Title: Astroparticle Physics â€“ Observations: Cosmic rays

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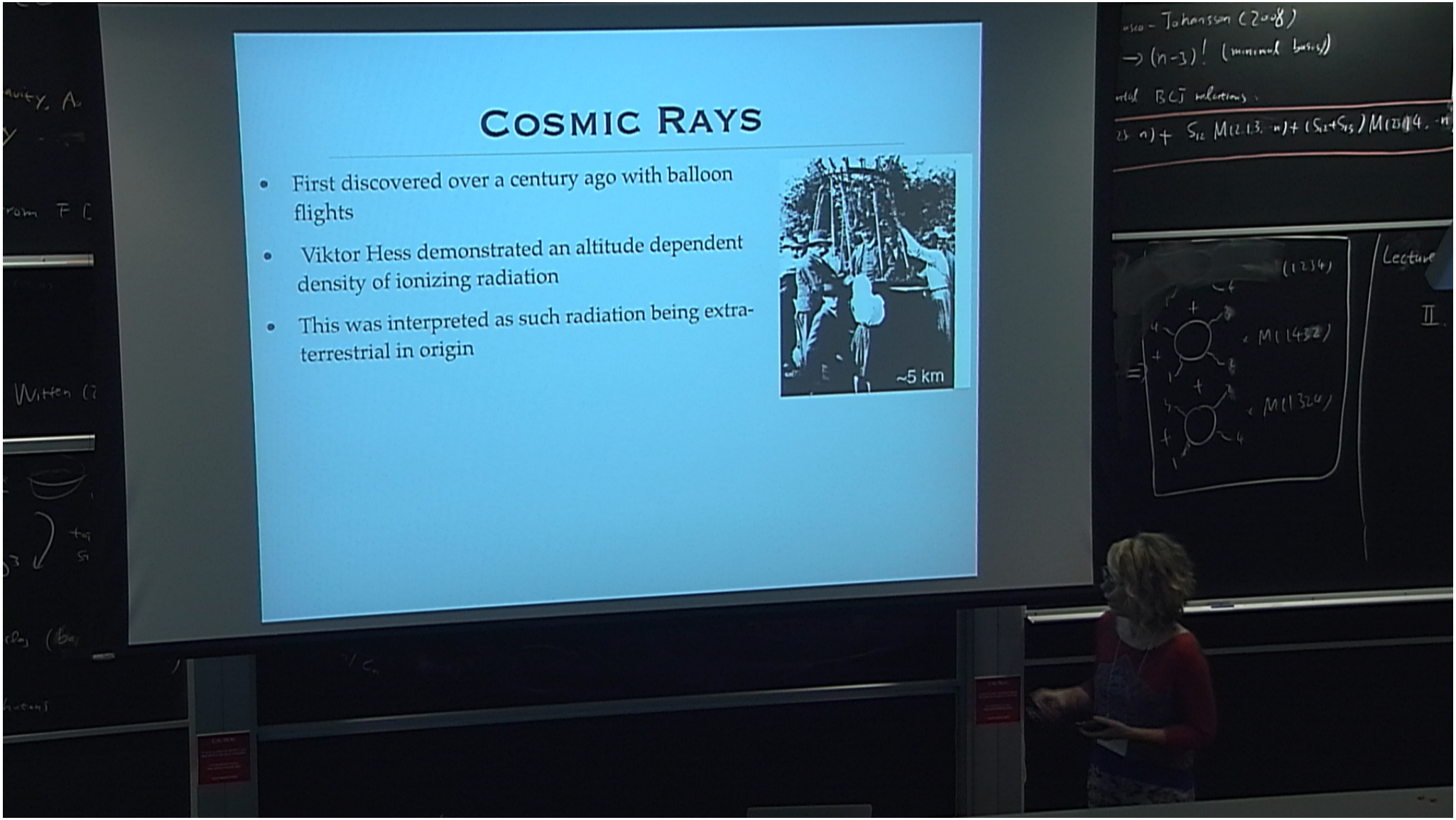
Abstract:

Cosmic Rays and Particle Accelerators in Space

Simona Murgia
University of California, Irvine

TRISEP 2015
13-14 July 2015, Perimeter Institute


Cosmic Rays
First discovered over a century ago with balloon flights
Viktor Hess demonstrated an altitude dependent density of ionizing radiation
This was interpreted as such radiation being extra-terrestrial in origin
~5 km
Johansson (2008)
(n-3)!
BCJ
Lecture
II

Cosmic Rays

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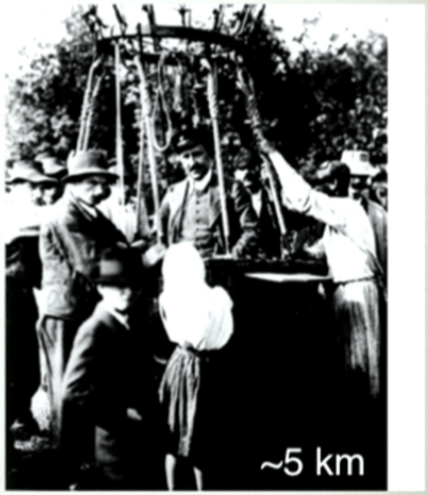
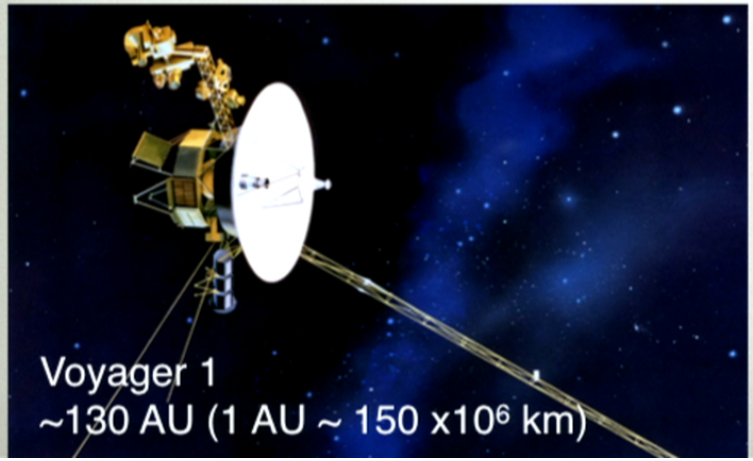
➡ Fast forward to today:

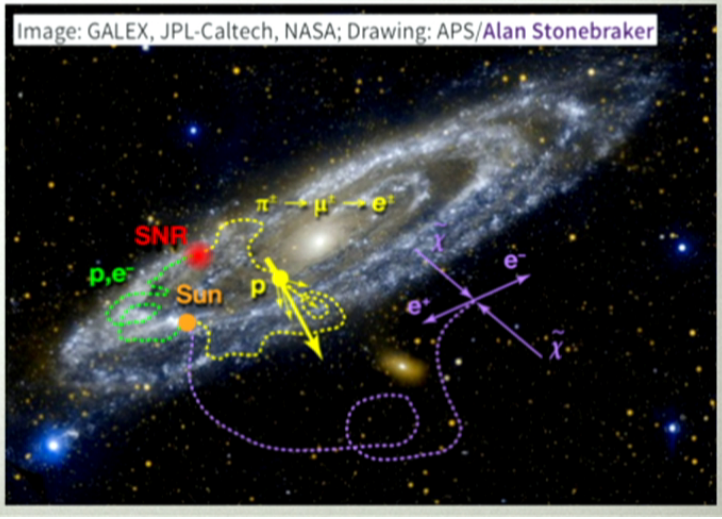




➡ **And many more experiments**

Things (We Think) We Understand

- The majority of observed cosmic rays (CRs) originate outside of our solar system and within our galaxy. Some, at the highest energies, are extra-galactic in origin
- Primarily protons, but also include heavier nuclei, electrons, photons, neutrinos, and antiparticles
- Mostly accelerated at *supernova remnants* (*primaries*)
- Some escape and propagate through the galaxy *diffusively*
- Anti-particle component is produced by primaries interacting with the *interstellar medium* (*secondaries*)
- Some might originate in dark matter annihilation or decay, and propagate



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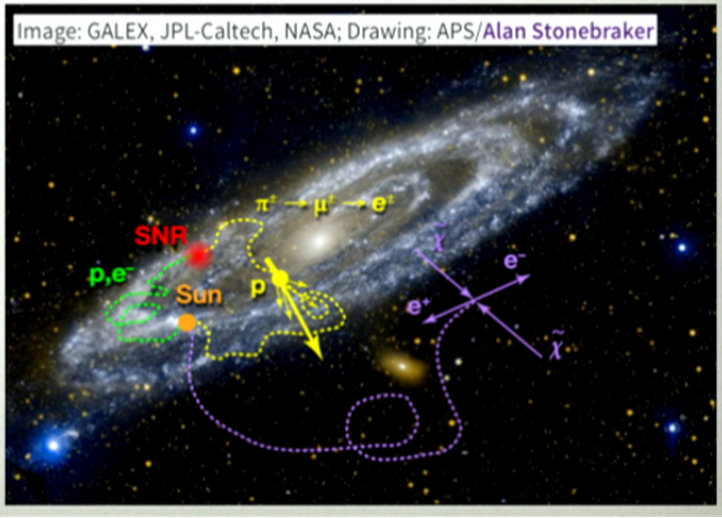
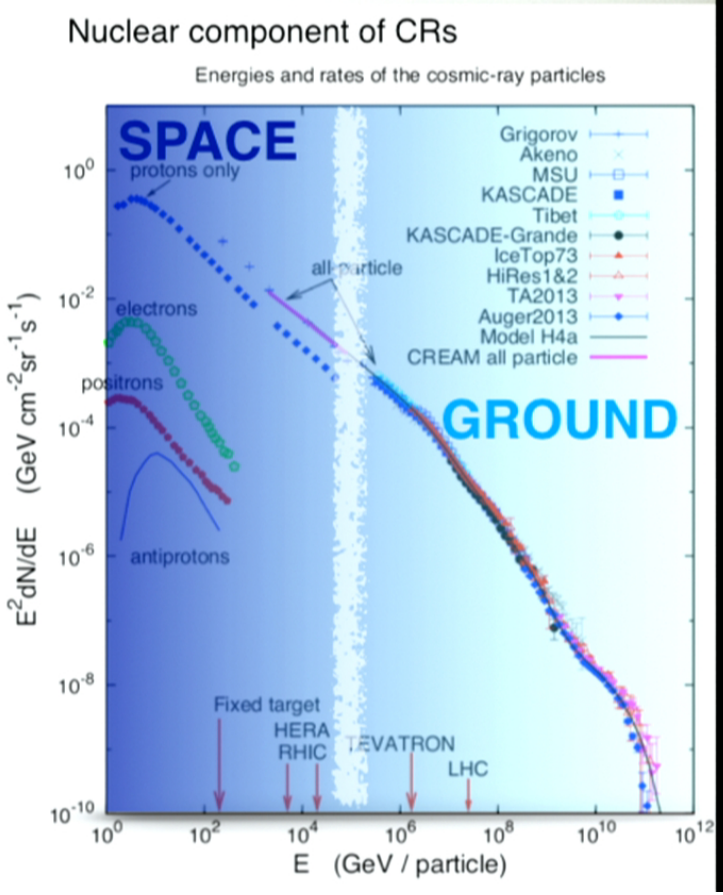


Cosmic Rays: Spectrum and Composition

- Several experiments on the ground and in space have measured the spectrum of CRs over several decades in energy



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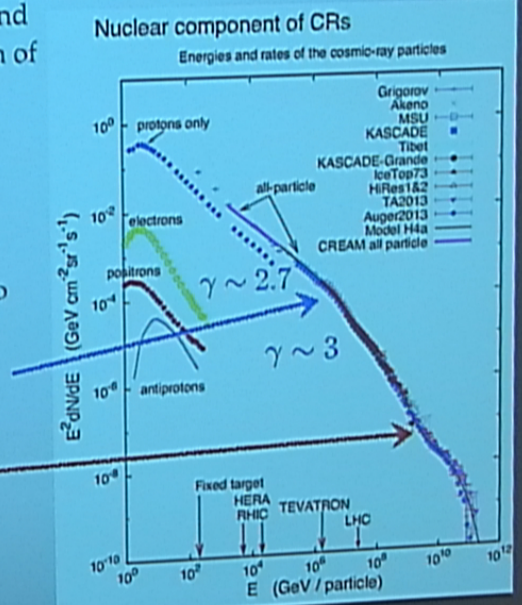
- Several experiments on the ground and in space have measured the spectrum of CRs over several decades in energy
- Power law spectrum:

$$\frac{dN(E)}{dE} \propto E^{-\gamma}$$

- Changes in the slope γ: transitions to different composition
- Knee: at ~10^{15} eV (10^6 GeV, 1 PeV)
- Ankle: at ~10^{17} eV, transition to extra-galactic CRs?
- GZK cutoff, interaction of CR protons with CMB



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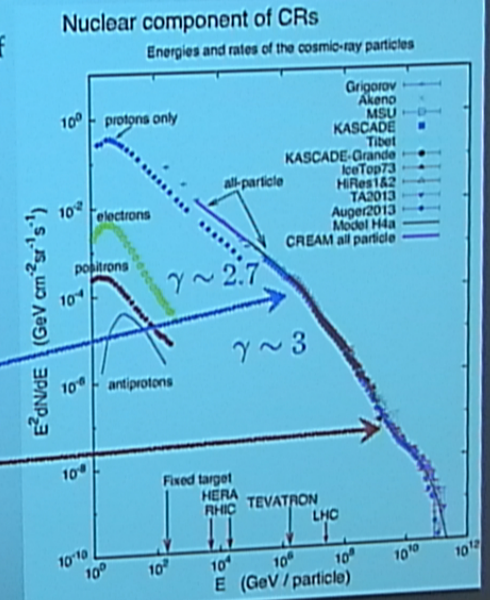

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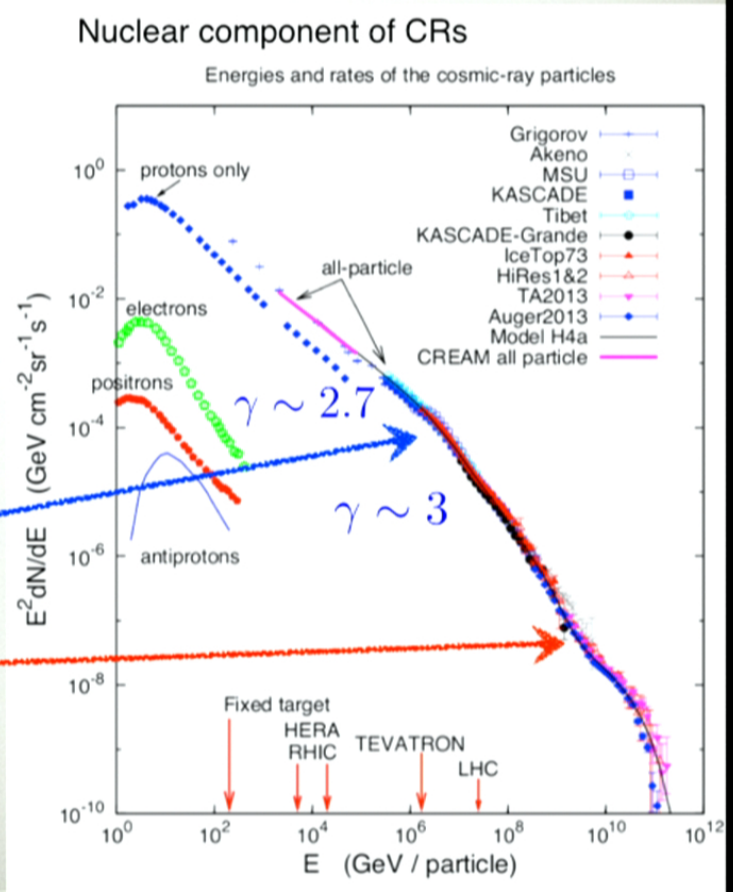
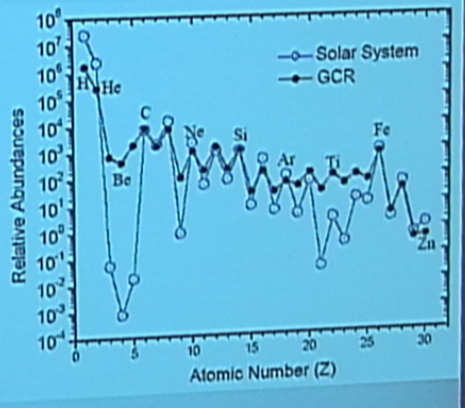


Cosmic Rays: Spectrum and Composition

- Energy density of CRs in the Galaxy: 1 eV/cm^3
- Number density of CRs in the Galaxy: 10^{-10}/cm^3
- Composition:
  - ~90% proton
  - ~10% helium
  - smaller fraction of heavier nuclei
  - electrons/protons ~1%
  - smaller fraction of antiparticles, but they carry crucial information
    antiprotons/protons ~ 10^{-4}
    positron/electron ~ 10%

➡ Some elements (e.g. B, Be, Li) are more abundant in CRs than in the solar system



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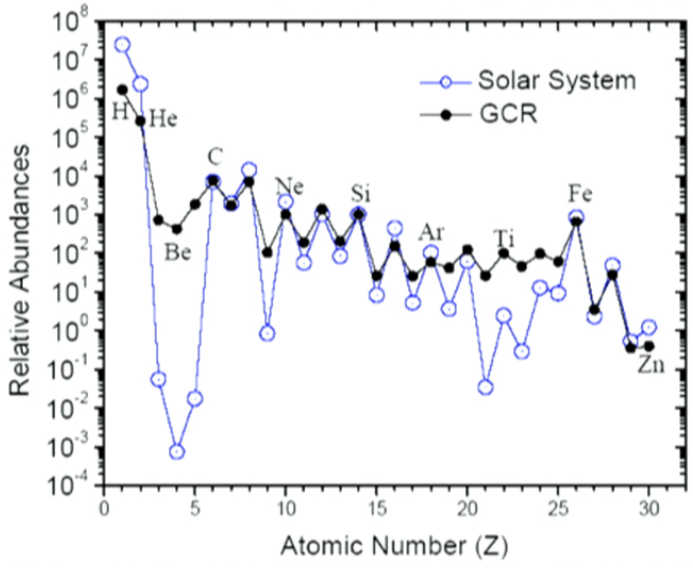

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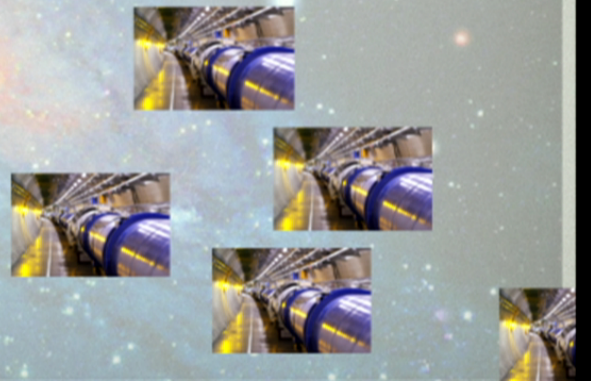
The Origin of Galactic Cosmic Rays

- Focus on Galactic CRs: where are they accelerated? Accelerator requirements:
  - accelerate particles to ~ 10^6 GeV (PeV) energies, ~ knee
  - dissipate enough energy into accelerating CRs: to generate an energy density of 1 eV/cm^3 (or 1.6x10^{-12} erg/cm^3), the luminosity of the galaxy in CRs must be 10^{41} ergs/s (include volume of the galaxy and escape time)
  - account for power-law energy spectrum of CRs



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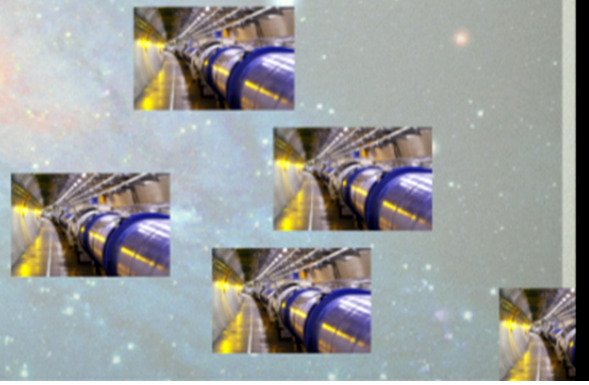

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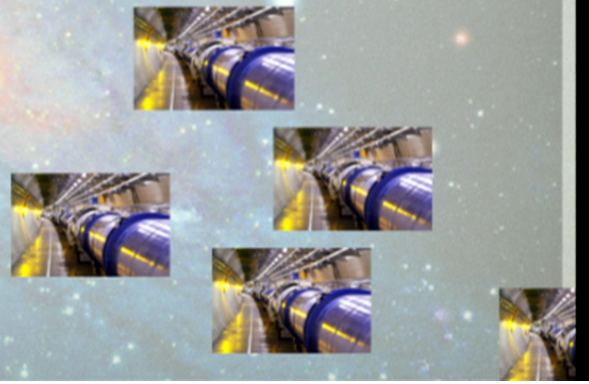


THE ORIGIN OF GALACTIC COSMIC RAYS

- Supernovae and their remnants are the site of the most energetic processes in the galaxy (first proposed by Baade and Zwicky 1934), and therefore good candidates for CR accelerators

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

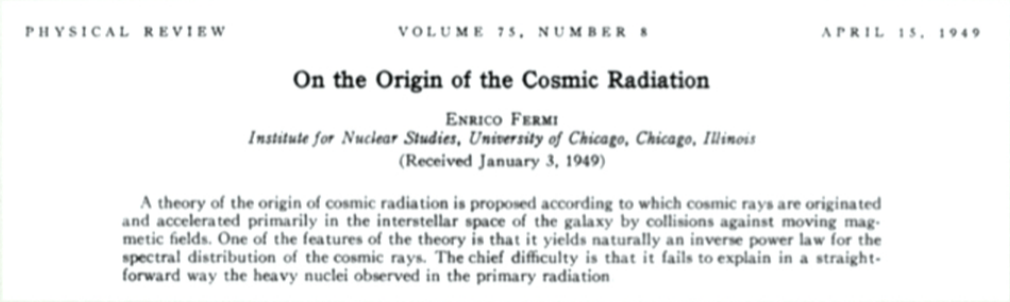
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

- A supernova explosion releases 10^{51} ergs. For ~1 supernova every 100 years, this contributes **10^{42} ergs/s**, i.e. if **~10% of the energy goes into accelerating CRs** the energetics required by CRs work out!

Acceleration Mechanism

- In 1949, Enrico Fermi proposed that moving magnetic fields in molecular clouds accelerate cosmic rays in interstellar space



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

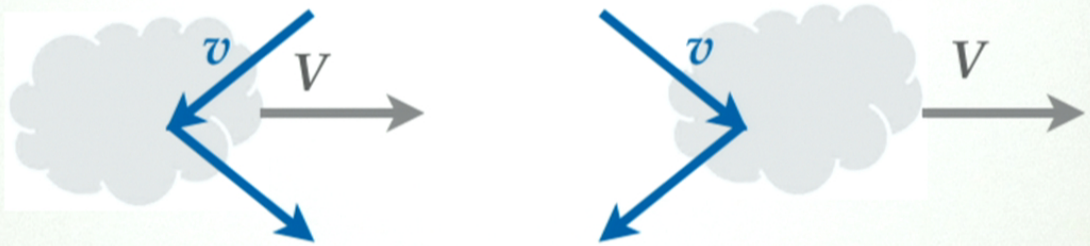
- For a charged particle in electric and magnetic fields:

$$\frac{d}{dt}(\gamma m\vec{v}) = q(\vec{E} + \vec{v} \times \vec{B})$$

- Need electric field to do non-zero work on the charged particle. Electric fields are generated by moving magnetic fields

Fermi Acceleration

- Consider a collision between a charged particle with velocity v and a moving, magnetized gas cloud, much more massive and unaffected by the collision, with velocity V



➡ The particle can gain or lose energy depending on whether the collision is head-on or not. In average, the probability for head-on collisions is larger, and the particle experiences overall an energy gain.

- It can be shown that in the relativistic limit ($v \sim c$), the average energy gain per collision is:

$$\frac{\Delta E}{E} = \frac{8}{3}\left(\frac{V}{c}\right)^2$$

2nd order Fermi acceleration

Generally $V/c <= 10^{-4} << 1$

- However: the velocity of gas clouds is small, and therefore it would require very long times to accelerate particles

Diffusive shock acceleration

- After the supernova explosion, the ejected material expands into the interstellar medium forming a shock front
- Particle ahead of the shock front are deflected in the turbulent magnetic fields of the shock front and accelerated outwards, till they are deflected again in the forward shock. During this process, the particle experiences a net energy gain at each crossing of the shock front

$$\frac{\Delta E}{E} \propto \frac{V}{c}$$

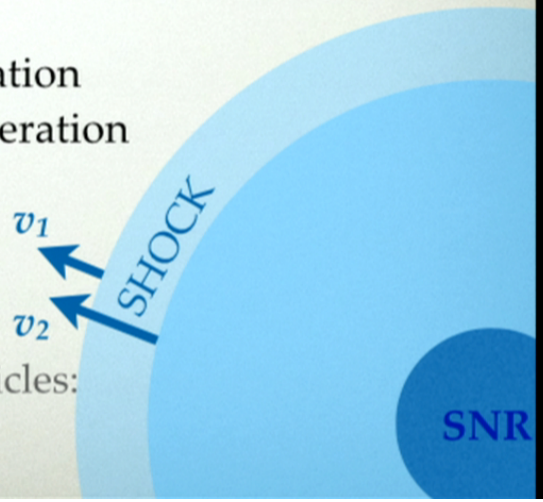
$V = v_2 - v_1$

$v_2 >> v_1$

1st order Fermi acceleration
or diffusive shock acceleration

- When the particle gyro-radius is large enough, the particle can escape into interstellar space
- Predicts power law spectrum for accelerated particles:

$$N(E) \propto E^{-2}$$



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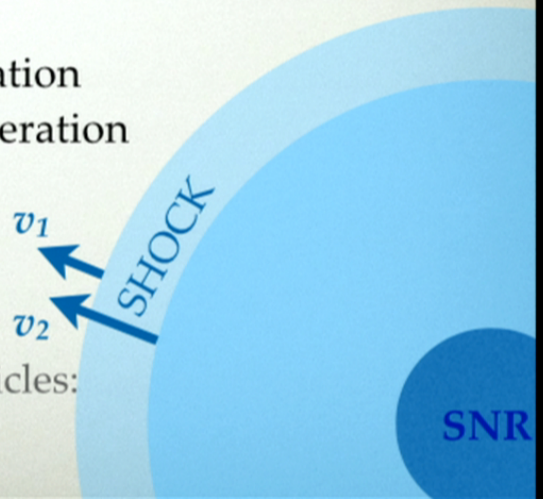
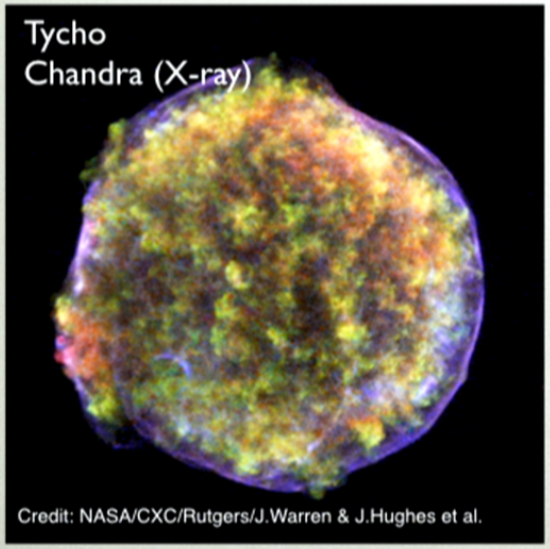


Supernova Remnants

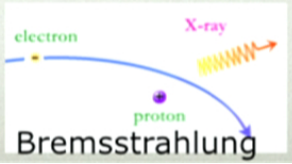
- SNRs as sites of acceleration of CRs: crucial information comes from multi-wavelength observations
- From synchrotron emission in radio and X-ray, it can be inferred they accelerated electrons up to high energy (1-10 GeV from radio, and ~10s TeV from X-rays with magnetic fields of ~0.1-0.2 mG)



- Are these the main main sites of CRs acceleration and can they accelerate particles to the knee?
- More information from gamma rays! Gamma rays can be generated by a population of high energy CR electrons and protons interacting with surrounding medium

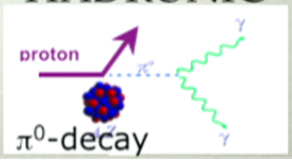
LEPTONIC

Inverse Compton



Bremsstrahlung

HADRONIC



π^0-decay

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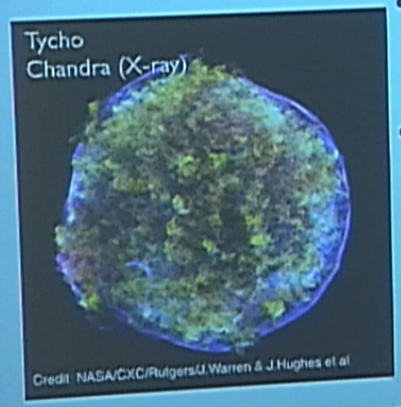
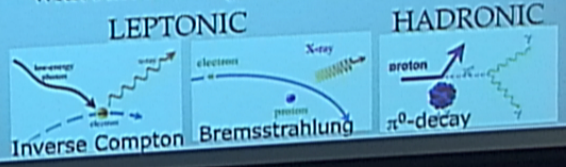
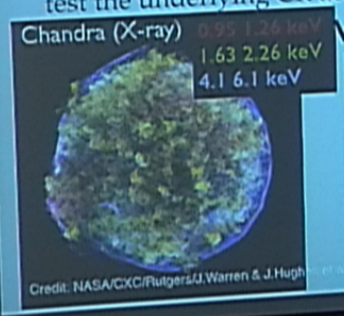


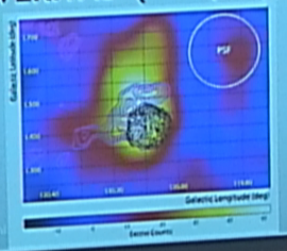


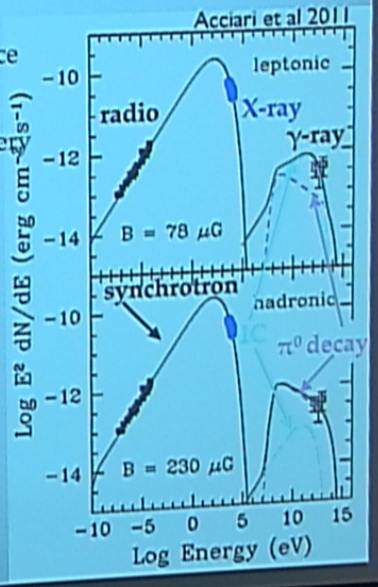
TYCHO

- Young SNRs are particularly good candidates as they can accelerate particles to very high energies
- Tycho: ~400 yrs old, 3.7 pc extension, 3-5 kpc distance
- X-ray observations show ejected material heated to many millions degrees and an expanding shell of very high energy electrons
- γ-rays: TeV observations indicate CRs must be accelerated to even higher energies; GeV γ-rays can test the underlying CR acceleration scenarios



VERITAS (TeV γ-ray)





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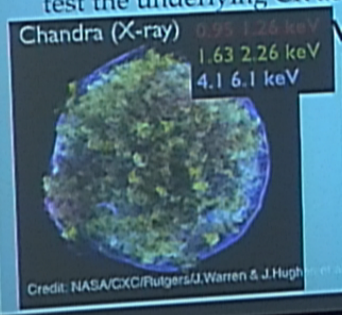

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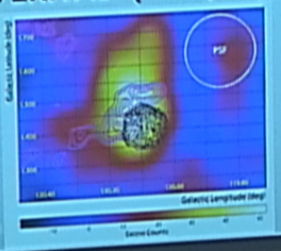

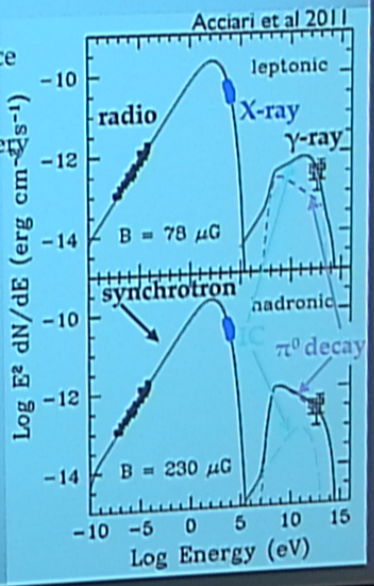

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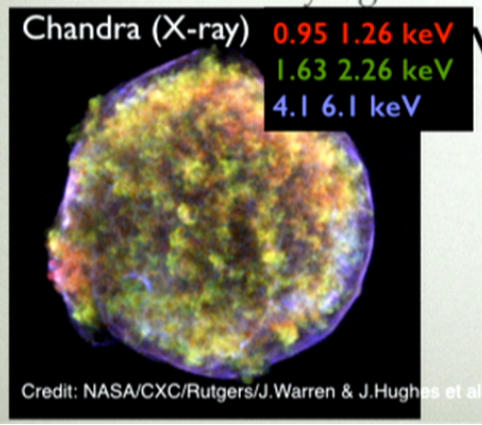
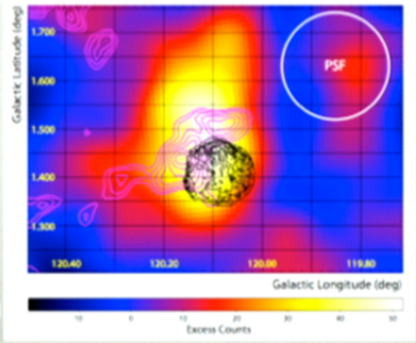
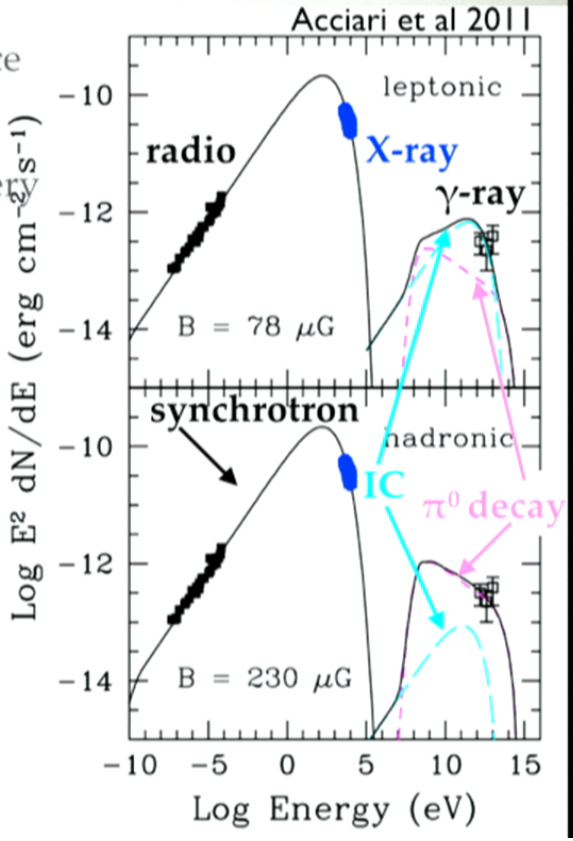
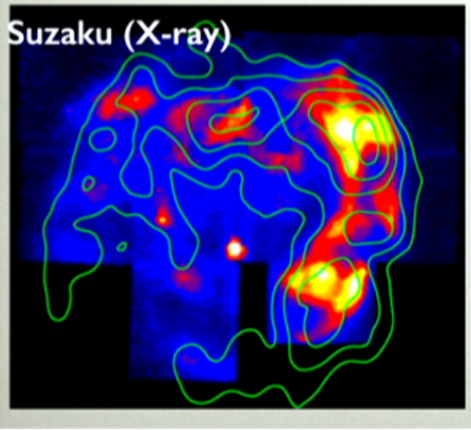




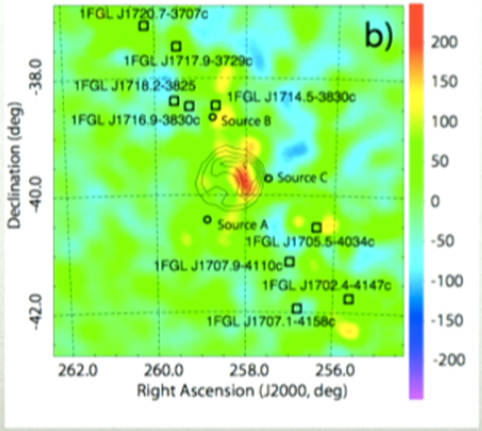


RX J1713.7-3946

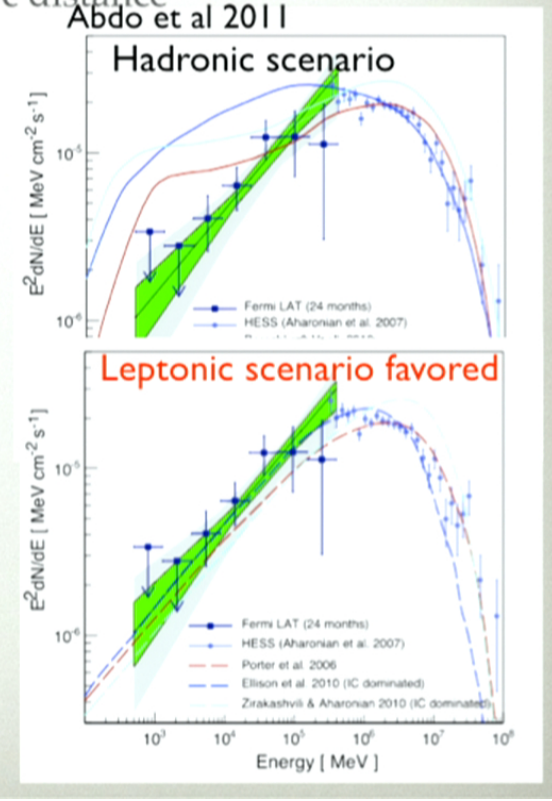
- However another young supernova remnant gives a different answer
- RX J1713.7-3946: ~1600 yrs old, 20 pc extension, 1 kpc distance
- The *hard* (i.e. less steep) spectrum (spectral index ~ 1.5) at GeV energies favors an underlying population of very high energy electron scattering off ambient photon fields via IC



Fermi LAT (GeV γ-ray)



Abdo et al 2011



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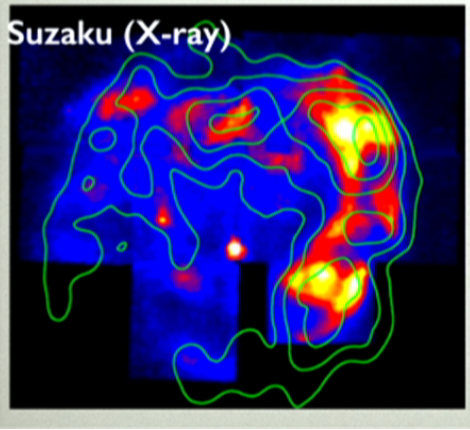
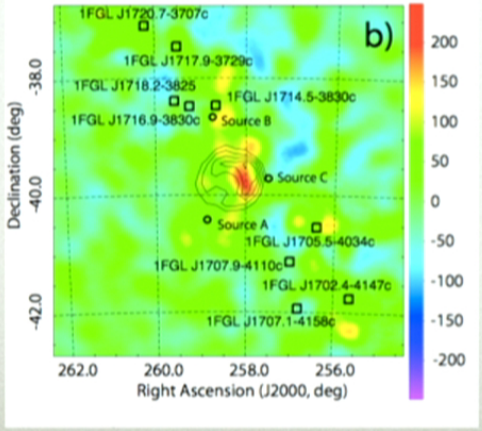
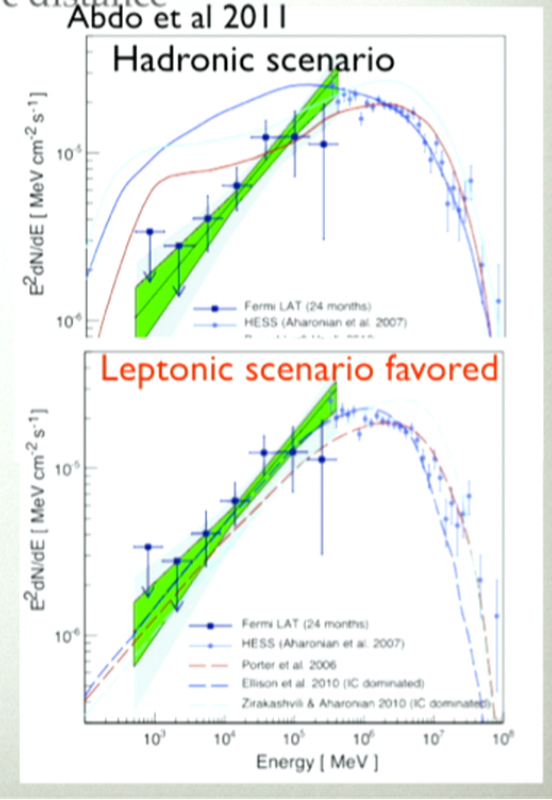


Fermi LAT (GeV γ-ray)



Abdo et al 2011



RX J1713.7-3946

- However another young supernova remnant gives a different answer
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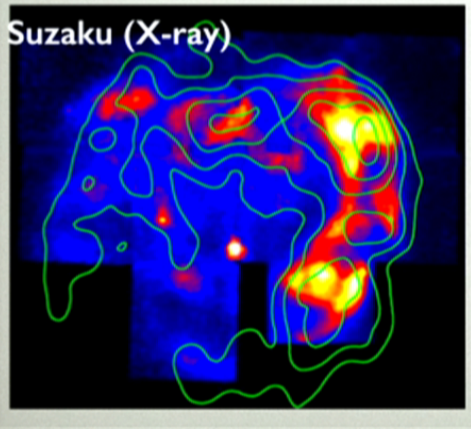

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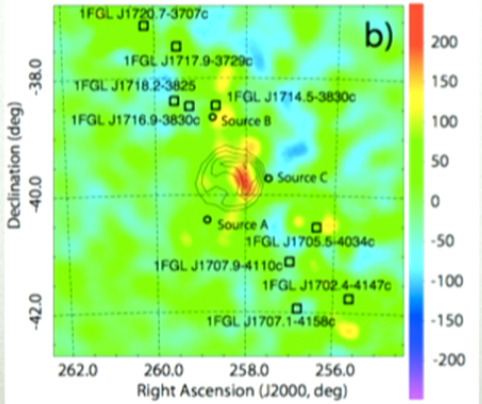

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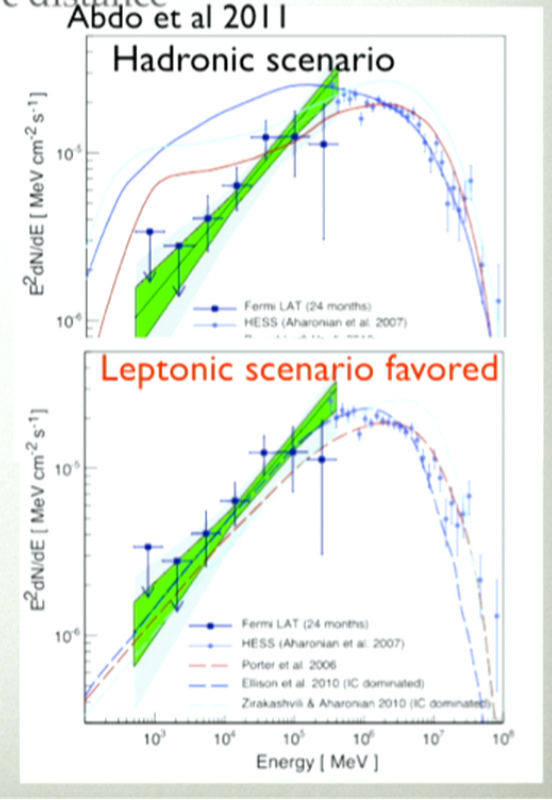
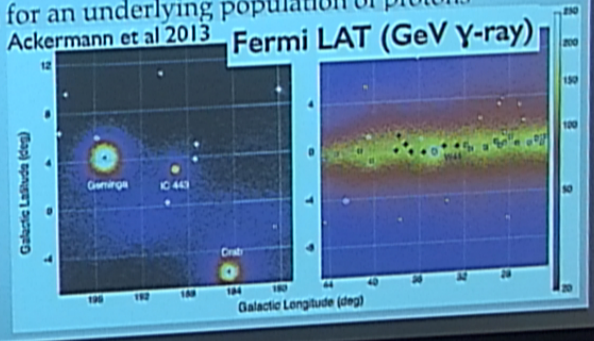


The case of IC 443 and W44

- Smoking gun spectral signature for hadronic production: pion decay bump
  - $p + p \rightarrow \pi^0 +$ other products, $\pi^0 \rightarrow 2\gamma$
  - In the rest frame of the π^0: $E_\gamma = m_{\pi^0} c^2/2 = 67.5$
  - It can be shown (Stecker 1971) that the photon spectrum dN/dE has a symmetric bump in log-log scale (and therefore rises steeply below 200 MeV in E^2dN/dE)
- Take advantage of energies down to 60 MeV to observe pion bump in SNR spectra! This is a smoking gun for an underlying population of protons
- Consider SNRs in the proximity of molecular clouds. Very bright in γ-rays!
- IC 443/W44 are: ~10,000 yrs old, 1.5/2.9 kpc distance

Ackermann et al 2013



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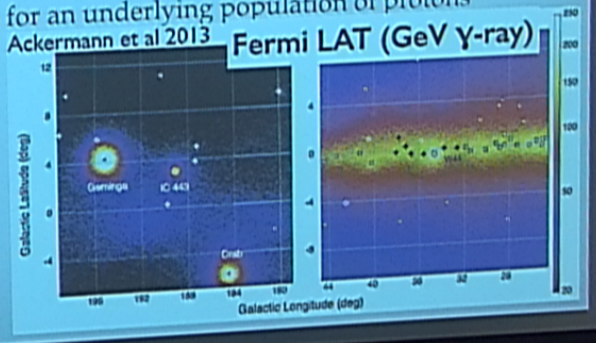

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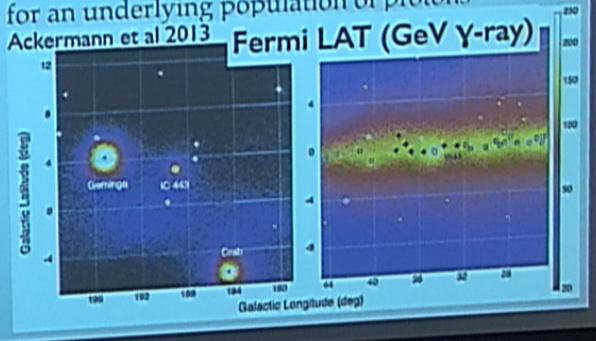

The case of IC 443 and W44

- Smoking gun spectral signature for hadronic production: pion decay bump
- Observed spectra: steeply rising <~ 200 MeV with a break at ~200 MeV
- Consistent with pion decay signature
- Underlying proton population (intensity/ spectrum inconsistent with electron IC/brem; a small brem contribution cannot be excluded)
- Bulk of the emission is believed to originate in the shock downstream of the cloud by protons confined in the SNR shell