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SCHOOL ON NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

VERY HIGH ENERGY NEUTRINOS AND GAMMA RAYS (2)

by

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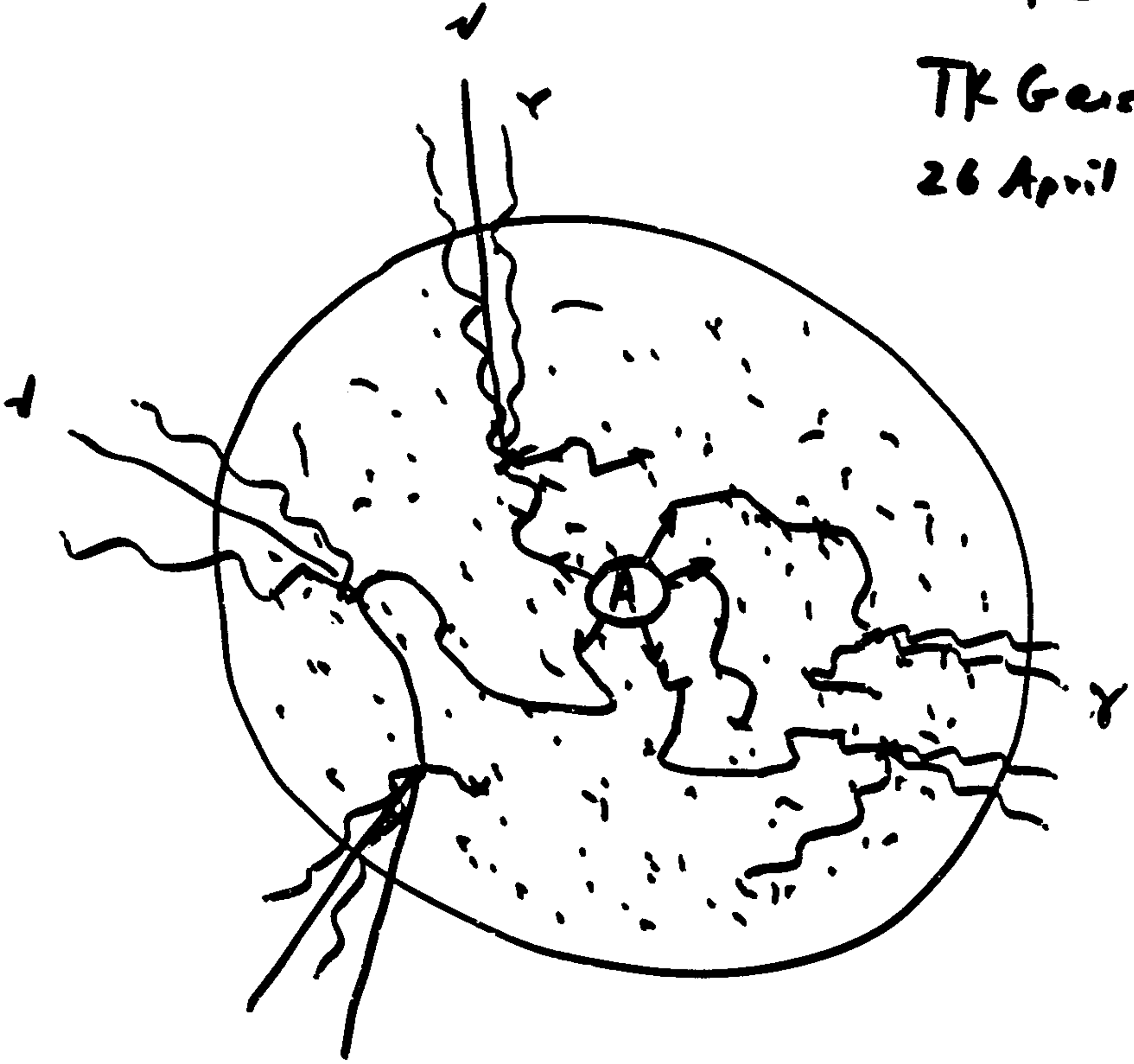
2. Astrophysical Beam Dumps

TK Gaisser
26 April '88



"generic" astrophysical

beam dump

e.g.
[Berezinsky, Castagnoli, Galeotti
N.C. 8C, 185 (1985).]

Flux of secondary ν, γ

from diffuse, [magnetized] astrophysical beam dump

$$(1) \quad \frac{dN_i}{dE_i} = \int \frac{dn_i(E_i, E_\pi)}{dE_i} \left[\int \frac{dn_\pi(E_\pi, E_p)}{dE_\pi} \frac{dN_p}{dE_p} dE_p \right] dE_1$$

$i = \nu$ or γ

(1) is for

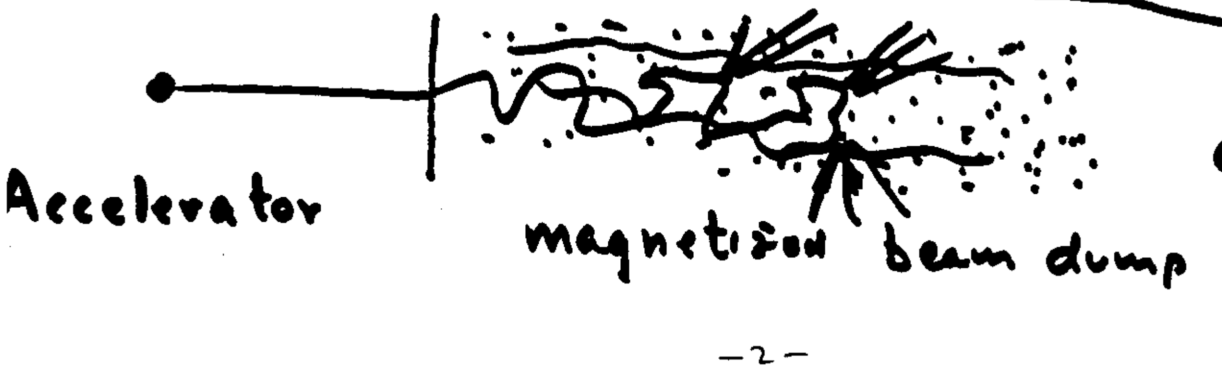
$$p + \text{gas} \longrightarrow \underset{\mu\nu}{\underset{\downarrow}{\pi^\pm}}, \quad \underset{\gamma\gamma}{\underset{\downarrow}{\pi^0}} + X$$

must add $\mu \to \nu$, $p \to K \to i$

All particles decay in this beam dump

Find $\frac{dN_p}{dE_p}$ given an accelerator beam

$$N_0(E_0) = K E_0^{-(\gamma+1)} \ \frac{\text{protons}}{\text{GeV} \cdot \text{s}}$$



t = accumulated path length

$$\frac{dN(E,t)}{dt} = -\frac{N(E,t)}{\lambda} + \frac{1}{\lambda}\int_E^\infty \frac{dn_N(E,E_0)}{dE} N(E_0,t)\, dE_0$$

Boundary condition: $N(E,0) = N_0(E) = K E^{-(\gamma+1)}$

Scaling: $E\frac{dn(E,E_0)}{dE} \longrightarrow F_{NN}\left(\frac{E}{E_0}\right)$

(only needed in forward fragmentation region)

Solution: $N(E,t) = N_0(E)\, e^{-t/\Lambda}$

$$\Lambda = \lambda\,(1 - Z_{NN})^{-1}$$

$x \equiv E/E_0$

$$Z_{NN} = \int_0^1 x^{\gamma-1} F_{NN}(x)\, dx$$

$\sim \frac{1}{\gamma+1}$ for flat nucleon spectrum

For $t \gg \Lambda$ total number of interactions

$$\sim \int_0^\infty \frac{dt}{\lambda} K E^{-(\gamma+1)} e^{-t/\Lambda} = \frac{\Lambda}{\lambda} N_0(E) = \frac{dN_p}{dE_p}$$

For thin target $\frac{\Lambda}{\lambda} \to \frac{\Delta t}{\lambda}$

If $E_\pi \frac{dn_\pi}{dE_\pi}(E_\pi, E_p) \longrightarrow F_{N\pi}\left(\frac{E_\pi}{E_p}\right)$

Then a similar change of variables

$$[\ ] \longrightarrow \frac{\Lambda}{\lambda} N_0(E_\pi) \int_{x_{min}}^{1} x^{\gamma-1} F_{N\pi}(x)\,dx$$

($X_{min} = \frac{E_\pi}{E_p(max)}$ is much more important here than for nucleon because $F_{N\pi}(x)$ is much more concentrated at small x)

If $X_{min} \ll 1$ and $\gamma > 1$ then

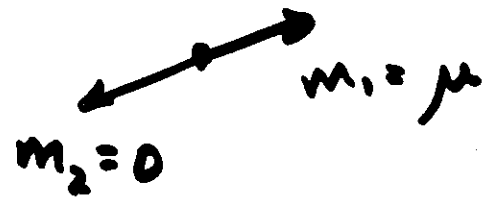
$$[\ ] \longrightarrow \frac{\Lambda}{\lambda} N_0(E_\pi)\, Z_{N\pi}\,, \quad Z_{N\pi} \equiv \int_0^1 x^{\gamma-1} F_{N\pi}\,dx$$

$$F_{N\pi}(x) \longrightarrow \frac{1}{\sigma_{inel}} \int d^2\vec{p}_T\, E_\pi \frac{d\sigma_{N\pi}}{d^3 p_\pi}$$

in c.m. forward fragmentation region

compute $\frac{dn_i}{dE_i}$ for 2-body decay of M:

($i = \nu$ or γ)



c.m. $p^* = \frac{M^2 - \mu^2}{2M} \cong 30$ MeV $\pi^\pm \to \mu^\pm \nu$

70 MeV $\pi^0 \to 2\gamma$

$\vdots$

$$E_i(\text{lab}) = \frac{E}{M}\left(p^* \cos\theta^* + E^*\right)$$

$$\frac{dn_i}{d\cos\theta^*} = \text{const} \Rightarrow \frac{dn_i}{dE_i(\text{lab})} = \text{const}$$

$$0 \le E_i \le \frac{2E}{M} p^* \begin{cases} \to 0.42\, E_\pi & (\pi \to \mu\nu) \\ \to E_\pi & (\pi^0 \to \gamma\gamma) \end{cases}$$

for i = massless

Note: $\langle E_{\nu_\mu} \rangle \sim 0.21\, E_\pi$, $\langle E_\mu \rangle \sim 0.79\, E_\pi$

in $\mu \to e\, \nu_e\, \nu_\mu$ $\quad E_\nu \sim \frac{1}{3} E_\mu$ so

$$\langle E_\nu \rangle_{\mu \to \nu} \sim \frac{.79}{3} E_\pi \sim \langle E_\nu \rangle_{\pi \to \nu}$$

put normalised distributions into (1)

$\underline{\pi^{\pm} \to \nu_\mu\ (\mu)}$ $\qquad\qquad$ $\underline{\pi^0 \to 2\gamma}$

$$\frac{dn_i}{dE_i} = \frac{m_\pi^2}{E_\pi (m_\pi^2 - \mu^2)} \qquad\qquad \frac{2}{E_\pi}$$

$$\frac{dN_i}{dE_i} = \int_{\frac{m_\pi E_i}{2p^*}}^{\infty} \frac{m_\pi^2}{m_\pi^2 - \mu^2} \frac{Z_{N\pi}}{E_\pi} \frac{\Lambda}{\lambda} K E_\pi^{-(\gamma+1)} \, dE_\pi$$

$\mu \to 0$ for $\pi^0 \to 2\gamma$

$\frac{m_\pi E_i}{2p^*} \to E_\gamma$ for $\pi^0 \to 2\gamma$

$\sim 2.3\, E_\nu$ for $\pi^{\pm} \to \nu\, \mu$

$$\frac{dN_i}{dE_i} \to \frac{\Lambda}{\lambda} Z_{N\pi} \frac{N_0(E_i)}{\gamma+1} \left(1 - \frac{\mu^2}{m_\pi^2}\right)^{\gamma}$$

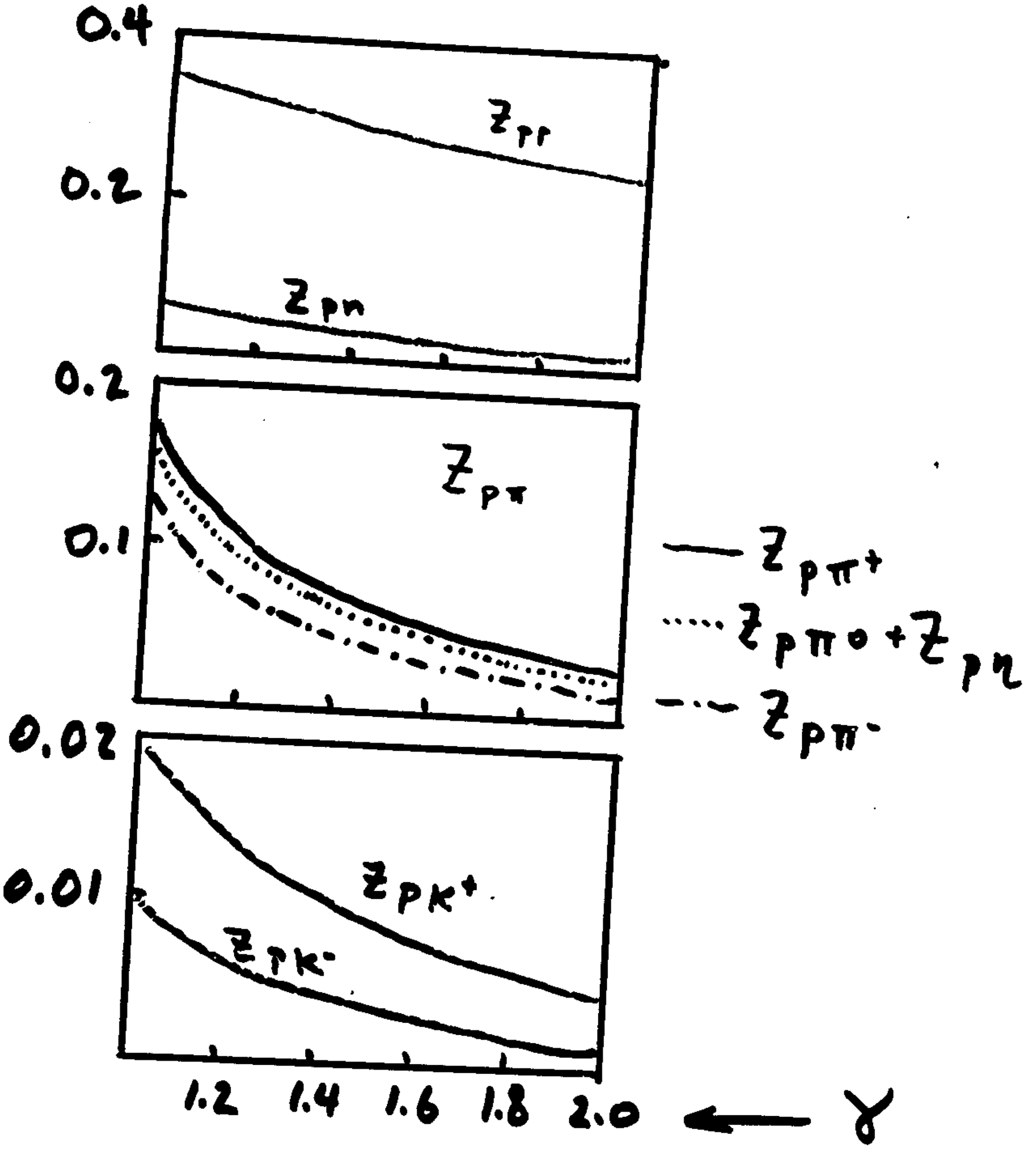
$\frac{\mu^2}{m_\pi^2}$: 0 for $\pi^0 \to 2\gamma$

$$\nu_\mu + \bar\nu_\mu \propto 2\,(Z_{N\pi^+} + Z_{N\pi^-}) \sim 4 Z_{p\pi^0}$$

2: because $E_{\nu(\mu)} \sim E_{\nu(\pi)}$

$$\gamma \propto 2 Z_{p\pi^0}$$ because 2γ per π^0

spectrum-weighted moments of inclusive cross sections ($E_{Lab} \sim TeV$)



momentum conservation $\Rightarrow$

$$\sum_{\text{all } i} Z_{pi}(\gamma=1) = 1$$

when all pions and muons decay

$$\frac{\nu_e+\bar{\nu}_e}{\nu_\mu+\bar{\nu}_\mu} \sim \frac{1}{2} \quad \text{and} \quad \frac{\nu_\mu+\bar{\nu}_\mu}{\gamma} \sim 2\left(1-\frac{\mu^2}{m_\pi^2}\right)^\gamma$$

Example: $L_p = 10^{40}\ \frac{\text{erg}}{\text{s}}$ at source

$$N_0(E) = K E^{-(\gamma+1)}, \quad 1 < E < 10^8\ \text{GeV.}$$

Normalization

$$K = 624 \times 10^{40}\ \frac{\text{GeV}}{\text{s}} \Big/ \int_1^\infty E^{-\gamma}\, dE$$

$\boxed{\text{for } \gamma > 1}$

$$\frac{dN_\gamma}{dE_\gamma} \sim 2\,\frac{\Lambda}{\lambda}\, Z_{N\pi^0}\, \frac{N_0(E_\gamma)}{\gamma+1}$$

$$F_\gamma(>E_\gamma)_{\text{Earth}} \sim 2\,\frac{Z_{N\pi^0}}{1-Z_{NN}}\,\frac{\gamma-1}{\gamma(\gamma+1)}\,\frac{6.24\times 10^{42}}{4\pi d^2} \times (E_\gamma)^{-\gamma}$$

d : distance to source $\cong$ 50 kpc for SN1987A

$\cong$ 10 kpc Cyg X-3

$10^{40}\ \frac{\text{erg}}{\text{s}}$ at 50 kpc

γ	$F_\gamma(>1000\ \text{GeV})$		$F_\gamma(>\text{GeV})$	
1.2	1.2×10^{-10}	1.3×10^{-10}	4.9×10^{-7}	7
1.4	3.3×10^{-11}	3.0×10^{-11}	5.2×10^{-7}	6.3
1.6	7.0×10^{-12}	5.9×10^{-12}	4.4×10^{-7}	5.0
1.8	1.4×10^{-12}	1.1×10^{-12}	3.5×10^{-7}	3.7
2.0	2.7×10^{-13}	2.1×10^{-13}	2.7×10^{-7}	2.7

analytic estimate

Full simulation

[T.K.G., Harding and Stanev, Nature 329, 314 (1987)]

Partial bibliography of related calculations

Berezinsky, Castagnoli, Galeotti, N.C. 8C, 185 (85)

T.K.G. & T. Stanev, PR D31 2770 (85)

" PRL 58, 1659 (87)

Auriemma, TKG & Lipari, submitted to N.C.

$\frac{\nu}{\gamma}$ ratio better than ν, γ separately.

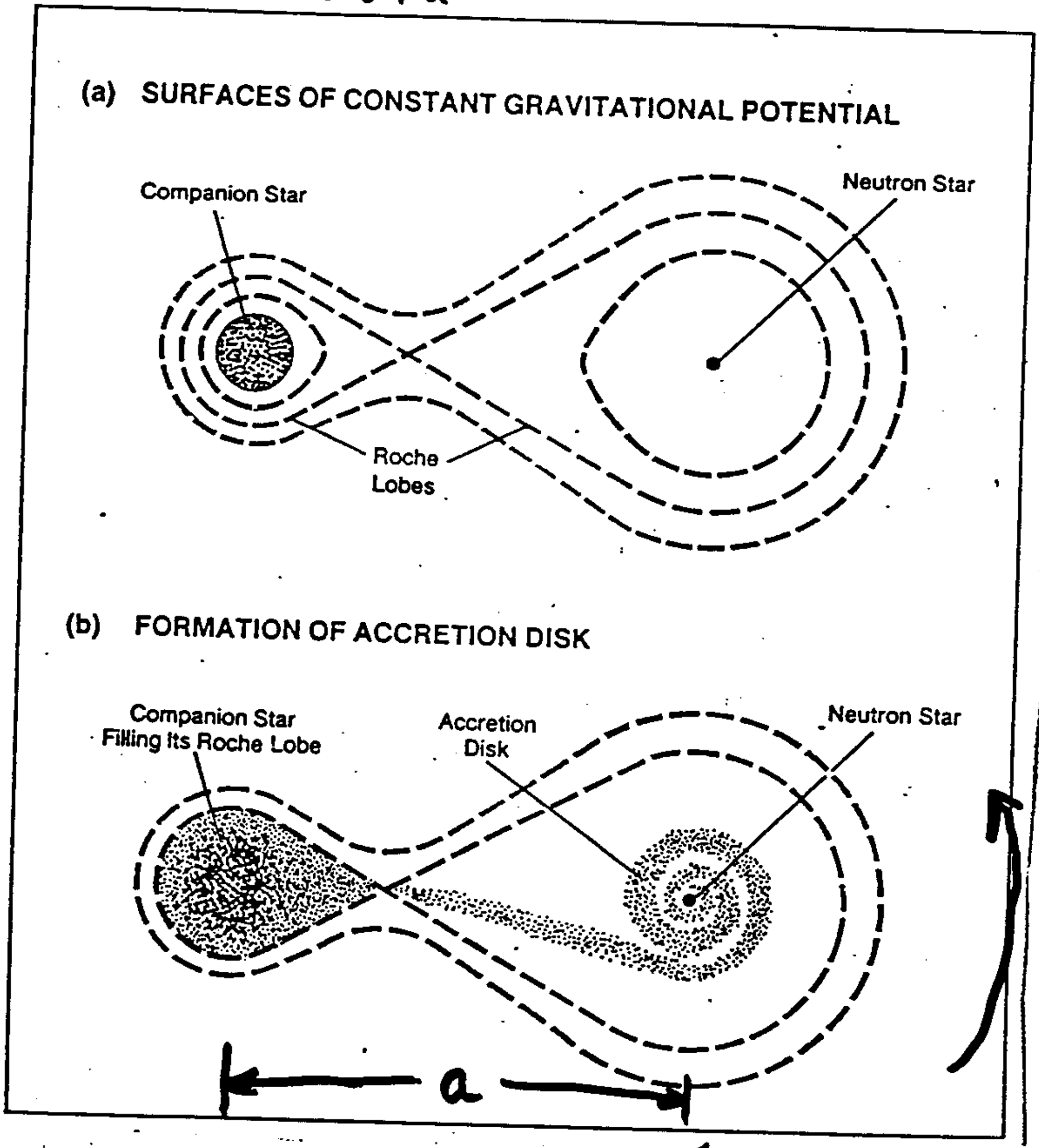
The kind of analysis described above IN PRINCIPLE allows us to predict ν flux given an observed photon flux from a source (provided the photons are from π^0 decay rather than radiation by electrons — probably true for $E_\gamma > 100$ TeV because of severe synchrotron losses by electrons)

Problem: reabsorption of photons

γ	$\frac{dN_\gamma}{dE_\gamma} / N_0(E_\gamma) \sim \frac{2}{\gamma+1} \frac{Z_{N\pi^0}}{1-Z_{NN}}$
1.0	.29
1.2	.13
1.4	.082
1.6	.054
1.8	.036
2.0	.025

These are upper bounds. For $E_\gamma > 100$ TeV E_{max} may be too low + more careful calculation is needed.

F. Cordova



what if some accretion energy also converted into high energy particles?

gravitational energy of accretion ⟹ X-ray production at n.s. surface neutron star parameters

$$M_* \cong 1.4\, M_\odot = 2.8 \times 10^{33}\ \text{g}$$

$$R_* \cong 10^6\ \text{cm}$$

$$\frac{G M_* m_p}{R_*} \sim 0.2\, m_p$$

emitted as thermal X-radiation

Eddington limiting luminosity
for spherical accretion

$$\frac{G M m_p}{R^2} \gtrsim \frac{L}{4\pi R^2 c}\, \sigma_{\text{Thomson}}$$

(Further accretion prevented from back pressure of radiation)

(Note cancellation of R here)

$$\boxed{L_E \sim 10^{38}\ \frac{\text{erg}}{\text{s}}\ \frac{M_*}{M_\odot}}$$

Accretion is not spherically symmetric, VHE γ's + all ν's have $\sigma \ll \sigma_T$, etc., yet $\lesssim 10^{38}$ $\frac{erg}{s}$ are commonly observed x-ray luminosities.

$$\dot{M}_{accretion} \sim 10^{18}\ g/s = 1.5 \times 10^{-8} \frac{M_\odot}{yr}$$

gives $L_{accretion} \sim L_E$

It would be noteworthy (but by no means impossible) to have $L_{particle} > L_{Eddington}$

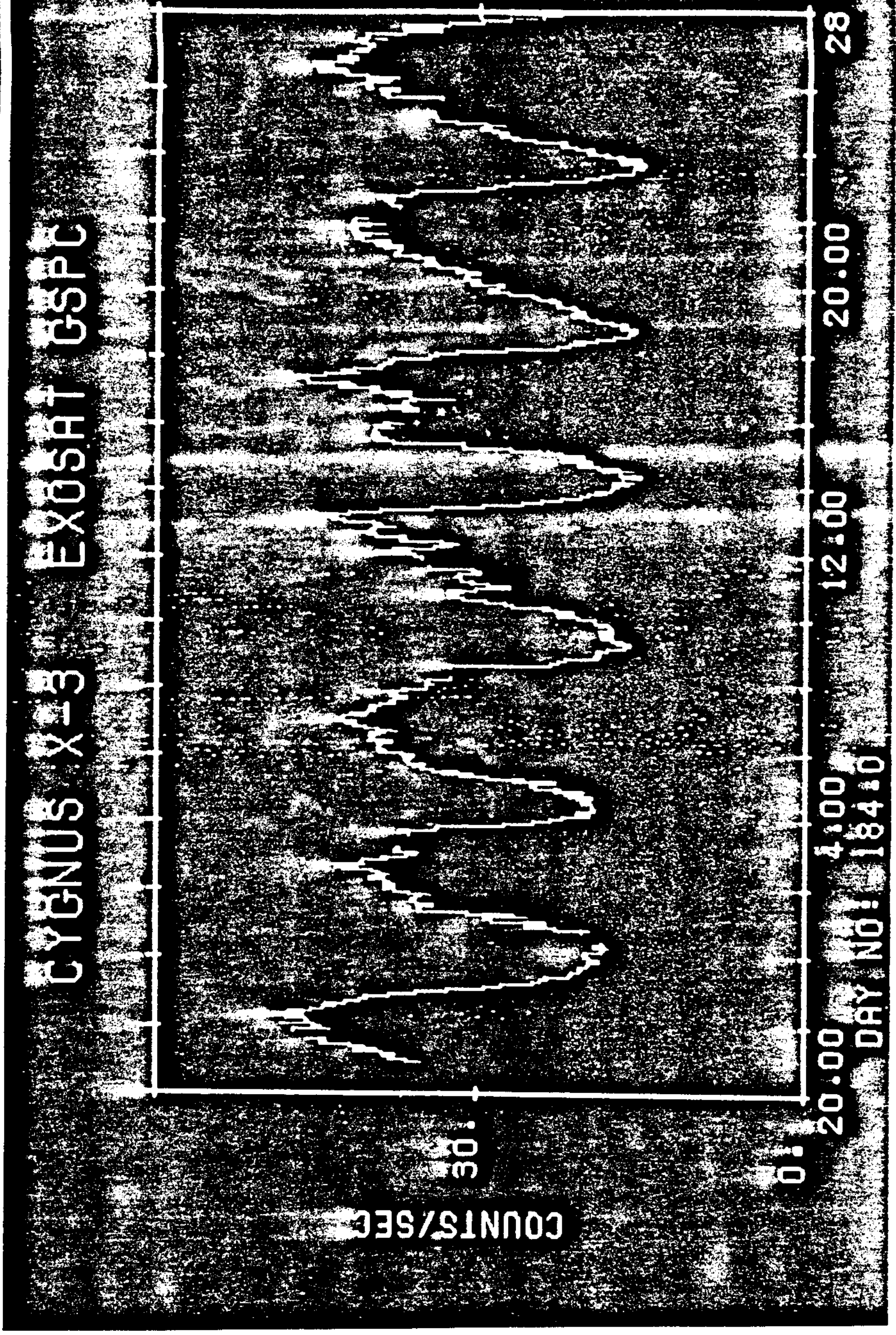
Period: $$P = 2\pi \sqrt{\frac{a^3}{G(M_* + M_2)}}$$

short period $\Rightarrow$ small separation

but M_2 must fit inside "Roche Lobe"

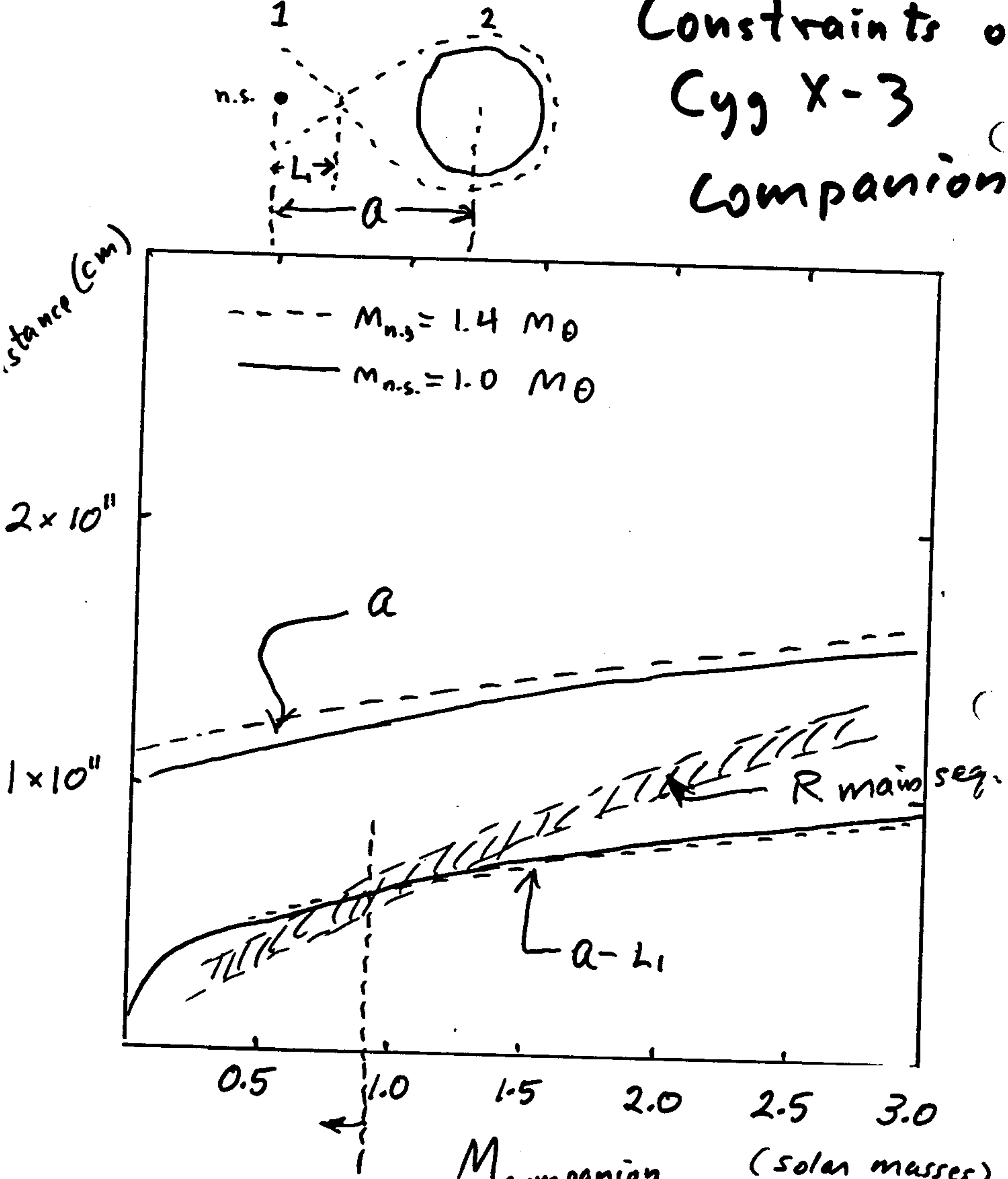
For accretion $R_2 \sim R_{Roche}$ $\Rightarrow$

$M_2 \lesssim M_\odot$ if P = hours; $M_2 \sim 10 M_\odot$, P = days



...ocated at the edge of our galaxy, Cygnus X-3 is a bright X-ray source which is ... have stimulated recent debate on

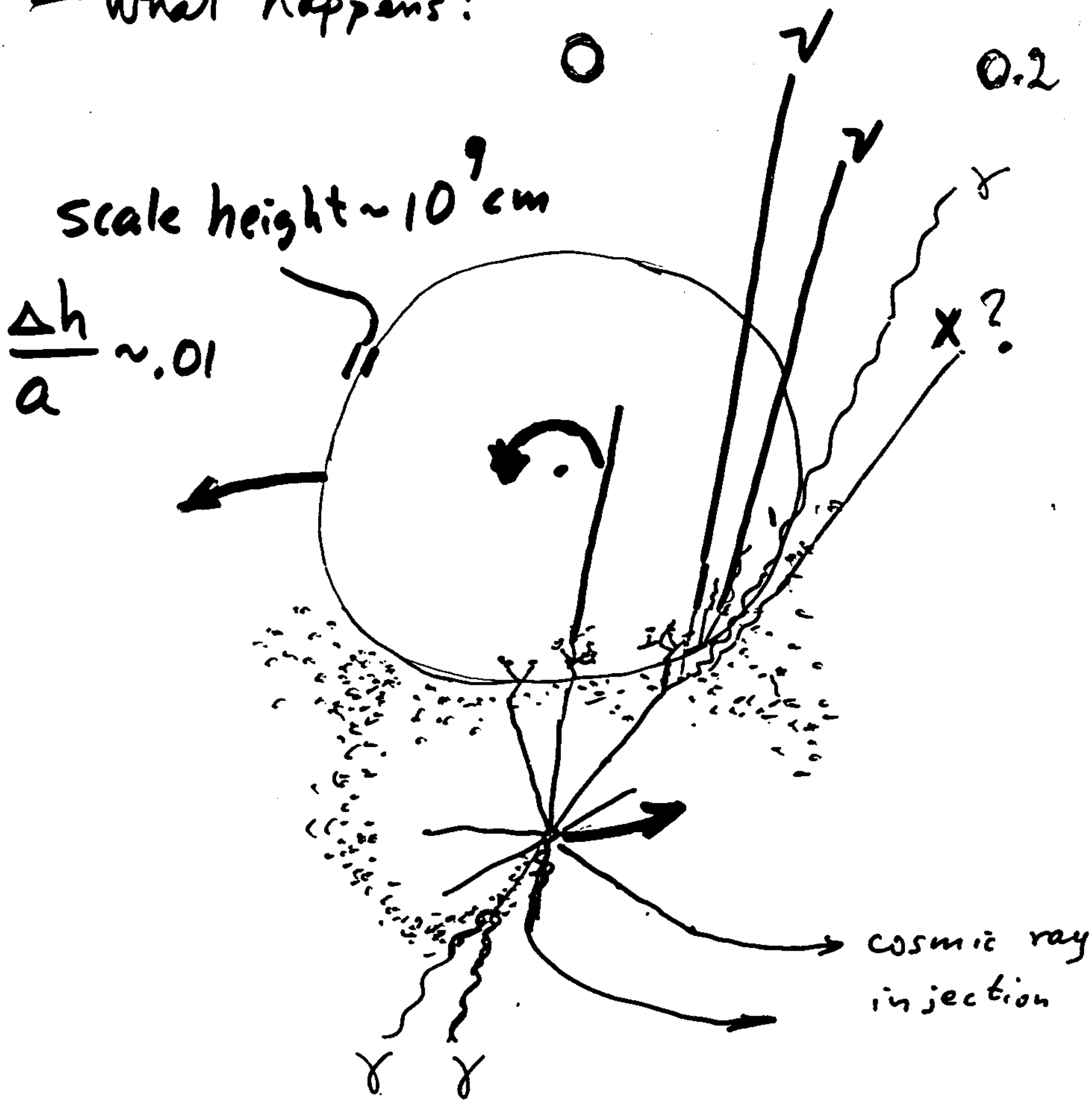
Constraints on Cyg X-3 Companion



a from $4.8 \text{ hours} = 2\pi\sqrt{\frac{a^3}{G(M_1+M_2)}}$

Powerful Accelerator in orbit around ~~star~~

— What happens?

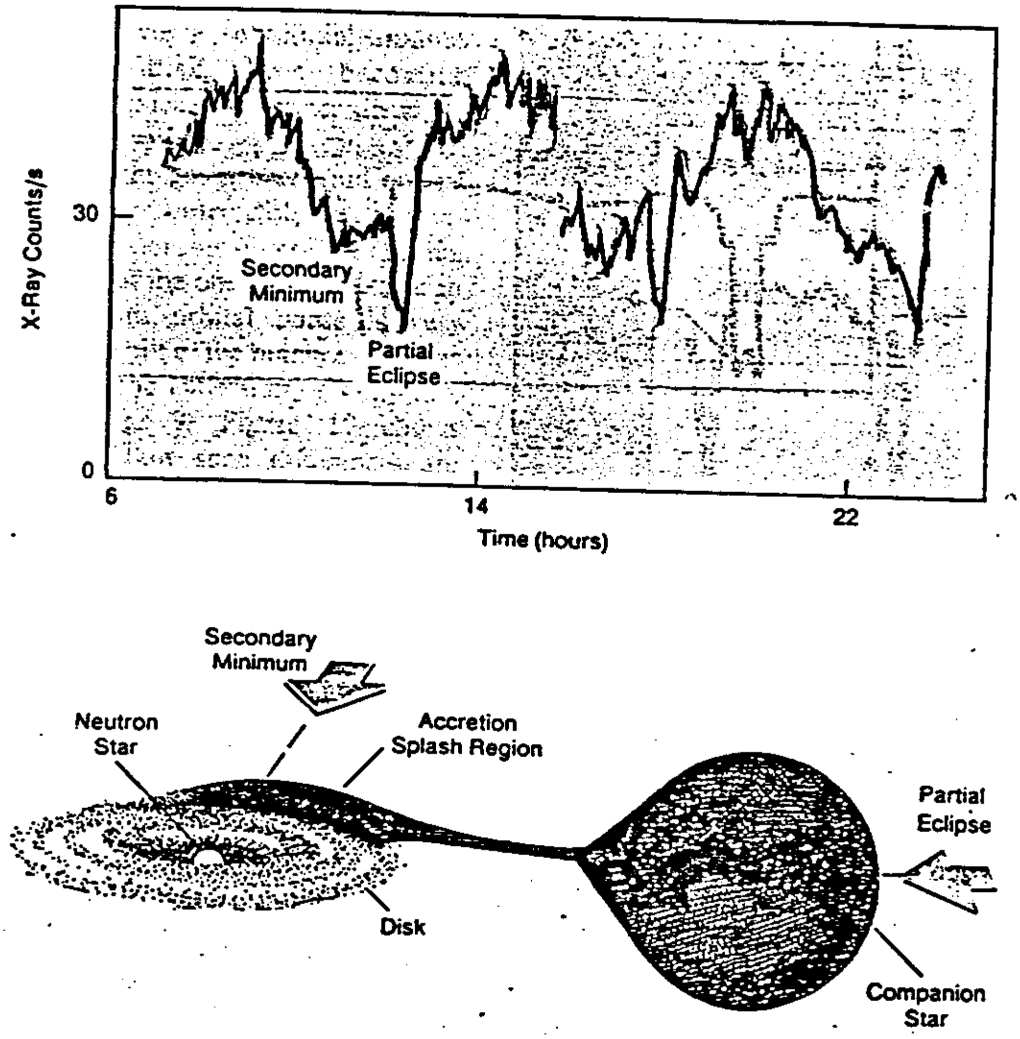


γ-production & escape is

<u>very</u> model-dependent

ν much less so

4U1822–37: A PARTIALLY ECLIPSING SOURCE



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R Epstein et al.

Accretion disk as target gives bigger duty factor

Require normalization of energy output at source:

$$L_{Cyg\,X\text{-}3} = \underbrace{\begin{pmatrix}\text{observed}\\ \text{flux}\\ \text{of EAs}\end{pmatrix}}_{\substack{\sim 10^{-10}\ \frac{\text{erg}}{\text{cm}^2\cdot\text{s}}\\ >10^{15}\text{eV}}} \underbrace{(4\pi R^2)}_{\gtrsim 10^{46}\,\text{cm}^2} \underbrace{\frac{1}{D_\gamma}}_{\substack{\text{Duty factor}\\ \text{for } \gamma\text{-production}\\ \lesssim .02\ (?)}} \underbrace{e^{R/\ell_\gamma}}_{\text{attenuation on } 3\,^\circ K\ \gamma\text{'s}} \frac{1}{\epsilon_\gamma} \overbrace{\boxed{\frac{\Delta\Omega}{4\pi}}}^{\text{beaming factor}}$$

$$\epsilon_\gamma = \frac{E(>10^{15}\text{eV})}{E_0} \cong 0.1$$

for $\Delta\Omega = 4\pi$

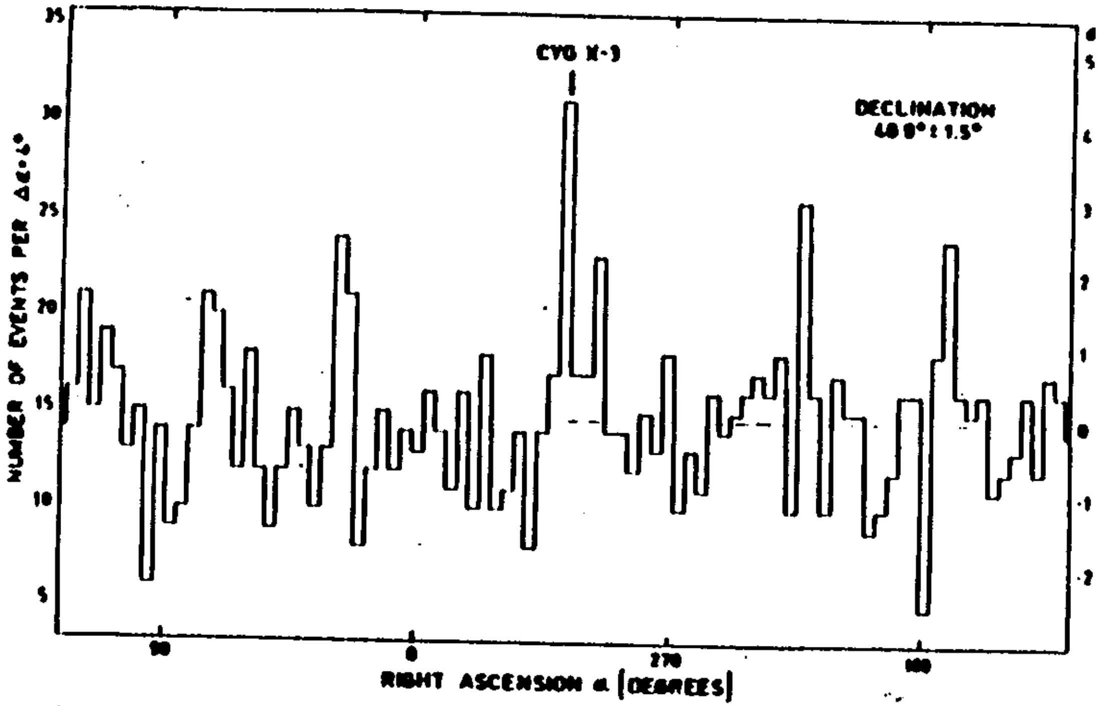
$L_{source} \gtrsim 10^{39}$ erg/sec — Hillas 1985

→ $\boxed{\text{ENERGY CRISIS!}}$

D_γ much more uncertain than D_ν because signal occurs only when $X \sim$ few radiation lengths

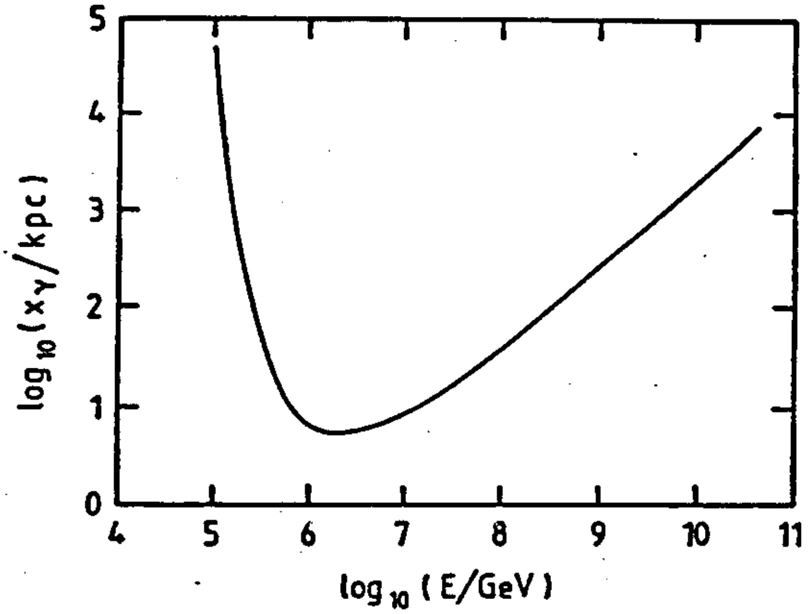
Complementary study of the neutrinos would be very helpful.

GAMMA-RAYS FROM CYG X-3



Number of detected extensive air showers of size $N_e \geq 10^5$ particles and age parameter $s \geq 1.1$ in the declination band 40°9 ± 1°5 as function of right ascension. The dashed line represents the average number of showers per bin over the total band.

R.J. Protheroe, Mon. Not. Roy. Ast. Soc. 221, 769 (1986)

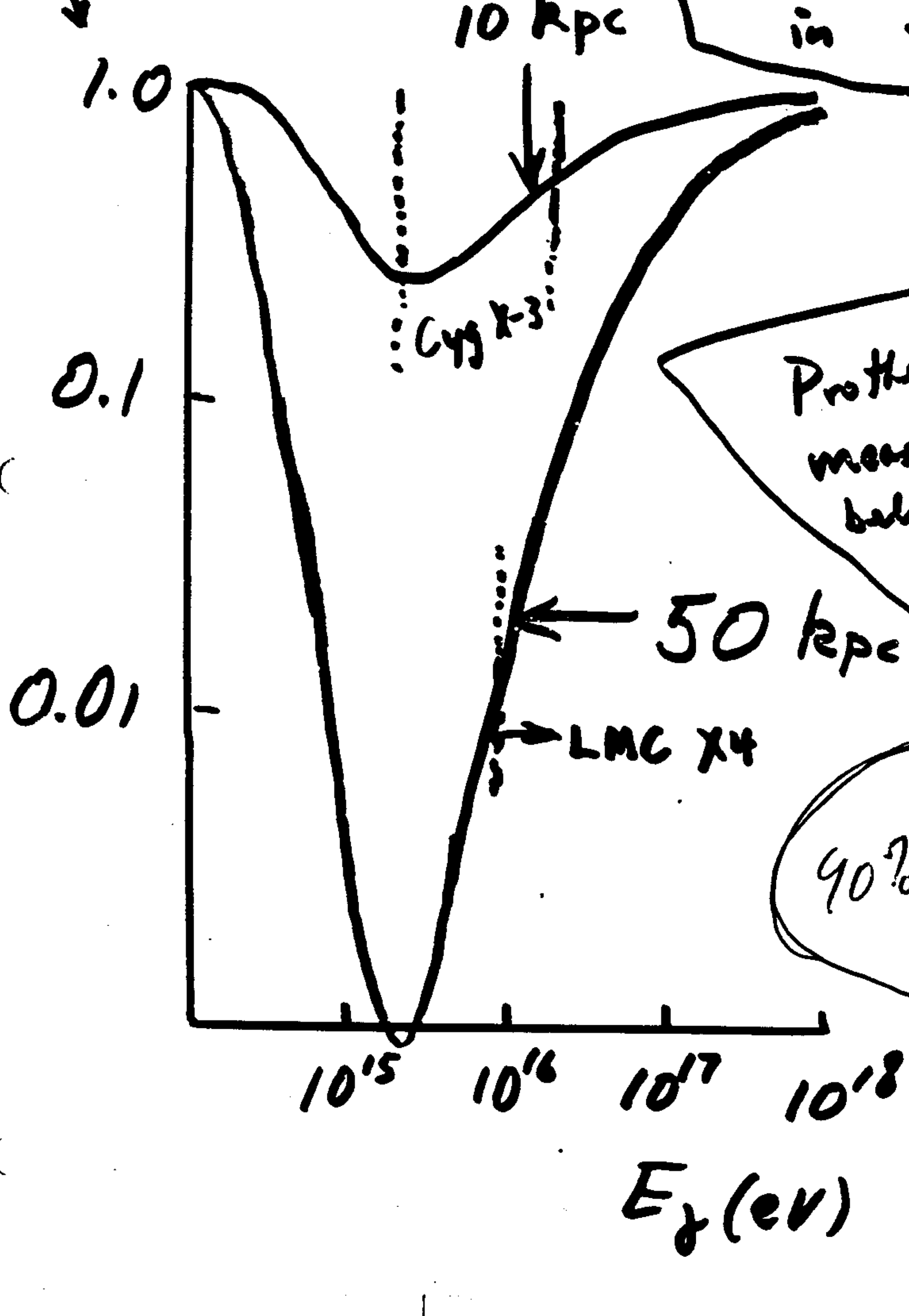


·e 2. The mean interaction length of photons for photon–photon interactions in the microwave background tion field, assumed to be blackbody at temperature 2.96 K.

$$\gamma + \gamma(3°) \rightarrow e^+ e^-$$

$$\sigma \propto \frac{\text{Threshold}}{s}$$

Transmission coefficient for $\gamma + \gamma_{2.7°} \to e^+e^-$



Cocconi: LMC X4 ~~should~~ might be ~20 x signal of Cyg X-3 in ν ($\sim 10^{-14}$* $\mathrm{cm^2}$ sec)

Protheroe: try to measure LMC X4 below 10^{16} eV and see dip

* note IMB 90% c.l. limit of $\lesssim 4 \times 10^{-14}$ $\mathrm{cm^{-2}s^{-1}}$

$\approx 20 \times$ Cyg X-3

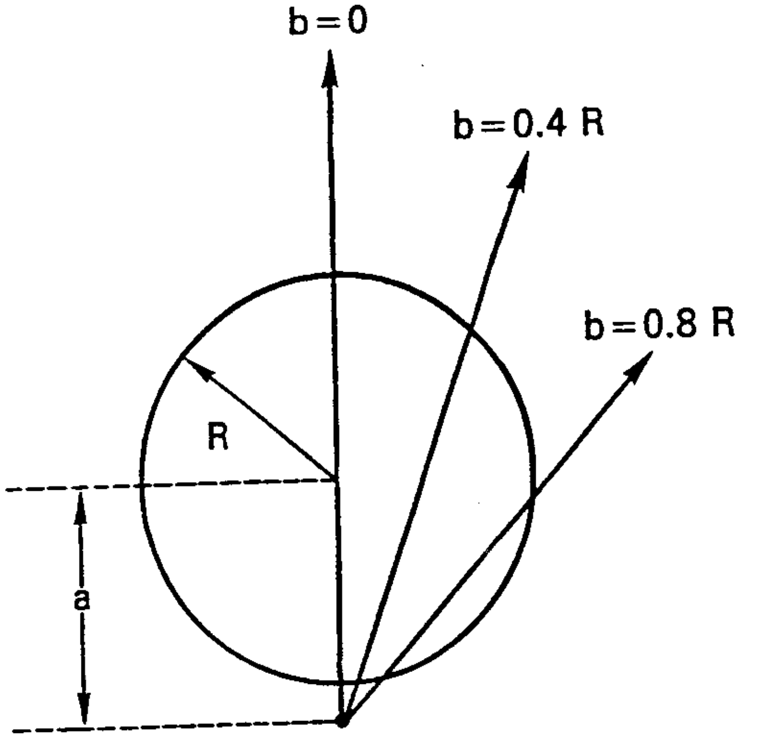


FIG. 2.—Geometry of the binary system with the compact object at a distance a from the center of the companion star of radius R, b being the impact parameter of the primary beam.

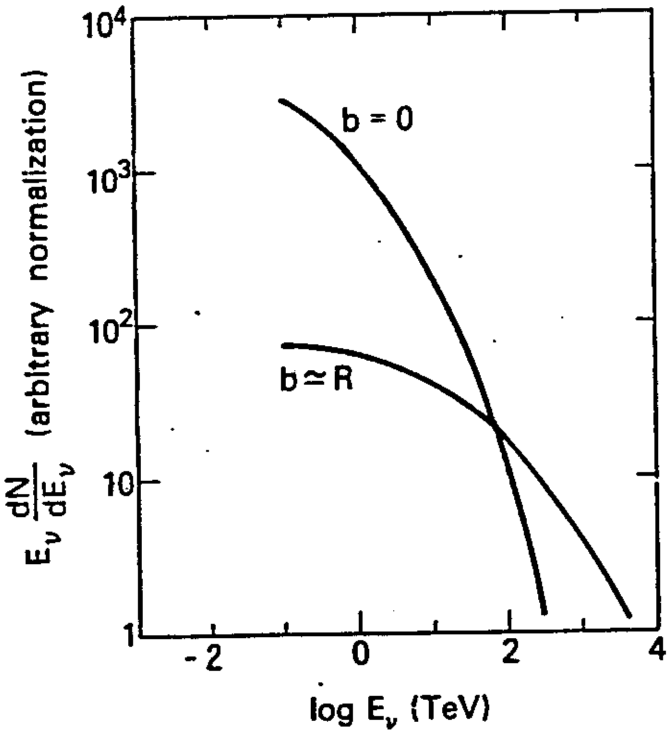


FIG. 3.—Neutrino spectrum at production, given a monoenergetic primary cosmic-ray spectrum of 10^{17} eV energy.

from TKG, Stecker, Harding & Barnard
Ap. J. 309, 674 (1986)

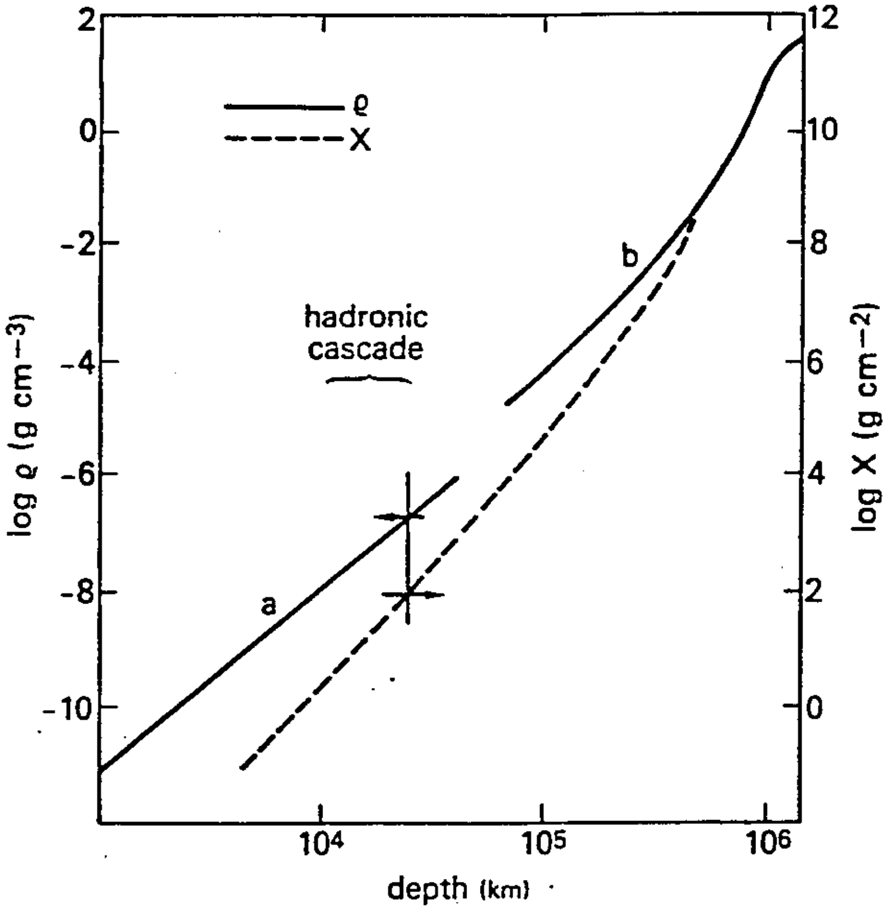


FIG. 1.—Density and grammage as a function of stellar depth for a 2.8 $M_{\odot}$ main-sequence star. Density curves (*a*) from stellar atmosphere model, (*b*) from stellar structure model.

$$l_\pi = \frac{\lambda_\pi}{\rho} = \frac{E_\pi}{m_\pi} c\tau \quad \text{gives}$$

$$E_\pi)_{critical} \sim \frac{m_\pi}{780\ cm} \times \frac{30 g/cm^2}{2\times10^{-7} g/cm^3} \sim 30\ TeV$$

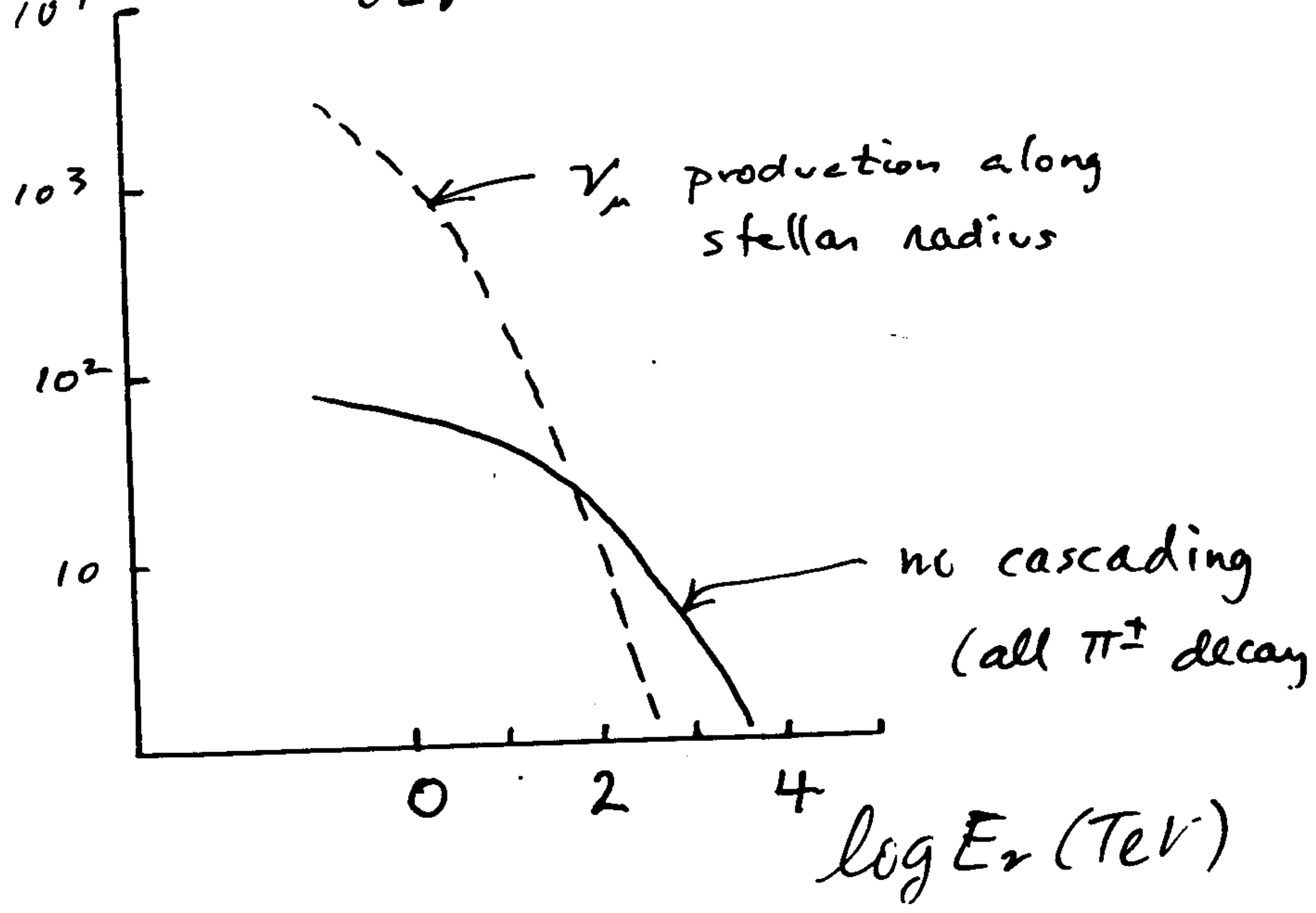
→ Outer part may be expanded making $E_{critical}$ larger

$E_\pi < E_{critical} \Rightarrow$ Decay

$E_\pi > E_{critical} \Rightarrow$ Interaction

Example: parent spectrum $\delta(E - 10^{17}$ eV

$E_\nu \frac{dN_\nu}{dE_\nu}$ (arbitrary normalization)

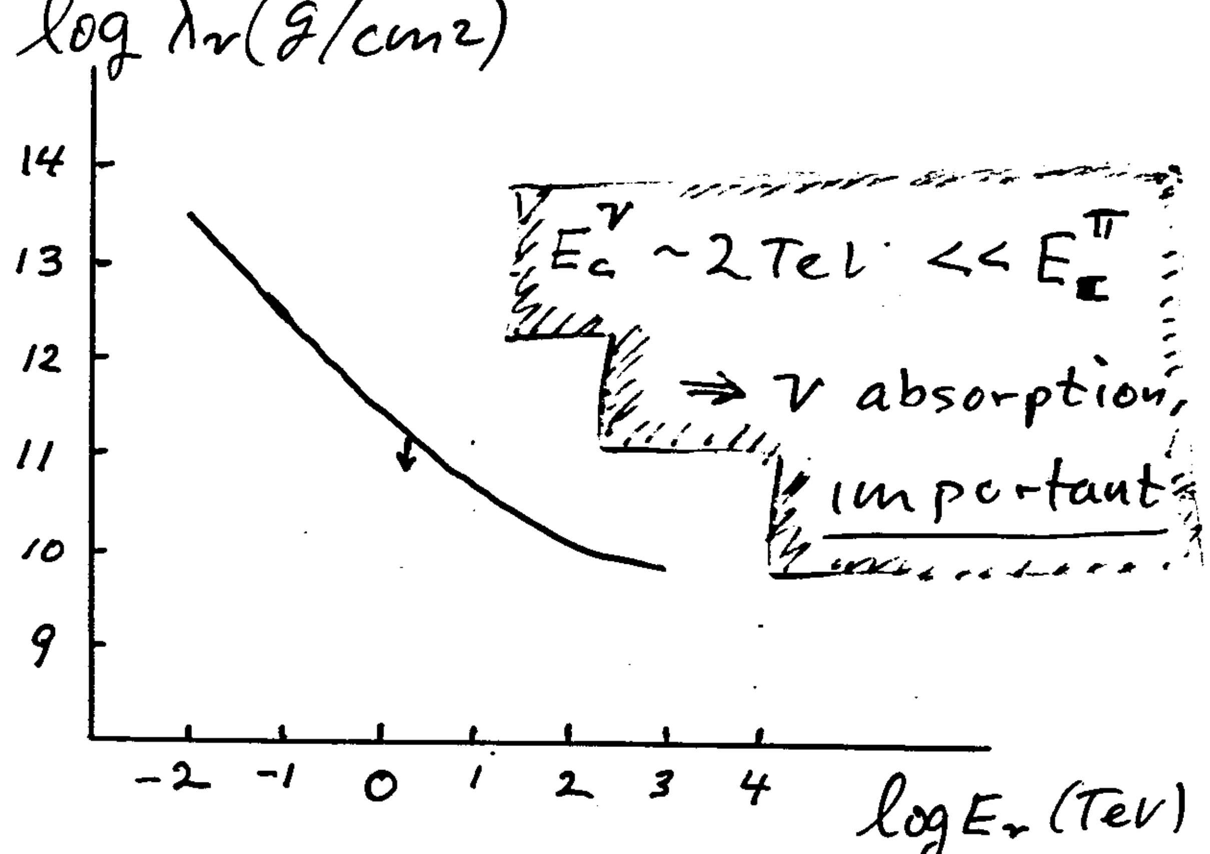


$$\lambda_\nu(E) = \frac{1}{N_A \sigma} \qquad \langle X \rangle = \frac{2M}{\pi R^2} \sim 2 \times 10^{11} \frac{g}{cm^2}$$

Absorption of ν important

for $\lambda_\nu(E) < \langle x \rangle$

$\lambda_\nu(E_c) = \langle x \rangle$ defines $E^\nu_{critical}$



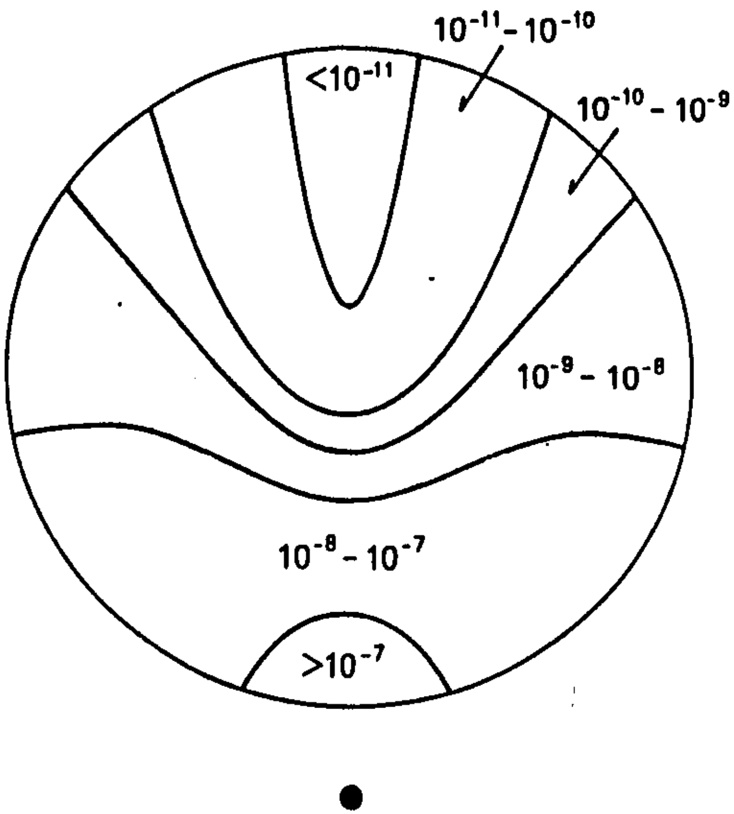


FIG. 5*a*

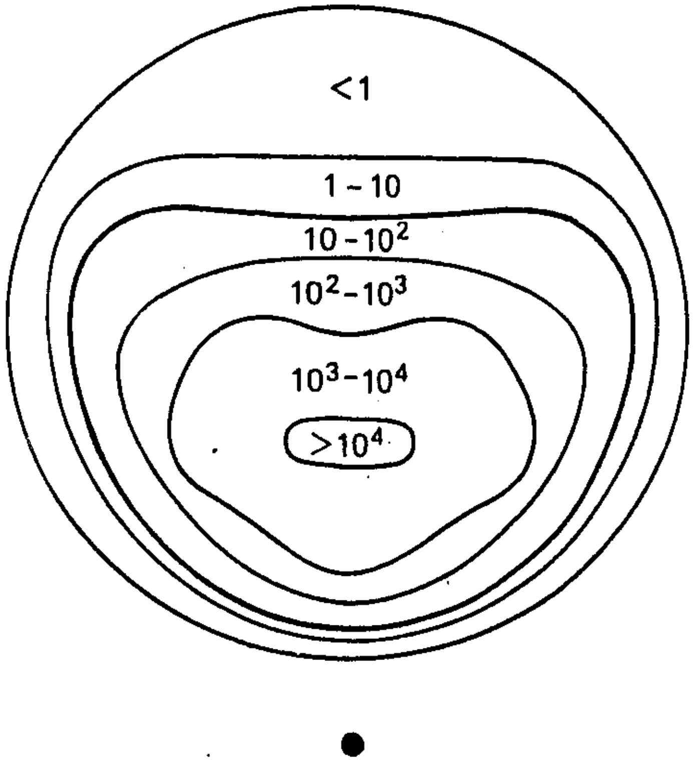


FIG. 5*b*

FIG. 5.—(*a*) Contour map of energy deposition per particle (eV per nucleon per second) for $M = 2.8\,M_\odot$, $a/R = 1.2$, and a $b = 0$ neutrino spectrum. The compact object is at the bottom of the figure. (*b*) Contour map of energy deposition per unit volume (ergs $cm^{-3}\,s^{-1}$) for $M = 2.8\,M_\odot$, $a/R = 1.2$, and the $b = 0$ neutrino spectrum.

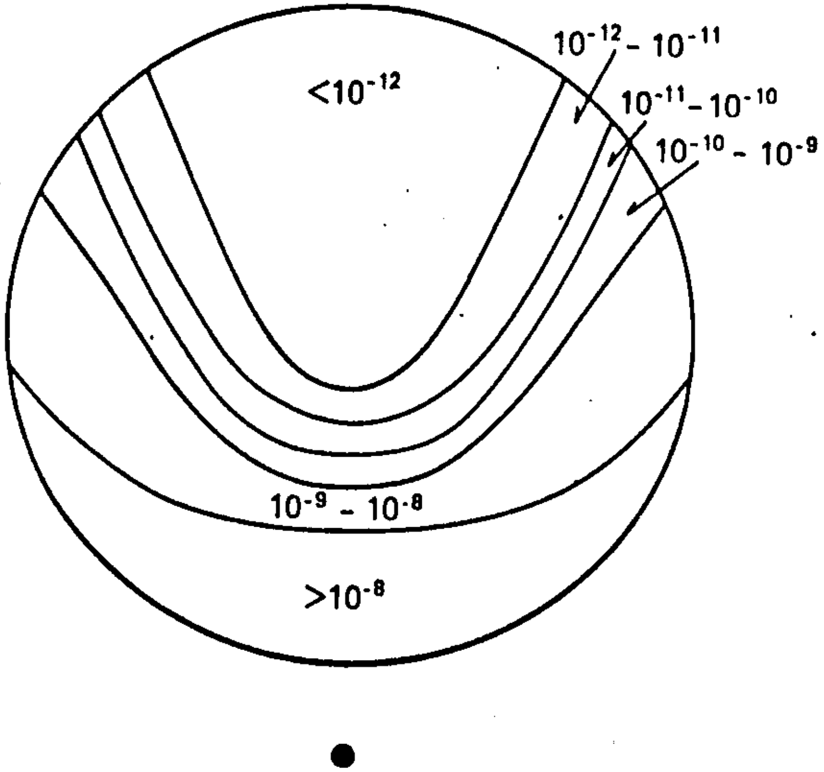


FIG. 6*a*

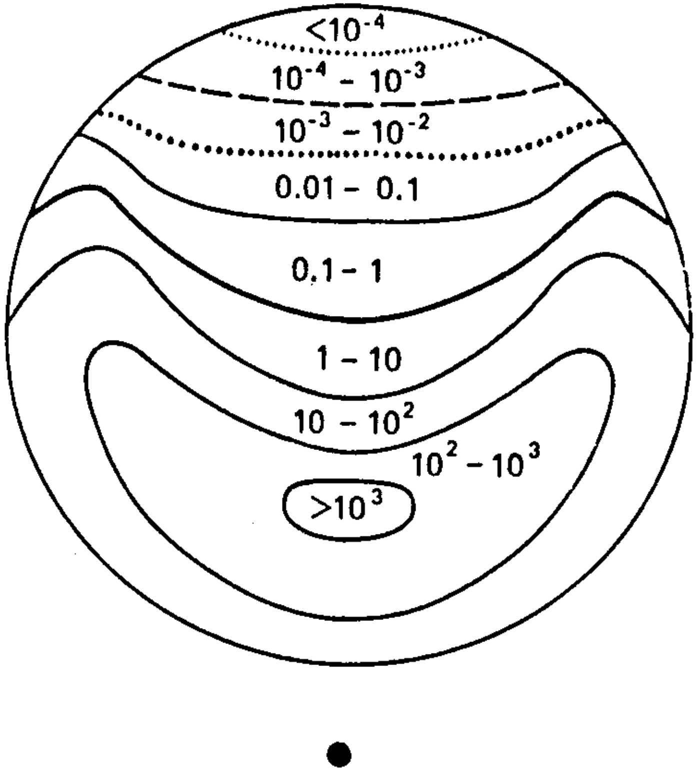


FIG. 6*b*

FIG. 6.—(*a*) Same as Fig. 5*a* for $M = 15\ M_{\odot}$, $a/R = 2$, and a $b \approx R$ spectrum. (*b*) Same as Fig. 5*b* for $M = 15\ M_{\odot}$, $a/R = 2$, and a $b \approx R$ spectrum.

Energy Crisis for Cyg X-3

$$\frac{G M_\odot^2}{R_\odot} \sim 4 \times 10^{48} \text{ ergs}$$

consider a companion with $M \gtrsim M_\odot$

$$P = 2\pi \sqrt{\frac{a^3}{G(M_{n.s.} + M_{companion})}} = 4.8 \text{ hr}$$

$$\Rightarrow a = 1.3 \times 10^{11} \text{ cm} \left(\frac{M_{n.s.} + M_{comp}}{2.4 \, M_\odot} \right)^{1/3}$$

$$\frac{\sigma_{companion}}{4\pi a^2} = .07 \left(\frac{R}{R_\odot} \right)^2 \sim .05$$

$$\frac{4 \times 10^{48}}{.05 \times 10^{39}} \sim 3000 \text{ yrs.}$$

$L_{CR} \propto \dot{M}$

→ Disaster

T.R.G., J. MacDonald, T.S.

$$4.8 \text{ hrs.} = P = 2\pi \sqrt{\frac{a^3}{G(M_{n.s.} + M_{companion})}}$$

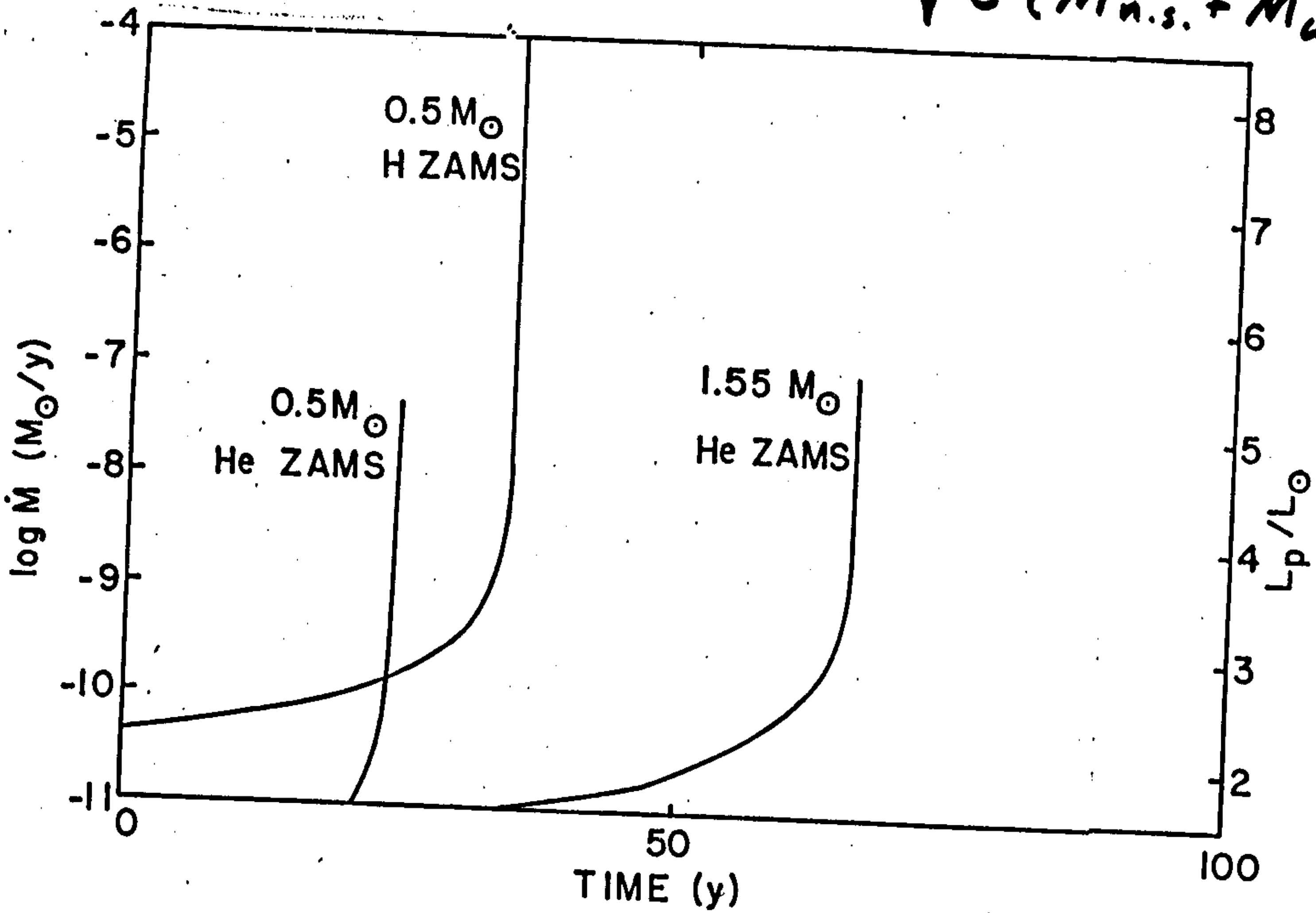


Figure 1

Summary

- spectrum of $\gamma + \nu$ from beam dump and ν/γ
- properties of X-ray binaries
- Required luminosity at Cyg X-3
- Energy crisis?