RUHR-UNIVERSITÄT BOCHUM

Foundations of Cosmic Ray Sources and Propagation

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FAKULTÄT FÜR PHYSIK & ASTRONOMIE
Theoretische Physik IV

Contents of part I

- Introduction: discussion of challenges
- The sources
- Observational evidence
- Part II (Ingo Büsching): Details on the theory of propagation

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The observed cosmic ray spectrum

- -9 < log(E/GeV) < 6: Supernova Remnants, …
- 6 < log(E/GeV) < 9.3: Leaky Box; Galactic sources; pulsars, X-ray binaries, SNRs …
- log(E/GeV) > 9.3: extragalactic (isotropy argument)

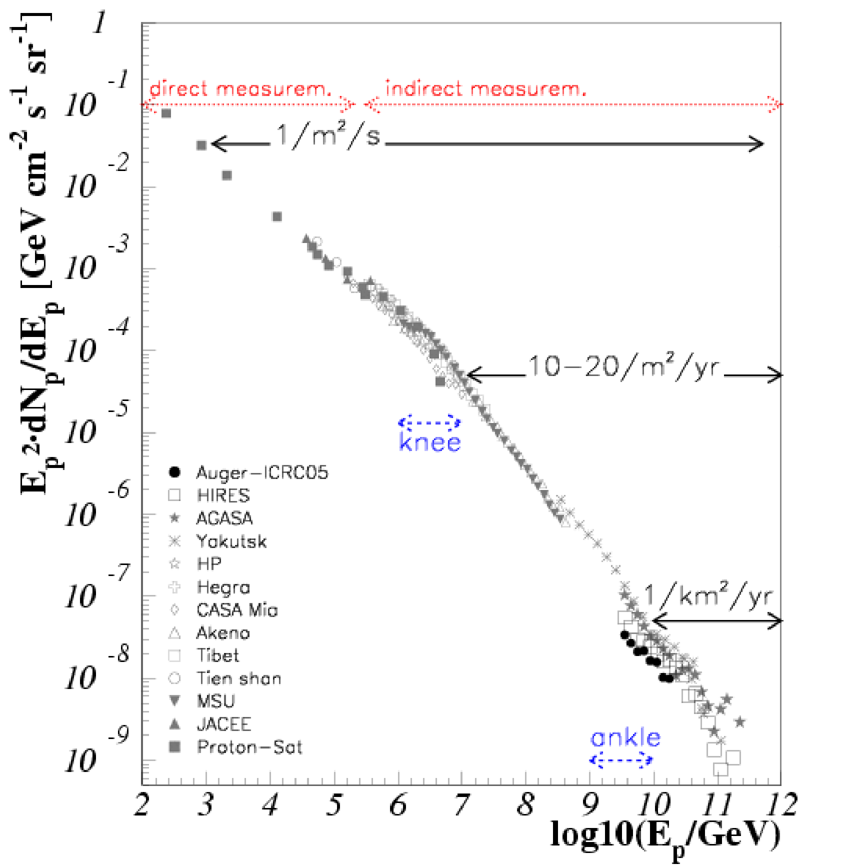
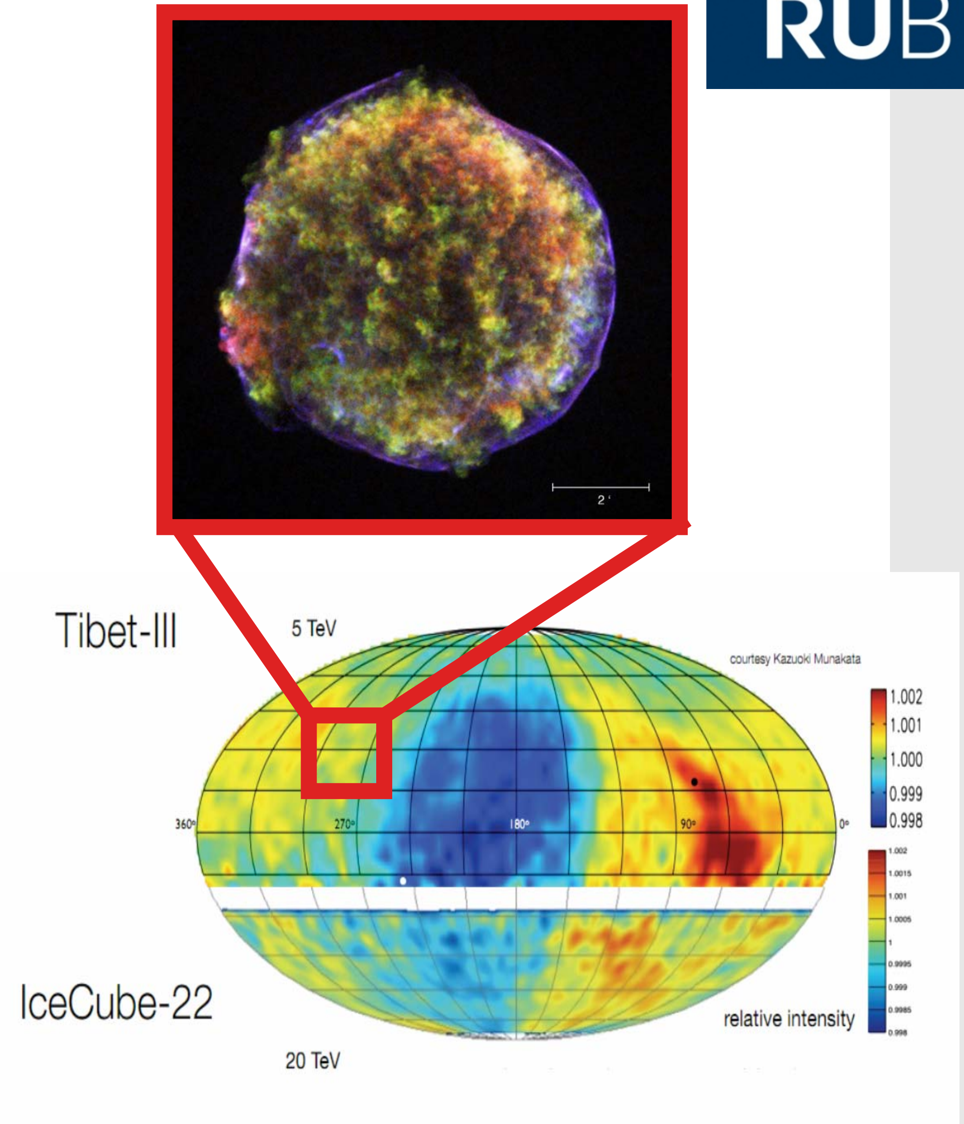


Figure: Becker (2008)

Interplay magnetic fields – cosmic rays



- Acceleration in turbulent electromagnetic fields
- Transport through large-scale B-fields (extragalactic & Galactic)
- And finally modifications at low energies by the solar magnetic field

The challenge

- Features in the charged CR spectrum always combination of effects from
  - **Source distribution**
  - **Magnetic field strength & orientation**

- Conclusion: only charged cosmic rays will not help to disentangle this → need other information
  - **Source distribution: ν, γ, synchrotron, line emission, …**
  - **Magnetic fields: measurements**

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Stochastic acceleration

- **Test particle, accelerated at time dependent, electromagnetic fields** $\delta B(t)$

- **Energy gain: fraction of initial energy**

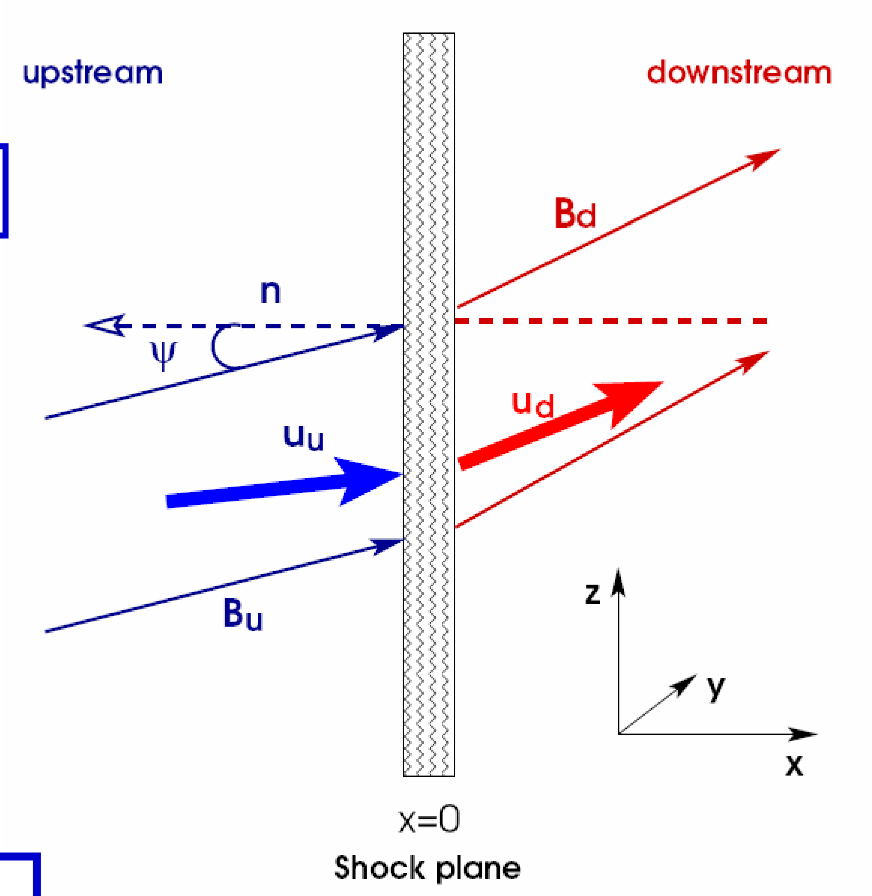
$$\Delta E = E - E_0 = \xi \cdot E_0$$

- **n acceleration cycles**

$$E_n = (\xi + 1)^n \cdot E_0$$

- **This leads to a power-law energy behavior**

$$N(>E) = \sum_{i=n}^{\infty} (1 - P_{esc})^{n(E)} = \ldots \propto E^{-\gamma}$$



Idea from Fermi (1949, 1954)

Further development by e.g. Axford (1974) and Bell (1978), Schlickeiser (1989)

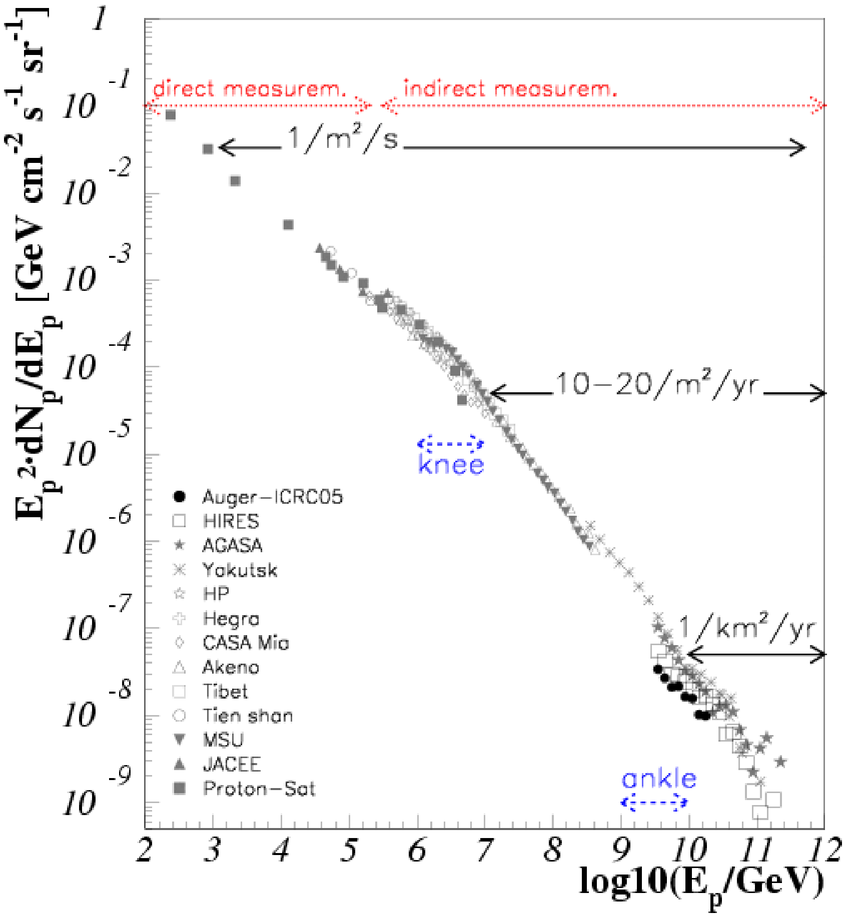
Textbook see e.g. Schlickeiser (2002) or Gaisser (1991)

Criteria to classify as a cosmic ray source candidate

- Calculation of power (“**luminosity**“) in Cosmic Rays?

$$L_{CR} \propto \int_{E_{\min}} \frac{dN}{dE} E dE$$

- **Maximum energy**? 10^{15}eV/3*10^{18}eV/ >3*10^{18}eV
  - Hillas criterion: **E < Z*e*B*L**



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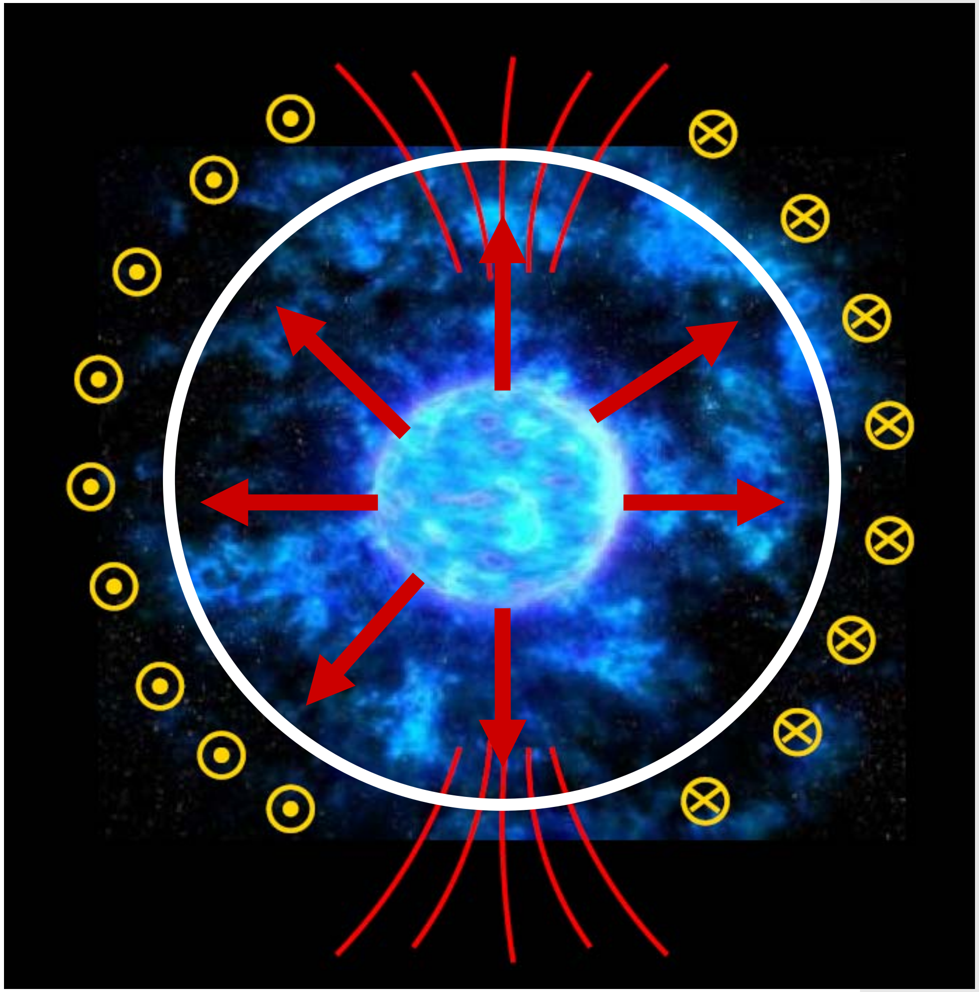
Simple model: particle acceleration in SNRs

- Radial component:
  - perpendicular shock → Fast acceleration and $dN/dE \sim E^{-2.3}$
- Polar cap:
  - parallel shock → Slow acceleration and $dN/dE \sim E^{-2}$



NASA picture, modified

Biermann et al;
PRL (2009), APJL (2010); ApJ (2010)

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Sources: available information from observations

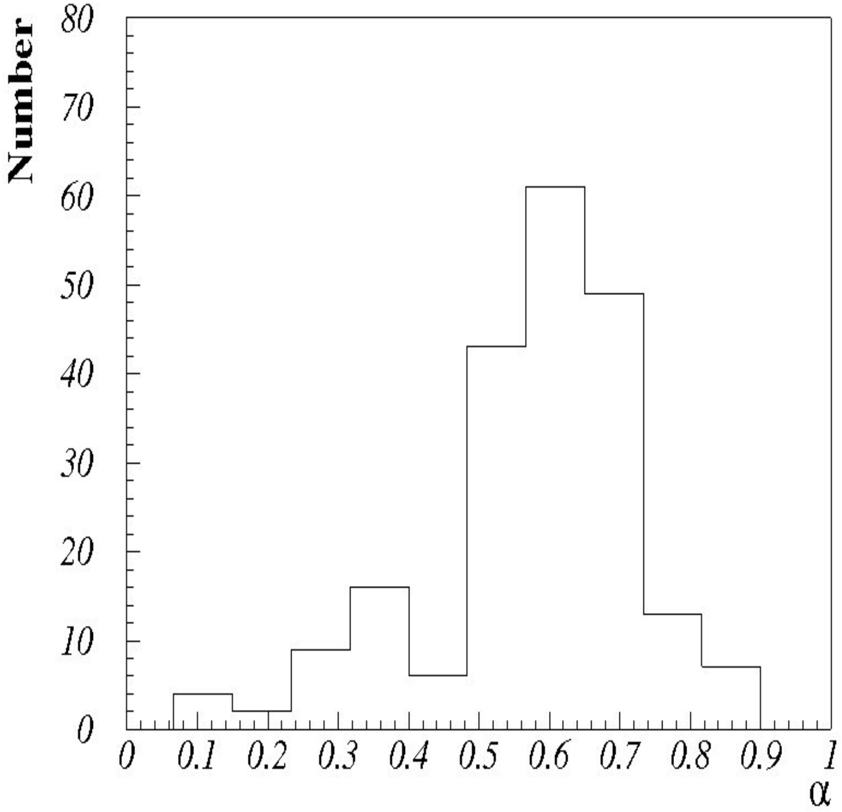
- **Radio observations → sources of electrons**
  - *Difficulty:* losses through synchrotron radiation change spectral behavior, dependent on B-field at the sources.
  - Signal can be influenced by other processes

- **Gamma-ray radiation → hadronic sources**
  - GeV – TeV radiation
  - *Difficulty:* Other radiation processes (IC/bremsstrahlung)

- **Molecular ions: lines**
  - Traces matter (→ tracer for proton-proton interactions)
  - *Difficulty:* CR spectrum at low energies not known

Synchrotron spectrum as electron spectrum tracer

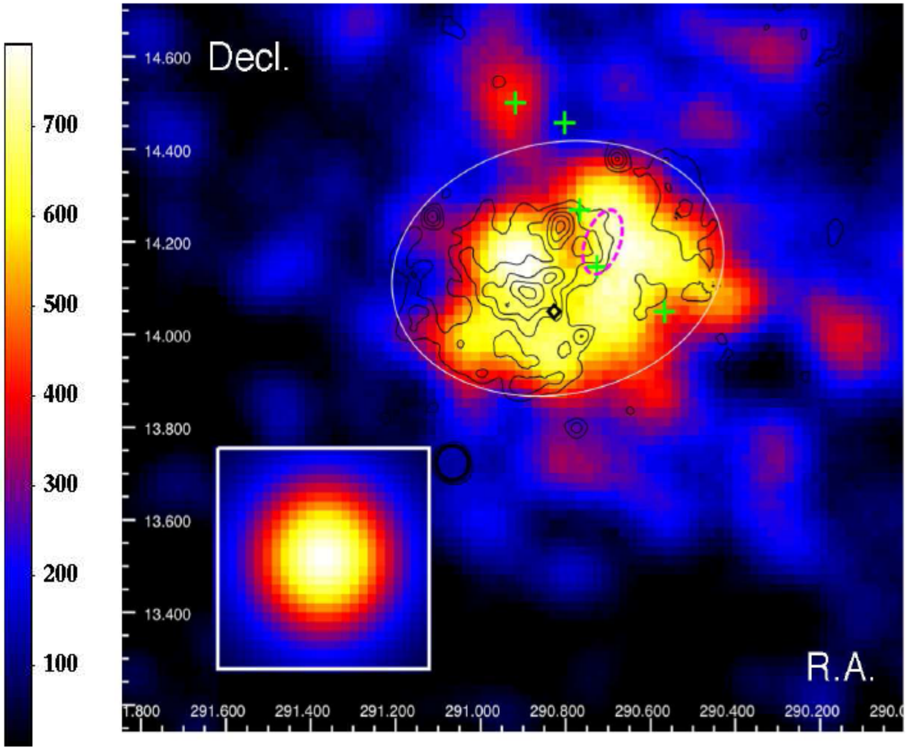
- Details of spectral behavior complex
- Distribution of SNR radio spectral indices, $S_\nu \sim n^{-\alpha}$
- $p = 2*\alpha+1$, $dN/dE \sim E^{-p}$
- Observations thus indicate that for e^- index can be smaller and larger than 2.
- Same true for protons?



Spectral index data from Green (2009)

Example: W51C

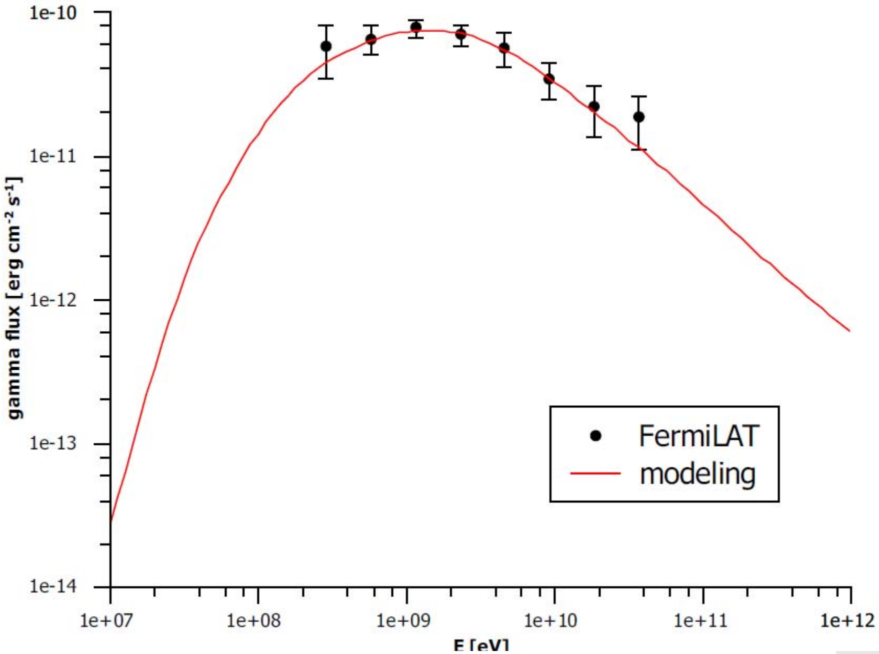
- GeV/TeV radiation reveals proton-proton interactions → spectral behavior, energy and target information
- But: other processes at same wavelength
- Low-energy signatures help to identify good candidates for interactions



Abdo et al (Fermi Coll.) (2009)

SNR gamma spectra as cosmic ray tracers

- Gamma-ray spectra reveal CR source population (electrons/hadrons)
- (Synchrotron spectra contribute to knowledge on e^- population)
- Catalog of 274 known SNRs: Green (2009); >15 SNRs @ GeV/TeV energies (+ unidentified sources)



$$j_p(E_p) = a_p \left(\frac{E_p}{E_0}\right)^{-s} \left(1 + \left(\frac{E_p}{E_{br}}\right)^2\right)^{-\Delta s/2}$$

W51C: Fermi data (2009)
Proton spectrum to fit gamma data: $s = 1.5$, $\Delta s = 1.4$, $E_{br} = 15$GeV

F. Schuppan, RUB, diploma thesis (2011)

Spectral index for old remnants (age > 10^4 yrs)

	W51C	W28	W44	IC443	W49B
Spectral index (< E_{br})	1.5	1.7	1.7	2.1	2
Spectral index (< E_{br})	2.9	2.7	3.7	2.9	2.7
E_{br}/GeV	15	2	9	4	69

F. Schuppan, RUB, diploma thesis (2011)

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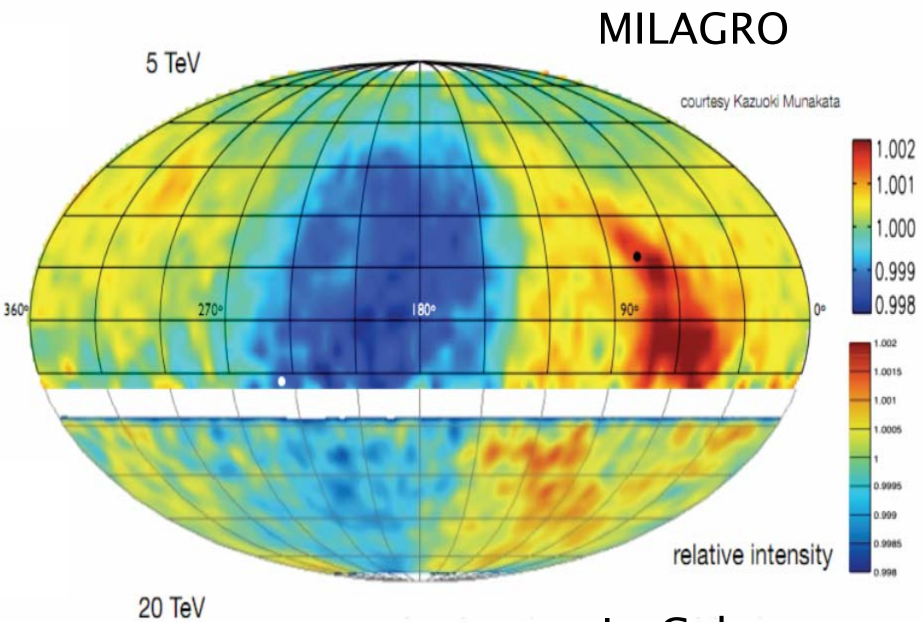
Available information from observations

- Electron spectrum (ATIC, Fermi, H.E.S.S.) → **primary electrons from local sources**
- Radio haze (WMAP, PLANCK) → **Synchrotron radiation**
- Hadron spectrum and composition → **primary ions, deduction of diffusion coefficient**
- Hadron anisotropy (MILAGRO, TA, IceCube) → **combination of sources and magnetic field?**
- Positrons (PAMELA) → **hadronic interactions (local sources)**

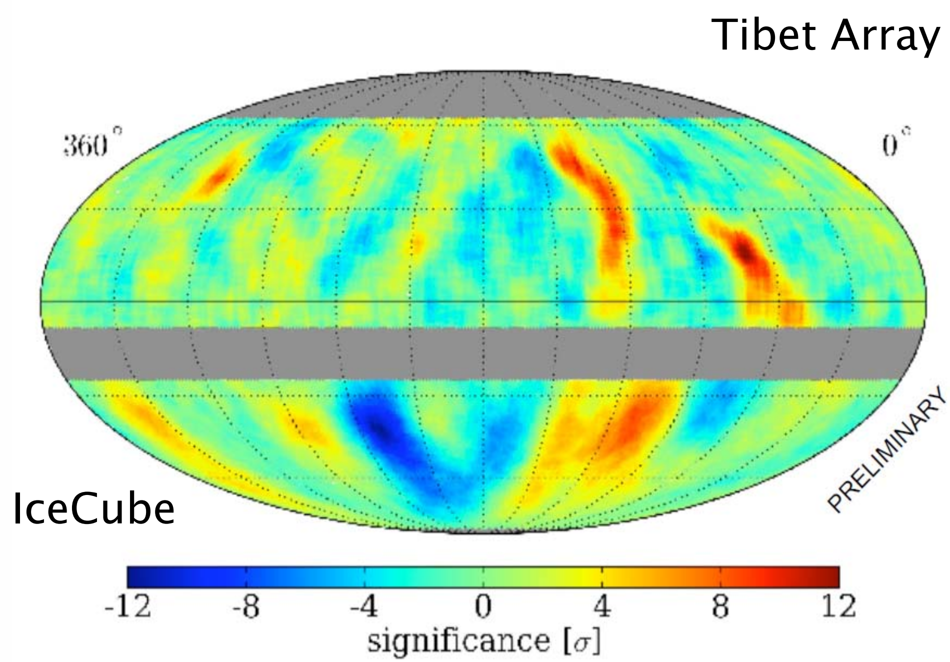
Cosmic ray anisotropy at <20 TeV

Dipole anisotropy @ ~0.1% level

Higher Multipoles @ <0.1% level



e.g. Abbasi et al (2010)



Large scale anisotropy: ISM → Magnetic field/CR source distribution
Small scale anisotropy: can also be local effects (e.g. Lazarian & Desiati 2010)

Now submitted to ApJ – arXiv:1109.1017

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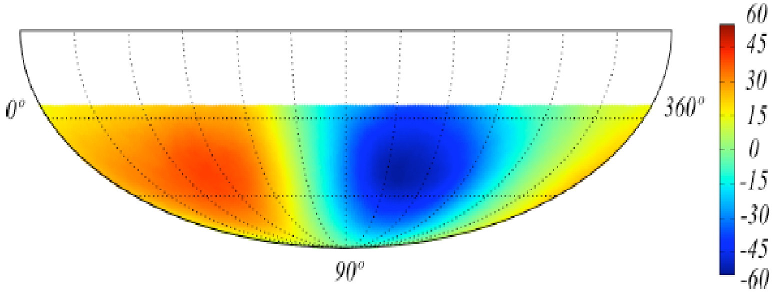
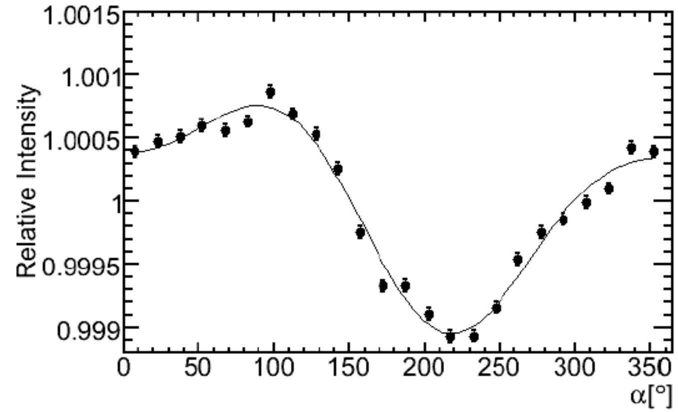
Anisotropy at 400 TeV

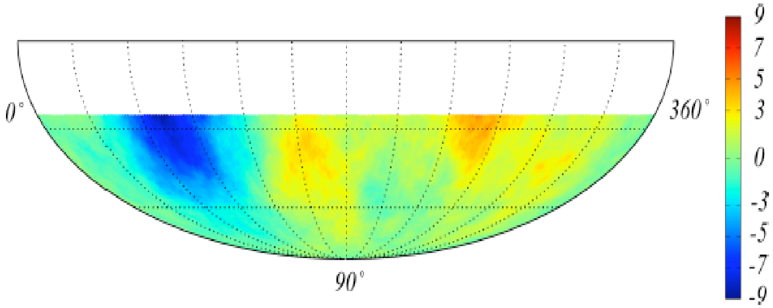


(a)

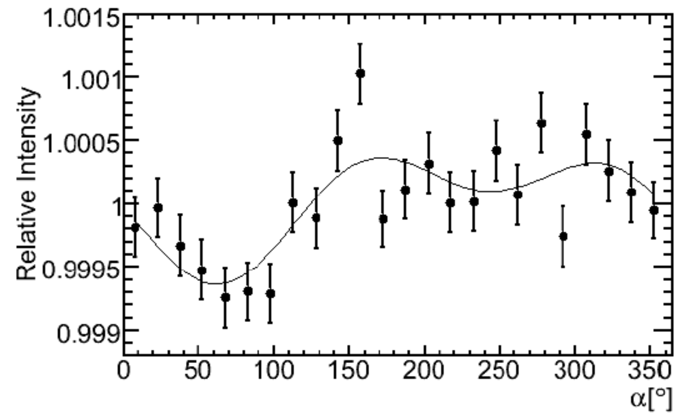


(a)

20 TeV



(b)



400 TeV

Abbasi et al (IceCube Coll.), submitted to ApJ (2011)

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Final discussion of part I

- A **large variety of measurements** is available today to help trace the sources of cosmic rays (e.g. Fermi/IACTs for gamma-rays, PAMELA/ATIC/CREAM for charged particles, radio telescopes, Herschel, …)

- A key to help pin-pointing the sources of cosmic rays lies in the **understanding of the source population and the large scale and local magnetic fields (Galactic and intergalactic!)**

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Appendix

Cosmic Ray Luminosity

- generally:

volume

$$L_{CR} = \rho_E \cdot V$$

- Energy density:

$$\rho_E = \frac{4\pi}{\tau \cdot c} \cdot j_E$$

- Energy flux:

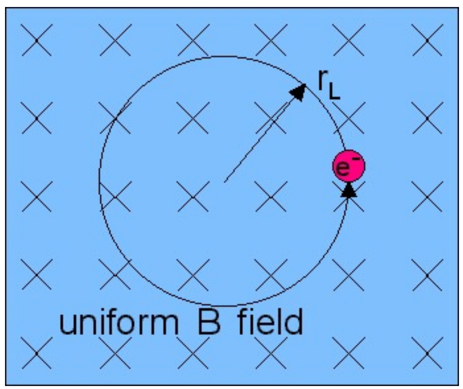
$$j_E = \int_{E_{\min}} \frac{dN}{dE} \cdot E \cdot dE$$

- Halflife of Cosmic Rays τ
  - galaxy: residence time
  - extragal.: Hubble time

Universe

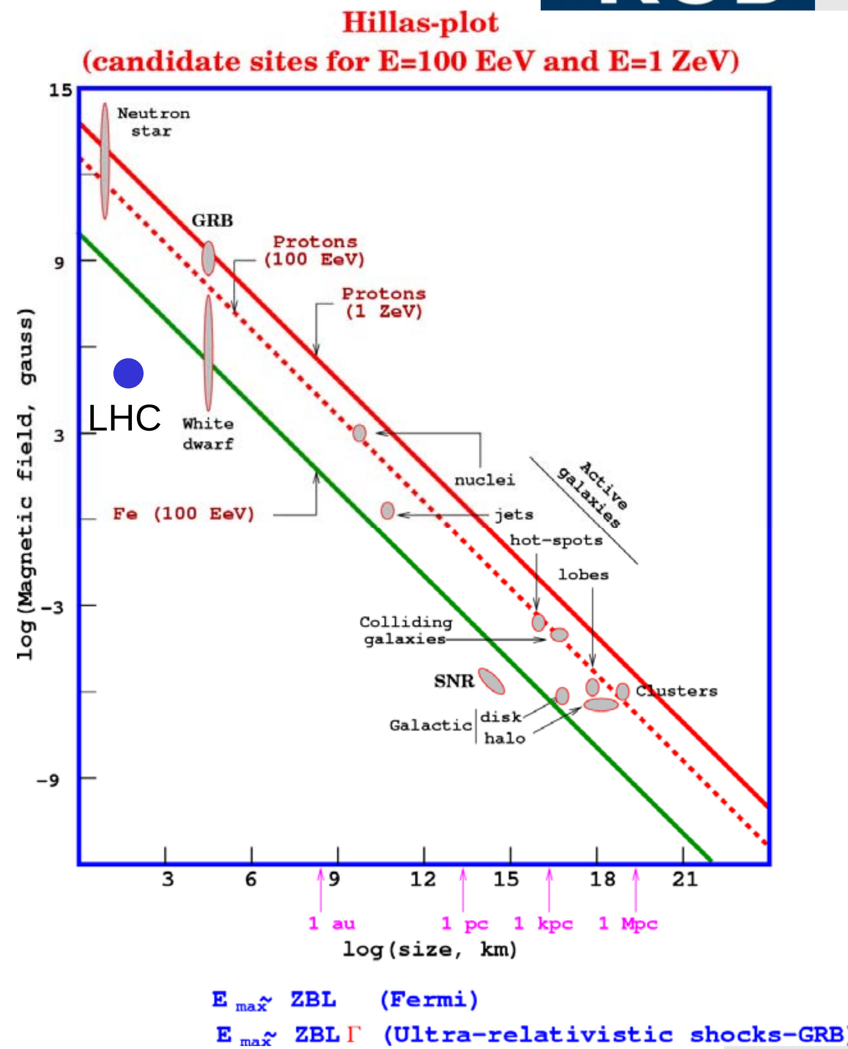
Maximum Energy

- For too high energies: particles get kicked out of accelerator (Larmor Radius) → necessary criterion



- Hillas plot:

- **E < Z*e*B*L**



http://www.pi1.physik.uni-erlangen.de/~kappes/lehre/WS05-VAT/V9/Hillas-plot.png

http://www.pulsedpower.net/applets/electromagnetics/larmorcyclotron/larmorcyclotron.html