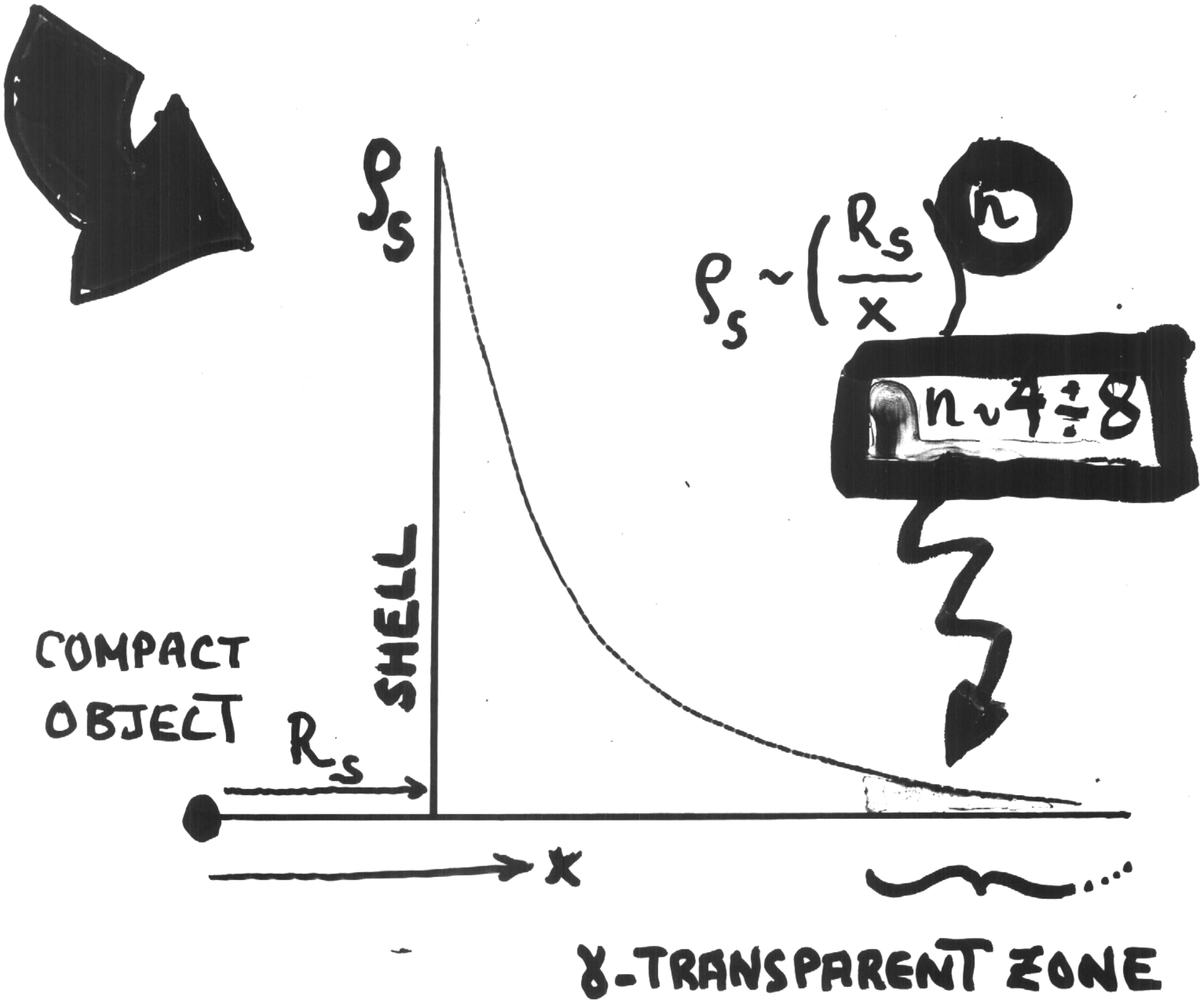
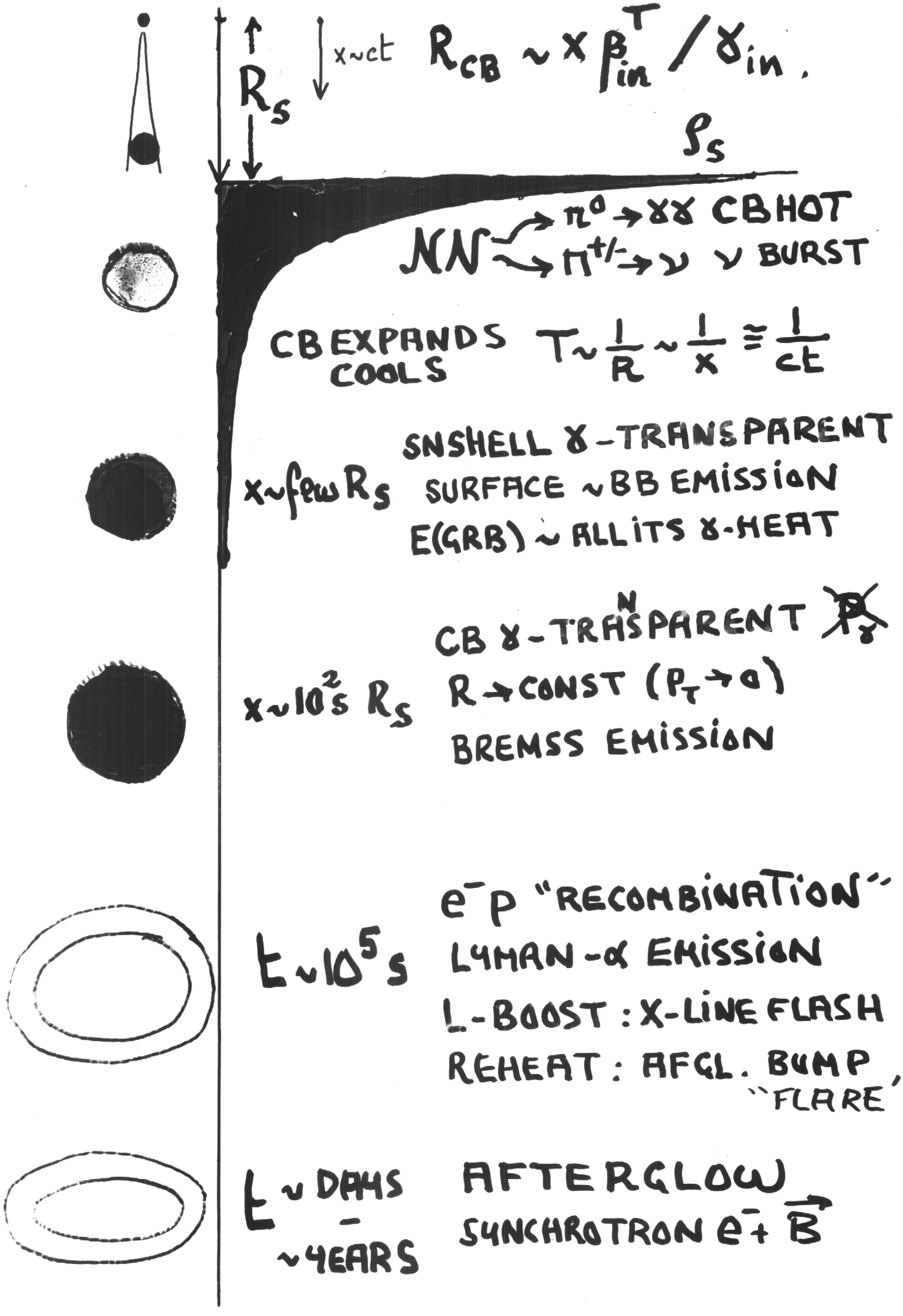
EVOLUTION OF THE SPECTRUM AND LINE FEATURES OF SUPERNOVAE



$\rho_s(x)$ - DETAILS INMATERIAL

$$\rho_s = \rho_s(R_s)\left(\frac{R_s}{x}\right)^n \theta(x - R_s)$$

THROUGHOUT

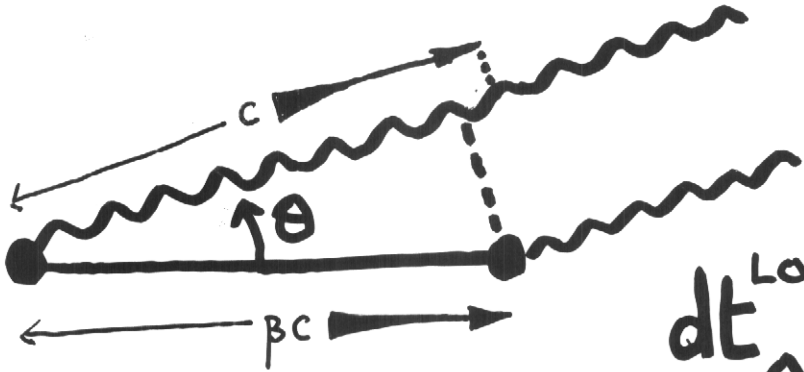


$x \sim ct$
$R_{CB} \sim x\, \beta_{in}^{T} / \gamma_{in}$.
R_S
ρ_S
$NN \to \pi^0 \to \gamma\gamma$ CB HOT
$\to \pi^{+/-} \to \nu$ ν BURST
CB EXPANDS COOLS $T \sim \frac{1}{R} \sim \frac{1}{x} \simeq \frac{1}{ct}$
$x \sim$ few R_S
SN SHELL γ-TRANSPARENT
SURFACE ~ BB EMISSION
E(GRB) ~ ALL ITS γ-HEAT
$x \sim 10^2$'s R_S
CB γ-TRANSPARENT
R → CONST ($P_T \to 0$)
BREMSS EMISSION
$t \sim 10^5$ s
$e^- p$ "RECOMBINATION"
LYMAN-α EMISSION
L-BOOST : X-LINE FLASH
REHEAT : AFGL. BUMP "FLARE"
t ~ DAYS – ~ YEARS
AFTERGLOW
SYNCHROTRON $e^- + \vec{B}$

"4 CLOCKS"

$$\gamma^{-1} = \sqrt{1-\beta^2} \qquad \gamma = \gamma(t)$$

$$dt_{univ.} = \frac{dx}{c} = \gamma \, dt_{CB}$$



$$dt_{OBS}^{LOCAL} = \frac{dt_{CB}}{\delta}$$

$$\delta = \frac{1}{\gamma(1-\beta\cos\theta)} \simeq \frac{2\gamma}{1+\theta^2\gamma^2} \qquad \begin{matrix}\gamma \gg 1 \\ \theta \ll 1\end{matrix}$$

$$dt_{OBS}^{DISTANT} = (1+z) \, dt_{OBS}^{LOCAL}$$

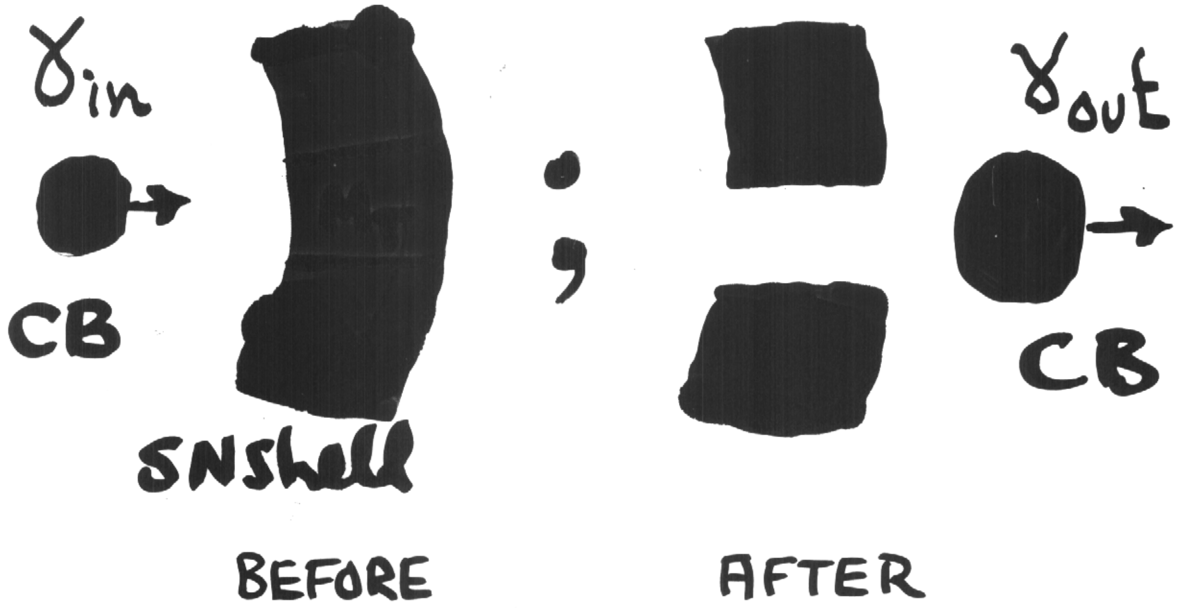
e.g. : $z = 1$, $\gamma = 10^3$, $\theta\gamma = 1$

$dt_{OBS}^{DIST.} = 2s$ $\qquad$ $dt_{CB} = 10^3 s$

$dt_{OBS}^{LOCAL} = 1s$ $\qquad$ $dt_{UNIV.} = 10^6 s$

$\sim 11.6 d$

ENERGY IN THE OUTGOING CANNONBALL



$$NN \to \pi^{\pm} \to \nu \ldots \sim 2/3 \text{ E is LOST}$$

$$ \to \pi^{0} \to \gamma\gamma \sim 1/3 \text{ E is RETAINED}$$

$$E_{CB}^{OUT} \sim E_{CB}^{IN} \, \frac{1}{3} \gg M_T, M_{CB}$$

E IN SN REST SYST.

$$E_{CB}^{OUT,\,REST} \simeq \frac{E_{CB}^{IN}}{3\gamma_{out}} > M_{CB} \text{ [IN BARYONS]}$$

INERTIAL MASS PROVIDED BY ENCLOSED RADIATION

COOLING AND EXPANSION

$$R_{CB} \approx \beta_T c \frac{t}{\gamma} \qquad \beta_T \sim \frac{1}{\sqrt{3}}$$

$$T \propto 1/R_{CB}$$

TOTAL EMITTED ENERGY

$$E_{TOT} \sim \frac{1}{e} E_{RAD}^{TRANS}$$

$$\sim \frac{1}{3e} \frac{E_{CB}}{\gamma_{in}} \frac{R_S}{x_{TRANS} - R_S} \frac{\beta_{in} \gamma_{out}}{\beta_{out} \gamma_{in}}$$

$$\approx 4.5\, 10^{45} \mathrm{erg}\, f_E(\mathrm{PARAMS})$$

BOOST TO OBSERVER'S FRAME

TIME AND ENERGY INTEGRATED FLUENCE

$$\frac{dF}{d\Omega} = \frac{1+z}{4\pi D_L^2} E_{TOT} \left[\frac{2\gamma_{out}}{1+\theta^2 \gamma_{out}^2} \right]^3$$

$\gamma \sim 10^3$, $\gamma\theta \sim O(1)$ } RIGHT BALLPARK $\leftrightarrow$ OBSERVATIONS

$$\frac{4\pi a}{3}\left(R_{CB}^{TRANS}\right)^3\left(T_{CB}^{TRANS}\right)^4 = E_{RAD}^{TRANS}$$

$$\Rightarrow T_{CB}^{TRAS} \sim 0.1\,\mathrm{keV} * f_T(\mathrm{PARAMS})$$

RIGHT BALLPARK FOR E_γ IN GRBs

WHEN BOOSTED BY

$$\delta = \frac{2\gamma}{1+\theta^2\gamma^2}$$

AND REDSHIFTED BY

$$\frac{1}{1+z}$$

GRB FLUENCE

$\Rightarrow \gamma \sim O(10^3)$

INDIVIDUAL γ-ENERGIES in GRB

$\Rightarrow \gamma \sim O(10^3)$

$$\frac{\Delta\Omega}{4\pi} \sim \frac{1}{4\gamma^2}$$

$\gamma \sim O(10^3)$: A ROUGHLY $1 \div 1$ SN-GRB ASSOCIATION

$$t_{tr} = t_{tr}\,(\text{PARAMS})$$

$$F = F\,(\text{PARAMS})$$

$$H = H\,(\text{PARAMS})$$

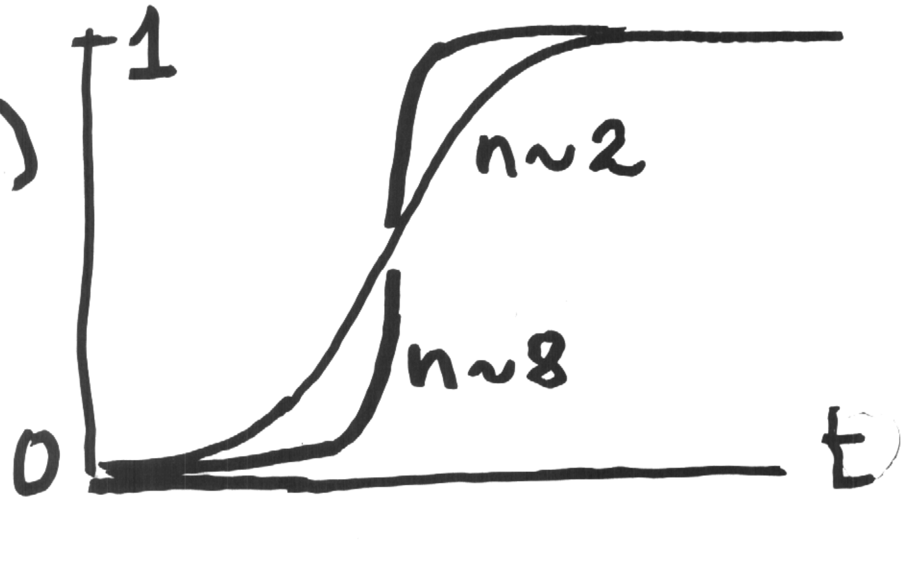
THERMAL EMISS. FROM THE CB's SURFACE $\propto [R_{CB}(t)]^2$

ABRUPT SN-SHELL TRANSPARENCY

$$\frac{dn}{dE\,dt} = F\, t^2 \,\frac{E^2}{e^{tE/H} - 1}\,\theta(t - t_{tr})$$

THERMAL SPECTRUM WITH $T \sim 1/t$

$1 - \text{Abs}(t)$



GRB Properties

The GRB fluences, integrated in energy and time, lie within one or two orders of magnitude of

10^{-5} erg cm^{-2}

(e.g., Paciesas et al. 1999)

Individual pulses are narrower in time, the higher the energy interval of their photons

(e.g., Fenimore et al. 1995)

Individual pulses rise and peak at earlier time, the higher the energy interval of their photons

(e.g., Norris et al. 1999; Wu and Fenimore 2000)

Individual pulses have smaller photon energies, the later the time-interval of observation

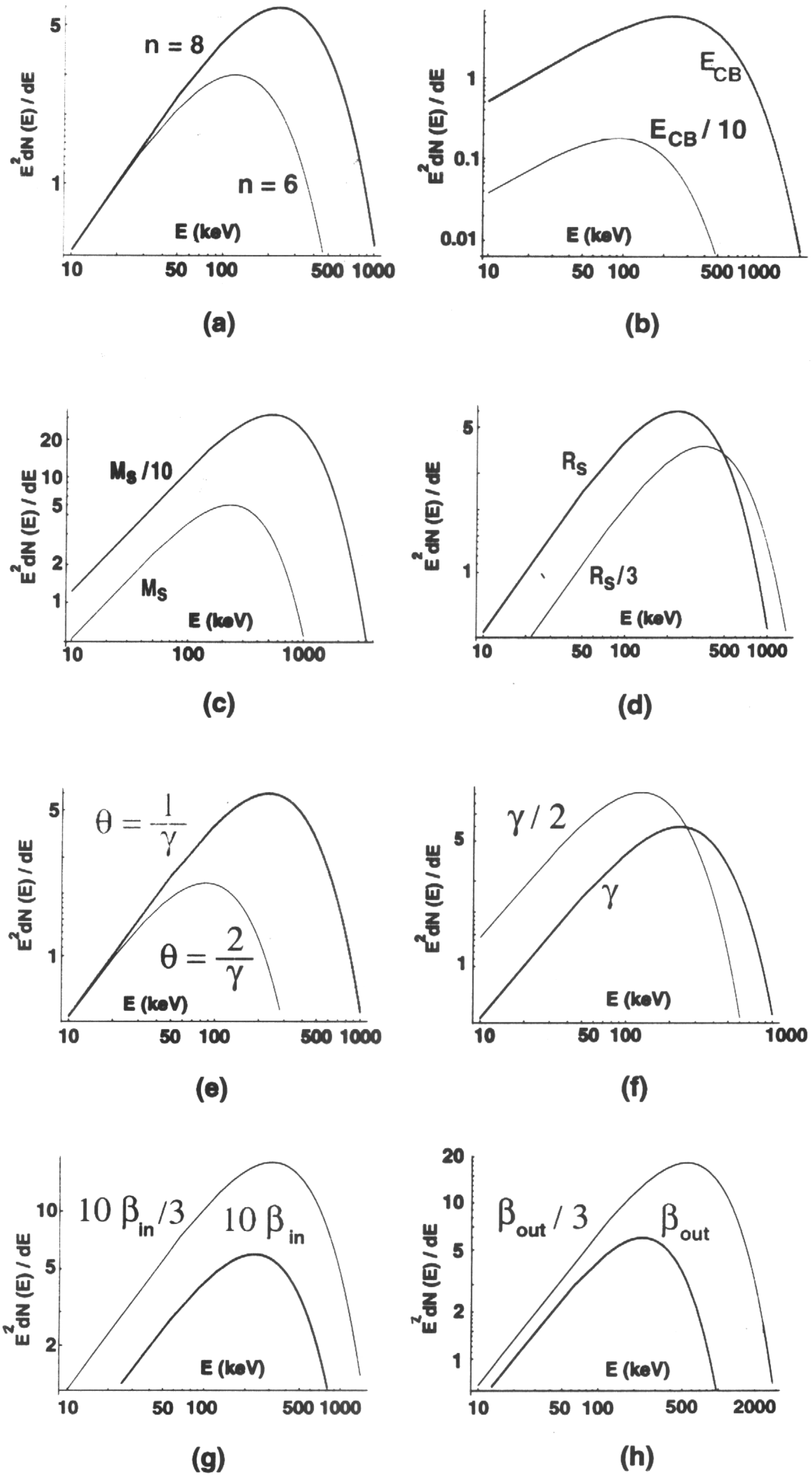
(e.g., Preece et al. 1998)

$E^2\,dN/dE$ rises as $E^{\approx 1}$, has a broad peak at 0.1 to 1 MeV, decreasing thereafter

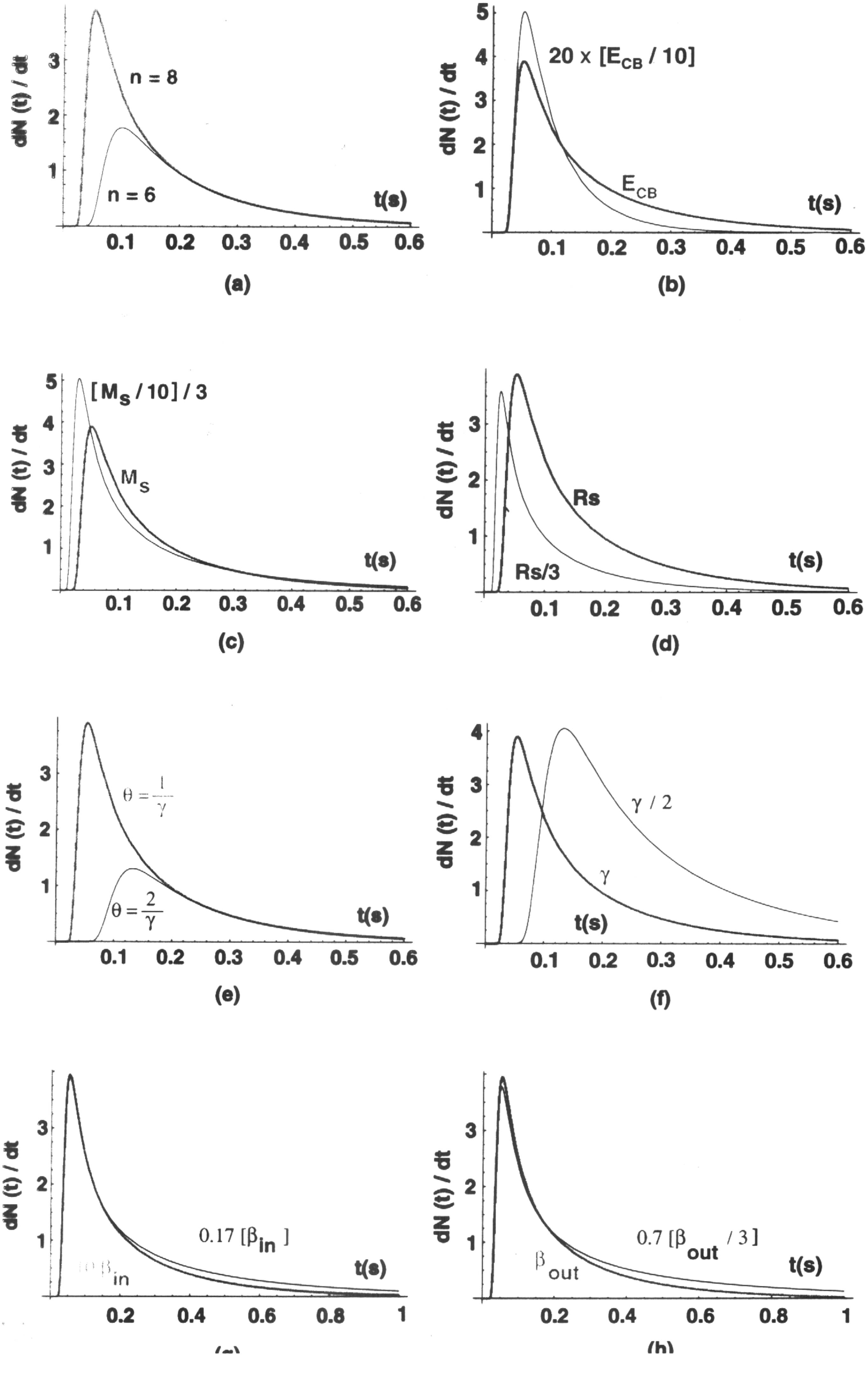
(e.g., Preece 2000)

Most pulses are FREDs, other $\approx$ symmetrical Non-FREDs. GRBs either all FRED or all Non-FRED

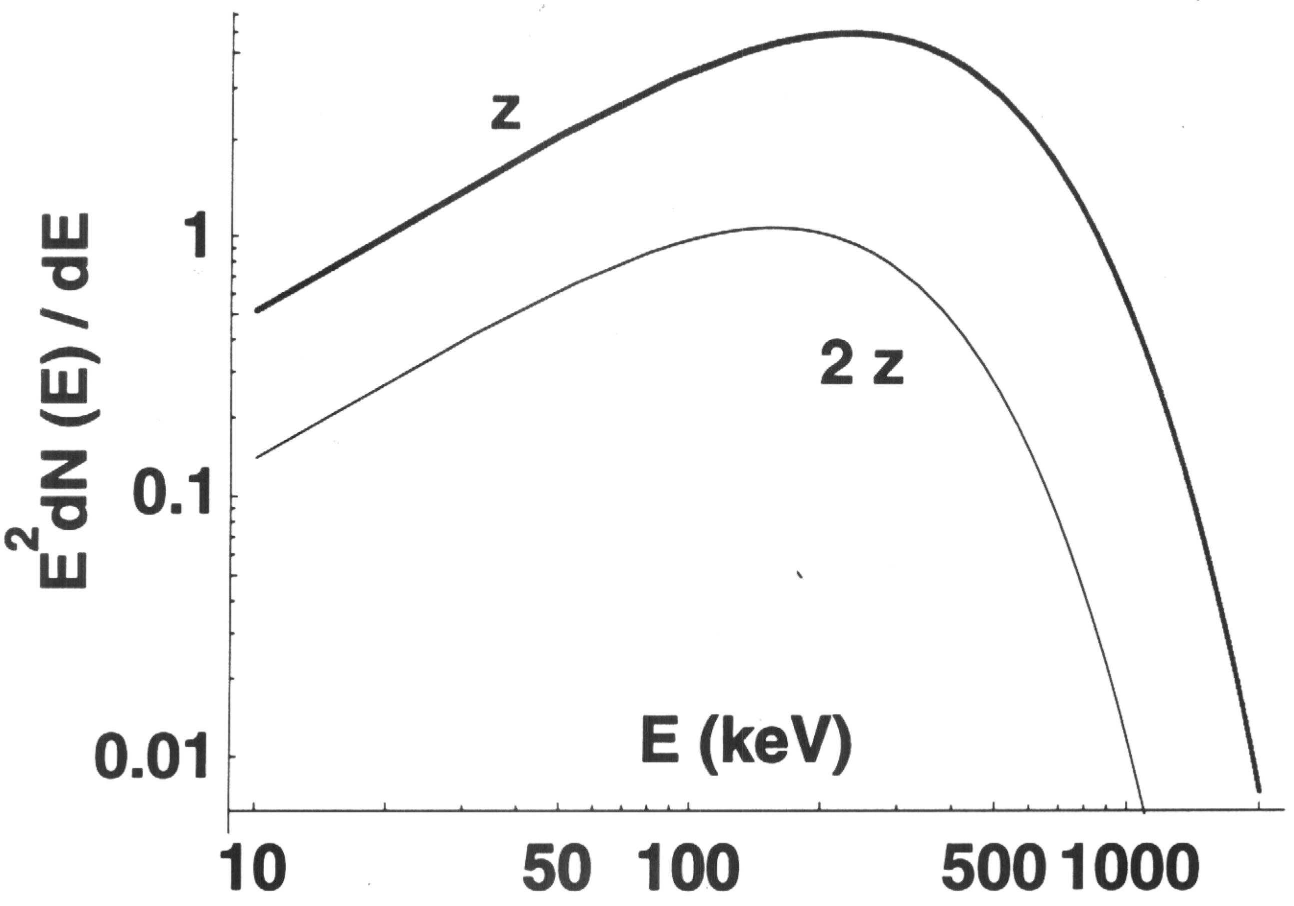
(e.g. Fenimore et al. 1995 and refs. therein)



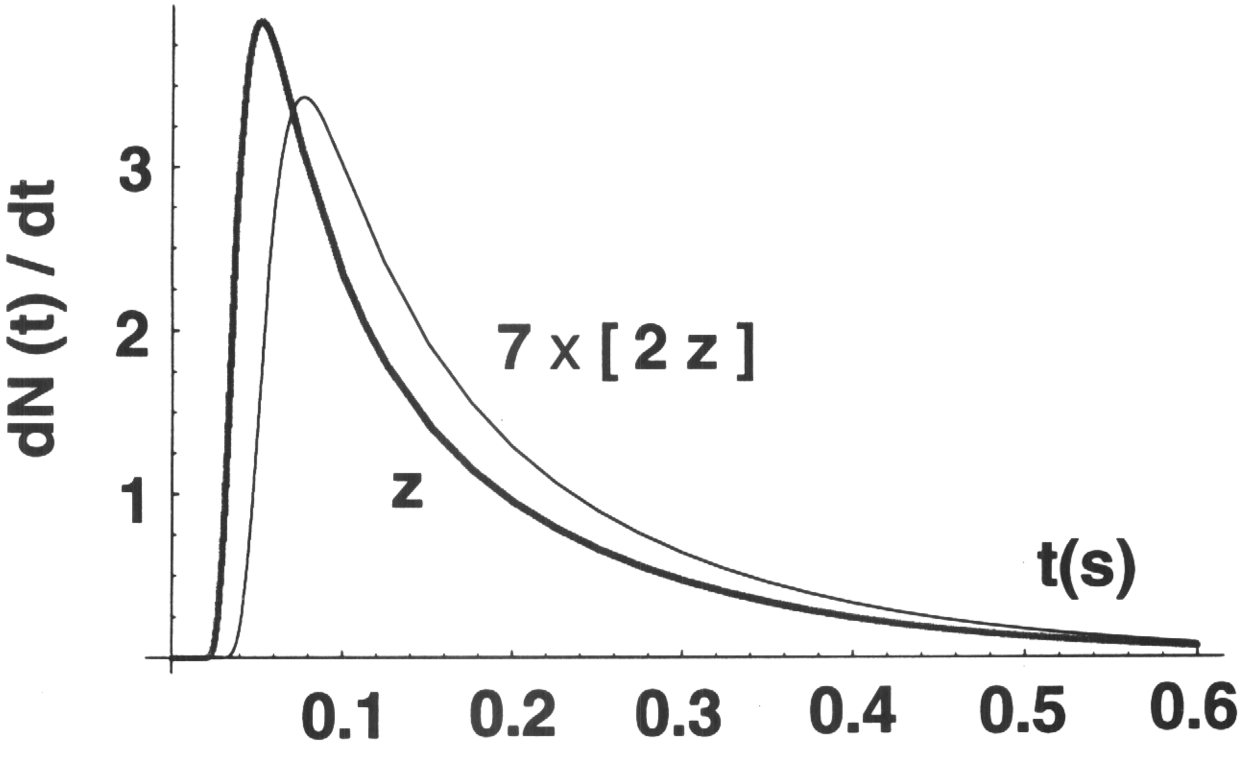
E²dN (E) / dE
E (keV)
n = 8
n = 6
(a)
E_CB
E_CB / 10
(b)
M_S /10
M_S
(c)
R_S
R_S/3
(d)
θ = 1/γ
θ = 2/γ
(e)
γ / 2
γ
(f)
10 β_in/3
10 β_in
(g)
β_out / 3
β_out
(h)



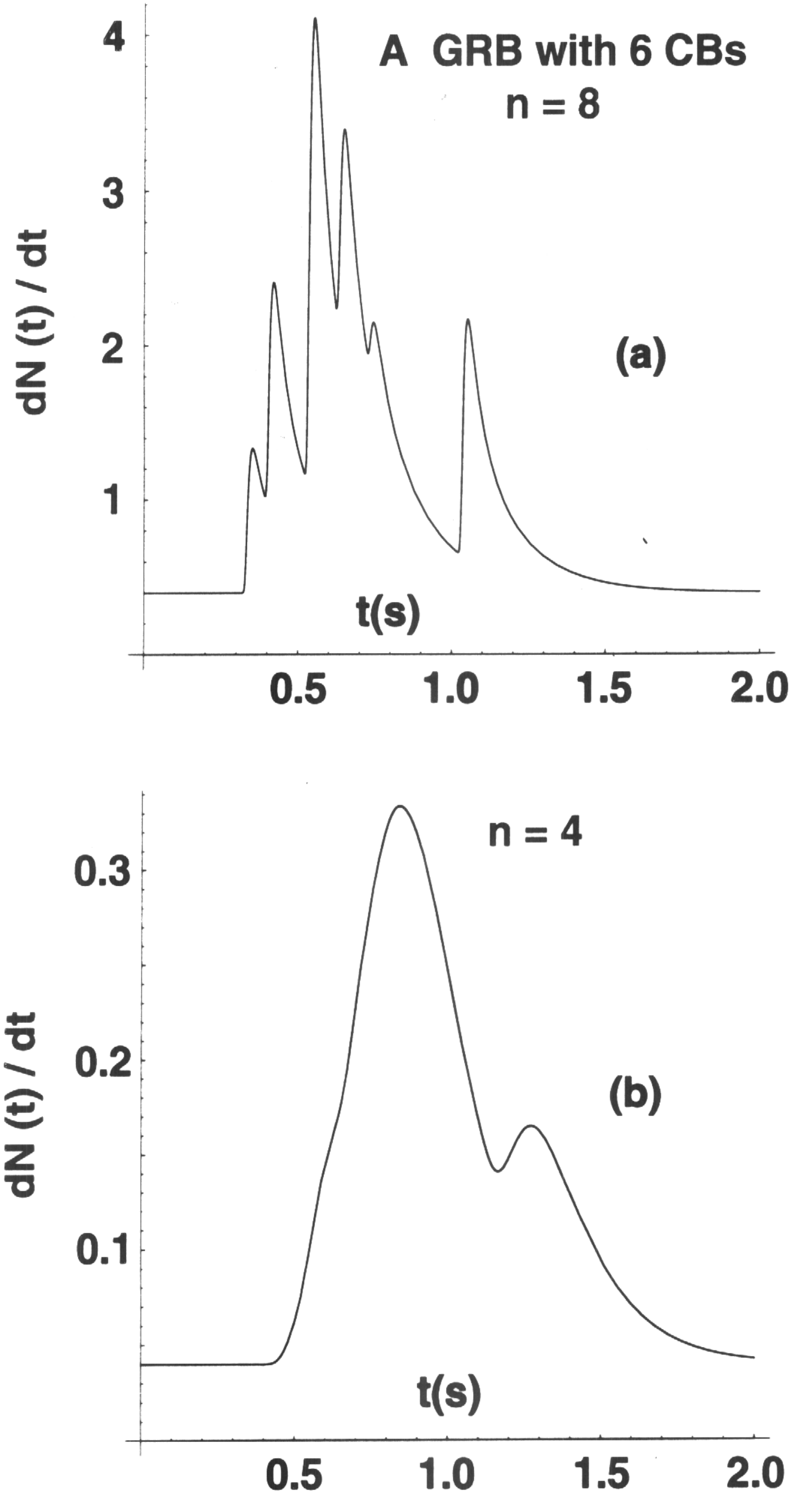
dN (t) / dt
n = 8
n = 6
t(s)
0.1 0.2 0.3 0.4 0.5 0.6
(a)
20 x [E_CB / 10]
E_CB
t(s)
(b)
[M_S / 10] / 3
M_S
t(s)
(c)
Rs
Rs/3
t(s)
(d)
θ = 1/γ
θ = 2/γ
t(s)
(e)
γ / 2
γ
t(s)
(f)
0.17 [β_in]
β_in
t(s)
0.2 0.4 0.6 0.8 1
0.7 [β_out / 3]
β_out
t(s)
(h)



$E^2 dN(E)/dE$
z
2 z
E (keV)
1
0.1
0.01
10
50
100
500
1000



dN (t) / dt
7 x [2 z]
z
t(s)
1
2
3
0.1
0.2
0.3
0.4
0.5
0.6



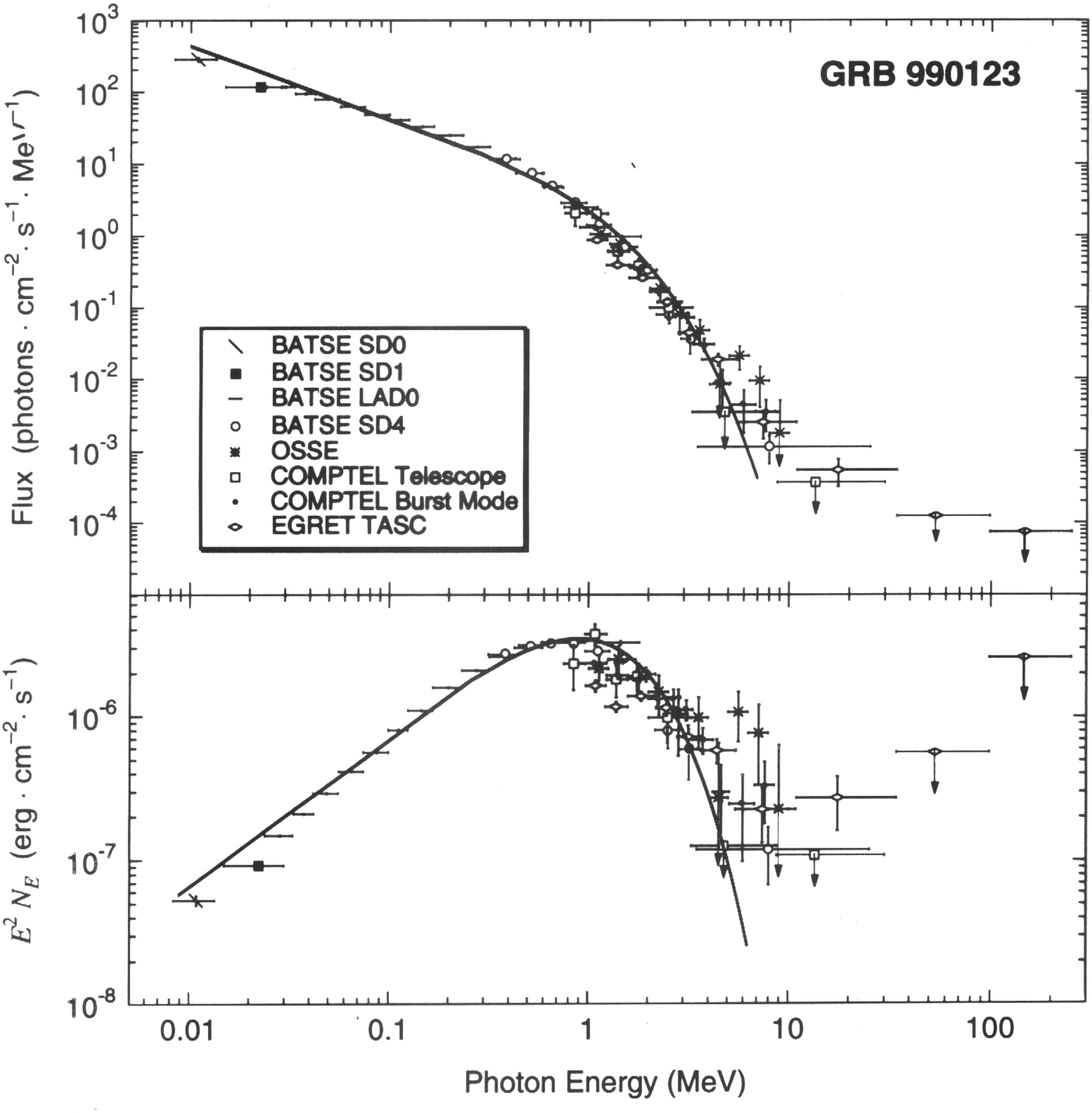
A GRB with 6 CBs
n = 8
(a)
dN (t) / dt
t(s)
4
3
2
1
0.5
1.0
1.5
2.0
n = 4
(b)
dN (t) / dt
t(s)
0.3
0.2
0.1
0.5
1.0
1.5
2.0

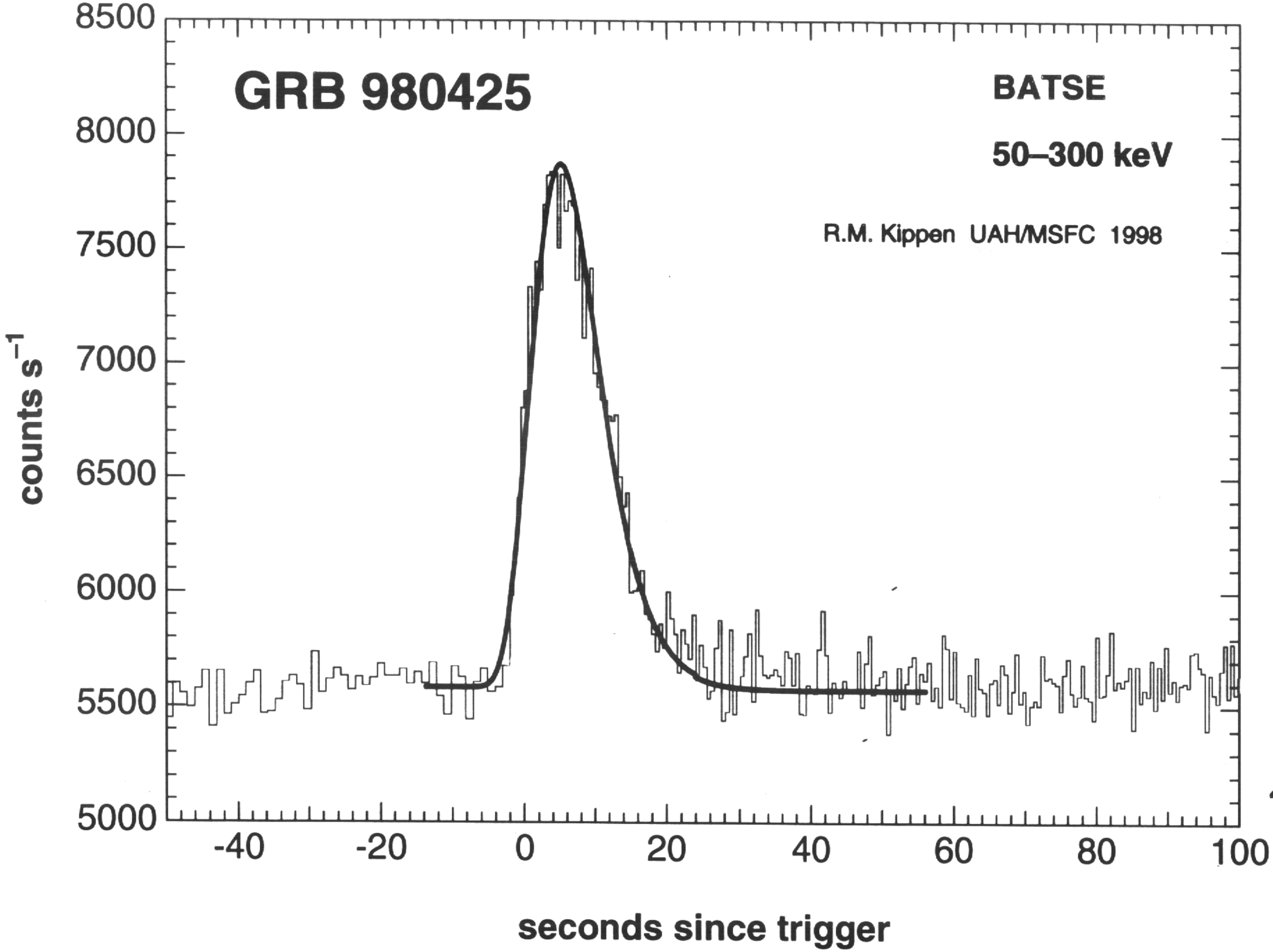
$\beta_{in} = \frac{1}{10\sqrt{3}}$, $\beta_{out} = \frac{1}{3\sqrt{3}}$, $E_{JET} = 5.10^{53}$ erg

$M_s = 2.5\, M_\odot$; $R_s = 0.3$ ld

$\gamma_{out} = 1.5\; 10^3$, $\theta = 1.5\; 10^{-3}$, $n = 6$

$z = 1.60$





$\beta_{in} = \frac{1}{3\sqrt{3}}$

$\beta_{out} = \frac{1}{2\sqrt{3}}$

$M_S = 10\,M_\odot$

$R_S = 0.2\,ld$

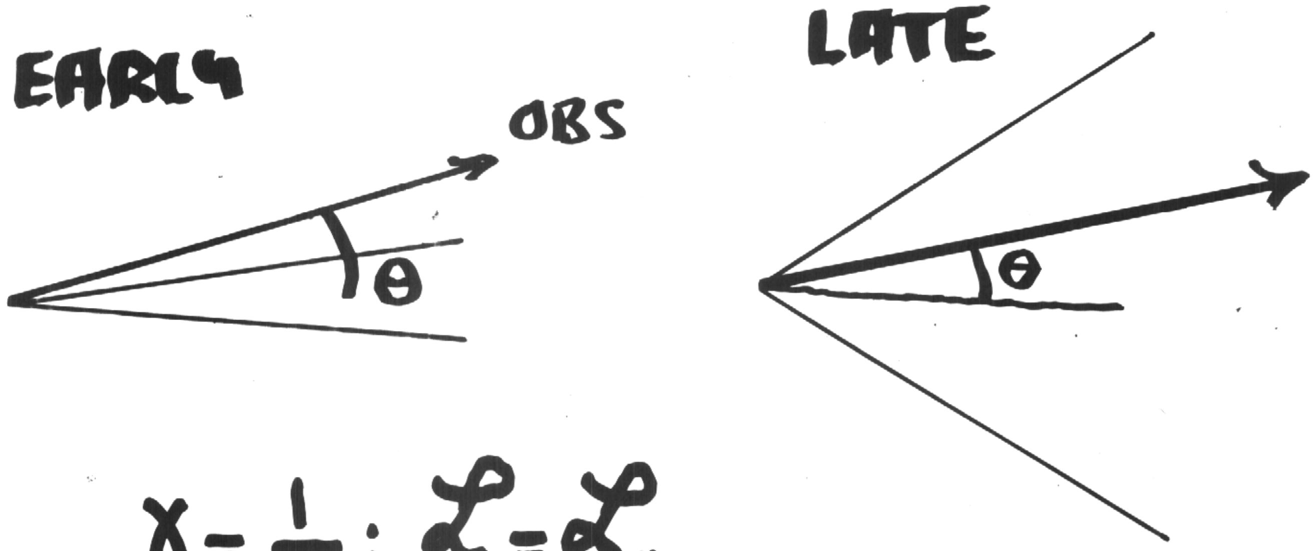
$E_{CB} = 10^{53}\,erg$

$\gamma_{out} = 333$

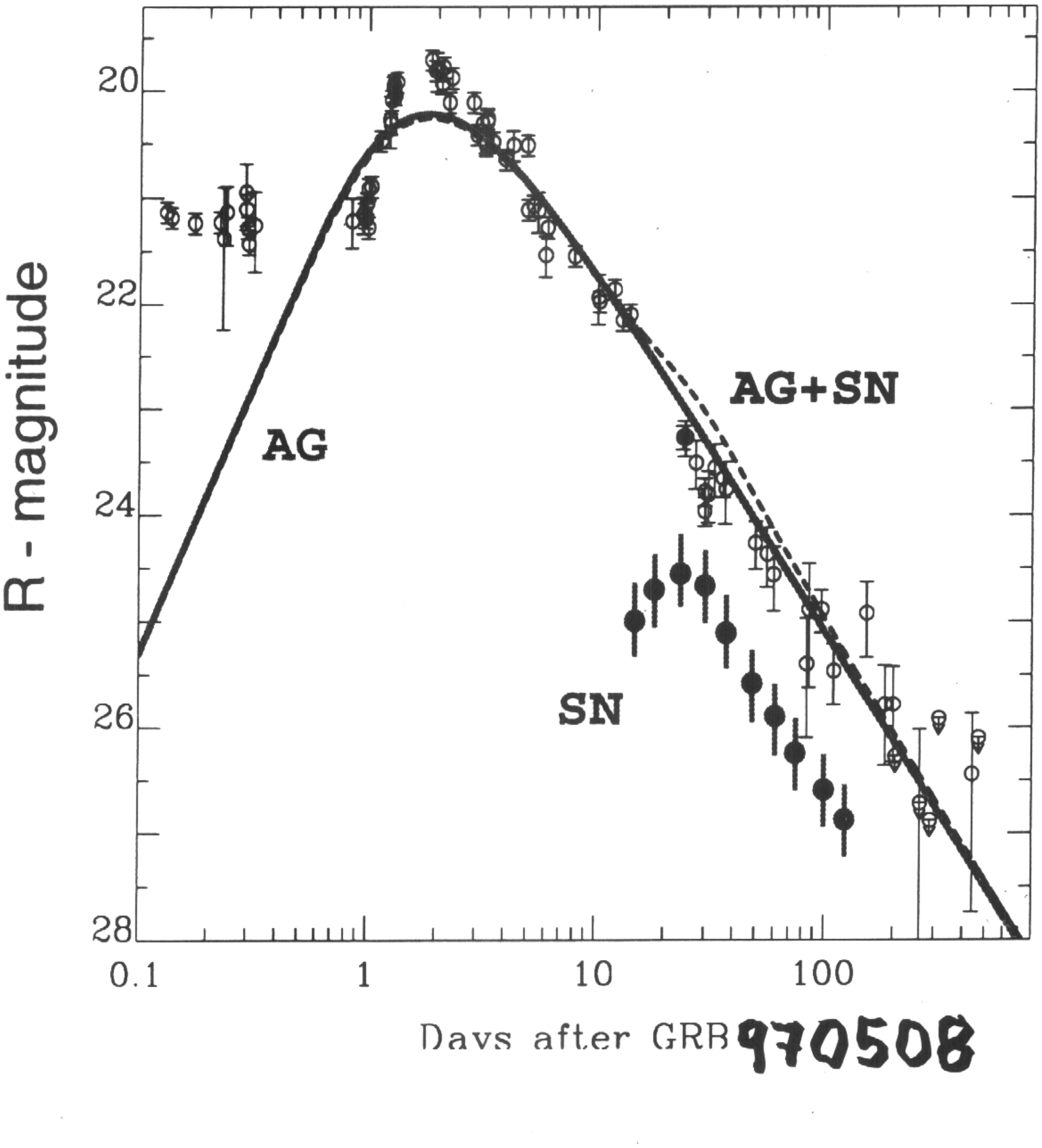
$\theta = 6\,10^{-2}$

$n = 8$

$z = 0.0085$



$$\gamma = \frac{1}{\theta} : \mathcal{L} = \mathcal{L}_{max}$$



$ep \to H\gamma$

CB COOLS BY BREMSS TO $\begin{cases} n_e/n_B \sim \frac{1}{2} \\ T \sim 4500\ K \\ n_e \sim 10^{5\div 6}\ cm^{-3} \end{cases}$

IN t(OBS) $\sim$ 1 DAY

Ly_α : 10.2 eV $\to \frac{10.2\ keV}{1+z}\left(\frac{\delta}{10^3}\right)$ EASY TO MISINTERPRET

Ly_∞ : 13.6 eV $\to \frac{13.6\ keV}{1+z}\left(\frac{\delta}{10^3}\right)$ AS Fe-LINES

$\delta \sim O(\gamma) \sim 10^3$

LINE FLUENCE

$$dN_\gamma / d\Omega \simeq N_B \frac{(1+z)^2 \delta^2}{4\pi D_L^2} \checkmark \quad \left.\begin{matrix} n_e \\ N_B \simeq N_e \end{matrix}\right\} \to R_{CB}(Ly_\alpha)$$

LINE-EMISSION Δt_α (DIFFUSION OF Ly_α γ's)

$$\Delta t_\alpha \simeq \frac{3 R_{CB} \tau}{c\,\delta}(1+z) \quad [\tau = \sigma_\alpha\, n_e\, R_{CB}(Ly_\alpha)]$$

$$\sim 10^5\ s \checkmark$$

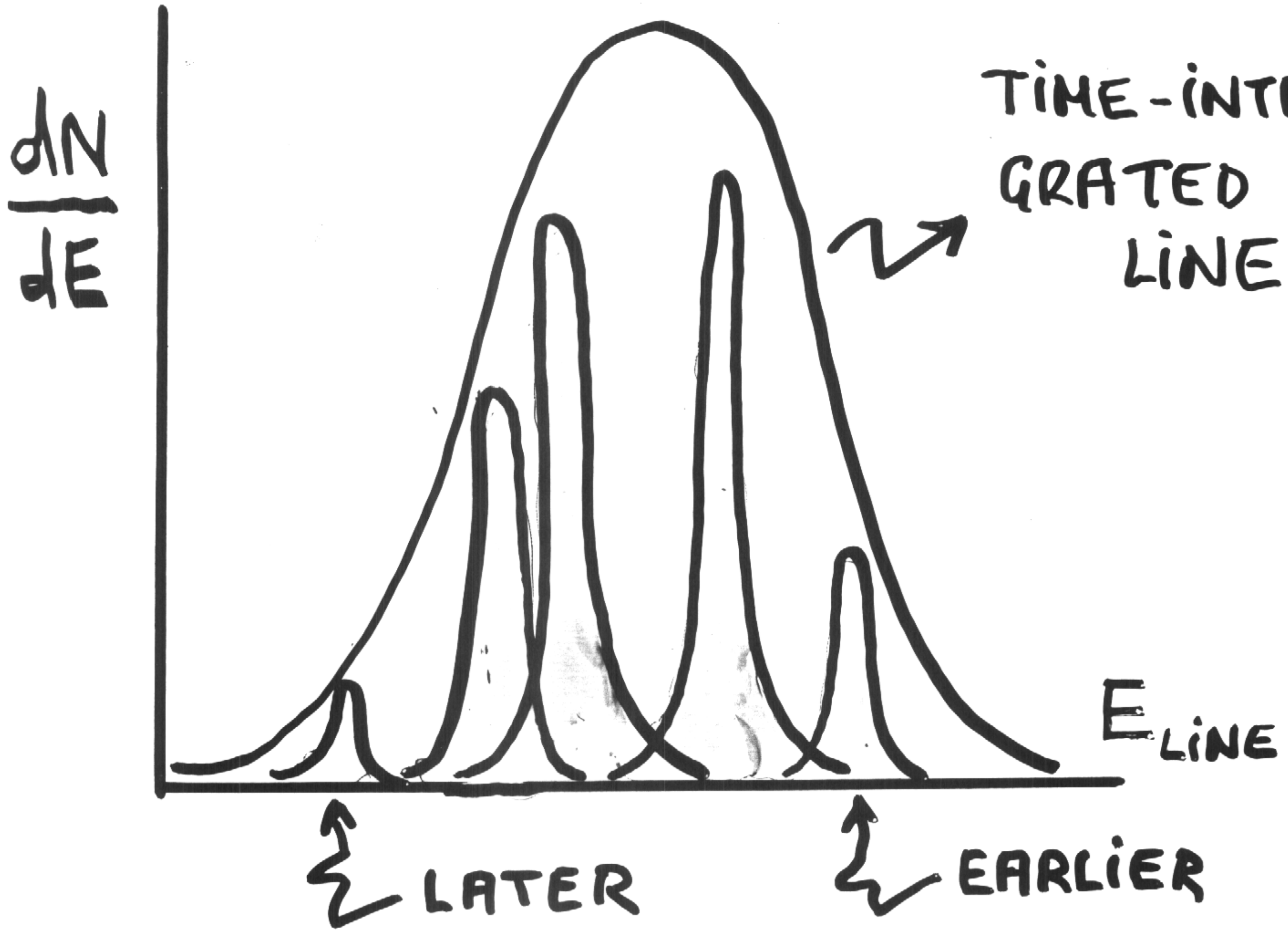
EXPANDING RADIUS

R_{CB} INCREASING FOR 1 MONTH AT THE SAME RATE AS IN 1RST DAY

$$R_{CB}(30d) = 30\, R_{CB}(Ly_\alpha) \sim 5\, 10^{16}\ cm$$

$\checkmark\checkmark$ SCINTILLATION MEASURE (TAYLOR et al.)

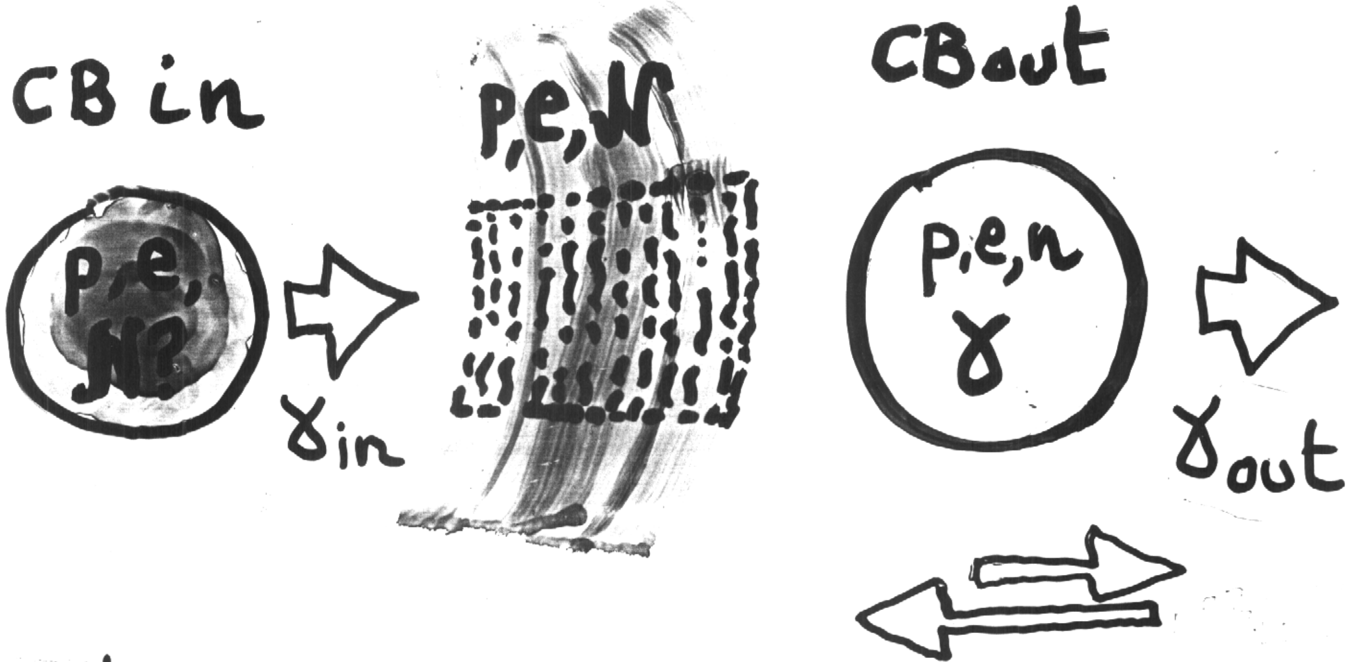
$E_{LINE} \propto \delta(t)$ ↓ AS t ↑



$$\delta(t) \simeq 2\gamma(t) \propto t^{-\frac{1}{3}}$$

$$\frac{\Delta E_L}{E_L} \simeq \frac{1}{3}\,\frac{\Delta t\,[\text{OBSERVATION}]}{t\,[\text{OBSERVATION}]}$$ √√√

ORIGIN OF HIGH-ENERGY ν'S



CLAIM : ALL OF THE INCOMING CB's BARYONS SUFFER HIGH CMS-ENERGY COLLS.

COROL²ARY : THEY LOSE MOST OF THEIR ENERGY IN HARD π-PRODUCING INTERACS.

PROOF ① MICROSCOPIC DESCRIPTION OF CB-SNS COLLISION

② SHORTCUT

ONE CAN CHECK :

BOTH CB AND SN SHELL ARE :

① MANY pp INTER. LENGTHS LONG $\sim 10^3$

② SUFFICIENTLY THIN (LOW ρ)

FOR ALL PRODUCED π, μ TO DECAY WITHOUT SIGN. ENERGY LOSS

⇓

IDEAL BEAM-DUMP FOR ν-PRODUCTION

EXAMPLE :

ICE OR WATER DETECTOR

LOOKING FOR

$$\nu_\mu \to \mu$$

$$x_\mu = \frac{E_\mu}{m_p \gamma_{in}}$$

MUON ENERGY HERE

PROTON ENERGY "THERE"

OBSERVED μ FLUX

(per CB)

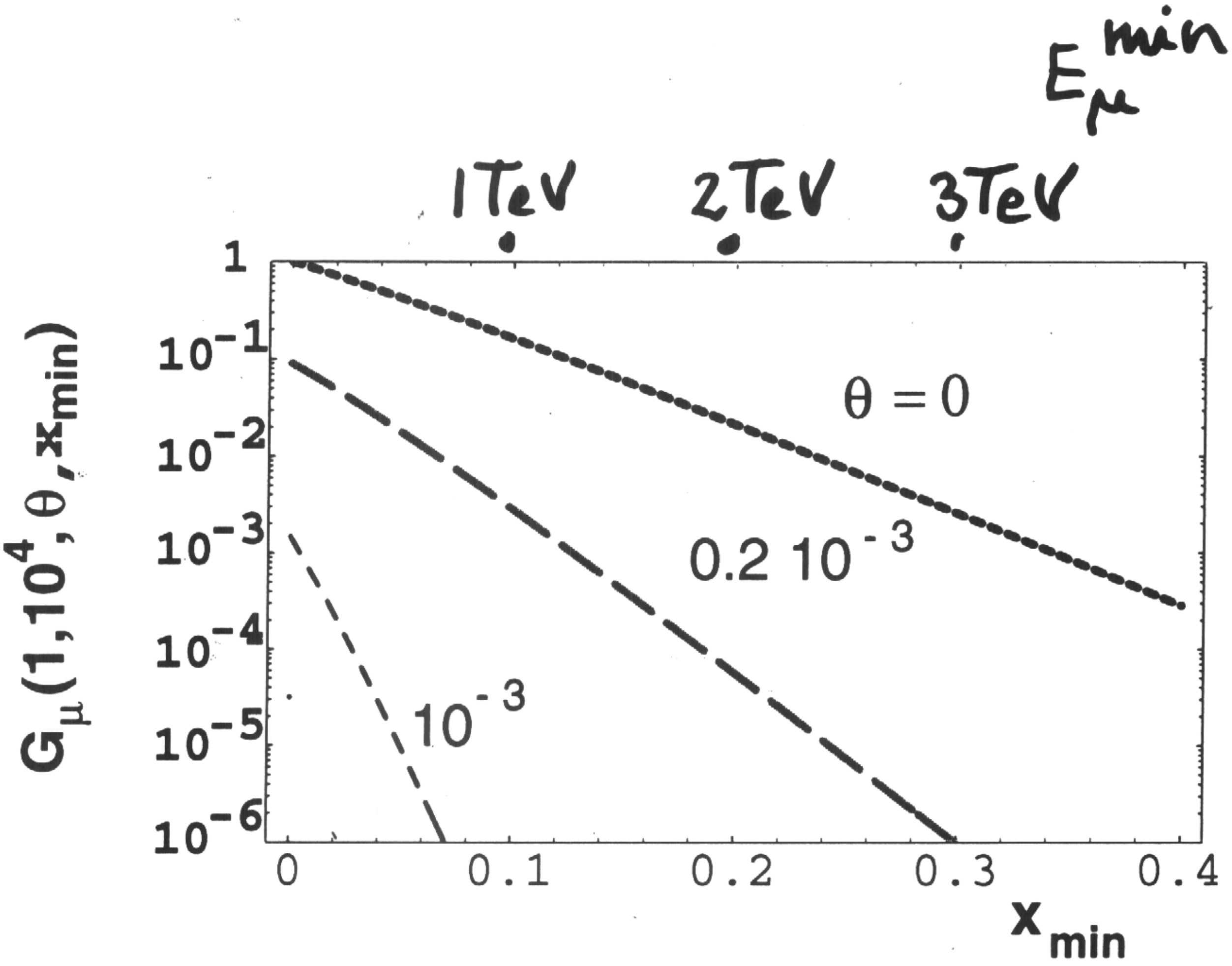
$$\frac{dF^T_\mu[x^\mu_{min},\theta]}{d\Omega} \sim \frac{dF^T_\mu[0,0]}{d\Omega}\, G_\mu(z,\gamma_{in},\theta,x^\mu_{min})$$

$$x^\mu_{min} \equiv \frac{E^\mu_{min}}{m_p\,\gamma_{in}}$$

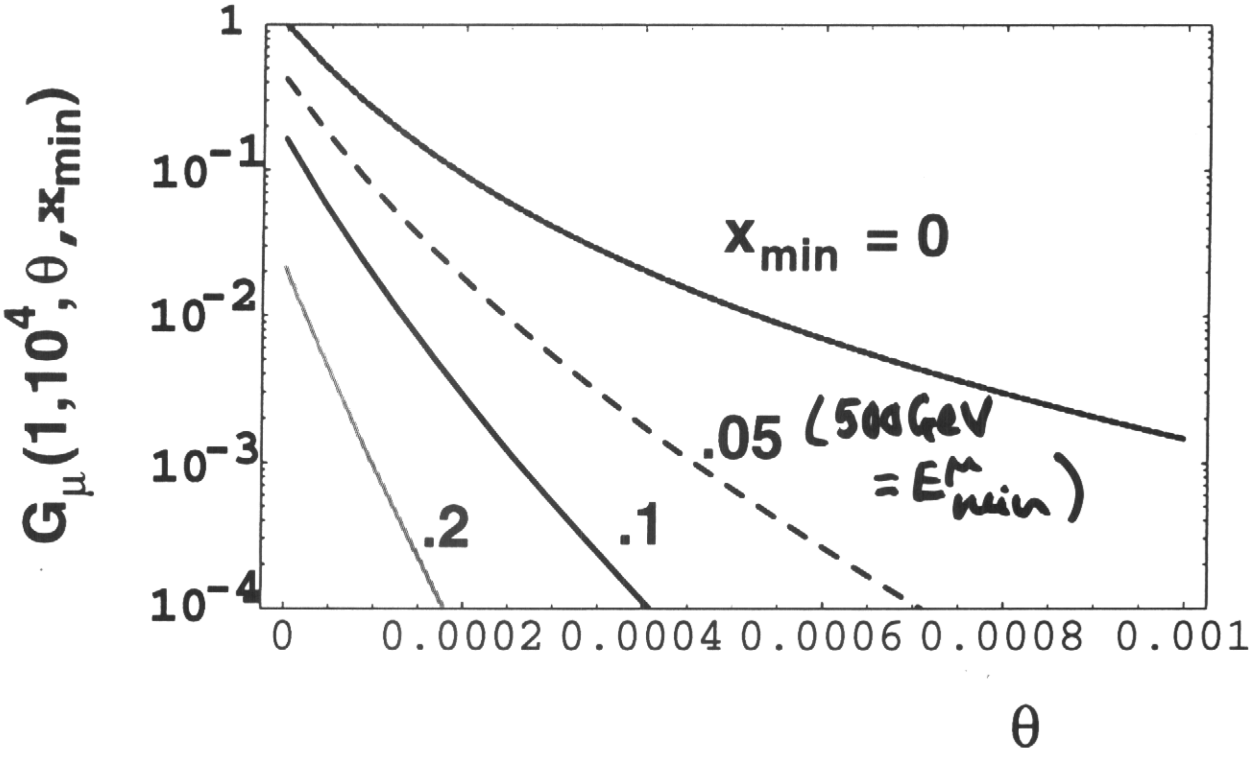
$$\frac{dF^T_\mu[0,0]}{d\Omega} \simeq \frac{1.2\times 10^4}{km^2}$$

$$\times$$

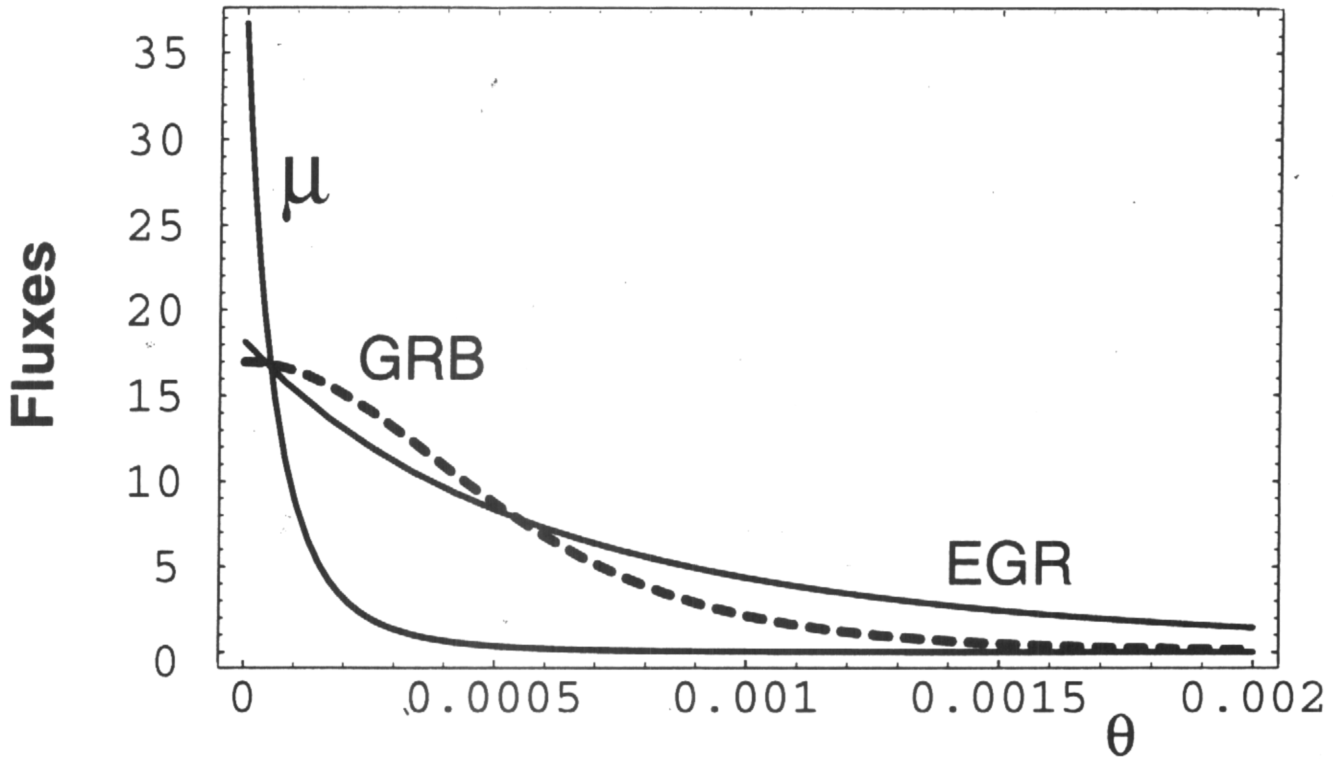
$$\frac{E_{CB}}{10^{52}\,erg}\left[\frac{\gamma_{in}}{3\,10^3}\right]^3\left[\frac{D_L(1)}{D_L(z)}\right]^2$$

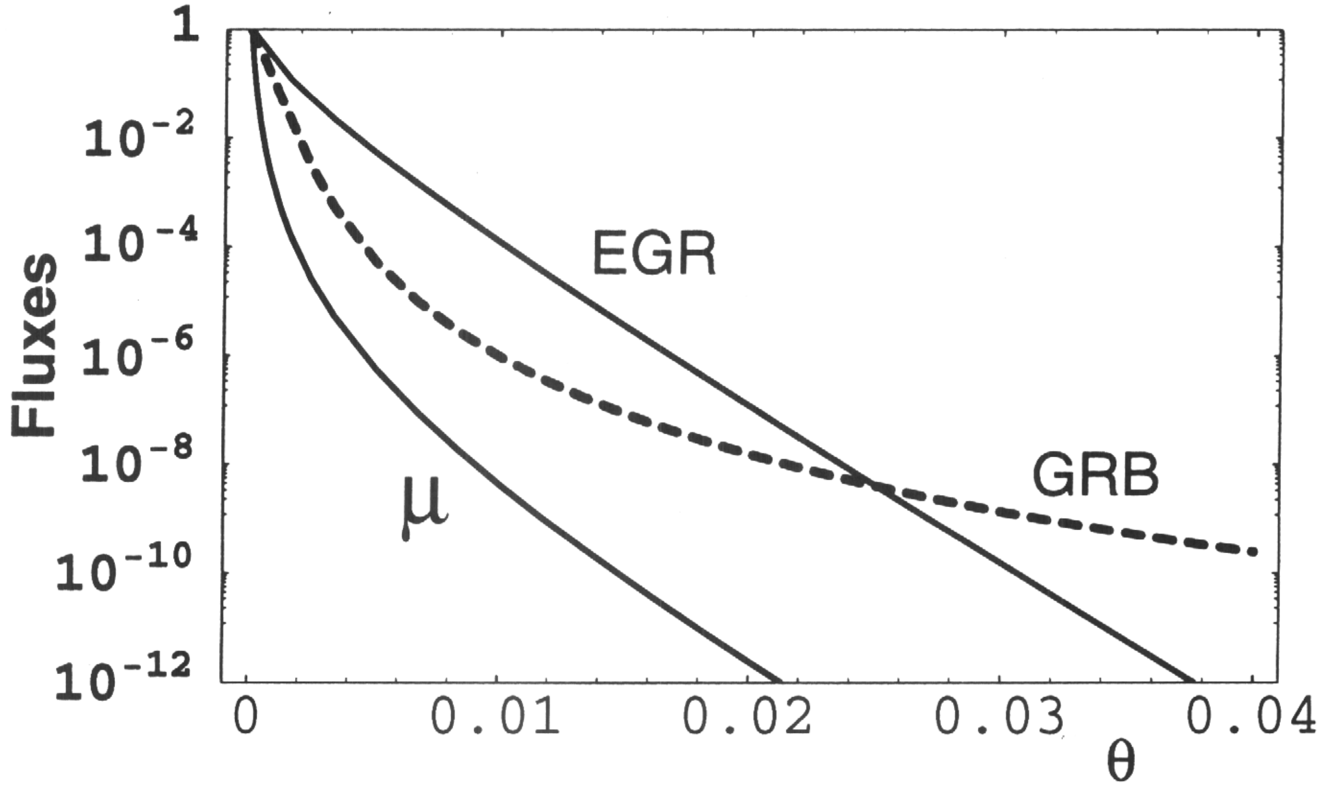


E_μ^{min}
1TeV
2TeV
3TeV
$G_\mu(1,10^4,\theta,x_{min})$
$\theta = 0$
$0.2\ 10^{-3}$
10^{-3}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
0.1
0.2
0.3
0.4
x_{min}



$G_\mu(1,10^4,\theta,x_{min})$
$x_{min} = 0$
.05 (500GeV $= E^\mu_{min}$)
.1
.2
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.0002
0.0004
0.0006
0.0008
0.001
θ





$\gamma_{in} = 10^4$ $E_\gamma^{min} = 50\,GeV$

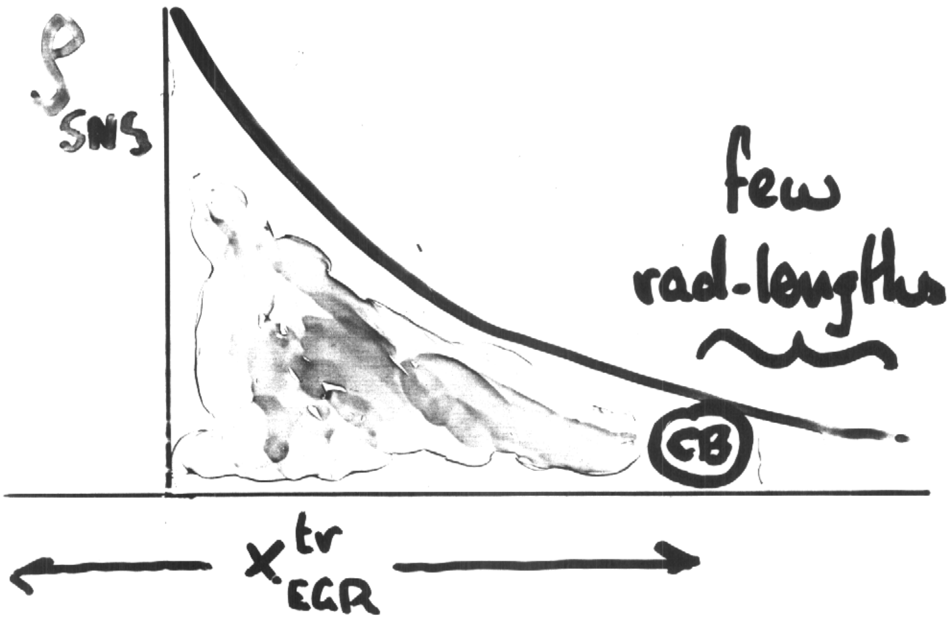
$\gamma_{out} = 10^3$ $E_\mu^{min} = 50\,GeV$

GRB : few(100) MeV γ's

EGR : ~ few(10) GeV γ's

HIGH ENERGY GAMMA RAYS

$$pN \rightarrow \pi^0 (\rightarrow \gamma\gamma) + \dots$$



$\gamma_{CB} \sim \gamma_{out}$

OF SNS NUCLEONS MAKING EGR WHICH GET OUT OF SNS N_p

$X_{EGR} \simeq 70 gr/cm^2$ (ABSORPTION LGTH)

$$N_p \simeq \pi \left[R_{CB}(x^{ECR}_{tr}) \right]^2 \frac{X_{EGR}}{m_p}$$

$$\approx 10^{49} \ll N_B \sim 10^{51}$$

OBSERVED γ FLUX

(per CB)

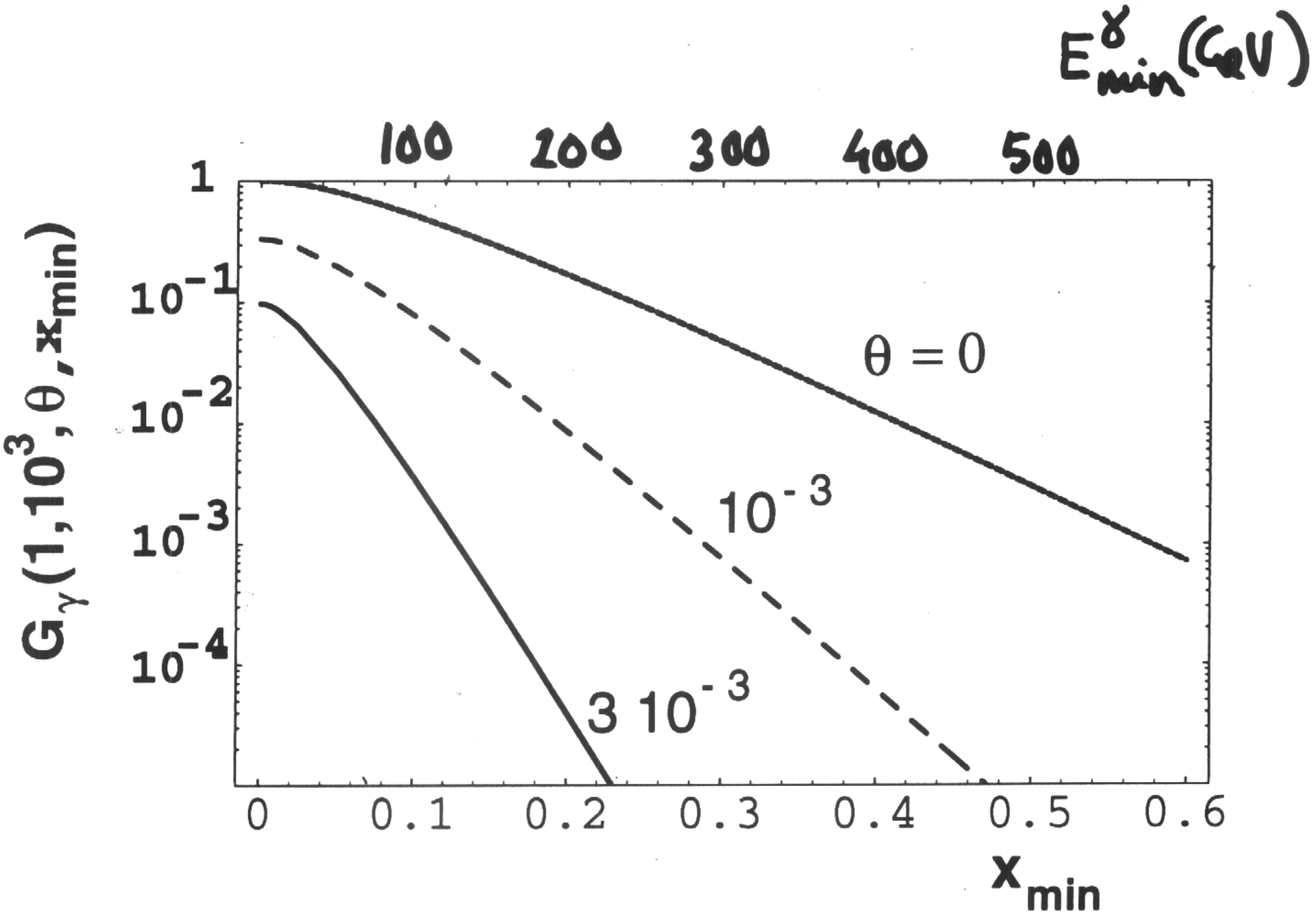
$$\frac{dF_\gamma^T[x_{min},\theta]}{d\Omega} \sim \frac{dF_\gamma^T[0,0]}{d\Omega}\, G_\gamma(z,\gamma_{out},\theta,x^\gamma_{min})$$

$$x^\gamma_{min} \equiv \frac{E^\gamma_{min}}{m_p\,\gamma_{out}}$$

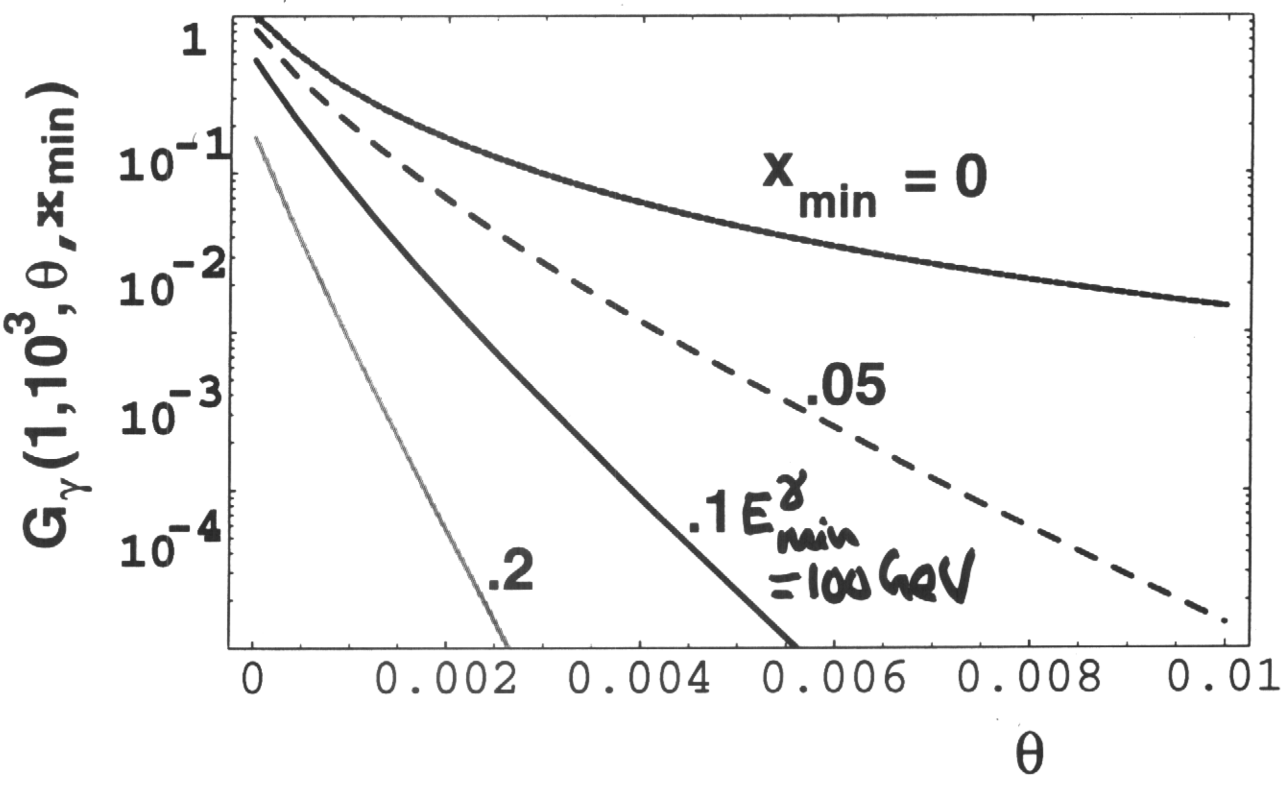
$$\frac{dF_\gamma^T[0,0]}{d\Omega} \simeq \frac{1.1\times 10^8}{km^2}$$

$$\times$$

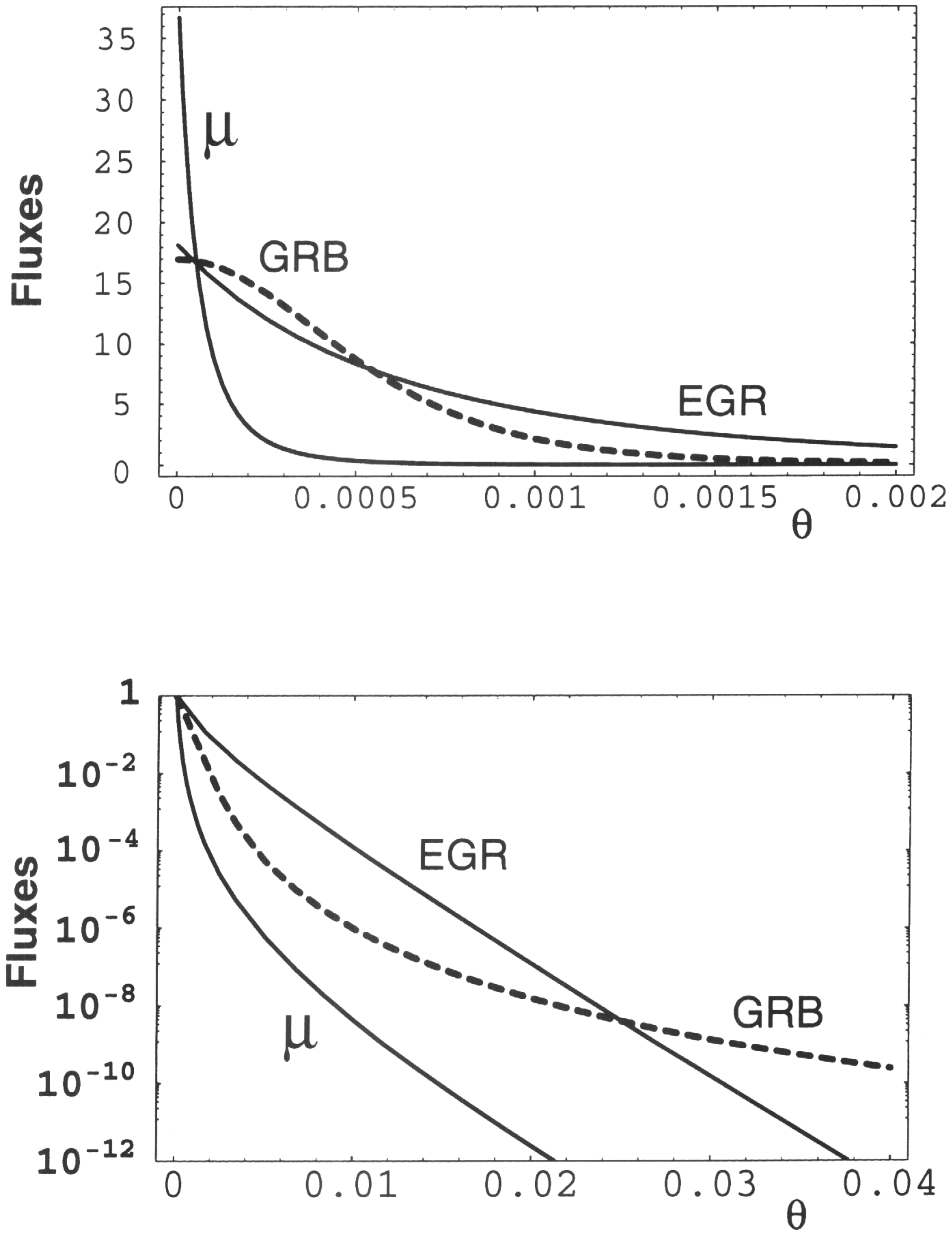
$$\frac{N_p}{1.4\;10^{49}}\left[\frac{\gamma_{out}}{10^3}\right]^2\left[\frac{1+z}{2}\right]^2\left[\frac{D_L(1)}{D_L(z)}\right]^2$$



E^{γ}_{min}(GeV)
100
200
300
400
500
$G_{\gamma}(1,10^3,\theta,x_{min})$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\theta = 0$
10^{-3}
$3\ 10^{-3}$
0
0.1
0.2
0.3
0.4
0.5
0.6
x_{min}



$G_{\gamma}(1,10^3,\theta,x_{min})$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$x_{min} = 0$
.05
.1 E^{γ}_{min} = 100 GeV
.2
0
0.002
0.004
0.006
0.008
0.01
θ


Fluxes
35
30
25
20
15
10
5
0
0
0.0005
0.001
0.0015
0.002
θ
μ
GRB
EGR
Fluxes
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
0
0.01
0.02
0.03
0.04
θ
EGR
GRB
μ

$$R \equiv \frac{\text{TOTAL ENERGY IN EGR}}{\text{TOTAL ENERGY IN GRB}}$$

$$\sim \frac{\left(X_\gamma[\sim 20\,\mathrm{GeV}]\right)^2}{X_\gamma(1\,\mathrm{MeV})} \frac{\sigma_T^2(\gamma e)}{m_p \sigma_{TOT}(pp)}$$

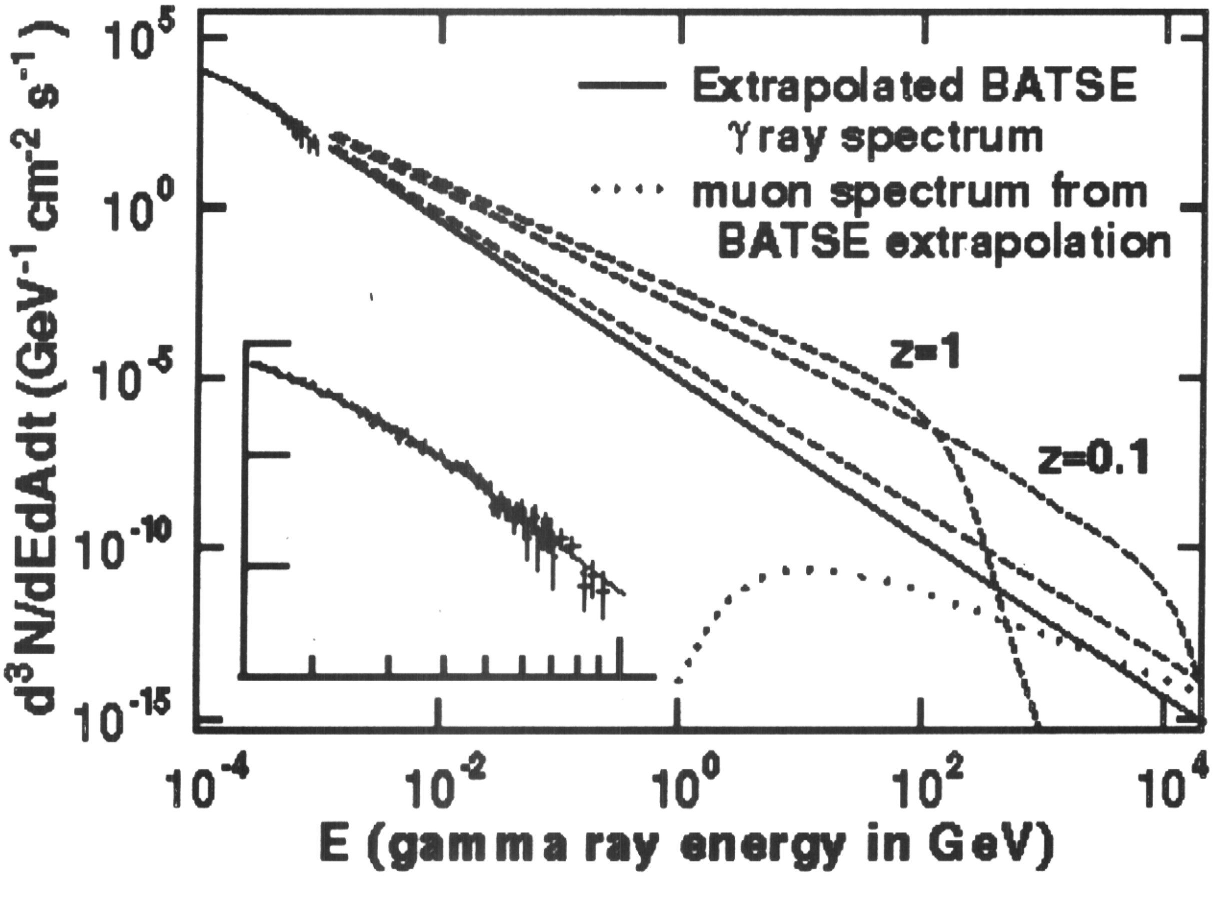
$$* \left[\frac{X_\gamma(1\,\mathrm{MeV})}{X_\gamma(\sim 20\,\mathrm{GaV})}\right]^{\frac{2}{n-1}}$$

$$\sim O(10^3)$$

GRAND

6 BATSE EVENTS NEAR ZENITH

GRB 971110 : HIGHEST GRAND ACCEPTANCE
HIGHEST GRB FLUX



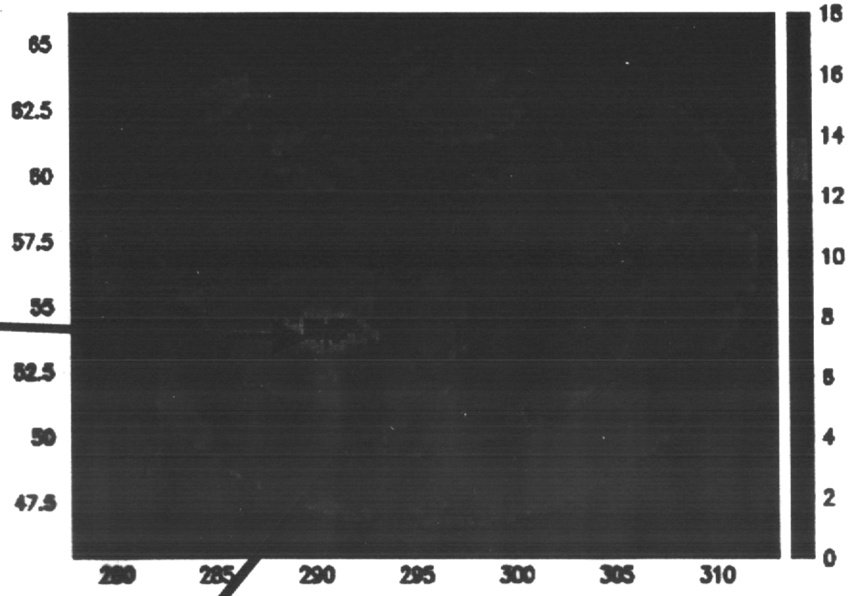
~ 3.2σ ABOVE BKGD
5 10^{-4} PROBABILITY IN 6 TRIALS

REQUIRES A LARGE NEW COMPONENT
WELL ABOVE GRB-FLUX EXTRAPOL.

Milagrito - GRB 970417a

- Searching 54 Batse bursts (T90)
- One burst 970417a showed 18 events w/background of 3.46
- This has a prob< 2.9×10^{-8}
- Accounting for all search trials – combined accidental chance 1/150
- This could mean TeV emission from GRBs

$10 - 10^4$ * GRB FLUENCE



Batse 1σ error circle

TESTS AND PREDICTIONS OF THE CB MODEL

γ-RAYS
- TOTAL FLUENCE ✓✓✓
- PULSE t-SHAPE ✓✓✓
- ENERGY SPECTRUM ✓✓
- E-t CORRELATION ✓(✓)

AFTER-GLOWS
- TEMPORAL EVOLUT. ✓✓✓
- SPECTRAL EVOL. WIP
- e-p RECOMB. FLARE ✓✓
- Ly-α RECOMB. LINE ✓✓
- SUPERLUM. MOTION ??

OTHER SIGNALS
- ν-BURST AT PULSES' ONSET ?
- $\pi^0 \to \gamma\gamma$ AT PULSES' ONSET ✓?

STATISTICAL SPECTRAL PROPERTIES
- VARIABILITY/LUMINOS. RELATION etc (PLAGA 2000) ★★

The GORDIAN KNOT of the GRB CONUNDRUM