

UNDARK School  
Annecy, March 2026



# High-Energy Astrophysical Engines: From Pulsars to AGNs

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## References

- **M. Longair**, *High-Energy Astrophysics*
  - [http://alpha.sinp.msu.ru/~panov/LibBooks/CR/1556\\_\\_legalreads.com.pdf](http://alpha.sinp.msu.ru/~panov/LibBooks/CR/1556__legalreads.com.pdf)
- **G. Ghisellini**, *Radiative Processes in High Energy Astrophysics*
  - <https://arxiv.org/pdf/1202.5949.pdf>
- Shock Acceleration:
  - <https://ui.adsabs.harvard.edu/abs/2023arXiv230700284C/abstract>
- Plasma Astrophysics (reconnection, turbulence)
  - **R. Kulsrud**, *Plasma Physics for Astrophysicists*

# COSMIC RAYS

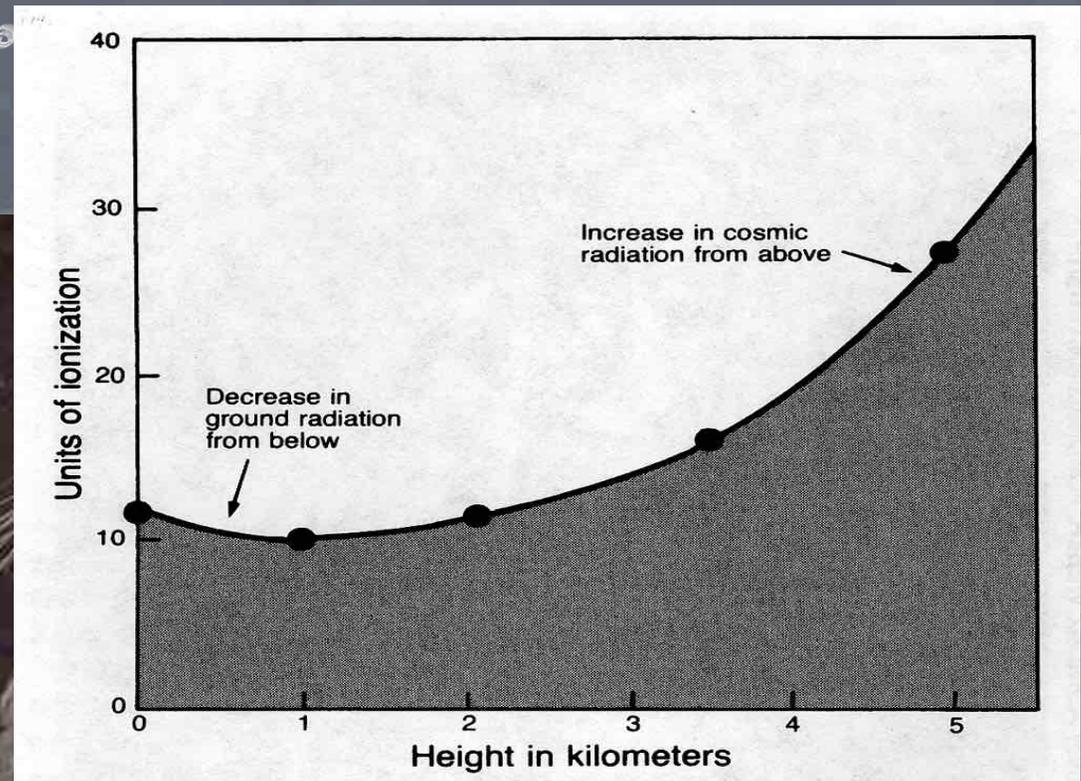


# An extraterrestrial radiation!



V. Hess, 1912

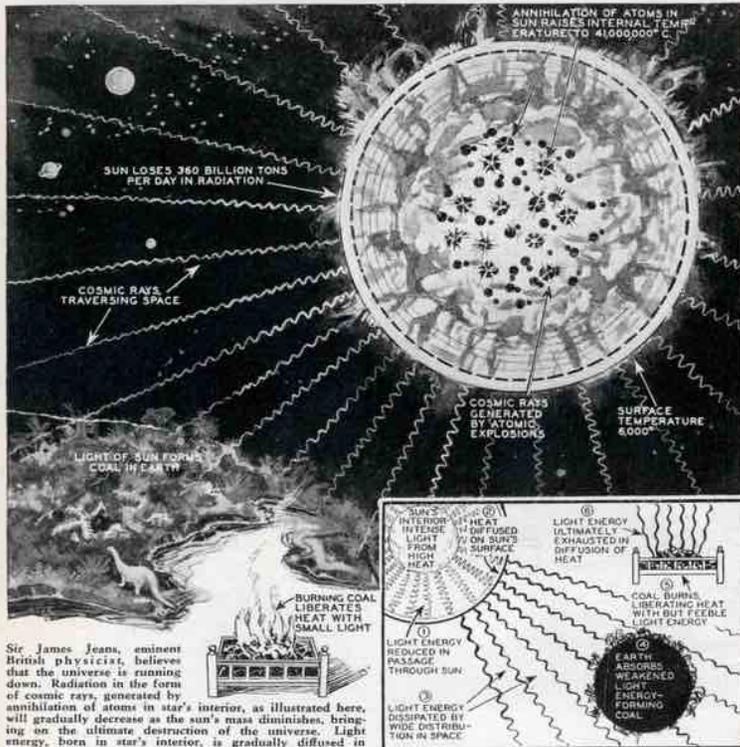
- 1912: **V. Hess** discovers an extraterrestrial source of ionization: Cosmic Rays!



1932



# Fate of UNIVERSE May Be



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, 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.

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

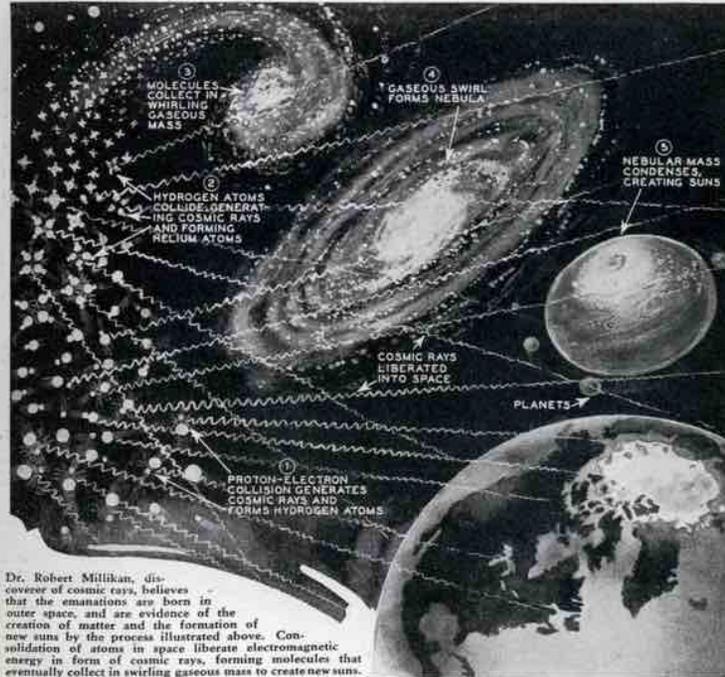
press named them "Millikan's rays," the cosmic emanation continues to be the baffling enigma on which scientists throughout the world are divided.

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 thou-

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.

# Told in Cosmic RAY Origin



sands 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)

- ① J. Jeans: produced in star interiors
- ② R. Millikan: "Cosmic Rays" are the "birth cry" of new atoms being created to withstand entropy
- ③ 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  $\sim 10^5$  GeV
- ...
- 1962: **J. Linsley** and **L. Scarsi**: ultra-high-energy CRs up to  $\sim 10^9$  GeV



B. Rossi



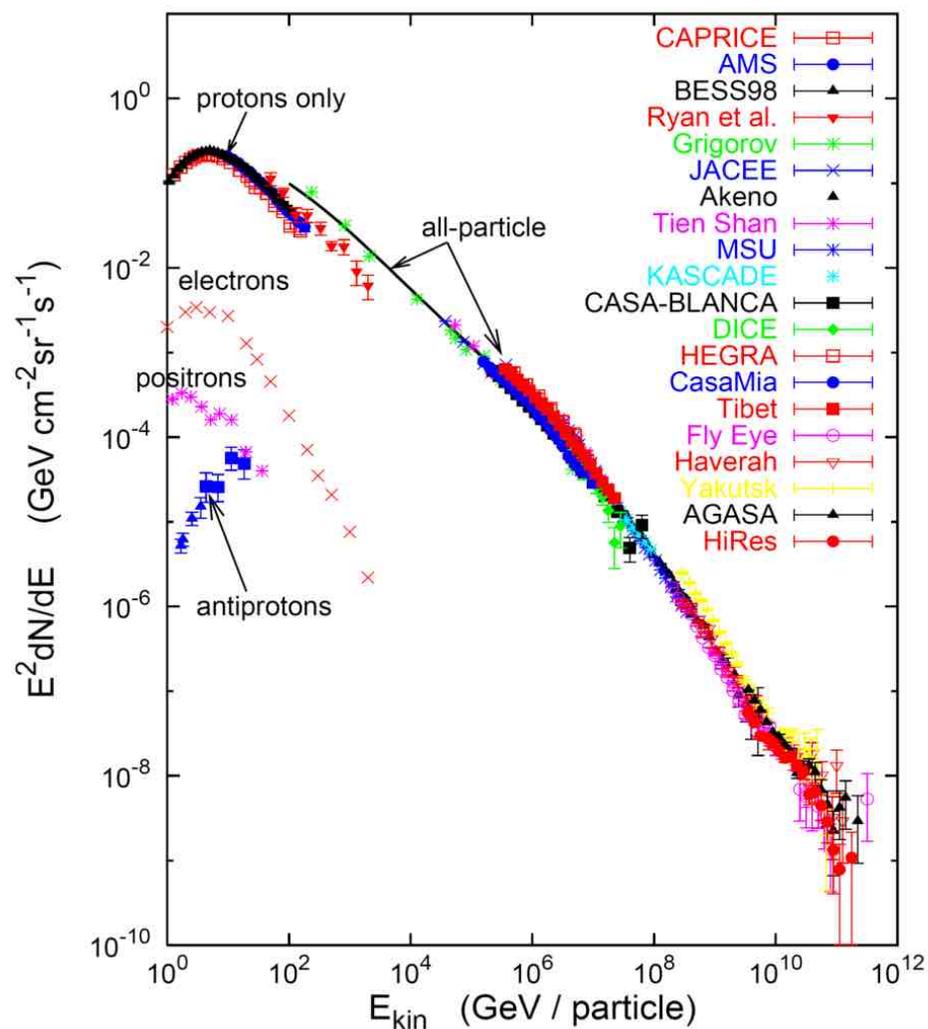
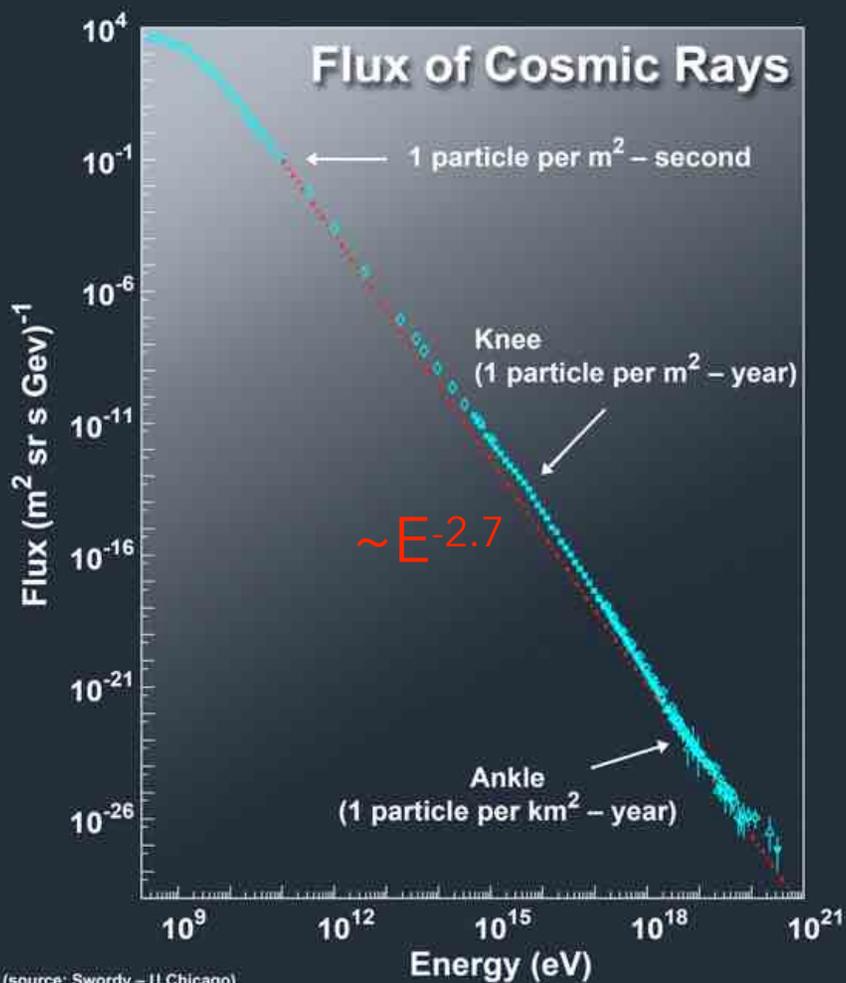
C. Anderson



P. Auger



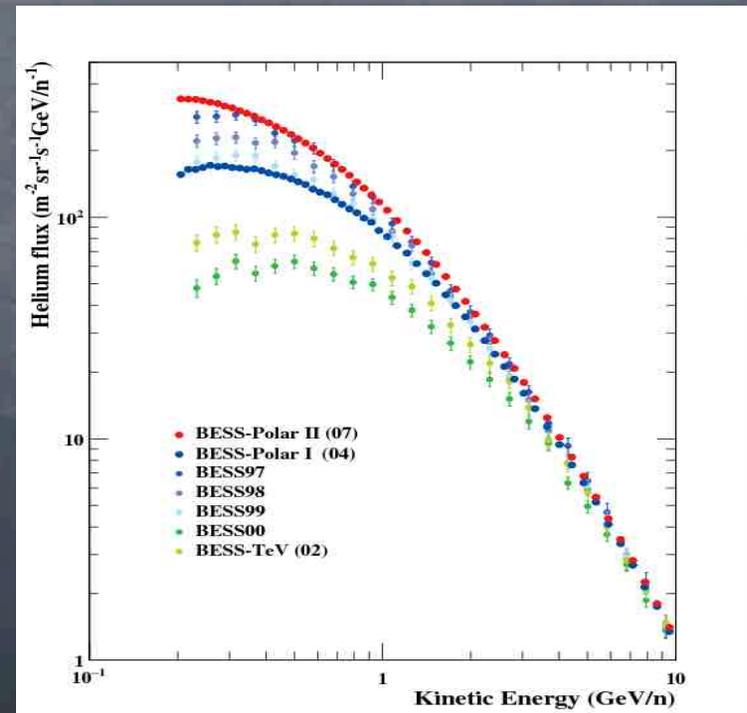
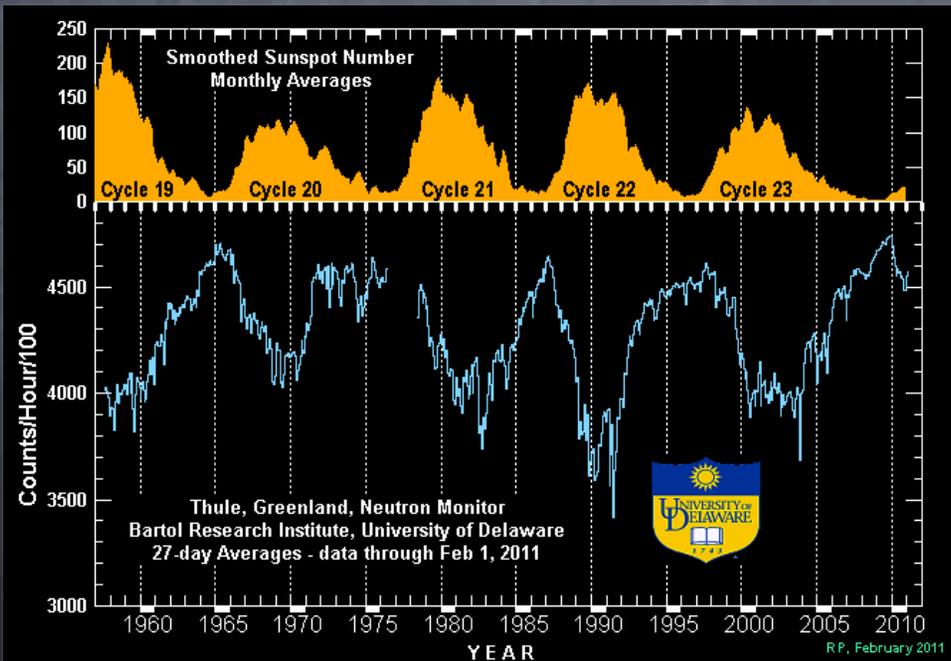
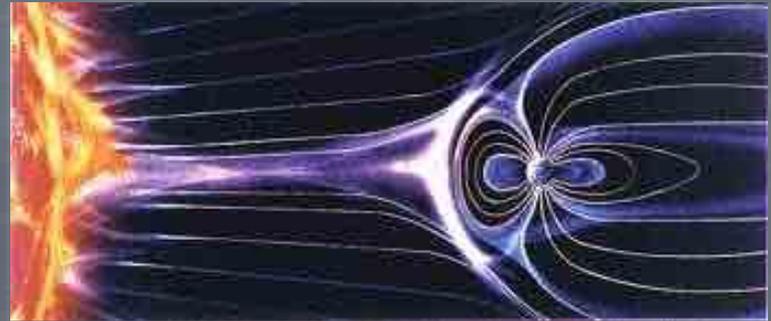
# The CR spectrum at Earth





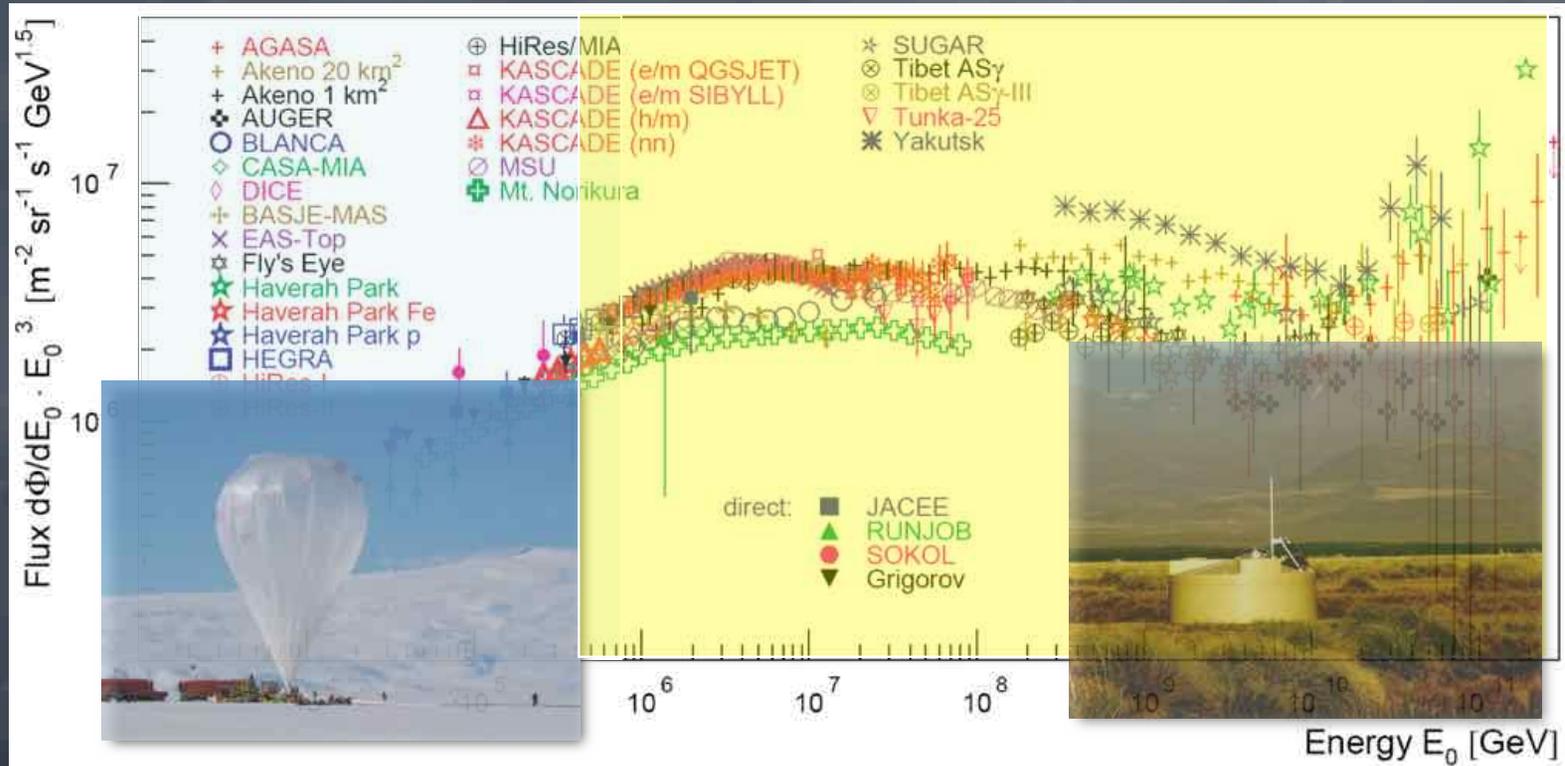
# Below ~10GeV: Solar Modulation

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



# Cosmic ray flux at Earth

Hörandel 2005



Below  $\sim 1$  PeV: **satellites** and **balloons**

Above: **ground-based arrays**, **fluorescence telescopes** for extensive air showers



# On the Origins of Cosmic Rays

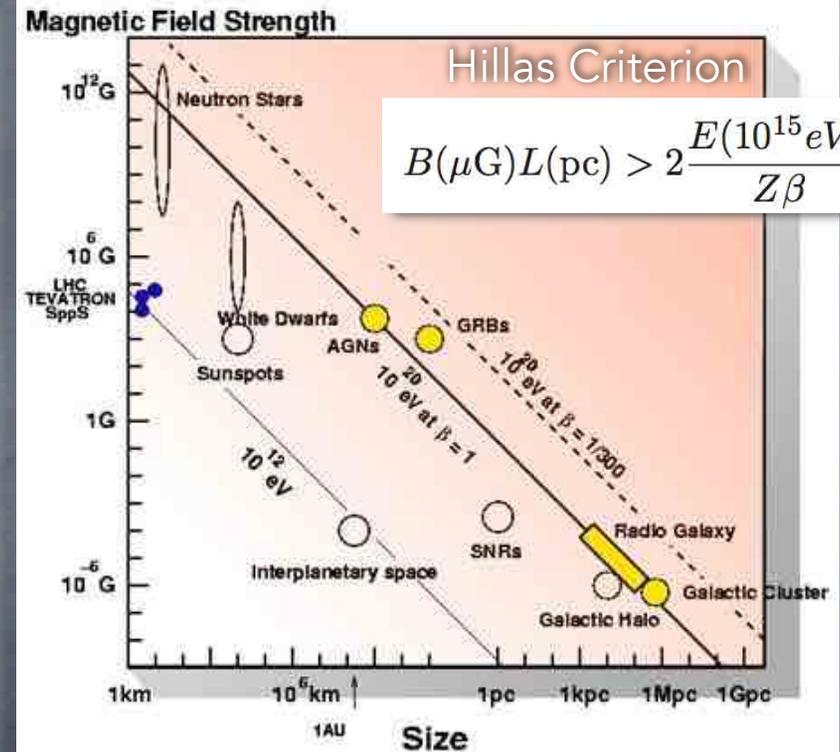
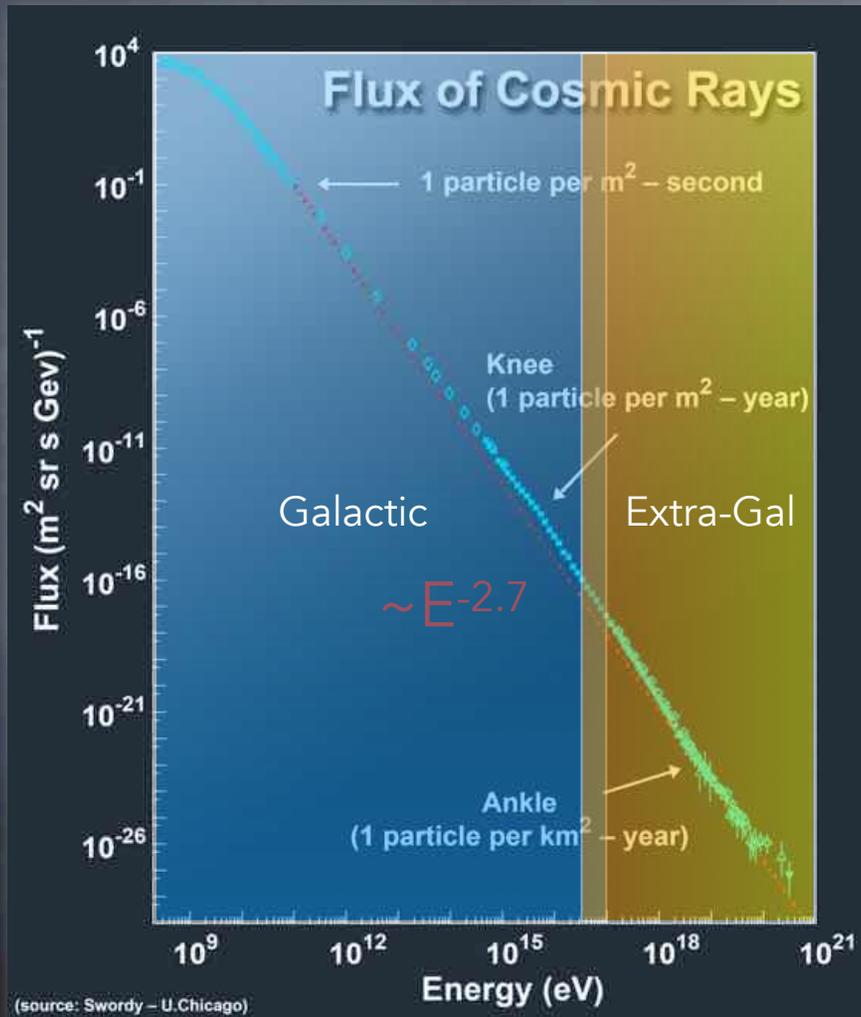
PHILIP MORRISON

*Department of Physics and Newman Laboratory of Nuclear Studies,  
Cornell University, Ithaca, New York*

**I**N 1954, Professor Einstein once remarked that there were two easily observable phenomena that, in his opinion, showed a deep fundamental lack in our knowledge of the physical world. These, he said, were the cosmic rays, and the terrestrial magnetic field. We can

of, say, the latitude effect. The idea was gained, and given quantitative support, that the cosmic rays were not given and immutable, something whose origin could not be approached because they were so far beyond ordinary experience. This idea was aided by

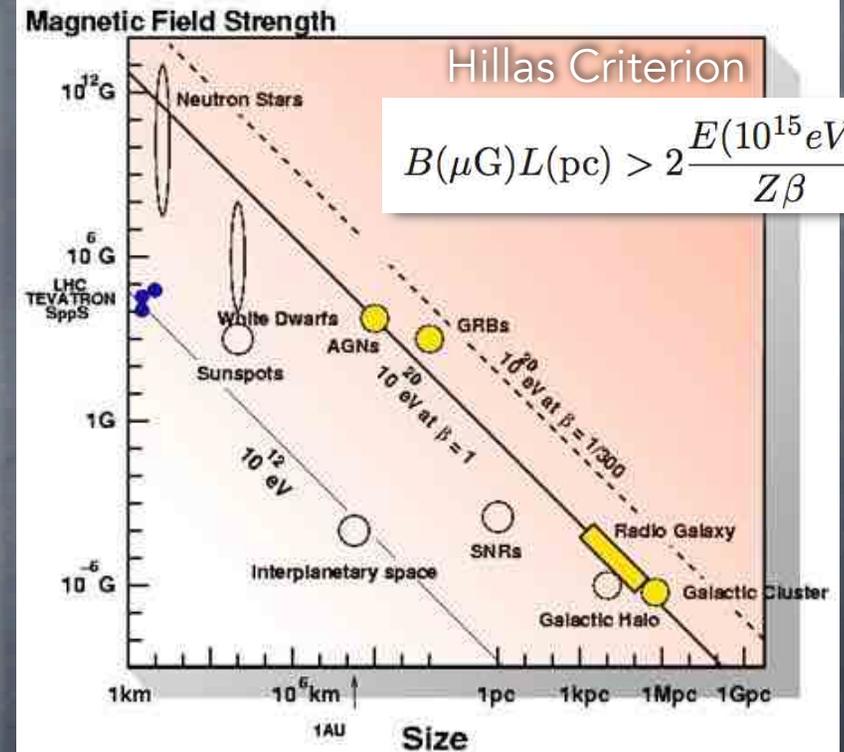
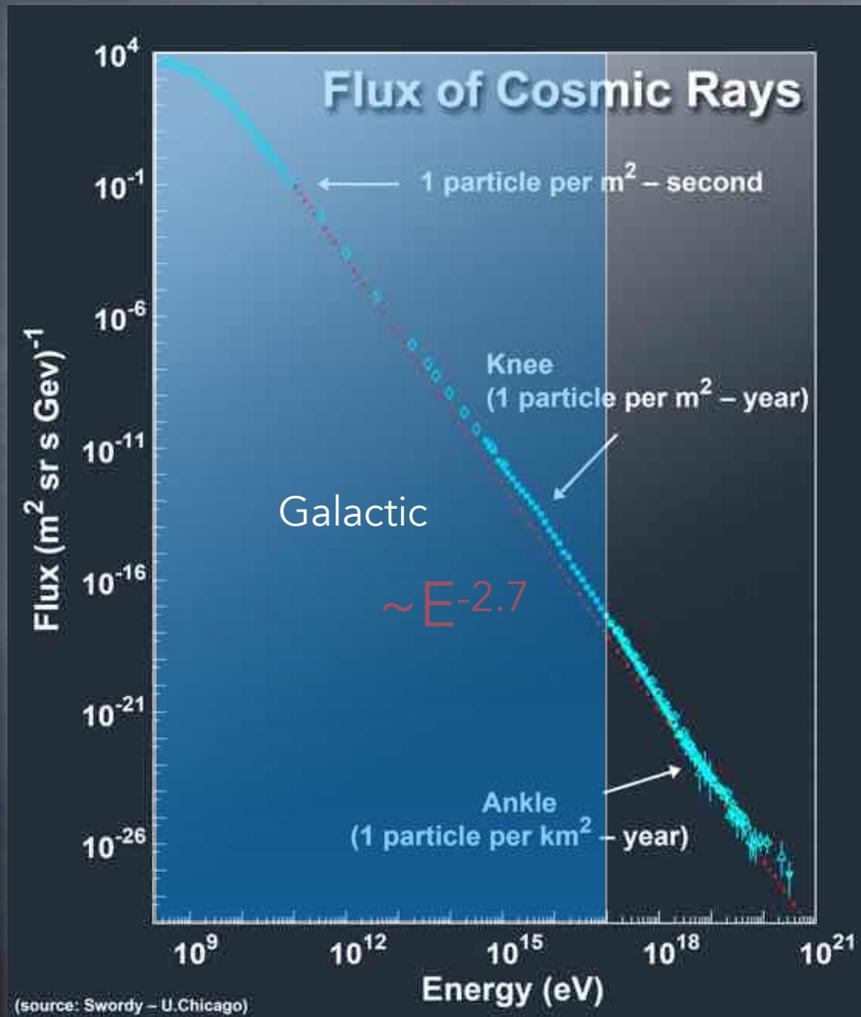
# Cosmic Rays: Hunt for Sources



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



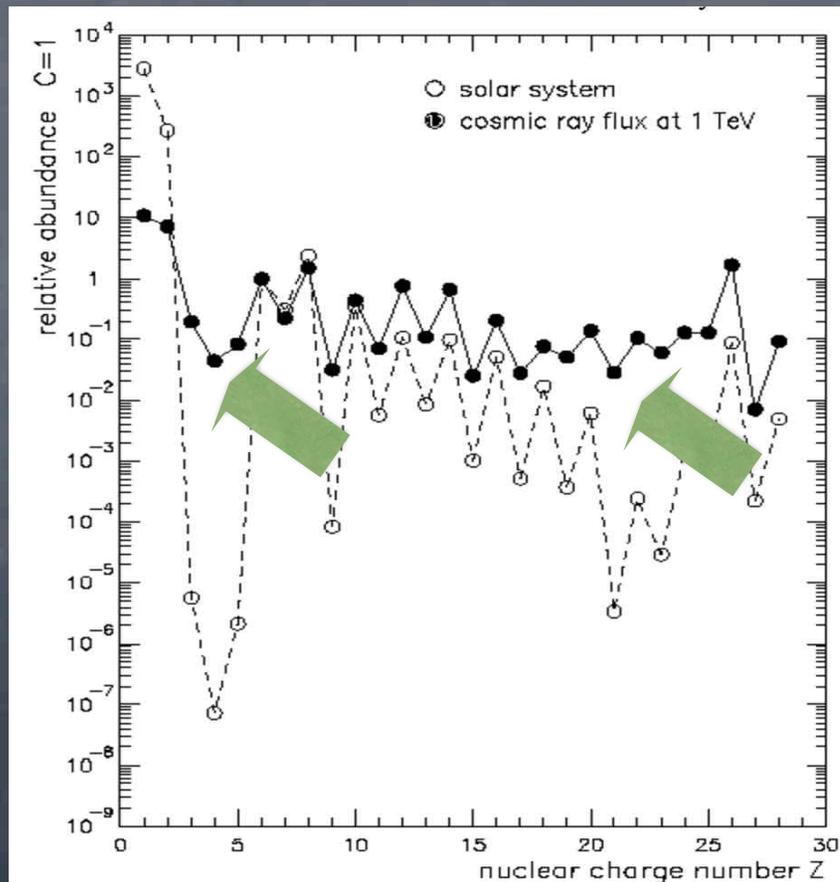
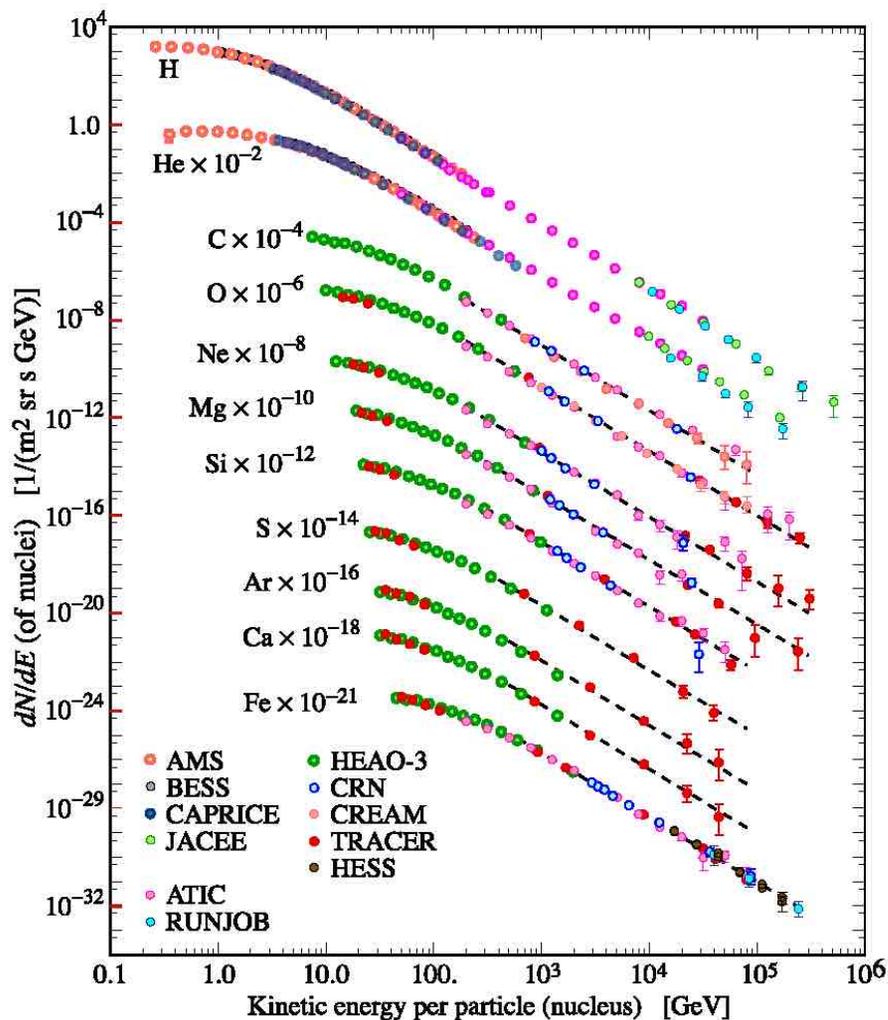
# Galactic Cosmic Rays



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

# Galactic CR composition

- 90% H, 9% He; 1% electrons; photons, neutrinos
- Anomalous abundances with respect to Solar!





# Propagation of Galactic CRs

- Secondary elements (e.g. Boron) produced via **spallation** in the Milky Way
- B/C prop. to the Galactic **residence time** (also radioactive isotopes:  $\text{Be}_{10}/\text{Be}_9$ , with  $T_{\text{Be}_{10}} \sim 1.4 \text{ Myr}$ )

Grammage needed:

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

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

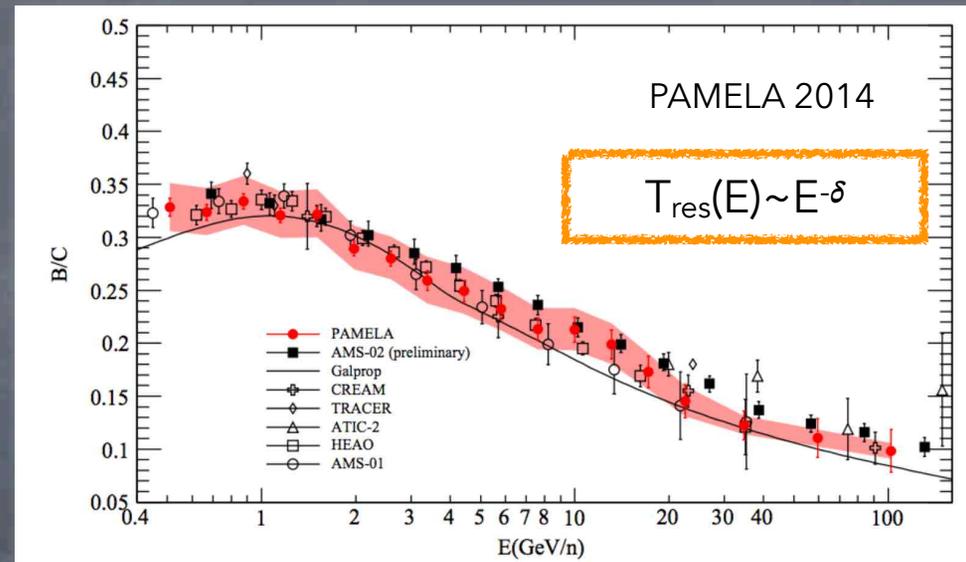
For leptons

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

Propagation **steepens** the injection spectrum  $E^{-\gamma}$  to

$\sim E^{-\gamma-\delta} \sim E^{-2.7}$  for hadrons

$\sim E^{-\gamma-1} \sim E^{-3}$  for electrons



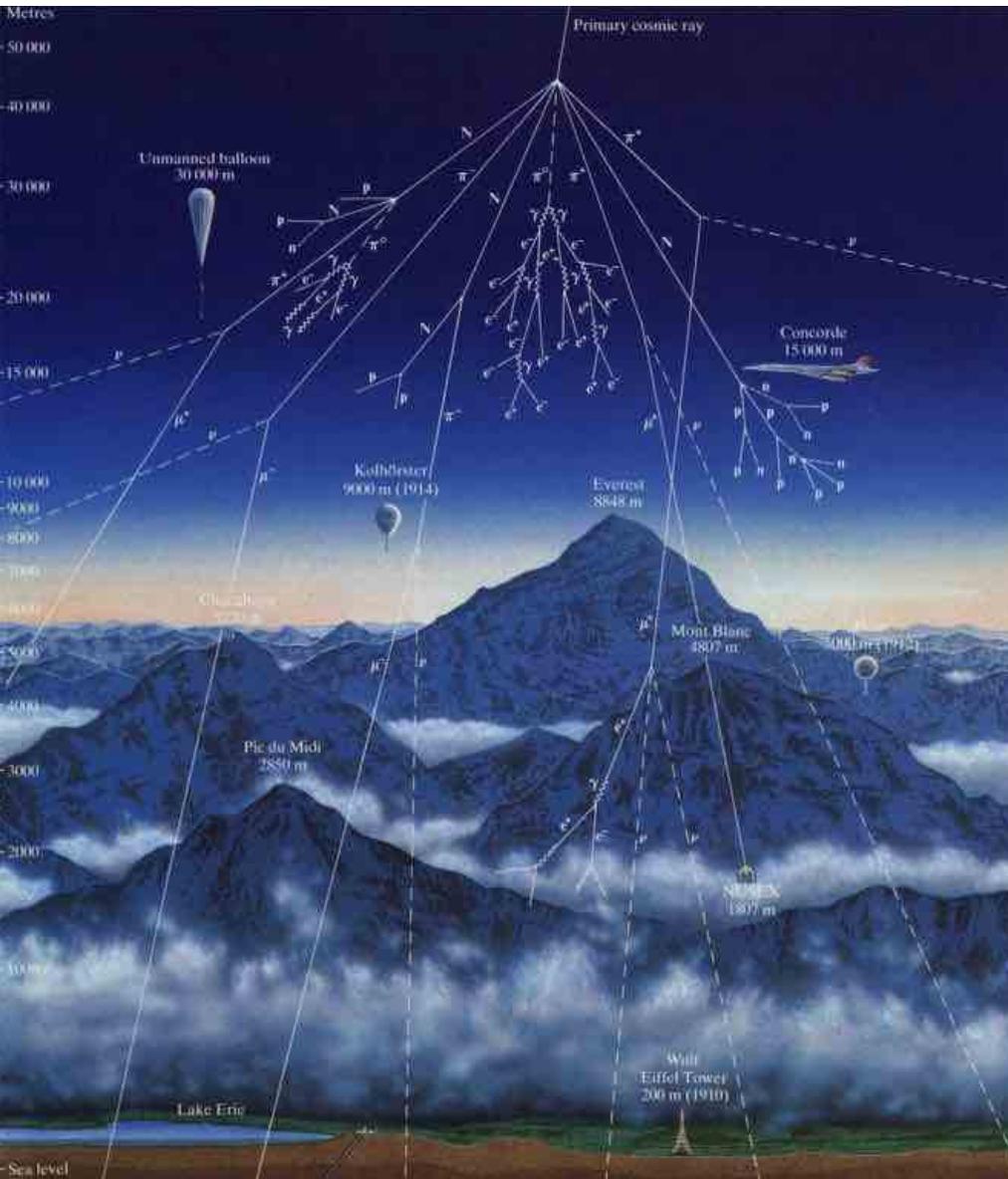
$$T_{res} \gg T_{cross} \sim \text{kpc}/c$$

**DIFFUSIVE PROPAGATION!**



# Extensive Air Showers

Indirect detection of CRs above hundreds of TeV



Nuclear disintegration

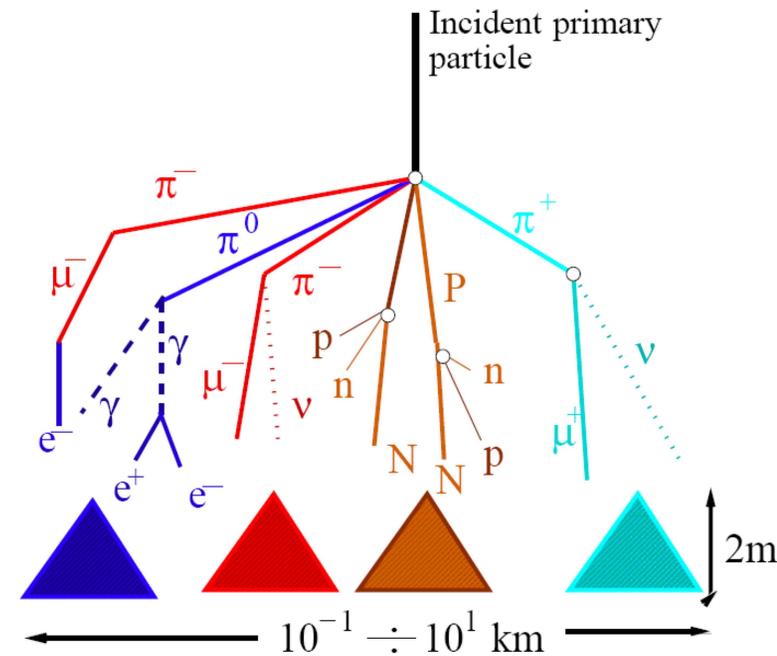
$N, P$  High energy nucleons

$n, p$  disintegration product nucleons

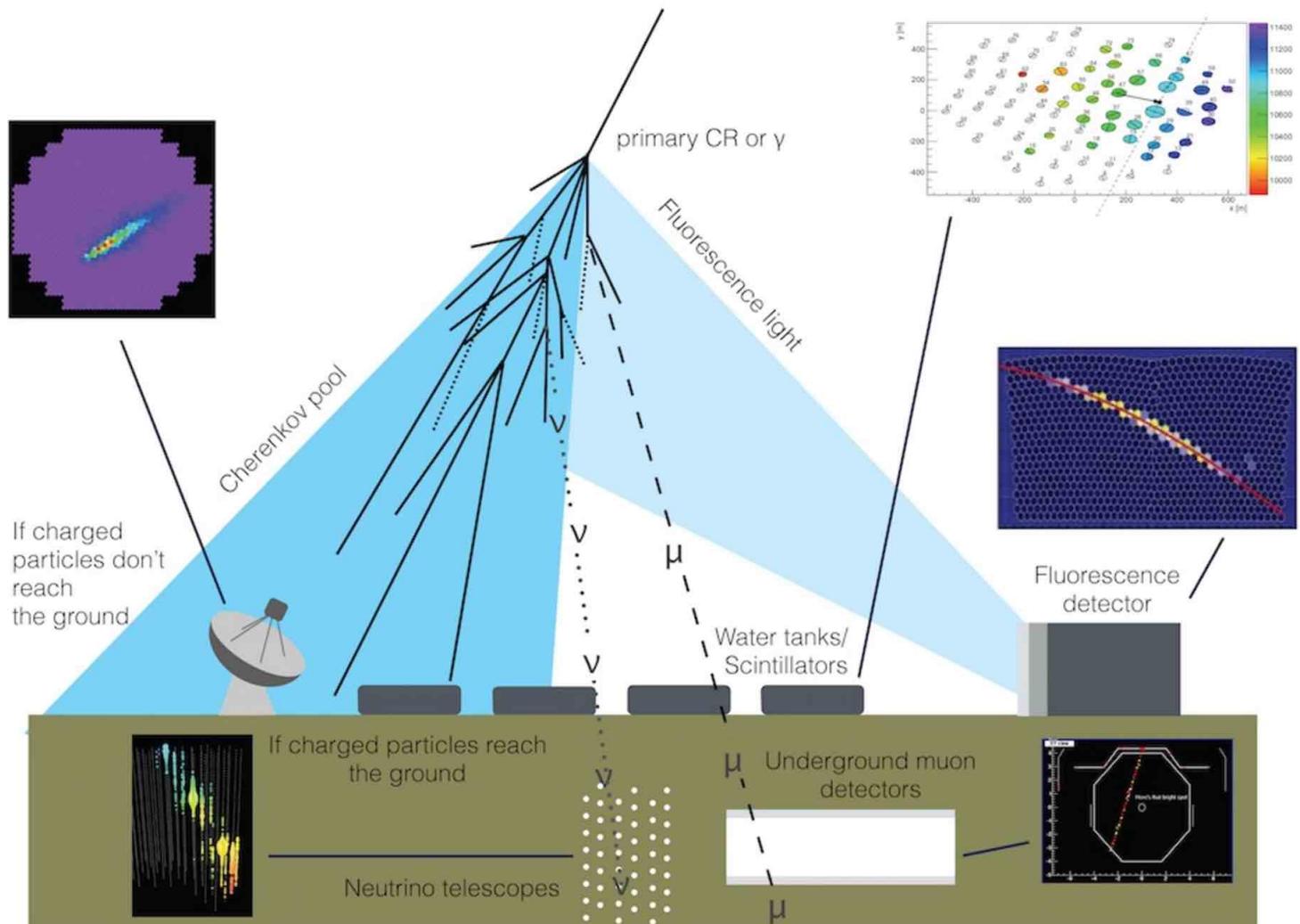
Hard component

Soft component

Nucleonic component

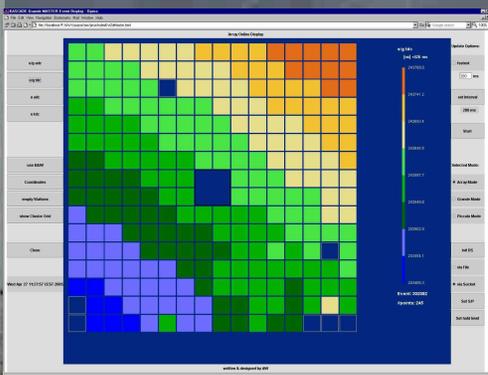


# Extensive Air Showers: Multiple detection



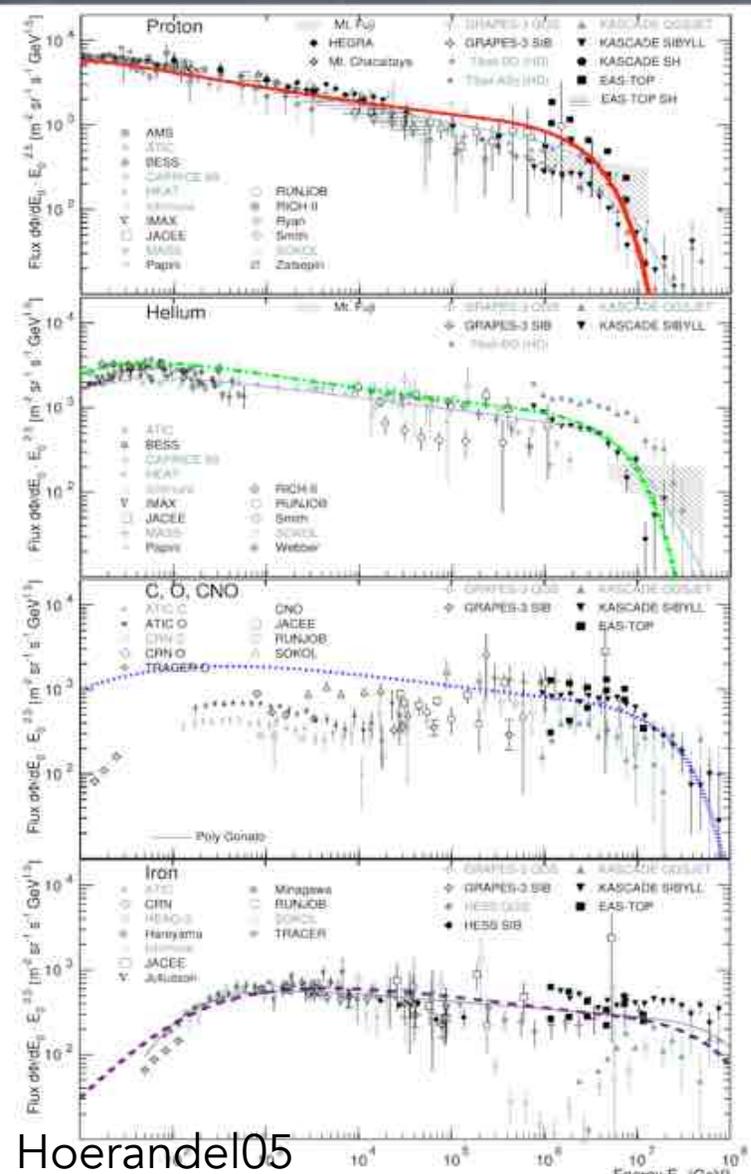
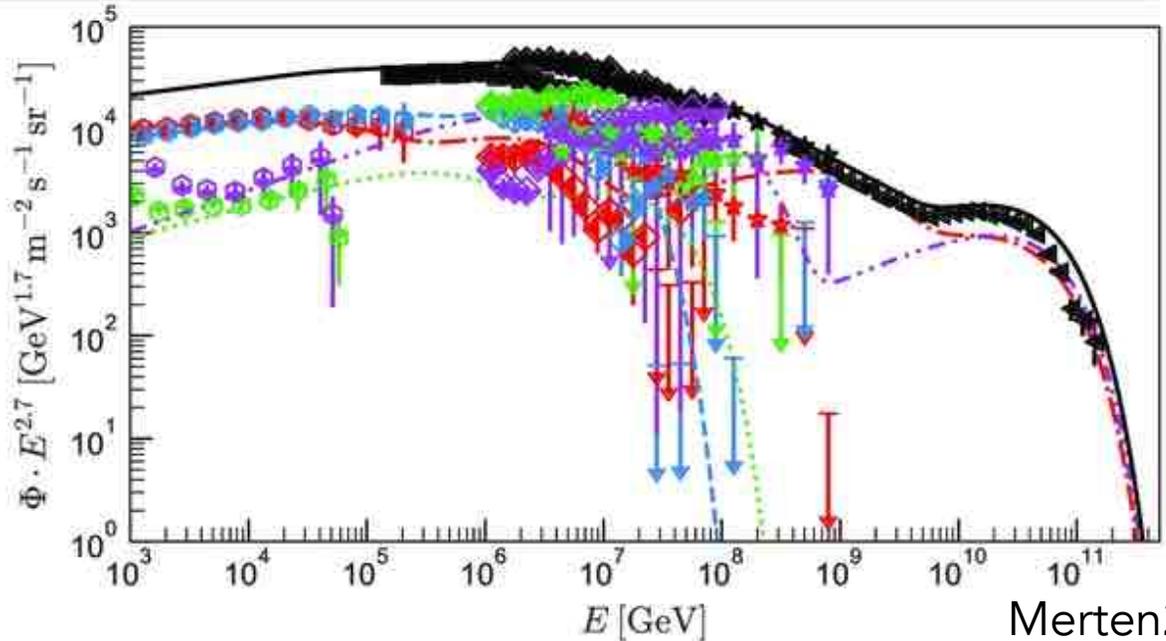
# Showers in the knee region

Kascade-GRANDE (Karlsruhe)



# The Knee

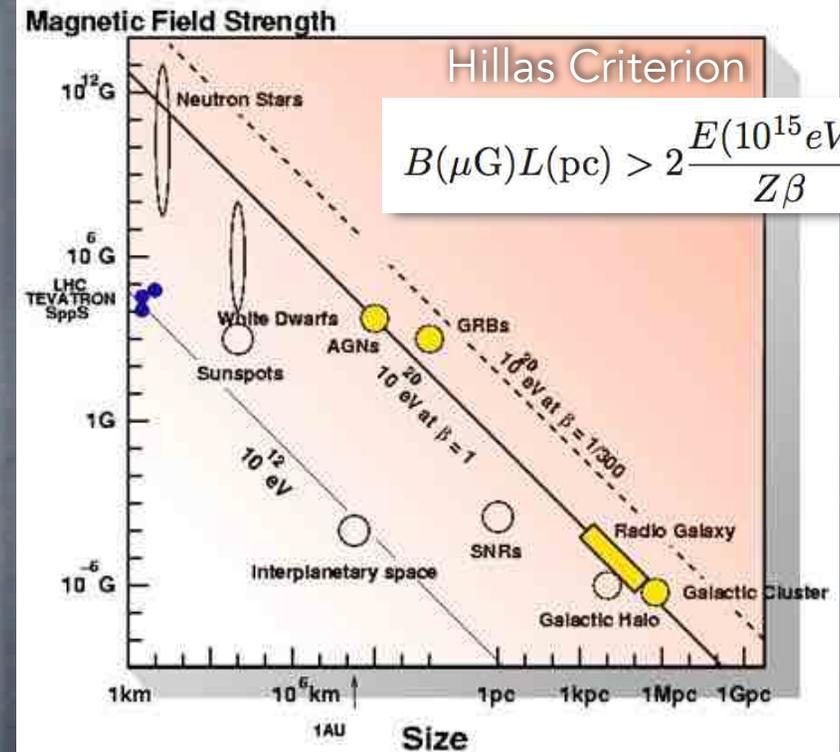
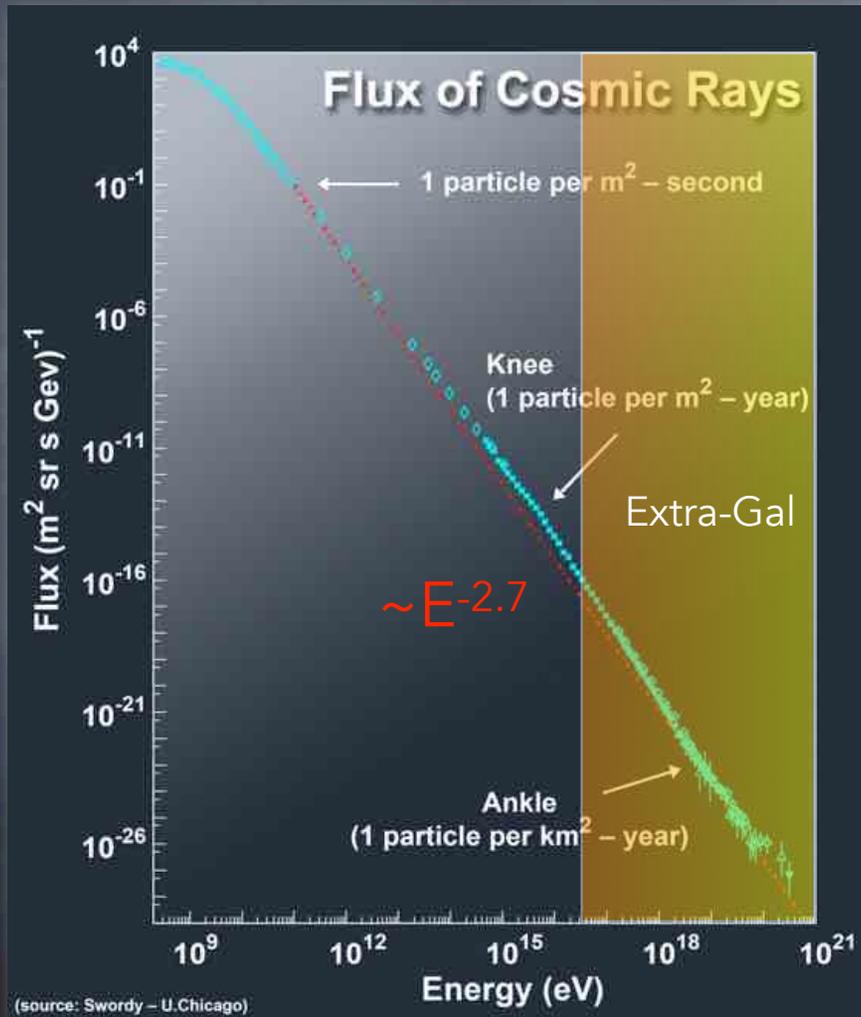
- Chemical composition heavier at  $\sim 1$  PeV
- Steepening due to convolution of exp cutoffs!



Hoerandel05

Merten20

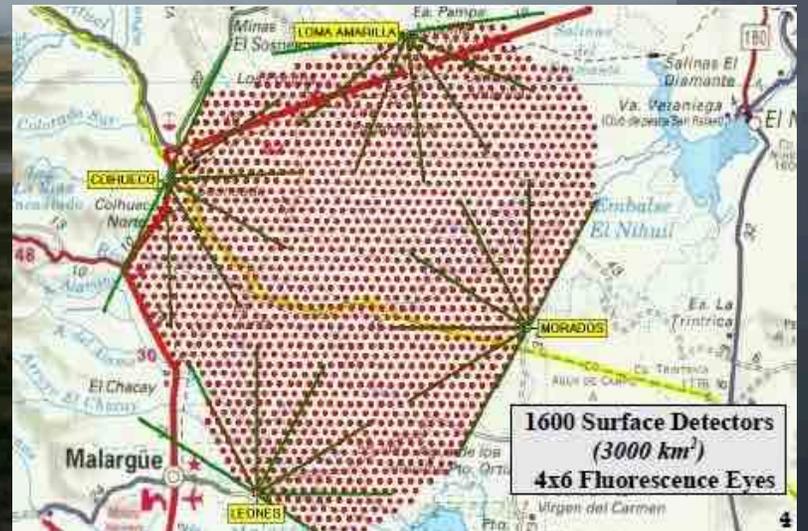
# Extra-galactic (Ultra-High Energy CRs)



Remarkable power-law (plus "leg" features)



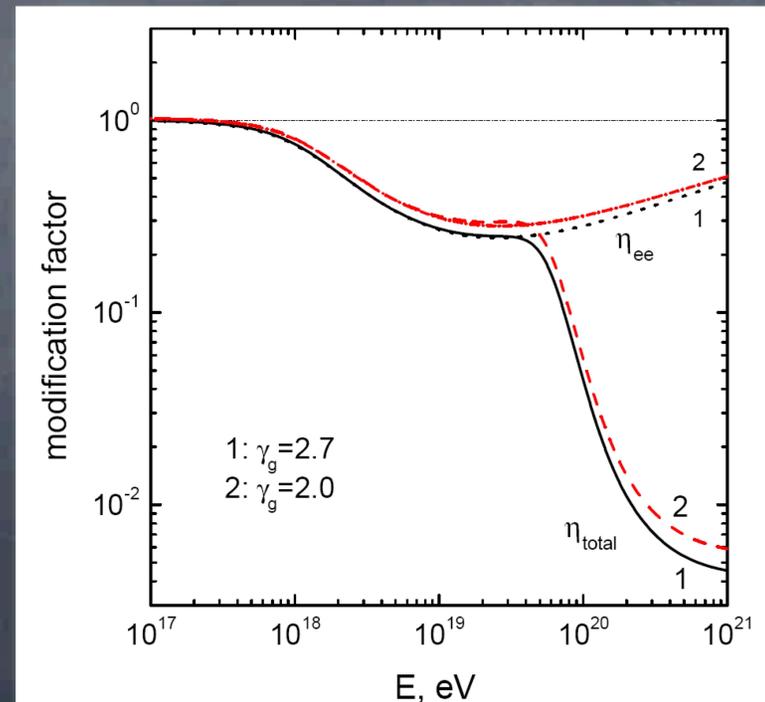
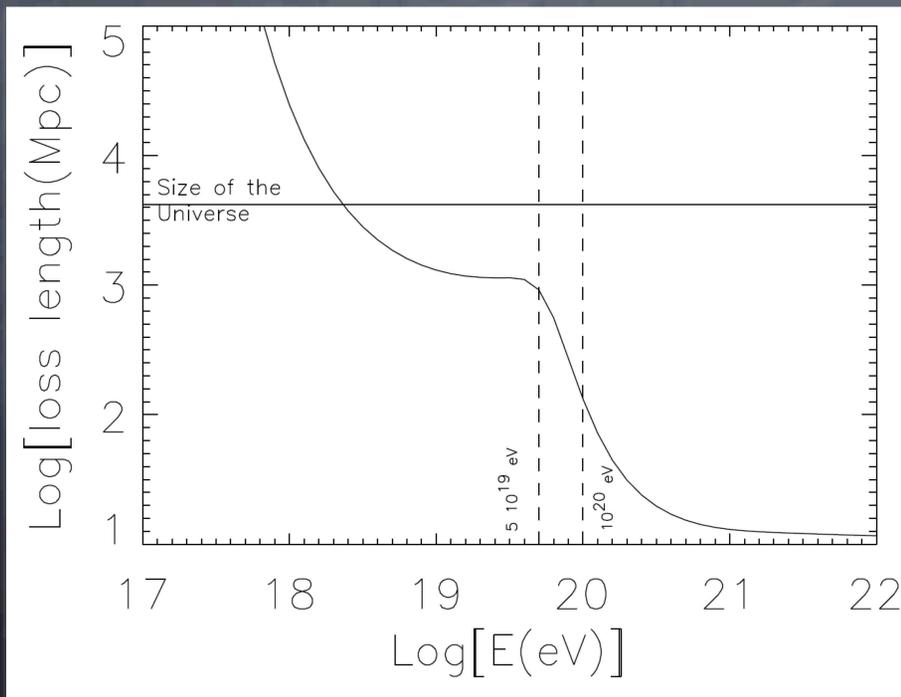
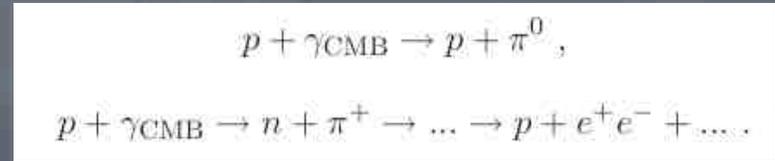
# Pierre Auger Observatory





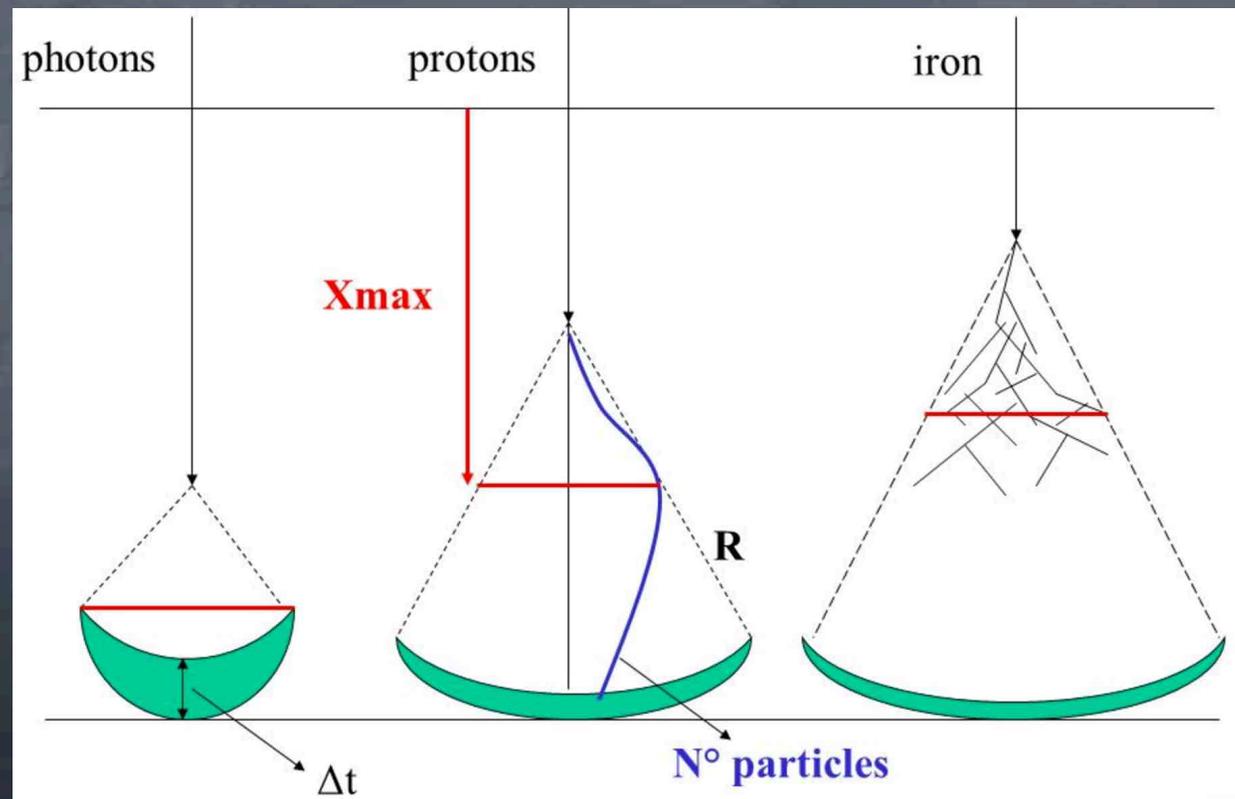
# Interactions with the CMB radiation

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



# UHECR composition

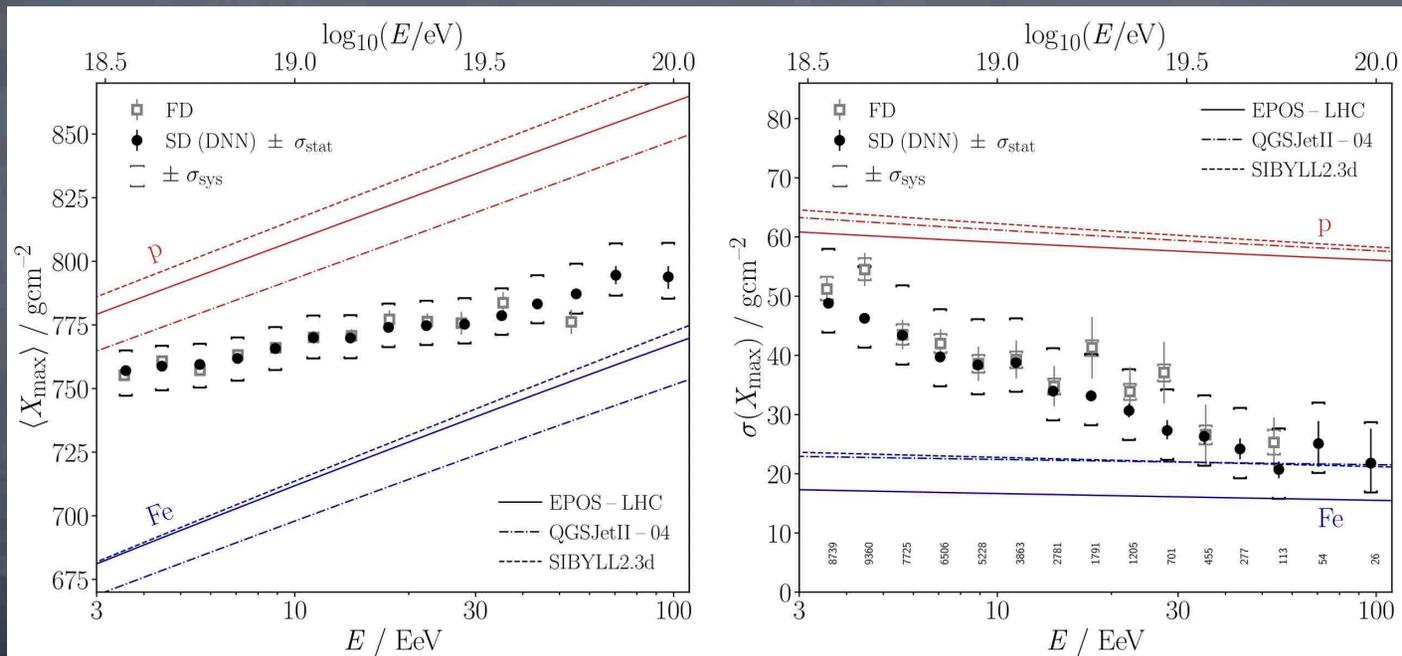
- Estimated by the **grammage** where the EAS reaches its maximum extent  $X_{\max}$
- Fluorescence telescopes are needed, now both at Auger and Telescope Array





# 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!

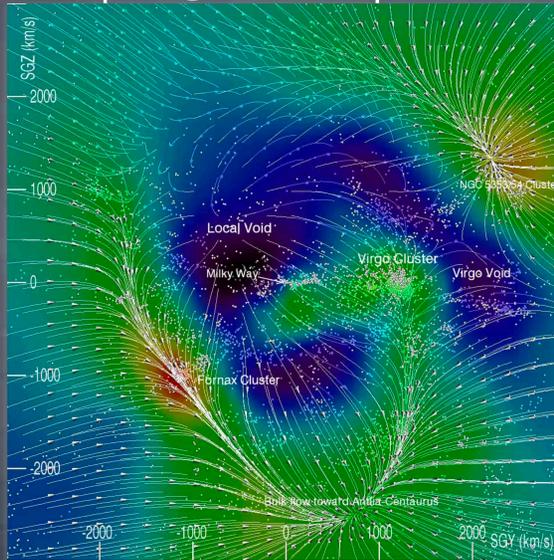


Auger 2024

- Implications for **cut-off**: no photo-pion, but **photo-disintegration** of Fe nuclei!
- Surprisingly, attenuation lengths turn out to be comparable  $\sim 100\text{Mpc}$

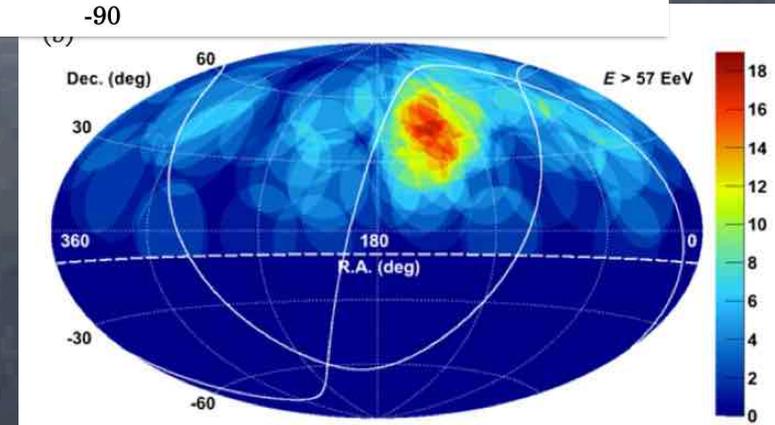
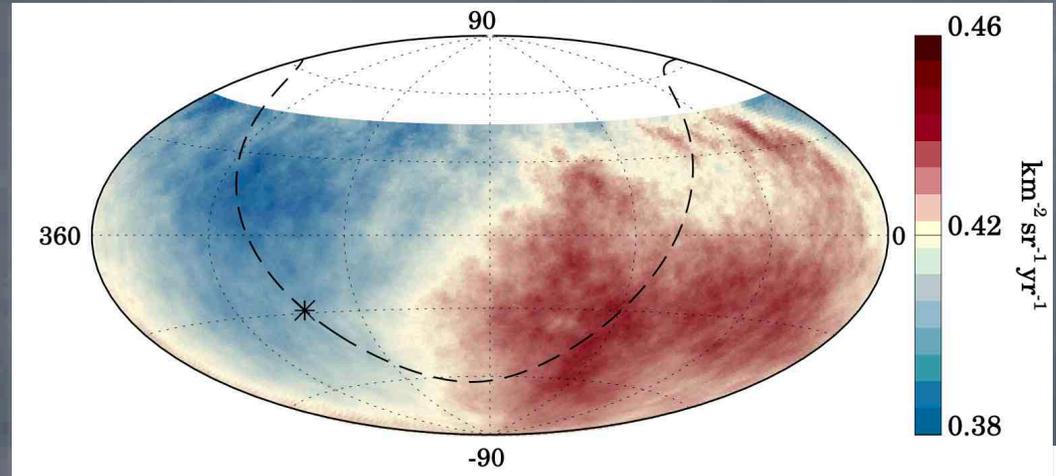
# Anisotropies in the arrival directions?

- Evidence of **dipole anisotropy** (6.5% amplitude) for  $E > 8 \times 10^{18}$  eV by Auger (2017)
- Perp to the supergalactic plane



Courtois+13

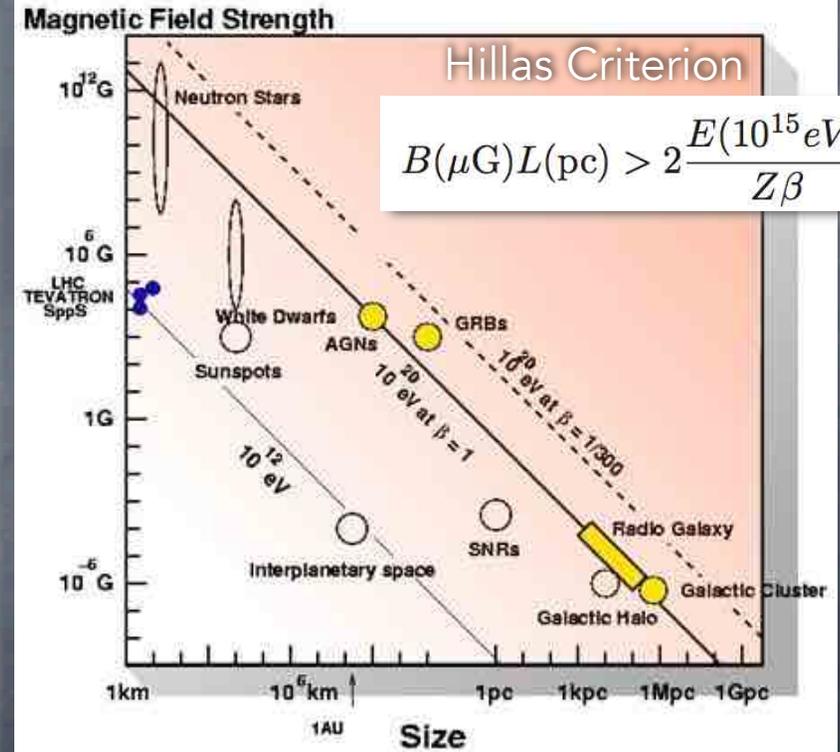
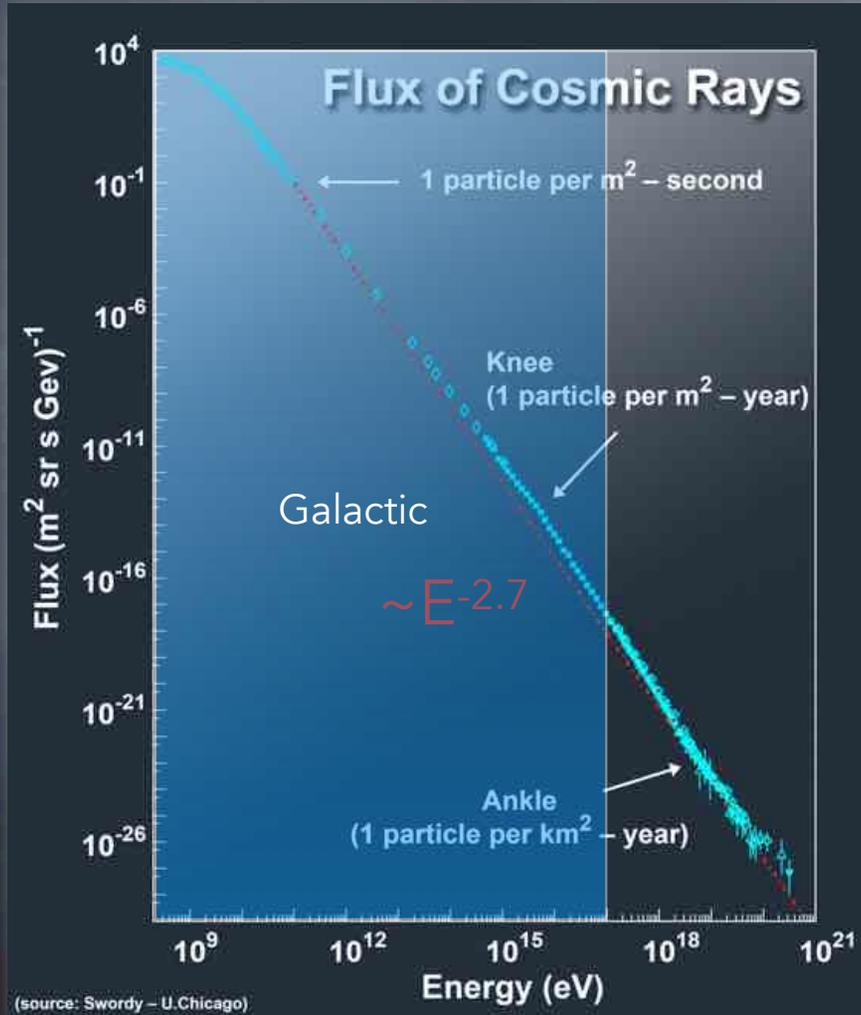
- Not obvious correlation with AGNs or starbursts
- Unlikely UHECR astronomy if heavy nuclei
- Telescope Array claimed an **hotspot** above 57EeV ( $\sim 3.4$  sigma CL)



# Galactic CRs



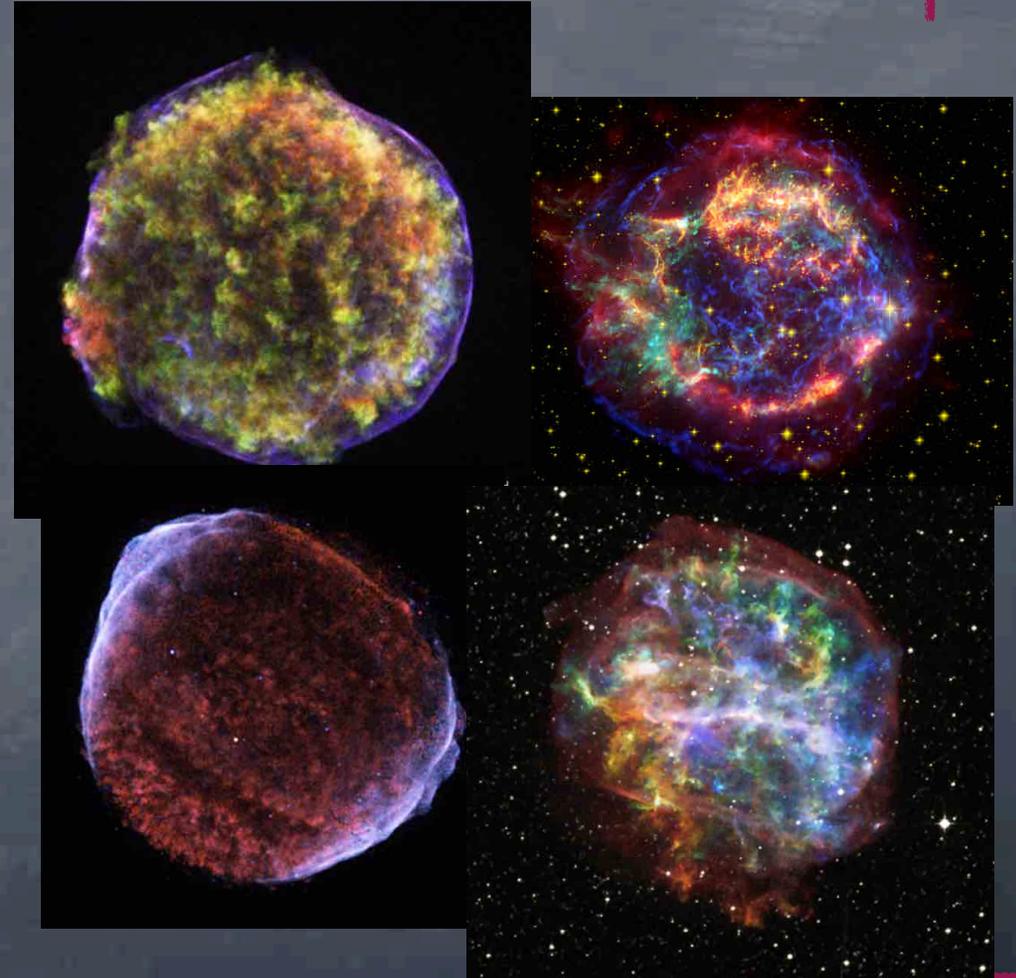
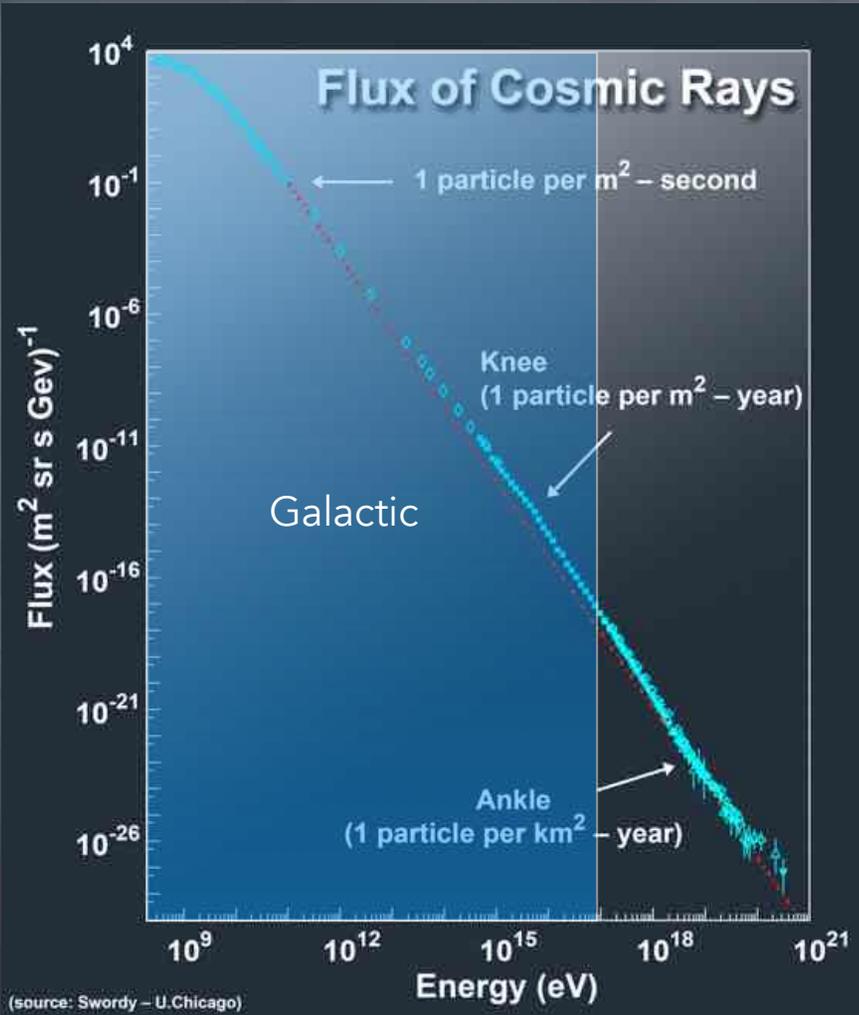
# Galactic Cosmic Rays



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



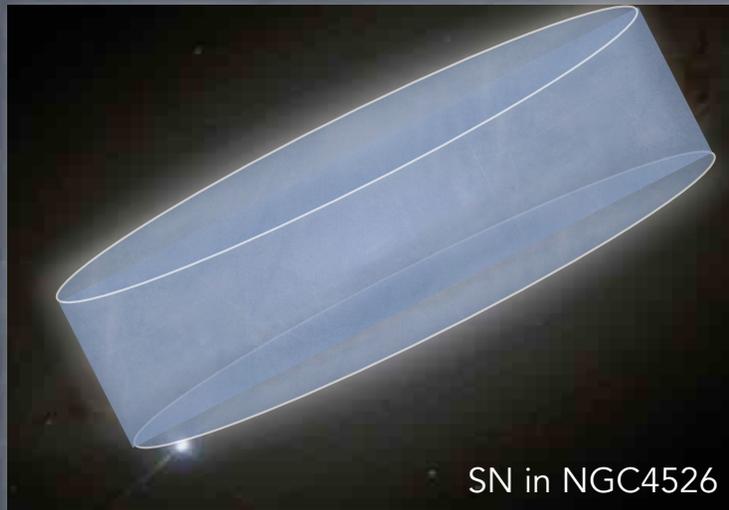
# SNR Paradigm for Galactic Cosmic Rays





## SNR paradigm: energetics

- Baade-Zwicky (1934) energetic argument, updated



SN in NGC4526

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

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

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

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

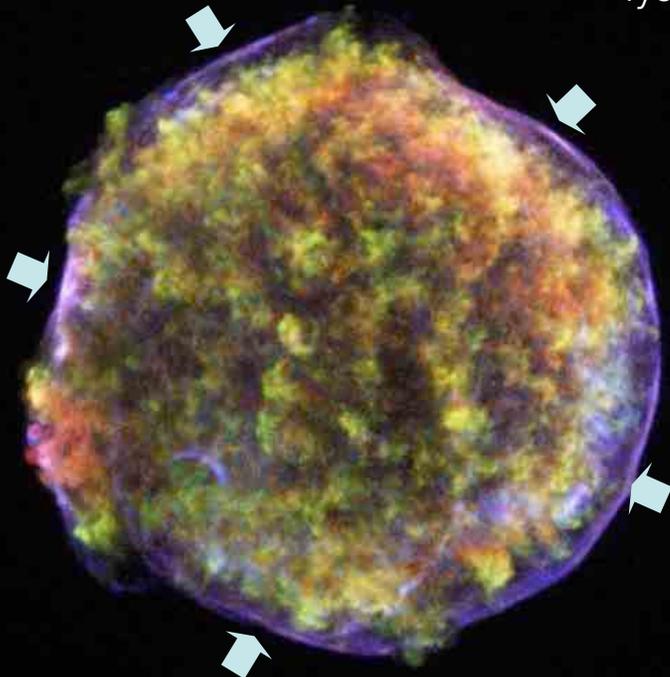
$$L_{\text{SN}} = R_{\text{SN}} E_{\text{kin}} \approx 3 \times 10^{41} \text{ erg s}^{-1}$$

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

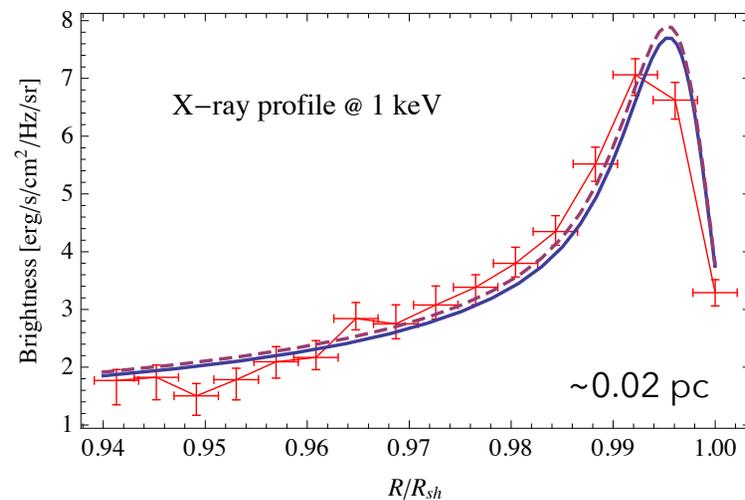


# Evidence of magnetic field amplification

Tycho



- **Narrow** (non-thermal) X-ray **rims** due to synchrotron losses of **multi-TeV** electrons...
- ...in fields as large as  **$B \sim 100\text{-}500 \mu\text{G}$**



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;  
Giufdrida et al. 2022



# SNR paradigm: maximum energy

- The magnetic field can be amplified by **CR-driven instabilities**
- The **coupling** between CRs and waves **enhances**  $v_A \propto B$



- **Maximum energy** achievable in a SNR:

$$T_{acc} \propto \frac{D(E)}{V_{sh}^2} = T_{age}$$

$$V_{sh} \sim 5 \times 10^8 \text{ cm/s}$$

$$T_{SNR} \sim 10^3 \text{ yr}$$

- With Galactic diffusion:  $E_{max} \sim \text{GeV!}$
- With Bohm diffusion  $D_B(E) = cr_L(E)/3$  in the Galactic B,  $E_{max} \sim 100 \text{ TeV} < E_{knee}$
- B needs to be **amplified by a factor of >10** (both UPS and DOWNS) to explain the knee!

# SNR paradigm



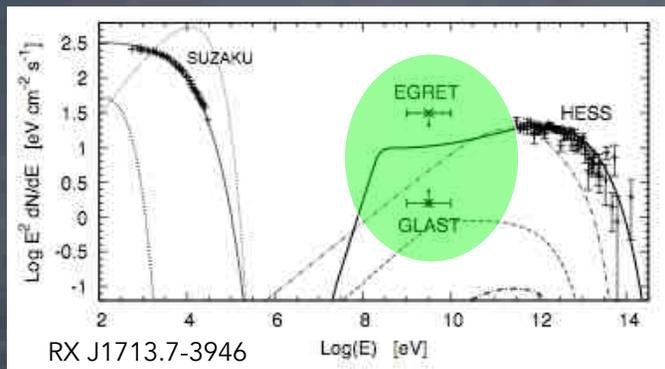
- SNRs have the right **energetics**
- **Diffusive shock acceleration** produces **power-laws**
- **B amplification** enhances particle diffusion



- Is there direct **evidence** of CR acceleration in SNRs?

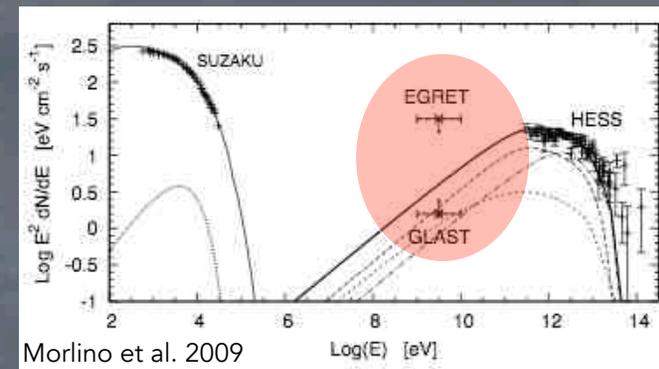
# Testing the SNR paradigm: $\gamma$ -rays from SNRs

## HADRONIC ( $\pi_0$ decay)



$\gamma$ -ray spectrum **parallel** to the proton one ( $\sim E^{-2}$ )

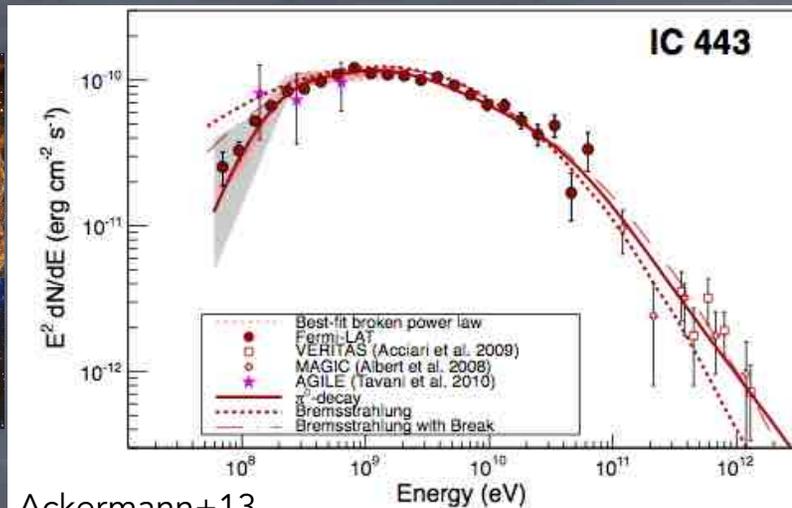
## LEPTONIC (Inverse Compton)



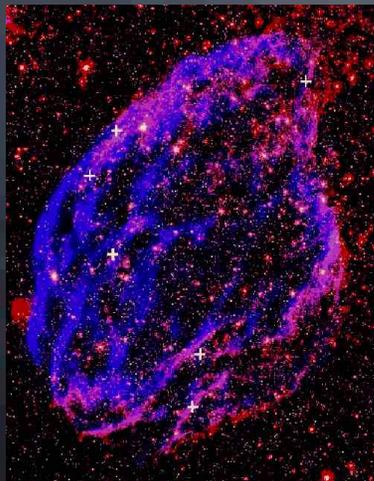
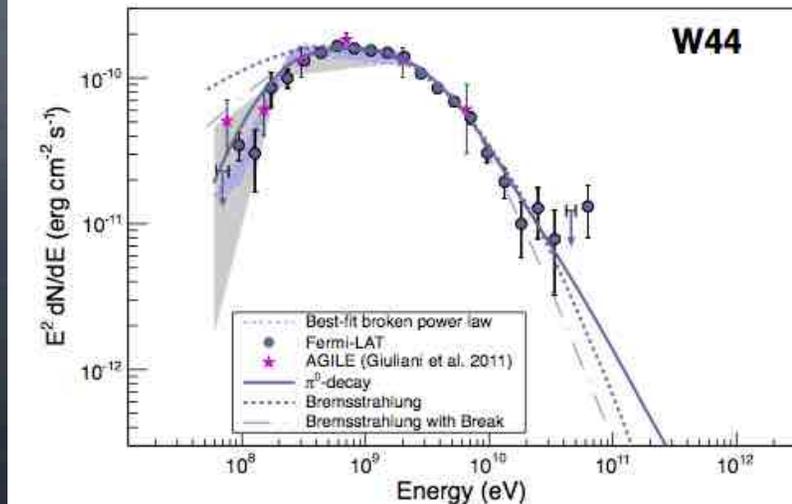
$\gamma$ -ray spectrum **flatter** than the proton (electron) one ( $\sim E^{-1.5}$ )

- Location: **gas-/photon-rich** environments  $\rightarrow$  **hadronic/leptonic** emission

# Hadronic emission from SNRs

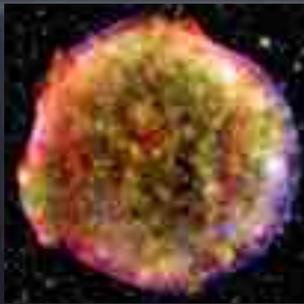
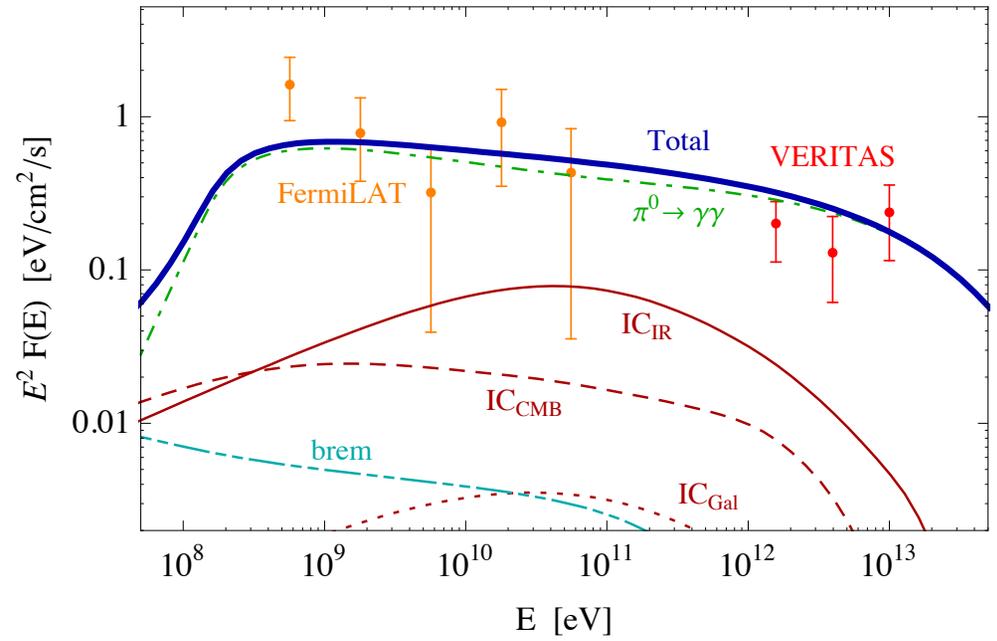
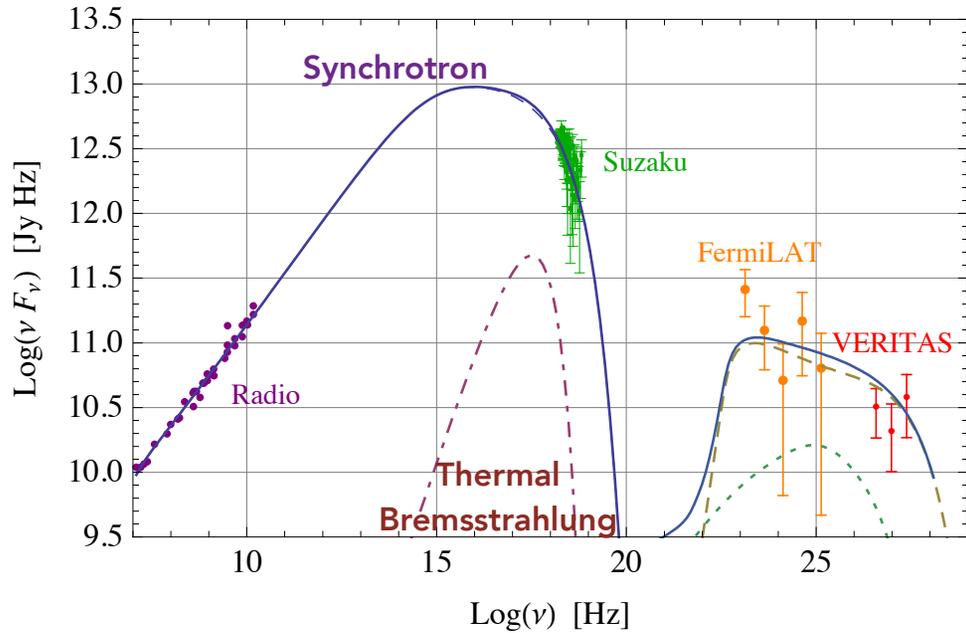


Ackermann+13



- ① Low-energy cut-off because of the  $\pi_0$  mass (135MeV)
- ① Overabundance of "targets"
- ① Overabundance of "bullets"?
- ① SNR, or diffuse CRs?
- ① Very steep spectra ( $E^{-3}$ )!!
- ① Shock propagating in partially-neutral plasmas are non-trivial

# Tycho: a clear-cut hadronic accelerator



Type Ia SN  
 $E_{SN} = 10^{51}$  erg  
 Age = 443 yr  
 Distance ~ 3 kpc

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

## Aside on Fermi Acceleration

# Simulating DSA

# Astroplasmas from first principles

## Full particle in cell approach

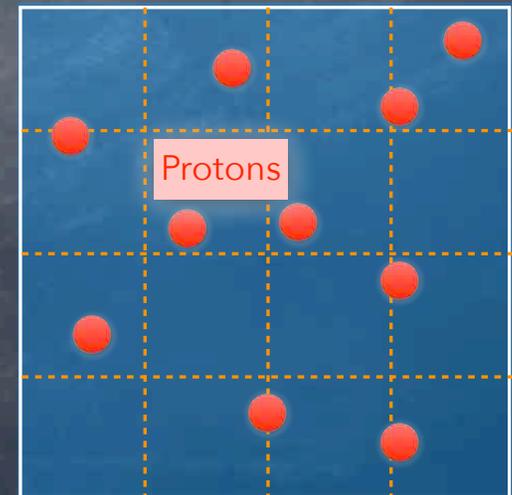
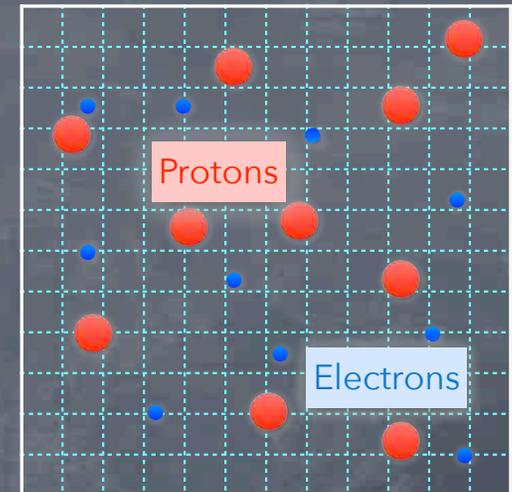
(..., Spitkovsky 2008; Amano & Hoshino 2007, 2010; Niemiec et al. 2008, 2012; Stroman et al. 2009; Riquelme & Spitkovsky 2010; Park et al. 2012; Guo et al. 2014; DC et al. 2015...)

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

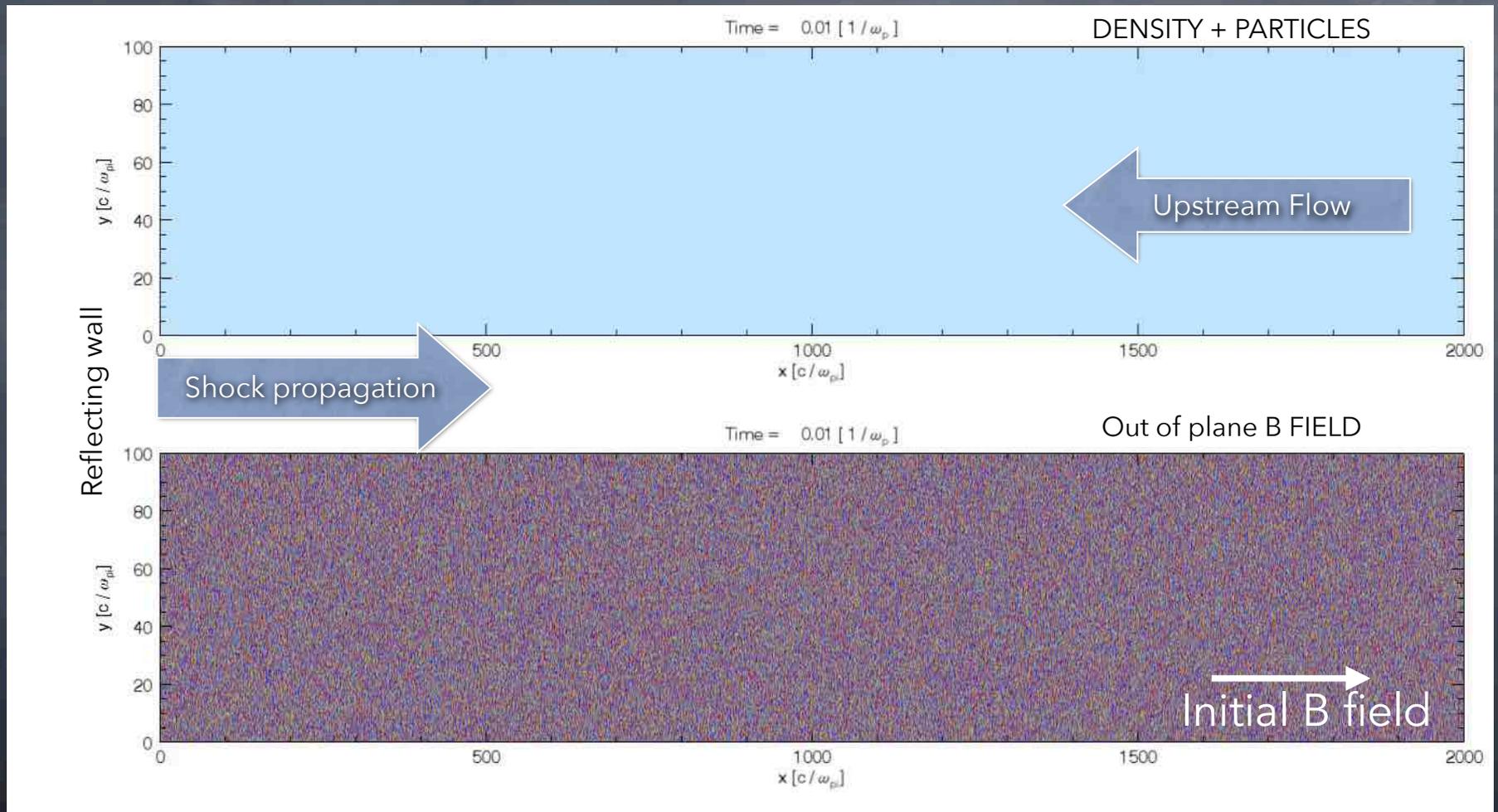
## Hybrid approach: Fluid **electrons** - Kinetic **protons**

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

- massless electrons for more **macroscopical** time/length scales



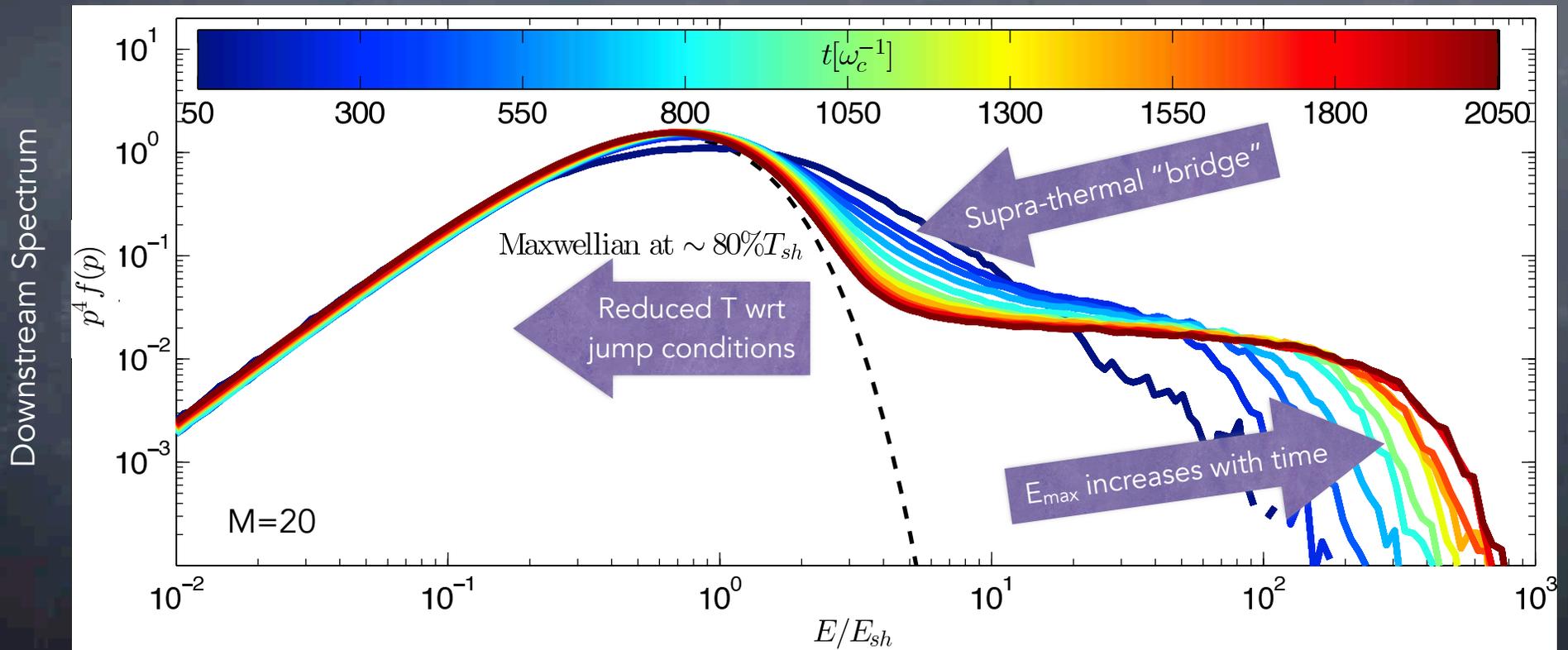
# Hybrid simulations of collisionless shocks





# Spectrum evolution

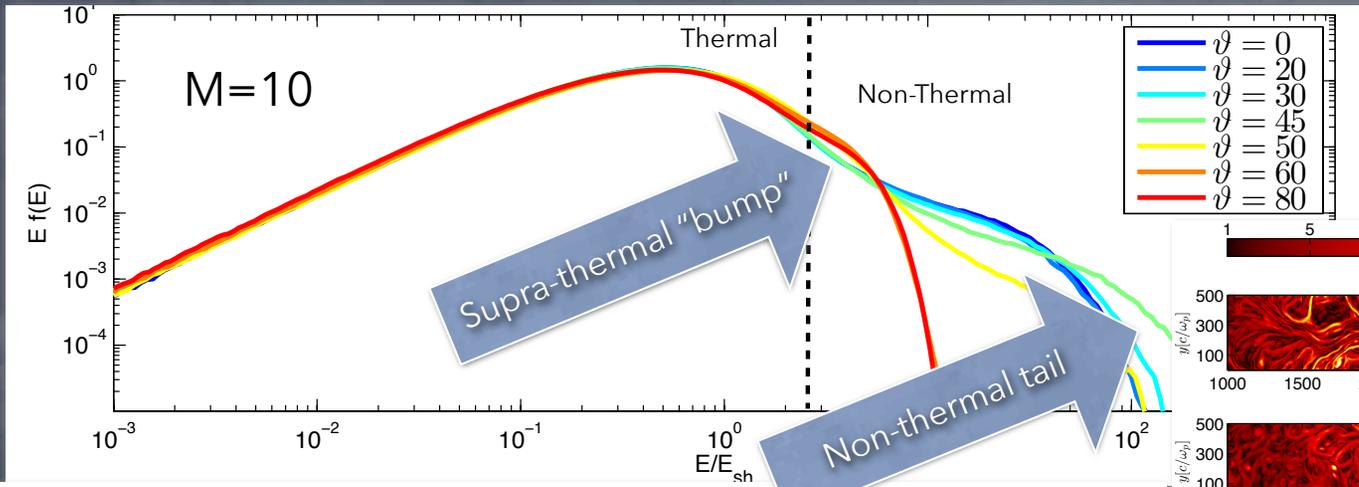
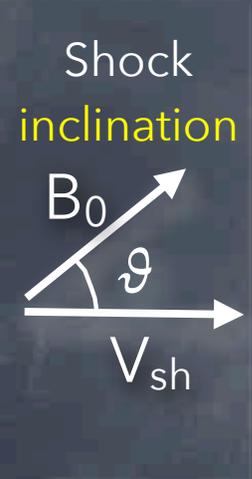
- Diffusive Shock Acceleration: non-thermal tail with universal spectrum  $f(p) \propto p^{-4}$
- Acceleration efficiency:  $\sim 15\%$  of the shock bulk energy!



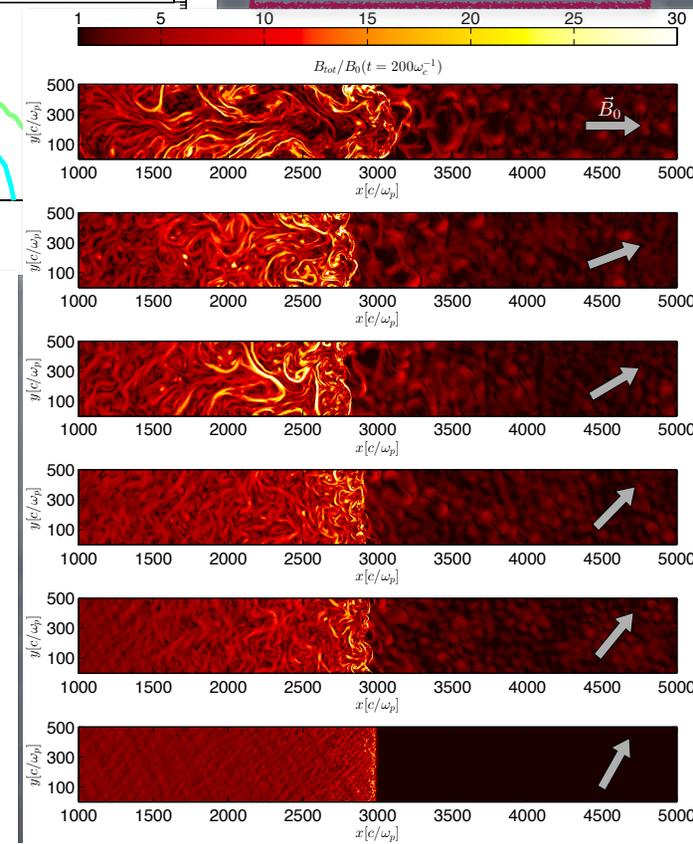
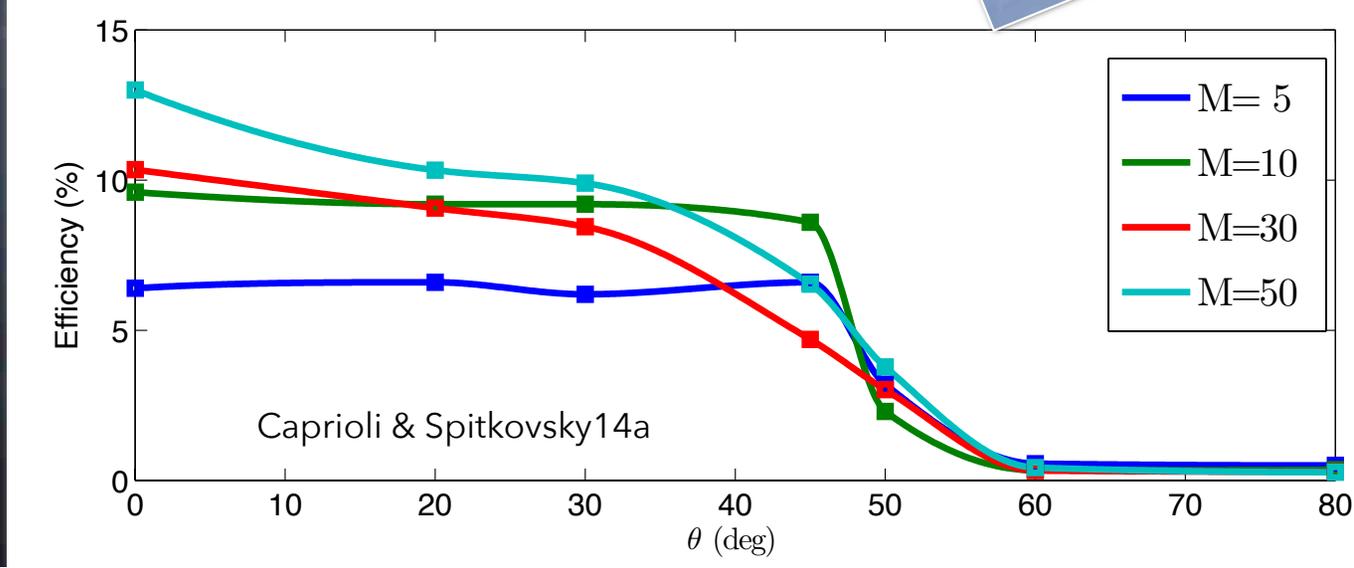
DC & Spitkovsky, 2014a



# Parallel vs Oblique shocks



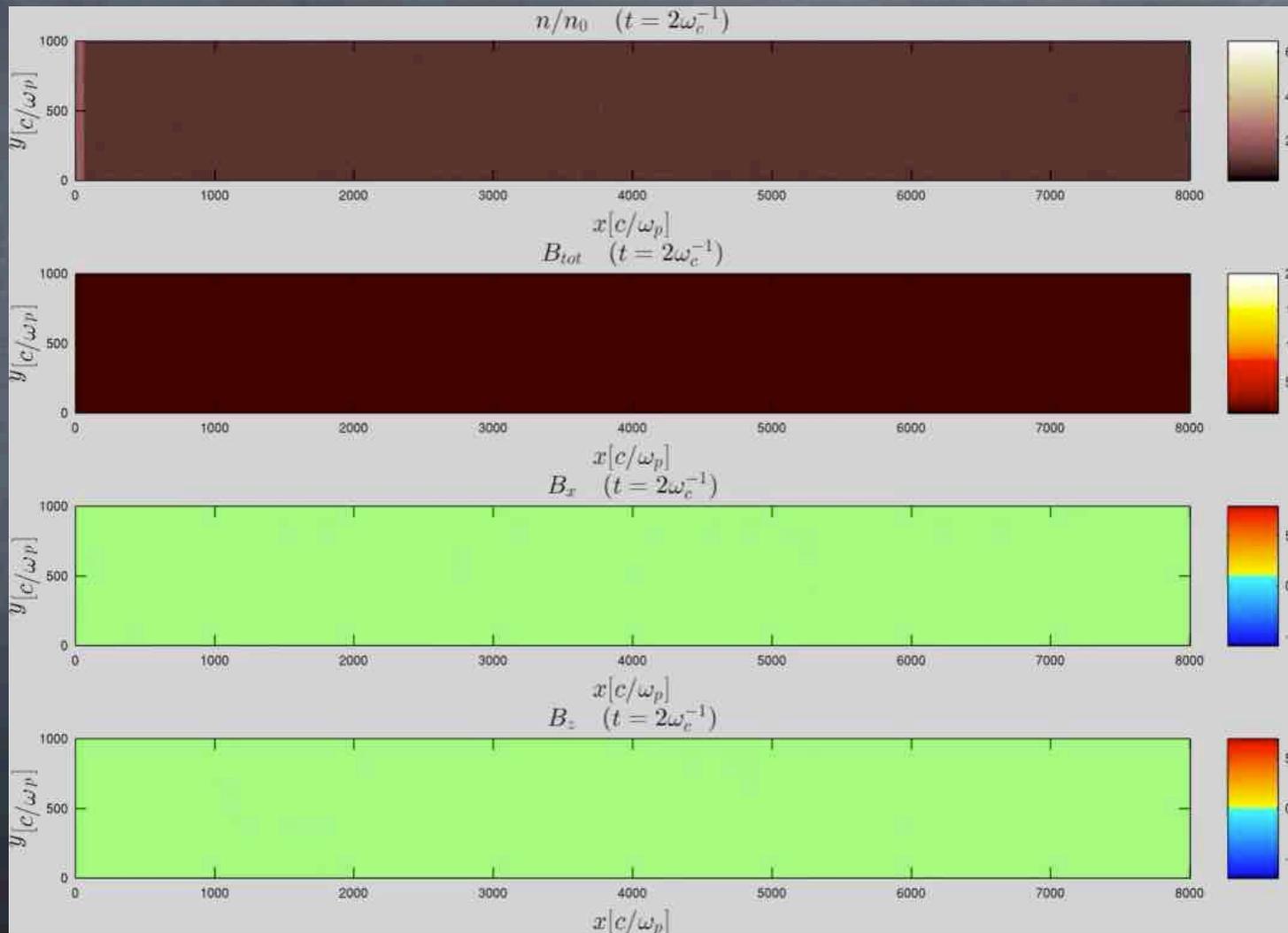
Ion acceleration correlates with B-field amplification





# CR-driven Magnetic-Field Amplification

Initial B field  
 $M_s = M_A = 30$

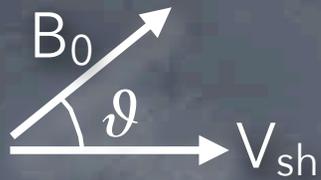


DC & Spitkovsky, 2013

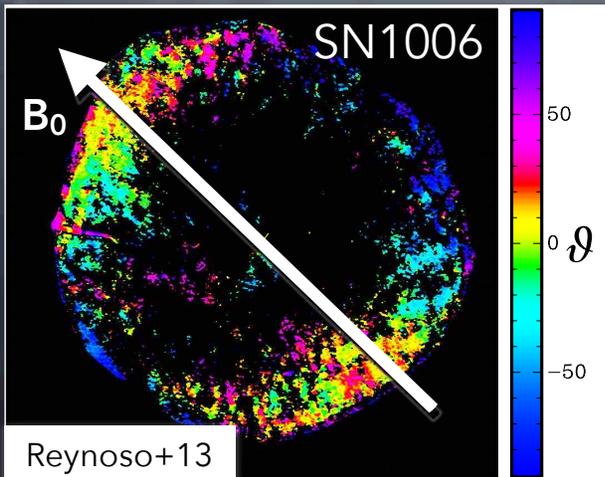
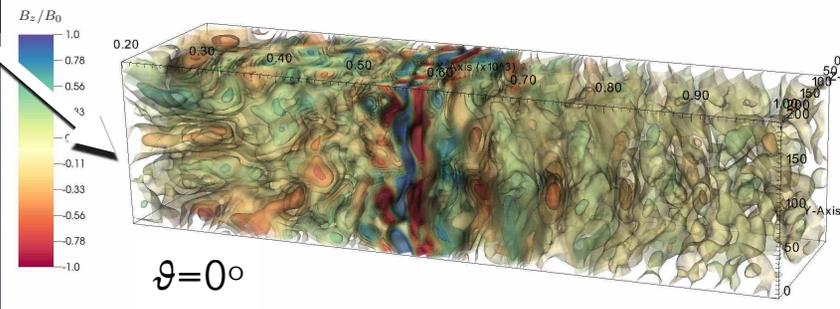
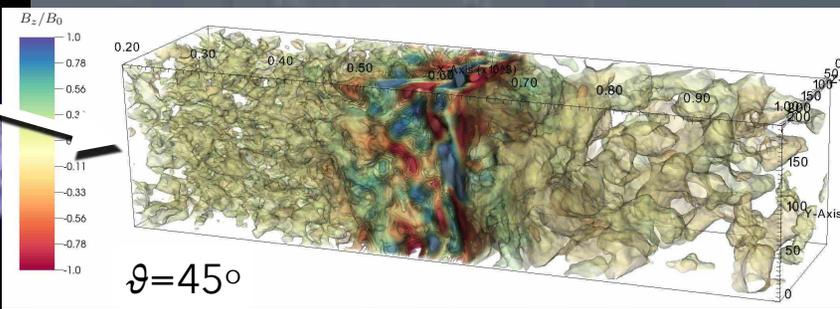
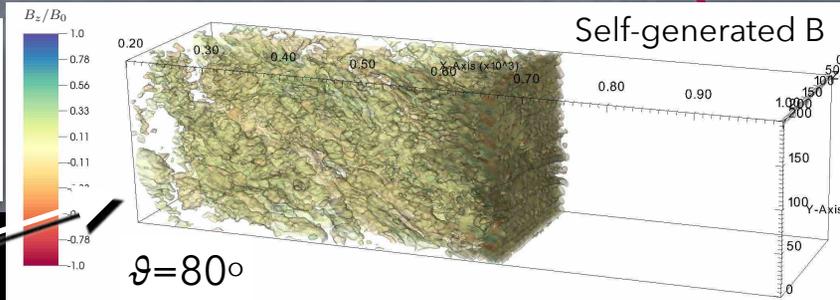
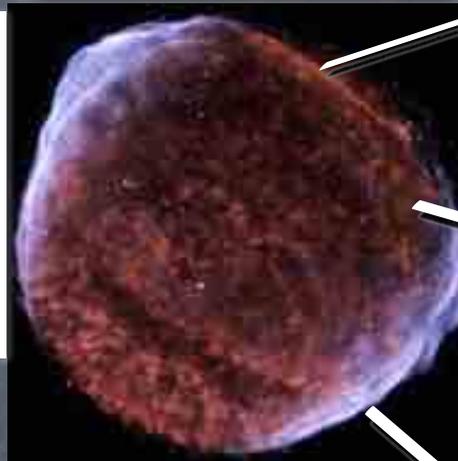
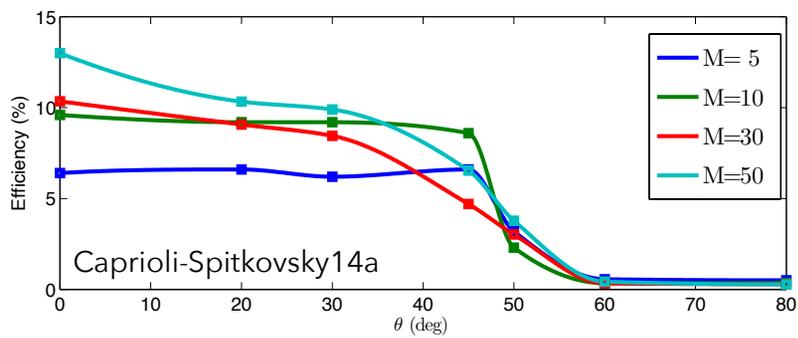


# DSA Efficiency

Acceleration depends on the shock **inclination**



X-ray emission:  
red=thermal  
white=synchrotron



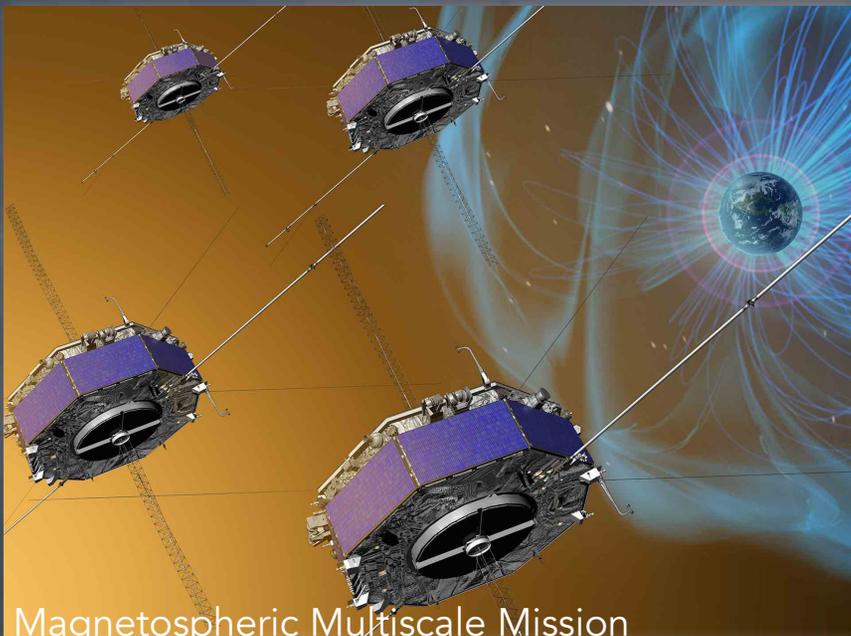
B amplification and ion acceleration where the shock is **parallel**

Caprioli-Spitkovsky14a,b,c

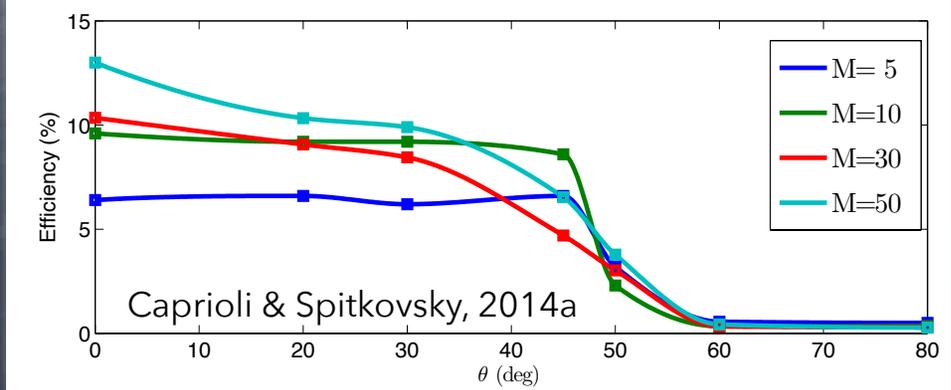
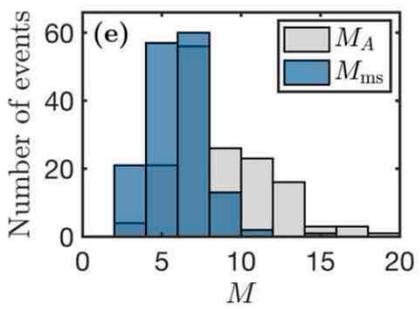
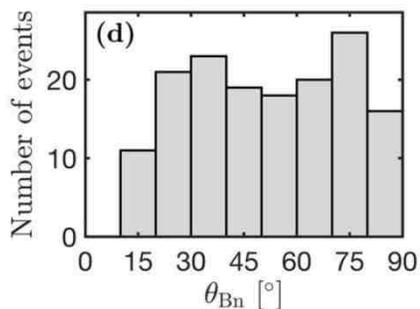
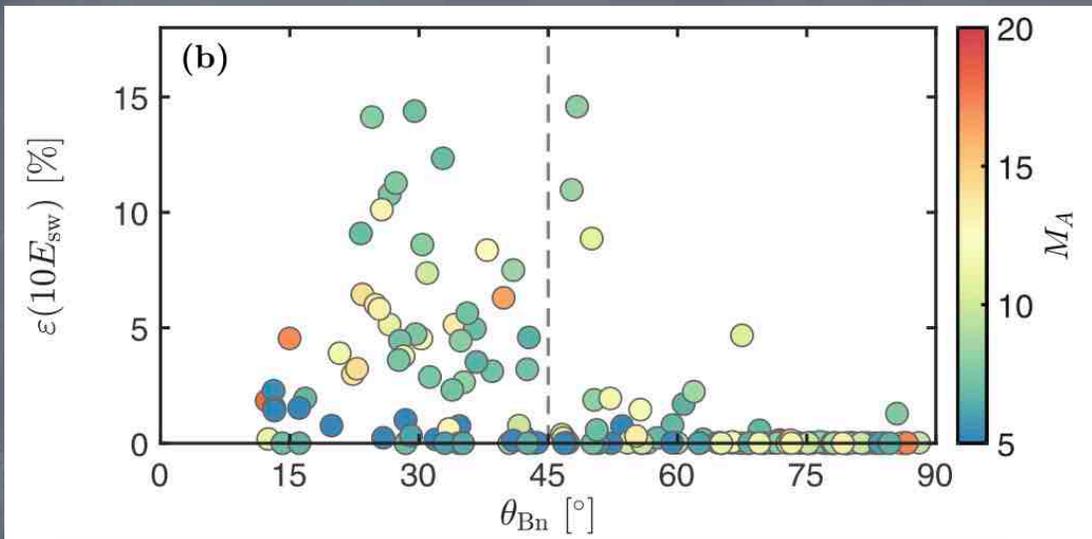


# Ion DSA at the Earth Bow Shock

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

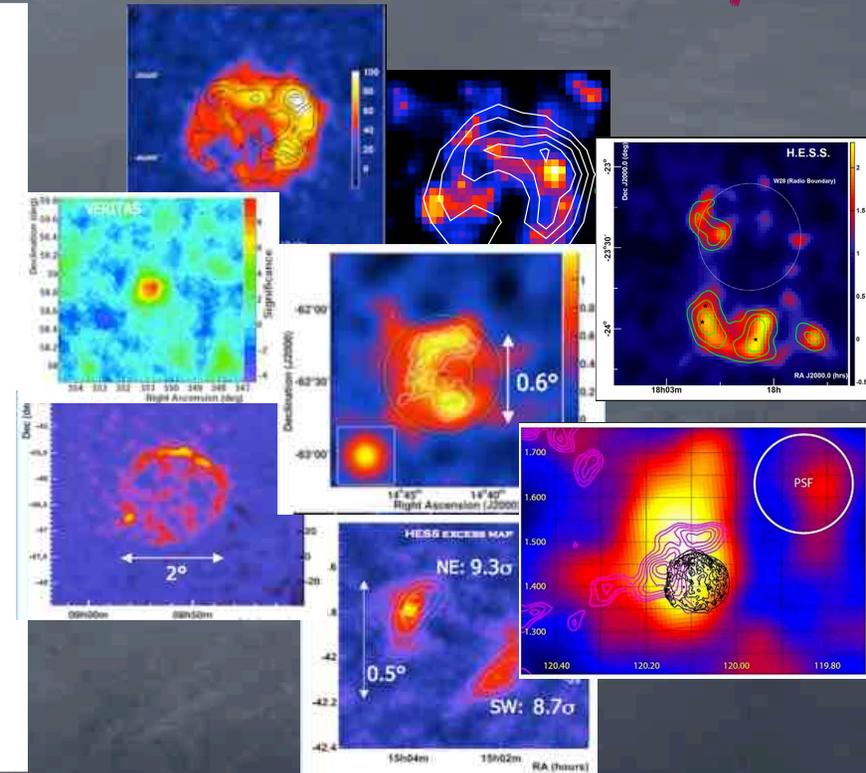
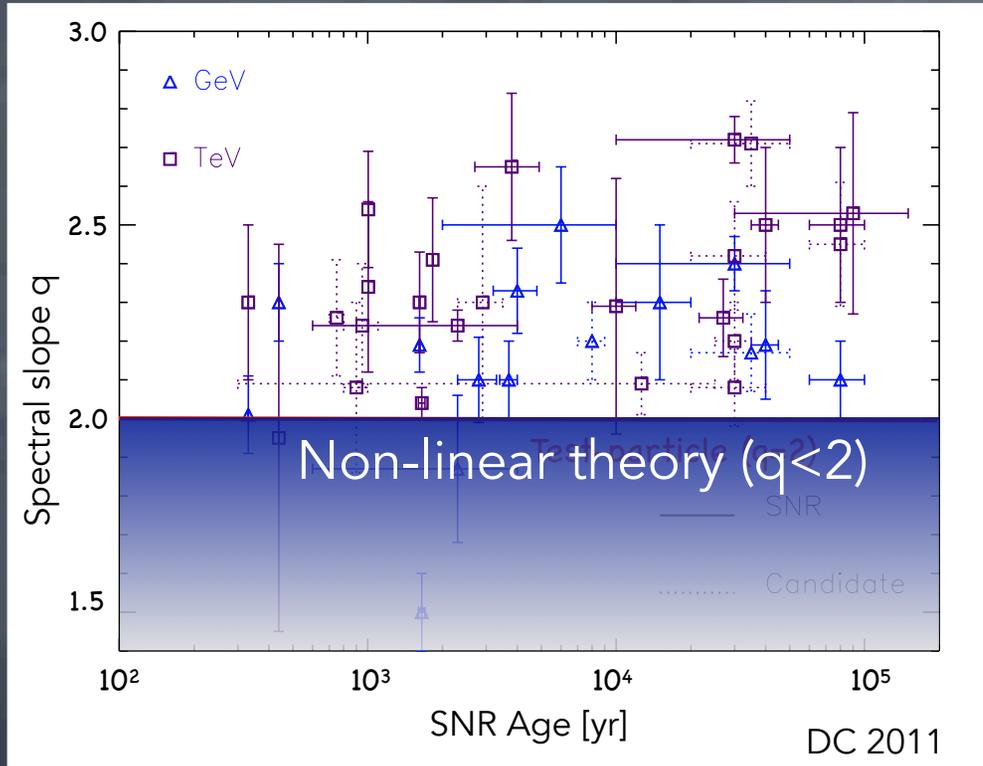


Magnetospheric Multiscale Mission



# The Issues with Observations

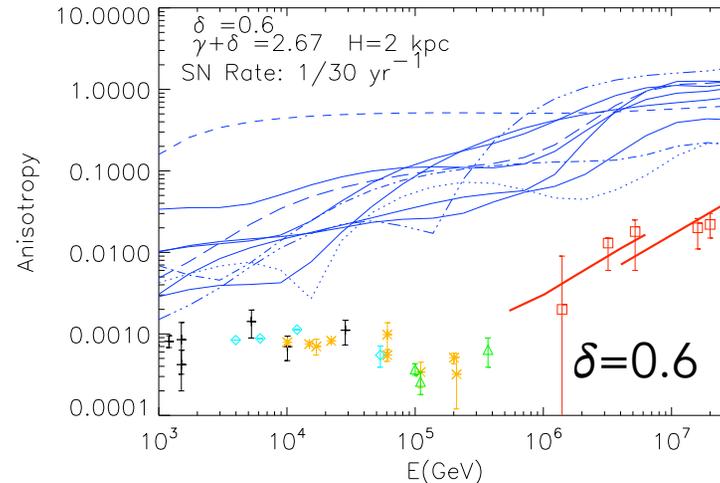
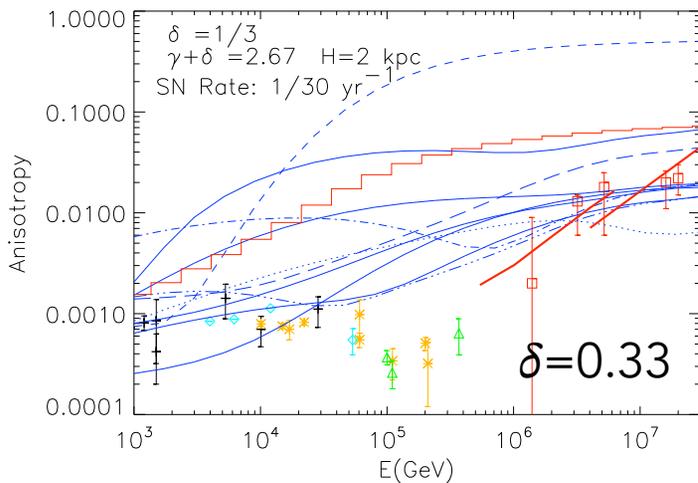
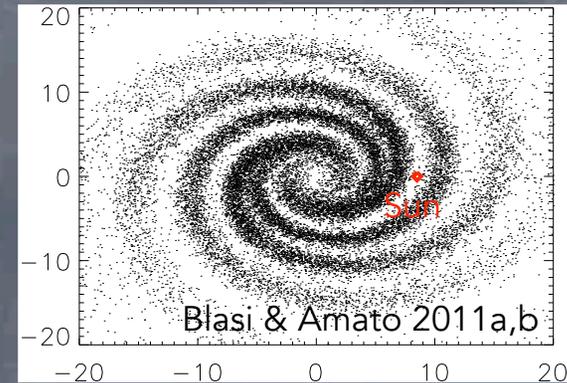
# SNRs With Agile, Fermi, HESS, VERITAS, MAGIC,...



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

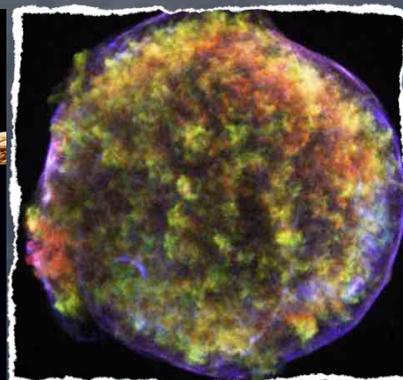


- $\delta = 0.33$  is preferred since it returns:
  - more universal CR spectra
  - less anisotropy

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

# 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  $\gamma$ -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)

- Efficiency  $\lesssim 15\%$  at parallel shocks

- Formation of upstream precursor

- $R$  increases with time, up to  $\sim 6$

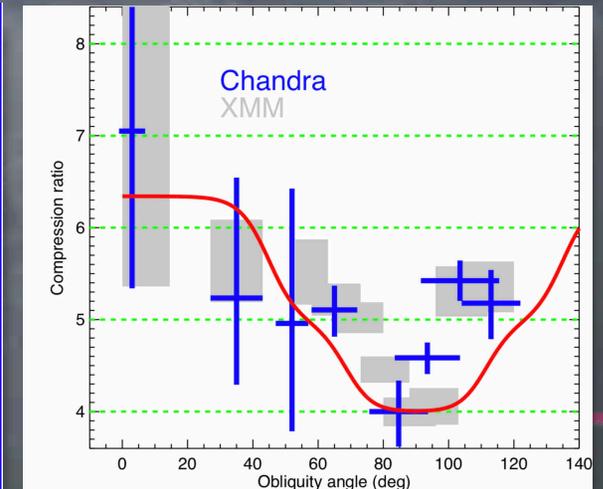
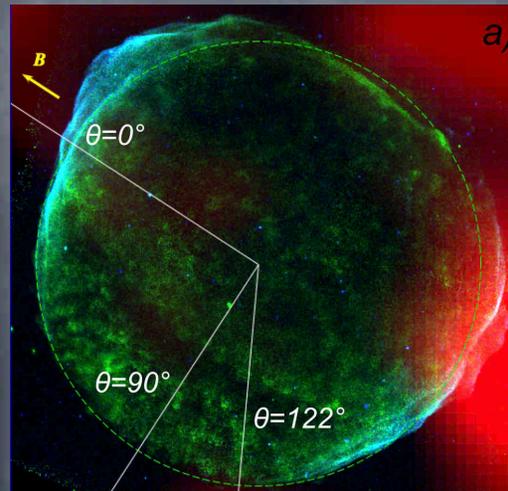
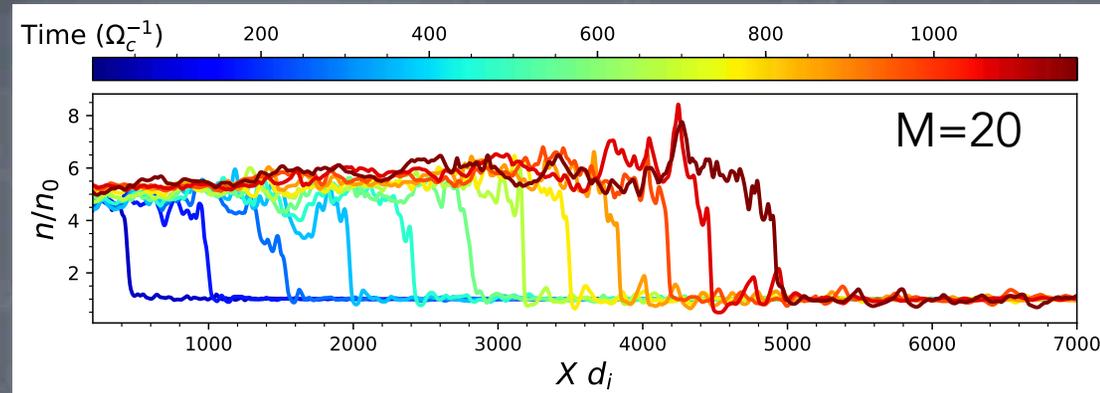
- $R \sim 6 - 7$  inferred in **Tycho** (Warren+05). In **SN1006**:  $R \sim 4 - 7$ , modulated with the azimuth/shock inclination (Giuffrida+21)

- If  $R \simeq 7 \rightarrow q_{\text{expected}} \simeq 3.5$

- Tycho: radio to  $\gamma$ -ray observations:

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

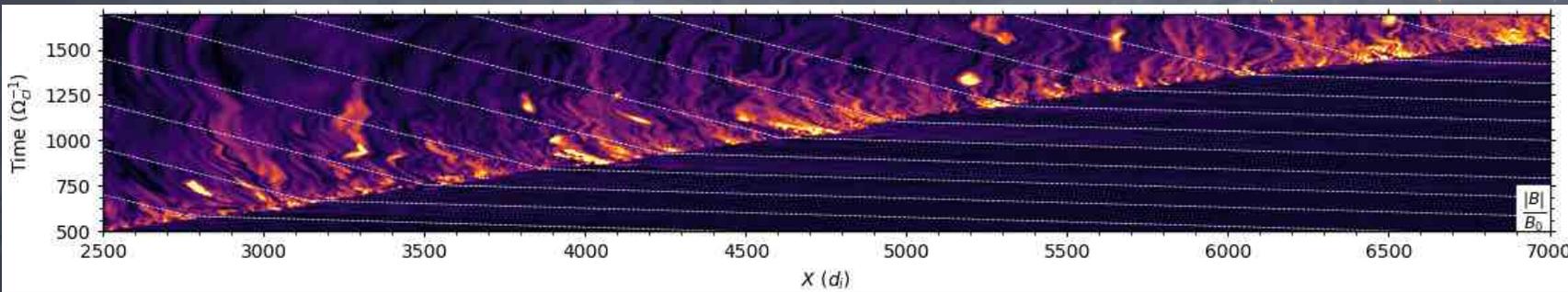
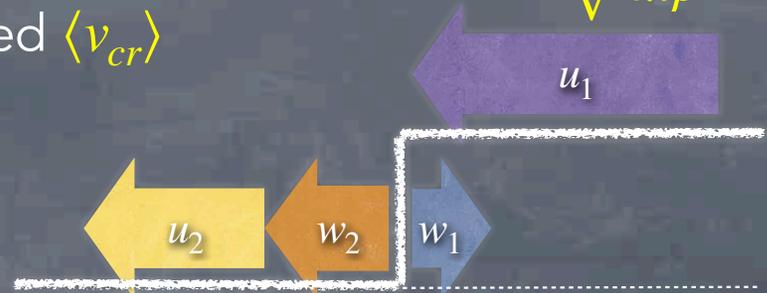
**A challenge to DSA theory!**





# The Role of Amplified Magnetic Fields

- CRs feel an **effective** compression  $R_{cr} = \frac{u_1 + w_1}{u_2 + w_2}$ ;  $w = \text{wave speed} \approx v_A = \frac{B}{\sqrt{4\pi\rho}}$
- 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:**  $\langle v_{cr} \rangle \simeq w_2 \simeq +v_{A,2}(\delta B_2) \equiv \alpha u_2$

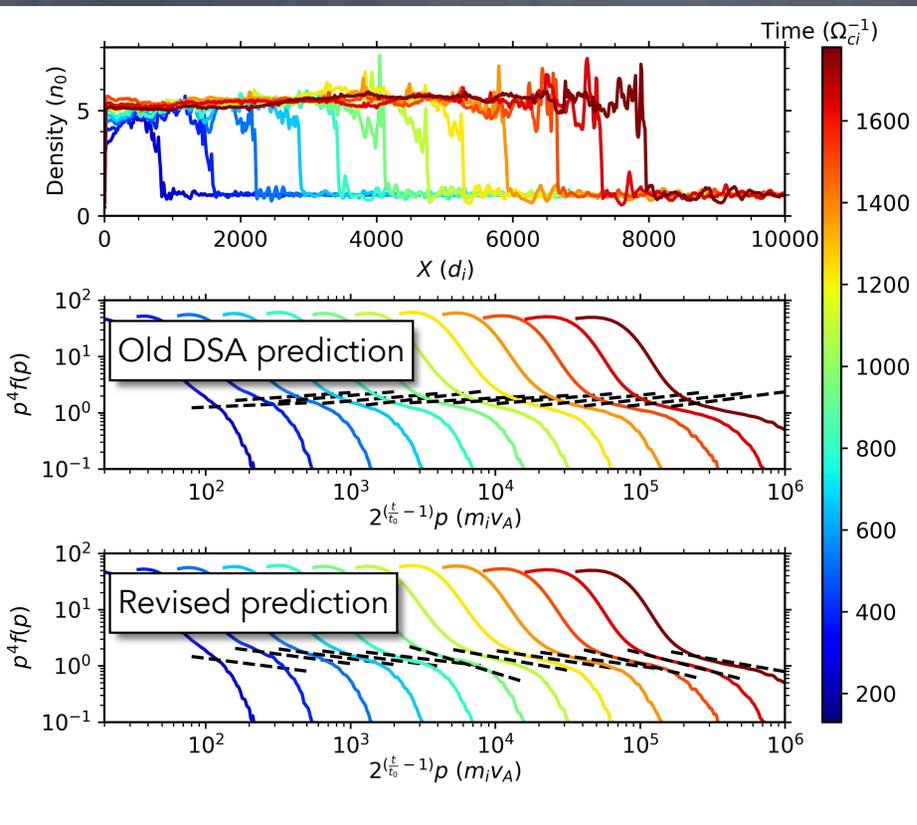


Haggerty-Caprioli20

- 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 B field*
- Ab-initio* explanation for the **steep spectra observed** in SNRs, novae, radio SNe...
  - Diesing-Caprioli21; Corso+23; Diesing+23,...
- In a multi-wavelength fit *B strength and particle slope are not independent!*

# Acceleration of Heavy Nuclei

# Injection and Acceleration of Heavy Nuclei

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.

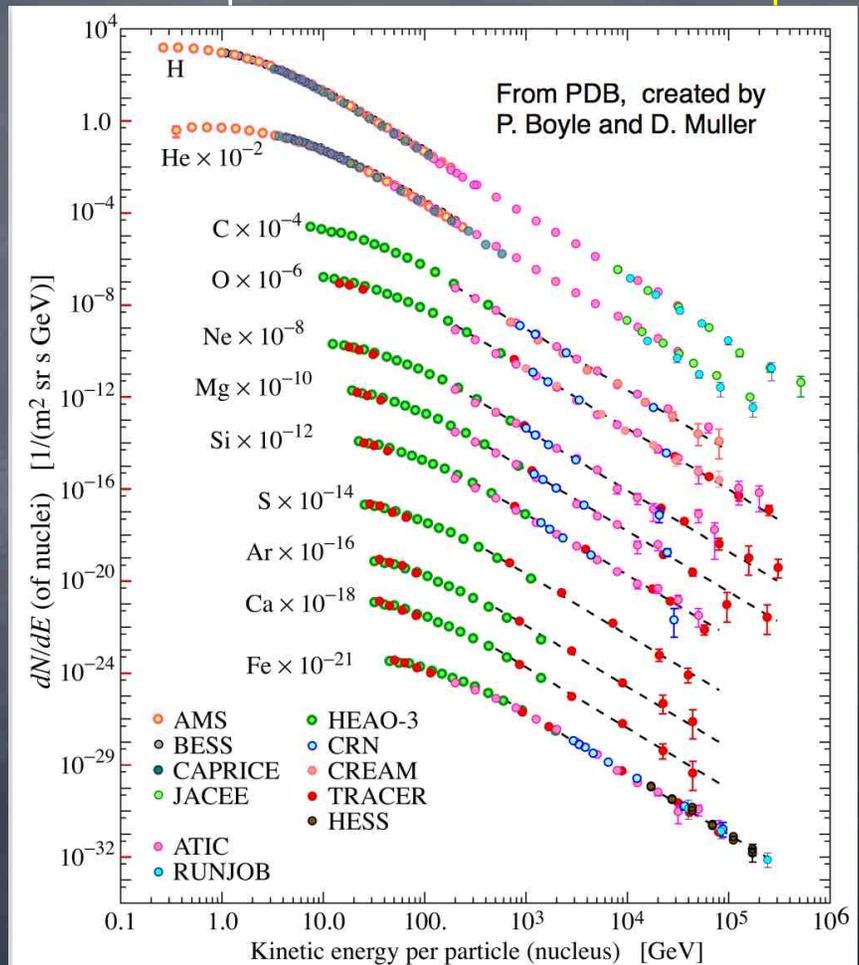
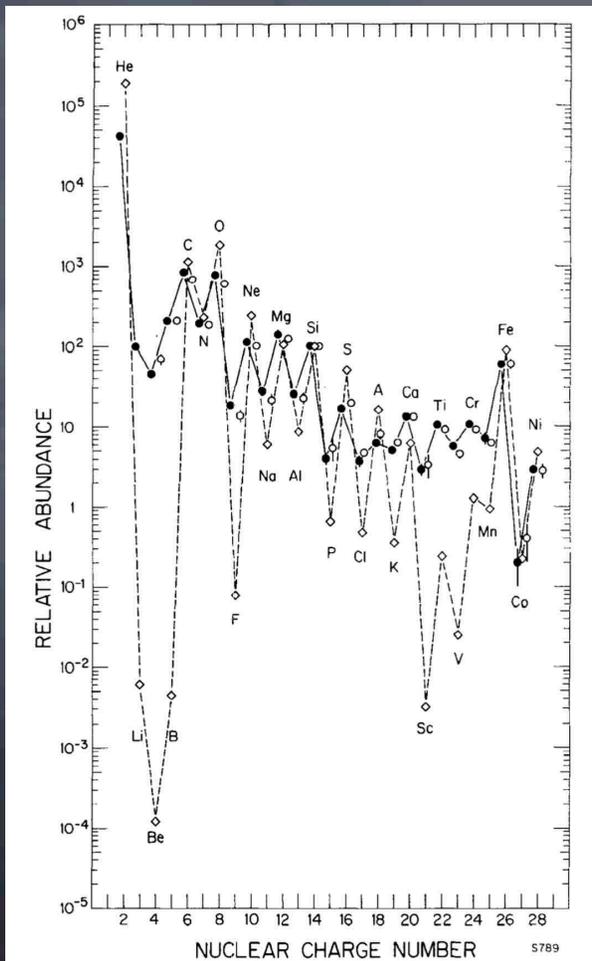
Spectra result from balance between acceleration and collisional losses: heavy ions should have steeper spectra!

$$\frac{dN}{dE} \propto E^{-(1+\tau_a/\tau_L)}$$



# Chemical Composition of Galactic CRs - I

Similar to **solar** at low energies (Simpson 1983); All species have the **same spectral slope**

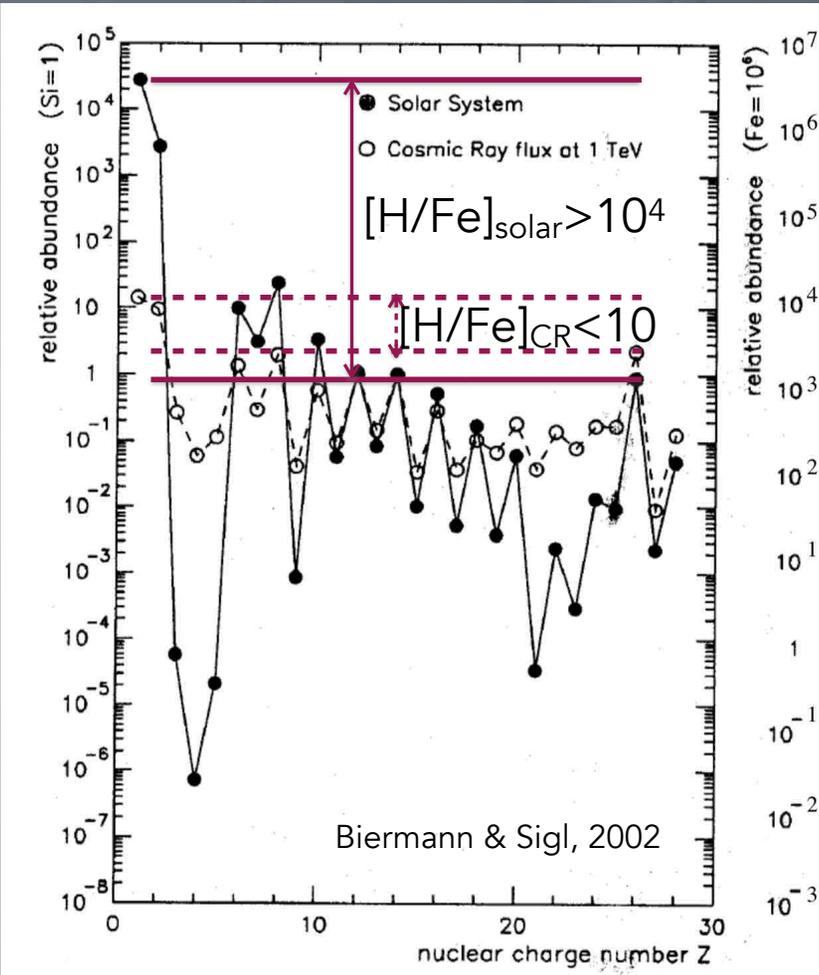
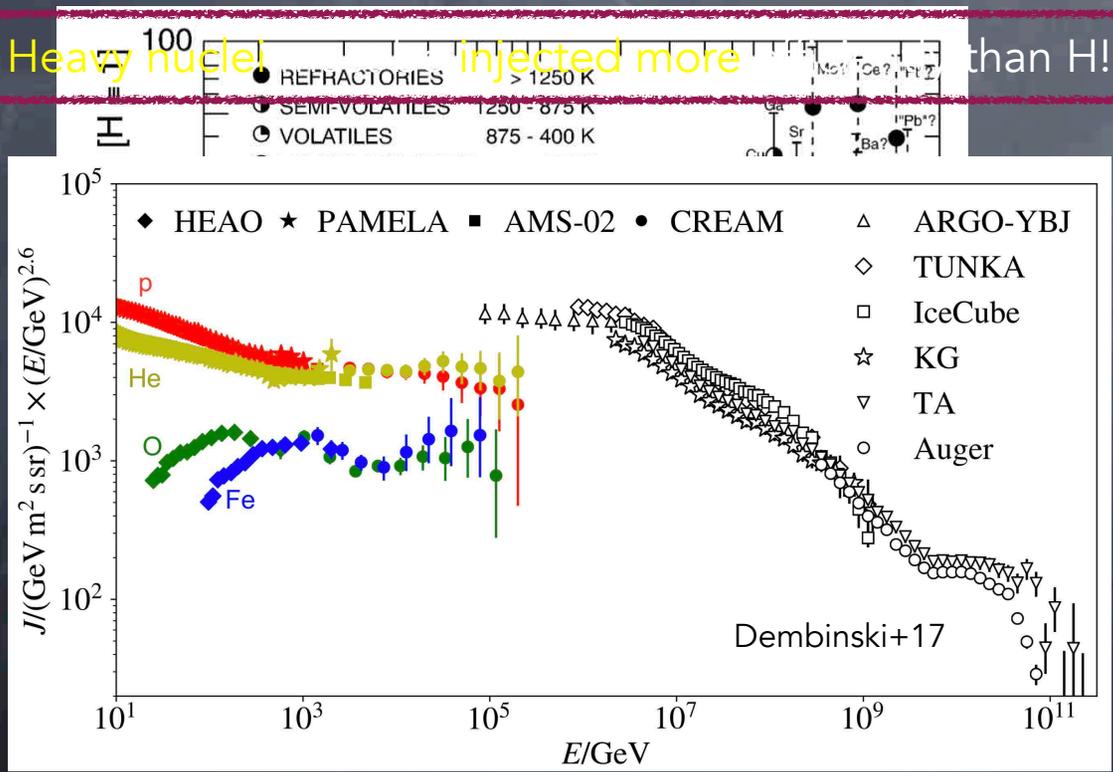




# Chemical Composition of Galactic CRs - II

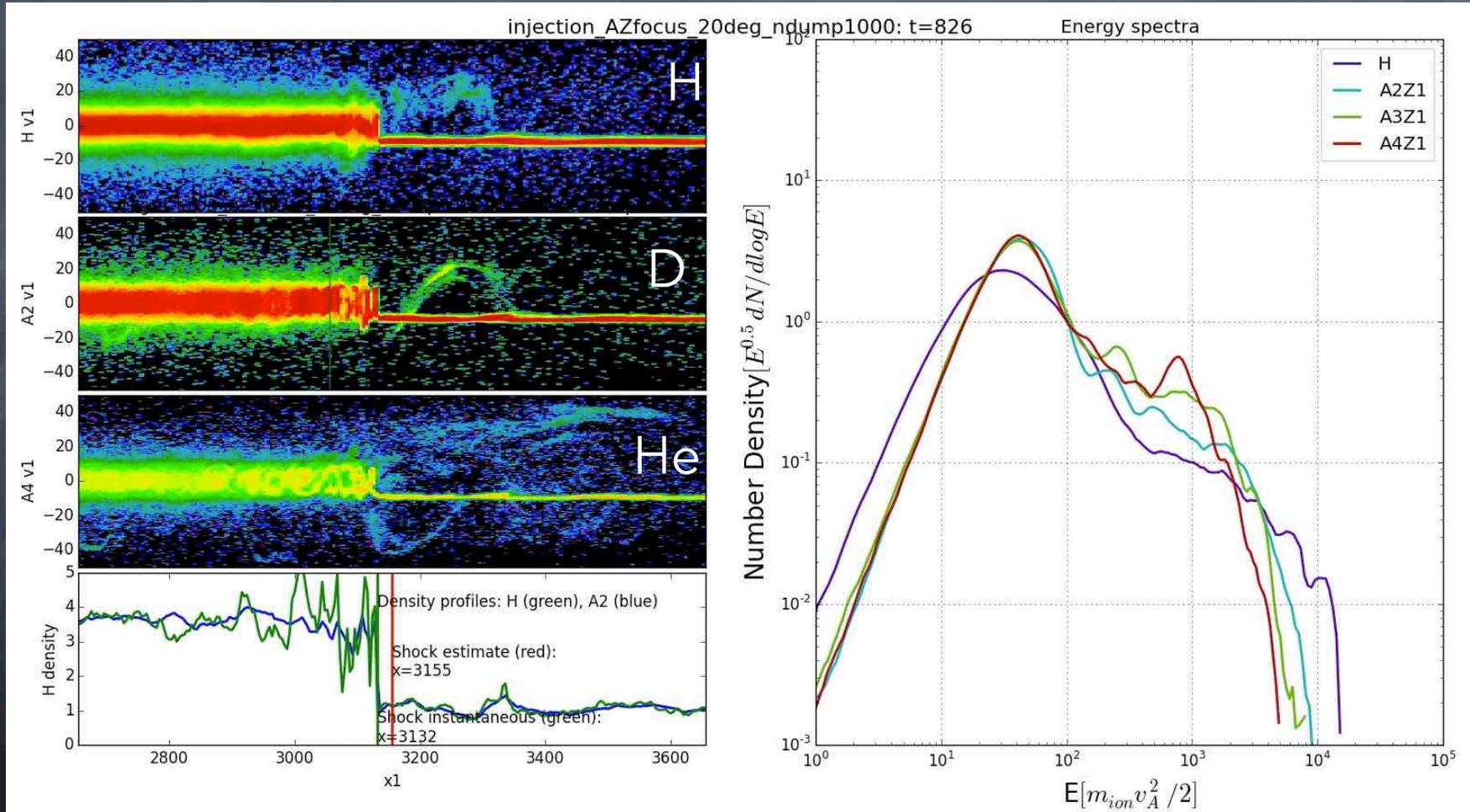
- Depends on **volatility** (refractory vs volatile elements), on atomic mass  $A$ , on first **ionization** potential...
- Above  $\sim 1$  TeV, fluxes of H, He, CNO, and Fe are **comparable**

Heavy nuclei injected more than H!



# Hybrid Simulations

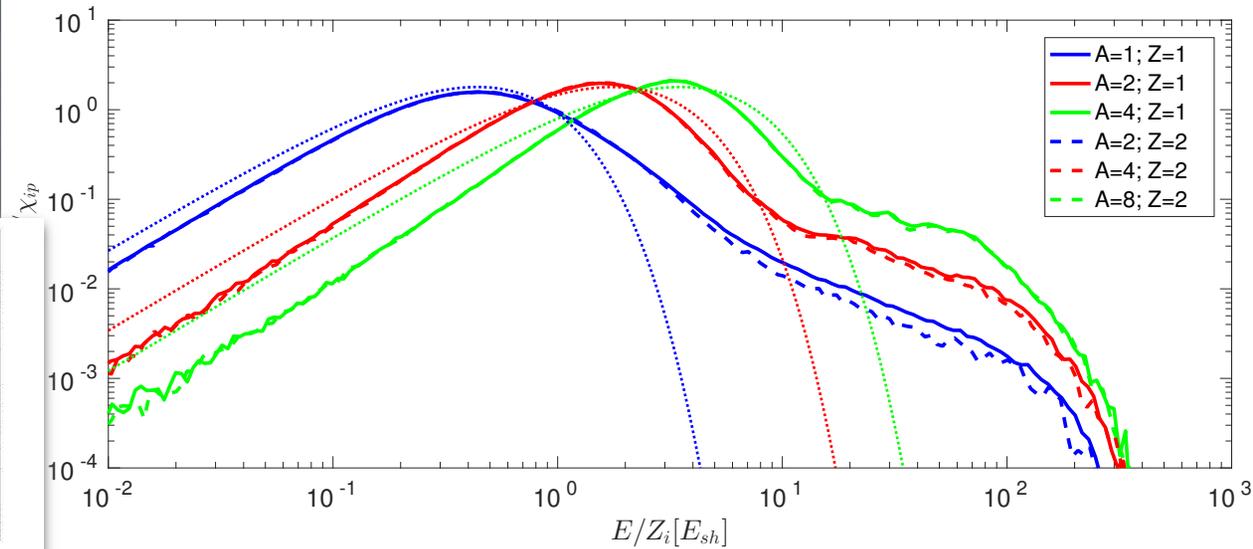
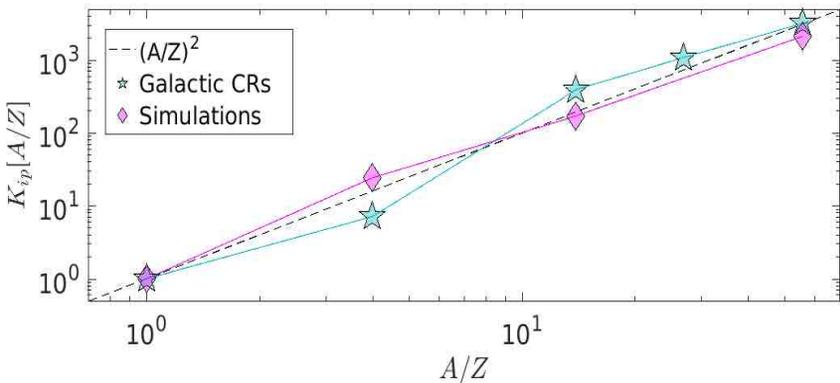
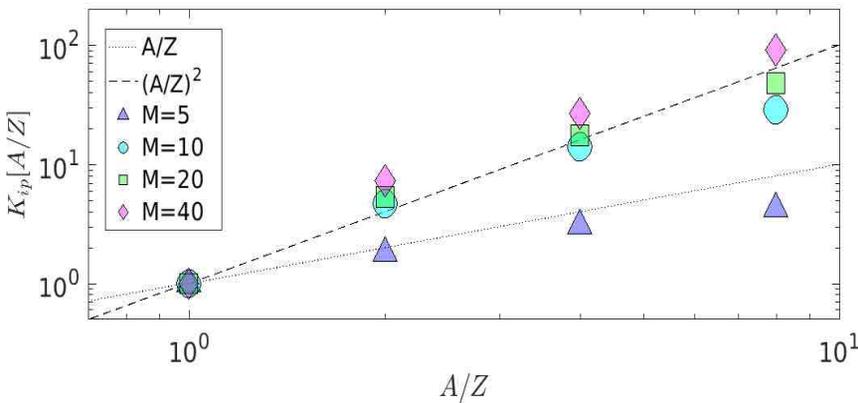
- M=10, parallel shock, with **singly-ionized** nuclei (DC, Yi, Spitkovsky 2017)



# 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!

# Helium is *not* test-particle!

- With cosmological He abundance  $\sim 10\%$  (Caprioli+25)

- He acceleration efficiency  $\sim 15\%$  (as H)

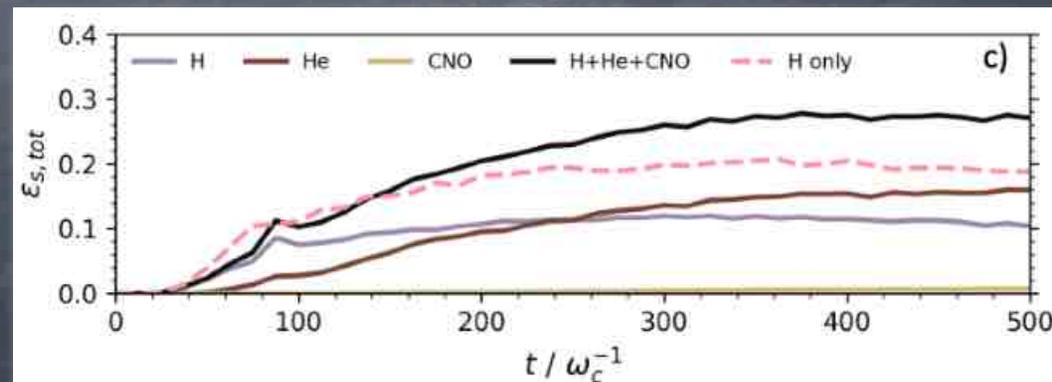
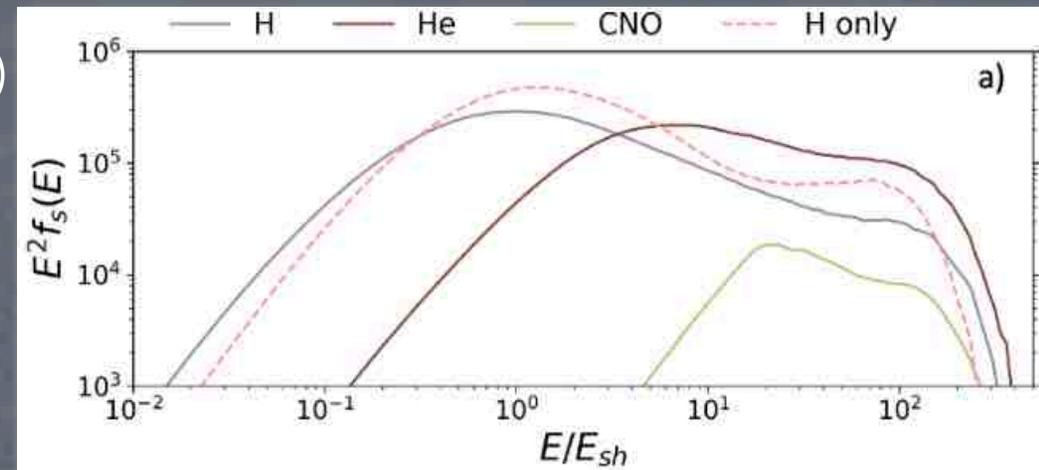
- Total* efficiency  $\sim 30\%$

- Increases shock modification

- He can *amplify B-field* as much as H

- $E_{\max} \sim 2x$  larger for both species

- Hadronic gamma-ray* emission can be boosted by a factor  $\sim 5$  (DC+11)



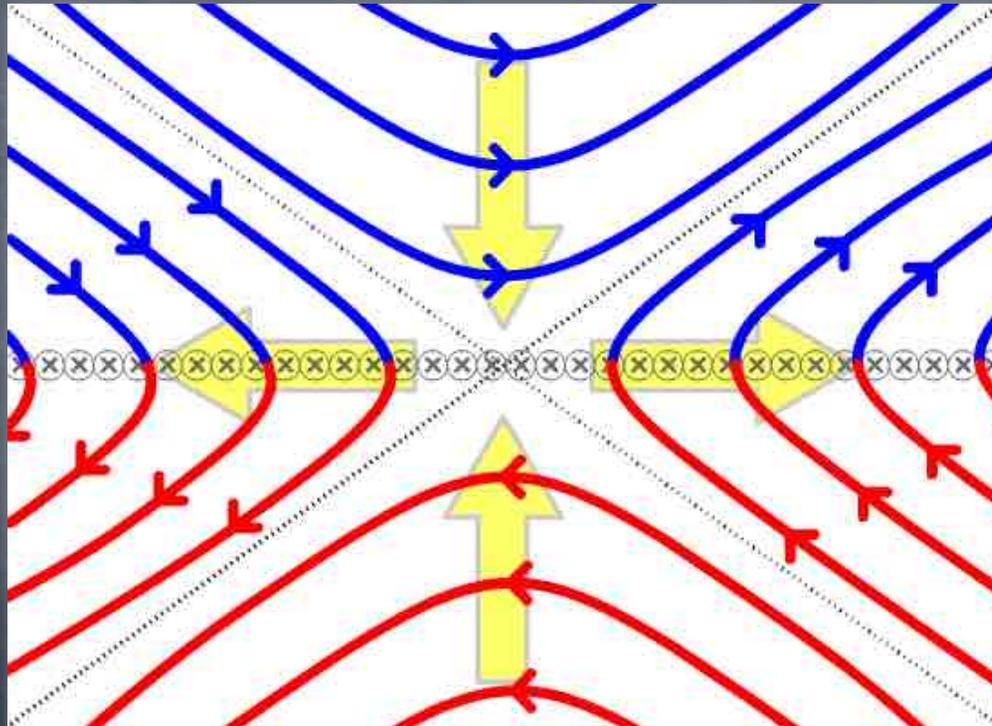
# Magnetic Reconnection



# Magnetic Reconnection

*R. Kulsrud at his 90<sup>th</sup> birthday party:*

*“[Enrico Fermi](#) told me to study reconnection for my PhD thesis, nearly 70 years ago. We have yet to understand it.”*



Wikipedia

- A change in the macro topology of the magnetic field, due to micro effects.
- This is often accompanied by an explosive energy release.

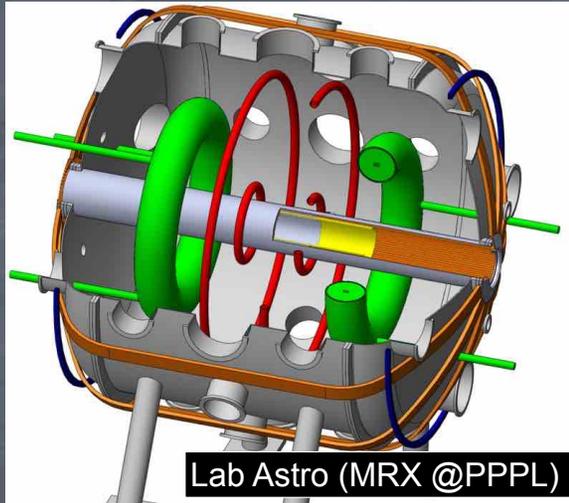
# Reconnection Regimes: Magnetization

$\sigma \ll 1$

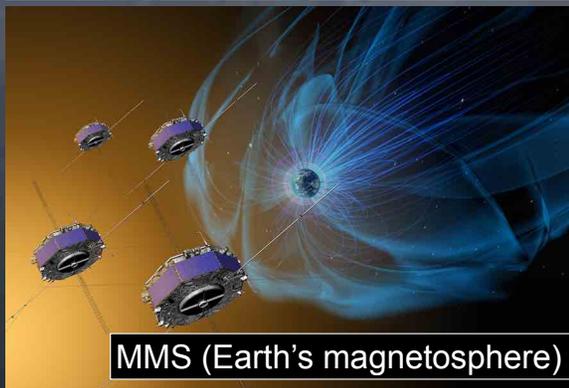
$\sigma \gg 1$



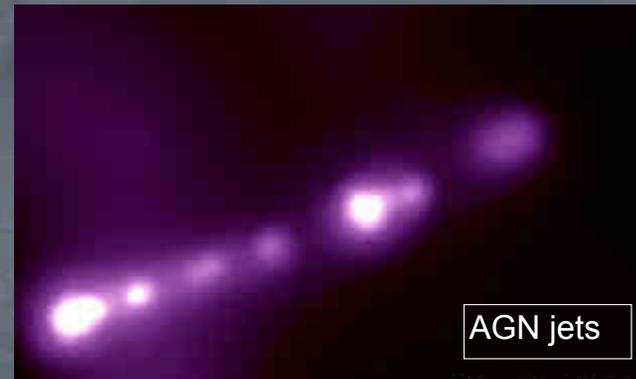
$$\sigma = \frac{B_0^2}{4\pi\rho c^2}$$



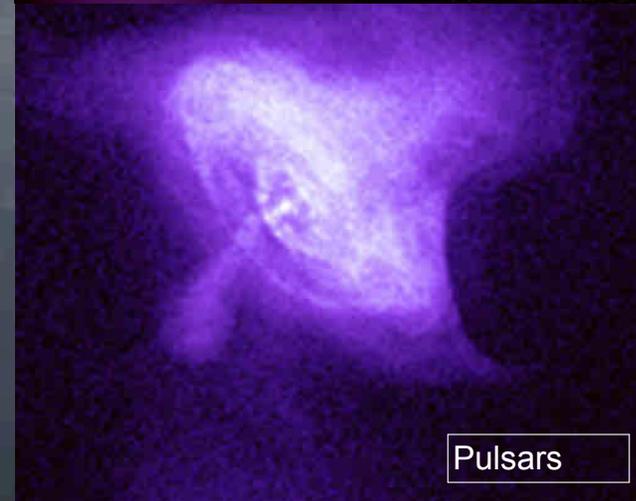
Lab Astro (MRX @PPPL)



MMS (Earth's magnetosphere)



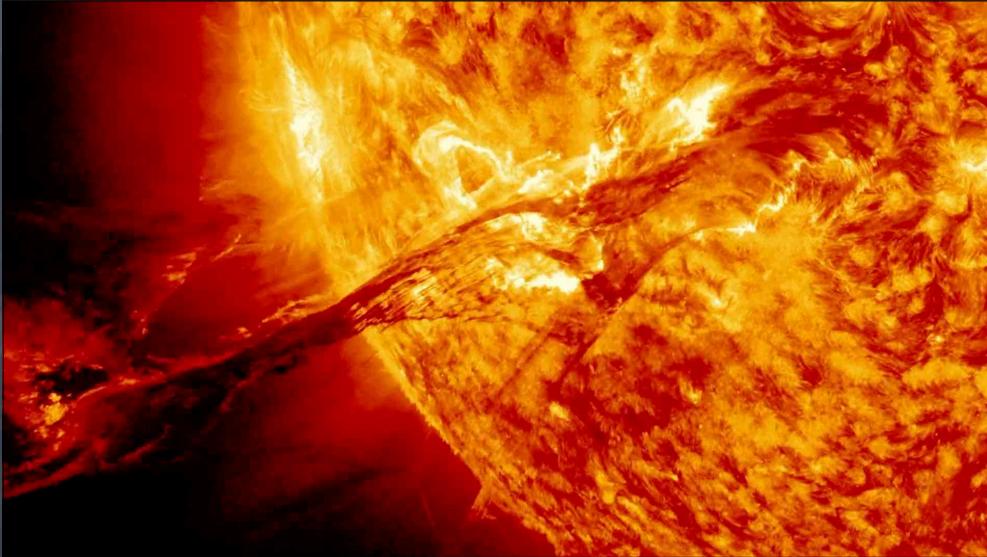
AGN jets



Pulsars



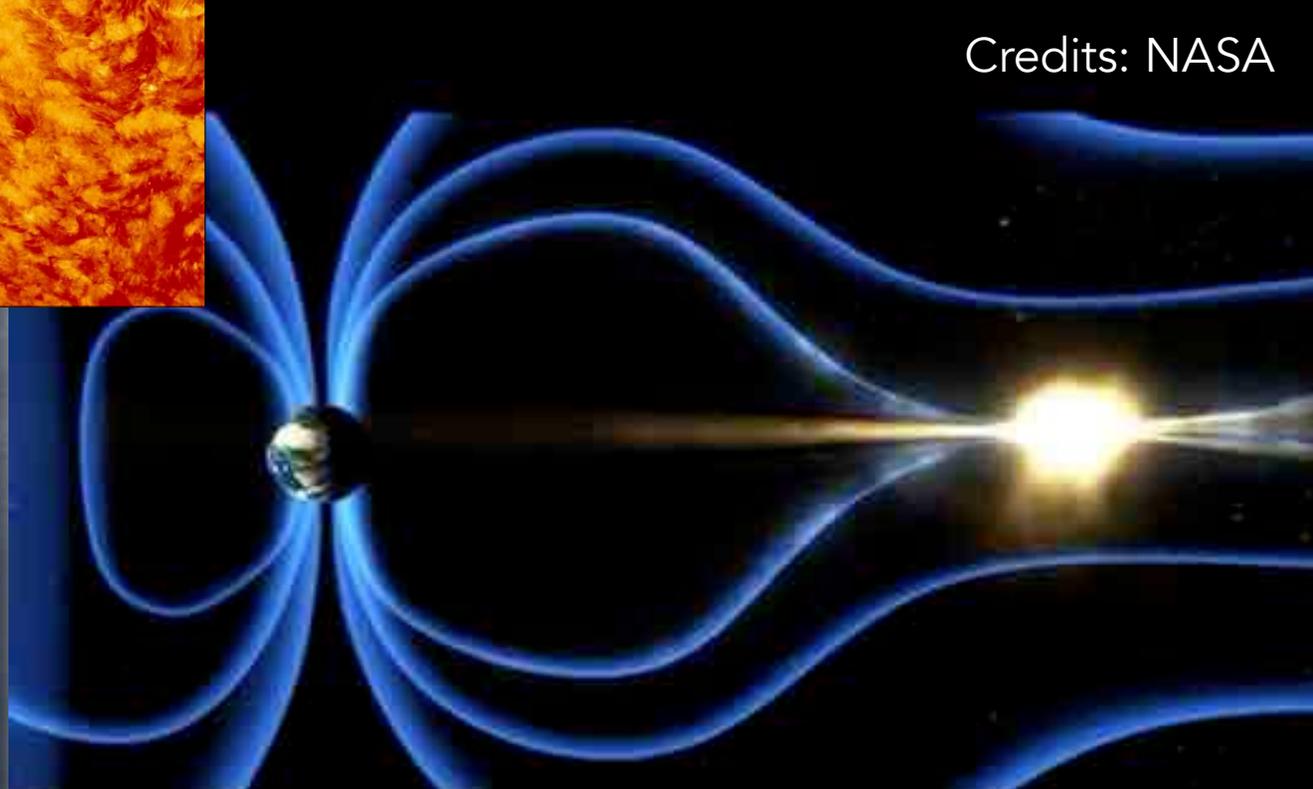
# Non-relativistic Magnetic Reconnection

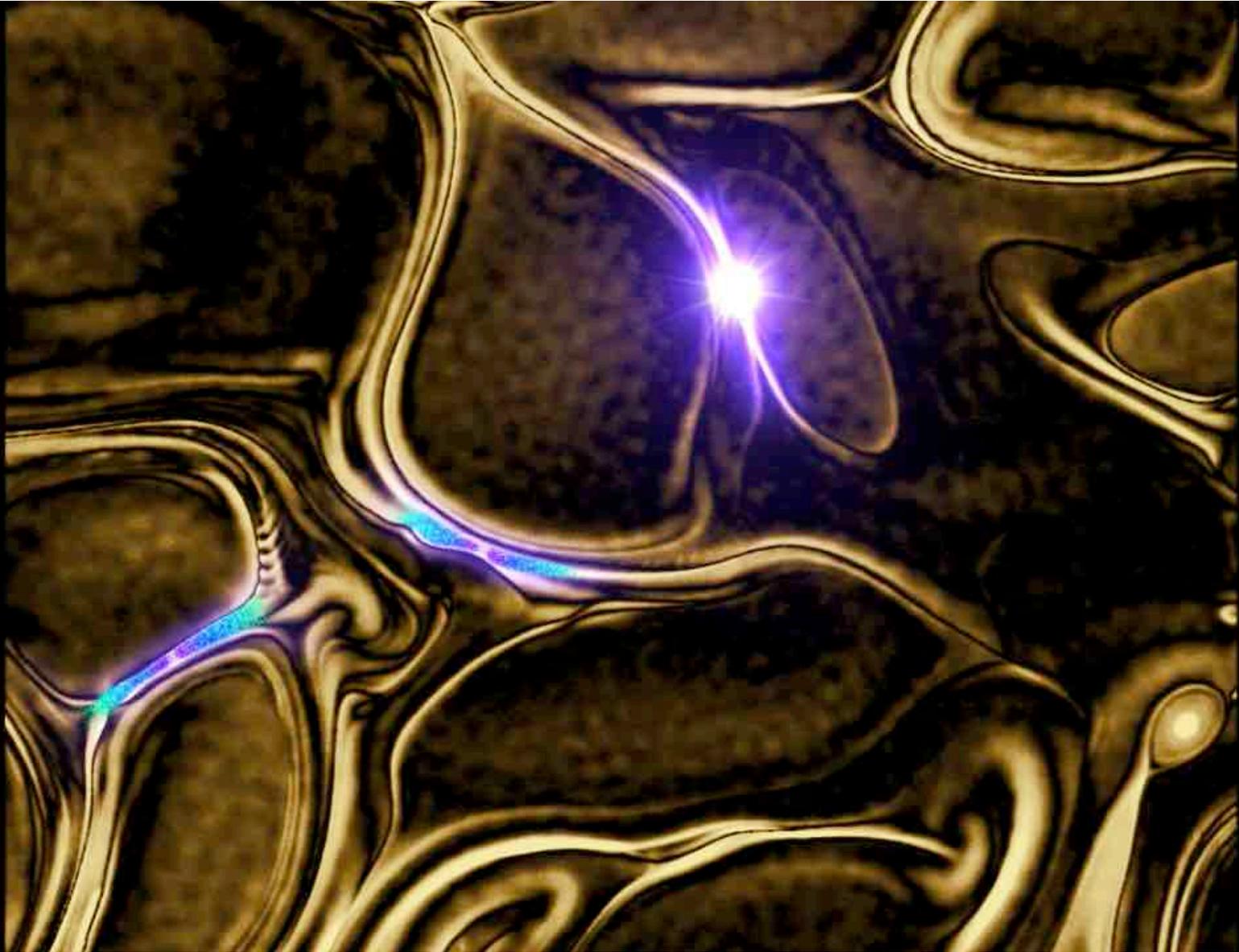


- Dissipation of magnetic field loops on the Sun surface triggers **solar flares**

Credits: NASA

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





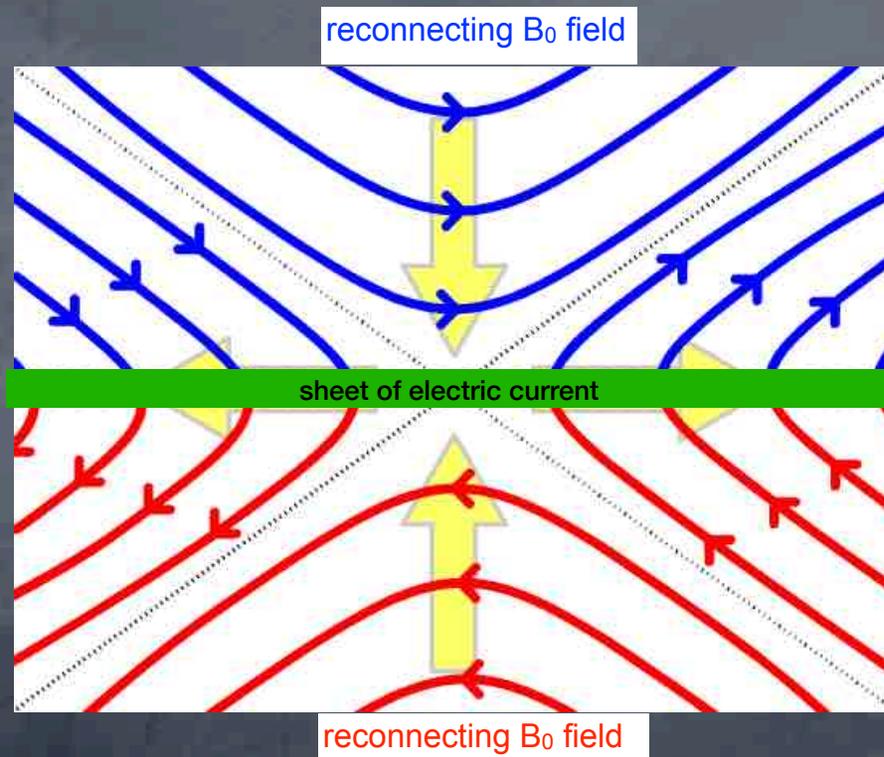
Credits:  
C. Haggerty  
(2018)  
NASA press  
release

# Relativistic, collisionless reconnection

for a recent ARAA review: Sironi, Uzdensky & Giannios, [arXiv:2506.02101](https://arxiv.org/abs/2506.02101)

$$\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$$

$$v_A \sim c$$

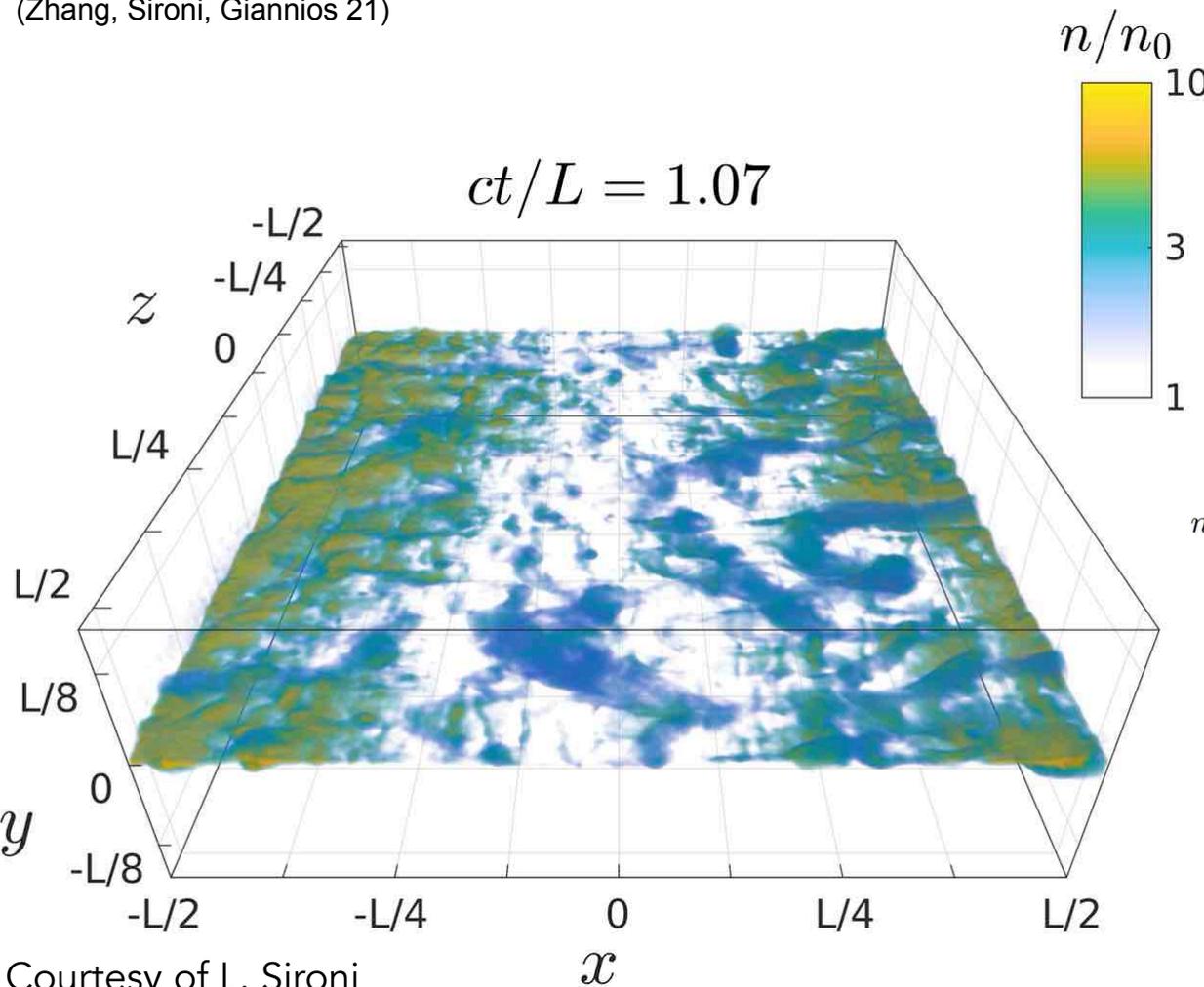


- The plasma flows into the reconnection region with  $v_{\text{in}} \sim 0.1v_A \sim 0.1c$   
→ Rel. reconnection can efficiently dissipate the field energy (at speed  $\sim 0.1 c$ ).



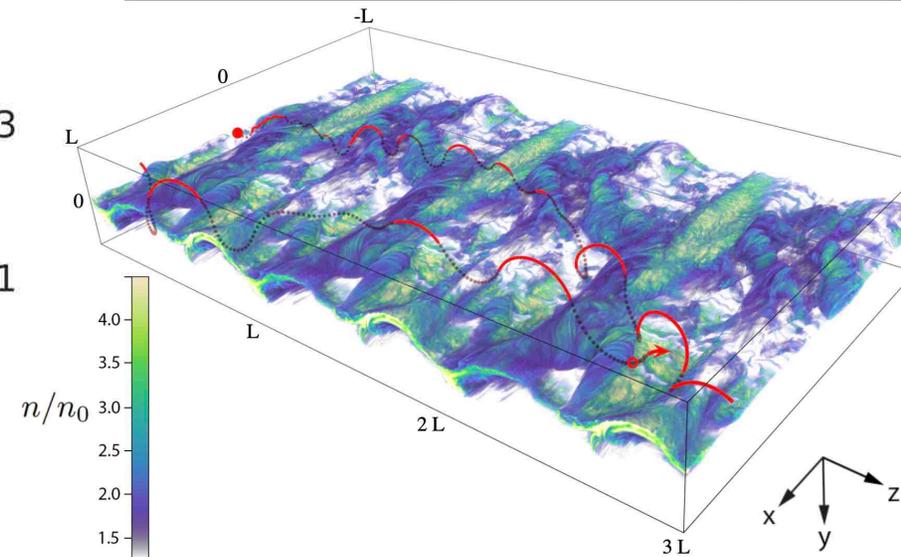
# 3D PIC Simulations of Relativistic Reconnection (Pair Plasma)

(Zhang, Sironi, Giannios 21)

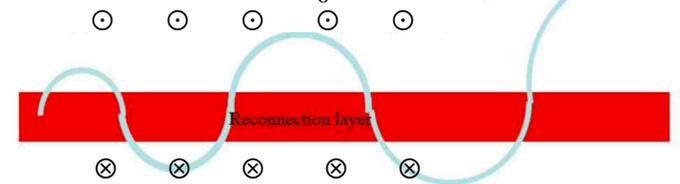


Courtesy of L. Sironi

Note the tearing mode and the formation of *plasmoids*

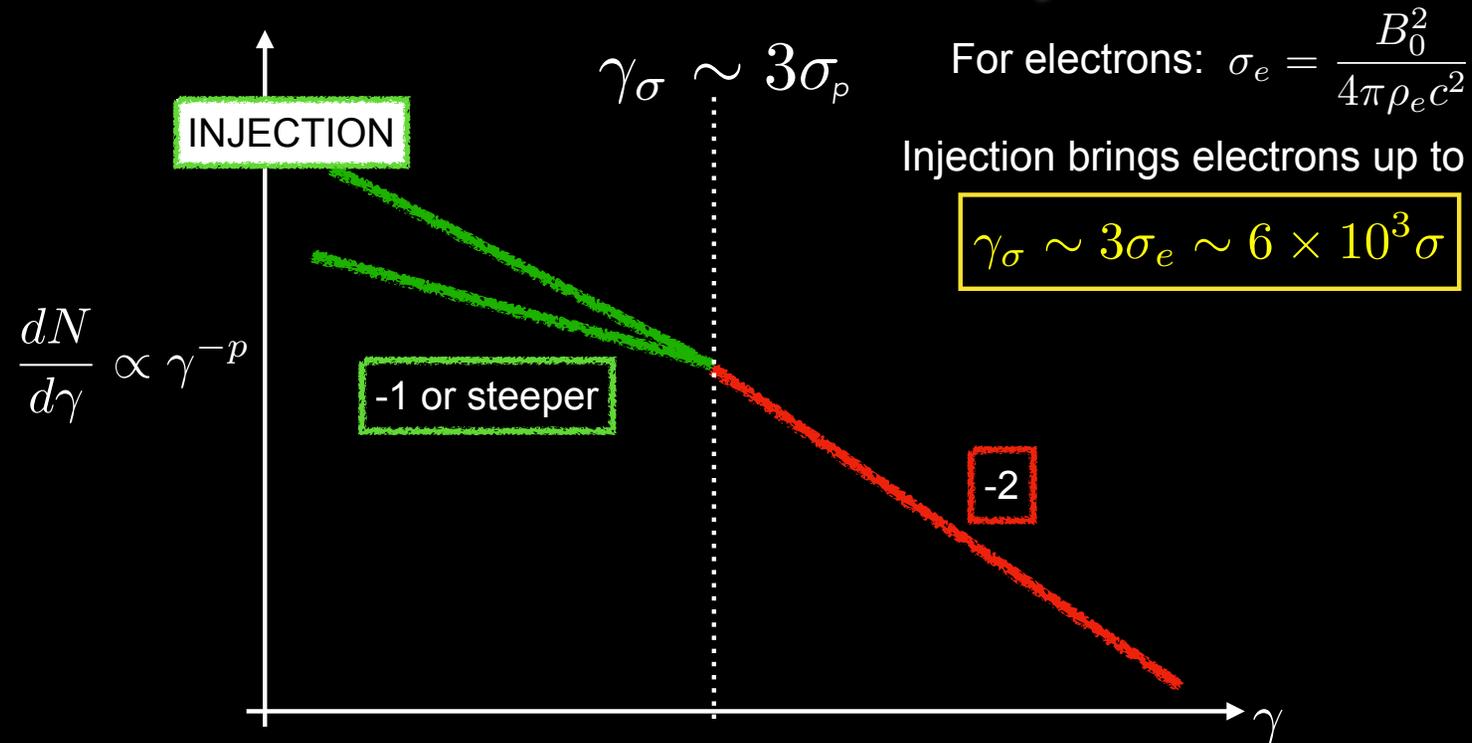


$$\vec{E} = -\vec{v}/c \times \vec{B}_0$$



(Lazarian +12)

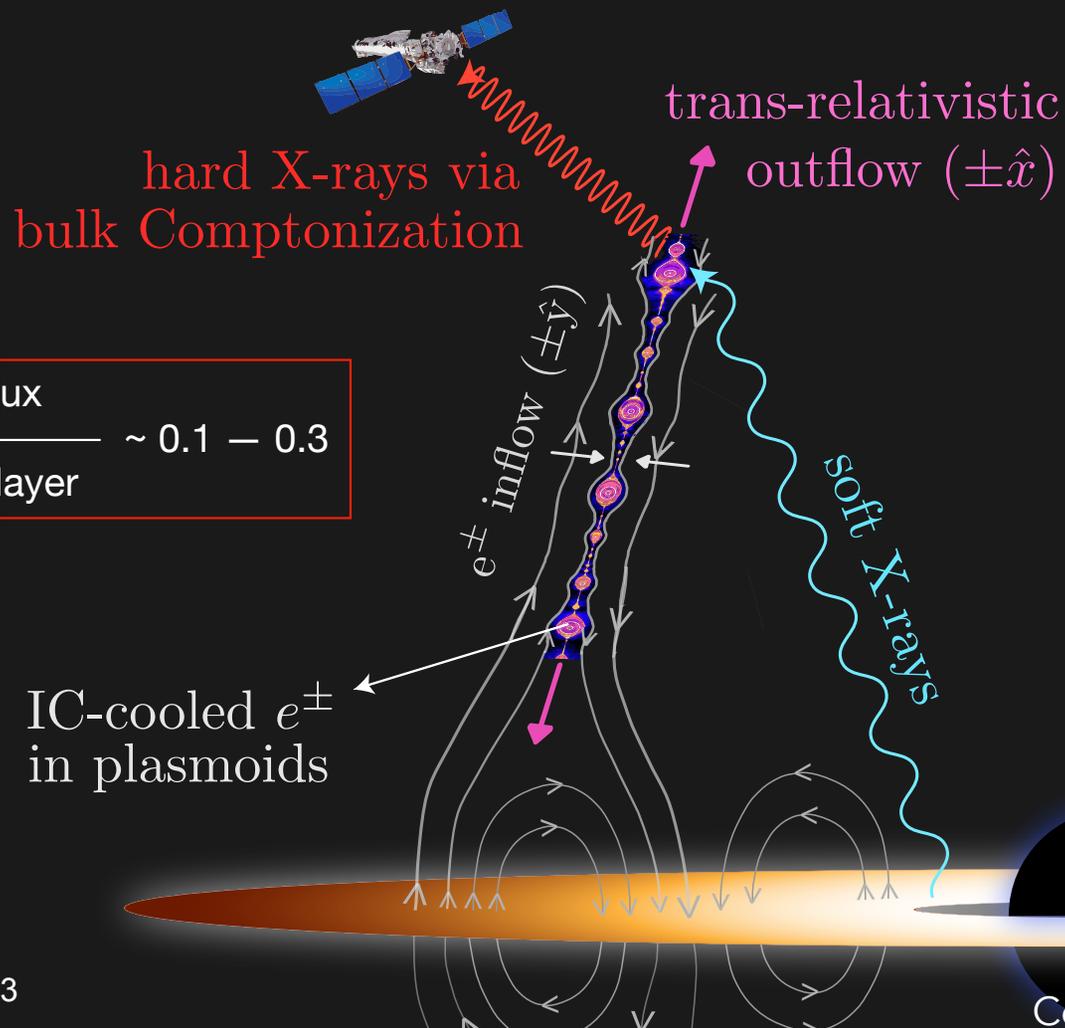
# Reconnection makes broken power laws



At  $\gamma \lesssim 3\sigma$  "injection" due to non-ideal E fields leads to  $\sigma$ -dependent slopes, with  $p \geq 1$ .

At  $\gamma \gtrsim 3\sigma$  3D strong reconnection leads to a  $\sim \sigma$ -independent slope (for  $\sigma \gg 1$ ) of  $p \sim 2$ .

# Black Hole Coronae

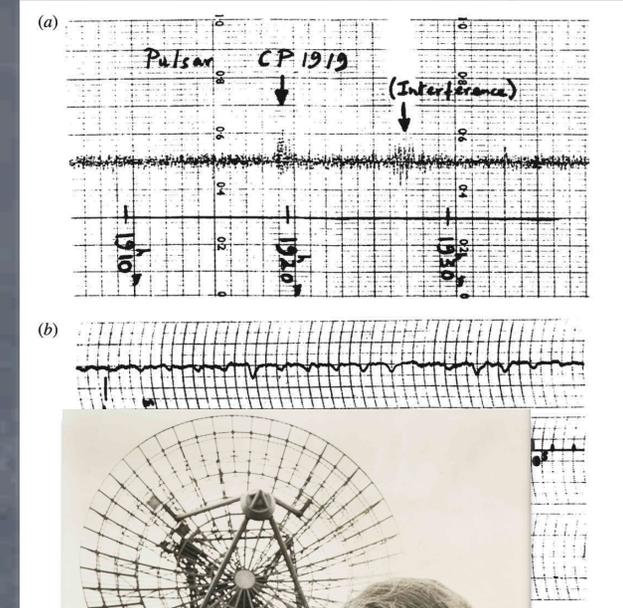


Hard X-ray radiation flux	~ 0.1 – 0.3
EM energy flux into the layer	

# Pulsars

# Pulsars

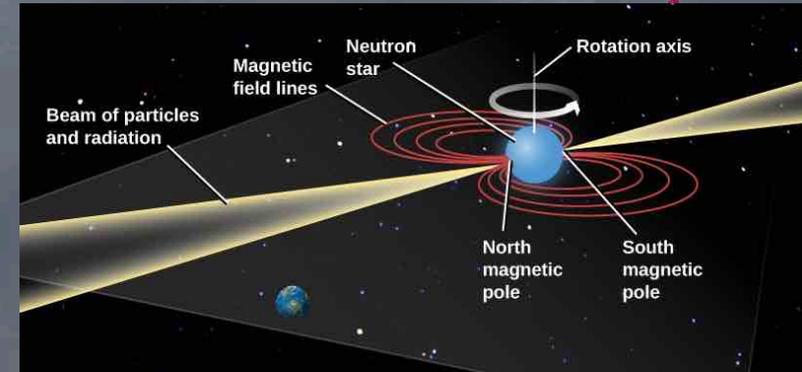
- Discovered in the radio by A. Hewish & J. Bell in 1967
- Actual discovery by **Jocelyn Bell** (Hewish's graduate student)
  - Source called **LGM-1** (then PSR B1919+21)
- Hewish was awarded the Noble prize in 1974 (unlike Bell)
  - Read her account of the story [here](#)
- Pacini (1967) and Gold (1968)**: pulsars are *spinning neutron stars with strong magnetic fields*
- A time-varying magnetic field launches radio signals



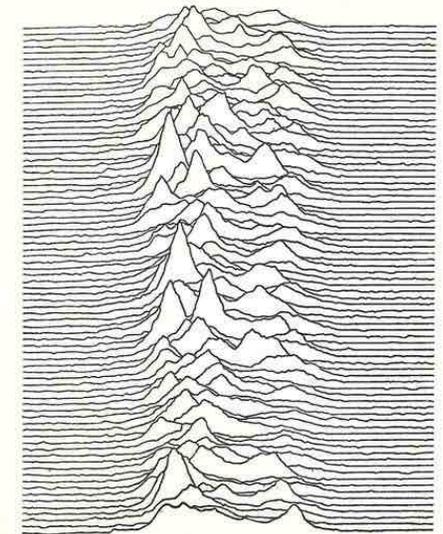


# Origin of Pulsars

- When a star collapses to a neutron star
- it **spins up** (conservation of angular mom.):  $T \gtrsim 1\text{ms}$
- its **magnetic field** is frozen-in and **increases**:
- Rotation and magnetic axes misaligned:
  - lighthouse effect*



6.7: Successive pulses from the first pulsar discovered, CP 1919, are here superimposed vertically. The pulses occur every 1.337 seconds. They are caused by a rapidly-spinning neutron star.



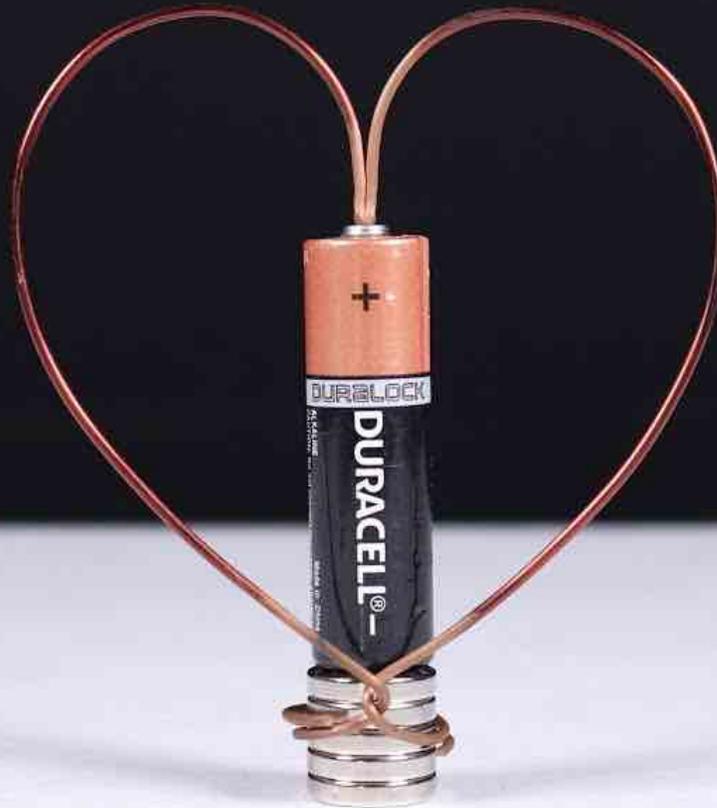
- Each pulse is different, but the **period** is extremely regular

- Hunt for gravitational waves with pulsar timing

Iconic Periodogram



# Unipolar Inductor

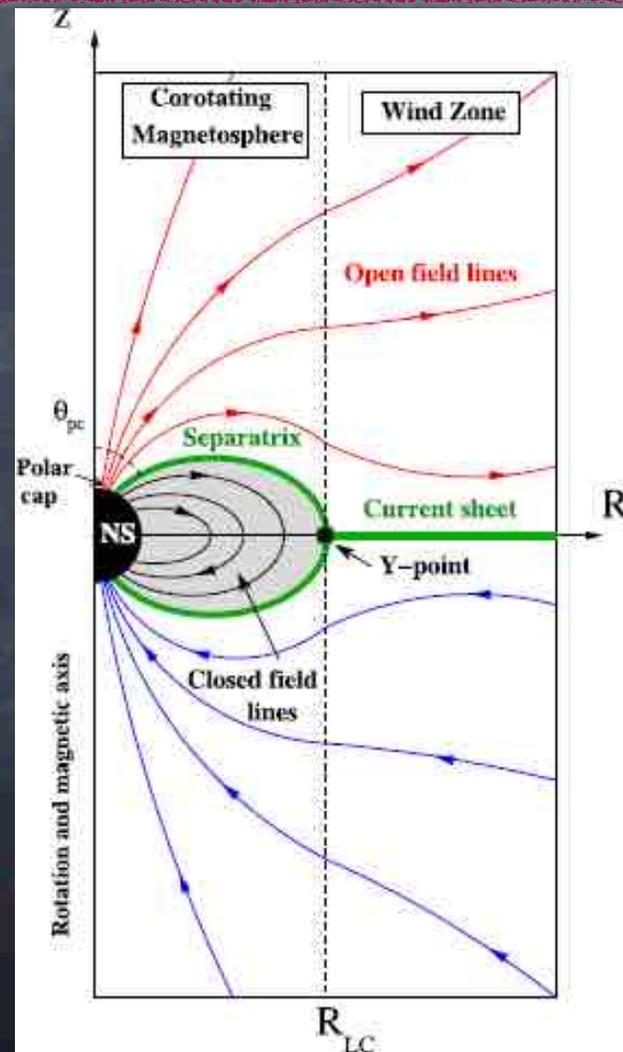


## INGREDIENTS:

- Potential drop
- Conductor
- Rotation
- Magnetic field

<https://www.youtube.com/watch?v=RGFtpOZxIhc>

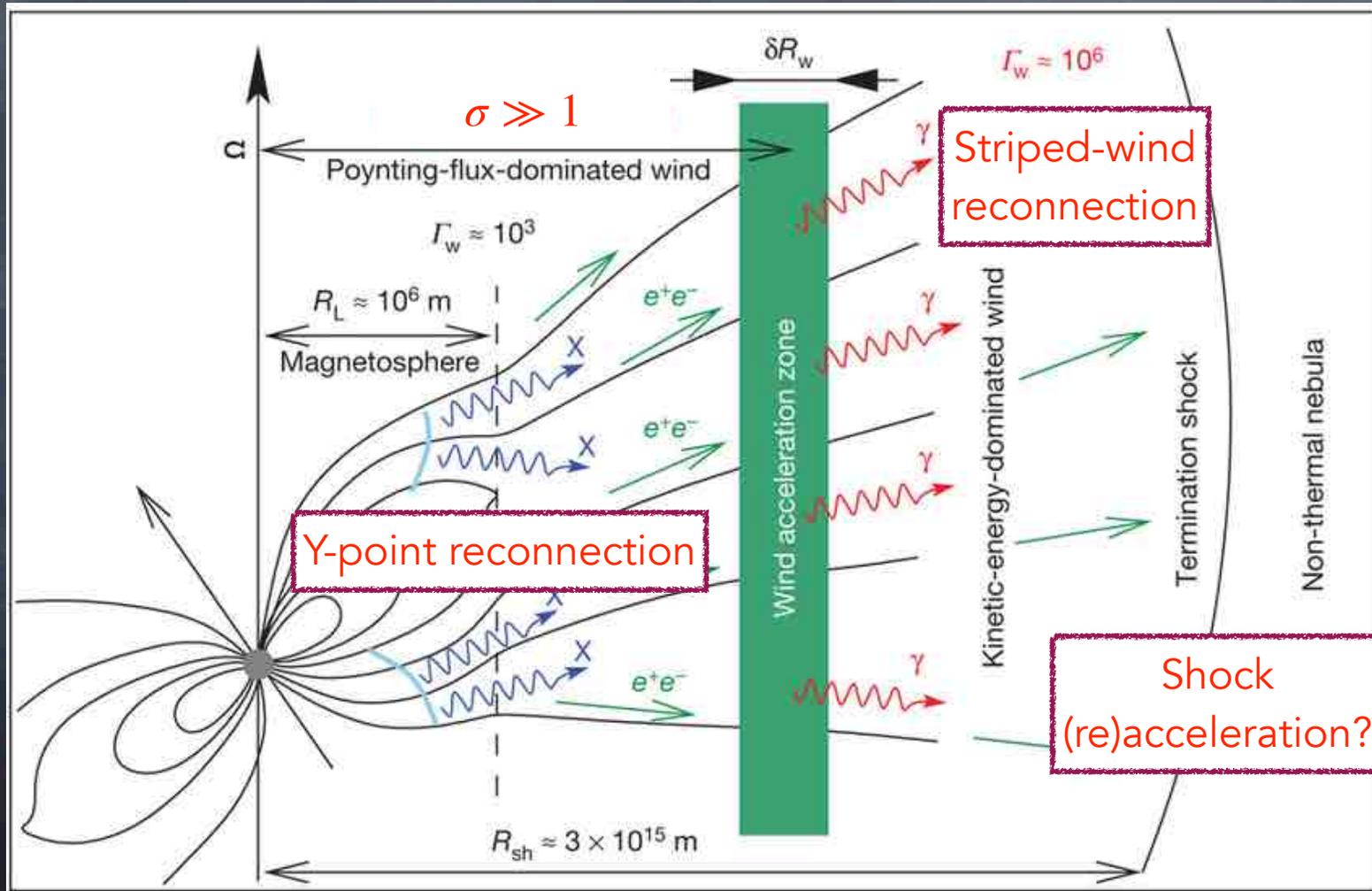
# Pulsar Magnetosphere



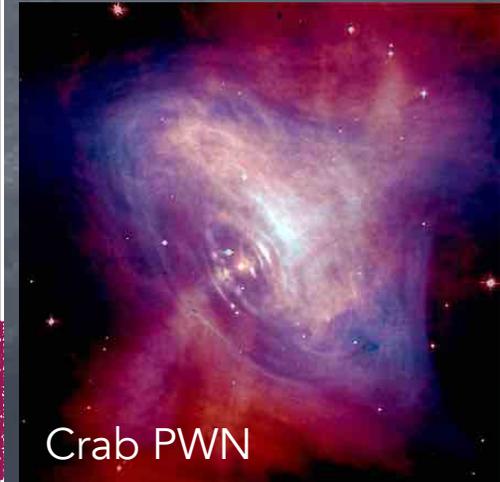
- Assume magnetic dipole + rotation
- On the surface EM forces win against gravity  
 $|\vec{E}| = \omega R_* B / c \gg |\vec{g}| \rightarrow$  charge extraction
- Particles accelerated by electric fields in "gaps"
- Radiation curvature  $\rightarrow$  gamma rays  $\rightarrow$  pair production
- Goldreich-Julian(1969) density:  $n_{GJ} = 7 \times 10^{10} \frac{B}{10^{12} G} \frac{1s}{P} \text{cm}^{-3}$
- Light cylinder: distance at which corotation  $\omega R_{LC} = c$
- Field line must be open beyond the light cylinder
- Potential drop:  $\Delta\Phi = \frac{\Omega^2 B_* R_*^3}{2c^2} = 10^{12} \text{ V} \left( \frac{P}{1s} \right)^{-2} \frac{B}{10^{12} G}$



# From the Pulsar to the Pulsar Wind

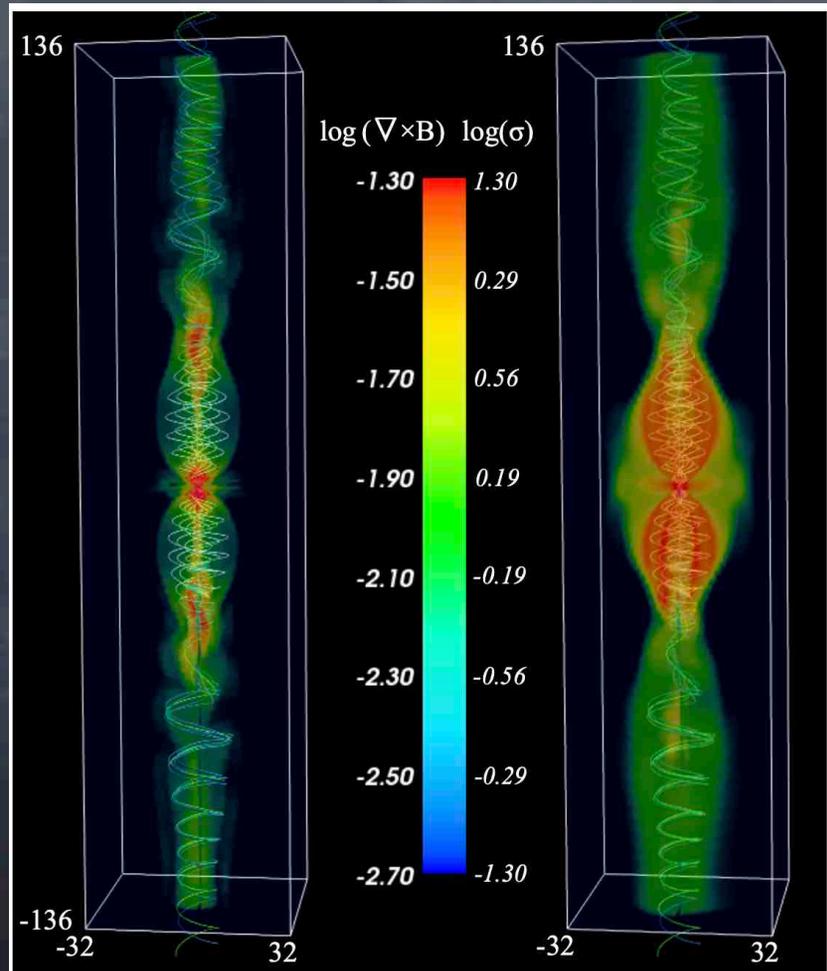


- Pulsed HE emission from the Y-point (up to GeV-TeV)
- Steady emission from the nebula past the term shock



# Relativistic Jets

# Relativistic Jets Launched by Black Holes

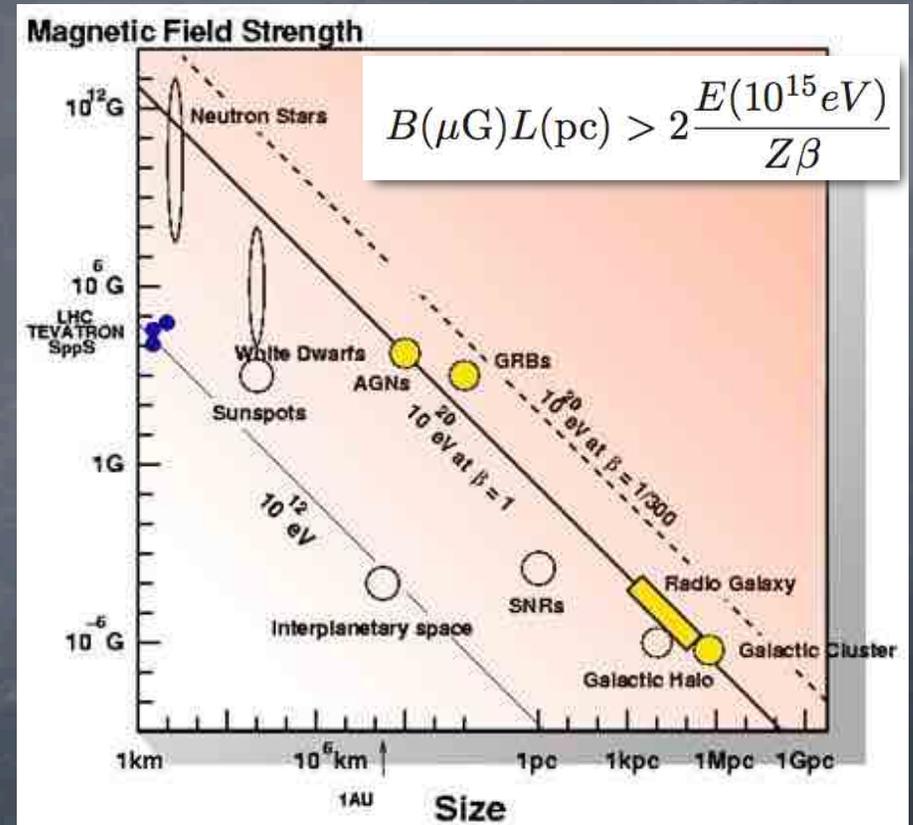
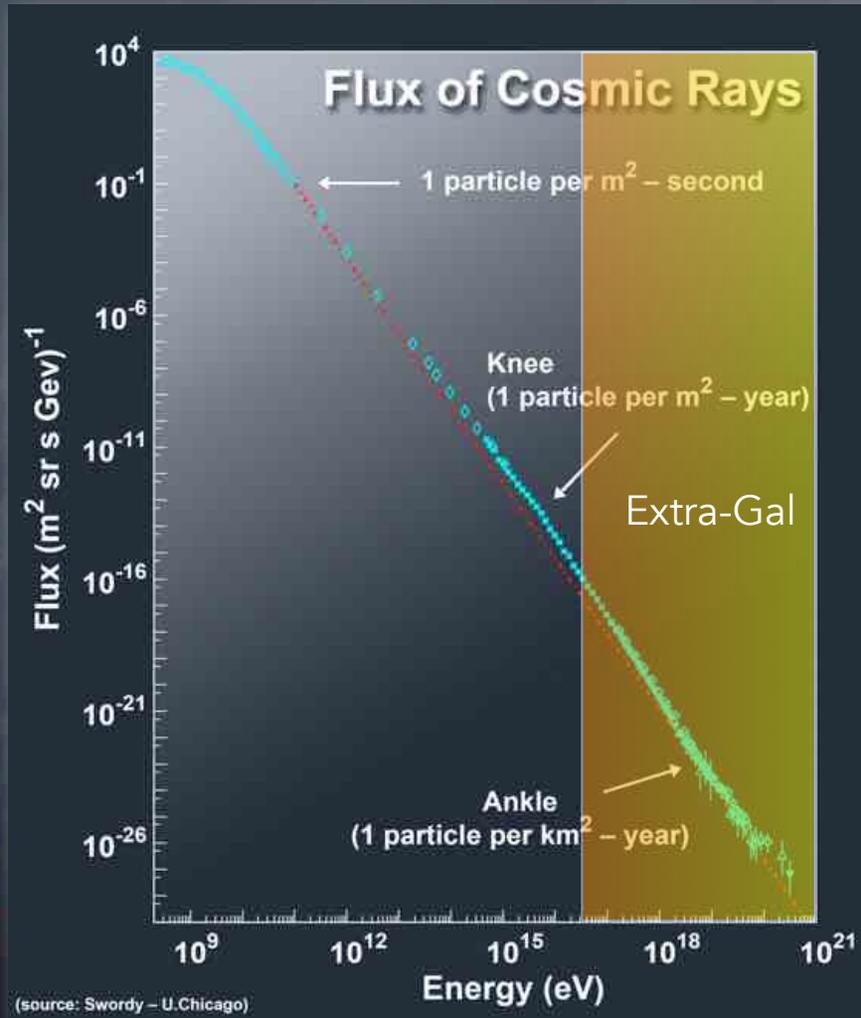


Bromberg & Tchekhovskoy 2016

- Starts **Poynting-dominated** from the BH magnetosphere
  - Blandford-Znajek77 (BH) or Blandford-Payne82 (disk spin)
- Poloidal B drops with z more than toroidal
  - Magnetic tower** of azimuthal B loops: unstable
  - Reconnection → magnetic to kinetic energy
- Acceleration** sources:
  - Reconnection
  - Shocks (internal, termination)
  - Shear acceleration (between spine and cocoon)
  - Turbulent (II-order Fermi in the cocoon)
  - Espresso re-acceleration for UHECRs

# Espresso Acceleration and UHECRs

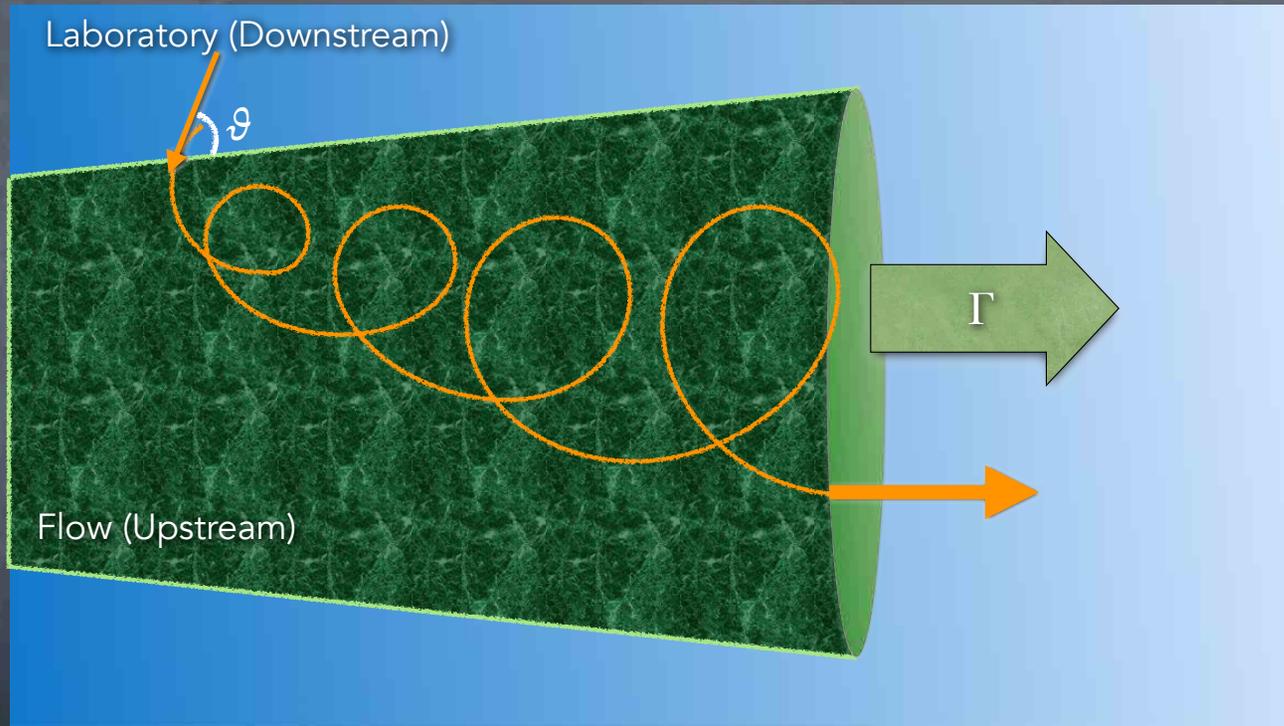
# Extra-galactic Cosmic Rays



- Hillas criterion restricts the origin of UHECRs to relativistic objects

# Acceleration in Relativistic Flows

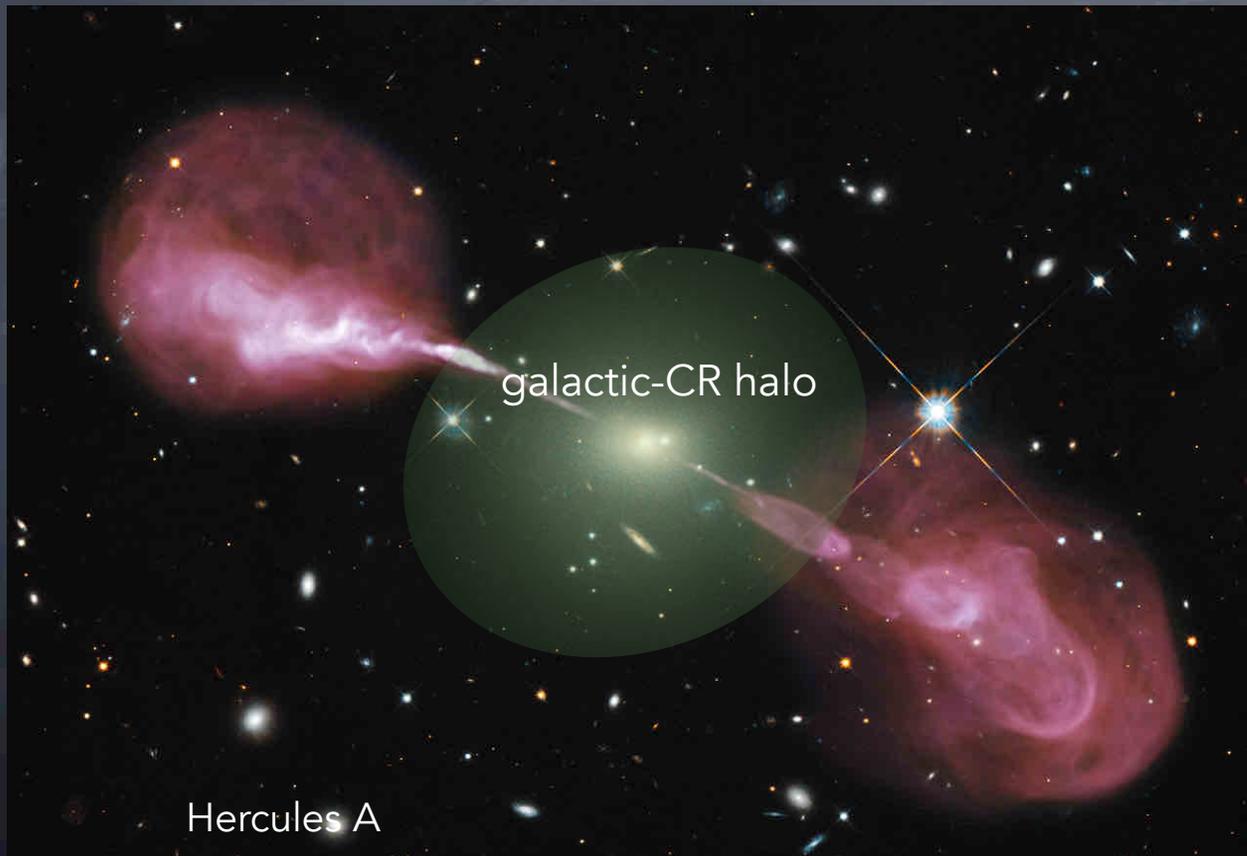
- Requirement: interface thickness  $\ll$  gyroradius  $\ll$  typical flow size



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

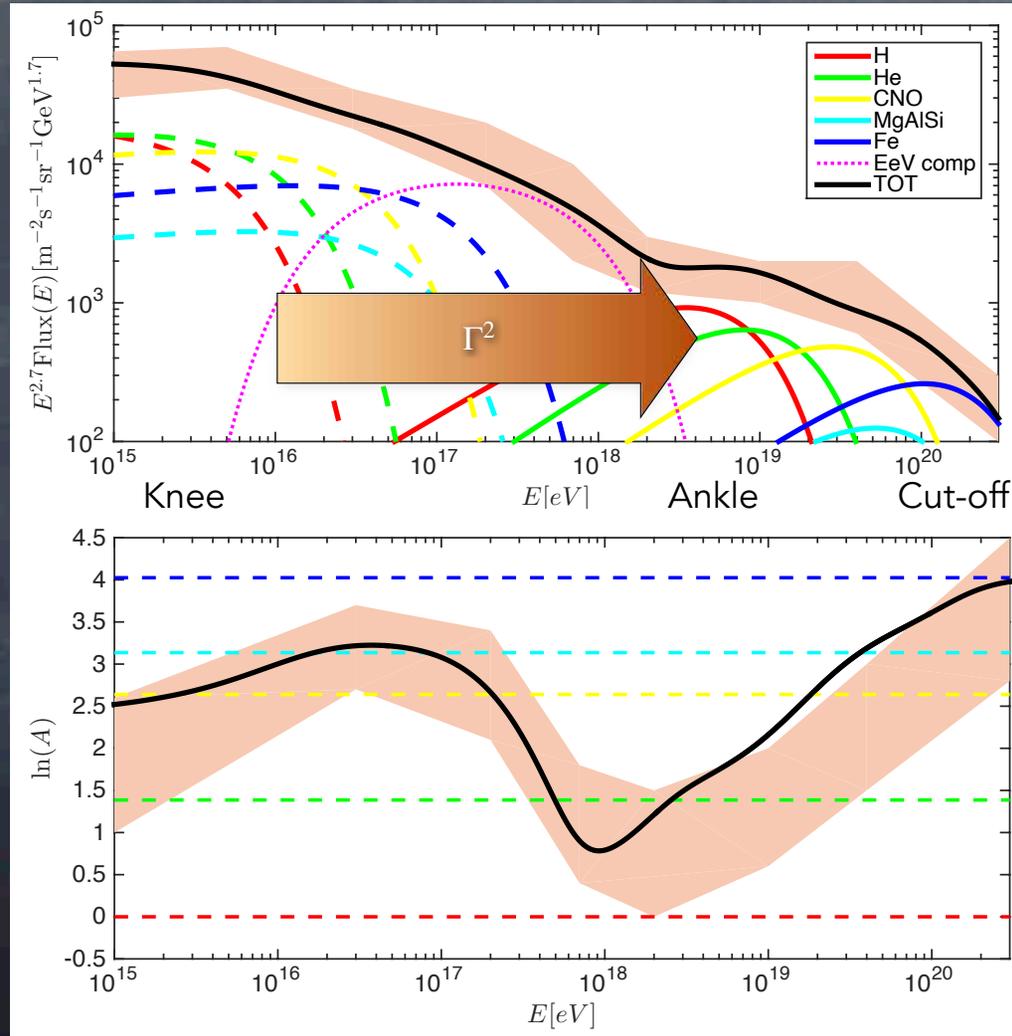
# Espresso Acceleration of UHECRs

- SEEDS: galactic CRs up to  $E_{knee} \sim 3Z \times 10^{15} \text{eV}$
- STEAM: AGN jets with  $\Gamma$  up to 20-30

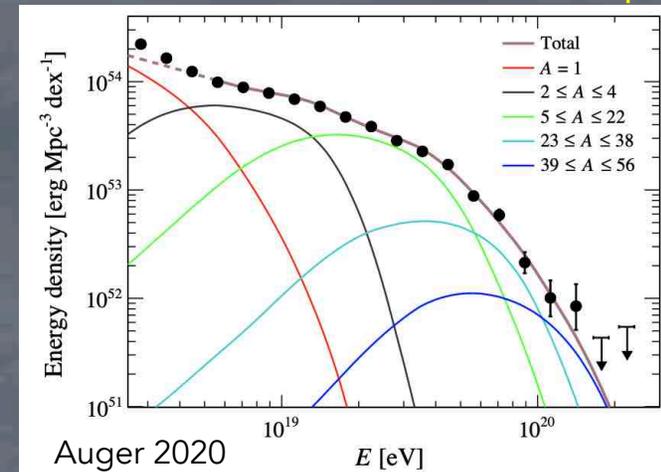


**ONE-SHOT**  
reacceleration can  
produce UHECRs up to  
 $E_{max} \sim 2\Gamma^2 E_{knee}$   
 $E_{max} \sim 5Z \times 10^{18} \text{eV}$

# Galactic CR + UHECR spectrum



Prediction of UHECR **chemical composition!**

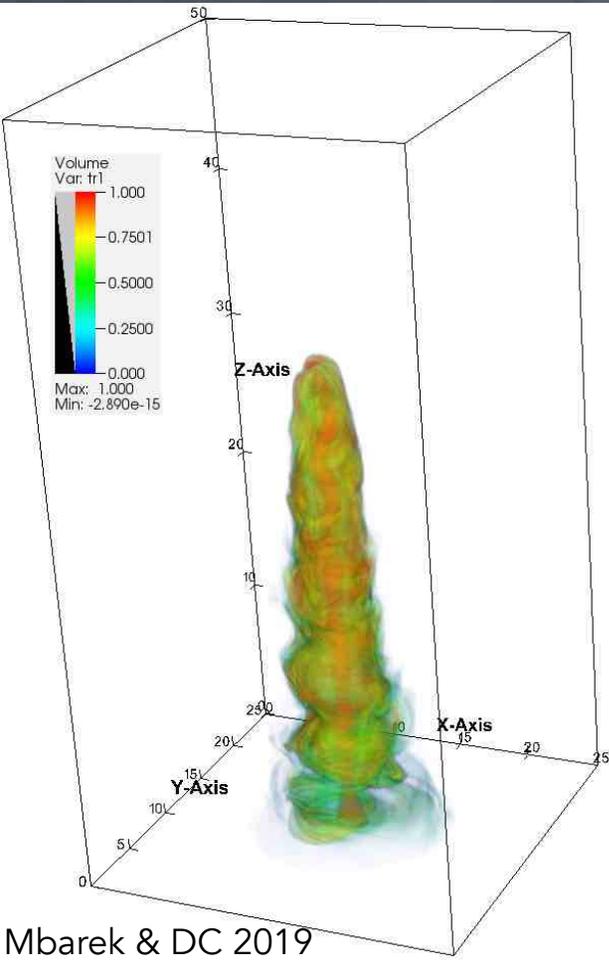


- What **kind of AGN** can contribute?
- Enough sources within the **horizon**?
- What if  $\Gamma \sim$  **a few** (e.g., FR-I galaxies)?
- Expected **anisotropy**?

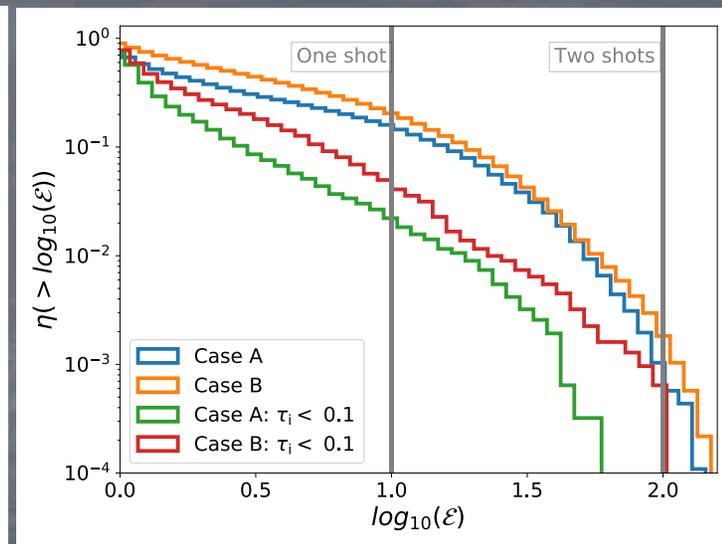
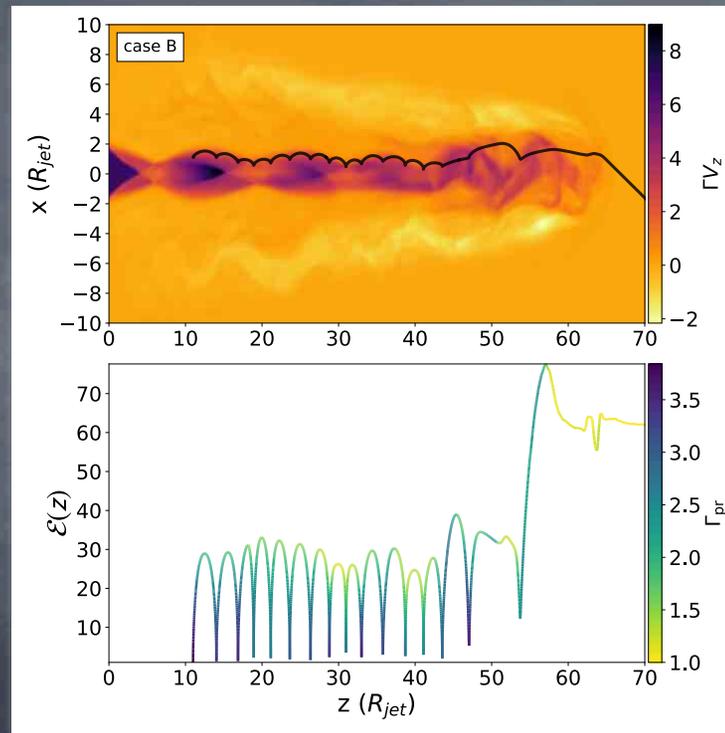
Caprioli 2015, 2018

# Testing Espresso Acceleration

Propagation of test particles in 3D RMHD simulations with *Pluto* (Mbarek & Caprioli19)



Mbarek & DC 2019

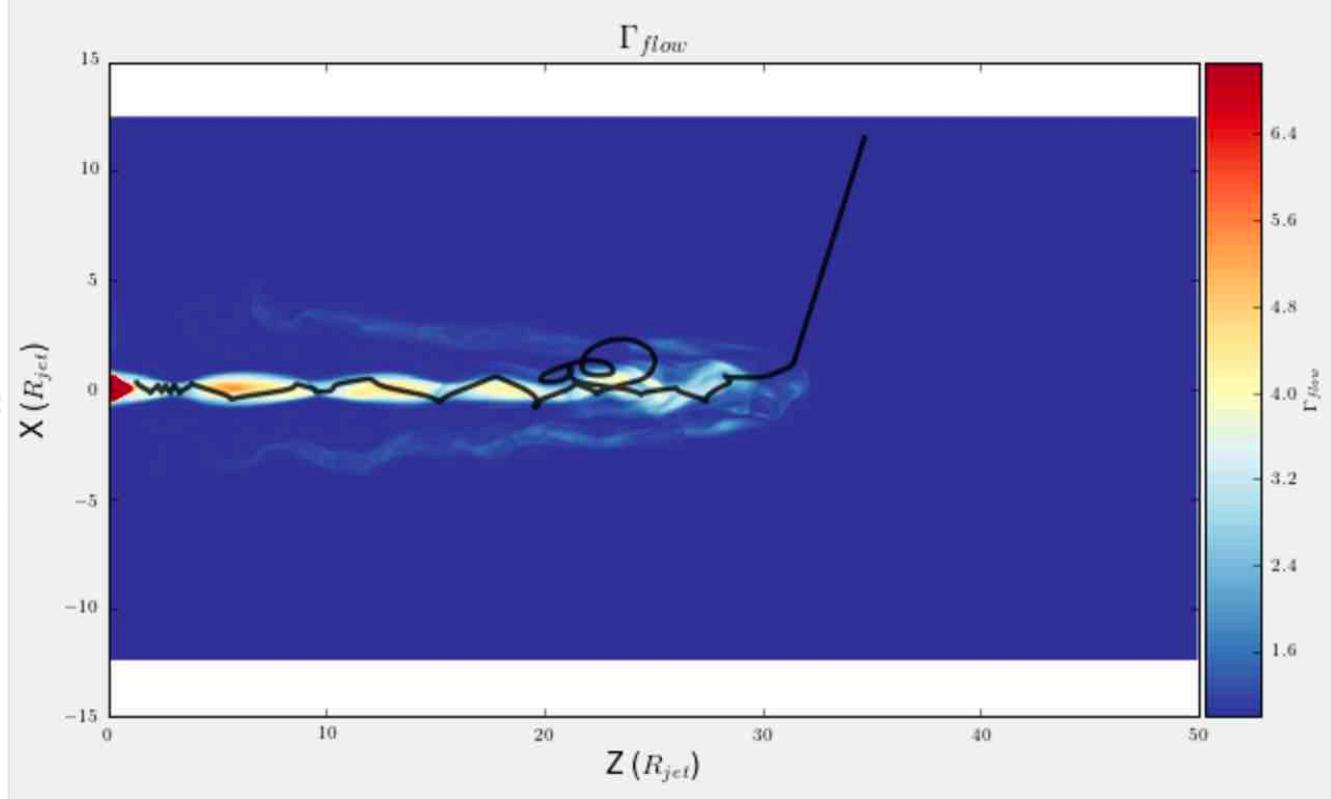
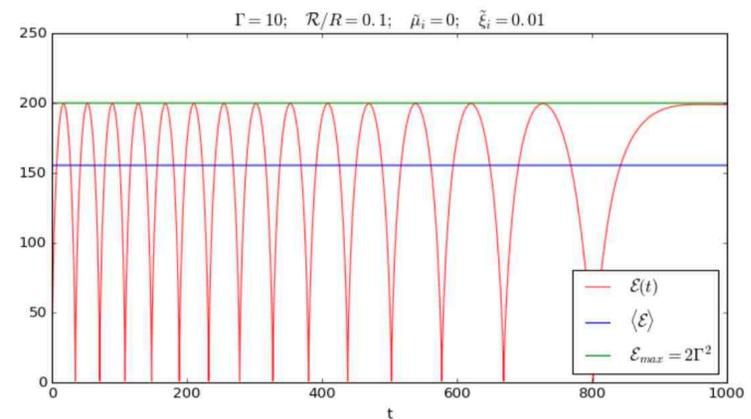
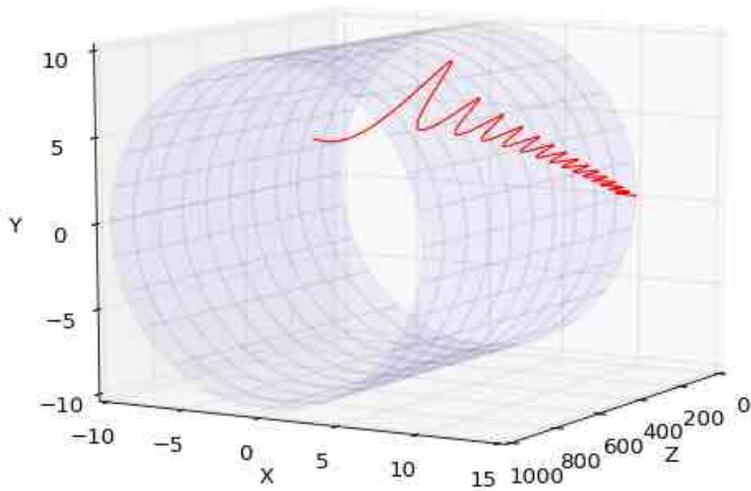


Effective Lorentz factor:  $\Gamma_{eff} \approx 3.2$

- Espresso works for  $> 1\%$  of the Galactic CR seeds
- Two-shot acceleration ( $\mathcal{E} \gtrsim \Gamma^4$ ) is also possible!

# Testing Espresso Acceleration

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

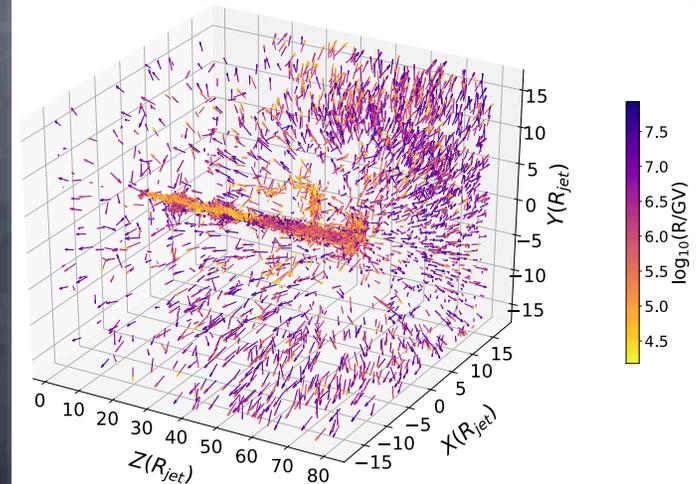
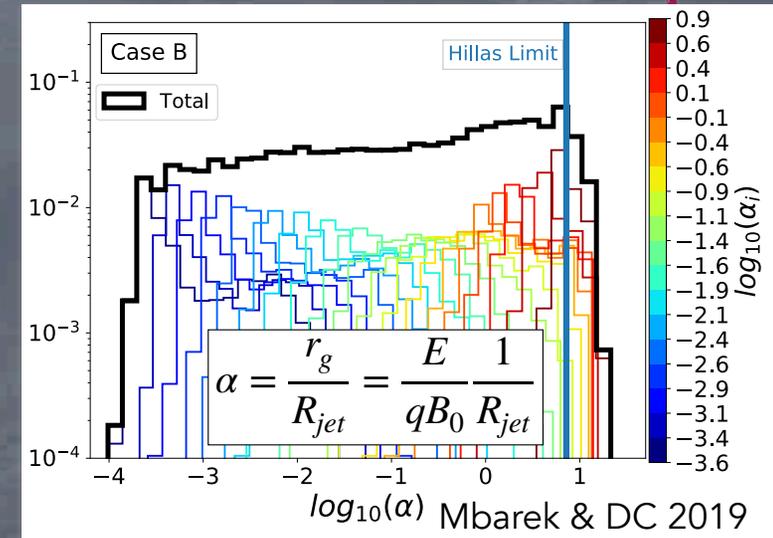


Espresso works! Even a few shots:  $E_f/E_i \sim \Gamma^4 - \Gamma^6!$

# Spectra and Anisotropy



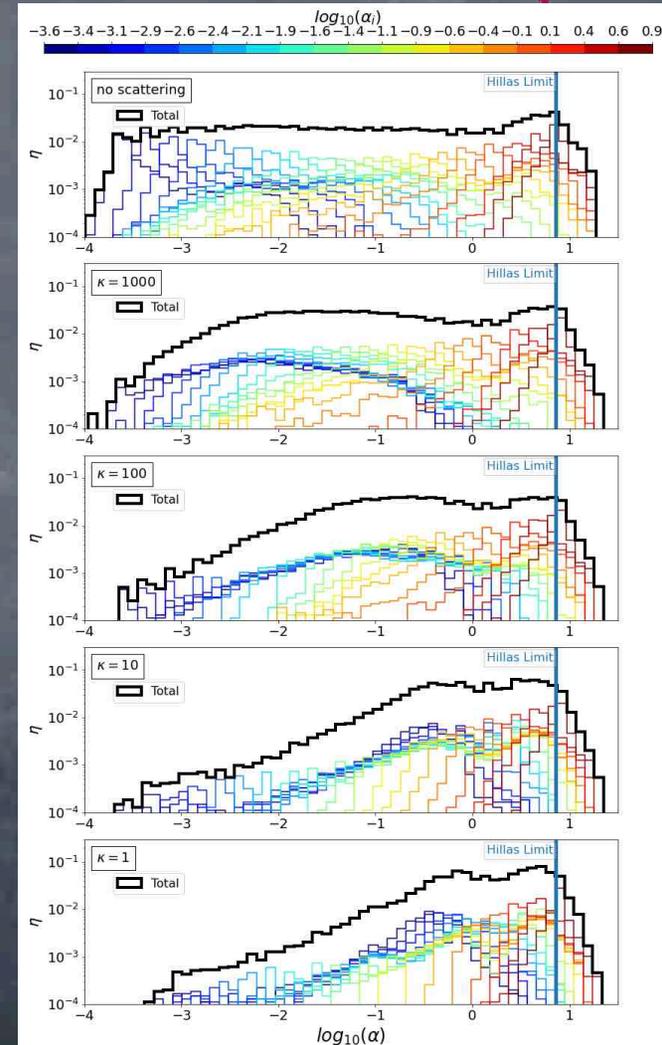
- Espresso acceleration occurs up to the **Hillas limit**
- First tested *bottom-up* mechanism for UHECRs
- Re-accelerated UHECRs released almost **isotropically**
  - Weak dependence on the sign of  $B_\phi$
- Astro implications of 3D RMHD simulations:
  - Multiple espresso shots allow FR-I galaxies with  $\Gamma \sim \text{few}$  (e.g., Cen A) to be UHECR sources, too
  - Even **non-blazar** AGNs may contribute to the UHECR flux at Earth



# Espresso vs Stochastic Shear Acceleration



- Shear acceleration at the jet-cocoon layer proposed as source of UHECRs (e.g., Ostrowski 1998, 2000; Kimura+2018)
- depends on poorly-known scattering rate
- Added sub-grid Monte Carlo scattering to our RMHD jet with  $\tau_{scatt} = \frac{\kappa}{\Omega_c}$  ( $\kappa = 1 \rightarrow$  Bohm diffusion)
- Scattering fosters acceleration of low-energy seeds
- The Hillas limit only achieved via espresso!
- Overall spectrum becomes flatter



Mbarek & Caprioli 2021

# UHECR attenuation in realistic AGNs

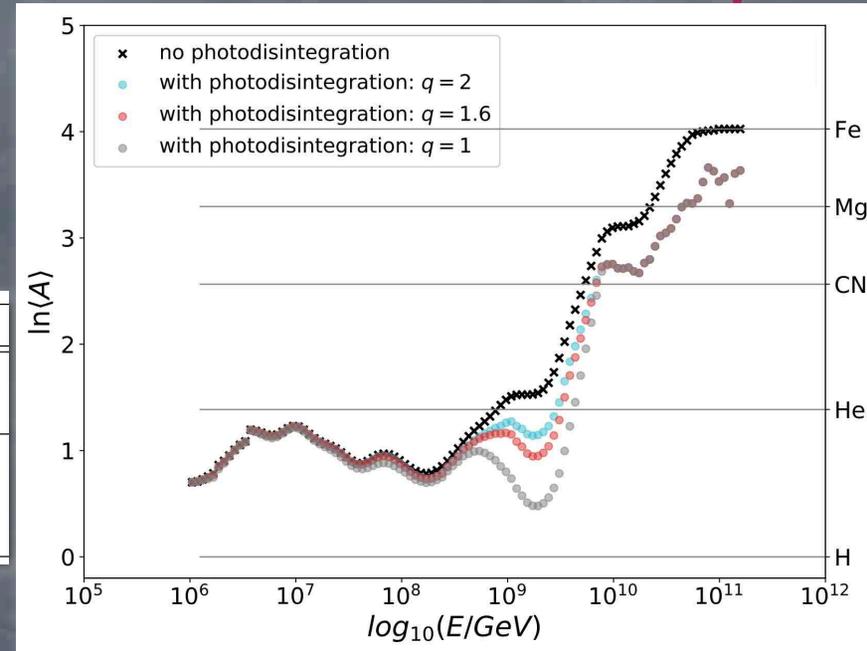
Included loss mechanisms for UHE protons and nuclei:

CR -  $p$  collisions

CR -  $\gamma$  collisions (nuclei photodisintegration)

Particle	Process	Reactions
Proton (p)	proton-proton ( $pp$ )	$p + p \rightarrow p + n + \pi^+ \rightarrow p + n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$
	photomeson ( $p\gamma$ )	$p + \gamma \rightarrow n + \pi^+ \rightarrow n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$
Nucleus (N)	photomeson ( $N\gamma$ )	$N + \gamma \rightarrow {}^{A-1}N + n + \pi^+ \rightarrow {}^{A-1}N + n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$
	photodisintegration	${}^A N + \gamma \rightarrow {}^{A-1}N + n \rightarrow {}^{A-1}N + p + e^- + \bar{\nu}_e$
	& neutron decay	${}^A N + \gamma \rightarrow {}^{A-1}N + p$

Mbarek, Caprioli & Murase 2022



Technically challenging & dependent on the AGN photon fields

Non-thermal emission (dominant), Broad-Line Region, dusty torus IR, CMB, starlight, ...

Even maximizing losses, UHECR composition should remain heavy at the highest energies

because espresso acceleration happens far from the jet basis

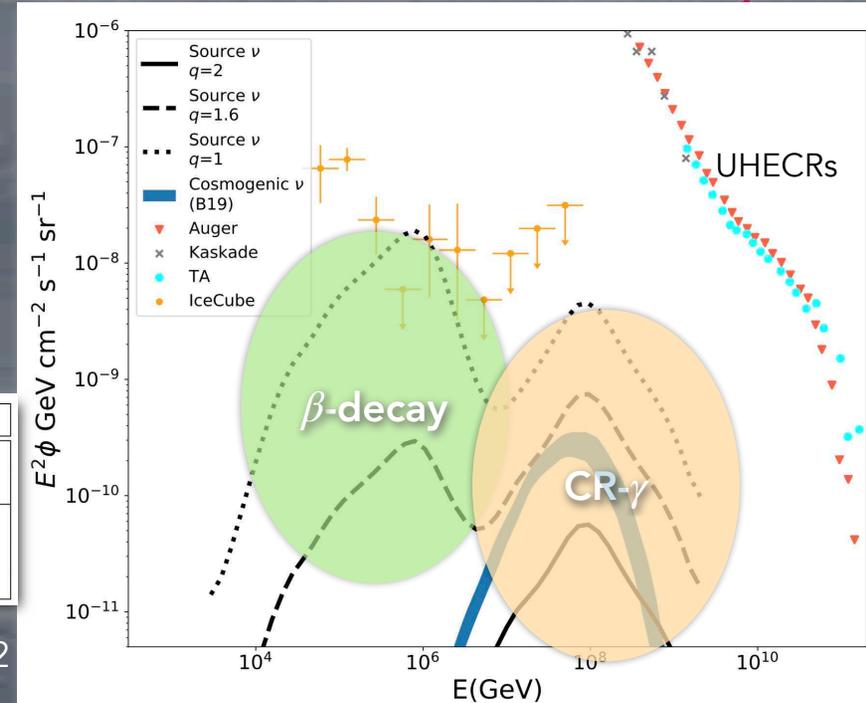
# Expected Flux of UHE Neutrinos from AGNs

3 channels for UHE neutrinos:

- CR -  $p$  collisions
- CR -  $\gamma$  collisions (nuclei photodisintegration)
- $\beta$ -decay of secondary nuclei (novel)

Particle	Process	Reactions	Neutrino Energy fraction
Proton (p)	proton-proton ( $pp$ )	$p + p \rightarrow p + n + \pi^+ \rightarrow p + n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$	$p:\nu \sim 20:1$
	photomeson ( $p\gamma$ )	$p + \gamma \rightarrow n + \pi^+ \rightarrow n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$	$p:\nu \sim 20:1$
Nucleus (N)	photomeson ( $N\gamma$ )	$N + \gamma \rightarrow {}^{A-1}N + n + \pi^+ \rightarrow {}^{A-1}N + n + e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$	$N:\nu \sim 20:1$
	photodisintegration & neutron decay	${}^A N + \gamma \rightarrow {}^{A-1}N + n \rightarrow {}^{A-1}N + p + e^- + \bar{\nu}_e$	$N:\nu \sim 10^3 A:1$
		${}^A N + \gamma \rightarrow {}^{A-1}N + p$	—

Mbarek, Caprioli & Murase 2022



- AGN contribution may dominate **cosmogenic neutrino flux** for  $E > 10^7$  GeV (ANITA, ARA, POEMMA)
- IceCube neutrinos** ( $E \sim 10^3 - 10^6$  GeV) may come from  $\beta$ -decay of secondary nuclei
- Due to the role of **non-thermal  $\gamma$** , likely correlation with AGN flares! (e.g., TXS0506+056)

# A Summary

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

