NSF/APS-GPAP

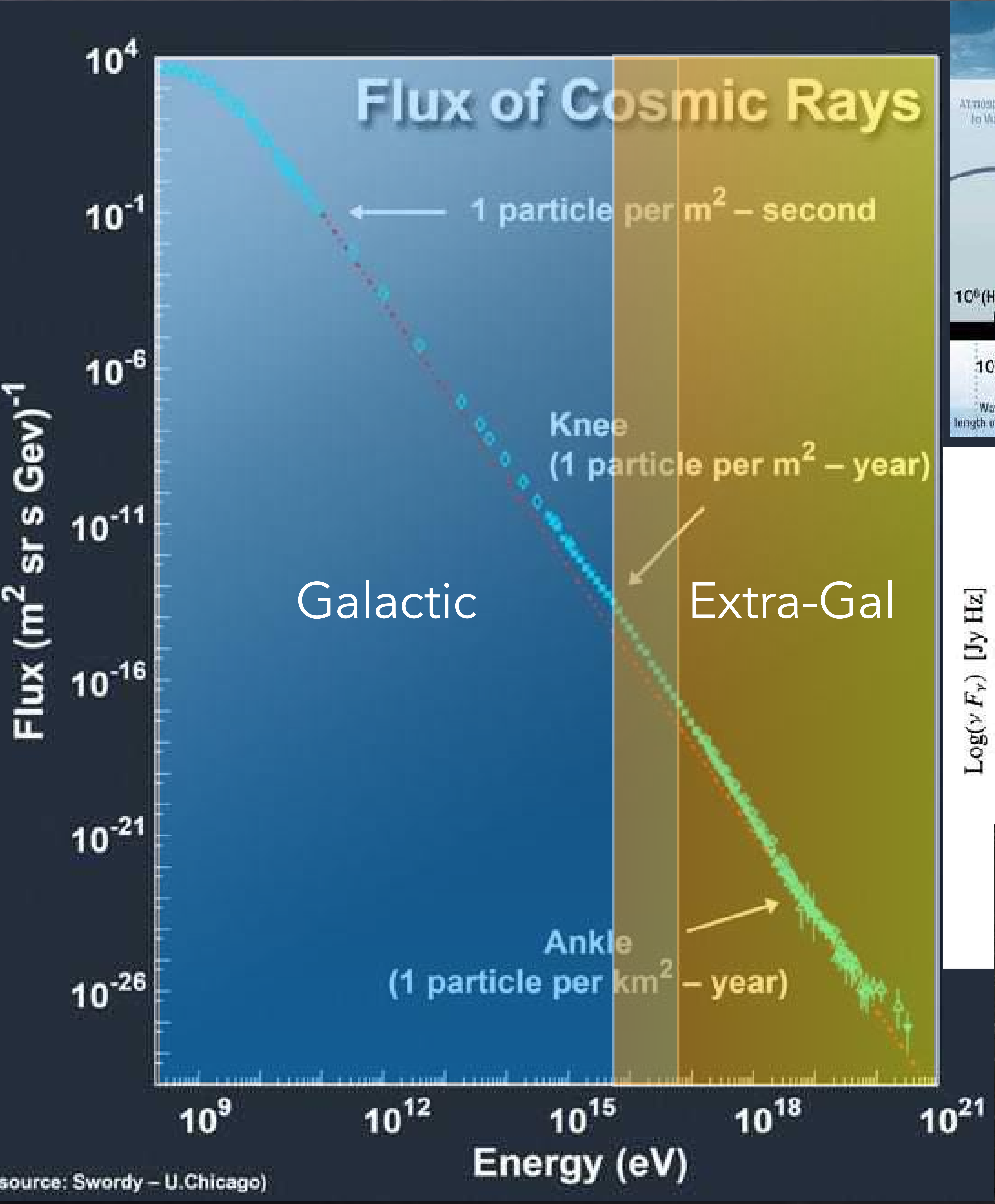
Swarthmore College - 2023

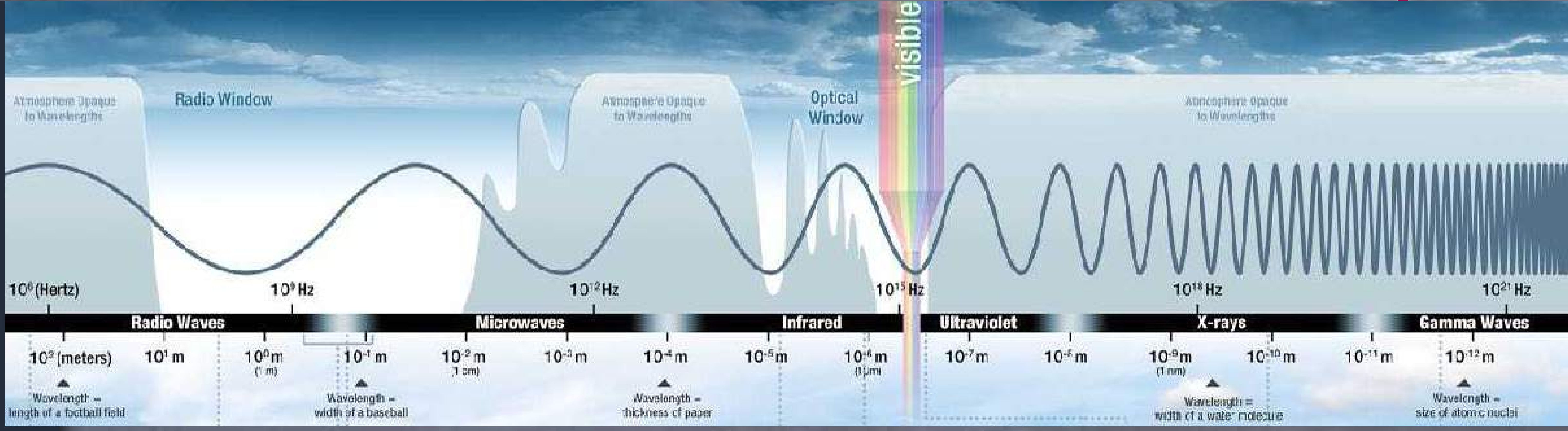
Non-thermal Particles

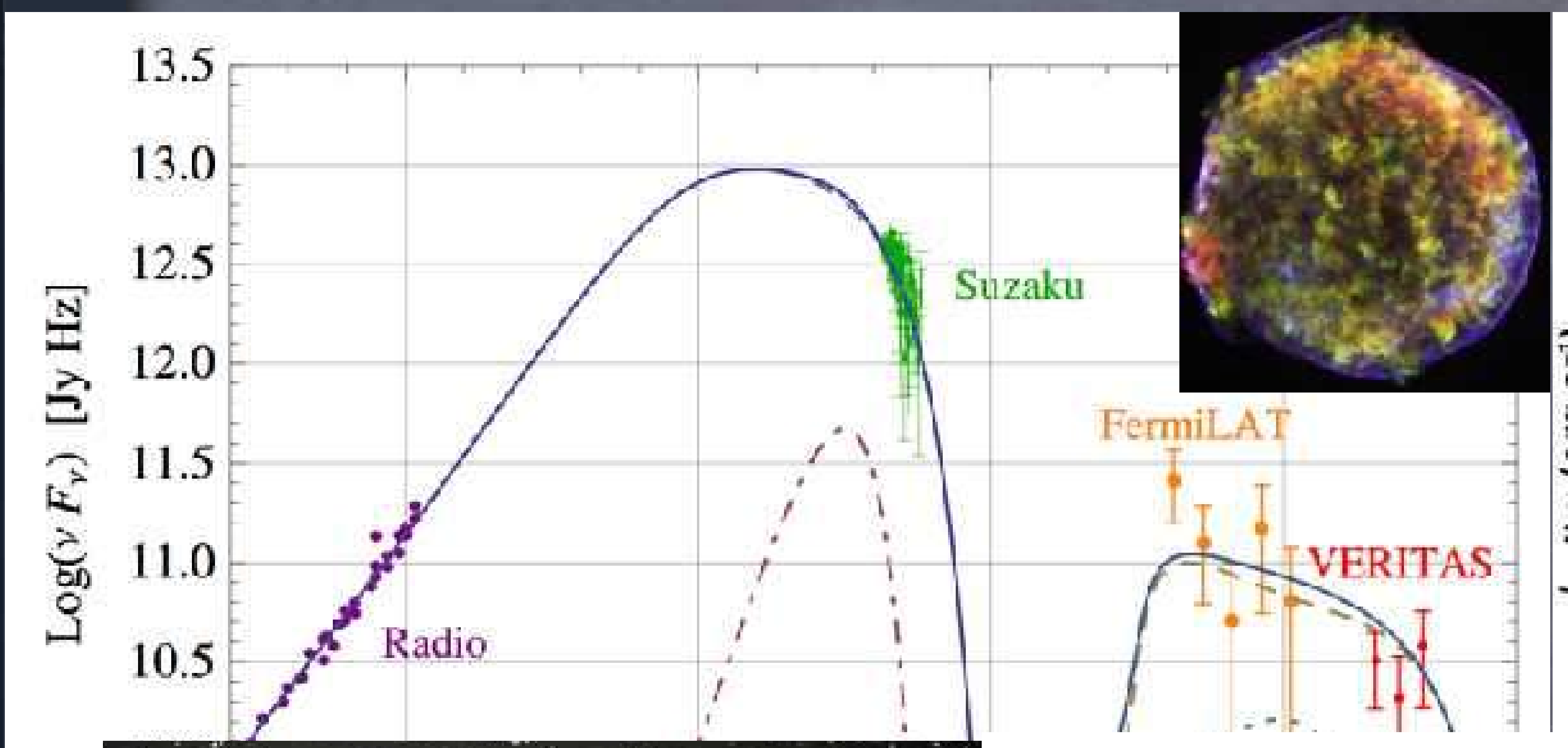
Damiano Caprioli

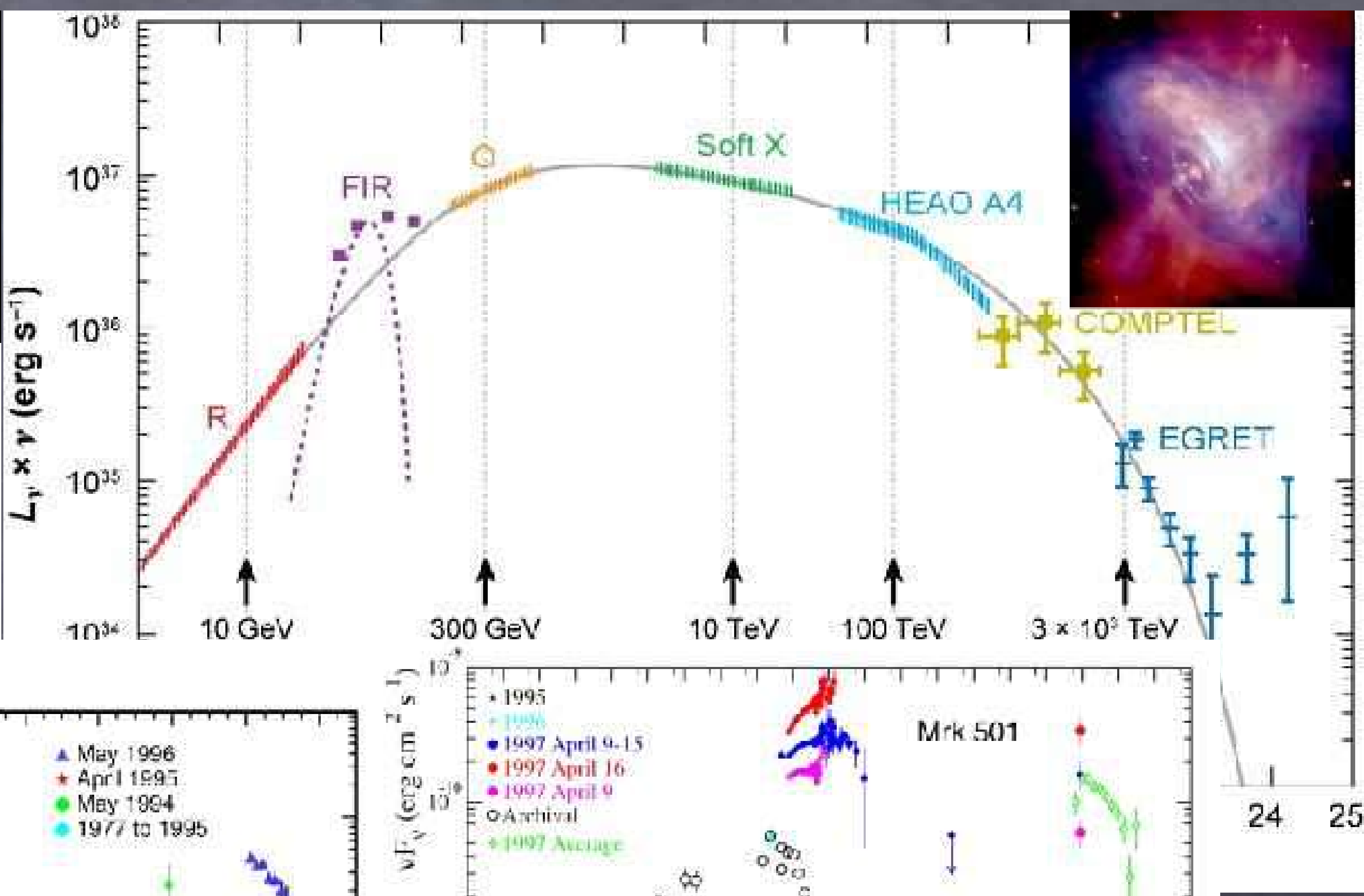
University of Chicago

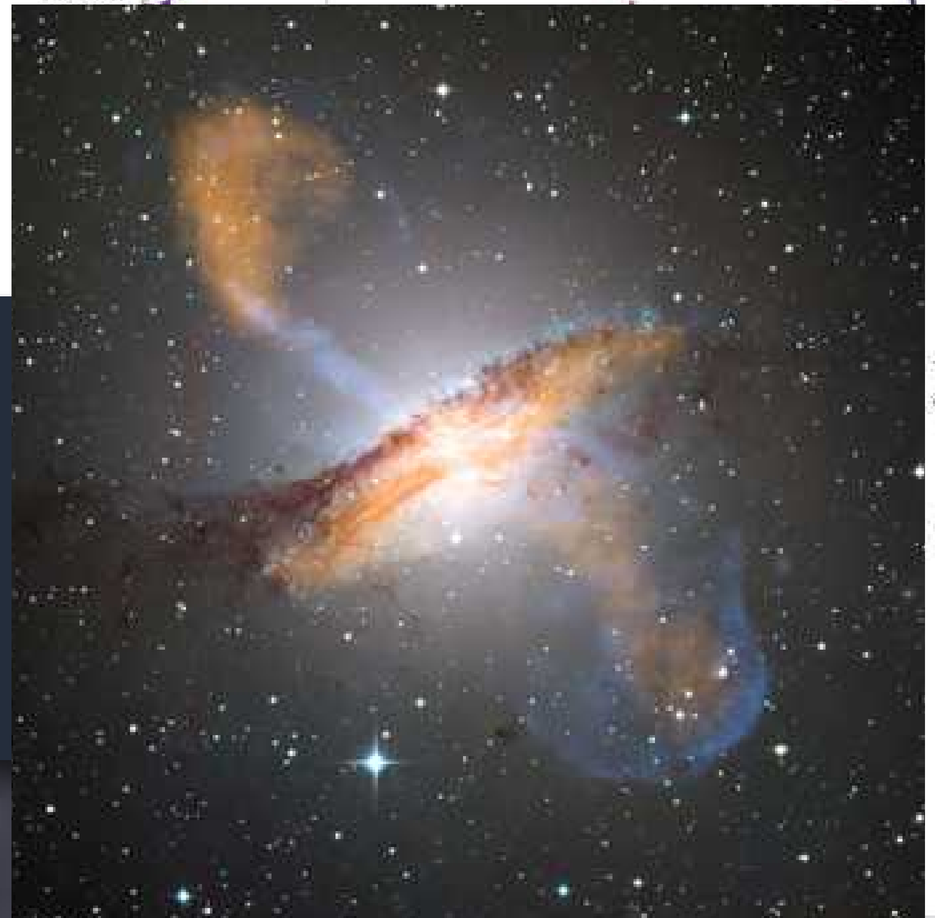
Non-thermal Particles and Radiation

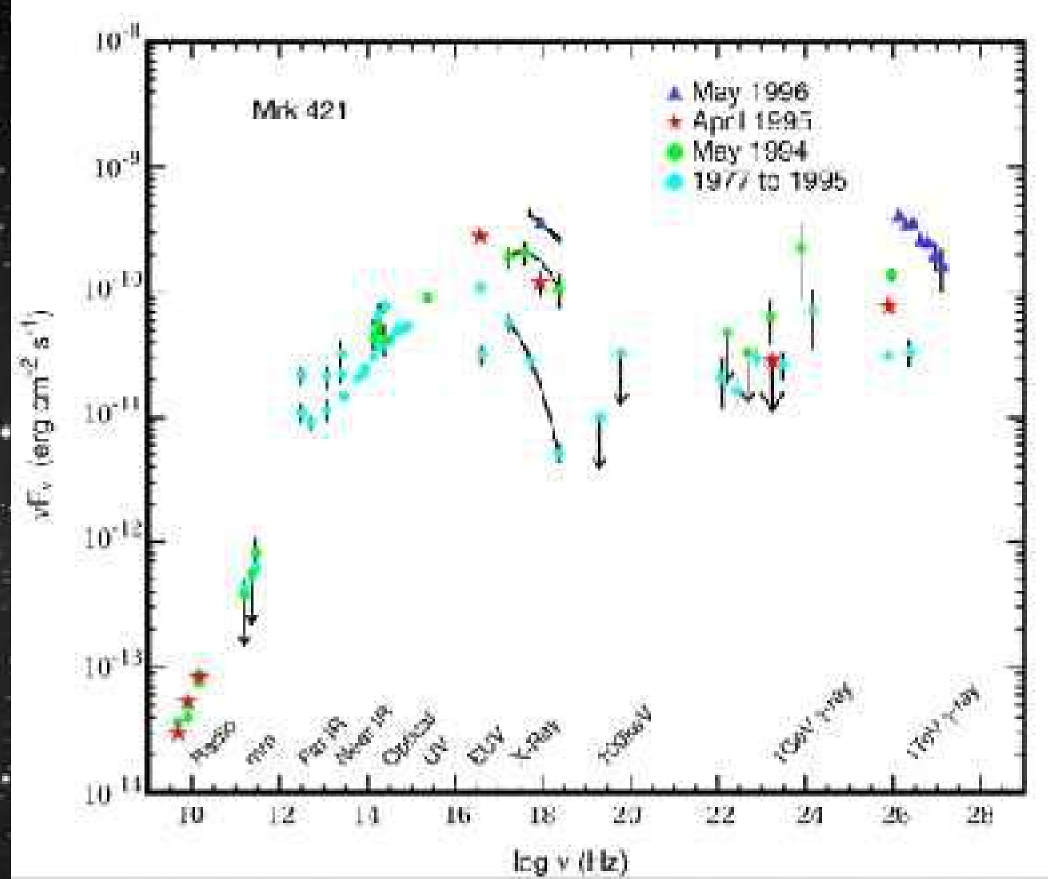


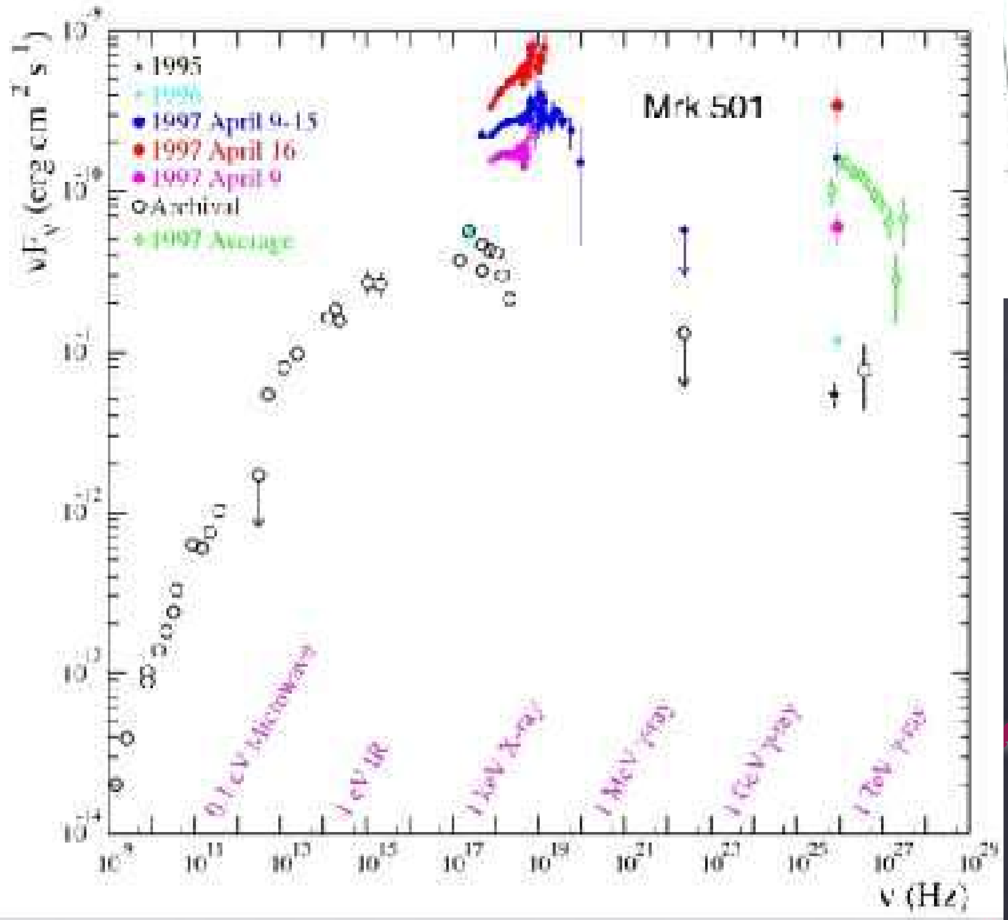












Non-thermal Plasma Physics

- PARTICLE ACCELERATION
  - Shocks
  - Magnetic reconnection
  - Turbulence
- B-FIELD GENERATION
  - CR-driven instabilities
- NON-THERMAL PLASMAS
  - Partially-ionized plasmas
  - CR viscosity

⇔

- ASTROPHYSICAL OBJECTS
- CRs & GALACTIC DYNAMICS
  - CR-excavated bubbles
  - CR feedback
- MULTI-MESSENGER ASTRO
  - CRs and UHECRs
  - UHE γ-rays and neutrinos
  - EM counterparts of GW events

Magnetic Reconnection

Living with a star

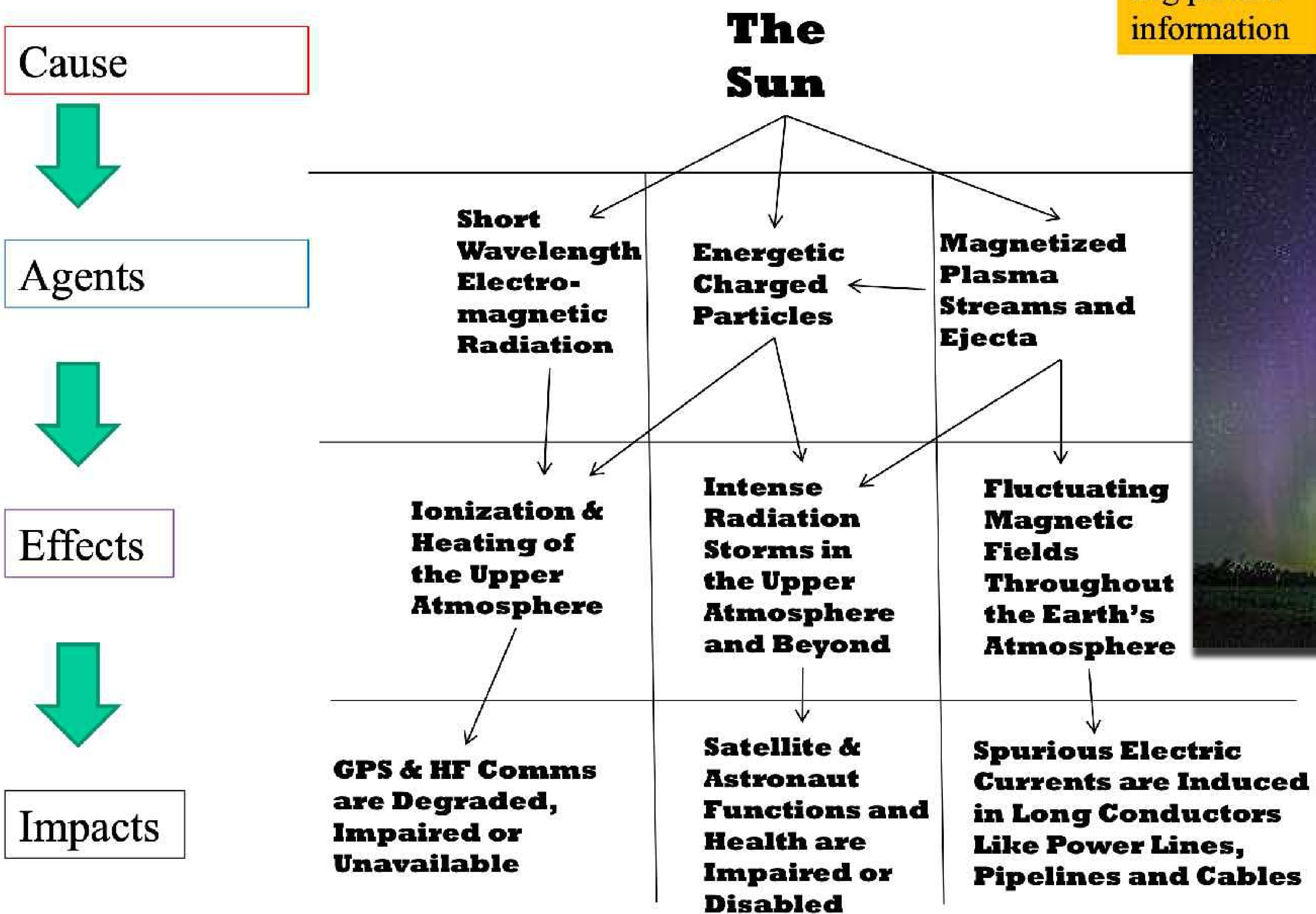
- Dissipation of magnetic field loops on the Sun surface triggers solar flares

Credits: NASA

- The coronal mass ejection reaches and *shakes* the Earth's magnetosphere
- Energetic particles produced in the magnetotail produce auroras

Space Weather

Big picture information

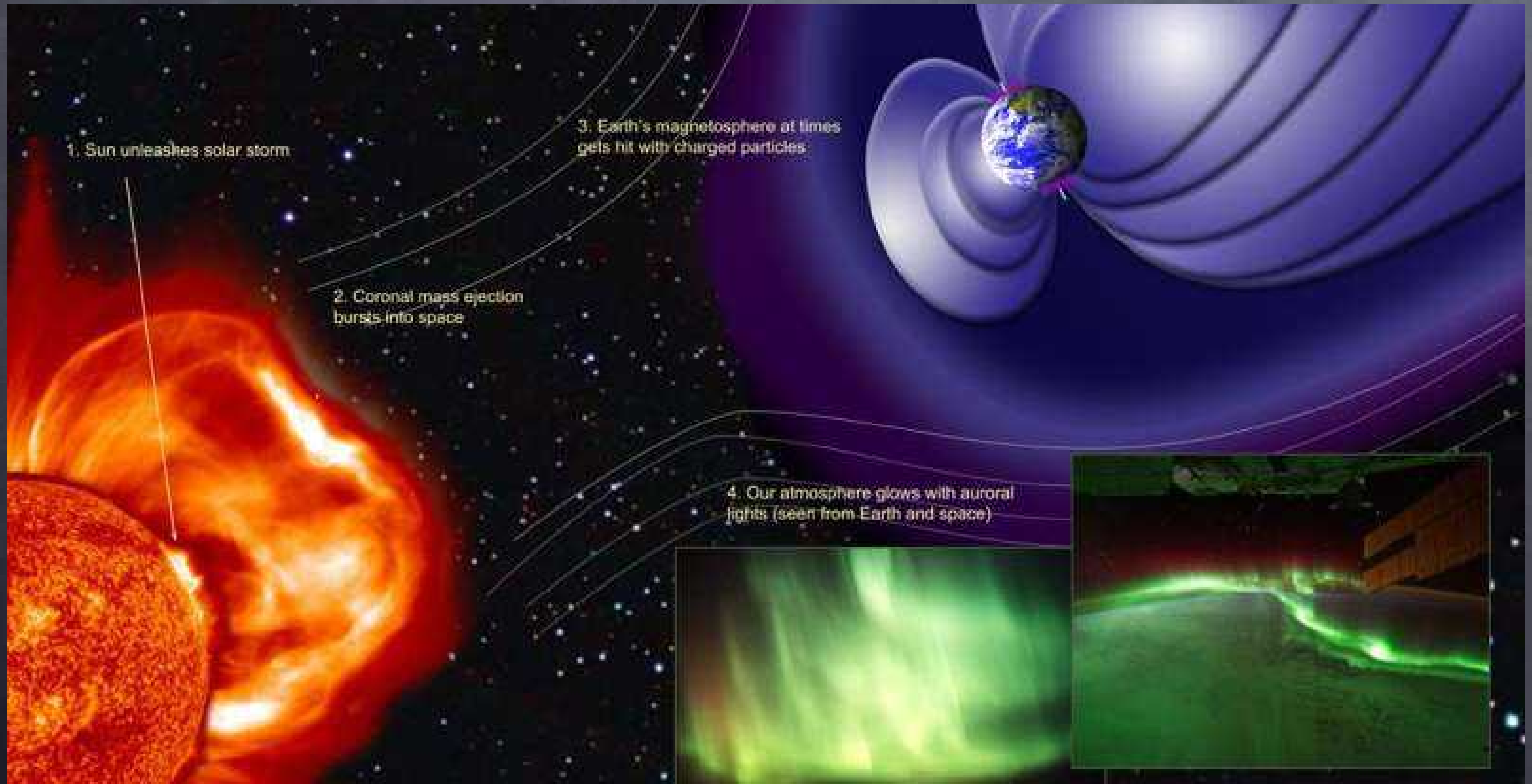


Aurorae (Northern/Southern lights)

Also seen from Intl. Space Station

Carrington Event

- Most powerful geomagnetic storm recorded on September 1–2, 1859
  - Lots of aurorae, but wrought havoc with telegraph systems
  - Such a solar storm today would cause widespread electrical disruptions, blackouts, and extended outages
    - Some *grid components are tailor made*: outages may last *months*, affecting *millions* of people
  - In March 1989 a weaker geomagnetic storm knocked out power across large sections of Quebec
  - In 2012 a Carrington-like event missed the Earth *by 9 days* only!



TURBULENCE

Reconnection ⟺ Turbulence

- Explosive stage of acceleration (strong motional E), followed by 2nd-order Fermi processes
  - No universal predictions for spectra of accelerated particles (slope, maximum energy…)

Credits: L. Comisso & L. Sironi

SHOCK ACCELERATION

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

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 $M_s = V_{sh}/c_s \gg 1$): $R = 4$ and $\alpha = 4$

DSA: Like playing ping pong (*without friction!*)

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.,:

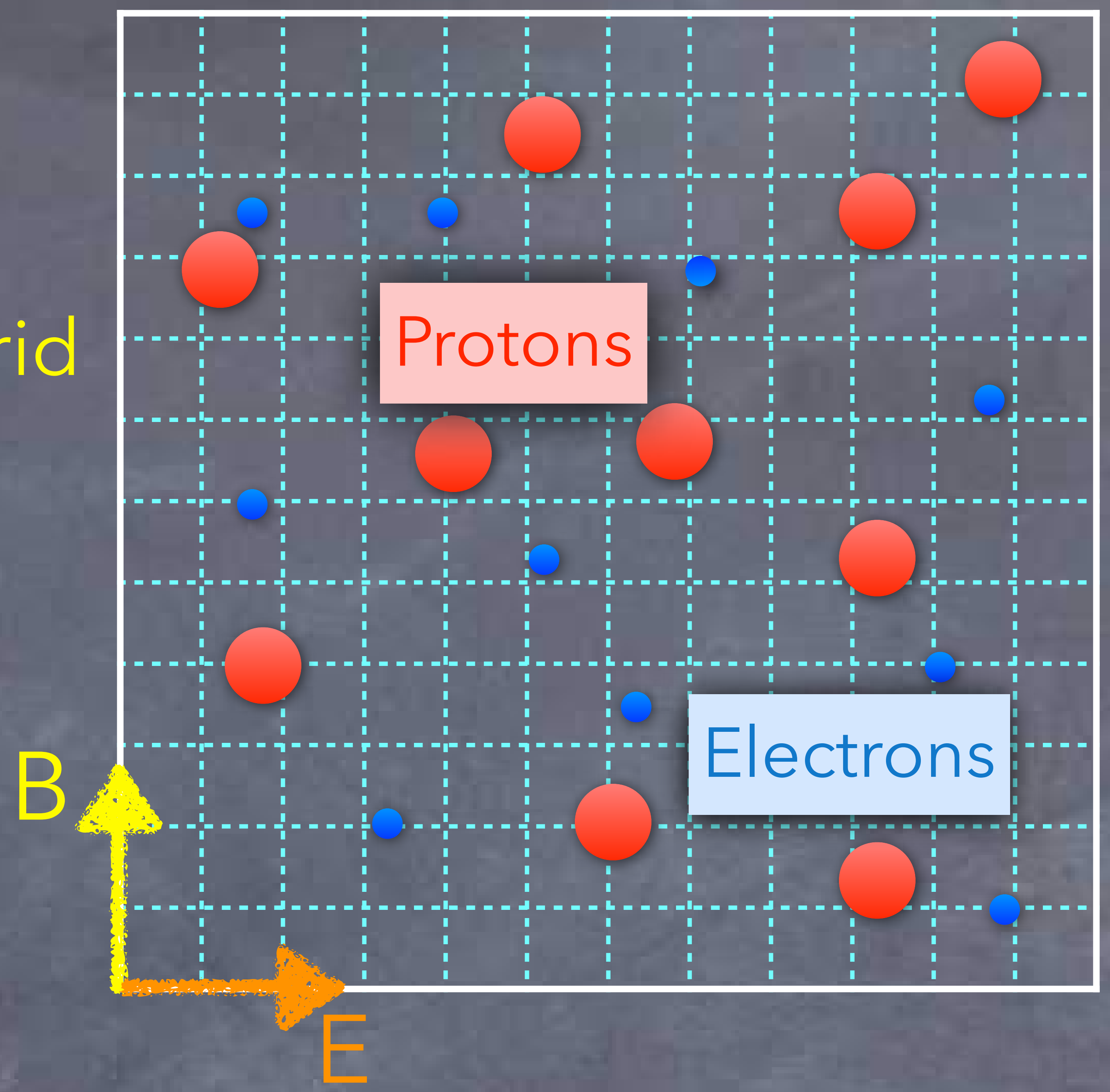
$$\frac{dN_k}{dE} = N_0 \left(\frac{E_k}{E_0}\right)^{-q_E}; \quad q_E = 1 - \frac{\log P}{\log G} \qquad G \simeq 1 + \frac{4}{3}\frac{u_1 - u_2}{c} \quad P \simeq 1 - \frac{4u_2}{c} \qquad q_E \simeq \frac{R+2}{R-1}; \quad R = \frac{u_1}{u_2}$$

- 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 $M = \dfrac{v_{sh}}{c_s} \gg 1 \to R = 4$ and spectra are $f(p) \propto p^{-4}$ or

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

Astroplasmas from first principles

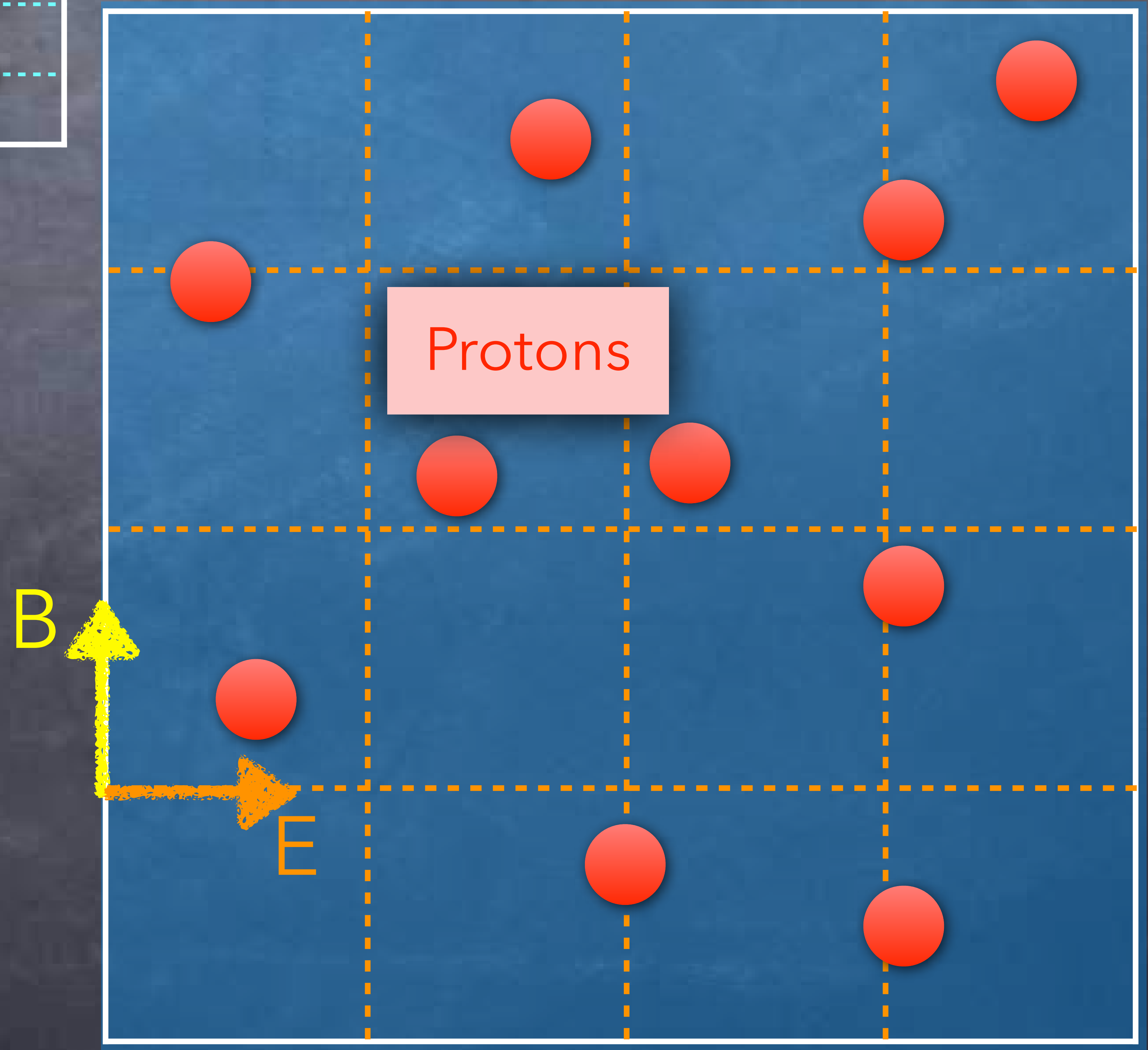
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



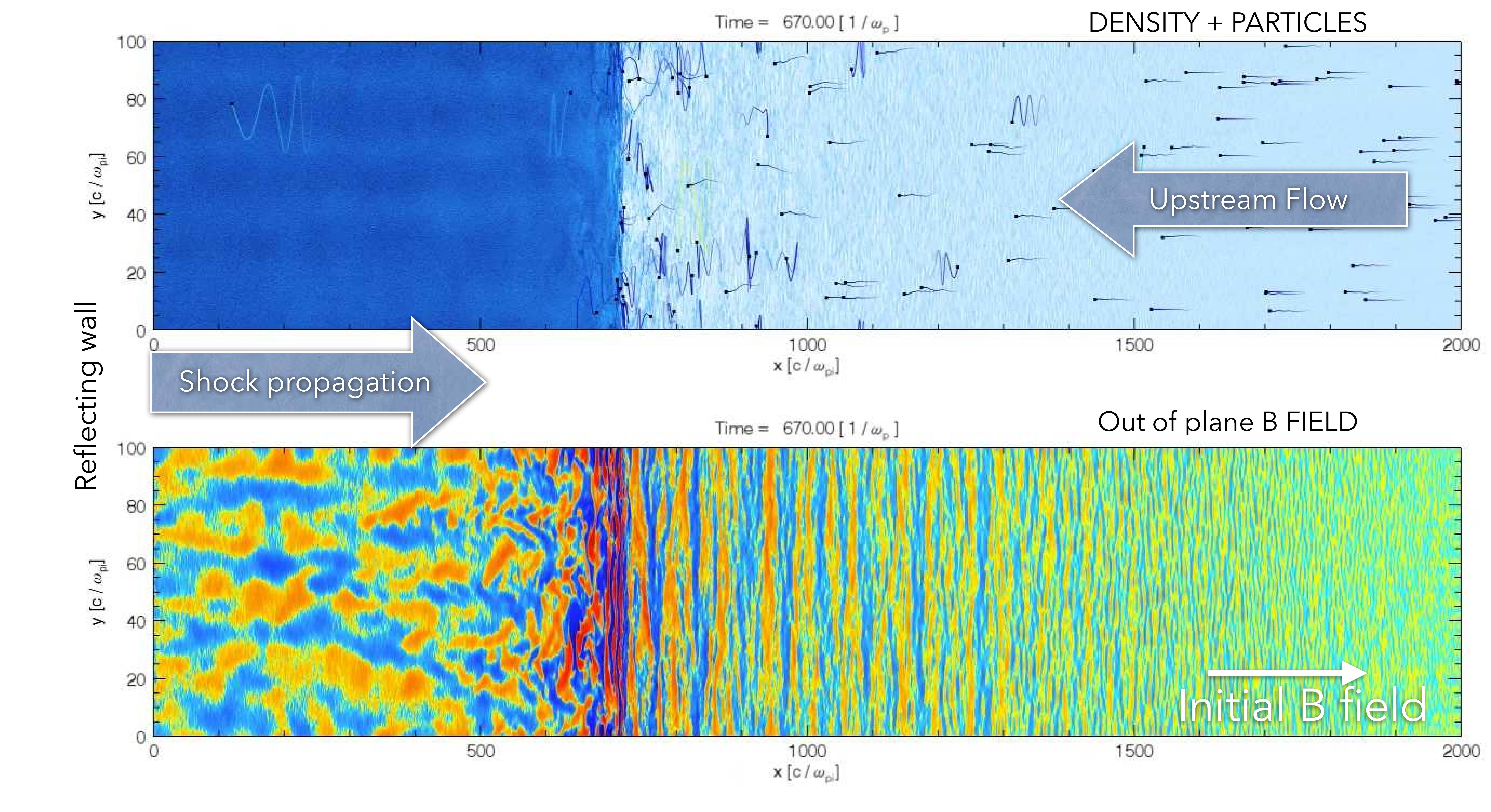
- Hybrid approach: Fluid electrons - Kinetic protons

(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

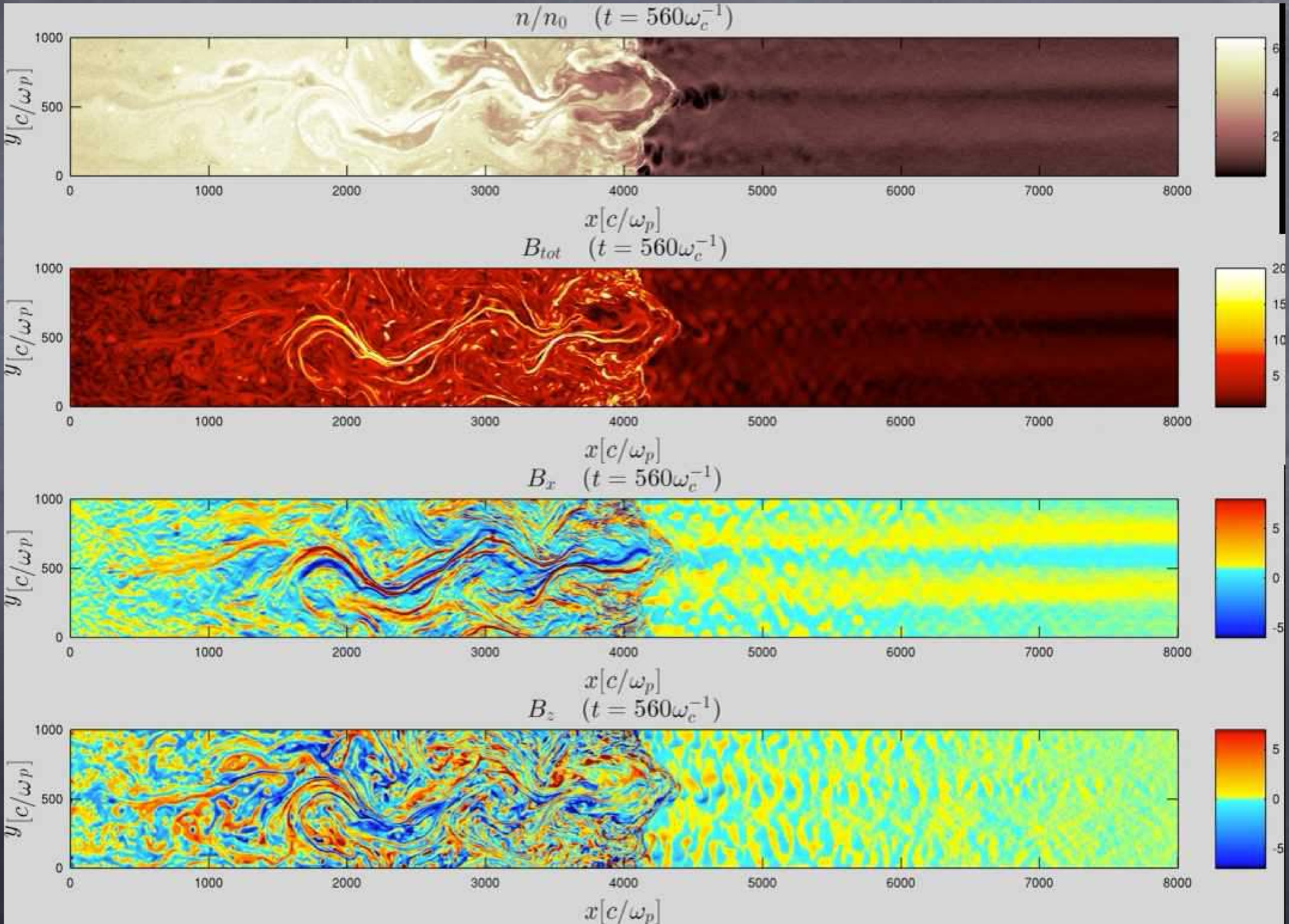


Hybrid Simulations of Collisionless Shocks



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

CR-driven Magnetic-Field Amplification



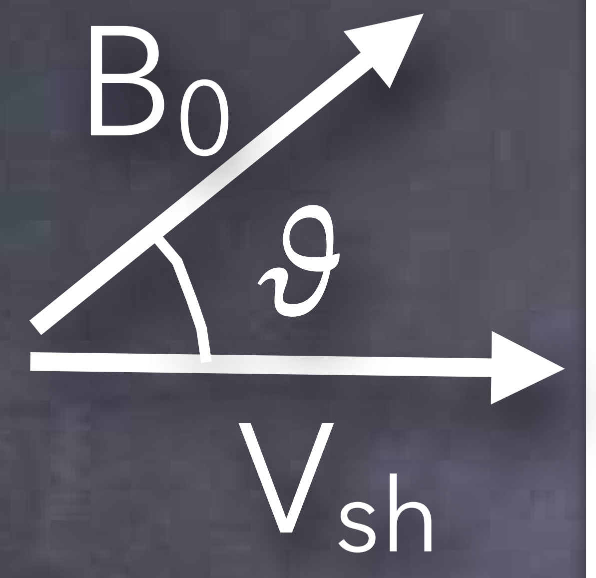
Initial B field

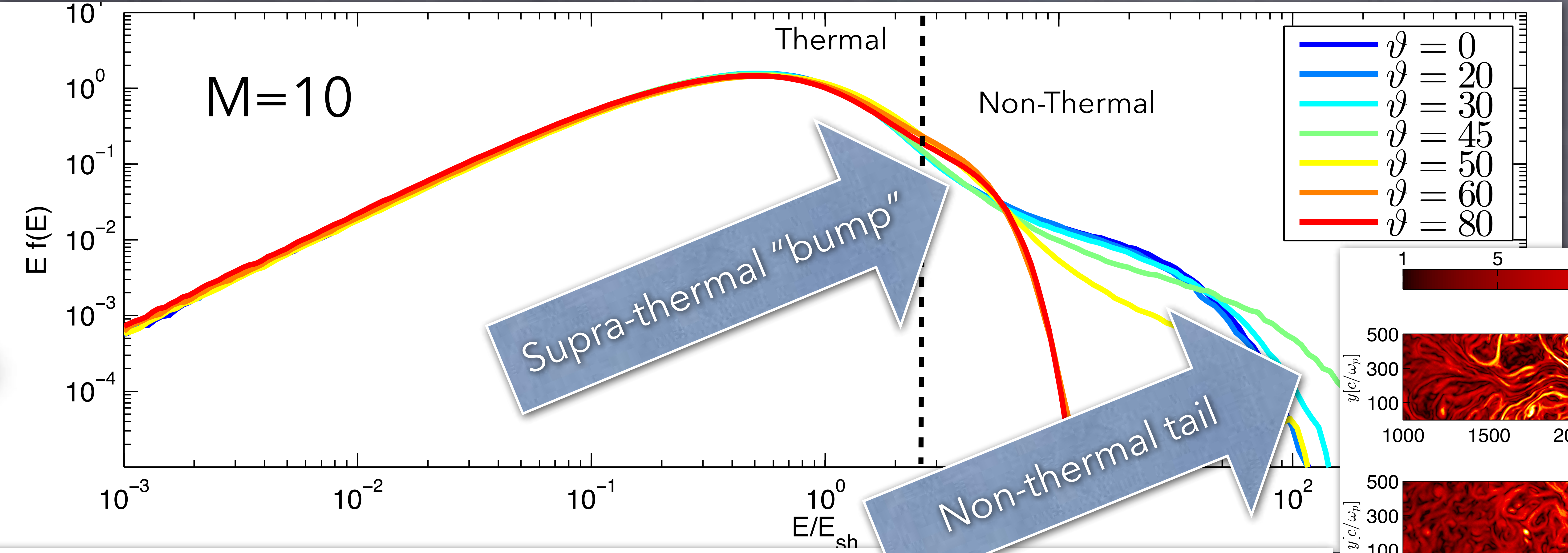
$M_s = M_A = 30$

DC & Spitkovsky, 2013

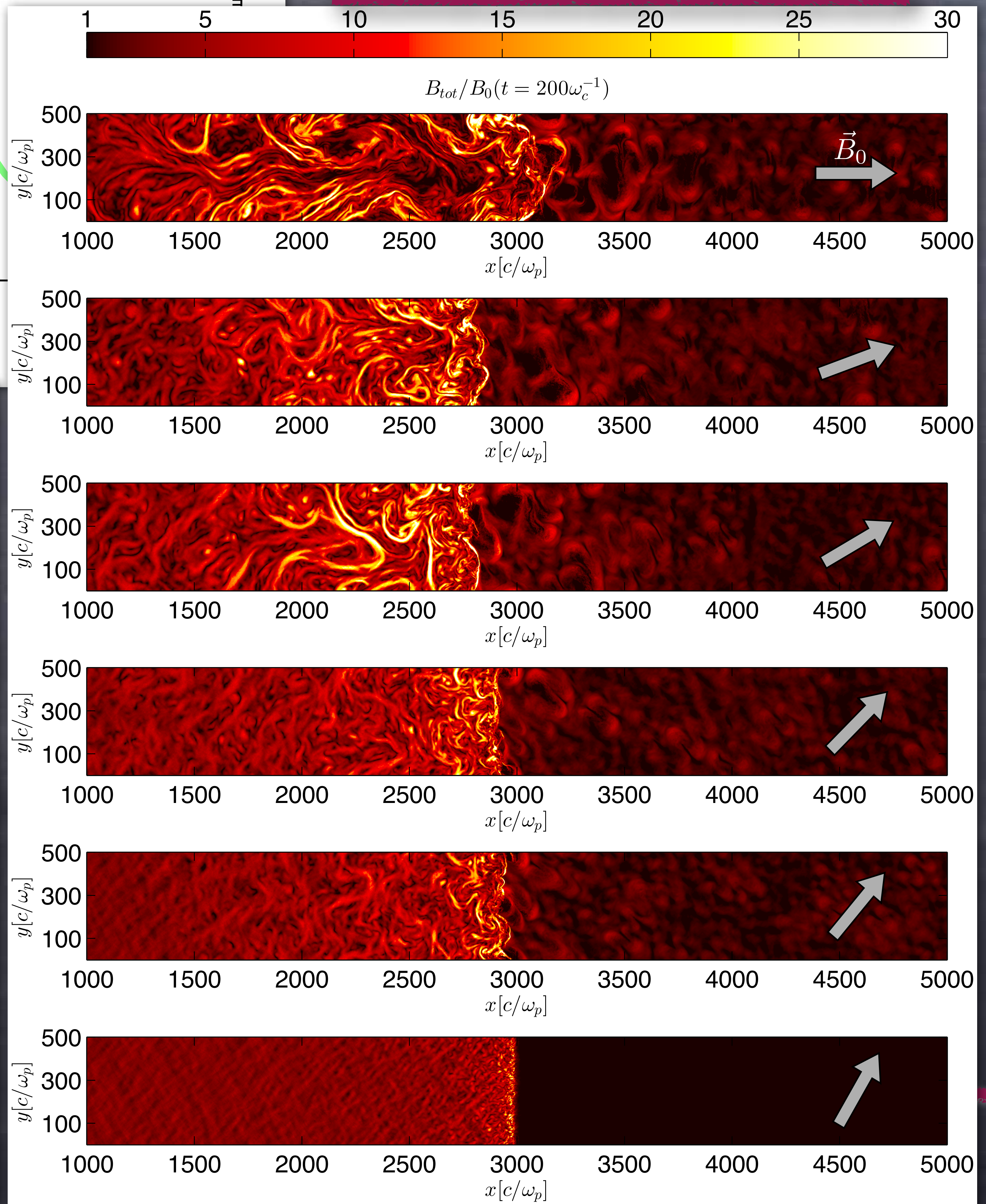
Parallel vs Oblique shocks (2D)

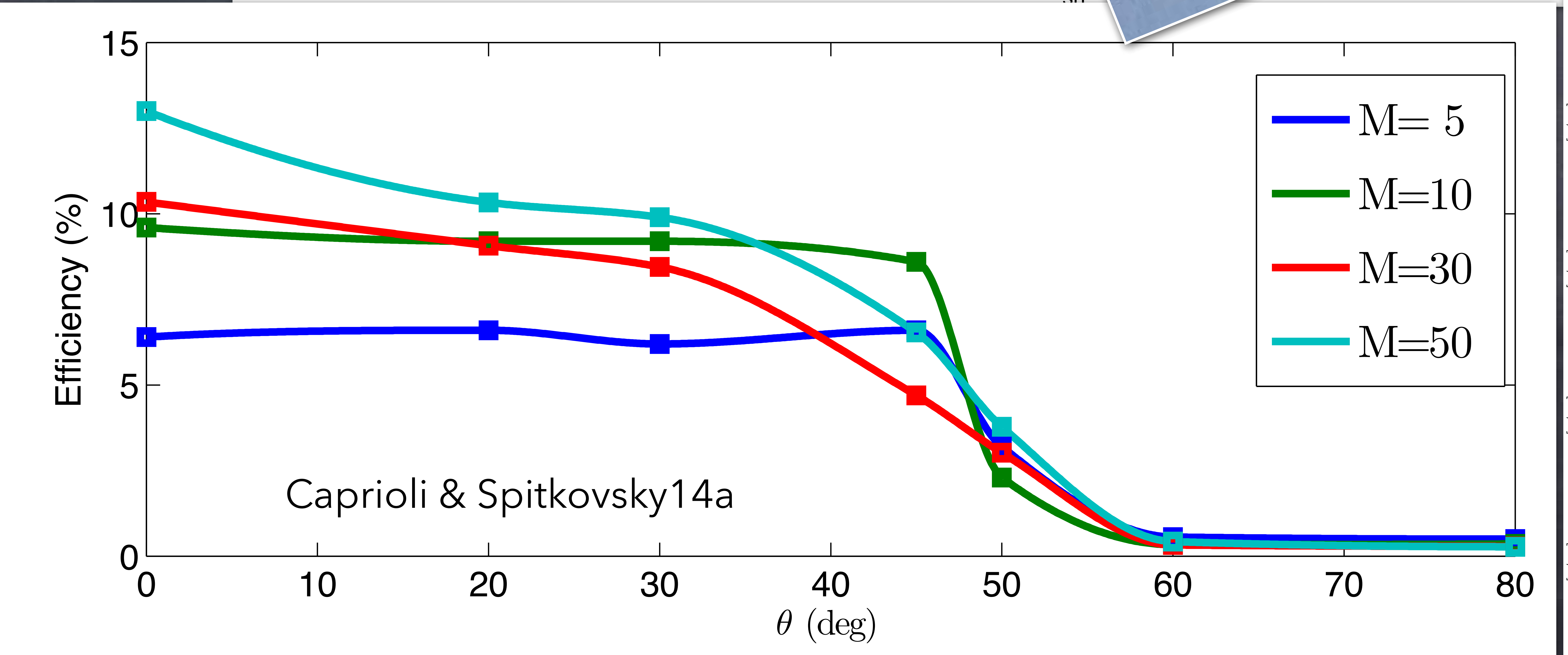
Shock
inclination





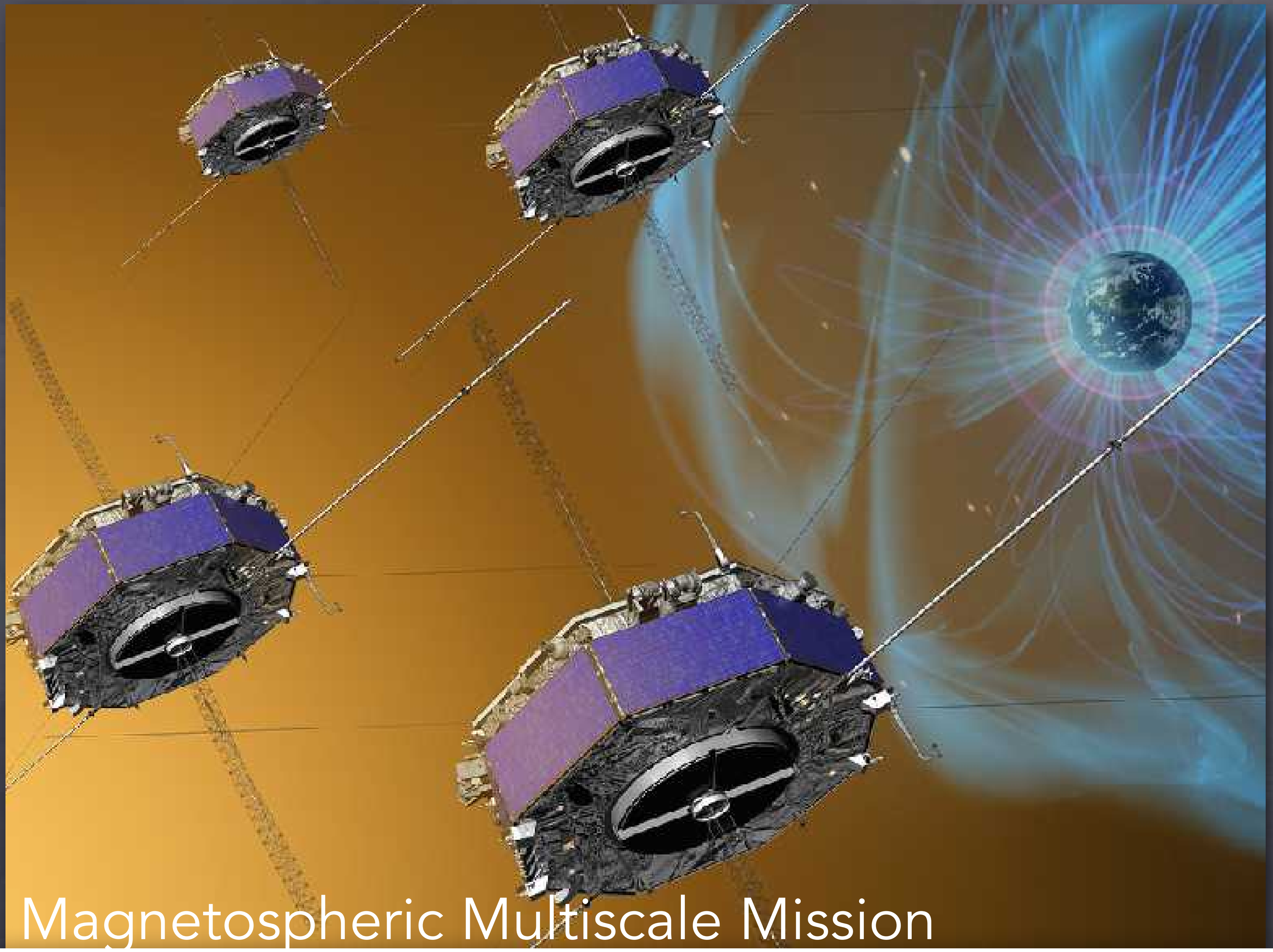
Ion acceleration correlates with B-field amplification

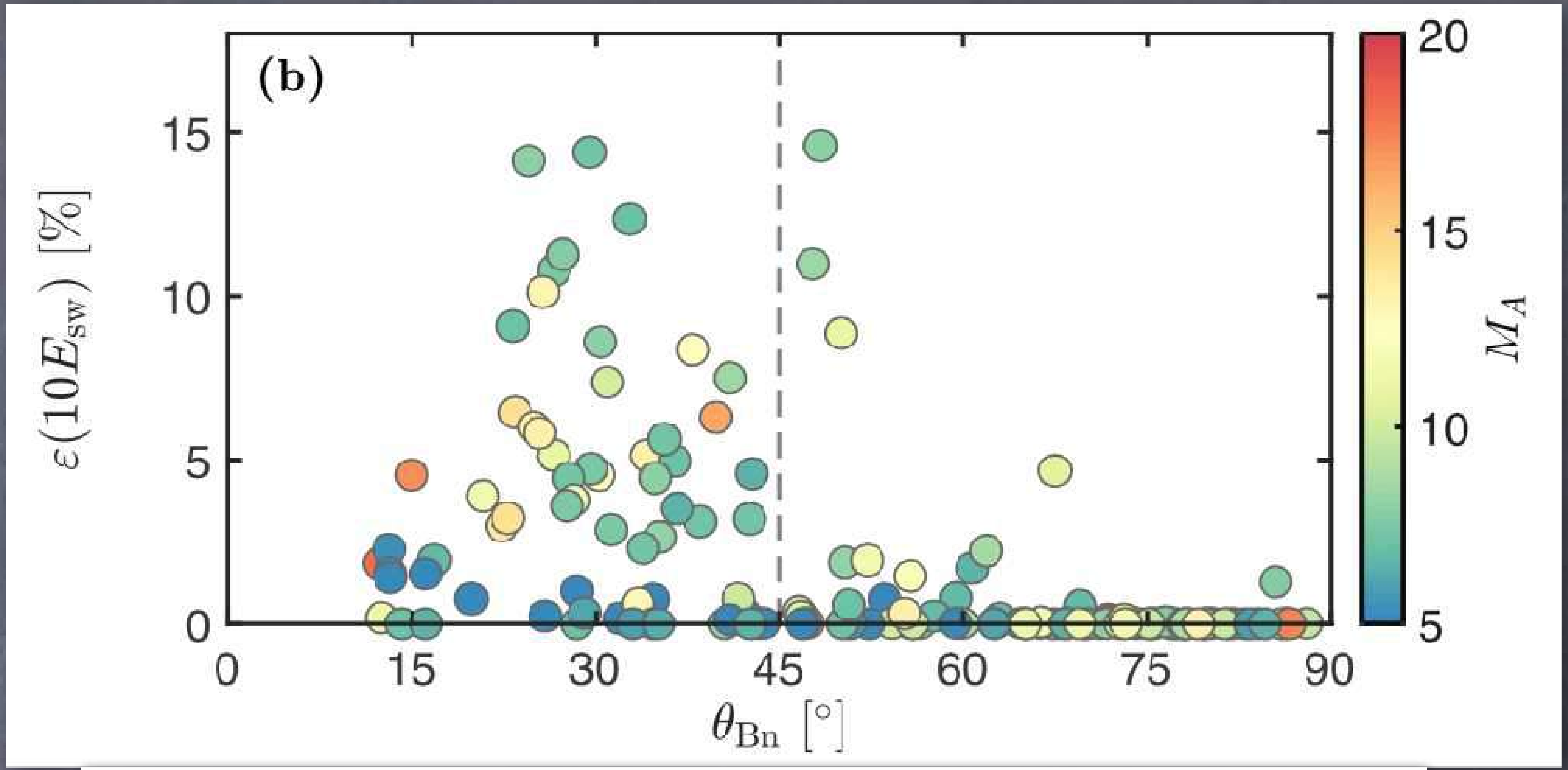


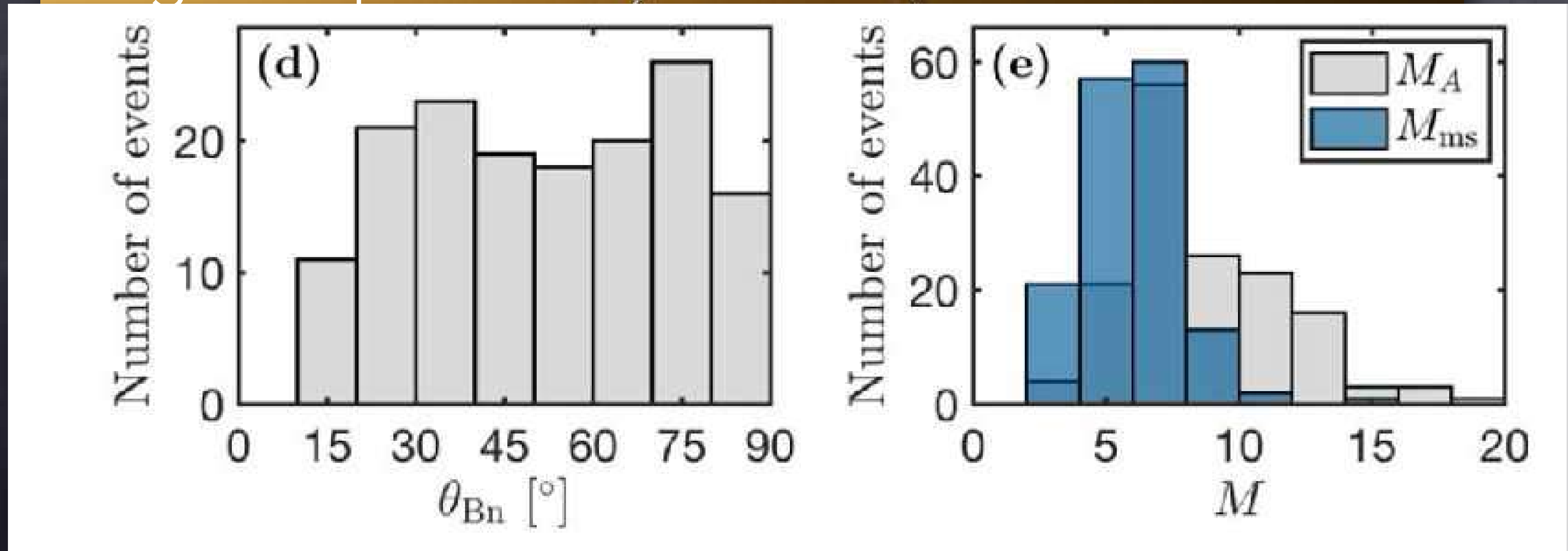


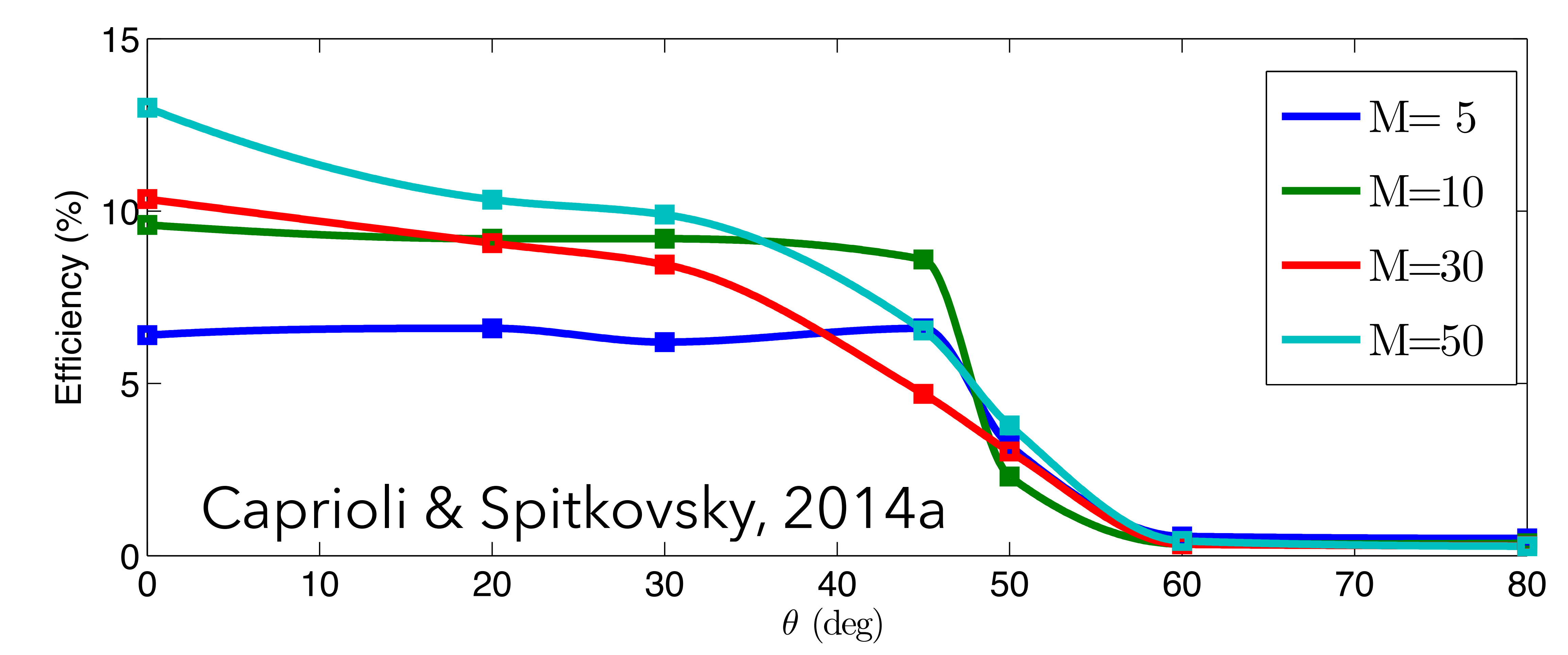
Ion DSA at the Earth Bow Shock

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



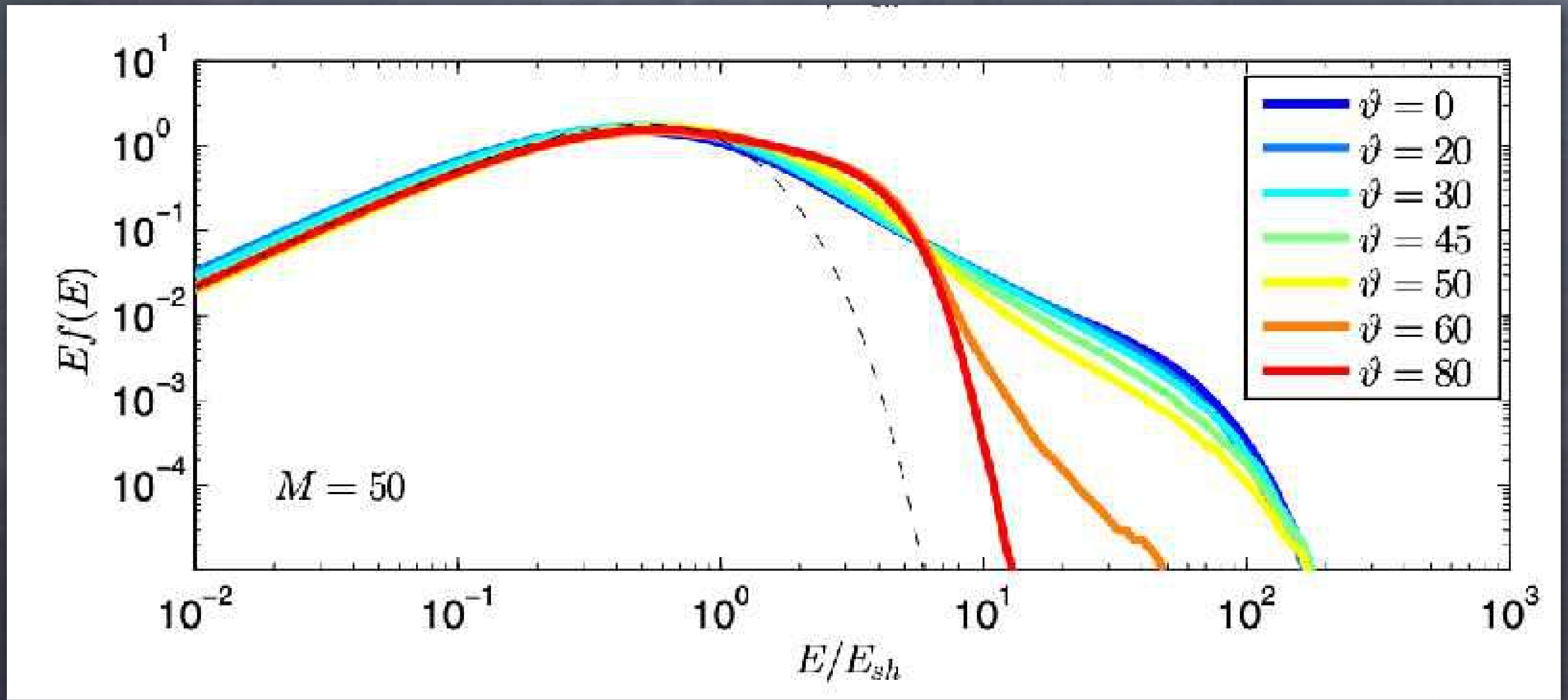


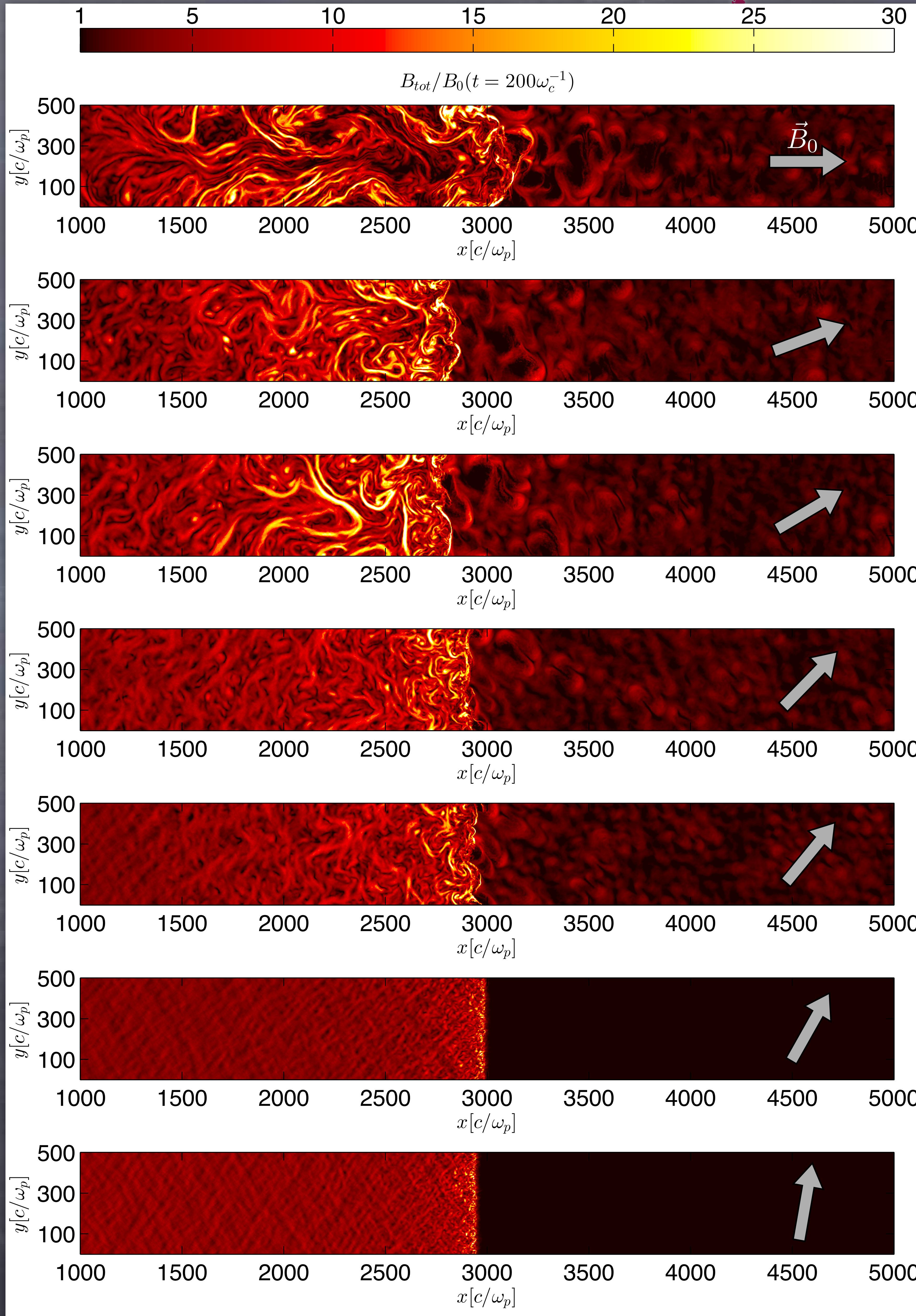




Oblique Shocks

- Oblique shocks are good accelerators but bad ion injectors (Jokipii82, Giacalone+00, Giacalone05, Caprioli+15)
- Is there a critical magnetization ($\propto 1/M_A^2$) below which ϑ becomes *irrelevant*?
  - No evidence in 2D hybrid sims w/o CR or B seeds



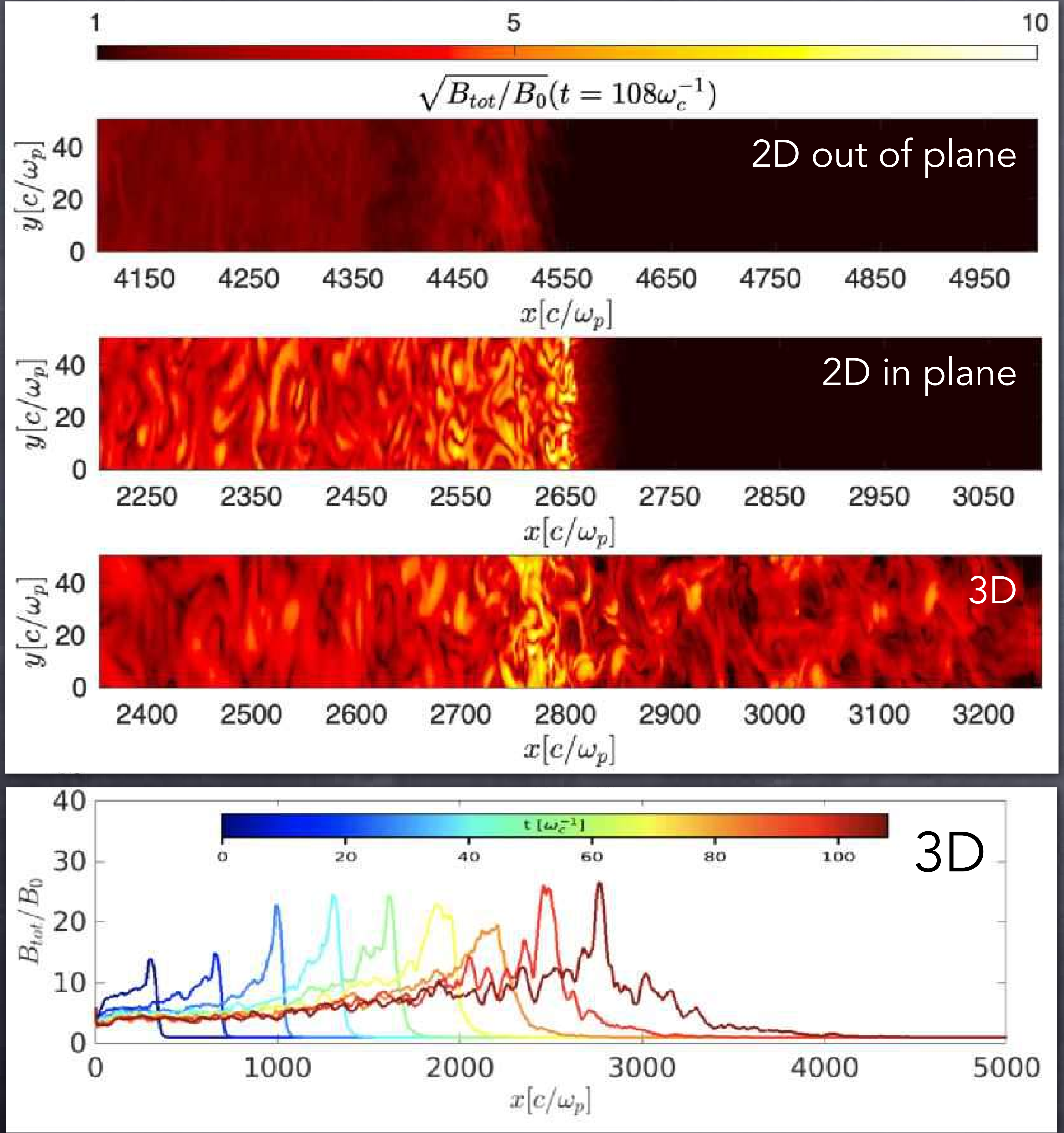


Caprioli & Spitkovsky14a,b

- Sironi+11 found $M_A^* \gtrsim 30$ for PIC relativistic shocks

Oblique Shocks: B-Field Amplification

- 2D/3D simulations of a shock with $M_A = 100,\ \theta_{Bn} = 80°$ (Orusa & Caprioli 2023)

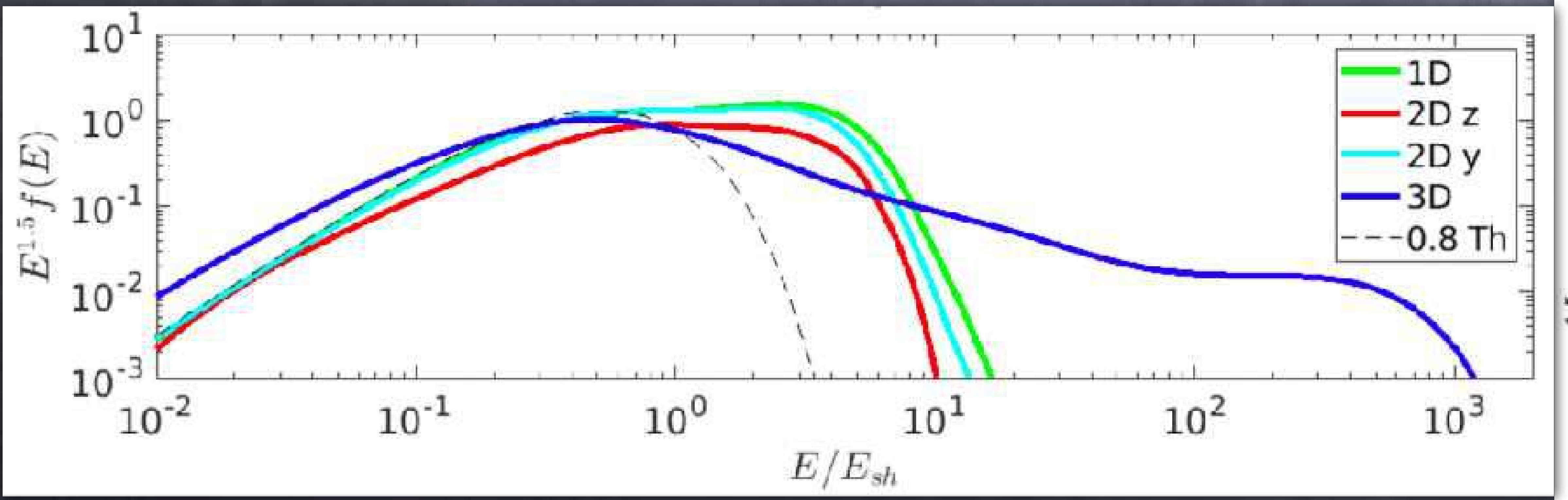


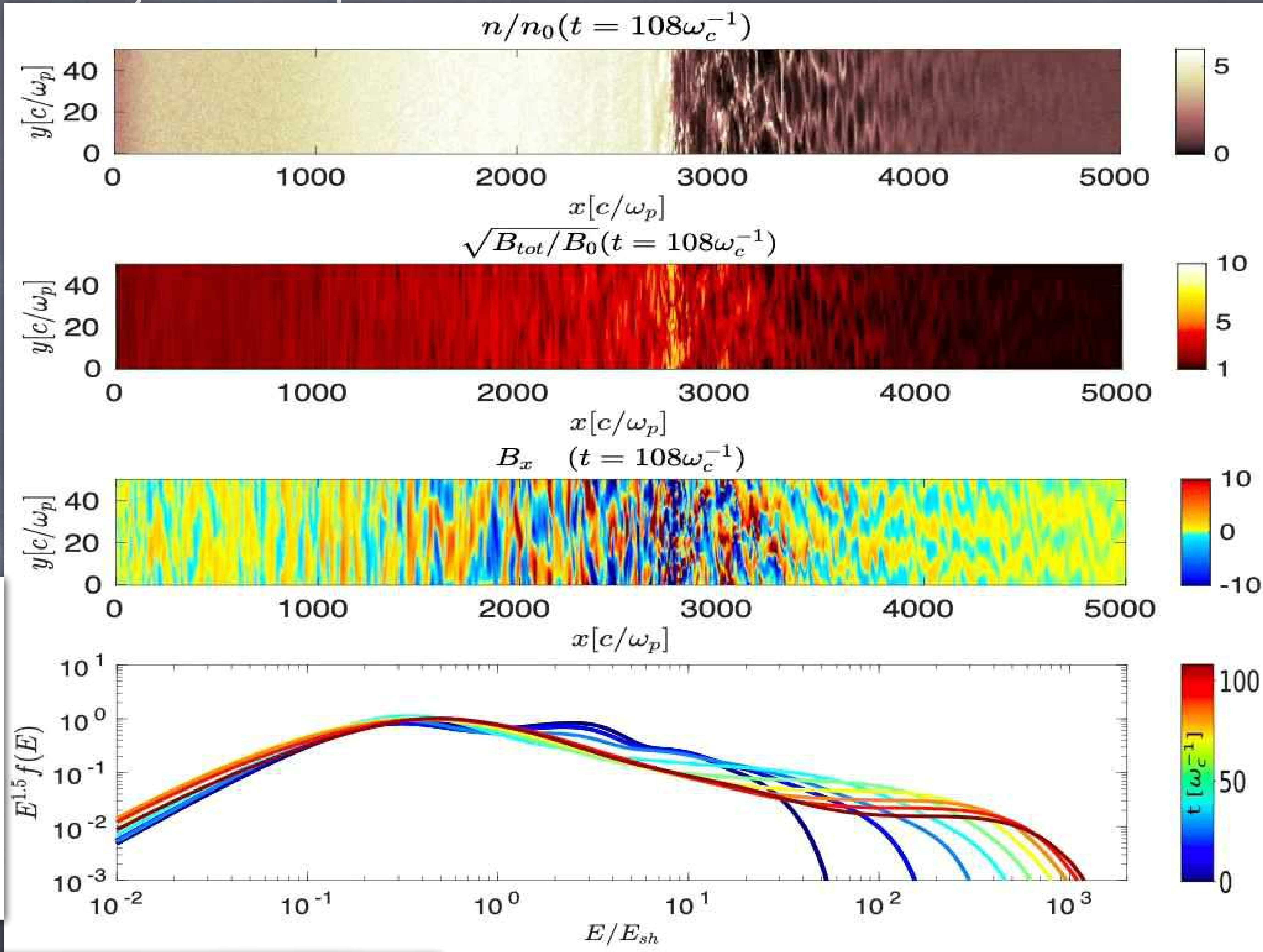
- Free energy in interpenetrating ion beams
  - 1D: simple compression (MHD)
  - 2D out-of-plane B: ~ compression
  - 2D in-plane B: $\delta B/B_0 \lesssim 40$ at the shock
  - 3D: $\delta B/B_0 \lesssim 40$ at the shock, but also $\delta B/B_0 \gg 1$ upstream
- Dimensionality matters! Why?
  - Importance of vorticity and baroclinity $\nabla p \times \nabla \rho$
  - Biermann battery/turbulent B amplification

Oblique Shocks: Ion Acceleration

- Self-generated B turbulence *solves the injection problem*!

- 3D geometry unlocks cross-field diffusion / B-field line wandering
  - Supra-thermal Ions can diffuse back from downstream
  - and develop a non-thermal tail



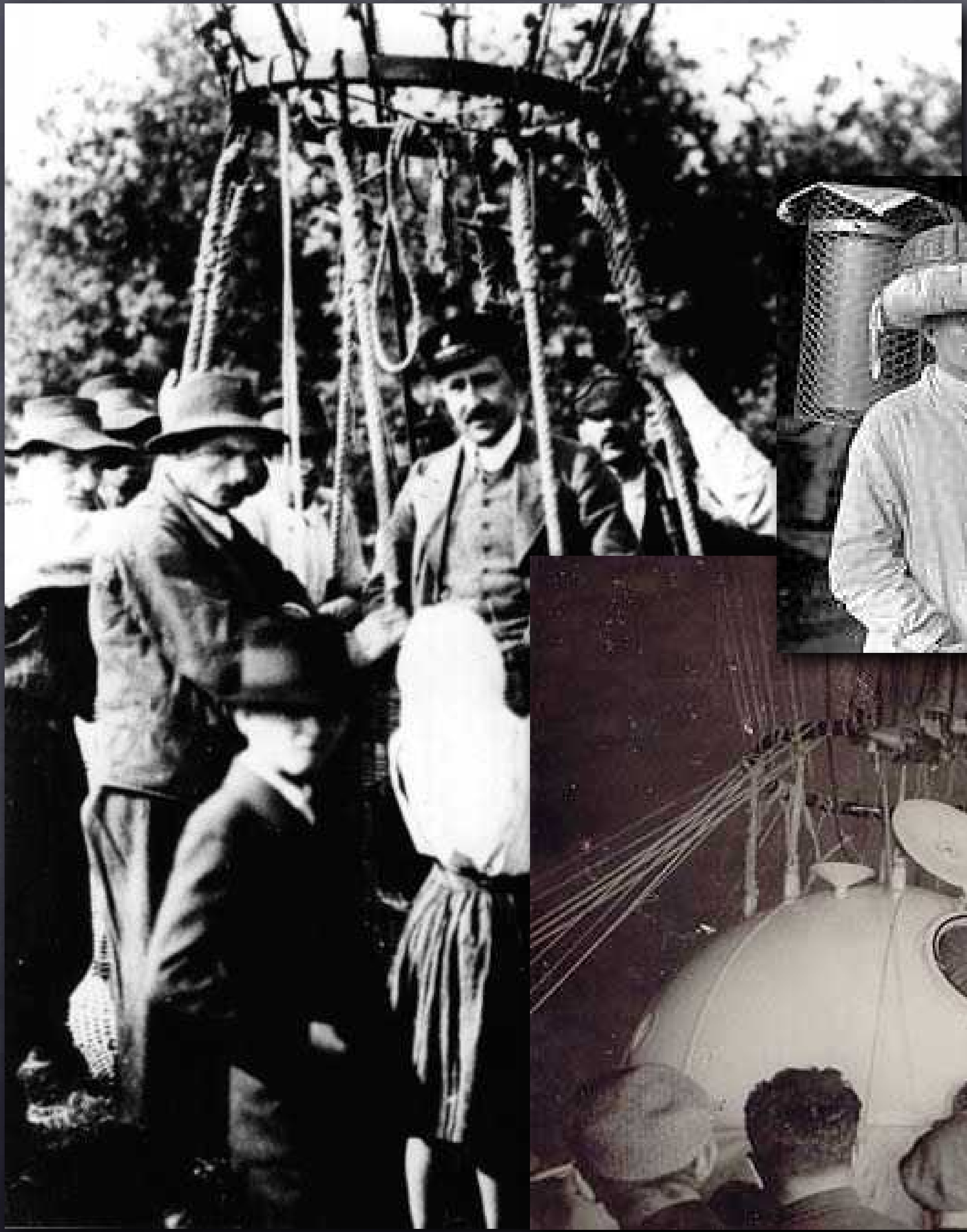


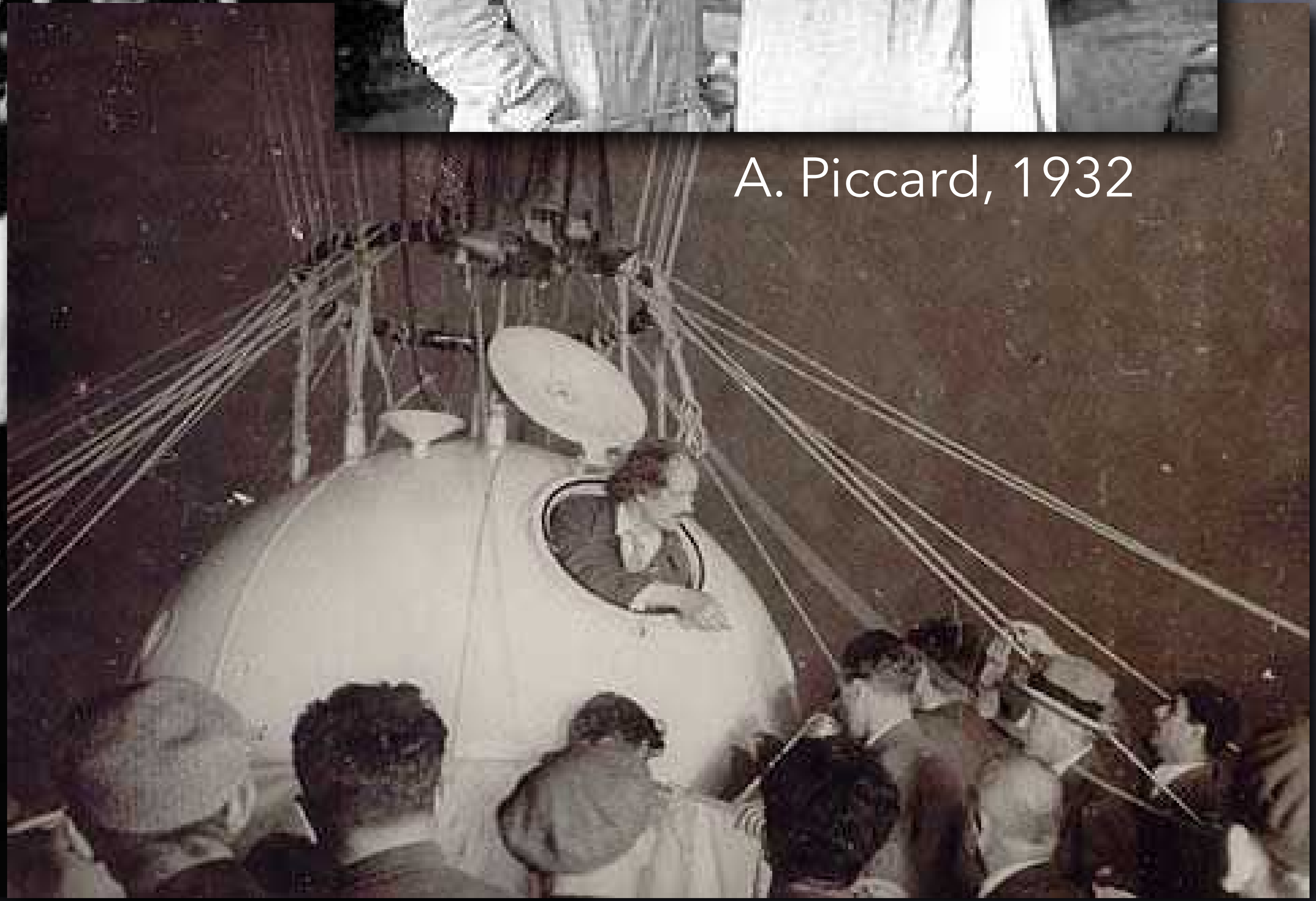
Sometimes 3D matters!

Orusa & Caprioli 2023

COSMIC RAY PHENOMENOLOGY

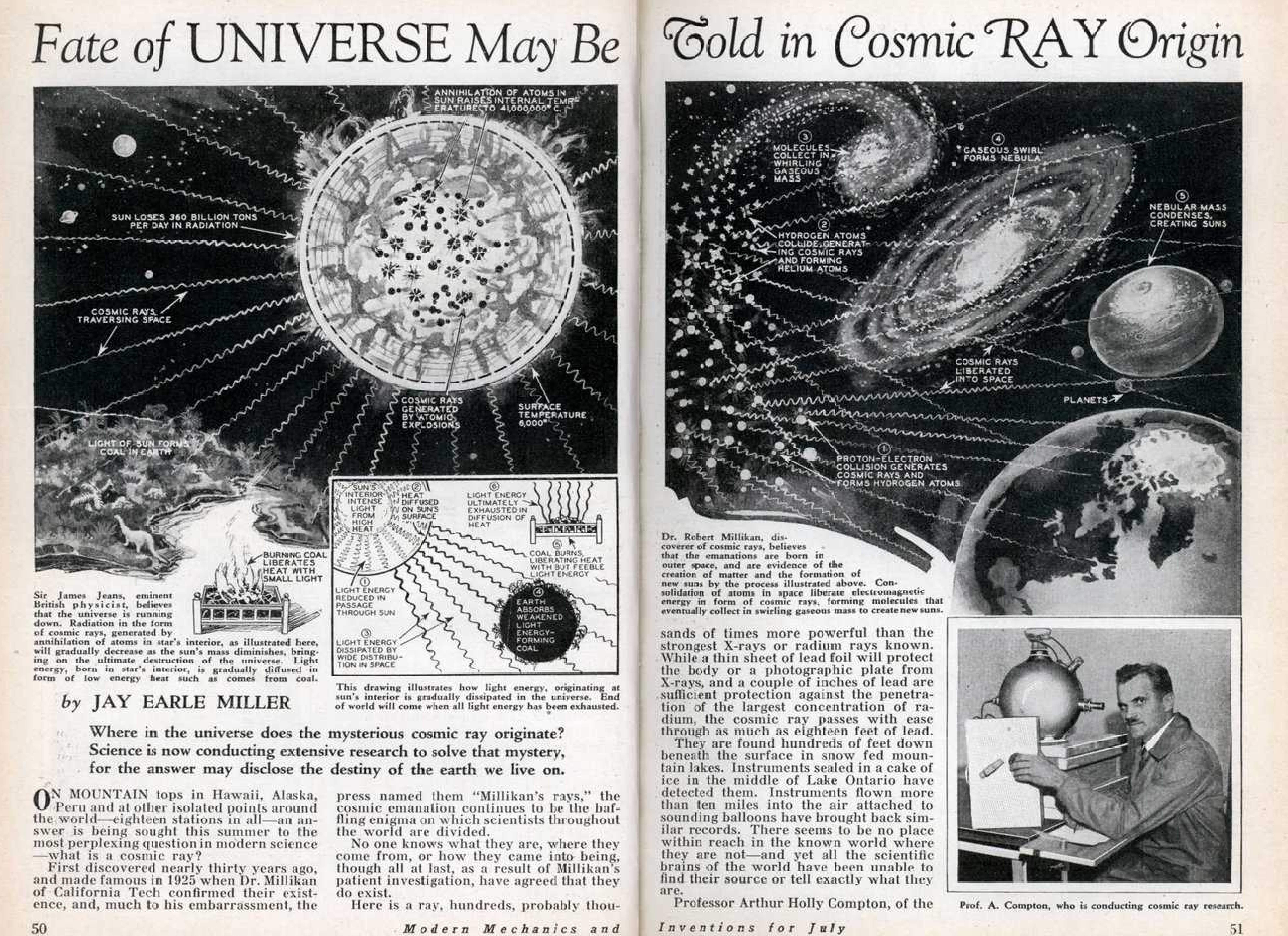
The Dawn of Cosmic Ray Physics





A. Piccard, 1932

- 1911-12: D. Pacini and V. Hess discover an *extraterrestrial* source of ionization
- 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



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

Modern CR History

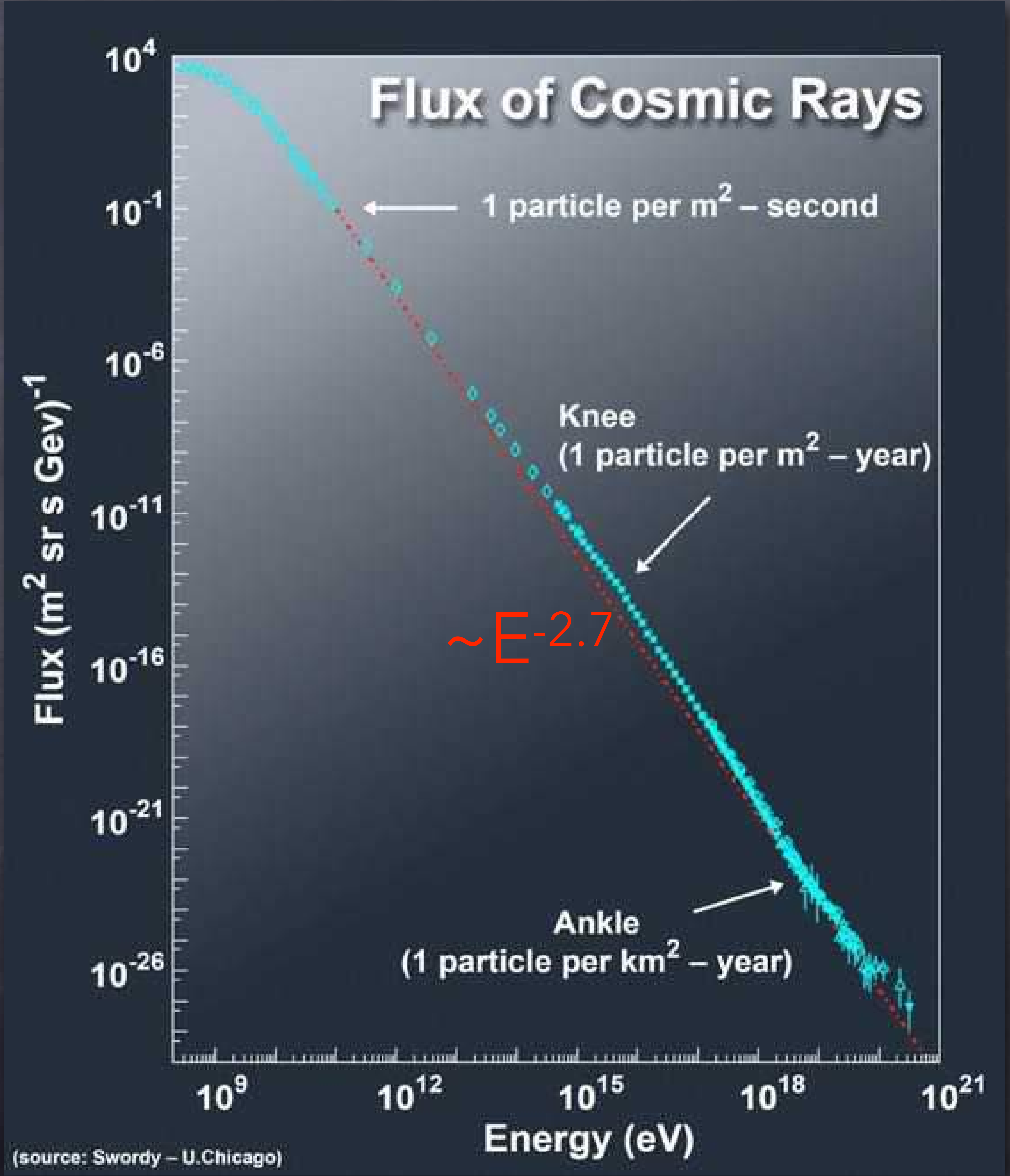
- 1930: B. Rossi predicts the East-West effect
- 1932: C. Anderson discovers the positron in CRs
- 1934: B. Rossi notices multiple correlated triggers at large distances: extensive showers!
- 1937: S. Neddermeyer and C. Anderson discover the muon
- 1939: P. Auger: showers up to ~10^5 GeV
- …
- 1962: J. Linsley and L. Scarsi: ultra-high-energy CRs up to ~10^9 GeV

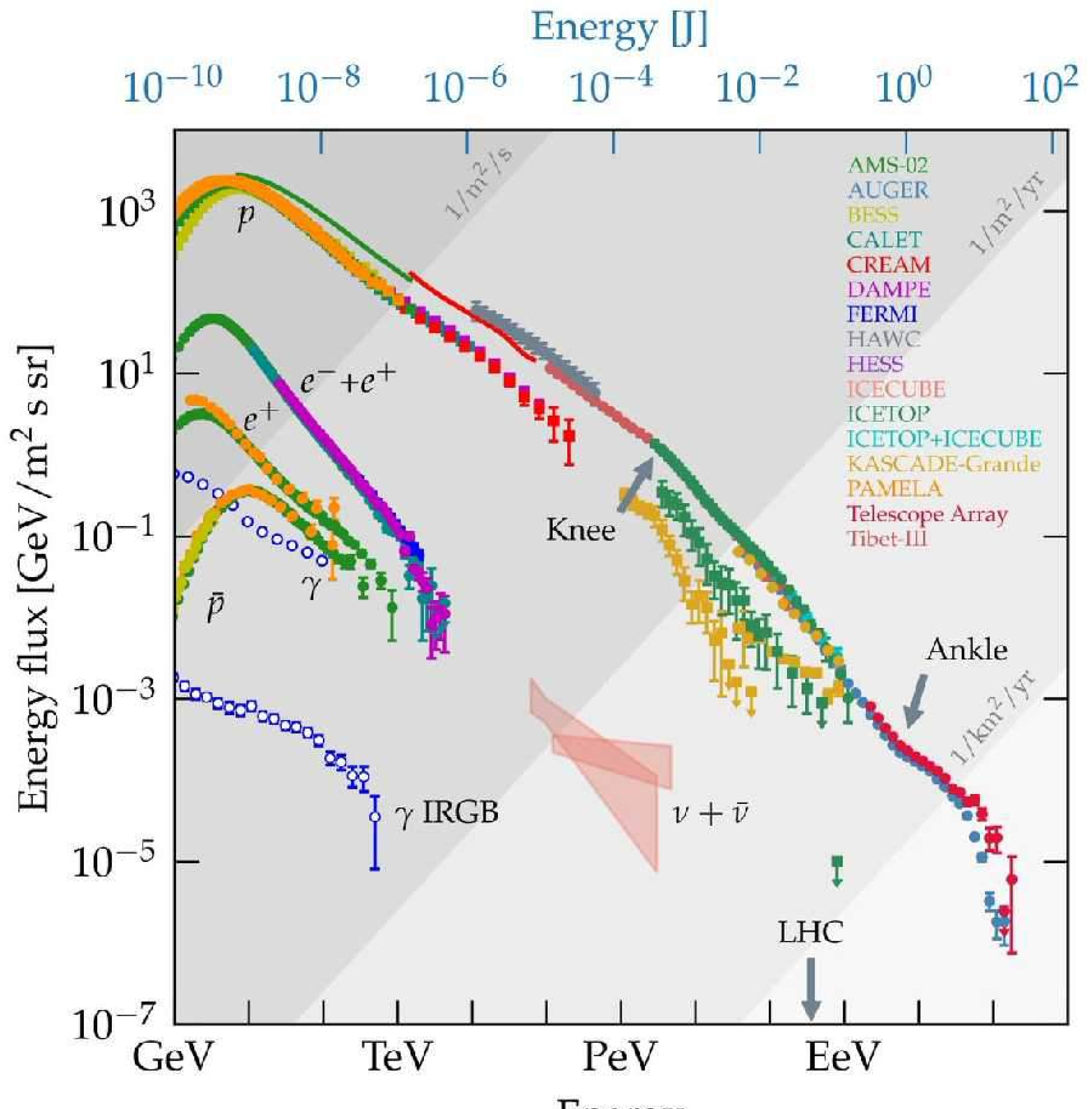
B. Rossi

C. Anderson

P. Auger

The CR spectrum at Earth

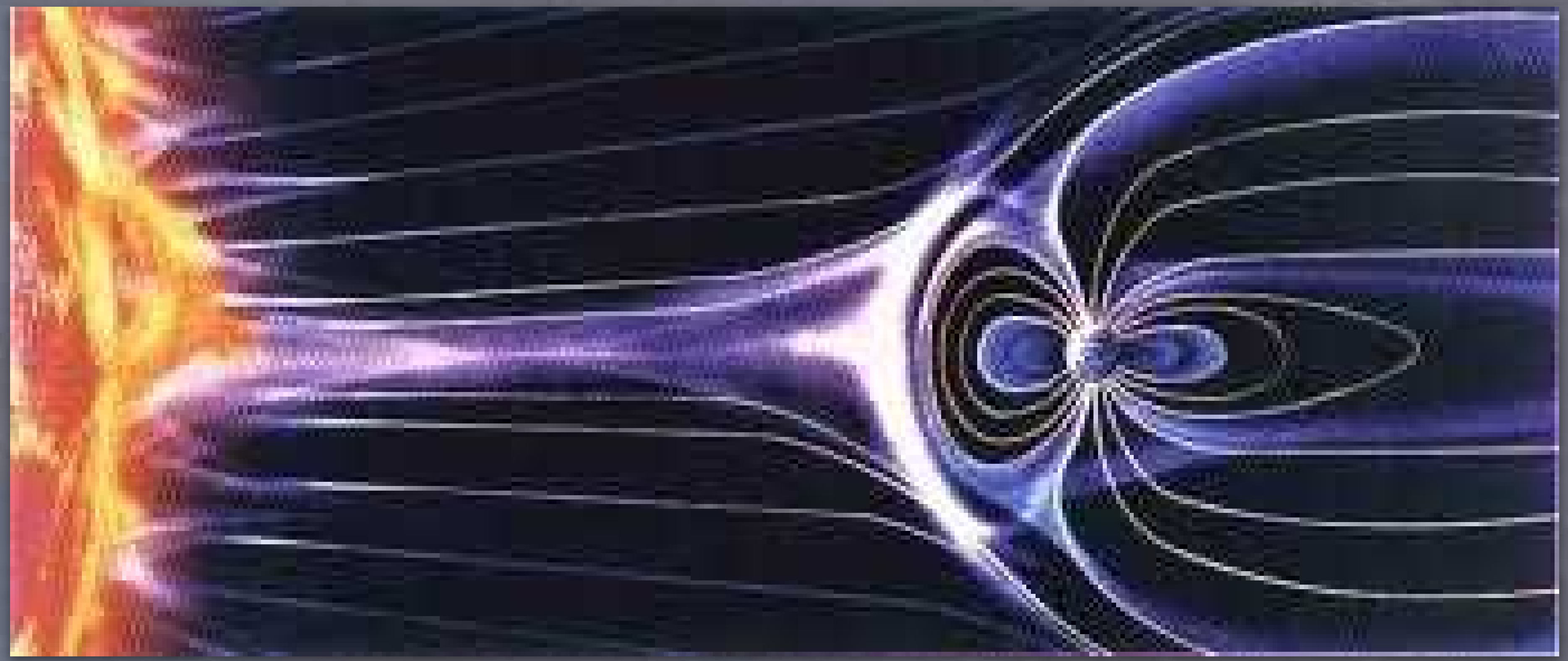


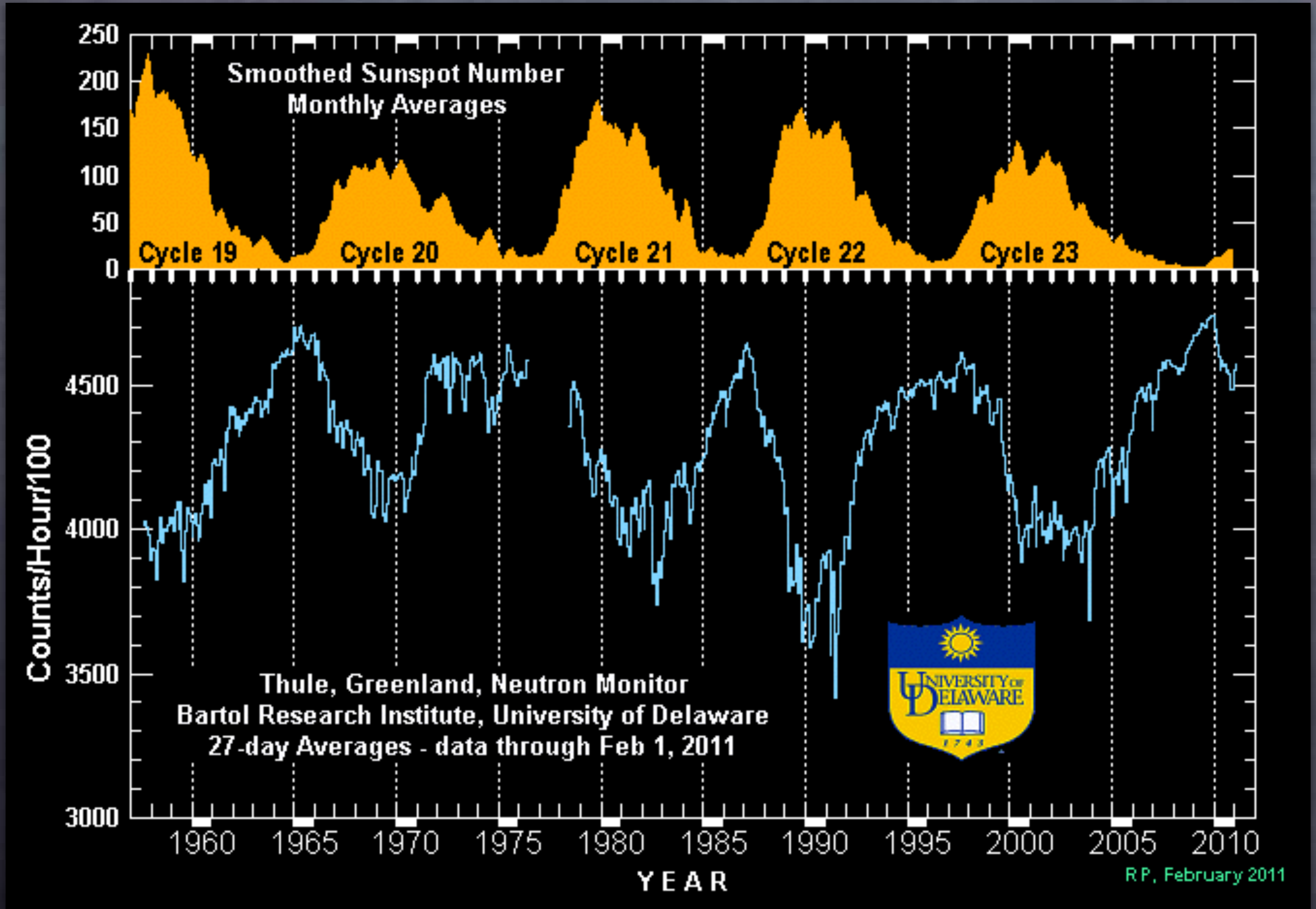


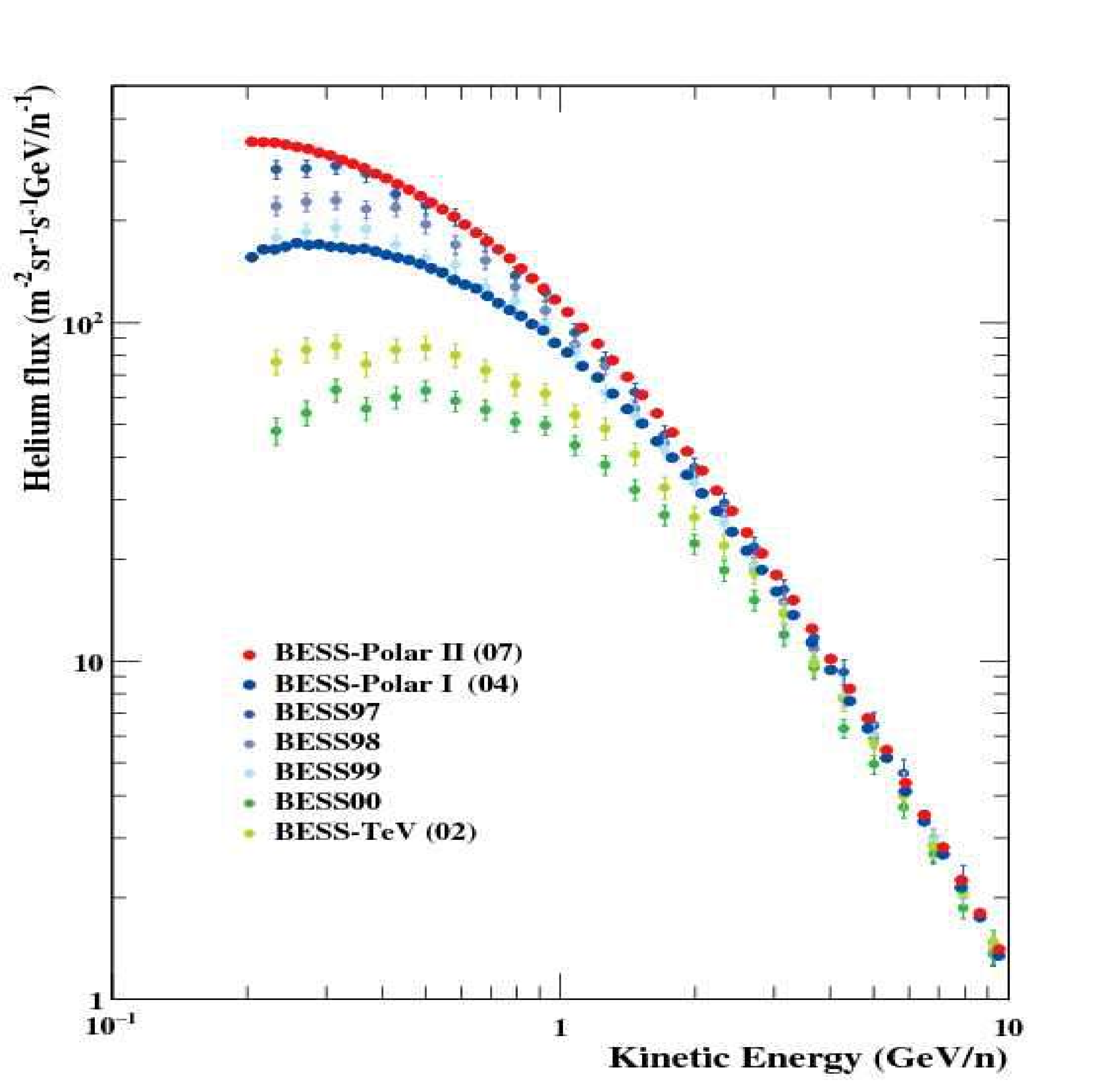
Credit: C. Evoli

Solar Modulation

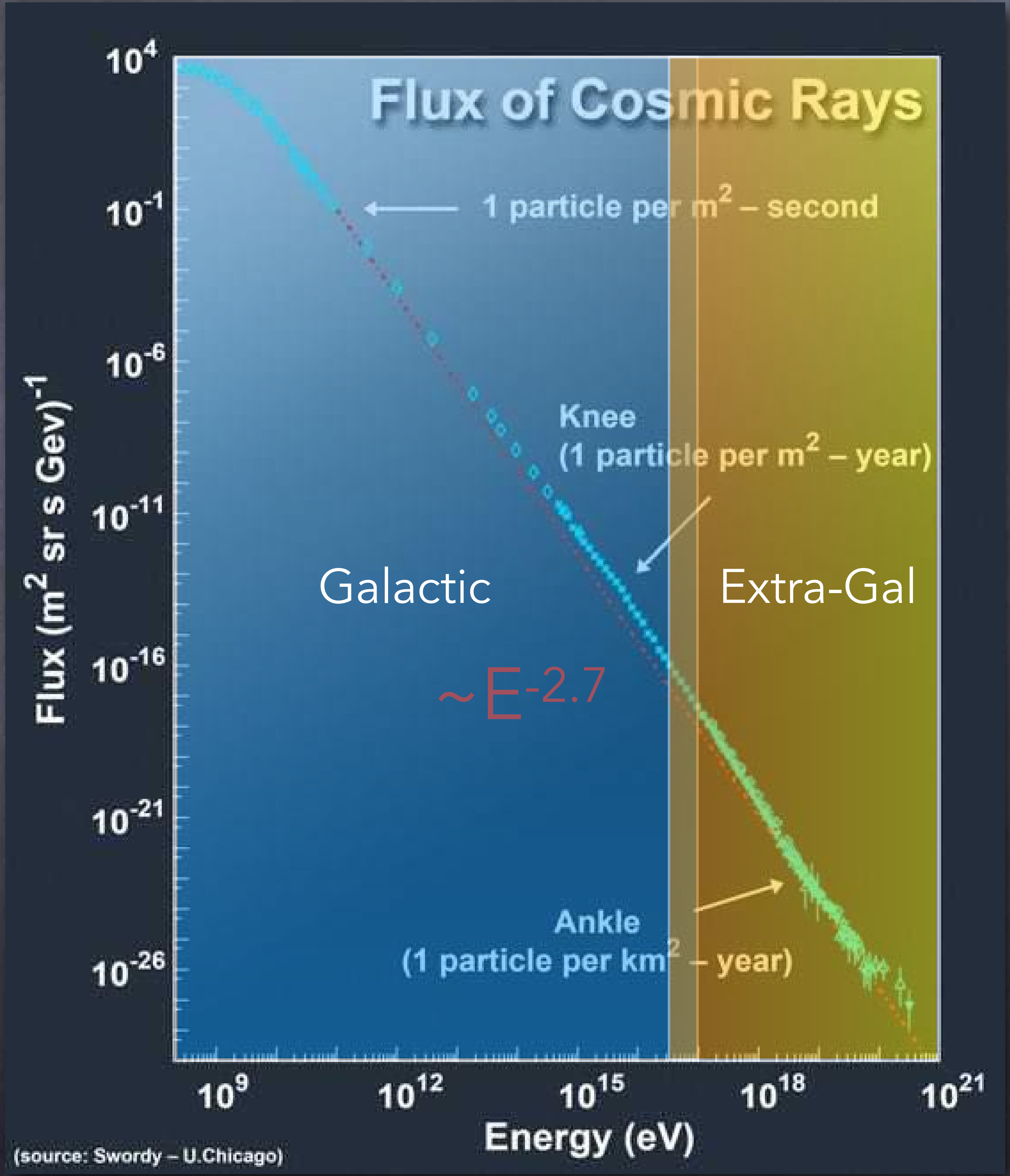
- Below ~10 GeV: solar modulation observed via neutron monitors over 50yr
- Charge-dependent anticorrelation with Sun activity

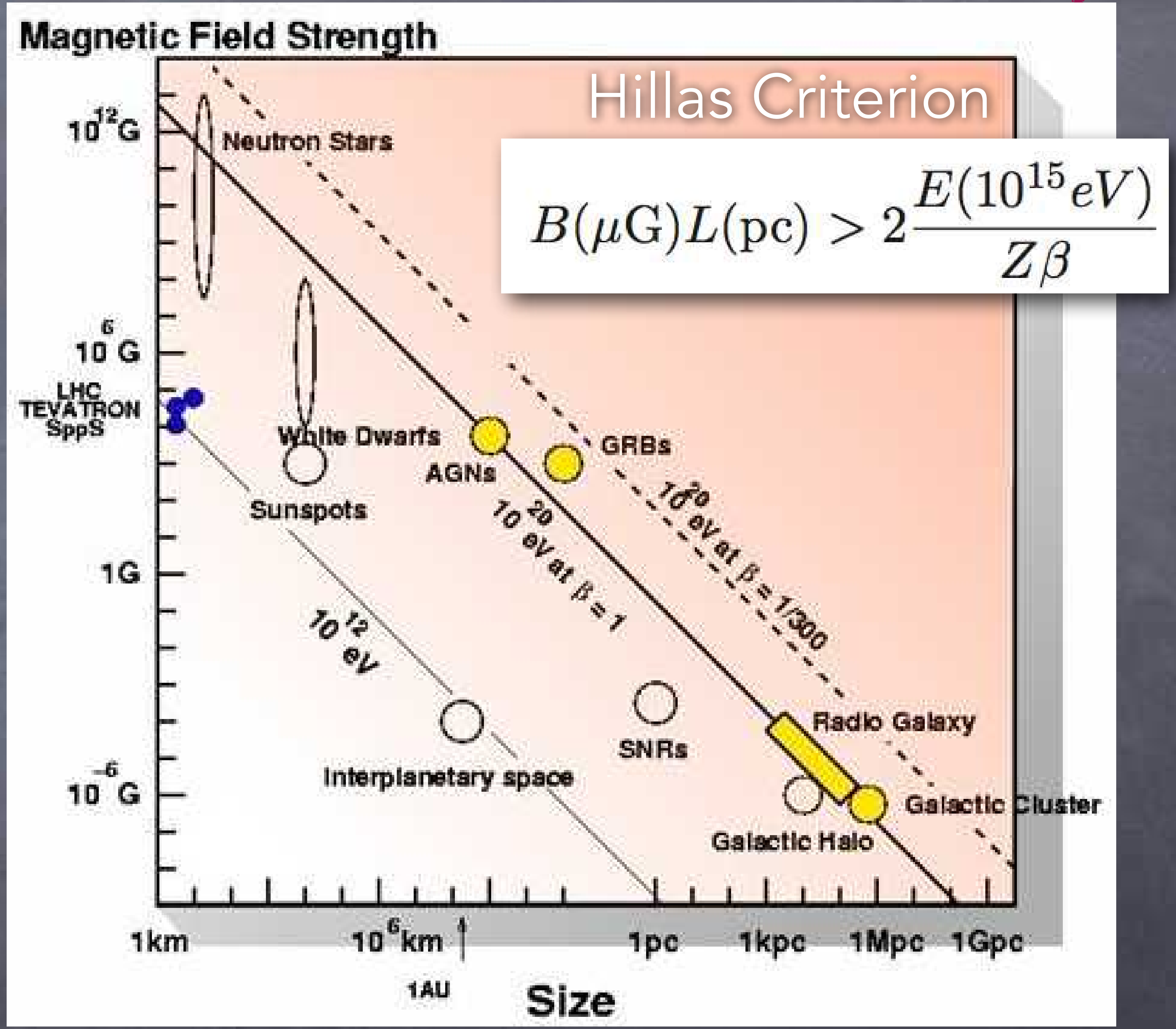






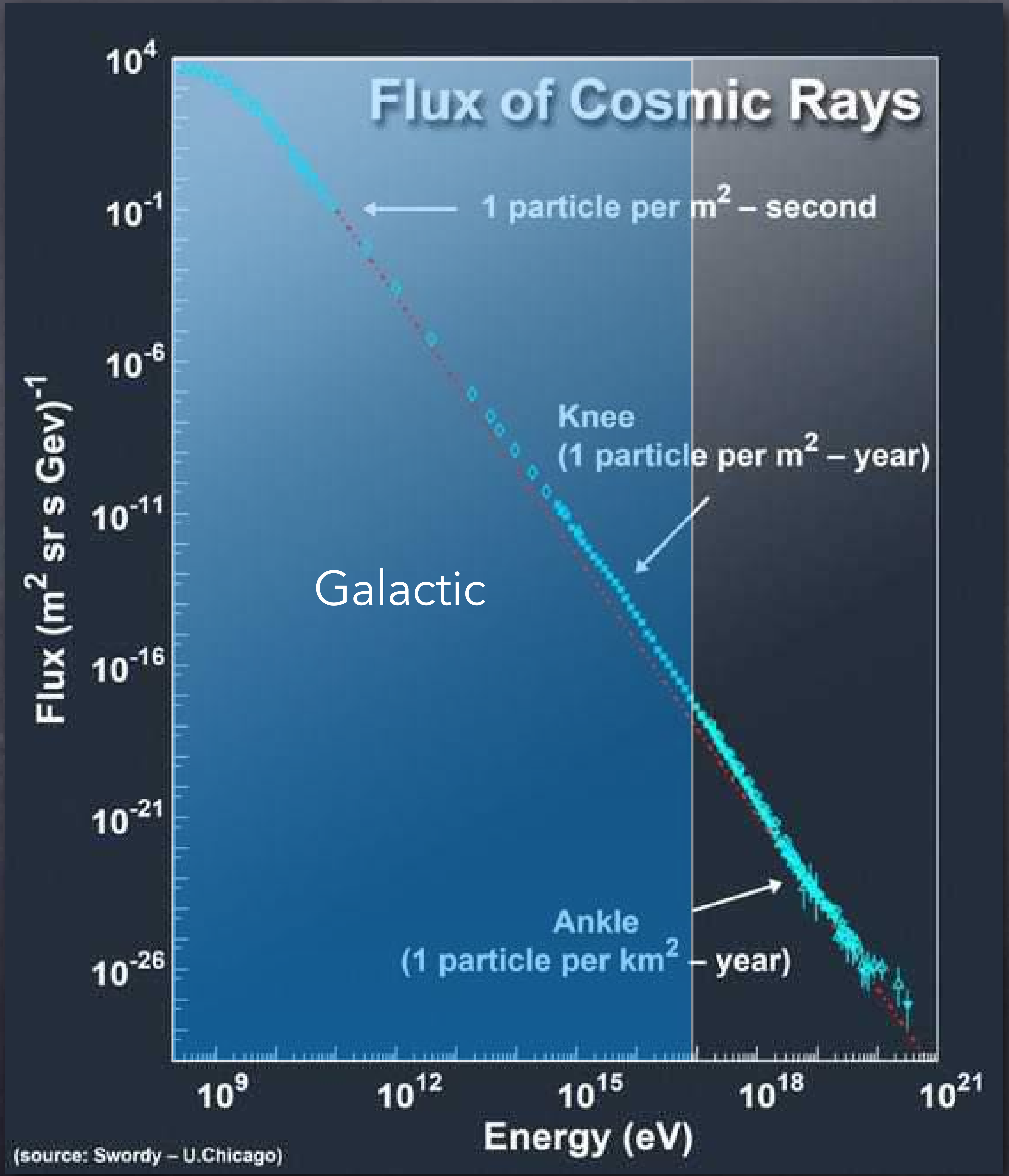
Cosmic Rays: Hunt for Sources

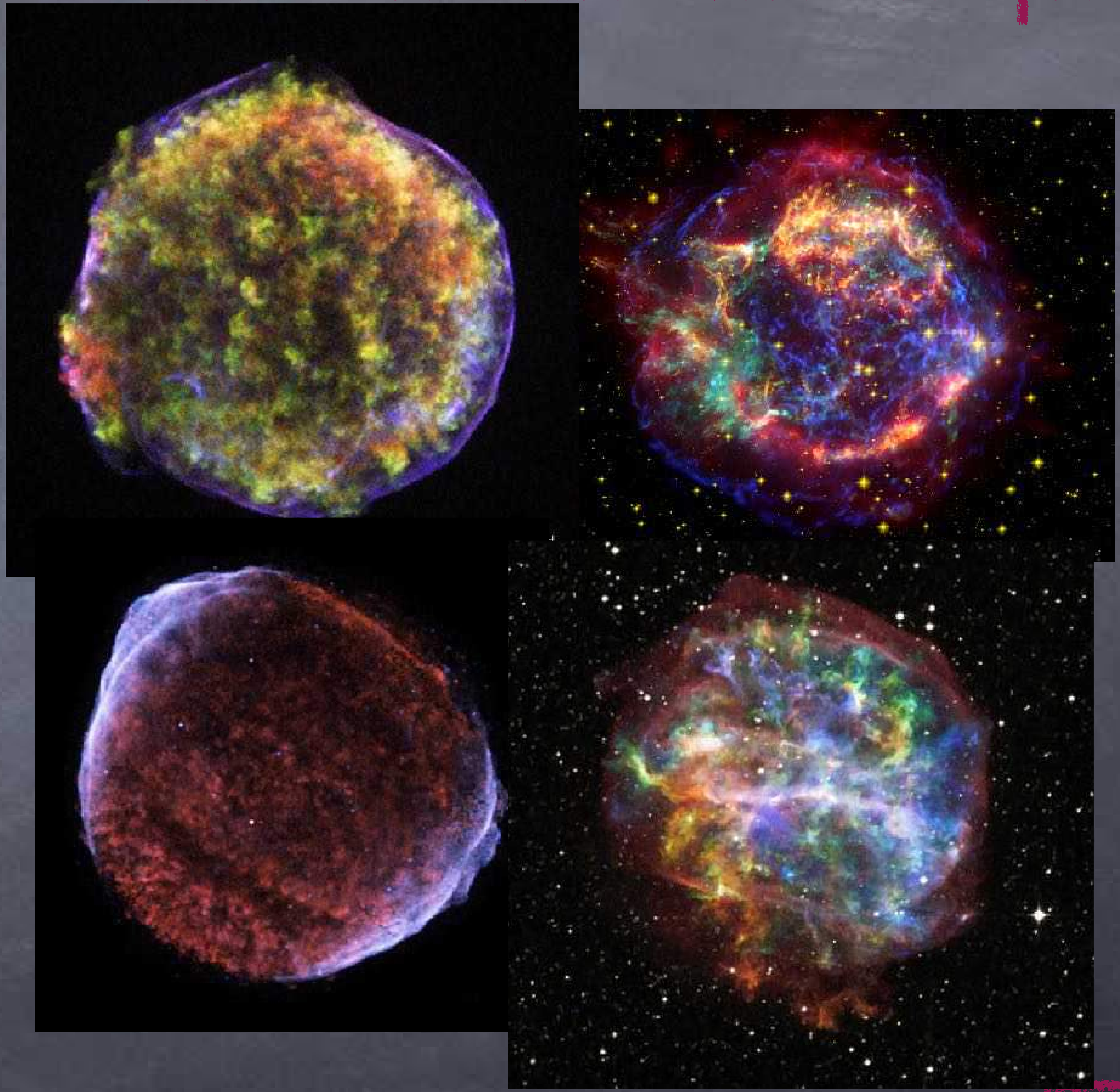




- Remarkable power-law (plus "leg" features)

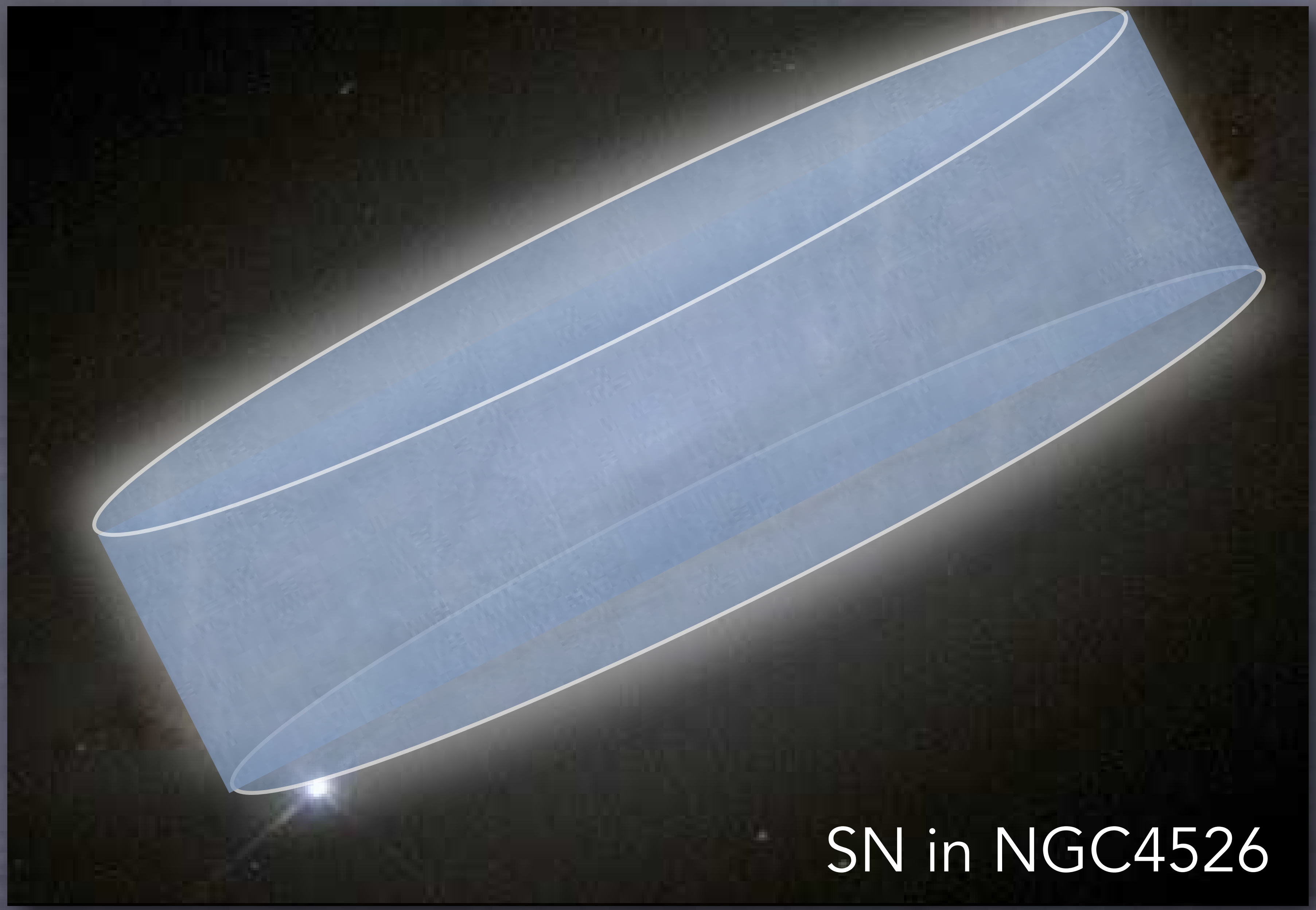
SNR Paradigm for Galactic Cosmic Rays





SNR paradigm: energetics

- Baade-Zwicky (1934) energetic argument, updated



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

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

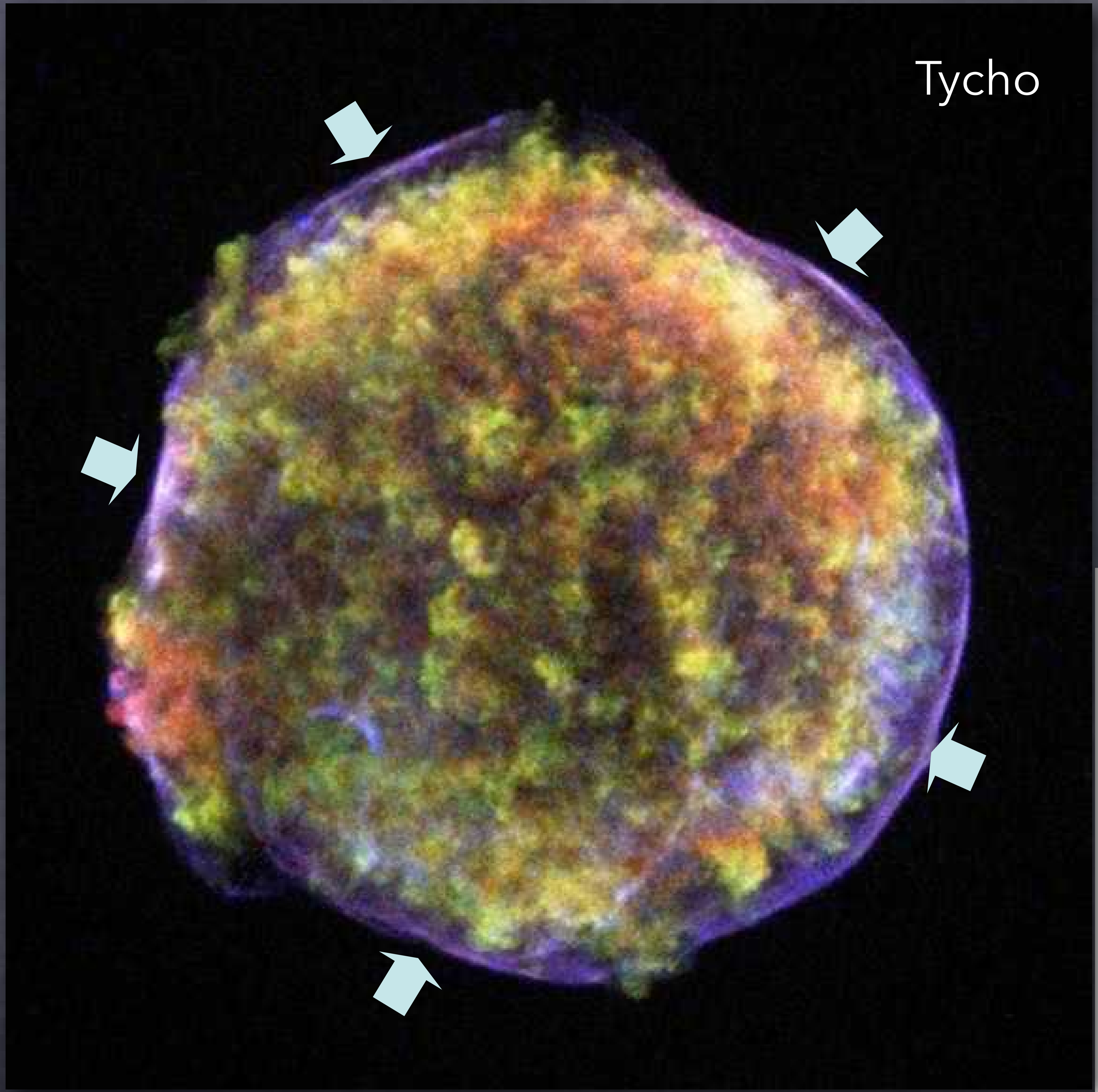
$$W_{CR} = \varepsilon_{CR} V_{conf} \approx 2 \times 10^{55} \text{ erg}$$

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

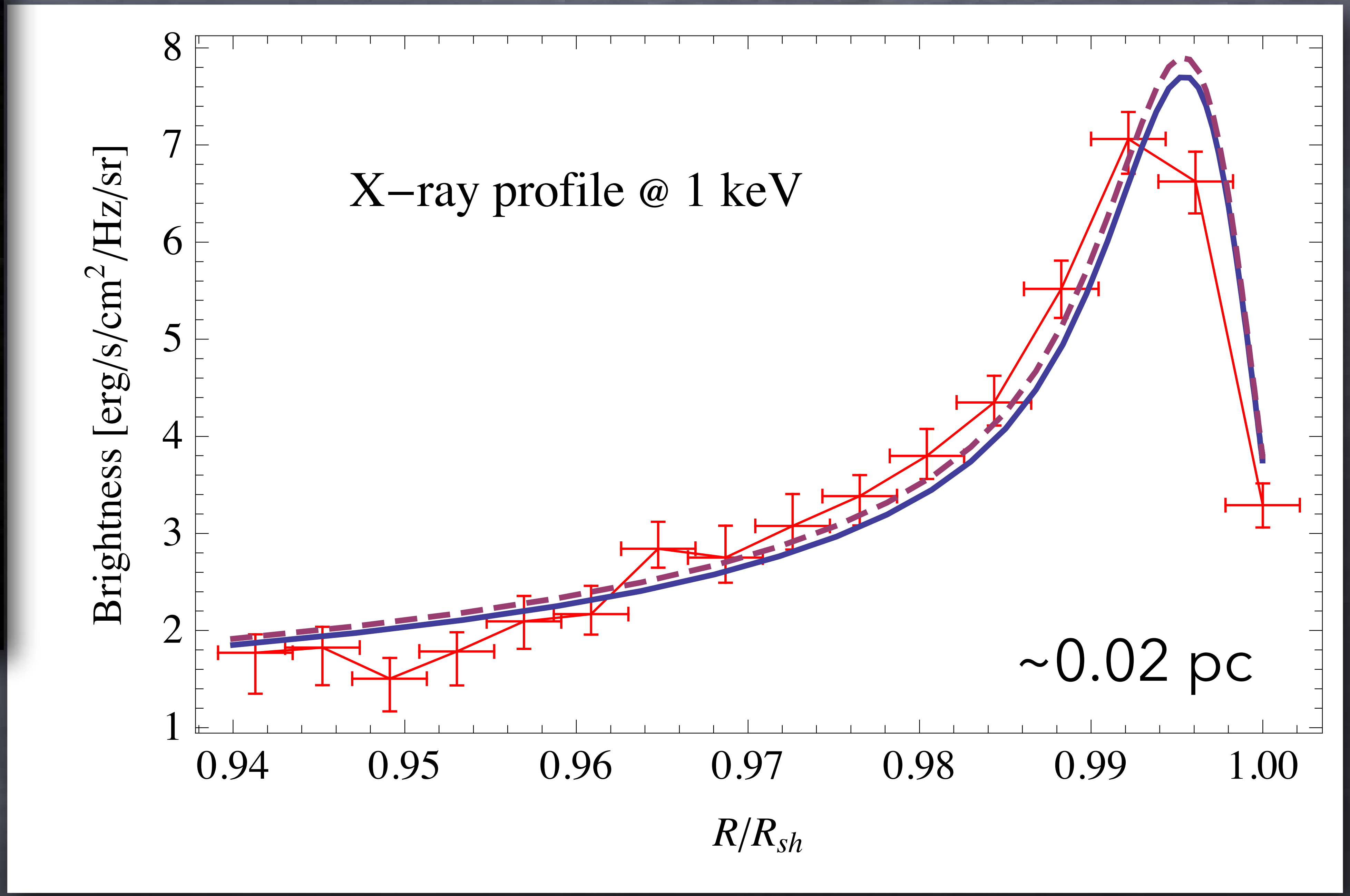
$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41} \text{ erg s}^{-1}$$

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

Evidence of magnetic field amplification

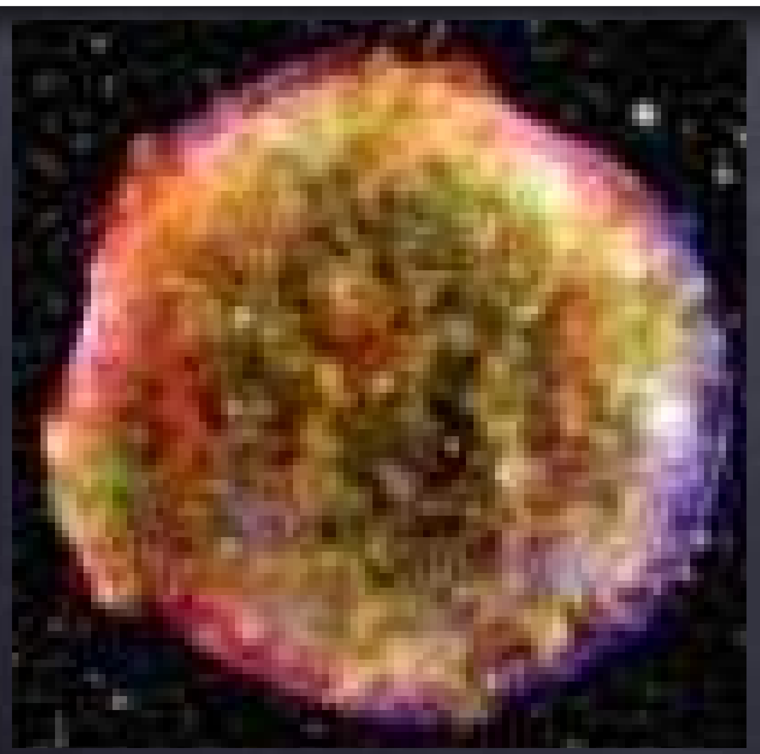


- Narrow (non-thermal) X-ray rims due to synchrotron losses of multi-TeV electrons…
- …in fields as large as B ~ 100-500μG



Völk et al, 2005…;
Warren et al, 2005;
Uchiyama et al. 2007;
Cassam-Chenaï et al. 2008;
Morlino & Caprioli 2012;
Slane et al. 2014;
Ressler et al. 2014;

Tycho: a clear-cut hadronic accelerator

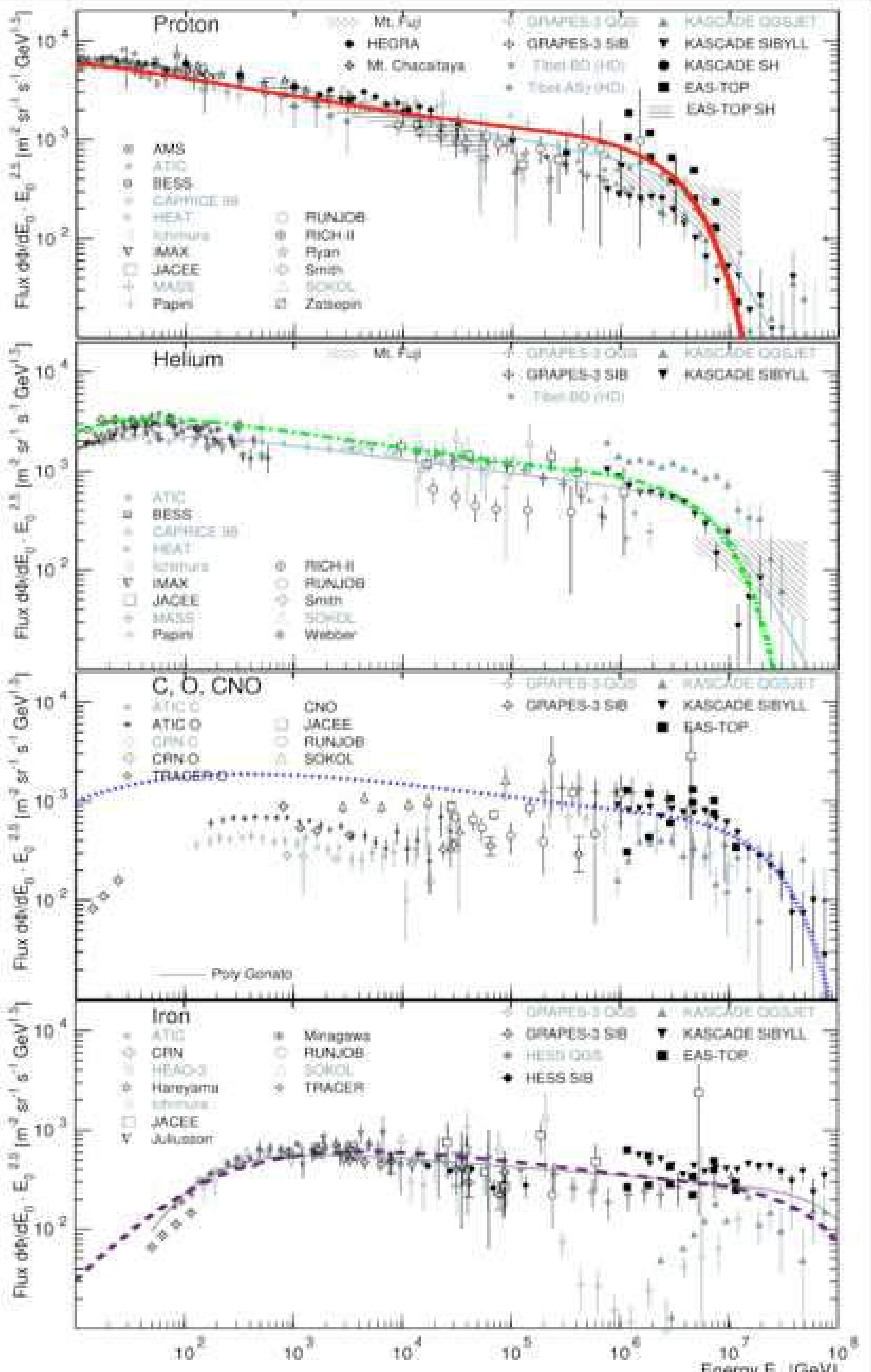


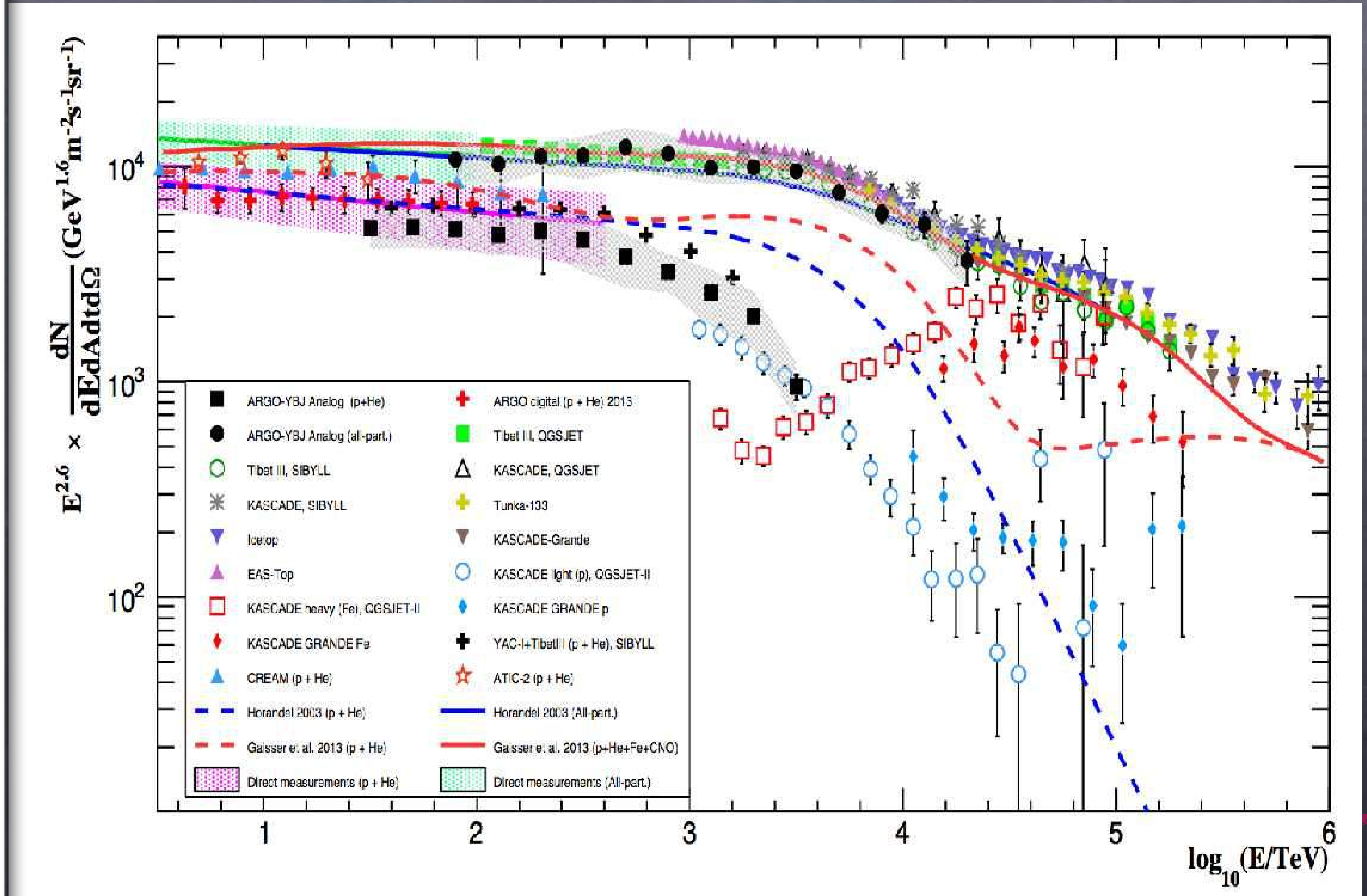
Type Ia SN
$E_{SN}=10^{51}$erg
Age=451yr
Distance~3kpc

- Proton acceleration efficiency ~10%
- Electron/proton ratio $K_{ep}\sim 3\times10^{-3}$
- Protons up to ~0.5 PeV

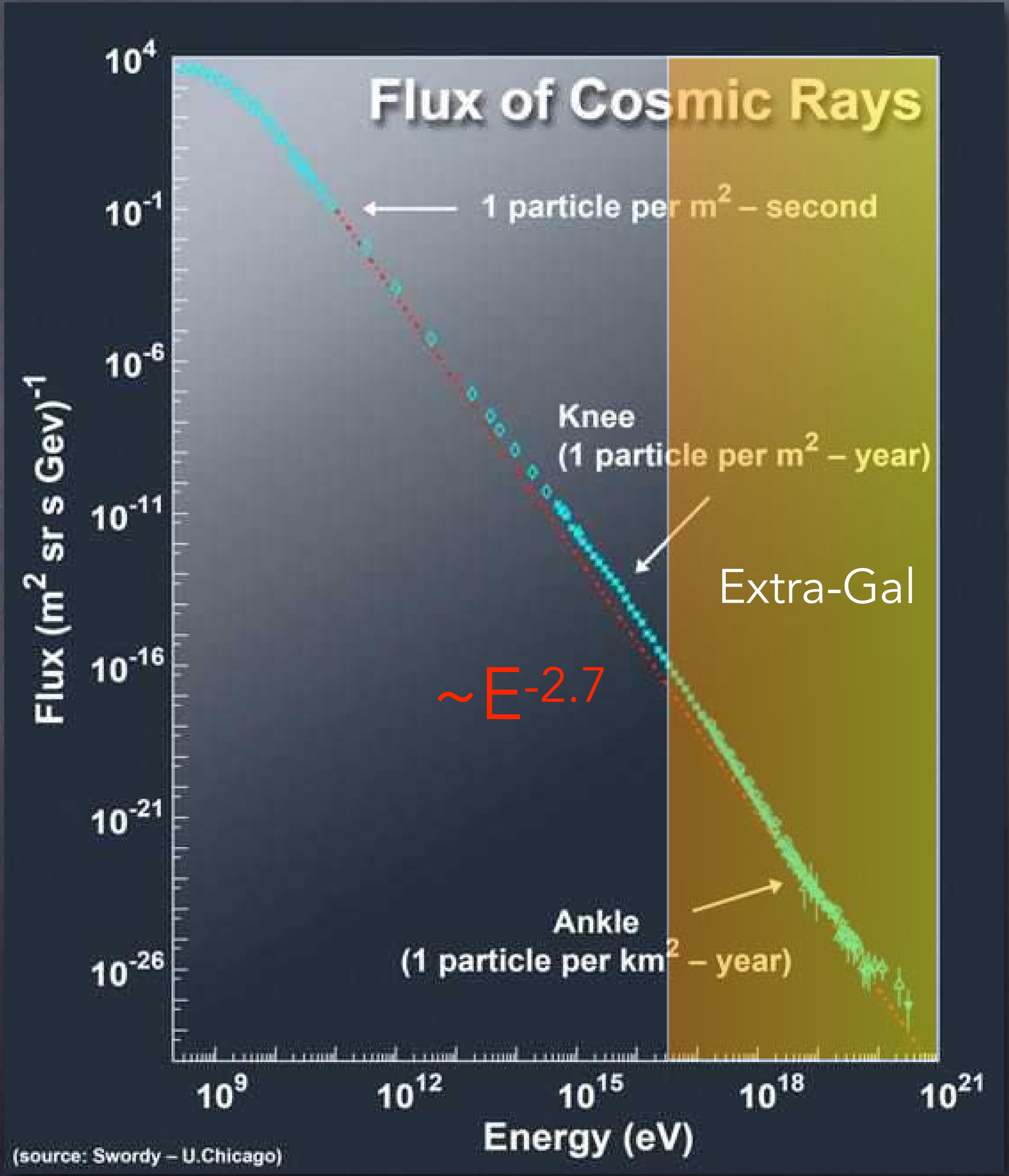
The Knee

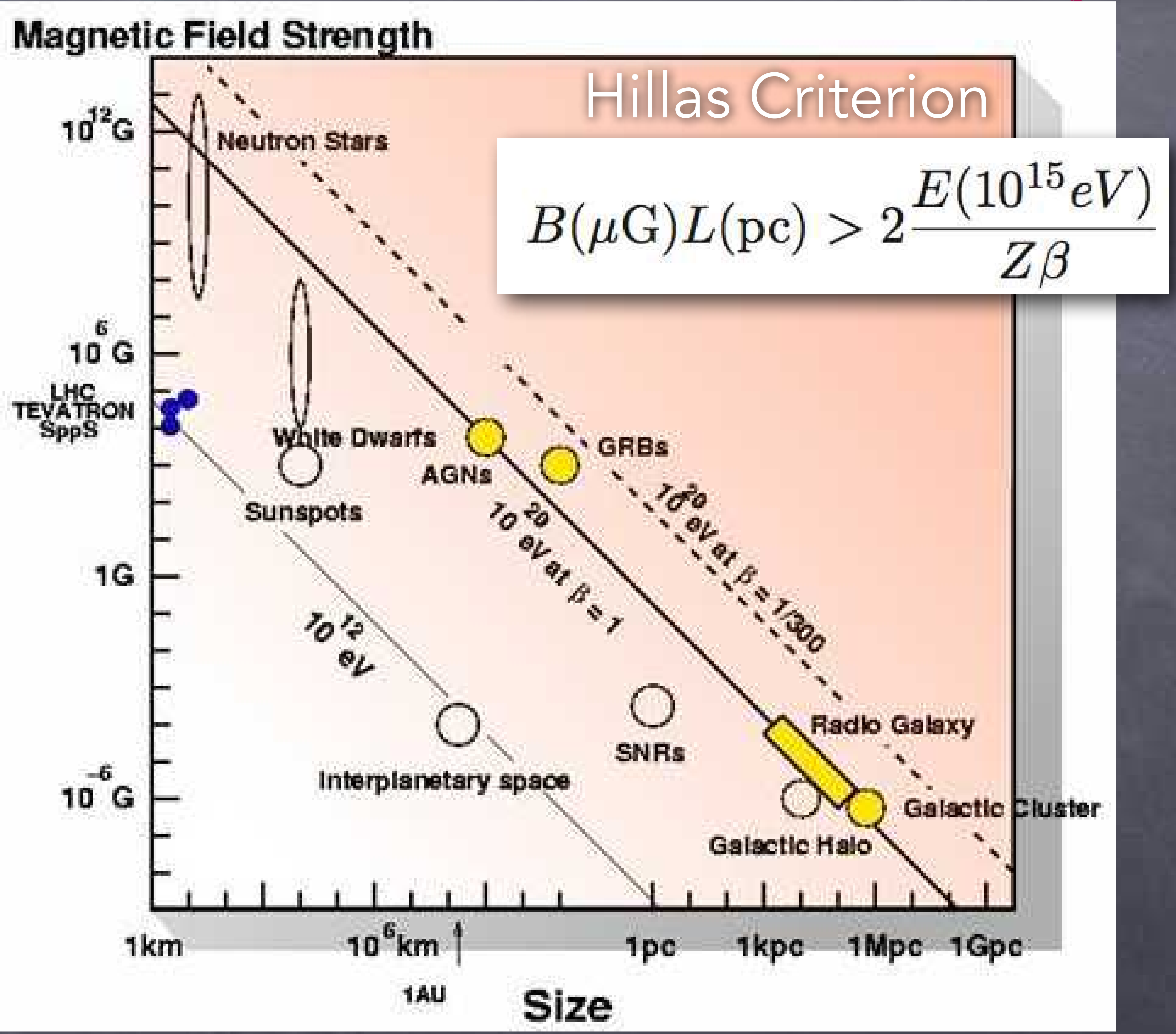
- Chemical composition heavier at ~1 PeV
- Steepening due to convolution of exp cutoffs!





Extra-galactic (Ultra-High Energy CRs)

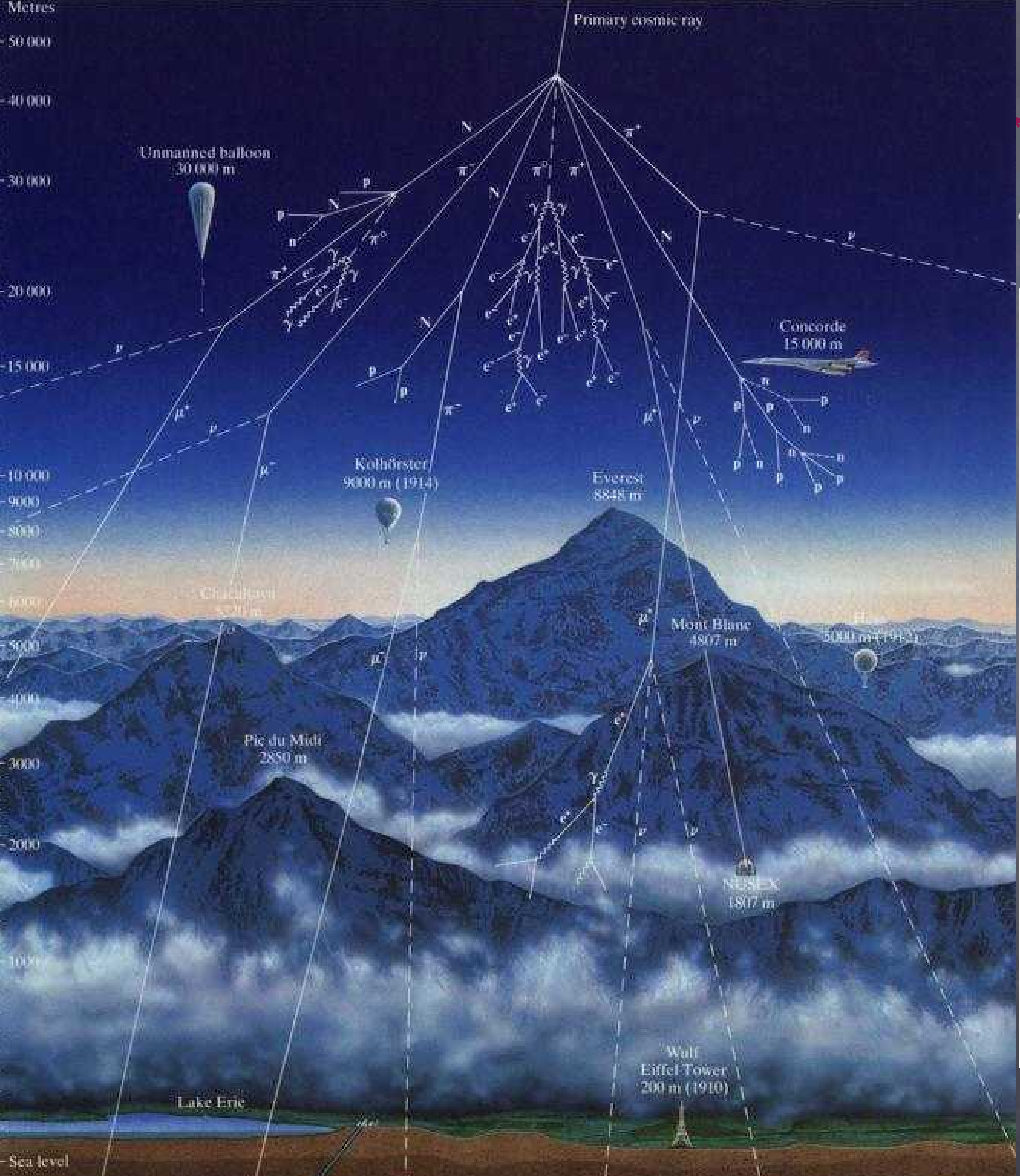


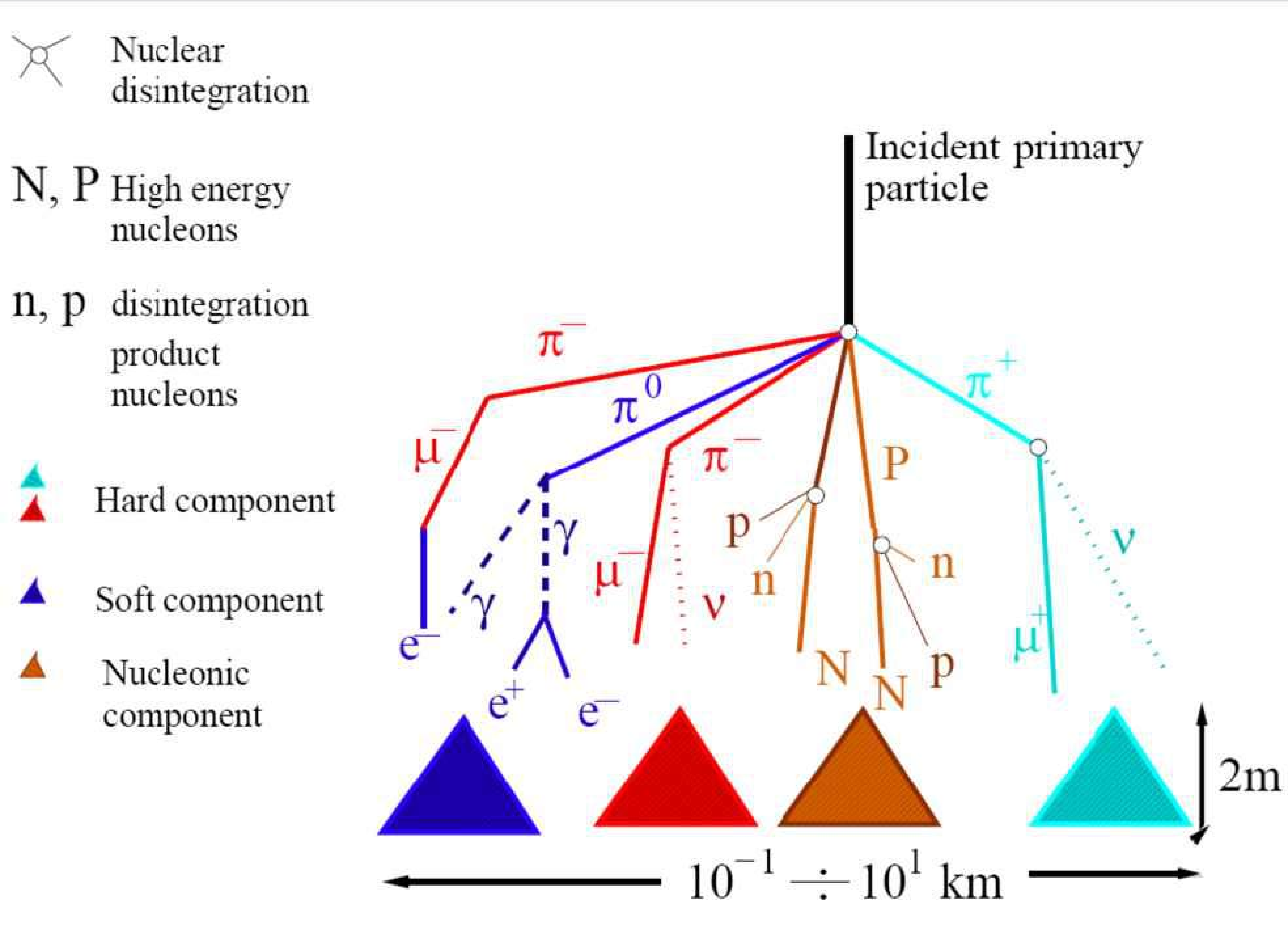


- Remarkable power-law (plus "leg" features)

Extensive Air Showers

- Indirect detection of CRs above hundreds of TeV



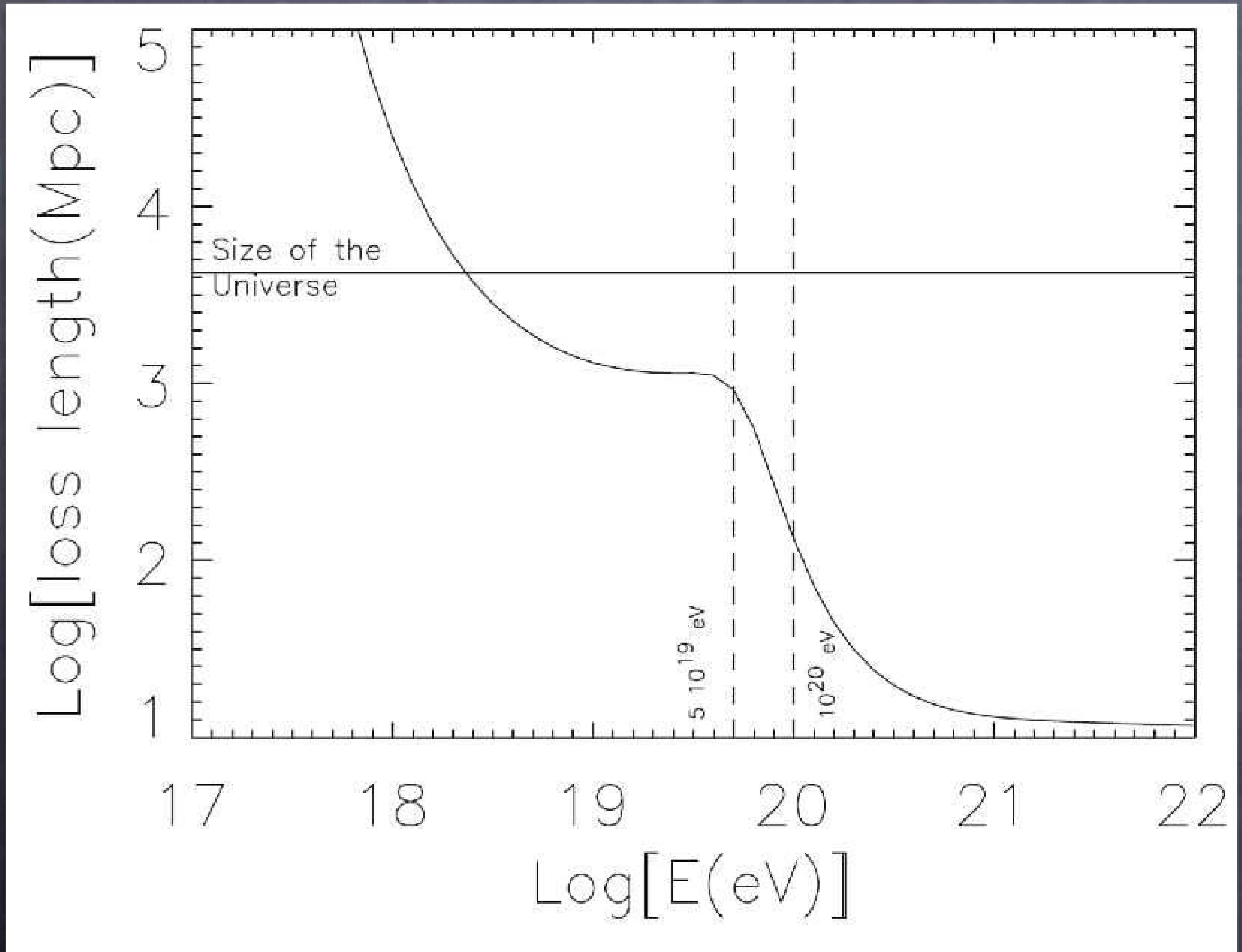


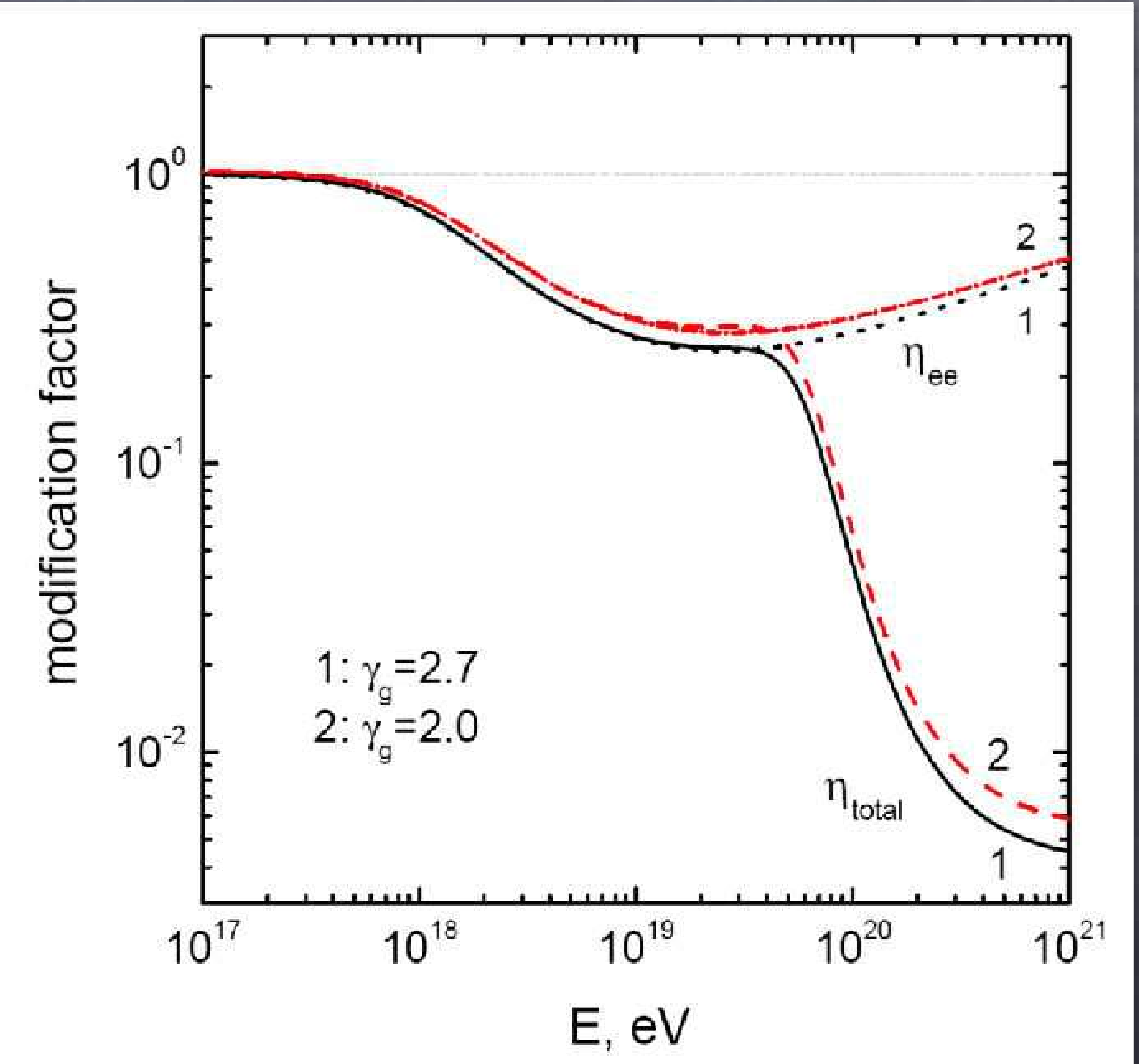
Interactions with the CMB radiation

- Photo-pair and photo-pion production
- Photo-pion has both a larger threshold and a larger inelasticity
- The flux of UHECR protons above 5×10^{19}eV is suppressed (Greisen 1966; Zatsepin & Kuz'min, 1966): GZK cut-off at ~100Mpc

$$p + \gamma_{\rm CMB} \to p + \pi^0 \,,$$

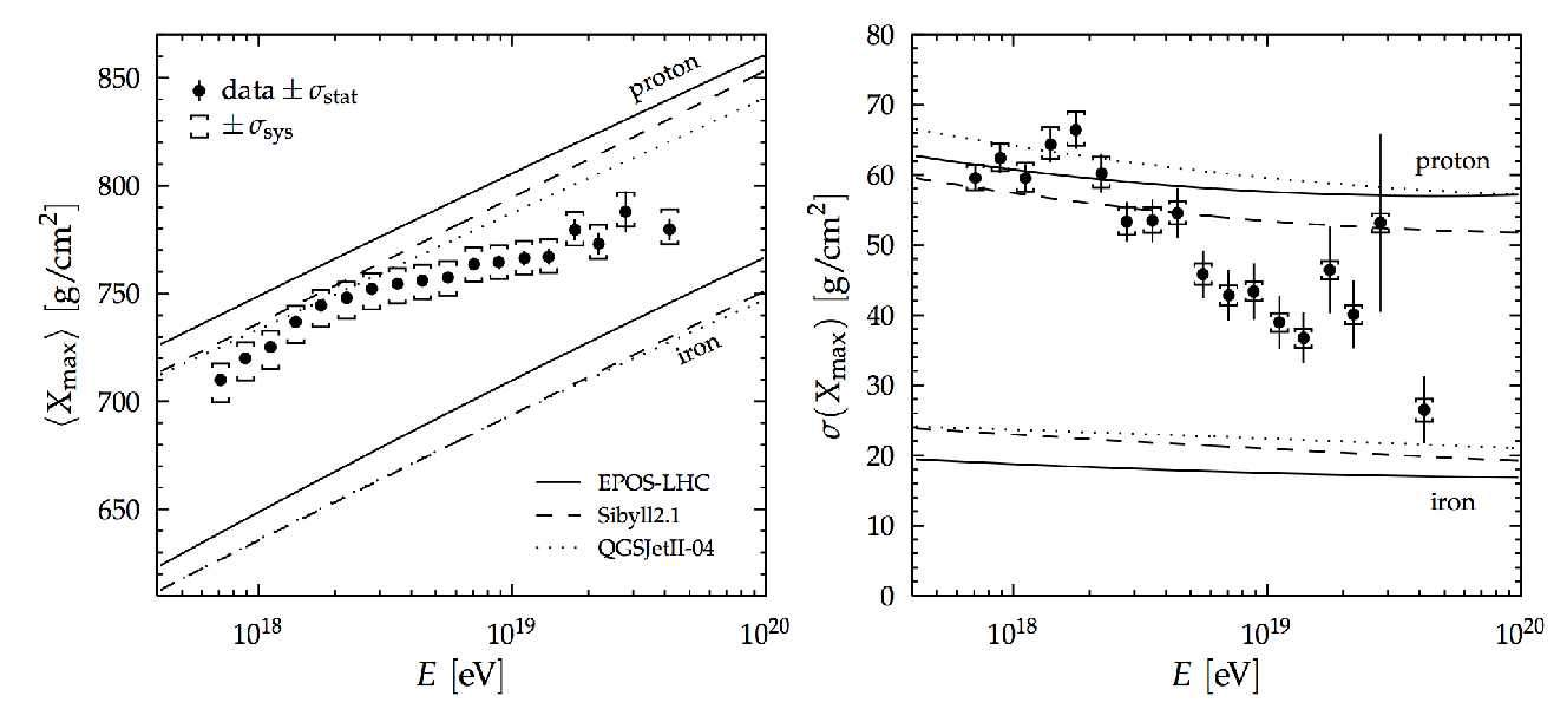
$$p + \gamma_{\rm CMB} \to n + \pi^+ \to \ldots \to p + e^+ e^- + \ldots \,.$$





UHECR (heavier and heavier) composition

- Variance in X_{max} at a given E better indicator of the average chem. comp.
- Composition becomes heavier at higher E!



- Implications for cut-off: no photo-pion, but photo-disintegration of Fe nuclei!
  - Surprisingly, attenuation lengths turn out to be comparable ~100Mpc

THE ROLE OF CRs IN THE GALAXY:

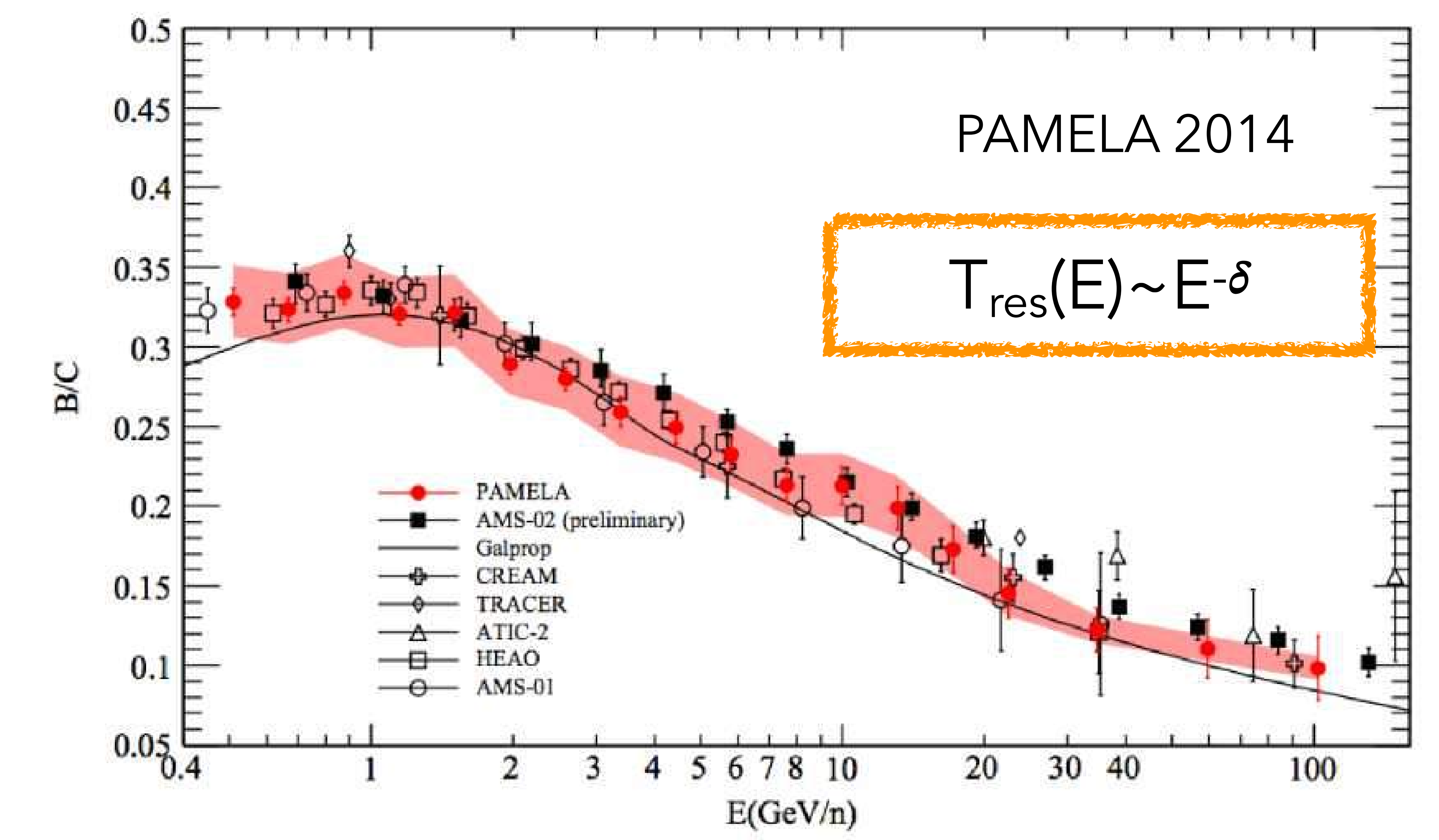
Self-confinement

Propagation of Galactic CRs

- Secondary elements (e.g. Boron) produced via spallation in the Milky Way
  - B/C $\propto T_{res}$, the Galactic residence time (also radioactive isotopes: Be^{10}/Be^{9}, with T_{Be10}~1.4Myr)
  - Grammage needed:

$$\langle \Xi \rangle = 4g/cm^2 \left(\frac{E}{10ZGeV}\right)^{-\delta}; \quad \delta = 0.3 - 0.6$$

$$T_{res}(E/Z) = \frac{\langle \Xi \rangle}{\rho_g c} \approx 2 \times 10^6 yr \left(\frac{E}{10ZGeV}\right)^{-\delta} \left(\frac{n_g}{cm^{-3}}\right)^{-1}$$



  - For leptons

$$T_{syn+IC}(E) \approx 320 \times 10^6 yr \left(\frac{E}{GeV}\right)^{-1}$$

- Propagation steepens the injection spectrum $E^{-\gamma}$ to
  - $\propto E^{-\gamma-\delta} \sim E^{-2.7}$ for hadrons
  - $\propto E^{-\gamma-1} \sim E^{-3}$ for electrons

$T_{res} >> T_{cross}$~kpc/c

DIFFUSIVE PROPAGATION!

Energy Partition in the Galaxy

$$P_{cr} \sim P_B \sim P_{gas}$$

Close to CR sources:

$$P_{cr} > P_B, P_{gas}$$

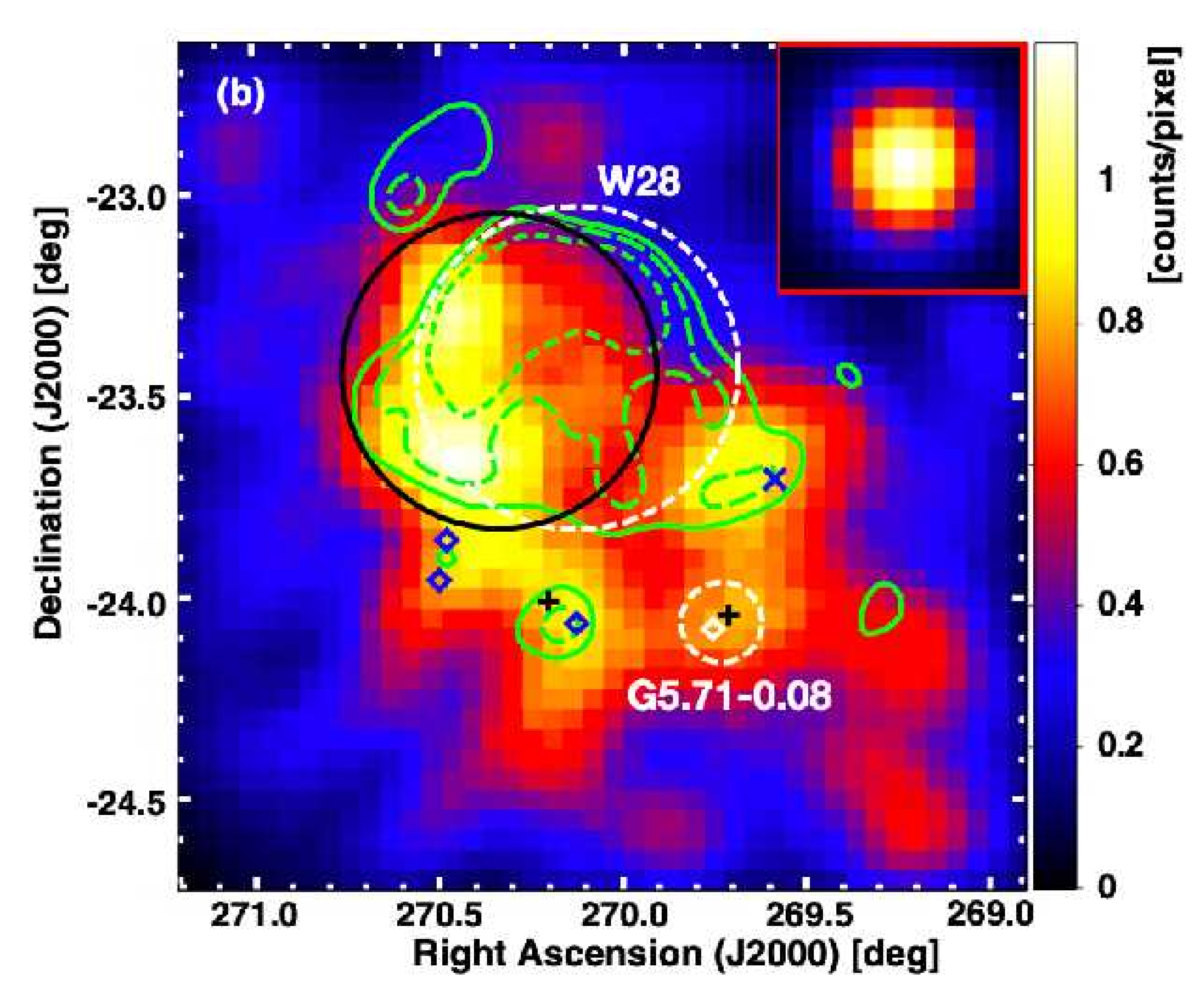
M31 (by D.Dayag)

Evidence of CR "*Spheres of Influence*"

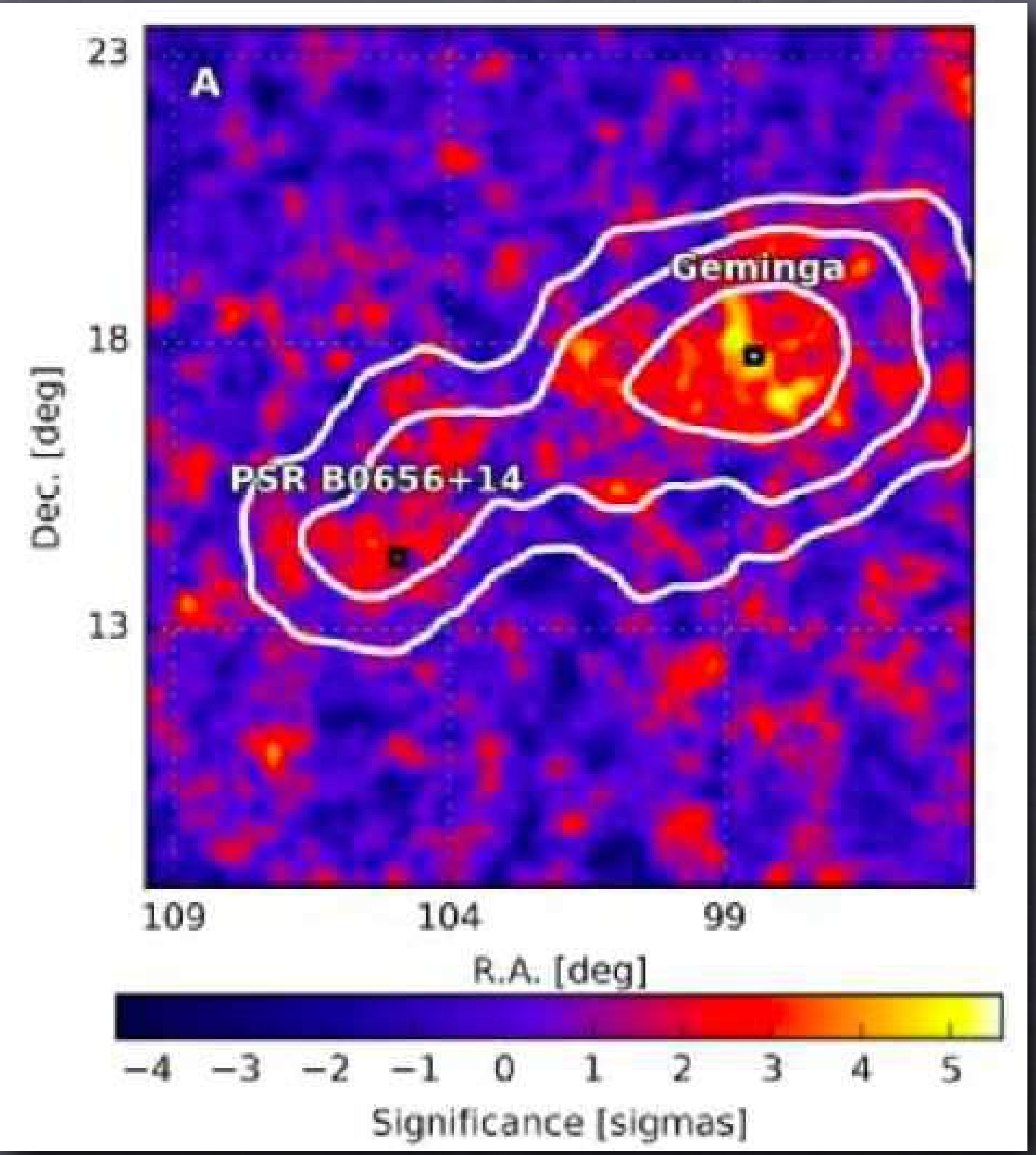
Supernova Remnants (SNRs) — Casanova+10, Hanabata+14,…

Pulsar Wind Nebulae (PWNe) — HAWC 18, …

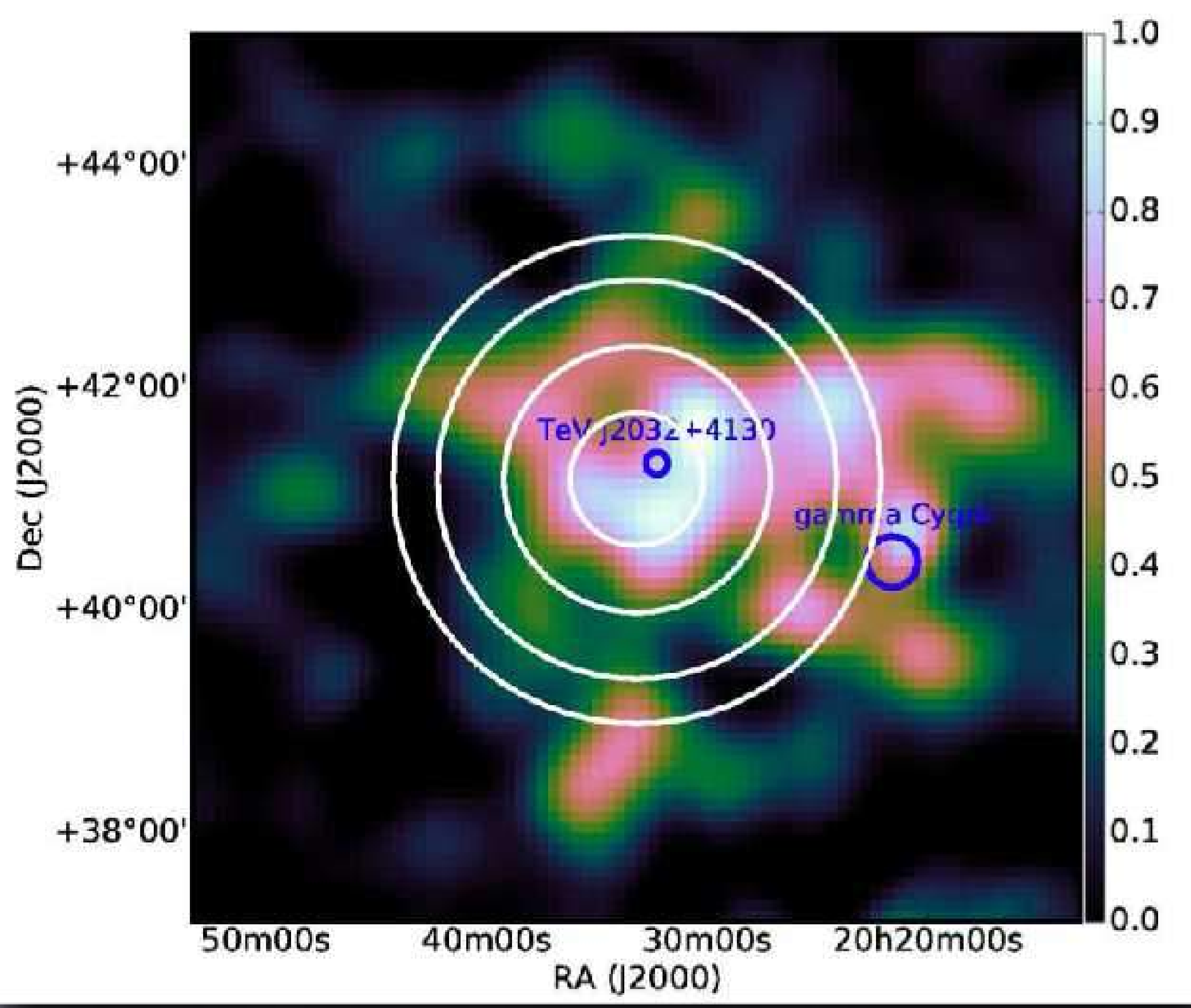
Stellar Clusters — Ohm+13, Aharonian+19, …



W28



Geminga

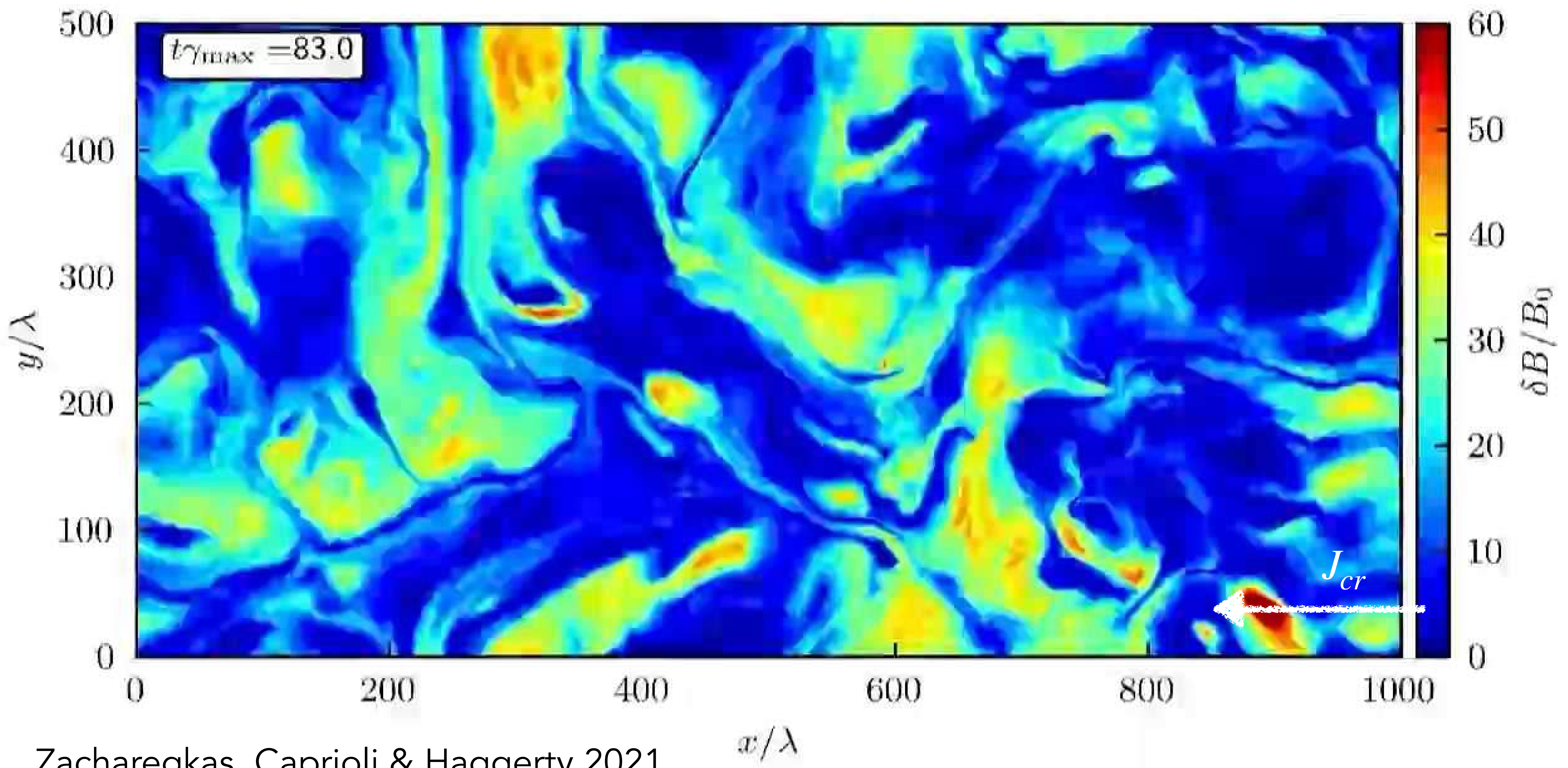


Cygnus Loop

- TeV haloes 50-100 pc wide are ubiquitous around CR sources. *Why*?
  - They require a diffusion coefficient ~100x smaller than the Galactic one

Controlled Simulations of CR-driven Instabilities

- Hybrid sims in periodic boxes in the Bell regime (e.g., Haggerty, Zweibel & Caprioli 2019)



Zacharegkas, Caprioli & Haggerty 2021

Note the large $\delta B/B_0$ at saturation

Can also be driven by leptons! (Gupta, Caprioli & Haggerty 2021)

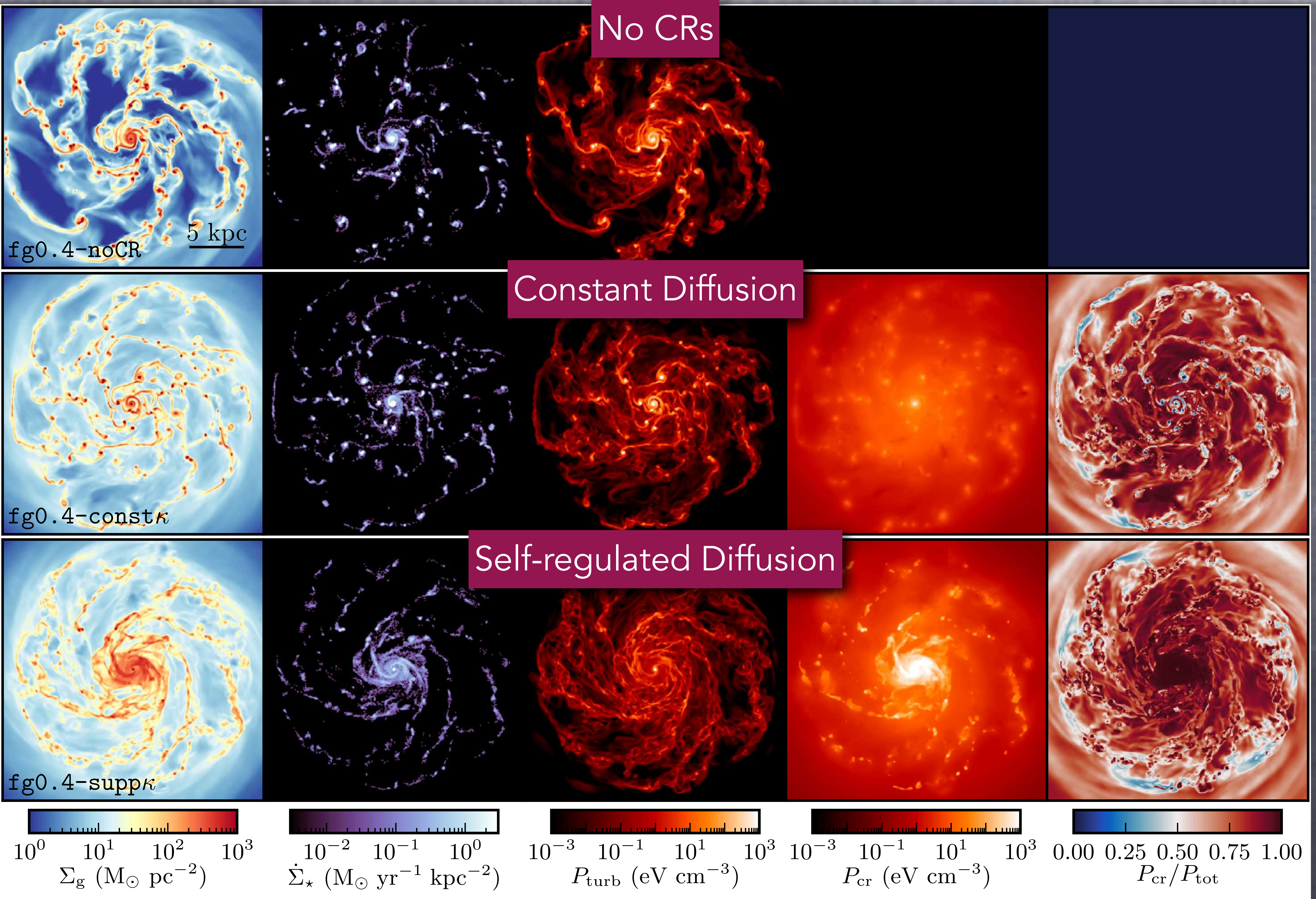
Global Hybrid Simulations of CR Escape

Schroer, Caprioli et al 2021

THE ROLE OF CRs IN THE GALAXY:

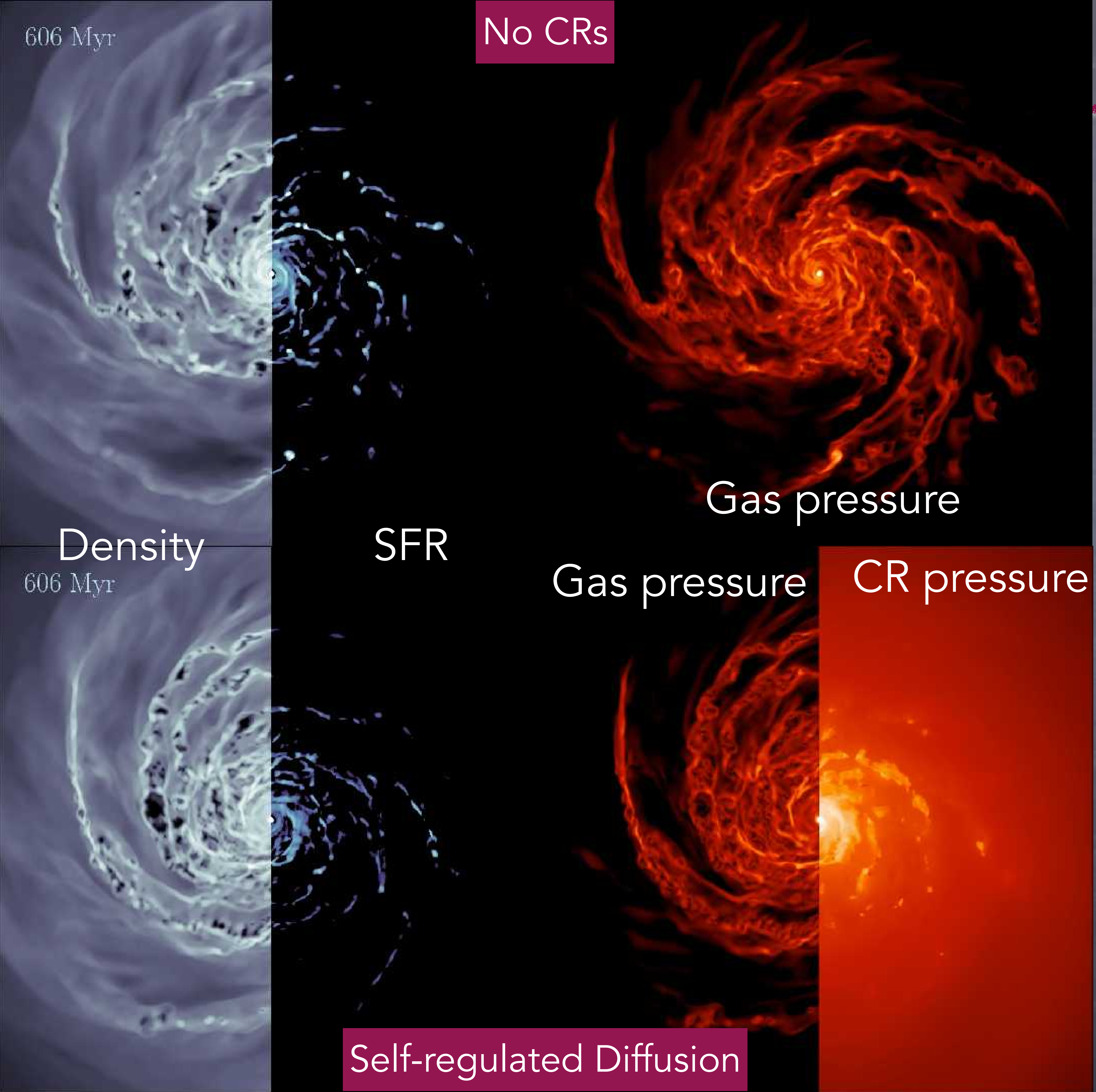
Self-generated diffusion

Galaxy Simulations with Self-reduced CR Diffusion



Semenov, Kravtsov, DC 21

Self-regulated diffusion in star-forming regions suppresses the formation of massive gaseous clumps and returns spirals and γ-ray emission consistent with observations



Punch Line

CRs do have a dynamical role in sculpting galaxies.

Microphysical (plasma) processes can affect the largest scale.
They need to be modeled accurately from first principles

Semenov, Kravtsov, Caprioli 21

Outstanding Problems in Plasma Astrophysics

- Space Weather: ability to predict solar storms
- Acceleration of electrons in shocks
  - Why the electron/proton ratio in CRs is $\sim 10^{-3}$?
- CRs self-confinement
  - Maximum energy achievable; Haloes around sources
  - CR transport in the Galaxy $\Longleftrightarrow$ Galactic turbulence
- What is the dynamical role of CRs/B fields in galaxy formation and evolution?
  - ISM heating, wind launching, stellar feedback,…
- Multi-messenger astrophysics (UHE neutrinos, UHECRs, EM transients, …)
  - What are the sources of UHECRs?