Plasma Astrophysics

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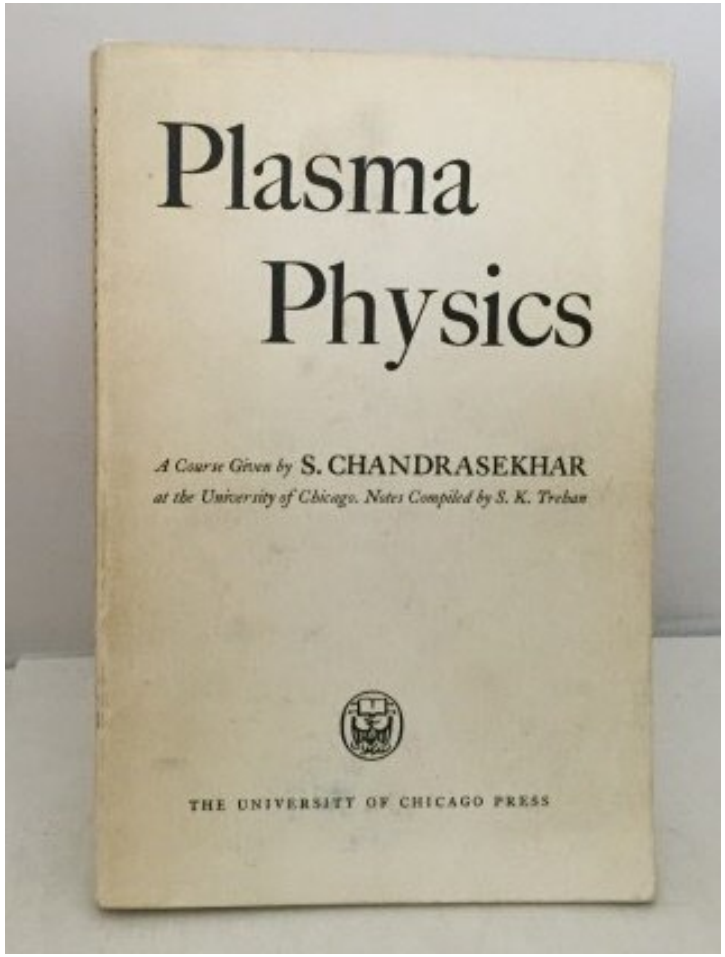
Who I Am, How I Got Here

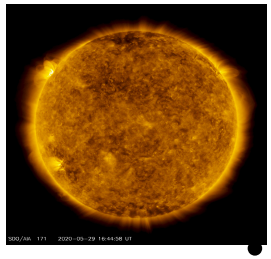
- Drawn to astronomy by the wonder of celestial objects.
- Came to love the idea of a Universe ruled by natural law.
- Majored in math at U. Chicago to avoid social awkwardness of all male physics labs & study groups.
- Two wonderful mentors: Patrick Palmer & Peter Vandervoort who saw a needle of scientific potential in a haystack of teenage angst.

Encountered This Book in College



- Classical mechanics, E&M, stat mech etc. all came together in plasma physics.
- Went to Princeton to study General Relativity, stayed for the plasma physics.

Space and Astrophysical Plasmas



Space Plasmas

- Magnetosphere
  - Plasma controlled by the magnetic field of Earth
- Heliosphere
  - Solar wind, solar system

Plasmas that can be directly probed, strongly influence life on Earth.

Astrophysical Plasmas

- Stars – their formation, evolution, deaths, explosions, mergers
- Accretion disks
- Galaxies – their formation, evolution, supermassive black holes formation & activity
- Galaxy clusters
- Intergalactic medium

Plasmas that are probed remotely & have wide range of properties

Lab Experiments relevant to both!

Cross Cutting Processes

- Magnetic reconnection: converts magnetic energy to plasma energy, changes magnetic topology
- Particle acceleration: a small fraction of particles are electromagnetically energized & don't follow Maxwell-Boltzmann statistics
- Dynamos: Magnetic induction converts flow energy to magnetic energy; ultimately responsible for the the magnetic fields we see in planets, stars and galaxies (great question in cosmology).

The Plan for Today

- A short course on galaxies
- A short course on cosmic rays

Follow the energy

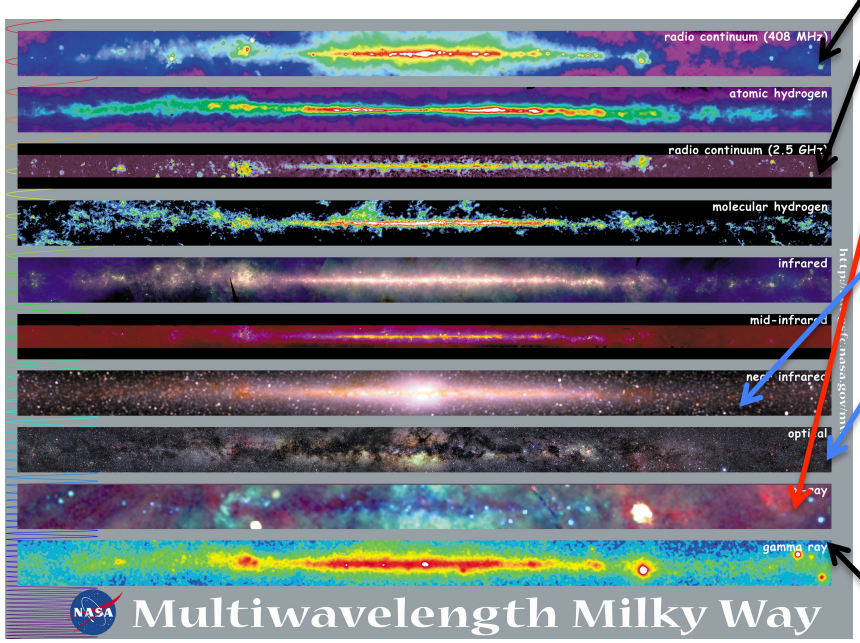
See where the plasma physics comes in

Galaxies

M31: NASA Astronomy Picture Of the Day

- Optically visible disk about 10 kpc across (kpc = 3000 light years)
- 10^{11} $M_\odot$
  - Mostly stars
  - Few % gas, mostly H
  - Central black hole, 10^7 $M_\odot$
- Massive *dark matter* halo, 10^{12} $M_\odot$

Breakdown by Components

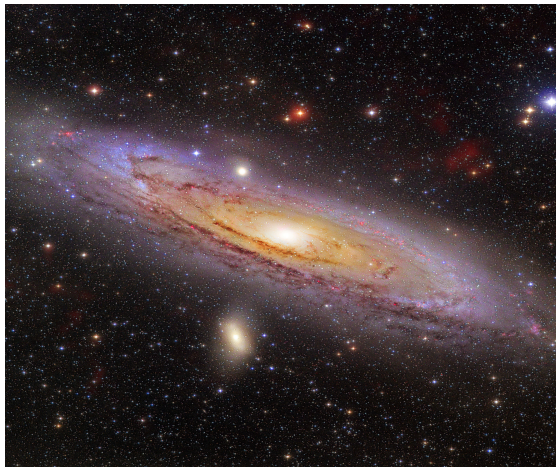


- Cosmic ray electrons
- Gas heated by supernova explosions
- Dust heated by starlight
- Starlight obscured by dust.
- Cosmic ray protons

NASA Composite

The Flow of Energy

Large scale gravitational field



Supernova remnant 1006 (NASA)

Gravitational binding energy of stars

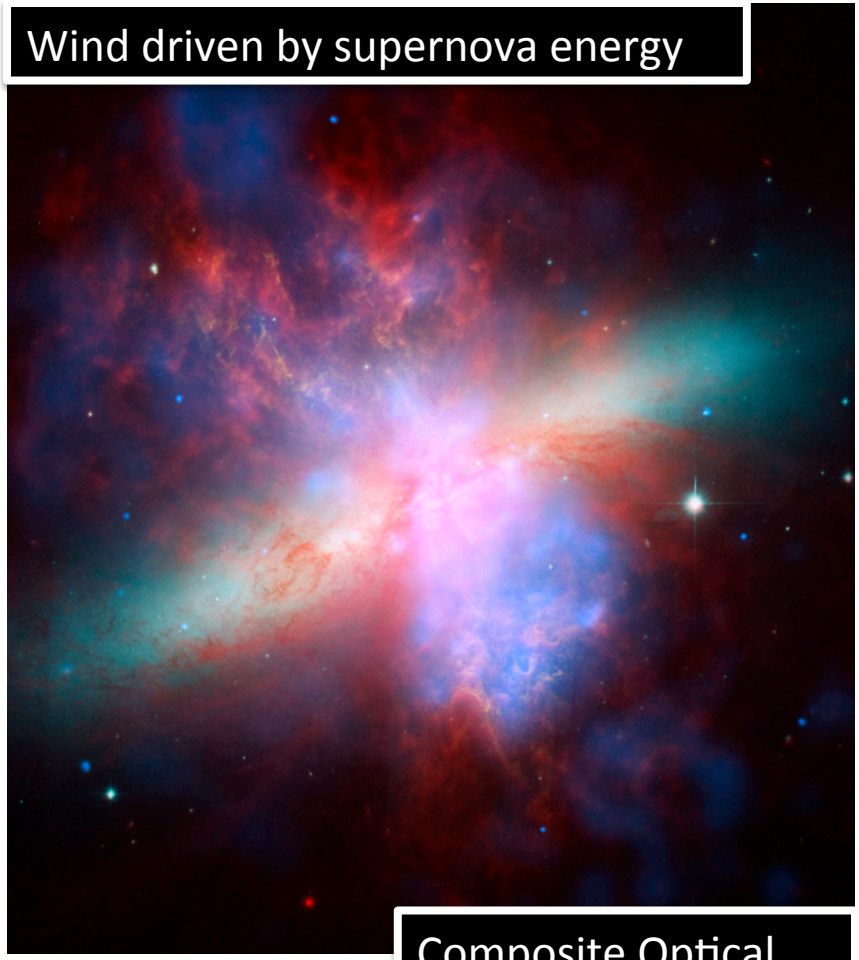
Energy budget of a *core collapse* supernova:

- 10^{53} ergs of gravitational binding energy: GM^2/R

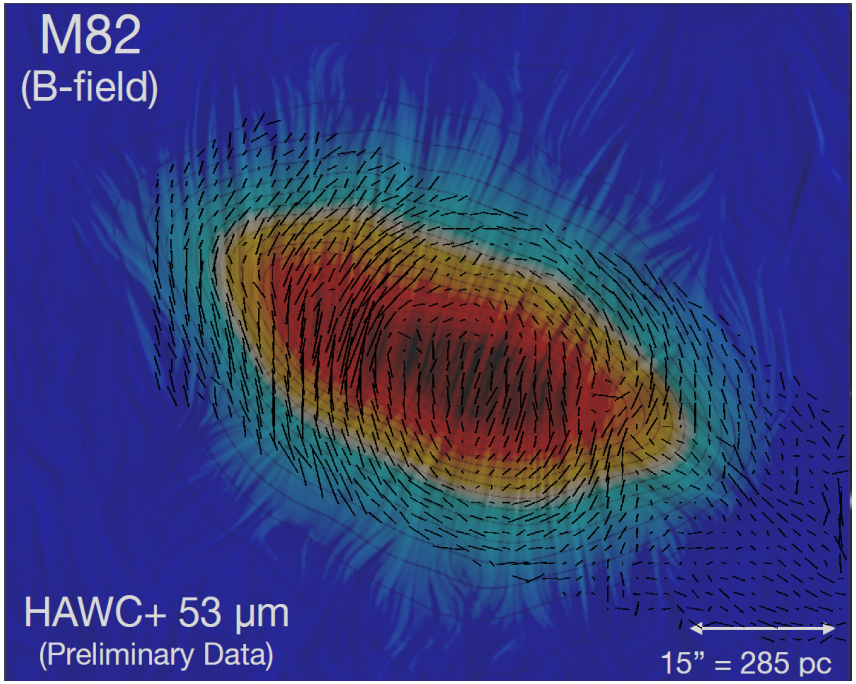
- 99% is emitted as neutrinos; freely escapes.
- 1% (10^{51} ergs) absorbed by surrounding medium
  - Shocked gas is heated & set in motion
  - About 10% goes to a miniscule fraction of particles which become relativistic *cosmic rays*

A More Active Example: "Starburst" Galaxy M82

Wind driven by supernova energy

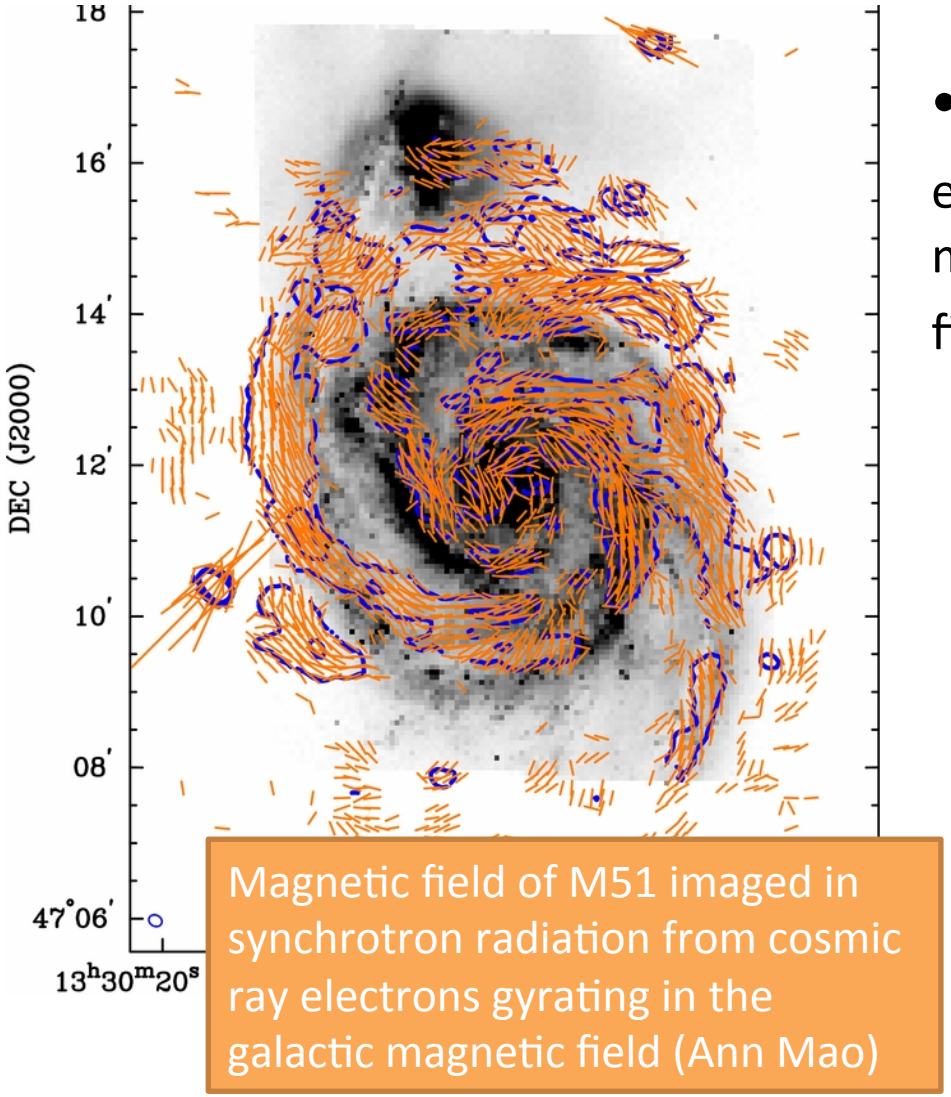


Composite Optical
& x-ray image: NASA



Polarized infrared emission from
Magnetically aligned interstellar dust shows
The magnetic field of M82 being dragged
Out of the disk by the wind

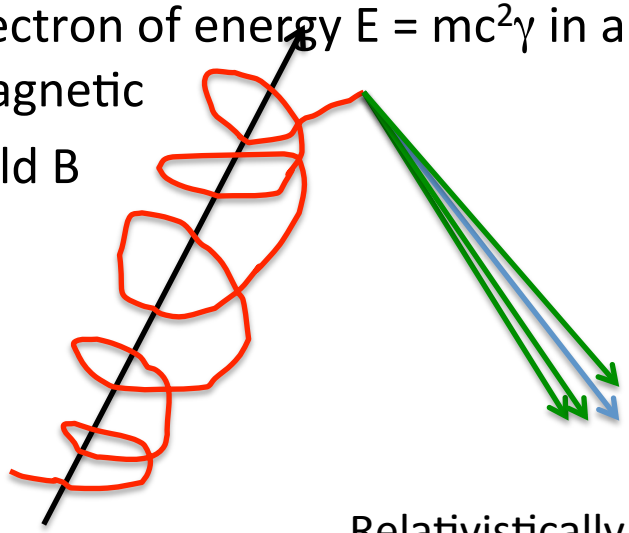
Galactic Magnetic Fields



Magnetic field of M51 imaged in synchrotron radiation from cosmic ray electrons gyrating in the galactic magnetic field (Ann Mao)

- Synchrotron radiation

electron of energy $E = mc^2\gamma$ in a magnetic field B



Relativistically beamed cone of radiation.

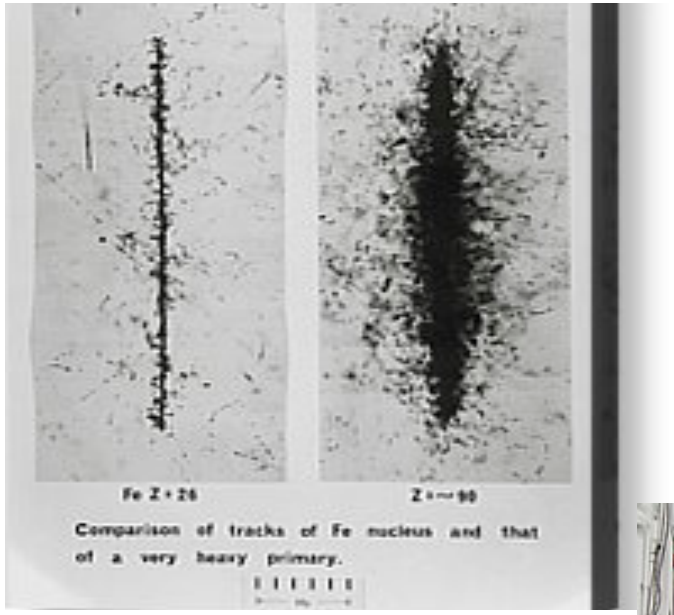
Frequency ν & power emitted go as E^2B

Cosmic Source of Atmospheric Ionization (known since 18th century)

Was tried previously with Eiffel Tower, but not tall enough.

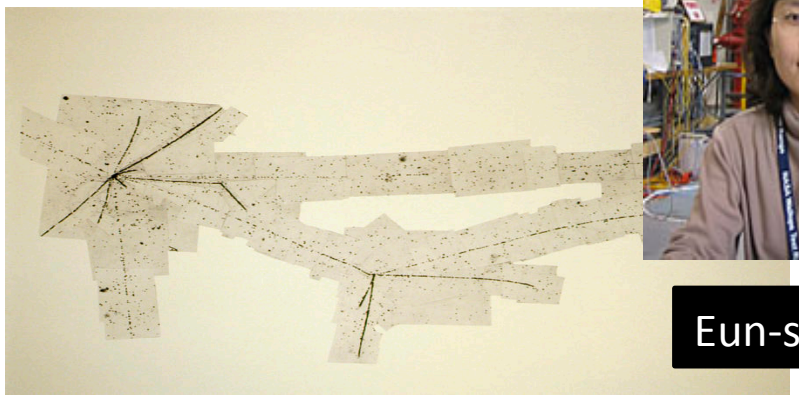
- 1911-1912; Victor Hess ascended to 5 km in balloons & showed ionization increases with height.
- To check whether the Sun was the source, he went up again during a solar eclipse.
- Awarded Nobel Prize for this work in 1936

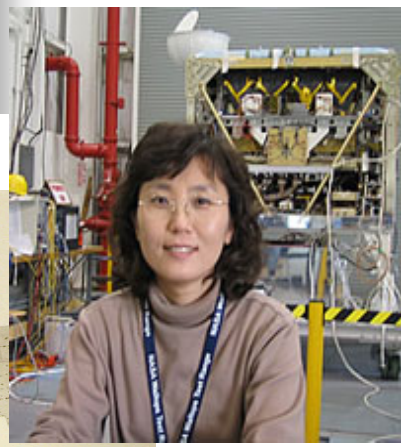
But it Was the Work of Many…



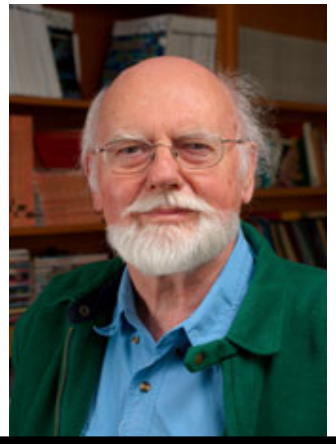
Marietta Blau

Stephen McGuire





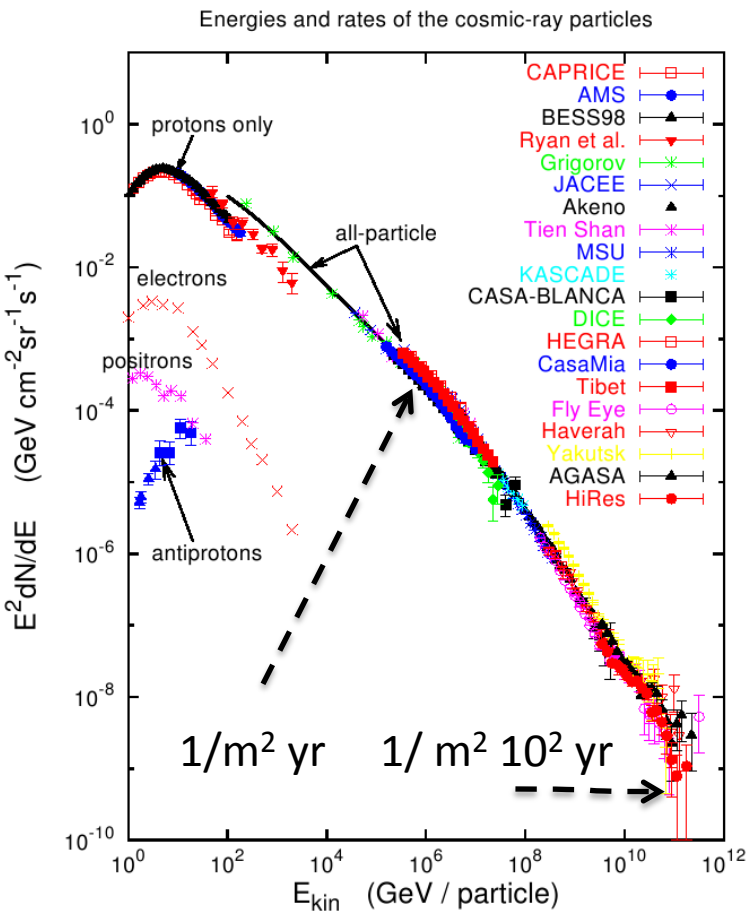
Eun-sook Seo



C. Jake Waddington

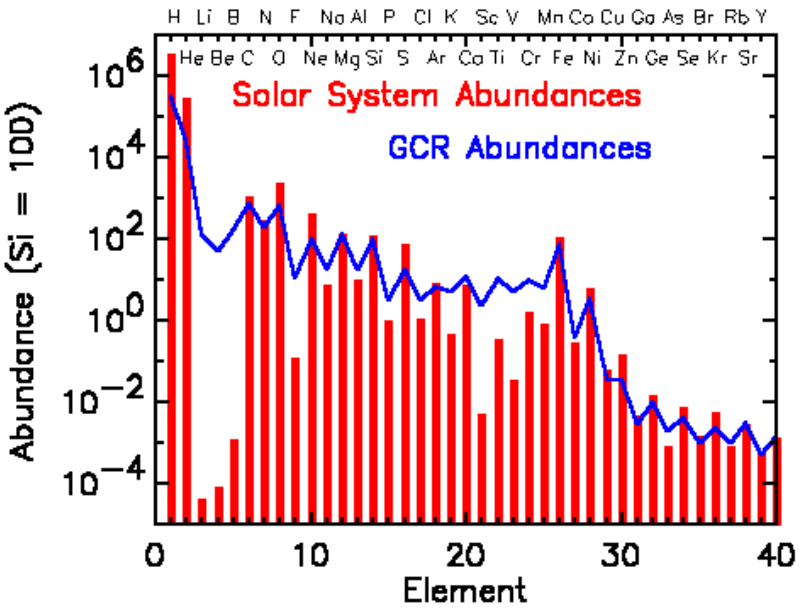
And many more!

Cosmic Ray Energy Spectrum



- Mostly ions
- $U_{cr} \sim 1$ eV cm^{-3}
  - Similar to magnetic, thermal, & radiation energy densities
- About one interstellar particle in 10^9 is a cosmic ray.

Composition



- Overabundance of Li, Be, B interpreted as spallation of CNO nuclei

  --> grammage

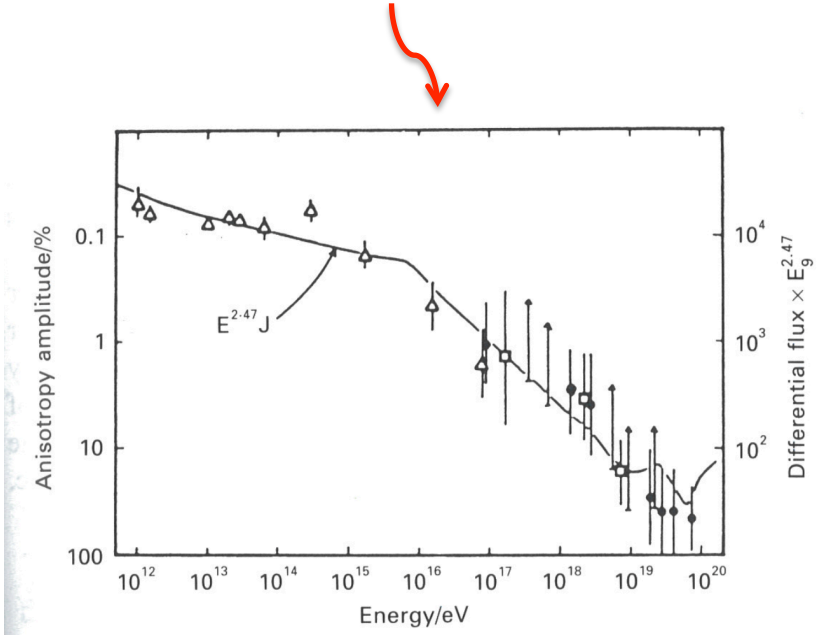
  --> age

- Lack of elements formed in supernovae

  -> accelerated from interstellar medium

Isotropy

Anisotropy increases with energy



Very small amplitude anisotropies at TeV+ energies

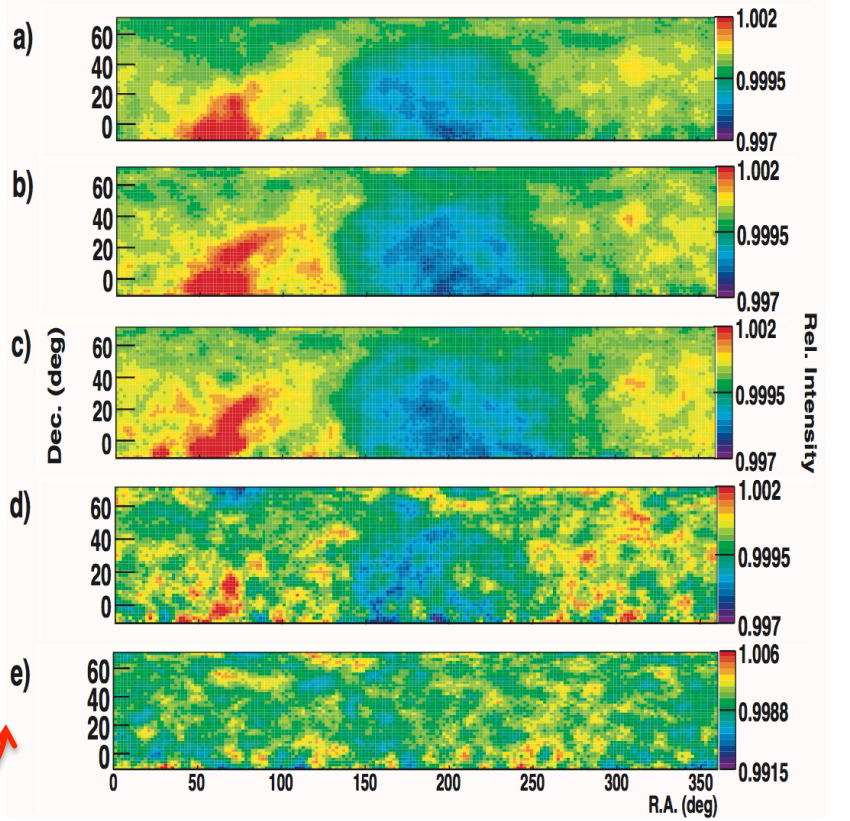


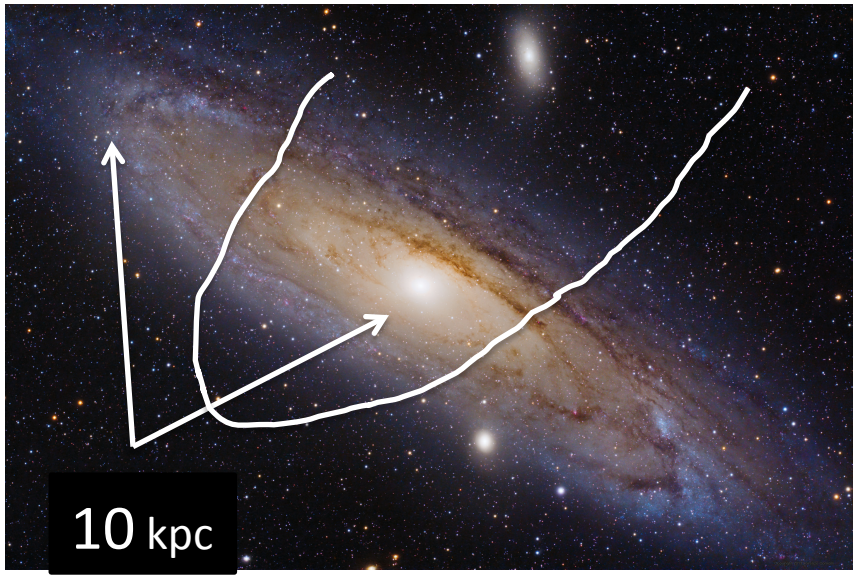
Figure 3: Celestial CR intensity map for different representative CR energies: (a) 4 TeV; (b) 6.2 TeV; (c) 12 TeV; (d) 50 TeV; (e) 300TeV. Data were taken during 1997−2005. The vertical color bin width is 2.5×10^{-4} in (a)−(d), while it is 7.25×10^{-4} in (e) for different statistics, all for the relative CR intensity.

Inferred Properties

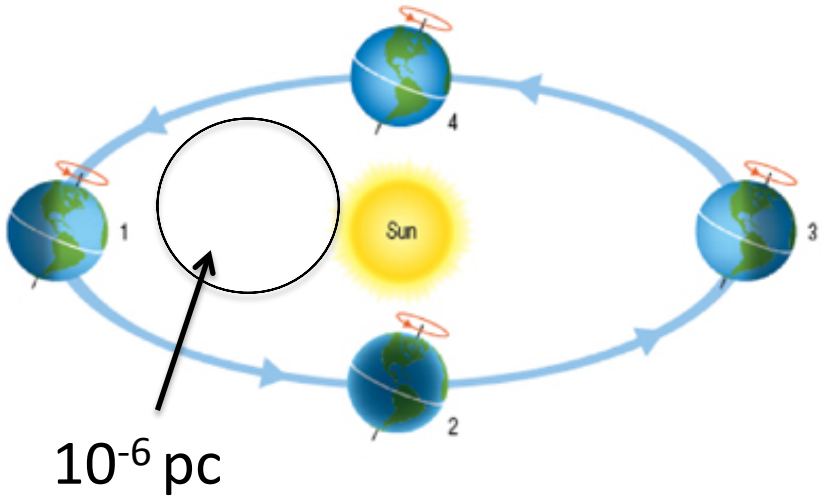
- Cosmic rays are accelerated from the interstellar medium in one time events that produce an E^{-2} spectrum.
- GeV cosmic rays are confined to the Milky Way for ~ 2 10^7 yr and scattered with a short mean free path λ ~ 1 pc.
- About 10% of the (non neutrino) energy in supernova explosions required for steady state.

Orbits of Cosmic Rays Depend on Their Energy: $r_g = E/(ZqB)$

1 parsec (pc) = 3.26 lt yr

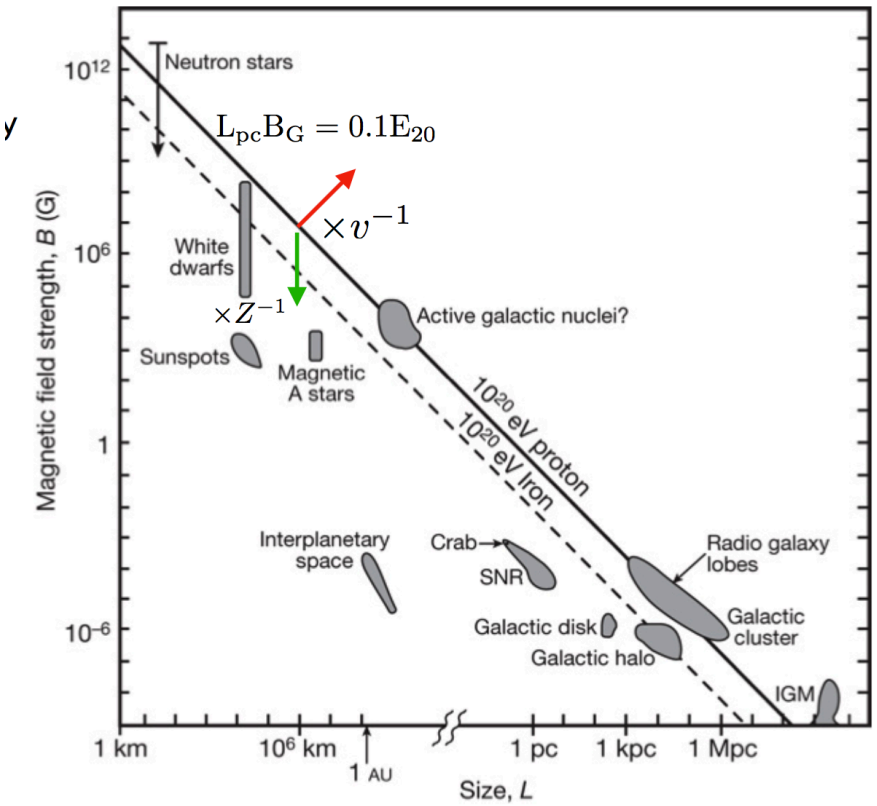


Ultra-High Energy Cosmic Ray encounter with Milky Way-like galaxy



Average cosmic ray gyro-orbit

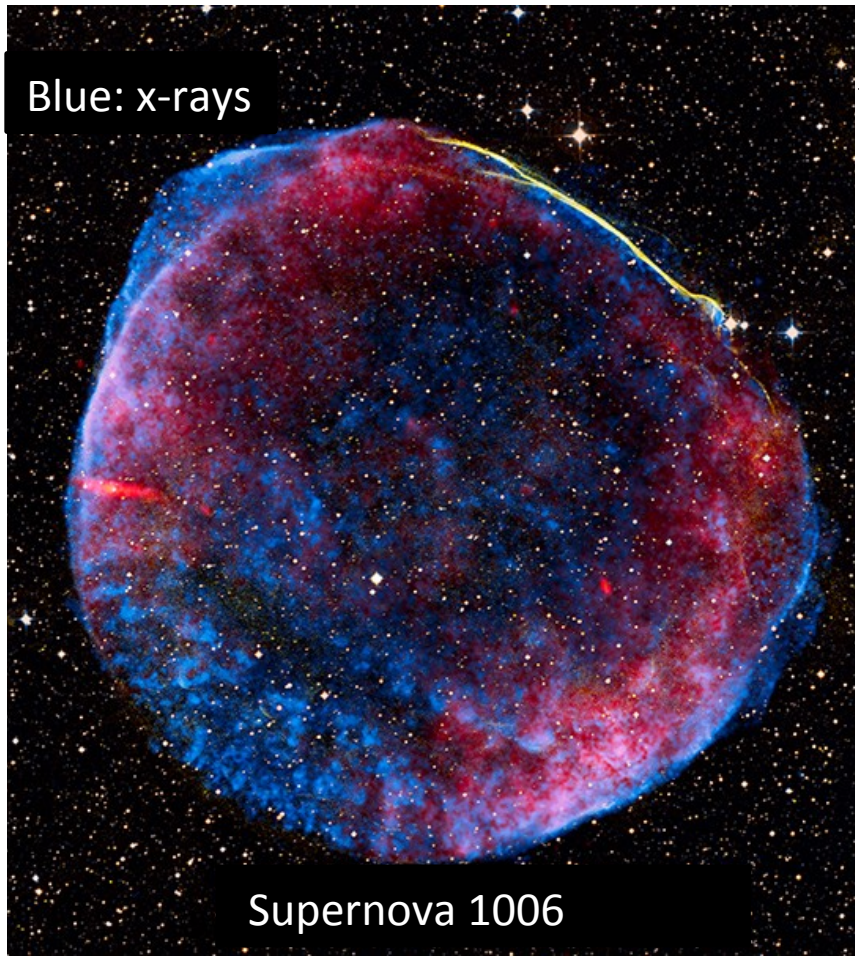
Where are Cosmic Rays Accelerated?

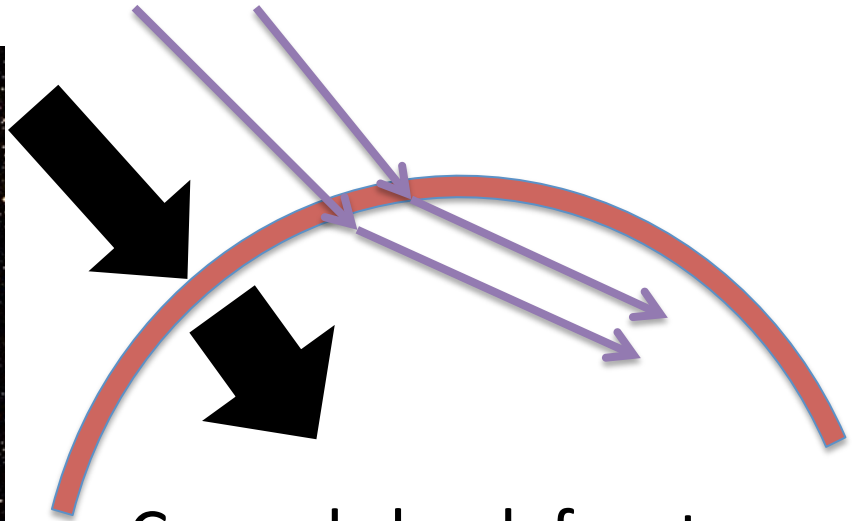


"Hillas Plot" (from F. Aharonian)

- A particle can't be accelerated beyond the energy at which its gyroradius equals the size of the system.
- The maximum energy is the energy reached after the lifetime of the system.

How are Cosmic Rays Accelerated?



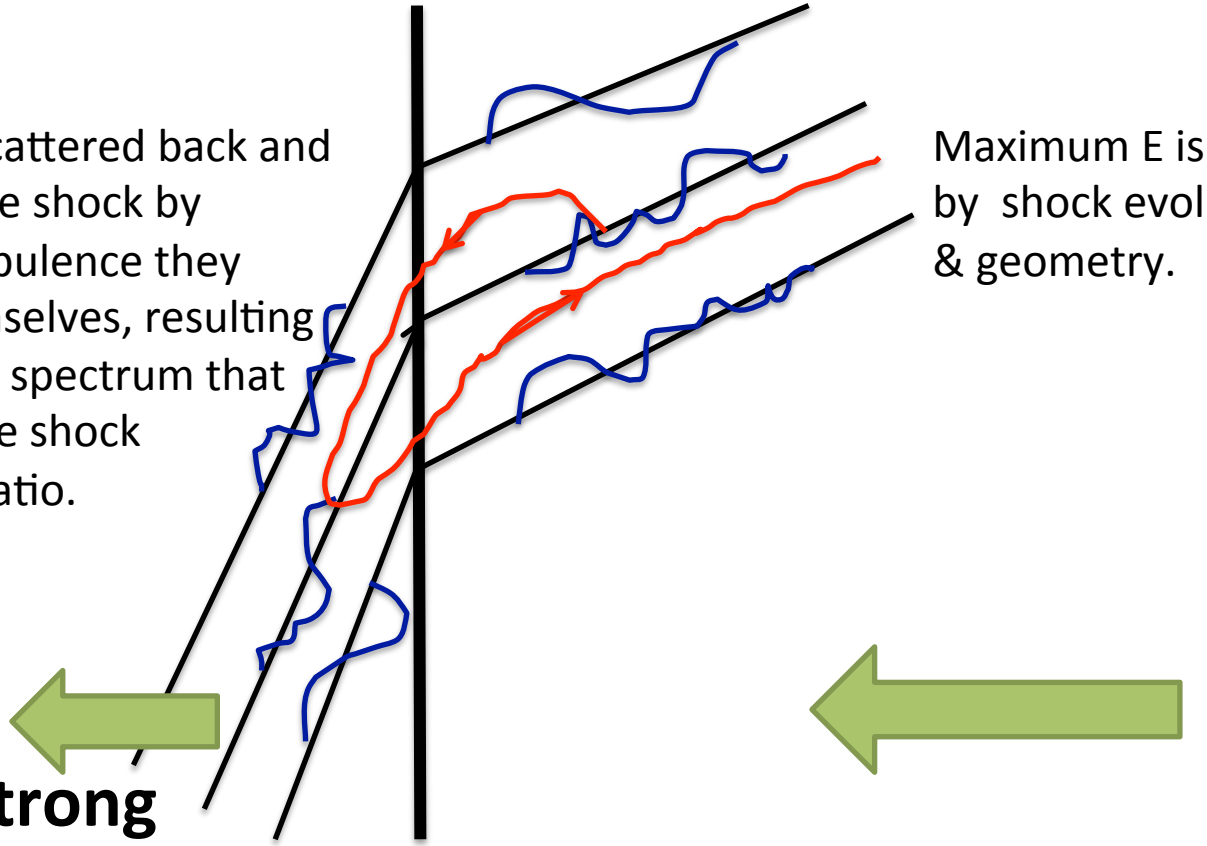


- Curved shock front (red), fluid flow in frame of shock (black arrows), magnetic fieldlines in purple.

NASA image

Diffusive Shock Acceleration

Particles are scattered back and forth across the shock by waves and turbulence they generate themselves, resulting in a power law spectrum that depends on the shock compression ratio.

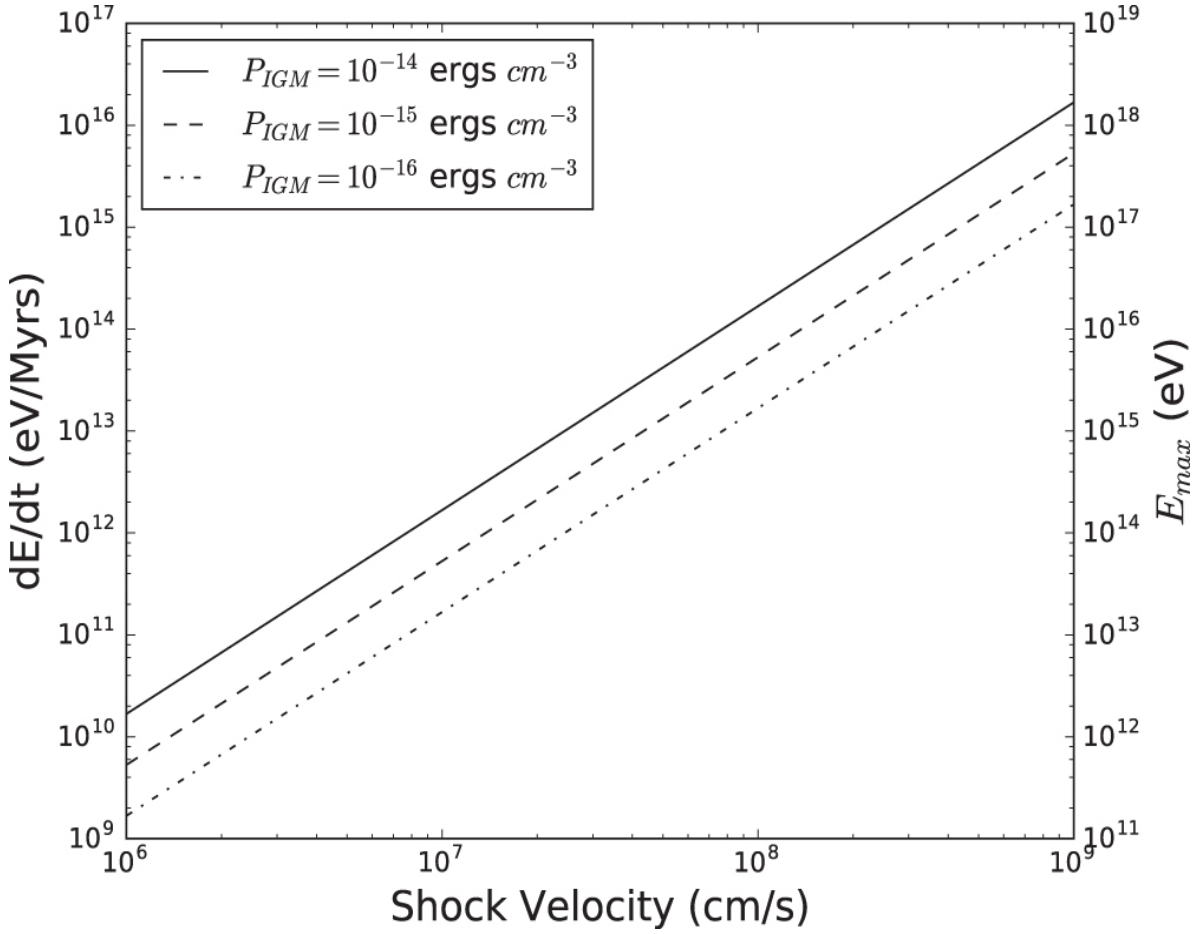


Maximum E is set by shock evolution & geometry.

E^{-2} for strong shock

This works up to a few PeV (10^{15} eV)

Termination Shock of the Galactic Wind: Here we Run into the Time Constraint



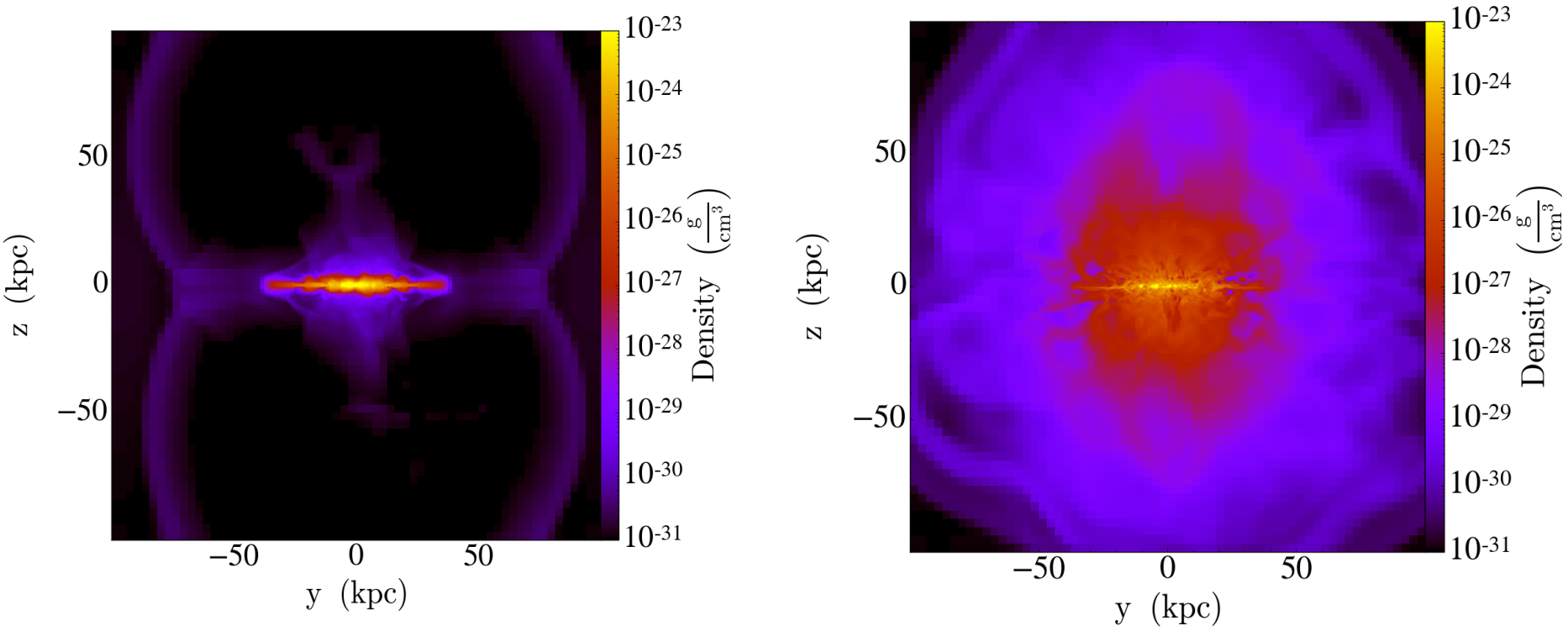
Work by Chad Bustard, soon to be a postdoc at at the Kavli Institute at UC Santa Barbara, & Cory Cotter, now a grad student at U. Chicago working on cryogenic detectors.

Best current guess: UHECR come from blazars, a type of active galaxy.

What do the less flashy, worker bee cosmic rays do in galaxies?

Galactic Winds

Numerical simulation of gas density in a star forming galactic disk, seen edge on.
Cosmic rays are injected where stars form (Ruszkowski, Yang, EZ 2017)



Left panel: Cosmic rays are frozen to the gas. Right panel: Cosmic rays stream at v_A relative to the gas.

Parker's Instability: Gas Falls, Magnetic Fields & Cosmic Ray Rise

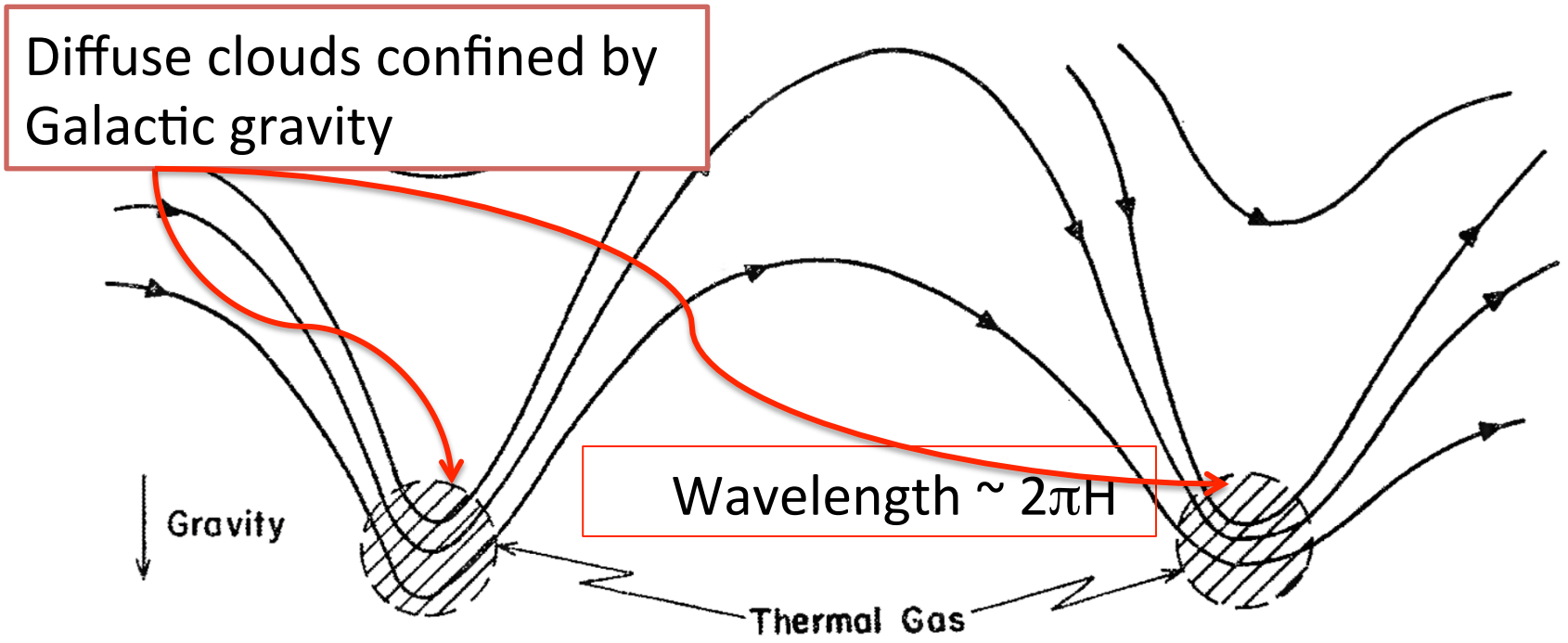
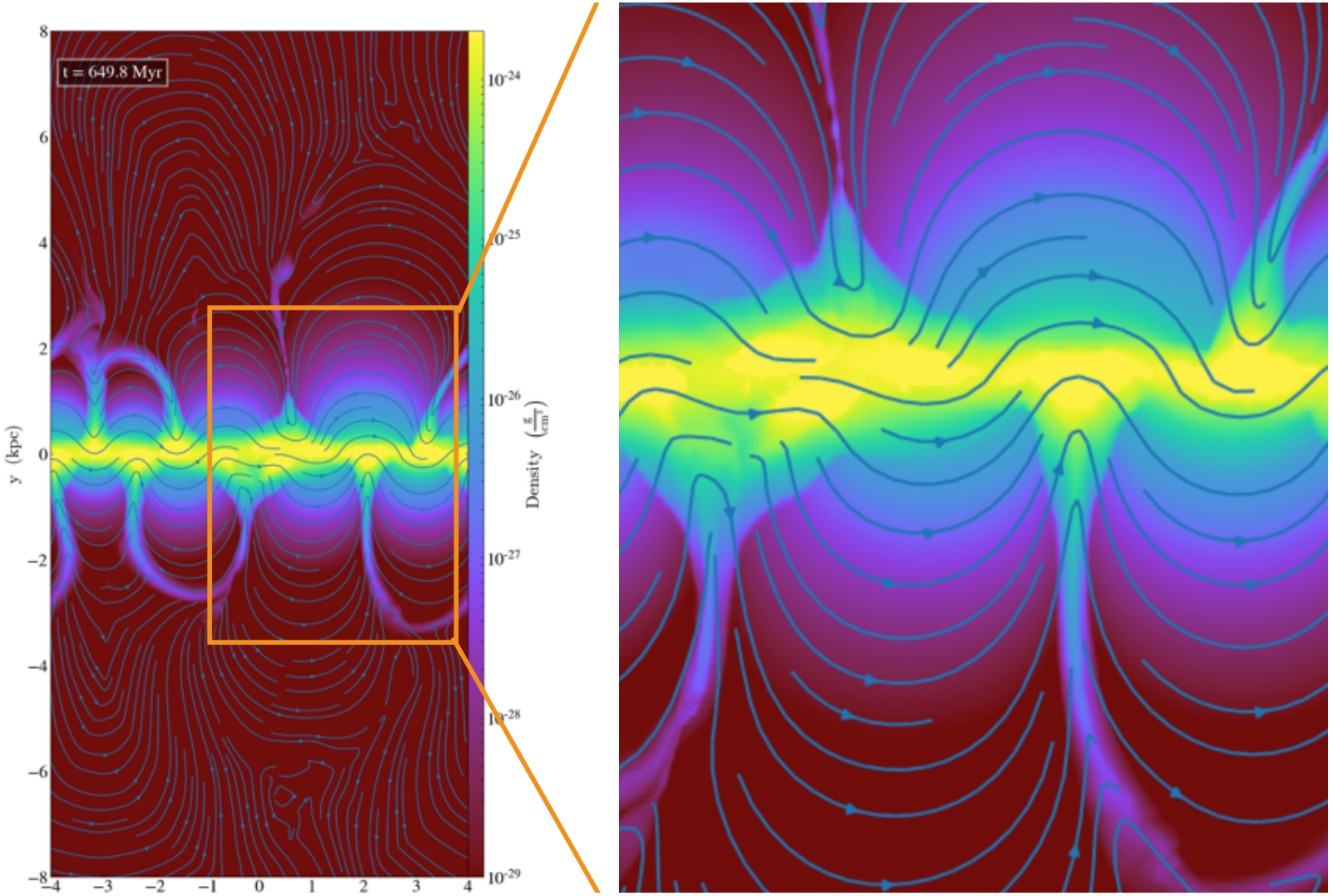
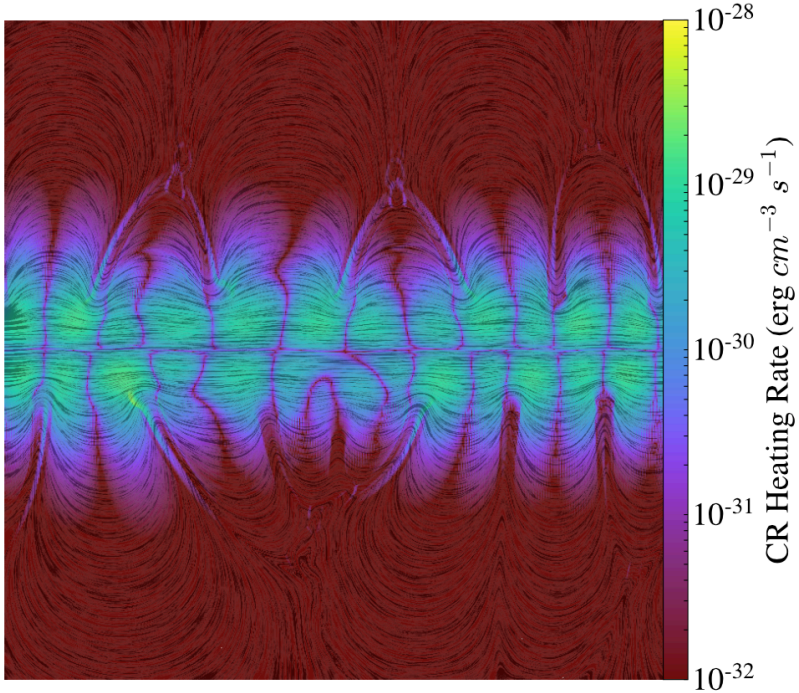


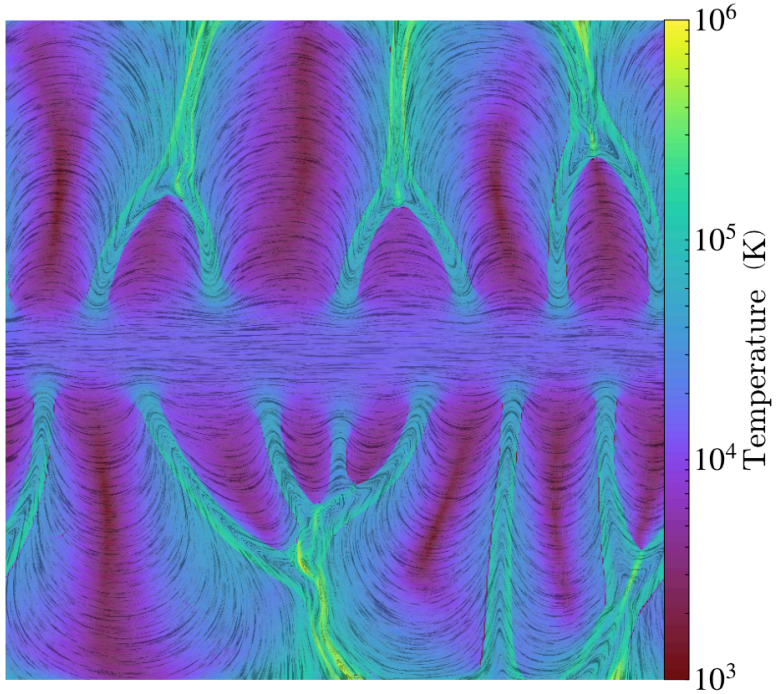
FIG 2.—Sketch of the local state of the lines of force of the interstellar magnetic field and interstellar gas-cloud configuration resulting from the intrinsic instability of a large-scale field along the galactic disk or arm when confined by the weight of the gas.

Density Evolution in Parker's Instability (Chad Bustard & Evan Heintz, also a PhD student)



Heating & Temperature





EH,CB, EZ

Radiative cooling is not included here.

Conclusions

- I hope you learned something about cosmic rays.
- You will never run out of problems in plasma astrophysics.
- The system you study will never be shut down or cancelled.
- You will encounter some of the most extreme conditions and forms of matter in the Universe.
- Thank you.