III : Production or Acceleration

How to achieve $E >$10^{20}eV??

2 mechanisms :

- Acceleration (Bottom-Up)
  - Supernova remnants (SNR)
  - Radio Galaxies (powerful ones!)
  - Neutron start EM fields.
- Decay (Top-Down)

  Super massive particles are the source of CR (no acceleration)
  - Topological defects (strings, Monopoles, super-conducting strings, vortons...)
  - Meta stable massive relic particles (MSRP), (inflation residuals)

- Acceleration : "Classical"

  Escaping the acceleration site is though, sources are far away ($> 100 Mpc$ ==> GZK, $< 100 Mpc$ invisible ?)

- Decay : "Exotic"

  Flux, ?? X $M_X \gg$ 10^{20}eV, cosmological distribution or DM like?

Top-Down Mechanisms

- Acceleration OK
- Power OK
- Invisibility OK

X (to be defined) : ——> quarks & leptons ——> jet (π, p, n) ——> γ, ν, l

Results :

Some very energetics $\nu, \gamma, e^+, e^-, \mu$ (dominant), a few protons and neutrons.

Conditions for observation :

- Recent decay ($< 100 Mpc$)
- $M_x \gg 10^{20}$eV (rem : GUT $\approx 10^{25}$eV)
- ρ_X / τ_X compatible with the observed UHECR flux.

Two classes of objects for X : (we will study them later)

1) Topological defects producing gauge bosons/Higgs/super-massive fermions. Residuals of the GUT symmetry breaking phase transition ($t \approx 10^{-35}$sec, order ?)
2) Relic from the inflation phase (potentially part or all of DM).

Before looking at X we investigate its decay

Decay and hadronisation

X ———> quarks and leptons ($\equiv$ squark and sleptons for $M_X \approx GUT$)

Unknown internal decay dynamics (spectra and quarks number) but hadronisation can be inferred.

3 steps :

$$\boxed{\text{Hard} \longrightarrow \text{Soft} \longrightarrow \text{Dk}}$$

Hard : perturbative QCD –> parton cascade.

Soft : $\Lambda_c \approx$ 1GeV ; quarks and gluons are glued in color singlets.

Dk : the primary "hadrons" (soft phase) decay in known hadrons.

LUND string fragmentation model : phases 2 and 3

LPHD (Local Parton Hadron Duality) : directly links 1 to 3.

$$\boxed{\text{–> hadrons spectra : } x\frac{dN_h}{dx} = f(E, x) \text{ where } x \equiv \frac{E}{e_q} \quad \in [0, 1]}$$

[Fig 2.1]

Remarks I

- up to 40% of the energy can be dissipated via LSP (if SUSY)
- if $E_h/M_x \ll 1$ then $\frac{dN_h}{dx} \propto E^{-\alpha}$ with $1 < \alpha < 2$ (Hard!)

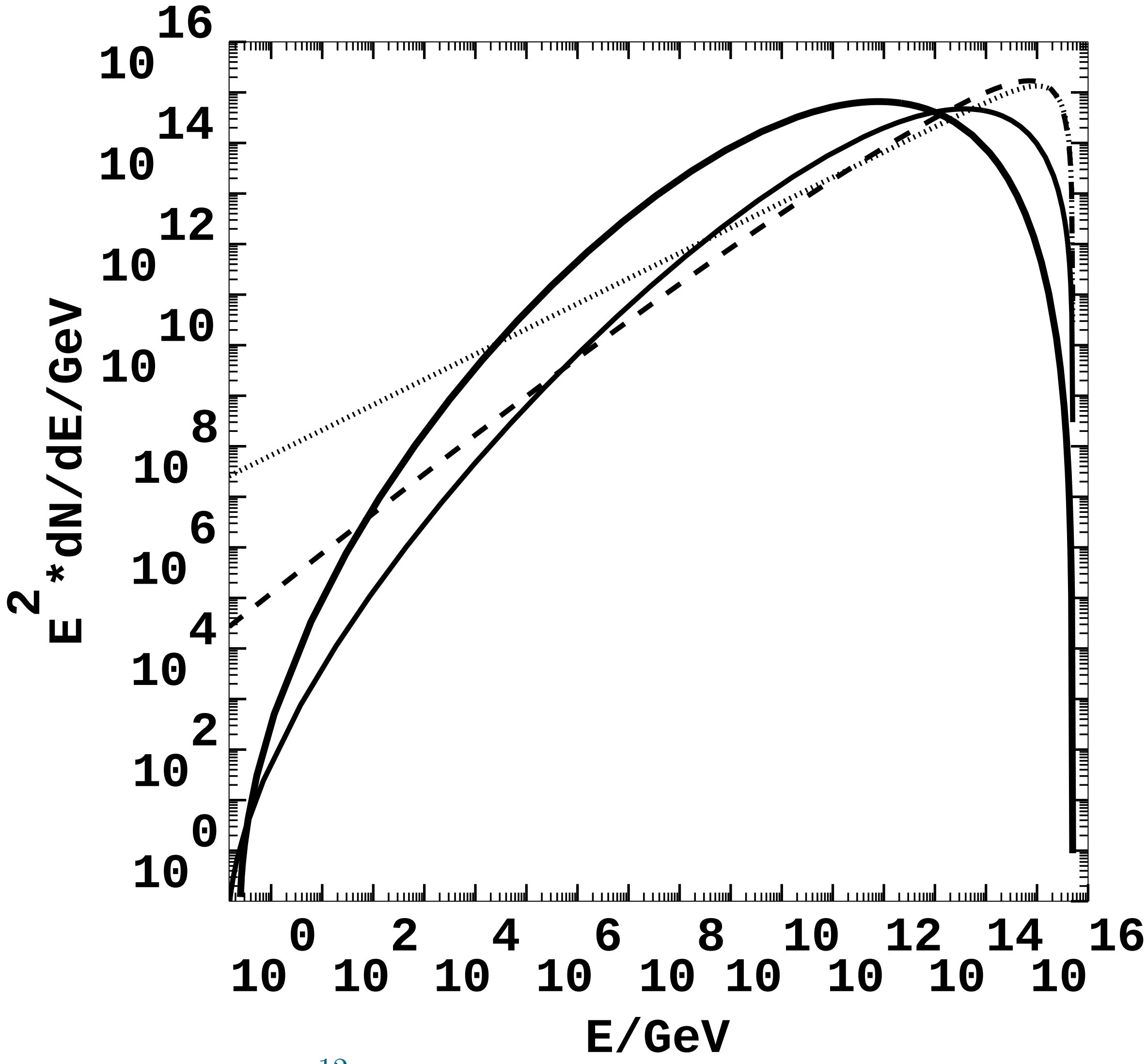
DSAM $\alpha > 2 \Longrightarrow$ in top-down scenarios the RC spectrum flattens10^{19}eV

Remarks II

- $N \propto E^{1-\alpha}$ and $E_{tot} \propto E^{2-\alpha}$
- $\alpha < 2$ "hard" spectra
- $\alpha > 2$ "soft" spectra

Hadrons spectra

fragmentation function $E_{jet} = 5 \times 10^{15}$GeV (MLLA).



- bold : SUSY at 10^{12} GeV
- thin : no SUSY
- dash : Hill's approximation
  $$\frac{dn_h}{dx} = \frac{3}{2} \times 0.08 \times exp\left[2.6\sqrt{ln(1/x)}\right] (1-x)^2 \left(x\sqrt{ln(1/x)}\right)^{-1}$$
- dot : $\frac{dN_h}{dx} \simeq \frac{15}{16} x^{-3/2}(1-x)^2$

[Fig 2.1]

Particles fluxes

Hadron fluxes:

$$\Phi_h(E,t) = \dot{n}_X(t) N_q \frac{dN_h}{dE}$$

$X \longrightarrow \tilde{N} = N_q + N_l$, $x = E/E_q$ and $E_q = M_X/\tilde{N}$ thus $dE = \frac{M_X}{\tilde{N}} dx$

Nucleon fluxes:

$$\Phi_N(E,t) = \dot{n}_X(t) N_q f_N \frac{\tilde{N}}{M_X} \frac{dN_h}{dx}$$

f_N nucleon fraction in a quark cascade.

Secondaries:

Gammas from π^0 :

$$\Phi_{\gamma(\pi^0)}(E,t) \simeq 2 \int_E^{\frac{M_X}{\tilde{N}}} \Phi_{\pi^0}(\epsilon,t) \frac{d\epsilon}{\epsilon}$$

Neutrinos from $\pi^{\pm}$:

$$\Phi_{\nu+\bar{\nu}(\pi^{\pm})}(E,t) \simeq 2.34 \int_{2.34E}^{\frac{M_X}{\tilde{N}}} \Phi_{\pi^+ + \pi^-}(\epsilon,t) \frac{d\epsilon}{\epsilon}$$

with $\Phi_{\pi^+ + \pi^-} \simeq 2\Phi_{\pi^0}$

Those spectrum must be transported to obtain the fluxes on Earth.

Recall that gamma propagation depends upon URB and EGMF.

Remark : $\Phi_{\pi^+\pi^-\pi^0}/\Phi_N \simeq (1-f_N)/f_N$ i.e. 10 times more π^0 or 20 time more $\pi^+\pi^-$ than nucleons for $f_N = 0.03$

$\boxed{\gamma \text{ and } \nu \text{ are dominant at the source}}$

They are " primaries" like nucleons.

What decay rate for X?

$\dot{n}_X(t)$ very model dependent (here TD production or MSRP decays).
$\Longrightarrow$ no clear prediction for the UHECR fluxes.

Back of the envelope
hypothesis : UHECR are gammas from top-down processes.

$$E_\gamma^{tot} \simeq \frac{1}{3}(\pi^0) \times \frac{1}{2}(q/l) \times M_X \times f_\pi$$

if

$$\frac{dN_\gamma}{dE} \propto E^{-\alpha} \qquad 1 < \alpha < 2$$

then

$$\frac{dN_\gamma}{dE} = \frac{0.15}{M_X}(2-\alpha)\left(\frac{f_\pi}{0.9}\right)\left(\frac{E}{M_X}\right)^{-\alpha}$$

neglecting cosmological evolution ($l_\gamma(E_\gamma) \ll 100Mpc \quad @ \quad 10^{20}eV$):

$$j_\gamma(E) \simeq \frac{1}{4\pi} l_E(E)\Phi_\gamma(E) \quad ; \quad \Phi_\gamma(E) = \frac{dN_\gamma}{dE} \times \dot{n}_X(t_0)$$

Thus, from the observed RC spectra at 10^{20}eV [Sigl]

$$\dot{n}_X \geq 10^{-46}\left(\frac{10Mpc}{l_E(E_\gamma)}\right)\left(\frac{E^2 j_\gamma(E)}{1eV\,cm^{-2}s^{-1}sr^{-1}}\right)\left(\frac{2E_\gamma}{10^{16}GeV}\right)^{\alpha-1.5}$$
$$\times\left(\frac{0.5}{2-\alpha}\right)\left(\frac{0.9}{f_\pi}\right)\left(\frac{M_X}{10^{16}GeV}\right)^{1-\alpha} cm^{-3}s^{-1}$$

for $\alpha = 1.5$, $M_X = 10^{16}GeV$ and $E^2 J(E) = 1eV\,cm^{-2}s^{-1}$
one obtains : $10^{-46\pm1}cm^{-3}s^{-1} \sim 10^{35\pm1}Mpc^{-3}yr^{-1}$
(X DK, fragmentation, URB and EGMF, EM cascade $L_E(E)$)

Sources and nature of X??

- Cosmic strings [m = 3; D = H_0]
- Cosmic supra conducting strings [m > 3; a lot of parameters]
- Monopoles network, necklace [m =3]
- Vortons [m=2; $r \approx 10^{-28}$cm, similar to relics]
- Monopolonium (bound state monopole-anti monopole) [m=3]
- Light Monopoles
- Inflation meta-stable relics (MSRP) [CDM]

In some scenarios Monopoles, monopolonium and vortons can directly be the UHECR (& CDM).

Topological defects

Production rate (and decay) of X :

General parameterization :

$$\dot{n}_X(t) = \dot{n}_X(t_0)\left(\frac{t}{t_0}\right)^{-m}$$

Giving for today's EM energy density (W_{em}) :

$$W_{em} \simeq \frac{1}{2} f_\pi M_X \int_{t_{min}}^{t_0} \dot{n}_X(t)\frac{dt}{(1+z)^4}$$

let $\alpha = \frac{11}{3} - m$

$$m < 11/3 \quad (\alpha > 0) \longrightarrow \qquad W_{em} \simeq \frac{1}{2\alpha} f_\pi M_X \dot{n}_X(t_0) t_0$$

$$m > 11/3 \quad (\alpha < 0) \longrightarrow \quad W_{em} \simeq -\frac{1}{2\alpha} f_\pi M_X \dot{n}_X(t_0) t_0 \left(\frac{t_{min}}{t_0}\right)^{\alpha}$$

Measurements on diffuse background by EGRET give :

$$w_{em} \sim 10^{-6} eV cm^{-3} s{-1}$$

Thus with $t_0 = 2 \times 10^{17}(\Omega_0 h^2)^{-1/2} s$:

$$\dot{n}_X(t_0) < \alpha \times \frac{10^{-48} \quad cm^{-3}s^{-1}}{M_X/10^{16}GeV}; \qquad \alpha > 0$$

and with $t_{min} = t_{dec} \sim 10^{-5} t_0$

$$\dot{n}_X(t_0) < |\alpha| \times \frac{10^{-48+5|\alpha|} \quad cm^{-3}s^{-1}}{M_X/10^{16}GeV}; \quad \alpha < 0$$

- if $\alpha > 0$, the constraint given by the diffuse background is hardly compatible with the observed UHECR flux.
- if $\alpha < 0$, the EM radiation at early time becomes incompatible with the CMB uniformity and the ^4H_e abundance.

Defect Distribution and fluxes on Earth

3 distance scales:

- D : distance between TD.
- $L_\gamma(E)$: gamma absorption length.
- $R_p(E)$: proton attenuation length [$\frac{1}{E}\frac{dE}{dt}$]

Normally $L_\gamma(E) < R_p(E)$ except above 10^{21}eV

[Fig 3.2]

1) $D > R_p(E)$

$\Rightarrow$ The flux is exponentially suppressed : $e^{-(\gamma-1)D/2R_p}$

Flux too low or very anisotropic if a source is by chance close enough.

2) $D < l_\gamma(E)$

Strong flux in the source direction. Gammas dominate EAS in the source direction.

3) $l_\gamma(E) < D < R_p(E)$

Protons dominate and the GZK cut-off is visible. Generally no close by source and thus no visible anisotropy below 10^{20}eV but eventually above (depends on $l_\gamma(E)$ and $R_p(E)$).

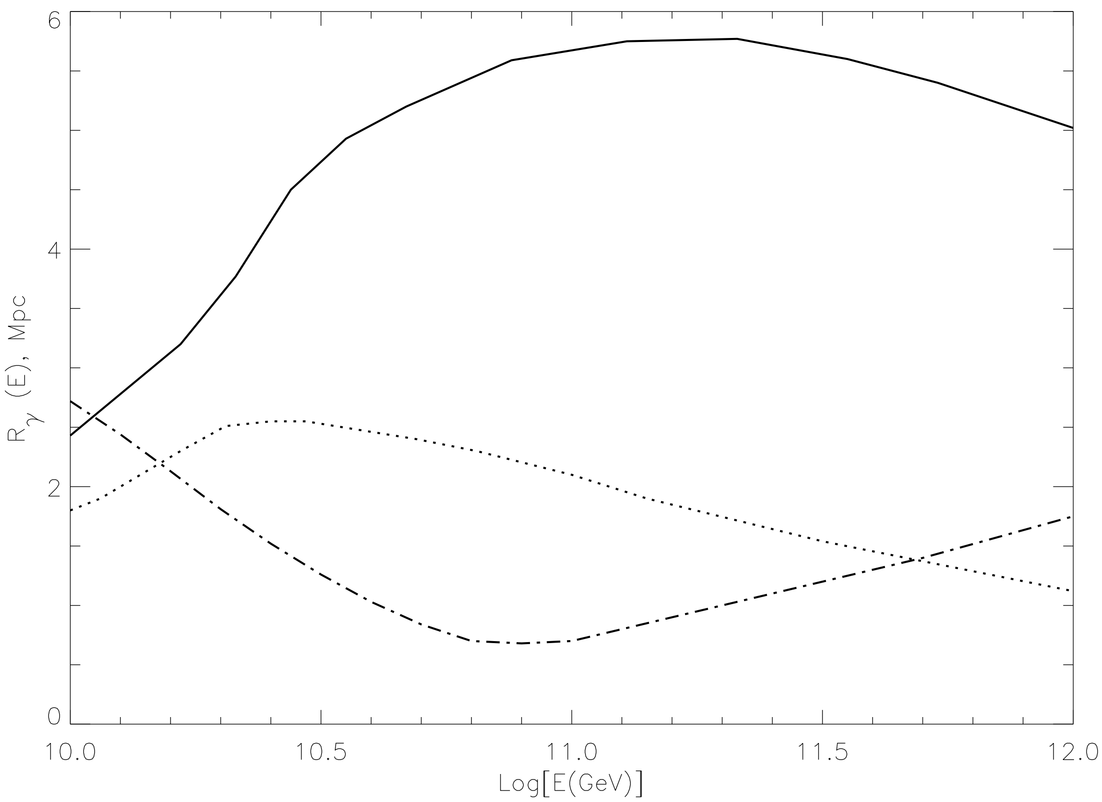
4) $D \ll l_\gamma(E)$

Protons dominate up to 10^{20}eV ($R_p(E) l_\gamma \sim 10$), the GZK cutoff is visible. ($\gamma/p \propto l_\gamma(E)/ < R_p(E)$).

[Fig 3.3]

astro-ph/9803271 v3 24 Aug 1998

Photon attenuation length

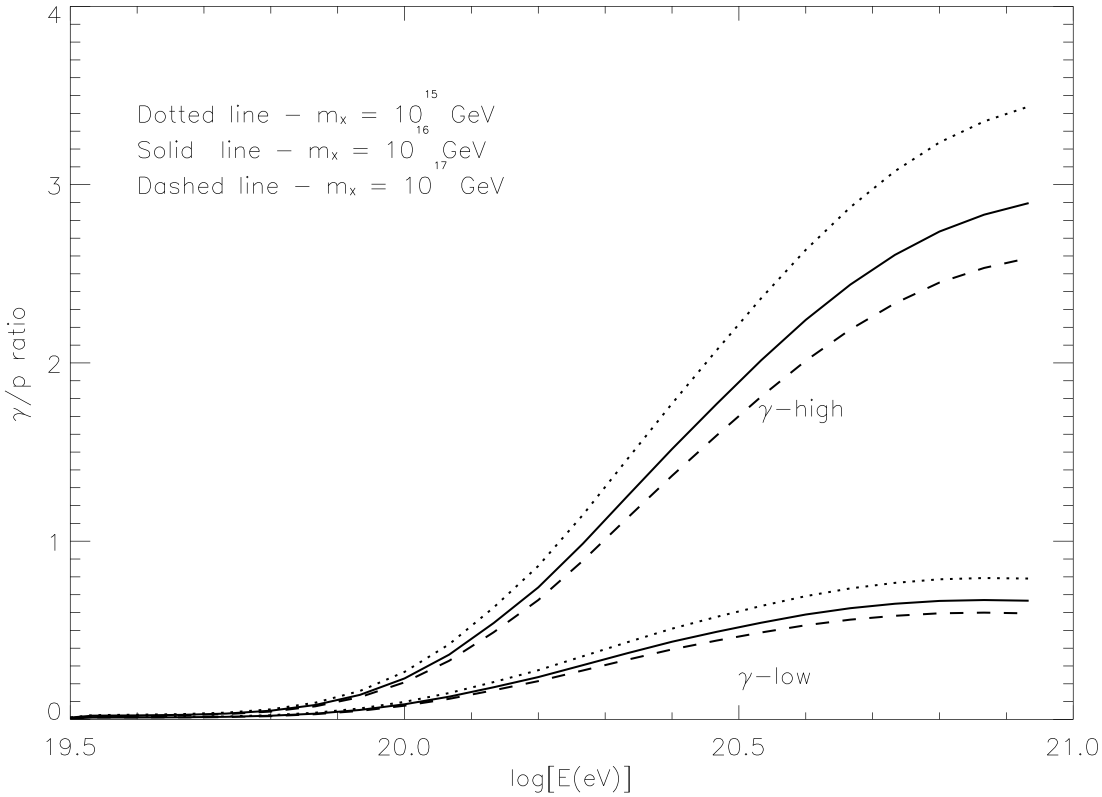


Photon attenuation length as a function of energy. Solid and dotted line give the upper and lower limit of a model by R. Protheroe, dashed line from Berezinsky.

[Fig 3.2]

Photons/protons ratio

V.Berezinsky, P.Blasi, A.Vilenkin, Phys.Rev.**D58** (1998)



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γ/p ratio for different values of M_X as a function of E_γ in the case where $D \ll l_\gamma(E)$. The upper and lower fluxes correspond to Protheroe's absorption models.

[Fig 3.3]

Inflation relics

MSRP = Meta-stable Super-heavy Relic Particles.

Relic masses of the order of $M_X \geq 10^{12}$GeV , lifetime $\tau \sim H_0^{-1}$. (symmetry only very weakly broken).

Neglecting cosmological effects :

$$\dot{n}_x = n_X/\tau$$

where

$$n_x = \frac{\rho_c(\Omega_X h^2)}{M_X} = 10^{-17}(\Omega_X h^2)\left(\frac{M_X}{10^{12}GeV}\right)^{-1}$$

Normalization (to the observed flux at 10^{20}eV) :
$\dot{n}_x(t_0) = 10^{-45}cm^{-3}s^{-1}(l_\gamma/100Mpc)^{-1}(M_X/10^{12}Gev)^{-1/2}$
then

$$\tau \sim 10^{21}(\Omega_X h^2)\frac{l_E}{100Mpc}\left[\frac{10^{12}GeV}{M_X}\right]^{1/2} yr.$$

and $\frac{t_0(\Omega_X h^2)}{\tau} \sim 10^{-11}$ (fine tuning).

Relics may clusterize ($\Longleftrightarrow$ CDM). Ratio of galactic and extra-galactic densities:

$$f \sim 15\xi\left(\frac{0.2}{\Omega_{CDM}h^2}\right)\left(\frac{R_H}{100kpc}\right)\left(\frac{100Mpc}{l_E}\right)$$

where ξ depends upon the relative distribution of X and CDM ($\xi \sim 1$ -10).

In the Galaxy $f \geq 15$ for $l_E \sim 100Mpc$. Then :

- At 10^{20}eV and above photons dominate the flux and come from the halo.

- For $l_E \gg$ 100Mpc (ν or protons $\ll 5\times$10^{19}eV) galactic (Halo) and extra-galactic fluxes are comparable.
- EGRET constraint do not apply ($R_H \ll l_E$)
- Visible anisotropy between 10% to 40% depending on ξ

Particular relics : Monopoles :

GUT relics : $M \sim 10^{10}$ to $10^{16} GeV$.

Good candidates to be directly the UHECR :

1) Parker limit is about the observed flux at 10^{20}eV.

2) Easy to accelerate at 10^{20}eV and above.

$$\Delta E = \frac{e}{2\alpha} \times B \times L \sim \left(\frac{B}{10^{-6}G}\right)\left(\frac{L}{kpc}\right) 10^{20} eV$$

Remarks: To make EAS M_X must be below 10^{20}eV

Details of the interaction with air nuclei still unknown.

Can Monopoles produce “normal” (as seen by Fly’s eye) showers?

(EM component q=137/2 calculable, hadronic component?)

Observational consequences :

1) Shower shape

2) Distribution and arrival angle w.r.t. the local mag. field.

A topological defect model

Sigl, Lee, Schramm and Coppi.

$p = 1$ **et** $M_x = 2 \times 10^{25} eV$

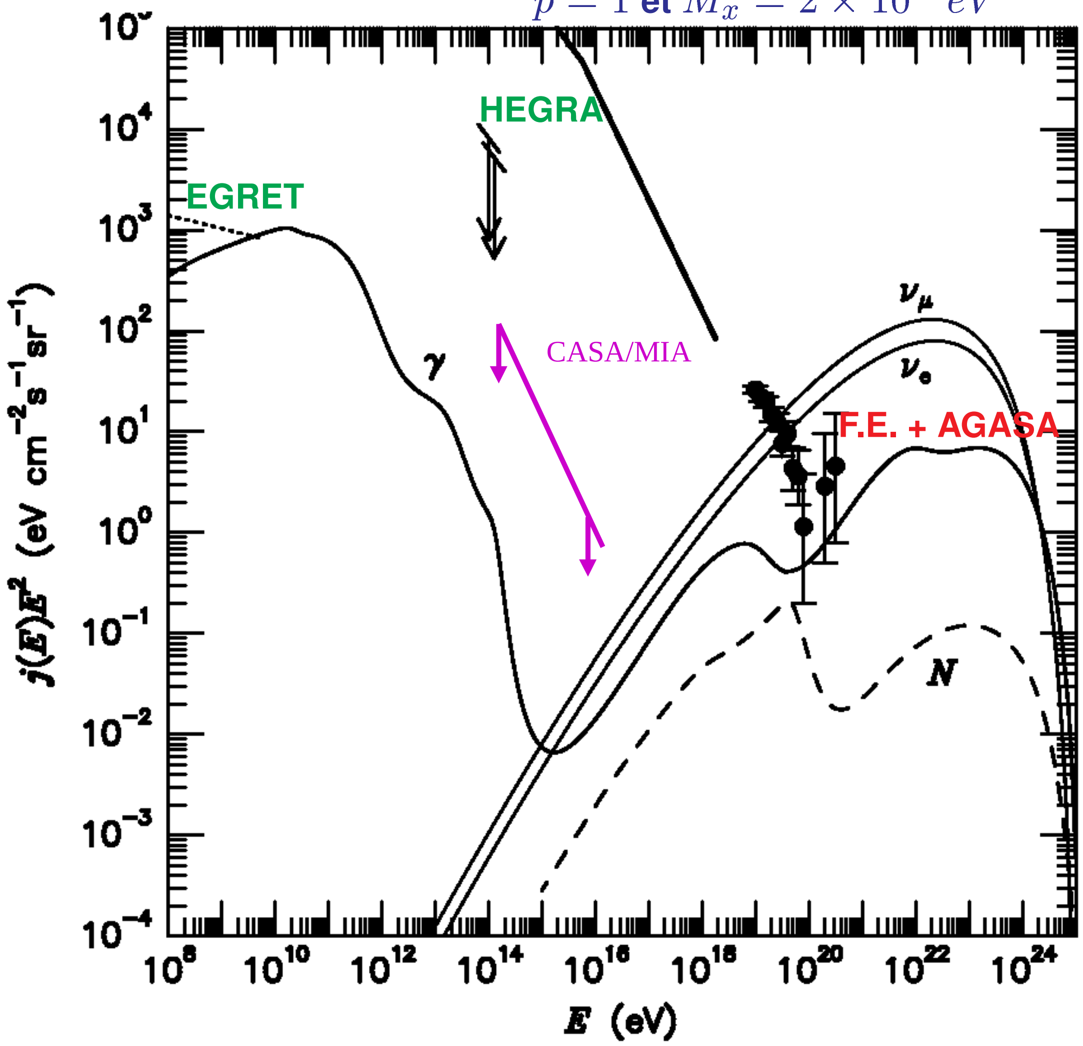


Figure 1: Predictions [Sigl, Lee, Schramm, & Coppi] for the differential fluxes of γ-rays (solid line), nucleons (dashed line), and ν_μ ($or\ \bar{\nu}_\mu$), ν_e ($or\ \bar{\nu}_e$) (thin solid lines in decreasing order) by the TD model characterized by $p = 1$, $m_X = 2 \times 10^{25}$ eV, assuming an EGMF of 10^{-12} G. Also shown are the combined data from the Fly's Eye and the AGASA experiments above 10 EeV (dots with error bars), piecewise power law fits to the observed charged CR flux (thick solid line) and experimental upper limits on the γ-ray flux at $1 - 10$ GeV from EGRET data (dotted line on left margin). The arrows indicate limits on the γ-ray flux from HEGRA.

Top-Down : Relics or TD?

No straight forward choice.

A lot of different models *“very imaginative”*...

The origin of UHECR is still an unresolved mystery...

For sure:

In Top-Down mechanisms there are no UHE nuclei.

Acceleration (Bottom-Up)

2 Bottom-Up mechanisms

1) Direct acceleration with an electric field
   - Neutron starts (variable magnetic fields)
   - Accretion disk around a compact object.

   Does not naturally give a power spectrum

2) Statistical acceleration in a magnetized plasma
   - Supernovas remnants
   - Radio galaxy hot spots
   - All systems with a shock wave.

   Fermi acceleration (DSAM, Diffuse Shock Acceleration Mechanism).
   Order one or two ($\Delta E \propto \beta$ or β^2).

[Fig 3.4a]

General (dimensional) rule :

$$E_{max} = \beta Z \left(\frac{B}{\mu G}\right) \left(\frac{R}{kpc}\right) 10^{18} eV$$

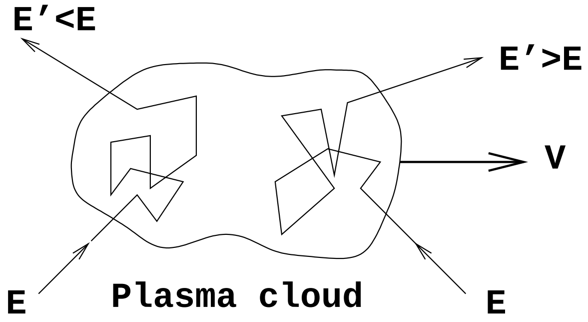
[Fig 3.4b]

Fermi mechanisms

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

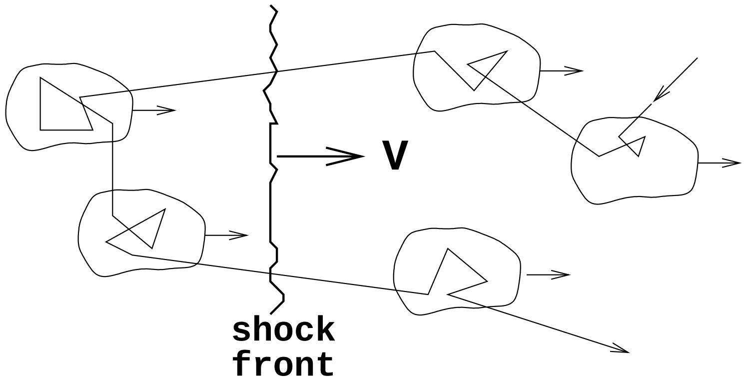
2nd order :
randomly distributed magnetic mirrors



$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

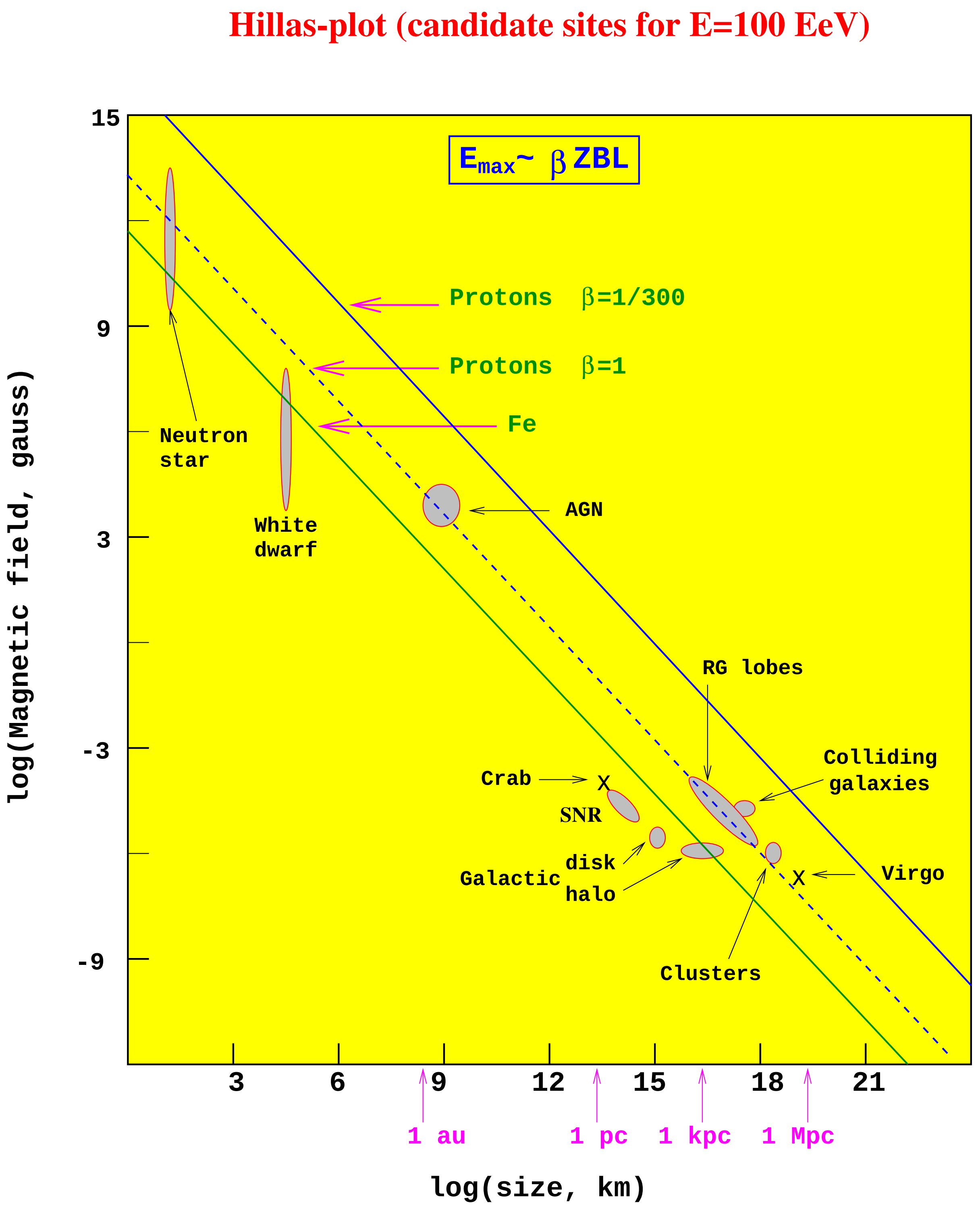
1st order :
acceleration in strong shock waves (supernova ejecta, RG hot spots...)



$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

[Fig 3.4a]

Diagramme d'Hillas



[Fig 3.4b]

DSAM

Case of test particles, random diffusions on magnetic inhomogeneities.

$$\Longrightarrow \frac{dN}{dE} \propto E^{-q}; \quad q = (r+2)/(r-1)$$

r is the compression ration between the (flow speed U_1/U_2 ration) stream behind and before the shock. Typically $r < 4$ thus $q > 2$ and we have "soft" spectra. For a more complete computation :

- Shock geometry
- "test" particles influence
- Ultra relativistic shock waves
- What are the magnetic inhomogeneities?

A more complete calculus gives :

$$E_{max} \sim Z\beta \left(\frac{B}{\mu G}\right) \left(\frac{R}{kpc}\right) \quad 10^{17} eV$$

(0.1 less than in Hillas's formula)

Candidates E_{max} >10^{20}eV

AGN : E_{max} ~10^{20}eV

$R \sim 0.02pc$, $B \sim 5G$

How to escape from the source?

$$P + \gamma \longrightarrow p + \pi^0 / n + \pi^+$$

+synchrotron radiation and Compton diffusions.

$$\Longrightarrow E_{max} \sim 10^{16} eV \quad !!$$

Radio Galaxies : $E_{max} \sim 10^{20} - 10^{21} eV$

The photon densities are low in the lobes (where the acceleration may occur) thus no photo-pion production. But no sources close by, transport?

Pulsars : $E_{max} \sim 10^{20} eV$

Potential drop in a varying magnetic field (Maxwell)

$$\Delta\Phi \propto \frac{B \times R^2}{\Delta T} \sim 10^{20} V$$

$B \sim 10^{13} G$, $\Delta T \sim 10^{-3} s$, $R \sim 10^4 m$.

In practice shorted by the e^+e^- plasma from the local cascades. Instead of 10^{20}eV one gets 10^{15}eV.

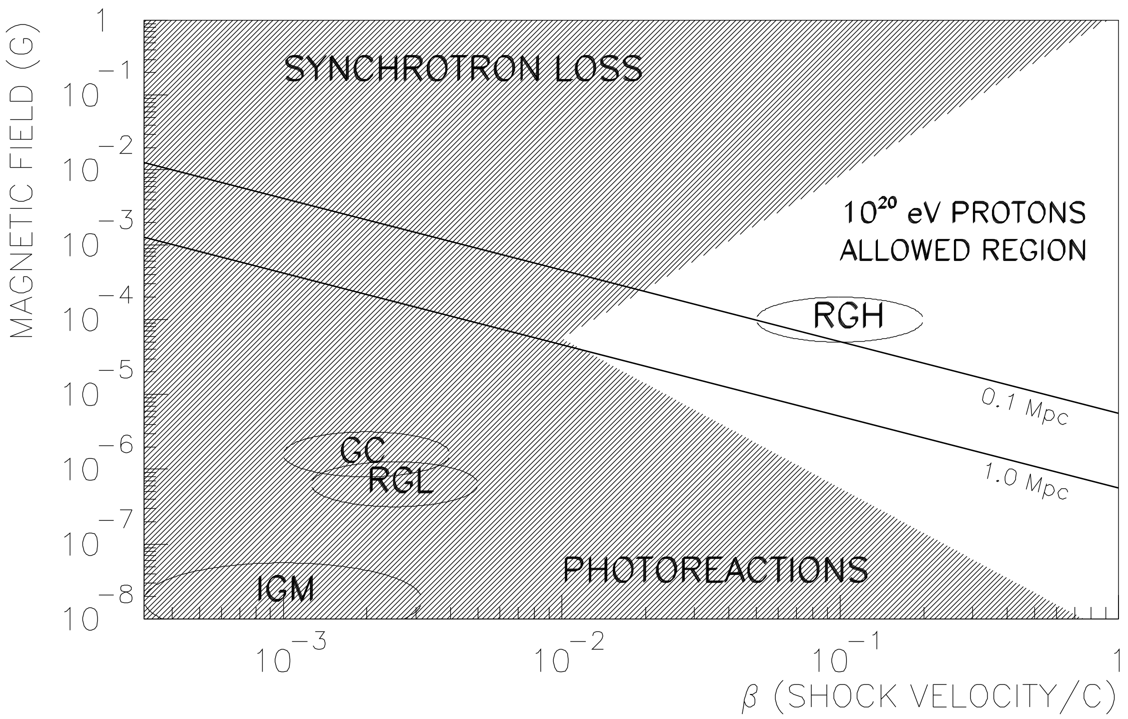
Beside this simple dimensional argument must be corrected for the proper geometry and the field orientation $R/(c\Delta T) < 0.1$.

Acceleration requirements

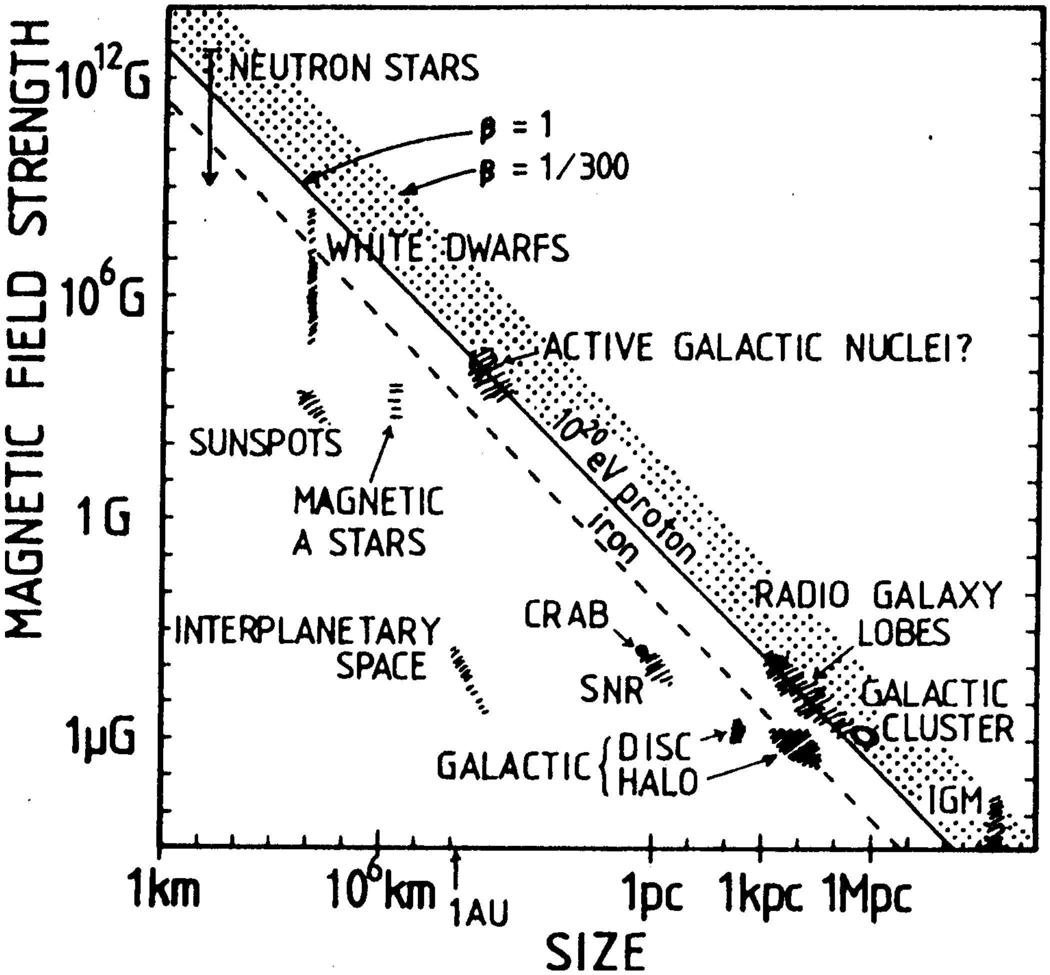
In general one cannot reach $E_{max} = ZBR$ because of synchrotron radiation or local gamma background.

- Synchrotron radiation $dE/dt = W \propto E^4/R^2 = B^2 \times E^2$
- dE/dx on local gamma bkg $dE/dt \approx -cte \times E.$
- dE/dt from Fermi mechanism $dE/dt \simeq \beta^2 \times B$

For a given maximum energy (e.g. 10^{20}eV), 2 triangles of the $Log(B), Log(\beta)$ plane are excluded.



Acceleration requirements (Cont'd)



Hillas diagram excluded zones:

- $R < 2.5 \times 10^{-1} pc \left(\frac{E}{10^{20} eV}\right)^3$ Synchrotron loss per turn $< E_{max}$.
- $T = \frac{E}{\beta^2 B} > 10 Mpc/c$ Acceleration time $< l_I(E)/C$.

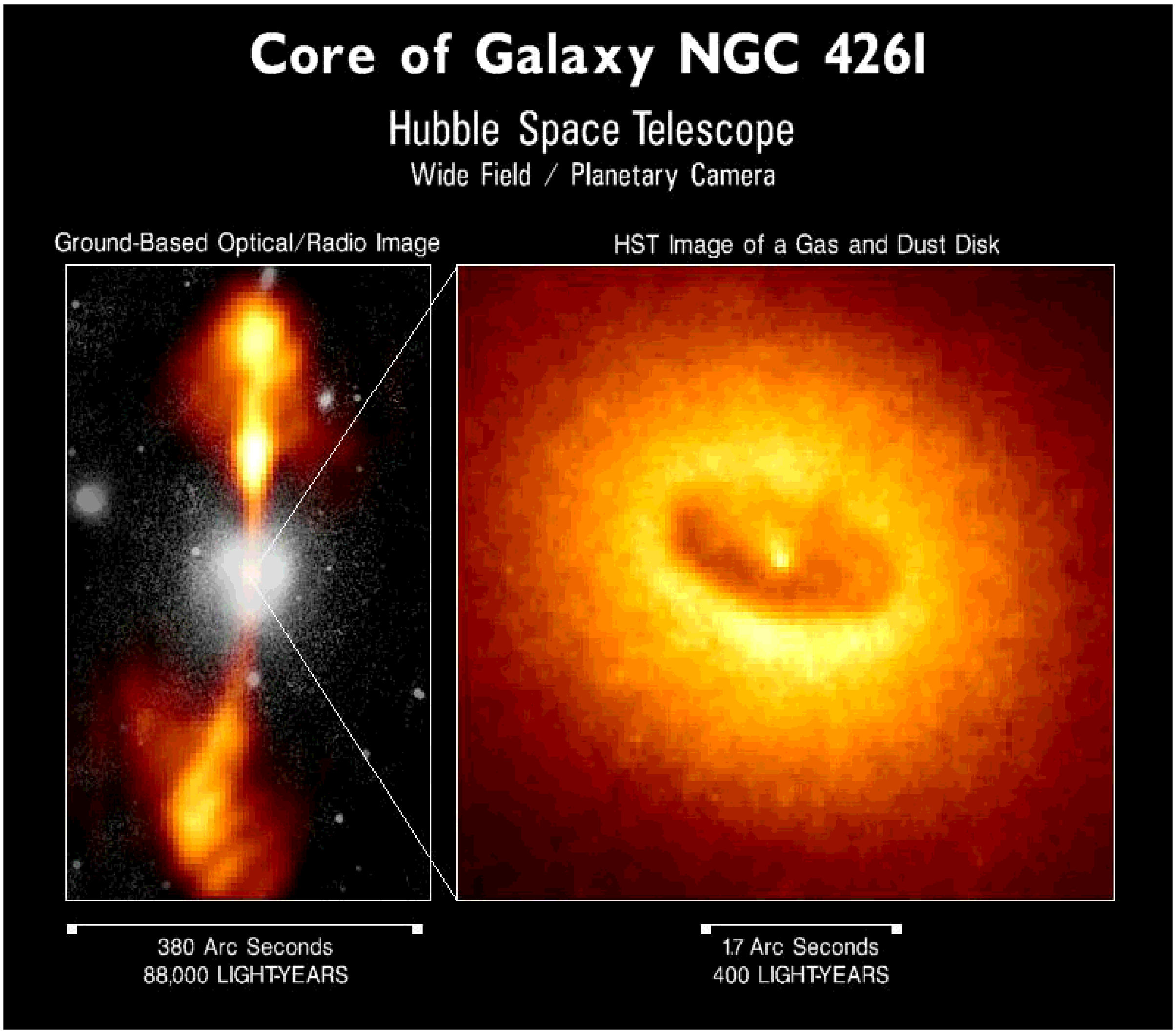
Gamma Ray Burst

- GRB : Powerful sources of gamma rays (0.1 to a few MeV) over a few seconds. Several hundreds observed (satellites).
- Expanding fireball model : Engine? Non thermal spectra ?
- Distribution : very likely cosmological (after glow). High luminosity (energy output)10^{52} ergs/sec (10^{53} ergs).
- Time delays: cosmological distribution $\Rightarrow$ a few local events. At most 1 every 50 years within 100 Mpc.

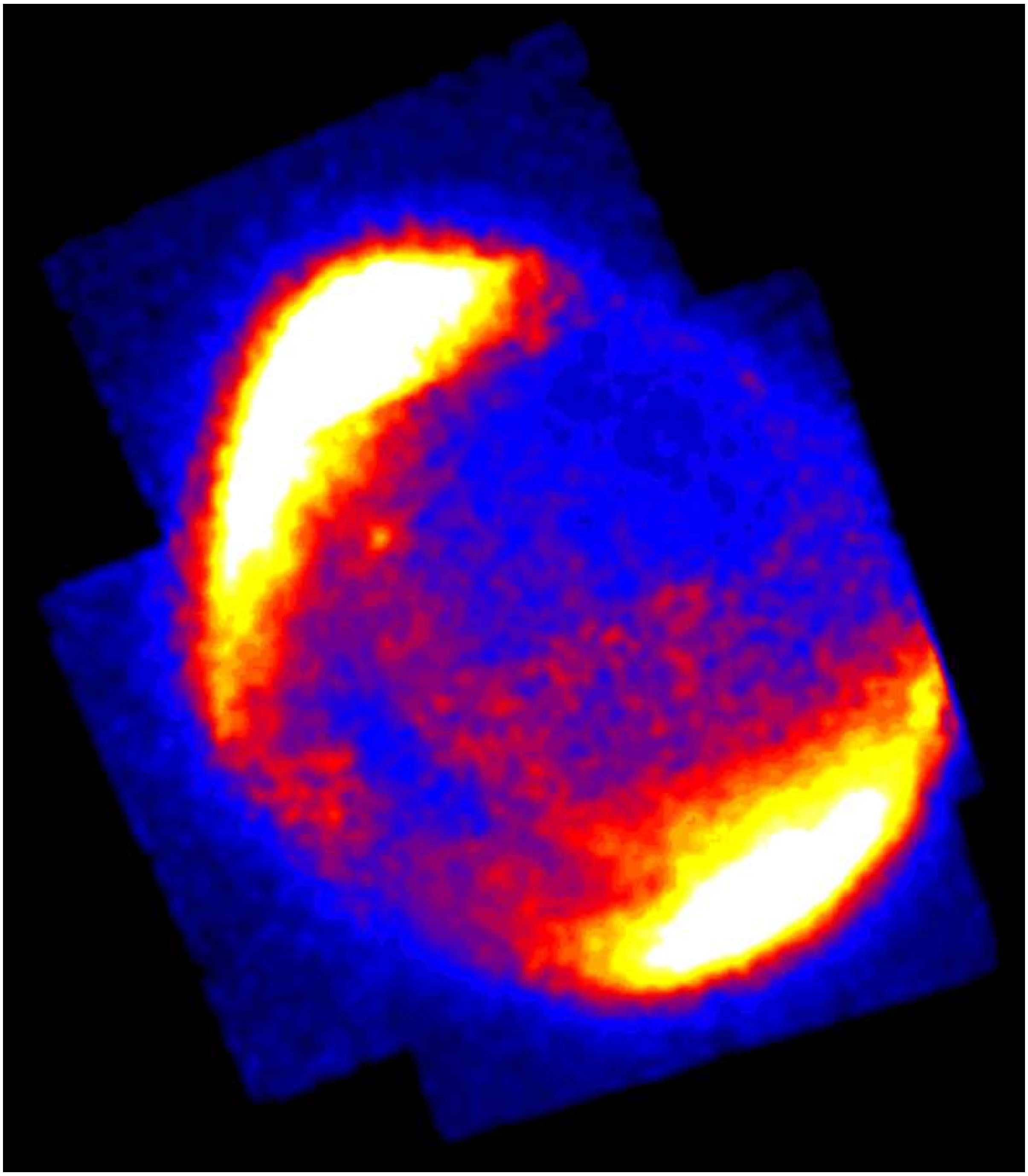
Two UHECR events observed by AGASA and Fly's Eye within 26 months and with $\Delta\Omega$ too large for a single source
$\Longrightarrow \Delta t \sim 100yr$ giving a lower bound on EGMF of $10^{-12}G$

Need more data but:

- If one observed a correlation between GRBs and UHECRs on a time scale smaller than 100 years then the GRB distribution cannot be cosmological and the common source would be galactic.
- If GRBs are in the Halo, more UHECR will be observed in correlation there will be no GZK and the distribution will essentially be isotropic.
- If GRBs are cosmological then GZK should be visible in the UHECR unless they come from different sources. (If associated with the visible matter distribution one should see anisotropy at the large scale structure level ($\sim$ 10 Mpc).
- Possibility of a gamma ray flux $\sim 10\,TeV$ delayed w.r.t. GRBs (EM cascades).



A radio galaxy with its jets and lobes.



A 1000 years supernova (SN 1006) in false color, observed in X rays.

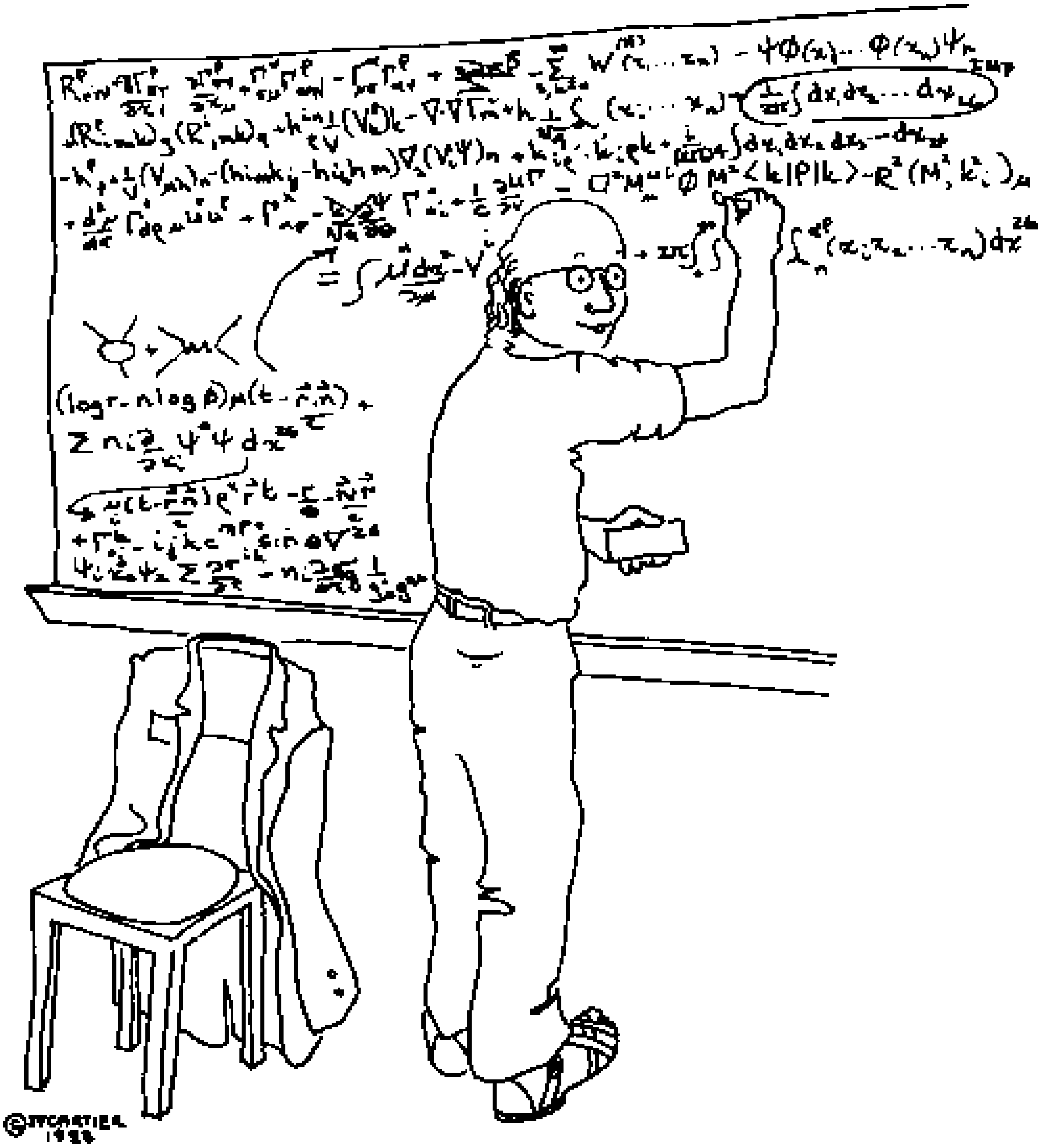
Conclusions

The question of the origin of ultra high energy cosmic rays is still open despite the large number of theoretical developments that it triggered.

Which way to go?

- An homogeneous distribution of sources over distances of the order of 100 Mpc (e.g. RG, GRB) would manifest through the GZK cutoff and a very low flux above 10^{20}eV. Are current observation still compatible with this?
- If there is no GZK cutoff then sources are close but we are not in a specially rich galaxy cluster neither close from a very bright source. What would then be the UHECR origin?
- Except for FR-II galaxy hot spots, DSAM are two slow to produce UHECR.
- TD models predict a spectrum similar to observations but the normalization is still arbitrary. Beside ad-hoc choices may give fluxes which are too large above 10^{20}eV or incompatible with the diffuse gamma ray background.

Conclusion (bis)



"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."