ORIGIN OF COSMIC RAYS

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Part of a Unified Theory of High Energy Astrophysical Phenomena produced by highly relativistic jets ejected by active galactic nuclei (AGN), microquasars, supernova explosions and pulsars. It includes :

Cosmic Rays (CR)
Gamma Ray Bursts (GRBs from ICS of light by CR e's)
X- Ray Flashes (XRF) (XRFs from ICS of light by CR e's)
High Energy Gamma Ray Astronomy (HEγ *from CR s)*
Radio Astronomy (Radio emission from CR e's)
High Energy Neutrino Astronomy (Nu's from CR Sources)

In coll. with A. De Rujula, S. Dado, R. Plaga

Energy Spectrum of CR

$$\frac{d^3N}{ds\,d\Omega\,dE}$$

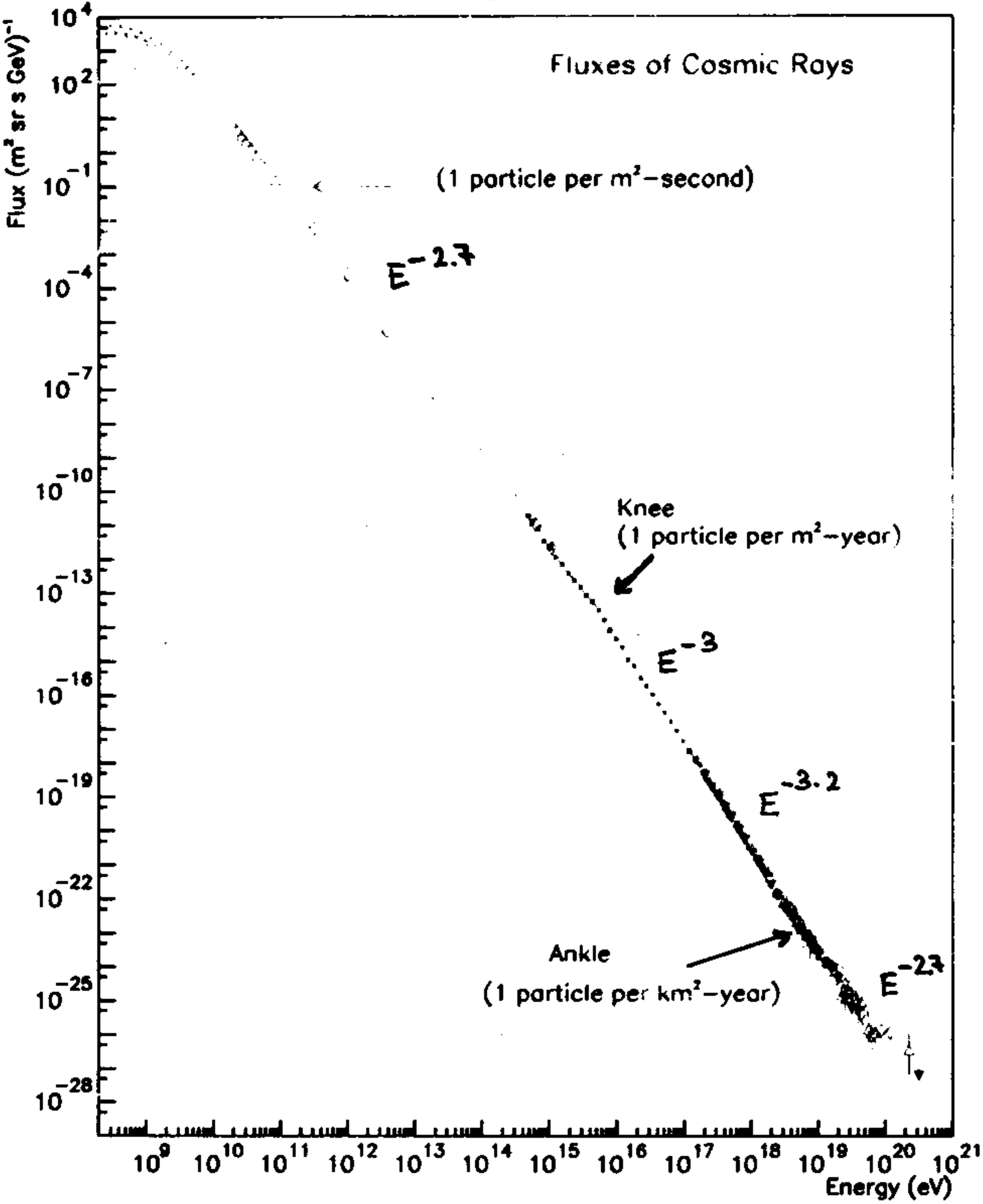


Figure 1: The CR all particle spectrum [509]. Approximate integral fluxes are also shown.

☆

THE ORIGIN OF COSMIC RAYS

NINETY-~~THREE~~-YEARS-OLD PUZZLES:

[WWW ?]:

- Who Are The Cosmic Accelerators ?
- Where Are They ?
- What Is The Acceleration Mechanism ?

THE ANSWERS MUST EXPLAIN:

- The Spectrum and Its Main Features:
  - the spectral power-laws
  - the origin of the Knee(s)/ A-dependence
  - the Origin of the Ankle
  - the absence (?) of the GZK Cutoff
- The Nuclear Composition
- The Degree of Isotropy
- The Galactic CR Luminosity

The answers must be consistent wi

- γ- Ray Astronomy
- Radio Astronomy
- ν- Astronomy

The answers must be falsifiable !

The main message:

Relativistic Jets Are Cosmic Ray Accelerators

(Simple Fermi Acceleration)

Relativistic Jets From SN Explosions Are The Main Source of Galactic CRs at All Energies !

Relativistic Jets From SN Explosions Produce GRBs Which Are Observable When They Point In Our Direction !

RELATIVISTIC JETS :

- JET ≠ Conical Ejecta

From observations with high spatial resolution:

- JET = Succession of cannonball

① Produce, through relativistic beaming, a <u>cone of cosmic rays</u>.

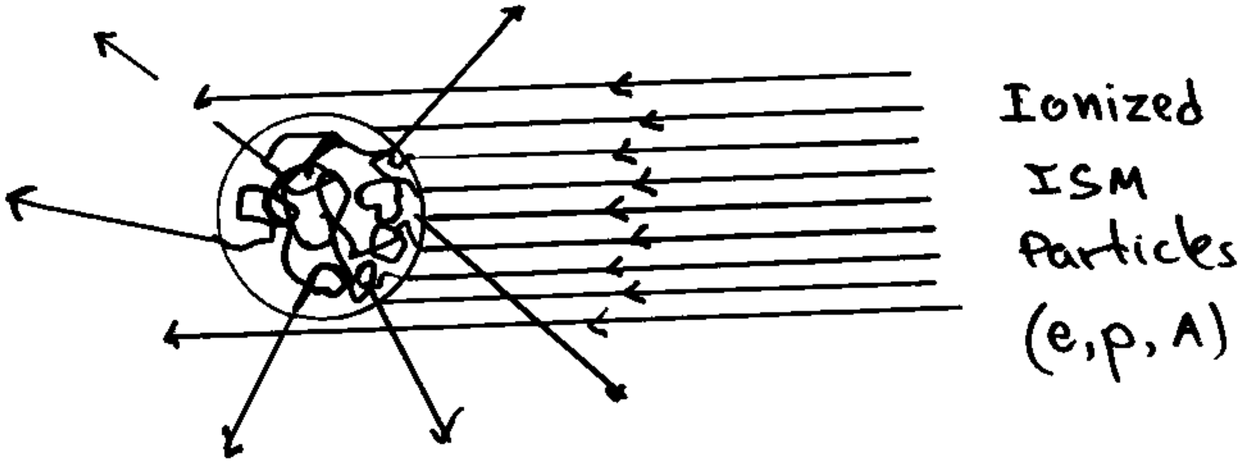
② Magnetic deflections isotropise the HE electrons in the CR beam

③ Inverse Compton scattering of CMB photons produces <u>x-trail</u>

④ The <u>Conical Trail</u> is Produced by Synchrotron Emissio (mainly from mildly rel. jets)

Relativistic Beaming

CB Rest Frame:



In the lab frame ($\gamma >> 1$)

$$\cos\theta = \frac{\cos\theta' - \beta}{1 - \beta\cos\theta'}$$

$$\frac{dn}{d\cos\theta} = \frac{dn}{d\cos\theta'} \frac{d\cos\theta'}{d\cos\theta} = \frac{dn}{d\cos\theta'} \delta^2$$

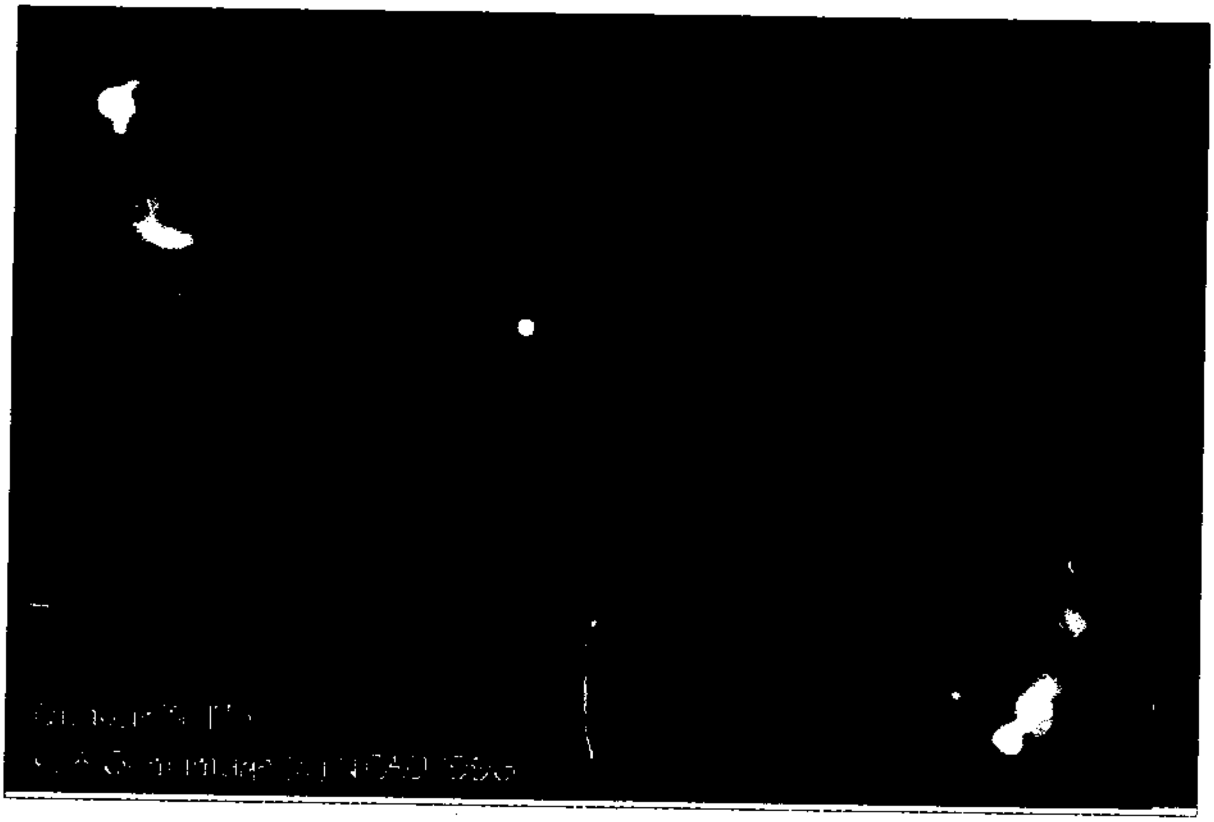
Doppler factor: $\delta \equiv \frac{1}{\gamma(1-\beta\cos\theta)} \approx \frac{2\gamma}{1+\gamma^2\theta^2}$ $\left\{ \begin{array}{l} \delta^2 >> 1 \\ \theta^2 << 1 \end{array} \right.$

$$\frac{dn}{d\cos\theta'} \cong \frac{n}{4\pi} \quad \text{(isotropic)}$$

$$\frac{dn}{d\Omega} = \frac{n}{4\pi}\delta^2 \cong \frac{n}{4\pi} \cdot \left[\frac{2\gamma}{1+\gamma^2\theta^2}\right]^2$$

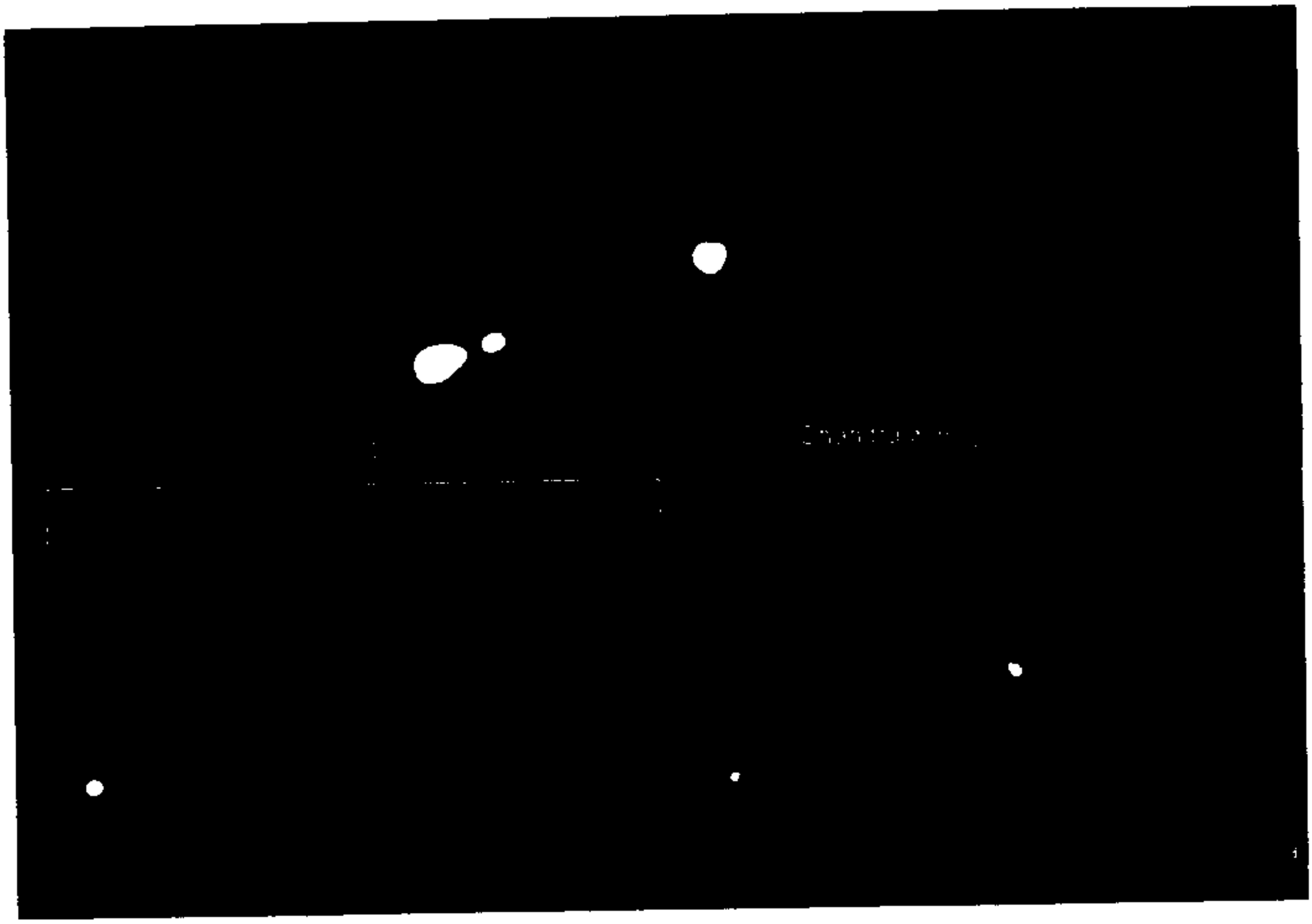
BIPOLAR REL. JETS FROM THE QUASAR 3C175

Quasar 3c175



The receding jet is not seen because of relativistic beaming which collimates its radiation into a cone of opening angle

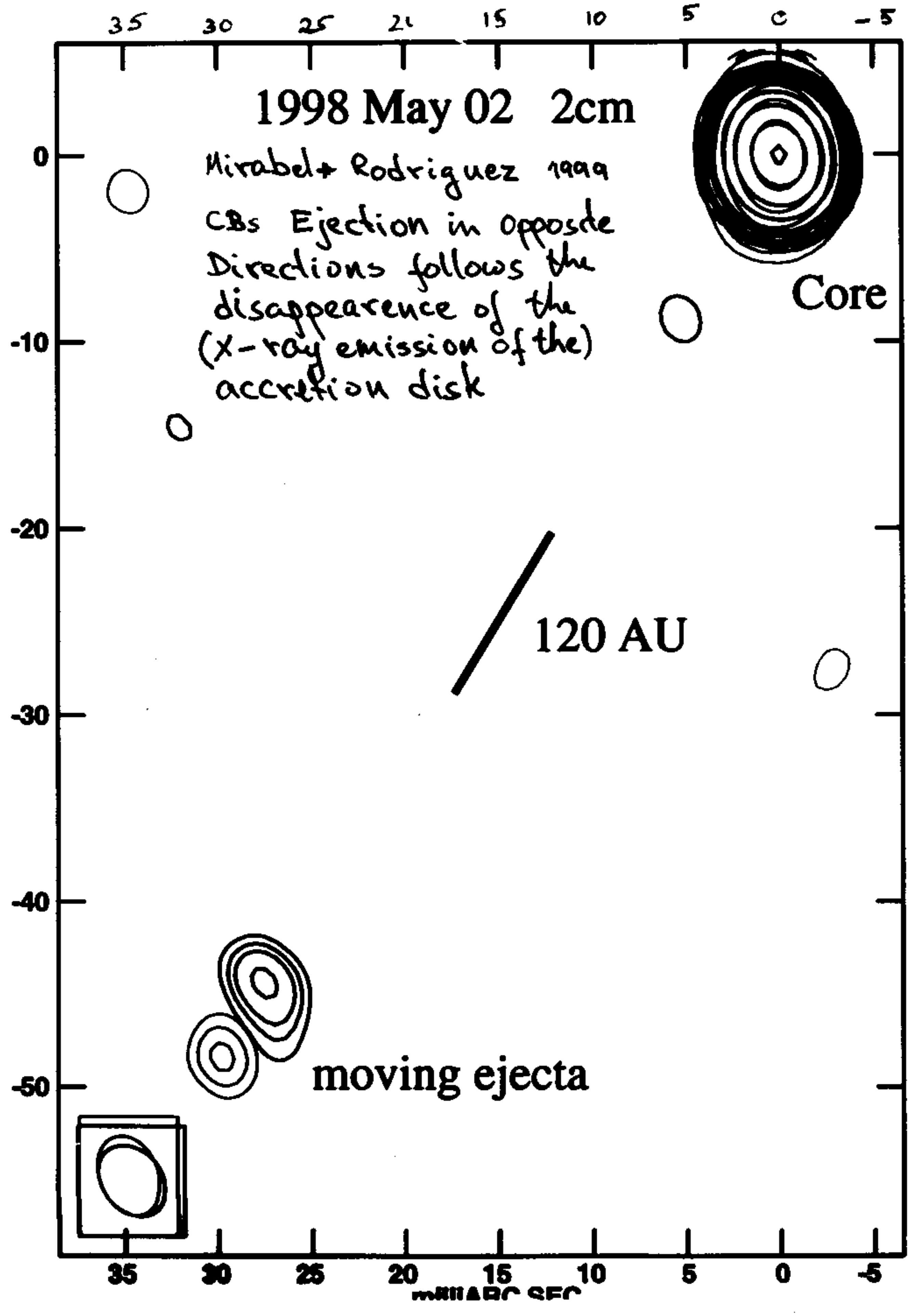
$$\theta \sim 1/\Gamma \qquad \Gamma = 1/\sqrt{1-\beta^2}$$



X-Ray, Optical and Radio Observations of the Jet emitted by M87

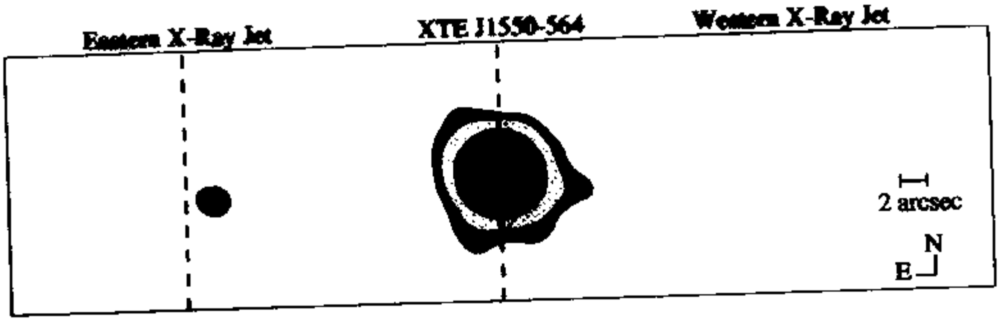
GRS 1915+105 : VLBA

(milliarc sec resolution)

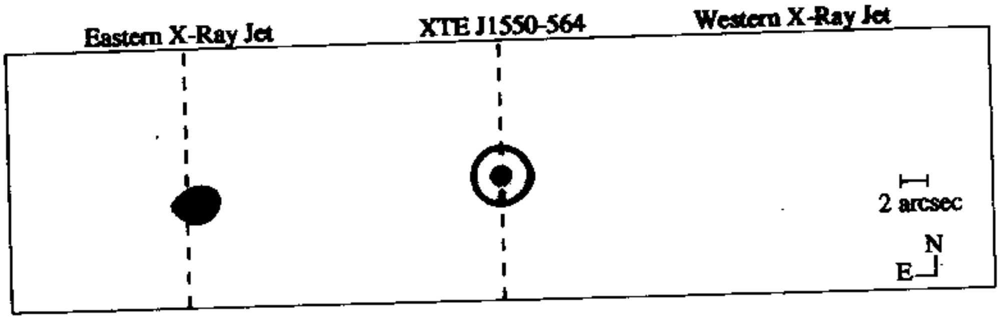


Mirabel+ Rodriguez 1999

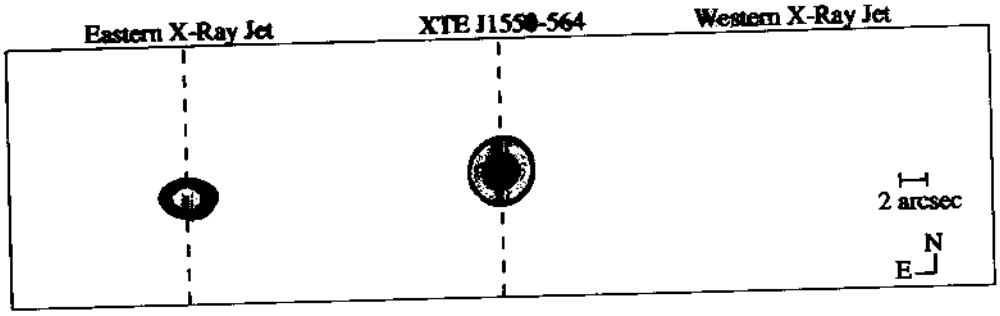
CBs Ejection in Opposite Directions follows the disappearence of the (X-ray emission of the) accretion disk



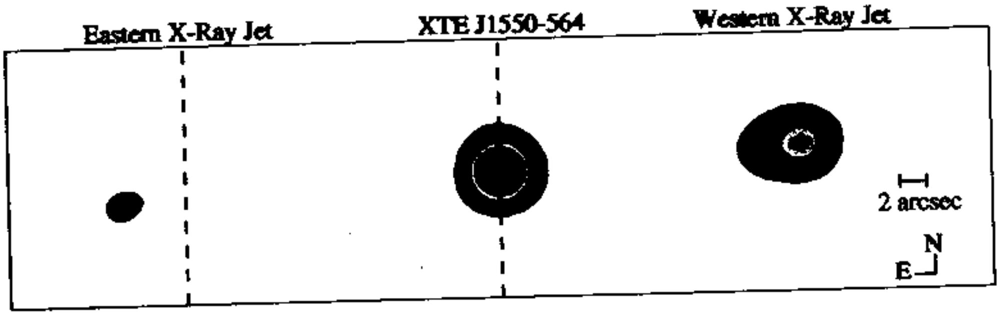
2000 June 9



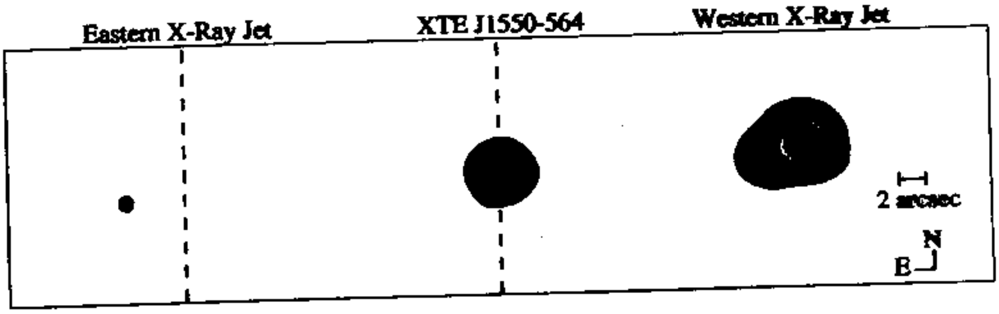
2000 August 21



2000 September 11



2002 March 11

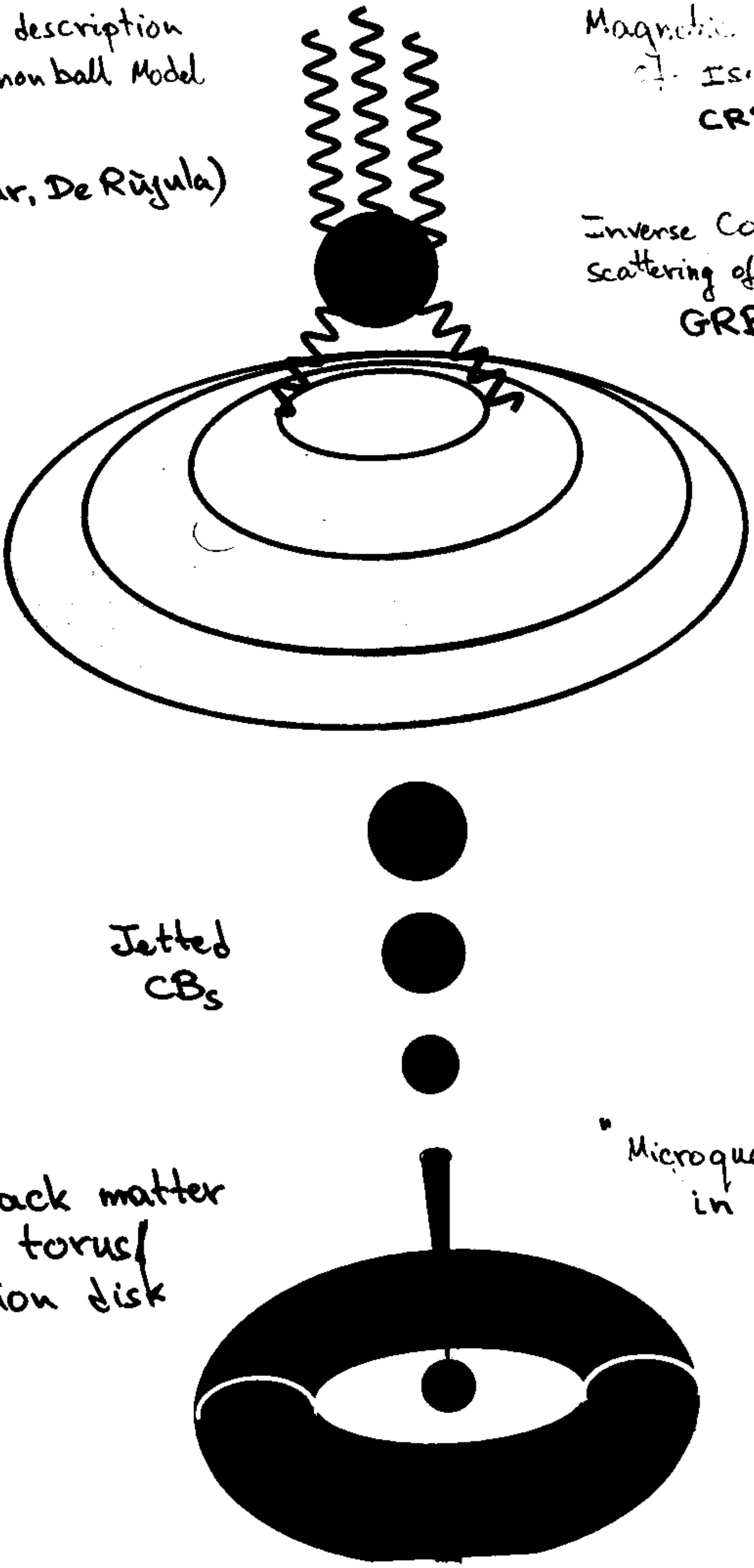


2002 June 19

Corbel 2004

Schematic description of the Cannonball Model of GRBs

(Dado, Dar, De Rújula)



Do SN Produce Highly Relativistic Jets ?

Evidence : GRB AFTERGLOW

Shaviv and Dar 1994: GRBs are produced by HR Jets from* core-collapse

Dado, Dar, De Rũjula 2000-2004: All relatively nearby GRBs ($z \lesssim 1$) show evidence/consistent with SN1998bw-like contribution to their afterglow.
Galama et al. 1998 → Staneck et al. 2003

Evidence: Super-luminal Ejecta ('Mystery Spots') by SN1987A

Nisenson and Papaliolios, ApJ 518 L29 (1999)

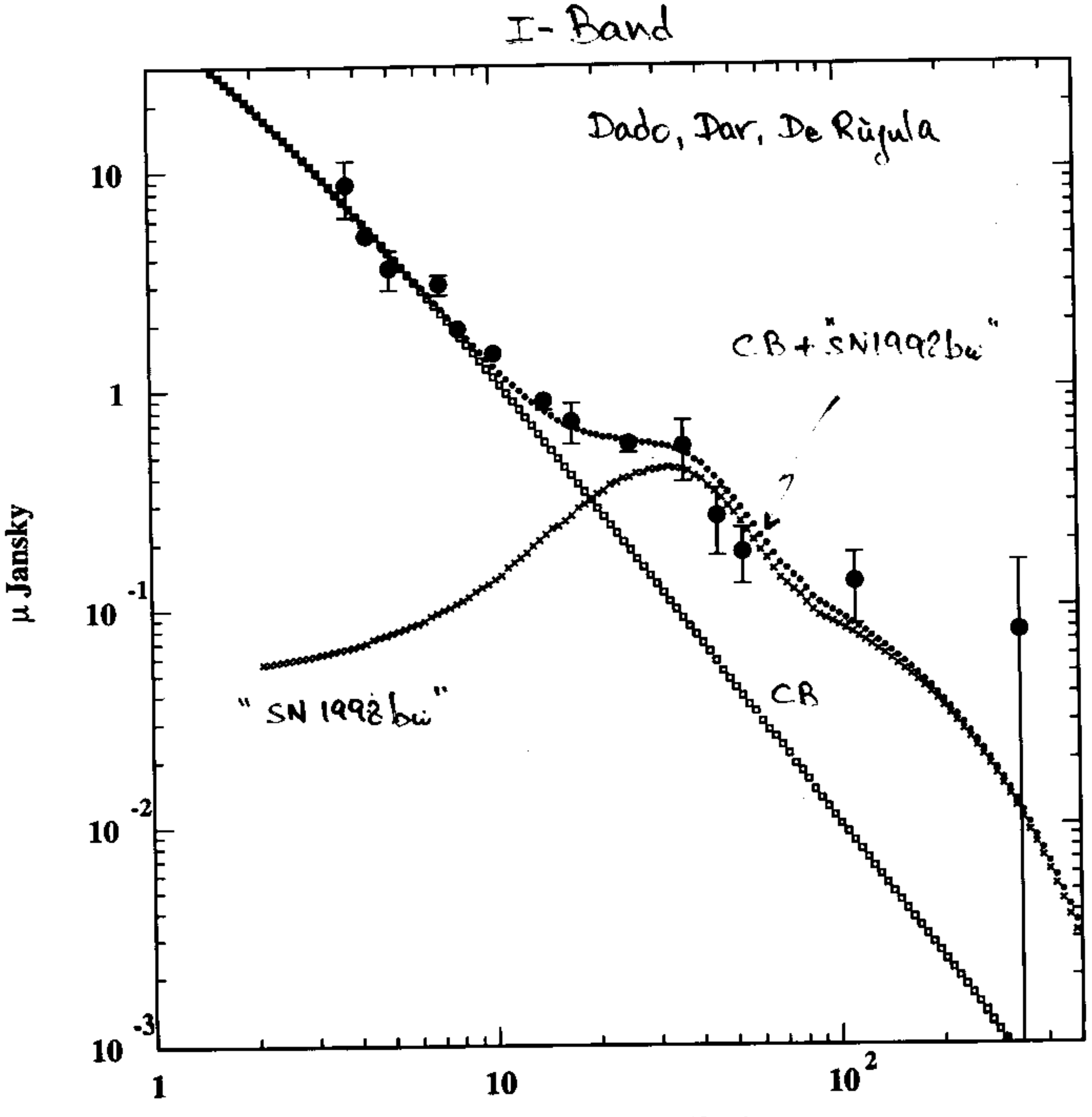
Evidence: Morphology of SNRs

e.g. Chandra observations of Cassiopia A
(Hwang et al 2004, ApJ)

GRB 00911

Cannonball Model Fit

(Dado, Dar and De Rūjula)



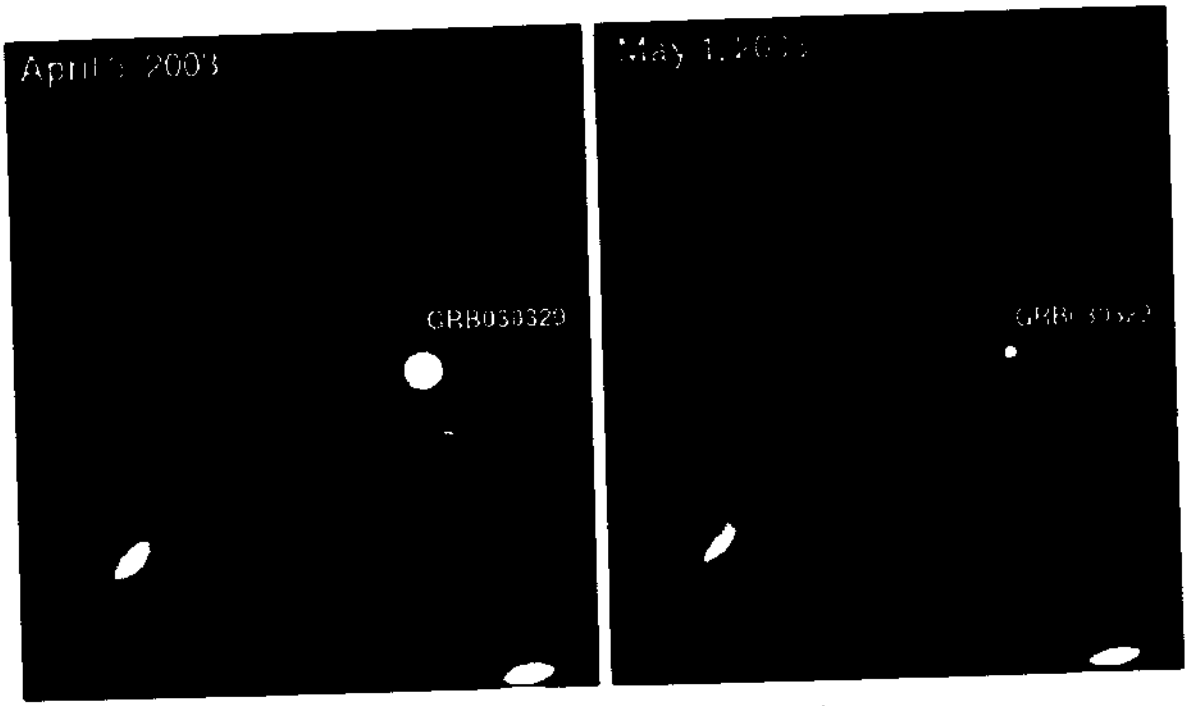


Image of Afterglow of GRB 030329
(VLT + FORS)

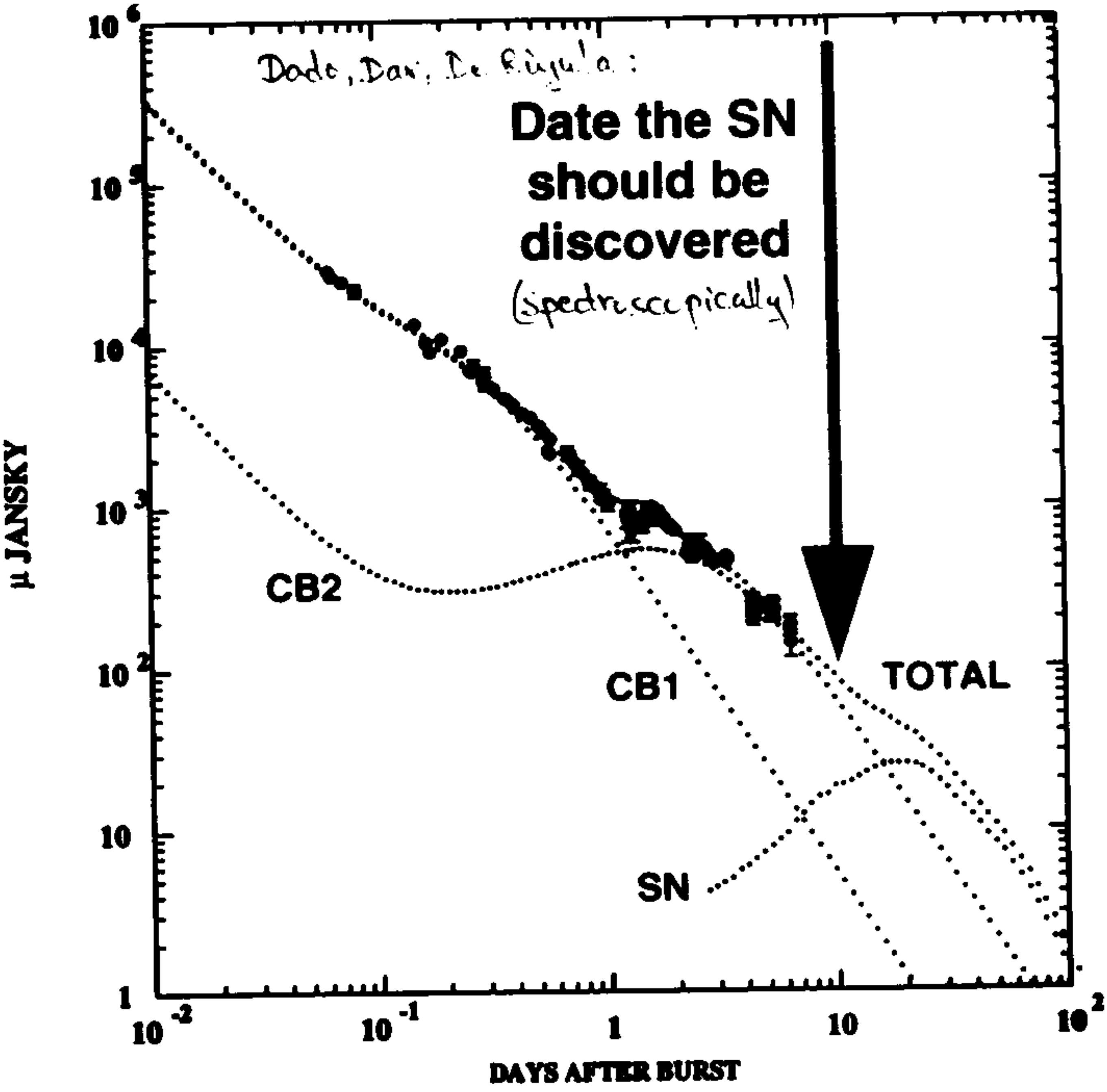
ESO PR Photo 17a/03 (18 June 2003)

© European Southern Observatory

הזוהר הנראה שנמשך לאחר התפרצות
קרינת ה γ
GRB 030329

$D^3 \equiv$ Dado, Dar, DeRujula made this CB Model Prediction on April 3, posted in astroph (0304106) and submitted to ApJL, on April 6 before the discovery

R-Band Light Curve of the Afterglow of GRB 030329



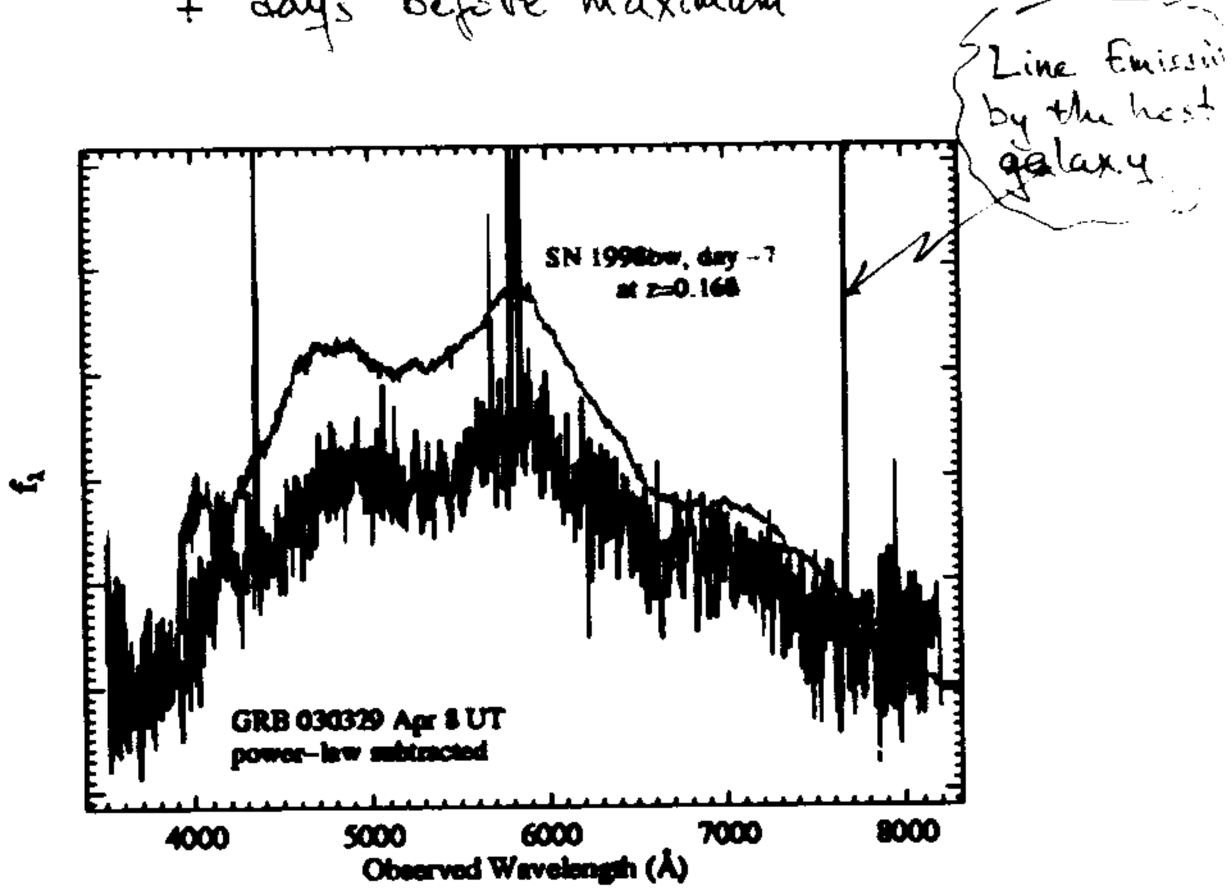
Dado, Dar, De Rujula:

Date the SN should be discovered

(spectroscopically)

Subtraction of a scaled version of the April 4.27 UT power-law spectrum ($F_\nu \sim \nu^{-0.93 \pm 0.02}$) from the April 8.13 UT spectrum*

Reveals the spectrum of SN1998bw 7 days before maximum



Line Emissi
by the host
galaxy

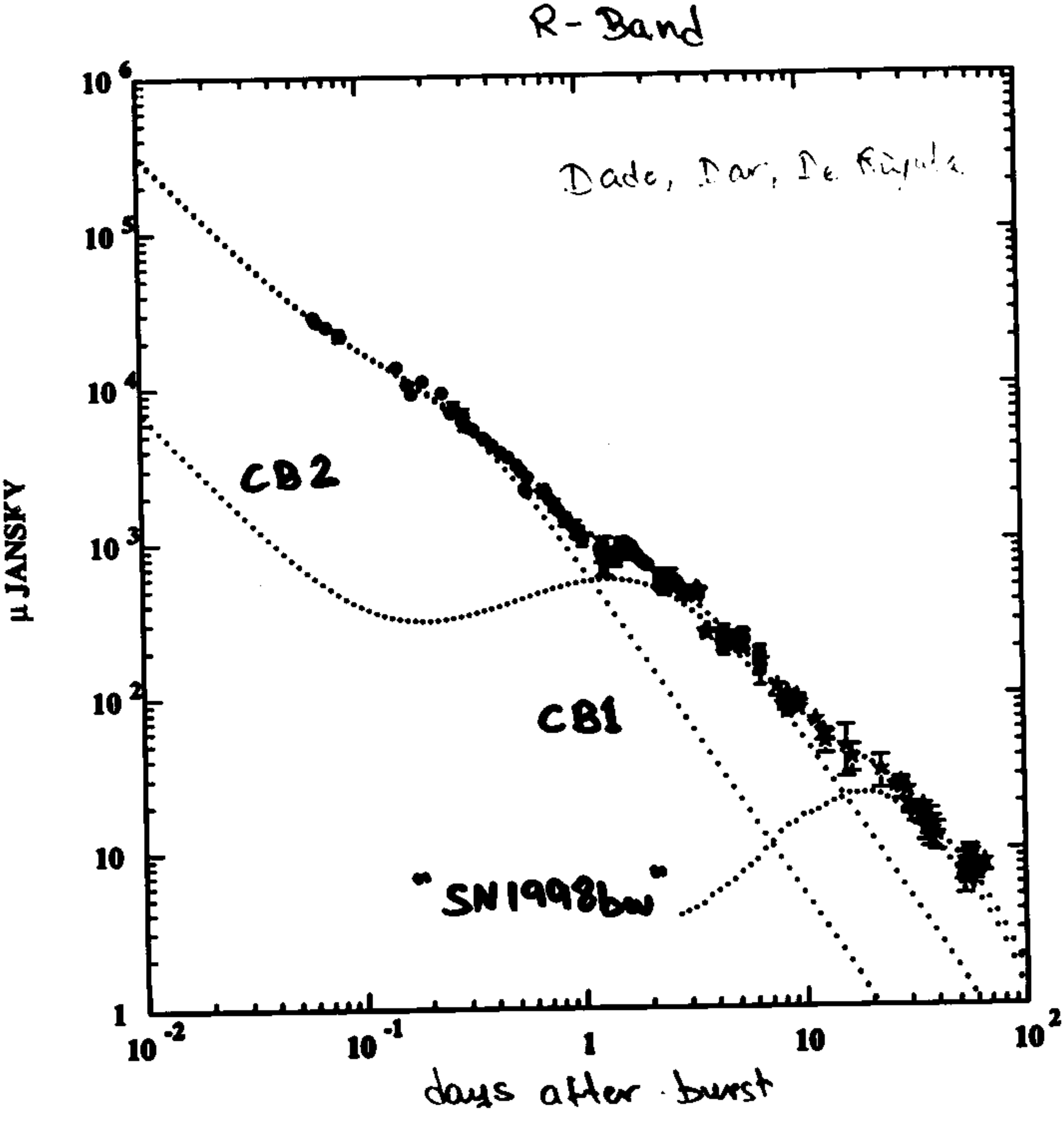
Matheson et al:

GCN 2120 April 8, 2003, 20:13:40 GMT

*

6.5M Multiple Mirror Telescope
6.5m Magellan Telescope

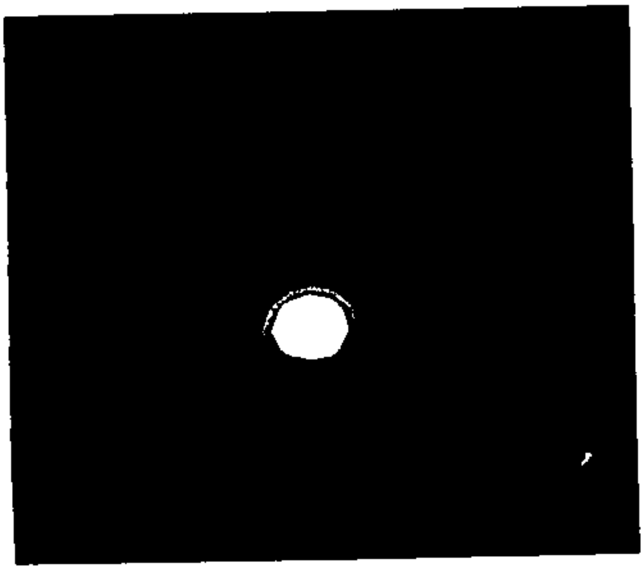
GRB 030329
CB Model Prediction

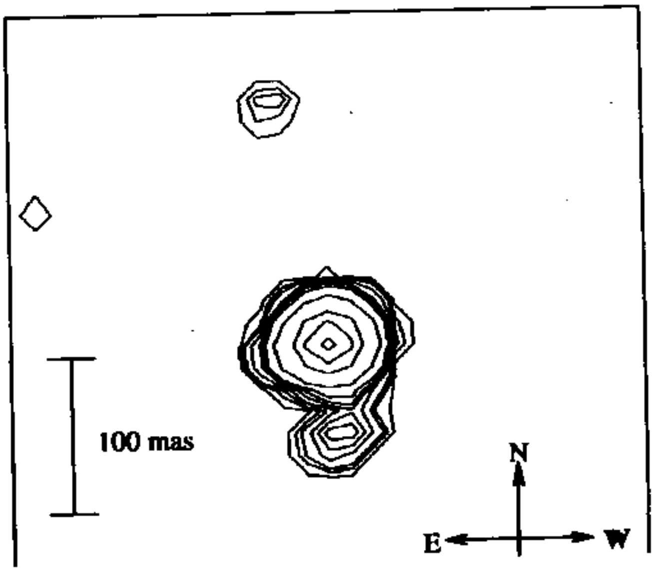


SN1987A

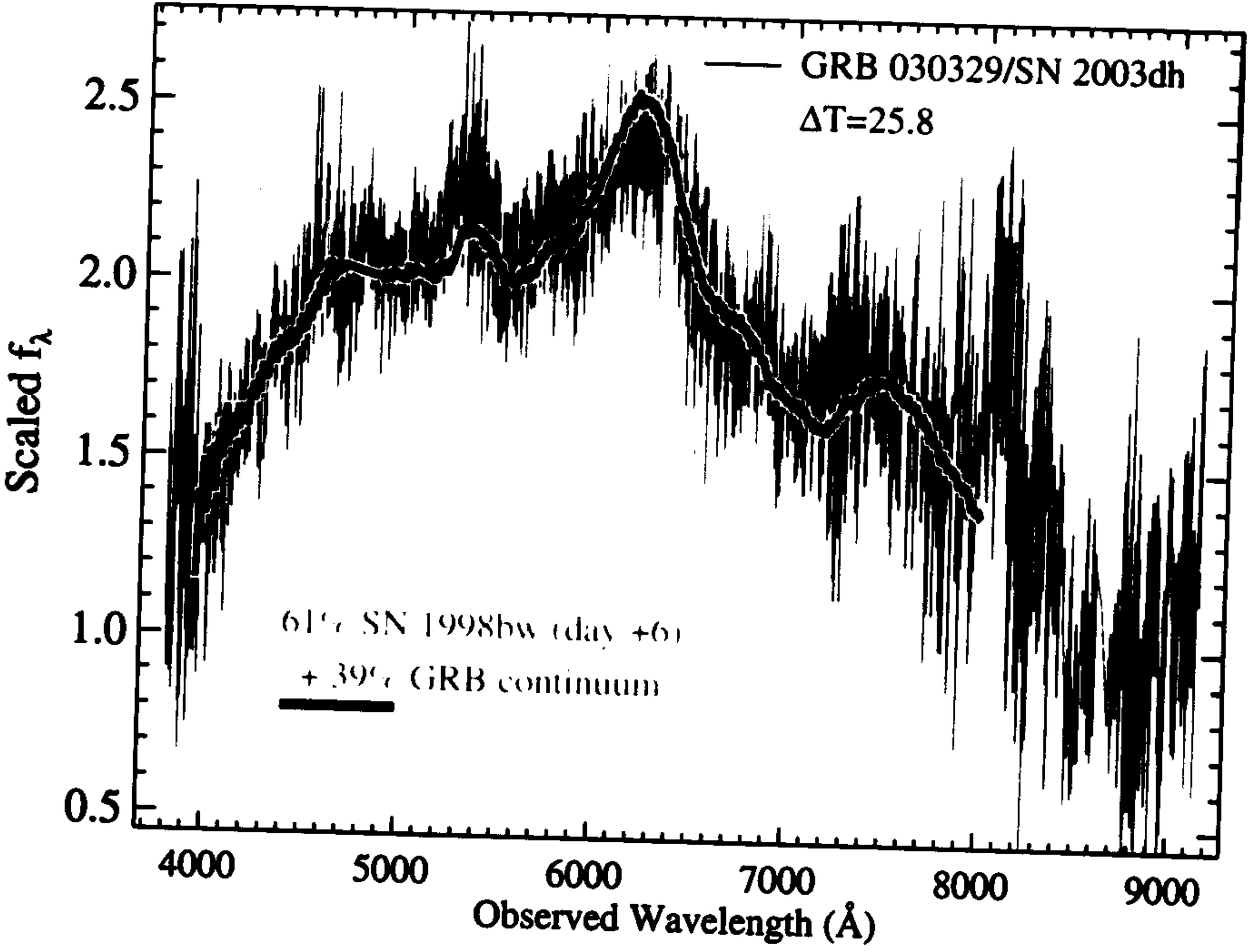
Mystery Spots: Super-luminal ejecta ($V = 0.8^{+0.3}_{-0.1}\,c$) Along the axis (45±5°).

Nisenson and Papaliolios: Specle interferomety of observations at three epochs.





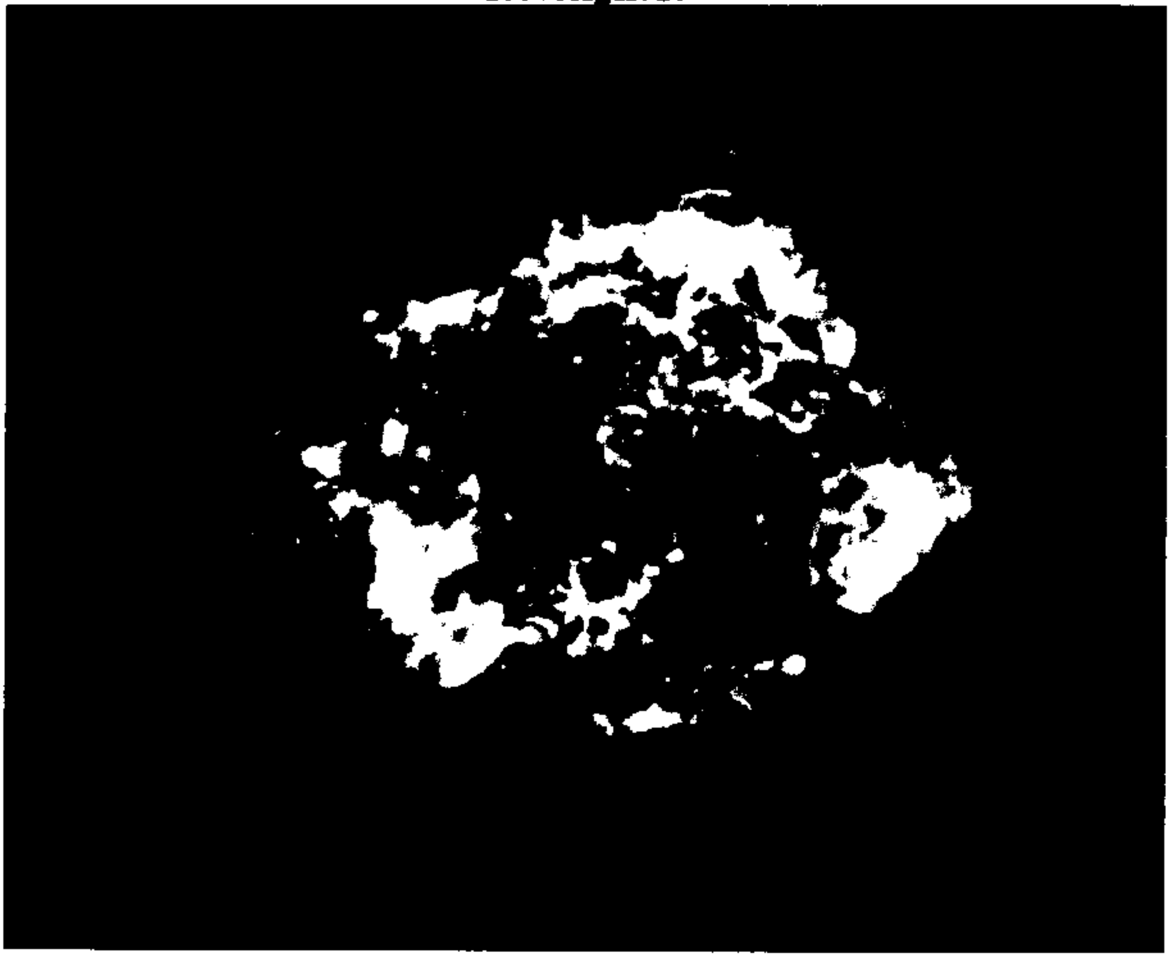
Matheson et al. 2003



Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2004 August 26



Cassiopeia A in a Million
Credit: U. Hwang (GSFC/UMD), J.M. Lamming (NRL), et al., CXC, NASA,

Explanation: One million seconds of x-ray image data were used to construct this view of supernova remnant Cassiopeia A, the expanding debris cloud from a stellar explosion. The stunningly detailed image from the Chandra Observatory will allow an unprecedented exploration of the catastrophic fate that awaits stars much more massive than the Sun. Seen in false-color, Cas A's outer green ring, 10 light-years or so in diameter, marks the location of the expanding shock from the original supernova explosion. At about 10 o'clock around the ring, a structure extends beyond it, evidence that the initial explosion may have also produced energetic jets. Still glowing in x-rays, the tiny point source near the center of Cas A is a neutron star, the collapsed remains of the stellar core. While Cas A is about 10,000 light-years away, light from the supernova explosion first reached Earth just over 300 years ago.

Tomorrow's picture: The Sedna Scenario

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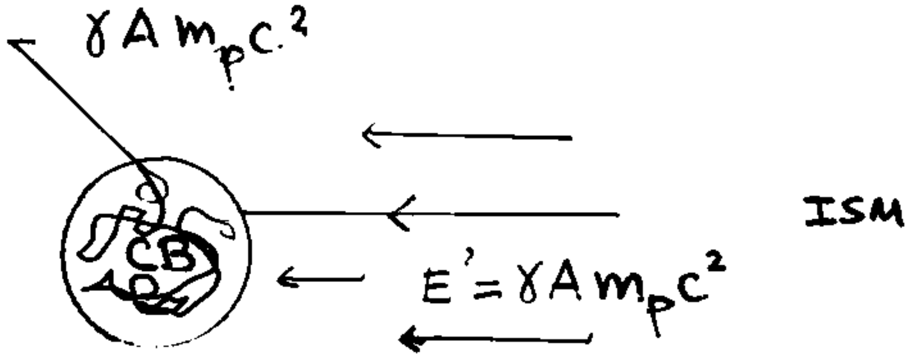
ACCELARATION OF ISM PARTICLES BY HIGHLY $(\gamma \gg 1)$ RELATIVISTIC JETS

In the CB's Rest Frame:

$\gamma = \frac{1}{\sqrt{1-\beta^2}} >> 1$



In the Observer Frame:

$$E_A = \gamma(E' + \beta P' \cos\theta') \approx \gamma^2 A m_p c^2 (1 + \beta \cos\theta')$$

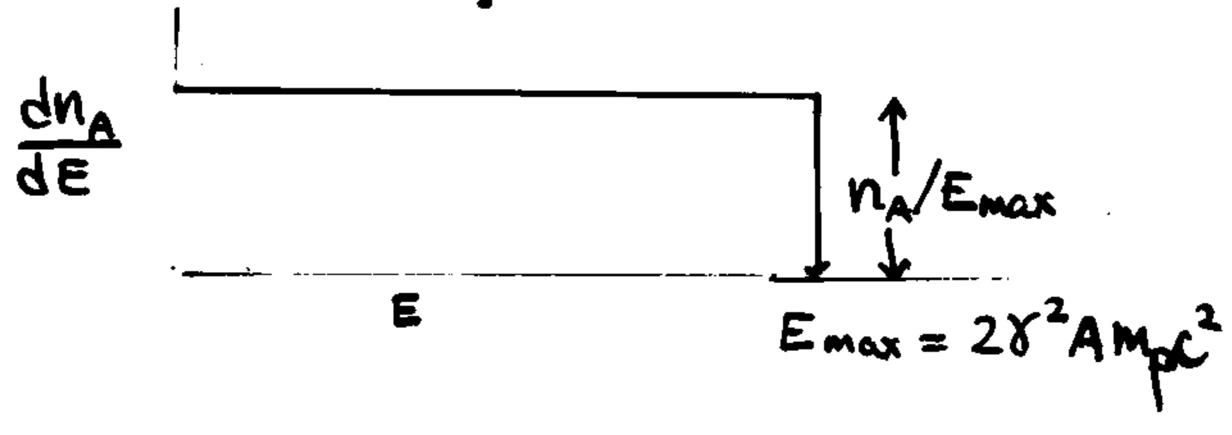
$$\Rightarrow \boxed{E_{max} = 2\gamma_0^2 A m_p c^2}$$

$$\gamma_0 \sim 10^3 \Rightarrow \boxed{E_{knee} \cong A \times 2 \times 10^{15}\ eV}$$

at fixed γ and for isotropic dist.:

$$\frac{1}{n_A}\frac{dn_A}{dE} = \frac{1}{n_A}\frac{dn_A}{d\cos\theta'}\frac{d\cos\theta'}{dE} = \frac{1}{E_{max}(\gamma)}$$

At fixed γ



(CB) Deceleration

Relativistic Energy/Momentum Conserv.

$$M\gamma = M_0\gamma_0$$

$$\Rightarrow \quad M d\gamma = - dM\,\gamma$$

$$dM = dn\, mc^2\gamma$$

$$\Rightarrow dn = \frac{M_0\gamma_0}{m}\frac{d\gamma}{\gamma^3}$$

$$E_{CR} = \gamma^2 m\,(1+\beta\cos\theta')$$

$$\frac{dN_{CR}}{dE} = \int\!\!\int \frac{dn}{4\pi}\,\delta(E-\gamma^2 m(1+\beta\cos\theta')\,d\gamma d$$

$$= \frac{\gamma_0 N_b}{2m_p}\left[\left(\frac{E}{m_p}\right)^{-2} - \left(\frac{E_{max}}{m_p}\right)^{-2}\right]\theta(E-E_{ma}$$

$$E_{max} \cong 2\gamma_0^2 m_p c^2$$

$dN/dE \sim E^{-2}$ <u>does not require!</u> <u>the</u> (quest

-able! assumptions underlying the collisionle relativistic shock acceleration mechan (Blandford Mckee Formalism · Ostroiker ...)

The Diffuse Gamma-Ray Background Radiation

$$\frac{dn_e}{dE} \sim E^{-3.2} \Rightarrow \frac{dn_\gamma}{dE} \sim E^{-\frac{3.2+1}{2}} = E^{-2.1}$$

Dar and De Rújula 2000

(GBR)

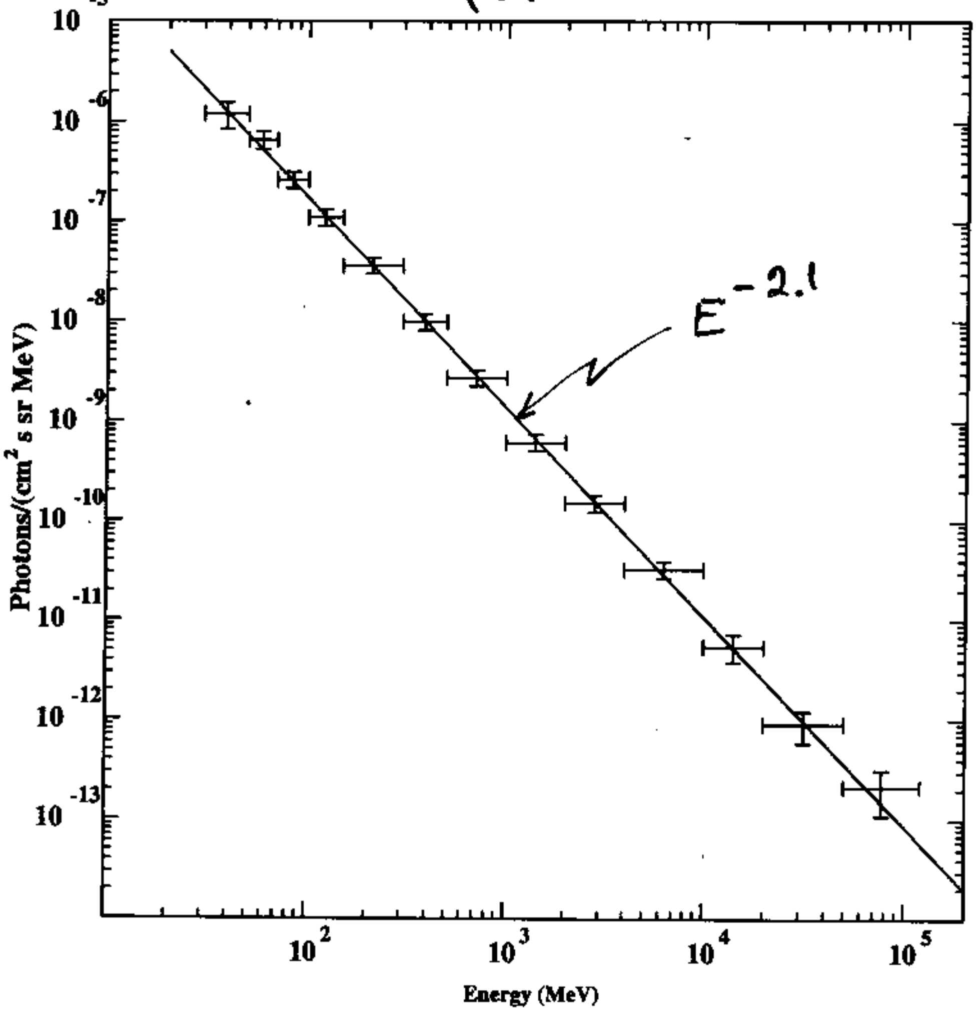


Figure 2: Comparison between the spectrum of the GBR, measured by EGRET [9], and the prediction for ICS of starlight and the CMB by CR electrons. The slope is the central prediction, the normalization is the one obtained for $R_e = 30$ kpc.

THE E-DEPENDENCE OF THE GALACTIC RESIDENCE-TIM MODIFIES THE SPECTRUM OF COSMIC RAYS :

$R_L = E/eZB$

$$\left(\frac{dn}{dE}\right)_{\text{Accel.}} \rightarrow \underset{\overset{\uparrow}{\sim E^{-2.2}}}{\left(\frac{dn}{dE}\right)_{\text{Accel}}} \cdot \underset{\overset{\uparrow}{Z^{0.5} E^{-0.50}}}{\tau_r(E/Z)}$$

Diffusion of CRs in Kolmogorov spectrum of MHD turbulen

$$\Rightarrow \boxed{\frac{dn_{CR}}{dE} \cong E^{-2.70}}$$

Supportive Evidence For $(dn/dE)_{accel} \sim E^{-2.2}$:
The escape-time of electrons from the Galaxy is much longer than their cooling time via inverse Compton scattering on the CMB photons $\tau \sim E^{-1}$

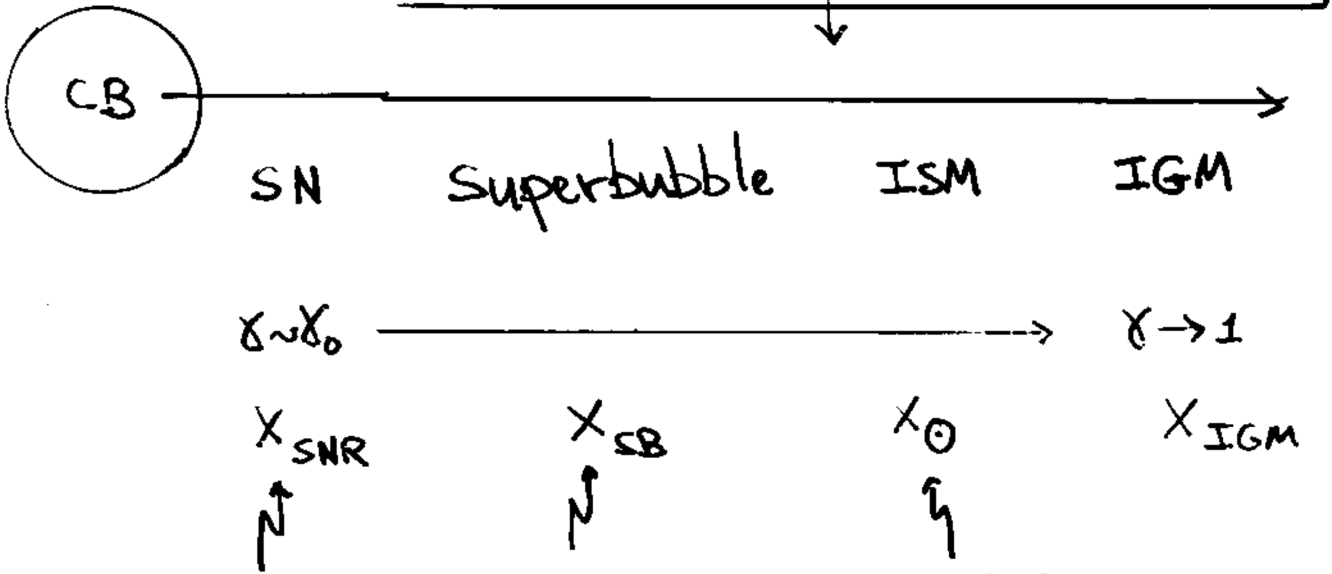
$$\Rightarrow \boxed{\frac{dn_e}{dE} \cong E^{-3.2}}$$

Acceleration of ISM Particles by Elastic Scat.

Spectrum: $$\frac{dN_A}{dE} \alpha \frac{X_A A^{1.2} Z^{0.5}}{\bar{m}} \left[\frac{E}{m_p}\right]^{-0.5} \left[\left[\frac{E}{m_p}\right]^{-2.2} - \left[\frac{E_{max}}{E_p}\right]^{-2.2}\right] \cdot \theta\left(m < E < E_{max}\right)$$

Knee: $$\boxed{E_{knee} \approx \bar{E}_{max} \approx 2 A m_p \gamma_0^2 \approx 3 A \text{ PeV}}$$

Composition: $$\boxed{X_A[CR] \cong X_A[E/A]\ A^{1.2} Z^{0.5}}$$



$$X_{SNR/SB}[\text{Metals}] \approx 4\, X_{\odot}[\text{Metals}]$$

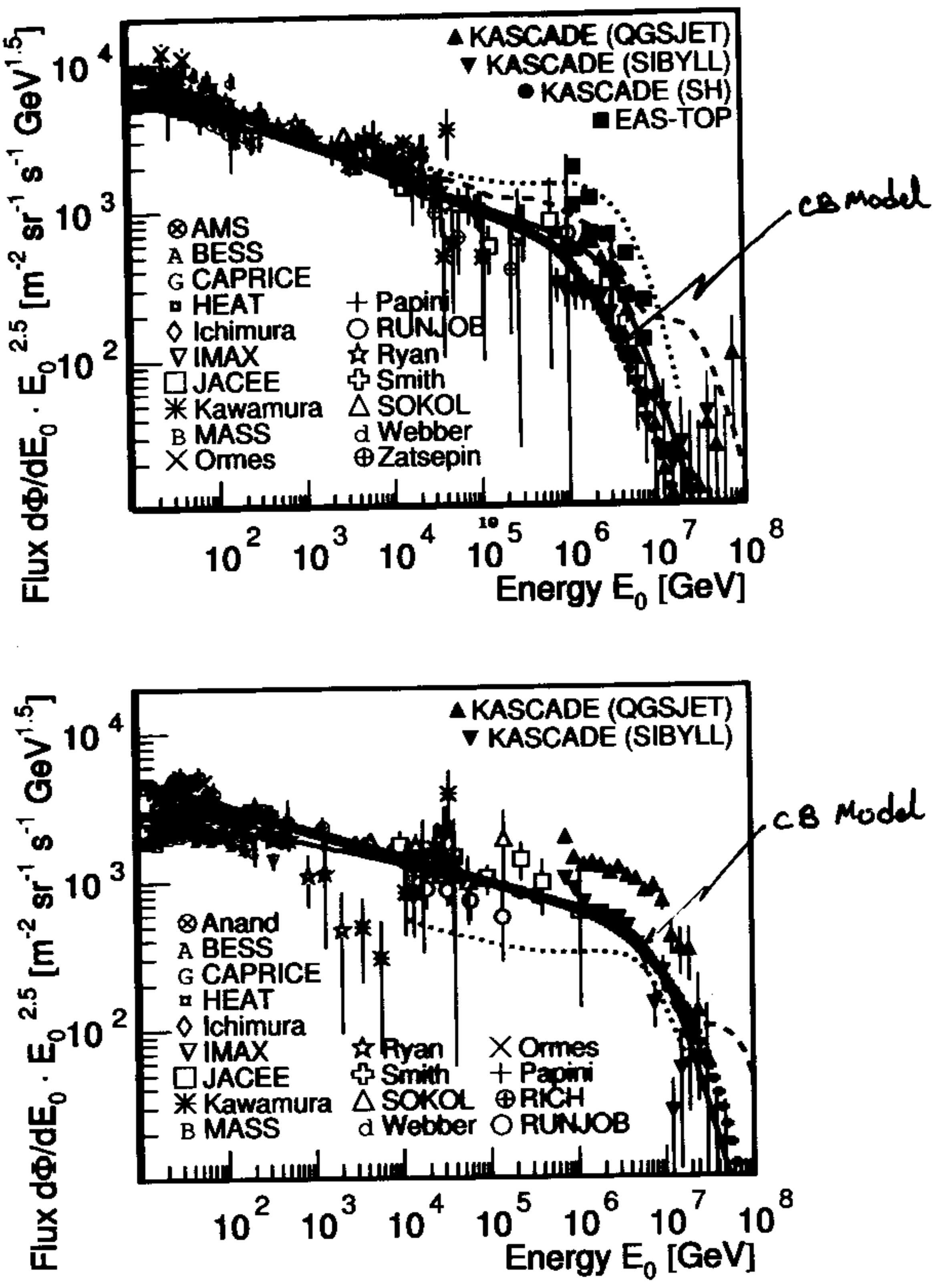
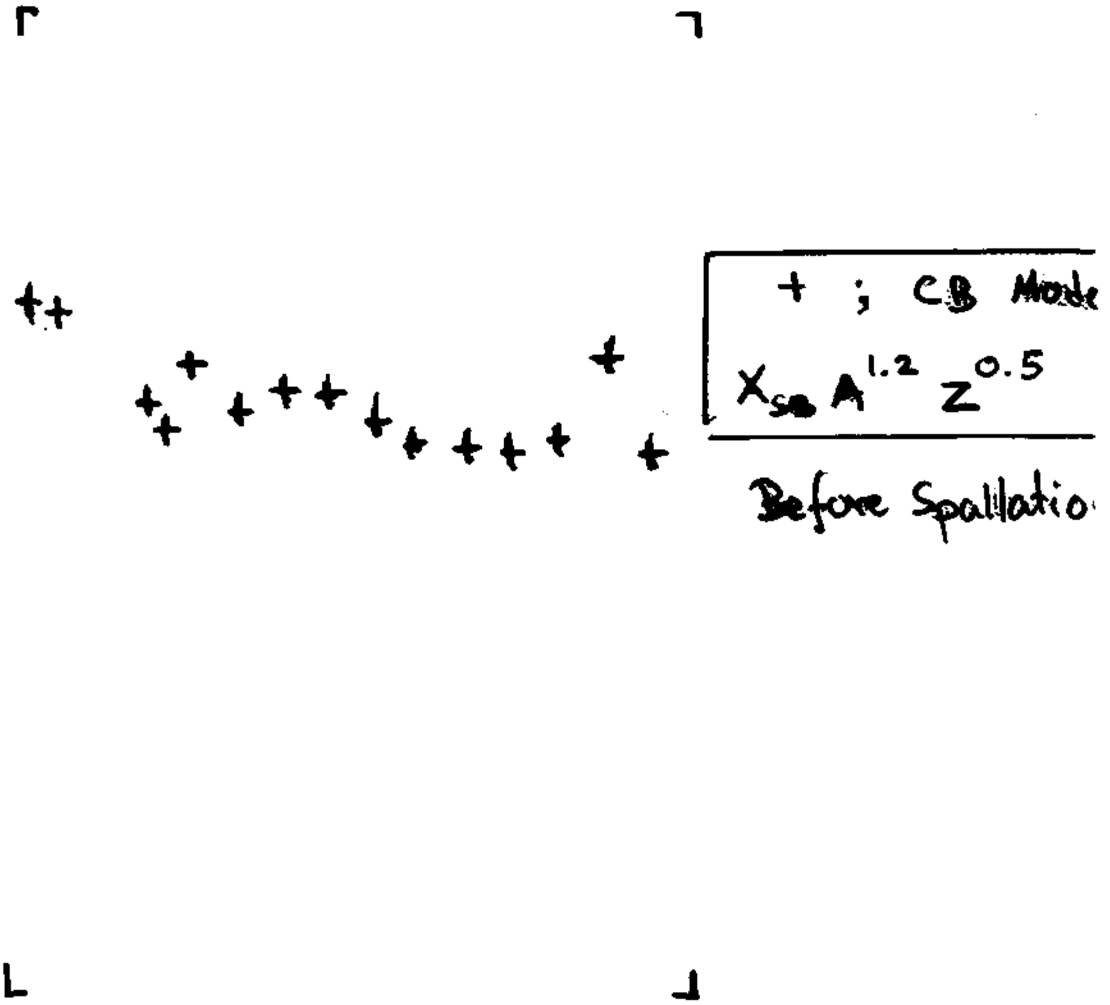
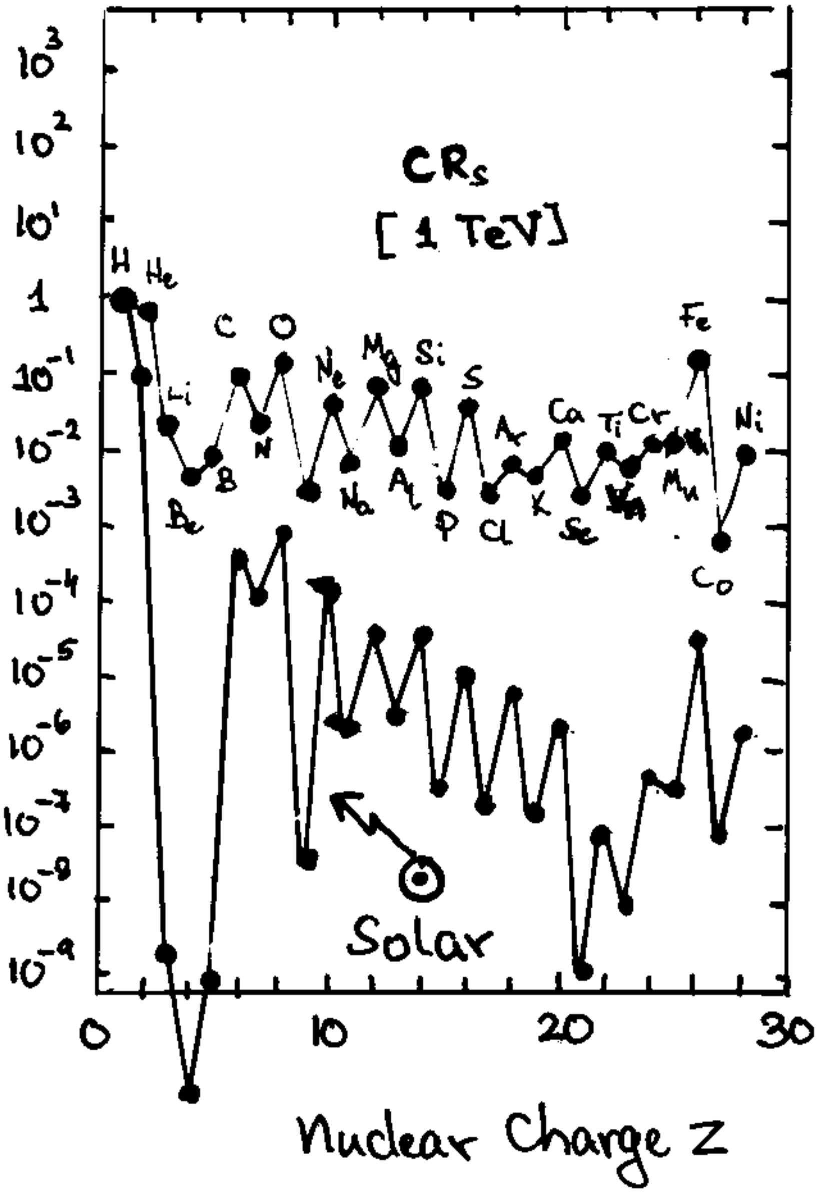


Fig. 3.— Comparison between the single-acceleration CB model predictions (thick line of crosses) for the energy spectrum of cosmic ray protons (top) and CNO nuclei (bottom) from various experiment and theoretical models as compiled by Hoerandel (2004).


+ ; CB Mode
X_SB A^1.2 Z^0.5
Before Spallatio

Relative Abundences

$$X_i \equiv \frac{N_i}{N_H} \quad \text{around } E \simeq \text{TeV}$$



Cosmic ray elemental abundances are entirely different from stellar (e.g. solar), ISM and IGM elemental abundances

$$\text{e.g.} \quad \left[\frac{Fe}{H}\right]_{CRs} \cong 3500 \left[\frac{Fe}{H}\right]_{\odot} \quad !!!$$

CB Model predicts:

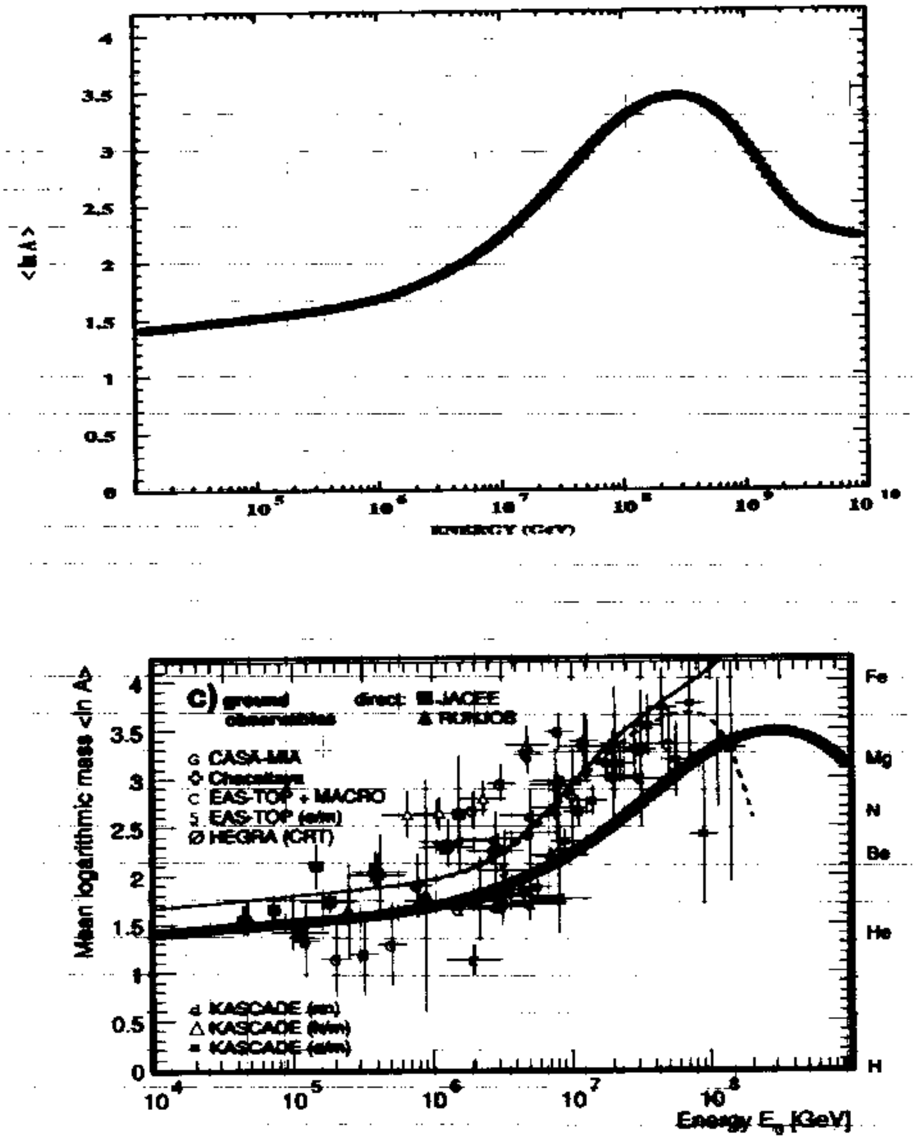


Fig. 4.— Comparison between the preliminary CB model prediction for the mean logarithmic atomic mass, $< lnA >$ as function of CR energy before the inclusion of photo-disintegration of extragalactic CRs nuclei by collision with the cosmic FIR and microwave background radiation, and $< lnA >$ as compiled by Hoerandel (2004) from experiments measuring electrons, muons and hadrons at ground level.

Acceleration Above The CR Knee

1. Fermi Acceleration Inside the CBs:

Dar and Plaga 1999
Dado, Dar and De Rujula 2002
De Rūjula 2004:

$$\frac{dn}{dE'} \propto E'^{-2.2}\,\theta\left(E' - \gamma m_{CR}\right)$$

2. Elastic Scattering of CRs by CBs:

Dar 2004:

$$\frac{dn}{dE_L} \propto E_L^{-2.7}\,\theta\left(E_L - 2\gamma^2 m_{CR}\right)$$

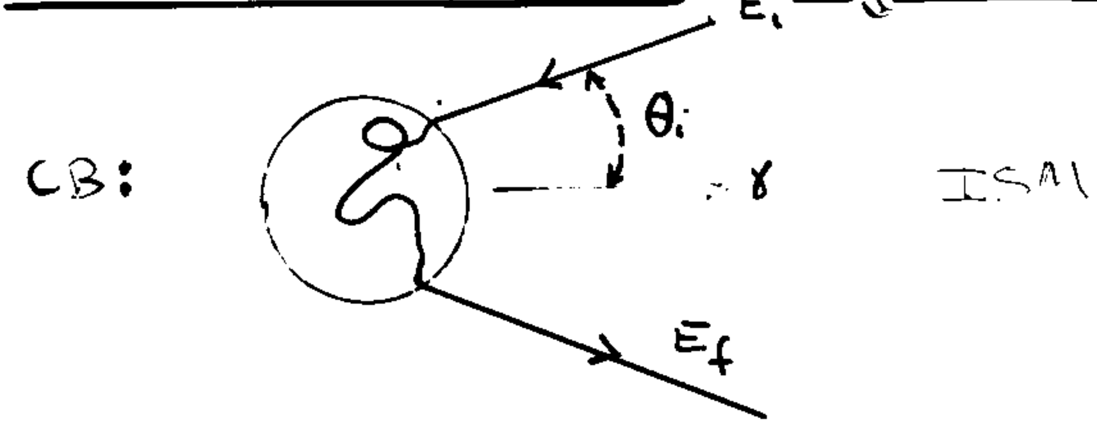
+ Residence time enhancement

$$\frac{dn}{dE_L} \sim E_L^{-3.2}\,\theta\left(E_L - 2\gamma^2 m_{CR}\right)$$

$$R_{CB} > R_L$$

$$\Rightarrow \quad E_{max} = 2\times 10^{20}\left[\frac{n}{10^{-3}\,cm^{-3}}\right]^{1/2}\left(\frac{x_0}{10^3}\right)^{-} Z\ eV$$

Reacceleration of CRs



$$E' = \gamma E (1+\beta_i \cos\theta_i)$$

$$\Rightarrow \quad E_f = \gamma^2 E_i (1+\beta_i \cos\theta_i)(1+\beta\cos\theta')$$

$$\max E_i \sim 2\gamma_c^2 m_{CR}$$

$$\Rightarrow \max \gamma_f \cong 8\gamma_0^4 \sim 10^{13} \quad (CRBs)$$

but! $R_L < R_{CB}$

$$R_L \cong E/eBz$$

CB: $B \cong \sqrt{2\pi mc^2}\,\gamma$

$$\Rightarrow \boxed{\max E_L = 2\times10^{20}\left[\frac{n}{10^{-3}\,cm^{-3}}\right]^{1/2}\left(\frac{\gamma_0}{10^3}\right)^2 Z\ eV}$$

The CR Ankle

Free escape of CRs from the Galaxy when the Larmor radius becomes larger than the coherence length of the Galactic magnetic field.

$$R_L \cong E/ezB$$

$R_{coherence} \simeq$ Galactic Scale Height

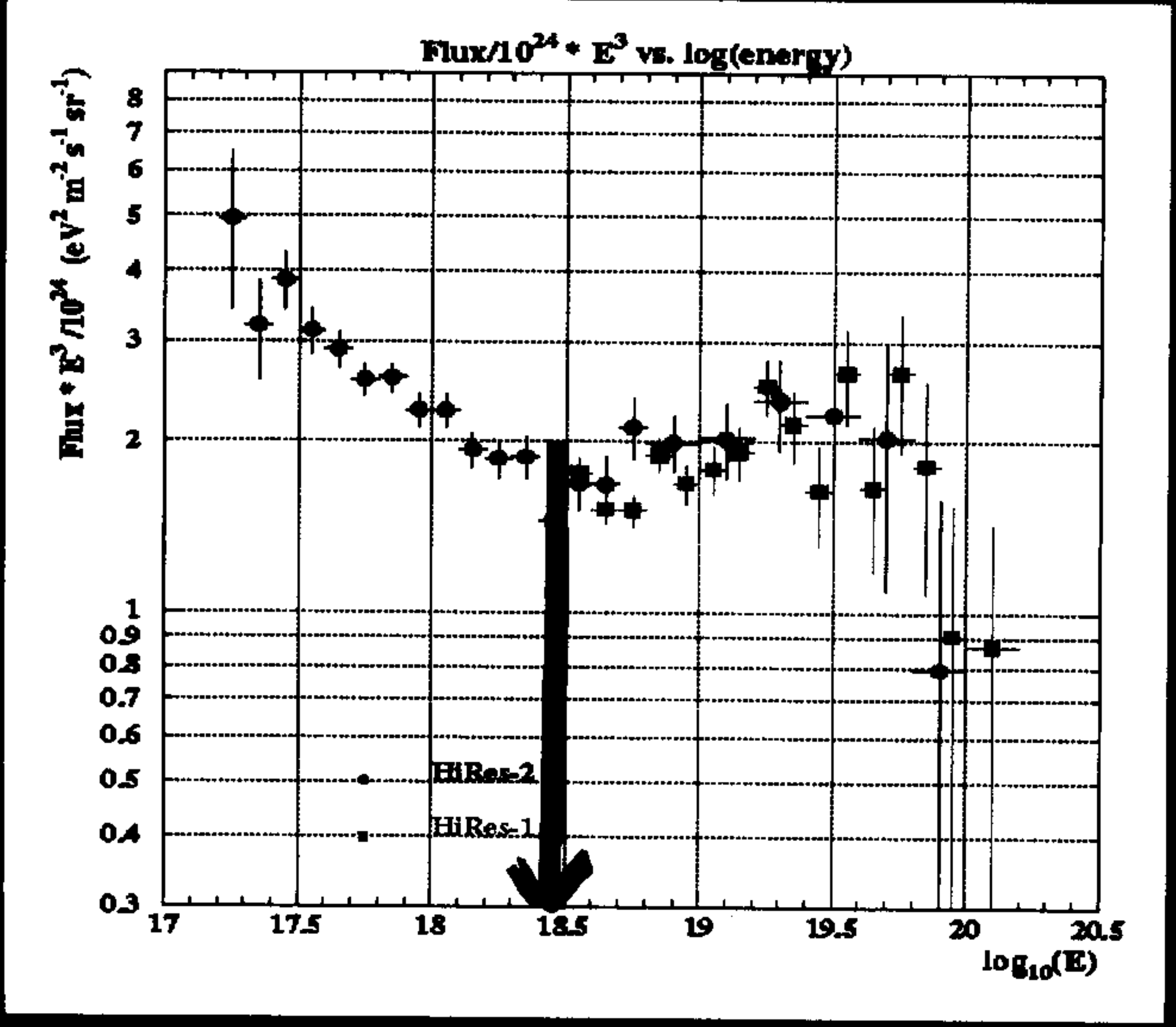
$$\Rightarrow E_{ankle} \sim ezBR_c$$

$$R_c \cong 40\,pc \;;\; B \sim 3\,\mu G$$

$$Fe:\ Z=26$$

$$\Rightarrow \underline{E_{ankle} \approx 3\times10^{18}\,eV}$$

The HiRes Mono Spectra



- HiRes-1

  [illegible] - '04

- HiRes-2

  '99 - '01

THE ANKLE

COSMIC RAY SPECTRA

①. Below the Knee

$$\frac{dn_A}{dE} \sim E^{-\overset{2.7}{(p+\delta)}} \; ; \quad \frac{dn_e}{dE} \sim E^{-\overset{2.2}{(p+1)}} \; ; \quad \frac{dn_\gamma}{dE} \sim E^{-\overset{2.1}{\frac{p+2}{2}}}$$

②. Above the knee

$$\frac{dn}{dE} \sim E^{-(p+2\delta)} \sim E^{-3.2}$$

③. Above the Ankle

$$\frac{dn_A}{dE} \sim E^{-(p+\delta)} \sim E^{-2.7}$$

Since $p \simeq 2.2$ $\delta \simeq 0.5$ →

$$\Rightarrow \begin{cases} \bullet \quad p+\delta = \underline{2.7} \qquad p+1 = \underline{3.2} \qquad \frac{p+2}{2} = \underline{2.1} \\ \bullet \quad p+2\delta = \underline{3.2} \\ \bullet \quad p+\delta = \underline{27} \end{cases}$$

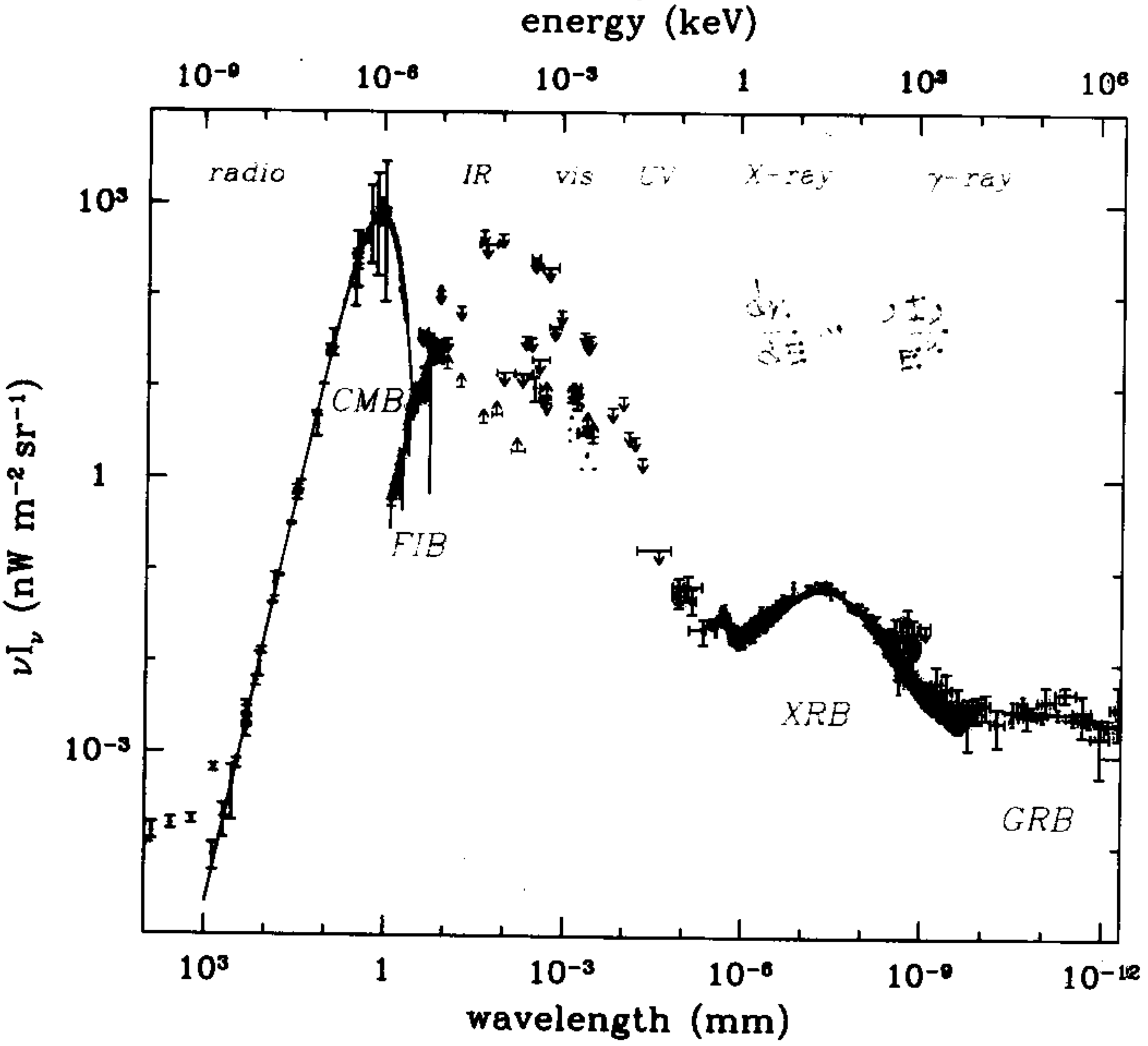
Photo disintegration in CR collisions with background radiation photons

$$A+\gamma \rightarrow A-1 + \begin{Bmatrix} n \\ p \end{Bmatrix}$$

GDR: $\sigma_p \simeq \begin{cases} 4\text{ mb} & {}^4He \\ 20\text{-}60\text{ mb} & \text{"Metals"} \end{cases}$ $E_p \sim 20$ MeV

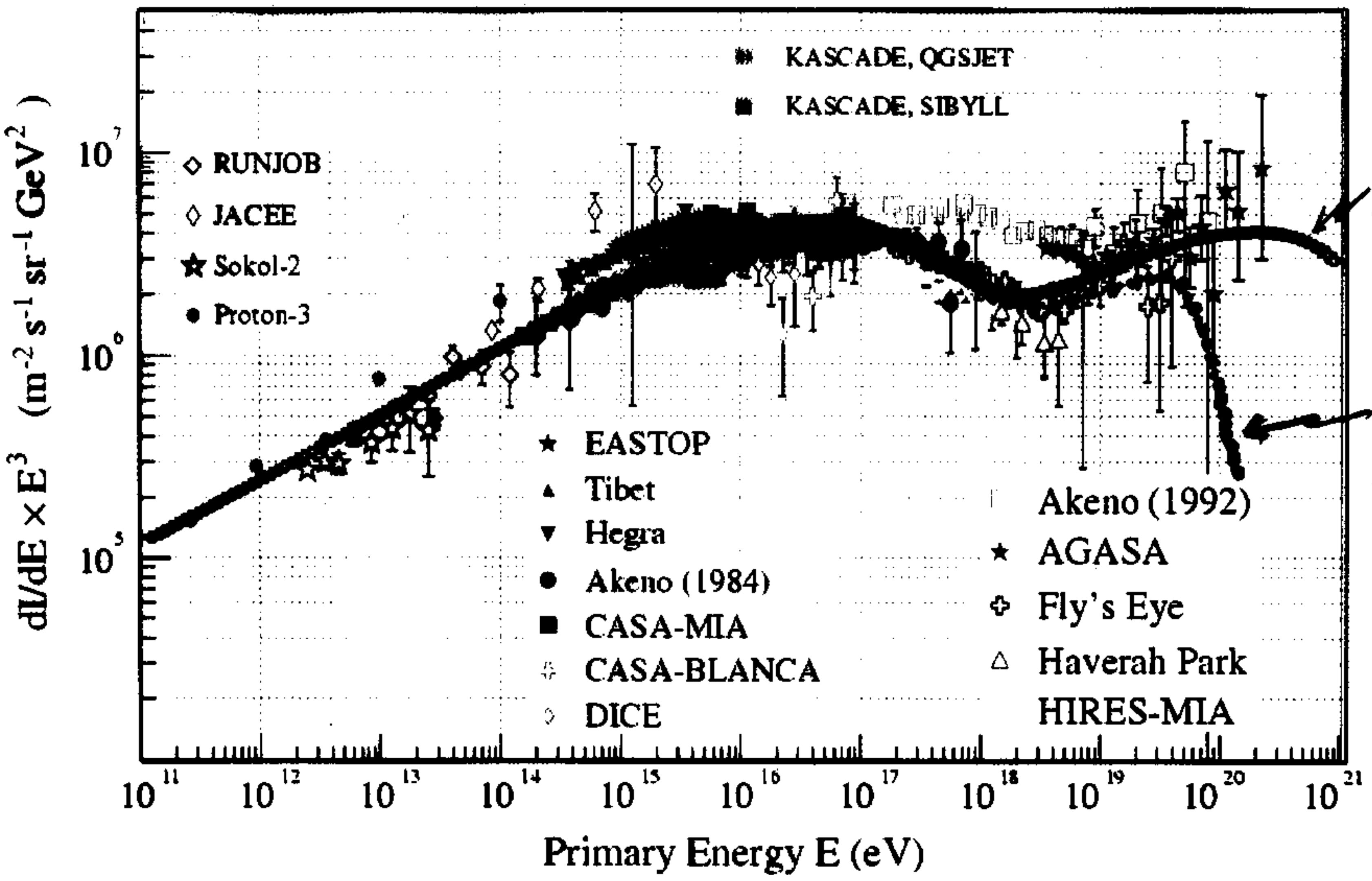
If $\langle \tau_{CR} \rangle \sim \tau_u/2 \sim 7\,GY \Rightarrow \lambda = \frac{1}{n\sigma} \ll \frac{\tau_u \cdot c}{2} \sim 10^{28}$ cm

If $\lambda_\gamma > 1\,\mu m$!



Only CRs from nearby sources (Cygnus A, M87 ? can survive photo-disintegration ⇒ The Bulk of the CRs <u>above</u> the ankle are protons and ⁴He!

$E^3 \frac{dN}{dE}$ Compiled by Ulrich, 2004



CB MODEL without photodisintegr.

CB MODEL WITH PHOTO-DISINTEGRATIC (FIR, CBM, RO

$L_{CR}(MW)$

(The Galactic luminosity in cosmic ray

Conjecture: The imbalance between the momentum of the two bipolar jets is the origin of the kick velocity of n^* $(\sim 400\ km \cdot s^{-1})$

$$\Rightarrow \quad E_{jets} \gtrsim M_{n*} V \cdot c \sim 2 \times 10^{51}\ erg$$

$$L_{CR}(MW) \approx R_{SN} \cdot 2 \times 10^{51}\ erg$$

$$\Rightarrow \quad \underline{L_{CR} \gtrsim 1 \times 10^{42}\ erg \cdot s^{-1}}$$

Dar and Plaga 1999
Dar and De Rújula 2000

IGM MAGNETIC FIELD

Deposition of CRs by CBs and Superbubble Winds Generates an Equipartion IGM Magnetic Field:

$$\frac{B^2}{8\pi} \cong (\dot{n}_{SN} t_H/3)\, E_{SN}(CRs)/\langle 1+z \rangle$$

$$\dot{n}_{SN} \simeq 10^{-4}\, SN/(Mpc)^3 \cdot y$$

$$t_H \simeq 14 \times 10^9\ y \quad (h=0.65;\ \Omega=1, \Omega_\Lambda \approx 0.7$$

$$\begin{cases} \rho_L \simeq \frac{1.84h \times 10^8 L_\odot}{Mpc^3} \\ L_{MW} \simeq 2.4 \times 10^{10} L_\odot \\ R_{SN}[MW] \simeq (50\ y)^{-1} \end{cases}$$

$$\Rightarrow \quad B_{IGM} \cong \frac{28}{\sqrt{1+z}} \left[\frac{E_{SN}[CR]}{1.79 \times 10^{51} erg}\right] \text{ n Gauss}$$

$$\Rightarrow \quad B_{IGM} \sim 10-20 \text{ n Gauss}$$

⇒ CONCLUSIONS

The bulk of the high energy cosmic Rays are produced by highly-relativistic bipolar jets ejected in supernova explosions.

Supernova Remnants, although accelerating electrons and nuclei to cosmic ray energies, are not the major source of Galactic cosmic rays.

The ultra high energy (E>10^{18}ev cosmic rays are of the same origin (galactic SN explosions) as the lower energy CR$_s$. Long residence time in an extragalactic magnetic field can produce a "GZK" cutoff"

The Cannoball Model of GRB$_s$ and CR$_s$ Explains both Incredibly Well !