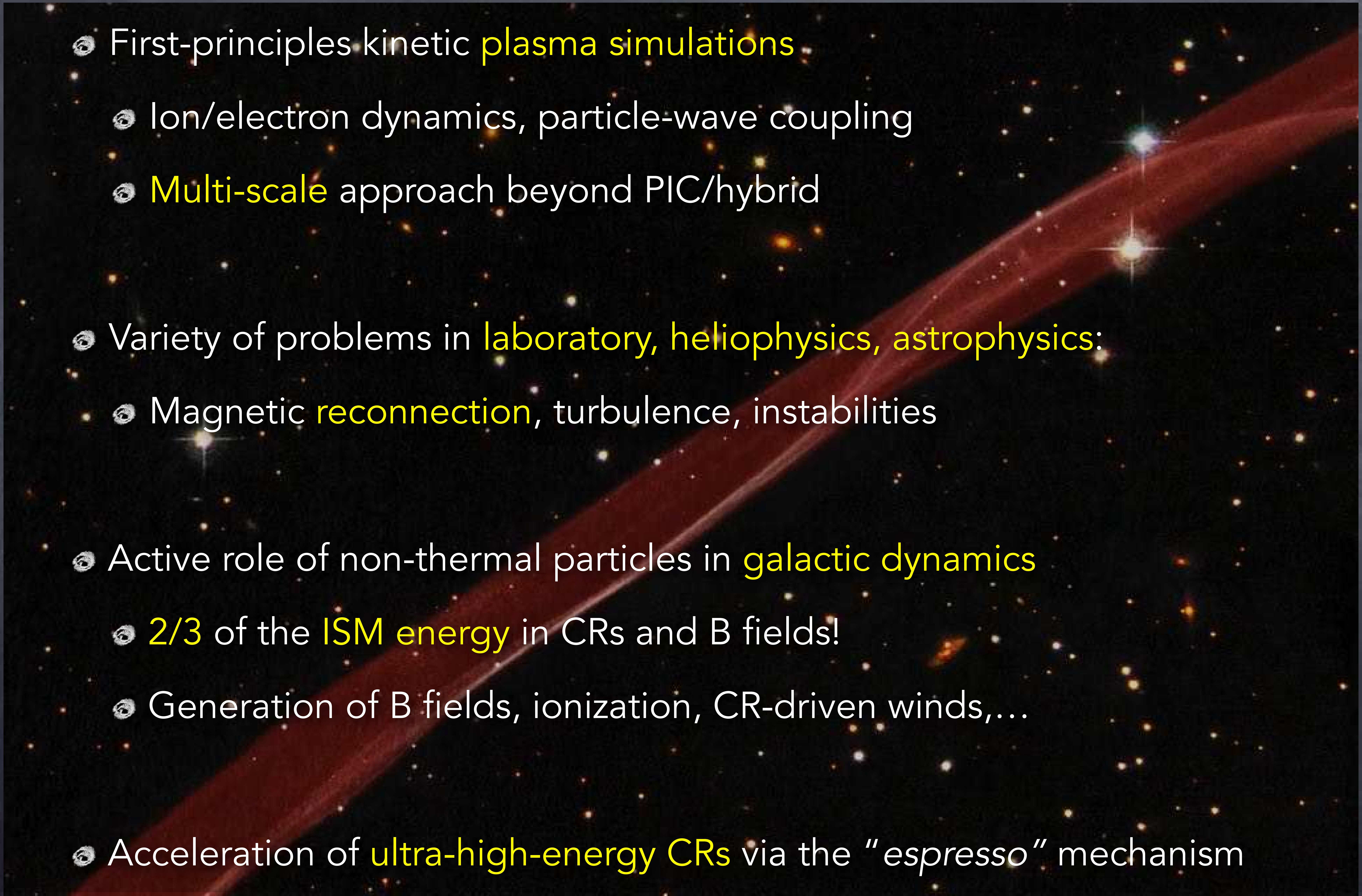
From kinetic to fluid scales



Hybrid simulations of a M=100 parallel shock

- Towards real shocks: going bigger up to space/ astrophysical scales
- Embedding microphysics in hydro/MHD simulations
  - Super-Hybrid: MHD+hybrid (Bai, DC, Sironi, Spitkovsky 2015)
  - CRAFT: CR Analytic Fast Tool (DC et al., in prep)

A Stairway to New Discoveries…



- First-principles kinetic plasma simulations
  - Ion/electron dynamics, particle-wave coupling
  - Multi-scale approach beyond PIC/hybrid

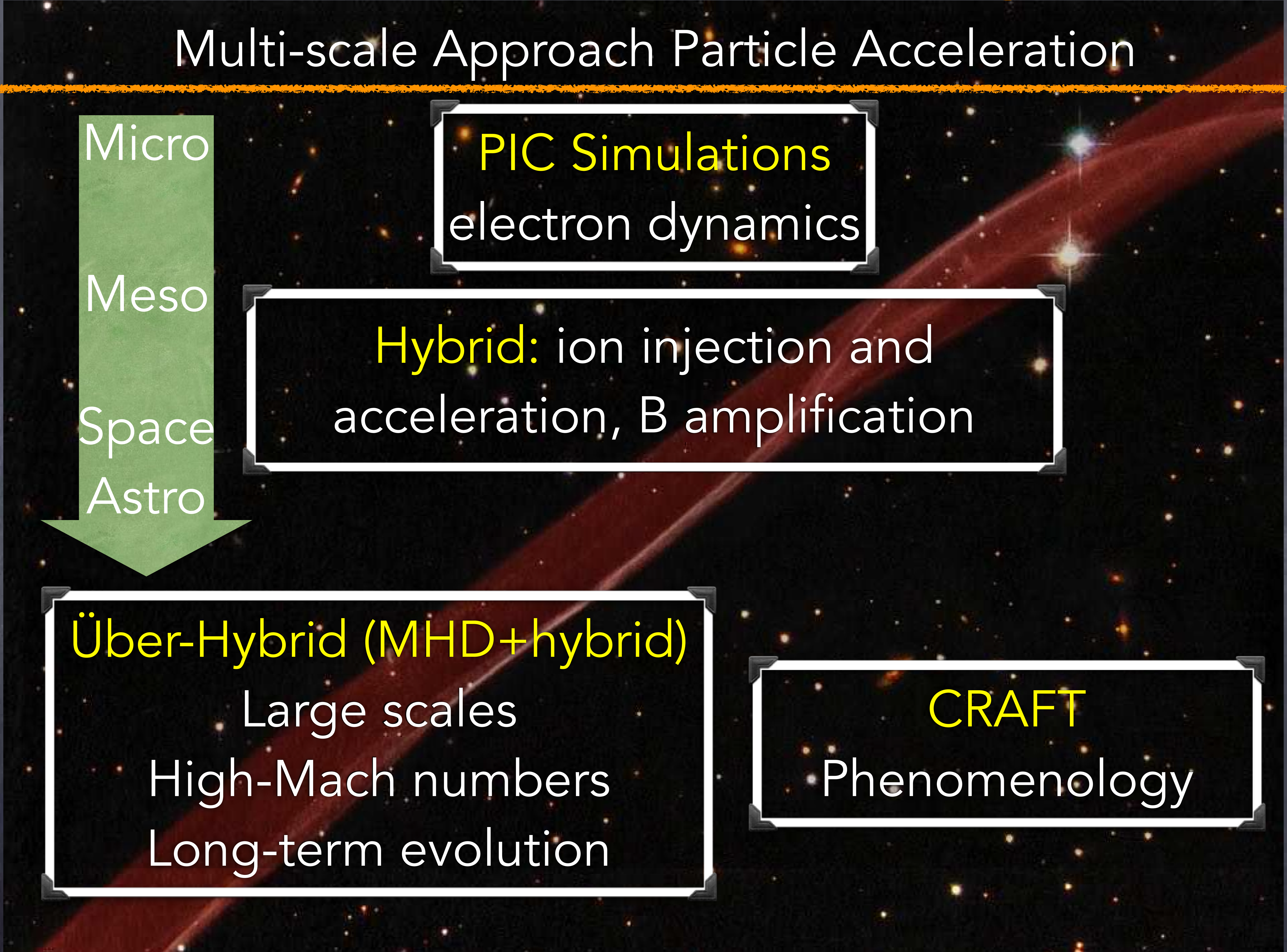
- Variety of problems in laboratory, heliophysics, astrophysics:
  - Magnetic reconnection, turbulence, instabilities

- Active role of non-thermal particles in galactic dynamics
  - 2/3 of the ISM energy in CRs and B fields!
  - Generation of B fields, ionization, CR-driven winds,…

- Acceleration of ultra-high-energy CRs via the "*espresso*" mechanism

End

Multi-scale Approach Particle Acceleration



Micro

Meso

Space

Astro

PIC Simulations
electron dynamics

Hybrid: ion injection and acceleration, B amplification

Über-Hybrid (MHD+hybrid)
Large scales
High-Mach numbers
Long-term evolution

CRAFT
Phenomenology

CRAFT

Large-scale kinetic approaches to non-linear DSA

- Solve CR transport and shock hydrodynamics self-consistently

1D Diffusion-convection (Parker) equation

$$\frac{\partial f(t,x,p)}{\partial t} + \tilde{u}(x)\frac{\partial f(t,x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(t,x,p)}{\partial x}\right] + \frac{p}{3}\frac{\partial f(t,x,p)}{\partial p}\frac{\mathrm{d}\tilde{u}(x)}{\mathrm{d}x}$$

  - **FULLY NUMERICAL**: time-dependent
    - Kang & Jones 1997-2008; Berezhko & Völk 1997-2007; Zirakashvili & Aharonian 2009; …
  - **MONTE CARLO:** account for anisotropic distributions f(p_x,p_y,p_z)
    - Jones & Ellison 1991; Ellison et al. 1990;1995; Vladimirov, Ellison, & Bykov 2006; …
  - **SEMI-ANALYTICAL**: versatile, computationally extremely fast
    - Malkov 1997; Blasi 2002; Amato & Blasi 2006, DC et al. 2009; 2010; DC 2012, …
- Require an a priori description of
  - Magnetic field generation, Particle scattering, CR injection

This information can be provided only by kinetic simulations

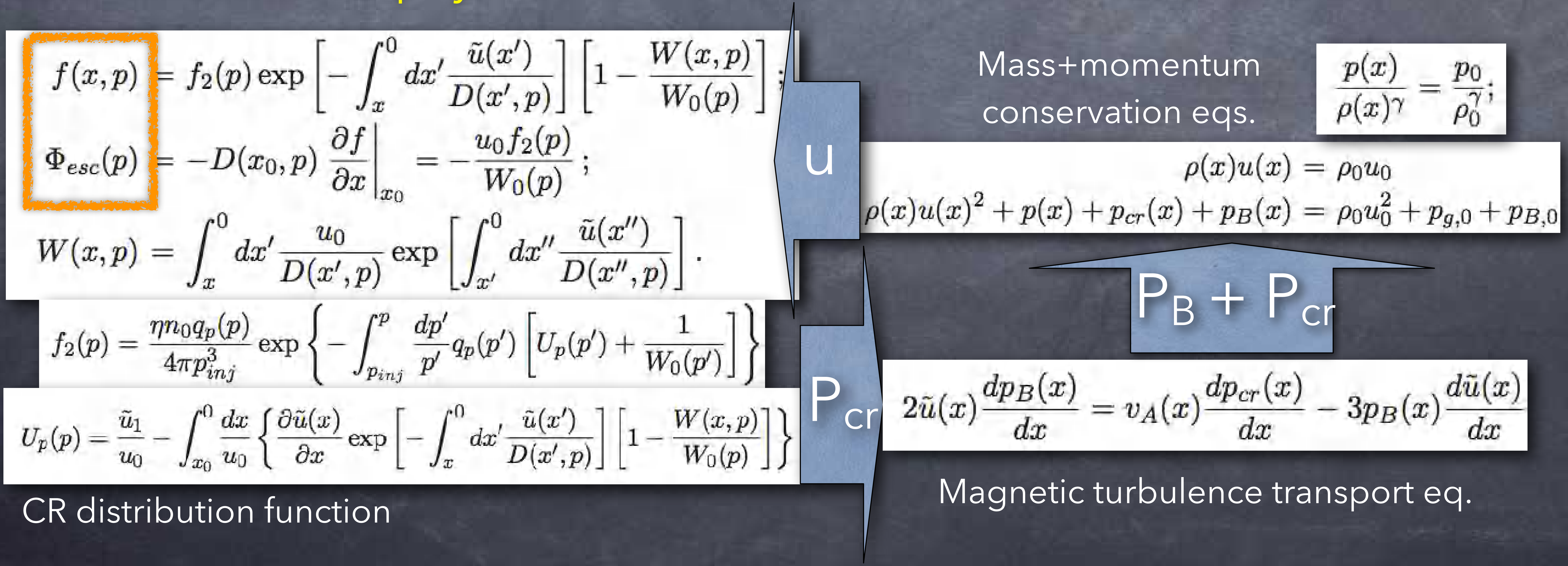
CRAFT: a Cosmic-Ray Fast Analytic Tool

(Caprioli et al. 2009-2015, to be publicly released soon)

- Iterative analytical solution of the 1D stationary CR transport equation:

$$\underbrace{\tilde{u}(x)\frac{\partial f(x,p)}{\partial x}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right]}_{\text{Diffusion}} + \underbrace{\frac{p}{3}\frac{\mathrm{d}\tilde{u}(x)}{\mathrm{d}x}\frac{\partial f(x,p)}{\partial p}}_{\text{Energy change}} + \underbrace{Q(x,p)}_{\text{Injection}}$$

- Very fast: a few seconds on a laptop (vs days on clusters: DC et al. 2010)
- Can embed microphysics from kinetic simulations into (M)HD



$$\boxed{f(x,p)} = f_2(p)\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right];$$

$$\boxed{\Phi_{esc}(p)} = -D(x_0,p)\left.\frac{\partial f}{\partial x}\right|_{x_0} = -\frac{u_0 f_2(p)}{W_0(p)};$$

$$W(x,p) = \int_x^0 dx'\frac{u_0}{D(x',p)}\exp\left[\int_{x'}^0 dx''\frac{\tilde{u}(x'')}{D(x'',p)}\right].$$

$$f_2(p) = \frac{\eta n_0 q_p(p)}{4\pi p_{inj}^3}\exp\left\{-\int_{p_{inj}}^p\frac{dp'}{p'}q_p(p')\left[U_p(p')+\frac{1}{W_0(p')}\right]\right\}$$

$$U_p(p) = \frac{\tilde{u}_1}{u_0} - \int_{x_0}^0\frac{dx}{u_0}\left\{\frac{\partial\tilde{u}(x)}{\partial x}\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right]\right\}$$

CR distribution function

Mass+momentum conservation eqs.

$$\frac{p(x)}{\rho(x)^{\gamma}} = \frac{p_0}{\rho_0^{\gamma}};$$

$$\rho(x)u(x) = \rho_0 u_0$$

$$\rho(x)u(x)^2 + p(x) + p_{cr}(x) + p_B(x) = \rho_0 u_0^2 + p_{g,0} + p_{B,0}$$

$$2\tilde{u}(x)\frac{dp_B(x)}{dx} = v_A(x)\frac{dp_{cr}(x)}{dx} - 3p_B(x)\frac{d\tilde{u}(x)}{dx}$$

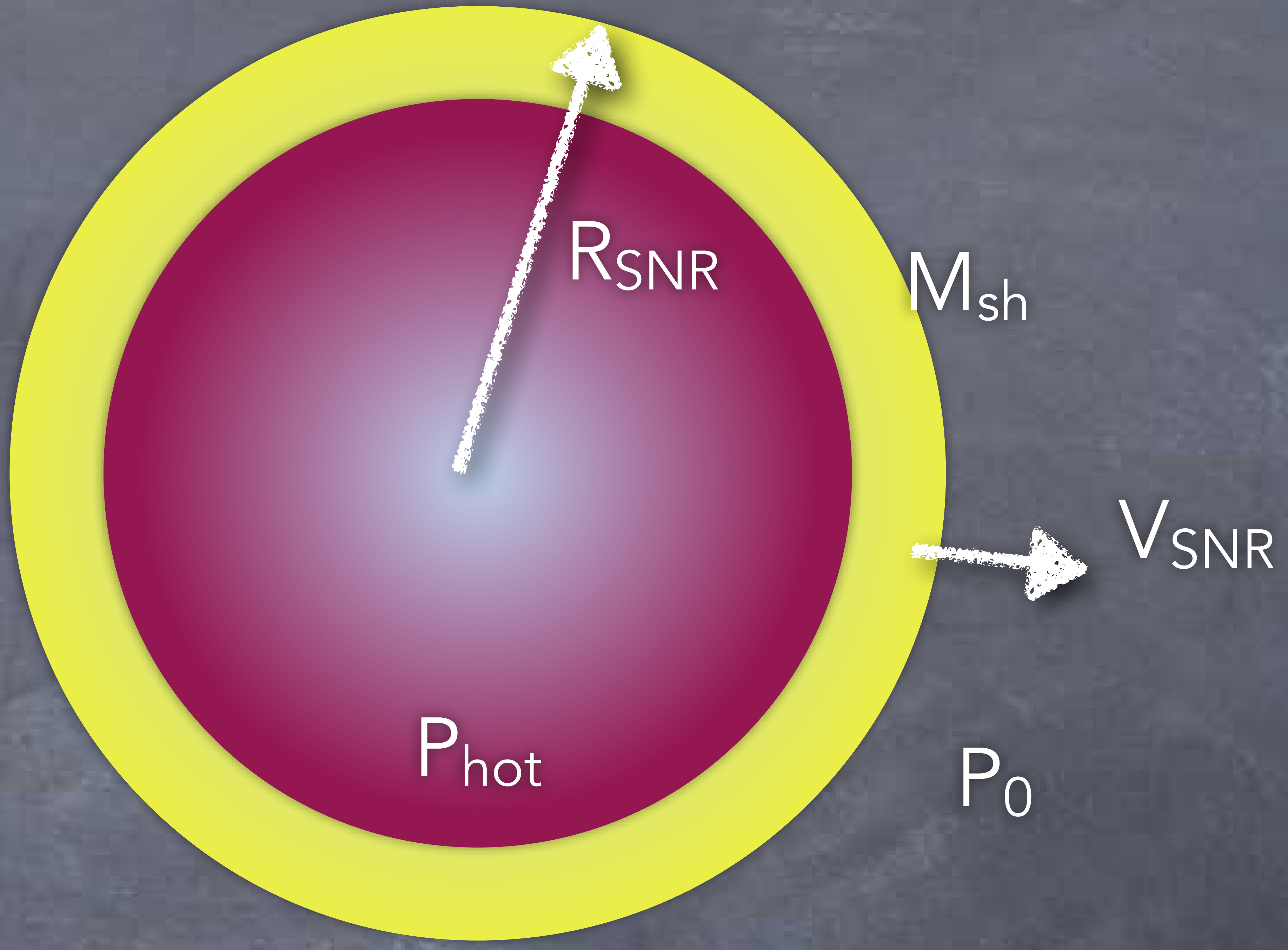
Magnetic turbulence transport eq.

CR FEEDBACK

What is the feedback of
CRs on SNR evolution?
(and eventually in galaxy formation?)

SNR Evolution in a Thin-Shell

- **Ejecta-dominated** stage: $R_{SNR} \sim V_{SNR}\, t$
- **Sedov-Taylor** (adiabatic) stage: $R_{SNR} \sim t^{2/5}$
- **Radiative stage** ($T_{sh} < \sim 10^6$K)
  - Pressure-driven snowplow ($P_{hot} > P_0$)
  - Momentum-driven snowplow ($P_{hot} \sim P_0$)

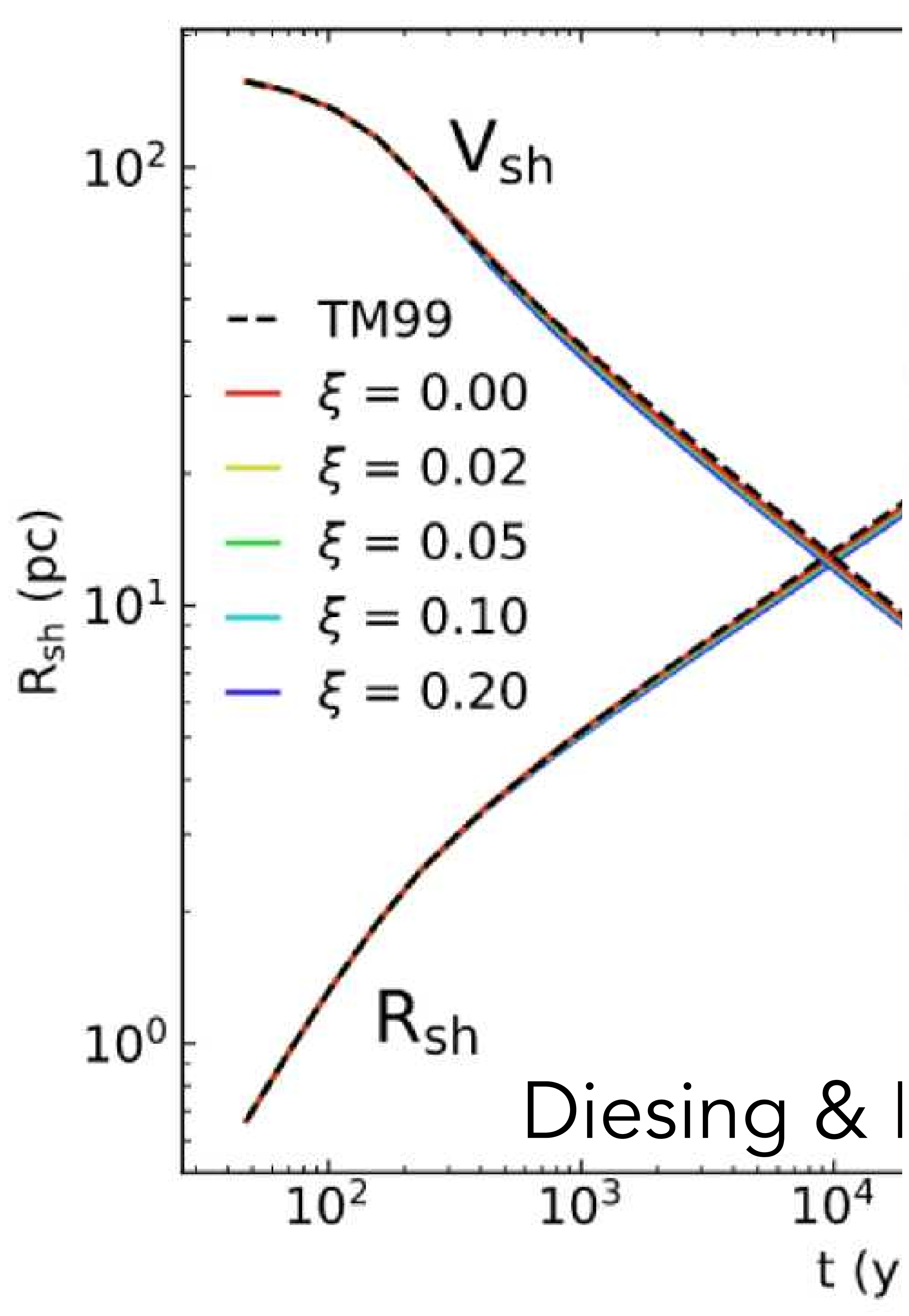


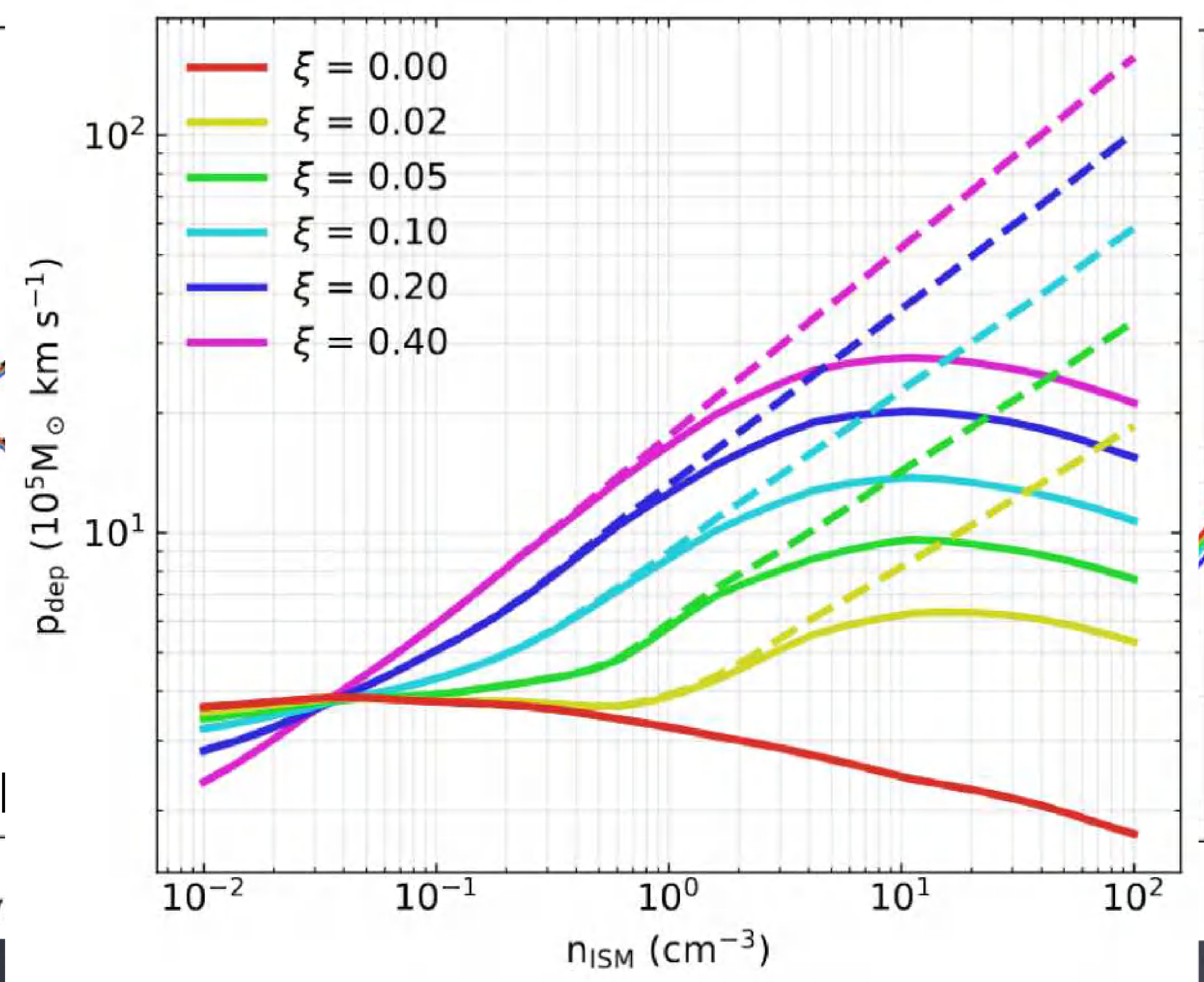
$$\frac{d\left(M_{\rm sh}\, v_{\rm SNR}\right)}{dt} = 4\pi r_{\rm SNR}^2 \left(P_{\rm hot} - P_0\right),$$

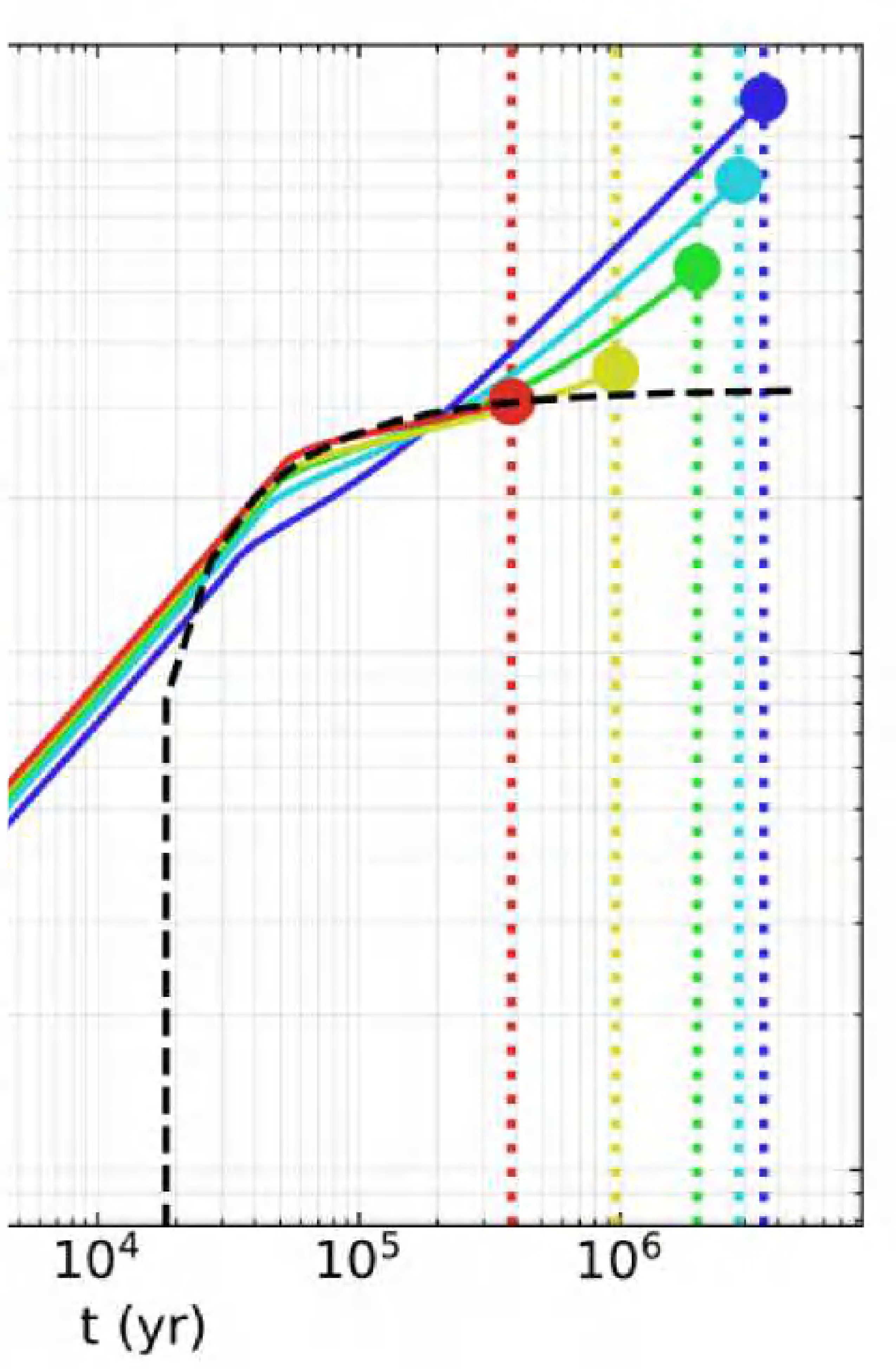
SNRs deposit energy and momentum in the ISM
Crucial for feedback that can suppress star formation

Momentum Deposition with Cosmic Rays

- SNR evolution for CR acceleration efficiency ξ (in energy): CRs do not radiate their energy away: more effective expansion!
- Thin-shell approximation reproduces the Sedov to radiative stage transition (first semi-analytical solution)
- CRs can boost the momentum deposition by factors of 2-10 for typical ISM conditions



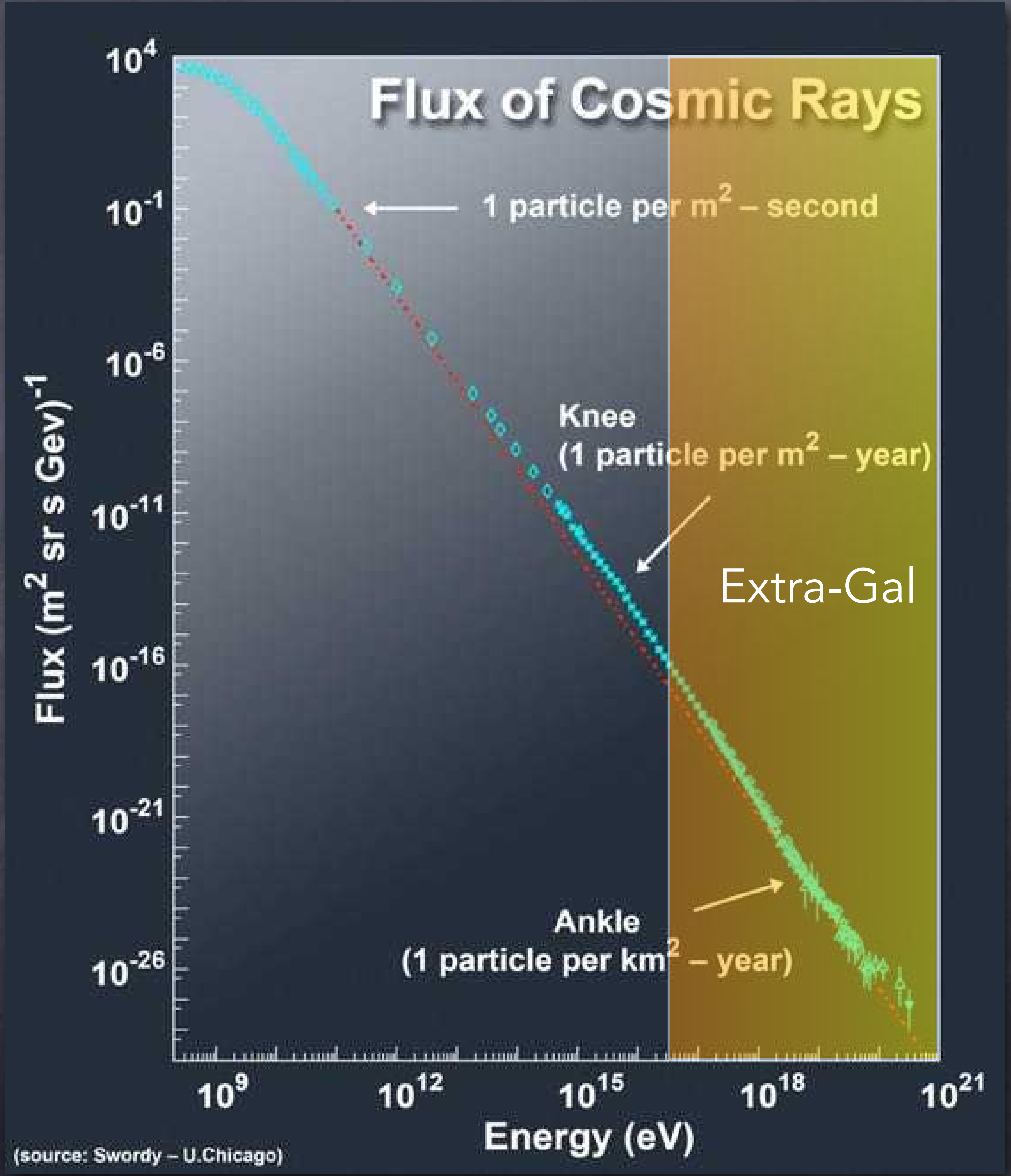




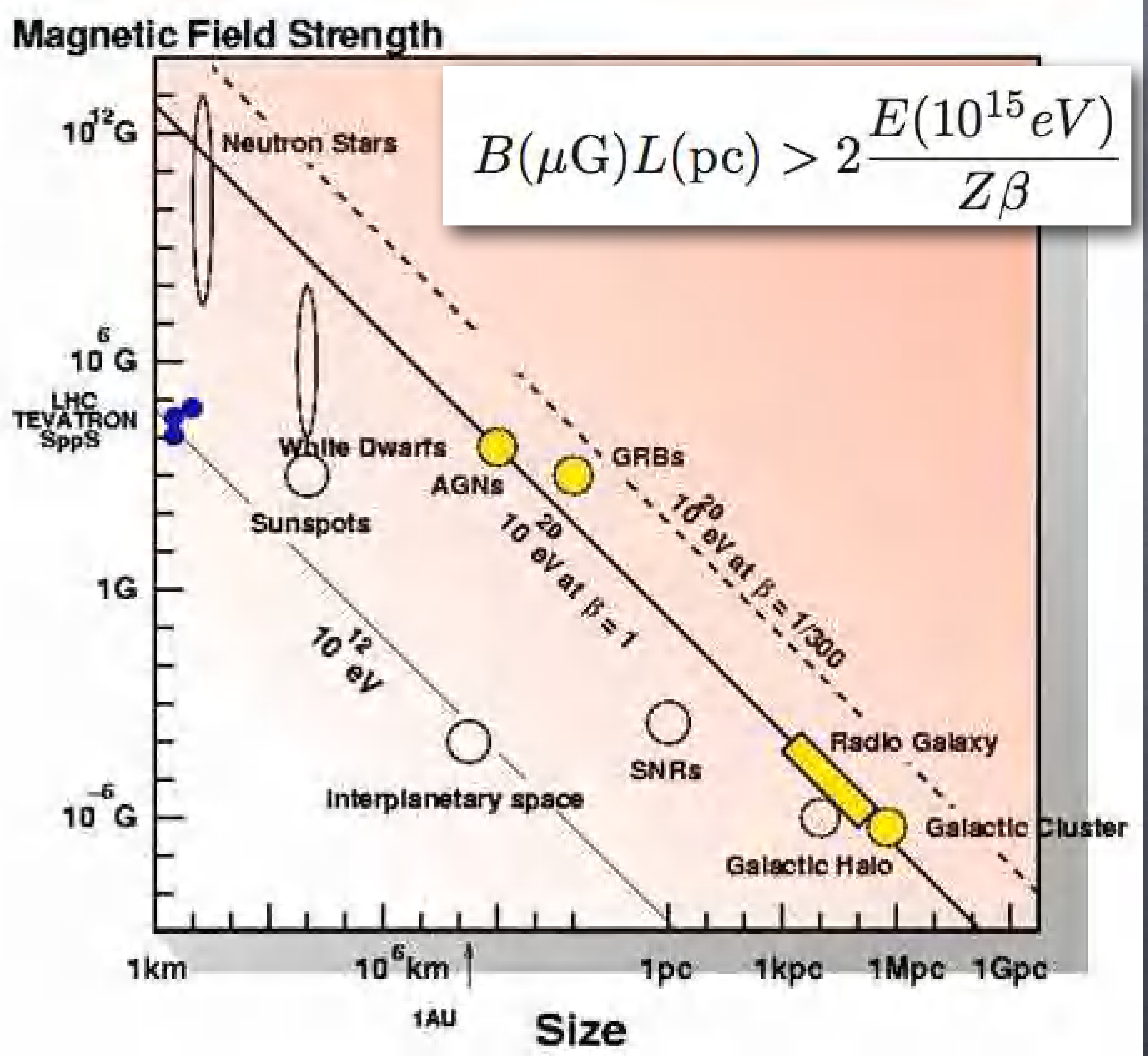
And now for something completely different…

ESPRESSO

Extra-galactic Cosmic Rays



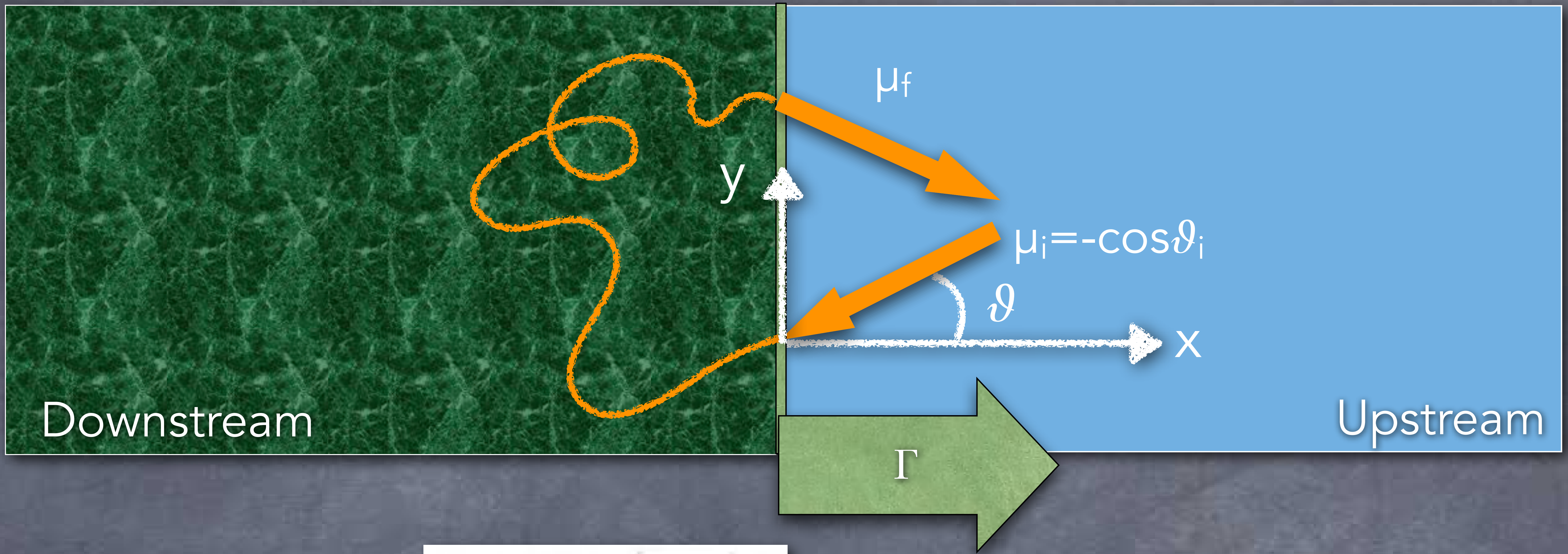
(source: Swordy – U.Chicago)



$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Sources typically involve relativistic flows

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 (e.g., gyration):

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

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

Back in the upstream:

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

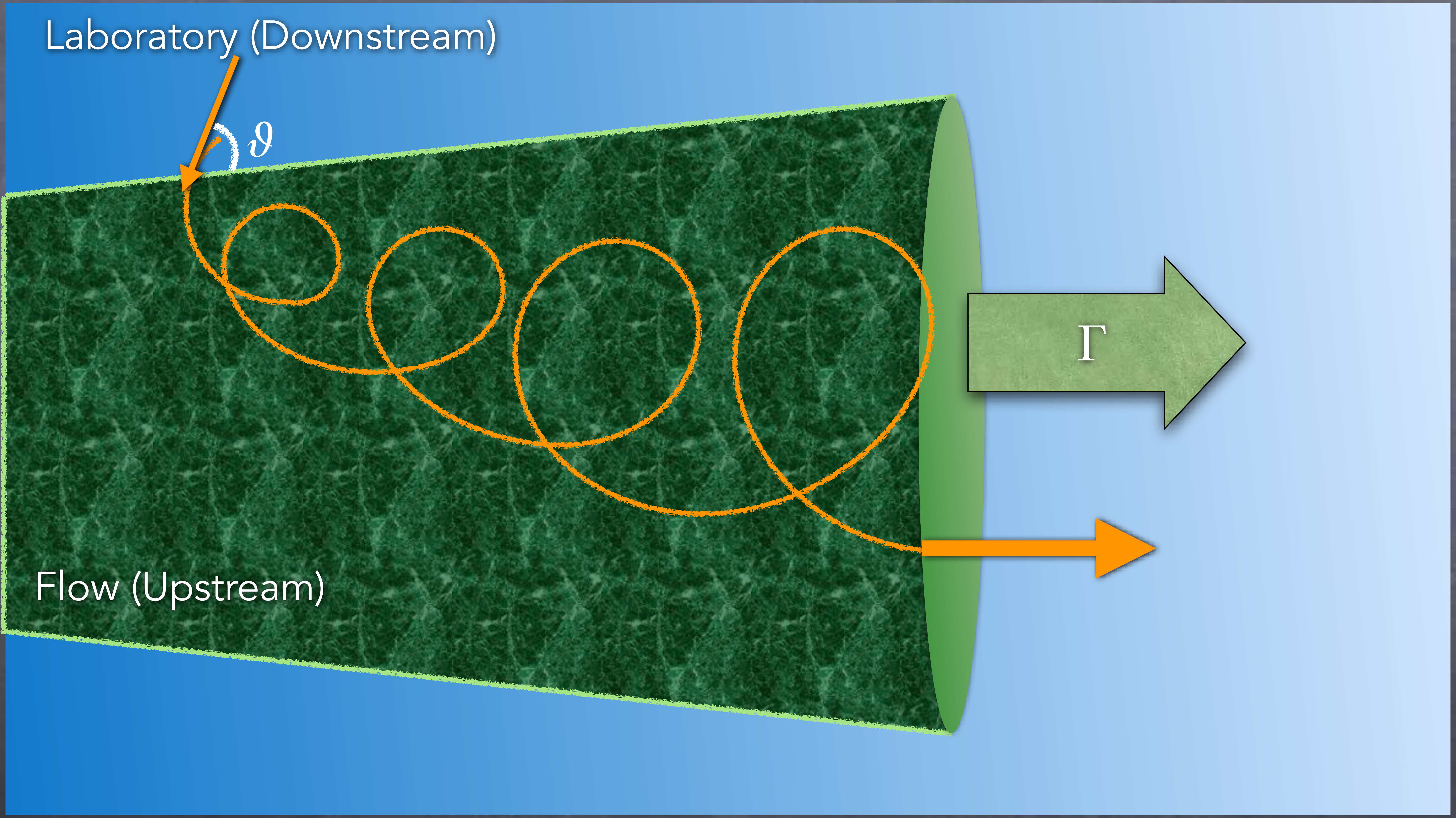
- Energy gain depends on $\mu_f - \mu_i$

First cycle: $E_f \sim \Gamma^2 E_i$ (~Compton scattering)

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

Acceleration in Relativistic FLOWS

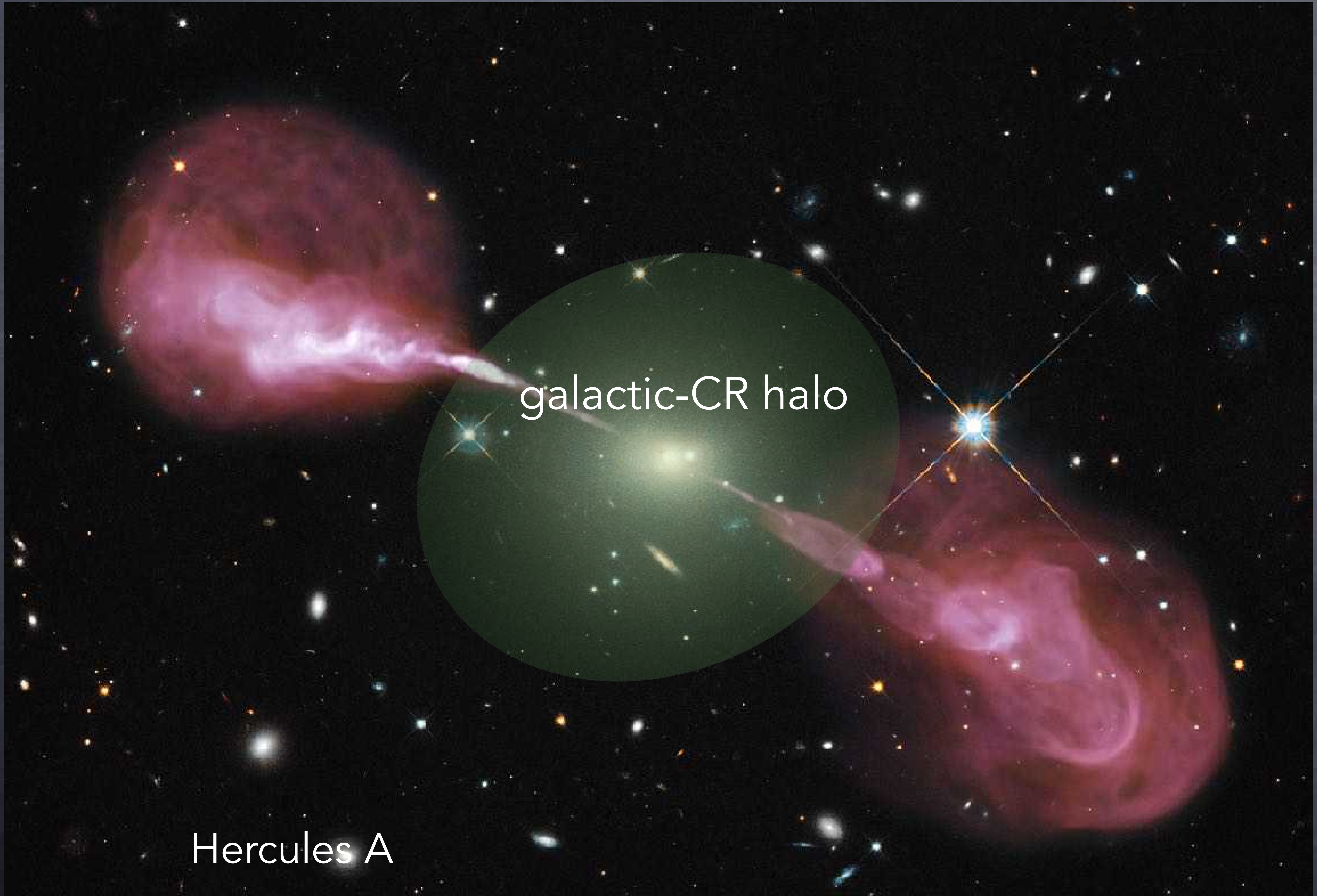
- **Requirement**: interface thickness << gyroradius << typical flow size



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

Espresso Acceleration of UHECRs

- **SEEDS:** galactic CRs with energies up to ~3Z PeV
- **STEAM:** AGN jets with Γ up to 20-30



ONE-SHOT

reacceleration can produce UHECRs up to

$E_{max} \sim 2\Gamma^2\, 3Z$ PeV

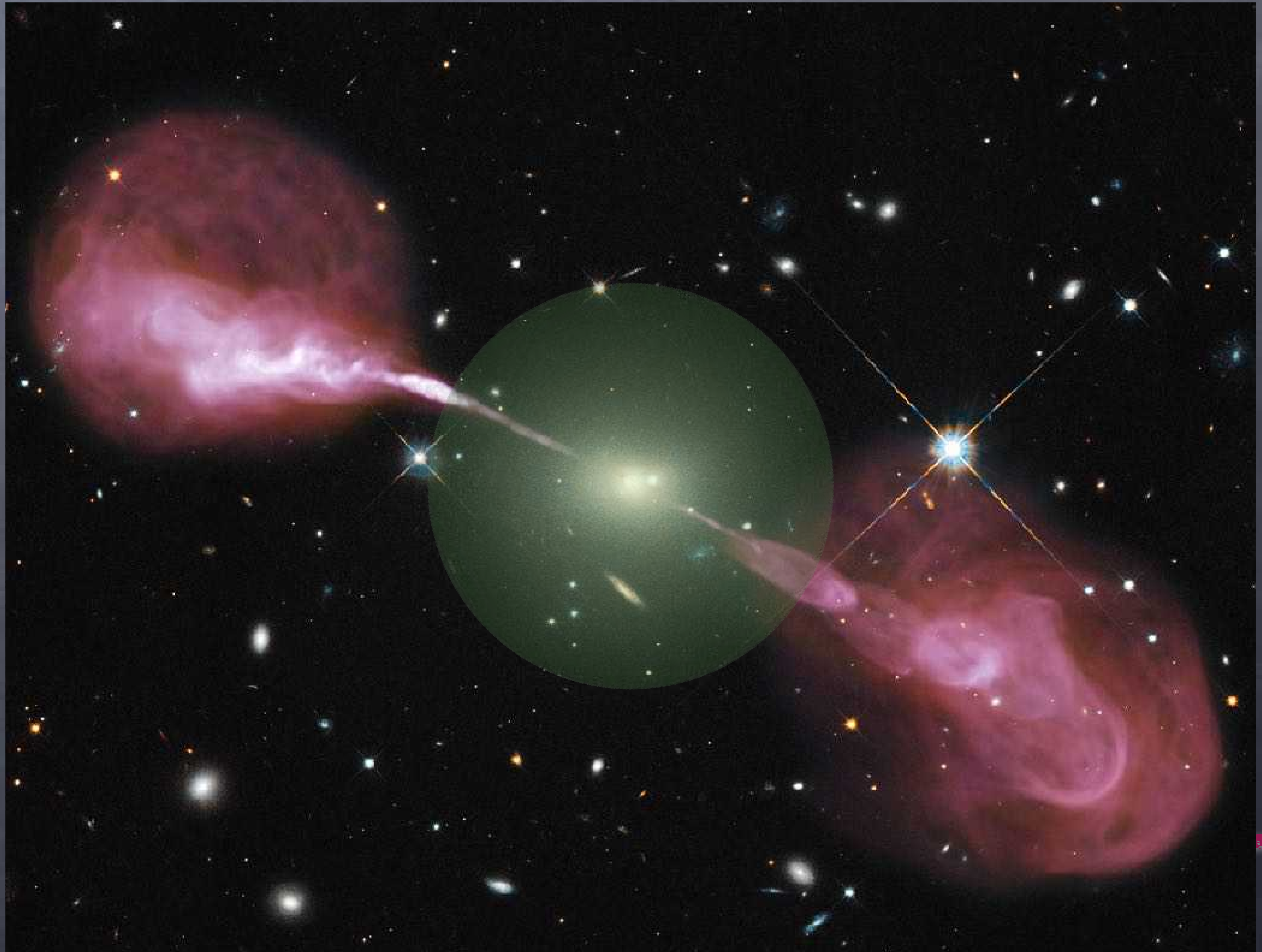
$E_{max} \sim 5Z\text{x}10^9$ GeV

UHECRs from AGN jets: constraints

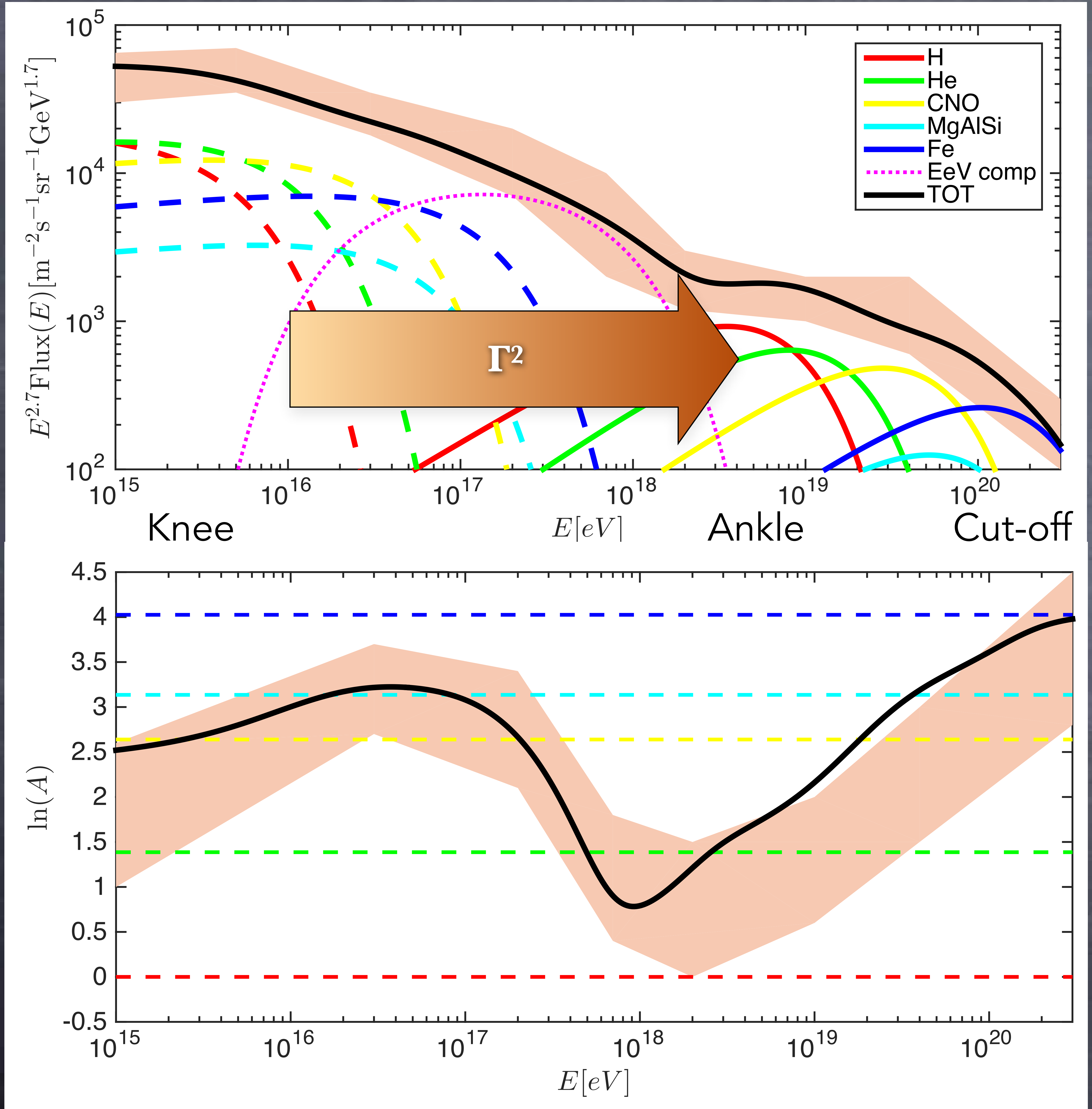
- Confinement (Hillas Criterion): $B_{\mu G} D_{\rm kpc} \gtrsim \frac{4}{Z_{26}} \frac{E_{\max}}{10^{20}{\rm eV}}$ ✓
- Energetics: $Q_{\rm UHECR}(E \gtrsim 10^{18}{\rm eV}) \approx 5{\rm x}10^{45}{\rm erg/Mpc^3/yr}$

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

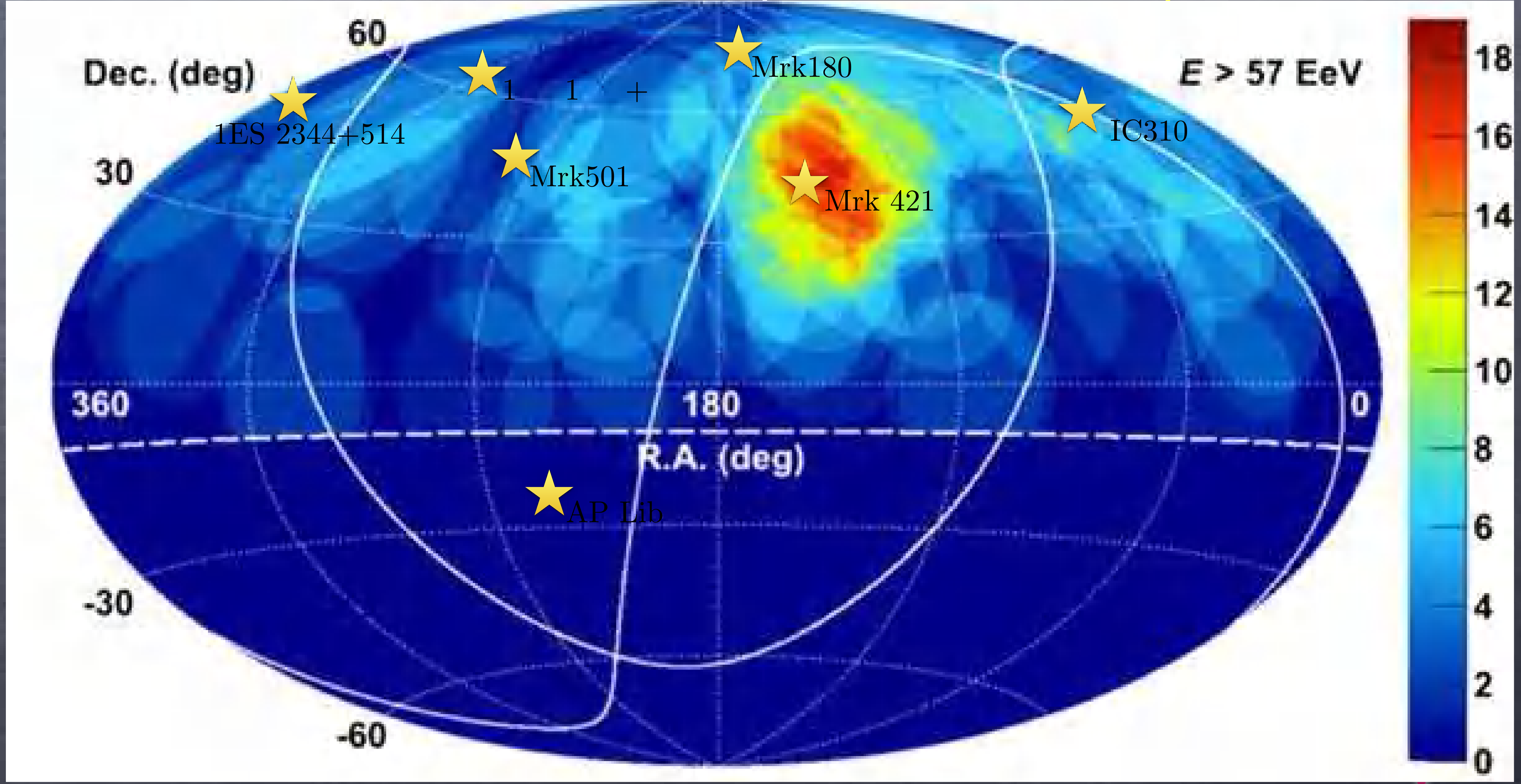
  $Q_{\rm AGN} \approx$ a few 10^{46}-$10^{48}{\rm erg/Mpc^3/yr} >> Q_{\rm UHECR}$ ✓
- Efficiency depends on:
  - Reacceleration efficiency ($\varepsilon >\sim 10^{-4}$)
  - Jet cross section
    (angle of a few degrees: $\varepsilon \sim 10^{-1}$-10^{-2})
  - Contributing AGNs
    - Likely radio-loud quasars, blazars, FR-I,..



Galactic CR + UHECR spectrum



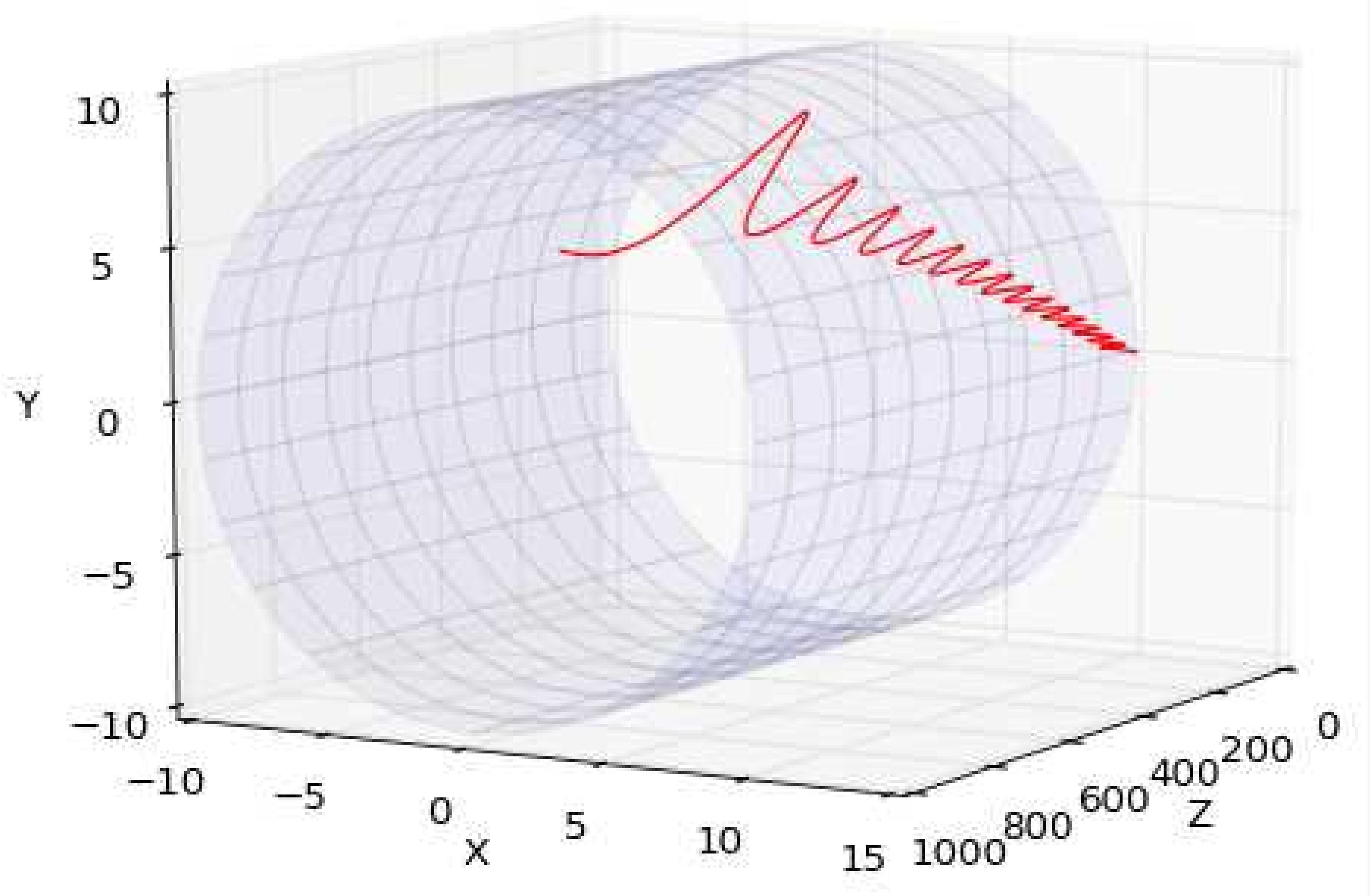
- Prediction of UHECR chemical composition!
  - UHECR spectra must be quite flat, ~$E^{-1.5}$ (Aloisio+13, Gaisser+13, Taylor 14,…)
- Different kinds of AGNs?
- Mrk 421 in the Telescope Array hotspot!

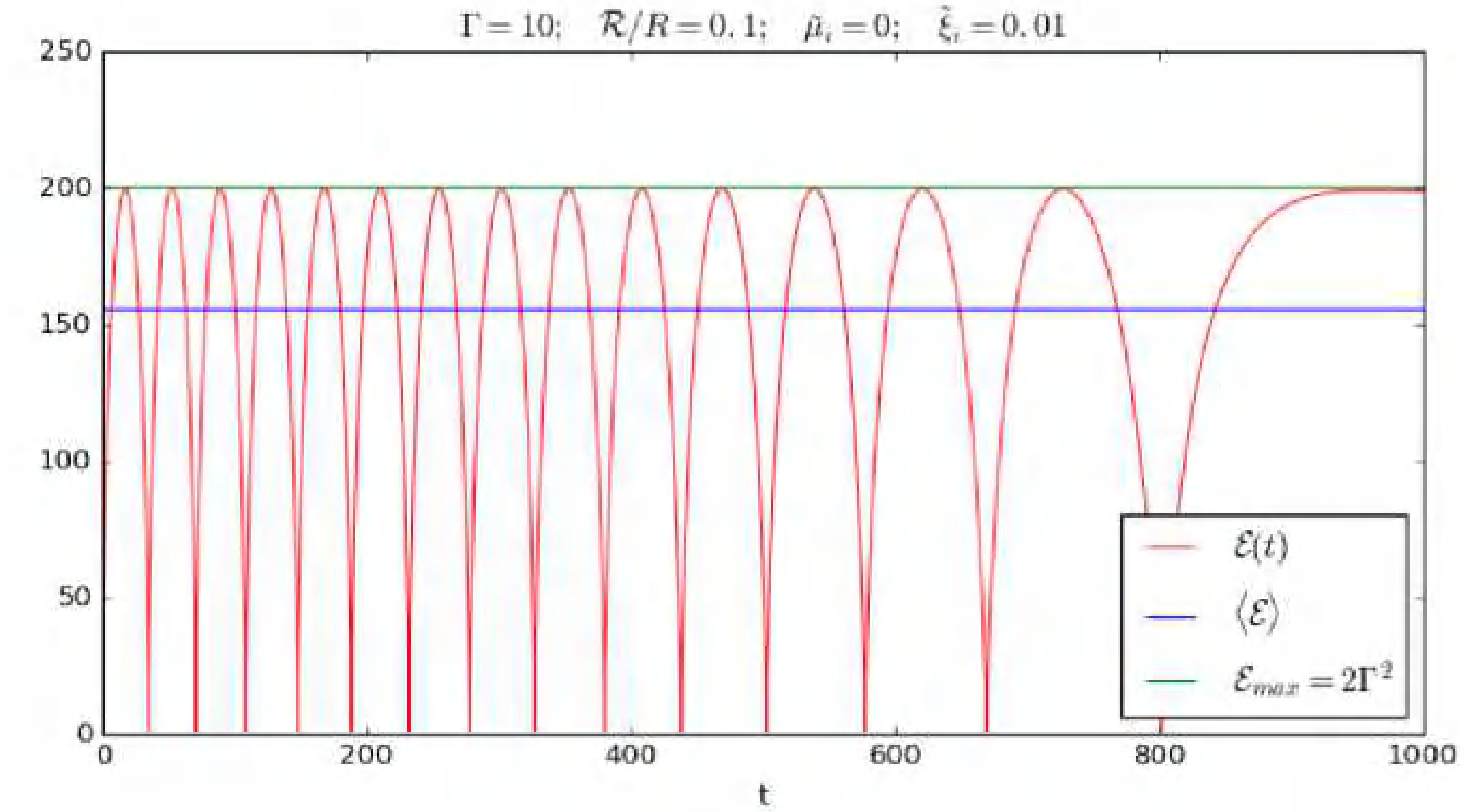


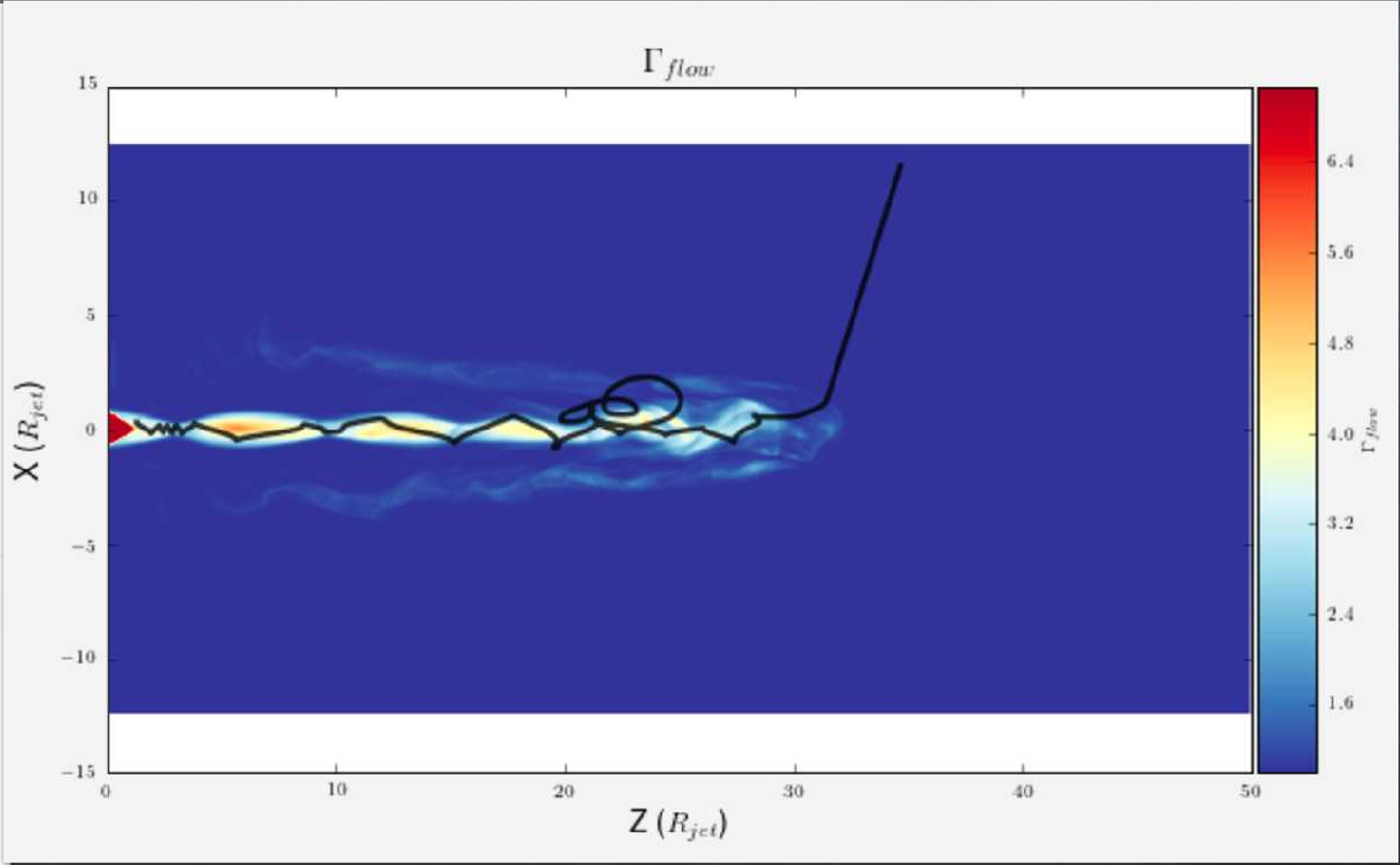
DC, 2015, 2016

Testing *Espresso* Acceleration

- Propagation in synthetic jets and in 3D MHD sims (DC 2016; DC & Mbarek, in prog)



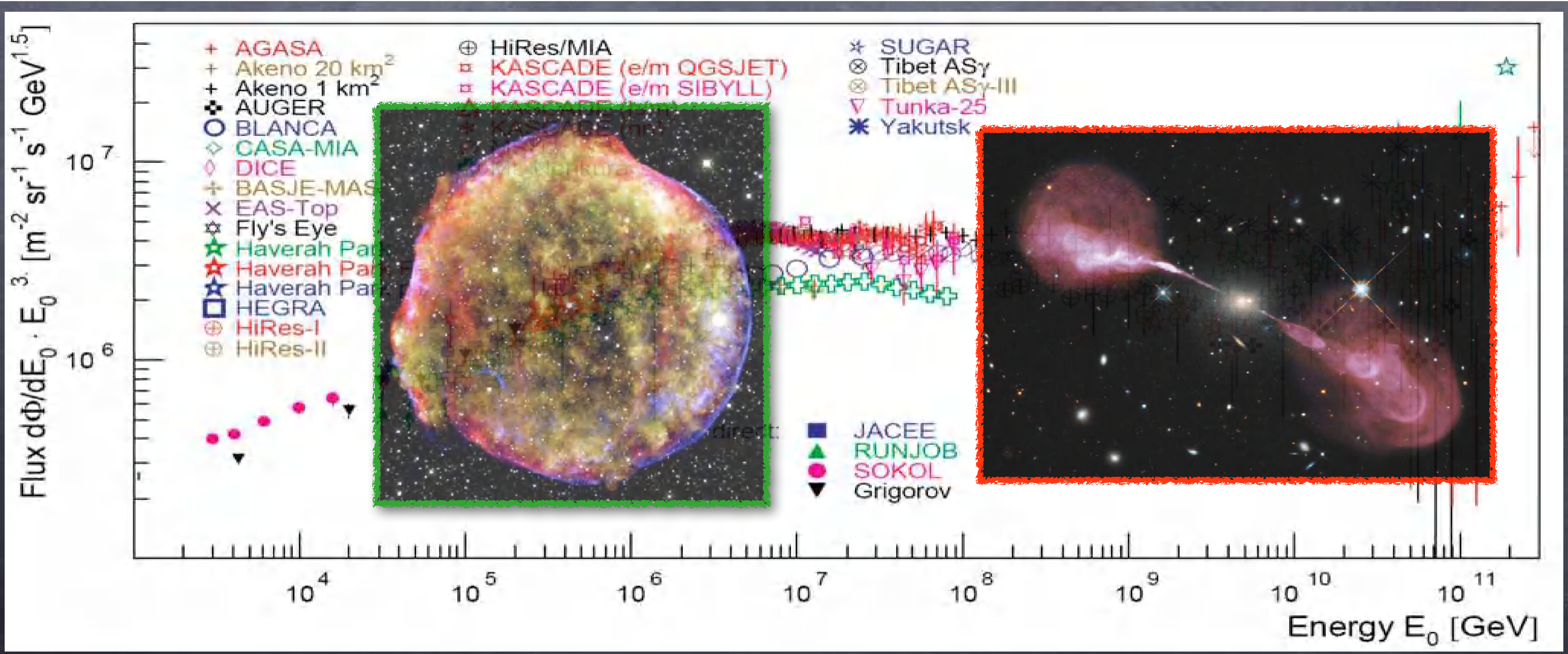




Espresso works! Even a few shots: $E_f/E_i \sim \Gamma^4$-Γ^6!

A Summary

Origin	Source	Mechanism	E_{max}	Spectrum	Evidence
Galactic	SNRs	Diffusive Acceleration at non-rel shocks	$3Z \times 10^6$ GeV	Universal $\sim E^{-2}$	gamma rays e.g., Tycho
Extragal	AGNs	Espresso in rel flows?	$5Z \times 10^9$ GeV	Galactic, boosted	Anisotropy? Neutrinos?



The Astroplasmas Group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Benedikt Schroer


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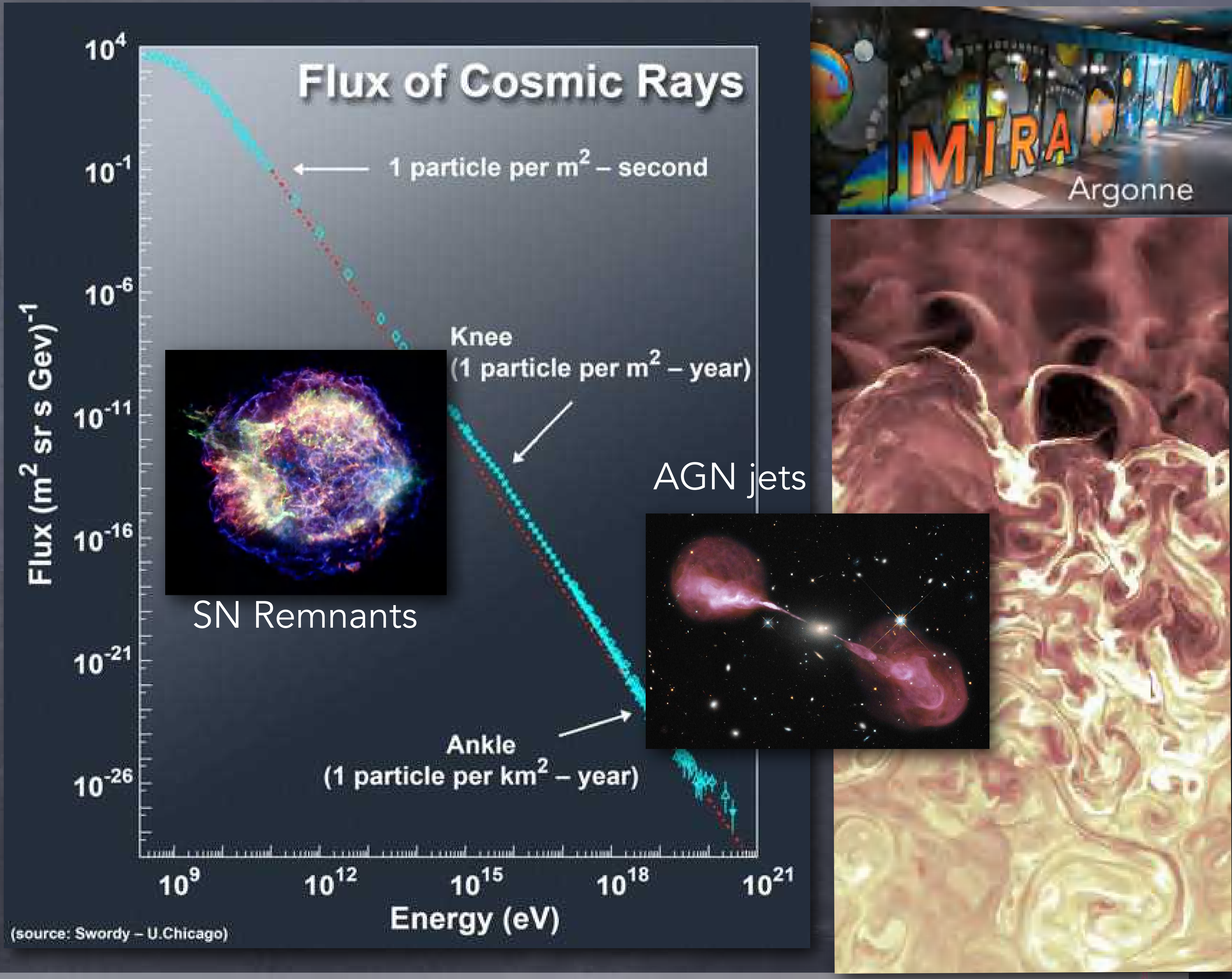
Thomas Fitzpatrick


Nick Corso


Naixin Liang


Mayur Sharma

- Origin of cosmic rays and magnetic fields
- Kinetic plasma simulations (with supercomputers!)



(source: Swordy – U.Chicago)

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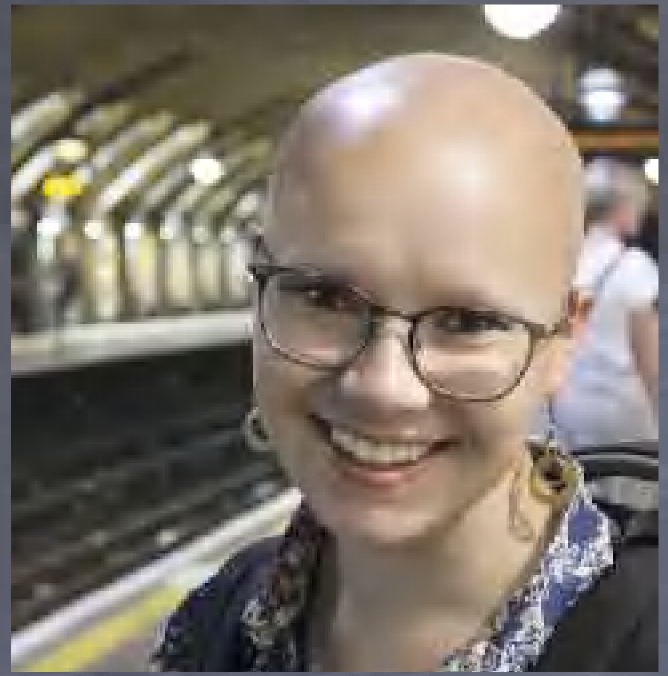
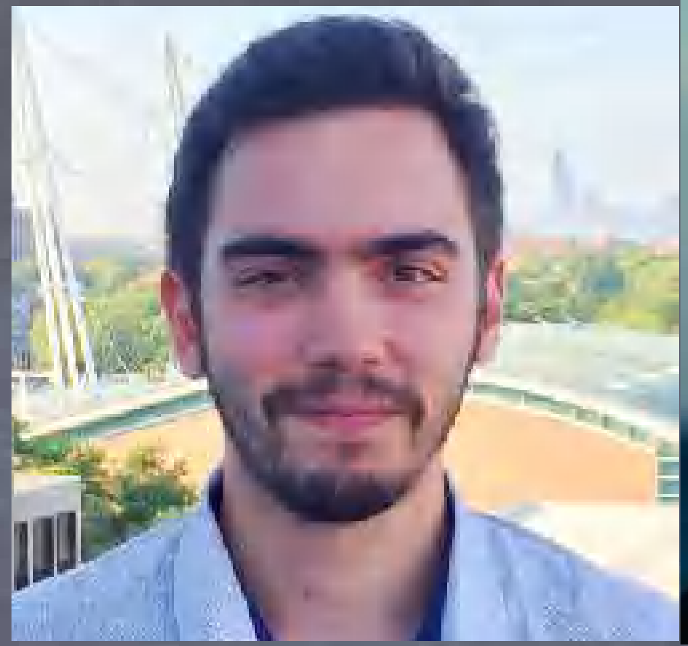

Rebecca Diesing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