清華大學天文系
Department of Astronomy, Tsinghua University

12. Nonthermal components of the ISM

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Energy partition in the local ISM

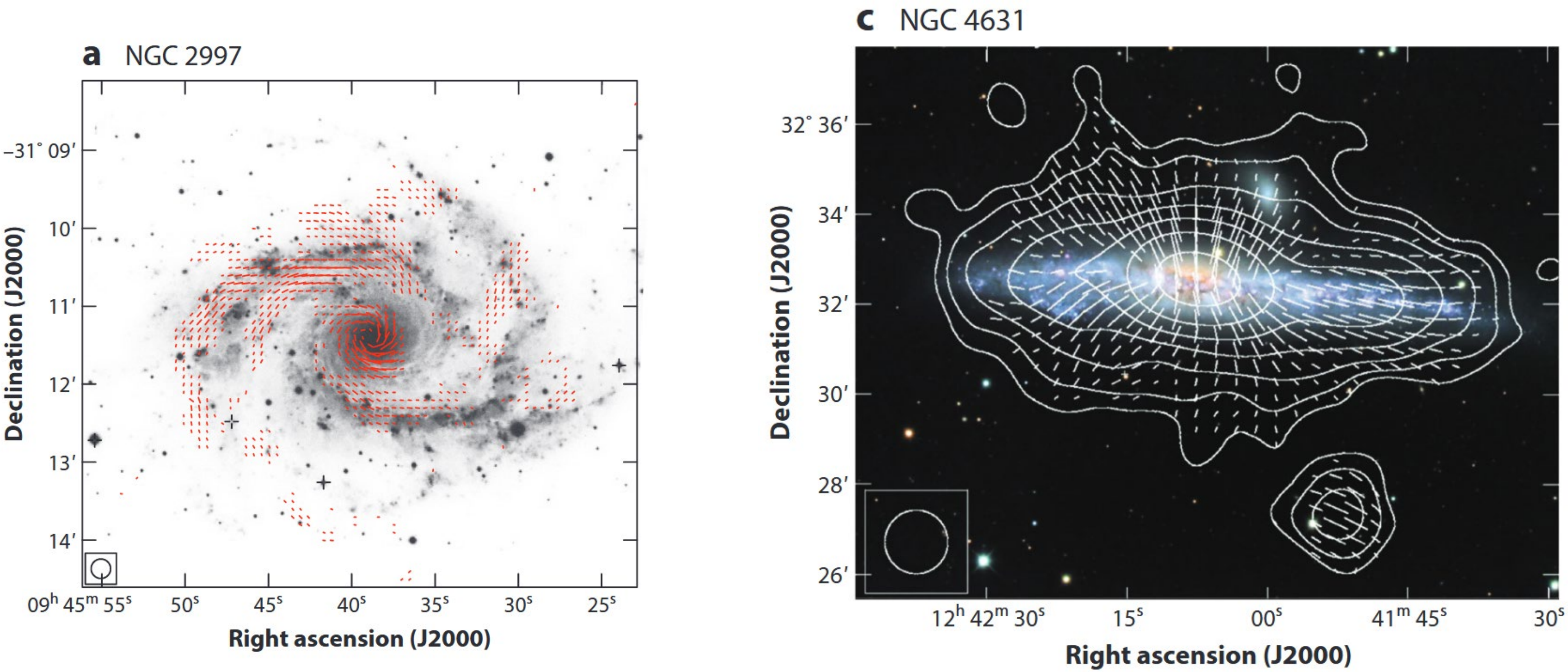
Component		$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background	$(T_{\mathrm{CMB}} = 2.725\,\mathrm{K})$	0.265	a
Far-infrared radiation from dust		0.31	b
Starlight ($h\nu < 13.6\,\mathrm{eV}$)		0.54	c
Thermal kinetic energy $(3/2)nkT$		0.49	d
Turbulent kinetic energy $(1/2)\rho v^2$		0.22	e
Magnetic energy $B^2/8\pi$		0.89	f
Cosmic rays		1.39	g

Measuring Magnetic Fields

- Starlight polarization and thermal dust emission by magnetically aligned grains
- Synchrotron emission and polarization
- Faraday rotation of polarized background sources
- Zeeman splitting of spectral lines
- Davis-Chandrasekhar-Fermi (DCF) method

$$B_{0,\mathrm{pos}} = \xi \sqrt{4\pi\bar{\rho}} \, \frac{\delta \mathrm{v}_{\mathrm{los}}}{\delta\phi}$$


NASA, ESA, Hubble, SOFIA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Declination (J2000)
09h 45m 55s
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Right ascension (J2000)
c NGC 4631
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Declination (J2000)
12h 42m 30s
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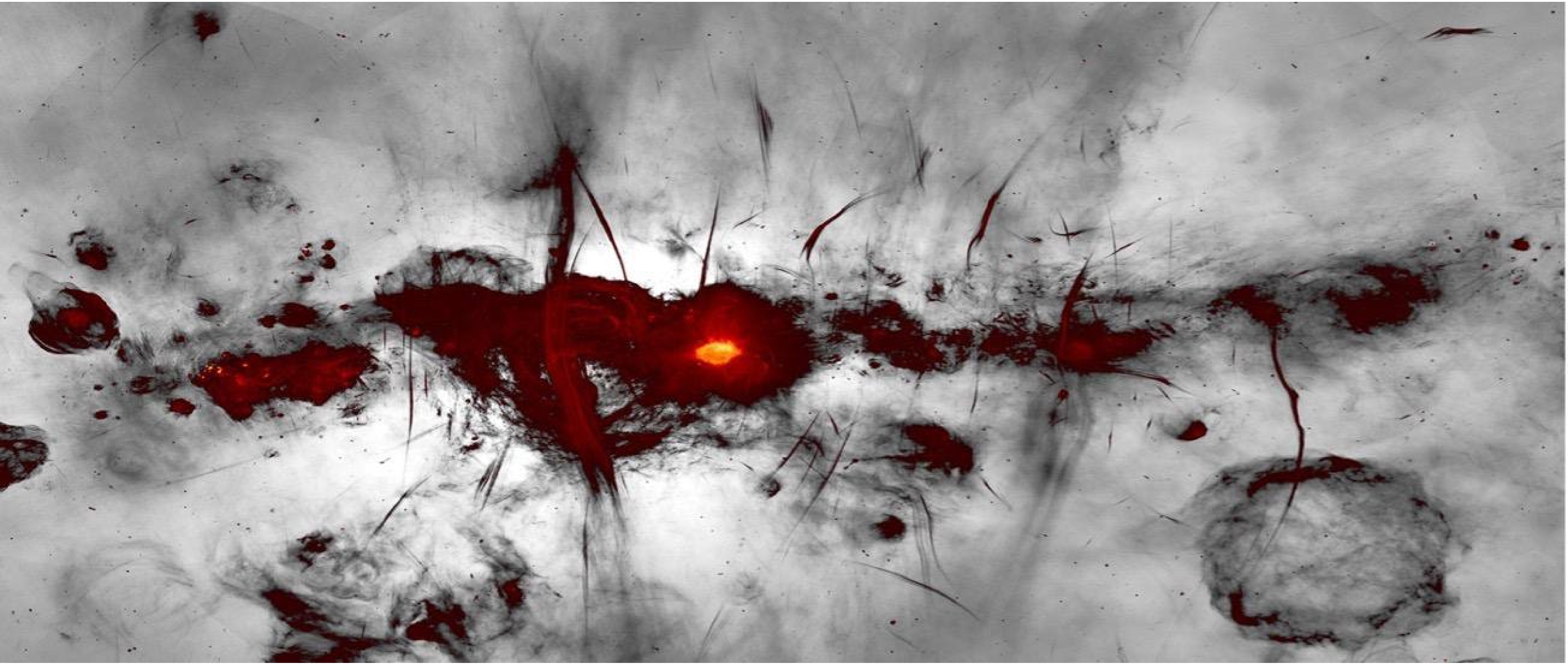
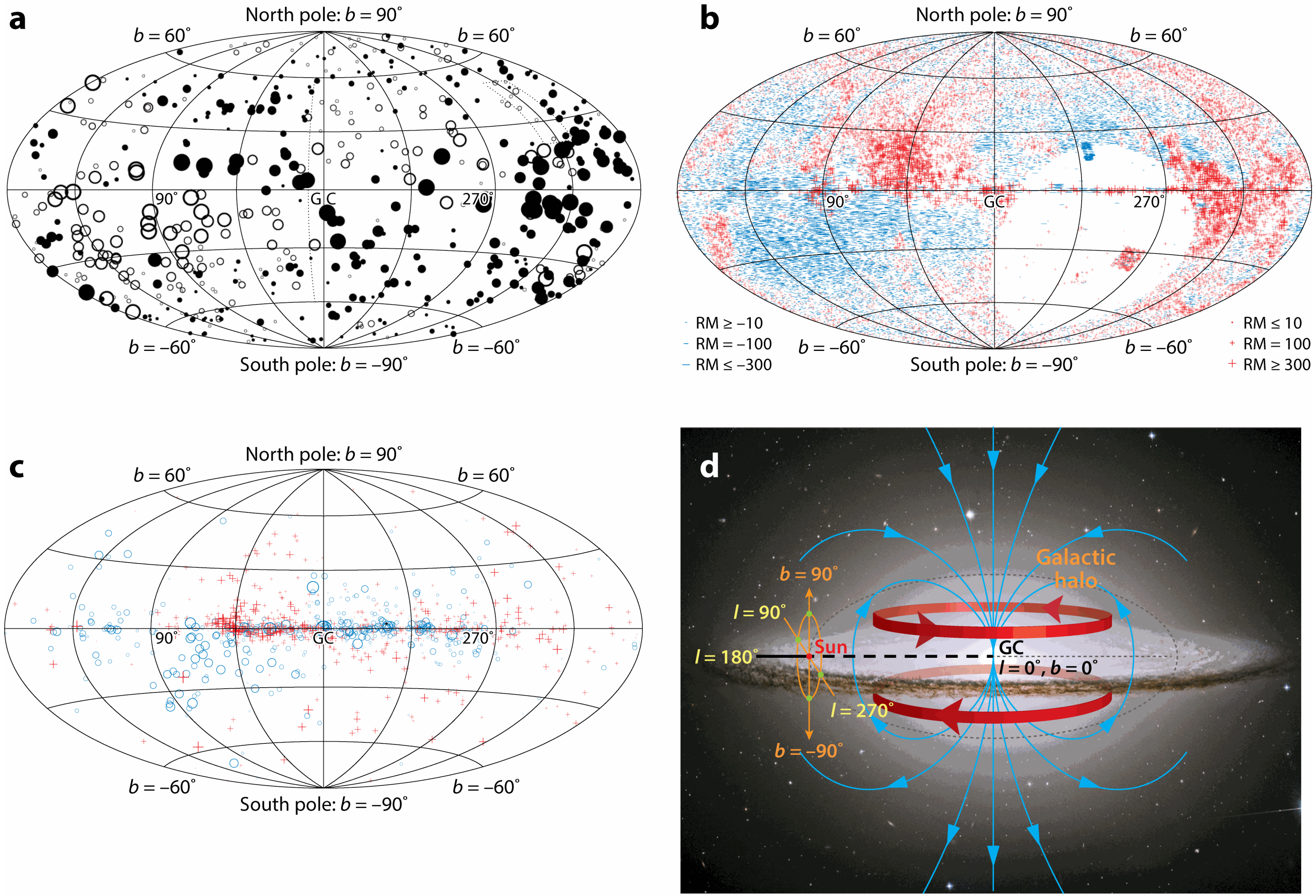
41m 45s
30s
Right ascension (J2000)

$$\dot{\gamma}_e = -\frac{\sigma_T B^2 \gamma_e^2}{6\pi m_e c} \propto -\gamma_e^2 B^2$$

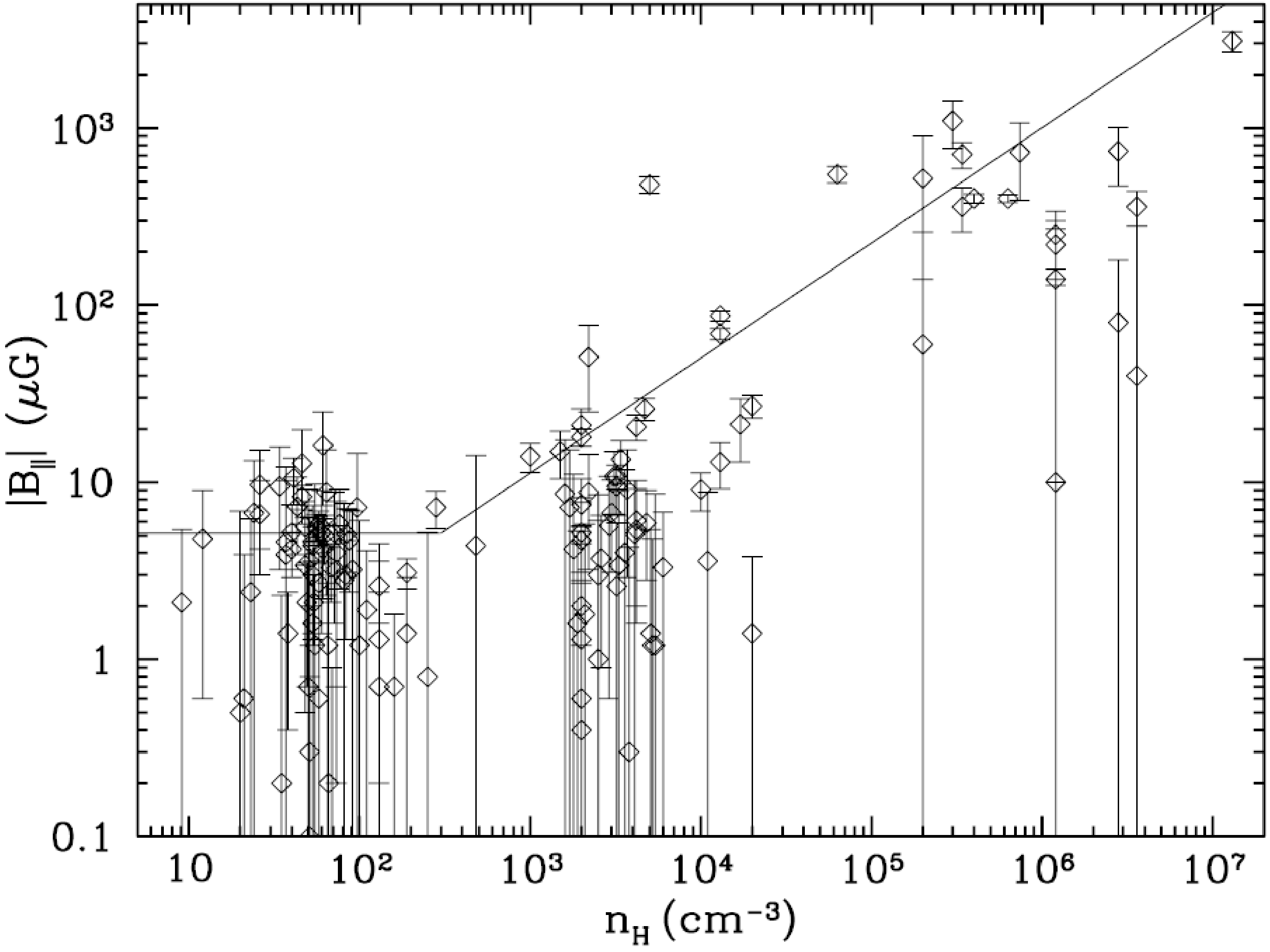
Relativistic electron cooling in strong magnetic fields





Han JL. 2017.
Annu. Rev. Astron. Astrophys. 55:111–57

Crutcher's relation: magnetic fields in GMCs



$$B_{0.5} \approx 5\,\mu\mathrm{G} \qquad \text{for } n_4 < 0.03$$
$$\approx 49 n_4^{0.65}\,\mu\mathrm{G} \qquad \text{for } 0.03 < n_4$$

$$\frac{(v_A)_{0.5}}{\sigma_v} \approx 0.85 \left(\frac{n_4}{1.3}\right)^{0.15+\gamma/(2-2\gamma)}$$

Astrophysical Dynamos

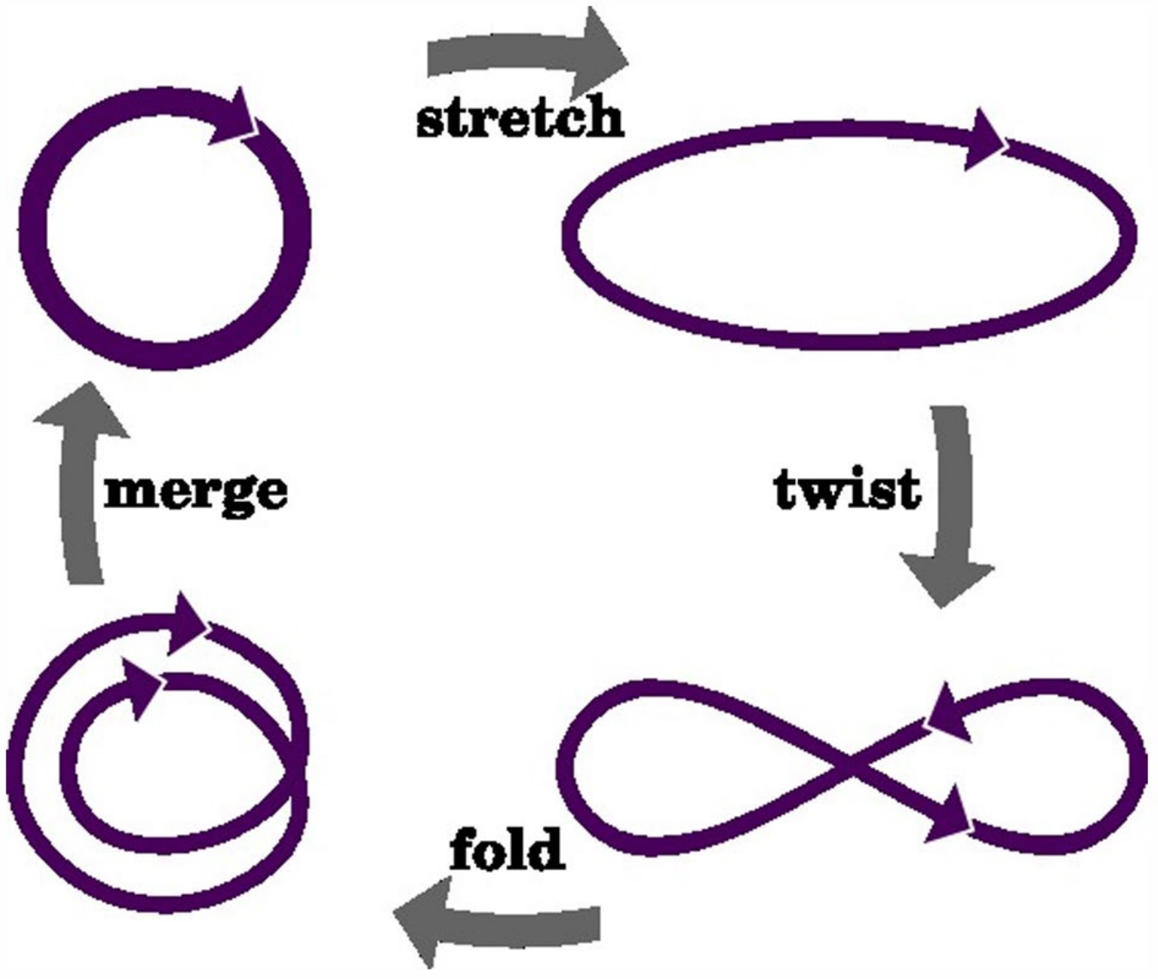
- The first term on the right-hand side is the advection of the magnetic field by the velocity while the second term describes collisional dissipation of the field.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\tau_\eta \sim L^2/\eta$$

- A dynamo is slow if it shuts off in the limit of low resistivity (e.g. the terrestrial dynamo). The dynamo operating time is compatible with the decay timescale and therefore dynamo can only "maintain" the fields and possibly flip them over similar timescale.
- A dynamo is fast if it can operate in the limit of low resistivity (e.g. galactic dynamos). The exponential growth timescale of the fields is shorter than the decay timescale.
- Parker's efforts on dynamo (1955) and solar winds open a new window on the theoretical front!

Dynamos in cartoon: stretch, twist, and fold by Zel'dovich 1972



Kinematic Mean Field Theory of Dynamo

- A complete mathematical description of MHD dynamo action requires the solution of the induction equation and also of the momentum equation, which accounts for the back-reaction of the magnetic field on the fluid flow through the Lorentz force J x B. Way too complicated!!
- Considering the evolution of the magnetic field under a prescribed velocity field simplifies the problem a bit, and is known as the kinematic dynamo problem.
- Linear perturbation on velocity and magnetic fields in the induction equation!

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{b}, \qquad \mathbf{U} = \mathbf{U}_0 + \mathbf{u}, \qquad \langle \mathbf{b} \rangle = \langle \mathbf{u} \rangle = 0.$$

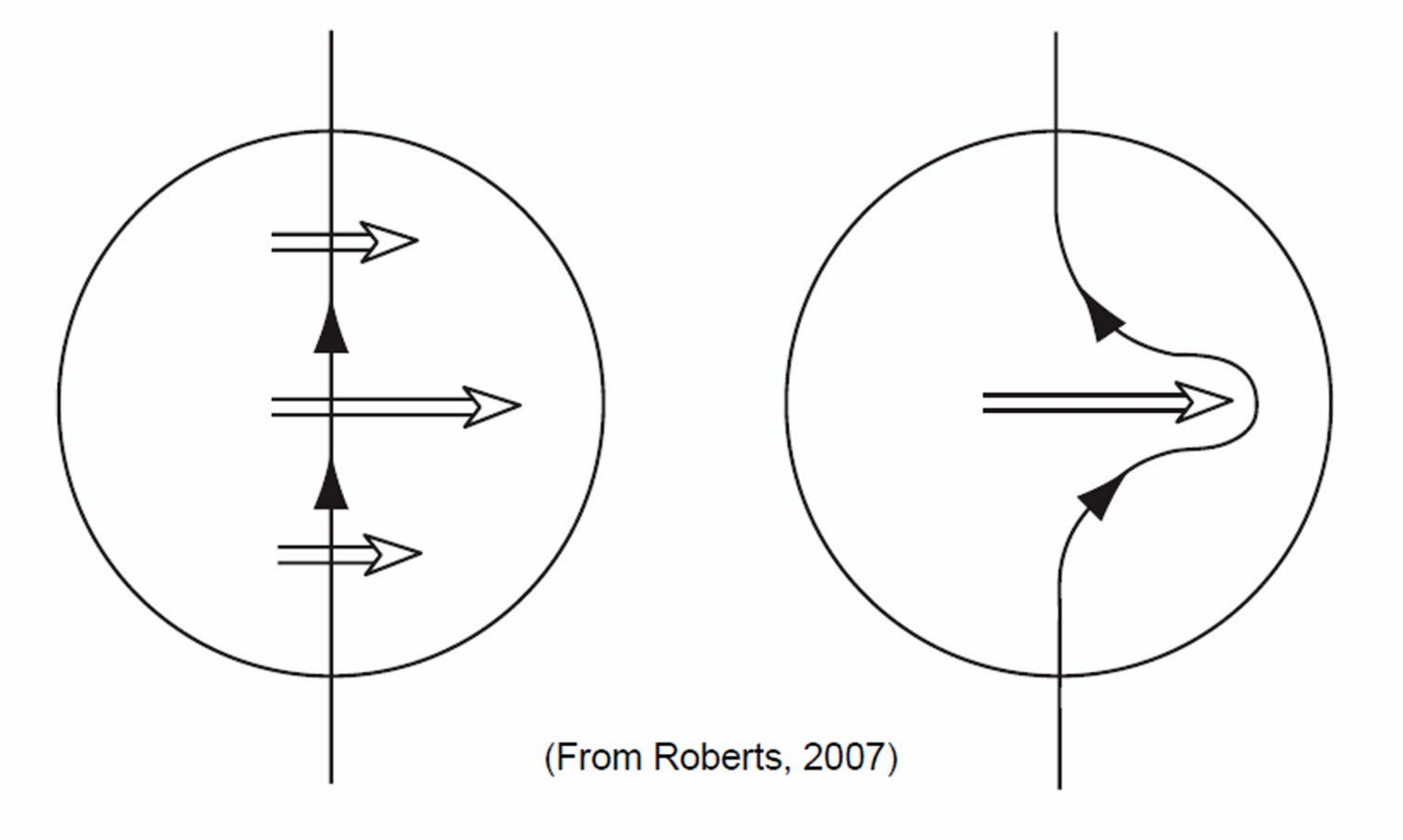
$$\frac{\partial \mathbf{B}_0}{\partial t} = \nabla \times (\mathbf{U}_0 \times \mathbf{B}_0) + \nabla \times \boldsymbol{\mathcal{E}} + \eta \nabla^2 \mathbf{B}_0$$

$$\boldsymbol{\mathcal{E}} = \langle \mathbf{u} \times \mathbf{b} \rangle$$

Omega-model dynamos!

$$\nabla \times (\mathbf{U}_0 \times \mathbf{B}_0)$$

- Omega-mode dynamos occurs when poloidal magnetic fields is pulled in the toroidal direction through differential rotation!



(From Roberts, 2007)

Alpha-mode dynamos! $\mathcal{E} = \langle \mathbf{u} \times \mathbf{b} \rangle$

- The equation for the evolution of the mean magnetic field from small-scale fluctuation:

$$\frac{\partial \mathbf{B}_0}{\partial t} = \nabla \times (\mathbf{U}_0 \times \mathbf{B}_0) + \nabla \times \mathcal{E} + \eta \nabla^2 \mathbf{B}_0$$

- $\mathcal{E} = \langle \mathbf{u} \times \mathbf{b} \rangle$ is the mean electromotive force that provides the generation of mean field from small scale velocity and magnetic fields interaction!
- The induced b is 'slaved' to the mean field B0; here b is driven solely by the inhomogeneous term V x (u x Bo) - in the absence of Bo the small-scale field simply decays to zero. So b is linearly and homogeneously related to Bo.

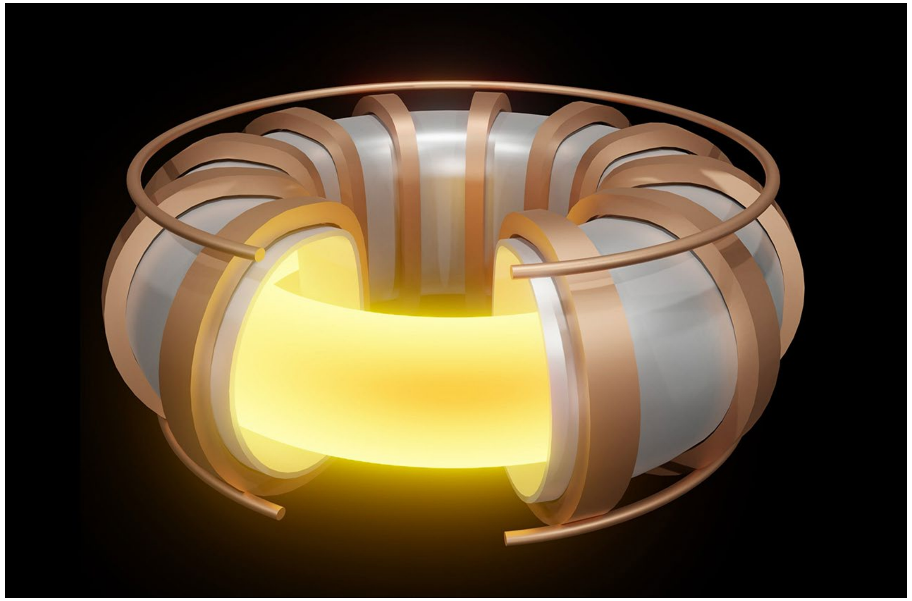
$$\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\mathbf{U}_0 \times \mathbf{b}) + \boxed{\nabla \times (\mathbf{u} \times \mathbf{B}_0)} + \nabla \times \mathbf{G} + \eta \nabla^2 \mathbf{b}$$

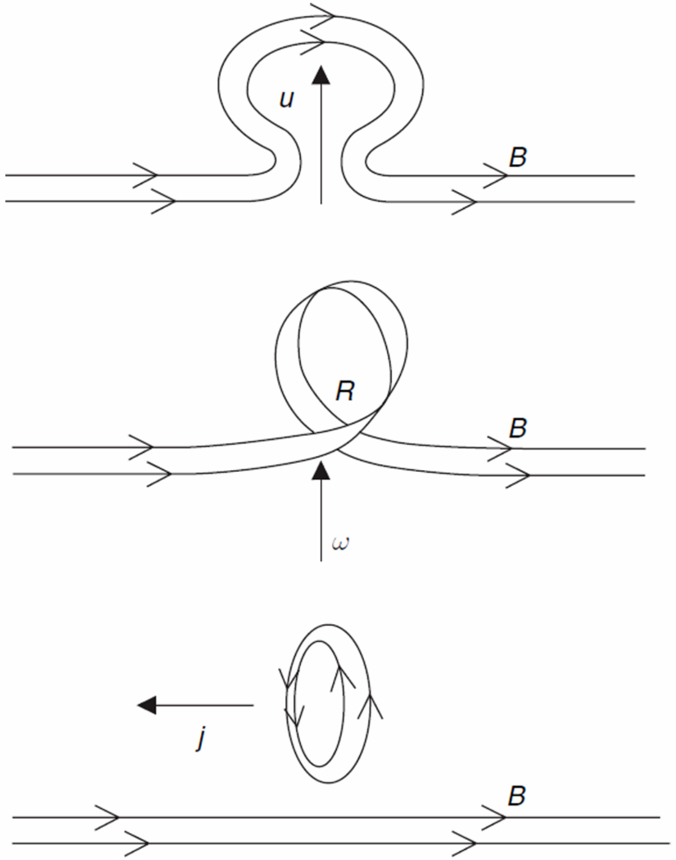
$$\mathcal{E}_i = \alpha_{ij} B_{0j} + \beta_{ijk} \frac{\partial B_{0j}}{\partial x_k} + \cdots$$

Alpha-mode dynamos!

$$\frac{\partial \mathbf{B}_0}{\partial t} = \nabla \times (\mathbf{U}_0 \times \mathbf{B}_0) + \nabla \times \alpha \mathbf{B}_0 + (\eta + \beta)\nabla^2 \mathbf{B}_0$$

- The most important term though is V x aB 0, the 'a-effect' of mean field dynamo theory, which may lead to growth of the mean magnetic field.
- The alpha-mode produces poloidal field from toroidal fields and enhance the overall field strength in turbulent medium.

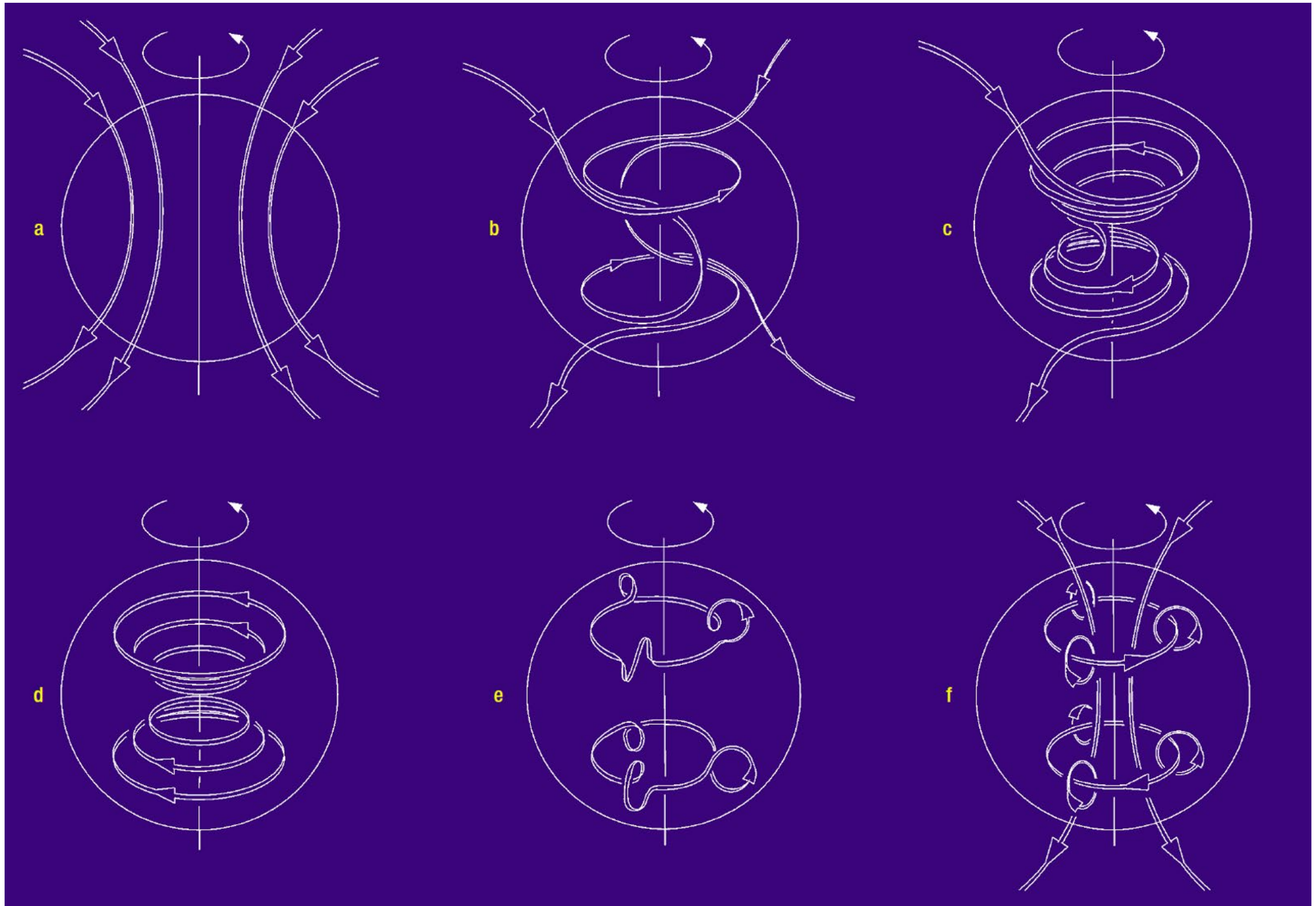




(From Roberts, 2007)

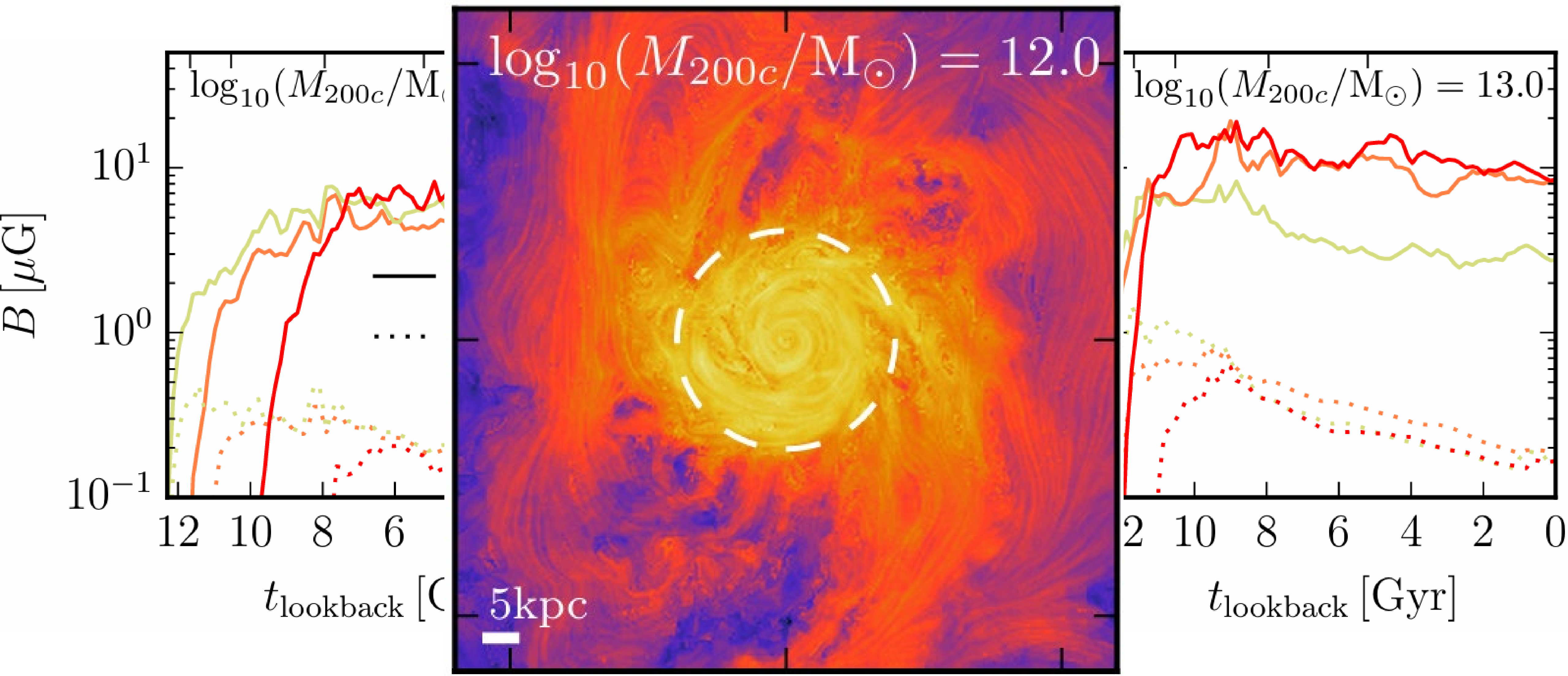
Alpha-Omega dynamo!

- Love 1999



2: The α-ω dynamo mechanism. Conventional geodynamo theory presupposes (a) an initial, primarily dipolar, poloidal magnetic field. The ω-effect consists of differential rotation, (b) and (c), wrapping the magnetic field around the rotational axis, thereby (d) creating a quadrupolar toroidal magnetic field. Symmetry is broken, and dynamo action maintained, by the α-effect, whereby helical upwelling (e) creates loops of magnetic field. These loops coalesce (f) to reinforce the original dipolar field, thus closing the dynamo cycle.

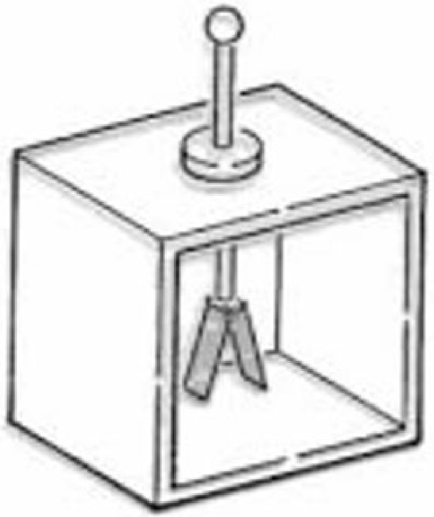
Cosmological Simulations of Magnetic Fields in Galaxies



Cosmic Rays

- Relativistic particles with energy that can reach the energy of macroscopic objects!

Discovery Missed in Cloud Chamber Experiments



1895: W.C. Roentgen, x-rays (1927)

1902: C.T.R. Wilson, cloud chamber (1927)

C.T.R. Wilson at Sydney Sussex College in Cambridge, England, had noticed earlier that even in a well-shielded ionization chamber a certain electrical leakage always occurred due to the production of ions in the chamber. Radioactive substances and X rays would have been stopped by the shields placed around the chamber. Therefore, Wilson theorized, some source of residual ionization must exist that could penetrate a great thickness of material.

Wilson suspected that the radiation might be cosmic. He set up his apparatus at Peebles in Scotland in a Caledonian Railway tunnel and found the same discharge rate outside and inside the tunnel. He concluded:

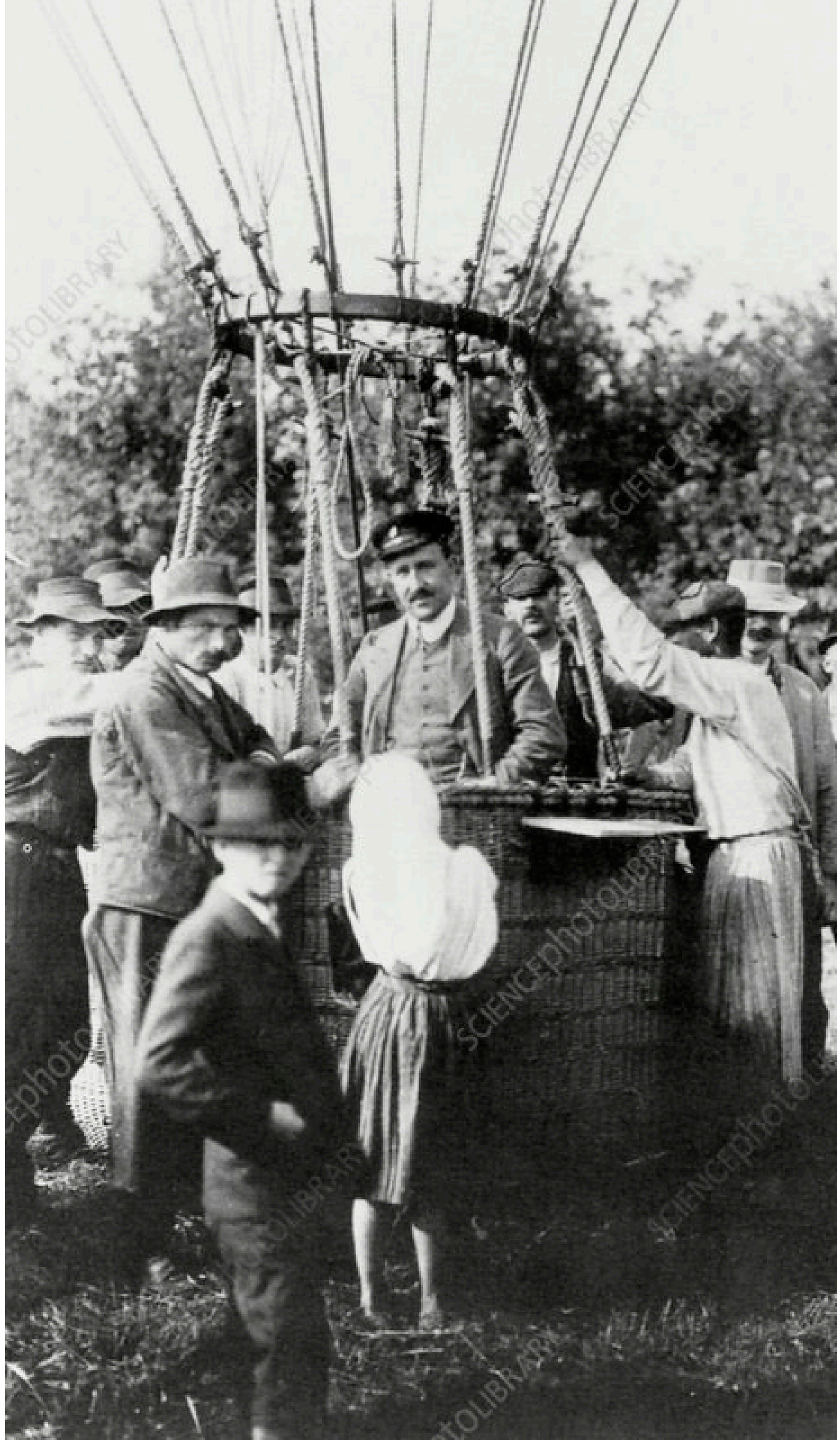
> There is thus no evidence of any falling off of the rate of production of ions in the vessel, although there were many feet of rock overhead. It is unlikely, therefore, that the ionisation is due to radiation which has traversed our atmosphere. . . .[203]

Discovery of Cosmic Rays

1912: V. Hess (1936)

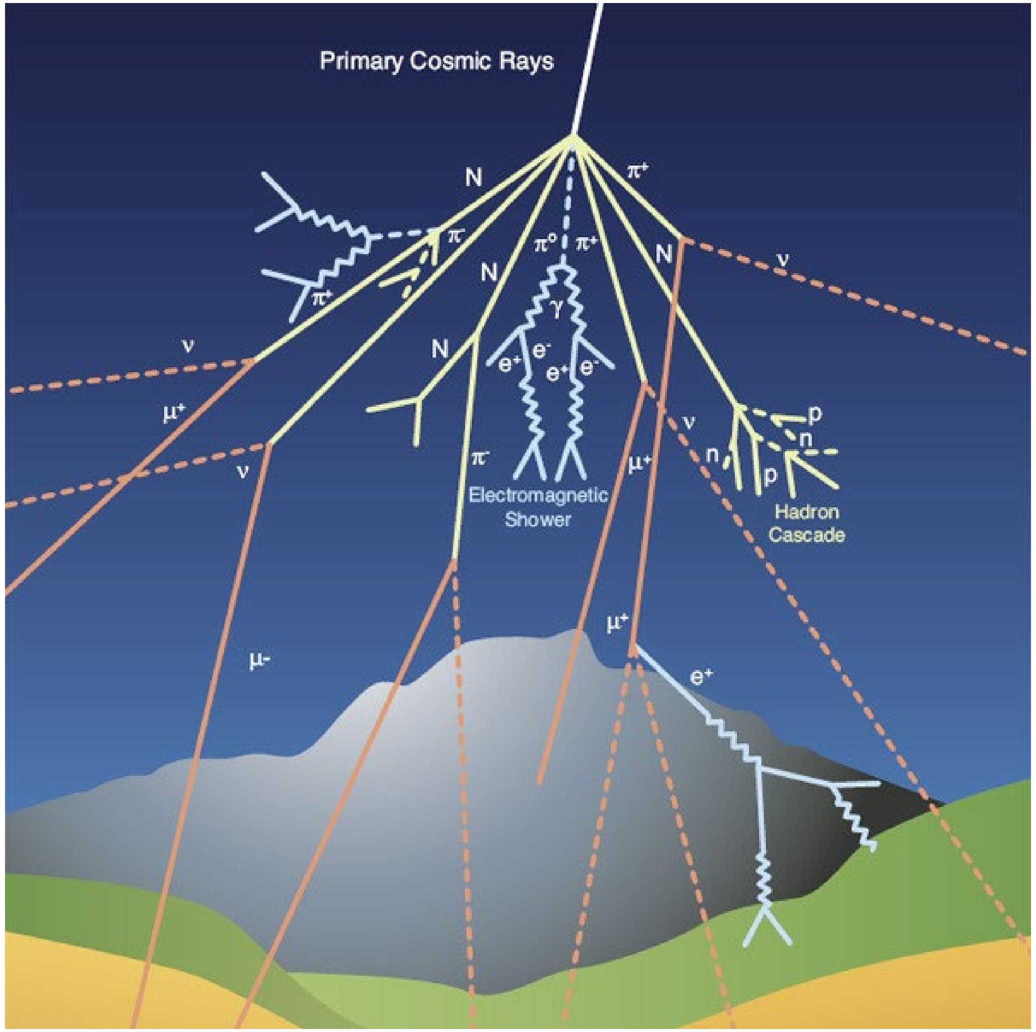
At six o'clock on the morning of August 7, 1912, the Austrian physicist Viktor Hess and two companions climbed into a balloon gondola for the last of a series of seven launches. The flight, which had started at Aussig on the Elbe, was under the command of Captain W. Hoffory. The meteorological observer was W. Wolf, and Hess listed himself as "observer for atmospheric electricity." Over the next three or four hours the balloon rose to an altitude above 5 kilometers, and by noon the group was landing at Pieskow, some 50 kilometers from Berlin. During the six hours of flight Hess had carefully recorded the readings of three electroscopes he used to measure the intensity of radiation and had noted a rise in the radiation level as the balloon rose in altitude.

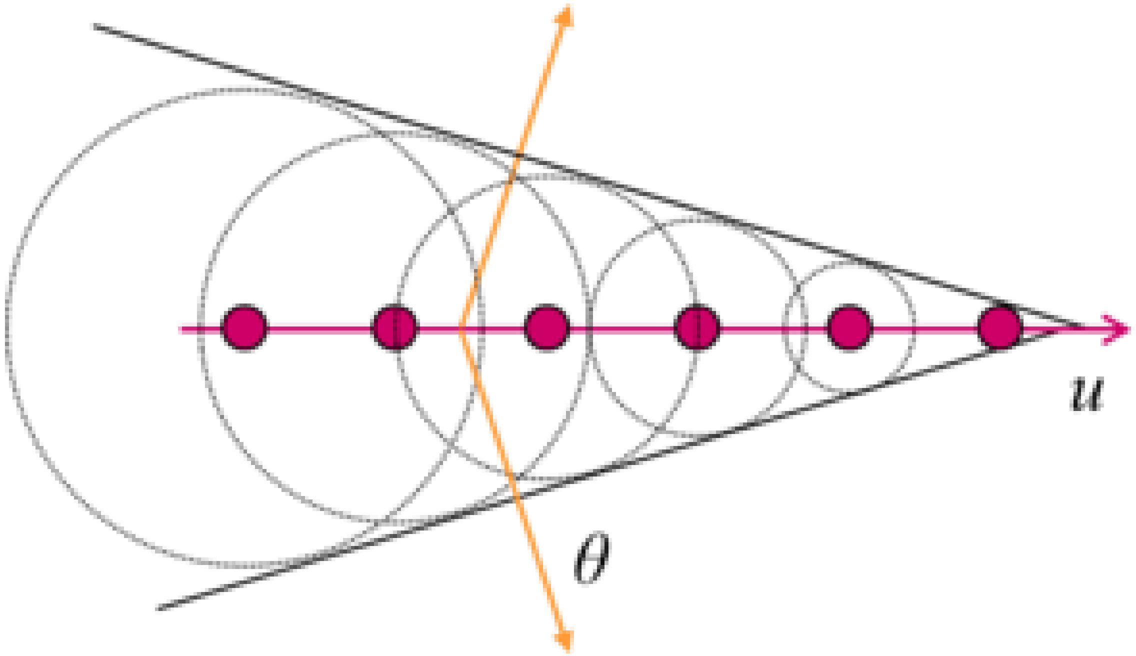
In the *Physikalische Zeitschrift* of November 1 that year Hess wrote, "The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above. . . ."[3] This was the beginning of cosmic-ray astronomy. Twenty-four years later Hess shared the Nobel Prize in physics for his discovery.



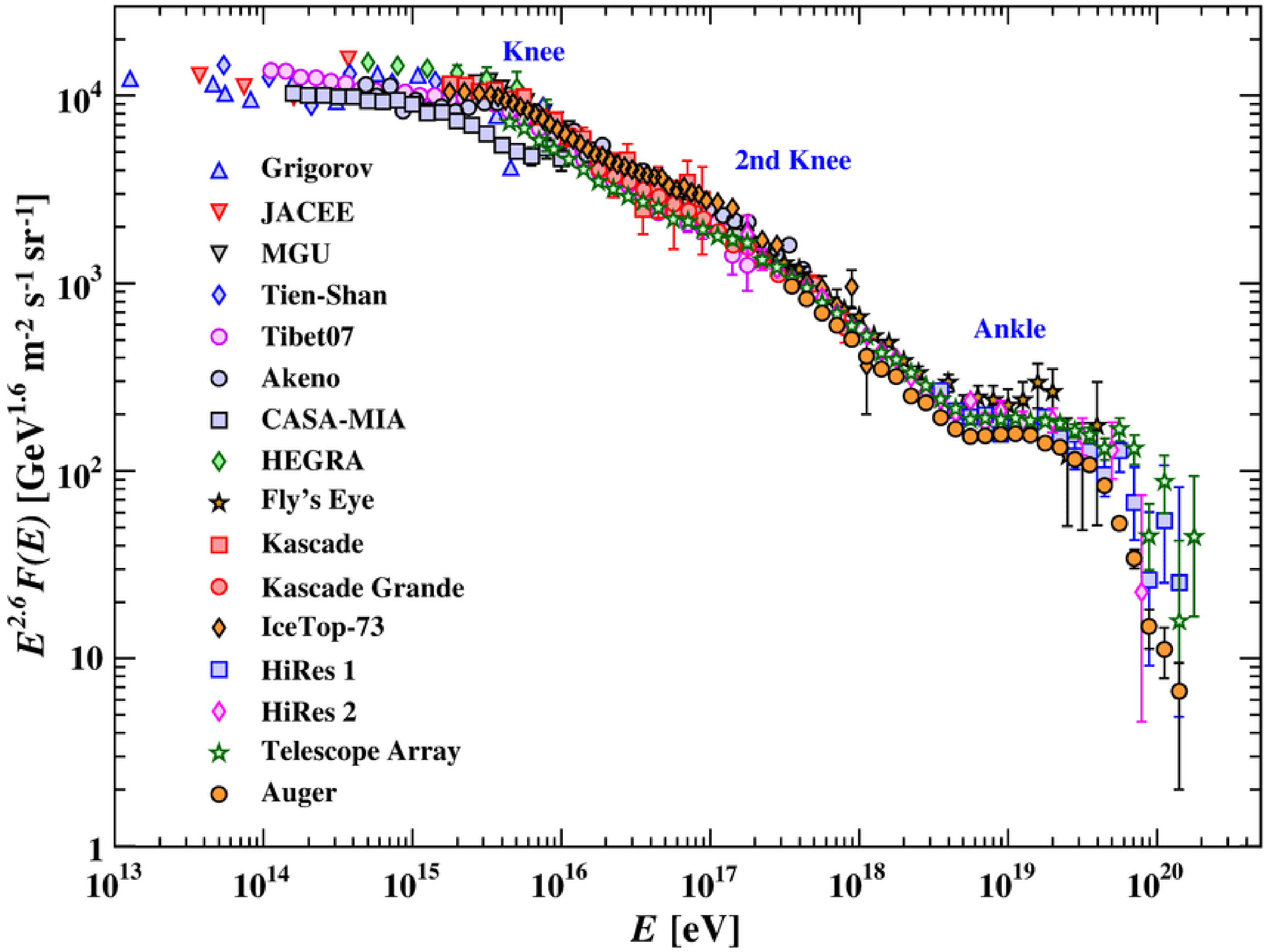
High Energy Stereoscopic System (HESS)

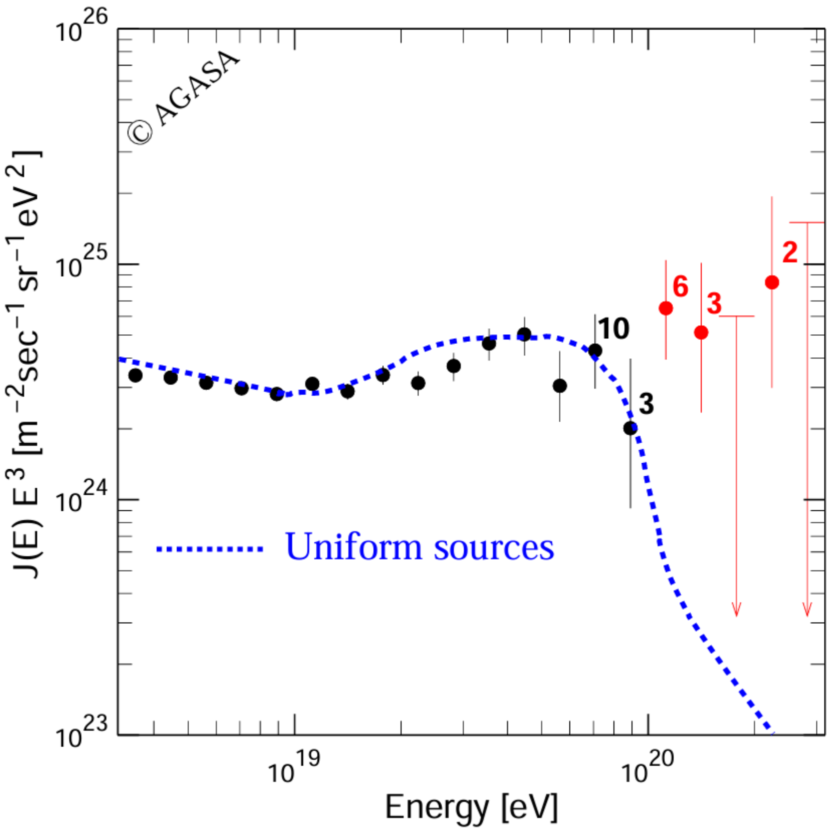
Cosmic Ray Cascade and Cherenkov Radiation





Cosmic Ray spectrum: knee, ankle, and GZK cutoff

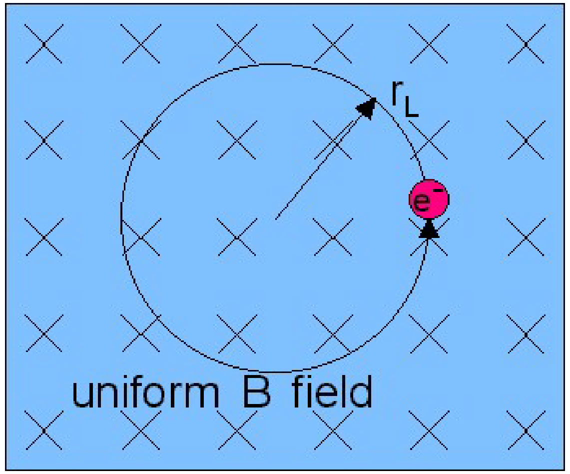


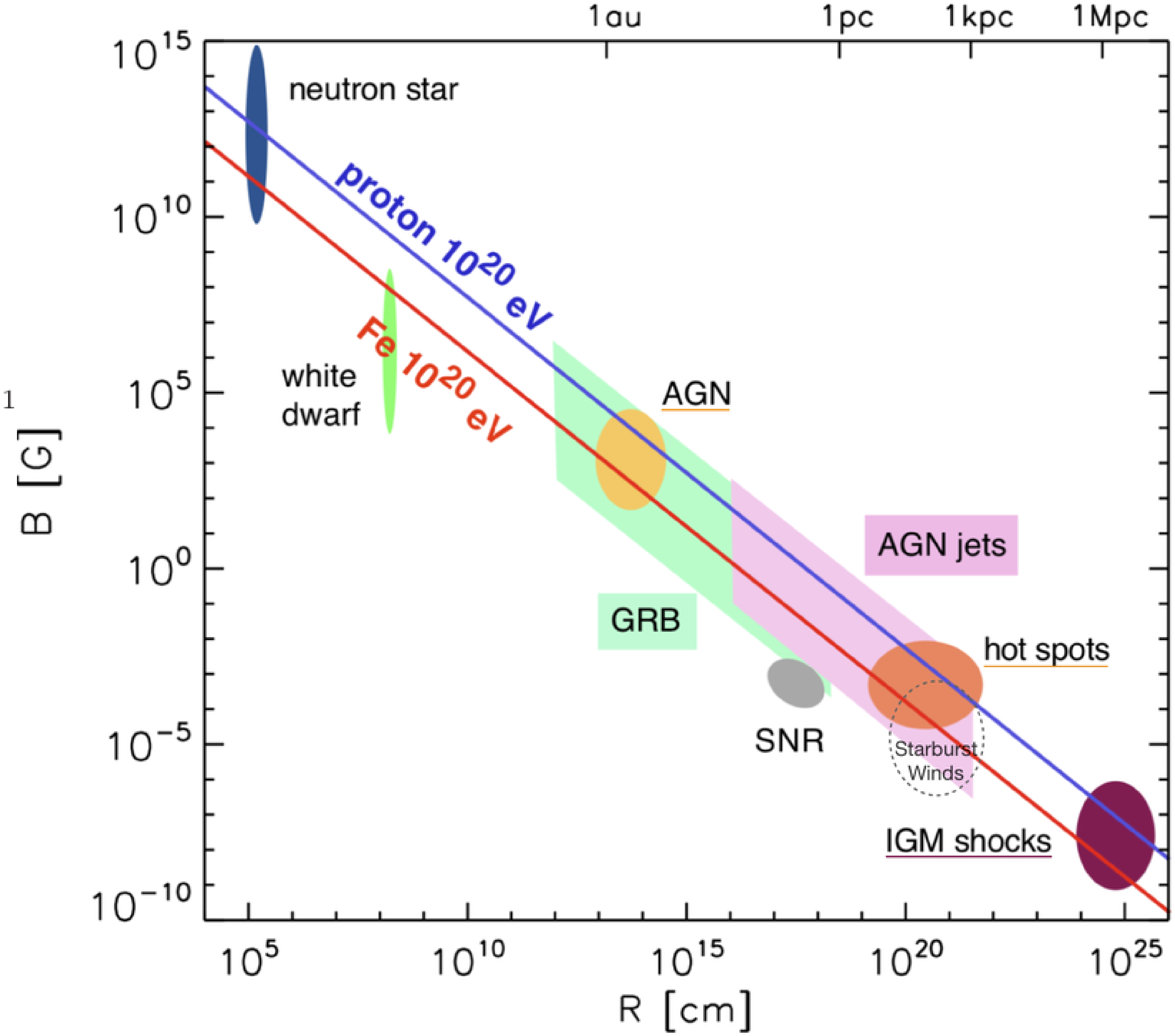


$$\gamma + p \rightarrow \Delta \rightarrow \pi + N$$

Hillas Diagram

$$r_L = 0.223\text{AU}\left(\frac{E}{\text{GeV}}\right)\left(\frac{B}{\mu\text{G}}\right)^{-1}$$
$$= 1.08 \times 10^{-6}\text{pc}\left(\frac{E}{\text{GeV}}\right)\left(\frac{B}{\mu\text{G}}\right)^{-1}$$





Second-order Fermi Acceleration

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

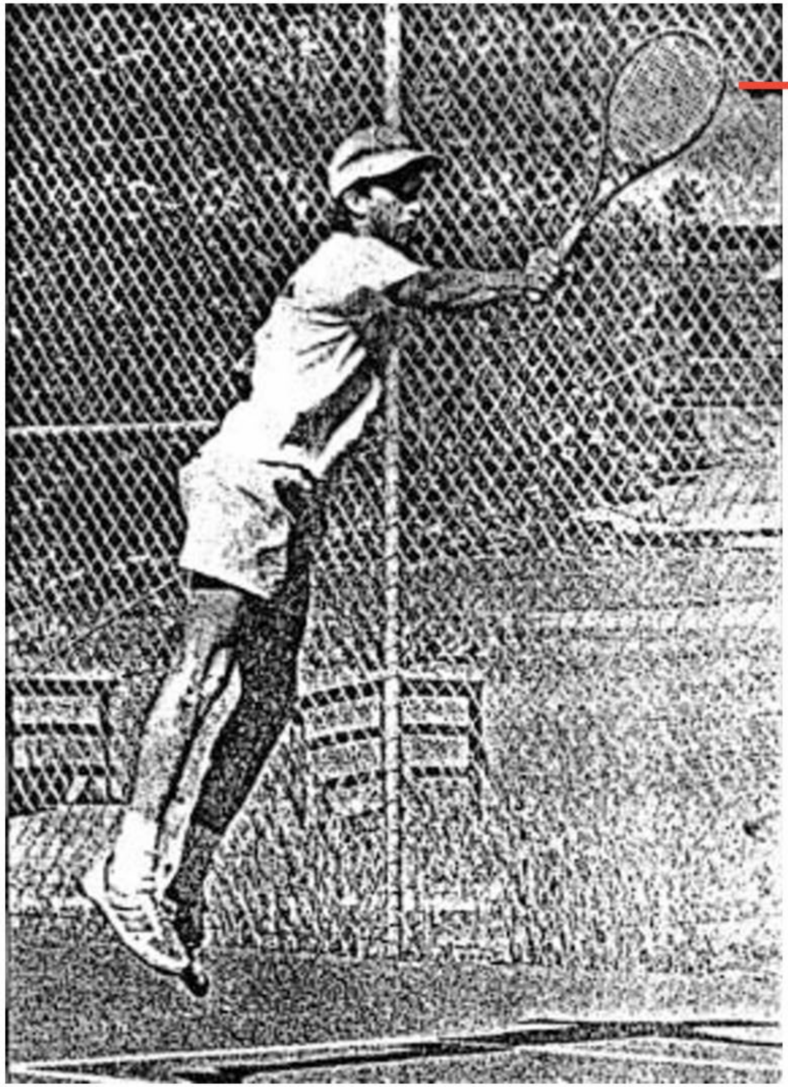
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

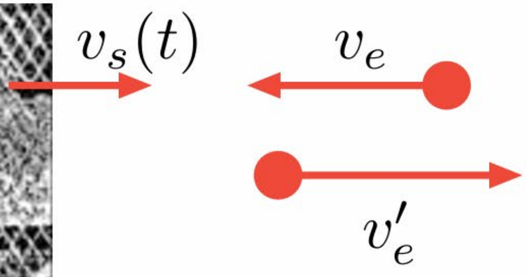
A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the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

It may happen that a region of high field intensity moves toward the cosmic-ray particle which collides against it. In this case, the particle will gain energy in the collision. Conversely, it may happen that the region of high field intensity moves away from the particle. Since the particle is much faster, it will overtake the irregularity of the field and be reflected backwards, in this case with loss of energy. The net result will be an average gain, primarily for the reason that head-on collisions are more frequent than overtaking collisions because the relative velocity is larger in the former case.

Second-order Fermi Acceleration

- Fermi (1949) proposed a model where particles can statistically gain energy by colliding with "moving magnetic fields".
- In reality, resonant interactions with random MHD waves/turbulence (which are moving!) are the most relevant process that scatter the particles.





$$v'_e = v_e + 2v_s(t)$$

- $v_s > 0$, energy gain
  $v_s < 0$, energy loss
- Let $v_s = v_{s0} \cos \omega t$
  $\langle v_e'^2 \rangle = v_e^2 + 2v_{s0}^2$

$\boxed{\text{A net energy gain}}$

Second-order Fermi Acceleration

- Lab frame of reference: V, p, E.

$$\gamma_V = (1 - V^2/c^2)^{-1/2}$$

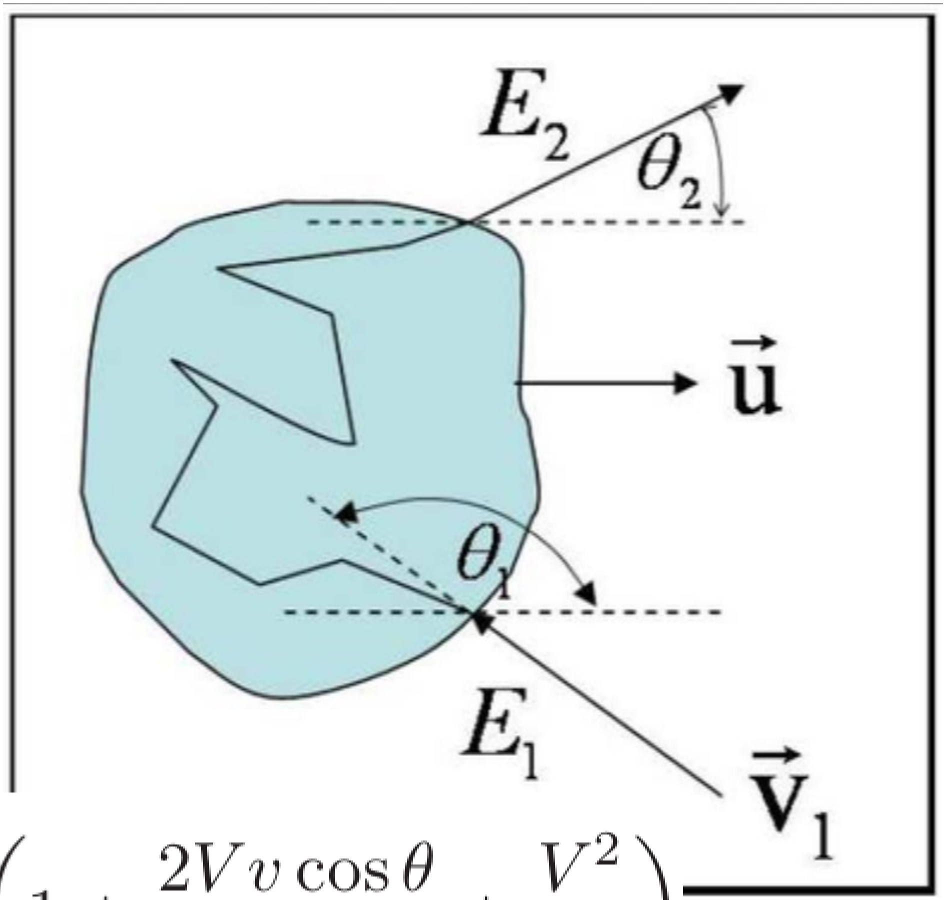
- Transform to the cloud frame:

$$E' = \gamma_V (E + V p_x) \ , \quad p'_x = \gamma_V \left(p_x + \frac{VE}{c^2} \right)$$

- Elastic collision:

$$E'_1 = E' \, , \, p'_{x1} = -p'_x$$

- Transform back to the lab frame:



$$E_1 = \gamma_V (E' - V p'_{x1}) = \gamma_V (E' + V p'_x) = \gamma_V^2 E \left(1 + \frac{2Vv\cos\theta}{c^2} + \frac{V^2}{c^2} \right)$$

Second-order Fermi Acceleration

- Total energy gain:

$$\frac{E_1 - E}{E} = \frac{\Delta E}{E} \approx \frac{2Vv\cos\theta}{c^2} + 2\frac{V^2}{c^2}$$

- Average over all collision angle, but notice that there is a slightly higher probability for head-on collision than trailing collisions:

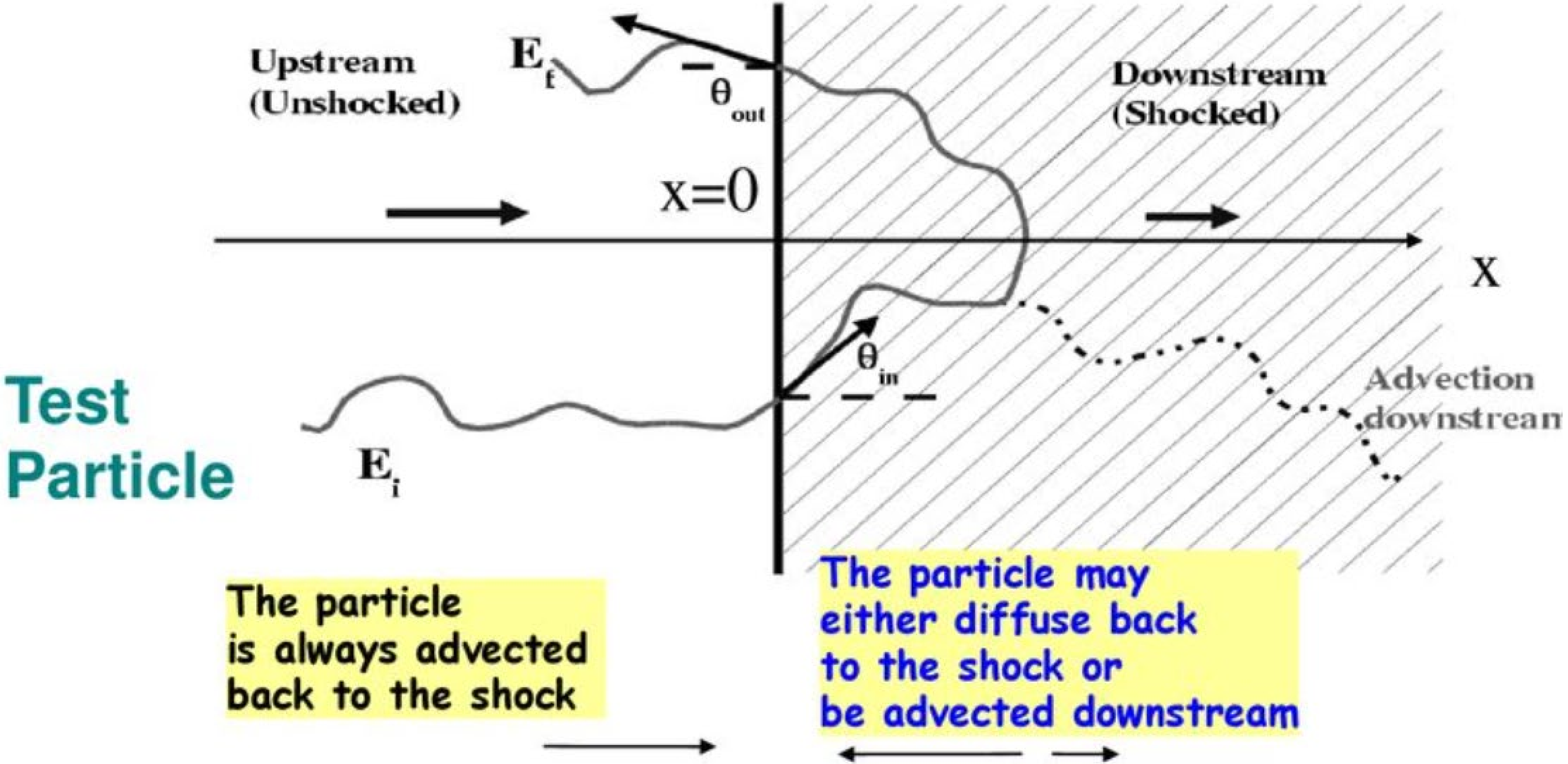
$$f(\theta)d\theta = \frac{1}{2}\left(1 + \frac{V\cos\theta}{c}\right)\sin\theta d\theta$$

- The mean energy gain at each collision is

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{2V}{c}\int_0^\pi f(\theta)\cos\theta d\theta + 2\frac{V^2}{c^2} = \frac{2}{3}\frac{V^2}{c^2} + 2\frac{V^2}{c^2} \approx \frac{8}{3}\frac{V^2}{c^2}$$

- The energy gain is proportional to (V/c)^2, second order!

First-order Fermi Acceleration at shocks



First-order Fermi Acceleration at shocks

- In the shock frame, the upstream and downstream velocity ratio depends on compression ratio r:

$$V_d = \frac{1}{r} V_u$$

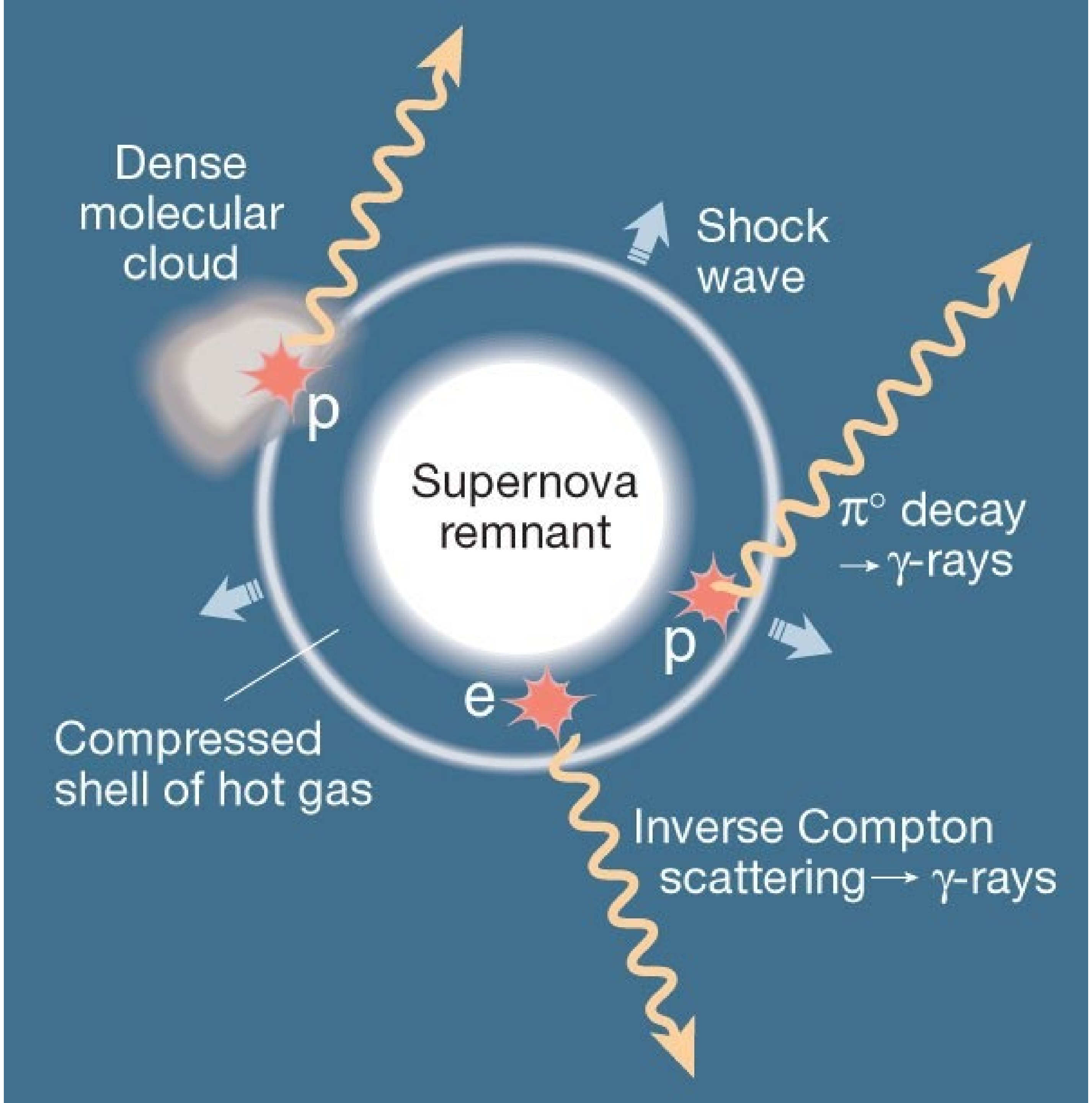
- The velocity difference between up and down stream is always larger than zero, suggesting a converging flow across the shock

$$V \equiv V_u - V_d = (r-1) V_d = \frac{r-1}{r} V_u$$

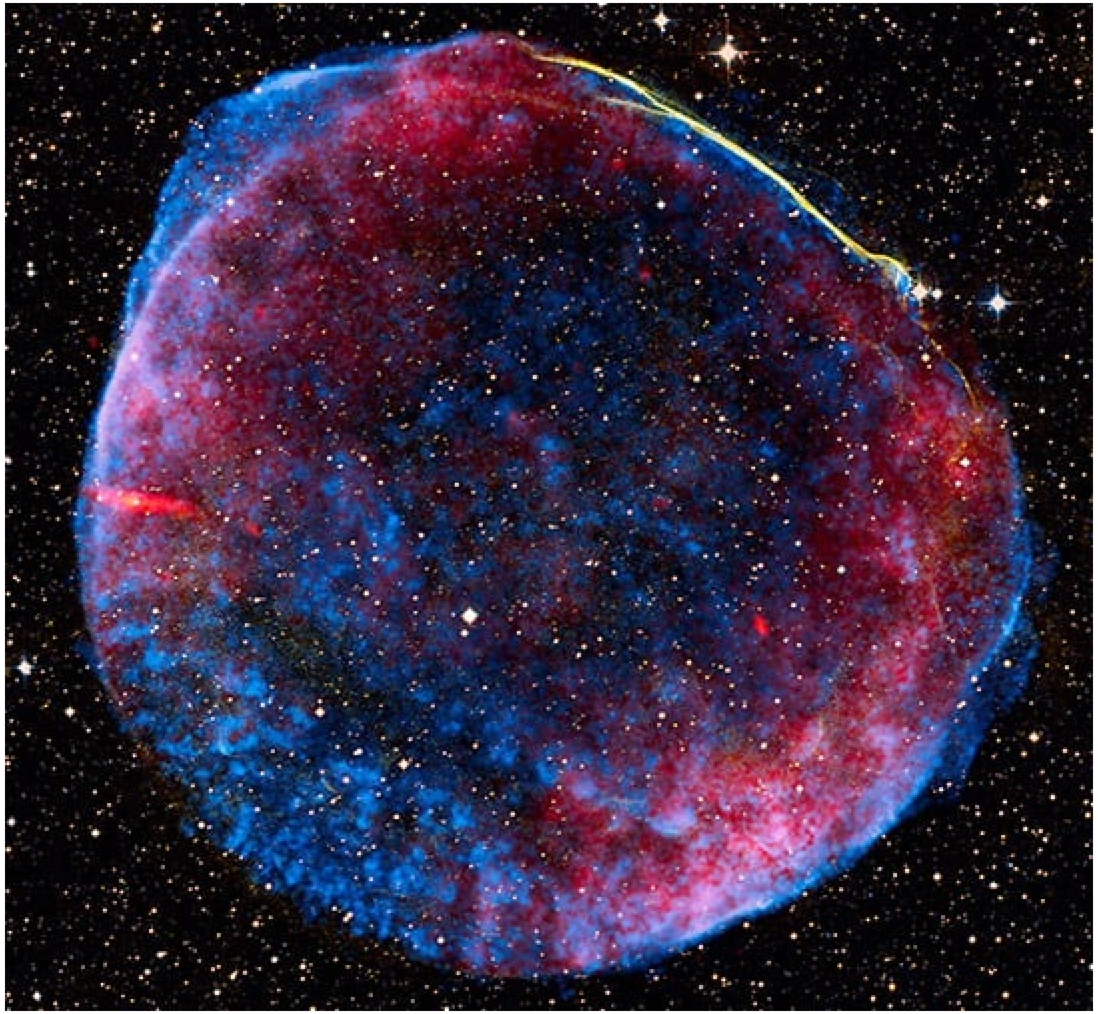
- The mean energy gain for a test particle in a full cycle of reflection is on the order of V/c.

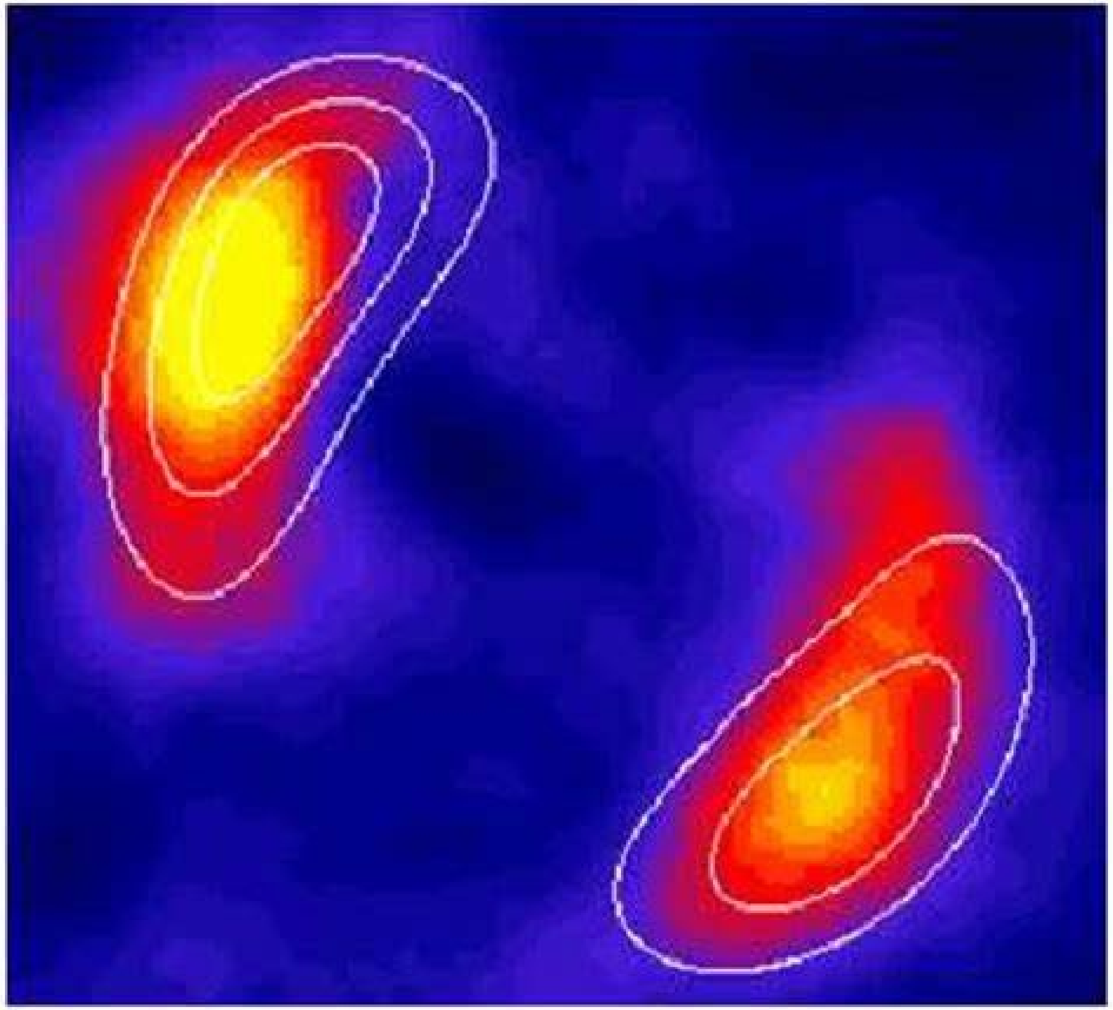
$$\left\langle \frac{\Delta E}{E} \right\rangle_{\text{cycle}} = \frac{4}{3} \frac{V}{c}$$

- The resulting spectrum of cosmic ray has a power law with a slope of $s = 1 - \frac{\ln P}{\ln A} \approx 1 + \frac{3V_d}{V} = 1 + \frac{3}{r-1}$

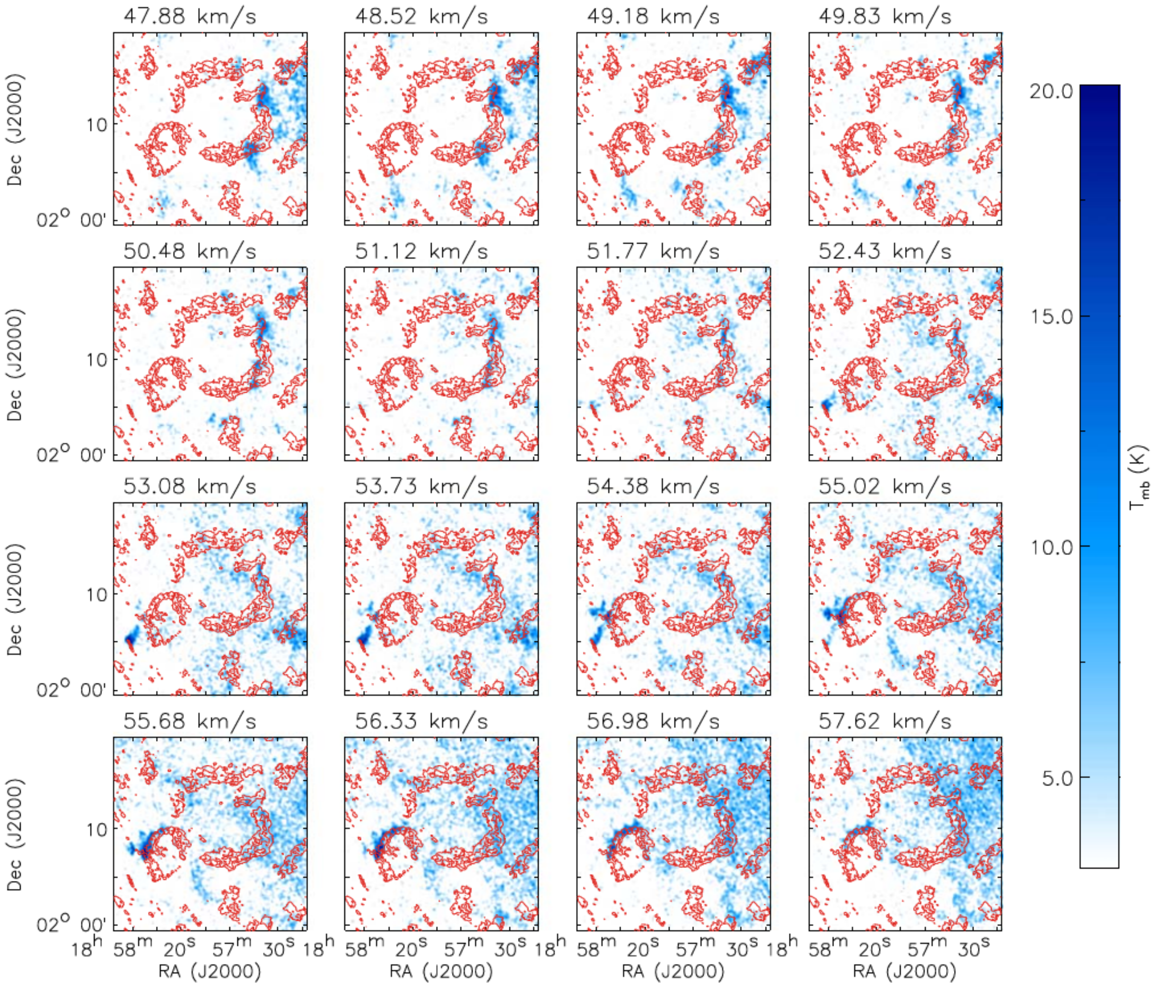

Dense molecular cloud
Shock wave
p
Supernova remnant
π° decay $\rightarrow \gamma$-rays
p
e
Compressed shell of hot gas
Inverse Compton scattering $\rightarrow \gamma$-rays

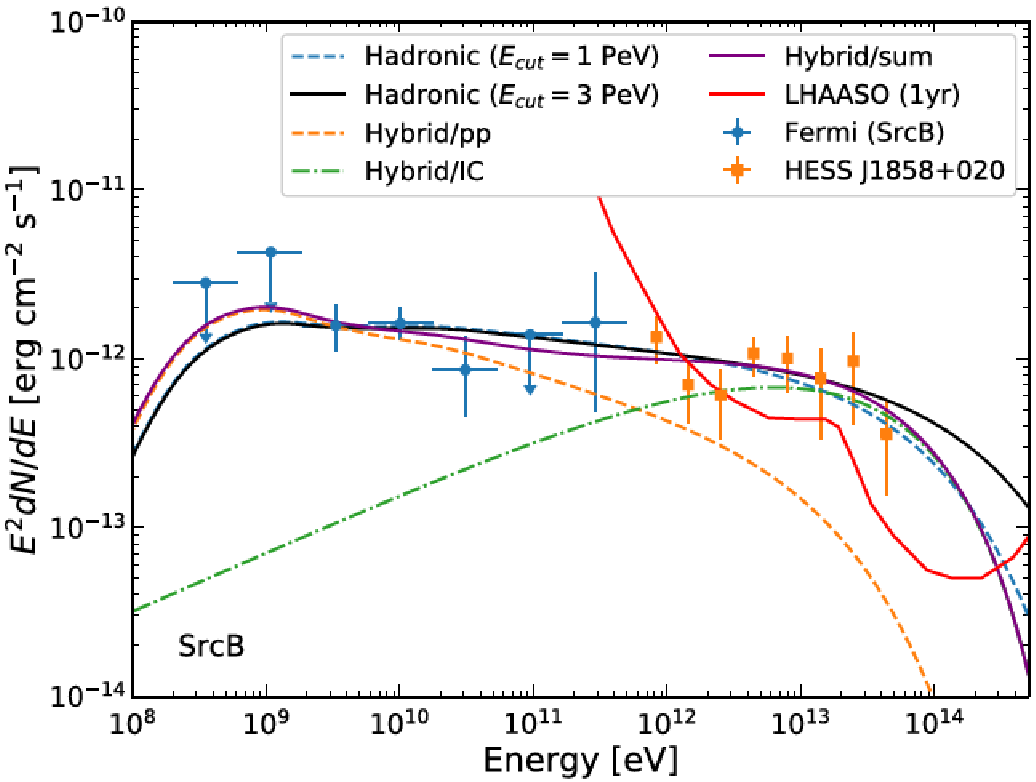
Emission of Cosmic Rays Electrons





Any evident on the acceleration of protons?





Interaction between magnetic fields and cosmic rays

- Cosmic ray acceleration depends on the plasma instability.
- Cosmic ray propagation is largely controlled by magnetic structure of the ISM.
- Cosmic ray electrons loss their energy in magnetic fields via synchrotron emission.
- Magnetic fields can be generated by wave-particle interactions between cosmic rays and background plasmas (e.g. Bell instability).
- Cosmic ray and magnetic pressures act together to support the multi-phase structure of the ISM, CGM, and IGM.