Astrophysics of Cosmic Ray Electrons and Positrons

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International School of Subnuclear Physics
42nd course:
How and Where to go beyond the Standard Model
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Introductory remarks

- *discovery of μ (Neddermeyer, Anderson, 1937)*
- *μ to e decay (Conversi, Pancini, Piccioni, 1943-47)*
- *discovery of e+ (Anderson, 1933)*
  → antimatter
- *π to μ decay (Powell et al., 1947)*
- *discovery of kaon (Rochester, Butler, 1947)*
  → strangeness
- *Future: New phenomena at very high energy?*

links between CR and subnuclear physics

International School of Subnuclear Physics

How and Where to go beyond the Standard Model

- *e+/e– ≈ 10% above few GeV*
  → e+ secondary, e– primary
- *e+, e– spectra represent Galactic averages*
- *e+, e– accelerated by (mostly recent and nearby) SN shock waves*
- *New picture: measeured e+, e– were accelerated by 1 source (very recent and nearby)*

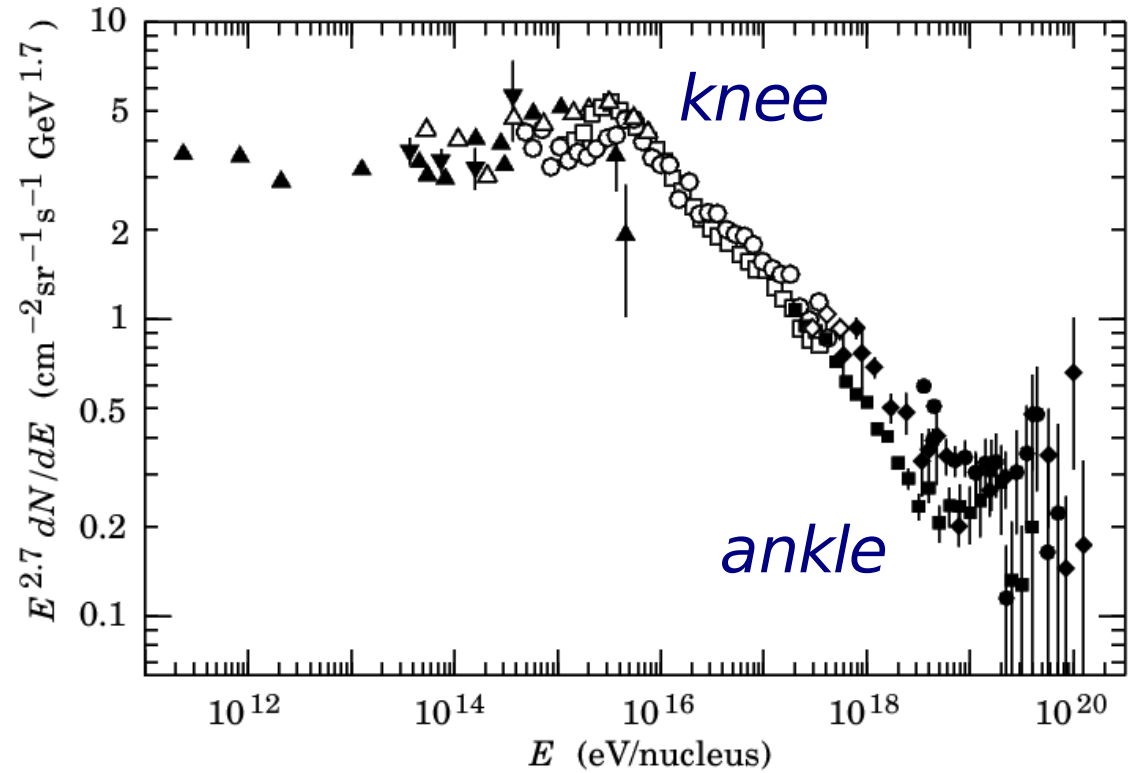
standard picture of CR e+/e– astrophysics

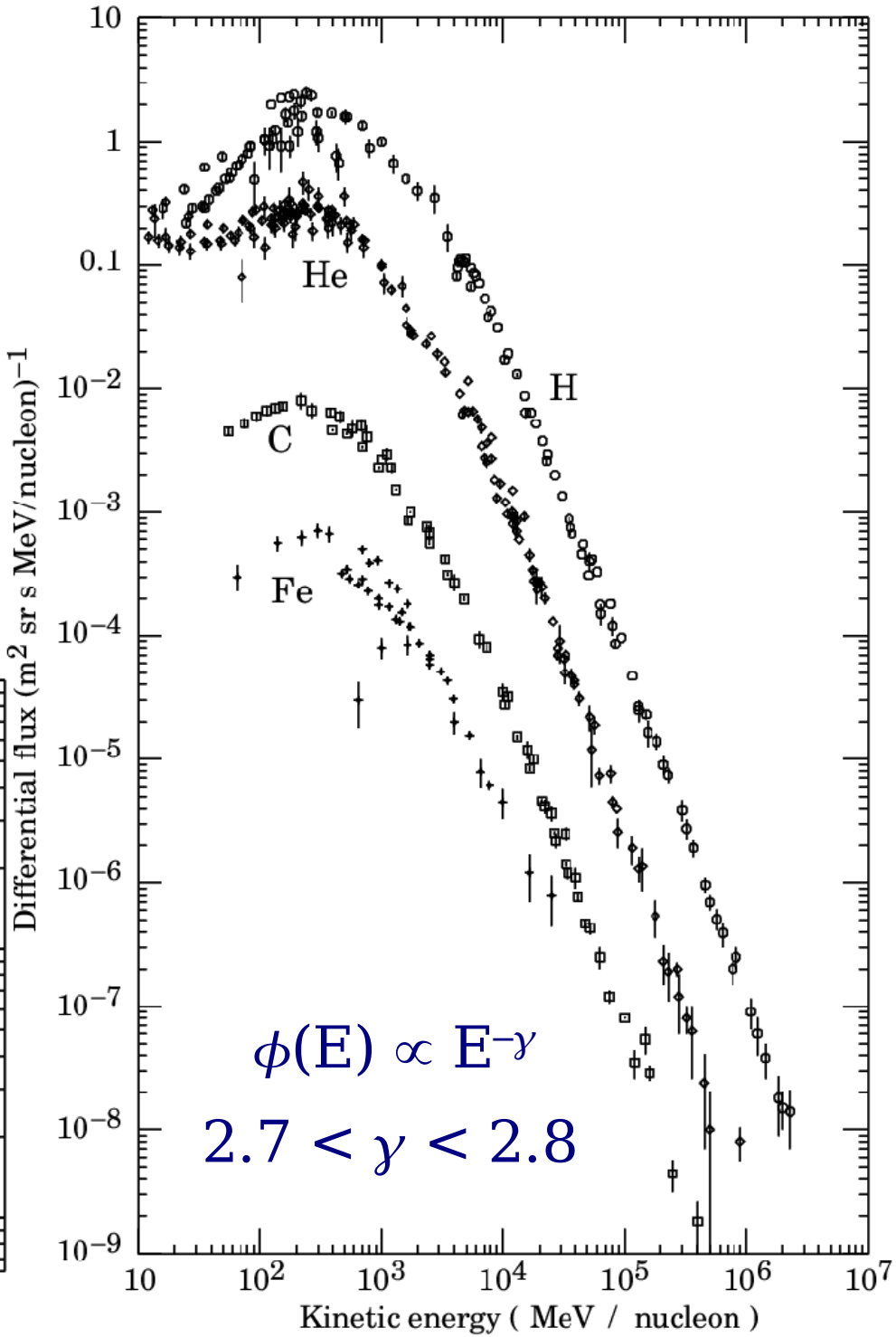
Cosmic Rays (1)

- CR are charged (p, α and almost all other nuclei) and neutral (γ and ν's) particles reaching the Earth atmosphere from the outer space.
- CR have energies ranging from 10^6 to 10^{21} eV per nucleon. The energy spectrum is well represented by a power-law (with few spectral index changes).
- Proton flux is ~95% of total flux up to several TeV (above this energy only indirect measurements based on atmospheric showers are available: no spectroscopy).
- Helium is the second most abundant species.
- Electron flux is ~1% of the total; positron flux 10 times smaller. Direct measurements of e+ and e– up to few TeV.

CR (2): Measured Spectra

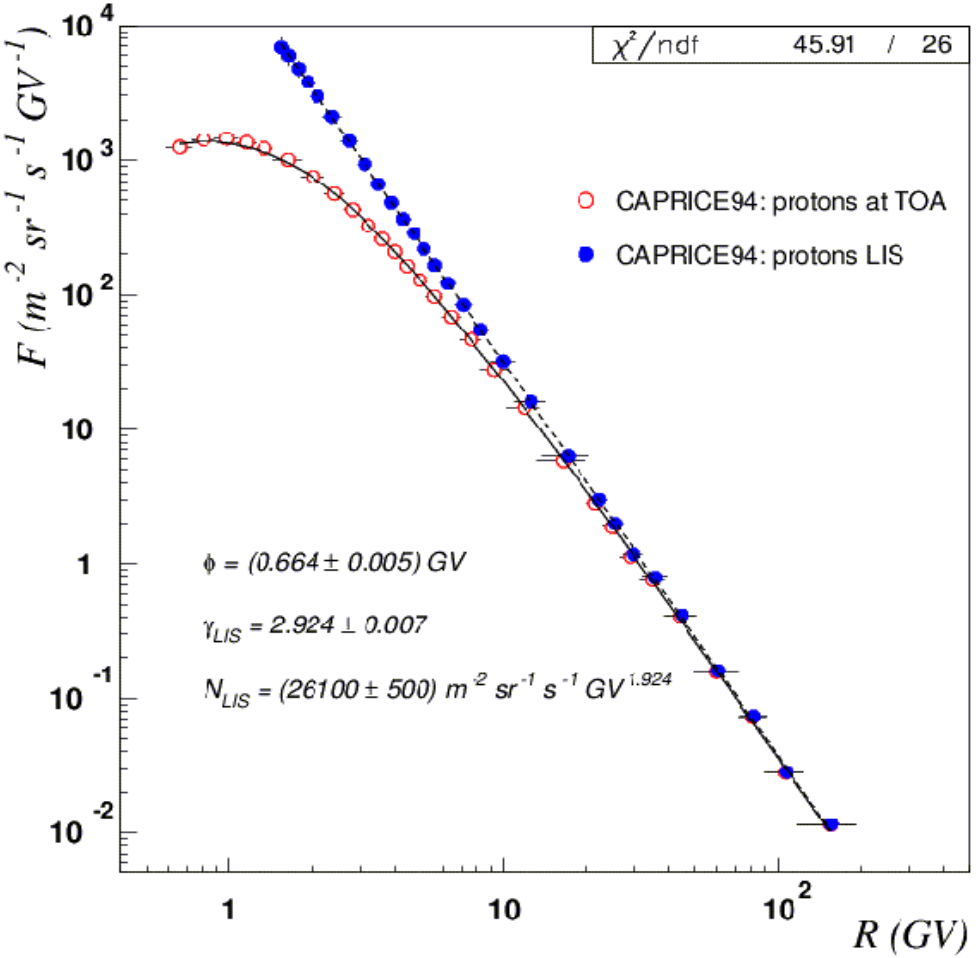
- Spectra of most important elements (N, O abundances just above Fe) shown here →

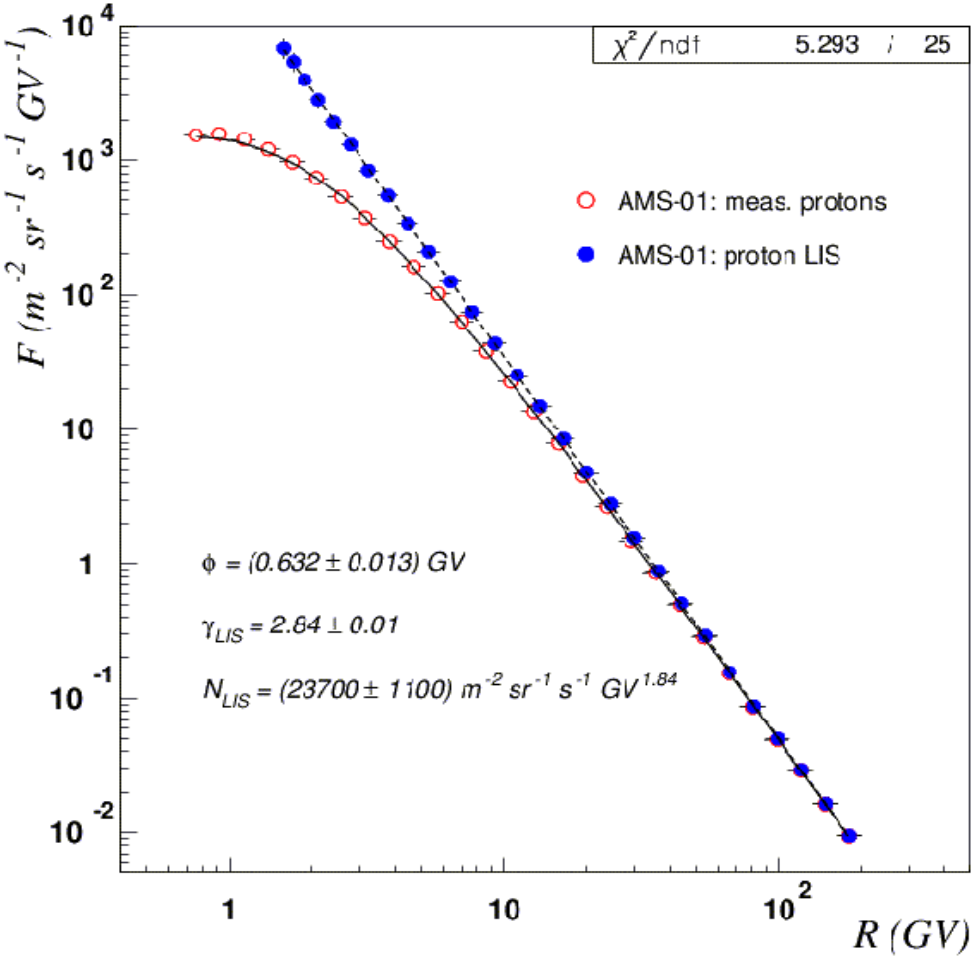




CR (3): Propagation

- CR protons and stable nuclei diffuse in the Galaxy for ~10^7 years, with a rigidity-dependent escape probability, a (small) interaction probability, and negligible convection.
- Entering the heliosphere, CR loose energy (*solar modulation*).





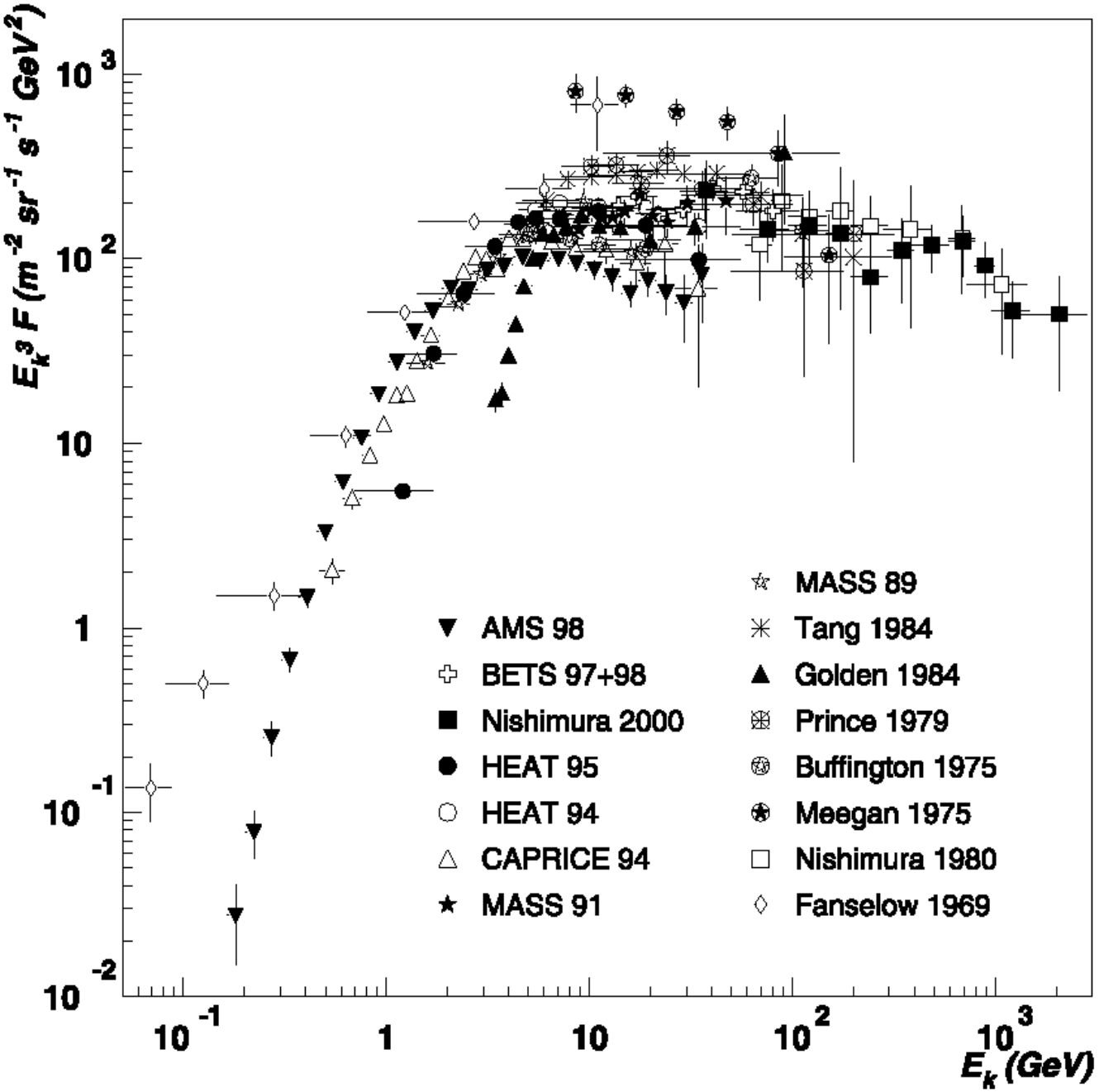
CR (4): Acceleration

- Energy budget comparable with Galactic SN rate (few percent efficiency is enough).
- Elastic scattering with shock waves (Fermi mechanism) naturally produces power-law spectra in momentum space.
- At the source the “natural” spectral index is –2,
- the diffusion coefficient above few GeV is a power-law in rigidity ($R=pc/Ze$) with spectral index –0.6:
- the “natural” spectral index on the Earth is –2.6, similar to the measured one.
- Hence SN explosions are the sources of CR (upper limit $R_{max} \sim 10^{14}$ GV).

Standard picture of CR e+/e-

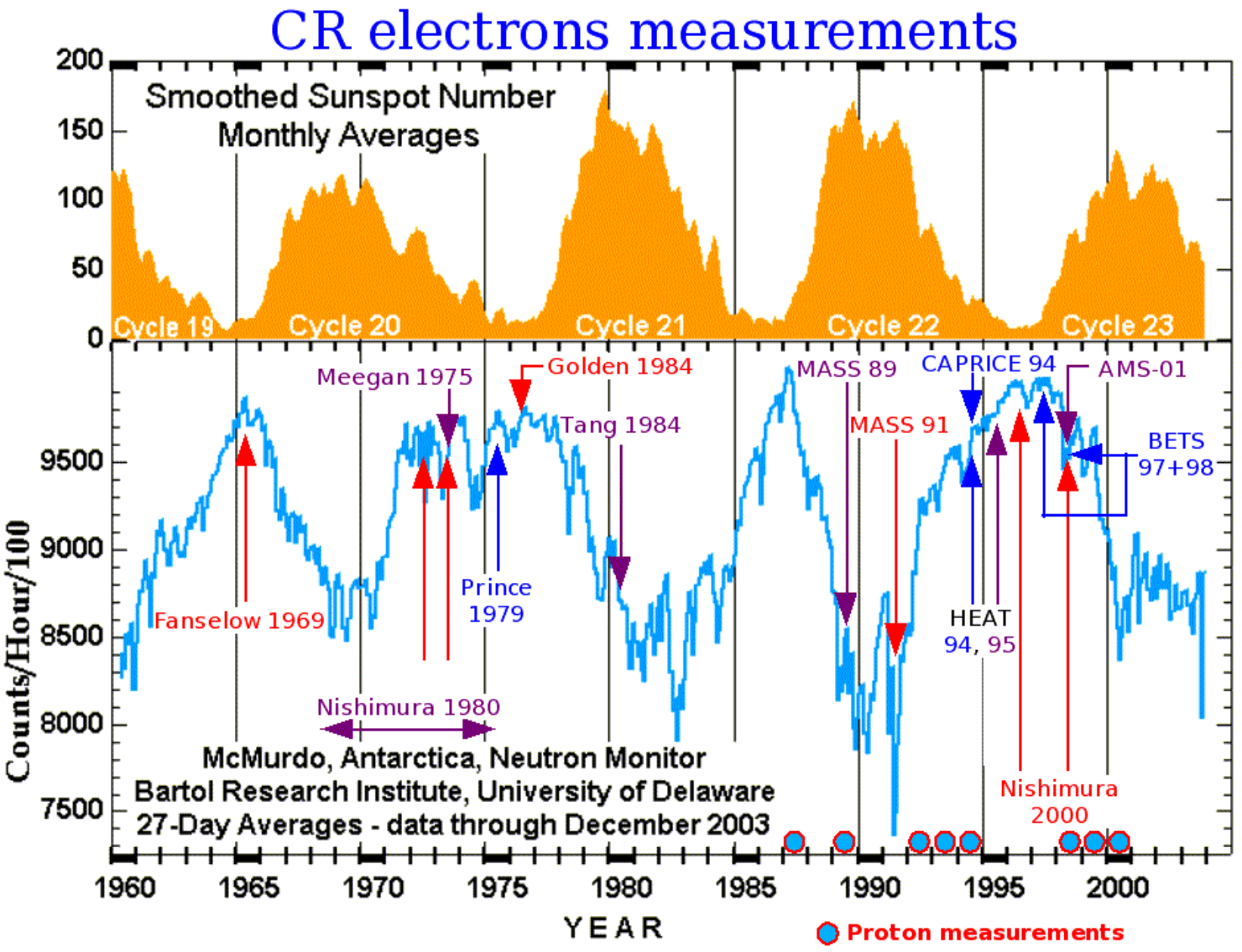
- Radio and X emission from SNRs demonstrate that electrons are accelerated by SN shocks.
- Synchrotron emission with spectral index *a* implies a power spectrum in momentum with spectral index $\alpha = 2a + 1$ at the source. On the average, $\langle a \rangle = 0.5$–0.6, hence $\alpha = 2.0$–2.2.
- During propagation, e+ and e– suffer large dE/dx: spectral index decreased by 1 in a short time, becoming $\gamma = 3.0$–3.2, similar to the measured spectrum.
- CR p interact with the ISM, producing equal amounts of e+ and e–. However, the measured ratio e+/e– ≈ 0.1 above few GeV:
- hence e+ have secondary origin whereas most of e– have primary origin.
- CR p spectral index=2.8, hence secondary e+ and e– should have $\gamma \approx 3.8$

Existing measurements



- There is a large spread between different experimental results,
- both in normalization and in spectral index

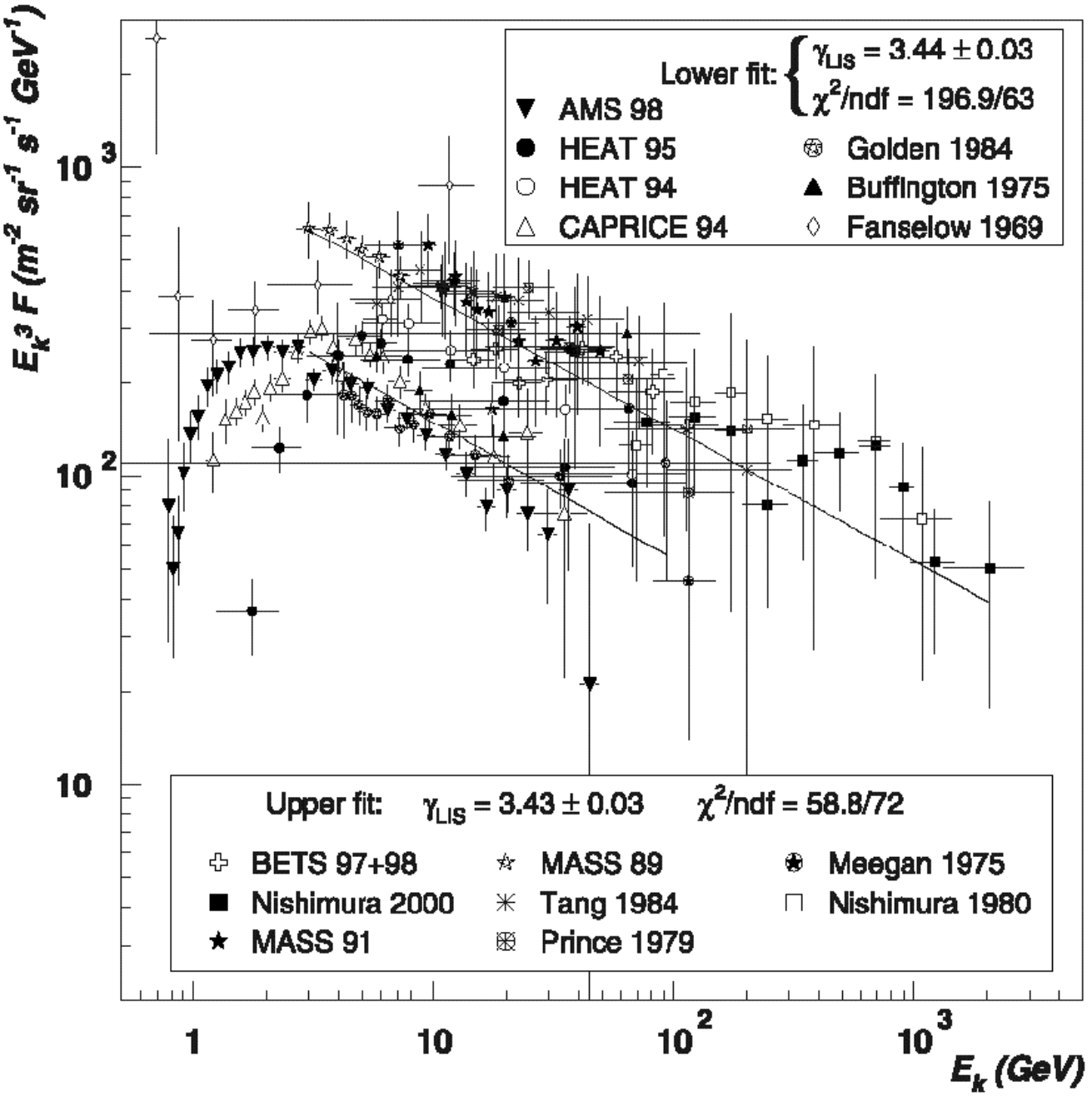
Solar modulation



Explaining the differences:

- solar modulation
- systematic errors

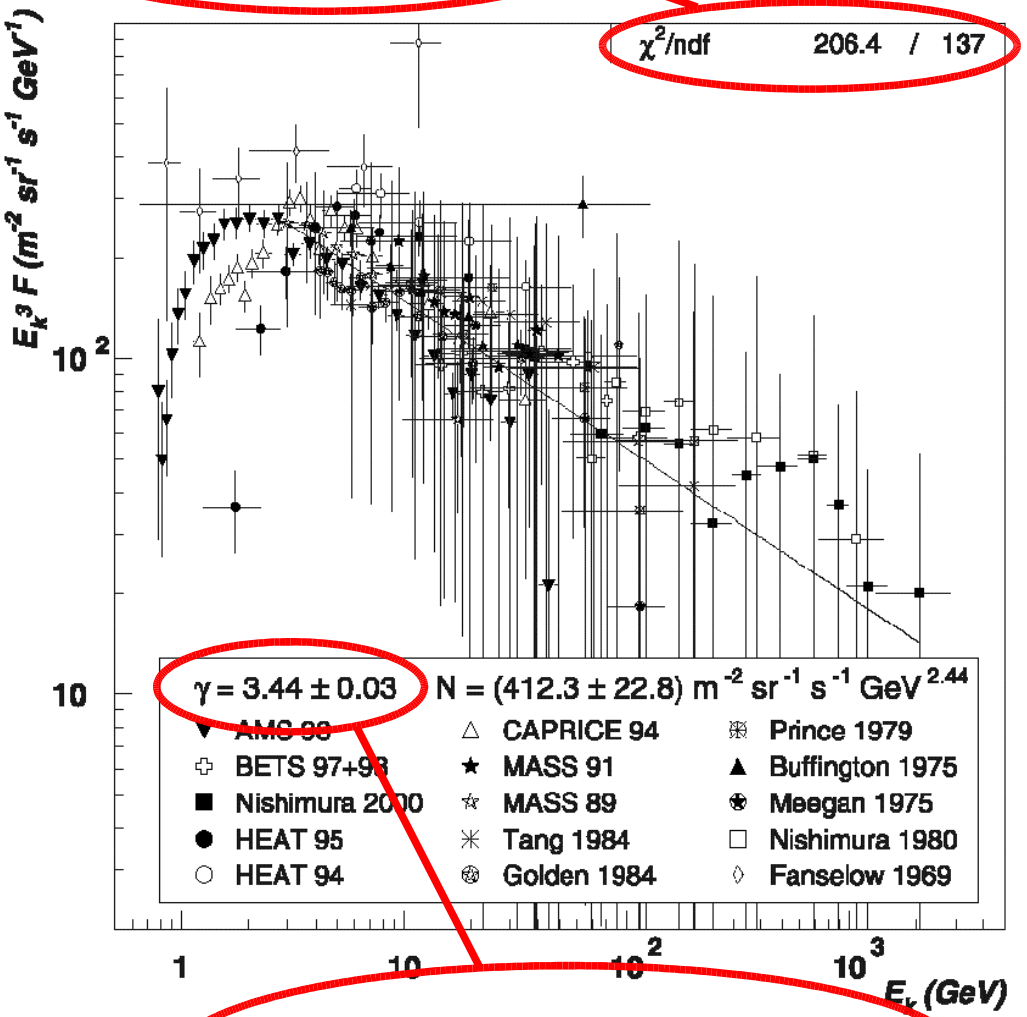
Local interstellar spectra



- The measured fluxes can be corrected for the solar modulation:
- the result is well representative of the solar system neighborhood.
- The LIS appear to be clustered into 2 sets, with the same spectral index:
- renormalization to the same integral flux.

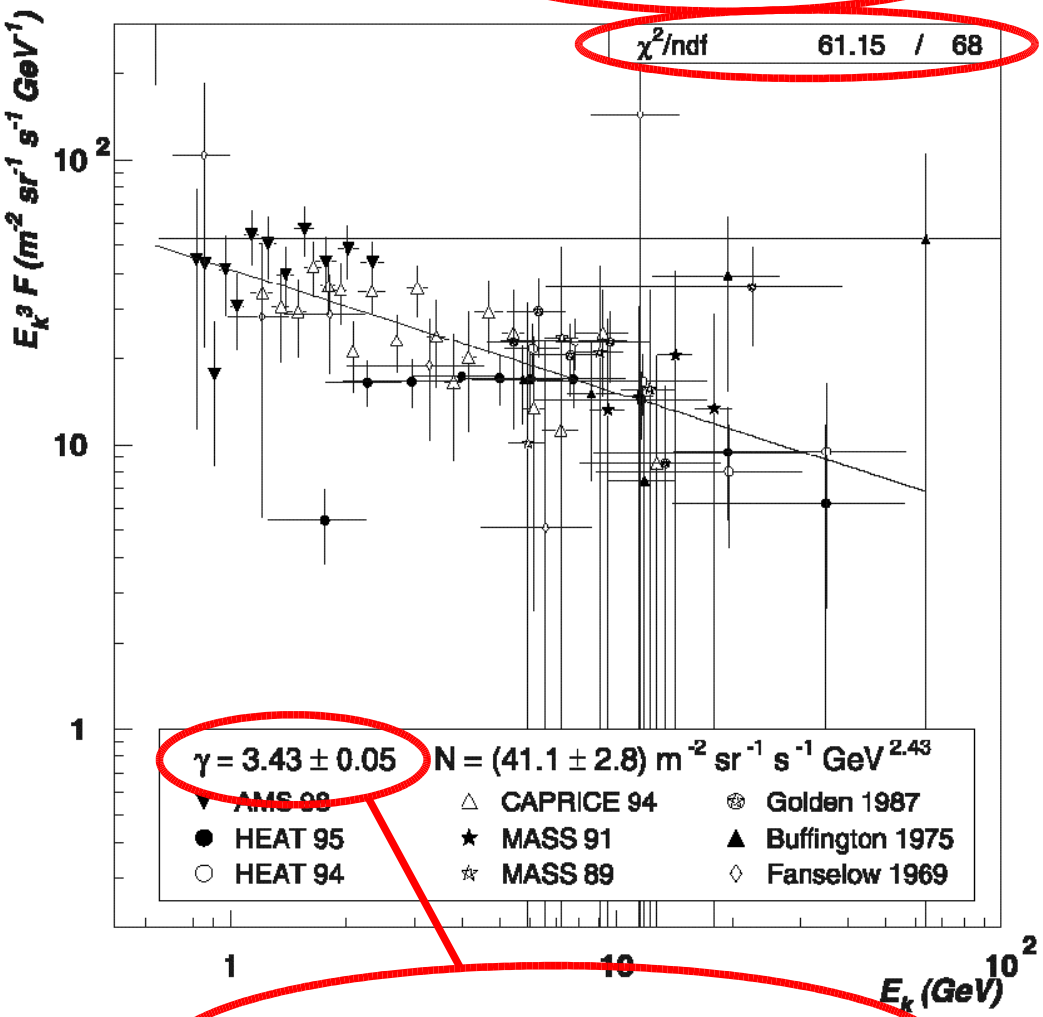
Result: same spectral index for e+ and e–

χ^2/ndf = 206/137



γ = 3.44 ± 0.03

χ^2/ndf = 61/68



γ = 3.43 ± 0.05

New interpretation

- The same spectral index strongly motivates the idea of a common acceleration mechanism.
- The power-law of CR e– shows no cut-off up to 1–3 TeV:
  - the source must be near, because

$$\text{range} \sim 1\ \text{kpc}\ (E/1\text{TeV})^{-1}$$

  - the source must be recent, because

$$t_{\text{rad}} \approx 2.1 \times 10^{5}\ (E/1\text{TeV})^{-1}\ \text{yr}$$

- The proposed source is a weak shock wave originated from the last SN explosion in the Local Bubble.

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THE ORIGIN OF COSMIC RAY ELECTRONS AND POSITRONS

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ABSTRACT

We use direct measurements of electrons and positrons corrected for solar modulation in the force-field approximation to obtain estimations of the local interstellar spectra. The resulting overall electron spectrum fits well with a single power law above a few GeV with spectral index $\gamma_- = 3.44 \pm 0.03$, consistent with the spectral index obtained for the positron spectrum $\gamma_+ = 3.43 \pm 0.05$, therefore suggesting a common acceleration process for both species. We propose that the acceleration engine was a nearby and recent shock wave originating from the last supernova explosion among those that formed the local bubble. This shock wave had to be quite soft, because no effect is seen on the proton spectrum. However, the large spread between different experiments clearly suggests the need for new, accurate measurements over a large energy range.

Subject headings: cosmic rays — elementary particles

Online material: color figure