第46回天文・天体物理夏の学校

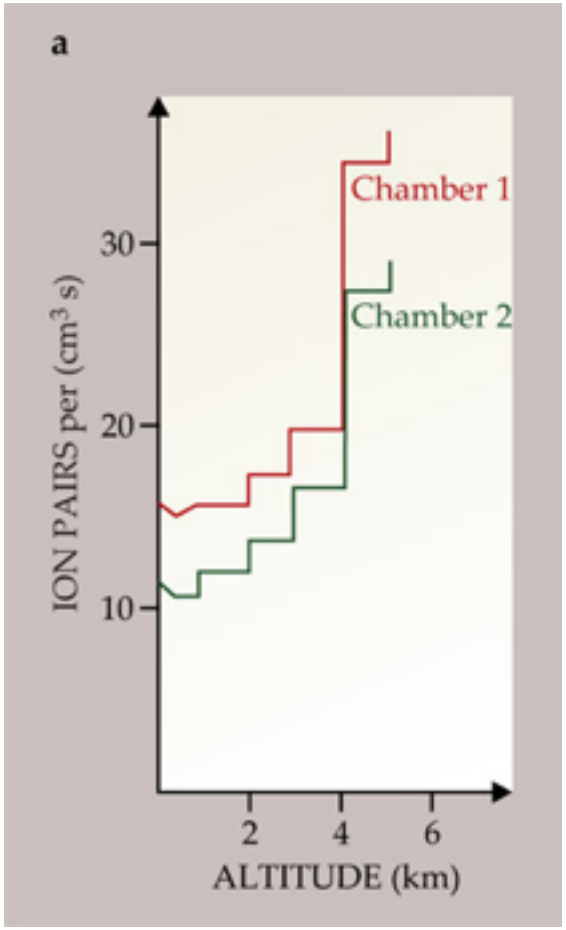
宇宙線の起源

２０１６ Ｊｕｌｙ　２８

高原文郎

大阪大

発見　１９１２年


a
Chamber 1
Chamber 2
ION PAIRS per (cm³ s)
30
20
10
2
4
6
ALTITUDE (km)

宇宙線研究の諸側面

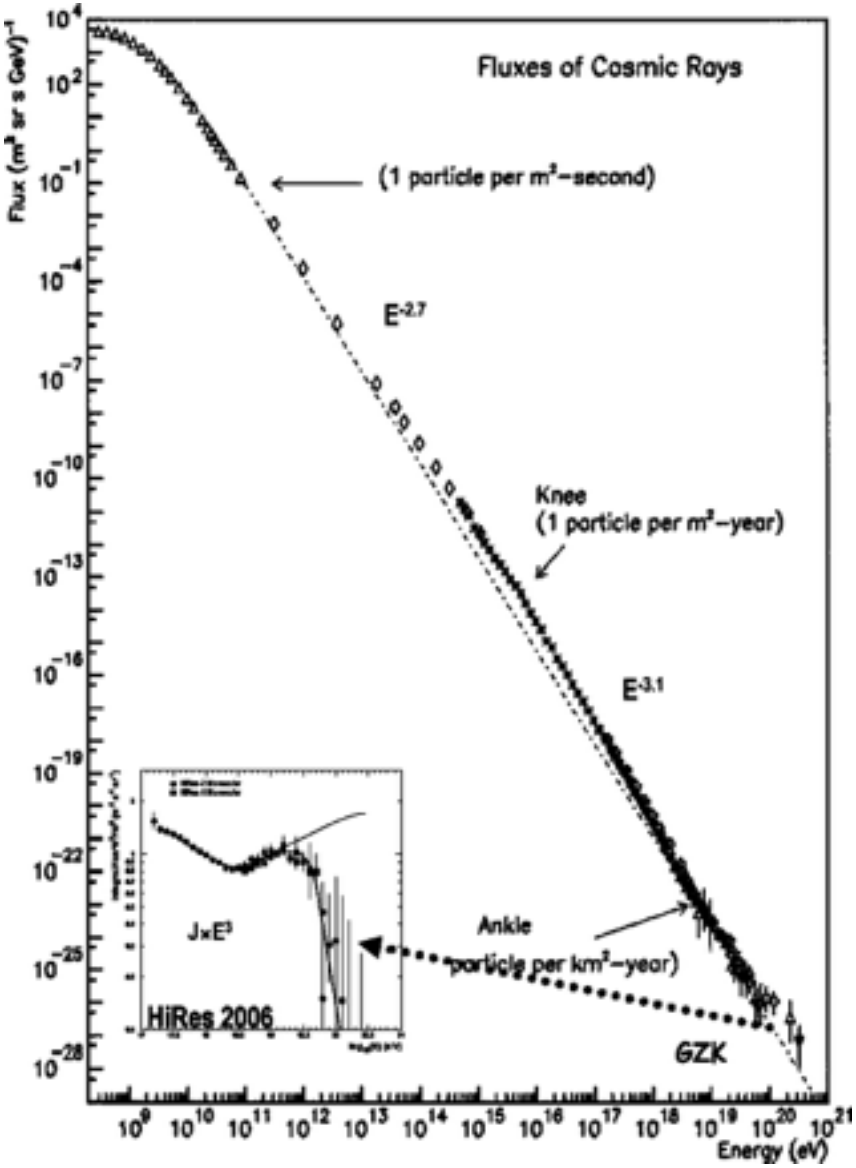
素粒子物理
- １９５０年代まで：　新粒子の発見
- 現在：　暗黒物質起源粒子の探索

起源・加速・伝播
- 1939年　Baade&Zwicky　超新星起源説
- 1949年　Fermi 統計加速機構

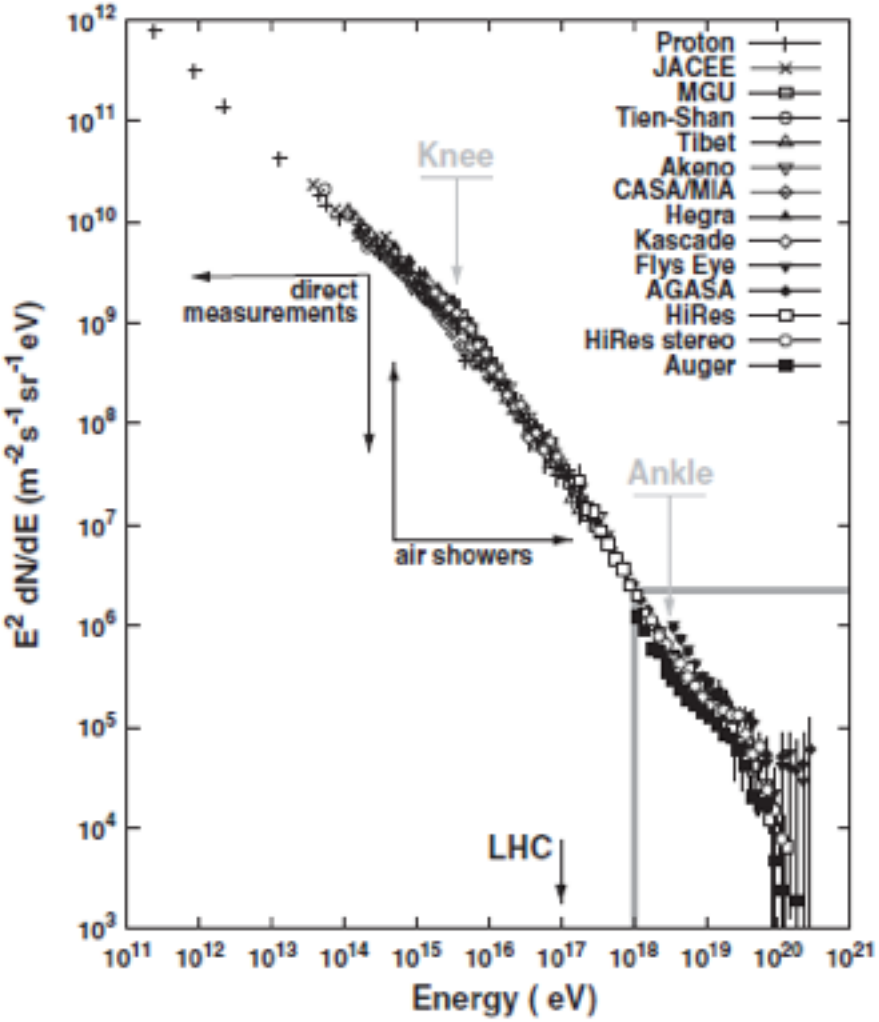
星間物質
- 星間ガスの加熱・電離源：　パーカー不安定：　Ｘ線・ガンマ線

宇宙線についての基礎知識

- 宇宙空間を満たす高エネルギー粒子
  - 陽子、原子核が主
- 銀河系空間で$1\mathbf{eV/cm^3}$
  - 磁場、乱流運動、背景光、CMBと同程度
- $10^8\mathbf{eV}$~$10^{20}\mathbf{eV}$にわたって、べき型分布で近似
  - Kneeやankleなどの構造
- Knee以下は超新星残骸起源説が有力
  - ガンマ線観測による検証が進んでいる
- Knee以上の宇宙線の起源は？

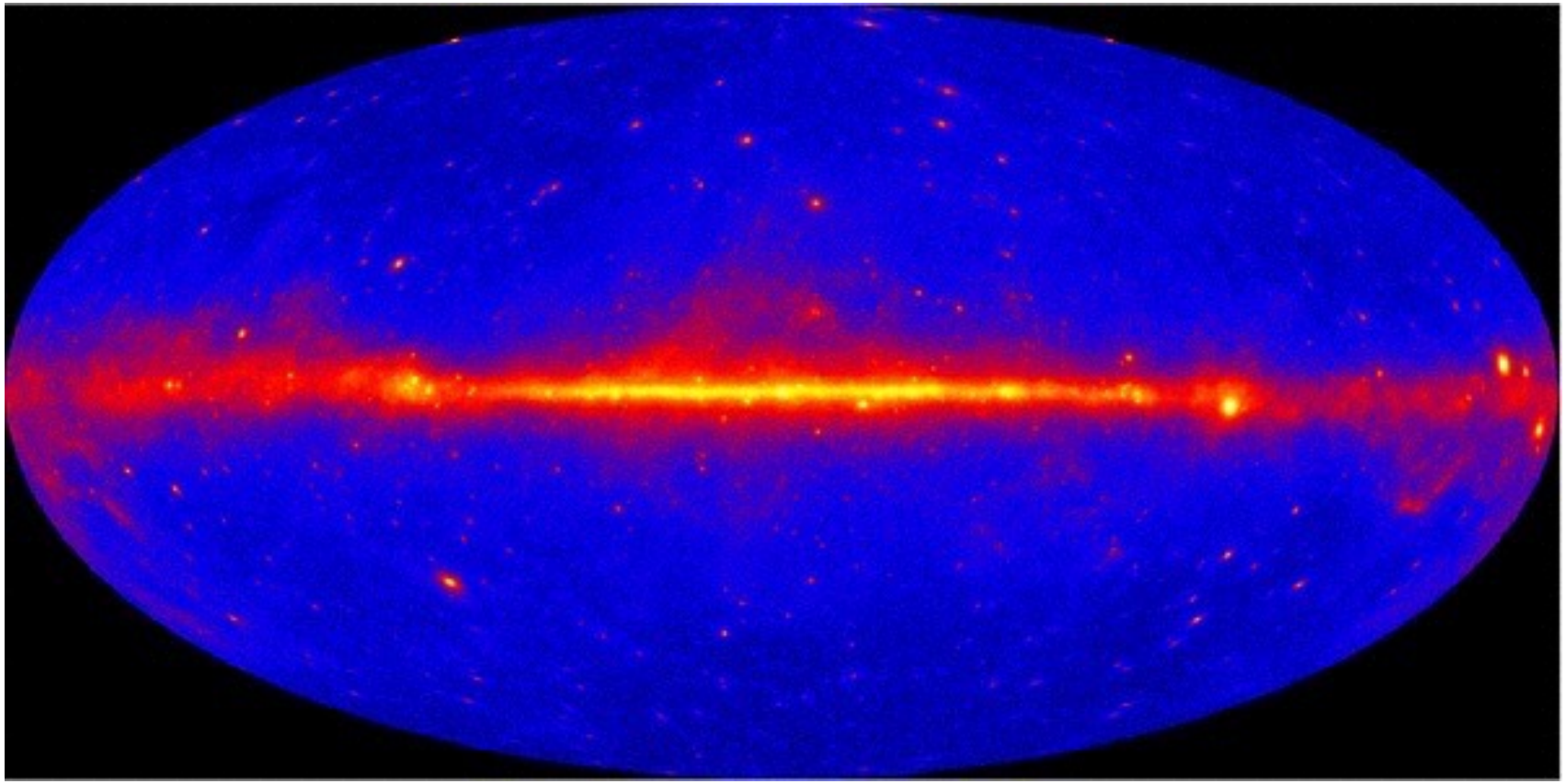


From Aharonian et al. 2011



From Letessier-Sevon & Stanev 2011

Fermi 2-year sky map



Outline
起源・加速・伝播

- 標準的理解
- 観測の進展
- 理論の課題のうちいくつか

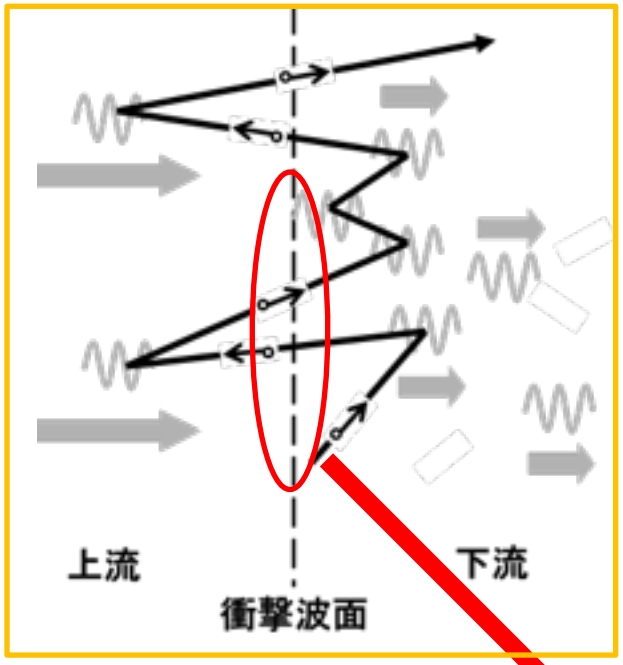
1. 超新星残骸衝撃波における宇宙線加速と逃走
2. 加速源における２次粒子生成と陽電子・反陽子問題
3. 宇宙線加速と輸送機構における散乱の役割
4. kneeからankleまでの宇宙線の起源

標準的理解

- Knee以下は超新星残骸起源
- 加速機構は衝撃波統計加速（DSA）
- 源のスペクトルは$\alpha \approx 2$の普遍的べき型
- 伝播（Leaky Box Model）でスペクトルは
  $\alpha \approx 2.7$まで変化
- 伝播は磁気乱流との相互作用
  - 運動はrigidity (p/q)のみによる
  - スペクトル指数は元素種によらない
- 2次粒子（Li, Be, B, sub-Fe, $\bar{p}$, $e^{\pm}$)のスペクトルは
  $\alpha \approx 3.4$程度となる

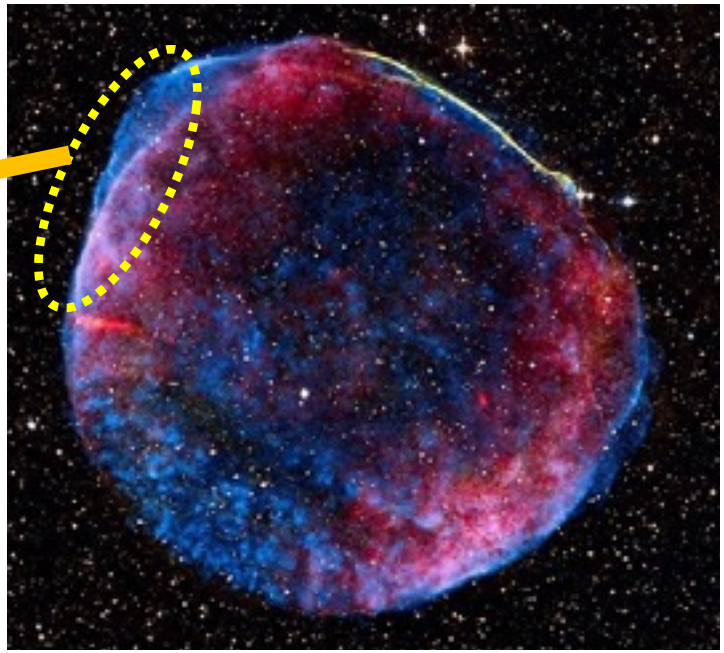
図 1

(b)流体スケール



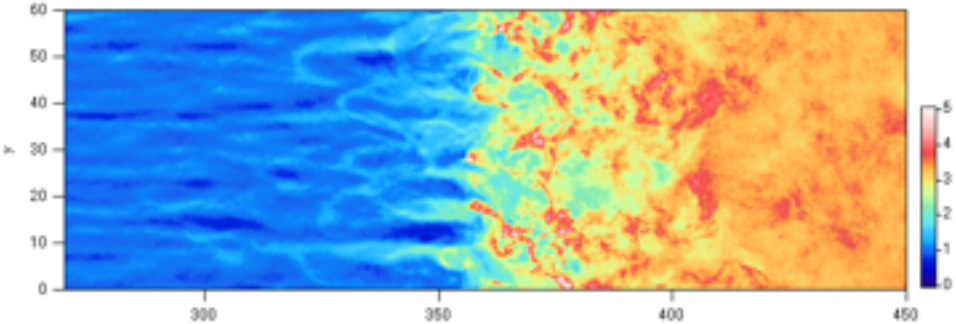
~10^{16}cm

(a)超新星残骸(SNR)



~10^{19}cm

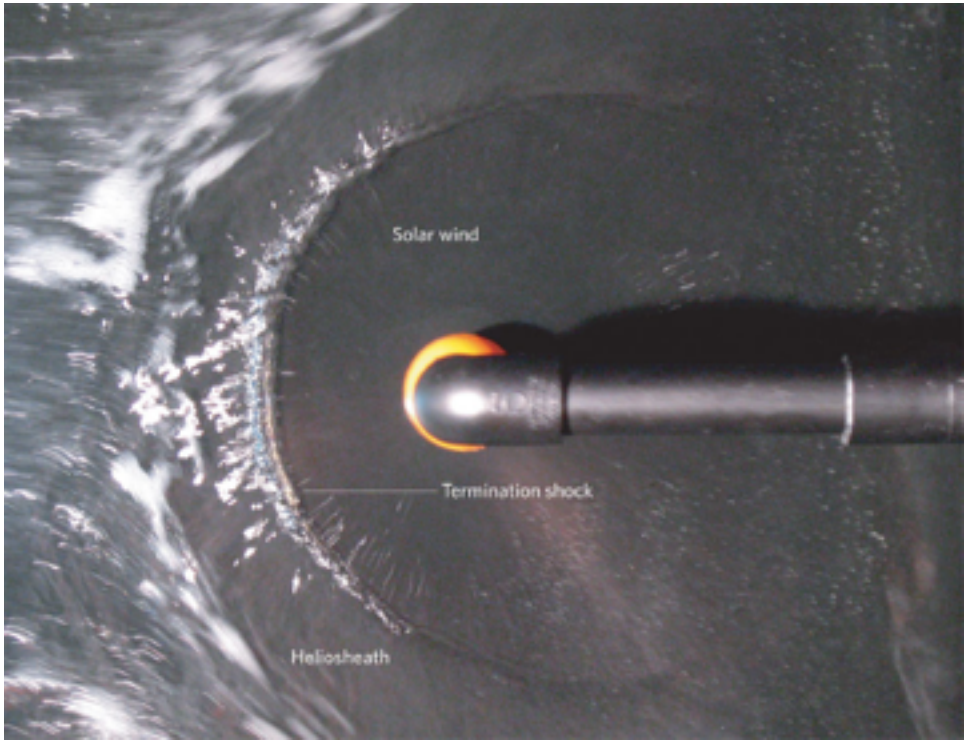
(c)粒子（運動論的）スケール



~10^{10}cm

無衝突衝撃波の直接観測

- Voyager 1 & 2
- solar wind termination shock

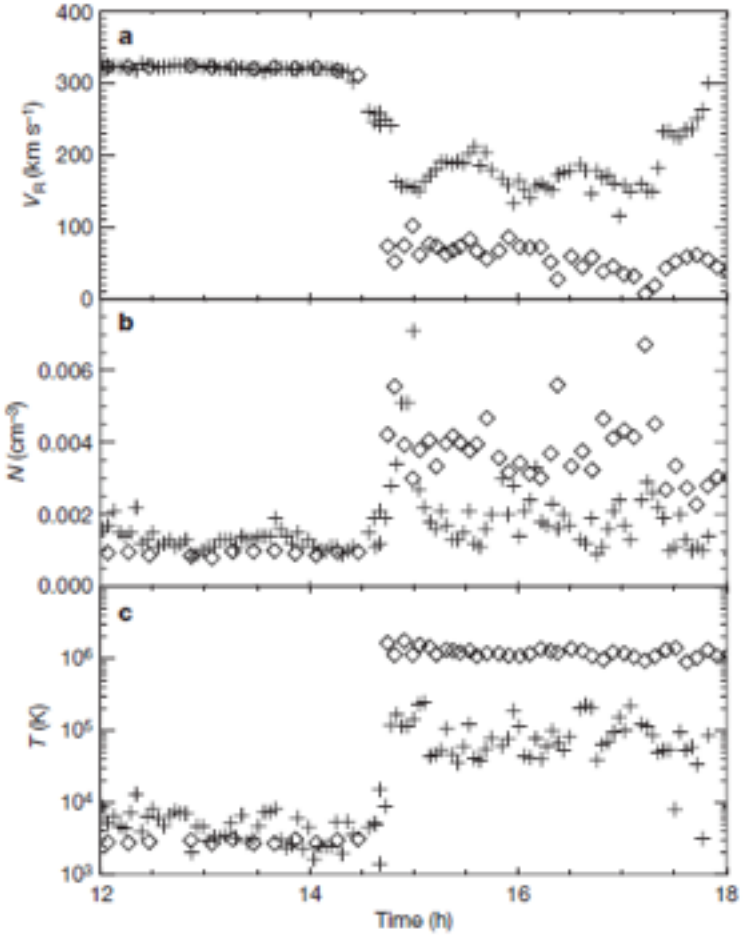


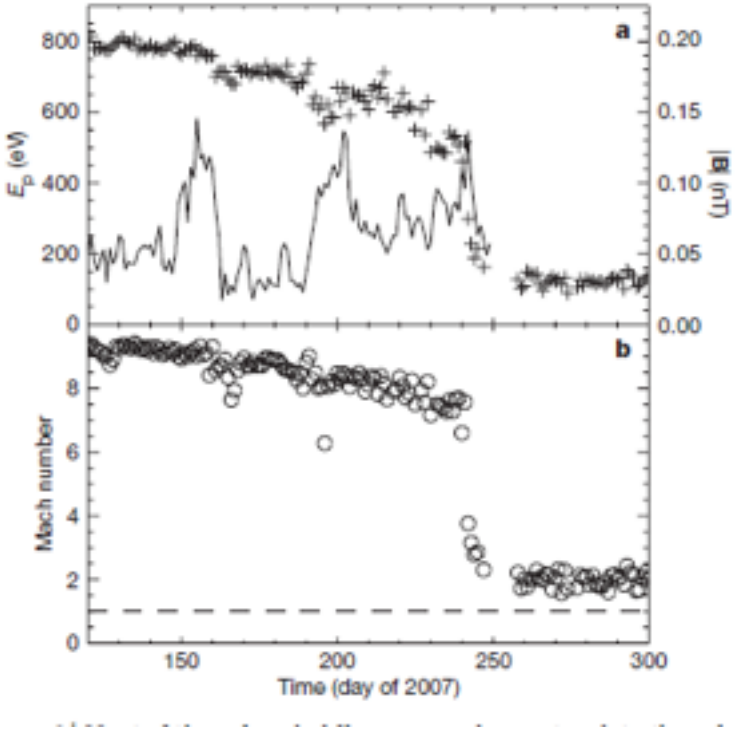
Termination shock vs
Neptune bow shock

downstream Mach number larger than 1

E_p: flow+ thermal energy

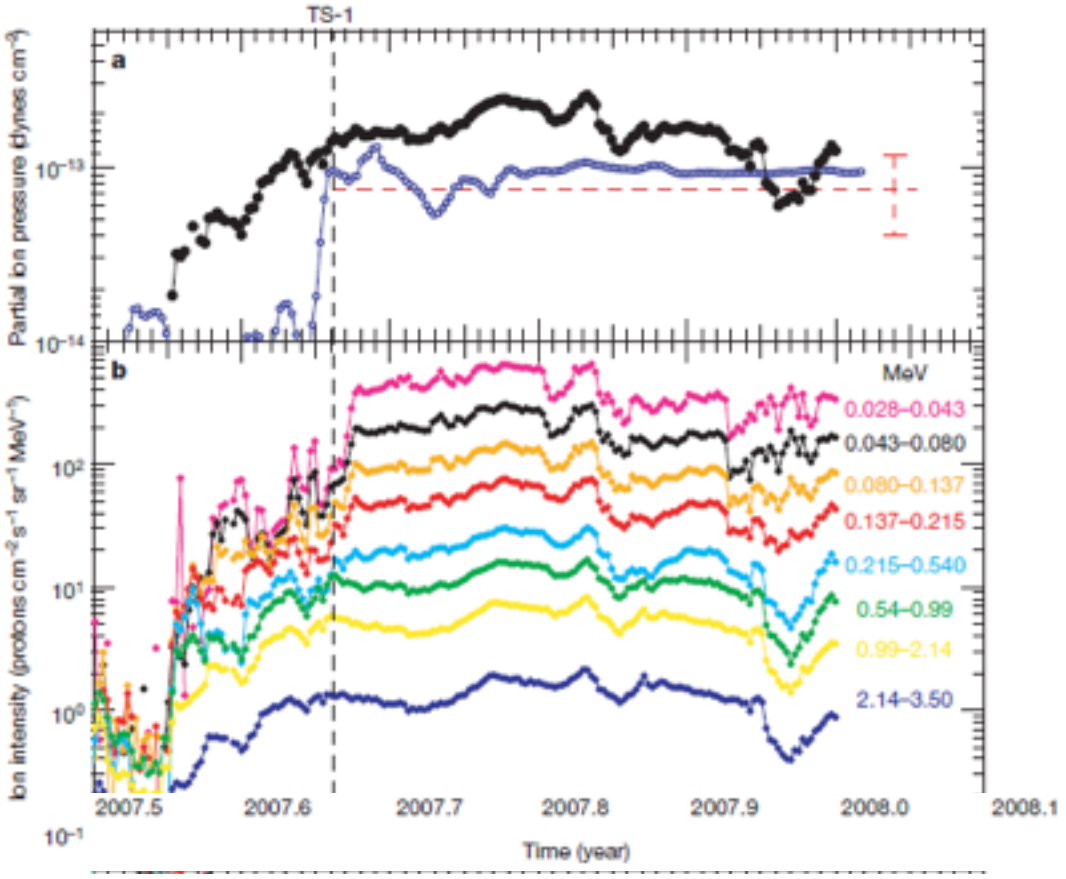
where does the energy go?





Richardson et al. 2008

80% of energy is carried by pick-up ions

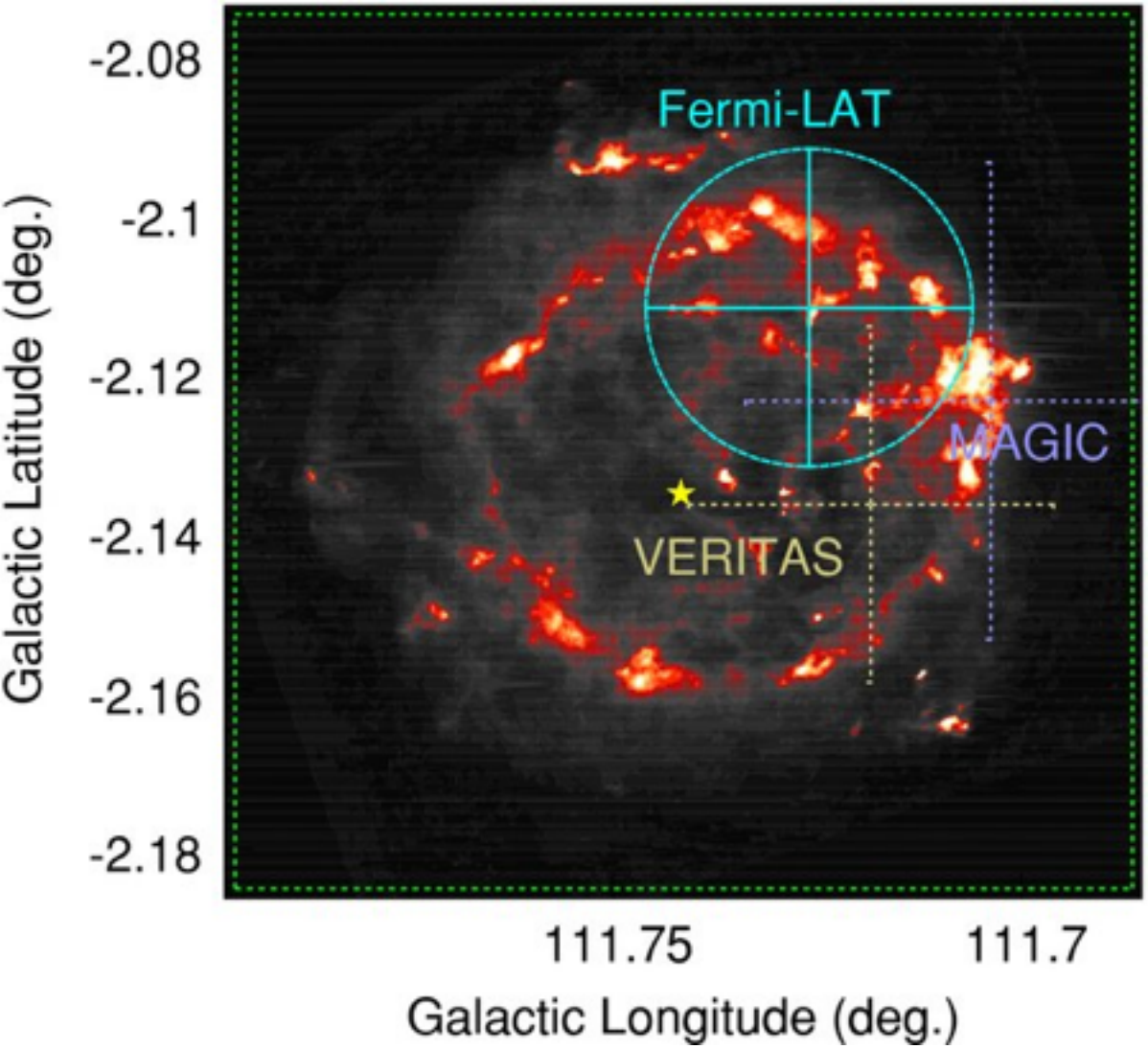


Decker et al. 2008

新たな観測
GeV-TeV γ-ray、CREAM, PAMELA, AMS,,,

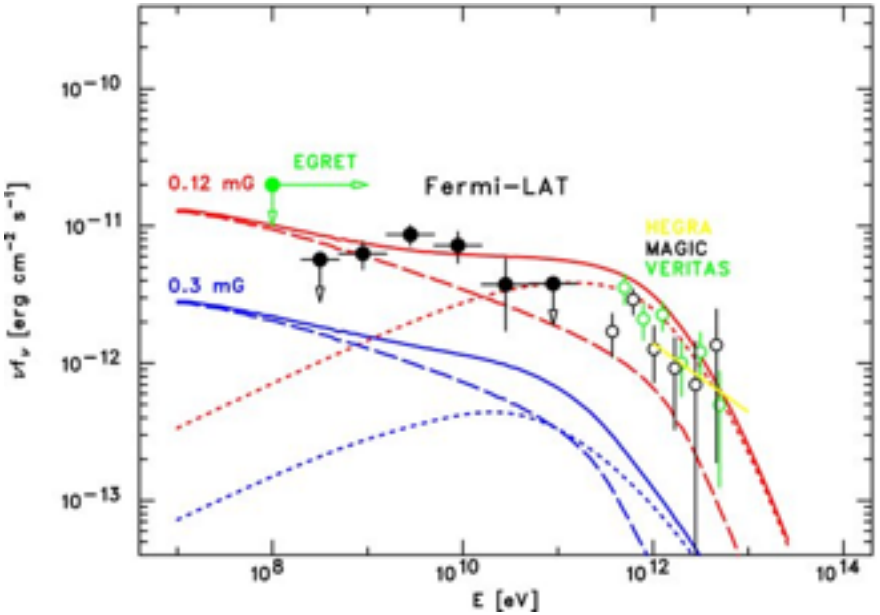
- 宇宙線研究の歴史
  - 長年の停滞がこの１０年で打破されつつある
- Ｘ線・ガンマ線
  - ＳＮＲではkneeまでは加速されていない
  - 源のスペクトル指数は普遍的ではない
- 直接観測
  - 核種によってスペクトルが少し異なる
  - 単一のべき型スペクトルではない
  - ２次粒子のスペクトルはよりhardである
  - 予期されなかった非等方性があるようである

Cas A (Abdo et al. 2010)

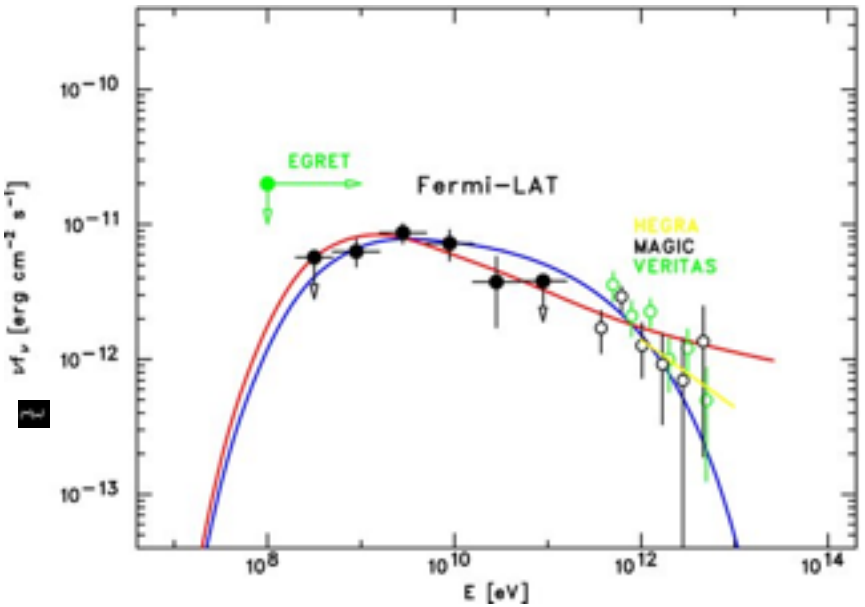


VLA 20 cm radio map of the Cas A supernova shell (Anderson & Rudnick 1995). The graph shows the GeV position with error bars as a cyan circle and the position of the CCO as a yellow star. Also shown in the plot are the best-fit positions for MAGIC (Albert et al. 2007) and VERITAS (Humensky 2008).

Cas A (Abdo et al. 2010)

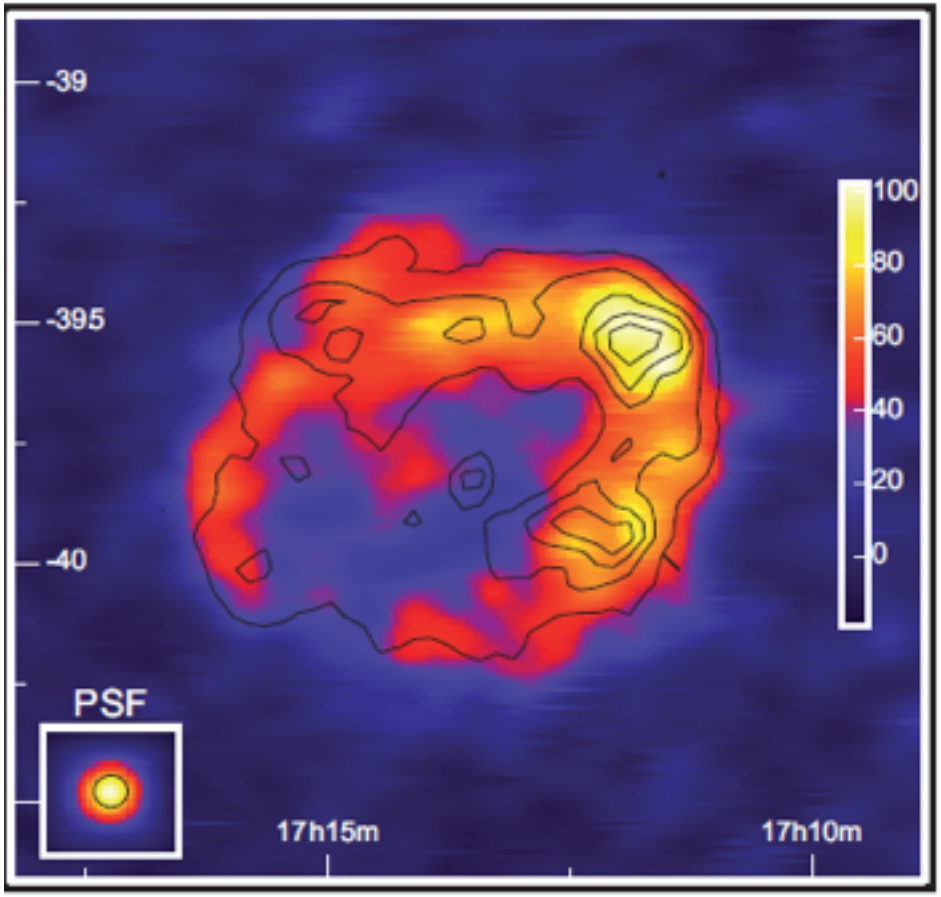


Energy spectrum of Cas A in a leptonic emission model. Shown is the *Fermi*-LAT detected emission (filled circles) in comparison to the energy spectra detected by MAGIC (black open circles; Albert et al. 2007) and VERITAS green open circles; Humensky 2008). The red curves show a leptonic model calculated for B = 0.12 mG while the blue curves show one for B = 0.3 mG. Dashed lines show the bremsstrahlung components with n_{eff} =26 cm^{-3}, and dotted lines show the IC component.



Same as Figure 3 but in a hadronic emission model. Shown are π^0 decay spectra for two possible proton spectra. The blue line shows a harder proton index of 2.1 with a cutoff energy of 10 TeV (W_p = 3.2 × 10^{49} erg for n_H = 10 cm^{-3}). The red line shows a softer proton index of 2.3 without a cutoff.

1713.7-3946
(Aharonian et al. 2007)

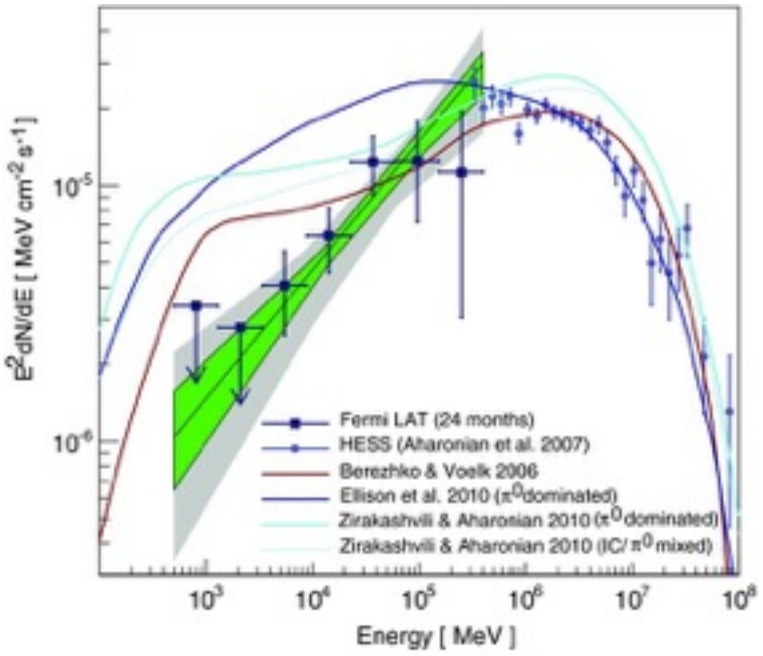


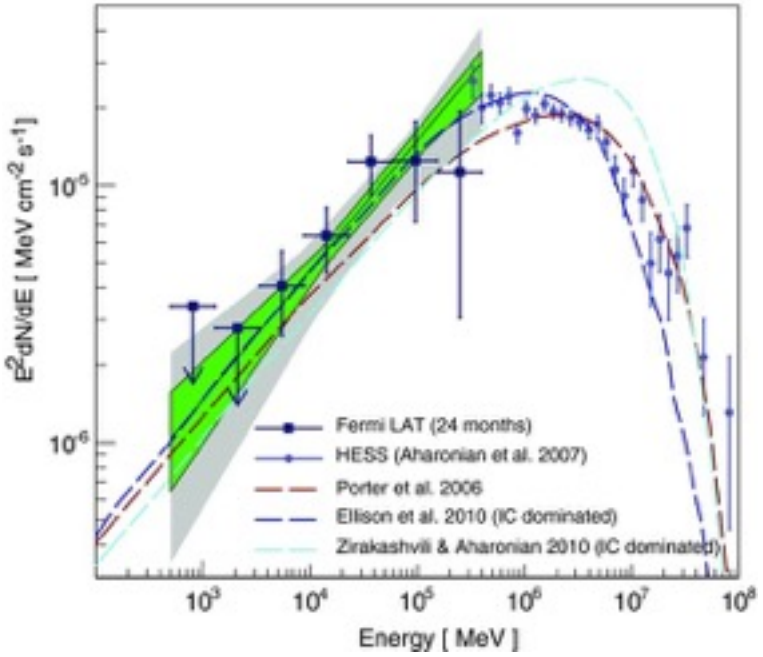
good correspondence between TeV and X-ray

puzzle:
thermal X-rays undetected

1713.7-3946
(Abdo et al. 2011)

- hard GeV spectrum
- leptonic scenario
  - low B
  - X-ray time variability
    requires high B
- hadronic scenario
  - hard spectrum with
    a sharp break
- hybrid scenario





Adriani et al. 2011 **電子陽電子**

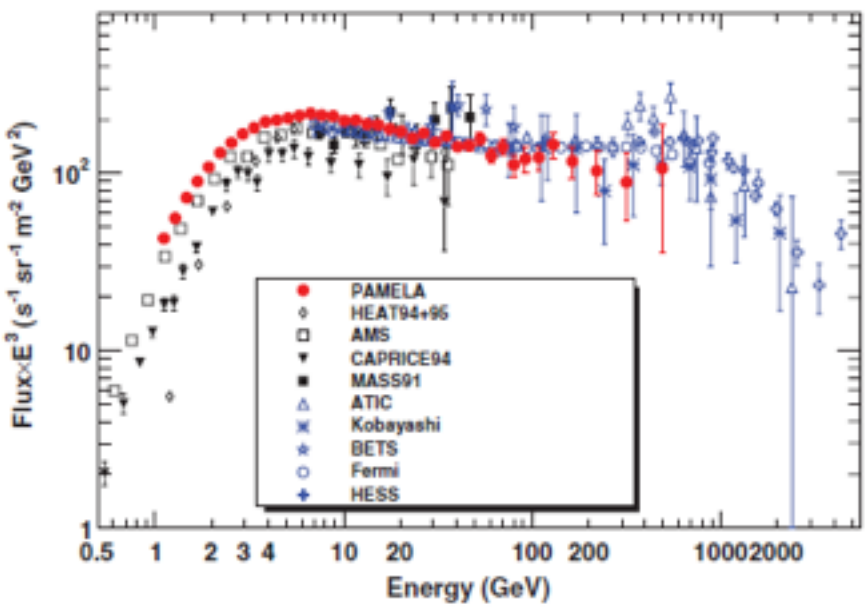


FIG. 2 (color). The electron energy spectrum obtained in this work compared with modern measurements: CAPRICE94 [19], HEAT [20], AMS [21], MASS91 [22], Kobayashi [23], BETS [24], ATIC [25], HESS [26], Fermi [27]. Note that the data points from [23–27], indicated with blue symbols, and the highest data point from HEAT [20] are for the electron and positron sum.

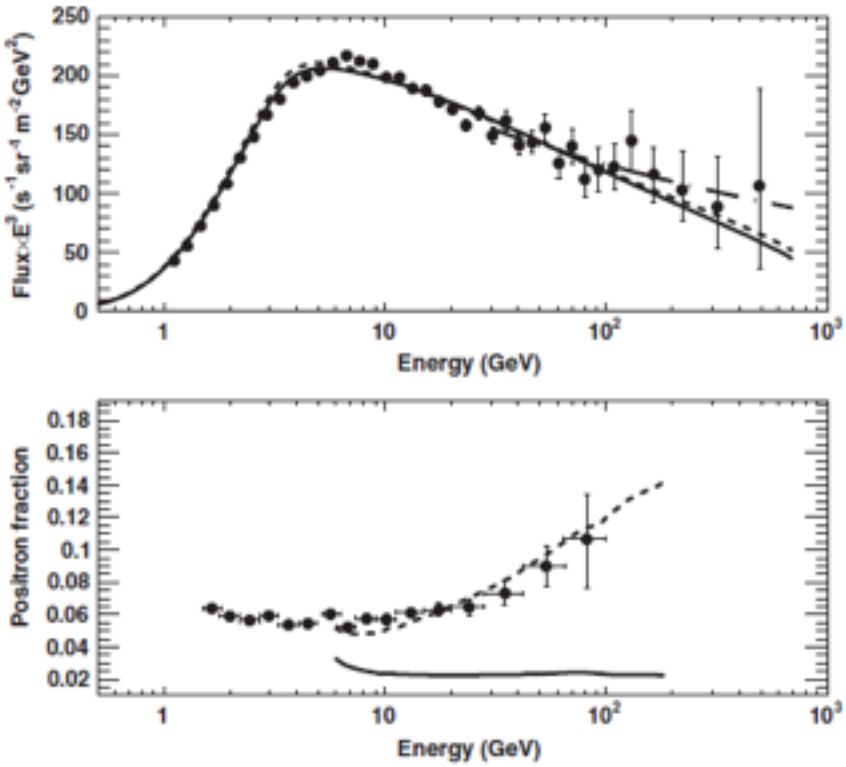
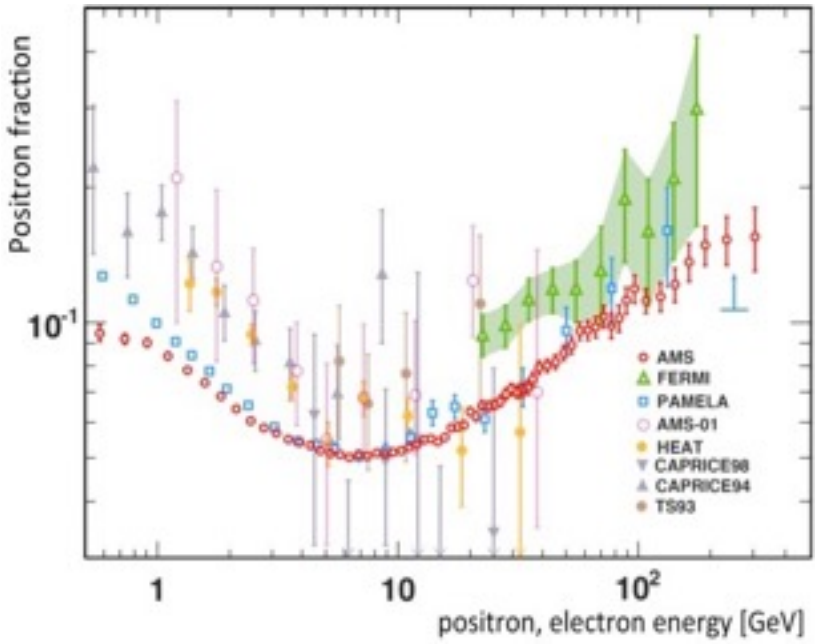
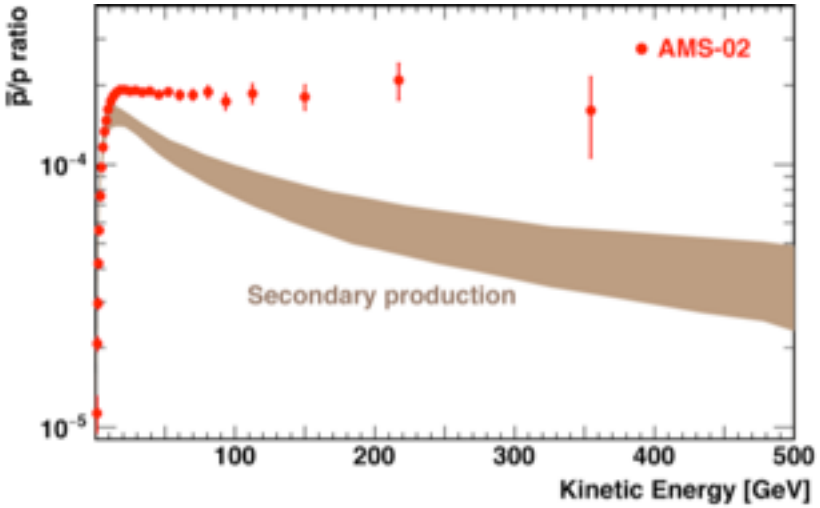


FIG. 3. Top: the e^- spectrum obtained in this work compared with theoretical calculations. The solid line shows the standard GALPROP calculation [29] for a diffusion reacceleration model; the long-dashed line is a single power-law fit to the data above 30 GeV; the short-dashed line is a GALPROP calculation including a component from additional cosmic-ray electron sources. Bottom: the PAMELA positron fraction [28] compared with the previous GALPROP calculations with no (solid line) and with additional e^- and e^+ components (short-dashed line). The error bars are statistical only and these were the only errors considered by the fitting procedures.



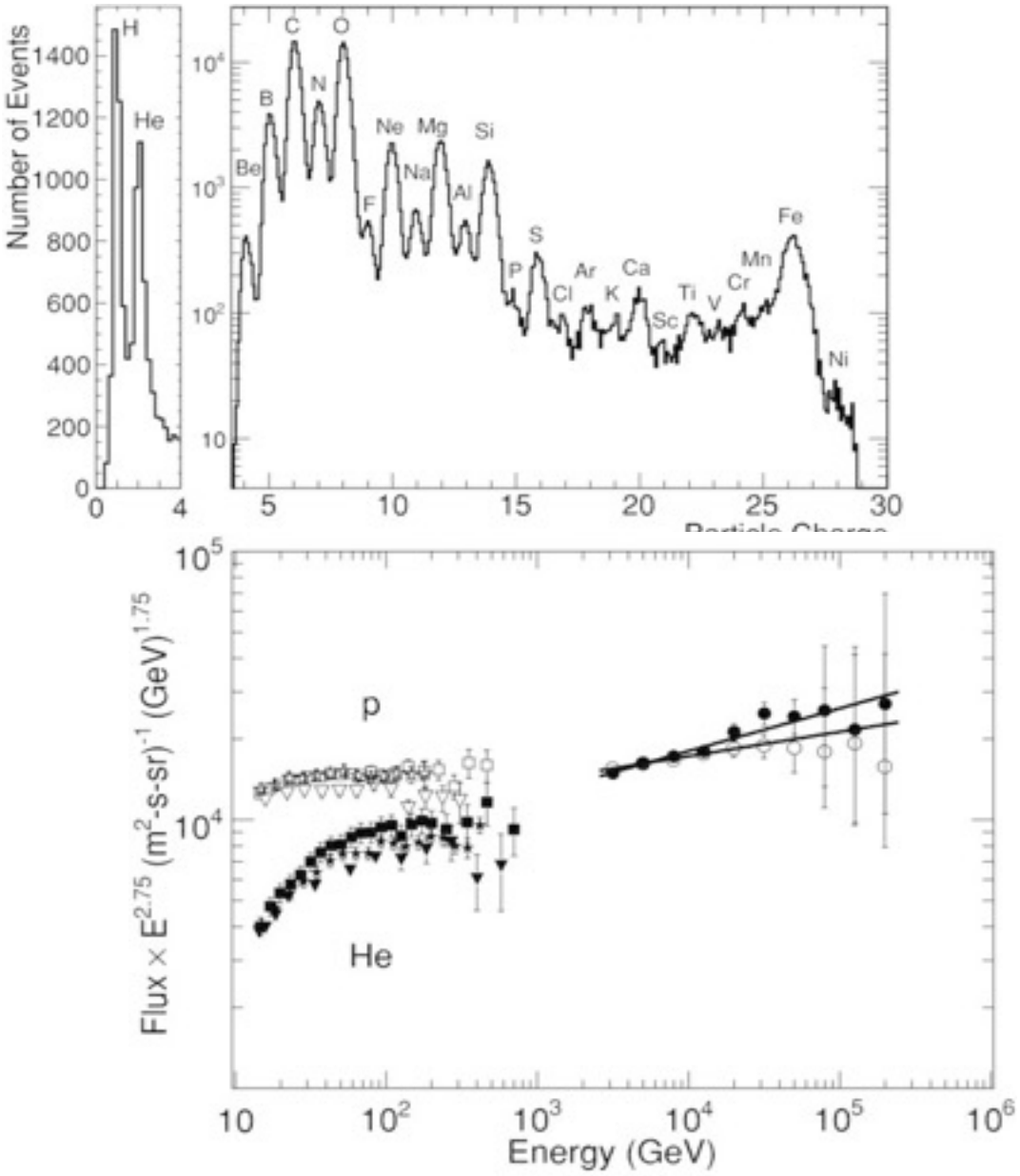
Positron excess

AMS homepage

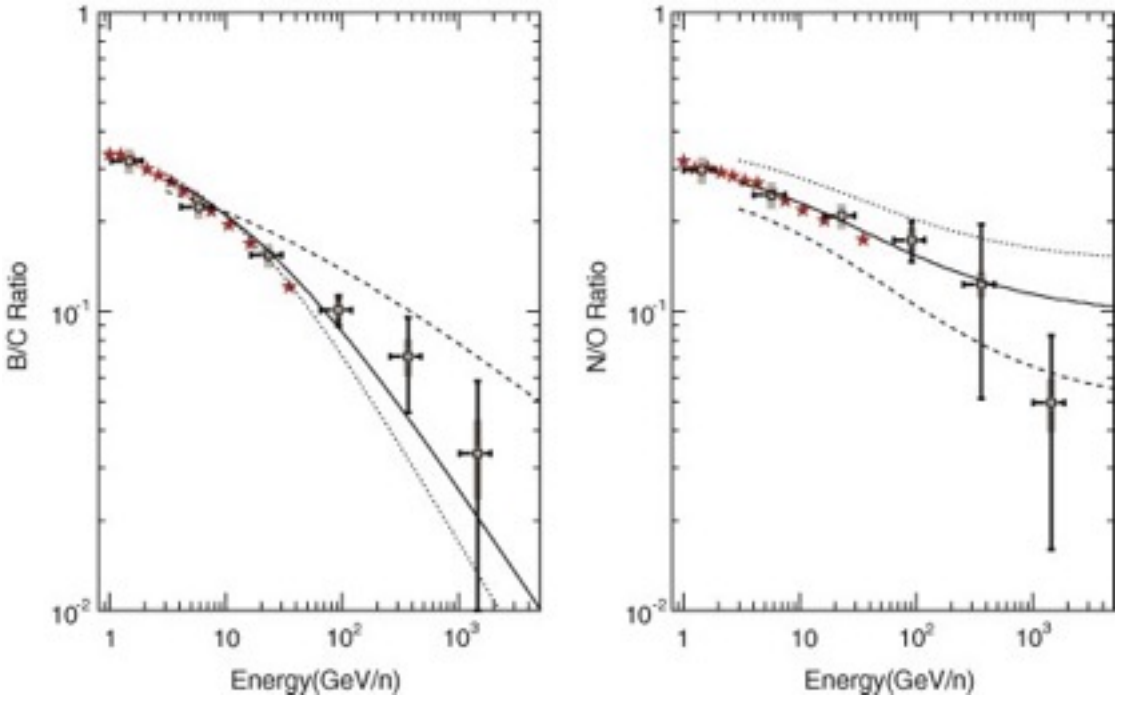


Anti-proton excess

Figure 2 from Discrepant Hardening Observed in Cosmic-ray Elemental Spectra
H. S. Ahn et al. 2010 ApJ 714 L89 doi:10.1088/2041-8205/714/1/L89



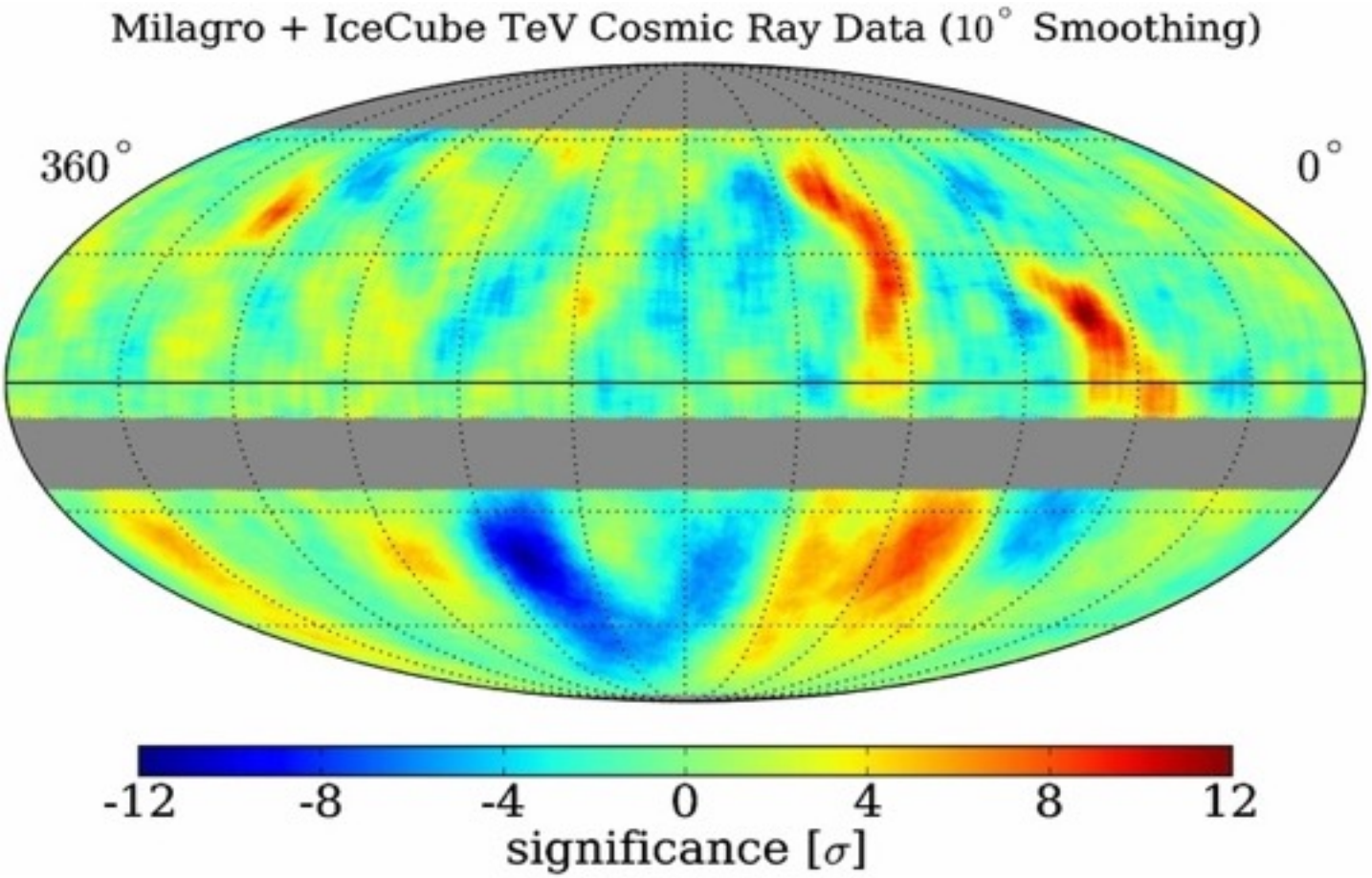
Measured energy spectra of cosmic-ray protons and helium nuclei. The CREAM-I spectra are compared with selected previous measurements (Alcaraz et al. 2000; Haino et al. 2004; Boezio et al. 2003) using open symbols for protons and filled symbols for helium: CREAM (circles), AMS (stars), BESS (squares), CAPRICE (inverted triangles).



Ahn et al. 2008

Left: Filled circles show the ratio of boron to carbon vs. energy after corrections. The lines represent model calculations for various values of the magnetic-rigidity dependence parameter, δ; solid line δ = 0.6, long-dashed line δ = 0.333, short-dashed line δ = 0.7. The stars are data from the space experiment, HEAO-3-C2 [5].
Right: Filled circles show the ratio of nitrogen to oxygen vs. energy. The lines represent model calculations of this ratio with δ =0.6). The different curves correspond to different assumptions on the amount of nitrogen in the source material. These are; solid line source N/O = 10%, long-dashed line source N/O = 5%, short-dashed line N/O = 15%.

Figure 17 from Observation of Anisotropy in the Arrival Directions of Galactic Cosmic Rays at Multiple Angular Scales with IceCube
R. Abbasi et al. 2011 ApJ 740 16 doi:10.1088/0004-637X/740/1/16



Combined map of significances in the cosmic ray arrival direction distribution observed by Milagro in the northern hemisphere (Abdo et al. 2008) and IceCube in the southern hemisphere (this analysis). Both maps have been smoothed with a 10° radius.

課題１

超新星残骸における宇宙線加速と逃走

- 最大エネルギーとKnee
  - $E_{max} \approx 10^{14} \frac{Z}{\xi} \frac{V_s}{c} \frac{B}{1\mu G} \frac{R}{1pc}$ eV
  - 理論的には2桁程度不足
- 存在スペクトルと供給スペクトル（閉じ込めと逃走）
  - 線形理論　$n(E) \propto E^{-p}$: $p = \frac{r+2}{r-1} \rightarrow 2$　（普遍的べきスペクトル）
  - 非線形理論　　べき型でなくなる
  - ガンマ線観測による検証　　源ごとに異なるスペクトル
- 宇宙線加速源としての超新星残骸の多様性
  - 宇宙線源としていくつものタイプがある？）（普遍性の否定）

非線形問題の例

Vladimirov et al. 2006

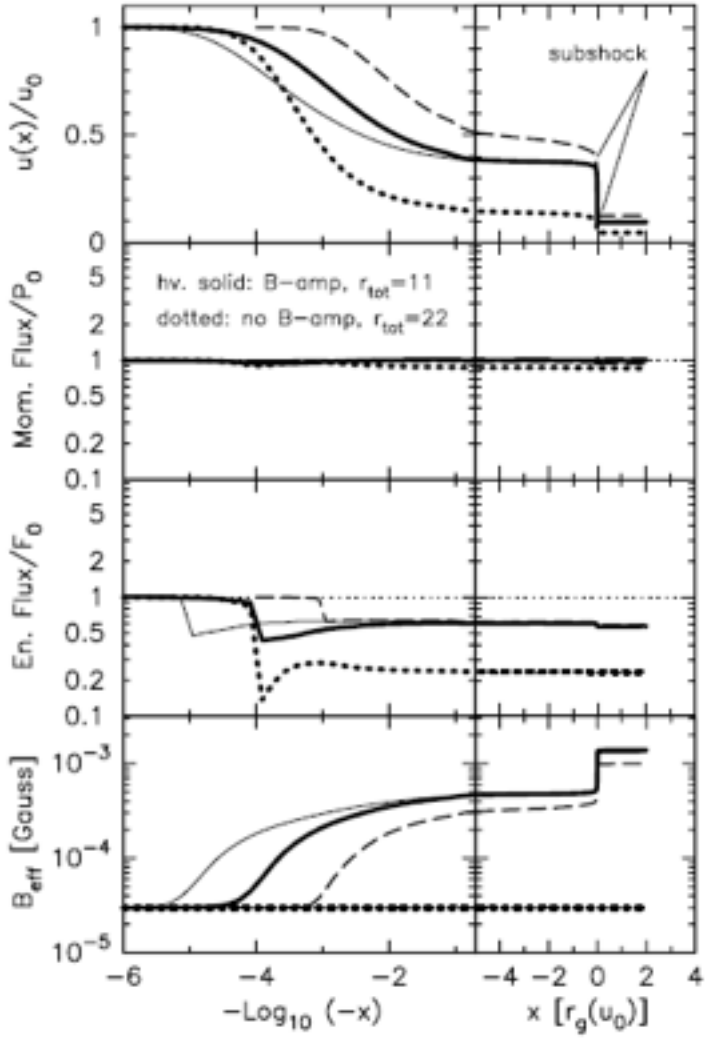


FIG. 1.— Shock structure including momentum and energy fluxes (in units of far upstream values) and the effective magnetic field vs. x. Note that the horizontal scale has units of $r_g(u_0) = m_p u_0/(eB_0)$ and is divided at $x = -5r_g(u_0)$ between a linear and log scale. In all panels, the heavy dotted curves show results without amplification, and all other curves are with amplification. The curves showing the energy flux drop sharply at the upstream FEB, which is at $-10^4 r_g(u_0)$ for the heavy solid and dotted curves, at $-1000 r_g(u_0)$ for the dashed curves, and at $-10^5 r_g(u_0)$ for the light solid curves, as particles freely leave the system. When this escaping flux is included, energy and momentum are conserved to within ±10%.

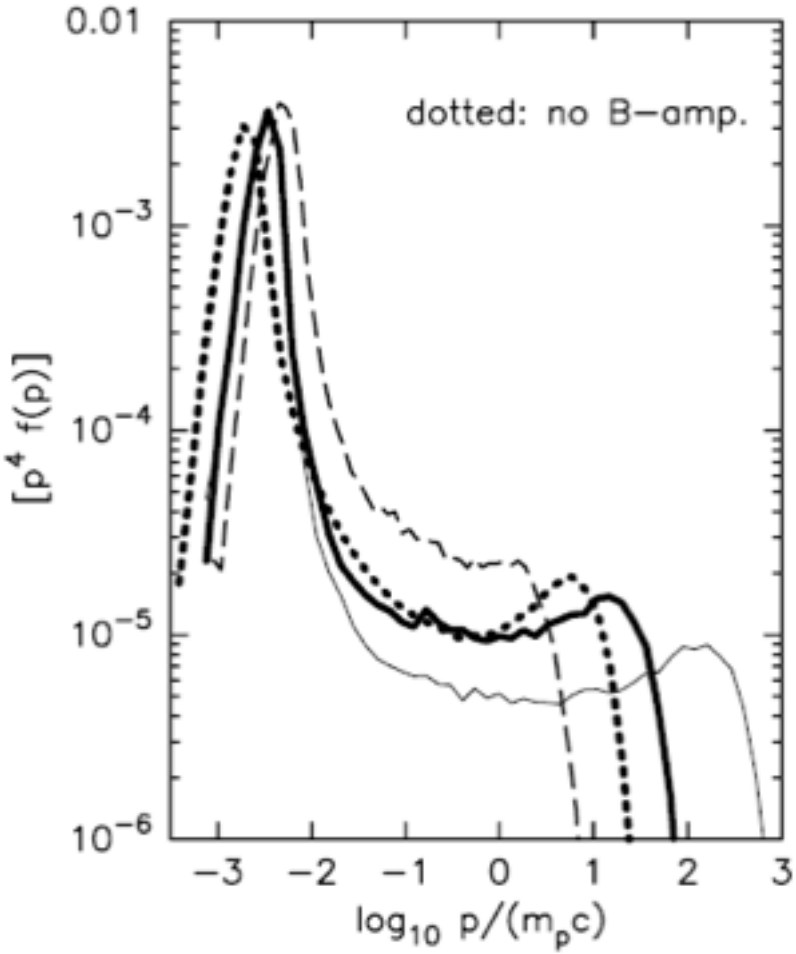


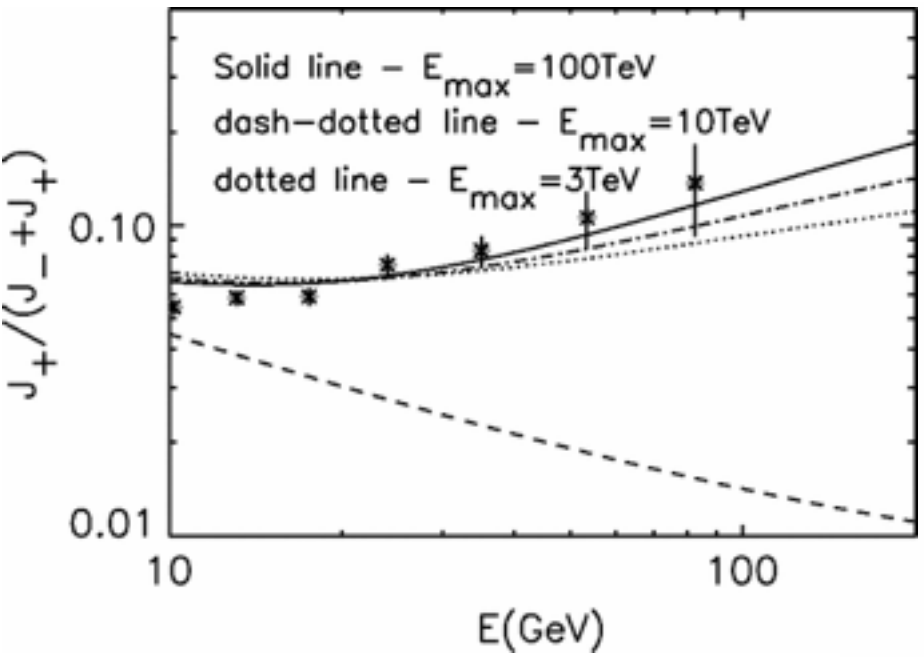
FIG. 2.— Phase-space distributions for the shocks shown in Fig. 1. These spectra are multiplied by $[p/(m_p c)]^4$ and are calculated downstream from the shock in the shock rest frame. As in Fig. 1, the heavy solid and dotted curves have $d_{FEB} = -10^4 r_g(u_0)$, the dashed curve has $d_{FEB} = -1000 r_g(u_0)$, and the light solid curve has $d_{FEB} = -10^5 r_g(u_0)$.

knee問題

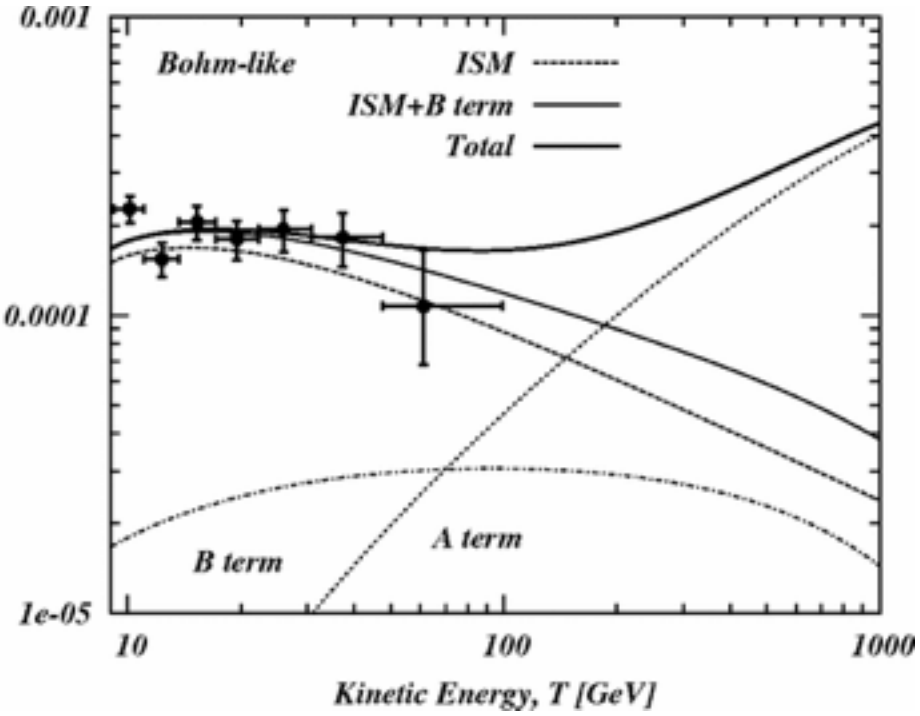
- – 磁場増幅で$E_{\max}$を増やす？
  - – V_sの大きい時期に加速？
    - 供給スペクトル問題と関係
    - $E(t)$:　$q(E)dE = -\dot{N}(t)E(t)dt$
  - – 特別な種類のSNRで加速？
    - 核種毎のスペクトル問題、スペクトル硬化問題と関係
    - superbubble説
  - – SNR以外の起源？
    - Knee-ankle間の宇宙線の起源と関係

2. 加速源における２次粒子生成と陽電子・反陽子問題

- **２次粒子の起源も一つではない**
- 星間物質：通過物質量　$10E^{-\beta}\,\mathrm{g\,cm^{-2}}$
- 源では？　$10^{-2}E^{-\gamma}\,\mathrm{g\,cm^{-2}}$
- 例　$\beta=\frac{1}{3},\gamma=0$なら　TeVでは同程度の寄与
- 100GeV以上では源での生成物のほうが多い
  - 電子陽電子対過剰
  - 反陽子スペクトル
  - B/C 比
- 他の解釈（別の源：パルサー星雲、暗黒物質、
  ：再加速、伝播の非一様性、、）



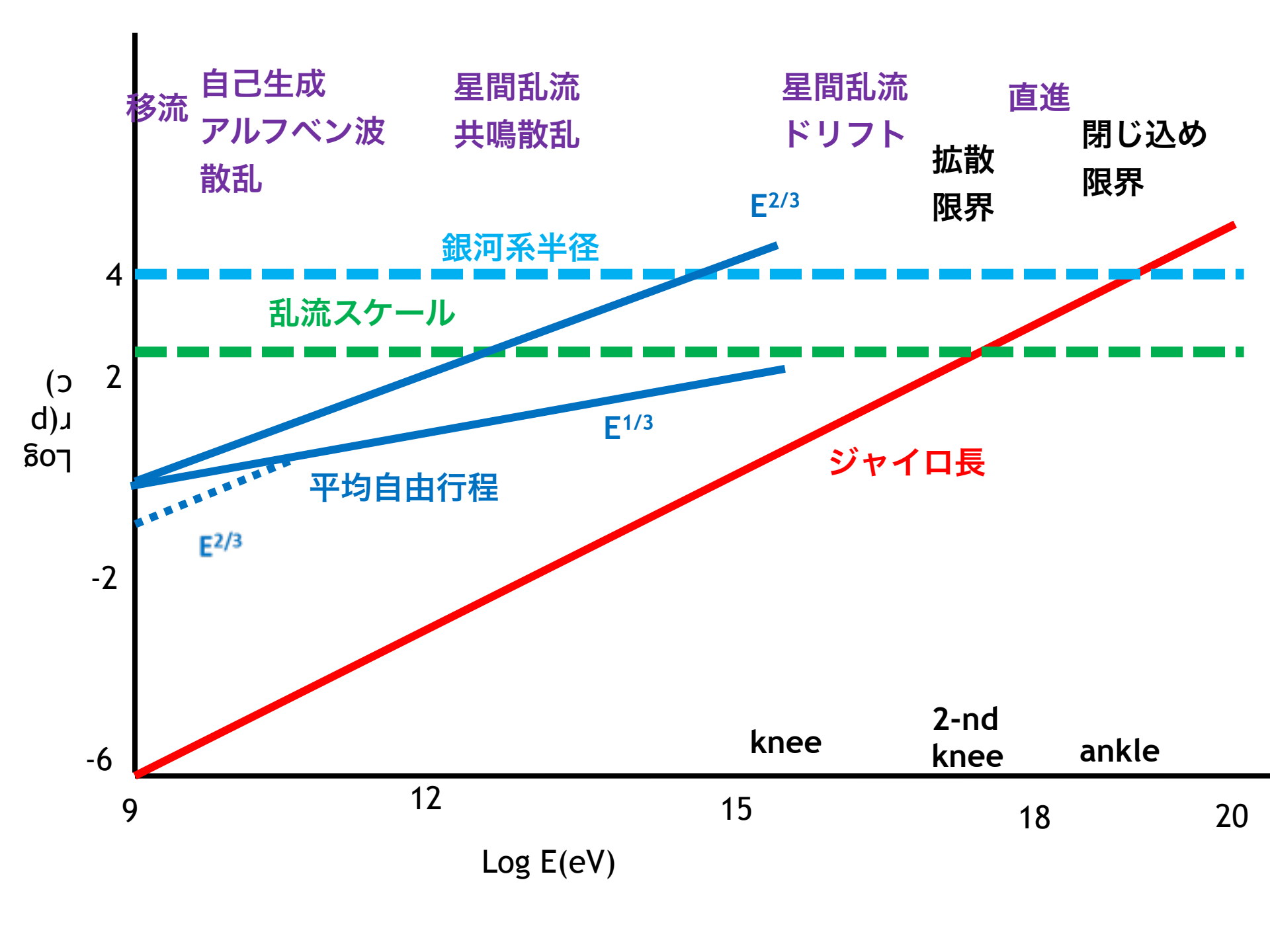
Blasi
PRL 103, 051104 (2009)



Blasi & Serpico
PRL 103, 081103 (2009)

３．宇宙線加速と輸送機構における散乱の役割

- ジャイロ半径
- 平均自由行程
  - 銀河磁場の乱れ
  - 自己散乱
  - ドリフト
- 非等方性


移流
自己生成
アルフベン波
散乱
星間乱流
共鳴散乱
星間乱流
ドリフト
直進
拡散
限界
閉じ込め
限界
E2/3
銀河系半径
乱流スケール
E1/3
平均自由行程
E2/3
ジャイロ長
knee
2-nd
knee
ankle
4
2
-2
-6
9
12
15
18
20
Log E(eV)
Log r(pc)

「散乱」の特徴

- 共鳴と非共鳴
- 共鳴　粒子軌道と磁場の空間揺らぎが一致
  - $v_{\parallel}\frac{2\pi}{\omega_g}=\frac{2\pi}{k_{\parallel}}$　（共鳴波長は粒子エネルギーに比例）
  - 共鳴波長が星間乱流の慣性領域にあることが必要
    - 注入スケールは$\ell_0=2\pi/k$ ≈100pc程度
    - Kolmogorov $\lambda=l_0\left(\frac{E}{E_0}\right)^{1/3}$
    - 散逸長は何で決まっているか？
    - イオン慣性長なら　$\frac{c}{\omega_{pi}}=\frac{v_A}{\omega_{ci}}\approx 10^8 cm$
    - イオンー中性粒子衝突による散逸はもっと長い波長でおこる（$10^{15}cm$）。

- 短波長では宇宙線によるアルフベン波の自己生成
  - $\frac{\lambda(E)}{r_g} \approx \frac{1}{kW(k)} \propto E^{-\alpha}$ $\quad [kW(k) = \frac{\delta B^2}{B^2} \propto k^{-\alpha} \propto E^{\alpha}]$

    $[kr_g \approx 1]$
  - 宇宙線の拡散速度 $v_{CR} \approx c\frac{\lambda}{H} \approx 10^7 E^{1-\alpha} \mathrm{cm\ s^{-1}} > v_A$
  - 共鳴モードの成長率 $\sigma \approx \frac{u_{CR}(E)}{kW(k)u_{mag}} \frac{v_A}{H}$
  - $\tau_{TO} \approx \frac{1}{kv_A} \frac{1}{(kW(k))^{1/2}}$
  - $\sigma\tau_{TO} \approx \frac{1}{(kW(k))^{1/2}} \frac{\lambda}{H} \frac{u_{CR}(E)}{u_{mag}} \propto E^{1-\frac{3\alpha}{2}-\beta}$ 低エネルギーほど有効

    $[\ u_{CR} \propto E^{-\beta}\ ]$

４．kneeからankleまでの宇宙線の起源

- Galactic vs extragalactic
- 必要な光度
- 源の数
  - Steady vs non-steady
- 組成　（H, He, CNO, Si, Fe）
- 加速源
  - Birth of magnetars
  - Gamma-ray burst in the Galaxy
  - Galactic wind shock

必要な光度（Galactic）

- GeV $10^{41}\mathrm{erg\,s^{-1}}$ 10^{7}年 (10^{5}個)
- Knee $10^{39}\mathrm{erg\,s^{-1}}$ 10^{5}年 (10^{3}個)
- 2-nd knee $10^{37}\mathrm{erg\,s^{-1}}$ 10^{5}年
- Ankle $10^{35}\mathrm{erg\,s^{-1}}$ 10^{4}年
  - Feだと1桁大きくなる
- Magnetar birth or Galactic GRB
- $10^{50}\mathrm{erg}/\ 10^{6}$年= $3\times10^{36}\mathrm{erg\,s^{-1}}$

必要な光度（extragalactic)

- Ankle $10^{36}\mathrm{erg\ Mpc^{-3}s^{-1}}$
- 2-nd knee $10^{37}\mathrm{erg\ Mpc^{-3}s^{-1}}$
- Knee $10^{39}\mathrm{erg\ Mpc^{-3}s^{-1}}$

- 比較
- $\epsilon_{RG} \approx 10^{37}\ \mathrm{erg\ Mpc^{-3}s^{-1}}$ Radio galaxies
- $\epsilon_{BH} \approx 10^{39}\ \mathrm{erg\ Mpc^{-3}s^{-1}}$

  Seyfert galaxies (X-ray background)

Galactic-extragalactic transition

- Ankle説
  - スペクトル的には自然
  - 2-nd kneeとankleの間は陽子の直進領域なので閉じ込め時間が短い
  - 重元素優勢の可能性
- 2-nd knee説
  - 銀河内伝播からは自然（陽子ならば）
  - スペクトル的にはやや不自然（ankleをBethe-Heitlerによるdipとみなす、2nd kneeは観測的に不確定）
  - エネルギー収支はかなり巨大となる

まとめ

超新星残骸衝撃波による加速
- 検証は一定の成功
- 多くの物理過程（磁場増幅、ピックアップイオ

伝播
- 加速源における２次粒子生成
- 宇宙線流による磁場生成

起源
- Knee 問題は未解決
- 超新星残骸での加速限界