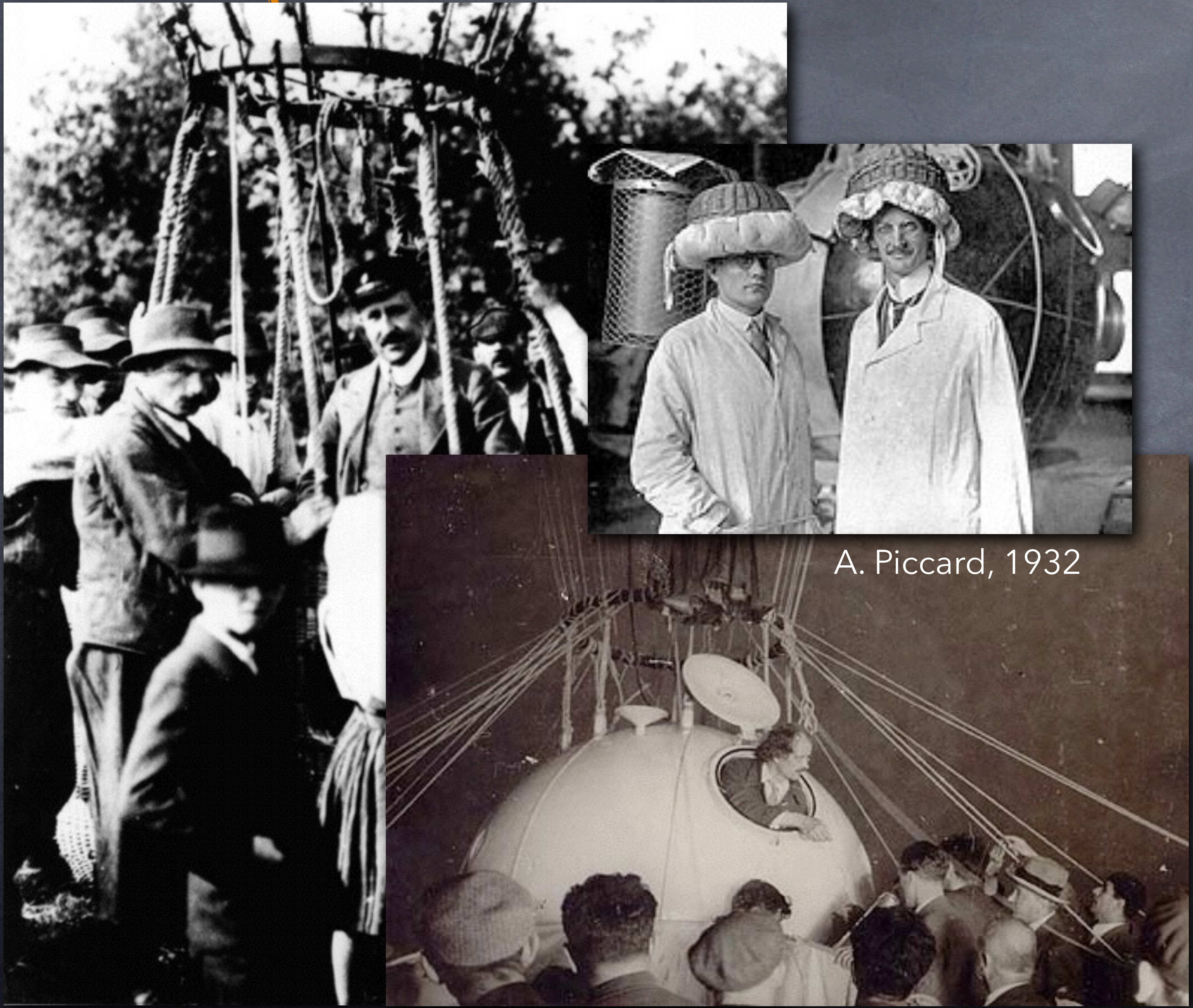
ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Acceleration and Propagation of Cosmic Rays

Damiano Caprioli
Princeton University

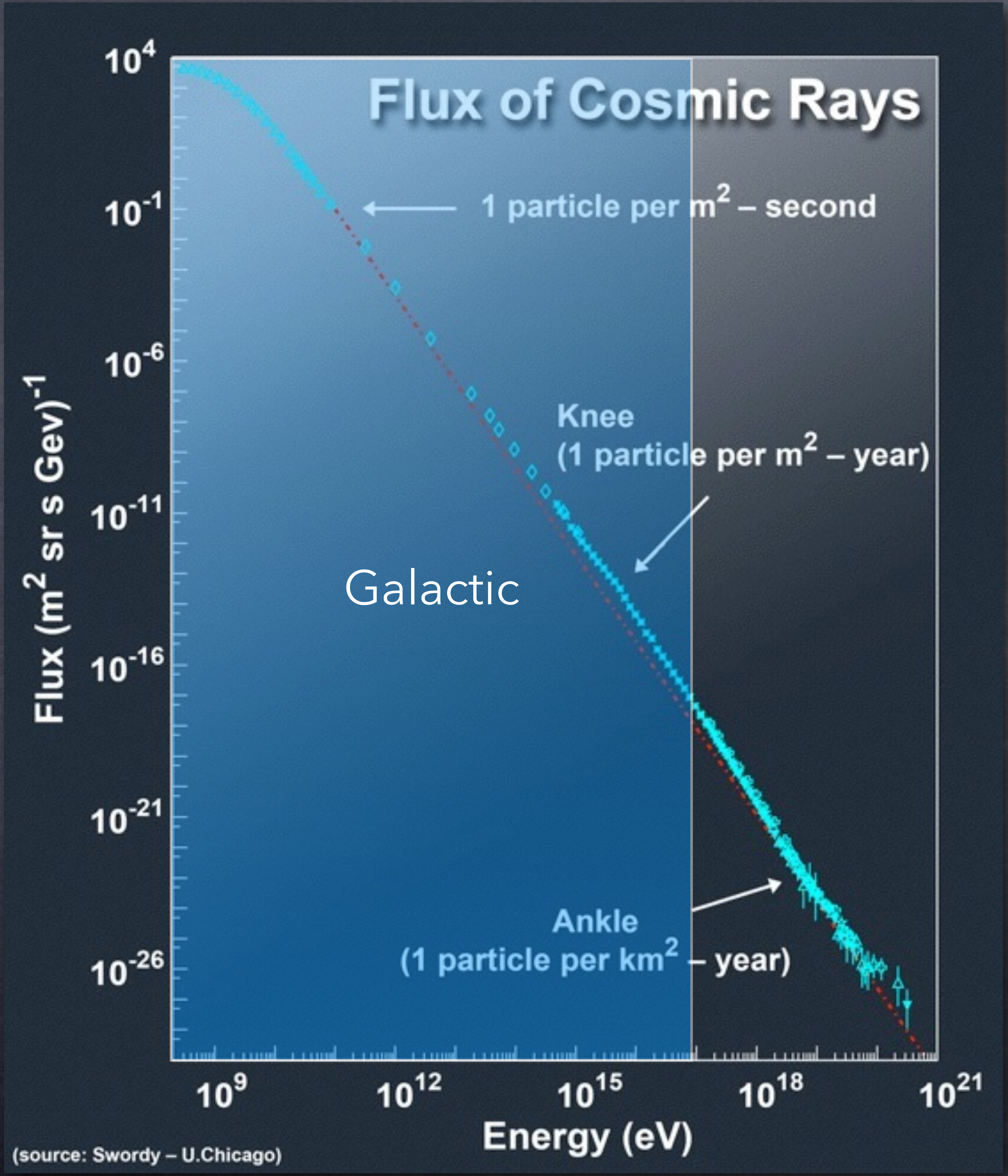
An extraterrestrial radiation!

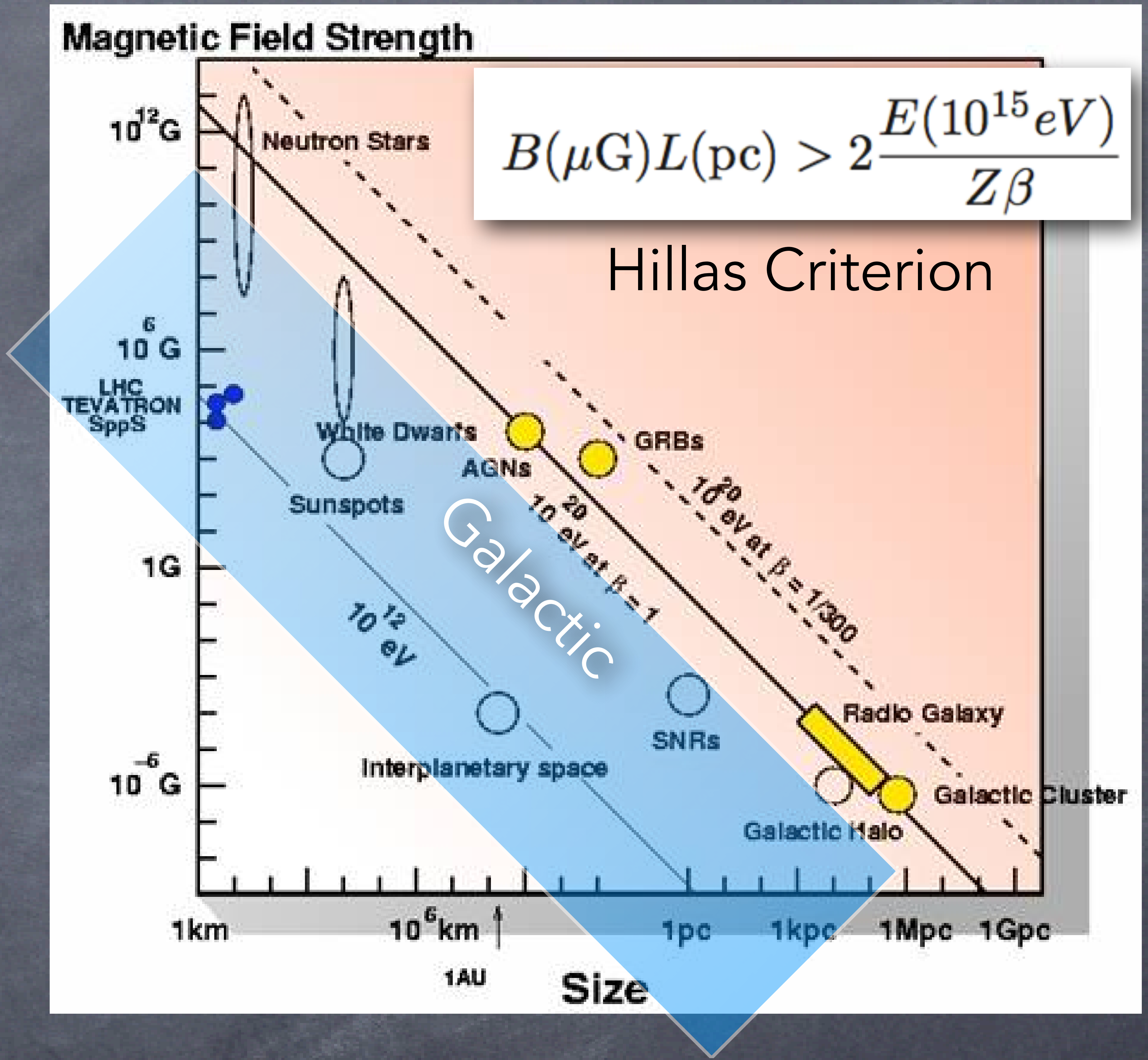


A. Piccard, 1932

- 1912: V. Hess discovers an extraterrestrial source of ionization: Cosmic Rays
- 1932: A. Piccard reaches the stratosphere (in a pressurized aluminum gondola attached to a ballon) to measure CRs!
- 1940: B. Rossi and P. Auger measure Extensive Air Showers up to ~10^5 GeV

Galactic Cosmic Rays





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

Hillas Criterion

- Remarkable power-law (see P. Serpico's talk)
- The steepening at ~3PeV suggests a rigidity-dependent cut-off

A universal acceleration mechanism

- Fermi mechanism (Fermi, 1954): random elastic collisions lead to energy gain
- In shocks, particles gain energy at any interaction (Krymskii 1977; Blandford & Ostriker; Bell; Axford et al.; 1978)

Diffusive Shock Acceleration (DSA)

Downstream (post-shock) Upstream (pre-shock)

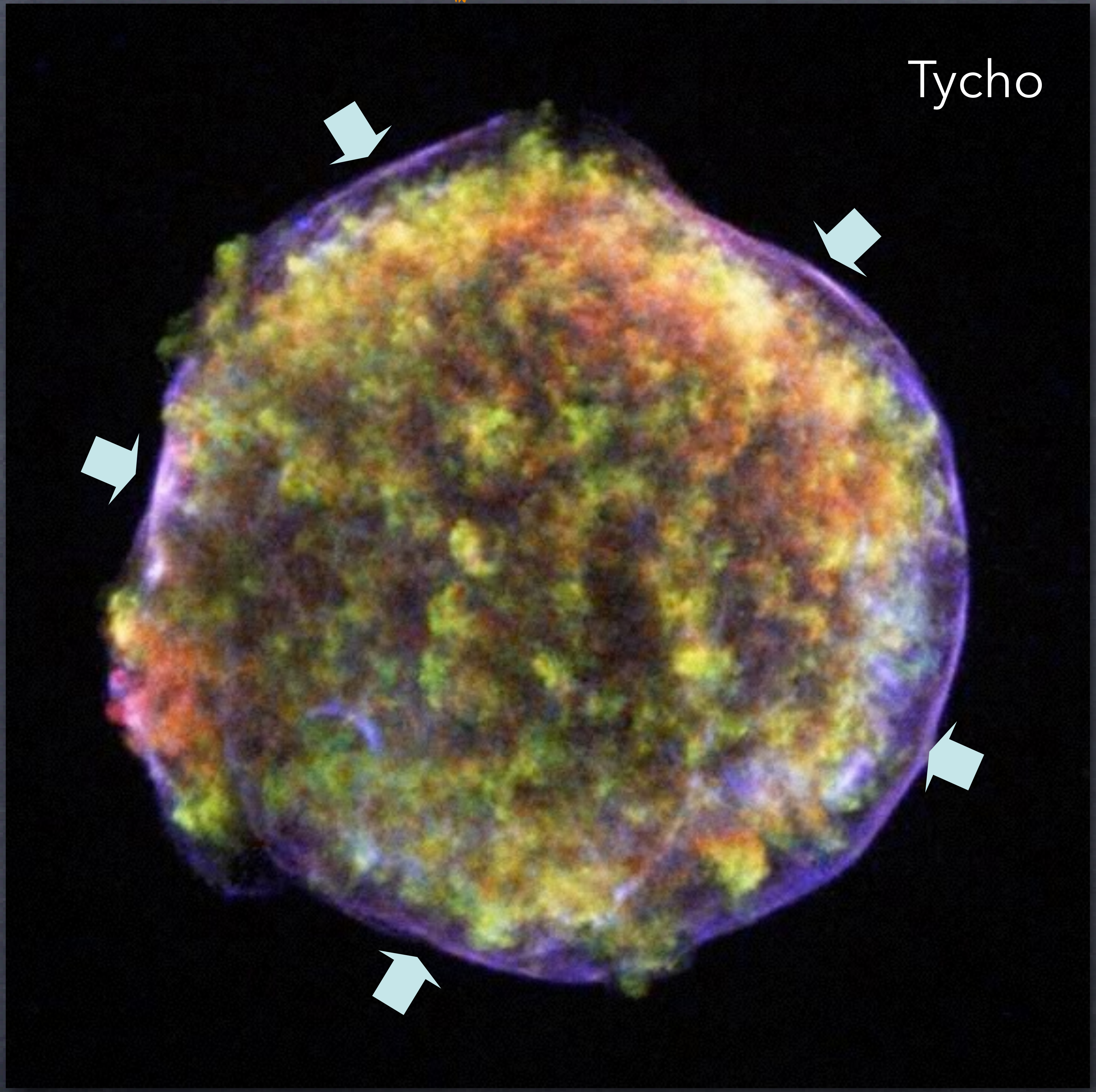
Test-particle squeezed between converging flows

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

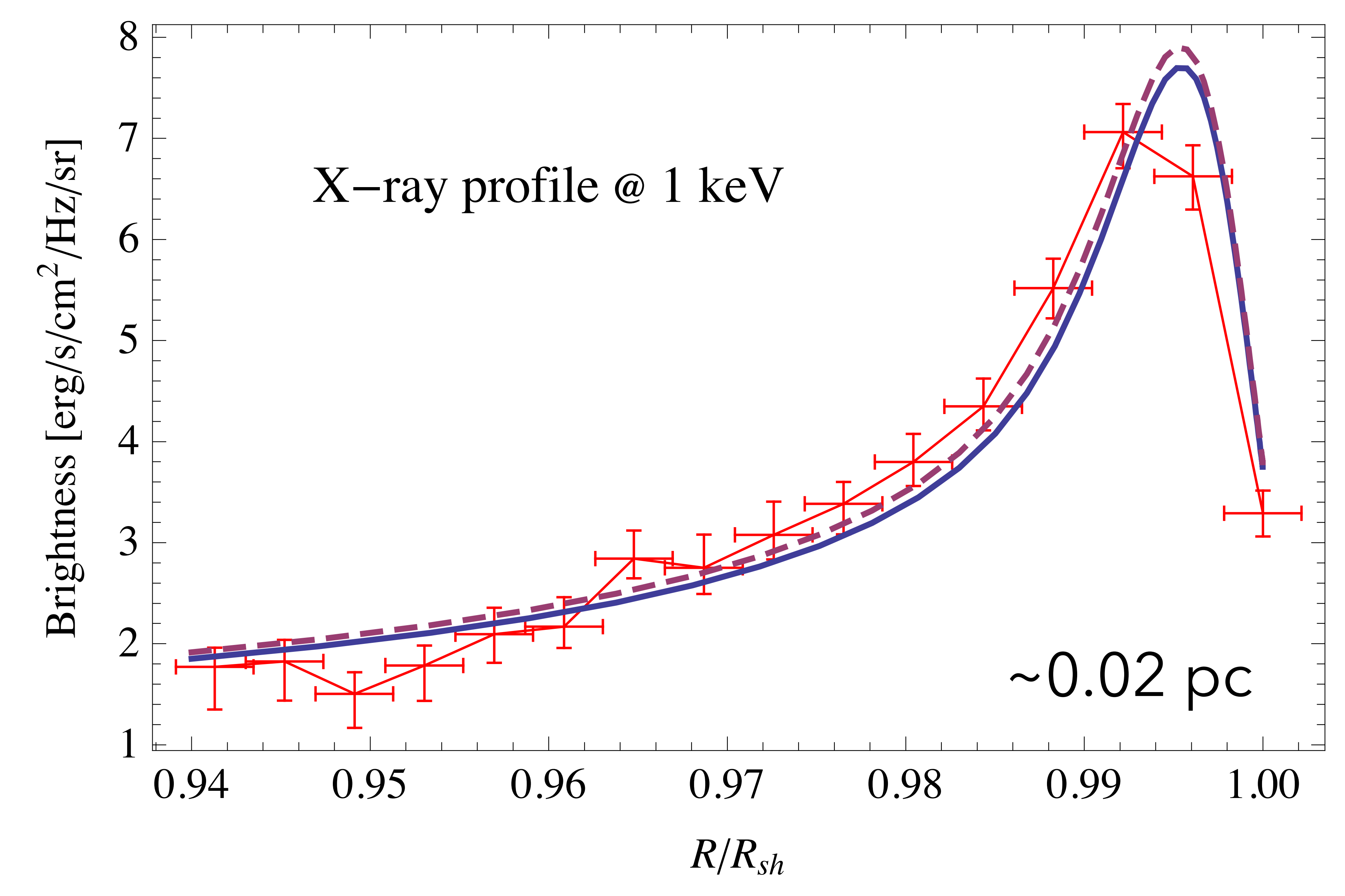
$$\boxed{R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}}$$

  - For strong shocks (Mach number $M_s>>1$): $R=4$ and $\alpha=4$

Evidence of magnetic field amplification



- Narrow (non-thermal) X-ray rims due to synchrotron losses of multi-TeV electrons…
- …in fields as large as B∼100-500μG



Völk et al, 2005…;
Warren et al, 2005;
Parizot et al., 2006;
Uchiyama et al. 2007;
Cassam-Chenaï et al. 2008;
Zirakashvili & Aharonian 2009;
Morlino et al. 2010;
Morlino & DC 2012;
Slane et al. 2014;
Ressler et al. 2014;
Tran et al. 2015;…

- Amplification due to CR-driven plasma instabilities

SNR paradigm: Conclusions?

- SNRs have the right energetics
- Diffusive Shock Acceleration produces power-laws
- B amplification enhances particle diffusion

BUT

- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- When is acceleration efficient?
- How are particles injected?

Collisionless shocks

- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity
- Now studied in laboratory with laser experiments!

Astroplasmas from first principles

- Full particle in cell approach

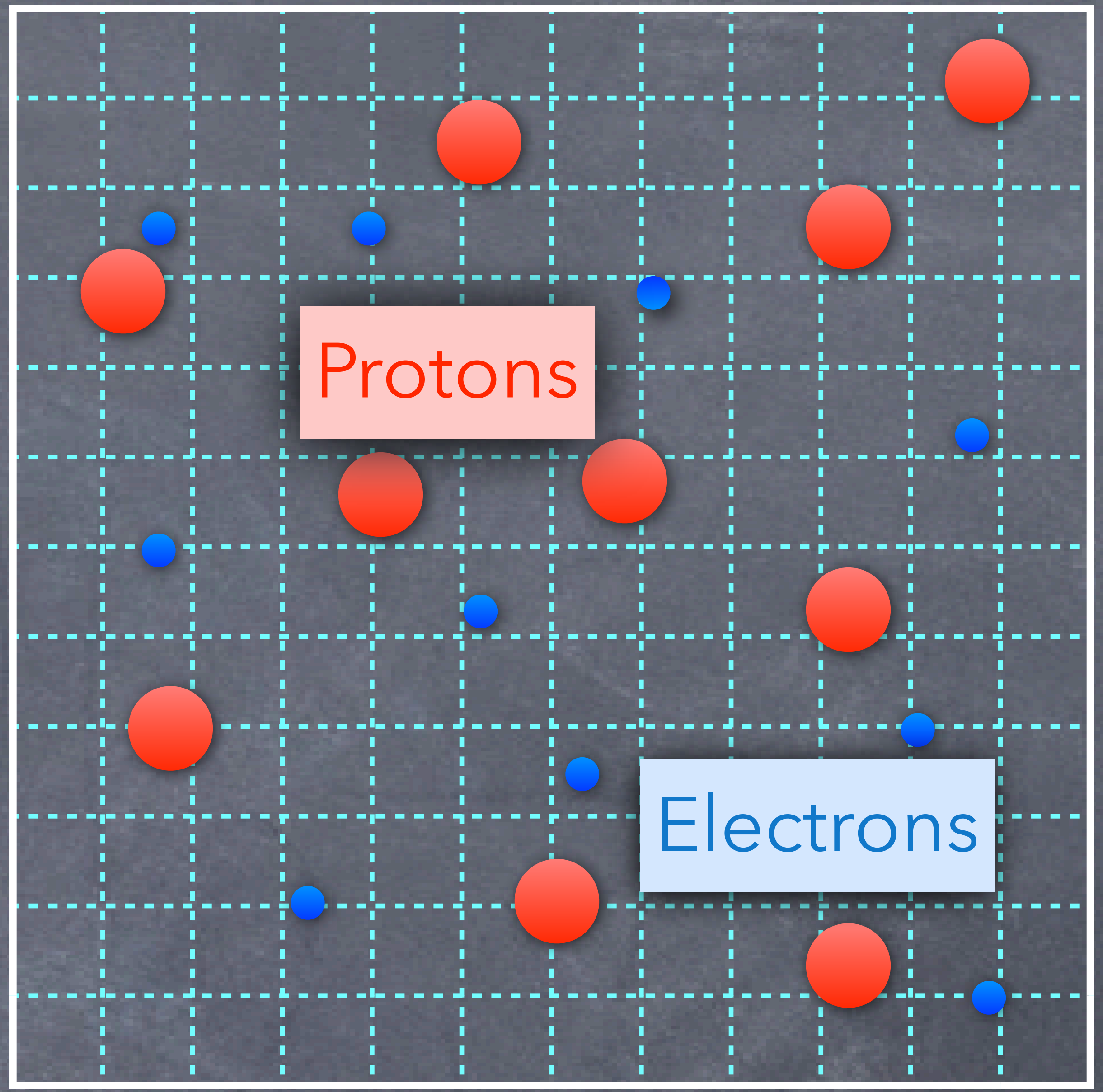
  (…, Spitkovsky 2008; Amano & Hoshino 2007, 2010; Niemiec et al. 2008, 2012; Stroman et al. 2009; Riquelme & Spitkovsky 2010; Park et al. 2012; Guo et al. 2014; DC et al. 2015…)

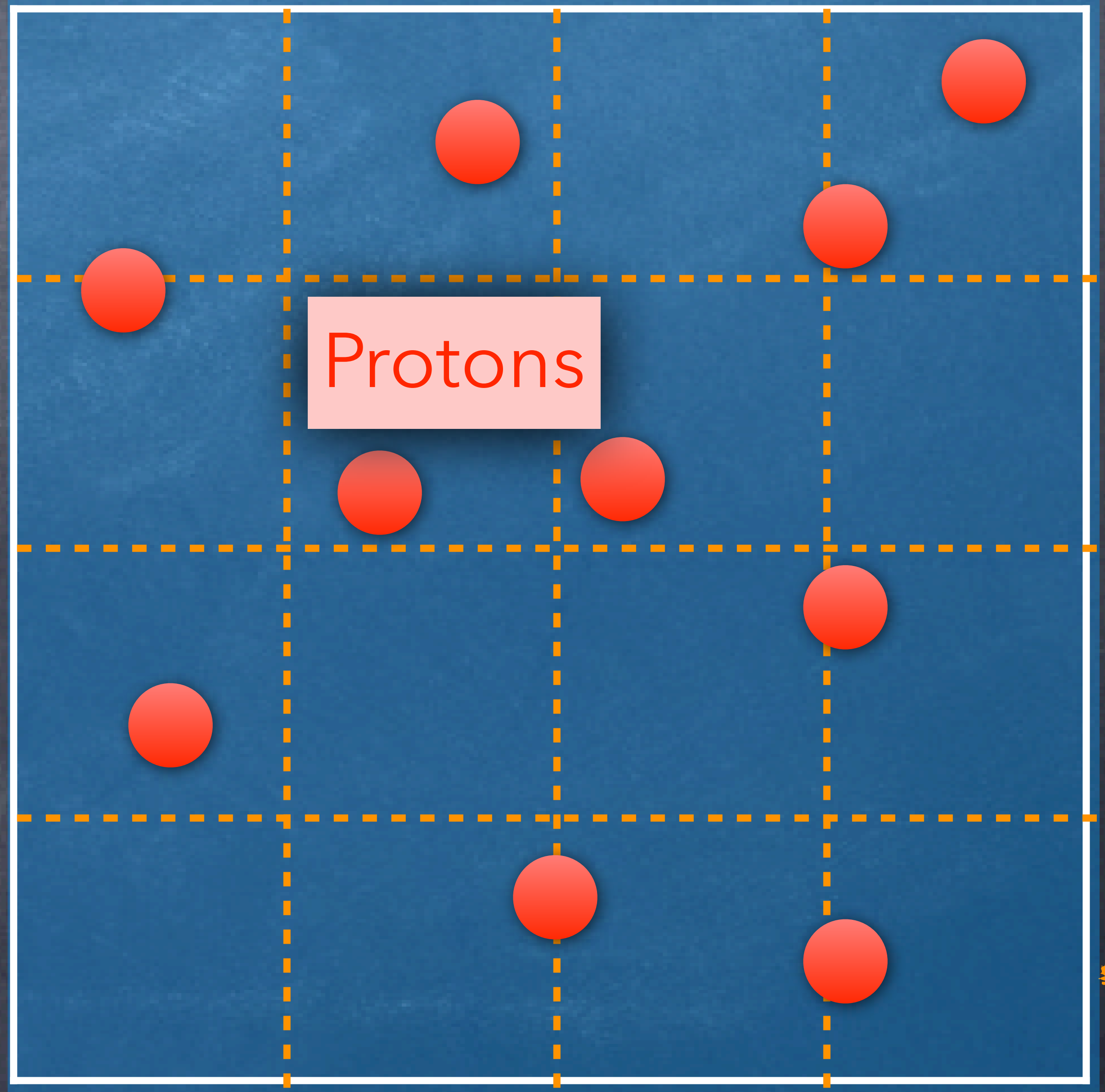
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!

- Hybrid approach: Fluid electrons - Kinetic protons

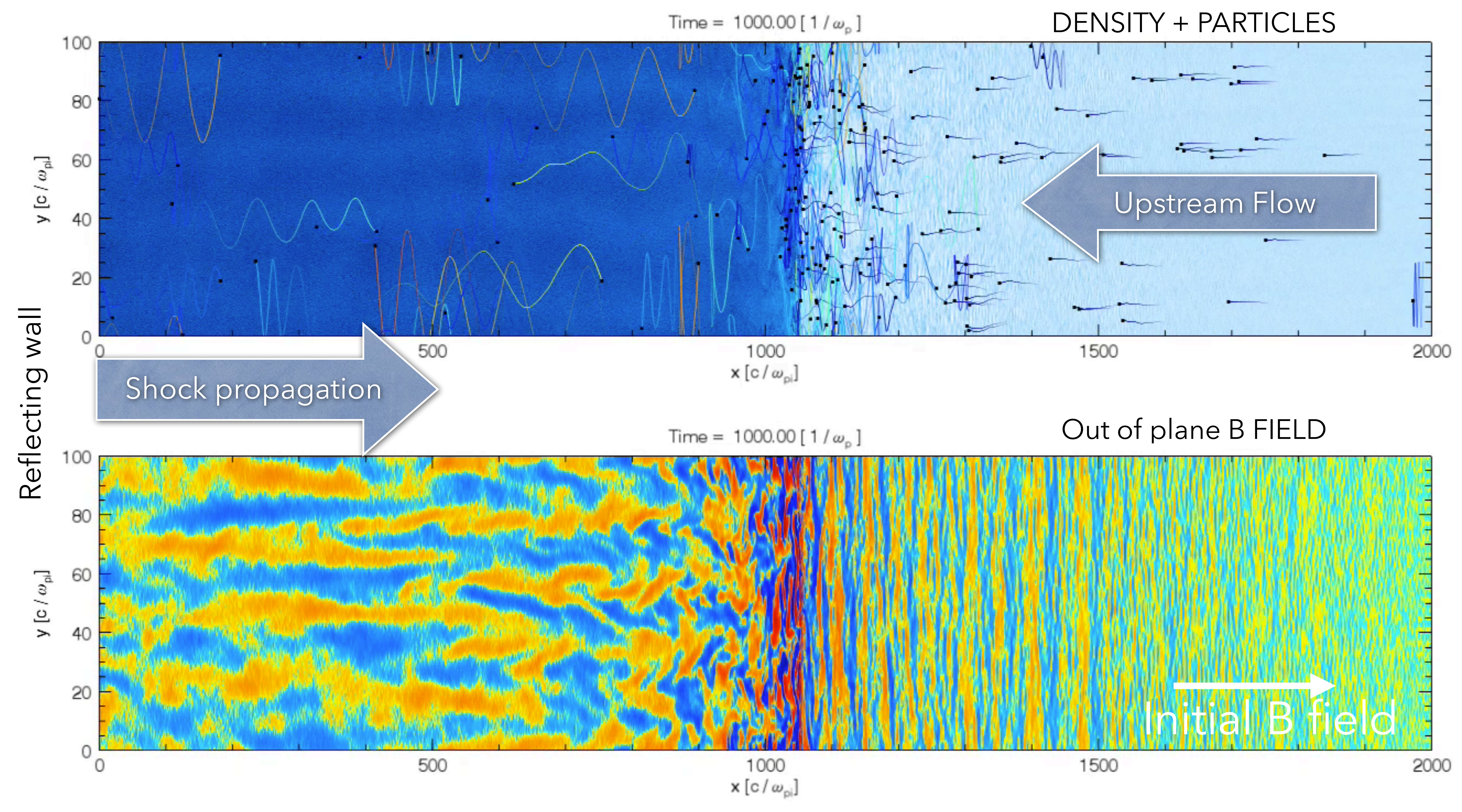
  (Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015,…)

  - massless electrons for more macroscopical time/length scales





Hybrid simulations of collisionless shocks

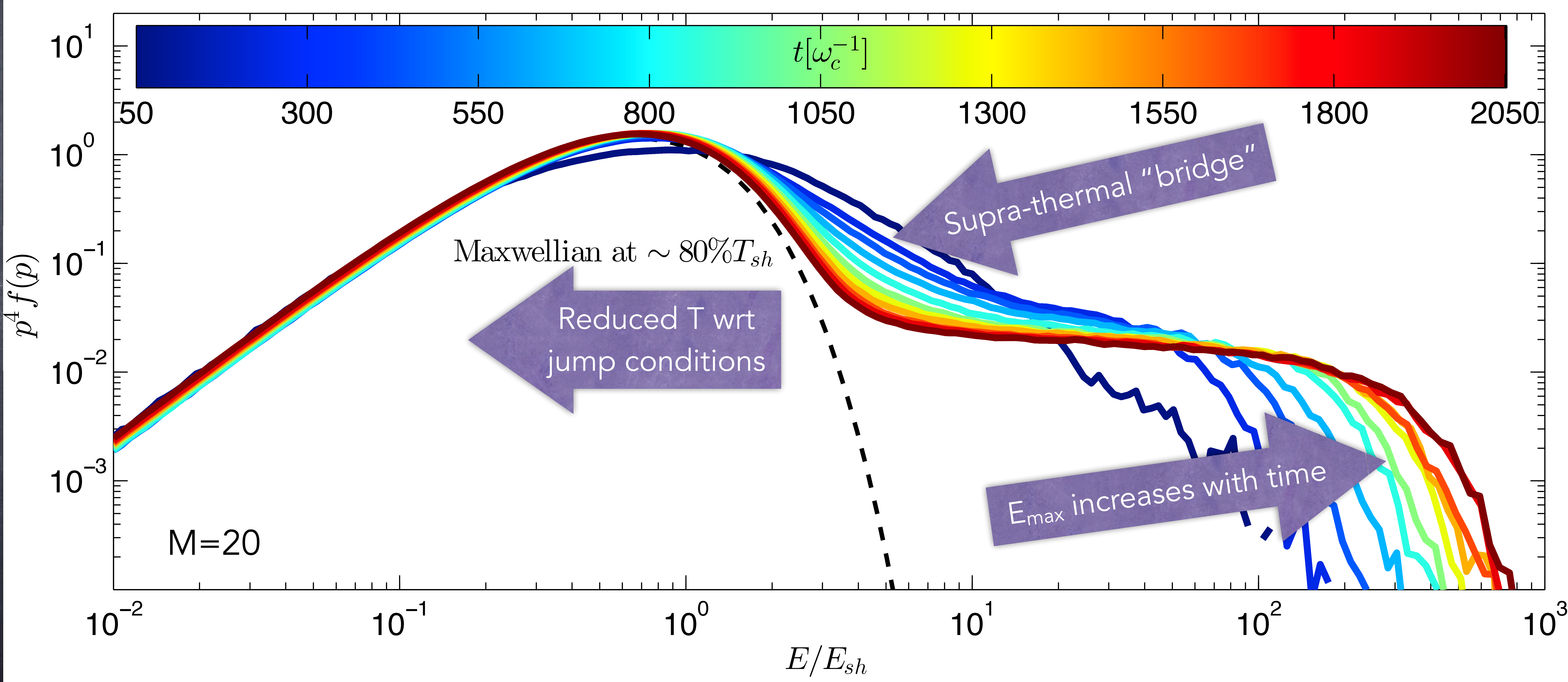


dHybrid code (Gargaté et al, 2007; DC & Spitkovsky 2014)

Spectrum evolution

- Diffusive Shock Acceleration: non-thermal tail with universal spectrum f(p)∝p^{-4}
- Acceleration efficiency: ~15% of the shock bulk energy!

Downstream Spectrum



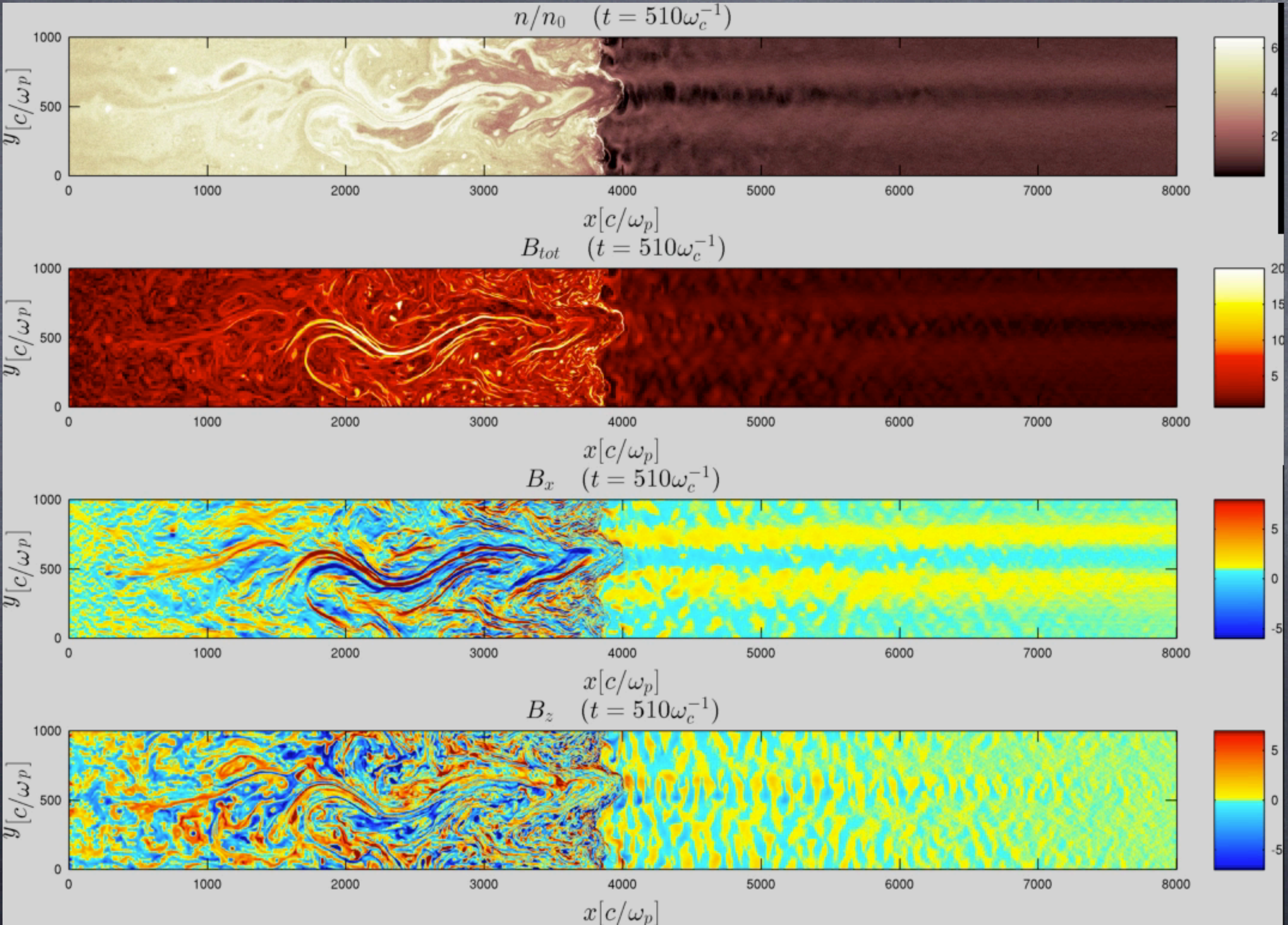
DC & Spitkovsky, 2014a

CR-driven instability

→

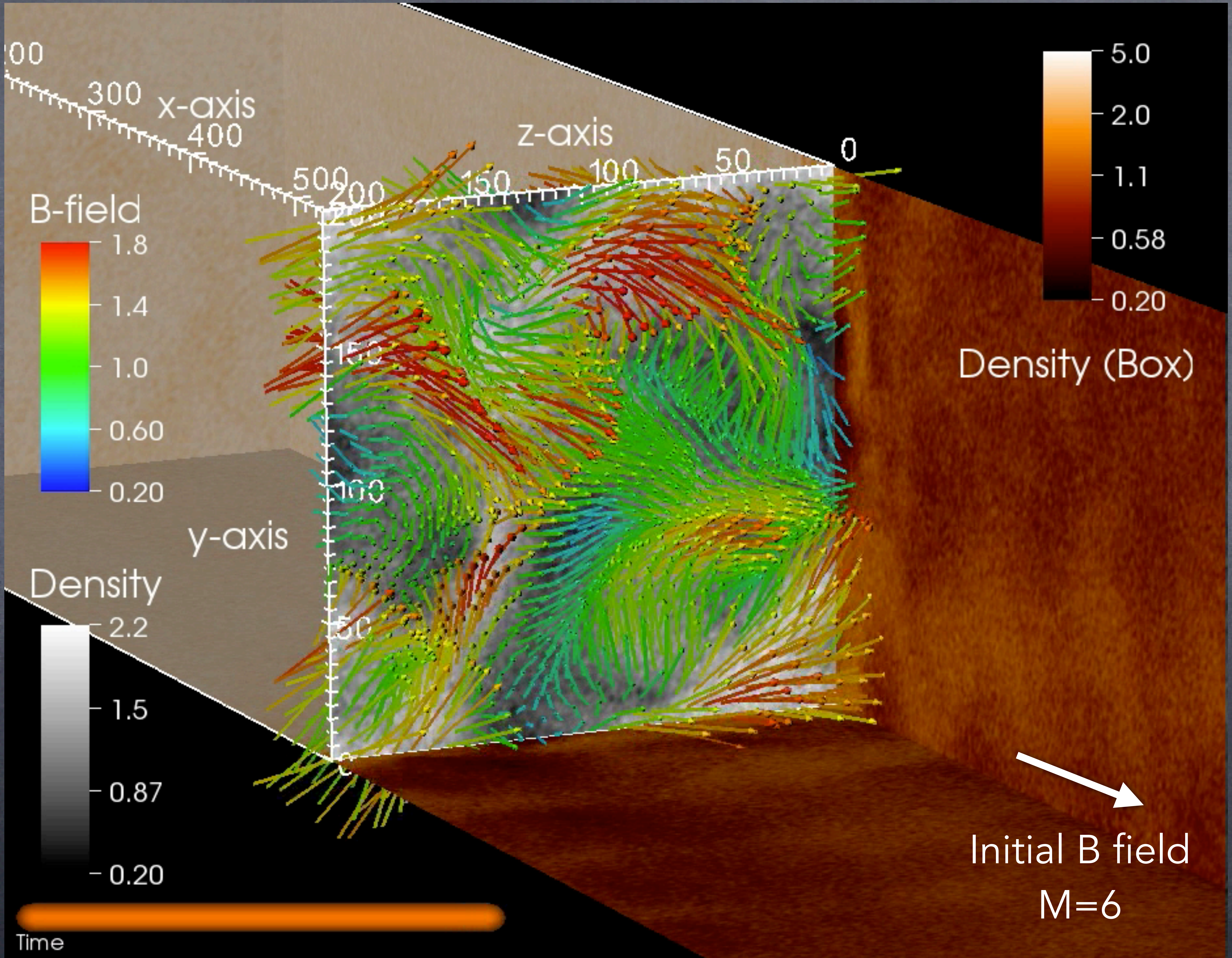
Initial B field

$M_s = M_A = 30$



DC & Spitkovsky, 2013

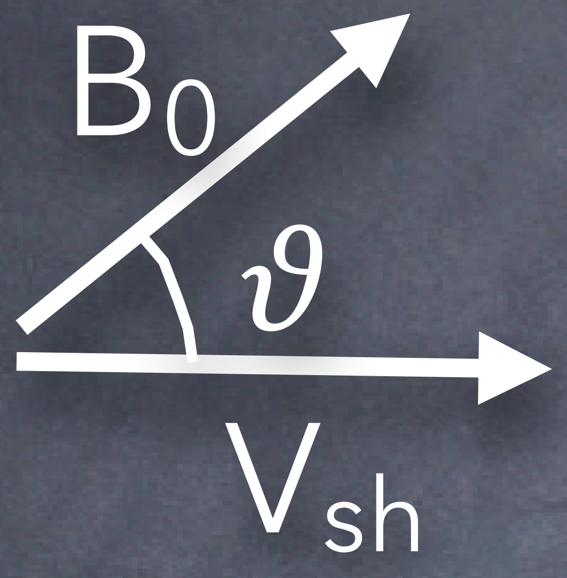
3D simulations of a parallel shock

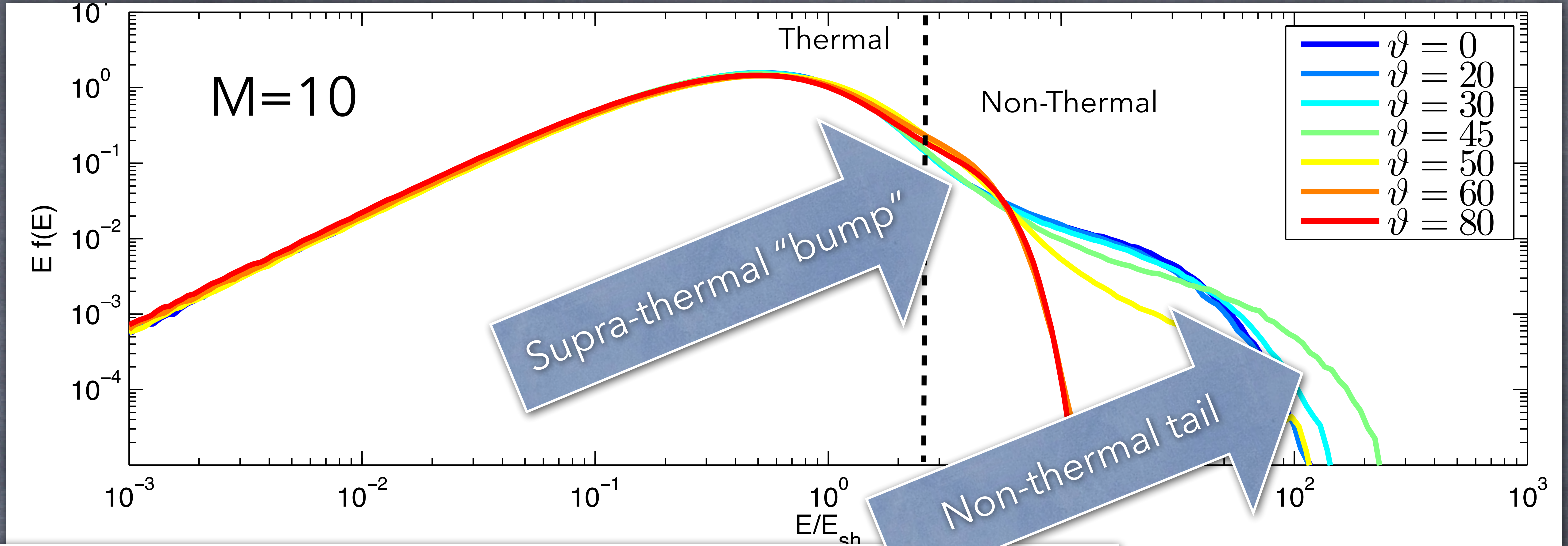


DC & Spitkovsky, 2014a

Parallel vs Oblique shocks

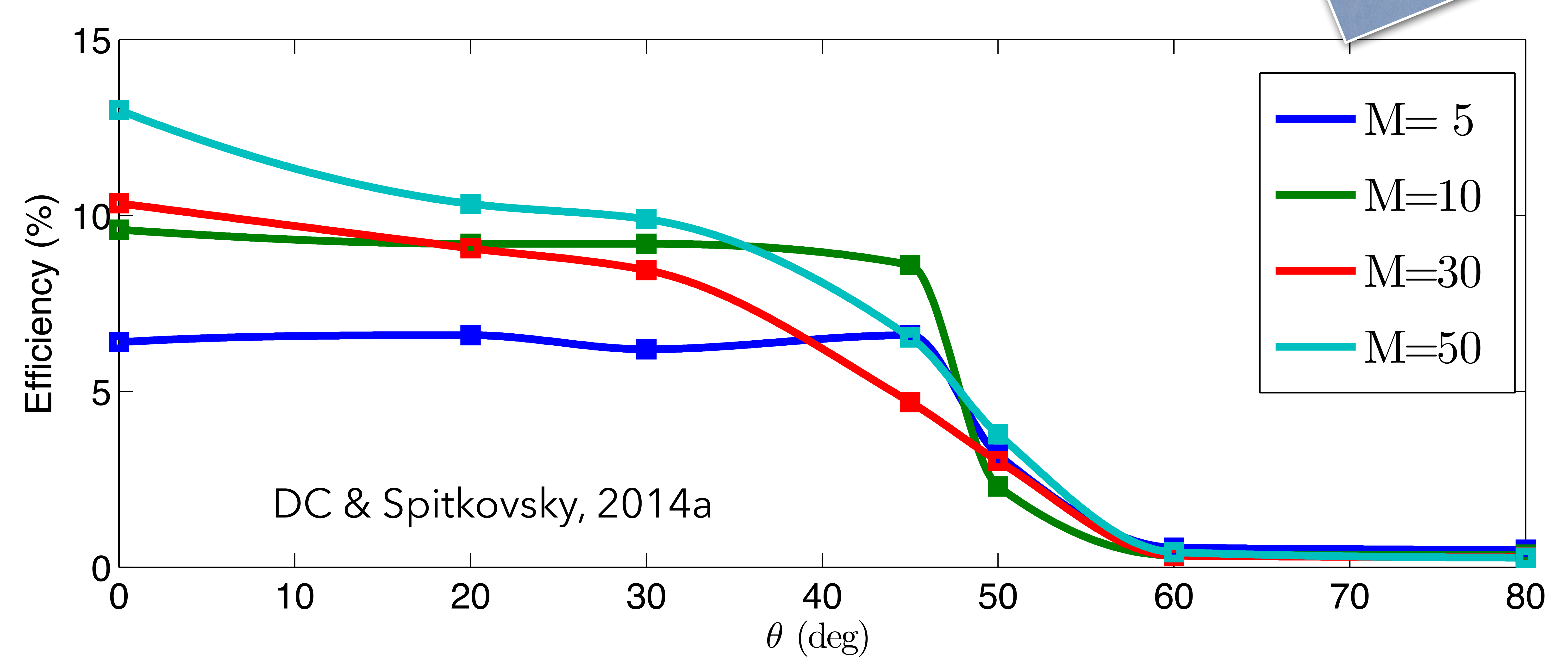
Shock inclination





Supra-thermal "bump"

Non-thermal tail

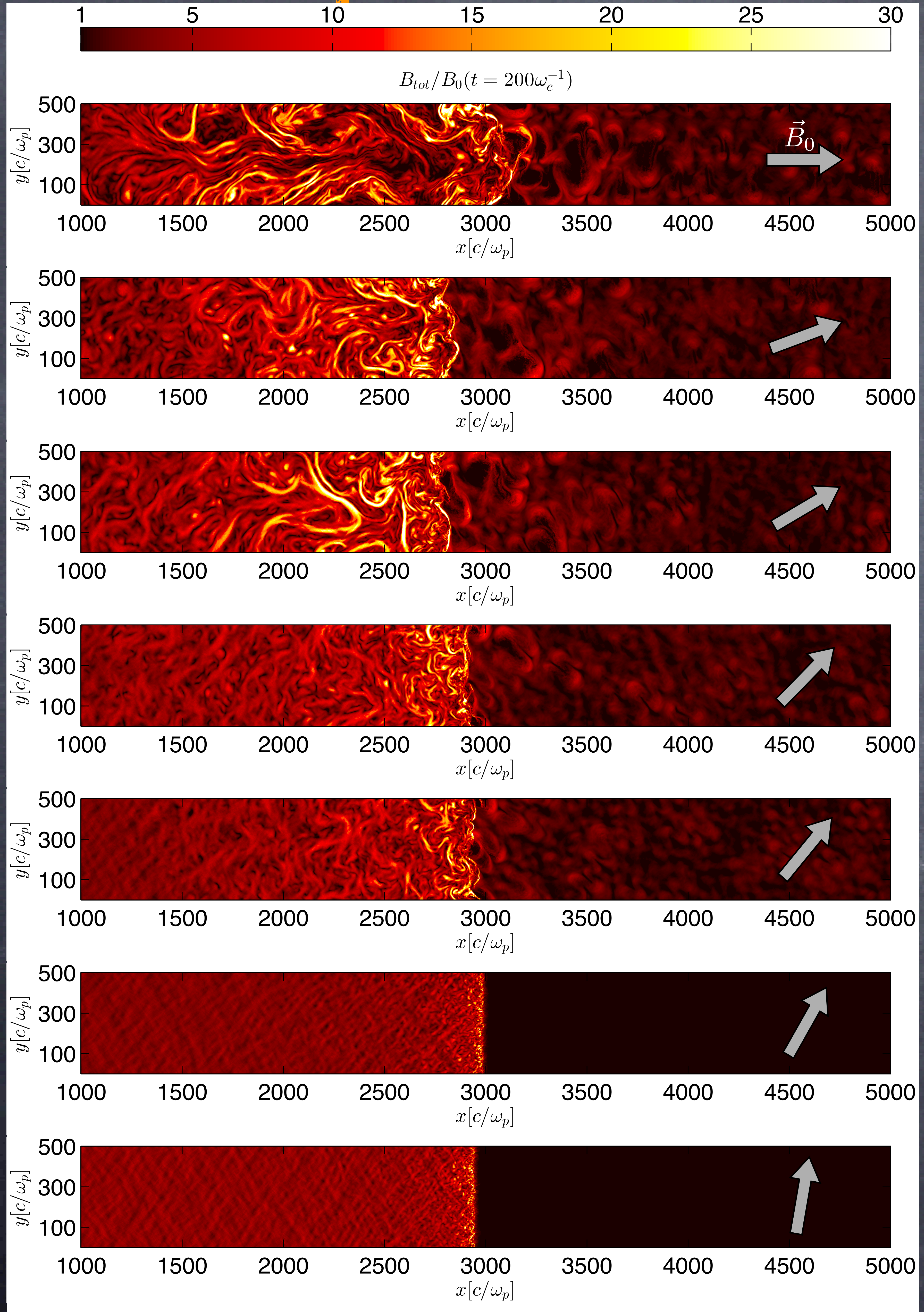


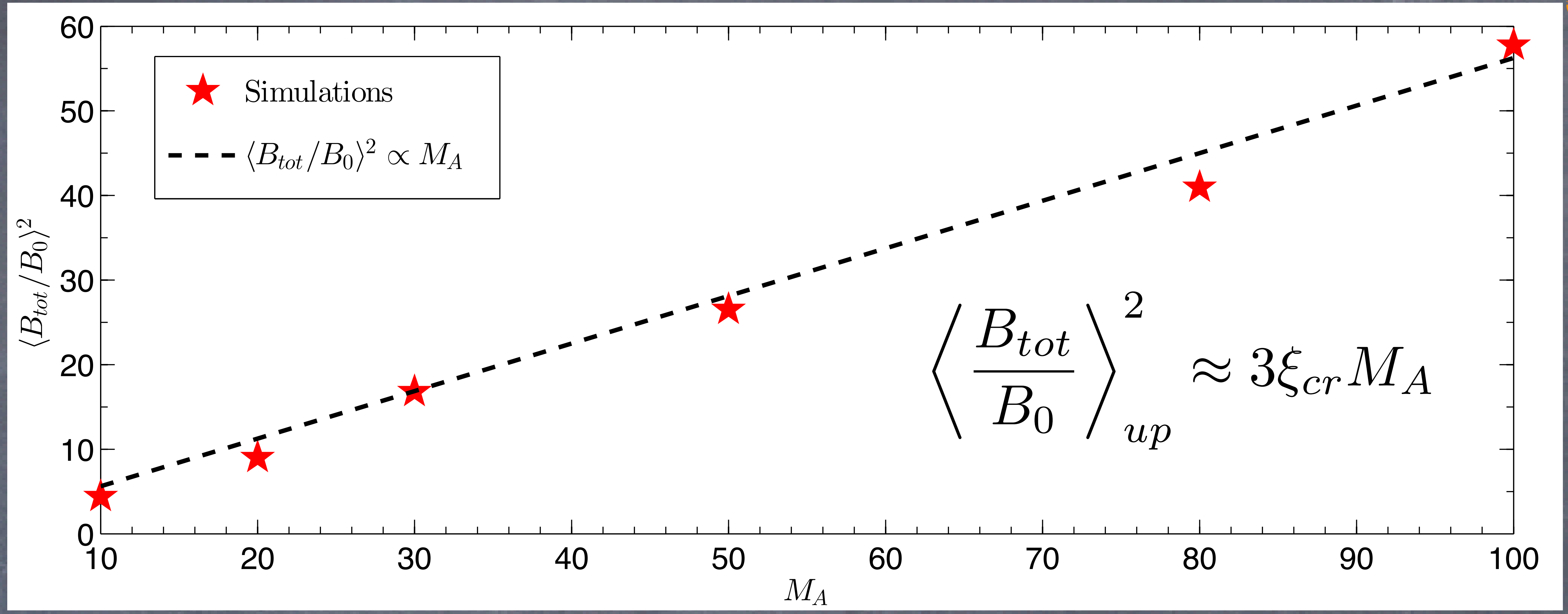
DC & Spitkovsky, 2014a

Each point is a simulation with billions of particles

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Dependence on shock strength (M_A) and inclination



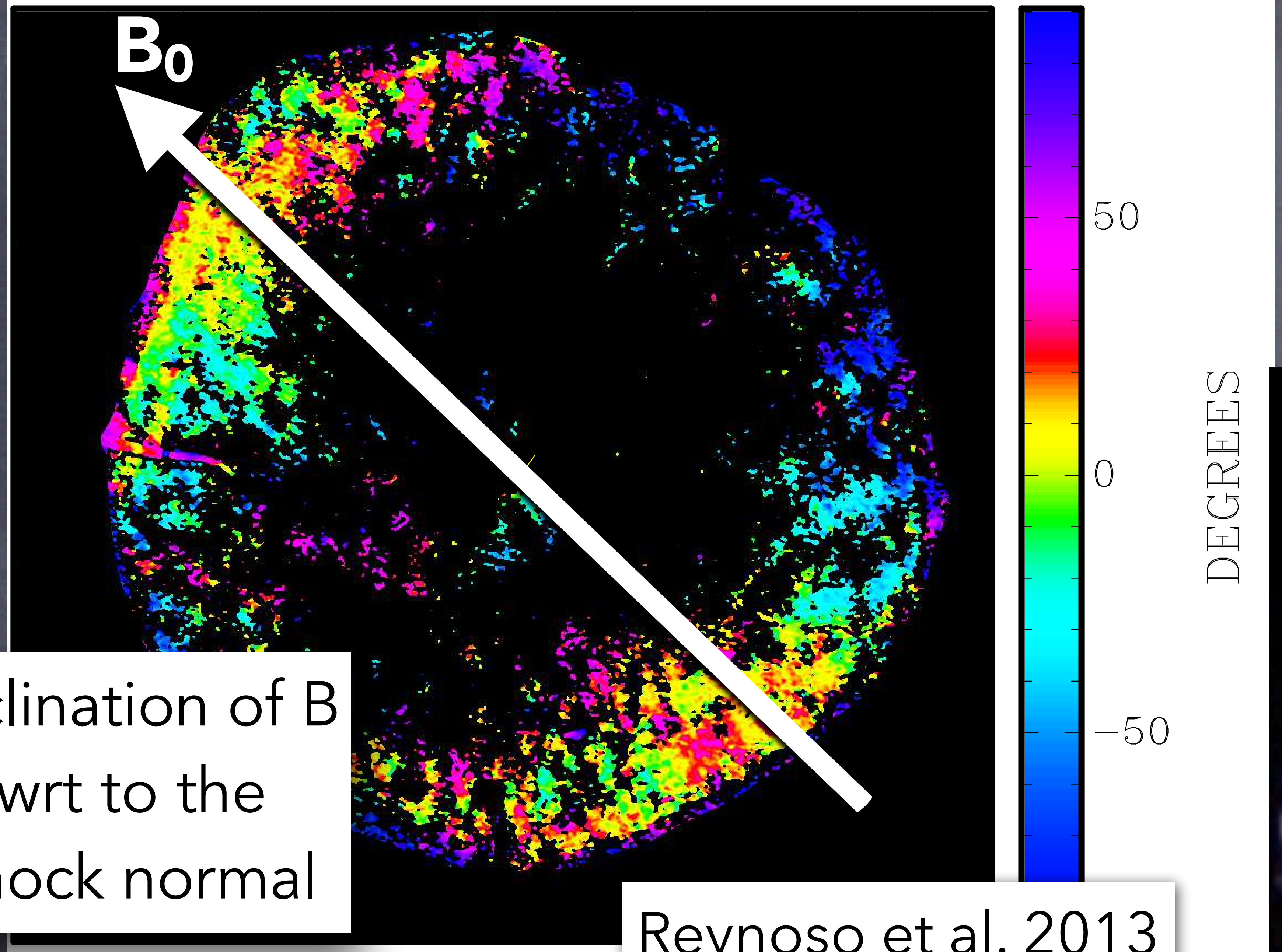


$$\left\langle \frac{B_{tot}}{B_0} \right\rangle_{up}^{2} \approx 3\xi_{cr} M_A$$

More B amplification for stronger (higher M_A) shocks

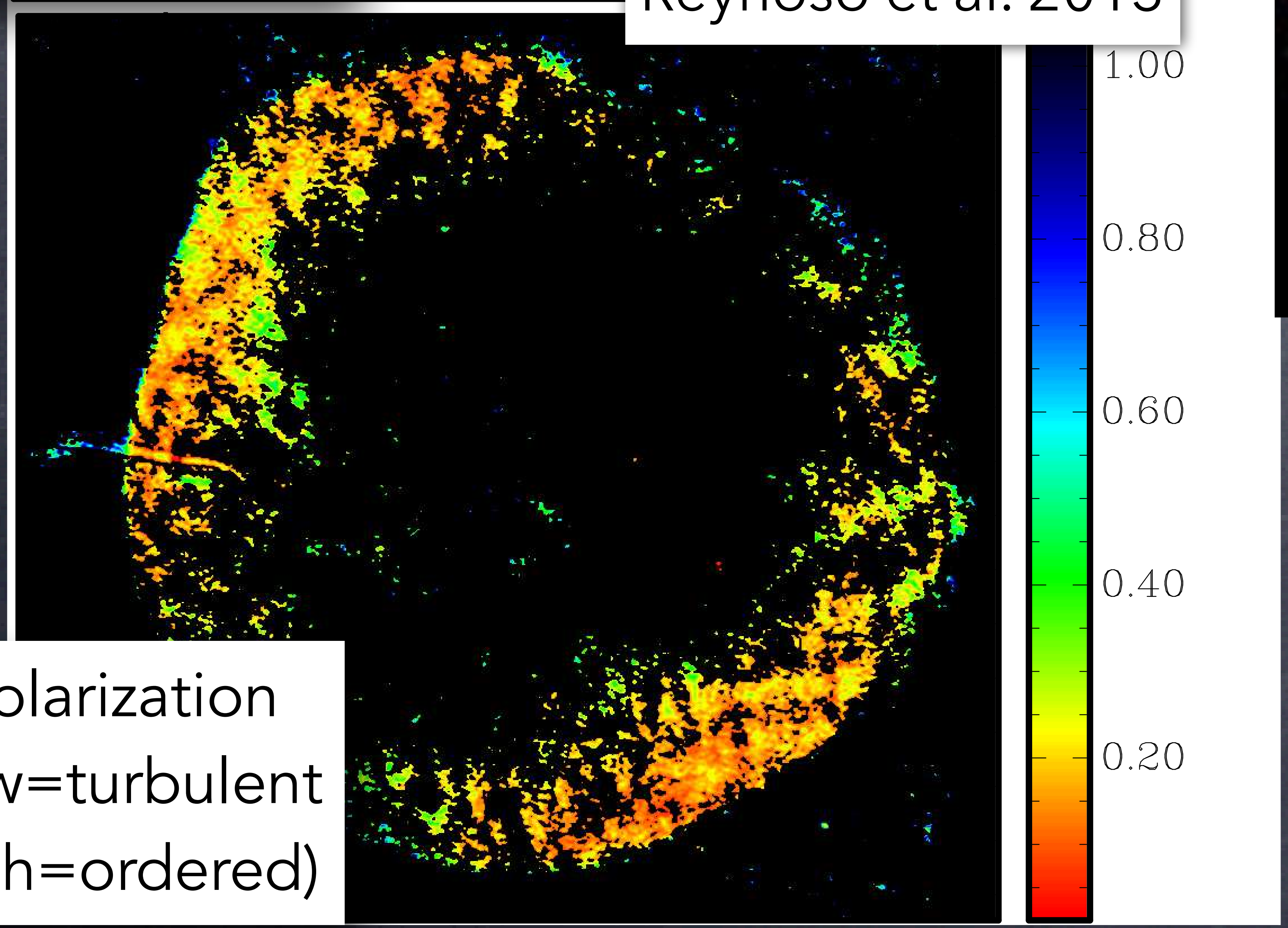
- Different flavors of CR-driven streaming instabilities
  (Amato & Blasi 2009; DC & Spitkovsky 2014b)
  - For M_A<30, resonant (cyclotron)
  - For M_A>30, non-resonant (Bell's): strongly non-linear!
- Bohm-like diffusion in the self-generated B
  (Reville & Bell 2013; DC & Spitkovsky 2014c)

SN 1006: a parallel accelerator



Inclination of B
wrt to the
shock normal

Reynoso et al. 2013

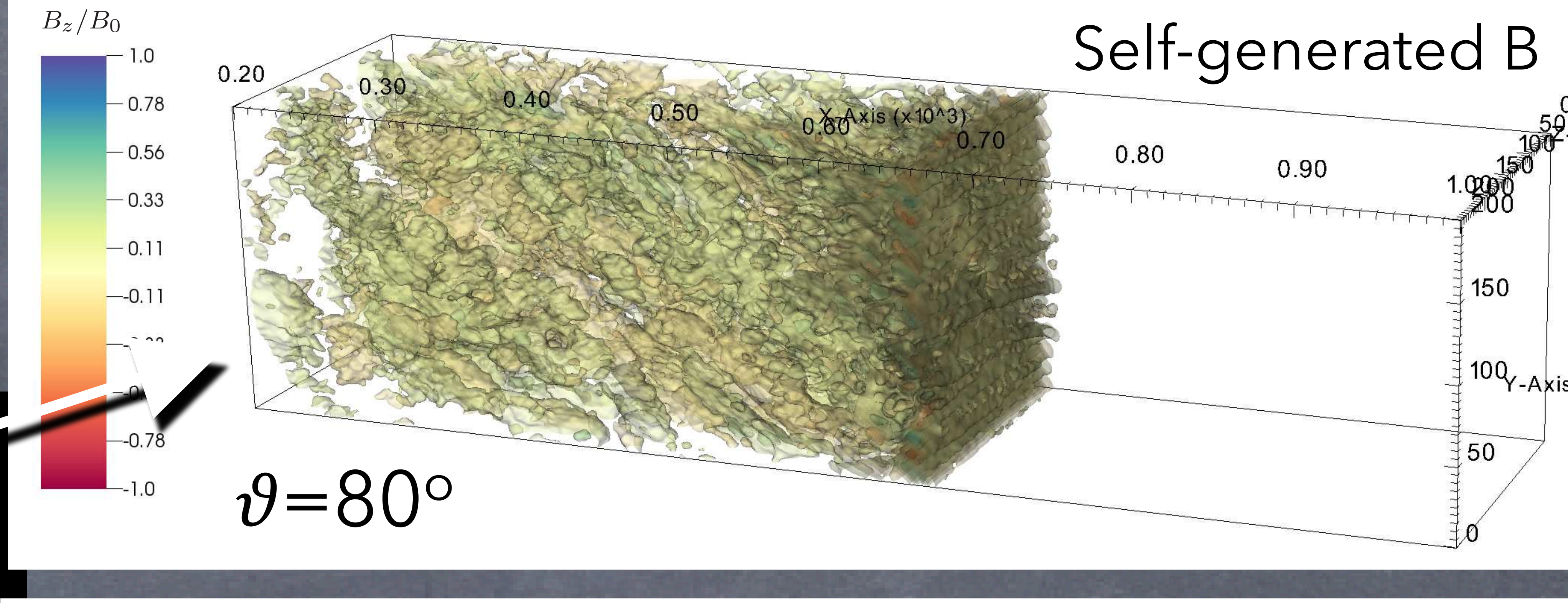


Polarization
(low=turbulent
high=ordered)

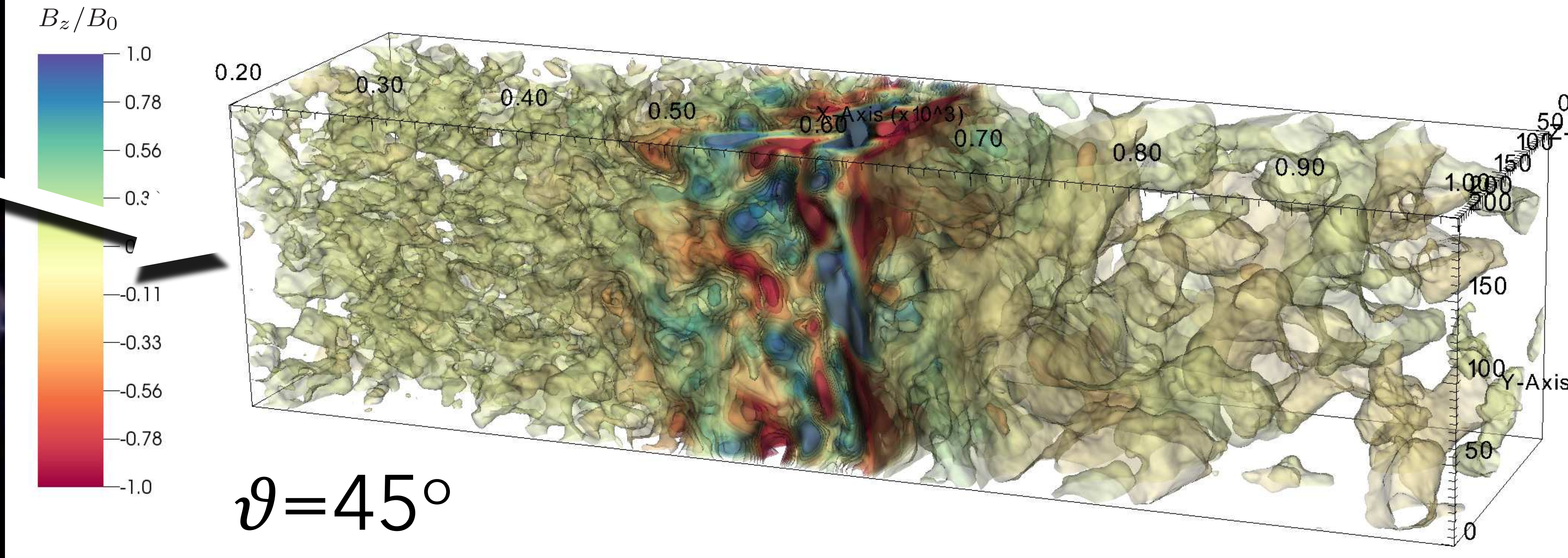
X-ray emission:
red=thermal
white=synchrotron

B amplification and
ion acceleration
where the shock is
parallel

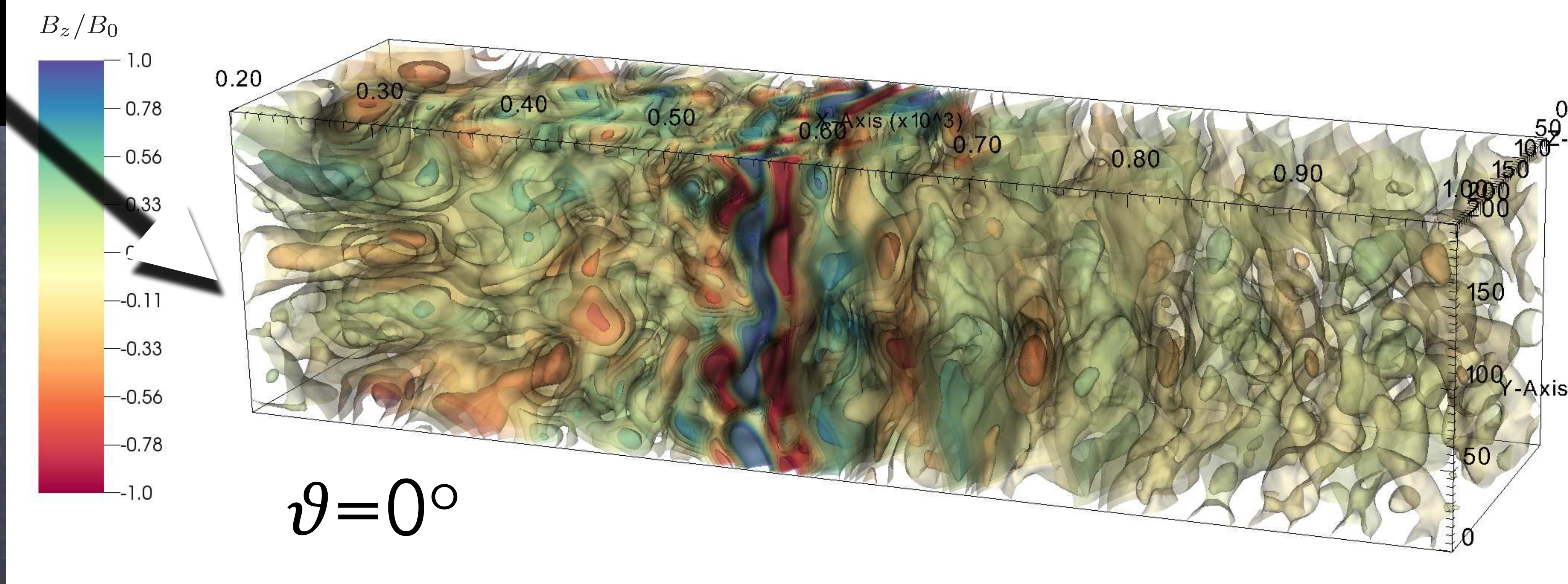
Self-generated B



$\vartheta=80°$



$\vartheta=45°$



$\vartheta=0°$

DC & Spitkovsky, 2014a

Ion Injection

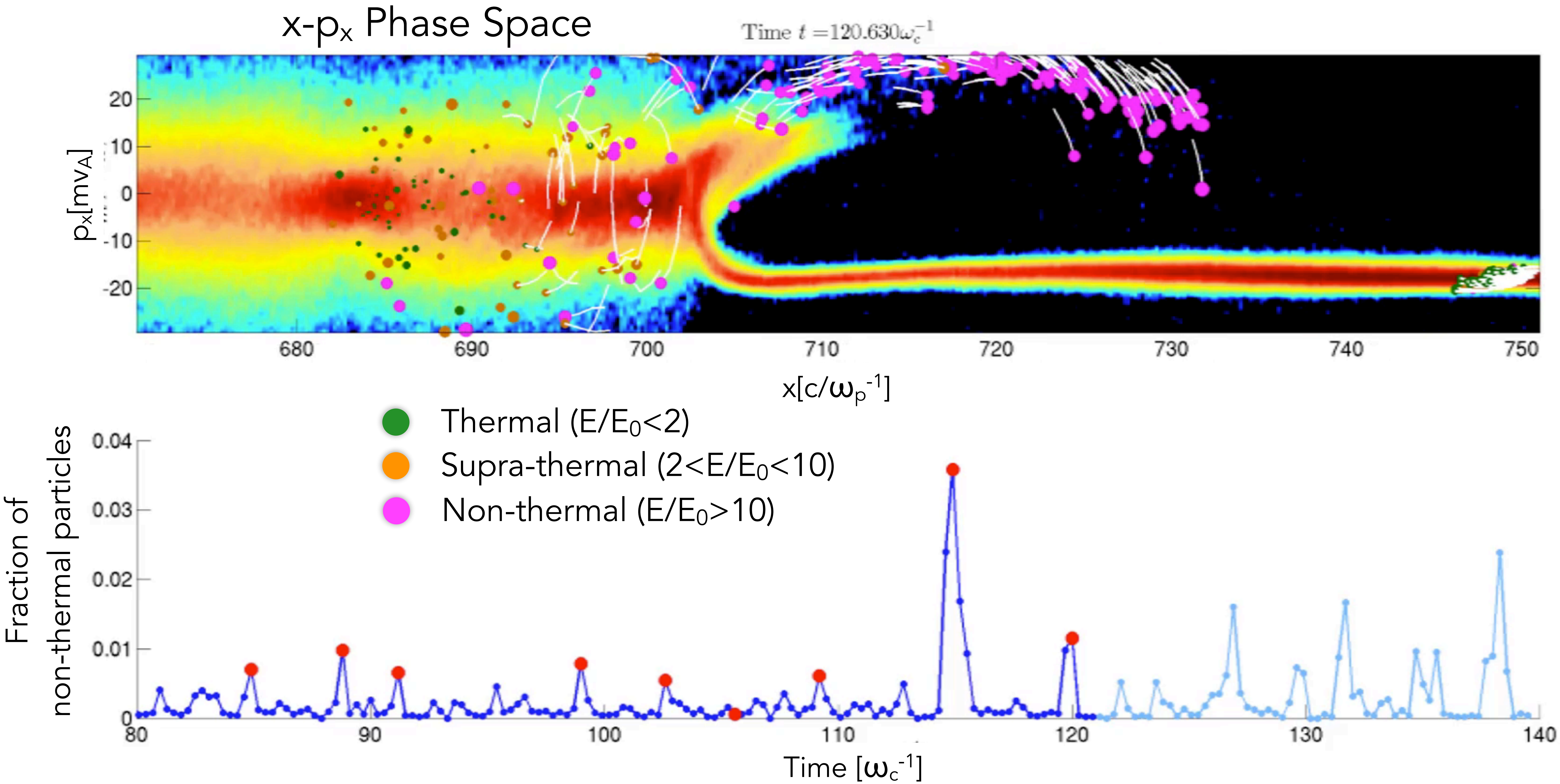
What determines the fraction of particles that become CRs?

3 golden rules of Real Estate:

LOCATION,
LOCATION,
LOCATION!

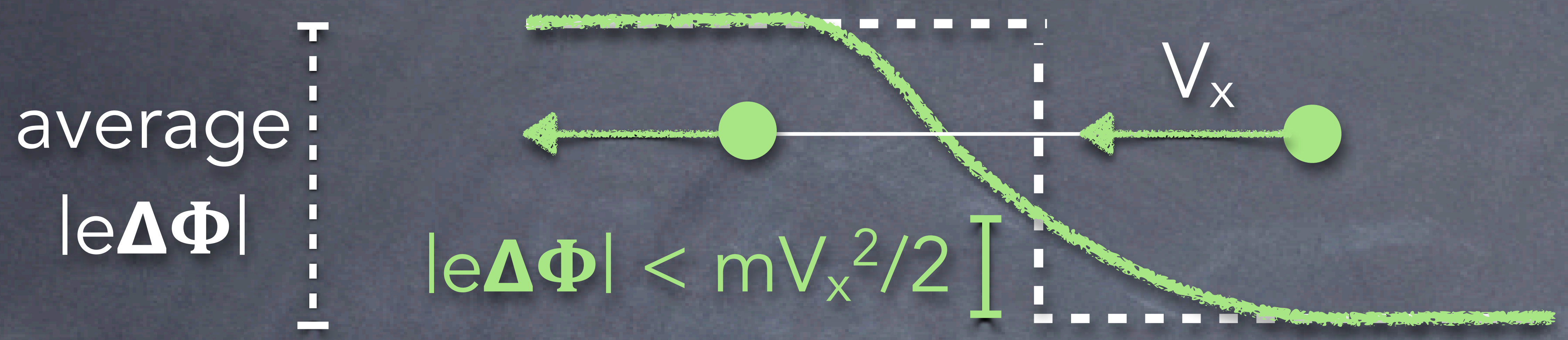
Particle Injection - Simulations

DC, Pop & Spitkovsky, 2015



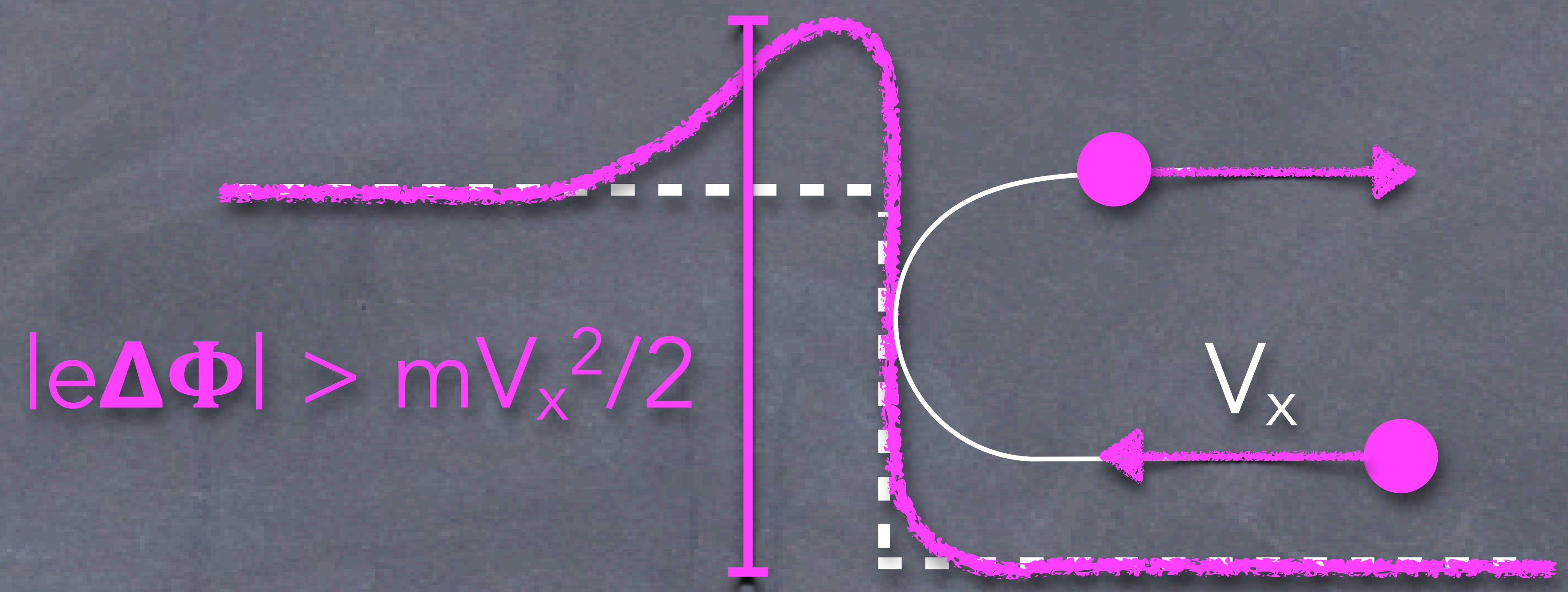
Encounter with the shock barrier

- Low barrier (shock reformation)



Ions advected downstream, and thermalized

- High barrier (overshoot)



Ions reflected upstream, and energized via Shock Drift Acceleration

E.g.: Burgess & Schwartz 1984; Kucharek & Scholer 1991; Guo & Giacalone 2013

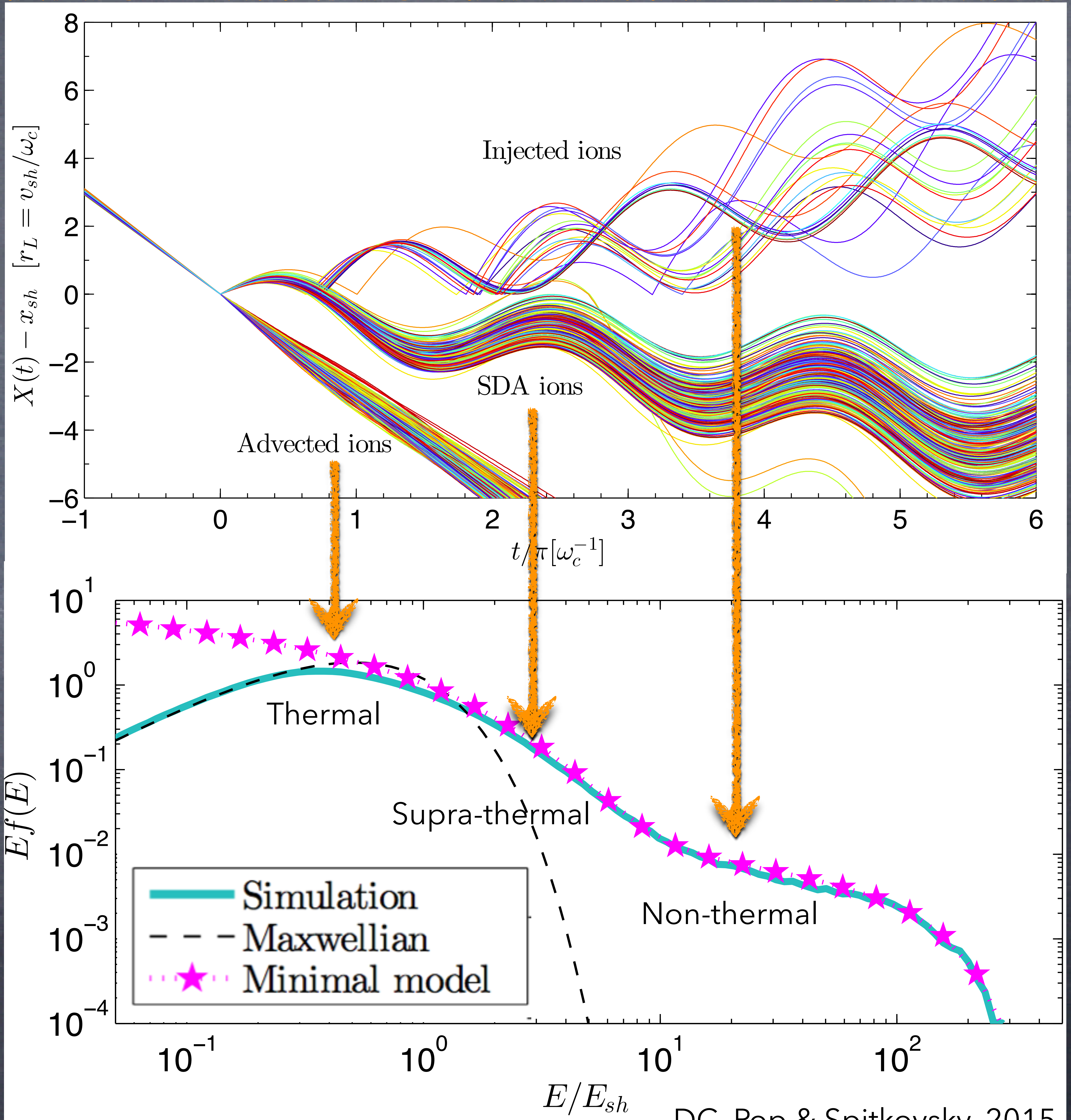
- Ion fate determined by barrier duty cycle (~25%) and shock inclination
  - The energy E_{inj} needed to escape upstream increases with ϑ (DC, Pop & Spitkovsky 2015)
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj} \sim 10E_0$, which requires N~3 -> $\eta \sim 1\%$

Minimal Model for Ion Injection

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

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

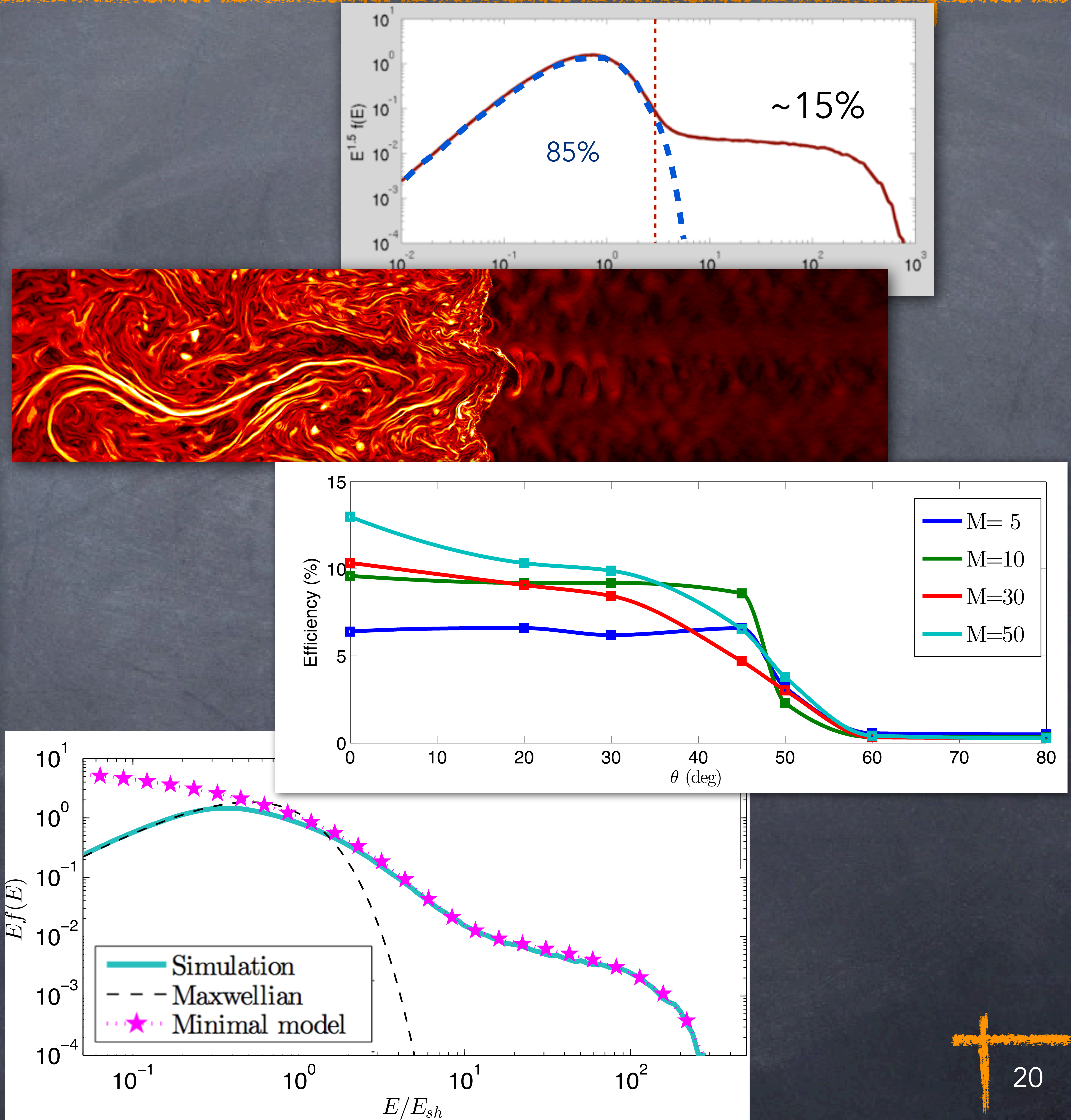
- P=probability of being advected
- ε=fractional energy gain/cycle



DC, Pop & Spitkovsky, 2015

Results from hybrid simulations

- Acceleration at shocks can be efficient: >10%
- CRs amplify the B field via streaming instability
- DSA efficient at parallel, strong shocks
- Ions injected via reflection and shock drift acceleration

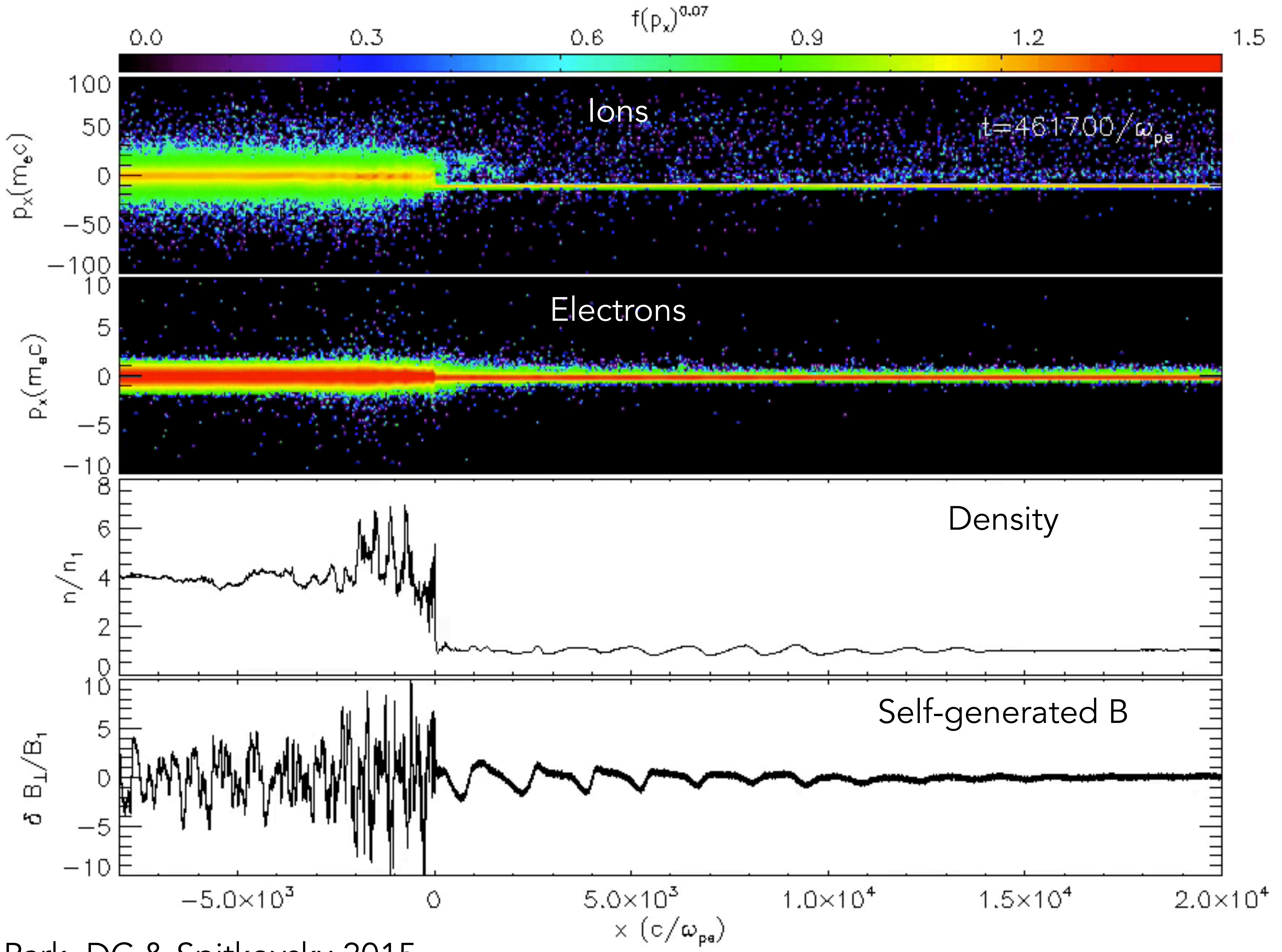


Outstanding questions

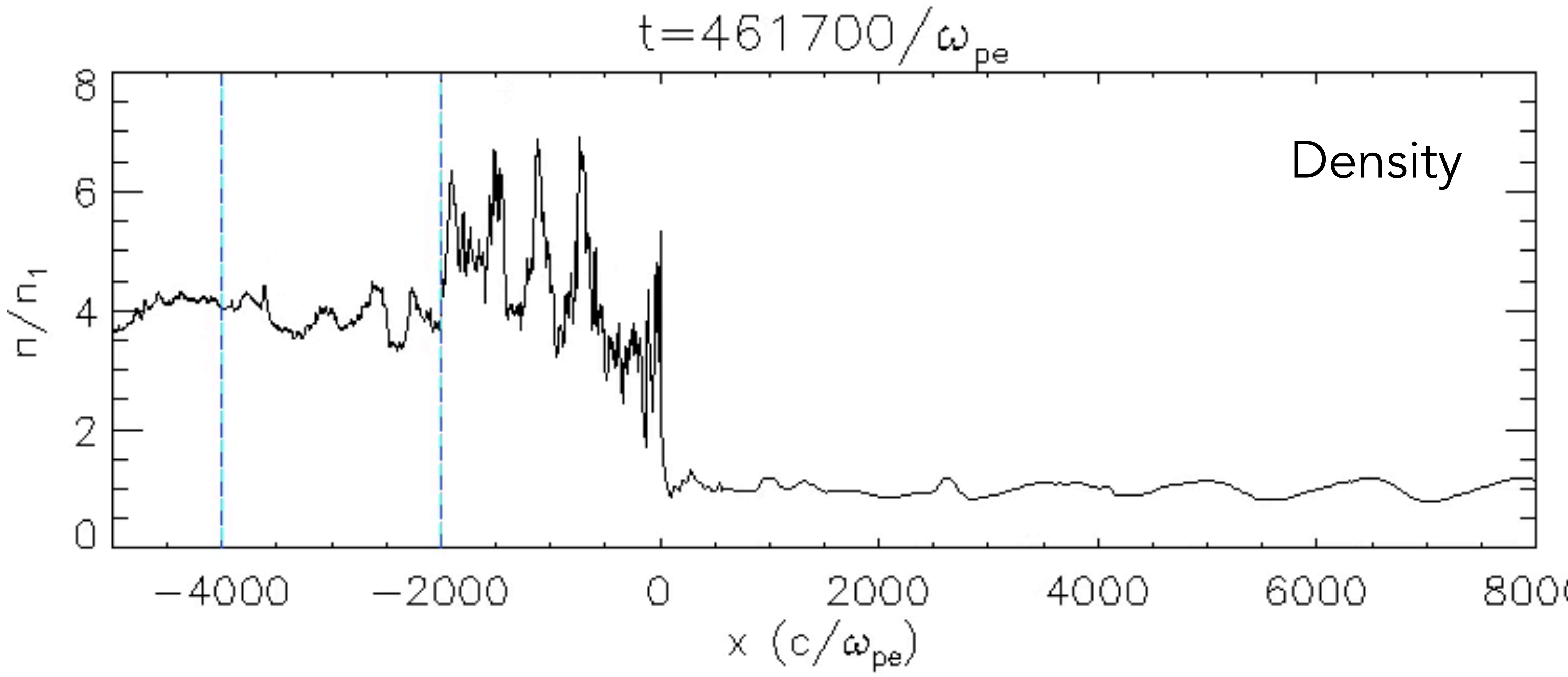
- How are electrons accelerated?
- Is there direct evidence of CR acceleration? (also see F. Aharonian's and E. Hays talks)
- Should we detect neutrinos from SNRs? (see C. Kopper's and M. Ahlers' talks)
- Are SNRs PeVatrons? (also see F. Aharonian's talk)
- How do accelerated particles escape and become CRs?
- Can (simple) diffusive models for propagation explain the features in the CR spectrum and in the diffuse emission? (see D. Gaggero's talk)
- How does B self-generation work in the Galaxy? (see P. Serpico's talk)
- What do we need to better understand particle acceleration?

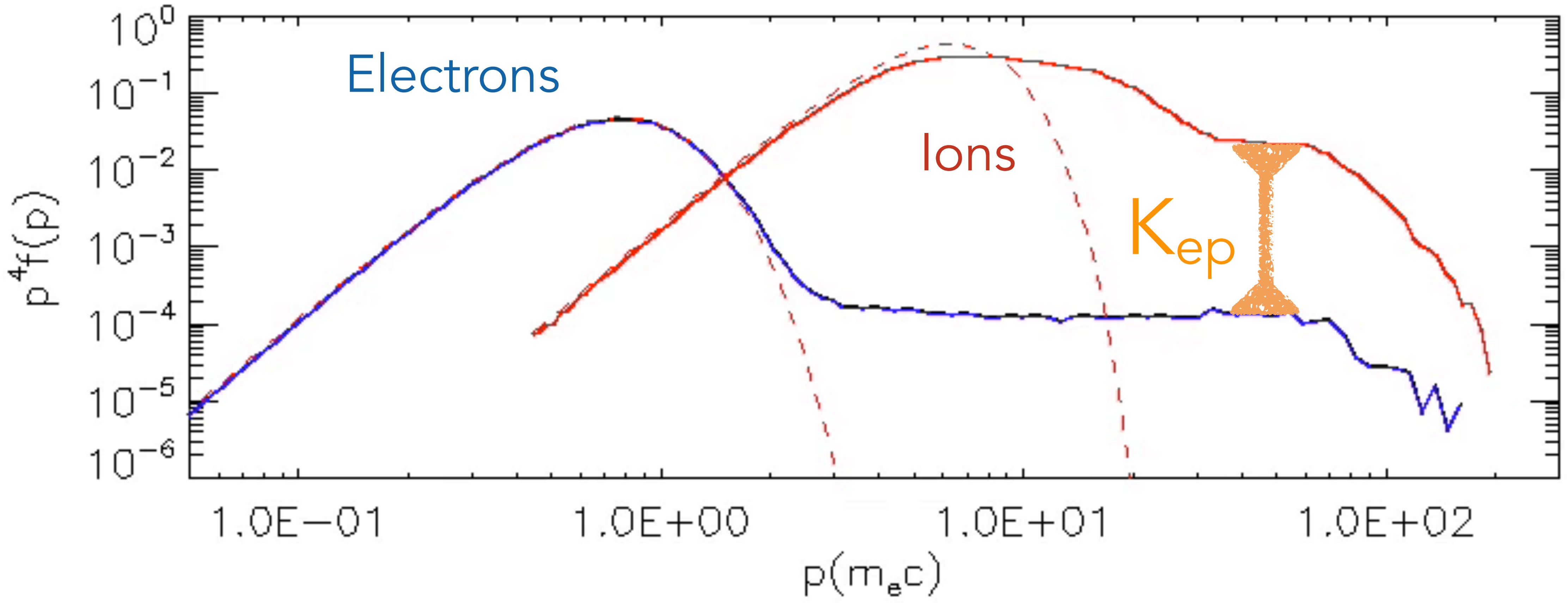
How are electrons accelerated?

- Full PIC simulations (Tristan-MP code) M=20, $V_{sh}=0.1c$, quasi-parallel ($\vartheta=30^o$) 1D shock



Park, DC & Spitkovsky 2015





Electron/proton ratio K_{ep}~0.01

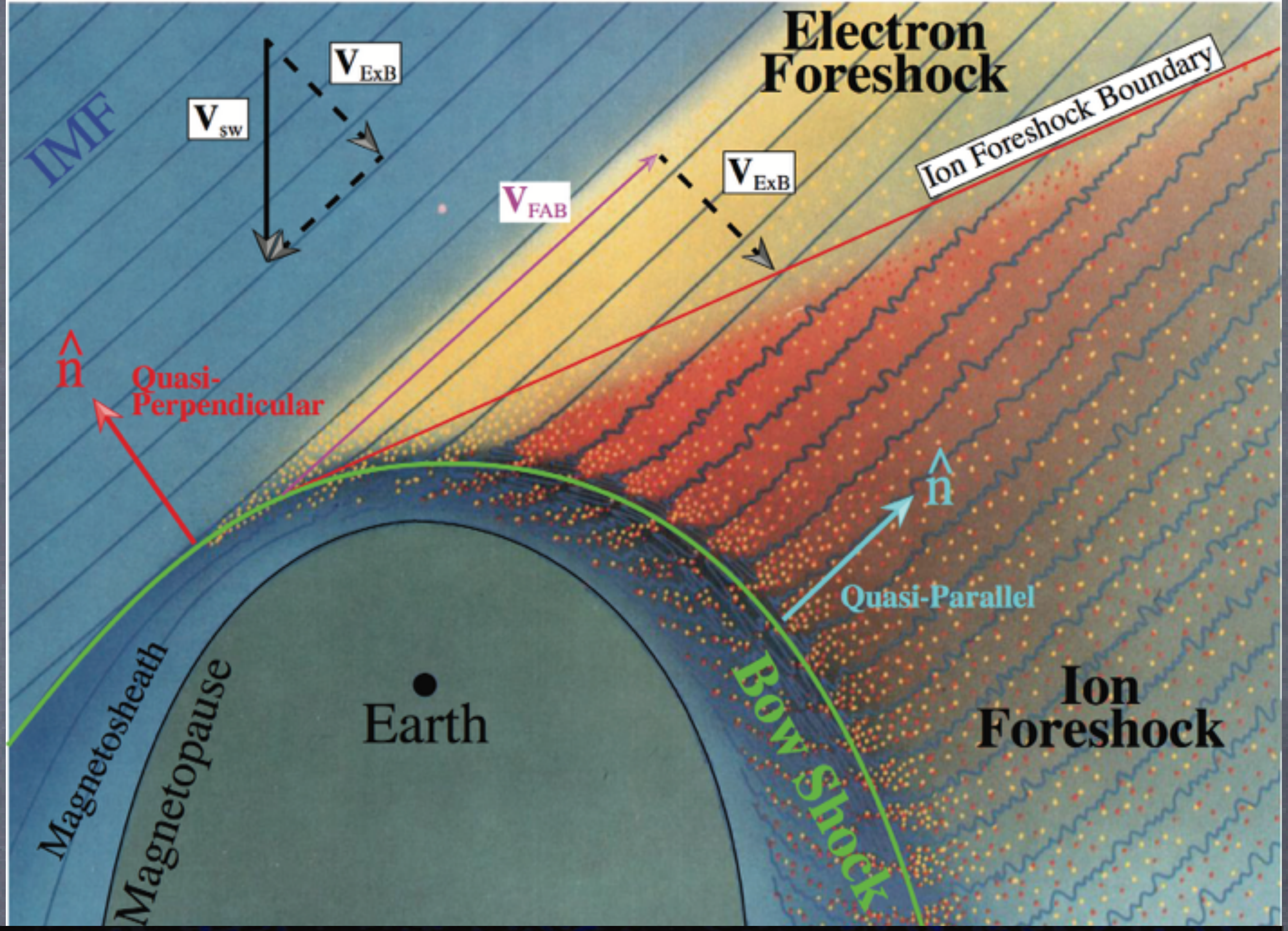
More on electron acceleration

- PIC simulations of oblique shocks ($\vartheta=60°$) (DC, Park, Spitkovsky, in prep.)

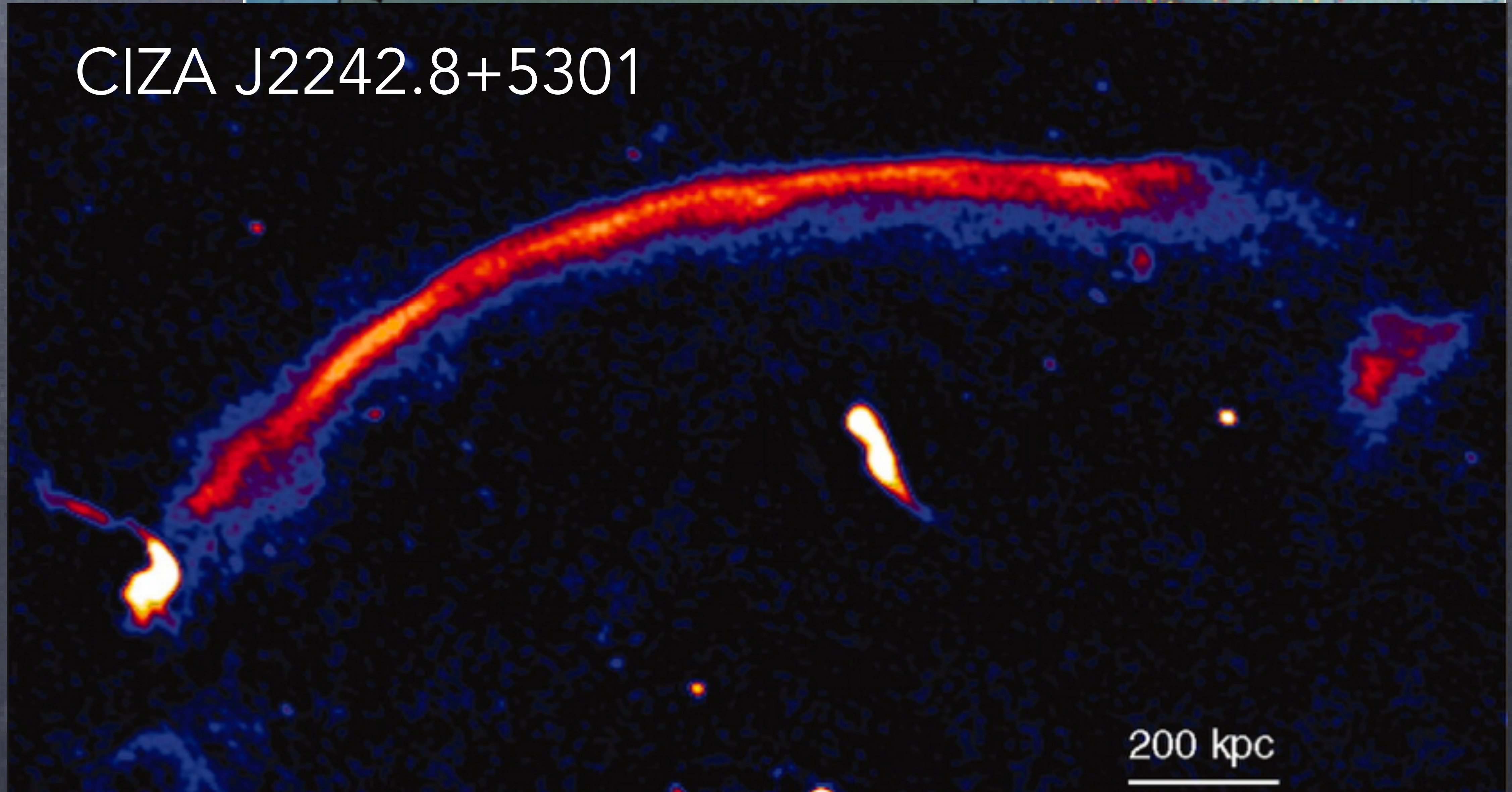
- DSA electron spectra!
- a few % in energy
- <~1% in number
- Stay tuned for scalings with M, β, V_{sh},…

Electron vs Ion acceleration

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

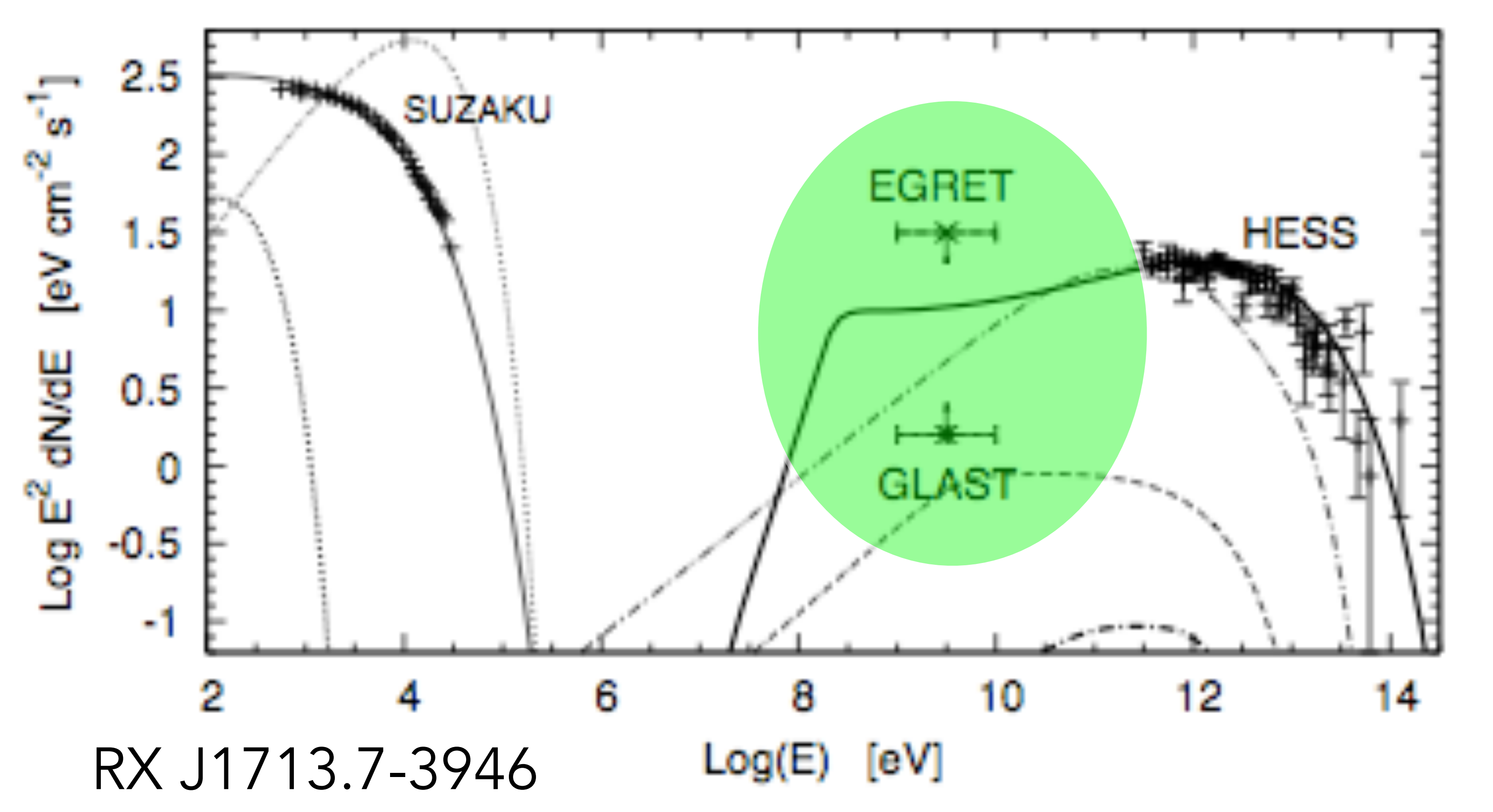


- Radio relics in galaxy clusters
- Extended polarized structures
- Fermi-LAT limits on γ-ray emission: constrain e/p ratio!



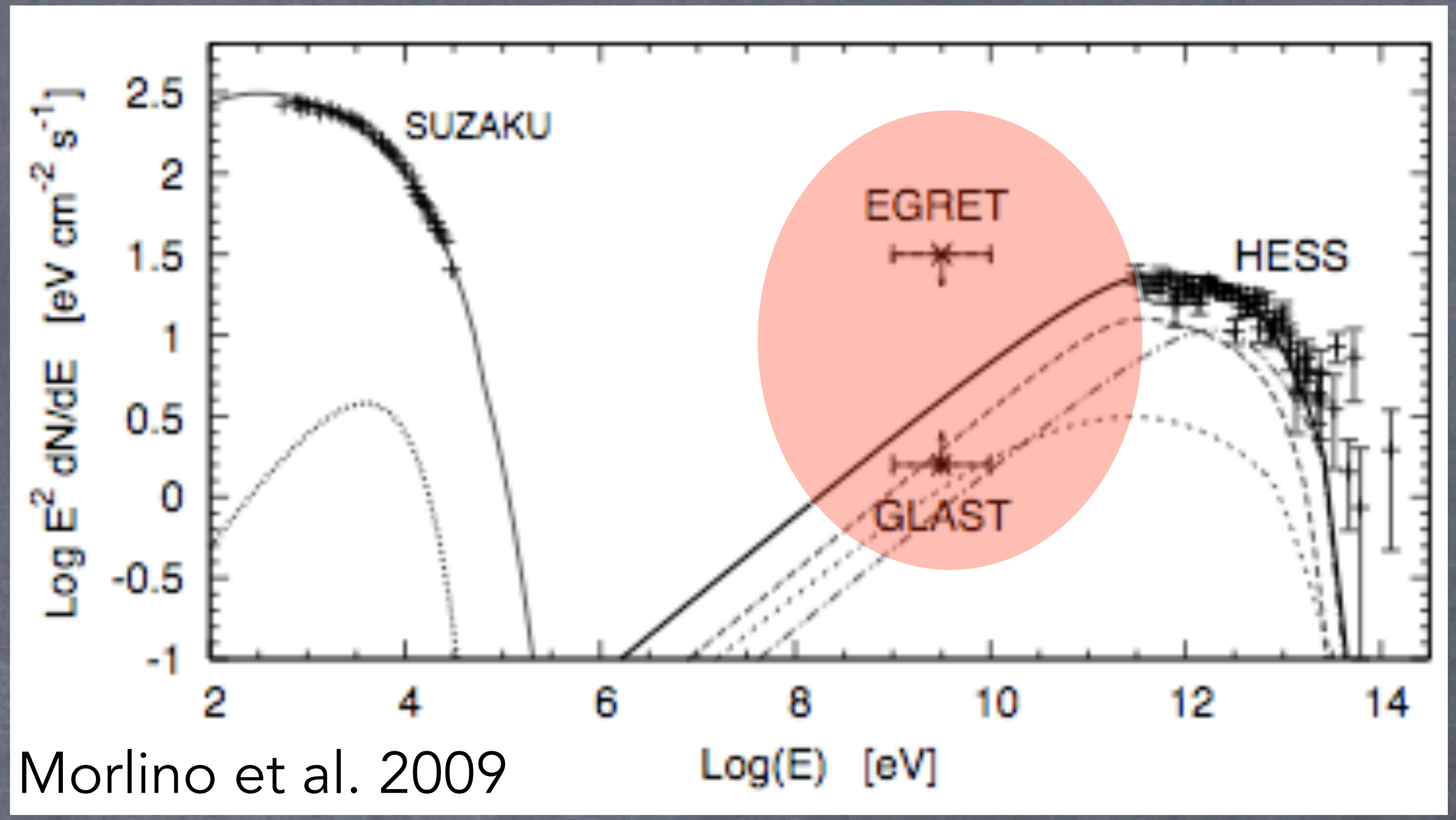
Direct evidence: γ-rays from SNRs

HADRONIC (π_0 decay)



RX J1713.7-3946

LEPTONIC (Inverse Compton)



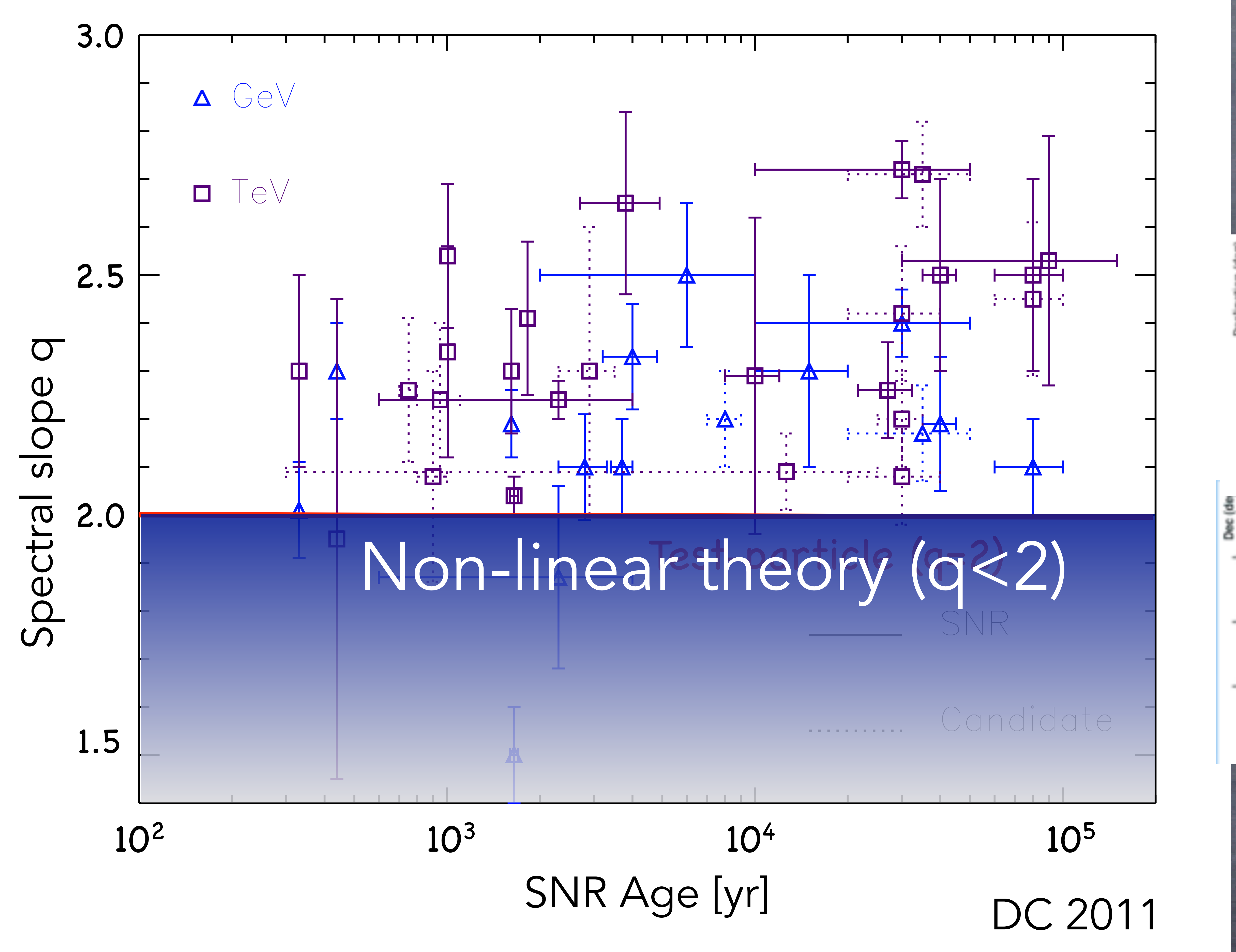
Morlino et al. 2009

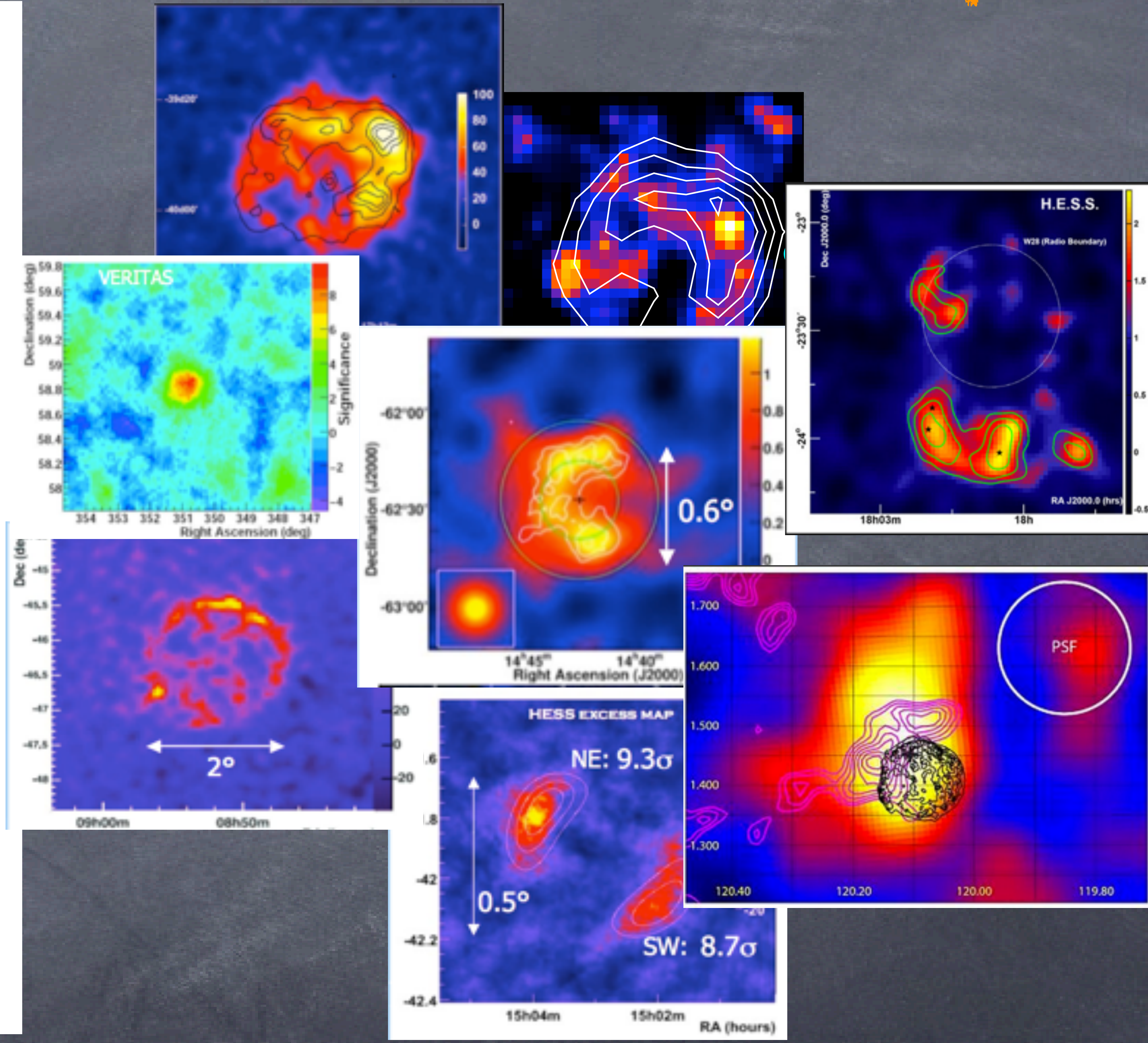
γ-ray spectrum parallel to the proton one (~E^{-2})

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

- Location: gas-/photon-rich environments -> hadronic/leptonic emission
  - Spectral variety not necessarily evolutionary, but environmental!

With Agile, Fermi, HESS, VERITAS, MAGIC,... CTA

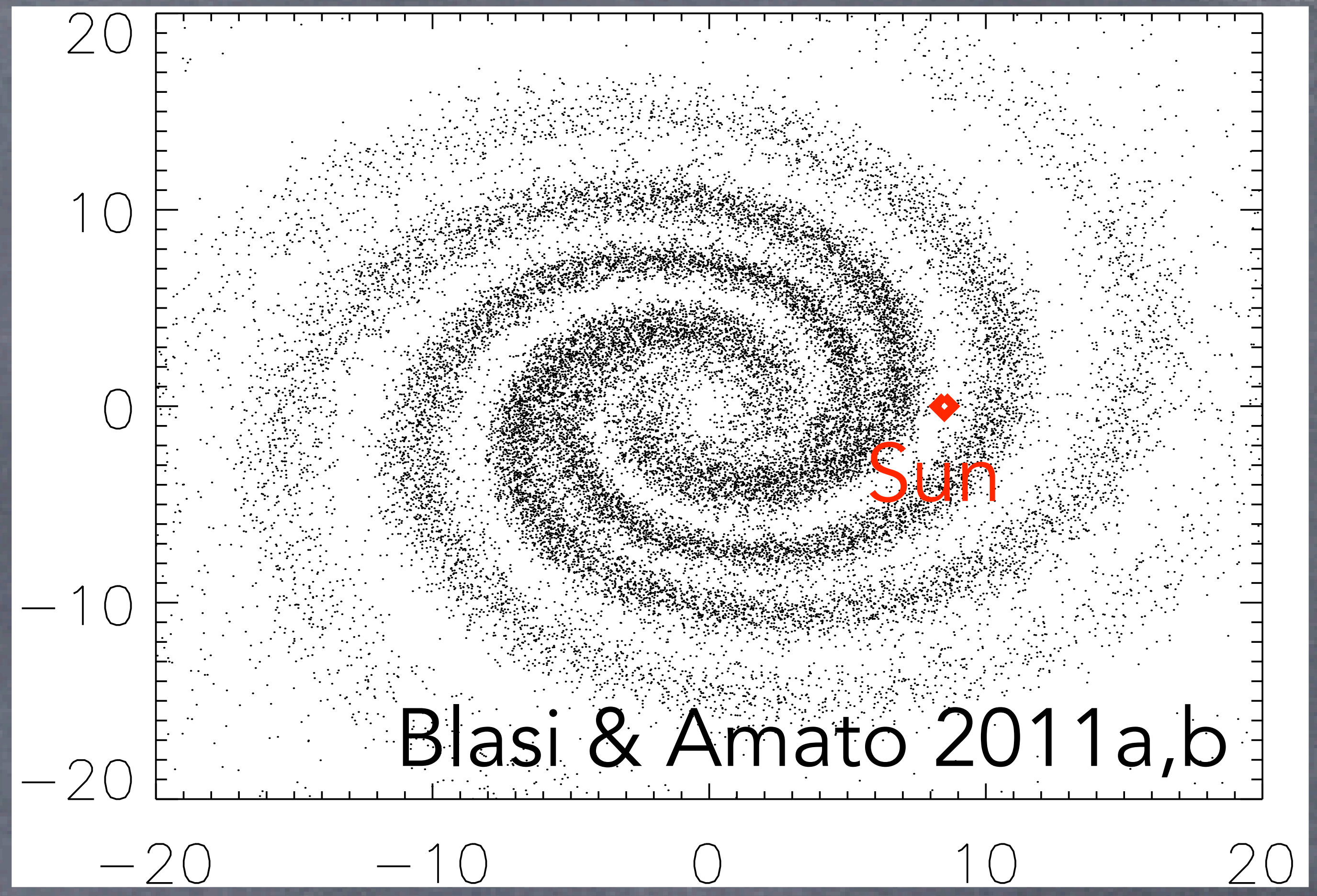




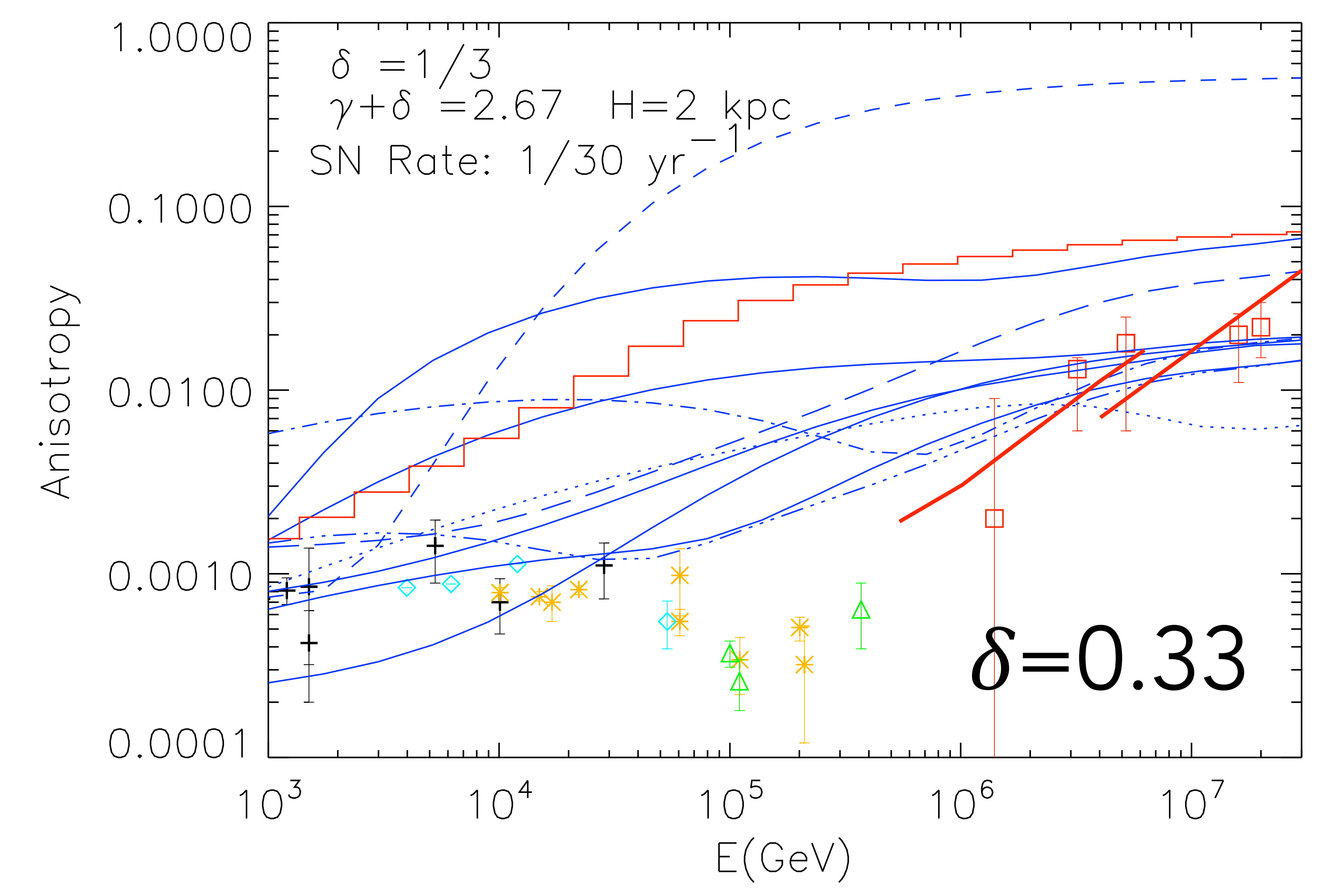
- Evidence of ion acceleration: spectra too steep to be leptonic...
- ...and to be consistent with non-linear DSA theory:
  - Efficient acceleration implies spectra flatter than E^{-2} (Jones & Ellison 1991, Malkov & Drury 2001)

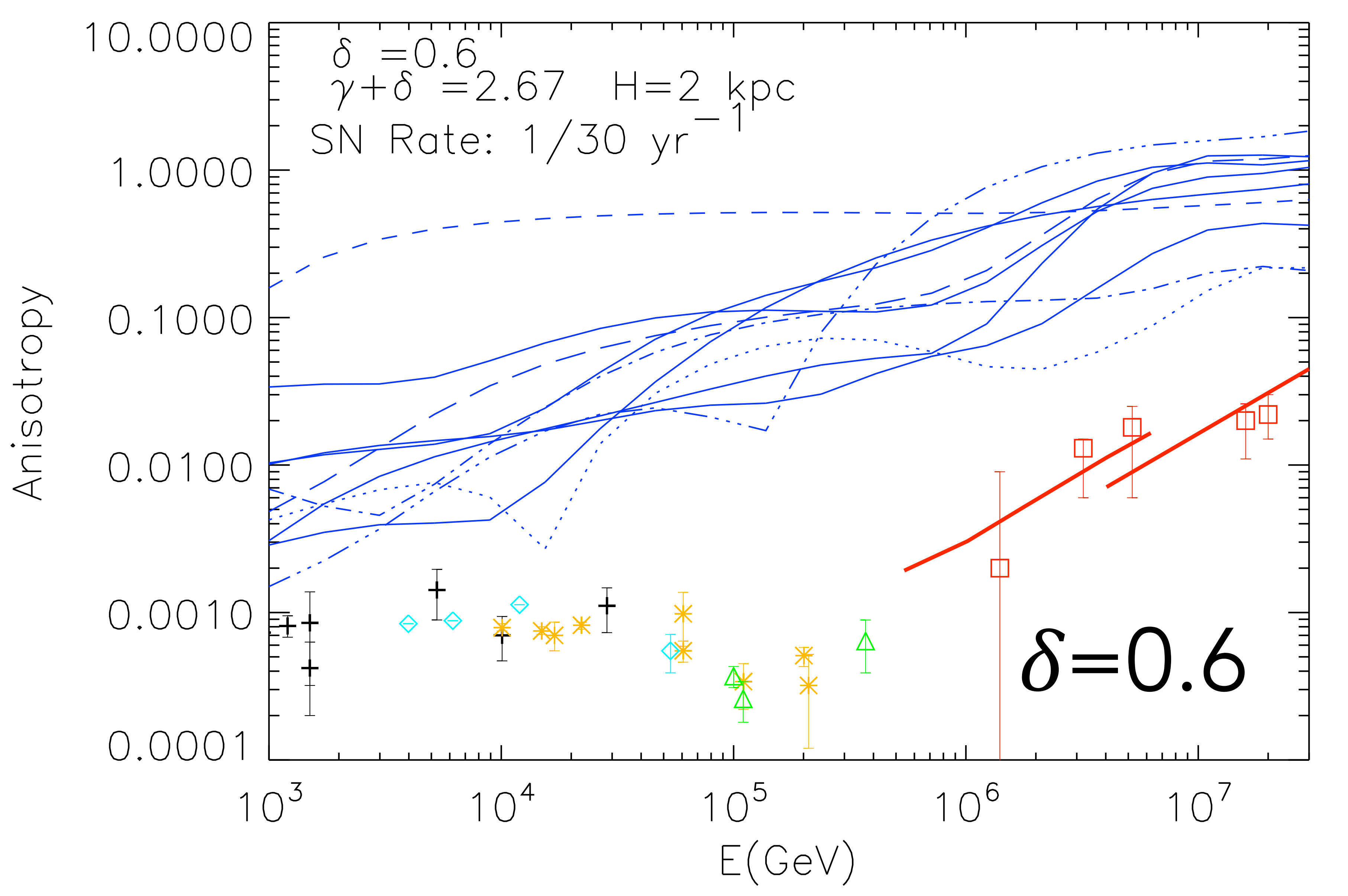
Steep spectra preferred by propagation, too

- Monte Carlo simulations of SNRs + CR transport
- Injection spectrum: ~$E^{-\gamma}$
- Residence time in the Galaxy: ~$E^{-\delta}$
    - Constraint: $\delta+\gamma\sim2.7$



Blasi & Amato 2011a,b



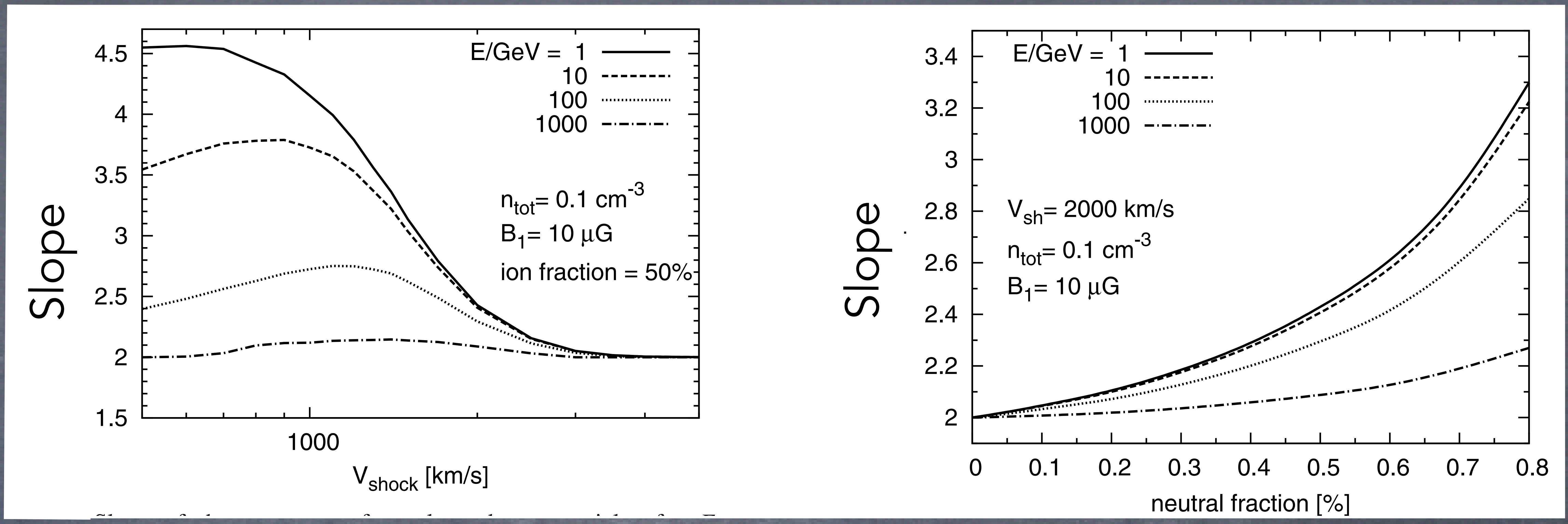


- $\delta=0.33$ is preferred since it returns:
    - more universal CR spectra
    - less anisotropy

Also in this case, an injection slope of $\gamma=2.7-0.33\sim2.35$ is required

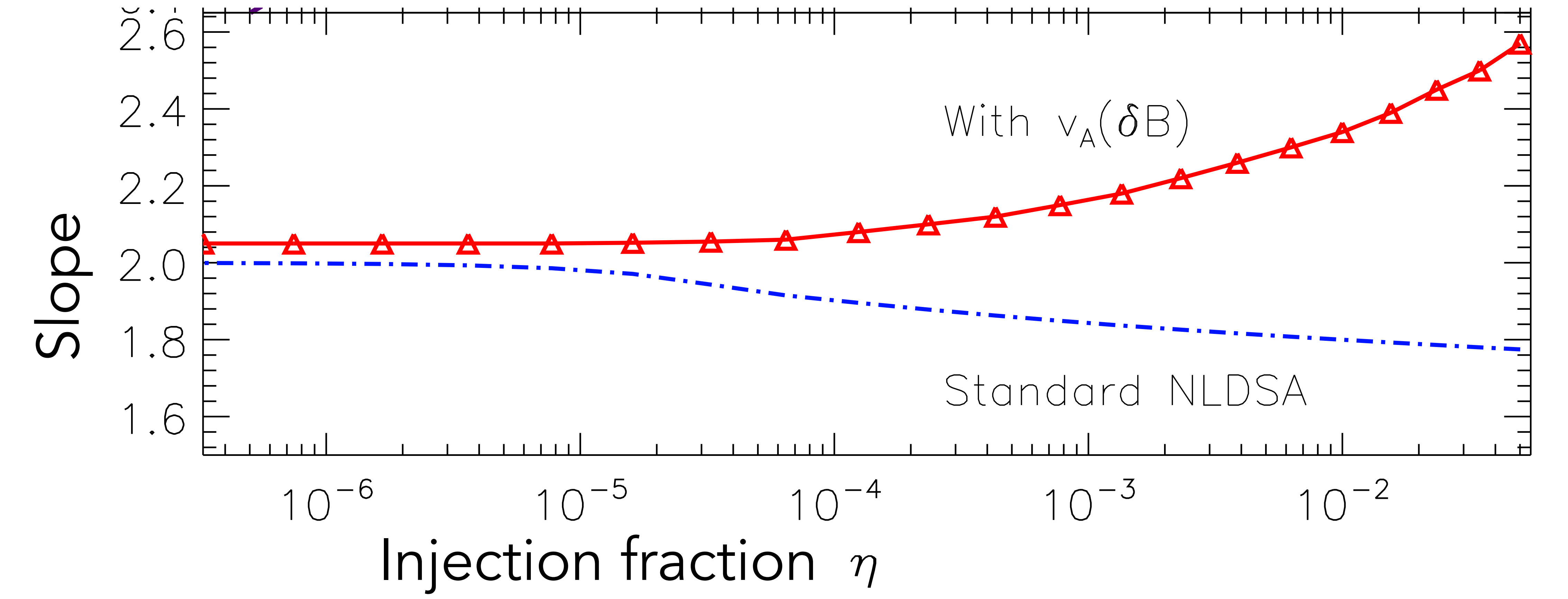
The challenge of producing steep spectra

- 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

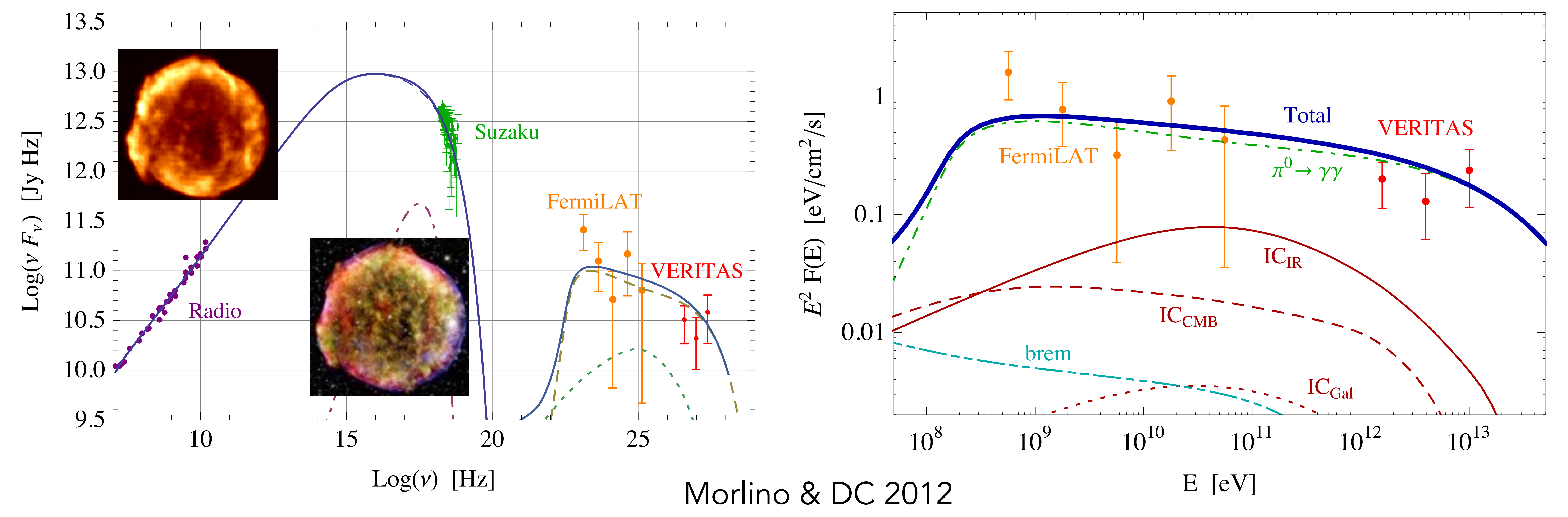
$$\boxed{R_{cr} \simeq \frac{U_{up} - V_{A,up}}{U_{down}}}$$



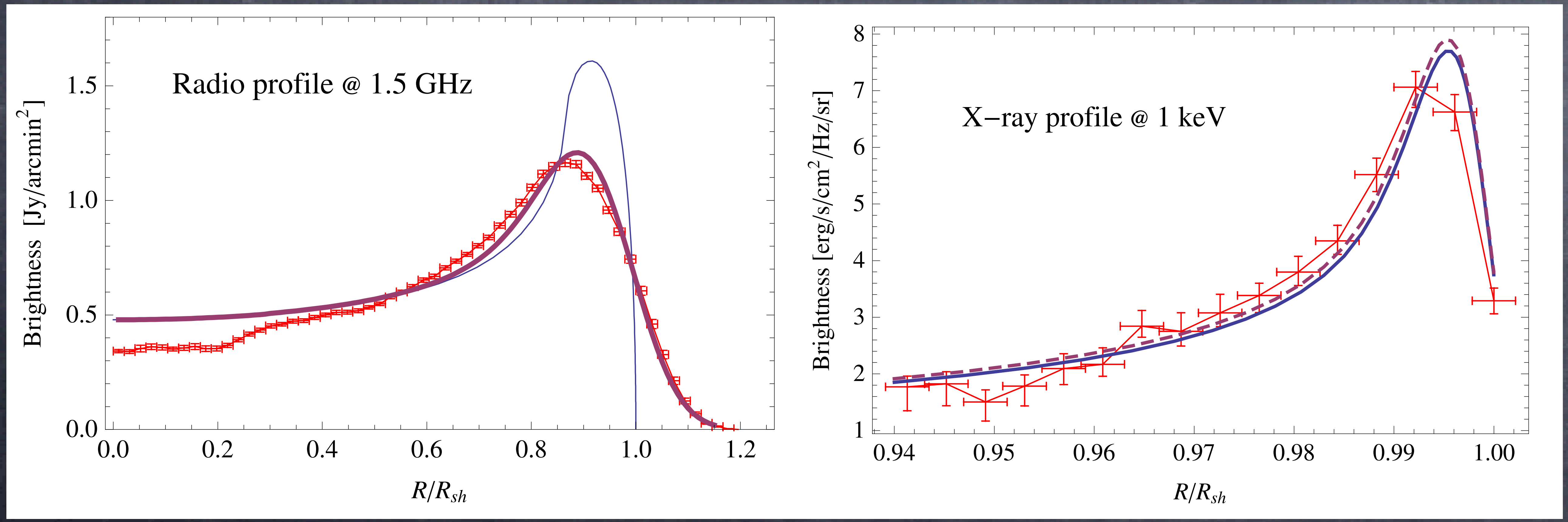
- Oblique shocks/modified diffusion (Kirk et al. 1996; Morlino et al. 2007; Bell et al. 2011, …)

Tycho: a clear-cut hadronic accelerator

Type Ia SN
Age=443yr
Distance~3kpc



Morlino & DC 2012

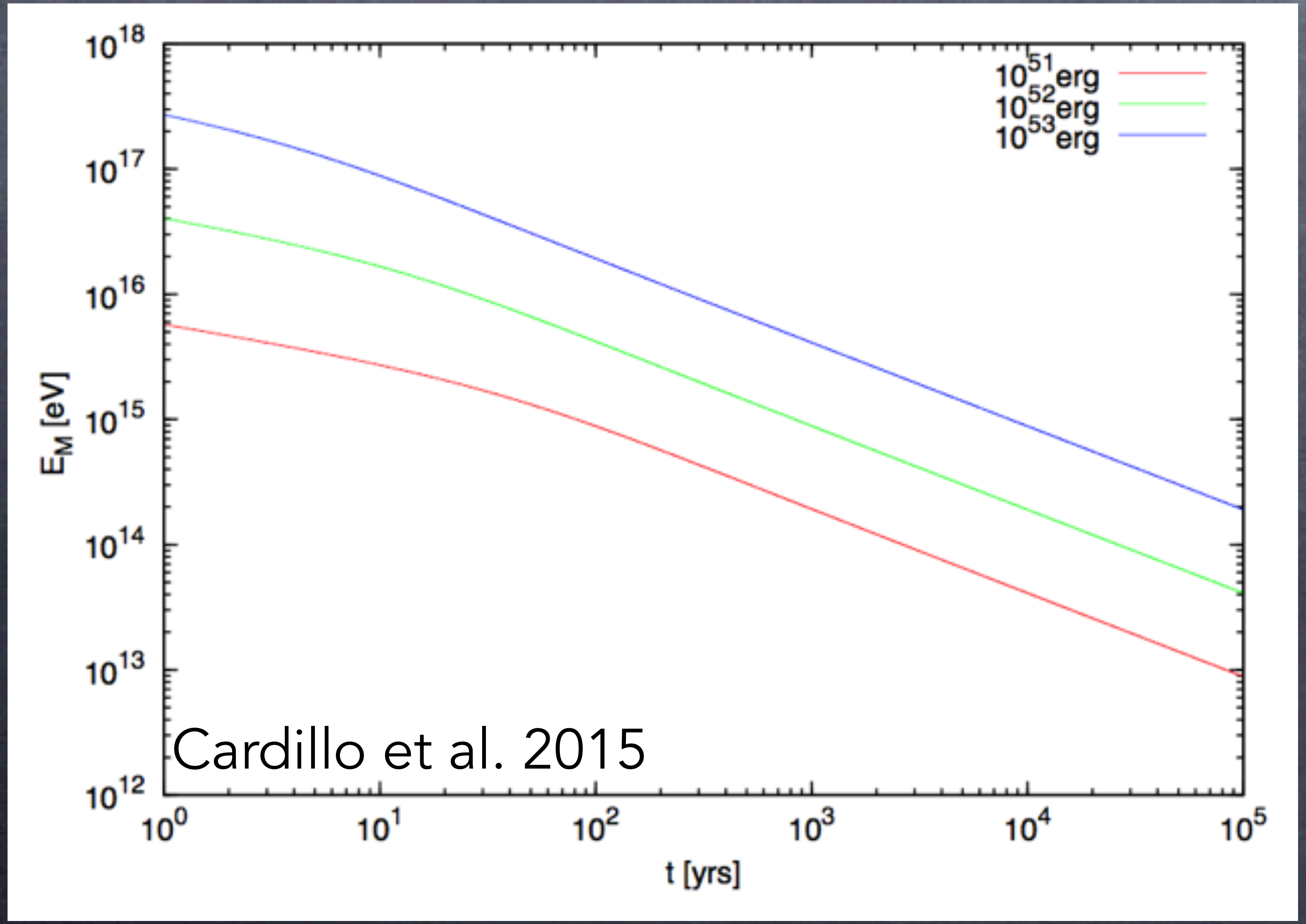


- CR spectra from diffusion-convection eq.
- Acceleration efficiency. ~10%
- SNR hydrodynamics
- Protons up to ~0.5 PeV

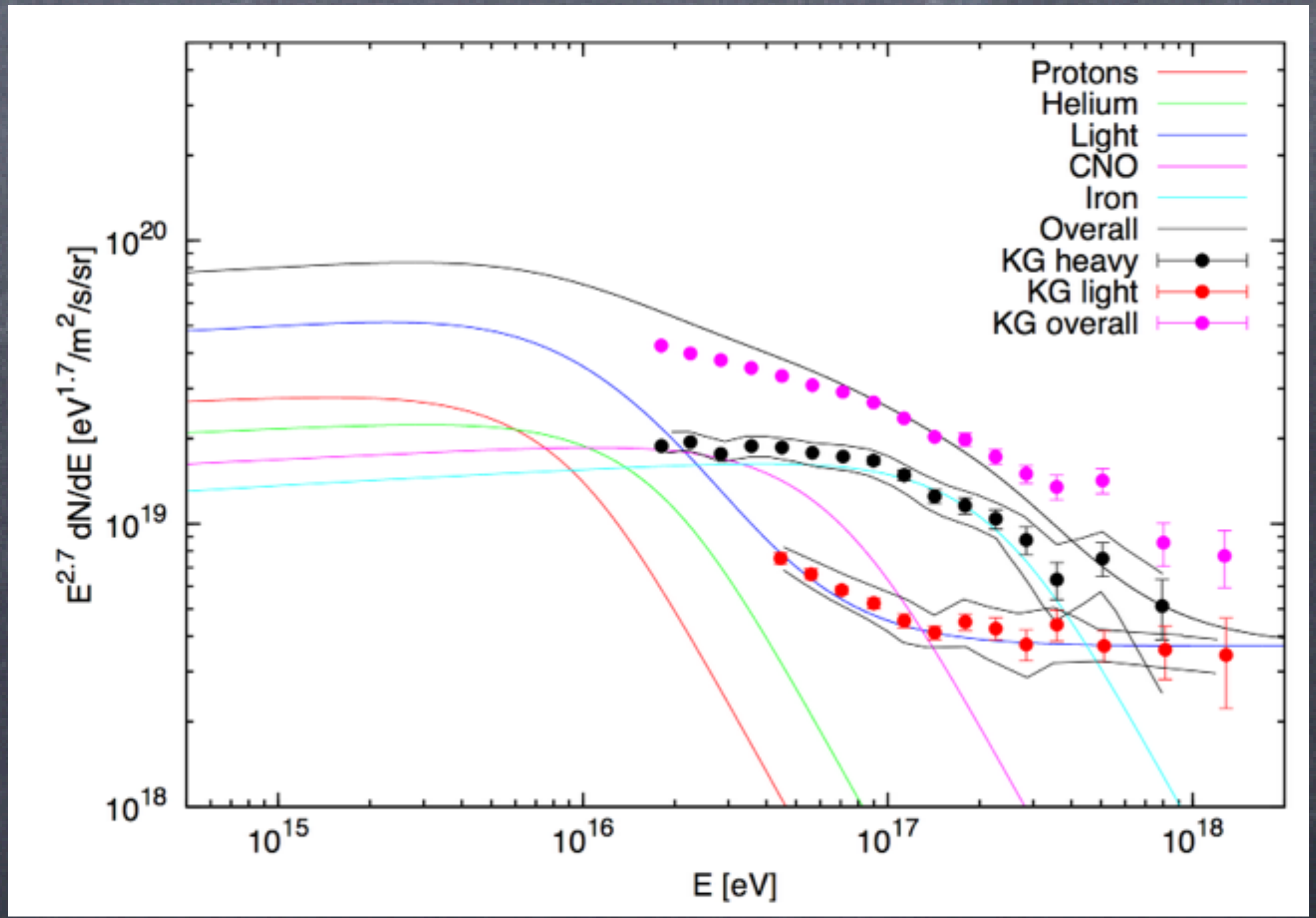
- Code publicly-available soon as CRAFT: *Cosmic-Ray Analytical Fast Tool* (DC et al. 2015)

Escape from PeVatrons

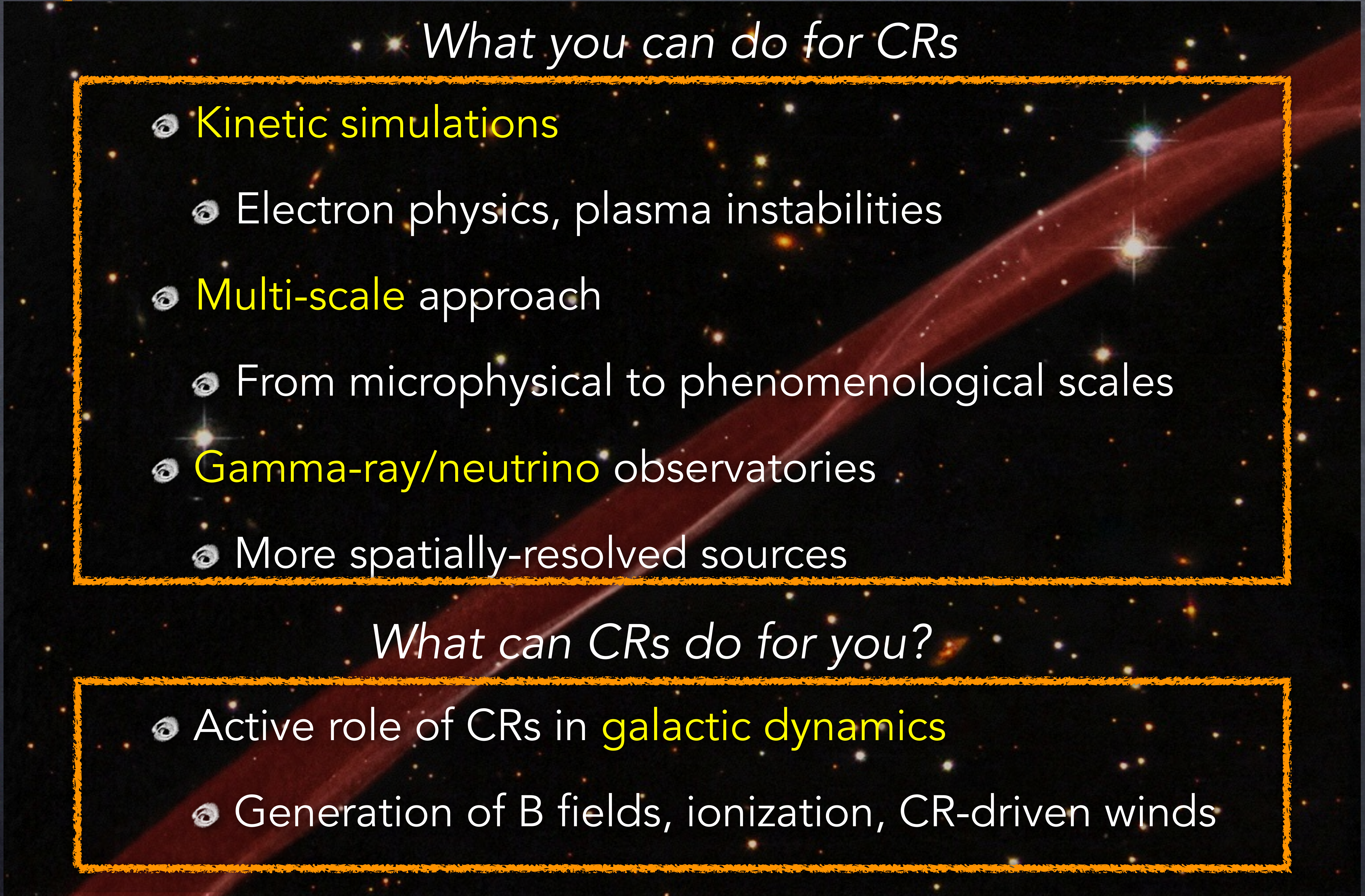
- The released spectrum is likely a convolution over instantaneous (monochromatic) spectra (Ptuskin & Zirakashvili 2005; DC et al. 2009, 2010; Bell et al. 2013; Cardillo et al. 2015)
  - The CR power-law may reflect the self-similar SNR evolution, rather than acceleration!
  - Escaping CRs illuminate 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



What do we need to better understand CRs?



What you can do for CRs

- Kinetic simulations
  - Electron physics, plasma instabilities
- Multi-scale approach
  - From microphysical to phenomenological scales
- Gamma-ray/neutrino observatories
  - More spatially-resolved sources

What can CRs do for you?

- Active role of CRs in galactic dynamics
  - Generation of B fields, ionization, CR-driven winds

End