European Cosmic Ray Symposium
September 7, 2016 — Turin, Italy

Cosmic-Ray Acceleration

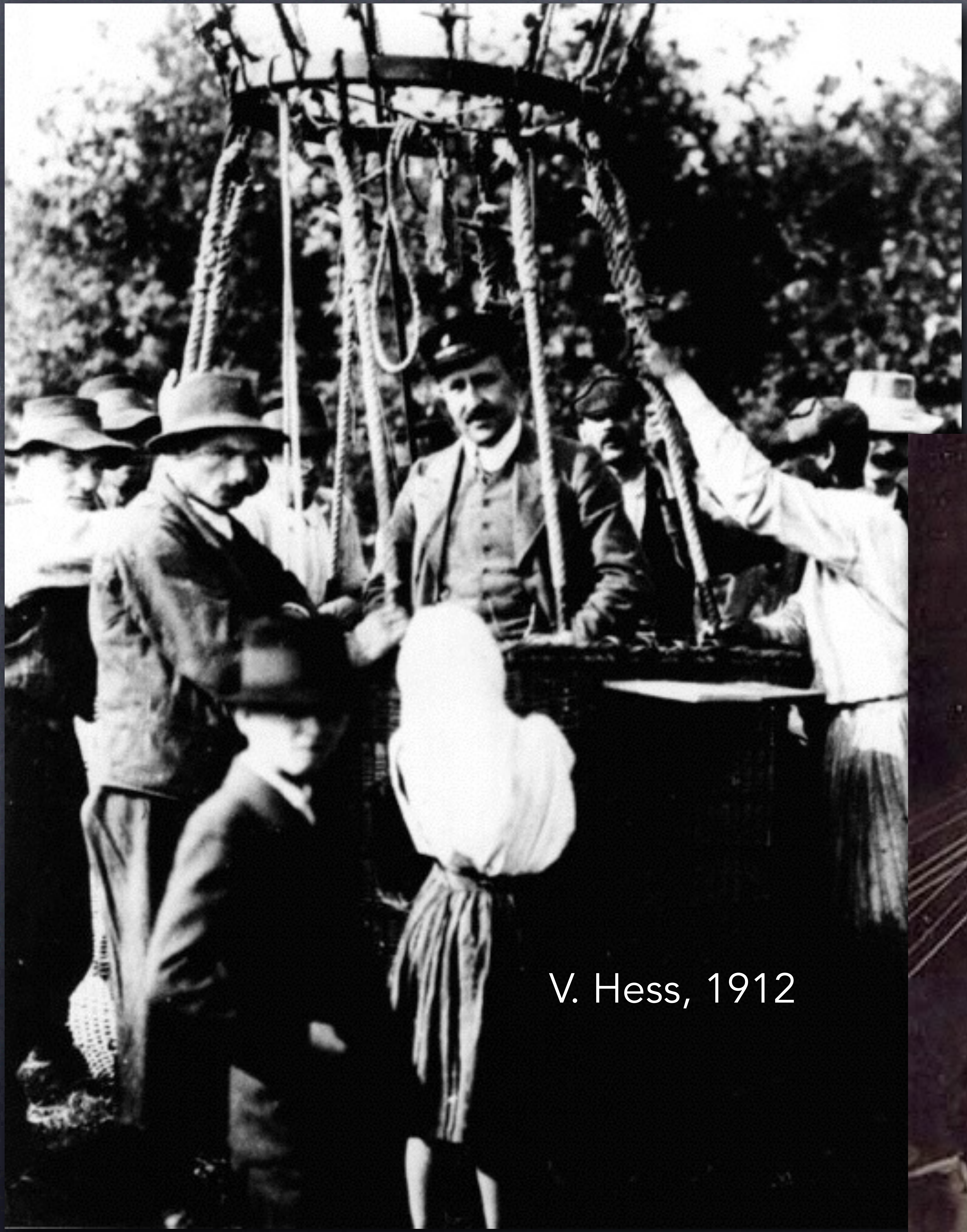
(and Propagation)

Damiano Caprioli
Princeton University

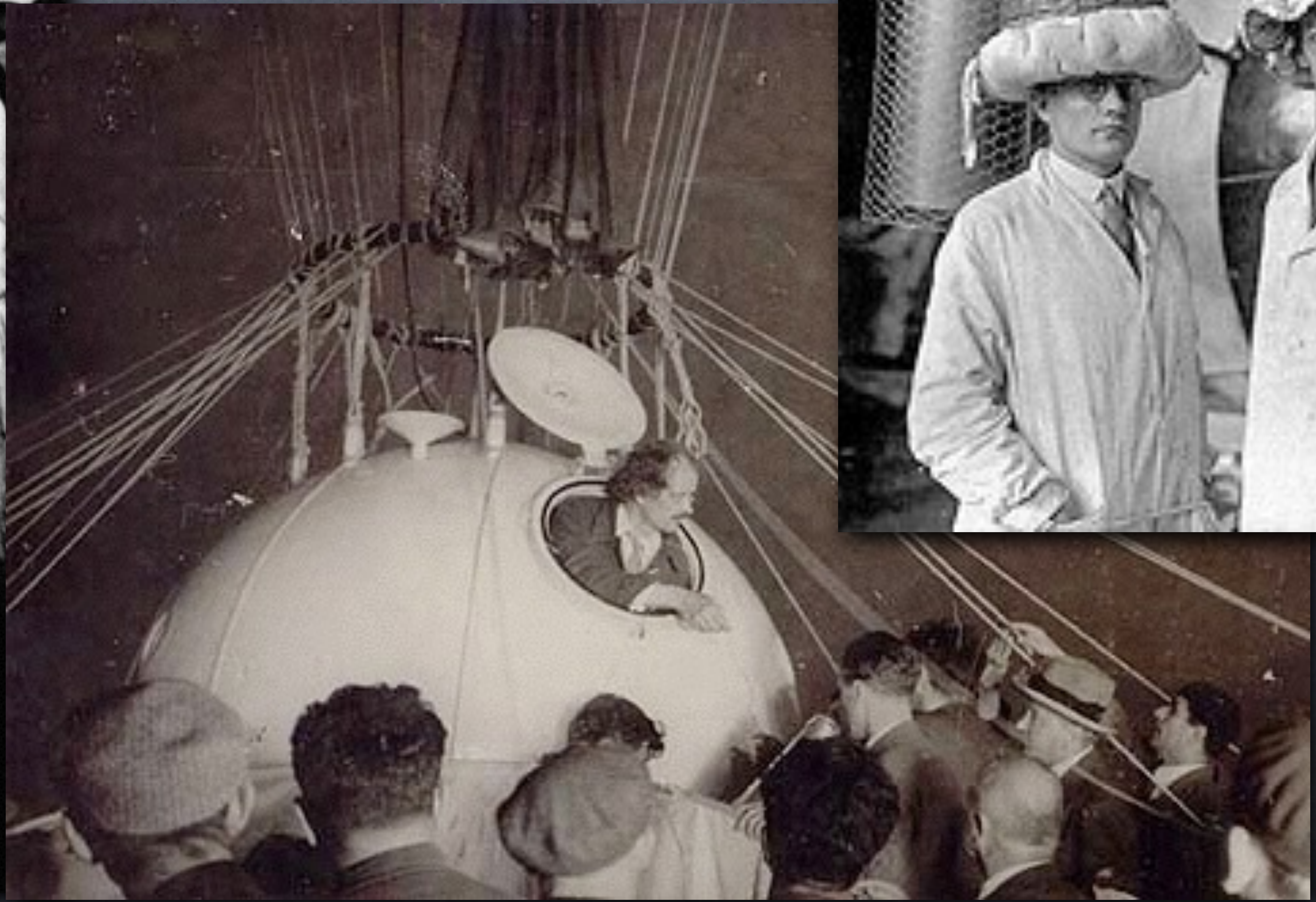
soon at the University of Chicago

An extraterrestrial radiation!

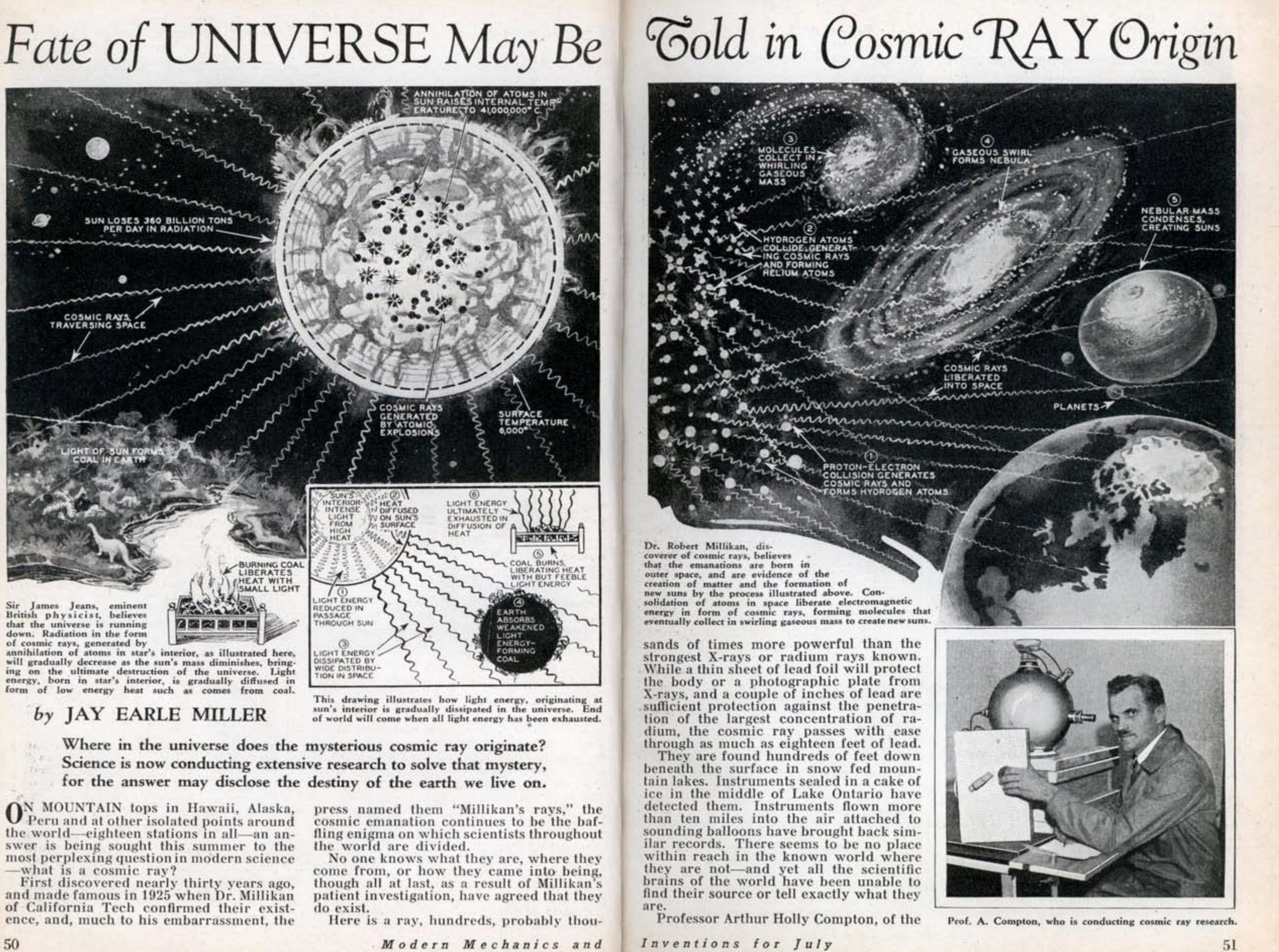
- 1912: V. Hess discovers an extraterrestrial source of ionization: Cosmic Rays!
- 1932: A. Piccard reaches the stratosphere (in a pressurized aluminum gondola attached to a ballon) to measure CRs!



V. Hess, 1912



A. Piccard, 1932



Fate of UNIVERSE May Be Told in Cosmic RAY Origin

Sir James Jeans, eminent British physicist, believes that the universe is running down. Radiation in the form of cosmic rays, generated by annihilation of atoms in star's interior, as illustrated here, will gradually decrease as the sun's mass diminishes, bringing on the ultimate destruction of the universe. Light energy, born in star's interior, is gradually diffused in form of low energy heat such as comes from coal.

This drawing illustrates how light energy, originating at sun's interior is gradually dissipated in the universe. End of world will come when all light energy has been exhausted.

Dr. Robert Millikan, discoverer of cosmic rays, believes that the emanations are born in outer space, and are evidence of the creation of matter and the formation of new suns by the process illustrated above. Consolidation of atoms in space liberate electromagnetic energy in form of cosmic rays, forming molecules that eventually collect in swirling gaseous mass to create new suns.

by JAY EARLE MILLER

Where in the universe does the mysterious cosmic ray originate? Science is now conducting extensive research to solve that mystery, for the answer may disclose the destiny of the earth we live on.

ON MOUNTAIN tops in Hawaii, Alaska, Peru and at other isolated points around the world—eighteen stations in all—an answer is being sought this summer to the most perplexing question in modern science—what is a cosmic ray?

First discovered nearly thirty years ago, and made famous in 1925 when Dr. Millikan of California Tech confirmed their existence, and, much to his embarrassment, the press named them "Millikan's rays," the cosmic emanation continues to be the baffling enigma on which scientists throughout the world are divided.

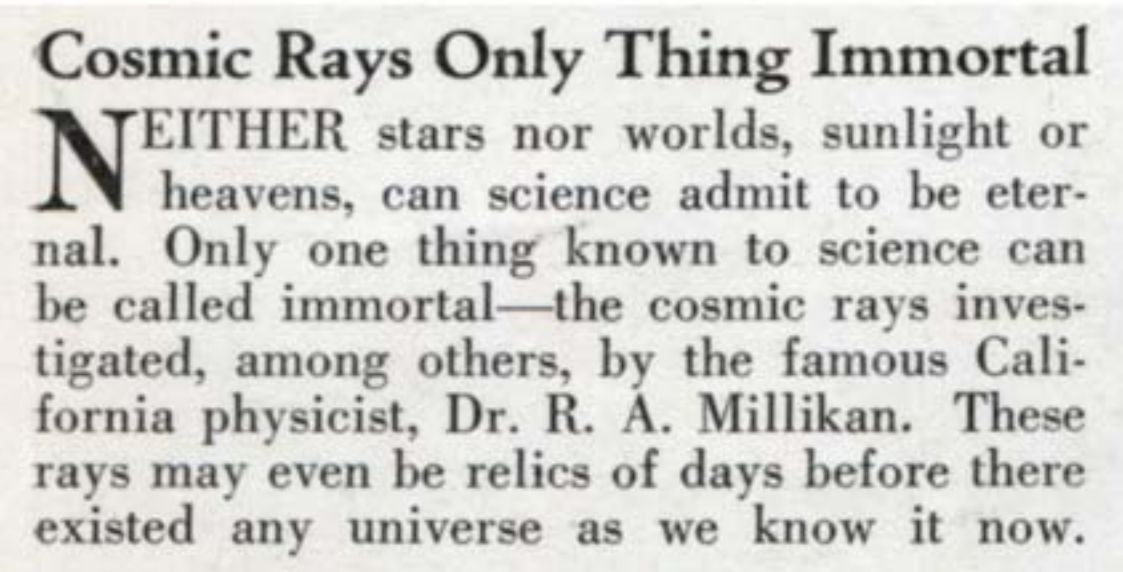
No one knows what they are, where they come from, or how they came into being, though all at last, as a result of Millikan's patient investigation, have agreed that they do exist.

Here is a ray, hundreds, probably thousands of times more powerful than the strongest X-rays or radium rays known. While a thin sheet of lead foil will protect the body or a photographic plate from X-rays, and a couple of inches of lead are sufficient protection against the penetration of the largest concentration of radium, the cosmic ray passes with ease through as much as eighteen feet of lead.

They are found hundreds of feet down beneath the surface in snow fed mountain lakes. Instruments sealed in a cake of ice in the middle of Lake Ontario have detected them. Instruments flown more than ten miles into the air attached to sounding balloons have brought back similar records. There seems to be no place within reach in the known world where they are not—and yet all the scientific brains of the world have been unable to find their source or tell exactly what they are.

Professor Arthur Holly Compton, of the

Prof. A. Compton, who is conducting cosmic ray research.



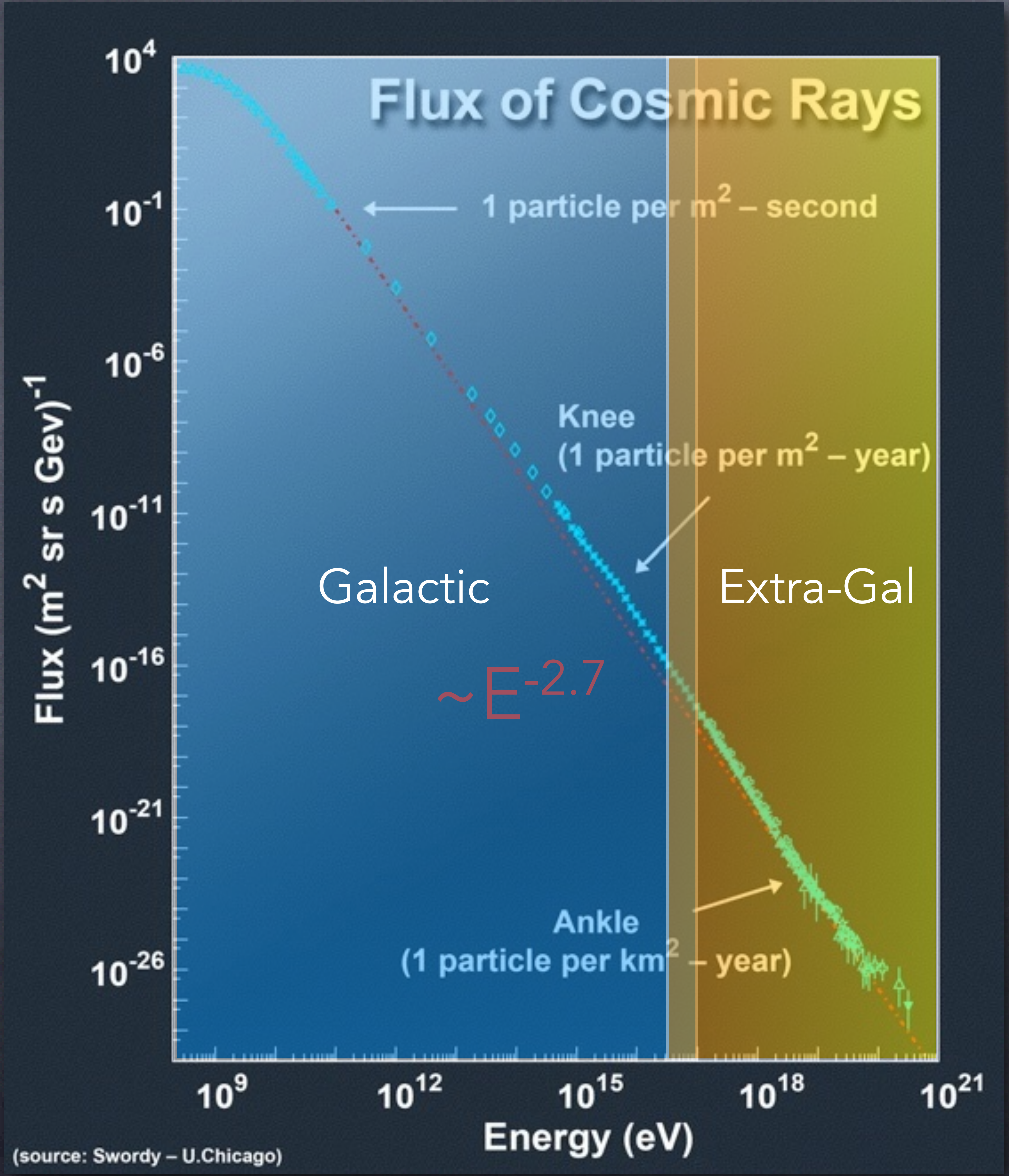
Cosmic Rays Only Thing Immortal

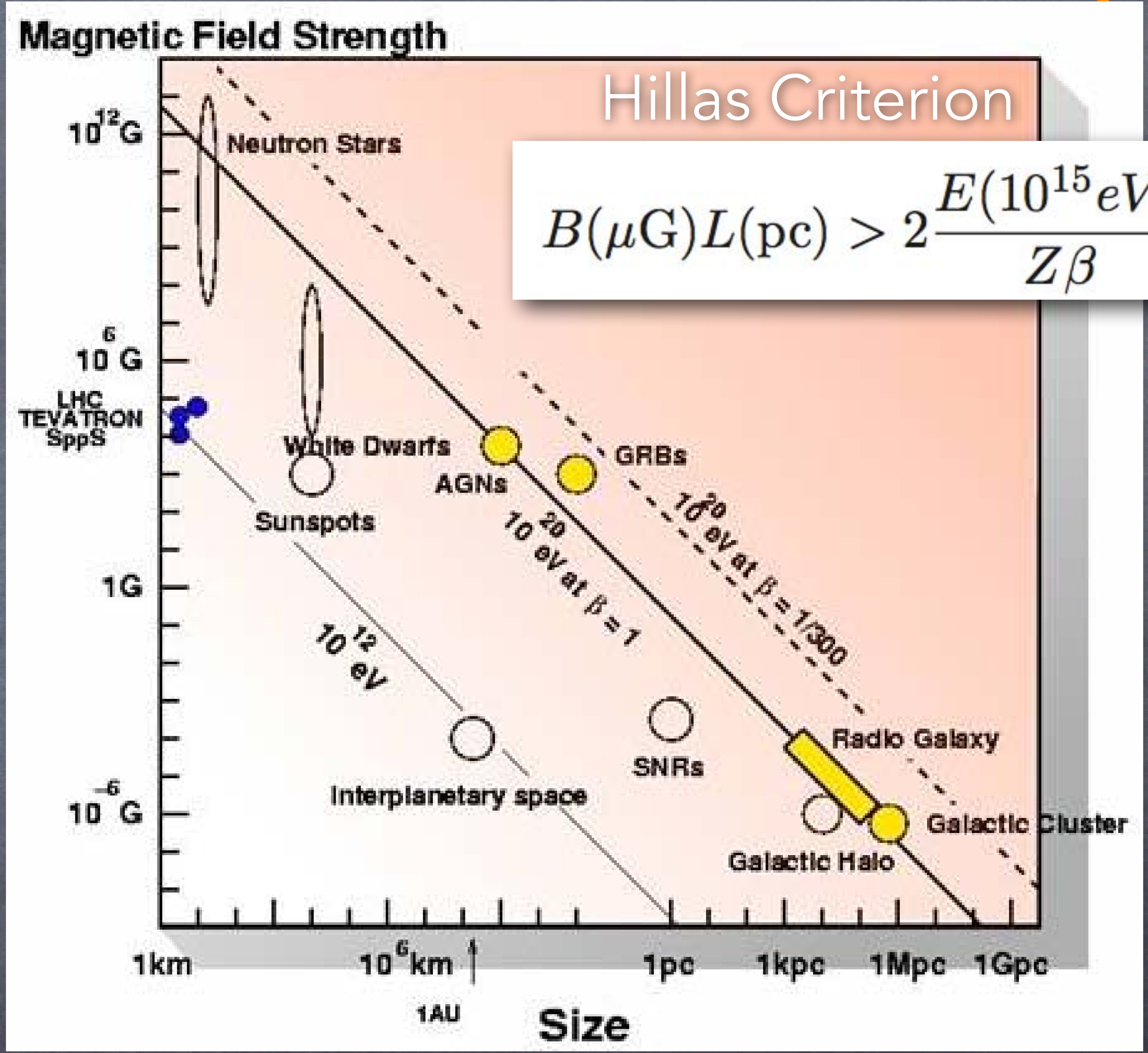
NEITHER stars nor worlds, sunlight or heavens, can science admit to be eternal. Only one thing known to science can be called immortal—the cosmic rays investigated, among others, by the famous California physicist, Dr. R. A. Millikan. These rays may even be relics of days before there existed any universe as we know it now.

Modern Mechanics (1932)

- J. Jeans: produced in star interiors
- R. Millikan: "Cosmic Rays" are the "birth cry" of new atoms being created to withstand entropy
- A. Compton: CRs charged particles

Cosmic Rays: Hunt for Sources

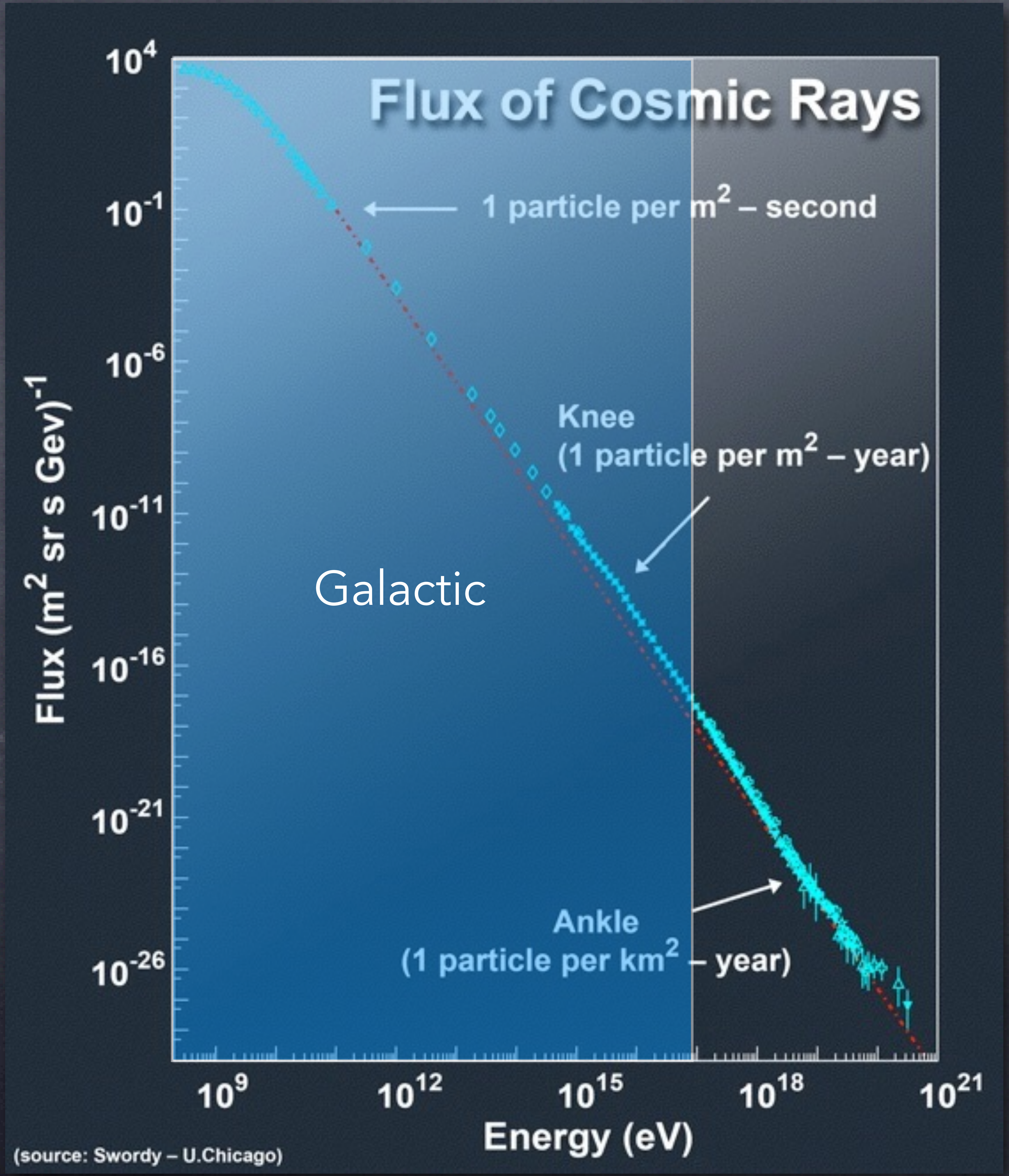


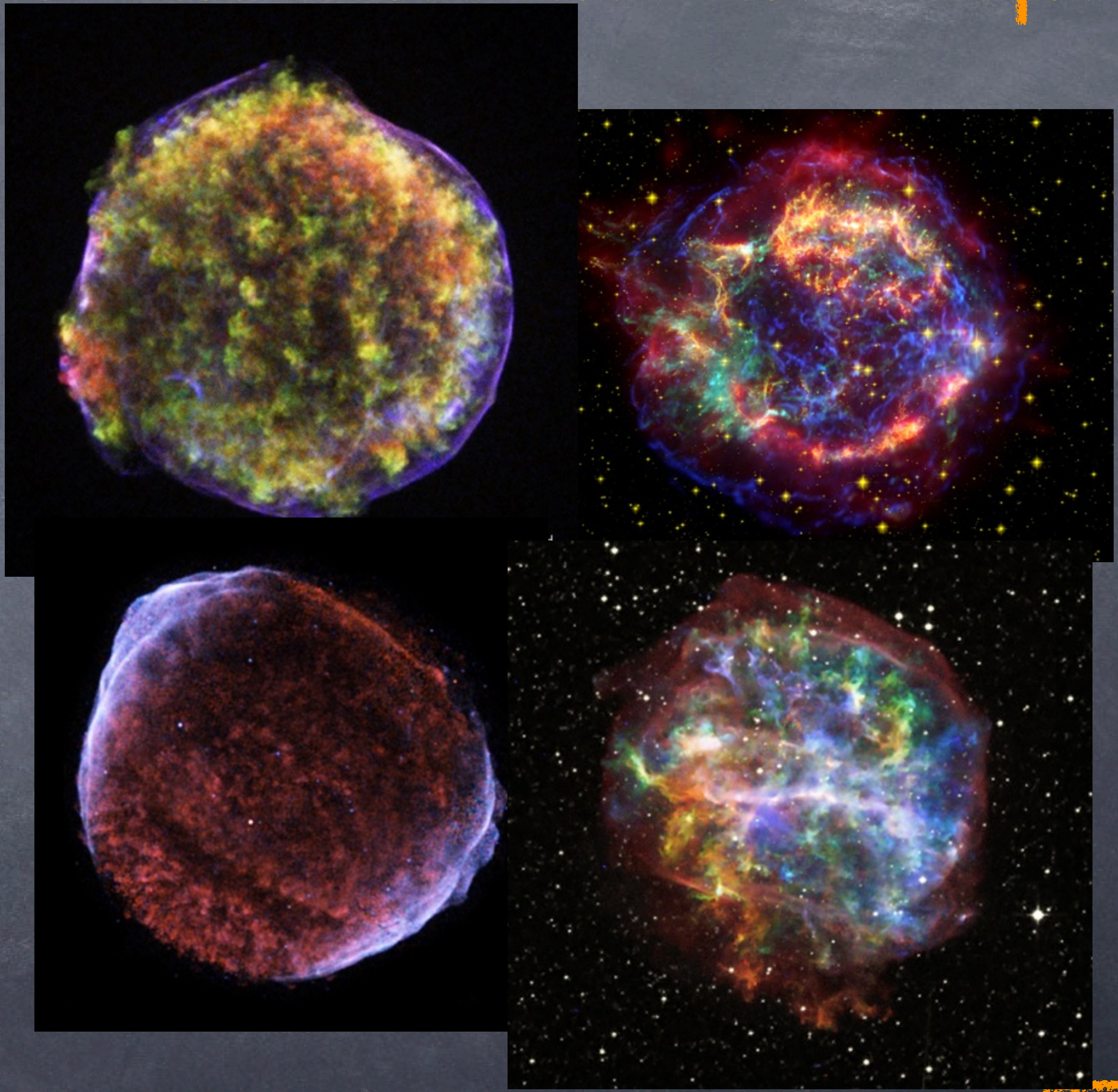


$$B(\mu\text{G})L(\text{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Remarkable power-law (plus "leg" features)
- The steepening at ~3PeV suggests a rigidity-dependent cut-off

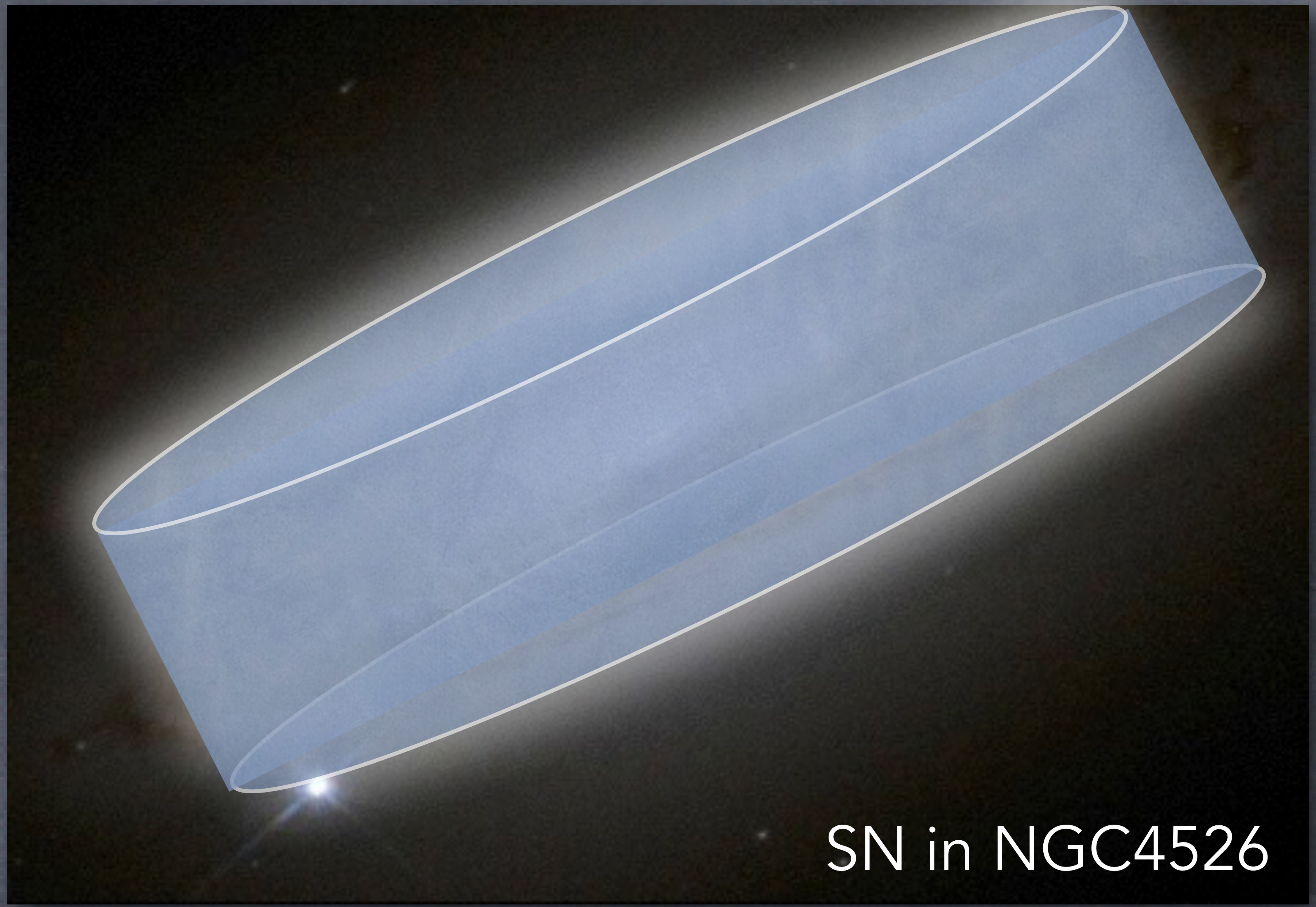
SNR Paradigm for Galactic Cosmic Rays





SNR paradigm: energetics

- Baade-Zwicky (1934) energetic argument, updated



$$\varepsilon_{CR} = 0.5 eV cm^{-3}$$

$$V_{conf} = \pi R^2 h = 2 \times 10^{67}\ cm^3$$

$$W_{CR} = \varepsilon_{CR} V_{conf} \approx 2 \times 10^{55}\ erg$$

$$L_{CR} \approx \frac{W_{CR}}{\tau_{conf}} \approx 5 \times 10^{40}\ erg\ s^{-1}$$

$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41}\ erg\ s^{-1}$$

~10% of SN ejecta kinetic energy converted into CRs can account for the energetics

A universal acceleration mechanism

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

- d et al.; 1978)

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

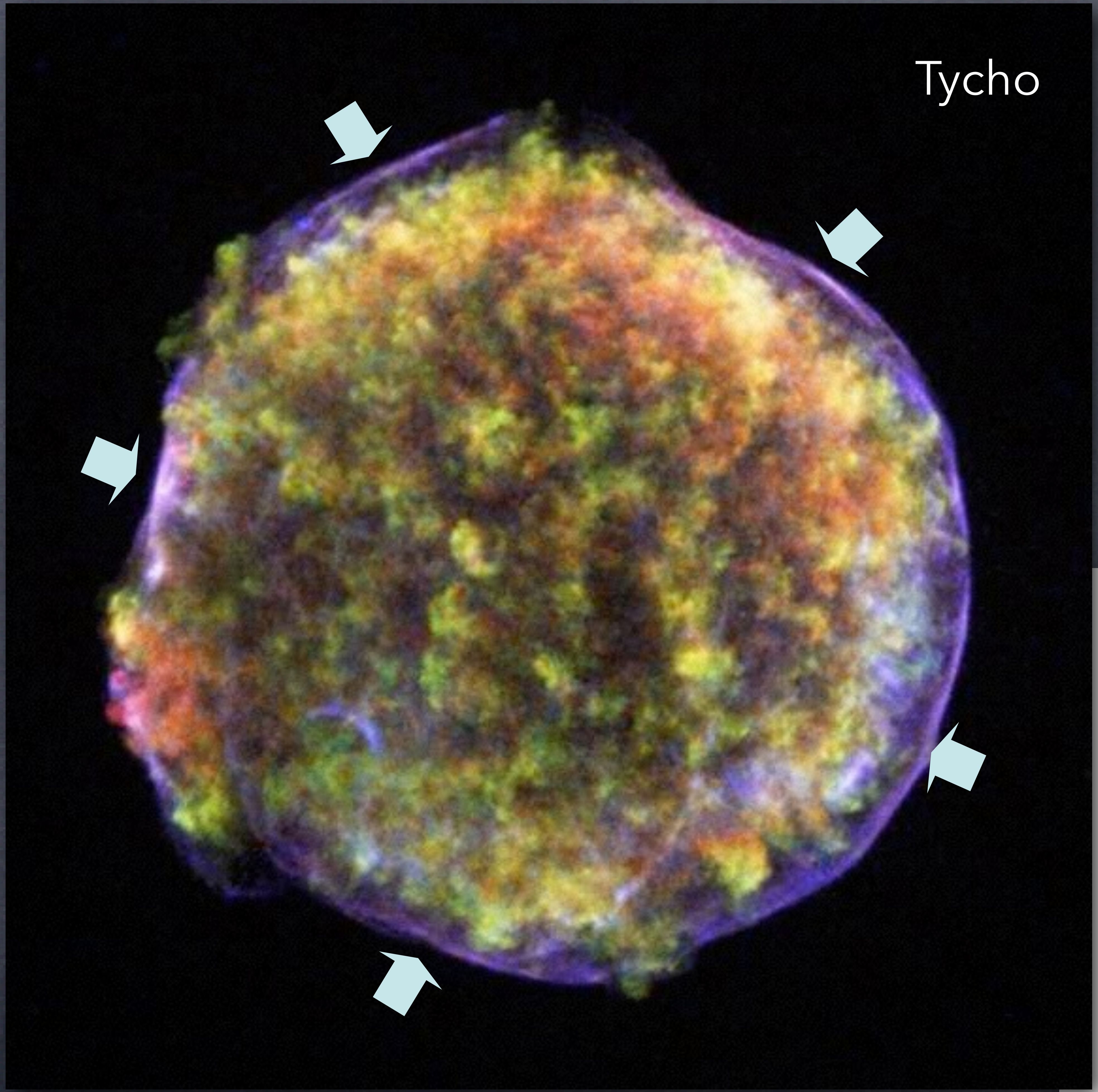
A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the 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.

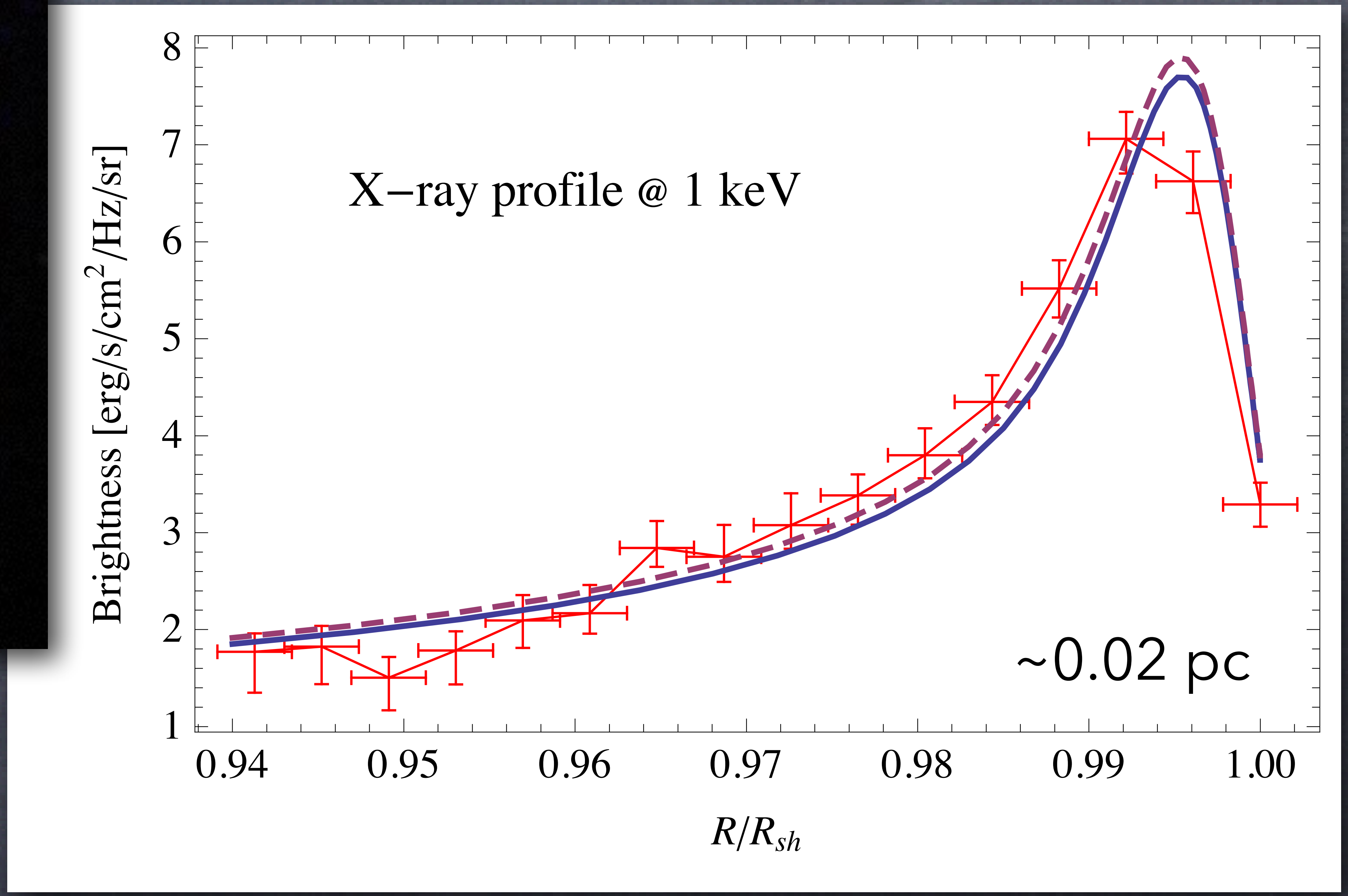
$$R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}$$

  - For strong shocks (Mach number $M_s=V_{sh}/c_s>>1$): 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;
Uchiyama et al. 2007;
Cassam-Chenaï et al. 2008;
Morlino & DC 2012;
Slane et al. 2014;
Ressler et al. 2014;

SNR paradigm: Conclusions?

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

BUT

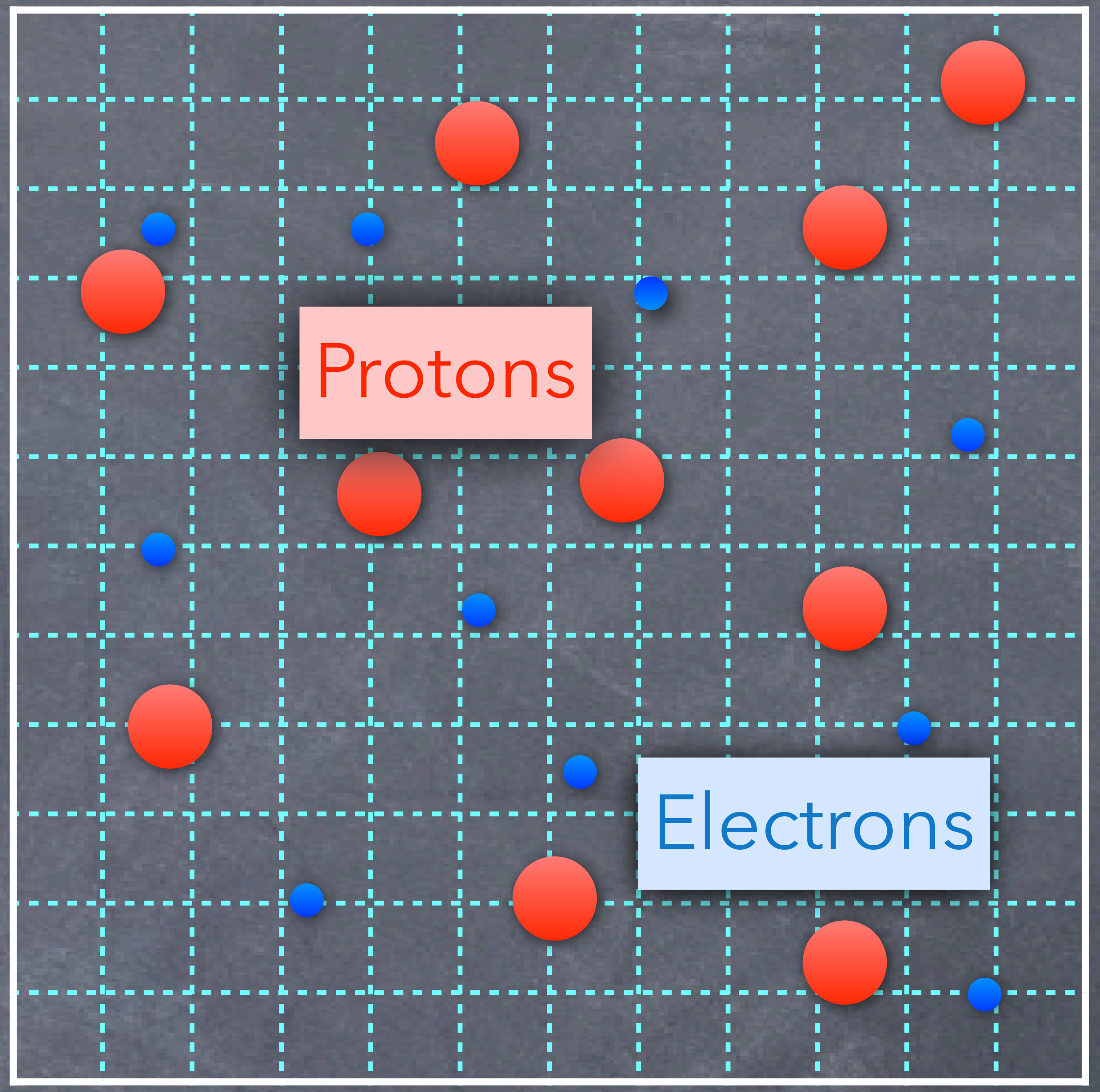
- Is acceleration at shocks efficient? When?
- How do CRs amplify the magnetic field?
- How are particles injected in DSA?

Collisionless shocks

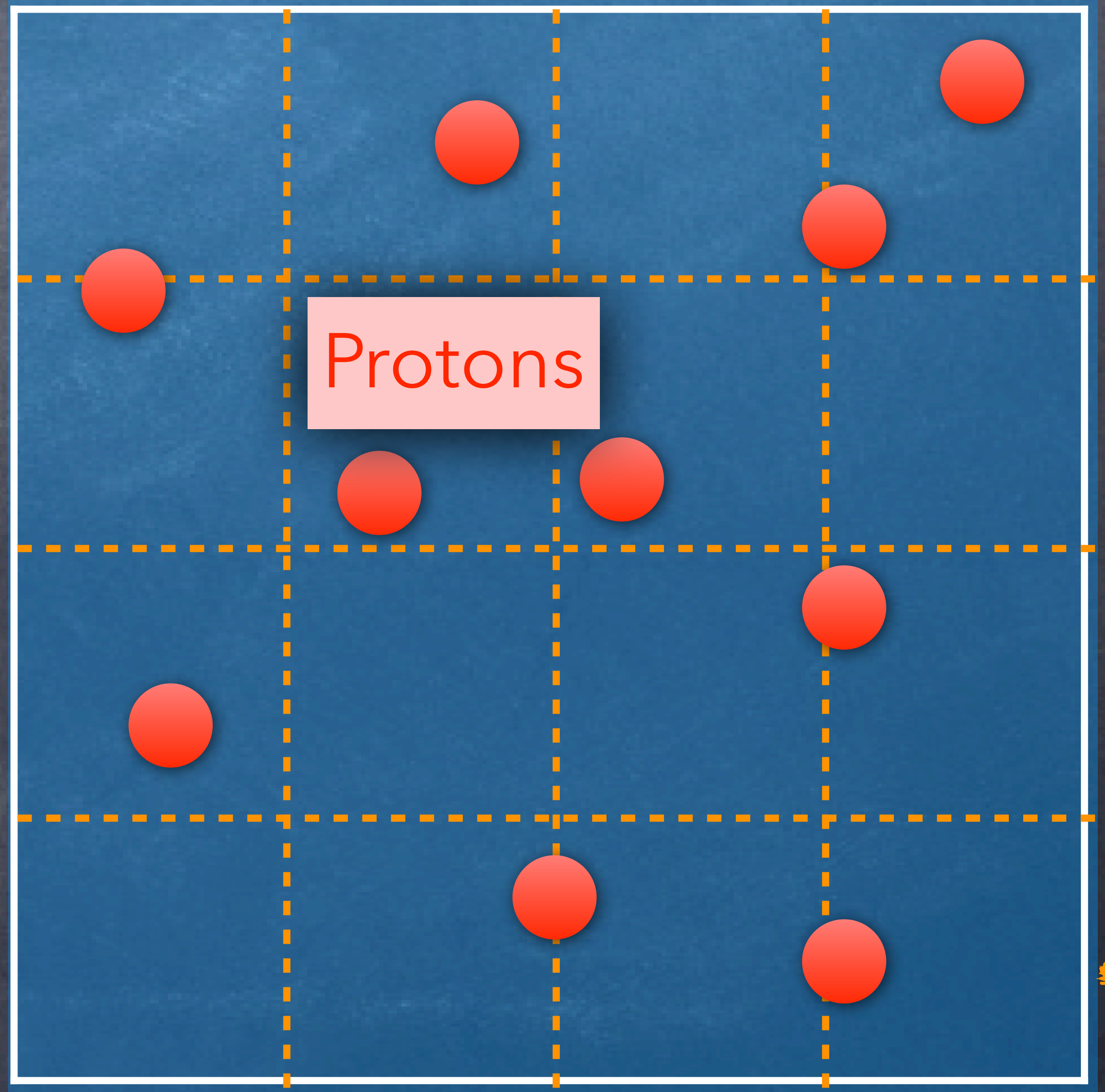
- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity

Astroplasmas from first principles

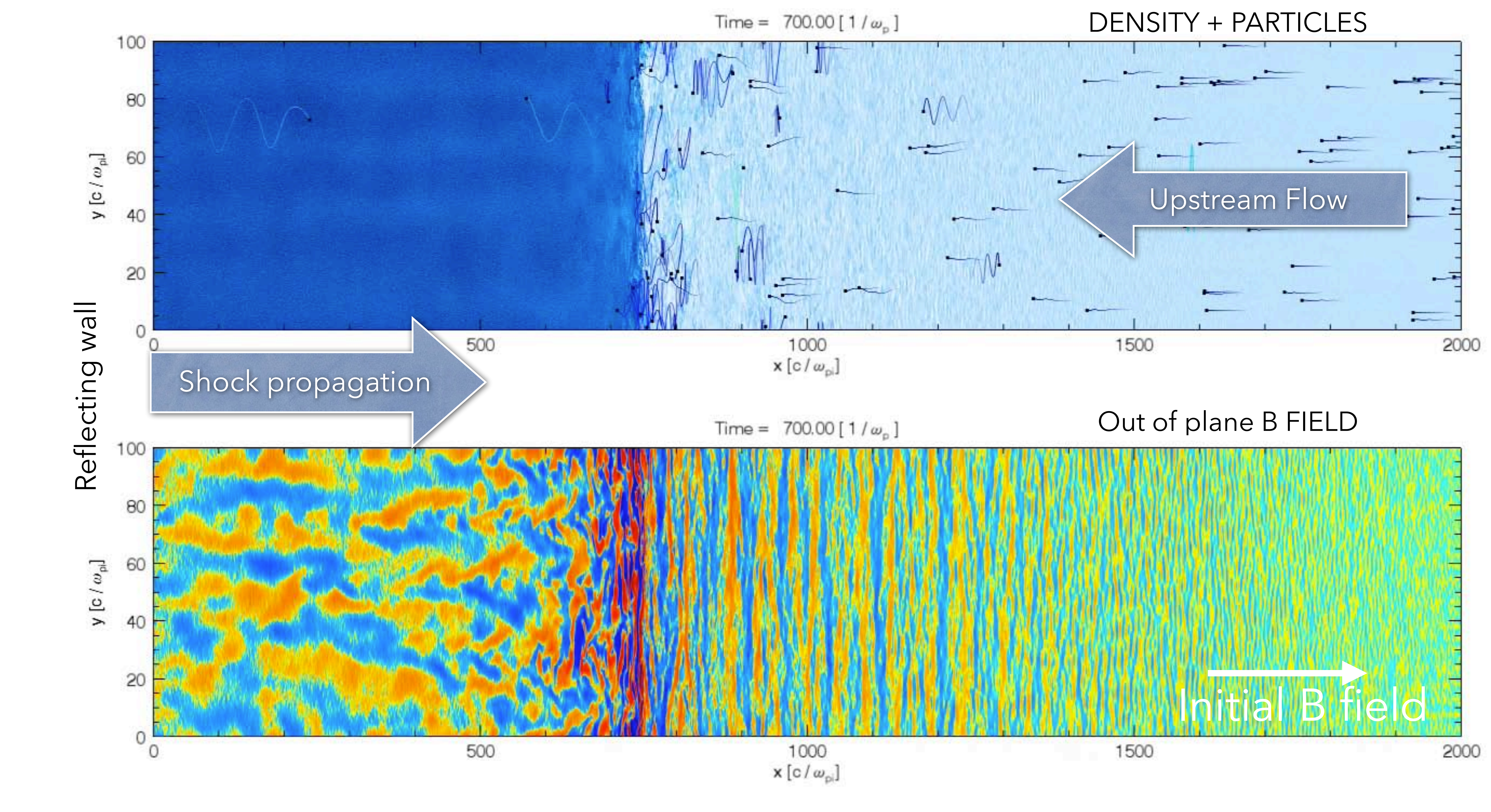
- Full particle in cell approach
  (…, Spitkovsky 2008; Amano & Hoshino 2007, 2010; Niemiec et al. 2008, 2012; Stroman et al. 2009; Riquelme & Spitkovsky 2010; Park et al. 2012; Guo et al. 2014; DC et al. 2015…)
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve 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



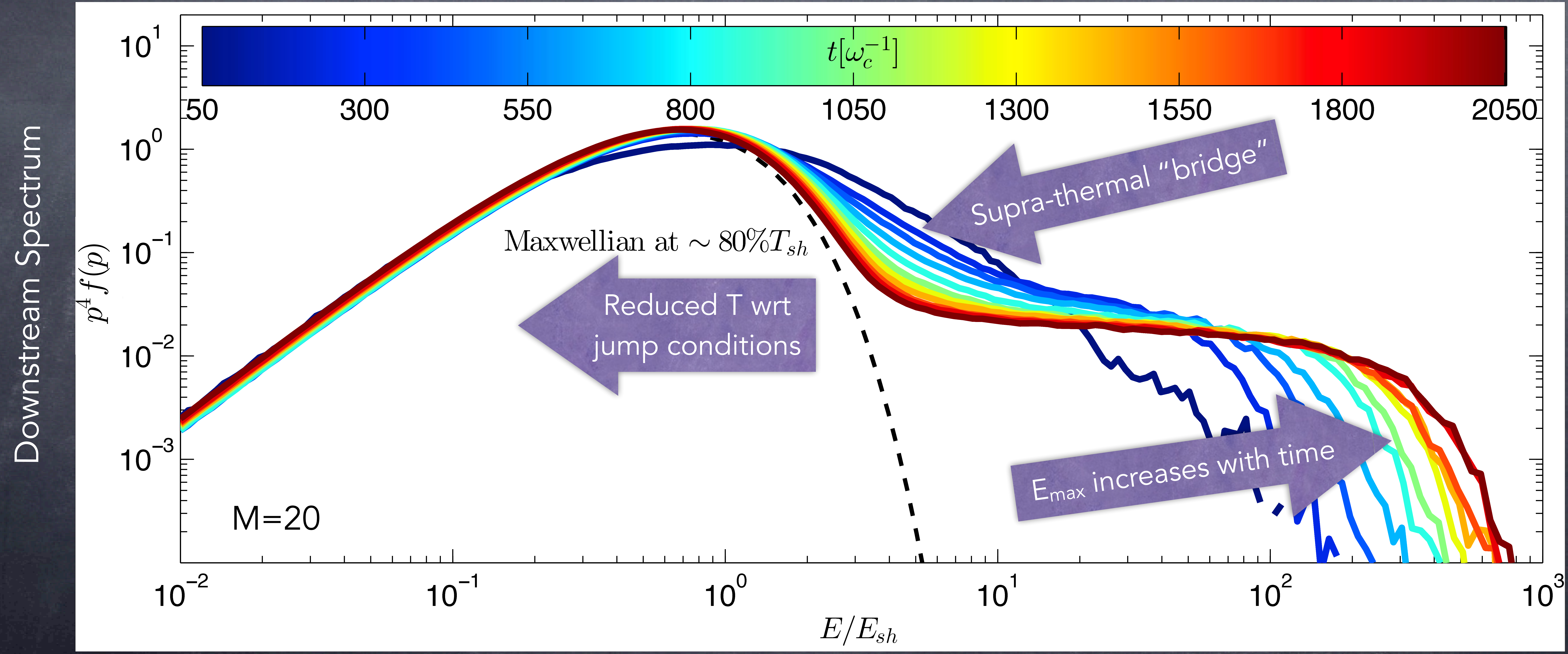
Hybrid simulations of collisionless shocks



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

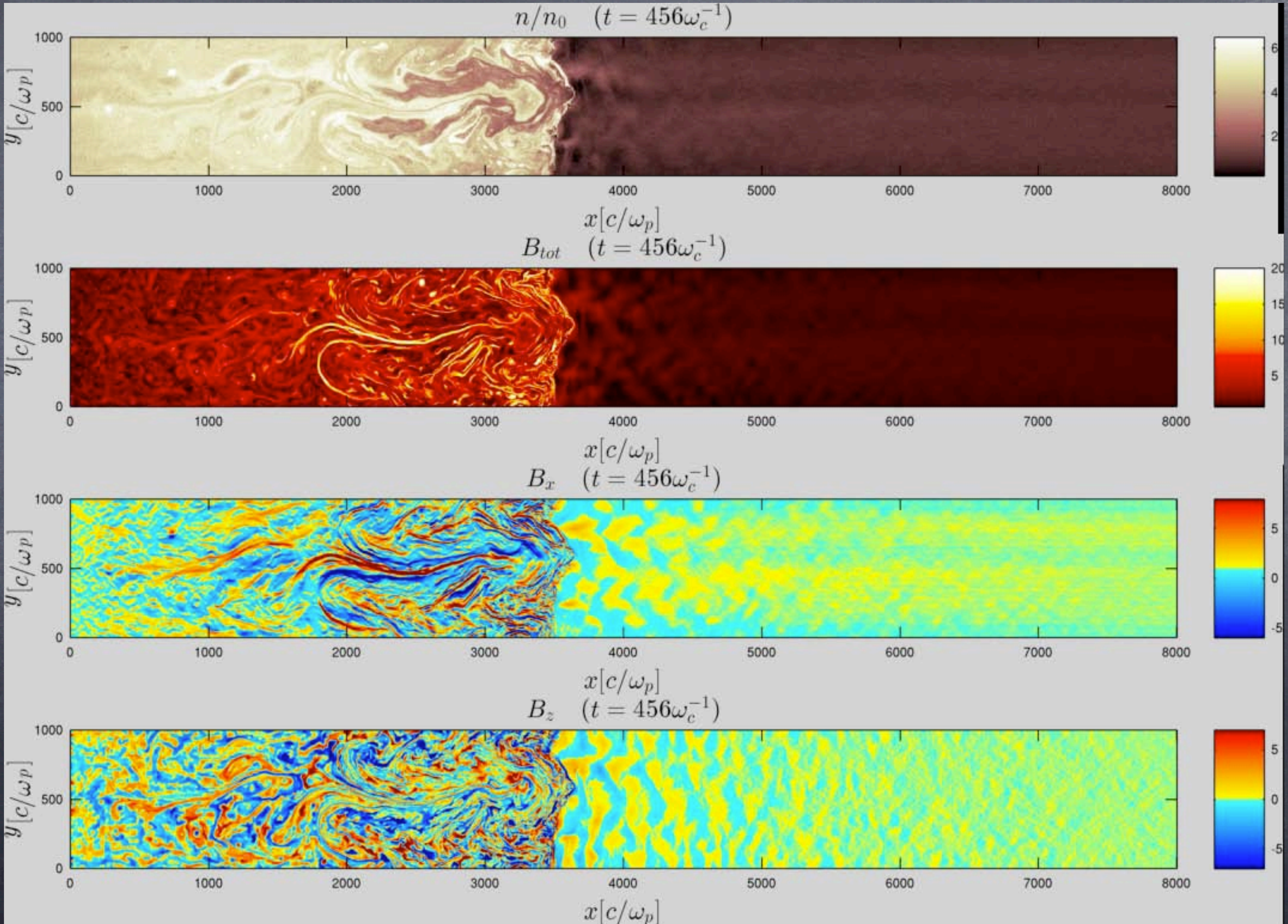
Spectrum evolution

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



DC & Spitkovsky, 2014a

CR-driven instability

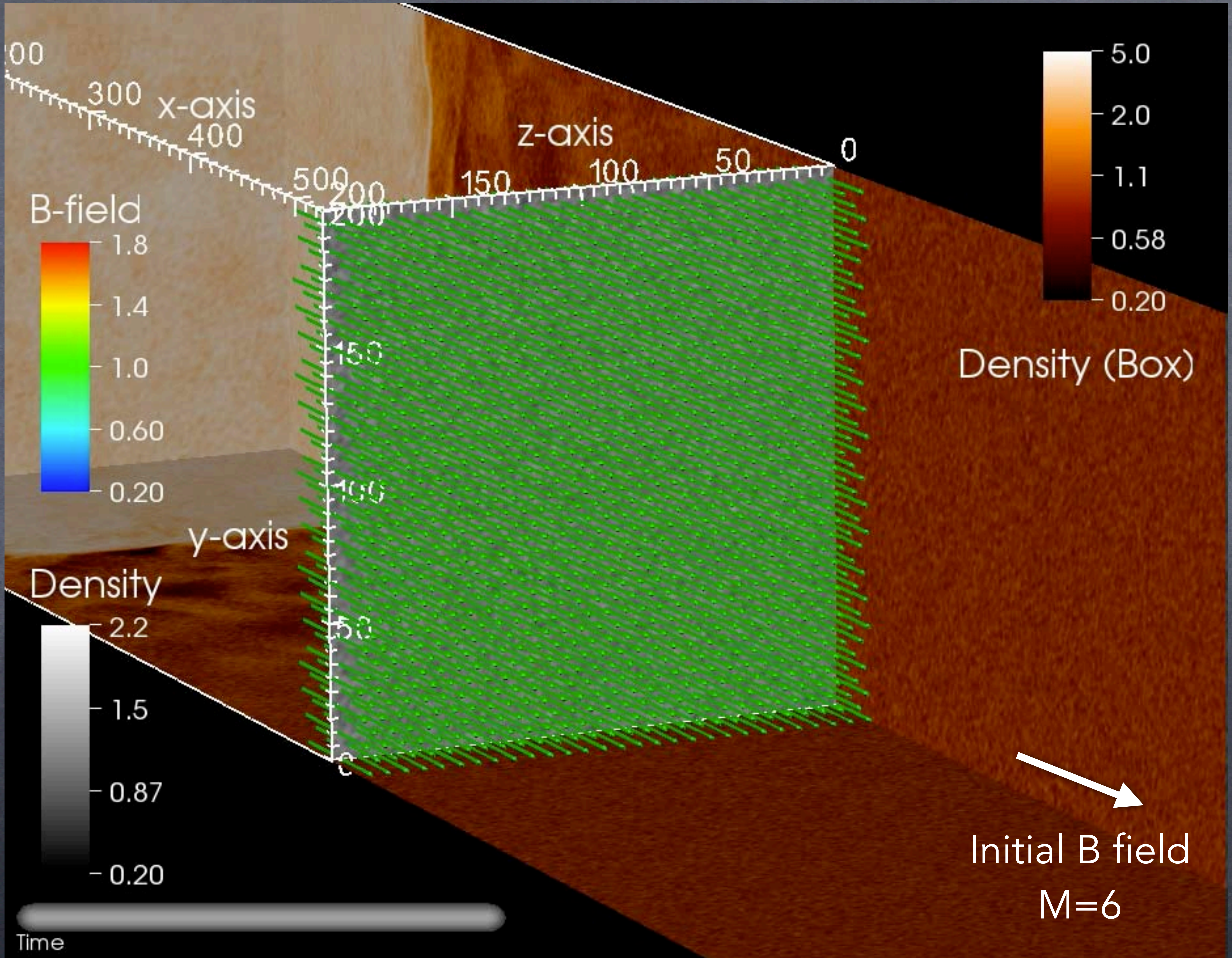


Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

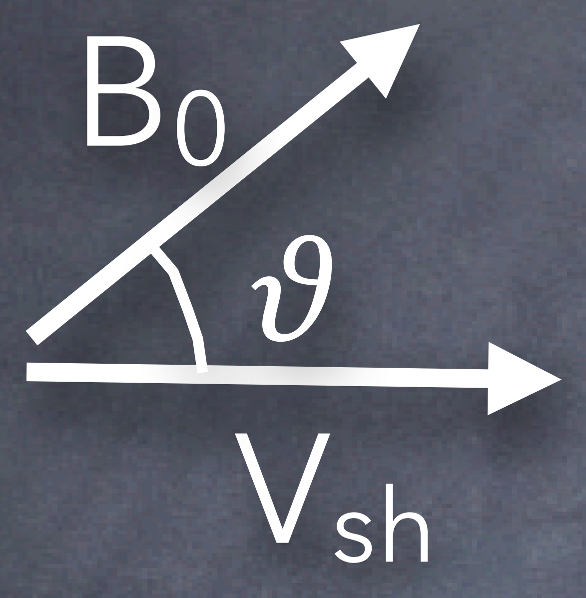
3D simulations of a parallel shock

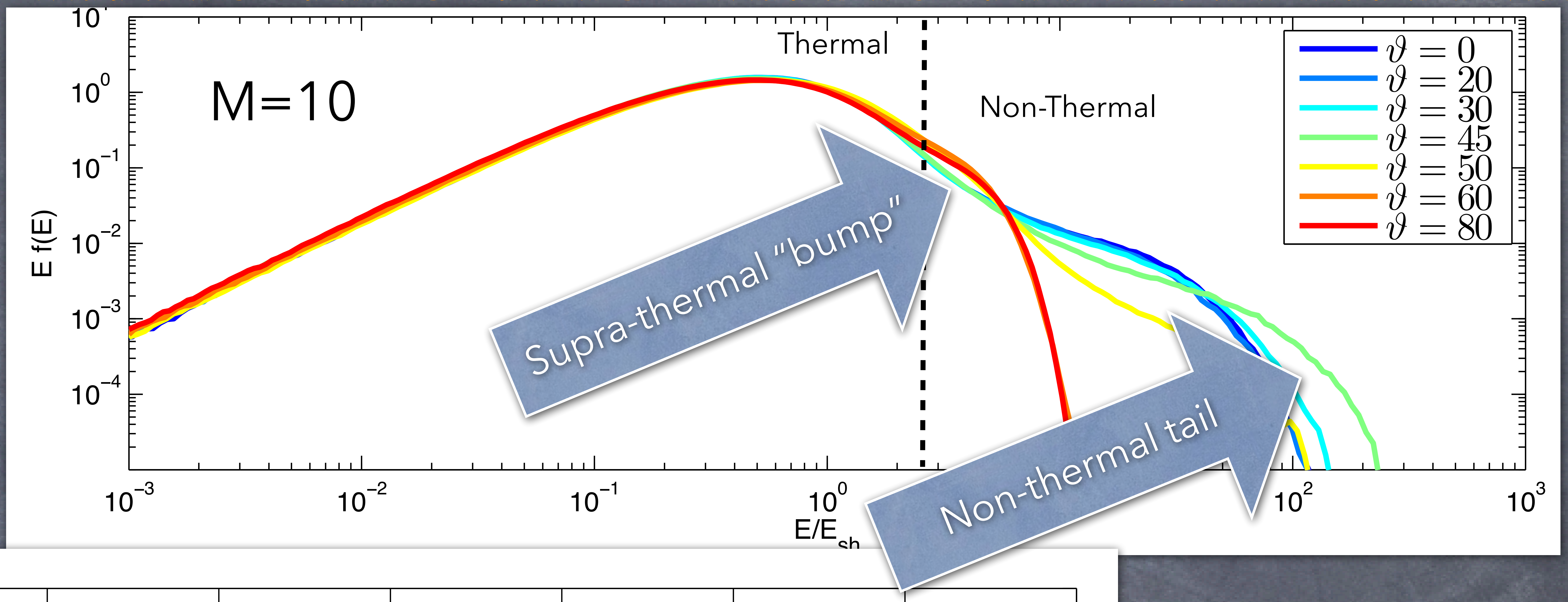


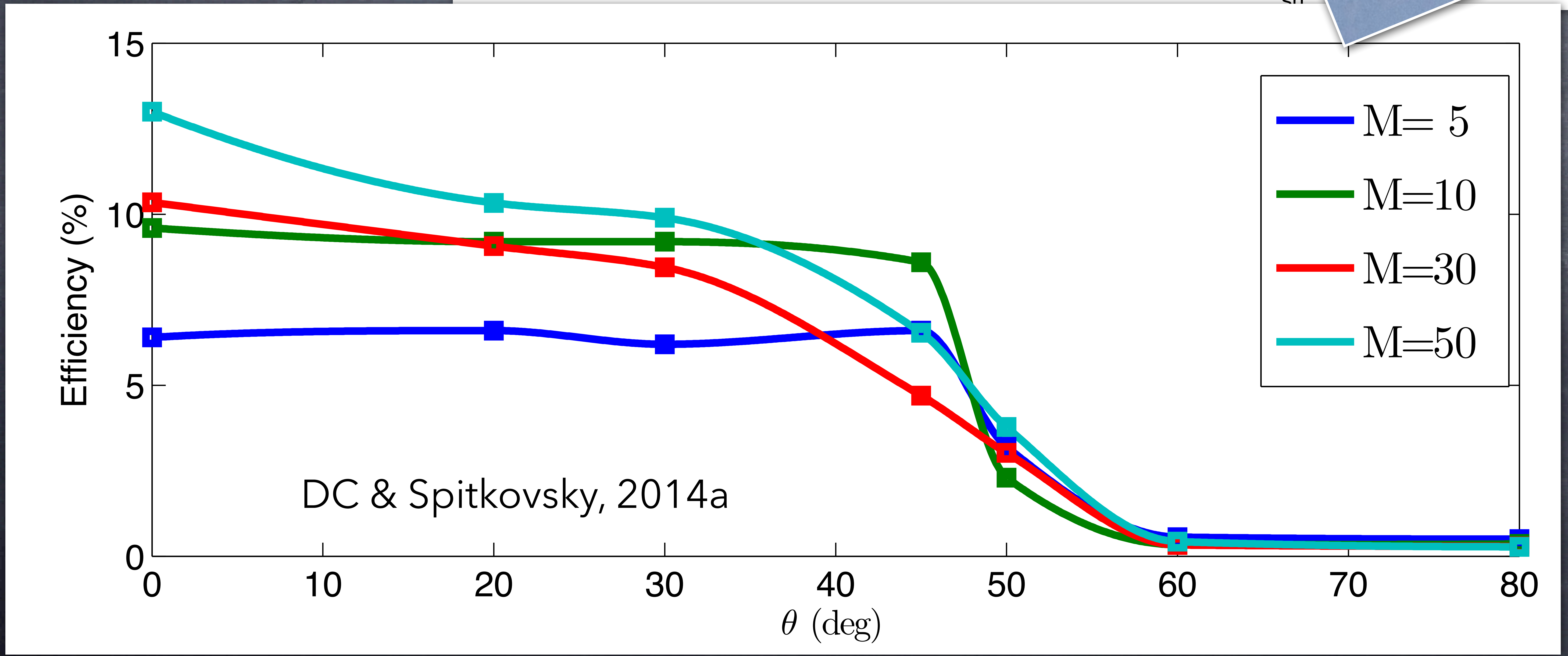
DC & Spitkovsky, 2014a

Parallel vs Oblique shocks

Shock inclination

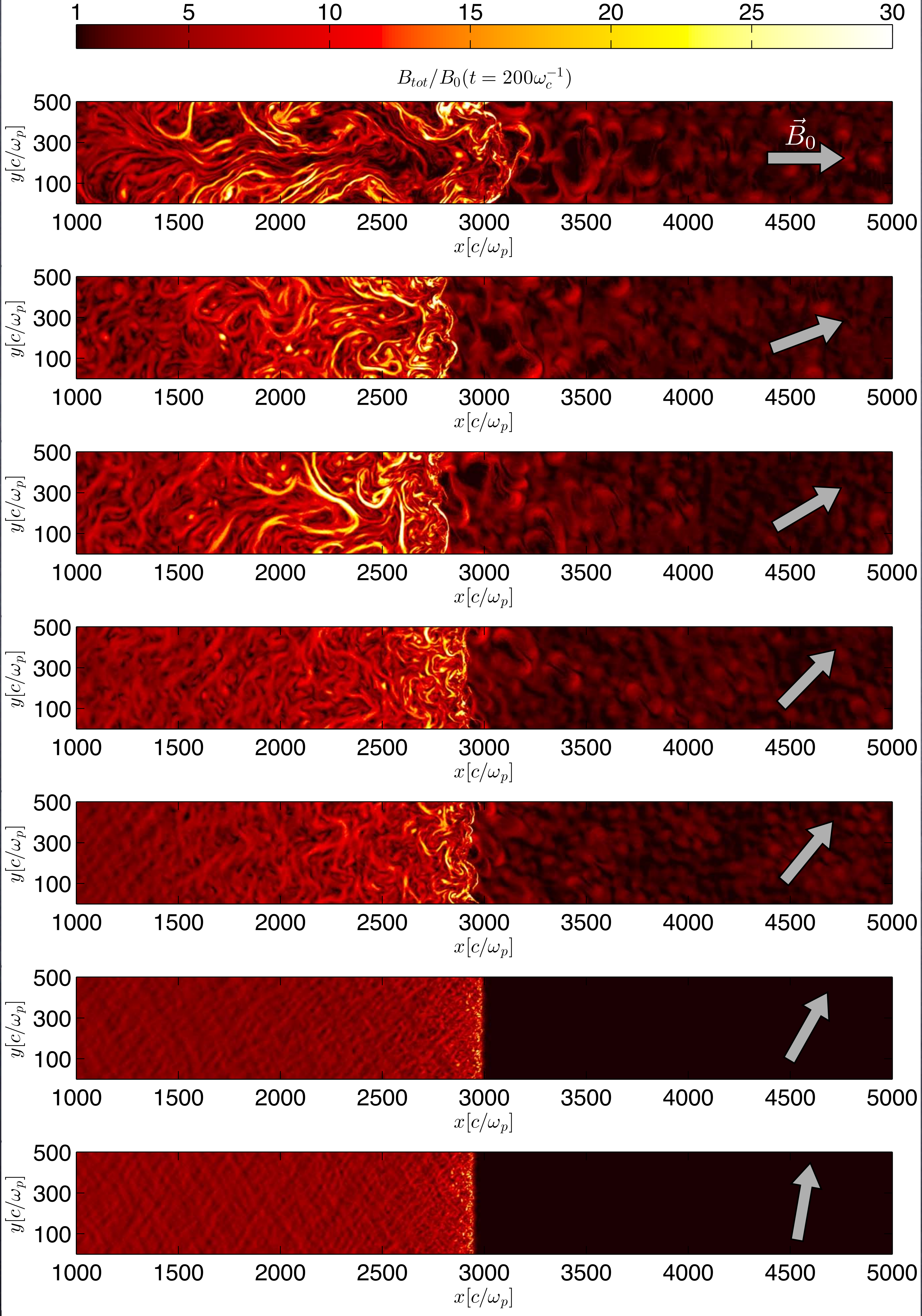


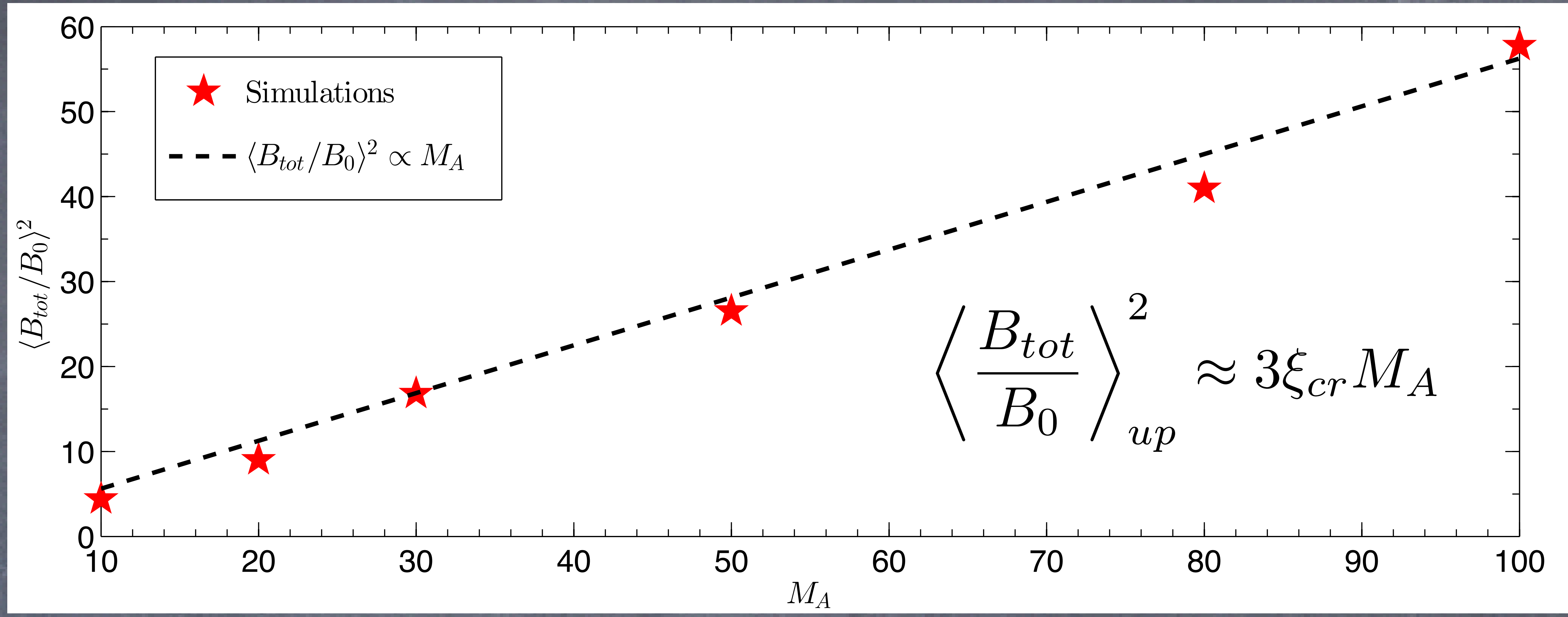




Each point is a simulation with billions of particles

Dependence on shock strength (M_A) and inclination

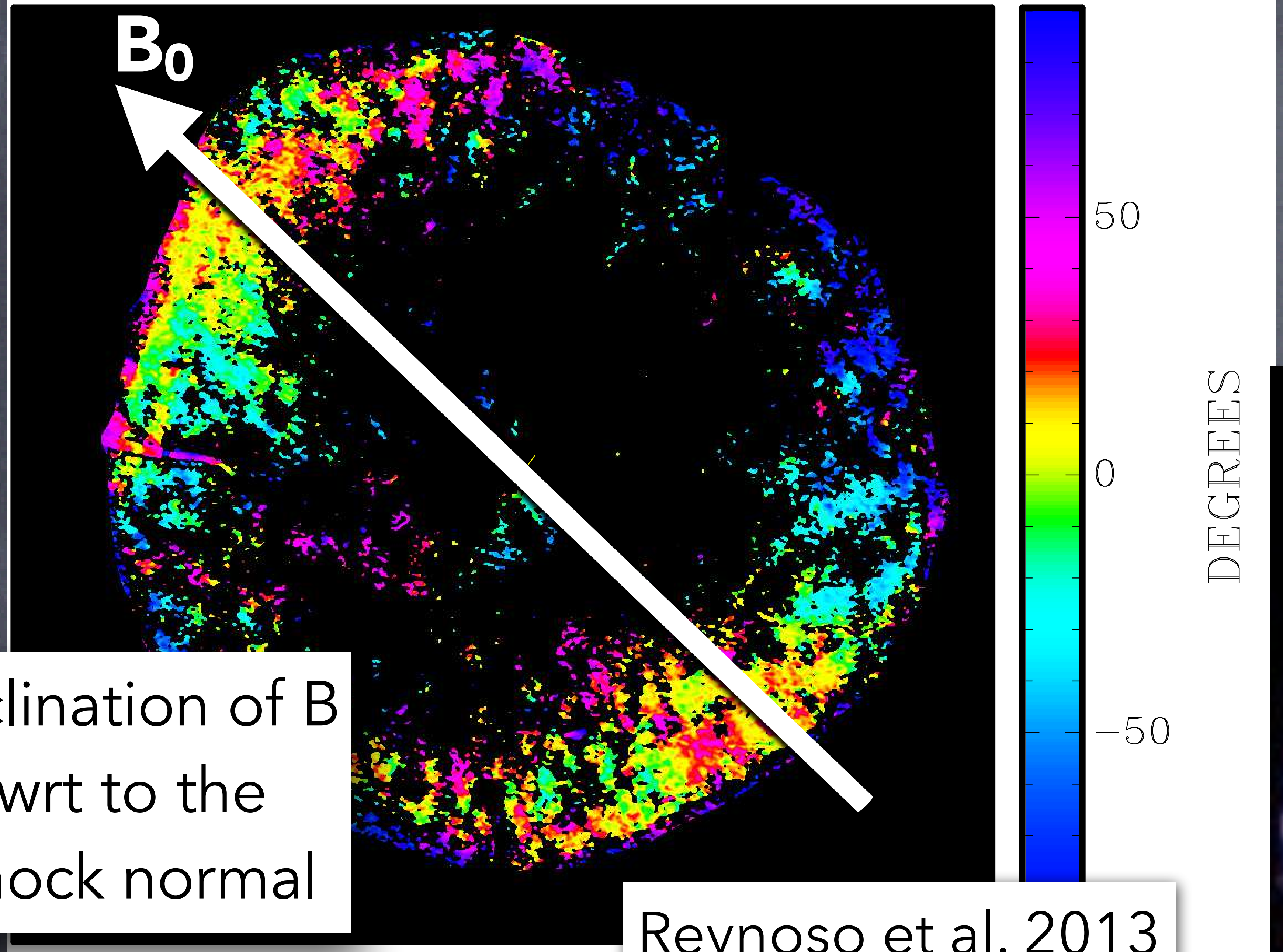




More B amplification for stronger (higher M_A) shocks

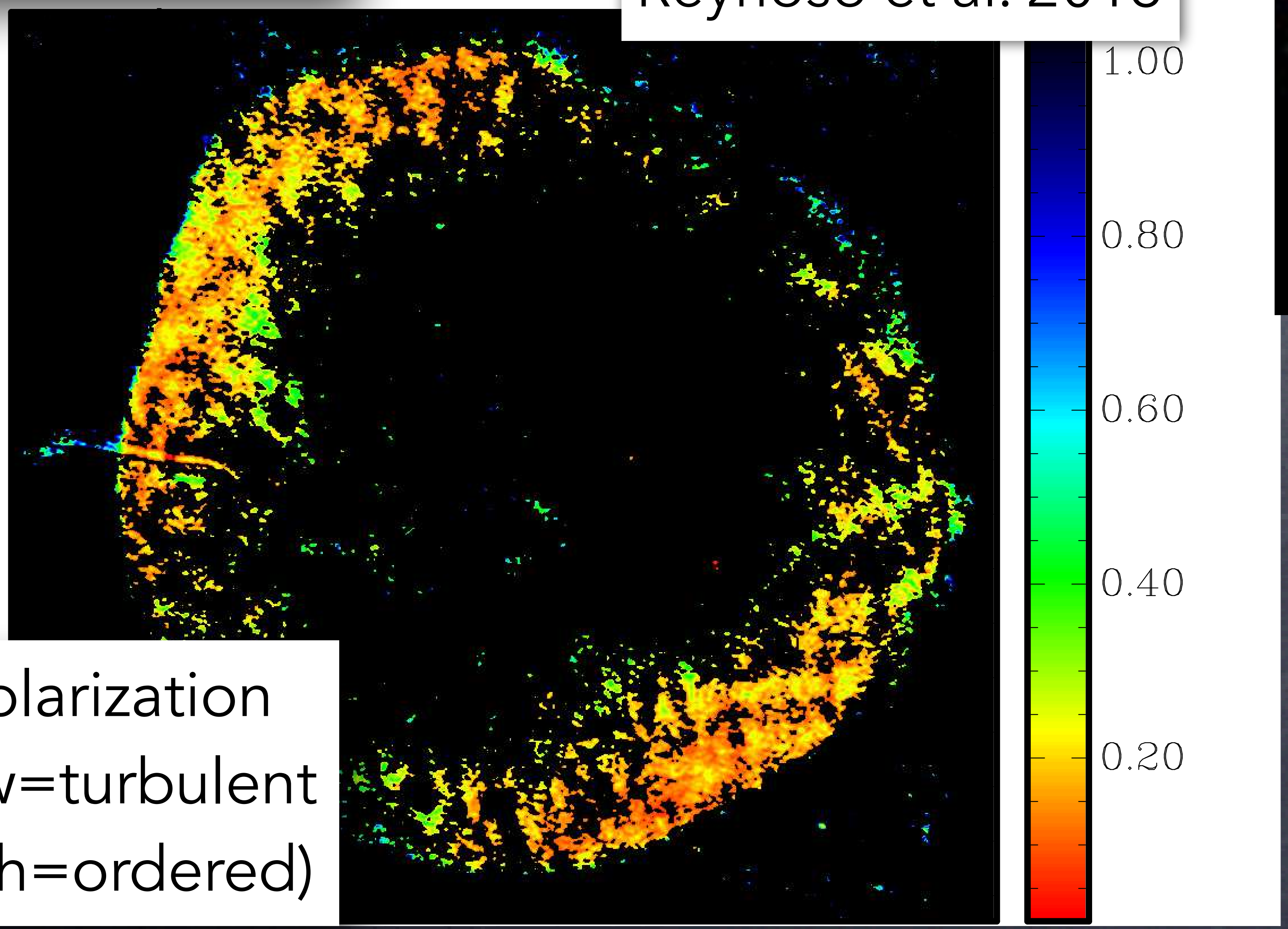
- Different flavors of CR-driven streaming instabilities (Amato & Blasi 2009; DC & Spitkovsky 2014b)
  - For M_A<30, resonant (cyclotron)
  - For M_A>30, non-resonant (Bell's): strongly non-linear!
- Bohm-like diffusion in the self-generated B (Reville & Bell 2013; DC & Spitkovsky 2014c)

SN 1006: a parallel accelerator



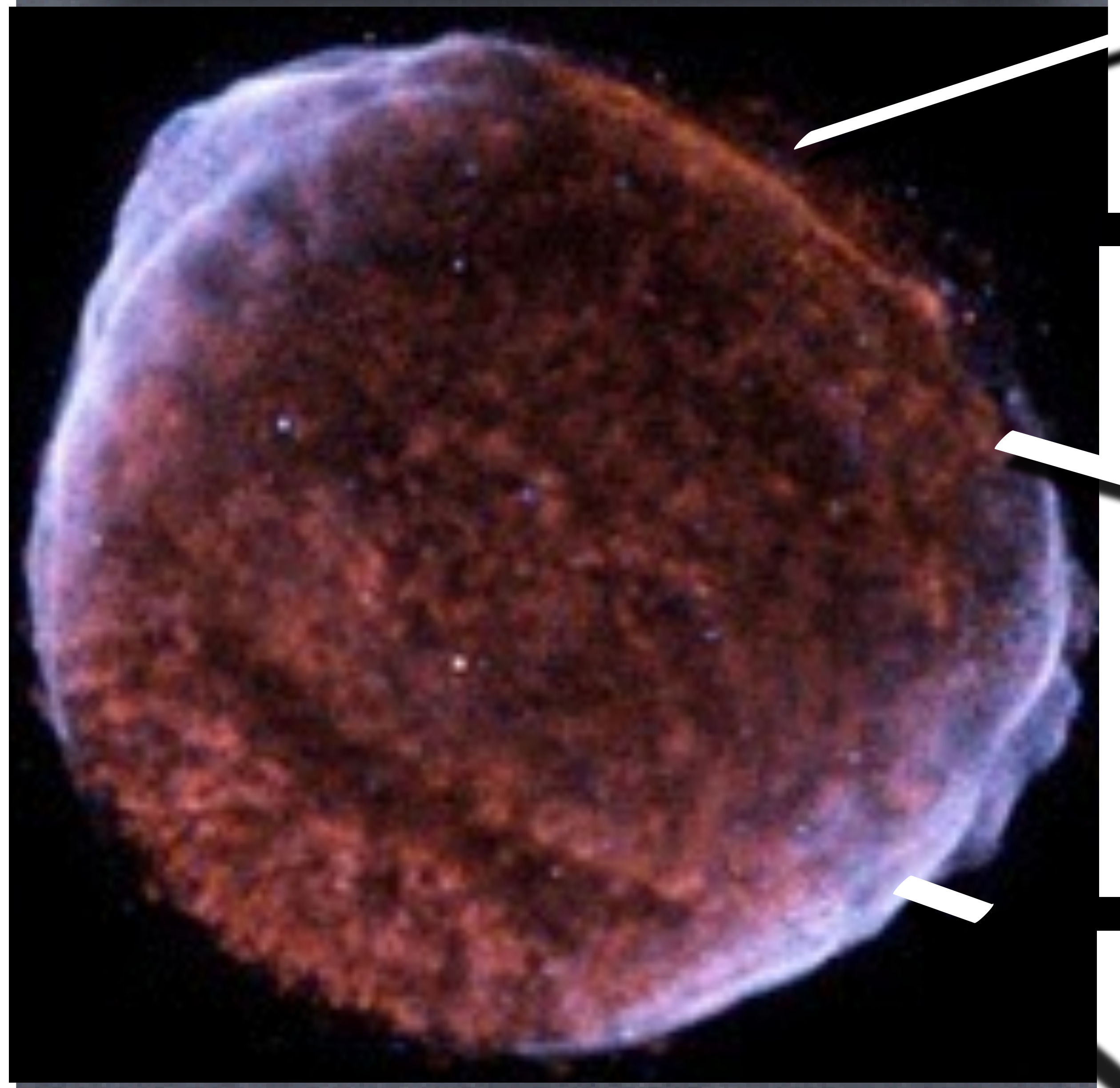
Inclination of B wrt to the shock normal

Reynoso et al. 2013



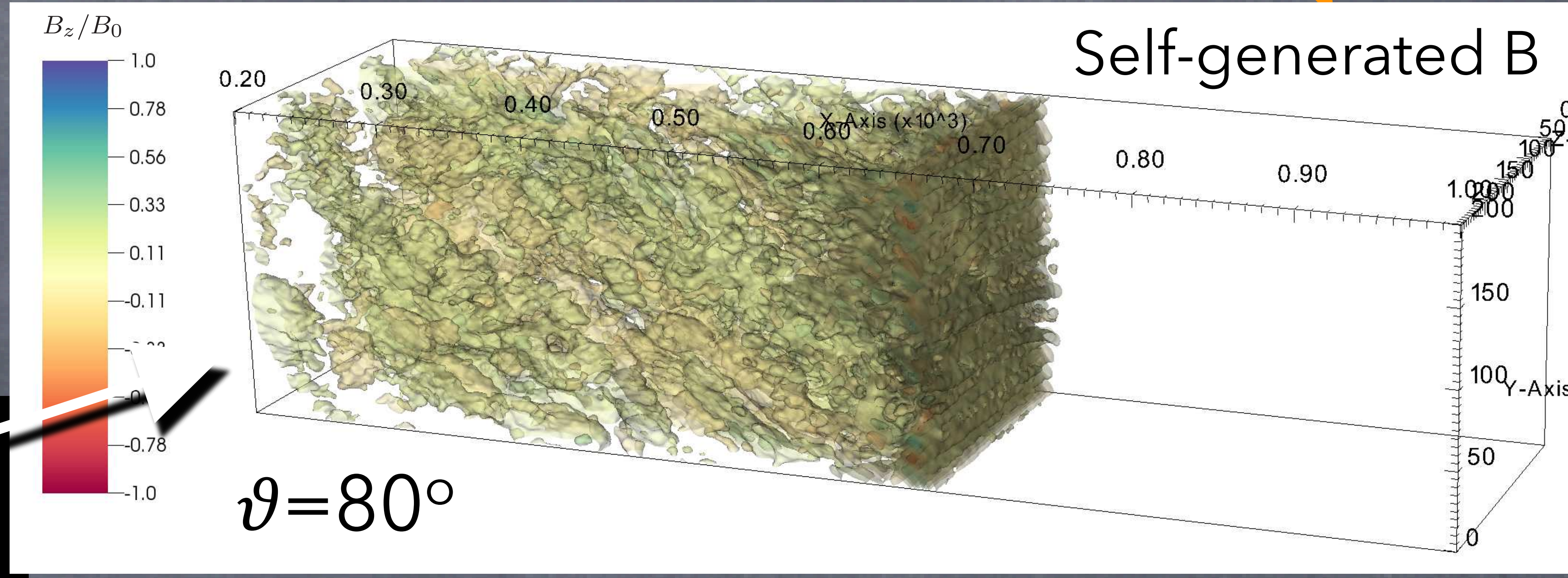
Polarization (low=turbulent high=ordered)

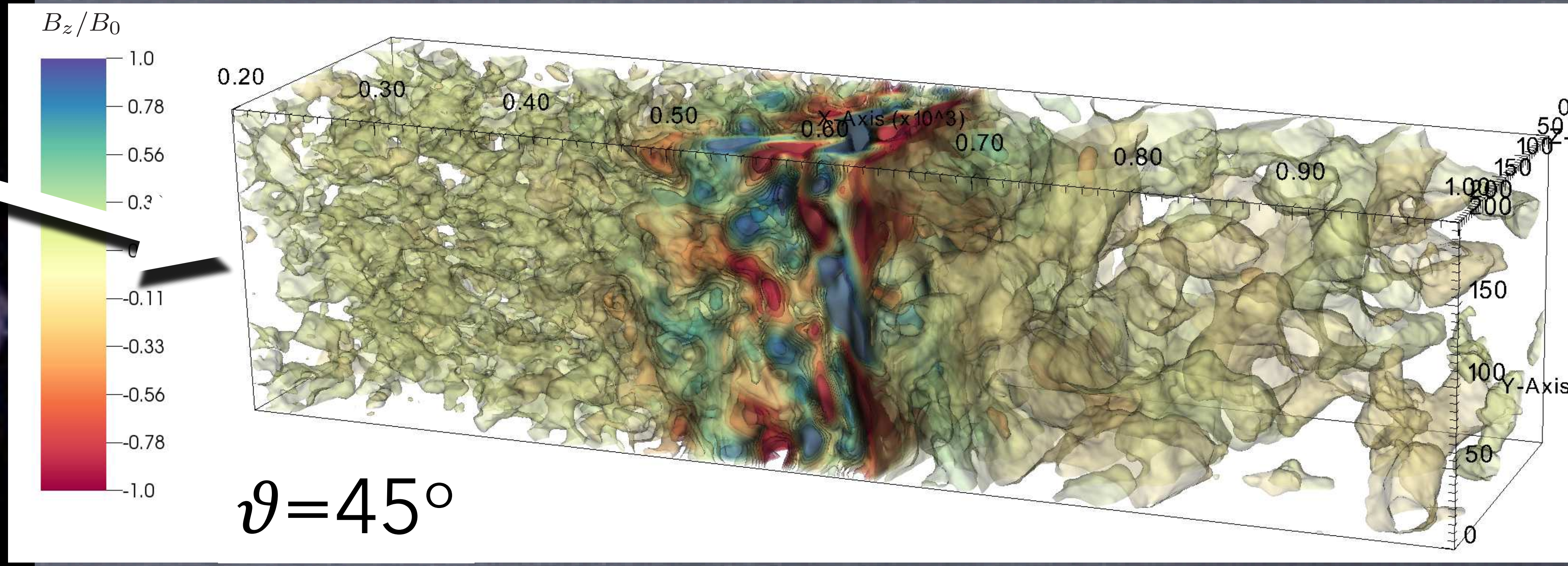
X-ray emission:
red=thermal
white=synchrotron

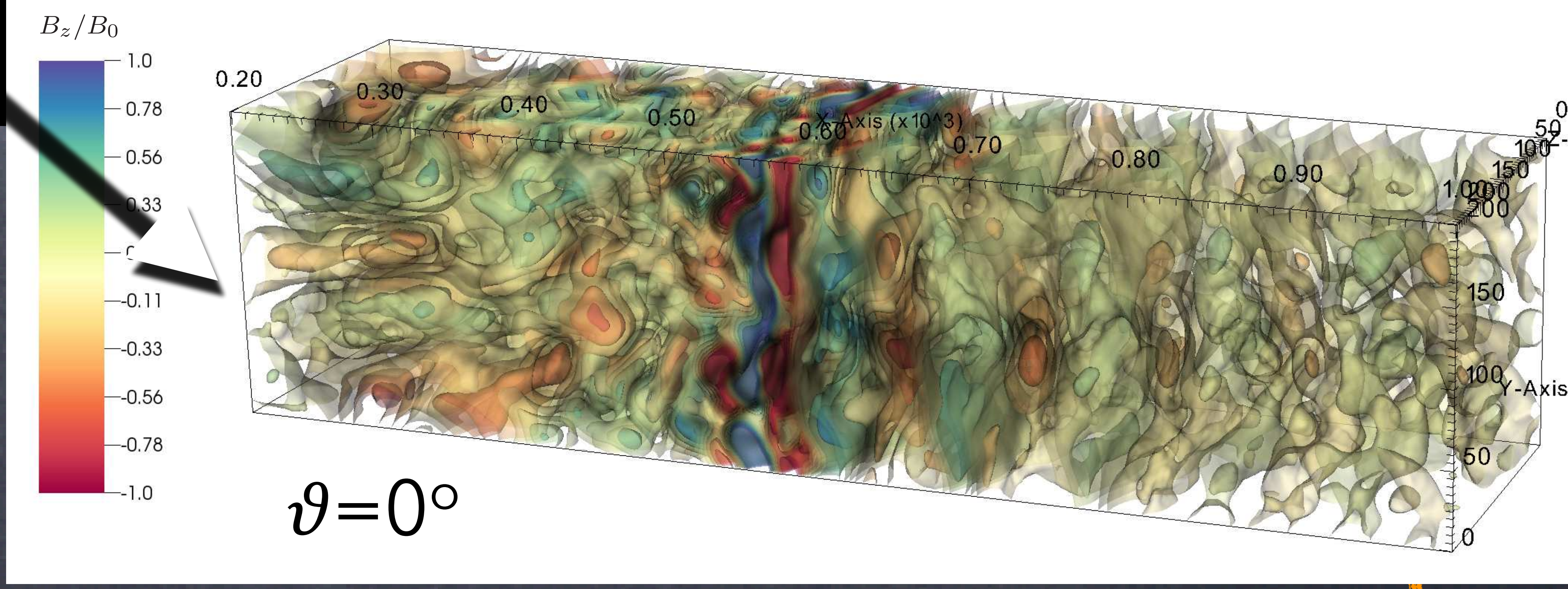


B amplification and ion acceleration where the shock is parallel

Self-generated B







DC & Spitkovsky, 2014a

Ion Injection

What determines the fraction of particles that become CRs?

3 golden rules of Real Estate:

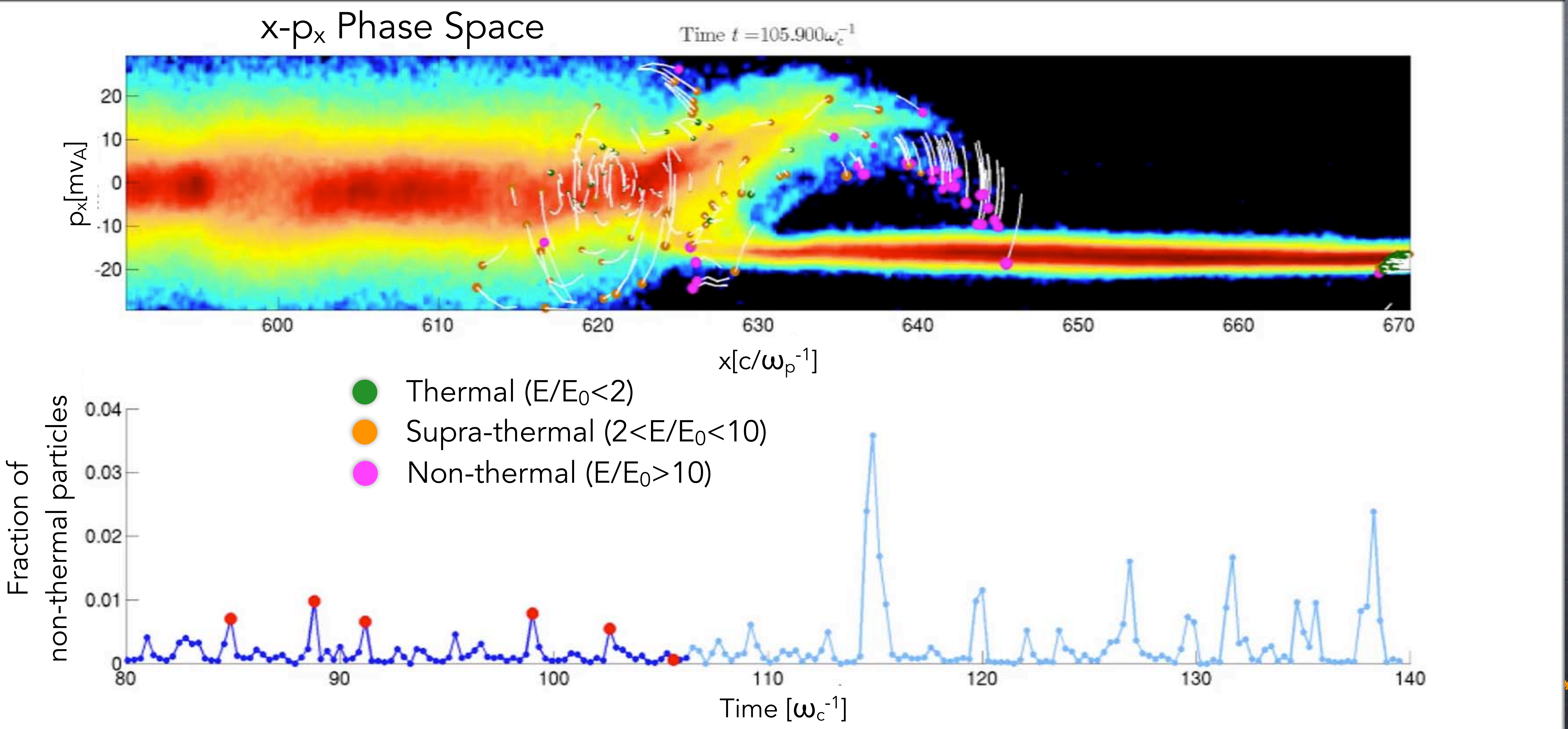
LOCATION,

LOCATION,

LOCATION!

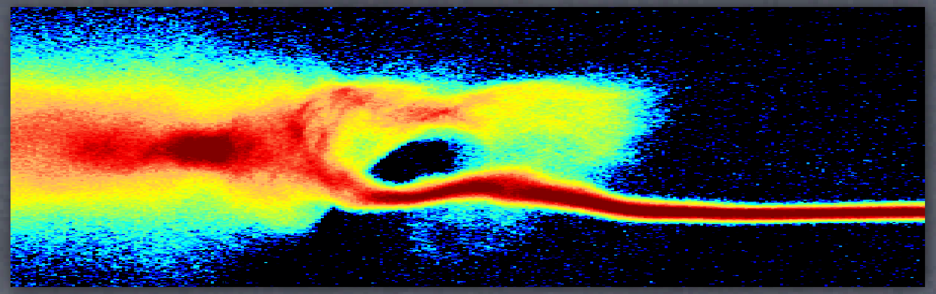
Particle Injection - Simulations

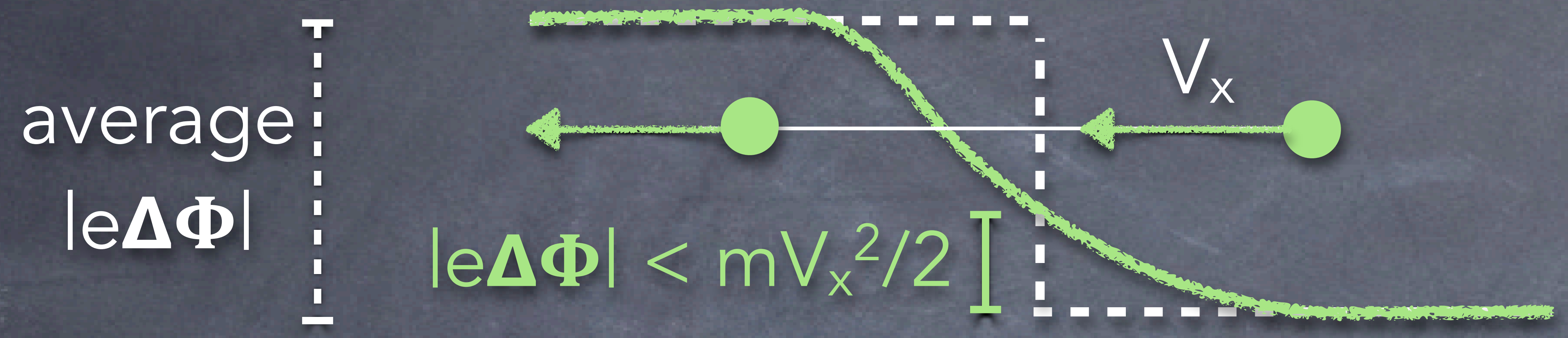
DC, Pop & Spitkovsky, 2015



The Theory of Ion Injection

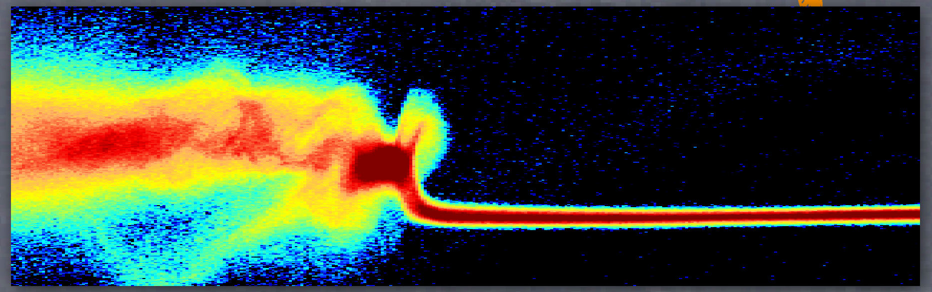
- Low barrier (reformation)

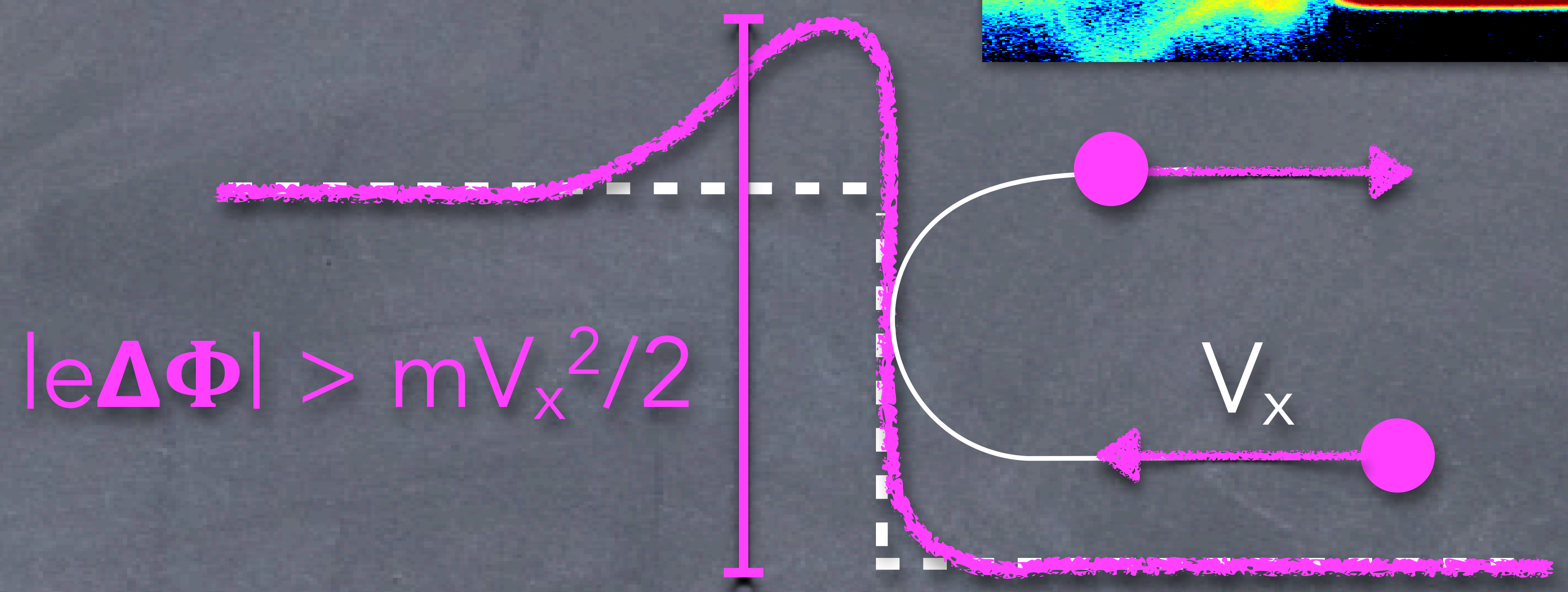




Ions advected downstream, and thermalized

- High barrier (overshoot)





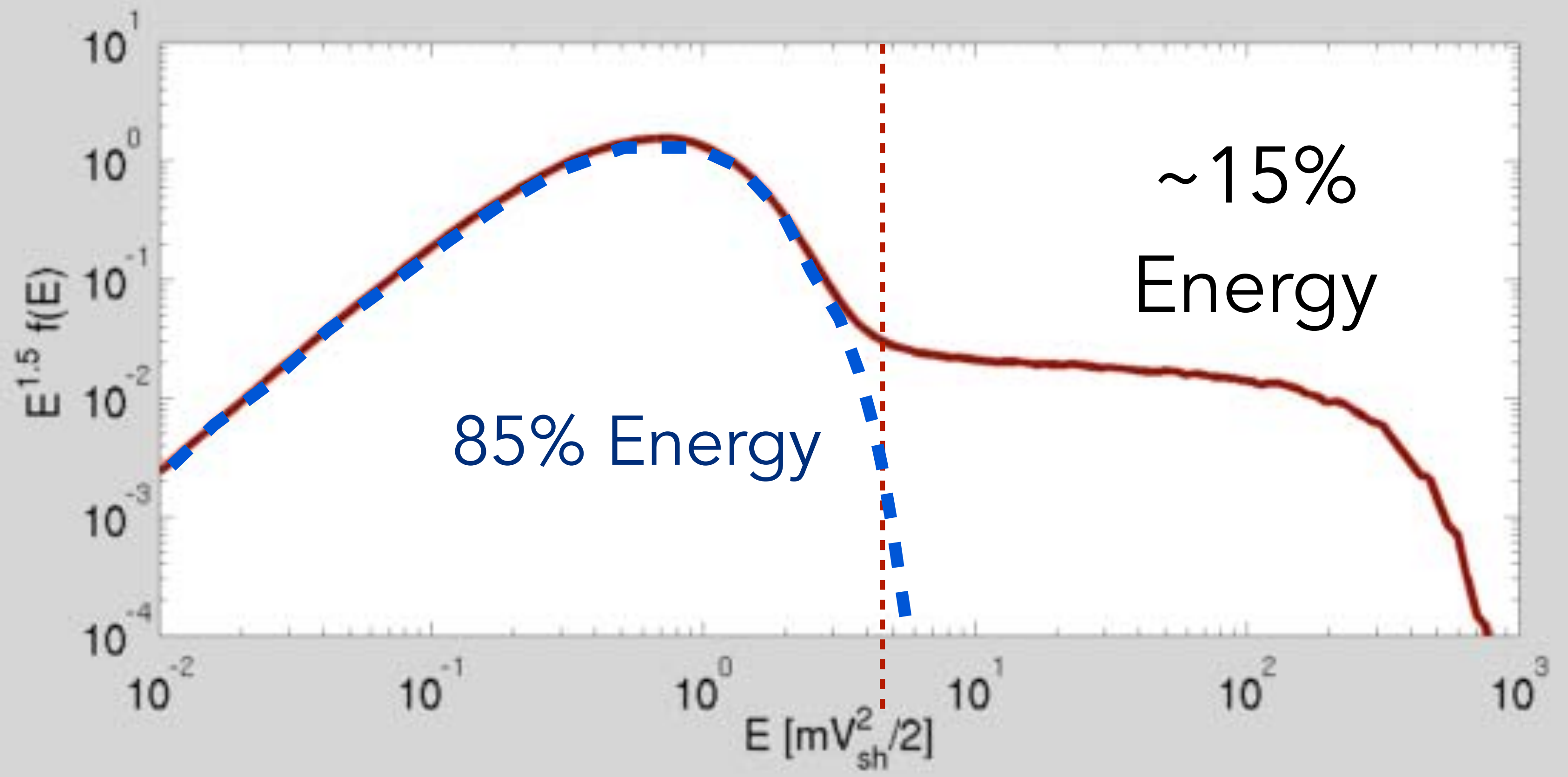
Ions reflected upstream, and energized via Shock Drift Acceleration (SDA)

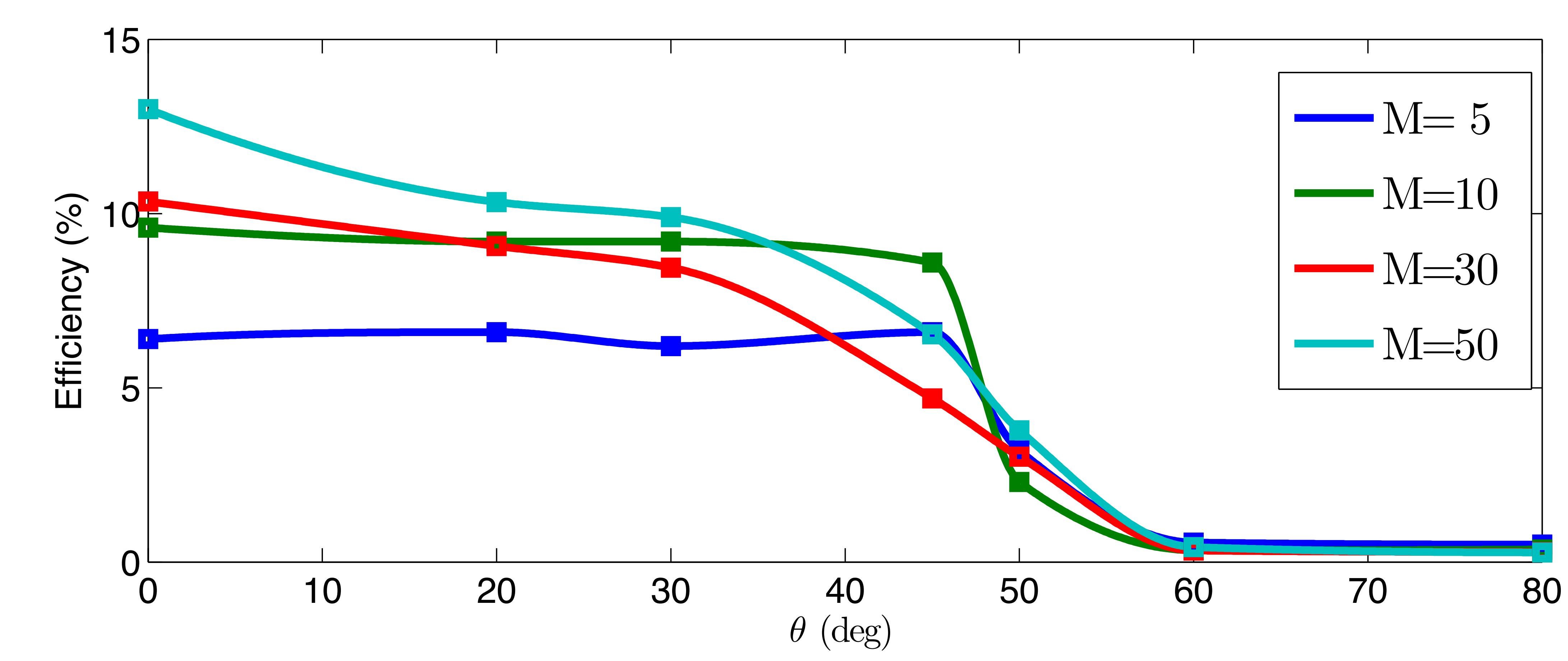
- To overrun the shock, ions need a minimum E_{inj}, increasing with ϑ (DC, Pop & Spitkovsky 15)
  - Ion fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj} \sim 10E_0$,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

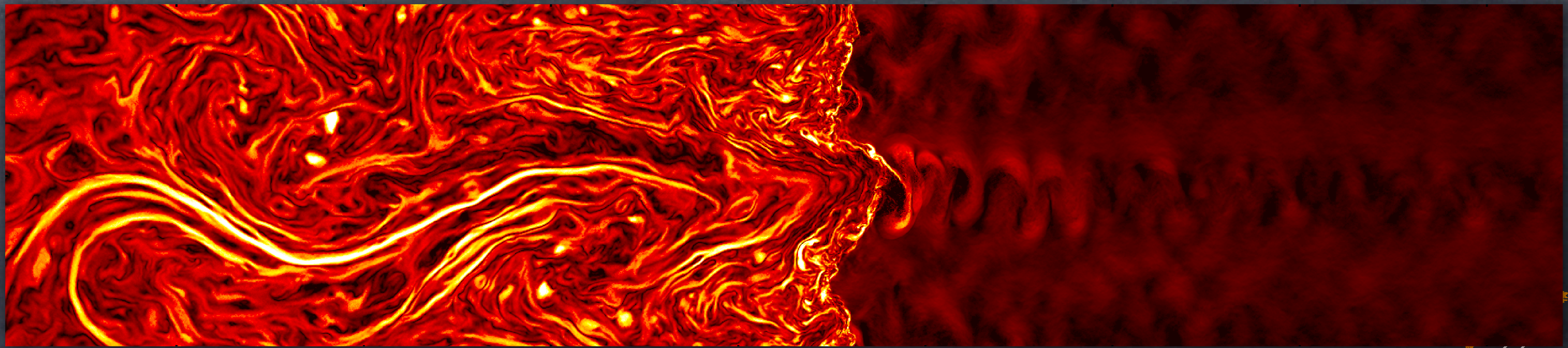
Hybrid Simulations: Summary

- DSA efficient at parallel, strong shocks
- CRs amplify B via streaming instability
- Injection via specular reflection and shock-drift acceleration

- What about electrons?
- Any direct evidence?

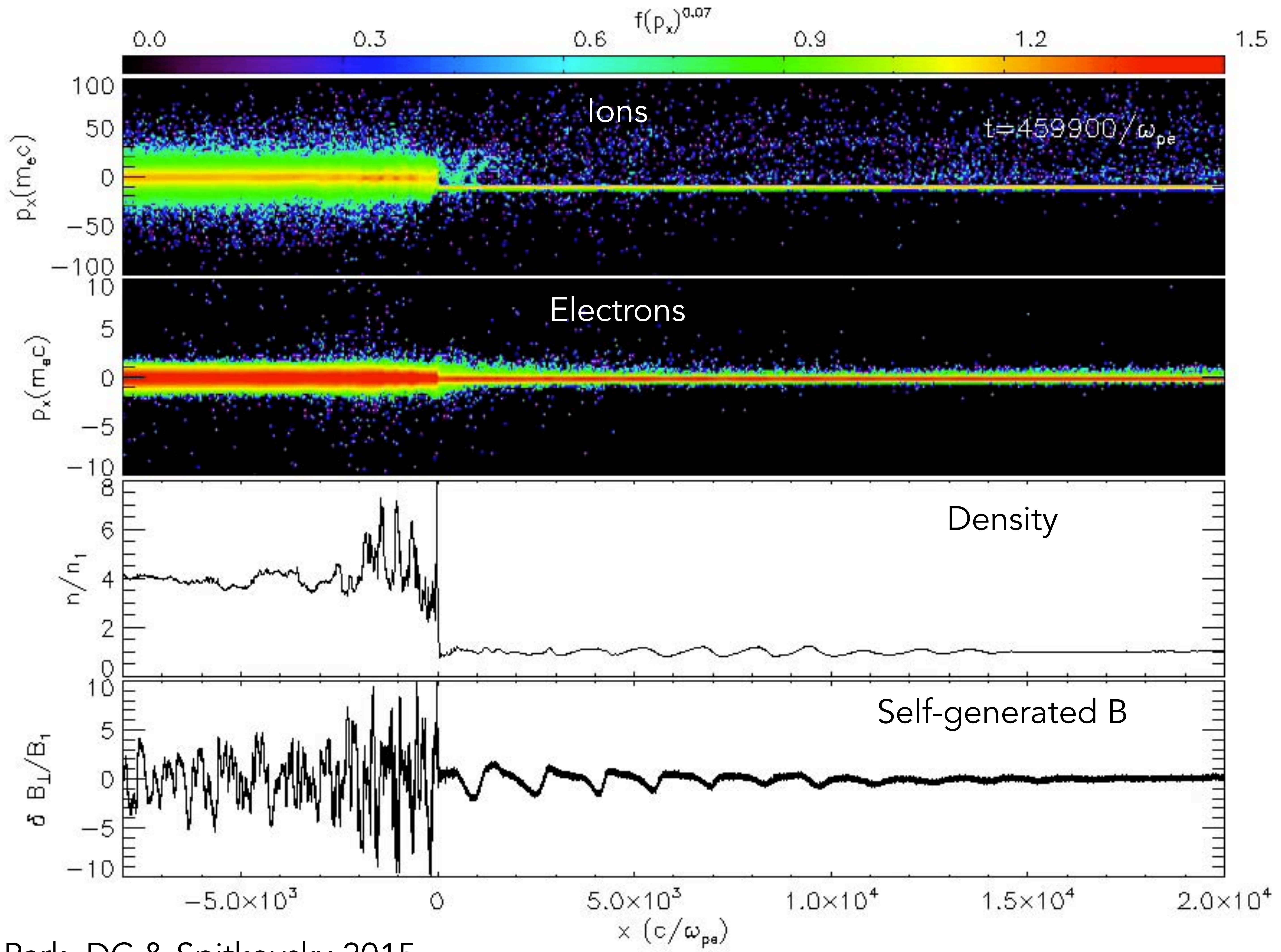




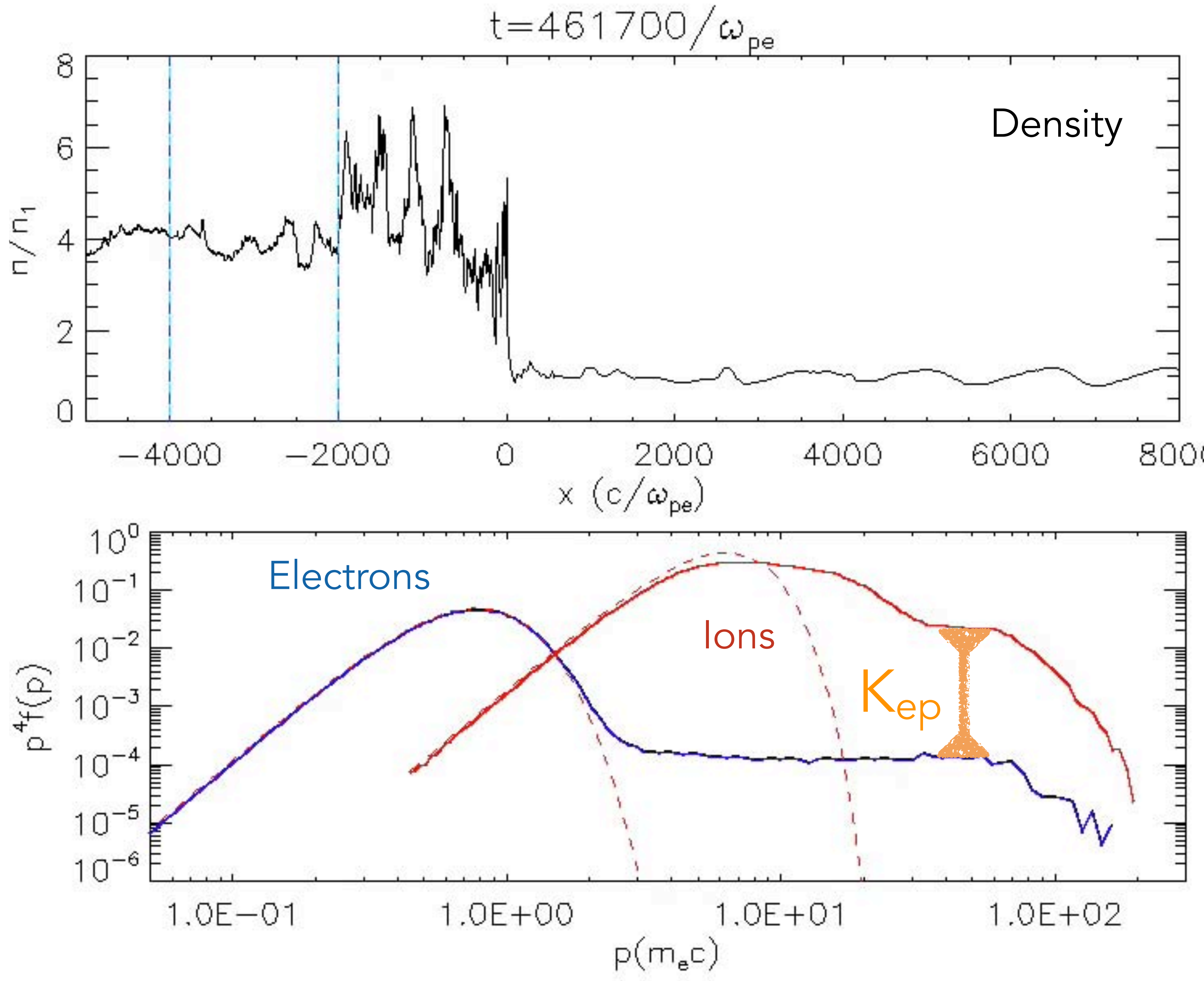


How are electrons accelerated?

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



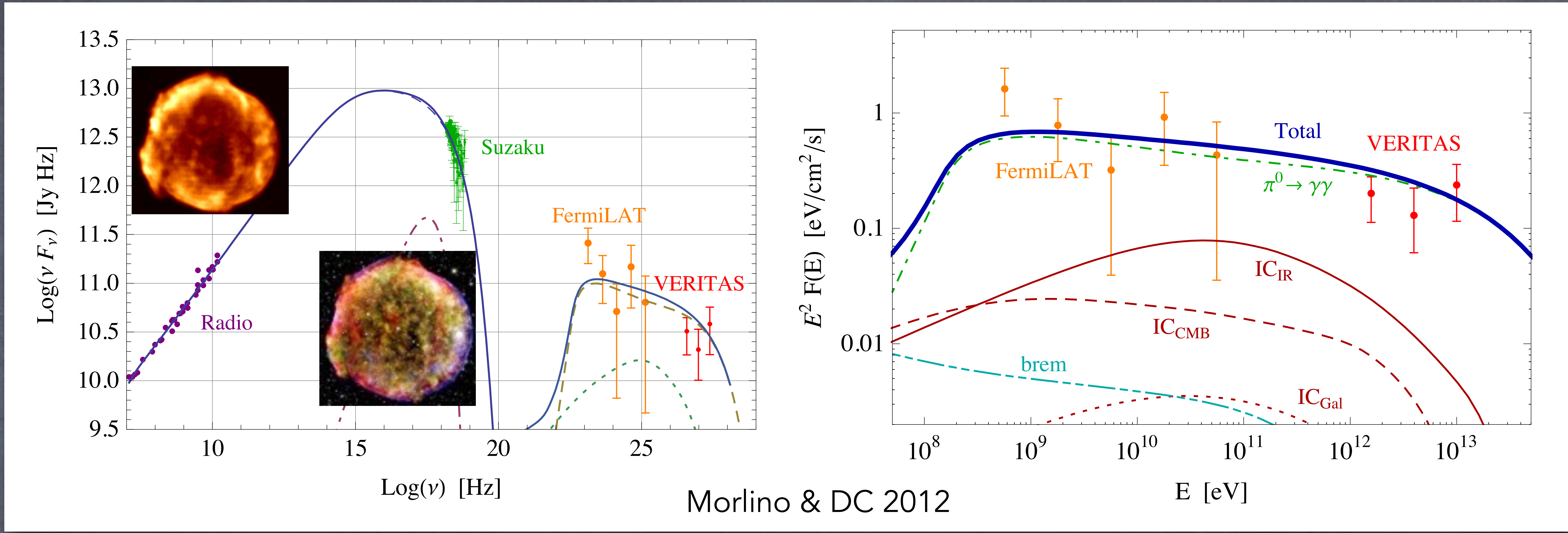
Park, DC & Spitkovsky 2015

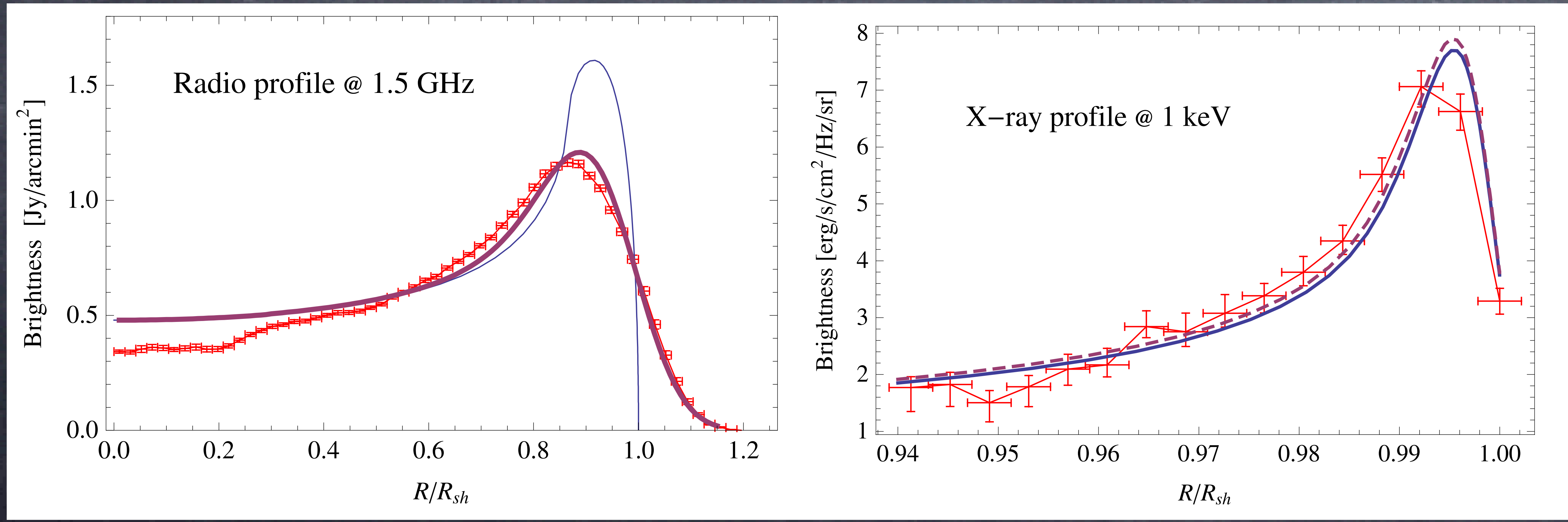


Electron/proton ratio K_{ep}~0.01

The direct evidence of CR acceleration in Tycho

Type Ia SN
Age=443yr
Distance~3kpc



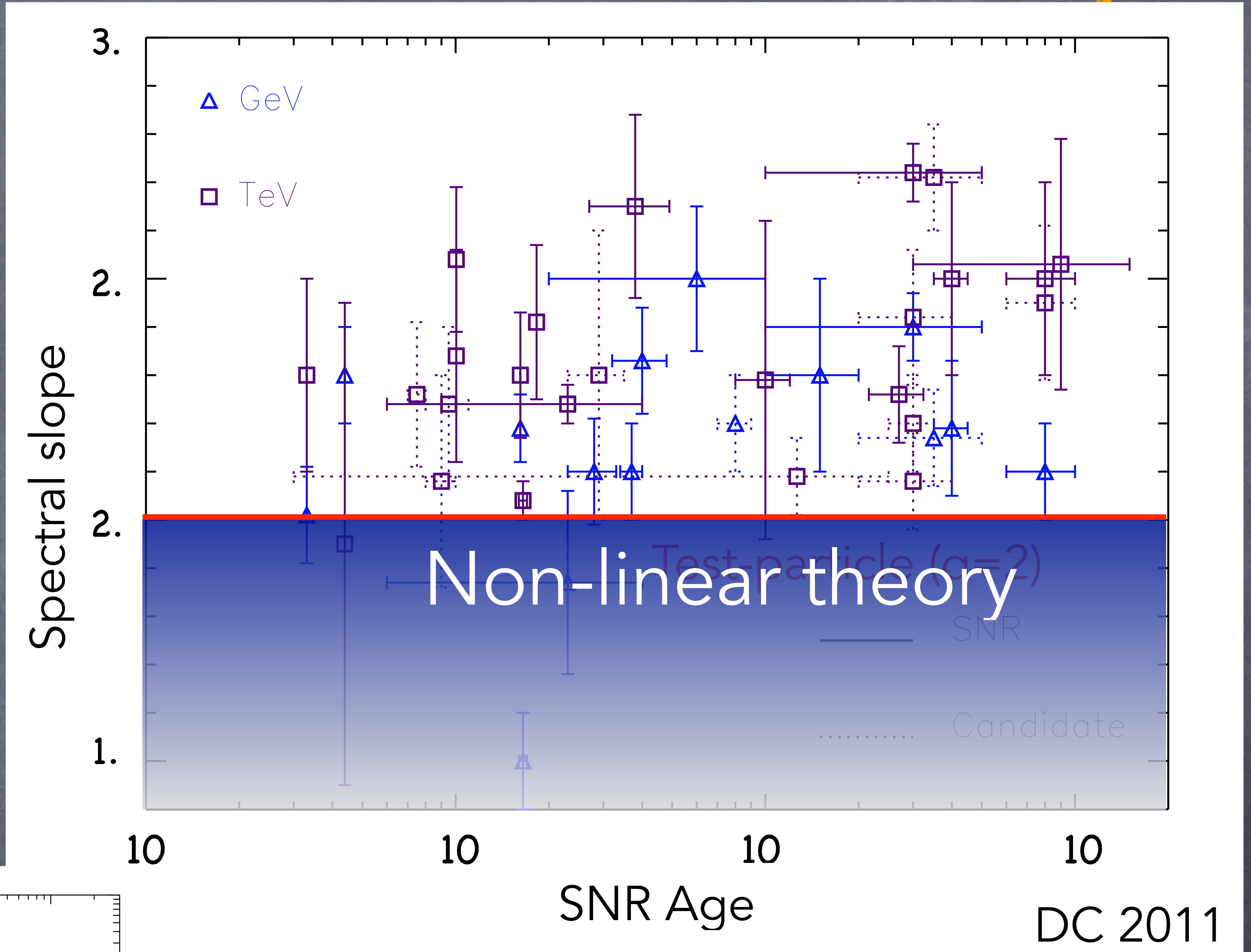


- CR spectra from diffusion-convection eq.
- Acceleration efficiency. ~10%
- SNR hydrodynamics
- Protons up to ~0.5 PeV

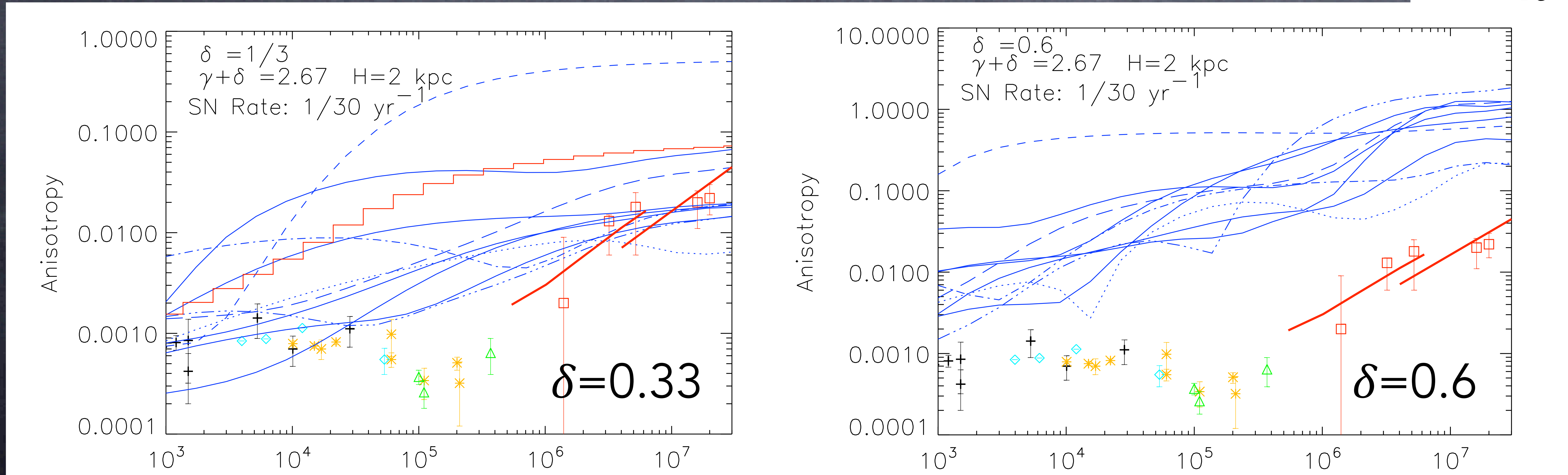
- Code publicly-available soon as CRAFT: *Cosmic-Ray Analytical Fast Tool* (DC et al. 2016)

Outstanding Questions - I

- *Is DSA universal slope consistent with observations?*
  - Gamma-ray-bright SNRs often imply hadron spectra steeper than E^{-2} (DC 2011,2012)
  - Also propagation prefers injection spectra $\sim E^{-2.3}$ (Blasi & Amato 2011a,b)



DC 2011

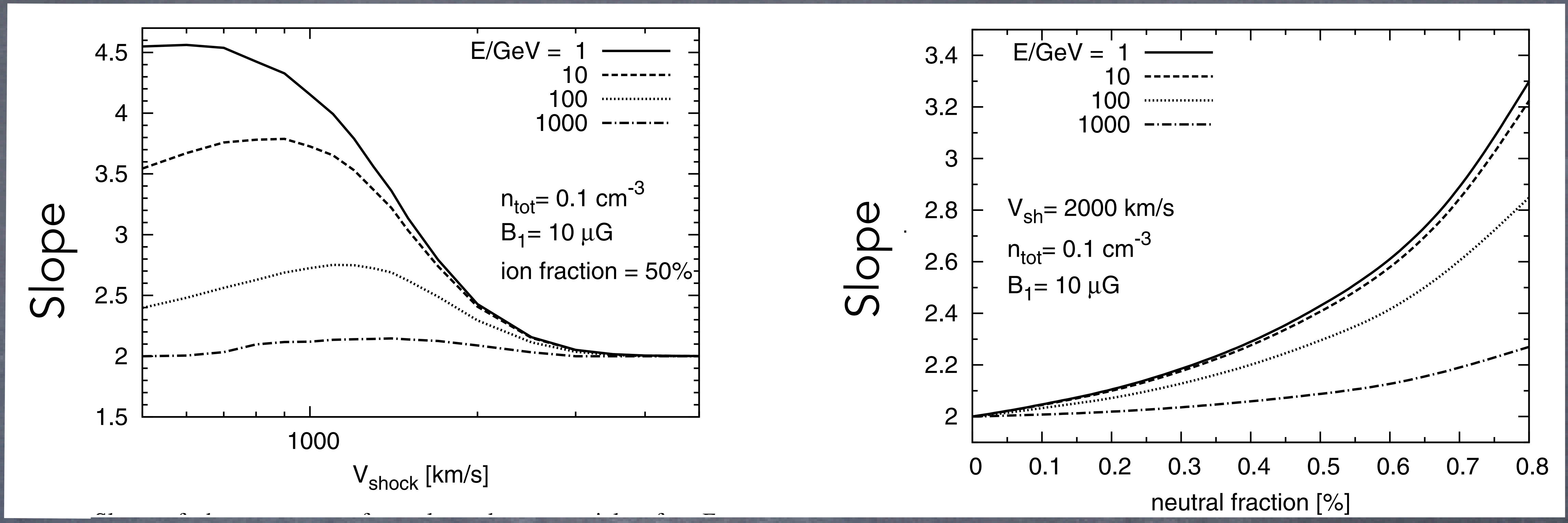


Blasi & Amato 2011a,b

- Injection spectrum: $\sim E^{-\gamma}$
- Residence time in the Galaxy: $\sim E^{-\delta}$
  - Constraint: $\delta+\gamma\sim 2.7$

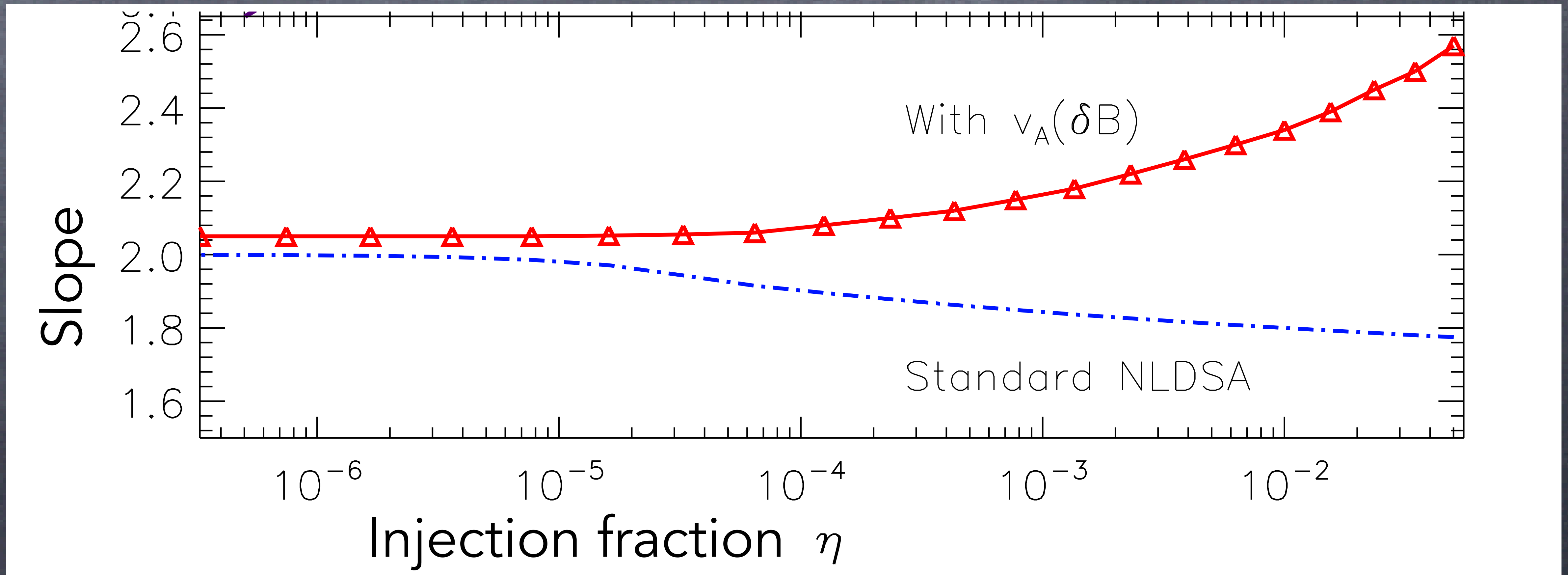
The challenge of producing steep spectra

- 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

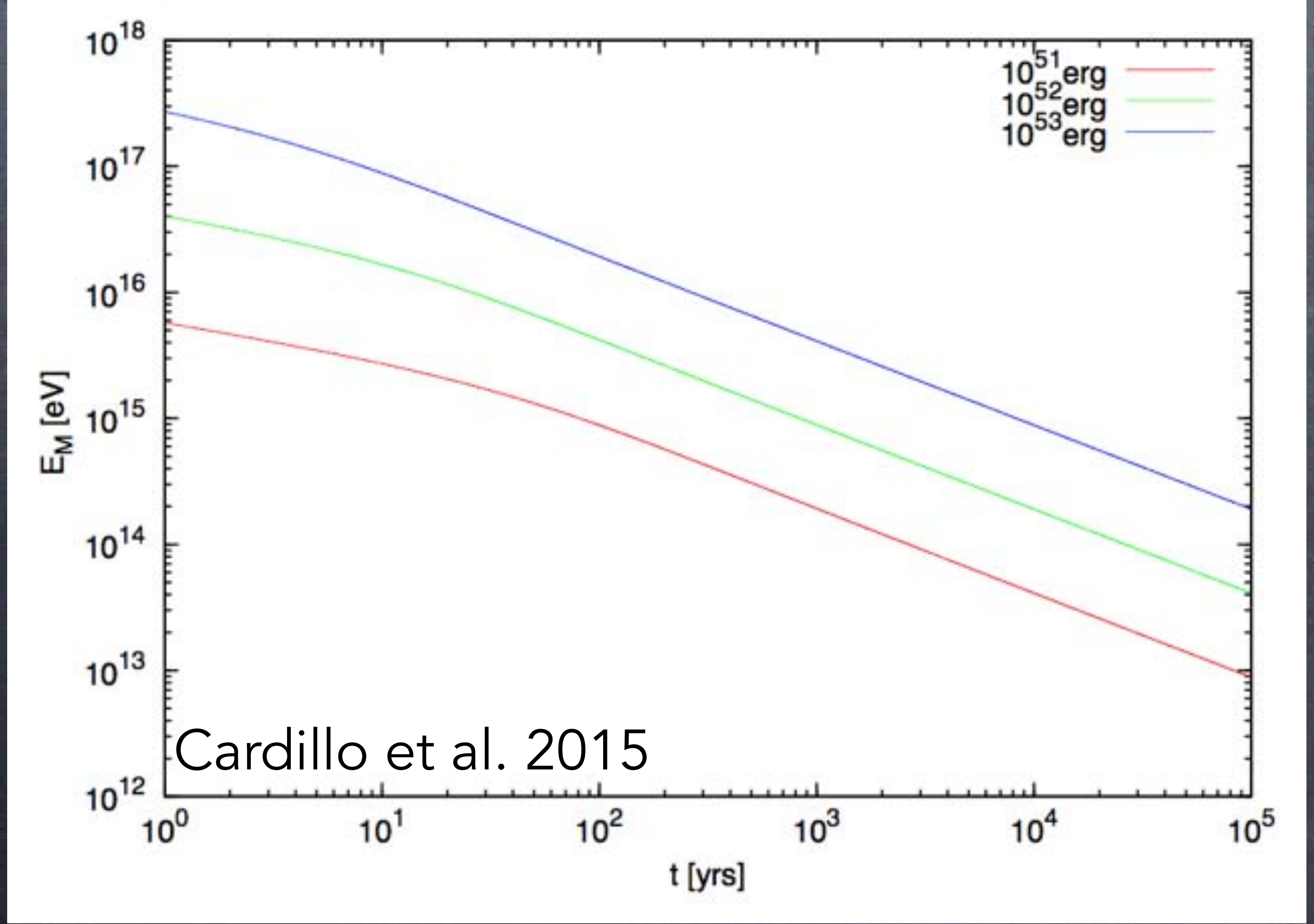
$$R_{cr} \simeq \frac{U_{up} - V_{A,up}}{U_{down}}$$

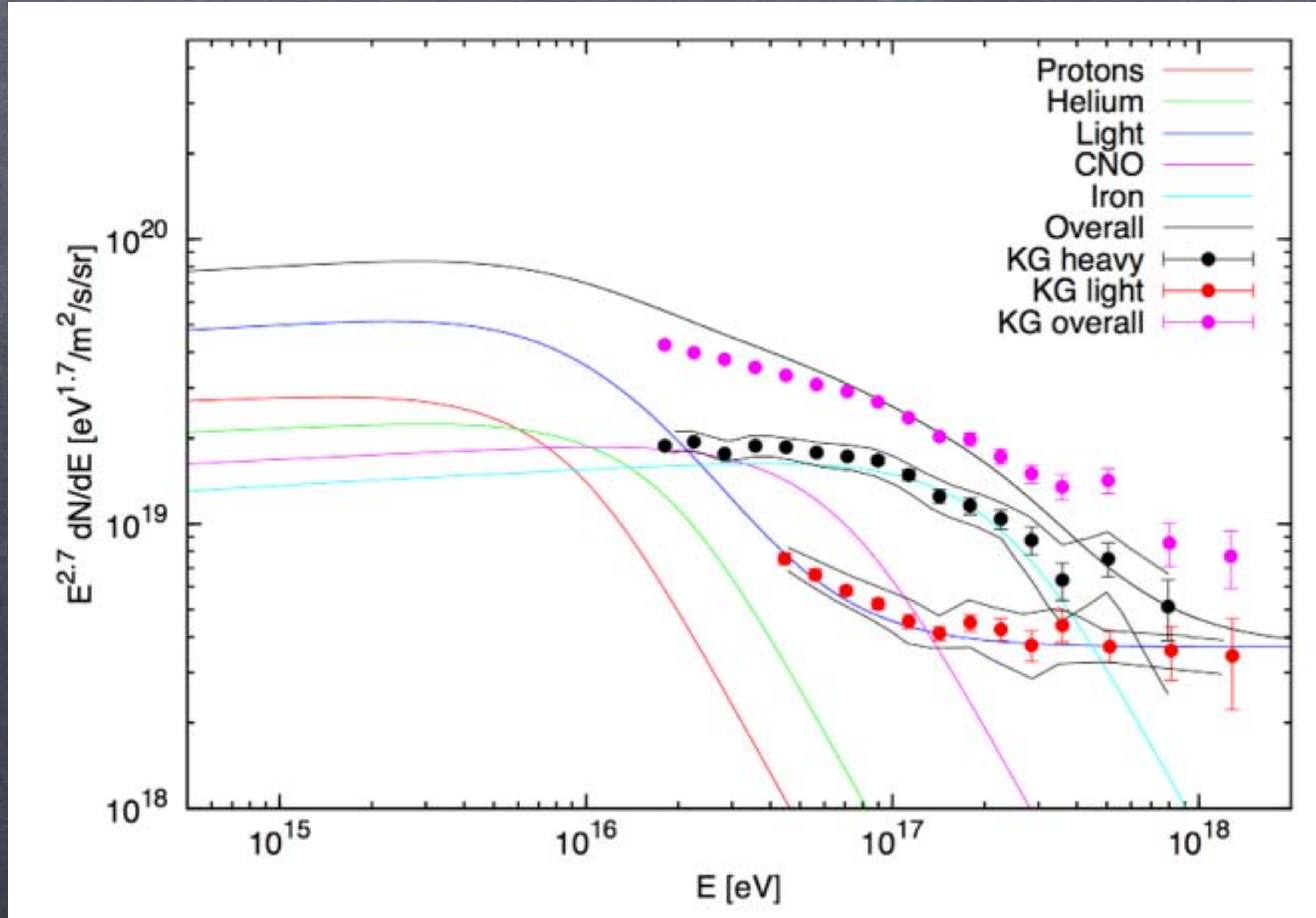


- Oblique shocks/modified diffusion (Kirk et al. 1996; Morlino et al. 2007; Bell et al. 2011, …)

Outstanding Questions - II

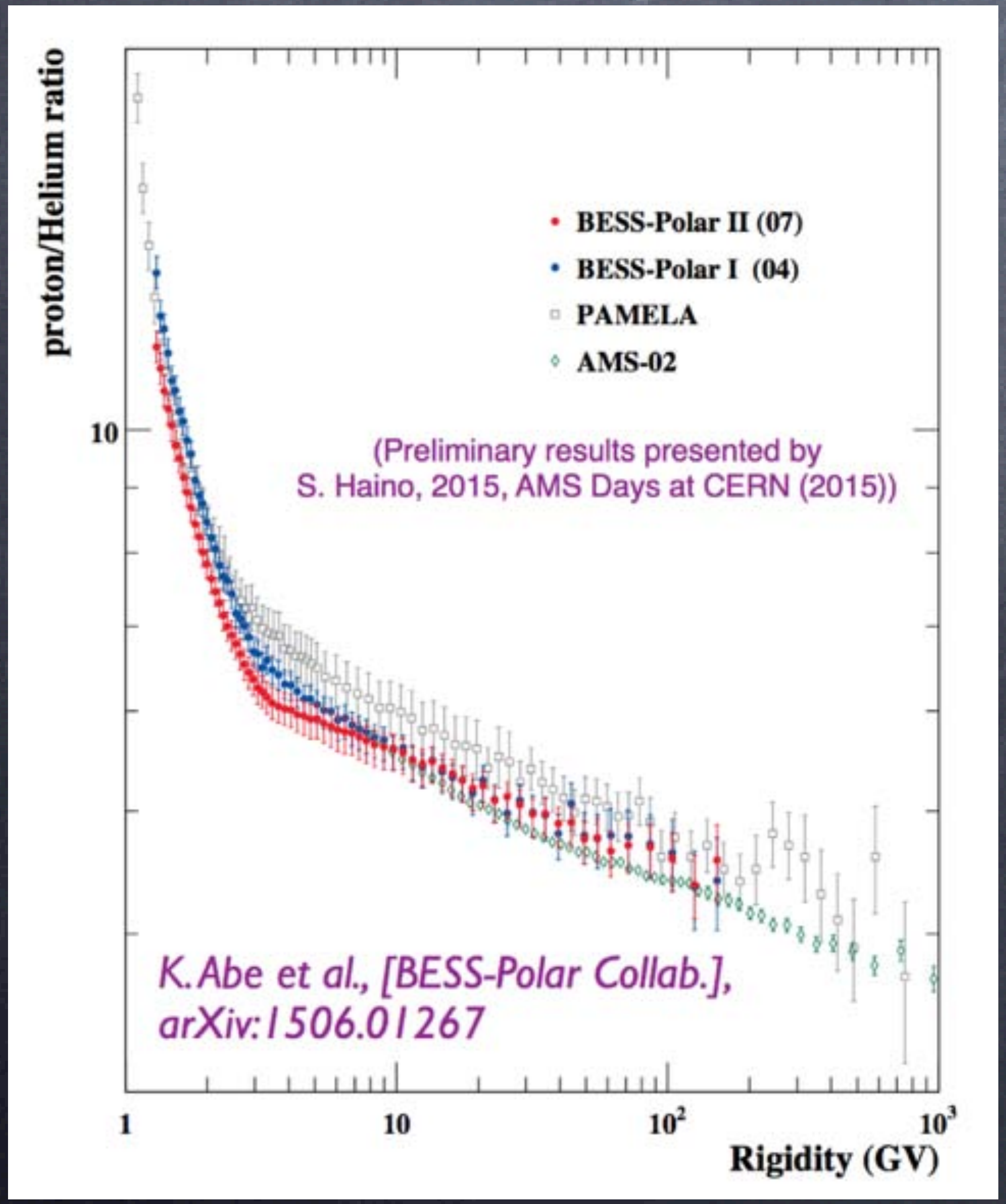
- *How do accelerated particles escape from SNRs and become CRs?*
  (Ptuskin & Zirakashvili 2005; DC et al. 2009, 2010; Bell et al. 2013; Cardillo et al. 2015)
  - The CR power-law may reflect the self-similar SNR evolution, rather than acceleration!
  - Escaping CRs illuminate molecular clouds (e.g., Gabici et al. 2007,2009; Castro & Slane 2010,…)
- *Can we observe SNRs as PeVatrons?*
  - E_{max} 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)

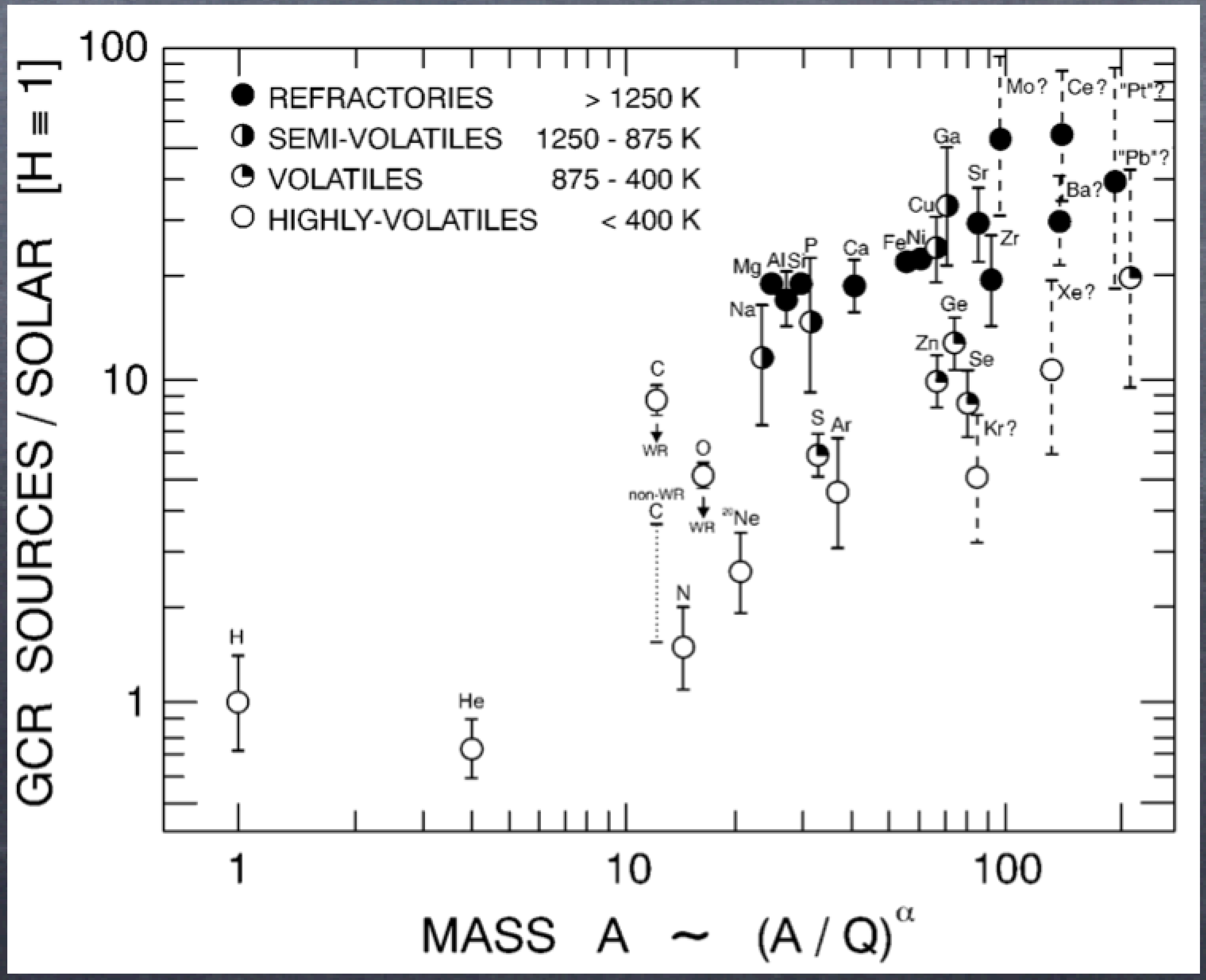


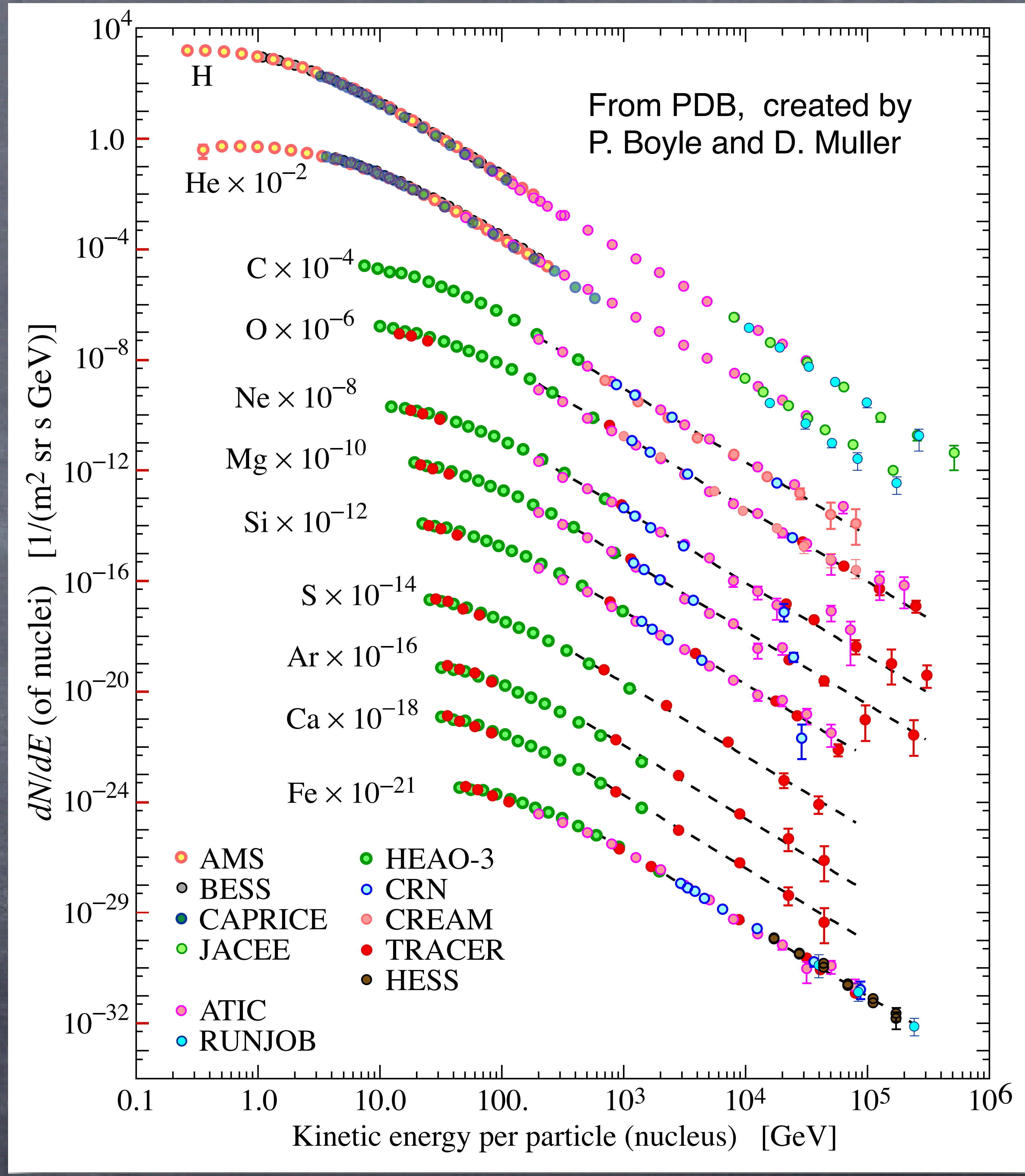


Outstanding Questions - III

- *Do current models of DSA+propagation explain spectral and chemical features?*
  - Power-laws break (steepen) at ~100 GV/nucleon
  - Discrepant hardening (PAMELA, AMS-02, BESS-Polar,…)
  - Enrichment of refractory vs volatile nuclei (Meyer, Drury, Ellison 1995)







What do we need to better understand CRs?

What you can do for CRs

- Kinetic simulations
  - Electron physics, heavy nuclei, 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