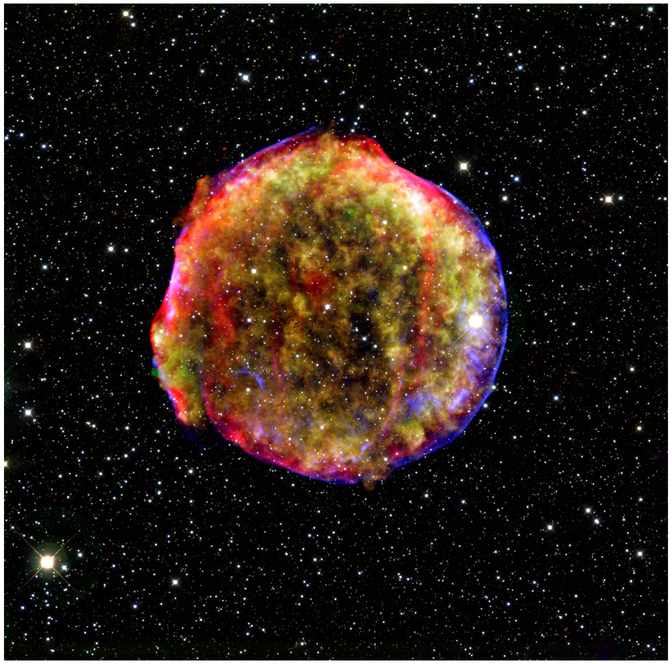
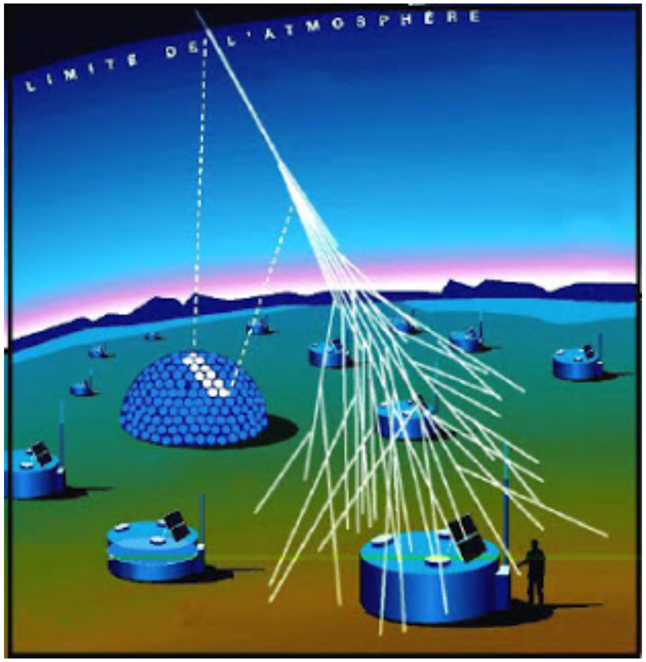
Astronomy 253, Plasma Astrophysics, Harvard University

Cosmic-rays and Particle Acceleration





Instructor: Xuening Bai

April 4-6, 2016

Introduction: what are cosmic-rays (CRs)?

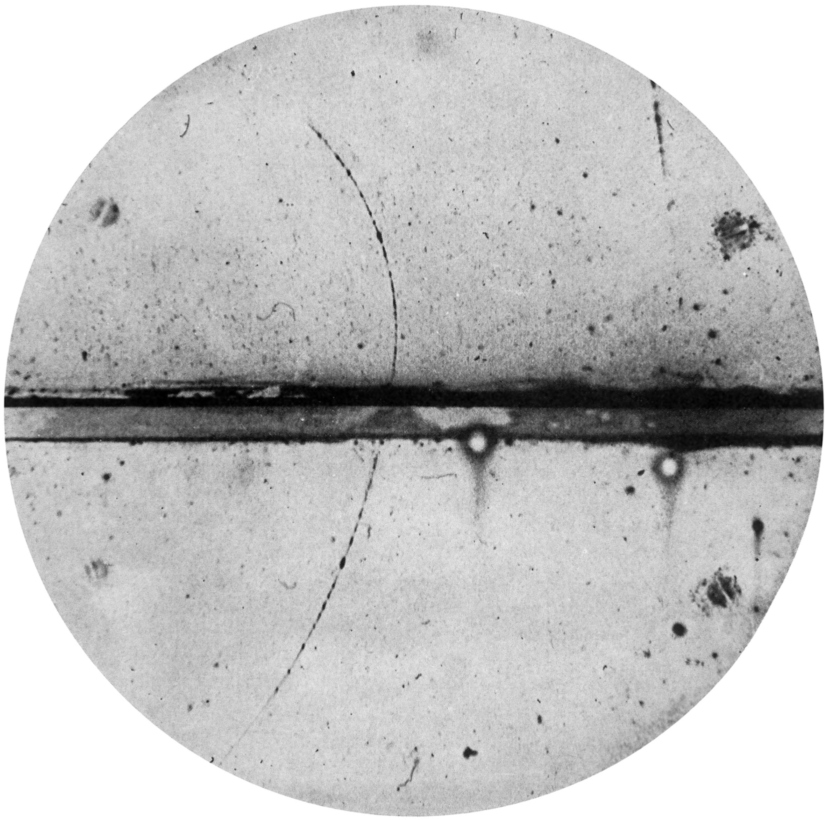
- CRs are very energetic (mostly) charged particles that originate beyond the Earth.
- CR number density is tiny, but its energy density is in rough equipartition with thermal and magnetic energies in the Galaxy.
- More broadly, any particle population that is significantly "non-thermal" may be considered as CRs.
- Major research area in high-energy astrophysics, and closely related to particle physics.
- Important window to probe the Universe.

Brief history

Victor Hess on his way to measure ionizing radiation around 1911-1912 from Vienna

- Discovered by Victor Hess in 1911-1913 in a series of balloon experiments aiming to search for ionizing radiation in the atmosphere.
- Name “cosmic-ray” coined by Robert Millikan in 1925
- Following the invention of Geiger counter in 1929, Bothe & Kolhörster showed that CRs are high-energy ($10^{9\text{-}10}$ eV) charged particles.
- Astrophysical study of CRs began in the 1960s with satellites, measuring their energy spectrum, spatial distribution, and composition
- Ground-based air shower arrays built in >1960s to detect very high energy CRs (>10^{14} eV)

CR research led to discoveries of new particles



The track of a positron observed in the cloud chamber in Anderson's experiment, bending to the opposite direction as expected for an electron

- Before particle accelerators, atmos-pheric CRs were the primary source of high-energy particles for particle physics
- Mostly are secondary particles produced in the air shower.
- Discovery of the positron (1932) and the muon (1936) by Anderson from the cloud chamber.
- "V-particles" discovered by Rochester & Butler in 1947, which later identified as Kaons (K meson).
- Pions were discovered in 1947 by Powell using photographic emulsion.

Impact of the CRs on the Earth/humans

- Atmospheric chemistry: $n + {}^{14}N \rightarrow {}^{14}C + p$

  Neutrons produced in the upper atmosphere by CRs generate ^{14}C, which then form CO_2 and get mixed into the entire atmosphere and biosphere.

  Basis of radiocarbon dating.

- Ambient radiation

  At sea level, CRs contribute to ~20% of ambient radiation (others being dominated by Radon). However, its contribution increases with height, and pilots have higher risk of CR exposure.

- Electronics

  It can produce errors and cause radiation damage in electronic devices.

- Space travel

  CRs are the major health hazard for space travel.

Importance of the CRs in astrophysics

- CRs are dynamically important in the interstellar medium.

  Provide pressure support and affect galactic dynamics (e.g., Parker instability, CR-driven dynamo, CR-driven galactic disk wind).

- CRs (particularly high-energy electrons) produce radiation across the electromagnetic spectrum.

  Cornerstone of high-energy astrophysics, crucial diagnostics in astrophysical environments such as in accretion disks/jets, supernovae, gamma-ray burst…

- CRs are the dominant source of ionization in dense medium, and are an important source of heating.

  Such ionization enables gas to be coupled with B field and is crucial in star/ planet formation. It is also the starting point of chemical reactions in cold gas.

- Feedback in astrophysical plasma processes

  Particle acceleration, magnetic reconnection, etc.

How to detect the CRs?

- Particle detectors: (directly measure mass, charge, energy)

  Early detectors: cloud chambers, bubble chambers, particle emulsion (all measure/track ionization losses)

  Modern CR observatories: combination of multiple detectors

  Satellite/balloon based: solid-state detector/tracker/calorimeter etc.

  Ground based: reconstruct by observing and modeling air shower from secondary particles

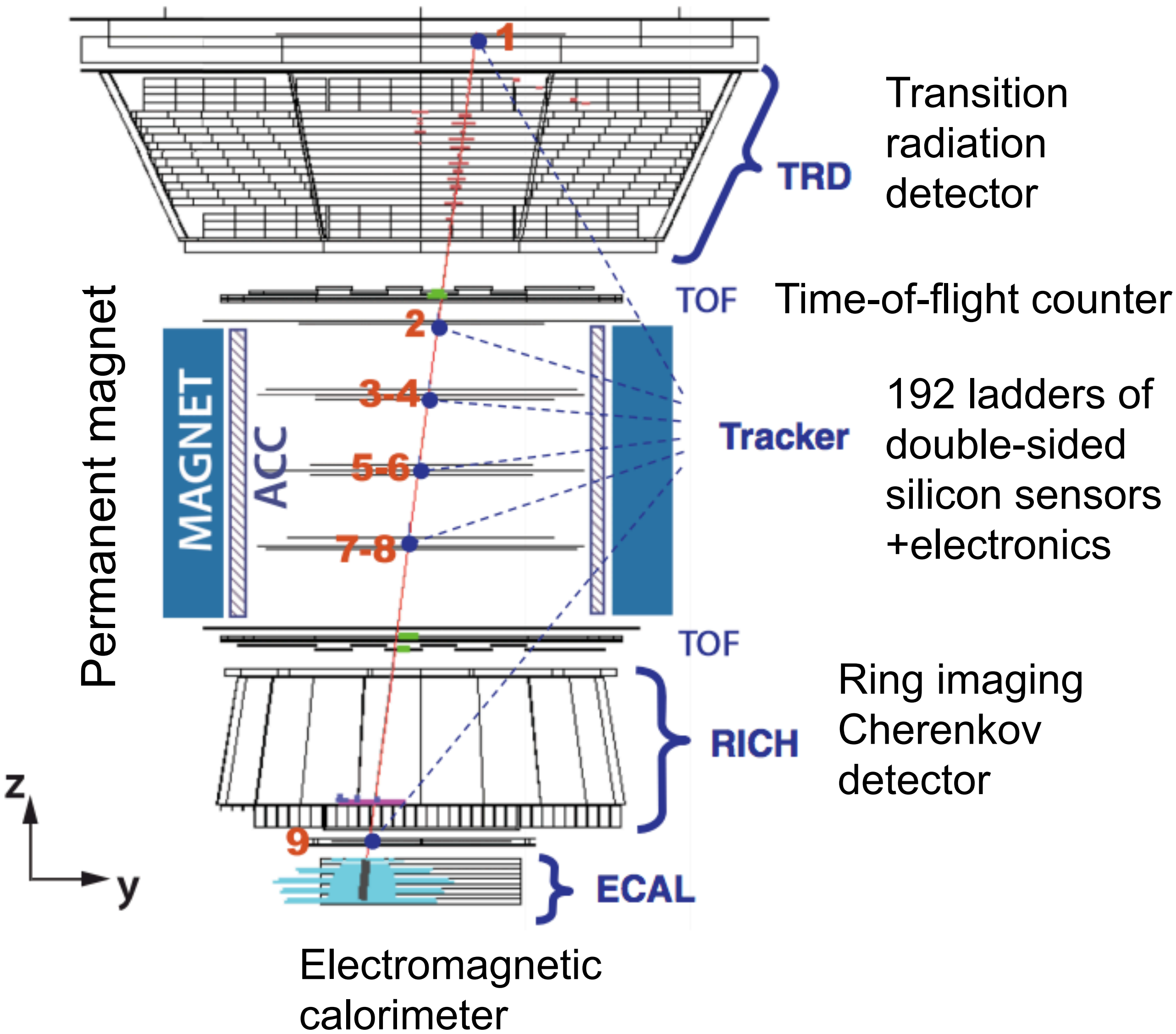
- Via EM radiation: (indirect inference)

  High-energy electrons: synchrotron/inverse Compton radiation

  Ion CRs: produce pions following a collision with a nuclei, which then decay into gamma-rays

$$\pi^0 \rightarrow 2\gamma$$ 67.5 MeV gamma-ray in rest frame

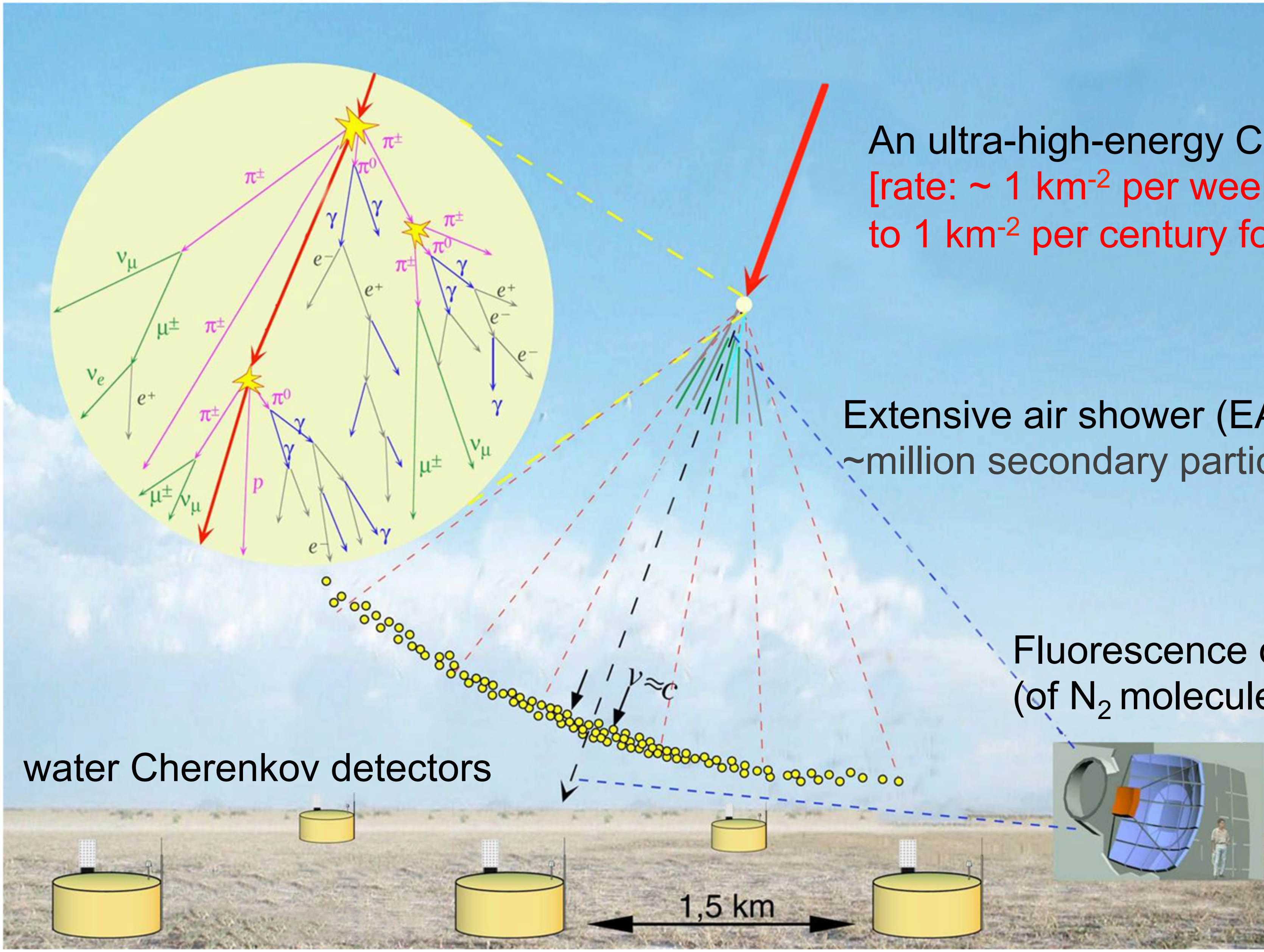
Alpha magnetic spectrometer (mounted on the ISS)



Precisely measuring energies of electron/ positron, ion/anti-ion up to a few 100 GeV.

Main science drive: search for anti-matter, dark matter

Pierre Auger Observatory (@ Argentina)



An ultra-high-energy CR (>10^{18} eV)
[rate: ~ 1 km^{-2} per week, and drops to 1 km^{-2} per century for E>10^{20} eV!]

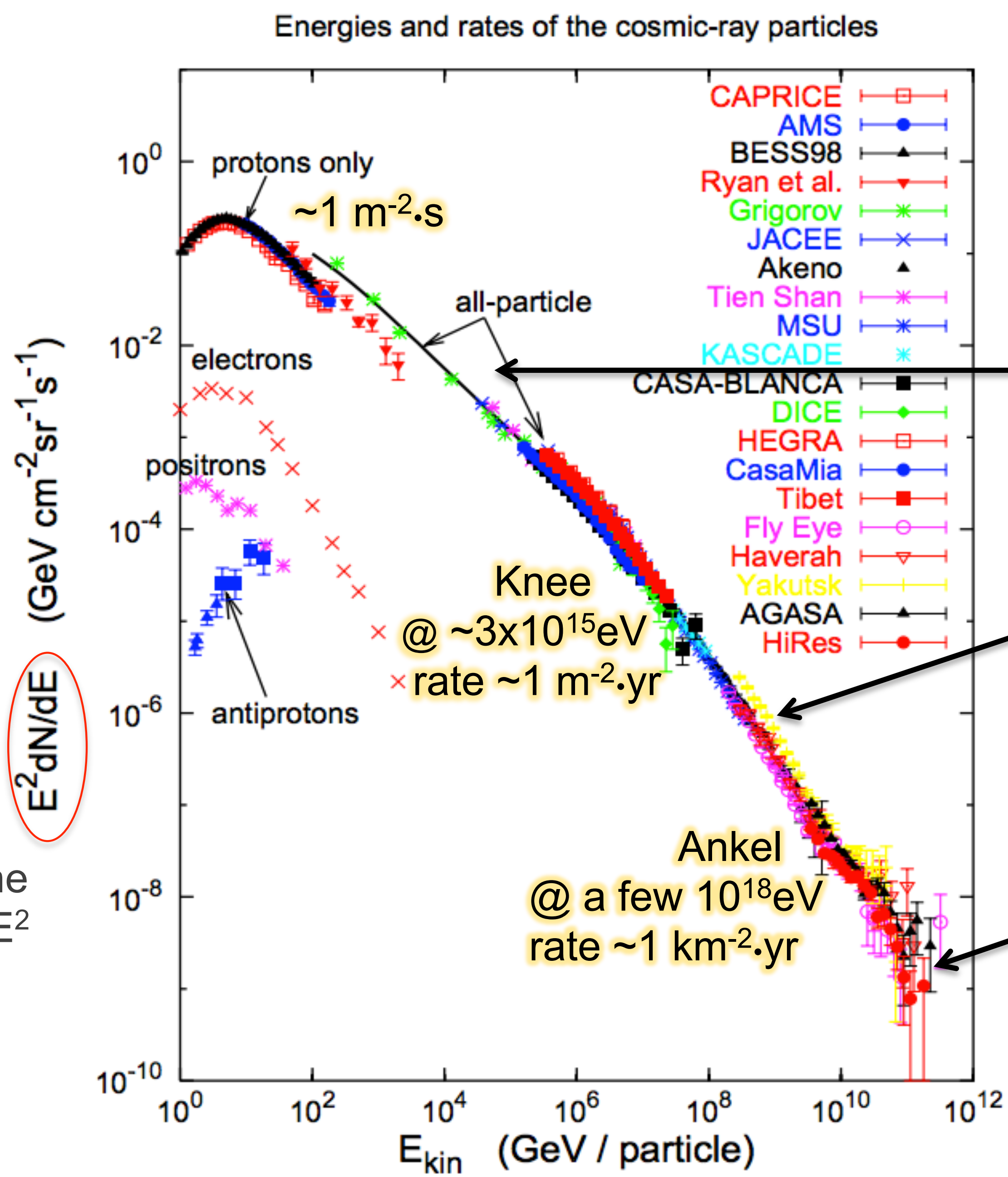
Extensive air shower (EAS)
~million secondary particles

Fluorescence detectors
(of N_2 molecule, in UV)

water Cherenkov detectors

Total surface area: ~3000 km^2 (1600 tanks)

CR energy spectrum



Note the factor E^2

Spectral features: must be related to CR acceleration mechanism and/or propagation effect

$$\frac{dN}{dE} \propto E^{-2.7}$$

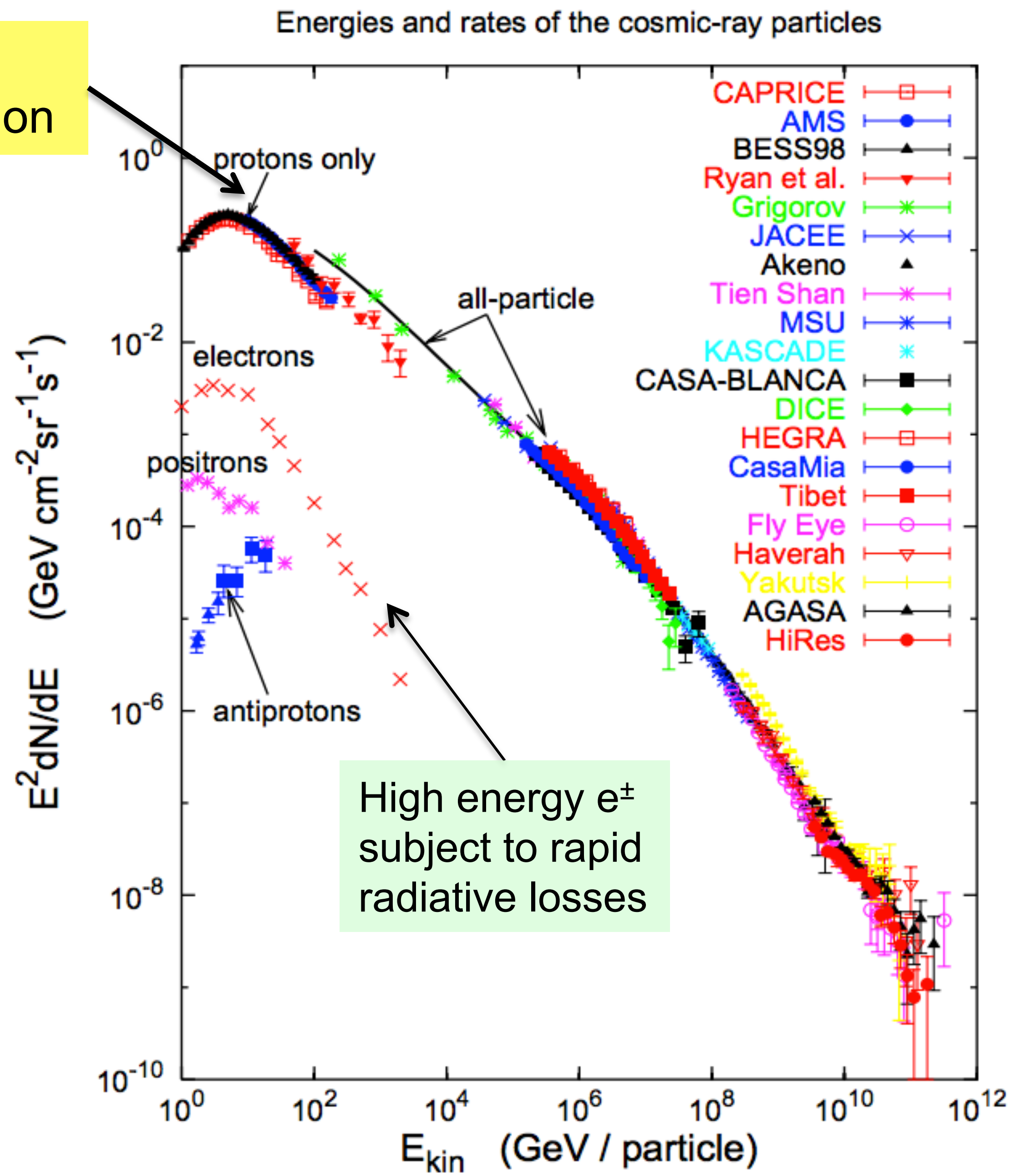
$$\frac{dN}{dE} \propto E^{-3.1}$$

GZK cutoff?

astro-ph: 0607109
From T. Gassier

CR energy spectrum

Solar modulation



Energy density ~1 eV cm^{-3}, comparable to thermal/ magnetic/turbulent energy density in the ISM

Most CR pressure from ~GeV particles.

Primarily protons (~89%) and helium (~10%), and ~1% of electron/positron.

Anomalies in positron/ electron ratio at a few GeV: suspected dark matter signal? [see PAMELA/ AMS-2 results]

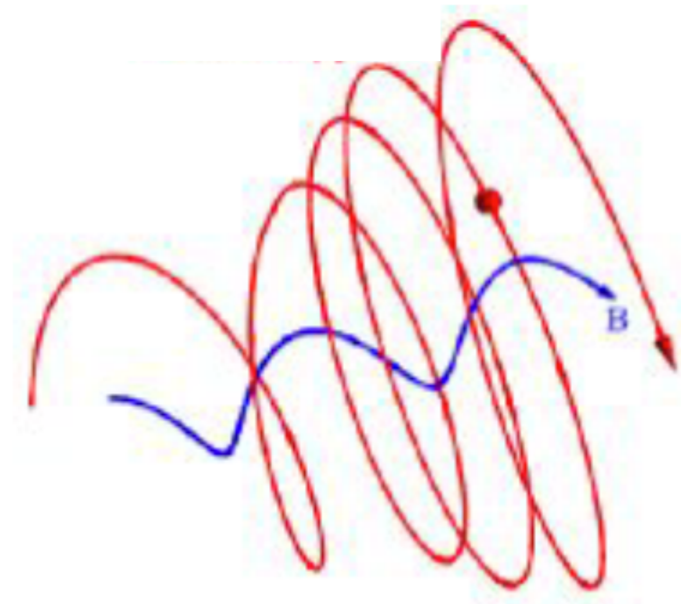
CR propagation in the Galaxy

- CRs are essentially collisionless:

  Coulomb cross section (GeV): ~10^{-30} cm^{-2}

  Mean free path (n~1 cm^{-3}): ~10^{30} cm =>

  1% chance of collision in a Hubble time



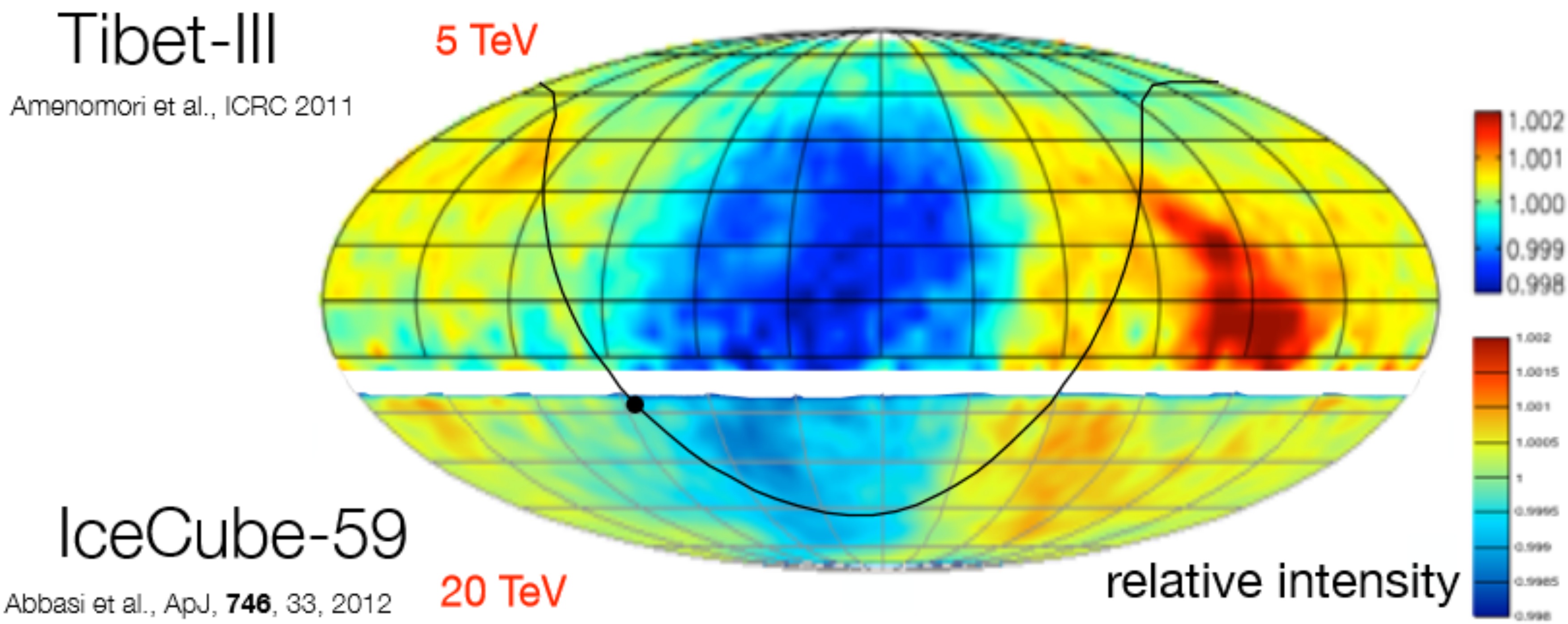
- Most CRs are well confined by magnetic field, and diffuse by resonantly scattering off MHD waves/turbulence.

  Recall: $$r_L = 1.08 \times 10^{-6}\text{pc}\left(\frac{E}{\text{GeV}}\right)\left(\frac{B}{\mu\text{G}}\right)^{-1}$$

  CR diffusion leads to a largely isotropic velocity distribution => source location information is lost.

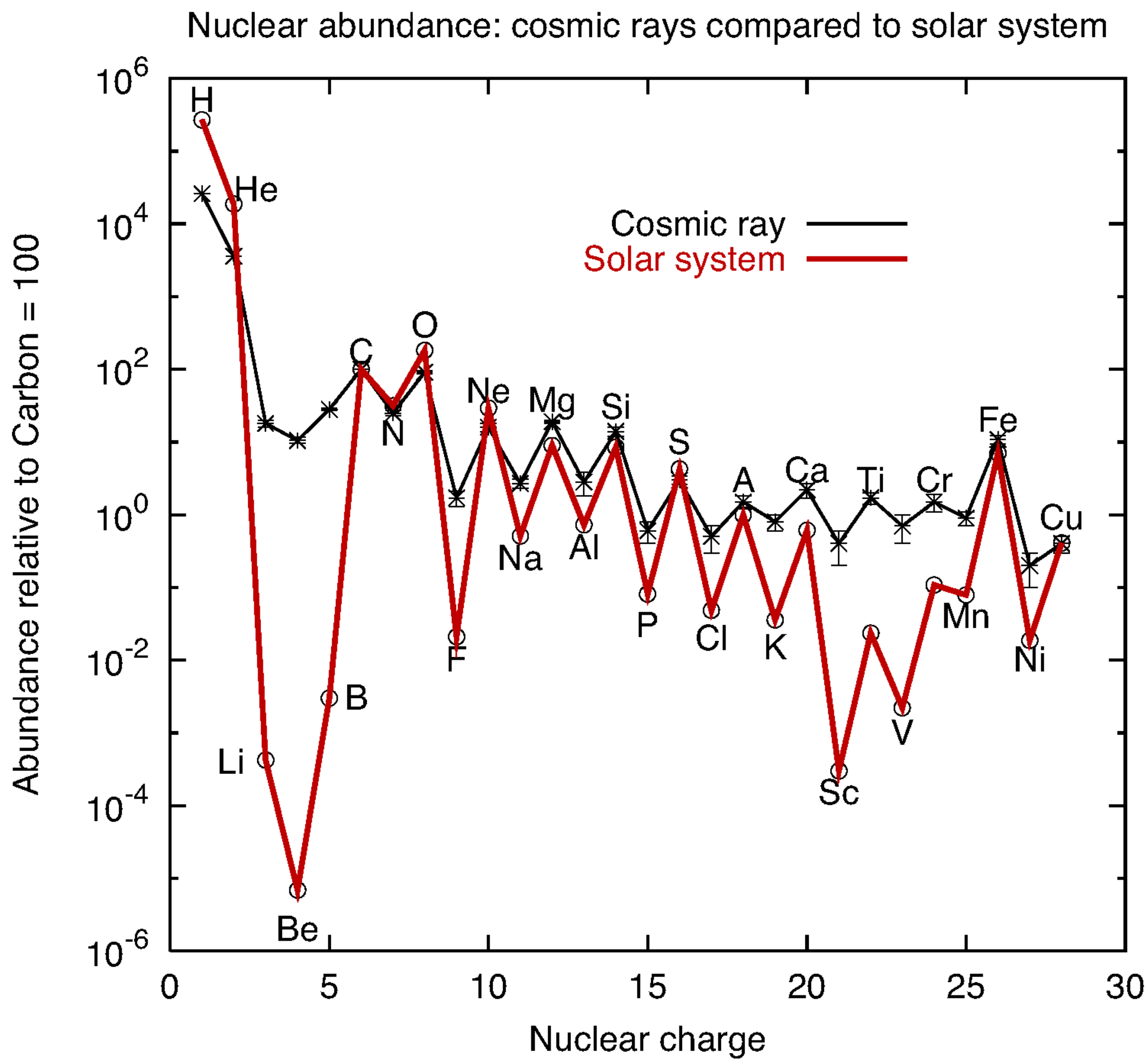
  Diffusion coefficient: κ~R^2/T~$10^{28} cm^2 s^{-1}$.

Spatial isotropy



- CR distributions are highly isotropic (to 10^{-3}) in the energy range of 1-100 TeV.
- Weak anisotropy is dominated by a dipole corresponding to motion of the Earth/solar system relative to the CR plasma, but details (propagation effects) not well understood.

Elemental abundance in CRs



Overall, abundance is similar to solar abundance: source of CRs is interstellar.

However, there is significant overabundance of Li, Be, B: they are secondary nuclei produced in the spallation of heavier elements (C, O) with the CRs.

Similarly, overabundance of Sc, V, Mn etc. is a result of fragmentation of Fe.

Spallation and lifetime in the Galaxy

- Ratio of secondary to primary CRs constrains the amount of matter passed through (also called "grammage", X) over the lifetime of the CRs spent in the Galaxy.

  Fraction of Li, Be, B from spallation of C, O: mean X >3 g cm^{-2}

  Fe is not substantially depleted: mean X < 5 g cm^{-2}.

  => Lifetime in the galactic disk ~ 3 Myrs

- Cosmic-ray clock from radioactive decay of spallation product:

  Radioactive decay of ^{10}Be to ^{10}B: half lifetime = 1.36 Myr

  => Total lifetime in the Galaxy ~ 20 Myr

- Summary: it takes ~20 Myrs for a typical galactic CR particle (~GeV) to escape from the Galaxy. Within its lifetime, it spends ~3 Myr in the disk, and the rest of time in the halo.

CR production rate

- To maintain the current energy density of the CRs in the Galaxy, CRs must be constantly produced to compensate for their escape.

$$\text{Production rate} \sim \frac{1\ \text{eV cm}^{-3} \times \text{volume}}{3\ \text{Myrs}} \sim 10^{40\text{-}41}\ \text{ergs s}^{-1}$$

(~10^{-4} of Galactic luminosity!)

- Supernova being the most energetically favorable source of the CRs:

Rate ~ 1-3 per centry, kinetic energy ~10^{51} erg

Sufficient if ~10% of its kinetic energy is converted to CRs.

Already speculated by Baade & Zwicky in 1934!

Key questions in CR research

- Where and how are CRs accelerated? (origin)

  This is a very broad question, involve acceleration of all different types of CR particles (e^-, ions, neutrinos, etc.), across the entire CR energy spectrum (particularly the ultra-high energy CRs), at different environments (shocks, reconnection, jets, galaxy clusters, etc.).

- How do CRs propagate in the Galaxy and beyond?

  Propagation effects are crucial for interpreting CR observation data, which involve rich set of physics such as CR acceleration, advection and diffusion in Galactic magnetic field/MHD turbulence. The state-of-the-art code "GALPROP" included most features, yet still under improvements.

- What are the dynamical role played by CRs?

  Really not much has been done, though it is well perceived to be important.

  Need include CRs in cosmological/galaxy formation simulations, but how?

Particle acceleration: general considerations

- General idea: $$\frac{d(\gamma \boldsymbol{v})}{dt} = \frac{q}{m}\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right)$$

  Magnetic fields do no work, can not be directly responsible for acceleration.

- Solution 1: $$\boldsymbol{E}_\perp = -\frac{\boldsymbol{v}_{\text{flow}}}{c} \times \boldsymbol{B}$$

  Work done by motional electric field: this is related to bulk plasma motion.

  Fermi acceleration

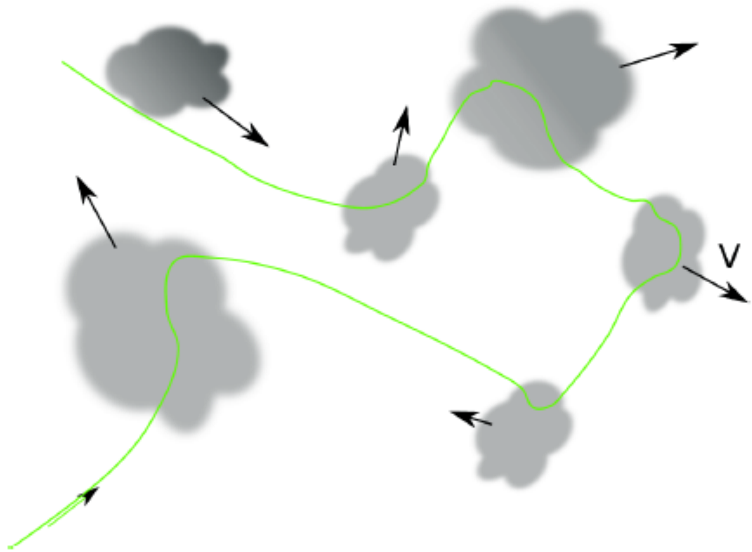
- Solution 2: $$\boldsymbol{E}_{||}$$

  Extremely efficient, but not present in ideal MHD. However, non-zero parallel E can be developed at kinetic scales.

  In particular, it plays an important role in magnetic reconnection, and pulsar magnetosphere.

Fermi acceleration: general picture

- Second order (Fermi 1949):



A fast particle get reflected when it "collides" against an "irregularity" in B field.

Particles gain/lose energy stochastically via reflections in "moving B fields", but on average gain energy:

$$\frac{\Delta E}{E} \propto \left(\frac{V}{c}\right)^2$$

- First order (Bell, 1978; Blandford & Ostriker, 1978):

Shock provides a "converging flow", where particles bouncing back and forth get accelerated with:

$$\frac{\Delta E}{E} \propto \left(\frac{V}{c}\right)$$

- Go to the blackboard.

Most powerful accelerator: SNR shocks

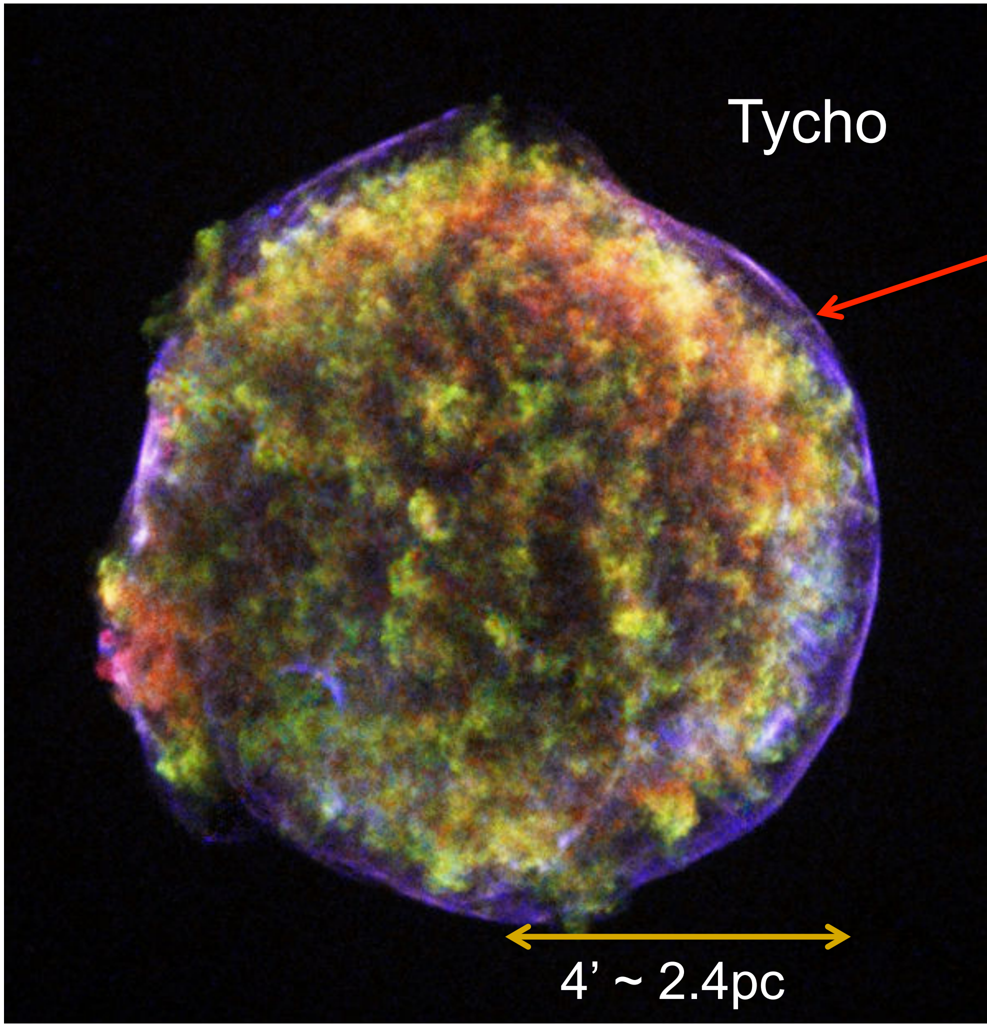


Image from Chandra

forward shock (primary site for particle acceleration)

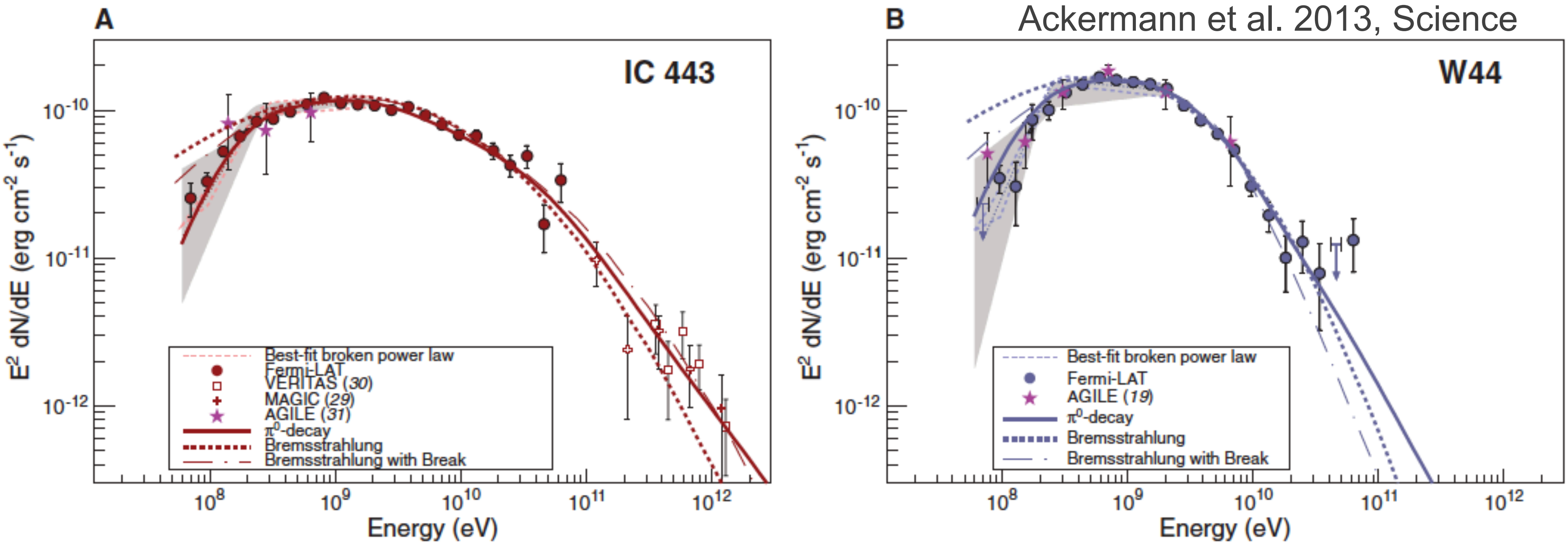
X-ray rims due to synchrotron radiation from accelerated electrons

Shock velocity: ~$10^{3\text{-}4}$ km/s

Free expansion for ~$10^{2\text{-}3}$ years where CR acceleration is most efficient

Evidence for ion acceleration (from Fermi)

Ackermann et al. 2013, Science



Many SNRs shine in γ-rays, but in most cases the spectrum can be equally well fit by either hardronic (ion CR) or leptonic (electron) models.

Supernova remnant interacting with molecular clouds allows the hardronic channel to be enhanced due more frequent p-p interactions.

Pion decay signature identified: steep γ-ray luminosity below ~200 MeV.

Magnetic field amplification

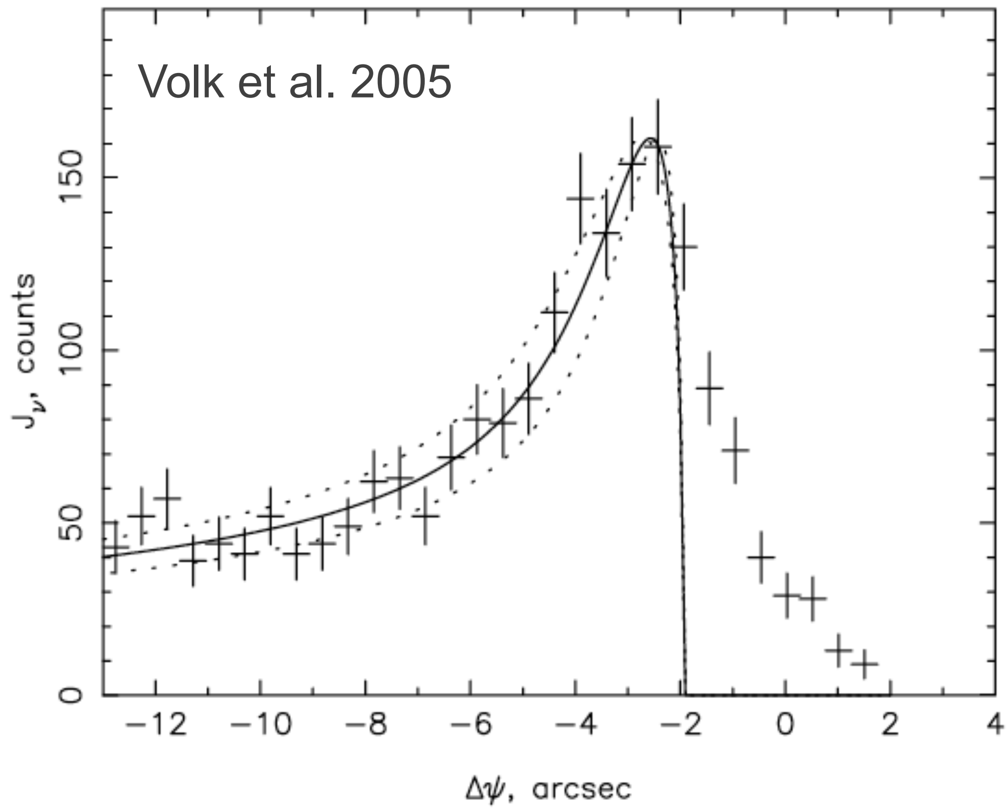


Table 1. Parameters for five well-studied SNRs.

SNR	u_0 (km s^{-1})	B_2(μG)
Cas A	5200 (2500)	250–390
Kepler	5400 (4500)	210–340
Tycho	4600 (3100)	300–530
SN 1006	2900 (3200)	91–110
RCW 86	(800)	75–145

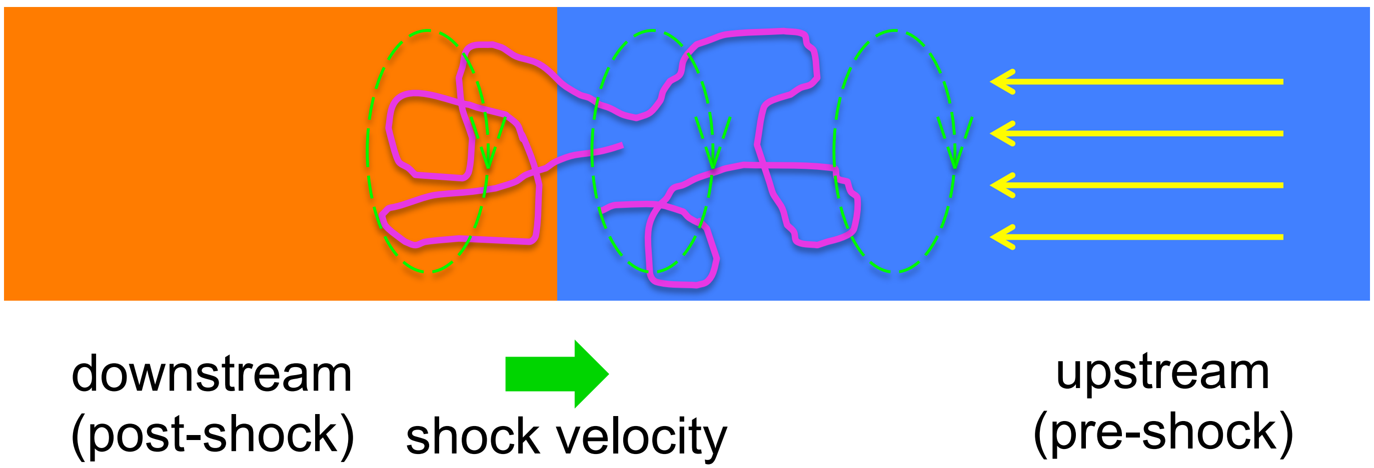
Data from Volk et al. 2005, Parizot et al. 2006, compiled by Caprioli et al. 2009

Sharp X-ray rims: sharpness reflects how rapidly electrons lose energy => constrain B field strength.

Downstream field strength ~30-100 times stronger than in ISM!

Microphysics of particle acceleration

- In the Fermi acceleration paradigm, we have assumed pre-existing turbulence so that particles can bounce back and forth across the shock front to gain energy. However, where is the turbulence from at first place?

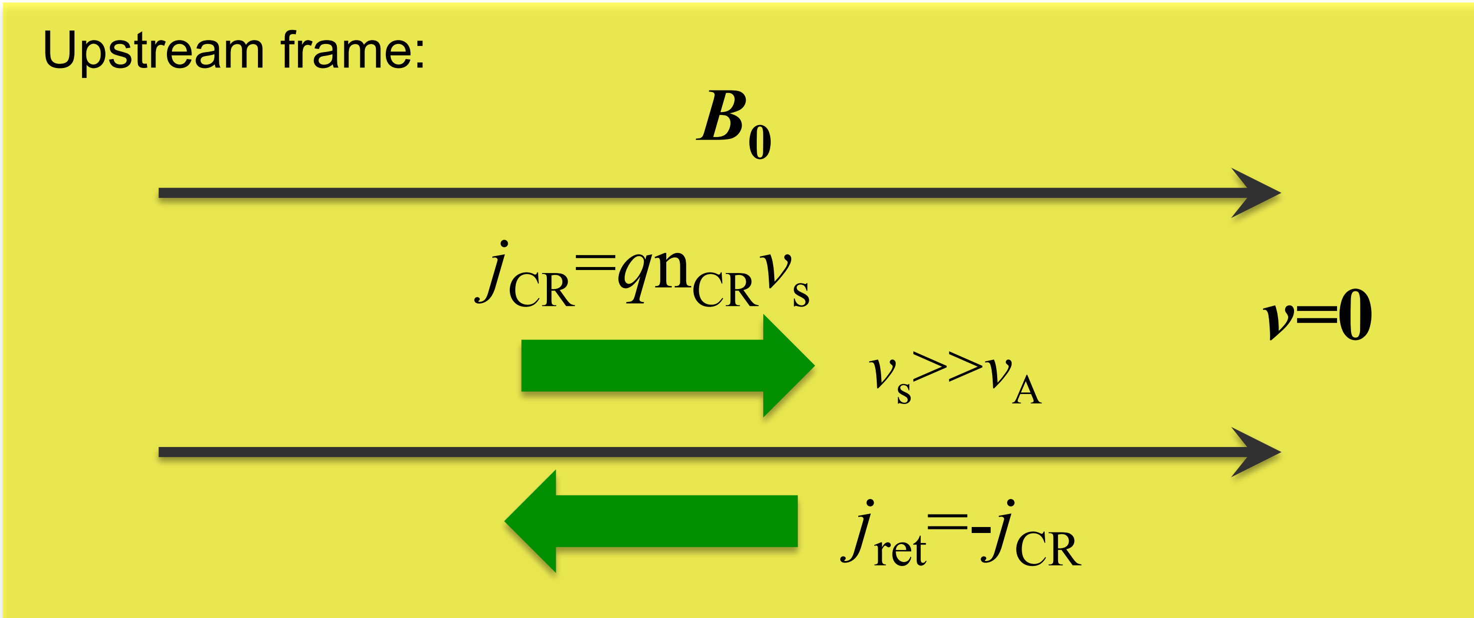


- Freshly accelerated CRs streaming into the upstream: source of free-energy to trigger plasma instabilities => turbulence

Many plasma instabilities can be relevant, depending on shock parameters (Mach numbers, magnetization), and scales (e.g., for e^-/ion acceleration).

The Bell instability

(Bell, 2004)



Composition of current: $\boldsymbol{J} = \nabla \times \boldsymbol{B} = \boldsymbol{J}_{\rm CR} + \boldsymbol{J}_g$

Changes to the MHD equation:

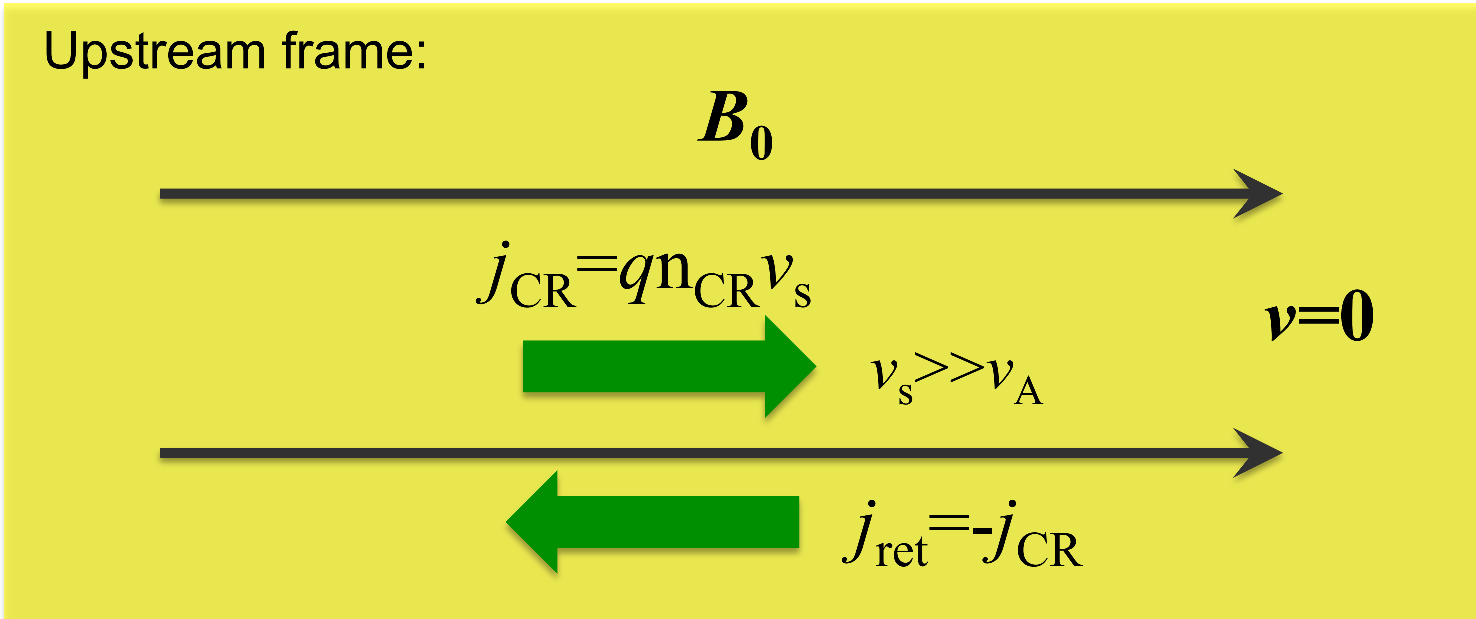
$$\rho \frac{d\boldsymbol{v}}{dt} = -\nabla P + \boldsymbol{J}_g \times \boldsymbol{B}$$

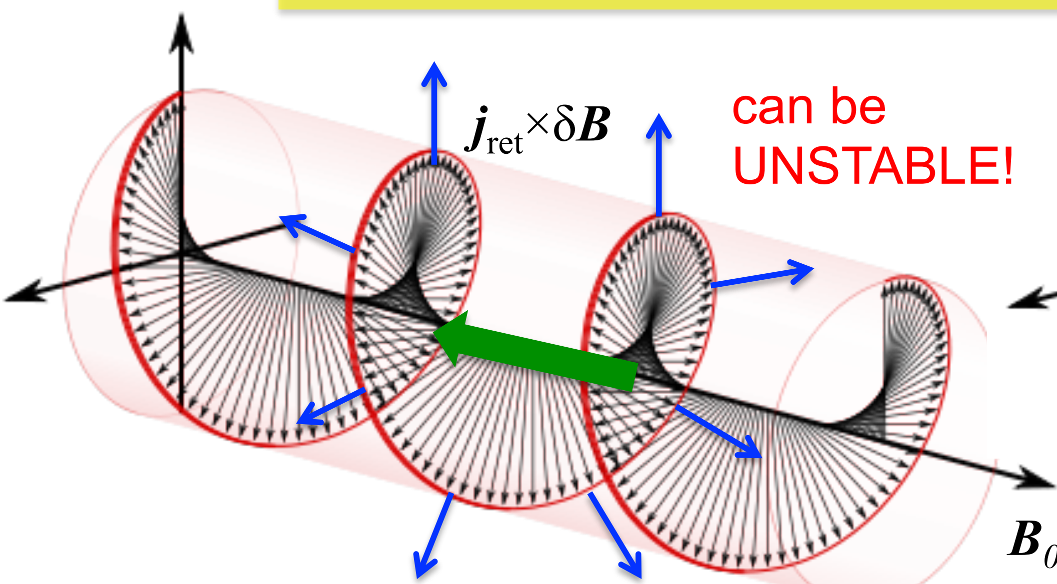
$$= -\nabla P + \boldsymbol{J} \times \boldsymbol{B} - \boldsymbol{J}_{\rm CR} \times \boldsymbol{B}$$

This is how CRs feedback to the upstream plasma

The Bell instability

(Bell, 2004)





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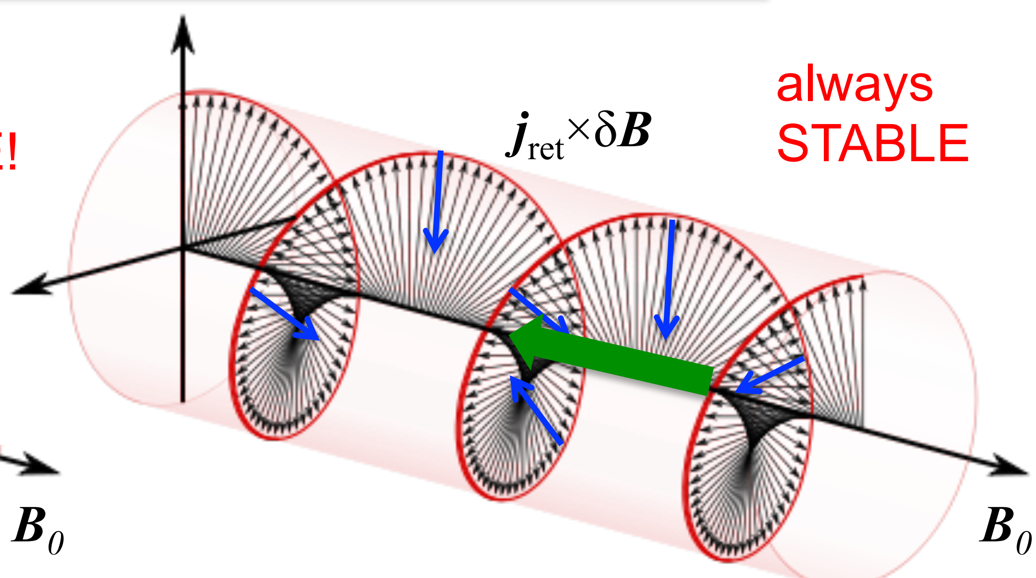


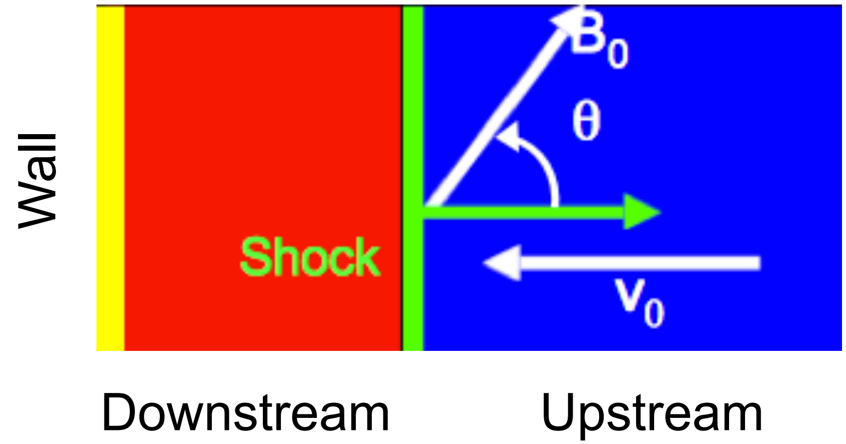
Left pol:

Microphysics of particle acceleration

- Injection problem: what determines how many particles get accelerated?
- Over decades, theoretical calculations always assume a certain fraction (injection fraction η) of particles get accelerated, which is a free parameter to be constrained observationally.
- Self-consistent PIC simulations are essential to determine η, which was not possible until recently, and the theory for (initial) ion injection is developed (Caprioli, Pop & Spitkovsky, 2015).
- Shocks do not always efficiently accelerate particles: depending on shock parameters and magnetic field configuration.
- In reality, η likely evolves (decreases) with time: as acceleration proceeds, total CR energy should not exceed shock energy.

Shock simulations: setup and parameters

- Colliding fast-moving flow into a reflecting wall: simulation is in the downstream frame, shock moves to the right.
- Particle-in-cell simulations: only cover a tiny patch of the shock



- Main parameters (non-relativistic shock):

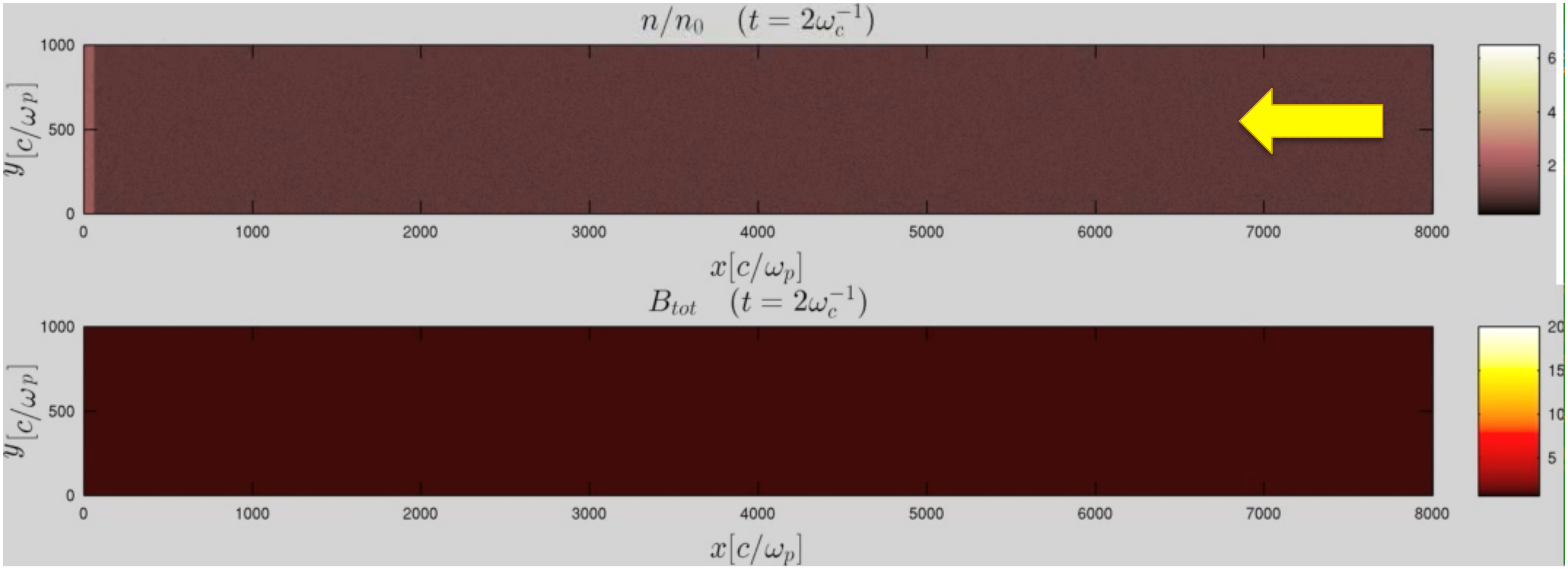
  Alfvenic Mach number: $M_A=v_0/v_A$

  Sonic Mach number: $M_s=v_0/c_s$

  Magnetic obliquity: θ (<45°: quasi-parallel; >45°: quasi-perp)

Young SNR shocks: $M_A \sim M_s \sim 300\text{-}1000$

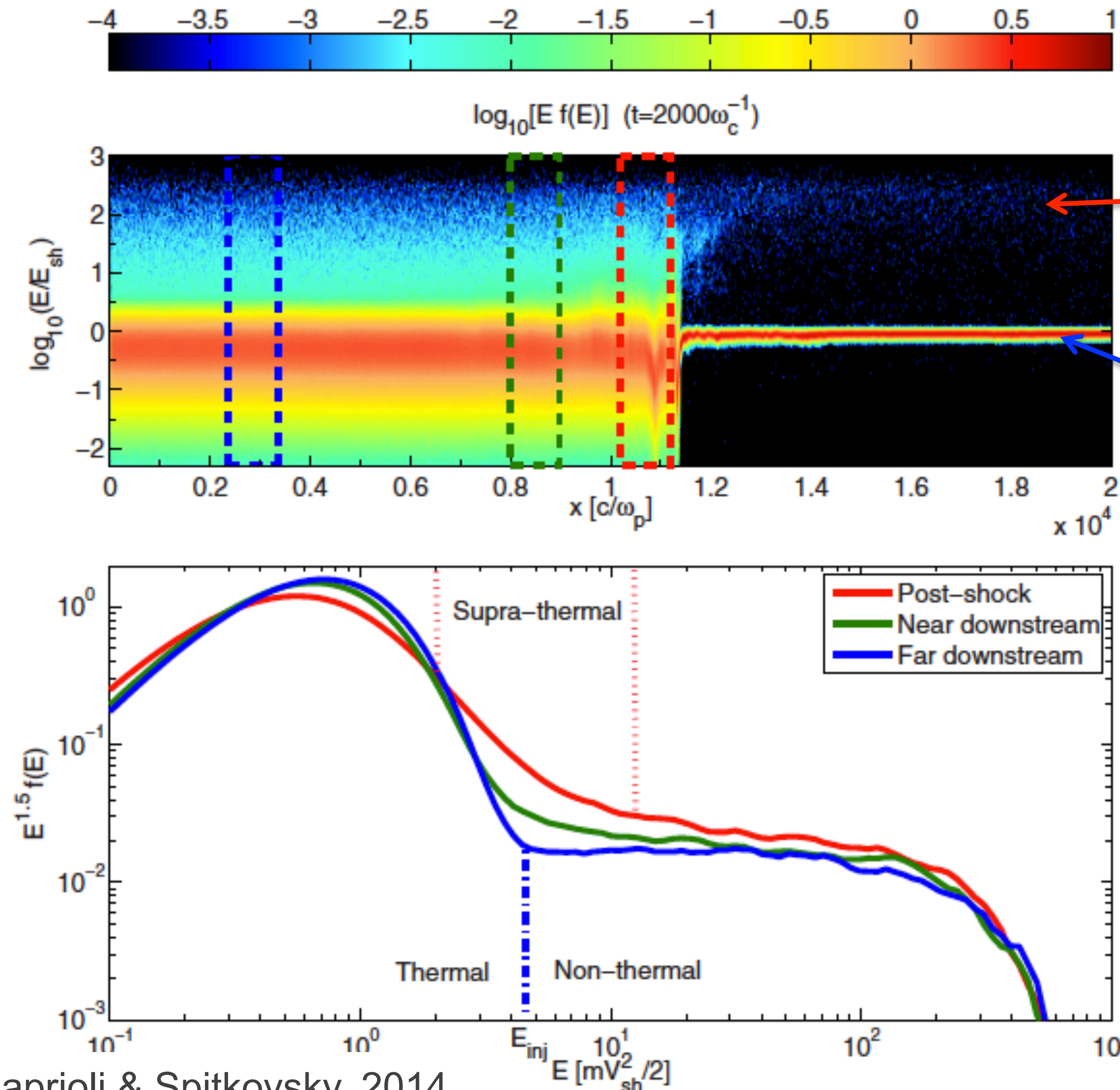
Ion acceleration in non-relativistic shocks



Caprioli & Spitkovsky (2013)

- Hybrid-Particle-in-cell simulation (ions are kinetic, electrons as massless fluid), over scales of ~10^3 ion skin depth (~10^{-8} pc!)
- Upstream: onset of instabilities and turbulence
- Downstream: strong magnetic field amplification.

Particle energy spectrum



accelerated particles streaming into upstream

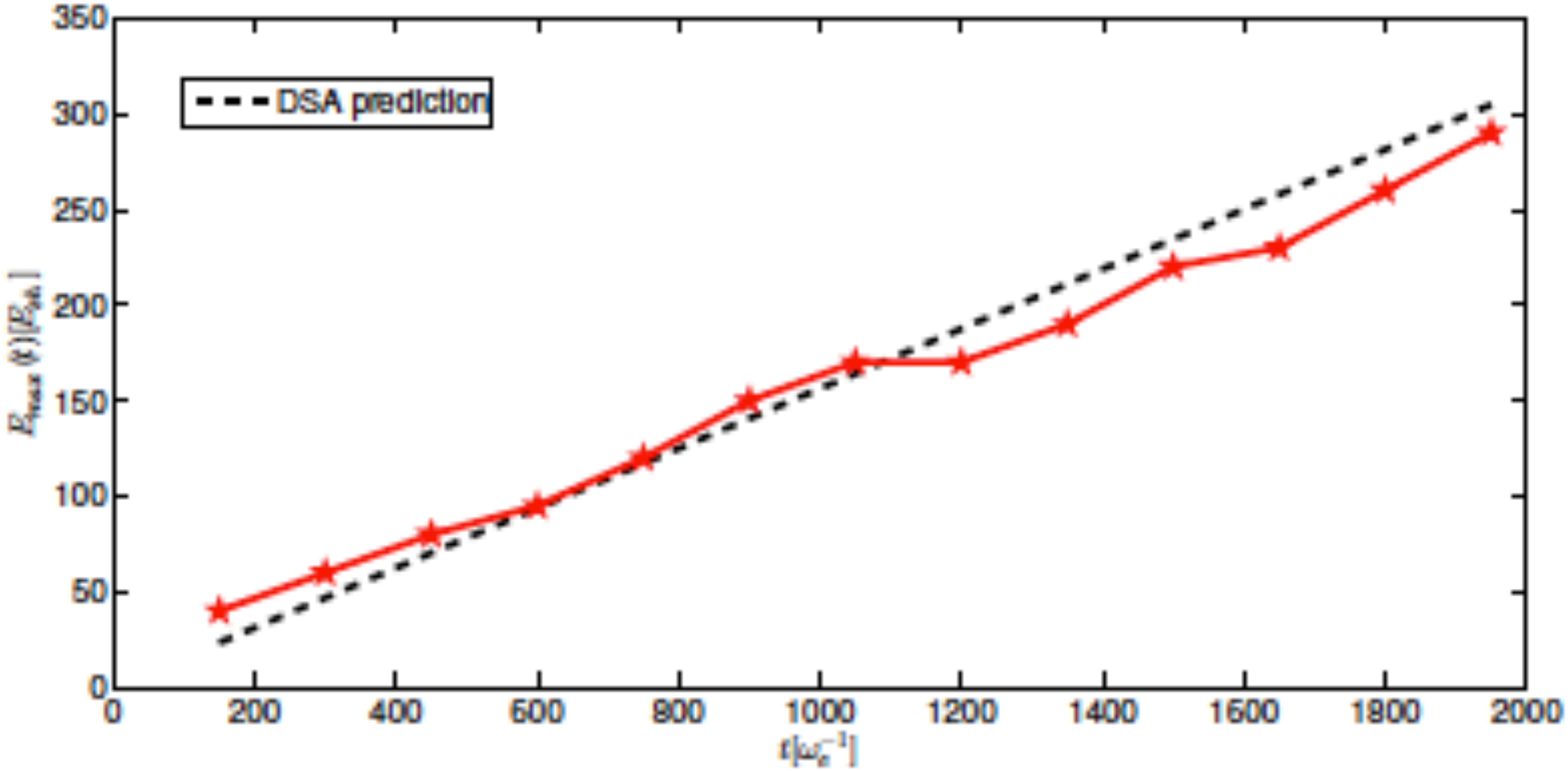
incoming cold upstream ion beam

~10-20% of shock kinetic energy converted to CRs.

Caprioli & Spitkovsky, 2014

Maximum particle energy

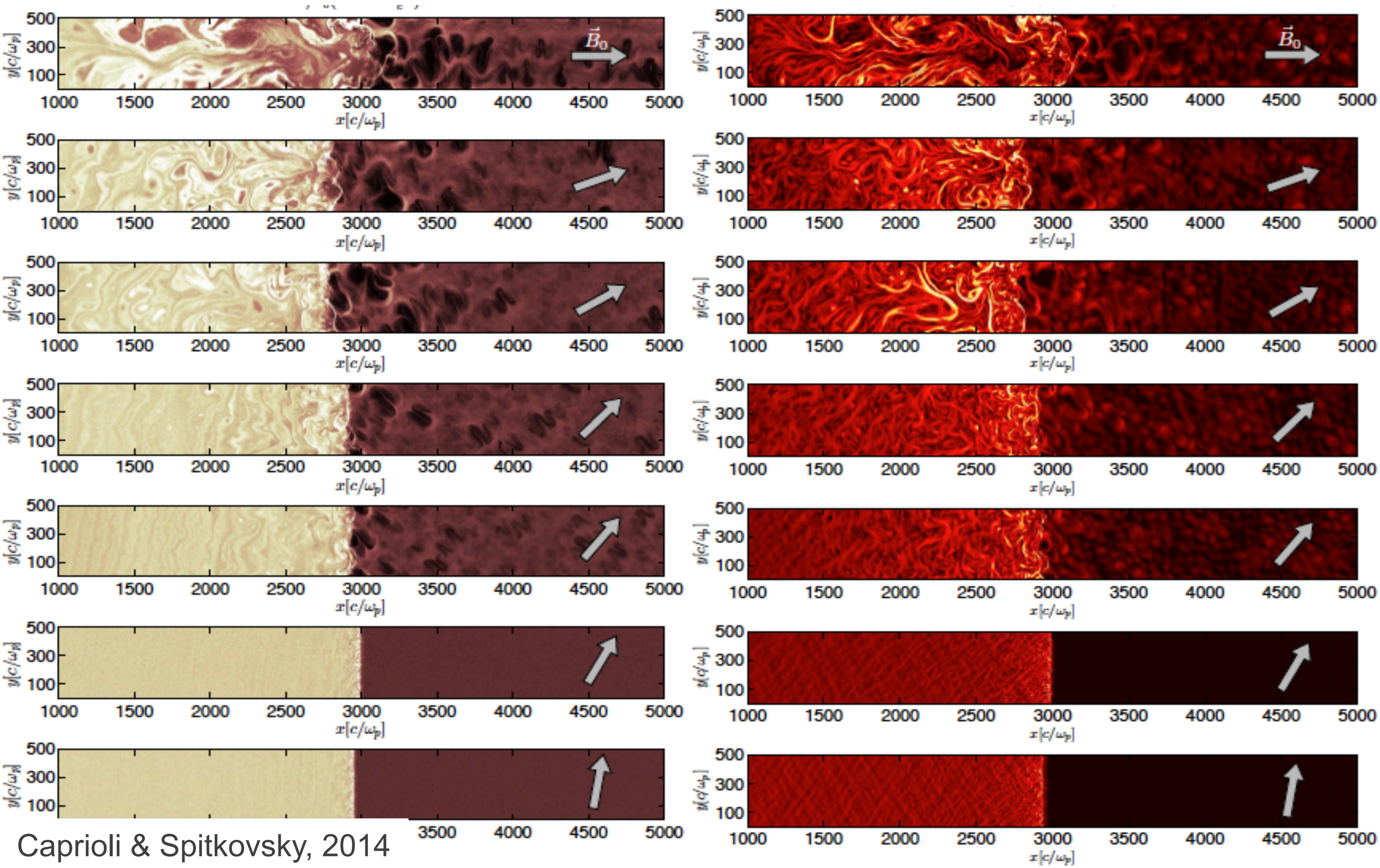
Caprioli & Spitkovsky, 2014



Efficient acceleration with: $E_{\max} \propto t$

Diffusion is roughly in the Bohm limit.

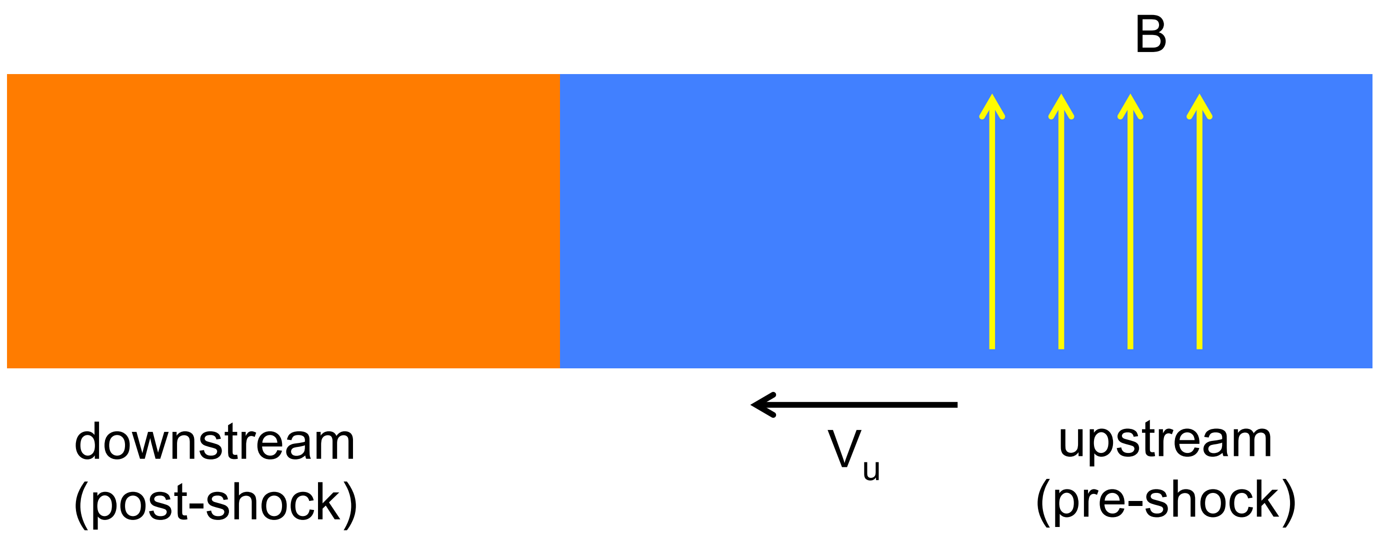
Ion acceleration favors quasi-parallel shocks



Caprioli & Spitkovsky, 2014

Why quasi-perp. shocks fail to accelerate ions?

- Ions returning to the upstream gyrate around the perpendicular B field: hard to return far upstream.



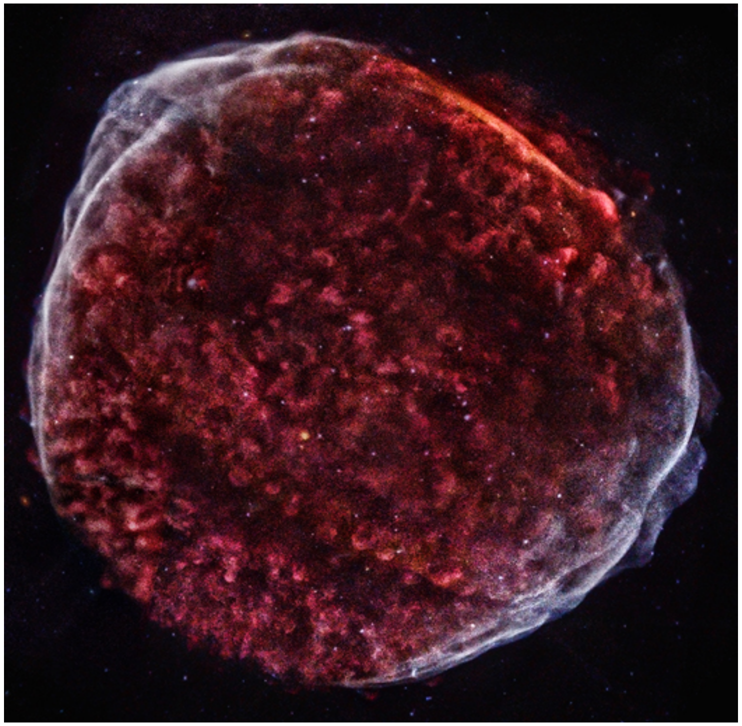
Upstream velocity = ExB drift velocity

Particles can travel into upstream for at most 1 Larmor radius.

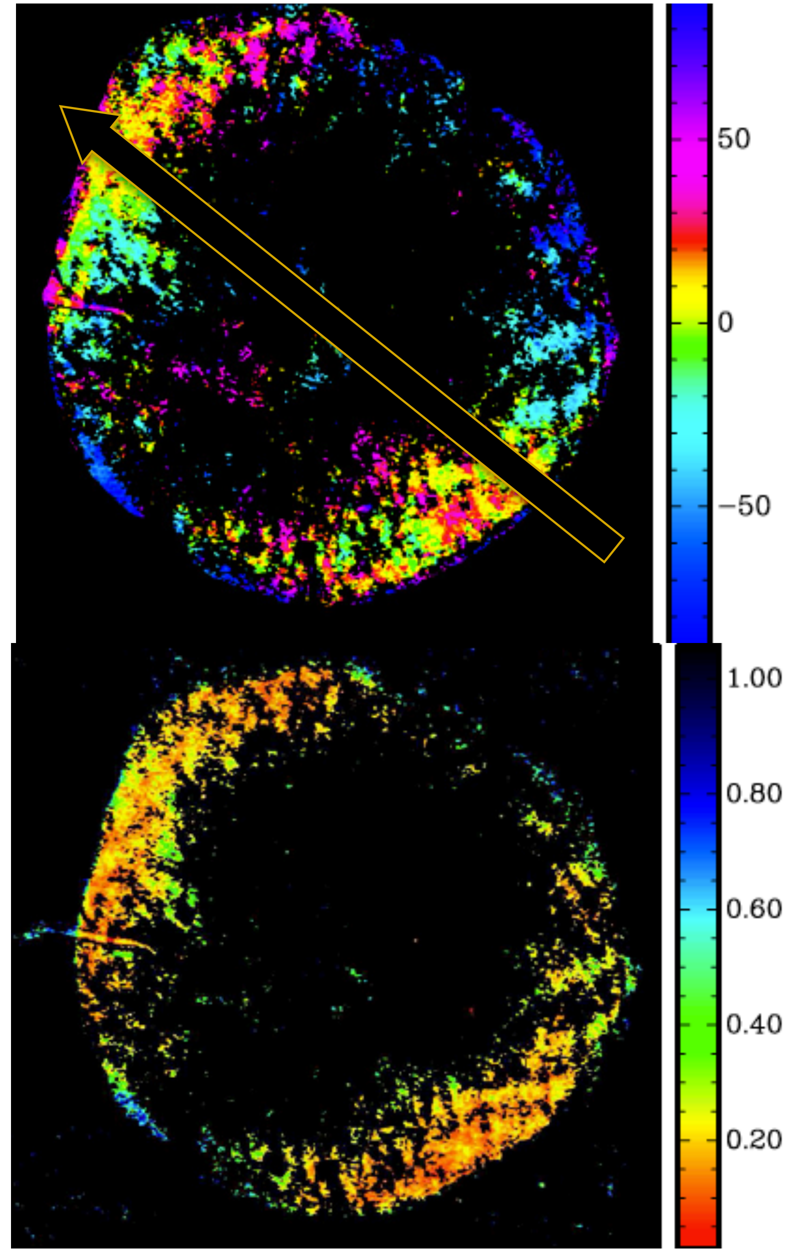
The story for electrons is different (1 ion gyro-radius = many electron gyro-radius) but not quite clear yet.

SN 1006: a parallel accelerator?

(Reynoso et al. 2013)



Chandra image



Top: field orientation angle inferred from radio polarization direction.
Bottom: polarization fraction.

Major open questions

- Electron acceleration in non-relativistic shocks still not well understood.

  Injection is the major problem: unless electrons are hot, otherwise, their gyro-radii are too small and easily advected downstream without returning.

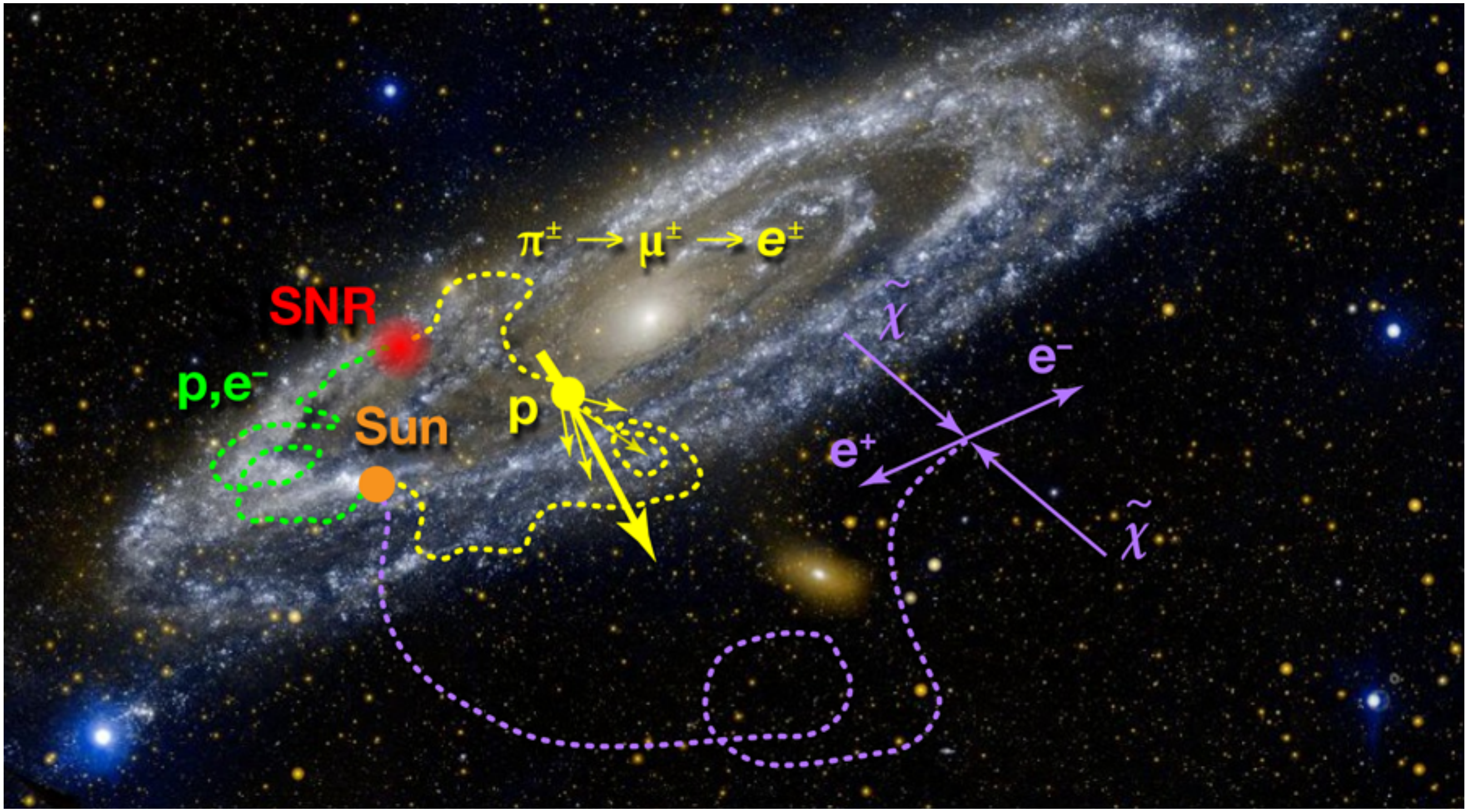
  PIC simulations for this problem are extremely expensive, but currently under active investigation (e.g., Amano & Hoshino 10, Riquelme & Spitkovsky 11, Guo+14, Park+15).

- What is the maximum energy that SNR shocks can achieve?

  The CR spectrum and composition around the knee are not yet measured with great precision, with evidence of heavier composition beyond the knee

  PIC simulations can only account for the very beginning stage of the acceleration. Extrapolation suggests PeV energy can be achieved.

CR propagation



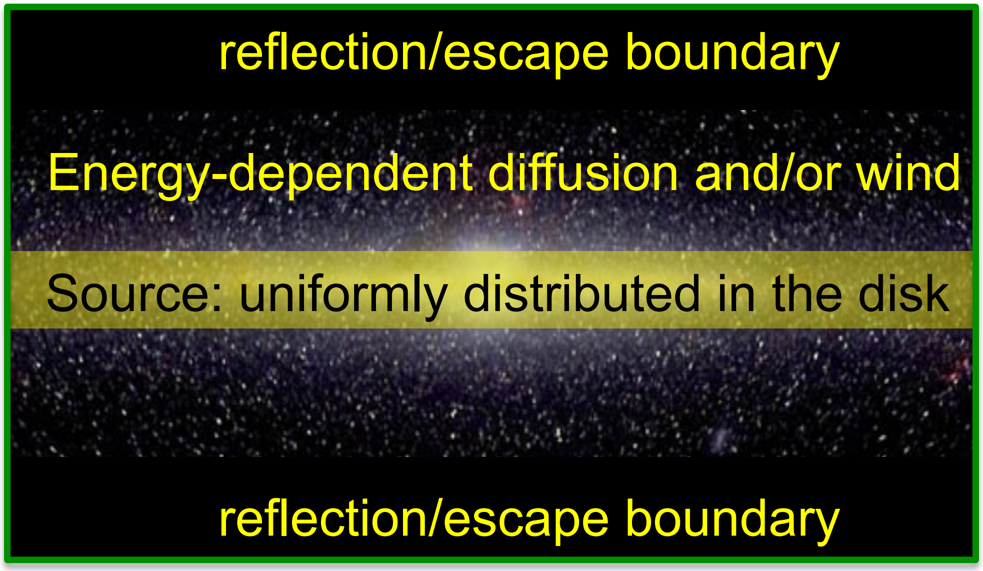
- How to interpret the observed CR energy spectrum, composition and spatial distribution?
- CRs interact with the ISM, interstellar radiation field, and magnetic fields to produce diffuse radiation from radio to gamma-rays.

CR propagation: leaky-box model

CRs are confined within a volume (box), with a constant escape probability per unit time, so that:

$$\frac{\partial n_i(E, \boldsymbol{x})}{\partial t} = -\frac{n_i(E, \boldsymbol{x})}{\tau_{\mathrm{esc}}}$$

Physical realization:



- Introduced in the 1960s to interpret CR data, to infer CR residence time, grammage, etc.
- Improved over decades towards more and more sophisticated models.

Ingredients of CR propagation:

CR propagation equation (Strong et al. 2007, ARA&A):

Define: $\psi(p)dp = 4\pi p^2 f(\vec{p})dp$

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla} \cdot \vec{V})\psi \right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi,$$

Spatial diffusion

Advection

CR source term

Momentum diffusion

External force

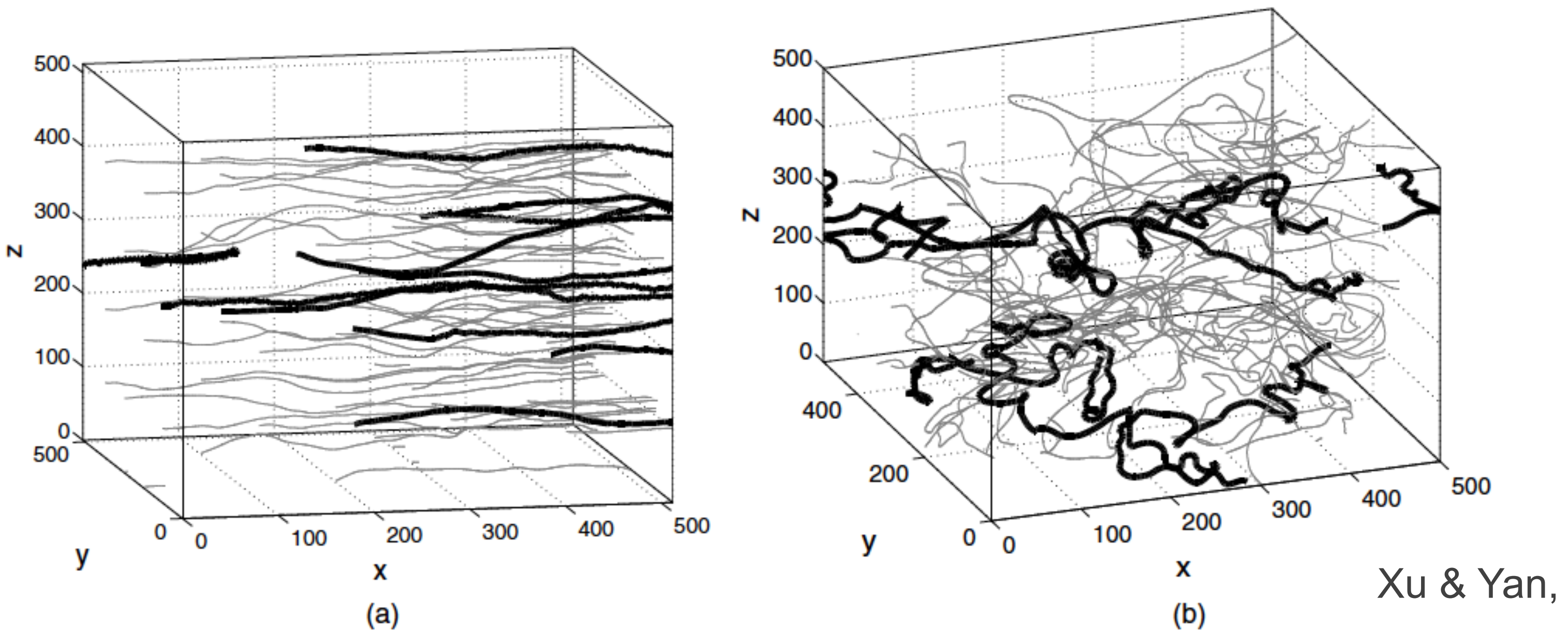
Adiabatic loss/gain

Loss by fragmentation and decay

All incorporated in the package **GALPROP**, and the details have constantly been updated and improved.

What determines the diffusion coefficients?

CR diffusion in MHD turbulence:



Xu & Yan, 2013

- Measure (test) particle diffusion coefficients: both spatially and in momentum space
- Result depends on Mach number and particle rigidity.
- Both gyro-resonance and transit-time damping are important.

CR diffusion turbulence in the ISM: scales

Turbulent ISM:

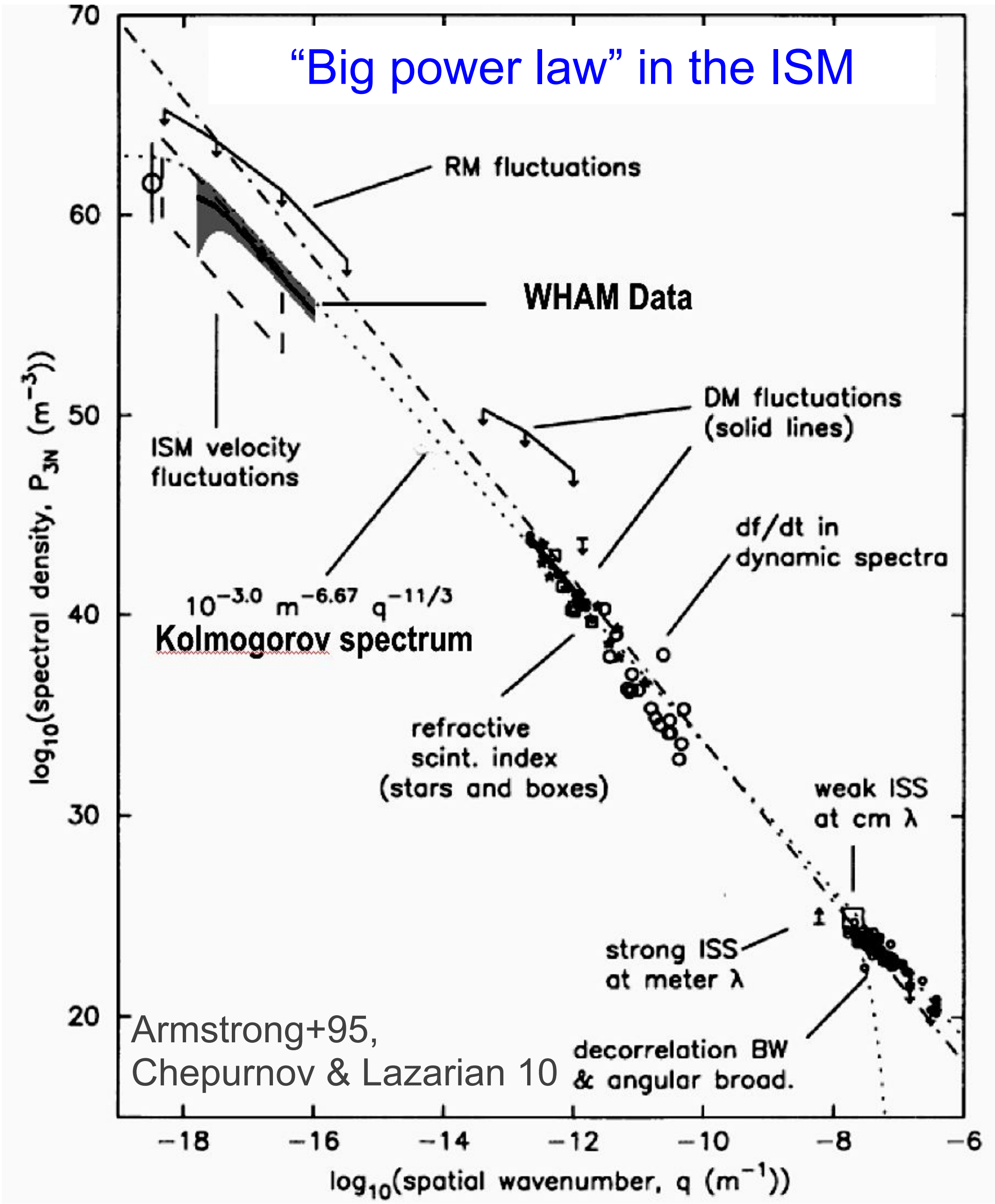
turbulence energy density
~ thermal energy
~ CR energy density

Resonant scales:

$$R_g \sim \left(\frac{E}{10^{15}\mathrm{eV}}\right)\left(\frac{B}{\mu G}\right)^{-1} \mathrm{pc}$$

Turbulence energy density concentrates on large scales => most efficiently scatter ~TeV-PeV CRs.

CR energy density concentrates in low-energy (GeV) CRs, where turbulence power is tiny.



The dynamical role played by the CRs

- CRs affect the dynamics of background plasma by exerting external current:

$$F = -\nabla_{\perp} P_{\mathrm{CR}} = -\frac{\boldsymbol{J}_{\mathrm{CR}} \times \boldsymbol{B}}{c}$$

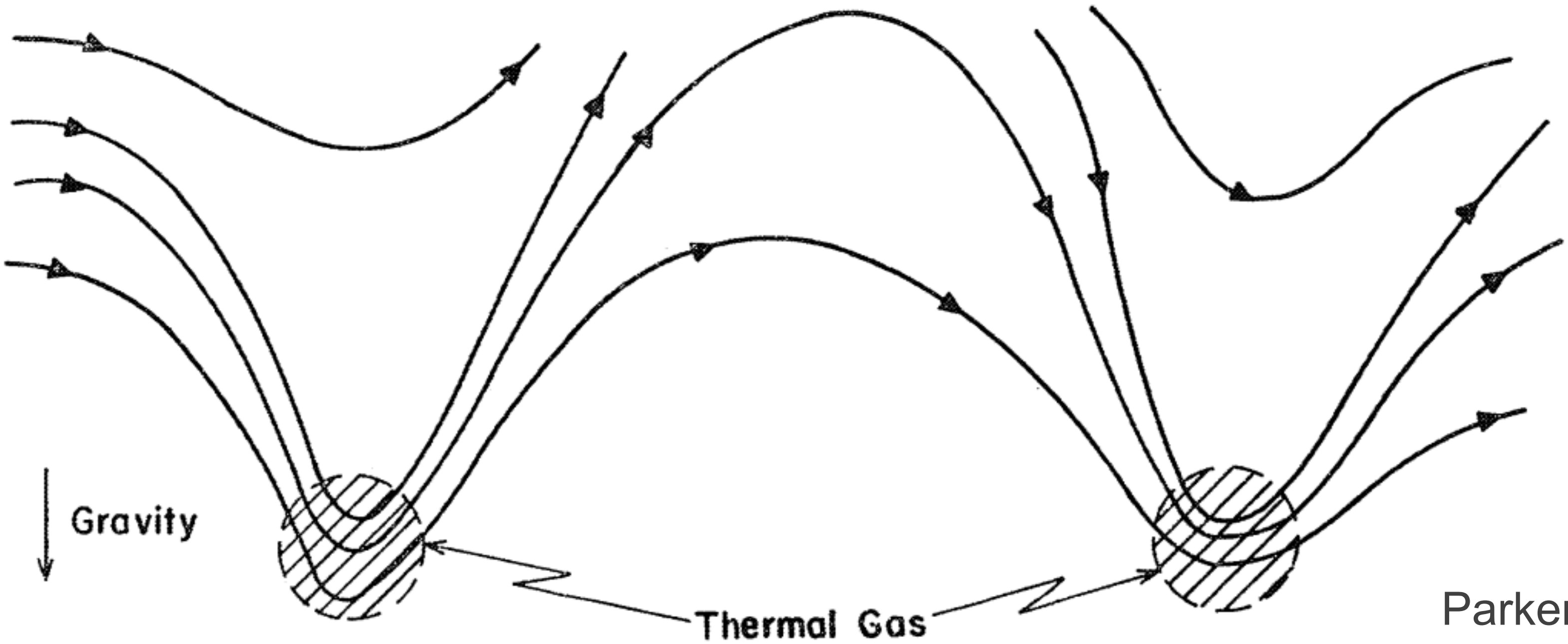
Effectively, it provides pressure support perpendicular to B.

- CRs streaming through background plasma faster than Alfven speed will excite instabilities.

CRs transfer energy and momentum to gas via Alfven waves.

(Kulsrud & Pearce, 1969, Bell, 2004)

Example: the Parker instability



Parker, 1966

Magnetic buoyancy: B fields are massless yet has pressure. A fluid can become unstable when magnetic field dominates pressure support.

Analogous to Rayleigh-Taylor instability.

Cosmic-rays behave similarly as B fields!

CR streaming instability

When CR drift velocity v_D exceeds v_A:

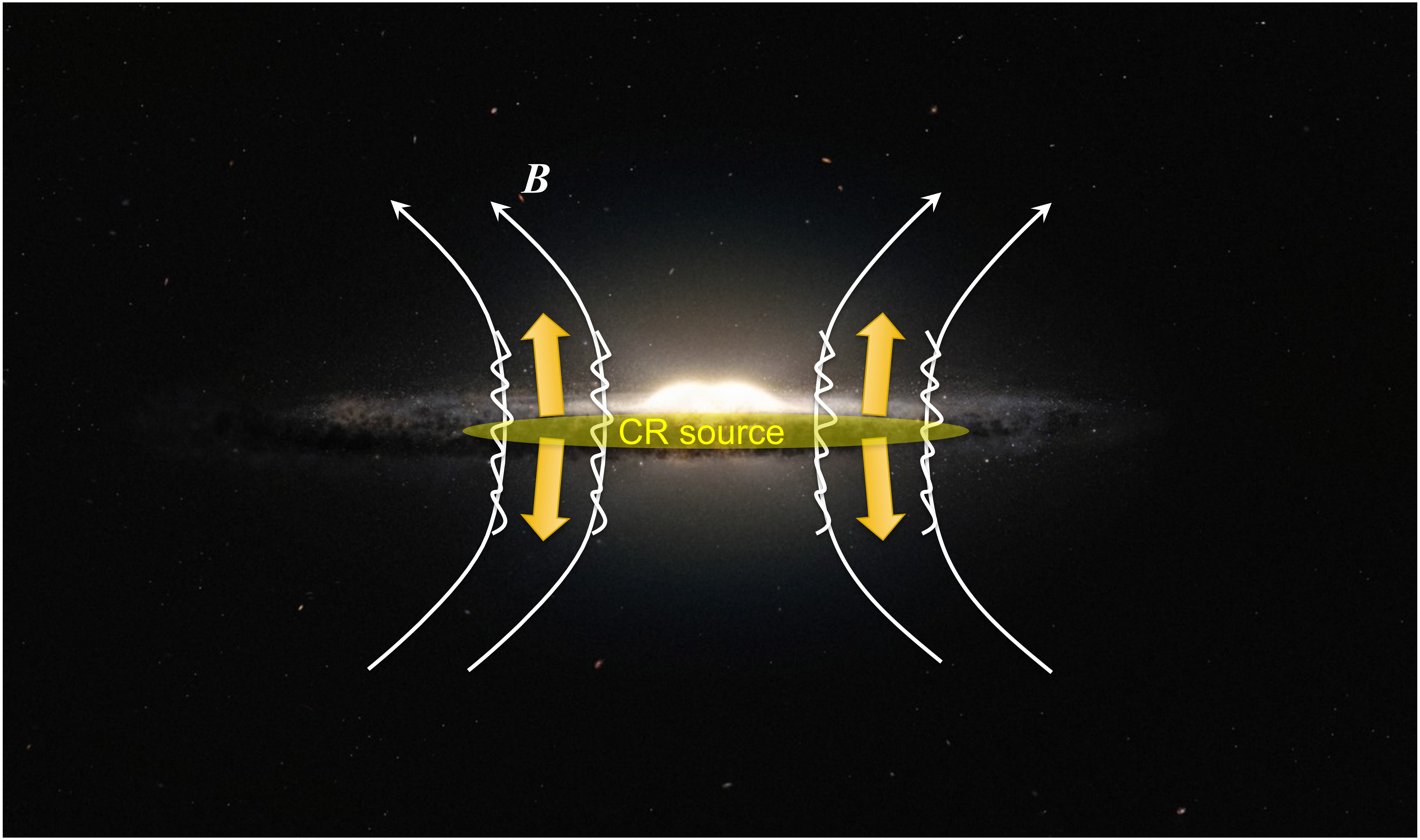
- Forward-traveling CRs resonantly excite (right) polarized, forward-propagating Alfven waves.
- Backward-traveling CRs resonantly excite (left) polarized, forward propagating Alfven waves.
- Backward-propagating Alfven waves are suppressed.

Characteristic growth rate: (Kulsrud & Pearce, 1969)

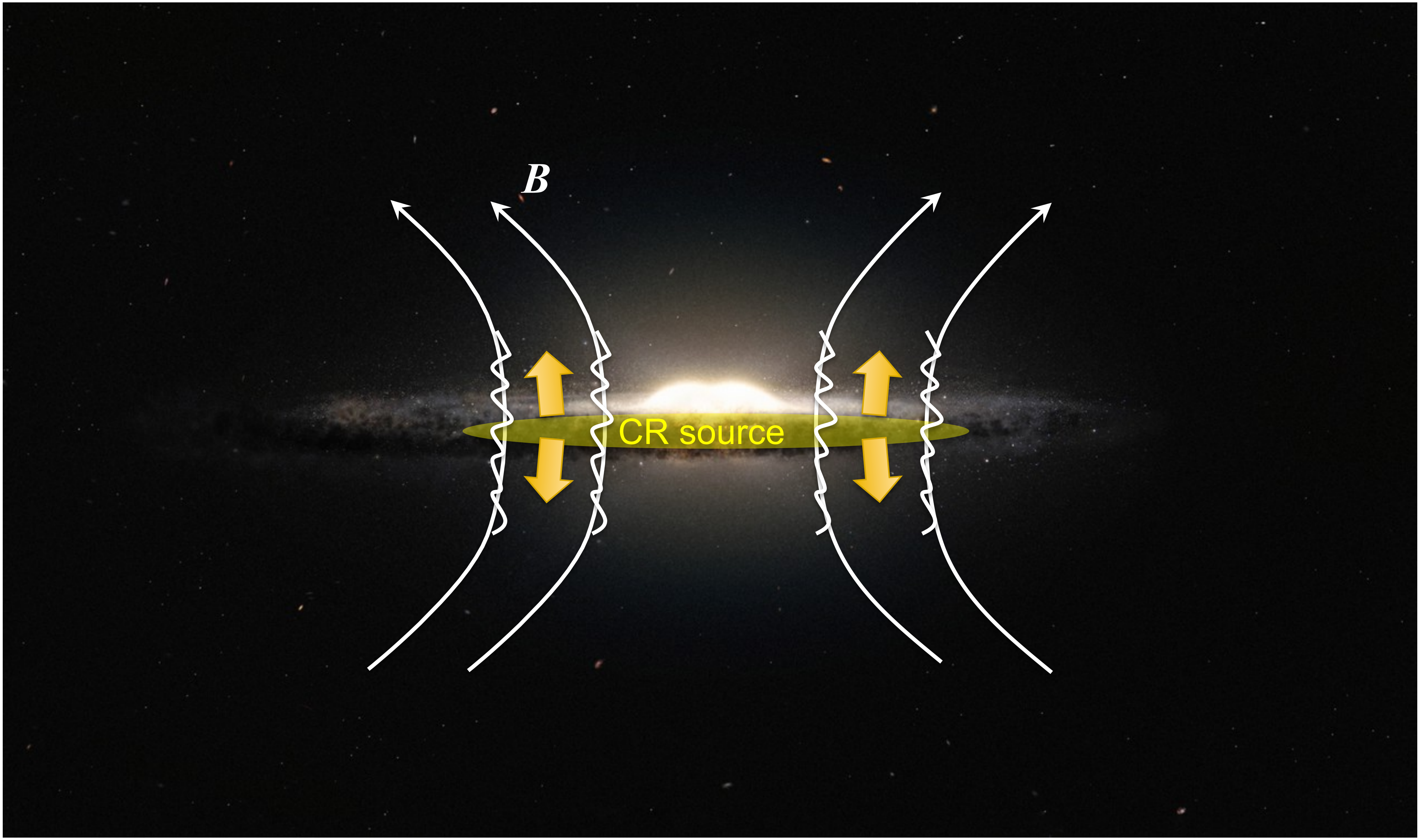
$$\Gamma(k) \approx \Omega_c \frac{N_{\rm CR}(p > p_{\rm res}(k))}{n_i} \frac{v_D - v_A}{v_A}$$

More generally, when CR anisotropy exceeds $\sim v_A/c$, certain Alfven modes become resonantly unstable.

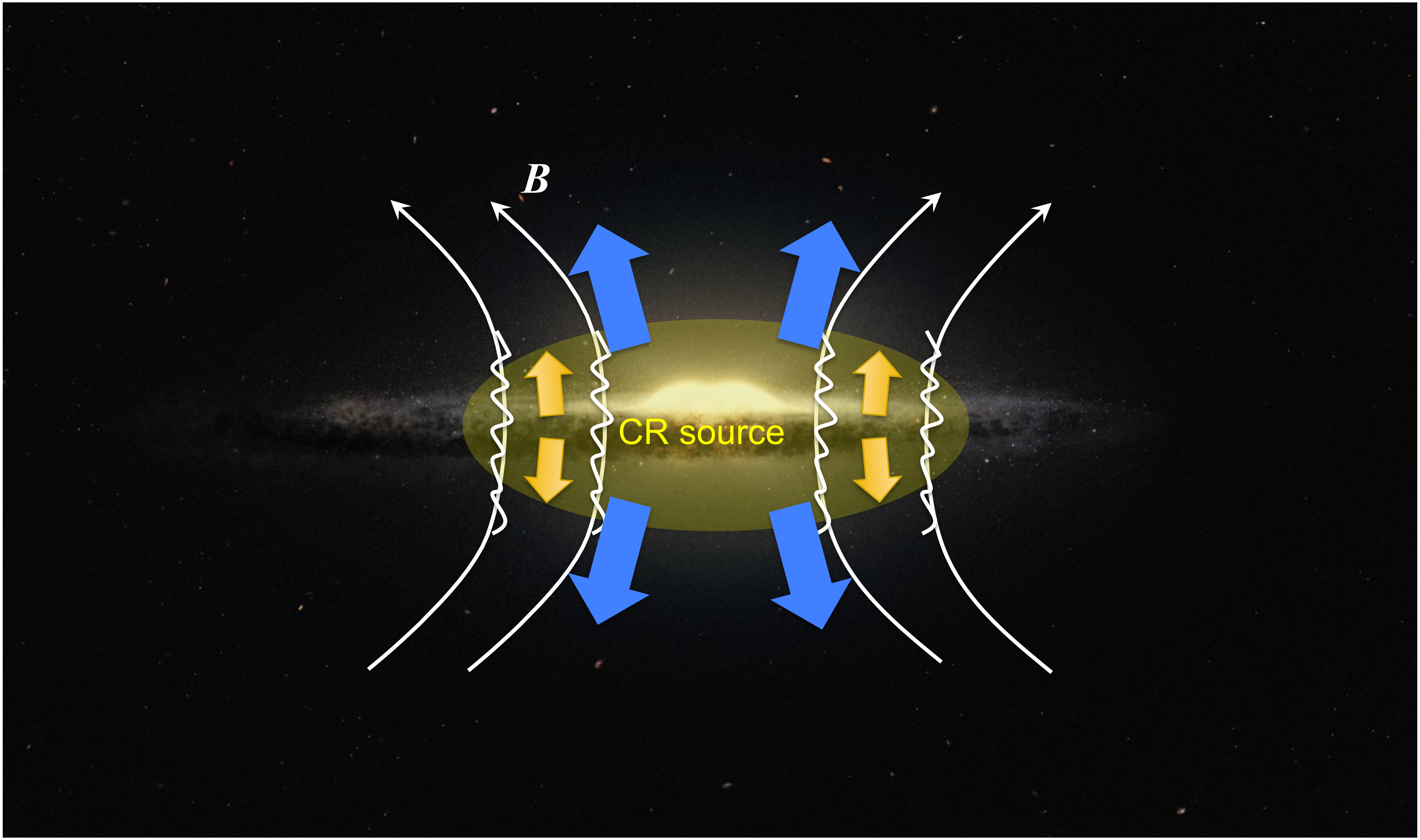
CR self-confinement and CR-driven wind



CR self-confinement and CR-driven wind

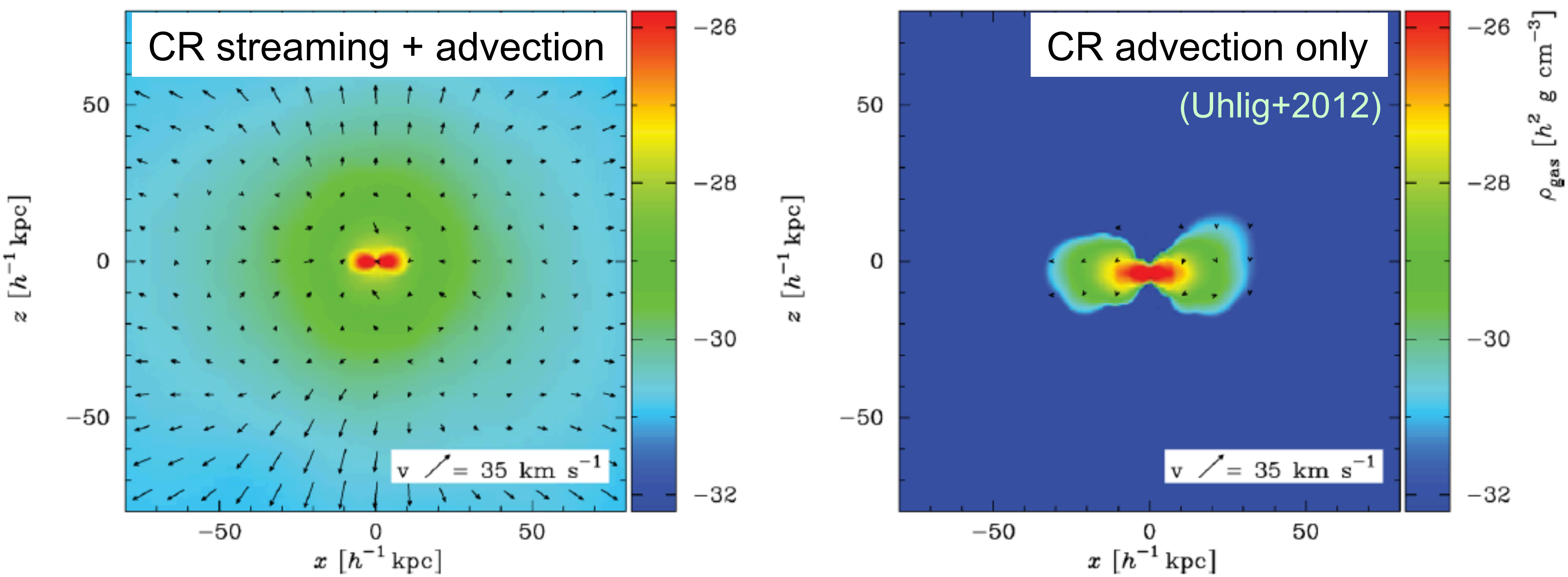


CR self-confinement and CR-driven wind



How to model CR in cosmological simulations?

- CRs are at the beginning of being incorporated into (hydro) cosmological simulations in a highly simplified form of streaming (Uhlig+12), or diffusion (Booth+13, Hanasz+13, Salem & Bryan14).



Prescription of CRs urgently needs improvement!

Ultra-high energy CRs (UHECR)

- Particles with energy beyond the ankle (10^{18-19} eV)

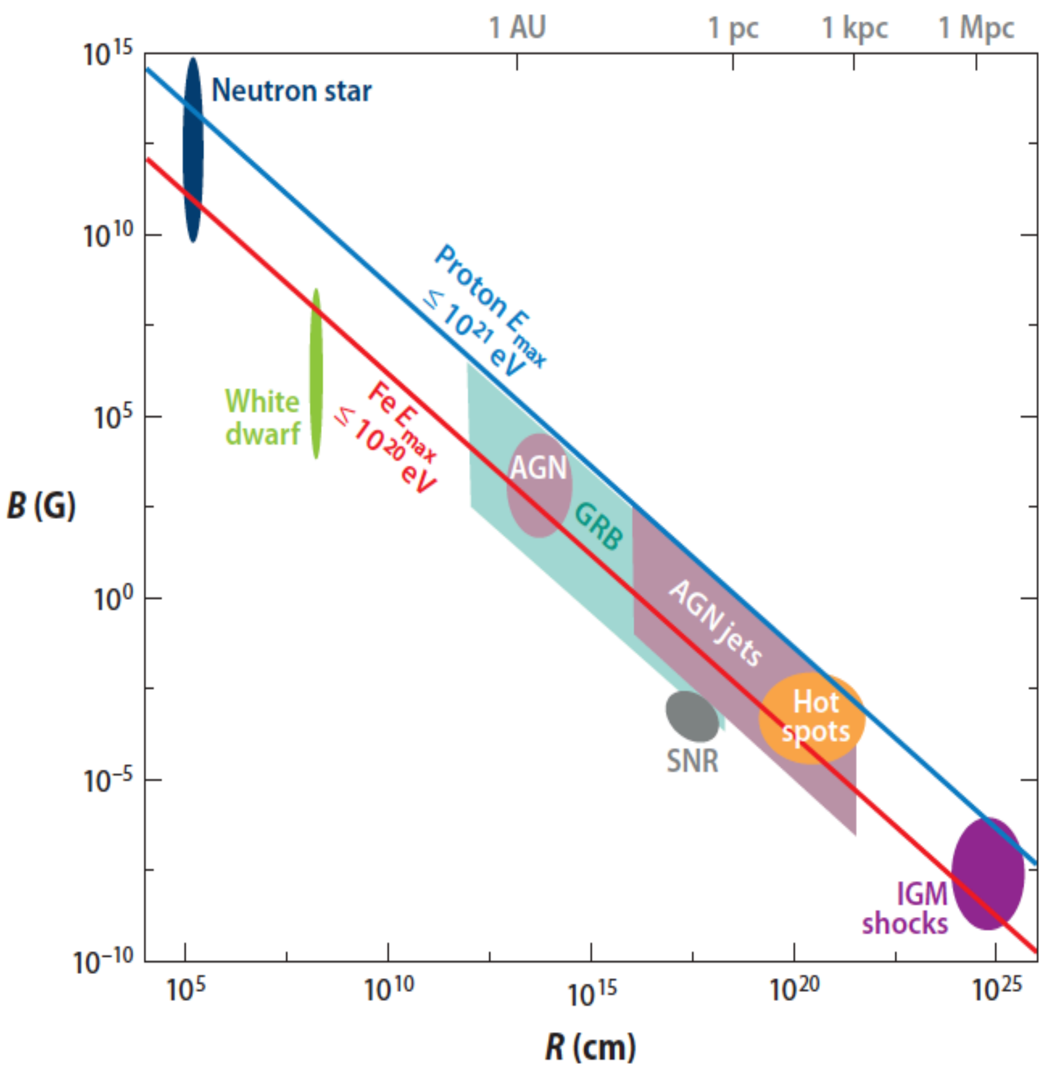
  Note: 1 eV = 1.6×10^{-12} erg = 1.6×10^{-19} J

  => a microscopic particle carries macroscopic energy!

- Extremely rare: reasonable statistics starts to build up only recently thanks to big observatories (HiRes Fly's Eye, Pierre Auger, the Telescope Array, etc.).
- Energy far beyond the reach from particle accelerators, of great interest to particle physicists.
- Their energy spectrum and composition remain not well constrained.
- Key question: what is the most powerful particle accelerator in the universe?

Origin of UHECRs

Kotera & Olinto, 2011, ARA&A



- Hillas criterion: the gyro-radius of particles cannot exceed the size of the acceleration site.

$$\epsilon_{\rm max} \simeq Z\left(\frac{B}{1\ {\rm G}}\right)\left(\frac{R}{1\ {\rm pc}}\right)\ 10^{20}\ {\rm eV}$$

The Milky Way can barely confine UHECRs. They must be of extragalactic origin.

Greisen-Zatsepin-Kuzmin (GZK) cutoff

In the frame of the UHE particle, a CMB photon becomes a gamma-ray photon => subject to pair/pion production.

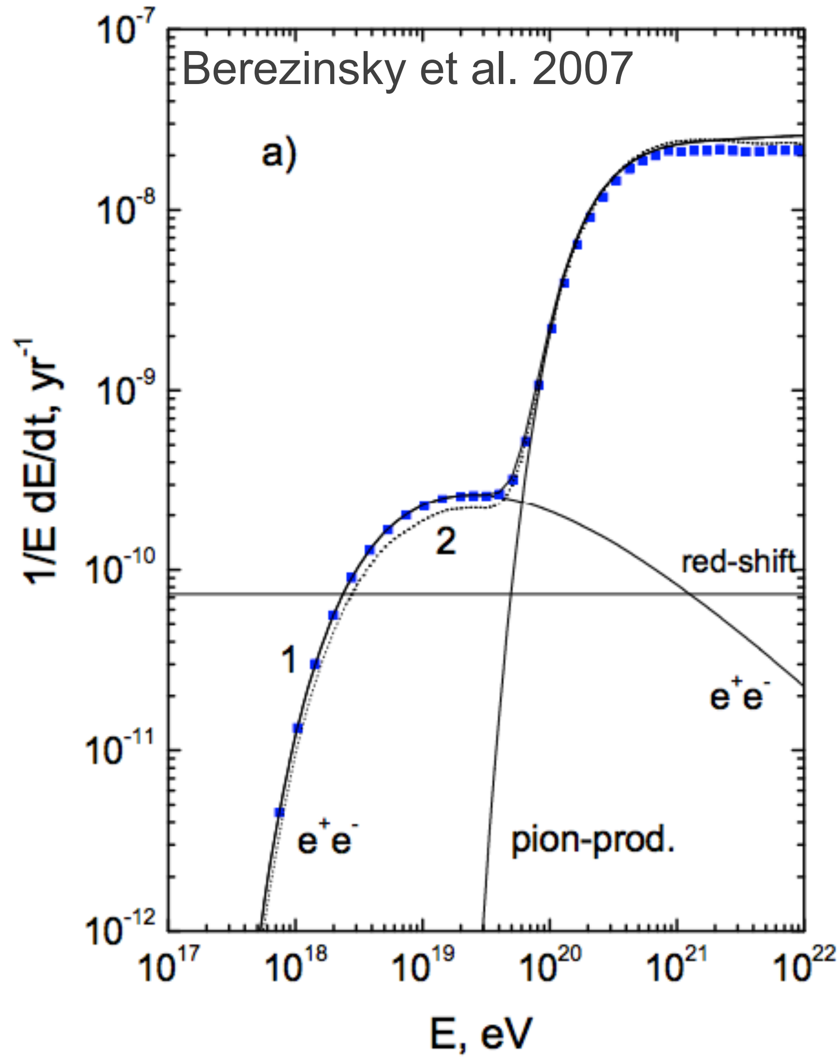
$$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$$

Energy threshold ~10^{18}eV but small cross section => give a dip in CR spectrum at 2×10^{18}-4×10^{19} eV

$$p + \gamma_{CMB} \rightarrow p + \pi^0$$

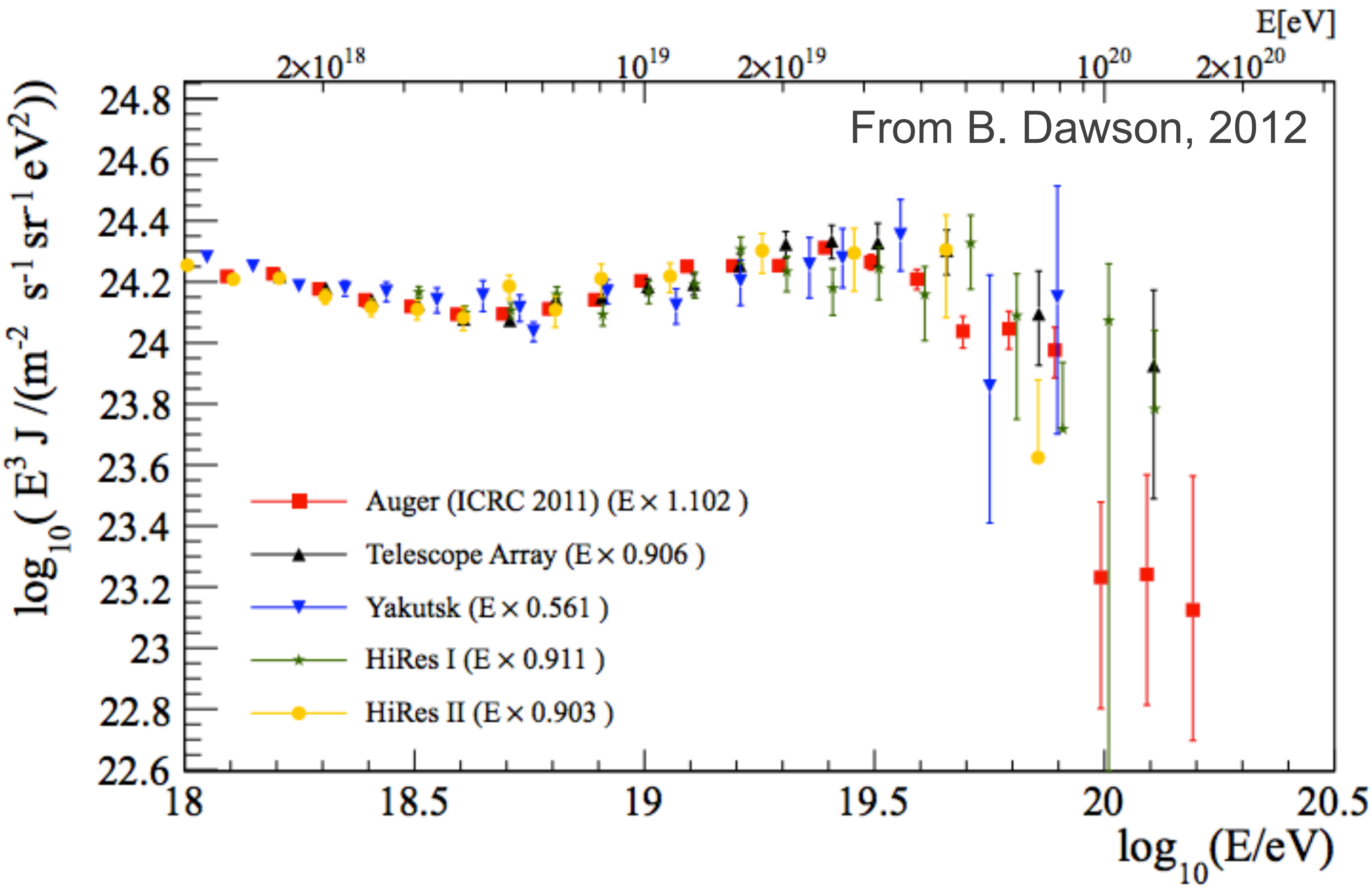
$$p + \gamma_{CMB} \rightarrow n + \pi^+$$

Higher energy threshold, larger cross section, gives GZK cutoff at ~6×10^{19} eV



- If UHECRs are produced at cosmological distances, a spectral cutoff is expected above this energy (GZK cutoff).

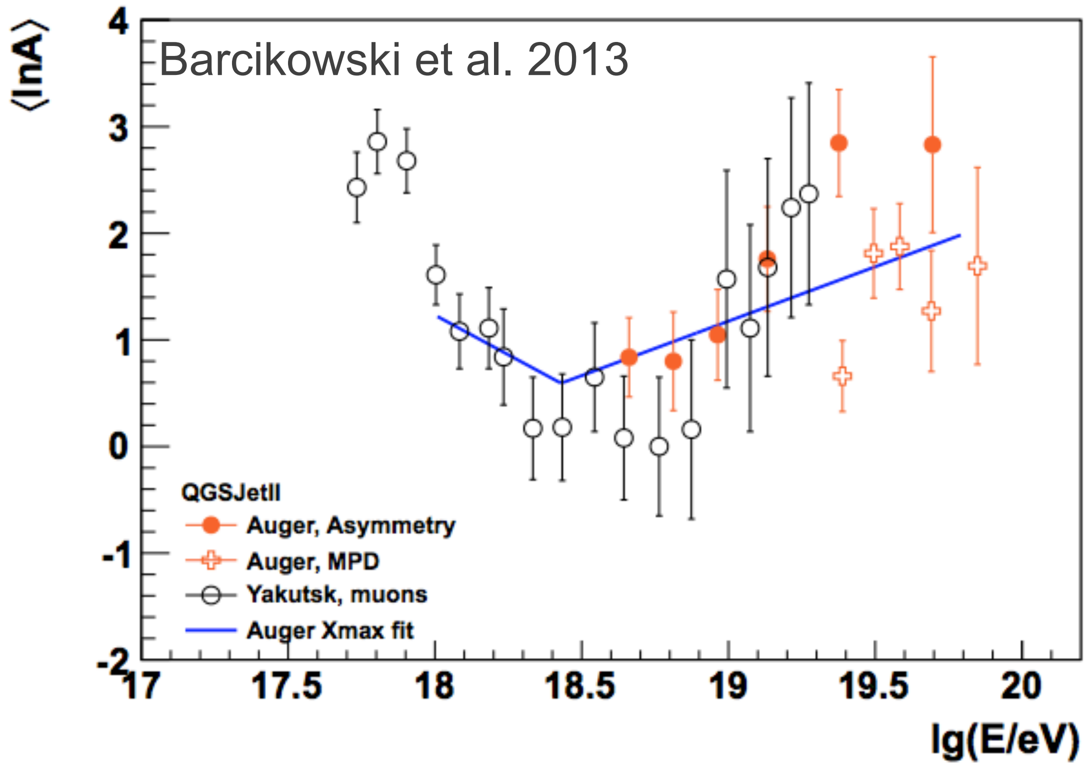
GZK cutoff: observations



- No cutoff was reported in early experiment AGASA (Takeda et al. 1998)
- More recent results show positive sign of the GZK cutoff (Abbasi et al. 2008, PRL; Abraham et al. 2008, PRL), but its interpretation is still uncertain because UHECR composition is poorly known.

Composition of UHECRs

- Evidence of increasing particle mass at energies between 10^{15} and 10^{17} eV (e.g., Kampert & Unger, 2012).



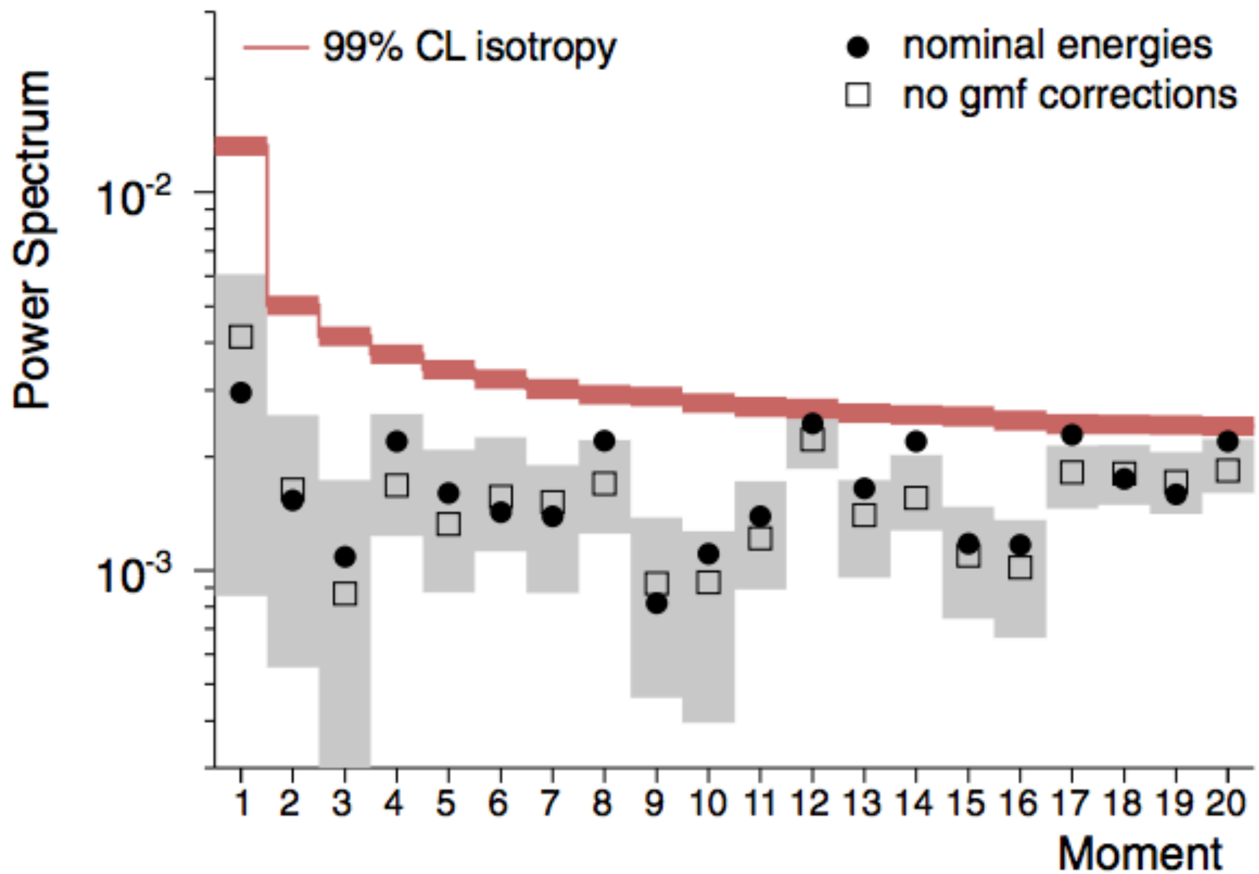
Mass measurement at UHE is very difficult in current CR observatories.

Currently, results are model dependent but tend to suggest light nuclei dominates at ~10^{18}eV while heavy nuclei dominate at ~10^{20}eV (e.g., Aab et al. 2014).

Spatial isotropy of UHECRs

(Aab et al. 2014, ApJ)

Early results from the Auger Observatory showed tentative correlation between the UHECR arrival directions and nearby AGNs.



However:

Joint analysis of data from the Telescope Array (US) and Pierre Auger Observatory (Argentina), spatial distribution of UHECRs with $E>10^{19}$eV is consistent with being isotropic.

Potential sources for UHECRs

- Debated over decades without resolution.
- Candidate acceleration sites include:

  Active galactic nuclei, particularly blazars/radio galaxies with relativistic jets (Ostrowski 2000, Murase et al. 2012)

  Gamma-ray burst (if similar energies in UHECRs and γ-rays, Waxman 1995)

  Newly born pulsars (by unipolar induction, Blasi et al. 2000, Fang et al. 2012)

- Ion acceleration in relativistic shock generally requires weak magnetization and is not very efficient (e.g., Sironi & Spitkovsky, 2013).
- Relativistic magnetic reconnection in high-sigma plasma? (revised Hillas criterion x0.02-0.04, Sironi, private communication).
- Still under active theoretical and observational investigation, multi-messenger (e.g., +neutrino/gamma-ray) approach needed.

Summary

- Basic properties of the CRs: energy spectrum, elemental abundance, spatial distribution
- CR acceleration:

  Diffusive shock acceleration (1^{st} order Fermi).

  Shock microphysics (CR-driven instabilities, injection mechanism)

- CR propagation and transport:

  Need to better understand the turbulence/field structure in the ISM.

- Dynamical role of CRs:

  Provide pressure support, and are subject to the streaming instability.

- UHECRs:

  Show sign of GZK cutoff, but more clues (especially composition) and theoretical works needed to tell their origin.